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Review

Dark matter studies entrain nuclear physics

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ABSTRACT

We review theoretically well-motivated dark-matter candidates, and pathways to their discovery, in the light of recent results from collider physics, astrophysics, and cosmology. Taken in aggregate, these encourage broader thinking in regards to possible dark-matter candidates — dark-matter need not be made of "WIMPs", *i.e.*, elementary particles with weak-scale masses and interactions. Facilities dedicated to nuclear physics are well-poised to investigate certain non-WIMP models. In parallel to this, developments in observational cosmology permit probes of the relativistic energy density at early epochs and thus provide new ways to constrain dark-matter models, provided nuclear physics inputs are sufficiently well-known. The emerging confluence of accelerator, astrophysical, and cosmological constraints permit searches for dark-matter candidates in a greater range of masses and interaction strengths than heretofore possible.

1. Introduction

A key problem in modern physics is the nature of the dark matter, and many facets of this issue overlap significantly with current theoretical and experimental efforts in nuclear physics. There is no doubt that much of the mass–energy content of the universe is dark and resides in as yet unknown forms. Disjoint astronomical observations provide compelling evidence for the existence of additional, non-luminous matter, or dark matter, in gravitational interactions. The current evidence includes the pattern of acoustic oscillations in the power spectrum of the cosmic microwave background (CMB) [1], the relative strength and shape of the galaxy-distribution power spectrum at large wave numbers [2], as well as observations of long-standing of galactic rotation curves at distances for which little luminous matter is present [3,4]. The cosmological evidence, taken collectively, implies that dark matter comprises some twenty-three percent of the energy density of the universe today, with a precision of a couple of percent [5]. Independent threads of observational evidence show that we live in a dark-dominated universe, with studies of Type Ia supernovae revealing the existence of dark energy [6,7]. The dark sector is diverse in that it separates into distinct dark matter and dark energy components, and the individual components themselves may also be of diverse origin. The complexity of the known universe gives such a possibility appeal, though Occam's razor argues for the simplicity of a single dark-matter component. Indeed, it has been long thought that dark matter could be explained by an as yet undiscovered, massive, weakly interacting elementary particle, a "WIMP", though we cannot currently say whether dark matter is comprised of particles of any sort. Alternatives to the usual cosmological paradigm of dark energy and dark matter appear to have less observational support [8], though observational tests continue [9–11] and are well-motivated as long as particle dark matter remains undiscovered.

A Weakly Interacting Massive Particle (WIMP) is still a leading candidate to comprise the bulk of the dark matter. In part this is because there is a robust prediction of this particle's contribution to the relic energy density based on the mass of the

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particle, its weak interaction cross section, and its attendant well-determined temperature scale at which it would fall out of equilibrium in the early universe. The compatibility of this estimate with the observed energy density in dark matter is the WIMP "miracle". Most known particles, *e.g.*, baryons and leptons, do not obey this relation between cross section, mass, and relic density. Nevertheless, we believe the criterion is more properly regarded as a simple test of whether a particular particle can be a credible candidate for a significant component of the dark matter. WIMPs have other appealing aspects. The lightest supersymmetric particle might well be the WIMP and, as a consequence, WIMPs can have a natural connection to the physics being probed in current collider experiments. Arguably though, the most attractive attribute of WIMPs is that they can be directly detectable. Their expected densities and spatial distributions in the Galaxy combined with their weak interactions position them for detection via several clever technologies. Direct detection searches have not produced a completely compelling signal, though the next generation of detector technologies is poised to push into WIMP mass and cross-section regimes where these particles may yet be found.

Much effort has been invested in devising and testing particle-physics models of dark matter, particularly those connected to the physics of the electroweak scale. The efforts in this direction have been recently and thoroughly reviewed, noting, *e.g.*, Refs. [12–16]. Nevertheless, very recent experimental results and observational measurements suggest important shifts in perspective which this review imbues. The recent discovery of a Higgs particle of 125 GeV in mass [17,18] has immediate implications for models of the weak scale and for would-be dark-matter models as well. Simple models with technicolor are ruled out, and the Higgs mass appears to be uncomfortably heavy for some popular models with minimal weak-scale supersymmetry, note, *e.g.*, Ref. [19]. The limits on the superpartner masses in such models also continue to strengthen, though they can be evaded [20]. Dark-matter candidates in supersymmetry continue to be well-motivated, but the recent experimental results prompt thinking of a broader compass, and models without weak-scale masses and interactions can successfully confront the observed relic density [21]. Paralleling these developments are exciting new opportunities for the study of particle physics from observational cosmology. The advent of precision cosmology and, particularly, the determination of a precise value of the baryon-to-photon ratio η from studies of the cosmic microwave background (CMB), with the promise of a sub-1% precision determination from Planck [22,23], promotes the study of the light element abundances from big-bang nucleosynthesis (BBN) to an exquisite probe of physics beyond the standard model (BSM) of particle physics and of non-standard cosmology [24]. At issue is the possibility of "late" energy injection in the evolving early universe, most plausibly from the decay of weakly-coupled matter, possibly of dark matter or its familiars. Thus strongly-coupled probes of new physics at the LHC act in counterpoint to observational probes of the weakly-coupled cosmos, and an era in which we have powerful, complementary probes of new physics is upon us.

Neutrinos are a known part of the weakly interacting universe, and their interactions as well as intrinsic nature are also probed by BBN constraints – note Ref. [25] for a recent review. Yet the BBN constraints realized from confronting the observed primordial element abundances, mindful of possible contamination from nonprimordial sources, with theoretical predictions are only one of several possibilities. We can also probe the energy density associated with weakly interacting sources directly by measuring the expansion rate of the early universe. In standard big-bang cosmology, the expansion rate is controlled by the Friedmann equation, namely, by the time-evolution of the Hubble constant $H(t) \equiv \dot{a}/a$, where $a(t)$ is the scale factor. We define the instantaneous closure parameter to be $\Omega(t) \equiv 8\pi G\rho(t)/3H^2$, with Newton's gravitational constant G and the energy density $\rho(t)$. Contributions to $\Omega(t)$ can be codified by their scaling behavior in $a(t)$, so that as $t \to -\infty$, the contribution with the highest inverse power in $a(t)$ dominates – consequently, that from relativistic species, or "radiation", dominates the energy budget at the earliest times. Photons, neutrinos, as well as relativistic electrons and positrons can contribute to it. Studies of the CMB at the epoch of photon decoupling can also limit the sum of the neutrino masses $\Sigma_i m_{\nu_i}$ [26], and the comparison of this result to terrestrial studies could reveal new physics, *e.g.*, the existence of sterile neutrinos [27]. Observations of the small and large scale structure of the cosmos are also key probes of dark matter. The various constraints act both to limit non-standard-model neutrino interactions as well as to probe various models of dark matter. The ability to separate the possibilities is under ongoing development; it is possible that new physics in the interactions of known neutrinos could be confused with evidence for dark matter [28]. Nevertheless, hints and signals as to the nature of dark matter can be inferred not only from the interplay of terrestrial and cosmological neutrino mass limits [27], but also from the observed departure from the expected relativistic energy density at the CMB epoch, as well as from a failure to confront the predictions of BBN.

Terrestrial studies of neutrons and nuclei play a key role in the interpretation of these cosmological tests, making the emerging picture of the cosmos from these studies an additional concrete outcome of such measurements. For example, the theoretically predicted light-element abundances from big-bang cosmology rely on measured nuclear reaction cross sections and the neutron lifetime. Despite the maturity of the subject, discussion and measurement of these fundamental quantities continue, in part because the terrestrial cross section measurements have not always been made at the center-of-mass energies relevant to BBN conditions [29]. The ^{4}He/H abundance is ultimately set by the neutron-to-proton ratio in the BBN epoch. This is controlled by the neutron lifetime in the standard model. Interestingly, the ^{4}He yield is particularly sensitive to a possible lepton asymmetry, specifically the electron neutrino and electron antineutrino imbalance, as well as to the relativistic particle energy density. The recent foment over the proper value of the neutron lifetime [30] has yielded a shift in its assessment by the PDG from $\tau_n = 885.7 \pm 0.8$ s to $\tau_n = 880.1 \pm 1.1$ s [31]. This yields a small but appreciable reduction in the ^{4}He/H abundance of $\mathcal{O}(0.001)$, and the resolution of this shift, if not yet observationally practical, is important in principle because behind it could lurk a nonzero lepton asymmetry, namely, in ν_e and $\bar{\nu}_e$—as well as information on the relativistic particle energy density. No method yet exists to probe the lepton asymmetry terrestrially, though the observation of neutrinoless double β-decay would change its interpretation; it would reflect an imbalance in neutrino chirality, rather than a particle–antiparticle asymmetry. Nollett and Holder [32] point out that improved measurements of the D/H abundance could also yield insight on BSM physics and cosmology, but the ^{4}He/H abundance is intrinsically more sensitive to relativistic particle energy density and a lepton asymmetry [25]. Although the D/H yield in BBN is much less sensitive to energy density and new BSM neutrino physics than is that of ^{4}H/H, if the primordial deuterium abundance can be measured accurately enough it could provide insights into, and competitive constraints on, BSM issues [33].

