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New, Light Weakly-Coupled Particles

[authors to be added]

1.1 Overview

The Standard Model (SM) of particle phasics has achieved remarkable success as a result of several decades of *exploration*, of constantly pushing the boundaries of our knowledge of theory, experiment, and technology. However, while the SM provides a theoretically consistent description of all known particles and their interactions (ignoring gravity) up to the Planck scale, it is clearly incomplete as it does not address several pieces of evidence for new physics beyond the SM.

One particularly powerful piece of evidence for new physics comes from the existence of dark matter (DM). DM dominates the matter density in our Universe, but very little is known about it. Its existence provides a strong hint that there may be a *dark sector*, consisting of particles that do not interact with the known strong, weak, or electromagnetic forces. Given the intricate structure of the SM, which describes only a subdominant component of the Universe, it would not be too surprising if the dark sector contains a rich structure itself, with dark matter making up only a part of it. Indeed, many dark sectors could exist, each with its own beautiful structure, distinct particles, and forces. These dark sectors may contain *new light weakly-coupled particles* (NLWCPs), particles well below the Weak-scale that interact only feebly with ordinary matter. Such particles could easily have escaped past experimental searches, but a rich experimental program has now been devised to look for several well-motivated possibilities.

Dark sectors are motivated also by bottom-up and top-down theoretical considerations. They arise in many theoretical extensions to the SM, such as moduli that are present in string theory or new (pseudo-)scalars that appear naturally when symmetries are broken at high energy scales. Other powerful motivations include the strong CP problem, and various experimental findings, including the discrepancy between the calculated and measured anomalous magnetic moment of the muon and puzzling results from astrophysics. Besides gravity, there are a few well-motivated interactions allowed by SM symmetries that provide a "portal" from the SM sector into the dark sector. These portals include,

"Vector" portal:	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion" portal:	Pseudoscalars	$\frac{\partial_\mu a}{f_a} \overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs" portal:	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino" portal:	Sterile neutrinos	$y_N L H N$

The Higgs and neutrino portal are best explored at high-energy colliders and neutrino facilities, respectively. Our focus here will be on the vector and axion portals, which are particularly well-motivated possibilitites and can be explored with low-cost, high-impact experiments.

This paper is a summary of the physics motivation and experimental opportunities of the Intensity Frontier subgroup "New, Light Weakly-coupled Particles" of the Community Summer Study 2013 ("Snowmass on the Mississippi"). The outline of the remainder of this summary is as follows. §1.2 discusses the (QCD) axion and more general "axion-like" particles (ALPs). §1.3 reviews dark photons, focusing on sub-MeV and MeV-GeV masses. §1.4 describes sub-GeV dark matter, milli-charged particles and other hidden-sector particles. §1.5 focuses on chameleons. In all cases, we describe the theoretical motivation, the phenomenological motivation, the current constraints, and the current and future experimental opportunities. §1.6 contains our conclusions.

1.2 Axions and Axion-Like Particles

1.2.1 Theory & Theory Motivation

One of the unresolved puzzles in the Standard Model is the lack of any observed CP violation in the strong 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 (unobserved) 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 [1, 2, 3].

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$/f_a$) [4] 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 allow the axion to be produced or detected in the laboratory and emitted by the sun or other stars.

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, 5, 7, 8, 9, 10, 11], with the natural size of their decay constant f_a being the string scale, varying typically between 10^9 and 10^{17} GeV.

1.2.2 Phenomenological Motivation and Current Constraints

Fig. 1-1 (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 exclude most values of $f_a < 10^9$ 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 parameter space for ALPs is shown in Fig. 1-1 (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.

1.2.2.1 Dark Matter

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 [12], but thermally produced ALP dark matter is still allowed in large parts of the parameter space. Non-thermal production can occur through the "vacuum misalignment mechanism" or the decay of axionic strings and domain walls. Axions with large f_a do not thermalize in the early universe and their abundance today is set by the initial state set during the Peccei-Quinn phase transition. There are two scenarios depending on whether the PQ transition took place after or before inflation. In the first case, the dominant contribution arises from the decay of cosmic strings and domain walls into axions. This scenario suggests values of $m_a \sim 80 - 400\mu$eV with large uncertainties arising from extrapolating the numerical result for the string and domain wall decays [13, 14]. In the second scenario, inflation homogenizes the initial axion field value in our observable universe and the dark matter density depends on this value. For natural values $a_{\rm initial} \sim f_a$ the observed DM density arises for $m_a \sim 12\mu$eV. Accepting fine-tuning, smaller values of the mass are possible when $a_{\rm initial} \ll f_a$ and somewhat larger masses (perhaps up to meV [15]) can be achieved by tuning towards $a_{\rm initial} = \pi f_a$.

All in all, the natural values $m_a \sim 10^{-5} - 10^{-4}$ eV present a clear experimental target. The Axion Dark Matter eXperiment (ADMX) will soon probe part of this preferred parameter space.

Extending these arguments to ALPs, a much larger parameter space needs to be explored as indicated in Fig. 1-1; see also *e.g.*, [16].

One important constraint on axion (or ALP) dark matter is the generation of isocurvature temperature fluctuations in the cosmic microwave background if the axion/ALP exists during inflation. CMB probes like the Planck satellite constrain these fluctuations, setting very strong constraints on the Hubble scale during inflation, $H_I \lesssim O(10^6)$ GeV. Observing tensor modes in the CMB allows to determine H_I, providing a crucial test of axion/ALP dark matter.

It is noteworthy that axion or ALP dark matter may also form a Bose-Einstein condensate [17], which may lead to caustic rings in spiral galaxies, which may already have been observed. This also has detectable consequences in terrestrial direct detection experiments like ADMX.

1.2.2.2 Hints from astrophysics

In the last few years some astrophysical anomalies have found plausible explanations in terms of axion/ALPs suggesting target areas in parameter space reachable by near-future experiments. We refer here to the apparent non-standard energy loss of white dwarf stars, *e.g.*, [18, 19, 20, 21, 22] (see however [23]) and the anomalous transparency of the universe for TeV gamma rays, *e.g.*, [24, 25, 26, 27, 28, 29]. The required

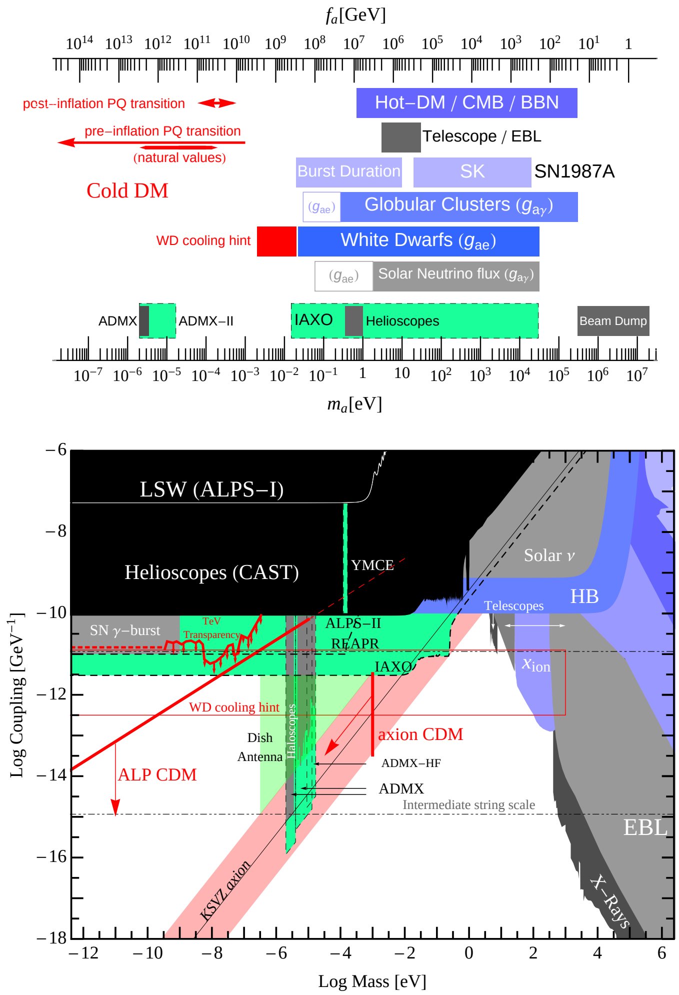

Figure 1-1. *Parameter space for axions (top) and axion-like particles (ALPs) (bottom). In the bottom plot, the QCD axion models lie within an order of magnitude from the explicitly shown "KSVZ" axion line (red band). Colored regions are: experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), and sensitivity of planned and suggested experiments (light green) [ADMX [30], ALPS-II [31], IAXO [32, 33], Dish antenna [34]]. 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.*

coupling strengths seem within reach in controlled laboratory experiments at the intensity frontier, and can serve as useful benchmarks, c.f. Fig. 1-1.

Ultra-light axion-like particles can contribute to the dark matter in the universe, but affect structure formation in a manner distinct from cold dark matter (CDM). The distinction arises due to a scale dependent sound speed in the ultra-light ALPs fluid [35, 36, 37]. Large scale structure and the CMB thus allow one to constrain the fraction of dark matter that can be made up of such ALPs across a wide range of masses $10^{-33}eV < m_a < 10^{-18}eV$. Constraints were last made in 2006 using a simple grid-based likelihood and constrain axion density contributions at the 1-10% level in masses intermediate in this range. Constraints are limited on large scales by lack of data on the matter power spectrum at large scales, and on small scales by lack of non-linear models and the use of older (and possibly unreliable) Lyman-alpha constraints.

These constraints can be updated to include recent data and using a more sophisticated nested sampling technique to account for all degeneracies. Future surveys such as Euclid stand to improve constraints down to the sub-percent level, with specific improvements at the lowest masses and with discerning differences between ultra-light ALPs and thermal neutrinos of eV mass [38, 39]. The effect of these ALPs on the CMB and weak lensing tomography has been explored in detail in [38, 40]. Euclid weak lensing tomography will, if systematics can be properly understood, be the most powerful future probe of ultra-light ALPs, tightening constraints to the sub-percent level [38].

Furthermore, if these ALPs are fundamental fields present during inflation then they carry isocurvature perturbations. These are distinct from QCD axion isocurvature perturbations in two ways. Firstly, the effect on clustering that constrains the density fraction allows one to give marginalised constraints to the energy scale of inflation that are data driven, rather than relying on untestable priors about the fine-tuning of the QCD axion. Secondly, the lower mass allows these isocurvature perturbations to co-exist with tensor CMB modes of observable amplitude, which may allow cross-checks and consistency checks on theories of inflation, if detected [40]. The marginalized constraints probe low-scale inflation models. Assuming the existence of a ultra-light ALPs they rule out many simple inflationary models more strongly than tensor constraints in Planck, but are consistent with, for example, string theory models discussed in [41].

Finally, in the mass range $10^{-24}eV \leq m_a \lesssim 10^{-20}eV$, large scale structure formation with ultra-light ALPs is analogous to warm dark matter (WDM), and is thus relevant to problems with CDM structure formation, such as the cusp-core, missing-satellites, and too-big-to-fail problems [36]. The virtue of ultra-light ALPs is that they avoid the so-called 'Catch 22' of WDM [42]. Work on these large scale structure problems with axions is also work in preparation.

1.2.3 Status and Plans for Terrestrial experiments

1.2.3.1 Laser Experiments

The simplest and most unambiguous purely laboratory experiment to look for axions (or light scalars or pseudoscalars more generally) is photon regeneration[43] ("shining light through the wall"). A laser beam traverses a magnetic field, and the field stimulates a small fraction of photons to convert to axions of the same energy. A material barrier easily blocks the primary laser beam; in contrast, the axion component of the beam travels through the wall unimpeded and enters a second magnet. There, with the same probability, the axions are converted back to photons. Because the photon-regeneration rate goes as $g^4_{a\gamma\gamma}$, the sensitivity of the experiment is poor in its basic form, improved only by increasing the laser intensity, the magnetic field strength, or the length of the interaction regions. As initially suggested by Hoogeveen and Ziegenhagen[44] and recently discussed in detail,[45, 46, 47] very large gains may be realized in both the photon-regeneration rate and in the resulting limits on $g_{a\gamma\gamma}$ by introducing matched optical resonators in both the axion production and the photon regeneration regions.

Detailed designs for such an experiment exist, including the scheme for locking two matched high-finesse optical resonators, the signal detection method, and the ultimate noise limits.[46, 47, 48] Such experiments would improve on present limits on $g_{a\gamma\gamma}$ by at least a factor of 10. We note also that these experiments, although challenging, are feasible using well-established technologies developed for example for laser interferometer gravitational-wave detectors.[49, 50] No new technology is needed. Two developed designs exist: the Resonantly Enhanced Axion-Photon Regeneration (REAPR) experiment, a Florida-Fermilab collaboration, and the Any Light Particle Search II (ALPS II) being mounted at DESY.

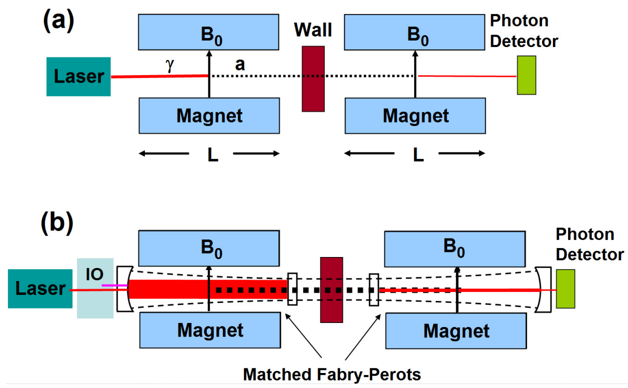

Figure 1-2. *(a) Simple photon regeneration. (b) Resonant photon regeneration, employing matched Fabry-Perot cavities. The overall envelope schematically shown by the thin dashed lines indicates the important condition that the axion wave, and thus the Fabry-Perot mode, in the photon regeneration cavity must follow that of the hypothetically unimpeded photon wave from the Fabry-Perot mode in the axion generation magnet. Between the laser and the cavity are optics (IO) which manage mode matching of the laser to the cavity, imposes RF sidebands for reflection locking of the laser to the cavity, and provides isolation for the laser. The detection system is also fed by matching and beam-steering optics. Not shown is the second laser for locking the regeneration cavity and for heterodyne readout.*

Figure 1-2(a) shows the photon regeneration experiment as usually conceived. If E_0 is the amplitude of the laser field propagating to the right, the amplitude of the axion field traversing the wall is $E_0\sqrt{P}$ where P is the conversion probability in the magnet on the LHS of Fig. 1-2a. Let P' be the conversion probability in the magnet on the RHS. The field generated on that side is then $E_S = E_0\sqrt{P'P}$ and the number of regenerated photons is $N_S = P'PN_0$ where N_0 is the number of photons in the initial laser beam.

It can be shown[51, 43, 52] that the photon to axion conversion probability P in a region of length L permeated by a constant magnetic field B_0 transverse to the direction of propagation, is given by ($\hbar = c = 1$)

$$P = \frac{1}{4}(g_{a\gamma\gamma}B_0L)^2. \tag{1.1}$$

This equation is written for the effect in vacuum and for the case where the where the difference between the axion and photon momenta $q = m_a^2/2\omega$ is small compared to $1/L$. The axion to photon conversion probability in this same region is also equal to P.

