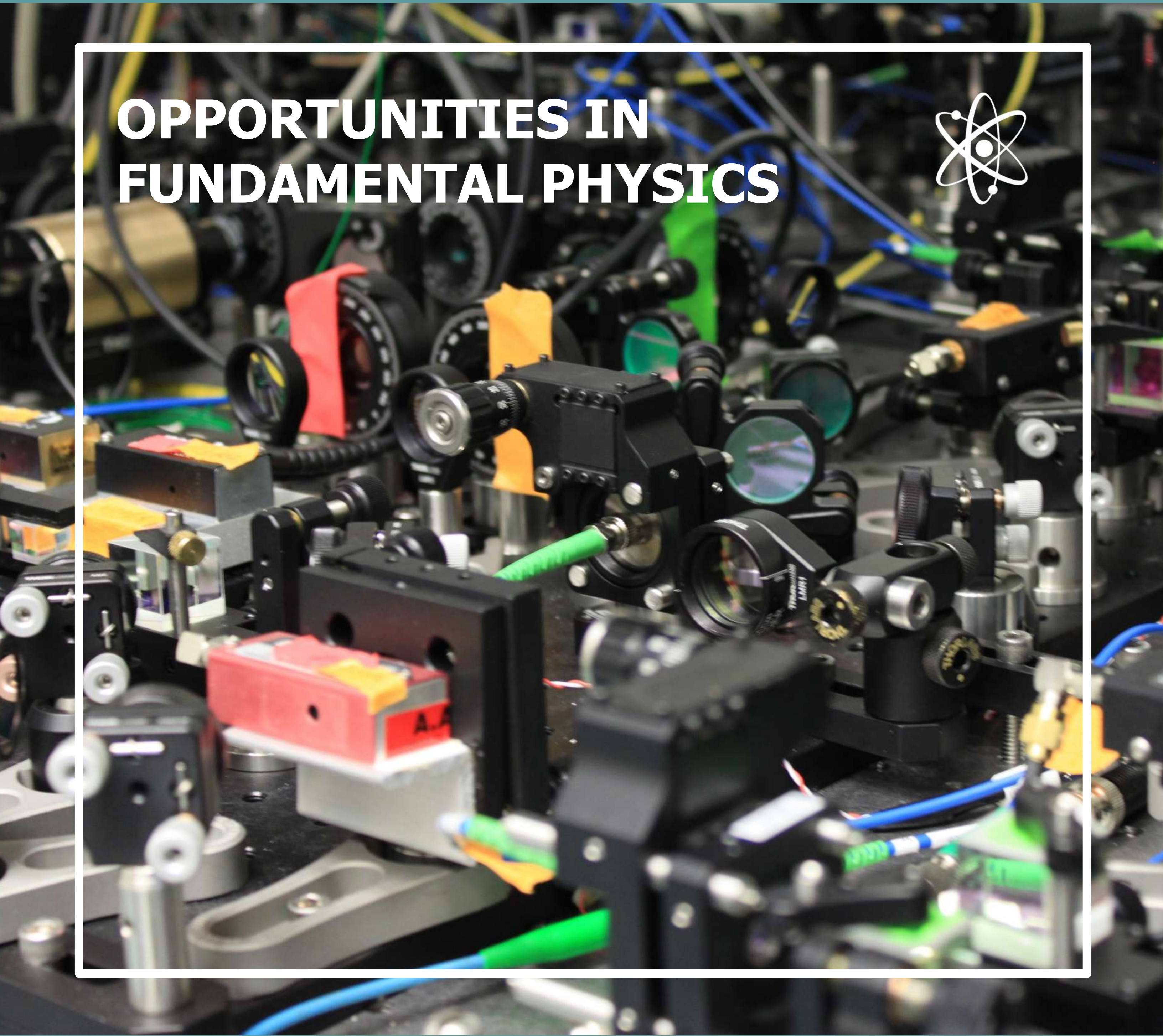
OPPORTUNITIES IN FUNDAMENTAL PHYSICS



GORDON AND BETTY MOORE FOUNDATION

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Executive Summary

Understanding matter and the forces of nature has been a longstanding quest. Tremendous progress throughout the 20th century has culminated in the Standard Model of particle physics, the most accomplished scientific theory in history. Despite its astounding success in describing all known particles, we know that fundamental physics is incomplete. For instance, there are important open questions about the structure of the Standard Model itself – such as why particles come grouped as triplet pairs – and about phenomena such as dark matter and dark energy which are outside of the Standard Model.

Efforts to develop a deeper understanding of nature have led to predictions of new phenomena ranging from new particles and forces to hypotheses of additional spatial dimensions and about the granular nature of spacetime itself. There are many possibilities, and a subset of them have become regarded as well-motivated, often because the ideas solve multiple open questions. Supersymmetry, for instance, is a key ingredient in many proposals to unify the forces. It predicts new particles that could be the dark matter and if these particles exist near the electroweak scale (~0.1 TeV) they could also solve the hierarchy problem, explaining why gravity is so weak.

Ultimately, experiments will determine which ideas are realized in our universe. While the particle collider has been a primary experimental tool in fundamental physics for many years, the prospects for collider guidance are dimmer than they have been in past decades given the absence of supersymmetric particles at the Large Hadron Collider combined with poor prospects for a new collider at significantly higher energy; the machines have become too large and costly and this path to advancing fundamental physics cannot continue indefinitely.

Importantly, a new path for exploration in fundamental physics is emerging. Precision instruments present an attractive opportunity to discover new physics by measuring small signals in university-scale experiments. These experiments address some of the same deep questions that colliders address, but at the physical and fiscal scale of a university laboratory. Discovery driven by ultra-precise experiments such as these has been dubbed "the precision frontier."

This precision frontier approach is attractive since comparatively modest cost – relative to collider experiments – means that ideas can be tested more rapidly, leading to faster progress. Similarly, the availability of new tools will challenge our best minds to find new innovative ways to test well-conceived ideas. University-scale efforts currently comprise only a small fraction of the experimental portfolio for particle physics. Moving towards an ecosystem with better balance across different scales of experimentation could prove beneficial as the different approaches feed back to guide one another and to guide theory.

Novel instruments that exploit quantum mechanics to achieve new measurement capabilities lie at the core of this emerging opportunity. These "quantum technologies" have exploded over the past two decades and currently offer capabilities such as ultra-precise force measurements well suited to discovering new forces, matter-wave interferometers that provide a new way to probe spacetime, and quantum-measurement protocols that take measurement sensitivity beyond the limits of classical physics. Specific instruments include atomic clocks and interferometers, high-Q quantum-limited resonators, new approaches to nuclear magnetic resonance, and ultra-sensitive electromagnetic field detectors based on quantum defects in solids, to name a few.

These and related technologies offer important opportunities to advance fundamental physics. “Tabletop” experiments such as searches for anomalous electric dipole moments or probes of fundamental symmetries constitute a longstanding leg of this new effort. These more traditional platforms are joined by an array of new experiments, such as the suite of novel tabletop experiments that search for light dark matter and which are motivated by new theoretical ideas or newly developed signatures of existing ideas.

The opportunities offered by new instruments are latent and actualizing the benefits requires close experiment/theory collaborations that focus on using precision instruments to address important problems in fundamental physics. Several recent theory/experiment collaborations have led to a handful of proposals for new, well-motivated exploratory paths in fundamental physics, offering a hint of what could be achieved if this nascent effort is nurtured.

Mindful of the promise of this emerging effort and aware of the challenges it faces due to its highly interdisciplinary and exploratory nature, the Gordon and Betty Moore Foundation convened a workshop in October 2016 to explore options for advancing fundamental physics via small-scale, precision experiments. While tabletop platforms took center stage, the meeting entertained a broader range of ideas such as global arrays of low-cost dark matter detectors or efforts to find signatures of new physics by analyzing archival GPS data.

This document offers a snapshot of some of the promising opportunities for advancing fundamental physics that were discussed at the workshop. It is comprised of reports from five workgroups, a theory group and four groups focused on experiments with a specific scientific theme. The Moore Foundation Science Program expresses sincere thanks to the advisors – Savas Dimopoulos at Stanford University, Frank Wilczek at the Massachusetts Institute of Technology, and Max Zolotorev at Lawrence Berkeley National Laboratory – who helped us identify scientific themes for the workshop: Light Dark Matter, Gravitational Wave Detectors, New Forces and Tests of Gravity, and Short Distance Physics from Precision Experiments.

Each group was asked to provide an overview of the major scientific questions confronting the sub-field, along with – for experimental groups – a summary of the sub-field’s experimental methods and promising new or emerging tools and research directions. Finally, the groups were asked to identify funding related obstacles to advancing their sub-field. Next, we present the workgroup reports, summaries first followed by full text reports.

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Report Summaries

1. Theory

The Standard Model of particle physics was established nearly a half-century ago and is the most successful theory in the history of science. Despite this success, there are important open questions such as the cause of the observed matter/antimatter asymmetry, why gravity is so much weaker than the other forces and whether nature's forces unify at high energy. Two principles have been central in attempts to answer the open questions, Unification and Naturalness. Unification aims at a single, compact quantum theory that describes all of nature's particles and forces. Naturalness seeks to understand how various parameters of the Standard Model obtained their very special numeric values; values that allow our universe and/or life to exist.

These guiding principles have led to theories that predict a range of new phenomena. String theory, for instance, predicts the existence of extra spatial dimensions that could cause gravity to deviate from inverse square law behavior at short distance. Observation of such a deviation would support claims of extra dimensions and could solve the hierarchy problem. Similarly, new particles such as axions, axion-like particles, chameleons, dilatons, galileons, symmetrons, etc. are ubiquitous across many candidate theories. These new particles could be observed in several ways. They could, for example, produce large electric dipole moments in fundamental or composite particles. Similarly, they could mediate new forces and/or be part of the dark sector.

Given the many possibilities, experiments will be critical to advancing our understanding. While the particle collider has been the primary experimental tool in fundamental physics for several decades, the prospects for collider guidance have dimmed somewhat given the current absence of supersymmetric particles at LHC combined with poor prospects for a new collider at significantly higher energy; the machines have become too large and costly. The theory workgroup emphasizes that tabletop or small-scale experiments can play a critical role in advancing fundamental physics; both due to an array of novel precision instruments and because comparatively low-cost experiments allow a broad range of ideas to be tested.

The workgroup points to the important role theory can and should play in helping to develop new paths of exploration for fundamental physics: theorists – working closely with experimentalists to understand the capabilities of frontier instrumentation – can propose novel experimental signatures of new physics, based either on new, well-motivated theoretical ideas or on newly developed signatures of existing ideas. By proposing such experimental searches, theorists working closely with experimentalists can start entirely new fields of exploration. The theory workgroup emphasizes that such an experimental revitalization is important to fundamental physics at this time and highlights the importance of the opportunity presented by small-scale platforms. Importantly, the working group also points out the difficulty in securing funding for theory work to develop this emerging area, a significant limitation that is essential to overcome.

Finally, three general areas were identified by the workgroups – taken together – as areas where theory work is needed.

- First, as discussed above, reasonably unconstrained explorations like the ones that have produced a new suite of light dark matter experiments; here a close coupling between theory and experiment leads to newly proposed signatures of novel physics.
- Second, more conventional theory work that is well within the Standard Model but which is needed in order to advance a certain experimental platform. Calculations to understand spectra or other properties of atoms or molecules fall in to this category.
- Third, work to guide experimental platforms sorely in need of a firm theoretical footing. This includes theory to guide experiments on phenomenological quantum gravity or experiments that probe fundamental symmetries in order to understand physics at ultra-high energy.

2. Short Distance Physics from Precision Experiments

Comparing precision measurements to highly accurate Standard Model calculations provides an attractive route to discovering new physics. The short distance physics workgroup draws attention to some specific instances where precision tabletop experiments could advance fundamental physics. These include measurement of the electron gyromagnetic ratio and of the fine structure constant which, taken together, can be used as a cross-check on calculations needed to interpret the muon g-2 anomaly. Similarly, atomic parity violation experiments can be sensitive to hypothesized analogues of the Z boson that may be difficult to directly detect at the Large Hadron Collider.

More broadly, the workgroup notes that there are many ways in which small-scale research can advance fundamental physics, often by developing new detector methods and technologies useful to small or large experiments. These methods and technologies span a diverse range of ideas including laser-based single-ion detection, cryogenic bolometers, new types of photon detectors, and DNA-based low-energy-deposition particle detectors. The workgroup also points out that a lengthy research and development process may be necessary to optimize a new detector technology.

Focusing on small-scale experiments designed to directly detect new physics, the workgroup mentions that there are experiments and ideas for experiments that are innovative and promising, but which require development of a sound theoretical framework for interpreting experimental results. These include phenomenological quantum gravity experiments (see below) as well as probes of fundamental symmetries which may be able to signature new physics at very high energy. Better grounded are experiments which search for asymmetries in the distribution of a particle's electric charge, i.e. a nonzero electric dipole moment (EDM).

While a nonzero EDM is consistent with the Standard Model, the predicted Standard Model values are tiny. For instance, the Standard Model predicts an electron EDM of $\sim 10^{-38}$ ecm, well below the state-of-the-art measured upper limit of $\sim 10^{-28}$ ecm [1]. For composite particles such as nucleons and nuclei, quantum chromodynamics uncertainties lead to less certain Standard Model predictions which – nonetheless – are still well below experimental upper limits. The Standard Model predictions for the neutron EDM range from $\sim 10^{-30}$ ecm to $\sim 10^{-34}$ ecm [2], both small compared to the measured upper limit of $\sim 10^{-26}$ ecm [3]. By contrast, theories that postulate new particles often predict much larger EDM values so that EDM experiments provide a way to detect signatures of new physics. Importantly, the signature – disagreement with the Standard Model prediction – does not rely on the correctness of any specific new theory so that these experiments test any and all theories predicting anomalously large EMDs.

In terms of the physics which EDM experiments might uncover, a non-zero EDM signatures explicit violation of time-reversal symmetry which, in turn, implies violation of charge parity symmetry given the assumption that nature respects charge-parity-time symmetry. EDM searches, therefore, may reveal additional sources of charge parity violation to explain the observed matter/antimatter asymmetry. Additionally, an anomalously large EDM can arise from the virtual exchange of new heavy/energetic particles, making EDM experiments sensitive to high energy phenomena. EDM experiments are already probing the electroweak scale (~0.1 TeV) and foreseeable advances may allow these experiments to probe physics at the PeV scale not likely accessed by foreseeable accelerators.

The workgroup forecasts significant advances in EDM experimentation based, for instance, on comparatively recent progress in using molecules rather than atoms. Molecules – particularly polar molecules – offer much higher internal fields than do atoms and this leads to EDM signatures that are many orders of magnitude stronger. However, since molecules have many more degrees of freedom than atoms, they are typically much harder to control. The workgroup indicates that advances in techniques for producing, cooling, manipulating and detecting molecules have opened the door to molecular EDM searches that put the PeV scale within reach. Beyond molecules, EDM searches based on deformed nuclei offer another promising frontier. The workgroup cautions that new EDM platforms, while promising, frequently require dedicated efforts to development new techniques such as new cooling methods, new quantum-enhanced measurement protocols, or similarly dedicated efforts to acquire new data such as detailed molecular spectra.

3. Light Dark Matter

Dark matter comprises more than 85 percent of all matter in the universe and yet we know very little about this dominant component of matter. To date, dark matter detection has largely focused on Weakly Interacting Massive Particles (WIMPs), with masses between 10 - 1000 GeV. Despite significant effort, there has been no conclusive sign of WIMP dark matter.

While the WIMP is theoretically well-motivated, observational limits permit dark matter over a vastly broader range from 10^{-31} GeV to 10^{48} GeV. The Light Dark Matter workgroup emphasizes the importance of broadening the search for dark matter and identifies two general factors important to covering the broad landscape over which dark matter could exist: theoretical guidance and methods to efficiently cover broad regions of experimental phase space.

Theoretically, a number of well-motivated candidates inhabit the vast parameter space of permissible dark matter mass, ranging from ultra-light axions and hidden photons to ultra-heavy composite dark matter. The workgroup emphasizes the importance of investing in work that connects dark matter models to novel signatures detectable with precision measurements. Ideas are needed for new experiments to probe the vast parameter space and the workgroup highlights precision tabletop searches for light dark matter as a vibrant, emerging area of research. As a key concept underlying this nascent effort, the phenomenology of both light (< 10 eV) and ultra-heavy (> 10^{19} GeV) dark matter is that of a classical field. While classical fields can be produced by a wide variety of dark matter models, the workgroup notes that there are only four "portals" through which dark matter can couple to ordinary particles and fields. Dark matter can couple by:

- coupling to photons
- exerting torques on atomic spins
- exerting a new – fifth – force
- causing apparent variations in fundamental constants.

This framing of the problem suggests a way to effectively search for dark matter: by developing a portfolio of tools to probe these four portals one can efficiently search for an enormous range of dark matter candidates. Accordingly, foreseeable precision instruments could lead to dramatic progress in the hunt for dark matter by allowing experimental exploration of dark matter over a mass range spanning 20 orders of magnitude, well beyond the presently probed WIMP parameter space.

Tabletop measurement techniques are well suited to this strategy and the light dark matter workgroup discusses promising precision measurement tools and methods. These include atomic sensors (e. g. atom interferometry and atomic clocks), magnetometry and nuclear magnetic resonance techniques, quantum-limited electromagnetic resonators, superfluid helium, and detector arrays. Each of these approaches offers numerous opportunities for research and development of new technology that could significantly expand the reach of these searches. We next summarize some of the existing and future-looking experimental platforms discussed in the report.

Portal 1: Coupling to the electromagnetic field

Resonant electromagnetic cavities: Resonant electromagnetic cavities – tuned to the particle mass of interest – provide an important platform for detecting new particles that couple to the electromagnetic field. The Axion Dark Matter Experiment (ADMX), for instance, began in the 1990s and uses an electromagnetic resonator to search for the so-called QCD axion via its electromagnetic coupling; axions in a magnetic field are converted to microwave photons. ADMX and closely related experiments can be extended to somewhat lower axion mass with a dedicated research and development effort to engineer lower-frequency quantum-limited devices. For somewhat higher axion mass it is unlikely that the present cavities can be extended to higher frequencies and new ideas are needed. As axions have not yet been detected, there is interest both in searching over a wider mass range and in considering a broader range of detection methods, both for axions and for a wider range of dark sector candidates expected, for instance, from string theory.

To date, resonant cavity searches for dark matter have principally used radio frequency and microwave cavity resonators. These techniques are limited to structures whose size is on the order of a wavelength; therefore, they are difficult to implement below about 100 MHz. As one strategy for extending to lower frequency, dark sector particles could interact with electrons in a material to generate a magnetic field that could be detected using a tunable, resonant LC circuit designed to couple to this field; a "dark matter radio." A dark matter radio has potential sensitivity many orders of magnitude beyond current limits over an extensive range of frequencies, from 100 Hz up to 700 GHz and potentially higher. Such dark matter radio experiments are attractive and require the development of lumped element resonators based on high-quality, low-loss, tunable capacitors and inductors optimally coupled to cavity-quality-preserving quantum amplifiers.

Quantum non-demolition measurements: Resonant cavities typically produce electrical currents as a signature of dark matter detection and detecting small currents is a measurement challenge. An important frontier is to circumvent quantum noise and extend searches to larger axion mass. Recent advances in the ability to prepare and measure quantum states of microwave frequency electrical circuits could speed up the rate at which axion parameter space is covered. Particularly impactful would be the ability to search for axions by performing a quantum non-demolition (i.e., nondestructive) measurement of microwave photon number. Such a measurement could accelerate an axion search by a factor of 100 or more compared to a quantum-limited search.

Advanced nuclear magnetic resonance: Zero-to-ultralow-field nuclear magnetic resonance (ZULF NMR) is an emerging magnetic-resonance modality that can be used to search for axions in the range of about 1-300 Hz. This is a well-motivated frequency range that corresponds to a spontaneous symmetry breaking energy scale close to the Planck energy ($\sim 10^{19}$ GeV).

Portal 2: Torques on Spins

The CASPEr experiments: A new set of experiments uses nuclear magnetic resonance techniques to detect spin precession caused by background axion dark matter. The Cosmic Axion Spin Precession Experiments (CASPEr), CASPEr Electric and CASPEr Wind, search for axions or axion-like-particles (ALPs) using different couplings than the axion-EM field coupling exploited in ADMX. This approach complements ADMX which is sensitive to higher axion mass; CASPEr covers lower mass axions.

CASPEr Electric exploits the axion-gluon coupling to generate a time-varying nuclear electric dipole moment. This precision experiment combines advances in ultra-sensitive magnetometry, nuclear magnetic resonance, and materials science, and has the potential to improve existing astrophysical bounds on axion coupling strengths by many orders of magnitude over a wide range of masses. CASPEr Wind relies on the coupling of nuclear spins to the spatial gradient of the axion or axion-like-particles dark matter field (the so-called "Axion/ALP wind"). In its present form CASPEr Wind will not have sufficient sensitivity to reach parameter space corresponding to the QCD axion so this experiment is currently focused on searching for ALP dark matter.

Ultra-precise spin measurement: A recently predicted new behavior for ferromagnetic objects in sufficiently small magnetic fields – precession about the magnetic field – could significantly reduce the quantum noise associated with spin orientation uncertainty and allow measurements of unprecedented precision to be performed, surpassing the present state-of-the-art by orders of magnitude.

Portals 3 and 4: New Forces and Variations of Constants

The atomic sensors discussed by the Gravitational Wave Detectors group provide platforms for searching for new forces and variations of fundamental constants. The Short Distance Physics group discusses using molecules rather than atoms to improve atomic sensors. Nuclei provide another route for improving atomic clocks and closely related technologies. While today's most precise time and frequency measurements are performed with optical atomic clocks, it has been proposed that they could be outperformed by a clock based on a nuclear transition in Thorium (^{229}Th). There is ongoing research to pin down the precise characteristics of the ^{229}Th nuclear transition.

Heavy Composite Dark Matter

On another front, dark matter may not be distributed uniformly throughout the galaxy but may be clumped to form dark stars or topological defects manifesting as domain walls. If the dark matter takes such a form, terrestrial detectors would not register a continuous signal associated with a light dark matter field, but rather infrequent transient events associated with the passage of the Earth through such a dark matter object. In this case effective vetoing of false positives requires a global network of detectors. The Global Network of Optical Magnetometers (GNOME) collaboration is searching for such transient signals due to passage of the Earth through dark matter objects that couple to atomic spins. Similarly, dark matter clumps or domain walls can also manifest themselves as glitches of atomic clocks onboard GPS satellites and the GPS.DM collaboration is mining a decade of archival GPS data to hunt for such objects. Other approaches to searching for dark matter via distributed detector arrays are under consideration. In general, the greatest flexibility is provided by hybrid networks consisting of different types of detectors sensitive to different possible interactions with the dark sector. Given the global scale of these detector arrays, the workgroup calls for support to develop relevant international collaborations.

4. New Forces and Tests of Gravity

Astrophysical observations indicate that 96 percent of the universe's mass/energy consists of dark matter and dark energy, and that the dark sector cannot simply be composed of known particles. Many theories propose new low-mass bosons that could be part of the dark sector and that would lead to new forces. These new forces could manifest as temporal oscillations of fundamental constants or as a new macroscopic force on top of gravity. Detection of a new force could validate a specific new-particle prediction, but it could also help explain the observed matter/antimatter asymmetry by revealing new sources of charge parity (CP) violation, such as new CP-odd spin-dependent forces that arise from axions or axion-like particles within supersymmetric extensions of the Standard Model. More speculative, violation of the principle of equivalence (i.e., a new force on top of gravity) could arise if dark energy is an evolving scalar field (quintessence).

The workgroup emphasizes the importance of gaining a deeper understanding of gravity. Gravity is the least understood of the fundamental forces, with basic open questions including: why is gravity so much weaker than nature's other forces? How can one construct a quantum theory of gravity? How does gravity behave in the strong field regime? The recent discovery of gravitational waves by LIGO opens a new avenue to the study of gravity in the strong field regime and provides an important test of general relativity. Advances in both gravitational wave detection technologies – covered in the Gravitational Wave Detectors report – and in high performance computing to calculate the waveforms predicted by general relativity will be needed to fully exploit this new observational tool. There is also growing interest in detection of primordial gravitational waves as they could provide a window to a hypothesized epoch of cosmic inflation.

String theory provides a framework for a quantum theory of gravity and requires extra spatial dimensions as well as new scalar particles; both of these features predict deviations of gravity from inverse square law behavior. Extra spatial dimensions would lead to gravity becoming stronger at short distances and help explain the weakness of gravity in our 4-D world. Virtual exchange of string theory's scalar particles would manifest as a new macroscopic force on top of gravity. Therefore, precise tests of gravity's inverse square law are important and could provide a window into the world of quantum gravity.

