

Oscillation tomography of the Earth with 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.

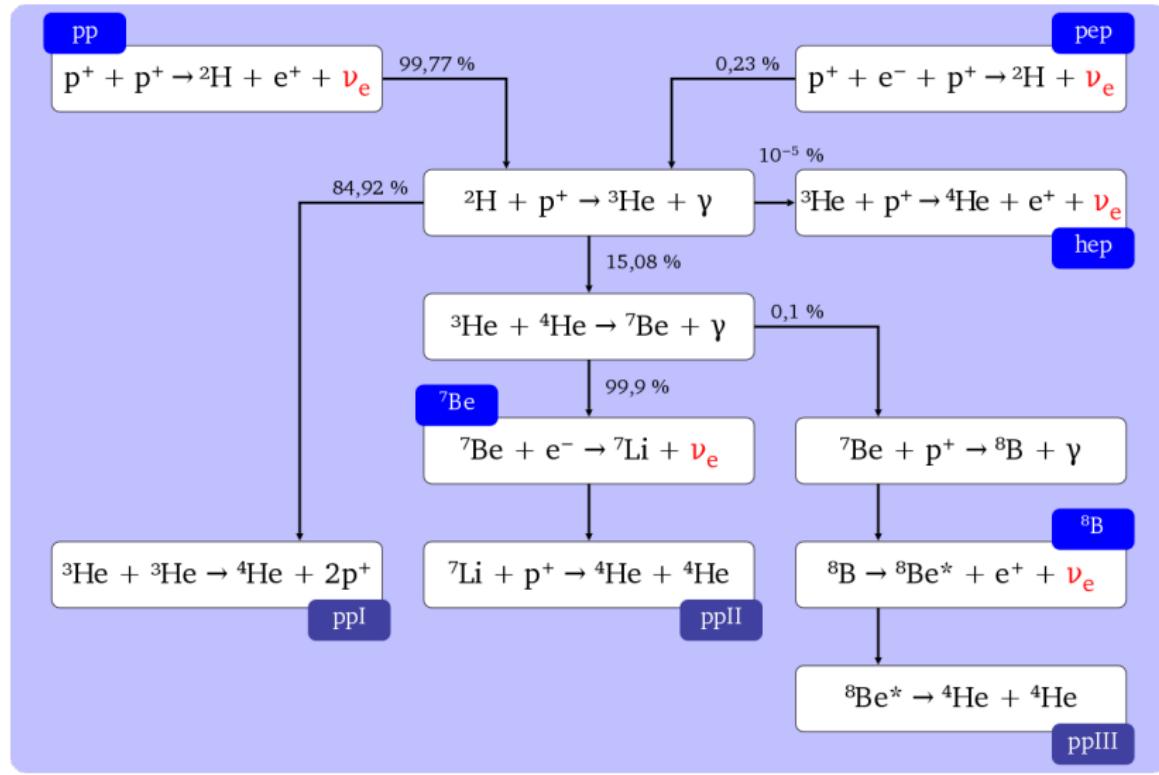
Overview

- 1 Solar Neutrino production
- 2 Solar Neutrino flavour conversion
- 3 Day-night asymmetry Earth tomography
- 4 Summary and Conclusion

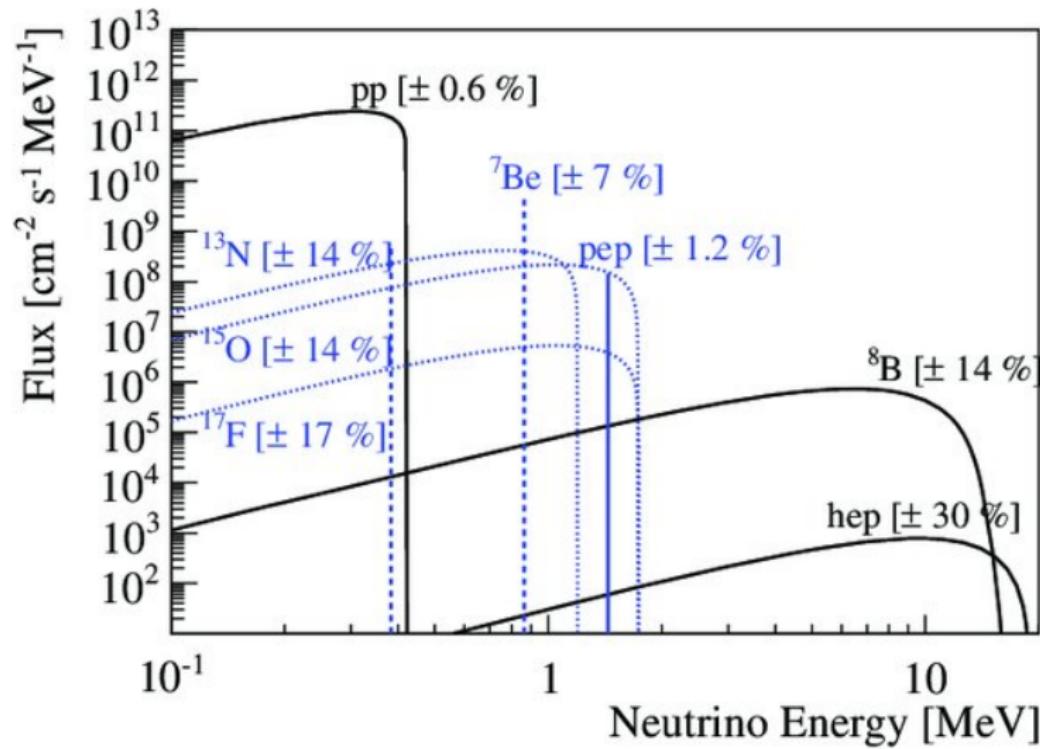
Solar Neutrino production

- Solar neutrinos are produced via pp chain and CNO cycle
- pp chain reactions provides 98.4% of the energy generation in the Sun
- All the produced neutrinos in the sun are electron neutrinos
- Standard Solar Model (SSM) and also other solar models calculated the spectrum of the produced neutrinos by the complete set of standard equations describing the evolution of stars, which based on conservation of mass, energy and momentum, energy transfer equations, etc, assuming spherical symmetry and fit the free parameters with helioseismology and solar neutrino data

