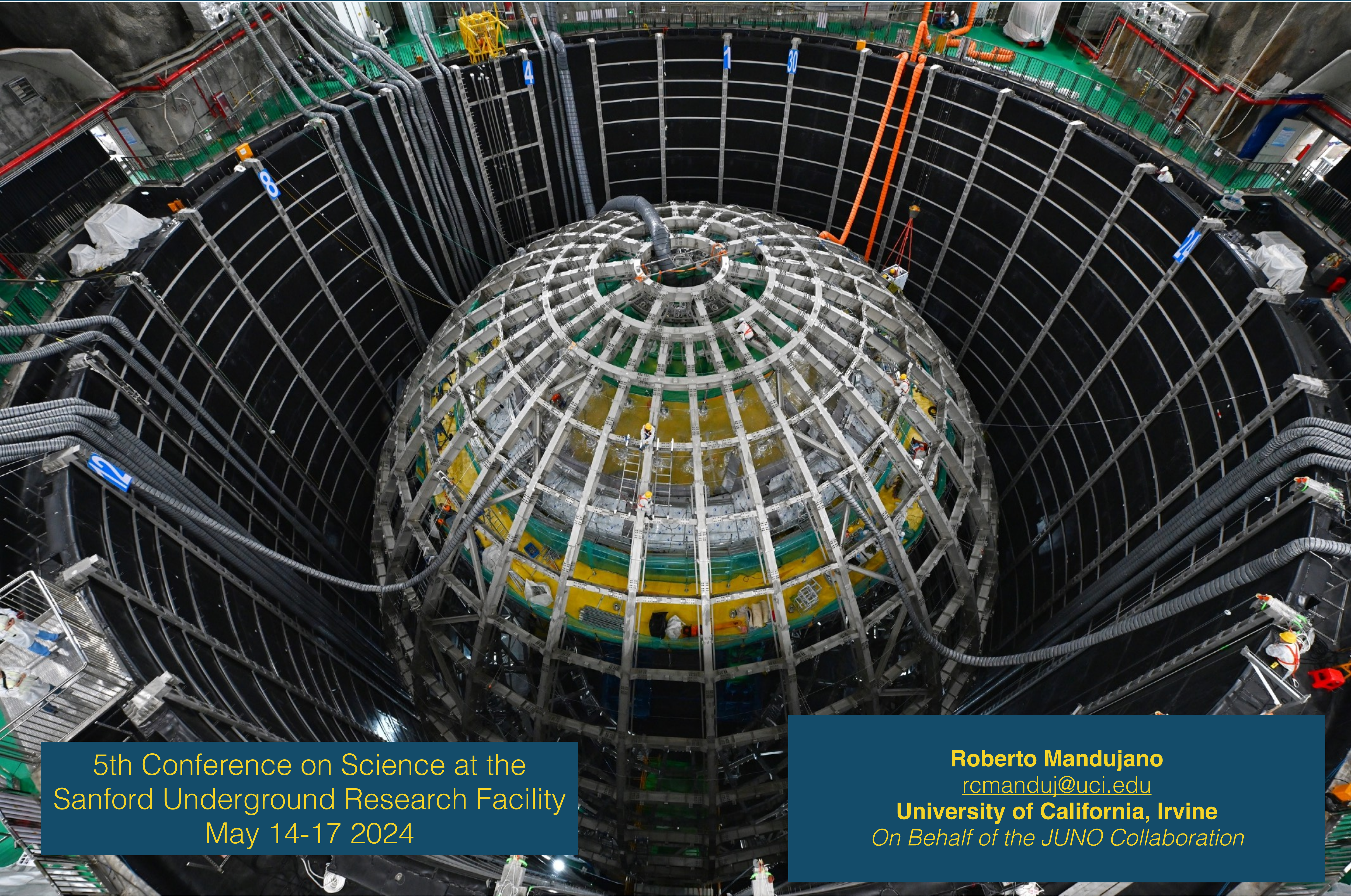
Reactor Antineutrino Oscillations and JUNO



5th Conference on Science at the
Sanford Underground Research Facility
May 14-17 2024

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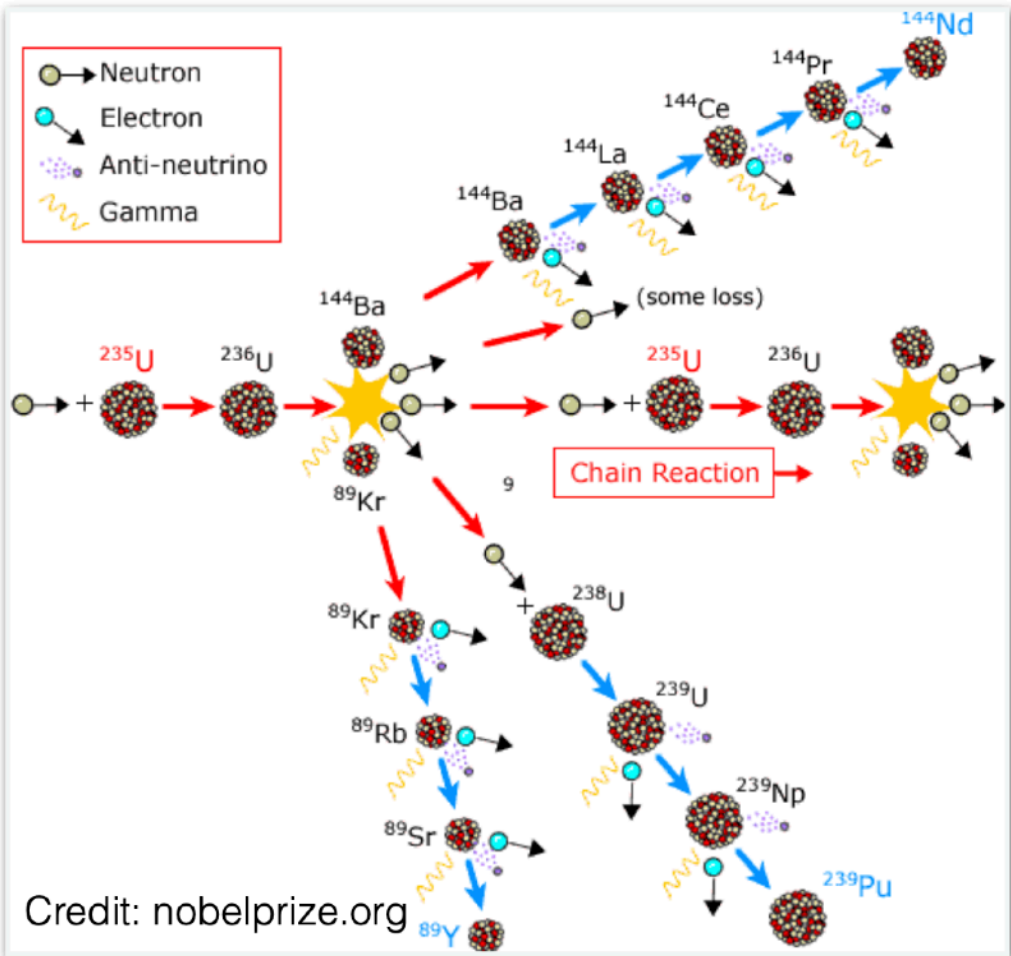
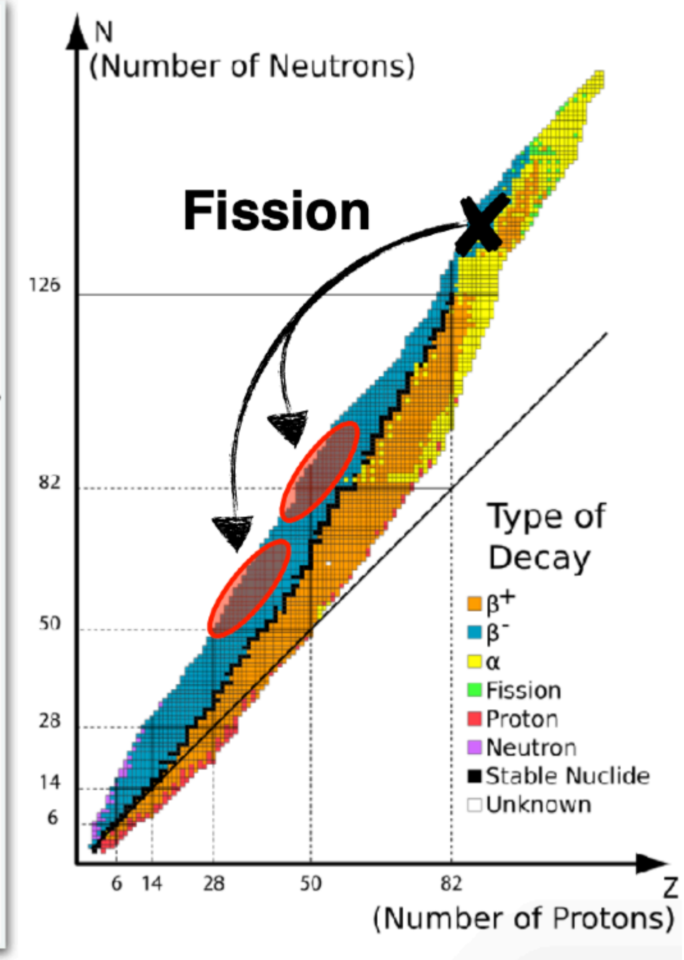
On Behalf of the JUNO Collaboration

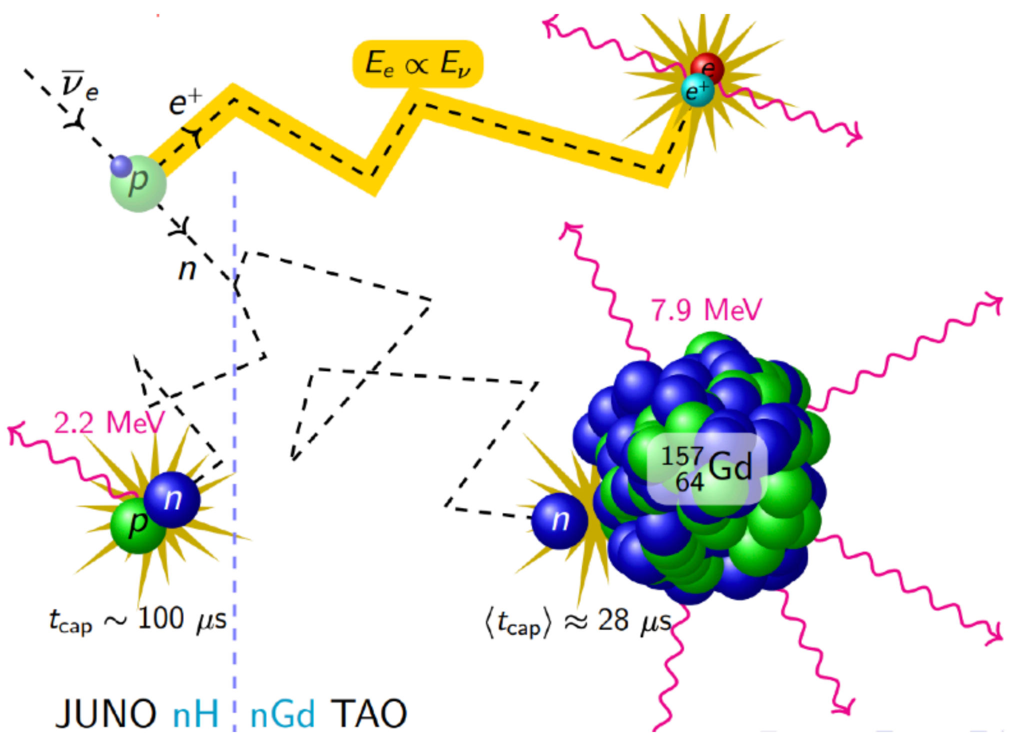
Reactors and Neutrinos

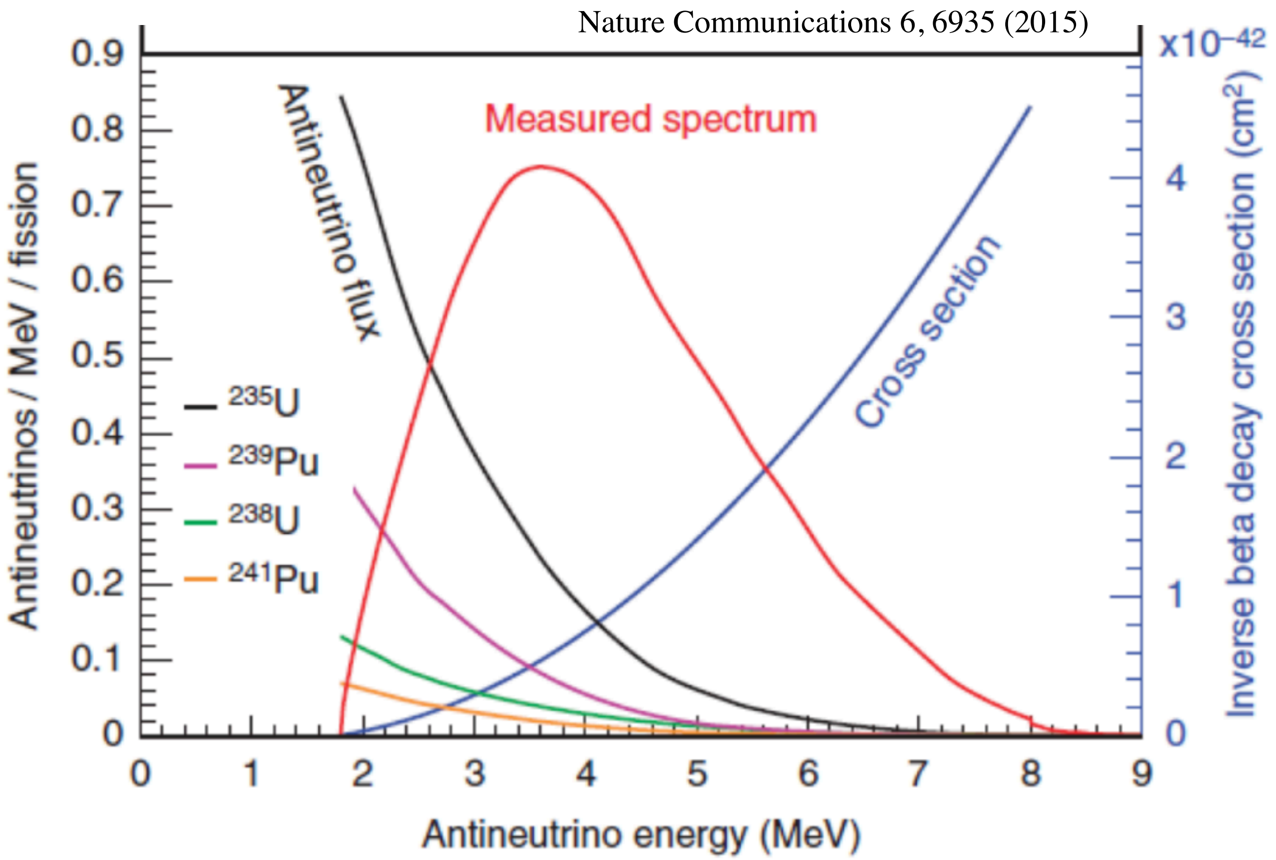




- **Intense, pure, and cost-effective source** of electron antineutrinos: $\sim 10^{20}\,\bar{\nu}_e/s$ per GW_{th}
- Produced in beta decays: $n \rightarrow p + e^- + \bar{\nu}_e$
- Used for neutrino discovery by Reines and Cowan
- Today's talk will focus on experiments with commercial Low-Enriched Uranium reactors
  - Fissions come from $^{235}\mathrm{U},^{239}\mathrm{Pu},^{241}\mathrm{Pu},^{238}\mathrm{U}$

