JUNO 实验进展与物理目标

何苗

中国科学院高能物理研究所

2024年11月1日

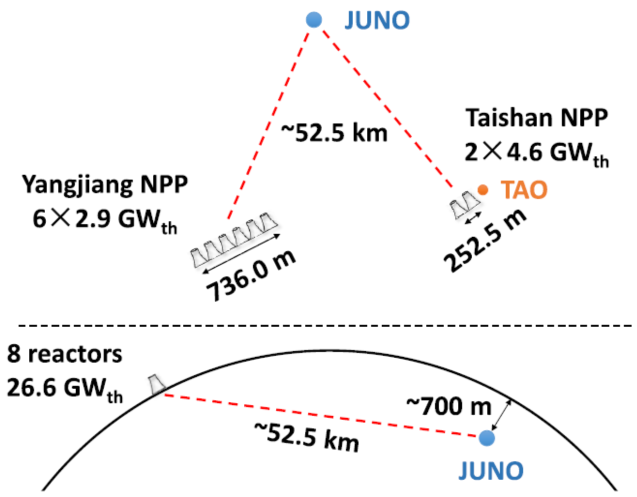
第一届基础物理研讨会暨基础物理平台年会

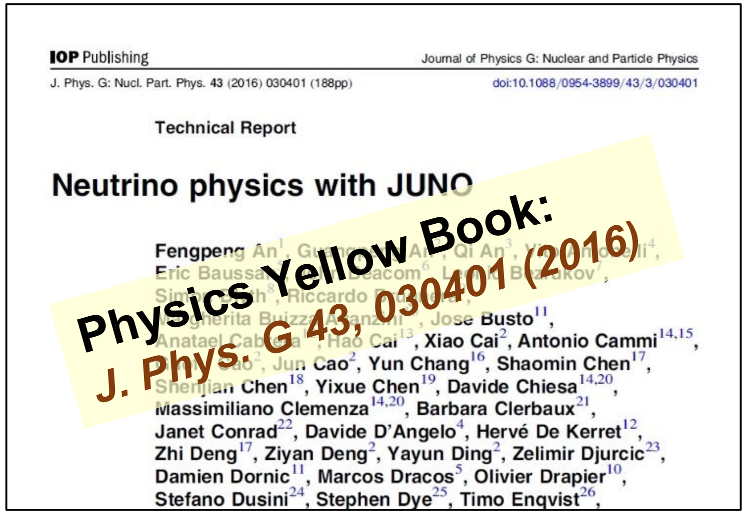
JUNO: a multipurpose neutrino experiment

Jiangmen Underground Neutrino Observatory

PRD78:111103,2008
PRD79:073007,2009

- Proposed as a reactor neutrino experiment for mass ordering in 2008
  - Driving the design specifications: location, 20 kton Liquid Scintillator, 3% energy resolution, 700 m underground
- Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches
- Approved in 2013. Construction in 2015-2024




IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401 (188pp) doi:10.1088/0954-3899/43/3/030401

Technical Report

Neutrino physics with JUNO

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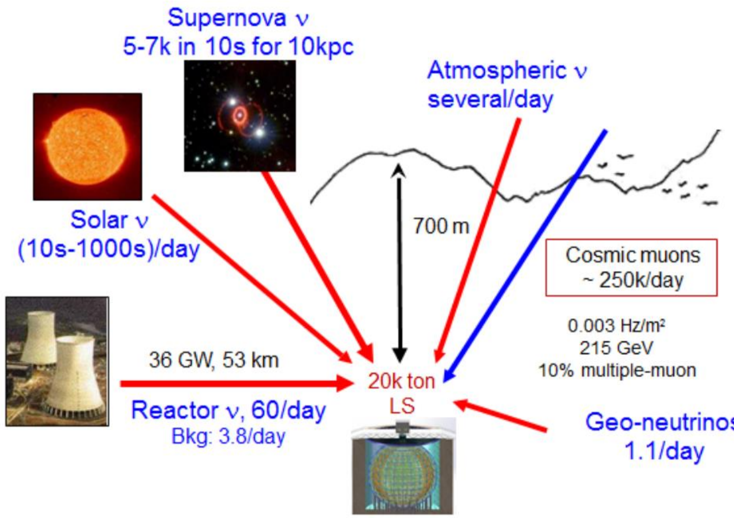
Physics Yellow Book:
J. Phys. G 43, 030401 (2016)



