Solar neutrinos and future experiments

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Reference

- 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

Solar Neutrino production

- $4p \rightarrow^4 He + 2e^+ + 2\nu_e + Q$
- $Q = 26.73$ MeV
- pp chain reactions provides 98.4% of the energy generation in the Sun
- 1.6% of energy is produced in the CNO cycle
- β^+ decay of proton in the presence of another proton
- $p + p \rightarrow d + e^+ + \nu_e$
- $Q_{pp} = 2M_p - M_d - m_e = 0.420\ MeV$, $\bar{E}_\nu = 0.24 MeV$ and energy peak at 0.31 MeV
- According to SSM, the pp neutrinos compose the majority (92%) of solar flux and therefore the average energy of all neutrinos is close to $\bar{E}_{pp}$
- The reaction is a weak interaction and has the Coulomb suppresion
- It is one of the slowest processess of the chain ($t_{pp} \sim 10^{10}$ years)

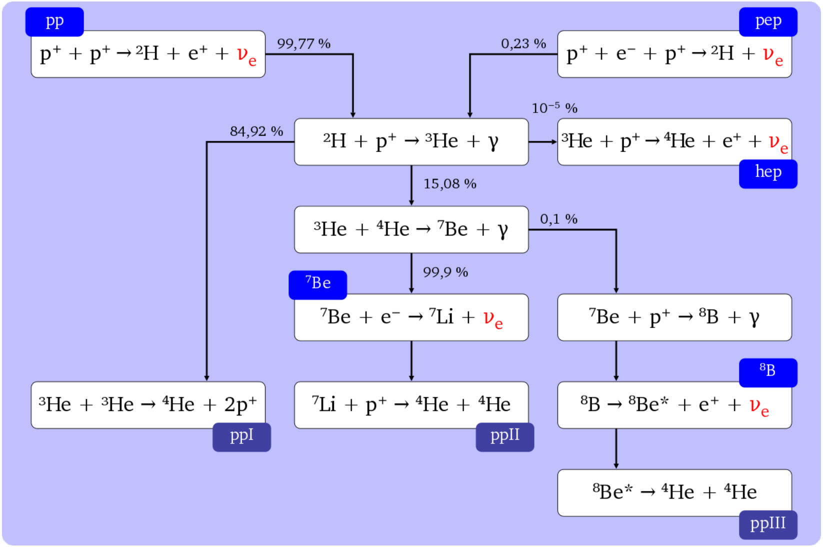
Solar Neutrino production

- Other reactions of the chain are faster (except pep)
- pep reaction is $p + e^- + p \to d + \nu_e$
- The rate is two orders of magnitudes smaller then pp reaction. Three body reaction.
- $t_{pep} \sim 10^{12}$ years
- $E_{pep} = 1.441$ MeV, monochromatic, witdth of 2 keV. $T_c = 10^7$K
- $d + p \to^3 He + \gamma$ is very fast ($t \sim 10^8$ years) and precise rate is not important
- The time of diffusion of photons from the center of the Sun to its surface is 10^5 years
- Neutrinos freely escape from the Sun without affecting dynamics of the Sun's evolution

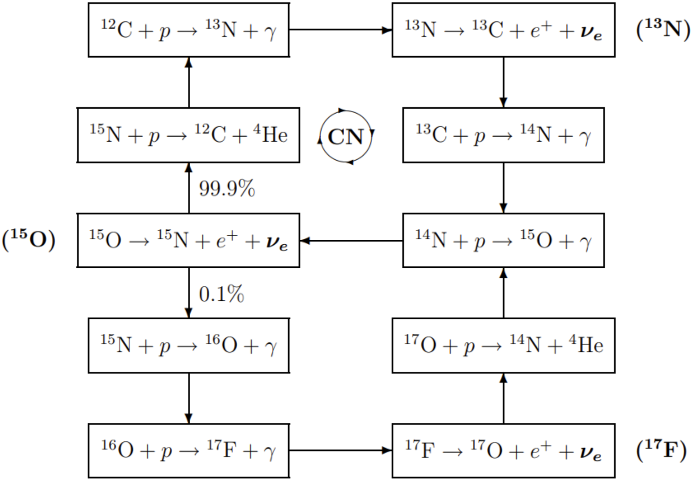
Solar Neutrino production

- ^3He has two comparable branchings fractions and a rare one
- $^3He +^3 He \rightarrow^4 He + 2p$ with branching fraction of 84.6% ($t \sim 10^5$ years)
- $^3He +^4 He \rightarrow^7 Be + \gamma$ with branching fraction of 15.4% ($t \sim 10^6$ years)
- The branching fractions depend on ratio of $^3He/^4He$ densities
- The reactions depend on temprature
- $^3He + p \rightarrow^4 He + e^+ + \nu_e$ has branching fraction of $2.5{\times}10^{-5}$%
- $Q = m_{^3He} + m_p - m_{^4He} - m_e = 19.8$ MeV
- peak of energy is 9.5 MeV
- 10^{-7} of pp neutrino flux, three orders of magnitude smaller than Boron neutrino flux

