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New light, weakly-coupled particles

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6.1 Overview

New light particles that couple only weakly to ordinary matter are ubiquitous in new physics extensions of the Standard Model. Their existence is motivated by several theoretical and observational puzzles, many of which are central in our quest to obtain a comprehensive understanding of the constituents of our universe and their interactions. These include the nature of dark matter and dark energy, the strong CP problem, and a variety of astrophysical puzzles and dark matter-related anomalies.

Our working group examines axions, axion-like particles, hidden-sector photons, milli-charged particles, chameleons, and related particles (see [1] for a recent review). Their masses can range anywhere from sub-femto-eV to the weak scale (~ 100 GeV), and they are characterized by their small coupling or mixing with the photon. This allows them to be produced with intense beams of photons, electrons, or protons and detected with sensitive equipment. This makes them, by definition, targets for the intensity frontier. We will sometimes refer to these weakly interacting sub-eV (or "slim") particles as "WISPs".

Axions are pseudo-scalar particles that solve the strong CP problem. They have extremely small masses, because they arise as pseudo-Nambu-Goldstone bosons of an almost exact symmetry, the "Peccei-Quinn" symmetry, which is spontaneously broken at a very high energy scale. The spontaneous breaking of other, non-Peccei-Quinn global symmetries is common in new physics models (including string theory) and can give rise to light axion-like scalar or pseudo-scalar particles, called ALPs. Axions and ALPs can constitute the dark matter of our universe and can explain a variety of astrophysical observations. The axion couples to gluons, photons, and Standard Model fermions, and it is the latter two that are the most easily detected. ALPs also naturally couple to photons, although this coupling is not guaranteed.

Hidden-sector photons, called A' bosons, are massive vector bosons that can mix with the ordinary photon via "kinetic-mixing." This mixing can permit photon-A' oscillations (observable for sub-eV A' bosons) and produces a small coupling of the A' to electrically charged matter. A sub-eV mass A' could be the dark matter particle or contribute to the observed number of relativistic degrees of freedom in the early universe. A MeV-GeV mass A' could explain the discrepancy between the measured and calculated muon anomalous magnetic moment in the Standard Model.

Intriguingly, an A' allows ordinary matter to have a small coupling to new particles in a "hidden-sector" that do not interact with the Standard Model's strong, weak, or electromagnetic forces. These hidden-sectors can have a rich structure and have thus far remained undetected. They appear in many extensions of the Standard Model, and are often required for consistency or phenomenological reasons. Dark matter could be part of such a hidden-sector and couple to an A', producing new dark matter interactions with ordinary matter that might explain some of the data of cosmic-ray, balloon-borne, or terrestrial dark matter experiments. A hidden-sector coupled to a massless A' would include particles that are milli-charged under the ordinary photon.

Chameleons are scalar particles that might be responsible for the "dark energy" that is accelerating our universe's expansion. They are one of only a few known ways to hide dark energy from local gravity (equivalence principle and inverse-square law) tests. Chameleons remain hidden because their mass depends on the local matter density. In high-density regions, such as on Earth where these tests are done, their mass is large, so the new force generated by the chameleons has a range too short to be detectable. In low-density regions, such as in the universe at large, their mass is small and they are a candidate for dark energy. They can couple to photons, allowing photons to oscillate to chameleons and vice versa.

Searches for these new particles are naturally part of the intensity frontier, since intense beams of photons, electrons, or protons are required to produce them in sufficient quantities to compensate for their weak coupling to ordinary matter. Several experimental proposals exist to search for these particles. Many existing facilities have not yet been fully exploited in this search. Technology and accelerator developments, in many cases very modest by current standards in both cost and effort, can allow exploration of even more of the motivated parameter space. Large-scale experiments are also under consideration, well-motivated, and require more substantial investments. In many instances, simple configuration changes can switch their sensitivity from one type of particle to another. All these experiments provide an amazing opportunity for major fundamental discoveries. The discovery of a new force of Nature, or a whole new sector of particles is within their reach. There is world-wide interest and competition in this physics, and the US needs to pursue it aggressively. The strong motivation for the existence of new light, weakly coupled particles combined with a very modest cost-to-benefit ratio implies that any sensible future intensity frontier program should include this physics as an important component.

The outline of the remainder of this section is as follows. §6.2 discusses the theory and physics motivation for axions, axion-like particles, hidden-sector photons, milli-charged particles, and chameleons. §6.3 provides an overview of the experimental searches for these various particles, including current and future planned experiments. In §6.4 and §6.5, we discuss the technologies and accelerators, respectively, needed for future progress. §6.6 contains our conclusions.

6.2 Physics Motivation

6.2.1 Axions and Axion-Like Particles

One of the biggest unresolved puzzles in the Standard Model is the lack of any observed CP violation in the strong nuclear interactions described by Quantum Chromodynamics (QCD). While the weak interactions are known to violate CP, the strong interactions also contain a CP-violating term in the Lagrangian, $\frac{\Theta}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$, where $G^{\mu\nu}$ is the gluon field strength. For non-zero quark masses, this term leads to (un-observed) CP-violating effects of the strong interactions. This so-called "strong CP problem" is often exemplified by the lack of observation of a neutron dipole moment down to a present experimental upper limit 10 orders of magnitude smaller than what is expected from a CP-violating QCD.

Solutions to this problem are scarce. Perhaps the most popular suggestion is the so-called Peccei-Quinn (PQ) $U(1)$ approximate global symmetry, which is spontaneously broken at a scale f_a. The axion is a hypothetical particle that arises as the pseudo-Nambu-Goldstone boson (PNGB) of this symmetry [2, 3, 4].

The axion mass is $m_a \sim 6$ meV (10^9 GeV$/f_a$). Its coupling to ordinary matter is proportional to $1/f_a$ and can be calculated in specific models. It couples to leptons and to photons, the latter being of the form $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$, where $g_{a\gamma} \sim 10^{-13}$ GeV (10^{10} GeV$/f_a$) [5] is a coupling that is model-dependent up to an $\mathcal{O}(1)$ factor. Moreover, since $m_a \ll \Lambda_{QCD}$, the axion's coupling to quarks should be described through its coupling to hadrons, which occurs through small mixing with the π^0 and η mesons. All of these interactions can play a role in searches for the axion, and allows the axion to be produced or detected in the laboratory and emitted by the sun or other stars.

Fig. 6-1 (top) shows the allowed axion parameter space as a function of f_a or, equivalently, m_a. Direct searches for such particles and calculations of their effect on the cooling of stars and on the supernova SN1987A excludes most values of $f_a \lesssim 10^9$ GeV. Some of these constrain only the axion coupling to photons ($g_{a\gamma}$), while others constrain the axion coupling to electrons (g_{ae}). Recent and future laboratory tests (the latter shown in light green) can probe $f_a \sim 10^9 - 10^{12}$ GeV, or even higher f_a.

The basic physical mechanism that leads to the axion — the spontaneous breaking at a high energy scale of a $U(1)$ approximate global symmetry, generating a light PNGB — also allows for other axion-like particles (ALPs). Unlike axions, which are linked to the strong interactions and whose masses and couplings are determined by a single new parameter f_a, ALPs are much less constrained, and their masses and couplings to photons are independent parameters. Searches for ALPs should not therefore be limited to the parameter space of the axion itself. Both ALPs and axions are generic in string theory [6, 7, 8, 9], with the natural size of their decay constant f_a being the string scale, varying typically between 10^9 and 10^{17} GeV.

The parameter space for ALPs is shown in Fig. 6-1 (bottom). The axion parameter space lies within an order of magnitude from the line labelled "KSVZ axion," which represents a particular QCD axion model. Experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical, or cosmological arguments (blue) are shown. Sensitivity of a few planned experiments are shown in light green.

Axions and ALPs can naturally serve as the universe's dark matter, meaning that the galactic halo may be formed partly or entirely from these particles. They can be produced thermally or non-thermally in the early universe. Thermally produced axions are disfavored by observations of the universe's large scale structure [10], but thermally produced ALP dark matter is still allowed in parts of the parameter space. Non-thermal production can occur through the "vacuum misalignment mechanism," and axions could provide all the observed dark matter within this mechanism for $f_a \sim 3 \times 10^{11}$ GeV ($m_a \sim 2 \times 10^{-5}$ eV) [11]. This presents a clear experimental target. The Axion Dark Matter eXperiment (ADMX) will soon probe part of this preferred parameter space.

More generally, however, a large number of non-thermal axion and ALP production mechanisms exist, including the decay of strings. Together with a whole range of possible initial conditions, a much larger parameter space needs to be explored as indicated in Fig. 6-1; see also *e.g.*, [12].

