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Chapter 1

Introduction

1.1 Dark matter in the Universe

It is widely accepted nowadays that about 80% of the total mass in the Universe exists in the form of some mysterious *dark matter*. Unlike the ordinary ("*luminous*" or "*baryonic*") matter, this substance is detected only through its gravitational force (hence the name "*dark*") and plays a dominant role in the dynamics of celestial objects at scales above $\sim 100\,\mathrm{pc}$ (typical size of the smallest galaxies — satellites of the Milky Way). The need for dark matter in explaining the dynamics of galaxies in the Coma cluster was first observed by F. Zwicky [1] in the 1930s (although some earlier results by Hubble suggested that there should be more "dark stars" than visible ones in the Solar neighborhood, see a historical overview in [2]). Since then a body of strong and convincing evidence for the existence of dark matter has emerged (see e.g. [3–5] and references therein). This conclusion has been supported by numerous independent tracers of gravitational potential at different scales:

- the dynamics of stars in galaxies of all types requires a presence of a significant fraction of non-luminous matter (from dwarf spheroidal satellites of the Milky Way, [6] to large ellipticals [7–9]). In contrast, the dynamics of the gravitationally bound systems of a smaller scale (e.g. globular clusters) seem to be explained by its stellar matter (see e.g. [10]);

- measurements of the circular velocity, using e.g. the hyperfine splitting of hydrogen in spiral galaxies [11, 12];

- emission of the hot ionized gas in galaxy groups and galaxy clusters [13, 14];
- both weak and strong gravitational lensing measurements demonstrate that the dynamics of galaxies and galaxy clusters cannot be explained by the Newtonian potential created by visible matter only [5, 15–20].

In addition to this *independent astrophysical evidence* for the existence of dark matter, cosmological data (analysis of the cosmic microwave background anisotropies and the statistics of galaxy number counts) show that the cosmic large scale structure started to develop much before decoupling of photons and baryons at recombination of hydrogen in the early Universe and, therefore, much before ordinary matter could start clustering [21–26]. As a result current body of cosmological data is well-described by the "concordance model" in which about 20% of the total energy density in the Universe is in the form of dark matter (and only about 5% are in the form of baryonic matter).

The relative abundance of baryonic dark matter is strongly constrained by numerous microlensing experiments probing the MAssive Compact Halo Objects (see e.g. [27–29], for an overview see [30] and references therein) and the results of Big Bang Nucleosynthesis [31]. Attempts to explain dark matter by the existence of primordial black holes has not been fully successful (see e.g. [32, 33]).

No attempts to explain the dark matter phenomenon by the modification of Eisteinian gravity and/or Newtonian laws of dynamics has been successful in explaining the dark matter at the cluster and cosmological scales (see the recent discussion in [34, 35], see also [36, 37] for alternative viewpoints).

Therefore, a microscopic origin of dark matter phenomenon (i.e. a new particle or particles) remains the most plausible hypothesis (see e.g. recent review of [38–41] and refs. therein).

1.2 Dark matter and elementary particle physics

To be a viable dark matter candidate particles must be

- stable or cosmologically long-lived;
- 'dark' (very weakly interacting with the electromagnetic radiation);

- produced in the early Universe by a sufficient amount;
- consistent with existing astrophysical and cosmological bounds.

The only electrically neutral and long-lived particle in the Standard Model are neutrinos. As the neutrino oscillation experiments (see e.g. [42] for details) show that neutrinos have mass, they could play the role of dark matter particles. Neutrinos are involved in weak interactions that keep these particles in the early Universe in thermal equilibrium down to the temperatures of a few MeV. At smaller temperatures, the interaction rate of weak reactions drops below the expansion rate of the Universe and neutrinos "freeze out" from the equilibrium. Therefore, a background of relic neutrinos was created just before primordial nucleosynthesis. As interaction strength and, therefore, decoupling temperature and concentration of these particles are known, their present day density is fully defined by the sum of the masses for all neutrino flavors. To constitute the whole dark matter this mass should be about 11.5 eV (see e.g. [43]). Clearly, this mass is in conflict with the existing experimental bounds: measurements of the electron spectrum of β-decay put the combination of neutrino masses below 2 eV [44] while from the cosmological data one can infer an upper bound of the sum of neutrino masses is 0.58 eV at 95% confidence level [21]. The fact that neutrinos could not constitute 100% of dark matter follows also from the study of phase space density of dark-matter dominated objects that should not exceed the density of degenerate Fermi gas: fermionic particles could play the role of dark matter in dwarf galaxies only if their mass is above a few hundred eV (the so-called 'Tremaine-Gunn bound' [45], for review see [46] and references therein) and in galaxies if their mass is above tens of eV. Moreover, as the mass of neutrinos is much smaller than their decoupling temperature, they decouple relativistically and become non-relativistic only deeply in the matter-dominated epoch ("*hot dark matter*"). For such dark matter the history of structure formation would be very different, and the Universe would look rather differently nowadays [26, 47]. All these strong arguments prove convincingly that the *dominant fraction of dark matter* can not be made up of Standard Model neutrinos, and therefore *the Standard Model of elementary particles does not contain a viable dark matter candidate.* Therefore, the dark-matter particle hypothesis necessarily implies an extension of the Standard Model and any resolution of this puzzle will have a profound impact on the development of particle physics. By constraining the properties of dark-matter particles one can differentiate among extensions of the Standard Model and learn about the fundamental properties of matter.

