The JUNO Experiment: Towards Data-Taking

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Snowmass Community
Summer Study
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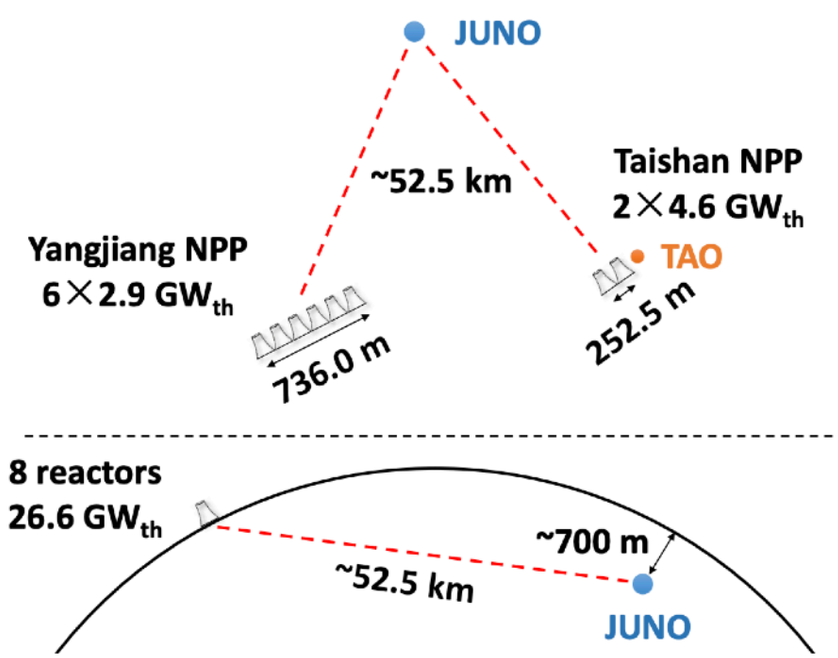
HELMHOLTZ ALLIANCE FOR ASTROPARTICLE PHYSICS

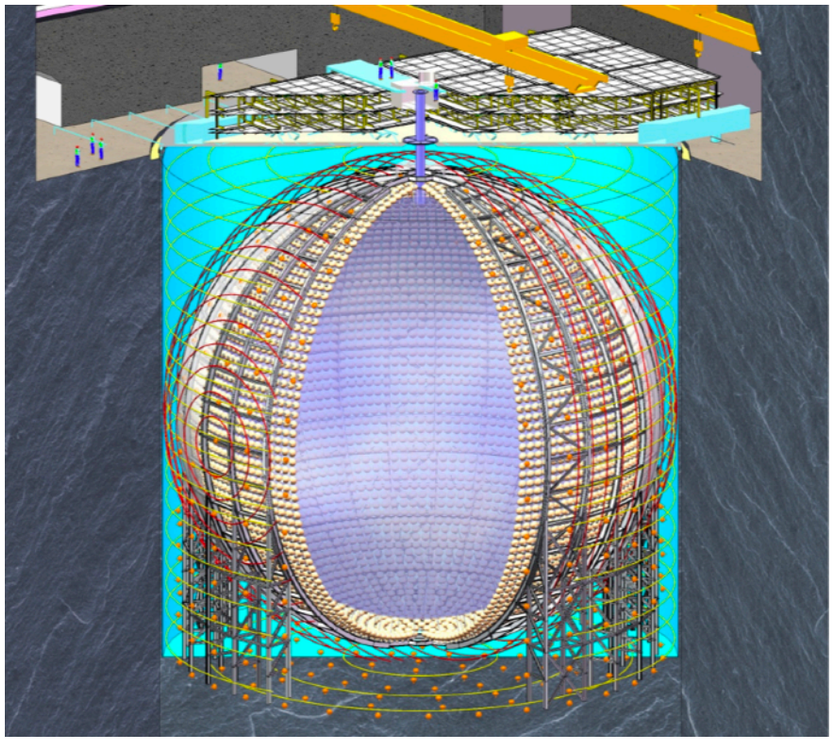
Outline

- Introduction to JUNO
- Physics Goals
- Timeline
- Summary
- US Participation in JUNO

JUNO Overview

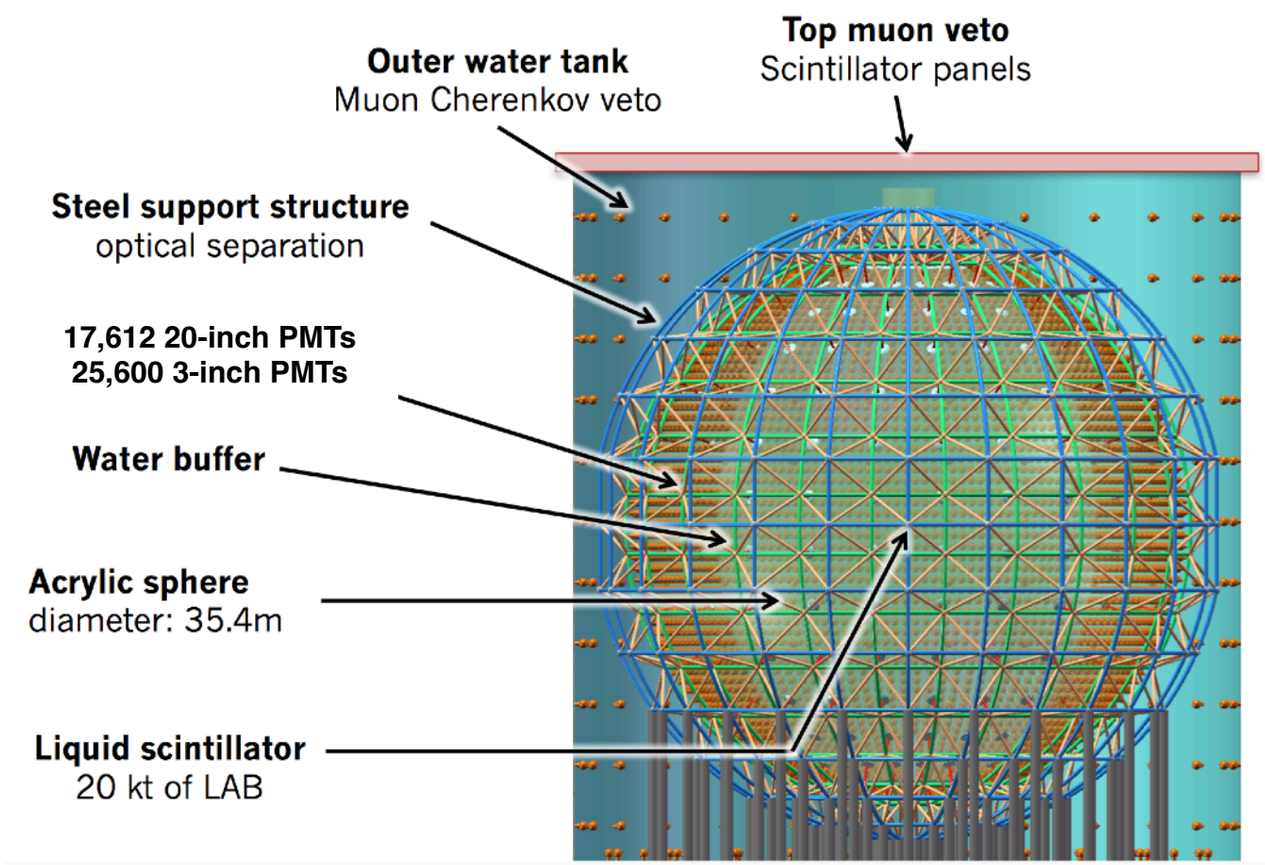
- The Jiangmen Underground Neutrino Observatory (JUNO) is a large liquid scintillator neutrino detector under construction in China
- At 20 kton, it will be the largest detector of its kind ever built
- Multi-purpose experiment with rich physics portfolio
- Main physics goals are neutrino mass ordering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



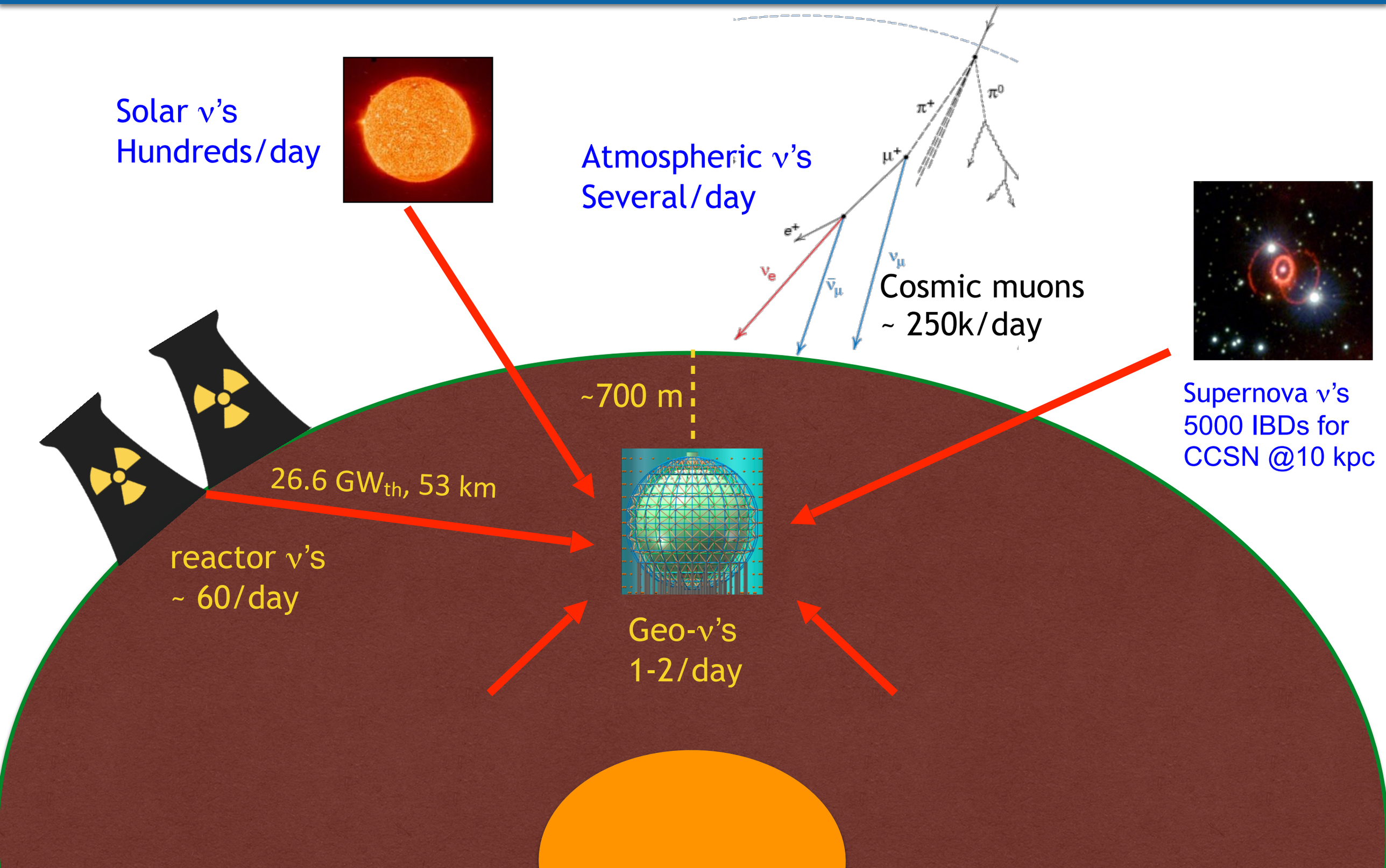


Detector Design

- 35.4 m diameter acrylic sphere filled with 20 kton of liquid scintillator (LS)
- 17,612 20” PMTs (LPMT) and 25,600 3” PMTs (SPMT)
  - >75% 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
- JUNO LS has high light yield and low attenuation length, tested in decommissioned Daya Bay detector
- Unprecedented 3% energy resolution at 1 MeV

