Neutrino Oscillation Physics with JUNO

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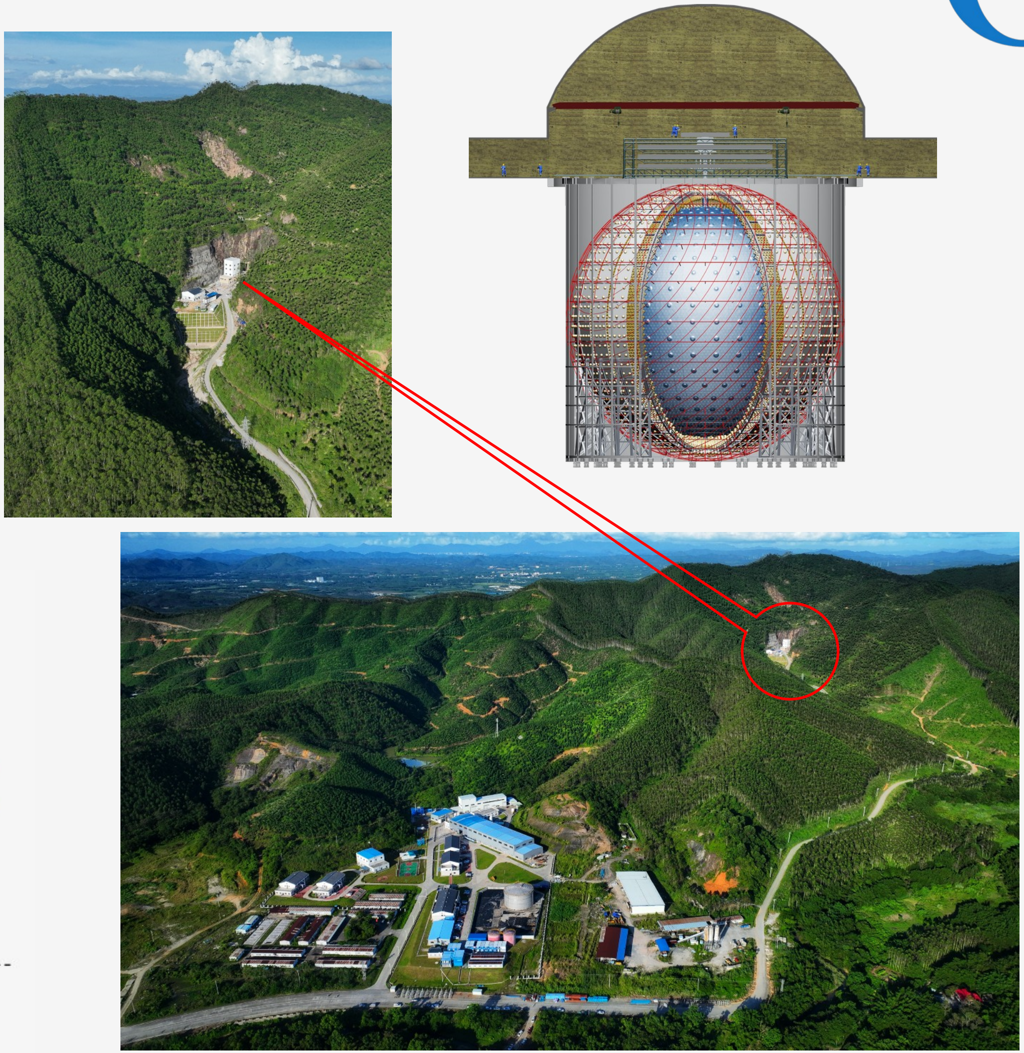
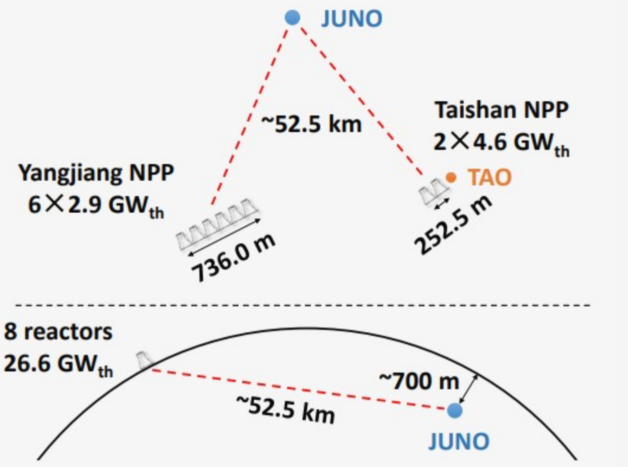
for the JUNO collaboration

NuFact 2024 | September 17th, 2024

JUNO at a glance

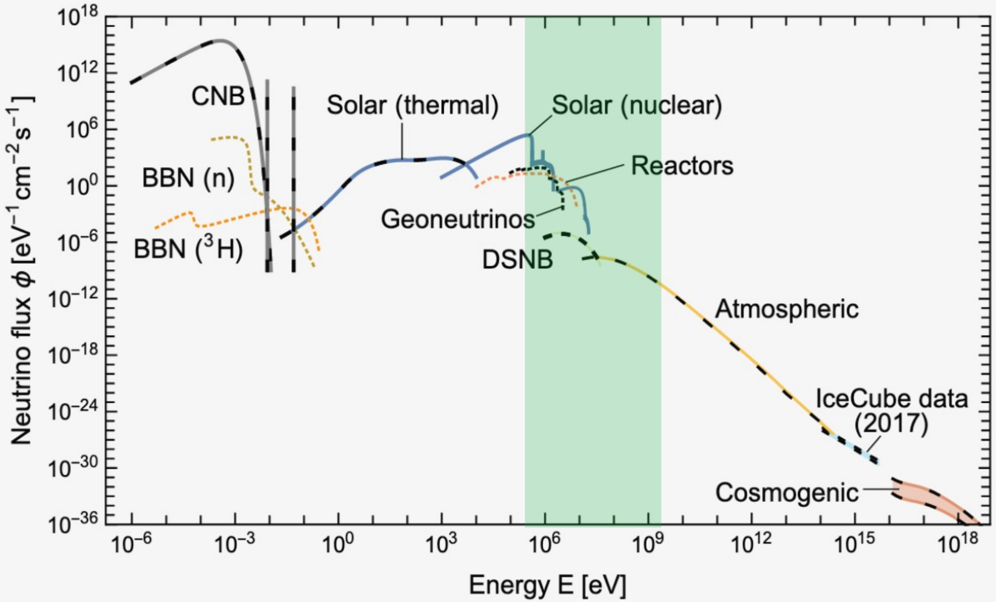
- The Jiangmen Underground Neutrino Observatory (JUNO) is a large multipurpose experiment under construction in China
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by water Cherenkov detector
- Unprecedented energy resolution of ≤3% at 1 MeV





JUNO: a multipurpose observatory

JUNO energy region



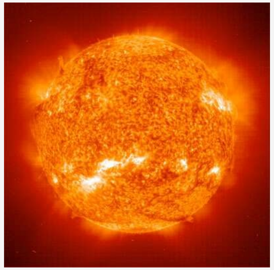
E. Vitagliano et al., Rev. Mod. Phys. 92 (2020) 045006

