VIEWPOINT

New approaches to dark matter detection

Yonit Hochberg, Yonatan F. Kahn, Rebecca K. Leane, Surjeet Rajendran, Ken Van Tilburg, Tien-Tien Yu and Kathryn M. Zurek

Abstract | Decades of searching for theoretically motivated dark matter candidates have yielded no results, so the research community is starting to adopt different strategies for detecting dark matter. Seven scientists discuss these new approaches.

Fishing for dark matter

Surjeet Rajendran. The problem of identifying the nature of dark matter can be stated as follows: we know that dark matter exists, but the weak observational limits on its properties allow its mass to lie anywhere between 10^{-21} eV and 10^{48} GeV (see FIG. 1). How can we probe this vast parameter space?

The fearsome vastness of this mass/energy range has led to a human tendency to artificially restrict the parameter space of interest by focusing on 'well motivated' dark matter candidates. In this context, 'well motivated' simply means dark matter candidates that theorists have written down to solve other problems in particle physics. Although it is certainly conceivable that the existence of dark matter may be tied to other problems in particle physics, such a requirement is hardly a guarantee. The complexity of the standard model (SM) of particle physics itself offers ample evidence that the particle content of the Universe is not particularly mindful of human philosophies. Physics is an experimental field — whether we like it or not, armchair mathematics is of little use in figuring out the contents of the Universe.

The scientific question that we ought to ask is: given this vast parameter space, how do we systematically probe it? Instead of focusing on specific models, one should look for general classes of experimental signatures that can probe several orders of magnitude in mass. It is possible to identify such general classes of signatures because the dark matter, being a particle, is highly likely to obey the principles of quantum field theory. The principles of quantum field theory restrict the possible interactions that the dark matter may have with the particles of the SM. By organizing the lines of inquiry along these directions, new classes of signatures of dark matter have been discovered, and there are now several experiments that are actively searching for these signatures. These include searches for dark-matter-induced spin precession, accelerations and currents. Many of these experiments are successfully leveraging the extraordinary sensitivity of quantum sensing platforms, resulting in the creation of an active and exciting interdisciplinary field.

This way of thinking about dark matter, where the focus is on broad experimental signatures rather than specific theories, has sometimes been pejoratively dismissed as a 'fishing expedition'. I actually fancy this description — whether one likes it or not, trying to find dark matter is similar to trying to catch fish in the ocean. The problem with the dark matter fish is that although we know this fish is in the ocean, we do not know much else about it. It could be as big as a whale shark or as small as a Nemo fish. The sensible way to try to catch this fish is to design a wide variety of nets that focus on generic properties of the fish (such as its size) instead of looking for a specific kind of fish that happens to have won the popularity contest of the day.

Dark matter at the precision frontier

Ken Van Tilburg. The SM does not predict the existence of dark matter, whose microscopic origin remains unknown. This is an unusual situation: fundamental particle physics has historically been steered by unexpected observations, rapid successions of predicted new particle discoveries, or clear indications of new physics existing at an energy scale achievable by the next particle collider. Attaining higher energies than those achieved by the Large Hadron Collider (LHC) (13.6 TeV) is important but slow and expensive, and does not guarantee a discovery of physics beyond the SM. No class of experiments, existing or proposed, currently enjoys such a guarantee, so it is imperative to cast a wide net, especially since we do not know along which axis the SM will finally crack.

Physicists think of particle colliders as the high-energy frontier, of high-mass dark matter scattering and other rare phenomena as the intensity frontier, and of astroparticle phenomena as the cosmic frontier. Another promising experimental direction is the 'precision frontier', where one looks for exceedingly feeble fields or other minuscule changes in observable quantities. In addition to probing physics at ever higher energies, one can also look for interactions involving much smaller couplings between the SM and new particles.

