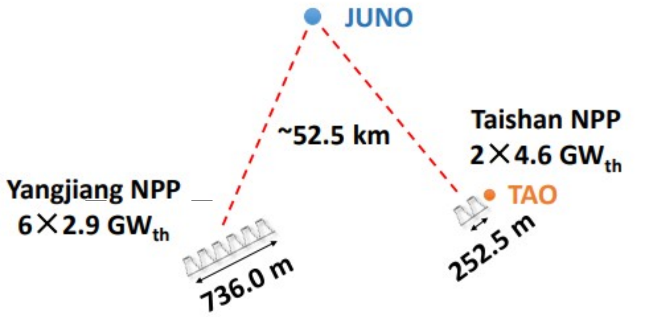
The JUNO experiment: Status and Prospects

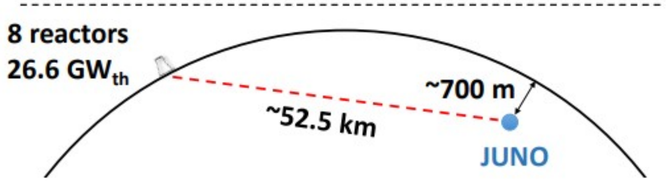
Sindhujha Kumaran, University of California Irvine
for the JUNO collaboration

Rencontres du Vietnam, 30^{th} anniversary, Aug 6-12, 2023

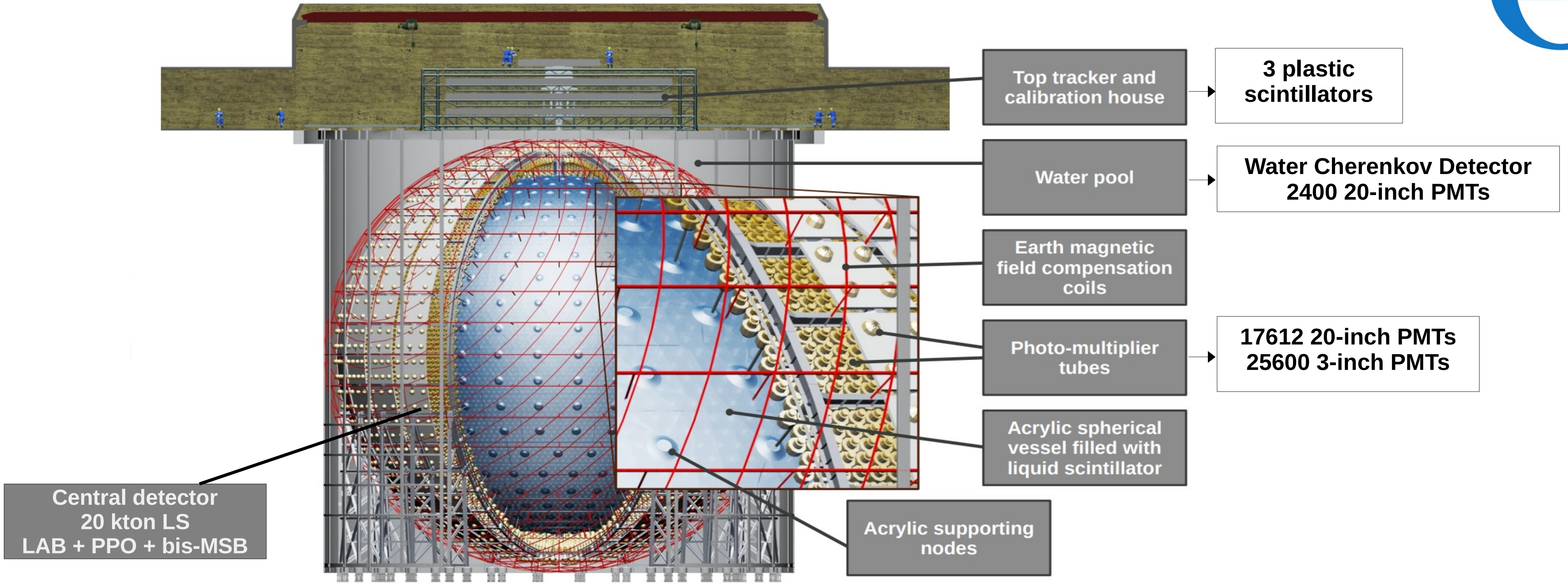
JUNO experiment overview

- The Jiangmen Underground Neutrino Observatory (JUNO) is located at Jiangmen, Guangdong, China
- 20 kton Liquid Scintillator (LS) detector
- Main goal: study reactor neutrino oscillations at medium baseline
- Wide range of physics prospects
- Small satellite detector TAO near one of the Taishan reactors





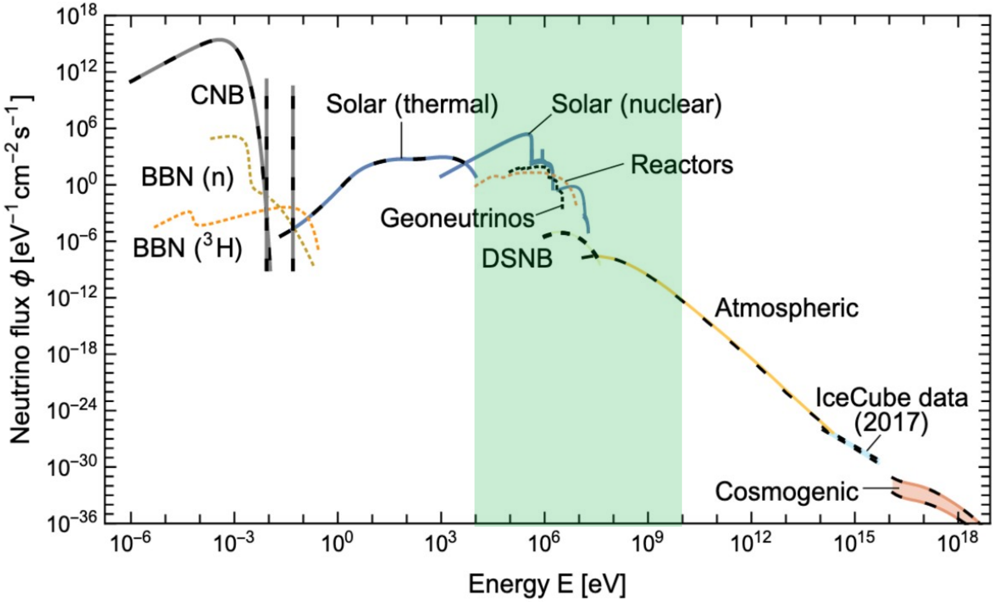
The JUNO detector



Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	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	> 1345 p.e./ MeV