A number of photon regeneration experiments have been reported,[53, 54, 55, 56, 57, 58, 59] with the best limits[56, 59] being $g_{a\gamma\gamma} < 3.5 \times 10^{-7}$ GeV^{-1}. None of these experiments used cavities on the photon regeneration side of the optical barrier; recycling on the production side has been used in two.[53, 59]

Photon regeneration is enhanced by employing matched Fabry-Perot optical cavities, Fig. 1-2(b), one within the axion generation magnet and the second within the photon regeneration magnet.[44, 45, 46] The first cavity, the axion generation cavity, serves to build up the electric field on the input (left) side of the experiment. It is easy to see that when the cavity is resonant to the laser wavelength, the laser power in the high-field region is increased by a factor of $\mathcal{F}_a/\pi$ where $\mathcal{F}_a = 4\pi T_{1a}/(T_{1a} + V_a)^2$ is the finesse of the cavity, T_{1a} is the transmittance of the input mirror, and V_a is the roundtrip loss of the cavity due to absorption of the coatings, scattering from defects, diffraction from the finite mirror size, and transmission through the end mirror. The increase in the laser power increases the number of created axions by a factor of $\mathcal{F}_a/\pi$. These axions propagate through the "wall" and reconvert into photons in the regeneration cavity at right. The intra-cavity photon field builds up under the conditions that the second cavity is resonant at the laser wavelength and that the spatial overlap integral η between the axion mode and the electric field mode is good. This overlap condition requires that the spatial eigenmodes of the two cavities are extensions of each other, e.g., when the Gaussian eigenmode in one cavity propagated to the other cavity is identical to the Gaussian eigenmode of that cavity.

To detect the regenerated field, a small part is allowed to transmit through one of the cavity mirrors. The number of detected photons behind the regeneration cavity is[44, 45, 46]

$$N_S = \eta^2 \frac{\mathcal{F}_\gamma}{\pi} \frac{\mathcal{F}_a}{\pi} P^2 N_{in} \tag{1.2}$$

Note that resonant regeneration gives an enhancement factor of $\sim (\mathcal{F}/\pi)^2$ over simple photon regeneration. This factor may feasibly be 10^{10}, corresponding to an improvement in sensitivity to $g_{a\gamma\gamma}$ of ≈ 300.

The resonantly-enhanced photon regeneration experiment, involving the design and active locking of high-finesse Fabry-Perot resonators and the heterodyne detection of weak signals at the shot-noise limit, is well supported by the laser and optics technology developed for LIGO.[49] We mention briefly the technical challenges and the means to address them planned by two realistic designs (REAPR and ALPS-II) and then discuss the expected sensitivities of these experiments.

The REAPR design utilizes a total of 12 Tevatron superconducting dipoles (each 5 T field, 6 m length, and 48 mm diameter bore), 6 for the axion generation cavity (total magnetic length of 36 m) and 6 for the photon regeneration cavity. ALPS-II plans to use 20 straightened HERA dipoles, with fields of 5.2 T and total magnetic length of 88 m. These magnets all exist and the magnet group at DESY has demonstrated that a dipole may be made almost straight and still function.

The layout requires that the optical cavities support mirror-image fundamental spatial modes, have a common or near common waist location, and should suppress all higher-order spatial modes. In addition, losses due to aperture effects should be kept very low, requiring not too big a divergence of the light away from the waist. These considerations, together with the dimensions of the available magnets, drive the design of the cavity paramters.[60]

The gain of the cavity and the circulating power stored in it is set by the input power, the transmission of the input mirror, absorption in both mirrors, scattering, clipping by finite apertures, and the residual transmission of the nominally 100% reflecting second mirror. Absorption values at 1064 nm of less than 1 ppm/bounce are commercially available.[61] Both REAPR and ALPS-II have designed cavities where clipping is not a limiting factor. The chosen parameters would allow a cavity finesse of comfortably above the anticipated value of 300,000 (REAPR) or 5000–40,000 (ALPS-II).

The efficiency of photon regeneration will also depend on alignment mismatches between the cavities. Angular or lateral misalignment of the optical axes would significantly reduce the spatial overlap between the two modes. Losses caused by a lateral shift δx scale with the beam size, those caused by an angular shift scale with the divergence angle, so that the overall efficiency is:

$$\eta \approx 1 - \frac{1}{2}\frac{\delta x^2}{w_1^2} - \frac{1}{2}\frac{\delta\alpha^2}{\Theta^2} \qquad \text{with :} \qquad \Theta = \frac{\lambda}{\pi w_1} \tag{1.3}$$

Requiring an efficiency $\eta > 0.95$, we obtain the following requirements on lateral and angular offsets for $\sim$50 m scale experiments:

$$\delta x < 1\,\text{mm} \qquad \delta\alpha < 10\,\mu\text{rad} \tag{1.4}$$

One of the main challenges of the experiment is to align correctly the two cavities and maintain the alignment throughout the experiment. Recall that it is the axion field which couples the two cavities and that axions, in contrast to light, do not experience any refraction in wedged mirror substrates. In addition, we have to avoid any leakage of photons from the production cavity into the photon generation cavity. Both conditions limit the number of possibilities for alignment sensing and control between the two cavities. Developing and testing the length and alignment sensing and control scheme is a key reason why both REAPR and ALPS-II have planned preliminary hidden-sector-photon searches prior to using magnets and full-length cavities.

The approach to alignment planned by REAPR has been described in some detail.[46, 47] The basic idea is first to align the two curved end mirrors as a single cavity and then to align the flat central mirrors of the two cavities to the axis defined by this initial step. The central mirrors, alignment sensing (quad) photodiodes, and other components are all mounted on a rigid, low-thermal-expansion optical bench. The central bench can be removed and reinserted during the construction process to verify the overall co-alignment of the two cavities. ALPS-II plans a similar approach.

Intrinsic to resonantly enhanced photon regeneration is the requirement that the axion generation and photon regeneration cavities are both on resonance at the same wavelength as that of the axion generating laser. The basic idea of REAPR is to use two lasers, with the second "offset locked" to the first one. The offset, set by a RF oscillator, is a multiple of the free spectral range of the cavities. This offset locking ensures that both cavities have common resonances while at the same time having the light used to lock the detection cavity be at a different frequency than the regenerated photons.[46, 47] ALPS-II will double the frequency of the generation laser into the a green, and use this 2× light to lock the regeneration cavity.

Error signals for controlling the cavity lengths and angular misalignments are obtained by using phase modulated light, giving sidebands that monitor the phase change in the carrier caused by mismatches between the laser and the cavity eigenmode. The length sensing method is known as the Pound-Drever-Hall technique[62] while the angular sensing technique is based on wavefront sensing and is standard in all interferometric gravitational wave detectors.[63]

The two experiments plan quite different means to detect the (very weak) regenerated light. ALPS-II will employ a superconducting transition-edge sensor, which has nearly single-photon sensitivity at the 1064 nm wavelength of these photons. REAPR will use heterodyne detection, with the regeneration cavity locking laser used as the local oscillator for the coherently regenerated optical field E_S, which occurs at the frequency of the axion-generation laser. When mixed at a photodetector with the laser field used for locking the regeneration-cavity, the beats between the two fields give a signal (written in terms of the number of photons N in both fields) of

$$S = N_{LO} + 2\sqrt{N_{LO}N_S}\cos\phi\cos\Omega t + 2\sqrt{N_{LO}N_S}\sin\phi\sin\Omega t \tag{1.5}$$

where Ω is the difference in laser frequencies, N_{LO} is the number of local oscillator photons, N_S is the number of signal (regenerated) photons. There are two quadrature components of the signal on account of the unknown phase ϕ from the distance between the two cavities.

The shot noise or variance in each quadrature can be calculated from the number of photons detected $\sigma_I = \sqrt{2\bar{N}} = \sqrt{2N_{LO}} = \sigma_Q$. These in-phase and quadrature components are added, making the signal-to-noise ratio be

$$\frac{S_\Sigma}{\sigma_\Sigma} = \sqrt{N_S}, \tag{1.6}$$

where N_S is the number of regenerated photons in the signal field. As expected, to obtain a signal to noise ratio of one requires one detected photon.

For a baseline of 36-m, 5 T, magnets, an input power of 10 W, a cavity finesse of $\mathcal{F} \sim \pi \times 10^5$ ($T = 10\,\text{ppm} = V$) for both cavities, and 10 days of operation, we find at signal-to-noise ratio of unity,

$$g_{a\gamma\gamma}^{min} = \frac{2\times10^{-11}}{\text{GeV}}\left[\frac{0.95}{\eta}\right]\left[\frac{180\,\text{Tm}}{BL}\right]\left[\frac{3\times10^5}{\mathcal{F}}\right]^{1/2}\left[\frac{10\,\text{W}}{P_{in}}\right]^{1/4}\left[\frac{10\,\text{days}}{\tau}\right]^{1/4}. \tag{1.7}$$

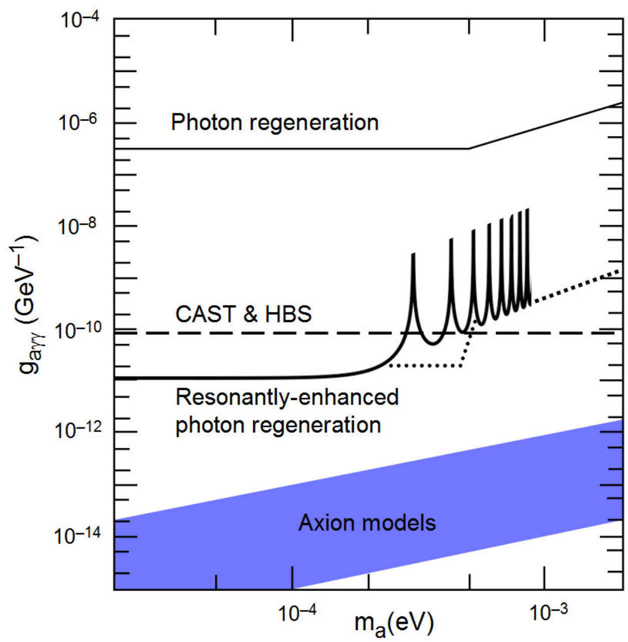

Figure 1-3. *Exclusion plot of mass and photon coupling* $(m_a, g_{a\gamma\gamma})$ *for the axion, and the 95% CL exclusion limit for the resonantly enhanced photon regeneration (REPR) experiment. The existing exclusion limits indicated on the plot include the best direct solar axion search (CAST collaboration),[64] the Horizontal Branch Star limit,[65] and previous laser experiments.[56, 59]*

The experiment yields a 95% exclusion limit (3σ) for axions or generalized pseudoscalars with $g_{a\gamma\gamma}^{min} < 2.0 \times 10^{-11}\text{GeV}^{-1}$ after 90 days cumulative running, well into territory unexplored by stellar evolution bounds or direct solar searches. Note that the exclusion sensitivity follows the inverse of $\text{sinc}(qL/2)$; for REAPR the first null sensitivity occurs at 2.8×10^{-4}eV and for ALPS-II at about half this value. The momentum mismatch between a massless photon and a massive axion defines the oscillation length of the process to be $L_{osc} = 2\pi/q$. (As pointed out in Ref. [43] however, there is a practical strategy to extend the mass range upwards if the total magnetic length L is comprised of a string of N individual identical dipoles of length l. In this case, one may configure the magnet string as a "wiggler" to cover higher regions of mass, up to values corresponding to the oscillation length determined by a single dipole.) The sensitivity of both nonresonant and resonant regeneration experiments, as well as other relevent limits, are shown in Fig. 1-3.

The optical prototypes being developed for the resonant regeneration experiment will also have sensitivity to photon-paraphoton oscillations.[66] Paraphotons are new weakly-interacting U(1) gauge bosons predicted to exist in generic models of beyond-the-standard-model physics including string theory.[67] They undergo kinetic mixing with the ordinary photon resulting in oscillations of photons to paraphotons and the possibility of performing a photon regeneration experiment. Unlike the case of photon-axion oscillations, photon-paraphoton oscillations do not require the presence of an external magnetic field, and so can be performed with just the prototype optics and data acquisition system. On account of the gain from the resonant cavities, a search with a REAPR or ALPS-II prototype with meter-length cavities supersede the LIPSS limit[68] in less than 1 second of running. With a 10-day run, the sensitivity will be improved by a factor of 300, reaching mixing angles $\chi \approx 10^{-9}$, sufficient to determine whether paraphotons generated from the cosmic microwave background play an important role in cosmology. [69] While not the primary goal of the project, a physics result on paraphotons will come for free during the development phase of a resonantly-enhanced axion-photon regeneration experiment.

1.2.3.2 Microwave Cavities (Haloscopes)

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 [70]. 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 [71] and the University of Florida [72] came within an order of magnitude of the sensitivity needed to reach plausible axion couplings. ADMX [73] 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 [74], 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 [75]. 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. 1-1, 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. 1-7.

1.2.3.3 Helioscopes

Axions could be produced from blackbody photons in the solar core via the Primakoff effect [76] in the presence of strong electromagnetic fields in the plasma. Since the interaction of these axions with ordinary matter is extraordinarily weak, they can escape the solar interior, stream undisturbed to Earth and reconvert in a strong laboratory transverse magnetic field via the inverse Primakoff effect [77, 78, 79]. The minimum requirements for such a helioscope experiment of high sensitivity are a powerful magnet of large volume and an appropriate x-ray sensor covering the exit of the magnet bore. Ideally, the magnet is equipped with a mechanical system enabling it to follow the Sun and thus increasing exposure time. Sensitivity can be further enhanced by the use of x-ray optics to focus the putative signal and therefore reducing detector size and background levels.

