Ultra-light scalar saving the 3+1 neutrino scheme from the cosmological bounds

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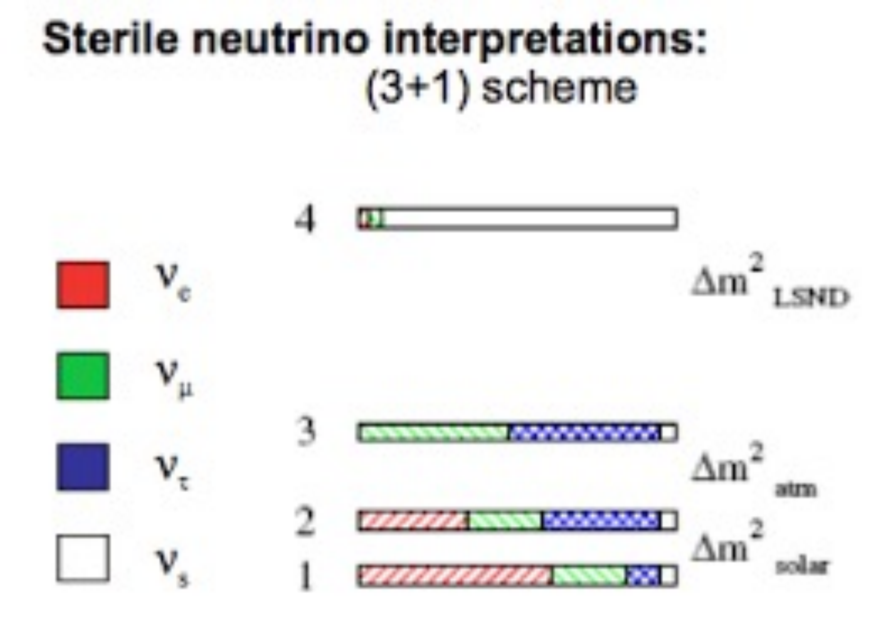
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Outline

- 3+1 neutrino scheme and ideas to relax cosmological bounds
- An introduction to ultralight dark matter (fuzzy dark matter)
- How to save 3+1 scheme with coupling to ultra-light dark matter
- Phenomenological consequences for KATRIN and PTOLEMY
- Summary

