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Gravitational searches for dark matter

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Abstract

Complementary to (or in the absence of) electromagnetic, high-energy astrophysical signatures, or direct detection of dark matter, another important test of its nature relies on looking for small-scale gravitational signatures. Such gravitational probes of dark matter on different astrophysical scales, are instrumental to bracket the theory space of dark matter scenarios. These probes will be decisive to test the cold dark matter scenario against alternatives, as well as scenario configurations in which the dark matter includes compact or dense small-scale objects.

1 Introduction

Disclaimer: many references are missing, and the domain is not fully covered in this contribution — see a more complete review in e.g. [1].

The cold dark matter (CDM) scenario leads to a compelling paradigm for structure formation, and allows to make sense of astrophysical observations from galactic to cosmological scales. However, in spite of well-identified scenarios motivated by theoretical particle physics beyond the standard model (BSM) [2], e.g. WIMP, QCD axion, or sterile neutrino dark matter, none has yet been confirmed experimentally. While part of the relevant parameter space has not been fully explored, past and present complementary searches have pushed the observational sensitivity such that these models are either about to lose relevance or about to be discovered. Besides, if one inspects the predictions of structure formation (here led by cosmological simulation studies) on small, subgalactic scales, there are hints for tensions between CDM predictions and observations [3]. In particular, the existence of both cored or cuspy dark matter density profiles in galaxies of similar masses, with a significant scatter, is difficult to explain even if baryons can generate efficient feedback and lead to core formation when the baryonic budget is sufficient: this is called the diversity problem, which is a refined formulation of the core-cusp problem. Besides, the gravitational pulls exerted by baryons and dark matter seem to be quite correlated. It is even harder to explain diversity on the one hand, and such a regularity on the other hand.

It is not clear yet whether such small-scale problems could be related to a lack of accuracy in the treatment of baryons in hydrodynamical cosmological simulations, and this issue currently represents an exciting challenge in this field. Part of the difficulty is the very non-linear aspect of the problem, where physics on very small scale (sub-pc here) can have impact on much larger scales. However, these issues, together with the unsuccessful searches for CDM (or WDM) candidates so far, have motivated alternatives to CDM, mostly along two classes: ultra-light dark matter (ULDM), where cores arise from quantum pressure set by the de Broglie wavelength of very light scalar dark matter [4], or self-interacting dark matter (SIDM), where cores are formed as a result of self-heating [5]. Note that another class of model, that of primordial black holes (PBHs [6, 7]), could have properties similar to SIDM due to gravitational self-interactions between these compact objects at the centers of galaxies (short relaxation time [8]). PBHs as viable dark matter candidates[1] were fully revived after the first detection of gravitational waves (GWs), which pointed toward unexpected masses for the progenitors [10]. Finally, there is actually no reason why dark matter could not be made of several types of such exotic proposals, which, interestingly enough, may completely change the current constraints on individual scenarios [11].

Irrespective of any electromagnetic or high-energy signature of dark matter [12], all these scenarios often lead to different gravitational imprints, which provides additional handle on the nature of dark matter — it is maybe worth recalling that so far, dark matter has only been evidenced through its gravitational effects. The strongest gravitational imprint is that of GWs, currently a nice probe of the merging of exotic massive compact objects like PBHs [13] or boson stars [14] (of any mass scale around the solar mass and above)—this field will strongly evolve in the future with increasing sensitivity, the growing use of pulsar arrays (e.g. with SKA), and cutting-edge space experiments like LISA. Another direct gravitational probe is that of lensing, which can explore dark matter features on many different scales, from exotic compact objects (microlensing) up to cosmological scales (strong lensing, weak lensing of galaxy clusters and of the CMB). Indirect gravitational imprints related to the different structuring properties of different scenarios on small (subgalactic) scales concern precise measurements of dark halo shapes (core-cusp issue), the search for subhalos (CDM vs. alternatives), and measurements of the (dark) matter power spectrum (CDM vs. alternatives). In the former cases, one relies on kinematic/phase-space studies based on accurate astrometric data (Gaia, LSST, etc.), which allow to probe the gravitational potential of target systems and perturbations thereof induced by dark matter components. The latter case is based either on the counting of structures, or on studies of the angular power spectra of observables sensitive to the matter power spectrum (CMB, Ly-α, 21 cm, etc.).

