REVIEW

Prototype of the CASPEr-electric experimental search for axion dark matter at Boston University.

Probing the frontiers of particle physics with tabletop-scale experiments

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The field of particle physics is in a peculiar state. The standard model of particle theory successfully describes every fundamental particle and force observed in laboratories, yet fails to explain properties of the universe such as the existence of dark matter, the amount of dark energy, and the preponderance of matter over antimatter. Huge experiments, of increasing scale and cost, continue to search for new particles and forces that might explain these phenomena. However, these frontiers also are explored in certain smaller, laboratory-scale "tabletop" experiments. This approach uses precision measurement techniques and devices from atomic, quantum, and condensed-matter physics to detect tiny signals due to new particles or forces. Discoveries in fundamental physics may well come first from small-scale experiments of this type.

The discovery of the Higgs boson at the Large Hadron Collider (LHC) was a remarkable triumph for the field of particle physics. It confirmed the final, crucial piece of the theoretical framework known as the standard model (SM) of particle physics. The SM is a quantum field theory, where each type of particle is an excitation of a corresponding type of field, and forces between a pair of particles arise when some third particle is exchanged between them. The SM has successfully predicted the existence of every particle detected, as well the laws of particle interactions, since its advent in the years around 1970. Its precise predictions have been tested in extraordinary detail over the intervening decades (*1*, *2*).

However, the SM cannot be the final theory of particle physics. A complete theory should describe the behavior of elementary particles and forces starting from the very early universe (shortly after the Big Bang) through its evolution into atoms, molecules, stars, and galaxies. The SM fails to explain several undisputed experimental observations about the universe. Instead, new particles, fields, and forces appear to be needed.

One well-known example is dark matter—a substance that obeys the laws of gravity, but is not composed of SM constituents (the electrons and quarks that make up atoms) (*3*). There is strong evidence that most of the mass of the universe is in the form of dark matter. A natural explanation is that dark matter consists of some new particles, or a permeating field of some yet-undiscovered type—long-lived remnants from just after the Big Bang. Several plausible theoretical models extend the SM to incorporate new quantum fields and associated particles with the right properties to act as dark matter.

Another prominent example is dark energy—a mysterious type of energy that causes the expansion of our universe to accelerate (*4*, *5*). Dark energy is the dominant form of energy in the universe today. A term arising in the theory of general relativity, known as the cosmological constant Λ, has the properties of dark energy; however, connecting it to the fundamental properties of quantum fields is problematic. The ever-present "vacuum energy" of the quantum fields in the SM may be connected to Λ, but would naïvely predict a value of $\Lambda \sim 120$ orders of magnitude larger than is observed (*6*). Although this remains very speculative, it has been suggested that certain new types of quantum fields could perhaps correctly account for dark energy (the final answer may have to wait for a viable theory of quantum gravity) (*7*).

Also unexplained is how the atoms that make up the visible universe managed to survive in the aftermath of the Big Bang (*8*). The difficulty is as follows. Via Einstein's relation $E = mc^2$, the energy of the Big Bang was converted into particles with mass, creating equal numbers of matter and antimatter particles. As the universe evolved and cooled, nearly all these particles collided and annihilated back into pure energy (electromagnetic fields). Only about one in a billion particles in the universe escaped this fate—and these surviving particles comprise the ordinary matter of the universe. This means there must be an asymmetry in the way matter and antimatter particles behave. [If equal amounts of antimatter remained in patches separated from the matter, evidence of annihilations at their boundaries would have been detected essentially anywhere in the observable volume of the universe (*9*).] Decades ago, the generic features that a quantum field theory must have to generate a matter-antimatter asymmetry were understood (*10*). The SM itself has these features, but its prediction for the proportion of particles that escaped annihilation is many orders of magnitude smaller than what is experimentally measured. By contrast, this proportion can be matched in certain theoretical extensions to the SM that incorporate new particles and forces with the correct properties.

