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Dark matter searches: Status and prospects

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In this proceeding, I give a broad overview on the current status of dark (DM) matter searches focusing on the latest developments of interest for the ICRC community. I start with revising what we know about this mysterious component which accounts for more than 25% of the whole matter-energy in the current universe. In particular, I explain what do cosmic probes tell us about the DM nature. I then provide the reader with some basics theory motivations of some of most relevant DM candidates, including *high-priority* targets and their extension. This theory overview is meant to illustrate the variety of the DM landscape. Finally, I offer a complementary approach to break the parameter space, based on the signatures these candidates leave in astroparticle observables. Focusing on specific examples I will show how one can use high-energy astrophysics to shed light onto the nature of DM.

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1. Dark matter in the universe

There is mounting evidence from kpc-sized galaxies up to cosmological scales which suggests that the majority of pressure-less matter in the universe is of non-baryonic nature. Representing about 27% of the total energy-matter content of the present universe, DM has played a key role in the evolution of the universe and the formation of large scale structures as we see them today. And it is indeed thanks to astronomical and cosmological observations that we do infer the existence of DM and its main properties. However, while the DM gravitational impact is well measured, its nature remains a mystery.

I collect below a non-exhaustive list of open questions in the DM quest, which have been compiled by the community in [1–3]:

- Is there cosmic evidence to go beyond the cold and collisionless paradigm?
- How is DM produced in the early universe, and how does this connect to late universe observables?
- Is DM fundamentally wave-like or particle-like?
- Is there a dark sector containing other new particles and/or forces? Does DM have important self-interactions?

From cosmic observations, we have identified the allowed properties of DM. The dominant component of DM in the universe must be: Produced sufficiently non-relativistically, i.e *cold*; stable or sufficiently long-lived; smoothly distributed at cosmological scales – although some degrees of granularity are still allowed at galactic scales –, sufficiently heavy, to behave *classically* in astrophysical systems. If it is a particle, it should be dark and dissipationless, i.e. with weak electromagnetic interactions, and, more generally, not very much interacting with the Standard Model (SM) sector of particle physics, i.e. not very collisional. Undoubtedly, the DM evidence requires new physics beyond *standard* theories.

A minimal scenario where DM is a new particle beyond the ones in the SM, and is stable, non-relativistic, and collisionless, i.e. the cold DM (CDM) model, is sufficient to explain this cosmic evidence. Nonetheless, the fundamental properties of the DM particles, such as mass, spin, interaction(s), and production mechanism(s), remain unspecified or, yet, a non-particle nature of DM it is still possible in light of astronomical and cosmological observations. A crucial discriminant for the microscopic properties of DM is its macroscopic distribution at galactic scales. Indeed, depending on its fundamental nature, many DM candidates can leave very specific imprints on observables such as the matter power spectrum, and/or the mass spectrum, distribution, and density profiles of DM halos, and, in general, predict a failure of the CDM paradigm at small scales.

In figure 1, I show the qualitative behaviour of the linear matter spectrum and some benchmark cases of DM models to show how sizeable imprints can be left of this cosmic observable by alternative models which can break CDM at small scales. Distinguishing CDM from models such as fuzzy DM, axion strings and sterile neutrinos is in the reach of future cosmic survey projects such as Rubin LSST and stage 5 spectroscopic surveys (Spec-S5). By using these upcoming cosmic probes, we will therefore be able, for example, to learn how warm (i.e. not non-relativistic) DM is during structure formation, if and how much of it is not collisionless, i.e. self-interacting. Moreover,

