7 keV sterile neutrino dark matter and its influence on reionization of the Universe

(JCAP06(2016)017, arXiv:1604.01341**)**

A. Rudakovskyi[1,2*], D.Iakubovskyi[1,3]

[1]Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine,

[2]Taras Shevchenko National University of Kyiv, Physics Department, Kyiv, Ukraine

[3]Discovery Center, Niels Bohr Institute, Copenhagen, Denmark

[*] rudakovskiy@gmail.com

A few basic questions about DM

Is evidence for DM convincing?

***Yes*.**

Nevertheless there are still other options.

Is DM made up of particles?

Plausible assumption.

But no hard evidence. More exotic possibilities such as primordial black holes or massive compact objects (MACHOs) are not completely ruled out.

"That isn't dark matter, sir—you just forgot to take off the lens cap."

Properties of dark matter particle candidate

DM is not baryonic.

Any DM particle candidate *must be:*

- Produced in the early Universe and have correct relic abundance.
- Very weakly interacting with electromagnetic radiation ("dark").
- Be stable or cosmologically long-lived.

Key properties of DM particles are their

- *mass;*
- *Initial velocity distribution;*
- *interaction strength with other particles.*

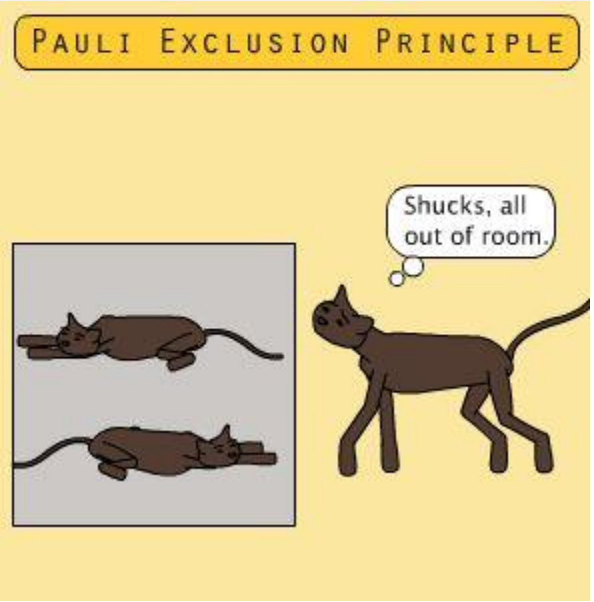
Standard Model neutrinos – the natural candidate. But they are excluded.

Phase-space bound on the mass of the DM particle

The model independent bound on the fermionic DM particle can be obtained from Pauli principle – each fermion can occupy at least some minimal volume in phase space.

Whence, for fermions with $s = \frac{1}{2}$:

$$\left(\frac{2R^3}{9\pi M}\right) \cdot \left(\frac{2G_N M}{R}\right)^{\frac{1}{2}} \geq \frac{\hbar}{g^{\frac{1}{3}} m^4}$$



For typical dwarf spherical galaxy ($M \sim 10^7 M_{sun}, R \sim 1\ kpc$) we get $m > 400\ eV$!

Whence, SM neutrino are excluded as DM particle candidate.

Free-streaming of DM

The process of structure formation is ruled by DM.

DM particles can have non-zero primordial velocities.

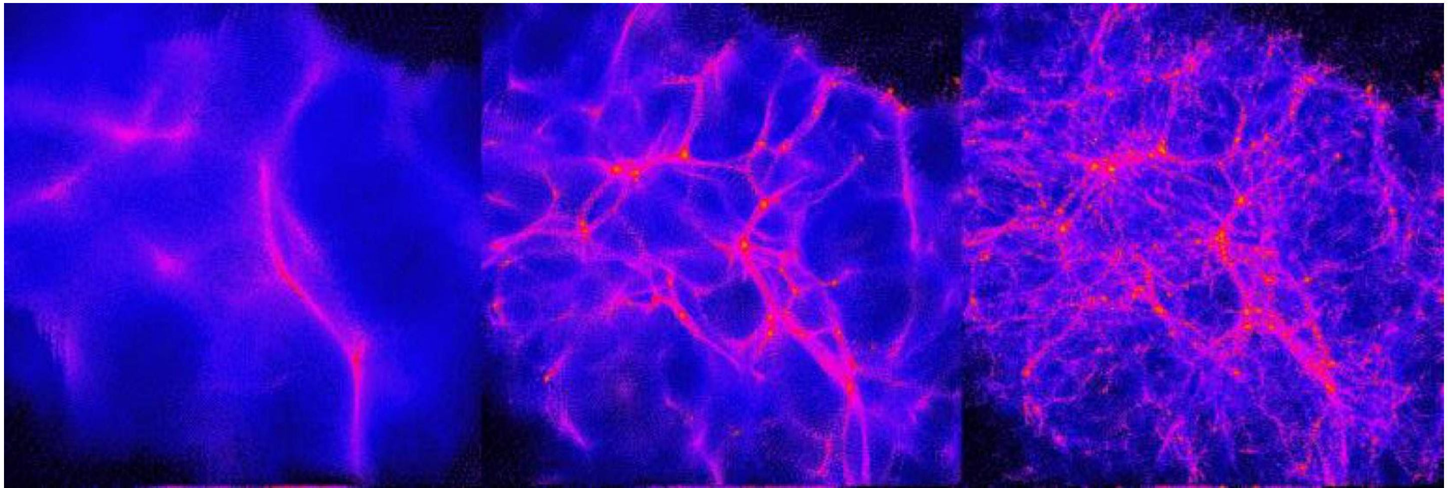
DM particles erase primordial spectrum of density perturbations on scales up to the DM particle horizon – free-streaming length

$$\lambda_{fs} = \int_0^t \frac{v(t')}{a(t')} dt'$$

Substructures with scales smaller than the λ_{fs} are erased.