The presence of an axion or ALP during inflation generates isocurvature temperature fluctuations that can be searched for by the Planck satellite [13]. The axion dark matter may also form a Bose-Einstein condensate [14], which may lead to caustic rings in spiral galaxies, which may already have been observed.

There are some astrophysical puzzles that may be solved by the existence of axions or ALPs, namely the apparent non-standard energy loss of white dwarf stars, *e.g.*, [15, 16], and the anomalous transparency of

the universe for TeV gamma rays, *e.g.*, [17, 18, 19, 20, 21]. The required coupling strengths seem within reach in controlled laboratory experiments at the intensity frontier, and can serve as useful benchmarks.

6.2.2 Hidden-Sector Photons

This section describes the theory and motivation for new forces mediated by new abelian $U(1)$ gauge bosons A' — also called "U-bosons," or "hidden-sector," "heavy," "dark," "para-," and "secluded" photons — that couple very weakly to electrically charged particles through "kinetic mixing" with the photon [22, 23].

Kinetic mixing produces an effective parity-conserving interaction $\epsilon e A'_\mu J^\mu_{\rm EM}$ of the A' to the electromagnetic current J^μ_{EM}, suppressed relative to the electron charge e by the parameter ϵ, which can be naturally small (we often write the coupling strength as $\alpha' \equiv \epsilon^2 \alpha$ where $\alpha = e^2/4\pi \simeq 1/137$). In particular, if the value of ϵ at very high energies is zero, then ϵ can be generated by perturbative or non-perturbative effects. Perturbative contributions can include heavy messengers that carry both hypercharge and the new $U(1)$ charge, and quantum loops of various order can generate $\epsilon \sim 10^{-8} - 10^{-2}$ [24]. Non-perturbative and large-volume effects common in string theory constructions can generate much smaller ϵ. While there is no clear minimum for ϵ, values in the $10^{-12} - 10^{-3}$ range have been predicted in the literature [25, 26, 27].

A hidden-sector consisting of particles that do not couple to any of the known forces and containing an A' is generic in many new physics scenarios. Hidden-sectors can have a rich structure, consisting of, for example, fermions and many other gauge bosons. The photon coupling to the A' could provide the only non-gravitational window into their existence. Hidden-sectors are generic, for example, in string theory constructions [28, 29, 30, 31]. Several other "portals" (connections between a visible and hidden-sector) beyond the kinetic mixing portal are possible, many of which can be investigated at the intensity frontier.

Masses for the A' can arise via the Higgs mechanism and can take on a large range of values. A' masses in the MeV–GeV range arise in the models of [32, 33, 34, 35] (these models often involve supersymmetry). However, much smaller (sub-eV) masses are also possible. Masses can also be generated via the Stückelberg mechanism, which is especially relevant in the case of large volume string compactifications with branes. In this case, the mass and size of the kinetic mixing are typically linked through one scale, the string scale M_s, and therefore related to each other. In Fig. 6-3, various theoretically motivated regions are shown [25, 26]. The A' mass can be as small as $M_s^2/M_{\rm Pl}$, i.e. $m_{A'} \sim$ meV (GeV) for $M_s \sim$ TeV (10^{10} GeV). Note that particles charged under a *massive* A' do not have an electromagnetic millicharge, but a *massless* A' can lead to millicharged particles (see §6.2.3).

A natural dividing line is $m_{A'} \sim 2m_e \sim 1$ MeV. For $m_{A'} > 1$ MeV, an A' can decay to electrically charged particles (*e.g.*, e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$) or to light hidden-sector particles (if available), which can in turn decay to ordinary matter. Such an A' can be efficiently produced in electron or proton fixed-target experiments [36, 38, 39, 40, 41, 42, 44, 45, 43] and at e^+e^- and hadron colliders [24, 33, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56]. Hidden-sector particles could be directly produced through an off-shell A' and decay to ordinary matter. An A' in this mass range is motivated by the theoretical considerations discussed above, by anomalies related to dark matter [57, 58], and by the discrepancy between the measured and calculated value of the anomalous magnetic moment of the muon [59].

Fig. 6-2 shows existing constraints for $m_{A'} > 1$ MeV [36] and the sensitivity of several planned experiments that will explore part of the remaining allowed parameter space. These include the future fixed-target experiments APEX [39, 40], HPS [41], DarkLight [38] at Jefferson Laboratory, experiments at MAMI [42] at the University of Mainz (whose reach are not shown, but which may probe similar parameter regions as other experiments), and another at VEPP-3 [43]. Existing and future e^+e^- colliders can also probe large
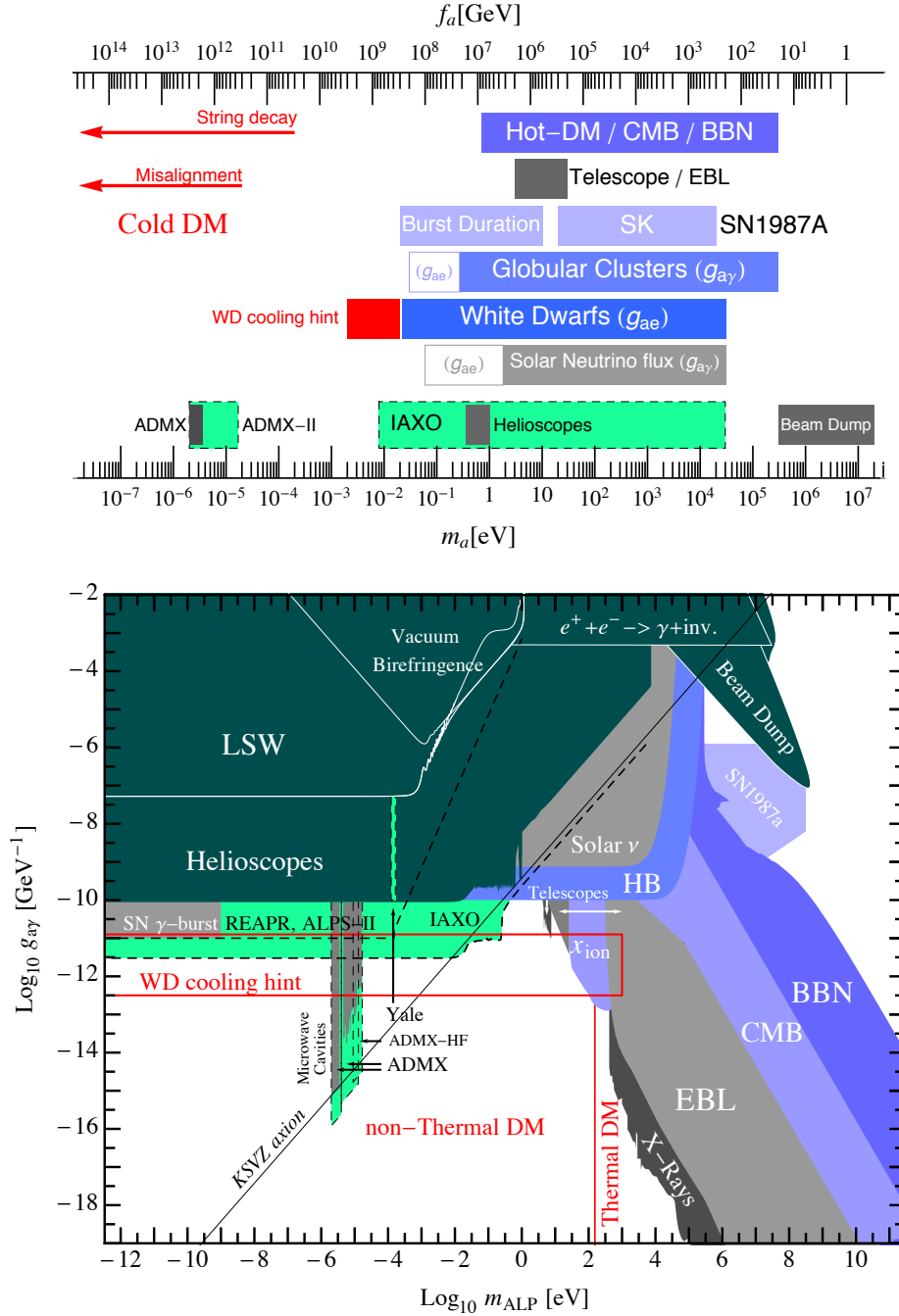
Figure 6-1. *Parameter space for axions (top) and axion-like particles (ALPs) (bottom). In the bottom plot, the QCD axion models lie within an order of magnitude from the explicitly shown "KSVZ" axion line. Colored regions are: experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), and sensitivity of planned experiments (light green). Shown in red are boundaries where ALPs can account for all the dark matter produced either thermally in the big bang or non-thermally by the misalignment mechanism.*
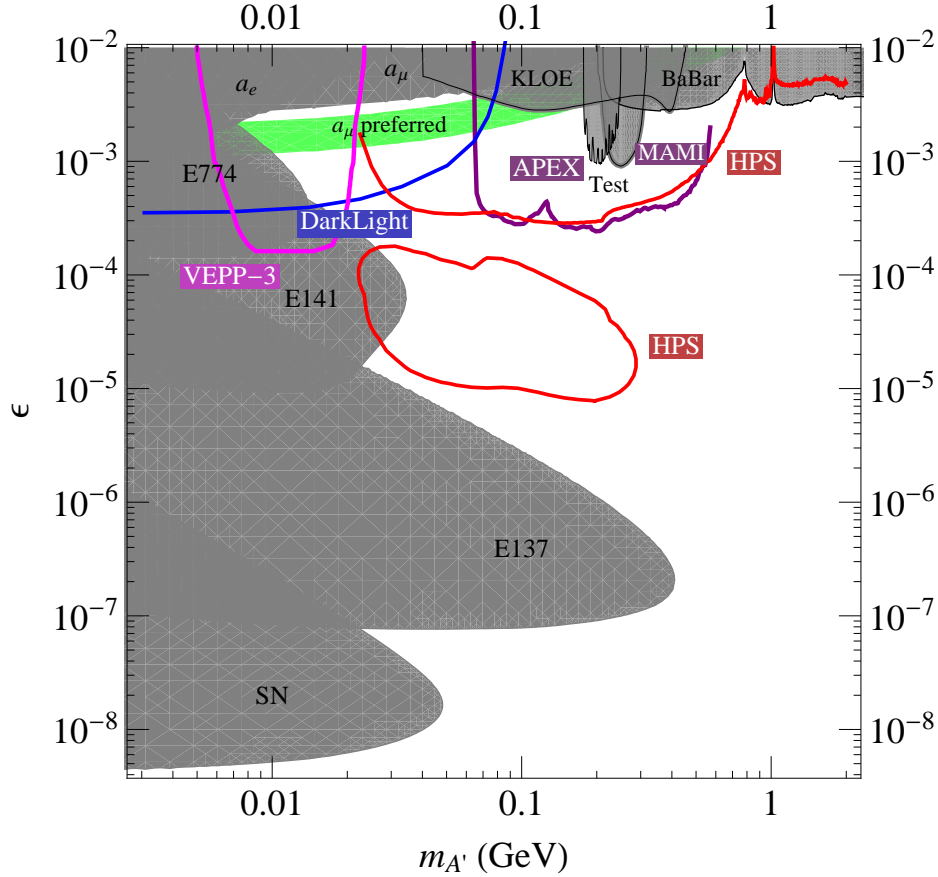
Figure 6-2. *Parameter space for hidden-photons (A') with mass $m_{A'} > 1$ MeV (see Fig. 6-3 for $m_{A'} \lesssim 1$ MeV). Shown are existing 90% confidence level limits from the SLAC and Fermilab beam dump experiments E137, E141, and E774 [86, 87, 88, 36] the muon anomalous magnetic moment a_μ [59], KLOE [54], the test run results reported by APEX [40] and MAMI [42], an estimate using a BaBar result [36, 47, 148], and a constraint from supernova cooling [36] (see also [37]). In the green band, the A' can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [59] at 90% confidence level. Projected sensitivities are shown for the full APEX run [39], HPS [41], DarkLight [38], and VEPP-3 [43]. MAMI has plans (not shown) to probe similar parameter regions as these experiments. Existing and future e^+e^- colliders such as BABAR, BELLE, KLOE, SuperB, BELLE-2, and KLOE-2 can also probe large parts of the parameter space for $\epsilon \gtrsim 10^{-4} - 10^{-3}$; their reach is also not explicitly shown.*

