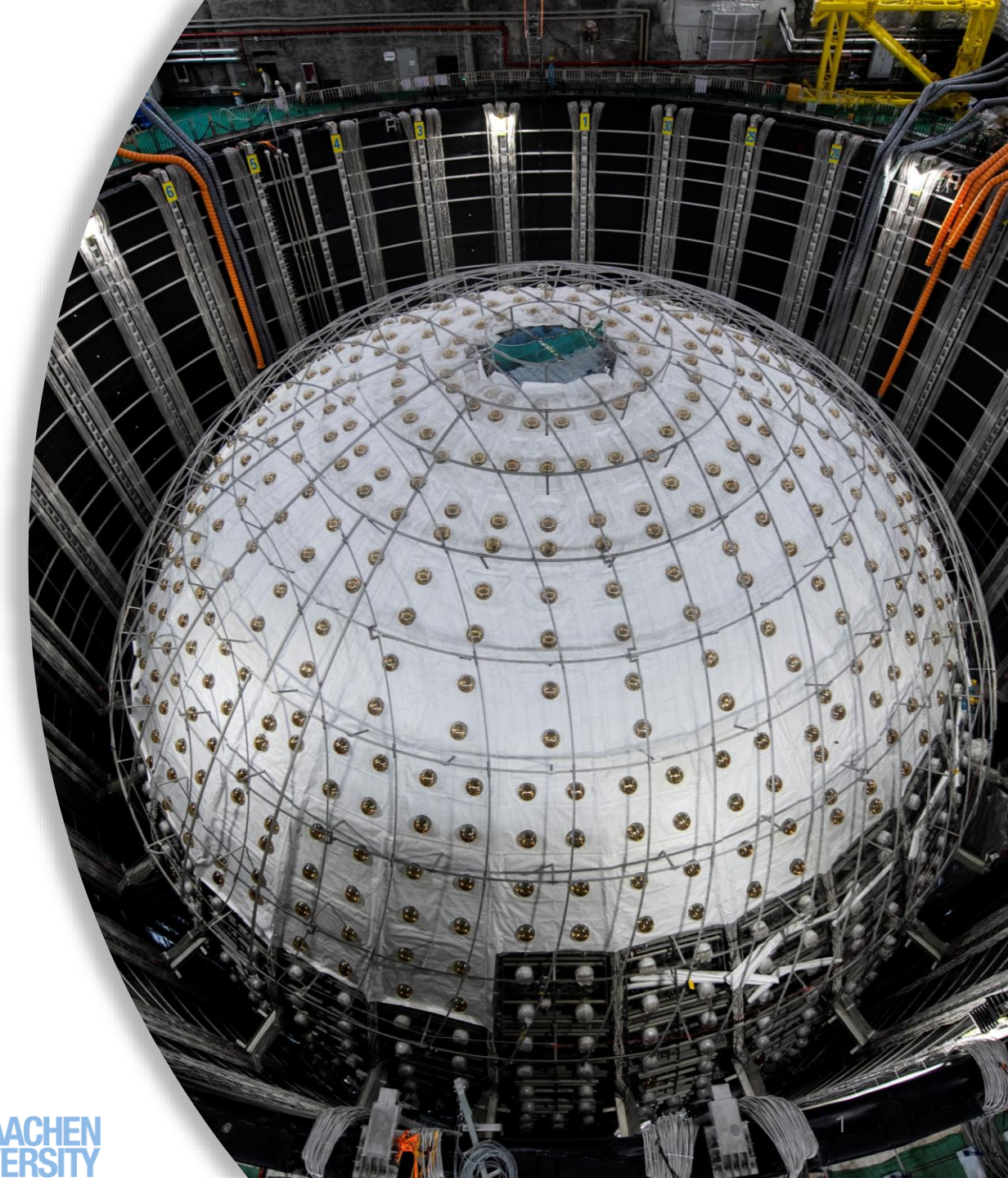
JUNO’s Sensitivity to Geoneutrinos

Cristobal Morales Reveco[1,3]
on behalf of the JUNO Collaboration

27th October 2025
Neutrino Geoscience 2025, Kingston, Canada

1. GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany
2. RWTH Aachen, Germany
3. Johannes-Gutenberg-Universität Mainz, Germany

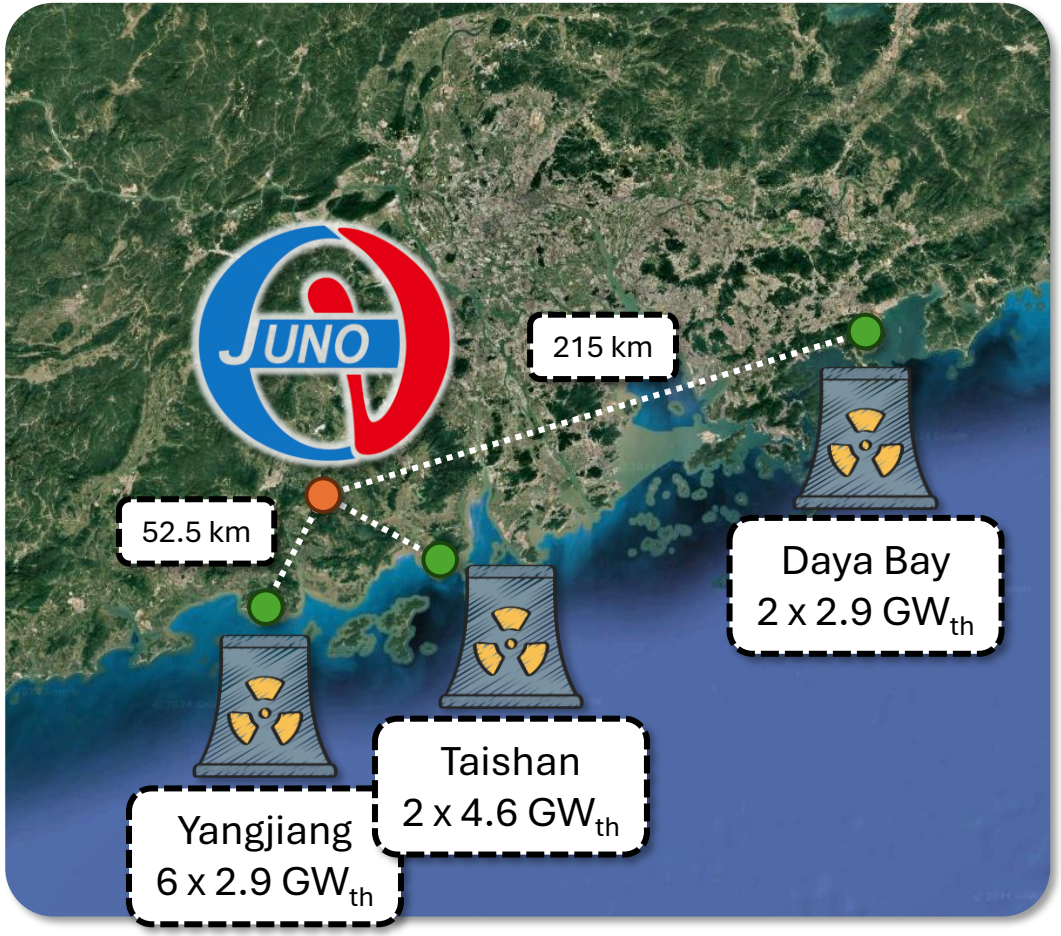


The JUNO Collaboration

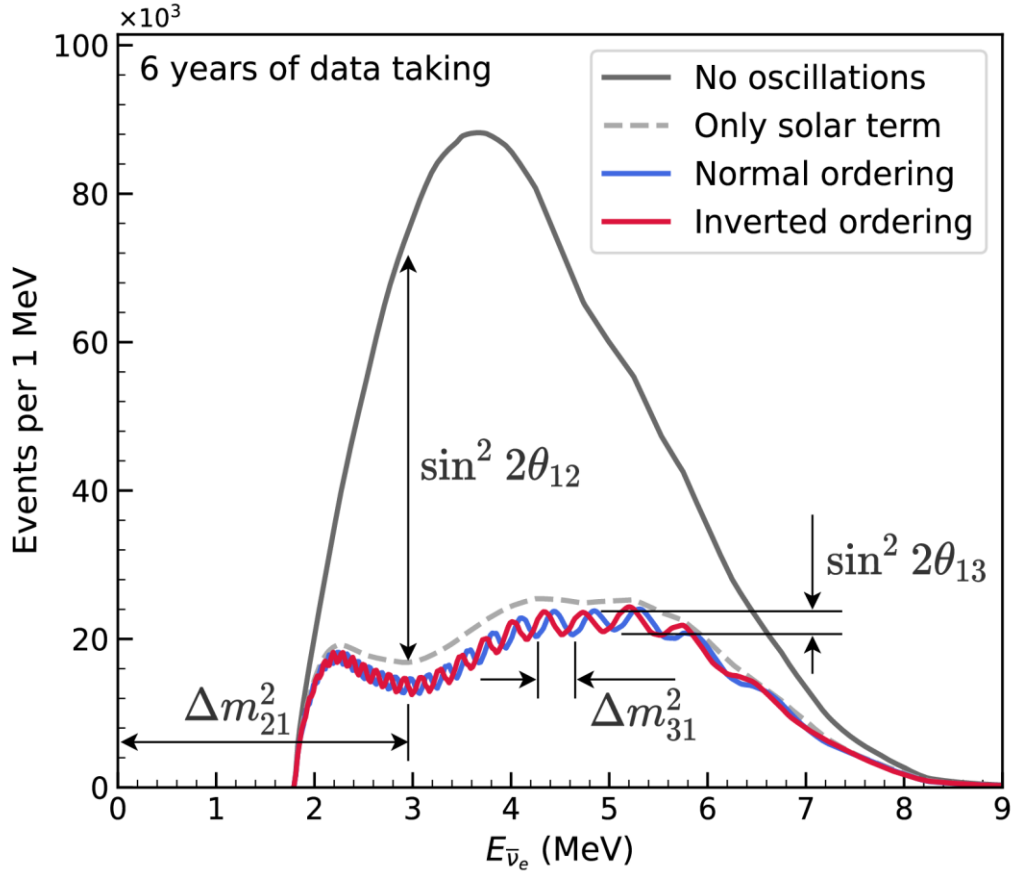
More than 700 collaborators from 74 institution in 17 countries/regions