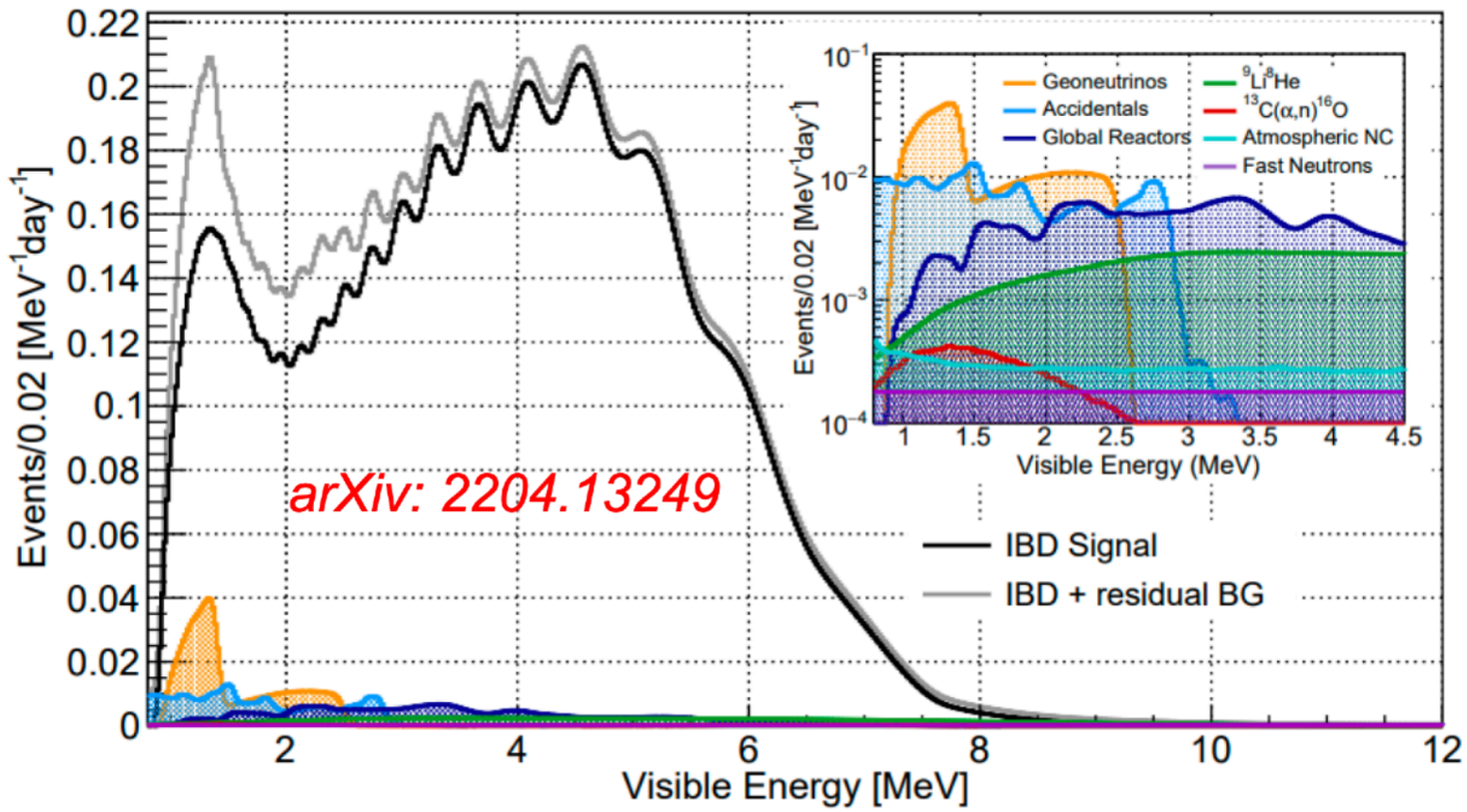


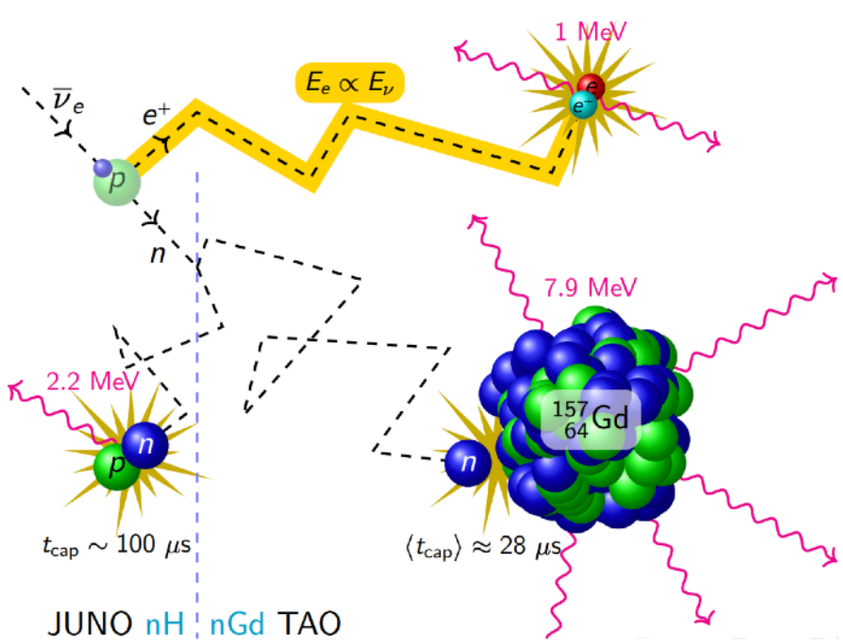
Neutrinos from Near and Far



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 slower neutron (delayed)
  - Coincidence of prompt and delayed signals (with no background events inside a time window) is a reactor neutrino signal
- Maximum matter effect correction of ~4% at 3 MeV

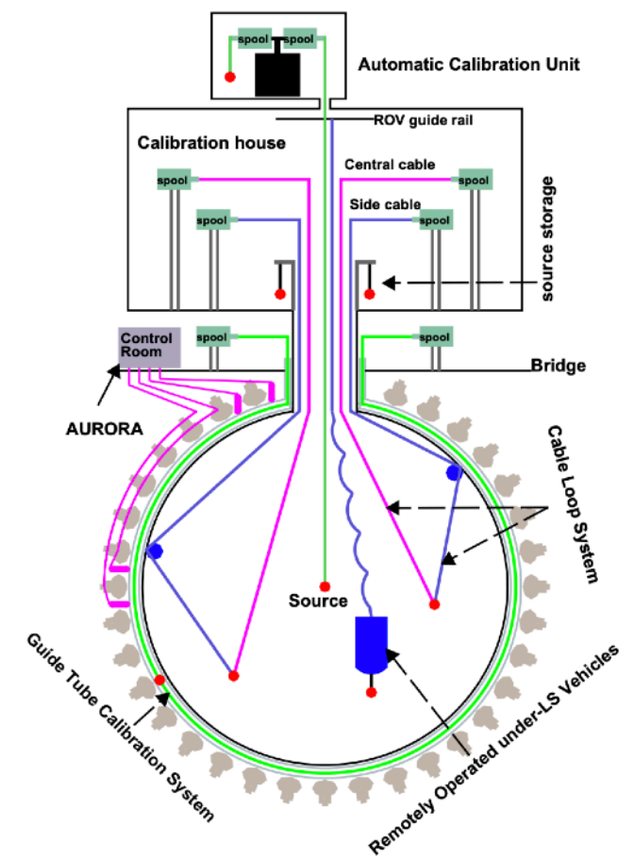




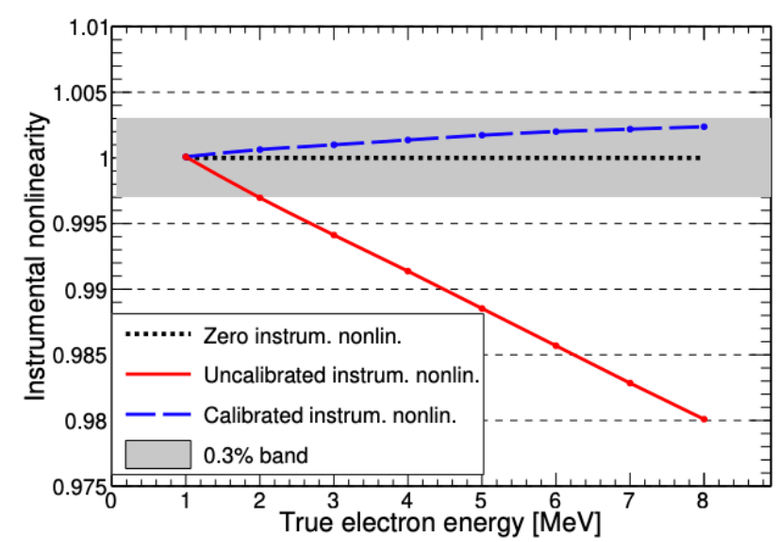
Event Type	Reactor IBD	Geo-ν	Accidentals	Fast-n	9Li/ 8He	Alpha-n	Global Reactor	Atm.-ν
Rate [per day]	47	1.2	0.8	0.1	0.8	0.05	1	0.16

