Reconciling eV Sterile Neutrinos with Cosmological Bounds

(and some connections with dark matter)

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YT, *arXiv:1501.00059*

P. Ko, YT, *arXiv:1404.0236(Phys.Lett.B)*

eV Sterile Neutrinos?

- Motivated by neutrino experiments to solve anomalies,
- accelerator, ($\bar{\nu}_\mu \to \bar{\nu}_e$) LSND and MiniBooNE
- reactor, (deficit of $\bar{\nu}_e$ flux)
- gallium anomalies ($^{71}Ga + \nu_e \to {}^{71}Ge + e^-$)

GALLEX and SAGE

$$\Delta m^2_{14} \sim \mathrm{eV}^2,\ \sin^2 2\theta_{14} \sim 0.05$$

Cosmological Bounds

- Extra radiation, $N_{\rm eff}$,
- eV sterile neutrinos as hot dark matter, BBN, CMB, LSS

Joint CMB+BBN, 95% CL preferred ranges *Planck 2015, arXiv:1502.01589*

$$N_{\rm eff} = \begin{cases} 3.11^{+0.59}_{-0.57} & \text{He+}\textit{Planck}\text{ TT+lowP,} \\ 3.14^{+0.44}_{-0.43} & \text{He+}\textit{Planck}\text{ TT+lowP+BAO,} \\ 2.99^{+0.39}_{-0.39} & \text{He+}\textit{Planck}\text{ TT,TE,EE+lowP,} \end{cases}$$

Constraints on sterile neutrino mass

$$\left.\begin{array}{r} N_{\rm eff} < 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.52\ \text{eV} \end{array}\right\} \ 95\%,\ \textit{Planck}\text{ TT+lowP+lensing+BAO.}$$

Difficulty

- With such mixing parameters,

$$\Delta m^2_{14} \sim \mathrm{eV}^2,\ \sin^2 2\theta_{14} \sim 0.05$$

- neutrino oscillation would bring sterile neutrino into equilibrium in the early universe, then contribute $\Delta N_{\rm eff} \simeq 1$, in tension with *CMB* and *LSS*
- This is not true in case there is a large lepton asymmetry, or a self-interaction for sterile neutrinos, which induces a matter potential $V_{\rm eff}$

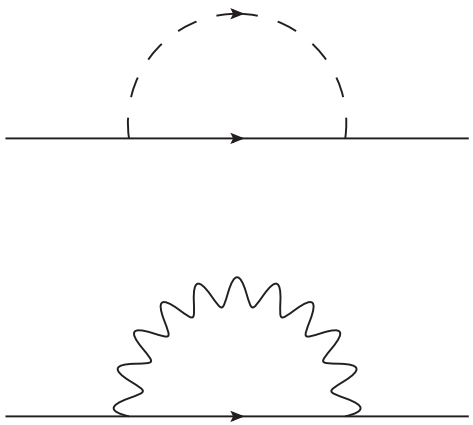
MSW effect, Akhmedov, hep-ph/0001264

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 - \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0},\quad V_{\rm eff} \sim \frac{G_X}{M_X^2} T^5$$

Hannestad et al, *1310.5926*, Dasgupta&Kopp *1310.6337*,

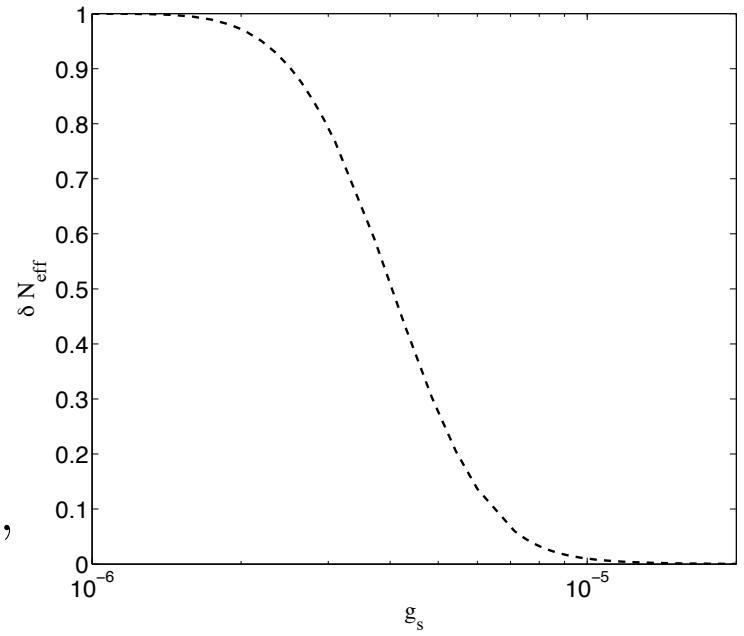
Interacting Sterile Neutrinos

- Partial thermalization at BBN



$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 - \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0},$$

