Solar Neutrinos as a Probe of Dark Matter-Neutrino Interactions

based on arXiv:1702.08464, with I. Shoemaker and L. Vecchi

FRANCESCO CAPOZZI
2.3 Distinct diagrams

A Feynman diagram represents all possible time orderings of the possible vertices, so the positions of the vertices within the graph are arbitrary. Consider the following two diagrams for $e^+ e^- \rightarrow \mu^+ \mu^- + X$:

In the left diagram it appears that the incoming particles annihilated to form a virtual photon, which then split to produce the outgoing particles. On the right diagram it appears that the muons and the photon appeared out of the vacuum together, and that the photon subsequently collided with the electron and positron, leaving nothing. Changing the position of the internal vertices does not affect the Feynman diagram – it still represents the same contribution to the amplitude. The left side and right side just represent different time-orderings, so each is just a different way of writing the same Feynman diagram.

On the other hand, changing the way in which the lines in a diagram are connected to one another does however result in a new diagram. Consider for example the process $e^+ e^- \rightarrow \gamma + X$.

In the two diagrams above the outgoing photons have been swapped. There is no way to move around the vertices in the second diagram so that it is the same as the first. The two diagrams therefore provide separate contributions to $M_{\text{final}}$, and must be added.
Almost all data from neutrino oscillation can be explained in a $3\nu$ framework. There are however a few anomalies observed at very short baseline:

- **LSND anomaly**
- **GALLIUM anomaly**
  \[
  \Delta m^2_{\text{SBL}} \sim 1 \text{ eV}^2
  \]
- **REACTOR anomaly**
  \[
  \sin^2\theta \sim 0.01
  \]
**Motivation: $\nu_s$ secret interactions**

$\nu_s$ secret interactions may reconcile SBL anomalies with Cosmology

- J. F. Cherry, A. Friedland and I. M. Shoemaker, 1411.1071.
- J. F. Cherry, A. Friedland and I. M. Shoemaker, 1605.06506.

**$\nu$ - DM interaction may solve the “missing satellite” problem**

Constraints

- Possibility that active-sterile oscillations turned on after CMB: no constraint from BBN or CMB.
  (L. Vecchi Phys. Rev. D 94 (2016) no.11, 113015)

- UHEν interaction with CNB converts νa to νs, depleting νa from distant sources: constraints from the isotropy observed by IceCube events.
  (J. F. Cherry, A. Friedland and I. Shoemaker, arXiv:1411.1071)

- ν-DM interaction introduces a cutoff in the matter power spectrum: constraints from Lyman-α (M_{cut} < 5 \times 10^{10} M_☉).

- DM-DM interaction modifies halo ellipticity, cluster mergers, as well as the mass profile of dwarf galaxies.
Constraints

$m_x = 5$ GeV

mediator mass, $m_A$ [eV]

gauge coupling, $g_A$

Solar Dark MSW (this work)
IceCube
SN1987A
Lyman – $\alpha$
DM halo ellipticity
Possible signature: solar neutrinos

DM clusters in the core of the Sun. DM-$\nu_s$ interaction creates a new matter potential which alters the expected number of $\nu_e$ observed on Earth.
Neglecting DM annihilation (asymmetric DM), evaporation ($M_X > 4$ GeV), and self-interactions, the equation describing DM clustering in the Sun is $N_X(t) = C t$:

\[ N_X / N_e \sim 10^{-21} \left( \frac{\sigma n_X}{10^{-45} \text{cm}^2} \right) \]

for spin-independent cross-section

After thermalization:

\[ n_X(r) = \frac{N_X}{r_X^3 \pi^{3/2}} e^{-r^2/r_X^2} \]

\[ r_X(r) = \sqrt{\frac{3T_\odot}{2\pi G_N \rho_\odot m_X}} \sim 0.05 \sqrt{\frac{5 \text{GeV}}{m_X}} R_\odot \]
DM in the Sun