JUNO collaboration

69 institutions, >600 collaborators

Asia: China (27), Taiwan, China (3) Thailand (3), Pakistan, Armenia
Europe: Italy (8), Germany (6), France (5), Russia (3), UK (2), Belgium, Czech, Finland, Slovakia
America: Brazil (2), Chile (2), USA (2)

Location


Huizhou
Guangzhou
Guang Zhou
Dongguan
Zhaoqing
CNS
2.5 h drive
Shen Zhen
Kaiping,
Jiangmen,
Guangdong
Zhongshan
Daya Bay
NPP
Hong Kong
Zhujiang River Estuary
Hong Kong
Macau
Macau
53 km
53 km
Taishan NPP
Yangjiang NPP
Yangjiang NPP
Taishan NPP

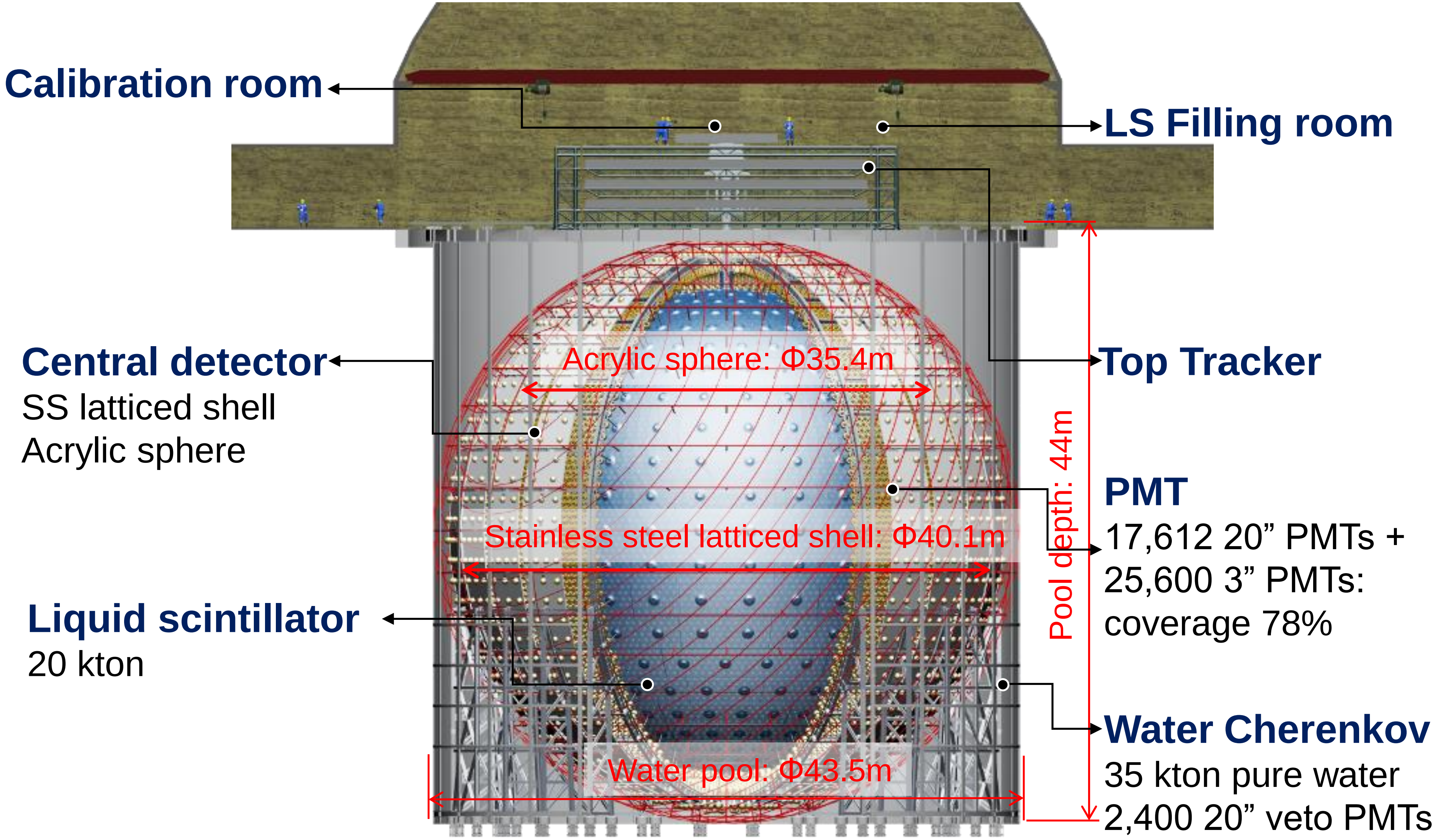
JUNO Site

Surface buildings / campus

- **Office / Dorm**
- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Computing
- Power station
- Cable train

~200 people working onsite now

The JUNO detector

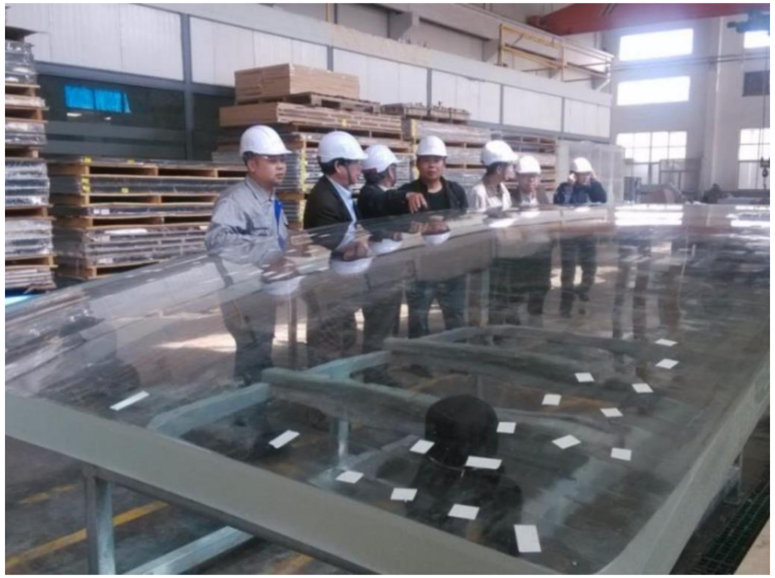


The main structure: stainless steel truss

- Φ41.1 m Stainless Steel structure
- Assembled by 120,000 bolts with >0.45 friction
- High accuracy to satisfy the PMT clearance (minimal 3 mm)
- Completed in 2022 (bottom 4 layers finished last week)

