Probing Fuzzy DM in Neutrino Experiments

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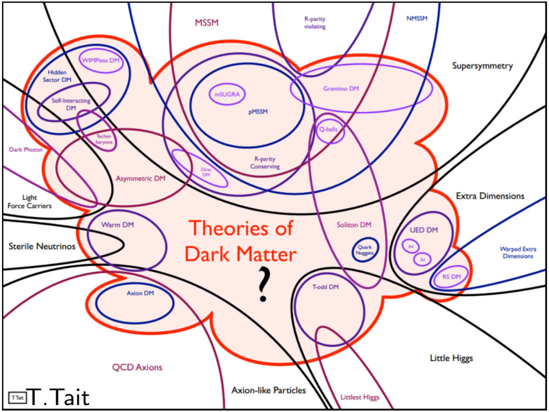
Dark Matter - vast number of candidates



- in this talk we will focus on the low end of DM spectrum – fuzzy DM with mass $\mathcal{O}(10^{-22})$ eV
- we consider both scalar and vector ultralight DM

Properties of Fuzzy DM candidate

Fuzzy DM can address:

- "core vs. cusp problem"– DM density profile discrepancy between measurements and simulations

→ DM delocalization
(huge Compton wave length $\lambda = 2\pi/m_\phi \simeq 0.4\,\mathrm{pc} \times (10^{-22}\mathrm{eV}/m_\phi)$)

- "missing satellites problem"–lower than expected abundance of dwarf galaxies

→ higher probability for tidal disruption of DM subhalos and suppression of the matter power spectrum at small scales (Hui et al. 1610.08297)

- "too big to fail problem"– apparent failure of many of the most massive Milky Way subhalos to host visible dwarf galaxies

→ Fuzzy DM predicts fewer such subhalos (Marsh et al. 1307.1705)

- admittedly, better treatment of baryonic physics in simulations (1602.05957,1202.0554) may solve these puzzles but the possibility that DM physics plays a crucial role is not excluded.

DM production

Arias et al. 1201.5902
Nelson & Scholtz 1105.2812
Golovnev et al. 0802.2068

Misalignment mechanism

- EOM for real scalar field ϕ

$$\ddot{\phi} + 3\,H\,\dot{\phi} + m_\phi^2\phi = 0.$$

- while $3\,H \gg m_\phi$, ϕ is "frozen"
- at $3\,H = m_\phi$ damping term stops dominating and the field can start to oscillate
- for vector DM ϕ^μ one introduces coupling to gravity $\sim R\phi_\mu\phi^\mu$
- The mass of ϕ^μ can be generated either through the Stückelberg mechanism or from spontaneous symmetry breaking in a dark Higgs sector
- we consider both polarized and unpolarized vector DM (polarization may be altered during structure formation)

Model

Relevant part of the Lagrangian:

$$\text{Scalar} \quad \mathcal{L}_{\text{scalar}} = \bar{\nu}_L^\alpha i\partial\!\!\!/ \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta - \frac{1}{2} y^{\alpha\beta} \phi \, \overline{(\nu_L^c)^\alpha} \nu_L^\beta .$$

The interaction term can be generated in a gauge invariant way by coupling ϕ to heavy right-handed neutrinos N_R (introduced in seesaw type-I)

- we assume $y = y_0 (m_\nu / 0.1\text{eV})$

$$\text{Vector} \quad \mathcal{L}_{\text{vector}} = \bar{\nu}_L^\alpha i\partial\!\!\!/ \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta + g Q^{\alpha\beta} \phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta \, .$$

- ϕ^μ as the $L_\mu - L_\tau$ symmetry gauge boson with couplings $Q^{\alpha\beta} = \text{diag}(0, 1, -1)$
- if $L_\mu - L_\tau$ breaking occurs at TeV scale, with $m_\phi \sim 10^{-22}$ eV we require coupling $g \sim 10^{-30}$ which can be probed