Reactor $\bar{\nu}_e$ Detection



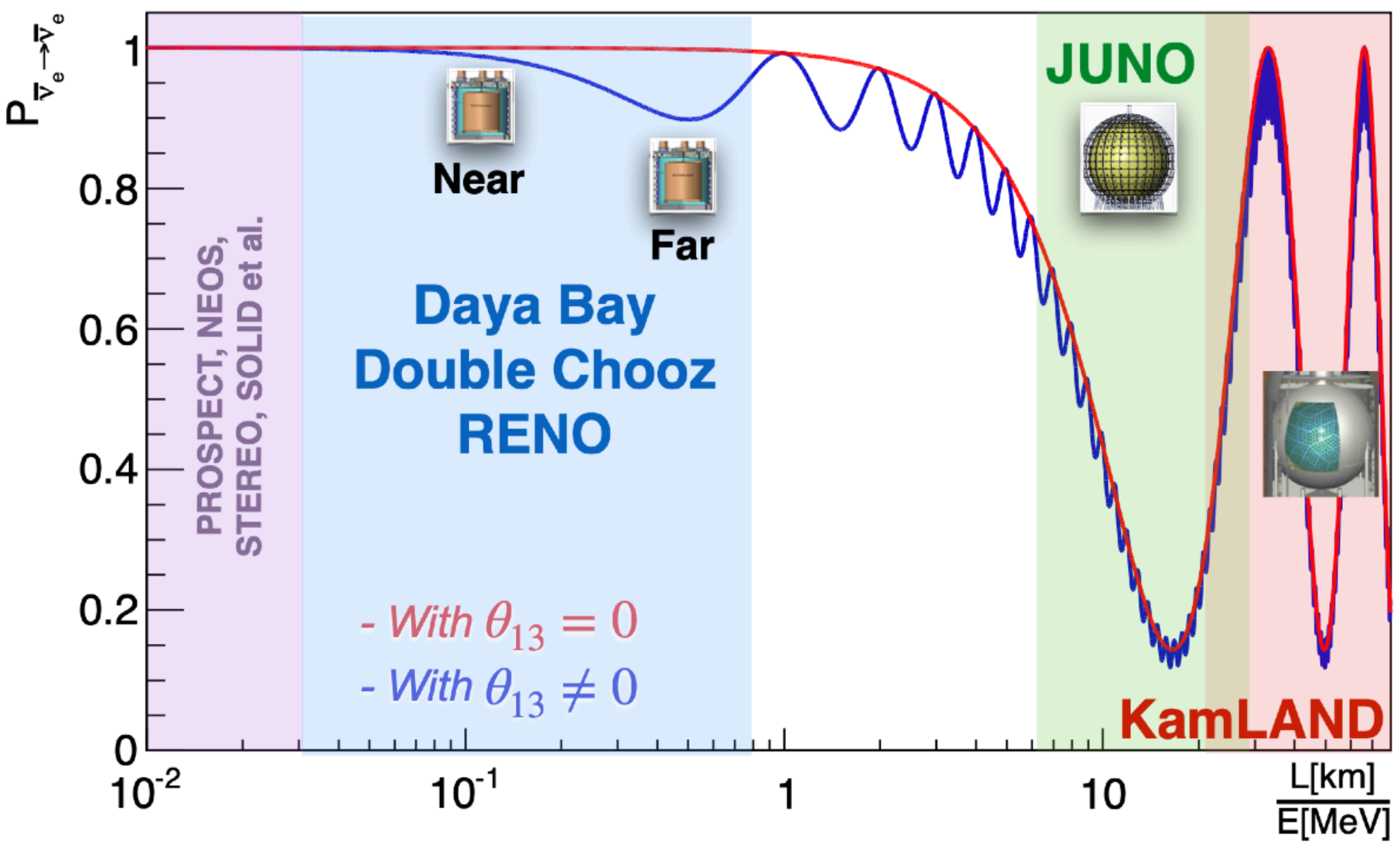


- Reactor $\bar{\nu}_e$ detected through Inverse Beta Decay (IBD) reaction
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Positron (prompt) signal followed by neutron capture (delayed) typically on Gd (nGd), H (nH), or C (nC)
  - Temporal and spatial coincidence of prompt and delayed signals is a powerful handle to extract reactor neutrino signal

Reactor $\bar{\nu}_e$ Oscillations

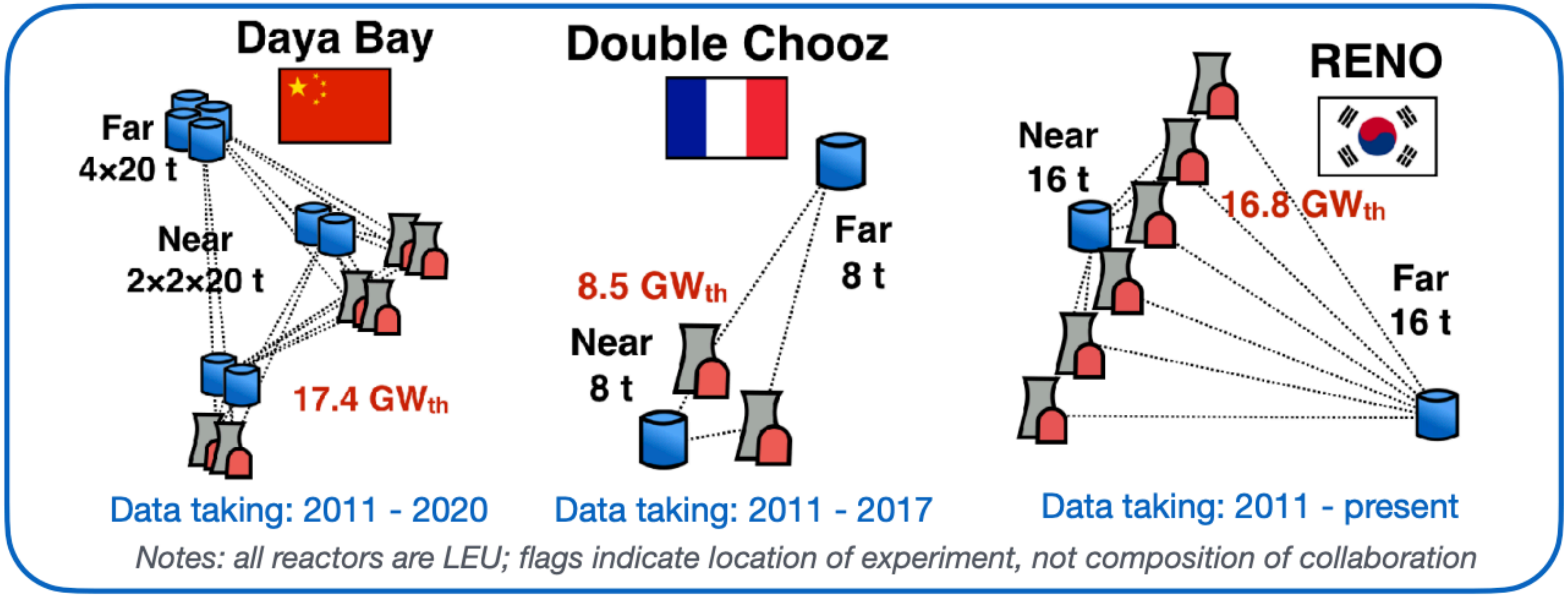
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \sin^2 2\theta_{13} \left(\cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right)$$

- Many avenues to explore oscillations with reactor neutrinos!
- Sensitive to $\theta_{13}, \theta_{12}, |\Delta m^2_{21}|, |\Delta m^2_{31}|$ and the mass ordering
- Independent from θ_{23}, δ_{CP}



Note: Reactor neutrino experiments often report an ordering-independent effective mass splitting:
$|\Delta m^2_{32}| = |\Delta m^2_{ee}| - \alpha \cos^2\theta_{12}\, \Delta m^2_{21}$, $\alpha = +1, -1$ for NO, IO

Measuring θ_{13}



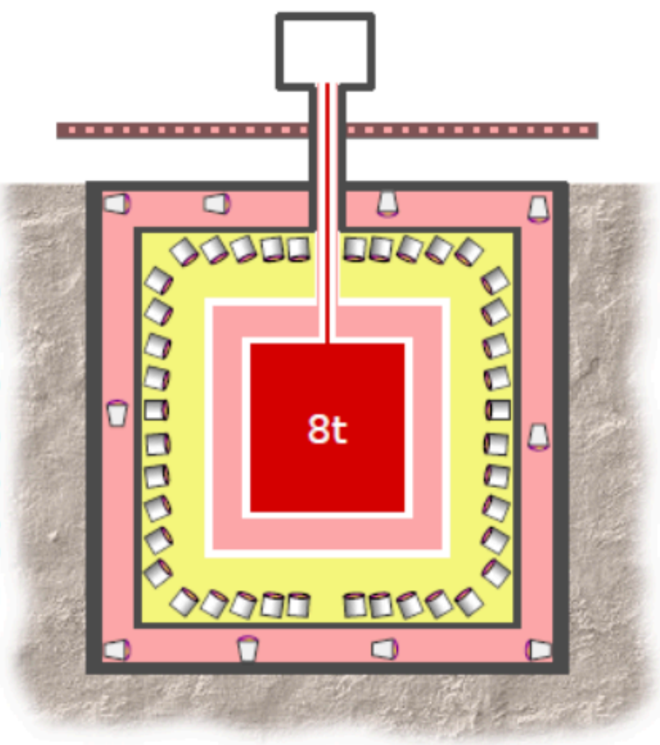
- O(10) ton liquid scintillator (LS) detectors at short (km) baselines
- Up to 8% disappearance effect
- Systematics control is key: near/far comparison cancels uncertainties in flux and correlated detection efficiencies

Measuring θ_{13}

- Multi-zone detectors lined with photomultiplier tubes (PMTs)
- Instrumented outer shields double as muon veto
- Mineral oil as additional shielding
- Middle LS volume serves as γ catcher
- Innermost volume comprised of Gd-doped LS
  - Gd improves IBD signal