In this document, we provide a short (and likely biased) review of targets and observations that are and will be important to assess the nature of dark matter. Among the big experimental projects supported by IN2P3 and directly connected to this contribution, GW experiments (VIRGO and extensions, LISA, etc.), and cosmological surveys at different wavelengths (e.g. LSST, SKA, next-generation CMB experiments, etc.), will be of prime interest. Other relevant projects to which scientists from IN2P3 may be directly or indirectly related are precision astrometry (positions and velocities, e.g. Gaia, WEAVE, etc.), interferometry (e.g. GRAVITY, EHT, etc.), and other big cosmological surveys (e.g. Euclid)—mostly supported by INSU and CNES (for space missions) in France. As pointed in previous documents, making progress in the field of dark matter searches must rely on a large diversity of expertises.

2 Dark matter structuring properties vs. dark matter candidates

The CDM scenario relies on the assumption of a collisionless fluid whose density perturbations are sourced by inflation in the early universe and collapse hierarchically in the matter era (from small to large scales) to form the structures we observed today in the form of galaxies (from dwarf galaxies to galaxy clusters) — a nearly scale-invariant power spectrum for the primordial density fluctuations is usually assumed (the simplest though not unique possibility in inflation scenarios; see the discussion on PBHs below). In this context, "cold" refers to any dark matter species which is highly non-relativistic when entering the matter era. However, in concrete realizations of this idea, for instance in terms of exotic particles, dark matter is barely infinitely cold nor fully collisionless. In thermal production

[1]We stress that the interests in PBHs are far from being restricted to the "dark matter community", see e.g. [9].

scenarios for instance[2], the power spectrum of density fluctuations is suppressed below some cutoff scale set either by free streaming (mean free path per Hubble time for thermally decoupled particles), or by collisional damping (interactions with the plasma or self-interactions which give rise to a Jeans length). This means that unveiling some cutoff in the matter power spectrum or in the structure mass function, soundly related to the primordial power spectrum in standard structure formation theory [15, 16, 17], provides some hints as for the nature of dark matter. In the CDM case, the cutoff corresponds to mass scales typically much lighter than the smallest observed galaxies, hence the interest of chasing fully dark subhalos. We emphasize that discovering dark subhalos would also allow to test the underlying inflation scenario. Indeed, while the primordial power spectrum is consistent with nearly scale invariance down to the scales of the smallest observed galaxies, it is basically unconstrained below (for wavenumbers $k > 5\,\mathrm{Mpc}^{-1}$)—departure from scale invariance is usually necessary to generate PBHs, whose formation is also boosted by phase transitions [18]; the presence of a tiny fraction of PBHs could then have strong consequences on the structuring properties of the dominant dark matter species.

CDM candidates notably include thermal dark matter with a particle mass $\gtrsim$ 0.1-1 MeV, QCD axions or axion-like particles (axions henceforth) produced from the misalignment mechanism, and PBHs — provided gravitational collapse on scales much smaller than the smallest galaxies, leading to cuspy density profiles in dark matter-dominated objects, is not prevented by self-interactions or quantum pressure. The former processes may affect thermal dark matter through the presence of quantum self-interactions (setting cores in big halos, while still possibly allowing for subhalos), or PBHs massive enough to reduce the relaxation timescale in structures by gravitational self-interactions (SIDM). Quantum pressure (related to the Compton or de Broglie wavelength) concerns ULDM, and sets incompressible cores at the centers of dark halos (preventing the formation of structures below the corresponding scale). We immediately see why being able to characterize the dark matter structuring properties on small scale acts as a strong filter for plausible scenarios.

Current constraints on the minimal clustering scale come from the existence and counting of very light dwarf galaxies ($\sim 10^8\,M_\odot$), and from the power spectrum inferred from the Ly-α forest. For thermal candidates, irrespective of their interaction channels, this corresponds to a lower mass bound of ~ 1 keV, leaving a tiny room for warmish dark matter (WDM) in the 1-100 keV thermal mass range (where usual sterile neutrino dark matter lives). For non-thermal dark matter candidates, fermions are constrained by Fermi statistics to be heavier than 0.1 keV [19, 20], while bosons are only constrained by quantum pressure to be heavier than $\sim 10^{-22}$-10^{-21} eV [4, 21, 22].

