Neutrino Non-Standard Interactions via Light Scalar

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Motivation

- The global neutrino oscillation program is now entering a new era, measurements being done with an ever-increasing accuracy.
- Sub-dominant effects in oscillation data are sensitive to the currently unknown parameters, namely the θ_{CP}, sign of Δm^2_{atm} and the octant of θ_{23}.
- Neutrino physics beyond the SM often comes with additional non-standard interactions (NSI).

Scalar NSI

- Consider the interaction of fermions f, ν with a light scalar ϕ, where Yukawa terms are of the form:

$$\mathcal{L}_{\text{Yukawa}}(\phi, f) = -y_{\alpha\beta}\bar{\nu}_\alpha \phi \nu_\beta - y_f \bar{f} \phi f$$

- For low-momentum transfer, we can write the effective lagrangian term as:

$$\mathcal{L}_{\text{eff}} \propto -\frac{y_f y_{\alpha\beta}}{m_\phi^2} \, \bar{\nu}_\alpha \nu_\beta \; \bar{f} f$$

- In a medium, this appears as a correction to the neutrino mass matrix.

Field theoretic origin

- The effect of matter on self-energy of a fermion can be calculated with the help of finite temperature Greens function for a free Dirac field.

$$S_f(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2 + i\epsilon} + i\Gamma(p)\right]$$

where,

$$\Gamma(p) = 2\pi\delta(p^2 - m^2)[n_f(p)\Theta(p_0) + n_{\bar{f}}(p)\Theta(-p_0)],$$

$$n_{f(\bar{f})} = \frac{1}{e^{(|p.u| \pm \mu)/T} + 1}, \qquad N_f = 2\int \frac{d^3p}{(2\pi)^3} n_f(p)$$

Field theoretic origin

- The relevant diagrams for mass correction to neutrino :

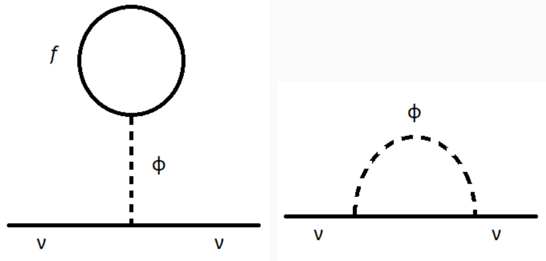


Figure 1: Neutrino self-energy corrections

- The mass correction at finite temperature and density evaluates to:

$$\Delta M^{\nu}_{\alpha\beta} = \frac{2m_f y_{\alpha\beta} y_f}{m_\phi^2} \int \frac{d^3p}{(2\pi)^3} \frac{n_f(p) + n_{\bar{f}}(p)}{E_p}$$

Field theoretic origin

- The form of sNSI expression for various domains :

$$\mathrm{M}^{\nu}_{\alpha\beta} : \begin{cases} \frac{y_f y_{\alpha\beta}}{m_\phi^2} N_f & \text{for Earth, Sun } (\mu, T < m_f) \\ \frac{y_{\alpha\beta} y_f}{m_\phi^2} \frac{m_f}{2} \left(\frac{3N_f}{\pi}\right)^{\frac{2}{3}} & \text{for Supernova } (\mu > m_f > T) \\ \frac{y_{\alpha\beta} y_f m_f}{6\, m_\phi^2} \left[\frac{\pi^2 (N_f + N_{\bar{f}})}{3\,\zeta(3)}\right]^{\frac{2}{3}} & \text{for Early Universe } (\mu < m_f < T) \end{cases}$$

- The result for Earth/Sun matches Ge and Parke, PRL ’19
- In this talk, we discuss constraints in the scenario with scalar coupling only to electron (y_e) and Dirac neutrinos (y_ν).

Finite Medium Effects

- A light scalar coupling to fermions can lead to long-range forces.
- Even when the neutrino propagates outside of the medium, such long-range forces can affect its propagation[1,2].

[1] Wise, Zhang JHEP 06 (2018)
[2] Smirnov, Xu JHEP 12 (2019)

Finite Medium Effects

- Our work presents generalized analytical results for finite medium effects extending to relativistic cases.

$$\Delta m_{\nu,\alpha\beta}(r) = \frac{y_f y_\nu}{m_\phi\, r}\left(e^{-m_\phi r}\int_0^r x\,\langle\bar{f}f\rangle\,\sinh\left(m_\phi\, x\right)dx + \sinh\left(m_\phi\, r\right)\int_r^\infty x\,\langle\bar{f}f\rangle\, e^{-m_\phi\, x}\,dx\right)$$

where,

$$\langle\bar{f}f\rangle = \frac{m_f}{\pi}\int_{m_f}^\infty dk_0\,\sqrt{k_0^2 - m_f^2}\left[n_f(k_0) + n_{\bar{f}}(k_0)\right].$$