As a less developed frontier, there has been recent interest in phenomenological quantum gravity, which aims to develop models of systems where both gravity and quantum mechanics play a significant role, hopefully eventually leading to a true quantum theory of gravity. Experimental systems include systems with large mass and with many degrees of freedom, and testing the Heisenberg uncertainty relationship is a typical goal for these experiments. While such experiments could conceivably shed light on physics at the Planck scale, this frontier is poorly developed and a firm theoretical footing is needed both to design well-conceived experiments and to interpret their results.

The workgroup has identified priorities in the field based upon the extent to which the scientific motivation is compelling and the experimental techniques promising. Tests of gravity's inverse-square law behavior and of the principle of equivalence lead the priorities, with advances possible across a range of relevant tools which include nano/micro resonators, levitated micro spheres, improved torsion balances, atomic clocks and atom interferometry, high-precision spectroscopy and lunar laser ranging. Technical advances important to the search for spin-dependent forces include advances in micro resonators, precision magnetometry and precision spectroscopy.

Finally, experiments at the interface of quantum mechanics and gravity could also benefit by advancing some of the above-mentioned tools, though continued development of novel micromechanical devices is most relevant. These devices involve force sensing oscillators that provide high sensitivity to new short-range forces, along with light coupled resonators that are useful in creating quantum states of macroscopic objects. Technology advances here would also benefit gravitational wave detection since quantum control of macroscopic objects is likely to play an important role in one path to a next generation of gravitational wave detectors.

5. Gravitational Wave Detectors

The recent detection of gravitational waves offers great promise for studying the earliest moments of our universe, promising insights into cosmological history and physics at energy scales far beyond those accessible by colliders. Maximizing the scientific output will require instruments to detect gravitational waves over a broad spectral range. Opportunities for small-scale experiments range from research to optimize the performance of large laser-interferometric detectors, to entirely new approaches to gravitational wave detection based on atomic sensors.

The Gravitational Wave workgroup report notes that advanced LIGO detectors are – at design sensitivity – limited by quantum optical noise and coating thermal noise. Reducing these two noise sources is critical to the design of any next-generation laser-interferometric gravitational wave detector and the workgroup summarizes several promising approaches to solving these challenges. These include lowering the thermal noise figure of optical coatings, improving squeezed states of light and reducing optical losses. Small-scale platforms are suitable for each of these directions and any improvements will benefit both laser interferometric and atomic sensor approaches to gravitational wave detection.

Specific to laser interferometry in space (LISA), the workgroup notes that while the prospects for a space mission in year 2034 are good, the data analysis tasks necessary to optimizing the scientific output pose significant challenges which have yet to be addressed. The difficulty is in large part due to the challenge of extracting multiple, overlapping gravitational wave signals from one another and from ambient detector noise. The report calls for a sustained effort to develop the analysis tools that will be needed to optimize the scientific output of LISA.

Finally, atomic sensors based on atom interferometers and/or atomic clocks offer a novel route to gravitational wave detection in the frequency band 0.1 Hz – 10 Hz, between LIGO and LISA. Beyond filling this scientifically interesting spectral gap, atom-based detectors can be run with only a single optical baseline, reducing the size and therefore cost/complexity of a gravitational wave detector.

Since atomic clocks and interferometers are closely related and share many underlying technologies, a unified research and development effort could advance both techniques and it is likely that an optimal detector will incorporate features of both. While many of the techniques required for atomic gravitational wave detection have been demonstrated, the techniques must be advanced further, and they have yet to be integrated into a full gravitational waves detector prototype. Additionally, there are many as yet untested routes to improving atomic sensors, routes which include quantum enhancement techniques like dynamical decoupling, entanglement, squeezing, and novel dynamical phases, as well as efforts to develop ultra-stable lasers. Lasers are a basic tool for producing and manipulating the cold atoms central to atomic sensors. Similarly, efforts to reduce optical coating noise are important and the workgroup describes a new and promising approach to improving optical coatings, one which relies on crystalline rather than amorphous materials.

The workgroup emphasizes that advancing atomic sensors would benefit other efforts to uncover new fundamental physics. Atomic sensors can – for instance – measure minute accelerations in a search for equivalence-principle-violating new forces. Additionally, they have been proposed as a basis for new approaches to searching for axions and other light dark matter candidates, for detecting time-variation of fundamental constants and for testing recently proposed theories that solve the hierarchy problem through cosmological relaxation. The workgroup indicates that a focused investment would enable the full design, construction and evaluation of a prototype gravitational wave detector based on atomic sensors. Such a prototype would demonstrate the viability of a full-scale gravitational wave detector based on atomic sensors, retiring the technical risk associated with this new approach and opening the way to government support for a large-scale 'atomic' gravitational wave detector.

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1. Science

The Standard Model of particle physics was essentially established in 1978. Since that time many of the fundamental questions of physics deepened and switched from *What* questions to *Why* questions, marking the beginning of theories beyond the Standard Model. The two principles that guided particle physicists in their attempts to build a theory beyond the Standard Model are Naturalness and Unification. Naturalness seeks an understanding of the small numbers of Nature, whereas Unification aims at a more economical theory with fewer components. Despite the success of the Standard Model, many fundamental mysteries remain including:

- Why is the universe so large? (cosmological constant problem)
- Why is gravity so weak? (hierarchy problem)
- Is Naturalness a broken principle in view of the absence of new physics at the Large Hadron Collider and especially the extreme smallness of the cosmological constant?
- Why is the electric dipole moment of the neutron so small? (strong charge parity problem)
- What is the nature of dark matter?
- Are there new forces, particles, or dimensions as suggested by string theory – the only known unified theory of all forces?

Recent results from the Large Hadron Collider and other experiments deepen many of these mysteries. For example, a solution to the hierarchy problem or the nature of dark matter has (so far) not been found at the weak scale, in tension with proposed solutions. It is not clear that a higher energy collider will answer these questions. Thus, it is crucial to explore many different directions. This is why new experiments are so important to fundamental physics right now, they allow us to try many directions and test many different ideas, much more rapidly than by building a bigger collider. Such experiments may make fundamental breakthroughs on a short timescale, for example possibly discovering dark matter.

A great example of how the principle Naturalness leads to paths other than the Large Hadron Collider, is the Strong Charge Parity problem. One of the open questions of the Standard Model is the smallness of the neutron's electric dipole moment. In the late '70s a new spin-0 particle with odd parity, the "axion", was proposed to address this question. Non-perturbative quantum chromodynamics effects generate a potential for the axion. When the axion rests at its minimum, the neutron's electric dipole moment is naturally small. The corresponding axion mass is small and depends on a single parameter, the axion decay constant, which provides the axion with a well-defined theory parameter space. The axion interacts extremely weakly, it is an excellent dark matter candidate, and it can mediate new interactions in matter. High precision tabletop experiments are the best way to probe this idea.

Another example of how new physics can appear in a variety of scales much different than those probed at colliders, is string theory. String theory is motivated by the principle of Unification: it tries to unify general relativity and quantum mechanics. Its mathematical consistency requires the existence of extra dimensions and these extra dimensions need to be compactified in order to give rise to our 4D world. The shape and complexity of the compactification naturally gives rise to a plenitude of boson particles, spin-0 and spin-1, that are axion-like (the "axiverse"), photon-like (the "photiverse"), or they are the moduli or dilatons that determine the fundamental constants of the Standard Model. These particles interact extremely weakly, they are excellent dark matter candidates, and they can mediate new forces in matter. Their parameter space is broad with their masses varying anywhere between the size of the Universe to sub-mm scales and beyond. Gravity can also be modified in such a scenario as the extra spatial dimensions "open up" on short length scales and change Newton's law. Experiments at the precision frontier are the best probe of this large class of phenomena.

The precision frontier may also seed another grand direction for the future, by creating new ways to observe gravitational waves. The recent discovery of gravitational waves by LIGO (Laser Interferometer Gravitational-Wave Observatory) is a historic event. It is the beginning of a new way to study the universe. The observation of gravitational waves will be a major part of the future of astronomy, astrophysics, and cosmology. Every new band of the electromagnetic spectrum opened (e.g. microwave, x-ray, etc.) has revealed a wealth of new and often unexpected information about the universe. Gravitational waves provide an entirely new spectral window through which the universe can be viewed.

Gravitational waves allow many observations that are impossible with normal electromagnetic telescopes. For example, black holes (and other compact objects) are probably best studied with gravitational waves. Further, gravitational waves allow us to look far back in the history of the universe, long before the cosmic microwave background, the earliest picture possible with light. Observing such early times teaches us not just about the beginning of our universe, but also about the highest energy, most fundamental laws of physics, far beyond the energies that can be probed using a collider. In order to fully realize the potential of gravitational waves we will need new ideas to improve our observational capabilities; to open up as much of the frequency spectrum as possible.

2. Theory

Theorists can add significantly to the search for new fundamental physics that addresses the deepest mysteries of nature. The highest value work in theory generally falls into two categories:

- **Inventing novel, well-motivated theories which give testable signals** – New ideas are needed to solve major outstanding questions such as the hierarchy problem, the nature of dark matter, and others. Ideally any new theories should lead to predictions testable in specific experiments.

- **Proposing new experiments/techniques to test well-motivated theories** – The second crucial element is connecting known (or newly invented) theories to experiments that can test them. Theorists can play a crucial role in finding new signals that are not currently being searched for and helping to design experiments to search for them. It is almost always the case that collaboration between theorists and experimentalists produces the most useful results.

Finding new solutions to major problems such as the cosmological constant problem, the hierarchy problem, the strong charge-parity problem, or the nature of dark matter is of major value to the entire field of fundamental physics. For example, ideas for the hierarchy problem including supersymmetry, large extra dimensions, or technicolor have led to many new experiments searching for the predicted signals.

Additionally, it is highly valuable in theoretical physics to propose new observables of well-motivated theories, signals that are not being searched for experimentally. By finding experimental techniques to search for such signals, theorists can start whole new fields of experimental exploration in fundamental physics. This has happened several times in the past. For example, Kip Thorne had a significant role in founding LIGO. Marc Kamionkowski proposed the search for B-modes in the cosmic microwave background, now a major experimental effort across the globe. Edward Witten helped start the field of weakly interacting massive particles direct detection, which has grown into a huge and highly valuable experimental direction. Pierre Sikivie proposed the axion cavity experiments, which have achieved impressive results in searching for the quantum chromodynamics axion. There is every reason to believe that new theory work being done now will continue to lead to major new experimental efforts. One crucial role for theorists then, is to know which theories are best motivated, and to find to ways to discover well motivated theories. For this work, close communication and collaboration between theorists and experimentalists is of great value and indeed often necessary to produce useful results.

3. Funding

A major obstacle to progress is that funding agencies for theoretical physics do not (yet) appreciate the emerging field of fundamental physics with novel small-scale experiments. Very few particle theorists can appropriately peer-review these grants. While it may be useful to have a small number of experimentalists reviewing a theory grant, they clearly cannot comprise the majority of reviewers on a theory grant (in the same way that theorists should not constitute a majority of reviewers for an experimental grant). Thus, the funding agencies generally support this area of theory at a very low level, if at all.

We recommend funding great people who are actively inventing novel ideas. In fact, funding top people with a proven track record who are having many significant ideas is more important than funding specific projects. A specific theoretical project may only last about a year. The most important issue is to find people who can invent many new, important ideas. The process of finding a workable project (e.g. an idea for a new axion detection experiment) can take a long time and requires inventing and exploring many new ideas along the way. The best theory work is exploratory, when theorists are free to think about any exciting new direction they find.

Funding for theory projects seeking to invent new experiments should mainly be for theorists who work closely with experimentalists. The resulting experimental ideas are significantly improved by working with experimentalists with expertise in the relevant techniques.

The ideal funding model would be grants to faculty PI's who can then hire students and postdocs. An ideal funding level would be about $250,000 per year per principal investigator (in either individual PI or small group grants) which could support one student, one postdoc, travel for the PI, student, and postdoc, some summer salary, and visitor (or possibly workshop) money. Visitor (or workshop) funds are useful because they significantly enhance interactions with great people at other institutions which often leads to valuable collaborations.

An ideal duration for an award is 5 years which gives enough time to support postdocs and students, and fully work out a research direction. Theory postdocs are hired for a 3-year term and the hiring decisions are made about 9 months in advance of the start date on an academic calendar. So after receiving a grant that funds a postdoc it usually takes almost a year to hire that postdoc. Thus, postdoc timescales would line up much better with a 5 (or 4) year award rather than a 3-year award. Similarly, theory students usually stay for around 5 years.

4. Additional comments: Theory calculations driven by experimental needs

Many of these experiments need specific theoretical calculations in order to interpret the data and extract the underlying physics results from the experiment. For example, LIGO needed theoretical calculations of templates for gravitational waveforms from merging black holes in order to improve sensitivity to see these events. Many other experiments need such calculations including many electric dipole moment experiments, neutrinoless double-beta decay experiments, etc. This is a very different kind of theory work from that discussed above. These calculations are very important, and in many cases crucial, to actually extracting useful results from the experiments. Thus, such calculations should clearly be supported. However, they are not useful theory in isolation. The field would not do these calculations as pure theory work, they are important only relative a particular experiment. These calculations should be done only once it is certain that the relevant experiment will definitely be performed. Thus, such a calculation should not be funded as part of this theory section, instead it should be funded along with the experiment to which it applies (assuming of course that experiment is funded and will definitely be performed).

5. Appendix: Table of Theoretical Ideas

The table below lists some theoretical ideas underlying possible routes to new physics and ranks the importance of looking for these ideas by using a scale of +10 (most important) to -10 (least important), with some extra credit designated by a star. Of course, the question of whether theoretical work on a particular topic is useful is a somewhat different question. For example, while electric dipole moments are excellent signals to search for experimentally, as reflected in the grades, for a theorist to make a major contribution to this field would require that theorist to come up with a totally new way to search for electric dipole moments that the experimentalists have not already considered. So these grades do not attempt to rank which topics are best for theorists to work on, they simply rank the theories themselves.

Note also that this is not a table of what experiments should be done. To make such a judgment requires weighing the theoretical soundness and motivation of the signal against details of the specific experiment including the required effort, time, cost, etc. of the experiment.

The first column of the table is a grade on the theoretical soundness of the idea, by which we mean: are there equations that underlie this idea, is it a real theory or a hunch? For example, attempting to measure vacuum energy fluctuations (motivated by holography) has no viable theory behind it.

The second column of the table ranks the theoretical motivation for the idea. For example, if the idea can address a major outstanding problem such as the quantum chromodynamics axion does for the strong charge parity problem, then it gains significant motivation. Another component is whether it is a consequence of well-motivated theoretical ideas. For example, hidden photons and general axions (the 'photiverse' and 'axiverse') follow generically from high energy physics (e.g. string theory) and can also solve the problem of dark matter. The quantum chromodynamics axion itself gets extra credit for following generically from natural high energy physics, being a natural dark matter candidate, and for solving the strong charge parity problem. Additionally, if the signal points to some future direction or provides extra information about new physics, then a search for the signal is well-motivated. For example, discovery of an electric dipole moment points to a scale which would influence the direction of future collider experiments. Gravitational waves are off this scale (extra credit) since they are known to be true, already discovered, and indeed are already starting to give us completely new information about the universe.

The third column of the table is the question: do we know where in parameter space to look for signals of this physics? Gravitational waves have already been seen and we certainly know other important places to look, so they get the maximum grade. Also, for electric dipole moments, neutrino masses, and the quantum chromodynamics axion we have a fairly constrained range of parameters that are best-motivated. The range of parameters is broad for the rest of the ideas.

Of course, there are signals/effects that are important to search for even though they are not fully theoretically sound. For example, there is a conjecture that Newtonian gravity may itself be modified around the 1-100 micron scale (at one times gravity) in order to potentially address the cosmological constant problem. However, there is no theory that actually realizes this possibility. Nevertheless, it remains an interesting idea to test.

Table 1: Ideas underlying possible routes to new physics. Grades indicate the relative importance of searching for evidence of the idea (higher grade = more important). The first column indicates whether there is a viable theory supporting the idea. Column two ranks the theoretical motivation for the idea, and column three asks whether we know where in parameter space to look for signals of this physics.

	Theoretically Sound?	Why?	Where?	Net Grade
Gravitational Waves	10	20*	10	40
Near weak-scale physics (e.g. EDMs, Flavor, g-2)	10	10	5	25
Neutrino masses (neutrinoless double beta decay)	10	10	5	25
QCD axion	10	15*	5	30
Axiverse, Photiverse	10	5	0	15
Moduli, Extra Dimensions	10	5	0	15
Lorentz, CPT Violation	5	0	0	5
Gravitational Decoherence	-5	-10	0	-15
Quintessence, Chameleons, Galileons	-5	-10	0	-15
Vacuum Energy, Holography	-10	-10	0	-20

Short Distance Physics from Precision Experiments

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1. Science

All members of this group are pursuing experiments and/or theory aimed at uncovering new short distance physics. Toward this end we also develop new tools for the next generation of experiments. Several members of our group also lead very diverse scientific programs and field experiments that, although they employ similar tools, are aimed at discoveries unrelated to Short Distance Physics. Since the workshop includes other working groups that cover some of this range (i.e. New Forces and Tests of Gravity, and Light Dark Matter), we limit the scope of this report to experiments probing new physics at scales at or above the reach of the Large Hadron Collider, and which will not be addressed in other working groups.

Some of the recurring questions that lie within this distinct charge for our group are:

- Can we detect evidence for new physics between the electroweak scale (~0.1 TeV) and the GUT scale (~10^{13} TeV), including new sources of charge-parity (CP) violation? If so, can we understand how it relates to fundamental physical mysteries such as the origin of dark matter, the cosmological matter-antimatter asymmetry, or the stability of the Higgs mass?
- Can we show that neutrinos are Majorana particles and that lepton number is not conserved? A discovery of such phenomena would provide strong (if indirect) evidence for new physics between the electroweak and GUT scales.

Each of these topics is being actively pursued using a variety of tools from low-energy experimental physics and shows significant potential for near-term progress. In particular:

- Searches for CP-violation and new physics related to electric dipole moments (EDMs) using atomic, molecular, and optical (AMO) tools are advancing very quickly at this time. Recent experiments are already probing new CP-violating physics well above the TeV scale (within a very broad range of theoretical models). In addition, a combination of both well-grounded and blue-sky ideas for further progress hold the promise to increase sensitivity by many orders of magnitude in coming years: the PeV scale is within reach. Predictions of EDMs in the range of current experimental sensitivity are ubiquitous in theoretical extensions to the Standard Model.

- Searches for neutrinoless double beta decay could verify the Majorana nature of neutrinos, and discover the violation of lepton number. Planned or conceived experiments will probe a significant fraction of the known range of possible neutrino masses in coming years. While these experiments will ultimately be of extremely large scale, critical research and development efforts on game-changing detector technologies that are needed to advance the field qualitatively can be performed on a small scale.

- A handful of other room-scale experiments using AMO tools can probe particular types of new physics around the TeV scale. These include e.g. electron g-2 and fine-structure constant measurements; together, these can be used as a cross-check on calculations needed to interpret the muon g-2 anomaly, which is now being checked in a new large-scale experiment at Fermilab. Another example comes from atomic parity violation experiments, which can be sensitive to "leptophobic" Z' particles (heavier analogues of the Z boson) that may be hard to detect directly at the LHC.

- Experiments to directly measure the electron neutrino mass may also provide information on physics at very high mass scales. The extreme smallness of the neutrino mass scale is most naturally explained via the Seesaw mechanism, which invokes the existence of heavy right-handed neutrinos at scales ranging from the electroweak scale to the GUT scale. Determination of the absolute neutrino mass scale may make it possible to identify the high scale associated with the Seesaw mechanism. Again, while these types of measurements will ultimately be very large experiments, small-scale research and development on detection methods that can transform the field are needed.

- Good quality theoretical calculations are often an indispensable part of the process to search for new physics. For example, interpreting the electron and muon g-2 measurements in terms of new physics depends critically on high-accuracy quantum electrodynamics calculations. Similarly, calculations of nuclear matrix elements are needed to relate neutrino masses to the half-life of neutrinoless double beta decay, to interpret the underlying physics scale associated with EDMs of diamagnetic atoms, etc. At present the uncertainties associated with these nuclear calculations add substantially to the overall uncertainty in interpretation of the fundamental physics of interest. Somewhat further afield, we note that some of the strongest constraints imposed on new physics come from mid-scale particle physics experiments using K, B mesons and τ and μ leptons. The main bottleneck in using this information is often of theoretical nature. The use of Lattice QCD promises to significantly improve probes of PeV-physics associated with existing data on CP-violating mixing and decays of K-mesons.

We note as well several other topics that lie further from the center of our scope, but which are of interest in our community. In particular:

- It has only recently become possible to extend the scope of truly quantum-mechanical experiments to systems with large mass, and with many degrees of freedom. There are speculations about the relation of gravity to the boundaries of quantum behavior, e.g. quantum information. Experiments with large-scale quantum systems could conceivably shed light on questions of physics at the Planck scale, but a solid theoretical framework will be needed to design targeted experiments.

- Certain experiments using AMO tools that test for the breakdown of fundamental symmetries such as CPT or Lorentz invariance can, in principle, be interpreted as probing very high energy scales – even (by dimensional analysis) possibly above the Planck scale. So far, the interpretation of these measurements has been done within a framework of effective theory that introduces nontrivial cosmological background fields, but their possible origins remain highly obscure. Therefore, a self-consistent theoretical framework for interpreting these measurements is badly needed; until then, the meaning of these experiments as a probe of high-energy-scale physics is speculative.

2. Experimental Methods and Technology

AMO methods, which are generally centered around resonant interactions and controllable quantum systems, are now being used to pursue a wide range of science, including condensed matter physics and chemistry, as well as probing new, short-range particle physics. As the use of these tools grows, we are also seeing a developing synergy between diverse areas of science as new AMO ideas and tools now migrate quickly across traditional boundaries. The core AMO tools of atomic/molecular beams, vapor cells, spin-precession measurements, interferometry, and fluorescence detection are central to many of the precision measurement experiments that fall within our working group's charge. However, the many advances that are made in other AMO-enabled areas (e.g. clocks, quantum simulation, ultracold quantum gases, etc.) feed naturally into the next generations of precision experiments. Research and development efforts are sometimes needed to refine these methods specifically for EDMs or other short-range physics experiments.

In the realm of AMO-based EDM experiments, there is currently an extraordinary blossoming of new techniques and experimental concepts. These are most prominently due to the increasing levels of control over quantum systems via trapping and cooling. For example, several recent experiments have leveraged new techniques for producing, cooling, manipulating, and detecting molecules. Though molecules are more difficult to control than the atoms that were historically used for such measurements, the effects of EDMs are many orders of magnitude stronger in molecules than in atoms, and with improved methods this amplification can now be exploited. These recent rapid advances in AMO methods seem poised to continue, using other newly-developed techniques such as direct laser cooling of molecules, sympathetic cooling of molecular ions, etc. Recent ideas for taking advantage of amplified EDM effects using deformed (often radioactive) nuclei also have a unique promise for advancing the frontier of searches for CP-violating effects due to new short-range physics. Pushing these ideas to viability for an improved EDM measurement frequently requires development of new techniques or specific data — ranging from development of new cooling methods, to collection of molecular spectroscopic data, to development of new quantum-enhanced measurement protocols such as spin squeezing — that can only be obtained through dedicated, independent efforts.

In the realm of neutrino experiments, the role of small-scale experiments is primarily in the development of new detection methods and technologies. Some of these are related to AMO methods, e.g. laser-based detection of single ions (to suppress backgrounds in double beta decay experiments) or measurement of cyclotron frequency (to detect electron energies in a direct neutrino mass measurement). Other technologies, such as cryogenic bolometers, cryogenic microwave detectors and amplifiers, DNA-based low-energy-deposition particle detectors, new types of photon detectors, etc. rely on methods from other areas of physics, particularly condensed-matter physics. Sufficient research and development effort in pursuit of the most revolutionary of these ideas might enable advances not only in neutrino physics, but also in searches for dark matter and other types of new particles. It should be recognized that a substantial time lag may separate the development of these techniques from the execution of the science measurements.

3. Funding

There is broad agreement among the members of the working group that this part of the field suffers greatly from grants that are simply too small to make rapid progress and too narrowly focused on short-term results to support key exploratory endeavors. One consequence of this is the need to write many grant proposals with distinguishable goals, and to submit them to different agencies, each with different policies, to support a single coherent project in this field. There is scant funding for high-risk, proof-of-concept experiments, as well as for instrument development outside the context of a very experiment-specific research and development program.