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%



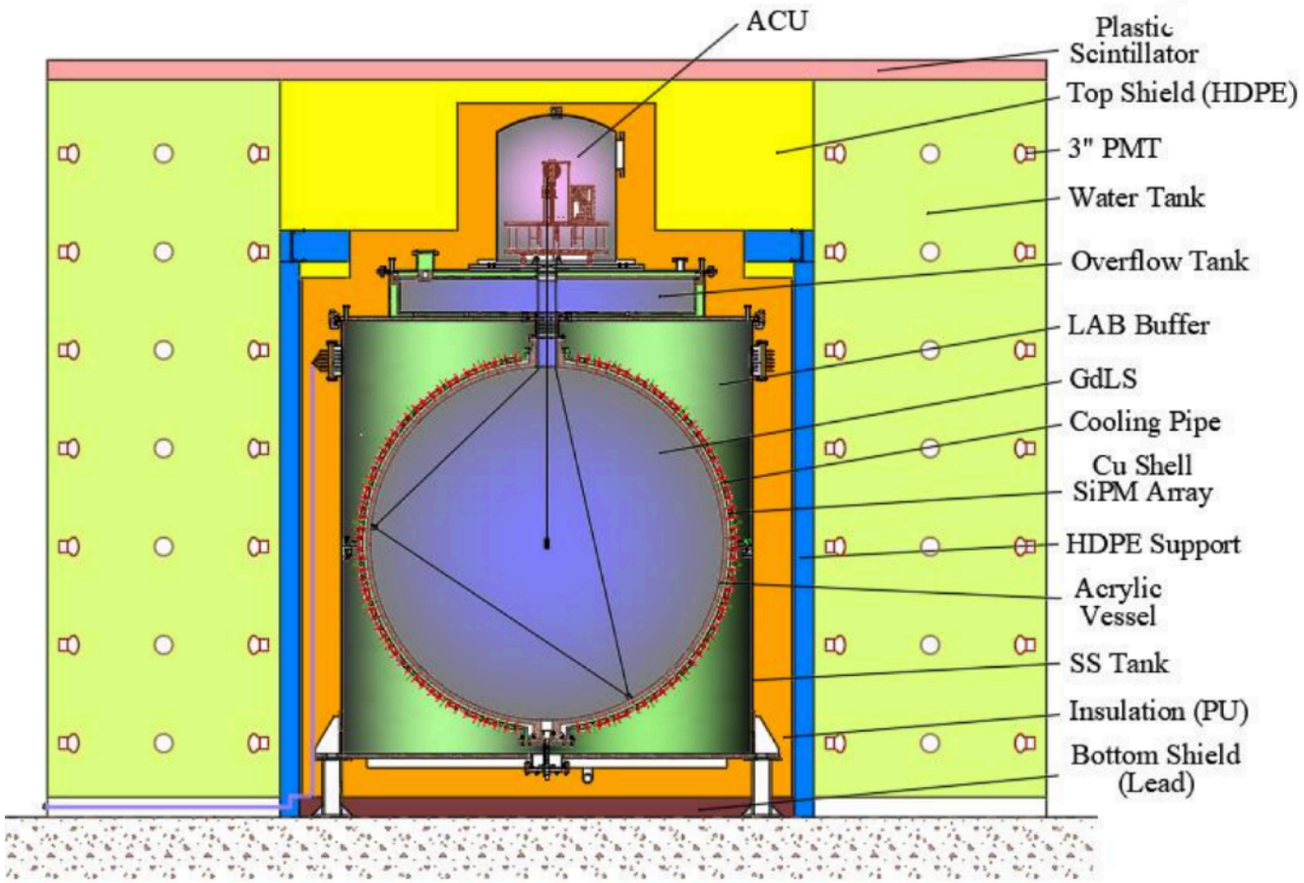
J. High Energy. Phys. **2021,** 4 (2021).



JUNO-TAO

- JUNO-TAO (Taishan Antineutrino Detector) will be a satellite detector
  - 35 m from 4.6 GW_{th} reactor
  - ~1 ton GdLS fiducial volume
  - Instrumented with SiPM providing <2% at 1 MeV energy resolution

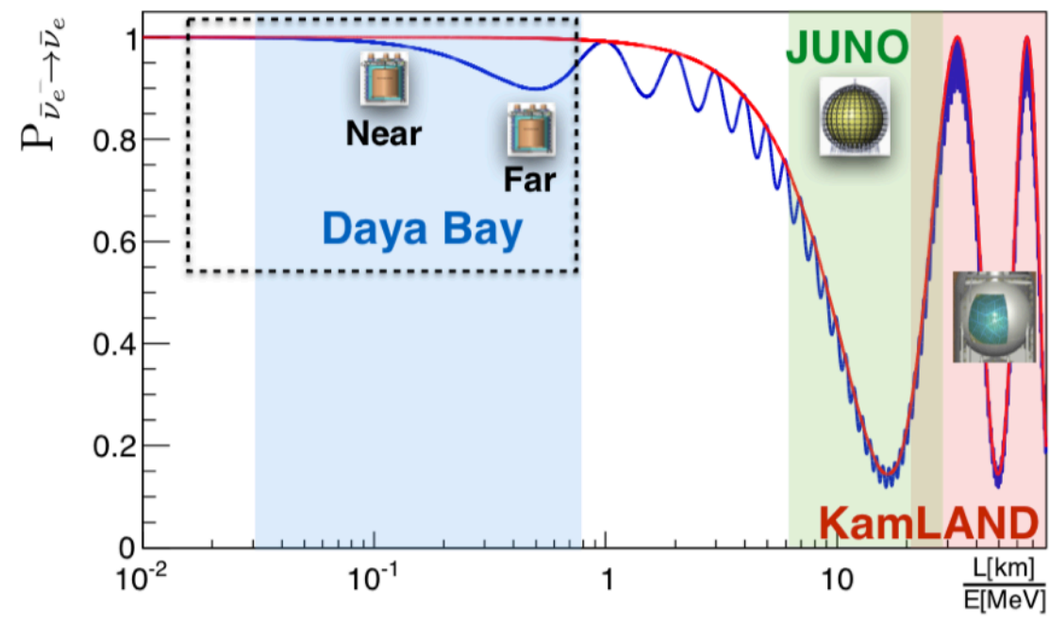
- **Measure reactor antineutrino energy spectrum** with excellent resolution
  - Reference spectrum for JUNO, removing possible model dependence from NMO measurement
  - Search for sterile neutrinos
  - Decomposition into isotopic spectra



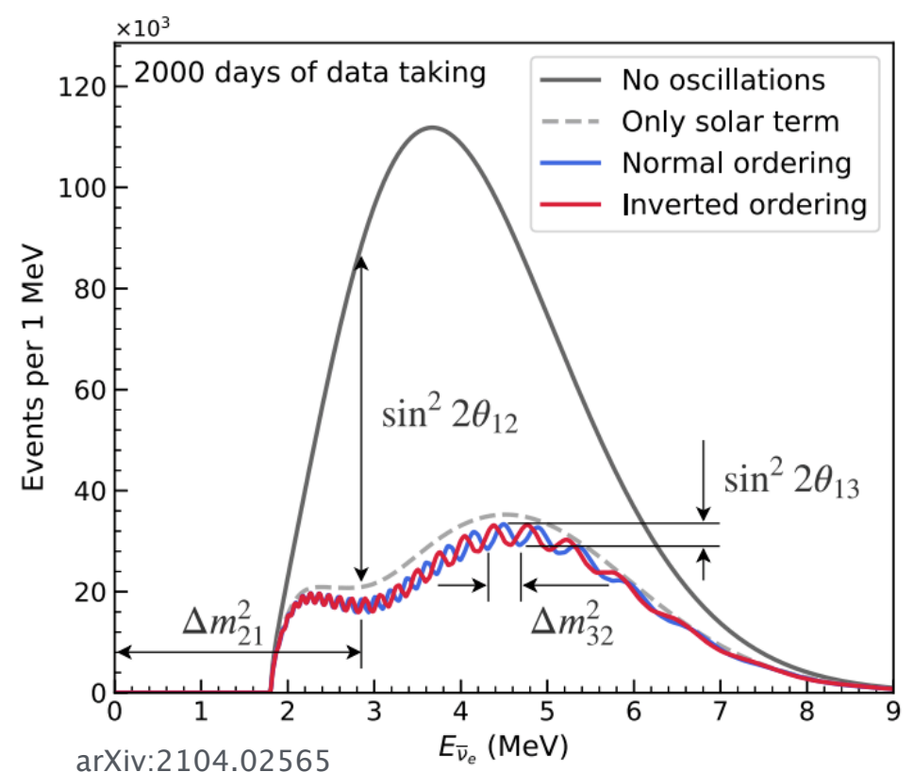
arXiv: 2005.08745

Reactor $\bar{\nu}_e$: Oscillations Program

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



- 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}
  - Complementary to accelerator measurement (different baseline and technology)



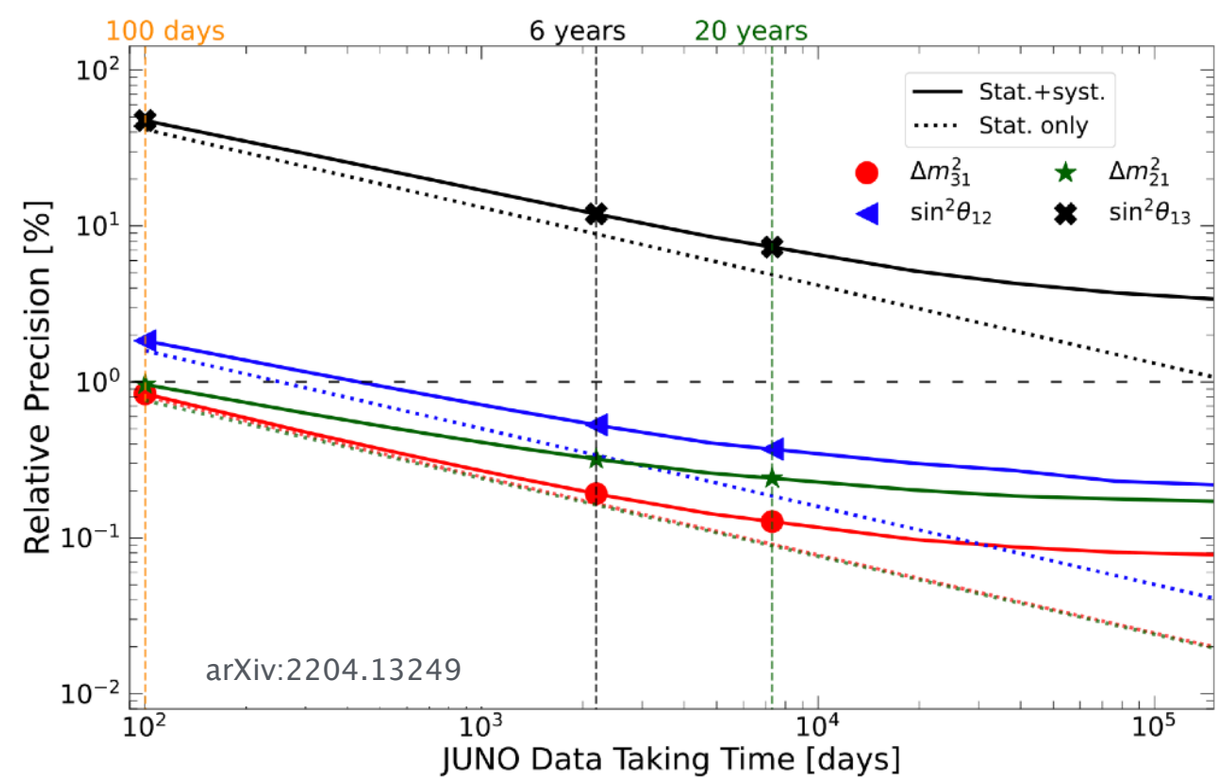
- Observation of $\theta_{12}, \theta_{13}, \Delta m^2_{21}$, and Δm^2_{32} driven oscillations

