JUNO analysis and future considerations

NuFact 2024

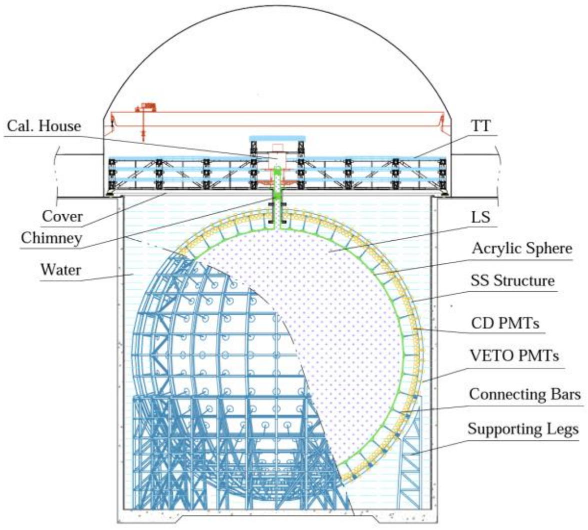
Steven Calvez on behalf of the JUNO collaboration

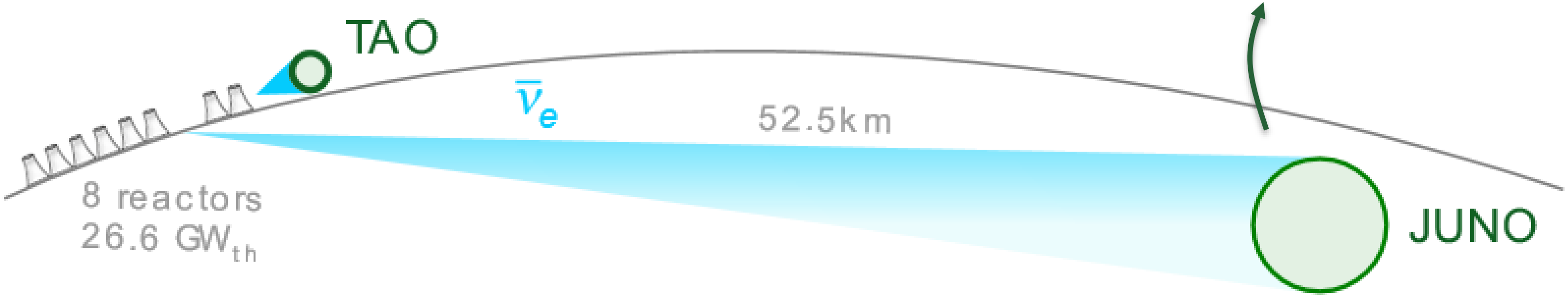
NuFact 2024

September 15th 2024

Jiangmen Underground Neutrino Observatory

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

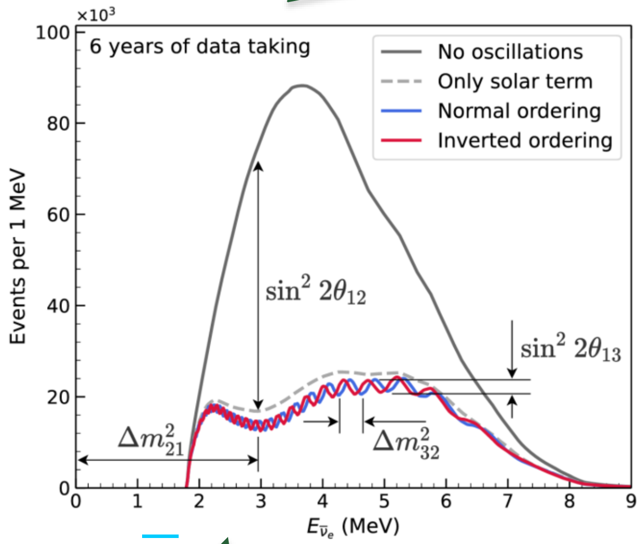


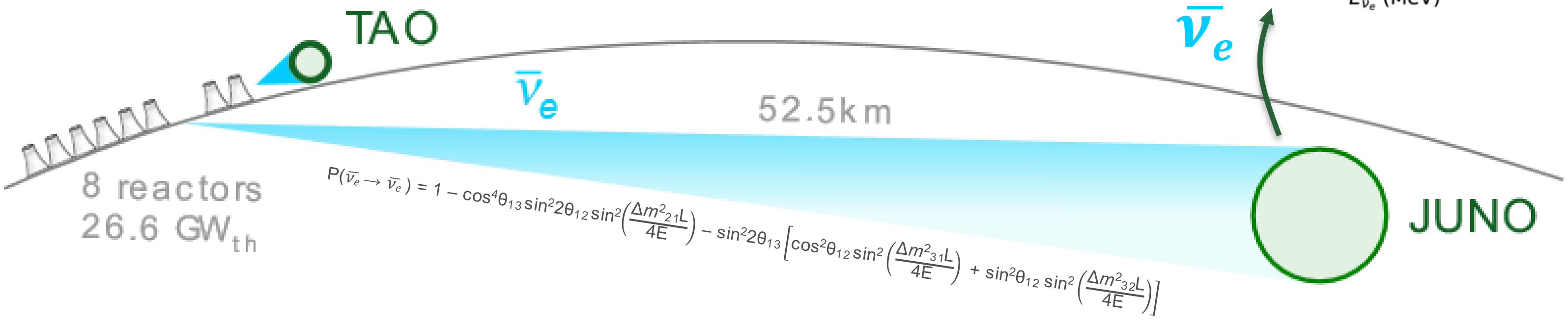


Jiangmen Underground Neutrino Observatory

JUNO plenary

- **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**

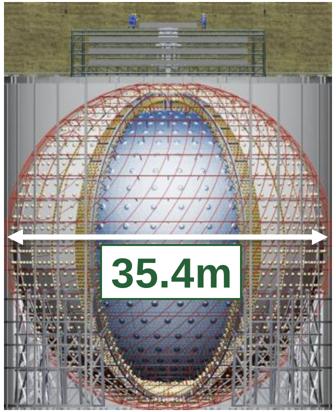
- **Energy resolution: 2.95% @ 1MeV**

- **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



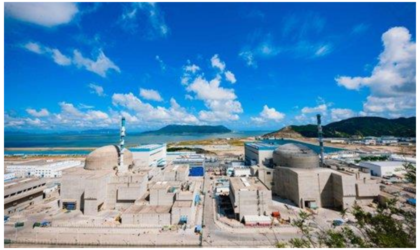
arXiv:2311.17314

- **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

- 17,612 **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		Eur. Phys. J. C 82:1168		NIM.A 1005 (2021) 165347

