REVIEW

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A new era in the search for dark matter

Gianfranco Bertone[1]* & Tim M. P. Tait[1,2]*

There is a growing sense of 'crisis' in the dark-matter particle community, which arises from the absence of evidence for the most popular candidates for dark-matter particles—such as weakly interacting massive particles, axions and sterile neutrinos—despite the enormous effort that has gone into searching for these particles. Here we discuss what we have learned about the nature of dark matter from past experiments and the implications for planned dark-matter searches in the next decade. We argue that diversifying the experimental effort and incorporating astronomical surveys and gravitational-wave observations is our best hope of making progress on the dark-matter problem.

The fall of natural weakly interacting massive particles

The existence of dark matter has been discussed for more than a century[1,2]. In the 1970s, astronomers and cosmologists began to build what is today a compelling body of evidence for this elusive component of the Universe, based on a variety of observations, including temperature anisotropies of the cosmic microwave background, baryonic acoustic oscillations, type Ia supernovae, gravitational lensing of galaxy clusters and rotation curves of galaxies[3,4]. The standard model of particle physics contains no suitable particle to explain these observations, and thus dark matter arguably represents a glimpse of physics beyond the standard model. Proposed candidates for dark matter span 90 orders of magnitude in mass, ranging from ultralight bosons (often referred to as 'fuzzy dark matter'[5]) to massive primordial black holes—a possibility that has received renewed interest after the detection of gravitational waves from the merger of black holes several tens of times more massive than the Sun by the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo[6,7].

The class of dark-matter candidates that has attracted the most attention over the past four decades is weakly interacting massive particles (WIMPs). WIMPs appeared for a long time as a perfect dark-matter candidate, as new particles at the weak-interaction mass scale (or weak scale; approximately between 10 GeV and 1 TeV) would be produced naturally with the right relic abundance in the early Universe[8] while possibly alleviating the infamous hierarchy problem[9], which has been a main driver of particle physics for roughly four decades[10]. Despite much effort, no particle other than a standard-model-compatible Higgs boson has been convincingly detected at the weak scale so far—a circumstance that, as long anticipated[11], raises the possibility that natural WIMPs may have been nothing more than an attractive red herring[12].

The hierarchy problem is a consequence of the fact that quantum mechanics inevitably mixes up phenomena from all energy scales by allowing virtual particles to participate even in reactions whose energies are far too small to actually produce them. As a result, low energy quantities, such as the Higgs mass, can potentially receive very large corrections from the virtual influence of much heavier particles. The influence of heavy particles is particularly pronounced for scalar bosons such as the Higgs boson and introduces corrections to the effective Higgs mass that are proportional to the masses of the virtual heavy states, so that the effective Higgs mass is the sum of a fundamental intrinsic value plus the correction terms.

Because it is generally expected that new particles will appear at the Planck energy scale, which is associated with quantum gravity, the observed Higgs mass at the weak scale appears highly unnatural, requiring an incredibly fine-tuned cancellation between the individually much larger intrinsic contribution and the correction terms, such that their sum is the value observed at the Large Hadron Collider (LHC). Natural theories introduce additional particles and symmetries, which are arranged so that these large corrections cancel each other out, protecting the Higgs mass from the influence of heavy mass scales.

The prototypical natural theory is the minimal supersymmetric (SUSY) standard model, which introduces an additional partner for each standard-model particle. In addition, the partners of electroweak bosons are predicted to be WIMPs and thus are natural dark-matter candidates. However, most of the parameter space of natural simple SUSY models is essentially ruled out[13]. Although it is still possible to identify 'natural' realizations of SUSY—for example, in regions of the parameter space of the phenomenological minimal SUSY model[14]—it is undeniable that null searches are constraining larger and larger portions of the parameter space of SUSY theories, which begs the question of how much fine-tuning one is willing to accept before giving up the hope of discovering SUSY[15].

