

High Energy Physics – Phenomenology

# Particle dark matter versus modified gravity

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## ABSTRACT

There are at least two possible solutions to the so-called Dark Matter problem. One is to introduce new particles and another one is to modify gravity. In these proceedings of the 182nd Nobel Symposium on dark matter, I question the particle dark matter hypothesis in light of new developments in the gravity sector. To this effect, I review how the CMB anisotropies and the details of structure formation have been used to test the dark matter microscopic properties. I explain how this has led to challenge the Hut-Lee & Weinberg argument and the introduction of light (thermal) dark matter scenarios and dark photon/light  $Z'$ . These developments have ultimately paved the way for a comprehensive exploration of the entire dark matter mass spectrum. I then discuss a new theory of modified gravity that appears to be a novel alternative to particle dark matter and ask the question: how to distinguish the two? I expect this question to become extremely relevant in absence of dark matter particle detection in Earth based experiments and in presence of ambiguous astrophysical and cosmological signals.

## 1. Introduction

Dark matter has been a long standing problem in both Cosmology and Particle Physics. The current consensus is that the matter in the Universe is likely to be made of a mixture of Standard Model particles (referred to in Cosmology as “baryonic matter” or “baryons”) and an unknown species, invisible to the naked eye. The particle dark matter hypothesis solves a series of puzzling observations, such as the strong lensing in clusters of galaxies, the flat rotation curves of galaxies and the complex evolution of the Universe. Are these apparent successes enough to guarantee that dark matter is indeed made of a new kind of particles? Probably not.

How can we confirm the nature of dark matter if there is no evidence of particle dark matter in Earth based experiments? Would one astrophysical signal (e.g. an anomalous gamma-ray signal or cosmic ray detection) consistent with particle dark matter be enough to validate this hypothesis in absence of other detection evidence? In my view, addressing these questions necessitates a holistic approach that takes into account all aspects of Particle Physics, Astronomy, Astrophysics, and Cosmology in a coherent manner. As a solution to the dark matter problem should explain the intricate details of structure formation at both large and small scales, studying the properties of Astronomy objects that live within them (such as black holes) can serve as a valuable tool for reconstructing the significant events that have shaped our Universe.

In the past, the study of small-scale-structures formation, albeit with limited data from cosmological surveys, has prompted the community, myself included, to question certain widely accepted assumptions. It has also paved the way for new ideas, such as the concept of light dark matter coupled to light mediators and a new theoretical framework for exploring the dark matter space, namely

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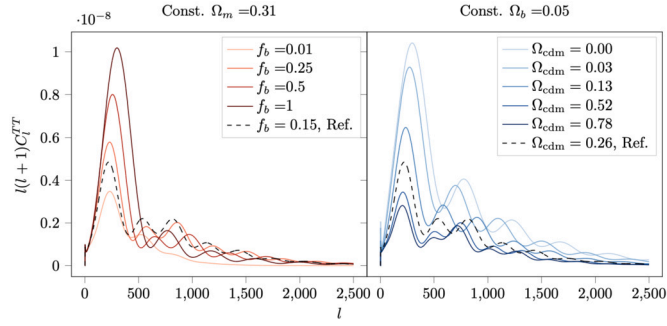


Fig. 1. Examples of CMB angular power spectrum as a function of the baryonic content. On the left panel the matter cosmological parameter is fixed and the baryon fraction ( $f_b$ ) allowed to vary. On the right panel, the baryonic cosmological parameter is fixed and the matter cosmological parameter allowed to vary.

simplified models [1]. With the new data from satellite missions, such as ESA/Euclid, LSST/Vera Rubin Observatory and JWST, we may find it necessary to reevaluate the very foundation of the particle dark matter hypothesis. We may have to take a more profound step and explore alternative avenues, such as a modification of gravity, or even consider more radical shifts, such as inventing new mathematical frameworks or theoretical concepts. Either way, it has become undeniable that the fundamental laws we are familiar with on Earth fall short in explaining the observable Universe. A scientific revolution is on the horizon, whatever it may be.

In these proceedings, I will provide a summary of the conceptual shifts that ultimately gave rise to an extensive experimental program dedicated to the search for light dark matter particles and a wide range of new techniques that extend far beyond the traditional domain of Particle Physics (see, to cite only very few [2–6]) and will contrast these with the new ideas that are being explored in the gravity sector.