For these reasons (and others), it is essentially certain that new particles and forces remain to be discovered. The central goal of experimental particle physics is exactly to discover such new phenomena. For decades, the primary approach to doing so has been to employ very-high-energy particle colliders that could produce particles with larger mass than any now known, as predicted by many SM extensions. The LHC represents the latest iteration of this vision: a machine spanning

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many kilometers, with contributions from many thousands of scientists over several decades (11). In parallel, other experiments are seeking direct evidence for the particle nature of dark matter. A well-publicized approach is a search for a new type of very heavy, weakly interacting massive particle (WIMP). These experiments use tons of purified cryogenically cooled liquid, or solid, as a large-scale, low-background detector for the rare event of a dark-matter WIMP striking an atom inside it (12). Both the LHC and WIMP search experiments have optimal sensitivity to particles with mass within roughly an order of magnitude of the Higgs boson mass (13).

To date, despite these heroic efforts, no new particles beyond those in the SM have been detected. Given the cost and complexity of these large-scale experiments, there is growing interest in different approaches to address these fundamental questions, which lie at the heart of modern particle physics and cosmology. Remarkably, it has become possible to meaningfully explore these questions with experiments small enough to fit in a single university laboratory room. These small-scale experiments rely on fundamentally different approaches compared to the more traditional large experiments. At their heart is the use of quantum-mechanical resonance behavior (Fig. 1), which enables exquisitely sensitive measurement of tiny energy shifts—shifts that can be caused by the existence of new quantum fields with exactly the properties needed to solve these known shortcomings of the SM. Breakthrough ideas, coupled with rapid advances in atomic, molecular, and optical physics techniques and quantum-limited measurement devices, are leading to a surge in progress. In the next sections, we discuss three exciting types of experiments in this vein. Each of these approaches is pushing the frontier of fundamental physics to a level that complements—and sometimes exceeds—the discovery potential of the traditional methods.

Electric dipole moments: Seeking the cause for the matter-antimatter asymmetry

Generating a cosmological matter-antimatter asymmetry requires forces that change strength when two operations are jointly performed: Matter and antimatter particles are interchanged (an operation called charge conjugation, denoted by *C*), and all particles are replaced by their mirror image (a parity transformation, *P*) (10). Forces of this type are said to violate *CP* symmetry. In quantum field theories, such as the SM, *CP* violation is always accompanied by an equivalent violation of time-reversal (*T*) symmetry such that the total symmetry *CPT* is preserved. All instances of *CP* and *T* violation measured to date are found to originate from a single mathematical term in the SM, which leads to *CP* violation in the nuclear weak force. However, the effects associated with this term are insufficient to account for the observed matter-antimatter asymmetry, even though the measured *CP* violation is nearly as large as mathematically allowed within the framework of the SM (8).

The physics of *CP* violation leads to a generic outcome: It causes ordinary particles (electrons, protons, etc.) to acquire an asymmetric distribution of charge—an electric dipole moment (EDM)—directed along the axis of their spin. (Atomic nuclei acquire a slightly different distribution, but for simplicity, we refer to this also as an EDM.) Such a situation is inherently *T*-violating: If you (say) run a movie of an electron backward, its spin direction will reverse but the static charge distribution will remain the same, so their relative directions will be different for the movie running forward and backward (14).

In theories with new particles and forces, new mathematical terms that lead to *CP* violation are ubiquitous (15). The size of the EDM predicted for any ordinary particle, in any given theory, depends on the strength of the *CP*-violating force and the mass of the new particles that carry it: The heavier the new particles and the weaker the *CP* violation, the smaller the EDM. In nearly all extensions to the SM, EDMs are predicted to be orders of magnitude larger than those predicted by the SM. EDMs of electrons and nuclei can arise from different types of new forces, so looking for both is important. Even in the SM, mathematically *CP* violation could appear in the strong interaction, inducing primarily nuclear EDMs—but experiments long ago showed that any such contribution must be extraordinarily small (16, 17). This absence of *CP* violation in the strong force is a theoretical conundrum known as the "strong *CP* problem." Attempts to explain it led to prediction of a new particle, the axion (16, 17), which we discuss in a subsequent section.