JUNO key experimental features

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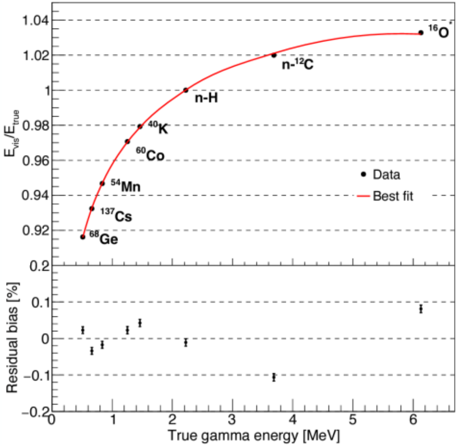
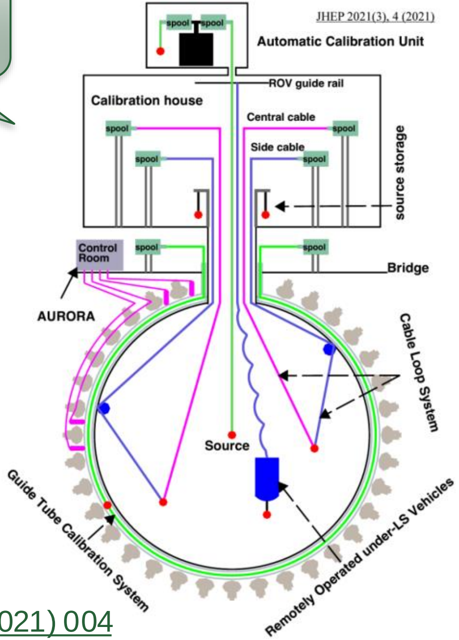
- Energy resolution: 2.95% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ Very high PMTs coverage (78 %)
  - ✓ High PMT efficiency (30%)
  - ✓ **Precise calibration**
- Low background
  - ✓ Material screening, clean environment
- Precise knowledge of reactor spectra

Detector calibration in the JUNO experiment





JHEP 03 (2021) 004

- Comprehensive **calibration strategy**:
  - – Understand **LS non-linearity**.
  - – Correct for **position-dependency.**
- ➢ Reach **<1% syst. uncertainty** on **energy scale**.

JUNO key experimental features

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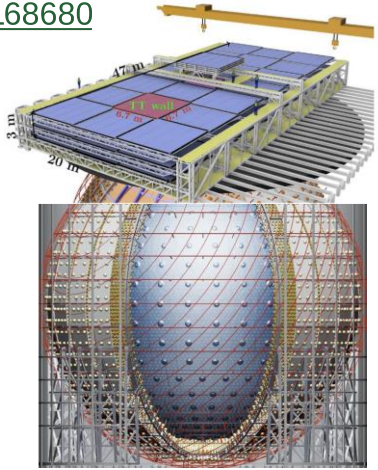
- Energy resolution: 2.95% @ 1MeV
  - ✓ High photon yield, highly transparent LS
  - ✓ Very high PMTs coverage (78 %)
  - ✓ High PMT efficiency (30%)
  - ✓ Precise calibration
- Low background
  - ✓ Material screening, clean environment
  - ✓ **650m or 1800 m.w.e overburden**
  - ✓ **Efficient veto system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

- **650m overburden**: 4Hz of cosmic muons in LS
- **Top Tracker**: NIM A 1057 (2023) 168680
  - Opera plastic scintillator

Reconstruction of Cosmic Muon with Machine Learning in JUNO



- **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)
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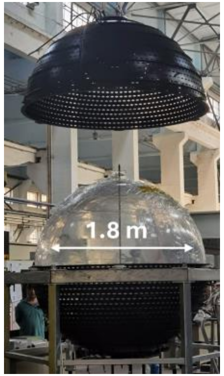
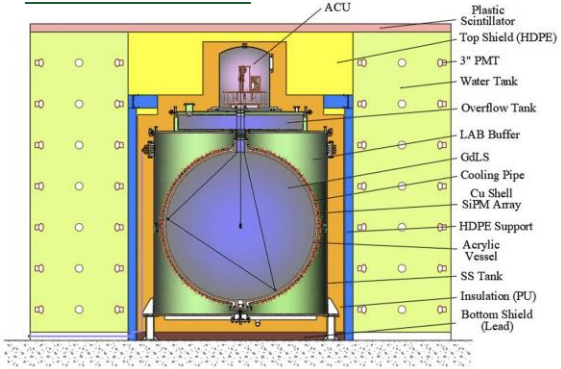
  - ✓ Precise calibration
- Low background
  - ✓ Material screening, clean environment
  - ✓ 650m or 1800 m.w.e overburden
  - ✓ Efficient veto system (>99.5%)
- Precise knowledge of reactor spectra
  - ✓ **Satellite detector TAO**



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

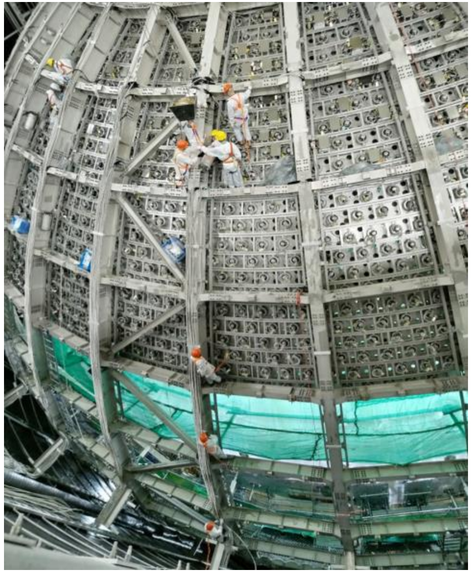
- **Support Structure** completed.

- **Acylic Vessel** :
  - Production complete.
  - 21/23 layers installed.

- More than **half** of **20"** and **3" PMTs installed**.

- **Detector completion** expected by **end 2024**.

➢ First **data taking** in **2025**.



