Potassium-40 Geoneutrinos Detection at Jinping

Haozhe Sun and Zhe Wang

Outline

- Motivation
- Geoneutrino detection gap
  - Missing K-40 geoneutrinos
- Directional geoneutrino detection
  - Directional detection concept
  - Background suppression
  - Main result
- Summary and outlook

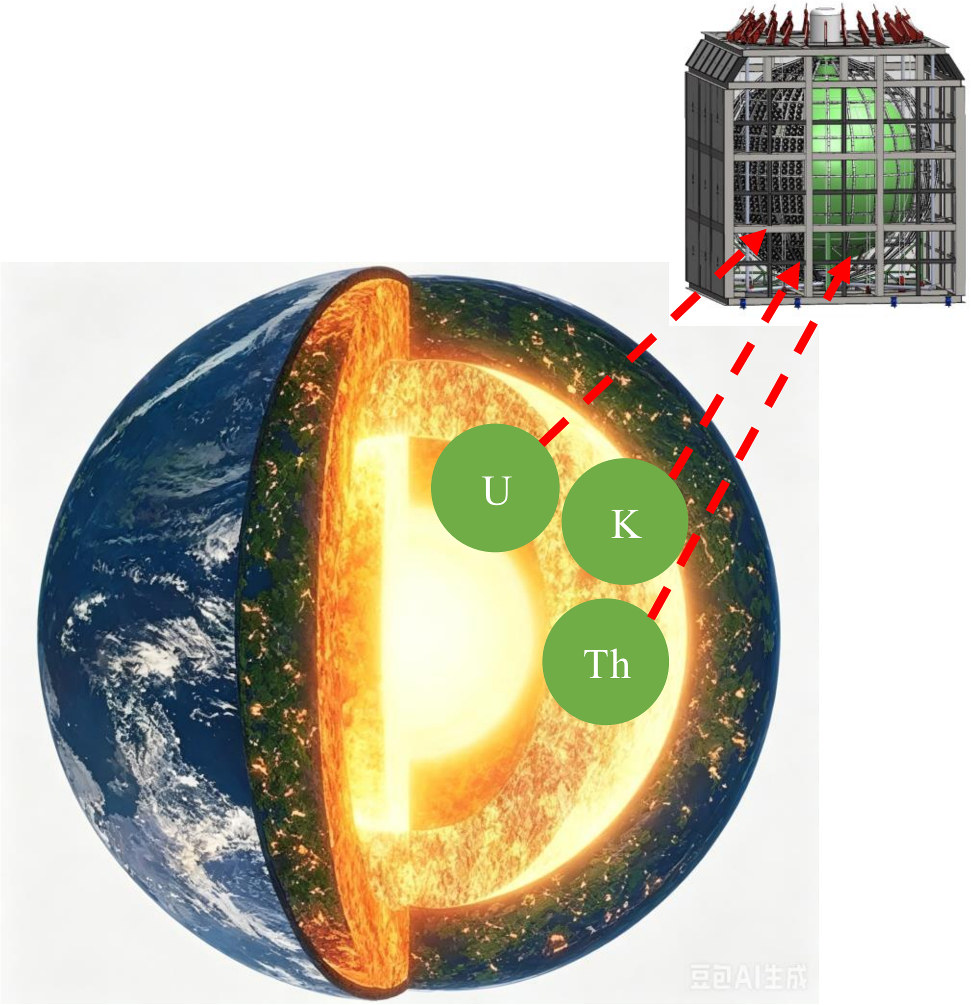
Outline

- ***Motivation***
- Geoneutrino detection gap
  - Missing K-40 geoneutrinos
- Directional geoneutrino detection
  - Directional detection concept
  - Background suppression
  - Main result
- Summary and outlook

Why Geoneutrinos Matter?

Direct probe of the Earth's deep interior

Constraining the Earth's rediogenic heat budget



Revealing mantle dynamics

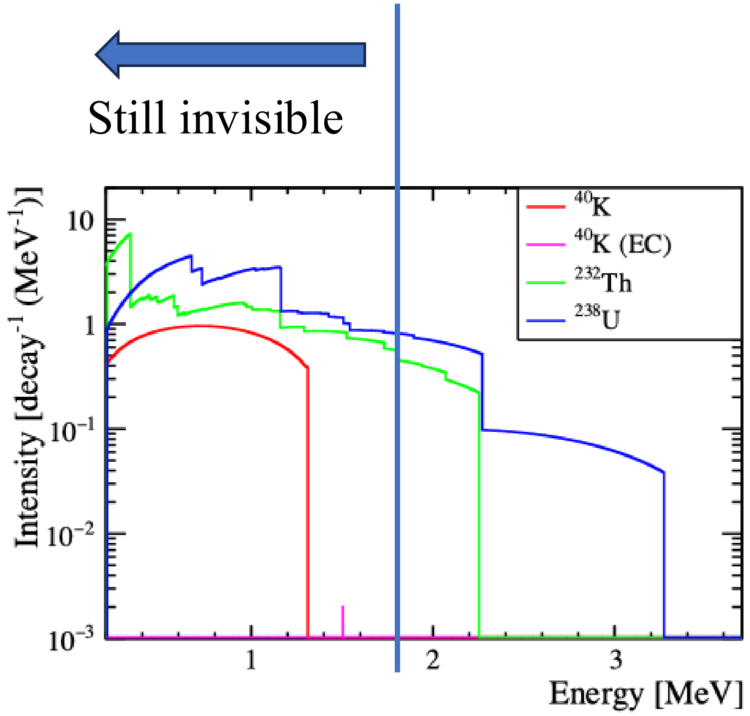
Testing fundamental Earth formation models

Outline

- Motivation
- ***Geoneutrino detection gap***
  - Missing K-40 geoneutrinos
- Directional geoneutrino detection
  - Directional detection concept
  - Background suppression
  - Main result
- Summary and outlook

Detection Gap

- Current status: IBD-based detection
  - KamLAND: The first measurement
  - Borexino and SNO+ also reported their results
  - JUNO: *"Will collect more geoneutrino events than all the other experiments with 1 year data"*

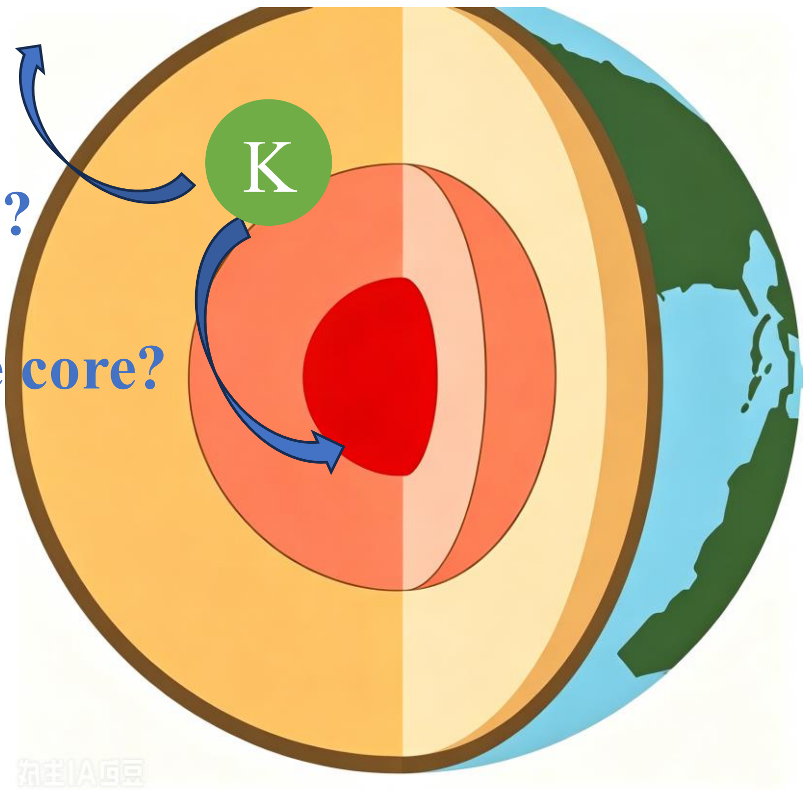


- Critical gap:
  - IBD threshold at 1.8MeV, above K-40 geoneutrino endpoint at 1.3MeV

Why Potassium Matters?

- ***Potassium is the only semi-volatile heat producing element.***

loss into space?
or
segregating into the core?



- The Earth show depleted potassium comparing to chondrites.
  - To space or to the core?
  - Total radiogenic heat?
- ***K-40 geoneutrino detection may answer this.***

New Channel: $\nu - e$ Elastic Scattering

	IBD	Elastic scattering
Reaction	$\bar{\nu}_e + p \rightarrow n + e^+$	$\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$ $\nu + e^- \rightarrow \nu + e^-$
Energy threshold	1.806 MeV	~keV
Detected elements	U, Th	U, Th, K
Directionality	Limited	Forward
Key chanllage	Reactor antineutrino	Solar neutrino & radioactive background