The JUNO Experiment

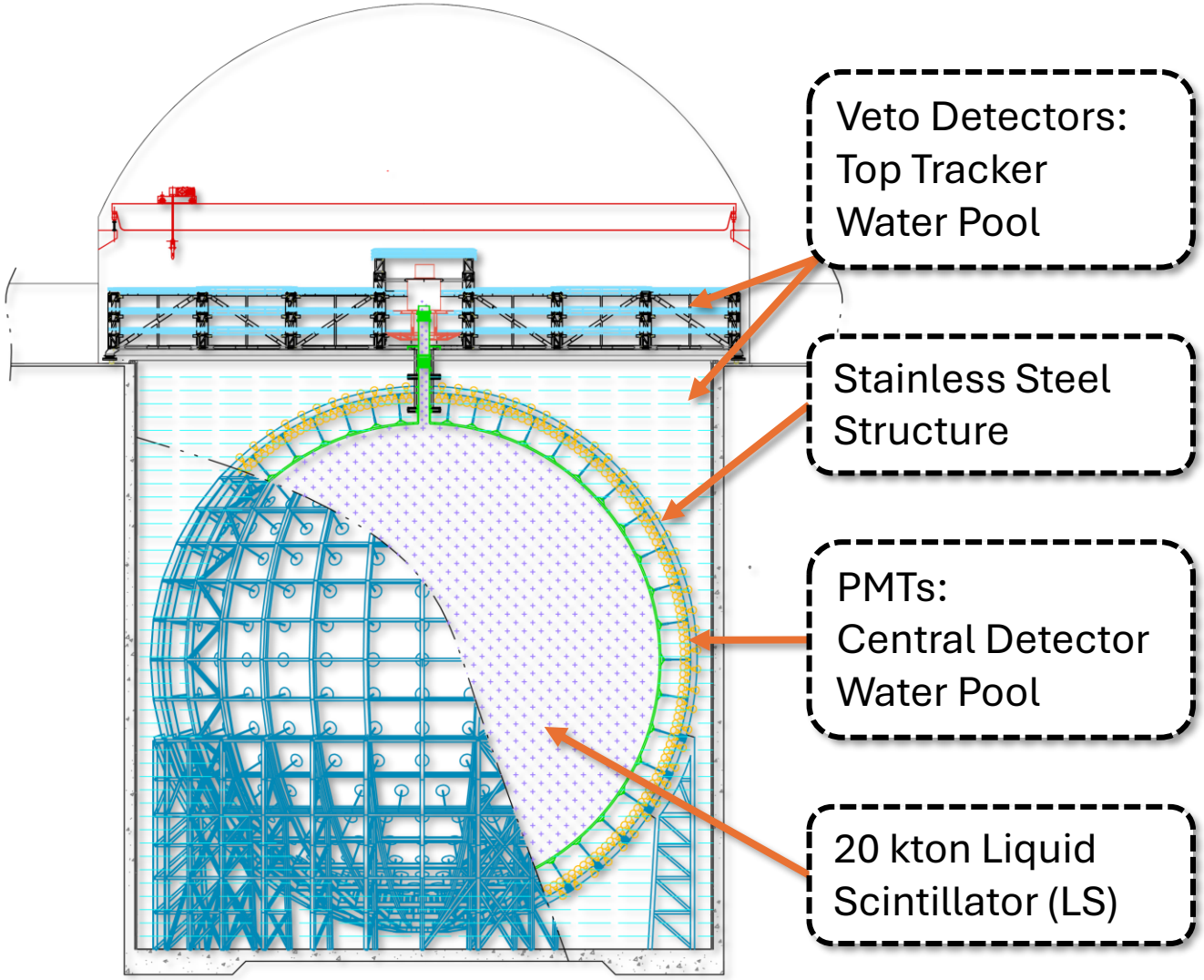
Located in Jiangmen region, China



Main goal: Determination of the neutrino mass ordering



The JUNO Detector

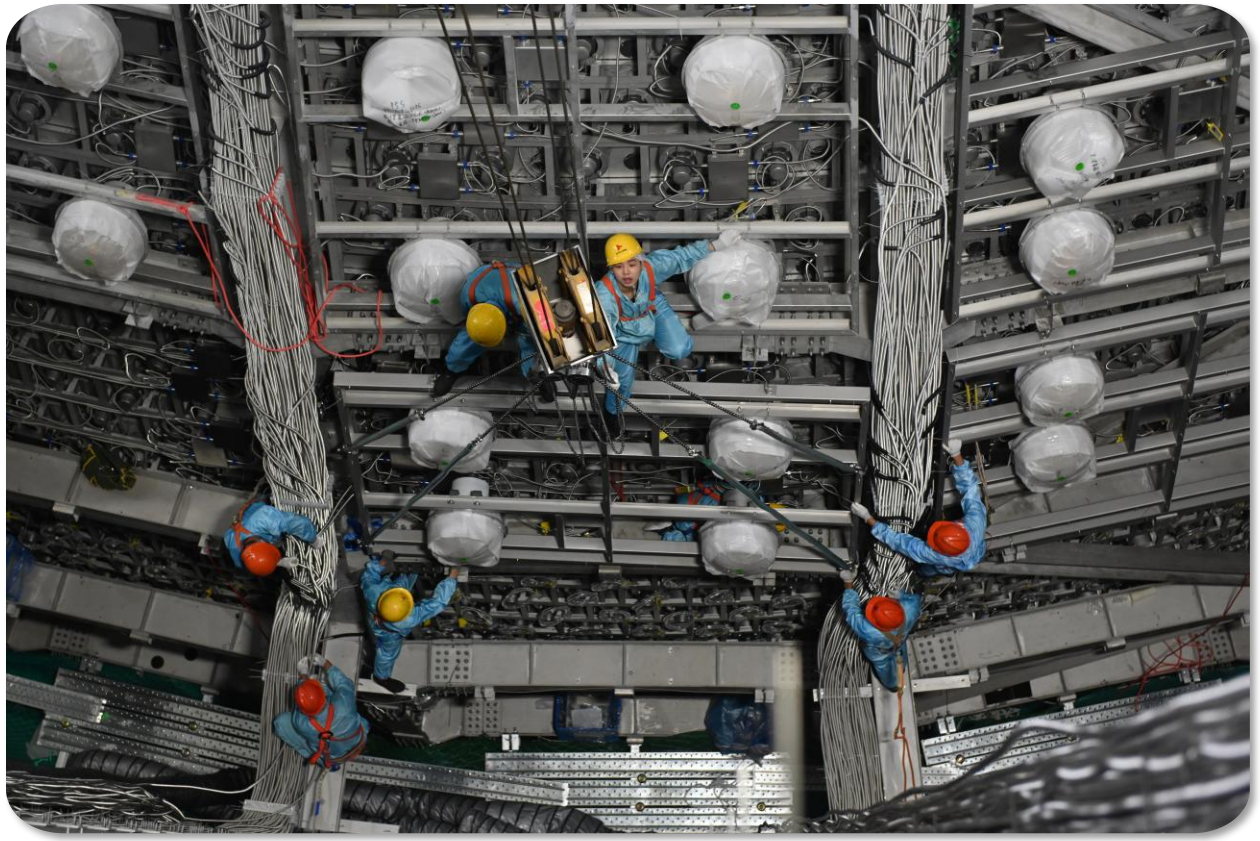


- Large statistics
  - 20 kton Liquid Scintillator (LS)
- High energy resolution: <3% @ 1 MeV
  - Large PMT coverage in Central Detector (CD) ~ 78%
  - High light yield (>1300 pe/MeV by design)
- Background control
  - Two veto detectors for muons: Top tracker (TT) and Water pool (WP)
  - Overburden of 650 m
  - Clean material selection and several steps of LS purification

Central Detector

November 2024

November 2024



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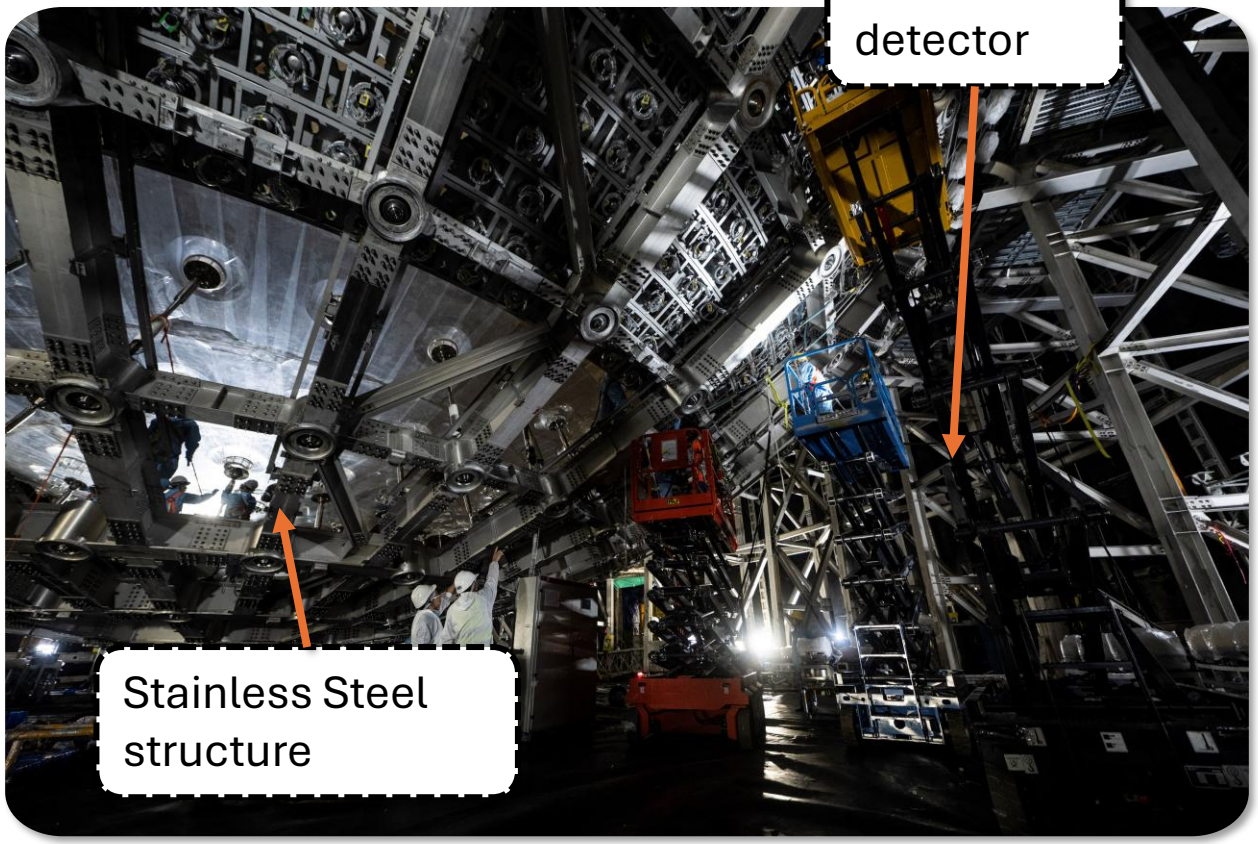
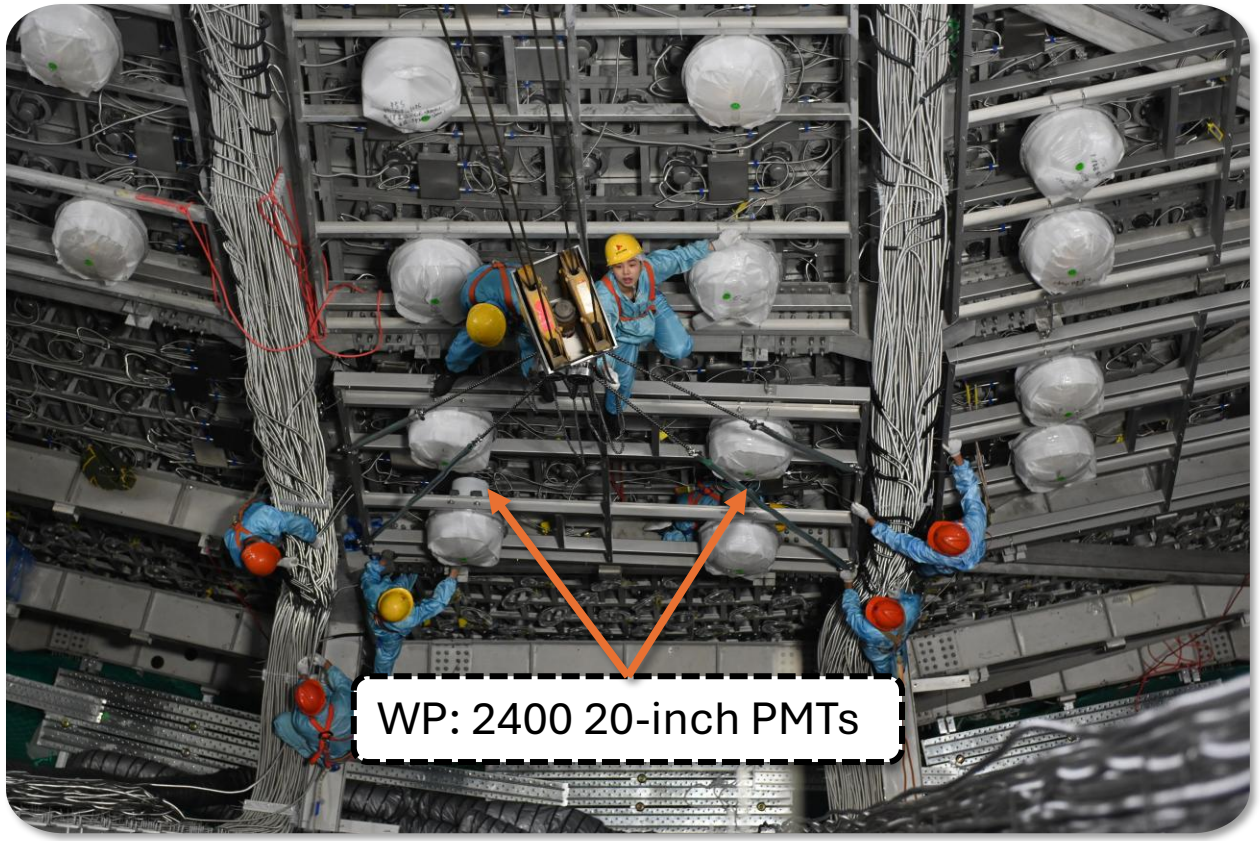