Acrylic sphere

- Φ35.4 m acrylic sphere, thickness 12 cm, 263 panels up to 3 m × 8 m

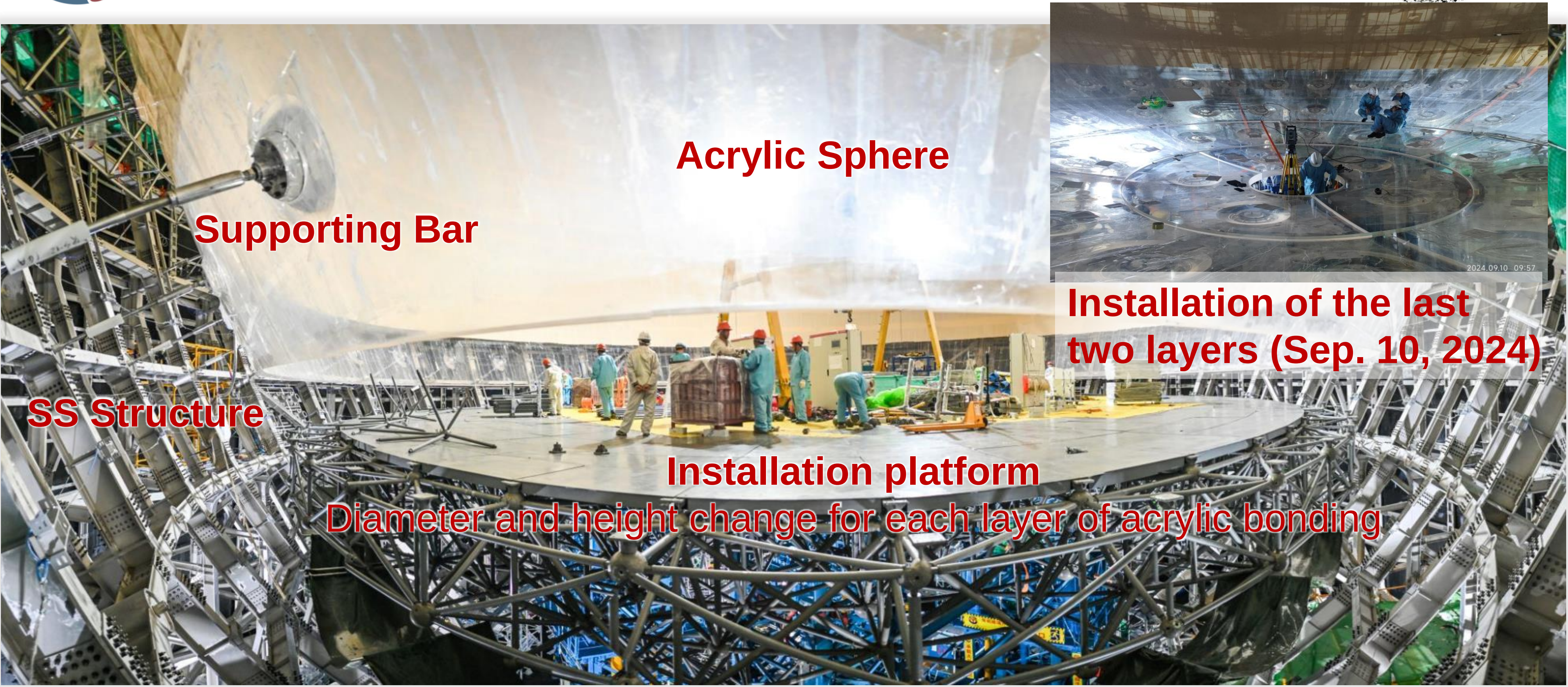


- A special production line for low backgrounds acrylic panels (< 1 ppt U/Th/K)
- Processed while maintaining high transparency (>96%)

- Built from the top to bottom, layer by layer, 23 layers in total
- All panels in the same layer were bonded together

- **Acrylic sphere finished construction in Oct.**

Inside the detector



Installation of the last two layers (Sep. 10, 2024)

Photomultiplier tubes (PMTs)

- 20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu)
- 3-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
- Instrumented with waterproof potting (failure rate < 0.5%/6 years) and implosion protection

	LPMT (20-in)		SPMT (3-in)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Charge Collection	Dynode	MCP	Dynode
Photon Det. Eff.	**28.5%**	**30.1%**	**25%**
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	**75%**		**3%**
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