If the velocity distribution of the DM particles is thermal, the three possible types of thermal –relic DM can be highlighted: cold, warm or hot dark matter.

Neutrinos have the $\lambda_{fs} \sim Gpc$ due to their light mass $(m_\nu < 1\ eV)$. SM neutrinos are excluded, because we observe galaxies.



Sterile neutrino as dark matter

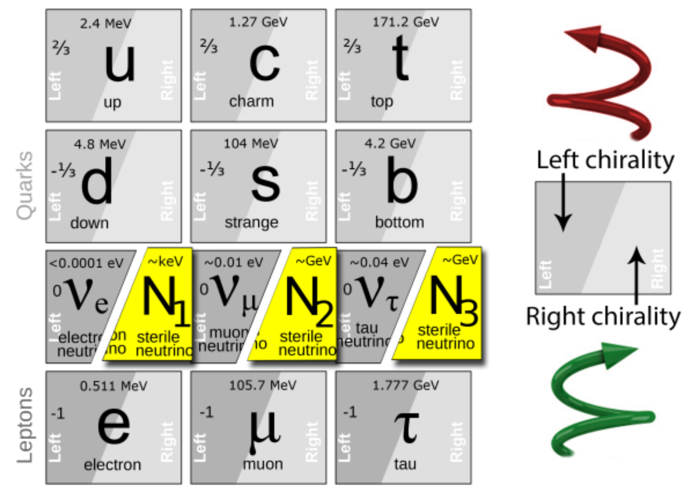
We can add the term to the lagrangian of Standard model:

$$\Delta L = \bar{N}_\alpha i\partial_\mu \gamma^\mu N_\alpha - f_{l\alpha} H \bar{N}_\alpha L_\alpha - \frac{M}{2} \bar{N}_\alpha^c N_\alpha + h.c.$$

This term corresponds to sterile neutrino minimal extension of Standard Model.

The sterile neutrino could be responsible for:

- Neutrino oscillations;
- Origin of dark matter particles;
- Observed 3.5 keV lines in spectra of several matter-dominated objects
- Barion assymetry in the Universe.



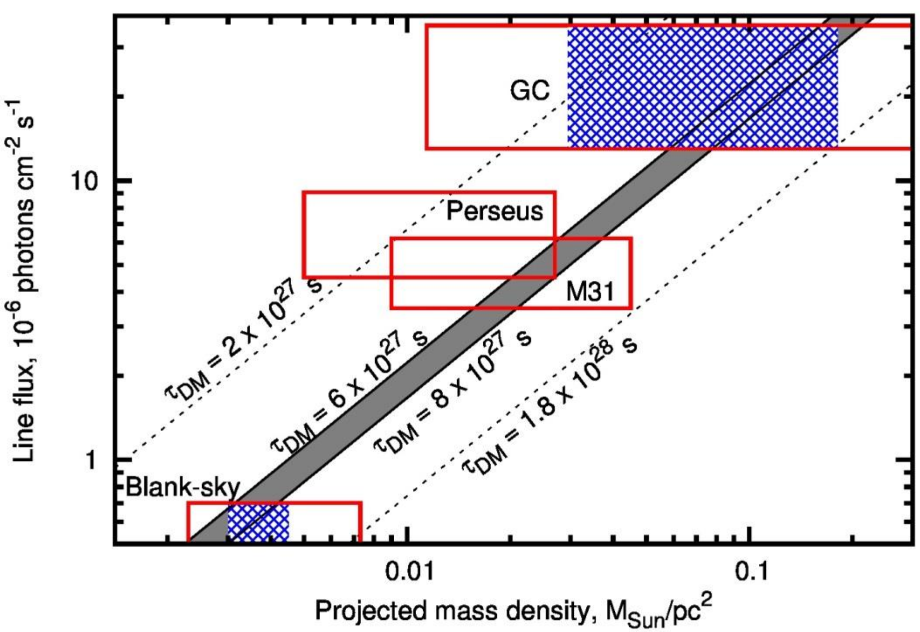
Three types of sterile neutrino: two heavier (N_2, N_3), with GeV masses, and light, with keV mass. Heavy neutrino were decayed in Early Universe, light neutrino may be corresponded to dark matter particles.

For sterile neutrinos the rate of interaction with plasma Γ is much less than the Hubble parameter. Sterile neutrino are never in thermal equilibrium