JUNO: physics potential

JUNO energy region

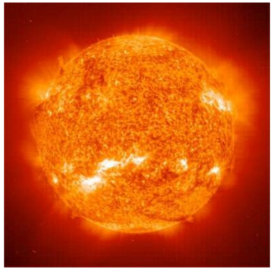


E. Vitagliano et al., Rev. Mod. Phys. 92 (2020) 045006
Note: fluxes are averaged

Reactor

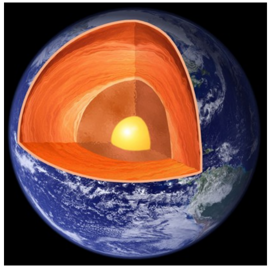
~50/day

Solar



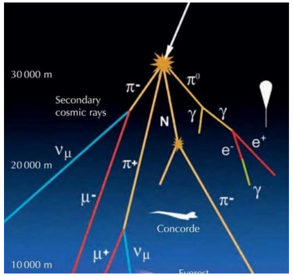
~2000/day

Geo



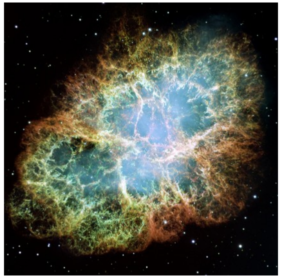
~1/day

Atmospheric



10-20/day

Supernova



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

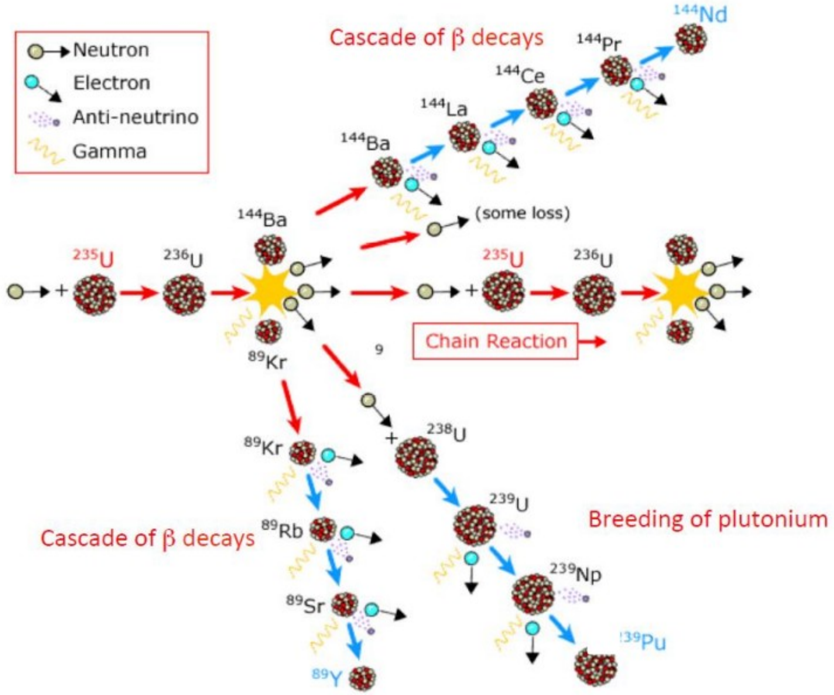
DSNB: few/year

\+ **New Physics**

Proton decay
NSI
Sterile neutrinos
Neutrino magnetic moment
.
.