November 2024



Acrylic Sphere and PMTs

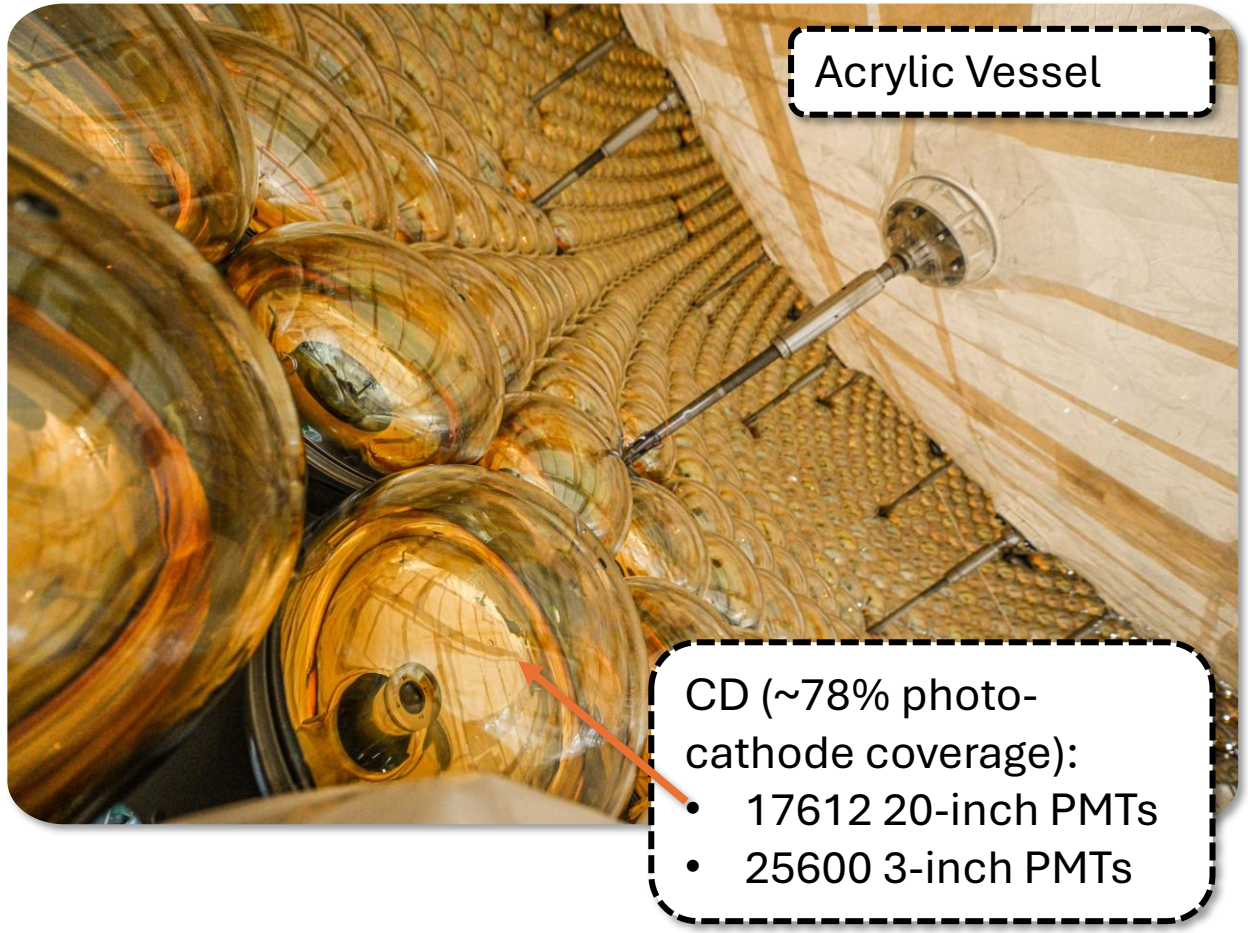
November 2024

October 2024

Acrylic Sphere and PMTs

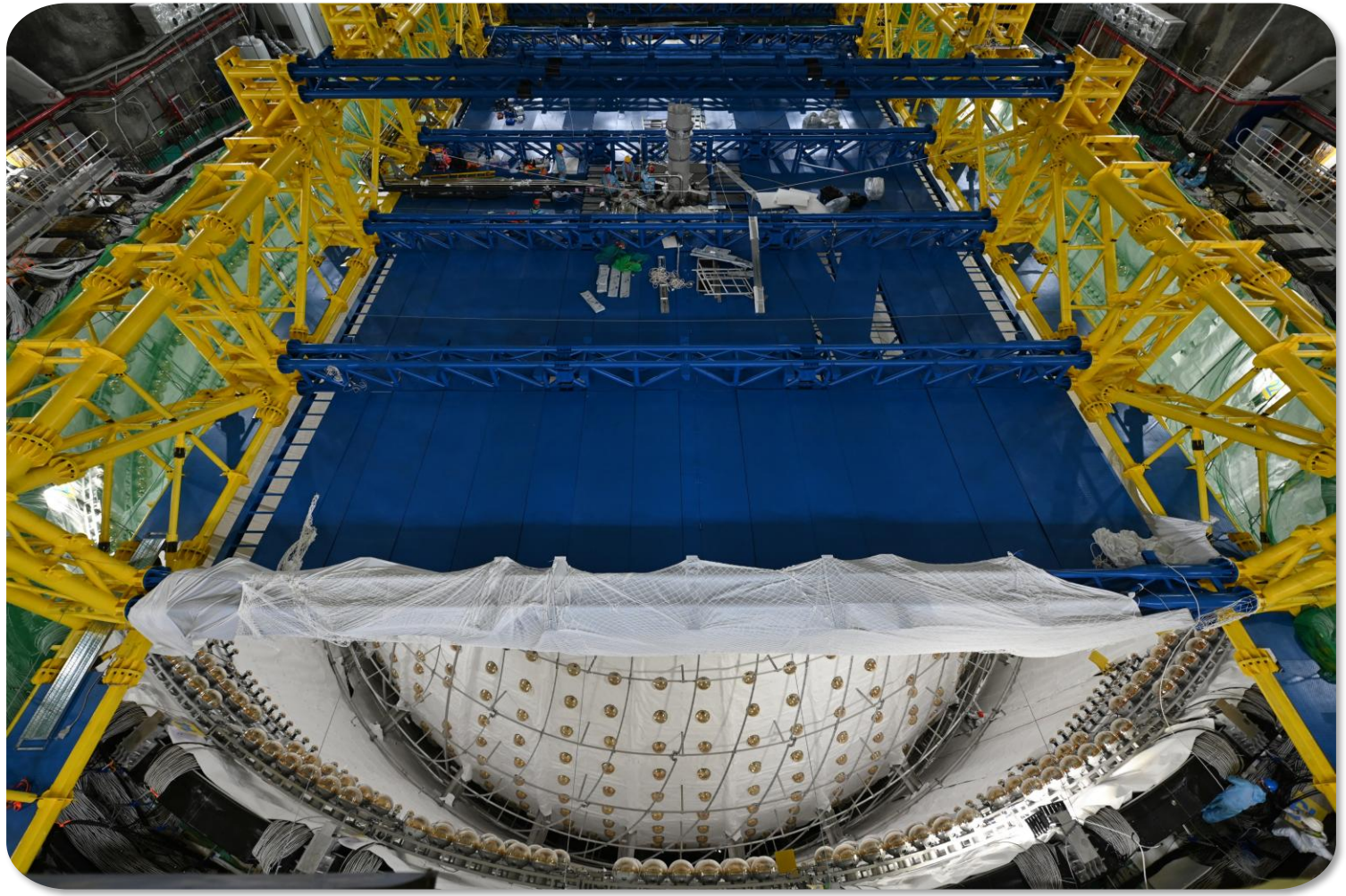
November 2024

October 2024



Before Filling...

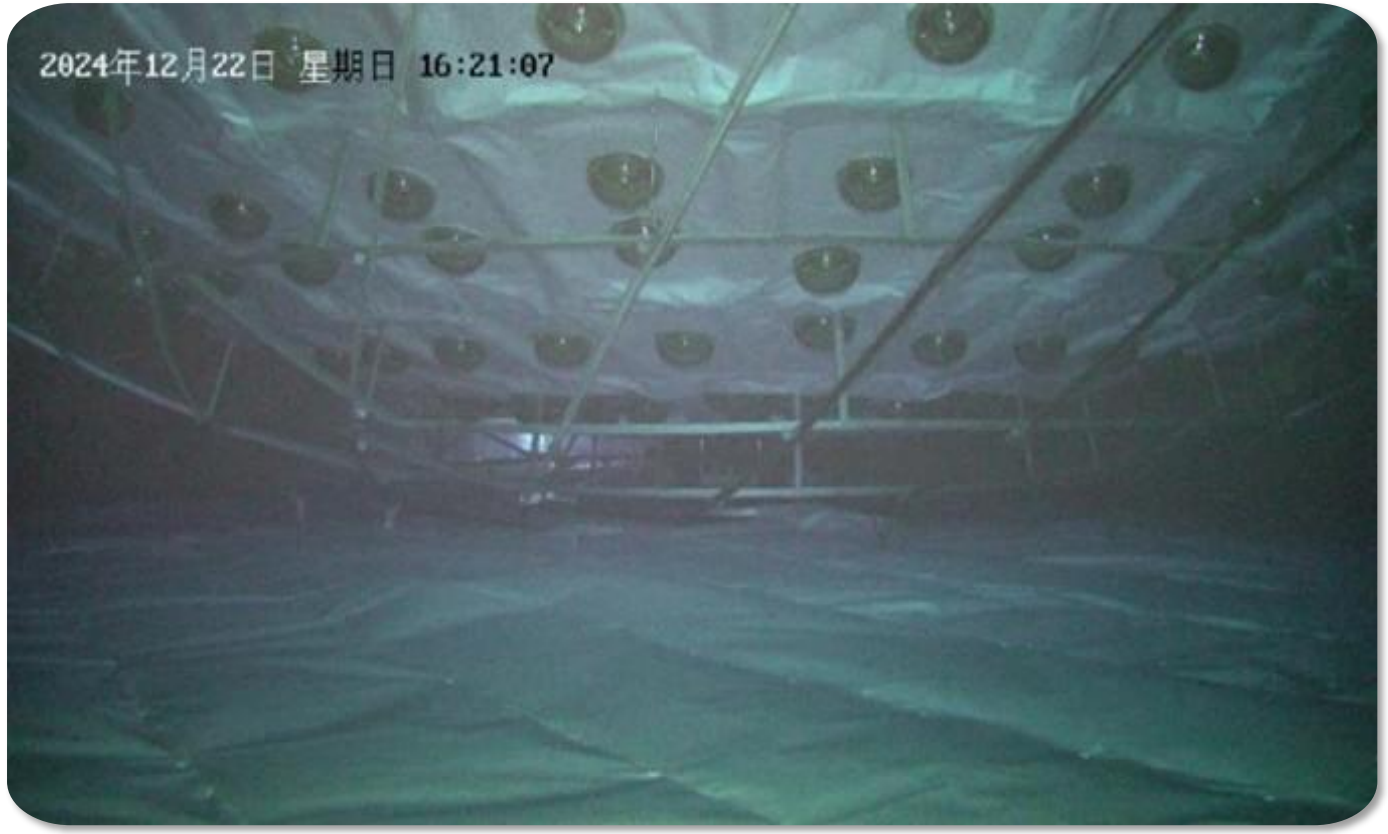
December 2024



JUNO Physics Phase

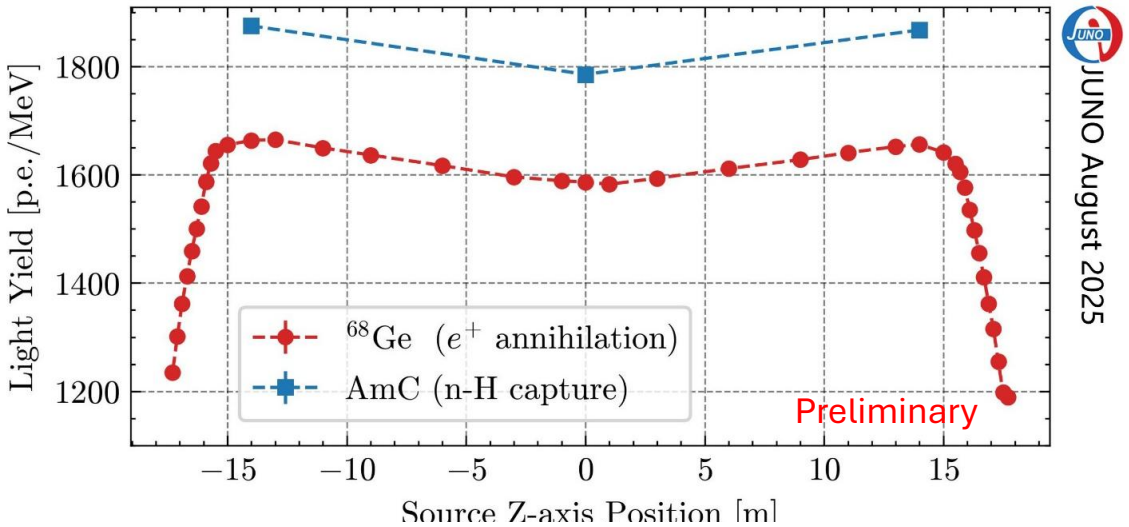
- End of construction and installation in December 2024
- Water filling from December to February
- Soon after replacement of water in the Acrylic Vesel with LS begun until 22nd of August
- After more than 10 years JUNO is taking data!