Geo / Solar ~ 1%
Direction cut is needed

Outline

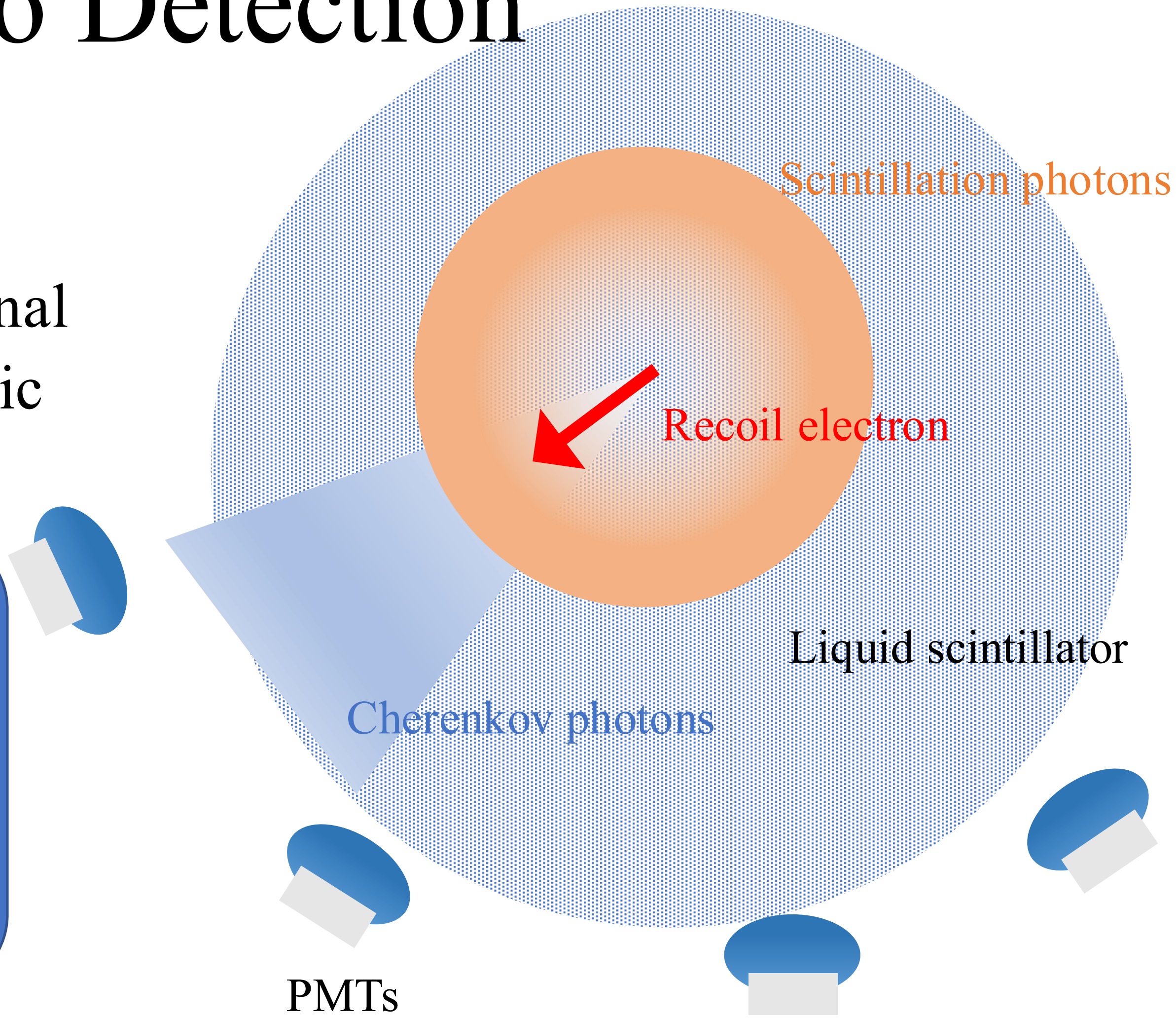
- Motivation
- Geoneutrino detection gap
  - Missing K-40 geoneutrinos
- ***Directional geoneutrino detection***
  - Directional detection concept
  - Background suppression
  - Main result
- Summary and outlook

Directional Geoneutrino Detection

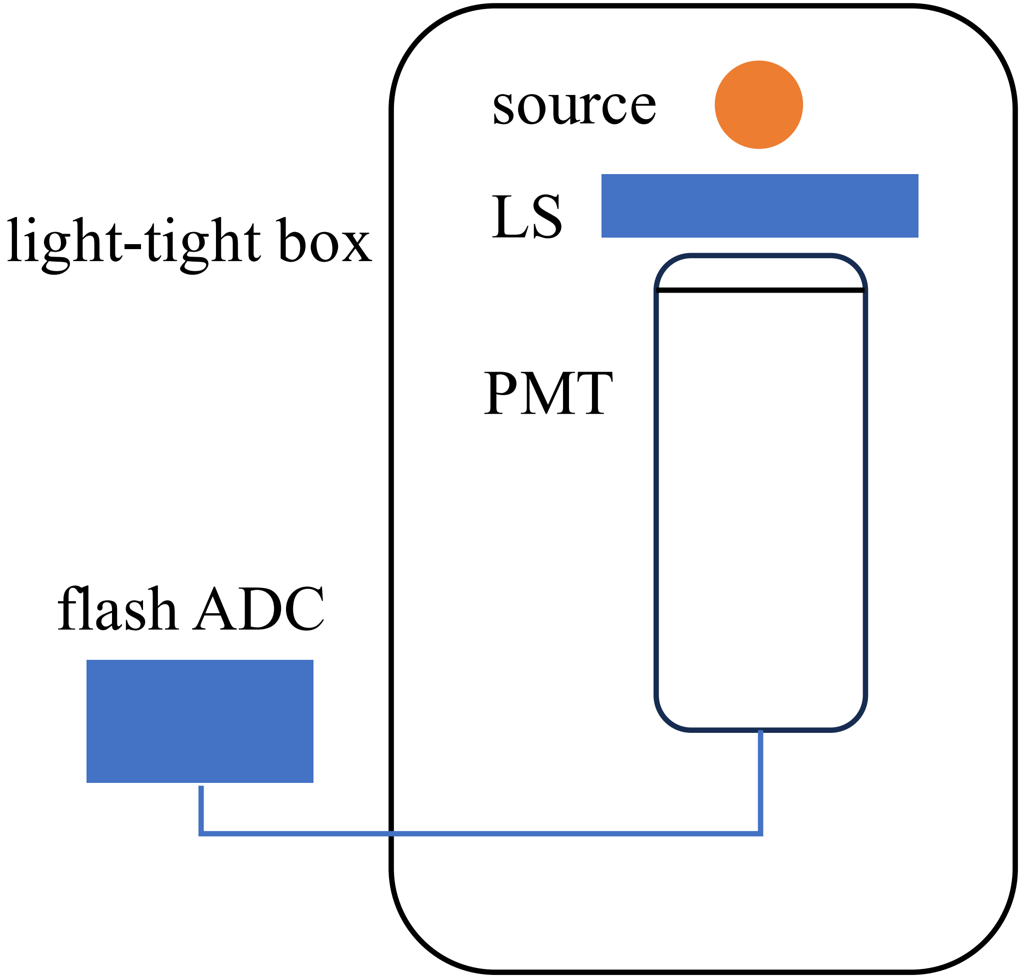
- Signal: recoil electron
  - Cherenkov photons: fast, directional
  - Scintillation photons: slow, isotropic

Requirement for equipment:

High light yield (LS)
→ energy resolution
Large time constant (LS) + small TTS (PMT)
→ angular resolution

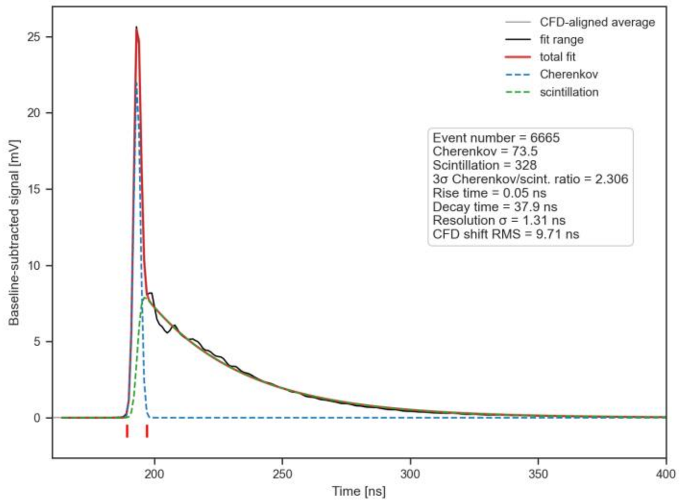


LS Performance Measurement

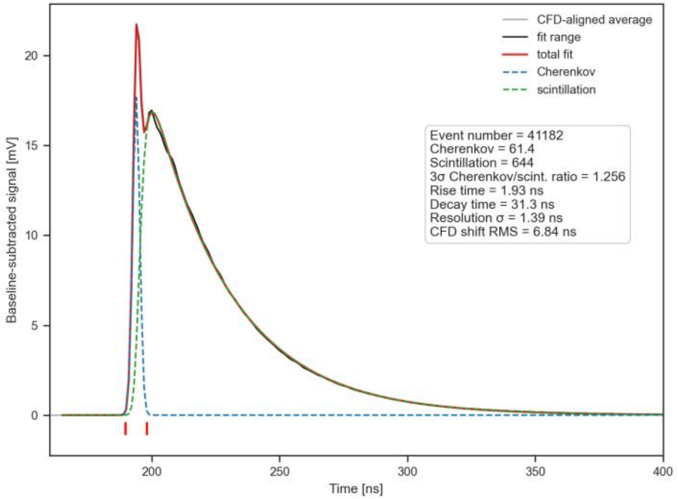


- Measure light yield via charge integration
- Measure time constant via averaged waveforms
- *Study slow-LS mechanisms combining light yields and time constants …*

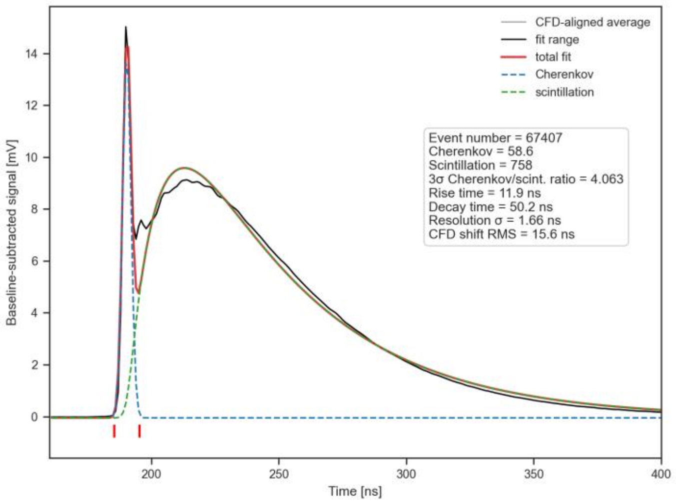
Slow LS Performance Measurement



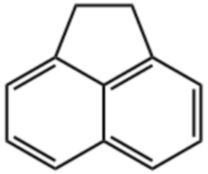
LAB



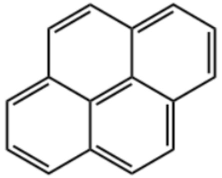
LAB + 4g/L Acenaphthene



LAB + 4g/L Pyrene



Acenaphthene



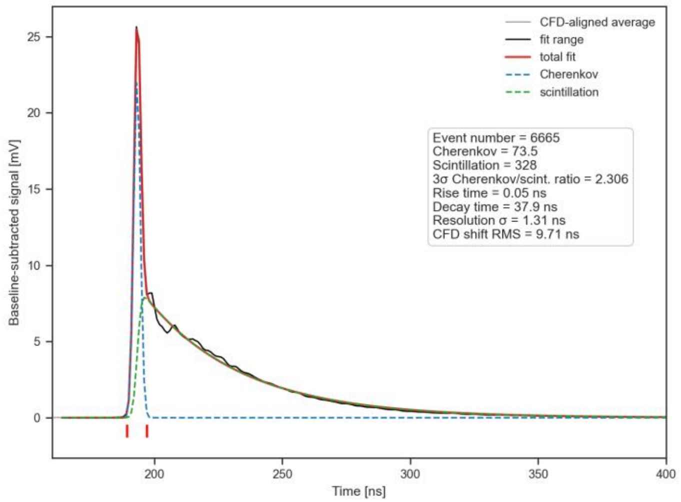
Pyrene

Biller, et al.

