Prospect for the Detection of the Geo-neutrino Signal with JUNO

Conference on frontiers of underground and space particle physics and cosmophysics

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on behalf of JUNO collaboration

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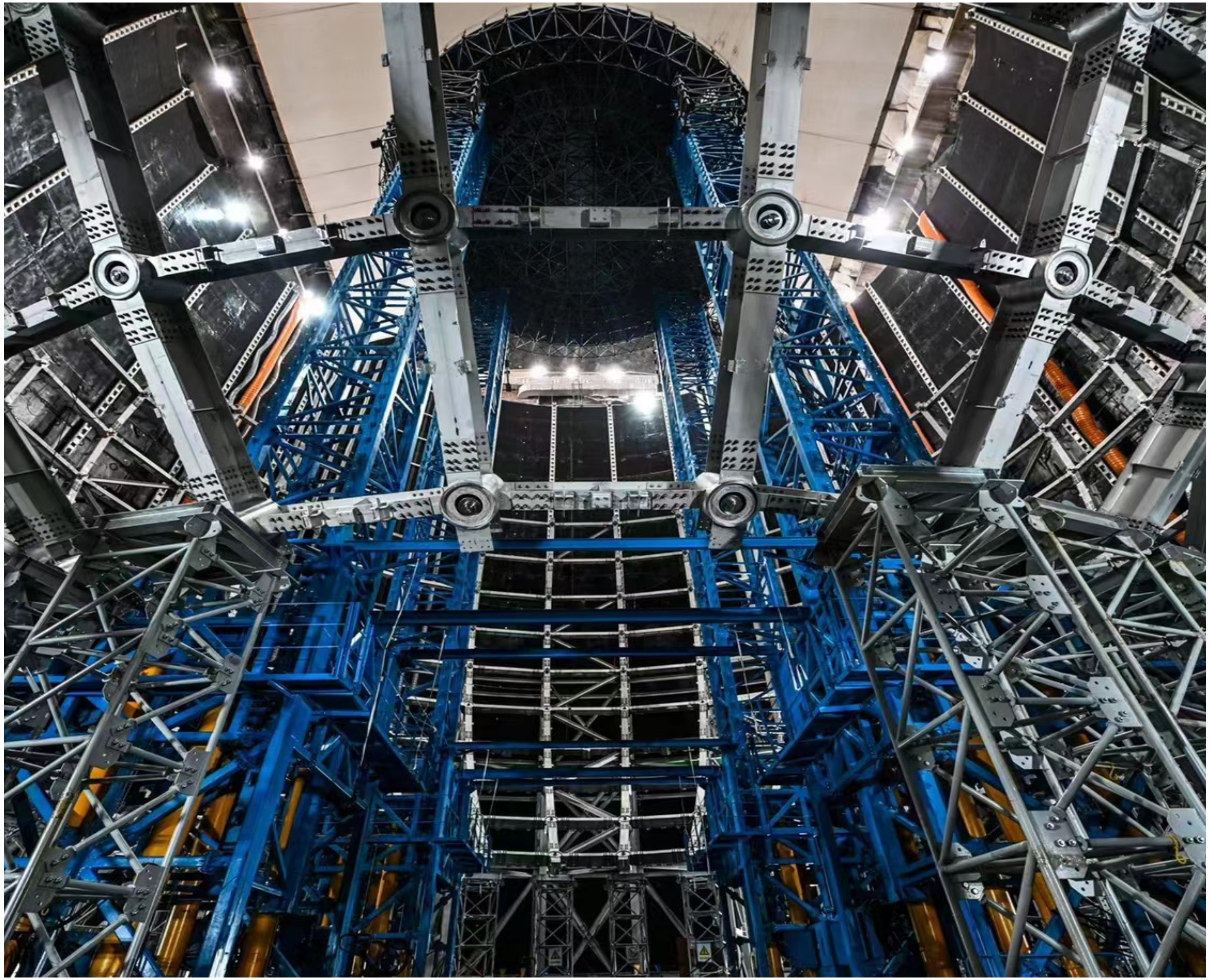
Outline

1. Motivation
2. JUNO Experiment
3. Geo-neutrino Sensitivity Study
4. Summary



Motivation

Geoneutrino is one of central topics of JUNO

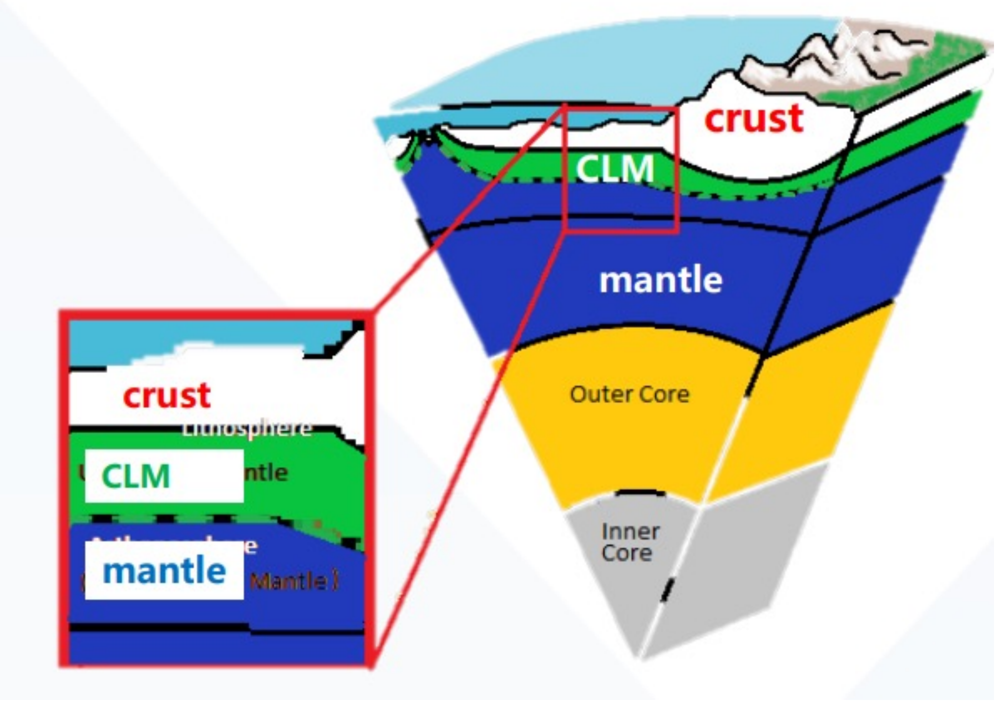
- The intersection of particle physics and geophysics
- An independent method to study the matter composition deep within the Earth