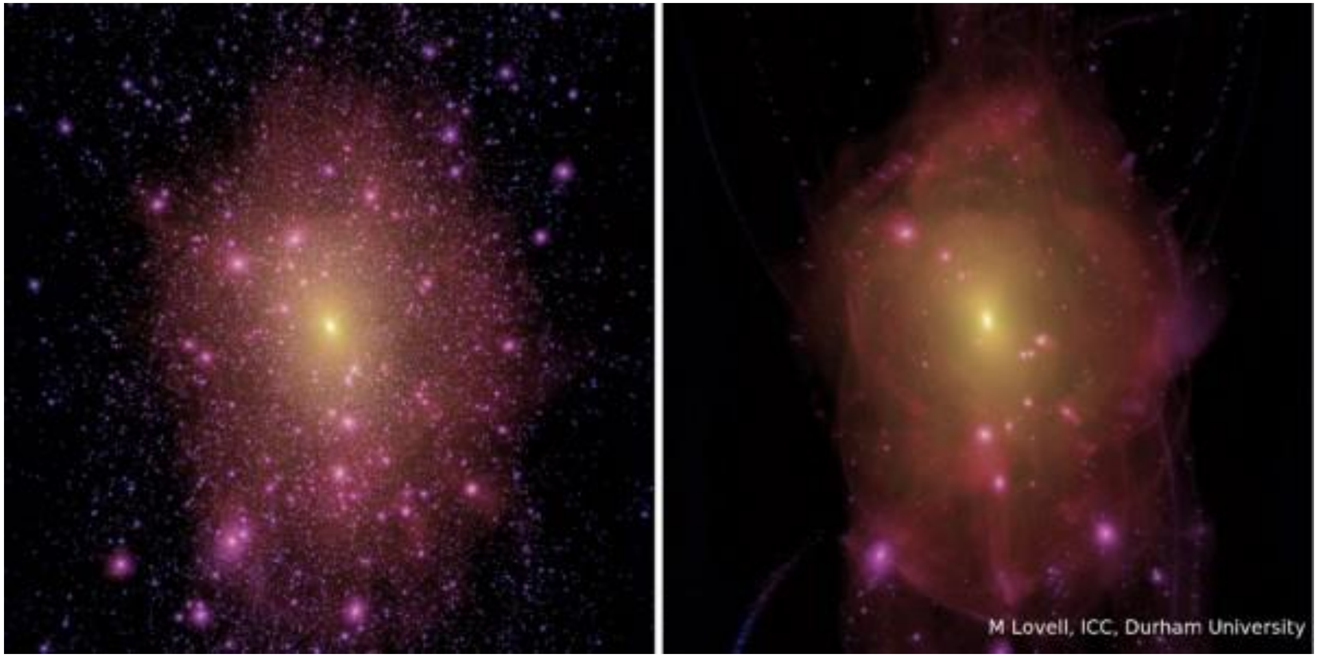
The properties of sterile neutrino dark matter in the *ν*MSM are determined by parameters – the mass of dark matter particle M_s, its mixing angle ϑ with Standard Model neutrinos or the value of lepton asymmetry during the particle production.

3.5 keV line as the signal of decaying DM (*[1402.2301], [1402.4119]*)

- Energy: 3.5 keV. Error of the position of the line: 30-50 eV
- Possible origin: decay $DM \to \nu + \gamma,\ \gamma + \gamma$
- Lifetime of the DM particles: $\tau_{DM} = (2 - 20) \cdot 10^{28} s$
- Apparent 2 σ tension with some non-observations.



Sterile neutrino: structure formation



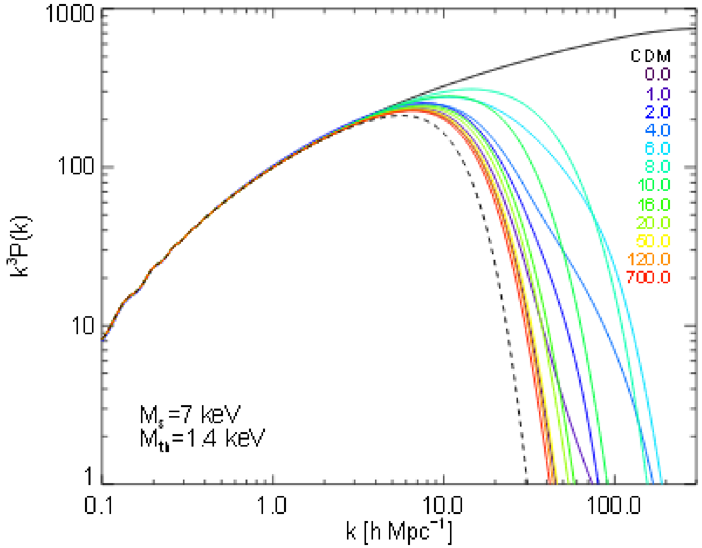
Comparison of Cold Dark Matter (CDM) and sterile neutrino simulations of Milky Way-like dark matter haloes (Lovell et al.2014)

The sterile neutrinos were generated with non-zero velocities and its initial distribution is non-thermal. Whence, the density fluctuations on scales that are smaller than free-streaming neutrino length are smoothed.

This fact lead to smaller number of small haloes in sterile neutrino dark matter model.

This could solve the problem of number of satellite in CDM cosmology.

Sterile neutrino: matter power spectrum



The power spectrum of CDM and sterile neutrinos with different lepton asymmetries $L_6 = 10^6 \frac{n_{\nu_e} - n_{\overline{\nu}_e}}{s}$ (s is entropy, $n_{\nu_e}, n_{\overline{\nu}_e}$ are) (Lovell et all 2015).

The fluctuation of matter density is $\delta(\vec{x}) = \frac{\delta\rho(\vec{x})}{\bar{\rho}}$

In Fourier space

$$\langle \delta_{\vec{k}} \delta_{\vec{k}} \rangle = 2\pi^3 P(k) \delta^{(3)}(\vec{k} - \overrightarrow{k'})$$

