

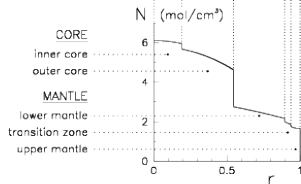
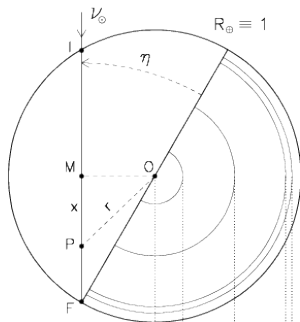
# Scanning the Earth's core with solar neutrinos at future very large neutrino detectors

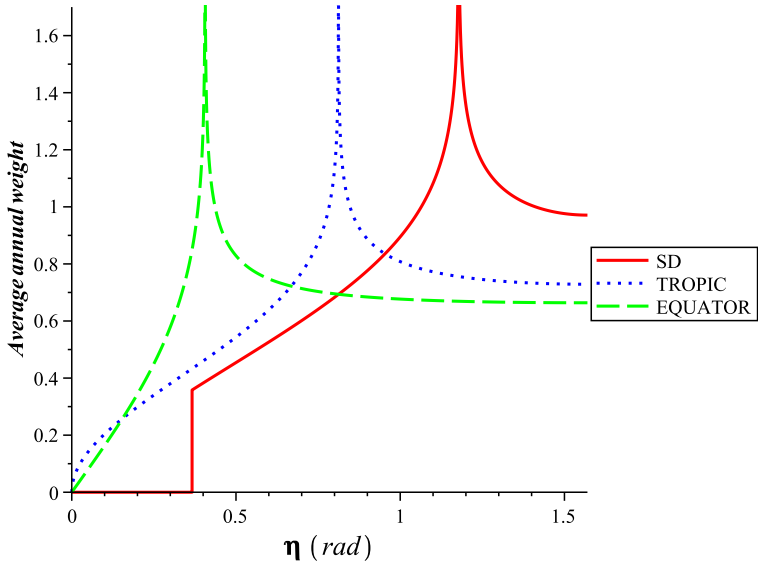
Ara N. Ioannisian

YerPhI and ITPM, Armenia  
CERN

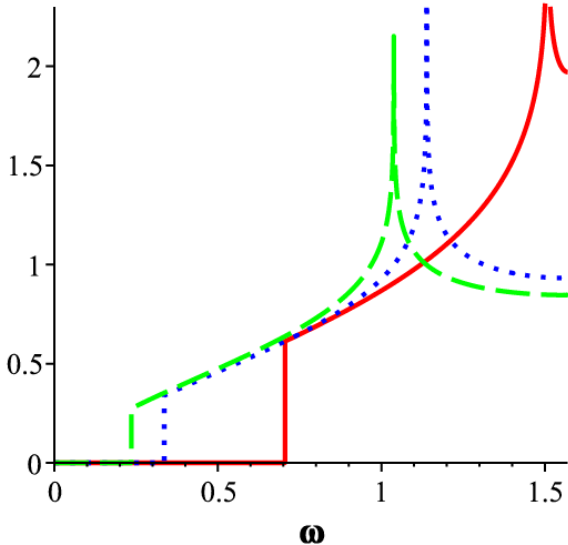
TAUP 2015, Turin

$I = \nu$  entry point  
 $F = \nu$  endpoint (detector)  
 $M =$  trajectory midpoint  
 $P =$  generic  $\nu$  position  
 $x = MP =$  trajectory coordinate  
 $r = OP =$  radial distance  
 $\eta =$  nadir angle





Dependance of average annual weight function on the nadir angle of neutrino trajectory ( $\eta$  is in radians). JUNO is on tropic. Outer core is "visable" at SD site about 9% of time



Dependance of average annual weight function on the nadir angle of neutrino trajectory ( $\omega$  is in radians). Outer core is "visible" at Kamioka site about 4.4 hours per day . Kamioka, SD, Finland