Phenomenologically, little is known about the properties of dark-matter particles. The mass of fermionic dark matter is limited from below by the 'Tremaine-Gunn bound'[1]. They are not necessarily stable, but their lifetime should significantly exceed the age of the Universe (see e.g. [50]); dark-matter particles should have become non-relativistic sufficiently early in the radiation-dominated epoch (although a sub-dominant fraction might have remained relativistic much later).

A lot of attention has been devoted to the class of dark matter candidates called *weakly interacting massive particles* (WIMPs) (see e.g. [38, 51] for review). These *hypothetical* particles generalize the neutrino dark matter: they also interact with the Standard Model sector with roughly electroweak strength, however their mass is large enough so that these particles become non-relativistic already at decoupling. In this case the present-day density of such particles depends very weakly (logarithmically) on the mass of the particle as long as they are heavy enough. This "universal" density happens to be within an order of magnitude consistent with the dark matter density [52] (the so-called "*WIMP miracle*"). Due to their large mass and interaction strength, the lifetime of these particles would be extremely short and therefore some special symmetry has to be imposed in the model to ensure their stability.

The interest for this class of candidates is due to their potential relation to electroweak symmetry breaking, which is being tested at the Large Hadron Collider in CERN. In many models trying to make the Standard Model "natural" like, for example, supersymmetric extensions of the Standard Model, there are particles that could play the role of WIMP dark matter candidates. The WIMP searches are important scientific goals of many experiments. Dozens of dedicated laboratory experiments are conducted to detect WIMPs in the Galaxy halo by testing their interaction with nucleons (*direct detection experiments*) (see e.g. [53] and refs. therein). In addition, cosmic ray experiments (measurements of antiparticles), as well as γ-ray and X-ray observations are used to search for WIMPs annihilation signal,

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[1] A much weaker bound, based on the Liouville theorem, can be applied for bosonic dark matter, see e.g. [48, 49].

see e.g. [54, 55] for details. These searches are called, “indirect detection experiments” as only in conjunction with accelerator or laboratory searches they would provide a definitive answer about the properties of the dark-matter particles.

No convincing signals have been observed so far in either “direct” or “indirect” searches. Additionally, no hints of new physics at the electroweak scale has turned up at the Large Hardon Collider (LHC) or in any other experiments. This makes alternative approaches to the dark-matter problem ever more viable.

However, WIMPs by no means exhaust the list of possible dark-matter candidates. Many particles were suggested with their masses ranging from micro-eV to 10^{13} GeV (see e.g. [40, 51]). All these candidates interact *superweakly* (i.e. much weaker than the Fermi interaction strength) with ordinary matter. They may thus be called super-weakly interacting massive particles (or “super-WIMP”). Super-WIMP dark matter particles differ from WIMPs in two crucial ways: *(i)* correct abundance of dark matter may be produced with the mass of dark matter particles as low as a few keV; *(ii)* super-WIMPs can decay into Standard Model particles. These candidates include: extensions of the Standard Model by right-handed neutrinos (sterile neutrinos, majorons) [56–58], axions [59–61], supersymmetric theories (gravitino, axino) [52, 62–69], models with extra dimensions [67] and string-motivated models [70, 71] The feeble interaction strength makes the laboratory detection of such super-weakly interacting dark matter challenging (see e.g. [72]). Fortunately, many super-WIMP particles possess a 2-body radiative decay channel: $\text{DM} \to \gamma + \nu$ (for fermionic dark matter), $\text{DM} \to \gamma + \gamma$ (for dark matter made up of bosons), producing a monochromatic photon with energy $E_\gamma = m_{\text{DM}}c^2/2$. Searching for such a line thus provides a major way of detection of super-WIMP dark matter particles. One can therefore search for the presence of such a monochromatic line with energy in the spectra of dark matter-containing objects [73–76].