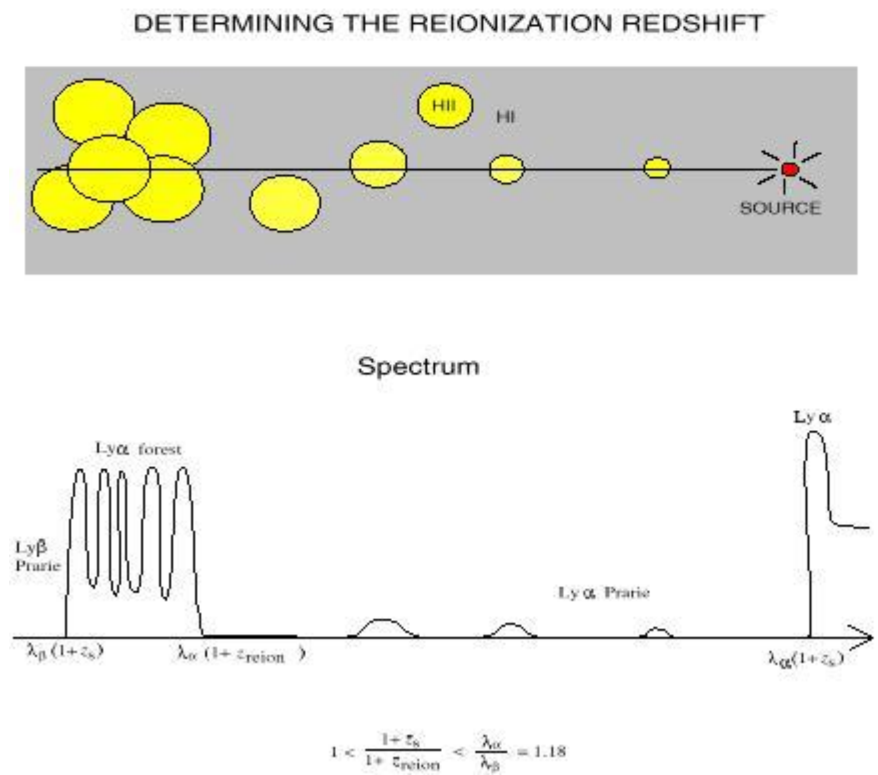
The rms fluctuation of density on scale M

$\sigma^2(M) = \int \frac{k^2 dk}{2\pi^2} P(k) W^2(k, M)$,

$W(k, M)$– “window function”.

Evidence of reionization

- Lyman-α forest transmission requires $Q_{II} \simeq 0.96 - 0.99$ at z = 6.2(Fan et al, 2006);
- the presence of Gunn-Peterson damping wings in high-z quasar spectra suggests *upper* bound $Q_{II} \simeq 0.97$ at $z \approx 6$ (Bosman& Becker, 2015);
- the absence of Gunn-Peterson damping wings in high-z GRB spectra implies 2σ bound $Q_{II} \geq 0.89$ at z = 5.913 (Chornock et al, 2013);
- electron scattering optical depth τ_{es} inferred from CMB measurements. Throughout this paper, we used the latest values $\tau_{es} = 0.058 \pm 0.012$ recently reported by *Planck* collaboration
- the observation of quasar at $z = 7.1$ suggest $Q_{I} = 0.40^{+0.41}_{-0.32}$ (2σ bound) (Greig et al, 2016)



Sketch of Gunn-Peterson damping origin (Barkana et al. 2001)

“Bubble model” of reionization

The“bubble” model’s main idea of reionization (Furlanetto et al. 2004, Yue&Chen2012) is that the galactic with mass m_{gal} could ionize the region with mass $M \leq \zeta m_{gal} - m_{rec}$ and the overdensity of ionized region crosses over the some linear barrier δ_x
Whence, we get

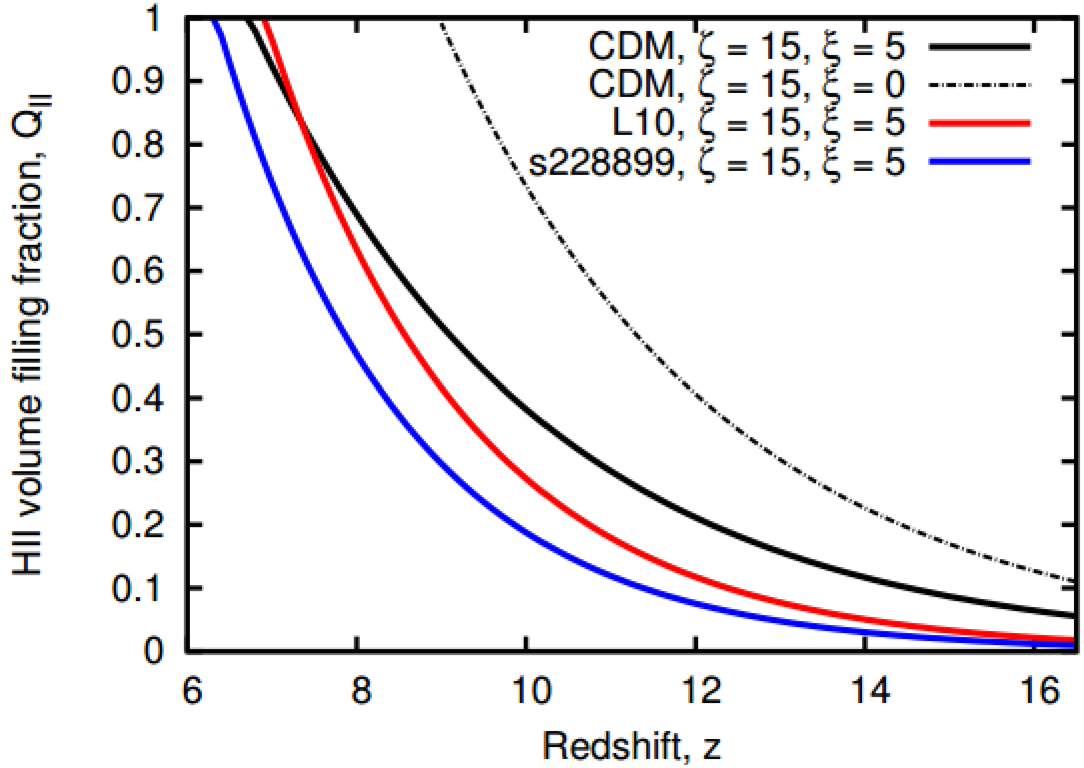
$$\zeta f_{coll}(\delta_x, M, m_{min}) \geq 1 + n_{rec}$$

$$n_{rec} = \xi f_{rec}(\delta_x, M, M_J)$$
$$\zeta = f_* \times N_{\frac{\gamma}{b}} \times f_{esc}$$

where f_*, $N_{\frac{\gamma}{b}}$, f_{esc} are the star formation efficiency, the number of ionizing photons emitted per baryon in stars, and the fraction of ionizing photons escaping from galaxies,