Archidiacono et al, 1404.5915



- T*he new interaction could lead to fl*avor equilibrium after BBN, A. Mirizzi *et al*, *1410.1385, inconsistent with cosmological neutrino mass bounds*

Kinetic Equations

two-flavor mixing for ν_a-ν_s

$$\rho = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix}$$

density matrix is evolving as

$$i\frac{d\rho}{dt} = [H, \rho] + C(\rho)$$

where $H = \begin{pmatrix} -\frac{\delta m^2}{2E}\cos 2\theta_0 + V_{\rm eff} & \frac{\delta m^2}{2E}\sin 2\theta_0 \\ \frac{\delta m^2}{2E}\sin 2\theta_0 & \frac{\delta m^2}{2E}\cos 2\theta_0 - V_{\rm eff} \end{pmatrix}$

and C(ρ) is the collision term.

Kinetic Equations

Reparametrize

$$\rho = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix} = \frac{1}{2} f_0 \left(P_0 + \vec{P} \cdot \vec{\sigma} \right), \quad f_0 = 1/(e^{E/T} + 1)$$

$$P_a \equiv P_0 + P_z = 2\frac{\rho_{aa}}{f_0}, \qquad P_s \equiv P_0 - P_z = 2\frac{\rho_{ss}}{f_0},$$

$$\dot{P}_a = V_x P_y + \Gamma_a \left[2\frac{f_{eq,a}}{f_0} - P_a \right],$$

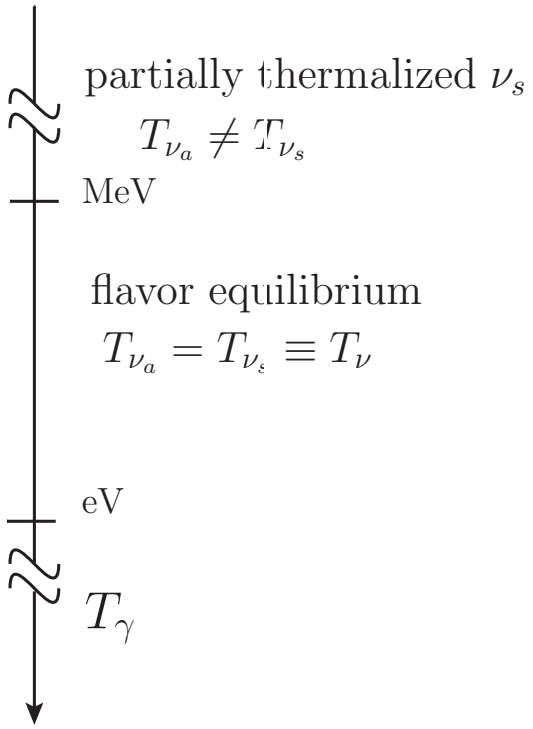
$$\dot{P}_s = -V_x P_y + \Gamma_s \left[2\frac{f_{eq,s}}{f_0} - P_s \right],$$