Vector DM I

- alternatively, ϕ^μ could couple to the SM via mixing with a much heavier $L_\mu - L_\tau$ gauge boson K^μ (term $\epsilon\phi^{\mu\nu}K_{\mu\nu}$)

$$\mathcal{L}_{\mu-\tau} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \bar{L}^\alpha\left(i\partial\!\!\!/ + g_{\mu-\tau}Q^\alpha_{\mu-\tau}\gamma_\mu K^\mu\right)L^\alpha + \bar{e}^\alpha_R\left(i\partial\!\!\!/ + g_{\mu-\tau}Q^\alpha_{\mu-\tau}\gamma_\mu K^\mu\right)e^\alpha_R$$

$$+ (D^\mu S)^\dagger(D_\mu S) + \mu_S^2 S^\dagger S - \lambda_S(S^\dagger S)^2$$

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}\epsilon\phi_{\mu\nu}K^{\mu\nu} + \frac{1}{2}\left(\partial_\mu\sigma + m_1\phi_\mu + m_2K_\mu\right)^2$$

kinetic and mass term in matrix form : $V = (\phi, K)^T$

$$\mathcal{L} \supset -\frac{1}{4}V^T_{\mu\nu}\begin{pmatrix}1 & -\epsilon\\ -\epsilon & 1\end{pmatrix}V^{\mu\nu} + \frac{1}{2}V^T_\mu\begin{pmatrix}m_1^2 & m_1m_2\\ m_1m_2 & m_2^2 + (g_{\mu-\tau}v_S)^2\end{pmatrix}V^\mu$$

after two unitary transformations

$$\begin{pmatrix}\phi\\ K\end{pmatrix} = U\begin{pmatrix}\tilde{\phi}\\ \tilde{K}\end{pmatrix} \equiv U_1U_2\begin{pmatrix}\tilde{\phi}\\ \tilde{K}\end{pmatrix}$$

we identify gauge boson masses and the effective coupling $\quad y_i = \frac{m_i}{g_{\mu-\tau}v_s}$

$$\mathcal{L}_{\text{int}} = \left(-\frac{y_1^2\epsilon}{1-y_1^2} - \frac{y_1y_2}{1-y_1^2}\right)g_{\mu-\tau}Q^\alpha_{\mu-\tau}\tilde{\phi}^\mu\left(\bar{L}^\alpha\gamma_\mu L^\alpha + \bar{e}^\alpha_R\gamma_\mu e^\alpha_R\right)$$

Vector DM II

Heeck,Rodejohann 1107.5238

- neutrino masses are generated by introducing 3 RH neutrinos with the following charges under $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau}$

$$N_1 \sim (1,1,0)(0), \quad N_2 \sim (1,1,0)(+1), \quad N_3 \sim (1,1,0)(-1)$$

$$\mathcal{L}_{yuk} = \frac{1}{2} a \bar{N}_1^c N_1 + \frac{1}{2} b \left(\bar{N}_2^c N_3 + \bar{N}_3^c N_2 \right) + \lambda_e \bar{L}_e \tilde{H} N_1 + \lambda_\mu \bar{L}_\mu \tilde{H} N_2 + \lambda_\tau \bar{L}_\tau \tilde{H} N_3 + h.c. + \lambda_S^{12} \bar{N}_1^c N_2 S + \lambda_S^{13} \bar{N}_1^c N_3 S^\star + h.c.$$

$$m_D = \begin{pmatrix} m_{\nu_e} & 0 & 0 \\ 0 & m_{\nu_\mu} & 0 \\ 0 & 0 & m_{\nu_\tau} \end{pmatrix}, \quad m_R = \begin{pmatrix} a & s & t \\ s & 0 & b \\ t & b & 0 \end{pmatrix},$$

$m_{\nu_j} \equiv \lambda_i v/\sqrt{2}$, $s \equiv \lambda_S^{12} v_X$ and $t \equiv \lambda_S^{13} v_X$.

$$m_\nu \simeq -m_D \cdot m_R^{-1} \cdot m_D \,.$$

MSW Potential

Ge, Murayama 1904.02518
Ge, Parke 1812.08376
Smirnov, Xu 1909.07505

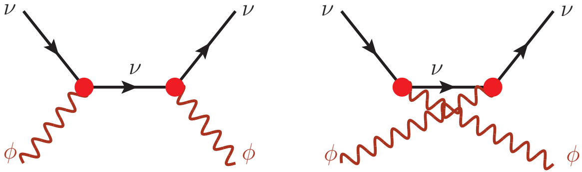
- Coherent Forward Scattering of Neutrinos on Fuzzy DM
- scalar DM

$$V_{\text{eff}} = \frac{1}{2E_\nu}\left(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\right), \qquad \phi = \frac{\sqrt{2\rho_\phi}}{m_\phi}\cos(m_\phi t)\ ,$$