## 2. Dark matter and the cosmic microwave background

A key evidence for dark matter comes from the study of the cosmic microwave background (CMB) anisotropies and the formation of large-scale-structure in the Universe. The angular power spectrum of the CMB can be explained using a set of coupled Boltzmann equations to describe the evolution of the matter and radiation densities and velocities under gravity (while also accounting for the viscosity stemming from their microscopic interactions). Two equations are key in particular to describe the evolution of the baryon and photon fluids and are given by:

$$\dot{\theta}_b = k^2 \psi - \mathcal{H} \theta_b + c_s^2 k^2 \delta_b - R^{-1} \dot{\kappa} (\theta_b - \theta_\gamma)$$

$$\dot{\theta}_\gamma = k^2 \psi - \mathcal{H} \theta_\gamma + k^2 \left( \frac{1}{4} \delta_\gamma - \sigma_\gamma \right) \delta_\gamma - \dot{\kappa} (\theta_\gamma - \theta_b)$$

where the overdot denotes a derivative with respect to the conformal time, and with  $k$  the comoving wavenumber,  $\delta_b$  and  $\theta_b$  the density and velocity divergence of the baryonic fluid respectively,  $\delta_\gamma$  and  $\theta_\gamma$  that of the photon fluid,  $\mathcal{H}$  the conformal Hubble rate,  $\dot{\kappa} = a\sigma_T c n_e$  the Thomson scattering rate,  $\sigma_\gamma$  the anisotropic stress associated with the photon fluid,  $\psi$  the gravitational potential,  $c_s$  the baryon sound speed, and  $R = \frac{3}{4} \frac{\rho_b}{\rho_\gamma}$  the baryon to photon ratio (for more details see [7,8]).

Examples of the CMB angular power spectrum thus obtained in a purely baryonic Universe are shown in Fig. 1 as a function of the cosmological parameter or the baryon fraction. The damping of the primordial fluctuations is apparent, with the first peak being very prominent, the 2nd peak much smaller, though higher than the 3rd, and so on. This damping (also referred to as Silk damping [9]) is the result of the dissipation that stems from the Thomson scattering of the photons off the electrons and protons (and vice versa). This process is inherent to the Standard Model and therefore cannot be circumvented.

This prompted J. Silk to ask the question of whether the primordial fluctuations needed to form large-scale-structures in the Universe would survive to an epoch when galaxy formation is possible [9]. Today, we may ask instead whether the number of Milky Way-size galaxies expected in a baryonic Universe is compatible with the large-scales survey data? The answer is negative and consistent with the fact that the angular power spectrum in a purely baryonic Universe is also in contradiction with the WMAP and PLANCK measurements. Hence, we can confidently exclude a purely baryonic Universe.

So how to explain the broad range of “anomalous” data in our possession? A solution might be to alter the cosmological model or to modify gravity. However, there is a considerably simpler approach: mitigating the dissipation experienced by ordinary matter by reducing the quantity of baryons while maintaining the overall density of matter in the Universe. This essentially means adding a new, collisionless, species. By introducing a new equation for the so-called dark matter component,

$$\dot{\theta}_{DM} = k^2 \psi - \mathcal{H} \theta_{DM}, \quad (1)$$

and adding some form of energy (dark energy), one can explain the CMB angular power spectrum over the observed range of multipoles. Remarkably, there are only two terms in this 3rd equation: one is associated with the gravitational potential and the

other one is associated with the Universe expansion. There is no information about the particle properties of the dark matter. As such, dark matter could be seen as a modification of gravity – a very specific one but one nonetheless.

Till very recently, this argument constituted the strongest evidence in favour of dark matter particles. However, this may no longer be true, now that a new theory of modified gravity can finally explain the Planck observations [10]. The latter builds on previous theoretical frameworks of modified gravity (such as TeVeS [11,12]) but, unlike other theories, it is able to reduce the impact of baryonic dissipation on the CMB anisotropies.

It is unclear whether this theory can reproduce all observations at late times as yet. Besides, in this scenario, gravity features some rather unusual behaviour on large scales which may eventually lead to its demise [13]. However the fact that there is now a relativistic theory able to explain the observed CMB angular power spectrum means that the particle dark matter scenario finally has a contender and there is a new pathway to construct alternatives.