$$\dot{P}_x = -V_z P_y - D P_x,$$

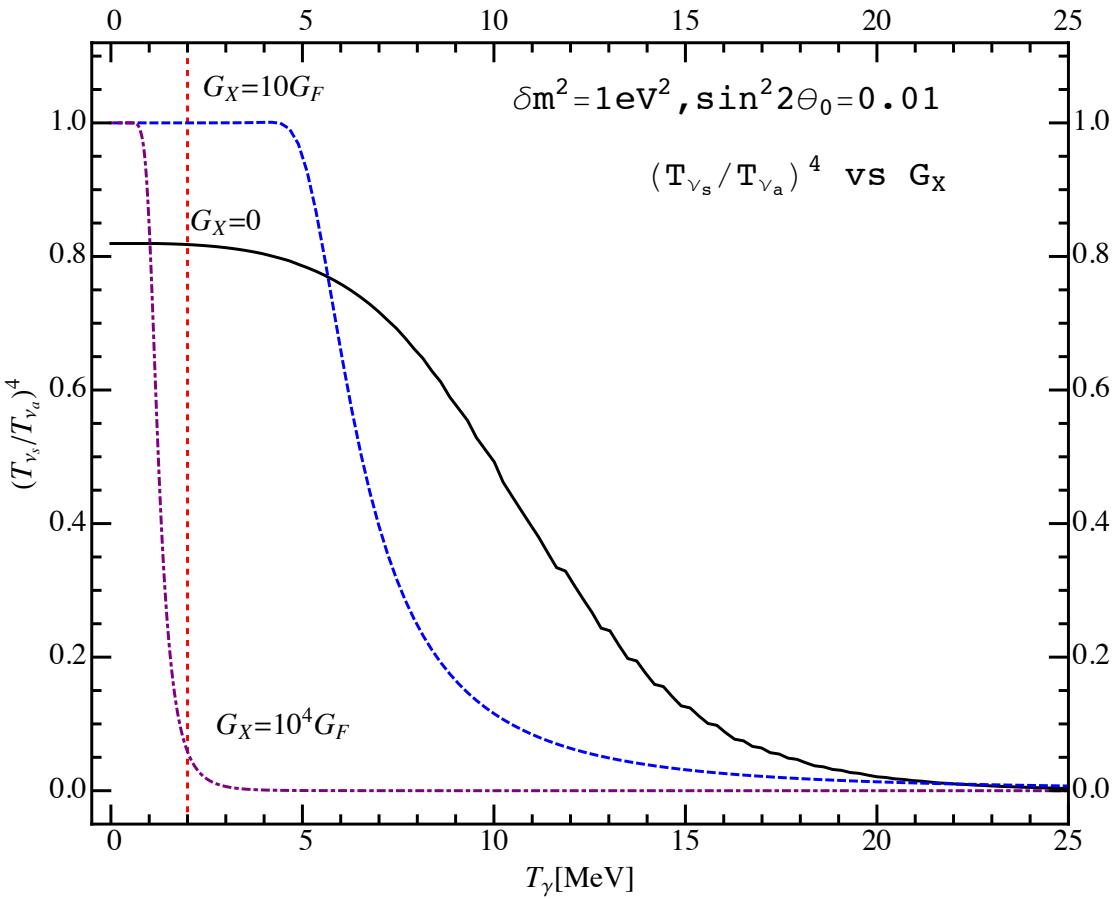
$$\dot{P}_y = V_z P_x - \frac{1}{2} V_x (P_a - P_s) - D P_y. \qquad D \simeq \frac{1}{2} (\Gamma_a + \Gamma_s)$$

Hannestad, Hansen, Tram, ***LASAGNA***

Flavor Equilibrium after BBN



YT, arXiv:1501.00059



$$\nu_e : \nu_\mu : \nu_\tau : \nu_s = 1 : 1 : 1 : 0 \Rightarrow \frac{3}{4} : \frac{3}{4} : \frac{3}{4} : \frac{3}{4}$$

Excluded for eV scale

Cosmological Mass bound

Planck2015

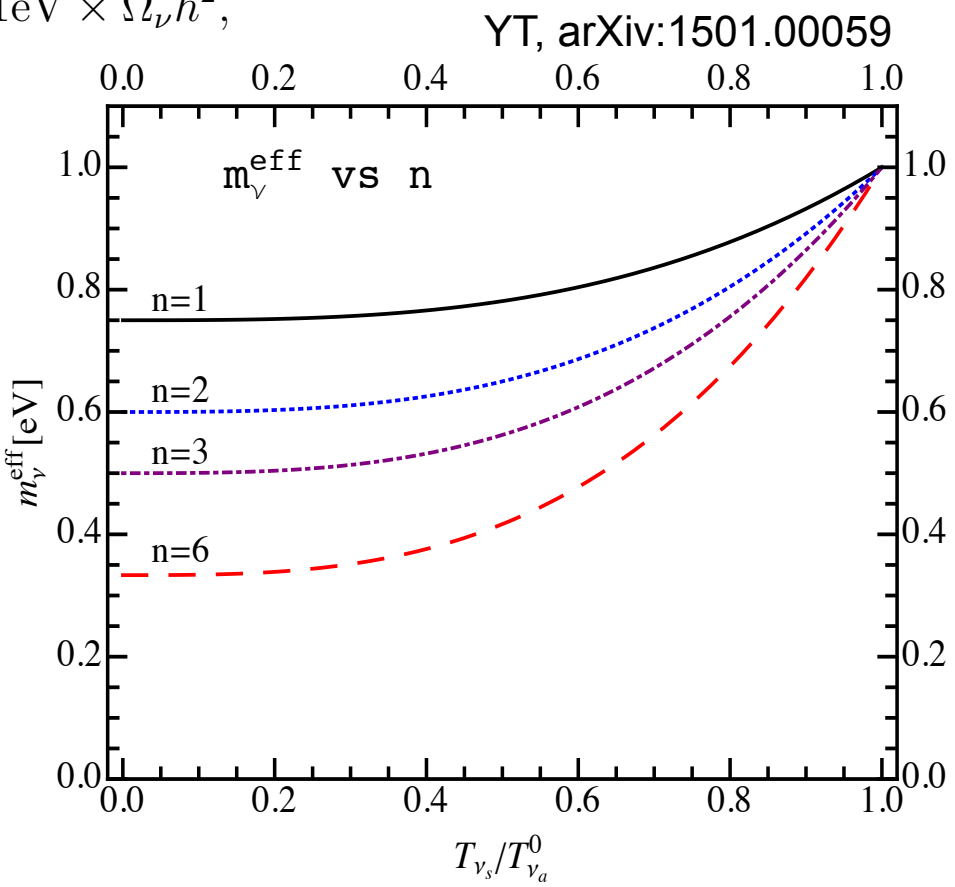
$$\left.\begin{array}{l} N_{\rm eff} < 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.52\ {\rm eV} \end{array}\right\}\ 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO.}$$