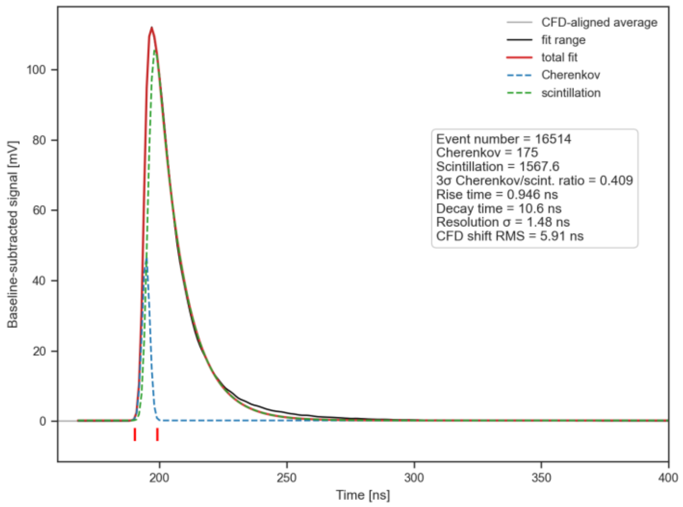
	Relative light yield	Decay time
LAB(reference)	1	37.9 ns
LAB + 4g/L Acenaphthene	1.96	32.1 ns
LAB + 4g/L Pyrene	2.31	50.0 ns

(Preliminary)

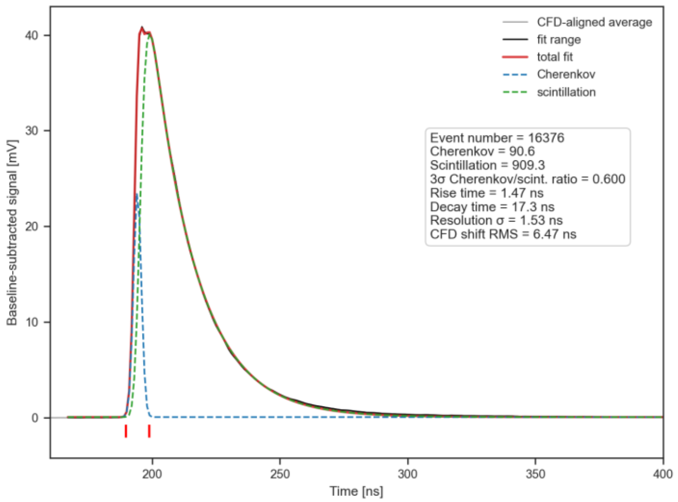
Slow LS Performance Measurement



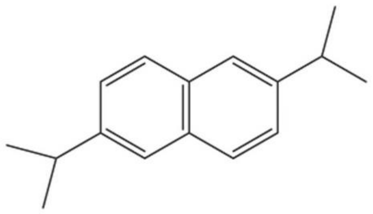
LAB



LAB +



LAB + 4g/L Pyrene



2,6-diisopropylnaphthalene (DIPN)

Steiger, et al.

	Relative light yield	**Decay time**
LAB(reference)	1	37.9 ns
LAB + 1g/L PPO	4.78	10.6 ns
LAB + 10% DIN + 1g/L PPO	2.77	17.3 ns

(Preliminary)

PMT Performance Measurement

- Test for NNVT 8-inch MCP-PMTs
  - Detection efficiency
  - Transit time spread
  - Dark rate

  - A new platform for non-uniformity measurement

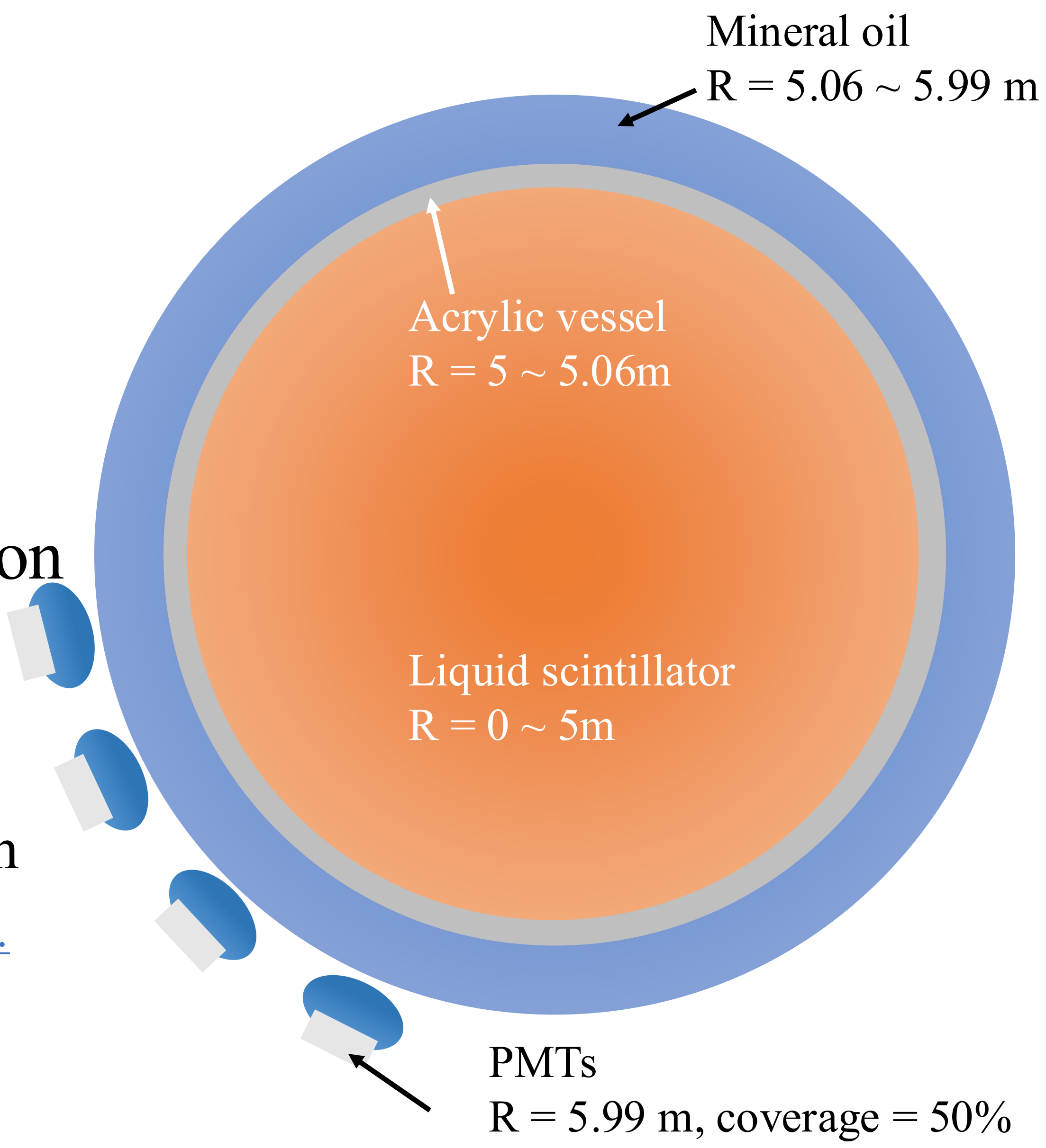
    (details in tomorrow's talk)

Parameters	Value	Criteria	Notes	Section
$\overline{Q}/Q_0$	1.8 ± 0.1		Entire-sample to main-peak gain ratio	3.2
$\nu_0 = \sigma_{Q_0}/Q_0$	0.25 ± 0.02		Peak resolution	3.2
$\nu = \sqrt{s_Q^2}/\overline{Q}$	0.69 ± 0.03		Sample resolution	3.2
N^{1e}/N^{hit}	0.59 ± 0.02		Main-peak fraction	3.2
P/V	5.9 ± 1.4	>5	Peak-to-valley ratio	3.3
t_r/ns	3.71 ± 0.15	<4	Rise time	3.4
t_f/ns	15.6 ± 1.8	<20	Fall time	3.4
σ_{SER}/ns	1.63 ± 0.06		Shape parameters of SER	3.4
τ_{SER}/ns	7.2 ± 1.1			
TTS/ns	1.73 ± 0.08	<1.8	Transit time spread	3.5
DCR/kHz	5.8 ± 1.6	~5	Dark count rate	3.6
P_{pre}	1E−6 ± 6E−6	<0.001	Pre-pulse probability	3.7
P_{after}	0.009 ± 0.005	<0.048	After-pulse probability	3.7
ϵ^0	1.71 ± 0.06	>1.6	Relative PDE	3.8

A. Zhang et al.

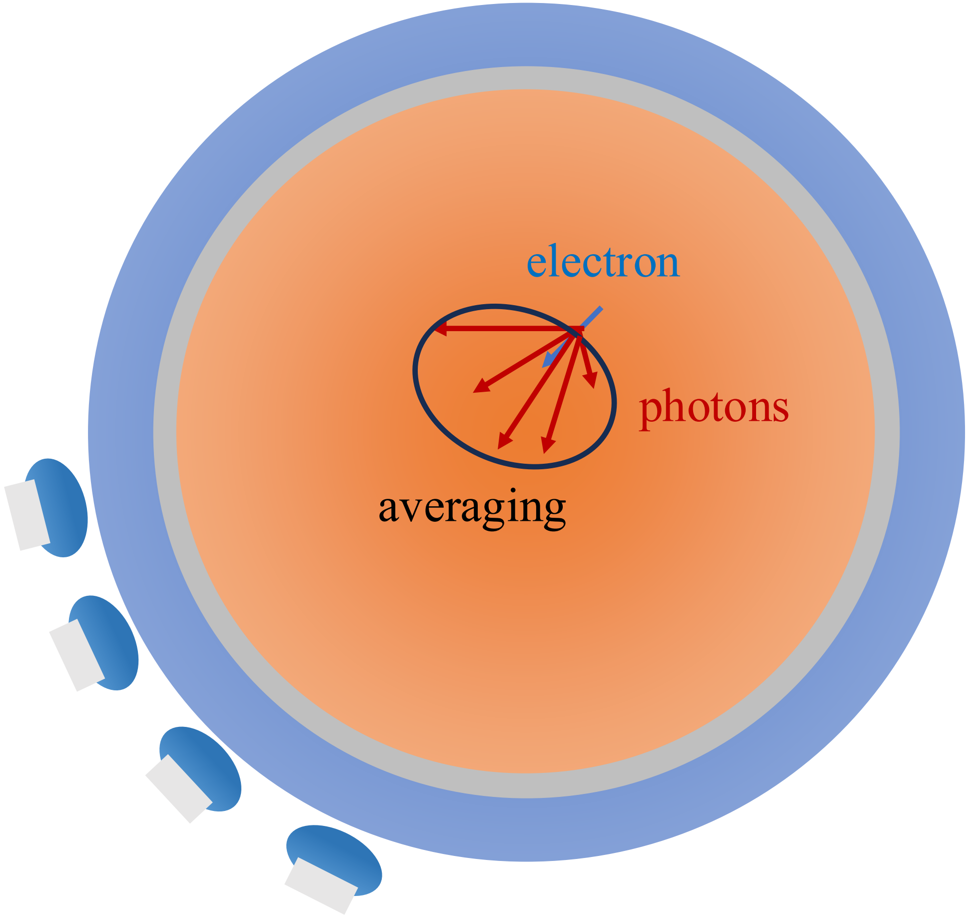
Resolution Simulation

- Geant4-based simulation
  - LS rise time = 7.7ns, decay time = 35ns
  - PMT TTS = 1ns (FWHM)
- Three methods to estimate angular resolution
  1. Average of the first 2ns photons from simulation's stack
  2. Average of the first 3ns photons from PMT hits, Assuming a position resolution of 30cm
  3. Likelihood-based reconstruction *W. Luo, et al.*
- Energy resolution: 400PE/MeV