The first axion helioscope search was carried out at Brookhaven National Lab in 1992 with a static dipole magnet [80]. A second-generation experiment, the Tokyo Axion Helioscope, uses a more powerful magnet and dynamic tracking of the Sun [81, 82, 83]. The CERN Axion Solar Telescope (CAST), a helioscope of

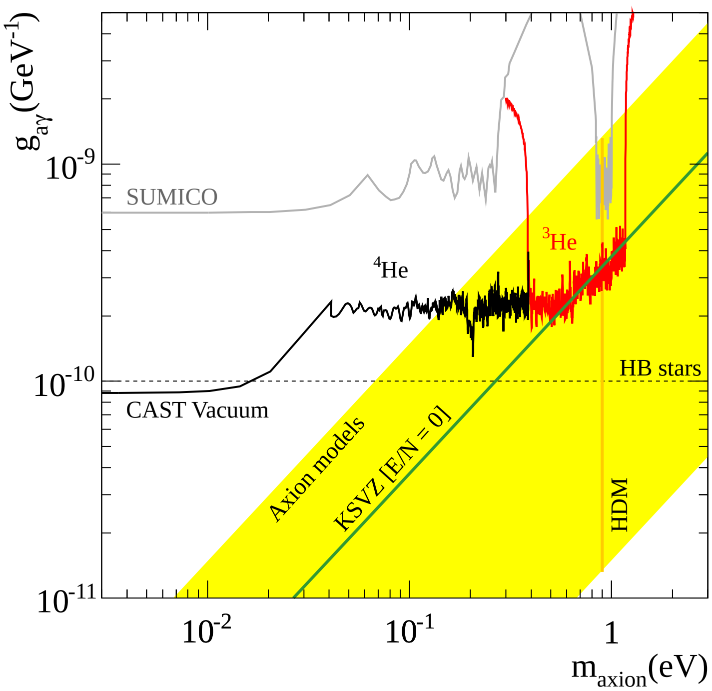

Figure 1-4. *Exclusion regions in the $m_a - g_{a\gamma}$ plane achieved by CAST in the vacuum [86, 87], ^{4}He [88], and ^{3}He phase [89, 90]. We also show constraints from the Tokyo helioscope, horizontal branch (HB) stars [91], and the hot dark matter (HDM) bound [92]. The yellow band labeled "Axion models" represents typical theoretical models with $|E/N - 1.95| = 0.07 - 7$. The green solid line inside the band corresponds to $E/N = 0$ (KSVZ model).*

the third generation and the most sensitive solar axion search to date, began data collection in 2003. It employs an LHC dipole test magnet of 10 m length and 10 T field strength [84] with an elaborate elevation and azimuth drive to track the Sun. CAST is the first solar axion search exploiting x-ray optics to improve the signal to background ratio (a factor of 150 in the case of CAST) [85]. 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 slightly larger value of $g_{a\gamma}$ for higher axion masses [86, 87, 88, 89, 90]. The exclusion plots are shown in Fig. 1-4. CAST has also established the first helioscope limits for non-hadronic axion models [93].

So far each subsequent generation of axion helioscopes has resulted in an improvement in sensitivity to the axion-photon coupling constant $g_{a\gamma}$ of about a factor 6 over its predecessors. To date, all axion helioscopes have used "recycled" magnets built for other purposes. The IAXO collaboration has recently shown [94] that a further substantial step beyond the current state-of-the-art represented by CAST is possible with a new fourth-generation axion helioscope, dubbed the International AXion Observatory (IAXO). The concept relies on a purpose-built ATLAS-like magnet capable of tracking the sun for about 10 hours each day, focusing x-ray optics to minimize detector area, and low background x-ray detectors optimized for operation in the $0.5 - 10$ keV energy band. Pushing the current helioscope boundaries to explore the range in $g_{a\gamma}$ down to a few 10^{-12} GeV^{-1} (see Fig. 1-5), with sensitivity to QCD axion models down to the meV scale and to ALPs at lower masses, is highly motivated as was shown in previous sections. Lowering x-ray detector thresholds to 0.1 keV would allow IAXO to test whether solar processes can create chameleons [95] and further constrain standard axion-electron models. 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

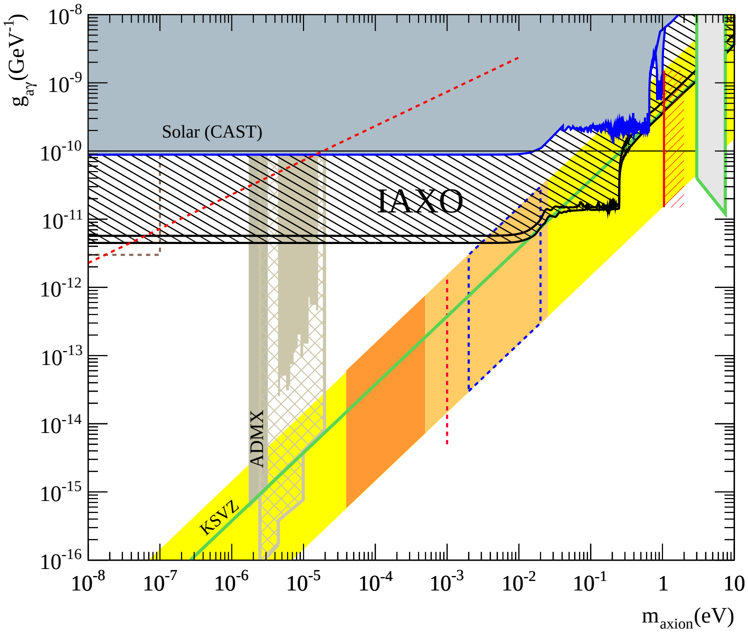

Figure 1-5. *Expected sensitivity of IAXO compared with current bounds from CAST and ADMX. Also future prospects of ADMX are shown (dashed brown region).*

solar and dark matter axions [*e.g.*, [96]]. Searches for solar axions and chameleons which exploit naturally occurring magnetic fields are described in [96, 97, 98] and reviewed in [99]. IAXO can carry out this task as one of the main experimental pathways in the next decade for the axion community. More generally, a detection with IAXO would have profound implications for particle physics, with clear evidence of physics beyond the SM.

1.2.3.4 Beam Dumps and Colliders

Axions and ALPs can also be searched for in beam dump and collider experiments. These types of experiments are described in greater detail in the search for dark photons and similar particles. Under the appropriate configuration, such experiments can also explore axion and ALP parameter space.

1.3 Dark Photons

1.3.1 Theory & Theory Motivation

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 [100, 101].

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

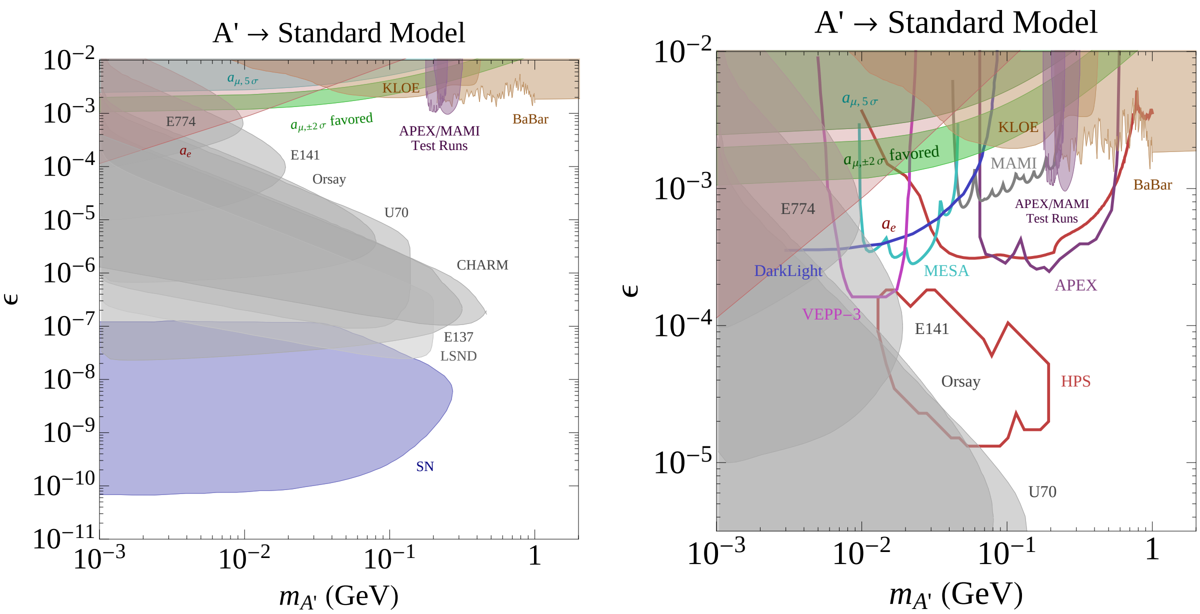

Figure 1-6. *Parameter space for hidden-photons (A') with mass $m_{A'} > 1$ MeV (see Fig. 1-7 for $m_{A'} <$ 1 MeV). Shown are existing 90% confidence level limits from the SLAC and Fermilab beam dump experiments E137, E141, and E774 [102, 103, 104, 105] the muon anomalous magnetic moment a_μ [106], KLOE [107], the test run results reported by APEX [108] and MAMI [109], an estimate using a BaBar result [105, 110, 111], and a constraint from supernova cooling [105] (see also [112]). In the green band, the A' can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [106] at 90% confidence level. On the right, we show in more detail the parameter space for larger values of ϵ. This parameter space can be probed by several proposed experiments, including APEX [113], HPS [114], DarkLight [115], VEPP-3 [116, 117], MAMI, and MESA [118]. 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 $\epsilon > 10^{-4} - 10^{-3}$; their reach is also not explicitly shown.*

(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 $\epsilon \sim 10^{-8} - 10^{-2}$ [119]. 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 [120, 121, 122].

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 [123, 124, 125, 126]. 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 [127, 128, 129, 130] (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. 1-7, various theoretically motivated regions are shown [120, 121].

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 §1.4.1.3).

The previous discussion focused on kinetic mixing between the hypercharge $U(1)_Y$ and the dark $U(1)$ gauge bosons, parametrized by ϵ. This can be generalized by allowing for the possibility of mass matrix mixing, parametrized by ϵ_Z, between the dark photon and the heavy Z boson of the SM [131]. Because of its expanded properties, the dark $U(1)$ vector boson has been dubbed the "dark Z" and labeled Z_d in such a picture, in order to emphasize its Z-like properties [131]. Overall, the Z_d couples to both the electromagnetic ($J_\mu^{\rm EM}$) and the weak neutral ($J_\mu^{\rm NC}$) currents of the SM, via [131]

$$\mathcal{L}_{\rm int} = -\left(\epsilon\, e\, J_\mu^{\rm EM} + \epsilon_Z\, \frac{g}{2\cos\theta_W}\, J_\mu^{\rm NC}\right) Z_d^\mu\,. \tag{1.8}$$

The additional interactions involving ϵ_Z violate parity and current conservation. Consequently, potential new phenomena such as "Dark Parity Violation" in atoms and polarized electron scattering can result [131, 132]. Enhancements in rare "dark" decays of the Higgs as well as K and B mesons into Z_d particles can also occur, suggesting new experimental areas of discovery [131, 133, 134].

1.3.2 Phenomenological Motivation and Current Constraints

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 [105, 115, 113, 108, 114, 109, 135, 136, 116] and at e^+e^- and hadron colliders [119, 128, 137, 110, 138, 139, 140, 141, 142, 143, 107, 144, 145]. 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 [146, 147], and by the discrepancy between the measured and calculated value of the anomalous magnetic moment of the muon [106].

Fig. 1-6 shows existing constraints for $m_{A'} > 1$ MeV [105] 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 [113, 108], HPS [114], DarkLight [115] at Jefferson Laboratory, experiments at MAMI [109] 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 [116]. Existing and future e^+e^- colliders can also probe large parts of the parameter space for $\epsilon > 10^{-4} - 10^{-3}$, and include *BABAR*, Belle, KLOE, Super$B$, Belle II, 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 [137]. This rich experimental program is discussed in more detail in §1.3.3.

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. 1-7 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 [149].

As axions or ALPs, A' bosons can also be dark matter through the vacuum-misalignment mechanism [150]. This intriguing possibility can be realized in a wide range of values for $m_{A'}$ and ϵ [16], see Fig. 1-7. It appears that experiments such as ADMX, looking for axion dark matter, can be very sensitive to A' bosons as well,

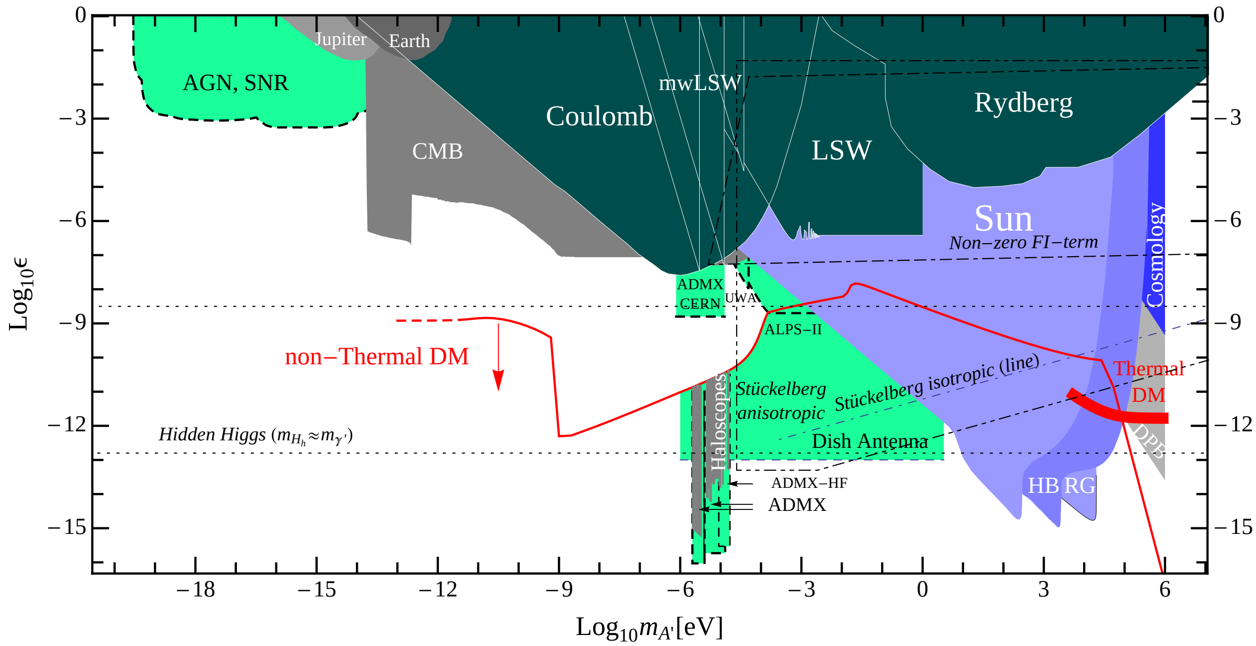

Figure 1-7. *Parameter space for hidden-photons (A') with mass $m_{A'} < 1$ MeV (see Fig. 1-6 for $m_{A'} > 1$ MeV). Colored regions are: experimentally excluded regions (dark green), constraints from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), and sensitivity of planned and suggested experiments (light green) [ADMX [30], ALPS-II [31], Dish antenna [34], AGN/SNR [148]]. 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.*

but in this case the use of magnetic fields to trigger the $A' \to$photon conversion is not required. 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. 1-7. A few experimental searches are planned and discussed in §1.3.3.6, but a large parameter space still remains to be experimentally explored.

1.3.2.1 Hints for MeV-GeV mass Dark Photons from Dark Matter

Couplings between dark matter and dark photons at the MeV-GeV scale can drastically modify the phenomenology of dark matter. In direct detection experiments, the scattering cross section can be increased due to the light mediator, or alternatively the kinematics of the scattering can be altered if the mediator couples to nearly-degenerate states. In indirect searches, the self-annihilation and self-scattering rates for the dark matter can both be enhanced at low velocities; the former can lead to striking signals in cosmic rays, photons and neutrinos, while the latter can significantly modify the internal structure of dark matter halos. While the search for dark photons has strong motivations entirely independent from their possible link to dark matter phenomenology, their detection could potentially provide an entirely new window on the dark sector.