Ongoing cosmological observations can give us fresh insights about dark matter, though we should emphasize all that we know now about its properties, as well as its existence, comes from astrophysics and cosmology. Observations of large-scale structure tell us that dark matter must be stable, or at least metastable, on Gyr time scales. Moreover, dark matter cannot be "hot" at the redshift at which it decouples from matter in the cooling early Universe [34]. Here we use temperature, *i.e.*, whether it is "cold" or "hot" to connote whether its thermal energy makes its non-relativistic or relativistic, respectively, at decoupling. For so-called thermal relics, this criterion selects the mass of the dark candidate as well, so that colder particles are heavier. However, alternative production scenarios can exist, and very light particles can also act as cold dark matter, as in the case of the axion [35]. Finally, dark matter appears to be weakly interacting, so that it appears to lack both electric and color charge, though infinitesimally charged dark matter is not completely excluded. The evidence in broad brush speaks to a universe with cold, collisionless dark matter; this in concert with dark energy as a cosmological constant gives rise to the ΛCDM paradigm.[1] We will, however, be more broad-minded in our description and consider warm, weakly self-interacting dark-matter models as well.

We begin our review in earnest with a more detailed description of what has been established observationally thus far in regards to dark matter, as well as an extended prospectus of what yet may come. We then survey a spectrum of DM models, which we regard as well-motivated because they happen to resolve more problems than simply giving identity to a dark-matter candidate. Enormous effort has been devoted to the study of dark matter and to the construction of models which can describe it. A comprehensive review of this vast literature is beyond the scope of our planned article; rather we select such topics which connect to facilities and expertise which exist in nuclear physics. We consider *supersymmetric* models, whose motivation lie in their connection to the resolution of the hierarchy problem. Such models have been thoroughly reviewed [15], so that we are more concerned with offering an overview of the broader possibilities, supplemented with a discussion of the computation and impact of certain needed hadron matrix elements. We pay particular attention to *hidden sector* models, in which dark matter dynamics are controlled by an internal gauge symmetry. In such models, the stability of dark matter is explained if it carries a hidden conserved charge. The hidden gauge bosons can potentially be probed through precision fixed-target experiments at intermediate energy facilities for nuclear physics, such as at JLab and MAMI, or through refined measurements of the $g-2$ of the muon. We also consider *asymmetric* models, whose motivation lie in their explanation of why the dark-matter and matter relic densities are commensurate in size. We round out our review with a discussion of sterile neutrino models of dark matter, which connect naturally to a relativistic energy density at the photon decoupling epoch in excess of standard-model predictions. We believe that were the existence of light, sterile neutrinos established in terrestrial experiments, a role for sterile neutrinos in the resolution of the dark-matter problem would become more strongly motivated. We note in passing that axion models are a very well-motivated class of models which resolve the strong CP problem, but we eschew detailed discussion of them here, noting that excellent reviews of that topic already exist [14,15]. As appropriate we include limits on dark-matter models from dark-matter direct and indirect detection efforts, noting that the physics reach of single experiments depend on particular astrophysical inputs, as well as assumptions in regards to dark-matter—matter interactions.

2. Dark matter from observations

Observational studies of the large-scale structure of the Universe, in concert with numerical simulations, as well as studies of galaxies and galactic clusters, constrain the nature of dark matter. We summarize these emergent, gross features because viable particle-physics models of dark matter must be compatible with them. In particular, in the context of standard Big-Bang cosmology, whether dark matter is hot or cold, that is, whether it is relativistic or not in the epoch at which it is sufficiently cool to decouple from its interactions with ordinary matter, impacts the formation of large-scale structure after the Big Bang. In the scenario in which dark matter is formed as a thermal relic in the cooling early Universe, this criterion also selects the mass of the candidate particle. If dark matter is cold and collisionless, then galaxy formation proceeds via a hierarchical clustering [37,38], namely, from the merging of small protogalactic clumps on ever larger scales; and this is supported by numerical simulations [36,39]. In contrast, if dark matter is hot, the hierarchy is inverted, so that large protogalactic disks, or "pancakes" [40], form first and then break into clumps [41,34,42]. Galaxies, however, are observed at much larger redshifts than the latter simulations predict [34,42]. Moreover, observations of particular classes of quasar absorption lines, the so-called damped Lyman-α systems, thought to be the evolutionary progenitors of galaxies today, also favor a cold-dark-matter scenario [43,44]. It has also been argued that hot dark matter, *i.e.*, most notably, light, massive neutrinos, cannot explain the galactic rotation curves [45]. However, the cold-dark-matter paradigm also generates significant clumpiness below the Mpc scale, so that a galaxy the size of the Milky Way should host many satellite subhaloes

[1] We note "CDM" is cold dark matter, see Ref. [36].

and indeed many observable satellite galaxies—many more than observed [46–48]. Recent discoveries of very faint Milky Way dwarf galaxies suggest that the problem could be, at least in part, of an observational origin; we refer to Ref. [49] for a review and further discussion. Warm dark matter has also been advocated as a way to alleviate these difficulties [50–52]. Limits on the mass of warm dark matter emerge from the comparison of the observations of the Lyman-α absorption spectrum with numerical simulations [53–57]; the limits depend on the particle considered and the manner in which it is produced [58], yielding, *e.g.*, a candidate mass $M > 12.1$ keV for a nonresonantly produced, thermal energy spectrum sterile neutrino at Bayesian 95% confidence interval [57].

Additional cosmological constraints exist on the mass of a dark-matter particle, in the event that it is produced as a *thermal relic*. If the particles annihilate via the weak interaction, then $\sigma_{ann} v$ is parametrically set by $\mathcal{N}_A G_F^2 M^2$, where G_F is the Fermi constant, $\mathcal{N}_A$ is a dimensionless factor, and we assume $\sigma_{ann} \propto 1/v$. In this case avoiding a dark-matter abundance in excess of the observed relic density bounds M from below. Indeed, under these conditions the mass of the cold dark-matter particle must exceed $\mathcal{O}(2 \text{ GeV})$ to avoid closing the Universe [59–61]. The resulting lower bound on M can be relaxed in different ways. Feng and Kumar [21], *e.g.*, have emphasized that the appearance of G_F in $\sigma_{ann} v$ is simply parametric, that G_F can be replaced with g_{eff}, and that the effective coupling g_{eff} can be small without having the precise numerical value of G_F. Thus if $g_{\text{eff}} > G_F$, the bound on M is weakened. Indeed, such considerations permit dark matter candidates which confront the relic density and big-bang nucleosynthesis constraints successfully but range from the keV to the TeV scale in mass [21,62].

We know other things about dark matter. For example, the consistency of the determinations of the fraction of the energy density of the universe in dark matter today suggest that dark matter must be at least metastable over roughly 10 Gyr time scales, though the anomalies noted at PAMELA [63,64] and Fermi [65] in the positron fraction of cosmic rays for energies in excess of roughly 20 GeV probe the possibility of decaying dark matter today [66]. Moreover, dark-matter self-interactions have been suggested as a way of alleviating some problems with the cold-dark-matter hypothesis at galactic distance scales [67]. However, we also know that dark matter cannot have an appreciable strong [68,69] or electromagnetic [70] charge, so that we can, in zeroth approximation, regard dark matter as collisionless.

The broad features which emerge from this summary are that dark matter is either cold or warm, stable or metastable, and lacks substantial self-interactions, via a strong or electromagnetic charge. Viable dark-matter models must be compatible with these features. However, these constraints do not preclude "secret", non-standard model self-interactions among dark matter particles, and these have been suggested as a way to explain observed Milky Way satellite galaxy morphology [71,72].