Alternatives to natural WIMPs

Non-natural WIMPs

As a result of the lack of evidence for supersymmetry, naturalness is beginning to lose its lustre as the guiding principle for constructing theories of physics beyond the standard model. Although the shift away from WIMPs, which arises from extensions of the standard model that address naturalness, is inevitable, WIMPs themselves remain viable dark-matter candidates in an appropriate context. For example, there are types of interaction that lead to highly suppressed indirect and direct signals, although such particles remain accessible to the LHC, provided that their masses are sufficiently small[16]. With naturalness removed as the primary guide to theories of WIMPs, such particles evolve into a more general class of particles that achieve the appropriate relic density through self-annihilation.

This wider definition of WIMPs—which is already reflected in the adoption of simplified models[17] and effective field theories[18] in the presentation of collider results—leads to a richer landscape of phenomenology. For example, the range of WIMP masses expands to encompass masses as low as around 1 MeV or as high as around 100 TeV. This wider parameter space demands new kinds of WIMP searches, such as scattering of WIMP-like particles with masses below 1 GeV from electrons[19] or the use of superconductors[20], superfluids[21] or Dirac

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[1]GRAPPA Institute and Institute of Physics, University of Amsterdam, Amsterdam, The Netherlands. [2]Department of Physics and Astronomy, University of California, Irvine, CA, USA.
*e-mail: g.bertone@uva.nl; ttait@uci.edu

materials[22]. Such light dark-matter particles would have already been observed if their annihilation cross-sections into standard-model particles were large enough to explain their abundance in the Universe. As a result, viable models typically invoke similarly light 'dark' force carriers into which the dark matter can annihilate, and which subsequently decay into standard-model states. Because they have small masses and must interact at some level with the standard-model particles, these dark force carriers can be probed using high-intensity, low-energy accelerators[23]. Another complementary avenue is the search for teraelectronvolt-energy γ-rays produced in the annihilation of ultraheavy dark-matter particles with the upcoming γ-ray Cherenkov Telescope Array (CTA)[24,25].

Axions

Another very popular class of dark-matter candidate is that of axions and axion-like candidates. Quantum chromodynamics (QCD) axions are light, very weakly coupled particles that arise as a byproduct in theories that solve the 'strong-CP problem' in QCD. The symmetries of the standard model of particle physics allow the strong nuclear force to include an electric dipole moment for the neutron, which represents an asymmetry in the charge distributions of its constituent quarks. However, measurements indicate that the neutron electric dipole moment is about 10^{-10} times smaller than expected, which necessitates a dynamical explanation. The dynamics that would cancel the neutron electric dipole moment also produces a new particle: the axion[26].

Many constraints exist on axions and axion-like models. A class of searches typified by the Axion Dark Matter Experiment (ADMX)[27] uses a magnetic field to convert the background of axions on Earth into an electromagnetic signal. Such searches have successfully excluded a window of axion parameter space with masses around 2 meV, and future measurements are expected to probe masses up to about 40 meV. In addition, there is vigorous theoretical activity exploring new ways to probe a wider range of axion masses[28–30].

Sterile neutrinos

Another well motivated candidate is the sterile neutrino, which experiences a diluted form of the weak nuclear force through mixing with 'ordinary' active neutrinos. Such particles are typically included in theories that explain experiments that have found neutrinos to be massive, in contrast to the predictions of the standard model. Although their residual weak interactions indicate that sterile neutrinos will ultimately decay if both their mass and mixing are small enough, this decay may occur slowly enough so that they remain in the Universe today as a form of dark matter. Such neutrinos can be produced in the early Universe through a variety of different physical mechanisms[31–34] with an appropriate abundance.

Although the lifetime of a sterile neutrino playing the role of dark matter must be long enough so that the vast majority of such particles have not yet decayed, quantum mechanics dictates that some will decay more rapidly, leading to a source of mono-energetic photons with energy close to half of the neutrino mass. In fact, an unidentified emission line at 3.5 keV in the stacked X-ray spectrum of 73 galaxy clusters might be a hint of the decay of sterile neutrinos[35], although debate about the origin of this line is still ongoing[36]. Future X-ray telescopes, such as eRosita, X-ray Astronomy Recovery Mission (XARM), Athena and Lynx, should help to clarify the origin of this emission[37], and future accelerator searches, such as with the Separator for Heavy Ion reaction Products (SHIP), will provide a complementary probe of the relevant parameter space.