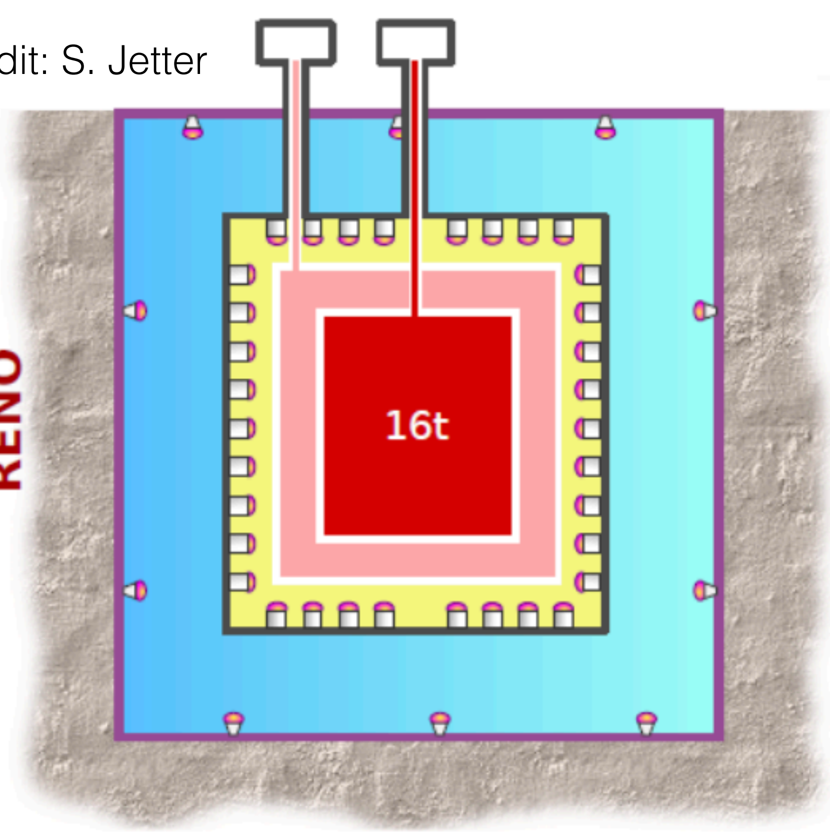
water, mineral oil, LS, GdLS

Double Chooz

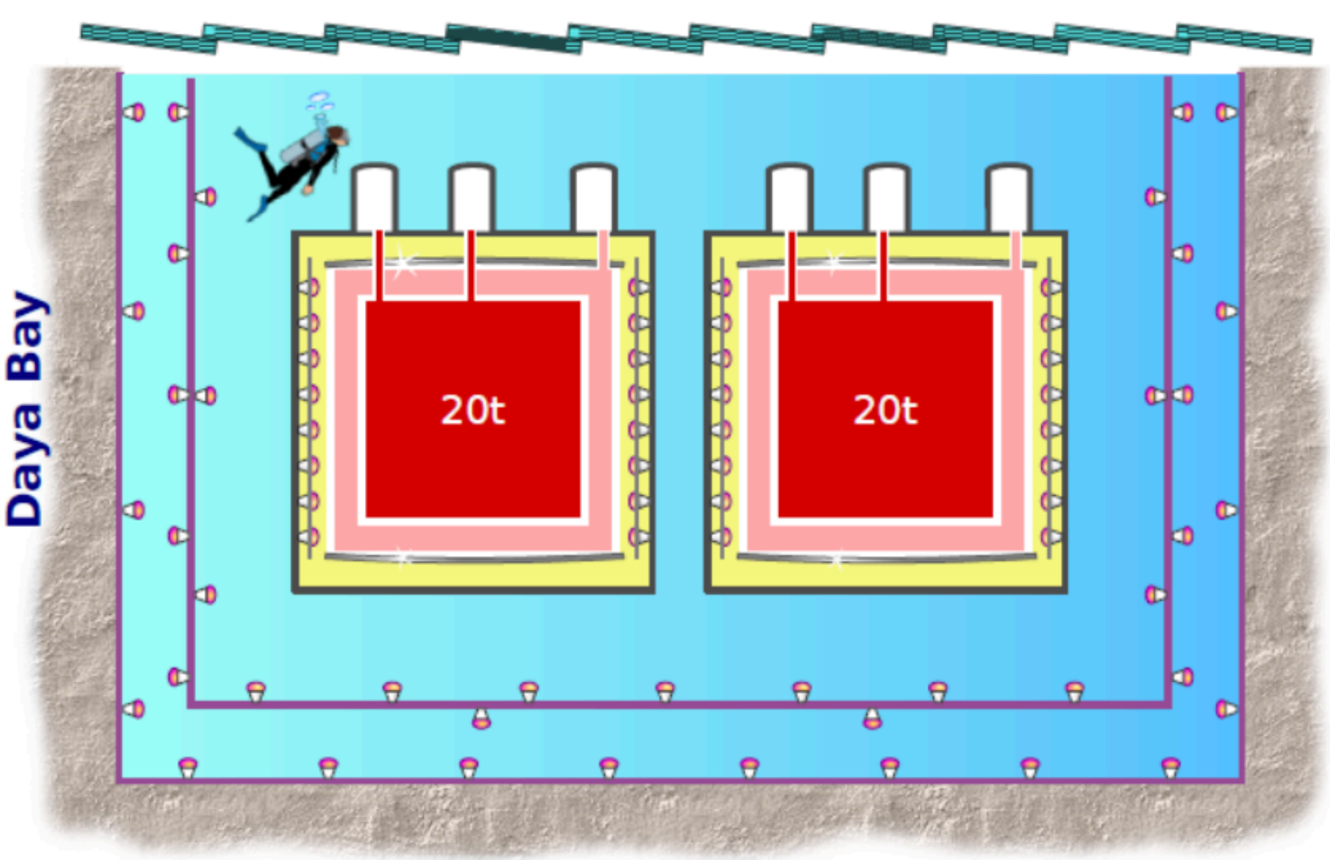


Credit: S. Jetter

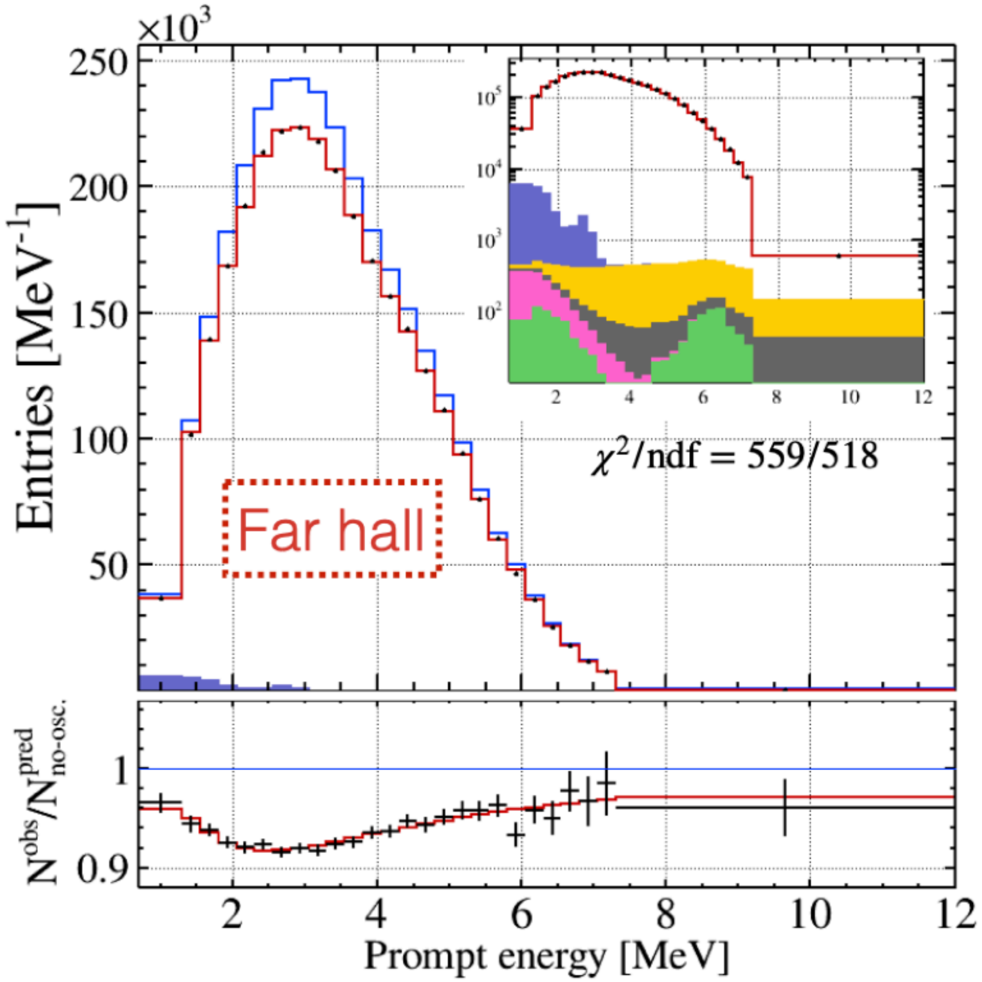
RENO



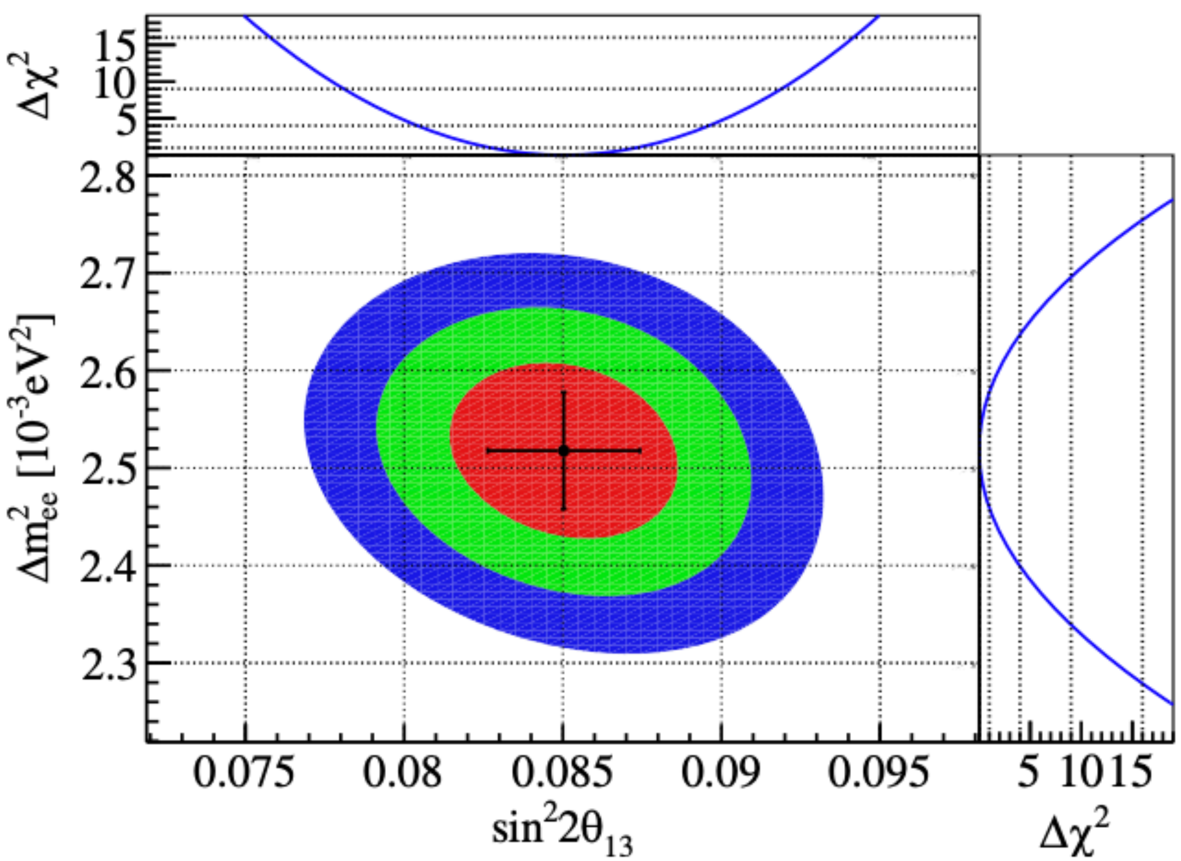
Daya Bay



Daya Bay



Phys. Rev. Lett. **130**, 161802 (2023)



- Latest results using neutron capture on Gd (nGd) with 3158 days of data
- Measure $\sin^2(2\theta_{13})$, Δm^2_{32} from spectral distortion and relative rates between detectors

$$\sin^2(2\theta_{13}) = 0.0851 \pm 0.0024$$

$$\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$

$$\Delta m^2_{32} = -\,(2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

RENO

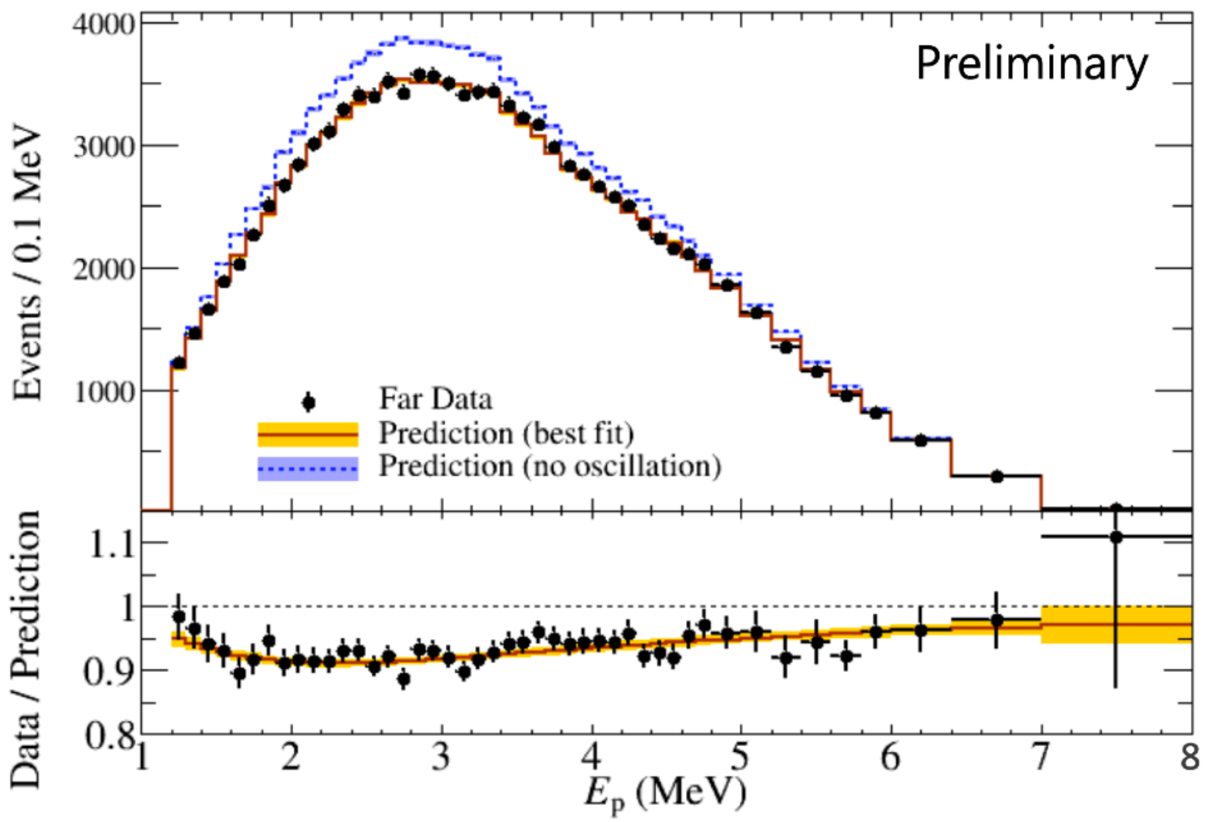
- Latest nGd results using 2900 day data set shown at NEUTRINO 2022
- Large reduction in statistical and systematic uncertainties from previous result