- For a relativistic medium with constant electron background,

$$\Delta m_{\nu,\alpha\beta}(r) \; = \; \frac{y_\nu \, y_f m_f}{2 m_\phi \, r} \left(\frac{3 N_f(0)}{\pi} \right)^{\frac{2}{3}} \times \begin{cases} F_< & (r \leq R) \quad , \\ F_> & (r > R) \quad , \end{cases}$$

where

$$F_< \; = \; 1 - \frac{m_\phi R + 1}{m_\phi \, r} e^{-m_\phi \, R} \sinh\left(m_\phi \, r\right),$$

$$F_> \; = \; \frac{e^{-m_\phi \, r}}{m_\phi \, r} \left[m_\phi \, R \cosh\left(m_\phi \, R\right) - \sinh\left(m_\phi \, R\right) \right] .$$

Constraints on y_ν

- If at time of nucleosynthesis ($T \simeq 1$ MeV), ν and ϕ are still in equilibrium then they contribute $\Delta N_{eff} = 3 + \frac{4}{7}$, which is in tension with allowed $\Delta N_{eff}^{BBN} \simeq 0.5$.
- If they decoupled earlier say at QCD phase transition temperature (~ 200 MeV), it contributes less to ΔN_{eff} at BBN.
- This yields a strong limit of $y_\nu < 2.6 \times 10^{-10}$.

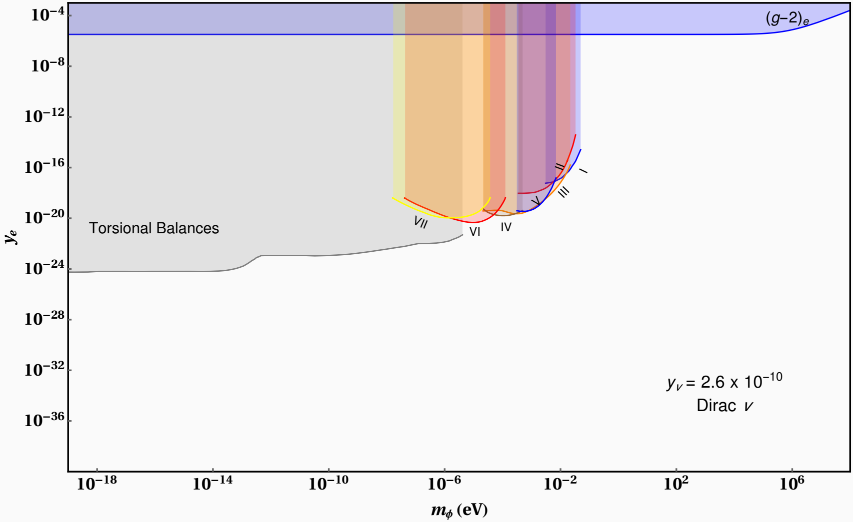
Experimental Constraints on y_e

- $(g-2)_e$: A scalar coupling to electron will contribute to the electron anomalous magnetic moment :

$$\Delta a_e = \frac{y_e^2}{8\pi^2}\int_0^1 dx \frac{(1-x)^2(1+x)}{(1-x)^2 + x(m_\phi/m_e)^2}$$

- Fifth Forces : A light scalar coupling to matter leading to a long range force appears as a violation of equivalence principle in experiments.

Experimental Constraints on y_e



Experimental Constraints on y_e

- Red Giants, HB Stars & SN1987A : The production of the light scalar ϕ in stellar bodies can lead to a new channel for energy loss leading to rapid cooling.
- These processes in red giants can delay their onset of helium ignition.
- It can change the helium-burning lifetime of the horizontal branch stars.

Experimental Constraints on y_e

- BBN : In early universe, the scalar mediator ϕ can be in thermal equilibrium with the SM through $(e^+e^- \to \gamma\phi)$ and $(e^-\gamma \to e^-\phi)$.
- The mediator thermalizes and decreases the deuterium abundance if

$$\langle \sigma v \rangle > H(T) \qquad \text{at } T = 1 \text{ MeV}$$

- This yields an upper bound of $y_e = 5 \times 10^{-10}$ for ultra-light scalar mediators.

Experimental Constraints on y_n

- Meson Decays : The scalar ϕ can be produced through decay of a charged Kaon and is constrained from the measurement of $K^+ \to \pi^+ +$ **Missing Energy**
- The production cross section for $K^+ \to \pi^+ + \phi$ is :

$$Br(K^+ \to \pi^+ \phi) = \frac{(3y_u G_F f_\pi f_K B)^2}{32\pi m_{K^+} \Gamma_{K^+}} |V_{ud} V_{us}|^2 \, \lambda^{1/2}(1, \frac{m_\phi^2}{m_{K^+}^2}, \frac{m_{\pi^+}^2}{m_{K^+}^2})$$

where, $B = \frac{m_\pi^2}{m_u + m_d}$
$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ac$