Solar Neutrino production



Solar Neutrino production



Solar Neutrino detection

- Due to loss of the propagation coherence, the solar neutrinos arrive at the surface of the Earth as independent fluxes of the mass eigenstates
- Electron neutrino survival probability during a day, as function of the neutrino energy, equals (MSW effect)

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

$$\cos 2\bar{\theta}_{12}^m \approx \frac{\cos 2\theta_{12} - c_{13}^2 \bar{\epsilon}_\odot}{\sqrt{(\cos 2\theta_{12} - c_{13}^2 \bar{\epsilon}_\odot)^2 + \sin^2 2\theta_{12}}} \quad (2)$$

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

Day-Night Asymmetry

- Inside the Earth, the mass states oscillate in a multilayer medium with smoothly changing density within layers

$$f_{reg} = |U_{e1}|^2 - P_{1e}^E = \frac{1}{2} c_{13}^4 \sin^2 2\theta_{12} \int_0^L dx V(x) \sin \phi^m \quad (3)$$

$$\Delta P(E) = \kappa(E) \left[\int_0^L dx V(x) \sin \phi^m(L-x, E) + I_2 \right] \quad (4)$$

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

Day-Night Asymmetry

$$I_2 \equiv \frac{1}{2} \cos 2\theta_{12} \left[\int_0^L dx \ V(x) \cos \phi^m(L-x) \right]^2 \quad (5)$$

$$\phi^m(L-x, E) \equiv \int_x^L dx \ \Delta_{21}^m(x) \quad (6)$$

$$\begin{aligned} \Delta_{21}^m &= \Delta_{21} \sqrt{(\cos 2\theta_{21} - c_{13}^2 \epsilon)^2 + \sin^2 2\theta_{21}} \\ &\approx \Delta_{21} (1 - c_{13}^2 \cos 2\theta_{12} \epsilon) = \frac{\Delta m_{21}^2}{2E} (1 - c_{13}^2 \cos 2\theta_{12} \epsilon) \end{aligned} \quad (7)$$

$$\phi^m(L-x, E) = \Delta_{21} \left[(L-x) - c_{13}^2 \cos 2\theta_{12} \int_x^L dx \epsilon(x) \right] \quad (8)$$

Day-Night Asymmetry

$$A_{ND}(\eta, E) \equiv \frac{\Delta N(\eta, E)}{N_D(E)} \quad \Delta N \equiv N_N - N_D \quad (9)$$

$$\Delta N(E^r) = D \int dE \ G_\nu(E^r, E) \Delta P(E) \quad (10)$$

$$N_D(E^r) = D \int dE \ G_\nu(E^r, E) P_D(E) \quad (11)$$

$$G_\nu(E^r, E) \propto g_\nu(E^r, E) \sigma(E) f_B(E) \quad (12)$$

$$\Delta N(E^r) = D \int_0^L dx V(x) \int_0^{E^{max}} dE \ G_\nu(E^r, E) \sin \phi^m(L-x, E) \quad (13)$$

Attenuation Effect

- Integration over the energy can be removed introducing of the attenuation factor

$$\int dE G_\nu(E^r, E) \sin \phi^m(L - x, E) = F(L - x) \sin \phi^m(L - x, E^r) \quad (14)$$

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

$$F(L - x) \simeq e^{-2\left(\frac{L-x}{\lambda_{att}}\right)^2} \quad (15)$$

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

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

- Number of events for Neutrino-nuclei scattering is given by

$$N_D(\Delta E_e^r) = Dz \int_{E^{min}}^{E^{max}} dE^r \sigma(E^r) f_B(E^r) P_D(E^r) \quad (16)$$

- Number of events for Neutrino-electron scattering is given by

$$\begin{aligned} N_D(E_e^r) = & \int_0^{E^{max}} dE f_B(E) g_\nu(E_e^r, E) \left[P_D(E) \sigma^e(E, E_e^{th}) \right. \\ & \left. + (1 - P_D(E)) \sigma^\mu(E, E_e^{th}) \right] \end{aligned} \quad (17)$$