3+1 neutrino scheme



Mass splitting of ~ 1eV

Phenomenological motivations

- LSND + MiniBooNE
- Reactor neutrino anomaly
- Gallium neutrino anomaly

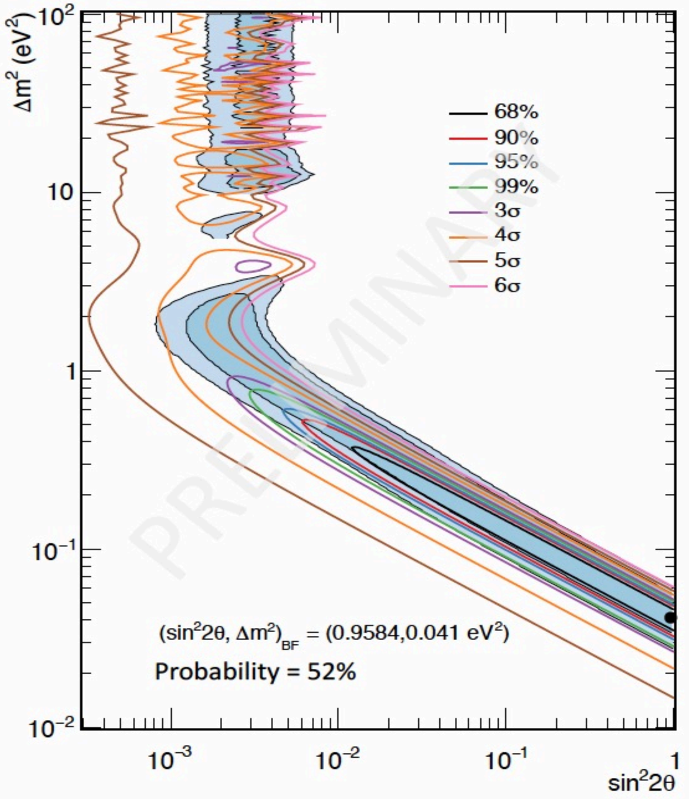
Short baseline appearance anomalies

- LSND and MiniBooNE

$$\frac{\Delta m^2_{21} L}{E}, \frac{\Delta m^2_{31} L}{E} \ll 1$$

$$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

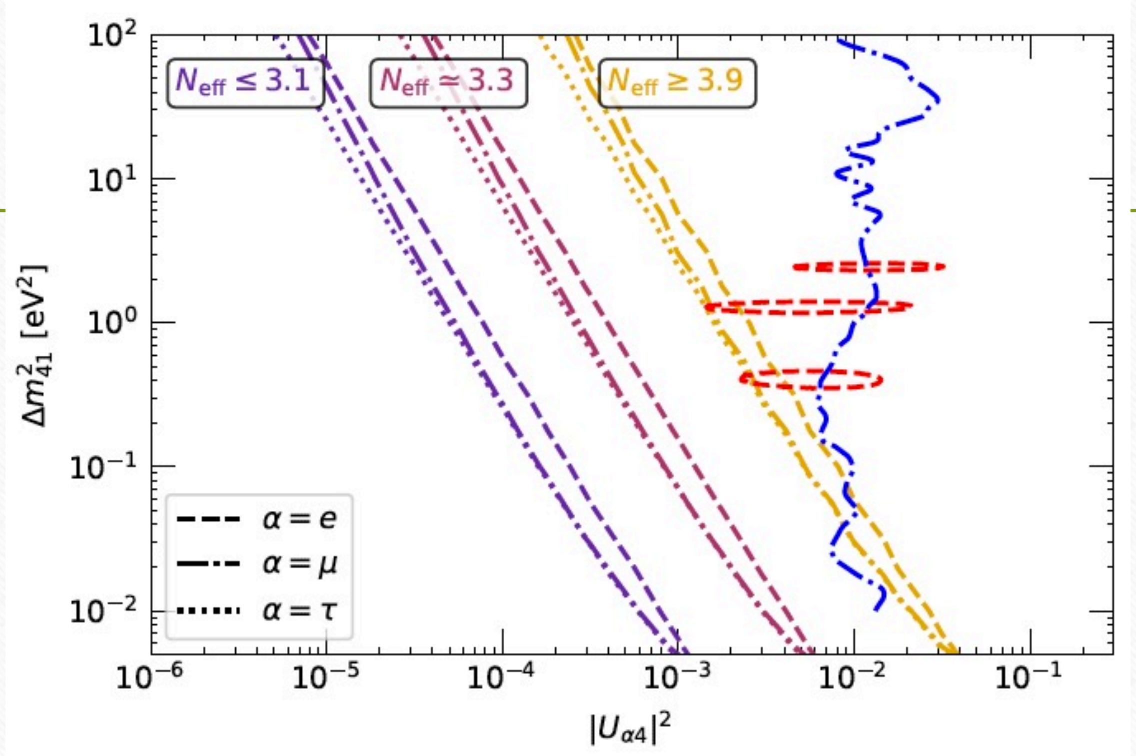
LSND and MiniBooNE



Neutrino 2018

MiniBooNE 4.8σ

MiniBooNE+LSND 6.1σ



Gariazzo, de Salas and Pastor, "Thermalisation of sterile neutrinos in the early universe in the 3+1 scheme with full mixing matrix," JCAP 1907 (2019) 014.

Two types of cosmological bounds

- Bound on extra relativistic degrees of freedom from BBN

- Upper bounds on the sum of neutrino masses from CMB+BAO

(free streaming at matter radiation equality)

Suppressed mixing

$$\begin{bmatrix} m_1 & m_2 \\ m_2 & M \end{bmatrix}$$

$$m_1, m_2 \ll M \quad \Rightarrow \quad \theta \simeq m_2/M \to 0$$

Self-interaction of sterile neutrinos

- Archidiacono et al, PRD 93 (2016); Kopp and Welter, JHEP 12 (2014); Hannestad et al, PRL 112 (2014); Chu et al, Astropart Phys 1811 (2018); Dasgupta and Kopp, PRL 112 (2014); Chu et al., Cosmol Astropart Phys. 1510 (2015); Paul et al, 1808.099706
- See however,

Mirizzi et al, PRD 91 (2015) Cherry et al, 1605.06506; Saviano et al, PRD 90 (2014) 113009

- Denton, YF and Shoemaker, "Activating the 4th Neutrino of the 3+1 scheme," PRD99 (2019) 035003

$$\mathcal{L} = -2\sqrt{2}\epsilon_\chi G_F(\bar{\nu}_s\gamma^\mu P_L\nu_s)(\bar{\chi}\gamma_\mu(1+b\gamma_5)\chi),$$

$$\boxed{\epsilon_\chi \gg 10^9}$$

$g_\chi \sim 3 \times 10^{-5}$ $\quad g_s \sim 3 \times 10^{-4}$ $\quad m_{Z'} \sim 10 \text{ eV}$

$$\epsilon_\chi = \frac{g_s g_\chi}{2\sqrt{2}m_{Z'}^2 G_F} = 10^{12}$$

$\boxed{n_\chi = n_B \text{ (and } m_\chi/m_p \simeq 5)}$

- Short introduction on light dark matter

Lower bounds on dark matter mass

- Standard thermal production: $m_{DM} > \text{few keV}$
- Gunn-Tremaine bound on fermionic dark matter: $m_{DM} > 400 \text{ eV}$
- Lower bound on bosonic dark matter: $m_{DM} > 10^{-22} \text{ eV}$

de Broglie wavelength

$$\lambda_{dB} > \frac{2\pi}{m_{DM} v}$$

Fuzzy dark matter

$$\lambda_{dB} \sim \text{Galaxy core}$$

Suarez, Robles and Matos, Astrophys Space Sci Proc 38 (2014) 107;
Rindler-Daller and Shapiro, Mod Phys Lett A 29; Chavanis, PRD 84 (2011) 43531;
Marsh, Phys Rep 643 (2016);
Hui, Ostriker, Tremaine and Witten, PRD 95 (2017) 043541

Lower bound on scalar

- Lyman alpha
- Rotation curves
- Superradiance M87*
- Precision cosmology
- …

$$m_{DM} \gtrsim 10^{-21}\ \mathrm{eV}$$

Sterile neutrino coupled to ultralight dark matter

Y. F., "Ultra-light scalar saving the 3+1 neutrino scheme from the cosmological bounds," PLB 797 (2019) 134911

$$\lambda\phi\nu_s^T c\nu_s + \text{H.c.}$$

$$c = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Classical limit

$$\lambda_{dB} \sim n_{DM}^{-1/3} = \left(\frac{m_{DM}}{\rho_{DM}}\right)^{1/3}$$

Real scalar:

$$\phi = A\cos(m_{DM}t)$$

$$T^{00} = \rho_{DM}$$

$$A^2 = \frac{2\rho_{DM}}{m_{DM}^2}$$

Complex scalar:

$$\phi = A\cos(m_{DM}t) + iB\sin(m_{DM}t + c)$$

$$A^2 + B^2 = \frac{\rho_{DM}}{m_{DM}^2}$$

Neutrino oscillations as a probe of light scalar dark matter

- A. Berlin, PRL 177 (2016) 231801

$$-\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_i \bar{\nu}_i \nu_i + g_\phi \phi \bar{\nu}_1 \nu_2 + \cdots$$