Reactor $\bar{\nu}_e$: Oscillation Sensitivities

- ~3σ NMO sensitivity in 6 years
  - Independent of δ_{cp}, octant of θ_{23}
  - Complementary to accelerator measurement (different baseline and technology)
- Measurement of $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to sub-percent precision
  - About an order of magnitude improvement in precision over existing constraints
  - Precision tests of neutrino oscillations and U_{PMNS} unitarity (1%)

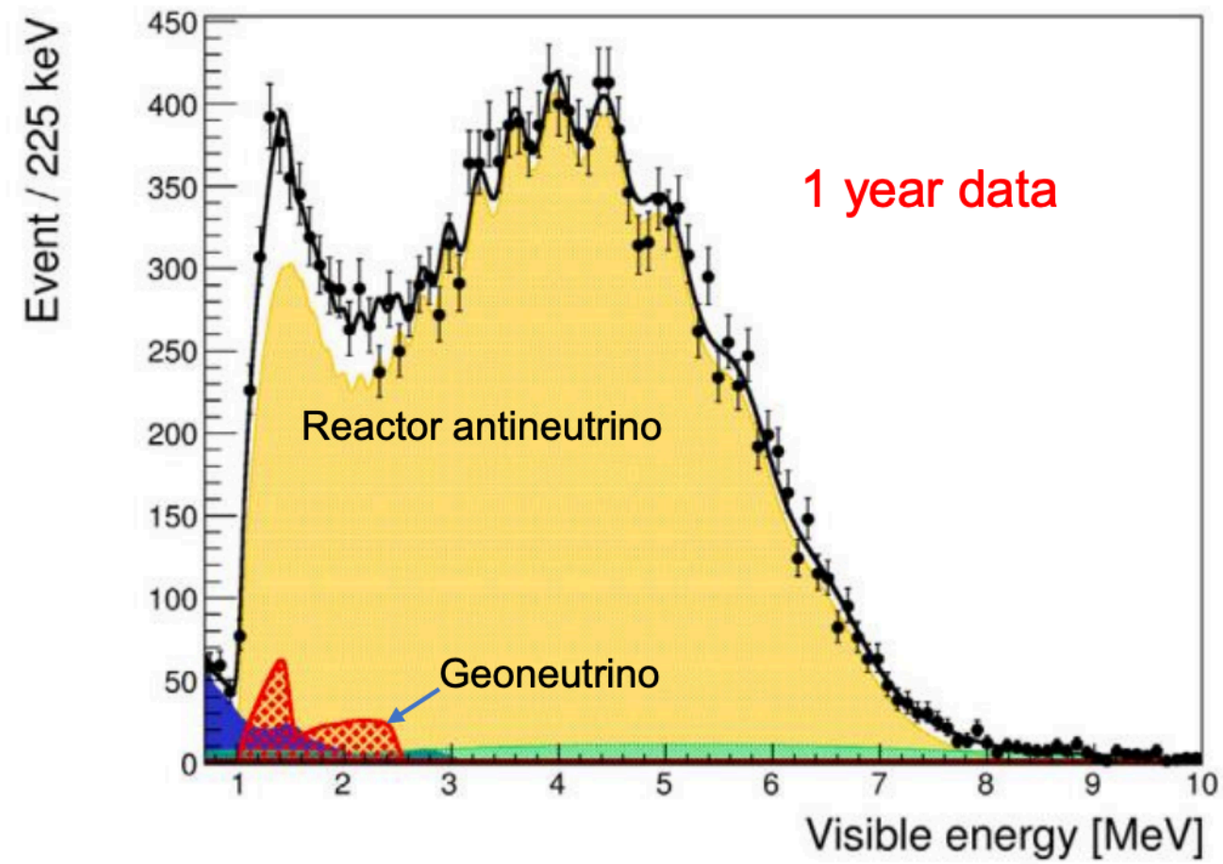
JUNO Relative Uncertainty vs. Leading Experiments

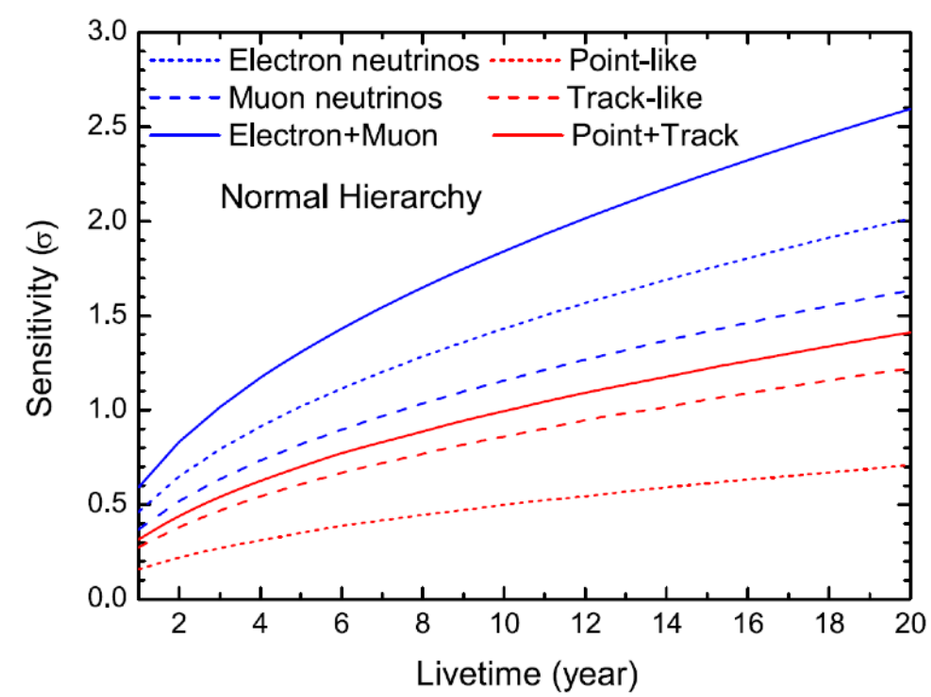
	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 100 days	0.8%	1%	1.9%	47.9%
JUNO 20 years	0.1%	0.2%	0.3%	7.3%
KamLAND	2.4%	-	-	-
T2K	-	2.6%	-	-
SNO+SK	-	-	4.5%	-
Daya Bay	-	-	-	3.4%



Geoneutrinos and Atmospherics

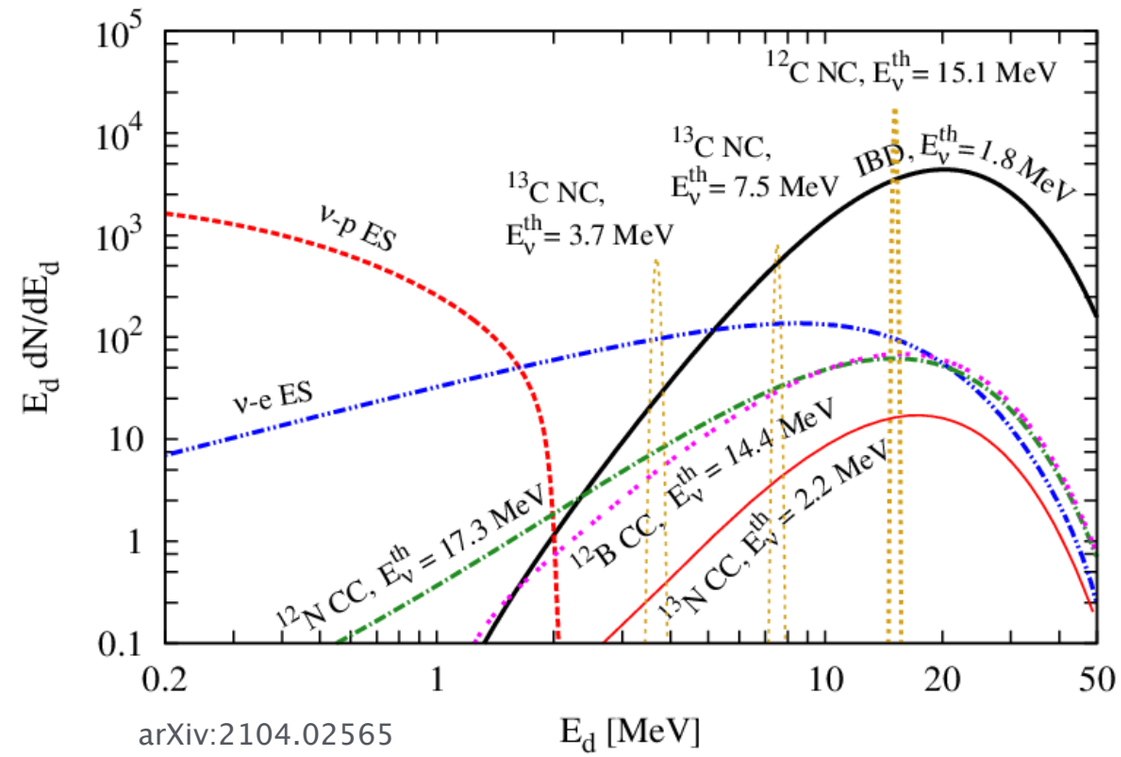
- Geoneutrinos $\bar{\nu}_e$ from $^{238}U/^{232}Th$ in Earth's crust and mantle
  - Development of local crust model underway
- 400-500 geoneutrino events a year:
  - ~5% precision on flux (fixed U/Th ratio) in 10 years
  - Will supersede combined KamLAND and Borexino statistics in less than a year
- Atmospheric Neutrinos: Independent constraint of NMO through matter effect