$\rho(r)$

$r/R_{\text{sun}}$

DM, $m_X = 15$ GeV
DM, $m_X = 5$ GeV

Francesco Capozzi - The Ohio State University
New matter potential

The coherent scattering of active neutrinos, via oscillations into $\nu_s$, is affected by DM. In the limit of zero average velocity of the DM: $\langle \bar{X} \gamma^\mu X \rangle = n_X \delta^{\mu 0}$ and

$$V_{\text{eff}} = \epsilon_s \epsilon_X \frac{g_A^2}{\partial^2 + m_A^2} n_X.$$

If $m_A > 10^{-14}\text{ eV} \sqrt{m_X/5\text{ GeV}}$ the gradient of $n_X$ can be neglected (contact interaction)

$$V_{\text{eff}} \simeq G_X n_X = \sqrt{2}\xi G_F n_e(0) e^{-r^2/r_X^2}$$

$$G_X = \epsilon_s \epsilon_X \frac{g_A^2}{m_A^2}$$

$$\xi \equiv \frac{G_X n_X(0)}{\sqrt{2} G_F n_e(0)}$$

In this range of $m_A$, we can have $G_X \gg G_F$ in order to compensate small $n_X$ ($\xi > 1$)
Neutrino oscillations: analytic approach

Assuming $\sin^2 \theta_{i4} V_s < \Delta m^2_{31}$, we have:

$$P_{ee, \text{day}} = c_{13}^4 c_{14}^4 \frac{1}{2} \left( 1 + \cos 2\theta_{12} \cos 2\theta_m \right)$$

$$+ s_{13}^4 c_{14}^4 + s_{14}^4 + \mathcal{O} \left( s_{i4}^2 V_s E / \Delta m^2_{31} \right)$$

$$\cos 2\theta_m = \frac{\Delta \cos 2\theta_{12} - V_x}{\sqrt{ \left| \Delta \sin 2\theta_{12} + V_y \right|^2 + \left( \Delta \cos 2\theta_{12} - V_x \right)^2}}$$
Constraints from solar neutrinos

We consider data on $^8B$ (SNO only), $^7Be$ and pep neutrinos. pp neutrinos are almost unaffected by $V_s$. $m_X$ is fixed to 5 GeV.

Presence of a Dark-LMA solution ($\theta_{12}>\pi/4$), as obtained by non-standard interactions (NSI)
Constraints from solar neutrinos

We vary $\theta_{14}$ and $\xi$, while $\theta_{24} = \theta_{34} = 0$. Solar parameters ($\Delta m^2_{21}, \theta_{12}$) held fixed to current global best fit.

Too large $\theta_{14}$ suppresses Pee.

$|\xi| \sin^2 \theta_{14} < O(10)$
Constraints from solar neutrinos

We vary $\theta_{14}$ and $\xi$, $\theta_{24}$ is fixed at SBL anomaly, while $\theta_{34} = 0$. Solar parameters $(\Delta m^2_{21}, \theta_{12})$ held fixed to current global best fit.

For large $|\xi|$ there are regions of the parameter space where $P_{ee}$ change abruptly.
Constraints from solar neutrinos

\[ \overline{P}_{ee}(E) = \int dr \, P_{ee,\text{day}}(r, E) \frac{\sum_i \phi_i(E) \rho_i(r)}{\sum_i \phi_i(E)} \]

\[ (\xi, \sin^2 \theta_{14}) = (70, 0.03) \]

\[ (\xi, \sin^2 \theta_{14}) = (-300, 0.004) \]
Conclusions

- The **Sun might be a probe of neutrino-DM interactions**

- For sufficiently light exotic sectors, $G_x/G_F$ **can be extremely large** and compensate the possibly small density of the DM

- It is mostly the physics of $^8\text{B}$, $^7\text{Be}$, and CNO **neutrinos** that is modified

- $|\xi| \sin^2 \theta_{14} < O(10)$

- Similarly to NSI, a **Dark-LMA solution** is mildly favored for $\xi < 0$

- Our framework **generalizes the more conventional neutrino-NSI**
Thank you
Backup
Model Lagrangian

\[\mathcal{L} \supset \bar{\nu}_s i \partial \nu_s + g_A A'_\mu J^\mu + y_s \bar{N} \phi \nu_s + y_a \bar{N} H L + \frac{m_N}{2} \bar{N} N^c + \text{hc.}\]

\[J^\mu = \epsilon_s \bar{\nu}_s \gamma^\mu \nu_s + \epsilon_X \bar{X} \gamma^\mu X\]