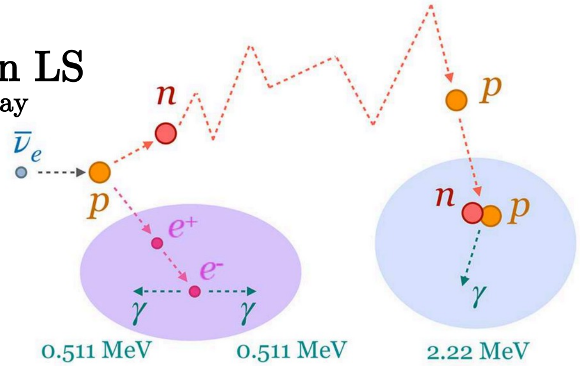
Reactor antineutrinos

Production



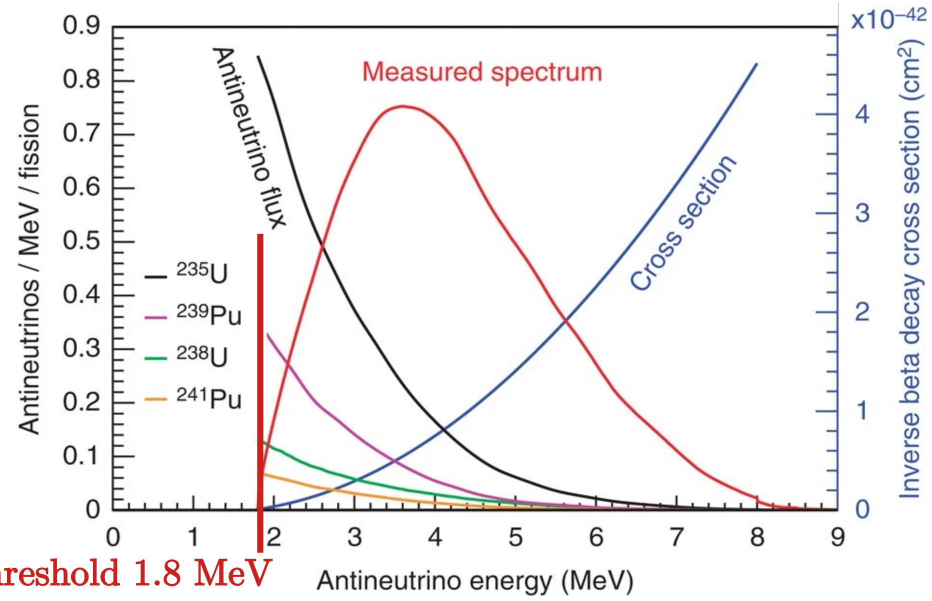
Detection in LS

Inverse Beta Decay



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

$$E_{vis}\ (e^+) \simeq E_\nu - 0.78\ \text{MeV}$$



Reactor neutrino oscillations

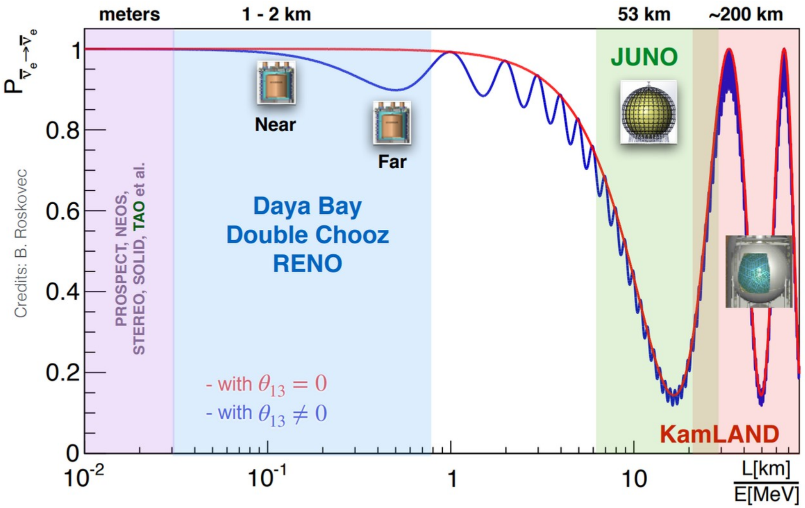
Survival probability:

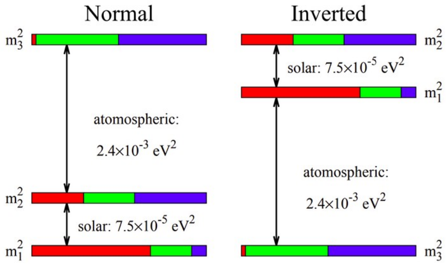
$$\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\widetilde{\theta}_{12}\, \widetilde{c}^4_{13} \sin^2 \widetilde{\Delta}_{21} - \sin^2 2\widetilde{\theta}_{13} \left(\widetilde{c}^2_{12} \sin^2 \widetilde{\Delta}_{31} + \widetilde{s}^2_{12} \sin^2 \widetilde{\Delta}_{32} \right)$$

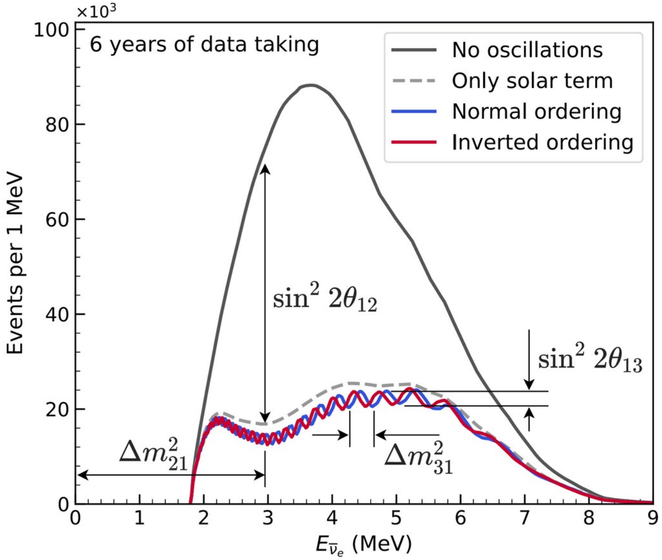
$$= 1 - \sin^2 2\widetilde{\theta}_{12} \widetilde{c}^4_{13} \sin^2 \widetilde{\Delta}_{21} - \frac{1}{2} \sin^2 2\widetilde{\theta}_{13} \left(\sin^2 \widetilde{\Delta}_{31} + \sin^2 \widetilde{\Delta}_{32} \right)$$

$$- \frac{1}{2} \cos 2\widetilde{\theta}_{12} \sin^2 2\widetilde{\theta}_{13} \sin \widetilde{\Delta}_{21} \sin(\widetilde{\Delta}_{31} + \widetilde{\Delta}_{32}),$$

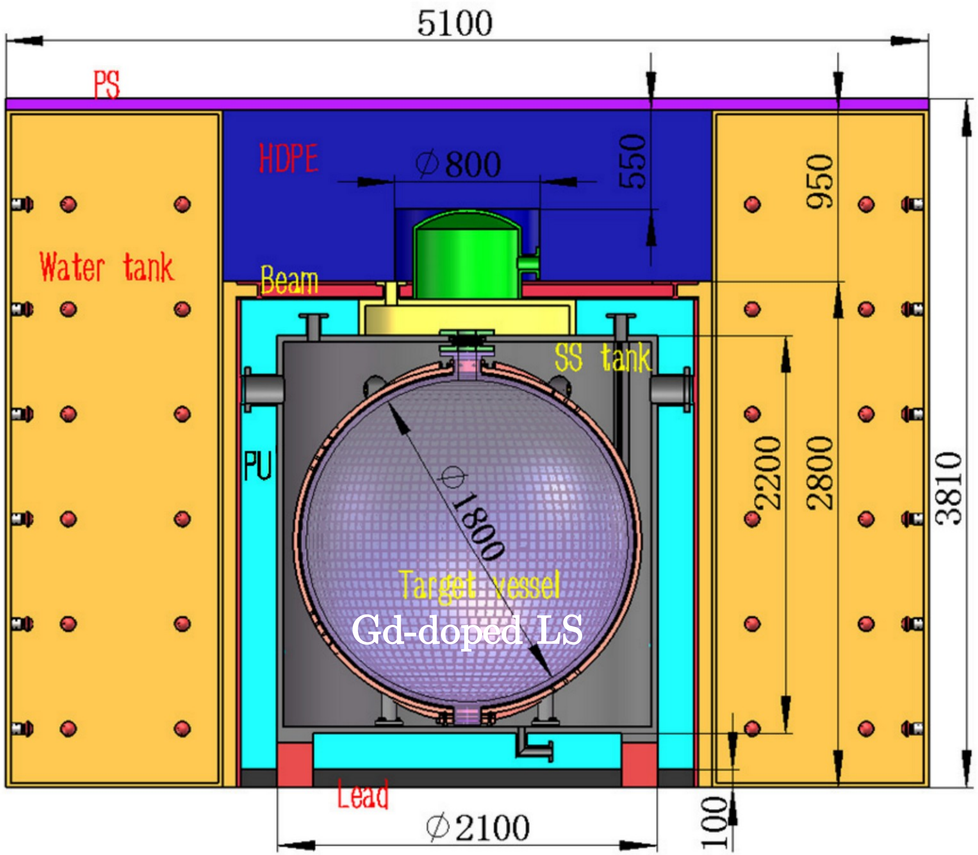
- JUNO has the potential to determine neutrino mass ordering as well as to measure Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ at $< 1\%$ precision level
- Requirements:
  - Large statistics
  - Excellent energy resolution (3% at 1 MeV)
  - Good knowledge of reactor antineutrino spectral shape
  - Low background (rock overburden ~650 m, efficient muon veto >99.5%)







