Fuzzy Dark Matter and Non-Standard Neutrino Interaction

Jia Liu
Chicago U., EFI

Coauthor: Vedran Brdar, Joachim Kopp, Pascal Prass, Xiao-Ping Wang

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The era for non-canonical DM

- ✦ Standard WIMP
- ✦ CDM@small scale structure
- ✦ Null result in direct detection

- Ultra-light bosonic DM
- If m~10^-22 eV, de Broglie wavelength ~ kpc, good for small scale
- Large occupation number

Connection to SM: photon, lepton, baryon, neutrino (Asher Berlin, Gordan Krnjaic, Pedro A. N. Machado, Lina Necib) etc

Ultralight bosonic DM

- Scalar DM model

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

- Vector DM model

$$\mathcal{L}_{\text{vector}} = \bar{\nu}_L^{\alpha} i\gamma^{\nu}\partial\nu_L^{\alpha} - \frac{1}{2}m_{\nu}^{\alpha\beta}\overline{(\nu_L^c)^{\alpha}}\nu_L^{\beta} + \boxed{gQ^{\alpha\beta}\phi^{\mu}\bar{\nu}_L^{\alpha}\gamma_{\mu}\nu_L^{\beta}}$$

- DM MSW effect for neutrinos
- Solve classic E.O.M (p^2 = m^2)
- $m \to m + y\phi$ $\qquad$ $p_{\mu} \to p_{\mu} + gQ\phi_{\mu}$

Ultralight bosonic DM

- Dispersion relation: $(E_\nu - V_{\rm eff})^2 = \vec{p}_\nu^{\,2} + m_\nu^2$
- Scalar DM model

$$V_{\rm eff} = \frac{1}{2E_\nu}\left(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\right)$$

- Vector DM model

$$V_{\rm eff} = -\frac{1}{2E_\nu}\left(2(p_\nu\cdot\phi)gQ + g^2Q^2\phi^2\right)$$

- Neutrino effective potential in DM medium
- Vacuum oscillation: $V_{\rm vac} = \frac{\Delta m^2}{2E_\nu}$
- MSW oscillation at Earth: $V_{\rm MSW} = \sqrt{2} n_e G_F$
- Schrödinger equation: $H = V_{\rm vac} + V_{\rm MSW} + V_{\rm eff}$

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Done!

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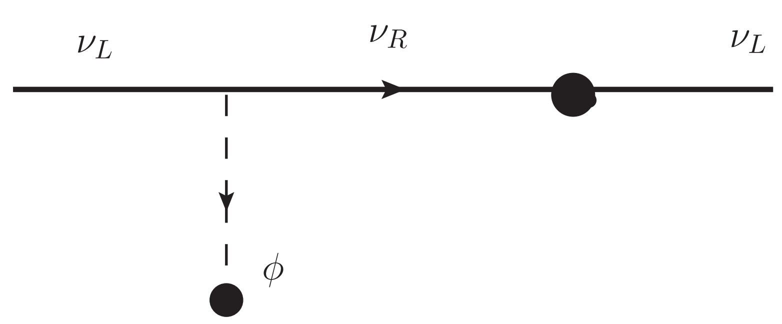
$$H_{\beta\alpha}|\alpha\rangle = i\partial_t|\beta\rangle$$