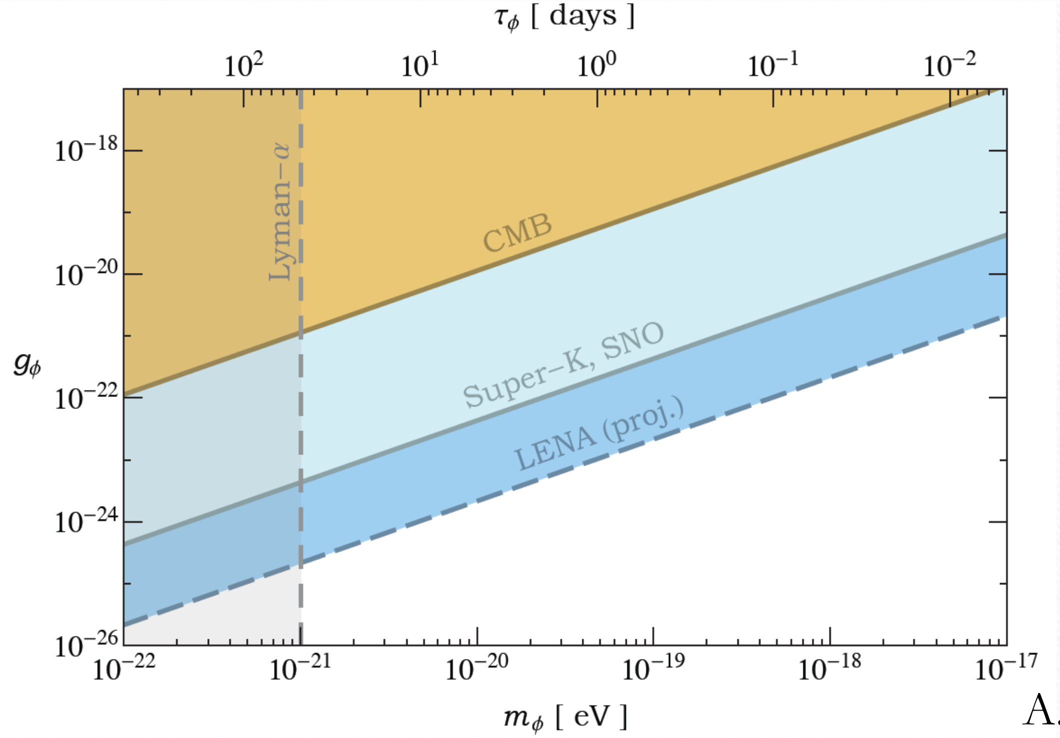
$$\phi(x) \simeq \frac{\sqrt{2 \rho_{\rm DM}(x)}}{m_\phi} \cos\left[m_\phi (t - \vec{v} \cdot \vec{x}) \right]$$

$$\sin\theta_{12}(t) \simeq \sin\theta_{12} + \frac{\cos\theta_{12}}{\Delta m_{12}} \frac{g_\phi \sqrt{2 \rho_{\rm DM}}}{m_\phi} \cos m_\phi t$$

$$\Phi_{\rm eff} = \Phi^{(0)} + \Phi^{(1)} \cos m_\phi t$$

$$\frac{\Phi^{(1)}}{\Phi^{(0)}} \simeq 2 \cot\theta_{12} \frac{g_\phi \sqrt{2 \rho_{\rm DM}}}{m_\phi \Delta m_{12}}$$

Bounds from time modulation of solar neutrinos



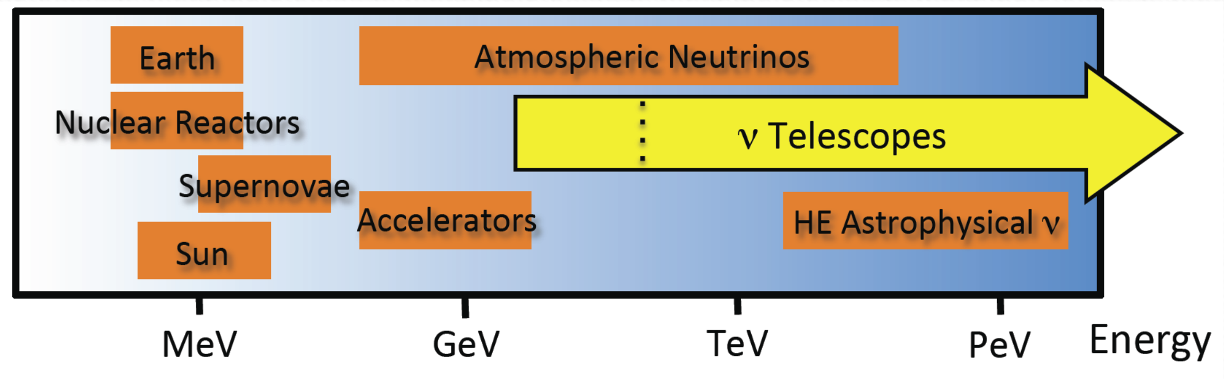
A. Berlin, PRL 177 (2016) 231801

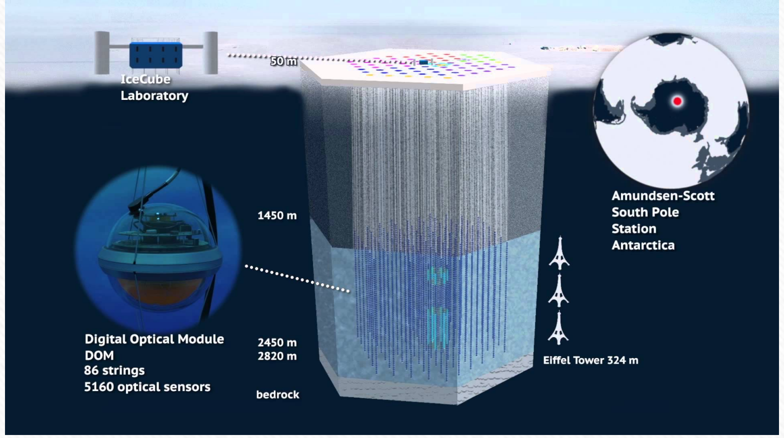
Time varying effects

- Krnjaic, Machado and Necib, PRD 97 (2018) 075017: JUNO and DUNE
- Brdar, Kopp, Liu, Prass and Wang, PRD97 (2018) 43001: T2K and solar