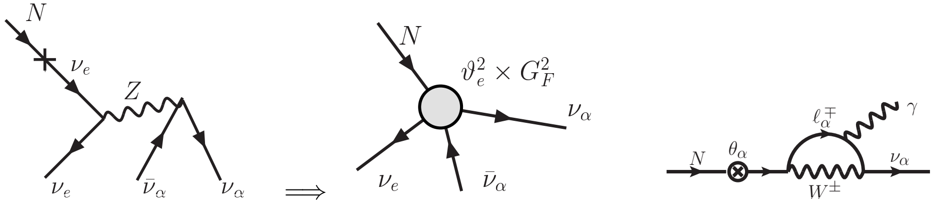
Although the lifetime of any realistic decaying dark matter should be much longer than the age of the Universe (see e.g. [50]), the huge amount of potentially decaying dark matter particles in a typical halo could produce a sizable decay signal. For example, there are $\sim 10^{75}$ dark matter particles with a ~ 1 keV mass in the halo of Andromeda galaxy. With the lifetime of the order of the age of the Universe, this would lead to $\sim 10^{57}$ decays per second, releasing $\sim 10^{45}$ erg/s. For comparison, the total X-ray luminosity of the Andromeda galaxy in the 0.1-2.4 keV band is 6 orders of magnitude smaller, $(1.8 \pm 0.3) \times 10^{39}$ erg/s [77], which immediately tells us that the lifetime of such particles should be at least 6 orders of magnitude longer than the age of the Universe.

In summary: the search for decaying dark matter is an important scientific goal. It can provide valuable constraints on the parameter space of extensions to the Standard Model, and may even lead to the discovery of a signal from dark matter particles. Unlike the search for annihilating dark matter (where the WIMP hypothesis limits the range of masses to the GeV energy range), there is no *a priori* preferred energy range for the searches of decaying dark matter signal.

In this thesis, a systematic program of searches for a decaying dark matter signal is conducted. The thesis starts from the identification of the most plausible mass range for decaying dark matter candidates; then discusses possible observational targets and the detection strategy; and, finally, derives new constraints for decaying dark matter, based on the novel method of analysis of observational data.

1.3 Sterile neutrinos: keV-mass decaying dark matter particles

This thesis concentrates mainly on determining the properties of dark matter particles in a *model-independent* fashion. However, it is instructive to consider a *baseline model* with respect to which the results are gauged. Therefore throughout this thesis we apply our results to the case of *sterile neutrino dark matter candidate* [56, 57, 73, 74, 78–81], see [82–84] for review. This model has recently attracted a lot of attention in the particle-physics community. Namely, it was shown that the minimal extension of the Standard Model by three sterile neutrinos provides a viable and unified description of three major “beyond the Standard Model” phenomena in particle physics – dark matter, neutrino oscillations and generation of baryon asymmetry in the Universe. This model, dubbed νMSM, is one of the very few models that provide testable resolution of the “beyond the Standard Model” puzzles in the situation when no new physics is found at the LHC (the so-called “nightmare scenario” [85]), and suggests how the nature of dark mat-



(a) Decay of sterile neutrino $N \to \nu_e \nu_\alpha \bar{\nu}_\alpha$ through neutral current interactions. A virtual ν_e is created and the quadratic mixing (marked by symbol "$\times$") is proportional to θ^2.

(b) At energies $E_N \ll M_Z$, the process in the left panel can be described by the Fermi-like interaction with the "effective" Fermi constant $\theta_e \times G_F$.

(c) Two-body decay of sterile neutrino. The energy of the photon is $E_\gamma = \frac{1}{2} M_N$.

Figure 1.1: Example of interactions of a sterile neutrino: decay $N \to \nu_e \nu_\alpha \bar{\nu}_\alpha$ (panel (a)) and its effective Fermi-like description (panel (b)) and loop-mediated decay $N \to \gamma + \nu_\alpha$ (panel (c)).

ter and other "beyond the Standard Model" phenomena may nevertheless be checked experimentally using existing experimental technologies and major infrastructure. Below, we describe it in more details.