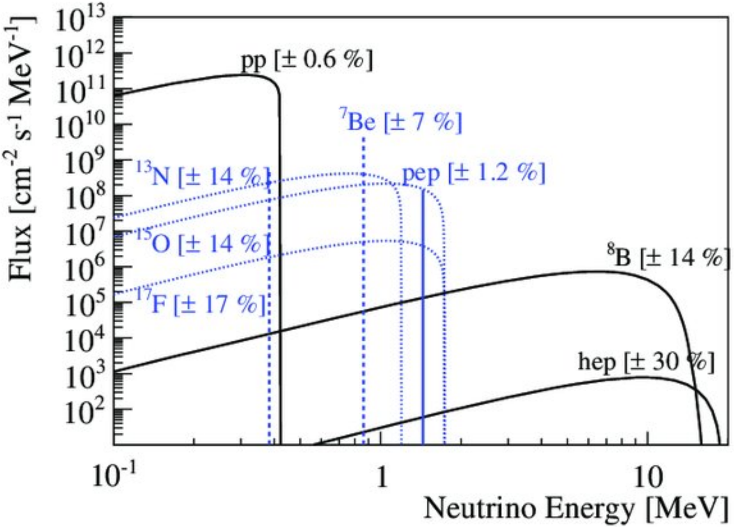
Solar Neutrino production



Solar Neutrino production



Solar Neutrino production



Solar Neutrino detection

- Homestake experiment:
  $\nu_e +^{37} Cl \rightarrow^{37} Ar + e,\ E_{th} = 0.814$ MeV
  $R_{Ar} = \frac{Q_{Ar}^{exp}}{Q_{Ar}^{SSM}} = 0.32 \pm 0.05$
- Kamiokande, SK
  $\nu + e \rightarrow \nu + e,\ E_{th} = 5$ MeV
  $R_{\nu e} = \frac{\phi_B^{exp}}{\phi_B^{SSM}} = 0.49 - 0.64(K) = 0.43 \pm 0.06(SK)$
- Ga-Ge experiments
  $\nu_e +^{71} Ga \rightarrow e^- +^{71} Ge,\ E_{th} = 0.233$ MeV
  $R_{Ar} = \frac{Q_{Ge}^{exp}}{Q_{Ge}^{SSM}} = 0.52 \pm 0.03$

Solar Neutrino detection

- SNO (The Sudbury Neutrino Observatory)
  $\nu_e + d \rightarrow p + p + e^-$ (CC)
  $\nu_\alpha + d \rightarrow p + n + \nu_\alpha$ (NC)
  $\nu_\alpha + e \rightarrow \nu_\alpha + e$
  $R = \frac{\phi_{CC}}{\phi_{NC}} = \frac{\phi_e}{\phi_{tot}} = 0.34 \pm 0.04(K)$
- Borexino: 1 kt scintillation detector, νe scattering, recoil electrons is measured down to 0.2 MeV, with the fiducial mass of 0.1 kt
  high energy resolution

Neutrino Oscillation

There is a mixing between mass and flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \,, \;\; \alpha = e, \mu, \tau, \quad i = 1, 2, 3 \tag{1}$$

PMNS mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \tag{2}$$

Neutrino oscillation in vacuum

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{kj} L}{2E}} \tag{3}$$

Neutrino Oscillation in Vacuum

$$H\left|\nu_k\right\rangle = E_k\left|\nu_k\right\rangle \tag{4}$$

$$i\frac{d}{dt}\left|\nu_k(t)\right\rangle = H\left|\nu_k(t)\right\rangle \tag{5}$$

$$\left|\nu_k(t)\right\rangle = e^{-iE_k t}\left|\nu_k\right\rangle \tag{6}$$

$$\left|\nu_\alpha(t)\right\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t}\left|\nu_k\right\rangle \tag{7}$$

$$\left|\nu_\alpha(t)\right\rangle = \sum_\beta \sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k}\left|\nu_\beta\right\rangle \tag{8}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j)t} \tag{9}$$

Neutrino Oscillation in Vacuum

$$E_k \simeq E + \frac{m_k^2}{2E} \tag{10}$$

$$E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E} \equiv \frac{m_k^2 - m_j^2}{2E} \tag{11}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* e^{-i \frac{\Delta m_{kj}^2 L}{2E}} \tag{12}$$

Neutrino Oscillation in Matter

- Forward elastic scattering processes affect neutrino oscillation

$$\mathcal{H}_f = \mathcal{H}_{vac} + \mathcal{H}_{mat} \tag{13}$$

$$\mathcal{H}_{mat} = \sqrt{2} G_F N_e diag(1,0,0) \tag{14}$$

$$\mathcal{H}_{vac} = U_{PMNS} \cdot \mathrm{Diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^{\dagger}_{PMNS} \tag{15}$$

- Considering 2ν Oscillation

$$i \frac{d}{dx} \psi_\alpha = \mathcal{H}_f \psi_\alpha \tag{16}$$

$$\mathcal{H}_F = \begin{bmatrix} -\Delta m^2 \cos 2\theta + A_{CC} & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - A_{CC} \end{bmatrix} \tag{17}$$

Neutrino Oscillation in Matter

$$\psi^T = (\psi_{ee}, \psi_{e\mu}) \tag{18}$$

$$A_{CC} = 2\sqrt{2}EG_F N_e = 2V_{CC}E \tag{19}$$

$$\mathcal{H}_M = U_M \mathcal{H}_F U_M \tag{20}$$

$$U_M = \begin{bmatrix} \cos 2\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos 2\theta_M \end{bmatrix} \tag{21}$$

$$\mathcal{H}_M = diag(-\Delta m_M^2, \Delta m_M^2) \tag{22}$$

Neutrino Oscillation in Matter

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \tag{23}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \tag{24}$$

$$A_{CC}^R = \Delta m^2 \cos 2\theta \tag{25}$$

$$N_e^R = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} E G_F} \tag{26}$$

In the case of anti-neutrino $V_{CC} \to -V_{CC}$ $(A_{CC} = 2EV_{CC})$

- For $\Delta m_{21}^2 > 0$ the resonance condition is fulfilled in the neutrino channel with $V > 0$ only. For antineutrinos $V < 0$.

Neutrino Oscillation in the Sun

$$P_{ee} = \sum_k |U^m_{ek}(n_i) U^{m\dagger}_{ek}(n_f) e^{-i\phi_k}|^2 = \sum_k |U^m_{ek}(n^0_e)|^2 P^E_{ek} \tag{27}$$

$$|U^m_{e1}| = \cos\theta^m_{13}\cos\theta^m_{12},\ |U^m_{e2}| = \cos\theta^m_{13}\sin\theta^m_{12},\ |U^m_{e3}| = \sin\theta^m_{13}$$

$$P_{3e} \approx s^2_{13}, \quad P_{1e} + P_{2e} = 1 - s^2_{13}$$

$$P_D(E) = \frac{1}{2} c^4_{13} \left[1 + \cos 2\theta_{12} \cos 2\bar{\theta}^m_{12}(E)\right] + s^4_{13} \tag{28}$$

$$\cos 2\bar{\theta}^m_{12} \ \approx \ \frac{\cos 2\theta_{12} - c^2_{13}\bar{\epsilon}_\odot}{\sqrt{(\cos 2\theta_{12} - c^2_{13}\bar{\epsilon}_\odot)^2 + \sin^2 2\theta_{12}}}. \tag{29}$$

$$\bar{\epsilon}_\odot \equiv \frac{2\bar{V}_\odot E}{\Delta m^2_{21}}, \quad V(x) = \sqrt{2} G_F n_e(x)$$