Cosmic rays:

In 2008 the PAMELA experiment reported an unexpected rise in the ratio of cosmic-ray (CR) positrons to CR electrons, beginning at ~ 10 GeV and extending to above 100 GeV [151]. This result was later confirmed by the Fermi Gamma-Ray Space Telescope [152] and most recently by AMS-02 [153]. The (largely model-independent) expectation from standard CR propagation models is that the positron fraction should fall with increasing energy[1]. Complementary measurements of the total e^+e^- spectrum by the Fermi Gamma-Ray Space Telescope [157] are consistent with a new source of e^+e^- pairs in the 10-1000 GeV energy range.

The annihilation of weak-scale dark matter provides an attractive hypothesis for the origin of this signal, but there are several difficulties with the conventional WIMP interpretation (e.g. [158])[2]. Dark matter annihilating to a dark photon which subsequently decays, however, naturally yields (i) an enhanced signal (by up to 2-3 orders of magnitude) and (ii) a sufficiently hard positron spectrum to match the observations, as well as forbidding the production of antiprotons, if the dark photon is lighter than twice the proton mass (an antiproton excess was searched for, and not observed) [146, 147]. Benchmark models of this type were computed for a range of dark photon masses ranging from 200-900 MeV in [161], and found to provide a good fit to the data.

The AMS-02 data, with their much smaller uncertainties, prefer a somewhat softer spectrum of positrons than PAMELA. In turn, this favors dark photon models where the dark photon is heavy enough to decay to muons and charged pions, or possibly multi-particle final states (e.g. via decays through the dark sector); the spectrum due to dark photon decay to an e^+e^- pair is (as the sole channel) somewhat harder than preferred by the data [162]. Direct leptophilic annihilation to SM particles no longer appears to provide a good explanation for the signal: the softer spectrum favors $\tau^+\tau^-$ final states, which are constrained by searches for gamma-rays from dwarf galaxies [163].

There are also gamma-ray bounds on $\mu^+\mu^-$, $\pi^+\pi^-$ and e^+e^- final states, but gamma-ray production in these decays is small, and so the bounds are generally much weaker (unless upscattering of ambient starlight by electrons is included, but this contribution also depends on the electron propagation). Constraints from the inner Galaxy are dependent on the slope of the dark matter density profile, which is not well-constrained by the data or theory; constraints from the outer halo and extragalactic gamma-ray background depend sensitively on the amount of small-scale substructure present, which is also poorly known. There is tension between gamma-ray observations and the predictions from models fitting the PAMELA signal (e.g. [164, 165, 166]), but stronger statements are limited by the astrophysical uncertainties.

A more robust constraint arises from measurements of the cosmic microwave background (CMB). Dark matter annihilation during the epoch of recombination can inject electrons and photons which modify the ionization history of the universe; this in turn modifies the scattering of CMB photons at late times and perturbs the observed anisotropy spectrum [167]. At present, the best constraints from this channel appear to be in tension with models explaining the AMS-02 signal at the factor-of-2 level [168]; the Planck experiment should improve this constraint by another factor of two when its polarization data is released (e.g. [169]). The current tension could be resolved by allowing the local dark matter density to be higher by a factor of $\sim \sqrt{2}$, or by permitting an $\mathcal{O}(1)$ contribution to the signal from local clumps of dark matter. This second option is particularly attractive for lighter dark photons ($m_{A'} \ll 1$ GeV), where the annihilation cross section continues to grow at velocities smaller than that of the main Milky Way halo, and so the constraints from the CMB (originating from an epoch when the dark matter was extremely slow-moving) grow even stronger;

[1] While there are proposals for generating the positron excess by modifications to CR propagation, they require non-trivial changes to the usual propagation paradigm, e.g. that the positrons do not suffer significant radiative losses over kpc distances [154], or that the positron production by proton scattering occurs primarily within the original CR acceleration site [155, 156].

[2] Non-dark matter explanations involving a new e^+e^- source have also been advanced, with the most popular being a population of pulsars; see e.g. [159, 160].

this conclusion can be evaded if the excess observed by AMS-02 largely originates from dark matter clumps with small internal velocity dispersions [170].

These constraints do not apply if the signal originates from decaying dark matter (e.g. [171]). In this case the size of the signal is not a difficulty, but the lack of antiprotons and the hard spectrum still motivate scenarios with decay through dark photons.

Light dark matter:

There have been several experimental results that might hint at the presence of $\mathcal{O}(1-10)$ GeV dark matter. The CDMS experiment has recently reported three events in their signal region [172], with the best fit WIMP hypothesis being favored over the background-only hypothesis at 99.8% confidence. The best-fit WIMP mass is 8.6 GeV/cm^2, with a 68% confidence contour extending from $6.5-20$ GeV. This region is in good agreement with earlier hints of a signal from CoGeNT [173]; it appears in tension with limits from XENON100, but the comparison does depend on the response of xenon to low-energy nuclear recoils and on the DM velocity distribution [174].

The preferred dark matter-nucleon scattering cross section for the CDMS events, $\sigma \approx 2\times10^{-41}$ cm^2, is quite large. The two Standard Model particles which might be expected to mediate such a scattering are the Z boson and the Higgs, both of which are constrained (for light dark matter) by bounds on the invisible decay width of the Z and the Higgs; the cross section preferred by CDMS seems clearly ruled out for Higgs portal dark matter [175], and barely consistent for scattering through the Z [176]. This observation motivates the existence of a new mediator particle, in the event that the signal is indeed due to dark matter. A dark photon mediator naturally enhances the cross section; if the mass of the dark photon is inherited from the weak scale, the relation $m_{A'} \sim \sqrt{\varepsilon} m_Z$ naturally predicts a dark matter-nucleon cross section comparable to that mediated by the Z, but the constraints on invisible decays no longer apply.

There have also been hints of possible annihilation signals from ~ 10 GeV dark matter in the Galactic Center and inner Galaxy [177, 178, 179, 180]; these signals can be accommodated by light dark matter annihilation to dark photons which subsequently decay to Standard Model particles [181].

Self-interacting dark matter:

Any coupling between MeV-GeV dark photons and dark matter will also give rise to a long-range self-interaction for the dark matter. This in turn can modify dark matter structure formation, flattening the cusps at the centers of halos [182] and reducing the concentration of subhalos [183]. These are two areas in which there are marked disagreements between the predictions of collisionless cold dark matter simulations and observations of galaxies, and the effect of self-interaction is to bring the two into closer agreement.

Recent work on the cross section required to achieve agreement has pointed to a low-velocity cross section in the range of $\sigma/m_{\rm DM} \sim 0.1-1$ cm^2/g [184]. In dark-photon scenarios where the potential due to self-interaction can be approximated as a Yukawa potential, the maximum transfer cross section is given by $\sigma_T \approx 22.7/m_{A'}^2$ (e.g. [183]). Setting this value, divided by $m_{\rm DM}$, to 1 cm^2/g, we find the required mass scale to be $m_{A'} \approx 70$ MeV $\times\sqrt{{\rm GeV}/m_{\rm DM}}$, in agreement with similar estimates in [170]. It is remarkable that this entirely independent line of enquiry suggests a mass scale in the range accessible by dark photon searches.

1.3.2.2 Hints for Ultra-light Dark Photons

The photon $\leftrightarrow A'$ oscillation mechanism can generate the required A' energy density for them to account for all the dark matter for $m_{A'} \sim 100$ keV and $\epsilon \sim 10^{-12}$ [185]. 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 [186].

1.3.3 Status and Plans for Terrestrial experiments

Our discussion here focuses on the case where the dark photon can only decay into Standard Model matter, with ϵ-suppressed decay width. Another possibility is that the dark photon has ϵ-unsuppressed couplings to some new species "χ" of fermions or bosons (dark-sector matter), which are neutral under the Standard Model gauge group, and in particular are electrically neutral. The latter will be discussed in detail in §1.4.

1.3.3.1 Electron Beam Dump Experiments

In electron beam dump experiments, a high-intensity electron beam dumped onto a fixed target provides the large luminosities needed to probe the weak couplings of dark photons. When the electrons from the beam scatter in the target, the dark photons can be emitted in a process similar to ordinary bremsstrahlung because of the kinetic mixing. The dark photons are highly boosted carrying most of the initial beam energy and get emitted at small angles in the forward direction. The detector is placed behind a sufficiently long shielding in order to suppress the Standard Model (SM) background. Dark photons can traverse this shielding due to their weak interactions with the SM and can then be detected through their decay into leptons (mostly e^+e^- for the mass range of interest). Therefore, a decay length of $\mathcal{O}(\mathrm{cm}-\mathrm{m})$ is needed in order for the dark photons to be observable by decaying behind the shield and before the detector. This is possible for dark photons with masses larger than $2m_e$ up to $\mathcal{O}(100)$ MeV and small values of the kinetic mixing ϵ (roughly $10^{-7} \lesssim \epsilon \lesssim 10^{-3}$). Electron beam dump experiments are thus well suited to probe this region of the parameter space.

Depending on the specific experimental set-up with respect to the decay length of the dark photon, the possible reach of an experiment is determined not only by the collected luminosity but also by the choice of the beam energy, the length of the shield and the distance to the detector. Large values of the kinetic mixing parameter ϵ for which the lifetime is very short are not accessible since the dark photon decays within the shield. At very small values of ϵ the sensitivity of these experiments is limited by statistics as there are too few dark photons which are produced and decay before the detector. The total number of expected events in an experiment from decays of dark photons has been determined in [105, 187].

Several electron beam dump experiments were operated in the last decades to search for light metastable pseudoscalar or scalar particles (e.g. axion-like particles or Higgs-like particles). Examples are the experiments E141 [103] and E137 [102] at SLAC, the E774 [104] experiment at Fermilab, an experiment at KEK [188] and an experiment in Orsay [189]. The measurements performed by the experiments at SLAC and Fermilab have been reanalysed in [105] to derive constraints on the dark photon mass and coupling. Updated limits for all experiments were presented in [187], where the acceptances obtained with Monte Carlo simulations for each experimental set-up have been included. These limits are shown in Fig. 1-6 together with all current constraints. Electron beam dump experiments cover the lower left corner of the parameter space in which the lifetime of the dark photon is sufficiently large to be observed behind the shield. In order to extend these limits with future experiments to smaller values of ϵ large luminosities and/or a long distance to the detector are needed since the lower limit of an experiment's reach scales only with the fourth root of those two parameters.

1.3.3.2 Fixed-Target Experiments

Fixed-target experiments using high-current electron beams are an excellent place to search for A's with masses $2m_e < m_{A'} <$ GeV and couplings down to $\epsilon^2 \equiv \alpha'/\alpha > 10^{-10}$. 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 [105]. The reach for recently proposed dark photon searches is shown in Fig. 1-6.

Existing dual-arm spectrometers at Hall A at Jefferson Lab (JLab) and MAMI at Mainz have been used to search for dark 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 performed short test runs (few days of data taking) and published search results with sensitivity down to $\alpha'/\alpha > 10^{-6}$ over narrow mass ranges [109, 108]. These results clearly demonstrate the high sensitivity which can be reached in fixed-target experiments. In the meantime the A1 collaboration has carried out two more data taking runs of approximately two weeks each. The analysis of data is ongoing. Preliminary results indicate that the A' mass range from 120 MeV down to 50 MeV could be covered with a sensitivity in α'/α similar to the test run published in 2011. Furthermore, A1 is developing a new experiment to search for dark photon decay vertices displaced from the target by approximately 10 millimeters. They hope to cover the A' mass range $40 < m_{A'} < 130$ MeV with a sensitivity in α'/α from 10^{-9} down to 10^{-11}.

The APEX test run in 2010 achieved sensitivity to $\alpha'/\alpha > 10^{-6}$ in a narrow mass range [108]. Using high-current beams ($\sim 100\mu$A) at four different beam energies on relatively thick targets (1-10% of a radiation length), the proposed full APEX experiment will probe A' masses from 65 to 550 MeV for couplings $\alpha'/\alpha > 10^{-7}$ [113]. A full APEX run has been approved by the JLab PAC pending a radiation review by JLab management. They are tentatively scheduled for 2016.

The HPS collaboration [114] has proposed an experiment to take place in Hall B at JLAB using a Si-strip based vertex tracker inside a magnet to measure the invariant mass and decay point of e^+e^- pairs and a $PbWO_4$ crystal calorimeter to trigger. HPS uses lower beam currents and thinner targets than the dual arm spectrometers, but compensates with large forward acceptance. HPS has high rate data acquisition and triggering to handle significant beam backgrounds. Because it can discriminate A' decays displaced more than a few millimeters from the large, prompt, trident background, HPS has enhanced sensitivity to small couplings, roughly $10^{-7} > \alpha'/\alpha > 10^{-10}$ for masses $30 < m_{A'} < 500$ MeV. Without requiring a displaced vertex, HPS will also explore couplings $\alpha'/\alpha > 10^{-7}$ over the same mass range. HPS has conducted a successful test run at JLab during the spring of 2012, which demonstrated technical feasibility and confirmed simulations of the background rates. The proposal for "full" HPS was reviewed by DOE in July, 2013. The Collaboration hopes for rapid approval and funding, and plans to build HPS during 2013-2014, install it at JLab in September, 2014, and commission and run it in late 2014 and 2015 at the upgraded CEBAF accelerator.

The DarkLight detector is a compact, magnetic spectrometer designed to search for decays to lepton pairs of a dark photon A' in the mass range 10 MeV $< m_{A'} <$ 90 MeV at coupling strengths of $10^{-9} < \alpha' < 10^{-6}$.

The experiment will use the 100 MeV beam of the JLaB FEL incident on a hydrogen gas target at the center of a solenoidal detector, comprising silicon detectors (for proton recoil), a low mass tracker (for the leptons), and shower counters (for photon detection). By measuring all the final state particles, Darklight can provide full kinematic reconstruction. The available information also permits searching for invisible A' decays via a missing mass measurement. A series of beam tests in summer 2012 verified that sustained, high-power transmission of the FEL beam through millimiter-size apertures is feasible [193]. JLAB has approved Darklight. A full technical design is underway and funding is being sought. The goal is to begin data-taking in 2016.

The MESA accelerator [194], which recently has been approved for funding within the PRISMA cluster of excellence at the University of Mainz, hopes to cover a mass range comparable to that covered by Darklight. The MESA accelerator (155 MeV beam energy) will be operated in the energy recovering linac mode with one recirculating arc as well as a windowless gas jet target. The Mainz group is considering to use two compact high-resolution spectrometers rather than a high-acceptance tracking detector. The project is several years off.

1.3.3.3 Proton Beam Dump Experiments

Proton beam dump experiments can also probe dark photons decaying to visible channels. Several reinterpretations of past experimental analyses from LSND [135],[136],[195], ν-Cal I [196],[197],[198], NOMAD [199],[200], PS191 [199],[201], and CHARM [202],[203] have resulted in limits on dark photons that are complementary to those coming from electron beam dumps, precision QED, and B-factories. One can take advantage of the large sample of pseudoscalar mesons (*e.g.*, π^0, η) produced in the proton-target collisions, which will decay to $\gamma A'$ with a branching ratio proportional to ϵ^2 if kinematically allowed [135]. These experiments probe of a similar region in A' mass and coupling parameter space as past electron beam dumps discussed in Section 1.3.3.1, but do have unique sensitivity in certain cases. It remains to be investigated whether future proton beam dump experiments can cover new regions of A' parameter space.