A sterile neutrino is a right-chiral counterpart of the left-chiral neutrinos of the Standard Model (called '*active*' neutrinos in this context). Adding these particles to the Standard Model Lagrangian makes neutrinos massive, and therefore their existence provides a simple and natural explanation of the observed neutrino flavor oscillations. These particles are *singlet leptons* because they carry no charges with respect to the Standard Model gauge groups (hence the name), and therefore along with their Yukawa interaction with the active neutrinos (='Dirac mass') they can have a Majorana mass term (see e.g. [76] for details). They interact with matter via the creation of a virtual active neutrino (quadratic *mixing*), and in this way they effectively participate in weak reactions (see e.g. Fig. 1.1a). At energies much below the masses of the W and Z-bosons, their interaction can be described by the analog of the Fermi theory with the Fermi coupling constant G_F suppressed by the *active-sterile neutrino mixing angle* θ — the ratio of their Dirac to Majorana masses (Fig. 1.1b):

$$\theta_\alpha^2 = \sum_{\text{sterile N}} \left| \frac{m_{\text{Dirac},\,\alpha}}{M_{\text{Majorana}}} \right|^2 \tag{1.1}$$

(this mixing can be different for different flavours α).

It was observed long ago that such particles could have been produced in the Early Universe through mixing with active neutrinos [56] and have a correct relic density for any mass [56, 78, 79, 81, 86–88].

Unlike WIMPs whose existence is motivated first of all by the theoretical considerations on the stability of the Higgs mass against quantum corrections that could require a fine-tuning of parameters of the model, the existence of sterile neutrinos is motivated by the *observational phenomena beyond the Standard Model*. Namely, sterile neutrinos would provide a simple and natural explanations of the *neutrino flavour oscillations* [89–92]. However, a *single* sterile neutrino would be unable to explain the two observed mass splittings between Standard Model neutrinos — at least two sterile neutrinos are needed for that. Moreover, should a sterile neutrino play the role of dark matter, the mixing with active neutrinos would be too small to contribute significantly to the flavor oscillations – its lifetime should be very large and, therefore, interaction strength should be too feeble [57, 93]. Therefore, in order to explain dark matter and neutrino mass (one for each Standard Model flavor), the minimal model should contain 3 right-handed neutrinos [57]. In such a model, the lowest mass eigenstate of the active neutrinos will be (almost) zero and the sum of neutrino masses $\sum m_\nu \approx \kappa\sqrt{|\Delta m^2_{\text{atm}}|}$, where $\kappa = 1$ or 2 for normal (inverted) hierarchy [93]. This is one of the predictions of such a model.

In spite of the fact that a dark-matter sterile neutrino plays essentially no role in the neutrino oscillations, the fact that 3 particles are needed to explain *both* dark matter and neutrino oscillations is crucial. As we will see below, primordial properties of sterile neutrino dark matter are determined by two other sterile neutrinos.

If the masses of the two sterile neutrinos, responsible for neutrino oscillations, are below ~ 2 GeV (mass of c-quark), such particles can be searched with existing experimental techniques [94, 95]. This is a unique situation when one can directly test the nature of neutrino oscillations in 'intensity frontier' [96] experiments. For masses above 2 GeV the searches become more difficult.

It turns out that in the mass region between 100 MeV and the electroweak scale, out-of equilibrium reactions with these two sterile neutrinos are capable of generating the observed matter-antimatter asymmetry of the

Universe (baryogenesis) [80, 97]. These observations motivated a lot of recent efforts for developing the νMSM — *Neutrino Minimal Standard Model* (see [82] for review). Finding these particles in intensity frontier experiments would provide an unparalleled possibility to test baryogenesis in the laboratory. Moreover, if some particles are found in such experiments it will be possible not only to check whether they are responsible for baryogenesis or not, but also unambiguously predict the properties of sterile neutrino dark matter.

Because its interaction with the Standard Model particles is very feeble, sterile neutrino does not need to be stable. The decay channel for sterile neutrinos of all masses is to 3 (anti)neutrinos (Fig. 1.1a).[2] However, the most characteristic feature of sterile neutrino dark matter is its ability to decay into a photon and a neutrino (with cosmologically long lifetime) [73, 74, 98], see Fig. 1.1c. The emitted photon is almost mono-energetic (the width of the dark matter decay line is determined entirely by the motion of dark matter particles). Although the lifetime of the dark matter particles turns out to be *much longer than the age of the Universe*, the humongous number of these particles around us implies that the combined emission may be sizable.

If dark matter is made of sterile neutrinos, detecting astrophysical signal from their decay (the "indirect detection") may be the only way to identify this particle experimentally. However, it may be possible to prove the dark matter origin of observed signal unambiguously using its characteristic properties.

In summary: three sterile neutrinos with the masses below electroweak scale form a minimal testable model that provides a unified description of three major *observational* problems "beyond-the-Standard-Model" [57, 80, 82, 97]:

1) neutrino flavour oscillations;
2) the absence of primordial anti-matter in the Universe;
3) existence of dark matter.

