Solar neutrinos and future experiments

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Reference

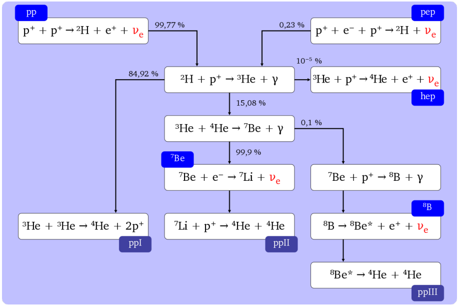
- P. Bakhti and M. Rajaee, S. Seo, S. Shin, “ Exploring Solar Neutrino at Yemilab and JUNO”, will be on arxiv soon.
- P. Bakhti and A. Y. Smirnov, “Oscillation tomography of the Earth with solar neutrinos and future experiments,” arXiv:2001.08030 [hep-ph], Phys. Rev. D **101** (2020) no.12, 123031.
- P. Bakhti and M. Rajaee, “Sensitivities of future solar neutrino observatories to nonstandard neutrino interactions,” Phys. Rev. D **102** (2020) no.3, 035024 [arXiv:2003.12984 [hep-ph]].

Overview

1. Solar Neutrino production
2. Flavour change of the Solar Neutrinos
3. Future solar neutrino experiments
4. Day-night asymetry Earth tomography
5. NSI and Solar Neutrinos
6. Summary and Conclusion

Solar Neutrino Production

- The Sun produces a large number of neutrinos through nuclear fusion reactions in its core, which are emitted into space and can be detected on Earth.
- The primary fusion process in the Sun is the proton-proton (pp) chain, which provides 98.4% of the energy generation. The remaining 1.6% is produced by the CNO cycle.



pp

$p^+ + p^+ \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

99,77 %

0,23 %

$p^+ + e^- + p^+ \rightarrow {}^2\mathrm{H} + \nu_e$

pep

84,92 %

${}^2\mathrm{H} + p^+ \rightarrow {}^3\mathrm{He} + \gamma$

10^{-5} %

${}^3\mathrm{He} + p^+ \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

hep

15,08 %

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

0,1 %

99,9 %

${}^7\mathrm{Be}$

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p^+ \rightarrow {}^8\mathrm{B} + \gamma$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p^+$

ppI

${}^7\mathrm{Li} + p^+ \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

ppII

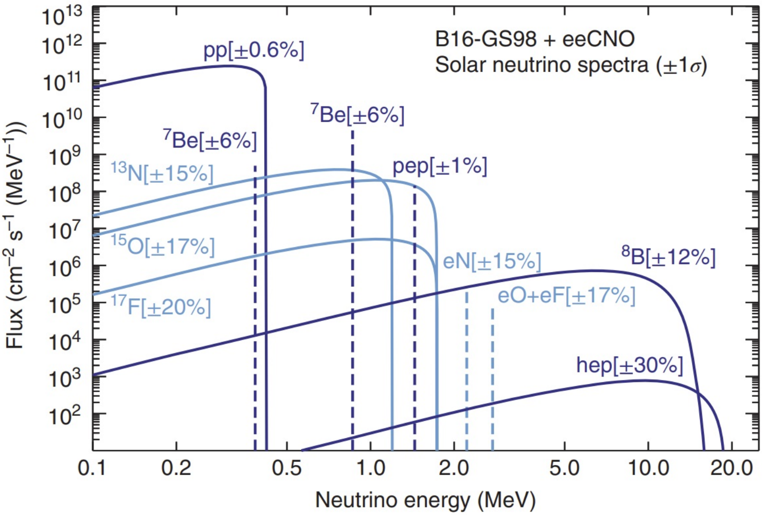
${}^8\mathrm{B}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

${}^8\mathrm{Be}^* \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

ppIII

Solar Neutrino production



Neutrino Oscillation in Matter

- Neutrino oscillations are affected by matter interactions, which introduce a potential term in the Hamiltonian

$$\mathcal{H}_f = \mathcal{H}_{vac} + \mathcal{H}_{mat} \tag{1}$$

$$\mathcal{H}_{mat} = \sqrt{2} G_F N_e diag(1,0,0) \tag{2}$$

$$\mathcal{H}_{vac} = U_{\mathrm{PMNS}} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^\dagger_{\mathrm{PMNS}} \tag{3}$$

- In the two-flavor approximation, the flavor evolution of neutrinos in matter is governed by the Schrödinger-like equation:

$$i\frac{d}{dx}\psi_\alpha = \mathcal{H}_f \psi_\alpha \tag{4}$$

Neutrino Oscillation in Matter

- The effective parameters are given by:

