Restrictions on sterile neutrino parameters from astrophysical observations

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Adding 3 right-handed (sterile) neutrino to the Standard Model (SM) can solve several “beyond the Standard Model” problems within one consistent framework: explain neutrino oscillations and baryon asymmetry of the Universe and provide a dark matter (DM) candidate. In this talk I will present current status of astrophysical searches for the DM sterile neutrino.

Sterile neutrino as the DM candidate. It was noticed long ago that the sterile neutrino with the mass in the keV range provides a valuable DM candidate. Recently it was shown that the extensions of the SM by 3 right-handed (sterile) neutrinos explains neutrino oscillations, allows for baryogenesis and provides the DM candidate within one consistent framework. Unlike the usual see-saw models, the masses of all new particles in νMSM are below electroweak scale, which makes this theory potentially testable. The baryogenesis requires two sterile neutrinos to have masses $\mathcal{O}(1−20)$ GeV and be quite degenerate. The third neutrino should be much lighter and plays the role of the DM.

Any DM candidate should (1) be stable or cosmologically long-lived; (2) be “dark” (interact very weakly with the SM matter); and (3) be produce in the correct amount in the early Universe. The sterile neutrino satisfies all these requirements. The sterile neutrino interacts with the rest of the SM only through mixing with active neutrinos. The mixing is parameterized by $\theta$ – the ratio of Yukawa interaction between left and right-handed neutrinos to the mass of the sterile neutrino. In the νMSM this mixing can be made arbitrarily small. Therefore, the light sterile neutrino is definitely “dark”. However, it is not completely dark. Due to this interaction, the sterile neutrino can decay into three active neutrinos. The life-time of such a decay exceeds the age of the Universe ($\tau = 5 \times 10^{26} \text{sec} \times \left(\frac{\text{keV}}{m}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)$). The sterile neutrino also has a (subdominant) decay channel into a photon and an active neutrino. The energy of the photon is $E_\gamma = \frac{M_s}{2}$ and the width of the decay line is determined by the Doppler broadening: $\Delta E/E_\gamma \sim 10^{-4} − 10^{-2}$. This means that one can search for the narrow line of neutrino decay in the spectra of astrophysical objects.

The mass of the sterile neutrino DM should be above $300 − 500$ eV (Tremain-Gunn bound), i.e. the lowest energy range to search for the sterile neutrino decay is the X-ray. The corresponding photon flux from the region with the DM overdensity
is related to the parameters of the sterile neutrino as

\[ F_{\text{DM}} \approx 6.38 \left[ \frac{M_{\text{DM}}}{10^{10} M_\odot} \right] \left[ \frac{\text{Mpc}}{D_L} \right]^2 \sin^2(2\theta) \left[ \frac{M_s}{\text{keV}} \right]^5 \text{ keV cm}^2 \text{ sec}^{-1} \]

where \( M_{\text{DM}} \) is the mass of DM within a telescope’s FoV and \( D_L \) is the luminous distance to the object, sterile neutrino has mass \( M_s \) and mixing angle \( \theta \) – measure of the interaction of the sterile neutrino with its active counterparts.

During the last year a number of works strengthened the bounds on parameters of sterile neutrino by several orders of magnitude. \(^6\)–\(^{14}\) Current exclusion region is shown on FIG. 1.

**Lyman-\( \alpha \) forest constraints.** Restrictions on the mass of the DM particles also come from the studies of the details of structure formation in the Universe, containing in the Lyman-\( \alpha \) forest data. Namely, by looking at the Lyman-\( \alpha \) absorption lines (absorption by the neutral hydrogen at \( \lambda = 1216 \AA \)) in the quasar spectra at different red-shifts, and comparing it with the results of numerical modeling of structure formation, one obtains a lower bound on the DM particle mass \( M_{\text{Ly}\alpha} \). The mass of the sterile neutrino is related to this lower mass bound as \( M_s = \frac{\langle p_s \rangle}{\langle p_a \rangle} M_{\text{Ly}\alpha} \). Here \( \langle p_s \rangle, \langle p_a \rangle \) are average momenta of sterile (active) neutrinos. The ratio \( \frac{\langle p_s \rangle}{\langle p_a \rangle} \) depends on the production mechanism of the DM sterile neutrino and on the physics beyond the \( \nu \)MSM. Results of \(^{15,16}\) show that this ratio can be anywhere between \( \sim 0.15 \) and 1. Therefore, the results of Ly\( \alpha \) constraint \( M_{\text{Ly}\alpha} > 14.5 \text{ keV} \) from \(^{17}\) imply that the DM mass can be as low as \( M_s > 2.5 \text{ keV} \) (results of Ly\( \alpha \) analysis of \(^{18}\) imply even lower bound \( M_s \gtrsim 1.5 \text{ keV} \)). The scenarios with large lepton asymmetries \(^{19}\)
also provide $\langle p_s \rangle \approx 0.2 \langle p_a \rangle$ and thus comparable limits on the $M_s \gtrsim 2$ keV.

While Ly$\alpha$ method is potentially very powerful, it is also very indirect and hinges on the ability to know the exact relation between Ly$\alpha$ optical depth and local gas density. This relation depends on local temperature, local velocities, hydrogen overdensity and its neutral fraction. The knowledge of all these quantities is based on a number of astrophysical assumptions.

Observational strategy. As shown in the signal from almost all nearby objects (dwarf galaxies, Milky Way, large elliptic galaxies, galaxy clusters) provide comparable (within an order of magnitude) DM decay signal. Therefore, observation of any astrophysical object where the underlying spectrum can be described by a convincing physical model is well suited for the DM search. The best candidates are the dSph galaxies of the Milky Way as they are expected to provide the strongest restrictions. Indeed, (i) they have smaller velocity dispersion and thus Doppler broadening as compared to large galaxies or galaxy clusters and (ii) they are very dark in X-ray, thus optimizing a signal-to-noise ratio.

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