Day-Night Asymmetry

- Due to loss of the propagation coherence, the solar neutrinos arrive at the surface of the Earth as independent fluxes of the mass eigenstates
- Inside the Earth, the mass states oscillate in a multilayer medium with smoothly changing density within layers

$$f_{reg} = |U_{e1}|^2 - P_{1e}^E = \frac{1}{2} c_{13}^4 \sin^2 2\theta_{12} \int_0^L dx V(x) \sin \phi^m \tag{30}$$

$$\Delta P(E) = \kappa(E) \left[\int_0^L dx \;\; V(x) \sin \phi^m (L - x, E) + I_2 \right] \tag{31}$$

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

Day-Night Asymmetry

$$I_2 \equiv \frac{1}{2}\cos 2\theta_{12}\left[\int_0^L dx\ V(x)\cos\phi^m(L-x)\right]^2 \tag{32}$$

$$\phi^m(L-x,E) \equiv \int_x^L dx\ \Delta_{21}^m(x). \tag{33}$$

$$\begin{aligned}\Delta_{21}^m &= \Delta_{21}\sqrt{(\cos 2\theta_{21} - c_{13}^2\epsilon)^2 + \sin^2 2\theta_{21}} \\ &\approx \Delta_{21}(1 - c_{13}^2\cos 2\theta_{12}\epsilon) = \frac{\Delta m_{21}^2}{2E}(1 - c_{13}^2\cos 2\theta_{12}\epsilon).\end{aligned} \tag{34}$$

$$\phi^m(L-x,E) = \Delta_{21}\left[(L-x) - c_{13}^2\cos 2\theta_{12}\int_x^L dx\epsilon(x)\right]. \tag{35}$$

Day-Night Asymmetry

$$A_{ND}(\eta, \Delta E) \equiv \frac{\Delta N(\eta, \Delta E)}{N_D(\Delta E)} \quad \Delta N \equiv N_N - N_D \tag{36}$$

$$\Delta N(E^r) = D \int dE \;\; G_\nu(E^r, E) \Delta P(E) \tag{37}$$

$$G_\nu(E^r, E) \propto g_\nu(E^r, E) \sigma(E) f_B(E) \tag{38}$$

$$\Delta N(E^r) = D \int_0^L dx V(x) \int_0^{E^{max}} dE \;\; G_\nu(E^r, E) \sin\phi^m(L - x, E) \tag{39}$$

Attenuation Effect

$$\int dEG_{\nu}(E^{r}, E) \sin\phi^{m}(L-x, E) = F(L-x) \sin\phi^{m}(L-x, E^{r}) \qquad (40)$$

$$\Delta N(E^{r}) = D \int dxV(x)F(L-x) \sin\phi^{m}(L-x, E^{r}). \qquad (41)$$

For the Gaussian form of $G_{\nu}(E^{r}, E)$

$$F(L-x) \simeq e^{-2\left(\frac{L-x}{\lambda_{att}}\right)^{2}} \qquad (42)$$

$$\lambda_{att} \equiv l_{\nu} \frac{E}{\pi\sigma_{E}} \qquad l_{\nu} = \frac{4\pi E}{\Delta m_{21}^{2}}$$

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

Day-Night Asymmetry

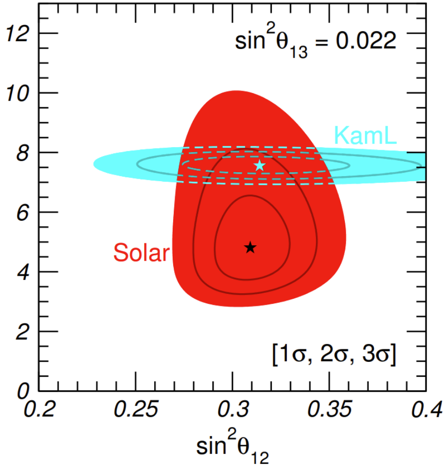
Neutrino-nuclei scattering

$$N_D(\Delta E_e^r) = Dz \int_{E^{min}}^{E^{max}} dE^r \sigma(E^r) f_B(E^r) P_D(E^r). \quad (43)$$

Neutrino-electron scattering

$$\begin{aligned} N_D(E_e^r) &= \int_0^{E^{max}} dE f_B(E) g_\nu(E_e^r, E) \Big[P_D(E) \sigma^e(E, E_e^{th}) \\ &+ (1 - P_D(E)) \sigma^\mu(E, E_e^{th}) \Big]. \quad (44) \end{aligned}$$

Global analysis of solar neutrino oscillation



M. Maltoni and A. Y. Smirnov, "Solar neutrinos and neutrino physics," Eur. Phys. J. A **52** (2016) no.4, 87 [arXiv:1507.05287 [hep-ph]].

LMA MSW solution and beyond

- The sign of Δm_{21}^2 determines the resonance of ν_e solar neutrinos
- About 2σ tension between KamLAND and solar neutrino data
- Increase of the ratio of the measured spectrum to the SSM one toward low energies (discrepancy)
- Discrepancy between measured and predicted day-night asymmetry
- Non-Standard neutrino Interaction
- Sterile neutrino, etc