Note: fluxes are averaged

Reactor

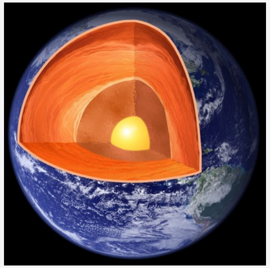
~50/day

Solar



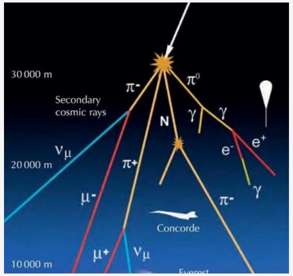
~2000/day

Geo



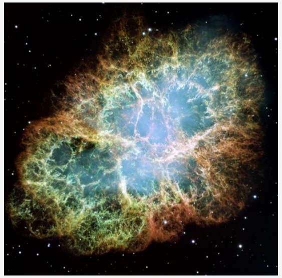
~1/day

Atmospheric



10-20/day

Supernova



O(1000)/s for core-collapse SN @10kpc

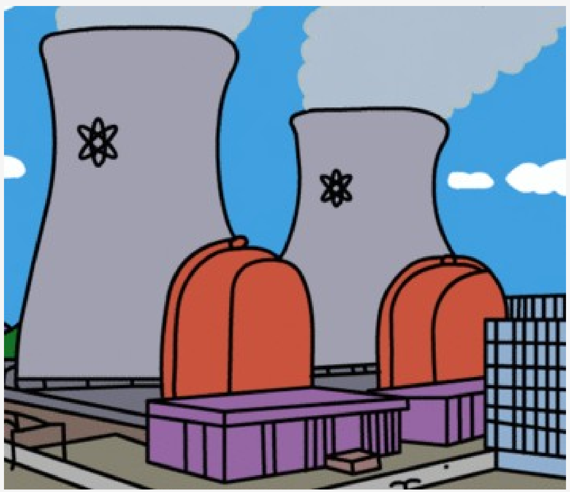
DSNB: few/year

\+ **New Physics**

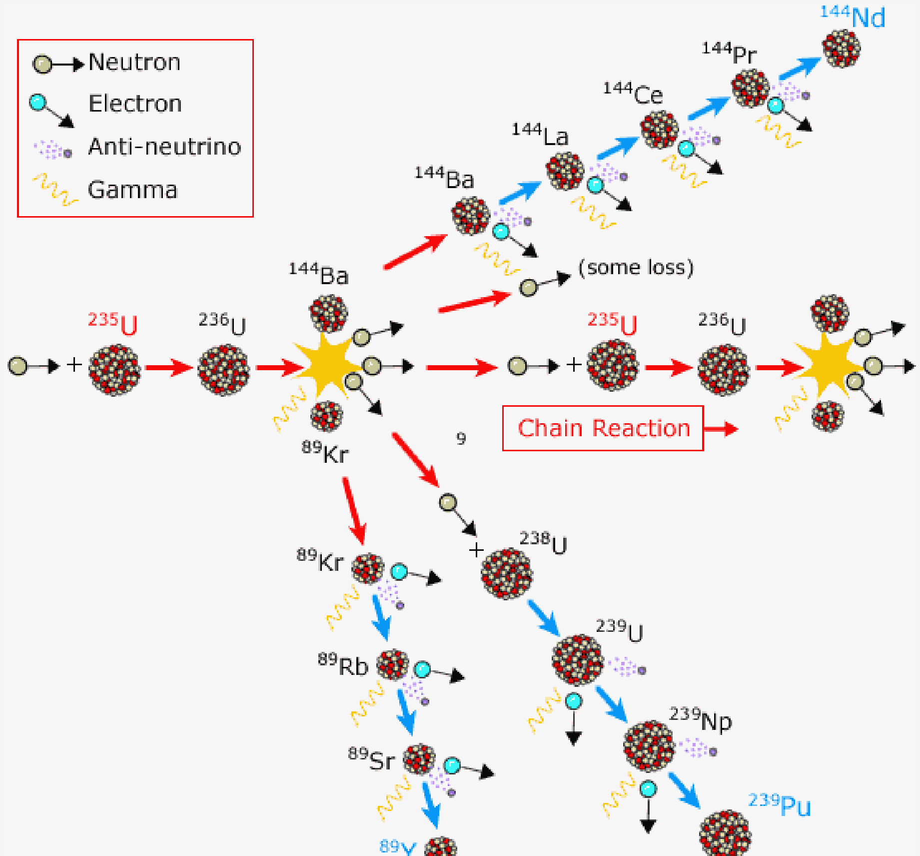
Proton decay, Non standard interactions, Sterile neutrinos, Neutrino magnetic moment, etc.

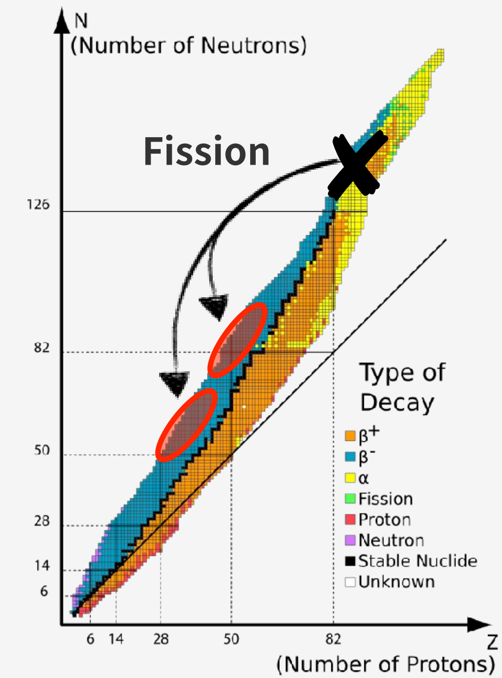
Reactor antineutrinos production

Nuclear reactors are a flavor-pure, widely available, cost-effective, extremely intense and well-understood source of electron antineutrinos



$\sim 10^{20}\ \overline{\nu}_e\ /\mathrm{GW_{th}}\ /\ \mathrm{s}$

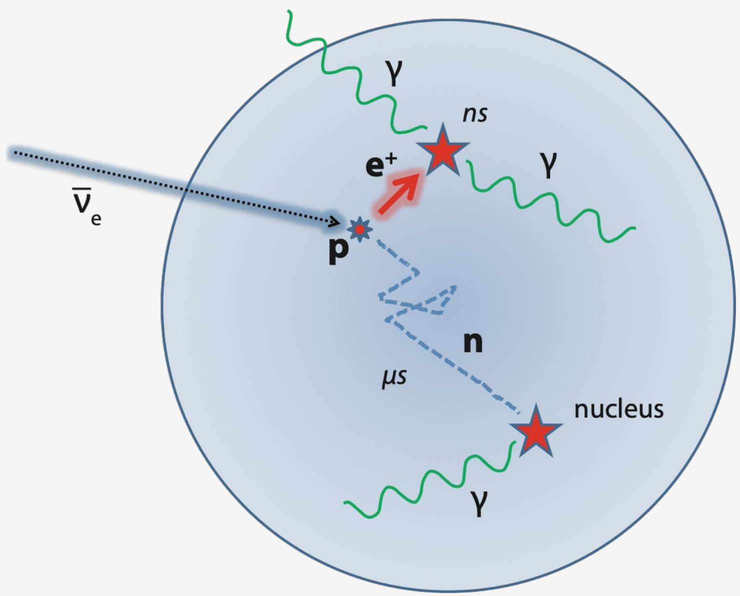




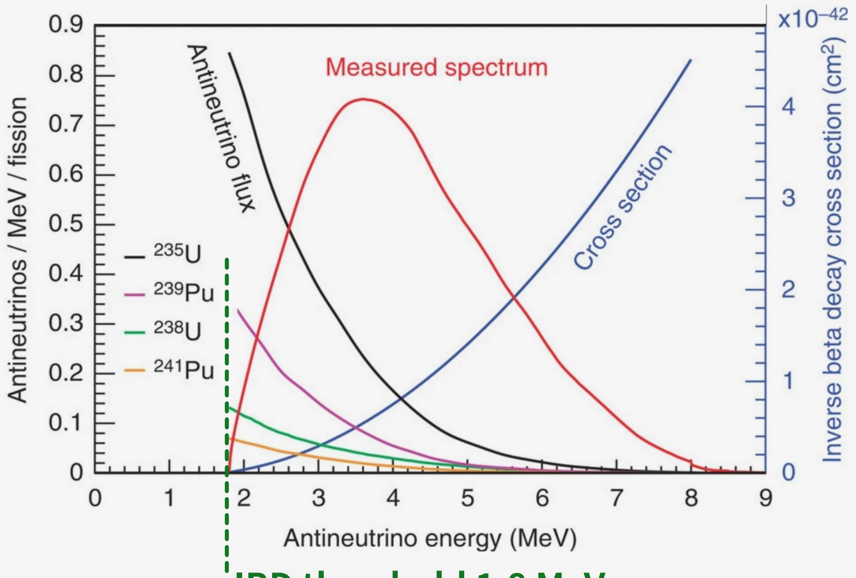
$n \rightarrow p + e^- + \overline{\nu}_e$