3. A prospectus of cosmological constraints

There are exciting new possibilities for the experimental and observational study of light, weakly coupled degrees of freedom, setting up a tightly constrained, nearly over-determined situation where physics beyond the standard model (BSM) may well show itself. Such studies may ultimately point to BSM neutrino interactions or to a modification of standard, big-bang cosmology, but they can also have implications for the nature of the dark sector.

Dark matter and dark energy together comprise some 95% of the closure or critical density. It is possible to determine its fractional components. For example, we know the baryon density from the observations of the ratio of the amplitudes of the acoustic peaks in the cosmic microwave background (CMB) radiation. This measurement corroborates the Big Bang Nucleosynthesis (BBN)-based determination of the baryon density from the deuterium abundance as measured in isotope-shifted hydrogen absorption lines in high redshift gas clouds along lines of sight to Quasi-Stellar Objects (QSOs) [73]. The baryon rest mass contribution to closure is modest, with a fit derived from the WMAP9 CMB data in one case [5] yielding $\Omega_b = 0.0463 \pm 0.0024$. In short, the baryon rest mass contributes about 20% of the non-relativistic dark matter content of the universe today. Neutrinos have small rest masses, and they may contribute a smaller fraction of closure as we will describe.

The total kinetic plus gravitational potential energy of the contents inside an arbitrary two-sphere, co-moving with the expansion in the universe, appears to be very close to zero. Expressed in terms of the fractional contribution to the closure energy density today, Ω_k, this energy is very small, consistent with zero. We note, *e.g.*, that $\Omega_k = -0.001 \pm 0.012$ from CMB data alone [5].

In summary, the universe appears to be flat, *i.e.*, with curvature parameter $k = 0$, to fair precision. This is significant because $k = 0$ is a fixed value in the evolution of the universe, a spacetime symmetry. This condition corresponds to a total mass–energy density always equal to the instantaneous critical value. Total Ω, once set to unity, must always be unity, *regardless of how the microphysics might transform mass–energy in the universe from one form into another*. Put another way, once established, $\Omega = 1$ will persist so long as the microphysics operating in the universe respects a key symmetry condition: at any time the overall spatial distribution of mass–energy must be homogeneous and isotropic.

The significance of this symmetry for the dark sector is at once obvious and profound: there is nothing in gravitation or spacetime physics itself to argue against there being many kinds of particles and other entities carrying mass–energy that contribute to $\Omega = 1$. We already know that there are several components to the dark sector, as we have described. One way that the dark sector is diverse is that it separates into distinct dark matter and dark energy components. Given that the spacetime symmetry implied by $\Omega = 1$ is blind to how the mass–energy is divided up among components, there is nothing to preclude the individual components themselves from being of diverse origin, with many kinds of dark matter and even dark energy. This perspective makes it particularly natural to consider a role for neutrinos in the dark sector, too.

Terrestrial experiments have told us the neutrino mass-squared differences and three (θ_{12}, θ_{23}, θ_{13}) of the parameters in the unitary transformation between neutrino energy (mass) states and the weak interaction (flavor) states [31]. Setting aside *CP*-violating phase(s), we lack only knowledge of the neutrino mass hierarchy, though it is of particular import for astrophysics, both for core collapse supernovae, and for the "measurement" of the neutrino mass through cosmological observations [26]. Future and planned observations promise sensitivity to the sum of neutrino masses at the 0.1 eV scale and smaller [26]; in this regard the prospect of the detection of the weak gravitational lensing of the CMB shows particular promise. Consequently, since the sum of the light neutrino masses should exceed 0.05 eV in the normal mass hierarchy and 0.1 eV in the inverted mass hierarchy such observations should be able to resolve the neutrino mass hierarchy and, in essence, provide a detection of the relic neutrino background. This would be a remarkable discovery, not least for its new window on the dark sector. We know this relic background must be present at the epoch of weak freeze-out in Big Bang Nucleosynthesis (BBN), $T \sim 1$ MeV, else we would not get the agreement that we have between BBN predictions and the observationally-inferred primordial abundances of deuterium and ^{4}He. Nevertheless, the relic density and/or energy spectra of the neutrinos between the BBN epoch and the decoupling of photons at $T_{\rm CMB} \approx 0.2$ eV can be modified by new physics, particularly by particle decay, and observations, not just of $\sum m_\nu \neq 0$, can limit this possibility.

The imprint of a generation of particles which have decayed away can be inferred not only from the interplay of terrestrial and cosmological neutrino mass limits [27], but also from the observed departure from the expected relativistic energy density at the CMB epoch, as well as from a failure to confront the predictions of BBN. For the moment we consider the latter two mechanisms explicitly. The next generation CMB experiments and telescopes will be able to provide relatively precise bounds on the energy density of particles with relativistic kinematics at the epoch ($T_{\rm CMB}$) of photon decoupling. By convention, this "radiation" energy density is parameterized as follows:

$$\rho_{\rm rad} = \left[2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \frac{\pi^2}{30} T_{\rm CMB}^4. \tag{3.1}$$

Standard model physics robustly predicts $N_{\rm eff} \approx 3.046(1)$ [74]. The excess over 3, corresponding to three flavors of neutrinos with black body, Fermi–Dirac-shaped energy spectra, arises from $e^{\pm}$-pair annihilation into out-of-equilibrium neutrino pairs near and during the BBN epoch. It is important to note that $N_{\rm eff}$ parameterizes *all* relativistic energy density at the photon decoupling epoch, not just that contributed specifically by the known active neutrinos. Any measurement of $N_{\rm eff}$ significantly different from 3.046, either lower or higher, signals new physics, either new particle physics, or some deviation in the history of the early universe from that predicted by the standard model.

Current CMB measurements of $N_{\rm eff}$ are not very precise, but consistent with the standard model; they are, nevertheless, tantalizing to some. For example, the South Pole Telescope reports $N_{\rm eff} = 3.71 \pm 0.35$ (quoting $1\,\sigma$ errors) [75], employing both Hubble parameter and Baryon Acoustic Oscillation priors, while WMAP9 reports $N_{\rm eff} = 3.84 \pm 0.40$ [5], and the Atacama Cosmology Telescope collaboration reports $N_{\rm eff} = 2.78 \pm 0.55$ [76]. All of these measurements are consistent with the standard model value within 2σ. The Planck satellite and future CMB polarization observations, by contrast, should give $N_{\rm eff}$ to better than 10% precision [23].[2] This will greatly heighten the prospects that this measurement will be able to constrain or signal new physics. For example, the neutrino reactor anomaly and the Mini-BooNE experiment can be interpreted as implying the existence of a light (mass ~ 1 eV) sterile neutrino or neutrinos with significant vacuum mixing with active neutrino species. Were this interpretation to be correct, it would imply ramifications for $N_{\rm eff}$, in that it would be closer to 4 than to 3, and BBN. And therein lies another way in which new physics is being boxed-in by observations. BBN predictions of light element abundances *also* depend on relativistic energy density, and specifically the energy spectra of ν_e and $\bar{\nu}_e$, all in ways different than, but complementary to the way $N_{\rm eff}$ depends on these quantities. The CMB acoustic peak amplitude ratios have given us a rather precise value of the baryon-to-photon ratio, $\eta \approx 6.11 \times 10^{-10}$, and the Planck mission promises to get this number to $\pm 0.74\%$ or better. This, coupled with the increasingly precise determinations of the primordial deuterium abundance, show us that the basic nuclear and weak interaction physics of BBN are well understood and, in broad brush, operate closely along the lines of what standard cosmology predicts. There are some problems, the ^{7}Li and ^{6}Li yields, for example; and these discrepancies have been argued to be signals of new physics, specifically signaling post-BBN cascade nucleosynthesis stemming from, *e.g.*, super-WIMP decay. However, there may be more prosaic explanations of these issues, and the real clincher may be the primordial helium abundance.

Though linear regression with compact blue galaxies yields a primordial helium abundance with very small statistical errors, some believe that there could be significant systematic errors in this approach. Thus, right now, for example, the linear regression-inferred helium abundance on its own is not widely viewed as ruling out a light sterile neutrino. However, the next generation of CMB experiments will be able to infer the primordial ^{4}He abundance from the Silk damping tail on the CMB power spectrum. In essence, the more baryons that are locked up in alpha particles as neutrons, the fewer electrons there will be, and the longer will be the photon mean free path at the CMB decoupling epoch—it is this quantity to which

2 The Planck cosmic microwave background collaboration [77] has just reported their first results. For example, they describe one analysis, done using their high wave number data, the WMAP polarization data, and BAO data, that yields $N_{\rm eff} = 3.30^{+0.54}_{-0.51}$ at 95 percent confidence. We note that $N_{\rm eff}$ is positively correlated with the Hubble constant H_0, and the existing tension between the Planck results and direct determinations of H_0 can be alleviated with a larger value of $N_{\rm eff}$.