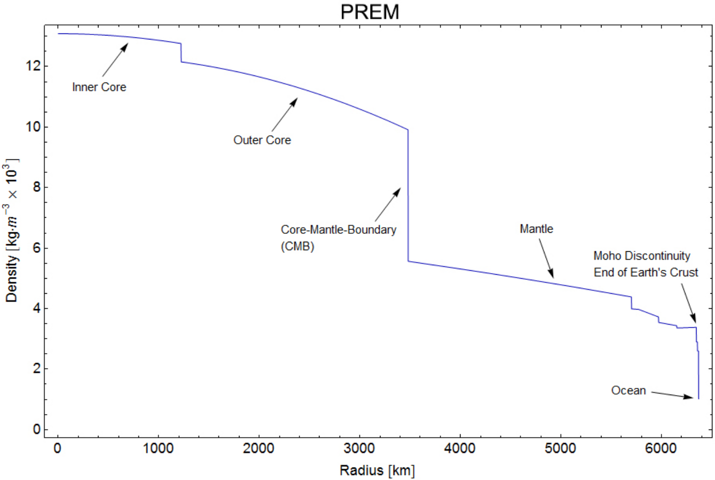
Future studies of solar neutrinos

- JUNO and RENO-50, determination of Δm^2_{21} and θ_{12} with sub percent precision. With a good energy resolution, these experiments will detect ^8B,^7Be and *pep* neutrinos
- Precision (at sub-percent level) measurements of neutrino fluxes with future solar neutrino observatories
- SNO+, 780 t of liquid scintillator fiducial mass of 390 t, energy threshold of 3 MeV, the threshold of the upgraded version decreased
- Jinping, 4 (2) kton liquid scintillator, detect low energy neutrinos with a good precision
- Yemilab solar neutrino detector, 2 kton liquid scintillator
- DUNE, 40 kton liquid argon, 10 MeV energy threshold
- Hyper-Kamiokande (KNO), energy threshold of 6.5 MeV, several 100 kt detectors
- THEIA, water-based liquid scintillator, 1% doping by ^7Li

Earth Structure

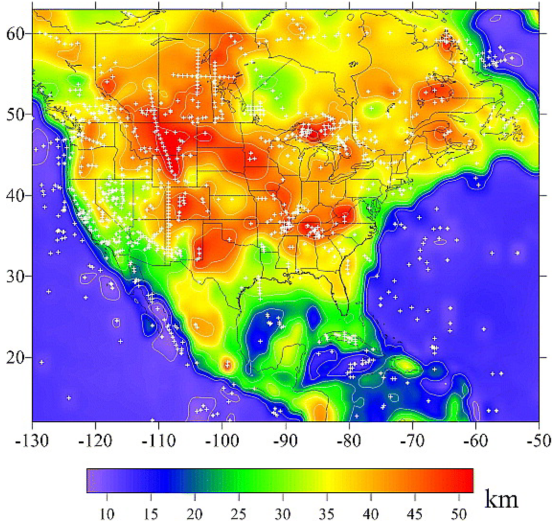
- P. Bakhti and A. Y. Smirnov, "Oscillation tomography of the Earth with solar neutrinos and future experiments," Phys. Rev. D **101** (2020) no.12, 123031 [arXiv:2001.08030 [hep-ph]].
- Due to the attenuation effect, A_{ND} mainly depends on shallow density structures: crust, upper mantle, and crust-mantle border called Moho, or Mohorovicic discontinuity.
- There are two types of crust: the oceanic crust (5 - 10) km and the continental crust (20 - 90) km
- Shen-Ritzwoller model: crust and uppermost mantle beneath North America, in the area with latitudes $(20^\circ - 50^\circ)$ and longitudes $(235^\circ - 295^\circ)$, from the sea level surface down to the depth of 150 km
- FWEA18, the Full Waveform Inversion of East Asia model: latitudes $10^\circ - 60^\circ$ and longitudes $90^\circ - 150^\circ$, from the surface down to 800 km
- SAW642AN: global model, from the depth of Moho, down to 2900 km
- CRUST1: global model, from Earth's surface down to the Moho

PREM

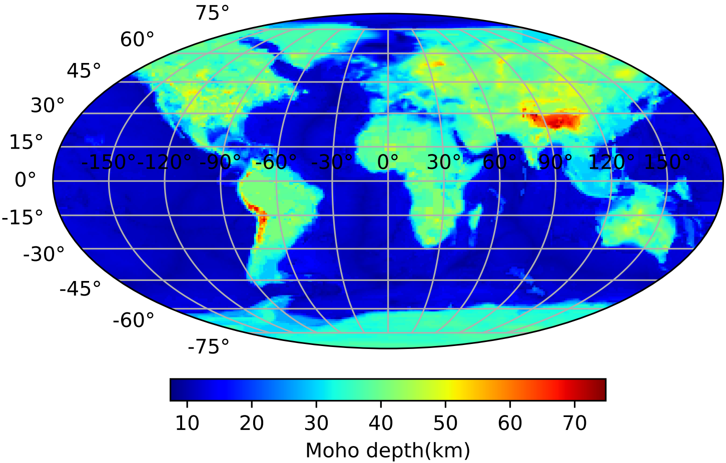


Preliminary Reference Earth Model (PREM)

Shen-Ritzwoller Moho depth



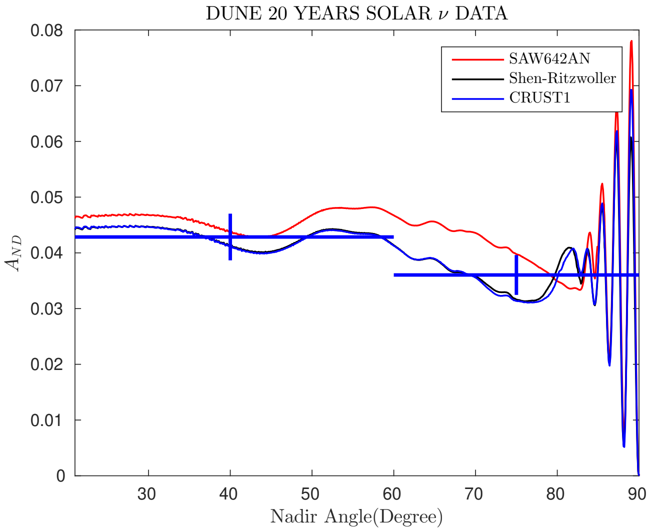
CRUST1 Moho depth



DUNE

- $$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K} + e^- \tag{45}$$
- $$\sigma_{CC}(E) = A p_e E_e \tag{46}$$
$$E_e = E_\nu - \Delta M, \qquad \Delta M = 5.8\ \mathrm{MeV}$$
- With $\sigma_E/E = 7\%$, $\lambda_{att} = 1800$ km for $E = 12$ MeV
- $L > \lambda_{att}$ is $\eta_{att} = 82^\circ$
- 27000 ν_e events detected annually with $E_\nu > 11\ \mathrm{MeV}$ in the 40 kt fiducial volume
- $\bar{A}_{ND} = 0.040$, 0.040 and 0.043, for CRUST1, S-R, and SAW642AN models, respectively
- precision of measurement of $\bar{A}_{ND}$ will be 0.002