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \tag{5}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \tag{6}$$

$$A_{CC}^R = \Delta m^2 \cos 2\theta, \qquad N_e^R = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} E G_F} \tag{7}$$

- In the case of anti-neutrino $V_{CC} \to -V_{CC}$ $(A_{CC} = 2EV_{CC})$
- Since $A_{CC} > 0$ for the neutrinos, for $\Delta m^2 > 0$ the resonance condition is fulfilled. For anti-neutrinos, since $A_{CC} < 0$ the resonance condition is fulfilled with $\Delta m^2 < 0$.

Solar Neutrinos on Earth

- Due to the loss of propagation coherence, the solar neutrinos arrive at the surface of the Earth as independent fluxes of the mass eigenstates.

$$P_{ee} = \sum_k |U^m_{ek}(n_i) U^{m\dagger}_{ek}(n_f) e^{-i\phi_k}|^2 = \sum_k |U^m_{ek}(n^0_e)|^2 P^E_{ek} \qquad (8)$$

  where $|U^m_{e1}| = \cos\theta^m_{13}\cos\theta^m_{12}$, $|U^m_{e2}| = \cos\theta^m_{13}\sin\theta^m_{12}$, and $|U^m_{e3}| = \sin\theta^m_{13}$.
- For the three-flavor mixing case, $P_{3e} \approx s^2_{13}$ and $P_{1e} + P_{2e} = 1 - s^2_{13}$.

Day-Night Asymmetry

- Inside the Earth, the neutrino mass eigenstates oscillate in a multilayer medium with smoothly changing density within layers which leads to the regeneration factor

$$f_{\text{reg}} = |U_{e1}^{m}|^2 - P_{1e}^{E} = \frac{1}{2} c_{13}^4 \sin^2 2\theta_{12} \int_0^L dx V(x) \sin \phi^m \tag{9}$$

  where ϕ^m is the matter potential phase and L is the total distance traveled by the neutrinos inside the Earth.

- During a night the probability equals $P_N = P_D \pm \Delta P$, where the difference of the night and day probabilities is

$$\Delta P(E) = \kappa(E) \left[\int_0^L dx \;\, V(x) \sin \phi^m(L - x, E) + I_2 \right]. \tag{10}$$

  where $\kappa(E) \equiv -\frac{1}{2} c_{13}^6 \cos 2\bar{\theta}_{12}^{\odot}(E) \sin^2 2\theta_{12} \approx 0.5$

Day-Night Asymmetry

- The correction of the order of ϵ^2 to the probability of neutrino oscillation in the Earth is I_2, which has an order of 0.01%

$$I_2 \equiv \frac{1}{2}\cos 2\theta_{12}\left[\int_0^L dx\ V(x)\cos\phi^m(L-x,E)\right]^2 \tag{11}$$

- ϕ^m is the adiabatic phase acquired by the neutrino from a given point of trajectory x to a detector at L

$$\phi^m(L-x,E) \equiv \int_x^L dx\ \Delta_{21}^m(x), \tag{12}$$

where

$$\Delta_{21}^m = \Delta_{21}\sqrt{(\cos 2\theta_{21} - c_{13}^2\epsilon)^2 + \sin^2 2\theta_{21}} \tag{13}$$

Day-Night Asymmetry

- The day-night asymmetry is a function of the nadir angle η

$$A_{ND}(\eta, \Delta E) \equiv \frac{\Delta N(\eta, \Delta E)}{N_D(\Delta E)}, \Delta N \equiv N_N - N_D \tag{14}$$

- $\Delta N(E^r)$ is the difference in the number of events observed during the day and night at a given reconstructed neutrino energy E^r

$$\Delta N(E^r) = D \int dE \; g_\nu(E^r, E)\sigma(E)\Phi(E)\Delta P(E) \tag{15}$$

$$\Delta N(E^r) = D \int_0^L dx V(x) \int_0^{E^{max}} dE \; G_\nu(E^r, E) \sin \phi^m(L - x, E) \tag{16}$$

- D is the factor that includes characteristics of the detection, such as the fiducial volume, exposure time, and others.