parts of the parameter space for $\epsilon \gtrsim 10^{-4} - 10^{-3}$, and include *BABAR*, Belle, KLOE, Super*B*, Belle-2, and KLOE-2 (the figure only shows existing constraints, and no future sensitivity). Proton colliders such as the LHC and Tevatron can also see remarkable signatures for light hidden-sectors [46]. This rich experimental program is discussed in more detail in §6.3.

For $m_{A'} < 1$ MeV, the A' decay to e^+e^- is kinematically forbidden, and only a much slower decay to three photons is allowed. Fig. 6-3 shows the constraints, theoretically and phenomenologically motivated regions, and some soon-to-be-probed parameter space. At very low masses, the most prominent implication of kinetic mixing is that, similar to neutrino mixing, the propagation and the interaction eigenstates are misaligned, giving rise to the phenomenon of photon $\leftrightarrow A'$ oscillations [60]. In the early universe, these oscillations convert thermal photons into A' bosons, generating a "hidden Cosmic Microwave Background" (hCMB) [61]. For $\sim$ meV masses and $\epsilon \sim 10^{-6}$, they occur resonantly after big bang nucleosynthesis and before the decoupling of the CMB, and the corresponding hCMB could lead to an apparent increase
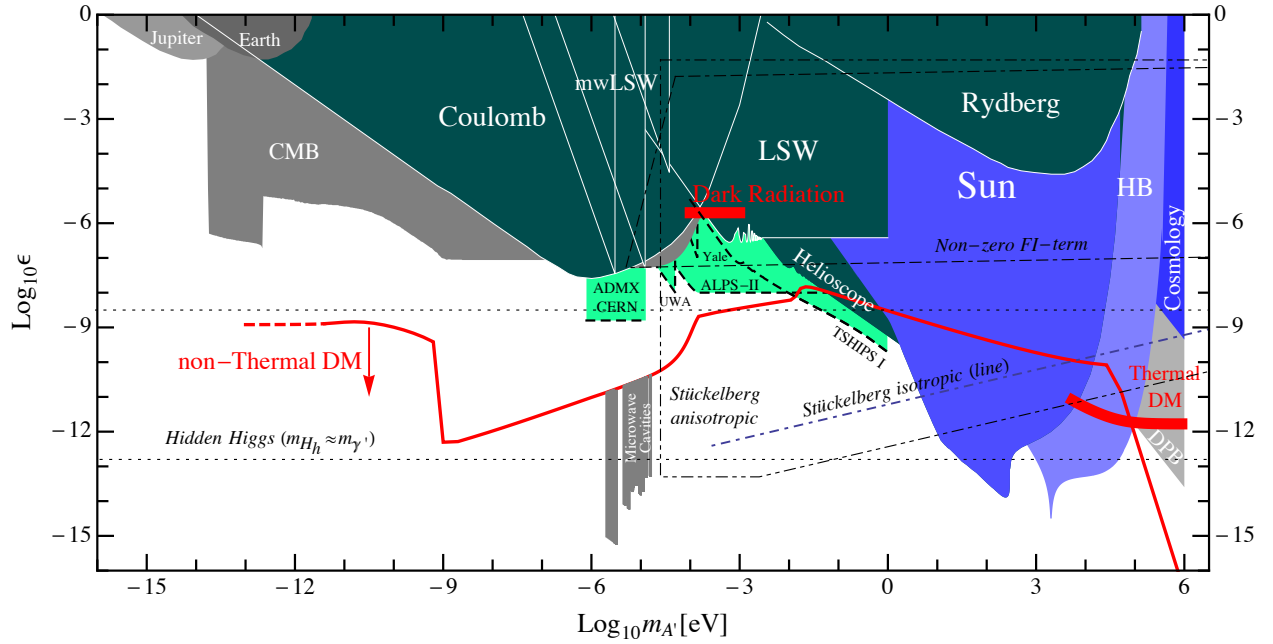
Figure 6-3. *Parameter space for hidden-photons (A') with mass $m_{A'} \lesssim 1$ MeV (see Fig. 6-2 for $m_{A'} > 1$ MeV). Colored regions are: experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), and sensitivity of planned experiments (light green). Shown in red are boundaries where the A' would account for all the dark matter produced either thermally in the big bang or non-thermally by the misalignment mechanism (the corresponding line is an upper bound). The regions bounded by dotted lines show predictions from string theory corresponding to different possibilities for the nature of the A' mass: Hidden-Higgs, a Fayet-Iliopoulos term, or the Stückelberg mechanism. In general, predictions are uncertain by factors of order 1.*

in the effective number of relativistic degrees of freedom, consistent with some recent global cosmological analyses [62, 63, 64, 61]. These observations will soon be tested by the Planck satellite. At the same time, an A' in the parameter range of interest can also be searched for in the laboratory by light-shining-through-wall experiments and helioscopes (see §6.3).