New physics may manifest at the precision frontier in three primary ways. Firstly, virtual quantum effects of physics at extremely small distances can give rise to anomalous electromagnetic moments (such as the muon's magnetic moment or the neutron's electric dipole moment) and other static properties of known SM particles (manifesting, for example, through energy shifts in atomic spectra, in tests of charge neutrality in atoms, and so on). Secondly, low-mass bosonic particles can be remnants of symmetry breaking at energy scales far above those attainable in the laboratory and mediate weak, long-range forces, potentials and other related effects (manifesting, for example, through apparent deviations of gravity at short distances or even spin-dependent forces). Thirdly, the same light bosons are generically produced in the early Universe and may comprise the abundance of dark matter today. If their mass is <1 eV, their behaviour should be akin to that of a 'slow' radio wave but at a frequency set by the mass of the dark matter particle.

The contributors

Yonit Hochberg is an associate professor at the Racah Institute of Physics at the Hebrew University of Jerusalem. Her research focuses on theoretical particle physics, with emphasis on new ideas for the particle identity of dark matter, along with avant-garde concepts for its detection in the laboratory. She has been named a Wolf Fellow, Chorafas Fellow, Rothschild Fellow, LHC Theory Initiative Fellow and Azrieli Fellow; has won the Israel National Women in Science Award, the Krill Prize and the Bekenstein Prize; and is an elected member of the Israel Young Academy of Science.

Yonatan (Yoni) Kahn is a theoretical physicist and assistant professor at the University of Illinois Urbana-Champaign, and core faculty at the Illinois Center for Advanced Study of the Universe. His research is focused on dark matter and its detection strategies. Yoni pursues a highly interdisciplinary approach, collaborating with particle experimentalists, condensed matter experimentalists and theorists, materials scientists, chemists and quantum science experts to develop new experiments to discover dark matter.

Rebecca Leane is an associate staff scientist in the Particle Theory Group at SLAC, and a Senior Member of the Kavli Institute for Particle Astrophysics and Cosmology at SLAC and Stanford University. Rebecca's research leverages the interplay of theoretical particle physics and astrophysics to investigate the fundamental nature of dark matter, and other Beyond the Standard Model physics. She identifies new search strategies for dark matter in astrophysical systems, and executes these searches using new theoretical calculations and the latest astrophysical datasets.

Surjeet Rajendran is an associate professor of physics at the Johns Hopkins University. He has invented new experimental methods to detect gravitational waves, dark matter and dark energy which are being implemented by many laboratories around the world. He has also developed theoretical tools to solve outstanding problems in particle physics, such as the hierarchy and vacuum energy problems via cosmological evolution. His recent theoretical interests have been in identifying new gravitational phenomena within General Relativity and developing consistent and testable modifications of quantum mechanics. Surjeet has been awarded the Sloan Fellowship and the 2017 New Horizons in Physics Prize, and is a Simons Investigator.

Ken Van Tilburg is an assistant professor in physics at New York University and an associate research scientist in the Center for Computational Astrophysics at the Flatiron Institute. His research interests cover a broad range of subjects in particle physics phenomenology and theory, interfacing between precision experimental physics, astrophysics and cosmology. The primary aim of his research is to develop new experimental and observational methods and theoretical approaches in the search for physics Beyond the Standard Model of particle physics. He has pioneered several techniques to search for weakly coupled phenomena — including dark matter — in the laboratory, at the precision frontier of atomic, molecular, optical and electromechanical physics.

Tien-Tien Yu is an associate professor of physics and member of the Institute for Fundamental Science at the University of Oregon. She is a theoretical particle physicist interested in Beyond the Standard Model physics and is primarily focused on understanding the nature of dark matter. She is the recipient of an NSF CAREER award and shared the 2021 New Horizons in Physics Prize for her work on the detection of sub-GeV dark matter.

Kathryn Zurek is a professor of theoretical physics at Caltech and a Simons Investigator. She is interested in how to use theoretical and experimental probes to understand the nature of dark matter and, more recently, also in observational signatures of holographic theories of quantum gravity. Kathryn developed the hidden valley models and established techniques to build models of natural low-mass hidden dark matter sector. She investigates connections between these theories and experimental physics at the Large Hadron Collider and astrophysical objects such as neutron stars and white dwarves. Kathryn is a fellow of the American Physical Society.