In addressing this topic, we note that the funding from federal sources for the experiments within the scope of this working group varies widely in structure, so the most important issues within each subfield are discussed separately.

For work connected with experimental neutrino physics, the funding model is generally based on that for larger-scale particle and nuclear physics projects. In recent times federal agencies are placing more and more emphasis on such construction “projects”, which are managed according to strict rules and provide most of the funds for engineering activities rather than for truly innovative development of paradigm-changing new ideas. Exploratory research is hence stifled.

For experimental work using AMO tools, the funding model derives its essence from the most typical experiments in the atomic physics field. These have shorter time scales and more rapidly-evolving goals than in high-precision experiments. For precision experiments, obtaining long-term continuing support can be difficult, and funding for multi-institution efforts is rare. This can be a major obstacle to making rapid progress in more complex experiments testing fundamental physics. For these types of experiments, there is a consistent difficulty in obtaining engineering support, which generally requires both a very long-term funding commitment and a critical mass of researchers with similar needs. This type of support can also be difficult to obtain for long term, research-intensive development efforts meant to merge into larger scale experiments.

We also highlight a specific funding concern for the AMO-style experiments, which we refer to as the need for support of small-scale, “bottleneck-breaking” work. Here, we mean small projects that provide key enabling information for fundamental physics measurements, but which are not directly parts of the project. Examples include collection of spectroscopic data about molecules (e.g. to test the viability of using new species with enhanced sensitivity to EDMs), precise low-energy calculations of atomic and/or molecular structure, or quantum electrodynamic effects (e.g. to reliably interpret various fundamental experiments), etc. This type of work often falls between the cracks at funding agencies - e.g. molecular spectroscopy is historically funding through Chemistry programs, which are reluctant to support work motivated only by questions in fundamental physics.

Overall, there is broad agreement that for maximum impact, the emphasis of any new funding should be on room-scale projects (which could include long-term, research-intensive development of methods needed for new concepts in larger-scale experiments).

In general, different funding schemes could address different types of problems for the field. We suggest that a mix of the following types of funding support would be optimal for the field:

- Long-term (5-year) grants devoted to supporting excellent individual PIs (rather than specific projects), in a model similar to the HHMI or National Security Science and Engineering Faculty Fellowship programs, that could enable high-risk efforts, instrument development, and various synergistic advances in a way not currently possible in the field. There is broad agreement that funding of ~$350K/year/PI, is the right scale for experimental PI-driven efforts of this type, while $100K/year/PI would be appropriate for theorists in the field.
- One-time equipment grants, to enable purchase of larger items (or systems) needed to initiate new lines of work (including occasional larger-scale, multi-PI projects). Here grants ranging from $250K to $500K would be appropriate.
- Shorter-term (1-2 year) grants devoted to high-risk, novel pilot projects and/or for "bottleneck-breaking" work of the type described above. These typically could be smaller grants, on the order of $100K/year.
- Opportunities for linked, collaborative grants for a small group of collaborating PIs to mount somewhat larger projects, similar to the model pioneered by the ACME electron EDM experiment, with potential for a transformative impact on the field. These could be structured as a linked package of a few single-PI plus equipment grants of the type described above.
- We would enthusiastically recommend funding for regular meetings (every 1-2 years) to help build and maintain a coherent community in the general area of fundamental physics with small-scale experiments. At present, there is no meeting that consistently brings together the well-constructed configuration of researchers and scientific topics represented at the recent Moore Foundation workshop.

4. Additional Comments

To summarize, there are most definitely sufficient new ideas and technologies to make rapid progress in this area. The primary barrier to this progress is an overall lack of funding, and sub-optimal mechanisms for distributing the funding that does exist. Removing these barriers would enable tremendous potential for breakthrough discoveries in fundamental physics, which are unlikely to be made through the Large Hadron Collider or any other type of experiment.

Funding priority research areas

- room-scale EDM experiments (leading examples: experiments exploiting enhancement from molecules, enhancement from deformed nuclei, advanced cooling & trapping methods, etc.) and development of key enabling techniques for them
- breakthrough techniques for neutrinoless double beta decay (leading example: daughter atom tagging, advances to minimize reliance on ultrapure materials)
- precision measurements (leading examples: electron magnetic moment, fine structure constant with atom interferometry, new frontiers in parity violation)
- breakthrough methods to measure neutrino mass (leading example: resonance-based and calorimetric electron energy measurement)
- bottleneck-breaking work (leading examples: nuclear and atomic theory to interpret experimental results, molecular spectroscopy to enable breakthrough EDM experiments)

Funding structure models

- Primary (~60%): investigator-based grants (~$350K/yr experiment; ~$100K/yr theory, 5-year duration) to accelerate significant, direct advances in the field.
- Supplemental (~30%): equipment grants and/or larger project starter grants. Typical size ~$250K-$500K, one-time.
- Bottleneck and Pilot (~10%): small grants (~$100K/yr) for high-risk pilot projects (e.g. demonstration of new concepts) and/or for auxiliary, enabling "bottleneck-breaking" work typically done by PIs from other subfields (low-energy nuclear theory, molecular spectroscopy, etc.)

Table 2: Science probed by experimental methods. Relevance of various experimental methods and technologies to major scientific questions and issues in short-distance physics. A blank entry indicates no anticipated use of a particular method to address a particular question.

Experimental methods/technologies	**Major scientific questions/issues**			
	CP-violating interactions above TeV scale	New electroweak-scale interactions	Majorana nature of neutrinos	Direct neutrino mass measurement
Cold molecular beams	x	x		o
Trapped ions (electrons, atoms, molecules)	x	x	o	o
Laser cooling and optical trapping	o	o		o
Laser spectroscopy	x	x	o	
Radiofrequency spectroscopy	x	x		o
Single-particle detection & manipulation		x	o	x

o Proposed for use   x Currently used, with prospective improvements

Light Dark Matter

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1. Science

A variety of astrophysical and cosmological measurements strongly suggest that over 85 percent of all matter in the universe is dark matter. Identification of the properties of dark matter is paramount in cosmology, astrophysics and particle physics, since it will not only reveal the origins of the dominant constituent of matter in the universe but also offer insights into the cosmology of the early universe, uncover new physical laws, and potentially lead to the discovery of other fundamental forces.

a) The scientific case for new searches for light dark matter

Experimental efforts to detect dark matter have largely focused on Weakly Interacting Massive Particles (WIMPs), with masses between 10 - 1000 GeV. Despite considerable effort, there are no conclusive signs of WIMP dark matter interactions, even as experimental sensitivities have improved rapidly in recent years. While the WIMP is theoretically well-motivated, it is by no means the only dark matter candidate. Observational limits permit the mass of dark matter to be as low as 10^{-31} GeV or as high as 10^{48} GeV. A number of theoretically well-motivated candidates inhabit this vast parameter space, ranging from ultra-light axions to complex dark sectors that lead to ultra-heavy composite dark matter states. New ideas are necessary to probe these candidates.

Aided by remarkable advances in fields such as optical and atomic interferometry, magnetometry, and atomic clocks, several promising new experimental concepts have been recently proposed to employ these technologies to search for dark matter candidates with masses between 10^{-31} GeV - 10^{-12} GeV. Methods to probe ultra-heavy dark matter candidates with astrophysical and terrestrial measurements have also emerged. These ideas were developed as a result of collaboration between theorists and experimentalists across multiple disciplines such as high energy particle physics, atomic physics, condensed matter physics, and precision measurement.

The key idea behind these concepts is the fact that light dark matter particles (with masses below 10 eV) have a large number density and their phenomenology is described by a classical field. Ultra-heavy dark matter candidates (with mass larger than 10^{19} GeV) have to be composite states and these could source long-range classical fields. While these classical fields can be produced by a wide variety of dark matter models, their effects on Standard Model particles are limited to a small set of possibilities: the classical field can cause precession of nuclear/electron spins, drive currents in electromagnetic systems, induce equivalence-principle-violating accelerations of matter, and/or change the values of the fundamental constants of nature. By developing a variety of tools that can measure these four effects, we become sensitive to an enormous range of dark matter candidates.

Precision measurement technologies such as nuclear magnetic resonance (NMR), atomic and SQUID (Superconducting QUantum Interference Device) magnetometry, quantum-limited electromagnetic resonators, atomic/optical interferometers, and atomic clocks can be used to search for these effects. When the dark matter mass is light, the classical dark matter field leads to persistent time varying signals that are localized in frequency at the dark matter mass, enabling rejection of technical noise while permitting signal amplification through resonant schemes. The classical fields sourced by ultra-heavy dark matter could cause large, transient signals that can be observed by correlating output from multiple, synchronized detectors. These table-top-scale experiments offer an exciting path for continued progress.

Investment in precision instruments that can detect the effects of the classical fields associated with dark matter could lead to dramatic progress in the hunt for its properties. Light dark matter composed of particles with masses between 10^{-31} GeV - 10^{-12} GeV and ultra-heavy composite dark matter objects with masses below 10^{33} GeV can be searched for with the techniques discussed in Sections 1.b and 2. This would allow experimental exploration of over 20 orders of magnitude of dark matter masses, well beyond the presently probed WIMP parameter space.

On the theoretical side, investments into work connecting dark matter models to novel signatures detectable with precision measurements are important. This includes modeling of the galactic structure which may provide insight into the properties of light dark matter allowing experiments to narrow the parameter space to be searched. In some cases, investment into data analysis (such as the search for transient effects of dark matter from archival GPS, atomic clock, or magnetometry data) is desirable as a cost-effective discovery tool.

b) Emerging research directions in light dark matter searches

The entire field of laboratory cosmology, where tabletop-scale precision measurement experiments search for terrestrial signatures of effects related to light dark matter, has emerged as a vibrant research area over the last few years with a number of promising new proposals.

As noted above, based purely on the known properties of dark matter, the range of parameter space to be explored is quite vast. However, experiments can be guided by clues from other fields of physics suggesting mysteries that can be solved by postulating, for example, new particles with particular properties – this is what distinguishes the most theoretically well-motivated light dark matter candidates.

i. QCD axions, axion-like-particles (ALPs), and possible axion/ALP masses

Among the most well-motivated light dark matter candidates is the QCD axion, originally proposed to solve the strong CP problem of quantum chromodynamics (QCD). CP is the combined symmetry between matter and antimatter (charge conjugation, C) and mirror symmetry (parity, P), which is unexpectedly found to be respected by the strong force at an extremely precise level (better than a part in 10 billion). The QCD axion is predicted by the theoretically most compelling explanation for this fine-tuning problem in the form of a spontaneously broken symmetry. QCD axions couple to photons, gluons, and fermion spins in predictable ways covering particular regions of parameter space and could also quite naturally constitute a significant fraction of dark matter.

There are robust astrophysical constraints (originally based on the observation of the neutrino signal from supernova 1987A) on QCD axions with masses $\gtrsim$ 10 meV. Heavier axions would have produced observable effects in astrophysical objects, and much heavier axions would have been seen in terrestrial detectors.

Constraints have also been considered for QCD axions with masses $\lesssim$ 1 μeV. However, these constraints depend upon assumptions about unknown initial conditions of the universe. Such lighter mass QCD axions were never ruled out either by experimental or astrophysical observations, but theory prejudice held that they were less likely based on cosmology. It has now been realized that this was based on a particular scenario for the earliest epochs in the universe, a time about which we know very little. Since the inception of this cosmological argument against lower mass QCD axions, inflation has become the dominant paradigm for the birth of the universe. This (along with other factors) led to alternative possibilities for axion production in the early universe. As several authors have pointed out, these allow a much larger mass range for the QCD axion, and in fact bestows the lighter axions with a strong theoretical motivation. For example, these recent theoretical developments even motivated P. Sikivie, the originator of the ADMX concept discussed below, to propose a variant of the ADMX experiment to attempt to reach these well-motivated lighter axions. More details about the specific theoretical arguments concerning QCD axions with masses $\lesssim$ 1 μeV are given in Sec. 5.b.

It should also be noted that none of the above constraints apply to "axion-like-particles" (ALPs). ALPs are spin-0 particles similar in nature to the QCD axion but that do not solve the strong CP problem, but rather emerge naturally in frameworks such as string theory. Theories going beyond the Standard Model also predict the existence of spin-1 particles, commonly referred to as dark or hidden photons, which could also conceivably constitute a substantial fraction of the dark matter. ALPs may also have the properties necessary to solve the hierarchy problem, as discussed in Sec. 5.b. In conclusion, it is thus important to search for such particles over a wide range of mass/frequency parameter space.

ii. Experimental searches

The first large experiment searching for light dark matter composed of QCD axions is the Axion Dark Matter eXperiment (ADMX), which began its work in the 1990s. This experiment exploits the coupling of the QCD axion to the electromagnetic field to convert axions into microwave photons in a strong magnetic field **B** (see the Fig. 1). ADMX presently plans a sensitive search for QCD axions with masses in the range between ≈ 1 μeV and ≈ 100 μeV by 2021. Other groups, notably the ADMX-HF collaboration in the U.S. and a major effort at the Center for Axion and Precision Physics Research (CAPP) at KAIST in South Korea, are also building RF-cavity experiments to search for axions. There are a number of ideas, discussed in Sec. 2.b., that can extend the range of ADMX-like experiments to somewhat higher mass scales (e.g., ADMX-HF), or significantly lower mass scales using a lumped-element resonator, e.g., the "dark matter radio" concept discussed below.

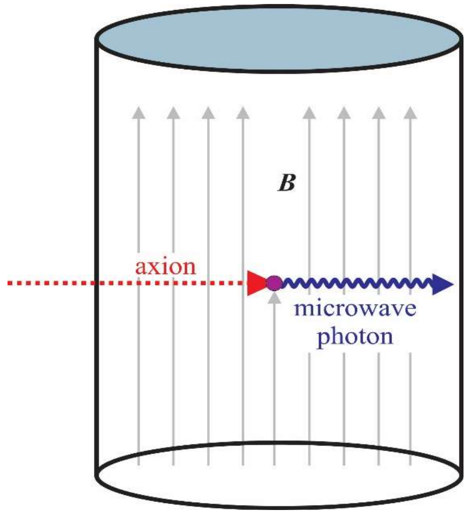

Figure 1: *Schematic diagram showing the concept of the ADMX experiment, where axions are converted into photons in the presence of a strong magnetic field **B** (the Primakoff effect). Axions penetrate into the cavity where they encounter the virtual photons comprising **B** and through the axion-photon interaction the axions impart their energy to the virtual photons thereby converting them to detectable microwave photons.*

A new experiment searching for lighter QCD axions using different couplings from those exploited in ADMX is the Cosmic Axion Spin Precession Experiment (CASPEr). CASPEr exploits both the axion-gluon coupling, which generates a time-varying electric dipole moment (EDM) of nuclei (CASPEr Electric), and the coupling of the axion to nuclear spins (CASPEr Wind). CASPEr uses nuclear magnetic resonance (NMR) techniques for detecting spin precession caused by background axion dark matter. This approach complements ADMX which is sensitive to higher axion masses, whereas CASPEr covers lower axion masses.

The key idea underlying the CASPEr concept is that axion dark matter can cause the rotation of nuclear spins, and axions can be detected if this rotation is observed. Nuclear spins in a non-centrosymmetric crystal, such as a ferroelectric, experience a large effective electric field, a phenomenon analogous to the large internal electric fields experienced by electrons in polar molecules. The coupling of the axion dark matter field to nuclear spins (via the generation of electric dipole moments through the axion-gluon coupling) in such a material has the form of a pseudo-magnetic field $\mathbf{B_1}^*$ oscillating at the axion Compton frequency. If the external bias magnetic field $\mathbf{B_0}$ is set to a value such that the nuclear spin splitting matches this frequency, a resonance condition is achieved, and the nuclear spins (and the corresponding magnetization **M**) tilt and undergo Larmor precession (see the Fig. 2). A precision magnetometer, such as a Superconducting Quantum Interference Device (SQUID), placed next to the sample, detects the oscillating transverse magnetization. The experimental protocol of CASPEr-Electric is to sweep the externally-applied bias magnetic field and search for a non-zero magnetometer response, which is a signature of spin coupling to the axion dark matter field.

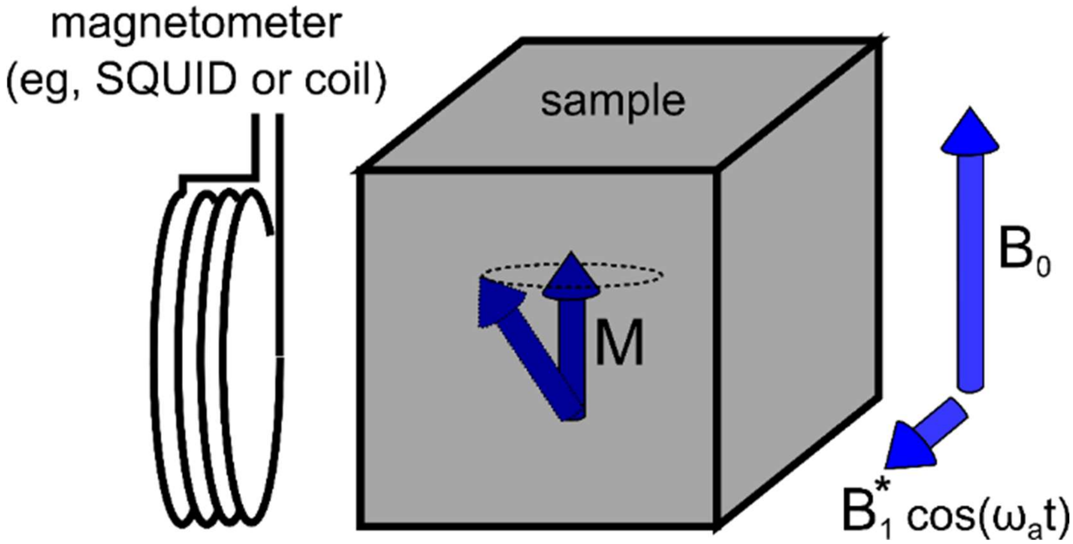

Figure 2: *Schematic diagram of the CASPEr experiments, where the oscillating axion field acts as a pseudo-magnetic field* $\boldsymbol{B_1}^*$ *that causes polarized nuclear spins to tip away from the leading field* $\boldsymbol{B_0}$ *and precess at the Larmor frequency. The approach is based on the principles of NMR experiments.*

CASPEr-Electric is a precision experiment that combines the advances in ultra-sensitive magnetometry, NMR, and materials science. The first experiments being built at Boston University will focus on using ^{207}Pb spins in ferroelectrics such as $PbTiO_3$ and PMN-PT, polarized in a strong magnetic field at temperature of 4.2 K. One of the notable features of this experimental approach is the very wide range of axion masses that it can be sensitive to, limited by the strength of the bias magnetic field that can be applied to the sample. The experimental reach is summarized in the Fig. 3. CASPEr has the potential to improve the existing astrophysical bounds on coupling of the axion-like dark matter field by many orders of magnitude, over a wide range of axion masses.

A detection of the QCD axion in an experiment such as ADMX or CASPEr would not only constitute the discovery of the nature of dark matter but would also provide insights into the high-energy scales from which the axion arises, near the fundamental scales of particle physics such as the scale of grand unification and the Planck scale. If a detection is made, a network of such experiments can be used to verify it, since the signal in all of them should be centered at the axion Compton frequency, which would be a fundamental constant. A network would also enable the study of the dynamics and coherence properties of the axion dark matter field.

CASPEr Wind is an example of an experiment specifically sensitive to ALP dark matter (at least in its present form it will not have sufficient sensitivity to reach parameter space corresponding to the QCD axion). CASPEr Wind is completely analogous to CASPEr Electric, except that the pseudo-magnetic field $\mathbf{B_1}^*$ is generated by a different mechanism: the coupling of nuclear spins to the spatial gradient of the ALP dark matter field (the so-called "ALP wind"). This enables the use of materials without electric fields, in particular samples such as liquid xenon that can be efficiently spin-polarized to enhance the signal.

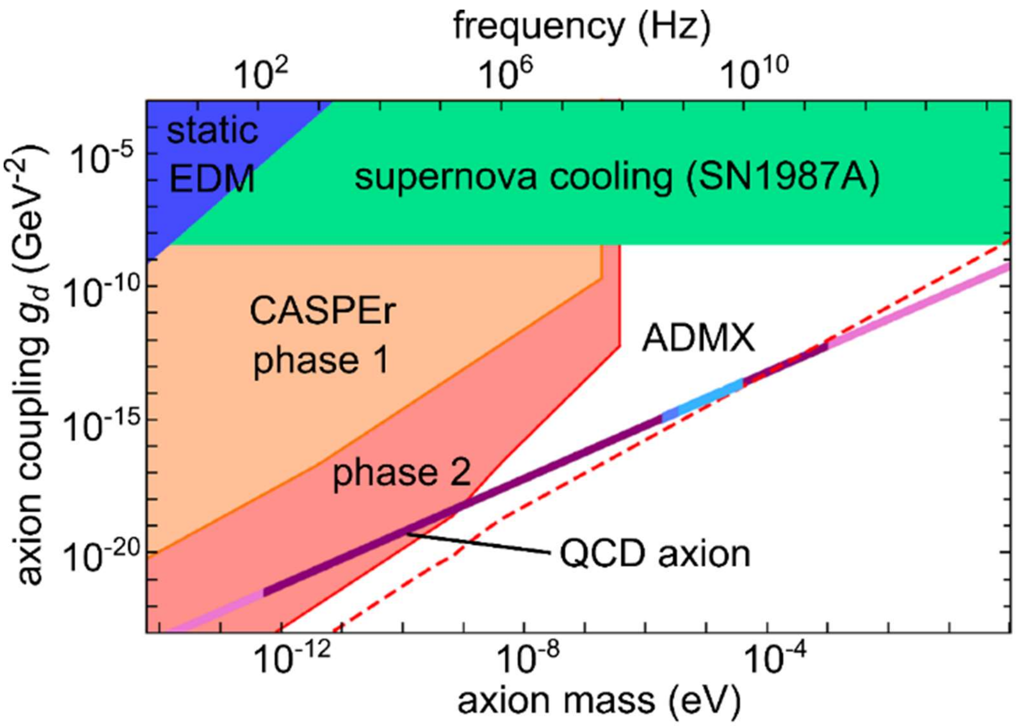

Figure 3: *A plot of the parameter space searched for in the CASPEr Electric experiment. The shaded blue region in the upper left corner is excluded by searches for static CP-violating permanent electric dipole moments (EDMs). The green shaded region at the top is excluded based on the observed cooling rate of supernova 1987A. The purple band labeled "QCD axion" represents the predicted mass/coupling parameter space corresponding to models of the QCD axion. The blue section of the QCD axion band shows the mass region probed by ADMX, although note that ADMX probes a different coupling than CASPEr. The light orange shaded region shows the predicted sensitivity of the first generation CASPEr experiment, the dark orange shaded region shows the predicted sensitivity of a future second generation experiment.*

Several experiments, including CASPEr Wind and DM Radio (discussed below), are also sensitive to another class of particles known as dark or hidden photons. Like ordinary photons, hidden photons are a vector particle with spin 1. However, hidden photons have mass and could constitute the dark matter. Hidden-photon dark matter can be described as a weakly coupled "hidden electric field," oscillating at the hidden photon Compton frequency, and able to penetrate any shielding. At low frequencies (where the wavelength is long compared to the size of the shielding), the interaction of electrons in the shielding material with the hidden photon field generates a real, oscillating magnetic field. It has recently been proposed that such hidden-photon dark matter can be searched for using a tunable, resonant LC circuit designed to couple to this magnetic field, a "dark matter (DM) radio." Hidden-photon dark matter has an enormous range of possible Compton frequencies, but current experiments (such as ADMX, which is also sensitive to hidden photons) search only over a few narrow parts of that range. In contrast, a DM radio has potential sensitivity many orders of magnitude beyond current limits over an extensive range of frequencies, from 100 Hz up to 700 GHz and potentially higher.