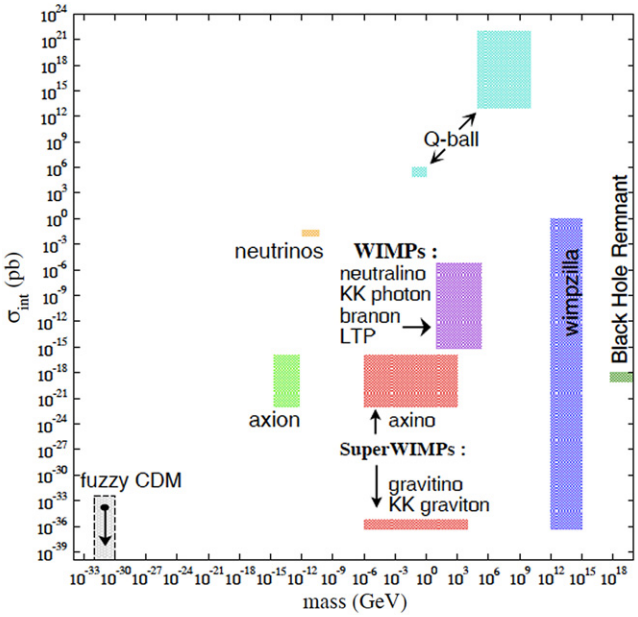

Fig. 1. Estimated loci of select dark-matter models in the space of candidate mass in GeV versus dark-matter–candidate-nucleon interaction cross section in pb.
Source: Figure taken from Ref. [83].

the CMB measurements are sensitive. CMB-Pol may be able to measure the primordial helium abundance to better than 2%. The situation is not perfect because, for example, the primordial helium abundance and $N_{\rm eff}$ are somewhat degenerate. Nevertheless, the prospects for precise helium and $N_{\rm eff}$ constraints are tantalizing.

Should there be evidence for light sterile neutrinos which stands up against, or shows itself in these new cosmological observations, the prospects that sterile neutrinos play a role in dark matter will be increased in the eyes of many. Likewise, decaying massive particles invoked to satisfy current collider constraints, or invoked for lithium production and tied to WIMP dark matter, may possibly leave telltale evidence that could be ferreted out with these observations.

4. Dark matter models

The standard model leaves many questions unanswered: it explains, *e.g.*, neither why the weak scale has the value it has, nor the baroque pattern of fermion masses and mixings seen in Nature, nor the size of the observed baryon asymmetry of the Universe (BAU). Most notably, in our current context, it fails to explain dark matter.

At the same time, the interpretation of astrophysical observations tells us that the needed dark matter candidate(s) must be either cold or warm, stable or metastable, and collisionless, to the extent that the bulk of it ought not have substantial strong or electromagnetic charge. It is challenging to devise a dark-matter model which is consistent with all its known features, particularly if one hopes the candidate to be discoverable albeit not yet discovered. The space of possibilities run the gamut in terms of possible masses and interaction cross sections with nucleons, and a sampling of the possibilities is shown in Fig. 1. Many more possibilities exist, and the field continues to evolve and produce new ones. We regard any model which can explain any of the observed dark-matter features and/or answer any additional question unanswered in the standard model as well-motivated and hence of interest, though we consider only a small fraction of the possibilities.

We note in passing that contributions to the non-luminous halo of our own Milky Way galaxy could come from still more massive, compact objects. Such lumps could be of conventional matter and include faded white dwarfs, brown dwarfs, black holes, and neutron stars—they are termed collectively ''Massive Astrophysical Compact Halo Objects'' or MACHOs. Their existence in the galactic halo has been probed primarily through searches for gravitational microlensing events associated with the stars in the Large Magellanic Cloud [78–81]. Nonobservation of such events beyond expectation exclude MACHOs of mass ranging from $0.6 \times 10^{-7} M_\odot < M < 15 M_\odot$ [80,81] at 95% CL, noting $M_\odot$ is the solar mass, as the dominant component of dark matter in our galactic halo [78–81]. Moreover, we should point out that the gravitational microlensing technique can be combined with Kepler results to search for primordial black hole dark matter in a black hole mass regime, such as that of planetary masses, not yet ruled out by other observations [82].

Although many dark-matter models possess candidates which can be produced directly at colliders, we believe that the definite resolution of the dark-matter problem in terms of a candidate from particle physics will require detection of that particle as a constituent of dark matter at the solar circle in a terrestrial experiment. Therefore we consider the notion of dark-matter direct – and indirect – detection more generally before turning to specific dark-matter models.

Candidates with weak-scale masses which couple to nuclei via weak neutral currents, or WIMPs, can be discovered through searches for nuclear recoil events from the aftermath of dark-matter–nucleus scattering [84,85]. We note, parenthetically, that candidates with sub-eV masses [86,87], as well as warm-dark-matter candidates [88,89], can be detected directly through laser experiments. The interpretation of an anomalous-nuclear-recoil experiment in terms of WIMP parameters contains three ingredients: (i) the assumed dark-matter–nucleon interaction, (ii) the dark-matter number density and velocity distribution at the solar circle, and (iii) the computation of the relevant nucleon matrix element of the appropriate current, or, more precisely, of the nuclear response it engenders. It has long been recognized that non-WIMP models can also be constrained through such experiments, noting, *e.g.*, Ref. [90], and recently model-independent frameworks for (i) in the context of elastic dark-matter–nucleus scattering have been devised using effective-field-theory techniques [91,92]. At fixed order in an expansion in momentum transfer different interactions – and nuclear responses – are possible [92,93]. This freedom is insufficient in itself to render inconsistent experimental results compatible with each other [93] albeit differing astrophysical input (ii) also relaxes such tensions [94].

As for (ii), assumptions about the dark-matter mass density and velocity distribution are invariably necessary because, unfortunately, the local dark-matter distribution function is not known. Observational bounds on the dark-matter mass density ρ_χ, *e.g.*, in our own solar system are poor and exceed the estimates typically employed by orders of magnitude [95,96]. Nevertheless, more direct-detection data and experiments should help constrain the distribution function once a signal is seen [97–101]. In the canonical model employed in the analysis of direct detection experiments, one assumes that the dark matter in the Milky Way resides in a non-rotating halo and that the velocity distribution $f(v)$ in that halo is that of an isothermal sphere [102]. The form of f is thus that of a Maxwell–Boltzmann distribution centered on v_0 truncated by the Galactic escape speed $v_{\rm esc}$, noting $\rho_\chi = 0.3$ GeV/cm^3, $v_0 = 220$ km/s, and $v_{\rm esc} = 544$ km/s as employed, *e.g.*, in Ref. [103]. We note that known astrophysical effects prompt several refinements [104]. The formation of the Milky Way halo has also been studied in the context of high-quality *N*-body simulations, which follow the accretion history of dark-matter clumps over billions of years: early mergers yield a smooth halo, but more recent mergers leave relic substructures, or subhaloes [105,106], and accretions of these clumps on the early galactic disk can bring additional complexities [107–109]. Tidal stripping of dark matter from subhaloes yields cold tidal streams and "debris flows" [110,111], so that simulations reveal a richly complex origin to dark matter at the solar circle, which, in turn, can impact direct detection experiments [112]. Turning to observations, the existence of the Sagittarius stellar stream, produced by the disruption and absorption of the Sagittarius dwarf galaxy by the Milky Way, could impact the determination of the local dark-matter density and its annual modulation; we refer to Ref. [113] for a discussion of the possibilities. Recently, the role of the Sagittarius impact has been revisited in detailed *N*-body simulations [114,115], and a effect on local dark matter has been found [115]. The effect could also drive the vertical wave recently observed in the number counts of the local stars, signaling a departure from vertical equilibrium [116], a connection itself supported by a numerical simulation [117]. Further observational studies of the local stars should help clarify the dark-matter distribution function at the Earth's location. In the next section we consider the role of (iii) in the context of supersymmetric models.