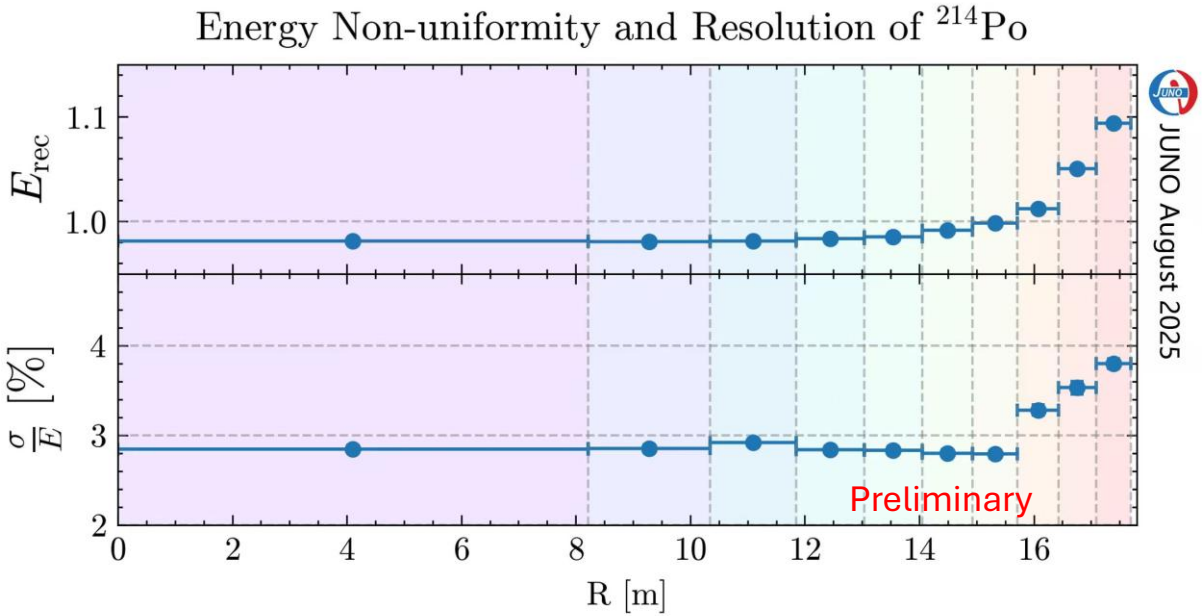
December 2024



Preliminary Detector Performance

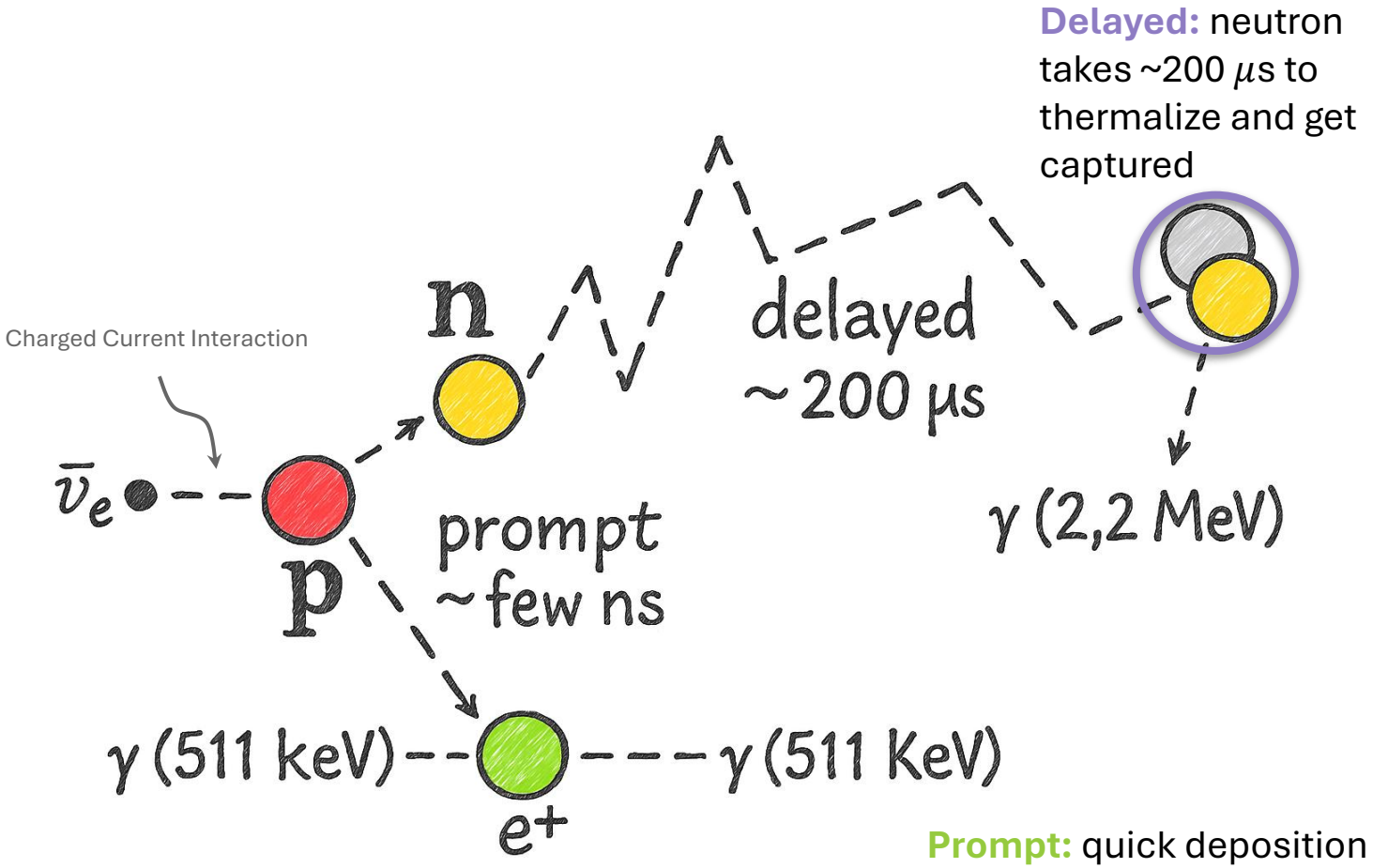
- Detector performance on first data
- Using calibration sources:
  - >1600 pe/MeV of light yield
  - Resolution ~3.4% @ (2 x 0.511) MeV – ^{68}Ge source at detector center
- Natural source of ^{214}Po (from ^{222}Rn) gives ~3% @ 0.92 MeV
- Further improvements on reconstruction, calibration, … are on the works!





Event Selection - IBD

Note: this slide and onwards are based on predictions and **not data**



$$E_\nu \simeq E_{e^+} + \Delta m_{n-p} + T_n$$

Prompt: quick deposition of kinetic energy plus subsequent annihilation of the positron

Selection
Muon Veto
Fiducial Volume R < 17.2 m
Prompt: [0.8, 12.0] MeV Delayed: [1.9, 2.5] U [4.4, 5.5] MeV
Time Prompt-Delayed: 1 ms
Distance Prompt-Delayed: 1.5 m
Efficiency: 82.2%

Angel Abusleme *et al* 2022 *Chinese Phys. C* **46** 123001

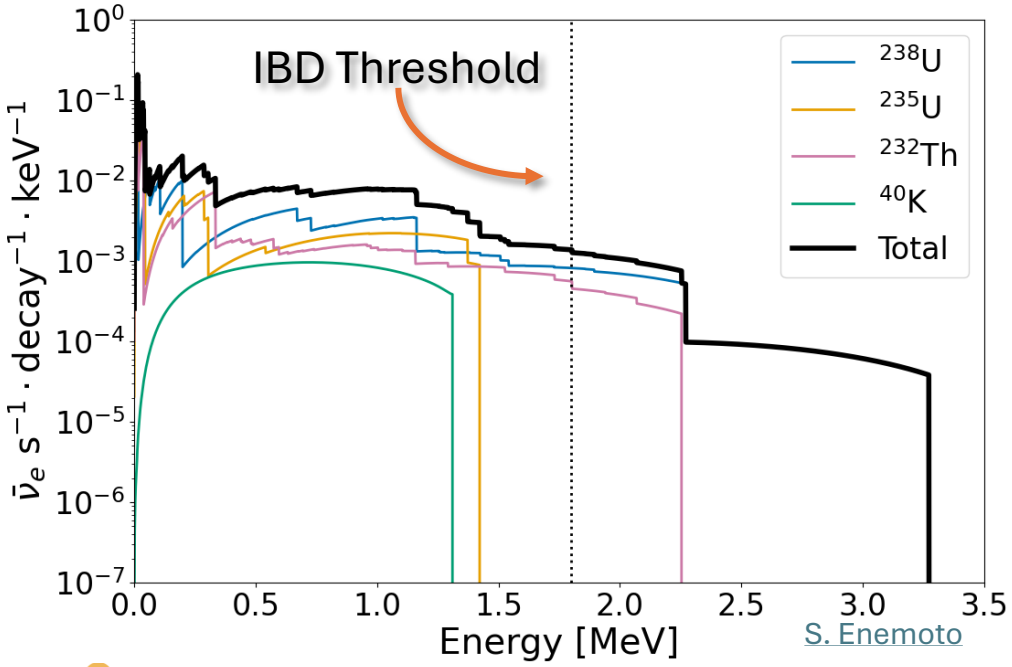
- Antineutrino signal detected via Inverse Beta Decay
- Relatively clean signal thanks to distinct time correlation

Geoneutrinos

- Dominant HPEs are Uranium, Thorium, and Potassium
  - HPE (Heat Producing Elements): natural radioactive elements on the Earth

- IBD interaction lower energy limit is ~1.806 MeV
  - ^{40}K and ^{235}U cannot be detected via this channel

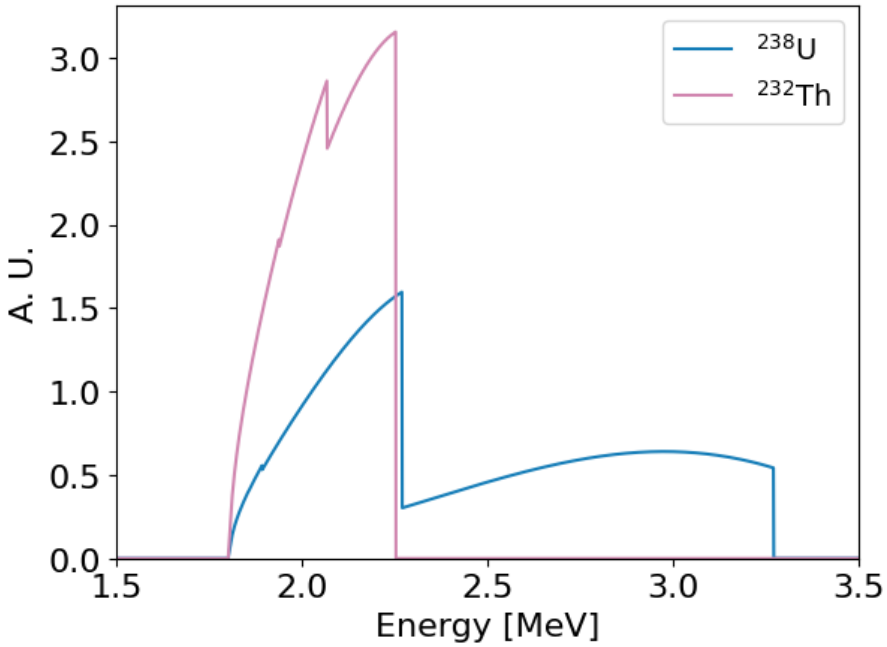
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e,\ \mathrm{Q} = 51.7\,\mathrm{MeV}$$
$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e,\ \mathrm{Q} = 46.4\,\mathrm{MeV}$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e,\ \mathrm{Q} = 42.7\,\mathrm{MeV}$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e,\ \mathrm{Q} = 1.31\,\mathrm{MeV}\ (89.3\%)$$
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e,\ \mathrm{Q} = 1.505\,\mathrm{MeV}\ (10.7\%)$$



S. Enemoto

IBD cross-section

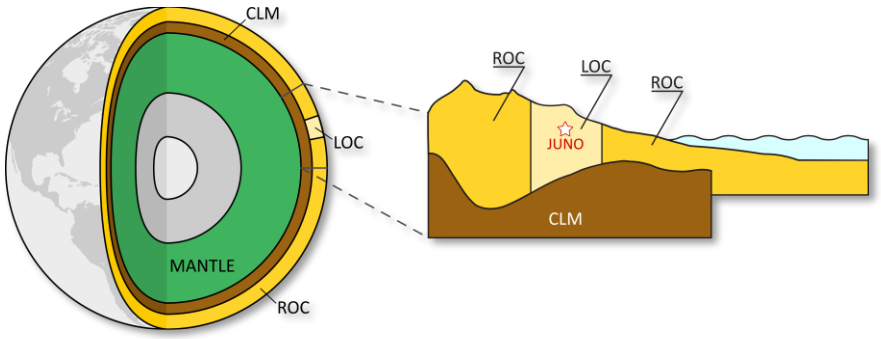
A. Strumia and F. Vissani

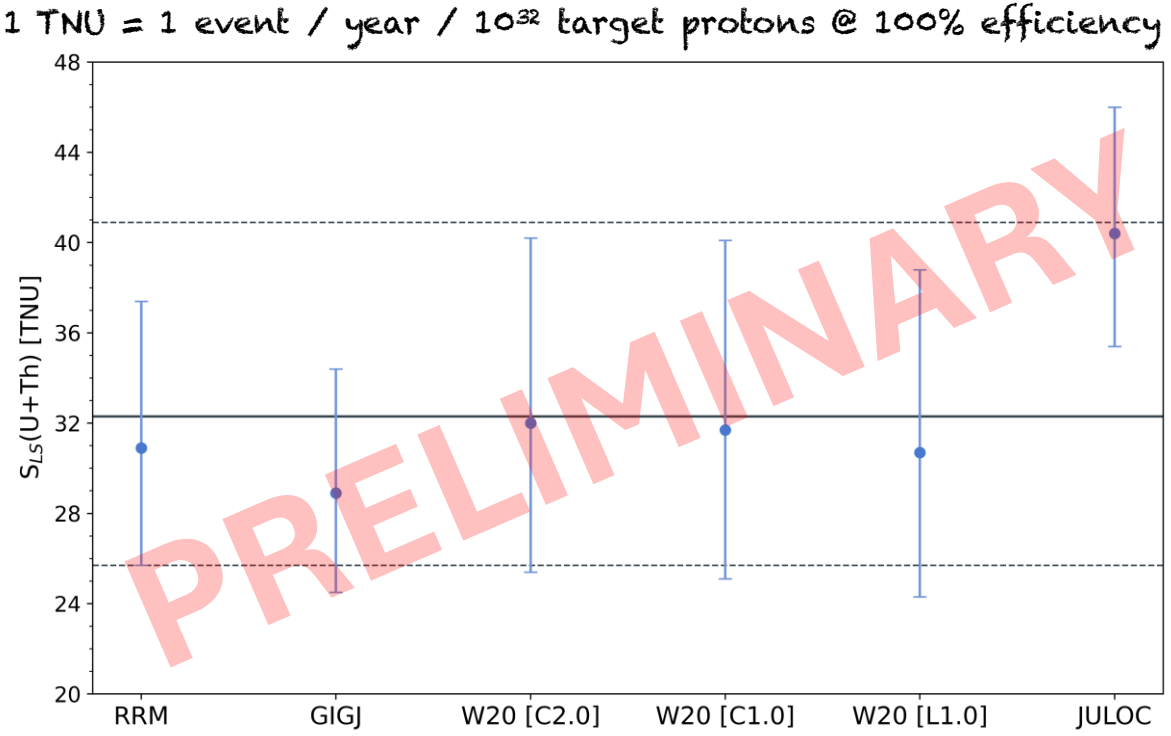


Geoneutrinos at JUNO - Lithosphere

- Local crust (LOC) geoneutrinos dominate the geoneutrino signal
  - LOC area within few hundred km from JUNO (~ 500 km)
  - Important to have a good description to determine mantle contribution