Abundance of the radioactive elements → Radiogenic heat

Abundance of the radioactive elements → Geo-neutrino flux → Radiogenic heat

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$
$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

$$S_{\mathrm{Total}} = S_{\mathrm{Crust}} + S_{\mathrm{CLM}} + S_{\mathrm{Mantle}}$$



- Crust: high U & Th
- CLM (Continental Lithospheric Mantle): relatively low U & Th
- Mantle: very low U & Th, large volume

How Geo-neutrinos Generate

Accessible via IBD reaction

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$
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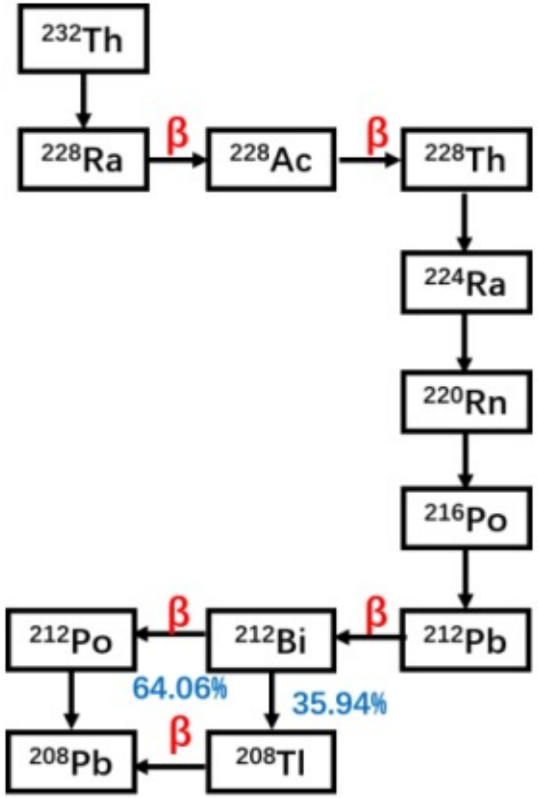
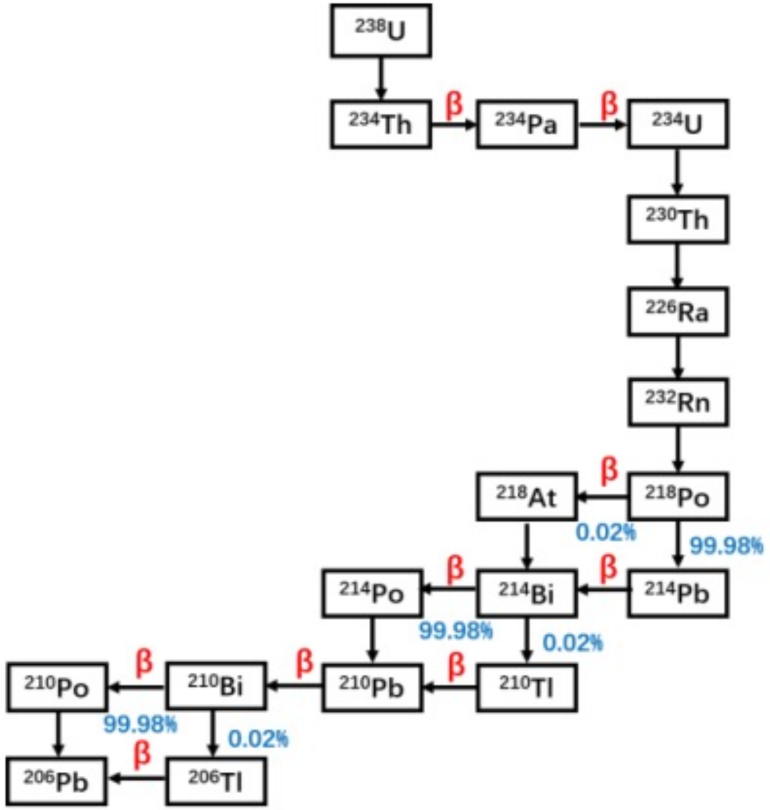
Contribution to Earth's heat