We assume \(\phi\) acquires a vacuum expectation value which generates a mass \(m_A\) for \(A'_\mu\), as well as a \(N, \nu_s\) mixing. Electroweak symmetry breaking the second line induces a mixing between active neutrinos and \(N\).

\[\sin^2 \theta \sim \min \left( \frac{y_a \langle H \rangle}{y_s \langle \phi \rangle}, \frac{y_s \langle \phi \rangle}{y_a \langle H \rangle} \right)\]
Constraints

- **UHEν interaction with CNB converts ν_a to ν_s**: constraints from the isotropy observed by IceCube events.

  (J. F. Cherry, A. Friedland and I. Shoemaker, arXiv:1411.1071)

The MFP of high-energy neutrinos as they scatter on the CNB cannot be too short, as most of the flux originating at cosmological distances would not reach us.

Even if one boosts the flux emitted by the nearby sources by a large factor, the observed flux would look highly anisotropic.

(J. F. Cherry, A. Friedland and I. M. Shoemaker, 1411.1071)
Constraints

- $\nu_s$-DM or DM-DM interaction introduces a cutoff in the matter power spectrum: constraints from Lyman-$\alpha$ ($M_{\text{cut}} < 5 \times 10^{10} \, M_{\odot}$).


Structure cannot grow as long as the momentum-transfer rate exceeds the Hubble rate. We compute the momentum-transfer rate via

$$\gamma(T) = \sum_i \frac{g_i}{6m_X T} \int_0^\infty \frac{d^3p}{(2\pi)^3} f_i (1 \pm f_i) \frac{p}{\sqrt{p^2 + m_i^2}} \int_{-4p^2}^0 dt(-t) \frac{d\sigma_{X+i \rightarrow X+i}}{dt}$$


The kinetic decoupling temperature is obtained by solving when the momentum transfer rate drops below the Hubble rate:

$$\gamma(T_{\text{KD}}) = H(T_{\text{KD}})$$

The mass of the largest gravitationally bound objects (i.e. the proto-halos) that can form causally is dictated by the mass enclosed in a Hubble volume at $T_{\text{KD}}$. We require $M < M(\text{Lyman-}\alpha)=5\times10^{10} \, M_{\odot}$, which corresponds to $T_{\text{KD}} > 0.15 \, \text{KeV}$.
Neutrino oscillations

\[ H = \frac{1}{2E} U \begin{pmatrix} 0 & \Delta m_{21}^2 \\ \Delta m_{31}^2 & \Delta m_{41}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{CC} & 0 \\ 0 & 0 & V_s \end{pmatrix}, \quad V_s = V_{\text{eff}} - V_{\text{NC}} \]

\[ V_{\text{eff}} = \sqrt{2} \xi G_F n_e(0) e^{-r^2/r_X^2} \]

\[ \xi \equiv \frac{G_X n_X(0)}{\sqrt{2}G_F n_e(0)} \]

\[ U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12} \]
Numerical analysis details

\[ \chi^2(p) = \chi^2_{\text{SNO}}(p) + \chi^2_{\text{Be7}}(p) + \chi^2_{\text{pep}}(p) \]

\[ \langle P_{ee}^i(p, E) \rangle \equiv \int dr \rho_i(r) P_{ee}(p, r, E) \]

\[ \chi^2_{\text{Be7}}(p) = \left( \frac{\langle P_{ee}^{7\text{Be}}(p, 862 \text{ keV}) \rangle - 0.51}{0.07} \right)^2 \]

\[ \chi^2_{\text{pep}}(p) = \left( \frac{\langle P_{ee}^{\text{pep}}(p, 1440 \text{ keV}) \rangle - 0.62}{0.17} \right)^2 , \]
Numerical analysis details

\[ \chi^2(p) = \chi^2_{SNO}(p) + \chi^2_{Be7}(p) + \chi^2_{pep}(p) \]