So is dark matter of particles? I would argue that it is still too early to respond positively at this stage. It is certainly the case that by adding a third equation to account for a non dissipative species, one can reproduce the many features of the angular power spectrum of the CMB to the required level of precision (and down to all observed multipoles) as well as the formation of structures in the Universe. It is harder for modified gravity theories. However, despite the seemingly simplicity of the particle solution, its many successes do not provide any information about its properties (mass, interactions with the visible sector etc), thus preventing to understand its origin and thereby the fundamental laws that govern the evolution of the Universe.

### 3. Probing the dark matter properties with cosmology

To gather more information about the nature of dark matter, one may ask whether the assumptions made in Cosmology are consistent with that in Particle Physics. Historically, in Cosmology, one assumed that dark matter had absolutely no interaction. In contrast, in Particle Physics, one usually assumed that dark matter interacted with the standard model of particle physics, even if the interactions were very weak. Three types of interactions were regularly considered: dark matter pair annihilation into fermions, dark matter scattering off fermions and the possibility to produce dark matter particles from the collision of a fermion-anti fermion pair. By adding these interactions into the set of equations that govern the evolution of the baryon, photon and dark matter fluids, it becomes possible to assess their influence on structure formation and the CMB. Consequently, one can determine the upper limit on the strength of dark matter interactions allowed by the existing data [7,14,15].

Focusing on elastic scattering processes, five types of couplings need to be considered: 1) dark matter-photon interactions [7,8,14–26], 2) dark matter-neutrino interactions [14,15,25,27–31], 3) dark matter-proton or electron interactions [14,15,17,18,32,33], 4) self-interactions [14,15,34–43], and finally 5) dark matter interactions with a dark sector and in particular dark radiation [44–52]. I will not discuss the latter in these proceedings.

The dark matter-photon interactions have of course to be suppressed otherwise dark matter would become visible. But how small do they have to be? The answer requires to generalise the Silk damping to the case of dark matter. This can be done analytically first, by defining a collisional damping scale [14,15]:

$$l_{\text{DM-i}}^2 = \frac{2\pi^2}{3} \int^{t_{\text{dec(DM-i)}}} \frac{\rho_i v_i^2}{\rho_{\text{tot}} a^2 \Gamma_i} dt,$$

where the upper bound corresponds to the kinetic decoupling of the dark matter with the species  $i$  (that can be either a photon, neutrino, baryon or the DM itself),  $v_i$  and  $\rho_i$  are the velocity and density of this species respectively and  $\Gamma_i$  the total interaction rate of this species. Once the dark matter has kinetically decouple from all species it interacts with, it is essentially free. The dark matter free-streaming further erases all surviving primordial fluctuations below the following scale

$$l_{fs} = \int_{t_{\text{dec(DM)}}}^{t_0} \frac{v}{c} dt$$

with  $v$  the dark matter velocity.

Applying the generic expression for the collisional damping to the different coupling cases, one gets

$$l_{\text{DM-}\gamma}^2 = \frac{2\pi^2}{3} \int^{t_{\text{dec(DM-}\gamma)}} \frac{\rho_\gamma c^2}{\rho_{\text{tot}} a^2 \Gamma_\gamma} dt,$$

$$l_{\text{DM-}\nu}^2 = \frac{2\pi^2}{3} \int^{t_{\text{dec(DM-}\nu)}} \frac{\rho_\nu c^2}{\rho_{\text{tot}} a^2 \Gamma_\nu} dt,$$

$$l_{\text{DM-b}}^2 = \frac{2\pi^2}{3} \int^{t_{\text{dec(DM-b)}}} \frac{\rho_b v_b^2}{\rho_{\text{tot}} a^2 \Gamma_b} dt,$$

$$l_{\text{DM-DM}}^2 = \frac{2\pi^2}{3} \int_{t_{\text{dec}}^{\text{(DM-DM)}}} \frac{\rho_{\text{DM}} v_{\text{DM}}^2}{\rho_{\text{tot}} a^2 \Gamma_{\text{DM}}} dt,$$

where one can see that the collisional damping lengths associated with DM self-interactions and DM-baryon interactions are naturally small, owing to the suppressed dark matter and baryon densities and velocities with respect to photons and neutrinos (unless dark matter is extremely light and stays relativistic for a long time). In contrast, both the DM-neutrino and DM-photon interactions naturally lead to a large collisional damping length, unless they decouple in the early Universe, since both species are relativistic and have the largest energy densities before the matter-radiation equality. Therefore both the DM-photon and DM-neutrino interactions have the potential to reduce the formation of small-scale-structures in the early Universe.