Detection of reactor antineutrinos

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



- Detection in LS via **Inverse Beta Decay (IBD)**
- Prompt: e^+e^- annihilation gammas + kinetic energy loss of e^+
- Delayed: n-capture on H (2.2 MeV) or other heavier nuclei

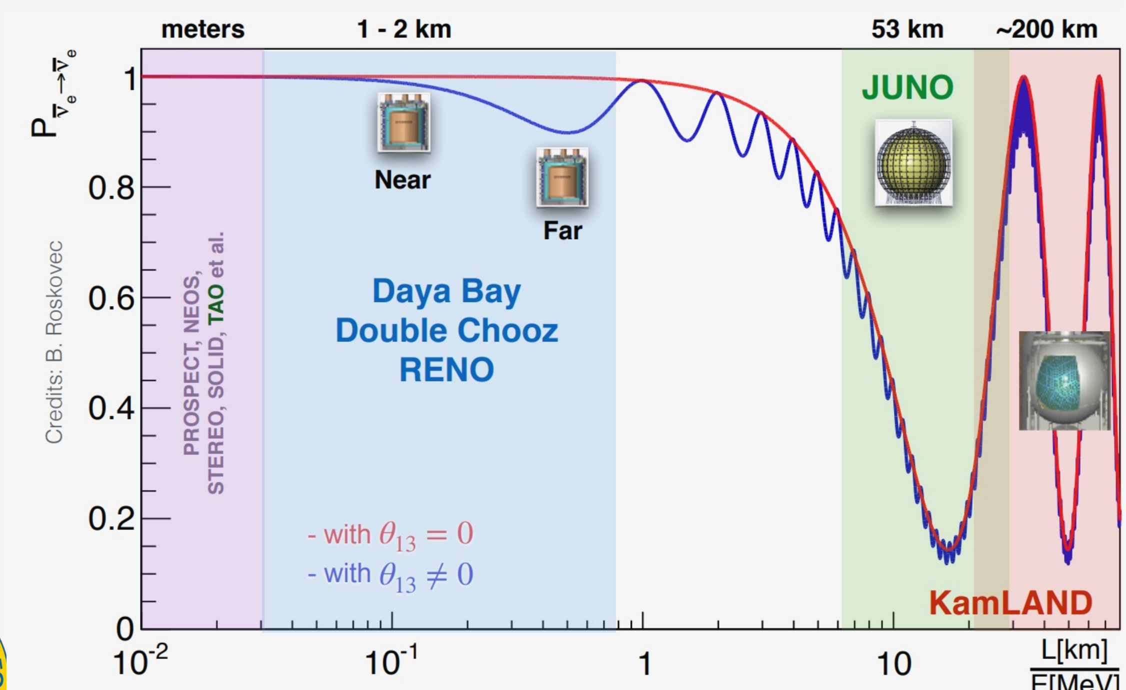


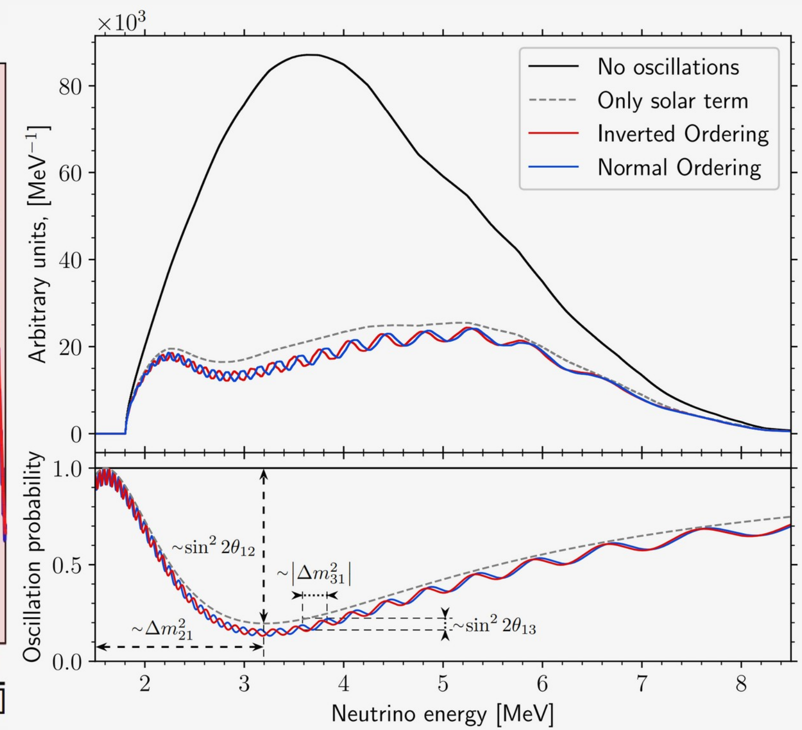
- Coincidence between prompt positron and delayed neutron signals allows for powerful background rejection
- Energy of positron preserves information about energy of incoming $\bar{\nu}_e$: $E_{vis}(e^+) \simeq E_\nu - 0.78$ MeV

Reactor antineutrinos oscillation probability at JUNO

$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)$$

- First experiment to observe both "atmospheric" and "solar" oscillations
- Access to $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, Δm^2_{21}, Δm^2_{31}, and Neutrino Mass Ordering (NMO)
- Independent of δ_{CP} and θ_{23}