Dark matter effect constant in time

- Y.F. and S. Palomares-Ruiz, "Flavor of cosmic neutrinos preserved by ultralight dark matter," Phys. Rev. D 99 (2019) 051702





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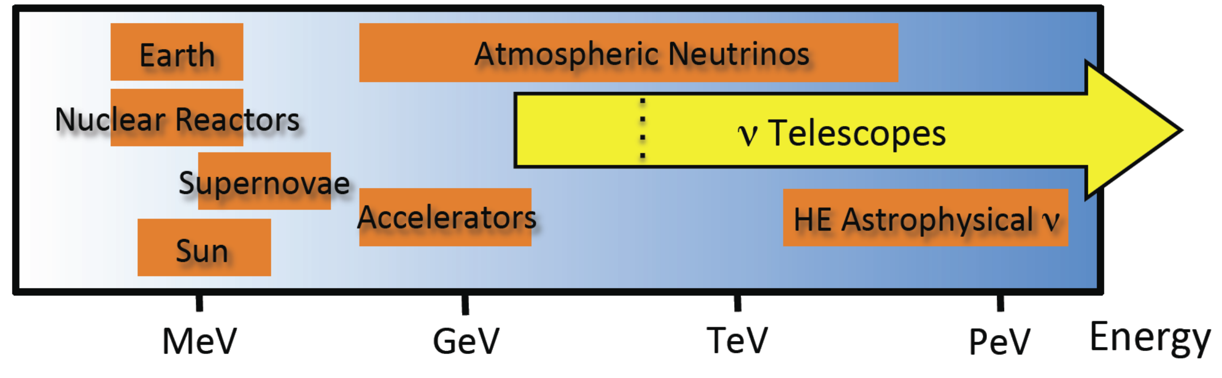
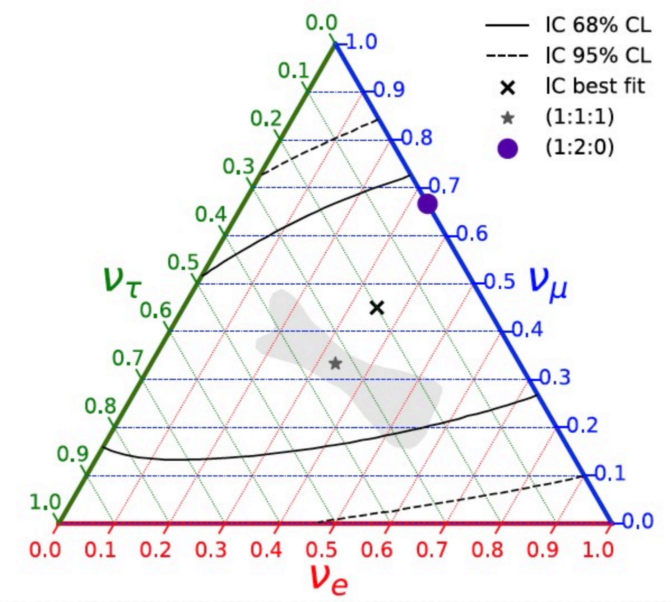




Sterile neutrino coupled to ultralight dark matter

Y. F., "Ultra-light scalar saving the 3+1 neutrino scheme from the cosmological bounds," PLB 797 (2019) 134911

$$\lambda \phi \nu_s^T c \nu_s + \text{H.c.}$$

$$c = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Euler-Lagrange Solution

$$\mathcal{L} = \frac{\partial_\mu \phi \partial^\mu \phi}{2} - \frac{m^2 \phi^2}{2}$$

$$\phi = \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t - \vec{p}_\phi \cdot \vec{x})$$

$$|\vec{p}_\phi| \ll m_\phi$$

$$T^{\mu\nu} = \frac{\delta \mathcal{L}}{\delta \partial_\mu \phi} \partial^\nu \phi - \eta^{\mu\nu} \mathcal{L}$$

$$\mathcal{L} = \frac{\partial_\mu \phi \partial^\mu \phi}{2} - \frac{m^2 \phi^2}{2}$$

$$\Rightarrow \begin{cases} T_{00} = \rho_\phi \\ T_{ii} = -\rho_\phi(\cos^2(m_\phi t) - \sin^2(m_\phi t)) \end{cases}$$

Solution

$$\phi = \frac{\sqrt{2\rho_\phi}}{m_\phi}\cos(m_\phi t - \vec{p}_\phi \cdot \vec{x})$$

$$|\vec{p}_\phi| \ll m_\phi$$

$t \ll 1/m_\phi$ $\quad T_{00} = -T_{ii}$ Or $\rho_\phi = -p_\phi$

$$T^{\mu\nu}_{\ ;\nu} = 0 \Longleftrightarrow \dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = 0$$

$t \ll 1/m_\phi \Longrightarrow \rho_\phi = cte$

Solution

$$\phi = \frac{\sqrt{2\rho_\phi}}{m_\phi}\cos(m_\phi t - \vec{p}_\phi \cdot \vec{x})$$

$$|\vec{p}_\phi| \ll m_\phi$$

$$t \gg 1/m_\phi \Rightarrow \langle p_\phi \rangle = 0$$

$$T^{\mu\nu}_{\ ;\nu} = 0 \Leftrightarrow \dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = 0$$

$$\rho_\phi(T) = \frac{T^3}{T_0^3}\rho_\phi(T_0)$$

Coupling and effective mass

$$\lambda \phi \nu_s^T c \nu_s + \text{H.c.}$$

$$\phi \bar{\nu}_s \nu_s$$

$$m_{eff} = \lambda \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t)$$

$$m_\phi < 5 \times 10^{-17}\ \text{eV} = \frac{1}{13\ \text{sec}}$$

$$\text{until}\ \ T \sim 0.22\ \ \text{MeV}(m_\phi/(5 \times 10^{-17}\ \ \text{eV}))^{1/2}$$