Using a Boltzmann code and assuming that DM was produced in the Early Universe, Refs. [8,26] found that the DM-photon cross section cannot exceed

$$\sigma v \lesssim 8 \times 10^{-31} \left( \frac{m_{\text{DM}}}{\text{GeV}} \right) \text{ cm}^2$$

from the CMB observations alone or

$$\sigma v \lesssim 1.3 \times 10^{-30} \left( \frac{m_{\text{DM}}}{\text{GeV}} \right) \text{ cm}^2$$

if one is very conservative and

$$\sigma v \lesssim 6 \times 10^{-40} \left( \frac{m_{\text{DM}}}{\text{GeV}} \right) \text{ cm}^2$$

for a temperature dependent cross section. Larger values lead to a too large damping scale. This essentially means that relatively weak dark matter interactions have an impact on cosmological observations and should not be neglected. Said differently, one should not assume that Dark Matter is collisionless. Instead, one should account for dark matter interactions in Cosmology and use the cosmological data that we have to constrain the dark matter microphysics. Furthermore, this result shows that dark matter could be coupled to photons.

For DM-neutrino interactions, the constraints are stronger because the Physics of neutrinos is altered by their coupling to dark matter. In particular, the neutrino free-streaming is reduced and so they tend to cluster more, thus increasing the power of the CMB spectrum around  $l \simeq 200$  and, consequently, producing an excess of very large-scale-structures with respect to observations. To be compatible with the data, one needs to adjust the cosmological parameters and in particular increase the value of the Hubble rate today ( $H_0$ ) to give neutrinos more time to free-stream and increase the number of degrees of freedom ( $N_{\text{eff}}$ ) to reduce the clustering.

Adding the CMB and Cepheids-calibrated Type Ia supernovae (SN1a) data, Ref. [30] found that the value of  $H_0$  in presence of DM- $\nu$  interactions can be as large as  $72.1^{+1.5}_{-1.7}$  km/s/Mpc. This could solve the so-called  $H_0$  tension. The latter refers to the difference between the value of Hubble rate today measured using late time (distance ladder and Supernovae) versus early time (CMB anisotropies) data. For a review, see [53]. Assuming  $\Lambda$ CDM and a FRLW metric, the latest Planck data indeed favours  $H_0 \sim 67.4 \pm 0.5$  km/s/Mpc [54] while the SHOES collaboration found  $H_0 \sim 73.04 \pm 1.04$  km/s/Mpc [55] or, more recently,  $H_0 \sim 72.3 \pm 1.3$  km/s/Mpc [56]. Hence the value found in Ref. [30] looks promising. Without the Cepheids-based data, and considering Planck data alone, one finds a value consistent with the  $\Lambda$ CDM value.

Either way, assuming that DM was produced in the early Universe, the limit on the DM-neutrino cross section was found to be

$$\sigma \lesssim 2 \times 10^{-33} \left( \frac{m_{\text{DM}}}{\text{MeV}} \right) \text{ cm}^2$$

[31], which is comparable to a weak strength cross section for a DM particle lighter than an electron. In other words, forming small-scale-structures in the early Universe (at high redshift) in these scenarios can be a challenge, especially if the dark matter is lighter than a proton. The lightest it is, the highest the cut-off scale in the linear matter power spectrum is. This translates into a suppression of the number of companion satellites in Milky Way-like galaxies [20,21] and the number of small-scale-structures in the Universe. It is important to note nevertheless that some small-scale-structures may be regenerated during the non-linear evolution of the Universe, as shown in [57], due to a transfer of power from the large-scales to small-scales (see Fig. 2).