The photon $\leftrightarrow A'$ oscillation mechanism can also generate the required A' energy density for them to account for all the dark matter for $m_{A'} \sim 100$ keV and $\epsilon \sim 10^{-12}$ [65]. This hypothesis can be tested in direct dark matter detection experiments or indirectly through the A' decay into three photons, which could be observed above the astrophysical diffuse X-ray backgrounds [66].

As axions or ALPs, A' bosons can also be dark matter through the realignment mechanism [67]. This intriguing possibility can be realized in a wide range of values for $m_{A'}$ and ϵ [12], see Fig. 6-3. It appears that experiments such as ADMX, looking for axion dark matter, can be very sensitive to A' bosons as well, but in this case the use of magnetic fields to trigger the $A' \rightarrow$ photon conversion is not required. As we will see in §6.3, the same experimental apparatus can often look for several kinds of particles.

Other existing constraints, theoretically and phenomenologically motivated parameter regions, and future experimental searches for A' bosons with $m_{A'} < 1$ MeV are shown in Fig. 6-3. A few planned experimental searches are discussed in §6.3, although a large parameter space still remains to be experimentally explored.
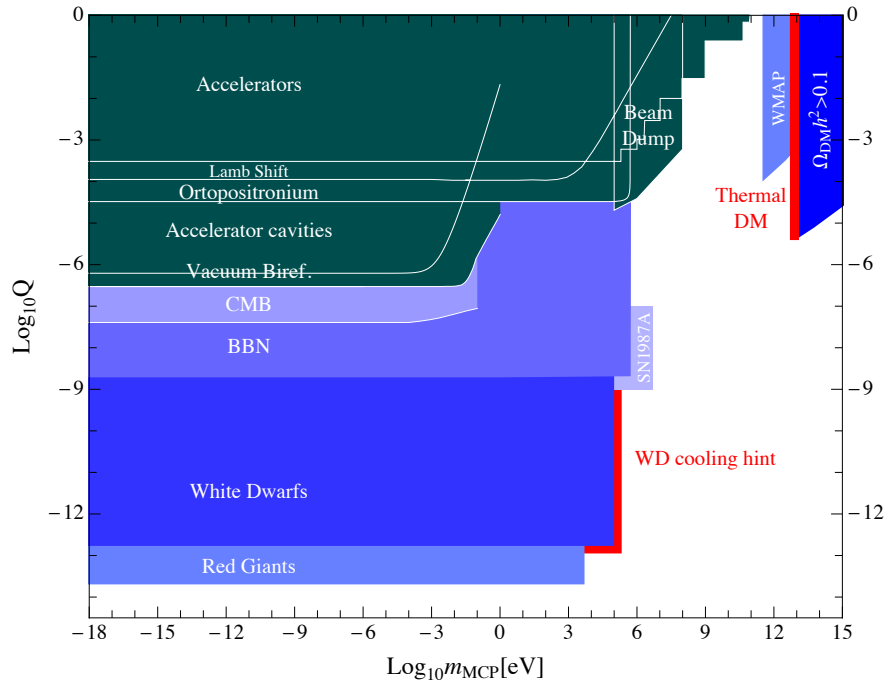
Figure 6-4. *Parameter space for milli-charged particles, where Q is the fractional charge in units of the electron charge. Colored regions are: experimentally excluded regions (dark green) and constraints from astrophysical or cosmological arguments (blue). Shown in red are regions where milli-charged particles could account for the dark matter in our universe or explain the energy loss in white dwarf stars; see §6.2.1.*

6.2.3 Milli-charged particles

Particles with small un-quantized electric charge, often called mini- or milli-charged particles (MCPs), also arise naturally in many extensions of the Standard Model. MCPs are a natural consequence of extra $U(1)$s and the kinetic mixing discussed in §6.2.2 for massless A' fields. In this case any matter charged (solely) under the hidden $U(1)$ obtains a small electric charge. MCPs can also arise in extra-dimensional scenarios or as hidden magnetic monopoles receiving their mass from a magnetic mixing effect [68, 69, 70]. Milli-charged fermions are particularly attractive because chiral symmetry protects their mass against quantum corrections, making it more natural to have small or even vanishing masses. MCPs have also been suggested as dark matter candidates [71, 72, 73].

Experiments as well as astrophysical and cosmological observation provide interesting constraints on MCPs. These are summarized in Fig. 6-4. It needs to be investigated whether currently planned experiments can probe any of the remaining parameter space.

6.2.4 Chameleons

The acceleration of the expansion of the universe, the discovery of which has won the 2011 Nobel Prize in Physics, remains the greatest mystery in modern cosmology. Any field responsible for this acceleration may couple directly to Standard Model particles. Chameleon fields are a compelling dark energy candidate, as
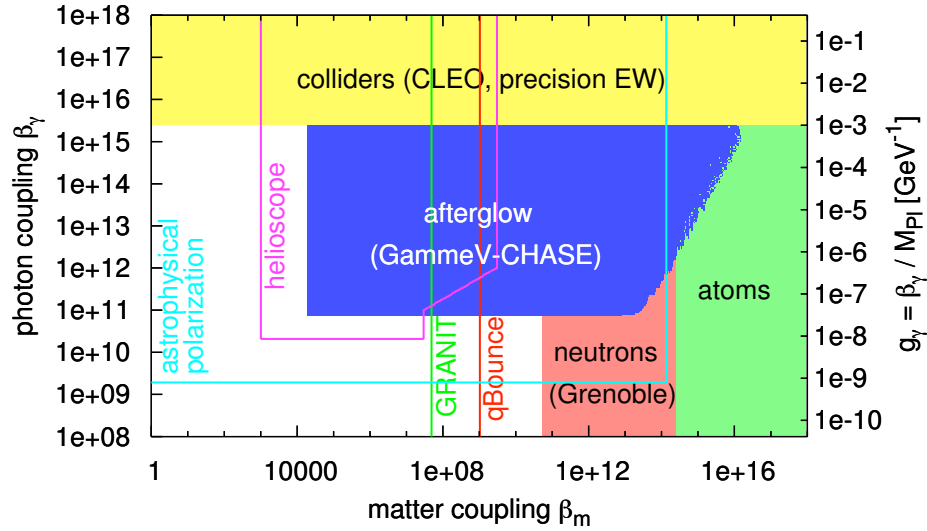
Figure 6-5. *Constraints on a specific chameleon dark energy model (see text for details). Solid regions labelled by horizontal text represent current constraints; curves labelled by vertical text represent forecasts.*

they would do exactly this without violating any known laws or experiments of physics. Importantly, these fields are testable in ways entirely complementary to the standard observational cosmology techniques, and thus provide a new window into dark energy through an array of possible laboratory and astrophysical tests and space tests of gravity. Such a coupling, if detected, could reveal the nature of dark energy and may help lead the way to the development of a quantum theory of gravity.

A canonical scalar field is the simplest dynamical extension of the Standard Model that could explain dark energy. In the absence of a self interaction, this field's couplings to matter — which we would expect to exist unless a symmetry forbids them — would lead to a new, fifth fundamental force whose effects have yet to be observed. However, scalar field dark energy models typically require a self interaction, resulting in a nonlinear equation of motion [75, 76]. Such a self interaction, in conjunction with a matter coupling, gives the scalar field a large effective mass in regions of high matter density [77, 78]. A scalar field that is massive locally mediates a short-range fifth force that is difficult to detect, earning it the name "chameleon field." Furthermore, the massive chameleon field is sourced only by the thin shell of matter on the outer surface of a dense extended object. These nonlinear effects serve to screen fifth forces, making them more difficult to detect in certain environments.

Current best theories treat chameleon dark energy as an effective field theory [74, 82] describing new particles and forces that might be seen in upcoming experiments, and whose detection would point the way to a more fundamental theory. The ultraviolet (UV) behavior of such theories and their connection to fundamental physics are not yet understood, although progress is being made [79].

A chameleon field couples to dark matter and all matter types, in principle with independent strengths. At the classical level, a chameleon field is not required to couple to photons, though such a coupling is not forbidden. However, when quantum corrections are included, a photon coupling about three orders of magnitude smaller than the matter coupling is typically generated [80]. The lowest order chameleon-photon interaction couples the chameleon field to the square of the photon field strength tensor, implying that in a background electromagnetic field, photons and chameleon particles can interconvert through oscillations.

The mass of chameleon fields produced will depend on the environmental energy density as well as the electromagnetic field strength. This opens the vista to an array of different tests for these fields on Earth, in space, and through astrophysical observations. Several astrophysical puzzles could also be explained by chameleons, *e.g.*, [81].