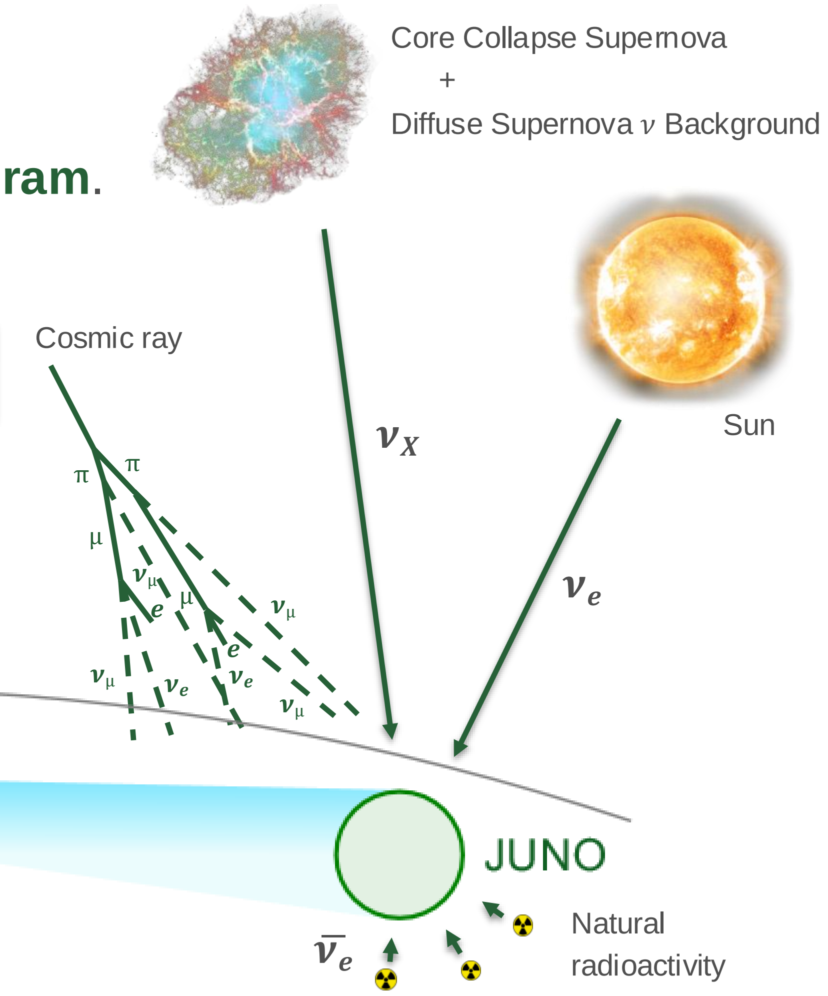
Physics searches with JUNO

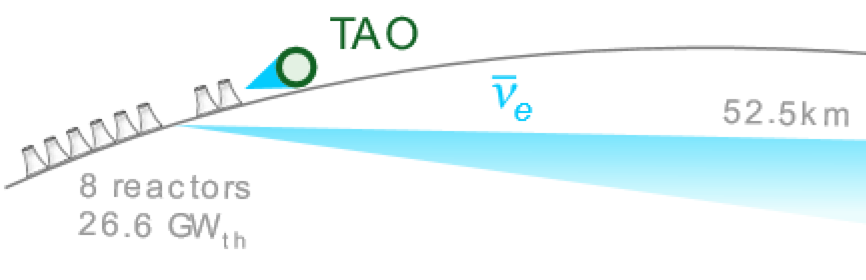
- **JUNO's design** enables a **rich physics program**.

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

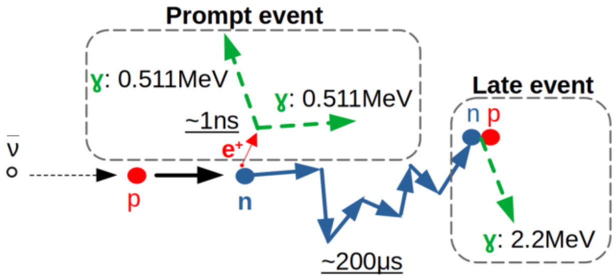
Prospects for Neutrinos from Natural Sources in JUNO

PPNP 123 (2022) 103927



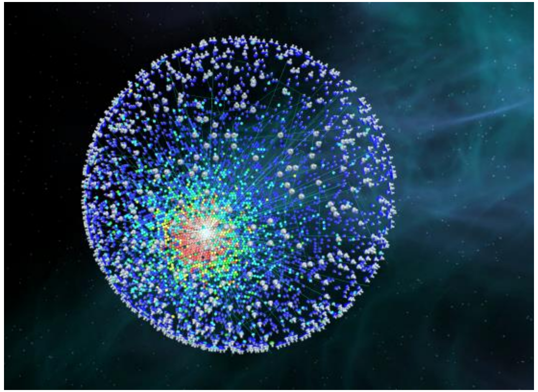


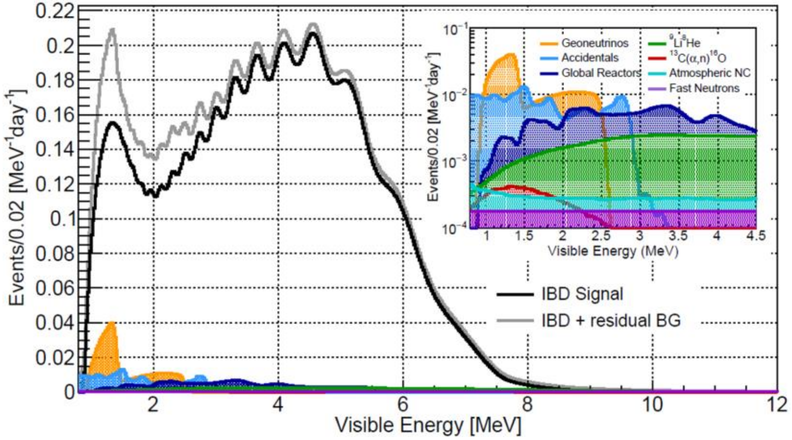
Reactor neutrino oscillations



- **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.
  - Machine learning reconstruction algorithms help reach excellent **energy resolution** (<3% @ 1 MeV).

Neutrino Oscillation Physics with JUNO

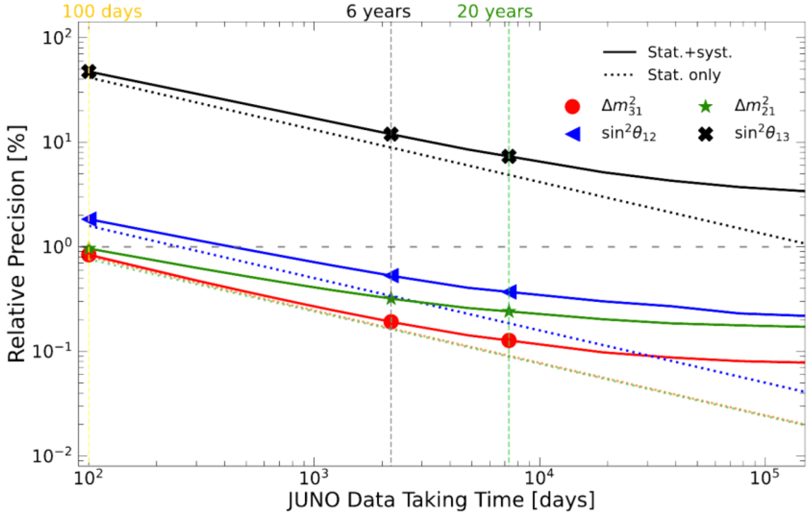




Precision measurement of neutrino oscillations parameters

- **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%)

Precision measurements

[Chin. Phys. C 46 (2022) 12]

- **After 6 years**, the measurements of:
  - **Δm^2_{21}** and **$\sin^2\theta_{12}$** are **systematics-limited**.
  - **Δm^2_{31}** and **$\sin^2\theta_{13}$** remain **statistics-limited**.

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
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- 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
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- 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
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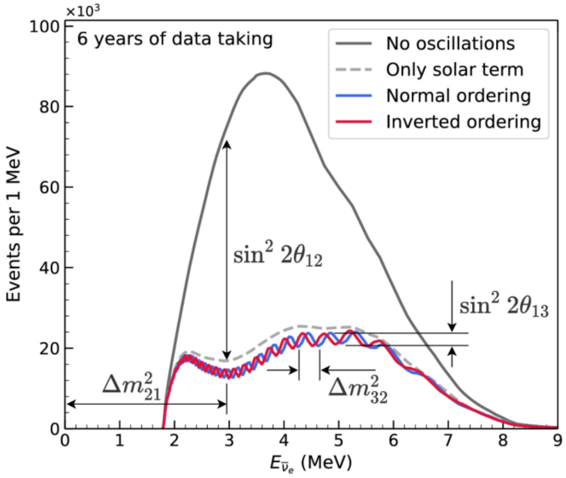