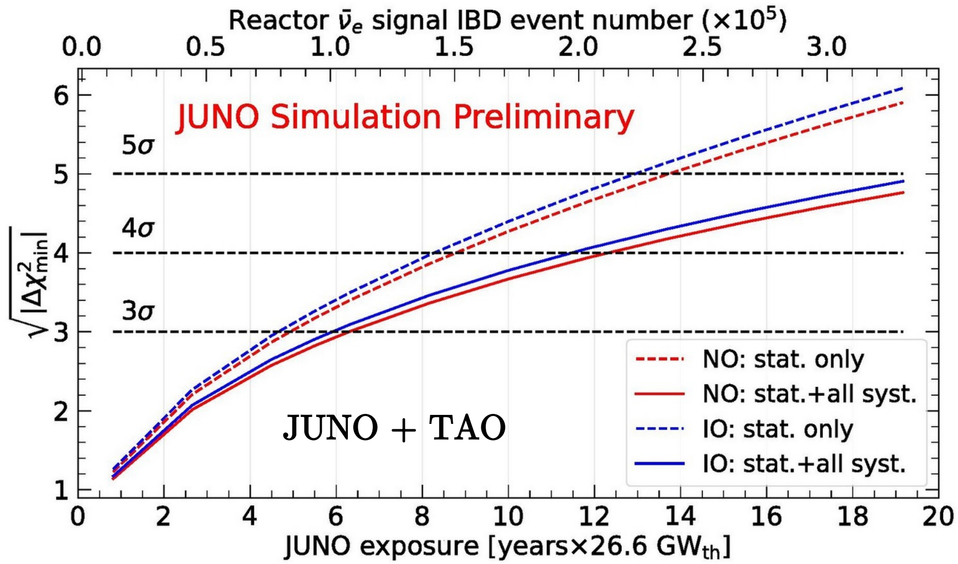
JUNO-TAO detector



arXiv:2005.08745

- Provide a reference spectrum for JUNO, eliminating the possible model dependence due to fine structure in the reactor antineutrino spectrum in determining the neutrino mass ordering
- ~40 m from one of Taishan's 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
- $\geq$94% photo-coverage
- 30× JUNO event rate

Neutrino mass ordering



Paper under preparation

- Fit the spectrum under the normal and inverted ordering hypotheses

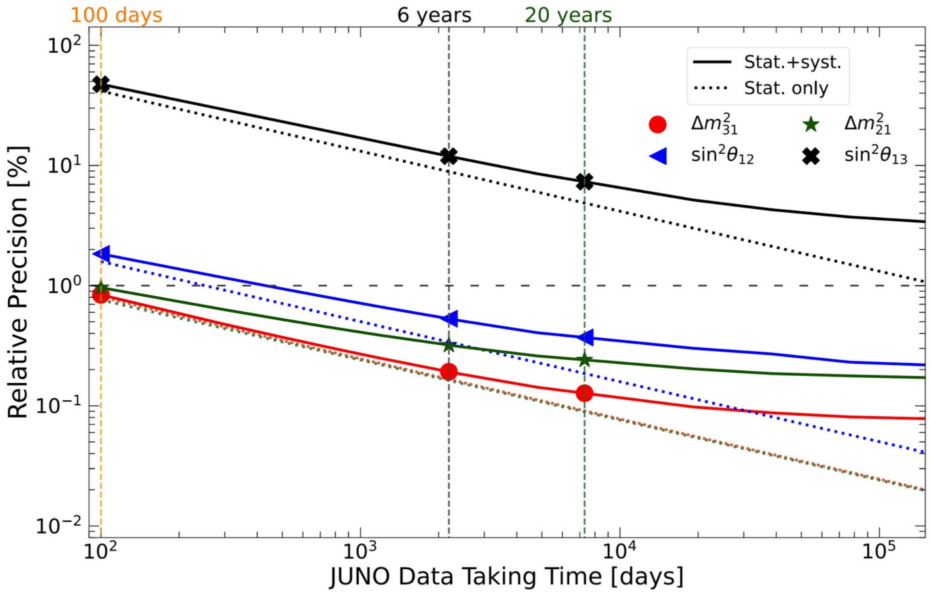
$$\Delta\chi^2_{min} = |\Delta\chi^2_{min}\ (NO) - \Delta\chi^2_{min}\ (IO)|$$