Proton beam dump experiments also have significant sensitivity to invisible decays of A', particularly when the decay products are stable and can re-scatter in the detector, (*e.g.*, as in the case of A' decaying to dark matter), and looking forward there is a proposal to do a dedicated beam dump mode run at MiniBooNE to search for light dark matter [190]. This subject is discussed in more detail in Section 1.4.

1.3.3.4 Electron-positron Colliders

During the past fifteen years, high luminosity e^+e^- flavor factories have been producing an enormous amount of data at different center-of-mass energies. In Frascati (Italy), the KLOE experiment running at the DAΦNE collider, has acquired about 2.5 fb^{-1} of data at the $\phi(1020)$ peak. B-factories at PEP-II (USA) and KEK-B (Japan) have delivered an integrated luminosity of 0.5-1 ab^{-1} to *BABAR* and Belle, respectively. In China, the Beijing BEPC collider is currently running at various energies near the charm threshold and has already delivered several inverse femtobarns of data to the BESIII experiment.

These large datasets have been exploited to search for dark photon production in the following processes:

- The radiative production of a dark photon (A') followed by its decay into a charged lepton or photon pair, $e^+e^- \to \gamma A', A' \to l^+l^-, \gamma\gamma$ $(l = e, \mu)$ [127].
- The pair production of a dark photon with a new light scalar particle, generally dubbed as h'. The existence of the latter is postulated in models where the hidden symmetry is broken by some Higgs

mechanism [140]. Similarly to the SM Higgs, the mass of the h' is not predictable by first principles and could be at the GeV scale as well. The phenomenology is driven by the mass hierarchy. While scalar bosons heavier than two dark photons decay promptly, giving rise to events of the type $e^+e^- \to A'h' \to 3A', A' \to l^+l^-, \pi^+\pi^-$, their lifetime becomes large enough to escape undetected for $m_{h'} < m_{A'}$, resulting in $e^+e^- \to A'h' \to l^+l^- + missing\ energy$ events.

- Radiative meson decays, which could also produce a dark photon with a branching ratio suppressed by a factor ϵ^2 [110].

The search for a light CP-odd Higgs (A^0) in $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$ conducted by *BABAR* [111] has been reinterpreted as constraints on dark photon production, as its signature is identical to that of $e^+e^- \to \gamma A', A' \to \mu^+\mu^-$. Limits on the coupling ϵ^2 at the level of 10^{-5} have been set. Future analyses based on the full *BABAR* and Belle datasets are expected to increase the sensitivity by an order of magnitude.

A search for dark photon and associated scalar boson has been performed at *BABAR* in the range $0.8 < m_{h'} < 10.0$ GeV and $0.25 < m_{A'} < 3.0$ GeV, with the constraint $m_{h'} > 2m_{A'}$ [144]. The signal is either fully reconstructed into three lepton or pion pairs, or partially reconstructed as two dileptonic resonances, assigning the remaining dark photon to the recoiling system. No significant signal is observed, and upper limits on the product $\alpha_D\epsilon^2$ are set at the level $10^{-10} - 10^{-8}$. These bounds are translated into constraints on the mixing strength in the range $10^{-4} - 10^{-3}$, assuming $\alpha_D = \alpha \simeq 1/137$. A similar search currently performed by Belle should improve these limits by a factor of two.

KLOE has searched for $\phi(1020) \to \eta A', A' \to e^+e^-$ decays, in which the η was tagged with either the $3\pi^0$ or the $\pi^+\pi^-\pi^0$ final states [204, 205]. The $A' \to \mu^+\mu^-, \pi^+\pi^-$ channels were not included due to a higher background level. After subtraction of the ϕ Dalitz decay background, no evident peak is observed, and the following limits are set at 90% CL: $\epsilon^2 < 1.5 \times 10^{-5}$ for $30 < m_{A'} < 420$ MeV, $\epsilon^2 < 5 \times 10^{-6}$ for $60 < m_{A'} < 190$ MeV.

The BESIII Collaboration has published a search for invisible decays of the η and η' mesons, motivated by the possible existence of light neutral dark matter particles [206]. Events are selected from $J/\psi \to \phi\eta(\eta')$ decays, where the ϕ is tagged by its charged kaon decay mode. No significant signal is observed, and 90% CL limits on the branching ratio $BR(\eta \to invisible) < 1.0 \times 10^{-4}$ and $BR(\eta' \to invisible) < 5.3 \times 10^{-4}$ are set. These bounds constrain the invisible dark photon decay through $\eta(\eta') \to A'A', A' \to invisible$.

Future perspectives

Further exploitation of the currently available datasets as well as the acquisition of larger samples at planned super-flavor factories should improve the aforementioned limits. The searches should proceed along two main directions: searches using current datasets and searches at future facilities.

Searches using current datasets

Current datasets have not been fully exploited to search for signatures of a dark sector. Current studies of the $e^+e^- \to \gamma A', A' \to l^+l^-, \pi^+\pi^-$ based on the full *BABAR* and Belle datasets are expected to probe values of the coupling ϵ^2 down to $\sim 10^{-6}$, and extend the coverage down to ~ 20 MeV, covering the full region favored by the $g-2$ discrepancy. KLOE is expected to probe values of ϵ^2 between $\sim 10^{-5}$ and $\sim 7 \times 10^{-7}$ in the range $500 < m_{A'} < 1000$ MeV using the $e^+e^- \to \mu^+\mu^-\gamma$ sample selected for the study of the hadronic contribution to the muon magnetic anomaly. Similarly, invisible dark photon decays could be studied in the $e^+e^- \to \gamma + invisible$ final state, using data collected at *BABAR* with a specific single-photon trigger. This search could probe dark photon masses $0 < m_{A'} < 5$ GeV, significantly extending the parameter space covered by proposed searches in neutrino experiments [190]. The calorimeter hermicity and energy resolution plays a crucial role for this study, as well as the amount of accidental background produced by the machine. Similar considerations apply to searches for purely neutral dark photon decays.

A search for a light h', pair produced with a dark photon is being performed at KLOE using $e^+e^- \to A'h' \to l^+l^- + missing\ energy$ events. This search fully complements the analysis performed by *BABAR* covering a totally different parameter space. Extensions to non-Abelian model could easily be probed using current datasets. The simplest scenario include four gauge bosons, one dark photon and three additional dark bosons, generically denoted W'. A Search for di-boson production has been performed at *BABAR* in the four lepton final state, $e^+e^- \to W'W', W' \to l^+l^-$ $(l = e, \mu)$, assuming both bosons have similar masses [207]. More generic setups could easily be investigated.

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 SM Higgs - dark scalar mixing angle and pseudo-scalar couplings constants are projected to be at the level of $10^{-4} - 10^{-3}$ and 10^3 TeV, respectively [208].

1.3.3.5 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 [129, 145, 209, 210], if new states are produced, they could decay to A' bosons and other hidden-sector states with very large branching ratios. For GeV-scale A' masses, the A' would be highly boosted when produced in such decays and its decay products would form collimated jets, mostly composed of leptons ("lepton-jets" [129]).

The general-purpose proton collider experiments at the Tevatron and LHC have all presented first searches for lepton-jets in heavy-particle decays [142, 143, 211, 212, 213]. 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 [214]. Results have often been interpreted in supersymmetric scenarios; the updated ATLAS analysis using 7 TeV pp data from 2011 excludes di-squark production with a squark mass up to about 1000 GeV or a weakly-produced state with mass up to about 400 GeV, decaying through cascades to two lepton-jets [215]. 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 has also been seen down to ~ 50 MeV (limited by photon conversions to e^+e^- pairs).

ATLAS has recently searched for decays of the Higgs boson to electron lepton-jets, excluding a branching ratio of about 50% [216]. Searches have mostly focused so far on prompt decays of dark photons, but ATLAS has now searched for decays of the Higgs boson to long-lived A' bosons decaying to muons in the muon chambers, constraining the branching ratio to be less than 10% for a proper lifetime between 10 and 100 mm [217].

Large datasets expected at the LHC in the future (300 fb^{-1} at 14 TeV) will contain billions of Z and millions of Higgs bosons, allowing branching ratios to lepton-jets as low as 10^{-7} (or $\epsilon \simeq 10^{-3}$) to be probed for Z decays and 10^{-3} for Higgs decays. Electroweak (strongly-produced) SUSY particles with masses up to 1 (2.5) TeV could be discovered through cascade decays to lepton-jets.

1.3.3.6 Laser Experiments (ultra-light dark photons)

Light dark photons ($\sim$ meV) may also be searched for through laser, cavity, and helioscope type experiments in much the same way as done for axions and ALPs. As those approaches have been described elsewhere, it is just mentioned that ordinary photons might be able to kinetically mix into the dark photon. Much of the parameter space for light shining through walls experiments has now been excluded although each configuration of a proposed experiment may still cover unexplored parameter space.

1.3.4 Opportunities for Future Experiments: New Ideas, Technologies, & Accelerators

The physics motivations for dark photons, as outlined in 1.3.1 above, easily motivate extending searches far beyond the present generation of experiments. Large parts of the mass-coupling parameter space, shown in Fig. ?, will remain uncovered after the experiments at JLAB and Mainz have run, and after data from the B and Phi factories will have been fully analyzed. If something is found in the present generation of experiments, it will of course have profound impact on high energy physics. In that fortuitous case, it will be incumbent on future experiments to confirm the findings, explore the detailed properties of the new particle, and to seek its cousins. That exercise will demand experiments with improved performance and reach. If nothing is found in the present searches, there remains a vast and viable region of parameter space to explore. Specific models for dark photons have been advanced which populate the virgin territory, and general considerations from theory and phenomenology do as well. So in this case too, extending searches for dark photons through the whole of the parameter space is a high priority.

Can new experiments be devised to explore the new territory? Of course! Future fixed target elec troproduction experiments, new searches at future e+e- colliding beam facilities, and new searches at the LHC will all contribute to the hunt.

At fixed target machines, several generic improvements look possible which can expand the reach significantly. First, in HPS-like experiments, it should be possible to boost the integrated luminosity by one or more orders of magnitude. Accommodating 10 or more times the current will require tracking detectors that avoid the highest occupancy/radiation damage environments yet preserve most of the acceptance , or new pixellated and rad hard detectors that can tolerate the higher rates. Second, studies have shown that catching the recoil electron, in addition to the A decay products, will boost the mass resolution by a factor of two, and can reduce a primary physics background due to the Bethe Heitler process by as much as a factor 4. Both will greatly improve the significance, signal/sqrt(background), and extend the reach accordingly. Third, Triggering on pions and muons will boost the sensitivity for As for masses beyond the dimuon mass by large factors below 1 GeV, where the rho dominates the A decays, and help significantly at higher masses too. Fourth, using low Z nuclear targets and maximal beam energies improves the reach in this 300-1000MeV range too, since the radiative A cross section increases with higher beam energies, and since form factor effects will be mitigated by going to smaller, lower Z nuclei. CEBAF12 at JLAB will provide 12 GeV beams. Even higher energies will improve future experiments if further upgrades at JLAB are realized. Fifth, note that the sensitivity of the searches depend inversely with the square root of the invariant mass resolution, and directly with the square root of the acceptance; vertex searches of course depend critically on the vertex resolution. All these quantities can be improved rather directly with more ambitious experiments. It is not unreasonable to assume a factors of2 improvement in the acceptance and 2-4 in the mass resolution. The vertex resolution can be improved in three direct ways: 1) thinner targets (with compensating higher currents); 2)shorter extrapolation distances from the first detector layer to the target; 3) thinner detectors, with correspondingly lower multiple coulomb scattering, and consequently better impact parameter resolution. Taken together, future experiments may be able to discriminate A decays just a few mm from the target (vs 15 mm in the current version of HPS). The list goes on. Finally, optimized analysis procedures and multivariate analyses may buy factors of two improvement in sensitivity. An estimate of the reach of a future experiment which exploits these various factors is given in Fig. XX. Note that this exercise exploits just one of the current approaches for fixed target electroproduction; other existing approaches may offer other gains. Brand new approaches may be even more powerful. While detailed performance estimates for new experimental layouts are not yet available, several new ideas are being discussed which may further improve experimental reach.

1.3.4.1 Searches at future facilities

e^+e^- colliding beam machines have conducted sensitive searches for dark photons over a wide range of masses. These searches, using existing data sets, are continuing. Since future facilities are already approved, it is comparatively straight-forward to extrapolate their performance for future searches. The coupling accessible by current datasets from e^+e^- colliders are at the level $\epsilon^2 \sim 10^{-6} - 10^{-5}$ for dark photon masses below a few hundred MeV. This limitation comes essentially by the available statistics, i.e. the luminosity that can be delivered by the accelerators. The luminosity typically scales quadratically with their center of mass energy, basically compensating the inverse scaling of the relevant production cross-sections.

Current factories reach instantaneous luminosities of a few times 10^{32} (10^{34}) cm^{-2}s^{-1} at 1 (10) GeV. Several next generation flavor factories have been proposed or are currently under construction. The upgraded KEK B-factory, SuperKEKB, is expected to start taking data in 2016 and should collect 50 ab^{-1} by 2022, about two orders of magnitude larger than the dataset collected by Belle. Several tau-charm factories operating between $2-5$ GeV with instantaneous luminosities at the level of $10^{35} - 10^{36}$ cm^{-2}s^{-1} have been proposed, but remain to be funded at the time of this writing. Their expected sensitivity would roughly be at the level SuperKEKB should reach. At Frascati, KLOE-2 will install a new inner tracker, a cylindrical GEM detector, to improve the momentum resolution of charged particles while keeping the amount of material at a minimum. This approach will hopefully reduce the background from photon conversions produced in $e^+e^- \to \gamma\gamma, \gamma \to e^+e^-$ events, allowing KLOE-2 to explore the very low mass region.

An alternative approach has been proposed by the authors of [117], colliding a *single* intense positron beam on an internal target. Specifically, the VEPP-3 collaboration has proposed to use a 500 MeV positron beam of VEPP-3 on a gas hydrogen internal target. The search method is based on the study of the missing mass spectrum in the reaction $e^+e^- \to A'\gamma$, which allows the observation of a dark photon independently of its decay modes and lifetime in the range $m_{A'} = 5 - 20$ MeV.

In summary, next generation flavor factories could probe values of the coupling ϵ^2 down to a level comparable to fixed target experiments for prompt decays, while significantly extending their mass coverage. Should a signal be observed, e^+e^- colliders will be ideally suited to investigate in detail the structure of a hidden sector, complementing dedicated experiments.

