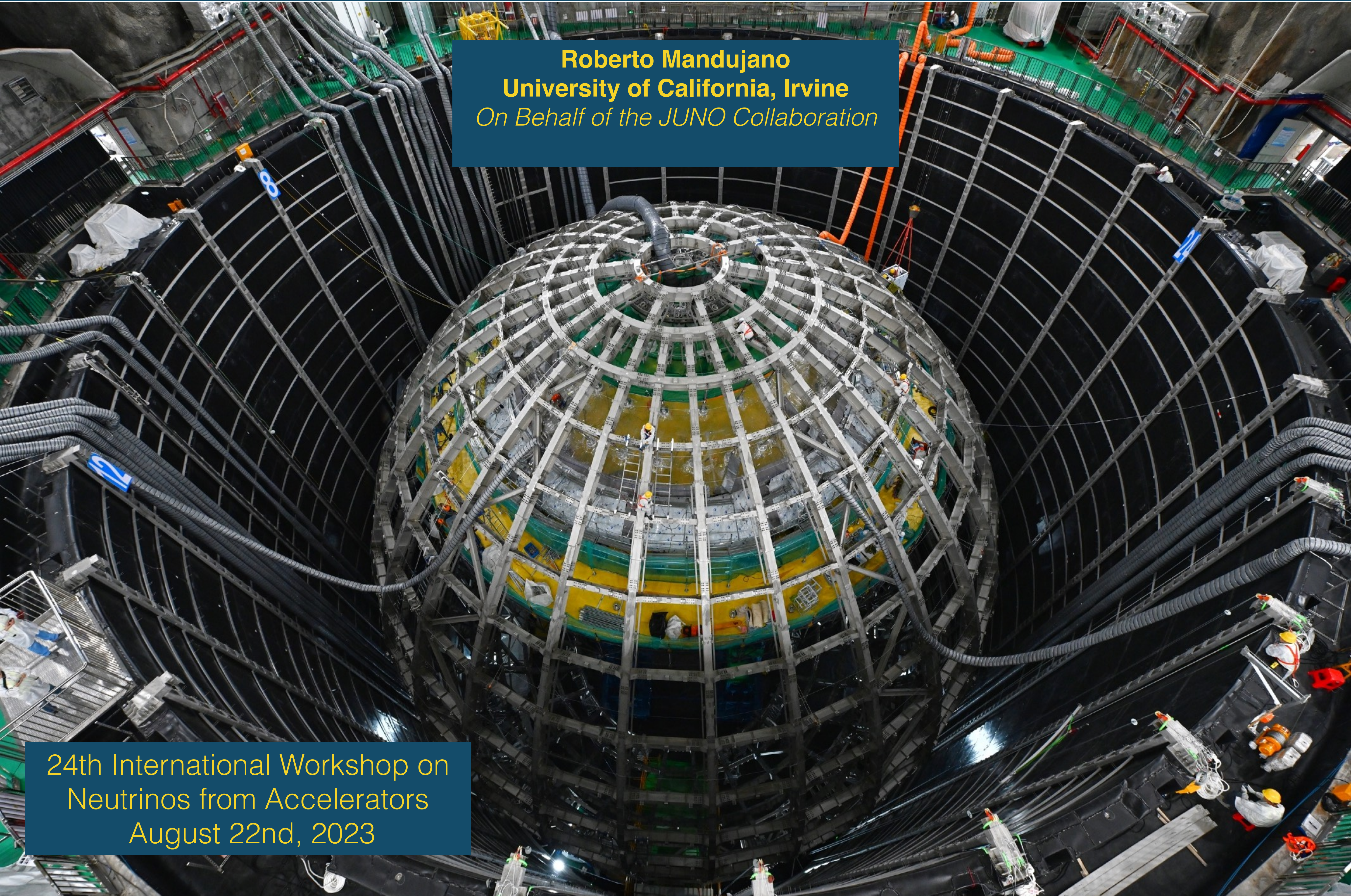
Reactor Antineutrino Oscillations with JUNO

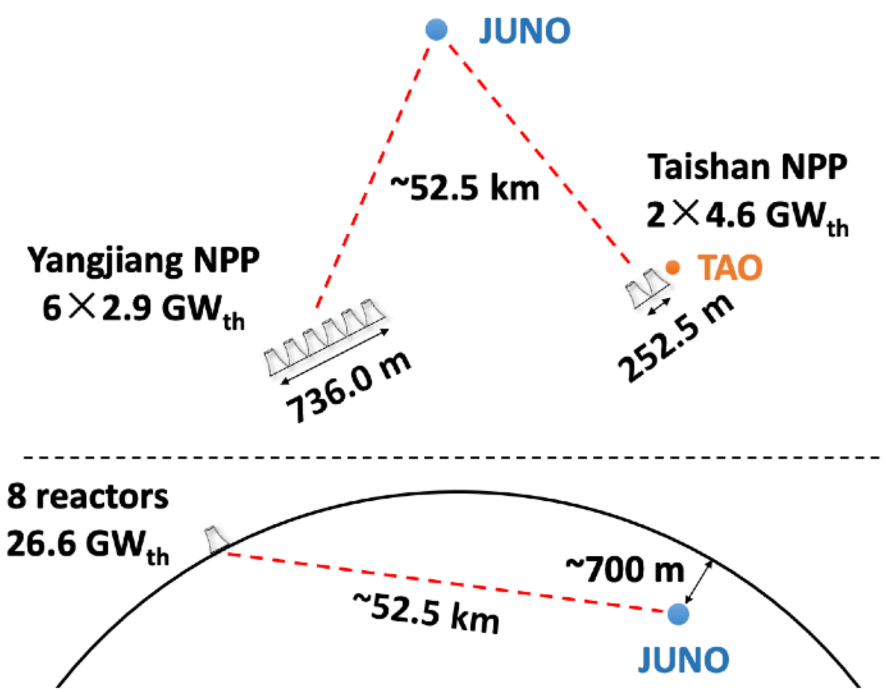


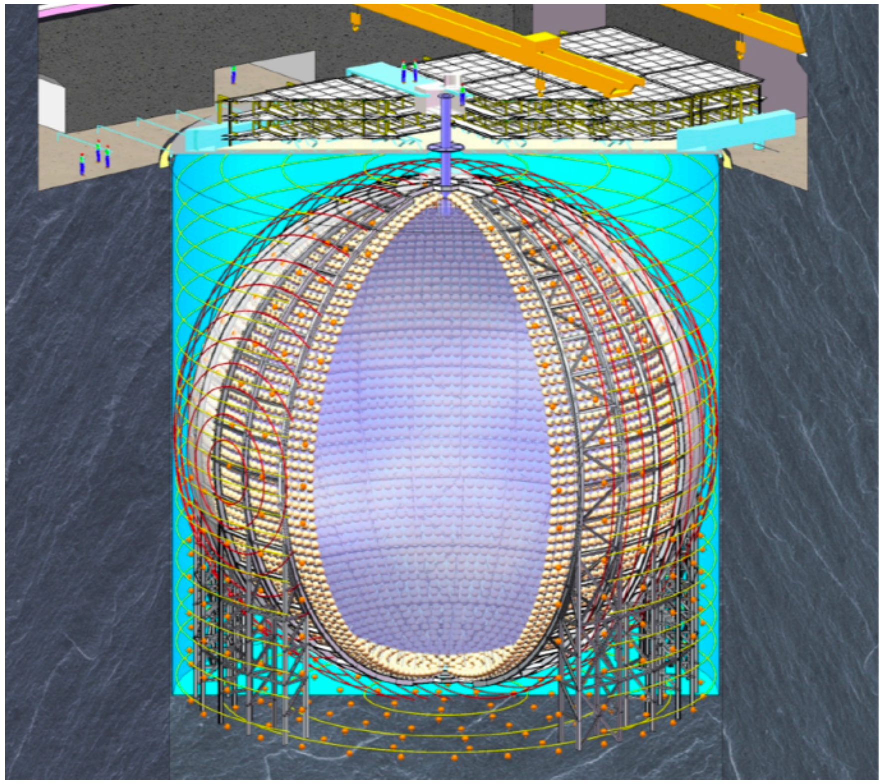
Roberto Mandujano
University of California, Irvine
On Behalf of the JUNO Collaboration