- 3σ (reactors only) with ~6 yrs × 26.6 GW_{th} exposure

	$\Delta\chi^2_{min}$
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

Precision measurement of oscillation parameters

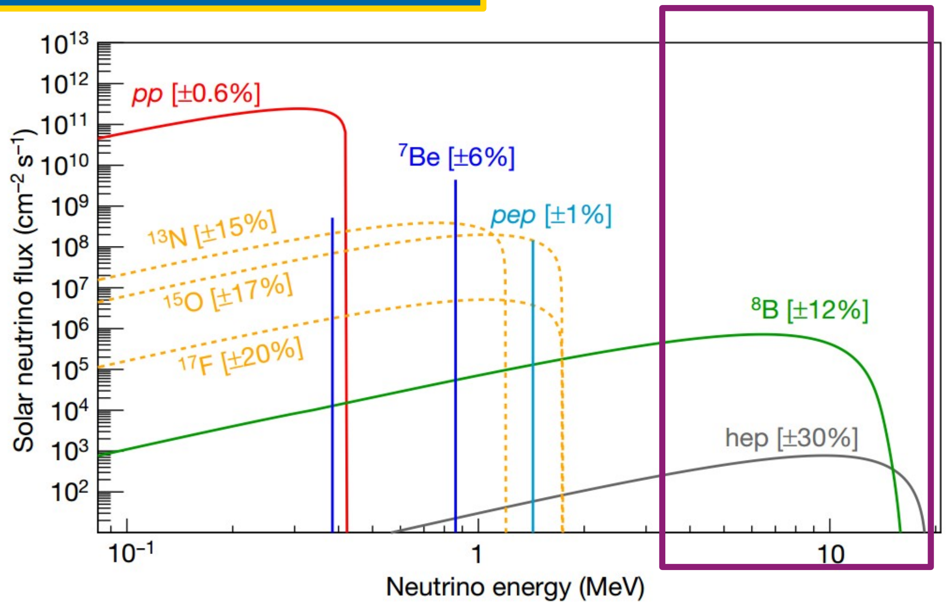


Abusleme et al 2022 Chinese Phys. C 46 123001

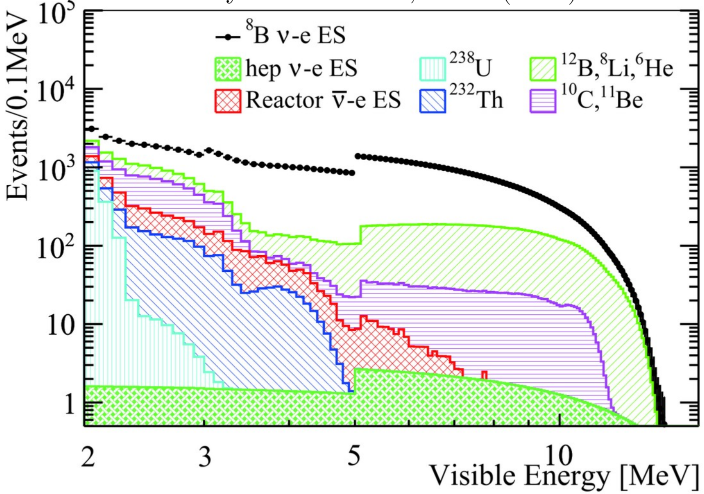
- Potential to measure Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ with roughly one order of magnitude better precision than current values, even with 100 days of data!
- Measurement of Δm^2_{21} and $\sin^2\theta_{12}$ can also be done with ^{8}B solar neutrinos (next slide)

	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2020	2.4%	1.3%	4.2%	3.2%
JUNO 100 days	1.0%	0.8%	1.9%	47.9%
JUNO 6 years	0.3%	0.2%	0.5%	12.1%