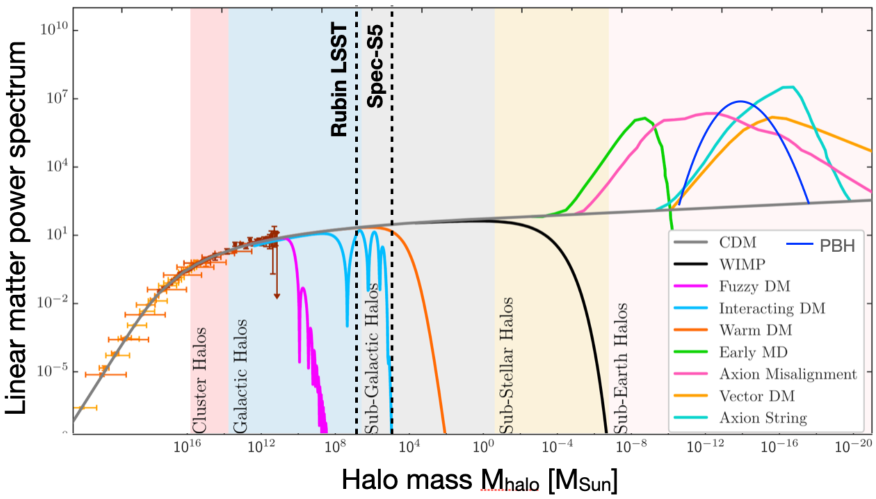

Figure 1: The dimensionless linear matter power spectrum: Current data (orange and dark-red points), CDM prediction (black line) and theoretical predictions from some exemplary models of alternative DM candidates which can break CDM at small scales (coloured lines). I also report the reach (in halo mass) of future cosmic surveys, such as Rubin LSST and a prototypical spectroscopic survey stage 5 (Spec-S5), as dashed vertical lines. Adapted from [2], with reach of future cosmic survey projects taken from [1] and primordial black holes (PBHs) power spectrum inferred from [4].

we will be able to gain insight onto its wave-like vs particle-like nature, and possibly its production mechanisms. Finally, with the ability to probe the matter power spectrum at very small scales, also the non-particle nature of DM can be tested. Among many others, one of the main theoretical challenges is disentangling DM imprints from effects of more mundane baryon physics. To this end, both theoretical and numerical developments for galaxy formation simulations are required.

2. Theory motivations, DM candidates and search status

No matter what DM ultimately is it should have been produced in the early universe. In the standard paradigm of particle DM, there exists, at least, two very plausible scenarios for how the DM could be produced in the early universe.

The first one is the *thermal freeze-out*: If DM has sizeable interactions with SM particles, the theory of the Hot Bing Bang and the successful description of the evolution of the universe as a thermodynamical system [5] –which can explain, among others, the formation of light elements during the Big Bang Nucleosynthesis and of the cosmic microwave background– predict that all particles in equilibrium within the primordial thermal bath decouple from it and are present today, as thermal relics of the early universe. For non-relativistic relics, as for example weak-scale particle DM candidates, the present cosmological abundance is set by the annihilation cross section averaged over the velocity distribution of particles at decoupling, i.e. the moment at which the interactions among DM particles and SM ones are not sufficient any longer to counteract the dilution in their number density due to the expansion of the universe. Very well known candidates produced via thermal freeze-out are the, so-called, Weakly interacting massive particles (WIMPs), whose existence independently offers a solution to the electroweak hierarchy problem in particle physics.

The second mechanism is the *mis-alignement mechanism*: When a bosonic DM field is displaced from the minimum of its potential, it rolls to the minimum releasing the initial vacuum energy as CDM. In this case, the DM abundance is set by the shape of the potential and by the initial displacement of the field [6]. This is the way in which QCD axions can be produced in the early universe. Initially postulated to provide a solution to the strong-CP problem, i.e. to explain the mysterious vanishing of the neutron electric dipole moment, axions arise when the strong CP-violating phase is promoted to a dynamical axion field. QCD axions represent quite appealing DM candidates.

Following the Snowmass community planning exercise [1], these main production mechanisms of DM in the early universe identify two major DM *high-priority* candidates, whose search has been tackled through a *delving deep* approach with terrestrial and astroparticle experiments. I provide below a quick (surely not exhaustive) summary of the status of current searches for WIMPs and axions, as well as of the reach of planned experiments.

