Preliminary Estimation of the Sensitivity of ^{8}B Solar Neutrino Earth Matter Effect

Ling Liu (Tsinghua University)
Ce Jiang (NanKai University)
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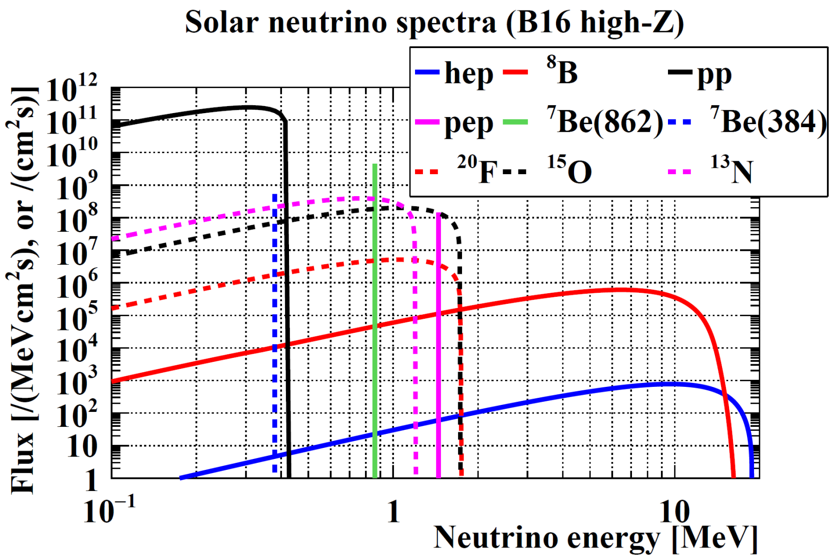
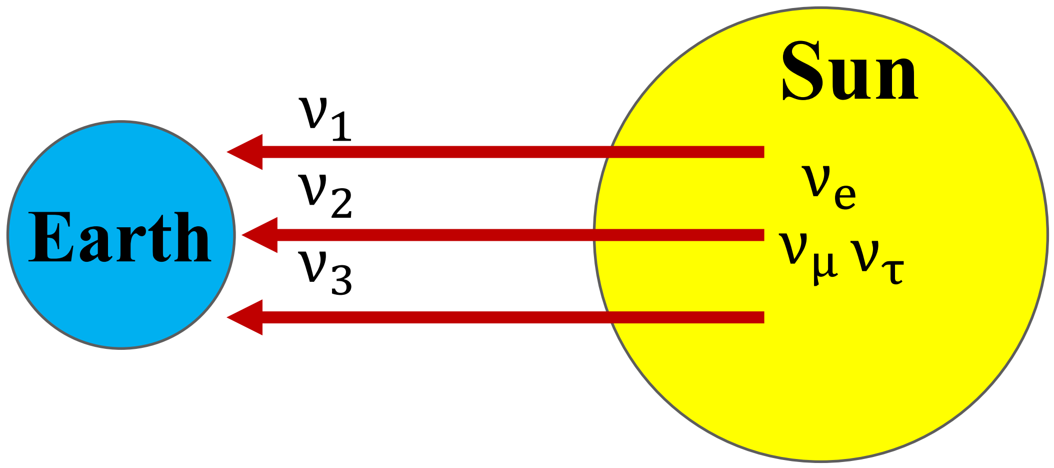
Introduction

Brief Introduction of Solar Neutrino

- Solar neutrinos are produced by thermonuclear fusion reactions occurring in the solar interior. Neutrinos from different reaction channels exhibit distinct energy spectrum shapes.
- After traversing the long-distance flight from the Sun to the Earth, solar neutrinos undergo decoherence and ultimately arrive at Earth as incoherent mass eigenstates.





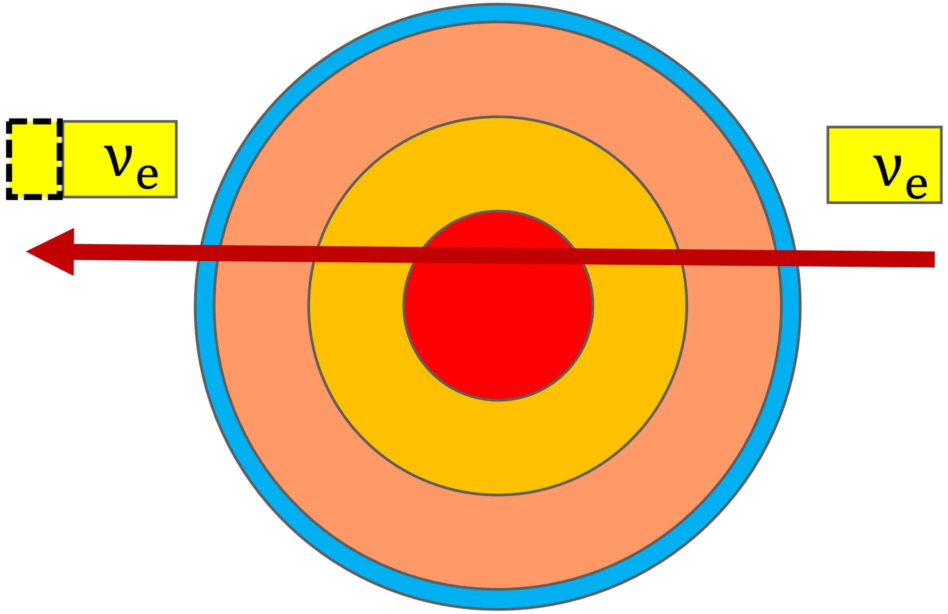
Earth Matter Effect

- According to the theoretical prediction of the MSW effect, when solar neutrinos pass through the Earth, the probability of the mass eigenstates splitting into ν_e flavor states increases under the influence of Earth's matter.