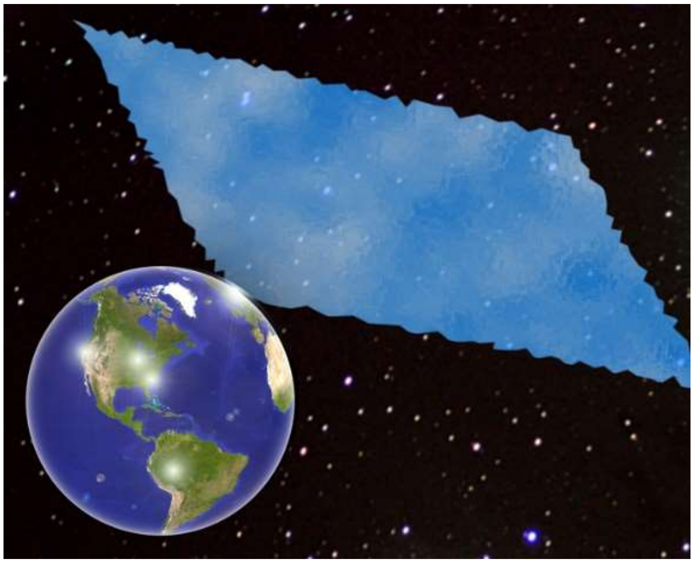

Figure 4: *The Earth encounters an invisible dark matter object such as an axion/ALP domain wall or clump of ALPs (shown in light blue). The encounter could produce transient signals detectable with a global network of sensors such as magnetometers or clocks, the concepts of the GNOME and GPS.DM experiments, respectively*.

Another distinct theoretical possibility is that the light dark matter is not distributed uniformly throughout the galaxy but rather occurs in the form of clumps or “dark stars” or even “topological defects” manifesting as domain walls. These scenarios can occur due to axion/ALP/hidden-photon self-interactions, gravitational interactions, or features of the light-dark-matter quantum vacuum states. If the dark matter takes such a form, terrestrial detectors would not register a continuous signal associated with the light dark matter field as is searched for in the ADMX, CASPEr, or DM radio experiments, but rather would observe infrequent transient events associated with the passage of the Earth through such a dark matter object.

The Global Network of Optical Magnetometers to search for Exotic physics (GNOME) collaboration is searching for such transient signals due to passage of the Earth through dark matter objects that couple to atomic spins (similar to the ALP wind coupling searched for by CASPEr). While a single magnetometer system could detect such transient events, it would be exceedingly difficult to confidently distinguish a true signal generated by light dark matter from “false positives" induced by occasional abrupt changes of magnetometer operational conditions (e.g., magnetic-field spikes, laser-light-mode jumps, electronic noise, etc.). Effective vetoing of false positive events requires an array of magnetometers. Furthermore, there are key benefits in terms of noise suppression and event characterization to widely distributing the magnetometers geographically. The Laser Interferometer Gravitational Wave Observatory (LIGO) collaboration has developed sophisticated data analysis techniques to search for similar correlated “burst" signals from a worldwide network of gravitational wave detectors, and the GNOME collaboration has demonstrated that these data analysis techniques can be adapted to analyze data from the GNOME. Presently the GNOME consists of 5-10 dedicated atomic magnetometers located at stations throughout the world.

Such dark matter clumps or domain walls can also manifest themselves as glitches of atomic clocks, for example those onboard GPS satellites. The glitches would propagate through the GPS constellation at galactic velocities, ~ 300 km/s, characteristic of dark matter. The GPS.DM collaboration is mining a decade of archival GPS data to hunt for such dark matter objects, effectively using the GPS constellation as the largest 50,000 km-aperture human-built dark matter detector. While the initial results at 5 sigma sensitivity have not found evidence for such objects yet, they improve the current constraints on certain dark matter couplings by several orders of magnitude. Further progress requires developing Bayesian statistics algorithms and increasing computational power. In addition, conceptual developments are underway to search for other dark matter candidates from both the GPS data and the GNOME data.

The variety of new proposed experiments designed to search for light dark matter emerging in the last few years exemplifies the vibrancy and excitement of this reinvigorated field of research resulting from fruitful collaborations between theorists and experimentalists.

2. Experimental Methods and Technology

At the outset it is important to note that in terms of technology applicable to light dark matter searches, there are many complementary tools that can target both different "portals" and different ranges of particle masses. Portals refer the mechanisms through which the light dark matter couples to ordinary matter. As noted in the introduction, there are a limited number of portals: light dark matter can couple to electromagnetic fields (photons) as searched for in the ADMX and DM radio experiments, can create torques on atomic spins as searched for in the CASPEr and GNOME experiments, or generate apparent violations of the equivalence principle or variations of fundamental constants that can be detected with atomic clocks (GPS.DM) or atom interferometers, for example. These portals can, in principle, be largely independent (especially in the case of ALPs and hidden photons) and can be probed over different frequency ranges corresponding to different ranges of axion masses. Thus technologies are not exclusive of one another: methods well-adapted to one region of parameter space may not be as useful in another region of parameter space and vice-versa.

A second important point is that the distinction between well-established "workhorse" technologies and "new and emerging" tools is not always clear, primarily because the entire field of research into light dark matter is new and emerging. There are many well-developed technologies that have received considerable investment over many decades but that have only recently been considered for application to light dark matter searches. Adaptation to a particular experimental goal pushes the technology beyond its usual sphere of use and often requires considerable research and development. An example of this is NMR technology, which has been widely researched and applied to an enormously diverse array of problems in physics, chemistry, biology, and medicine over many decades. NMR technology is the central experimental tool employed in CASPEr, but in order to effectively probe the wide range of targeted axion masses at the required level of sensitivity, research must be carried out on hyperpolarization techniques, reduction of spin-relaxation, techniques to scan large ($\sim$ 10T) magnetic fields while maintaining ppm field homogeneity, and detectors. The corollary to this is that research into technology useful for light dark matter searches often has exciting spin-off potential and can be applied in other areas.

a) Workhorse technologies

i. ADMX and CAPP experiments

As discussed in Sec. 1.b, the ADMX and CAPP experiments are successful, well-developed experiments positioned for significant advances in the near future. The range of the ADMX and CAPP experiments can be extended to somewhat lower axion masses with a dedicated research and development effort to engineer lower-frequency quantum-limited devices: in particular, the amplifiers currently employed in ADMX become less useful at lower frequencies, and suitable dc SQUID amplifiers may need to be developed. In parallel, suitable low-frequency resonant structures (a variant of "transverse slow wave" cavities) need to be developed. For somewhat higher axion masses, however, it is unlikely the present ADMX/CAPP cavities can be extended to higher frequencies and new ideas are needed. For instance, Fabry-Perot resonators have the requisite high frequency and high Q, but research and development would need to occur on their use in axion search experiments and the suitable microwave readout. Parallel development of high-frequency bolometric receivers would also need to happen.

ii. Global networks of sensors

Another way that investment in "workhorse technologies" (such as atomic clocks, magnetometers, atom interferometers, and torsion pendulums) can pay dividends for light dark matter searches is through the development of international collaborations enabling coordinated searches for transient events. Traditionally, precision measurement experiments searching for new physics have focused on effects that are either time independent or subject to periodic modulation due to changes of a local laboratory source of the new effect or due to Earth's rotation or orbit. Recently it has been realized that precision measurements could be sensitive to transient signals from light dark matter. As mentioned in Sec. 1.b, to search for nonuniform distributions of dark matter (or even dark energy), researchers have proposed networks of atomic magnetometers (GNOME) and clocks (GPS.DM). The readings of remotely located network sensors are synchronized – for example, using the timing provided by GPS – and analyzed for specific transient features.

iii. Hybrid networks

Also being discussed are hybrid networks consisting of different types of sensors that would be sensitive to different possible interactions with the dark sector. For example, it may well be that the axion spontaneous decay rate is adequate to enable dedicated astrophysical searches employing, for example, radio telescopes. These could work in tandem with terrestrial detectors that evaluate candidates handed to them from radio telescopes.

b) New and emerging technologies

i. Quantum information processing in ADMX and DM radio

As previously noted, one strategy for sensing the presence of light dark matter is to detect its ability to generate electrical currents. This strategy is at the heart of the ADMX and DM radio searches. Detecting these feeble electrical currents is a measurement challenge in which one eventually encounters a limiting background of quantum fluctuations. It is now possible to detect at the quantum limit. But especially for currents flowing at microwave frequencies (corresponding to axion masses greater than 40 μeV), this quantum background is unacceptably large. A frontier of this type of search is to circumvent the quantum noise and extending searches to larger axion masses.

Fortunately, in the context of quantum information processing there have been recent advances in the ability to prepare and measure quantum states of microwave frequency electrical circuits. Bringing these capabilities to axion searches could speed up the rate at which parameter space is covered. In one concept, squeezed states of the microwave field can be used to suppress quantum fluctuations. This strategy can accelerate an axion search by factors of 2 - 4. This is certainly helpful when one can only scan 1/1000th of the favorable mass range in a year. Much more impactful would be the ability to search for axions by performing a nondestructive (quantum nondemolition, QND) measurement of microwave photon number. Such a measurement could accelerate an axion search by a factor of 100 or more compared to a quantum-limited search.

ii. High quality factor (Q) lumped-element resonators

To date, resonant cavity searches for dark matter have principally used RF and microwave cavity resonators with high quality factor. These techniques are limited to structures with a size on the order of a wavelength, and thus are difficult to implement below about 100 MHz. Resonant experiments to probe dark matter in the frequency range 100 Hz to 100 MHz, such as DM Radio, require the development of lumped element resonators based on high-quality, low-loss, tunable capacitors and inductors optimally coupled to quantum amplifiers that do not degrade the cavity quality factor. The development of designs, materials, and amplifiers that can achieve quality factors Q of order a million, with very large scan ranges, will open up new search possibilities for both axions and hidden photons over a much larger low-frequency range.

iii. Zero to ultralow field nuclear magnetic resonance techniques in CASPEr

The CASPEr-Wind experiment may be extended to lower frequencies using the techniques of zero- to ultralow-field nuclear magnetic resonance (ZULF NMR). ZULF NMR is an emerging magnetic-resonance modality where measurements are performed in a magnetically shielded environment such that "internal" spin-spin interactions are dominant and couplings to "external" or applied magnetic fields are small enough to be treated as perturbations.

For a liquid-state sample, this means that the resonant frequencies are determined primarily by electronic structure of the analyte molecule, and additional shifts can be induced by applying small static fields. Recently, it has also been shown that low-amplitude, ultralow frequency oscillating magnetic fields can be used to manipulate ZULF NMR spectra by selectively driving nuclear spin transitions. Because nuclear spins cannot differentiate between a real oscillating magnetic field and the pseudo-magnetic field induced by the axion wind, precision measurement of ZULF NMR spectra can be used to search for axions. By choosing an appropriate set of molecules, such an experiment can be sensitive in the range of about 1 - 300 Hz, a well-motivated frequency range that corresponds to a spontaneous symmetry breaking energy scale close to the Planck energy ($\sim 10^{19}$ GeV).

iv. Superfluid helium detectors

Superfluid helium is a promising material for detecting very small energy depositions, such as those produced by the interactions of light dark matter particles. Superfluid provides three types of excitations: scintillation light (likely with very high yield), metastable triplet excimers that move ballistically through the medium and can be detected directly by immersed calorimeters, and rotons/phonons of sufficient energy to cause quantum evaporation of helium atoms from the liquid helium surface. The evaporated atoms are then adsorbed onto the surface of an athermal calorimeter, releasing a binding energy that is an order of magnitude larger than the original roton/phonon energy, thereby amplifying this signal channel within the detector itself. Finally, superfluid helium offers the capability of recognizing nuclear recoils through the measurement of branching ratios between the various signal channels described above. With a volume of superfluid helium surrounded by sensitive calorimeters, all three of these signal channels may be detected with the same readout sensors. This detector scheme can operate at temperatures of order 100 mK, and the helium target material is low in cost. Because the helium nucleus is low in mass, it is able to efficiently extract the kinetic energy of low-mass dark matter particles through elastic scattering. With a small neutron number and charge, helium nuclei exhibit intrinsically low backgrounds from neutrinos and gamma rays. Superfluid helium has intrinsically low sensitivity to vibrational noise because a critical wall velocity must be exceeded to create superfluid excitations. Finally, the superfluid helium detector scheme requires no applied electric field, thus eliminating noise from dark current, which troubles many detectors that are based on charge detection. These detectors can search for light dark matter such as hidden photons with mass in the eV range.

v. Precessing ferromagnetic needle magnetometer

There are also a number of new experimental ideas that could significantly impact light dark matter searches that have yet to be realized in the lab. One of these is a recent prediction of a new behavior for ferromagnetic objects in sufficiently small magnetic fields: instead of aligning along the magnetic field (like a compass needle) they will precess about the magnetic field (like polarized nuclei in NMR experiments). In this regime a ferromagnetic needle behaves as a gyroscope with angular momentum generated by the intrinsic spins of polarized electrons. If a precessing ferromagnetic needle is used to measure magnetic fields (or to search for light dark matter), a remarkable feature emerges: the quantum noise associated with the uncertainty in the spin orientation can be rapidly averaged away. This may allow measurements of unprecedented precision to be performed, surpassing the present state-of-the-art by orders of magnitude.

vi. Thorium nuclear clock

Another example of a potentially transformative technology not-yet-realized in the laboratory is the thorium nuclear clock. Today's most precise time and frequency measurements are performed with optical atomic clocks. However, it has been proposed that they could be outperformed by a nuclear clock, which employs a nuclear transition instead of an atomic transition. There is only one known nuclear state that could serve as a nuclear clock using currently available technology, namely, the isomeric first excited state of ^{229}Th. There is ongoing research by several groups aiming to pin down the precise characteristics of the ^{229}Th nuclear transition.

3. Funding

a) Funding obstacles

There are a number of key funding obstacles impeding progress in the field of light dark matter research:

- Traditional funding sources (especially government) tend to be conservative and fund established research directions with existing, well-established communities. This institutional inertia makes it particularly challenging to adequately support new research directions, such as the search for light dark matter over a broad parameter space.

- Similarly, this institutional inertia makes it difficult to find seed funding for demonstration of new, unproven ideas and technology development: high-risk, proof-of-concept, pioneering experiments seldom receive necessary support to see if they are viable.

- Searches for light dark matter naturally involve interdisciplinary work and medium-sized collaborations bringing together researchers from several different institutions. Grants supporting interdisciplinary, collaborative work on this scale do not fit into the existing governmental funding schemes.

- Precision measurements of the kind necessary to search for light dark matter have always taken considerable time, much longer than the usual grant cycle. This is the inevitable course when experiments push the precision frontier: new effects (arising from standard model physics) are routinely discovered that require careful, time-consuming study.

- It is extremely difficult to progress from small-scale, proof-of-principle funding to the medium-scale funding ($1-3 million per year) necessary to fund the multi-institution collaborations needed to effectively pursue some of the proposed light dark matter searches.

b) Suggested models

The search for light dark matter requires the scientific community to cast a wide net (within reason) and to pursue various strategies deeply (within reason). Of course, the best ideas should be funded and we want to maximize the "science return per dollar" while at the same time taking into account the significant uncertainty with regards to where in the parameter space the light dark matter may be hiding. Private foundation support could play a critical role in advancing the field of light dark matter research by mitigating the funding obstacles identified above by providing:

- Seed funding for high-risk, proof-of-concept experiments that have transformative potential;

- Funding for medium-sized, multi-institution collaborations – including travel funding for longer-term visits between researchers such as sabbaticals and host lab visits;

- Extended periods of support (∼ 5 years) enabling collaborations to pursue research deeply.

4. Conclusions and Outlook

In summary, the injection of new funding can make a deep and broad impact on light dark matter research. As we have noted above, there are essentially four ways in which light bosons can couple to ordinary matter through the various portals to Standard Model particles and fields: (1) by coupling to photons, (2) by exerting torques on atomic spins, (3) via new forces, and (4) by causing apparent variations in fundamental constants. Tabletop precision measurement techniques offer a portfolio of experiments which can investigate significant regions of unexplored parameter space for all four of these basic light boson couplings by using, respectively: (1) electromagnetic resonators, as in the ADMX, CAPP, and DM radio experiments; (2) magnetometry and NMR techniques, as in the CASPEr and GNOME experiments; (3) atom/light interferometers; and (4) atomic clocks, as in GPS.DM. Furthermore, each of these approaches offers numerous opportunities for research and development of new technology that could significantly expand the reach of these searches.

Adopting a funding model of supporting about five medium-sized collaborations at a level of $1 million per year and 10-20 proof-of-concept research and development projects at a level of $200k - $500k per year could support nearly all the research described in this report, completely transforming the field of light dark matter research.

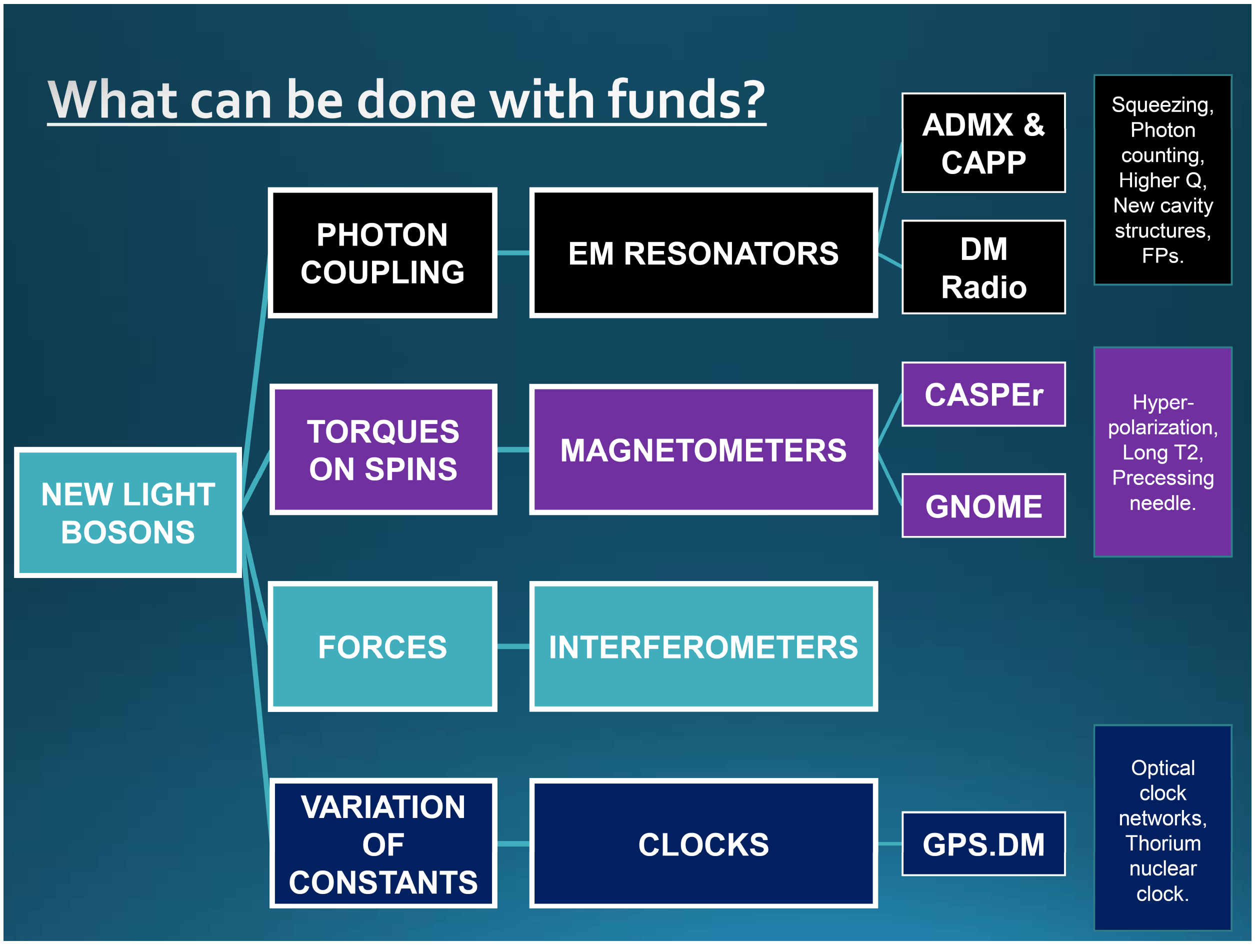

Figure 5: *The scope of experimentally observable effects induced by dark matter consisting of light bosons (second column from the left), the types of experimental tools useful for detecting such effects (third column), and existing and potential future experiments pursuing these methods (fourth and fifth columns, respectively). Crucially, there are a limited number of portals through which new light bosons can couple to standard model particles and fields, allowing a focused experimental search effort. Funding support for the field of laboratory cosmology can facilitate exploration of all these possibilities.*

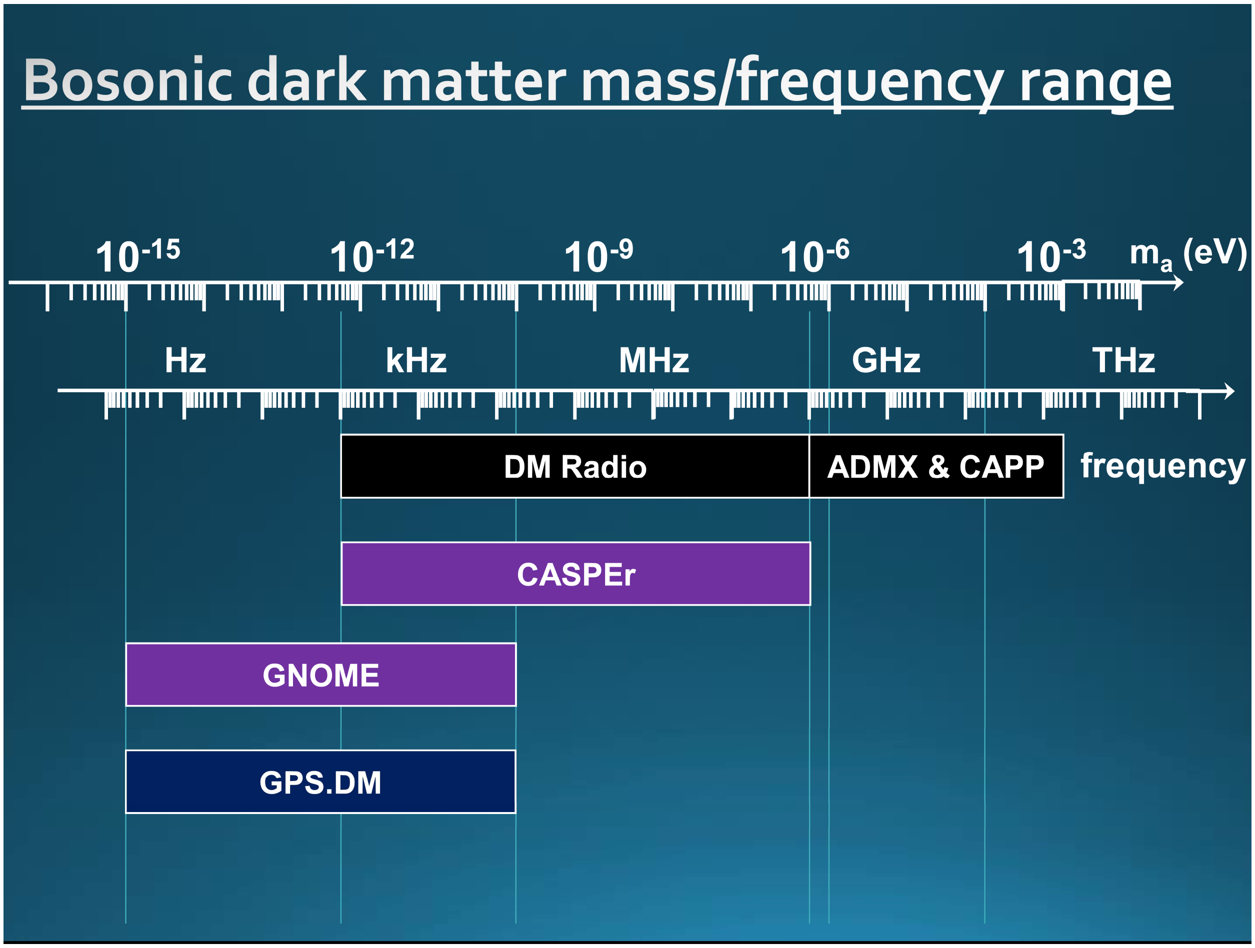

Figure 6: *The range of boson masses and corresponding Compton frequencies, which corresponds to the oscillation frequencies of the light dark matter field, to be explored by the portfolio of experiments described in this report. Significantly, different experiments cover different regions of the boson mass parameter space. Experiments in black shaded boxes measure the photon couplings, experiments in purple-shaded boxes measure torques on spins, and experiments in blue-shaded boxes measure variations of constants (corresponding to the color-coding of Fig. 5).*

5. Additional Comments

a) Early career support

The funding challenges facing the field of light dark matter research can also be discouraging to young researchers passionate about pursuing such work. Additional support for this field could mitigate this problem and provide a viable career path for the best and brightest young scientists passionate about fundamental physics research.

b) QCD axions with masses $\lesssim$ 1 μeV

QCD axions with masses $\lesssim$ 1 μeV can produce too much dark matter and thereby "over close" the universe, meaning that the universe would gravitationally collapse shortly after the Big Bang.