2.1 Weakly Interacting massive particles

WIMPs between 1 GeV up to 100 TeV couple to SM particles through electroweak-bosons-mediated interactions (H, Z). Direct detection experiments, looking at recoil signatures in underground detectors as a consequence of the scattering of DM particles with target nuclei, are nowadays almost excluding Z-mediated couplings and strongly constraining the H-mediated ones [7]. Similarly goes for the indirect detection strategy, which aims at detecting fluxes of cosmic particles produced in astrophysical environments by DM decay and/or annihilation. For WIMPs, gamma rays and charged cosmic rays are setting among the strongest constraints to date. Nonetheless, there is still part of the parameter space that remains to be probed [8]. In figure 2, I report projection plots adapted from [**?**]. In the left panel, we can see what are the values of the spin-independent scattering cross section with nucleons currently excluded by direct detection as a function of WIMP mass, the reach of currently-operating (e.g. LZ, XENONnT in green) and future experiments (e.g. SuperCDMS, DarkSide-20k in blue and yellow). Similar constraints are also set on the spin-dependent DM-nucleon cross section. In this parameter space, competitive limits come from the search of a DM-induced neutrino flux from the Sun and the Earth. In the right panel, instead, I show the currently excluded region for annihilating WIMPs, i.e. the velocity-averaged annihilation cross section as a function of DM mass. Below 1 TeV the most competitive limits come from searches of DM signals from dwarf spheroidal galaxies with the *Fermi*-LAT, in the anti-proton fluxes measured by AMS-02, and from the radio emission of the Large Magellanic Cloud. Above 1 TeV, gamma rays from the H.E.S.S. imaging air Cherenkov telescope array are key to probe thermally produced TeV-scale WIMPs, up to the unitarity bound.

2.2 The QCD axion

The axion is a good cold DM candidate if the Peccei-Quinn scale f_a is of the order of $10^{10} - 10^{13}$ GeV. The misalignment production mechanism sets a fundamental connection between Peccei-Quinn scale and axion mass, so that DM axion is expected to have a mass around $10^{-5} - 10^{-3}$

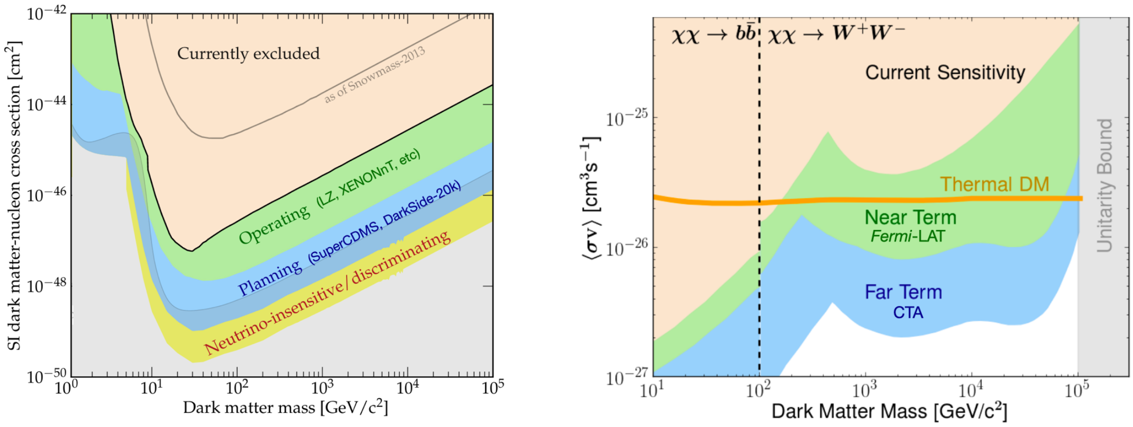

Figure 2: *Left:* Direct detection limits and projections on WIMPs for the spin-independent (SI) scattering cross section on nucleons. *Right:* Indirect detection limits and projections on WIMPs for the velocity-averaged annihilation cross section. Adapted from [1].