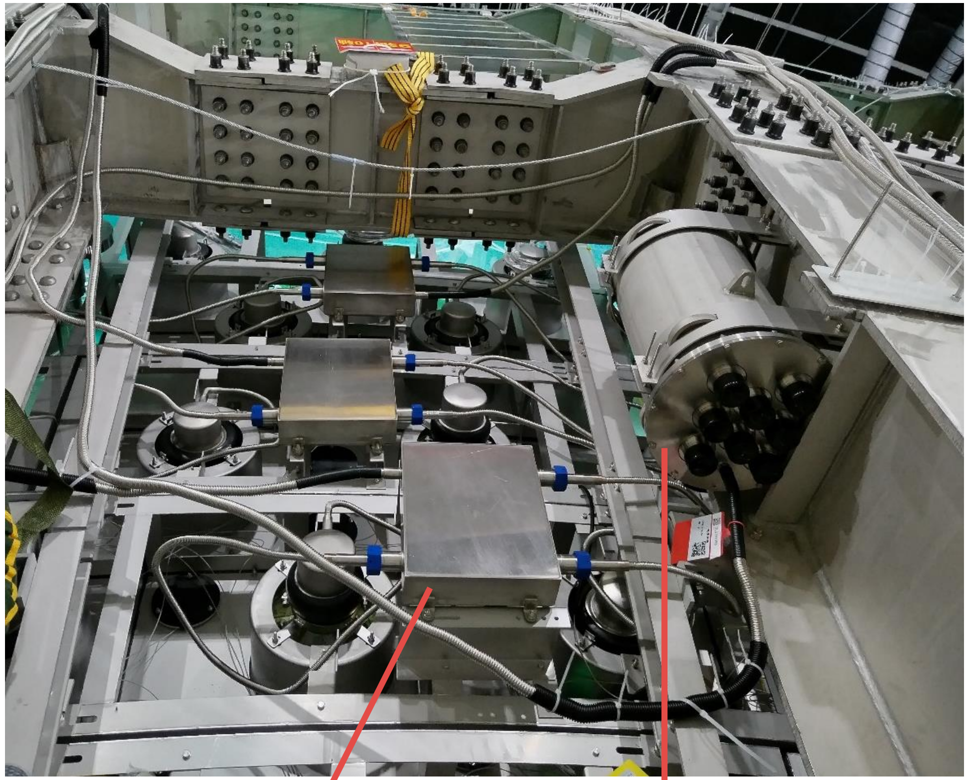
Developed by Chinese institutes and industries

PMT installation

- 95% PMTs installed in the JUNO detector, to be finished in November.

Electronics

- 20-inch PMT electronics: 20012 channels
  - Dynamic range: 1- 4000 PE, Noise: <10% @1 PE, Resolution: <10%@1 PE, <1%@100 PE
  - 1 GHz FADC in an underwater box (3 ch./box), connected to PMTs by water proof connectors
  - Failure rate: < 0.5% / 6 years
- 3-inch SPMT electronics: 25600 channels
  - 200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips
- 90% electronics installed in the detector, to be finished in November.

