Probing the properties of dark matter particles with astrophysical observations

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Chapter 1

Introduction

Attempts to phenomenologically explain subatomic physics together with the well-rounded theory of electrodynamics have culminated in the development of the most advanced description of particle physics to date. The Standard Model (SM) of particles unites the models of the electromagnetic, weak and strong interactions in a rigid and elegant theoretical framework.

The SM is a very successful theory that passed a very large number of experimental checks [1]. The Standard Model has also performed very well in the *precision tests* where its predictions were tested not only to the leading order of perturbation theory, but also to next or to next-to-next leading order. The *last prediction* of the SM, the Higgs boson, was discovered at the LHC in 2012 [2, 3]. In the subsequent years it was confirmed that the interactions of the discovered particles are exactly as predicted by the Standard Model [4]. This means that the Standard Model provides a complete and closed description of particle physics as observed at accelerators. It is also a mathematically consistent theory that can be valid up to very high energies, probably up to the Planck scale (see e.g. [5] and references therein).

Nevertheless, it is established today that the SM has to be extended.

This knowledge is based on several observations that can not be incorporated into the Standard Model. These phenomena include:

- **Neutrino masses**: *Within the SM, neutrinos are massless. However, the observation of neutrino oscillations suggests however that these particles have small masses.*
- **Dark matter**: *Astrophysical observations indicate that the mass of matter in the Universe is dominated by a form of matter that does not interact with light – dark matter. None of the SM particles have the required properties.*
- **Baryon asymmetry of the Universe**: *The laws of particle physics, as described by the SM, are the same for matter and anti-matter. Therefore, the SM fails to explain a*

tiny matter-antimatter imbalance in the Early Universe that results in the present day that the Universe is almost completely missing anti-matter.

Experimental challenges "beyond the Standard Model" suggest that some additional physics beyond the SM exists.

From theoretical point of view, the spectrum of possible resolutions of the Beyond SM (BSM) puzzles are essentially boundless. At the same time, we have no firm knowledge about the masses, interaction strength, spin and charges of the new particles responsible for neutrino masses, dark matter and generation of the baryon asymmetry in the Universe. The main science goal of Tevatron [6, 7] and then the LHC [8] was to search for the Higgs boson. Of course, in this situation, it was motivated to search for new physics that could be found together with the Higgs boson, at the same machine. After the results of the LHC Run I and Run II [1], that did not reveal any confirmed signatures of new physics, it has become even more important to search for new physics in a wider context. After the discovery of the Higgs boson [2, 3] the era of "guaranteed discoveries" of particles with predicted properties has finished.

A special role is played in this respect by the data from cosmology and astrophysics. Laboratory experiments are typically sensitive to some specific models or narrow classes of models. At the same time, cosmological and astrophysical data can provide model independent constraints on the properties of new particles and give insights on the nature beyond Standard Model problems. Of course, the problem of dark matter is the one that is the most related to astrophysics and cosmology.

1.1 Dark Matter

Historically, the name "Dark Matter" (DM) was attributed to different phenomena that seemed to indicate that the mass of galaxies or galaxy clusters, that could be deduced from the velocities of their parts, was many times larger than the mass of matter that can be deduced from the luminosity of these objects (or the absorption of light in them). The first observations of this kind (the study of dynamics of the Coma cluster) were performed by F. Zwicky in 1933 [9]. For a long time, this was considered by many researchers as a problem specific for astronomy and, probably, related to observational uncertainties, the existence of non-luminous objects like cold stars or star remnants, planets or some form of dust.

However, currently, it is widely accepted that the Universe is permeated by a form of matter that does not emit or absorb light and manifests itself so far only through the gravitational field it creates. Together with observations that: a) dark matter is much more abundant than normal "luminous matter" and b) there is no candidate within the Standard Model of particle physics that can make such matter – makes the nature of Dark Matter one of the very few most important mysteries of today's physics and astronomy.

Why do we believe that DM exists? The modern evidence for the existence of dark matter comes from at least 5 observationally independent sources each providing very rich data [10]. Moreover, this evidence comes not only from the study of individual galaxies or clusters but from the data describing the observed Universe as a whole. These cosmological arguments, as well as observations of merging clusters (see below) leave very little room for alternative explanations such a modified gravity or modified Newtonian dynamics as a candidate for a unique mechanism behind all observed "DM phenomenology".