$$P_{\alpha\beta}(t) = |\langle\alpha(t)|\beta(0)\rangle|^2$$

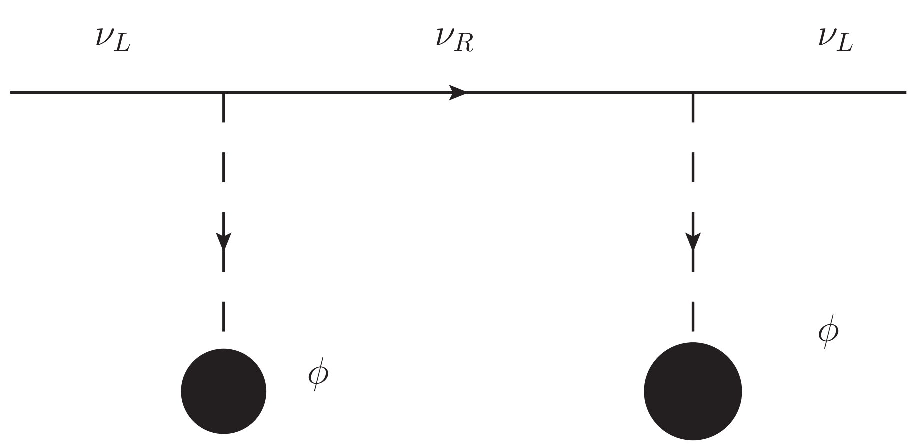
Scalar DM case

$$V_{\text{eff}} = \frac{1}{2E_\nu}\Big(\phi\,(y\,m_\nu + m_\nu\,y) + \phi^2 y^2\Big)$$

- Linear term (classic)



- Quadratic term (classic = QFT forward scattering)



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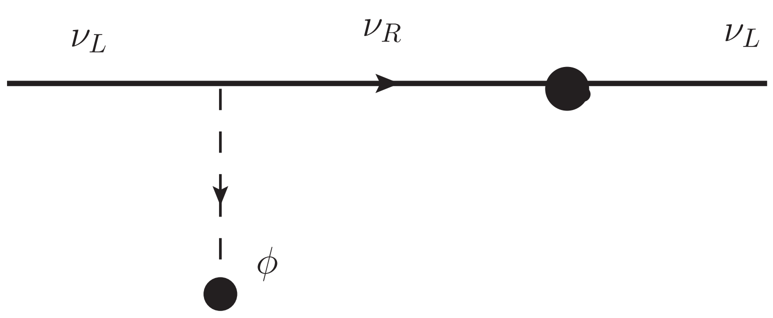

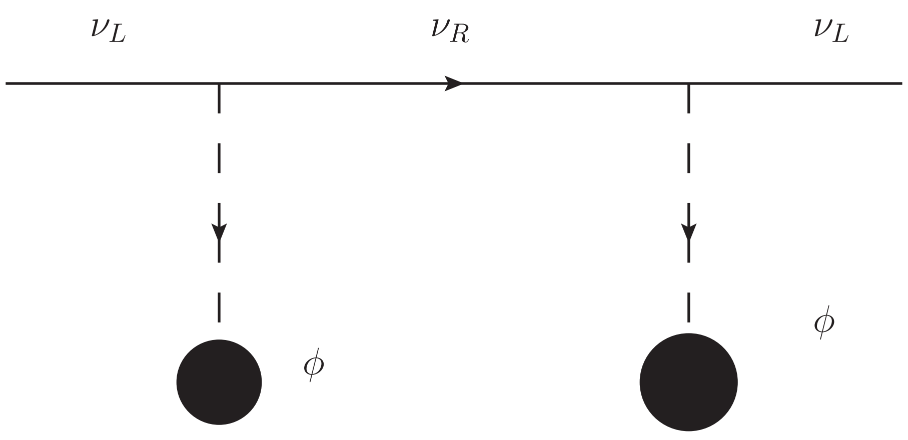

- DM from Misalignment

$$\partial_t\partial_t\phi + 3H\partial_t\phi + m^2\phi = 0$$

$$\phi = \phi_0\cos(m_\phi t) \qquad \rho_\phi = \frac{1}{2}m_\phi^2\phi_0^2$$

Scalar DM case

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

- Naive estimation of constraints: $y\phi \sim m_\nu$
- Local DM density: 0.3 GeV/cm^3 $\rho_\phi = \frac{1}{2} m_\phi^2 \phi_0^2$

$$y/m_\phi \sim \mathcal{O}(eV)$$

- Expansion on Probability:

$$P_{\alpha\beta} = P_0 + P_1 \cos(m_\phi t) + P_2 \cos^2(m_\phi t)$$

- Modulation effect and Average shift
- Modulation resolution for 1/m>10 min.