Decay chain for ^{232}Th



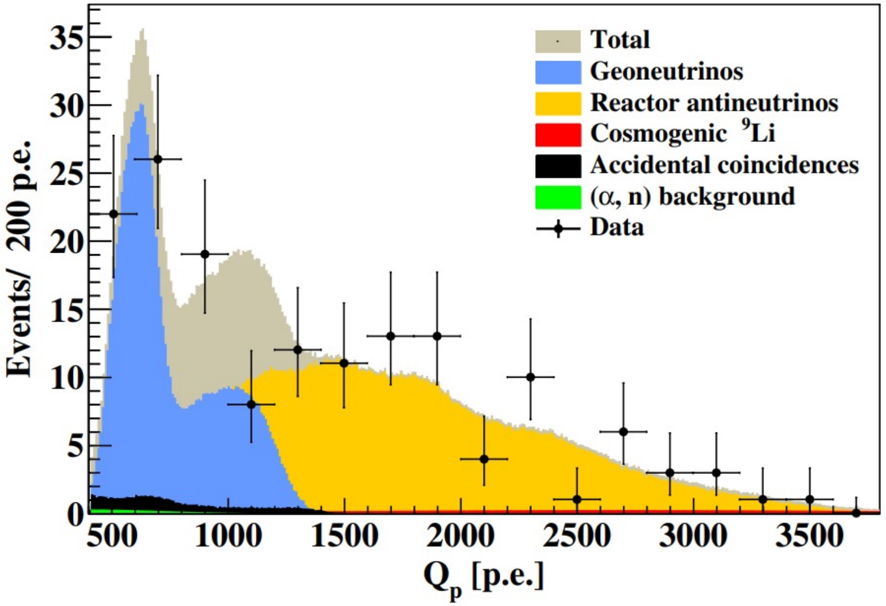
Decay chain for ^{238}U



Current Measurements

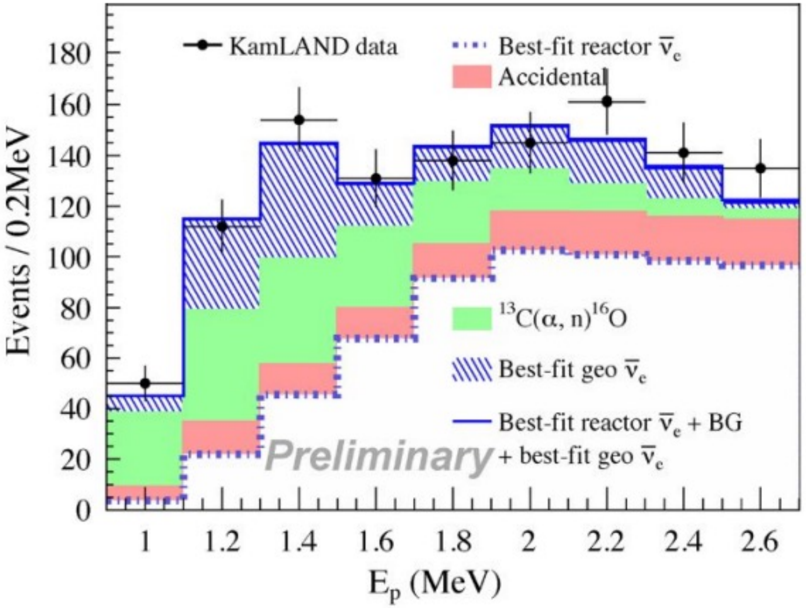
Borexino (2020) Phys. Rev. D 101, 012009

- Located in Gran Sasso, Italy
- Liquid Scintillator ~ 0.3 kton
- In 10 years ~ 50 geoneutrinos
- Precision ~ 17%



KamLAND (2022) Phys. Rev. C, 80, 015807

- Located in Hida, Gifu, Japan
- Liquid Scintillator 1 kton
- In almost 18 years ~ 170 geoneutrinos
- Precision ~ 15%

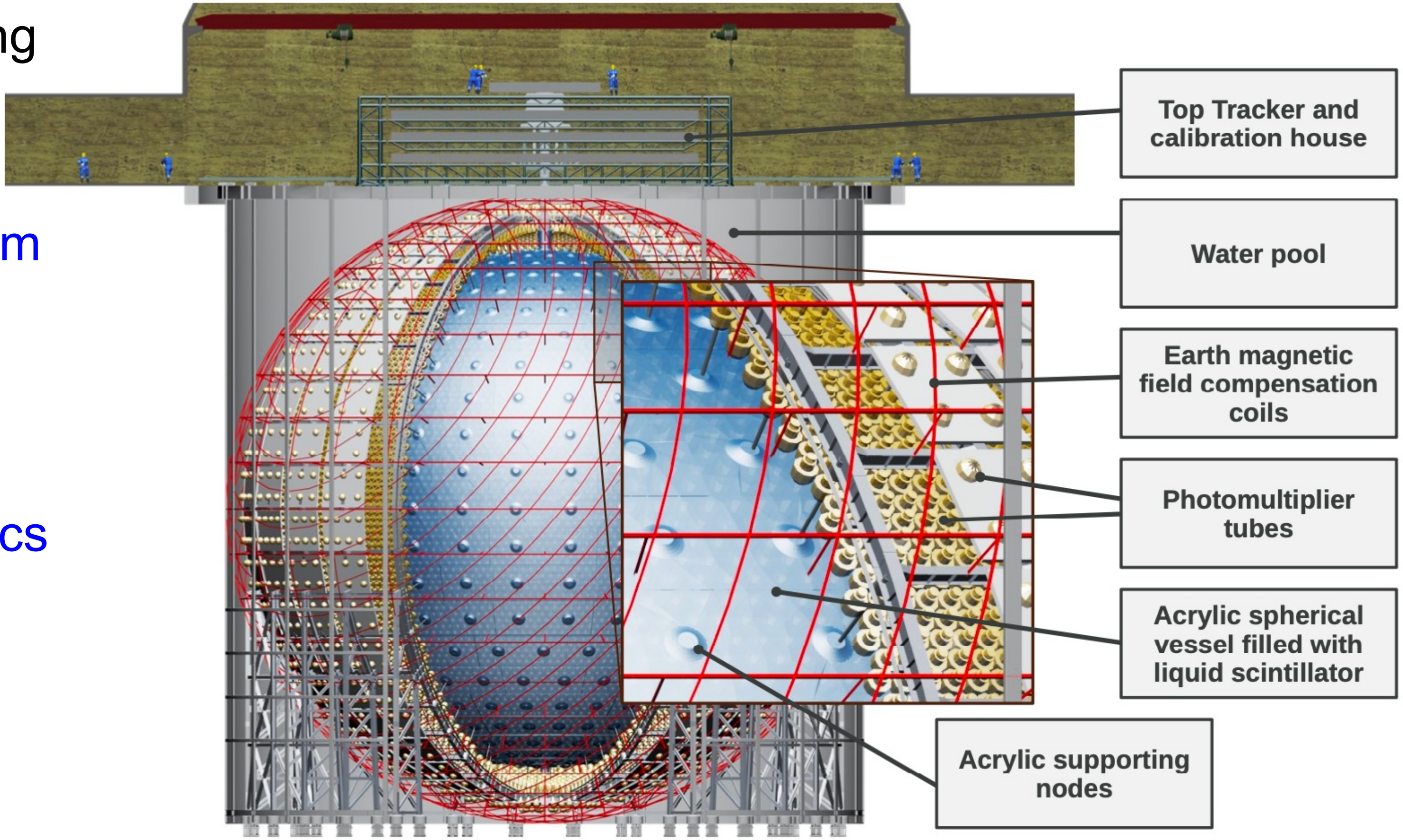


- JUNO will collect more geo-neutrino events than all the other experiments with 1 year data !

