Oscillation tomography of the Earth with solar neutrinos and future experiments

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Abstract

We study in details the Earth matter effects on the boron neutrinos from the Sun using 3D models of the Earth. The nadir angle (η) dependences of A_{ND} are computed for future detectors DUNE, THEIA, Hyper-Kamiokande and MICA at Antarctica. DUNE, THEIA and HK will discriminate among different models $(1-2)\sigma$. MICA can detect the ice-soil borders and perform unique tomography of Antarctica.

Introduction

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 multi-layer medium adiabatically. Due to the attenuation effect, only structures sufficiently close to a detector, and therefore to the surface of the Earth (crust, upper mantle), relevant for observation.

Day-Night Asymmetry

The ν_e survival probability during a day as function of the neutrino energy equals

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

where $c_{13} \equiv \cos\theta_{13}$, $s_{13} \equiv \sin\theta_{13}$, and

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

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

During a night the probability equals $P_N = P_D + \Delta P$, where

$$\Delta P(E) = \kappa(E)\int_0^L dx\, V(x)\sin\phi^m(L-x,E) \quad (3)$$

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

$$A_{ND}(\eta,\Delta E) \equiv \frac{\Delta N_N(\eta,\Delta E)}{N_D(\Delta E)}, \quad \Delta N_N \equiv N_N - N_D \quad (4)$$

Attenuation

$$\Delta N(E^r) = D\int dE\, g_\nu(E^r,E)\sigma(E)f_B(E)\Delta P(E) \quad (5)$$

D is the factor which includes characteristics of detection: fiducial volume, exposure time, *etc.*

Let us introduce the attenuation factor $F(L-x)$ such that the integral over E equals

$$\int dE G_\nu(E^r,E)\sin\phi^m(L-x,E) = F(L-x)\sin\phi^m(L-x,E^r) \quad (6)$$

$$\Delta N(E^r) = D\int dx V(x)F(L-x)\sin\phi^m(L-x,E^r) \quad (7)$$

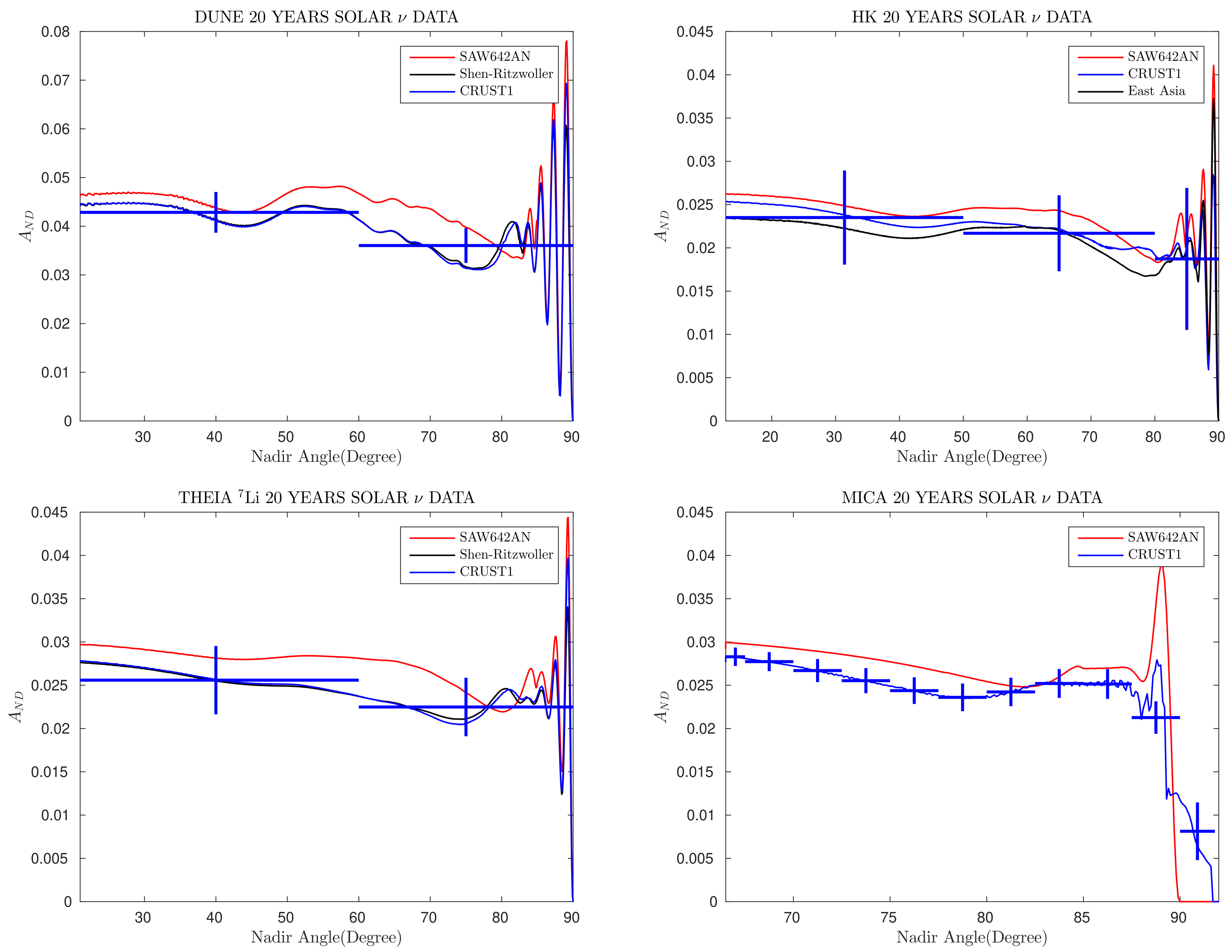
For a Gaussian energy resolution the attenuation factor is