Neutrino decoupling occurs at T~1 MeV

Effective mixing

$m_{eff} \gg m_{\nu_s}$

$$\sin 2\theta_m|_T = \sin 2\theta \frac{m_{\nu_s}}{m_{eff}}$$

$$= \begin{cases} \sin 2\theta_m^{int} & \text{at} \quad t \ll m_\phi^{-1}, \\ \sin 2\theta_m^{int} \left(\frac{0.22 \text{ MeV} \sqrt{m_\phi / 5\times10^{-17} \text{ eV}}}{T} \right)^{3/2} & \text{at} \quad t \gg m_\phi^{-1}, \end{cases}$$

Lorentz structure of the effective mass

$\nu_s^T c \nu_s$ Versus $\nu_a^\dagger \nu_a$

↓ Added to neutrino mass

↓ Added to $m_\nu^2/(2p)$

τ_ν^{-1} is the interaction rate of neutrinos $\tau_\nu^{-1} \sim G_F^2 T^5$

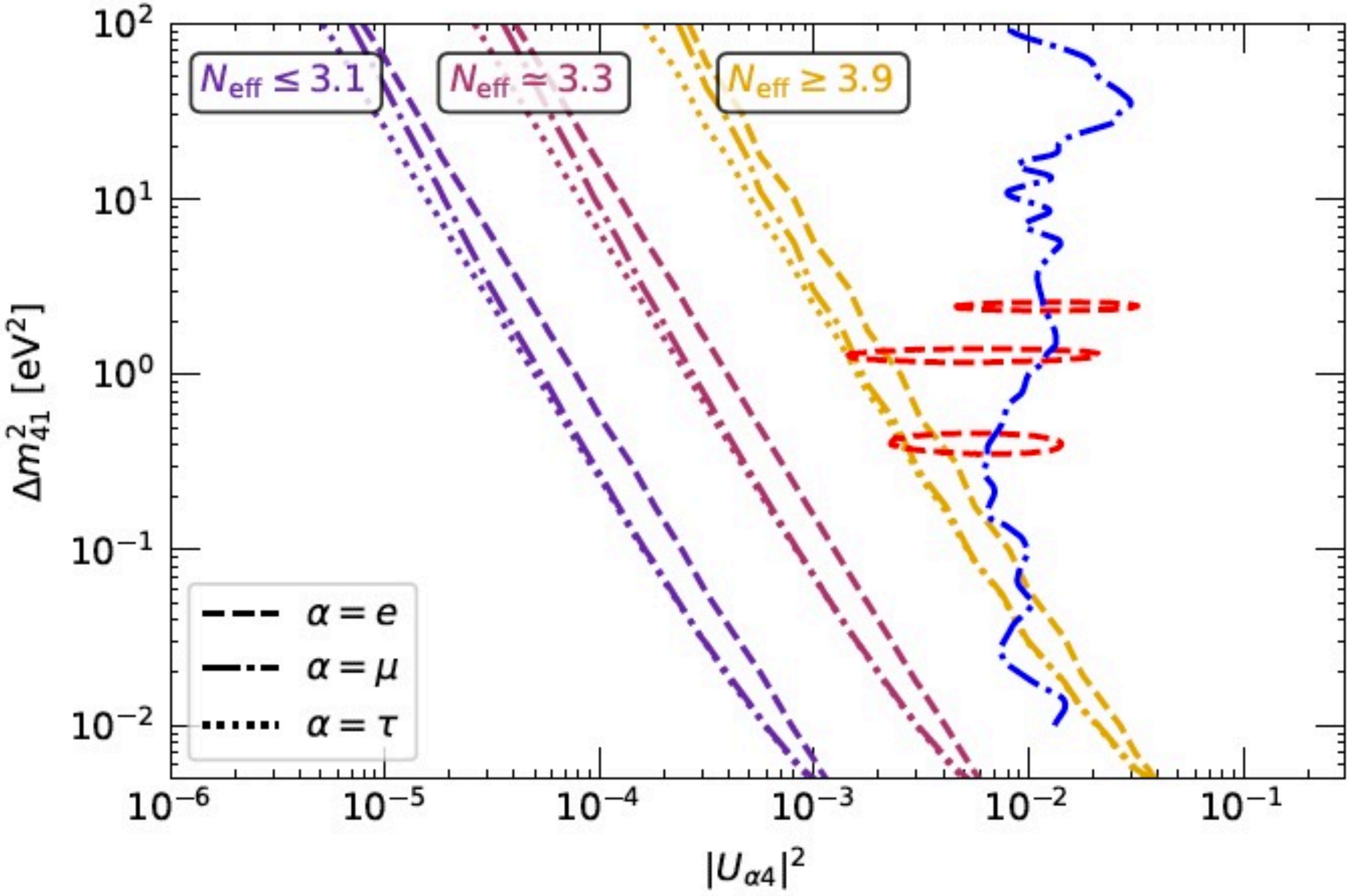
$$\frac{\tau_\nu \Delta m^2}{E} \gg 1$$

$$\Gamma_{\nu_a \to \nu_s} = \frac{\sin^2 2\theta_m^{int}}{4\tau_\nu}$$

$$\delta N_{eff} = \int_{T_{min}}^{T_{max}} \Gamma_{\nu_a \to \nu_s} dt = \frac{\sin^2 2\theta_m^{int}}{4} \int_{T_{min}}^{T_{max}} \frac{1}{\tau_\mu} dt$$