The astrophysical evidence for dark matter can be derived from:

- **Rotational velocities in spiral galaxies**

  For any matter emitting or absorbing light with a clear spectral feature (most importantly, emission and absorption lines), the Doppler effect allows measuring the projection of the velocity of this matter along the line of sight of the observer. To use these velocities to reconstruct gravitational force acting on the source (or the absorber), one needs to know the absolute value of the full 3D velocity. In spiral galaxies, this is in principle possible since stars and interstellar gas in these objects form spiral structures embedded in a relatively thin disk (see Fig. 1.1 for an illustration). Geometry and overall dynamics of this disk allow in many cases to reconstruct the direction of 3D velocity and therefore deduce its absolute value from the measured line-of-sight projection. Velocities measured in such a way can be split into the velocity of the galaxy as a whole and rotational velocities of stars and gas inside the galaxy $v(r)$.

  Then, the total mass can be calculated as

  $$M(r) = \frac{v^2(r)r}{G_N}, \tag{1.1.1}$$

  where G_N is the Newton's constant.

  Far enough from the center of the galaxy, where the enclosed mass does not grow with the radius anymore, gravitational force starts to get weaker and we expect (from Newton's gravity law) $v \sim 1/\sqrt{r}$. In particular, if the mass of a galaxy is mainly due to gas and stars, such a picture should be observed in the dark regions, where the emission and absorption of light drops by an order of magnitude and the densities of gas and stars are also expected to be orders of magnitude lower. However, in many galaxies [11–14] the rotation curves $v(r)$ become flat far from the center (e.g. see Fig. 1.2). Such a behavior can be explained if a dominant part of the mass of a galaxy is due to some dark matter that does not interact with light and extends to much larger distances from the center (as compared to the ordinary luminous matter).

- **Velocities of stars in dwarf spheroidal satellites of the Milky Way**

  Dwarf spheroidal satellites (dShps) are small galaxies with masses from $10^7 M_\odot$ to $10^{10} M_\odot$ that are part of the Milky Way (or some other galaxy) halo. These objects

Figure 1.1: A spiral galaxy (NGC 1232) in the constellation Eridanus. *Credit: ESO.*

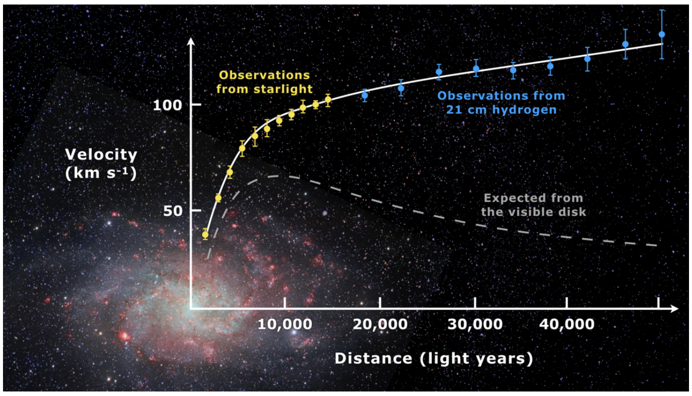

Figure 1.2: The rotation curve for a galaxy M33. *Credit: Wikipedia.*

stopped their independent history a long time ago because they were confined by the Milky Way. As a result, these galaxies do not contain any significant amount of gas and they do not form disks. The absence of the disk does not allow to reconstruct the direction of the total 3D velocity and therefore mass distribution can not be reconstructed using rotation curves. Instead, one can measure the dispersion of the line-of-sight projections of the velocities of stars. Assuming isotropic velocity distribution (having the same dispersion in all directions) one can use Jeans equation to reconstruct the gravitational potential and, therefore, mass (assuming Newtonian gravity). Such an analysis demonstrates that the observed dShps of the Milky Way are extremely dark matter dominated.

DShps have the largest known mass-to-light ratios $(M/L)_\odot \sim 100$ or even more in some cases (e.g. [15, 16] and references therein). It should be noted, however, that the main uncertainty in the Jeans analysis is that the velocity anisotropy is largely unknown. This uncertainty can significantly affect measurements of the inner mass distributions in dwarf galaxies. However, it is minimized for the mass with the so-called half-light radius [16] and therefore this mass is known with relatively small errors. It may be difficult to reconstruct the total mass of a dSph galaxy or measure the masses around the very center. However, the well-measured mass inside the half-light radius is sufficient to claim that the dynamics of these objects cannot be explained by the masses of its member stars or other luminous matter. Within Newtonian gravity and dynamics, it requires the existence of dark matter dominating these objects.