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[2] For masses above $1\ \mathrm{MeV}$ additional decay channels become kinematically possible.

1.3.1 Production of sterile neutrinos in the early Universe

The active-sterile neutrino mixing is strongly suppressed at temperatures above a few hundred MeV and peaks roughly at [56]

$$T_{peak} \sim 130 \left(\frac{M_{N_{\rm DM}}}{1\,\mathrm{keV}}\right)^{1/3} \text{ MeV} , \qquad (1.2)$$

Sterile neutrino dark-matter candidates are *never in thermal equilibrium* and their number density is significantly smaller than that of the active neutrinos (that is why they can account for the observed dark matter abundance without violating the 'Tremaine-Gunn bound'). In particular, the shape of the primordial momentum distribution of the sterile neutrinos is roughly proportional to that of the active neutrinos [73]:

$$f_{N_{\rm DM}}(t,p) = \frac{\chi}{e^{p/T_\nu(t)} + 1} , \qquad (1.3)$$

where the normalization $\chi \sim \theta^2_{\rm DM} \ll 1$ and where $T_\nu(t)$ is the temperature of the active neutrinos.[3] Comparing the production temperatures Eq. (1.2) of dark matter sterile neutrinos with their masses shows that they are produced relativistically in the radiation-dominated epoch. Indeed, for the primordial dark matter distribution of the form (1.3) one has $\langle p\rangle \sim T_{peak} \gtrsim M_{N_{\rm DM}}$ for $M_{N_{\rm DM}} \lesssim 40\,\mathrm{GeV}$. Relativistic particles stream out of the overdense regions and erase primordial density fluctuations at scales below the *free-streaming horizon* (FSH) – particles' horizon where they becomes nonrelativistic (for a detailed discussion of characteristic scales see e.g. [99] and references therein). This effect influences the formation of structures. If dark matter particles decouple nonrelativistically (*cold* dark matter models, CDM) the structure formation occurs in a "bottom-up" manner: specifically, smaller scale objects form first and then merge into the larger ones [100]. CDM models fit modern cosmological data well. In the case of particles, produced relativistically and *remaining relativistic* into the matter-dominated epoch (i.e. *hot* dark matter, HDM), the structure formation goes in a "top-down" fashion [101], where the first structures to collapse have sizes comparable to the Hubble size [102–104]. The HDM scenarios contradict large-scale structure (LSS) observations [47]. Sterile neutrino dark matter that

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[3] The true distribution of sterile neutrinos is in fact colder than that shown in Eq. (1.3). Specifically, the maximum of $p^2 f_{N_1}(p)$ occurs at $p/T_\nu \approx 1.5 - 1.8$ (depending on $M_{N_{\rm DM}}$), as compared with $p \approx 2.2 T_\nu$ for the case shown in Eq. (1.3) [81, 86].

is produced relativistically and is then redshifted to nonrelativistic velocities in the radiation-dominated epoch is an intermediate, *warm dark matter* (WDM) candidate [73, 79, 105]. Structure formation in WDM models is similar to that in CDM models at distances above the free streaming scale. Below this scale density fluctuations are suppressed, compared with the CDM case. The free-streaming scale can be estimated as [103]

$$\lambda_{\text{FS}}^{co} \sim 1\,\text{Mpc}\left(\frac{\text{keV}}{M_{N_{\text{DM}}}}\right)\frac{\langle p_N\rangle}{\langle p_\nu\rangle}\ . \tag{1.4}$$

where $1\ \text{Mpc}$ is the (comoving) horizon at the time when momentum of active neutrinos $\langle p_\nu\rangle \sim 1\ \text{keV}$. If the spectrum of sterile neutrinos is nonthermal, then the moment of non-relativistic transition and λ_{FS}^{co} is shifted by $\langle p_N\rangle/\langle p_\nu\rangle$.

This mechanism specifies a *minimal* amount of sterile neutrinos that will be produced for given M_1 and θ_1. The requirement that 100% of dark matter be produced via such mixing places an *upper bound* on the mixing angle θ_1 for a given mass. This conclusion can only be affected by entropy dilution arising from the decay of some heavy particles below the temperatures given in Eq. (1.2) [106, 107].