Jiangmen Underground Neutrino Observatory

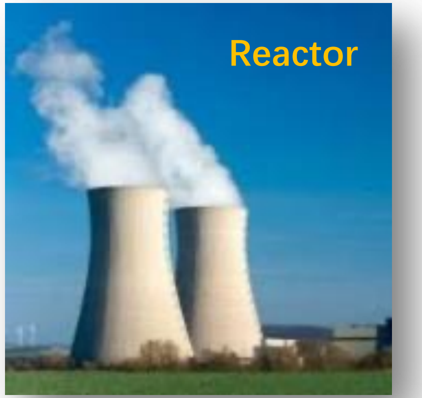
Jiangmen Underground Neutrino Observatory

- Located in Kaiping, Jiangmen, Guangdong province in China
- Designed to measure reactor neutrinos from 2 NPPs at 52.5 km distance (~ 650 m overburden)
- 17,612 20-inch PMTs and 25,600 3-inch PMTs. → Large PMT coverage (~78%)!
- 20 kton of liquid scintillator → high statistics
- Designed for unprecedented energy resolution (~ 3% at 1 MeV)
- Potential to study various sources of neutrinos.



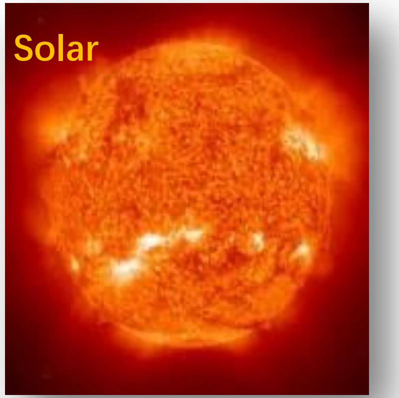
Chin.Phys.C 46 (2022) 12, 123001

A Multi-purpose Observatory



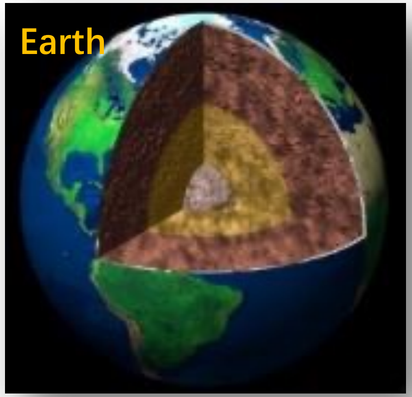
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



1~2 IBDs per day

\+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

Geo-neutrino Prediction

Geo-neutrino Rate

based on lithosphere and mantle models

Geo-$\bar{\nu}_e$ = Lithosphere + Mantle

Lithosphere model	Signal [TNU]
Global model Prog. in Earth and Planet. Sci. **2**, 5 (2015)	$30.9^{+6.5}_{-5.2}$
JULOC model Phys.Earth Planet.Interiors 299 (2020) 106409	$40.4^{+5.6}_{-5.0}$

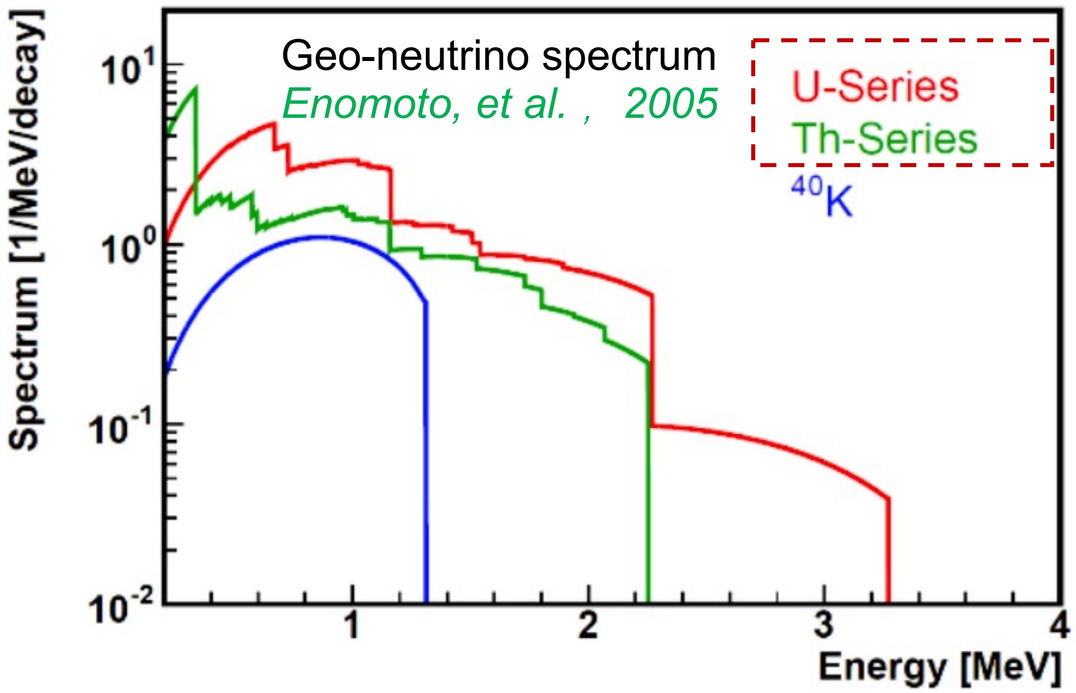
Mantle model	Signal [TNU]
Cosmochemical (CC)	~ 2
Geochemical (GC)	~ 10
Geodynamical (GD)	~ 20

1 TNU (Terrestrial Neutrino Unit): one interaction over a year-long fully efficient exposure of 10^{32} free protons.

Geo-neutrino Shape

based on Enomoto flux model

- ^{238}U and ^{232}Th decay chains (above 1.8 MeV)
- Summation model



https://www.awa.tohoku.ac.jp/~sanshiro/research/geoneutrino/spectrum/

Event Selection (IBD signals)