The chameleon dark energy parameter space is considerably more complicated than that of axions, but constraints can be provided under some assumptions. With the caveat that all matter couplings are the same but not equal to the photon coupling, and the assumption of a specific chameleon potential, $V(\phi) = M_\Lambda^4(1 + M_\Lambda^n/\phi^n)$ in which we set the scale $M_\Lambda = 2.4 \times 10^{-3}$ eV to the observed dark energy density and, for concreteness, $n = 1$, our constraints and forecasts are provided by Figure 6-5. This choice prevents us from including Casimir force constraints [83], which are most powerful for negative n, as well as torsion pendulum constraints [84, 85], which have been computed only for $n = -4$. Current constraints (solid regions) and forecasts (curves) are discussed in §6.3 with an emphasis on afterglow experiments and astrophysics expectations.

6.3   Experimental Searches

This section discusses various experimental searches for axions, axion-like particles (ALPs), hidden-photons, chameleons, and milli-charged particles. Minor modifications to a given experimental technique often allows sensitivity to more than one type of particle, so rather than organizing the discussion according to particle type, we here organize it according to experimental technique. The proposed sensitivities of several currently planned experiments are shown in Figs. 6-1 to 6-5, but *several other experiments have been proposed and many more are possible, and not all proposed experiments discussed below appear in the figures.*

6.3.1   Microwave Cavities

Soon after the axion was realized to be a natural dark matter candidate, a detection concept was proposed that relies on the resonant conversion of dark matter axions into photons via the Primakoff effect [89]. Though the axion mass is unknown, various production mechanisms in the early universe point to a mass scale of a few to tens of μeV if the axion is the dominant form of dark matter. The detection concept relies on dark matter axions passing through a microwave cavity in the presence of a strong magnetic field where they can resonantly convert into photons when the cavity frequency matches the axion mass. A 4.13 μeV axion would convert into a 1 GHz photon, which can be detected with an ultra-sensitive receiver. Axions in the dark matter halo are predicted to have virial velocities of $10^{-3}c$, leading to a spread in axion energies of $\Delta E_a/E_a \sim 10^{-6}$ (or 1 kHz for our 1 GHz axion example).

Initial experiments run at Brookhaven National Laboratory [90] and the University of Florida [91] came within an order of magnitude of the sensitivity needed to reach plausible axion couplings. ADMX [92] was assembled at Lawrence Livermore National Laboratory and consists of a large, 8 T superconducting solenoid magnet with a 0.5 m diameter, 1 m long, open bore. Copper-plated stainless steel microwave cavities are used and have $Q_C \sim 10^5$, low enough to be insensitive to the expected spread in axion energies. The TM$_{010}$ mode has the largest cavity form factor and is moved to scan axion masses by translating vertical copper or dielectric tuning rods inside the cavity from the edge to the center. TE and TEM modes do not couple to the pseudoscalar axion.

Using the ADMX setup and an estimated local dark matter density of $\rho_{DM} = 0.45$ GeV/cm^3 [93], an axion conversion power $P_a \sim 10^{-24}$ W is expected for plausible dark matter axions, with the possibility of scanning

an appreciable frequency space (hundreds of MHz) in just a few years. Initial data runs were cooled with pumped LHe to achieve physical temperatures of < 2 K and used SQUID amplifiers to reach plausible dark matter axion couplings [94]. Recently the ADMX experiment has been moved to the University of Washington where it will be outfitted with a dilution refrigerator that will increase sensitivity and scan rate. A second ADMX site, dubbed ADMX-HF, is being constructed at Yale and will allow access to > 2 GHz while ADMX scans from 0.4 - 2 GHz. To achieve a greater mass reach, near-quantum limited X-band amplifiers and large volume resonant cavities will have to be developed.

As shown in Fig. 6-1, ADMX and ADMX-HF are uniquely sensitive to axion and ALP dark matter in the range of a few to tens of μeV. The experiments also have exceptional sensitivity to hidden-photons in the same mass region, as shown in Fig. 6-3.

6.3.2   Light Shining Through A Wall

The "Light Shining through a Wall" (LSW) technique is a method where photons of light, γ's, are injected against an opaque barrier, and a search is made for photons on the other side of this wall. A positive result would suggest that incoming photons transform into weakly interacting particles that traverse the barrier, and then reconvert back into detectable photons. This technique was originally envisioned as a method suitable for searching for axion-like particles that couple to two photons [95, 96], with previous mention in the context of paraphoton searches [60]. A laser beam was shone into the bore of a dipole magnet where a laser photon and magnetic field photon could interact and produce an ALP that could traverse the wall. In the magnetic field region on the other side of the wall, the ALP could regenerate back into a detectable photon.

A first experimental search using spare accelerator magnets [97] in the early 1990s excluded ALPs with a mass below 1 meV and a coupling to photons $g_{a\gamma} > 7 \times 10^{-7}$ GeV^{-1}. Motivated by a possible positive ALP signal reported in 2006 [98], recent LSW experiments have not found evidence for ALPs with $g_{a\gamma} > 7 \times 10^{-8}$ GeV^{-1} [99]. This limit amounts to one rare reconversion process in 10^{25} interactions.

The LSW technique can also be used to search for processes where photons might transform into very light (< 1 eV) weakly interacting slim particles (WISPs) such as light hidden-sector photons or milli-charged particles [100]. In this case, kinetic mixing would allow the process to take place even in the absence of a magnetic field. Experiments [99] have excluded important regions of WISP parameter space.

In the short term, LSW experiments will continue to explore open regions of WISP parameter space. In the mid term, optimized future LSW experiments will make use of advanced techniques such as matched Fabry-Perot optical cavities on both sides of the wall to increase the incident laser power and to build up the regenerated signal resonantly. Such efforts can reach sensitivities of $g_{a\gamma} < 1 \times 10^{-11}$ GeV^{-1} [101]. A comprehensive review of LSW experiments can be found in [102]. The reach of early LSW experiments and REAPR and ALPS-II are shown in Fig. 6-1. LSW sensitivity to low mass hidden-photons is given in Fig. 6-3.

6.3.3   Axion Helioscopes

Axions can be created inside the sun via the Primakoff effect [103]. Due to their extraordinarily weak coupling to matter, these particles can escape from the solar interior. An axion helioscope relies on the inverse Primakoff effect [104, 105, 106], i.e., reconversion into $0.1 - 10$ keV photons in an intense transverse magnetic field to detect them. The minimum requirements for a helioscope are therefore a powerful magnet

and an X-ray sensor. Sensitivity can be enhanced by providing a mechanical system to allow for solar tracking, and by use of X-ray optics to reduce detector size and with it the backgrounds.

The first axion helioscope search was carried out at Brookhaven National Lab in 1992 with a stationary dipole magnet [107]. A second-generation experiment, the Tokyo Axion Helioscope, used a more powerful magnet and dynamic tracking of the sun [108, 109, 110]. A third-generation experiment, the CERN Axion Solar Telescope (CAST), began data collection in 2003. It employs an LHC dipole test magnet [111] with an elaborate elevation and azimuth drive to track the sun. CAST is also the first helioscope to use an X-ray optic to focus the photon signal [112]. Each generation of axion helioscope has achieved a six-fold improvement in sensitivity to the axion coupling constant over its predecessors. For $m_a < 0.02$ eV, CAST has set an upper limit of $g_{a\gamma} < 8.8 \times 10^{-11}$ GeV^{-1} and a larger value of $g_{a\gamma}$ for higher axion masses [113, 115, 116, 114]. These sensitivities are shown in Fig. 6-1 and Fig. 6-3.

To date, all axion helioscopes have "recycled" magnets built for other purposes. A significantly improved sensitivity is to be expected from a custom-built magnet. The fourth-generation axion helioscope proposed in [117], dubbed the International Axion Observatory (IAXO), envisions an ATLAS-like magnet, a detection system consisting of large X-ray telescopes coupled to ultra-low background X-ray detectors, and a large, robust tracking system. IAXO would enable the search for solar axions and ALPs in a broad mass range, with sensitivity down to a few 10^{-12} GeV^{-1}, with sensitivity to QCD axion models down to the meV scale. Lowering X-ray detector thresholds to 0.1 keV would allow IAXO to test whether solar processes can create chameleons [118]. More speculative, but of tremendous potential scientific gain, would be the operation of microwave cavities inside IAXO's magnet, to allow a simultaneous search for solar and dark matter axions [*e.g.*, [119]]. Searches for solar axions and chameleons which exploit naturally occurring magnetic fields are described in [120, 119, 121] and reviewed in [122].