Scalar DM case

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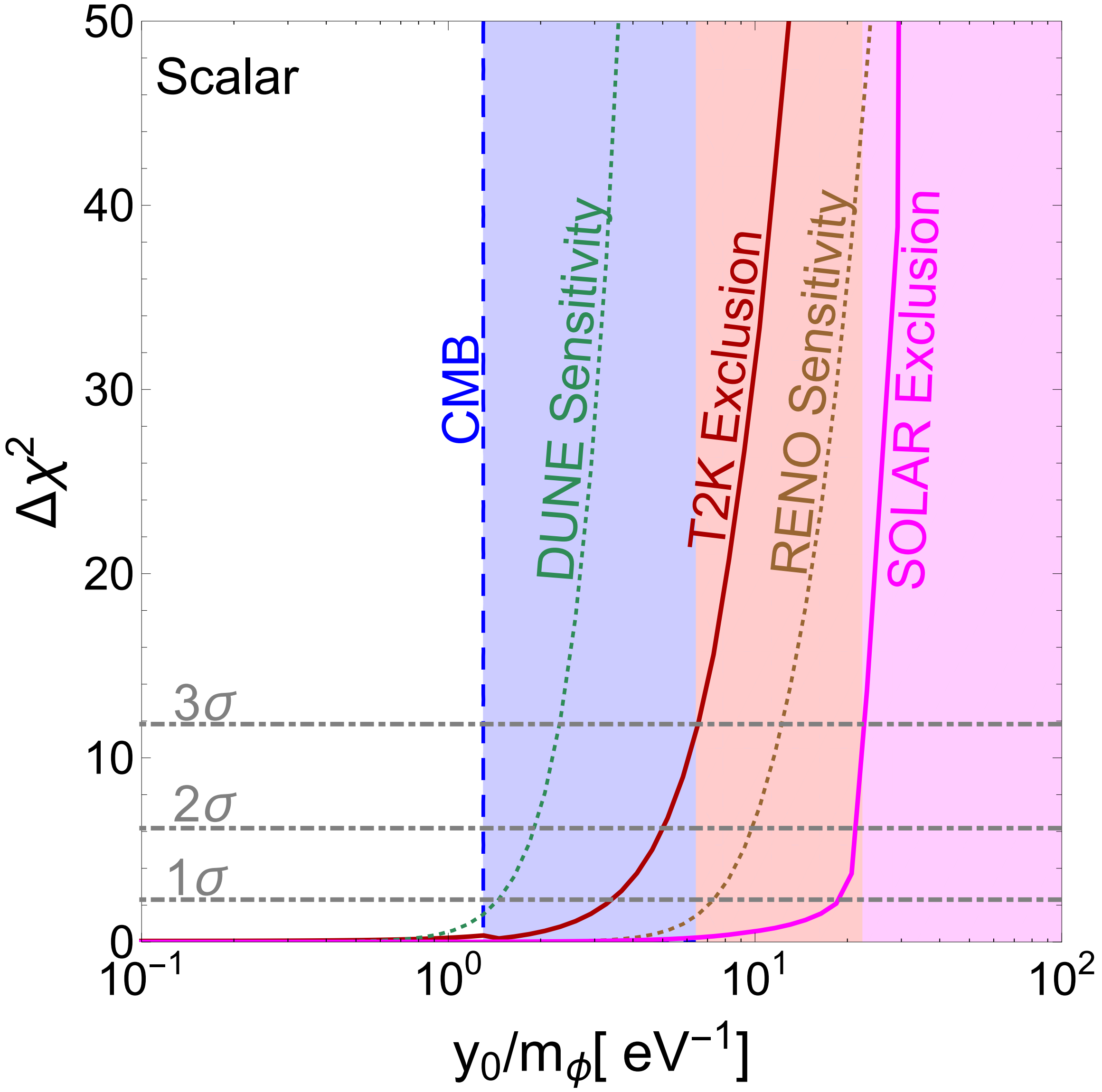


- Interaction assumption:

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

- CMB constraint on neutrino mass

$$\left.\begin{array}{l}\sum m_\nu < 0.23\text{ eV}\\ \Omega_\nu h^2 < 0.0025\end{array}\right\}\ 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}$$