Method 1

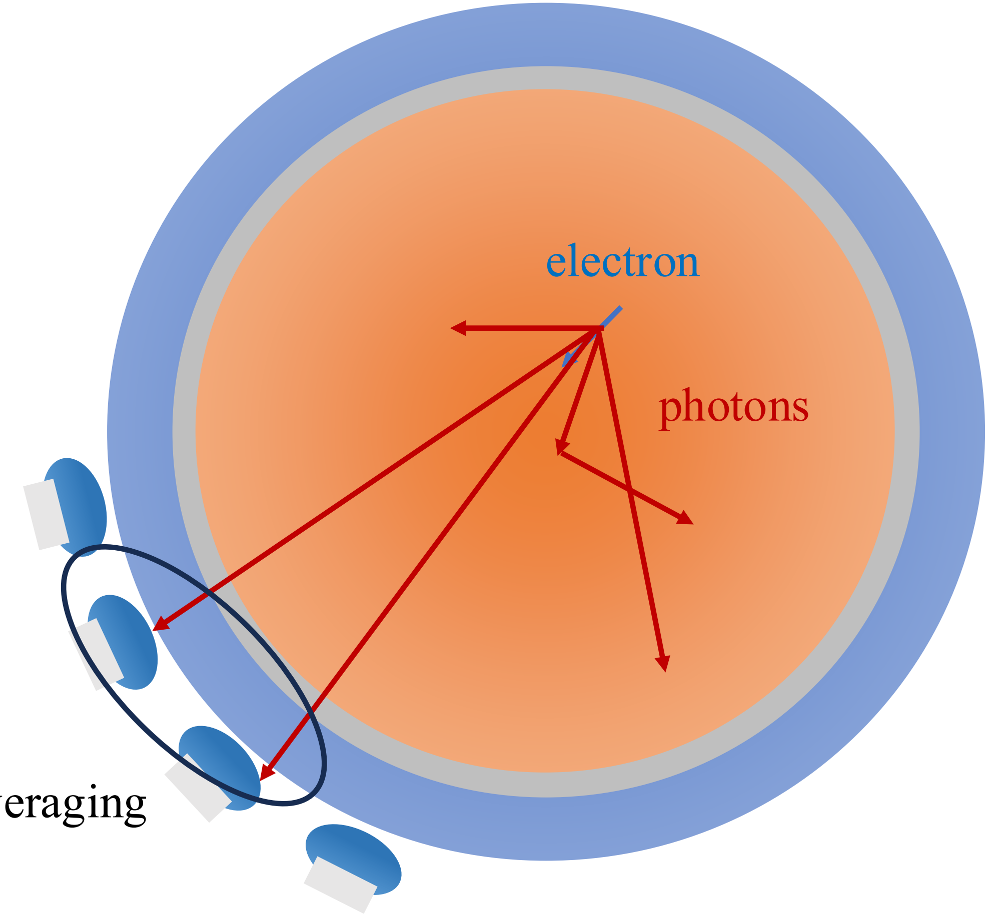
(An ideal limit)



- A detection efficiency of 20% is assumed for each photon
- Average direction of photons within the first 2 ns read from Geant4's stack

Method 2

(Relatively realistic)



- A position resolution of 30 cm is assumed for the detector
- Calculate direction and production time of each PMT hit photon

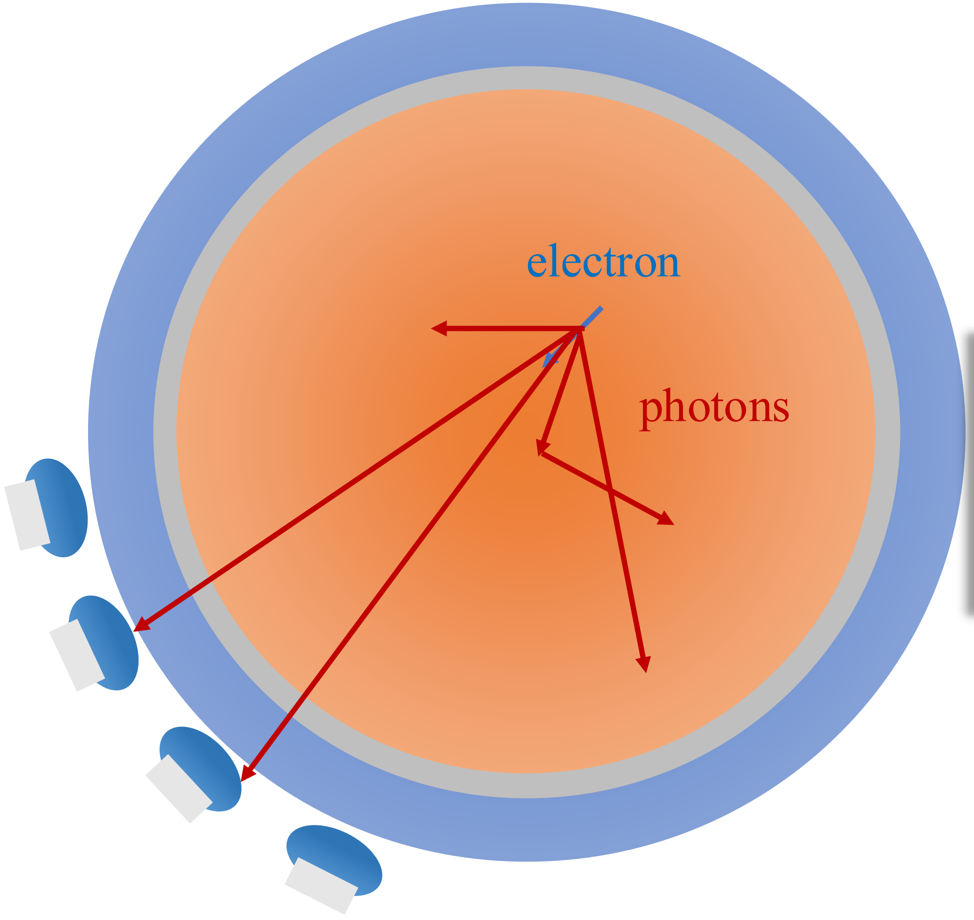
$$t = t_{\mathrm{hit}} - \frac{n|\vec{r}_{\mathrm{hit}} - \vec{r}_{\mathrm{rec}}|}{c}$$

$$\hat{p} = \frac{\vec{r}_{\mathrm{hit}} - \vec{r}_{\mathrm{rec}}}{|\vec{r}_{\mathrm{hit}} - \vec{r}_{\mathrm{rec}}|}$$

- Average direction of photons within the first 3 ns

Method 3 [W. Luo, et al.](#)

(With more factors considered)



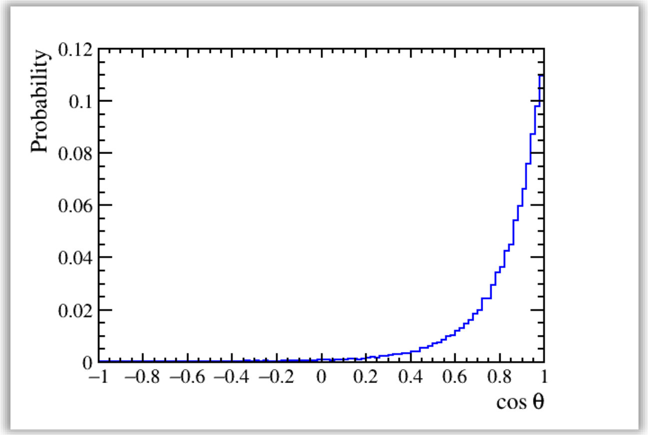
- Record the hit time of each hit photon in each PMT
- Construct likelihood

$$\mathcal{L}\left(\boxed{n_i^{\mathrm{Obs}}, t_{ij}} \middle| \boxed{E, x, y, z, t_{\mathrm{event}}, \vec{d}_{\mathrm{Fit}}}\right) = \prod_{i}^{N_{\mathrm{PMT}}} \boxed{P_i^{\mathrm{C}}} \prod_{j}^{n_i^{\mathrm{Obs}}} \boxed{P_{ij}^{\mathrm{T}}}$$

Known quantities Fit parameters Probability of the Charge and Time

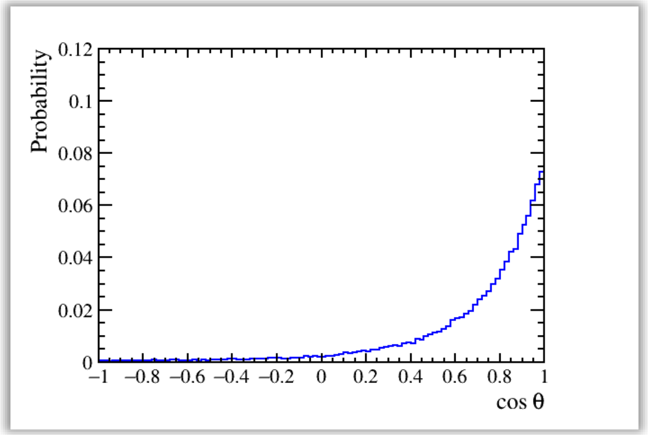
- Dark rate and electronic is also take into consideration

Angular Resolution



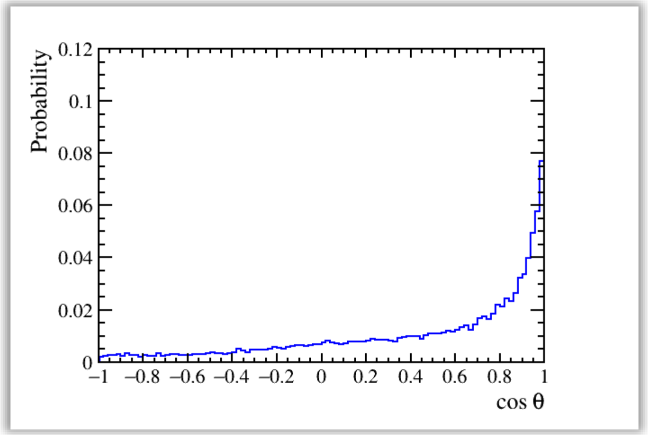
Resolution 1 @ 1MeV

38° (68% contained)
$P(\cos\theta < 0) = 1.45\%$



Resolution 2 @ 1MeV

48° (68% contained)
$P(\cos\theta < 0) = 4.93\%$



Resolution 3 @ 1MeV

71° (68% contained)
$P(\cos\theta < 0) = 19.0\%$

Geoneutrino Signal Prediction

$$\frac{\mathrm{d}^2 N}{\mathrm{d}E\mathrm{d}t} = \sum_i \rho_i A_i \frac{N_A}{M_r} \lambda \frac{1}{4\pi L_i^2} f(E) P_{ee}(E, L_i) \sigma(E) \Delta V$$