Inverse Beta-Decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

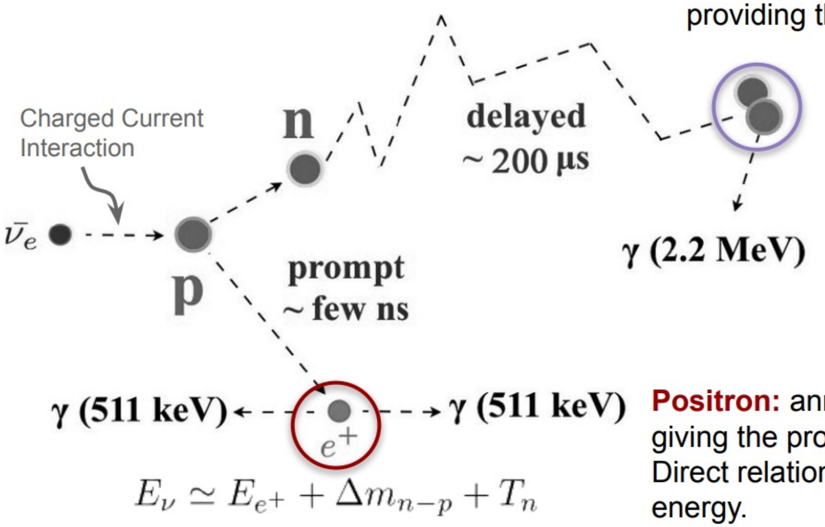
Selection of IBD candidates:

- Muon veto
- Selection cuts ($\sim 10^4$ suppression of IBD-like events):
  - Prompt energy: [0.7, 12.0] MeV
  - Delayed energy: [1.9, 2.5] MeV & [4.4, 5.5] MeV
  - Time difference: 1 ms
  - Distance: 1.5 m

Neutrino selection efficiency: $\mathbf{82.2\%}$

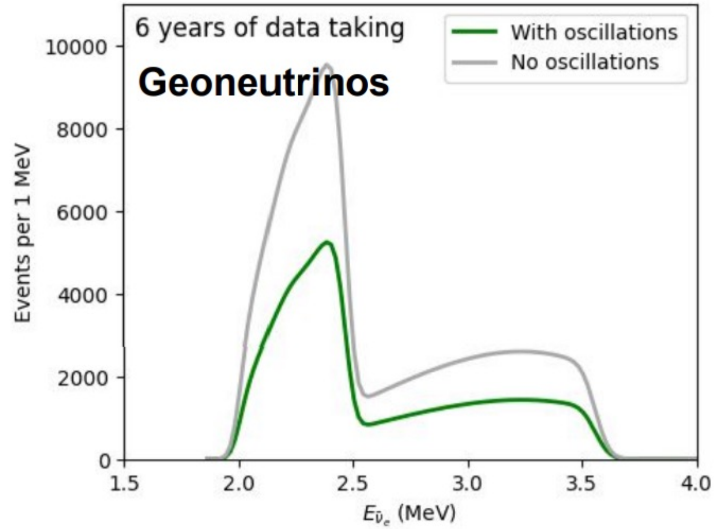
Neutron: Thermalize in the LS and captured after ~ 200 μs, providing the delayed signal

Delayed signals



Positron: annihilates quickly giving the prompt signal. Direct relation with neutrino energy.

Prompt signals



Geo-neutrino Signal and Backgrounds at JUNO

Geo-neutrino signals
- From the decay chains of ^{232}Th and ^{238}U
- About 1 event per day

Reactor neutrinos
- contributed by two near NPPs (52.5 km) and Daya Bay NPP (~200 km)

World reactor neutrinos
- contributed by the NPPs (>300km)

JUNO will measure in 1y ~400 geo-neutrinos events more than Borexino and KamLAND in >10y!

Neutrino selection efficiency: **82.2%**

	Rate [cpd]	Rate uncert.	Shape uncert.
Geo-neutrinos	1.2	-	5%
Reactor neutrinos	47.1	-	Daya Bay/ TAO
Accidental	0.8	1%	-
^{9}Li/^{8}He	0.8	20%	10%
^{13}C(α, n)^{16}O	0.05	50%	50%
Fast neutron	0.1	100%	20%
World reactor neutrinos	1	2%	5%
Atmospheric neutrinos	0.16	50%	50%

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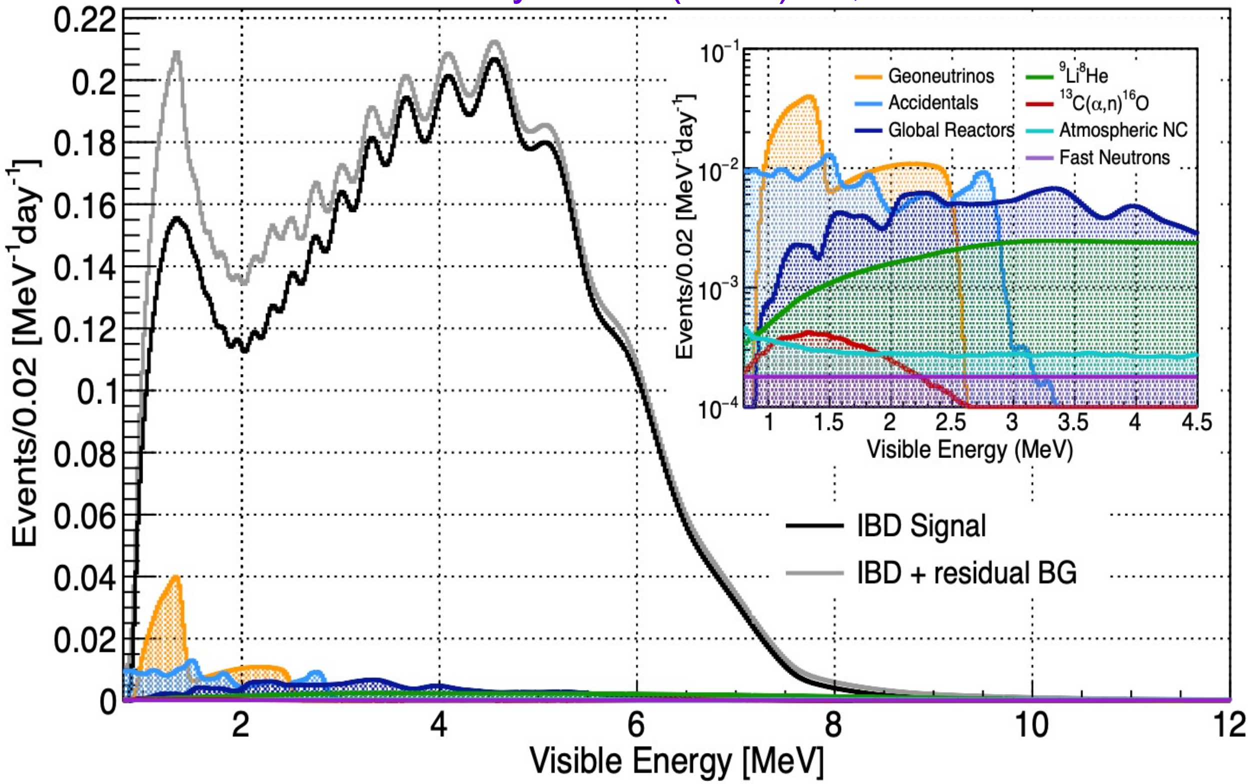