eV, as also confirmed by simulations of axion production in pre- and post-inflationary scenarios. In terms of experimental efforts, a range of innovative techniques has been developed to search for QCD axions. One prominent method involves the use of haloscopes. These experiments detect axions by observing their conversion into photons within a strong magnetic field. Notable haloscopes include the Axion Dark Matter Experiment (ADMX), HAYSTAC, and DMRadio, which are designed to detect these photon signals resulting from axion conversion. Another approach is employed by helioscopes, which search for axions produced in the Sun's core. The CERN Axion Solar Telescope (CAST) and the future International Axion Observatory (IAXO) are leading examples of such experiments, aiming to detect solar axions via their conversion in magnetic fields. Additionally, pulsar-based searches represent another avenue for detecting axions [9]. These new (indirect) probes focus on investigating axion production and conversion within the magnetospheres of pulsars, utilising radio telescopes such as the Green Bank Telescope to identify signals from axion interactions in these highly magnetised environments. Collectively, these varied experimental efforts reflect a comprehensive search program aimed at probing the axion DM scenario. Through these methods, researchers continue to advance our understanding of axions and their potential role in the DM landscape. Figure 3 (left) summarises the current status of axion searches, which are touching the QCD axion predictions. The figure is taken from `https://github.com/cajohare/AxionLimits`.

2.3 Broadening the landscape: Dark sectors, axion-like particles & primordial black holes

Theoretical exploration has recently extended beyond the traditional DM models to encompass a broader scenarios that can include additional particles and forces. This theoretical activity has progressed in parallel to the development of new experimental opportunities to provide sensitivity to the new theory-space.

One approach involves portal DM models, which introduce messengers that interact weakly with the SM sector. These models range from very simple extensions of the SM containing a single new particle to complex dark sectors containing multiple dark matter states, even towers of

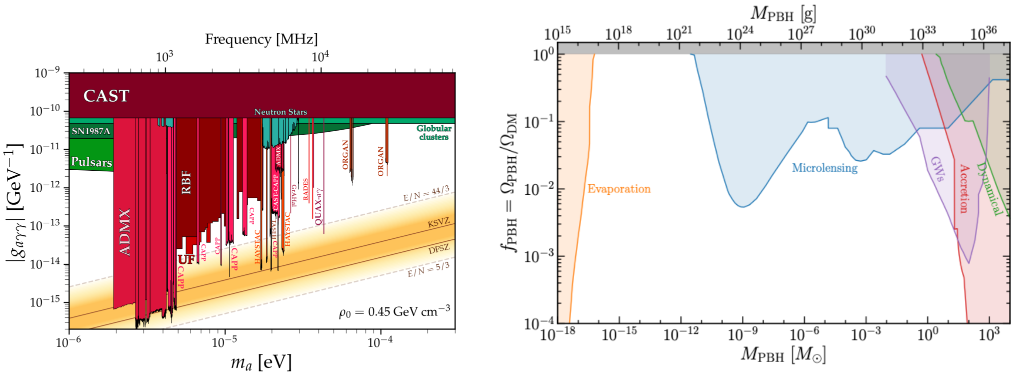

Figure 3: *Left:* Summary of QCD axion searches through haloscopes, helioscopes and pulsars-based probes. Figure from `https://github.com/cajohare/AxionLimits`. *Right:* Summary of PBHs searches, taken from [10].

dark particles that could constitute several different components of dark matter simultaneously, see e.g. [11]. For instance, vector messengers, such as massive dark photons, can interact with SM particles through kinetic mixing with the hypercharge field strength portal. Scalar or pseudo-scalar messengers, such as dark Higgs particles, can mix with the SM Higgs through the mass portal. These models offer new ways to explore DM interactions and can be tested through experimental searches for new particles and forces. For a recent review on light DM candidates see [12]. Thermal production of DM particles can occur across a range of masses, from eV up to GeV, but constraints from Big Bang Nucleosynthesis (BBN) limit feasible DM production below 1 MeV [13]. Low-mass particles should be produced non-thermally, through for example dark phase transition at low temperatures or freeze-in at low reheating temperatures. In the keV mass range, sterile neutrinos remain a viable DM candidate, offering another avenue for exploration [14]. The search for light DM involves collider, direct and indirect detection methods, each with its own set of challenges. Direct detection of light DM aims to observe extremely low recoil energies in the μeV to keV range. Calorimetric detectors are particularly well-suited for this purpose, but detecting DM interactions requires overcoming significant experimental challenges, see e.g. [15]. In the sub-GeV mass range, Indirect detection limits already generically rule out the simple thermal freeze-out scenario for s-wave annihilation. But p-wave models (most of the portals) remain still viable. The challenge for light DM searches is overcoming the, instrumental, MeV sensitivity gap. Searches in the MeV band have the potential for sufficient sensitivity to probe thermal freeze-out even when the dominant annihilation is p-wave, see contributions in [11].

