


Neutrino oscillation physics in JUNO

ICHEP 2024

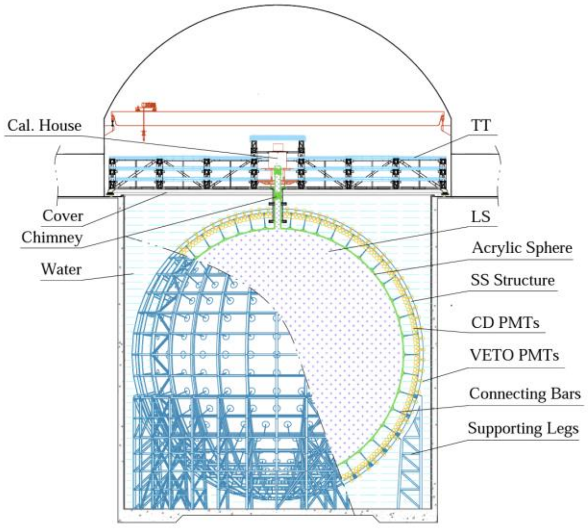
Steven Calvez on behalf of the JUNO collaboration

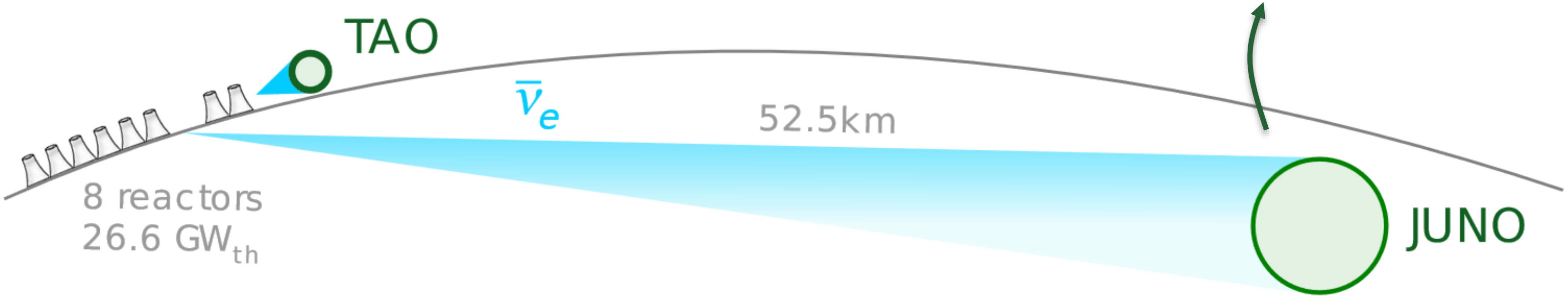
ICHEP 2024

July 18th 2024

Jiangmen Underground Neutrino Observatory

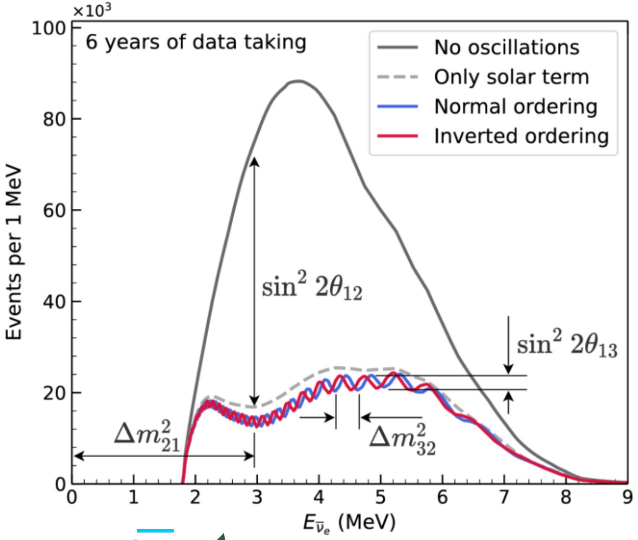
- **JUNO** is a **20-kton Liquid Scintillator** neutrino observatory located in Southern China.

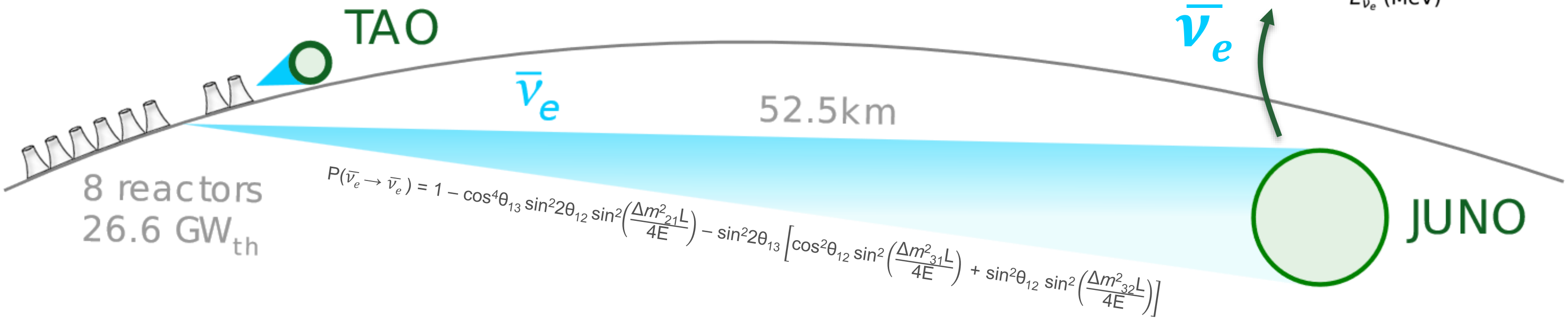




Jiangmen Underground Neutrino Observatory

- **JUNO** is a **20-kton Liquid Scintillator** neutrino observatory located in Southern China.
- JUNO studies **reactor electron antineutrino oscillations** over a 52.5 km medium baseline to:
  - Determine the **neutrino mass ordering.**
  - Measure $\boldsymbol{\Delta m^2_{31}}$, $\boldsymbol{\Delta m^2_{21}}$, and $\boldsymbol{\sin^2 2\theta_{12}}$ with sub-percent precision.