- **Temperature of gas in galaxy clusters and elliptical galaxies**

  A cluster consists of hundreds of galaxies that look more or less like point sources inside the cluster (see right panel of Fig. 1.3). X-ray observations (see left panel of Fig 1.3) show that the intergalactic medium inside a cluster is filled with a diffuse source of thermal X-ray emission with temperatures in the range of 1-10 keV. Modeling shows that the mass of the gas is ~ 15 times larger than the mass of the member galaxies (e.g. [17] and references therein).

  In clusters one can, therefore, apply several methods of mass measurements: using the motion of galaxies to reconstruct mass (with some uncertainty); using the temperature of the X-ray emitting gas; using weak and sometimes also strong gravitational lensing.

  The most common method for galaxy clusters is based on X-ray observations. X-ray surface brightness and spectrum allow reconstructing the gas temperature. The average temperature (i.e. the average kinetic energy) is roughly related to the gravitational potential energy, i.e. the total mass. As the mean free path of the gas particles is much smaller than the size of the cluster, the thermal equilibrium and the temperature of the gas are local. We can measure the temperature profile $T(r)$ and use it for more detailed mass modeling to reproduce $M(r)$ by solving the hydrostatic equilibrium equation

  $$\frac{dp}{dr} = n_{\text{gas}}(r)\frac{dT(r)}{dr} + T(r)\frac{dn_{\text{gas}}(r)}{dr} = -\frac{GM(r)n_{\text{gas}}(r)}{r^2}. \tag{1.1.2}$$

  Mass measurements in clusters reveal the same picture: only 1% of the total mass is given by galaxies, 15% by X-ray gas and 84% by dark matter, see e.g. [18] and references therein. At large enough distances from the center the clusters are very much DM dominated. It was observed long ago [19] that the ratio between the DM density and the density of normal matter in clusters is very close to the average value of this ratio in the whole Universe (see below).

- **Gravitational lensing**

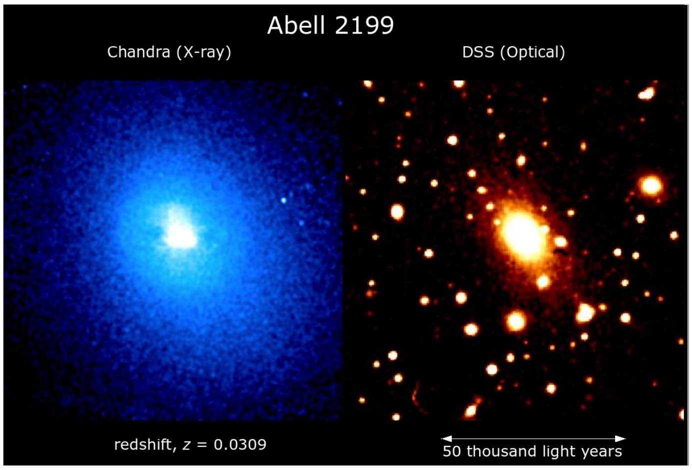

Figure 1.3: The distribution of X-ray gas (left) and galaxies (right) in the cluster of galaxies Abell 2199. *Credit: DSS.*

A prediction of general relativity is that mass can bend light and therefore act as a gravitational lens. The image of a background object, for example a galaxy, therefore gets distorted if its light passes through a massive object, for example a galaxy cluster (see [20] for a review). The degree of the distortion depends critically on the mass density of the gravitational lens, see Fig. 1.4. We might observe a galaxy behind a cluster either as a very thin arc or even as multiple images or a ring ("Einstein ring"), if the cluster is very massive ("strong gravitational lensing") or just slightly elongated ("weak gravitational lensing"). In both cases, the degree of distortion reveals the gravitational mass of the object acting as gravitational lens. Applying this method to galaxies and clusters we see once again that the baryonic mass is not enough to explain the lensing effects.