$(\Delta m^2/T)t \gtrsim 1$

T_{min} is the neutrino decoupling temperature

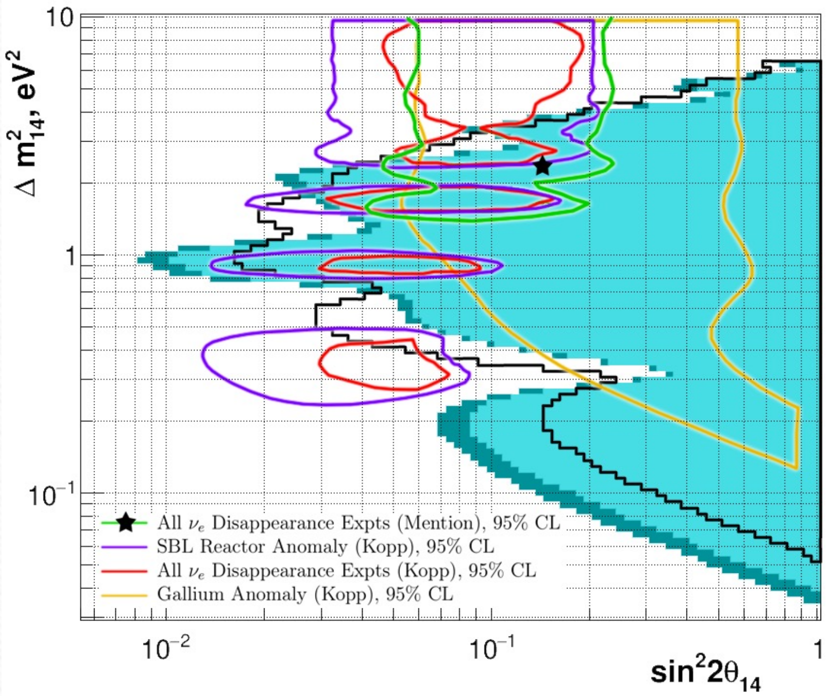


$$\varrho(p,t) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$$

Gariazzo, de Salas and Pastor, "thermalisation of sterile neutrinos in the early universe in the 3+1 scheme with full mixing matrix," JCAP 1907 (2019) 014.

$\sin^2 2\theta_m^{int} = 4 \times 10^{-5}$, the contribution will be less than $O(0.01)$

DANSS and other reactor neutrino experiments



DANSS Collaboration, arXiv:1911.10140

PoS EPS-HEP2019 (2020) 401

$$\Delta m^2 \sim 3 \ \text{eV}^2 \ \text{and} \ |U_{e4}|^2 \sim 2 \times 10^{-2}$$

Effective mixing

$$\sin^2 2\theta_m^{int} = 4 \times 10^{-5}$$

$$m_{eff}^{int} > 40 \text{ eV}$$

$$\lambda > 2 \times 10^{-23}$$

- These results are confirmed by

J. Cline, "viable secret neutrino interactions with ultralight dark matter," Phys. Lett B 802 (2020) 135182, arXiv:1908.0227

$$\lambda \phi \nu_s^T c \nu_s + \text{H.c.}$$

$$m_s \nu^T c \nu_s$$

$$\phi = \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t - \vec{p}_\phi \cdot \vec{x})$$

Cancelation

$$m_{eff} = \lambda \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t).$$

$$m_s + m_{eff} = 0$$

$$\phi \to \nu_s \nu_s$$

Perturbative lifetime $\dfrac{4\pi}{\lambda^2 m_\phi}$

However, parametric resonance

$$\rho_\phi \ll \rho_{\nu_a}$$

Traschen and Brandenberger, PRD 42 (1990);
Kofman Linde Starobinsky, PRL 73 (1994);
Shtanov, Traschen and Brandenberger, PRD 51 (1995)
Kofman et al, JHEP 405 (2004)

Neutrino oscillation after $1/m_{DM}$

Coherence between mass eigenstates are lost already at T<MeV so we deal with $\nu_{m1}, \nu_{m2}, \nu_{m3}$ and ν_{m4}

Contribution of ν_{m4} : $\sum_{\alpha \in \{e,\mu,\tau\}} |U_{\alpha 4}|^2$

Important question

$$m_{eff} = \lambda \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t).$$

Resonance condition: $m_{eff} = m_\nu \cos 2\theta$

- Is the transition adiabatic?

Reminder of solar oscillation

$$i\frac{d}{dt}\begin{pmatrix} A_e(t,t_0) \\ A_\alpha(t,t_0) \end{pmatrix} = \begin{pmatrix} -\epsilon(t) & \epsilon' \\ \epsilon' & \epsilon(t) \end{pmatrix} \begin{pmatrix} A_e(t,t_0) \\ A_\alpha(t,t_0) \end{pmatrix}$$

$$\epsilon(t) = \frac{1}{2}[\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e(t)], \quad \epsilon' = \frac{\Delta m^2}{2E}\sin 2\theta$$

$$|\nu_e\rangle = |\nu_1^m\rangle \cos\theta_m + |\nu_2^m\rangle \sin\theta_m$$
$$|\nu_\alpha\rangle = -|\nu_1^m\rangle \sin\theta_m + |\nu_2^m\rangle \cos\theta_m$$

Adiabaticity vs Non-adiabaticity

$$A_e(t,t_0) = A_1(t,t_0)\cos\theta_m(t) + A_2(t,t_0)\sin\theta_m(t)$$
$$A_\alpha(t,t_0) = -A_1(t,t_0)\sin\theta_m(t) + A_2(t,t_0)\cos\theta_m(t)$$

$$i\frac{d}{dt}\begin{pmatrix} A_1(t,t_0) \\ A_2(t,t_0) \end{pmatrix} = \begin{pmatrix} E_1^m(t) & -i\dot{\theta}_m(t) \\ i\dot{\theta}_m(t) & E_2^m(t) \end{pmatrix} \begin{pmatrix} A_1(t,t_0) \\ A_2(t,t_0) \end{pmatrix}$$

$$\frac{\dot{\theta}_m}{\text{Effective mass splitting}}|_{resonance} = \frac{\lambda\sqrt{2\rho_\phi}\sin(m_\phi t)}{8m_{\nu_s}^2\sin^2\theta}|_{resonance} \simeq \frac{m_\phi(T/T^{int})^{3/2}}{8m_{\nu_s}\sin\theta\sin\theta_m^{int}} \ll 1$$