Attenuation Effect

- Introducing the attenuation factor

$$\int dE G_\nu(E^r, E) \sin\phi^m(L-x, E) = F(L-x) \sin\phi^m(L-x, E^r) \qquad (17)$$

For the Gaussian form of $G_\nu(E^r, E)$, the attenuation factor is given by

$$F(L-x) \simeq e^{-2\left(\frac{L-x}{\lambda_{att}}\right)^2} \qquad (18)$$

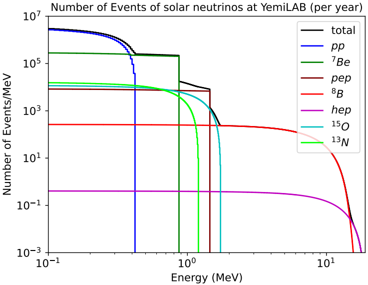
$$\lambda_{att} \equiv l_\nu \frac{E}{\pi\sigma_E} \qquad l_\nu = \frac{4\pi E}{\Delta m^2_{21}}$$

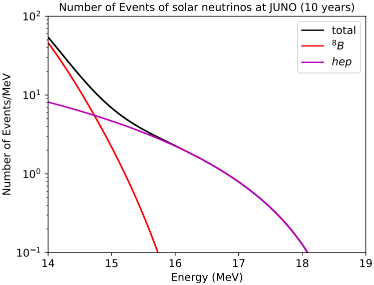
For $L-x \gg \lambda_{att}$, the attenuation factor $F(L-x) \approx 0$, a detector with the energy resolution ΔE is not sensitive to remote structures

Future studies of solar neutrinos

- Yemilab (Jinping): 2 kt scintillation detector for ν_e scattering, with high energy resolution (5%) and low-energy threshold (0.1 MeV) to detect low-energy neutrinos with good precision.
- Reactor experiment JUNO will determine Δm^2_{21} and θ_{12} with sub-percent precision, while also detecting ^{8}B, ^{7}Be, and *hep* neutrinos with good energy resolution.
- SNO+: 780 t of liquid scintillator fiducial mass, with an energy threshold of 3 MeV. The upgraded version will have lower threshold.
- DUNE: 40 kton liquid argon detector with a 10 MeV energy threshold, aiming to study not only solar neutrinos but also neutrinos from supernovae and atmospheric neutrinos.
- Hyper-Kamiokande (KNO): energy threshold of 6.5 MeV, with several 100 kt detectors planned, offering unprecedented sensitivity to solar neutrinos.
- THEIA: water-based liquid scintillator with 1% doping by ^{7}Li, allowing for low-energy threshold and good background rejection.

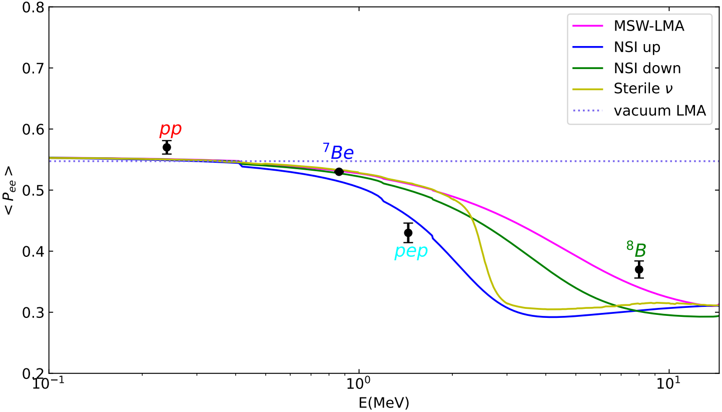
Number of events of the solar neutrinos at Yemilab and JUNO





- The number of events per MeV as a function of the kinetic energy of the electron at YemiLAB and JUNO
- We expect six events of hep neutrinos and one event of ^8B neutrinos at energies larger than 14.8 MeV after ten years of data taking at JUNO.