- the ν_e neutrino flux at night is enhanced compared to that during the day, leading to an asymmetry in the number of day-night events. This is known as the day-night asymmetry effect. The day-night asymmetry is defined as

$$A_{DN} = \frac{N-D}{D}.$$

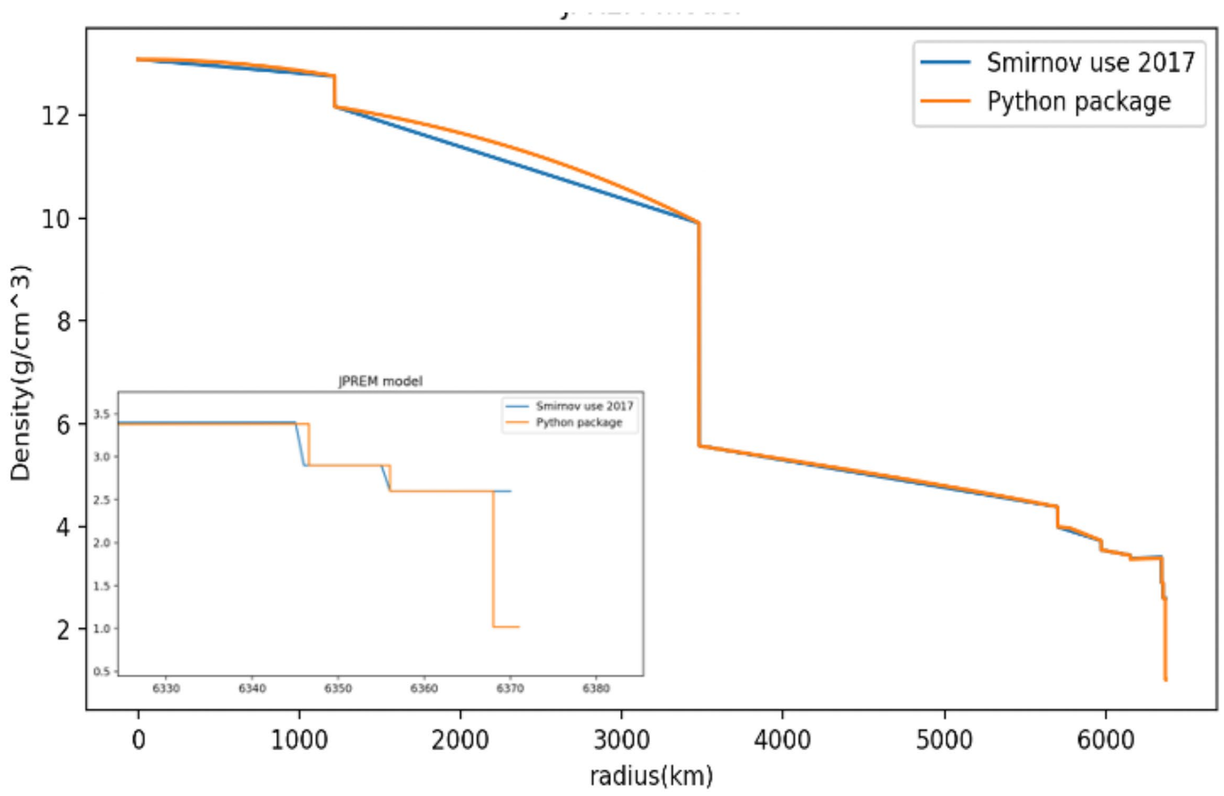
  - *N: the number of night events*
  - *D: the number of day events*



Earth Matter Effect

- The density distribution of the Earth exhibits a layered structure, where the adiabatic condition is disrupted at density discontinuities, causing neutrinos to undergo non-adiabatic evolution.

- A one-dimensional Earth model (PREM) will be employed to estimate the confidence level of the Earth matter effect.