Dark matter can also be probed indirectly through the contribution of its decay and annihilation products to the budget of observed gamma and cosmic rays [118,119]. Generally the interpretation of such studies in favor of the presence of dark matter requires an understanding of the high-energy ejecta from conventional astrophysical sources [120]. Two-body annihilation, however, yields a monoenergetic line and thus is nominally background-free; the discovery of such lines would be experimentally challenging, though possible [121]. The dark-matter distribution, particularly the appearance of a dark disk, can also impact the annihilation rates [107,122], as well as the morphology of the signal [108]. In recent years there has been much excitement over the discovery of excess gamma-ray or photon emission in various contexts, driven by the interpretation of such as signals of dark matter, be it, *e.g.*, in the Galactic center [123,124], in bubbles extending from the Galactic center [125], or in the WMAP-Planck haze [126]. In all the cases considered thus far, emission from conventional astrophysical sources, particularly milli-second pulsars [124,127], could mimic the effects observed. It is worth noting that the angular distribution of the diffuse gamma-ray background can put constraints on, or even suggest a detection, of dark matter annihilation [128].

We note in passing that indirect limits on dark-matter can also be realized in terrestrial experiments, through collider studies [129], as well as through tests of the equivalence principle [130]. Torsion-balance experiments, both with and without spin-dependence, limit novel long-range forces [131], which can be interpreted in a model-independent way [132], or as limits on particular models, such as axion models [133].

We now review particular dark-matter models, starting with models with weak-scale supersymmetry.

5. Supersymmetric models

Models with weak-scale supersymmetry appeal for many reasons: (i) they can resolve the hierarchy problem, making the weak scale stable under electroweak radiative corrections and thus technically "natural", in a manner consistent with precision electroweak measurements, (ii) they provide all the ingredients needed for successful electroweak baryogenesis, (iii) they can provide a suitable dark-matter candidate, and (iv) they allow gauge coupling unification, at very high energy scales, to occur. A variety of theories fall under the aegis of weak-scale supersymmetry, and the minimally supersymmetric standard model (MSSM) is a particularly popular variant. A particularly attractive feature of the MSSM is its ability to draw together many issues in cosmology and particle physics [134]; it also has the ability to generate electroweak symmetry

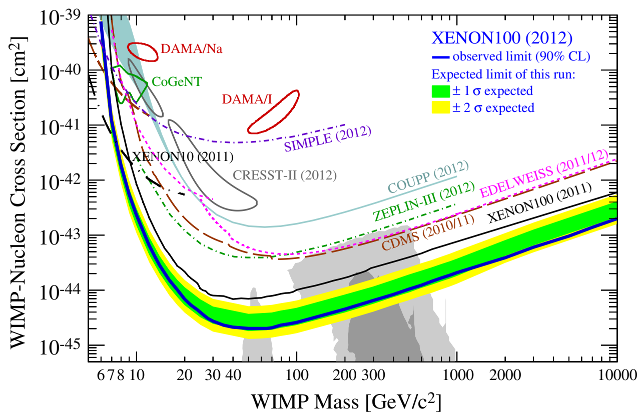

Fig. 2. Constraints on the spin-independent WIMP–nucleon scattering cross section as a function of WIMP mass. The 90% exclusion limit from the XENON100 (2012) experiment is shown in blue, as well as their expected sensitivities at 1σ (green) and 2σ (yellow) [103]. Recent experimental results from the CDMS, CoGenT, COUPP, CRESST-II, EDELWEISS, SIMPLE, and ZEPLIN-II collaborations are also shown, as are the results from the DAMA, XENON10, and XENON100 (2011) experiments. The regions at 1σ and 2σ preferred in particular (CMSSM) supersymmetric models are shown as well; we refer the reader to Ref. [103] for all details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) *Source:* Figure reprinted with permission from the online supplemental material of Ref. [103].

breaking radiatively, in contrast to the standard model in which it is put in by hand. Nevertheless, the MSSM has flavor and CP problems in that the flavor-violating (*e.g.*, an enhanced $B_s \to \mu^+\mu^-$ rate) and CP-violating (*e.g.*, a non-zero permanent electric dipole moment of ^{199}Hg) effects it induces in low-energy observables have not been observed to occur, and direct searches for superpartner masses have also yielded null results thus far. The null results are interconnected in that the low-energy problems can be remediated by simply making the superpartners more massive, note, *e.g.*, Ref. [135], but this also makes the weak scale less natural. We refer to Ref. [136] for a review of the current status of naturalness and supersymmetry.

It has been long thought that the dominant component of dark-matter is a WIMP, and the MSSM offers a candidate in the form of the neutralino [137].[3] It is worth noting that the dark-matter stability requirement is challenging: it requires the imposition of an additional discrete symmetry, termed "*R*-parity" [141,142]. As we have noted, an appealing aspect of such a dark-matter candidate is that it is amenable to direct detection through searches for anomalous elastic scattering events from nuclei, where we refer to Fig. 2 for a succinct summary of the current results. The exclusion limits have nearly reached the 10^{-45} cm^2 scale, which is 10^{-9} pb – a quick check of Fig. 1 shows that we have eliminated at best half of the expected WIMP parameter space.[4] The loci of points in shaded gray indicate the phenomenologically acceptable parameter space associated with a particular variant of the MSSM with far fewer free parameters: the CMSSM. As one observes, it is "easy" to build models without an appreciable direct detection signature, and that is not the least of it. We do not know the mechanism of supersymmetry breaking, and the MSSM reflects that ignorance through the appearance of free parameters which characterize "soft" supersymmetry breaking – there are an unwieldy number, some 150 in all, and there are also neutrino parameters to consider. In making assumptions to limit the parameter space, we may fail to appreciate the scope of possibilities within the theory [145]. For example, it is possible to arrange neutralinos which are much lighter than the weak scale in mass, and, indeed, they are not massless simply because cosmology bounds their mass from below [146–148]. It is also possible to arrange supersymmetric models with multi-component dark matter, such as a WIMP with a particle akin to a sterile neutrino [149]. Moreover, it is possible to arrange supersymmetric models in which the lightest supersymmetric particle is a gravitino, through mechanisms in which flavor physics problems are absent. We note that very light gravitino candidates can connect to $N_{\rm eff}$, but only if they are not thermal relics [150]. The sweep of possibilities in regards to supersymmetric dark matter is vast, and it may prove immensely challenging in this context to falsify supersymmetry as a phenomenological construct.

The direct detection of dark matter entwines astro-, particle, and nuclear physics, and as a final topic we examine, recalling (iii) of the previous section, the computation of the hadronic matrix elements germane to WIMP–nucleon scattering. In nuclear physics, the decipherment of the flavor and spin structure of the proton and neutron is a topic of ongoing intense interest, and it also has broad implications for the search for physics BSM [151,152]. In our current context, the strange-quark structure of the nucleon impacts the interpretation of experiments which hunt for WIMP dark matter in that it impacts the mapping of the loci of supersymmetric parameter space to the exclusion plot of WIMP mass versus the WIMP–nucleon cross section, as per Fig. 2. The spin-independent neutralino–nucleon cross section is particularly sensitive to the strange scalar density, namely, the value of $y = 2\langle N|\bar{s}s|N\rangle/\langle N|\bar{u}u + \bar{d}d|N\rangle$ [153], because the neutralino coupling increases with quark mass; accordingly, the spin-dependent neutralino–nucleon cross section is sensitive to the strange

3 Other models, such as models with universal extra dimensions [138,139] and branon models [140], also offer WIMP dark-matter candidates.

4 We refer to Refs. [143,144] for WIMP exclusion limits from indirect detection experiments.

quark axial vector matrix element, a topic of intense interest for many years in nuclear physics [154]. Here we focus on the spin-independent case in order to interpret Fig. 2. Earlier studies relate y to the πN sigma term $\Sigma_{\pi N}$ via $y = 1 - \sigma_0/\Sigma_{\pi N}$ for fixed $\sigma_0 \equiv m_l \langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$ [153], with $m_l \equiv (m_u + m_d)/2$, so that the predicted neutralino–nucleon cross section would seem to depend strongly on the phenomenological value of the $\Sigma_{\pi N}$ term [155], for which there is a spread of determined values [156]. However, $m_s\langle N|\bar{s}s|N\rangle$ and $\Sigma_{\pi N} \equiv m_l\langle N|\bar{u}u + \bar{d}d|N\rangle$ can be computed directly in lattice QCD, via different techniques, and the final neutralino–nucleon cross section is not nearly as sensitive to $\Sigma_{\pi N}$ as earlier thought [155]. Several lattice QCD groups have addressed this problem and new results continue to emerge [157]; we refer to Ref. [156] for a recent review. The outcome of this body of work is that the spin-independent WIMP–nucleon cross section can be predicted to much better precision than previously thought, though the cross section tends to be smaller than that previously assumed [155], diminishing the new physics reach of a particular WIMP direct detection experiment. The allowed CMSSM parameter space of Fig. 2 does not seem to incorporate these updates [156], so that the constraints on the CMSSM parameter space may not be as strong as had been thought [103]. Heavier quark flavors can also play a significant role in mediating the gluon coupling to the Higgs, and hence to the neutralino, and the leading contribution in the heavy-quark limit is well-known [158,137]—and this treatment should describe elastic scattering sufficiently well. Recently, interpreting the conflicting tangle of possible dark-matter signatures has led to the suggestion of composite dark-matter candidates [159,160]; here the intrinsic heavy quarks could play a more interesting role in mediating transitions to excited dark-matter states in scattering experiments [152]. We note in passing that WIMP–nucleon [161] and WIMP-nucleus [162,163] scattering have also been studied in effective-field theory.