Why can JUNO detect geo-neutrinos?

Reactor neutrinos Irreducible background

- Much higher rate ($4 \sim 10$ times than geo-neutrino rate in geo-neutrino energy window)
- No way to distinguish ➡ Reactor shape is very precise → **TAO or Daya Bay constraint**
- Affected by neutrino oscillation ➡ JUNO's measurement can reach sub-percent precision
- Neutrino oscillation parameters are the largest systematic uncertainties (Δm^2_{21} is the most important one)

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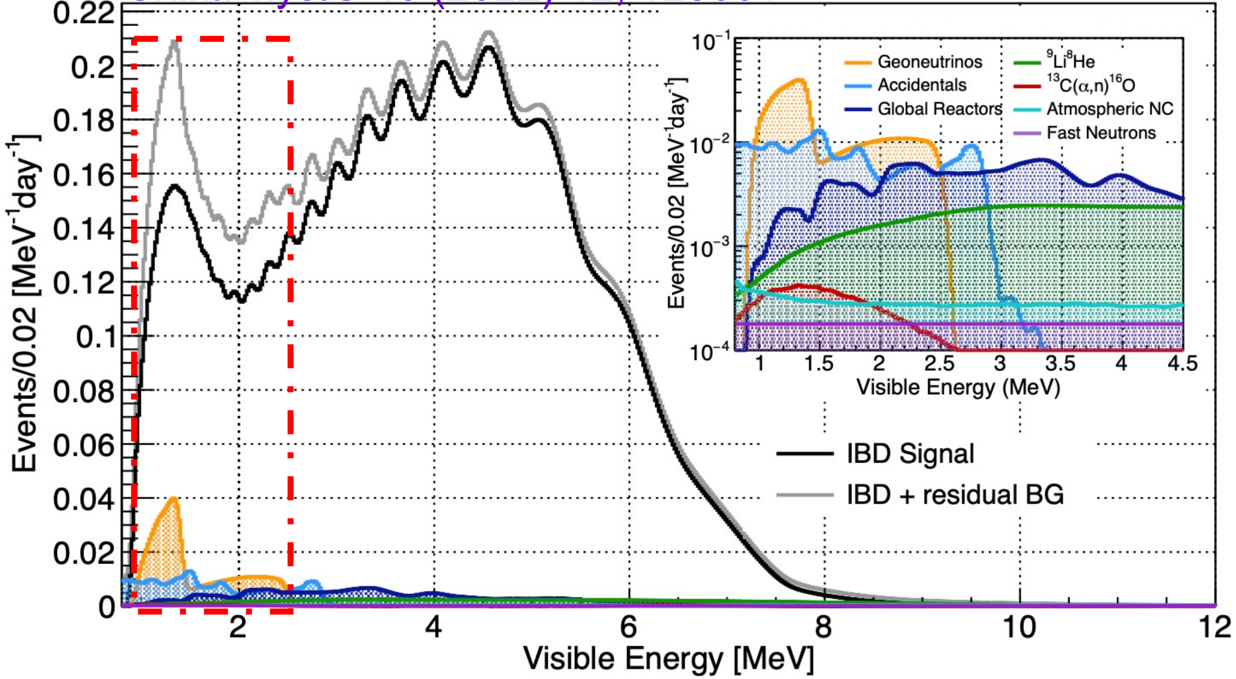
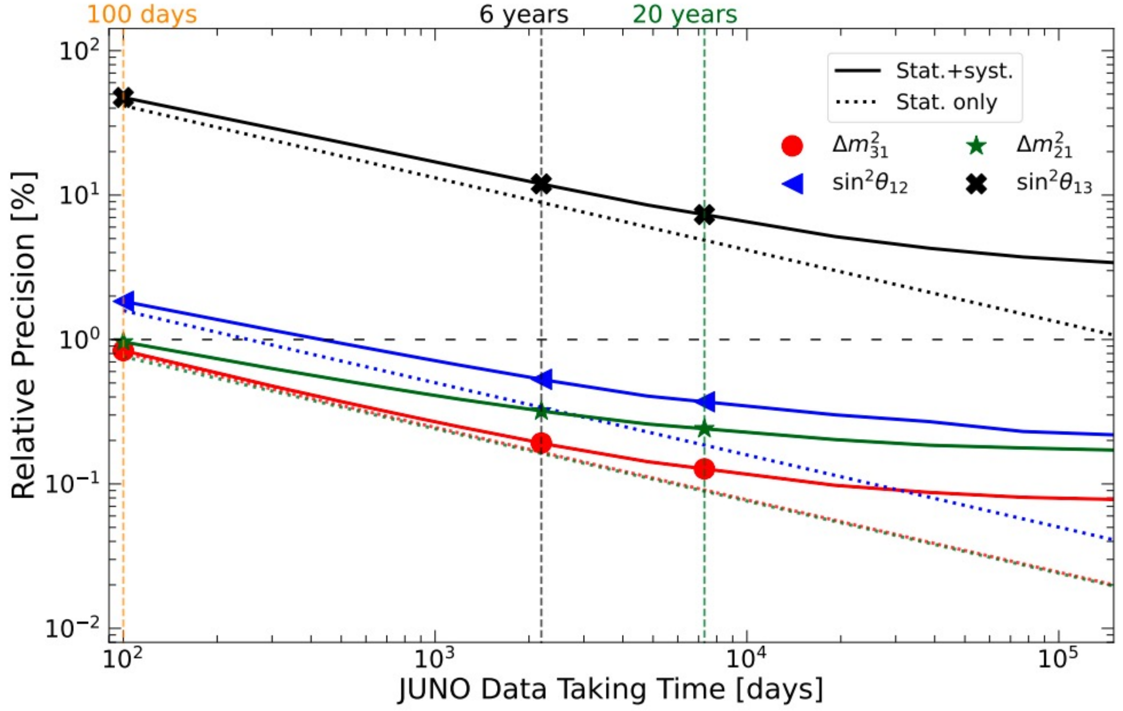
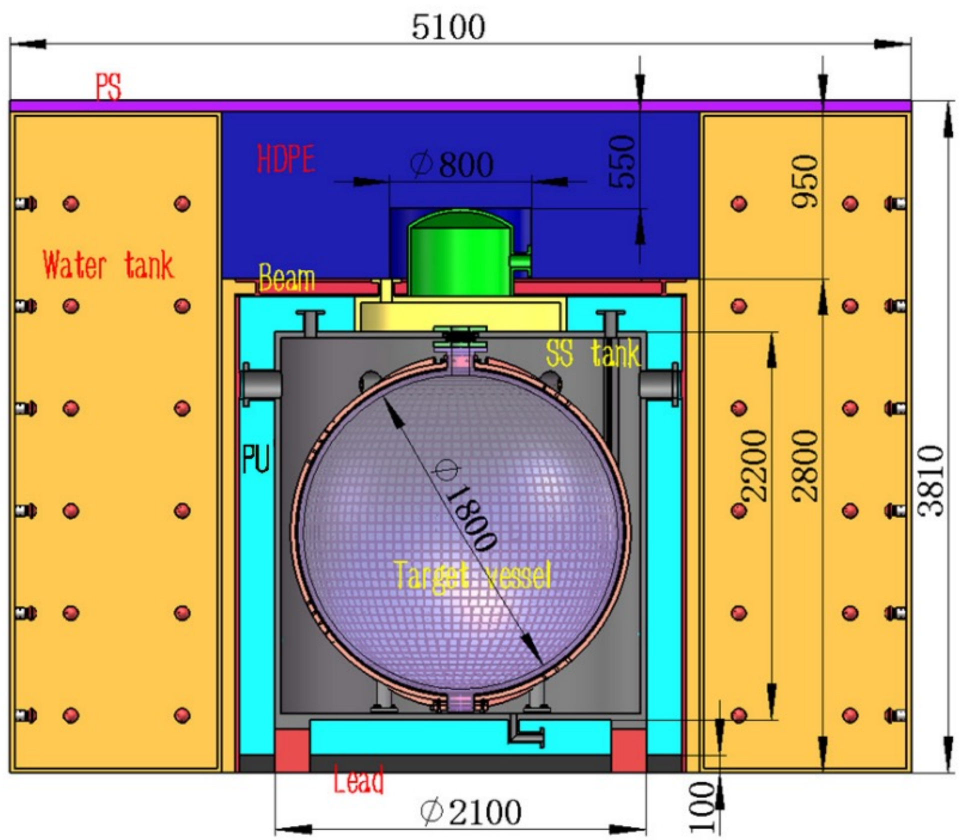