\[ \langle P_{ee}^i(p, E) \rangle \equiv \int dr \rho_i(r) P_{ee}(p, r, E) \quad \langle P_{ee}^{SNO}(p, E) \rangle = \frac{\langle P^{8B}_{ee}(p, E) \rangle}{1 - \langle P^{8B}_{es}(p, E) \rangle} \]

\[ A(p, E) = 2 \frac{\langle P^{8B}_{ee,\text{night}}(p, E) \rangle - \langle P^{8B}_{ee,\text{day}}(p, E) \rangle}{\langle P^{8B}_{ee,\text{night}}(p, E) \rangle + \langle P^{8B}_{ee,\text{day}}(p, E) \rangle} . \]

\[ \chi^2_{SNO}(p) = \min_\Phi \left\{ \sum_{i,j=0}^5 [a_i(p) - a_i^{SNO}] \Sigma_{ij}^{-1} [a_j(p) - a_j^{SNO}] + \chi^2_{SSM}(\Phi) \right\} \]

\(a_1, a_2, a_3\) derive from a quadratic fit of \(P_{ee}(\text{day})\).

\(a_4, a_5\), derive from a linear fit of \(A\).

\(a_0\) is the total \(^8\text{B}\) flux \(\Phi\).

\(\Sigma\) is a correlation matrix given by the SNO collaboration
Neutrino oscillations: analytic approach

Assuming $\sin^2 \theta_{i4} V_s < \Delta m^2_{31}$, we have:

$$P_{ee, \text{day}} = c_{13}^4 c_{14}^4 \frac{1}{2} (1 + \cos 2\theta_{12} \cos 2\theta_m) + s_{13}^4 c_{14}^4 + s_{14}^4 + \mathcal{O}(s_{i4}^2 V_s E/\Delta m^2_{31})$$

$$\cos 2\theta_m = \frac{\Delta \cos 2\theta_{12} - V_x}{\sqrt{\Delta \sin 2\theta_{12} + V_y}^2 + (\Delta \cos 2\theta_{12} - V_x)^2}$$

$$V_x = \frac{1}{2} \left[ V_{CC} c_{13}^2 c_{14}^2 + V_s (|A|^2 - |B|^2) \right]$$

$$V_y = V_s A B$$

$$A = e^{-i\delta_{14}} c_{13} c_{24} c_{34} s_{14} - e^{-i\delta_{13}} s_{13} \left( c_{34} s_{23} s_{24} + e^{-i\delta_{34}} c_{23} s_{34} \right)$$

$$B = c_{23} c_{34} s_{24} - e^{i\delta_{34}} s_{23} s_{34}$$
Constraints from solar neutrinos
Comparison with NSI

\[ H_{\text{NSI}} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} e_{ee}^f & e_{e\mu}^f & e_{e\tau}^f \\ e_{\mu e}^f & e_{\mu\mu}^f & e_{\mu\tau}^f \\ e_{\tau e}^f & e_{\tau\mu}^f & e_{\tau\tau}^f \end{pmatrix} \]

In our model, in the limit \( \sin \theta \rightarrow 0 \) and \( \sin \theta \xi \) held fixed, oscillations are described by the standard 3x3 Hamiltonian, plus:

\[ H_{\text{new}}^{ij} = V_s(R_{34} R_{24} R_{14})_{4i}^* (R_{34} R_{24} R_{14})_{4j} \rightarrow \sqrt{2} \xi G_F n_e(0) e^{-r^2/r_x^2} \theta_i \theta_j \]

The potential \( H_{\text{new}} \) has the same appearance of NSI, provided we identify

\[ \sqrt{2} \xi G_F n_e(0) e^{-r^2/r_x^2} \theta_i \theta_j = V_{CC} \varepsilon_{ij} \]
Constraints from solar neutrinos

\[
\bar{P}_{ee}(E) = \int dr \, P_{ee,\text{day}}(r, E) \frac{\sum_i \phi_i(E) \rho_i(r)}{\sum_i \phi_i(E)}
\]

\[P_{ee} \sim \cos^2 \theta_{12}\]

\[|\Delta \sin 2\theta_{12} + V_y| \ll |\Delta \cos 2\theta_{12} - V_x|\]