Therefore, the minimal mass scale for subhalos can range between $\sim 10^8\,M_\odot$, corresponding to the mass scale of satellite dwarf galaxies (an observational upper limit set by local observations as well as Ly-α constraints), down to $\sim 10^{-12}\,M_\odot$, with rather diverse properties for their inner concentration. An illustration of the former case would be warm, or warmish, dark matter (WDM), for instance sterile neutrinos with masses of ~ 10 keV [23], while the latter case would come about for multi-TeV WIMPs [24] or QCD axions [25]. PBHs represent a class with dark compact objects, characterized by an individual mass, and also by the minimal size expected for clusters of PBHs (containing ~ 100 objects). Note that below $\sim 10^6\,M_\odot$, dark matter subhalos are expected to be completely dark, and should not contain any gas or star [26, 27].

Besides, the core-cusp and diversity issues mentioned above would find potential solutions assuming SIDM with self-interaction cross section of $\sigma/m_{\rm dm} \sim 1\,\mathrm{cm}^2/\mathrm{g} \sim 2\,\mathrm{b}/\mathrm{GeV}$ (though constrained to have a strong velocity dependence). Therefore, the precise census of cusps and cores in galaxies provides an important test for CDM, ULDM, and SIDM altogether. Moreover, self-interactions also induce gravitational instabilities which may serve as another observational handle on SIDM [28].

Finally, since we are interested here in gravitational probes, it is important to recall that dark matter can be made of compact objects (depending on the mass scale, this can be strongly relevant to current searches with GWs). PBHs are an obvious example, and are accompanied by a series of stringent features: (i) their mass function depends of both the primordial power spectrum induced by inflation and the possible phases and phase transitions in the early universe; (ii) there is a Poissonian

[2]We will refer here as thermal dark matter to any candidate which is produced from the primordial plasma, even if it never reaches thermal equilibrium—according to this definition, WIMPs, FIMPs, sterile neutrinos are thermal dark matter candidates, while axions are not.

contribution to the matter density power spectrum which may affect the structure mass function [29]; (iii) 2-body relaxation sets the minimal size of structures (typically, the smallest structures are made of $\mathcal{O}(100)$ objects). Note that axion dark matter can also lead to the existence of compact objects, usually dubbed boson stars, though with different properties [30]. The mass and size of these objects are related to the mass and self-coupling of the axions [31, 32], and GWs may help find or constrain such exotic objects. These axion stars can also cluster through the standard processes entering structure formation, leading to a clustering mass function that may depart from predictions of CDM on very small scales [33].

It is therefore clear that unveiling the distribution of dark matter in galactic halos, finding dark subhalos, detecting exotic compact objects, or finding ways to measure the matter power spectrum beyond the reach of Ly-α will have a tremendous impact in our understanding of the nature of dark matter. Irrespective of the specific candidates, gravitational probes are obviously perfectly suited to address these goals. Moreover it is important to stress that accurately predicting and observationally measuring or constraining the (phase-space) distribution of dark matter in halos and assessing its granularity or clustering properties is of paramount importance for

- Direct dark matter searches at underground experiments or haloscopes: very sensitive to the local density of dark matter, and to the level of clustering: if a significant fraction is in the form of clumps or compact objects, this strongly alters the current exclusion curves on axions and WIMPs; for the latter, the shape of the velocity distribution has also a strong impact on the low mass threshold.

- All constraints inferred from dark matter capture by stars: sensitive to the local density, the velocity distribution, and the abundance of substructures. This includes indirect WIMP searches with neutrino telescopes toward the Sun.

- Indirect dark matter searches: the annihilating or decaying dark matter rate is sensitive to the halo shape and its granularity. Annihilation may also strongly depend on the velocity distribution of dark matter (Sommerfeld enhancement, p-wave suppression).

- The merging rate of PBHs or exotic compact objects depends crucially on clustering and its evolution, hence the sensitivity of GWs.

- Inflation: any means to probe the power spectrum on small scales will help constrain scenarios of inflation.

- Etc.