Efforts to detect EDMs have recently reported substantial progress. In these experiments, the spin of an electron or a nucleus is oriented in a known direction, using polarized laser light resonant with a transition between atomic or molecular energy levels. An electric field, directed perpendicular to the spin, exerts a torque on the particle if it has an EDM. This torque will cause the spin axis to precess about the direction of the field (much like the axis of a spinning top precesses about the vertical direction of gravity). Lasers then probe the final direction of the spin.

To detect the smallest possible EDM, experiments maximize the strength of the electric field, the time over which it acts, and the number of particles observed (for optimal signal-to-noise ratio). Very different experimental approaches

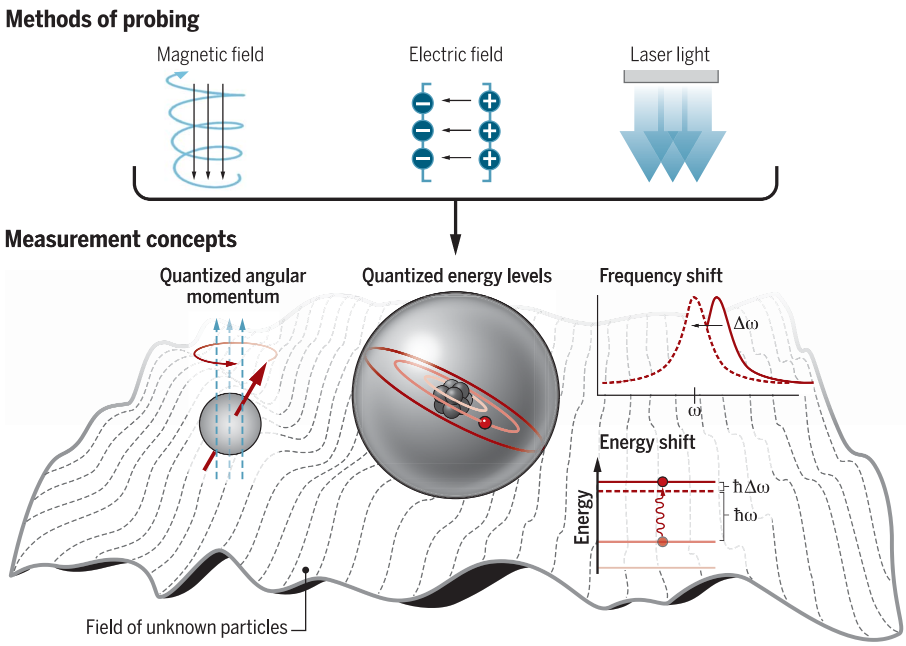

Fig. 1. Probing fundamental physics with resonance experiments. Atoms and molecules have states of quantized energies and angular momenta. Scientists can study the behavior of such systems by exciting resonant transitions between these energy states and measuring how they respond to various external perturbations, such as magnetic fields, electric fields, and so forth. For example, an atom with a quantized angular momentum (spin), placed in a magnetic field *B*, has energy states corresponding to spin along or against *B*. Their splitting is $\hbar\omega$, where ω is proportional to *B*, and $\hbar$ is the reduced Planck's constant. In a quantum superposition of these states, the spin axis undergoes Larmor precession around *B*, with angular frequency ω. When excited by fields that affect the spin, the response of such an atom (the rate at which the spin axis tilts away from *B*) is peaked at the resonant frequency ω. Another example is the quantized energy levels in an atom. Atomic clocks use lasers to excite transitions between these levels, measuring the corresponding frequencies with a precision approaching one part in 10^{18}. The effect on these systems of a new force (for example, caused by a dark-matter field) or new particles and their associated quantum fields (such as those that may cause an electron to have an EDM) is to excite these transitions or to introduce tiny shifts in these transition energies that can be detected in precision experiments.