24th International Workshop on
Neutrinos from Accelerators
August 22nd, 2023

JUNO Overview

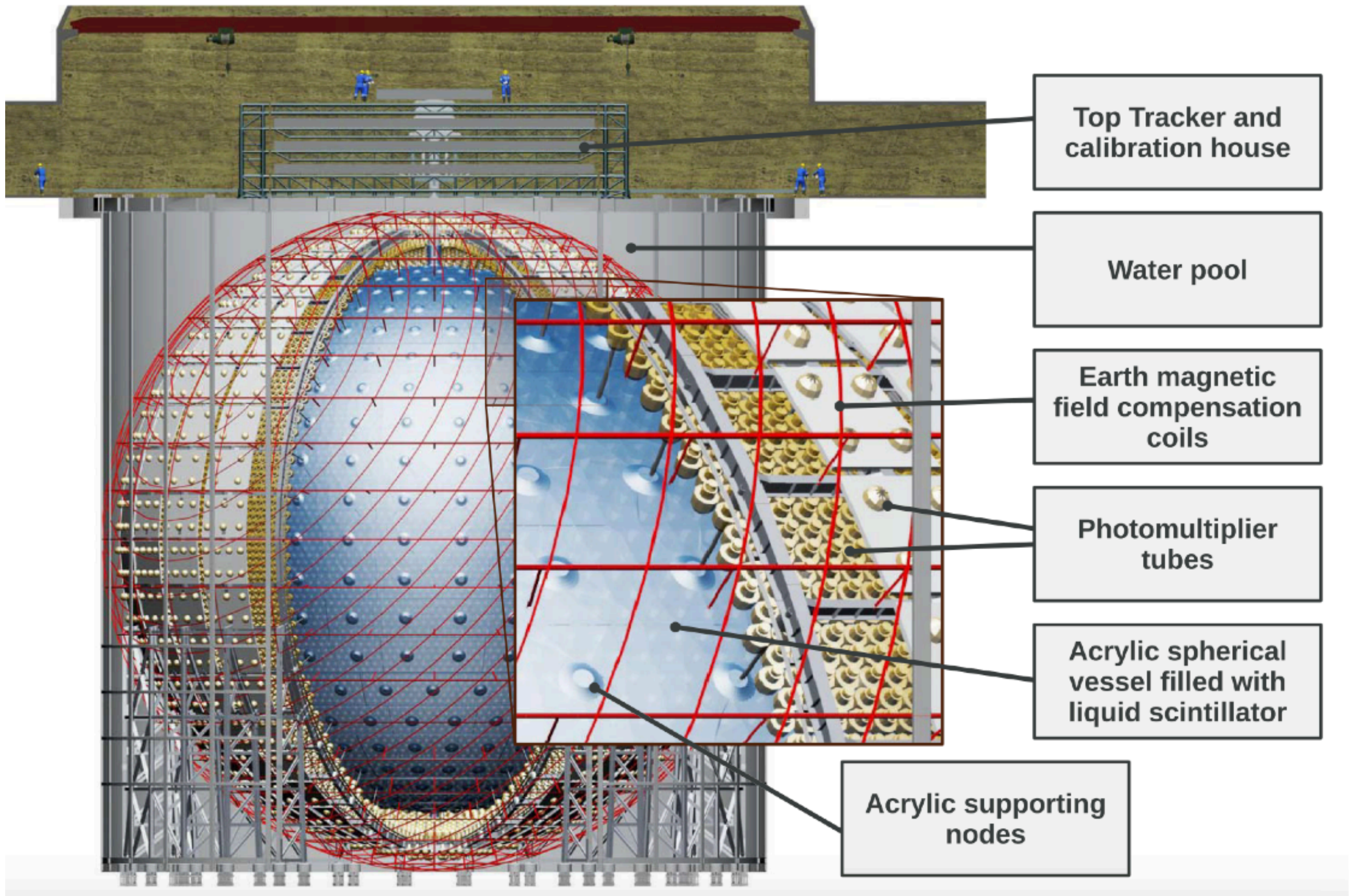
- The Jiangmen Underground Neutrino Observatory (JUNO) is a large liquid scintillator neutrino detector under construction in China
- At 20 kton, it will be the largest detector of its kind ever built
- Multi-purpose experiment with rich physics portfolio
- Main physics goals are neutrino mass ordering (NMO) determination and precision measurement of neutrino oscillation parameters