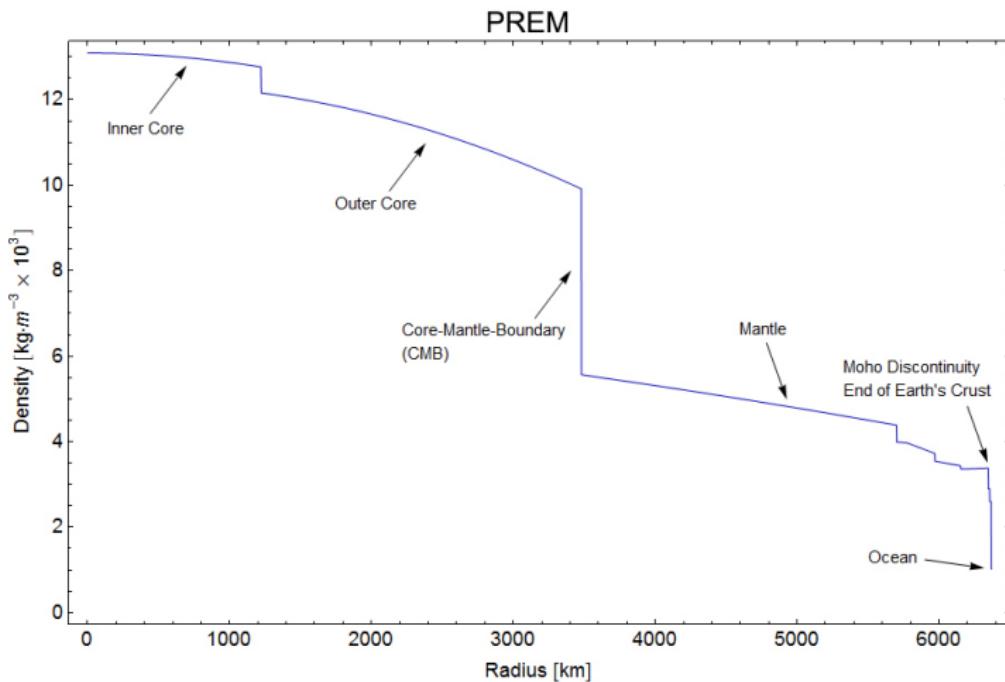
Future studies of solar neutrinos

- JUNO determine Δm_{21}^2 and θ_{12} with sub percent precision
- Precision (at sub-percent level) measurements of neutrino fluxes with future solar neutrino observatories
- DUNE, 40 kton liquid argon, 10 MeV energy threshold
- Hyper-Kamiokande, energy threshold of 6.5 MeV, several 100 kt detectors
- THEIA, water-based liquid scintillator, 1% doping by 7Li
- MICA is a 10 Mton proposed solar neutrino detector at Antarctica

Earth Structure

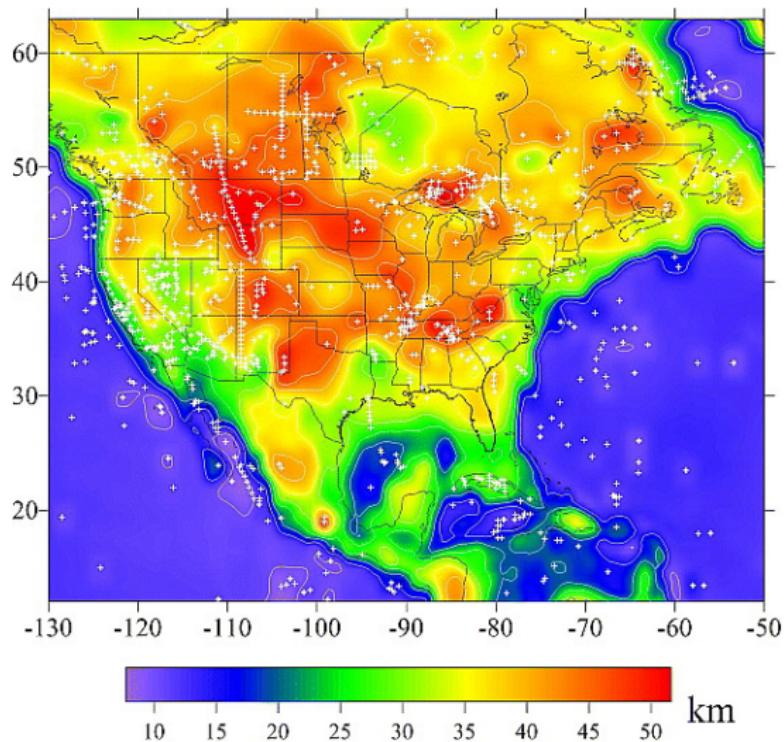
- Due to the attenuation effect, A_{ND} mainly depends on shallow density structures: crust, upper mantle, and crust-mantle border called Moho, or Mohorovicic discontinuity.
- There are two types of crust: the oceanic crust (5 - 10) km and the continental crust (20 - 90) km
- Shen-Ritzwoller model: crust 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

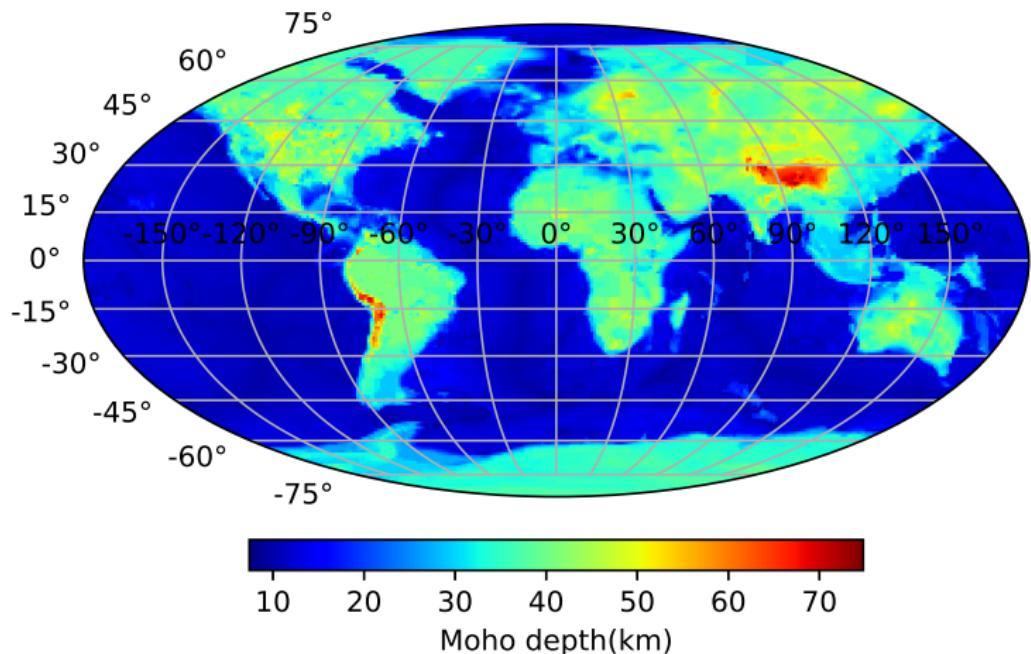


Preliminary Reference Earth Model (PREM)