In the latter case, low-mass dark matter can coherently excite LC circuits (like a radio wave), electromagnetic cavities and mechanical resonators, produce energy and phase shifts in atomic clocks and interferometers, and lead to an anomalous precession of electron and nuclear spins, to name just a handful of possible beyond-SM effects. This sprawling research area is interdisciplinary: one needs to be comfortable with calculations of low-energy (signal and background) processes in systems ranging from nuclei and atoms to macroscopic materials and the Cosmos, with all their emergent, complex responses to weak perturbations. The rapid experimental progress in atomic, molecular and optical physics, interferometry, force sensing, electromechanical resonators, amplifiers and photodetectors presents a unique opportunity to leverage these advancing technologies in the search for beyond-SM phenomena.

The dark matter hidden valley

Kathryn M. Zurek. The search for dark matter had originally been focused on the weakly interacting massive particle (WIMP) and the axion. These particles were proposed to solve a couple of puzzles in the SM but turned out to potentially explain all the dark matter in the Universe. Now, after decades of homing in on just these two dark matter candidates, with no actual observation, scientists are searching instead for a broad range of other dark matter candidates. A motivated, and extremely general, alternative to axions and WIMPs is light hidden sectors — dark matter particles with masses between approximately 1 keV and 10 GeV. These hidden sectors are sometimes called hidden valleys because their mass is much lower than the high energies where experiments, such as CERN's LHC, have traditionally looked for new particles like the WIMP (a few GeV and a few TeV). Whereas WIMP and axion dark matter are theorized to exist because of the problems they solve in the SM, hidden-sector dark matter is independent of these problems. In other words, instead of being parasitic on the SM, hidden sectors have a life of their own, with their own dark forces and interactions.

Since hidden-sector dark matter cannot be seen in experiments looking for the WIMPs and axions, one must invent new types of experiments to look for hidden-sector dark matter. This has been the focus of intense research over the past decade. Experiments looking for WIMPs search for dark matter depositing energy on individual nuclei; because these interactions happen very rarely, these experiments must be very clean and free from any other process that could mimic a dark matter interaction. Due to their smaller mass, searches for hidden-sector dark matter must be sensitive to even smaller whispers, or energy deposits, from dark matter. Because the hidden-sector dark matter deposits so little energy in an interaction, the electrons and nuclei can only be moved collectively. So one way to look for these tiny whispers is to make use of collective excitations in materials: phonons and magnons. Experiments are now under way to develop these ideas and search for whispers from the dark sector.

Hidden-sector dark matter also leaves imprints on the Cosmos. In general, dark matter can be detected because of the way it causes ordinary visible matter to respond to its gravity. But if dark matter also has its own forces, it does not only respond to gravity. These additional interactions could actually change the way that dark matter affects galaxy formation. It could even impact the ways stars evolve. Researchers are looking for these cosmic imprints in many different ways.