We can conclude therefore that measurements of gravitational potential in various types of galaxies and clusters of galaxies, with masses from $10^8 M_\odot$ for small galaxies to $\sim 10^{15} M_\odot$ for clusters, using 4 different observational methods (velocities of gravitation ally bound objects, X-ray emission of intergalactic gas, weak and strong gravitational lensing) consistently require some additional mass that is not related to absorption and emission of light and dominates the dynamics of these objects.

The analysis of the evolution of the whole Universe at large provides other, **cosmological evidence** for the existence of dark matter and allows us to measure it *average density*.

- **Relic radiation and formation of structures.**

  This line of reasoning start from the observation that we know experimentally that all matter that interacted with light was initially homogeneous to a very large extent.

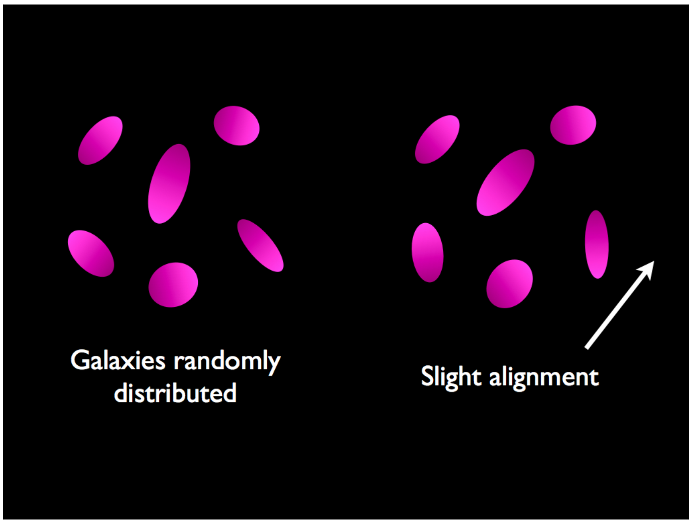

Figure 1.4: An illustration of the effect of weak gravitational lensing. *Credit: E. Grocutt, IfA, Edinburgh* [www.cfhtlens.org].

Indeed, cosmic micro-wave background (CMB), the most ancient light that we can detect, is at the level $\delta T/T \sim 10^{-5}$ [21]. CMB decoupled from matter at recombination of hydrogen, when most of the normal matter in the Universe was combined into a neutral state. This means that already at that moment of recombination (described by the red-shift $z_{\rm CMB} \approx 10^3$) gas of photons was also homogeneous to the same extent [1]. At the same time, photons dominated "normal" matter – the number of photons exceeded the number of baryons by 10 orders of magnitude, as we know both from the properties of CMB and from primordial nucleo-synthesis (see Section 3). Therefore, before recombination, normal matter was also as homogeneous as $\delta\rho/\rho \sim 10^{-5}$ as it interacted strongly with light. Indeed, photons can not be confined in the gravitational field of small overdensities and their scattering on charged particles would stop any clustering of matter. Therefore, these very small (10^{-5}) perturbations of the density of normal matter could start growing only after decoupling of light at recombination.

On the other hand, small density perturbations ($\delta\rho/\rho < 1$) grow linearly with the scale factor in the matter-dominated epoch. Therefore, we would naively expect that today such perturbations are still rather small

$$\delta\rho/\rho = 10^{-5} \cdot \left(\frac{1+z_{\rm CMB}}{1+z_0}\right) \approx 10^{-2} \qquad z_{\rm CMB} \approx 10^3. \tag{1.1.3}$$

This is very different from the Universe that we observe today – densities in galaxies are many orders of magnitude larger than the average matter density in the Universe. This means that some other, "dark" matter that did not interact with light started

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[1] After recombination interactions of CMB with matter where minimal and could not make it much more homogeneous than it was at recombination

to cluster significantly before recombination. Its over-densities would grow with a scale factor logarithmically in the radiation dominated epoch and linearly in the matter-dominated epoch. After recombination, the dark structures are already quite developed and ordinary matter (in its neutral state) quickly catch up and fall in the gravitational potential formed by DM.

Additionally, the spectrum of anisotropies of CMB (even if their amplitude is so small) is sensitive to the parameters that define the expansion rate of the Universe and the physics of CMB, such as the density of dark matter. The latest results from the Planck collaboration [21] allow to say the the abundance of DM is $\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$.

We can conclude, that the evidence for dark matter is overwhelming and comes from both theoretically and observationally independent sources. This evidence is based on the data describing dynamics of a large number of individual objects of various types, probed by 4 independent observational techniques as well as on the global picture of structure formation in the Universe as a whole as well as the properties of its Cosmic Microwave background (see e.g. [22–25]).