The production of sterile neutrino dark matter may substantially change in the presence of lepton asymmetry when the resonant production (*RP*) of sterile neutrinos [78] occurs, analogous to the Mikheyev–Smirnov–Wolfenstein effect [108, 109]. When the dispersion relations for active and sterile neutrinos cross each other at some momentum p, the effective transfer of an excess of active neutrinos (or antineutrinos) to the population of dark matter sterile neutrinos occurs. The maximal amount of sterile neutrino dark matter that can be produced in such a way is limited by the value of lepton asymmetry, $\eta_L \equiv |n_\nu - n_{\bar\nu}|/s$, where s is the entropy of relativistic species in plasma. The present dark matter abundance $\Omega_{\text{DM}} \sim 0.25$ translates into the requirement of $\eta_L \sim 10^{-6}\left(\frac{\text{keV}}{M_{N_{\text{DM}}}}\right)$ in order for resonnatly produced sterile neutrinos to constitute the dominant fraction of dark matter. One notices that the resonant production occurs only for values of lepton asymmetry, η_L much larger than the *measured* value of *baryon asymmetry of the Universe*: $\eta_B \equiv \frac{n_B}{s} \sim 10^{-10}$ [21]. Such a value of η_L does not contradict to any observations though. Indeed, the upper bounds on η_L are based on either primordial nucleosynthesis (BBN) or CMB measurements (as chemical potential of neutrinos would carry extra radiation density) [110, 111]. These bounds read $|\eta_L| \lesssim \text{few} \times 10^{-3}$ (see e.g. [112–114]). We see, therefore, that the lepton asymmetry, required for resonant sterile neutrino production is still considerably smaller than the upper limit. Notice, that at epochs prior to BBN even $\eta_L \sim 1$ is possible (if this lepton asymmetry disappears later). Such a scenario is realized e.g. in the *Neutrino Minimal Standard Model*, νMSM (see [82] for review), where the lepton asymmetry keeps being generated below the sphaleron freeze-out temperature and may reach $\eta_L \sim 10^{-2} \div 10^{-1}$ before it disappears at $T \sim$ few GeV [87].

1.3.2 Structure formation with sterile neutrino dark matter

Non-negligible velocities of 'warm' sterile neutrinos alter the power spectrum of density fluctuations at scales below the *free-streaming horizon* scale. Additionally, the suppression of the halo mass function below a certain scale [115] and different history of formation of first structures affects the way the first stars were formed and therefore the reionization history of the Universe, abundance of the oldest (*Population III*) stars, etc. [116–121].

The effects of suppression of the matter power spectrum are probed with the **Lyman-α forest method** [122–125] (see [99] for critical overview of the method and up-to-date bounds). Using neutral hydrogen as a tracer of overall matter overdensity, one can reconstruct the power spectrum of density fluctuations at redshifts $2 < z < 5$ and scales $0.3 - 5$ h/Mpc (in comoving coordinates) by analyzing Lyman-α absorption features in the spectra of distant quasars.

If all dark matter is made of sterile neutrinos with a simple Fermi-Dirac-like spectrum of primordial velocities (1.3), the matter power spectrum has a sharp (cut-off like) suppression (as compared to ΛCDM) at scales below the free-streaming horizon (1.4) (similar to the case of 'thermal relics' [105]). In this case the Lyman-α forest data [99, 122–126] puts such strong constraints at their free-streaming length, which can be expressed as the *lower bound* on their mass $M_{N_{\text{DM}}} \geq 8\,\text{keV}$ (at 3σ CL) [99]. Such WDM models produce essentially no observable changes in the Galactic structures (see e.g. [99, 127–130]) and therefore, from the observational point of view such a sterile neutrino dark matter (although formally 'warm') would be indistinguishable from pure CDM.

On the other hand, resonantly produced sterile neutrinos have spectra that significantly differ from those in the non-resonant case [78, 88]. The primordial velocity distribution of RP sterile neutrinos contains narrow resonant (*cold*) *plus* a nonresonant (*warm*) components – CWDM model (see [99, 131] for details).[4] In the CWDM case, however, Lyman-α constraints allow a significant fraction of dark matter particles to be very warm [99]. This result implies for example, that sterile neutrino with the mass as low as $1-2$ keV is consistent with all cosmological data [131].

The first results [133] demonstrate that resonantly produced sterile neutrino dark matter, compatible with the Lyman-α bounds [131], do change the number of substructure of a Galaxy-size halo and their properties. Qualitatively, structures form in these models in a bottom-up fashion (similar to CDM). The way the scales are suppressed in CWDM models is more complicated (and in general less severe for the same masses of WDM particles), as comparable with pure warm dark matter models. The first results of [133] demonstrate that the resonantly produced sterile neutrino dark matter models, compatible with the Lyman-α bounds of [131], do change the number of substructure of a Galaxy-size halo and their properties. The discrepancy between the number of observed substructures with small masses and those predicted by ΛCDM models (first pointed out in [134, 135]) can simply mean that these substructures did not confine gas and are therefore completely dark (see e.g. [136–139]). This is not true for larger objects. In particular, CDM numerical simulations invariably predict several satellites “too big” to be masked by galaxy formation processes, in contradiction with observations [134, 135, 140, 141]. Resonantly produced sterile neutrino dark matter with its non-trivial velocity dispersion, turns out to be “warm enough” to amend these issues [133] (and “cold enough” to be in agreement with Lyman-α bounds [131]).