Other forms of interaction

$\phi^2 \nu_s^T c \nu_s$

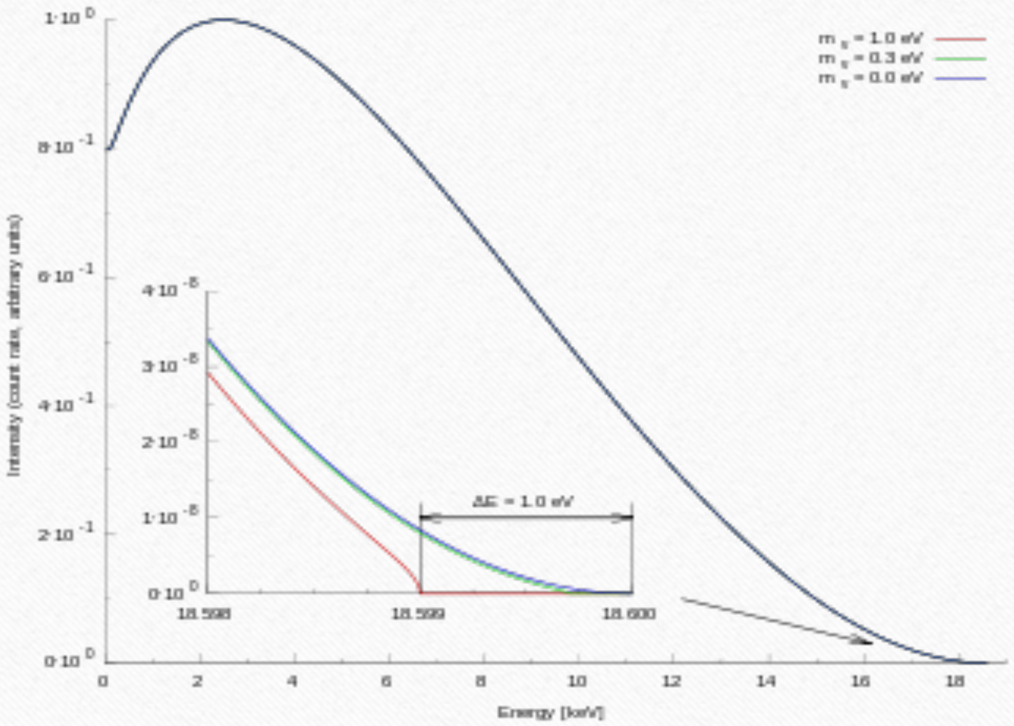
Y. Zhao, Phys. Rev. D 95 (11) (2017) 115002,

$i(\phi^* \partial_\mu \phi - \phi \partial_\mu \phi^*) \bar{\nu} \gamma^\mu \nu$

Y. Farzan, S. Palomares-Ruiz, Phys. Rev. D 99 (5) (2019) 051702,

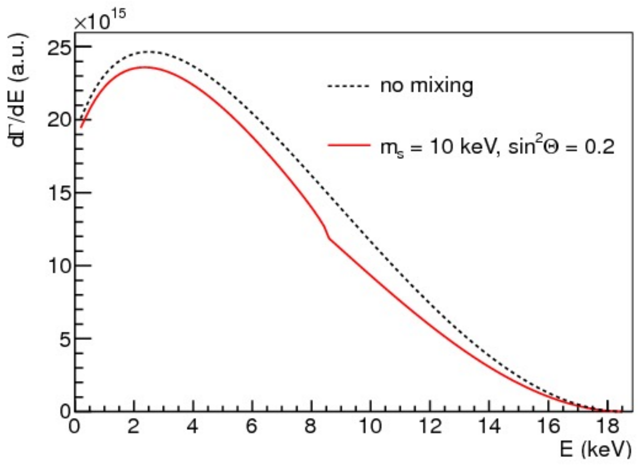
KATRIN

Shift of end-point



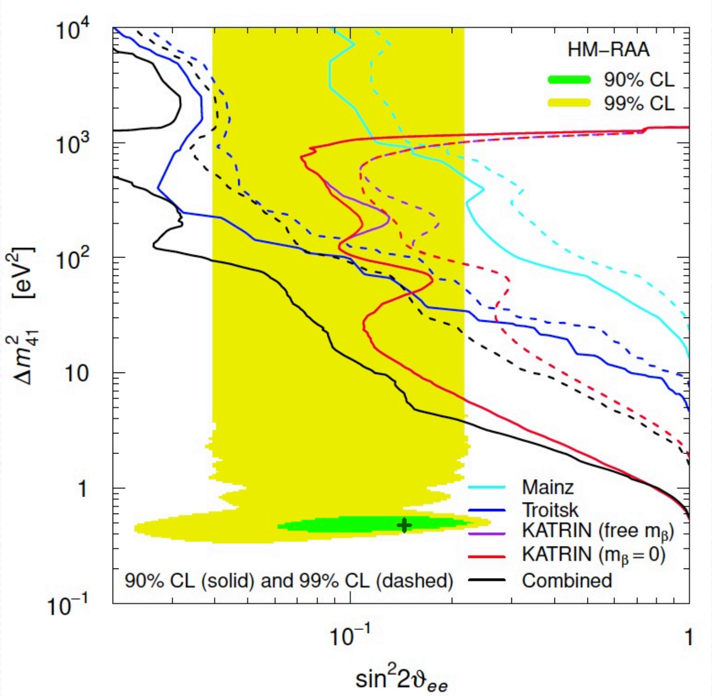
$$^3H \rightarrow ^3He + e + \bar{\nu}_e$$

Kink



×10^15
dΓ/dE (a.u.)
25
20
15
10
5
0
0 2 4 6 8 10 12 14 16 18
E (keV)
no mixing
m_s = 10 keV, sin^2Θ = 0.2