1.4 Light Dark-Sector States (including Sub-GeV Dark Matter)

1.4.1 Theory & Theory Motivation

Dark matter and neutrino mass provide strong empirical evidence for physics beyond the Standard Model (SM). Arguably, rather than suggesting any specific mass scale for new physics, they point to a hidden (or dark) sector, weakly-coupled to the SM. Dark sectors containing light stable degrees of freedom, with mass in the MeV-GeV range, are of particular interest as dark matter candidates as this regime is poorly explored in comparison to the weak scale. Experiments at the intensity frontier are ideally suited to explore this light dark-sector landscape, as discussed in this section.

Before going into details, it is useful to recall a general parametrization of the interactions between the SM and a dark sector. A natural assumption is that any light dark sector states are SM gauge singlets. This automatically ensures weak coupling to the visible (SM) sector, while the impact of heavier charged states is incorporated in an effective field theory expansion at or below the weak scale, $\mathcal{L} \sim \sum_n \frac{c_n}{\Lambda^n} \mathcal{O}^{(k)}_{\rm SM} \mathcal{O}^{(l)}_{\rm hidden}$, where k and l denote operator dimensions and $n = k + l - 4$. The generic production cross section for hidden sector particles then scales as $\sigma \sim E^{2n-2}/\Lambda^{2n}$. Thus lower dimension interactions, unsuppressed by the heavy scale Λ, are preferentially probed at lower energy. Such interactions are natural targets for the intensity frontier more generally. The set of lowest-dimension interactions, or *portals*, which generalizes the right-handed neutrino coupling, is quite compact. Up to dimension five ($n \leq 1$), assuming SM electroweak symmetry breaking, the list of portals includes: $-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$ (dark photons kinetically mixed with hypercharge), $(AS + \lambda S^2) H^\dagger H$ (dark scalars coupled to the Higgs), $y_N LHN$ (sterile neutrinos coupled the lepton portal), and $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$ (axion-like pseudoscalars coupled to an axial current). On general grounds, the couplings of these lowest dimension operators are minimally suppressed by any heavy scale, and new weakly-coupled physics would naturally manifest itself first via these portals in any generic top-down model. Thus portals play a primary role in mediating interactions of light dark sector states with the SM.

1.4.1.1 Light Dark Matter

Dark matter provides one of the strongest empirical motivations for new particle physics, with evidence coming from various disparate sources in astrophysics and cosmology. While most activity has focused on the possibility of weakly-interacting massive particles (WIMPs) with a weak-scale mass, this is certainly not the only possibility. The lack of evidence for non-SM physics at the weak scale from the LHC motivates a broader perspective on the physics of DM, and new experimental strategies to detect its non-gravitational interactions are called for. A wider theoretical view has also been motivated in recent years by anomalies in direct and indirect detection [151, 218, 219], possible inconsistencies of the ΛCDM picture of structure formation on galactic scales [220], and the advent of precision CMB tests of light degrees of freedom during recombination.

The mass range from the electron threshold $\sim$0.5 MeV up to multi-TeV characterizes the favored range for dark matter candidates with non-negligible SM couplings (on the scale of terrestrial particle physics experiments). The simple thermal relic framework, with abundance fixed by freeze-out in the early universe, allows dark matter in the MeV-GeV mass range if there are light (dark force) mediators which control the annihilation rate [221]. Related scenarios, such as asymmetric dark matter, also require significant annihilation rates in the early universe, and thus light mediators are a rather robust prediction of models of MeV-GeV scale dark matter which achieve thermal equilibrium. Current direct detection experiments searching for nuclear recoils lose sensitivity rapidly once the mass drops below a few GeV, and experiments at the intensity frontier provide a natural alternative route to explore this light MeV-GeV scale dark matter regime. Crucially, the light mediators required for DM annihilation to the SM provide, by inversion, an accessible production channel for light dark matter that can be exploited in high luminosity experiments.

Models of sub-GeV dark matter are subject to a number of terrestrial and cosmological constraints, as discussed below. However, simple models interacting through one or more of the portal couplings are viable over a large parameter range; e.g. an MeV-GeV mass complex scalar charged under a massive dark photon can be thermal relic DM, with SM interactions mediated by the kinetic mixing portal.

1.4.1.2 Light Dark-Sector States

There is no compelling argument, beyond simplicity, for cold dark matter to be composed of a single species, or even a small number. Light stable thermal relics require the presence of additional light mediators as discussed above, and the dark sector may be quite complex. Indeed, the annihilation channels required for (thermalized) dark matter in the early universe could occur within the dark sector itself if there are additional light states, subject to constraints from cosmology on the number of relativistic degrees of freedom. Indeed, since SM neutrinos do contribute a (highly dub-dominant) fraction of hot dark matter, we already know that in the broadest sense dark matter must be comprised of multiple components. Thus care is required to assess the experimental sensitivity according to the underlying assumptions about the stability of the dark sector state in cosmological scales, and whether or not stable dark sector states under study comprise some or all of dark matter.

1.4.1.3 Millicharged 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 §1.3.1 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 [222, 223, 224]. 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 [225, 226, 227].

Terrestrial experiments as well as astrophysical and cosmological observations provide interesting bounds on MCPs. These limits in addition to comments on future prospects are summarized in Sec. 1.4.2.2.

1.4.2 Phenomenological Motivation and Current Constraints

1.4.2.1 Constraints on Light Dark Matter and Dark Sectors

A variety of terrestrial, astrophysical and cosmological constraints exist on light dark matter and dark sector states, which we now summarize. We focus on the scenario with dark sector states χ (including dark matter) interacting with the SM through a dark photon, emphasizing the assumptions going into each limit. These limits, along with prospects for various future experiments to be discussed below, are displayed in Fig. 1-8.

Constraints that rely only on the presence of a kinetically mixed dark photon come from precision QED measurements [106]. Precision tests of the fine-structure constant α (including the electron anomalous magnetic moment) constrain the kinetic mixing parameter $\epsilon \lesssim 10^{-4}(10^{-2})$ for a dark photon mass $m_{A'} \sim 1\,\mathrm{MeV}(100\,\mathrm{MeV})$. The muon anomalous magnetic moment provides a stronger constraint for heavier dark photons, with $\epsilon \lesssim$ few $\times\, 10^{-3}(10^{-2})$ as the dark photon mass increases from $m_{A'} \sim 50\,\mathrm{MeV}(300\,\mathrm{MeV})$. Furthermore, model independent constraints from the measurements of the Z boson mass, precision electroweak observables, and e^+e^- reactions at a variety of c.o.m energies constrain $\epsilon \lesssim 3 \times 10^{-2}$ independent of $m_{A'}$ [228].

The next class of constraints relevant to this scenario relies on the assumption that the dark photon decays invisibly (but not necessarily to stable states e.g., dark matter). Measurements of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching

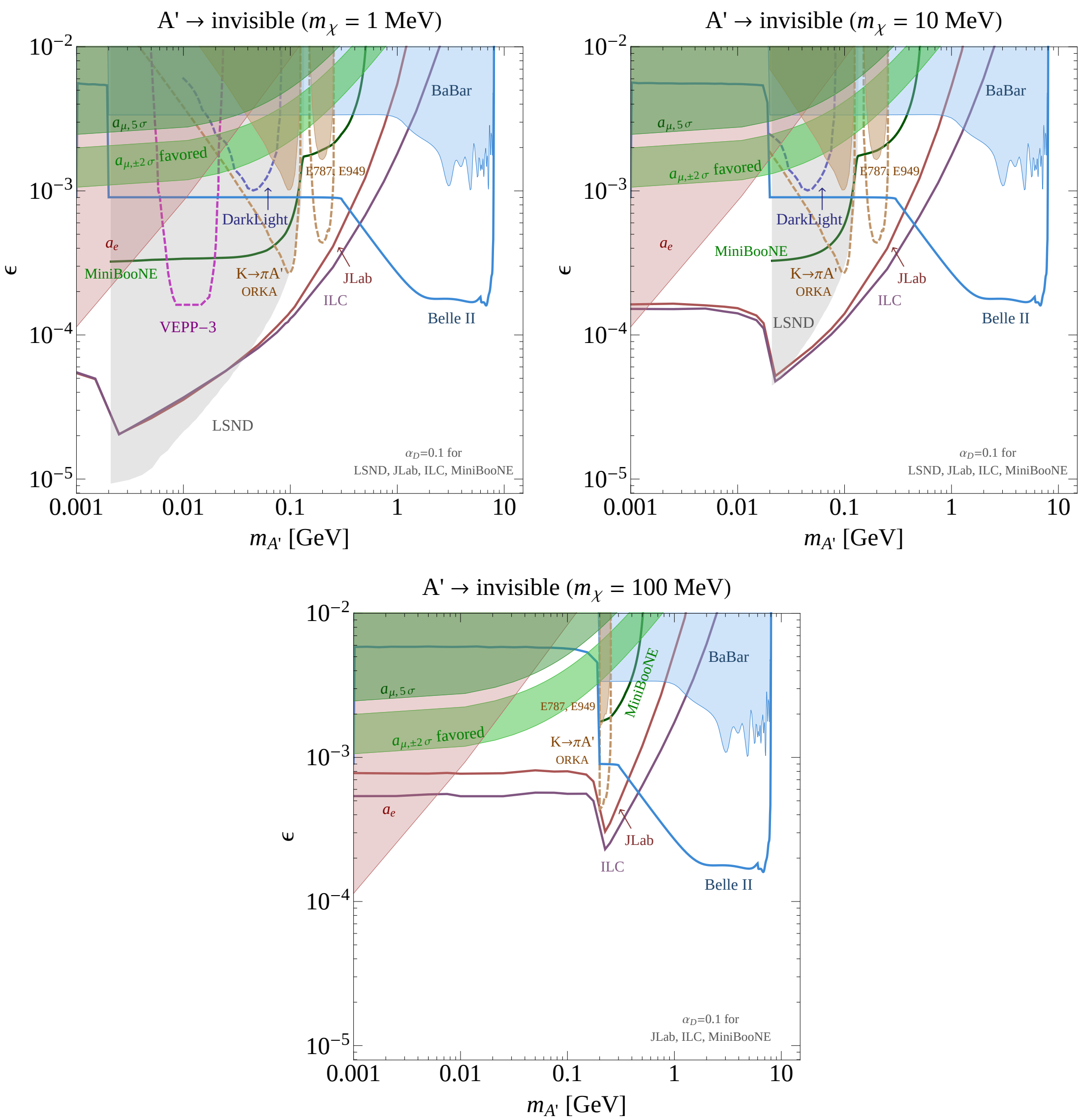

Figure 1-8. *Parameter space for invisible A's. Precision QED tests of α (red) and the muon anomalous magnetic moment (dark green) constrain the low m_A', large ϵ region. In the green band, the A' can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [106]. Constraints from invisible A' decays arise from the measured $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio [230, 106, 190] (brown) from an mono-photon search at BABAR [231, 243, 192] (blue). LSND (gray) constrains A's decaying to dark matter for masses $m_A' < m_{\pi^0}$, $m_\chi < m_A'/2$ [233]. We also display projections from future searches/experiments, including the DarkLight experiment [229] (dark blue dashed), the MiniBooNE beam off target run [190], future electron beam dump experiments at JLAB (dark red) and the ILC (purple) [192], and BELLE II (blue).*

ratio [230] place limits on ϵ in the range $10^{-2} - 10^{-3}$ if the decay $K^+ \to \pi^+ A'$ is kinematically allowed. Strong constraints on ϵ exist in a narrow region $m_{A'} \sim m_{J/\psi}$, in which case the the decay $J/\psi \to$ invisible is resonantly enhanced. Furthermore, a limit on the branching fraction $\Upsilon(3S) \to \gamma + A^0$, $A^0 \to$ invisible (with A^0 a scalar [231]) can be recast as a limit on the continuum process $e^+e^- \to \gamma A'$, $A' \to$ invisible, leading to $\epsilon \lesssim$ few $\times 10^{-3}$ [192].

If the dark sector states χ are stable (e.g., if χ is the dark matter), or at least metastable with lifetimes of $O(100\text{m})$, then proton- and electron- beam fixed target experiments are sensitive to the scattering of χ with electrons or nuclei, which depend on α_D. The LSND measurement of the electron-neutrino elastic scattering cross section [232] places a limit in the range $\epsilon \lesssim 10^{-5} - 10^{-3}$ for $\alpha_D = 0.1$, $m'_A < m_{\pi^0}$, $m_\chi < m'_A/2$ [233]. Furthermore, the SLAC MQ search for milli-charged particles [234] is senstive to A's heavier than π^0, and constrains values of ϵ as low as 10^{-3} [191].

Direct detection experiments can probe light dark matter χ in the halo through its scattering with electrons [235]. An analysis of the XENON10 dataset has placed limits on the χ-electron scattering cross section $\sigma_e < 10^{-37}\,\text{cm}^2$ for χ masses in the range 20 MeV - 1 GeV.

Late time dark matter annihilation to electromagnetic particles can distort the CMB. Assuming χ saturates the observed relic density and annihilates to charged particles through an s-wave reaction, then the CMB essentially rules out this scenario [167, 168, 169]. These bounds are, however, model dependent and may be avoided in several ways: 1) χ may annihilate through a p-wave process, e.g. scalar DM annihilating through an s-channel dark photon to SM fermion pairs [233], 2) the dark sector may contain new light states, opening up new annihilation modes for χ which do not end with electromagnetic final states, 3) the dark matter may be matter-asymmetric [236], and 4) χ may comprise a sub-dominant component of the DM.

1.4.2.2 Additional constraints on Millicharged Particles

Several portions of the charge-mass parameter space for MCPs can be excluded based upon available experimental results. Some of these bounds, *e.g.* direct measurements, rely on relatively few assumptions, while others are dependent on the accuracy of astrophysical and cosmological models. Fig. 1-9 illustrates the parameter space for MCPs and a brief summary of the most stringent bounds follows.

Direct measurements cover a large portion of the parameter space of MCPs for $Q \sim e$. The ASP (Anomalous Single Photon) search at SLAC looked for $e^+e^- \to \gamma X$ final states, where X is any weakly interacting particle. It set a bound of $Q > 0.08e$ for $M_{\text{MCP}} \lesssim 10$ GeV [237, 238]. Data from a proton beam dump experiment, E613, at Fermilab excludes charges between $10^{-1}e$ and $10^{-2}e$ for $M_{\text{MCP}} < 200$ MeV [239]. The results of an electron beam dump experiment at SLAC that looked for trident production $e^-N \to e^-NQ^+Q^-$ were reanalyzed and set a bound of $Q > 0.03e$ for $M_{\text{MCP}} < 1$ GeV [237]. Moreover, the SLAC MilliQ experiment set a bound of $5.8 \times 10^{-4}e$ for $M_{\text{MCP}} < 100$ MeV [234]. In addition to these accelerator-based experiments, the results of a search for orthopositronium decays into invisible particles can be recast into bounds on MCPs. This measurement gives a bound of $Q < 8.6 \times 10^{-5}e$ for $M_{\text{MCP}} < 500$ KeV [240]. Finally, the precise agreement between the measured and calculated values for the Lamb shift can be used to set a bound of $Q < (1/9)M_{\text{MCP}}e$ for $M \gtrsim 3$ KeV [241, 237].