3 Fine-grained properties of dark matter in structures, and clustering statistics

The theoretical bases to estimate the mass function, concentration, phase-space distribution, and clustering properties of dark halos are rather well established. Since structure formation proceeds through non-linear processes, numerical simulations have played and are still playing a major role in our understanding of the structuring of dark matter on galactic and sub-galactic scales. This effort is ongoing [34], and many challenges are still to be faced in this domain: better understand and control the physics and impact of baryons, better investigate the alternatives to CDM (e.g. ULDM, SIDM, etc.), reduce the mass and spatial resolution down to the pc or sub-pc scale to better probe subhalos, study the detailed interplay between dark matter and baryons in the dark ages, etc. The cosmological simulation community is barely represented at the IN2P3 (but see [35]), and it is crucial to reinforce links with it to collectively progress on these issues in the context of dark matter searches. Note that on scales not resolved by current simulations, there is still a nice room left for analytical studies, which are of particular importance for dark matter searches and where IN2P3 theorists could invest some time: subhalos, clusters of compact objects, etc. We also stress that all cosmological studies related to the generation and/or evolution of density perturbations in the linear or mildly non-linear regime and in the early universe are strongly complementary to structure formation. All these topics are currently being investigated and are among current priorities.

It is worth emphasizing that cosmological simulations will never give rise to objects exactly like our Milky Way, whose components are so much constrained that it is way more consistent to build dynamically consistent mass models, still with some assumptions coming from structure formation but consistent with the observed kinematics, than using a similar virtual galaxy to make predictions. On the other hand, simulations are strongly helpful to determine the statistical properties of structures (mass function, concentration, etc.). Since many dark matter searches are focused on the dark matter lying in the Galaxy (or its satellites), another topic where gravity (its impact on dynamics) plays a decisive role is brought therefore to light: theoretical galactic dynamics [36]. Galactic dynamics allows to feature the dark matter properties from their impact on the motion of visible matter. Theoretical tools developed in this field are instrumental to identify the set of observables which will improve current constraints on the dark matter distribution in the Milky Way and its satellites. It can also help identifying dark subhalos or compact objects from their impact on the distribution of stars. Again, the IN2P3 expertise in this field is scarce, and it is crucial to establish strong link with this community to make progress. Some of the authors of this contribution have tackled these issues through both data-driven and theory-driven approaches studies [37, 38, 39]. In the theory-driven case, it is important to assess the relevance of analytical predictions by comparing with numerical simulations (the goal is to train the analytical method on simulations where all ingredients are known in full phase space, to quantify the theoretical uncertainties of the method itself before applying it to real kinematic data).

In order to really assess the sensitivity of gravitational probes, it is essential, in the meantime, to make progress on predictions of the detailed dark matter distribution and clustering properties in structures on all scales, which are model dependent (within the CDM, SIDM, and ULDM cases). Even in the CDM case, the complete characterization of dark matter subhalos on very small scales is not yet under control (tidal evolution and interactions with baryons), and there is currently a big effort to try to make progress on this aspect [40, 41, 42]. Subhalos are among priority targets in the field of indirect searches [43, 44, 45], but most predictions for Milky Way searches are currently based on irrealistic extrapolations from cosmological simulations, not consistent with kinematic constraints existing on the Milky Way dark halo—predictions for extragalactic statistics are more reliable. Some of the authors of this contribution have started to build up analytic models of dark matter subhalo populations in galaxies, and applied them to the Milky Way [46, 47, 48]. The most difficult part of such studies is to really quantify the gravitational impact of baryons (stars and galactic disks) on the subhalo population. This is a crucial step to investigate in detail as all signatures (gravitational or not) related to subhalos are affected. Moreover, since these analytical models are based upon the standard dynamics of structure formation and on gravitational interactions, they can be applied to any dark matter candidate. This topic of refining our understanding the granularity properties of dark matter halo is important to assess the possibility on singling out CDM from other scenarios on subgalactic scales.

Theoretical developments in this field are needed as many observational windows are being opened — this contribution is about the gravitational window, but there are others. Such developments should be based upon intimate collaborations between particle/astroparticle physicists (linking dark matter scenarios to small-scale properties of structures), cosmologists (linear theory and cosmological simulations), and astrophysicists (galactic dynamics, general relativity). Most authors of this contribution are involved in the GaDaMa (Galactic dark matter) project supported by the ANR (2018-2022), which precisely tries to put these different communities together, but this should obviously be generalized. IN2P3 could play a role in promoting such interdisciplinary efforts, which have to rely on complementary inputs from other CNRS institutes (see the specific contribution on general theory developments by the same authors).

4 Some promising gravitational probes

Disclaimer: The authors of this contribution have recognized expertise relevant mostly to Sect. 4.1 and Sect. 4.5, but only minor excursions to the other paragraphs which are written here to minimize the incompleteness, and also to sketch goals for future works. What concerns gravitational waves will be better described in the science report of the GDR Ondes Gravitationnelles supported by the IN2P3.