The Nature of dark matter There are probably three main possibilities concerning the nature of dark matter. It could consist of some very *special particles* that do not (or almost do not) interact with light; it could be made of some *macroscopic objects* (of some primordial origin?) or it can be a consequence of some *modifications to Newtonian gravity* or dynamics. In fact, all three scenarios require some new physics. The hypothesis of a new dark matter particle can arguably be considered as the simplest and minimal from a theoretical point of view. Moreover, it is very difficult to simultaneously explain *all* the evidence for dark matter with macroscopic objects or modified gravity/dynamics. In addition, massive compact objects (MACHOs) are strongly constrained as dominant DM candidate by microlensing surveys [26, 27].

There is, of course, a possibility that dark matter is not one phenomenon and different observations are explained by different underlying mechanisms. In Physics, however, it is important to study the simplest possibilities first, as required by the *Occam's razor* principle. Indeed, the simplest possibilities are typically also testable to a much larger extent. Therefore, in what follows we will assume that there is only one reason for all the phenomena described above as “evidence for dark matter” and that this reason is microscopic: *all dark matter is made of one particle*. Already this simplest option still requires an enormous and diverse research program, as we have (incomprehensibly) sketched below.

We study below the option that DM is made of particles. These particles should be stable (or be cosmologically long-lived), massive, and electrically neutral. Among known particles, in the Standard Model of particle physics, there are three such particles – three neutrinos of different flavors.

Can SM neutrinos constitute all dark matter in the Universe? As it was shown first in [28], one can put a robust bound on the mass of any fermionic dark matter particle (see [29–32] for more recent discussion). To obtain this so-called *Tremaine-Gunn bound*, one can consider a dwarf galaxy inside the Milky Way halo. The phase space density of the DM particle can be estimated from above (using a lower bound on the mass within a given radius and an upper bound on the velocity of the DM particle that is confined inside this radius). Dividing by the mass of each DM particle, we obtain a lower bound on phase-space number density that should not violate the Pauli exclusion principle and therefore be smaller than the phase space number density of degenerate Fermi gas. This requirement gives a lower bound on the mass of a DM fermion:

$$\frac{M}{\frac{4\pi}{3}r^3}\frac{1}{\frac{4\pi}{3}v^3} \leq \frac{2m_{\mathrm{DM}}^4}{(2\pi\hbar)^3}. \tag{1.1.4}$$

Let us apply this bound to a so-called *classical* dSphs of the Milky Way, where velocities of many stars are measured. For example, for Sculptor dwarf galaxy [16] we can take as a proxy of the object size its half-light-radius $r_h = 283$ pc, the mass inside this radius $M_h = 1.4 \cdot 10^7 M_\odot$ and as a characteristic velocity we take the velocity dispersion $v = \sigma_v = 9.2$ km/s. Substituting these values into Eq. (1.1.4) we get $m_{\mathrm{DM}} > 460$ eV. Other dSphs give similar constraints.

On the other hand, a primordial abundance of relic neutrinos expected in SM of particle physics also depends on the mass of neutrinos and can be easily estimated. Weak interaction keep neutrinos in the equilibrium in the early Universe as long as temperatures are large enough $T > 1$ MeV. Below this temperature weak interactions are too slow (as compared to the expansion of the Universe). As a results, the number density of neutrinos becomes constant in the co-moving frame. Calculating the density of neutrinos at decoupling, we can calculate its present value

$$n_{\nu,0} \sim T_\nu^3(t_0) \simeq 112\,\mathrm{cm}^{-3}, \tag{1.1.5}$$

with $T_\nu(t_0) \approx 1.95$ K being the temperature of neutrino decoupling. This gives

$$\Omega_{\nu\mathrm{DM}}h^2 = \frac{1}{\rho_{c,100}}\sum m_\nu n_{\nu,0} = \frac{\sum m_\nu\ \mathrm{eV}}{94\ \mathrm{eV}}, \tag{1.1.6}$$

where $\rho_{c,100} = \dfrac{3H_{100}^2}{8\pi G}$ with $H_{100} = 100$ km/s/Mpc. We see that only if

$$\sum m_\nu \simeq 11\ \mathrm{eV} \tag{1.1.7}$$

then the SM neutrino can constitute the correct abundance $\Omega_{\rm DM}h^2 = 0.12$ [21].