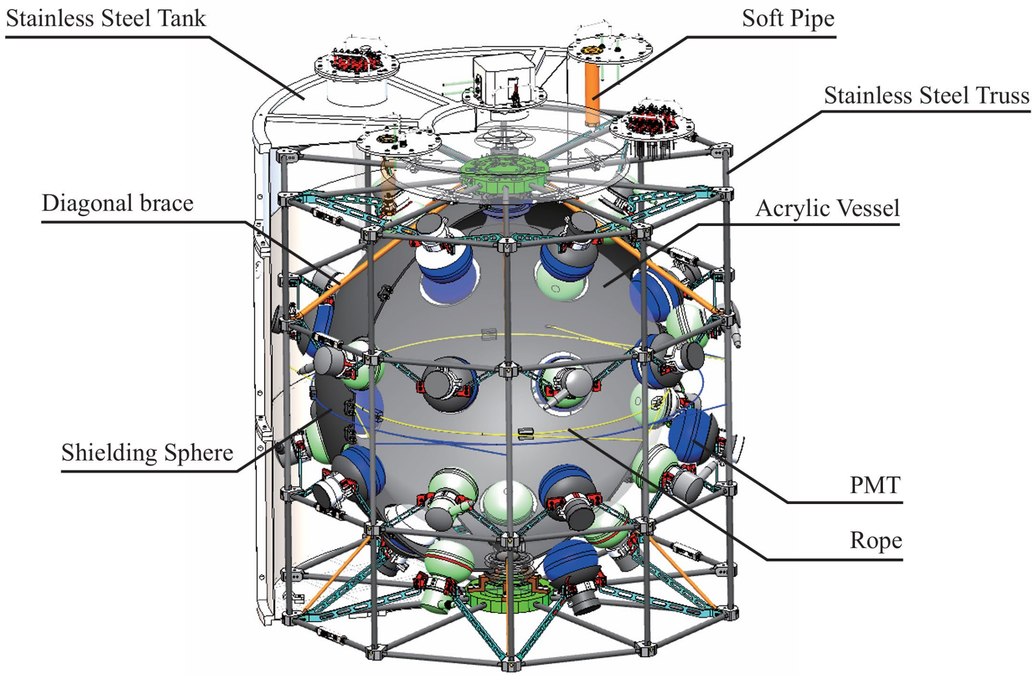


Jinping Neutrino Experiment

1 ton detector

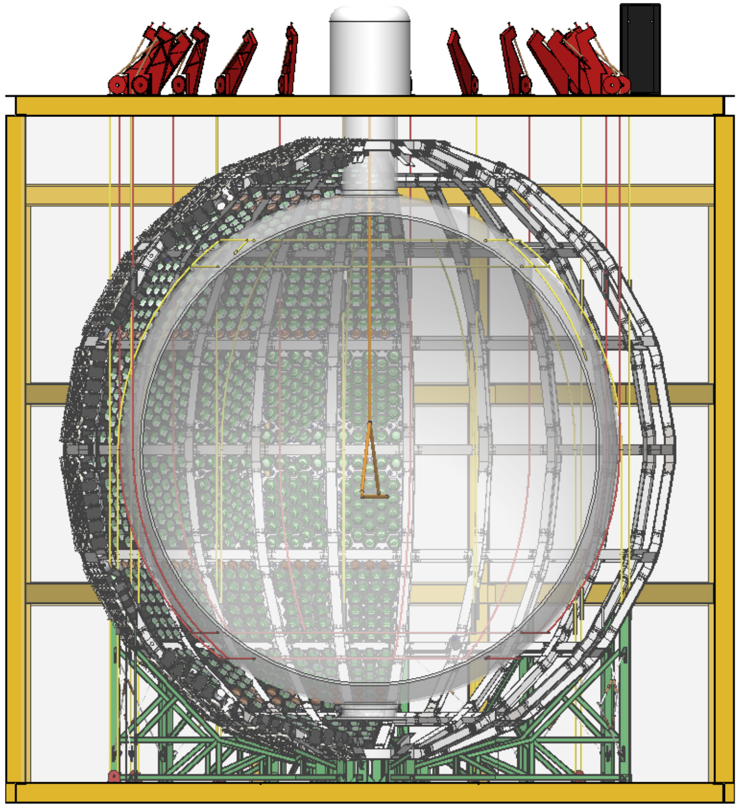
The Jinping Neutrino Experiment (JNE) is conducted at the China JinPing underground Laboratory (CJPL). Currently, a one-ton detector is in operation, and a series of tasks have been completed, including:

- background measurement and optimization,
- preparation and property characterization of liquid scintillator,
- performance testing of photomultiplier tubes,
- detector calibration.



500 ton Detector

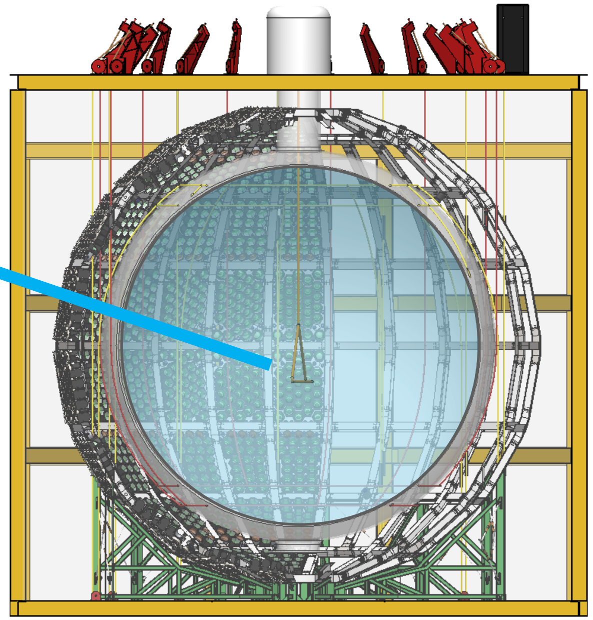
- For the main component used in slow liquid scintillator, one approach is to use a saturated aqueous solution of lithium chloride (LiCl).



Main Interaction Process of ν_e in the detection medium

The detection medium is assumed to be a saturated aqueous solution of LiCl at 10℃.

- Its density is approximately 1.2 g/ml,
- the solubility of LiCl is about 45%,
- The molar concentrations of ^{7}Li and e^{-} are 11 and 610 mol/L respectively.



Under this premise, we consider the two scattering processes that occur between neutrinos and the detection target material:

- LiCC Scattering Process: $\nu_e + {}^{7}\mathrm{Li} \rightarrow {}^{7}\mathrm{Be} + e^{-} (+\gamma)$
- Elastic Scattering Process: $\nu_\alpha + e^{-} \longrightarrow \nu_\alpha + e^{-} \quad (\alpha = e, \mu, \tau)$

The two main reaction processes of ^{8}B solar neutrinos with the detector target material

Process I: Charged-current Scattering on ^{7}Li Nuclei

^{8}B solar neutrinos undergoing charged-current scattering on ^{7}Li nuclei (LiCC):

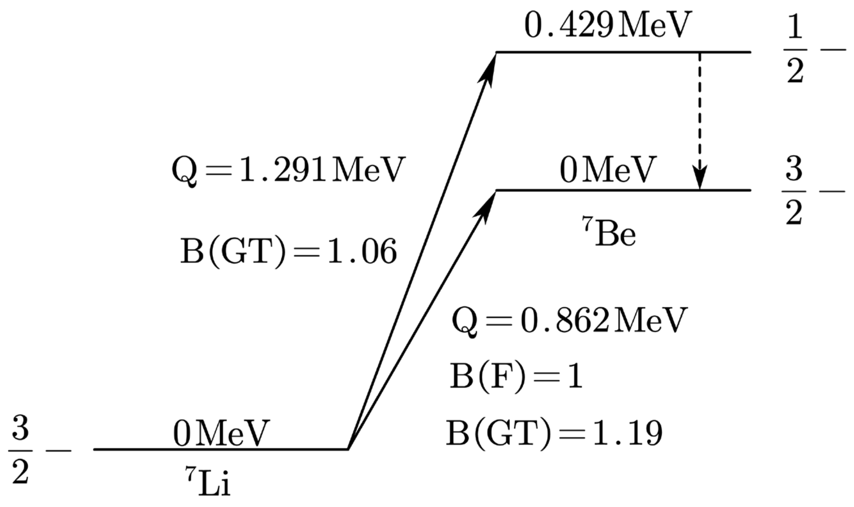
$$\nu_e + {}^7\mathrm{Li} \rightarrow {}^7\mathrm{Be} + e^-(+\gamma)$$