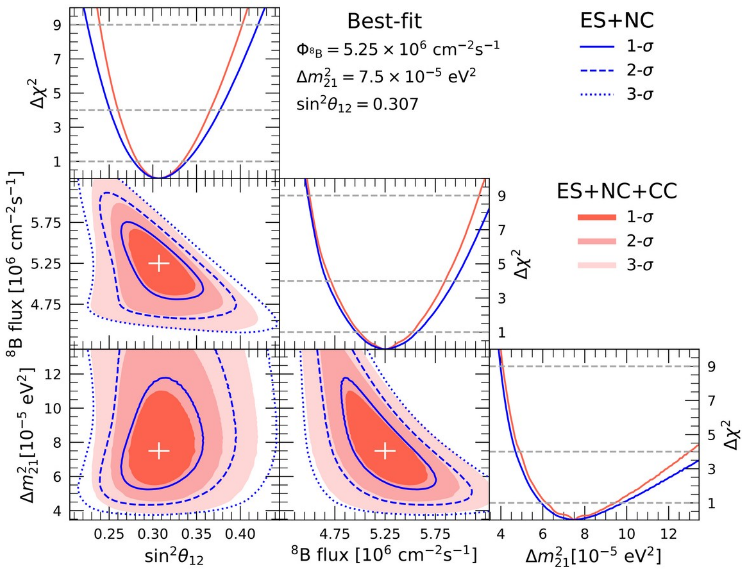
Solar neutrinos



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



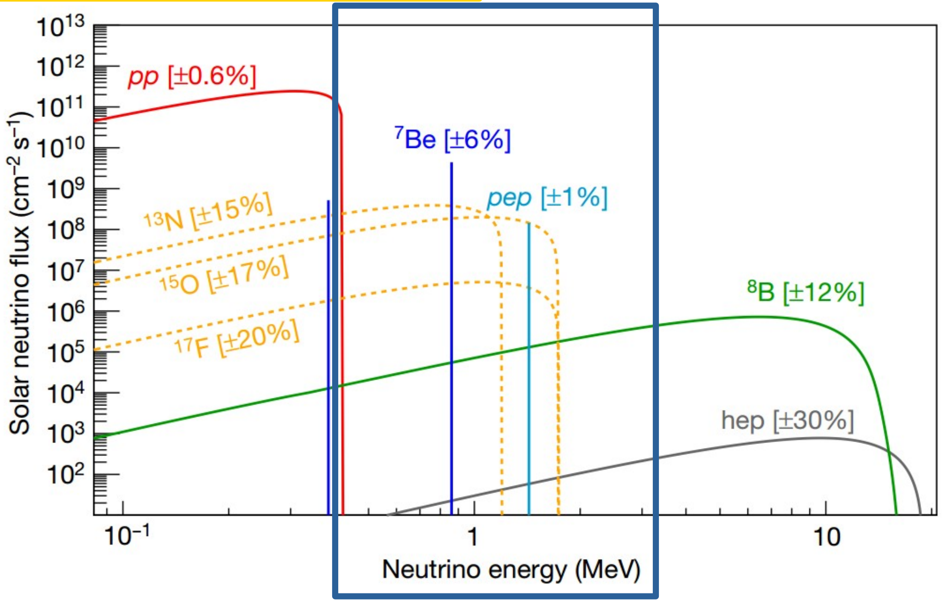
arXiv:2210.08437

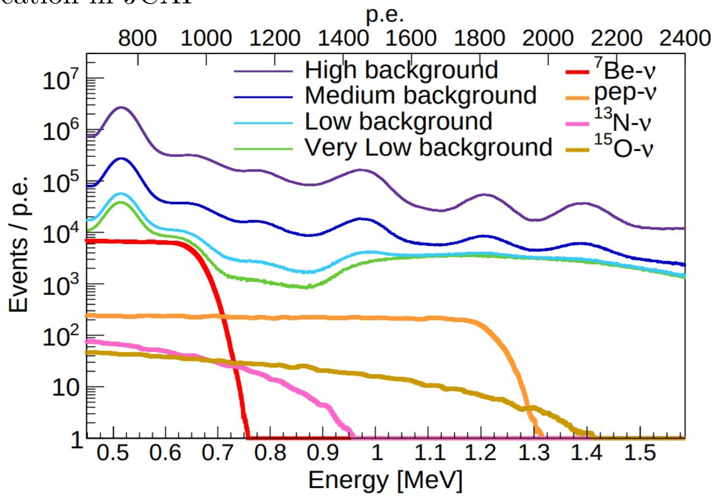


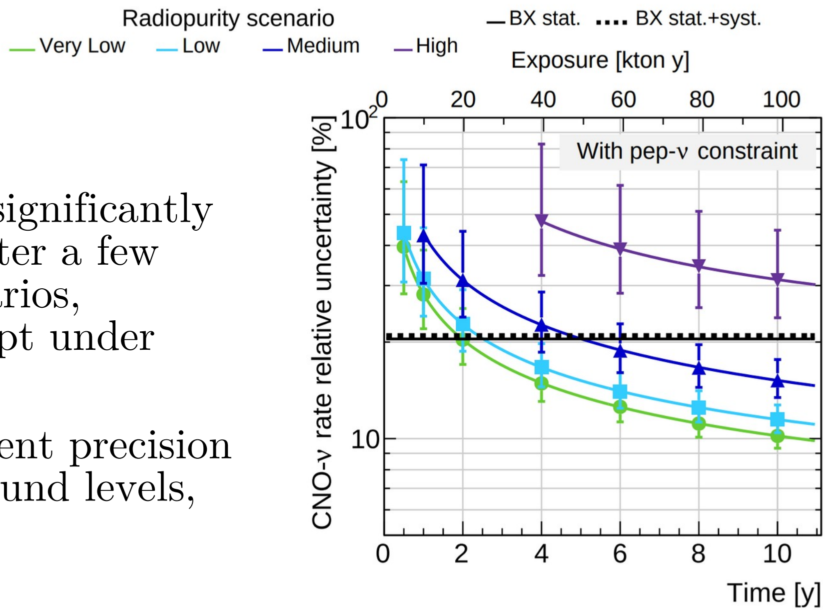
- Simultaneous measurement of ^{8}B solar neutrinos, Δm^2_{21}, and $\sin^2\theta_{12}$
- ^{8}B flux can be measured with ~5% precision using ES+NC+CC channels in 10 years. $\sin^2\theta_{12}$: 8%, Δm^2_{21} : 20%

Solar neutrinos

arXiv:2303.03910, accepted for publication in JCAP

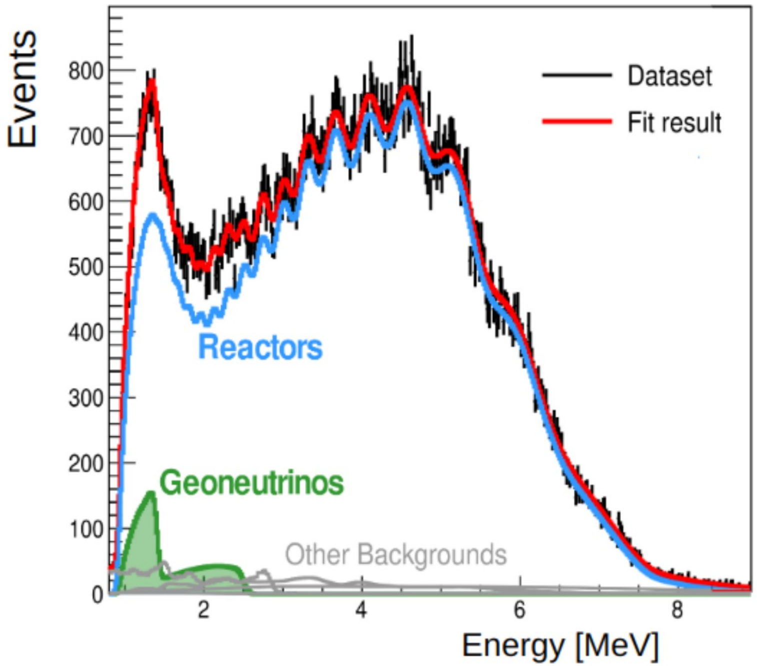






- ^{7}Be and *pep* neutrino flux uncertainties will significantly be improved w.r.t. current precision levels after a few years of data taking for all background scenarios, provided that the systematic error will be kept under control (^{7}Be $\lesssim$ 1 year, *pep* $\lesssim$ 6 years)
- CNO neutrino flux precision will exceed current precision levels with a *pep-ν* constraint for all background levels, except for the worst background scenario

Geoneutrinos



$$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \text{MeV}$$

$$^{235}U \rightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ \text{MeV}$$

$$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \text{MeV}$$

$$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.31\ \text{MeV}\ (89.3\%)$$

$$^{40}K + e^- \rightarrow {}^{40}Ar + \nu_e + 1.505\ \text{MeV}\ (10.7\%)$$

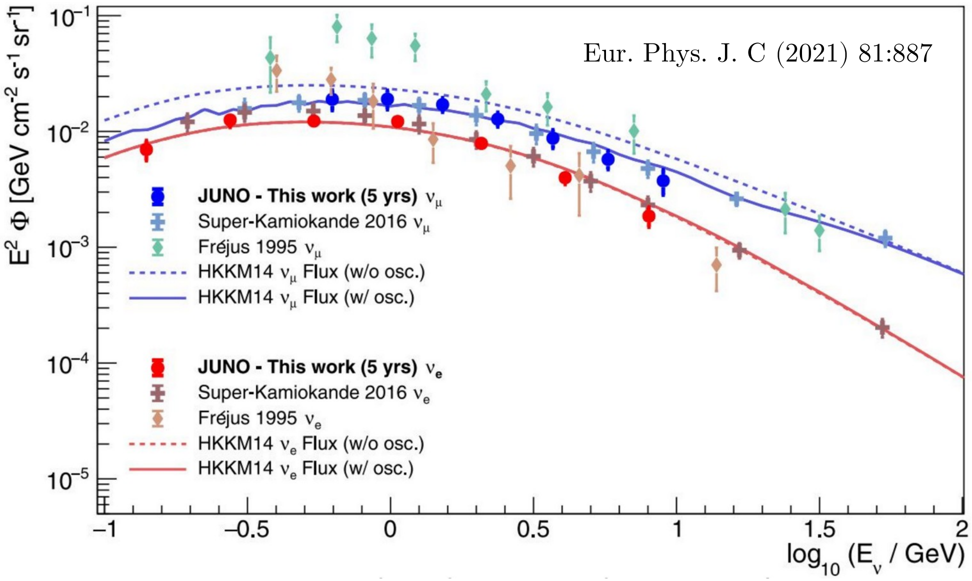
- Geoneutrinos help study the abundance of radioactive elements inside the crust and mantle, as well as the amount of heat emitted from them
- High statistics: more events in one year (~400) than global geoneutrino sample accumulated to date
- JUNO also has the potential for the discovery of mantle geoneutrinos
- Updated sensitivity results since 2016 (Ran Han et al. 2016 Chinese Phys. C 40 033003). Paper under preparation.