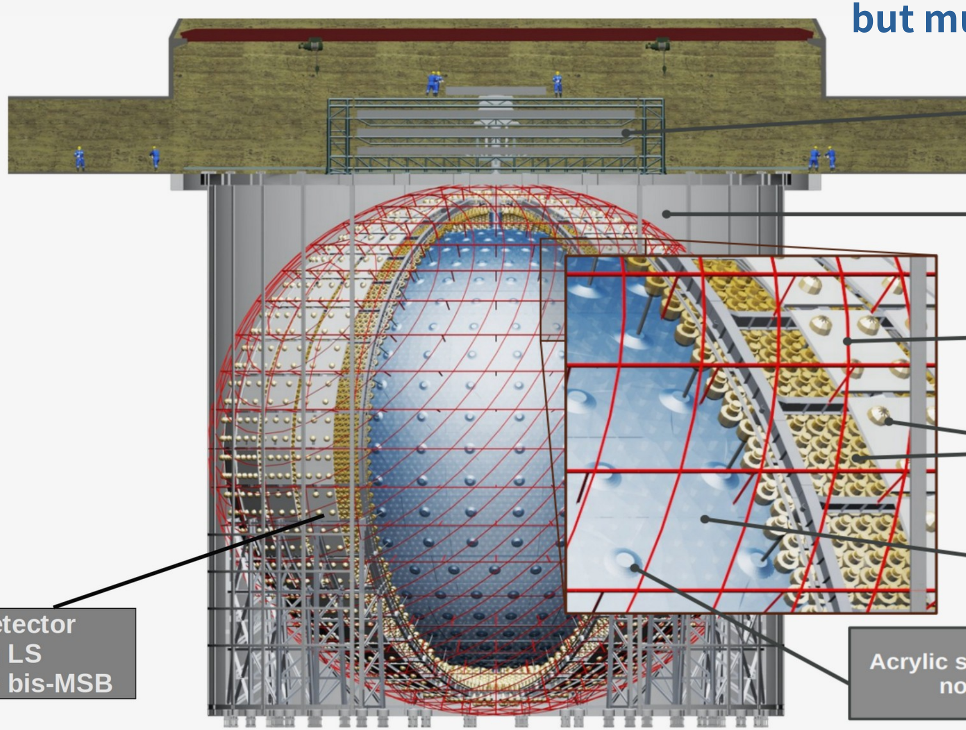


Detector requirements

- Optimal baseline (~53 km)
- High statistics
  - 20 kton mass
  - Powerful reactors
- Unprecedented energy resolution ($\lesssim$ 3% at 1 MeV) + control of energy response systematics ($\lesssim$ 1%)
  - Optimized LS, efficient PMTs, high photo-coverage
  - Comprehensive calibration
- Background reduction (~10% of IBDs)
  - 700 m underground (muon rate: 0.004 Hz/m^2)
  - LS purification, material screening
  - Top tracker for muons in addition to outer water pool
- Accurate knowledge of reactor spectrum (TAO satellite detector)

Detector design overview

Similar concept to previous LS experiments, but much larger and more precise!



Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	8 x 20 ton	~300 ton	~1 kton	20 kton
PMT coverage	~12%	~34%	~34%	~78%
Energy resolution	~8%	~5%	~6%	~3%
Light yield	~160 p.e./ MeV	~500 p.e./ MeV	~250 p.e./MeV	> 1665 p.e./ MeV

Pushing the energy resolution limits

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{stoch}}{E} + \sigma^2_{non-stoch}}$$

stochastic term: depends on photostatistics

non-stochastic term: residual issues (stability, uniformity, linearity)

Comprehensive calibration including a complementary small PMT system

Improvements on multiple fronts to solve the challenge!

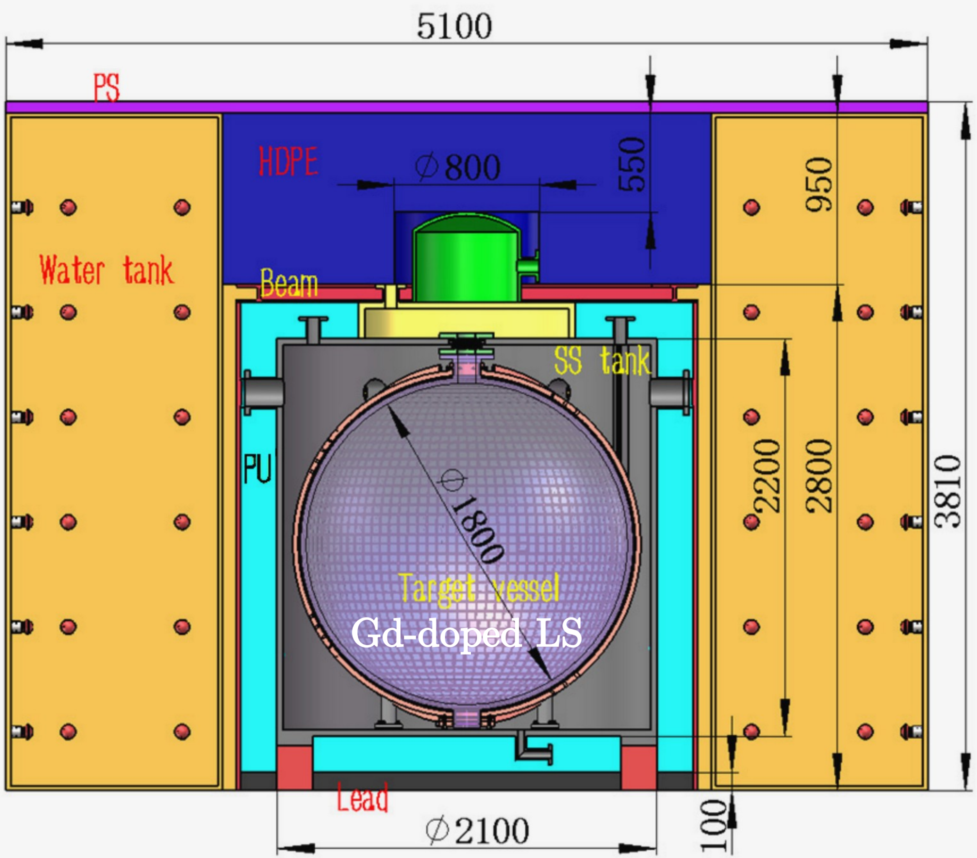
Property	KamLAND	JUNO	Relative Gain
Total light level	**250 p.e. / MeV**	**>1200 p.e. / MeV**	**5**
Photocathode coverage	34%	~78%	~2
Scintillation fluor	1.5 g/l PPO	2.5 g/l PPO	~1.5
Attenuation length / R	15/16 m	20/35 m	~0.8
PMT QE×CE	20%×60% ~ 12%	~30%	~2

Lots of PMTs (→ Photocathode coverage)

Optimized LS (→ Photocathode coverage, Scintillation fluor)

More efficient PMTs (→ Attenuation length / R)

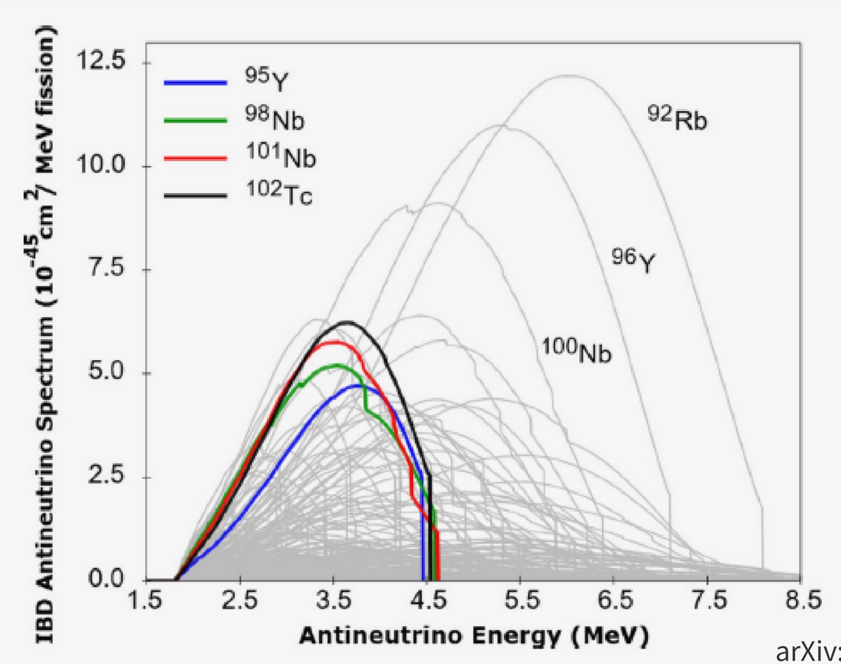
The Taishan Antineutrino Observatory (TAO)