Additional constraints can be placed on MCPs from indirect cosmology and astrophysics results (See [237] and references therein). Photons travelling in a plasma acquire an effective mass and can decay into MCPs. Therefore MCPs produced inside stars can contribute to their cooling. White Dwarfs and Red Giants provide laboratory settings which allow to place bounds on MCPs by requiring that the rate of energy going into MCP production not exceed the rate of nuclear energy production. The limits apply for $M_{\text{MCP}} \lesssim$ KeV.

The constraints from cosmology are discussed in what follows. BBN bounds on the effective relativistic degrees of freedom can be used to set limits on the parameter space of MCPs. WMAP data of the CMB is also an indirect test ground for new invisible states that inject charged particles into the CMB. In addition, requiring that the MCPs relic density not over-close the universe excludes $M_{\rm MCP} \sim$ TeV for $Q \sim e$ charges.

New electron and proton beam dump experiments, planned or proposed to search for light DM, could also cover new parameters space of MCPs, particularly the $M_{\rm MCP} \sim$ GeV region. The primary modes of production are $pN \to pNQ^+Q^-$ or $pp \to Q^+Q^-$ at proton beam dump experiments, and $e^-N \to e^-NQ^+Q^-$ at electron beam dump experiments. MCPs produced at the beam dump would then travel and scatter elastically off of nuclei at a detector situated downstream of the target and able to look for neutral current scattering events. The detection of MCPs relies on an experiment sensitive to low momentum recoil channels, such as electron recoils and/or coherent nuclear scattering, see Sec. 1.4.2.1.

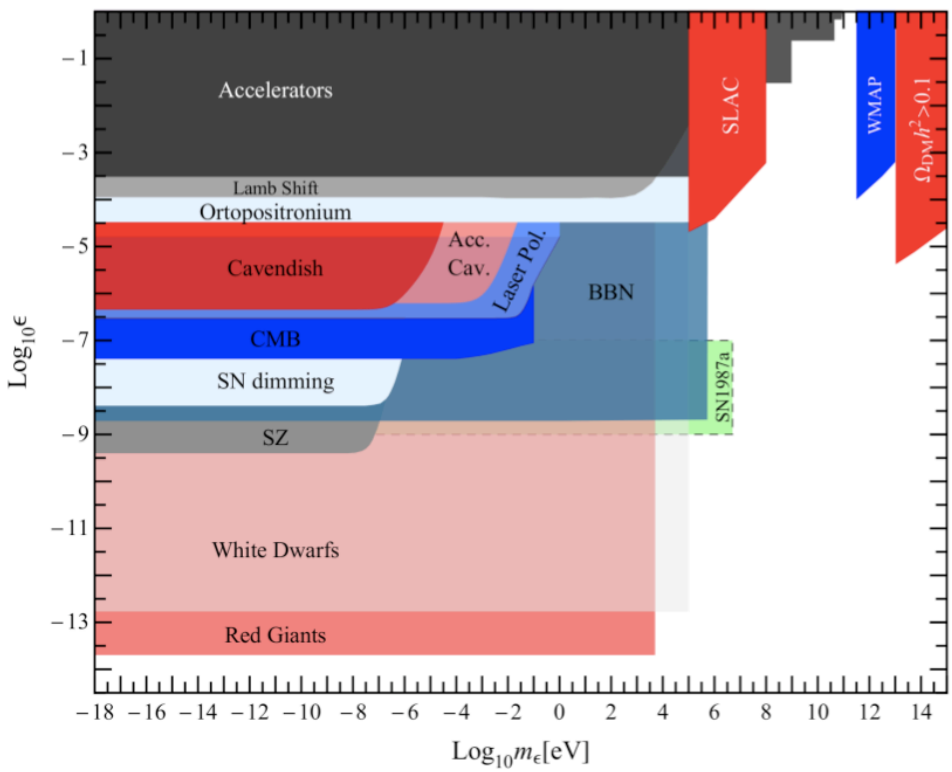

Figure 1-9. *Bounds on the charge ϵ vs millicharged mass m_ϵ parameter space from various experiments.*

1.4.3 Proposed and Future Searches

1.4.3.1 Proton-fixed Target

Proton beam-fixed target-detector setups have significant potential to search for light dark matter and other long-lived dark sector states. An intense source of dark sector states can be produced in the primary proton-target collisions and detected through their scattering [135, 233, 242] or visible decays [135, 136] in a near detector. Of particular importance to this experimental program are the existing and future Fermilab neutrino factories such as MiniBooNE, MINOS, NOνA, MicroBooNE, and LBNE, which have an unprecedented opportunity to search for light dark matter. The studies of Refs. [135, 233, 242] demonstrate the existence of a large dark matter signal in existing neutrino experiments for motivated regions of dark matter parameter space. However, numerous experimental challenges remain to maximize the sensitivity to the dark matter signal, foremost among them competing with the large neutrino neutral current background.

A proposal for a dedicated search for light dark matter at MiniBooNE is described in Ref. [190]. Dark matter particles χ, interacting with the SM through a kinetically mixed dark photon (here denoted as V, with kinetic mixing parameter κ), can be produced through the decays of secondary pseudoscalar mesons, $\pi^0, \eta \to \gamma V$, $V \to \chi\chi^*$. Such dark matter particles can travel to the detector and scatter via V exchange, leaving the signature of a recoiling electron or nucleon. The MiniBooNE sensitivities to dark matter masses of 1, 10, 100 MeV are represented by the green contours in Figure. 1-8.

In order to mitigate the neutrino background Ref. [190] proposed to run in a beam-off target configuration, in which the protons are steered past the target and onto either 1) the permanent iron absorber located at the end of the 50 m decay volume, or 2) a deployed absorber positioned 25 m from the target. A one week test run in the 50 m absorber configuration measured a reduction of the neutrino flux by a factor of 42. Additional improvements in distinguishing χ signal from the neutrino background are possible by exploiting the fine ns-level timing resolution between the detector and proton spill, since heavy $O(100\,\text{MeV})$ dark matter particles will scatter out of time.

The MiniBooNE sensitivity to light dark matter interacting via a dark photon mediator is represented in Figure. nlwcp:fig:invisible-A'. MiniBooNE can probe motivated regions of dark matter parameter space in which the relic density is saturated and the muon anomalous magnetic moment discrepancy is explained. The signal significance for several operational modes is can be found in [190].

The experimental approach to search for light dark matter employed by MiniBooNE is applicable to other neutrino experiments and intense proton sources, such as MINOS, NOνA, MicroBooNE, LBNE and Project X. For instance, the MicroBooNE LAr detector can also perform a search with comparable sensitivity to that outlined for MiniBooNE with a long enough beam-off-target run. More generally, the dark matter mass range that can be covered is governed by the proton beam energy and the production mechanism, as well as the ability to overcome the neutrino neutral current background. For instance with the FNAL Booster (8.9 GeV) and Main Injector (120 GeV) as well as a future Project X, the accessible DM mass range is from a few MeV up to a few GeV.

The search for light dark matter provides an additional physics motivation for intense proton beam facilities. Given the significant investment in existing and future infrastructure for neutrino experiments, it is critical to take advantage of the unique opportunity afforded by these experiments to probe the non-gravitational interactions of light dark matter and more generally explore the possibility of of a dark sector with new light weakly coupled states.

1.4.3.2 B-factories

B-factories like *BABAR* and Belle and future super-B factories like Belle 2 are powerful probes of light dark matter with a light mediator. An existing mono-photon search by *BABAR* [231] already places important constraints on this class of models [243, 192] (see also [244, 127, 119]), and similar search at a future B-factory can probe significantly more parameter space [243]. Such searches are more powerful than searches at other collider or fixed-target facilities for mediator and hidden-sector particle masses between a few hundred MeV

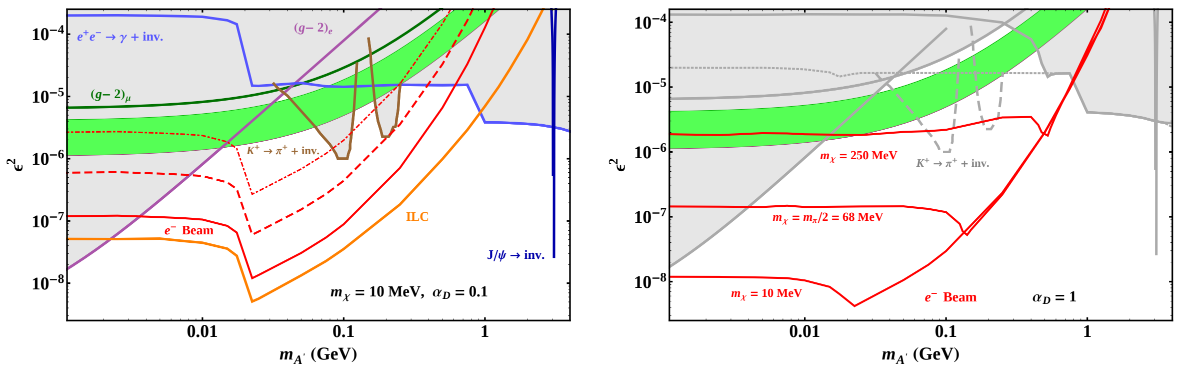

Figure 1-10. *The ϵ^2 sensitivity of electron-beam fixed-target experiments for benchmark values of m_χ. Left: the solid, dashed, and dot-dashed red curves mark the parameter space for which the basic setup — a 12 GeV beam impinging on an aluminum beam dump, with a $1\,\text{m}^3$ mineral oil detector placed $20\,\text{m}$ downstream of the dump — respectively yields 40, 10^3, and $2 \cdot 10^4$ χ-nucleon quasi-elastic scattering events with $Q^2 > (140\ \text{MeV})^2$ per 10^{22} electrons on target. The orange curve shows the 10 event reach for a pulsed ILC style 125 GeV beam using the same detector. Comparable sensitivity can be achieved with much smaller fiducial volumes than we consider, especially for detectors with active muon and neutron shielding and/or veto capabilities. Right: the 40 event yield with a 12 GeV beam for different m_χ. For $2m_\chi > m_\pi$, this parameter space is inaccessible via pion decays to NLWCP at neutrino factories.*

to 10 GeV. Mediators produced on-shell and decaying invisibly to hidden-sector particles such as dark matter can be probed particularly well. Sensitivity to light dark matter produced through an off-shell mediator is more limited, but may be improved with a better theoretical control of backgrounds, allowing background subtraction and a search for kinematic edges. The implementation of a mono-photon trigger at Belle II would be a necessary step towards providing this crucial window into such light hidden sectors.

1.4.3.3 Electron tixed target

Electron beam fixed target experiments enable powerful low-background searches for new light weakly-coupled particles and can operate parasitically at several existing facilities [192]. Electron-nucleus collisions feature a NLWCP production rate comparable to that of neutrino factories, but the production mechanism is analogous to QED bremsstrahlung. Importantly, beam related neutrino and neutron backgrounds are negligible. Electron beam production also features especially forward-peaked NLWCP kinematics, so for multi GeV beam energies, experimental baselines on a 10m scale, and meter-scale detectors, the signal acceptance is of order one for sub-GeV NLWCP masses. This approach is sensitive to any new physics that couples to leptonic currents and is limited only by cosmogenic backgrounds, which are both beatable and systematically reducible; even a test implementation with no cosmogenic neutron reduction (see Fig. 1-10 red dot-dashed curve) offers sensitivity to well motivated regions of parameter space. Previous generations of electron beam experiments, such as the MilliQ experiment at SLAC have already demonstrated sensitivity to NLWCP [191].

The minimal setup requires on a cubic-meter fiducial volume (or smaller) detector sensitive to neutral current scattering placed 10s of meters downstream of an existing electron beam dump. At low momentum transfers, NLWCP scattering predominantly yields elastic electron and coherent nuclear recoils in the detector. At higher momentum transfers, inelastic hadro-production and quasi-elastic nucleon ejection dominate the signal yield. The approach cab offer comparable sensitivity using either continuous wave (CW) or pulsed electron beams, but CW sensitivity is limited by cosmogenic background so background reduction strategies are required to achieve optimal sensitivity; for pulsed beams timing cuts render cosmogenic backgrounds negligible. This approach can be realized parasitically at several existing electron fixed target facilities including SLAC, Jefferson Laboratory, and Mainz. It may also be possible to utilize pulsed beams at the SuperKEK linac beam and (in the future) at the ILC.

Fig. 1-10 (left) shows the senstivity projections for a 1 m^3 detector placed 20 m downstream of an Aluminum beam dump. The dot-dashed, dashed, and solid red curves show yields for $2 \cdot 10^4$, 10^3, and 40 signal events using a 12 GeV CW beam modeled after JLab's CEBAF-12 upgrade. These projections correspond 2σ ϵ sensitivity assuming 0%, 95%, and 99.9% cosmogenic neutron reduction with 0%, 1% and 2.5% systematic uncertainties respectively. The orange curve is the ϵ sensitivity for a pulsed ILC style beam operating at 125 GeV. For comparison with neutral current studies in the at neutrino factories [245], the red and orange curves assume a mineral oil detector with sensitivity only to quasi-elastic nucleon scattering, however, a dedicated study of various detector materials and scattering processes (e.g. electron, coherent-nuclear, and inelastic scattering) can optimize this proof of concept to greatly enhance signal sensitivity and reduce cosmogenic backgrounds.

1.5 Chameleons

1.5.1 Theory & Motivation

Cosmological observations are able to pinpoint with great precision details of the universe on the largest scales, while particle physics experiments probe the nature of matter on the very smallest scales with equally astounding precision. However, these observations have left us with some of the greatest unsolved problems of our time, most notably the remarkable realisation that the most dominant contribution to the energy density of our universe is also the least well understood. Dark energy, credited with the observed accelerated expansion of the universe, makes up around 70% of the total matter budget in the universe however there is no single convincing explanation for this observation nor is there a clear pathway to distinguishing between different models through cosmological observations. If this acceleration is not caused by a cosmological constant then the most convincing explanations come in the form of scalar field models that are phenomenological but with the hope of being effective field theories of ultra-violet physics. If a scalar field is indeed responsible for this observed acceleration it would need to be very light $m \sim H_0$ and evolving still today. These light fields should couple to all forms of matter with a coupling constant set by G_N. A coupling of this kind would cause an as yet unobserved fifth force and should be observable in a plethora of settings from the early universe through big bang nucleosynthesis, structure formation and in all tests of gravity done today. Thus, we are left with a puzzle as to how a scalar field can both be observable as dark energy and yet not be observed to date in all other contexts.

A solution to this puzzle was presented in [246, 247, 248] with so-called chameleon fields. Chameleon fields are a compelling dark energy candidate, as they couple to all Standard Model particles 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 forbidden by some symmetry — 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 [249, 250]. Such a self interaction, in conjunction with a matter coupling, gives the scalar field a large effective mass in regions of high matter density [246, 247]. 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 [248, 251] 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 [252, 253, 254, 255].

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 [256]. 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.*, [257]. Their coupling to photons, combined with their light masses in certain environments, allows chameleons 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. In fact chameleon particles are a natural bridge between the cosmic frontier and the intensity frontier; not only do they hold the possibility of being a dark energy candidate but they are testable through astrophysical and laboratory means.