$$m_\nu^{\rm eff} \equiv \frac{\sum_i n_{\nu_i} m_{\nu_i}}{n^0_{\nu_a}} = \sum_i \left(\frac{T_{\nu_i}}{T^0_{\nu_a}}\right)^3 m_{\nu_i} \simeq 94.1{\rm eV} \times \Omega_\nu h^2,$$

- Assuming one ~ eV, and all others are light

$$m_\nu^{\rm eff} \simeq \left(\frac{T_\nu}{T^0_{\nu_a}}\right)^3 m_{\nu_4}.$$

Increasing n would make the number density of each species decrease.



δNeff < 0 ?

- Neff at BBN and CMB

$$\delta N_{\rm eff}^{\rm bbn} = n \times \left(\frac{T_{\nu_s}}{T^0_{\nu_a}}\right)^4 .$$

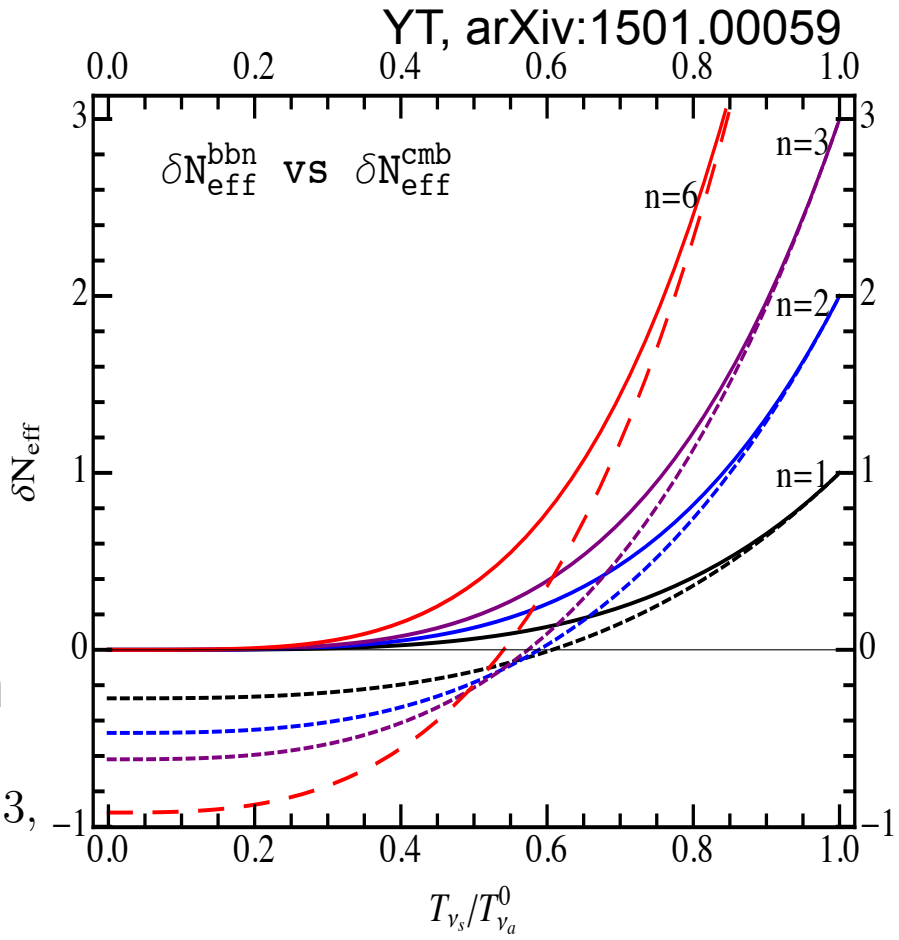
- Flavor equilibrium:

number density is conserved

$$3 \times \left(T^0_{\nu_a}\right)^3 + n \times T^3_{\nu_s} = (3+n) \times T^3_{\nu},$$

Assume Fermi-Dirac Distribution

$$\delta N_{\rm eff}^{\rm cmb} = (3+n)^{-1/3} \times \left[3 + n \times \left(\frac{T_{\nu_s}}{T^0_{\nu_a}}\right)^3\right]^{4/3} - 3,$$



Neff can be even reduced.