6.3.4 Chameleon Searches: Afterglow Experiments + Others

Afterglow experiments, similar in design to axion searches, produce chameleon particles through oscillations inside a vacuum chamber, which traps them in the chamber walls if their energies are less than their effective mass. The trapped chameleon particles oscillate back into photons and emerge from the vacuum chamber as an "afterglow" after the photon source has been turned off. The GammeV experiment [123] constrained chameleon fields by modifying the earlier GammeV axion search [124]. The recent afterglow search GammeV-CHASE [125, 126] implemented better control of systematic effects, significantly improving on GammeV constraints. A proposed afterglow experiment based upon a modification of the LIPSS axion search can further improve sensitivity to chameleon-photon interactions by use of a higher-intensity photon beam [127].

Chameleon particles produced by astrophysical sources may also be detectable. The sun is a well-understood source whose large magnetic field could produce chameleon particles capable of reaching the Earth. These could regenerate detectable photons in the high magnetic field of a helioscope [128, 129]. Yet more distant sources could be dimmed or polarized due to photon-chameleon oscillation [130, 131]. Since these provide preliminary constraints subject to systematic uncertainties, we include them in Fig. 6-5 as forecasts.

Colliders exclude very large chameleon-photon couplings β_γ [132, 80, 133, 134] (see Fig. 6-5). At large chameleon-matter couplings β_m, limits are provided by measurements of the energy levels of atoms [135], as well as of neutrons bouncing in a gravitational field [136, 137]. Upcoming neutron bouncing experiments are expected to improve constraints on β_m at low β_γ by orders of magnitude [138].

It is worth noting that these constraints are model dependent, and providing completely model independent constraints is very challenging. Present constraints cluster in the very large coupling regions for both matter

and photon couplings. Order-one couplings can be probed by space tests of gravity that are proposed but yet to launch.

6.3.5   Electron Fixed-Target Experiments

Fixed-target experiments using high-current electron beams are an excellent place to search for A's with masses $2m_e < m_{A'} \lesssim$ GeV and couplings down to $\epsilon^2 \equiv \alpha'/\alpha \gtrsim 10^{-10}$. In these experiments, the A' is radiated off electrons that scatter on target nuclei. Radiative and Bethe-Heitler trident production give rise to large backgrounds. Generally speaking, three experimental approaches have been proposed: dual-arm spectrometers, forward vertexing spectrometers, and full final-state reconstruction. In most cases, the detectors are optimized to detect the e^+e^- daughters of the A'. The complementary approaches map out different regions in the mass-coupling parameter space. General strategies for A' searches with electron fixed-target experiments were laid out in [36]. The reach for recently proposed heavy photon searches is shown in Fig. 6-2.

Existing dual-arm spectrometers at Hall A at Jefferson Lab (JLab) and MAMI at Mainz can be used to search for heavy photons. These experiments use high-current beams ($\sim 100~\mu$A) on relatively thick targets (radiation length $X_0 \sim$ 1-10%) to overcome the low geometric acceptance of the detectors ($\sim 10^{-3}$). Beam energy and spectrometer angles are varied to cover overlapping regions of invariant mass. Searches for A' involve looking for a bump in the e^+e^- invariant mass distribution over the large trident background, which requires an excellent mass resolution. Two groups, APEX at JLab and the A1 collaboration at Mainz, have recently performed short test runs and published search results with sensitivity down to $\alpha'/\alpha > 10^{-6}$ over narrow mass ranges [42, 40]. Both groups have plans for more extensive searches in the near future [39].

The HPS collaboration [41] has proposed an experiment to take place in Hall B at JLAB which would use a Si-strip based vertex tracker inside a magnet to measure the invariant mass and decay point of e^+e^- pairs. It uses lower beam currents and thinner targets than the dual arm spectrometers, but has much greater acceptance. Because it can discriminate A' decays displaced more than a few millimeters from the large, prompt, trident background, HPS is sensitive to roughly $10^{-7} \gtrsim \alpha'/\alpha \gtrsim 10^{-10}$ for masses $30 < m_{A'} < 500$ MeV. Without requiring a displaced vertex, HPS will also explore couplings $\alpha'/\alpha > 10^{-7}$ over a similar mass range. HPS has been approved by JLab for a test run with a scaled-down detector in the spring of 2012, and plans to take data with the full detector after the 12 GeV upgrade at the lab's CEBAF accelerator.

Finally, the experiment DarkLight is proposing to run at the JLab FEL [38]. DarkLight proposes to collide the FEL's 10mA, 100MeV beam on a hydrogen gas jet target surrounded by a high-acceptance detector in a magnetic field. A key component to the experiment is a proton-recoil detector, which would allow for a full reconstruction of the event and should greatly reduce accidental background. This experiment will explore the low-mass region and coupling $\alpha'/\alpha > 10^{-7}$, which covers almost all of the parameter space needed to explain the measured anomalous magnetic moment of the muon. DarkLight plans to submit a full proposal to JLab in 2012.

Future experiments will need to fill the gaps in $m_{A'} - \alpha'/\alpha$ parameter space. To explore the gap region at medium mass with medium coupling strengths, they will need to handle more intense beams and have improved vertexing and invariant mass resolution. To search for higher-mass A' decays, higher beam energies, particle ID, and very high luminosities are needed.

6.3.6   Proton Fixed-Target

Proton beam fixed-target experiments, especially the neutrino experiments CHARM [139], LSND [140], MiniBooNE [141], MINOS [142], MINERvA [143], T2K [144], and a future Project X facility [145], provide an opportunity to search for new light, weakly coupled states from a hidden-sector. The basic experimental setup begins with an intense proton beam impinging on a target, producing large numbers of secondary hadrons, most of which subsequently decay into neutrinos and other particles. After passage through a shield or earth, all the other particles are absorbed, leaving a neutrino beam. If light, weakly coupled hidden-sector particles exist, a beam of hidden-sector particles might be produced in similar fashion, and leave distinctive signatures in a downstream detector.

To illustrate the essential experimental principle, consider the case of a heavy photon A' that kinetically mixes with the photon γ, with mixing angle ϵ. Due to the kinetic mixing, neutral pions produced in primary collisions will decay a small fraction of the time into a $\gamma A'$ pair. The heavy photon A' may travel to the detector and decay into, or interact to produce, an e^+e^- pair. The neutrino experiments listed above are sensitive to this signature and thus have the potential to probe a large part of the $m_{A'} - \alpha'/\alpha$ parameter space of the heavy photon, including regions that cannot be tested by any other experiment [44, 45].

Proton fixed-target experiments are unique among particle physics experiments in being sensitive to some hidden-sector particles, such as axions and ALPs [45]. In addition they are sensitive to heavy photons and hidden sector scalars and Higgs bosons [44] and light dark matter [44, 146]. An example of a specific search at proton accelerators is for a paraphoton (which is similar to the A', but with slightly different couplings) [147]. This can be produced in the extreme forward direction (less than a few milliradians w.r.t. the proton beam) by bremsstrahlung off the incident protons. In the case of the MiniBooNE experiment at FNAL, with $\sim 1.8 \times 10^{21}$ protons on target, the paraphoton can decay or shower in the detector. The signature is thus electromagnetic-like events directly in line with the incident proton beam. Furthermore, if these events scatter off electrons, then the recoil electron would point in the very forward direction and could thus be easily disentangled from the neutrino background. This is only one of many examples of the unique event signatures that hidden-sector particles may have in neutrino experiments, which enhance the overall search sensitivity relative to simple event counting.

Besides distinct event signatures, the other driving factor in sensitivity is the number of protons on target. With the possibility of Project X, the protons on target intensities could easily be increased by two orders of magnitude at 8 GeV and about an order of magnitude at 120 GeV over current FNAL rates. These searches could form an important part of the motivation for Project X.

6.3.7   Electron-Positron Colliders

Due to their large luminosities and low background environments, low-energy e^+e^- colliders are ideal for searching for a light hidden-sector and probing its structure.

A hidden-sector (dark) photon can be produced in the reaction $e^+e^- \to \gamma A'$, and decay subsequently into a lepton pair. This signature is similar to that of light CP-odd Higgs production, A^0, in $\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to l^+l^-$. Searches for narrow di-muon resonances in $\Upsilon(3S)$ and $\Upsilon(2S)$ decays at *BABAR* based on ~ 40 fb^{-1} of data [148] can be readily reinterpreted as constraints on dark photon production. Limits on the ratio α'/α at the level of 10^{-5} have been set. Future analyses based on the full *BABAR* and Belle data sets are expected to increase this sensitivity by an order of magnitude and extend the coverage down to ~ 10 MeV.

In particular, the region favored by an explanation of the muon anomalous magnetic moment [149] can be almost entirely probed, see Fig. 6-2.