Systematic uncertainties

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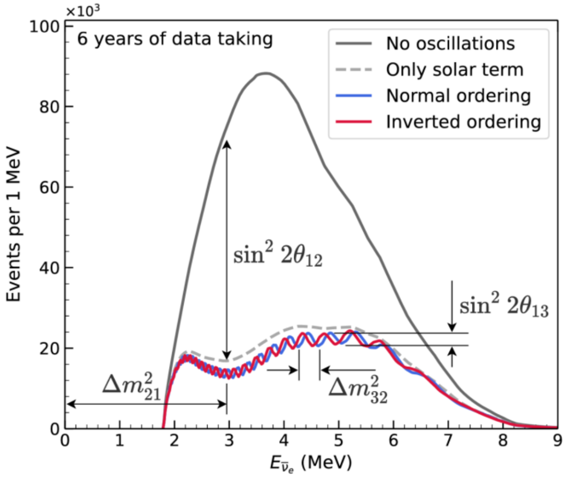
Δm^2_{31}

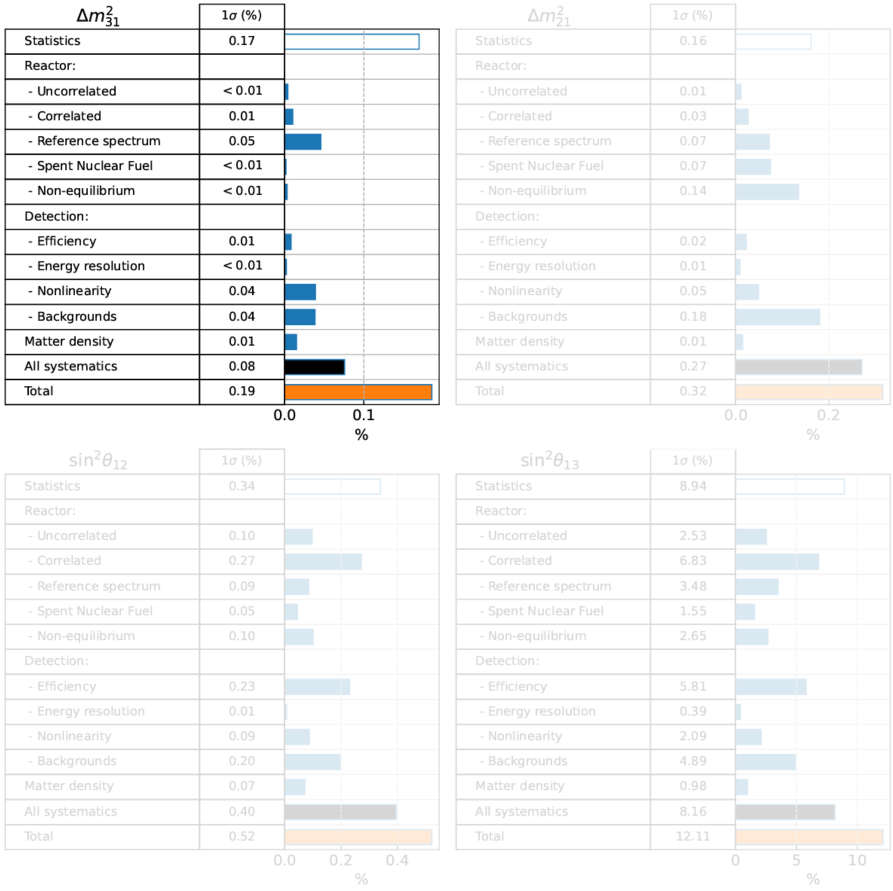
⇳

Fast oscillation pattern

⇧

Precise knowledge of
spectrum shape





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Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
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$\sin^2\theta_{12}$	1σ (%)
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- Reference spectrum	0.09
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- Energy resolution	0.01
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Matter density	0.07
All systematics	0.40
Total	0.52

$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
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Systematic uncertainties

[Chin. Phys. C 46 (2022) 12]

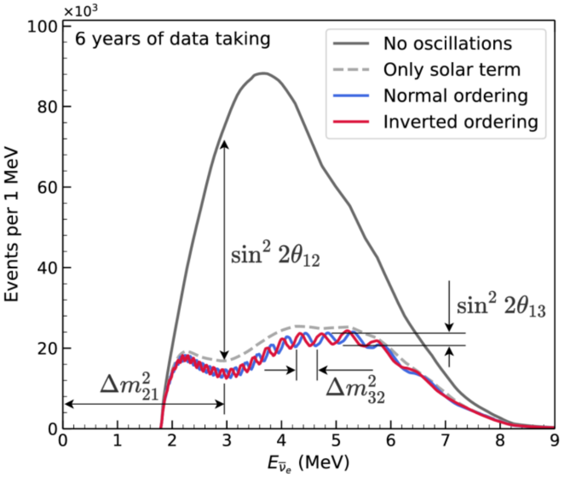
Δm^2_{21}

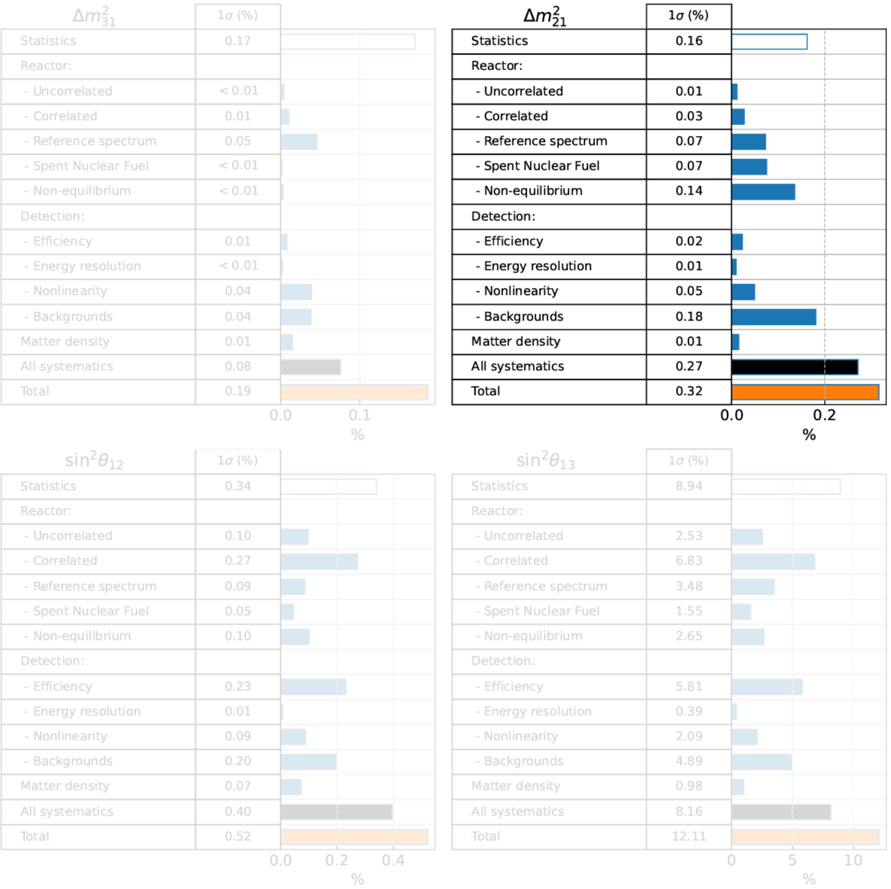
⇳

Position of **maximum disappearance**

⇧

Low energy **backgrounds**
(geoneutrinos, accidentals, etc.)