#### 4. Light (thermal) dark matter

The fact that the effect is more prominent for light dark matter particles prompts the question of how light the dark matter can be. For thermal DM, the famous Hut-Lee & Weinberg limit [58,59] indicates that dark matter cannot be lighter than a proton. Indeed solving the Boltzmann equation that describes the evolution of the number density of thermal dark matter particles in an expanding Universe

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{\text{eq}}^2)$$

leads to a very simple relationship between the dark matter pair annihilation cross section and the dark matter cosmological parameter:

$$\langle\sigma v\rangle \simeq \frac{3 \times 10^{-27} \text{ cm}^3/\text{s}}{\Omega_{\text{DM}} h^2},$$

that is  $\langle\sigma v\rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$  for  $\Omega_{\text{DM}} h^2 \simeq 0.1$  as measured by PLANCK. In other words, if dark matter particles can pair annihilate into Standard Model particles and have been in thermal equilibrium at least before and during its non-relativistic transition, then it is expected to annihilate through weak strength interactions.

Assuming that the pair annihilation cross section behaves as  $\sigma v \propto m_{\text{DM}}^2/m_W^4$ , Hut-Lee & Weinberg could further conclude that dark matter had to be heavier than a proton. However in Ref. [1], I showed – using the concept of simplified models – that there are exceptions to this thermal bound. In particular, if the dark matter is made of scalar particles and the mediator of the dark matter interactions with SM particles is a fermion, then the thermal cross section is given by

$$\sigma v \propto \frac{1}{m_F^4} ((C_l^2 + C_r^2) m_f + 2 C_l C_r m_F)^2$$

which is mostly independent of the dark matter mass. Therefore, imposing the thermal value on the cross section (i.e.  $\langle\sigma v\rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$ ) constrains the mass of the mediator as well as its couplings to other particles but it does not constrain the dark matter mass itself. This eventually means that thermal dark matter particles can be much lighter than a proton, thus providing an exception to the Hut-Lee & Weinberg limit. A similar conclusion was reached five years later and dubbed the “Wimless miracle” [60]. The lower limit on the mass of dark matter is eventually constrained by CMB data, which dictate that dark matter must be heavier than a few MeV (for precise values see [61]).

In [1], it was observed that thermal Dark Matter could also be light (independently of its spin) if the mediator of its interactions with SM particles is a light, neutral, vector or pseudo vector boson (nowadays refer to dark photon if it is purely vectorial or light  $Z'$  otherwise). Indeed, in this case the thermal annihilation cross section is proportional to

$$\sigma v \propto \frac{m_{\text{DM}}^2}{m_{Z'}^4}$$

and while it does depend on the dark matter mass, it can match the thermal value ( $\langle\sigma v\rangle \simeq 10^{-26} \text{ cm}^3/\text{s}$ ) if the mediator is light and weakly coupled to both the dark matter and the Standard Model particles. A number of constraints (including from the electron  $g-2$ ) were initially derived in [1]. However this field has essentially boomed in the last decade and given rise to a plethora of experiments looking for dark photons and light mediators. In an interesting twist, the field eventually evolved to include searches for light, non-thermal, candidates and somehow merged with searches for axion-like and feebly interacting particles. New mechanisms, such as the concept of freeze-in [62], were also introduced to explain the current dark matter relic density for non-thermal, possibly very light, dark matter particles.

What used to be an unexplored territory is now a very contrived parameter space, as summarised in [63]. This might mean that dark matter is unlikely to be light after all (or if it is, its interactions will have to be very suppressed). However, I see this as one of the biggest achievements of our field – and one that has been extremely fast, whereby both theoreticians and experimentalists have been extremely creative.

## 5. Reconstructing the dark matter power spectrum

A key question if we cannot find any concrete evidence of particle dark matter in particle physics experiments is going to be how to distinguish a possible alternative to particle dark matter from a scenario whereby dark matter does not interact at all or so weakly that it is difficult to find in experiments on Earth (see Fig. 3).