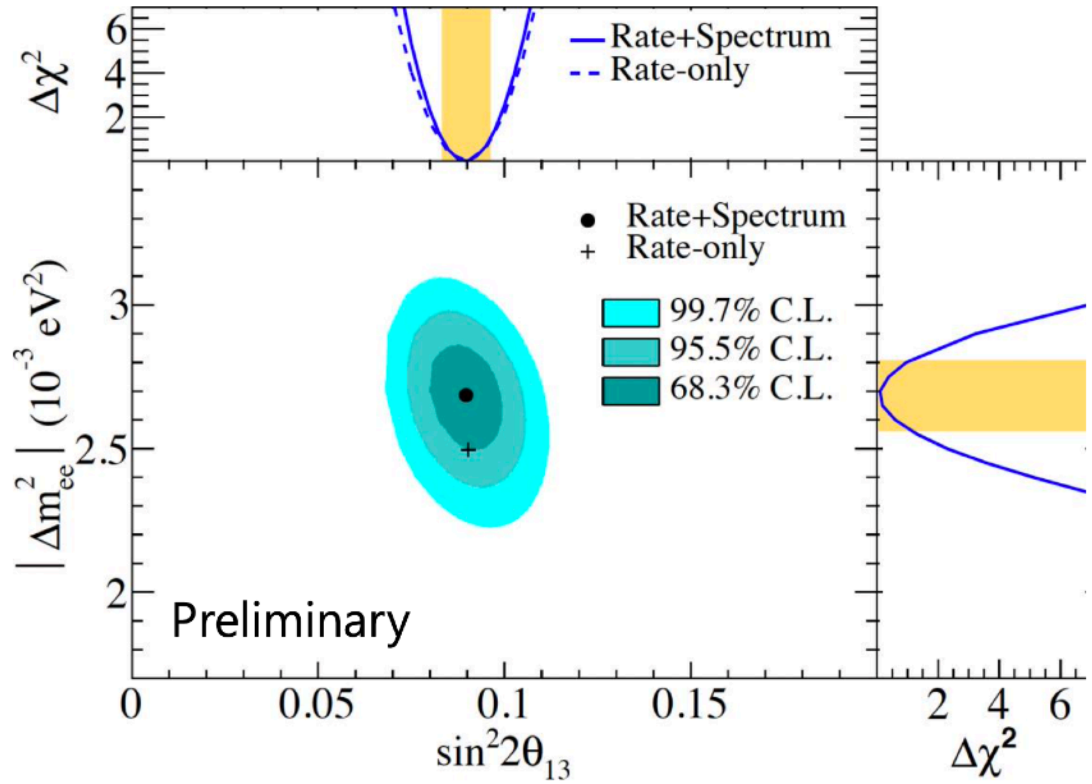
$$\sin^2(2\theta_{13}) = 0.0892 \pm 0.0089$$

$$|\Delta m^2_{32}| = (2.68 \pm 0.14) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$

$$|\Delta m^2_{32}| = (2.79 \pm 0.14) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

NEUTRINO 2022



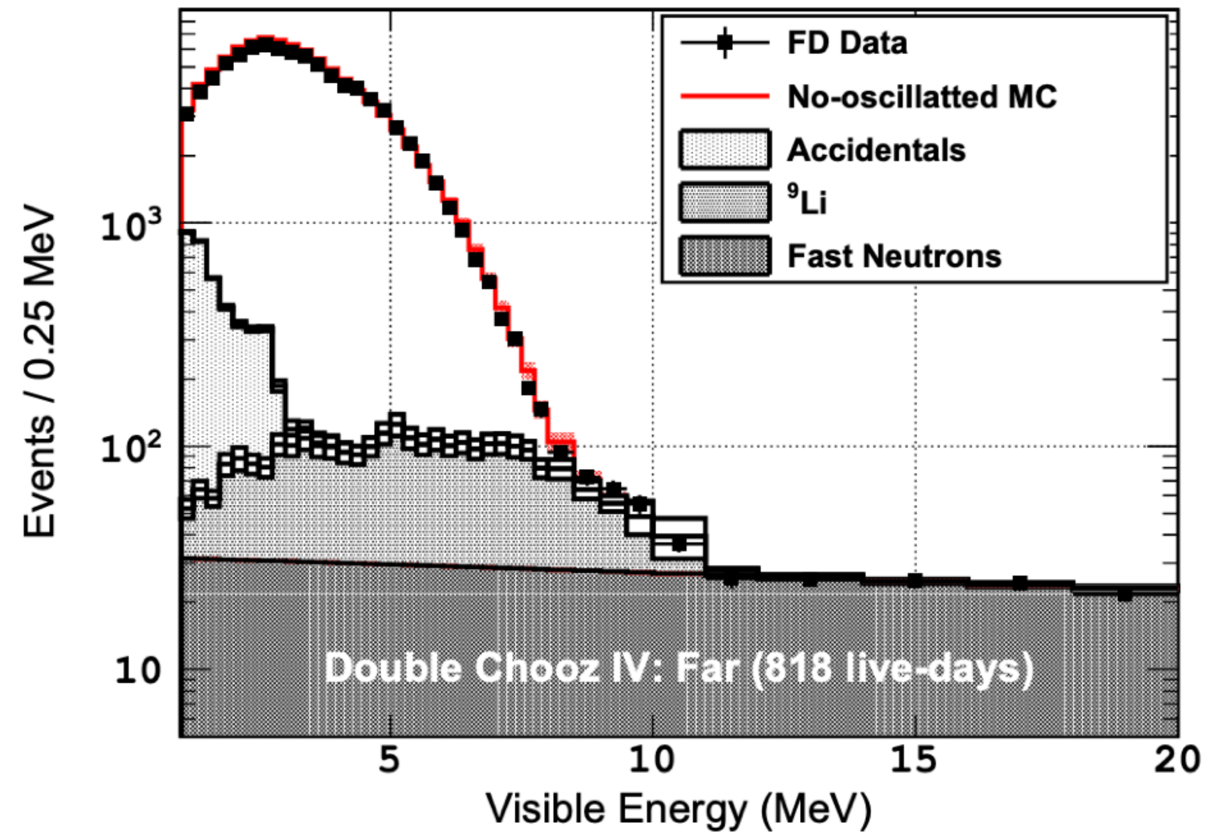


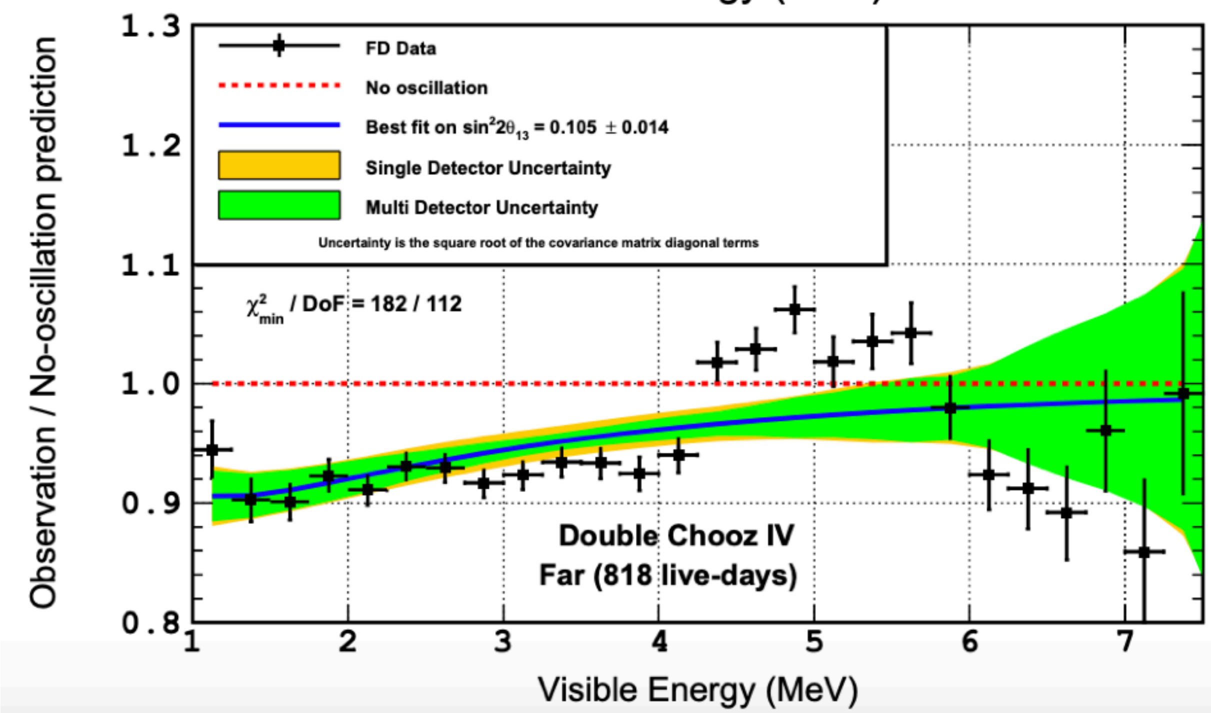
Double Chooz

Nature Phys. 16 (2020) 5, 558-564

- 818 live day data-set using total neutron capture
  - nGd +nH+nC
  - Control of detection systematics and increased volume (γ catcher)
- Slightly higher $\sin^2(2\theta_{13})$ w.r.t similar experiments
  - $< 2\sigma$ difference

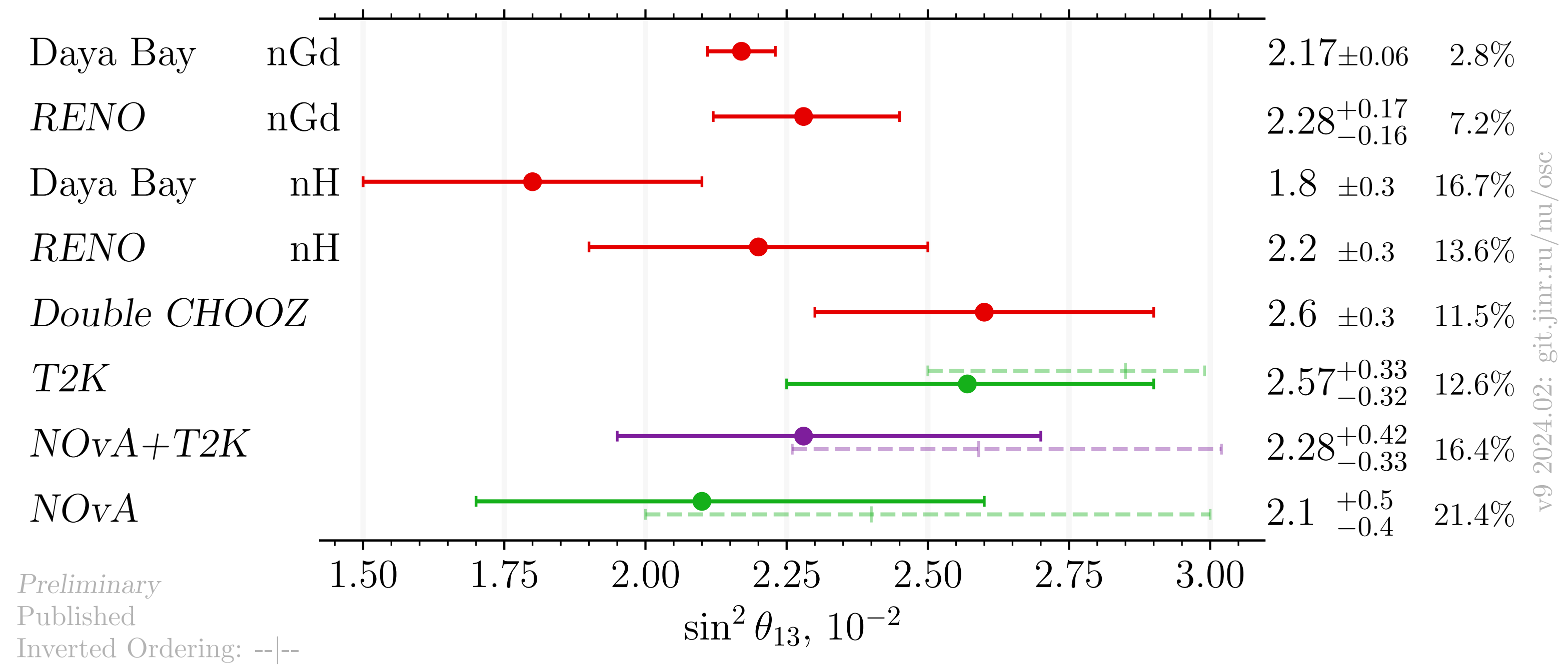
$$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$$