Developing experimental and observational tensions with the predictions of supersymmetric models encourage broader thinking in regards to the composition of dark-matter, and we consider some well-motivated alternatives in the sections to follow.

6. Hidden sector models

If dark matter is not made of WIMPs, its stability need not be guaranteed by a discrete symmetry, and its relic density need not be fixed by thermal freezeout. These features could potentially be explained in very different ways. What mechanisms, then, could be operative?

- Its stability could be guaranteed by a hidden gauge symmetry.
- Its relic density could be related to the baryon asymmetry. If so, dark matter ought be *asymmetric*.

In this section we begin with the first possibility: models which possess a hidden gauge symmetry. We note that models which simultaneously explain dark matter and the baryon asymmetry invariably possess hidden gauge symmetries as well [164], though we reserve discussion of such models for the moment.

The study of hidden-sector models has gained impetus from hints of new physics in indirect detection experiments. The PAMELA experiment, *e.g.*, can detect charged particles, *i.e.*, e^-, e^+, p, and $\bar{p}$, from space, and observes excess events in the ratio of e^+ to e^- final states but no anomalies in the ratio of $\bar{p}$ to p final states [165,63,64]. Such a pattern, if from dark matter, would not easily arise in a supersymmetric model; rather, these results can be taken to suggest that dark matter has preferential couplings to leptons [166]. Taken in concert with the results from the DAMA experiment, the results promote the notion that the dark-matter candidate has internal structure [160], which is also suggestive of a hidden gauge symmetry. The cosmic ray excess in leptons can also be explained if dark matter annihilates into an intermediate state lighter than the proton in mass [167], which can be arranged in models with a hidden-sector gauge symmetry [168–170]. The excesses found by PAMELA are supported other experiments, such as FERMI [65], though an explanation may ultimately be found to derive from conventional astrophysical sources. We note that the AMS experiment has the capacity to study the cosmic ray spectrum at yet higher energies, where presumably conventional sources play less of a role. We regard the existing results as evocative of the possibilities, and a hidden sector operating under a $U(1)$ gauge symmetry is merely the simplest among them. Interestingly the narrow value of the determined Higgs mass and a possible vacuum stability problem can also point to the existence of new $U(1)$ interactions [171], and this possibility is under evaluation [171,172]. In what follows we organize our discussion in terms of the manner in which hidden degrees of freedom could connect to the particles of the standard model, for that predicates their detectability. Note that models which couple to the hidden sector through a Higgs portal have also been considered [173–180], though we do not discuss them.

Hermetic Models are those in which the dark sector is blind to all standard model gauge interactions. Yet even in such cases observational constraints can be made. Suppose, *e.g.*, an exact $U(1)$ symmetry operates in the hidden sector [62,181]—a dark electromagnetism. Dark matter would then carry a hidden charge and be stable just as the electron is stable. An explicit example of such a model with a hidden MSSM-like sector is considered in Ref. [181], so that the putative dark-matter has both hidden weak and electromagnetic interactions. Such a model can have the right dark-matter relic density and yield cold dark matter, and can generally be cosmologically indistinguishable from usual WIMP models. Dark matter in this model is significantly self-interacting, however, with long-range forces. This makes it subject to observational constraints, most notably the self-interaction constraint from observations of the Bullet Cluster and the observed ellipticity of dark-matter halos, as kinetic energy transfer through dark-matter elastic scattering would tend to isotropize the mass distribution [181,182]. Such considerations give constraints on the hidden fine-structure constant α_χ as a function of candidate mass

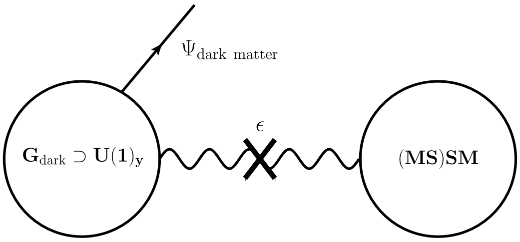

Fig. 3. A non-abelian dark sector can contain an abelian ideal, which permits kinetic mixing with the gauge bosons of the standard model, or MSSM, through a marginal operator.
Source: Illustration reprinted with permission from Ref. [183].

M_χ, yielding, *e.g.*, $\alpha_\chi < 10^{-7}$ for $M_\chi \sim 1$ GeV [181]. Self-interaction constraints from halo morphology have recently been revisited, and some argue that *evidence* exists for self-interacting dark matter [71,72].

Models with Abelian Connectors are inspired, in part, by the astrophysical anomalies we have described, though broader possibilities also exist, which are not tied to such signals. *E.g.*, a hidden sector electromagnetism with a "paraphoton", which mixes with the photon through kinetic mixing, is an idea of long standing [184,185]. It is also amenable to experimental test, perhaps most notably through searches for "light shining through walls" [14] – tests which are also possible at the FEL at JLab [186]. This also has consequences for dark matter, in that if the hidden gauge mediator is massless, although this is not a necessary condition [187], dark matter can have a *millicharge* [185]. Consequently these ideas are also tested through millicharged particle searches. Interestingly, if we determine that dark matter has a nonzero millicharge εe, no matter how small, we establish that dark matter is stable by dint of a gauge symmetry – it cannot decay and conserve its electric charge. We refer to Ref. [188] for a comprehensive review. We note that a direct limit on the dark-matter (milli)electric-charge-to-mass ratio can be realized from the time delay of radio afterglows from gamma-ray bursts, yielding $|\varepsilon|/M < 1 \times 10^{-5}$ eV^{-1} at 95% CL [189]. This limit can be enormously bettered if "prompt" radio afterglows can be detected at extremely low frequencies, such as possible at LOFAR [190]. Millicharged matter limits also follow from the nonobservation of the effects of millicharged particle production, and these typically prove to yield the best limits. The strongest such bound from laboratory experiments is $|\varepsilon| < 3$–4×10^{-7} for $M \le 0.05$ eV [191], so that for $M \sim 0.05$ eV the limits are crudely comparable. Indirect limits also emerge from stellar evolution constraints, for which the strongest is $|\varepsilon| < 2 \times 10^{-14}$ for $M < 5$ keV [188], as well as from the manner in which numerical simulations of galactic structure confront observations [70,181,182]. Such limits can be evaded; in some models, the dynamics which gives rise to millicharged matter are not operative at stellar temperatures [192]; other models evade the galactic structure constraints [193].

We now turn to the models spurred by the intriguing astrophysical anomalies we have noted. The visible and hidden sectors are connected through the kinetic mixing of the gauge bosons of their respective $U(1)$ symmetries, notably through a standard model hypercharge $U(1)_Y$ portal [184,168,183,194,195].[5] We refer to Fig. 3 for an illustration; it is worth noting that $G_{\rm dark}$ can be a rich choice; the hidden sector could be, e.g., MSSM-like, as in the model of Ref. [181]. Constraints on long-range interactions between dark-matter particles are sufficiently severe [67,182,181] that in the models we consider the dark gauge symmetries are also broken through a dark Higgs sector, note, *e.g.*, Ref. [183], giving a mass to the hidden gauge boson—and dark matter no longer has a millicharge. If we suppose A' is the gauge field of a massive dark $U(1)'$ gauge group, then the standard model Lagrangian $\mathcal{L}_{SM}$ is enlarged to [195]

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon_Y}{2} F^{Y,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F^{\prime,\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}, \tag{6.2}$$

where, *e.g.*, $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$. Moving from the gauge to mass eigenstate basis, we can redefine the photon and paraphoton fields so that the kinetic mixing term disappears, namely via $A_\mu \to \tilde{A}_\mu = A'_\mu - \epsilon A'_\mu$, with $\epsilon \equiv \varepsilon_Y \cos\theta_W$; and we discover that A'_μ couples slightly to the electromagnetic current. It couples to the Z_μ as well, but this effect is suppressed by a factor of $m_{A'}^2/m_Z^2$ [183,195]. Since the kinetic mixing term is of mass dimension 4 it can be thought of as a UV boundary condition; equivalently, one notes there is no energy at which it must cease to be valid. If heavy particles exist which are charged under both $U(1)$ groups, an estimate of ϵ follows from the computation of the associated loop-induced effect, indicating that ϵ is no greater than $\mathcal{O}(10^{-2})$; moreover, if the $U(1)$ symmetry-breaking effects are connected to the weak scale, such effects reveal that the A' can range from the MeV- to GeV-scale in mass.