GRAPHIC: A. KITTERMAN AND V. ALTOUNIAN/*SCIENCE* have led to improved sensitivity. For example, the ACME experiment (*18*) uses electrons bound inside the polar molecule ThO, where they experience an effective electric field of ~100 billion V/cm. By the use of cryogenic methods, the molecules are produced in an intense, slow beam that is probed for about 1 ms. Another experiment (*19*) achieved similar sensitivity using molecular ions trapped by a rotating electric field; here many fewer molecules are detected, but each can be observed for nearly 1 s. The most sensitive search for a nuclear EDM uses ^{199}Hg nuclei bound in Hg atoms, exposed to fields of 10,000 V/cm and confined in small transparent cells (*20*) where nuclear spins remain polarized for more than 100 s. So far, none of these experiments has detected a finite EDM. However, their sensitivity is remarkable. For example, if a ^{199}Hg nucleus were blown up to the size of Earth, a charge asymmetry equivalent to moving a slice roughly 100-nm-thick from the Southern to Northern Hemisphere would have been detected.

What do these results mean? It is generally expected that *CP* violation will be as strong as possible in any given theory—as it is in the SM, and as is usually needed to explain the cosmological matter-antimatter asymmetry (*8*). With this assumption, EDMs should have been detected according to most theories where new particles have mass near that of the Higgs boson (with rest mass energy $M_h c^2$ ~ 0.1 TeV) (*21*). For example, in theories based on supersymmetry (where each known particle is accompanied by a heavier partner with a quantized spin differing by a half-integer multiple of $\hbar$), these tabletop-scale EDM experiments arguably rule out some classes of new particles with a rest mass energy Mc^2 lower than a few tera–electron volts (TeV) (*22*). This already exceeds the mass range detectable at the LHC for such particles (Fig. 2) (*23*).

Discovery of a nonzero EDM would herald the existence of new particles, likely with mass beyond the direct reach of any conceived accelerator. A broad class of models predicts such particles, giving rise to EDMs that are typically within a factor of ~30 of current experimental reach (*24*). New EDM experiments are underway with projected sensitivity approaching this level within the next few years (*19*, *25*–*28*).

Axions: A prime candidate for dark matter

Existence of dark matter is another puzzle that the SM cannot solve. The WIMP is a well-known candidate that has inspired a large number of ultrasensitive experiments of increasing complexity and scale (*29*), but so far there has been no unambiguous detection, and recent experiments at the LHC, as well the EDM limits discussed above, have placed stringent constraints on theoretical frameworks, such as supersymmetry, that support WIMP dark matter (*30*). It is important to broaden the search, and there are other theoretically well-motivated dark-matter candidates, including ultralight particles such as axions and axion-like particles (we call all these "axions" for brevity). Axions emerge naturally from theories of physics at ultrahigh energies, such as grand unified theories, extra-dimensional models, and string theory (*31*). As mentioned in the previous section, the "QCD axion" is a specific axion particle that emerges when the strong *CP* problem of quantum chromodynamics (QCD—the theoretical description of the strong force) is resolved by introducing a new symmetry that is broken at a very high-energy scale (*16*, *17*). Axion mass is inversely proportional to this energy scale, which can be as high as the Planck scale (~10^{16} TeV), the energy at which effects of quantum gravity are expected to play an important role. Experiments hunting for axions carefully look for signatures of their interactions with the standard particles around us. Three types of interaction are possible: an interaction with an electromagnetic field that can convert axions into photons and vice versa; a "QCD" interaction with nuclei that produces nuclear EDMs; and an "axion wind" interaction that rotates electron and nucleon spins. If axions make up dark matter, their rest mass energy $m_a c^2$ must be below milli–electron volts, lighter than even neutrinos. Then, their density is large enough that they act like a quantum field that oscillates at the Compton frequency $\omega_a = m_a c^2/\hbar$, which can range from hertz to terahertz. This would act as a universal "radio station" broadcasting its presence across the cosmos. To search for axion dark matter, one must tune in to a frequency that is currently unknown—there is lots of spinning the dial.