- vector DM

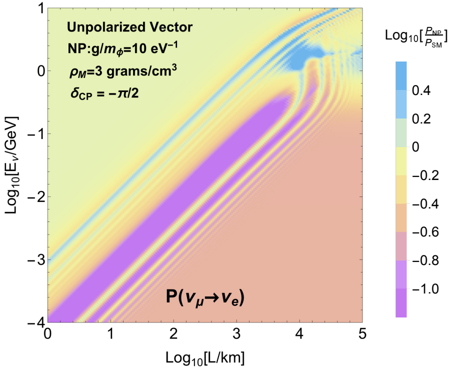
$$V_{\text{eff}} = -\frac{1}{2E_\nu}\left(2(p_\nu\cdot\phi)gQ + g^2Q^2\phi^2\right). \qquad \phi^\mu = \frac{\sqrt{2\rho_\phi}}{m_\phi}\xi^\mu\cos(m_\phi t)\,.$$

- $V_{\mu\mu}^{(T,U)} = V_{\tau\tau}^{(T,U)} = \frac{g^2\rho_\phi}{E_\nu m_\phi^2}\cos^2(m_\phi t)$
- for polarized DM we evaluate $p_\nu\cdot\phi$ assuming the polarization axis to be parallel to the ecliptic plane



Methods

- We have implemented the potential in GLoBES Huber et al. 0701187,0407333
- the time dependence of matter potential induces time dependent oscillation probabilities
- we evaluate the oscillation probabilities at several fixed times and interpolate using a second order polynomial in $cos(m_\phi t)$



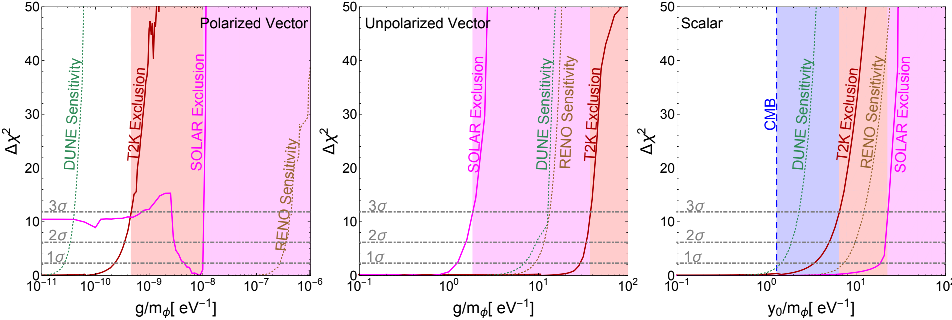
$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = P_0^{\alpha\beta}(E_\nu) + P_1^{\alpha\beta}(E_\nu) \cdot V(t) + P_2^{\alpha\beta}(E_\nu) \cdot V(t)^2 + \ldots$$

- the probability is then averaged in a given time interval T

https://github.com/koppj/fuzzy-dm

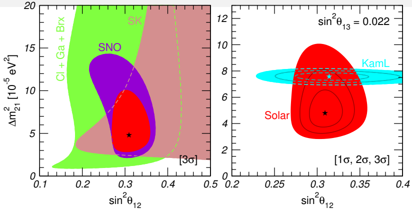
$$\bar{P}(E) = \frac{1}{T}\int_0^T dt P(E_\nu, t)$$

Constraints

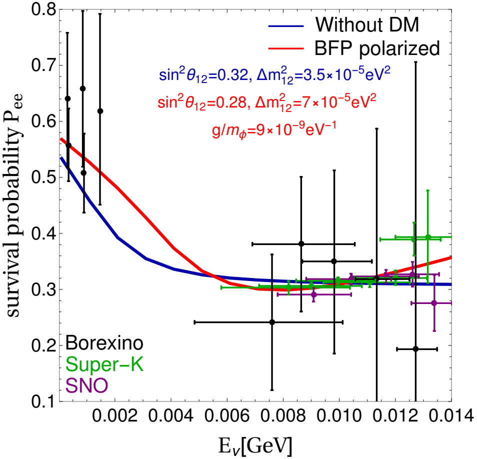


- for vector DM, the sensitivity is more than ten orders of magnitude better in the polarized case
- for scalar and polarized vector DM acceleration-based experiments give stronger limits and sensitivities
- for unpolarized vector DM, experiments at lower energies are better (energy dependence of the potential)