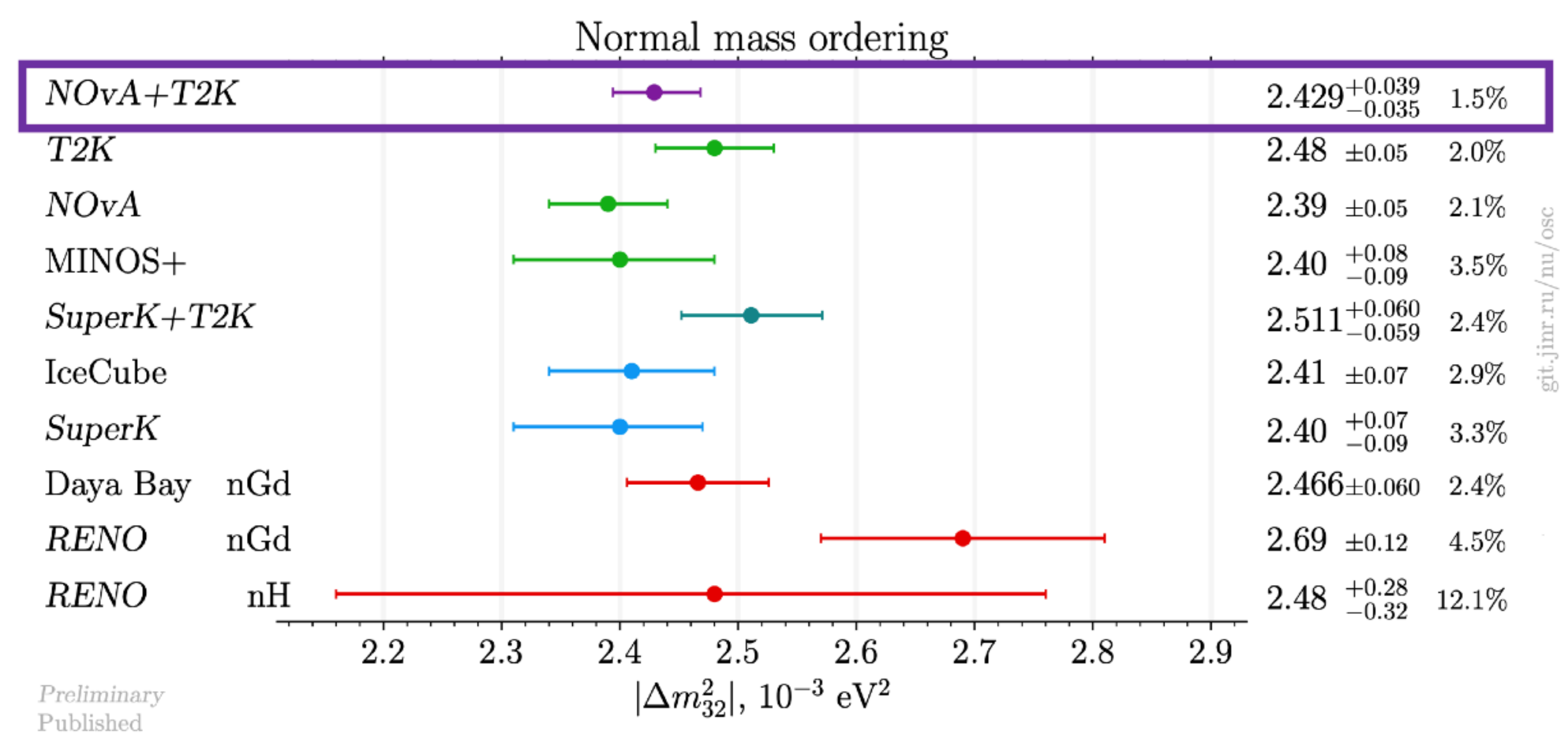




Present Picture

- θ_{13} measurement with reactor $\bar{\nu}_e$ will remain the most precise for years to come
    - Best known angle in PMNS matrix! (for now…)
- Good sensitivity to Δm^2_{32}, in agreement with accelerator experiments

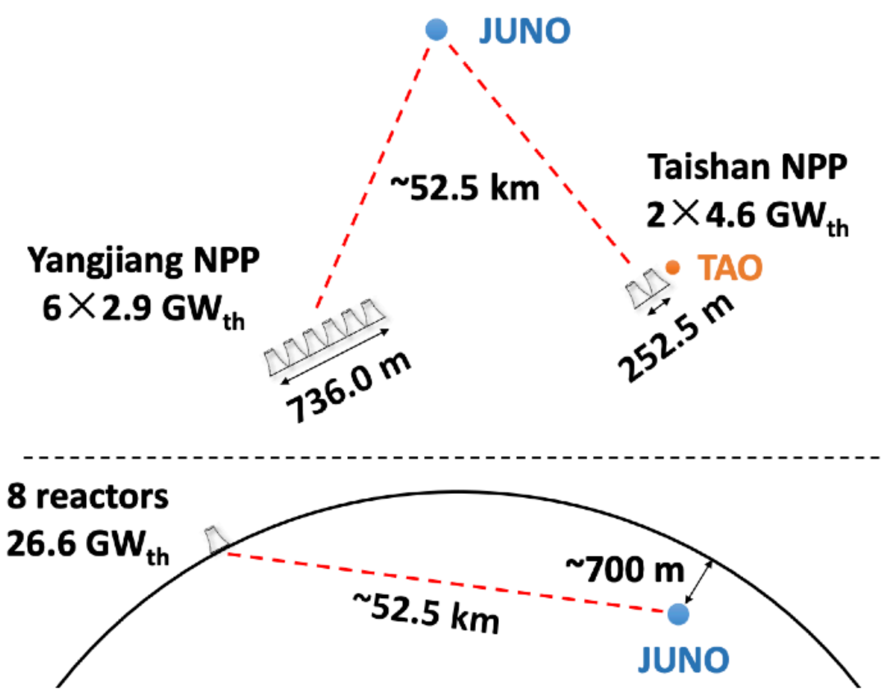


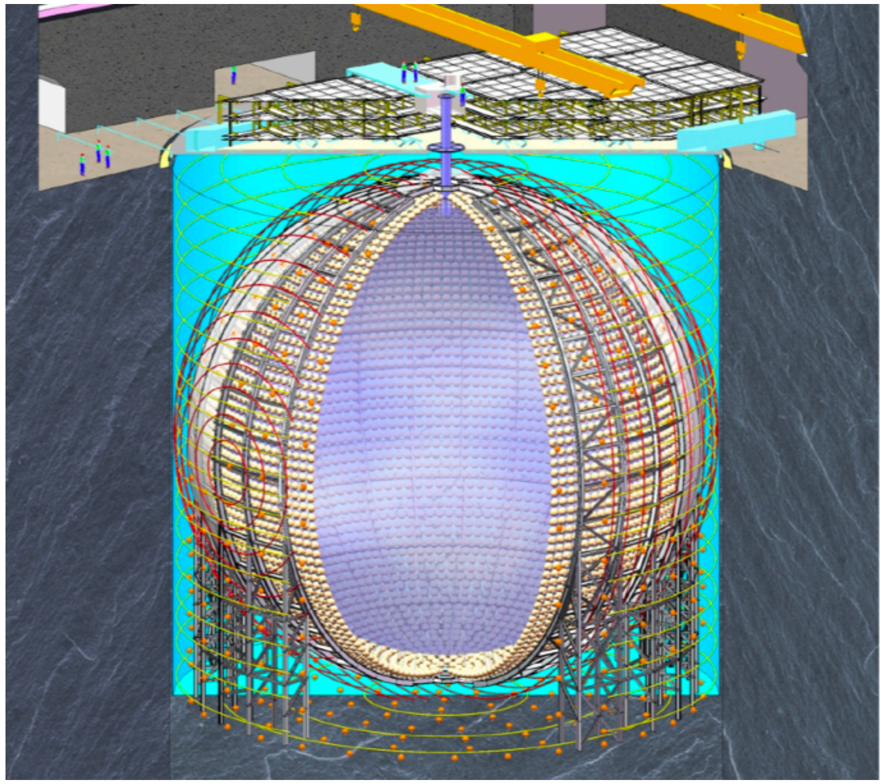



JUNO

JUNO Overview

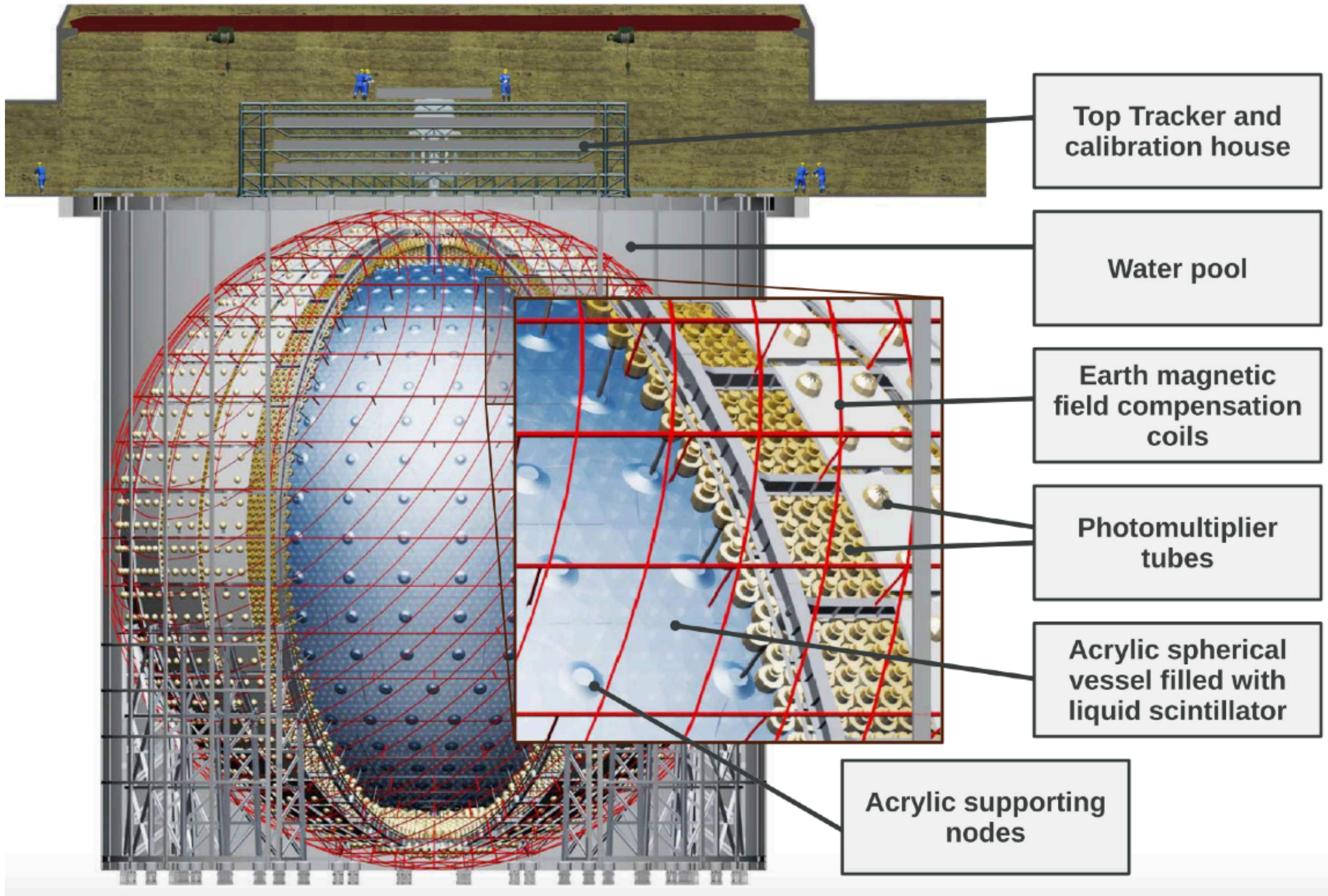
- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a large liquid scintillator neutrino detector, ~650 m underground in southern China
- 20 kton mass: the largest detector of its kind ever built
- Multi-purpose experiment with rich physics portfolio
- Main physics goals are neutrino mass ordering (NMO) determination and precision measurement of neutrino oscillation parameters