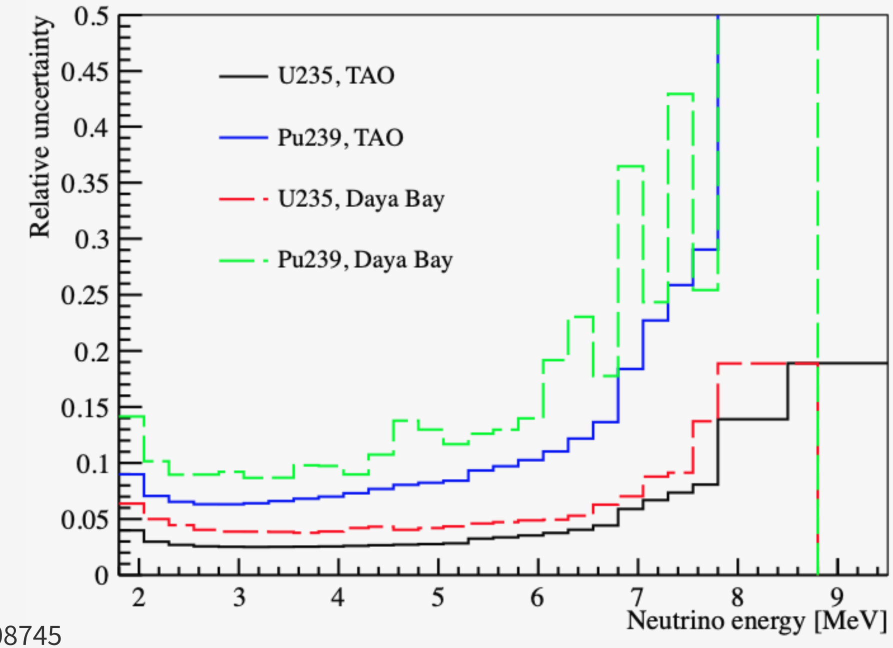
- Satellite detector: provide precise measurement of reactor antineutrino spectrum
- ~40 m from one of Taishan 4.6 GW_{th} reactor core
- 1 ton fiducial volume with Gd-LS
- 10 m^2 SiPM of 50% photon detection efficiency operated at -50 ° C
- ≥94% photo-coverage
- 30× JUNO event rate
- Start of operations: around the same time as JUNO

Physics with JUNO+TAO

- See fine structure due to Coulomb corrections
- Study reactor neutrino flux and spectrum shape with fuel composition evolution and decompose isotopic spectra
- **Main goal: serve as a benchmark for JUNO** (also other experiments and nuclear databases)
- Search for sterile neutrinos



arXiv:2005.08745

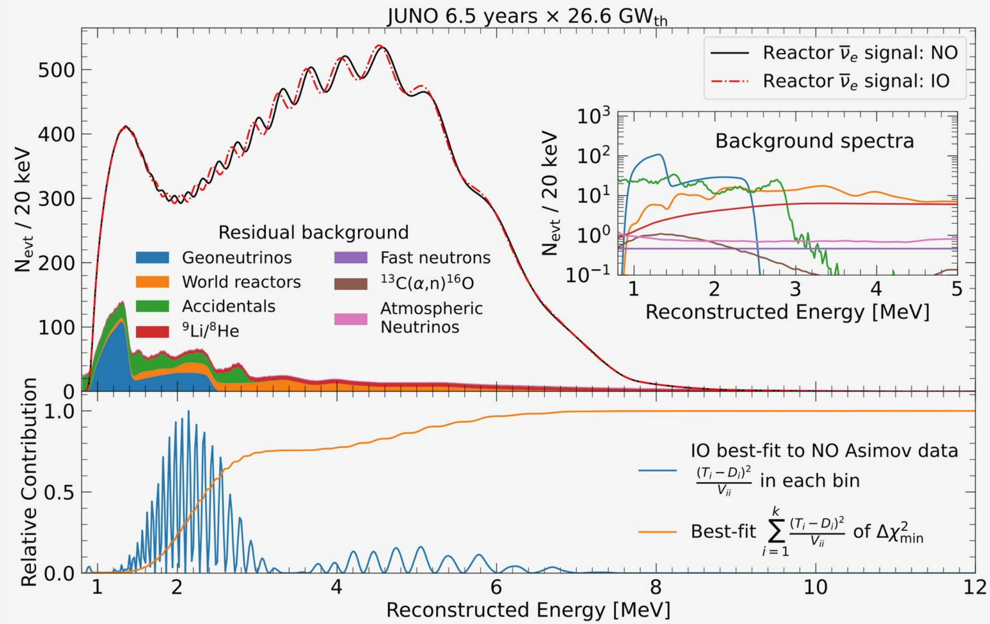


Neutrino mass ordering: recent update

JUNO sensitivity to the neutrino mass ordering updated since 2016

- Updated signal and background rates
- Improved predicted energy resolution
- Reactor shape uncertainty from TAO included

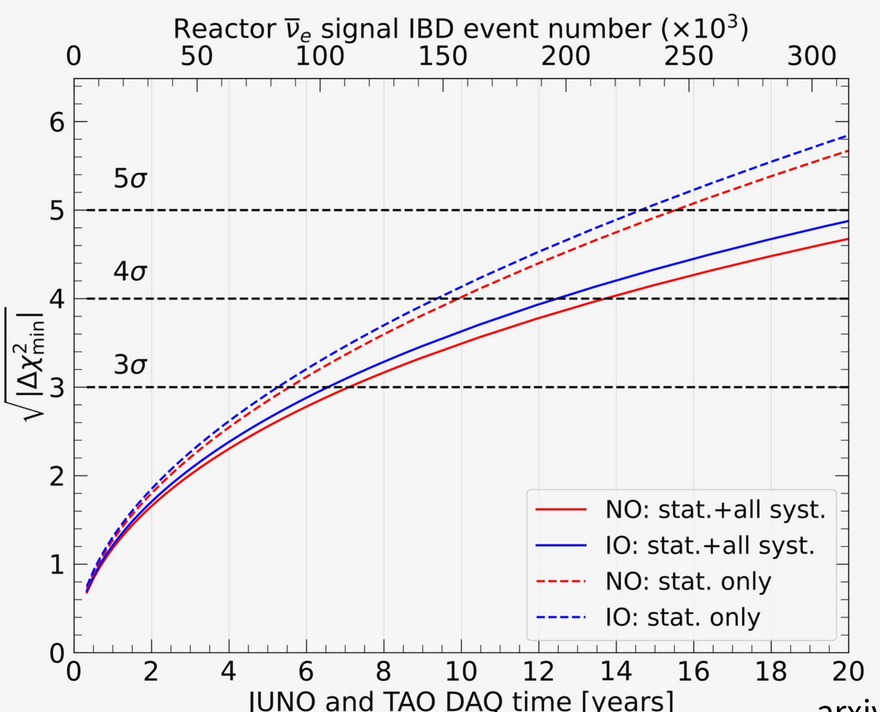
Property	2016	2024
Thermal power	36 GW_{th}	26.6 GW_{th} ↓
Signal rate	60 / day	47.1 / day ↓
Overburden	~700 m	~650 m ↓
Muon flux in LS	3 Hz	4 Hz ↓
Muon veto efficiency	83%	91.6% ↑
Backgrounds	3.75 / day	4.11 / day ↓
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV ↑
Shape uncertainty	Daya Bay	JUNO + TAO ↑