In the absence of additional physics, this statement is robustly true if inflation precedes axion creation. On the other hand, if inflation occurs after axion creation, the axion abundance in our universe depends upon the unknown initial "misalignment" angle of the axion field. If this angle is assumed to be on the order of unity, such lighter mass axions can be ruled out. However, this bound rapidly disappears if the initial misalignment angle is only somewhat smaller.

The conventional picture of the production of axions in the early universe stated that the QCD axion mass was most likely to lie in a relatively narrow mass range between about 1 μeV and 1 meV. The lighter mass QCD axions were never ruled out either by experimental or astrophysical observations, but theory prejudice held that they were less likely based on cosmology.

Even though it has been argued that the mass range for the QCD axion should lie between 1-100 μeV, axions in this mass range raise other theoretical issues. Such axions would have to emerge from a symmetry-breaking scale ~10^{12} GeV that is much lower than the theoretically preferred fundamental scales of particle physics such as the string scale or the Grand Unified Theory (GUT) scale (~10^{16} GeV) or the Planck scale (~10^{19} GeV). Moreover, generic models that produce axions in the range 1-100 μeV are ruled out since they produce a large density of domain walls which would affect cosmological structure in a way inconsistent with observation. The simple so-called "N=1" axion model is unaffected by this constraint, but this model does not sufficiently protect the QCD axion from potential quantum gravity corrections that would ruin the axion's solution to the strong CP problem. However, both of these issues can be solved in more complicated axion models.

Thus it turns out from a theoretical perspective that there is motivation to search for lighter QCD axions with masses in the neV range. Fundamental theories of particle physics beyond the Standard Model such as string theory naturally produce axions at these masses. Since observational bounds require inflation to have occurred below these scales, these neV scale axions would be observationally consistent as long as their initial misalignment angle is somewhat small (~1/30). These models also do not suffer from the problems of domain wall over-production since inflation would naturally remove them. Thus, at the price of a minor tuning, this scenario fits well within the landscape of theoretical particle physics. (These light axions can be constrained by isocurvature measurements if high-scale inflation is experimentally observed, although it should be noted that these bounds are also model dependent.)

QCD axions with masses lower than ~1 neV would require more fine tuning. For example, the initial angle must be ~10^{-4} for axions at the peV scale, corresponding to QCD axions emerging from symmetry breaking scales at the Planck scale. In this case, the initial fine-tuned abundance of the QCD axion could be naturally explained by anthropic considerations: namely the idea that there is an initial random distribution of misalignment angles in the universe so that, of course, humans exist in regions of the universe where the misalignment angle is such that life is possible. Such anthropic arguments are the only known explanation for the observed coincidence in the energy density of dark matter and the baryon content of the universe. This puzzle is particularly sharp for dark matter particles such as axions where the dark matter and the baryon abundances arise from completely different physics. It should be noted that such "tuned" values of the axion misalignment angle also naturally emerge in models such as the relaxion scenario where the axion solves the hierarchy problem.

In summary, there have been a number of arguments over the past 30 years on the theoretically preferred range of axion masses. In the absence of hard observational evidence, it is not surprising that these discussions have been inconclusive. It is highly likely that this question will need to be settled by experiment.

Table 3: **Searching for Light Dark Matter**. The table lists some light dark matter dedicated experiments and relevant technologies, indicating for each experiment / technology the type of particle and its assumed coupling to standard model particles.

		Light dark matter particle					Light dark matter portal			
		QDC axions	Axion-like particles		Dark/hidden photons	Composite objects (topological defects, clumps, etc.)	Photon coupling	Torques on spins	New forces	Variation of "constants"
Dedicated experiments	ADMX	•	•	•	•		•			
	CAPP	•	•	•	•		•			
	CASPEr Electric	•						•		
	CASPEr Wind		•					•		
	DM Radio			•	•		•			
	GNOME		•			•		•		
	GPS.DM		•			•				
Existing and emerging technologies	Microwave cavities						•			•
	Biometric receivers						•			
	Fabry-perot cavities						•			
	Squeezing and QND						•	•		
	High-Q lumped resonators						•			
	ZULFNMR							•		
	Superfluid Hellum								•	
	Precessing ferromagnetic needle							•		
	Thorium nuclear clock									•

New Forces and Tests of Gravity

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1. Science

The community of researchers doing small and medium scale searches for new forces and tests of gravity come from a variety of scientific backgrounds. They share the goal of both applying state of the art techniques and developing new high precision techniques to study the constituents and forces of nature. The diversity of backgrounds has led to creative and disparate approaches toward experiments that address the science questions discussed below. These experiments are complementary to accelerator driven particle physics and are likely to play an increasingly important role in the goal to better understand our universe.

The Dark Sector

Multiple lines of astrophysical evidence (Fig. 7) show that 96 percent of the mass in the universe exists as dark matter and dark energy (Fig. 8). Detecting dark sector particles directly through their interaction with normal matter and studying them is of paramount importance, as it will reveal the dominant constituents of the universe. Knowledge of the dark sector is also essential to understanding the early evolution of the cosmos. Physicists have therefore built enormous detectors to search for heavy dark matter particles, and combed data from particle colliders. None of these efforts has produced uncontested evidence for the dark sector, creating truly a cosmic mystery.

From the astrophysical evidence that is already available, we understand that the dark sector cannot simply be composed of the known particles. Also, the requirement to match all confirmed observations is a strong constraint and guide for developing new theories. Theorists have proposed new low-mass bosons (axions, axion-like particles, chameleons, dilatons, $f(R)$ theory, galileons, symmetrons and so on), some better motivated than others that could be part of the dark sector. These particles would lead to new forces with macroscopic ranges that could be detectable as coherent fields rather than as discrete quanta, and could lead to apparent oscillations of fundamental constants. These ideas have motivated a variety of new experimental techniques for the detection of ultra-light particles.

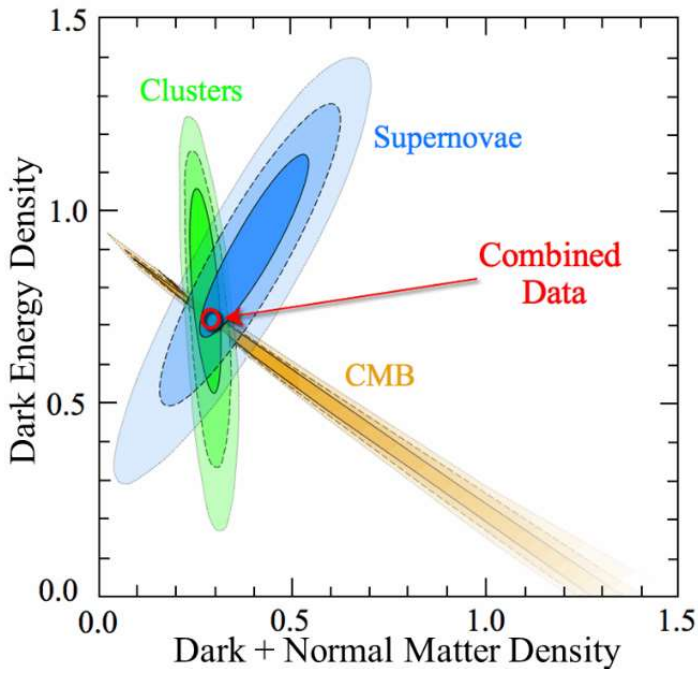

Figure 7: *Evidence supporting a universe of dark matter and energy. The matter required to form galaxy clusters, the accelerating expansion rate of the universe as measured by distant supernovae, and the exquisite measurements of the cosmic microwave background provide independent measures of the matter and energy density of the universe. The methods are in agreement with a universe of 30% matter and 70% dark energy Image: Kowalski et al, Astrophys. J.* ***686,*** *794 (2008).*

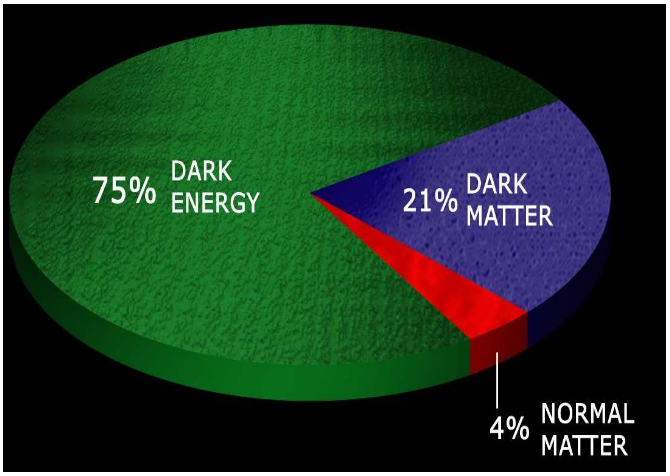

Figure 8: *Our best estimate for the composition of the universe. Image: ADMX et al, Astrophys. J. 686, 794 (2008)*

Quantum Nature of Gravity

Gravity is the least understood of the fundamental forces. Open questions include why gravity is so much weaker than the other forces in nature, how to construct a quantum theory of gravity, and the behavior of gravity in the strong field regime. String theory, which can provide a quantum theory of gravity, requires extra spatial dimensions and new scalar particles such as the dilaton, moduli, and radion. The extra spatial dimensions would lead to gravity becoming stronger at short distances and help explain the weakness of gravity in our 4-dimensional world while other speculations about an extended (fuzzy) graviton would have gravity become weaker at short distances. Both scenarios can be addressed by new tests of the inverse-square law of gravity at short distances. Virtual exchange of the scalar particles of string theory would manifest as an apparent breakdown of the principle of equivalence; a new macroscopic force on top of the gravity of General relativity. The strong principle of equivalence, a cornerstone of general relativity, states that gravitational binding energy experiences gravity the same as other forms of energy and is a prediction that can be tested by experiments. More precise tests of the principle of equivalence over wide length scales and tests of the inverse-square law at ever shorter distances may provide a window to the world of quantum gravity.

There has also been recent interest in phenomenological quantum gravity, which aims to connect models (not necessarily theories, hence the phenomenological) of quantum gravity with observation or experiment. In this context, quantum gravity means anything that is able to reconcile the seeming conflict between gravitational and quantum theories. Early ideas related to gravitationally induced decoherence were discussed by Penrose in the context of macroscopic quantum superpositions. While many proposals are out there, a conservative idea that is appealing and popular lately is to observe the evolution of the Wigner function of a single macroscopic object in a squeezed state and see whether it is consistent with so-called Schrodinger-Newton equation. But considerations of how to really perform such an experiment, and the true consequences of a positive or null result, are in very early stages.

The recent discovery of gravitational waves by the LIGO collaboration will open a new avenue to the study of gravity in the strong field regime and provide an important test of general relativity. Advances in both gravitational wave detection technologies and high performance computing to calculate the waveforms predicted by general relativity will be needed to fully exploit this new observational tool. There is also growing interest and ideas toward the detection of primordial gravitational waves, providing a window to the epoch of cosmic inflation.

Beyond the Standard Model Physics

The Standard Model of particle physics is known to be incomplete. In addition to not including the dark sector and quantum gravity discussed above, the Standard Model does not include enough charge-parity (CP) violation to explain the matter/anti-matter asymmetry observed in the universe. Neutrino masses remain to be explained. The nature of the quantum vacuum is still an open question and the smallness of the cosmological constant (vacuum energy) raises the question of whether "naturalness" is a good guiding principle. The fine tuning of the parameters of the Standard Model that is required to provide a universe with life raises the question of a multiverse.

Not all of these questions can be addressed by experiments within this sub-group, but two examples come to mind where searches for new forces and tests of gravity may provide guidance. If dark energy arises from an evolving scalar field (quintessence), then this scalar field would couple to matter at some level and lead to an apparent violation of the principle of equivalence. In this case, general relativity may not require a cosmological constant, although it would remain to explain the smallness of the vacuum energy. Extensions to the Standard Model, such as supersymmetry, provide new sources for CP violation that could help explain the observed matter/anti-matter asymmetry. Experimental searches for electric dipole moments (EDMs) of elementary particles, atoms, and certain molecules provide our most precise tests for these new sources of CP violation. (EDMs are likely to be discussed more fully in the Short Distance Physics from Precision Experiments sub-group.) Within our subgroup, searches for new CP-odd spin-dependent forces e.g. from axions or axion-like particles can also make a relevant contribution to this area.

2. Experimental Methods and Technology

The experimental methods and technologies in this sub-group are truly diverse. The systems studied include single particles (electrons, ions) in traps, laser cooled and quantum-degenerate clouds of atoms in optical and magnetic traps, matter wave interferometers using neutrons, cold atoms, or even molecules, polarized atoms in vapor cells, nano and micro-scale oscillators and resonators, optically levitated micro-spheres, superfluid helium, and polarized and unpolarized macroscopic test bodies on torsion balances. It is not possible in this report to provide details on all of the experimental methods; there are nearly as many methods and technologies as there are experiments in the field. Rather, we will make more general comments about broad classes of technologies.

As shown in Fig. 9, impressive advancements have occurred in the field of frequency measurements. The tools involve laser cooling, ultrahigh-stability lasers, frequency combs, and optical lattice trapping. Put together, these methods have led to ever more stable atomic clocks, which in turn have become one of our best measurement tools, with possible applications for gravity wave detection, short-range force sensing, measurements of fundamental constant stability, determinations of the proton size radius, and recent attempts to extend to even richer possibilities with molecules. In the above, the measured quantities are frequencies, and precise frequency measurements allow sensitivity to extremely weak effects.

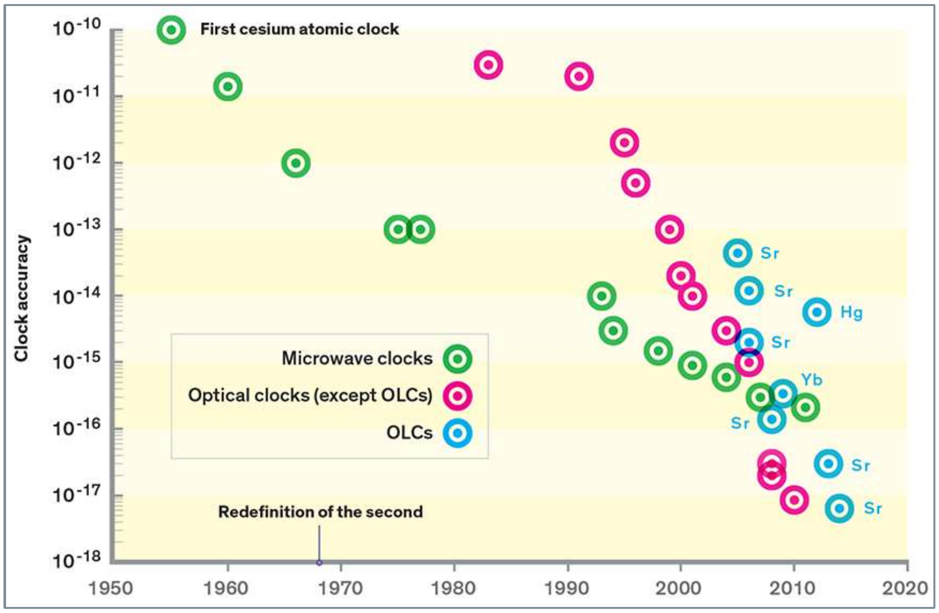

Figure 9: *The precision of atomic clocks has doubled every two years since 1960, to the point where effects of Einstein's general relativity on time, once thought to matter only in astrophysics, can now be seen in the lab. OLC = optical lattice clock. Image: Spectrum.IEEE.org*

In addition to more precise clocks, atomic/molecular/optical (AMO) techniques are ubiquitous in our field. The continuing development of laser technology to higher power, higher stability, wider frequency reach and tunability, and variable pulse width has been essential to the evolving technologies of ultrahigh precision spectroscopy of atoms, ions, and molecules including the laser cooling and trapping of atoms and molecules, matter wave interferometry, high sensitivity magnetometry, and levitated nano and micro-particles. High precision spectroscopy is being used to search for EDM's, test QED to high energy scales, search for new forces, and to address the proton size radius puzzle. Matter wave interferometry is being used to search for new forces, to measure the Newtonian constant, G, and to push tests of the principle of equivalence of general relativity to higher levels of precision. High sensitivity magnetometry is employed in searches for axions or axion-like particles and for EDM's. Levitated micro-particles are being used to search for new forces at short distances.

Another technology that is experiencing continuing development is micromechanical devices in the form of force sensing oscillators and light coupled resonators. The force sensing oscillators, at low temperature, provide high sensitivity to new short-range forces. The light coupled resonators as well as compliant metallic capacitor plates coupled to LC circuits, and superfluid helium oscillations, again in conjunction with low temperature techniques, are used to create quantum states of macroscopic objects in attempts to reconcile the seeming conflict between gravitational and quantum theories. Both the quality factor, Q, and the quantum coherence are important factors in these systems. Quantum control of macroscopic objects is likely to play an important role in the next generation of gravitational wave detectors.

The most classical technology being used is the torsion balance; macroscopic test masses suspended by a long thin fiber. Torsion balances are being used to test the principle of equivalence, to test the inverse square law of gravity at short distances, and to search for new spin dependent forces. Efforts are underway to investigate cryogenic versions of torsion balances which may provide lower noise floors to the experiments just mentioned and for possible application to cryogenic gravity wave detectors.

At even larger length scales, lunar laser ranging provides a record of the earth-moon separation to a precision of 1 mm, providing the best tests we have of the weak and strong principles of equivalence and inverse square law at large distances, as well as the time stability of the Newtonian Constant, G.

Scientific Priorities

The working group has identified priorities in the field, based upon how compelling is the scientific motivation and how promising are the experimental techniques. The priority list follows.

1. Tests of the inverse-square law (motivated by the dark energy length scale, hierarchy problem, extra dimensions)

   a. nano/micro resonators
   b. levitated micro-spheres
   c. high precision spectroscopy atoms, ions, molecules
   d. improved torsion balances

2a. Tests of the principle of equivalence (motivated by general relativity and string theory)

   a. atom interferometry
   b. lunar laser ranging
   c. improved torsion balances

2b. Spin dependent forces (motivated by light dark matter, e.g. axions or axion-like particles, and extra dimensions)

   a. macroscopic spin dot spin experiments (precision magnetometry)
   b. macroscopic spin-dot-r experiments (precision magnetometry and micro-resonators)
   c. microscopic spin experiments (precision spectroscopy of atoms, ions, molecules)

3. Experiments at the interface of quantum mechanics and gravity

   a. atom interferometer tests of gravity and dark photons
   b. nano/micro resonators creating massive entangled states

Table 4: **Physics addressed by high precision experiments**. Experimental techniques that provide high precision can be employed to study questions of fundamental physics. The table shows which physics questions are currently being addressed by a variety of high precision experimental techniques.

Technique	**Tests of Gravity**				**New Forces**			
	Inverse Square Law (ISL)	Principle of Equiv.	Strong Principle of Equiv.	Vacuum Energy (ISL at 10's of microns)	Dark Matter	Time Stability of Fund. Constants	Phenomenological Gravity	Strong CP Problem
Atomic Clocks	•				•	•		
High Precision Spectroscopy					•	•	•	•
High Precision Magnetometry					•	•		•
Atom Interferometry		•			•	•	•	
Levitated Micro-Spheres	•	•		•				
Nano/Micro Resonators	•	•		•	•		•	•
Lunar Laser Ranging	•	•	•		•	•		
Torsion Balances	•	•	•	•	•			•

3. Funding

Three funding related obstacles were identified by this sub-group: inadequate grant size and duration, limited funding agencies, and research that often falls between the cracks of established fields.

Most of the funding for speculative tabletop fundamental physics experiments comes from the National Science Foundation (NSF) with typical single PI grant awards of $120k/yr - $150k/yr for 3 years. This is often too little money and too limited duration for a speculative project to be successful. Precision measurements are always long-term experiments. Funding for 5-10 year projects, a typical timescale in our field, is nearly unavailable outside of national labs these days.

Furthermore, precision atomic physics experiments typically require two graduate students and a postdoc and perhaps $300-600k in equipment over 5 years. Taking the cost (salary + benefits) of a graduate student as $45k/yr and that of a postdoc as $75k/yr, with a 12.5% indirect cost, the personnel costs come to $185k/yr. Folding in the equipment costs over 5 years as well as $5k/yr for supplies, **the funding model that best fits with precision tabletop experiments is $275k/yr to $350k/yr for 5 years.**

A second obstacle is that apart from the NSF, the Department of Energy and other federal agencies have not been interested in funding experiments in gravitational physics. Even within the NSF, the tabletop fundamental physics experiments that reside within either high-energy physics or gravitational physics represent a small fraction of the funding in these disciplines. This undermines their importance, leaving them vulnerable to cuts whenever agency budgets are tight.

Many tabletop experiments in our field use techniques from atomic, nuclear, condensed matter, or gravitational physics to study questions that reside in the realm of particle physics. As a result, grant proposals lie at the boundary of two fields where experts in one field reviewing the proposal may not fully appreciate the impact of the proposed work in the other field. This places a significant burden on young PI's who may not have an established record in either field.

It is particularly troublesome to find funding for projects that fall "between the cracks" of established programs with a lot of inertia. For instance the Department of Energy has significant funds, and has a panel that prioritizes research efforts to be carried out over a long time frame e.g. 5 years. If a new experiment or idea comes along there is a significant barrier to getting funding if it is not included in this previous panel report. Thus it must wait years before the community can consider supporting it. NSF is a source of support with more flexibility, although award dollar amounts are significantly less. NSF supports some larger efforts like LIGO, which require (and merit) substantial research support but can potentially reduce the pot of money available for trying new innovative high risk smaller scale approaches and technologies that may have big payoffs.

The tabletop experimental approach to fundamental physics is an emerging field, which will become more feasible as complex fabrication technologies further develop and recently developed metrologies are used. With that said, it is our belief that tabletop experiments are typically orphans within the traditional funding agencies. We therefore recommend that if new research funding is made available to our field, it should be concentrated on tabletop experiments, whether the experiments involve a single or multiple PI's. It is likely that new technologies and metrology concepts will emerge as more tabletop experiments search for methods to achieve ever higher precision.

Funding Recommendation

1. Awards of $275k-$350k/y for 5 years.

2. Both single PI and multiple PI awards should be considered dependent on the nature of the project.

3. Emphasis should be given for equipment/instrument development.

4. Priority should be given to tabletop experiments. These are likely to play an increasingly important role in advancing fundamental physics.

4. Additional Comments

Gravitational tests on galactic and cosmological scales have not been included in this report. Astrophysical data exists from many surveys, yet it is difficult to secure funds for students/postdocs to analyze the data with the goal of testing general relativity on these scales.

Lately, a significant portion of tabletop experiment funding, particularly in atomic and molecular physics, is attracted to "centers" such as MIT/Harvard and JILA. This makes such centers unusually productive, but also makes the funding barrier quite difficult to break through for people at other institutions who are pursuing alternative original ideas. A related issue is that most physics departments in the U.S. have no technical support such as mechanical or electronics shops.

Total dependence on the relatively small, 3-year-long grants makes it very stressful and impractical for PIs to attempt original ideas with high risk. Moreover, this short-term grant model does not encourage continuity of personnel, making it difficult to hold on to highly trained postdocs, for example. We wonder if anyone has investigated how successful the Howard Hughes investigator program is. Removing from the PI the burden of writing many proposals is potentially a game changer.

It is important to identify and fund novel and well-conceived experimental proposals. It is also important to fund collaborations between theorists and experimentalists. By continued communication between theorists and experimentalists, which lacks in many cases, the advancement of the field is guaranteed.

Gravitational Wave Detectors

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1. Introduction

The recent discovery of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) is a historic event akin to Galileo's invention of the optical telescope to study the heavens. It is a re-affirmation of general relativity, but its main significance is as the beginning of a new way to study the universe. The observation of gravitational waves will be a major part of the future of astronomy, astrophysics, and cosmology. Every new band of the electromagnetic spectrum opened (e.g. microwave, x-ray, etc.) has revealed a wealth of new and often unexpected information about the universe. Gravitational waves are an entirely new spectrum in which to view the universe.

Gravitational waves allow many observations that are impossible with normal electromagnetic telescopes. For example, black holes (and other compact objects) are probably best studied with gravitational waves. Further, the earliest picture of the universe possible with light comes from the time of cosmic microwave background formation, since prior to that all photons were thermalized. But gravitational waves do not thermalize and can carry information about the earliest epochs in the universe, back to and even including inflation. The universe at that time was very hot. Thus observing such early times teaches us not just about the beginning of our universe, but also about the highest energy, most fundamental laws of physics, far beyond the energies that can be probed in a collider.