## Averaging over solar neutrino production size

From the Earth  $^8B$  neutrino production region in the Sun is seen as a disk where more neutrinos come from the center of the disk. It turns out that that distribution can be approximated as a normal one with a variance  $\delta_\eta \simeq 1.9 \times 10^{-4}$  :

$$f(\eta', \eta) = \frac{1}{\delta_\eta \sqrt{2\pi}} e^{-\frac{(\eta - \eta')^2}{2\delta_\eta^2}} = \frac{1}{\delta_\eta \sqrt{2\pi}} e^{-\frac{(L - 2R_\oplus \cos \eta)^2}{8\delta_\eta^2 R_\oplus^2 \sin^2 \eta}}$$

the change of the solar neutrino flux due to the eccentricity of the Earth orbit ( $\pm 3\%$ ) must be taken into account.

$$\epsilon \equiv \frac{2V_e E}{\Delta m_{21}^2} \approx 0.03 \left( \frac{\rho}{3 \frac{\text{g}}{\text{cm}^3}} \right) \left( \frac{7.5 \cdot 10^{-5} \text{eV}^2}{\Delta m_{21}^2} \right) \left( \frac{E}{10 \text{ MeV}} \right) \left( \frac{Y_e}{0.5} \right)$$

$$l_\nu \approx 330 \left( \frac{7.5 \times 10^{-5} \text{eV}^2}{\Delta m_{21}^2} \right) \left( \frac{E}{10 \text{ MeV}} \right) \text{km}$$

$$\phi_{x_k \rightarrow x_n}^m \equiv \int_{x_k}^{x_n} dx \frac{\Delta m_{21}^2}{2E} \sqrt{(\cos 2\theta_{12} - \epsilon(x))^2 + \sin^2 2\theta_{12}}$$

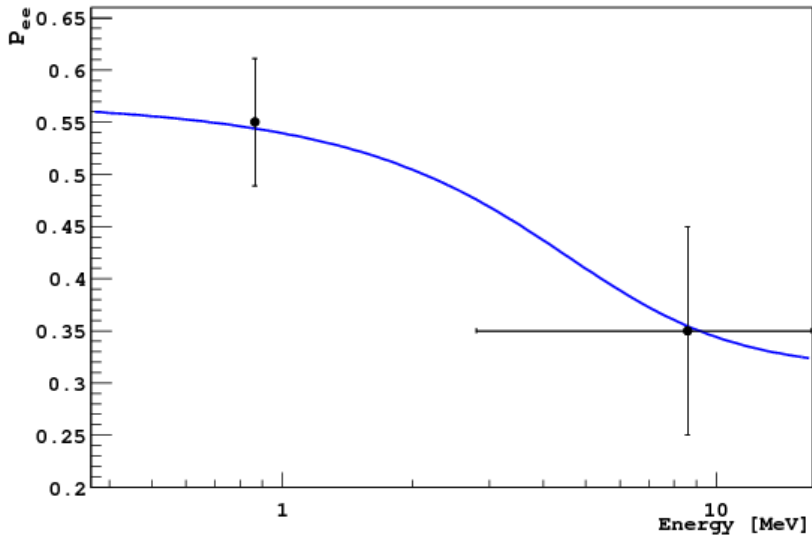
$$\frac{P_N - P_D}{P_D} = -f(\Delta m_{21}^2, \theta_{12}) \frac{1}{2} \int_0^L dx V(x) \sin \phi_{x \rightarrow L}^m$$

where

$$f(\Delta m_{21}^2, \theta_{12}) = \frac{2 \cos 2\theta_{12}^{\odot} \sin^2 2\theta_{12}}{1 + \cos 2\theta_{12}^{\odot} \cos 2\theta_{12}} = \frac{(2P_{ee} - 1) \sin^2 2\theta_{12}}{P_{ee} \cos 2\theta_{12}}$$

$f(\Delta m_{21}^2, \theta_{12}) \simeq -2.3$  for  $\tan^2 \theta = 0.45$  ( $\theta = 34^\circ$ ) and  
 $\Delta m^2 = 7.5 \times 10^{-5} \text{ eV}^2$  ( $P_{ee} \simeq 1/3$ )

$$V \rightarrow V \cdot \cos(\theta_{13})^2 \simeq V \cdot 0.98$$



$$P_D \equiv P_{ee} = \frac{1}{2}(1 + \cos 2\bar{\theta}_{12}^{\odot} \cos 2\theta) + s_{13}^4$$

## Averaging over neutrino energy

$$A_e = \int dE' g(E', E) \frac{P_N - P_D}{P_D} .$$

$$A_e = -f(\Delta m_{21}^2, \theta_{12}) \frac{1}{2} \int_0^L dx V(x) F(L-x) \sin \phi_{x \rightarrow L}^m,$$

The decrease of  $F$  means that contributions from the large distances to the integral are suppressed.