Earth model

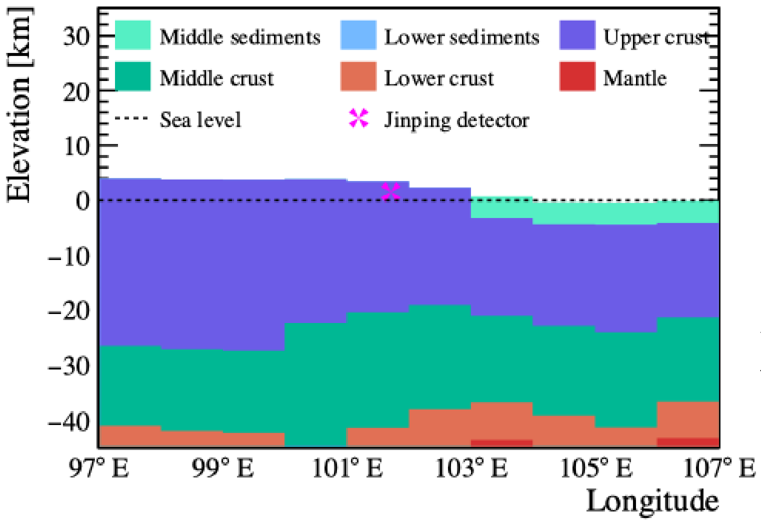
Neutrino oscillation

Elastic scattering
cross-section

Neutrino spectrum

Geoneutrino Signal Prediction

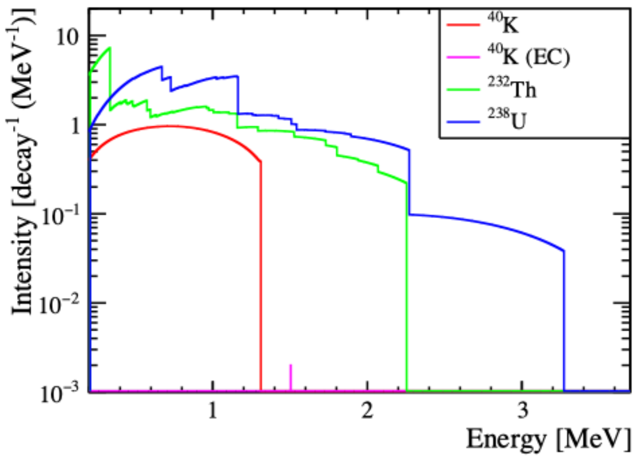
- Earth model
  - Density:
    - Crust: CRUST1.0, a 1° × 1°, 8-layers topological map — *G. Laske, et al.*
    - Mantle: (CLM + DM + EM, constant density) — *Y. Huang, et al.*
  - Heat producing elements abundance:
    - A medium-Q BSE model — *O. Sramek, et al.*

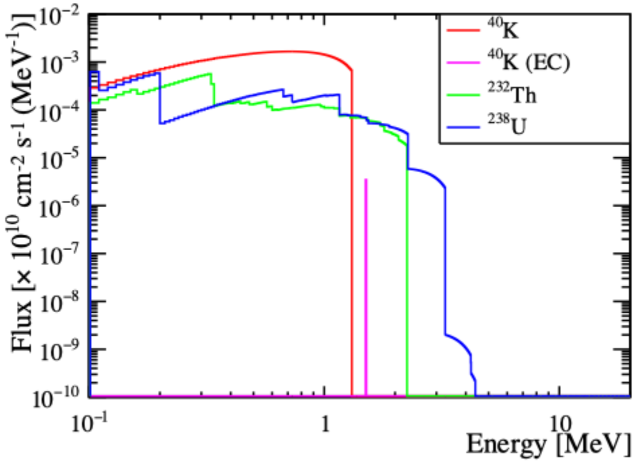


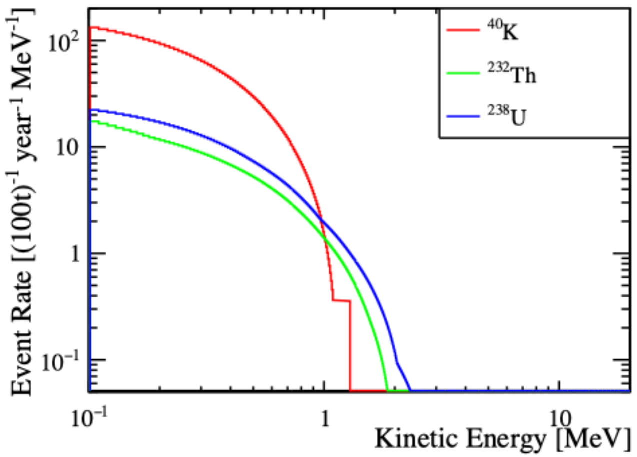
The crustal model near Jinping provided by CRUST1.0

Geoneutrino Signal Prediction

- Recoil enectron spectrum at Jinping







Neutrino spectrum

Earth model

Neutrino oscillation

Neutrino flux at Jinping

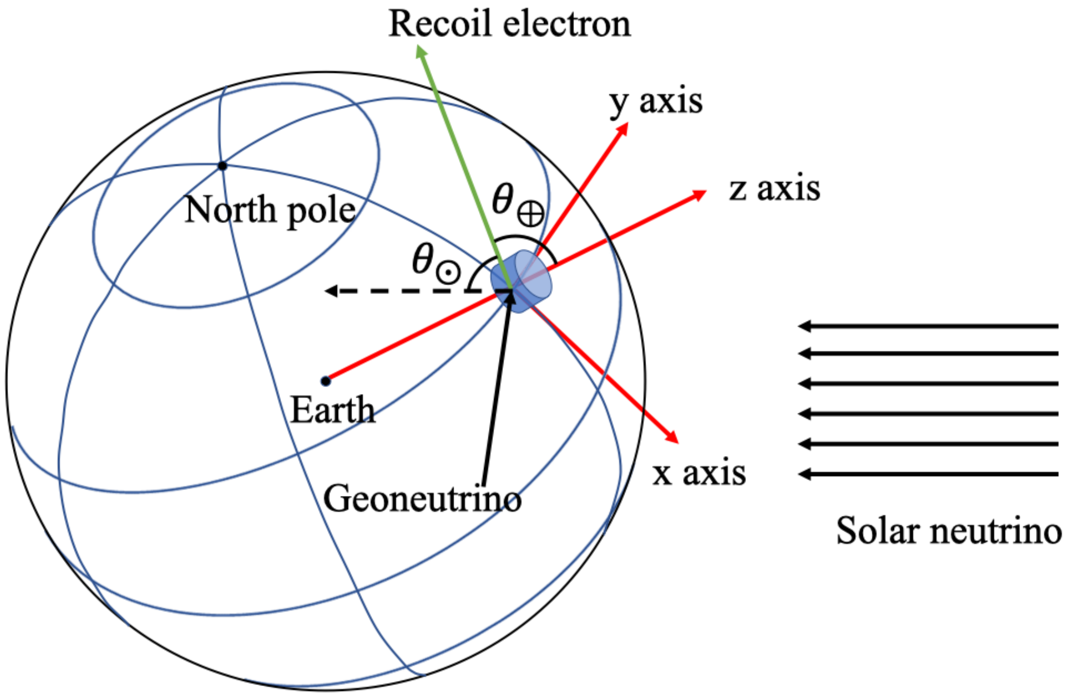
ES cross-section

Recoil electron spectrum at Jinping

400 PE/MeV smear

Subsequent analysis

Solar-neutrino Suppression

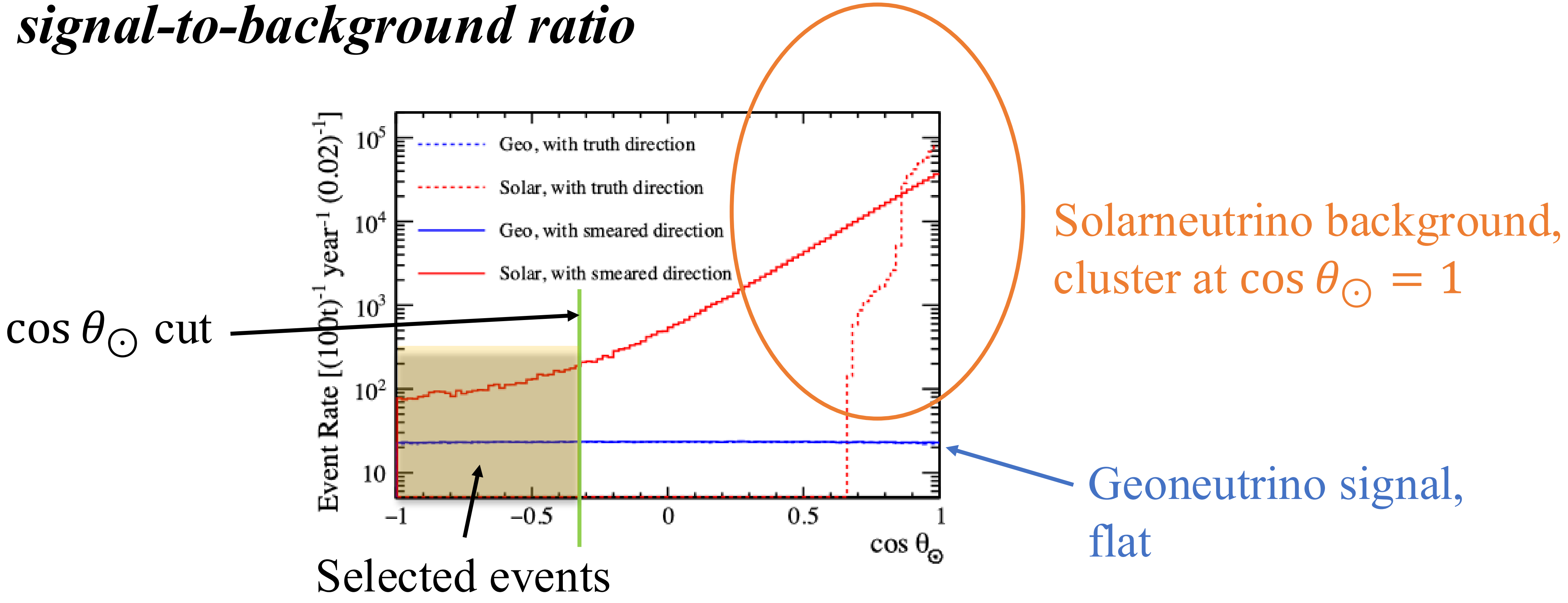


- Two sets of coordinate systems are established to describe the directional correlation.