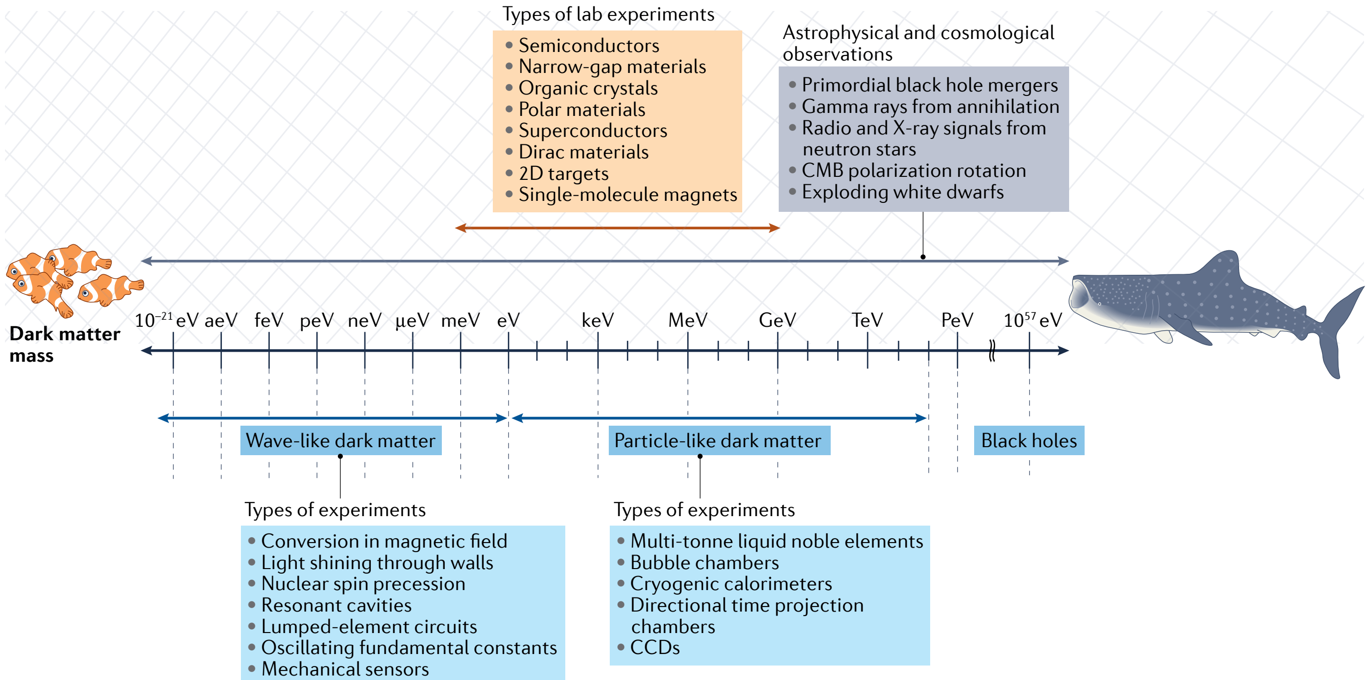

Fig. 1 | **The mass/energy range in which dark matter could be found is enormous, spanning from zeV (10^{-21} eV) to well over PeV (10^{15} eV).** Various detectors, themselves spanning the range of nanogram-scale to tonne-scale, have been devised to probe different regions of this vast parameter space. The figure provides a non-exhaustive list of such detectors broadly categorized by the type of dark matter they are designed to detect (wave-like or particle-like) or by the approach used (laboratory experiments, or astrophysical and cosmological observations). With this net of widely varying mesh sizes, scientists are hoping to catch the metaphorical dark matter fish no matter where it hides. CCD, charge-coupled device; CMB, cosmic microwave background.

Delve deep, search wide

Tien-Tien Yu. The idea of looking for the effects of dark matter scattering off atomic targets, known as the direct detection of dark matter, has been around since the mid-1980s. Since then, there has been great experimental development with a primary focus on searching for WIMPs. These dark matter models have masses that can range from a few GeV to a few hundred TeV. The largest and most sensitive of these experiments use liquid noble element targets such as liquid xenon and liquid argon, and are particularly efficient at detecting the coherent scattering of dark matter off atomic nuclei. Some of these experiments are slowly approaching and probing parameter space that is known as the 'neutrino fog' where the detectors become sensitive to the scattering of atmospheric and solar neutrinos off the atomic nuclei and the search for the signal from dark matter candidates becomes more nuanced. However, there still exist theoretically well-motivated dark matter models that live in this parameter space. Therefore, it is important to further the sensitivity of these detectors into the neutrino fog to fully explore WIMP dark matter. Semiconductor targets are complementary to noble element targets and have sensitivity to GeV-scale dark matter masses where the noble element targets lose sensitivity.