Taishan Antineutrino Observatory

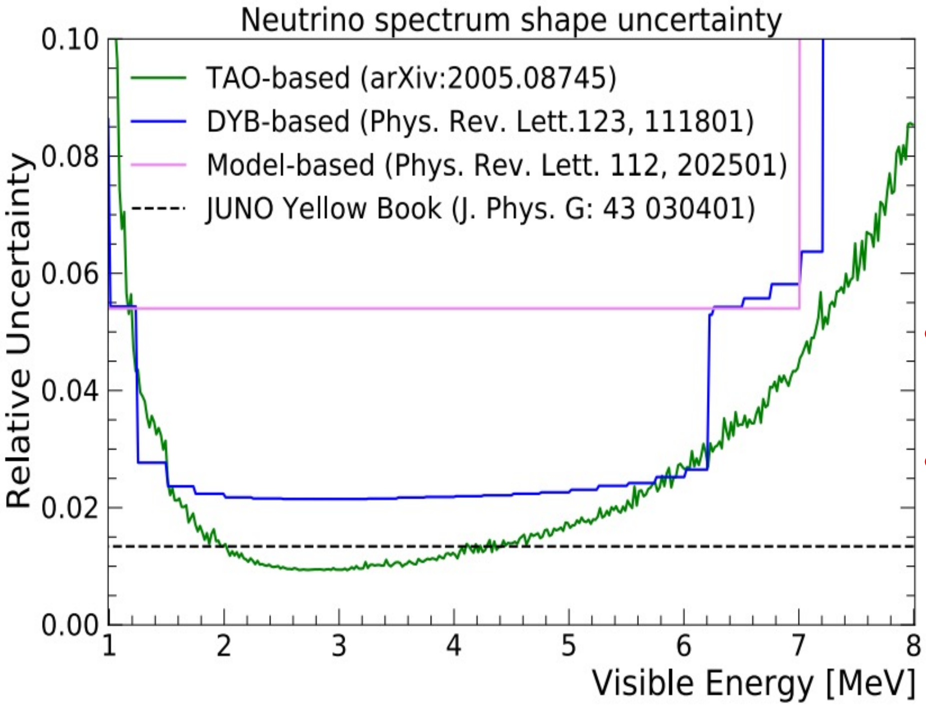


TAO Conceptual Design Report [arXiv: 2005.08745]