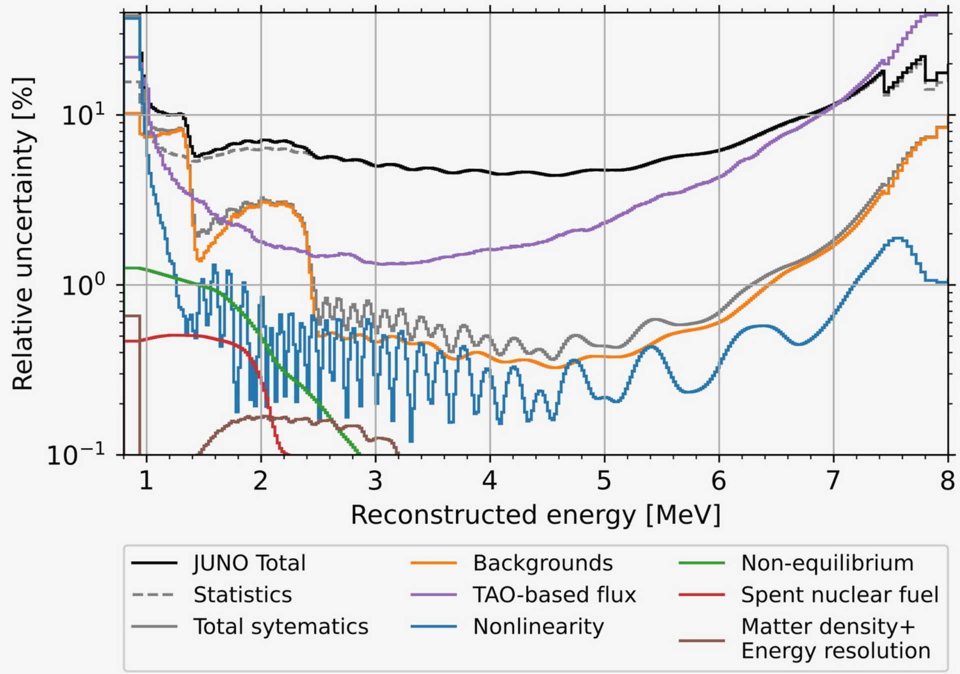


arxiv:2405.18008

Neutrino mass ordering: sensitivity results

- Fit the spectrum under the normal and inverted ordering hypotheses
  $\Delta\chi^2_{min} = |\chi^2_{min}\ (NO) - \chi^2_{min}\ (IO)|$
- 3σ (reactor vs only) with 6.5 yrs × 26.6 GW_{th} exposure (7.1 years of data taking)
- Independent of and complementary to other experiments. High potential to achieve 5σ in combination with other experiments!

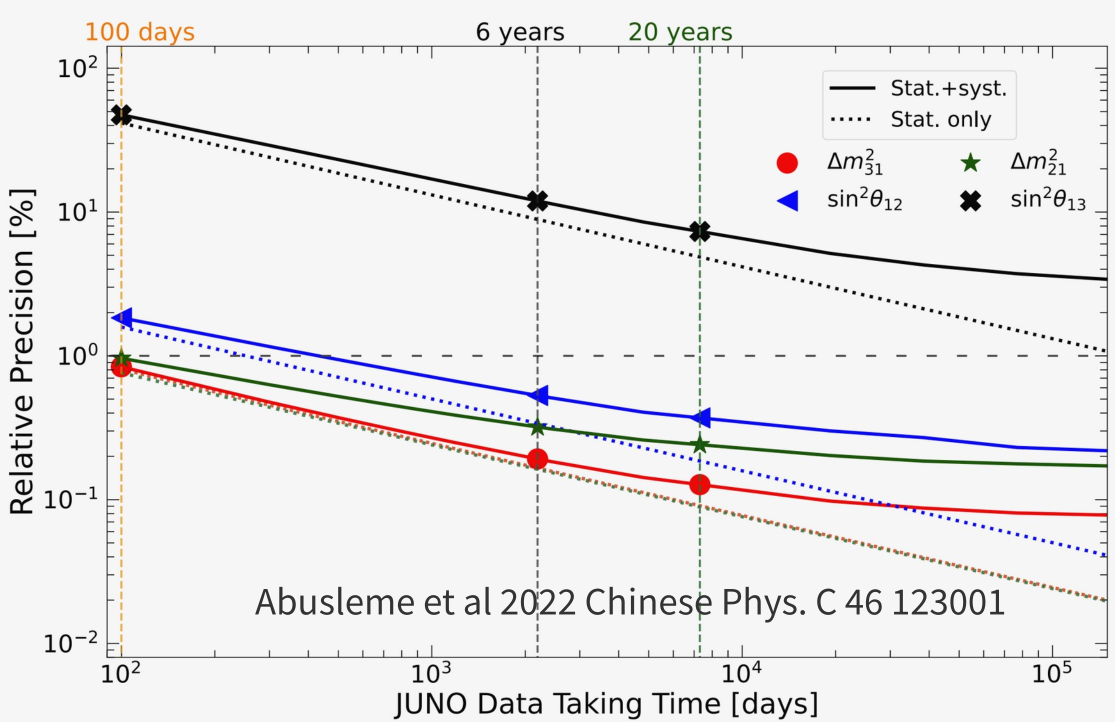




arxiv:2405.18008

Precision measurement of oscillation parameters

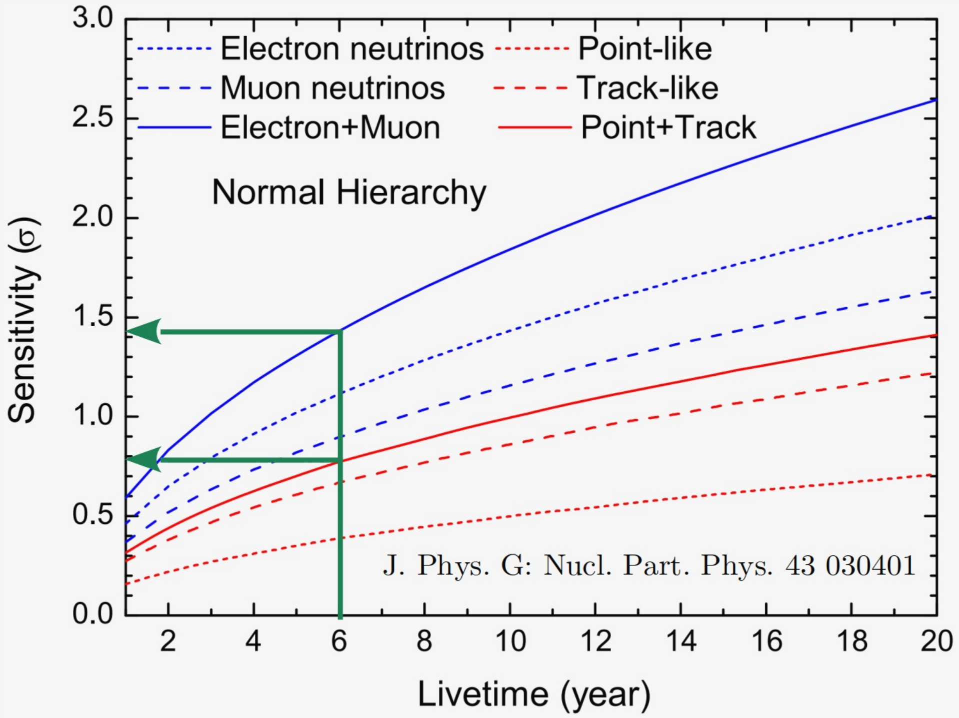
- Potential to measure Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ with roughly one order of magnitude better precision than current values!
- World-leading measurements even with 100 days of data!