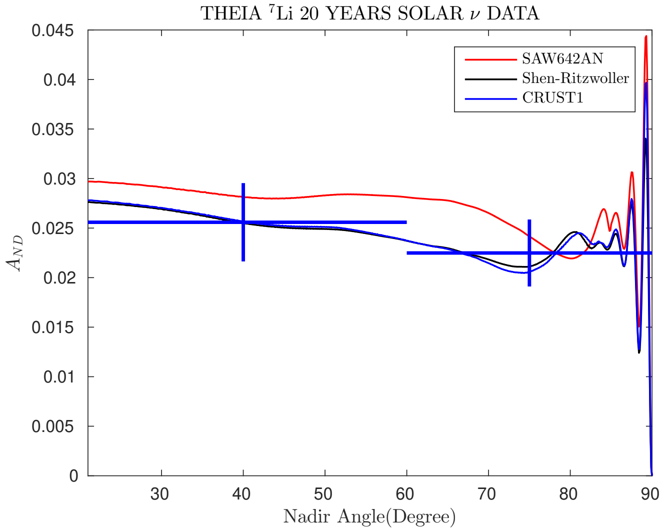
$A_{ND}(\eta)$ at DUNE



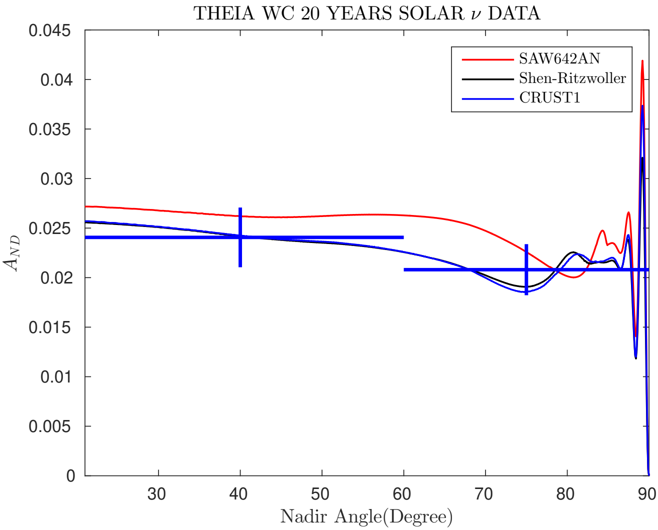
THEIA

- 100 kT water-based liquid scintillator detector loaded with 1% ^{7}Li
- $$\nu_e +^7 \mathrm{Li} \to^7 \mathrm{Be} + e. \qquad (47)$$
- The cross-section of this process is known with high precision.
- $\nu - e$ elastic scattering with 6.5 MeV threshold
- 17000 ^{7}Li and 15000 $\nu - e$ elastic scattering events are expected annually with $E_\nu > 5$ MeV
- $\sigma_E/E = 12\%$ for ^{7}Li and $\sigma_E/E = 15\%$ for $\nu - e$ elastic scattering
- $\bar{A}_{ND} = 0.024$ (CRUST1 and S-R) and 0.027 (SAW642AN) for ^{7}Li, and $\bar{A}_{ND} = 0.022$ (CRUST1 and S-R) and 0.025 (SAW642AN) for elastic scattering events
- precision of measurement of $\bar{A}_{ND}$ will be 0.005

$A_{ND}(\eta)$ at THEIA



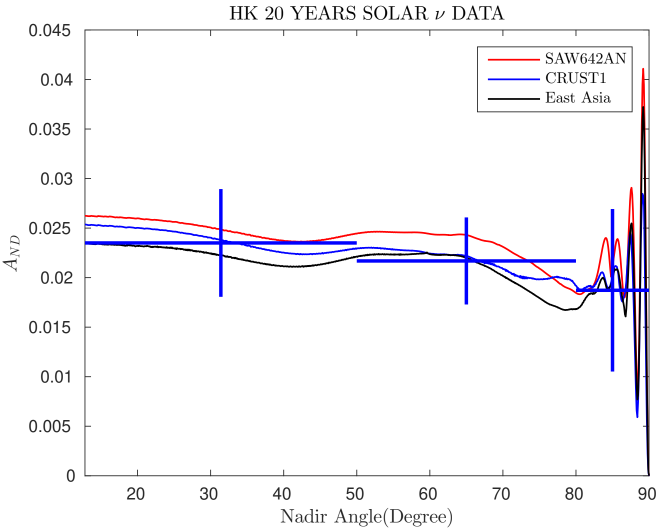
$A_{ND}(\eta)$ at THEIA



HK

- $\nu - e$ elastic scattering with 6.5 MeV threshold
- $\sigma_E/E = 15\%$
- $\lambda_{att} = 700$ km for $E = 10$ MeV
- 80 events are expected per day
- $\bar{A}_{ND}$ =0.020 (FWEA18), 0.022 (CRUST1) and 0.024 (SAW642AN)
- precision of measurement of $\bar{A}_{ND}$ will be 0.002
- Smaller $\bar{A}_{ND}$ than DUNE: damping due to contribution from NC scattering, which is 0.76, and difference of averaged energies $E_{HK}/E_{DUNE} = 0.75$
- HK will distinguish between EA and SAW642AN, with 1.5σ, CRUST1 is recognizable from EA and SAW642 with 0.7σ and 1.2σ respectively

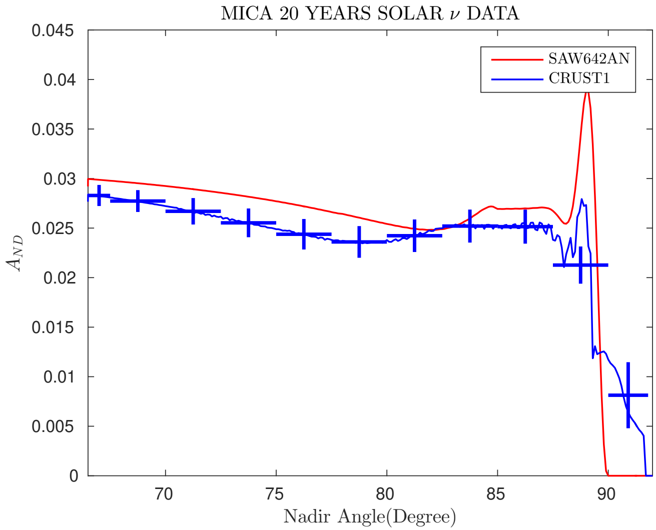
$A_{ND}(\eta)$ at HK


HK 20 YEARS SOLAR ν DATA
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
A_{ND}
20
30
40
50
60
70
80
90
Nadir Angle(Degree)
SAW642AN
CRUST1
East Asia