## Gaussian energy resolution function

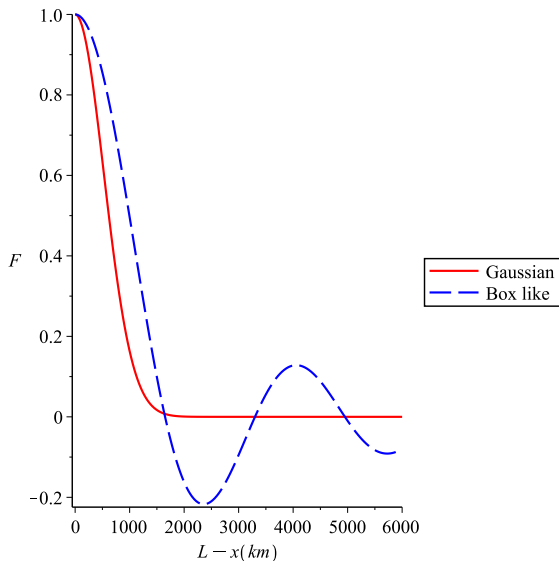
$$g(E, E') = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2}}, \quad F(L-x) \simeq e^{-2\left(\frac{\pi\sigma(L-x)}{E l_\nu}\right)^2}$$

## Box like energy resolution function

$$A_e = \frac{1}{2\sigma} \int_{E-\sigma}^{E+\sigma} dE' \frac{P_N - P_D}{P_D}$$

$$F(L-x) \simeq \frac{1}{Q(L-x)} \sin Q(L-x), \quad Q(L-x) \equiv \frac{2\pi\sigma(L-x)}{E l_\nu},$$





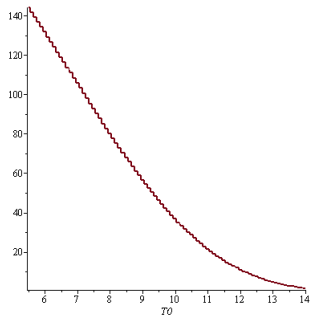
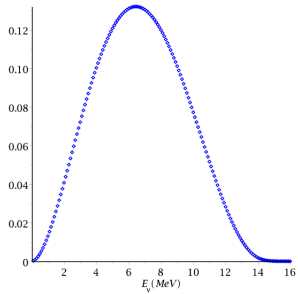
The attenuation factor  $F$  as function of  $(L-x)$  (distance from detector).  $E = 10$  MeV,  $\sigma = 1$  MeV, and  $\Delta m_{21}^2 = 7.5 \cdot 10^{-5}$  eV<sup>2</sup>

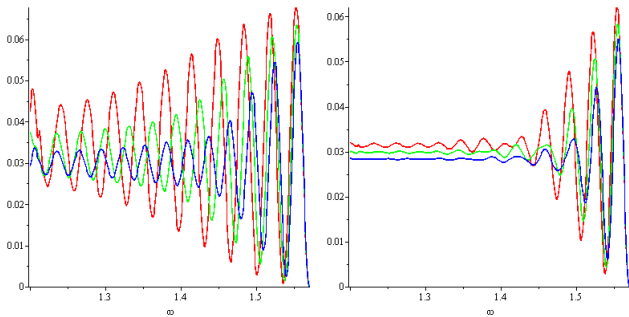
WC

$$A_e(T, \eta) = \frac{\int dT' g(T, T') \int_{T+\frac{m_e}{2}} dE \Delta P_{ee}(E) j_B(E) \left( \frac{d\sigma_{\nu ee}}{dT'} - \frac{d\sigma_{\nu \alpha e}}{dT'} \right)}{\int dT' g(T, T') \int_{T+\frac{m_e}{2}} dE j_B(E) \left( P_{ee} \frac{d\sigma_{\nu ee}}{dT'} + (1 - P_{ee}) \frac{d\sigma_{\nu \alpha e}}{dT'} \right)}$$