Shen-Ritzwoller Moho depth

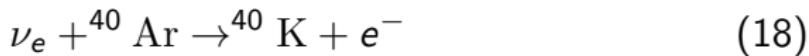


CRUST1 Moho depth



DUNE

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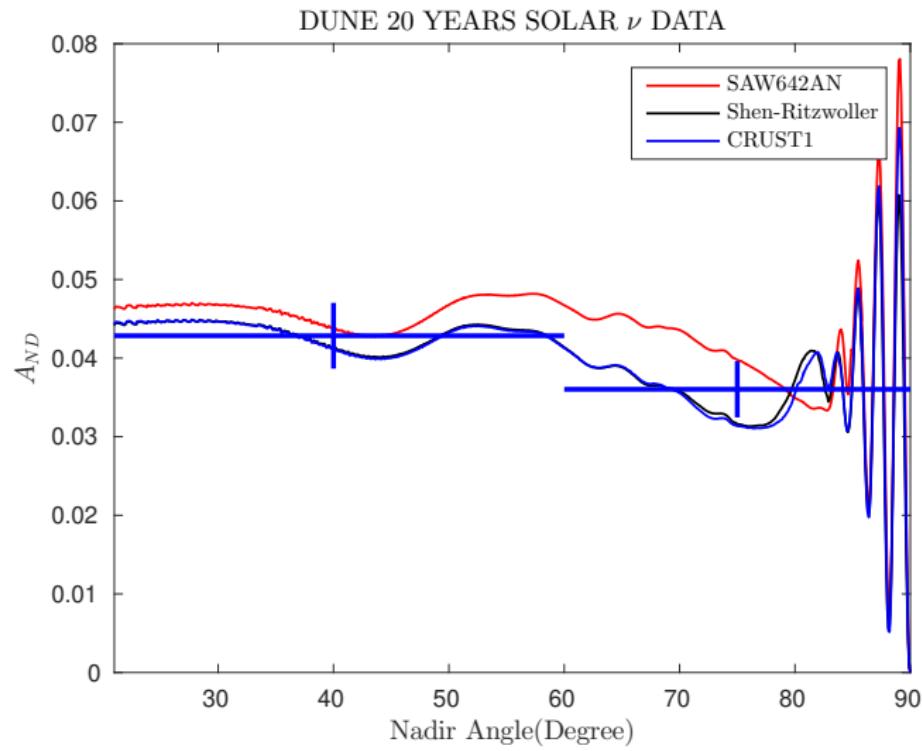
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$$\sigma_{CC}(E) = A p_e E_e \quad (19)$$

$$E_e = E_\nu - \Delta M, \quad \Delta M = 5.8 \text{ MeV}$$

- With $\sigma_E/E = 7\%$, $\lambda_{att} = 1800 \text{ km}$ for $E = 12 \text{ MeV}$
- $L > \lambda_{att}$ is $\eta_{att} = 82^\circ$
- 27000 ν_e events detected annually with $E_\nu > 11 \text{ MeV}$ 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

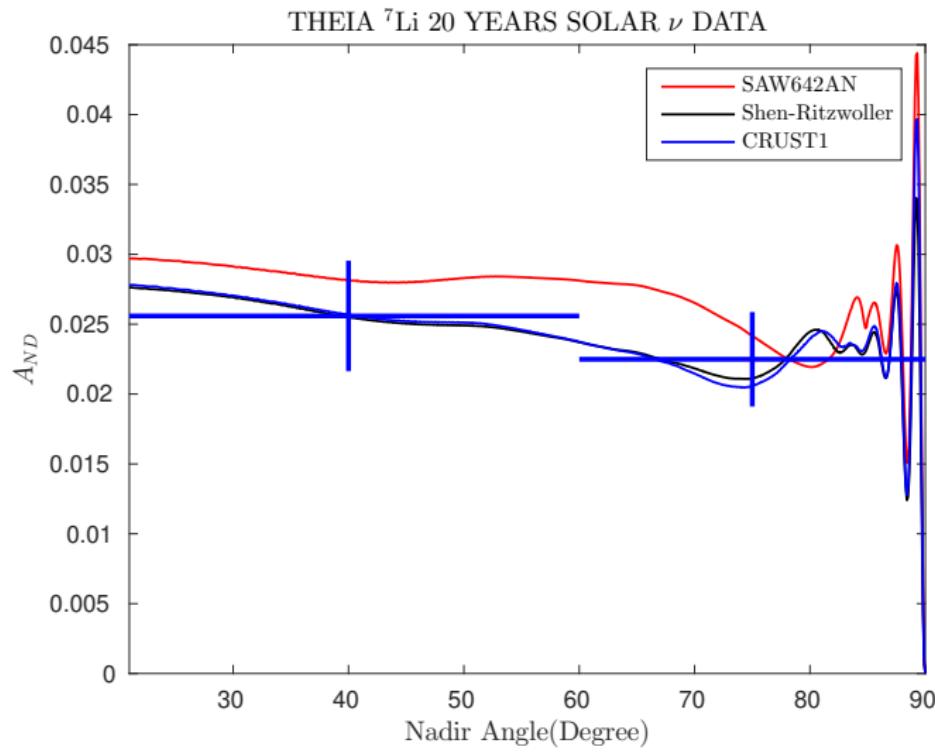
- 100 kT water-based liquid scintillator detector loaded with 1% ^7Li