Preliminary KATRIN bounds

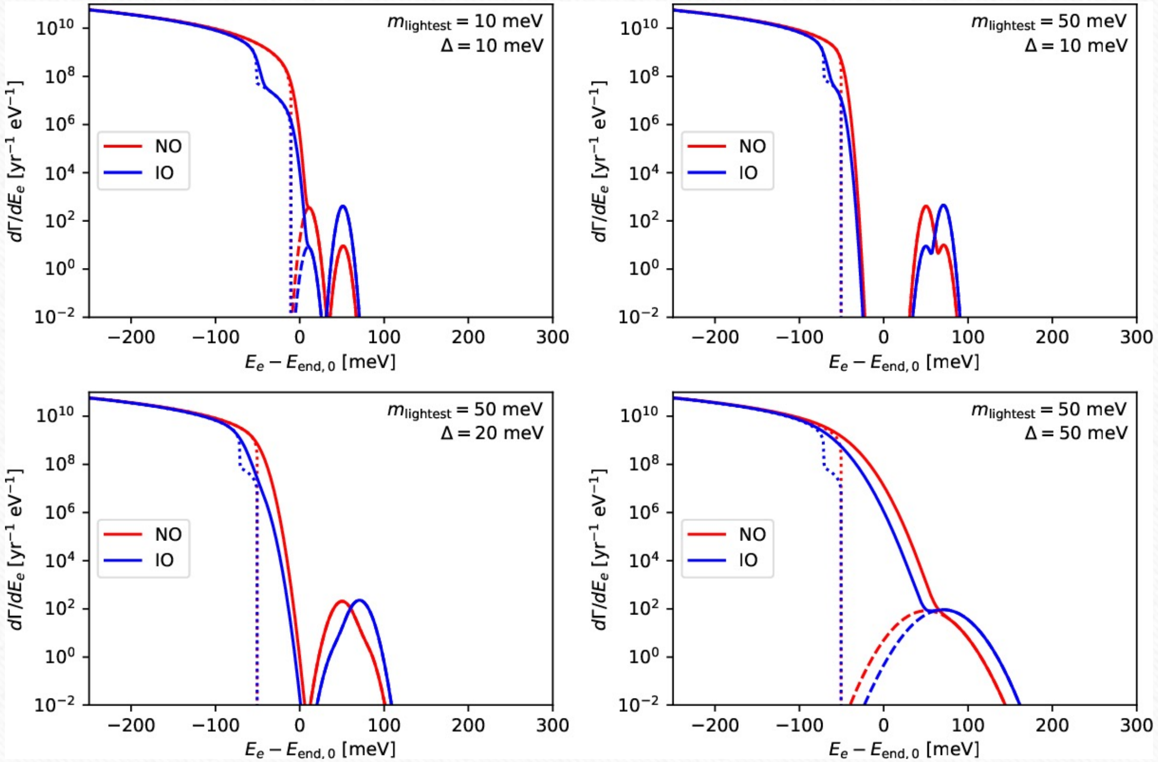


Giunti, Li and Zhang, *JHEP* 05 (2020) 061

PTOLEMY

$$^3H \rightarrow ^3He + e + \bar{\nu}_e$$

$$^3H + \nu_e \rightarrow ^3He + e$$



PTOLEMY collaboration, JCAP 1907 (2019) 047

$$^3H + \nu_4 \rightarrow ^3He + e^-$$

Conclusions

- It is possible to save 3+1 scheme from cosmological bounds by coupling it to ultralight scalar DM

- Hope to see kinks at KATRIN

Backup slides

Light but cold

$$\Phi = |\Phi| e^{i\phi/f_0}$$

$$(-f_0\pi\,,\, f_0\pi)$$

D.J.E. Marsh, Phys. Rep. 643 (2016) 1

$$\rightarrow \quad \langle\phi\rangle \neq 0$$

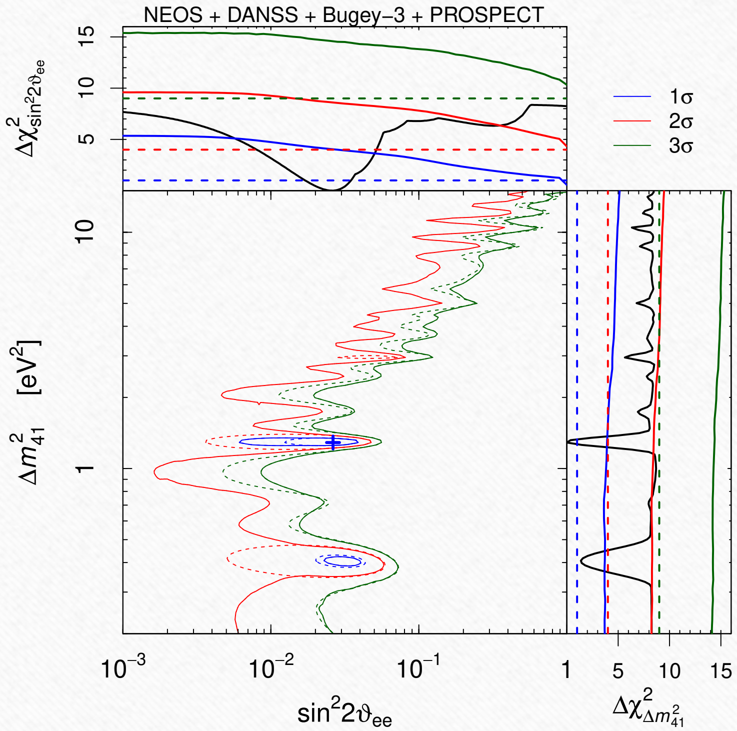
de Broglie wavelength >> average distance between particles

Force between DM

- Repulsive force (like gauge coupling) stable
- Attractive force (like Yukawa coupling) unstable

Chavanis, PRD84 (2011) 043531

Reactor neutrino experiments



C. Giunti,
"Statistical Significance of Reactor Antineutrino Active-Sterile Oscillations," *Phys.Rev.D* 101 (2020) 9, 095025

Sterile neutrino decay

$$\nu_i \to \nu_j \bar{\nu}_k \nu_l$$

$$\Gamma_i = \frac{g_s^4 |U_{si} U_{sj} U_{sk} U_{sl}|^2}{192\pi^3} \frac{m_i^5}{m_{Z'}^4} \frac{m_i}{E_\nu}$$

Decay before recombination and free streaming at recombination

$$3 \times 10^{-4} \left(\frac{0.1}{U_{si}}\right)^{3/2} \lesssim g_s \lesssim 5 \times 10^{-4} \left(\frac{0.1}{U_{si}}\right)^2$$