An appealing feature of the A' is that it can be discovered in fixed-target experiments at nuclear-physics facilities; we note an illustration of how it may do so in Fig. 4. Constraints on the A' follow from searches for fractionally charged particles in beam dump experiments, from studies of meson decays, and from measurements of the anomalous magnetic moment of the electric and muon [197,198]—we refer to Ref. [195] for a comprehensive study. Fig. 5 illustrates the existing limits on the mass of the A' and its hidden fine-structure constant $\alpha' \equiv \varepsilon^2/4\pi$, as well as the constraints which can emerge from future experimental studies at JLab, MAMI, and Novosibirsk.

[5] The consistency of these ideas with quantum gravity and string theory has been discussed in Ref. [196].

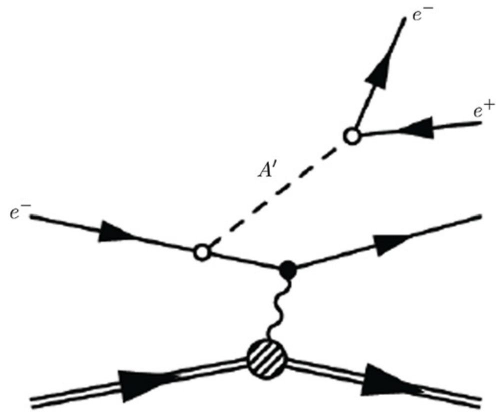

Fig. 4. An illustration of the manner in which a hidden gauge boson A'^{μ} can participate in a fixed-target experiment.
Source: Figure reprinted with permission from Ref. [212].

Models with non-Abelian Connectors are those in which the connection between the hidden and visible sector is through a non-Abelian portal. The notion of a hidden sector of strongly coupled matter is of some standing [199,200], and has more recently been discussed in the context of models which provide a common origin to baryons and dark matter [201,202], though the mechanism need not be realized through strong dynamics [203,204]—we note Ref. [164] for a recent review. We consider a non-Abelian portal [205], mediated, *e.g.*, by heavy scalars Φ which transform under the adjoint representation of the non-Abelian group SU(3); such an interaction can also be realized through kinetic mixing, generalizing from Ref. [183], through $\mathrm{tr}(\Phi F_{\mu\nu})\mathrm{tr}(\tilde{\Phi}\tilde{F}^{\mu\nu})$, as well as $\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}(\Phi F_{\mu\nu})\mathrm{tr}(\tilde{\Phi}\tilde{F}_{\rho\sigma})$, where $F^{a\,\mu\nu}$ is the standard model $\mathrm{SU}(3)_c$ field strength, and $\tilde{\Phi}^a$ and $\tilde{F}^{a\,\mu\nu}$ are fields and field strengths of a hidden strongly-coupled sector, nominally based on $\mathrm{SU}(3)_{\tilde{c}}$. We anticipate that the dark matter candidate is a composite particle and a color singlet, so that there are no dark long-range forces to negate. The connector is not a marginal operator, so that the model does not have a clear UV completion – it represents an effective theory. We note that the appearance of QCD-like couplings should make it more important in the infrared. At low energies the physics of confinement prompt the use of the hidden-local-symmetry model of QCD: the ρ meson emerges as its dynamical gauge boson. Thus the coupling of visible and hidden sectors can be modeled in terms of a kinetic mixing model with two massive gauge bosons – a ρ and ρ', both with isospin 1. The appearance of the ρ' is hidden under hadronization uncertainties, but one can hope to detect its presence through its possible CP-violating effects, as through the study of pseudo-T-odd momentum correlations in radiative β decay of neutrons and nuclei [205,206], which can be studied at existing and future radioactive beam facilities. More generally we can think of the ρ' as a mediator in realizing a difference in the radiative n and $\bar{n}$ β decay rates, motivating a measurement of the $\bar{n}$ lifetime. If there were a $U(1)_Y$ portal as well, we would have a composite dark-matter candidate with a magnetic moment, which could be detected through its elastic scattering from nuclei [207] or through a laser experiment, such as through detection of a magnetic Faraday effect [89].

These discussions naturally lead us to our final topic: of *asymmetric* dark matter, in which baryons and dark matter share a common origin. A key take-away message of the observations is that the baryonic rest mass contribution to closure is roughly 20% of the overall dark matter contribution. This is not a small fraction, and its magnitude begs the question of why, *e.g.*, the baryon and CDM contributions to closure are so close in size. In these models dark matter is a fermion, and thus it possesses its own particle *asymmetry*, which can discovered through a measurement of a non-zero magnetic Faraday effect [88,89]. For detailed models we simply note the review of Ref. [164]. From the viewpoint of low-energy physics, it is worth noting that interesting features such as dark-matter particle–antiparticle oscillations can appear in such models [208,209]. Moreover, considerations of stellar evolution and neutron star stability can also constrain asymmetric dark matter models [210,211].

7. Sterile neutrinos

The advances in experimental neutrino physics in the last decade have been unprecedented. The laboratory measurements have given us the neutrino mass-squared differences and three (θ_{12}, θ_{23}, θ_{13}) of the four parameters which characterize the unitary transformation between neutrino energy states ("mass" states) and the weak interaction eigenstates (flavor states) in vacuum. All we are missing is the fourth parameter, the CP-violating phase, though we note that there are potentially also additional Majorana CP phases. Of course we are also ignorant of the actual vacuum neutrino mass eigenvalues and the way these are ordered, *i.e.*, the neutrino mass hierarchy.

However, even absent this missing information there are two overwhelming standout features of the experimental results: the neutrinos have rest masses; and these are very small compared to the rest masses of the other elementary particles in their respective families. Once an active neutrino has a nonzero mass it could flip its spin from left- to right-handed. Right-handed Dirac neutrinos and left-handed Dirac antineutrinos do not interact via the weak force. These particles really would be sterile. However, models can be made where these particles mix in vacuum with ordinary active neutrinos

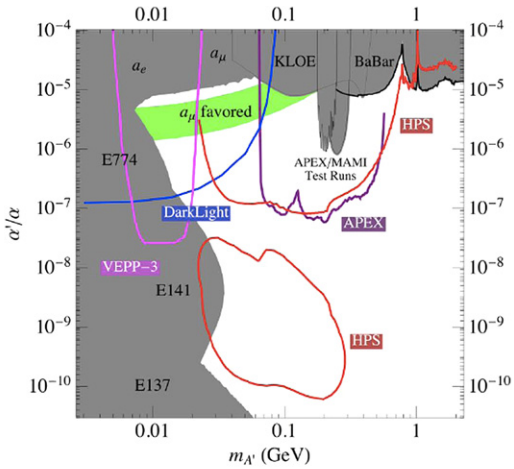

Fig. 5. Constraints on the hidden-sector fine-structure constant α' as a function of the A' mass $M_{A'}$. Shaded regions show the limits at 90% CL which emerge from the beam dump experiments E137, E141, E774, from KLOE and BaBar, and from the test run results reported by APEX (JLAB) and A1 (MAMI). The limits from the muon and electron anomalous magnetic moments, a_μ and a_e, are shown as well. The shaded band labeled "a_μ favored" shows the region in which the A' can resolve the observed discrepancy in $g-2$ of the muon at 90% CL [198]. The improved theoretical computation of a_e [214] sharpens the interpretation of its measurement [215,216] and removes some of the "a_μ favored" region; see Ref. [217] for an illustration. Projected sensitivities of the APEX, DarkLight, HPS, and VEPP3 experiments are shown as well. We refer the reader to Ref. [213] for all details.
Source: Figure reprinted from Ref. [213] with the kind permission of The European Physical Journal (EPJ).

which can be either Majorana or Dirac in character. The designation "sterile", was inspired by how a massless Dirac right-handed neutrino or left-handed antineutrino would behave. But by sterile neutrino here we shall mean any chargeless spin-1/2 fermion which has sufficiently sub-weak interaction coupling that it is not ruled out by the Z^0 width limits, *e.g.*, from LEP.