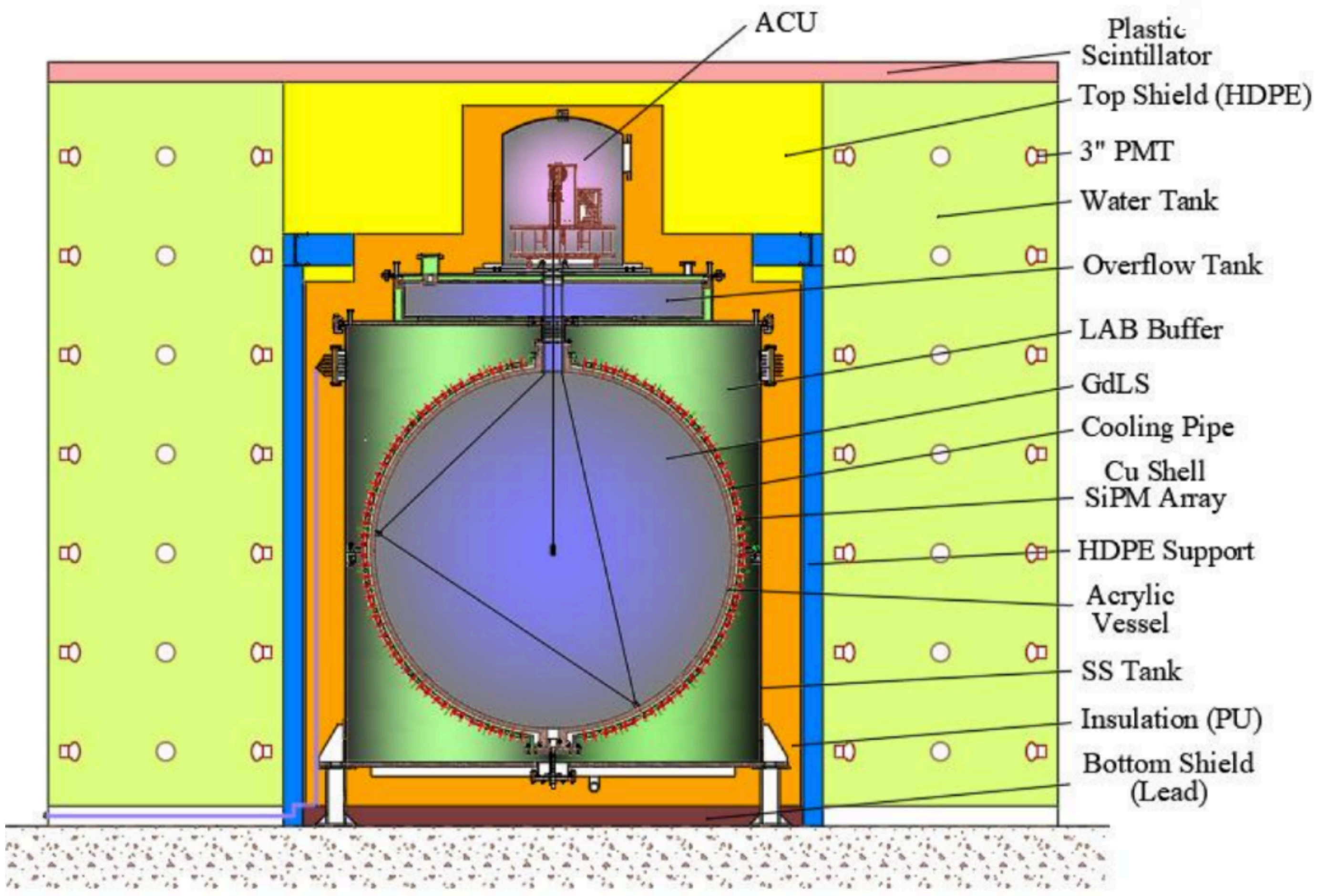


Detector Design

- 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 (LPMT) and 25,600 3” PMTs (SPMT)
  - ~78% photo-coverage
  - ~30% detection efficiency (LPMT)
- Instrumented outer water tank and top scintillator panels serve as muon background veto, reconstruct muon tracks, and provide shielding from natural radiation
- Unprecedented 3% energy resolution at 1 MeV



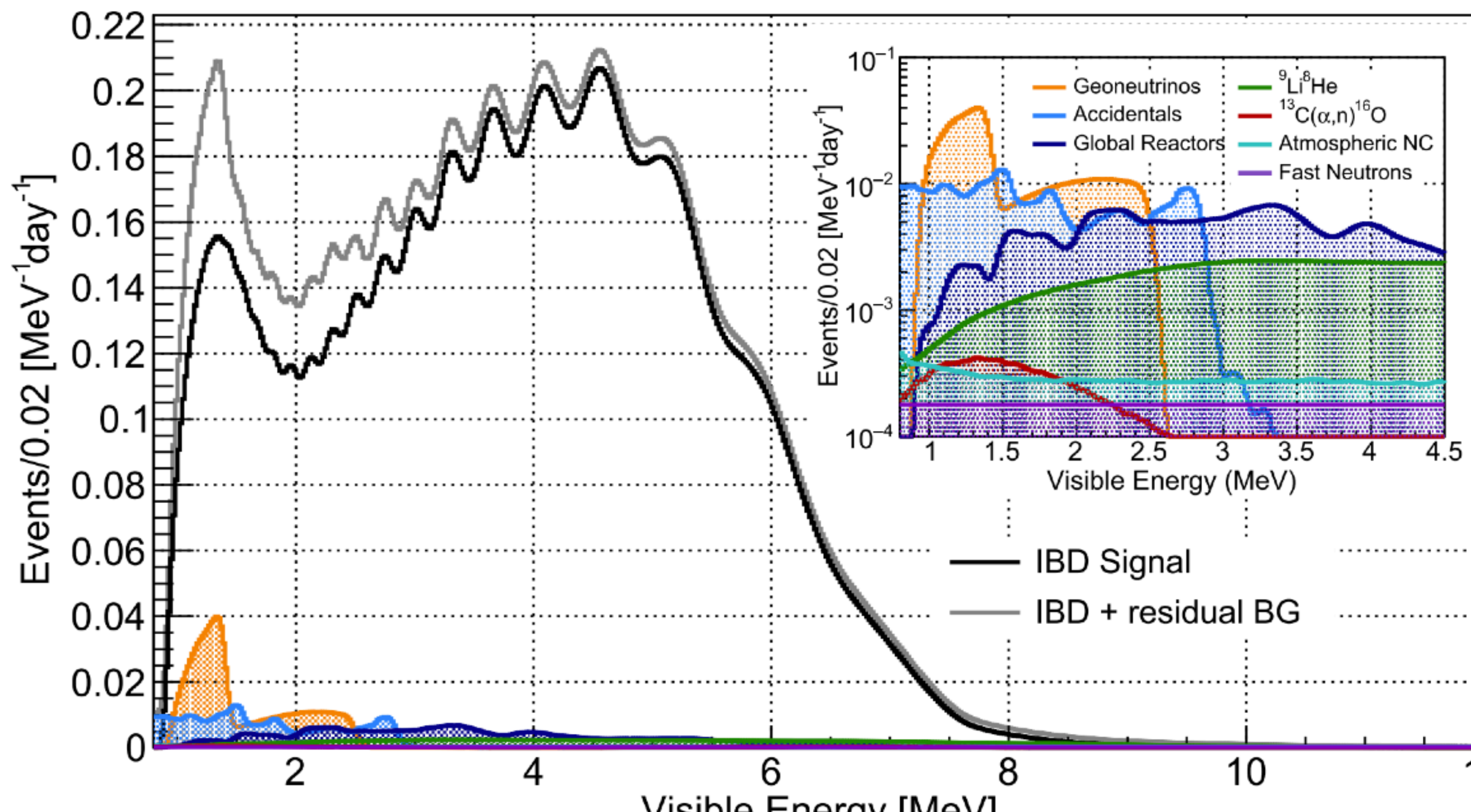
- JUNO-TAO (Taishan Antineutrino Detector) will be a satellite detector
  - 44 m from 4.6 GW_{th} reactor
  - ~1 ton GdLS fiducial volume
  - Instrumented with SiPM providing <~2% at 1 MeV energy resolution
  - Operates at -50 C
- **Measure reactor antineutrino energy spectrum** with excellent resolution
  - Reference spectrum for JUNO, removing possible model dependence from NMO measurement
  - Search for sterile neutrinos



arXiv: 2005.08745

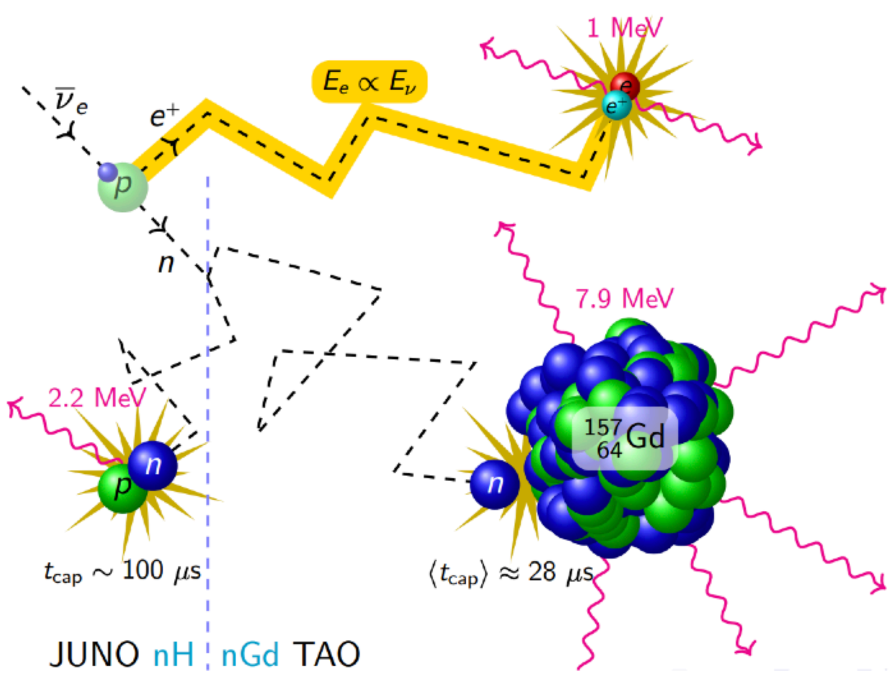
Reactor $\bar{\nu}_e$ Detection

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



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

		Correlated					Uncorrelated	
Event Type	Reactor IBD	Fast-n	9Li/8He	Alpha-n	Geo-ν	Global Reactor	Accidentals	Atm.-ν
Rate [per day]	47	0.1	0.8	0.05	1.2	1	0.8	0.16