4.1 Astrometry

Being able to reconstruct to good precision the density profiles of dark matter halo and potentially its granular structure are important as (i) this helps better characterize the cusp/core or diversity problem; (ii) this reduces the astrophysical uncertainties in assessing the potential detectability of dark matter through direct and indirect searches; and (iii) this is a key to tell apart CDM from SIDM from ULDM, etc. The advent of high-precision astrometry is instrumental in this field.

There are several complementary types of measures in precision astrometry that can shed light on dark matter. We will discuss here interferometry and massive stellar surveys.

Interferometry instruments relevant to dark matter seacrches are exemplified by Gravity (VLTI) [49], and, maybe less a pure gravitational probe, by the Event Horizon Telescope [50]. Measurements made by these instruments allow to characterize the distribution of (dark) matter at the vicinity of the supermassive central black holes (SMBH) of our Galaxy, SgrA*, or a few others more distant. For Gravity, the very precise measurement of part of the orbit of only one star closely orbiting SgrA*, the star S2 [49], provided an incredibly accurate estimate of the our distance to the SMBH $R_\odot = 8.178 \pm 0.02$ kpc [51], which is about to improve a lot complementary kinematic studies about the dark matter halo [52]. This measurement also makes it possible to probe dark matter at the vicinity of the SMBH, in the form of CDM [53], or in the form of ULDM [54]. In the CDM case, indeed, there are theoretical arguments to support the possible compression of the dark halo density profile, making it spiky very close to SMBHs [55]. Beside, the Event Horizon Telescope could probe annihilation of dark matter precisely because of the gravitational effects induced by the central SMBH in M87 [56]—not a fully gravitational signature though.

On the other hand, astrometry through large-volume stellar survey is also living a breakthrough with the Gaia space mission [57]. Thanks to direct-imaging techniques, Gaia provides absolute astrometry (positions, parallaxes, and proper motions) for nearly a billion stars, with cutting-edge photometric data. This allows to probe the kinematic details of the Milky Way up to the Local Group. Such a wealth of data is a change of paradigm as for the reconstruction of the dark matter properties in the Milky Way and its neighbors. This will strongly improve our knowledge on:

- the local density of dark matter (important for direct searches of WIMPs and axions);
- the global distribution of dark matter in the Galactic halo, notably in the inward regions (a cusp or a core?) — important for indirect dark matter searches as well as dark matter interactions with stars;
- the velocity distribution of dark matter in the Milky Way;
- the presence of subhalos in the Milky Way;
- the distribution of dark matter in Galactic satellites up to all structures of the Local Group.

Important progress has already been achieved through analyses of the Gaia data [58]. There has been basically three types of results. The first type is related to genuine discoveries, the second one to data-driven modeling, and the third one to theory-driven results.

An example of the first type is the discovery of many new stellar streams [59], which are very useful tracer of the overall Galactic gravitational potential. Such streams may also have some impact on predictions of the dark matter velocity distribution, which can be empirically inspected from data-driven methods [60]. Intermediate between data-driven and theory-driven methods, one can cite the inspection of stellar kinematics in dwarf galaxies, where some of the authors have been active [38, 61, 62], and Galactic mass modeling [63, 52].

Examples of theory-driven approaches use for instance the action space to probe for dark matter features. The stellar population is very sensitive to gravitational perturbations, and this led some of us to test the impact of a Galactic masss model with a cored dark matter halo on the local properties of stars. Taking the cored halo favored by studies of the central Galactic bar [64], some of us have shown that features in the local stellar action-space distribution should be observed, which are actually present in the Gaia data [65]. If this turns out to be true, this has impact on both non-gravitational dark matter searches and on the dark matter scenario itself, as cusps are expected in Milky Way-like galactic centers. Another theory-driven example is that of attempts to renconstruct the velocity distribution of dark matter in the Milky Way, which enters predictions for direct dark matter searches, indirect searches for velocity-dependent signals, and capture by stars. The phase-space distribution of dark matter can actually be indirectly reconstructed from astrometry, by constraining the global gravitational potential and the baryonic distribution. Indeed, assuming equilibrium, dark matter responds to gravity through the Boltzmann equation, which one can use to make predictions. Some of us studied this kind of approaches in detail [37, 39]. Preliminary tests of these analytical methods against zoom-in cosmological simulations show that one can get predictions with moderate theoretical uncertainties at the 15% level (to be published soon)— note that predictions are not fits. Further examples include the search for dark matter subhalos by measuring the phase-space perturbations of stellar streams [66]. These theory-driven approaches can therefore be quite powerful in assessing the dark matter details. To be as complete and relevant as possible, further development must again involve experts from different theoretical communities.