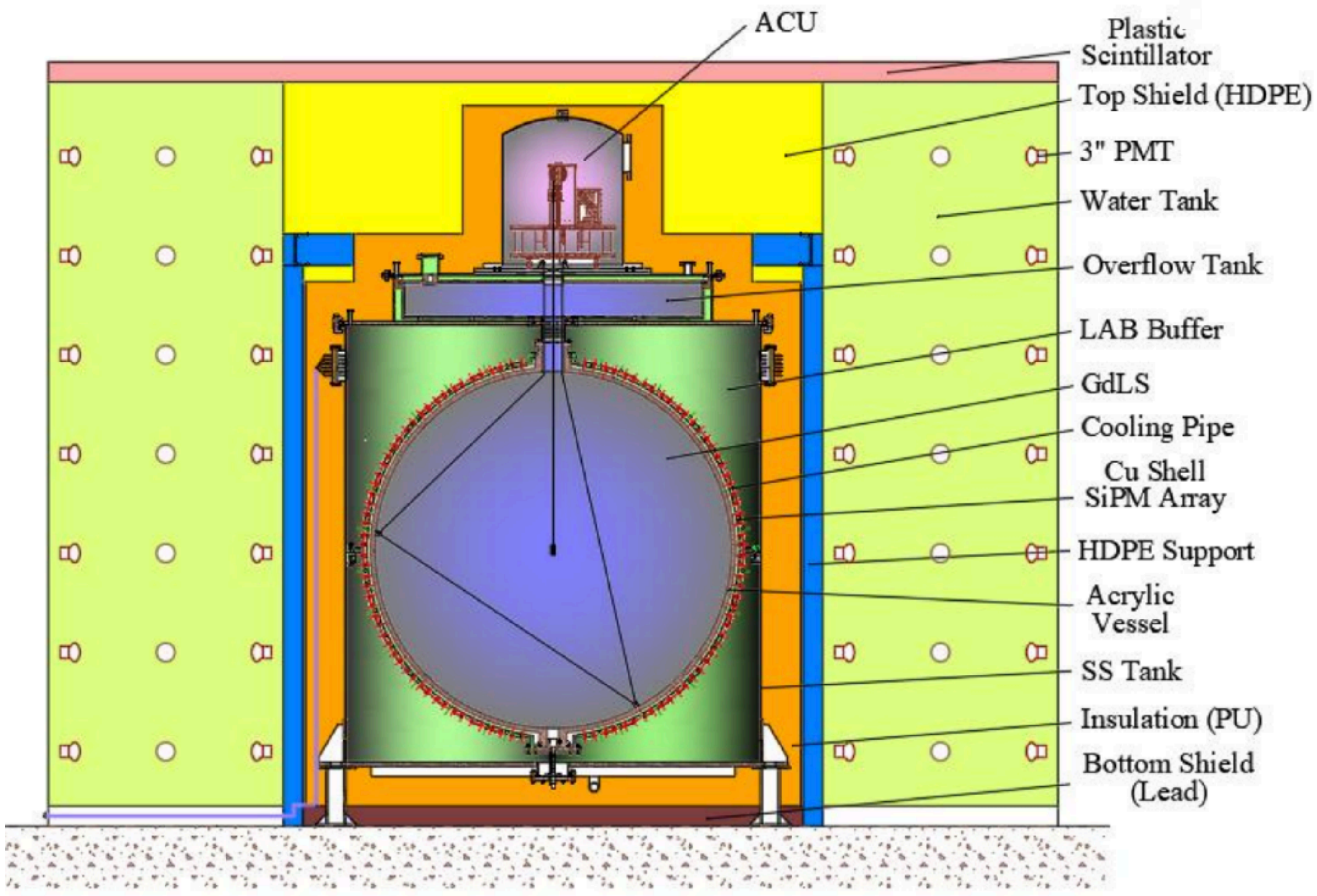
Detector Design

- 35.4 m diameter acrylic sphere filled with 20 kton of liquid scintillator (LS)
  - LS designed for high light yield and low attenuation
- 17,612 20” PMTs (LPMTs) and 25,600 3” PMTs (SPMTs)
  - ~78% photo-coverage
  - ~30% detection efficiency (LPMT)
- Instrumented outer water tank and top scintillator panels
- Unprecedented 3% energy resolution at 1 MeV



JUNO-TAO

- JUNO-TAO (Taishan Antineutrino Detector) will be a satellite detector
    - 44 m from 4.6 GW_{th} reactor
    - ~1 ton GdLS fiducial volume
    - Instrumented with SiPM providing <2% at 1 MeV energy resolution and >90% photo-coverage
    - Operates at -50^{o}C
- **Measure reactor antineutrino energy spectrum** with excellent resolution
    - Remove possible model dependence from JUNO NMO measurement
    - Search for sterile neutrinos
    - Isotopic $\bar{\nu}_e$ rate and shape
    - Important inputs for experiments and nuclear databases

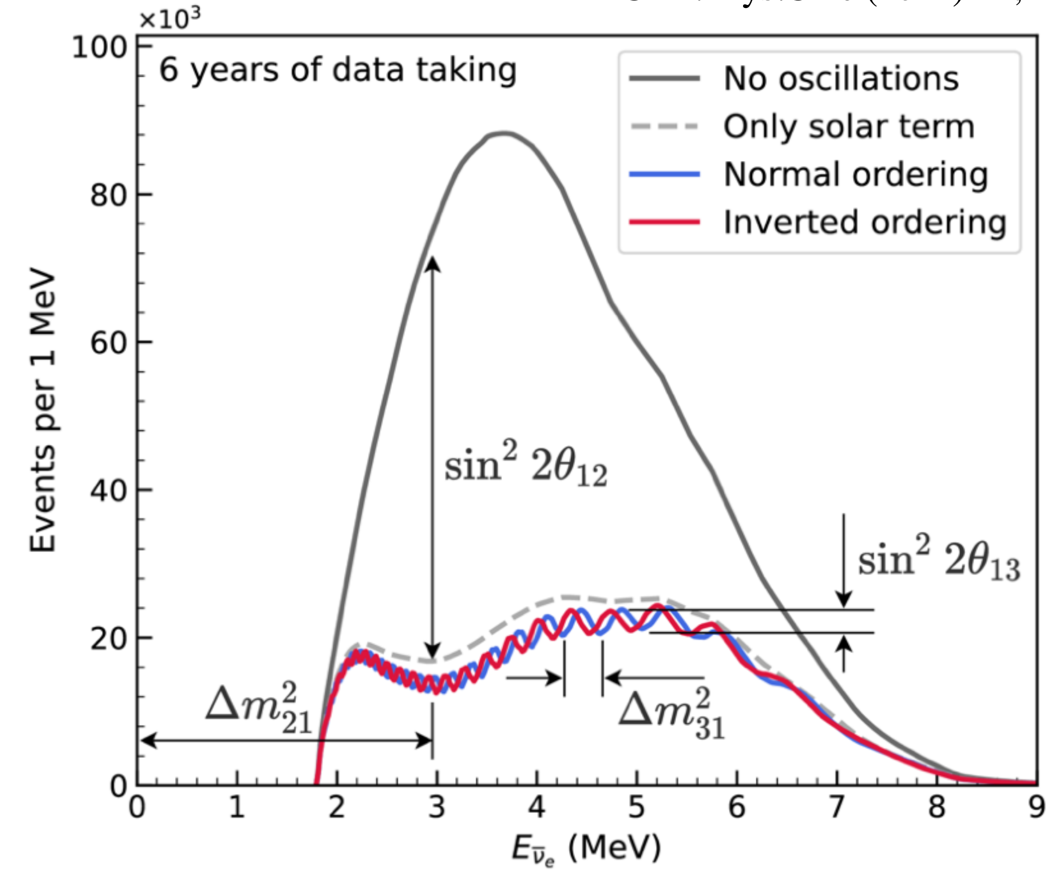


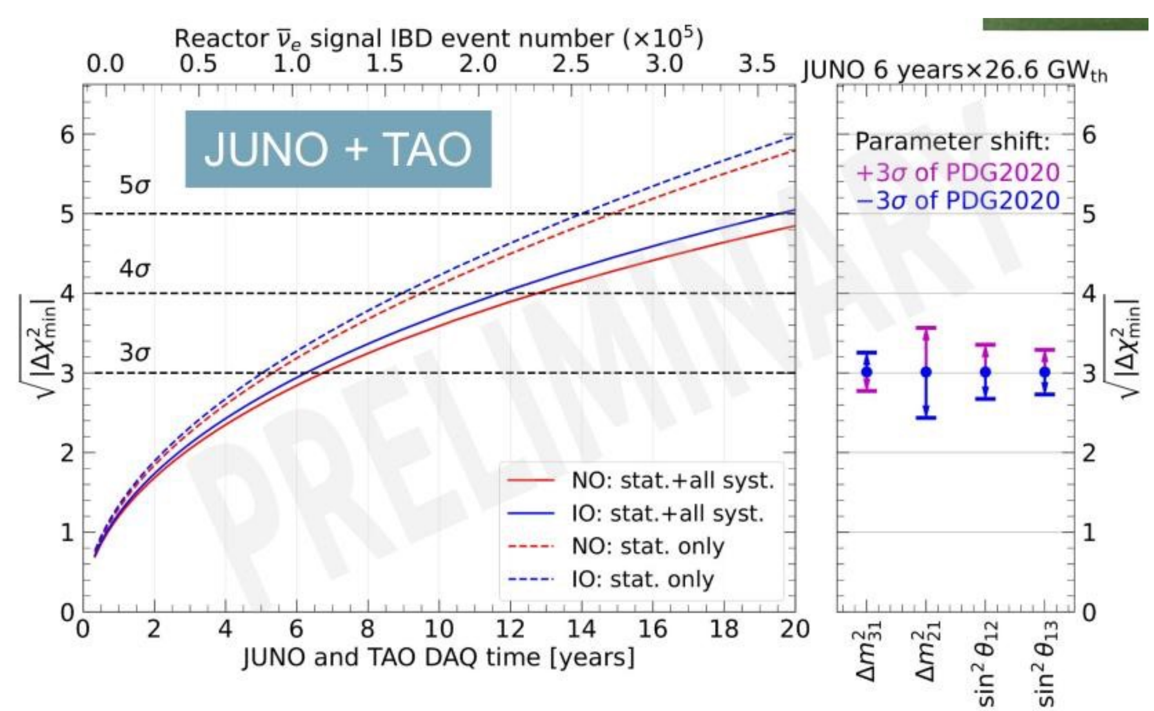
arXiv: 2005.08745

JUNO $\bar{\nu}_e$ Oscillations

- Observation of $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ and θ_{13} driven oscillations
- Determination of NMO through interference effects in fine structure of oscillated spectrum (allowed by large θ_{13})
  - Precise energy spectrum reference from JUNO-TAO
  - Independent of δ_{CP}, octant of θ_{23}
  - Complementary to accelerator and atmospheric measurement (different baseline, energy, and technology)
  - Reach ~5σ in combination with other experiments (*PRD 101, 032006 (2019), Sci Rep 12, 5393 (2022)*)