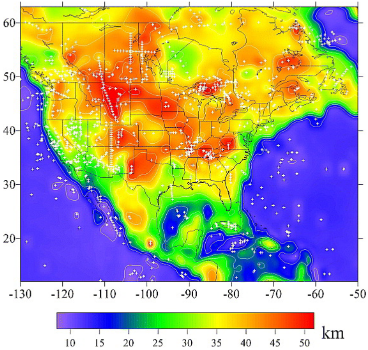
NSI and Sterile neutrinos at YemiLAB

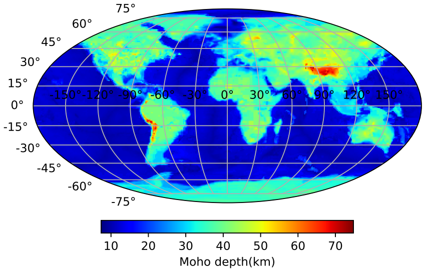


Earth Structure and Solar Neutrinos

- Solar neutrinos can be used to probe the Earth's structure through the Day-Night assymetry, A_{ND}, due to attenuation effect mainly depends on shallow density structures such as the crust, upper mantle, and the crust-mantle border Moho discontinuity.
- The Earth's crust can be divided into two types: the oceanic crust (5-10 km) and the continental crust (20-90 km).
- Models of Earth's structure:
  - Shen-Ritzwoller model: crust and uppermost mantle beneath North America, latitudes $(20^\circ - 50^\circ)$ and longitudes $(235^\circ - 295^\circ)$.
  - FWEA18: Full Waveform Inversion of East Asia model, latitudes $10^\circ - 60^\circ$, longitudes $90^\circ - 150^\circ$, depth up to 800 km.
  - SAW642AN: global model, from Moho depth down to 2900 km.
  - CRUST1: global model, from Earth's surface down to the Moho.

Shen-Ritzwoller and CRUST1 Moho depth

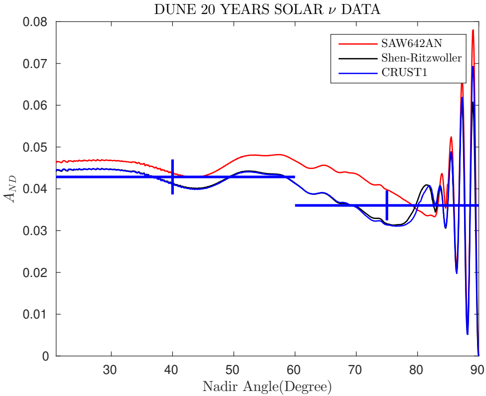




In Preliminary Reference Earth Model (PREM) the Moho depth is 24 km.

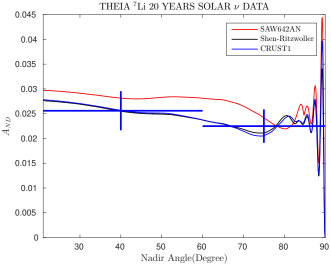
Solar neutrinos at DUNE

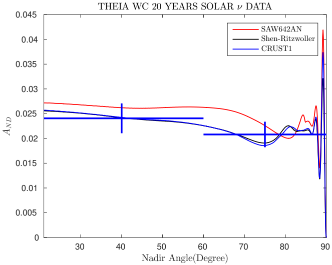
- Detection channel: $\nu_e +^{40} \mathrm{Ar} \rightarrow^{40} \mathrm{K} + e^-$
- Day-night asymmetry: $\bar{A}_{ND} = 0.040$, 0.040 and 0.043 for the CRUST1, S-R, and SAW642AN Earth models, respectively
- Expected precision of $\bar{A}_{ND}$ measurement: 0.002



Solar neutrinos THEIA

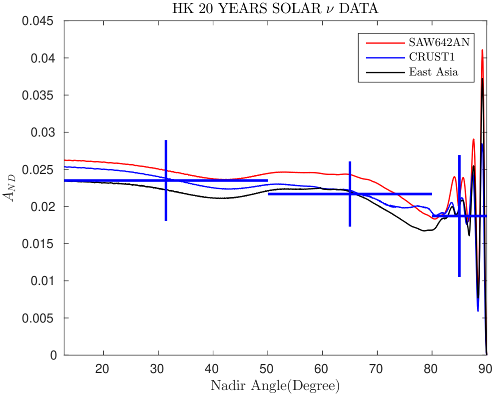
- THEIA is a water-based liquid scintillator detector with a 100 kT fiducial volume, loaded with 1% ^{7}Li.
- Neutrino-electron elastic scattering and $\nu_e + {}^7\text{Li} \rightarrow {}^7\text{Be} + e^-$ interactions are the detection channels.
- The average, $\bar{A}_{ND}$, is 0.024 (CRUST1 and S-R) and 0.027 (SAW642AN) for ^{7}Li, and 0.022 (CRUST1 and S-R) and 0.025 (SAW642AN) for elastic scattering events.