1σ (%)	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
Statistics	0.17	0.16	0.34	8.94
Reactor:				
- Uncorrelated	< 0.01	0.01	0.10	2.53
- Correlated	0.01	0.03	0.27	6.83
- Reference spectrum	0.05	0.07	0.09	3.48
- Spent Nuclear Fuel	< 0.01	0.07	0.05	1.55
- Non-equilibrium	< 0.01	0.14	0.10	2.65
Detection:				
- Efficiency	0.01	0.02	0.23	5.81
- Energy resolution	< 0.01	0.01	0.01	0.39
- Nonlinearity	0.04	0.05	0.09	2.09
- Backgrounds	0.04	0.18	0.20	4.89
Matter density	0.01	0.01	0.07	0.98
All systematics	0.08	0.27	0.40	8.16
Total	0.19	0.32	0.52	12.11

Systematic uncertainties

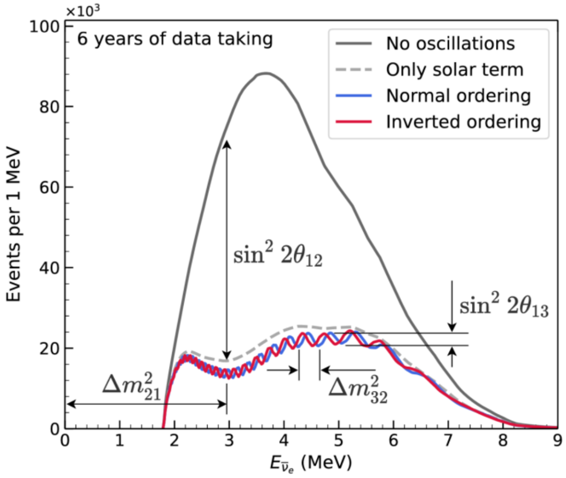
$\sin^2\theta_{13}$ and **$\sin^2\theta_{13}$**

⇕

Normalization factors

⇧

Reactor flux, detector **efficiency**, etc.



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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
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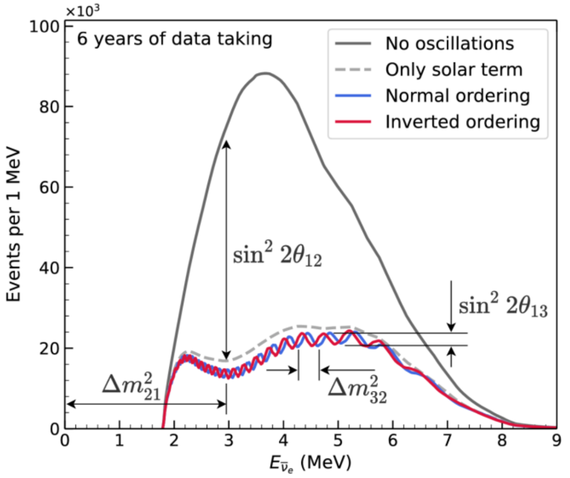
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

Systematic uncertainties

[Chin. Phys. C 46 (2022) 12]

- Main **systematics uncertainties** in **JUNO's reactor analysis** are **not common** with **accelerator** and **atmospheric experiments**.



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- 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 (%)
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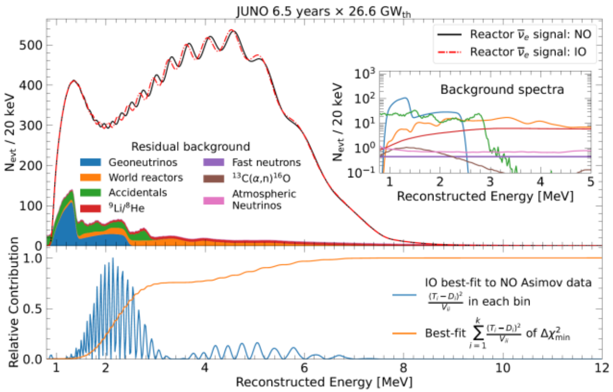
All systematics	0.40
Total	0.52

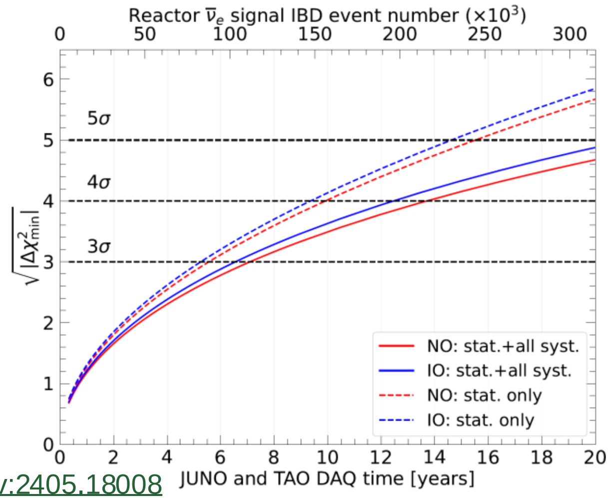
$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16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

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
  - JUNO+TAO combined analysis

➢ JUNO reactor neutrino oscillation analysis alone provides a median **3σ sensitivity** to **NMO** in **6.5-7 years**!



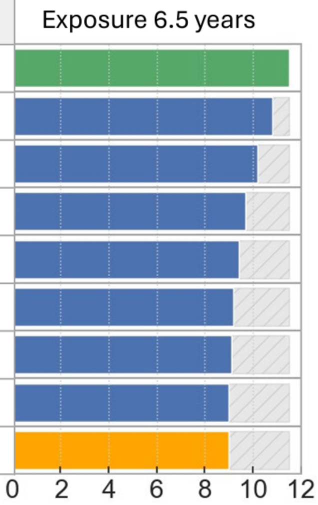


arxiv:2405.18008

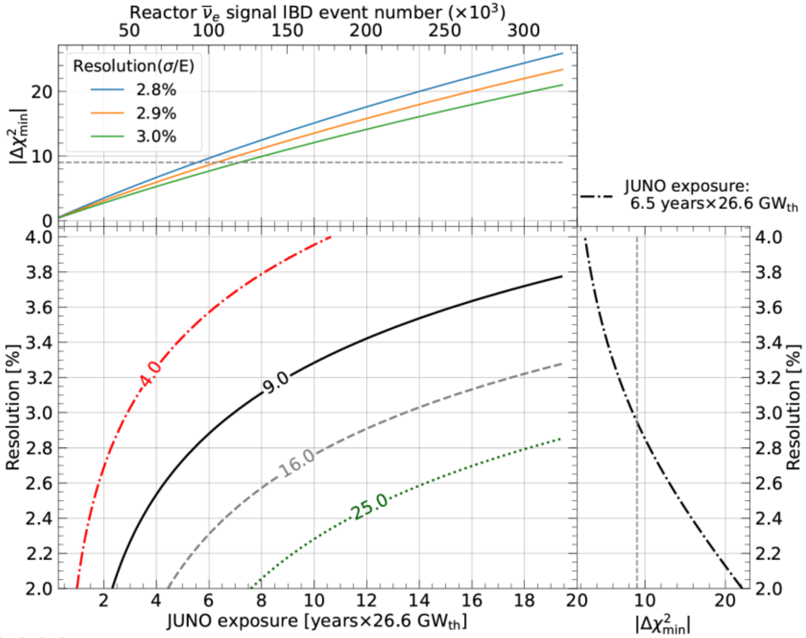
Determination of the neutrino mass ordering

- Main **systematic uncertainties** in the **NMO analysis** come from the **spectrum shape**.