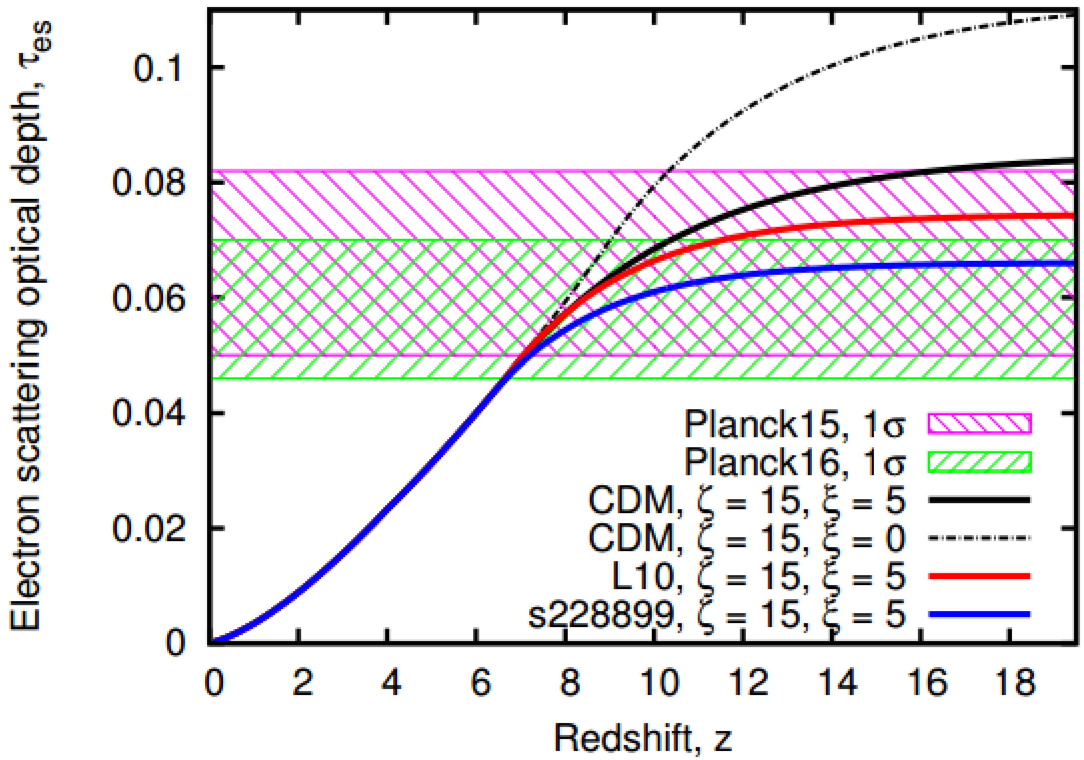
f_{coll} is fraction of baryons, that collapsed into the galaxies with mass $> m_{min}$, f_{rec} is the fraction of minihaloes, where the recombinations occurs, ξ is the average number of recombinations per atom in collapsed mini-haloes during the whole epoch of reionization.

We use extended Press-Schechter method with some modification and matter power spectrums of realistic 7keV sterile neutrino (Lovell et al 2015) to find this barrier $\delta_x(z, M)$. Using this barrier we construct the mass function of ionized region and calculate the ionized volume fraction Q_{II} as in Furlanetto et al 2004.