- Using nucleon scalar charges, $y_n \simeq 18.8\, y_u$

Quantum Mechanical Bound on m_ϕ

- Consider $\nu_\alpha - e$ elastic scattering, the uncertainty principle of quantum mechanics sets a lower limit on the minimum q^2.
- Recoil momentum of the electron is subject to the uncertainty relation. Its position is not precisely known inside the atom, so we have

$$\Delta p \, \Delta x \sim \hbar$$

- Using $\Delta x = 140 \times 10^{-8}$ cm, the radius of ^{26}Fe – most of Earth's matter, one obtains for the uncertainty in q^2 to be

$$q^2 \approx (14.14 \text{ eV})^2$$

Experimental Limit on Max. Scalar NSI

- Sun : The χ^2-analysis of the Borexino data sets a 3σ upper bound on the scalar NSI in Sun[3] :

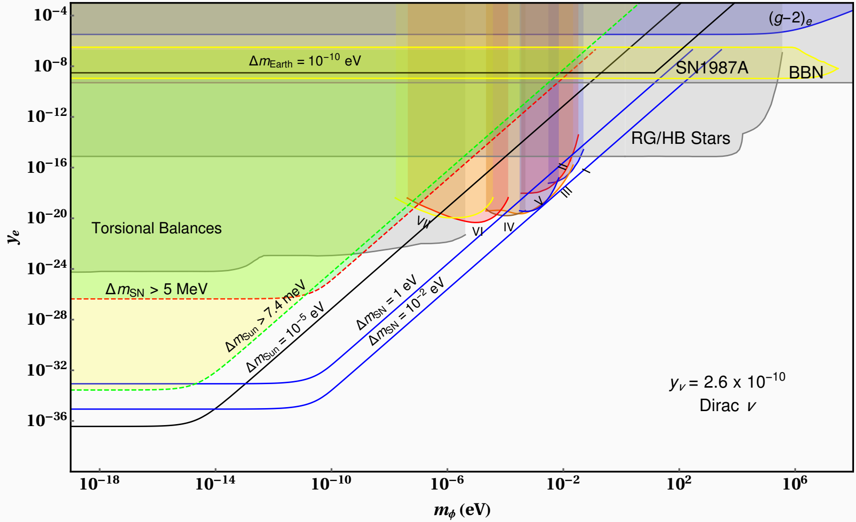
$$\Delta m_{\text{Sun}} = 7.4 \times 10^{-3}\ \text{eV}$$

- Supernova : If Δm_{SN} becomes too large, then neutrino production will be affected, in direct conflict with observations from SN1987A [4]. For typical core temperature around $T = 30MeV$, we constrain :

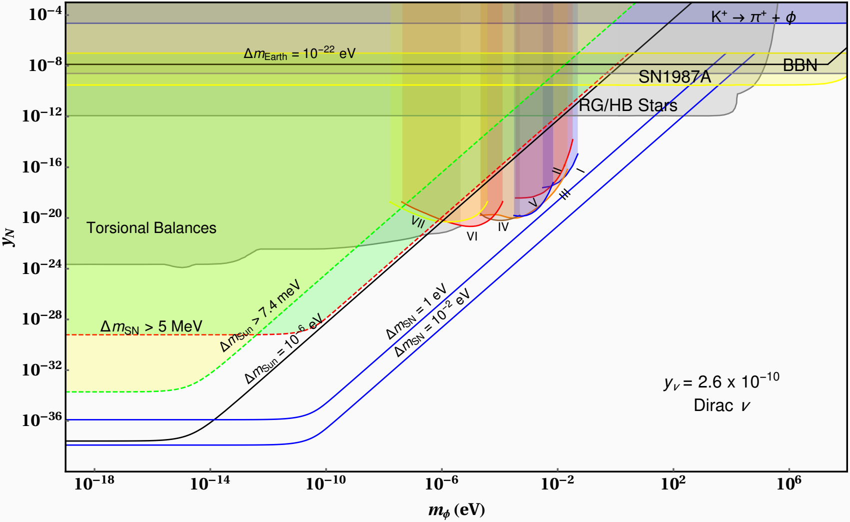
$$\Delta m_{\text{SN}} < 5\ \text{MeV}$$

[3] Ge and Parke, PRL 122 (2019)
[4] Smirnov, Xu JHEP 12 (2019)

Scalar NSI : Electron



Scalar NSI : Nucleon



Conclusion

- Neutrino NSI with matter mediated by a light scalar induces medium-dependent neutrino masses.
- A general field-theoretic derivation of the scalar NSI is presented, which is valid at arbitrary temperature and density environments.
- We extended the analysis of long-range force effects for all background media, including both relativistic and non-relativistic limits.
- Observable scalar NSI effects, although precluded in terrestrial experiments, are still possible in future solar and supernovae neutrino data.

Thank you ! Questions ?

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