Impact on Solar and Astrophysical neutrinos



Maltoni,Smirnov 1507.05287
Gonzalez-Garcia, Maltoni 1307.3092
Ge, Murayama 1904.02518



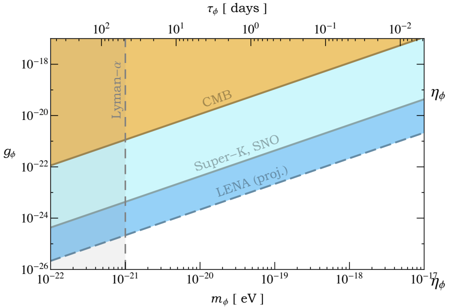
Solar

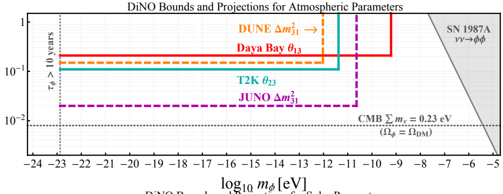
- adiabatic evolution in the sun Sun
- survival probability of electron flavor $P_{ee}(E_\nu) = \sum_i |U^{\odot}_{ei}|^2\, |U^{\oplus}_{ei}|^2$
- fitted data from Borexino, Super-K and SNO

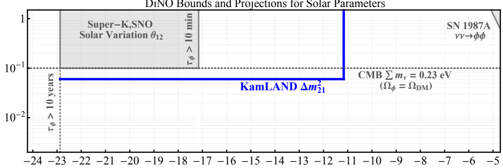
Astrophysical

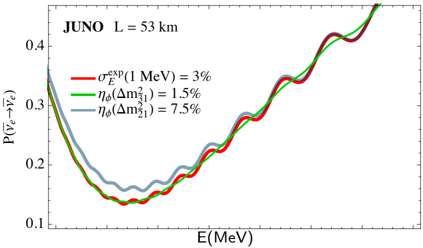
- obtaining constraints from optical depth $\tau_\nu(E_\nu) = \sigma_{\nu\phi}(E_\nu) X_\phi m_\phi^{-1}$ with $X_\phi \equiv \int_{\text{l.o.s}} dl\, \rho_\phi$
- much weaker limits in comparison to oscillation exp.

Distorted Neutrino Oscillation









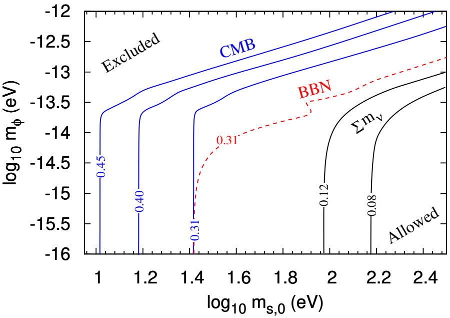
- A. Berlin, 1608.01307, PRL (2016)
- Krnjaic et al., 1705.06740, PRD (2018)
- Super-K does not find modulation at $\gtrsim 10\%$ (see however Sturrock et al. 1907.11749)

eV-scale sterile neutrino

- see talks by Giunti (3+1 in oscillation experiments) and Dasgupta (sterile neutrino in cosmology)
- recent idea: couple scalar fuzzy DM to sterile neutrino

Y. Farzan, 1907.04271
J. Cline, 1908.02278

$$\mathcal{L} \supset \lambda \bar{\nu}_s \nu_s \phi$$



- this coupling induces an effective mass for m_s in the early Universe, successfully suppressing $\nu_a \leftrightarrow \nu_s$ oscillations, and subsequent production of ν_s

Summary

- fuzzy DM is an interesting alternative to WIMP
- several groups have recently considered interactions of such DM with neutrinos
- unique opportunities exist at current and future neutrino oscillation experiments to probe such interactions
- the eV-sterile neutrino can be reconciled with cosmology if it couples to scalar ultralight DM