- Several models available at JUNO location – Adopt the range
  - **Central values between 28.8 – 40.4 TNU**

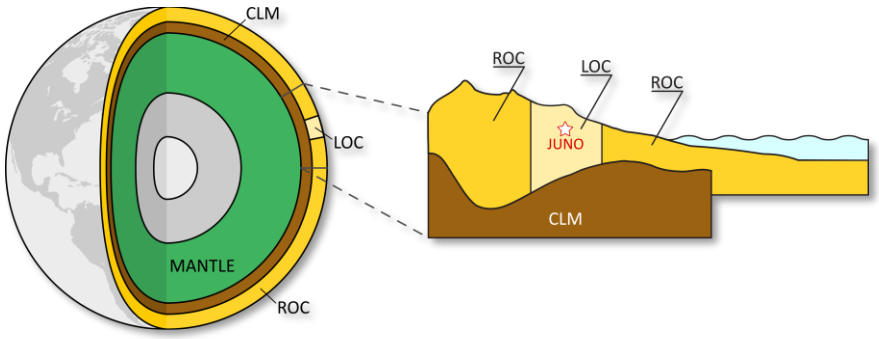


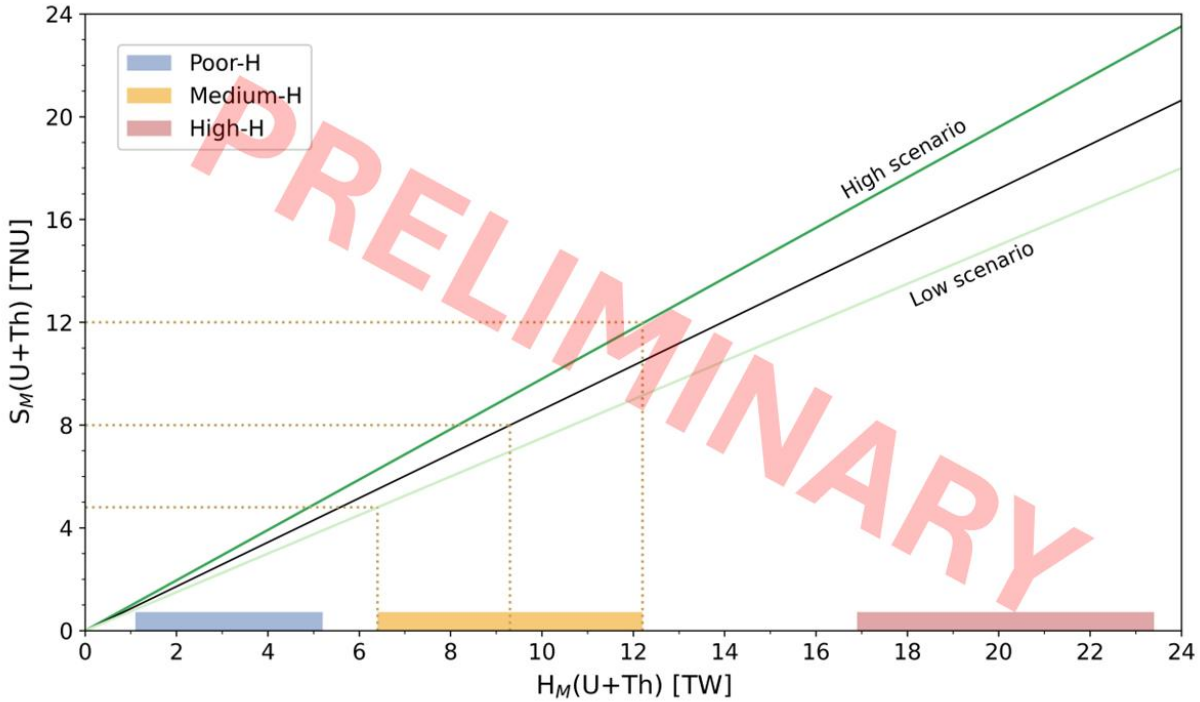


Geoneutrinos at JUNO - Mantle

- Prediction of Mantle's contribution using different classes of Bulk Silicate Earth models based on the estimated radiogenic contribution (H)

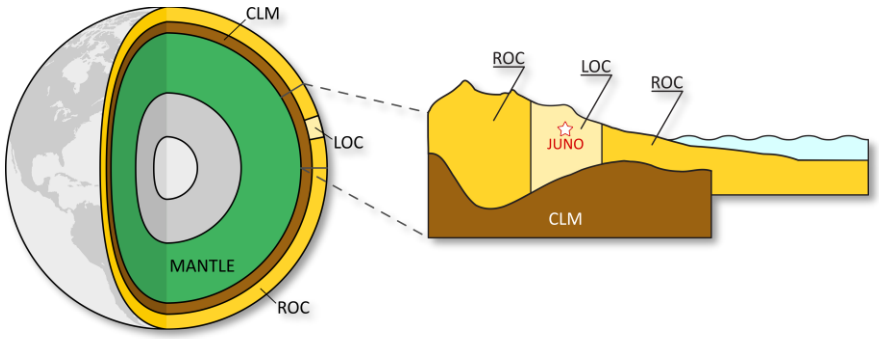
- Three different estimations of mantle geoneutrino signals:
  - Poor-H: $2.8^{+2.1}_{-1.7}$ TNU
  - Medium-H: $8.0^{+4.0}_{-3.2}$ TNU
  - Rich-H: $17.4^{+5.7}_{-4.7}$ TNU





Geoneutrinos at JUNO – Total Signal

- The total geoneutrino rate expected in **JUNO is 28.6 to 60.3 TNU**
  - Range combination of lithosphere and mantle contributions



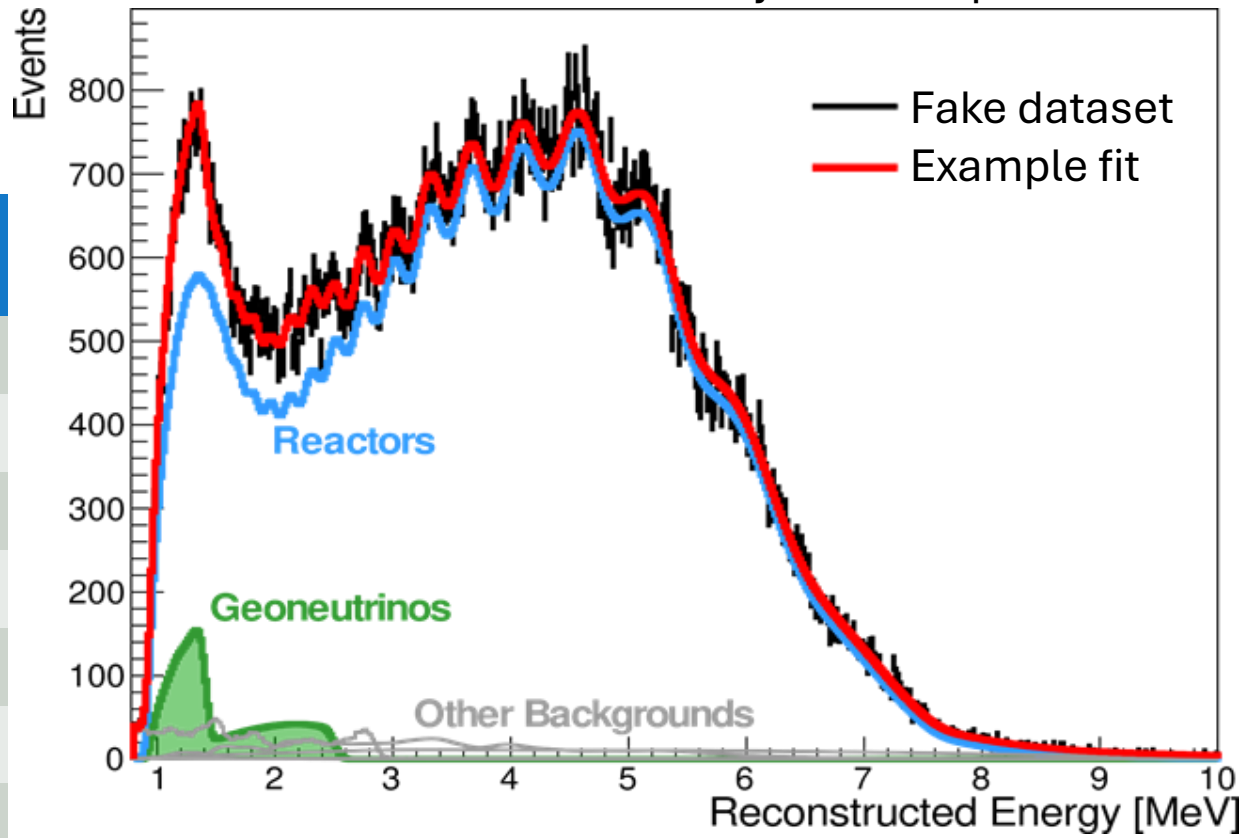
Preliminary	S(U) [TNU]	S(Th) [TNU]	S(U+ Th) [TNU]	S(Th)/S(U)
Poor-H	$28.1^{+8.2}_{-6.2}$	$8.1^{+2.3}_{-1.8}$	$36.0^{+9.6}_{-7.4}$	0.29
Medium-H	$32.0^{+7.9}_{-6.4}$	$9.1^{+2.4}_{-1.9}$	$41.0^{+9.5}_{-7.7}$	0.29
Rich-H	$39.1^{+8.3}_{-6.9}$	$11.3^{+2.5}_{-2.1}$	$50.2^{+10.1}_{-8.5}$	0.29

JUNO Expected Signal and Background

- Latest rate and shapes for all components
- Asimov and Toy Monte Carlo sensitivity studies

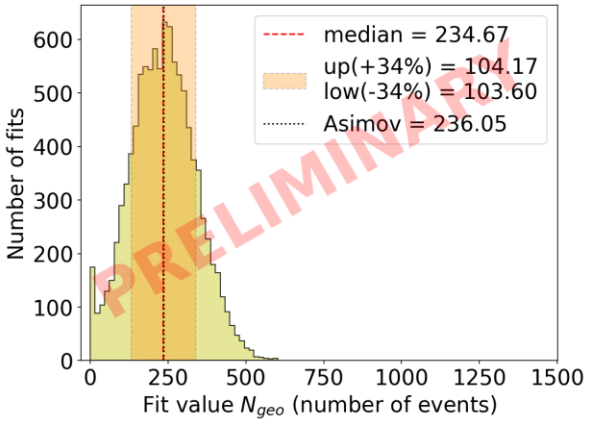
	Rate [cpd] (82.2% eff.)	Rate Unc. [%]	Shape Unc. [%]
Geoneutrinos	0.92 – 1.95	-	5
Reactor nu	43.2	-	Daya Bay
Accidentals	0.8	1	0
LiHe	0.8	20	10
Alpha-n	0.09	25	25
Fast-n	0.1	100	20
World Reactor	1.4	10	5
Atmospheric NC	0.16	50	50

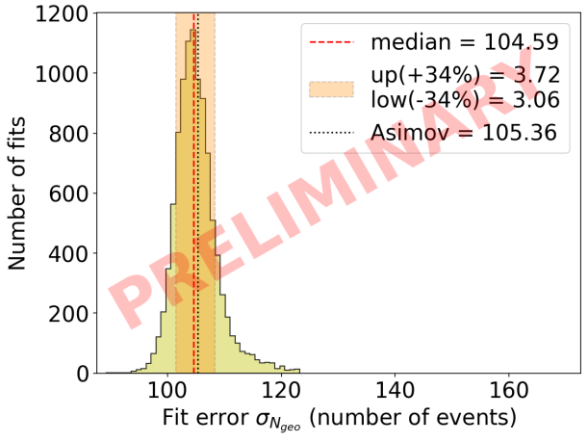
Pseudo-dataset fit for 10 years of exposure

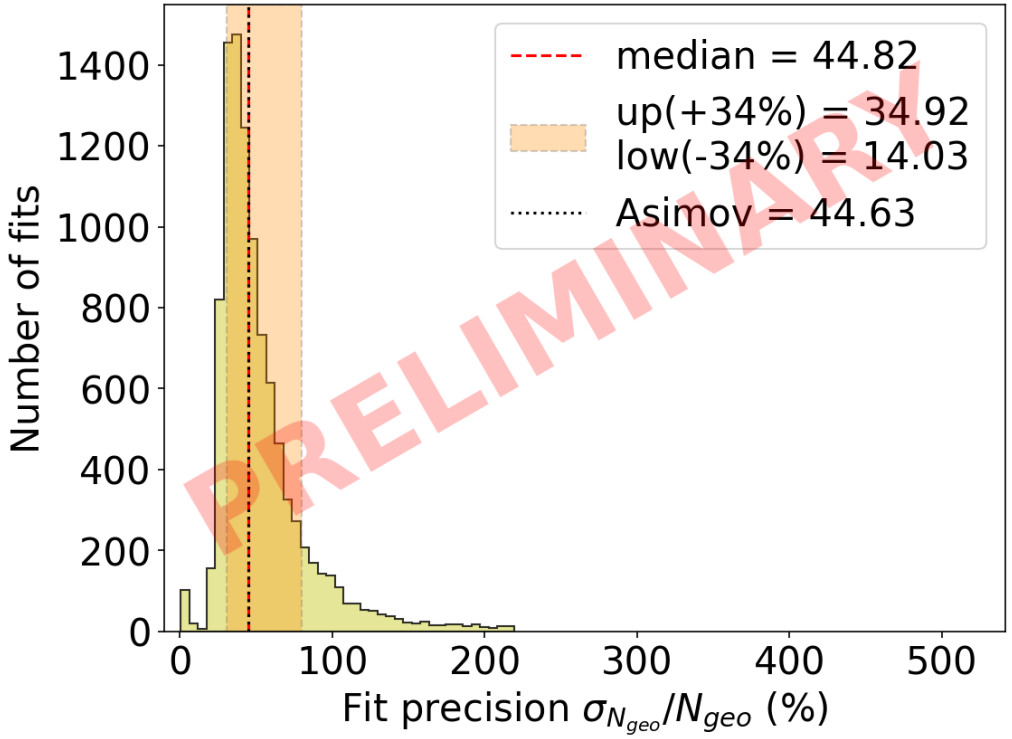


Analysis Method

- **Asimov approach:** fit single total spectrum with no statistical fluctuations
- **ToyMC approach:** produce and fit many pseudo-dataset using realistic statistical fluctuations