Uncertainty	$\lvert\Delta\chi^2_{min}\rvert$
Statistics (JUNO+TAO)	**11.5**
+ reactor and response	−0.7
+ TAO unc.	−0.6
+ JUNO geoneutrinos	−0.5
+ JUNO world reactors	−0.3
+ JUNO accidentals	−0.2
+ JUNO $^{9}Li/^{8}He$	−0.1
+ JUNO other bkg.	−0.05
Full systematics	**9.0**



- **NMO sensitivity** highly dependent on **energy resolution**.

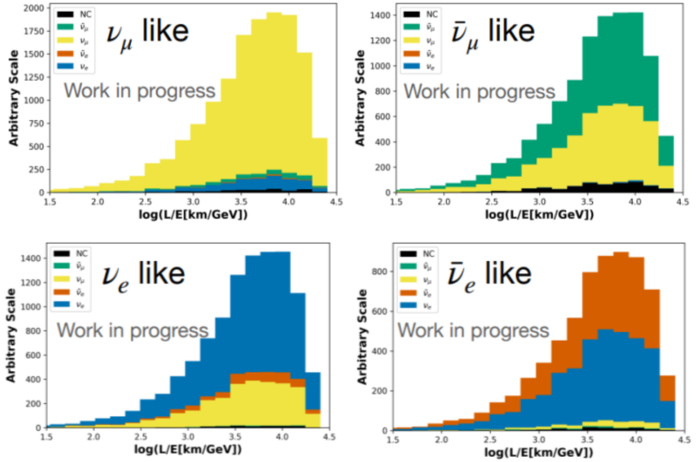


arxiv:2405.18008

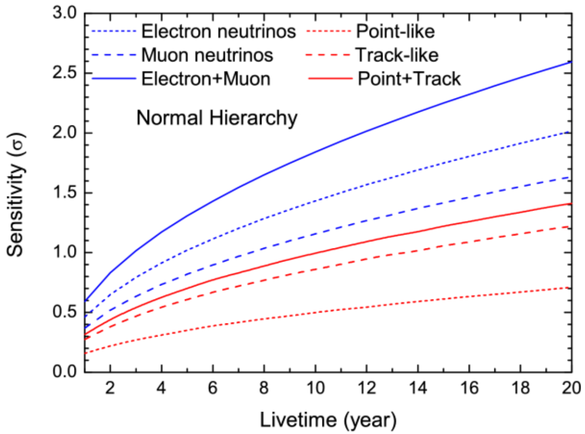
Atmospheric neutrino oscillations

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

Phys.Rev.D 109 (2024) 5, 052005



J. Phys. G: Nucl. Part. Phys. 43 030401



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

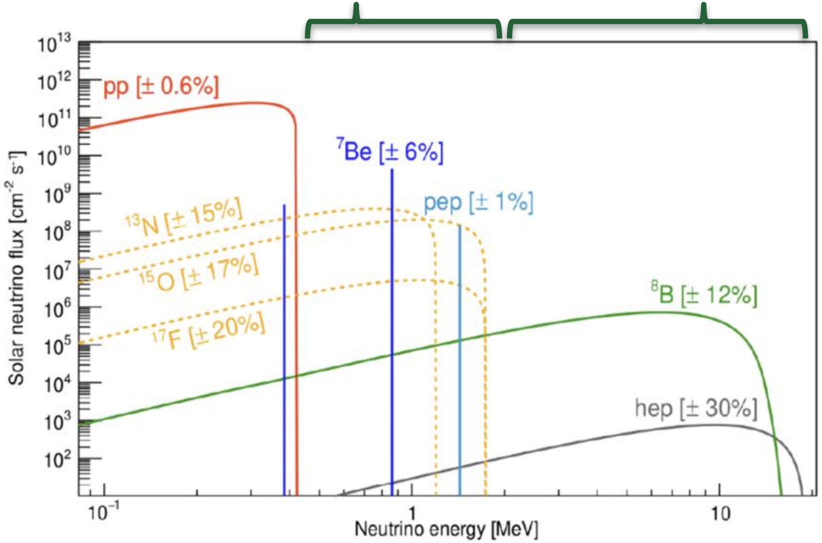
➢ **Combination** with **reactor analysis** in progress to boost **JUNO's NMO sensitivity.**

Solar neutrinos

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

JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos
JCAP 10 (2023) 022

Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program
Astrophys. J. 965.2: 122 (2024)

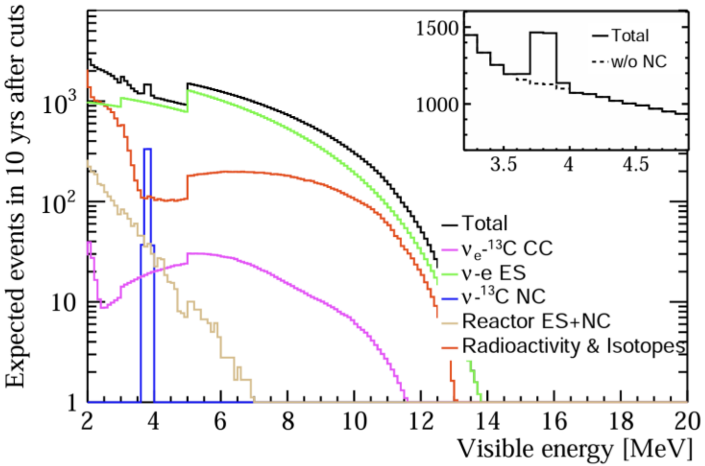


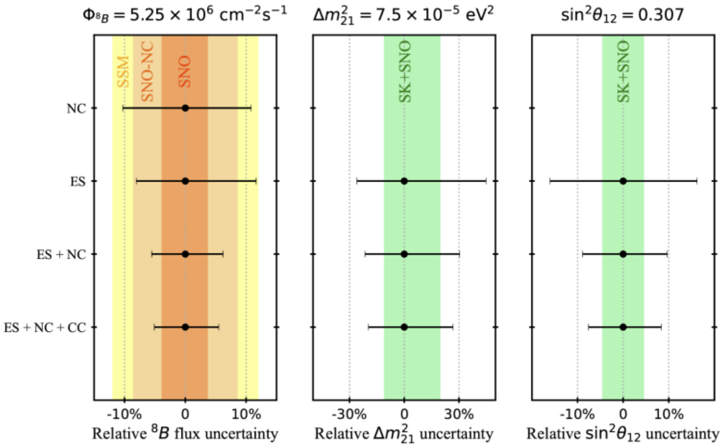
High energy solar neutrinos

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

Astrophys. J. 965.2: 122 (2024)





Future considerations

- **JUNO** is paving the way towards a **precision era** in **neutrino physics**.
  - Precision tests of models: non unitarity of PMNS, new physics, etc.

- **JUNO's high-precision measurements** and **determination of the NMO** will profoundly impact the field:
  - Will inform the **neutrinoless double beta decay program**.
  - **Unique** and **complementary** measurements through **vacuum neutrino oscillations**.
  - Will allow **accelerator** and **atmospheric** experiments to **better constrain the parameter space:** δ_{CP} and θ_{23}.
  - Little overlap in **systematic uncertainties** makes **combining measurements easier**.
  - Comparing precision measurements of Δm^2_{31} in the **electron** and **muon neutrino disappearance channels** can **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 $\boldsymbol{\Delta m^2_{31}}$, $\boldsymbol{\Delta m^2_{21}}$, and $\boldsymbol{\sin^2\theta_{12}}$ with unprecedented accuracy <0.5%.

