The New Dark Matter Landscape

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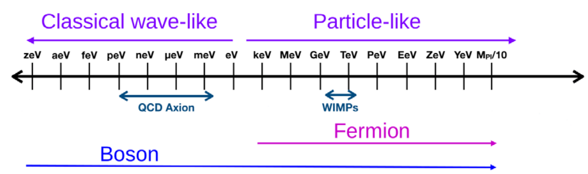
What is Dark Matter?

There is a wide range of evidence for the existence of "dark matter" in the Universe. This evidence ranges from measurements of the early Universe, such as the cosmic microwave background, to the motion of galaxies and galaxy clusters. The question for most particle physicists is not whether dark matter exists, but rather what type of particle–or particle*s*–make up the dark matter. We want to know what the properties of these particles are: their mass, their spin, whether they interact with ordinary matter with forces other than gravity, whether they interact among themselves, and whether they are part of a rich dark sector that still awaits discovery.

Beyond WIMPs. The search for dark matter has undergone a drastic shift recently. For decades, the main dark matter candidate has been a Weakly Interacting Massive Particle, or "WIMP," which, despite its meek name, has dominated experimental searches. A WIMP–a particle that feels the Weak force of the Standard Model with a mass between about 1 to 10,000 times the proton mass–would be produced in the early Universe shortly after the Big Bang with a calculable abundance that roughly matches the one observed. This makes them exciting candidates, especially since many theories of physics that go beyond the Standard Model often contain new stable particles with precisely the required properties of a WIMP. However, for more than a decade, there have been no signs of new physics beyond the Standard Model at the Large Hadron Collider, and a wide array of experimental searches still see no evidence for WIMPs. This has led dark matter physicists to broaden the theoretical possibilities for what constitutes dark matter and to dramatically expand searches for it.



The landscape of masses for dark matter particle candidates. Traditional searches for WIMP particle-like dark matter have thus far not yielded a clear discovery, and the abundance of options, from the lightest bosons to extremely massive particles require new strategies to be conceived

A Wide Dark Matter Mass Range. The landscape of possibility for particle dark matter that is now under active investigation from theorists and experimentalists spans about 50 orders of magnitude in dark matter mass alone (see Figure 1): from about 10^{-22} eV to the Planck mass. Below $\sim$1 keV, the dark matter must be a boson, since a fermion, which has to obey Pauli exclusion principle, would not be able to form a structure the size of observed dwarf galaxies. On the other hand, the de Broglie wavelength for a bosonic dark matter particle would be larger than the size of observed dwarf galaxies if its mass is below 10^{-22} eV.

Dark-Sector Dark Matter. Quite generically, the dark matter in this entire mass range could be part of a "dark sector," (see Figure 2), which consists of particles and force mediators that do not feel any of the known Weak, Strong, or Electromagnetic forces; interactions with ordinary matter could occur with new force particles. While the possibilities are diverse, this is not a matter of "anything goes," since many constraints need to be satisfied; moreover, one needs to account for the way these particles can be produced during the history of the Big Bang to reach the abundance we observe today. Several well-motivated production scenarios exist that make sharp testable predictions for the dark matter mass and interactions. A large range of experiments and astrophysical probes need to be developed in order to probe dark matter across such vastly different mass scales, and decipher which candidate has been realized by nature.

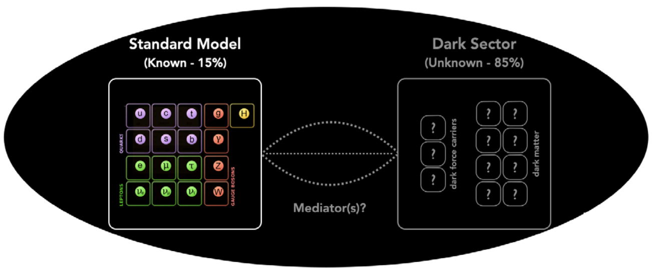
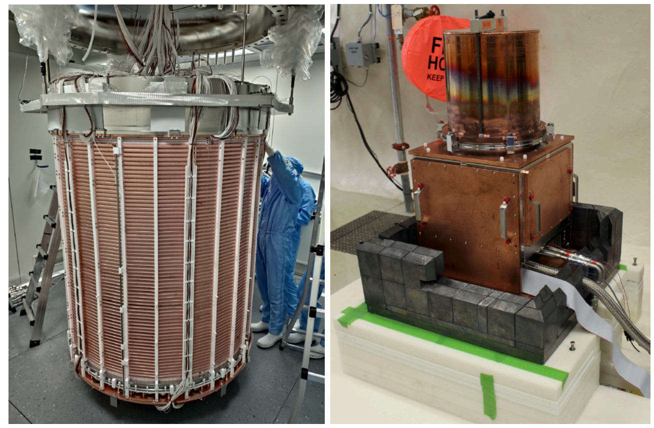