Designing an experiment sensitive to the axion dark-matter field is not easy, given that the strengths of axion interactions are very small (Fig. 3). Most of the laboratory searches for axions to date have been based on the axion-photon interaction (*32*). This concept is used by ADMX (Axion Dark Matter eXperiment): Inside a high magnetic field, axions can resonantly convert to photons in a microwave cavity tuned to the axion frequency. ADMX is currently searching in the 500- to 800-MHz range, corresponding to a cavity size of ~1 m, and is sensitive enough to detect the QCD axion, the ultimate sensitivity goal of such experiments (*33*). Future upgrades are planned to extend the tuning range up to ≈10 GHz. One experiment already exploring higher frequencies is HAYSTAC, approaching QCD axion sensitivity near 5.75 GHz (*34*). Such remarkable sensitivity is enabled by the use of quantum-limited amplifiers to detect microwave photons, and in the future, quantum squeezing techniques could be used to extend the sensitivity beyond the quantum limit. Microwave cavity searches are inherently limited to axion masses near 10 μeV, corresponding to frequencies near gigahertz, because this is where high–quality-factor cavities of reasonable size (experimental sensitivity scales with the cavity volume) can be fabricated. To search for lower-mass axions, the LC circuit, DM radio, and ABRACADABRA experiments instead use lumped element resonant circuits (*35*). At the much larger experimental scale, the CERN Axion Solar Telescope (CAST) searches for axions originating from the hot plasma inside the core of the Sun, recently producing a new bound on axion-photon coupling in a wide range of axion masses (*36*), and the Any Light Particle Search

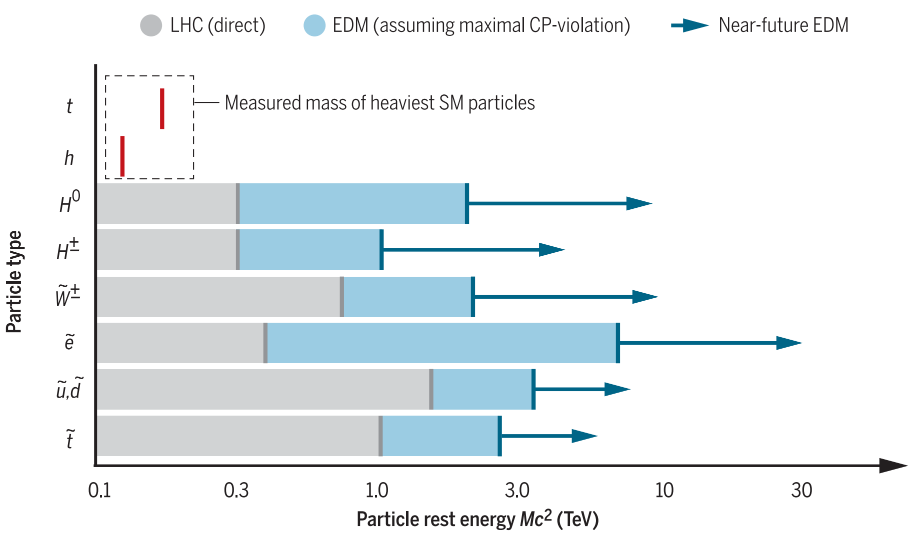

Fig. 2. Masses of known and hypothetical particles. Red bars show the measured masses of the heaviest SM particles, the top quark (*t*) and Higgs boson (*h*). So far, no particles outside the SM have been discovered, but experiments can rule out their existence below a certain mass. Areas shaded in gray and blue show excluded ranges for hypothetical but highly plausible new particles such as additional neutral or charged Higgs (H^0, $H^\pm$) and supersymmetric partners (denoted by tildes) of SM particles such as $W^\pm$ bosons, electron (*e*), and up (*u*), down (*d*), and top quarks. Direct searches at the LHC rule out the gray regions; blue regions are ruled out by limits from EDM experiments (if maximal *CP* violation is assumed). The arrows show projected sensitivity for planned new EDM experiments. We caution that exclusion limits of both types rely on various theoretical assumptions, and should be taken as representative of typical conclusions rather than strict statements. Data compiled from (*18*, *20*, *22*, *23*, *55*).