One possibility is to exploit the fact that the matter power spectrum evolves with time and therefore has a strong redshift dependence. As highlighted in [57], a cut-off in the linear power spectrum ( $P(k)$ ) will disappear eventually during the non linear evolution of structure formation. As a result a Warm Dark Matter (WDM) linear  $P(k)$  with a cut-off at  $10^8$  or  $10^9 M_\odot$  at  $z \simeq 30$  may look like a Cold Dark Matter (CDM) spectrum today, while being significantly different at higher redshift. It was therefore suggested to use the SKA to access the matter distribution at high redshift to probe Warm DM (WDM) and Interacting DM (IDM) scenarios [64]. This work can be generalised to any alternative whereby the matter power spectrum is not strictly that of CDM. As such, my view is that in the future we will need to move away from specific DM scenarios and instead test parametric matter power spectra with data. The SKA may not be the right instrument to reconstruct the matter power spectrum due to its lack of sensitivity to small scales (where WDM and IDM models differ from CDM) but it certainly is a step in the right direction.

Recently we showed that gravitational waves produced by binary black hole mergers could turn out to be a very powerful tool to reconstruct the matter power spectrum [65]. Indeed, the binary black hole merger rate depends on the number and properties of the cosmic structures which in turn depends on the dark matter microscopic properties. As such, measuring gravitational waves and determining the Binary Black Hole merger rate with redshift could be a good tracer of cosmic evolution. This would help to infer the distribution of dark matter at high redshift and distinguish different dark matter scenarios and possible alternatives to particle dark matter [65]. As shown in Fig. 3,  $\Lambda$ CDM may well already be in tension with observations so I am very eager to see gravitational wave data at high redshift, to see which scenarios will end up being ruled out.