Gravitational wave observations have just begun. In order to fully realize the potential of gravitational wave observations we will need to improve the sensitivity of existing observatories and create new detectors to cover as many different frequency bands as possible. Improving the sensitivity of the LIGO detectors will for example allow observation of a much greater volume of the universe, seeing many more events and gaining greater information on each source. Additionally, frequencies below LIGO's range carry important information about the early universe and many other sources. We will need new ideas to improve our observing capability and open up as much of the gravitational wave spectrum as possible. Achieving the levels of precision needed will be challenging, but the potential payoff is huge.

Below we discuss some promising options for improving our ability to observe gravitational waves. We focus on existing detectors such as LIGO, as well as the two main ideas for future detectors – LISA and atomic sensors – which have been discussed extensively in the literature and endorsed, for example, by the recent European Space Agency panel on gravitational waves (GOAT). The approaches cover complementary frequency ranges. LIGO observes gravitational waves above about 10 Hz, LISA is designed to observe frequencies around 10^{-4} Hz to 10^{-2} Hz, and atomic sensors could observe roughly 10^{-1} to 10 Hz. Multiple different types of telescopes were necessary to observe the entire electromagnetic spectrum. It is likely that we will similarly need several different technologies to observe the gravitational wave spectrum as broadly as possible.

2. LIGO

At design sensitivity, Advanced LIGO detectors will be limited by two fundamental noise sources: quantum optical noise and coating thermal noise. Understanding and further reducing these two noise sources is critical to the design of any laser interferometric gravitational wave detector beyond Advanced LIGO.

Quantum optical noise arises from the quantization of light. At the high-frequency end of the LIGO band (above ~100 Hz), the sensitivity is limited by photon counting statistics or shot noise in the photo-detection process. At the low-frequency end of the LIGO band (below ~100 Hz) momentum kicks to the mirrors by an uncertain number of photons gives rise to the quantum radiation pressure noise (QRPN) limit. A unified picture of quantum noise that accounts for correlations between shot noise and QRPN allows for quantum engineering to reduce quantum noise through, e.g., the use of squeezed vacuum states of light.

Coating thermal noise (CTN) is another important limitation for laser interferometer gravitational wave detectors. Coating thermal noise arises from mechanical dissipation in the dielectric, thin film coating on the mirror surface, and not the bulk mirror material. The Advanced LIGO design is arranged so that CTN equals quantum noise in the most sensitive part of the detection band around 100 Hz. CTN can be reduced either directly through low-temperature operation, or indirectly through careful engineering and/or selection of material properties as a function of temperature. In the Advanced LIGO detectors, for example, the deleterious effects of CTN are minimized by maximizing the laser spot sizes on the mirrors (at the expense of alignment stability in the interferometer). In the Japanese Kagra detector, on the other hand, cryogenic operation is used to mitigate thermal noise.

The LIGO community is taking a staged approach to improved sensitivity detectors. First, and near-term, is to implement upgrades to Advanced LIGO, with the upgrades constrained to fit within the current facilities (4km long, L-shaped vacuum envelope operating at 10^{-8}Torr). This can lead to modest gains in sensitivity at the level of a factor of 2 to 3 at best. Second, and longer-term, is to design brand new facilities that can be significantly longer (10 to 40 km long arms), and would allow for reconsidering the best geometry (L-shaped or triangular), the best orientation, and include options for cryogenic operation and use of different materials (such a silicon for the mirrors, e.g.), and different laser technologies and wavelengths.

A plausible target sensitivity for a 40 km long third generation gravitational wave detector is shown in Figure 10 [13]. The sensitivity from 10 Hz to a few kilohertz is limited by quantum noise, while the lower limit to the sensitive band is determined by local gravitational disturbances (known as Newtonian noise). The other significant in-band noise source is CTN. Other noise sources, such as residual gas noise, seismic noise and suspension thermal noise are sub-dominant, and not discussed here. The astrophysical promise of the 40 km instrument, immodestly known as "Cosmic Explorer" (CE), is remarkable. CE would be capable of observing binary neutron star mergers out to a redshift $z \approx 6$, binary black hole mergers out to $z \approx 10$, and supernovae out to 20 Mpc (very roughly, a rate of 2 per year).

Whether targeting modest upgrades or bold new facilities, quantum noise and coating thermal noise must both be reduced relative to current capabilities to fully exploit the promise of laser interferometric gravitational wave detectors.

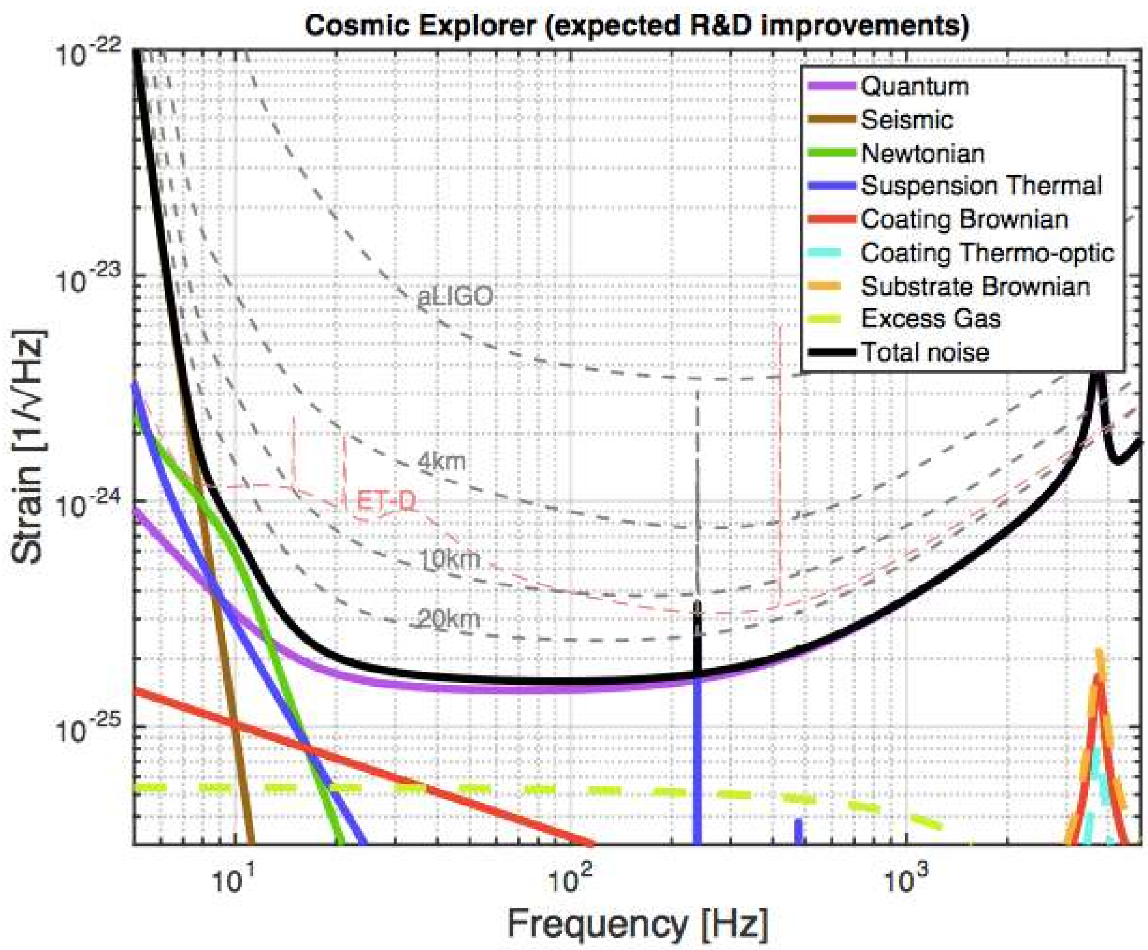

Figure 10: *Target sensitivity for a third generation gravitational wave detector, known as Cosmic Explorer for its ability to receive signals from cosmological distances. The solid curves are for a 40km long detector, while the dashed grey curves show the sensitivity of shorter, but technologically similar detectors with lengths of 4, 10 and 20 km. The Advanced LIGO and Einstein Telescope design sensitivities are also shown for comparison. Substantial advances in coating thermal noise, outlined in Sec. II B, are assumed here. Figure from Ref. [13].*

a) Quantum noise and squeezed light

Squeezed light is an important technology for determining the quantum limited sensitivity of future gravitational wave detectors. Squeezed states of light were demonstrated to be effective in reducing quantum noise in first-generation gravitational wave detectors [14, 15], and are currently planned for implementation in Advanced LIGO. To be useful for gravitational wave detectors, we must generate squeezed vacuum states that have substantial (6 to 10 dB of) squeezing in the 10 Hz to 10 kHz band. Moreover, to realize broadband improvement, the squeezing quadrature must be rotated as a function of frequency, known as a frequency-dependent squeezed state. In the past decade, there has been significant progress in generation of several dB of audioband, frequency-dependent squeezing for gravitational wave detection [16]. Even as this technology has matured, there remains one major obstacle to further progress – optical losses. To achieve further reduction in quantum noise, optical losses must be reduced. This could come in the form of new or improved optical materials, or different laser wavelengths where more efficient detection is possible, or entirely new technologies for generation of squeezed light (such as optomechanical squeezing). While traditional funding agencies have invested in squeezed light research, it has been hard to get funding for a comprehensive program to study optical losses in the cross-disciplinary way necessary to make progress on this front. The development of new optical coatings for future LIGO detectors has the potential to also address this gap.

b) Coating thermal noise

The thermal fluctuations of the mirror surface are dominated by the Langevin thermal forces generated in the high-reflectivity dielectric optical coatings [17]. The optical coatings have very good optical qualities, but have large internal friction. The mechanical loss depends on the coating material, the number of thin film layers, and the structure of the layers.

The mechanical dissipation – and consequently the thermal noise – of nearly all amorphous, thin film materials is higher than that of crystalline materials. Almost universally, the cause of the dissipation is known to be due to the presence of a set of low energy modes (which are not frozen out). Tunneling into this vast sea of available modes leads to the observed mechanical dissipation. Of all amorphous solids, fused silica seems to be singular in its extremely low dissipation at room temperature and above. Unfortunately, the high quality factor (Q) of the bulk material does not translate into high Q for the silica thin films used for optical coatings. Advanced LIGO coatings are multilayer coatings of alternating silica and tantala, with loss angles of $\sim 10^{-4}$.

Despite progress with lowering the mechanical loss in the high-mechanical-loss amorphous materials [18], an attractive alternative is crystalline coatings – potentially lower-loss materials that can be configured as Bragg reflectors. The availability of promising materials has advanced significantly with the development of epitaxial deposition techniques such as chemical vapor deposition, molecular beam epitaxy, and atomic layer deposition to support the development of electronic circuits and optoelectronics.

A promising technological advance has come in the form of trinary AlGaAs layers grown on GaAs substrates and then attached to silica or silicon mirrors. Structures grown on GaAs substrates showed 30 times larger mechanical Q than the best amorphous high-reflectivity coatings [19], and direct bonding to substrates maintained the high Q [20]. More recently, substrate-transferred single-crystal semiconductor heterostructures were shown to achieve optical performance rivaling that of ion-beam-sputtered amorphous multilayers [21], but with much lower thermal noise. Mirrors with these crystalline coatings not only have much lower Brownian noise than those with amorphous coating, but also achieve high thermal conductivity, low optical losses (scatter and absorption), and wide spectral coverage.

Another possibility for crystalline coatings is to grow AlGaP:GaP layers directly onto silicon substrates, since the lattice matching is good [22]. The matching is expected to reduce thermal stresses and would allow for cryogenic operation of the interferometer to further reduce thermal noise.

Clearly, crystalline coatings hold enormous promise for overcoming the ever-vexing CTN in gravitational wave detectors. But the LIGO mirrors are 35 to 50 cm in diameter, so the crystalline coating technology must be scaled up from present tests at the few centimeter scale to be useful. This requires substantial financial investment in crystal growth and transfer technology that has remained unfunded, despite the recognized importance of crystalline coatings to future gravitational wave detectors. These epitaxial coatings have the potential to expand the astrophysical reach of future gravitational wave detectors by a factor of 3 to 10 in the most critical frequency band, if the low mechanical dissipation and low absorption and scatter can be maintained through scale up [17]. High optical and mechanical quality crystalline mirrors have applications beyond gravitational wave detectors; they are a critical technology for precision interferometry and quantum sensing (e.g. the squeezed light sources of Sec. II A), for narrow-linewidth laser systems, for optical atomic clocks, for cavity QED experiments, and for tests of fundamental physics.

3. LISA

The frequency range between 10μHz and 100mHz is probably the signal richest frequency band in gravitational waves. Signals in this frequency band include the mergers between 3000 to 100 million solar mass black holes out to redshifts of $z \sim 20$. It also includes signals from around one hundred thousand compact binary systems in our own galaxy that are formed between white dwarfs, neutron stars, and also solar origin black holes; thousands of those signals will be isolated and often allow synchronized electromagnetic and gravitational wave observations. Binary systems between ten to a few hundred solar mass black holes provide signals which allow to forecast their merger a few months or years in advance with minute type accuracy and in some cases sub deg^2 sky localization. These mergers will then be visible by LIGO and, if accompanied by an electro-magnetic signal, by classical telescopes. The science opportunities provided by the Laser Interferometer Space Antenna (LISA) are dramatically different from any other observatory ever flown and will revolutionize our knowledge and understanding of the universe.

It is this revolutionary science case that let the European Space Agency (ESA) select The Gravitational Universe [23] as the science theme for their third large mission L3. Last fall, ESA released a call for mission concepts and it is widely believed that the proposal submitted by the eLISA consortium in January 2017 will be selected as the baseline for L3 [24]. The proposed mission will use three spacecraft (S/C) forming an equilateral triangle with a 2.5Gm baseline. Inside each S/C will be two freely floating gold-platinum test masses which define the end points of two interferometer arms. Local laser interferometry will measure the distance between the test masses and a fiducial optical bench with pm/ Hz sensitivity. A far laser interferometer will measure the distance between optical benches located on two different S/C. Combining two local and one far interferometer allows one to measure changes in the distance between the two test masses.

A similar set of measurements allows one to measure the changes in the distance between the test masses in the second arm. Combining these two distance measurements allows cancellation of the common laser frequency noise while maintaining the differential length changes and the gravitational waves.

Gravitational wave observatories require test masses, or gravitational reference sensors (GRS), that are in free fall in the frequency band of interest as well as a means to measure changes in their distance. The free-fall requirement can be expressed as a requirement on the residual acceleration noise of the test masses. The LISA Pathfinder (LPF) demonstrated a GRS with a residual acceleration noise of

$$\delta\tilde{a}(f) \leq 3 \times 10^{-15} \frac{ms^{-2}}{\sqrt{Hz}}$$

between 1mHz and 50mHz, fully meeting the LISA requirements defined more than 20 years ago [25]. In the high frequency part above 50 mHz, LPF was limited by its ability to measure the distance changes but it is believed that the acceleration noise is mostly frequency independent up until at least a few Hz which would allow use of the LPF GRS also for shorter arm length gravitational wave observatories to bridge the gap between LISA and LIGO.

Gravitational wave observatories also require laser interferometric distance measurements. The proposed LISA mission carries a one way distance measurement sensitivity of

$$\delta\tilde{x}(f) \leq 10 \frac{pm}{\sqrt{Hz}}$$

ranging from 1Hz to ~1mHz and then increasing by a factor 100 per decade towards lower frequencies. The main challenge in LISA will be the far interferometer which has to measure these minute changes on top of the meter per second length changes caused by the different orbits of the S/C. However, several tabletop experiments have demonstrated this sensitivity and the main challenge will be to realize this between and within two spacecraft separated by 2.5 million km and not just in a tabletop proof of principle experiment (See [24] for many references to relevant technical papers).

A third and often overlooked challenge is the data analysis. In contrast to LIGO, LISA will continuously receive scientifically valuable gravitational waves from potentially several hundred thousand sources at once. In theory, the most valuable signals will stand out from these low amplitude, low frequency background signals as high amplitude and/or high frequency signals. However, these signals still have to be identified and isolated from the rest before the full science can be extracted. This requires the generation of data sets which include realistic gravitational wave signals as well as realistic representations of instrumental noise. These data sets will then be mined by data analysts to train their search algorithms. Such a Mock LISA Data Challenge (MLDC) started in the last decade but never matured due to the first cancellation of the original LISA project in 2011.

Data Analysis Challenge

LISA has been through 15 years of technology development and its design is mature and many parts and subsystems have been tested and demonstrated at or near the LISA requirements. The LISA Pathfinder has demonstrated the critical parts that cannot be tested on the ground. NASA, ESA and the European member states are currently discussing and dividing responsibilities for the LISA project. These agencies are expected to develop the needed technologies in a well-coordinated, coherent and industrialized approach. While additional funding could be used to explore a few optional techniques and approaches for individual subsystems, it is unlikely that investments into LISA technology development would lead to cutting edge and highly visible breakthroughs. Any progress in an optional technology will have to be vetted by the LISA project office and, once the option becomes the baseline, will be matured with space agency funding.

However, this is not the case for the data analysis challenge. Funding at the space agencies is often scarce and the development of data analysis techniques is often neglected and left for the community to do on its own. This will unlikely lead to satisfying results in the case of LISA as there is no history in analyzing data from a gravitational wave mission and even the LIGO experience does not count as LISA is working in a signal rich environment compared to the sporadic individual signals in LIGO.

What would such an effort encompass and where could it lead us?

The final goal of the MLDC exercise is to generate realistic data streams which include instrumental noise, instrumental artifacts and all expected and potentially some unexpected gravitational wave sources. These data streams will have to be generated via software, maybe including some hardware in the loop emulator [27]. They have to include technical noise from the LISA pathfinder, also from optical testbeds and expected and maybe even some less expected noise sources which can only be simulated. Gravitational wave signals will have to be added. These data streams will then have to be released to the community to test, develop and train the algorithms which will later be needed to analyze the LISA signals.

The development of the MLDC data streams will be a process which will continue over many years. The initial data sets might just include some frequency dependent Gaussian noise and a few large SNR signals from massive black hole mergers. Later sets will include more and more noise sources and signals until the community has developed the tools required to analyze the data streams. In the best of all cases, this work might directly lead to a US-based science center which would be responsible for analyzing the LISA data and providing source catalogues but which also releases the data streams and tools which allow the community to analyze the data independent from the science center.

4. Atomic Sensors

Atomic sensors may allow a novel type of gravitational wave detector in the frequency band 0.1 Hz - 10 Hz, between LIGO and LISA. This band is scientifically rich. For example, the lower end of this range would allow observation of white dwarf binary mergers, while the higher frequency region (around 1 Hz and above) is potentially a valuable region for searching for more speculative cosmological sources such as inflation and reheating. There are also sources that may be observed both in this band and in the LIGO or LISA bands. For example, sources such as black hole or neutron star binaries may be observed in this band, and then observed later by LIGO once they pass into the higher frequencies. Such joint observation would be a powerful new source of information, giving for example a prediction of the time and location in the sky of a merger event in LIGO. This would allow optical, x-ray, gamma ray, and other telescopes to observe these mergers as well, simultaneously with LIGO, yielding a wealth of new information about such sources. Since the sources generally live a long time in this mid-frequency band, they can be localized in the sky even by a single-baseline atomic detector since the detector will change orientation and position significantly during the time spent observing a single source.

There are two closely related approaches to gravitational wave detection with atoms, relying on atom interferometry and atomic clocks. Many of the fundamental technologies are common between these two approaches, enabling a joint research and development effort to advance these techniques. It is likely that an optimal detector design will incorporate features from both detection schemes, with technology development and maturation informing the design.

A strategic investment can enable the full design, construction and evaluation of a prototype gravitational wave detector based on atomic sensors. Such a prototype would demonstrate the viability of these sensors for full-scale gravitational wave detectors, both terrestrial and satellite-based, retiring the technical risk inhibiting possible government support. This demonstration is required before construction of a full observatory in this intermediate frequency band. Such an observatory will open a new window into the universe, allowing observation of a new part of the gravitational wave spectrum.

a) Atom interferometry

Atom interferometry offers a novel technique for gravitational wave detection [1, 2]. This technique is based on a fusion of recent work in optical atomic time standards and atom interferometry [3, 4], and appears capable of detecting faint signals from astrophysical and cosmological gravitational waves. In addition, it can search for new fundamental forces of nature and new particles which could be dark matter [5, 6]. The technique relies on the operation of two atom interferometers on either end of a long laser baseline. The interferometers are operated simultaneously with common laser pulses. In a terrestrial experiment this technique can reach interesting sensitivities at frequencies below the LIGO band, around 1-10 Hz, which is impossible for laser-based terrestrial experiments because of seismic noise. A satellite experiment can reach lower frequencies $\sim 10^{-1}$ to 10 Hz and sensitivity levels needed for many exciting sources (see Fig. 11).

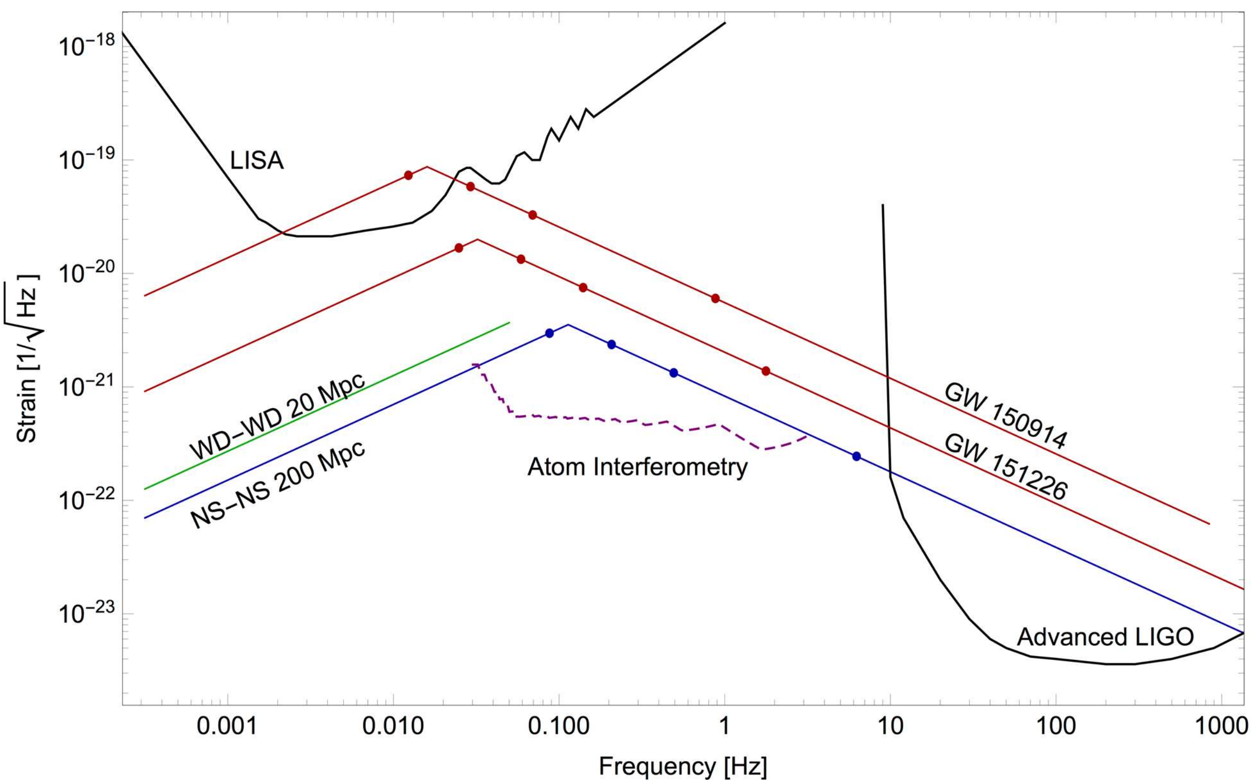

Figure 11: *The gravitational wave sensitivity for a satellite-based atom interferometer detector is shown (dashed purple), along with sensitivity curves for LIGO and LISA. The purple curve shows the envelope of the resonant sensitivity for this detector. The Advanced LIGO curve is the design sensitivity (not current sensitivity). The two black hole merger events observed by LIGO are shown in red. A white dwarf-white dwarf binary at 20 Mpc (with masses $0.5M_\odot - 0.5M_\odot$) is shown in green. A NS-NS binary at 200 Mpc (with masses $1.4M_\odot - 1.4M_\odot$) is shown in blue. The dots on the GW150914, GW151226 and neutron star-neutron star 200 Mpc curves indicate remaining lifetimes of 10 yrs, 1 yr, 0.1 yrs, and 1 hour (reading left to right). Degree scale sky localization appears feasible with atom interferometry for in-spiraling sources.*

There are several benefits to the atomic physics-based approach. Atom-based detectors can be run with only a single optical baseline, rather than multiple baselines [3, 4]. In a satellite mission, this would require only two satellites instead of three – reducing the cost and complexity of the mission. Additionally, many of the core detector sub-systems can be verified on the ground, prior to flight, unlike for an optical interferometer-based detector. This allows a significant reduction in the risk of the mission. As atom technologies continue to mature, it is realistic to expect further sensitivity gains, for example, through the use of quantum state entanglement [7].