Formula for calculating the scattering cross section:

$$\sigma = \sigma_0 \frac{w_e P_e}{2\pi\alpha Z} F(w_e, Z)$$

Expression for calculating σ_0:

$$\sigma_0 = \frac{2\alpha Z m_e^2 G_F^2 |V_{ud}|^2}{\hbar^4} \left(\frac{2J_f + 1}{2J_i + 1}\right) \left(B(F) + g_A^2 B(GT)\right)$$



- The final-state atom produced by the LiCC process may be in the ground state or the first excited state, with different states corresponding to different nuclear transition matrix parameters.

The Correction of Fermi Function

The Fermi function needs to be corrected by performing an average over a finite nuclear volume:

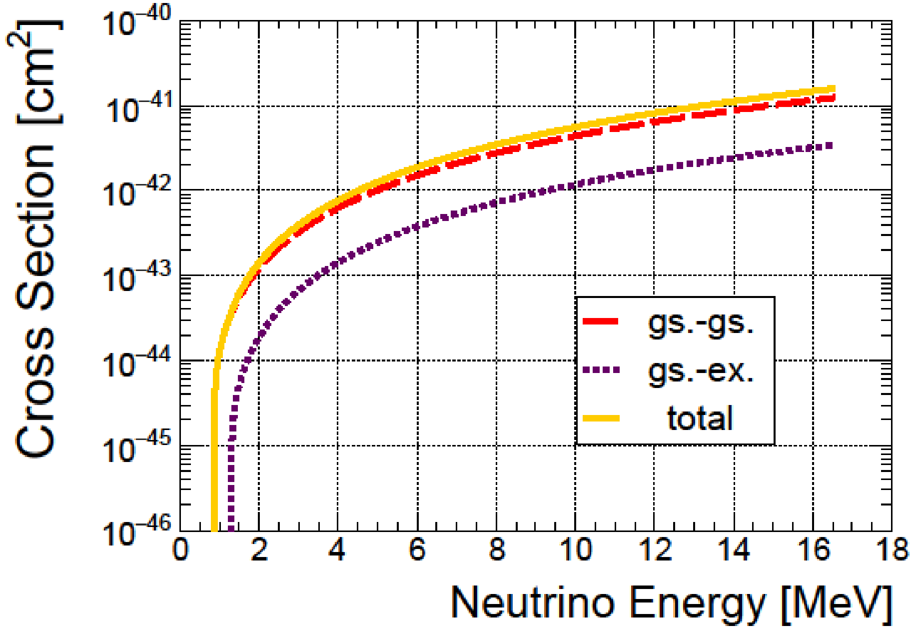
$$F(W_e, Z) = \frac{1}{V}\int_0^R F\,(W_e, Z, r)dV$$
$$= \left[\frac{3}{2\gamma_0 + 1}\right] F(W_e, Z; r = R)$$

- $w_e = W_e/m_e c^2$ is the energy (in units of the electron's mass) of the electron that is produced
- P_e is the electron's momentum (in units of $m_e c$)

Considering the electron screening effect of the final-state atom, a further correction is applied to the Fermi function.

$$F(W_e, Z) \rightarrow F(W_e - V_0, Z)\left[\frac{(W_e - V_0)^2 - m_e^2 c^4}{W_e^2 - m_e^2 c^4}\right]^{\frac{1}{2}} \left(\frac{W_e - V_0}{W_e}\right)$$

The Cross Section of LiCC Process



Weighted by the ^{8}B neutrino energy spectrum, the ratio of the weighted averages of the two types of scattering cross sections $\frac{\bar{\sigma}_{gs.-gs.}}{\bar{\sigma}_{gs.-ex.}} \simeq 3.8$.

Process II: Elastic Scattering

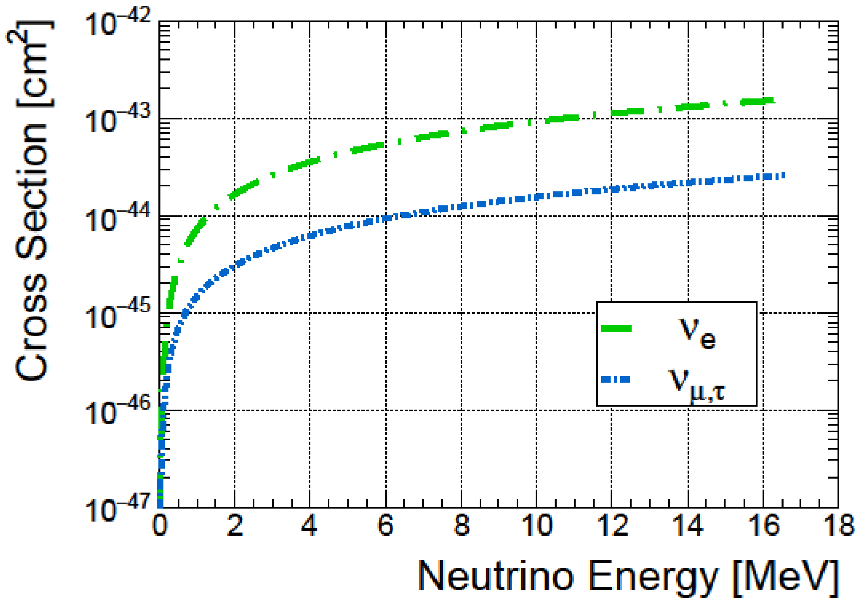
Neutrino - electron elastic scattering process :

$$\nu_\alpha + e^- \longrightarrow \nu_\alpha + e^- \qquad \alpha = e, \mu, \tau$$