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

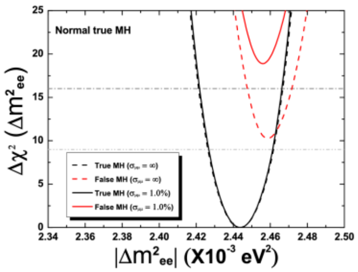
76 institutes, 18 countries, >700 collaborators

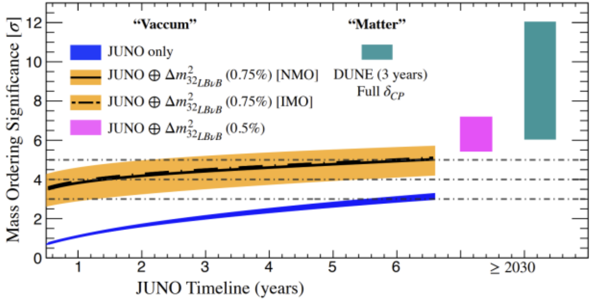
Backup

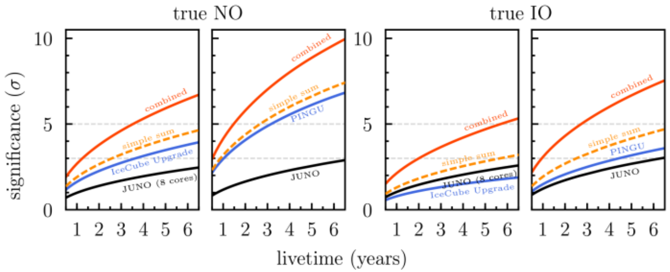
Synergy between JUNO, NOvA, T2K, IceCube/PINGU, KM3NeT/ORCA

- **Complementarity** and **synergy** between **reactor**, **accelerator** and **atmospheric experiments**.

- **Early 5σ NMO sensitivity** possible by combining:
  - ➢ **JUNO** and **NOvA/T2K**'s measurements:
    - See J. Phys. G 43, 030401, Phys. Rev. D **72**,013009, Phys. Rev. D **88**, 013008, Sci Rep **12**, 5393, arXiv:2404.08733.
  - ➢ **JUNO** and **IceCube/KM3NeT**'s measurements:
    - See Phys. Rev. D 101, 032006, JHEP 03, 2022, 055





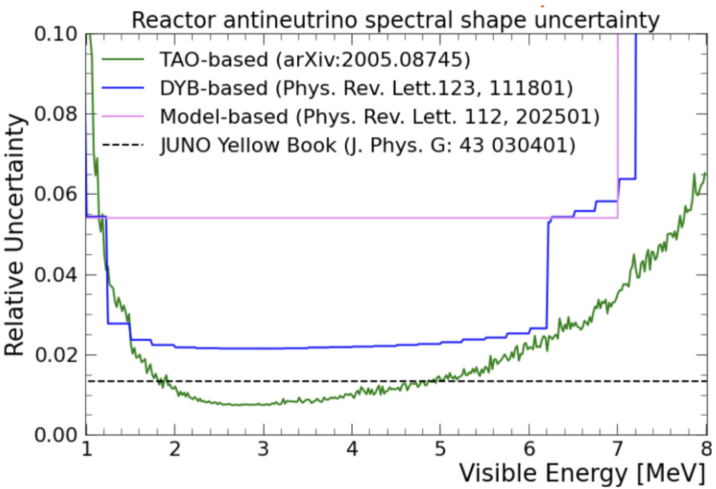


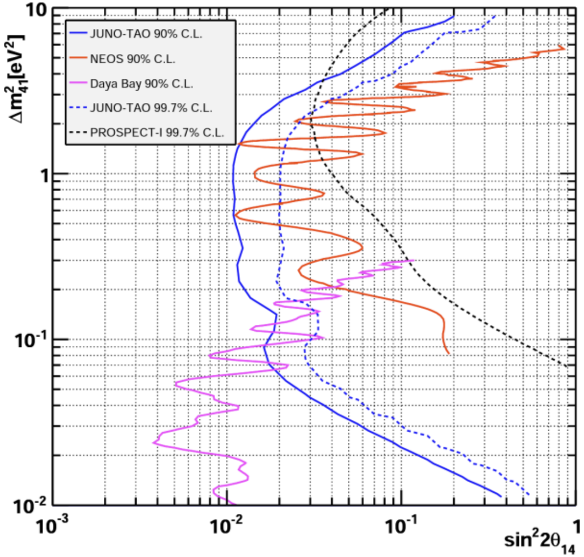
TAO

- **Best precision (subpercent)** on reactor neutrino **spectrum shape:** useful for other experiments and nuclear databases.

- Sensitive to reactor spectra **fine structure**.

- **TAO** can search for **sterile neutrinos**.