A lot more is expected in the near future related to the Gaia data and other surveys, which will be also very important in the preparation of LSST science (see e.g. the contribution by J. Cohen-Tanugi et al. to this call). The prime targets are those appearing in the list above, and the science goal is really to select among the CDM, SIDM, WDM, and ULDM proposals.

4.2 Gravitational waves

It is obvious that GWs are now playing and will play an important role is constraining the clustering of compact exotic objects, and this is likely to be addressed by experts who meet at the GDR Ondes Gravitationnelles in France. Stellar mass objects can be probed by current and next-generation ground-based experiments like LIGO/VIRGO and successors, in particular the merging rate of PBHs [13], while the stochastic background induced e.g. by the formation of PBHs in the early universe will be probed by LISA [67]. LISA will also be able to detect PBHs of $\sim 10^{-4}\,M_\odot$ at the vicinity of the SgrA* [68]. The development of theoretical tools is still active in this field, with strong connection with analytical or numerical works on general relativity and beyond [9].

4.3 Pulsar timing

Millisecond (ms) pulsars, whose rotation frequency is incredibly stable, can be used as astronomical clocks to detect the gravitational acceleration or redshift induced by the passage of a dark object, compact (PBHs, axion stars) or more diffuse (subhalos). The change in the gravitational potential close to a pulsar may affect photon trajectories and produce a Shapiro time delay [69], and the acceleration of the pulsar itself (or of the observer) can also modify the pulsar period through a Doppler effect [70]. It was recently showed that a pulsar timing array (PTA) build from a projection of 200 to 1000 ms pulsars within 10 kpc detected by SKA could allow to cover the full relevant range for PBH dark matter, complementary to lensing studies [71]. The same analysis also showed the relevant sensitivity on dark matter subhalos is obtained in the $\sim 10^{-9}M_\odot$ mass range. These preliminary studies are encouraging and push to explore this possibility in more detail.

4.4 Gravitational lensing

4.4.1 Femtolensing

Femtolensing probes compact objects in the range 10^{-17}-$10^{-13}M_\odot$ by means of lensed gamma-ray bursts (GRBs) [72]. The projected sensitivity for PBH dark matter has been revised recently and found to be modest, but still provides constraints on the possibility to have 100% of dark matter in the form of PBHs in this mass range [73].

4.4.2 Microlensing

The technique of microlensing [74], focusing on the apparent magnification of a Galactic target star induced by the passage of a compact object on the line of sight, has gained its fame thanks to the role it played in the search for massive halo compact objects (MACHOs) in the Milky way and its neighbors — see the results of the EROS and MACHO collaborations. Microlensing is also widely used in the search for exoplanets. Microlensing has long been promoted as a "killer" of PBH dark matter, as it constrains a low fraction of invisible compact objects in the 10^{-10}-$1M_\odot$ mass range, which is somewhat a natural range for PBHs [18, 75]. The HSC survey of M31 [76] and the OGLE experiment focused on the Milky Way [77] are the successors to these pioneering searches. Although the sensitivity of current surveys is extremely good, it remains to understand more clearly how the clustering of exotic compact objects [78]. There is room for progress in this line of research.

4.4.3 Lensing on larger scales

Weak lensing and strong lensing are well-known techniques in the study of galaxy clusters. They have provided and are still expected to provide significant constraints on alternatives to CDM, like SIDM [79]. It turns out that they can play a role on much smaller scale in the census of subhalos [80]. Weak lensing can even be constructed from stellar positions and motions instead of galaxy images, providing an interesting handle on dark matter subhalos [81].

4.5 Cosmological probes of the matter power spectrum

This section is complementary to a full contribution about the cosmological probes of dark matter by the same authors. Cosmological probes allow to explore dark matter properties on the largest scales and all along the history of the Universe. Moreover, they have the particularity of being sensitive to both gravitational and non-gravitational properties of dark matter. As such, they are sensitive to processes with no detectable signals in terrestrial-scale experiments or in the local Universe. Probably, the best example of their power is attested by the fact they provide us with the most accurate measurement of the cosmological dark matter abundance[3] $\omega_{\rm cdm} = 0.11933 \pm 0.00091$ (*Planck* 2018 TT,TE,EE+Lensing+BAO [82]). But cosmological probes can also provide very strong constraints on various properties of dark matter such as the underlying particle mass (e.g. [21, 83] — already constraining the ULDM scenario), its decay or annihilation rate (e.g. [84, 85, 86, 87, 88, 89, 90, 91, 82]), or its scattering rate with baryons (e.g. [92, 93, 94]). Here we discuss the constraints related to gravitational effects only.