Axion-like particles (ALPs) represent another extended category of DM candidates. These light particles, with masses as low as ZeV and very weak couplings with SM particles, offer yet another broad, theoretical landscape [16]. Unlike QCD axions, ALPs do not address the strong CP problem but are prevalent in many extensions of the SM. Their detection involves diverse experimental approaches, including searches for interactions with photons and other particles. In this context, astrophysical searches are very powerful in constraining both light ALPs with masses below the neV – looking for the signatures of ALPs converting into photons (and vice-versa) in external magnetic fields, such as the Galactic one –, and heavy ALPs DM decaying into photons in the early universe or in the Galactic halo.

Finally, primordial black holes (PBHs) offer another intriguing possibility for DM. For a complete review, I refer the reader to [10]. They formed via the collapse of large overdensities from inflation in the early universe, before matter-radiation equality. As an example, inflation can provide a mechanism for generating primordial perturbations, via quantum fluctuations of scalar fields. The threshold for collapse depends significantly on the shape of the density perturbation, while the PBH abundance is linked to the form of the primordial power spectrum. PBHs are subject to Hawking evaporation, which implies that PBHs can have lifetimes longer than the age of the universe, and so be good DM candidates, if their masses exceed 10^{14} g. On cosmological scales, PBHs behave like cold DM, but they can exhibit granularity at Galactic scales. Searches for PBH DM extend over a broad mass range, and are very diverse: searches for evaporation products in fluxes of cosmic particles, microlensing and structure formation observables, imprints in gravitational wave events, etc. So far, there is only one remaining window for PBH to contribute to all the DM in the universe: The so-called asteroid-mass gap. If PBHs have masses between $\sim 10^{17}$ g and 10^{20} g there is currently no robust observational probe able to exclude them. A summary of the current status is presented in figure 3 (right), taken from [10].

3. Using astroparticle observables to break down the parameter space

The theoretical DM landscape is undoubtely very diverse. A way to break-up this vast parameter space is by focusing on signatures and observables, and in particular astroparticle ones. How DM interact with the environment defines different search strategies that are then declined specifically for each of the candidates depending on the signatures these models can entail.

3.1 The gamma-ray diffuse emission

Gamma-ray diffuse emission is observed from energies $O(100)$ keV with INTEGRAL/SPI, up to the highest energies with LHAASO and Tibet ASγ. In the standard paradigm, the gamma-ray sky should evolve in energy from being dominated by photons produced in collisions of cosmic rays with gas and ambient radiation at the lowest energies, to a sky where high-energy Galactic gamma-ray emitters (above and below the telescopes source-detection threshold) are the main contributors. Evidence for additional DM signals can be looked for on top of these astrophysical backgrounds. Here, the main challenge is understanding the contribution of diffuse cosmic-ray processes as well as point sources. The multi-messenger connection can play a key-role in this respect. Most remarkably, anomalies in the gamma-ray sky are present, like the so-called *Fermi* GeV excess. This mysterious emission detected in the data of the LAT telescope towards the Galactic center more than 15 years ago remains one of the major mysteries of gamma-ray astrophysics, see [17] for a review. As mentioned above, soft gamma rays are of utmost importance to probe light DM but also PBHs. The soft gamma-ray diffuse emission was recently measured up to 8 MeV with INTEGRAL/SPI [18], and exploited to set constraints on cosmic-ray transport at MeV energy but also on exotic emission mechanisms: particle and non-particle DM [19–21]. At the highest energies, the PeV frontier represents another promising area for DM searches. In this case, observations probe heavy DM candidates, mostly decaying into the SM particles and produced non-thermally in the early universe. Recent analyses exploiting Tibet ASγ and LHAASO diffuse gamma-ray emission measurements have demonstrated that strong constraints on PeV DM can be obtained [22, 23]. Theoretical challenges at these energies are represented by the limited knowledge on the production and propagation of ultra-high-energy gamma rays, as well as by the modelling of DM signals at energies well above energies achievable at colliders.