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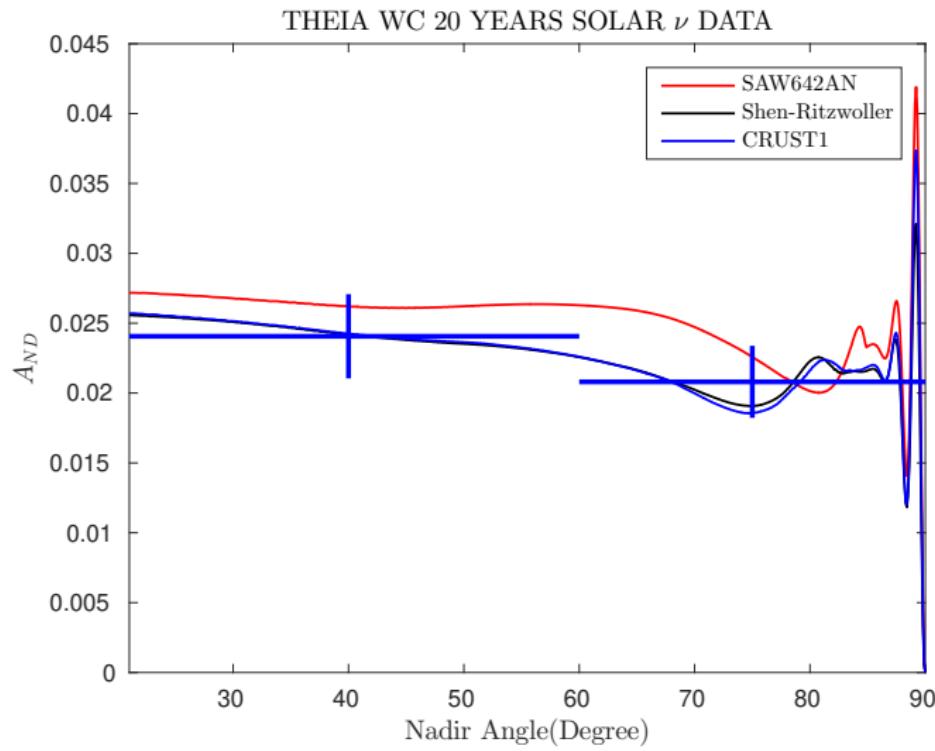


- The cross-section of this process is known with high precision.
- $\nu - e$ elastic scattering with 6.5 MeV threshold
- 17000 ^7Li and 15000 $\nu - e$ elastic scattering events are expected annually with $E_\nu > 5$ MeV
- $\sigma_E/E = 12\%$ for ^7Li and $\sigma_E/E = 15\%$ for $\nu - e$ elastic scattering
- $\bar{A}_{ND} = 0.024$ (CRUST1 and S-R) and 0.027 (SAW642AN) for ^7Li , 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

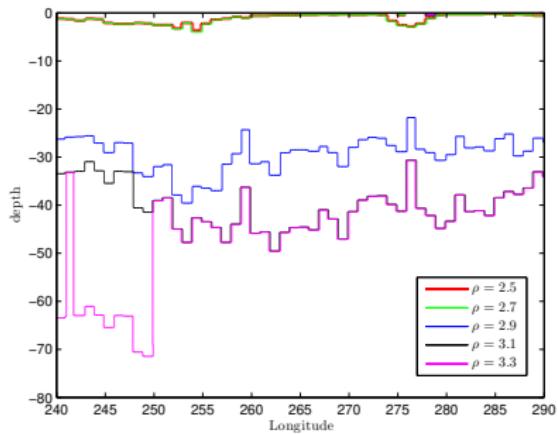
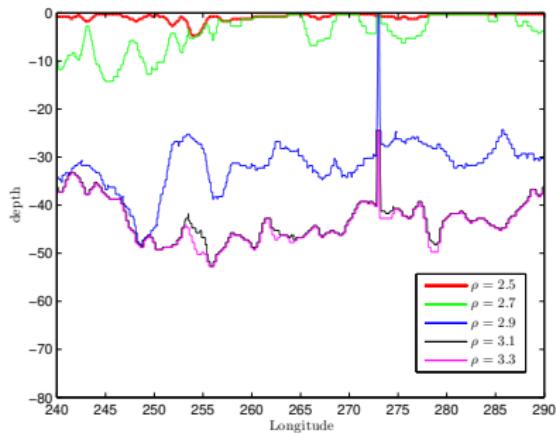
$A_{ND}(\eta)$ at THEIA



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



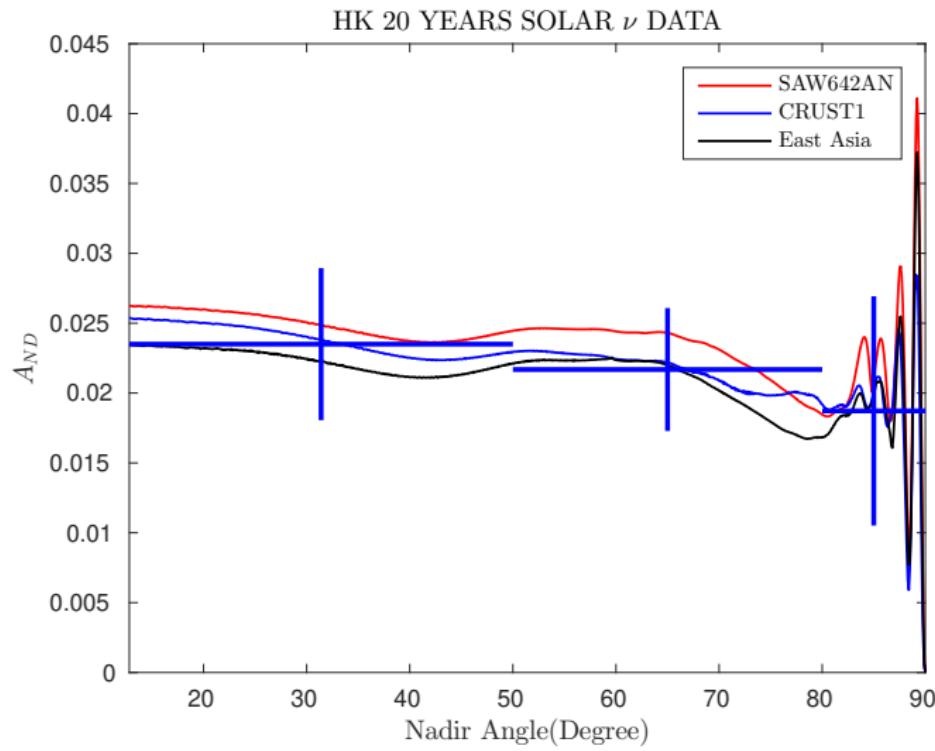
S-R. vs. CRUST1 model beneath homestake mine