Generically, any new physics affecting the growth of structures along cosmic history affects cosmological observables. This is best quantified in terms of their modification of the matter power spectrum $P(k)$, i.e. the Fourier transform of the 2-point correlation function of the matter field, where k is the modulus of the wavenumber associated to a scale λ, which can be probed for instance with galaxy surveys, weak lensing surveys, or quasars Ly-α forest. In the recent years, measurements of the matter power spectrum have most notably been performed by the SDSS collaboration[4], DES collaboration[5] and KiDS collaboration[6]. Additionally, the CMB can be used to explore the growth of structures at low redshift because it leads to a number of *secondary* anisotropies, as opposed to primary anisotropies coming from the pre-recombination era. In particular, lensing of the CMB and y-type spectral distortions from galaxy clusters have been accurately measured by the *Planck* collaboration, leading to robust constraints on the matter power spectrum [95, 96].

Such measurements have been used to provide constraints on a variety of models. One of the best examples of the constraining power of cosmological surveys is the limit on the sum of neutrino masses from a combination of datasets, reaching now $\sum m_\nu < 0.12$ eV/c^2 [82]. This can be compared to current constraints from laboratory experiments such as the Mainz Neutrino Mass experiment, yielding $m_{\nu_e} < 2.3$ eV/c^2 [97]. The KATRIN experiment (whose data acquisition started in 2018), is

[3]Hereafter, error bars on measurements are given at the 68% C.L. while constraints are given at the 95% C.L.
[4]https://www.sdss.org/
[5]https://www.darkenergysurvey.org/
[6]http://kids.strw.leidenuniv.nl/

expected to be sensitive to $m_{\nu_e} \sim 0.2$ eV/c^2, which implies $\sum m_\nu \sim 0.6$ eV/c^2 [98], a factor of ~ 5 weaker than *current* cosmological bounds. One gets bounds on dark matter from in a similar way, providing us with the most constraining bounds on the mass of fermionic and bosonic dark matter particles. In the case of thermal fermions, the Ly-α forest data from XQ-100 and HIRES/MIKE impose $m_{\rm dm} > 4-5$ keV/c^2 [21]. For light scalar field dark matter, the same set of data enforces $m_{\rm dm} > 2-4\times10^{-21}$ eV/c^2 [83].

Cosmological data can also be used to explore multi-component dark sectors, for instance light scalar fields which would be a fraction of the total dark matter, providing the strongest constraint to date on the presence of such fields [99].

Finally, we mention that in recent years a number of "tensions" have emerged, potentially holding information about properties of the dark datter. In particular, the Hubble constant as measured by local probes (supernovae, strongly lensed quasars) is discrepant at $4-6\sigma$ with what is inferred from *Planck*. Additionally, the value of $S_8 \equiv \sigma_8(\Omega_M/0.3)^{0.5}$ inferred from CMB is about 2.5σ larger than what is deduced from weak lensing surveys. Theoretical and experimental efforts in the next decade will be crucial to robustly assessing whether these tensions unambiguously reveal the presence of new physics in the dark matter sector.

5 Conclusion

Gravitational probes offer exciting ways to select among the different scenarios of dark matter. Theoretical works in this field should be encouraged in the coming decade, which should take advantage of close collaboration between different experts coming from astroparticle/particle physicists, cosmologists, and astrophysicists. The interested community should get prepared to tackle these scientific challenges. Favoring funding for interdisciplinary projects, and also the hiring of theoretical physicists with strong skills in astrophysics and cosmology, will be important aspects on the way to decisive progress. As pointed out in other contributions, a strong connection with experimentalists and observers is also fundamental in this field, and finding a way to make the whole community interact more efficiently will be crucial (where gravitational probes would be discussed along with other probes, e.g. direct and indirect searches for WIMPs, axions, sterile neutrinos, PBHs, etc.) — a GDR Matière Noire could be one of the possible solutions.

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