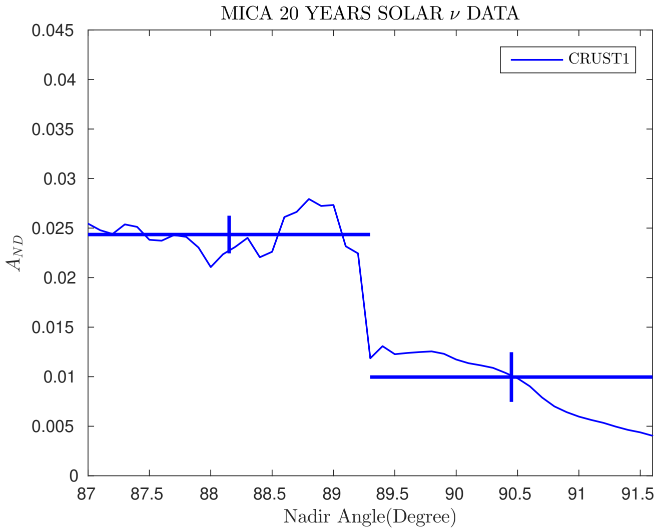
MICA

- $\nu - e$ elastic scattering with 10 MeV threshold
- 10 Mton fiducial mass
- $\sigma_E/E = 15\%$
- 5×10^5 solar $\nu e-$ scattering events are expected per year
- MICA detector at a depth of 2.25 km below the icecap (as the Deep Core). The height of icecap at the location of MICA is 2.7 km above the sea level.
- $\bar{A}_{ND} = 0.026$ (CRUST1)
- precision of measurement of $\bar{A}_{ND}$ will be 0.00045

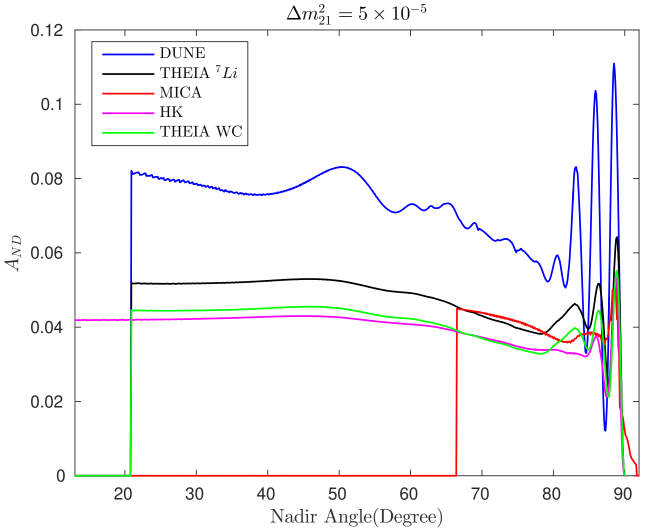
$A_{ND}(\eta)$ at MICA



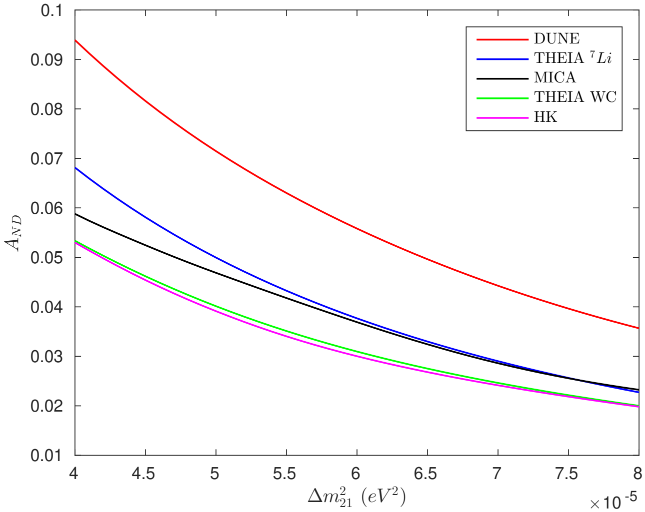
$A_{ND}(\eta)$ at MICA and Ice-Soil borderline



$A_{ND}(\eta)$ with $\Delta m^2_{21} = 5 \times 10^{-5}$



$\bar{A}_{ND}$



DUNE
THEIA ^7Li
MICA
THEIA WC
HK
A_{ND}
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
4
4.5
5
5.5
6
6.5
7
7.5
8
Δm^2_{21} (eV^2)
$\times 10^{-5}$

NSI for Solar Neutrinos

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]].

$$\mathcal{L}_{\mathrm{NSI}}^{NC} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fC} \left(\overline{\nu_\alpha} \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_C f\right) \tag{48}$$

Since $\frac{\Delta m_{31}^2}{E_\nu} \gg G_F N_e$ for solar neutrinos, it is possible to work on one mass dominate approximation, using 2×2 effective Hamiltonian as following

$$H_{\mathrm{vac}}^{\mathrm{eff}} = \frac{\Delta m_{21}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix}, \tag{49}$$

$$H_{\mathrm{mat}}^{\mathrm{eff}} = \sqrt{2} G_F N_e(r) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_f N_f(r) \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}. \tag{50}$$

NSI for Solar Neutrinos

$$\epsilon_D^f = -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)$$
$$+\text{Re}\left[c_{13}s_{13}e^{i\delta}\left(s_{23}\,\epsilon_{e\mu}^f + c_{23}\,\epsilon_{e\tau}^f\right) - \left(1+s_{13}^2\right)c_{23}s_{23}\epsilon_{\mu\tau}^f\right] \quad (51)$$