No stone left unturned

There is a plethora of other possible explanations for the nature of dark matter (see Fig. 1 for a diagrammatic representation), including fuzzy dark matter (10^{22} eV), gravitationally produced WIMPzillas[38], superfluid dark matter[39], macroscopic objects such as macros (10^{22}–10^{24} g)[40] and primordial black holes ($10M_\odot$, where $M_\odot$ is the mass of the Sun). Therefore, the new guiding principle should be 'no stone left unturned': we should look for dark matter not only where theoretical predictions dictate that we 'must', but wherever we can. Casting a wider theoretical net offers the possibility of discovering new classes of dark-matter candidates and new experimental opportunities to search for them, and also helps assemble a 'composite image' of everything that we currently know about the space of possibilities that are consistent with existing measurements.

Probing dark matter with astronomical observations

Departures from the lambda cold dark matter model

Given the current absence of evidence for dark-matter particles from laboratory experiments, it is of utmost importance to extract as much information as possible from astronomical observations. Dark-matter couplings other than that of gravity with itself or with standard-model particles, or a non-negligible velocity dispersion, could lead in principle to measurable differences between observations and lambda cold–dark matter (LCDM) model predictions[41]. It is generally important to search for 'cracks' in the LCDM model by carefully testing its underlying assumptions and observational predictions. An intriguing example is the discrepancy at the 3.7σ level between cosmological[3] and local measurements of the Hubble constant[42]. We stress that systematic errors in observations, or mismodelling of specific physical processes, should not be mistaken for failures of the underlying LCDM model. It is perhaps not a surprise in this sense that most of the claimed problems of standard cosmology, such as the cusp–core, too-big-too-fail and missing-satellites problems[41], arise in the deeply nonlinear regime. Model predictions are in this case based on numerical simulations that encode complex processes, such as stellar formation and supernova and black-hole feedback, by means of an effective 'sub-grid' description[43], which is by construction a potential source of systematic errors. This should not of course deter us from extensively testing the predictions of standard cosmology by exploiting the wealth of information that will arise from upcoming astronomical surveys—such as those using the Large Synoptic Survey Telescope (LSST), Dark Energy Spectroscopic Instrument (DESI), Euclid and the Wide-Field Infrared Survey Telescope (WFIRST)—while improving the quality and predictive power of numerical simulations.

Self-interactions

A key property of dark matter that astronomical observations might help disproving is its collisionless nature. Dark matter self-interactions might actually help alleviate claimed tensions between numerical simulations and observations at small cosmological scales[44,45]. We can search for the imprint of dark-matter self-interactions in a number of ways. First, self-interactions can modify the shapes of dark-matter haloes[44]; in fact, they tend to make the central parts of dark-matter haloes more spherically symmetric than expected in collisionless scenarios. By comparing the shape of galaxy clusters in numerical simulations with that inferred from lensing and X-ray observations, it is possible to set an upper limit[46] on the velocity-independent, elastic cross-sections σ of self-interacting dark matter of mass m: $\sigma/m \approx 1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$. Only very recently the first full simulations of galaxy clusters that incorporate both baryonic processes and dark-matter self-interactions have been obtained[47]. Although much remains to be understood, it is encouraging that these simulations appear to support the analytical models tying the properties of self-interacting dark matter to the observed distribution of baryons[48].

Second, the trace of dark-matter self-interactions could be found in merging systems such as cluster mergers and minor infalls[49,50]. The observables in this case would be the offset between the galaxies and the dark matter (in addition to the offset between dark matter and gas) due to the possible non-collisional nature of dark matter[51], and the amount of 'sloshing' and 'wobbling' of galaxies around the centre of the dark-matter halo[41,52]. As in the case of halo shapes, it is urgent to further investigate the complex interplay between gas cooling, active-galactic-nuclei feedback and dark-matter physics using full hydrodynamical simulations, and understand the mapping between the

Fig. 1 | Possible solutions to the dark-matter problem. Visualization of the possible solutions to the dark-matter problem in the form of a mind-map diagram. The label 'little Higgs' refers to dark-matter candidates that arise in the framework of little Higgs models[1] and 'extra dimensions' indicates candidates related to theories with extra space dimensions[1]. TeVeS, tensor–vector–scalar theory; MOND, modified Newtonian dynamics; MaCHOs, massive compact halo objects[1].

properties of self-interacting dark matter and observables, in preparation for the wealth of observational data that will arise from upcoming astronomical surveys.