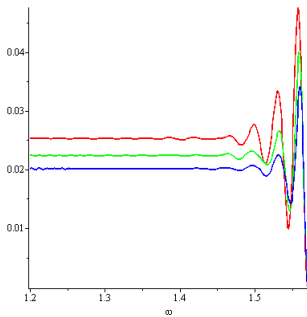
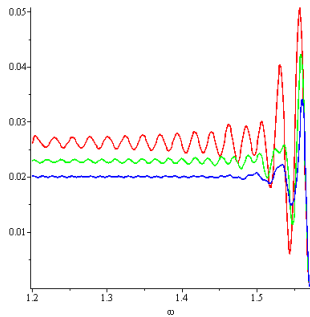
$$\Delta P_{ee} = P_N - P_D = \left( \frac{1}{2} - P_{ee} \right) \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \int_0^L dx V(x) \sin \phi_{x \rightarrow L}^m$$

$$\frac{d\sigma_{\nu ee}}{dT'} / \frac{d\sigma_{\nu \alpha e}}{dT'} \simeq 6$$

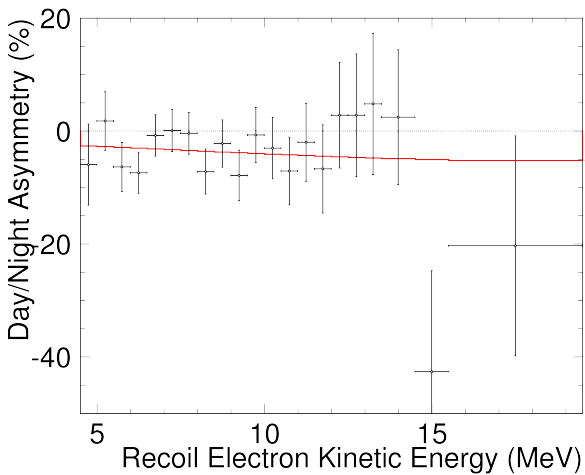




▶  
 $T_e = 13, 12, 11$  MeV



$T_e = 9, 7, 5 \text{ MeV}$



SK First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation  
Phys. Rev. Lett. 112, 091805, 2014

SK recent result  $A = 3.2 \pm 1.1 \pm 0.5$  and got  $\Delta m^2 \simeq 5 \cdot 10^{-5} \text{ eV}^2$  2  
sigma away from KamLAND  $\Delta m^2 \simeq 7.5 \cdot 10^{-5} \text{ eV}^2$

FULL 3D analyse of the data

fit with Kamland  $\Delta m^2 = 7.5 \cdot 10^{-5} \text{ eV}^2$

make use "periodograms"

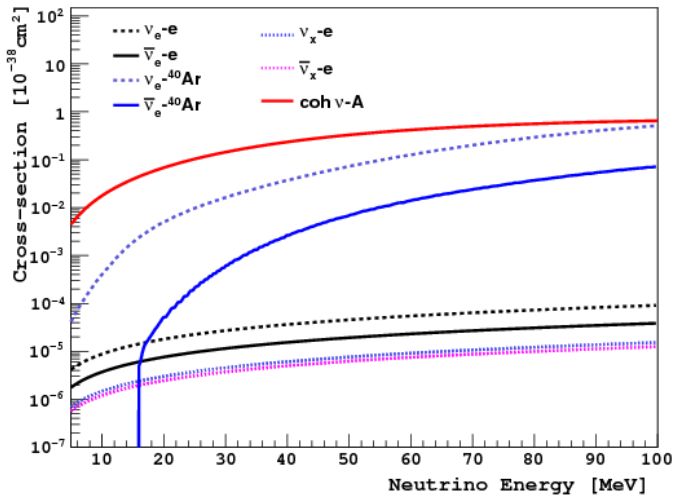
look to the high energy edge of the spectrum