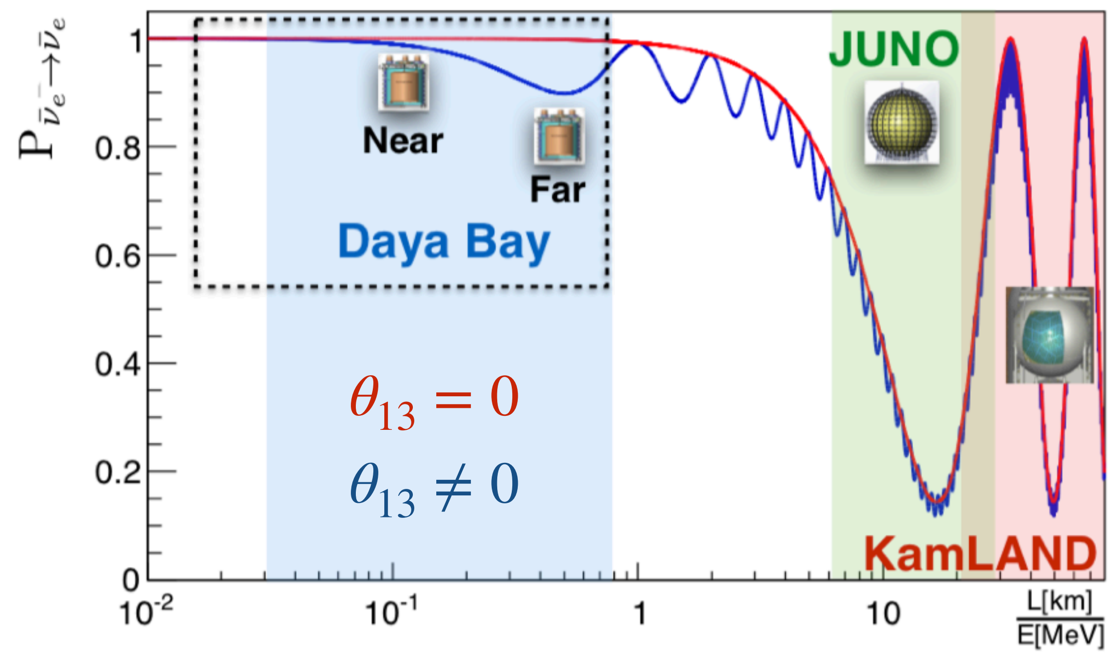


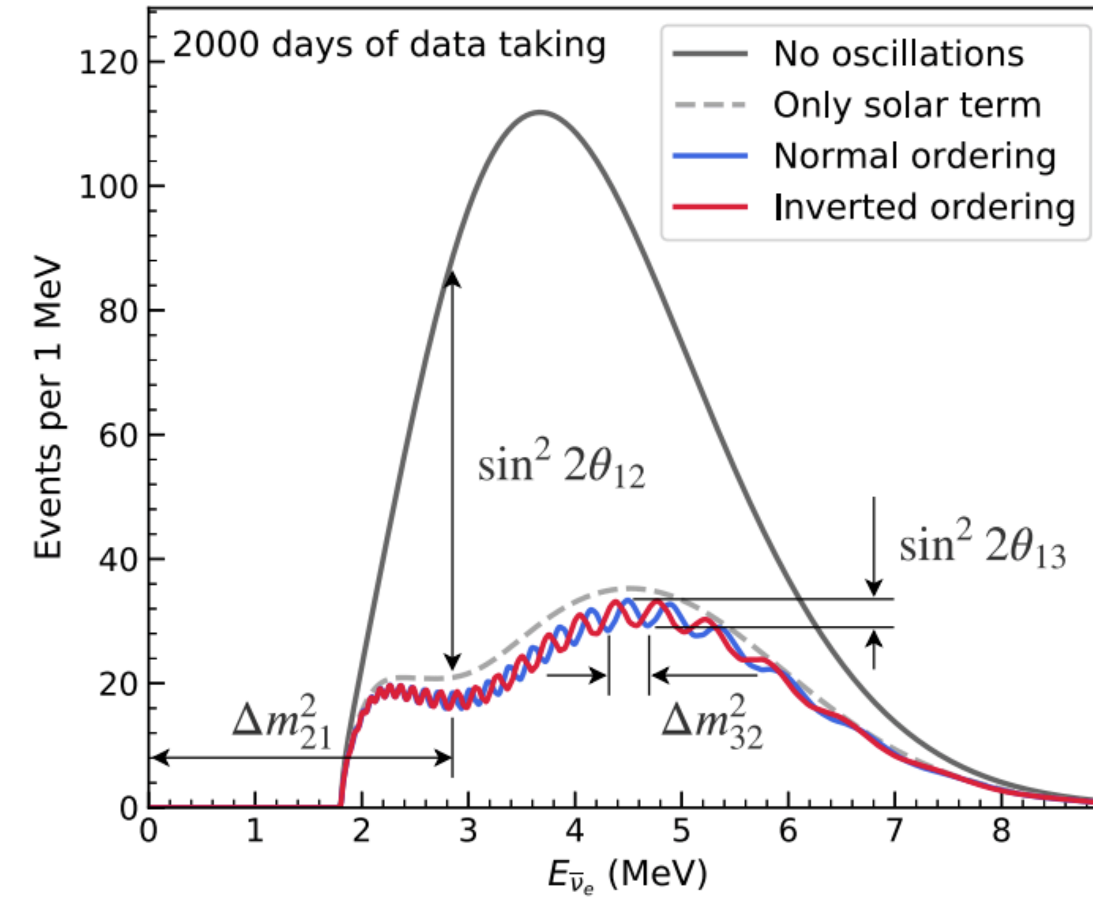
Reactor $\bar{\nu}_e$ Oscillations

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

- Observation of $\theta_{12}, \theta_{13}, \Delta m^2_{21}$, and Δm^2_{32} driven oscillations
- Determination of NMO through interference effects in fine structure of oscillated spectrum (allowed by large θ_{13})
  - JUNO-TAO energy spectrum provides precise reference of un-oscillated JUNO energy spectrum
  - Independent of δ_{cp}, octant of θ_{23}, no reliance on matter effects
  - Complementary to accelerator and atmospheric measurement (different baseline, energy, flavor and technology)