3.2 Local cosmic-ray fluxes

Recent advancements in the precision of local cosmic-ray measurements have significantly enhanced our ability to test and constrain DM signals. Among these, anti-protons have emerged as the most effective tool to date for constraining the properties of weak-scale particle DM. The relatively well-understood background of secondary anti-proton production [24] allows for tighter constraints on any excess that could be attributed to DM, e.g. [25]. The correlated signal of heavier antinuclei, such as anti-deuterons (anti-d) and anti-helium (anti-He), offer a promising avenue to set stringent limits placed on DM [26]. Upcoming experiments, notably the General Antiparticle Spectrometer (GAPS), are expected to improve our understanding of anti-proton (anti-p) and anti-deuteron fluxes, particularly in the low-energy range below 200 MeV. However, the prediction of DM-induced anti-He flux remains highly uncertain, with the potential for new production channels that have not yet been fully explored. Finally, leptons, particularly electrons and positrons, present additional challenges for DM detection. While there is a notable hardening of the positron fraction at high energies – a potential signature of DM – there are also discrepancies in the expected secondary production of these particles at lower energies. This complexity makes it difficult to unambiguously attribute observed features to DM processes, in favour of an astrophysical origin from Galactic pulsars and pulsar wind nebulae [27]. On the theoretical front, a significant challenge lies in accurately modelling the production of electrons and positrons from local astrophysical sources, such as pulsars and their associated halos. A better understanding of these sources is crucial for disentangling potential DM signals from astrophysical backgrounds, which is necessary for refining the interpretation of cosmic ray data in the context of DM research [28].

3.3 Light messengers from celestial objects

The concept that DM can be captured by celestial bodies through scattering off nucleons and electrons dates back to the 80s [29]. In Galactic halos, DM particles can interact with the nuclei (or electrons) within celestial objects, causing them to lose energy and eventually become gravitationally bound to the object. This process, known as thermalisation, leads to the accumulation of DM within the celestial body. Evaporation plays a crucial role in determining whether DM can accumulate in a celestial object. The hotter the object, the higher the mass required for DM particles to avoid evaporation. As a result, evaporation sets a lower limit on the DM mass necessary for accumulation to occur [30]. Different types of celestial objects, such as planets, neutron stars, white dwarfs, and brown dwarfs, can be exploited to study DM capture. The interaction of DM with these objects depends on the nature of the DM interactions and the subsequent states that result. For example, if SM particles emitted by DM interactions get absorbed in the planet or stellar interior, this can cause extra heating of the object observable in the infrared and optical spectra. On the other hand, if DM consists of feebly interacting particles, these may escape the object, leading to the emission of neutrinos and gamma rays as signatures of their production in the star or planet. This signature is expected for example when DM annihilate into light mediators or can arise in

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core-collapse supernovae, where ALPs and other feebly interacting particles might be copiously produced. Celestial body capture has provided so far bounds competitive to DM direct detection for sub-GeV masses.

4. Conclusions

In conclusion, the search for DM requires new physics beyond the SM. The landscape of particle and non-particle models is vast and diverse, demanding a comprehensive approach to exploration. Current strategies emphasize a "delve deep, search wide" methodology, aiming to probe both classical WIMPs and QCD axions in the coming decade. Astroparticle observables play a crucial role in detecting DM and exploring different models. A diversified experimental program, coupled with advances in theoretical understanding, will continue to push the boundaries of DM research and uncover new opportunities for detection.

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