There are also several well-motivated models that live outside the range of traditional WIMP models of a few GeV to few hundred TeV. Detecting such candidates requires modifications to the traditional direct dark matter detection programme, and the past decade has seen tremendous efforts, both theoretical and experimental, to broaden the scope of dark matter searches particularly to sub-GeV masses. The first efforts to search for sub-GeV dark matter relied on the reinterpretation of data from noble element WIMP detectors. Although these detectors were optimized for dark matter–nuclear interactions, they also had a hardware trigger that recorded single- and a few-electron events. These electron events could be analysed in the context of dark-matter–electron interactions, thus serving as a proof-of-concept that direct detection experiments could probe sub-GeV dark matter. The SENSEI experiment, which uses silicon CCD chips, is the first dedicated effort for sub-GeV dark matter searches and has already produced world-leading results in this mass range. Several other experimental efforts using semiconductor targets have also joined in to set constraints on sub-GeV dark matter, as have some of the large noble liquid target experiments. More recent proposals that leverage the interactions of dark matter with collective modes, such as phonons and magnons, in solid state materials or use new detector technology such as quantum sensors further widen the breadth of dark matter searches to the sub-MeV range.

From tonne-scale to gram-scale detectors

Yonatan Kahn. The overwhelming gravitational evidence for dark matter, combined with the null results from tonne-scale WIMP experiments (such as liquid noble element detectors), has led theorists and experimentalists to search for dark matter that may be invisible to such experiments. For example, dark matter lighter than the proton mass (about 1 GeV) carries kinetic energy well below the keV thresholds of standard WIMP experiments. Over the past decade, an active programme has yielded many new ideas (and several currently running experiments) for detectors with eV thresholds. Because the dark matter number density is inversely proportional to its mass, the flux of these light dark matter candidates should be considerably larger than for WIMPs, and thus the theoretically motivated parameter space may be covered by gram- or kilogram-scale detectors, rather than tonne-scale. The first proposals for such small-scale, low-threshold detectors involved semiconductors like silicon and germanium, but close collaborations between particle physicists, condensed matter physicists, chemists and materials scientists have yielded numerous other candidate detector materials optimized for different dark matter models and observables, such as organic scintillator crystals.

Dark matter could also be lighter than 1 eV, in which case its large number density means that it is better described as a wave than as a particle. Such 'wave-like' dark matter, of which axions are a familiar example, acts as an oscillating background source at a fixed, yet unknown frequency, proportional to its mass. The challenge in searching for this kind of dark matter is that the signal is extremely weak and may exist over many orders of magnitude of possible dark matter masses. A fruitful collaboration between particle physicists, electrical engineers, and quantum sensing experts has led to a number of new experiments that aim to detect feeble oscillating electromagnetic signals from wave-like dark matter, using superconducting radiofrequency cavities, nuclear magnetic resonance in hyperpolarized targets, and squeezed states of light that are read out with phase-sensitive amplifiers. Although the dark matter signal typically scales with the volume of the experiment, the first iterations of these ideas are genuine tabletop experiments at the centimetre- to metre-scale.

A new analysis strategy particularly well suited to small-scale dark matter experiments is the search for daily modulation. As the Earth rotates, the mean dark matter incoming direction in the lab frame rotates over a day even as the lab-frame speed stays constant, yielding a potential smoking-gun signature for dark matter with oscillations on a period of a sidereal day. For WIMP–nuclear scattering, observing this daily modulation requires tracking the direction of the recoiling nucleus, which could be accomplished by using a dilute gaseous detector such as a time projection chamber; however, since the target density is lower than in a liquid, the event rate is generally lower. For light dark matter interacting with condensed matter systems, the excitation probability may be anisotropic so that the daily modulation may be observed directly in the event rate without the need to observe the direction of any final-state excitation (which may not even be a momentum eigenstate). Observing this daily modulation is also possible for wave-like dark matter by exploiting interference effects between spatially separated experiments. For both wave-like and particle-like dark matter, new backgrounds will inevitably appear as thresholds are lowered and new experimental techniques are used, so daily modulation will be a key observable to separate the signal from the noise.