JUNO key experimental features

- **Large statistics**

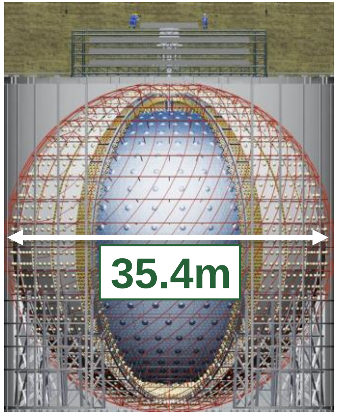
- **Energy resolution: 2.95% @ 1MeV**

- **Low background**

- **Precise knowledge of reactor spectra**

JUNO key experimental features

- Large statistics
  - ✓ **20-kton Liquid Scintillator (LS)**
- Energy resolution: 2.95% @ 1MeV
  - ✓ **High photon yield, highly transparent LS**
- Low background
  - ✓ **Material screening, clean environment**
- Precise knowledge of reactor spectra



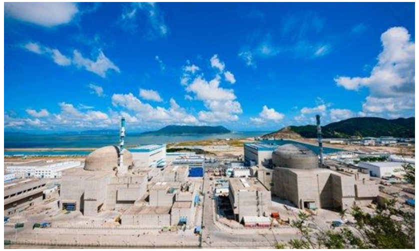
Status of the Liquid Scintillator for JUNO

- **20kton LS**: LAB + 2.5g/L PPO + 3 mg/L bis-MSB
  - ➢ **1665 PE/MeV** arXiv:2405.17860
- **Osiris**: measures radiopurity of LS.

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ **Powerful nuclear reactors (26.6 GW_{th})**
- Energy resolution: 2.95% @ 1MeV
  - ✓ High photon yield, highly transparent LS
- Low background
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra

Taishan



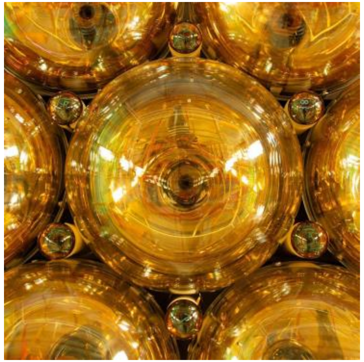
Yangjiang

- Two nuclear power plants
- 8 reactor cores
- **26.6 GW_{th}**

Reactor	Power (GW_{th})	Baseline (km)	IBD Rate (day^{-1})	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 2.95% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ **Very high PMTs coverage (78 %)**
  - ✓ **High PMT efficiency (30%)**
- Low background
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra



- 17,512 **20” PMTs** + 25,600 **3” PMTs**

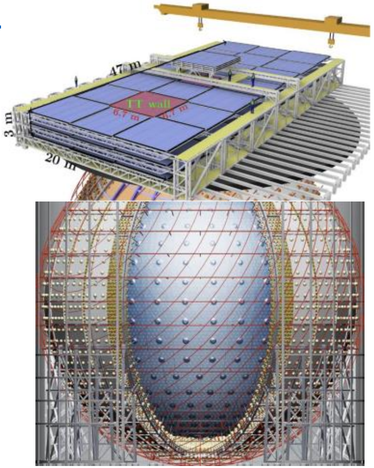
		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 2.95% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ Very high PMTs coverage (78 %)
  - ✓ High PMT efficiency (30%)
- Low background
  - ✓ Material screening, clean environment
  - ✓ **650m or 1800 m.w.e overburden**
  - ✓ **Efficient veto system (>99.5%)**
- Precise knowledge of reactor spectra

- **650m overburden**: 4Hz of cosmic muons in LS
- **Top Tracker**: arXiv:2303.05172
  - Opera plastic scintillator

The Top Tracker of the JUNO experiment



- **Outer Cherenkov Detector**:
  - 35 kton ultrapure water
  - 2400 20” PMTs
- **Veto strategy** :

57 reactor $\bar{\nu}_e$ + 127 ^{9}Li + 40 ^{8}He events/day

⬇

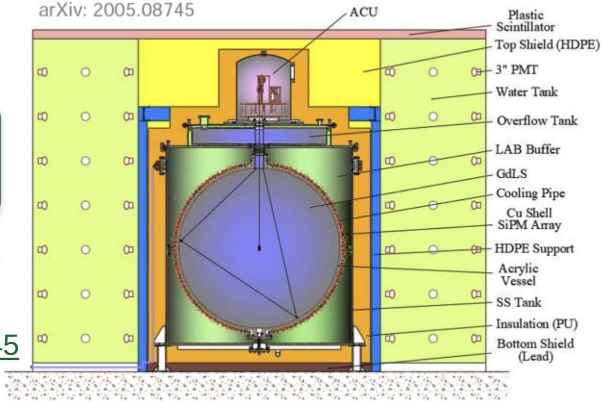
47 reactor $\bar{\nu}_e$ + 0.8 ^{9}Li/^{8}He events/day