- Complex y
- Pseudo-scalar: axion

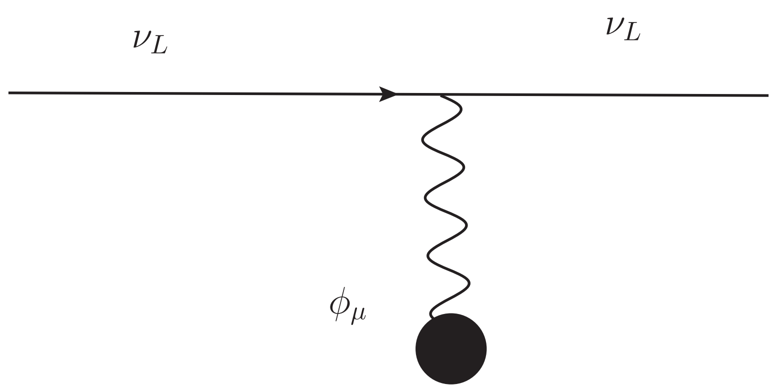
Vector DM case

$$V_{\rm eff} = -\frac{1}{2E_\nu}\Big(2(p_\nu \cdot \phi)gQ + g^2Q^2\phi^2\Big)$$

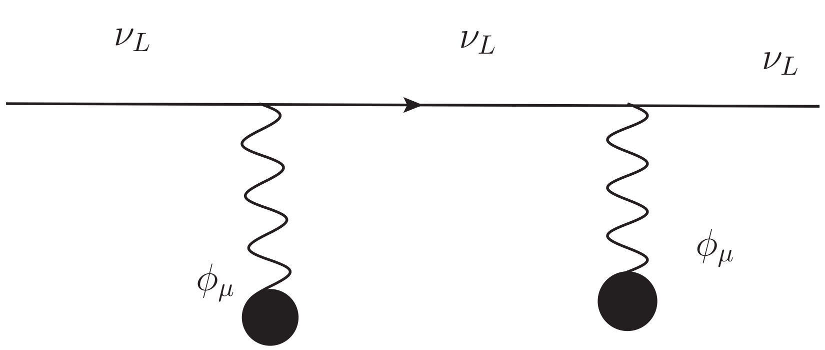
$$Q_{\mu-\tau} = 0, 1, -1$$

$$\phi_\mu = \xi_\mu \phi_0 \cos(m_\phi t)$$

- Linear term (classic): Only for fully polarized vector DM



- Quadratic term (classic = QFT forward scattering): both fully polarized or unpolarized



Vector DM case

$$V_{\text{eff}} = -\frac{1}{2E_\nu}\Big(2(p_\nu \cdot \phi) g Q + g^2 Q^2 \phi^2\Big)$$

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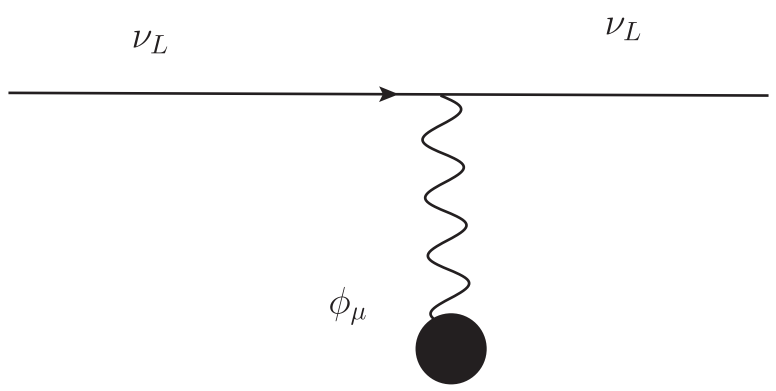

$$\phi_\mu = \xi_\mu \phi_0 \cos(m_\phi t)$$

$$E_\nu g \phi_0 \sim m_\nu^2$$

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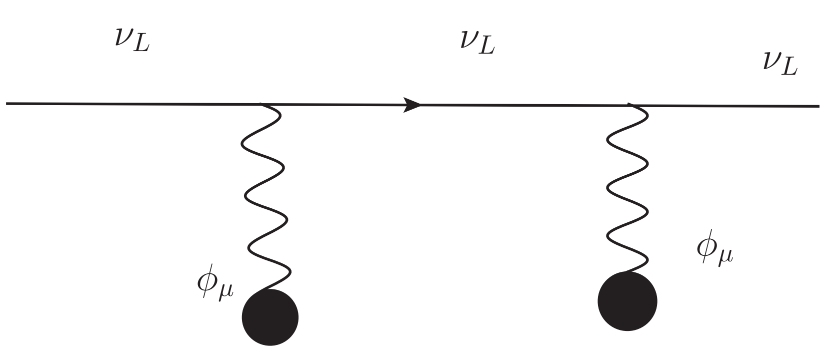