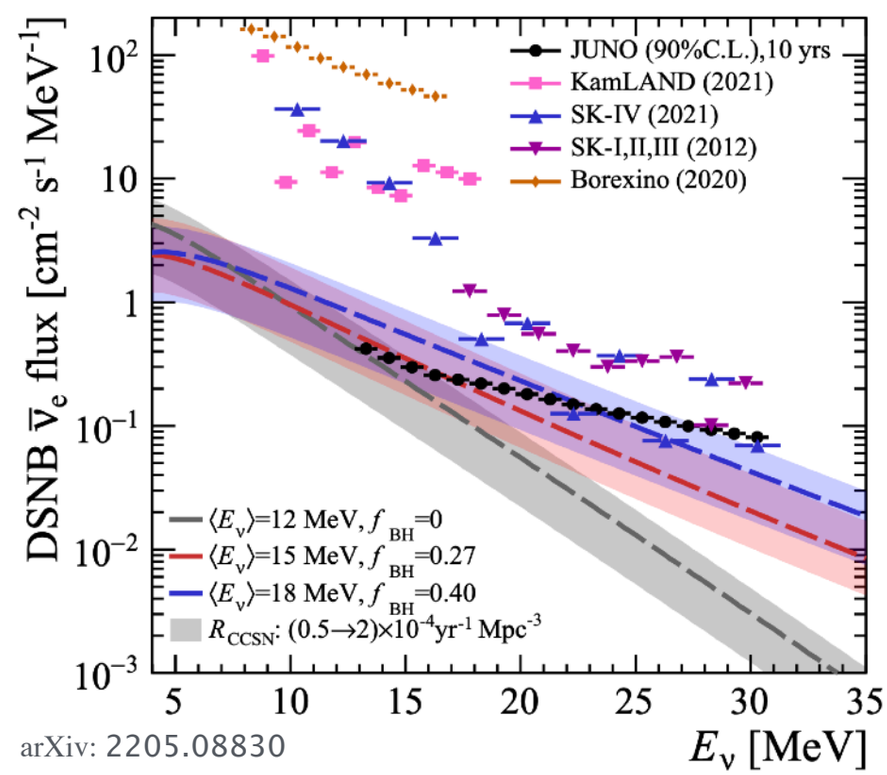
Supernova Neutrinos

- Study of flavor composition, time evolution, and energy spectrum of supernova (SN) burst neutrinos
  - Low detection threshold (sub-MeV)
  - 5000 detected IBDs for SN @ 10 kpc



arXiv:2104.02565

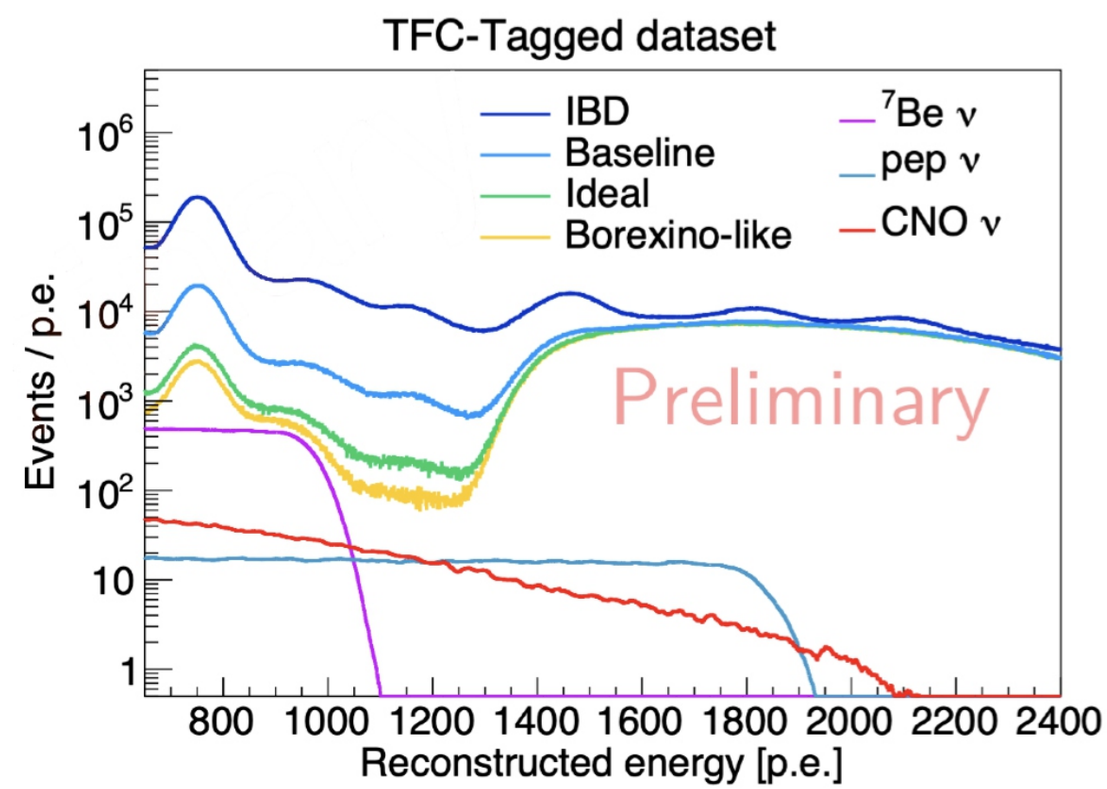
- Diffuse Supernova Neutrino Background
  - Expected detection significance of ~3σ after 10 years

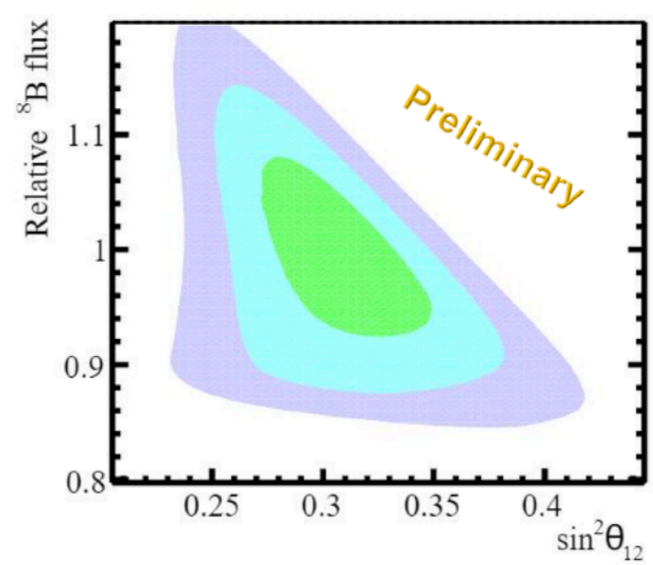


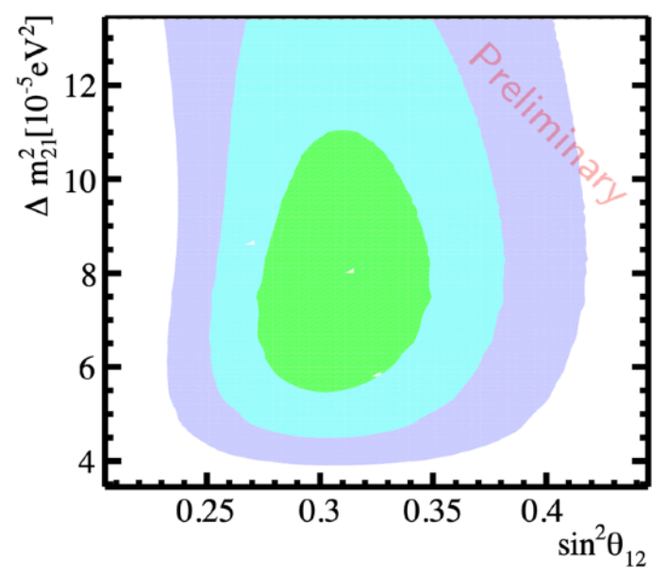
arXiv: 2205.08830

Solar Neutrinos

- Measurement of ^{8}B and ^{7}Be neutrino fluxes
- Background a challenge for this analysis: aiming for 10^{-17} g/g U/Th isotopes
- Δm^2_{21} measurement with reactor and solar neutrinos in one detector
- Explore solar metallicity problem
- Observe ν_e regeneration through MSW effect caused by solar neutrino propagation through Earth at night