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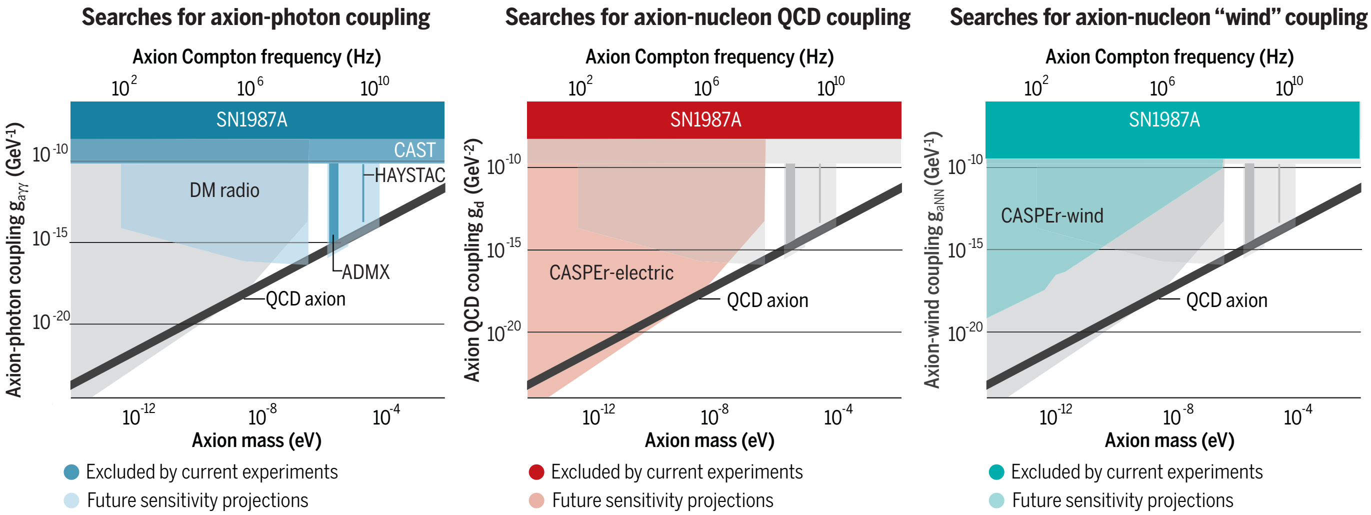

Fig. 3. Experimental constraints and projected sensitivities of some axion dark-matter searches. QCD axion models lie in the dark gray region, with coupling strength proportional to axion mass. The solid regions labeled "SN1987A" are excluded by observations of supernova SN1987A.

(ALPS) experiment is looking for axions using a "light shining through a wall" concept that relies on the photon-axion-photon double conversion (*37*).

Experiments searching for axions via their interactions with nuclei and/or spins employ the techniques of precision magnetic resonance. The Cosmic Axion Spin Precession Experiments (CASPEr) use nuclear magnetic resonance (NMR) (*38*). The axion dark-matter field exerts a tiny torque on nuclear spins, and, if the axion frequency ω_a matches their Larmor frequency (see Fig. 1), their response is resonantly amplified and can be detected by a sensitive magnetometer. By tuning the magnetic field applied to the sample, the nuclear spin Larmor frequency can be scanned in a wide range, thus covering multiple decades of axion masses. CASPEr-electric uses nuclear spins in a ferroelectric solid sample, where spins experience an enormous effective electric field, similar to the ACME EDM experiment described above, and is sensitive to the QCD coupling that produces oscillating EDMs of nuclei. CASPEr-wind uses hyperpolarized liquid xenon and is sensitive to the "axion-wind" coupling.

The discovery of axions could open a new window on fundamental physics at ultrahigh energies and solve many of the mysteries facing physicists today, such as the nature of dark matter and the strong *CP* problem of the SM. The possibility of solving such problems in a laboratory-scale experiment makes axion searches an exciting and dynamic field, which has seen a resurgence in the last few years (*39*).