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

$$U' = \begin{pmatrix} \cos\tilde{\theta}_{12} & \sin\tilde{\theta}_{12}e^{-i\phi} \\ -\sin\tilde{\theta}_{12}e^{i\phi} & \cos\tilde{\theta}_{12} \end{pmatrix} \quad (52)$$

$$\tan 2\tilde{\theta}_{12} = \frac{|\sin 2\theta_{12} + 2\hat{A}_E\epsilon_N|}{\cos 2\theta_{12} - \hat{A}_E(c_{13}^2 - 2\epsilon_D)} \quad (53)$$

$$\phi = -\text{Arg}\left(\sin 2\theta_{12} + 2\hat{A}_E\epsilon_N\right). \quad (54)$$

Day-Night Asymmetry and NSI

$$P_D(E) = \frac{1}{2} c_{13}^4 \left[1 + \cos 2\theta_{12} \cos 2\tilde{\theta}_{12}(E)\right] + s_{13}^4 \quad (55)$$

$$N_{D(N)} = A \int dE g_\nu(E^r, E)\sigma(E) f_B(E) P(E)_{D(N)} \quad (56)$$

$$\Delta P(E, \eta) = P_N - P_D = \kappa(E) \left[\int_0^L dx \ V(x) \sin \phi^m(L - x, E)\right] \quad (57)$$

$$\kappa(E) \equiv -\frac{1}{2} c_{13}^4 \cos 2\tilde{\theta}_{12}^s \sin 2\theta_{12}(\sin 2\theta_{12}(c_{13}^2 - 2\epsilon_D^E) + 2 \cos 2\theta_{12}\epsilon_N^E) \quad (58)$$

$$\phi^m(L - x, E) \equiv \int_x^L dx \ \Delta_{21}^m(x) \approx \int_x^L dx \Delta_{21}(1 - c_{13}^2 \cos 2\theta_{12} a_{CC}^E) \quad (59)$$

Neutral Current NSI Effect on Electron Neutrino Scattering

$$\frac{d\sigma}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g_1)^2 + (g_2)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2}\right] \quad (60)$$

within the standard model

$$g_1^{\nu_e} = g_2^{\bar{\nu}_e} = \frac{1}{2} + \sin^2\theta_W = 0.73 \quad (61)$$

$$g_2^{\nu_e} = g_1^{\bar{\nu}_e} = g_2^{\nu_\mu} = g_1^{\bar{\nu}_\mu} = \sin^2\theta_W = 0.23 \quad (62)$$

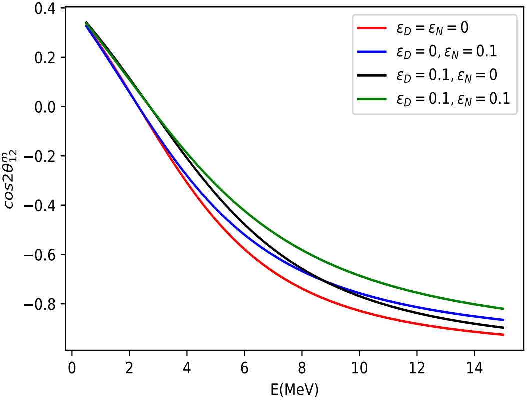
$$g_1^{\nu_\mu} = g_2^{\bar{\nu}_\mu} = -\frac{1}{2} + \sin^2\theta_W = -0.27 \quad (63)$$

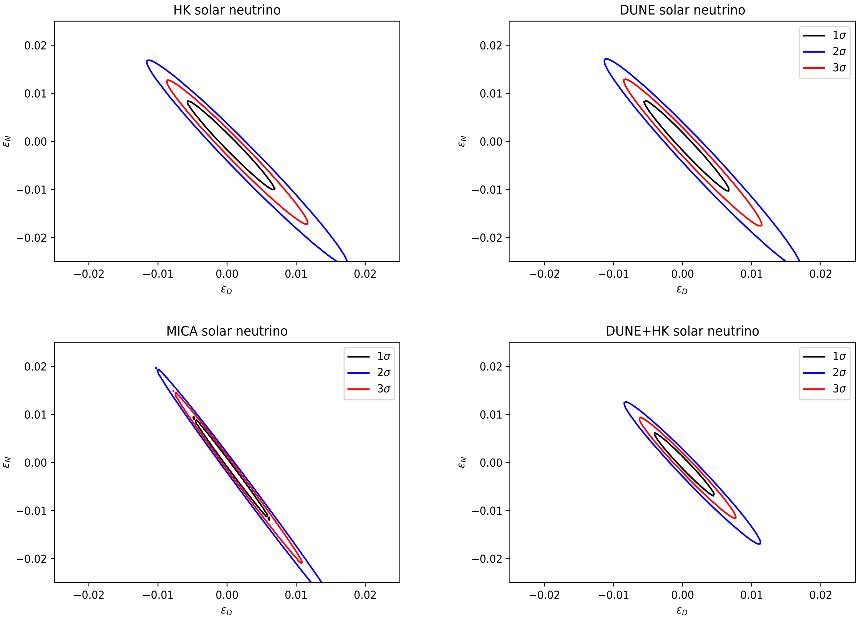
Considering the neutral current NSI

$$g_1^{e\ NSI} = g_1^e + \epsilon_{ee}^{eL} \quad (64)$$

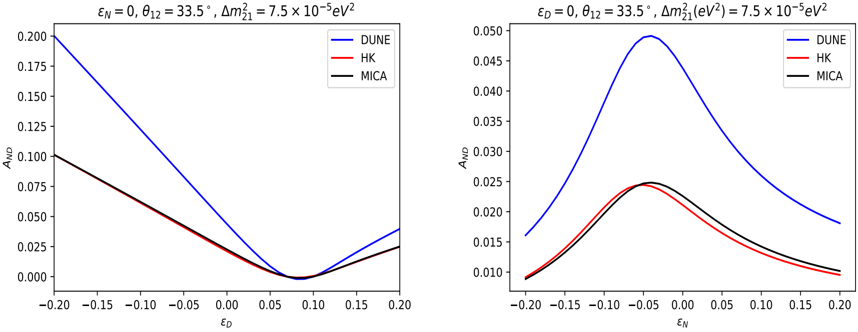
$$g_2^{e\ NSI} = g_2^e + \epsilon_{ee}^{eR} \quad (65)$$