1. The solar coordinate system
   - $\theta_\odot = < \vec{p}_{\text{recoil electron}}, \vec{r}_{\text{Sun-Det}} >$
   - Rotating with the Sun
2. The terrestrial coordinate system
   - $\theta_\oplus = < \vec{p}_{\text{recoil electron}}, \vec{r}_{\text{Core-Det}} >$
   - Fixed on the Earth

Directional Correlation of Neutrino Signals

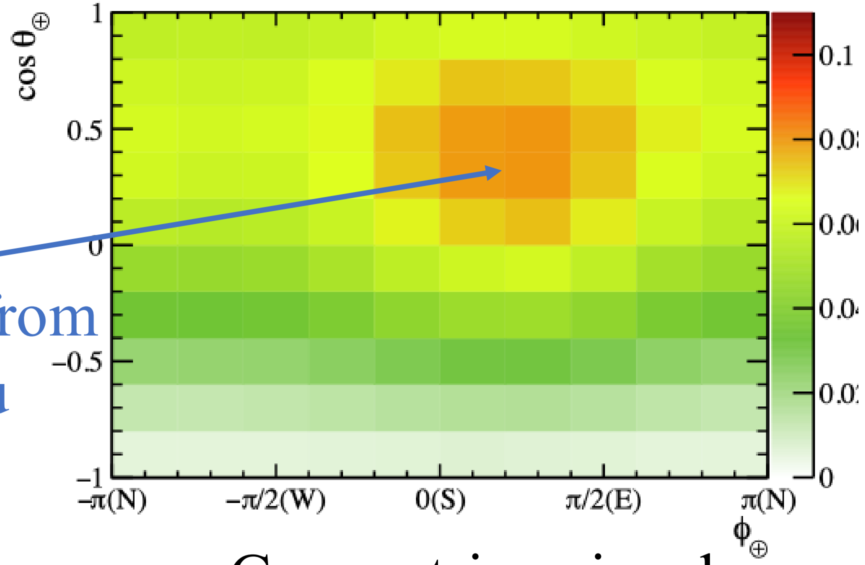
- ***In solar coordinate system, applying the $\cos\theta_{\odot}$ cut to improve signal-to-background ratio***



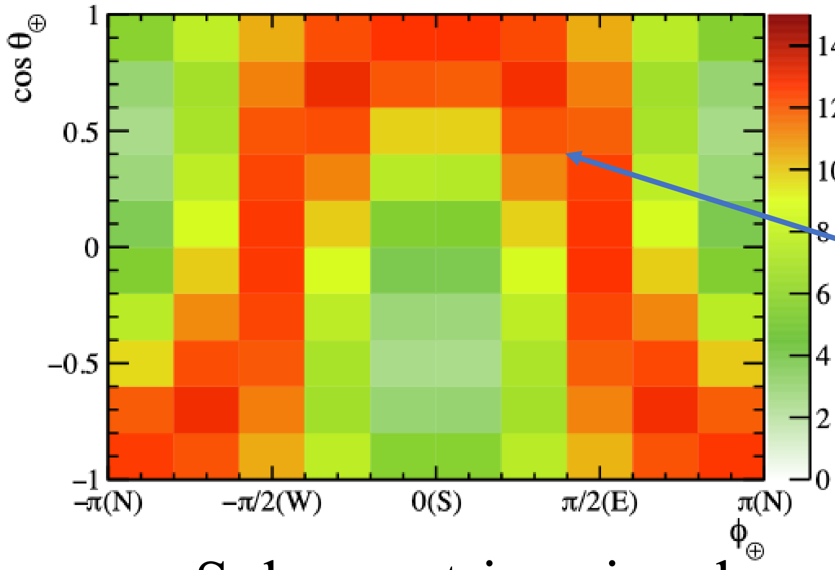
Directional Correlation of Neutrino Signals

- ***In terrestrial coordinate system, optimizing the $\cos\theta_{\odot}$ cut to improve signal-to-background ratio further***

Geoneutrinos from Tibetan Plateau



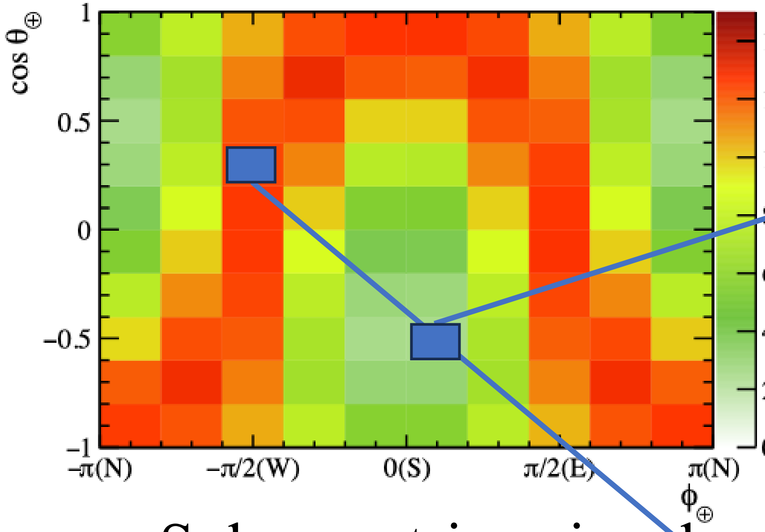
Geoneutrino signal



Solar-neutrino signal

Caused by periodic motion

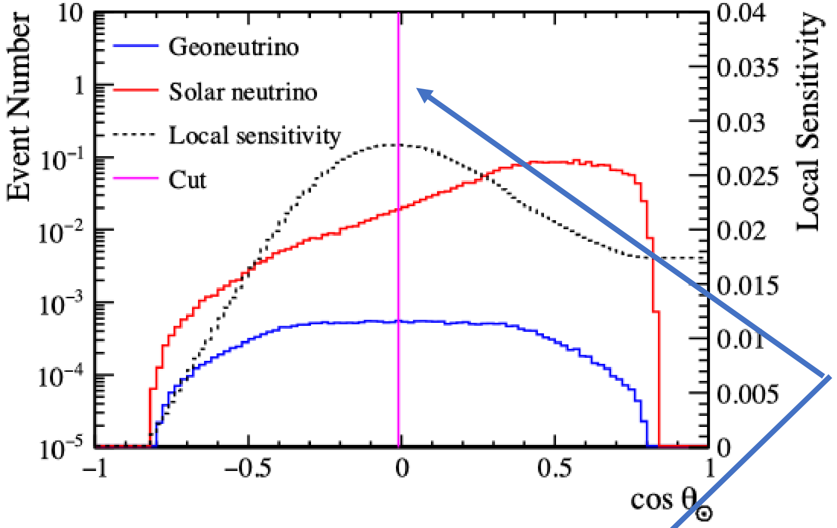
$\cos\theta_\odot$ Cut Optimization

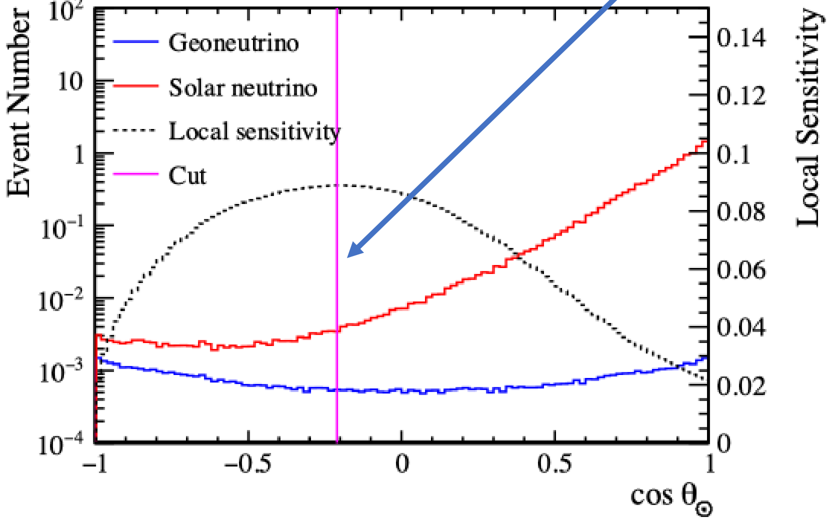


Solar-neutrino signal

Define local sensitivity

$$\mathrm{Sen_{loc}} = \frac{N_{\mathrm{geo}}}{\sqrt{N_{\mathrm{geo}} + N_{\mathrm{solar}}}}$$





Extend $\cos\theta_\odot$ cut to improve sensitivity

Solar-neutrino Suppression

- Solar-neutrino background event rate (per kiloton-yera)

		0.7 – 1.1 MeV		1.1– 2.3 MeV		0.7 – 2.3 MeV	
Resolution		Before	After	Before	After	Before	After
38°@1MeV	Geo	36.0	15.6	9.5	4.5	45.5	20.1
	Solar	7095.4	103.1	1746.2	25.5	8841.6	129.1
48°@1MeV	Geo	36.0	16.0	9.5	4.3	45.5	20.2
	Solar	7095.4	365.6	1746.2	78.1	8841.6	435.2
71°@1MeV	Geo	36.0	25.1	9.5	6.3	45.5	31.3
	Solar	7095.4	2607.5	1746.2	525.9	8841.6	3109.9

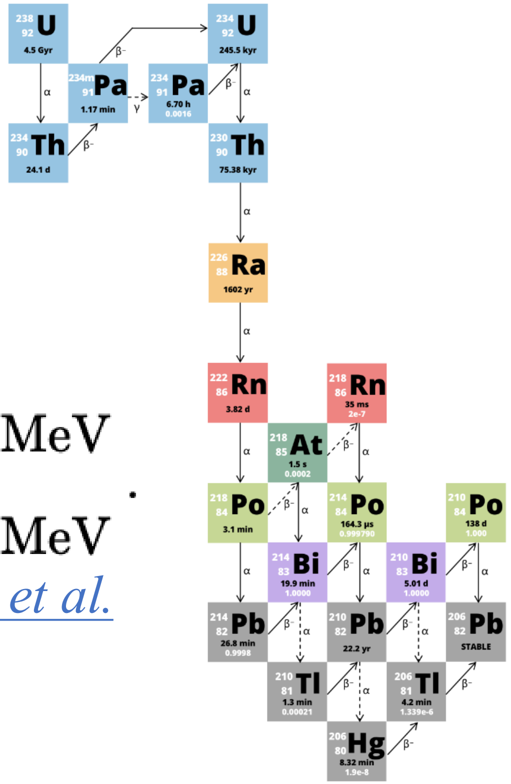
Radioactive Background (^{238}U, ^{232}Th)

- Decay chains are in secular equilibrium
- α particles quench in LS

$$E_{\text{vis}}\,[\text{MeV}] = \begin{cases} 0.031(E\,[\text{MeV}])^{1.689}, & E < 6.76\,\text{MeV} \\ -0.505 + 0.190\,E\,[\text{MeV}], & E > 6.76\,\text{MeV} \end{cases}.$$

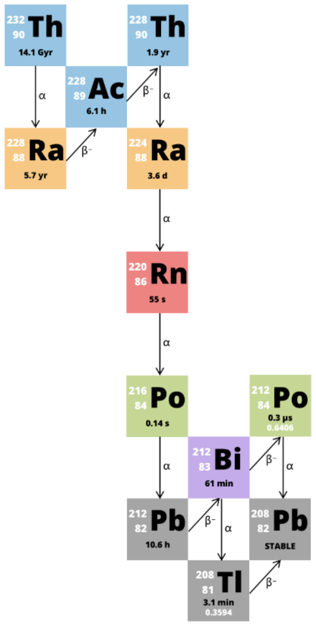
[B. von Krosigk, et al.]