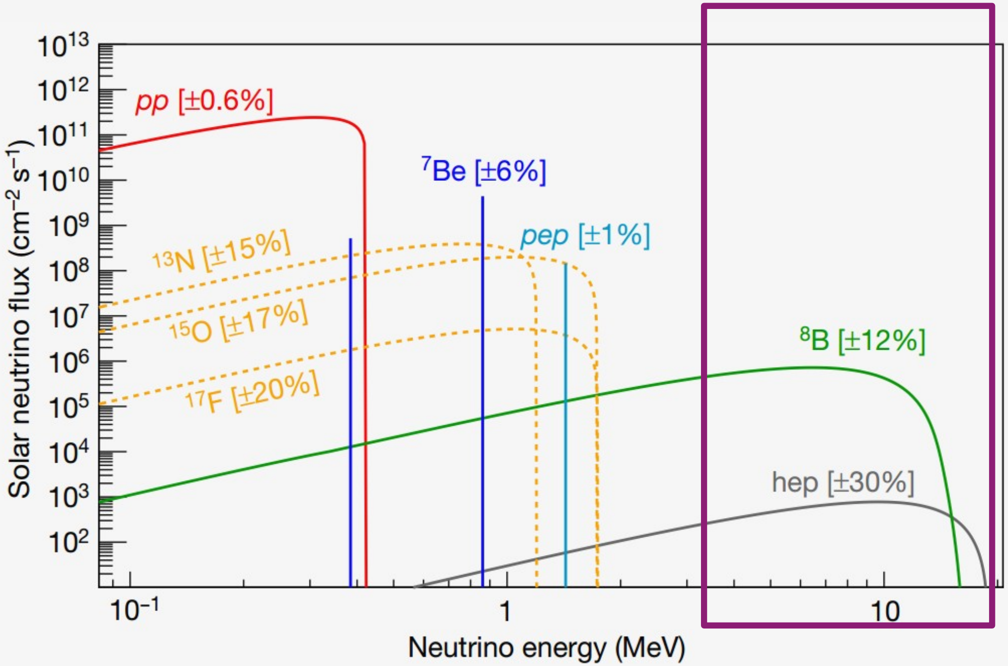
	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2024	2.4%	1.2%	4.0%	3.2%
JUNO 100 days	1.0%	0.8%	1.9%	47.9%
JUNO 6 years	0.3%	0.2%	0.5%	12.1%

Atmospheric neutrino oscillations

- Complementary to reactor neutrino NMO analysis using matter effects from atmospheric neutrinos crossing the Earth (~0.7-1.4σ with ~6 yrs exposure)
- Re-evaluation of sensitivity in progress: improved separation of e/μ and $\bar{\nu}/\nu$ and estimation of neutrino energy and track direction

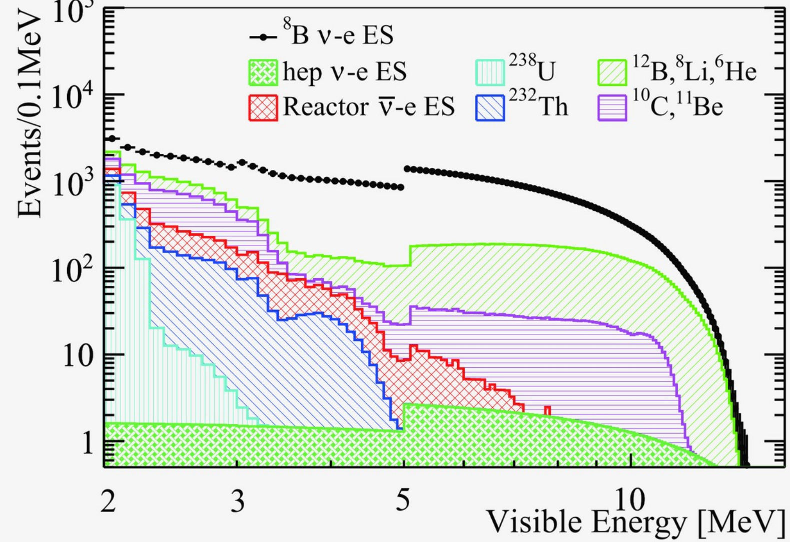


Solar neutrino oscillations

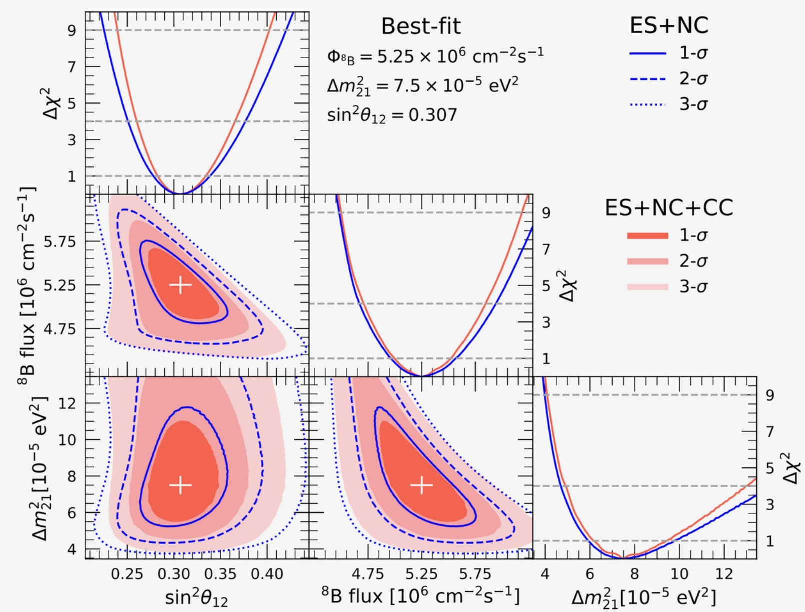


- Simultaneous measurement of ^{8}B solar neutrinos, Δm^2_{21}, and $\sin^2\theta_{12}$
- ^{8}B flux can be measured with ~5% precision using ES+NC+CC channels in 10 years. $\sin^2\theta_{12}$: 8%, Δm^2_{21} : 20%

Chinese Physics C Vol. 45, No. 2 (2021) 023004



ApJ 965 (2024) 122



Summary & Conclusions

- JUNO is a multipurpose neutrino observatory with a main goal of measuring neutrino oscillations:
  - Determination of Neutrino Mass Ordering (NMO): ~3σ after 7.1 years of data taking with reactor antineutrinos only. Sensitivity boost expected from combining atmospheric neutrinos
  - Precision measurement of oscillation parameters Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ (can exceed current precision levels in ~100 days)
  - Solar oscillation parameters can also be independently measured using ^8B solar neutrinos
- JUNO will have an unprecedented energy resolution energy resolution (2.95% @ 1 MeV) and low energy scale uncertainty (1%) to achieve its NMO goal
- Progress is well underway, and expect to begin filling LS early next year
- Anticipate some exciting results (and maybe some surprises?)

Other JUNO related talks and poster

JUNO

20 Sep 2024, 16:15
30m
APS- Building 402 (Argonne National Laboratory)

Plenary session

Speaker

Davide Basilico (Milano)

Prospects for Neutrinos from Natural Sources in JUNO

20 Sep 2024, 13:45
20m
A1100 (#401)

Talk: in-person | WG1: Neutrino Oscil... | Parallel: WG1

Speaker

Iwan Morton-Blake (Tsung-Dao Lee Insti...

Detector calibration in the JUNO experiment

19 Sep 2024, 13:45
20m
E1200 (#402)

Talk: in-person | WG6: Detectors | Parallel: WG6

Speaker

Akira Takenaka (Tsung-Dao Lee Insti...

Design and status of the JUNO detector

19 Sep 2024, 16:55
20m
E1100 (#402)

Talk: in-person | WG6: Detectors | Parallel: WG6

Speaker

Marco Beretta (University of Milan - ...