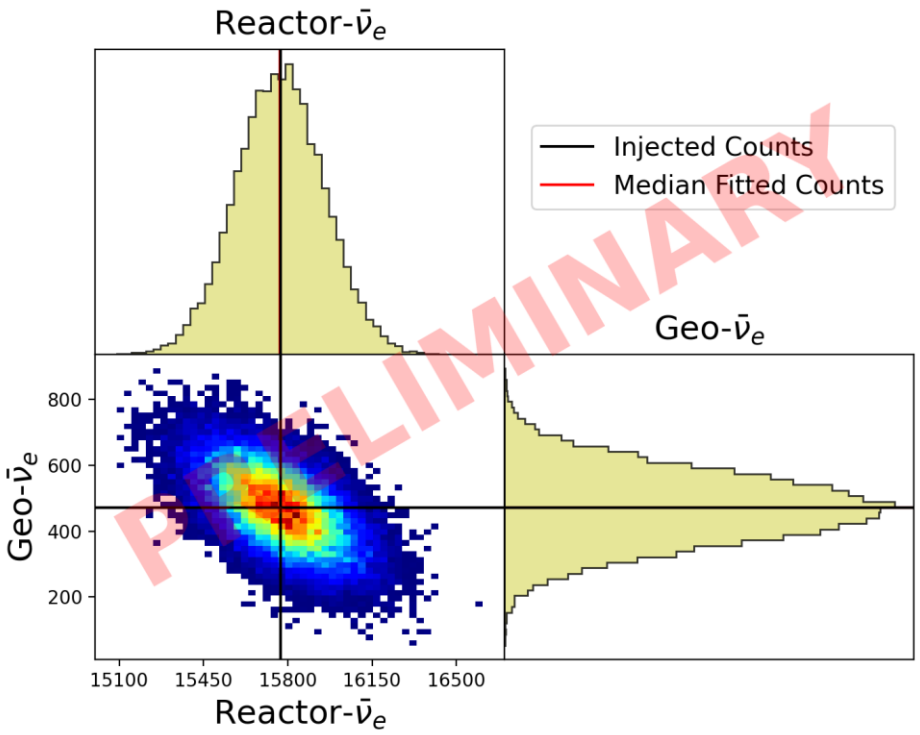


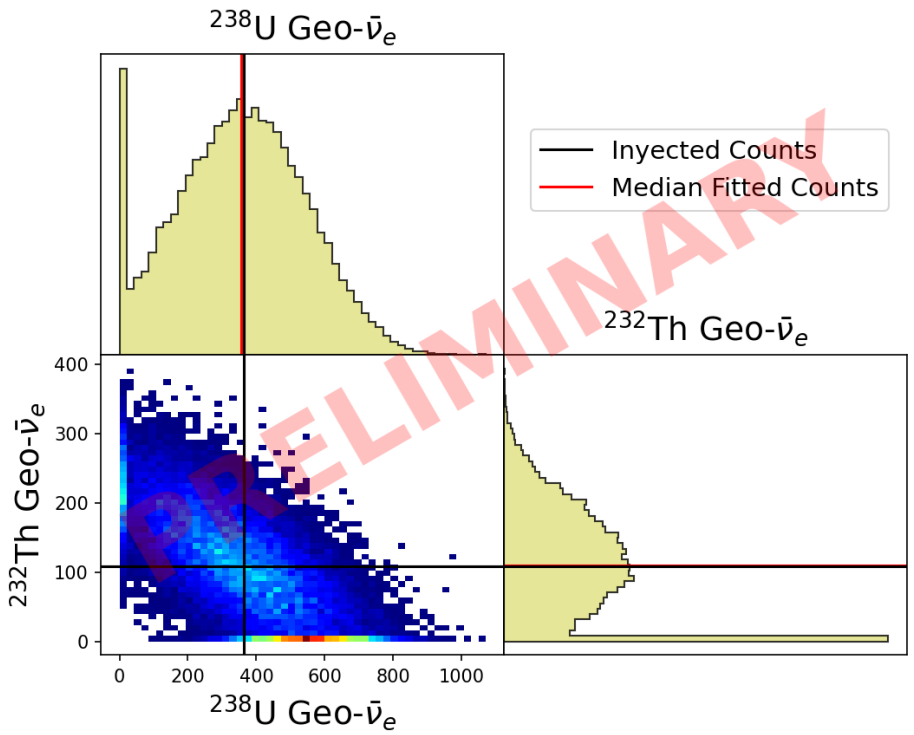




Toy Monte Carlo Approach

- Produce and fit many pseudo-datasets with realistic statistical fluctuations
- Enables to understand correlations of parameters
- Low statistics cases when geo-neutrino signal rails to zero are removed – less than 3σ significance

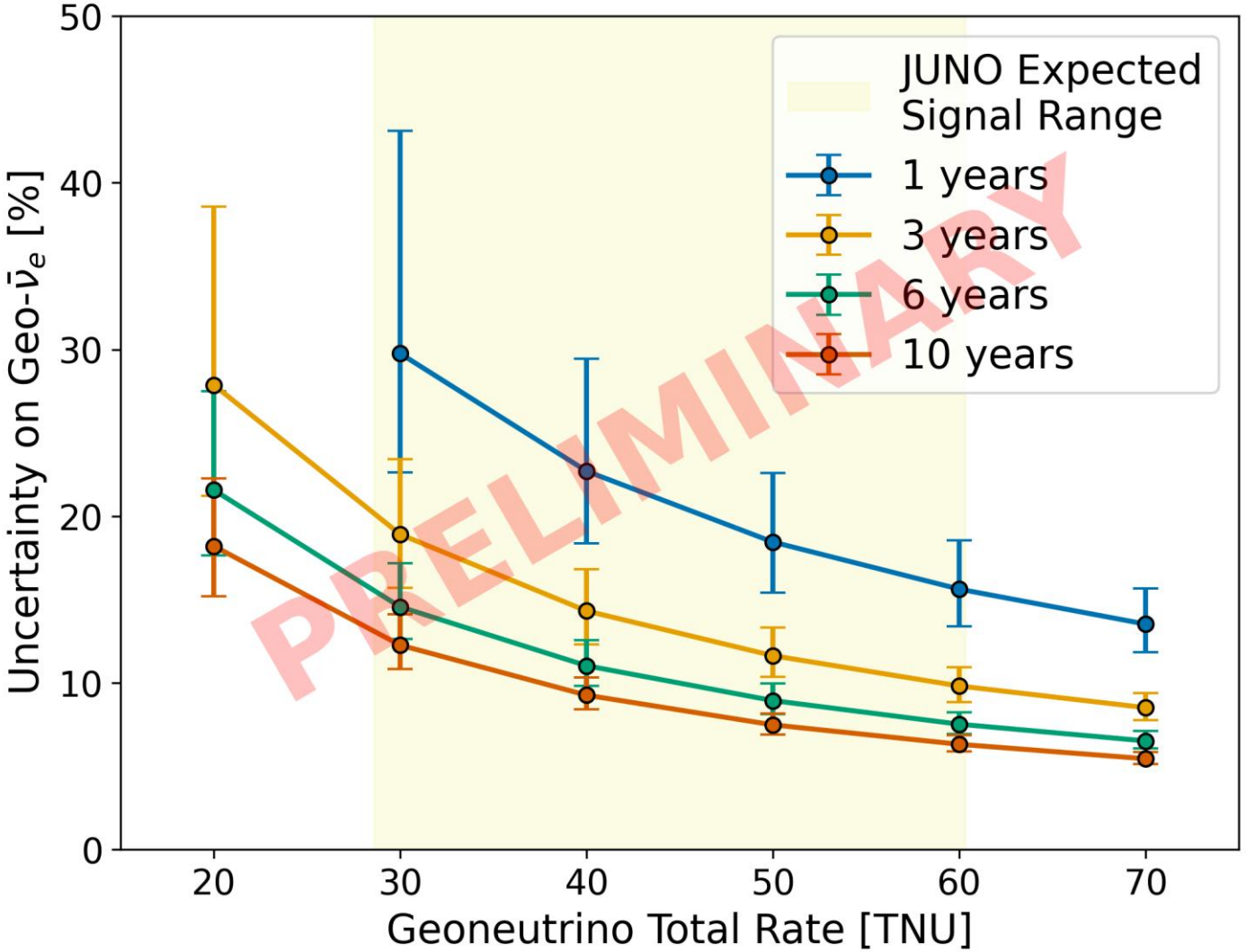




Total Geoneutrino Signal

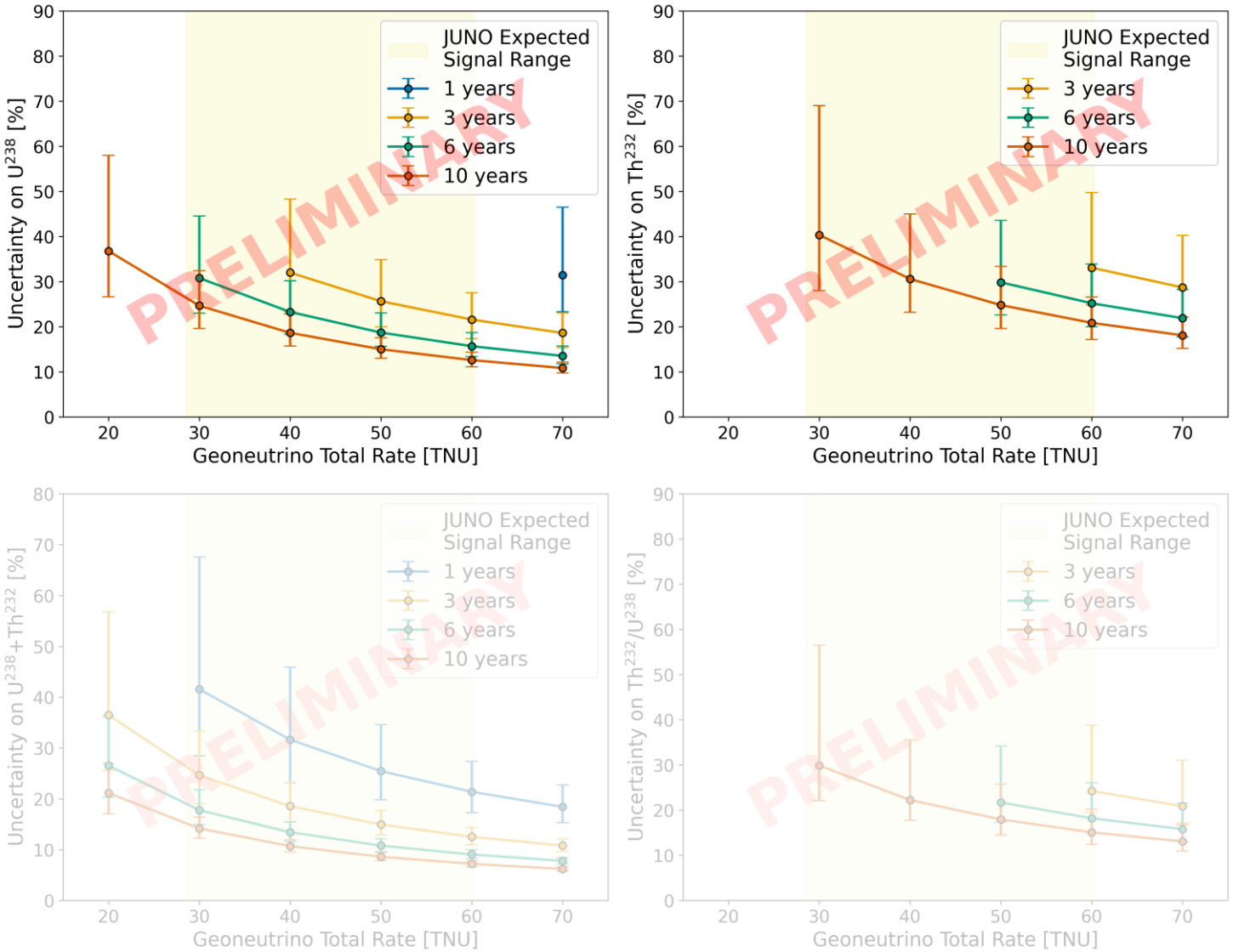
1. M. Agostini et al., Phys. Rev. D **101**, 012009
2. S. Abe et al., Geophys. Res. Lett. 49 (16), 2022

- JUNO sensitivity to total signal of geoneutrinos
  - Assume S(Th)/S(U) = 0.29
- Reach current Borexino and KamLAND's precision in about 3 - 6 years
  - Borexino ~17% in 8.9 years[1]
  - KamLand ~15% in 14.3 years[2]



Independent U and Th Contribution

- Ratio between U and Th is left free – independent contributions on the fit
- Large statistics is important – ^{238}U can be measured in 3-4 years while ^{232}Th will take at least 6 years