Formula for calculating the scattering cross section:

$$\sigma(E_\nu, T_e^{th}) = \frac{\sigma_0}{m_e}\left[(g_1^2 + g_2^2)(T_e^{max} - T_e^{th}) - \left(g_2^2 + \frac{g_1 g_2 m_e}{2E_\nu}\right)\left(\frac{T_e^{max2} - T_e^{th2}}{E_\nu}\right) + \frac{1}{3} g_2^2 \left(\frac{T_e^{max3} - T_e^{th3}}{E_\nu^2}\right)\right]$$

- $\sigma_0 \simeq 88.06 \times 10^{-46} \mathrm{cm}^2$
- For ν_e： $g_1 = \frac{1}{2} + \sin^2\theta_W$， $g_2 = \sin^2\theta_W$
- For ν_μ、 ν_τ： $g_1 = -\frac{1}{2} + \sin^2\theta_W$ 、 $g_2 = \sin^2\theta_W$
- $T_e^{max} = \frac{2E_\nu^2}{m_e + 2E_\nu}$,
- T_e^{th} is the kinetic energy threshold of the recoil electron, used to reject background. In this calculation, it is set to 0.



The Distribution of ^{8}B Solar Neutrino Events

Calculation of the Number of ^{8}B Solar Neutrino Events: The Number of LiCC Process Events

$$N_{LiCC}(T_e,\eta)=\left[P_{ee}(E_{\nu1},\eta)\times f_B(E_{\nu1})\times\sigma_G\times\frac{\boxed{\sigma_G}}{\sigma_G+\sigma_{FE}}\right.$$

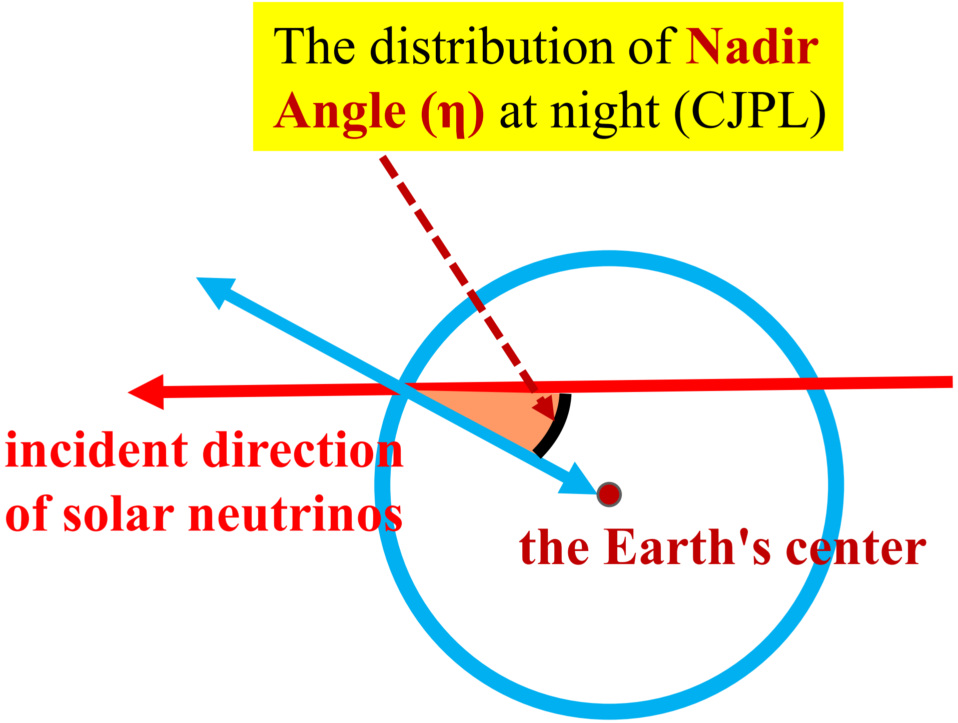
$$\left.+P_{ee}(E_{\nu2},\eta)\times f_B(E_{\nu2})\times\sigma_{FE}\times\frac{\boxed{\sigma_{FE}}}{\sigma_G+\sigma_{FE}}\right]\times\Phi\times N_{Li}\times T_{exposure}(\eta)$$