The simplest extension to a non-Abelian model contains four gauge bosons, one dark photon, and three additional dark vector bosons, generically denoted W'. A search for di-boson production has been performed at *BABAR* in the four lepton final state, $e^+e^- \to W'W'', W'(W'') \to l^+l^-$ ($l = e, \mu$), assuming both the W' and W'' have similar masses [150]. No significant signal is observed and limits on the product $\alpha_D\epsilon^2$ at the level of $10^{-10} - 10^{-7}$ have been set, assuming equal branching fractions of a dark gauge boson to e^+e^- and $\mu^+\mu^-$ (here $\alpha_D = g_D^2/4\pi$, where g_D is the hidden $U(1)$ gauge coupling).

The dark boson masses are usually generated via the Higgs mechanism, adding a dark Higgs (h') to the theory. *BABAR* has searched for dark Higgs boson production in $e^+e^- \to A'^* \to A'h', h' \to A'A'$, with the constraint $m_{h'} > 2m_{A'}$ [55]. No signal was seen, and limits on the product $\alpha_D\epsilon^2$ have been set at the level of $10^{-10} - 10^{-8}$, depending on the dark photon and dark Higgs boson masses. A search at Belle is in progress.

The large number of photons produced by light meson decays offers another gateway to the dark sector. KLOE has performed a search for dark photon production in $\phi \to \eta A', \eta \to \pi^+\pi^-\pi^0, A' \to e^+e^-$ decays using 1.5 fb^{-1} of data collected at DaΦNe [54]. No signal has been seen, and limits on α'/α at the level of 10^{-5} have been derived in the range $80 - 400$ MeV (Fig. 6-2).

The existence of a dark scalar or pseudo-scalar particle can also be investigated in $B \to K^{(*)}l^+l^-$ decays. The sensitivity of *BABAR* and Belle searches to the mixing angle between the Standard Model Higgs and the dark scalar, as well as the pseudo-scalar coupling constants, is projected to be $\sim 10^{-4} - 10^{-3}$ and 10^3 TeV, respectively [151].

The next generation of flavor factories, Super*B* and SuperKEKB, are expected to collect an integrated luminosity of $50 - 75$ ab^{-1}, increasing the current *BABAR* and Belle datasets by two orders of magnitude. The sensitivity of the searches described above is therefore expected to improve by a factor of $10 - 100$, depending on the level of background. In particular, super flavor factories could probe values of α'/α down to a level comparable to dedicated fixed-target experiments like APEX, with a significantly larger mass coverage.

6.3.8   Proton Colliders

Proton colliders have the ability to reach high center-of-mass energy, making it possible to produce Z bosons, Higgs bosons, and perhaps other new, heavy particles (such as supersymmetric particles, W'/Z' states, or hidden-sector particles) directly. As pointed out in many theoretical studies [34, 56, 152, 153], if new states are produced (*e.g.*, supersymmetric particles), they could decay to A' bosons and other hidden-sector states, sometimes with very large branching ratios. For GeV-scale A' masses, they would be highly boosted when produced in such decays and their decay products would form collimated jets, mostly composed of leptons ("lepton-jets" [34]).

The existing general-purpose proton collider experiments at the Tevatron and LHC have all presented first searches for lepton-jets in heavy-particle decays [52, 53, 154, 155, 156]. The searches usually employ a specialized lepton-jet identification algorithm to distinguish them from the large multi-jet background. Events with additional large missing transverse energy (from other escaping hidden-sector particles) or a particular di-lepton mass (corresponding to the A' mass) have also been searched for. Results have often been interpreted in supersymmetric scenarios, and typically exclude di-squark production with a squark mass of 500 GeV decaying through cascades to two lepton-jets.

With large datasets now available at the LHC (20 fb^{-1} expected by 2012) and even 10–100 times larger data sets expected in the future, good sensitivity to new, heavy particles decaying to lepton jets will be achievable. Current searches have mostly focused on A' bosons heavy enough to decay to muon pairs, since this offers a cleaner signal than electron pairs, but good sensitivity is expected in the future down to ~ 20 MeV (limited by photon conversions to e^+e^- pairs). Large datasets will contain billions of Z and millions of Higgs bosons, allowing branching ratios to lepton-jets as low as 10^{-6} (or $\epsilon \simeq 10^{-3}$) to be probed for Z decays and 10^{-3} for Higgs decays. Searches have also mostly focused so far on prompt decays of dark photons, but studies are under way to perform searches for longer-lived decays in the tracking chambers and even muon chambers, allowing sensitivity down to $\epsilon \simeq 10^{-6}$, if a new, heavy particle with a large branching ratio into A' bosons exists and can be produced at a high enough rate.

6.3.9   Satellite Based Experiments

The OMEGA Explorer Project [157], which has been proposed to NASA, uses strong gravitational lensing to search for light dark matter as well as additional hidden-sector particles that interact with the dark matter [157, 158, 159]. Dark matter clumps generate large gravitational potentials that lense the light from distant sources. The observed multiple images (and time-delayed light) from the original source allow precise measurements of the dark matter halo and "clumpiness." The potential for observing light dark matter, such as axions, is described in [159]. The impact of mediator particles, such as dark photons, is described in [158]. For brevity, we focus on the latter in order to complement the accelerator-based searches discussed above.

The light dark matter, described above, gravitates into clumps with a maximum mass that depends sensitively [160, 161] on the dark matter kinematic decoupling temperature $M_{cut} \simeq 10^{-4}(T_d/10 \text{ MeV})^{-3}M_\odot$ where $M_\odot$ is the sun's mass. The dark matter decoupling temperature in turn sensitively depends on the dark matter particle physics as $T_d = (M_\sigma^4 M/M_{\rm pl})^{1/4}$, where M is the dark matter mass and M_σ is the mass scale associated with the dark matter–dark photon interaction cross section. The dark matter elastically Compton scatters with the dark photon and is parametrized by $\sigma \approx T^2/M_\sigma^4$. For $M_\sigma \sim 1$ GeV (which is common for Compton scattering), $M_{\rm cut} \sim 10^4$ which is within OMEGA's sensitivity in [158]. Thus depending on the dark matter mass, the OMEGA project is potentially sensitive to $m_{A'} \lesssim \mathcal{O}(10)$ GeV.

6.4   Technologies Needed for Future Progress

Searches for axions, ALPs, and WISPs need the highest possible beam intensities to generate these weakly interacting particles. On the other hand, detection requires the ultimate in sensitivity to extract extremely weak signals from noise. Improved technologies will significantly improve detection sensitivity.

Increased magnetic field strength would have the greatest impact on detector sensitivity. Current magnet technology used in these searches typically employs NbTi wire, giving fields of 8 T in solenoids and 5 T in dipole magnets. A number of steps may increase the maximum field strength. Nb$_3$Sn magnets would be a first step; current technology points to a rough doubling of the field with this material, to 16 T (solenoid) and 10 T (dipole) by a change in metal. Cooling to 1.7 K from 4.2 K can produce another 1-2 T. Note that the sensitivity goes as B^2, where B is the field strength, so the resulting gain would be substantial.

In the longer term, development of magnets from one of the "new" superconductors, such as MgB$_2$ or one of the cuprate high-T_c materials, could yield fields in the 40 T range. To develop such a magnet will require substantial R&D, but could impact many fields in physics. Magnets with fields above 40 T already exist at

the National High Magnetic Field Laboratory, but have small field volumes (few tens of cm^2) and consume huge amounts of power ($\sim$ 25 MW).

Increasing the magnetic field volume will also boost sensitivity, since the full figure of merit is $B^2 V$, with V the volume. (For laser experiments, the factor is usually written as $B^2 L^2$, with L the length of the magnetic region, but the laser beam spreads in proportion to its length, so an increase in length requires a corresponding increase in diameter to avoid clipping.) Current experiments have magnetic volumes in the range of 0.035 (OSQAR) to 0.2 m^3 (ADMX). Laser experiments on the drawing board use similar volumes, but one may imagine 5–10 times increases in length and diameter without reaching unreasonable sizes, giving magnetic volumes of several cubic meters. IAXO requires a large aperature magnet of 3–5 T, with a total length of 17–23 m to provide great sensitivity to axions and ALPs.

Many searches for hidden-sector photons, axions, and WISPs employ resonators, used either to increase intensity in generation of these particles or for resonantly enhanced conversion to photons. There are performance gains to be had by improving the designs of these cavities. Microwave experiments may improve cavity quality factor Q by plating a thin layer of type-II superconductor on the portions of the cavity wall where the magnetic field is parallel to the wall. Experiments to develop this idea are under way. Laser resonators are typically limited by the damage threshold in the mirror coatings. Mirrors with improved damage thresholds would translate immediately to higher stored power in the cavities and increased production rates.