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

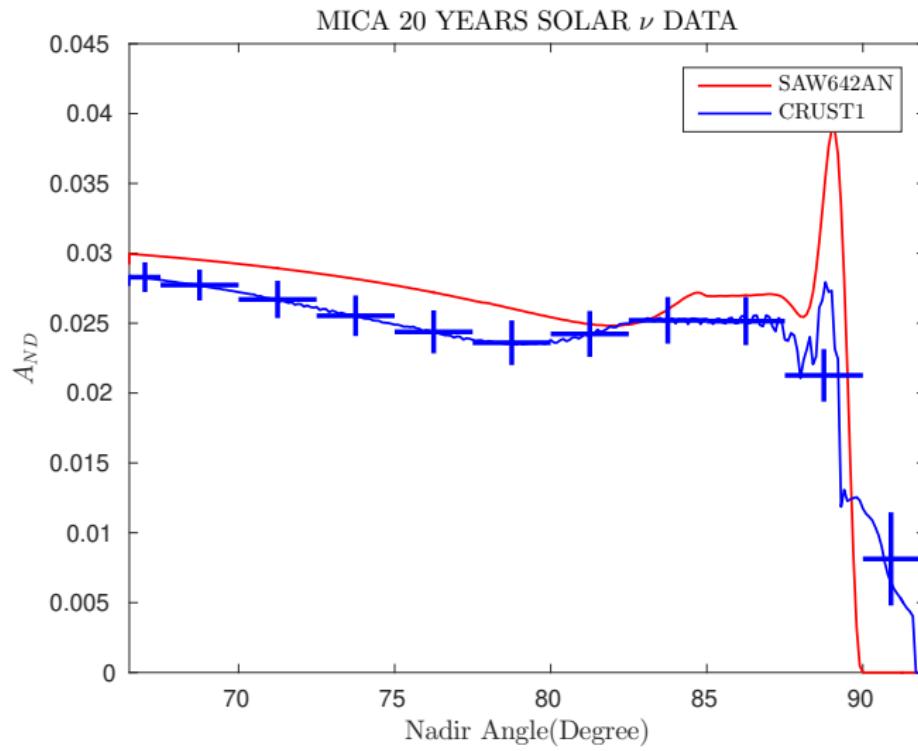
$A_{ND}(\eta)$ at HK



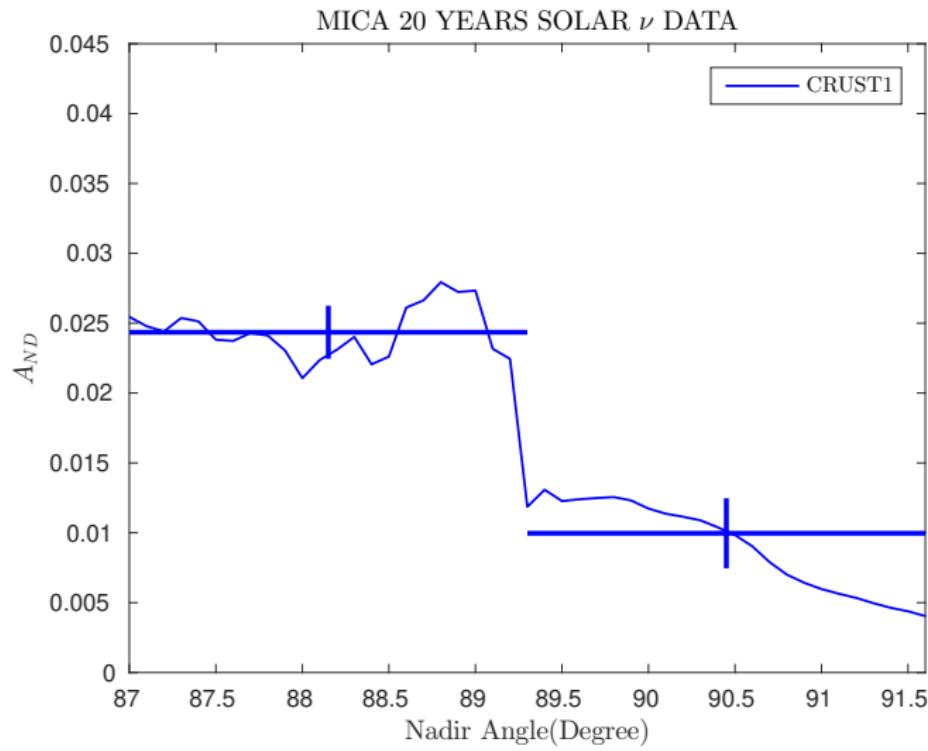
MICA

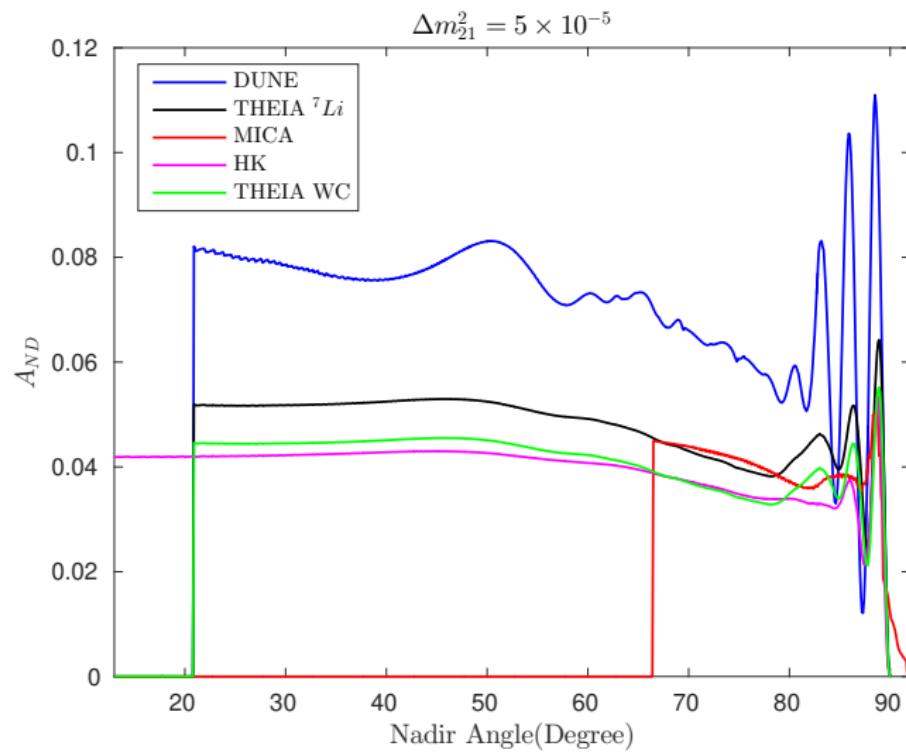
- Megaton scale Ice Cherenkov Array (MICA)
- $\nu - e$ elastic scattering with 10 MeV threshold
- 10 Mton fiducial mass
- $\sigma_E/E = 15\%$