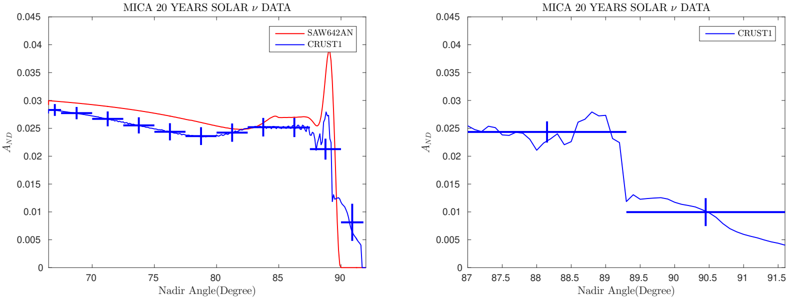
Solar neutrinos at HK

- $\bar{A}_{ND}$ =0.020 (FWEA18), 0.022 (CRUST1) and 0.024 (SAW642AN)
- Precision of $\bar{A}ND$ measurement: 0.002
- Smaller $\bar{A}_{ND}$ than DUNE due to contribution from NC scattering (0.76) and energy difference ($E_{HK}/E_{DUNE} = 0.75$)



Solar neutrinos at Million ton Ice Cherenkov Array (MICA)

- MICA has 10 million tons fiducial mass and detect neutrinos with $\nu - e$ elastic scattering with $10\ \mathrm{MeV}$.
- $\bar{A}_{ND} = 0.026$ (CRUST1) with precision of 0.00045
- MICA will exclude the SAW642AN and PREM more than 5σ and it will be sernsitive to ice-Earth border



NSI and Solar Neutrinos

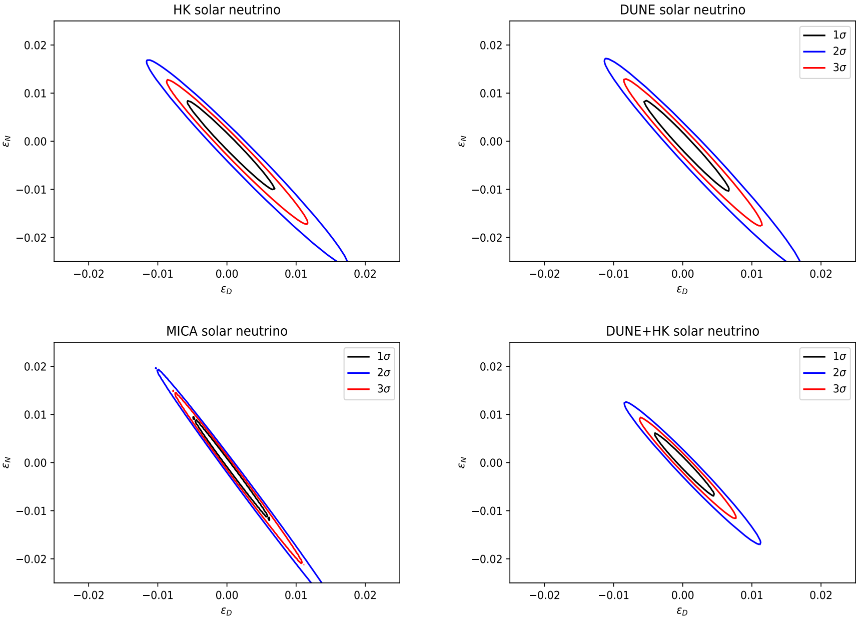
- Nonstandard neutrino interactions (NSI) can affect the propagation of neutrinos through matter.

$$\mathcal{L}_{\mathrm{NSI}}^{NC} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fC} \left(\overline{\nu_\alpha} \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_C f\right) \tag{19}$$

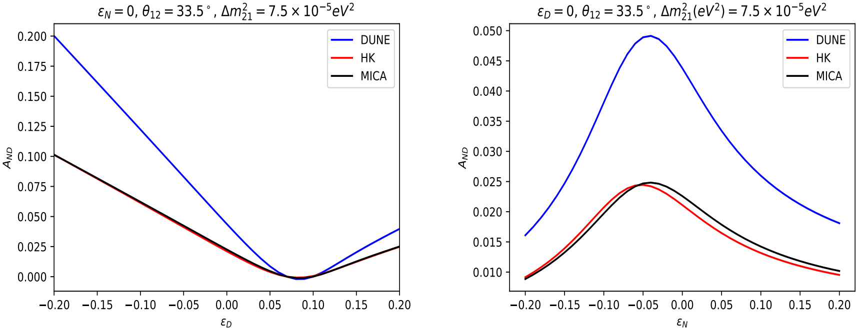
- The relevant solar NSI parameters are

$$\begin{aligned} \epsilon_D^f &= -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \\ &+\mathrm{Re}\left[c_{13} s_{13} e^{i\delta}\left(s_{23}\,\epsilon_{e\mu}^f + c_{23}\,\epsilon_{e\tau}^f\right) - \left(1 + s_{13}^2\right) c_{23} s_{23} \epsilon_{\mu\tau}^f\right] \end{aligned} \tag{20}$$