The lowest value of the dark matter particle mass required by the Tremaine-Gunn bound is inconsistent with the cosmological requirement on the neutrino's mass by a factor of ~ 30. This rules out the possibility that SM neutrinos constitute all dark matter. In fact, SM neutrinos give a very sub-dominant contribution to the DM density.

Independently, if DM would be made of particles as light as 100 eV or less that were in thermal equilibrium once (like SM neutrinos), the structure formation in the Universe would happen in a qualitatively different way as compared to what is observed [33]. Indeed, so light DM particles would have velocities close to the speed of light at their decoupling. These velocities would remain relativistic even in the matter-dominated epoch, homogenizing primordial plasma, erasing the overdensities smaller than the "free streaming length" of DM particles. This would mean that clusters of galaxies would form earlier than galaxies. Observationally, however, the galaxies are seen at much larger red-shifts than clusters [18].

We have convincing evidence that the dominant part of dark matter is not made of the only available Standard Model candidates – neutrinos. Therefore, some new physics beyond the Standard Model is needed to explain dark matter.

1.1.1 Dark matter candidates and their possible properties

If dark matter particle is not a part of the Standard Model we have to consider hypothetical new particles as DM candidates. Particle physics literature offers a wide range of such candidates, motivated by various logic and different approaches [18]. These candidates can be bosons (scalars or vectors) or fermions, have masses from 10^{-20} eV till many TeV or even more. For a long time the so-called WIMPs (weakly interacting massive particles) [34] – heavy fermions involved in weak interactions and decoupling from the primordial plasma like ordinary SM neutrinos (the so-called "thermal relics") – were considered by many scientists as the "most probable" DM candidate (whatever "the most probable" means for a hypothetical particle). This interest was bases on: (i) the so-called "WIMP miracle" – the fact that a particle with mass above 5 GeV and interaction cross-section close to that of ordinary neutrinos has primordial abundance that is an order of magnitude correct, almost independently of its mass; (ii) on general expectation to find new physics at the LHC, more or less together with the Higgs boson – and a WIMP DM particle could be a natural part of such a new physics; (iii) WIMPs could be efficiently search by the so-called direct detection experiments [18, 35–37] as well as colliders, including the LHC [36, 38–41].

The results of the LHC Run I and Run II [1] as well as many years of (so far) unsuccessful searches for WIMPs at the direct detection experiments as well as the general situation in particles physics create additional motivation to address the problem of dark matter in a maximally model-independent way. Possible properties of DM as we know them today are compatible with many very different particle physics models.

> Model independent astrophysical and cosmological constraints on the properties of dark matter particles provide invaluable information for particle physics. These results can potentially disfavor the whole directions in particle physics beyond its Standard Model.

Let us try to describe possible properties of DM particles in a maximally model-independent way by their:

- *Self-interaction*: completely ballistic or having potentially observable self-interacting cross-section;
- *Primordial velocities and free streaming*: cold, warm and hot dark matter (see below for definitions);
- *Life-time*: completely stable particles that could only annihilate or particles that could decay (but with cosmologically long life-time).

Cold, Warm dark matter and Hot dark matter This classification is based on the primordial properties of DM particles that depend on the production mechanism in the early Universe and the mass of the particle.

Probably the simplest option is that DM particles are produced with non-relativistic momenta. The examples of particle physics model include: (i) WIMPs, that are "freeze out" from thermal equilibrium at the temperatures smaller than their mass; (ii) axions that are created via the so-called misalignment mechanism [42] that naturally produces particles with very small momenta.

DM particles that are created non-relativistic form the so-called cold dark matter (CDM). Such dark matter is easy to be confined gravitationally and can form haloes of various sizes, including very small ones (e.g. for WIMPs the smallest halo size is set by the horizon at kinetic decoupling in the early universe, see e.g [43]).