JUNO key experimental features

- Large statistics
  - ✓ 20-kton Liquid Scintillator (LS)
  - ✓ Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution: 2.95% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ Very high PMTs coverage (78 %)
  - ✓ High PMT efficiency (30%)
- Low background
  - ✓ Material screening, clean environment
  - ✓ 650m or 1800 m.w.e overburden
  - ✓ Efficient veto system (>99.5%)
- Precise knowledge of reactor spectra
  - ✓ **Satellite detector TAO**

Status of JUNO's Taishan Antineutrino Observatory

arxiv:2005.08745



- **TAO** can perform a precise measurement of **reactor $\bar{\nu}_e$ spectrum**:
  - 44m from reactor → 10^3 IBD events per day
  - 2.8 ton Gd-LS, 1 ton fiducial volume
  - 4500 PEs/MeV
  - SiPM: 94% coverage with 50% PDE
  - ➢ Energy resolution <2% @ 1 MeV
  - ➢ Sub-percent shape uncertainty

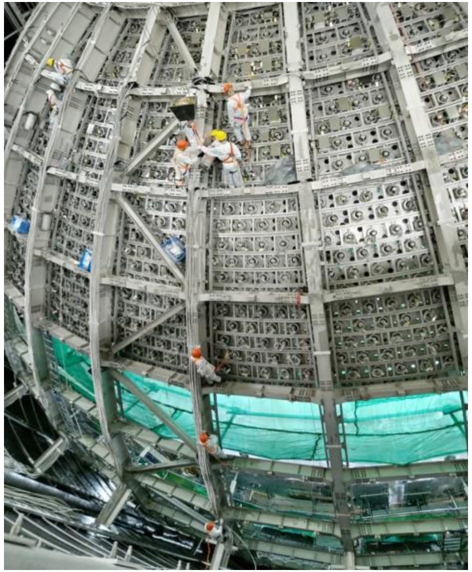
➢ Tested at **IHEP**. **Installation** at **Taishan** power plant in **2024**. **Data taking** in **2025**.

Updates on JUNO construction

- **Support Structure** completed.
- **Acrylic Vessel** :
  - Production complete.
  - 17/23 layers installed.
- More than **half** of **20"** and **3" PMTs installed**.
- **Detector completion** expected by **end 2024**.

➢ First **data taking** in **2025**.

Status of the JUNO detector



Physics searches with JUNO

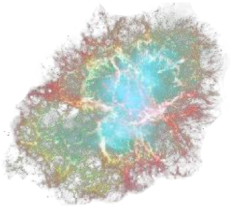
- **JUNO's design** enables a **rich physics program**.

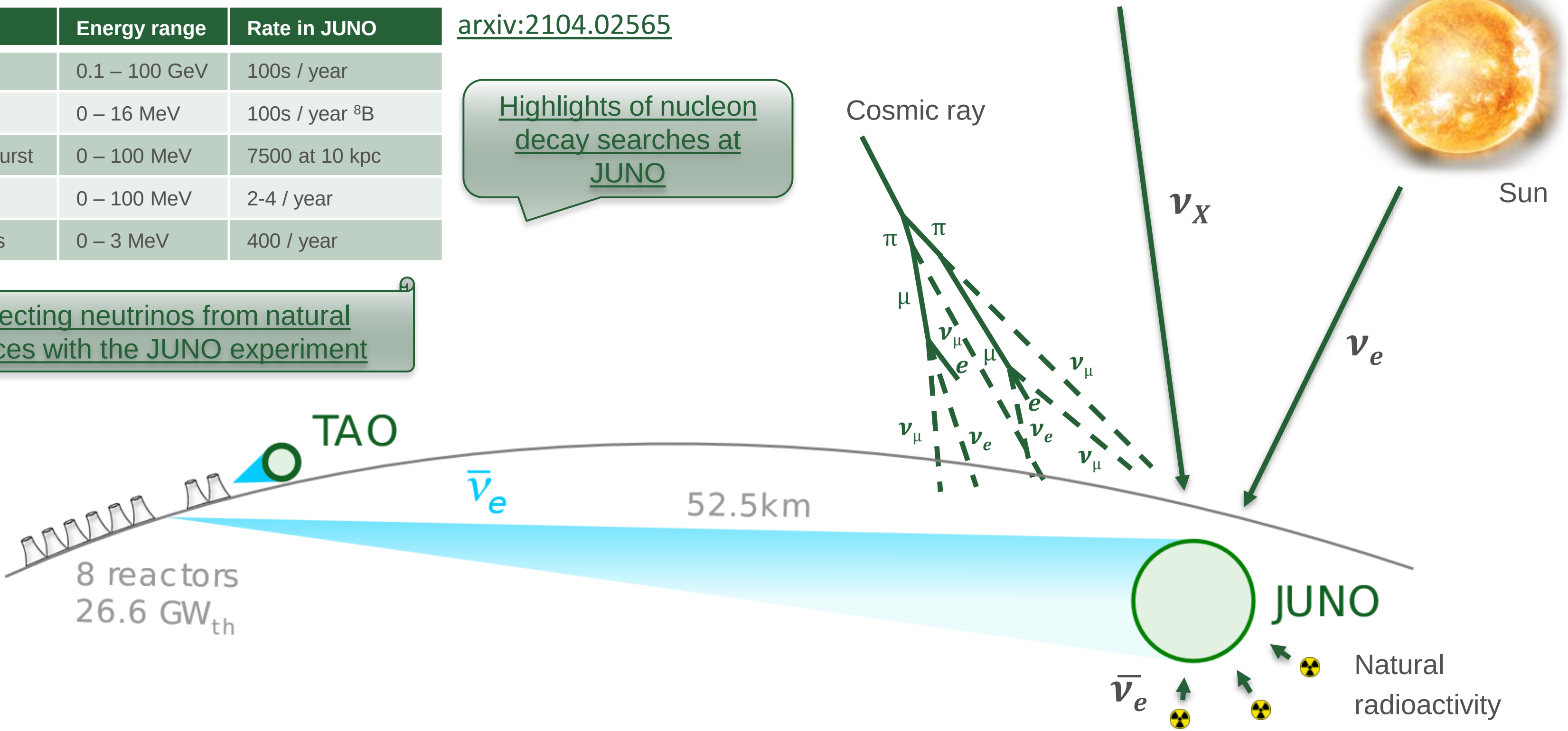
Neutrinos	Energy range	Rate in JUNO
Atmospheric	0.1 – 100 GeV	100s / year
Solar	0 – 16 MeV	100s / year ^{8}B
Supernova burst	0 – 100 MeV	7500 at 10 kpc
DSNB	0 – 100 MeV	2-4 / year
Geoneutrinos	0 – 3 MeV	400 / year