$$\epsilon_N^f = c_{13}\left(c_{23}\,\epsilon_{e\mu}^f - s_{23}\,\epsilon_{e\tau}^f\right) + s_{13} e^{-i\delta}\left[s_{23}^2\,\epsilon_{\mu\tau}^f - c_{23}^2\,\epsilon_{\mu\tau}^{f*} + c_{23} s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right]$$


HK solar neutrino
DUNE solar neutrino
MICA solar neutrino
DUNE+HK solar neutrino
1σ
2σ
3σ
ϵ_N
ϵ_D
0.02
0.01
0.00
−0.01
−0.02

Day-Night Asymmetry



- constraints on ϵ_N will be 0.014, 0.014, and 0.007 respectively by DUNE, HK, and MICA
- constraints on ϵ_D will be 0.004, 0.004, and 0.002 respectively by DUNE, HK, and MICA

Neutral Current NSI Effect on Electron Neutrino Scattering

$$\frac{d\sigma}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g_1)^2 + (g_2)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2}\right] \tag{21}$$

within the standard model

$$g_1^{\nu_e} = g_2^{\bar{\nu}_e} = \frac{1}{2} + \sin^2\theta_W = 0.73 \tag{22}$$

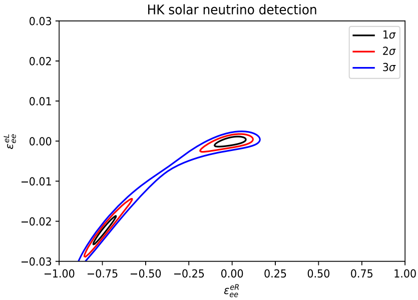
$$g_2^{\nu_e} = g_1^{\bar{\nu}_e} = g_2^{\nu_\mu} = g_1^{\bar{\nu}_\mu} = \sin^2\theta_W = 0.23 \tag{23}$$

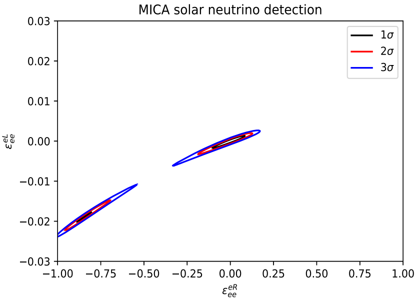
$$g_1^{\nu_\mu} = g_2^{\bar{\nu}_\mu} = -\frac{1}{2} + \sin^2\theta_W = -0.27 \tag{24}$$

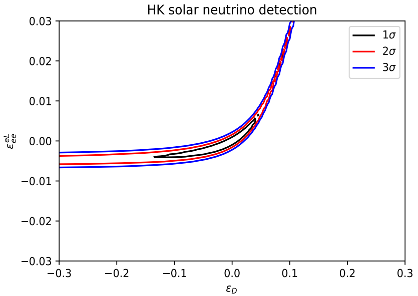
Considering the neutral current NSI

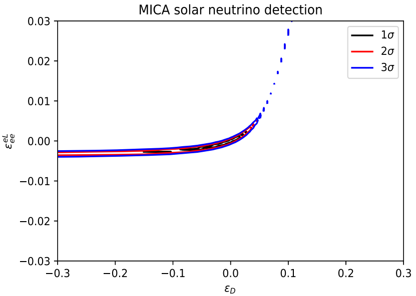
$$g_1^{e\ NSI} = g_1^e + \epsilon_{ee}^{eL} \tag{25}$$

$$g_2^{e\ NSI} = g_2^e + \epsilon_{ee}^{eR} \tag{26}$$


HK solar neutrino detection


MICA solar neutrino detection


HK solar neutrino detection


MICA solar neutrino detection

Summary

- Solar neutrino detection will determin solar neutrino oscillation parameters with sub-percent precision.
- Future precision measurements of all components of the solar neutrino spectrum will provide new insights into solar models, neutrino propagation, and transformations.
- Solar neutrino observatories can also probe the shallow structure of the Earth, particularly the crust and upper mantle, through the Day-Night asymmetry resulting from the attenuation effect.
- Solar neutrino observatories can probe new physics such as Non-Standard Interactions (NSI) and Sterile neutrinos.