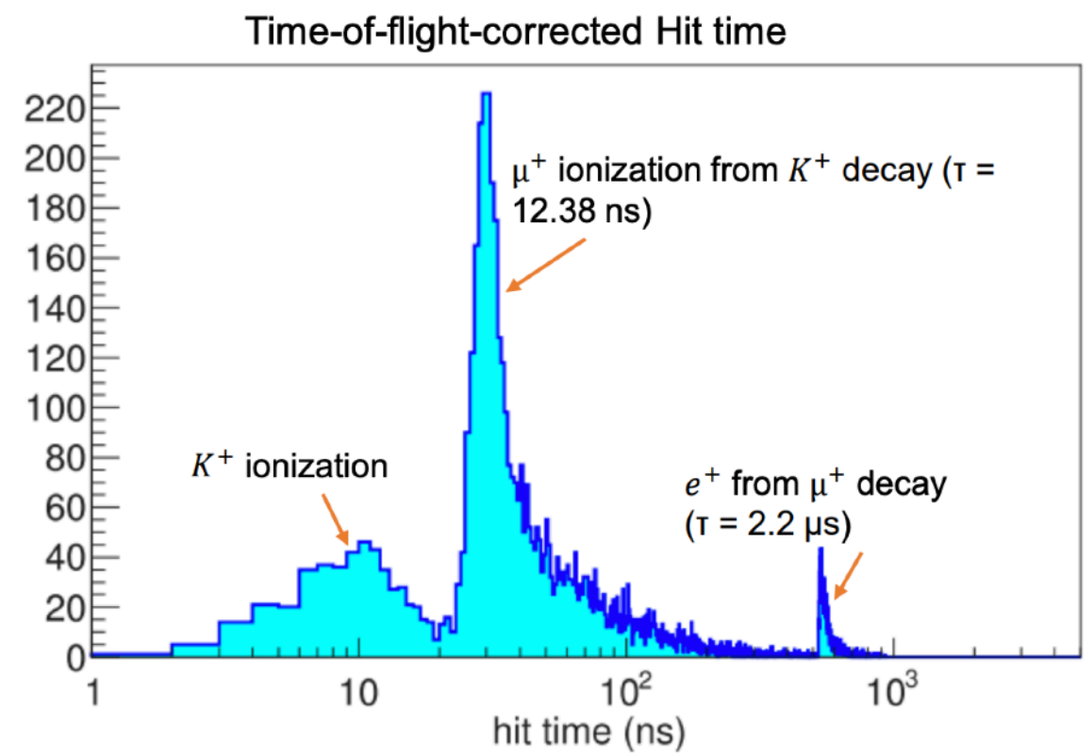


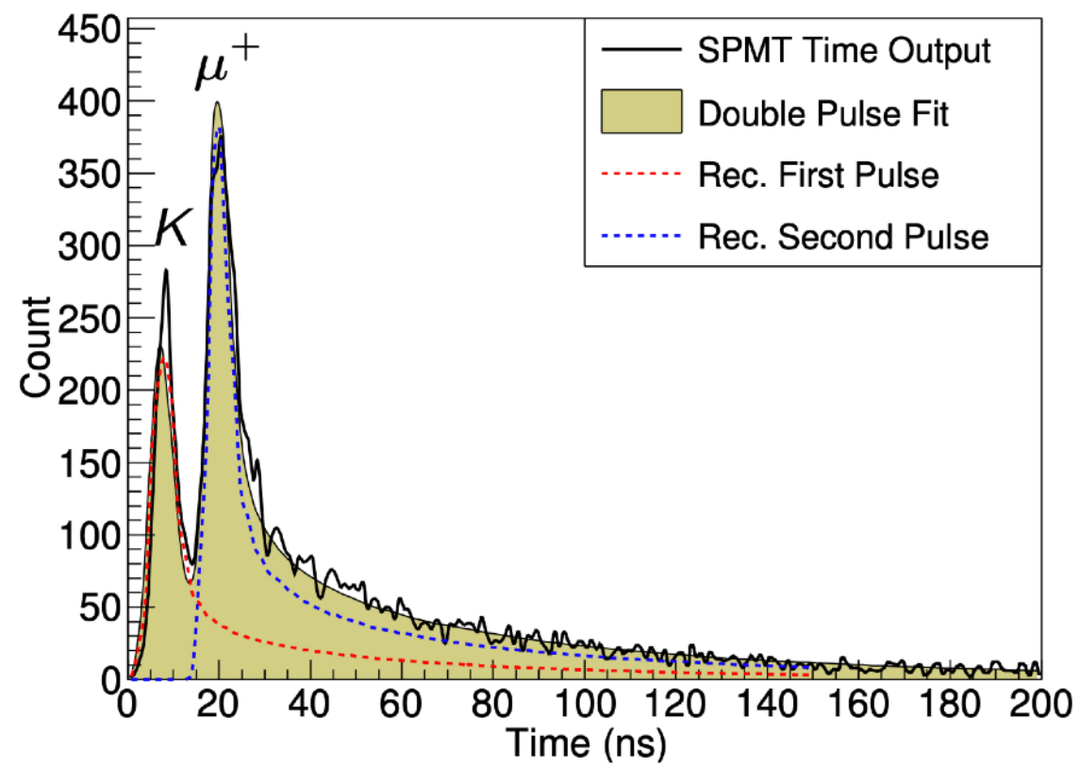




Nucleon Decay

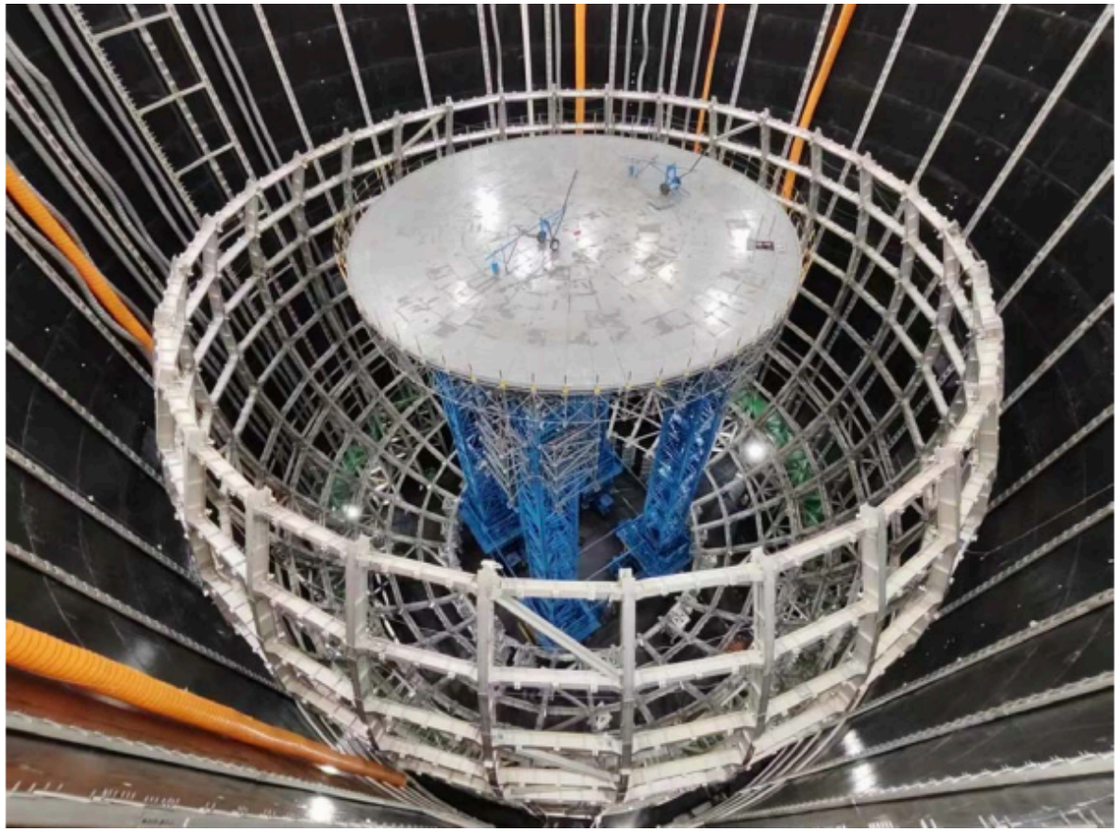
- Will exploit triple coincidence in $p \rightarrow \bar{\nu} + K^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ channel
- Nanosecond time discrimination of first two signals allowed by 3-inch PMT system
- Good sensitivity: 8.34×10^{33} **s** 90% CL in 10 years for $p \rightarrow \bar{\nu} + K^+$ channel



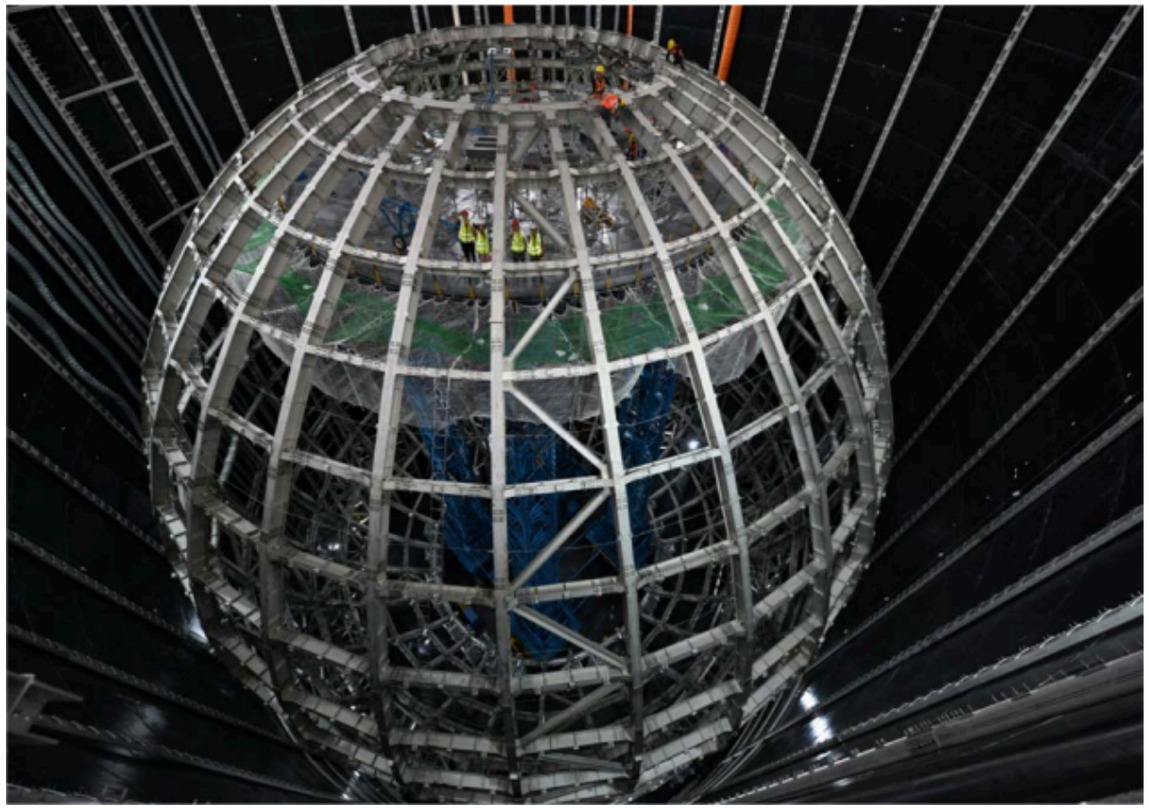


Construction Progress

Installation Platform finished (May 2022)



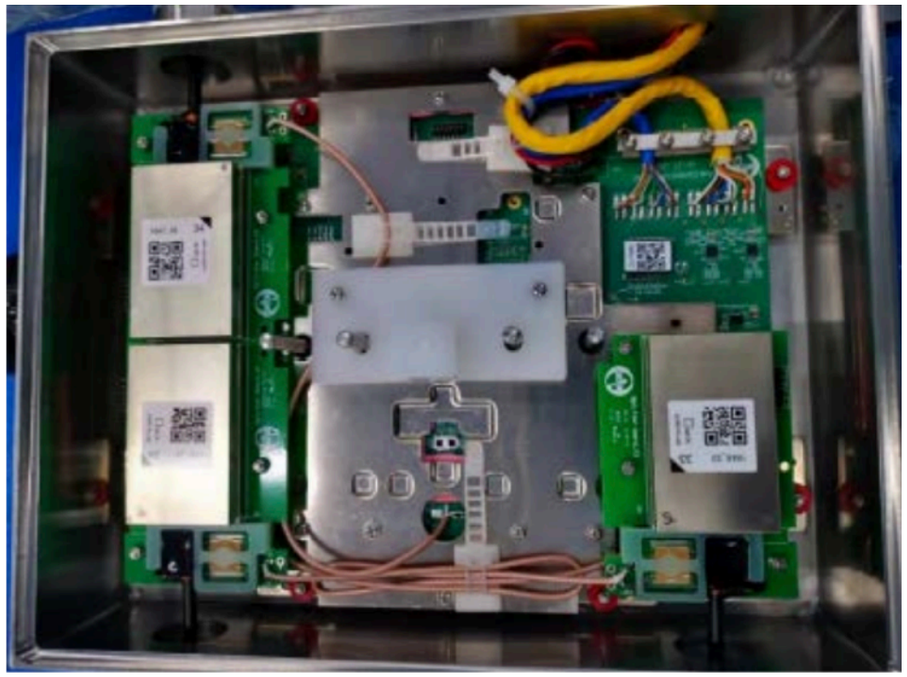
Steel Support Structure finished (June 2022)



Construction Progress (cont.)