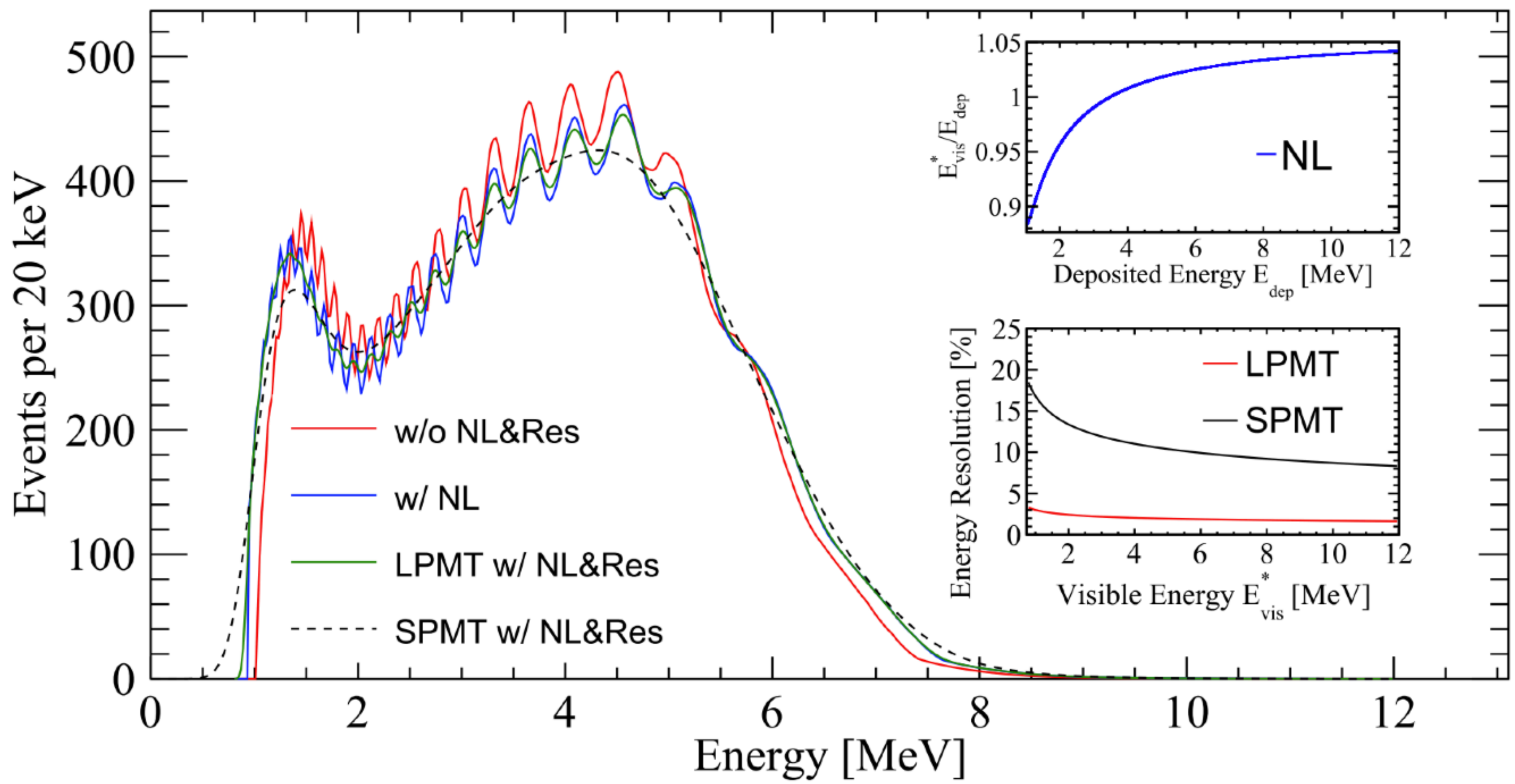
Chin.Phys.C 46 (2022) 12, 123001





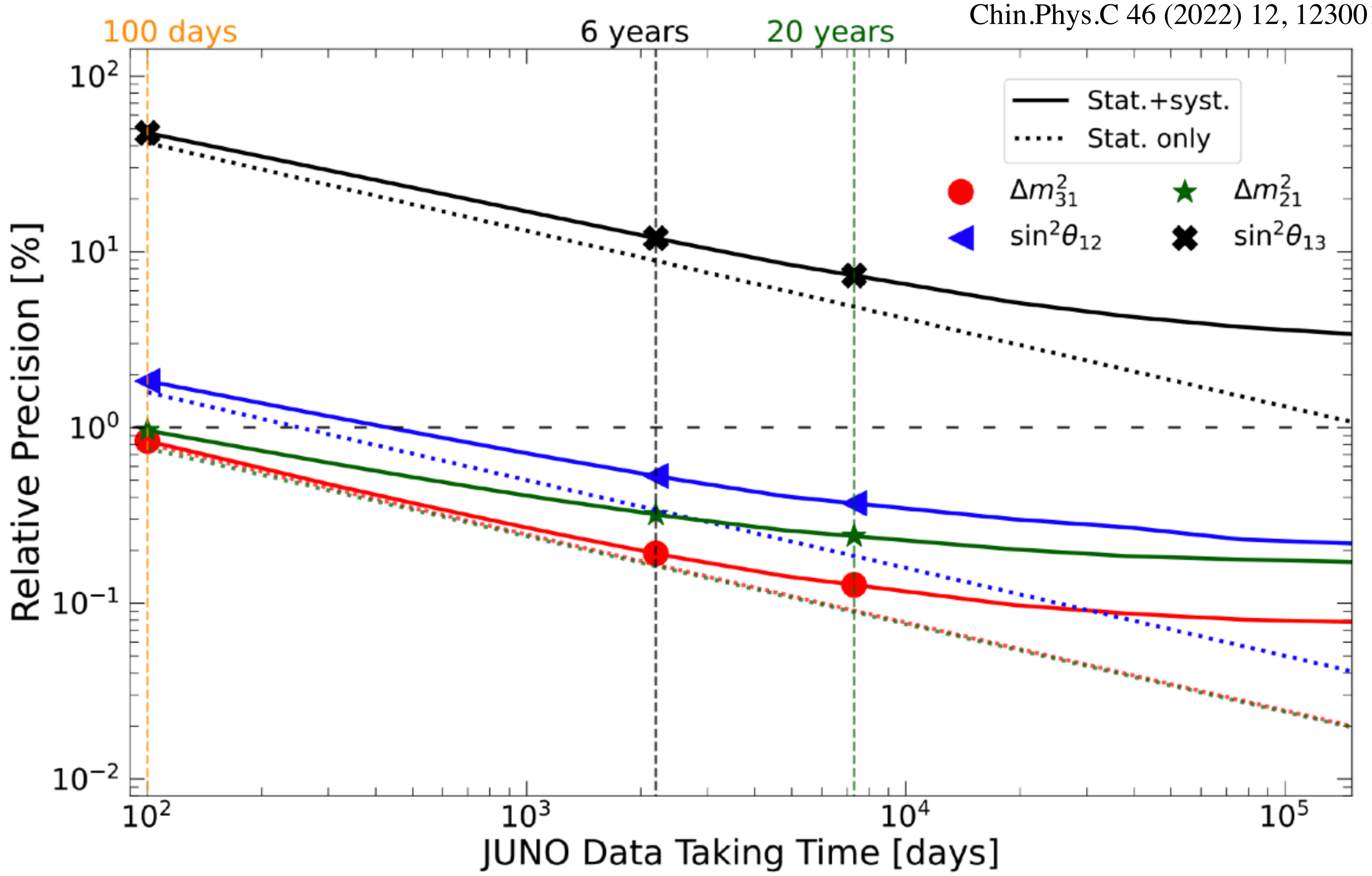
Updated Sensitivities

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



- Recent sensitivity study with full treatment of systematics using best knowledge of detector response to date:
  - Updated number of reactors
  - Realistic simulation and veto efficiencies
  - Final detector overburden and location information
  - Spectral shape constraints from JUNO TAO included

Oscillation Parameters



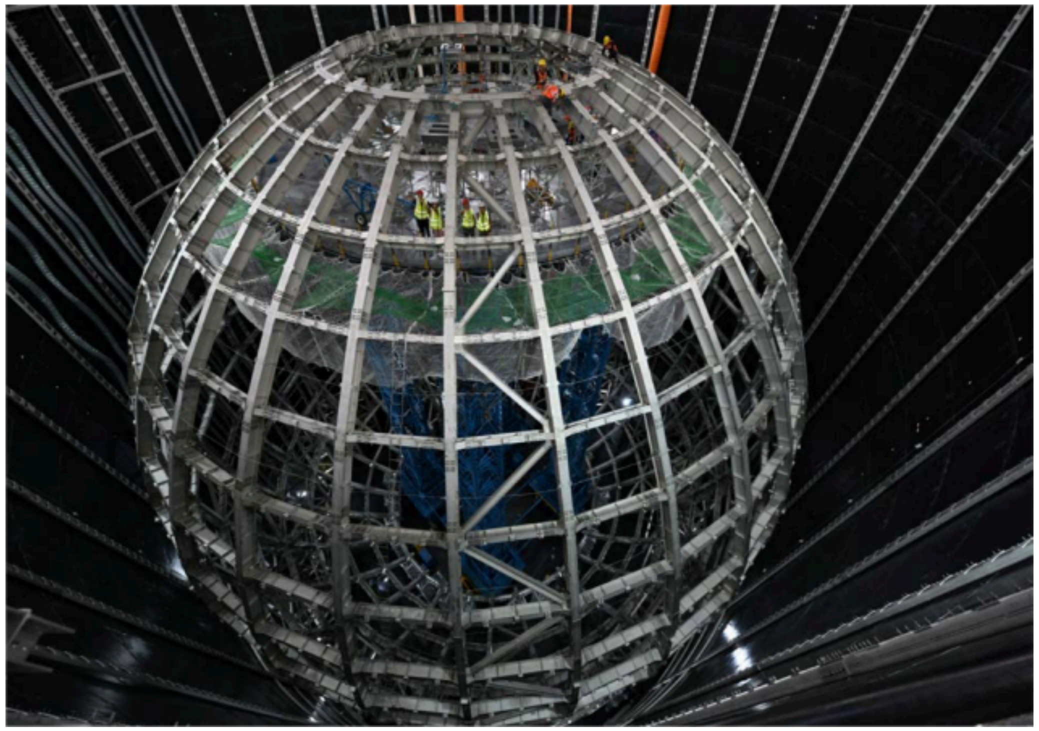
JUNO Relative Uncertainty vs. Leading Experiments

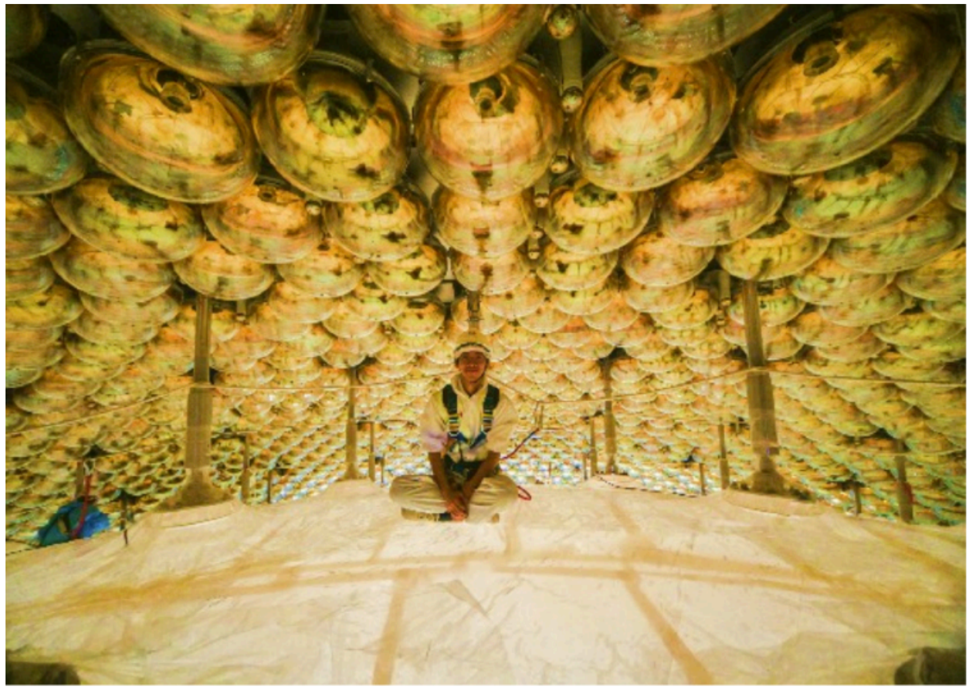
	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 100 days	0.8%	1%	1.9%	47.9%
JUNO 6 years	0.3%	0.2%	0.5%	12.1%
KamLAND	2.4%	-	-	-
T2K	-	2.6%	-	-
SNO+SK	-	-	4.5%	-
Daya Bay	-	-	-	3.4%

- Measurement of $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to ~**1% precision with O(100 days) data**
  - 6 years for **order of magnitude improvement over existing constraints**
  - Precise tests of neutrino oscillations and U_{PMNS} unitarity (1%)

Construction Progress

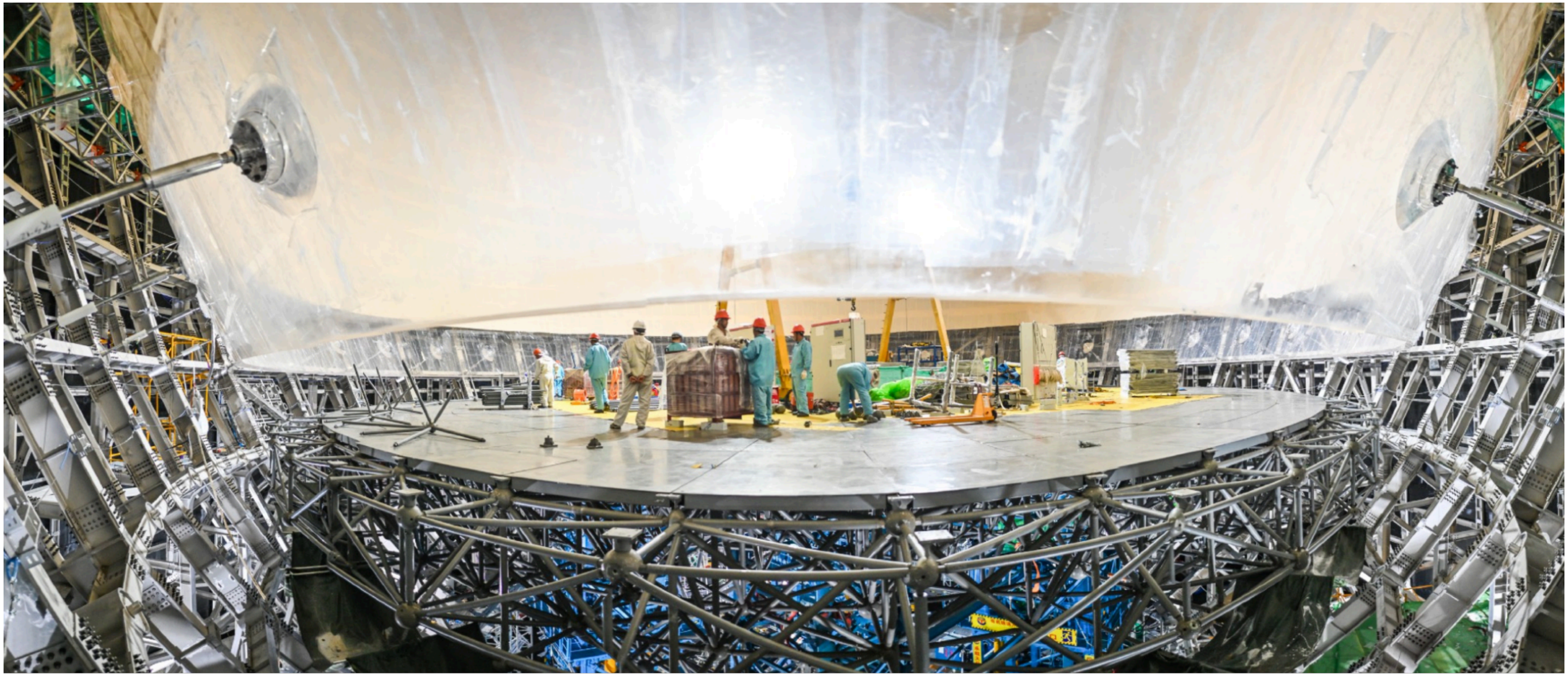
Steel Support Structure finished





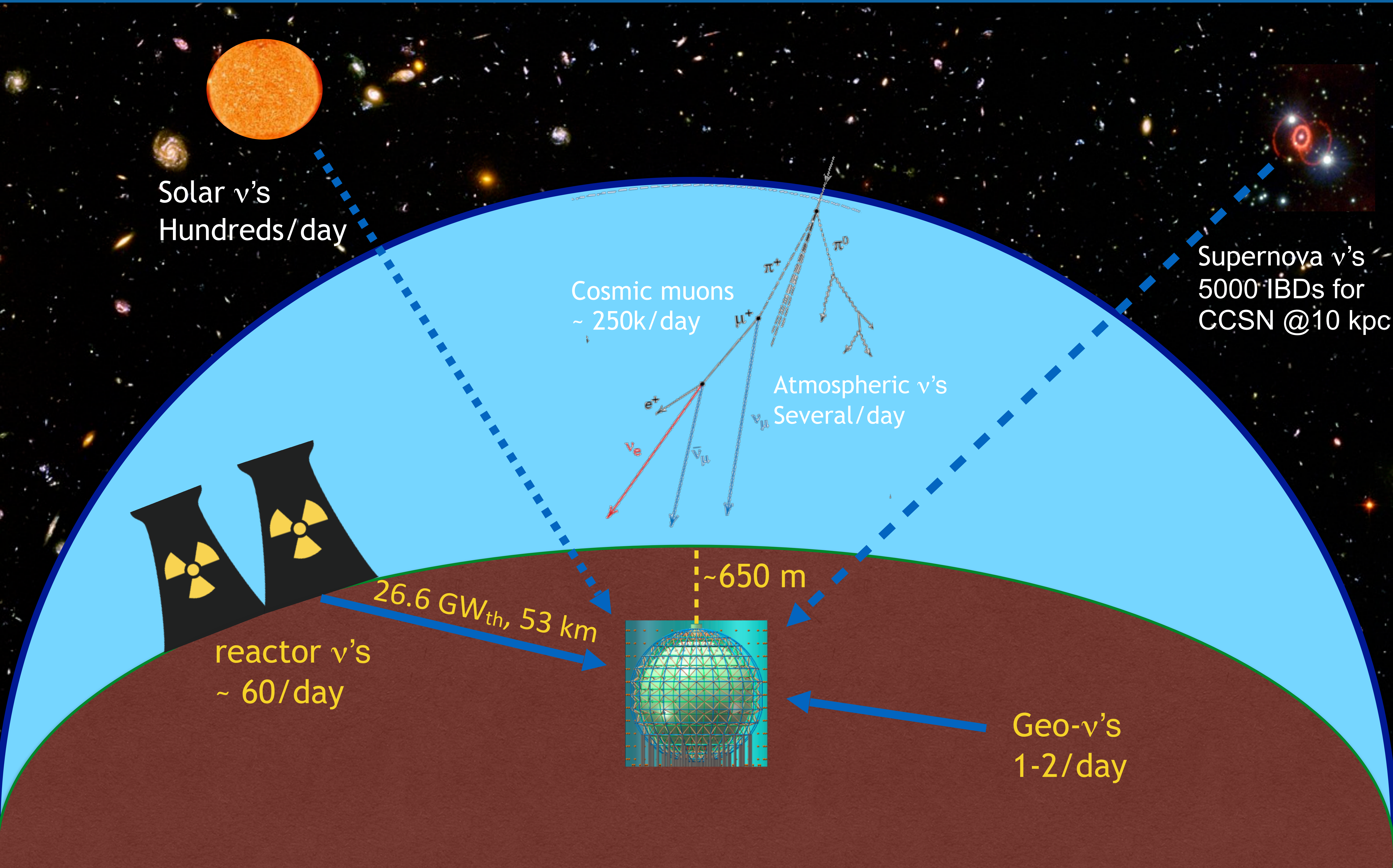
PMT and electronics installation ongoing!