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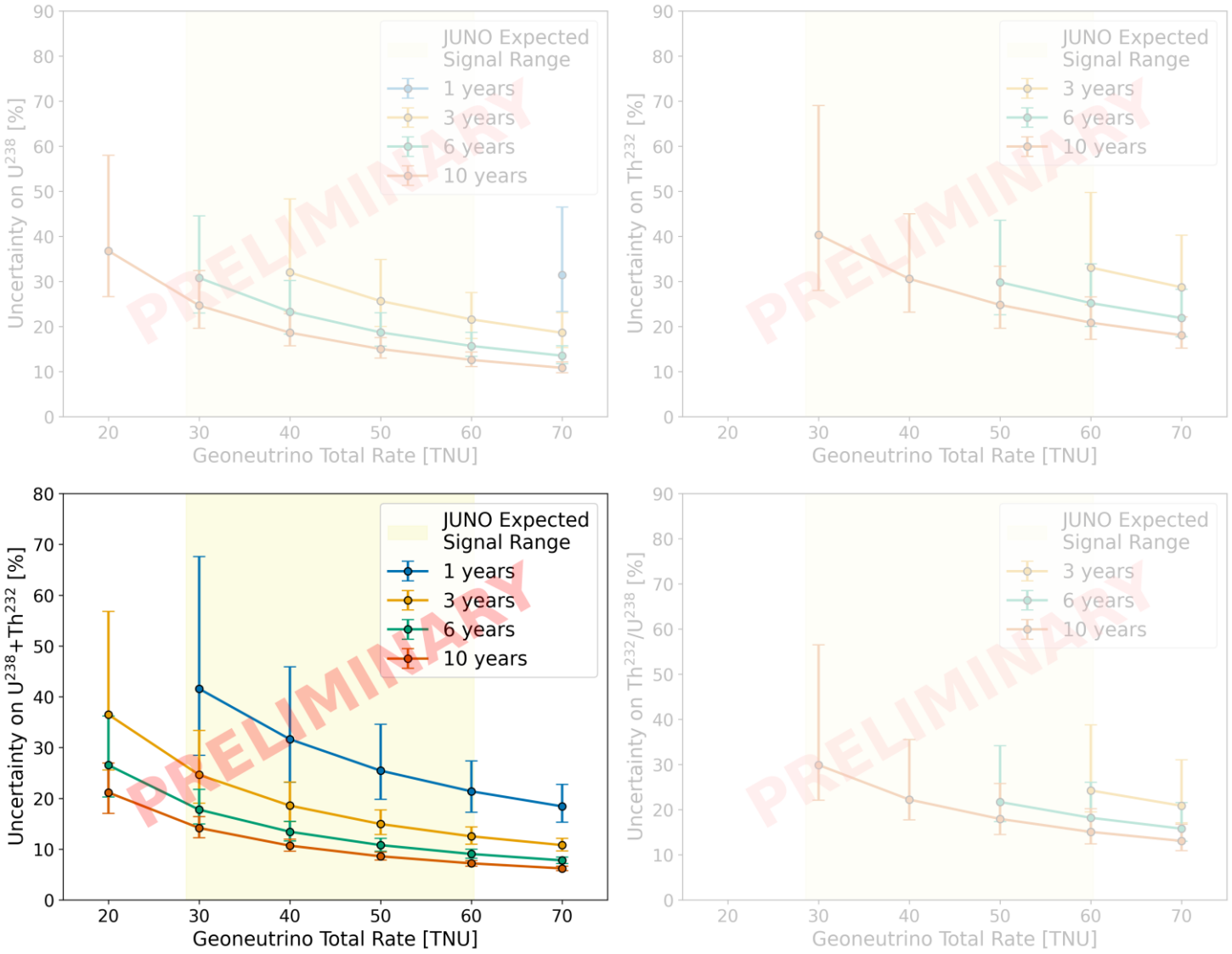
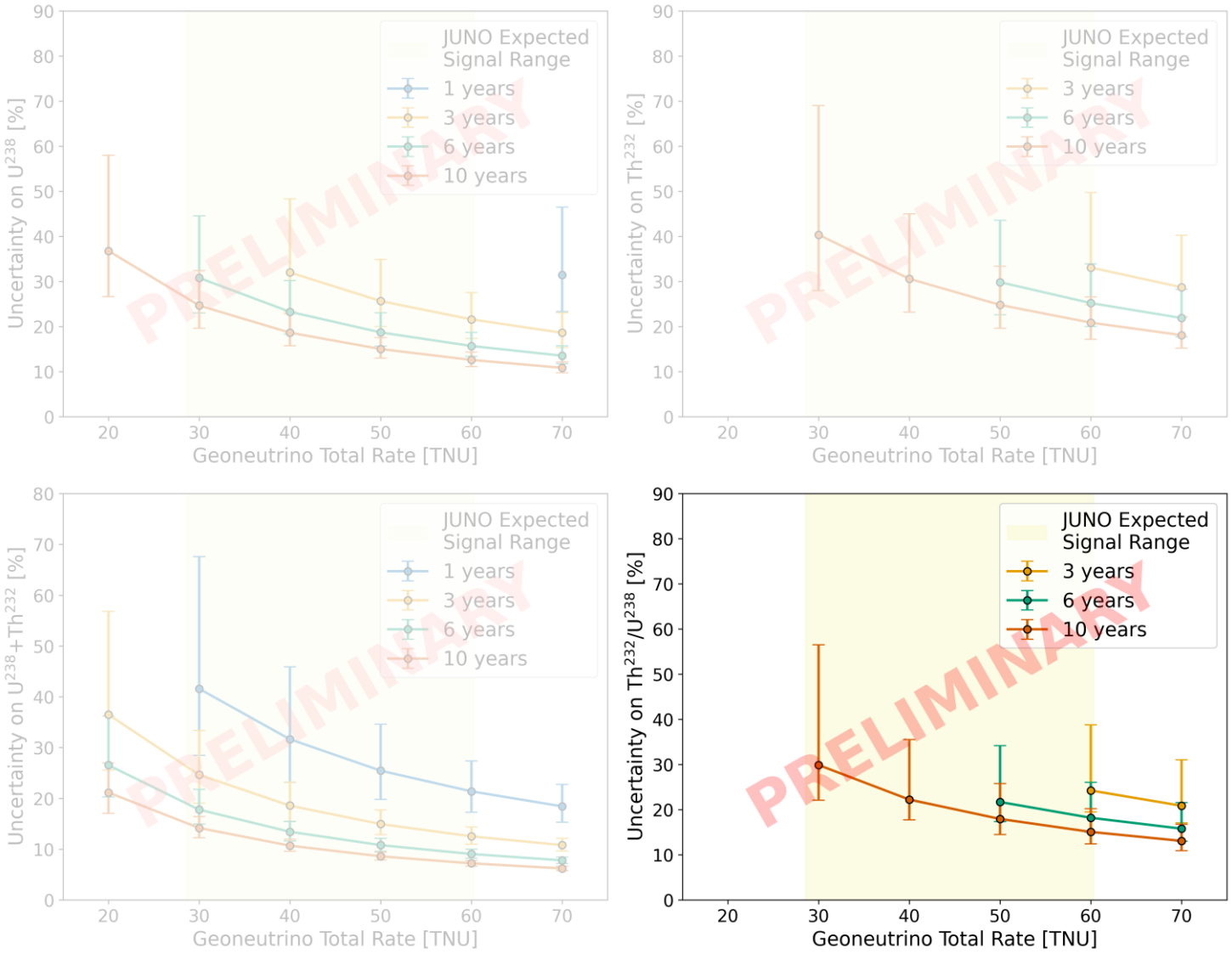
- Combined rate is possible thanks to the anti-correlation



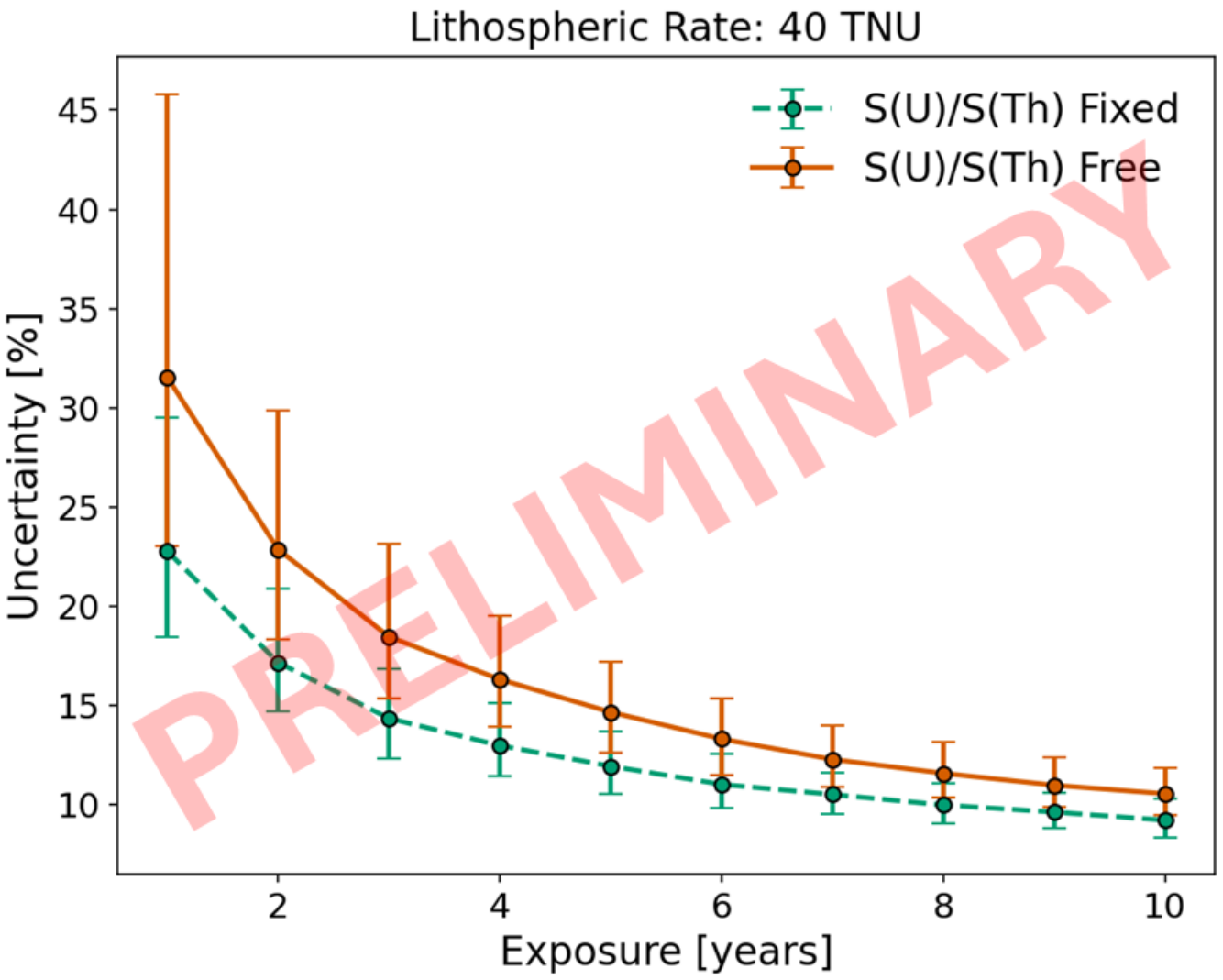
Independent U and Th Contribution

- Ratio between U and Th is left free – independent contributions on the fit
- Large statistics is important – early exposures have no enough sensitivity
- Combined rate is possible thanks to the anti-correlation
- JUNO could be able to constrain Th/U in 10 years