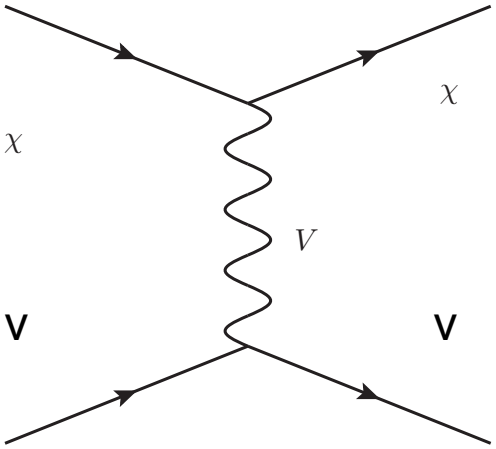
Similar observations in Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042 and Mirizzi, Mangano, Pisanti, Saviano, PRD 91 (2015) 025019. Cherry@BLV2015

Discussions

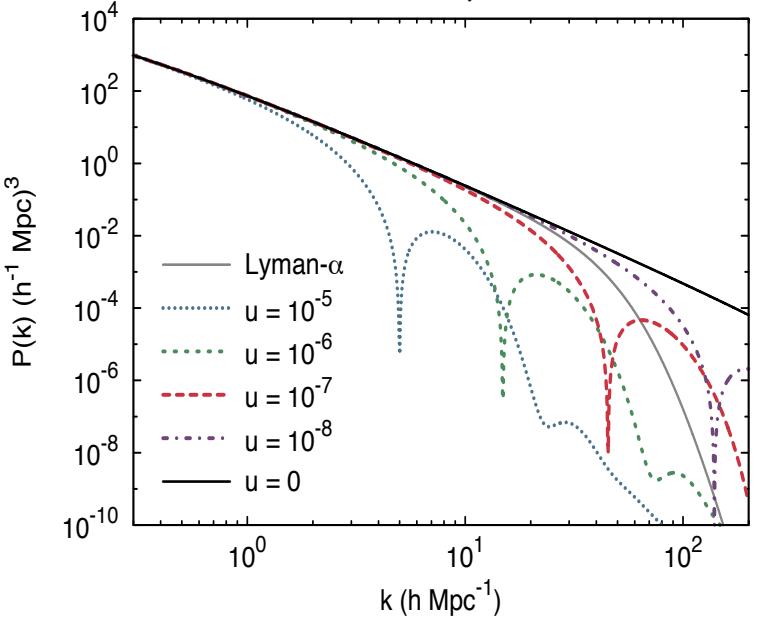
- Large lepton asymmetry [Foot and Volkas, 1995; Hannestad, Hansen, Tram, 2013]
- Secret interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad, Hansen,Tram, arXiv:1404.5915; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019;Cherry, Friedland,Shoemaker, arXiv:1411.1071;Bertoni, Ipek, McKeen and Nelson, arXiv:1412.3113; Tang, arXiv:1501.00059]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]
- Modified primordial power spectrum [Gariazzo, Giunti, Laveder, arXiv:1412.7405]

Connection with DM

- Three controversies in CDM paradigm, *cusp-vs-core, too-big-to-fail, and missing satellites* problems,
- Interaction with relativistic particles can induce a cut-off in the matter power spectrum by collisional damping, solving the "*missing satellites*" problem.



Boehm et al, 1401.7597



Example:vΛMDM

P. Ko, YT, 1404.0236(PLB)

We introduce two right-handed gauge singlets, a dark sector with an extra $U(1)_X$ gauge symmetry,

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{\rm SM} + \bar{N}_i i\partial\!\!\!/ N_i - \left(\frac{1}{2} m^R_{ij} \bar{N}^c_i N_j + y_{\alpha i} \bar{L}_\alpha H N_i + h.c\right) - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} \\ &+ \bar{\chi}\left(iD\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!/ - m_\psi\right)\psi + D^\dagger_\mu \phi^\dagger_X D^\mu \phi_X - \left(f_i \phi^\dagger_X \bar{N}^c_i \psi + g_i \phi_X \bar{\psi} N_i + h.c\right) \\ &- \lambda_\phi \left[\phi^\dagger_X \phi_X - \frac{v^2_\phi}{2}\right]^2 - \lambda_{\phi H}\left[\phi^\dagger_X \phi_X - \frac{v^2_\phi}{2}\right]\left[H^\dagger H - \frac{v^2_h}{2}\right],\end{aligned}$$

$v_\phi \sim \mathcal{O}\,(\mathrm{MeV})$ for our interest

Various Mixings

- Kinetic mixing term $\frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$ leads to three physical neutral gauge boson mixing,
- Scalar interaction term $\lambda_{\phi H}\left[\phi_X^\dagger\phi_X-\frac{v_\phi^2}{2}\right]\left[H^\dagger H-\frac{v_h^2}{2}\right]$ leads to Higgs mixing,

$$h = H_1\cos\alpha - H_2\sin\alpha,$$
$$\phi = H_1\sin\alpha + H_2\cos\alpha,$$

- $y_{\alpha i}\bar{L}_\alpha H N_i,\ f_i\phi_X^\dagger\bar{N}_i\psi,\ g_i\phi_X\bar{\psi}N_i$ give rise to neutrino mixing.