Experiment (years)	Borexino (8.9 years)	KamLAND (14.3 years)	JUNO (6 years)	JUNO (10 years)
^{238}U + ^{232}Th (fixed Th/U)	~17%	~15%	~10%*	~8%*

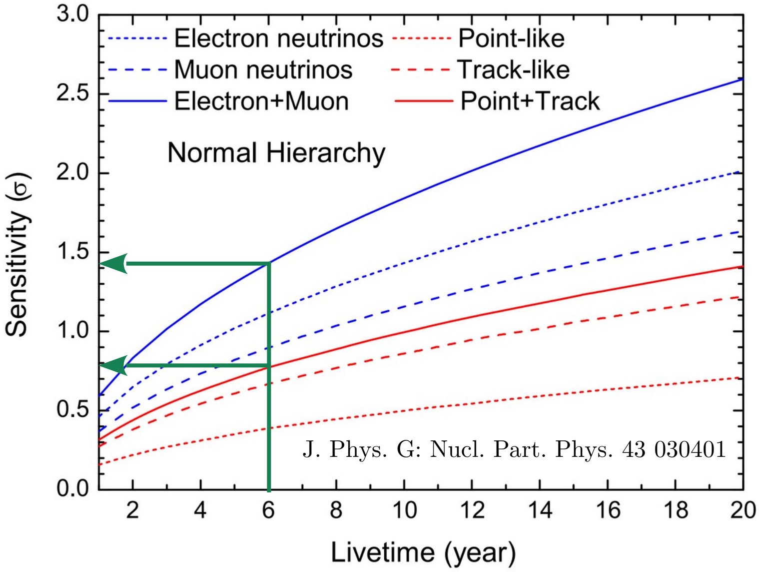
PRELIMINARY

*Reported for the first time at the MMTE workshop, 2023, Paris, France
https://indico.in2p3.fr/event/30001/contributions/126865/

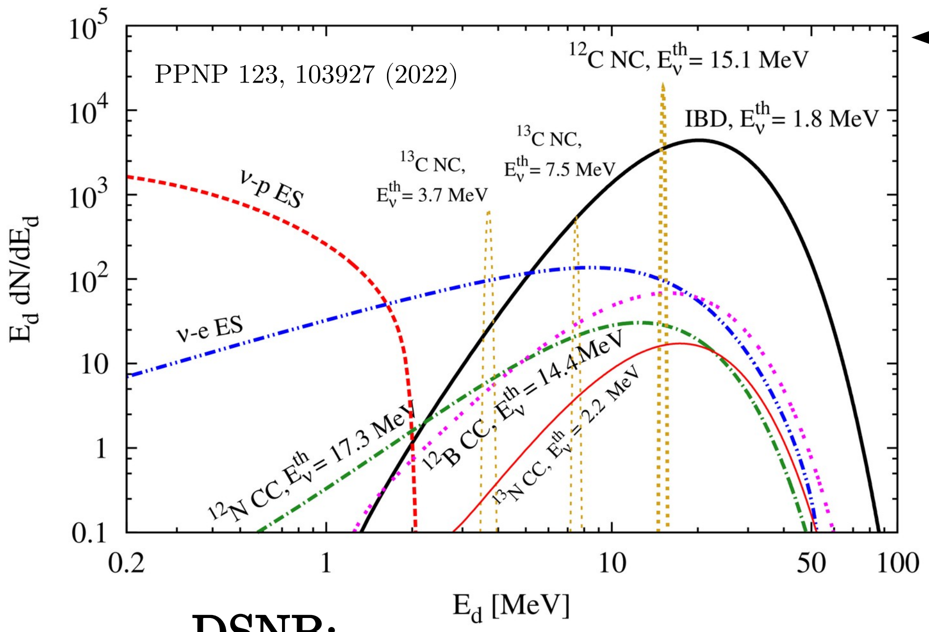
Atmospheric neutrinos



- ~0.7-1.4 σ (atmospheric only) with ~6 yrs exposure
- Complementary to reactor neutrino NMO analysis using matter effects from atmospheric neutrinos crossing the Earth



Supernova neutrinos

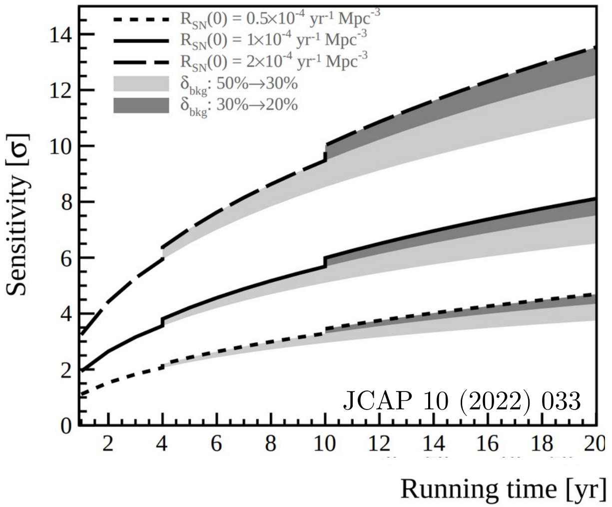


Core-collapse SN in our vicinity:

- Large SN neutrino sample with high energy resolution and low threshold (~0.02 MeV with multi-messenger trigger)
- Capability to detect pre-SN neutrinos from close SN-candidates

DSNB:

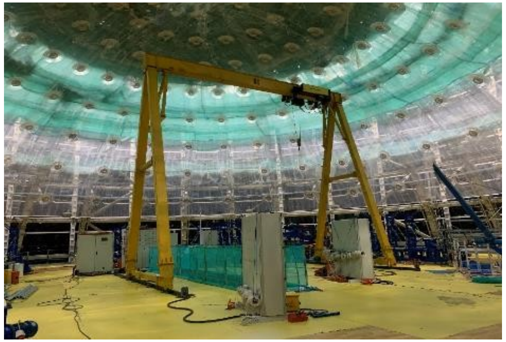
- Diffuse Supernova Neutrino Background: flux of neutrinos reaching the Earth from all the core-collapse supernovae in the universe
- Potential to observe DSNB with $\sim 3\sigma$ significance in ~3 years assuming a nominal reference model