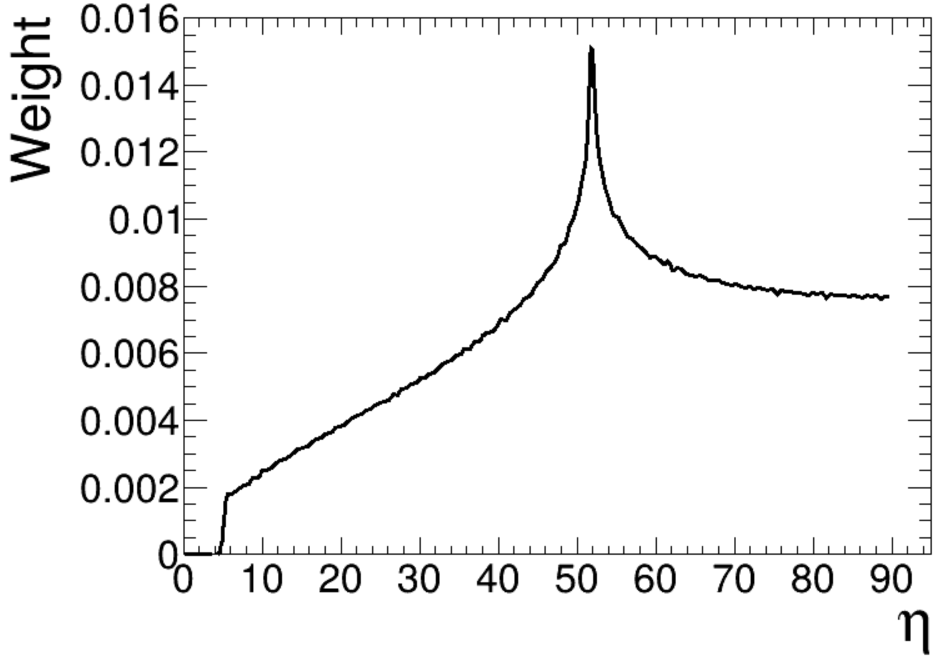
The cross section of ground state

The cross section of first excited state

- η denotes the nadir angle of the incident neutrino;
- P_{ee} denotes the survival probability of ν_e;
- f_B denotes the normalized energy spectrum of ^{8}B neutrinos;
- Φ denotes the flux of ^{8}B solar neutrinos;
- N_{Li} denotes the number of Li nuclei;
- $T_{exposure}(\eta)$ denotes the exposure time corresponding to each nadir angle.

The Distribution of Nadir Angle at Night





Calculation of the Number of ^{8}B Solar Neutrino Events Elastic Scattering Process

$$\mathrm{N_e}(\mathrm{E}_\nu, \eta) = \Phi \times \mathrm{f_B}(\mathrm{E}_\nu) \times \mathrm{P_{ee}}(\mathrm{E}_\nu, \eta) \times \sigma_\mathrm{e} \times \mathrm{N_e} \times \mathrm{T_{exposure}}(\eta)$$

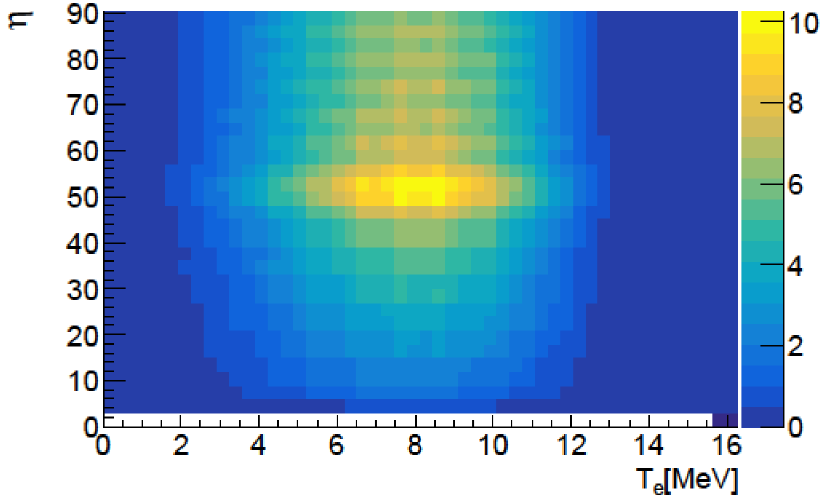
$$\mathrm{N}_{\mu,\tau}(\mathrm{E}_\nu, \eta) = \Phi \times \mathrm{f_B}(\mathrm{E}_\nu) \times [1 - \mathrm{P_{ee}}(\mathrm{E}_\nu, \eta)] \times \sigma_{\mu,\tau} \times \mathrm{N_e} \times \mathrm{T_{exposure}}(\eta)$$

- *The number of ν_e events and the number of ν_μ,ν_τ events are both included.*

Events Distribution at Night

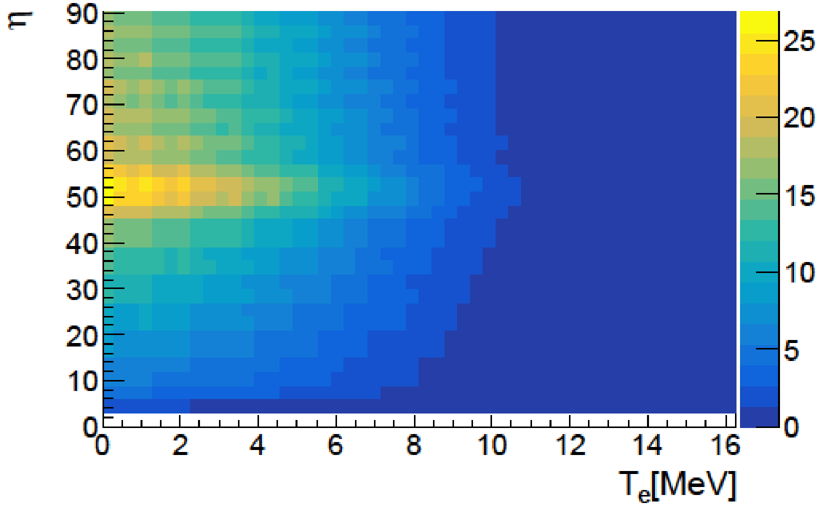
- **10 kiloton-year** of a saturated aqueous solution of LiCl