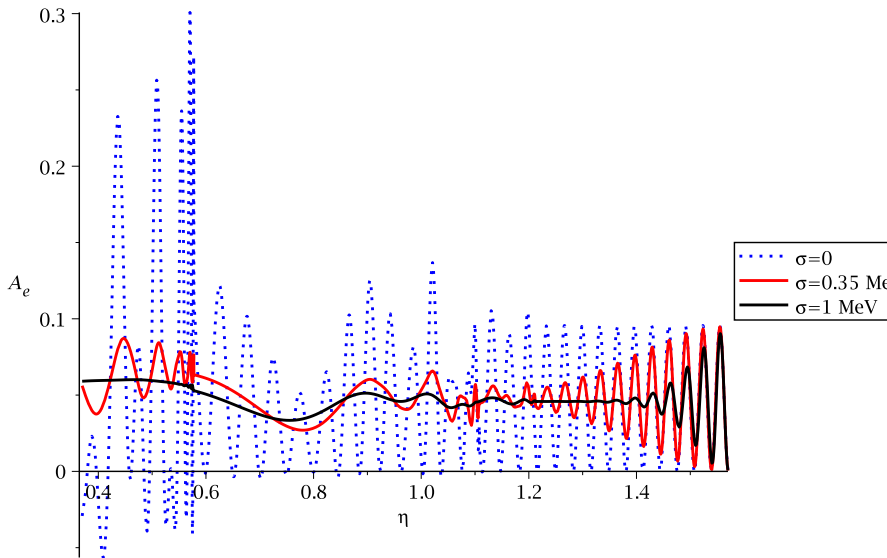
## Liquid Argon

$$A_e(E) = \frac{\int dE' g(E, E') \sigma_{\nu Ar}(E') f_{B8}(E') \Delta P_{ee}(E')}{\int dE' g(E, E') \sigma_{\nu Ar}(E') f_{B8}(E') P_{ee}(E')}$$

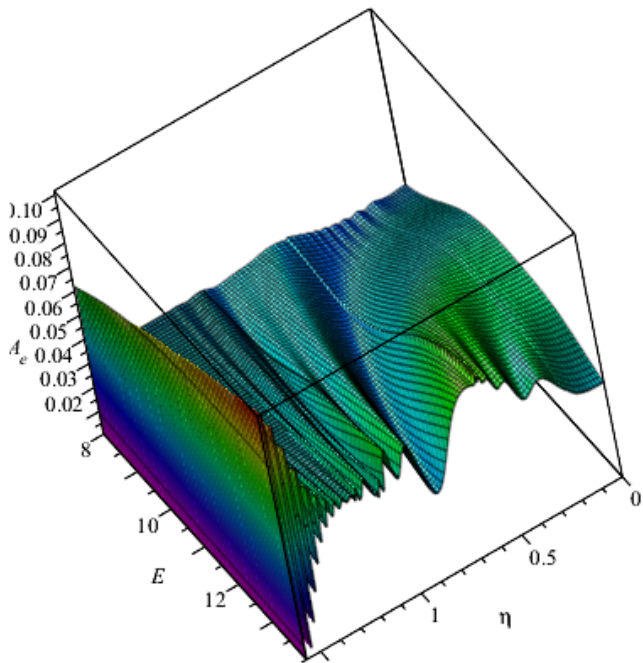
$$\Delta P_{ee} = P_N - P_D = \left(P_{ee} - \frac{1}{2}\right) \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \int_0^L dx V(x) \sin \phi_{x \rightarrow L}^m$$

