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Chapter 7

Conclusions

In this thesis, we *undertook a systematic model-independent program of studying the properties of decaying dark matter.* We do not limit ourselves by any particular model, and are agnostic about the mass and the interaction type/interaction strengths of dark matter. We concentrate on limiting possible lifetime and decay rate of dark matter particles, as a function of the mass, by performing searches for the signatures of decays of dark matter particles.

We have revised the existing theoretical approaches and developed a new method that allows to derive strong yet robust bounds on the mass of dark matter particles. By analyzing the experimental data for the objects with the largest dark matter phase-space density – dwarf spheroidal galaxies – it was shown that the mass of dark matter fermion should exceed $\sim$0.4 keV, and therefore *the X-ray energy range is a preferred region when searching for radiatively decaying dark matter*.

By analyzing dark matter distribution in different types of galaxies and in galaxy clusters it was shown that the expected dark matter decay signal increases slowly with the mass of the object. We demonstrate that the average central dark matter column density, defining the expected signal, follows, as a function of total halo mass a universal scaling law. This result allowed us to select dwarf and spiral galaxies as the observational targets with the optimal signal-to-noise ratio.

When taking into account the existing bounds on dark matter decay lifetime our results imply that it would be very challenging to obtain robust improvements on the existing constraints (even by as little as a factor of

2) by individual observations of dark matter dominated objects. Therefore *to further improve the existing bounds and probe the theoretically interesting regions of particle physics models we performed a combined analysis of a very 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) requires a very good control of systematic errors and of the instrumental backgrounds and does not allow to use the standard tools of data analysis. To tackle these problems, we developed a novel method of data reduction, constructing the largest to-date dataset of *XMM-Newton* observations.

Our method had revealed several new narrow line candidates. After careful analysis, all these candidates were quantified as faint instrumental lines that have not been observed previously. No "suspicious" lines at more than 2σ level had been detected.

Non-observation of candidate lines allowed us to improve the existing bounds by more than a factor of 8 at some energies. (Formally, such an improvement would require increase of exposure of an individual observation from $\sim 100\,\mathrm{ksec}$ to $\sim 6.5\,\mathrm{Msec}$ – half of the annual observation programme of *XMM-Newton*). Our results are summarized in Fig. 5.26, page 116.

To understand the significance of our results, we converted the upper bound on the flux in line into the bounds on the interaction strength of sterile neutrino dark matter in our baseline model. We were able to advance into the cosmologically interesting region of parameter space for masses between 5 and 20 keV (see Fig. 5.28, page 118). The significant part of the parameter space, nevertheless, remains unexplored. We were not able to probe cosmologically interesting region at masses below ~ 4 keV (upper gray region in Fig. 5.28) and did not probe the parameter range above ~ 22 keV (while the allowed mass range goes all the way to 50 keV).

At first sight it may seem that the searches for decaying dark matter using existing X-ray missions (*XMM-Newton*, *Chandra*, *Suzaku*) had reached their limit. Indeed, significant (factor of few) increase of exposure beyond that of our combined dataset (6–9 Msec) seems unrealistic. This is however, not true and *below we discuss the further possible directions to improve our results*.

First of all, as Fig. 5.27 demonstrates, our bounds are overly conservative at some energies, especially between 3 and 5 keV, where crosses extend down below the pink shaded region. The reason for this has not been understood yet and we expect that eventually we will be able to improve our upper bounds by a factor of few at these energies.

Secondly, when converting upper limits on the line flux into the interaction strength of dark matter models, we have conservatively included only the signals from the Milky Way halo and the halo of Andromeda galaxy for appropriate observations. The total dark matter content in our field of view is much higher (as all observations contain at least one nearby galaxy in its field of view). Proper estimates of dark matter contributions of about 100 galaxies, used in this dataset, should further increase our bounds on the interaction strength of sterile neutrino dark matter in the whole range of probed masses.

Thirdly, the gaps (in positions of strong instrumental lines) can be filled (at least partially) by doing similar analysis with the different instrument. As Table 7.1 demonstrates the positions of strong instrumental lines differ between different instruments and therefore similar analysis with *Chandra* or *Suzaku* could help to increase the sensitivity. Notice, however, that among all these missions the grasp (product of the effective area and of the field of view, controlling the total statistics for diffuse sources) of *XMM-Newton* is *at least factor of 5 larger*, than for *Chandra* and/or *Suzaku* and therefore the loss of statistics should be compensated by a longer exposure. Reaching the sensitivity, comparable to our results with e.g. *Suzaku* observations would require about 5 times bigger collection of observations of dark matter-dominated objects (i.e. at least 30 Msec of cleaned exposure). While total archival of observations with *Suzaku* is about 85 Msec, we found only 10 Msec of observations of galaxies from our dataset, (as described in the Section 5.1). On the other hand, the instrumental background of *Suzaku* is significantly lower, than that of *XMM-Newton* (as *Suzaku* is flying on a low earth orbit).

An improvement of bounds for masses lower 5 keV is extremely challenging. First of all, at energies $2.3-2.5$ keV the mirrors of all X-ray satellites have an absorption edge, and the effective area is highly uncertain. Next, all instruments possess several strong instrumental lines at energies ~ 1.5 keV (see Table 7.1). Finally, at even lower energies emission of the Milky Way is the dominant signal, which may allow to reach a similar sensitivity with a somewhat lower exposure.

Finally, we discussed an ultimate way to probe the whole parameter

Energy (keV)	*XMM-Newton* EPIC	*Chandra* ACIS	*Suzaku* XIS
1.486 (Al Kα)	+	+	+
1.740 (Si Kα)	+	+	+
2.123 (Au Mα)	–	+	+
4.511 (Ti Kα)	+		–
5.415 (Cr Kα)	+	–	–
5.895 (Mn Kα)	+	–	+
6.404 (Fe Kα)	+	–	–
6.490 (Mn Kβ)	–	–	+
7.470 (Ni Kα)	+	+	+
8.048 (Cu Kα)	+	–	–
8.265 (Ni Kβ)	–	–	+
8.639 (Zn Kα)	+	–	–
8.905 (Cu Kβ)	+	–	–
9.572 (Zn Kβ)	+	–	–
9.671 (Au Lα)	+	+	+
11.51 (Au Lβ)	+	+	+

Table 7.1: Prominent instrumental lines for *XMM-Newton*/EPIC, *Chandra*/ACIS and *Suzaku*/XIS cameras. Shaded rows show energy intervals at which *Chandra* and/or *Suzaku* do not have strong instrumental lines, while *XMM-Newton* does. Notice, however, that the grasp of *Chandra* is inferior to that of *XMM-Newton* by the factors ranging from 10 at 1 keV, 20 at 5 keV and as large as 50 at 10 keV. The grasp of *Suzaku* is factor 5–6 worse than that of *XMM-Newton* over the whole energy range (meaning that the exposure should be increased by the same factor to arrive to the similar restrictions.

space of minimal models of decaying dark matter, including the region of soft, (~ 1 keV) X-rays. We argue that a new X-ray telescope with the energy resolution comparable to the intrinsic width of the dark matter decay line is needed for that. Such a mission would include an X-ray microcalorimeter with $\sim$ 10 deg field-of-view and large grasp. Parameters of such a mission and possible observational programme is discussed.