Liquid Scintillator Hall under construction

Electronics produced and undergoing testing



Large PMTs potted and tested

Acrylic panels finished

Timeline

2014
Collaboration formed

2015
Civil construction started

2016
PMT production and testing started

2018
Testing PMTs
Central Detector 1:12 prototype

2019
LPMT potting started

2020
PMT preparation ends

2021
PMT installation begins

2022 - Now
Installation and Construction

2023
Detector Completion

Detector Completion Expected in 2023

US Participation in JUNO

- University of California, Irvine
  - SPMT system hardware: HV system, underwater boxes, commissioning, etc.
  - Measurement of Oscillation Parameters
  - Double Calorimetry Calibration (Large + Small PMT)
- University of Maryland, College Park
  - Characterization of the global and local geoneutrino signal

Summary

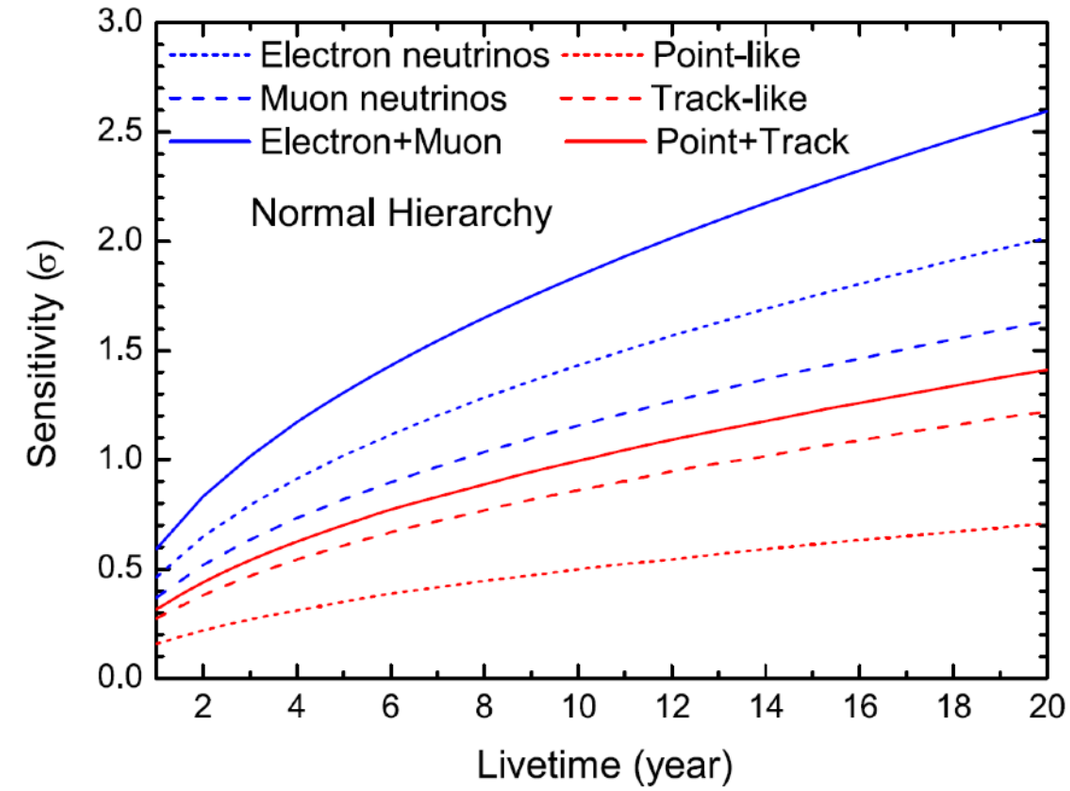
- JUNO is a multi-purpose experiment with a rich portfolio in neutrino, astroparticle, and exotic physics
- JUNO is pushing the envelope of liquid scintillation detection technology, with innovative ideas in calibration and design to take it to unprecedented sensitivity and results
- Much progress has been done, with detector construction to finalize in 2023
- Stay tuned for our exciting results!

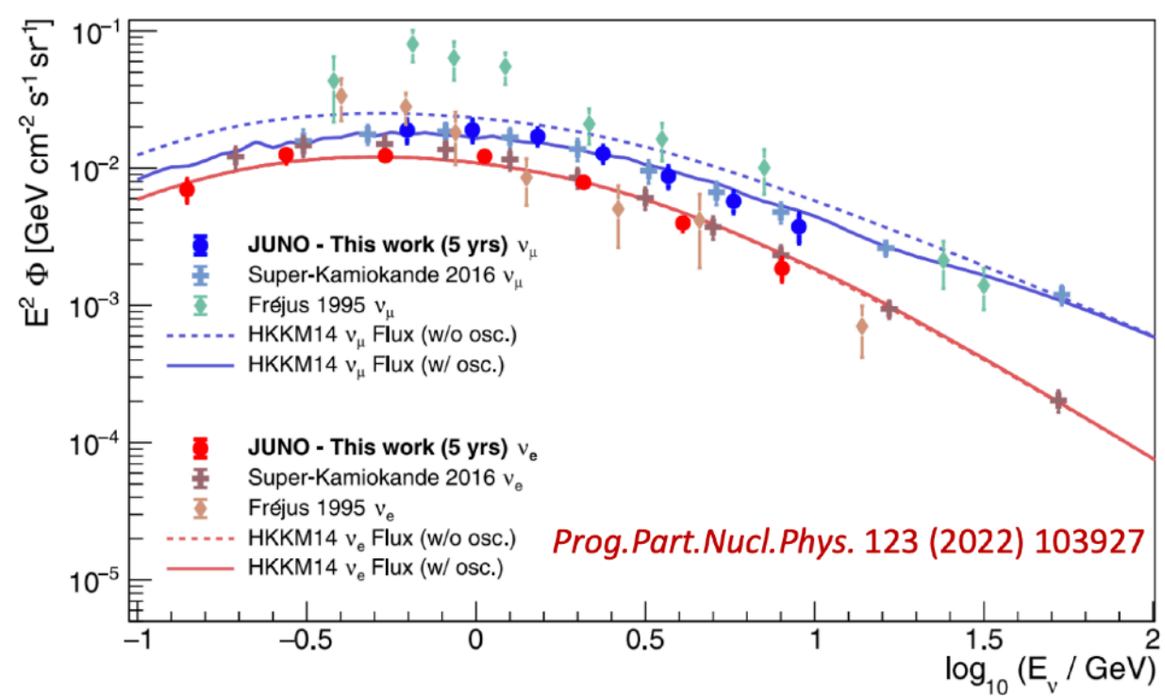
Backup: Atmospheric Neutrinos

- Independent constraint of NMO through matter effect

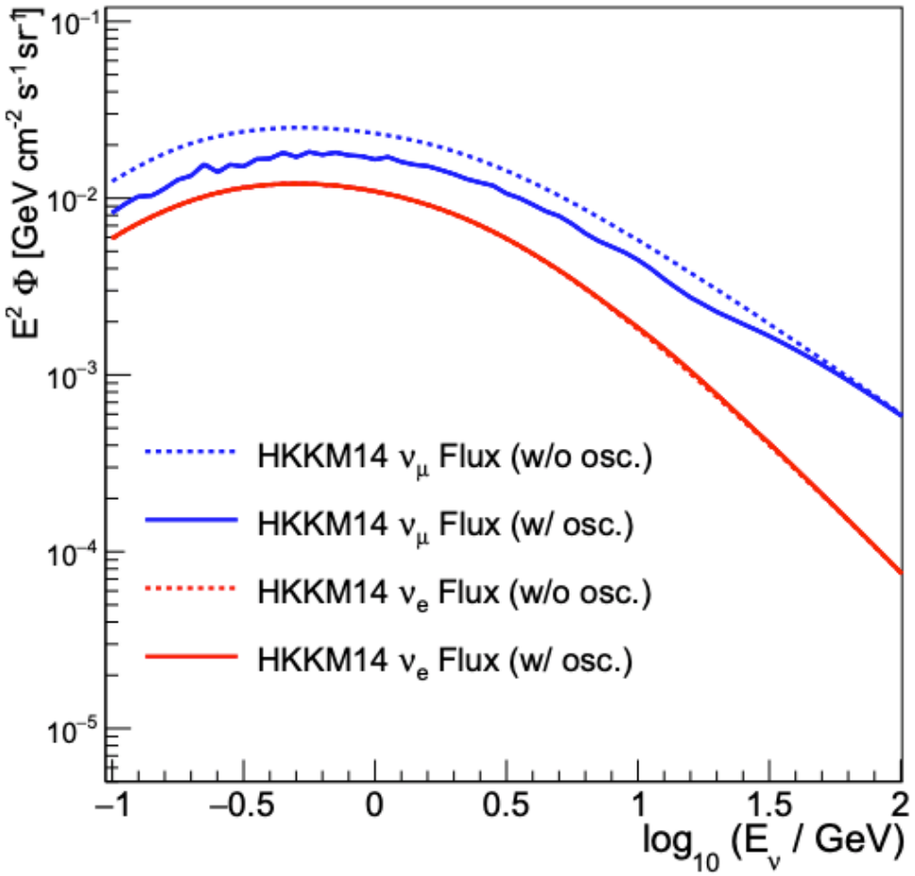
- Measurement of low energy atmospheric neutrino spectra (100 MeV - 10 GeV)