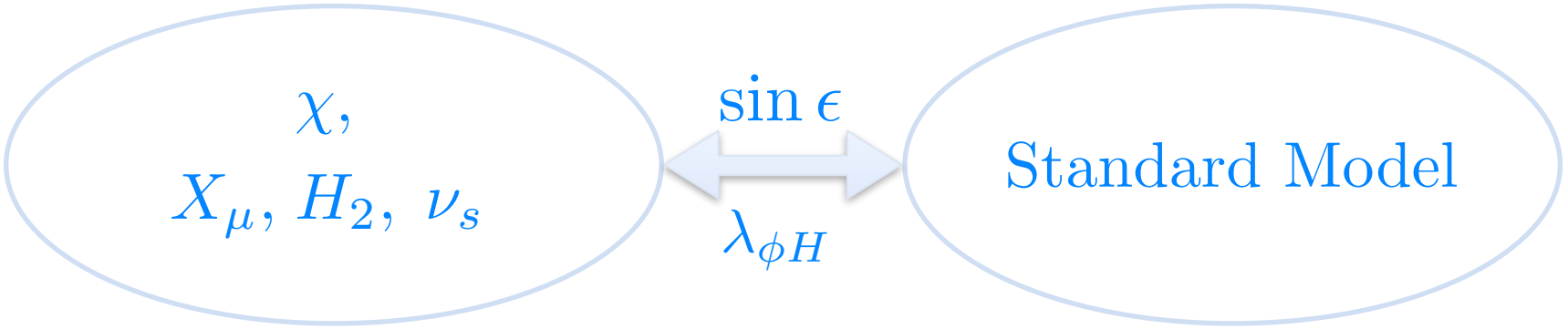
Physical Spectrum

- Neutrino Mixing

$$\begin{pmatrix} \nu_\alpha \\ N_i^c \\ \psi_L \\ \psi_L^c \end{pmatrix} = U \begin{pmatrix} \nu_a \\ \nu_{s4} \\ \vdots \\ \nu_{s7} \end{pmatrix}_L , \mathbb{M} = \begin{pmatrix} 0_{3\times3} & \frac{v}{\sqrt{2}}[y_{\alpha i}]_{3\times2} & 0_{3\times2} \\ \frac{v}{\sqrt{2}}[y_{\alpha i}]^T_{2\times3} & \left[m^R_{ij}\right]_{2\times2} & \frac{v_\phi}{\sqrt{2}}(f_i\ g_i)_{2\times2} \\ 0_{2\times3} & \frac{v_\phi}{\sqrt{2}}(f_i\ g_i)^T_{2\times2} & \begin{pmatrix} 0 & m_\psi \\ m_\psi & 0 \end{pmatrix} \end{pmatrix}.$$

- Dark Matter, dark gauge boson X_μ, dark Higgs H_2, and 4 sterile neutrinos ν_s,

Thermal History



- DM chemically decoupled, determining its relic density,
- Then the whole dark sector decoupled from SM thermal bath, and entropy is conserved separately. Effective number of neutrinos can be calculated.
- Relativistic particles at CMB time contribute as hot dark matter. Sterile neutrinos are not thermalized due to the new interaction, and heavy ones can decay.