Figure 2: Dark matter may be part of a dark sector, which could consist of several particles and force carriers, and which could be connected with ordinary matter (described by the Standard Model) through mediators. This simple possibility leads to a remarkably rich set of predictions for a wide range of terrestrial and cosmological observations

A Multitude of New Searches

Terrestrial Probes

Traditional Searches for WIMPs. Terrestrial probes, such as accelerator, direct-detection, and precision measurements, have played a crucial role in the search for WIMPs. Accelerator experiments hope to produce dark matter particles in collisions of Standard Model particles. These can be in the form of colliding-beam experiments, in which collisions of electron-positron pairs or proton-(anti)proton pairs produce dark matter particles, which then appear as missing energy with other Standard Model particles. On the other hand, direct-detection experiments search for the small signals created when a dark matter particle in our halo scatters off a target material. These experiments are usually located deep underground and are well-shielded to avoid contamination from radioactive backgrounds and cosmic rays.



Left: The XENONnT WIMP dark matter experiment being installed in the LNGS laboratory in Italy (photo credit: the XENON collaboration). Right: The SENSEI dark matter experiment being assembled at SNOLAB in Canada.

Traditional searches for dark matter with masses above the proton, including WIMPs, are mature. CERN's Large Hadron Collider sees no evidence for excess missing energy events that could indicate the production of dark matter. The direct-detection experiments that are searching for WIMPs that scatter elastically off nuclei now consist of multi-ton scale detectors with noble-liquid targets (xenon and argon), led by the XENONnT (see Figure 3 (left)), LZ, PandaX-4T, and DarkSide-20k experiments [M$^+$21, A$^+$22a, A$^+$23a, A$^+$18]. At the center of these detectors, one can find the least number of radioactive background events anywhere on Earth, with only $\sim$100 events/tonne/year, compared with hundreds of events every second that a person experiences on Earth's surface. Despite the detectors' large target mass and low backgrounds, they have seen no evidence for WIMPs.

Particle-like Versus Wave-like Dark Matter. To search for dark matter with masses below the proton, both new and a range of different detection concepts are needed. In particular, dark matter with mass much below 50 eV behaves like a "wave," while dark matter with masses much above 50 eV behaves like a "particle." To understand why, it is useful to recall some basic properties of dark matter in our solar system, in particular the local phase space density and their energy. The local dark matter density is $\rho_{\rm DM,0}$ $\sim$0.4 GeV/cm^3, so that the local number density is $n_{\rm DM,0} \sim \frac{8\ \text{billion}}{\text{liter}}(1\ \text{eV}/m_{\rm DM})$. Given the dark matter's mean local velocity of $v_{\rm DM,0} \sim 220$ km/second, its de Broglie wavelength is

$$\lambda_{\rm dB} \sim \frac{h}{p} \sim \frac{h}{m_{\rm DM}\, v_{\rm DM,0}} \sim 34\ \mu\text{m} \left(\frac{50\ \text{eV}}{m_{\rm DM}}\right),$$

where h is Planck's constant and p is the momentum, while the mean distance between the dark matter particles is

$$d \sim \left(\frac{3}{4\pi n_0}\right)^{1/3} \sim 30\ \mu\text{m} \left(\frac{50\ \text{eV}}{m_{\rm DM}}\right)^{1/3}.$$

The ratio of the de Broglie over the mean distance is

$$\frac{\lambda_{\rm dB}}{d} \sim 1.1 \left(\frac{50\ \text{eV}}{m_{\rm DM}}\right)^{4/3}.$$

For $\lambda_{\rm dB}/d \gg 1$ (i.e., $m_{\rm DM} \ll 50$ eV) the occupation number in any given volume of space is very large, and the dark matter behaves like a coherently oscillating wave, whose frequency is given by $m_{\rm DM}c^2/\hbar$ (c is the speed of light, $\hbar = h/2\pi$). In the opposite limit, the occupation number is low, and we can think of a single dark matter particle interacting with a detector.

Terrestrial Searches for Wave-like Dark Matter. Perhaps the most famous "wave-like" dark matter candidate is the "QCD axion," which would also explain why the strong force described by Quantum Chromodynamics (QCD) does not violate the charge conjugation-parity symmetry [Wei78, Wil78]. The Axion Dark Matter eXperiment (ADMX) [B+21] is based on an old idea and uses a strong magnetic field in a cavity to convert dark matter axions to detectable microwave photons [Sik83]. However, the past decade has seen dozens of new ideas emerge for how to probe the QCD axion, as well as more general axion-like particles (or "ALPs"), scalars, and vector bosons. Several experiments have been proposed to probe the large frequency range corresponding to the entire wave-like dark matter mass range (about 10^{-22} eV to ∼50 eV), as well as to probe different hypothetical interactions between the dark matter and ordinary matter (e.g., ADMX-HF, NASDUCK, HAYSTAC, CASPEr, ABRACADABRA, DM-Radio etc.) [A+22b, A+22c].