- α/β decays are always accompanied with de-excitation γ decays



U-238

$8\alpha + 6\beta^- + n\gamma$



Th-232

$6\alpha + 4\beta^- + n\gamma$

Radioactive Background

β energy or quenching α energy

de-excitation γ energy

$\Delta t < 100ns$

combined as *1* event

α/β decay 1

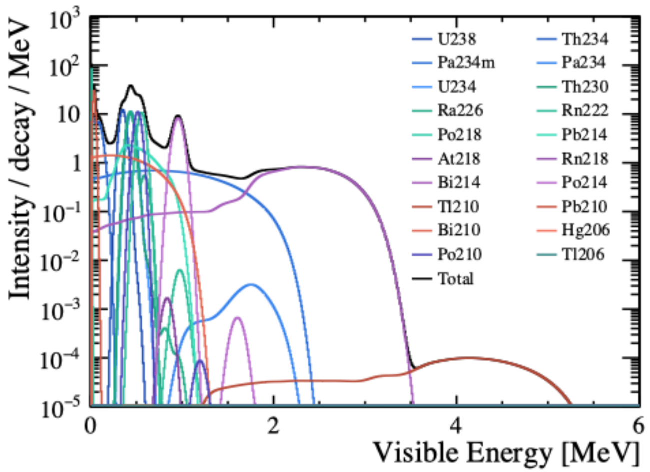
α/β decay 2

$\Delta t > 100ns$

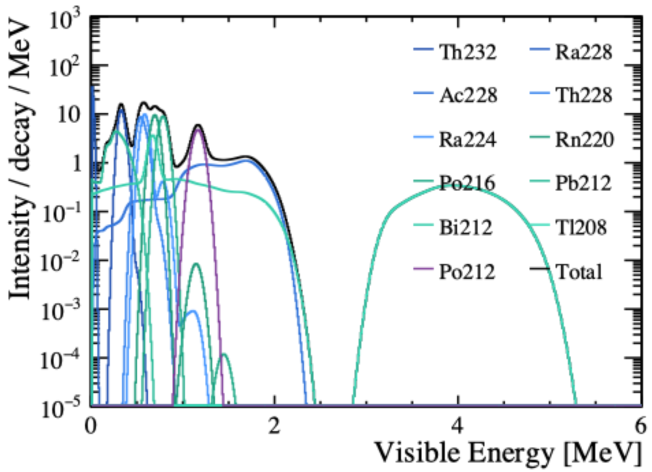
separated as *2* events

Radioactive Background

- Radioactive background event rate (per kiloton-year) $@10^{-18}\ g/g$



U-238



Th-232

	0.7 – 1.1 MeV	1.1– 2.3 MeV	0.7 – 2.3 MeV
U238	630.4	306.8	937.2
Th232	184.5	214.6	399.1
Total	814.9	521.4	1336.3

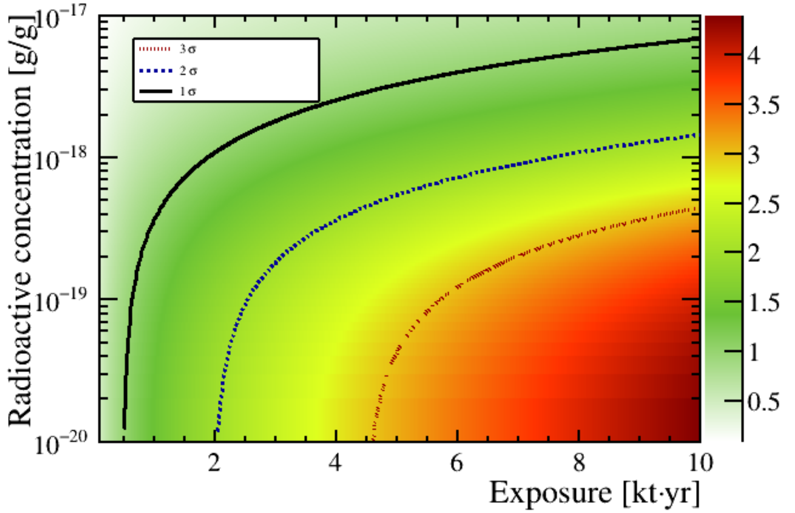
Event Rate Summary

Dominated by K *Dominated by U,Th*

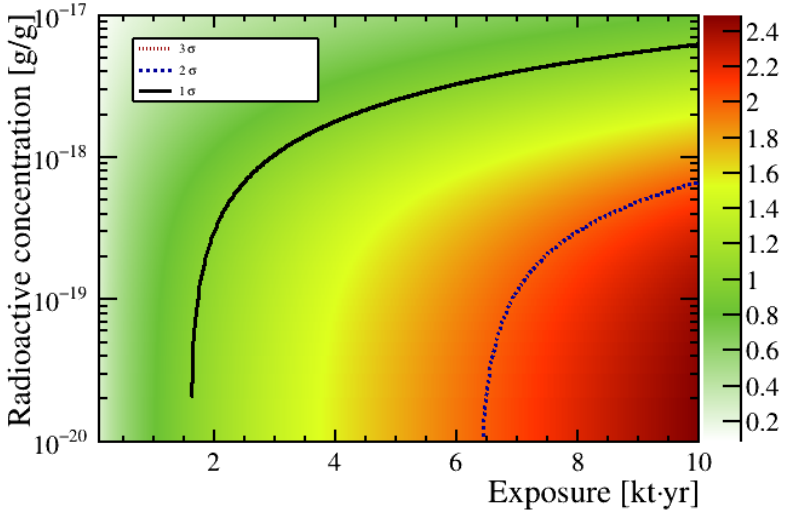
		0.7 – 1.1 MeV		1.1– 2.3 MeV		0.7 – 2.3 MeV	
Resolution		Before	After	Before	After	Before	After
38°@1MeV	Geo	36.0	**15.6**	9.5	4.5	45.5	20.1
10^{-18} g/g	Solar	7095.4	**103.1**	1746.2	25.5	8841.6	129.1
	Radioactive	814.9	**334.1**	521.4	234.6	1336.3	561.2
48°@1MeV	Geo	36.0	**16.0**	9.5	4.3	45.5	20.2
10^{-18} g/g	Solar	7095.4	**365.6**	1746.2	78.1	8841.6	435.2
	Radioactive	814.9	**342.3**	521.4	219.0	1336.3	561.2
71°@1MeV	Geo	36.0	**25.1**	9.5	6.3	45.5	31.3
10^{-18} g/g	Solar	7095.4	**2607.5**	1746.2	525.9	8841.6	3109.9
	Radioactive	814.9	**554.1**	521.4	333.7	1336.3	895.3

Results

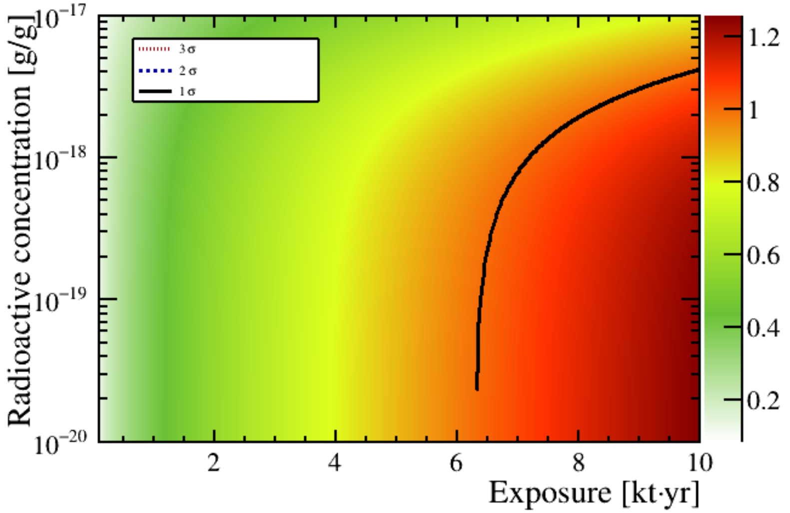
- Sensitivity (detection geoneutrinos in K-dominate energy region)