LiCC Process



Total Events $\simeq$ 3300

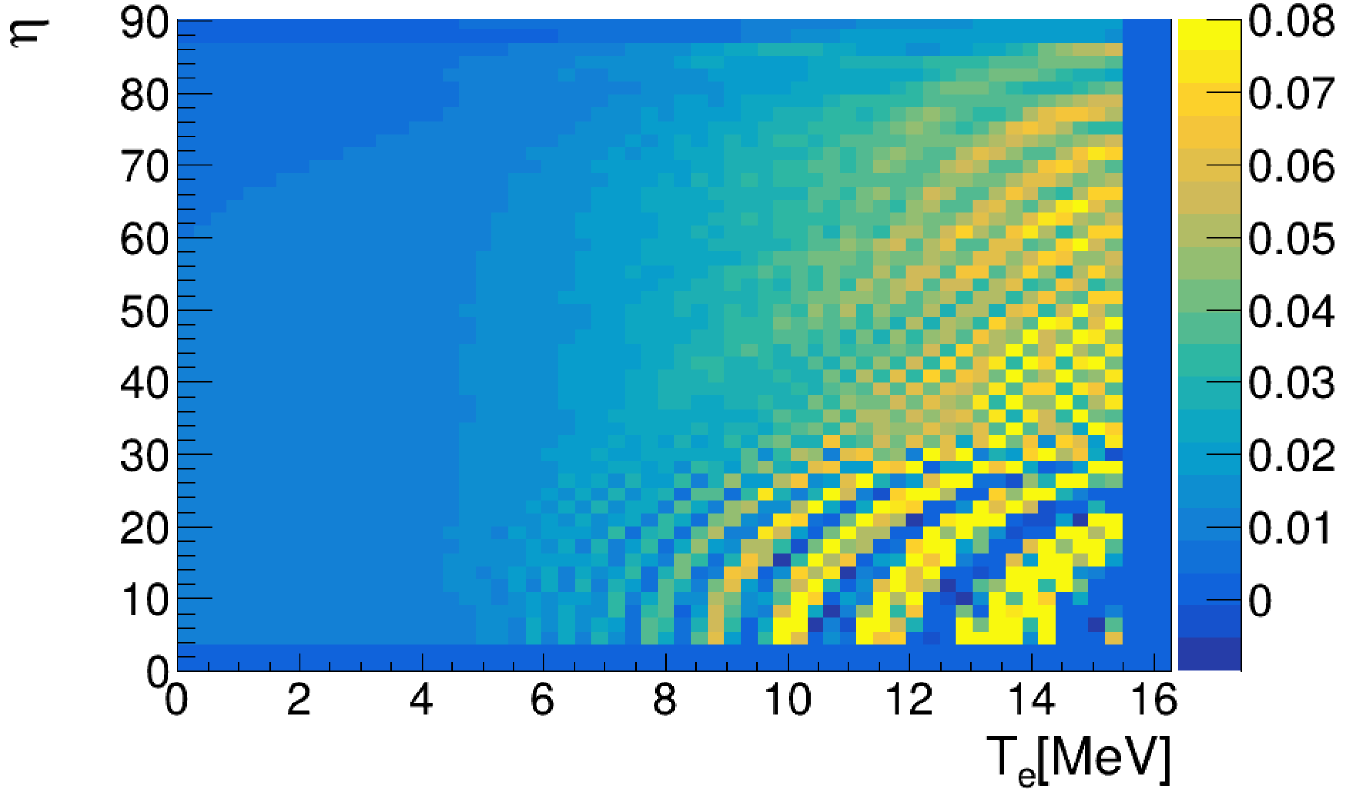
Elastic Scattering Process



Total Events $\simeq$ 7300

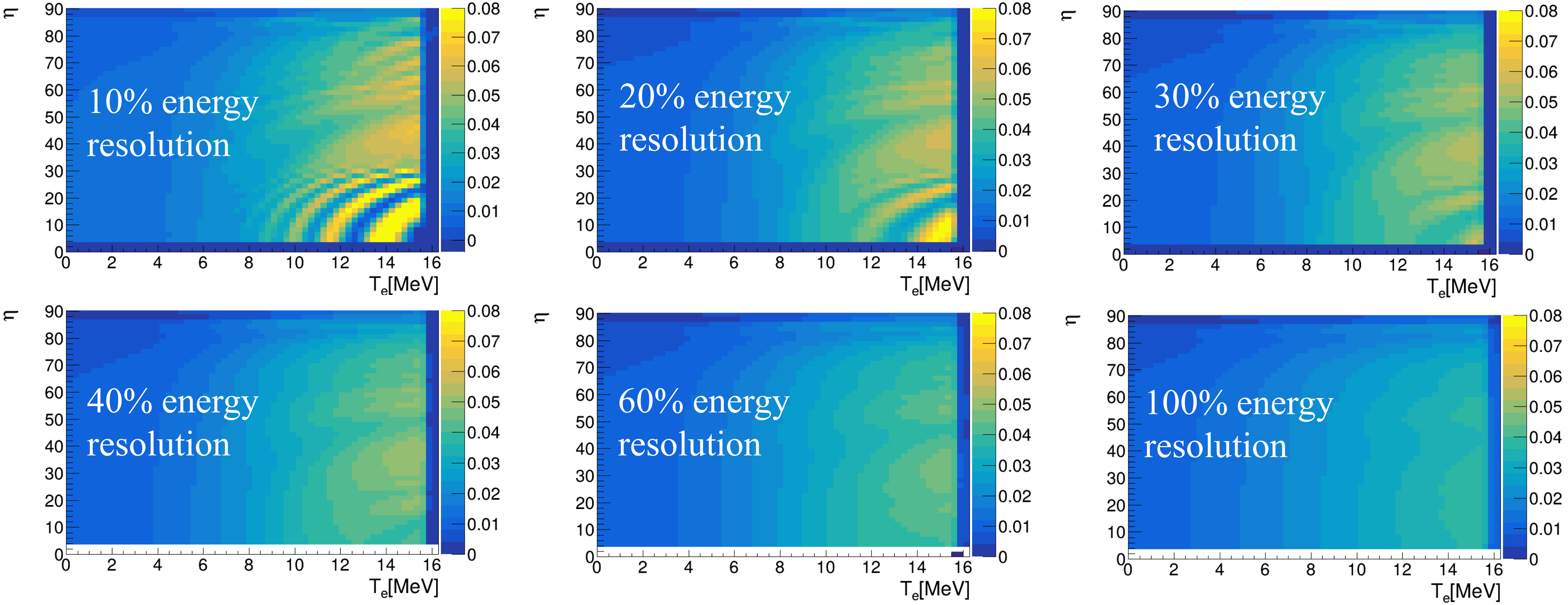
Distribution of $(N - D)/D$
LiCC scattering + Elastic scattering

- $A_{DN} = \frac{N-D}{D}$
- 10 kiloton-year
- The energy resolution in the perfect case.