Terrestrial Searches for Particle-like Dark Matter. Particle-like dark matter, with masses below the proton, have historically been scarcely explored. This has changed in the past decade, and now many new ideas exist. New accelerator-based probes have been proposed and several new searches have already been realized. For example, the FASER experiment [A+19] has augmented the LHC with a detector placed in the far-forward region to catch elusive dark-sector particles produced in the proton-proton collisions of the LHC. The MiniBooNE experiment [AA+18] conducted a special run in which it searched for dark matter particles produced in the proton beam dump and subsequently scatter in their detector. The LDMX experiment [r+18] proposes to use an electron beam incident on a fixed target and search for missing momentum of the electron after it passes through the target, which could be caused by the radiation of dark matter particles.

A plethora of new direct-detection experiments has also been proposed to search for dark matter with mass below the proton. The challenge of probing such light dark matter is that the standard WIMP search for the elastic scattering of dark matter with a nucleus is very challenging, as the recoil energy of the nucleus quickly falls below detector thresholds. In particular, just as a table tennis ball would transfer little of its energy to a heavy bowling ball, a light dark matter particle would transfer very little energy to a nucleus, namely only

$$E_{\rm NR} = \frac{q^2}{2m_{\rm N}} \sim 1\ \text{eV} \left(\frac{m_{\rm DM}}{100\ \text{MeV}}\right)^2 \left(\frac{28\ \text{GeV}}{m_{\rm N}}\right).$$

However, inelastic interactions, such as dark matter-electron scattering, the Migdal effect (in which dark matter-atom scattering is accompanied by the ionization of the atom), or dark matter scattering off collective excitations (phonons or magnons) do allow for the transfer of the dark matter's entire kinetic energy,

$$E_{\rm kin} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 100\ \text{eV} \left(\frac{m_{\rm DM}}{100\ \text{MeV}}\right).$$

Armed with these new detection concepts, a new generation of experiments has been proposed (e.g., SENSEI [B+20] (see Figure 3 (right)), DAMIC-M [A+23b], Oscura [AA+22], TESSERACT [M+20]) and a wide array of target materials are being employed or considered (e.g., semiconductors, scintillators, quantum dots, doped semiconductors, Dirac materials etc.) [E+22].

Cosmological Probes

The growing number and quality of astrophysical and cosmological measurements, side by side with improvements in theoretical understanding (such as numerical N-body simulations), has led to a plethora of new opportunities to constrain the physical nature of dark matter, even in the absence of interactions with ordinary matter. The observations span times from tiny fractions of a second following the Big Bang to our own time and place, and scales from the entire visible Universe down to dwarf galaxies and clusters of stars. We mention two examples that can be confronted with data of how dark-sector dark matter may impact the formation of structure in the Universe.

Self-Interacting Dark Matter. One exciting possibility is that dark matter particles can meaningfully interact among themselves [SS00, TY18]. This allows the particles to exchange energy, which affects structure formation, especially on sub-galactic scales. For self-interactions to be relevant for observations, each dark matter particle needs to interact at least once within the age of the Universe. Setting the interaction timescale, τ, equal to the age of the Universe, we require

$$\tau = (n_{\rm DM}\sigma_{\rm SIDM}v_{\rm DM})^{-1} = \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\sigma_{\rm SIDM}v_{\rm DM}\right)^{-1} \sim 14 \text{ billion years}\,.$$

Taking the dark matter density and velocity to be the local density $\rho_{\rm DM,0} \sim 0.4$ GeV/cm^3 and local mean velocity $v_{\rm DM,0} \sim 220$ km/second, the required self-interaction cross-section over the dark matter mass is given by

$$\frac{\sigma_{\rm SIDM}}{m_{\rm DM}} \sim 1\,\frac{\text{barn}}{\text{GeV}}\,.$$

Remarkably, nature already contains "particles" with such large interactions: protons, neutrons, and nuclei. For example, elastic neutron-proton scattering at a relative velocity of $\mathcal{O}$(100 km/s) is mediated by the strong force and has $\sigma_{\rm np}/m_n \sim \mathcal{O}$(20 barn/GeV). A dark sector that is strongly coupled at a scale Λ_D has

$$\frac{\sigma_{\rm SIDM}}{m_{\rm DM}} \sim 1\,\frac{\text{barn}}{\text{GeV}}\left(\frac{75\text{ MeV}}{\Lambda_D}\right)^3.$$