arxiv:2104.02565

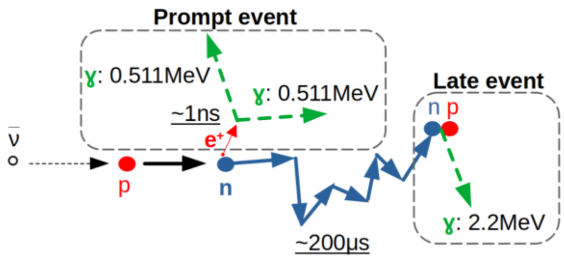
Detecting neutrinos from natural sources with the JUNO experiment

Highlights of nucleon decay searches at JUNO

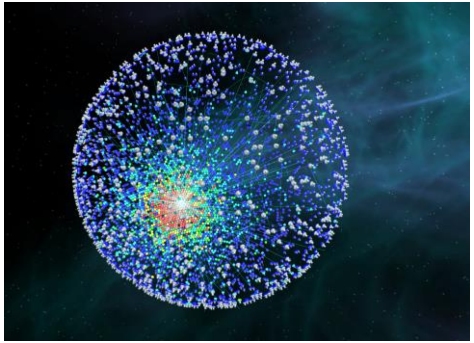


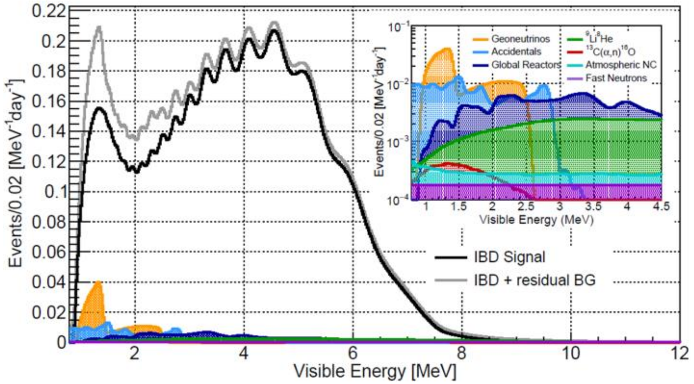


Reactor neutrino oscillations



- **47 Inverse Beta Decay events per day** expected:
  - Prompt + delayed signals to strongly suppress backgrounds.
  - **7% backgrounds**, mostly below 3MeV.
  - ~10^5 IBD candidates in 6 years.
  - Excellent **energy resolution** (<3% @ 1 MeV) also ensured by:





Calibration of the JUNO detector

Overview of Machine Learning applications in JUNO

Sub-GeV events energy reconstruction with 3-inch PMTs in JUNO

Online Event Classification in JUNO

Data Quality Monitoring System for the JUNO Experiment

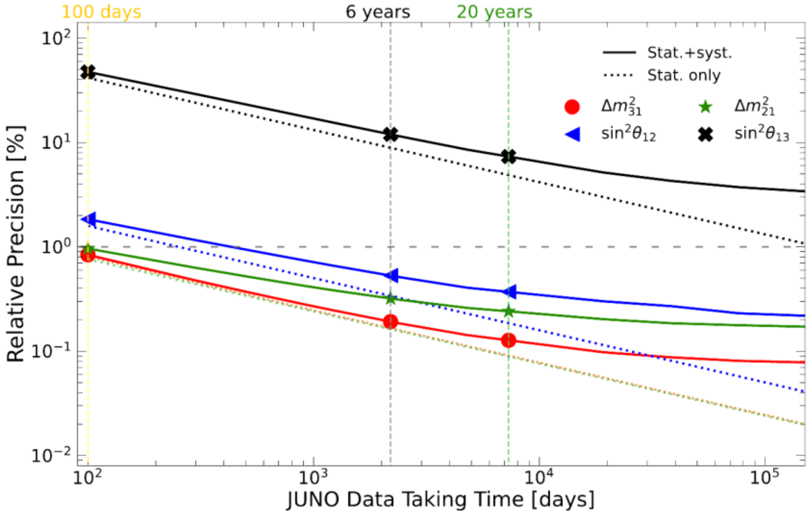
Detector identifier and geometry management system in JUNO experiment

Precision measurement of neutrino oscillations parameters

- **Most precise** measurements of half of the **neutrino oscillation parameters** in **100 days.**

- Ultimately, an **order of magnitude** improvement over current knowledge of **Δm^2_{31}, Δm^2_{21}**, and **$\sin^2\theta_{12}$.**