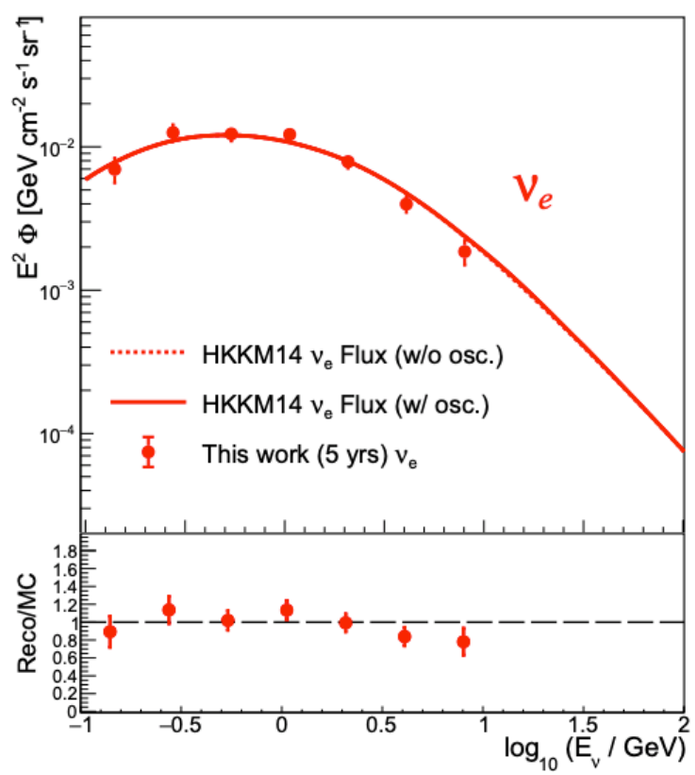
- Combined reactor + atmospheric NMO analysis in progress

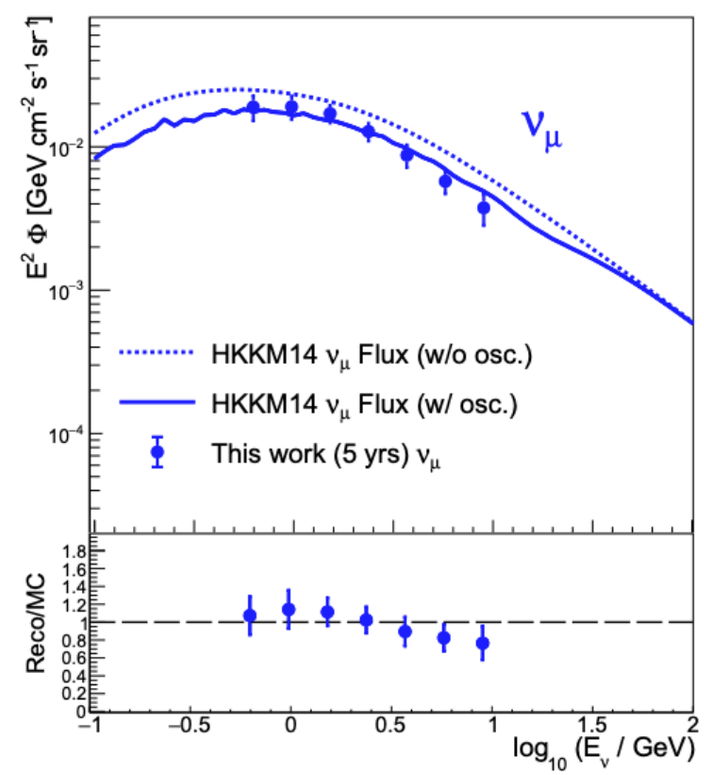




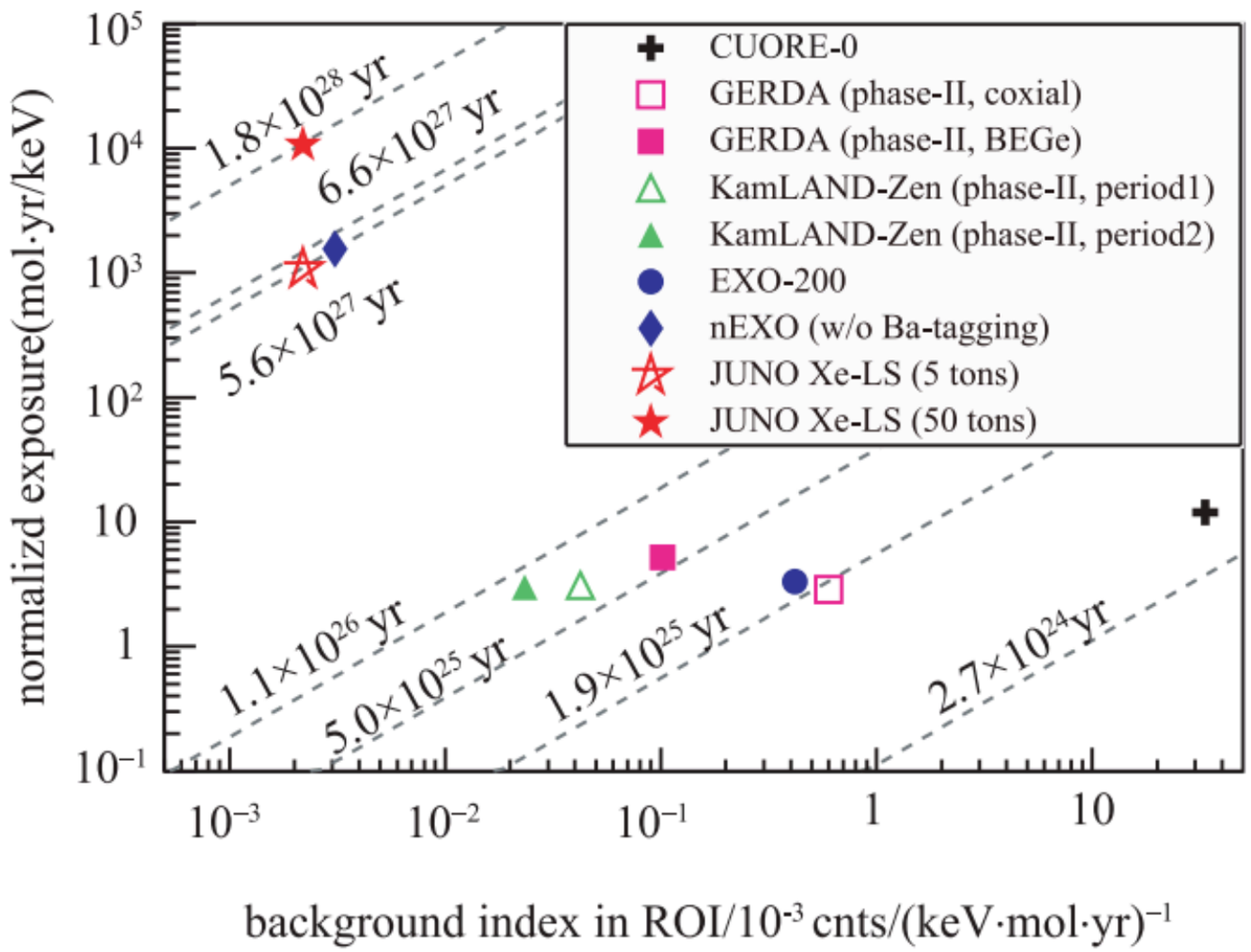
Backup: Atmospheric Fluxes

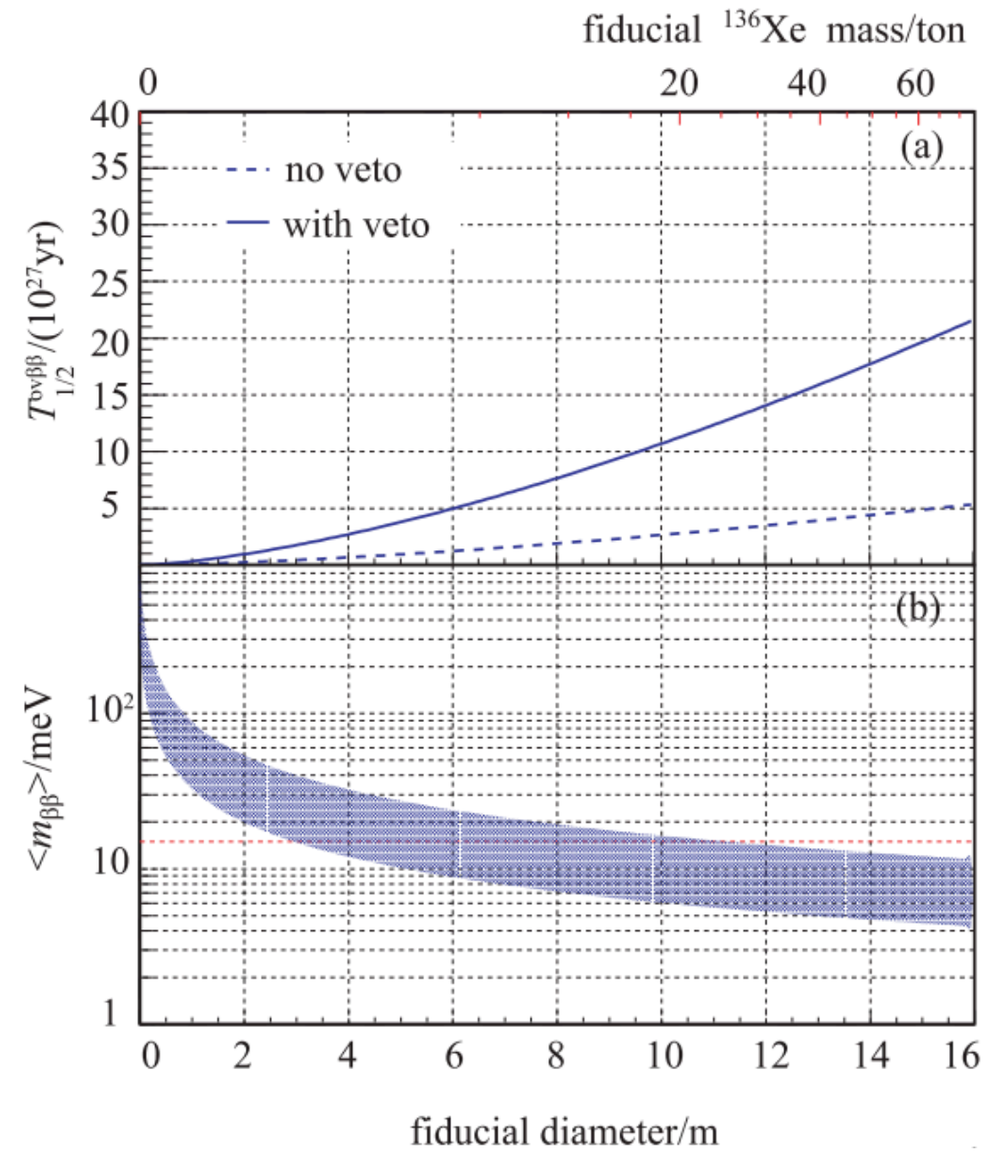






Backup: Neutrino-less Double Beta





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