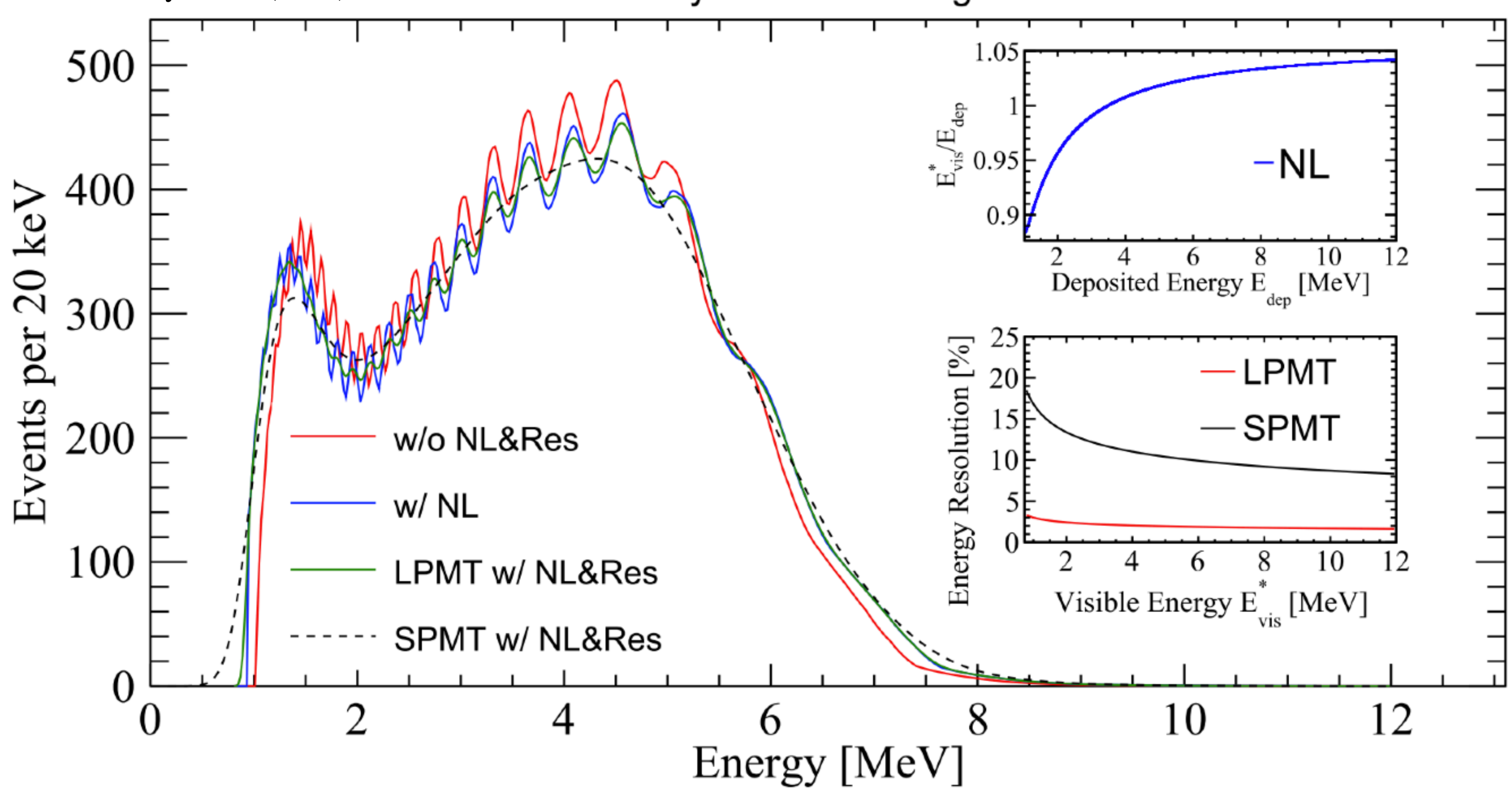
Chin.Phys.C 46 (2022) 12, 123001





Updated Sensitivities

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



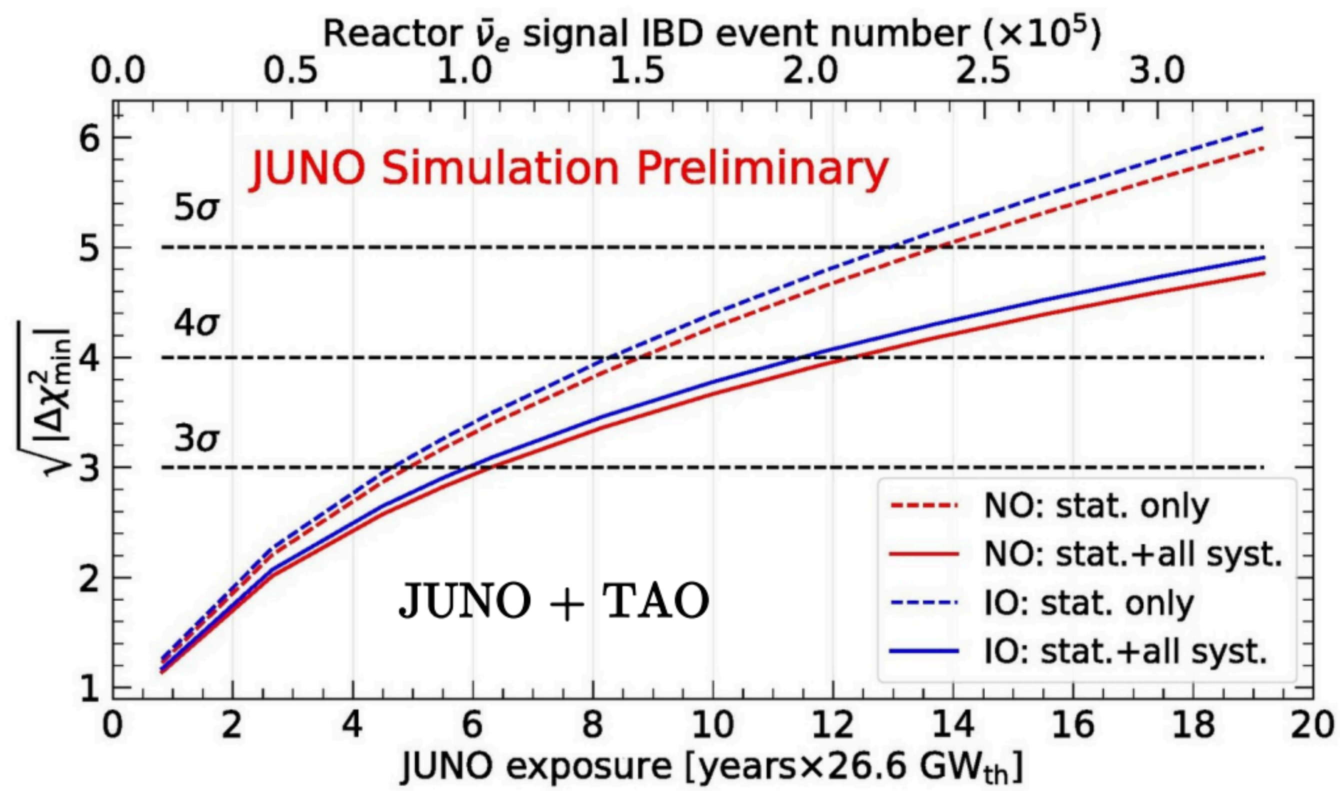
- Recent sensitivity study with full treatment of systematics using updated assumptions and measurements:
  - Updated number of reactors
  - Realistic simulation and veto efficiencies
  - Final detector overburden and location information
  - Spectral shape constraints from JUNO TAO included

Neutrino Mass Ordering

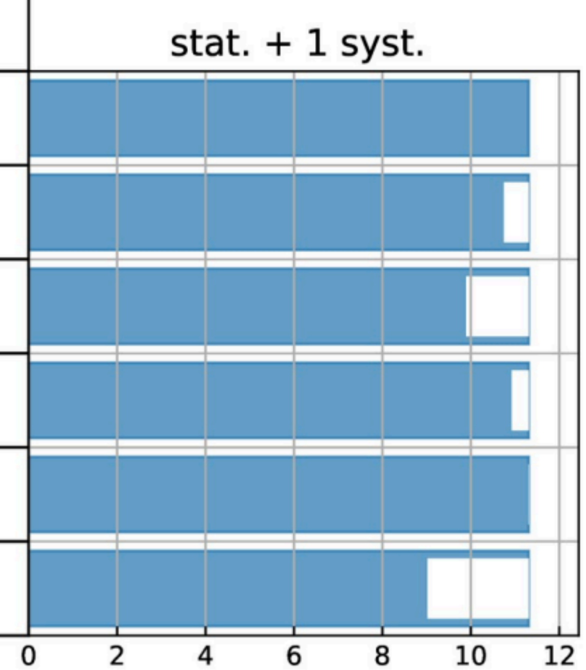
- Fit energy spectrum under normal and inverted ordering hypotheses

$$\Delta\chi^2_{min} = |\ \Delta\chi^2_{min}(NO) - \Delta\chi^2_{min}(IO)\ |$$

- ~3σ NMO sensitivity in 6 years
    - Independent of δ_{cp}, octant of θ_{23}
    - Complementary to accelerator measurement (different baseline and technology)
    - Paper under preparation