velocity dependent σ

DM self-scattering is the transfer cross section

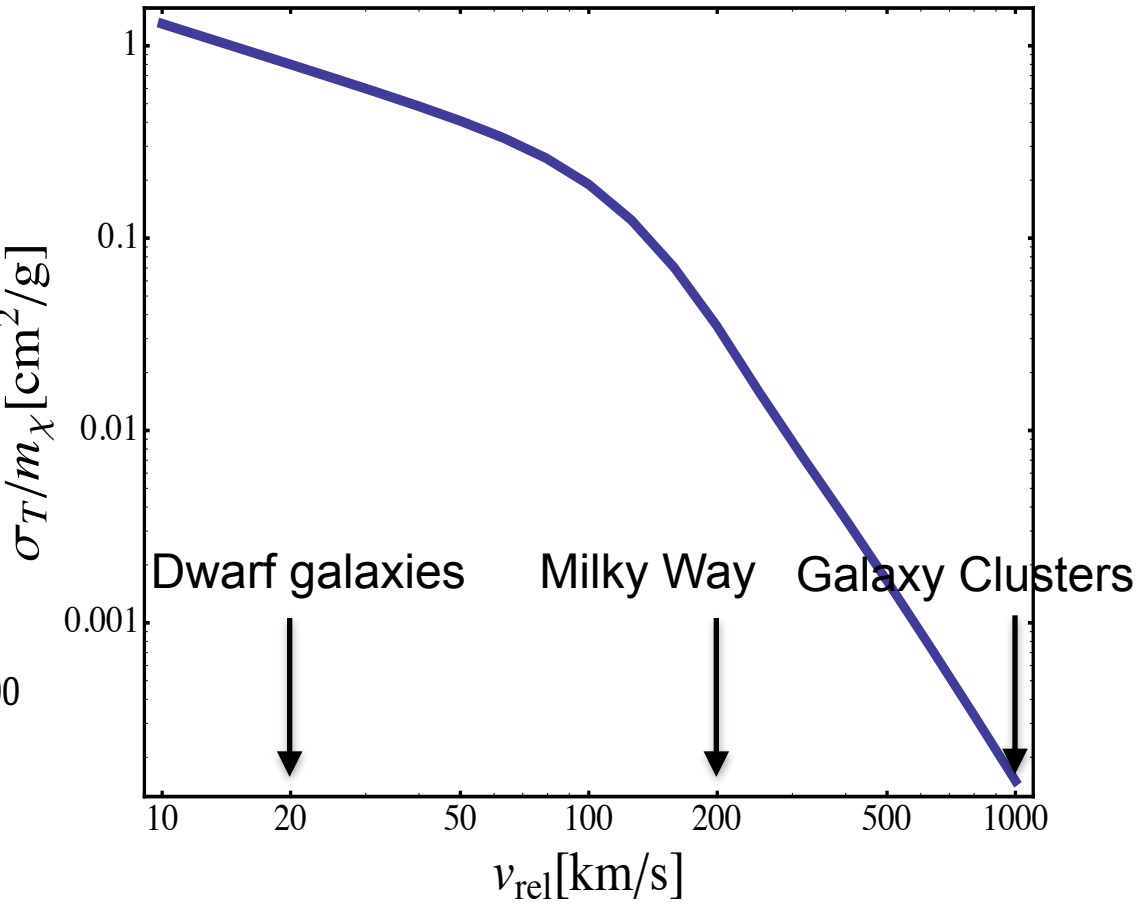
$$\sigma_T \equiv \int d\Omega (1-\cos\theta)\frac{d\sigma}{d\Omega}.$$

$$\sigma_T = \frac{8\pi}{m_X^2}\beta^2\left[\ln\left(1+R^2\right) - \frac{R^2}{1+R^2}\right],$$

$$\alpha_X = \frac{g_X^2}{4\pi}, \qquad \beta = \frac{2\alpha_X m_X}{m_\chi v_{\rm rel}^2}, \qquad R = \frac{m_\chi v_{\rm rel}}{m_X},$$

$$\sigma_T = \begin{cases} \frac{4\pi}{m_X^2}\beta^2\ln(1+\beta^{-1}) & \beta \lesssim 0.2 \\ \frac{8\pi}{m_X^2}\beta^2/(1+1.5\beta^{1.65}) & 0.2 \lesssim \beta \lesssim 1300 \\ \frac{\pi}{m_X^2}(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta)^2 & \beta \gtrsim 1300 \end{cases}$$

m_χ=1TeV, m_X=4MeV, g_X=0.5



Kinetic decoupling

Kinetic decoupling of χ from ν_s happens when the elastic scattering rate for $\chi\nu_s \leftrightarrow \chi\nu_s$ drops below Hubble parameter H. The decoupling temperature is given by

$$T_\chi^{\rm kd} \simeq 1{\rm keV}\left(\frac{0.1}{g_X}\right)\left(\frac{T_\gamma}{T_{\nu_s}}\right)^{\frac{3}{2}}_{\rm kd}\left(\frac{m_\chi}{\rm TeV}\right)^{\frac{1}{4}}\left(\frac{m_X}{\rm MeV}\right),$$

The kinetic decoupling of DM from the relativistic particles imprints on the matter power spectrum, for which there are two relevant scales: the comoving horizon $\tau_{\rm kd} \propto 1/T_\chi^{\rm kd}$ and free-streaming length $\left(T_\chi^{\rm kd}/m_\chi\right)^{1/2}\tau_{\rm kd}$. For our interested regime, $\tau_{\rm kd}$ is much larger and relevant. Thus $T_\chi^{\rm kd}$ can be translated into a cutoff in the power spectrum of matter density perturbation with