For the cases of warm (WDM) and hot (HDM) dark matter, primordial velocities of DM particles are relativistic. Relativistic particle can not be gravitationally confined by the small density perturbations that exist in the early Universe. An average distance traveled by a dark matter particle before it falls into a potential well is called the *free streaming length*. At the scales smaller than the free streaming length, the density becomes more homogeneous, small density perturbations are washed out by random movements of the particles. Density perturbations that are larger than free-streaming length remain untouched by this process. The proper comoving free-streaming length is given by:

$$\lambda_{\rm FS}(t) \equiv a(t) \int_{t_i}^{t} d\tau \, \frac{v(\tau)}{a(\tau)} \approx 1\,\mathrm{Mpc} \left(\frac{1\mathrm{keV}}{M_{\rm DM}}\right) \frac{\langle p_{\rm DM}\rangle}{\langle p_\nu \rangle} \tag{1.1.8}$$

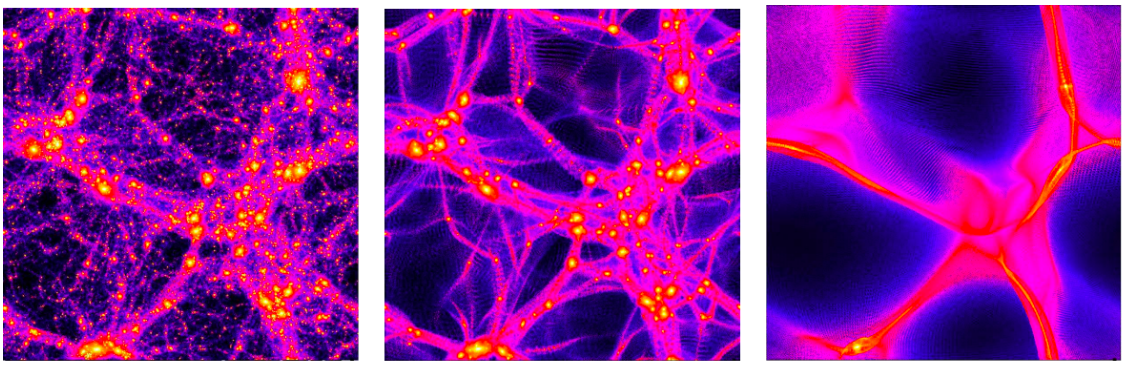

Figure 1.5: Simulation of the large scale structure for the cases of CDM, WDM and HDM (from left to right) cosmologies. *Credit: Maccio et al.* [44].

where $v(t)$ is a typical velocity of DM particles, t_i is the initial time (its particular value plays no role); $a(t)$ is the scale factor as a function of (physical) time. In the last equality, $\langle p_{\rm DM}\rangle$ and $\langle p_\nu\rangle$ are the average absolute values of momentum of DM particles and active neutrinos. The integral is saturated at early times when DM particles are relativistic ($v(t) \approx 1$).

The resulting picture is presented in Fig. 1.5, i.e. CDM forms structures of almost any size, WDM washes out small structures and HDM creates only large structures.

DM candidates can be classified as:

- *Cold dark matter*: particles that are created non-relativistic;
- *Warm dark matter*: particles that are initially relativistic, but became non-relativistic in the radiation-dominated epoch;
- *Hot dark matter*: particles that are still relativistic at the beginning of the matter-dominated epoch.

As discussed above in the context of SM neutrinos, Hot dark matter predict the top-down structure formation and is therefore excluded. Cold and Warm DM models have different predictions at the small scales only and therefore are *equally successful at large scales*. Both models correctly describe the data on large scale structure (e.g. galaxy-galaxy correlation functions), CMB, the properties of clusters of galaxies etc. [45, 46]. Only at the smallest observable scales one could try to see a difference between this two models [47, 48].

The work described in this thesis is mostly related to the attempts to distinguish between warm and cold dark matter. In the next section we describe a popular candidate for a warm dark matter particle – sterile neutrino (or heavy neutral lepton, HNL) as well as its particle physics origin, context and motivation. In the Section 3 we describe how one of the pillars of modern cosmology – primordial nucleosynthesis – can be used to constraint properties of new particles and derive the most up to date bounds on the parameters of sterile neutrinos. Then we proceed with the discussion of how to distinguish CDM from WDM observationally. For this, we review the theory of structure formation in the Section 4. In the following Section 5 we introduce on of the promising approaches to distinguish between CDM and WDM – the Lyman-α forest method. After describing the method itself and its limitations, we review the data available by now, discuss in details possible interpretations of these data and main uncertainties related to this. At the end we present the constraints on warm dark matter and sterile neutrinos that can be derived from Ly-alpha forest.