38°@1MeV



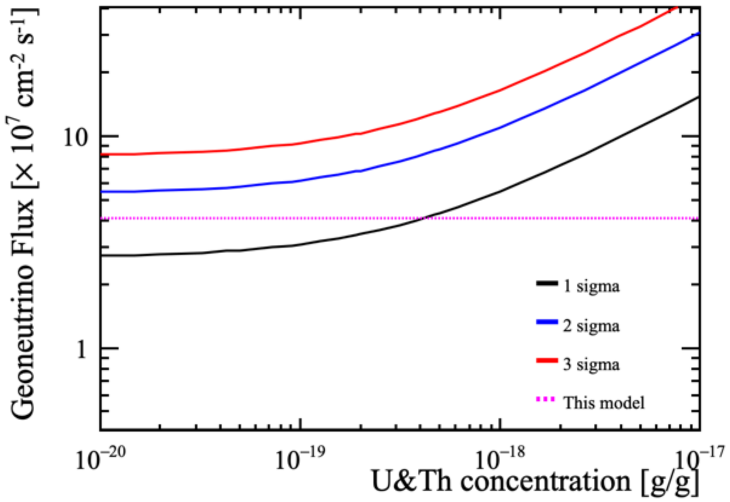
48°@1MeV



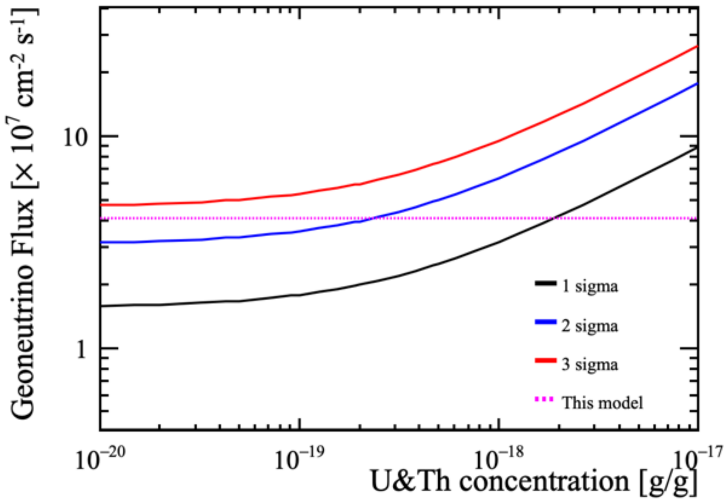
71°@1MeV

Results

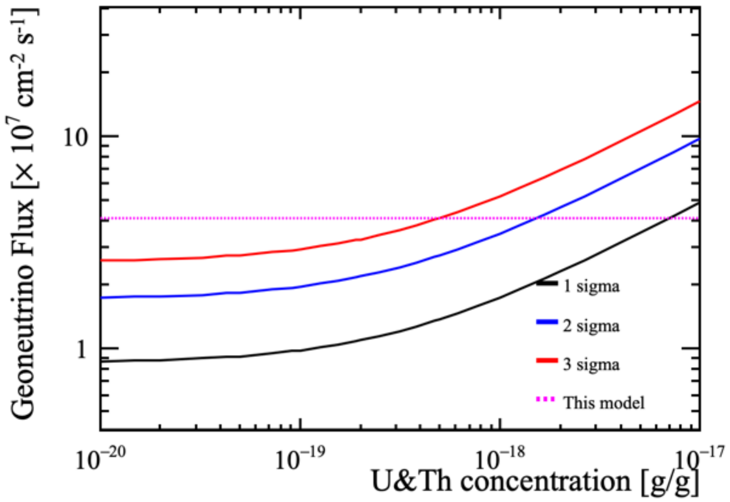
- Capacity to reject Earth model



1 kiloton-year



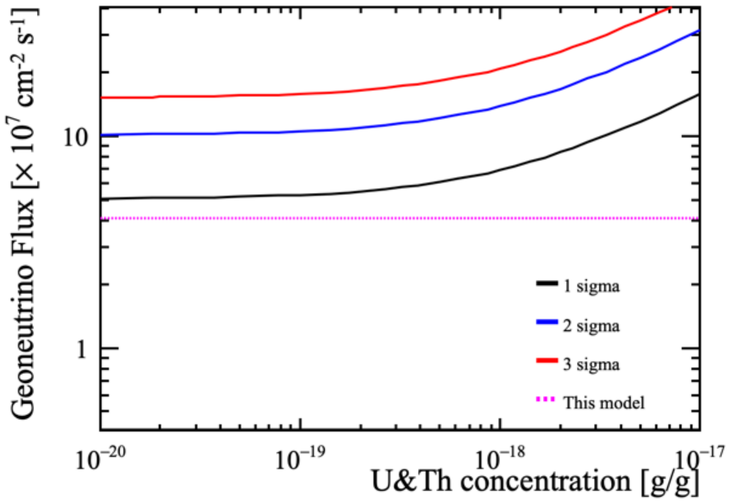
3 kiloton-year



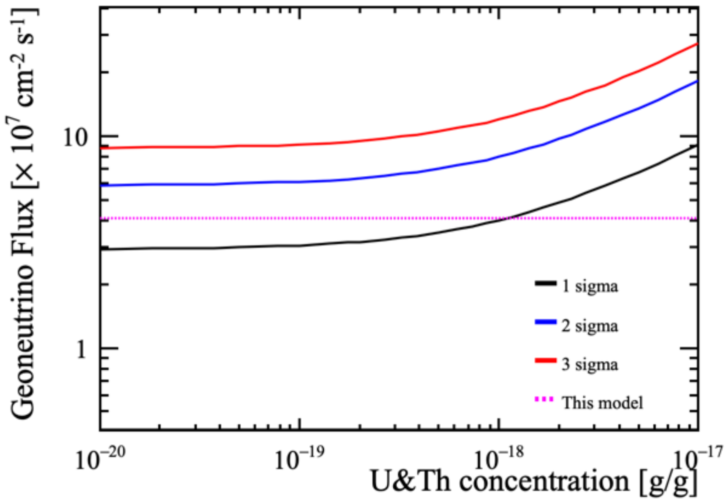
10 kiloton-year

Results

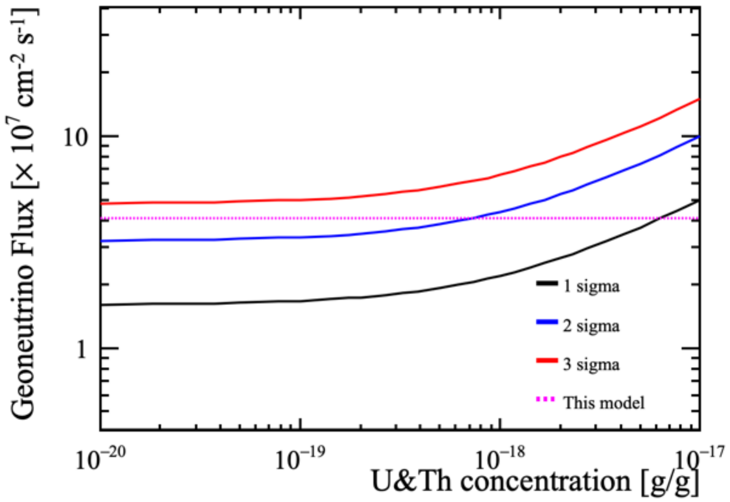
- Capacity to reject Earth model



1 kiloton-year



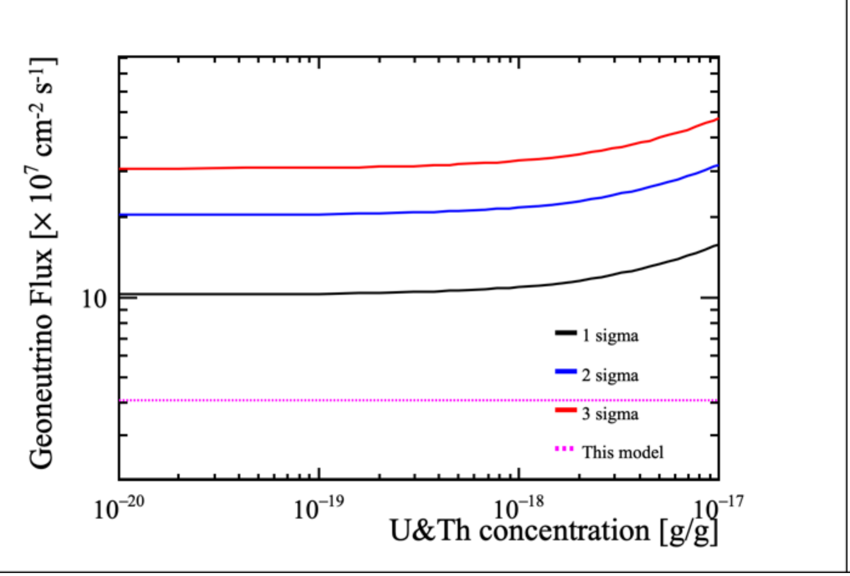
3 kiloton-year



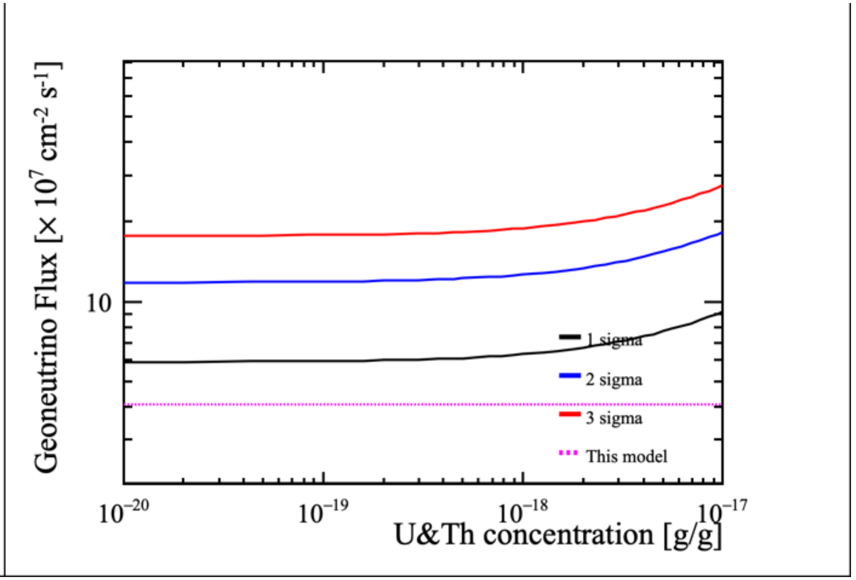
10 kiloton-year

Results

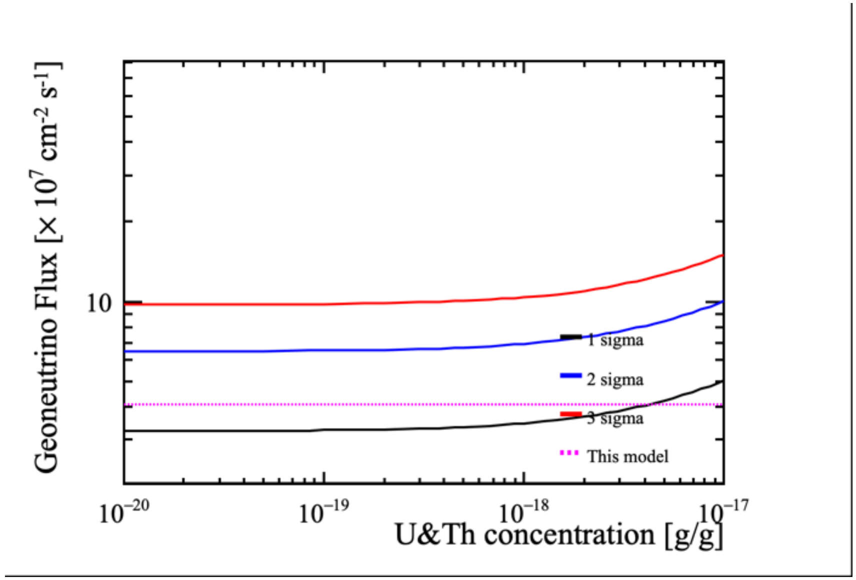
- Capacity to reject Earth model



1 kiloton-year



3 kiloton-year



10 kiloton-year

Outline

- Motivation
- Geoneutrino detection gap
  - Missing K-40 geoneutrinos
- Directional geoneutrino detection
  - Directional detection concept
  - Background suppression
  - Main result
- ***Summary and outlook***

Summary

- The event rate of geoneutrino-electron elastic scattering is calculated.
- Three angular resolution are derived using a Cherenkov liquid scintillator detector simulation.
- The $\cos\theta_{\odot}$ cut is optimized to enhance detection sensitivity.
- The detection sensitivity to potassium-40 geoneutrinos is investigated using the three angular resolutions under various radioactive purity conditions.

Outlook

- Develop novel liquid scintillators with longer time constants and higher light yields.
- Optimize event reconstruction algorithms to improve angular resolution and further boost detection sensitivity.
- Apply particle identification to suppress radioactive background.
- Realize tomographic imaging of Earth’s interior structure via directional geoneutrino detection.

Thanks for listening!