$$(g\phi_0)^2 \sim m_\nu^2$$

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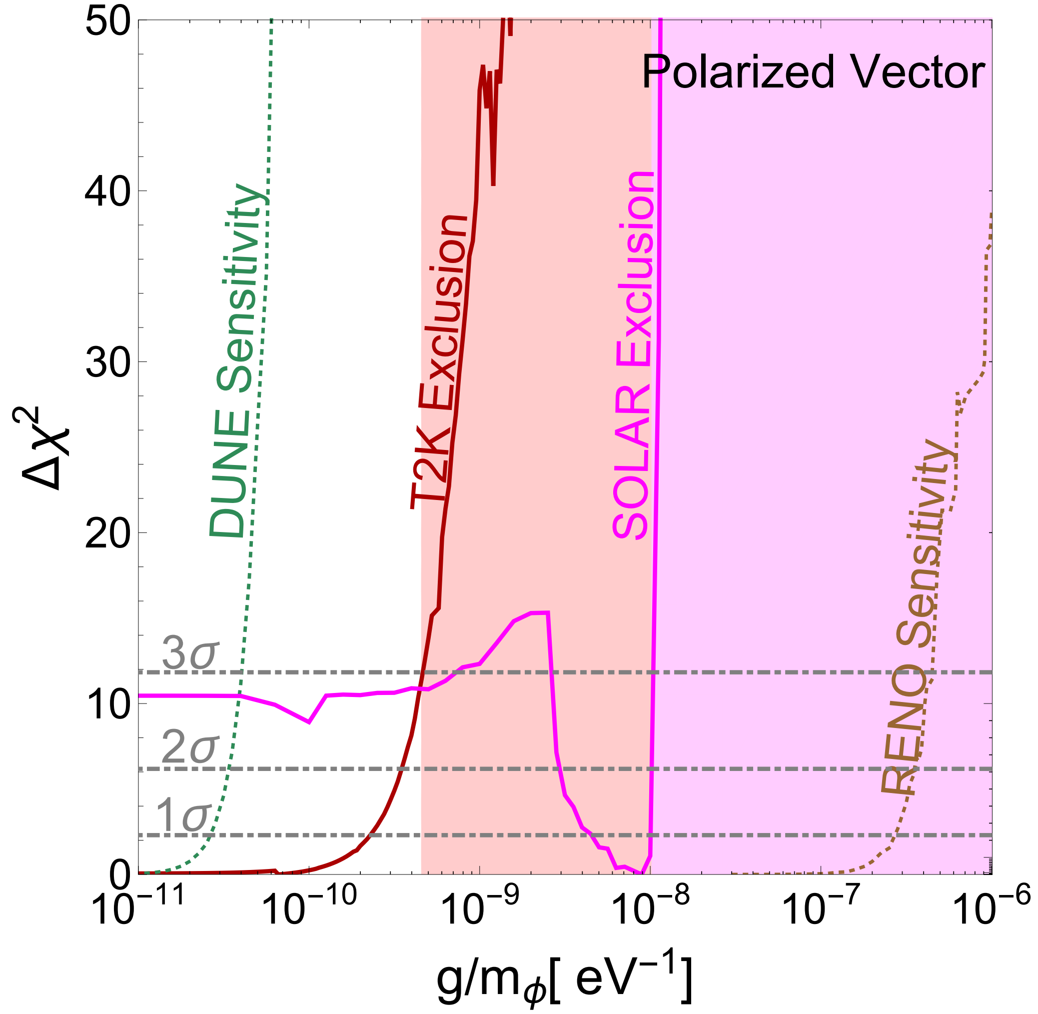
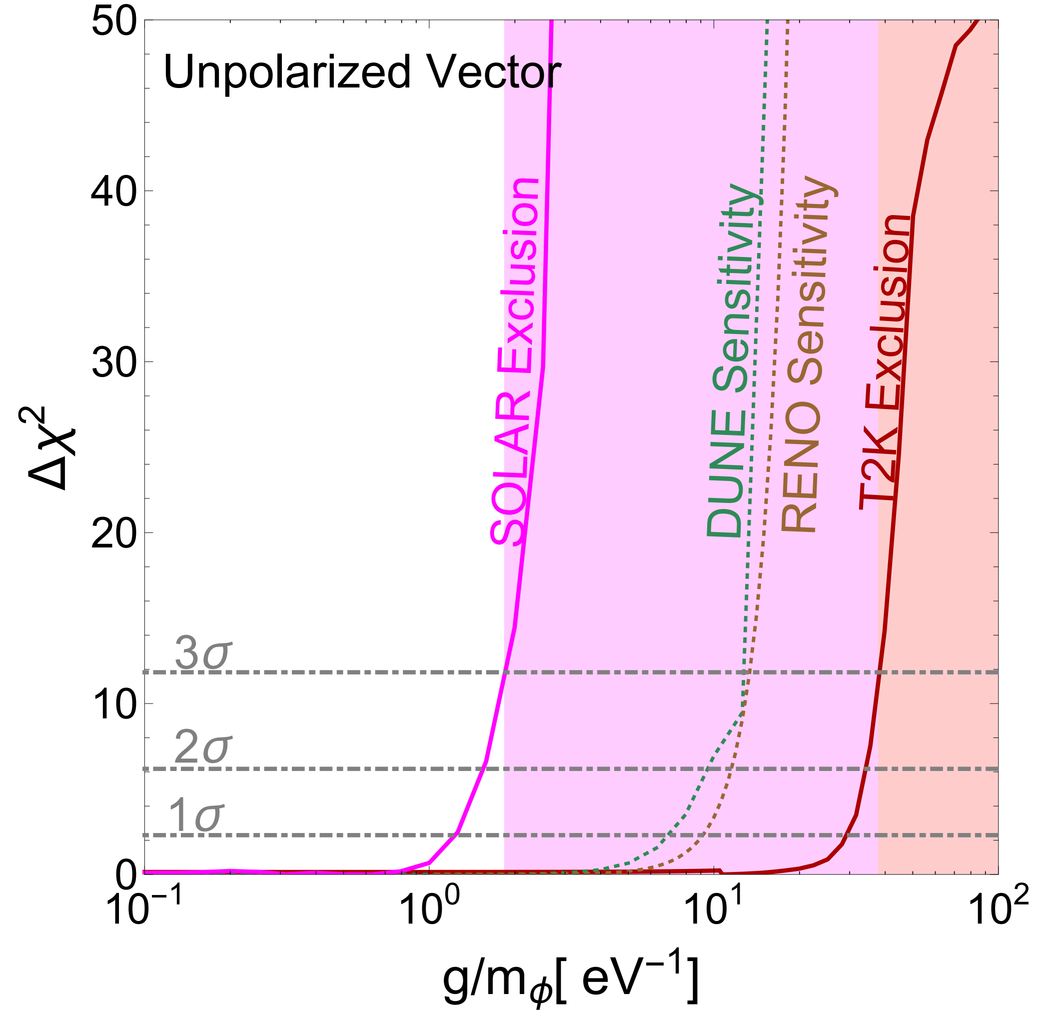
Vector DM case

$$V_{\text{eff}} = -\frac{1}{2E_\nu}\left(2(p_\nu \cdot \phi)gQ + g^2Q^2\phi^2\right)$$





- Some thoughts: m~10^-22 eV, g<10^-30!!!!

Ultralight DM Summary

- We introduce ultralight bosonic DM and non-standard interaction with neutrinos
- Stringent constraints from oscillation:
  - Scalar, unpolarized Vector: y/m <~ eV
  - Polarized Vector: y/m<~10^-10 eV
- Linear term apply when classic field description holds, #>>1 (m<10^-16 eV, if neutrino coherent length L ~ 10^-10m)
- Quadratic term always applies (QFT forward scattering), valid for any DM mass