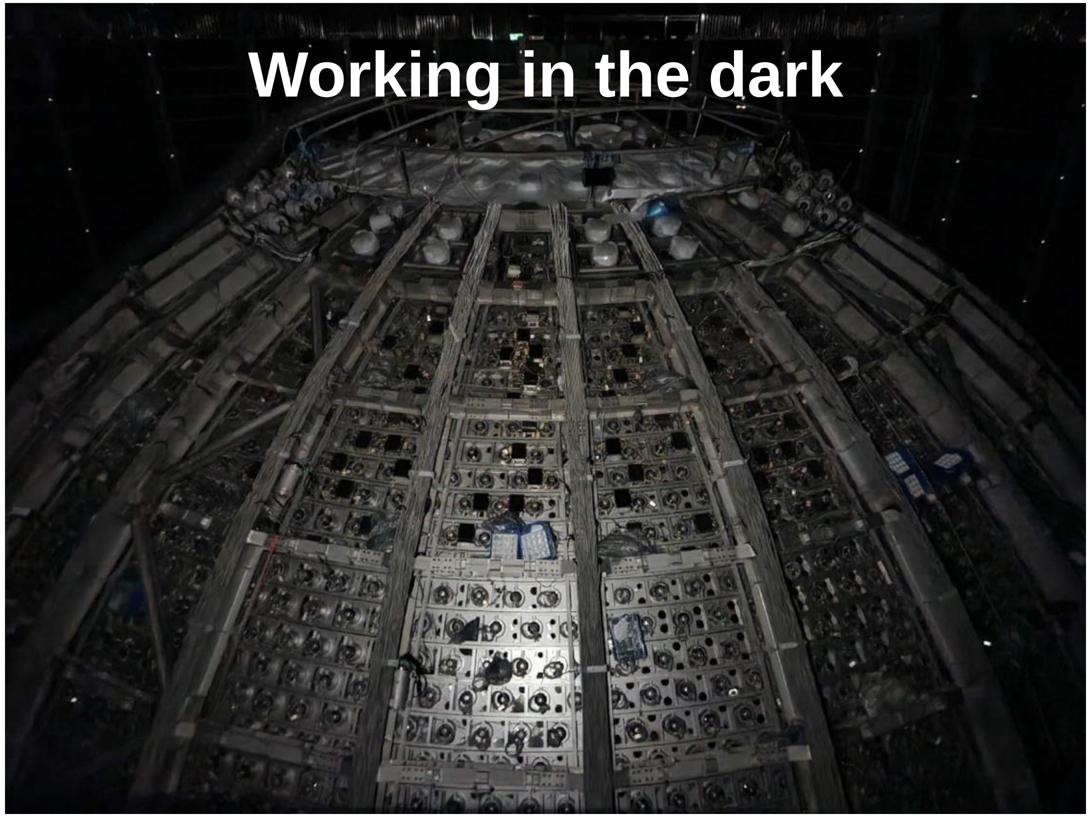


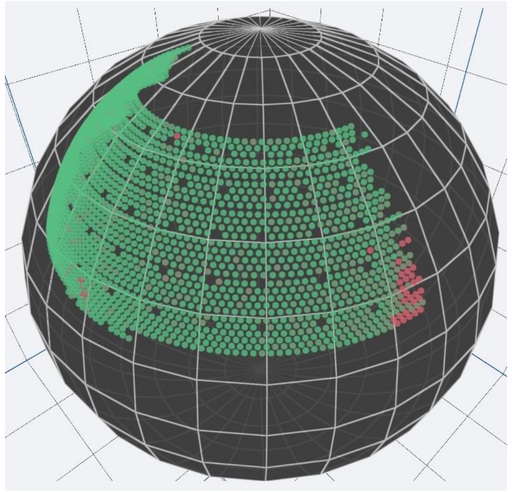
20-inch PMT underwater box: 3 channels

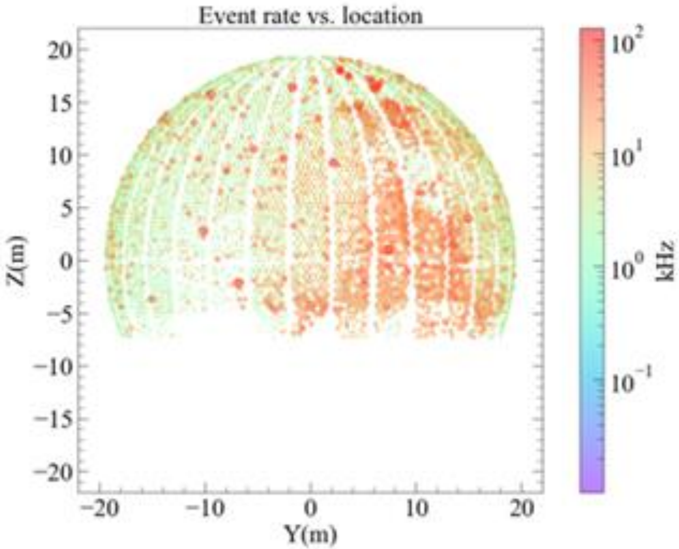
3-inch PMT underwater box: 128 channels

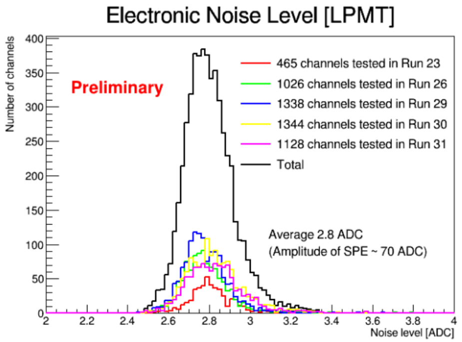
Commissioning

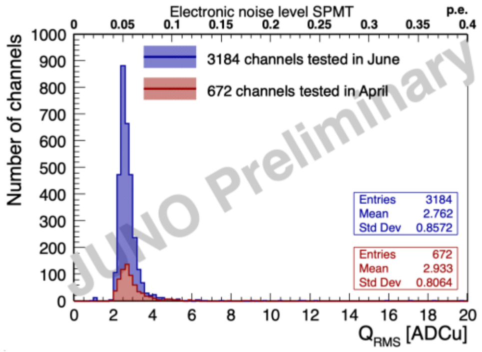
- Lights-off tests during installation
- Performances of PMTs and electronics are good