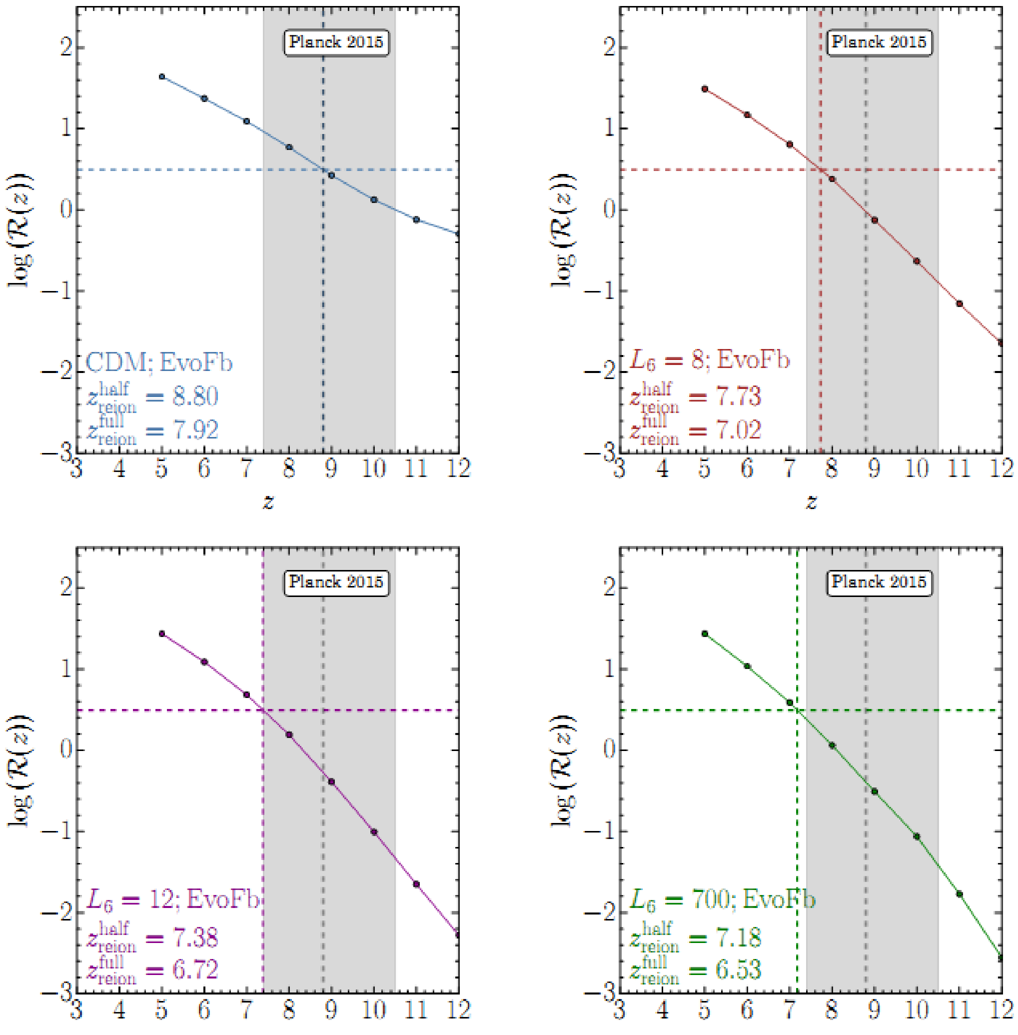
Dependence of the HII volume filling fraction *Q*II on redshift *z* for our fiducial dark matter models. L10 indicates the value of electron lepton asymmetry *L* 6 = 10 for models of (Lovell et al. 2015), while s228899 indicates the values mixing angle of $\sin^2(2\theta) = 2.8899 \cdot 10^{-11}$

Results



The dependence of electron scattering optical depth τ_{es} on redshift z, plotted against the latest measurements by *Planck* satellite

Results of Bose et al, 1605.03179



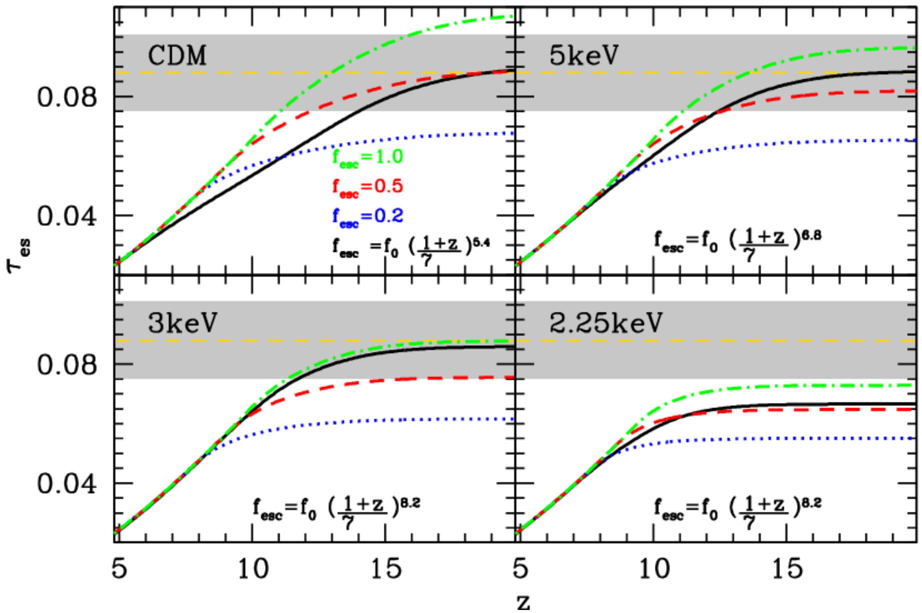
CDM, sterile neutrino with $L_6 = 8{,}12{,}700$ were used.