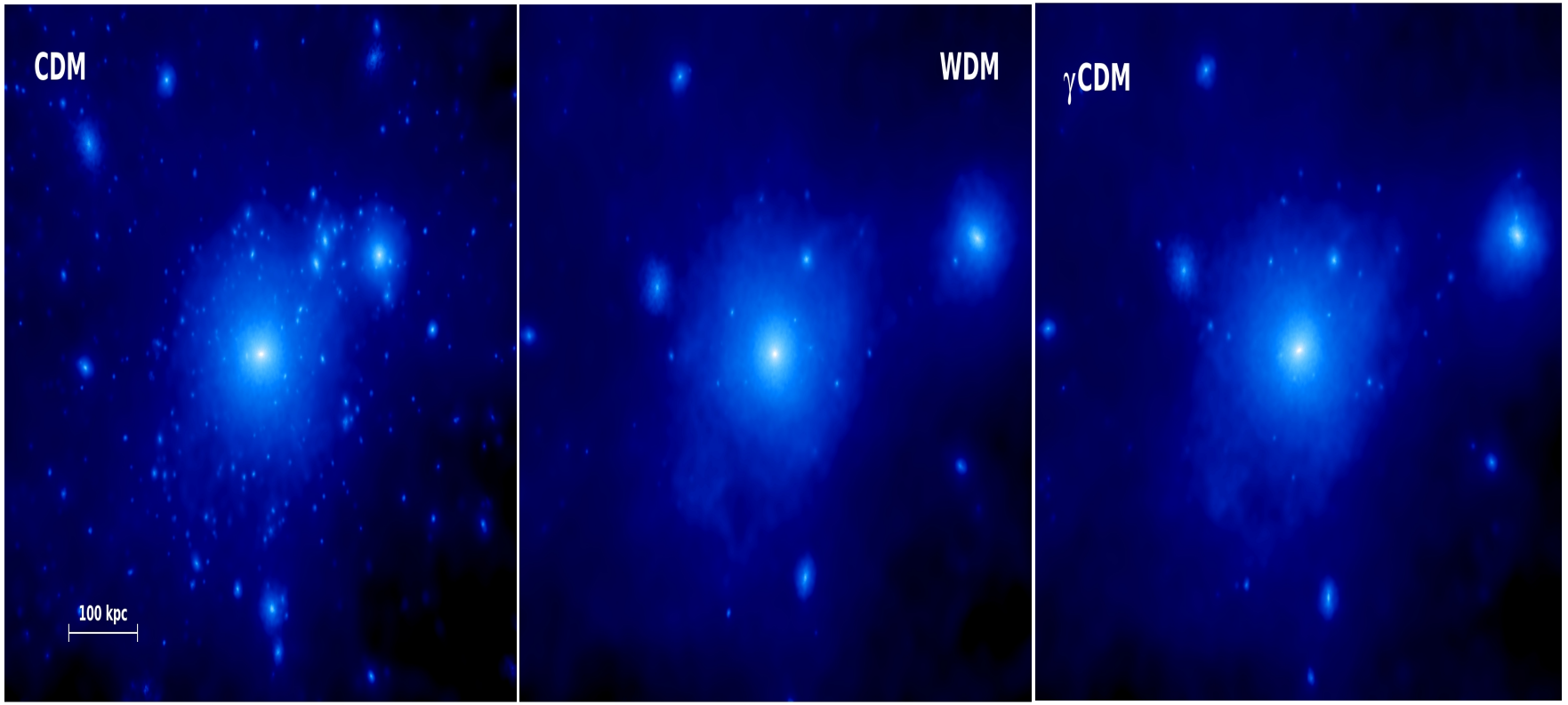
$$M_{\rm cut} = \frac{4\pi}{3}\rho_{\rm M}\left(c\tau_{\rm kd}\right)^3 \sim 2\times 10^8\left(\frac{T_\chi^{\rm kd}}{\rm keV}\right)^{-3} M_\odot,$$

Then $M_{\rm cut} \sim \mathcal{O}(10^9)M_\odot$ can be easily obtained for explanation of *missing satellites problem* for $\mathcal{O}({\rm TeV})$ χ and $\mathcal{O}({\rm MeV})$ X_μ.

Simulation

- DM-γ/v interaction ~ $2 \times 10^{-9}\ \sigma_{\rm Th}\ (m_{\rm DM}/{\rm GeV})$

Boehm, Schewtschenko, Wilkinson, Baugh and Pascoli, *1404.7012*



Summary

- Introduction of the tension between eV-scale sterile neutrino and cosmological bounds,
- These bounds could be relaxed if there is self-interaction for sterile neutrinos, further relaxed with more light species.
- *A renormalisable* model for CDM and eV sterile neutrinos. DM's *self-scattering* and *scattering-off* sterile neutrinos can resolve three possible controversies for cold DM on small scales.

Thanks a lot!