Ultimate investigation of the influence of *dark matter decays* and of *modifications in the evolution of large scale structure* in the ‘sterile neutrino Universe’ as compared with the ΛCDM model requires a **holistic approach**, where all aspects of the systems are examined within the same set-up rather than studying the influence of different features one-by-one. Potentially observable effects of particles’ free streaming and decays are expected in terms of

- formation and nature of the first stars [117, 118, 142, 143];
- reionization of the Universe [119, 121, 144–146];

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[4] Axino and gravitino models may have similar spectra of primordial velocities, c.f. [132].

- the structure of the intergalactic medium as probed by the Lyman-α forest [99, 124–126, 131, 147–149];
- the structure of dark matter haloes as probed by gravitational lensing [149–153];
- the structure and concentration of haloes of satellite galaxies [133, 154–157].

The results of this analysis will be confronted with measured cosmological observables, using various methods: Lyman-α analysis (with BOSS/SDSS-III or X-Shooter/VLT [158]), statistics and structure of dark matter halos, gravitational lensing, cosmological surveys).

The weak lensing surveys can be used to probe further clustering properties of dark matter particles as sub-galactic scales, as the next generation of these surveys will be able to measure the matter power spectrum at scales down to $1 - 10$ h/Mpc with a few percent accuracy. The next generation of lensing surveys (such as e.g. KiDS, LSST, WFIRST, Euclid) can provide sensitivity, compatible with the existing Lyman-α bounds [150, 151]. As in the case of the Lyman-α forest method the main challenge for the weak lensing is to properly take into account baryonic effects on matter power spectrum. The suppression of power spectrum due to primordial dark matter velocities can be extremely challenging to disentangle from the modification of the matter power spectrum due to baryonic feedback [148, 159, 160]. Finally, the modified concentration mass relation, predicted in the CWDM models, including those of resonantly produced sterile neutrinos ([131, 161]) can be probed with the weak lensing surveys (see e.g. [162, 163]) if their sensitivity can be pushed to halo masses below roughly $10^{12} M_{\odot}$.

1.4 The structure of the thesis

I. We begin in Chapter 2 with the *determination of the lower bound on the mass of dark matter particles* and the energy range of possible searches. If the dark matter particles are fermions, there is a very robust bound on their mass. Namely, due to the Pauli exclusion principle, there exists the densest "packing" of the fermions in a given region of the phase space (known as "*Tremaine-Gunn bound*", [45]). Decreasing the mass of the dark matter particles, one increases their number (and, hence, phase-space density) in any dark matter-dominated object. The requirement that this phase-space density did not exceed that of the degenerate Fermi gas thus leads to the *lower mass bound*. With additional assumptions, this bound can be further strengthened (and even generalized to the case of bosonic dark matter). We overview existing approaches and their limitations and propose a new method that allows to derive strong yet robust bounds on the mass of dark matter particles, improving on the original Tremaine-Gunn bound. By considering the existing data on different types of galaxies, we conclude that the strongest bound on the mass of dark matter fermions comes from the dwarf satellite galaxies of the Milky Way. Using recent results of the mass modeling of dwarf spheroidal galaxies and paying special attention to systematic uncertainties in relevant parameters, it is shown that the mass of dark matter fermion should exceed $\sim$0.4 keV, and therefore the dark matter decay signal should be searched in X-ray and γ-ray energy ranges. As the decay width increases with the mass of the particle, *we conclude that the X-ray range is the preferred range of searches for fermionic decaying dark matter*.

II. We proceed with the identication of the best observational targets for decaying dark matter searches (Chapter 3). To this end we analyze dark matter distributions in several hundreds of dark matter-dominated objects in the local Universe (redshift $z < 0.1$). We consider different types of galaxies (dwarf, spiral, and elliptical); galaxy groups and galaxy clusters – all types of dark matter-dominated objects, with their masses spanning eight orders of magnitude. We demonstrate that the expected dark matter decay signal (proportional to the "*dark matter column density*") increases slowly with the mass of the object. We determine a relation between the dark matter column density and the mass of the halo and demonstrate that the *scatter of this relation* can be predicted based on the existing numerical simulations of structure formation. Therefore, decaying dark matter would produce a unique all-sky signal, with a known slow-varying angular distribution. Such a signal can be easily distinguished from any possible astrophysical background and therefore makes the astrophysical search for decaying dark matter *another type of a direct detection experiment*.