	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



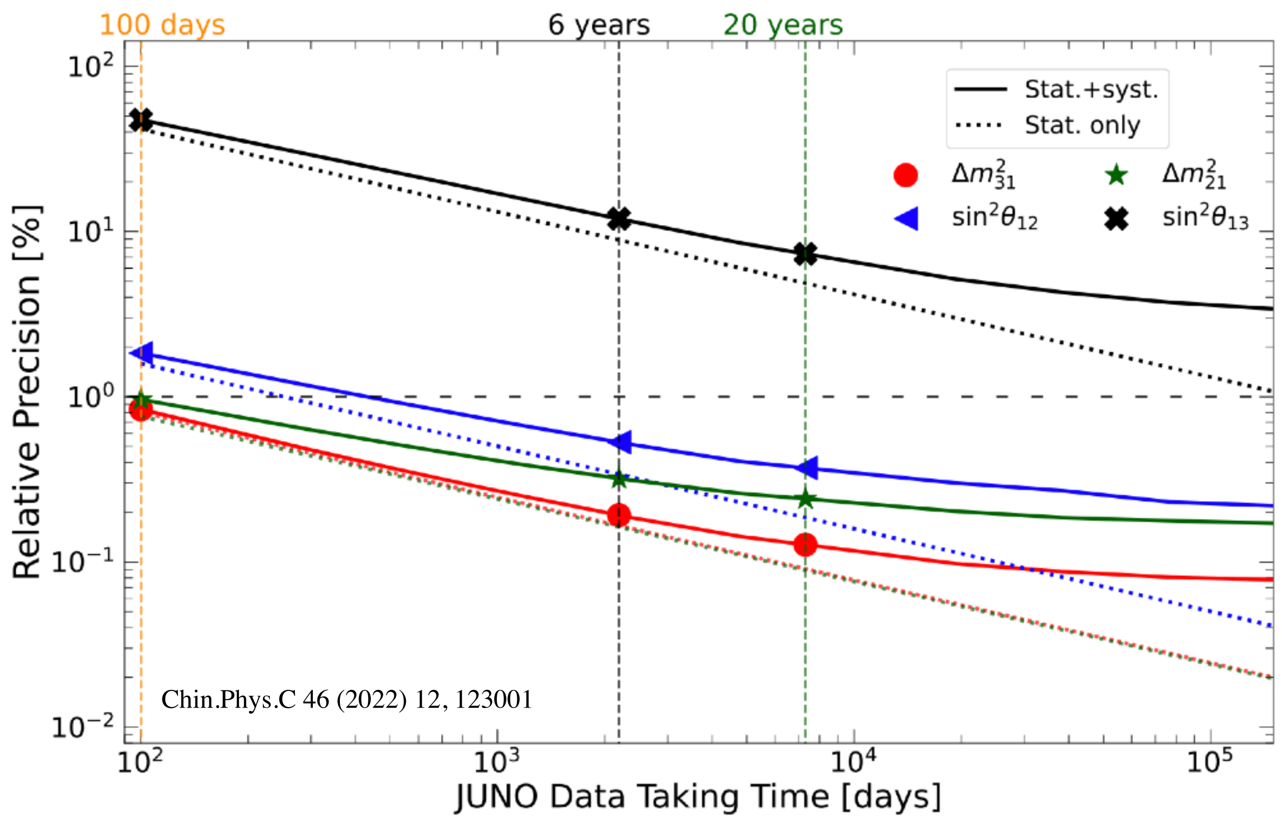
JUNO Simulation Preliminary

Oscillation Parameters

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

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 20 years	0.1%	0.2%	0.3%	7.3%
KamLAND	2.4%	-	-	-
T2K	-	2.6%	-	-
SNO+SK	-	-	4.5%	-
Daya Bay	-	-	-	3.4%



Systematics

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

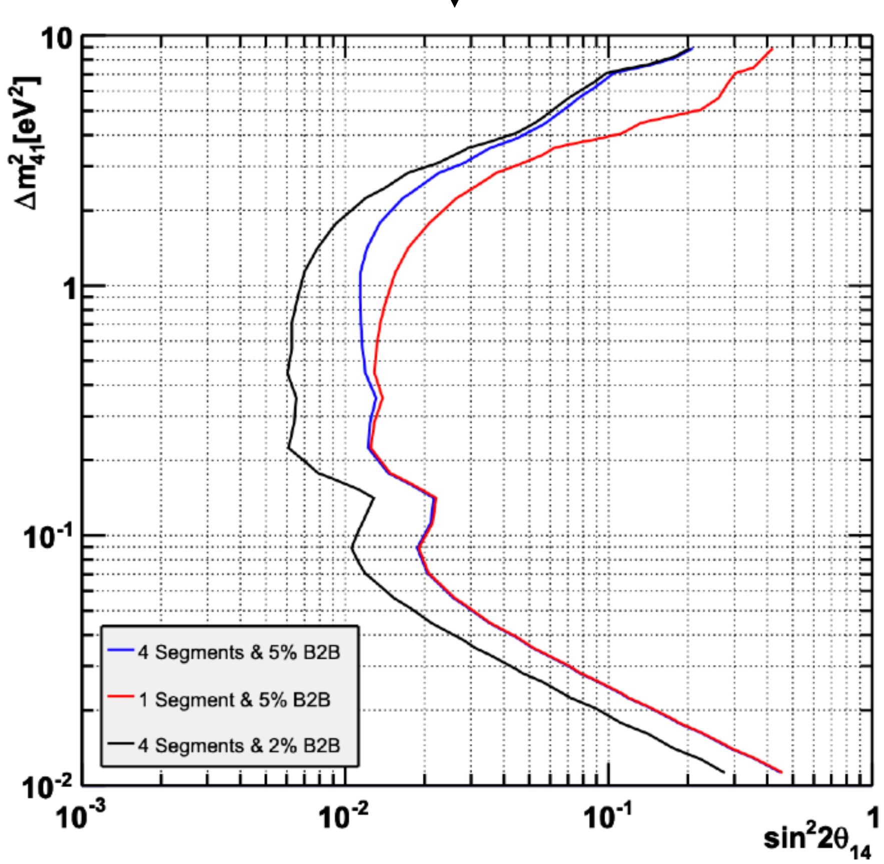
Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total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