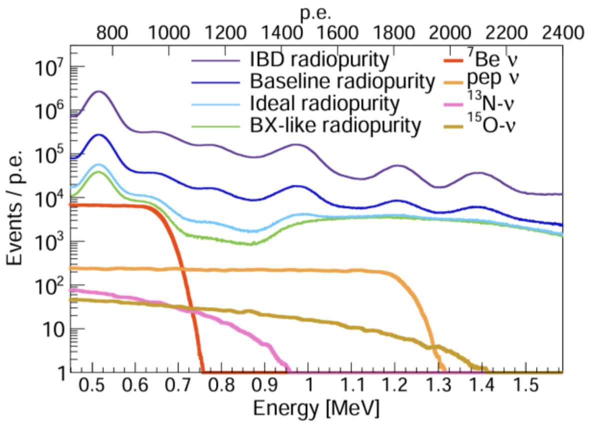




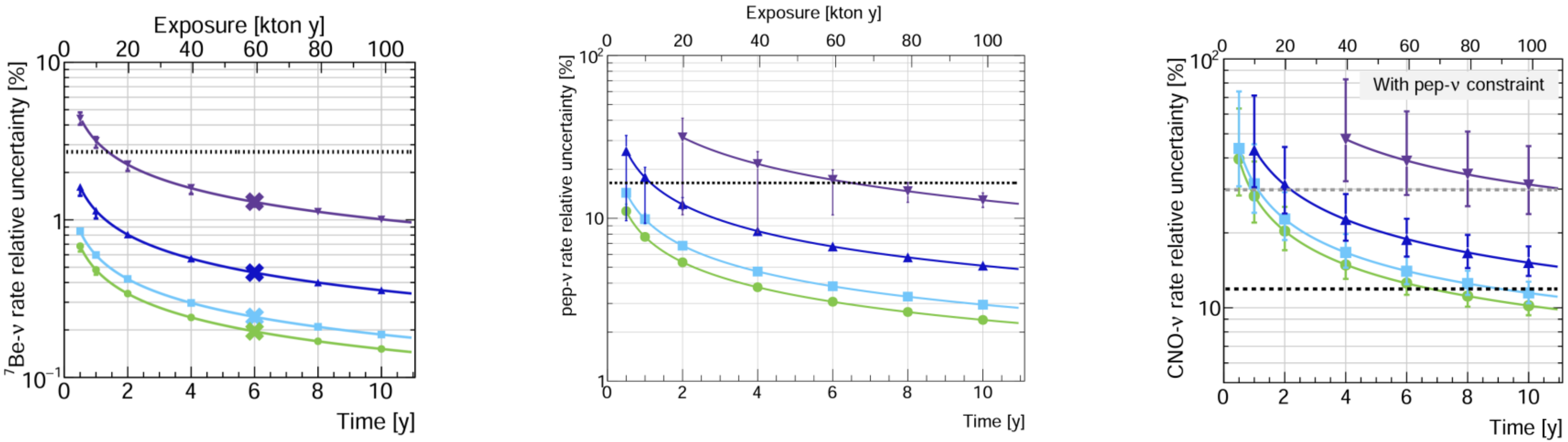
Intermediate energy solar neutrinos

arXiv:2303.03910

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

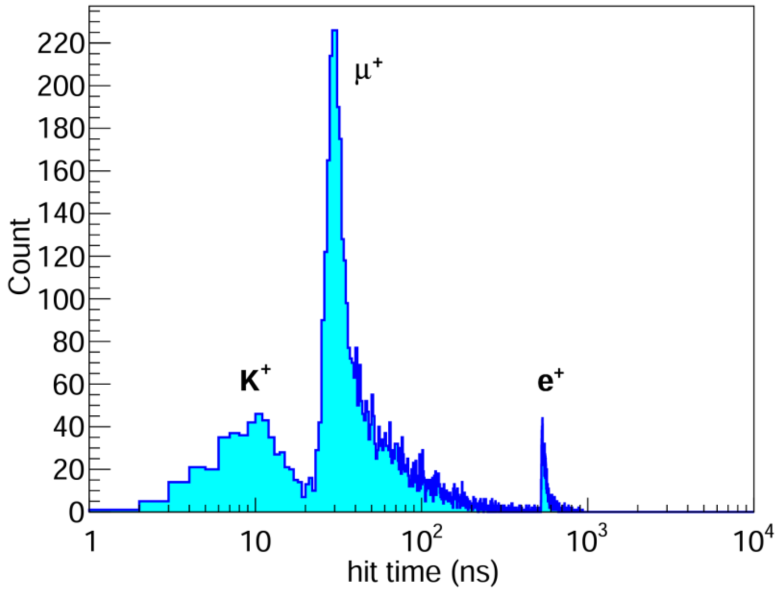


Radiopurity scenario: BX-like Ideal Baseline IBD



Proton decay

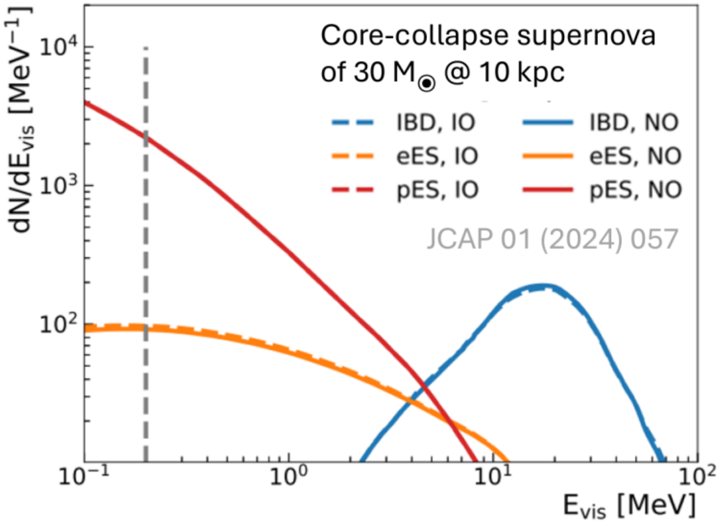
- **$p \rightarrow \bar{\nu}\ K^+$** : three-fold coincidence to detect proton decay with high efficiency (36.9%).
- Good energy resolution helps reduce the backgrounds: less than 0.2 events after 10 years.
- Competitive limit on **proton lifetime** of **9.6×10^{33} years** for 200 kton-year exposure.
- More details in Chin.Phys.C 47 (2023) 11, 113002



Core collapse supernova neutrinos

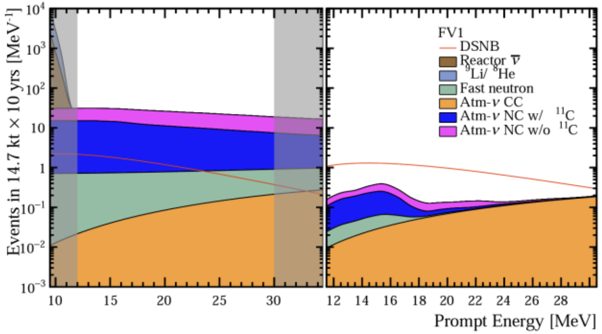
- Multiple core collapse supernova neutrinos **detection channels**.
- Sensitive to **all flavors** via CC + ES channels.
- Can detect neutrinos and **alert hours before supernova explosion**.
- Can study **supernova neutrinos** after explosion.

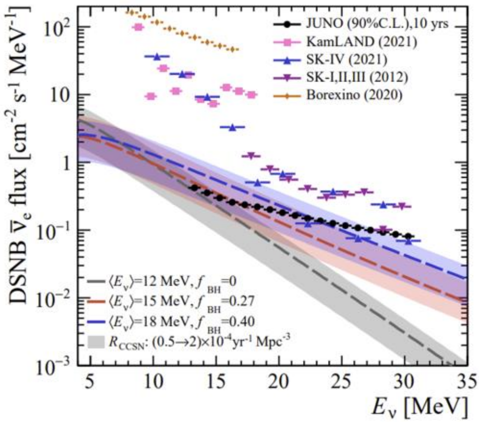
Process		Num. Events (E_{thr} = 0.2MeV)
IBD	$\bar{\nu}_e + p \to e^+ + n$	~5000
pES	$\nu + p \to \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~2000
eES	$\nu + e \to \nu + e$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~400
CC	$\overset{(-)}{\nu}_e + {}^{12}C \to e^{-(+)} + {}^{12}N({}^{12}B)$	~200
NC	$\nu +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

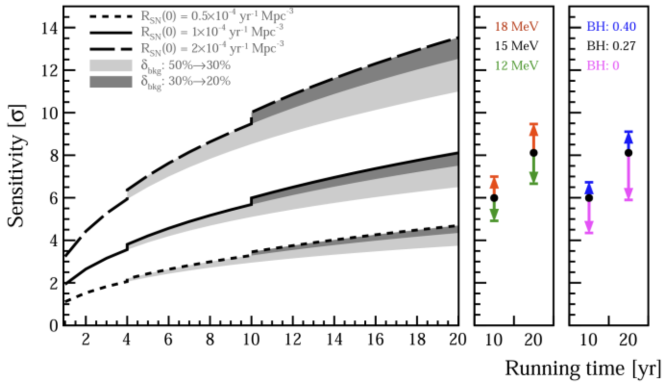


DSNB

- **DSNB** 2-4 per year (w/o PSD)
- **3σ discovery** potential in **3 years** (reference model).
- See Universe 2022, 8, 181







Geoneutrinos

- Decay of **radionuclides** (U/Th/K) within the Earth.
- **Geoneutrinos**: 400 $\bar{\nu}_e$ per year (0-3MeV)
  - More than Borexino and KamLAND combined in 1 year. To date, Borexino + KamLAND = ~200 events.
- 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