Distribution of $(N - D)/D$ with Energy Resolution

- Using a Gaussian-form energy resolution function: $g^{(i)}\left(T_e^j\right) = \frac{1}{\sigma_E\sqrt{2\pi}} e^{-\frac{\left(T_e^i - T_e^j\right)^2}{2\sigma_E^2}}$
- 10 kiloton-year of a saturated aqueous solution of LiCl.



Estimation of the Sensitivity of ^{8}B Solar Neutrino Earth Matter Effects

Simple VS Simple Likelihood Ratio Test

1) Define the null hypothesis H_0 and the alternative hypothesis H_1

H_0: Without earth matter effect

H_1: With earth matter effect

2) Defining the statistic χ^2

$$\chi^2 = 2 \times \sum_i \sum_j \left(N_{i,j}^{pre} - N_{i,j}^{obs} + N_{i,j}^{obs} \log_e \frac{N_{i,j}^{obs}}{N_{i,j}^{pre}} \right)$$

- i and j are bin indices, where i denotes the i-th bin of the nadir angle and j denotes the j-th bin of the recoil electron kinetic energy.
- $N_{i,j}$ is the number of events in that bin. To ensure sufficient statistics, a certain number of bins must have event counts greater than 5.
    - $N_{i,j}^{pre}$ denotes the theoretically predicted number of events;
    - $N_{i,j}^{obs}$ denotes the number of events observed in the experiment, which in practice is obtained from a pseudo-experiment.

Simple VS Simple Likelihood Ratio Test

3) Defining test statistic $\Delta\chi^2$

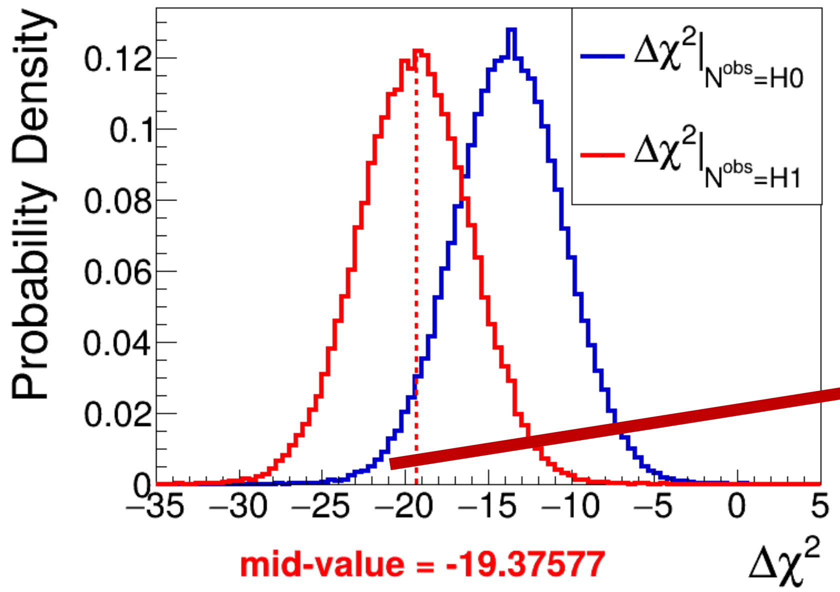
$$\Delta\chi^2(\mathrm{N}^{\mathrm{obs}}) = \chi^2_{\mathrm{N}^{\mathrm{pre}}=\mathrm{H}_1} - \chi^2_{\mathrm{N}^{\mathrm{pre}}=\mathrm{H}_0}$$

- $\mathrm{N}^{\mathrm{pre}} = \mathrm{H}_1$represents the theoretically predicted number of events under the H_1 hypothesis, while $\mathrm{N}^{\mathrm{obs}} = \mathrm{H}_1$ represents the number of events obtained from the pseudo-experiment under the H_1 hypothesis.

The Distribution of Confidence

4) P-Value and Confidence

- The energy resolution in the perfect case.



	Exposure (kton - year)			
	10	**15**	**20**	**40**
P-Value	0.04289	0.0162	0.00656	0.00016
Confidence	1.72σ	2.14σ	2.48σ	3.60σ

The Distribution of Confidence

- For different energy resolution.

Energy Resolution	Exposure (kton - year)			
	10	15	20	40
10%	0.04659(1.68σ)	0.01943(2.07σ)	0.00958(2.34σ)	0.00027(3.46σ)
20%	0.04762(1.67σ)	0.02044(2.05σ)	0.01008(2.32σ)	0.00027(3.46σ)
40%	0.04975(1.65σ)	0.02244(2.01σ)	0.01054(2.31σ)	0.00063(3.23σ)
60%	0.05254(1.62σ)	0.0241(1.98σ)	0.01176(2.27σ)	0.00068(3.20σ)
100%	0.05793(1.57σ)	0.02739(1.92σ)	0.01409(2.20σ)	0.00068(3.20σ)

Summary

- The distributions of the scattering cross sections for the LiCC process and the elastic scattering process were calculated.

- Using the "Simple VS Simple Likelihood Ratio Test" method, the sensitivity of the solar ^{8}B neutrino Earth matter effects was preliminarily estimated.

Thanks

Backup

The Definition of P-Value

P-Value

- Conditions:
  - An exposure of 10 kton - year
  - An energy resolution of 10%.
- Using P-Value to get the confidence to reject the H_0 hypothesis.