- 5×10^5 solar $\nu e -$ scattering events are expected per year
- MICA detector at a depth of 2.25 km below the icecap (as the Deep Core). The height of icecap 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

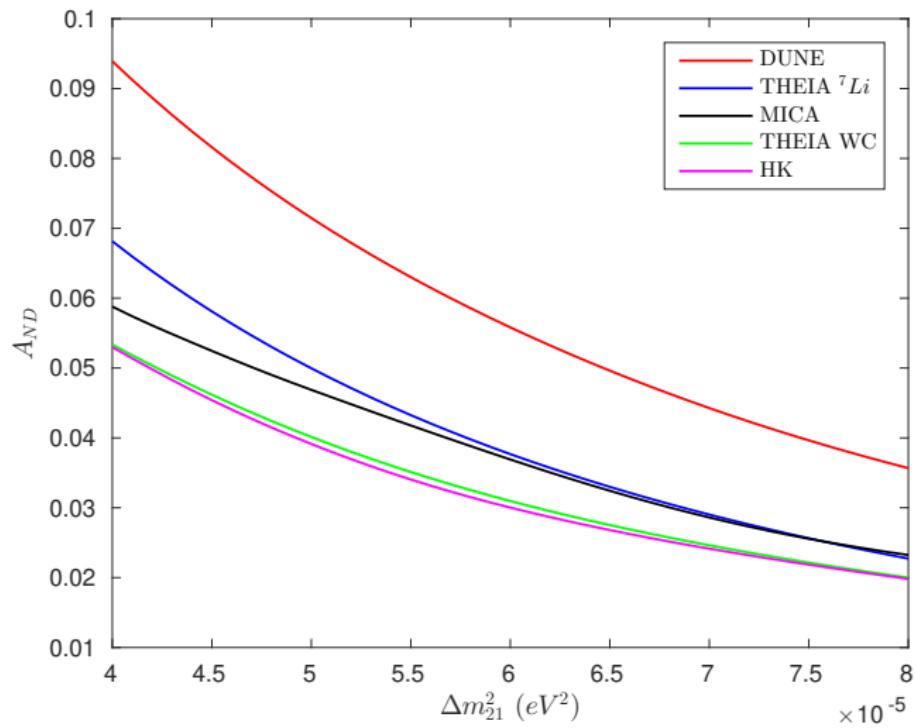
$A_{ND}(\eta)$ at MICA



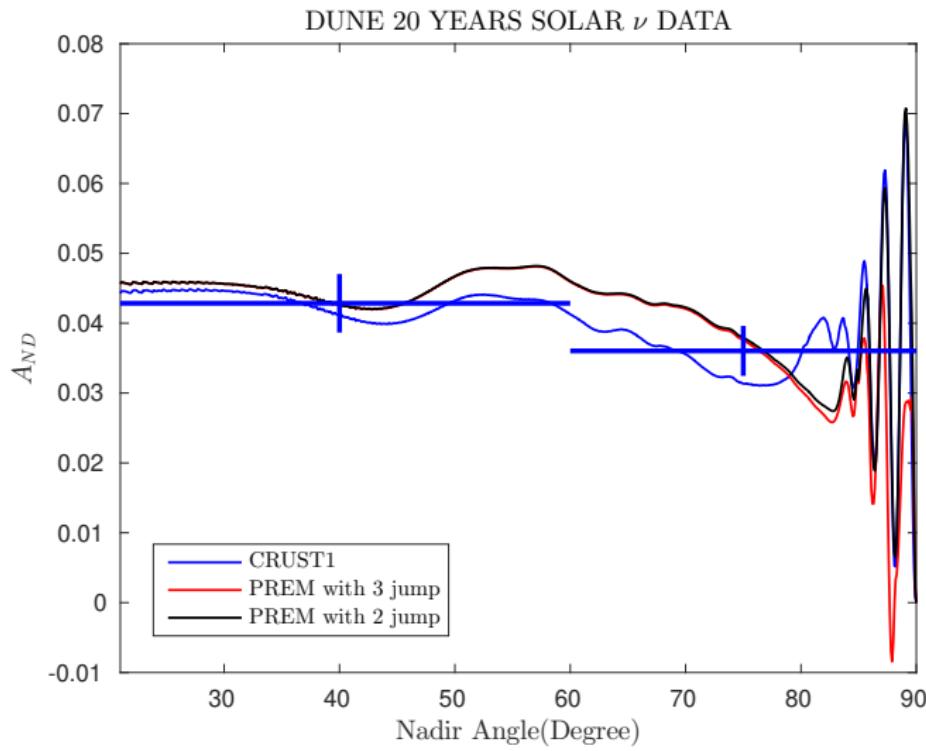
$A_{ND}(\eta)$ at MICA and Ice-Soil borderline