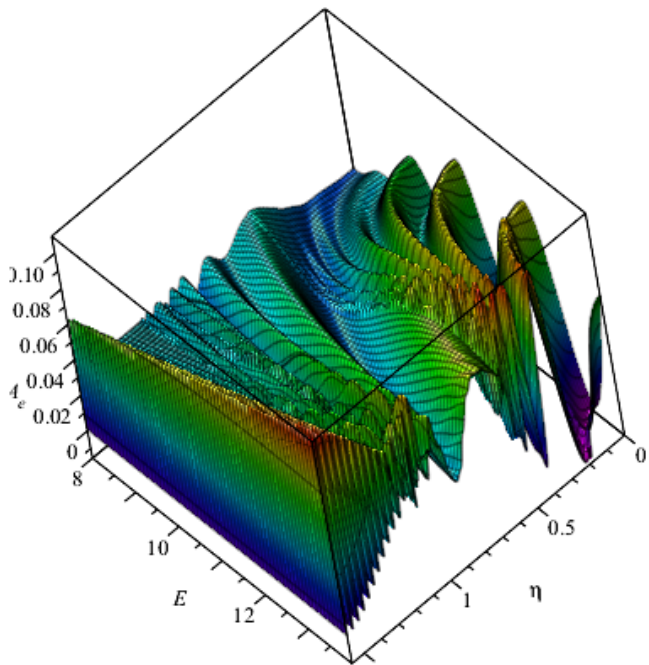






E=12 MeV





the change of the solar neutrino flux due to the eccentricity of the Earth orbit ( $\pm 3\%$ ) must be taken into account.

Each bin must cover nadir angle diapason larger than the visible sun size ( $(\eta_{i+1} - \eta_i) > 6 * \delta_\eta \simeq 4 * 10^{-4}$ )

if one chooses the bins in such a way that in each bin (without regeneration effect) it is expected to have an equal detected neutrinos

$$(\eta_{i+1} - \eta_i) = y_0 / W(\eta_i)$$

where  $W(\eta)$  is average annual weight function.

Then the  $\chi^2$  method gives

$$\chi^2 = \frac{1}{N} \sum_i^n (y(\eta_i) - y_0 - y_0 A(\eta_i))^2$$

Here  $y_i$  is number of registered neutrinos at the  $i$ -rd bin and  $A(\eta_i)$  is expected regeneration effect at nadir angle  $\eta_i$ .  $N$  is number of all detected neutrinos during the night time.

Let rewrite it

$$\chi^2 = 1/N \sum_i^n (y(\eta_i) - y_0)^2 + y_0^2 A(\eta_i)^2 + y_0^2 A(\eta_i) - 2y(\eta_i)A(\eta_i))$$

During the run of variables ( $\Delta m_{21}^2$  and  $\theta_{12}$ ) for minimization of  $\chi^2$  the second and third terms under the sum are averaged to  $\simeq y_0^2 \bar{A}$  and  $\simeq y_0^2 \bar{A}^2 3/2$ . ( $\bar{A}$  is an average value of relative change of the electron neutrino flux). And they are weakly depend on neutrino oscillation parameters.

Only the last term variate strongly and we may write the following periodogram

$$\sum_i^n y(\eta_i) A(\eta_i)$$

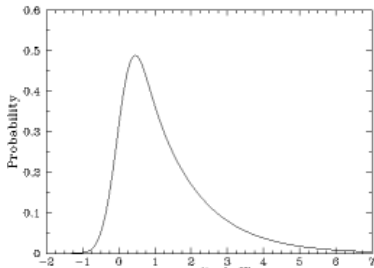
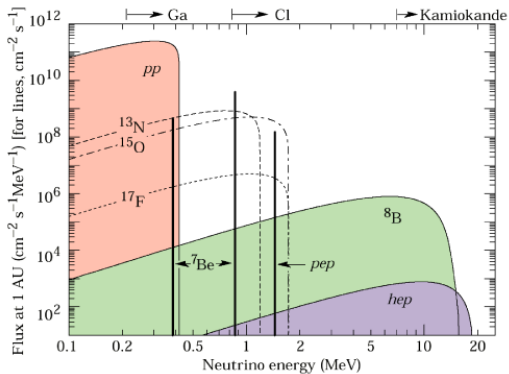
and look for its *maximum* for determination of solar  $\Delta_{21}^2$  with high precision.

Due to excellent energy resolution LiAr DUNE far detector may see deep layers of the Earth

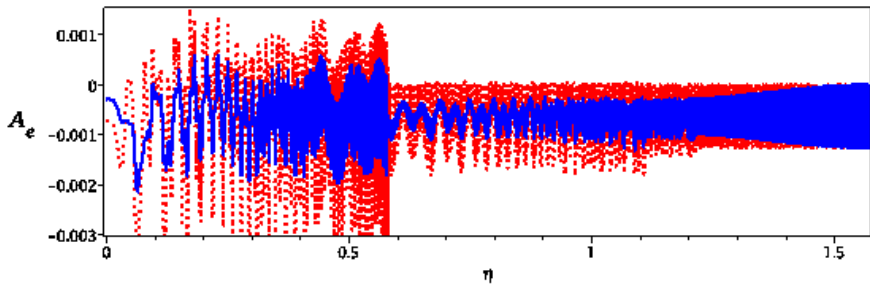
DUNE expected to detect about 100 solar neutrinos per day. Even with 3 captured neutrinos per day DUNE can see the Day-Night effect with over 2 sigma in just one year. It can determine solar  $\Delta m_{\odot}^2$  with 10 % accuracy (or better).

independent measurement of electron number density  $\rightarrow$  chemical composition of the Earth matter.