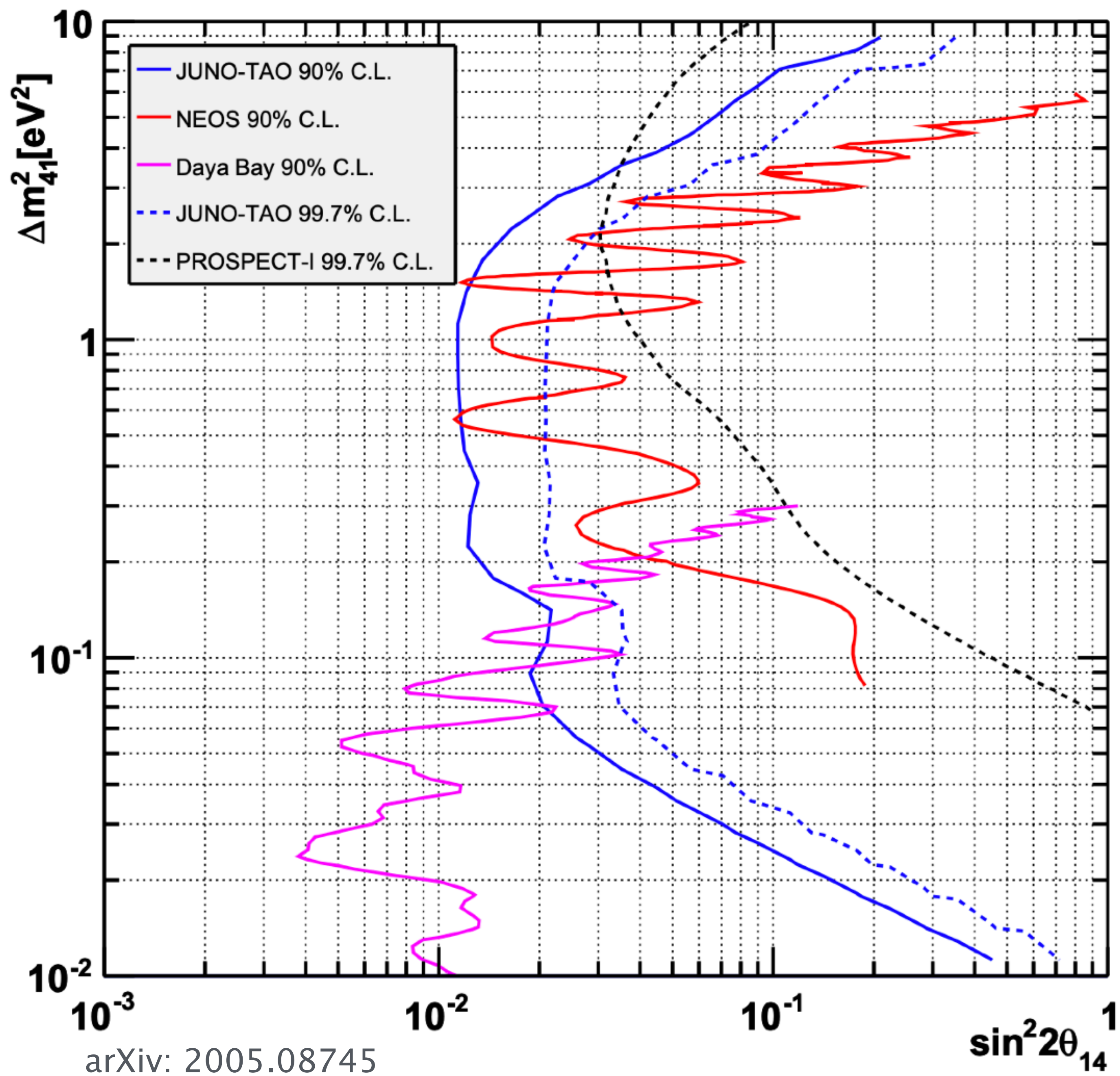
Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