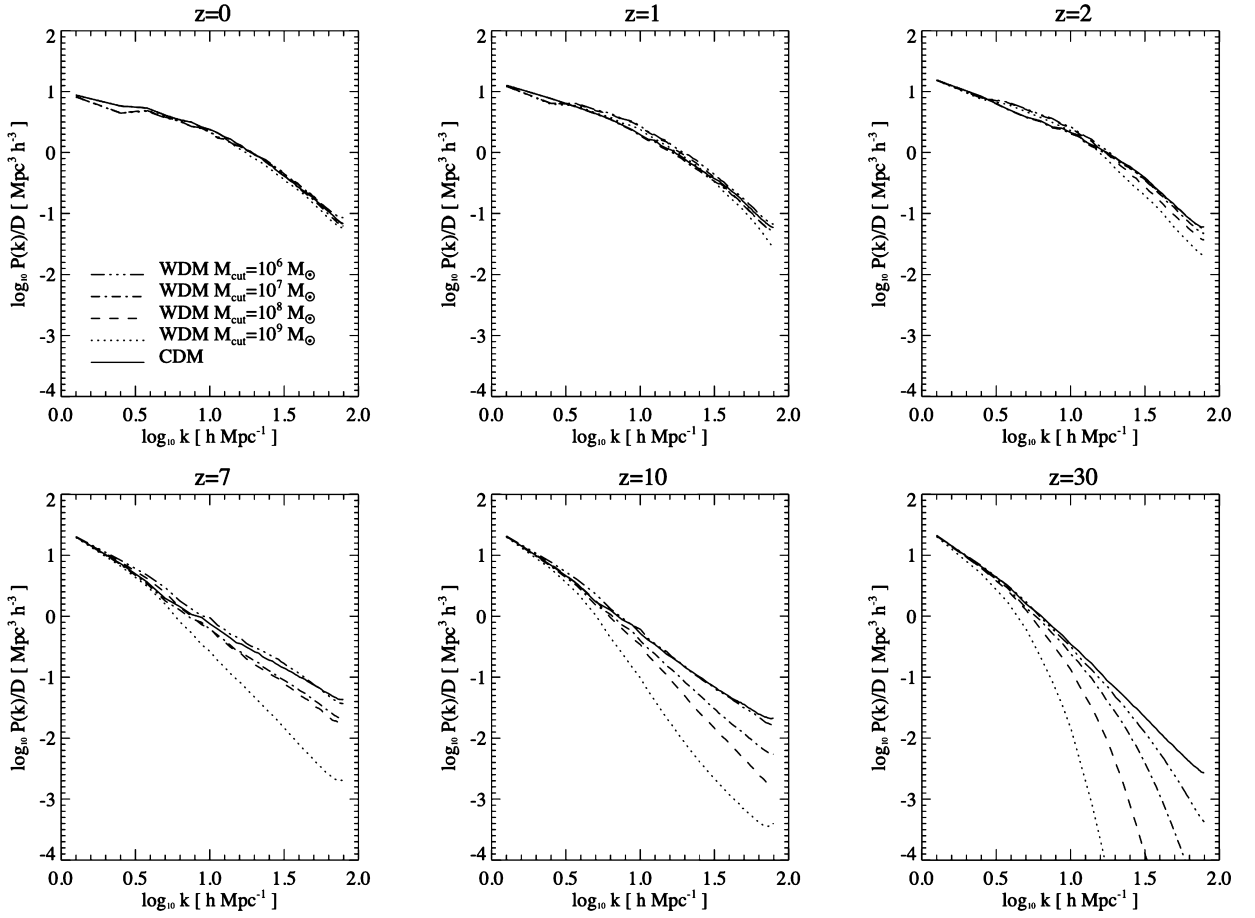


Fig. 2. Evolution of the matter power spectrum with redshift [57]. See [64] for a modern version.

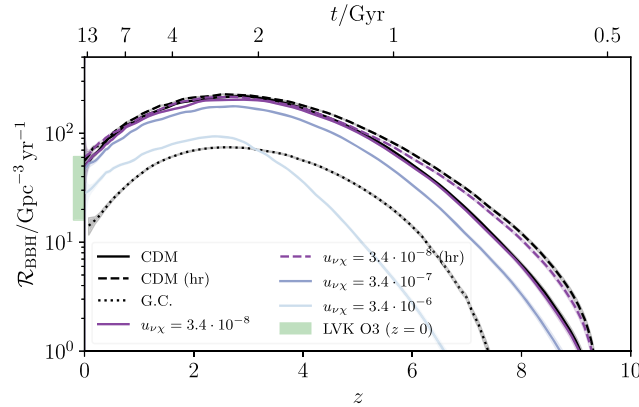


Fig. 3. The binary black hole merger rate density over cosmic time, as predicted in [65].

### 6. Towards a successful theory of modified gravity

The first effort to build a relativistic theory of modified gravity was attempted by [11,12]. It included a gravitational metric Tensor, a Vector and a Scalar which, combined together, leads to a second metric tensor that can be used to compute the geodesics of ordinary matter. Despite some very problematic shortcomings (such as the presence of ghosts), this bi-metric theory can generate the same amount of gravitational lensing as expected in presence of dark matter and predicts a matter power spectrum that is in agreement with observations [66,67].