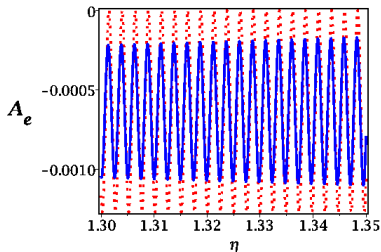
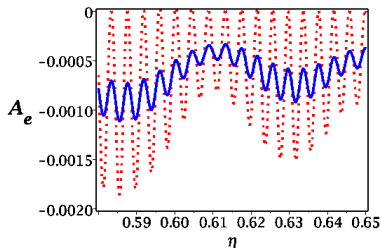
some lights on chemical composition of the Earth's core.



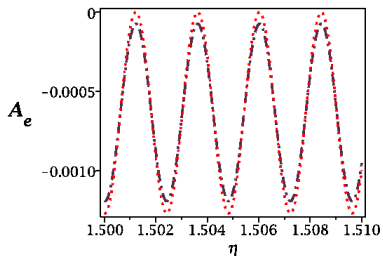
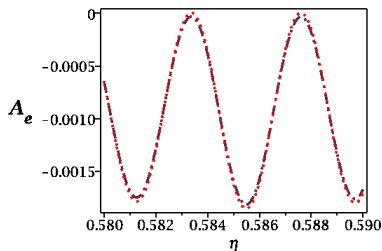




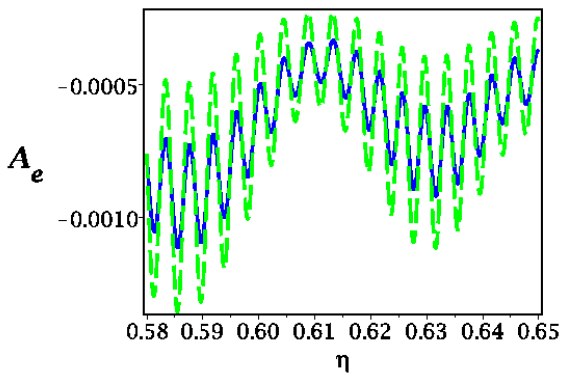
The relative variations of the electron neutrino flux as function of the nadir angle of the neutrino trajectory. Dotted (red) line shows  $A_e^0$  without averaging; solid (blue) line is  $A_e$  which corresponds to the variations averaged over the energy spectrum of the  ${}^7\text{Be}$  neutrinos. Spherical symmetry of the Earth is assumed.



with two zoomed regions:  $\eta = [0.58 - 65]$  (left) and  $[1.3 - 1.35]$  (right).



Effect of averaging over the production region of  ${}^7\text{Be}$  neutrinos in the Sun. The relative change of the electron neutrino flux for mantle crossing trajectories with  $\eta = 0.58 \dots 0.59$  (left) and  $1.5 \dots 1.51$  (right) without (dotted line) and with (dash-dotted line) averaging.



The relative change of the electron neutrino flux for the mantle crossing trajectories as the function of  $\eta$  for two different values of width of the  ${}^7\text{Be}$  line which correspond to two different temperatures in the center of the Sun: Solid line for sun central temperature  $T_{\odot} = 15.55 \times 10^6$  (solid line)  $7.77 \times 10^6$  degree (dashed line).

# Summary

WC detectors are "shortsighted" and cannot see deep layers of the Earth

LS JUNO has excellent location (tropic) and will be able to see the core of the Earth.

LiAr DUNE has very good energy resolution, it can measure the electron number density profile of the Earth, chemical composition of the mantle, and chemical composition of the core.

THANK YOU