$\sin^2\theta_{12}$	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

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

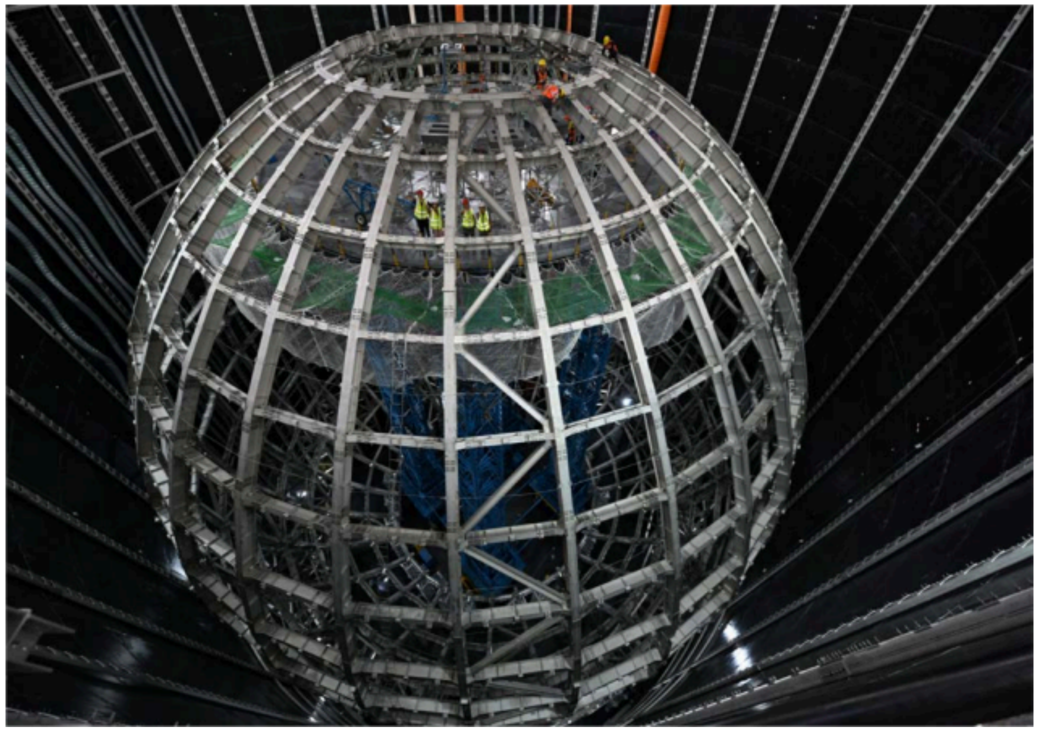




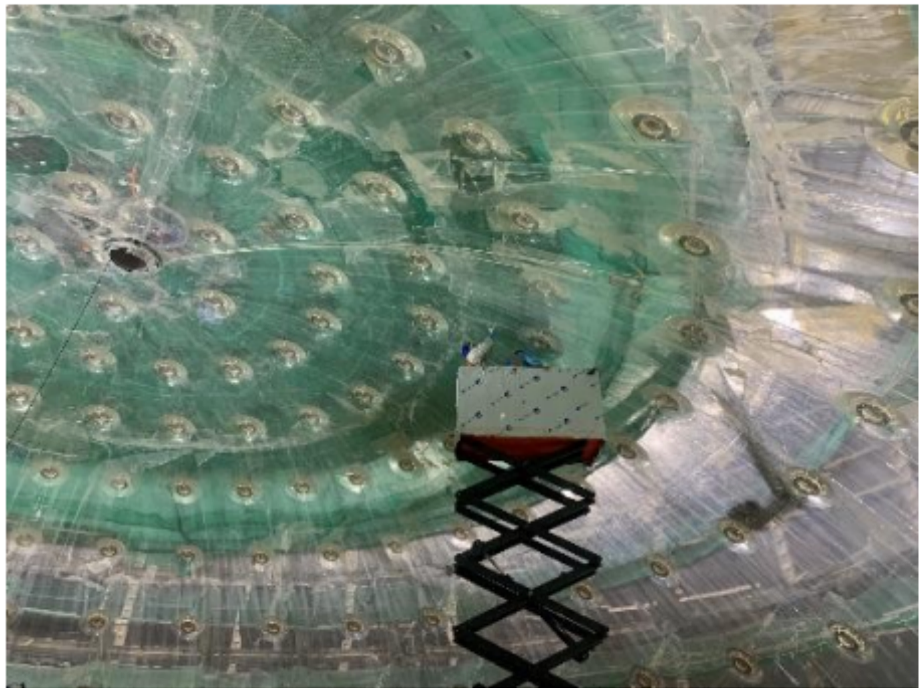
arXiv: 2005.08745

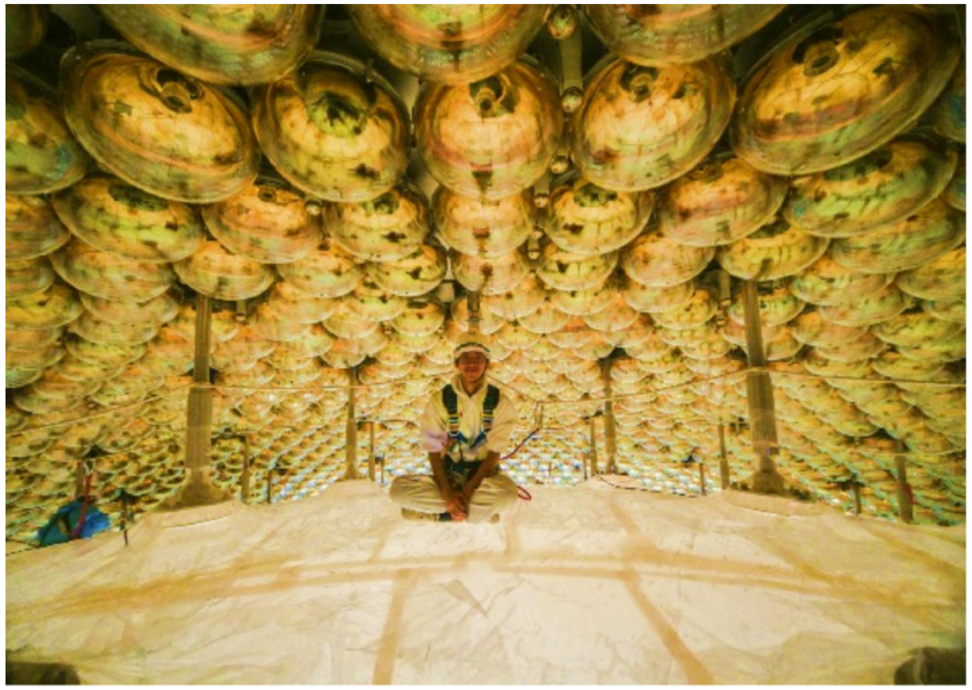
Construction Progress

Steel Support Structure finished



Top hemisphere of acrylic vessel finished



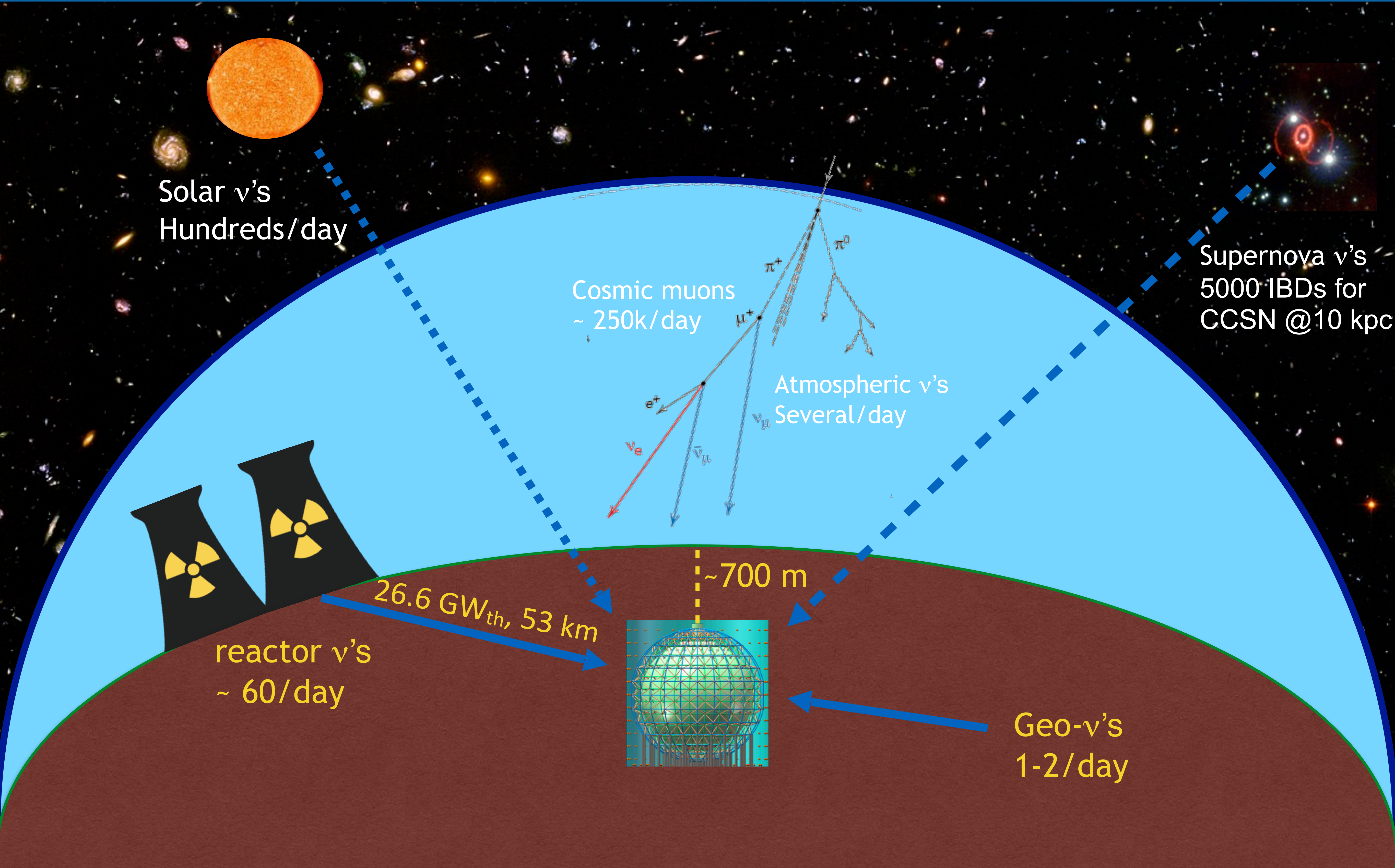


PMT and electronics installation ongoing!

Summary

- JUNO is a precision, multi-purpose experiment with a rich portfolio in neutrino, astroparticle, and new physics searches
- Using its reactor $\bar{\nu}_e$ dataset:
  - NMO measurement to 3σ in about 6 years
  - 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 **data-taking starting next year!**
- Stay tuned for our exciting results!

Neutrinos from Near and Far



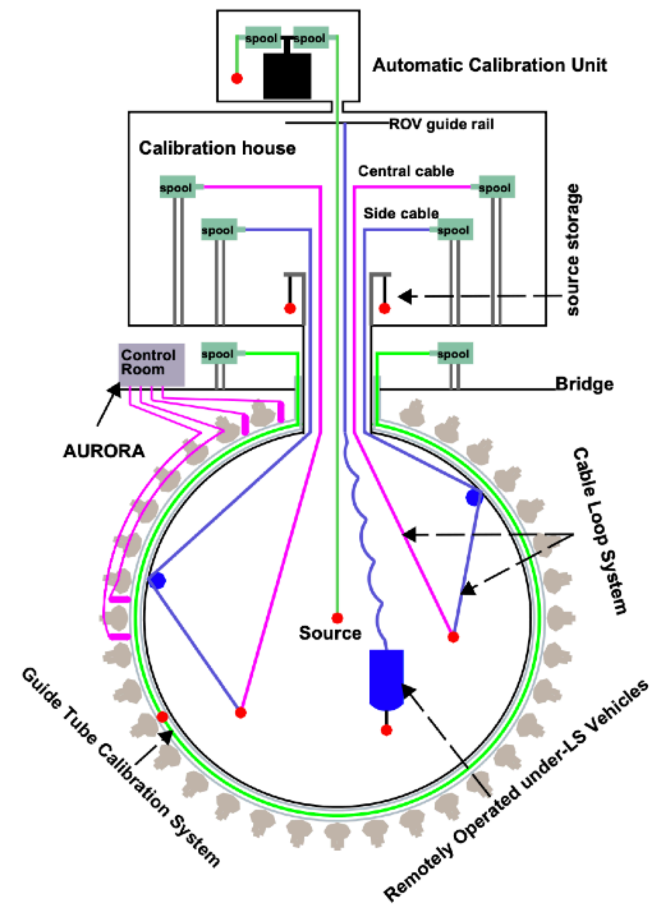
BACKUP

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).