Notable progress has been made in recent years in demonstrating important technical milestones required for such a detector. Detecting low frequency gravitational waves benefits from long duration (10-100 seconds) atom interferometers. Atomic coherence over a record-setting time interval in a 10 meter tall rubidium atomic fountain has been demonstrated, dividing the atoms quantum mechanically and then recombining them more than two seconds later [8]. Ultra-cold temperatures are required for atom interferometer gravitational wave detectors. New atom cooling techniques have been demonstrated that minimize the ballistic expansion of the atomic ensemble. In a proof- of-concept experiment, a delta-kick cooling protocol was demonstrated effectively bringing atom temperature down to below 50 picokelvin [9]. This record low temperature is one of the key technological steps required for highly sensitive gravitational wave detection with atom interferometry. Using sequential Bragg transitions, large-momentum transfer atom optics with 90 photon recoil momentum transfer has now been demonstrated in a Rb interferometer [10]. This gave a separation of the two halves of the atom's wavefunction of more than 50 cm (see data in Fig. 12). This level of large-momentum transfer atom optics was a critical part of the technology that had to be demonstrated for gravitational wave detection.

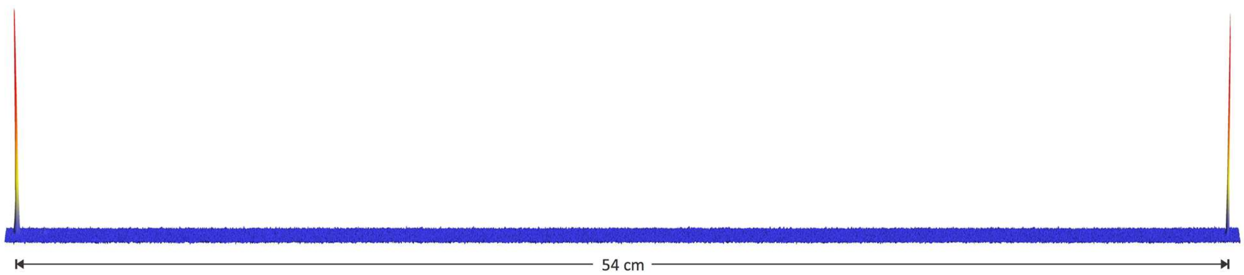

Figure 12 : *Wavepackets separated by 54 cm from [10]. Image of the atomic wavefunction separation at the midpoint of an atom interferometer using 90 k atom optics. The false color peaks at each end of the image show that the probability distribution for each atom is split in two halves separated by 54 cm. This large-momentum transfer demonstration is a key part of the technology needed for gravitational wave detection.*

While these proof-of-concept demonstrations for many of the required techniques have been accomplished, they have yet to be integrated into a full gravitational wave detector prototype. Such a demonstrator apparatus would consist of two atom interferometers in a gradiometer configuration separated by a modest baseline and will incorporate delta-kicked cooled atom sources and single-photon, large momentum transfer, atom optics. The key enabling technologies to demonstrate include: 1) large momentum transfer atom optics using Sr; 2) interleaved atom interferometer operation (to enable high signal-to-noise detector operation); and 3) novel atom optics methods (based on extended sequences of wavepacket manipulation pulses [11]) which are suited to detection of gravitational radiation of cosmological origin and narrow-band sources.

This work is relevant to other major science goals. It can be used to measure the relative acceleration between two different freely falling atomic species, serving as a test for new equivalence principle violating forces between the Earth and the atoms, extending bounds on such forces by a factor of 100. Further, this apparatus can also search for ultralight dark matter such as axions [5, 6]. Additionally, it can serve to test recently proposed theories that solve the hierarchy problem through cosmological relaxation [12].

b) Atomic clocks and quantum metrology

The continued progress of modern atomic physics and quantum metrology will provide new classes of precision measurements for future exploration of gravitational physics as well as the search for dark matter and new physics beyond the Standard Model. For example, some work group members recently put forward a concept design for a satellite-based gravitational wave detector using optical atomic clocks. Two spatially separated, drag-free satellites share ultra-stable laser light. Each satellite contains an optical lattice atomic clock, which serves as a sensitive, narrowband detector of the effective Doppler shifts induced by incident gravitational waves on the shared laser light, with unique sensitivity across a wide range of frequencies (in particular including 0.1 Hz - 10 Hz). This type of sensor may also be operated in modes that search for new forces, for example due to coupling with dark matter, or for time-variation of fundamental constants.

More generally, a promising platform is a world-wide or space-based network of optical clocks and other quantum metrology tools to enable a broad portfolio of transformative fundamental physics experiments. Such clock-type experiments will complement conventional big physics experiments (e.g., particle accelerators, large telescopes) and in many cases provide unique information (e.g., Planck-scale sensitivity for certain classes of fundamental symmetry violations). There is a great opportunity to support key technology development and readiness studies to enable such quantum metrology networks. As one example, one could explore in the laboratory whether clock networks could achieve the stability necessary to serve as a tunable gravitational wave observatory. The use of quantum enhancement techniques such as dynamical decoupling, entanglement, squeezing and novel dynamical phases can also be explored.

Importantly, lasers are an enabling technology for an enormous range of measurements in physics. Recent efforts have reached the ultimate limit for the technology of stable lasers using conventional reference cavity materials, namely, ultralow expansion glass, with a fractional frequency stability of 1×10^{-16} from 1 s to 1,000 s, limited by the thermal noise of the cavity. To further advance optical coherence times, one can develop a qualitatively new generation of optical resonators with vastly reduced thermal noise. The key is that all three components of the optical reference cavity (1) the spacer, (2) the mirror substrate, and (3) the optical high reflectivity coatings, be made of crystalline materials. Specifically, single-crystalline silicon can be used for both the cavity spacer and the mirror substrates. This step alone has already improved the laser stability to 4×10^{-17} at 1 s. The remaining critical issue that limits optical precision interferometry is the fundamental thermal noise in the mirror optical coatings (i.e., high reflectivity multilayers). This so-called coating noise was experimentally verified to be the ultimate show-stopper for further improvements in optical interferometry. Minimizing this noise has been an outstanding challenge for more than a decade, but even the concerted efforts of the LIGO collaboration have been unable to improve this noise level by more than a factor of two. Some members of the work group recently found a novel, and yet practical, approach that allowed one to experimentally demonstrate a ten-fold reduction in the thermal noise characteristics of conventional optical coating. Monocrystalline semi-conductor materials can exhibit high qualities in both mechanical and optical properties. As a result, high reflectivity (99.999%) for crystalline coatings has been demonstrated. Moreover, a rigorous measurement of these new mirrors implemented in a conventional optical reference cavity directly confirmed an order-of-magnitude reduction in thermal noise due to the high mechanical quality of the crystalline coatings. Motivated by the enormous promise shown in these initial experiments, we next plan to design, implement, and demonstrate an ultrastable all-crystalline optical cavity. In order to minimize thermal expansion, we will cool the cavity to either 124 K or 4 K where silicon has a minimum thermal expansion. We expect to reach laser linewidths on the order of 1 mHz as a result. The development of this project will directly impact research on LIGO and will also enable the next generation of optical atomic clocks.

The development of ultra-stable lasers together with ultracold atomic matter has led to multi-order-of-magnitude advances in the performance of atomic clocks operating in the optical wavelength regime. Optical atomic clocks are currently the most precise and accurate measurement system. The JILA Sr optical-lattice clock holds the present world record in clock uncertainty at 2.1×10^{-18}. Strontium atoms provide a platform for precision measurement and quantum-state engineering in a many-body system that enables a qualitatively new regime for quantum metrology and optical clocks. The use of a large number of atoms provides a dramatic enhancement of the clock signal-to-noise, resulting in the record precision. However, high atom numbers combined with tight spatial confinement, which is required to suppress Doppler and recoil frequency shifts, also lead to large atomic densities and the potential for non-zero collisional frequency shifts via atomic interactions. To continue improving clock performance one must control many-body interactions. Some members of the workgroup have envisioned a scalable solution to clock precision and accuracy during the next few years. One can increase the atom number for the clock by 100-fold, dramatically enhancing the clock performance. A Fermi degenerate quantum gas can be produced and loaded into a three-dimensional optical lattice, resulting in a fermionic band insulator. Quantum statistics naturally prevents the occupation of more than one fermionic atom per site so long as the thermal energy is sufficiently low to suppress population of higher bands of the lattice. Operating the clock in a 3D lattice would help realize a new generation of clocks that reach high stability and accuracy with atoms at quantum degeneracy. This is an important step for overcoming the major compromise between precision and accuracy when a many-body system is employed. One can implement identical trapping conditions for the two clock states in a 3D lattice by precisely controlling the scalar, vector and tensor light shifts. When one needs to use two stretched nuclear spin states to average away linear Zeeman and Stark effects, one can rely on the strong on-site interaction to suppress frequency shifts due to the large energy cost of having two atoms on the same lattice site. It will be important to determine the optimal operating condition for a 3D optical lattice clock in terms of filling fraction, lattice depth and geometry, using the interplay of tunneling, atomic interactions, and quantum statistics.

With the removal of contact interactions, the next accuracy milestone for a 3D optical lattice clock will rely on a thorough understanding of collective dipole couplings between optically excited atomic radiating dipoles. In fact, since the lattice wavelength is comparable to the clock probe wavelength, atoms at neighboring lattice sites will interact via both near- and far-field terms as well as dispersive and dissipative components. Consequently, the next generation of clocks will offer a unique platform for the investigation of long-range interacting many-body systems, akin to other long-range-interaction systems. One can investigate the optimal trapping conditions, lattice geometries and polarization states under which undesirable frequency shifts arising from dipolar interactions can be mitigated for clock operation. Moreover, with proper control, atom-atom interactions can be utilized to create correlated atomic states that can actually improve precision measurements schemes. Recent advances demonstrating the efficacy of quantum enhancement techniques such as entanglement (squeezing) and quantum control (dynamic decoupling) for precision sensing, already offer new paths to further enhance sensitivities. Furthermore, one can explore whether novel non-equilibrium phases of matter can be created in driven strongly interacting atomic ensembles; and also, if they can be used to create stable quantum states while enhancing the sensitivity to specific external perturbations, as well as the bandwidth. One specific example involves the use of the recently demonstrated time crystalline order for precision measurement applications.

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[26] An orphant MLDC website still exists (https://astrogravs.gsfc.nasa.gov/docs/mldc/) and provides some information about this activity. The MLDC activities ended prior to the end of the initial LISA project due to the unavailability of funding from the space agencies. The last published paper I found which includes MLC in the title is Tria at al, Class.Quant.Grav.25:184028 (2008).

[27] Shawn Mitryk, LASER NOISE MITIGATION THROUGH TIME DELAY INTERFEROMETRY FOR SPACE-BASED GRAVITATIONAL WAVE INTERFEROMETERS USING THE UF LASER INTERFEROMETRY SIMULATOR (UFLIS), Dissertation, University of Florida, https://gwic.ligo.org/thesisprize/2012/mitryk-thesis.pdf. This simulator was used to experimentally generate data streams with injected signals to then extract the signals.

Workshop Agenda

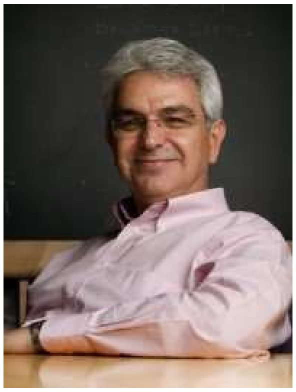
Monday, October 24, 2016	
7:30am	Bus leaves the hotel for the Moore Foundation
7:45-8:30am	Breakfast
8:30-9:00am	**Robert Kirshner and Ernie Glover**, Welcome and overview
9:00-10:00am	**Savas Dimopoulos**, Theoretical Perspective on Small-Scale
10:00-10:30am	Coffee break
10:30-11:00am	Science report and discussion: Short Distance Physics
11:00-11:30am	Science report and discussion: New Forces and Tests of Gravity
11:30am-12:00pm	Science report and discussion: Light Dark Matter
12:00-1:30pm	**Lunch**
1:30-1:45pm	**Marc Kastner, President, The Science Philanthropy Alliance**
1:45-2:15pm	Science report and discussion: Gravitational Wave Detectors
2:15-2:45pm	Science report and discussion: Theory
2:45-3:00pm	Coffee break
3:00-3:30pm	**John Doyle,** The ACME Collaboration
3:30-5:30pm	Breakout sessions
5:30-6:00pm	Group photo and transit to restaurant
6:00-8:30pm	Dinner at Reposado restaurant and return to hotel

Tuesday, October 25, 2016	
8:00am	Bus leaves hotel for Moore Foundation
8:15-9:00am	Breakfast
9:00-9:30am	Breakout groups present: Light Dark Matter
9:30-10:00am	Breakout groups present: New Forces and Tests of Gravity
10:00-10:30am	Breakout groups present: Gravitational Wave Detectors
10:30-11:00am	Coffee break
11:00am-12:00pm	**Wim Leemans, LBNL**, Prospects for Laser Plasma Based Compact Accelerators

12-1pm	**Lunch**
1:00-1:30pm	**Dane Boysen, Chief Technologist**, Cyclotron Road
1:30-2:00pm	Breakout groups present: Short Distance Physics
2:00-2:30pm	Breakout groups present: Theory
2:30-3:00pm	Coffee break
3:00-4:00pm	Funding discussion
4:00-4:15pm	Concluding remarks

Contributor Profiles

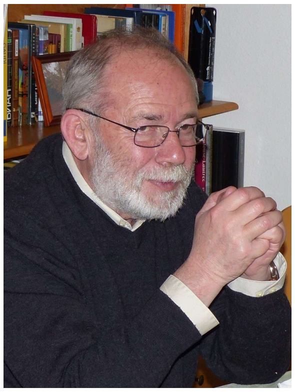
Savas Dimopoulos



Savas Dimopoulos is well-known for his work on constructing theories beyond the Standard Model, which are currently being searched for and tested at particle colliders and in other experiments. His most famous work was on the Minimal Supersymmetric Standard Model (MSSM) which he proposed in 1981 jointly with Howard Georgi. He also proposed the theory of large extra dimensions, together with Nima Arkani-Hamed and Gia Dvali. For the proposal of these theories and developments in the field of theoretical particle physics he won the Sakurai award in 2006.

Most recently he put forward the theory of split supersymmetry with Nima Arkani-Hamed. This theory is motivated by the possible existence of an enormous number of ground states in the fundamental theory, as suggested by the cosmological constant problem and recent developments in string theory and cosmology. It can be tested at the large hadron collider and, if confirmed, it will lend support to the idea that our universe and its laws are not unique and that there is an enormous variety of universes each with its own distinct physical laws.

Max Zolotorev



Max graduated with a Ph.D. in Physics from Novosibirsk State University, Russia in 1974. He worked as a scientist at the Novosibirsk Institute of Nuclear Physics and taught at his alma mater.

In 1989 Max emigrated to the USA. His first research position here was at Lawrence Berkeley Laboratory (UC Berkeley). From 1990 to 1996 he worked at Stanford Linear Accelerator Center (Stanford University), and after 1996 - again at Lawrence Berkeley Lab.

Max has wide interests spanning high energy, atomic, and solid state physics. Working with L. Barkov in Novosibirsk he discovered parity violation in atomic transitions. Later in the USA Max participated in the design and operation of the source of polarized electrons and polarimeter for the measurement polarization of 50 GeV electron beam. Max proposed "optical stochastic cooling" technique for decreasing face volume of beams of heavy particles. He observed and explained Total Charge Limit in semiconductor photocathodes, investigated nonlinear Faraday rotation, and proposed a femtosecond X-ray pulse generation technique, among other ideas.

Max has over 200 scientific publications and is a fellow at the American Physical Society.

Frank Wilczek

Frank Wilczek has received many prizes for his work in physics, including the Nobel Prize of 2004 for work he did as a graduate student at Princeton University, when he was only 21 years old. He is known, among other things, for the discovery of asymptotic freedom, the development of quantum chromodynamics, the invention of axions, and the exploration of new kinds of quantum statistics (anyons).

Frank grew up in Queens, NY and attended the University of Chicago. After getting his Ph.D. from Princeton, he spent time on the faculty there and at the Institute for Advanced Study, as well as at UCSB's Institute for Theoretical Physics, now the KITP. Frank is currently the Herman Feshbach professor of physics at MIT.

Theory Group

Asimina Arvanitaki (also part of New Forces and Tests of Gravity group)

Asimina Arvanitaki is the Stavros Niarchos Foundation Aristarchos Chair in Theoretical Physics at Perimeter Institute. She is a world-leading particle theorist making connections between theoretical predictions and experiments employing the latest advances in other fields of physics such as atomic clocks and precision metrology as well as gravitational wave detectors. Asimina has pioneered new Dark Matter searches as well as experiments that look for new forces in nature. She showed that astrophysical black holes can be used to diagnose the presence of new particles in our nature through the effect of superradiance. This effect can also give rise to new gravitational wave signals at experiments such as LIGO.

She is the recipient of the 2017 New Horizons Prize in Physics from the Breakthrough foundation and she holds a PhD from Stanford University.

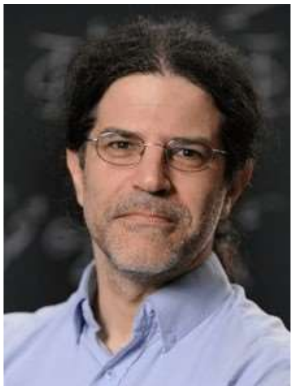
Peter W. Graham (also part of Gravitational Detectors group)

After completing his undergraduate work at Harvard, Peter Graham received his PhD from Stanford in 2007. He was a postdoctoral research associate for one year with the particle theory group at SLAC and then took a postdoctoral position with the Stanford Institute for Theoretical Physics in the Physics Department.

He is broadly interested in theoretical physics beyond the Standard Model which often involves cosmology, astrophysics, general relativity, and even atomic physics. The Standard Model leaves many questions unanswered including the nature of dark matter and the origins of the weak scale, the cosmological constant, and the fundamental fermion masses. These clues are a guide to building new theories beyond the Standard Model. He recently proposed a new solution to the hierarchy problem which uses dynamical relaxation in the early universe instead of new physics at the weak scale.

Peter is also interested in inventing novel experiments to discover such new physics, frequently using techniques from condensed matter, atomic physics, or astrophysics. He is a proposer and co-PI of the Cosmic Axion Spin Precession Experiment (CASPEr) and the DM Radio experiment. CASPEr uses nuclear magnetic resonance techniques to search for axion dark matter. DM Radio uses high precision magnetometry and electromagnetic resonators to search for hidden photon and axion dark matter. He has also proposed techniques for gravitational wave detection using atom interferometry.

David E. Kaplan



David E. Kaplan received his PhD from the University of Washington in 1999. He had postdocs at the University of Chicago/Argonne National Lab and SLAC and joined the faculty at Johns Hopkins in 2002. David discovers possible theoretical extensions to the standard model of particle physics and cosmology, and then novel ways to discover those and other models. David is a Fellow of the APS and has been named an Outstanding Junior Investigator by the DOE, a Kavli Frontiers Fellow of the NAS, and an Alfred P. Sloan Fellow.

Maxim Pospelov (also part of Short Distance Physics from Precision Experiments group)

Maxim Pospelov is the professor of physics and astronomy at the Univeristy of Victoria, and an associate member of Perimeter Institute. He works at the intersection of particle, nuclear and atomic physics with cosmology. He is known for seminal works in Big Bang Nucleosynthesis, methods of detecting light dark matter, and precision calculations for tests of fundamental symmetries of particle physics. Maxim is the recent recipient of Craigdarroch Silver Medal for Excellence in Research from the Univeristy of Victoria. He holds a PhD from Budker Institute of Nuclear Physics, Novosibirsk, Russia.

Surjeet Rajendran (also part of Light Dark Matter group and Gravitational Wave Detectors group)

Surjeet Rajendran graduated from Caltech in 2004 with a degree in mathematics and subsequently pursued a Ph D in Physics from Stanford (Graduated 2009). He was the Madansky postdoctoral fellow at Johns Hopkins and is presently the Henry Shenker Professor of Physics. He joined the UC Berkeley Physics Department in July 2014.

Nima Arkani-Hamed

Nima Arkani-Hamed is a Professor in the School of Natural Sciences at the Institute for Advanced Study. He is a leading particle physicist who has developed theories on emergent extra dimensions, "little Higgs theories" and recently proposed new models that can be tested using the Large Hadron Collider (LHC) at CERN in Switzerland. He is also a member of the Perimeter Scholars International faculty.

Short Distance Physics from Precision Experiments

David DeMille

David DeMille is a Professor of Physics at Yale University. David received his Ph.D. from the University of California, Berkeley in 1994 and joined the faculty at Yale in 1998. He is the recipient of awards including the Francis M. Pipkin Award of the American Physical Society (APS) (2006), the Cottrell Scholars Award from Research Corporation (2000), a Sloan Foundation Fellowship (2000), and a Packard Foundation Fellowship (1999), and he was named a Fellow of the APS in 2005.

David's research interests span a wide range of topics in atomic, molecular, and optical physics, with a particular focus on the study of processes that violate discrete symmetries. His group has developed pioneering techniques that use polar molecules to enhance the sensitivity of precision measurements to these symmetry-violating effects. Most notably, several of his group's experiments have searched for a time reversal-violating electric dipole moment of the electron, a property predicted in many theories of particle physics beyond the Standard Model. His group is also pursuing experiments to constrain poorly-known parameters of the Standard Model, via measurements of parity-violating effects.

In parallel, David's group has developed methods for producing samples of ultracold molecules, for example by direct laser cooling and trapping of diatomic species. They have proposed many potential applications for ultracold molecules, such as for quantum information processing and for next-generation electric dipole moment searches, including a search for the electric dipole moment of the proton.

Eric Cornell

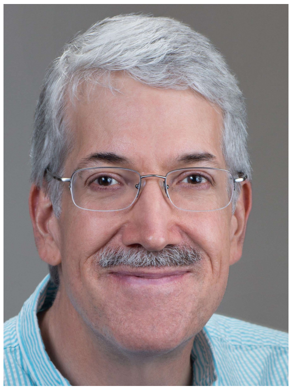
After studying at Stanford University (B.S., 1985), Eric Cornell earned a Ph.D. from the Massachusetts Institute of Technology in 1990. In 1992 he joined the faculty of the University of Colorado. That year he also became a senior scientist at the National Institute of Standards and Technology.

In the early 1990s he began searching for the Bose-Einstein condensate, which had been predicted some 70 years earlier by Albert Einstein and the Indian physicist Satyendra Nath Bose. In this state atoms are so chilled and slow that they, in effect, merge and behave as one single quantum entity that is much larger than any individual atom. In June 1995, working with Wieman, Eric used a combination of laser and magnetic techniques to slow, trap, and cool about 2,000 rubidium atoms to form a BEC. Eric's work provided insight into the laws of physics and led to studies on possible practical uses of BECs. He became a member of the National Academy of Scientists in 2000.

Joseph Formaggio

Joseph Formaggio received his B. S. degree from Yale University in physics in 1996. Thereafter, he received his Ph.D. in physics from Columbia University, where he did his dissertation on neutrino physics by analyzing data taken at the NuTeV experiment located at the Fermi National Laboratory. His research focused on searches for exotic particles predicted by certain theoretical extensions of the standard model of particle physics. In 2001, he joined the Sudbury Neutrino Observatory as a postdoctoral fellow at the University of Washington, where he was later appointed as a research assistant professor. He joined the MIT faculty in 2005. He is currently the division head for the Nuclear Experimental Nuclear and Particle Physics.

John Doyle



John Doyle obtained his PhD from the Massachusetts Institute of Technology. He is the Henry B. Silsbee Professor of Physics at Harvard University, the director of the Harvard Center for Quantum Optics, and co-director of the Harvard/MIT Center for Ultracold Atoms. He has published over one hundred refereed papers in the areas of ultracold atoms, molecules, spectroscopy, precision measurement, neutrons and dark matter detection and supervised the PhDs of over thirty students. John is a Humboldt, Fulbright, and American Physical Society Fellow.