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Atomic clock comparisons: Probing the nature of dark energy and dark matter

The universe expands at an ever-increasing rate over very large scales owing to the mysterious "dark energy." If spacetime itself is dynamic, the question arises: Might the quantities that we think of as fundamental constants of nature also themselves be changing? It turns out this question is closely linked to the nature of dark energy: A new (near massless) quantum field that permeates space and varies with time and/or position could possibly account for dark energy, and in addition would lead to a variation of measured physical quantities otherwise expected to remain constant. The existence of ultralight fields is independently motivated by several theories, including string theories, that seek to unify the forces of nature (*40*); such fields would also lead to "fifth forces" that would violate the Einstein equivalence principle [effects that other tabletop experiments, not discussed here, probe directly (*41*)]. Other versions of new, light quantum fields (including, but not limited to, axions) can have the properties needed to account for dark matter, as discussed in the previous section. Depending on the exact nature of a new field's inhomogeneities, this variation could take place at very different time scales, e.g., from cosmological to human (*40*). Thus, studies of variation of constants both look far back in time [using, for example, light from distant quasars (*42*)] and take place in the present day (lab-based measurements looking for year-to-year or other transient variation).

Present-day lab searches for variation are made possible primarily by highly sensitive atomic clocks (*43*). Although the time scales for measuring the variation in the lab are much smaller than cosmological, the control and sensitivity of new clocks is extraordinary, and rapidly, improving. Atomic clocks use physical effects inside an atom to create an oscillating signal. Specifically, the energy splitting E between a pair of quantum levels in the atom determine the frequency ω of atom-based oscillators via Planck's relationship $E = \hbar\omega$ (Fig. 1). The energy splitting itself depends on the fundamental constants of nature—which might vary, depending on the fields permeating all of empty space. The primary energy scale in atoms and molecules is the quantum scale of electrostatic energy, $E_e = e^2/a_0$, where e is the electron charge and a_0 is the Bohr radius, the typical size of the atom. Additional energy scales are set by E_e in combination with dimensionless constants such as the fine structure constant, $\alpha = e^2/(\hbar c)$, and the ratio of proton to electron masses, μ.

The only way to determine if any given clock's oscillation frequency is changing is to compare it to some other clock—either one at a different location or one based on a different set of energy levels. The ratio of oscillation frequencies of two different clocks is a dimensionless number; hence only changes in dimensionless combinations of fundamental constants are meaningful. Different types of clocks depend on different combinations of fundamental constants. For example, the quantized energies of rotation in a molecule depend on μ via the mass of the nuclei. Relativistic effects within atoms cause corrections to optical-frequency transitions that depend only on α, whereas microwave transitions, for example in Cs atoms (the current internationally recognized time standard), are sensitive to both α and μ.

Different underlying physical effects could lead to variation of constants on different temporal and spatial scales. For example, changes in dark energy over cosmological time scales, if caused by the changing amplitude of a background quantum field, would look like a slow drift in constants such as α or μ in the laboratory (*43*). The newest variety of clock, based on ultranarrow resonances in optical transitions in either trapped ions or neutral atoms in an optical lattice, can measure fractional shifts on the level of 10^{-18} (*43*) (Fig. 4). If a quantum field is responsible for dark matter, it could cause constants to oscillate sinusoidally at the Compton frequency of the associated particles. Alternatively, it could cause transient changes in the constants as Earth moves through regions of space where the field changes amplitude or direction (*44*). Finally, because the amplitude of the field can be modified by the presence of matter, constants might be seen to vary when