Substructures

A generic key property of dark matter in the standard cosmological model is that it is cold—that is, non-relativistic—at the epoch of structure formation and has a free-streaming length much smaller than the size of galaxies. This implies the existence of a large number of sub-dwarf galaxy dark structures in galactic haloes. If dark matter is warm or, more generally, if its power spectrum is suppressed at small astrophysical scales, then we might identify it by probing the actual number of substructures in the Universe. A powerful probe of the power spectrum at small scales is the Lyman-α forest in the spectra of high-redshift quasars[53]. This technique allows us to set a 2σ lower limit of 5.3 keV on the warm-dark-matter particle mass[54] and a 2σ lower limit of 37.5×10^{-22} eV on the mass of fuzzy-dark-matter particles[55]. Observations with the future high-resolution spectrograph of the European Extremely Large Telescope (E-ELT) and with low-resolution, low-signal-to-noise-ratio quasar spectra measured by DESI should allow to substantially improve the current bounds thanks to a larger statistical sample and a better determination of the thermal state of the intergalactic medium.

Another interesting strategy to detect these dark substructures is the search for perturbations induced by sub-dwarf galaxy clumps on cold stellar streams[56–58]. Thanks to surveys such as Gaia, which is currently taking data, and LSST, it should be in principle possible to detect impacts induced on stellar streams by subhaloes with masses[59] as low as $10^7 M_\odot$. By analysing the power spectrum of the fluctuations of the stellar density, stream observations might even enable us to probe subhaloes with masses[58] down to $10^5 M_\odot$. This method should allow us to set stringent constraints on the mass of thermal dark-matter relics using LSST data, and possibly yield an actual measurement of the dark-matter particle mass if this mass[60] is of the order of 1 keV.

A more direct way of detecting dark-matter substructures is via gravitational lensing. Although dark-matter subhaloes are not compact enough to be detectable, for example, with microlensing searches, they can modify the flux ratio of multiply lensed quasars[61–64] and are potentially detectable via gravitational imaging, as a perturbation of magnified arcs and Einstein rings[65]. In addition to lens substructures, low-mass dark-matter haloes along the line of sight of the lens can act as perturbers and dominate the signal by an amount that depends on the lensing configuration and the dark-matter properties[66]. This field will soon be revolutionized by upcoming astronomical surveys. The LSST, for instance, is expected to detect more than 8,000 lensed quasars, 13% of which are predicted to be quadruple lenses[67], which should allow us to probe the subhalo mass function below $10^8 M_\odot$, whereas observations in the optical and near-infrared wavelengths with Euclid and the E-ELT, as well as in radio wavelengths with the Atacama Large Millimeter Array (ALMA) and the global Very-Long-Baseline Interferometry (VLBI) instruments, should allow us to probe the subhalo mass function at high redshift[68].

Gravitational wave portal

Primordial black holes

The detection of gravitational waves[69] has opened up new opportunities to explore the physics of dark matter[70]. It has been suggested that the binary black holes whose merger produced the gravitational waves detected by LIGO might be primordial, that is, they might have formed in the very early Universe, before Big Bang nucleosynthesis[6,7,71]. The rate of binary black-hole mergers would however be too high if such primordial black holes made up all of the dark matter in the Universe[72–74]—a possibility that is also disfavoured from a variety of constraints, including the dynamical heating of dwarf galaxies, distortions of the cosmic microwave background, supernova lensing, and radio and X-ray emission due to the accretion of interstellar gas onto primordial black holes[75]. Although such constraints are becoming stringent, it is important to search for these objects, even if they represent a subdominant component of dark matter. For instance, if we discovered a population of primordial black holes in the Universe, we would know that dark matter is not made of WIMPs, otherwise we should have already detected the annihilation radiation produced by WIMPs around them[76]. A number of observations, such as the identification of black holes lighter than $1M_\odot$ or the existence of black holes at a redshift greater than[77] 40, may in principle provide strong evidence for the existence of primordial black holes.