Solar Neutrino NSI

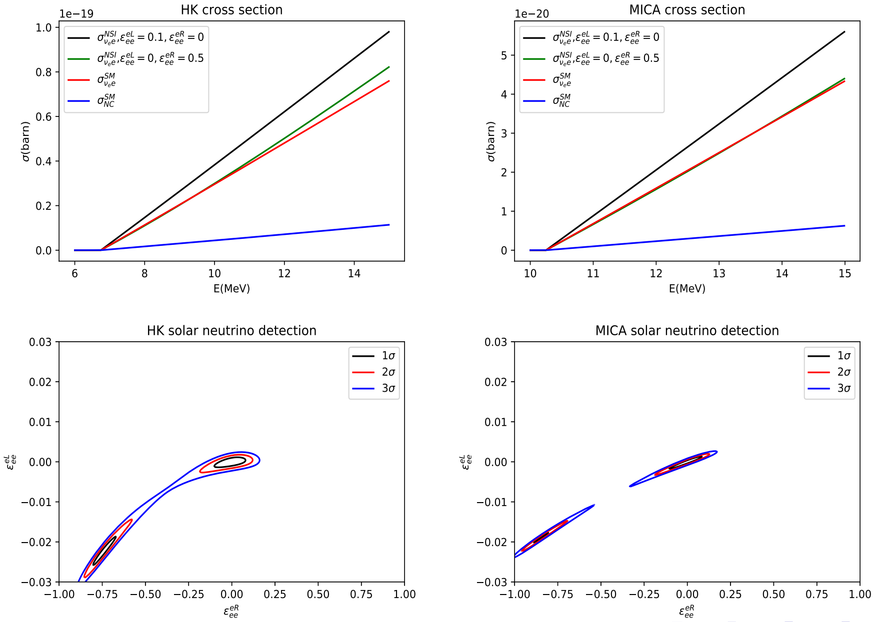


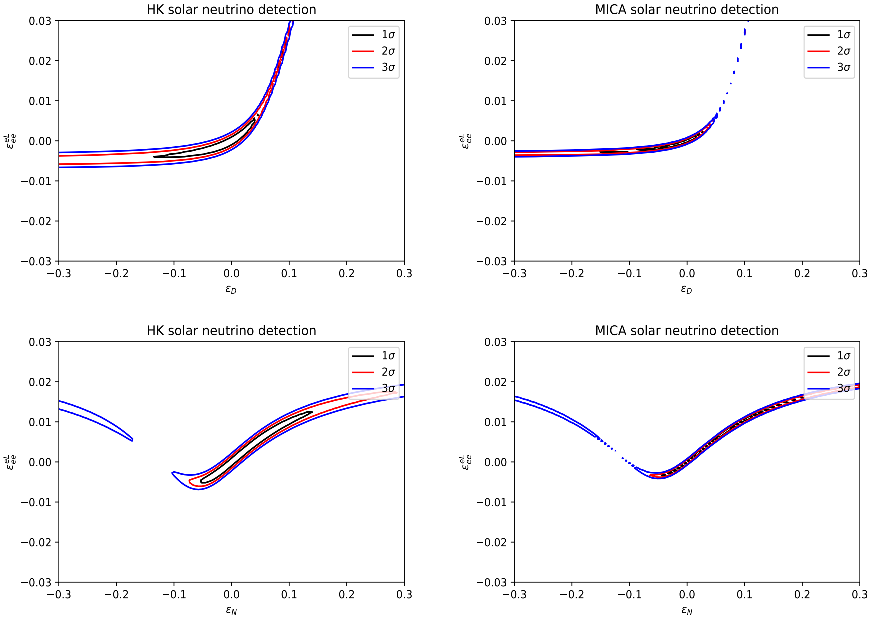

HK solar neutrino
DUNE solar neutrino
MICA solar neutrino
DUNE+HK solar neutrino
1σ
2σ
3σ
ϵ_N
ϵ_D
0.02
0.01
0.00
−0.01
−0.02

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


HK cross section
1e−19
$\sigma^{NSI}_{\nu_e e}, \epsilon^{eL}_{ee} = 0.1, \epsilon^{eR}_{ee} = 0$
$\sigma^{NSI}_{\nu_e e}, \epsilon^{eL}_{ee} = 0, \epsilon^{eR}_{ee} = 0.5$
$\sigma^{SM}_{\nu_e e}$
σ^{SM}_{NC}
σ(barn)
E(MeV)
1.0 0.8 0.6 0.4 0.2 0.0
6 8 10 12 14
MICA cross section
1e−20
$\sigma^{NSI}_{\nu_e e}, \epsilon^{eL}_{ee} = 0.1, \epsilon^{eR}_{ee} = 0$
$\sigma^{NSI}_{\nu_e e}, \epsilon^{eL}_{ee} = 0, \epsilon^{eR}_{ee} = 0.5$
$\sigma^{SM}_{\nu_e e}$
σ^{SM}_{NC}
σ(barn)
E(MeV)
5 4 3 2 1 0
10 11 12 13 14 15
HK solar neutrino detection
1σ
2σ
3σ
ϵ^{eL}_{ee}
ϵ^{eR}_{ee}
0.03 0.02 0.01 0.00 −0.01 −0.02 −0.03
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
MICA solar neutrino detection
1σ
2σ
3σ
ϵ^{eL}_{ee}
ϵ^{eR}_{ee}
0.03 0.02 0.01 0.00 −0.01 −0.02 −0.03
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00


HK solar neutrino detection
MICA solar neutrino detection
1σ
2σ
3σ
ε_{ee}^{eL}
ε_D
ε_N
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3

Summary

- JUNO and RENO-50 determines solar neutrino oscillation parameters with the sub-percent precision
- We will be sensitive to the shallow structure of the Earth, especially the crust and upper mantle from Day-Night asymmetry due to the attenuation effect
- Solar neutrino observatories combined with JUNO and RENO-50 will be sensitive to new physics such as NSI
- Future precision measurements of all the components of the solar neutrino spectrum will bring us to a new level of checks of solar models, physics of neutrino propagation, and transformations