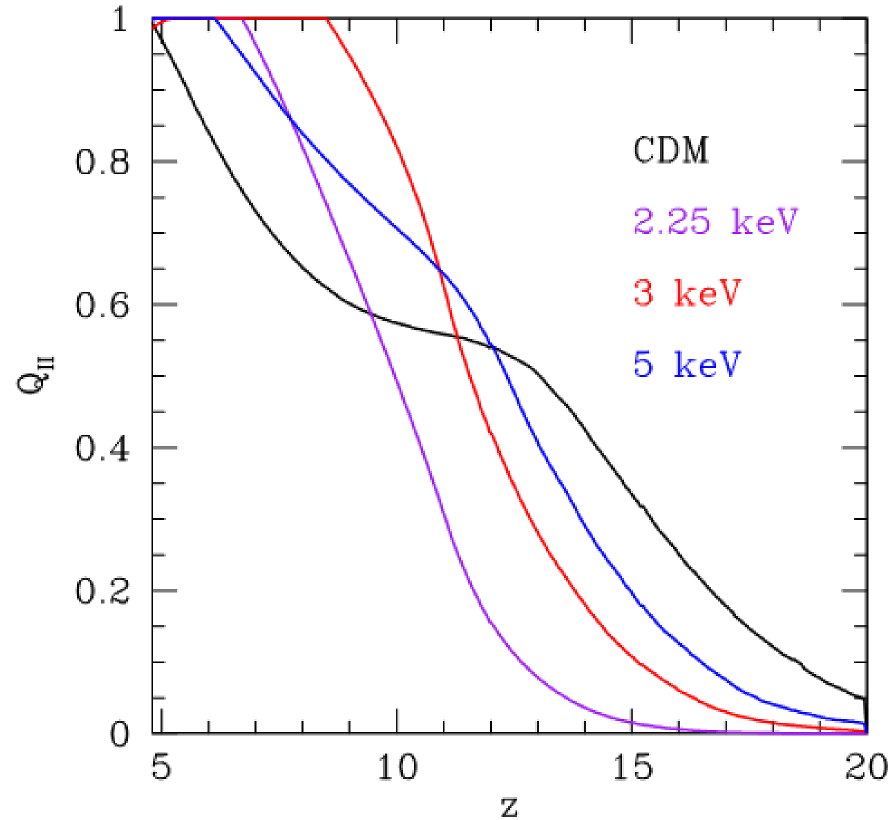
Here

$$R(z) = \frac{n_\gamma}{n_H}$$

If the $R(z) = 6.25$ – the reionization is completed.

Results of Dayal et al, 1501.02823

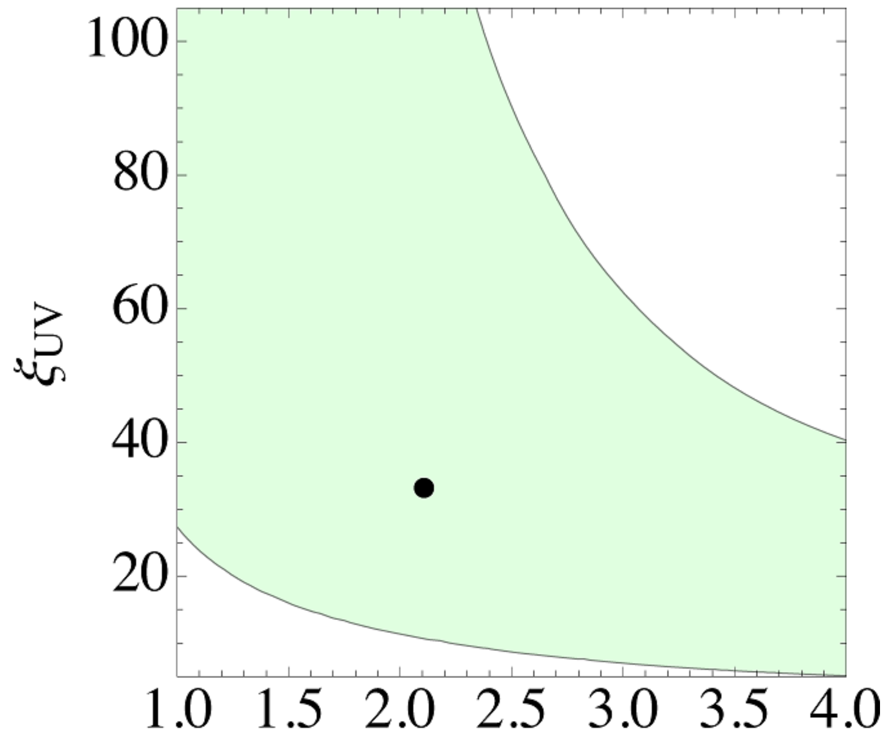




Left figure: Optical depth of CMB scattering on free electrons for CDM and WDM models.

Right figure: Volume filling fraction of ionized hydrogen for CDM and WDM models.

Results of Lopez-Honorezet al, 1703.02302



Contours in the (m_X, ζ_{UV}) plane corresponding to 90% CL.

Black dot corresponds to the best-fit value of mass of DM part of reionization.

Conclusions

For 7 keV sterile neutrinos DM we obtain that :

- sterile neutrino DM would produce significantly sharper reionization compared to CDM models, impossible to ‘imitate’ within the CDM scenario under any reasonable choice of our model parameters, providing better consistency with the recent kinetic Sunyaev-Zeldovich data;

- sterile neutrino DM would have a clear tendency of lowering both the redshift of reionization and the electron scattering optical depth (although the difference is still below the existing model uncertainties);

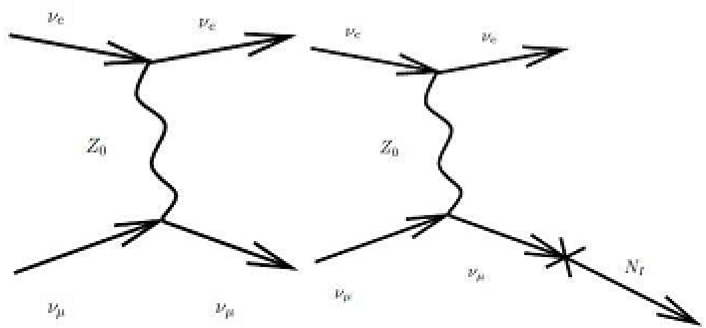
- our results have been qualitatively confirmed by an independent studies 1605.03179, 1501.02823, 1703.02302.

Thank you for attention!

Mixing angle

Then it is convenient to introduce the mixing angle θ_1 with active neutrinos and the lightest sterile neutrino

Thus, the only interaction of N_I with matter field is mixing with active neutrinos. To agree with the SM experiments, θ_1 should be $\ll 1$.