Chin. Phys. C 46 (2022) 12



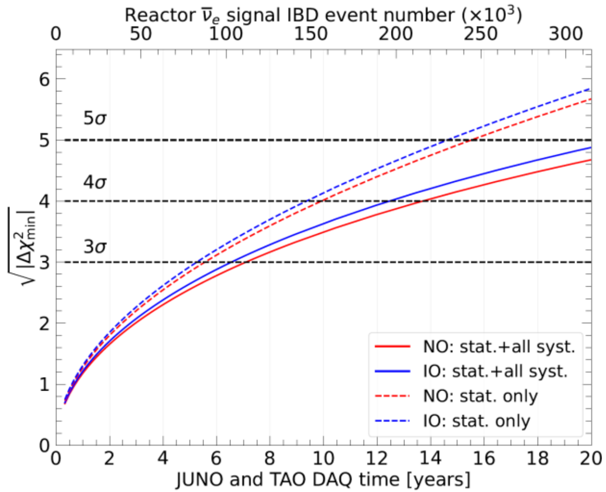
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

Determination of the neutrino mass ordering

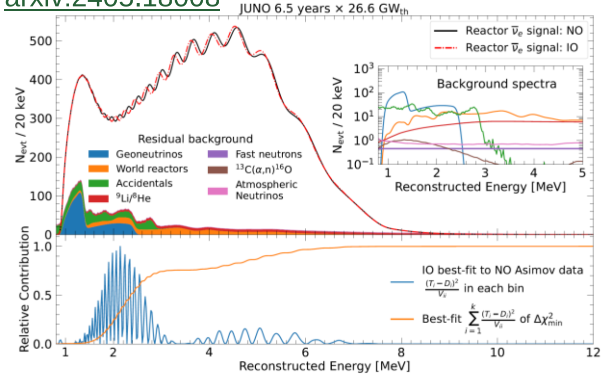
- JUNO sensitivity to the **neutrino mass ordering**: arxiv:2405.18008
  - Updated signal and background rates
  - Improved predicted **energy resolution** arXiv:2405.17860
  - Reactor shape uncertainty from **TAO**

➢ JUNO reactor neutrino oscillation analysis alone provides a median **3σ sensitivity** to **NMO** in **6.5 years**!

- Combination with **atmospheric neutrino oscillation analysis** in progress.



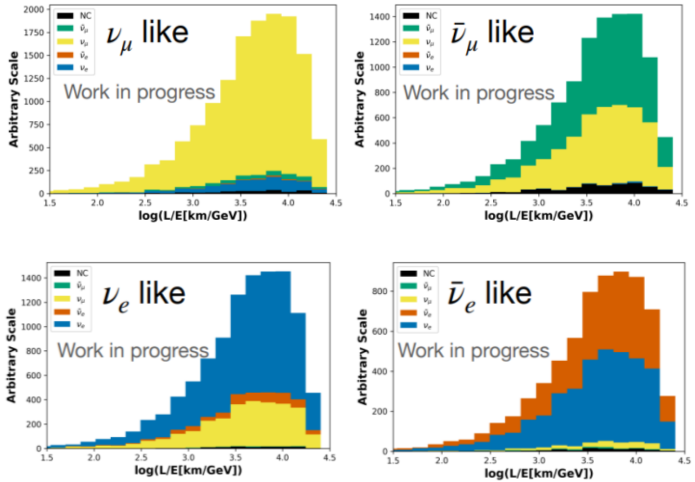
arxiv:2405.18008



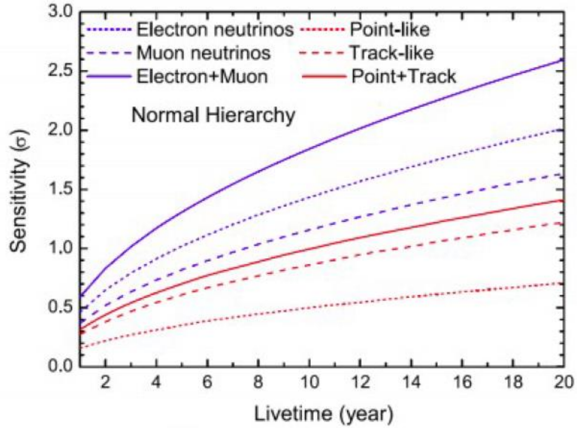
Atmospheric neutrino oscillations

- **First time** atmospheric neutrino oscillations will be studied with **liquid scintillator**:
  - e / μ separation
  - ν / $\bar{\nu}$ separation
  - Neutrino energy
  - Track direction

Flavor identification of atmospheric neutrinos in JUNO



- Plan to install all **spare PMTs** on top of water pool to further **improve PID** and **direction reconstruction**.



➢ Combine **reactor** and **atmospheric analyses** to boost the **NMO sensitivity**.

Conclusions

- Multipurpose 20-kton Liquid Scintillator neutrino observatory with a **rich physics program**.

- **JUNO detector construction** well underway: **first data** next year!

➢ JUNO will measure Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ with unprecedented accuracy <0.5%.

➢ JUNO can determine the **Neutrino Mass Ordering** at **3σ significance in 6.5 years.**

76 institutes, 18 countries, >700 collaborators

Backup

Precision measurement

- **Statistical** and **systematic uncertainties** for **6 years**.

Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

Solar neutrinos

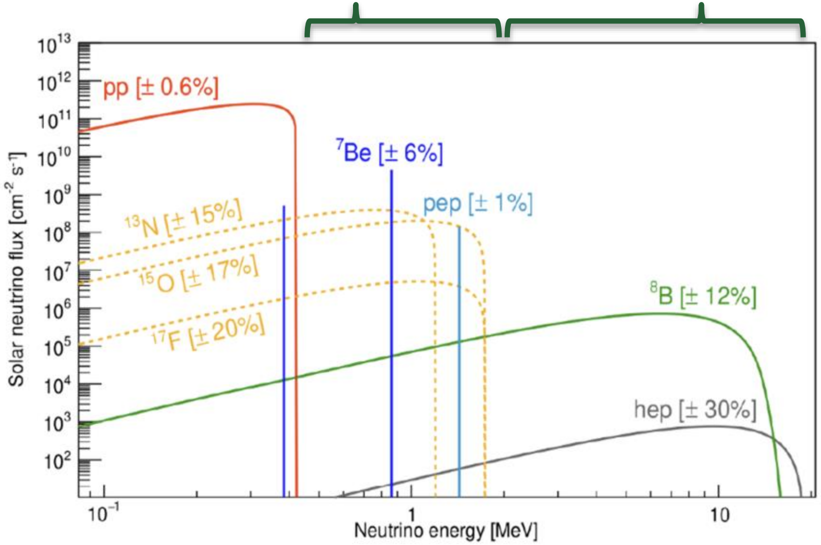
- **JUNO** sensitive to both **high** and **intermediate energy** solar neutrinos.

JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos

arXiv:2303.03910

Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program

arXiv:2210.08437

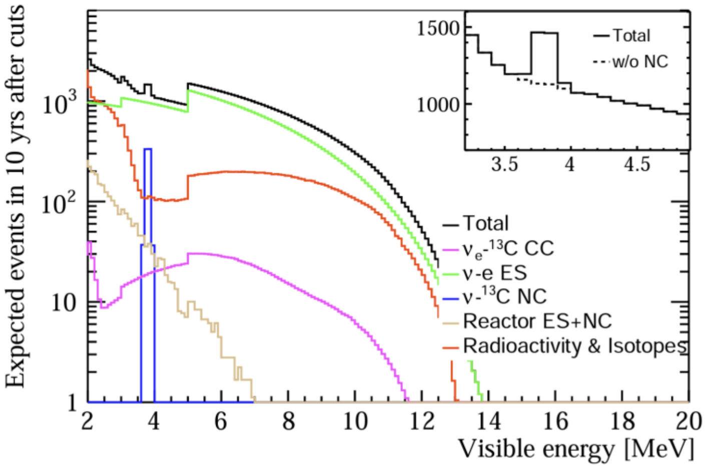


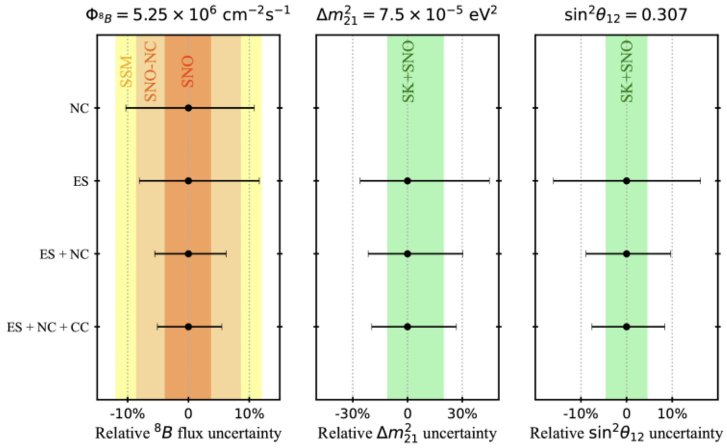
arXiv:2210.08437

High energy solar neutrinos

- Model independent detection of **^{8}B neutrinos** via three interaction channels **CC, NC** and **ES**:
  - ➢ 5% uncertainty on **^{8}B neutrino flux**
  - ➢ 20% uncertainty on **Δm^2_{21}**
  - ➢ 8% uncertainty on **$\sin^2\theta_{12}$**

Channels		Threshold [MeV]	Signal	Event numbers	
				[200 kt×yrs]	after cuts
CC	$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-;\,\mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}\mathrm{N}$ decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \to \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-;\,3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \to \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