III. These results allows us to define a *detection strategy for radiatively decaying dark matter* (Chapter 4). First of all, one has a freedom of choosing the observational targets, avoiding complicated astrophysical backgrounds. In particular, although galaxy clusters possess in general the highest dark matter column density, due to their high emission in X-rays the expected signal to noise ratio is not optimal (for spectral resolution of modern X-ray missions). The best targets thus become dwarf and spiral galaxies. The expected decay signal from these targets varies within a factor of few and although lower, than that of the galaxy clusters can be searched for against much lower astrophysical background.

Our findings also demonstrate that if a candidate spectral line is found, its surface brightness profile may be measured, distinguished from astrophysical emissions, and compared among several objects with similar expected signal. This allows to *unambiguously* discriminate decaying dark matter signal from possible astrophysical or instrumental backgrounds. To illustrate the power of this approach, we investigate the recent claim of that a spectral feature at ~ 2.5 keV in the *Chandra* observation of Willman 1 can be interpreted a dark matter decay line. We demonstrate that such an interpretation is ruled out by archival observations of M31 and Fornax/Sculptor dwarf spheroidals with high significance.

We conclude Chapter 4 with the review of the current status of decaying dark matter searches. We collect all existing bounds on decaying dark matter lifetime in the keV energy range. These results are obtained from the analysis of medium exposure (about 100 kilo-seconds) observations of individual objects of different types. We argue that with the current generation of X-ray telescopes there are two possible ways to further improve the existing bounds and probe the theoretically interesting regions of particle physics models:

(a) Deep (few mega-secounds) observations of the most X-ray quiet objects. "*Classical*" dwarf spheroidal galaxies (Ursa Minor, Draco, Sculptor, Fornax), where the dark matter content can be determined robustly are the preferred targets. The problem with this approach is the limited visibility of some of these objects and large investment (about 10%) of the annual observational time of the satellite (total observational time available each year for *XMM-Newton* and *Chandra* satellites is about half of the calendar year, i.e. 14–15 Msec). Allocating time for such an observation in the absence of a candidate line is hardly possible. On the other hand, observations of these objects would provide an important confirmation of the signal, detected with some other means.

(b) Total exposure of all observations of dark matter-dominated objects with the X-ray satellites is several orders of magnitude longer than any possible single observation. Therefore a possible way to advance with the existing X-ray instruments is *to combine a large number* of X-ray observations of different dark matter-dominated objects. The idea is that the spectral position of the dark matter decay line is the same for all these observations, while the astrophysical backgrounds in the combined spectrum would “average out”, producing a smooth continuum against which a small line would become visible. Naively, such a dataset, uniformly processed, should allow to improve the existing bounds by at least an order of magnitude *and* study spatial dependence of each candidate line.

IV. Chapter 5 is devoted to this goal – *analysis of a large dataset of archival XMM-Newton observations of galaxies*. Extremely large combined exposure of this dataset (two orders of magnitude longer than a typical single observation) presents several new challenges. Indeed, large number of counts in each energy bin mean that the statistical errors become very small (sub-% level). To extract meaningful bounds one needs therefore to control systematic errors at the comparable level. The level of systematics of the *XMM-Newton* is considered to be much higher (5-10%) due to the instrument’s degradation with time, variability of the instrumental background, imperfect knowledge of the instrument’s response functions, etc. To tackle these problems, a novel method of data analysis has been developed that delivers the required control over the level of systematics. We demonstrate the sensitivity of this method and search for the presence of lines in the 2.5–11 keV energy range. We find several new line candidates. After careful analysis, all these candidates are quantified as faint instrumental lines which have not been observed previously. Finally, we construct strongest to-date upper bounds on decaying dark matter parameters probing significant part of the parameter space of the corresponding particle physics models.

V. We conclude Chapter 6 with the discussion of the prospects of searching for decaying dark matter line with new instruments. The real progress requires at least an order of magnitude improvement of energy resolution for diffuse sources, combined with the high throughput instruments. We argue therefore that the X-ray micro-calorimeters (rather than present-day CCD-based detectors) should be used for this goal. Such a micro-calorimeter delivers required spectral resolution in the energy range from sub-keV to tens of keV. Parameters of such a mission and its tentative observational programme is discussed.