20-inch PMT Noise level
~0.04 PE

3-inch PMT Noise level
~0.05 PE

Liquid scintillator

- LAB + 2.5 g/L PPO + 3 mg/L bis-MSB
  - Attenuation length: LAB > 24m, LS > 20 m
  - Minimum U/Th requirement (for NMO) < 1e-15 g/g, aiming at 1e-17 g/g for solar and future $0\nu\beta\beta$

- ◆ **All 60 ton PPO delivered, U/Th < 0.1 ppt**
- ◆ **Bis-MSB complete production soon (< 5 ppt)**
- ◆ **Plants commissioned individually and jointly**
- ◆ **20 kton LAB to be delivered, U/Th ~ 1 ppq**

5000 m^3 LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

2.4%

Mixing LAB with PPO and bis-MSB

97.6%

Mixing

ICP-MS & sensitivity sub-ppq level (10^{-16} g/g)

1800 m SS pipes to underground

3) Water extraction to remove radioactive impurities

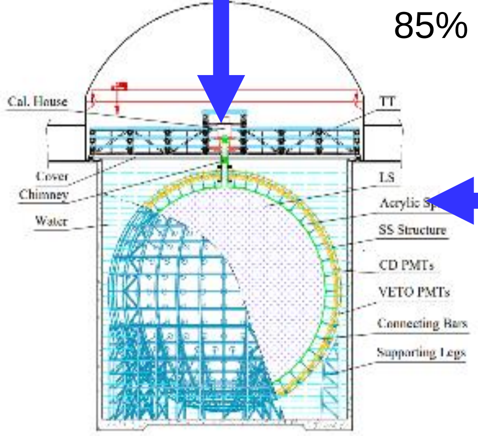
4) Gas stripping to remove Rn and O_2

15%

Commissioning

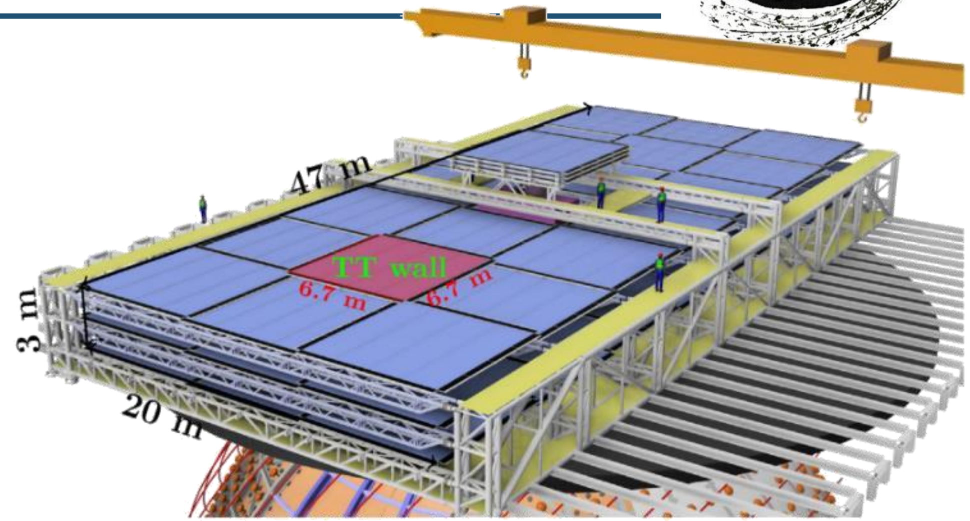
Monitoring pre-detector (OSIRIS)