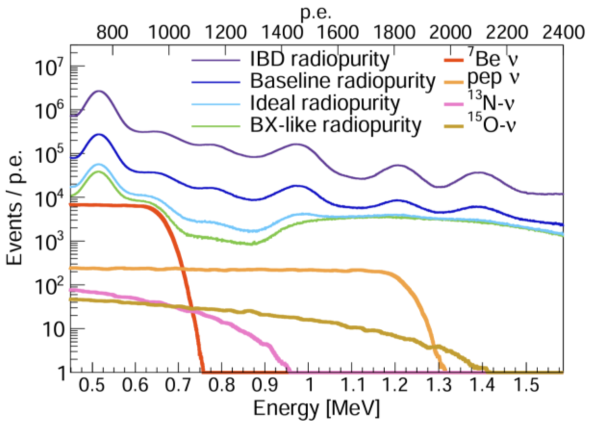




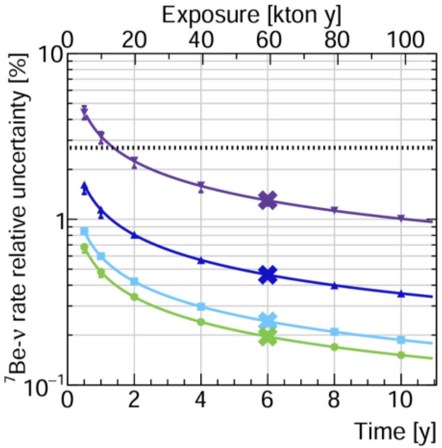
Intermediate energy solar neutrinos

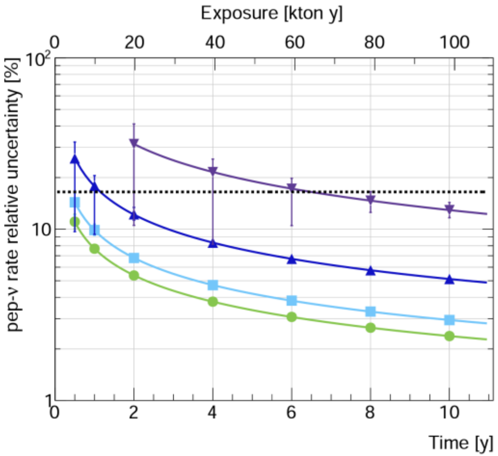
arXiv:2303.03910

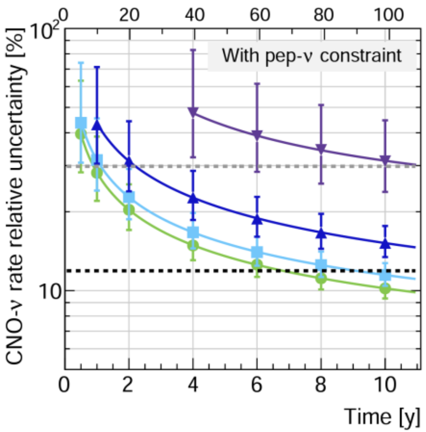
- Possible thanks to **radiopurity** efforts.
- **World leading constraints** after a few years.
- Day/Night asymmetry sensitivity <1%.



Radiopurity scenario: BX-like Ideal Baseline IBD

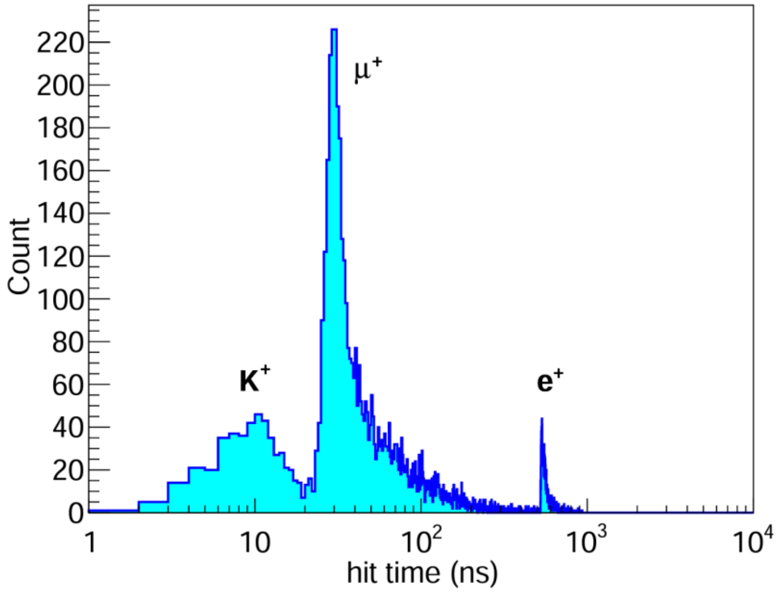






Proton decay

- **$p \rightarrow \overline{\nu}\ K^+$** : three-fold coincidence to detect proton decay with high efficiency (36.9%).
- Good energy resolution helps reduce the backgrounds: less than 0.2 events after 10 years.
- Competitive limit on **proton lifetime** of **9.6×10^{33} years** for 200 kton-year exposure.
- More details in arXiv:2212.08502 .

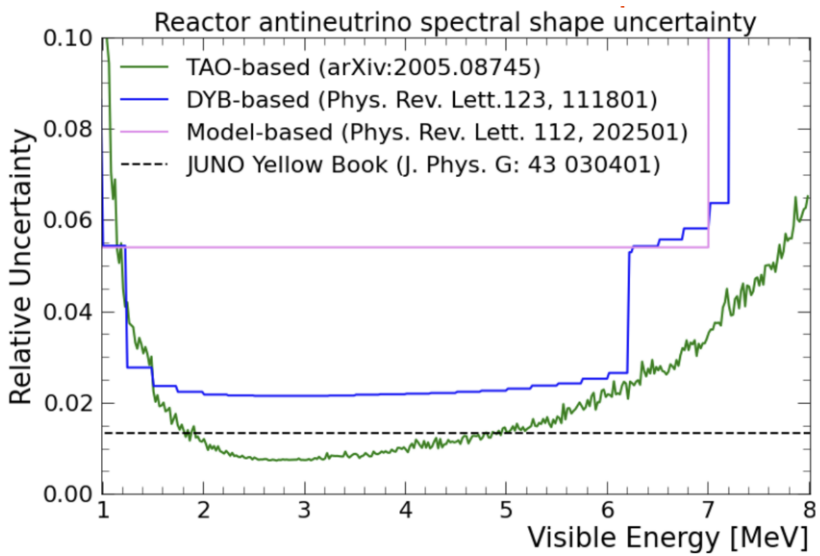


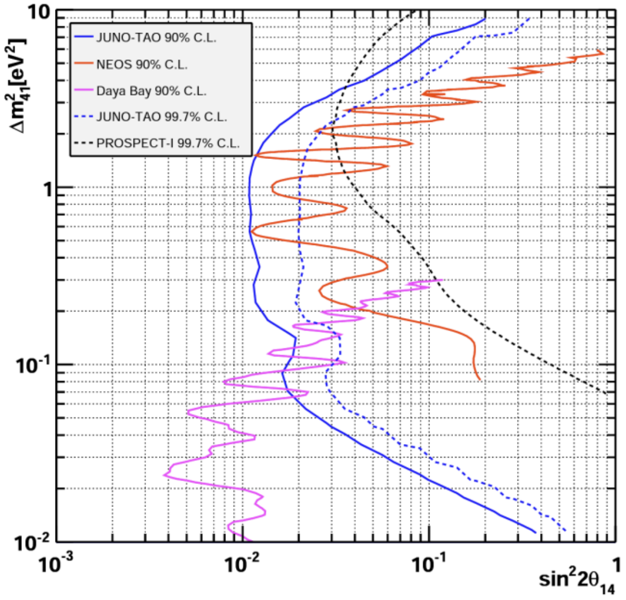
Highlights of nucleon decay searches at JUNO

TAO

- **Sub-percent precision** on reactor neutrino **spectrum shape**.
- **TAO** can search for **sterile neutrinos**.