Gerald Gabrielse

Gerald Gabrielse is the Leverett Professor of Physics at Harvard and a member of the NAS. His ideas and demonstrations launched and guide the low energy antiproton and antihydrogen physics being pursued by hundreds at a storage ring built for this purpose.

Gerald chaired the Harvard Physics Department and the DAMOP division of the APS. His many awards include both Harvard's Levenson prize for exceptional teaching and its Ledlie prize for exceptional research. The APS awarded him both its Davisson-Germer Prize and its Lilienfeld Prize. Germany awarded the Humboldt Research Award and Italy the Tomassoni and Chisesi Prize. He is widely sought after for lectures on his physics research, for science lectures to high school students, teachers and the general public, and for lectures on science and religion. For the latter he received the Trotter Prize.

Giorgio Gratta

Giorgio Gratta completed his studies in physics in Rome, Italy, in 1986. He then spent three years at SLAC building the first silicon strip vertex detector for a collider and six years at CERN (as a Caltech scientist) studying the physics of the Z-boson at LEP.

In 1995 he joined the Physics Department at Stanford, where is now professor of physics, and shifted his activity to neutrinos. He participated in the Palo Verde oscillation experiment and was US co-spokesman for the KamLAND experiment that, in 2002, for the first time observed neutrino oscillations from an artificial source. In 2005 KamLAND also provided the first measurement of neutrinos from the interior of the Earth, a measurement relevant for geophysics. Giorgio has also studied ultra-high energy neutrinos in cosmic rays using, for the first time, acoustics techniques and is currently involved in a novel "table top" experiment to investigate the behavior of gravitational interactions at scales below 0.1 mm. He received the Enrico Persico Prize of the Italian Accademia dei Lincei in 1981, is a fellow of the American Physical Society and co-recipient of the 2016 Breakthrough prize.

Christopher Monroe

Christopher Monroe is a quantum physicist who specializes in the isolation of individual atoms for applications in quantum information science. After graduating from MIT, he earned his Ph.D. in Physics in 1992 from the University of Colorado, under Carl Wieman and Eric Cornell, where he paved the way toward the achievement of Bose-Einstein condensation. From 1992-2000 he was a postdoc then staff physicist at NIST, in the group of David Wineland.

With Wineland, Christopher led the team that demonstrated the first quantum logic gate in 1995, and exploited the use of trapped atoms for the first controllable qubit demonstrations. In 2000, Christopher became Professor of Physics and Electrical Engineering at the University of Michigan, where he pioneered the use of single photons to couple quantum information between atoms and also demonstrated the first electromagnetic atom trap integrated on a semiconductor chip.

From 2006-2007 was the Director of the National Science Foundation Ultrafast Optics Center at the University of Michigan. In 2007 he became the Bice Zorn Professor of Physics at the University of Maryland and a Fellow of the Joint Quantum Institute. In 2008, Christopher's group succeeded in producing quantum entanglement between two widely separated atoms and for the first time teleported quantum information between matter separated by a large distance. Since 2009 his group has investigated the use of ultrafast laser pulses for speedy quantum entanglement operations, pioneered the use of trapped ions for quantum simulations of many-body models related to quantum magnetism, and has proposed and made the first steps toward a scalable, reconfigurable, and modular quantum computer.

Light Dark Matter

Derek F. Jackson Kimball

Derek Jackson Kimball received his Ph.D. in 2005 from the University of California at Berkeley under the mentorship of Prof. Dmitry Budker, where he studied nonlinear magneto-optical rotation and its application to precision measurement of atomic spin precession. Derek is the co-author of Atomic Physics: an exploration through problems and solutions (Oxford University Press, 2008), Optical Magnetometry (Cambridge University Press, 2013), and 52 peer-reviewed research articles.

Derek's research focuses on using techniques of experimental atomic physics and nonlinear optics for precision tests of the fundamental laws of physics. In particular, his research focuses on searches for exotic spin-dependent interactions that may have a connection to dark matter or dark energy.

Derek's work with several collaborators on a number of different projects has established some of the most stringent constraints on exotic dipole-dipole interactions of electrons, neutrons, and protons at the atomic scale. An experiment searching for a spin-gravity (or long-range monopole-dipole) coupling of the proton recently improved laboratory constraints on such effects by three orders-of-magnitude. He is a co-inventor of the Global Network of Optical Magnetometers to search for Exotic physics (GNOME) and is presently acting as the GNOME collaboration's scientific coordinator. He is also the scientific coordinator of the Cosmic Axion Spin Precession Experiment (CASPEr).

Derek served as the Chair of the California State University – East Bay Department of Physics from 2011-14 and also during 2016. He was California State University – East Bay's 2011-12 George and Miriam Phillips Outstanding Professor.

Dmitry Budker

Dmitry Budker was born in the USSR and graduated with honors from the Novosibirsk State University in 1985. After working as Junior Researcher at the Novosibirsk Institute of Nuclear Physics, he moved to the USA, where he obtained his PhD in physics from the University of California, Berkeley in 1993. He stayed at Berkeley, joining the faculty in Physics in 1995. In 2014, he became a Professor at the Johannes Gutenberg University and the Leader of the Matter-Antimatter-Asymmetry Section at the Helmholtz Institute Mainz in Germany.

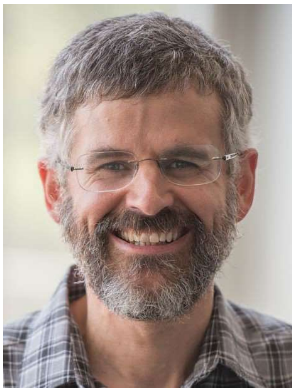
He remains on the Berkeley faculty in the role of Professor of Graduate School. Professor Budker's research interests span a broad range of topics, including sensitive magnetometry, experimental tests of fundamental symmetries, experimental searches for dark matter, magnetic resonance, and spectroscopy of complex systems. He is a Fellow of the American Physical Society (APS), and a former Chair of the APS Group on Precision Measurements and Fundamental Constants.

Andrei Derevianko

Andrei Derevianko is a Hartmann professor of physics at the University of Nevada, Reno. He has authored over 100 refereed publications in theoretical physics. He is a fellow of the American Physical Society, Simons fellow in theoretical physics, and a Fulbright scholar. He completed undergraduate studies at the Moscow Institute of Physics and Technology, earned his Ph.D. at Auburn and did a postdoctoral work at Notre Dame and at the Harvard-Smithsonian Center for Astrophysics. He has been a UNR faculty since 2001.

Among a variety of research topics, he has contributed to the development of several novel classes of atomic clocks and precision tests of fundamental symmetries with atoms and molecules. Recent interests include detection of ultralight dark matter and using archival data to search for new physics signatures.

Kent D. Irwin



Kent Irwin is a Professor in the Physics Department at Stanford University and in the Particle Physics and Astrophysics Department and Photon Science Department at SLAC National Accelerator Lab. He is a member of the Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) and the Hansen Experimental Physics Laboratory (HEPL). Kent's research focuses on fundamental physics experiments including the direct search for dark matter candidates including axions and hidden photons, and cosmological probes of inflation through the cosmic microwave background. Kent has done foundational work in instrumentation for dark matter and CMB experiments, and has participated in all of the CMB experiments presently in the field.

He is presently a member of the DOE-HEP group "Cosmic Visions – CMB" and served on the Concept Definition Task Force for CMB-S4. He is a Fellow of the American Physical Society (2007), and has received several awards including the Keithley Award (APS), the Flemming Award (George Washington University), and the Award for Continuing and Significant Contributions in Applied Superconductivity (IEEE).

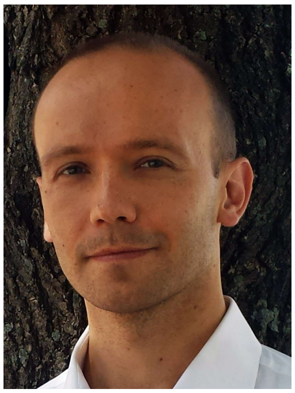
Kent received his PhD in Physics from Stanford University in 1995 and held a postdoctoral position at the NIST laboratories in Boulder Colorado before joining NIST as a scientist in 1996, where he founded and led the NIST Quantum Sensors Group. He was elected a NIST fellow in 2007. In 2013, he joined the faculties of Stanford University and SLAC.

Konrad W. Lehnert

Konrad W. Lehnert is a JILA Fellow, NIST physicist, and Professor of Physics at the University of Colorado. His research group studies the behavior of superconducting circuits and micromechanical devices in the quantum regime. He is known for developing quantum-limited microwave measurements that have impacted quantum information processing and that are now used in searches for dark matter. In addition, he is a pioneer in establishing quantum control and measurement over micromechanical systems.

He has published over 60 papers in scholarly journals, is a Fellow of the American Physical Society, and his collaborative work with Cindy Regal received the 2016 Colorado Governor's award for high impact research.

Alexander O. Sushkov



Alexander Sushkov received his Ph.D. from UC Berkeley, where he worked with Dmitry Budker on precision magnetic field measurements, and electro-optical effects in superfuid liquid helium. He then moved to Yale University, where he worked with Steve Lamoreaux on experiments studying fundamental physics. He developed and carried out an experiment that uses a solid ferroelectric material (Eu,Ba)TiO_3 to search for the permanent electric dipole moment of the electron, which would violate the time reversal symmetry of nature. In a separate experiment, using a torsion pendulum, he performed the first measurement of the thermal Casimir effect, and set new limits on non-Newtonian forces in the micrometer range, placing constraints on theories with extra dimensions.

After moving to Harvard University to work with Misha Lukin, Alex worked on precision sensing experiments at the nanoscale, using nitrogen-vacancy centers in diamond. He performed experiments demonstrating magnetic resonance detection of individual proton nuclear spins on the surface of a diamond crystal, under ambient conditions, with applications to nanoscale magnetic imaging of molecules and materials. He also demonstrated all-optical detection of individual single-atom electron spins, and performed some of the first NMR experiments on single protein molecules, using quantum logic with nuclear spins in diamond. He also participated in developing the methods for application of quantum error correction to metrology and precision measurements.

Alex is currently an Assistant Professor at Boston University. His group is focused on laboratory-scale experiments that address fundamental physics problems using precision measurements. These include the CASPEr search for axion-like dark matter using solid-state magnetic resonance, and a study of the interplay between interactions and disorder, as well as thermalization and nanoscale transport in quantum many-body systems, using nitrogen-vacancy centers in diamond.

New Forces and Tests of Gravity

Andrew Geraci

Andrew Geraci completed his undergraduate work in Physics and Mathematics at the University of Chicago. He received a Ph.D. in physics at Stanford University in 2007 working with Aharon Kapitulnik. His dissertation was entitled, "Developments in the search for non-Newtonian gravity below the 25 micron length scale".

He was subsequently a postdoctoral researcher at NIST in Boulder, CO in the group of John Kitching (2007-2010), where he worked on interfacing cold atoms with mechanical resonators for potential applications in quantum information science and quantum limited sensing. He was a National Research Council postdoctoral Research Associate from 2007-2009.

Andrew joined the University of Nevada Reno in 2011 where he is currently Associate Professor of Physics. His research interests include tests of the gravitational inverse square law at the micron length scale using levitated microspheres, optical trapping and cooling of nanoparticles for ultrasensitive force detection, quantum opto-mechanics with cold atoms coupled to mechanical resonators, and NMR-based laboratory searches for the QCD axion, a notable Dark Matter candidate. Geraci serves as PI of the Axion Resonant InterAction Detection Experiment (ARIADNE) collaboration.

He is an elected member of the executive committee of the Topical group on Precision Measurements and fundamental constants of the Americal Physical society and is a Member of the Optical Society of America.

Cindy Regal

Cindy Regal is an Associate Professor of Physics at the University of Colorado and a JILA fellow. She received her PhD at JILA in 2006 studying under Deborah Jin, and was subsequently a postdoctoral researcher in the group of Konrad Lehnert at JILA. After a Millikan postdoctoral fellowship at Caltech in the group of Jeff Kimble she returned to JILA as an Assistant Professor in 2010.

At JILA, Cindy's research explores quantum science by developing new experimental platforms for quantum information, metrology, and simulation. Her group is interested in how optical control of motion of isolated degrees of freedom can help us build increasingly complex and extended quantum systems.

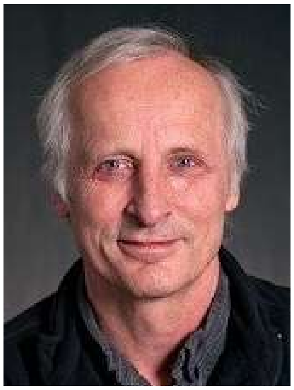
Aharon Kapitulnik

Aharon Kapitulnik is the Theodore and Sydney Rosenberg Professor in Applied Physics at the Departments of Applied Physics and Physics at Stanford University. His research focuses on experimental condensed matter physics, while opportunistically, also apply his methods to tabletop experimental studies of fundamental phenomena in physics. His recent studies cover a broad spectrum of phenomena associated with the behavior of correlated and disordered electron systems, particularly in reduced dimensions, and the development of effective instrumentation to detect subtle signatures of physical phenomena.

Aharon's accomplishments include the development of the Sagnac Interferometer for sensitive detection of time-reversal symmetry breaking effects in solids, and its use for the study of unconventional superconductors, and novel cantilever-based instrumentation for testing the inverse-square-law of gravity at sub-mm distance. He has also been engaged in Scanning Tunneling Spectroscopy studies of correlated electron systems and was one of the pioneers in applying this technique for the study of the cuprate superconductors and topological insulators.

Among other recognitions, his activities earned him the Alfred P. Sloan Fellowship (1986-90), a Presidential Young Investigator Award (1987-92), a Sackler Scholar at Tel-Aviv University (2006), the Heike Kamerlingh Onnes Prize for Superconductivity Experiment (2009), a RTRA (Le Triangle de la Physique) Senior Chair (2010), a Moore-Foundation EPiQS investigator award (2014-2019), and the Oliver Buckley Condensed Matter Prize of the American Physical Society (2015). Aharon Kapitulnik is a Fellow of the American Physical Society, and Fellow of the American Academy of Arts and Sciences, and a member of the National Academy of Sciences. Kapitulnik holds a Ph.D. in Physics from Tel-Aviv University (1983).

Blayne Heckel



Blayne Heckel is professor of physics and chair of the Department of Physics at the University of Washington. His research interests focus on tests of fundamental symmetries: torsion balance tests of spatial isotropy, the equivalence principle, and the gravitational inverse square law, and searching for time reversal symmetry violation in the electric dipole moments of atoms.

Tanya Zelevinsky

Tanya Zelevinsky graduated from MIT in physics and math, and received her physics PhD at Harvard University where her thesis work involved precise spectroscopy of helium atoms for testing QED and measuring the fine structure constant. She came to Columbia University in 2008, after spending a few years building and improving the optical lattice atomic clock at JILA in Boulder, Colorado. Her current research interests and work at ZLab involve precision measurements via state-of-the-art optical spectroscopy and quantum manipulation of diatomic molecules.

Her group uses laser light to create ultracold molecules trapped in an optical lattice. Lattice-clock style spectral resolution then allows quantum control of the molecules, leading to studies of molecular quantum physics and ultracold chemistry. The latter is investigated via the photodissociation process in the ultracold regime. On a fundamental level, the molecules provide an ensemble of tiny clocks where the vibrations determine the ticking rate. This type of quantum clock allows ZLab to test molecular QED at a high level as well as constrain possible new physics at the nanometer scale. ZLab also explores ways to directly cool molecules in order to manipulate and study them. An exciting future possibility is to apply the ultracold photodissociation technique to produce exotic ultracold gases for a variety of scientific applications. ZLab is also collaborating with Yale University and University of Massachusetts to use cold diatomic molecules in combination with optical techniques to measure time-reversal symmetry violation in atomic nuclei (Cold Molecule Nuclear Time Reversal Experiment, or CENTREX).

Holger Mueller

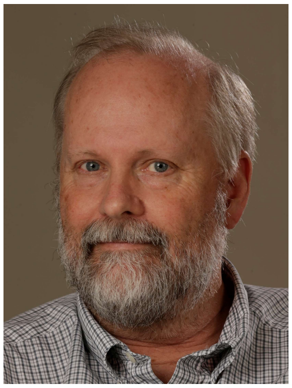
Holger Müller successfully applied for his first patent when he was 14. Later, he did his undergraduate thesis with Jürgen Mlynek at the University of Konstanz, Germany. He graduated from Humboldt-University, Berlin, with Achim Peters as advisor. Holger received a fellowship of the Alexander von Humboldt foundation and joined the group of Steven Chu in Stanford as a postdoc. In July 2008, he joined the physics faculty at U.C. Berkeley.

Yannis Semertzidis

Yannis Semertzidis, a fellow of the American Physics Society and a tenured, senior physicist at Brookhaven National Laboratory in New York, was appointed as director of the IBS research center in October 2013 in recognition of his experiments in precision particle physics and his experimental plan to search for the dark-matter axion.

The IBS center was set up at KAIST with a new IBS building location already chosen to house the experiment and a number of other IBS centers at KAIST. Until recently, he focused mainly on two experimental projects: one exploring the dark-matter axion, and another doing precision physics in storage rings including the muon g-2 experiment and searching for the electric dipole moment (EDM) of protons with unprecedented sensitivity. According to the theory of quantum mechanics (QM) the existence of the EDM of protons would violate the discrete symmetries of P-parity and T-time reversal symmetries. Those symmetries are linked to the matter-anti-matter asymmetry problem and an observed proton EDM will help solve that mystery.

Christopher Stubbs



Christopher William Stubbs is the Samuel Moncher Professor of Physics and of Astronomy at Harvard University, and was chair of Harvard's Physics Department from 2007 to 2010. His research interests lie at the intersection of cosmology, particle physics, and gravitation. Stubbs received an International Baccalaureate diploma from the Tehran International School in 1975, a BSc in physics from the University of Virginia in 1981, and a PhD in physics from the University of Washington in 1988. His research career started with tabletop tests of gravitation, performing precision measurements to explore possible modifications to gravity.

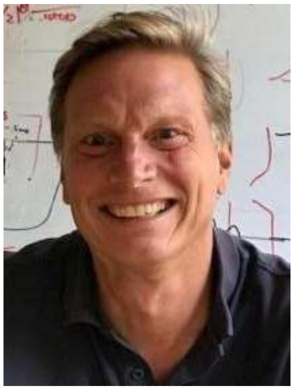
After then searching for dark matter (even-handedly seeking both WIMPs and MACHOs, and finding neither) he was a member of one of the two teams that discovered of the accelerating expansion of the Universe. His subsequent work has been primarily focused on exploring the nature of the Dark Energy that is thought to be responsible for the accelerating cosmic expansion. Christopher is a Fellow of the American Physical Society, a recipient of the National Academy of Sciences Award for Initiative in Research, the NASA Achievement Medal, and is a co-recipient (with other members of the High-z Supernovae Team) of the Gruber Foundation Cosmology Prize and the Breakthrough Prize in Fundamental Physics.

Gravitational Wave Detectors

Jun Ye

Jun Ye is a Fellow of JILA, a joint institute of NIST and University of Colorado. He is a member of the National Academy of Sciences, a Fellow of NIST, a Fellow of the American Physical Society, and a Fellow of the Optical Society of America. His research focuses on the frontier of light-matter interactions and includes precision measurement, quantum physics and ultracold matter, optical frequency metrology, and ultrafast science. He has co-authored over 300 scientific papers and has delivered 500 invited talks. Awards and honors include US Presidential Rank (Distinguished) Award, three Gold Medals from the U.S. Commerce Department, Frew Fellowship from the Australian Academy of Science, I. I. Rabi Prize from the American Physical Society, European Frequency and Time Forum Award, Carl Zeiss Research Award, William F. Meggers Award and Adolph Lomb Medal from the Optical Society of America, Arthur S. Flemming Award, Presidential Early Career Award for Scientists and Engineers, Friedrich Wilhem Bessel Award from Alexander von Humboldt Foundation, and Samuel Wesley Stratton Award from NIST.

Mark A. Kasevich



Mark Kasevich is a Professor of Physics and Applied Physics at Stanford University. He received his B.A. degree (1985) in Physics from Dartmouth College, a B.A. (1987) in Physics and Philosophy from Oxford University as a Rhodes Scholar, and his Ph.D. (1992) in Applied Physics from Stanford University.

He joined the Stanford Physics Department faculty in 1992. From 1997-2002 he was a member of the Yale Physics Department faculty. He returned to Stanford in 2002. His current research interests are centered on the development of quantum sensors of rotation and acceleration based on cold atoms, application of these sensors to tests of General Relativity, investigation of many-body quantum effects in Bose condensed vapors, investigation of quantum-enhanced imaging and measurement methods, and investigation of ultra-fast laser-induced phenomena. He co-founded AOSense, Inc. (2004) and serves as the company's Consulting Chief Scientist.

Mikhail D. Lukin

Mikhail Lukin's research is in the areas of quantum optics and atomic physics. The emphasis is on studies of quantum systems consisting of interacting photons, atoms, molecules and electrons coupled to realistic environments. He is developing new techniques for controlling the quantum dynamics of such systems, and studying fundamental physical phenomena associated with them. These techniques are used to explore new physics, as well as to facilitate implementation of potential applications in emerging areas such as quantum information science and in more traditional fields such as nonlinear optics. In the course of this work Mikhail are also exploring the emerging interfaces between quantum optics and atomic physics on the one hand, and condensed matter and mesoscopic physics on the other.

Ronald L. Walsworth

Ronald Walsworth is on the Physics faculty of Harvard University and is also a Senior Physicist at the Smithsonian Institution. He leads an interdisciplinary research group with a focus on developing precision measurement tools and applying them to important problems in both the physical and life sciences — from quantum physics and astrophysics to bioimaging and brain science. Current areas of research include: precision tests of fundamental physical phenomena, such as the search for dark matter; studying the Sun-as-a-star to enable detection of Earth-like planets around other stars; the development of quantum sensors and the pursuit of applications ranging from condensed matter physics to neuroscience to Earth & planetary science; and the development of novel NMR and MRI tools, with applications to basic spin physics and medical imaging.

Jason M. Hogan

Jason Hogan is an Assistant Professor of Physics at Stanford University. He received a B.S. in Physics from Harvey Mudd College in 2003 and a Ph.D. in Physics from Stanford in 2010. He held a Postdoctoral position at Stanford from 2010-2014 and then joined the faculty in 2014.

His current research interests are in precision atom interferometry for tests of gravity and quantum mechanics, including work on atom interferometry with alkaline earth atoms for application to gravitational wave detection and dark matter searches.

Nergis Mavalvala

Nergis Mavalvala, Marble Professor of Astrophysics at MIT and a 2010 recipient of a MacArthur "genius" award, is a physicist whose research focuses on the detection of gravitational waves and quantum measurement science. She is a longtime member of the scientific team that announced in 2016 the first direct detection of gravitational waves from colliding black holes by the Laser Interferometer Gravitational-wave Observatory (LIGO). The gravitational waves that LIGO detected are ripples in the spacetime fabric caused by the motion of compact, massive astrophysical objects such as black holes and neutron stars. Since the nature of gravitation is inherently different from electromagnetism, gravitational wave astrophysics provides a radically different window into the universe.

In the quest for ever greater sensitivity in the LIGO detectors, Nergis has also conducted pioneering experiments on generation and application of squeezed states of light, and on laser cooling and trapping of macroscopic objects to enable observation of quantum phenomena in human-scale systems.

Professor Nergis Mavalvala received a B.A. from Wellesley College and a Ph.D. from MIT. She was a postdoctoral fellow and research scientist at the California Institute of Technology before joining the Physics faculty at MIT in 2002. She was appointed Associate Department Head of Physics in February 2015. In 2017, Mavalvala was elected to the National Academy of Sciences.

Guido Mueller

Dr. Mueller is a member of the UF-LIGO group and works on research and development for terrestrial gravitational wave detectors. His responsibilities include the input optics of LIGO and Advanced LIGO and advanced interferometer designs. He is also working on the interferometry for LISA, a space-based gravitational wave observatory which will be launched as ESA's L3 mission. Dr. Mueller was and continuous to be a member of several working groups, analysis, interest and advisory teams for NASA. Dr. Mueller also started to work on detection schemes for axions and axion-like particles and is a member of the ALPS collaboration. Over the past 10 years, Guido Mueller has helped to spearhead the development of the Advanced LIGO interferometer, the leading project in the detection of gravitational waves. Mueller played a key role in the design of the main interferometer, the tool that measures specific distances based on the interference of light waves.

Mueller is also interested in exploring the applications of laser interferometry in areas other than the detection of gravitational waves. He hopes to use the technology for the detection of "dark matter," a form of matter that makes up about 27 percent of the universe but that is so far only observable by its gravitational effects.

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