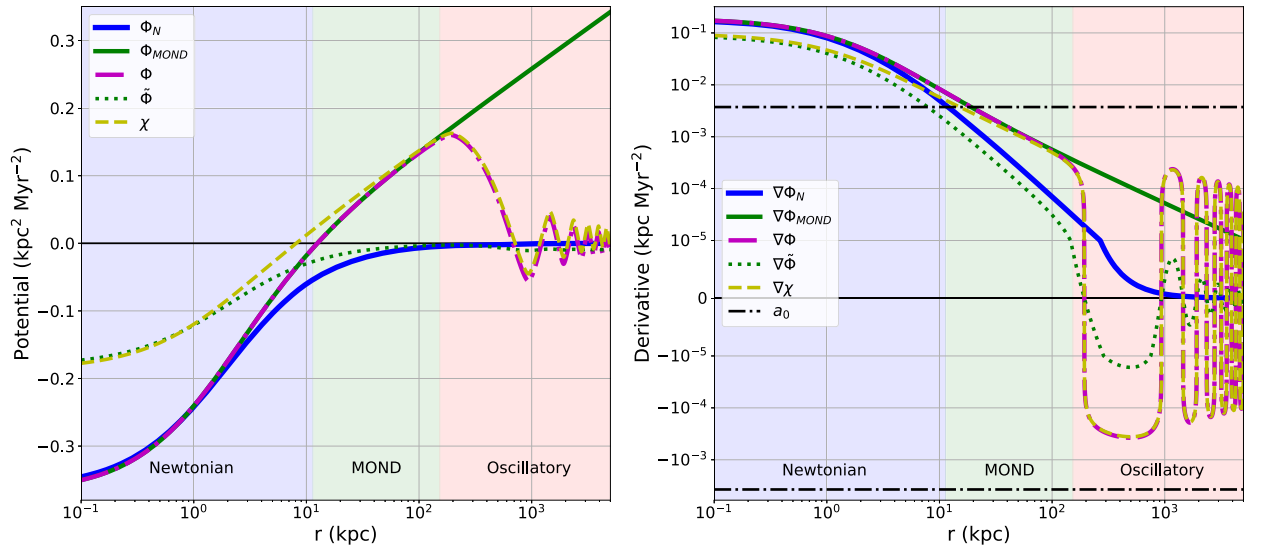


Fig. 4. Numerical solution for the potentials (left) and their derivatives (right) for the Hernquist density profile and the fiducial model parameters of the AeST theory with  $(\lambda_s, \mu) = (1, 1 \text{ Mpc}^{-1})$ . For details see [13].

Yet such a theory cannot explain the CMB anisotropies [66]. In particular, the 3rd peak of the CMB angular power spectrum remains considerably smaller than the 2nd one, as expected in a purely baryonic Universe where there is dissipation (Silk damping). Adding a cosmological constant and massive neutrinos to the theory help fitting the very large-scale data but does not enable to counteract the Silk damping enough to increase the size of the 3rd peak and explain the rest of the anisotropies. Moreover, TeVeS leads to tensor mode gravitational wave speed  $c_{GW}$  differs from the speed of light  $c_{EM}$  and is therefore ruled out by the simultaneous observation of the GW170817 and GRB170817A events [68].

Recently however a new theory of modified gravity [10] has proven that one can successfully explain the CMB, the matter power spectrum, the lensing and the speed of the gravitational waves using a Tensor-Vector-Scalar structure but with some alterations, and using one metric only.

As this recent proposal retains the unit-timelike vector field dubbed “aether fields” in other works [69], the theory was named Aether Scalar Tensor (or AeST). Owing to similarities with the k-essence scenarios [70], the energy density of the scalar fields in AeST evolves like a dust component and leads to spontaneous breaking of time diffeomorphisms as in the Ghost condensate (GC) theory [71]. As a result, the metric potential  $\psi$  acquires a mass term  $\mu$  which mimics the dark matter evolution on very large scales and lead to CMB anisotropies in agreement with observations.

The twist however is that the matter power spectrum in this theory slightly differs from  $\Lambda$ CDM at very large scales. Moreover, it was shown that, for idealised spherical galaxies and far away from the centre, the gravitational force could oscillate between being attractive and repulsive [13], see Fig. 4. While more studies are required to establish the validity of this framework, its merit is to finally provide an example of a modification theory that does explain the CMB anisotropies and large-scale data in general. This is a great achievement – one that took twenty years in the making!

While AeST is unlikely to be the most viable alternative to particle dark matter, its mere existence generates a paradigm shift. Not only does it pave the way to build new theories of modified gravity but it may also help to understand why the particle dark matter hypothesis works so well on various scales. Ironically, I cannot help thinking that such attempts to find alternatives to the particle dark matter hypothesis will eventually provide the directions to search for dark matter.

## 7. Conclusion

In these proceedings, I have shown that the study of small-scale-structure formation has opened up new directions to search for particle dark matter. In particular, questioning the collisionless assumption has led to the introduction of light (lighter than a proton) dark matter scenarios, light gauge mediators (dark photon or  $Z'$ ) coupled to dark matter [1] and a plethora of new experiments.

In the last two decades following [1], we have witnessed remarkable theoretical and experimental efforts to explore the whole range of particle dark matter masses. This was inconceivable prior to the 2000s. Exploring the dark matter interactions is obviously much harder but we have witnessed an explosion in experimental techniques and a level of creativity that is also unexpected. The new techniques which have been proposed (and which sometimes stem from advances in industry, like for CMOS detectors) have often brought theoreticians and experimentalists closer together as well as different fields and communities.

Yet, despite these great advances, it still is the case that we have not discovered any dark matter particles. And now that a theory of modified gravity can finally explain the CMB anisotropies, we are back to the initial question: is dark matter made of particles and what will it take to prove it? It could be that, in the end, understanding the nature of dark matter may necessitate new mathematical ideas and a radically novel theoretical framework.

## CRediT authorship contribution statement

Single author paper based on my various contributions to the field.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Celine Boehm reports financial support was provided by The University of Sydney. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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