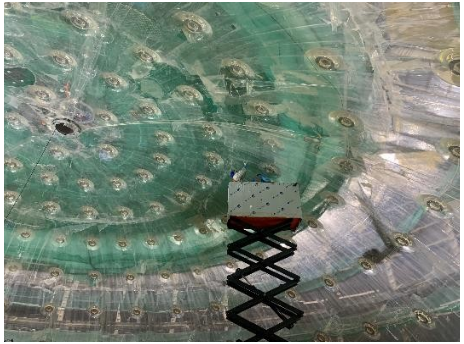


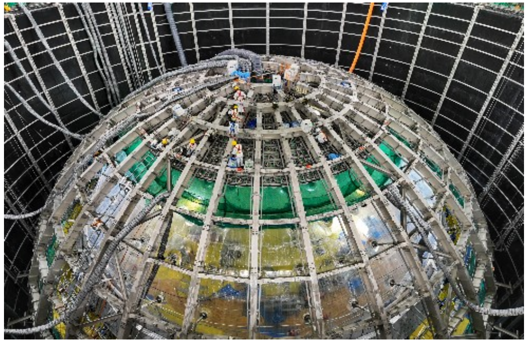
JUNO installation status

Construction of stainless steel structure completed

Acrylic vessel in the center detector: installation in progress → upper half-hemisphere completed







JUNO installation status

PMT, electronics, muon veto system installation ongoing

JUNO installation status

Installation of purification plants for the LS completed

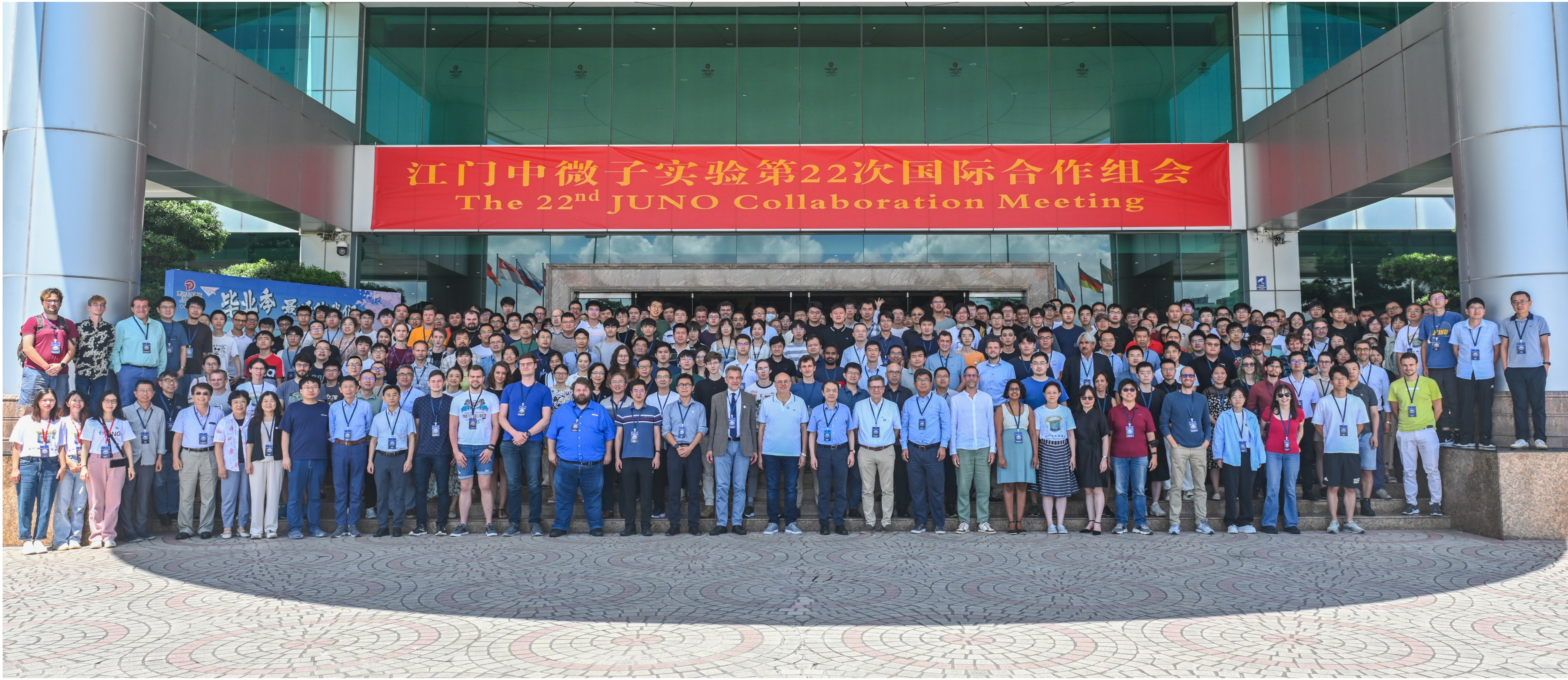
Ultra-pure water almost ready for water phase

- 2013 — Approval
- 2015 — Start of civil construction
- 2022 — Beginning of detector installation
- 2024 — Expected end of detector installation

Summary

- JUNO is a 20 kton liquid scintillator detector under construction in Jiangmen, China and it is designed to study reactor neutrino oscillations
- Main goals:
  - Determination of Neutrino Mass Ordering (NMO): ~3σ in ~6 years
  - Precision measurement of oscillation parameters Δm^2_{21}, Δm^2_{31}, and $\sin^2\theta_{12}$ (can exceed current precision levels in ~100 days)
- In addition:
  - Solar neutrinos: JUNO can provide competitive results on ^{7}Be *pep*, CNO, and ^{8}B solar neutrinos. ^{8}B solar neutrino measurement includes simultaneous measurement of Δm^2_{21} and $\sin^2\theta_{12}$
  - Geoneutrinos: JUNO will also observe a large number of geoneutrinos (~400/ year) and will reach current precision levels within few years of data taking. It also has potential to observe mantle signal
  - Atmospheric neutrinos: Study of matter-induced atmospheric neutrino oscillations can act complementary to reactor NMO analysis
  - Supernova neutrinos: Potential to observe huge amount of neutrinos from nearby supernovae. A large DSNB flux expected: ~3σ observation in ~3 years assuming a nominal reference model
- Detector installation on track in spite of pandemic-related delays

Thank you!



June 24th, 2023, Kaiping, China