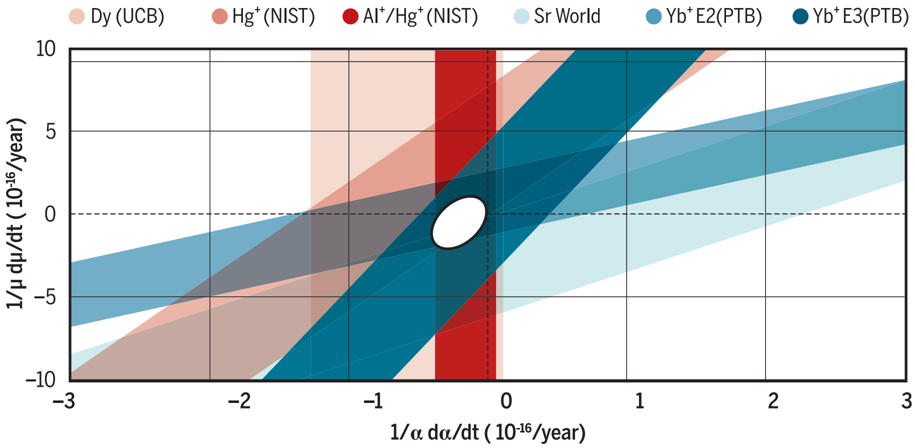

Fig. 4. Variation of fundamental constants. Overlapping constraints from a variety of clock-based measurements constrain slow drifts in α and μ in the current era [reprinted with permission from (*56*); copyright (2014) by the American Physical Society]. Bands are 1σ uncertainty regions. Comparison with cosmological constraints is highly model-dependent. However, very roughly, the astrophysical data sets limits on fractional changes of <0.1 part per million (ppm) for μ (*57*) and <2 ppm for α (*42*) over roughly 6 billion years. Thus, clock work is highly complementary to astro-observational measurements.

their position relative to some massive object is changed (*45*).

The current best limits are primarily based on systems optimized for general performance as clocks, but certain systems have properties that enhance their sensitivity to variations in constants. This can take place when contributions to the energies from two physical mechanisms accidentally cancel such that two energy levels are far closer than normal. Tiny changes in a fundamental constant can then have disproportionately large effects in the energy-level splitting. Examples include Dy atoms [where current experiments are competitive with standard clocks (*46*)], molecules [where vibrational energies can cancel electronic energy differences (*47–49*)], highly charged atomic ions (*50*), and the ^{229}Th nucleus [where strong-force and electromagnetic effects cancel to make a pair of levels close enough to excite with a laser (*51*, *52*)]. These systems have the promise to enable orders-of-magnitude improved sensitivity in variations to μ and α. Finally, clocks will likely continue to improve at a rapid pace, potentially greatly improving searches for time variation of constants.

Whether the sort of ultralight quantum fields that could give rise to varying constants actually exist is anybody's guess. What seems to be certain is that the steady improvements in clocks and related high-precision measurements of quantized energy levels are leading to a new series of unprecedented tests about the nature of the fabric of space itself. Because the expansion of the universe we observe is faster than ever before, now is a good time, in this way, to look for dark energy.

Conclusion

We have highlighted a few types of tabletop-scale experiments that are exploring the frontiers of fundamental physics. The recent progress in these experiments has been enabled by remarkable advances in techniques from the fields of atomic, molecular, optical, and condensed-matter physics. This includes methods such as laser-based manipulation of molecular states (used for EDM searches), cooling and trapping of atoms (used for clocks), the advent of new materials, and development of detectors and devices that operate at the quantum limits (both used for axion searches). These fields continue to thrive and will likely produce even better tools in the near future. For example, techniques now under development, such as quantum entanglement–based methods to surpass classical limits on statistical sensitivity (*53*), are likely to yield big improvements in sensitivity for both EDM searches and clock-based searches for variation of fundamental constants. With other new methods, such as laser cooling and trapping of molecules (*54*), it is conceivable, within a decade, to reach a sensitivity to EDMs that would probe for particles with masses ~1000 times heavier than those accessible to the LHC. Likewise, quantum squeezing techniques could be used to substantially improve the sensitivity of axion searches. This widening range of new experimental approaches to studying fundamental physics may hold the keys to unlocking some of the deepest puzzles about our universe.

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