Furthermore, large self-interactions are also possible if dark matter is coupled weakly to a low-mass mediator (with coupling α_D),

$$\frac{\sigma_{\rm SIDM}}{m_{\rm DM}} \sim 1\,\frac{\text{barn}}{\text{GeV}}\left(\frac{\alpha_D}{\alpha_{\rm EM}}\right)^2\left(\frac{m_{\rm DM}}{10\text{ GeV}}\right)\left(\frac{40\text{ MeV}}{m_{\rm mediator}}\right)^4,$$

where $\alpha_{\rm EM}$ is the electromagnetic fine-structure constant. It is worth noting that such a large cross section is not ruled out by data—in fact, some observations (such as the diversity of rotation curves of spiral galaxies) might be better explained with self-interacting dark matter.

Dissipative Dark Matter. If the dark sector contains new low-mass mediators, these can be produced when dark matter particles collide, allowing for the rapid dissipation of energy, in analogy to ordinary matter being able to radiate energy through the emission of photons. Even if only a small component of the dark matter has such dissipative interactions, this could affect the abundance and structure of low-mass halos and lead to the formation of exotic compact.

A New Era in Dark Matter Research

Today's hunt for the nature of dark matter has expanded to an exciting variety of experimental and theoretical ideas, spanning many scales and ideas and bridging technologies and disciplines. Particle theorists now regularly collaborate with condensed matter and AMO theorists to describe particle interactions in a wide range of materials and targets. Theoretical astrophysicists, including numerical N-body simulators, are constantly refining the accuracy of their simulations and are only beginning to understand the consequences of the wide range of dark-sector models. Observers are beginning to confront dark-sector models with the latest precision cosmological data. Experimentalists are refining the sensitivity of their instruments to detect even the tiniest deposition of energy and to reduce backgrounds. This concerted effort among these wide range of disciplines is not only exciting, but also necessary for us to maximize our chances of successfully identifying the dominant matter component in our Universe.

REFERENCES

[A+18] C. E. Aalseth et al., *DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS*, Eur. Phys. J. Plus **133** (2018), 131.

[A+19] Akitaka Ariga et al., *FASER's physics reach for long-lived particles*, Phys. Rev. D **99** (2019), no. 9, 095011.

[A+22a] J. Aalbers et al., *First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment.*

[A+22b] C. B. Adams et al., *Axion Dark Matter*, Snowmass 2021, 3 2022.

[A+22c] D. Antypas et al., *New Horizons: Scalar and Vector Ultralight Dark Matter.*

[A+23a] E. Aprile et al., *First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment.*

[A+23b] I. Arnquist et al., *First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons,* Phys. Rev. Lett. **130** (2023), no. 17, 171003.

[AA+18] A. A. Aguilar-Arevalo et al., *Dark Matter Search in Nucleon, Pion, and Electron Channels from a Proton Beam Dump with MiniBooNE*, Phys. Rev. D **98** (2018), no. 11, 112004.

[AA+22] Alexis Aguilar-Arevalo et al., *The Oscura Experiment*.

[B+20] Liron Barak et al., *SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD*, Phys. Rev. Lett. **125** (2020), no. 17, 171802.

[B+21] C. Bartram et al., *Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range*, Phys. Rev. Lett. **127** (2021), no. 26, 261803.

[E+22] Rouven Essig et al., *Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade*, Snowmass 2021, 3 2022.

[M+20] Daniel McKinsey et al., *The tesseract dark matter project*, Snowmass2021 LOI, 2020.

[M+21] Yue Meng et al., *Dark Matter Search Results from the PandaX-4T Commissioning Run*, Phys. Rev. Lett. **127** (2021), no. 26, 261802.

[r+18] Torsten Åkesson et al., *Light Dark Matter eXperiment (LDMX).*

[Sik83] P. Sikivie, *Experimental Tests of the Invisible Axion*, Phys. Rev. Lett. **51** (1983), 1415–1417, [Erratum: Phys.Rev. Lett. 52, 695 (1984)].

[SS00] David N. Spergel and Paul J. Steinhardt, *Observational evidence for selfinteracting cold dark matter*, Phys. Rev. Lett. **84** (2000), 3760–3763.

[TY18] Sean Tulin and Hai-Bo Yu, *Dark Matter Self-interactions and Small Scale Structure*, Phys. Rept. **730** (2018), 1–57.

[Wei78] Steven Weinberg, *A New Light Boson?*, Phys. Rev. Lett. **40** (1978), 223–226.

[Wil78] Frank Wilczek, *Problem of Strong P and T Invariance in the Presence of Instantons*, Phys. Rev. Lett. **40** (1978), 279–282.