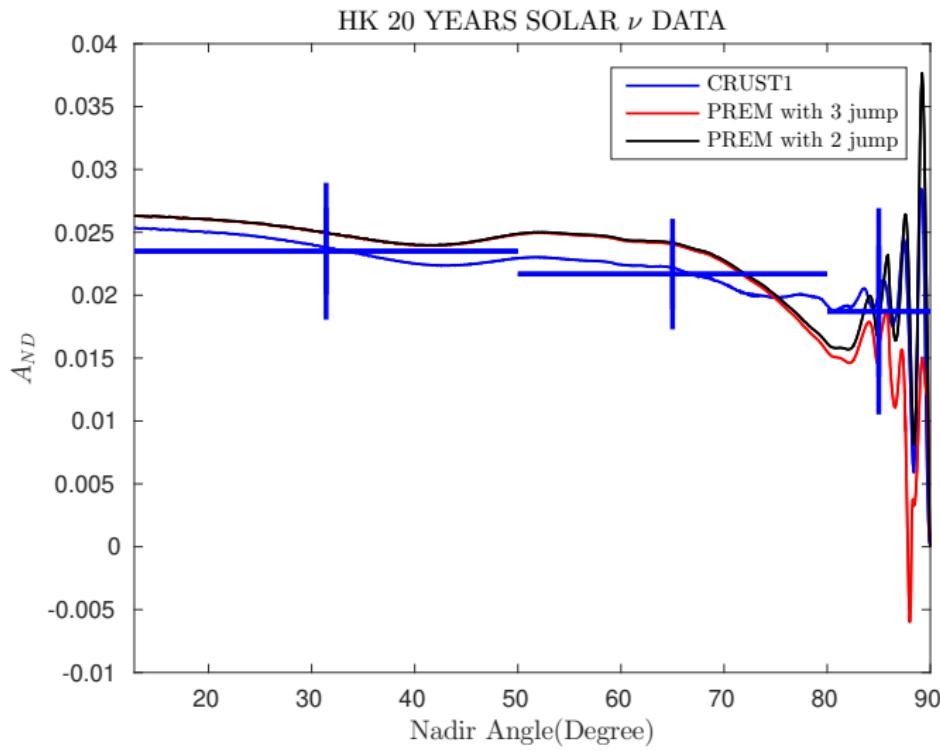
$A_{ND}(\eta)$ with $\Delta m_{21}^2 = 5 \times 10^{-5}$ 

\bar{A}_{ND} 

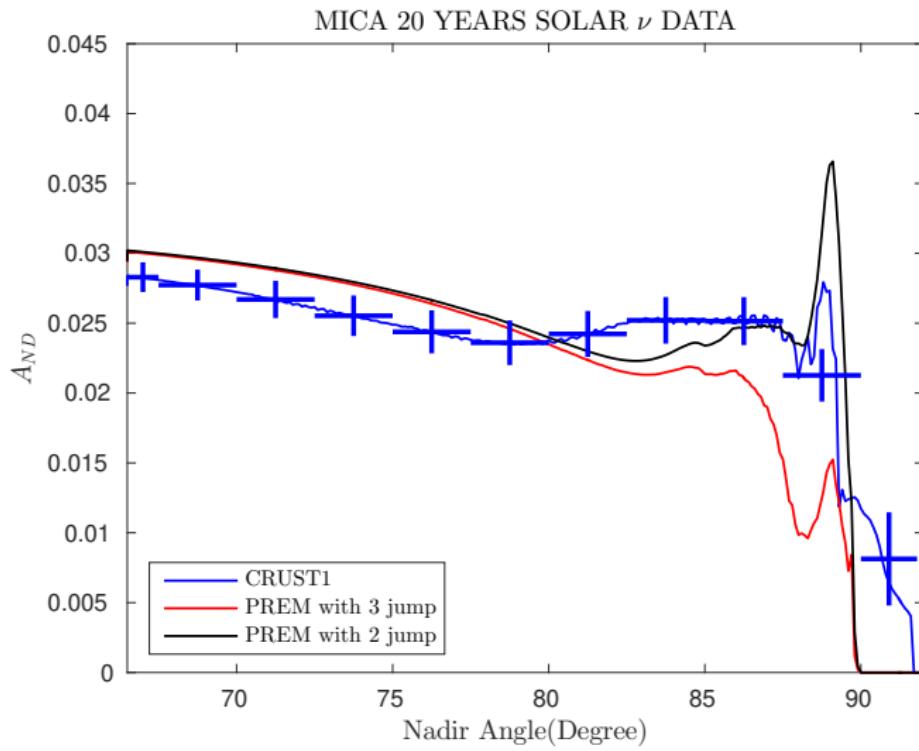
DUNE and PREM



HK and PREM



MICA and PREM



Summary

- JUNO 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
- We will be sensitive to the depth of Moho, and 3D earth models with $1\sim 2 \sigma$ C.L. at DUNE, HK, THEIA
- For high-level discrimination, the Megaton scale (MICA) experiments are required
- 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

Thank you for your attention.