Status of JUNO's Taishan Antineutrino Observatory





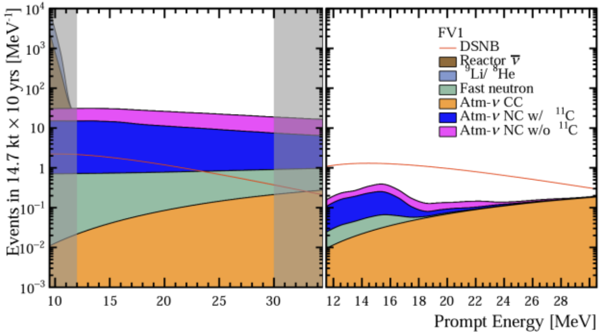
Core collapse supernova neutrinos

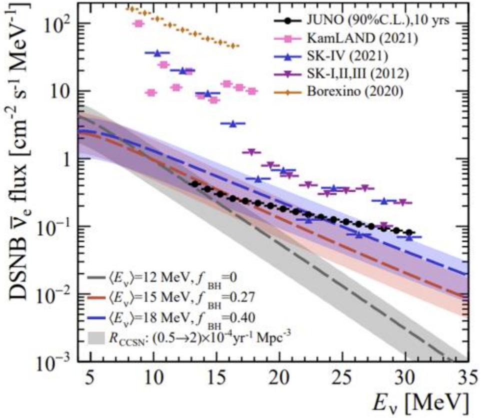
- Core collapse supernova neutrinos detection channels :

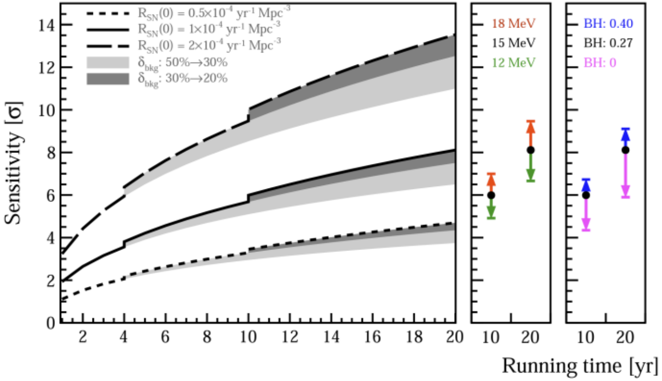
Process	Num. Events (E_{thr} = 0.2MeV)
IBD | $\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
pES | $\nu + p \rightarrow \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~2000
eES | $\nu + e \rightarrow \nu + e$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~400
CC | $\overset{(-)}{\nu}_e +^{12} C \rightarrow e^{-(+)} +^{12} N(^{12}B)$	~200
NC | $\nu +^{12} C \rightarrow \nu +^{12} C^*$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$ $\rightarrow \gamma(15.11\text{MeV})$	~300

DSNB

- **DSNB** 2-4 per year (w/o PSD)
- **3σ discovery** potential in **3 years** (reference model).



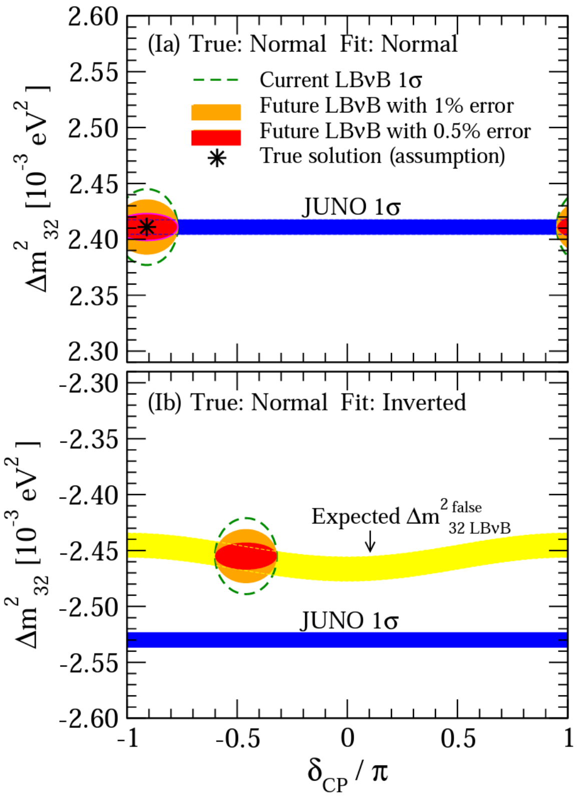




Geoneutrinos

- **Geoneutrinos**: 400 $\bar{\nu}_e$ per year (0-3MeV)
  - More than Borexino and KamLAND combined in 1 year. To date, Borexino + KamLAND = ~200 events.
- Decay of radionuclides (U/Th/K) within the Earth.
- Measure U and Th abundances, **U/Th ratio** in crust and mantle **: 30% uncertainty in 10 years**.
- **Probes** : Earth's formation, Mantle convection, Plate tectonics,Earth's magnetic field production

Synergy between JUNO and NOvA+T2K



- A **5σ determination of NMO** is possible by combining **JUNO** and **NOvA+T2K's results**.
- See arXiv:2008.11280