The many attempts to explain the disparity in rest mass scales between the known neutrinos and the other elementary particles mostly revolve around "see-saw" models [218–222]. In these schemes it is posited that the product of the mass scale associated with the known active neutrinos and the mass scale of some "sterile" species is the square of an extremely large mass-scale, such as the unification scale, for example. Very heavy sterile neutrinos then imply very light active neutrinos, "explaining" why active neutrinos are so light and why sterile states do not show up in accelerator experiments and in astrophysical settings such as core collapse supernovae and BBN.

We can conclude only that the existence of sterile neutrinos is at least plausible. Ref. [223] provides a comprehensive review of sterile neutrinos, evidence for these particles and constraints on them, and their possible effects in astrophysical settings ranging from the early universe to compact objects.

Disturbingly, though the LEP results require only three active neutrinos with standard weak interactions, there is no limit on the number of sterile neutrinos. Furthermore, there are no compelling arguments for what the rest masses of sterile neutrinos should be. In fact, there are credible, if not persuasive, arguments for sterile neutrino rest masses ranging from the sub-eV scale to the unification scale (see for example Refs. [224,225]). The see-saw mechanism usually is based on invoking $\mathcal{O}(1)$ Yukawa couplings to the Higgs and, of course, on heavy right-handed neutrino masses. Interestingly, however, the split seesaw mechanism [226] can reconcile active neutrino masses with a relatively light sterile neutrino, *e.g.*, one with a mass well below the electroweak scale. Such a sterile neutrino is a natural dark matter candidate.

The idea of an electroweak singlet (sterile neutrino) as a dark matter candidate has a long history at this point [227–242]. The sterile neutrino dark matter candidates in many models have rest masses of $\sim$1 keV. In most of these models the sterile neutrinos mix in vacuum with active neutrino species. This gives the sterile neutrino an effective interaction in vacuum and in a medium (*e.g.*, in the early universe). These interactions imply that sterile neutrinos can have effects in astrophysical environments that can lead to constraints.

There are many examples of such effects and constraints derived from them. Sterile neutrinos have also been studied as a potential source of early re-ionization in the dark ages in the adolescent universe [243–245]. They have been invoked to produce large pulsar kicks [246–250], and in baryogenesis scenarios [251,252]. Interestingly, they also can play havoc in the core collapse supernova environment [253–256].

At root, sterile neutrinos can affect the world only through their small vacuum mixing with active neutrinos, but this also allows several decay modes, one of which is the simple beta decay-like mode, where a heavier, nonrelativistic, mostly sterile neutrino decays into a light, mostly active neutrino and a photon. The rate of this decay scales like five powers of the sterile neutrino rest mass scale, and is proportional to the square of the appropriate active-sterile vacuum mixing angle. Sterile neutrino dark matter candidates with $\sim$keV rest masses produce X-rays via this decay mode, and there are many existing and future X-ray observatories. This is where the best constraints on sterile neutrino dark matter come from [257].

Most of the simplest models for production of a relic sterile neutrino density in a range to be a significant component of the dark matter require vacuum mixing and rest mass parameters that run afoul of the X-ray constraints [229,258,259].

However, there are models that would produce the right relic densities for sterile neutrinos, yet can evade all existing cosmological and laboratory bounds. Examples of these include models which rely on matter enhancement [228], or models for producing a relic density that are built on Higgs decay [226]. It should be noted that not all effects of sterile neutrinos are necessarily bad.

Sterile neutrinos, mixing in a medium with ν_e's and $\bar{\nu}_e$'s, could solve the alpha effect problem in neutrino-heated r-process nucleosynthesis models [260–262]. This model has the virtue that it can enable active-sterile neutrino medium-enhanced mixing to engineer an extreme neutron excess which, in turn, can lead to fission cycling in the r-process. Such cycling may be necessary to explain the observational fact that the nuclear mass 130 peak and 195 peak abundances are comparable, and that is difficult to understand absent some mechanism to drive the equilibrium between the abundances in these mass regions. Fission cycling does this naturally. This is a key point of contact between an outstanding and vexing problem in nuclear physics and astrophysics, *i.e.*, the origin of the r-process elements such as iodine and uranium, and the speculative physics associated with a possible sterile neutrino sector. As a consequence, nuclear physicists have a vested interest in sterile neutrinos, and not just because these particles could be dark matter candidates.

Moreover, finding one kind of light sterile neutrino, *e.g.*, one with a mass scale $\sim$1 eV, immediately buttresses the arguments for looking for other light sterile species, *e.g.*, those with $\sim$1 keV mass scales which could be a significant component of the dark matter.[6] If, for example, nuclear physicists could establish that the r-process cannot operate in supernovae or compact object mergers *without* a sterile neutrino, then the interest in sterile neutrino dark matter is heightened across the board. Of course, presently we are nowhere near drawing any such conclusion. All we can say at this point is that with the anticipated advent of Advanced LIGO, and direct observation of compact object mergers, we will understand more. We can also say that these topics are right in the heart of important frontline issues in nuclear physics.

This is just one example, and certainly not the only one, in which sterile neutrino dark matter physics issues overlap with other thrusts in modern nuclear physics. Consider another example, one which overlaps with important physics being studied in relativistic heavy ion collisions and in fundamental lattice QCD calculations. Some models for production of a cosmologically significant sterile neutrino relic density produce that relic density through active-neutrino scattering-induced de-coherence in the early universe. The production rate in this case in the early universe is negligible at very high temperatures, where the active neutrino scattering rate is so high that quantum mechanical suppression of active sterile mixing (*i.e.*, the quantum Zeno effect) is dominant. Likewise, at low temperatures the sterile neutrino production rate is low because the scattering rate is low.

The bulk of sterile neutrino production lies between these scales, in fact right in the QCD epoch, where the temperature scale is $\sim$100 MeV. At issue is how active neutrinos interact in the dense, hot (high entropy) nuclear matter that comprises the early universe medium at these temperatures. Though the QCD community concentrates, as they should, on studying the bulk properties of this medium, such as the baryon number susceptibility, the sterile neutrino dark matter models bring up new topics for investigation. For example, what is the active neutrino transport mean free path in this medium? What are the relevant weak interaction degrees of freedom? There is another way that sterile neutrino dark matter ideas tie together nuclear astrophysics and astronomy. A rapidly developing arena of research is the origin of galaxies and, especially, reconciling ideas on dark matter with this subject, as described above. An unresolved issue there is the chemical (nuclear abundance) evolution of dwarf galaxies and other structures. Understanding this may allow insights into whether the perceived troubles with small-scale structures such as the dwarf spheroidal galaxies stem from lack of understanding of how prosaic processes such as gas physics operate, or whether they come from some key misunderstanding about the nature of the dark matter itself. Examples of the latter include questions of whether dark matter is warm or cold (sterile neutrinos can be either), or self-interacting.

8. Summary

Astrophysical observations tell us that we live in a dark-dominated universe, though the precise mechanisms which give rise to its nature have not yet been determined. We have worked under the assumption that particle physics, and particularly the physics of the weak scale, might yet explain it. In this context we have reviewed the astrophysical observations and simulations and experiments which inform us about dark matter.

Recent results from collider physics, astrophysics, and cosmology encourage broader thinking in regards to possible dark-matter candidates—dark-matter need not be made exclusively of "WIMPs". Facilities dedicated to nuclear physics are well-positioned to investigate certain non-WIMP models, and we have discussed the models which are probed at such facilities in some detail. In parallel to this, developments in observational cosmology permit probes of the relativistic energy density at early epochs and thus provide new ways to constrain dark-matter models, provided nuclear physics inputs are sufficiently well-known. The emerging confluence of constraints from diverse sources, be they accelerator, astrophysical,

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[6] One of the authors of the present work has dubbed this argument the "Cockroach Principle", meaning that if you find one, there are likely to be others. The author of Ref. [223], being of Russian origin, deems this the "Mushroom Principle", because where you find one mushroom there are likely to be others nearby. And you actually *want* to find mushrooms, not cockroaches.

or cosmological, permit searches for dark-matter candidates in a greater range of masses and interaction strengths than heretofore possible, and we conclude that a bright future exists for the discovery of things dark.

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