Improved detection of extremely weak signals would also improve the sensitivity of these experiments. This has already happened in some areas. ADMX has moved from semiconductor-based to superconductor-based (SQUID) radio-frequency amplifiers, reaching nearly the quantum limit. There is a need for technology development to push the operating frequencies of such amplifiers to the next decade. Similarly, there are conceptual designs for heterodyne detection schemes for laser-based detectors that offer shot-noise limited measurements, *i.e.*, the standard quantum limit. The next step in both cases would be to apply squeezing or quantum non-demolition schemes to the detector.

An approach suggested to search for axions with f_a between the GUT and Planck scale uses molecular interferometry to detect time-varying energy shifts in CP-odd nuclear moments [162]. These effects are enhanced in the light Actinides [163, 164] and in molecules in background electric fields, which show spontaneous parity violation. Technology developments in producing and manipulating molecules containing light Actinides [165] and improving molecular interferometry [166] are needed to realize these experiments.

Finally, large diameter reflective X-ray optics and low background x-ray detectors are needed for future helioscopes to improve sensitivity over present experiments. Fabrication techniques developed for X-ray telescopes deployed on current satellites would be one cost-effective approach for building the required x-ray optics. Further reductions in the background levels in MicroMEGAS detectors would make them satisfy requirements for low background X-ray detectors.

Advances in traditional particle physics detector technology will benefit searches for more massive hidden-sector particles. Very fast, very radiation hard, very thin pixel detectors will benefit vertex searches for $\sim$ 100 MeV hidden-sector photons by allowing more intense beams and improving vertex resolution. Developments in very high rate data acquisition, including faster high-level triggering, will enable experiments to run with more intense beams and thereby probe smaller couplings.

Facility	Type	Operations	Energy (GeV)	$\mathcal{L}$ (cm^{-2}s^{-1})
CEBAF (6 GeV)	e^- fixed target	now-2012	0.5-6	10^{39}
JLab FEL	e^+ energy recovery linac	now-	0.14	10^{35}
MAMI	e^- fixed target	now-	0.855 & 1.55	10^{39}
KLOE-2	e^+e^-	now-	m_Φ	5×10^{32}
VEPP-3	e^+ storage ring	now-	0.5 - 2	10^{32}
CEBAF (12 GeV)	e^- fixed target	2014-	1-12	10^{39}
MESA@Mainz	e^- energy recovery linac	2016-	0.1	10^{35}
Belle-II	e^+e^-	2016-	$m_{\Upsilon(4S)}$	10^{36}
Super-B	e^+e^-	2017-	$m_{\Upsilon(4S)}$	10^{36}

Table 6-1.   *List of present and proposed electron collider and fixed-target facilities with their operational dates, energies and luminosity. Fixed-target luminosities assume a 0.1 radiation length Tungsten target and 100 μA beam current. Searches at the VEPP-3, JLab FEL and MESA facilities propose to use a internal gaseous hydrogen target.*

6.5   Accelerators Needed for Future Progress

Accelerator-based searches for hidden-sector photons with $2m_e < m_{A'} \lesssim 1$ GeV have been performed at e^+e^- colliders [54], e^- fixed-target facilities [86, 87, 88], and proton colliders [52, 53, 154, 155, 156]. New searches with increased luminosity and improved detector sensitivities will significantly increase the coverage of the allowed parameter space. This section briefly describes the accelerator facilities that are envisioned for these searches.

Existing e^+e^- collider data sets have not yet been fully exploited in searches for hidden-sector particles. Improved limits should be forthcoming. Proposed e^+e^- colliders [167, 168, 169] will provide an increased coverage in the A' parameter space due to the improved luminosity (factor of 10- to 100-fold increase). This increase in luminosity will result in an increased coupling strength sensitivity ($\alpha'/\alpha = \epsilon^2$) by more than an order of magnitude: $\epsilon^2 \approx 10^{-7}$. The mass range explored by searches at e^+e^- colliders will remain in the range $m_{A'} > 10$ MeV due to backgrounds at low $m_{e^+e^-}$.

The high luminosity ($\mathcal{O}(1 \text{ ab}^{-1}/\text{day})$) presently available at electron accelerators, CEBAF [170], MAMI [171] and the JLab FEL [172], and their beam characteristics make them well suited for A' searches. This potential is just beginning to be exploited. The beam parameters of the fixed-target machines (see Table 6-1) are well suited for exploring α'/α values as low as 10^{-11} with a mass coverage of $10 < m_{A'} < 1000$ MeV. In addition to well-matched beam parameters, both MAMI and CEBAF have double-arm spectrometers that are well suited for A' searches with little or no modifications. Short test runs at both these facilities have recently led to published results [42, 40]

CEBAF and MAMI with their flexible configurations, multiple end-stations and large luminosities, can explore a large fraction of the available A' mass and coupling range (see Figure 6-2). However, the coverage is not complete, and new proposals are needed to fill in the gaps. The wide range of beam energies and currents available at CEBAF and MAMI allows flexibility in experimental approaches. If an A' is discovered within their kinematic reach, they would be in a good position to explore the A' properties in detail.

In addition to the GeV range continuous wave (CW) electron experiments, coverage in range $m_e < m_{A'} < 10$ MeV has been proposed by using electron beams (at the JLab FEL and the proposed MESA accelerator at Mainz) or positron beams (at the VEPP-3 storage ring) with energy of order 100 MeV (see Table 6-1). These energies are available from the VEPP-3 storage ring, JLab FEL, and the proposed MESA facility at Mainz.

Searches at proton accelerators, both collider and fixed-target experiments, are sensitive to heavy photons produced in decays of new particles or secondary particles. Exploring the possibility of performing A' searches in neutrino experiments should be encouraged. Current data sets need to be fully exploited, and next-generation neutrino experiments, with their very high luminosities and sensitive detectors, may be ideal hunting grounds for heavy photons.

In summary, much of preferred parameter space for heavy hidden-photons can be explored with existing and proposed accelerator facilities. Specifically, the luminosity and flexibility of the electron fixed-target facilities are well suited for A' searches in the mass range $2m_e < m_{A'} < 1$ GeV. More generally, exploring the capabilities of all facilities and further exploiting current data sets to search as much of the allowed region as possible is a priority. A great deal can be done with existing facilities and planned upgrades.

6.6   Conclusions

Searches for new light, weakly coupled particles are motivated by some of the most important questions in particle physics. They are dependent on the tools and techniques of the intensity frontier, *i.e.*, intense beams of photons and charged particles, and on extremely sensitive detection techniques. These searches reside at the nexus of the cosmic, energy, and intensity frontiers: new light particles may constitute the dark matter, or be the force carriers responsible for its interactions; they may even help explain the origin of dark energy, or be low-energy remnants of physics at the highest energy scales. These searches expand our notion of the energy frontier to the very high and the very low, and explore new and exciting territory.

The Intensity Frontier Workshop brought together two related, but largely independent communities, both exploring particles that either couple directly to the photon or mix with it to couple to electrically charged particles. One is focusing on axions, axion-like particles, and low-mass hidden-sector photons. The other is searching for higher-mass particles residing in hidden-sectors, heavy "photons," hidden-Higgs bosons, and the like. The resulting interchange was exciting and will likely provoke some new directions, experiments, and insights. Both communities are exploring vast parameter spaces in particle mass and coupling, holding the potential for truly momentous discoveries. However, this is done utilizing what are really modest experimental efforts, compared to the general trend in particle physics.

A great deal remains to be done with existing tools and techniques, especially in searching for heavy photons. Existing facilities can support many new experiments, extending experimental reach significantly. A great deal more territory can be explored for the low-mass hidden-sector and axion-like particles, including theoretically favored regions, with relatively modest advances in superconducting magnets, microwave detection, and resonant optical cavities. Large-scale experiments are also under consideration, well-motivated, and require more substantial investments for their implementation.

Searches for new, light, weakly interacting particles are ongoing around the world, but essentially all the experimental efforts have strong US participation or strong US leadership. Continued support in the US is essential if the present US role is to continue, and the potential for truly fundamental discoveries preserved.

The cutting-edge physics experiments searching for new low-mass, weakly interacting particles provide ideal educational opportunities for undergraduate, graduate, and post-graduate students. These experiments are

small, and so demand and deliver the full breadth of experimental opportunity: design, hardware construction and commissioning, software implementation, data taking, and analysis. These experiments have also joined experimentalists and theorists into common enterprises to an uncommon degree, providing a considerable benefit for the field and pleasure for the participants.

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