Construction Progress



- Filling set to start this year!

Neutrinos from Near and Far



Summary

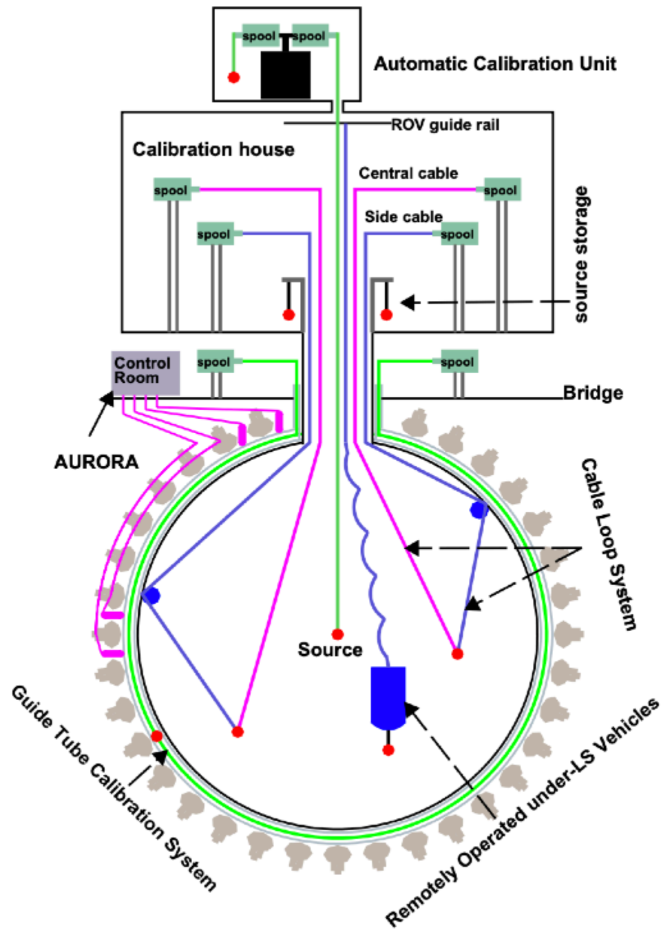
- **Reactor antineutrinos** have been **key to neutrino science**: and there are **exciting prospects in the near future!**
    - Discovery of non-zero θ_{13} performed with reactor $\bar{\nu}_e$
    - Will be its most precise measurement for the foreseeable future
- JUNO is a next-generation, precision, multi-purpose experiment with a rich program in neutrino, astroparticle, and new physics searches
- Using its reactor $\bar{\nu}_e$ dataset:
    - NMO measurement to 3σ with about 6 years of data-taking
    - Sub-percent precision for $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} with as little as O(100) days of data
- Much progress has been done in construction and commissioning, with **LS data-taking starting next year!**

Thank you!

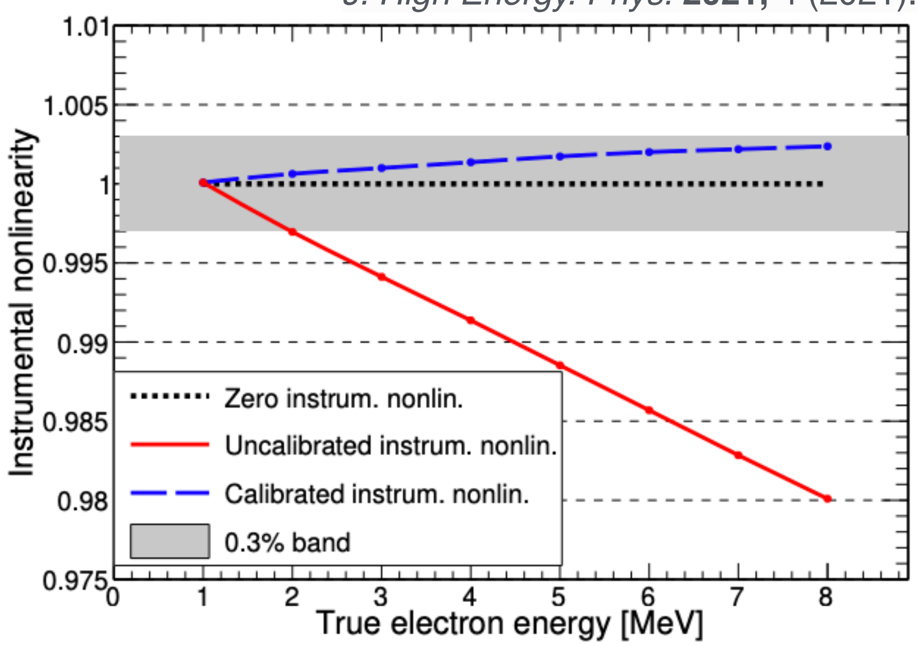
BACKUP

Calibration

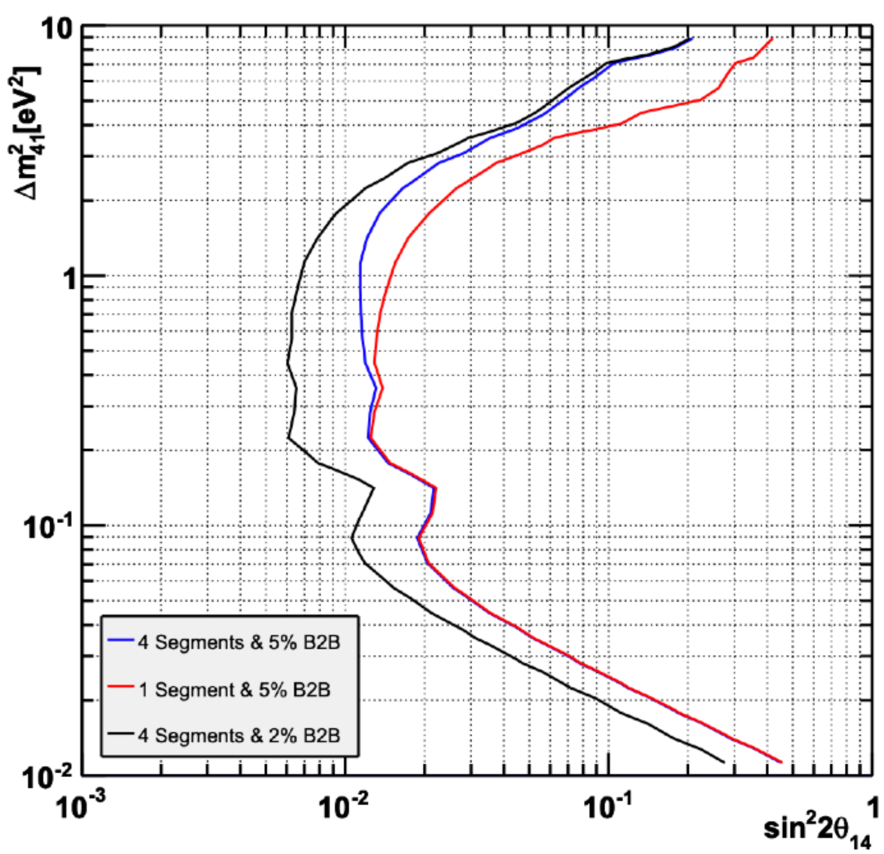
- Comprehensive calibration strategy
  - Gamma/neutron sources, cosmogenic ^{12}B and UV laser
  - Multi-positional source deployment
- SPMTs serve as linear reference for LPMT non-linearity
  - Operate in photon-counting mode for ~1-10 MeV
- Dual Calorimetry Calibration compares LPMT charge to SPMT charge under same source
  - Channel-wise LPMT charge vs. total SPMT charge
  - UV laser energies span region of interest
  - Gamma sources match time profile of neutrino (positron) signal
  - Absolute energy scale uncertainty <1%

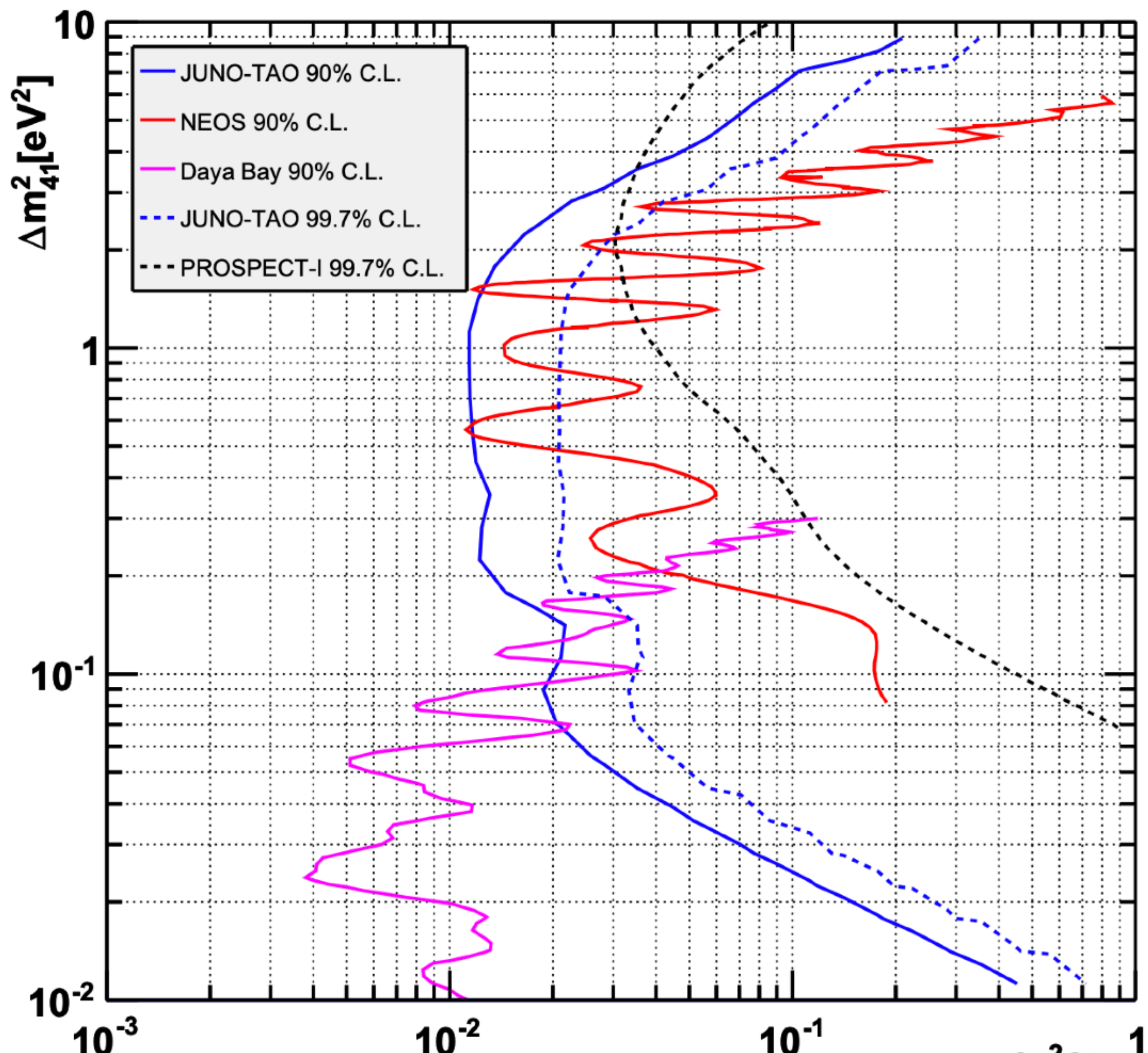


J. High Energy. Phys. **2021,** 4 (2021).



- With its short baseline, TAO has great potential in sterile oscillation searches
  - Sensitivity improved by virtual segmentation of detector





arXiv: 2005.08745

Systematics

- Updated treatment of systematics
  - Values for 6 year exposure shown
- Rate systematics mitigated by spectral shape constraint on normalization

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