- 2.8 ton detector
- Energy resolution (< 2% at 1 MeV)
- ~94% coverage with SiPM (50% PDE)
- Detector at -50℃ (reduce SiPM dark noise)

Measurement of reactor antineutrino spectrum with no oscillations (within Taishan NPP building)

- Sensitive to fine structure with better precision
- **Model-independent reference spectrum for JUNO**



- **High statistics**
- **Precision spectrum**

Sensitivity to the Total Geo-neutrino Flux (U/Th Ratio Fixed)

Fit configuration:

- Th/U abundance fixed to the chondritic ratio (3.9)
- Geo- and reactor neutrino rates are free
- Geo- and reactor neutrino shape uncertainty included
- Other background rates are constrained
- **Oscillation parameters free**

⬇

the largest systematic uncertainties

Expected geoneutrino precision*
(assuming Th/U mass ratio fixed to 3.9)

1 year	**~22%**
6 years	**~10%**
10 years	**~8%**

PRELIMINARY

Phys. Rev. D 101, 012009

Borexino 17% with 8.9 years

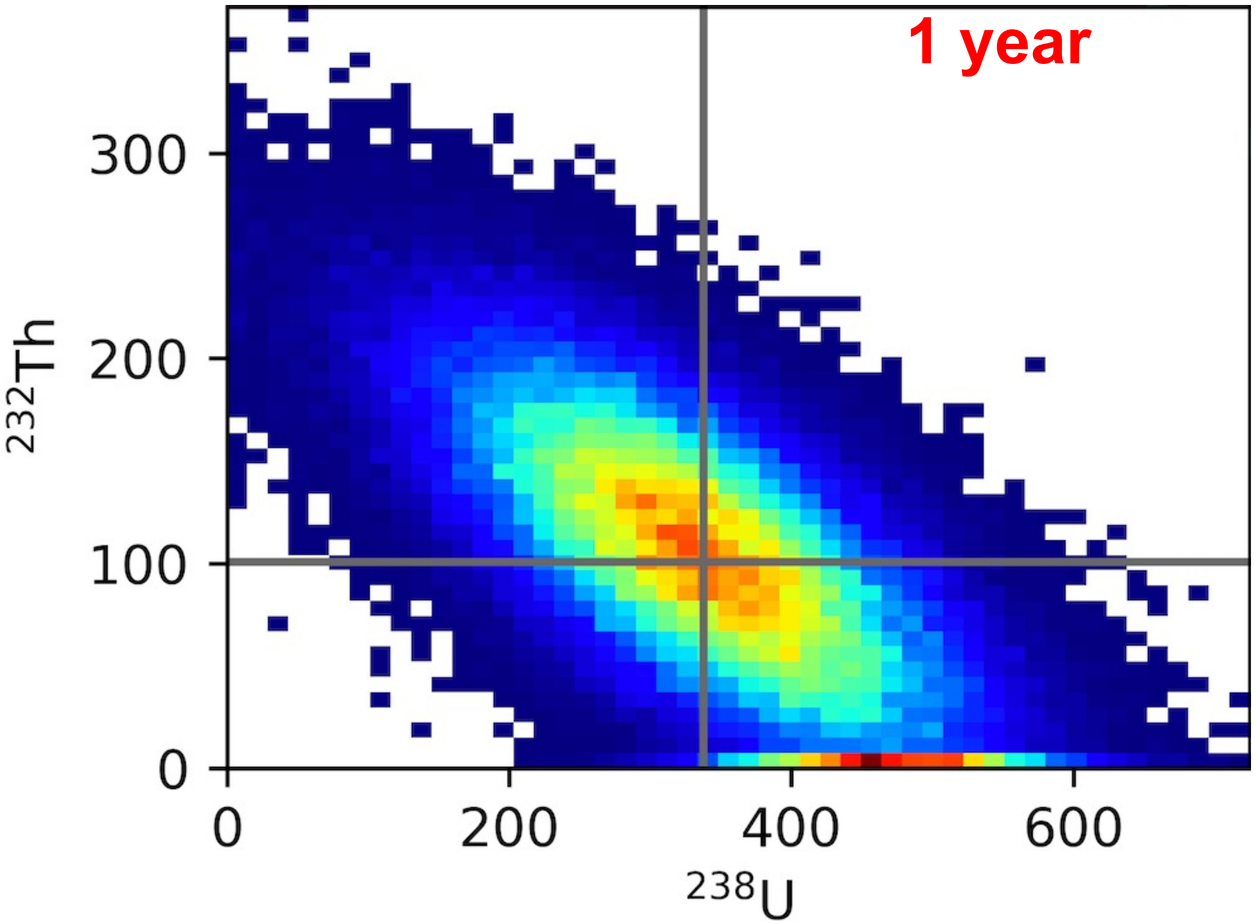
KamLAND 15% with 14.3 years

Phys. Rev. C, 80, 015807

Sensitivity to the Total Geo-neutrino Flux (U/Th Ratio Free)

fit results with **fixed oscillation parameters**

Only for illustration



Th and U are strongly anticorrelated:

JUNO can disentangle the Th and U contributions and make a very good measurement of their sum

Expected precision

fit results with **free oscillation parameters**

	6 years	10 years
^{232}Th:	~40%	~35%
^{238}U:	~35%	~30%
^{232}Th+^{238}U:	~18%	~15%
^{232}Th/^{238}U ratio:	~70%	~55%

PRELIMINARY

Summary

- Geo-neutrinos can provide a unique probe to the **Earth's composition and structure**
- **JUNO will collect the highest geo-neutrino statistics**
  more geo-neutrino events than all the other experiments with 1 year data
- Precise measurement of total geo-neutrino flux:
  - Borexino $\sim 17\%$ precision (10 years)
  - KamLAND $\sim 15\%$ precision (18 years)
  - **JUNO $\sim 22\%$ precision (1 year) and $\sim 8\%$ precision (10 years)**

  ➡ JUNO will provide the World's most precise measurements
- JUNO can measure U and Th individual contributions with high statistical significance
- The study of potential to observe **signal from mantle** in JUNO is ongoing
- **Full release of updated sensitivities soon**

Thanks for your attention !

Thanks!