An interdisciplinary effort

Yonit Hochberg. When I was a graduate student, I was taught that if dark matter is a thermal relic, we will surely discover it in upcoming experiments. The hidden assumption behind this statement was, of course, that a thermal relic must be a weak-scale particle like a WIMP, and as such, it would be detectable in the incredible experimental programme the community had constructed to hunt it down via nuclear recoils. The past decade has shattered this certainty.

From the theory side, new mechanisms of dark matter interactions in the early Universe that predict significantly lighter particles are gaining traction, suggesting that dark matter far from the weak scale is, in fact, also well motivated. From the experimental side, new ideas to search for lighter dark matter in the laboratory are abundant. Many systems, materials and detection philosophies have emerged, casting a wide net over a span of three to twelve orders of magnitude below the proton mass — from the MeV- to meV-scale — where existing experiments are typically blind. These notions include the use of semiconductors such as silicon, germanium and diamond; two-dimensional materials such as graphene; superconductors such as aluminium; Dirac materials with interesting topological properties; polar materials such as gallium arsenide; superfluid helium; and aromatic organic compounds, among others.

The proposed new methods to detect dark matter in the laboratory are truly interdisciplinary: they bring together particle physics theory and experiment, condensed matter physics, quantum sensing, material science, and atomic, molecular and optical physics. Harnessing the knowledge and expertise from different fields and applying them in the dark matter hunt offers promising prospects for real scientific breakthroughs. Take, for example, superconducting nanowire single-photon detectors (SNSPDs). SNSPDs are a mature technology, developed originally for quantum information science. In a collaboration between particle physics theorists and quantum sensing experts, we used data from a 3-hour surface run of a tiny SNSPD prototype device to set the strongest terrestrial constraints to date on dark matter with sub-MeV masses. Just imagine what could be achieved with a dedicated larger-scale device actually designed for dark matter searches!

Theoretical concepts for new dark matter experiments are now becoming an experimental reality. The SENSEI and SuperCDMS collaborations have set limits orders of magnitude lower in dark matter mass scale than we could ever have imagined a decade ago, realizing a theory vision some 10 years old. Existing technologies developed for entirely different purposes are simultaneously breaking new dark matter ground. The diversity of proposed new materials and technologies to search for dark matter in the laboratory, along with collaborative efforts bringing together different scientific communities, holds promise to finally shed light on the nature of dark matter.

New astrophysical searches

Rebecca K. Leane. The dark matter experiments of the past decade, which were thought to potentially reveal new physics, have not found anything conclusive so far. As a result, we currently don't have any strong guiding theoretical particle model telling us where, or how, to look for dark matter. This leaves us in a difficult situation: how do we go about discovering dark matter?

I don't think the solution lies in new sets of theoretical models; after all, it is hard to know what will be realized in nature. I think that instead, the best thing we can do is identify new search strategies that probe potential dark matter properties as widely and as model-independently as possible. My favorite arena is astrophysical searches, because they allow us to probe dark matter at much more extreme scales compared to anything in the lab. For example, high-energy cosmic ray collisions act as ultrahigh-energy astrophysical colliders, providing a high-energy probe of dark matter in the sky. The long astrophysical timescales offer sensitivity to weaker dark matter interactions and longer decay lifetimes. These benefits of astrophysical searches for dark matter open opportunities for discovery or exclusion paths for dark matter.

The fact that the Universe has been running this diverse range of dark matter experiments for us is too good to ignore.

The richness of astrophysical systems allows us to test a wide range of particle physics models. Furthermore, right now there are several new telescopes and instruments, and we already have some excellent-quality data on many astrophysical objects, with a lot more to come in the next decade. For example, the launch of the JWST opened a new infrared window that could reveal dark matter in many unexpected places, including dark-matter-heated exoplanets. Or perhaps the next generation of gamma-ray telescopes will reveal that dark matter has been secretly producing gamma rays in planets such as Jupiter. Finding dark matter might just be a matter of realizing what and how dark matter might already be produced in these astrophysical systems, and looking more closely at a diverse range of astrophysical objects, through the multiwavelength lenses of new telescopes. Now is the time to get creative.

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