Constraints on modified gravity

Since a pioneering work on modified Newtonian dynamics published in 1982[78], numerous attempts have been made (for example, with modified gravity approaches such as the modified gravity model (MOG)[79] and emergent gravity[80]) to eliminate dark matter by modifying Einstein's theory of general relativity. The success of these efforts, however, remained limited to the rotation curves of galaxies, and it is today clear that the only way that these theories can be reconciled with observations is by mimicking the behaviour of cold dark matter on cosmological scales effectively and very precisely. The coincident observation of gravitational waves and electromagnetic radiation from GW170817[81] has allowed us to set very stringent constraints on the propagation velocity of gravitational waves. The fact that this velocity does not differ from the speed of light by more than one part in 10^{15} severely constrains all modified-gravity theories in which gravitational waves travel on different geodesics with respect to photons and neutrinos[82–84]. This has in particular allowed us to rule out Bekenstein's tensor–vector–scalar theory[85].

Black-hole environment

Interestingly, dark matter might manifest itself as a perturbation in the waveform of binary black holes. If dark matter is made of cold and collisionless particles, then their density around black holes will inevitably be higher (possibly much higher) than their average density in the Universe. In particular supermassive black holes at the centre of galaxies might host dark-matter 'spikes'[86], although dynamical effects, such as mergers with other black holes and interactions with stellar cusps, might disrupt them[87,88]. Large dark-matter overdensities are possible around intermediate-mass black holes[89] and around primordial black holes[90]. The presence of dark matter around black holes would modify the dynamics of the merger and induce a potentially detectable dephasing in the waveform[70]. If dark matter is made of ultralight bosons, as in the aforementioned case of fuzzy dark matter, the field 'cloud' that forms around black holes with masses comparable to the Compton wavelength of bosons can be revealed in the gravitational-wave signal from single or binary black holes through direct monochromatic emission, stochastic background or gaps in the black-hole mass–spin Regge plane[91–93]. Future analyses will allow to further elucidate possible 'environmental' effects due to dark-matter particles and to discriminate among different dark-matter models[70].

The future

In the quest for dark matter, naturalness has been the guiding principle since the dark-matter problem was established in the early 1980s. Although the absence of evidence for new physics at the LHC does not completely rule out natural theories, we argue that a new era in the search for dark matter has begun, with the new guiding principle being 'no stone left unturned': from fuzzy dark matter (10^{-22} eV) to primordial black holes ($10M_\odot$), we should look for dark matter wherever we can. It is important to fully exploit existing experimental facilities—most notably the LHC, whose data might still contain some surprises—and to complete the search for WIMPs with direct-detection experiments until their sensitivity reaches the so-called neutrino floor[94].

At the same time, we believe that it is essential to diversify the experimental effort and to test the properties of dark matter with gravitational-wave interferometers and upcoming astronomical surveys because they can provide complementary information about the nature of dark matter. New opportunities in extracting such information from data arise from the booming field of machine learning, which is currently transforming many aspects of science and society. Machine-learning methods have been already applied to a variety of dark-matter-related problems, including the identification of WIMPs from particle and astroparticle data[95,96], the detection of gravitational lenses[97], radiation patterns inside quark and gluon jets at the LHC[98] and real-time gravitational-wave detection[99]. In view of this shift of dark-matter searches towards a more data-driven approach, we believe that it is urgent to fully embrace and, whenever possible, to further develop big-data tools that allow us to organize in a coherent and systematic way the avalanche of data that will become available in particle physics and astronomy in the next decade.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-018-0542-z

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Additional information

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Correspondence and requests for materials should be addressed to G.B. or T.M.P.T.