$$F(d) \simeq e^{-2\left(\frac{d}{\lambda_{att}}\right)^2}$$

where $\lambda_{att} \equiv l_\nu \frac{E}{\pi\sigma_E}$ and $l_\nu = \frac{4\pi E}{\Delta m_{21}^2}$.

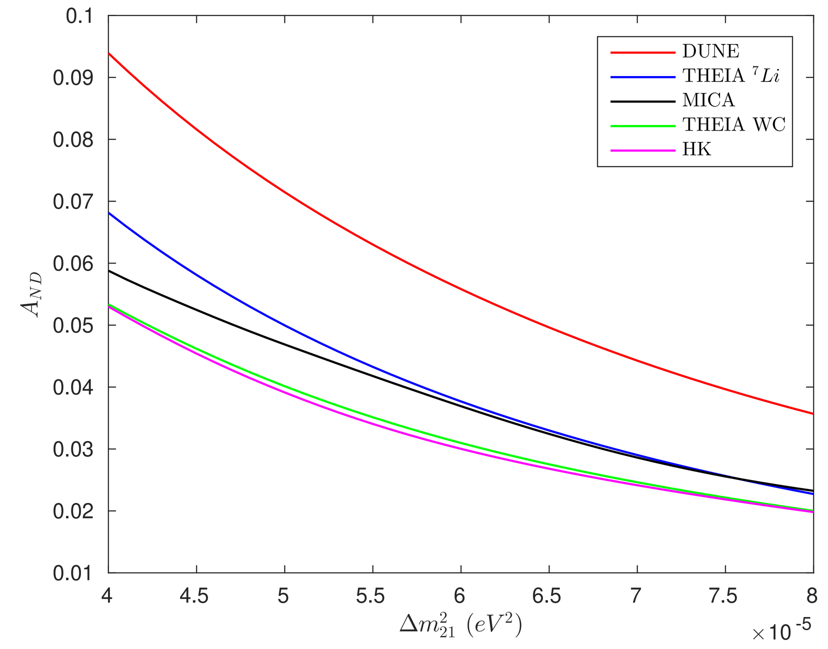
According to (7) for $d \gg \lambda_{att}$ the attenuation factor $F(d) \approx 0$, and therefore contributions of remote structures to the integral (7) and therefore to observable oscillation effect is suppressed.

Predictions of A_{ND} For Future Experiments



$A_{ND}(\eta)$ for different experiments, considering $\Delta m_{21}^2 = 7.5\times 10^{-5}$.
DUNE, THEIA and HK will discriminate among different models $(1-2)\sigma$. MICA, 10 Mton ice detector at Antarctica, will discriminate models with 5σ. MICA can detect the ice-soil borders.

A_{ND} for Different Δm_{21}^2 and PREM model



- For different values of Δm_{21}^2, $A_{ND}(\eta)$ has a similar η dependence.
- We have calculated A_{ND} for different values of Δm_{21}^2.
- Results of 1D PREM model is close to that of SAW642AN model which has a similar depth of Moho.
- The results show that usage of PREM model causes up-to 10% relative systematic error in A_{ND}.

Earth Models

There are two types of crust, continental crust and oceanic crust: The width of oceanic crust is about (5 - 10) km, while the continental crust is thicker: (20 - 90) km.
Crust-mantle border is called Moho. There is a density jump at Moho. A_{ND} is sensitive to depth of Moho.
We have considered four different 3D earth models: CRUST1, Shen-Ritzwoller, FWEA18, SAW642AN

Conclusion

We performed detailed analysis of the Earth matter effects on solar neutrinos using 3D models of the Earth. The key feature of profiles that determines the $A_{ND}(\eta)$ is the depth of Moho that differs substantially in different models. MICA can discriminate between models at 5σ C.L. and will be sensitive to the ice-soil border. DUNE, THEIA and HK exposure, they discriminate $(1-2)\sigma$.