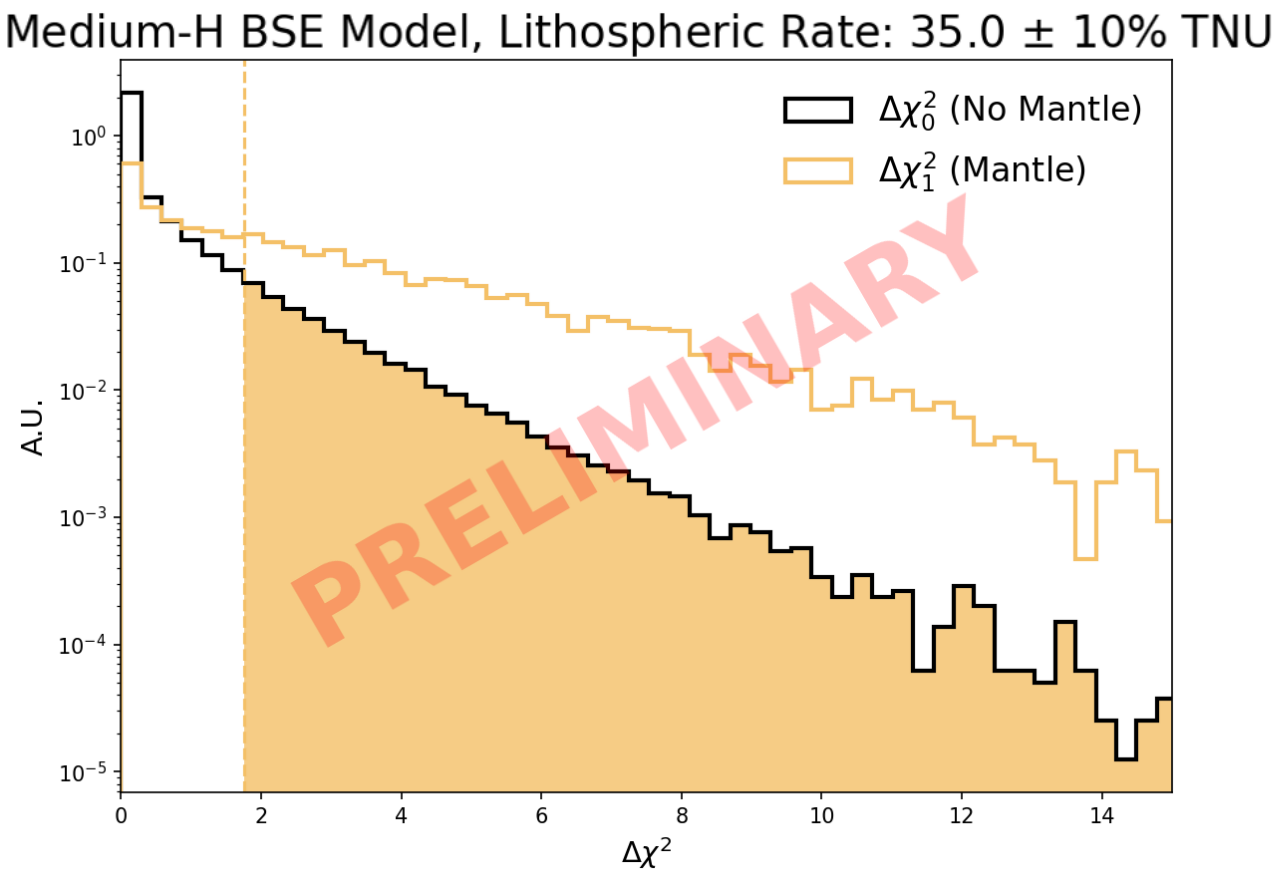
Comparison of Th/U Scenarios

- Consider scenario of 40 TNU of total geoneutrino signal with chondritic Th/U ratio
- Expected degradation of precision by leaving Th/U free
- With increase exposure the difference is smaller
- Nonetheless, JUNO can provide comparable results in 3 years to existing measurements



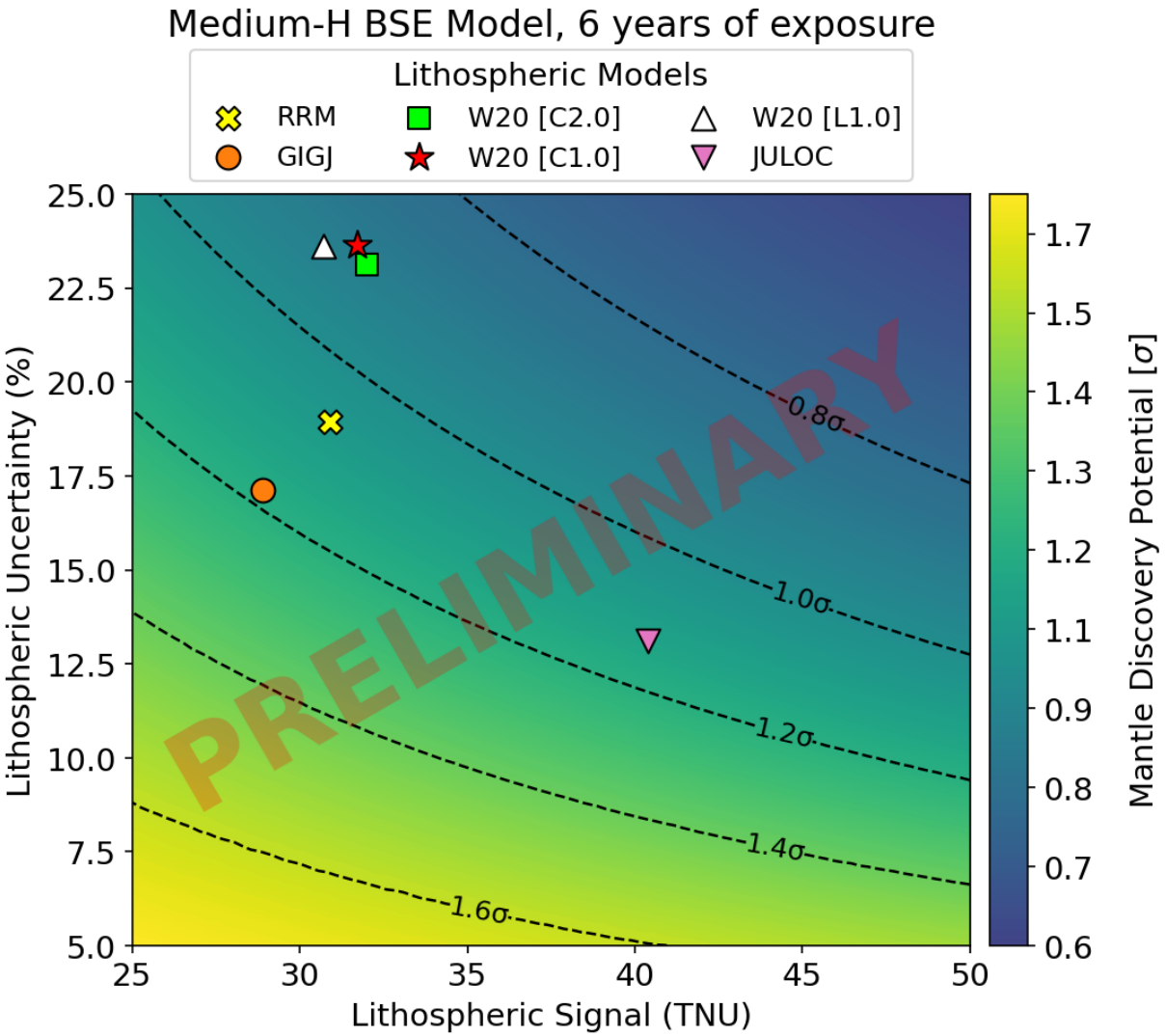
Mantle Discovery Potential – Statistics Test

- Mantle discovery potential using a test statistics
  - $\Delta\chi_0^2$: no-mantle dataset
  - $\Delta\chi_1^2$: mantle dataset
- Each dataset fitted twice: model with mantle and model without mantle contribution
- Calculate p-value as the probability of $\Delta\chi_0^2$ being larger than the $\Delta\chi_1^2$ median
- Yields similar result as Asimov approach
  - Sensitivity: $\sigma = \sqrt{\Delta\chi^2}$



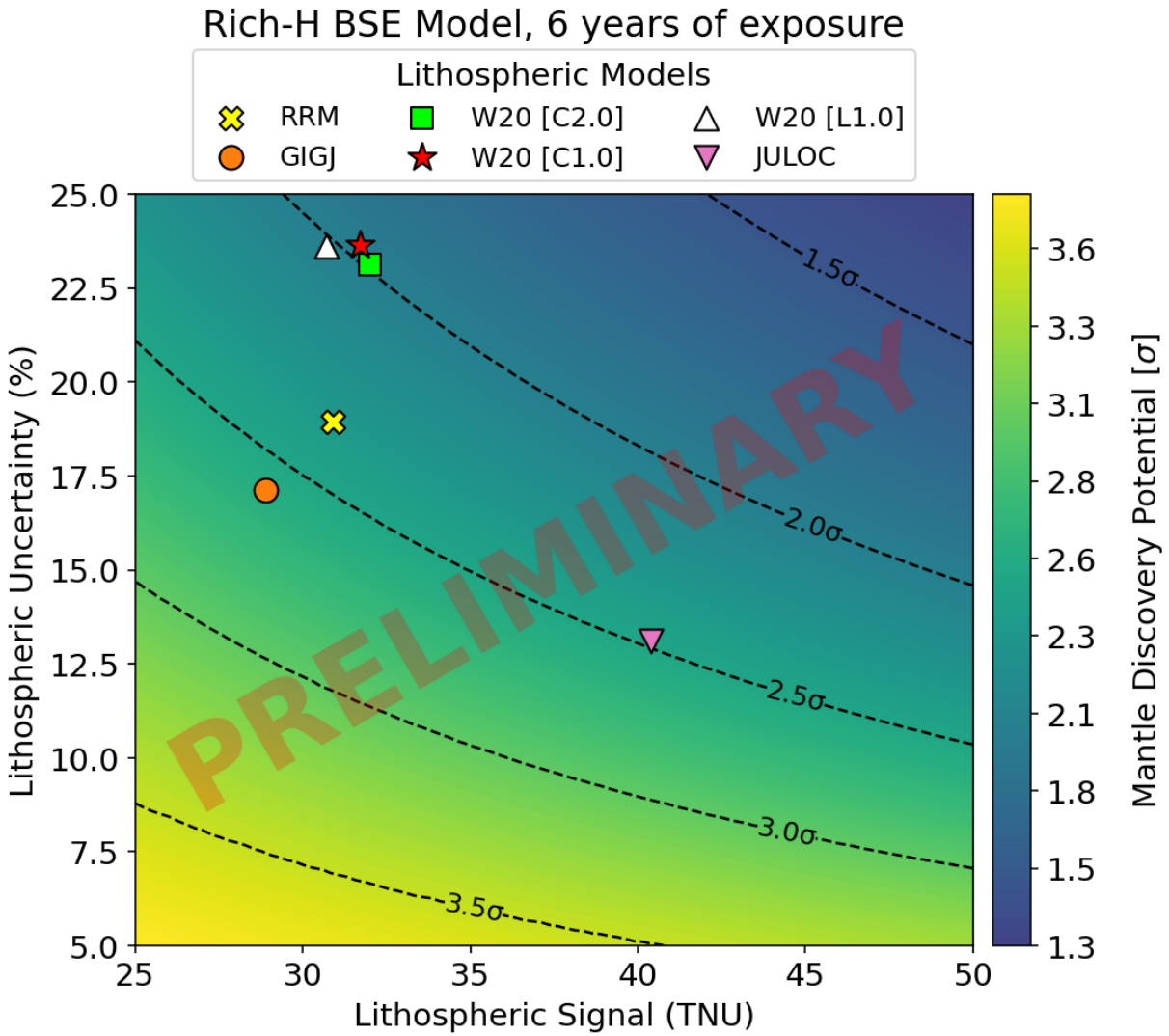
Mantle Discovery Potential (Medium-H)

- Asimov scan assuming **medium-H (8 TNU) model of the mantle**
- Scan over lithospheric prior
  - Model uncertainty and rate
- With current models JUNO would only achieve **<1.2σ in 6 years**
  - Low-H scenario has no enough sensitivity



Mantle Discovery Potential (High-H)

- Asimov scan assuming **high-H (17.4 TNU) model of the mantle**
- Scan over lithospheric prior
  - Model uncertainty and rate
- With current models JUNO would only achieve **<3σ in 6 years**
- Good knowledge of LOC is needed!



Summary

- JUNO experiment will be able to provide contributions to the geophysics community
  - Big experiment, large statistics! ~400 geoneutrinos per year
- Within 3 – 6 years competitive results to current published measurements could be achieved
- In 10 years, JUNO could constrain the Th/U ratio
- Mantle contribution measurement is complicated
  - With high mantle prediction models, 3σ can be reached if lithospheric flux can be known better than 15%
- JUNO will provide an extra complementary location of geoneutrino measurement
- Exciting times in JUNO with physics data taking!

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Back up

Why to Study Geoneutrinos?

Geoneutrinos: (anti)neutrinos from the decay of long-lived particles (HPE)

Abundance of the radioactive elements → Radiogenic Heat

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8\ \mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.32\ \mathrm{MeV}$$

Measured/Observed

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Distribution of the radioactive elements on the Earth

Prediction

Geoneutrino flux

Measured/Observed

Why to Study Geoneutrinos?

Geoneutrinos: (anti)neutrinos from the decay of long-lived particles (HPE)

Small signal - Big detectors!

Abundance of the radioactive elements

Radiogenic Heat

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8\ \mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.32\ \mathrm{MeV}$$

- Test and discriminate geomodels
- Mantle homogeneity

Distribution of the radioactive elements on the Earth

Prediction

Interpretation

Geoneutrino flux

Measured/Observed

Lithospheric Model Predictions

Model	S_{LS}(U) [TNU]	S_{LS}(Th) [TNU]	S_{LS}(U+ Th) [TNU]	S_{LS}(Th)/S_{LS}(U)
RRM	$23.2^{+5.9}_{-4.8}$	$7.3^{+2.4}_{-1.5}$	$30.9^{+6.5}_{-5.2}$	0.31
GIGJ	$22.0^{+5.4}_{-4.1}$	$6.6^{+1.7}_{-1.2}$	$28.9^{+5.5}_{-4.4}$	0.30
W20 [Crust 2.0]	$24.5^{+6.4}_{-5.1}$	$7.4^{+2.1}_{-1.7}$	$32.0^{+8.2}_{-6.6}$	0.30
W20 [Crust 1.0]	$24.2^{+6.5}_{-5.1}$	$7.4^{+2.2}_{-1.7}$	$31.7^{+8.4}_{-6.6}$	0.31
W20 [Litho 1.0]	$23.6^{+6.4}_{-5.0}$	$7.1^{+2.0}_{-1.6}$	$30.7^{+8.1}_{-6.4}$	0.30
JULOC	$30.3^{+4.9}_{-4.4}$	$9.2^{+1.7}_{-1.4}$	$40.4^{+5.6}_{-5.0}$	0.30
Combined	$24.7^{+6.7}_{-5.5}$	$7.5^{+2.2}_{-1.8}$	$32.3^{+8.6}_{-6.6}$	0.30

- Predicted geoneutrino signals for the different lithospheric models
- Corresponding ratio S(Th)/S(U).
- The combined signal represents a statistically integrated result