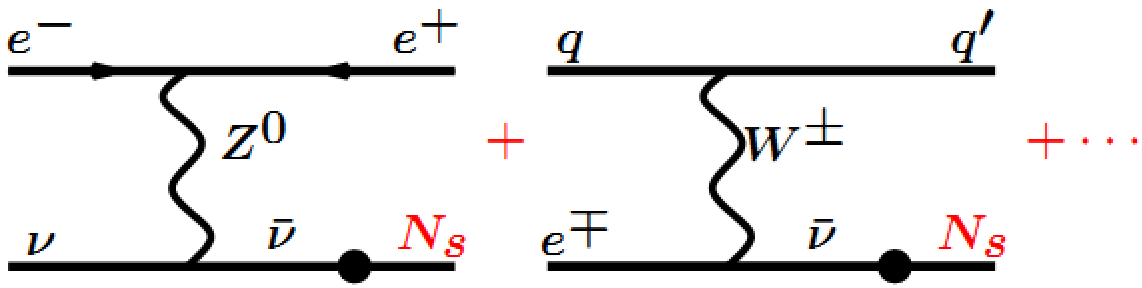
Sterile neutrino interaction : similar to Standard Model neutrinos but the interaction strength is suppressed by the mixing angle θ

How sterile neutrino DM is produced?

Phenomenologically acceptable values of θ_1 are so small, that the rate of this interaction Γ of sterile neutrino with the primeval plasma is much slower than the expansion rate ($\Gamma \ll H$)

⇒ Sterile neutrino are never in thermal equilibrium

Simplest scenario: sterile neutrino in the early Universe interact with the rest of the SM matter via neutrino oscillations:



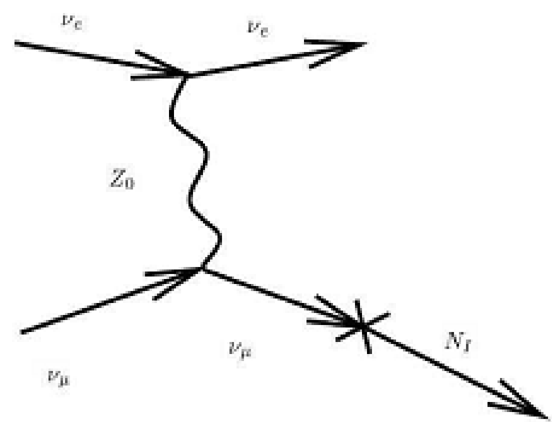
Sterile neutrinos have non-equilibrium spectrum of primordial velocities, roughly proportional to the spectrum of active neutrinos:

$$f_s(p) \sim \frac{\theta^2}{\exp\left(\frac{p}{T_\nu}\right) + 1}$$

Mixing angle in a hot medium

In a hot medium, the mixing angle becomes dependent on temperature

At the absence of lepton asymmetry (non-resonant production), the effective mixing angle is



$$\theta(T) = \frac{\theta_0}{1 + \left(\frac{T}{T_0}\right)^6}$$

Non-resonant production

Because sterile neutrinos were not in thermal equilibrium, their distribution function is evolved according to kinetic equation:

$$\frac{df_s}{dt} = \Gamma_s f_\nu$$

Where

$$\Gamma_s \sim \theta^2 G_F^2 T^5$$

is the sterile neutrino reaction rate

$$f_\nu = \frac{1}{\exp\left(\frac{p}{T_\nu}\right)+1}$$

$$T \ll T_0 \rightarrow \ \frac{df_s}{dt} \sim T^5$$

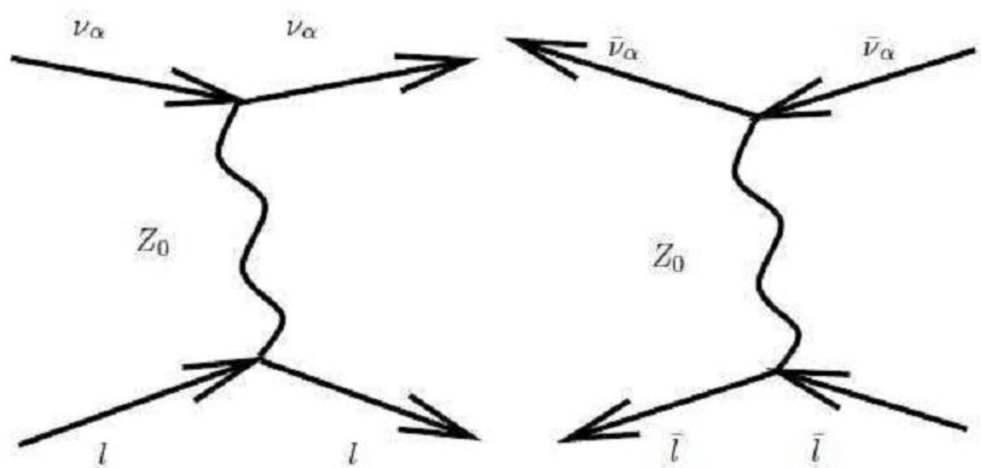
$$T \gg T_0 \rightarrow \ \frac{df_s}{dt} \sim T^{-7}$$

The maximum production rate is near T_0.

$T_0 \cong 130\ MeV$ for $m = 1keV$

Resonant production of sterile neutrinos

If $n_L \neq n_{\bar{L}}$



are not the same.

The neutrino interaction potential in a medium

$$V_{Fermi} = -L_{Fermi} = \sqrt{2}G_F\left(\bar{\nu}_L\gamma_\mu\nu_L\right)\left(\bar{l}_L\gamma^\mu l_L\right) = -2G_F(n_L - \bar{n}_L)\nu_L^+\nu_L$$

is proportional to lepton asymmetry $(n_L - \bar{n}_L)$

Resonant production of sterile neutrinos

Whence, the effective mixing angle becomes

$$\theta(T) = \frac{\theta_0}{1 + \left(\frac{T}{T_0}\right)^6 \pm c(n_L - \overline{n}_L)}$$

where "+" corresponds to neutrinos and "-" to anti-neutrinos.