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 Fig. 1-11. Current constraints (solid regions) and forecasts (curves) are discussed below.

1.5.2 Current laboratory constraints

Laboratory constraints on chameleon dark energy come from two different types of experiments: fifth force searches, and photon coupling experiments, both of which are shown as shaded regions in Figure 1-11. Gravitation-strength fifth forces can be measured directly between two macroscopic objects, such as the source and test masses in a torsion pendulum. Currently the shortest-range torsion pendulum constraints on gravitation-strength forces come from the Eöt-Wash experiment [258]. The source and test masses in

Experiment	Type	Couplings excluded
Eöt-Wash	torsion pendulum	$0.01 \lesssim \beta \lesssim 10$
Lamoreaux	Casimir	$\beta \gtrsim 10^5$ (ϕ^4)
Grenoble	bouncing neutron	$\beta \gtrsim 10^{11}$
GRANIT	bouncing neutron	forecast: $\beta \gtrsim 10^8$
NIST	neutron interferometry	forecast: $\beta \gtrsim 10^7$
CHASE	afterglow	$10^{11} \lesssim \beta_\gamma \lesssim 10^{16}$ subject to $10^4 \lesssim \beta_m \lesssim 10^{13}$,
ADMX	microwave cavity	$m_{\rm eff} = 1.952\ \mu$eV, $10^9 \lesssim \beta_\gamma \lesssim 10^{15}$
CAST	helioscope	forecast: $\beta_m \lesssim 10^9$, $\beta_\gamma > 10^{10}$

Table 1-1. *Laboratory tests of dark energy. Approximate constraints on chameleon models with potential $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$ and $M_\Lambda = 2.4 \times 10^{-3}$ eV (unless otherwise noted).*

Eöt-Wash are parallel metal disks a few centimeters in diameter with matched sets of surface features. As the lower disk is rotated, gravity and any fifth forces induce torques in the upper disk so as to align the surface features. The separation between the disks can be varied, and the torsional oscillations in the upper disk can be compared with predictions. Another type of fifth force experiment uses an ultracold gas of neutrons whose bouncing states in the gravitational field of the Earth are quantized, with energy splittings ~ 1 peV [259]. If the neutrons feel a fifth force from the experimental apparatus comparable to the gravitational force of the Earth, then the energy splittings will be altered. The Grenoble experiment measures these energy splittings at the $\sim 10\%$ level, excluding very strong matter couplings $\beta_m \gtrsim 10^{11}$.

Dark energy may couple to the electroweak sector in addition to matter. Such a coupling would allow photons propagating through a magnetic field to oscillate into particles of dark energy, which can then be trapped inside a chamber if the dark energy effective mass becomes large in the chamber walls. An "afterglow experiment" produces dark energy particles through oscillation and then switches off the photon source, allowing the population of trapped dark energy particles to regenerate photons which may emerge from the chamber as an afterglow. Current afterglow constraints from the CHASE experiment exclude photon couplings $10^{11} \lesssim \beta_\gamma \lesssim 10^{16}$ for $\beta_m \gtrsim 10^4$, as shown in Fig. 1-11 for an inverse-power-law chameleon potential [260, 261, 262]. At yet higher photon couplings the trapped dark energy particles regenerate photons too quickly for CHASE to detect them. However, collider experiments can exclude such models, by constraining chameleon loop corrections to precision electroweak observables [263].

1.5.3 Forecasts for Terrestrial experiments

Proposed experiments promise to improve constraints on chameleon dark energy by orders of magnitude over the next several years. Fig. 1-11 summarizes forecasts and preliminary constraints, shown as solid lines. The next-generation Eöt-Wash experiment, currently under way, will have an increased force sensitivity and probe smaller distances. This will allow it to detect or exclude a large class of chameleon models with well-controlled quantum corrections [264, 265]. Improvements to fifth force measurements using neutrons should improve constraints on the chameleon-matter coupling considerably. Also proposed is a neutron interferometry experiment at NIST, which should be competitive with the bouncing neutron experiments. A neutron interferometer splits a neutron beam and sends the two through two different chambers, one containing a dense gas which suppresses chameleon field perturbations, and the other a vacuum chamber in which scalar field gradients are large. These gradients will retard the neutron beam passing through

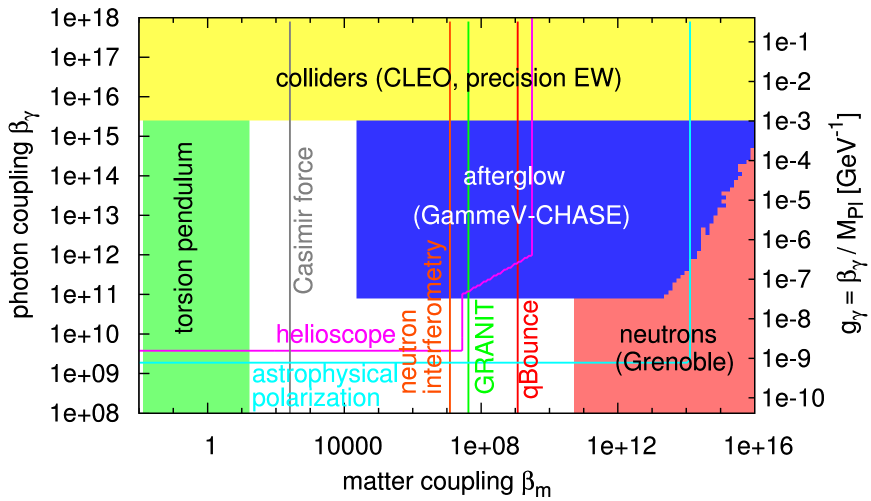

Figure 1-11. *Constraints on the matter and photons couplings for a chameleon dark energy model with $V(\phi) = M_\Lambda^4(1 + M_\Lambda/\phi)$. Current constraints are shown as shaded regions, while forecasts are shown as solid lines.*

the vacuum chamber, resulting in a phase shift which varies nonlinearly with the gas pressure. Potentially more powerful are the next-generation Casimir force experiments [266]. However, these currently suffer from systematic uncertainties including the proper calculation of thermal corrections to the Casimir effect. The forecasts shown require that the total uncertainty in the Casimir force be reduced below 1% at distances of $5 - 10\ \mu$m.

Other planned experiments search for photon-coupled chameleons. Afterglow experiments have been proposed at JLab and the Tore Supra tokamak, while a microwave cavity-based afterglow experiment is under way at Yale. Since forecasts for these experiments are not available for the chameleon potential assumed in Fig. 1-11, we are unable to include them in the figure. However, the JLab and Tore Supra experiments are expected to fill in some of the gap between CHASE and torsion pendulum experiments, while the microwave cavity search is a precision experiment capable of targeting a model with a specific mass in response to hints from an afterglow experiment. Yet another type of experiment is the helioscope, which uses a high magnetic field to regenerate photons from scalar particles produced in the Sun [267]. Since such particles do not need to be trapped prior to detection, helioscope forecasts extend down to arbitrarily low matter couplings. One proposed helioscope adds an X-ray mirror to the CAST axion helioscope at CERN in order to increase its chameleon collecting area; forecasts for this experiment are shown.

1.5.4 Tests of the Chameleon Mechanism by Astrophysical Observation

Complimentary to detector based experiments, chameleons offer a rich phenomenology of unique astrophysical signatures. Combining data from astrophysical observations with laboratory experimental data will allow us to constrain chameleon models. Below we review some of the more intriguing astrophysical signatures predicted in chameleon models. One benefit of observational tests of chameleons is that these observations may be performed complimentarily with observations taken for reasons not related to chameleon gravity. Ordinary matter interacting via a low mass particle ($m \sim H_0$) leading to a new fifth force typically requires a very small coupling. Bounds on any additional fifth force have been set by measuring the frequency shift of photons passing near the Sun from the Cassini satellite on their way to Earth [268].

The screening mechanism from chameleons has significant consequences for the formation of structure. These modifications to structure formation include an earlier collapse of density perturbations compared to the prediction from ΛCDM and clumpier dark matter halos [269]. Another effect on structure formation in chameleon gravity is that the critical density required for collapse depends on the comoving size of the inhomogeneity itself [270]. Also, galactic satellite orbits become modified based on the size of the satellite itself due to a backreaction from the satellite causing a velocity difference of up to 10% near the thin shell [271].

Due to the existence of the two-photon vertex ($\mathcal{L}_{\phi\leftrightarrow\gamma} = F^{\mu\nu}F_{\mu\nu}\phi/4M$), chameleons mix with photons in the presence of a background magnetic field. This mixing is the result of the propagation eigenstates being different from the photon polarization-chameleon eigenstates. The result of this mixing is a non-conservation of photons. In the case of type Ia supernovae, [272] demonstrated that photons convert to chameleons in the interior of the supernova, pass through the surface of the supernova, and than convert back to photons in the intergalactic magnetic field. The net result is an observed brightening of supernovae. This scenario provides an explanation for the discrepancy between distance measurements of standard candles and standard rulers beyond $z \sim 0.5$ [273].

Another prediction of chameleon gravity is that in unscreened environments, (such as voids) stellar structure is modified, most notably in the red giant branch of stars. The authors of [274] found that chameleons affect the size and temperature of red giant stars where they tend to be smaller ($\sim$ 10%), and hotter ($\sim$ 100s of Kelvins). Also, observations of circularly polarized starlight in the wavelength range $1 - 10^3$Å could be a strong indication of chameleon-photon mixing [275].

Astrophysical tests of chameleons in $f(R)$ theories may be parameterized by how efficiently bodies self-screen (χ) and the strength of the fifth force (α) [276]. For the case of chameleon $f(R)$ gravity, $\chi \equiv df/dR$ is measured at present time. The additional force is parametrized by rescaling Newton's constant $G \to G(1+\alpha)$ for unscreened objects and $G(r) \to G[1+\alpha(1-M(r_s)/M(r))]$ for partially screened objects. Fifth forces are screened at radii $r < r_s$, unscreened for radii $r_s < r$, and $M(r)$ is the mass contained within a shell at radius r. For an object to be unscreened, $\Phi_N \ll \chi$ where Φ_N is the Newtonian potential. The Sun and Milky Way (coincidentally) possess a similar gravitational potential: $\Phi_\odot \sim 2 \times 10^{-6}$ and $\Phi_{MW} \sim 10^{-6}$. Stars in the tip of the red giant branch of the HR diagram and Cepheid variables have gravitational potentials $\Phi_N \sim 10^{-7}$. These stars will have their outer layers unscreened provided they reside in smaller galaxies in a shallow gravitational potential. For fifth forces of a strength described by $\alpha = 1/3$, values of χ greater than 5×10^{-7} may be ruled out at 95% confidence. This upper bound is moderately lower for fifth force strength defined by $\alpha = 1$, where values of χ greater than 1×10^{-7} may be ruled out at a 95% confidence level [276] (also see Fig.(5) of [276]). These constraints on χ and α from local universe observations are stronger than current cosmological constraints on chameleon fifth forces [277]-[278] which typically give an upper limit not less than $\chi \sim 10^{-6}$.

1.5.5 Space tests of Gravity

Remarkably, the original predictions of signatures in space for chameleon models would still be the most striking [246, 247]. The proposed experiments discussed there have not yet taken place. However, the MicroSCOPE [279] mission and STE-QUEST [280] are future satellite experiments that hold the promise of testing these theories in a way complementary to the terrestrial and astrophysical methods discussed here.

The expected signatures are large and for example an $\mathcal{O}(1)$ observed difference in Newton's constant for unscreened objects would be a smoking gun for these models.

There is great potential for testing chameleon theories in the laboratory, the sky and through astrophysics ; both at the cosmic and the intensity frontiers. The possibilities for astrophysics are discussed further under the Novel Probes of Dark Energy and Gravity in the Cosmic Frontier.

1.6 Conclusions

Establishing the existence of Hidden Sectors, and the new light weakly-coupled particles they may contain, would revolutionize particle physics at the Copernican level: once again our simple conception of Nature would be fundamentally altered, and here we would realize that there is more than just the Standard Model sector. Searches for hidden sectors are strongly motivated and possible at presently accessible energies with existing technologies. New physics need not reside beyond the TeV scale, but could hide at the low-energy frontier. Axions, invented to solve the strong CP problem, are perfect dark matter candidate. Dark photons, and any hidden-sector particles that they couple to, can be equally compelling dark matter candidates, could resolve outstanding puzzles in particle and astro-particle physics, and may also explain dark matter interactions with the Standard Model. Other hidden sector particles could account for the Dark Energy. Discovery of any of these particles would redefine our worldview.

Existing facilities and technologies, modest experiments, and experimental cleverness enable the exploration of hidden sectors. Searches for new light weakly-coupled particles depend on the tools and techniques of the intensity frontier, i.e. intense beams of photons and charged particles, on technological means of dealing with high intensities, and on extremely sensitive, needle-in-the-haystack detection techniques. A rich, diverse, and low-cost experimental program is already underway that has the potential for one or more game-changing discoveries. Current ideas for extending the searches to smaller couplings and higher masses increase this potential markedly. The US high-energy physics program needs to include such experimental searches, especially when the investment is so modest, the motives so clear, and the payoff could be so spectacular. At present, nearly all the experimental efforts world wide have strong US contributions or significant US leadership, a position that should be maintained.

Axions, ALPS, dark photons, milli-charged particles, and light dark matter are all naturally connected by their hidden sector origins, and by the fact that all these particles couple to the photon, either directly, or through induced couplings generated by kinetic mixing. Microwave cavities and light-shining-through-wallls experiments designed to search for axions and ALPs have been adapted to search for dark photons. So have helioscopes looking for solar axions. A series of beam dump experiments, originally motivated as axion searches, have set important limits on dark photon couplings and masses. More recently, a new series of electron and proton beam dump experiments, the latter capitalizing on existing neutrino detectors and eventually Project X beam intensities, will hunt for the interactions of light dark matter produced in the dump by dark photon decays.

Searches for new, light weakly-coupled particles are, compared to typical contemporary particle physics experiments, small, accessible, hands-on, and personal in a way that is impossible with a 1000-person collaboration. This environment offers ideal educational opportunities for undergraduates, graduate students, and post docs, and revitalizes more experienced physicists too, who are all forced to deal with the full breadth of experimental activities: theory, design, proposal writing and defense, hardware construction and commissioning, software implementation, data taking, and analysis. These experiments have already joined theorists and experimentalists into close collaboration to their and to their field's benefit.

A great deal remains to be done with existing tools and techniques, in searching for QCD axions that could account for the dark matter, in extending searches for dark photons throughout the favored parameter space, and in searching for new hidden-sector particles like light dark matter. Even more will be done with the addition of relatively modest investments in superconducting magnets, more sensitive microwave detection, resonant optical cavities, high rate, highly pixilated silicon detectors, and new higher energy electron accelerators, high intensity proton facilities, and upgraded e^+e^- and pp colliding beam facilities. Modest investments will pay great dividends. The hunt for the hidden sector is on in earnest, and prospects for its future look very bright indeed.

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