Reconstruction of Cosmic Muon with Machine Learning in JUNO

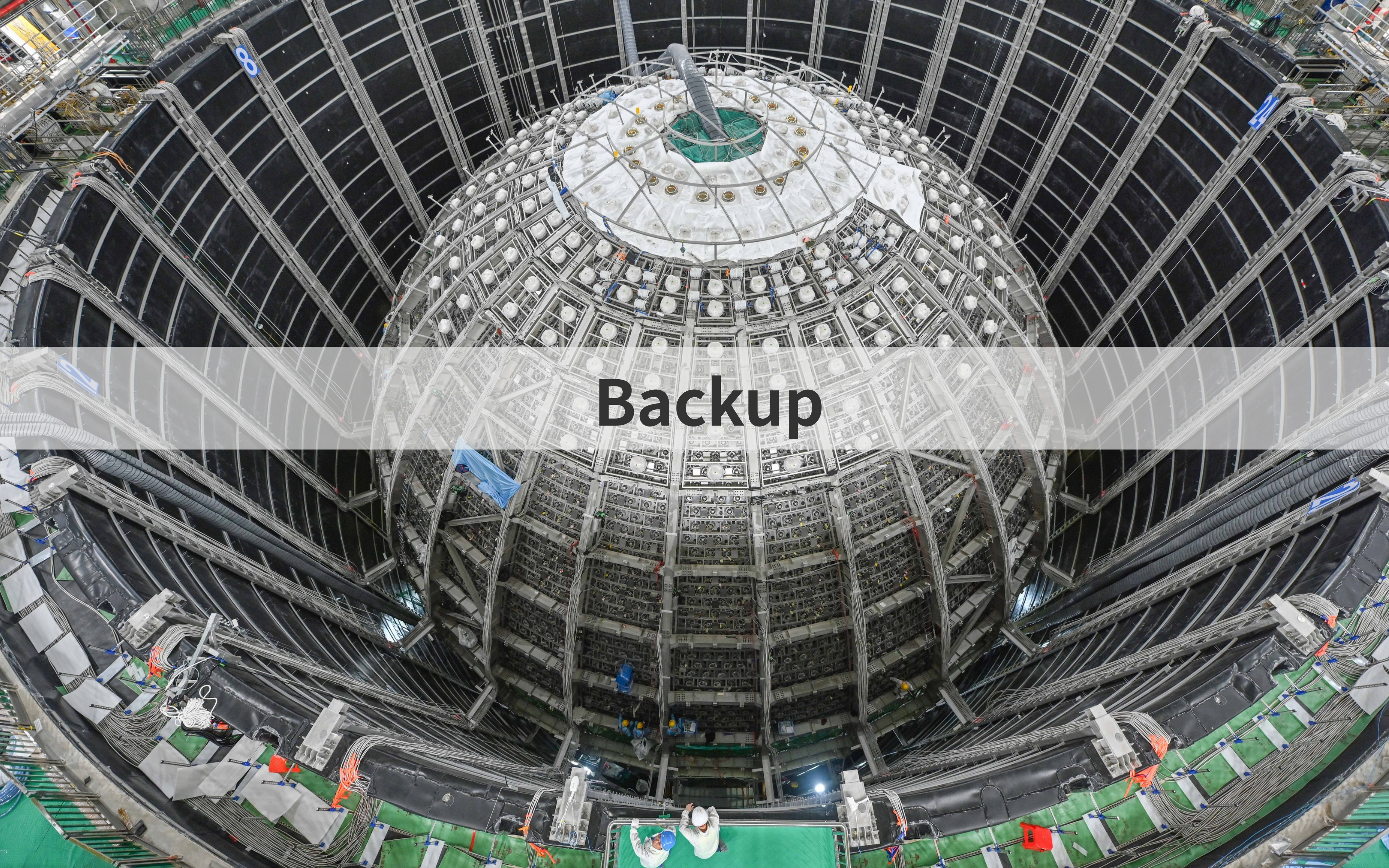
16 Sep 2024, 16:05
1h
APS- Building 402 (Argonne National Laboratory)

Poster | WG4: Muon Physics | Poster session

Speaker

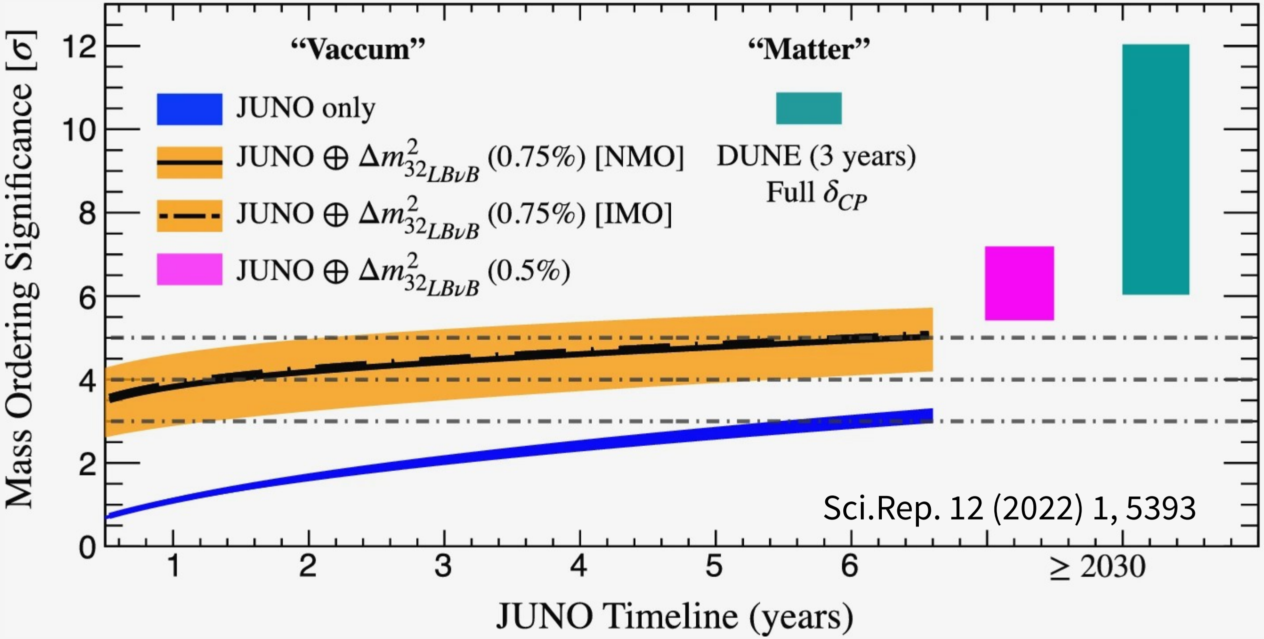
Zekun Yang (Shandong University)


Thank you!

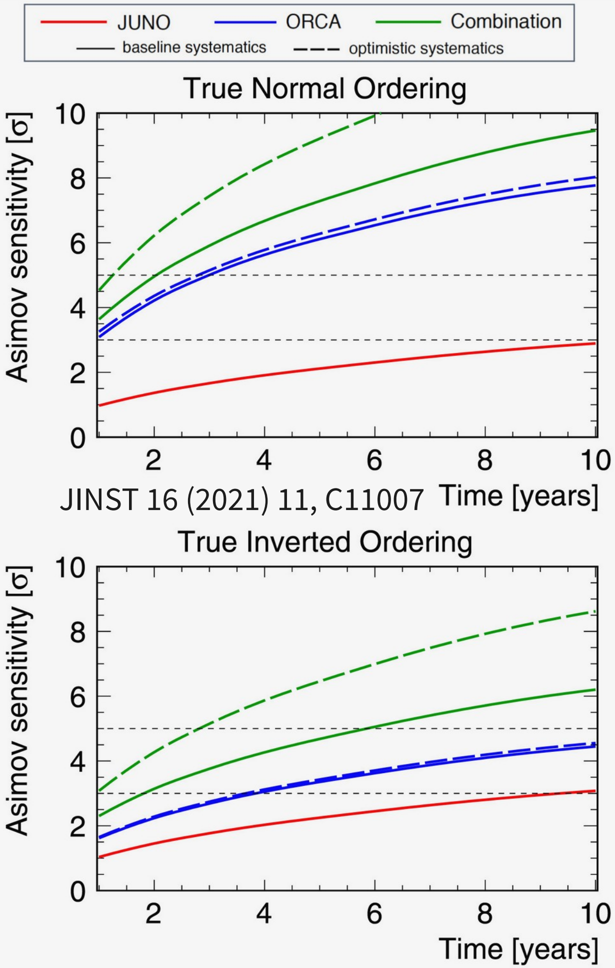


Backup

NMO sensitivity with other experiments



Sci.Rep. 12 (2022) 1, 5393



JINST 16 (2021) 11, C11007

Dependence on energy resolution