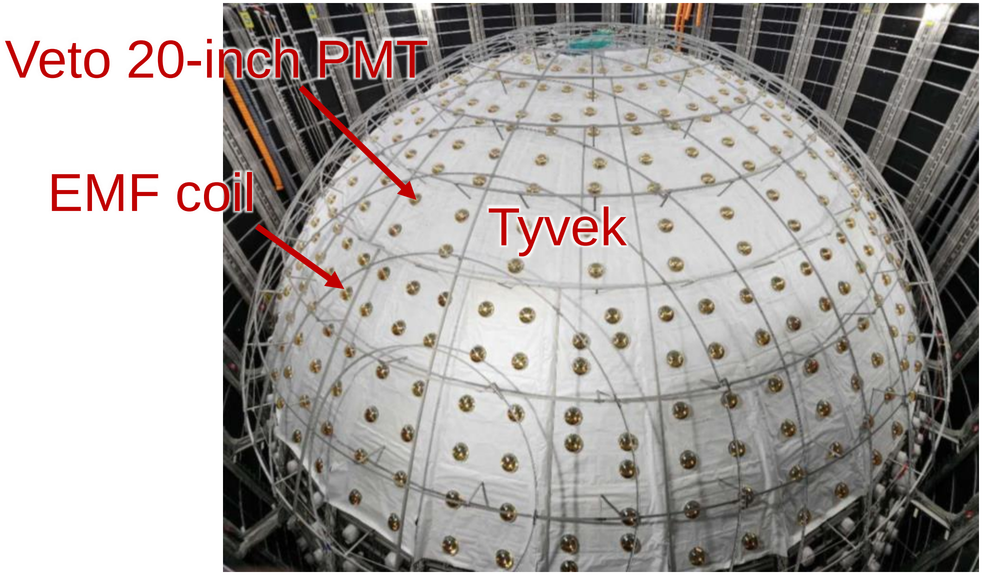
85%



Veto detector

- Water Cherenkov + Top tracker
- Water Cherenkov detector
  - 35 kton water to shield backgrounds from the rock
  - Instrumented w/ 2400 20-inch PMTs on SS structure
  - Water pool lining: 5 mm HDPE (black) to keep the clean water and to stop Rn from the rock, will cover w/ tyvek
  - 100 ton/h pure water system installed. Requirement: U/Th/K<10^{-14} g/g and Rn<10 mBq/m^3, attenuation length>40 m, temperature controlled to (21±1) °C
- Top tracker (to be installed) NIMA 1057 (2023) 168680
  - Refurbished OPERA scintillators
  - 3 layers, ~60% coverage on the top
  - $\Delta\theta$ ~ 0.2°, ΔD ~ 20 cm
- Earth Magnetic Field compensation coil



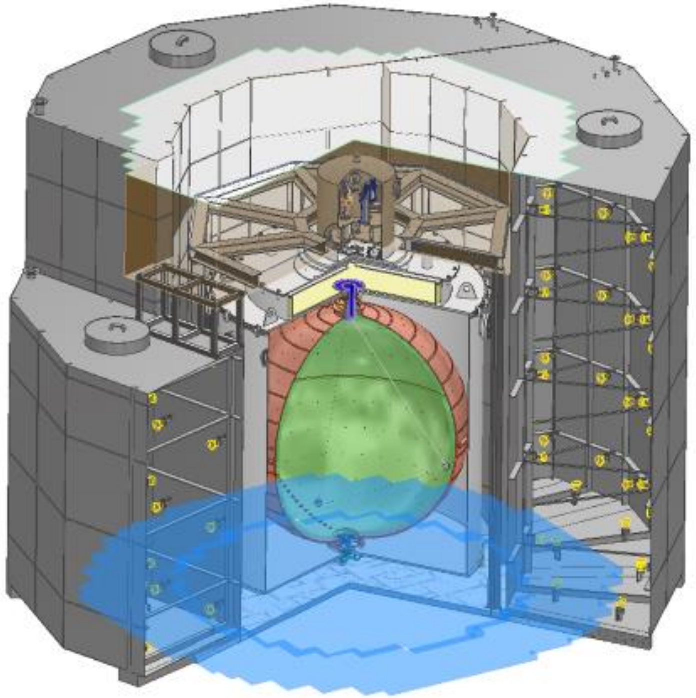


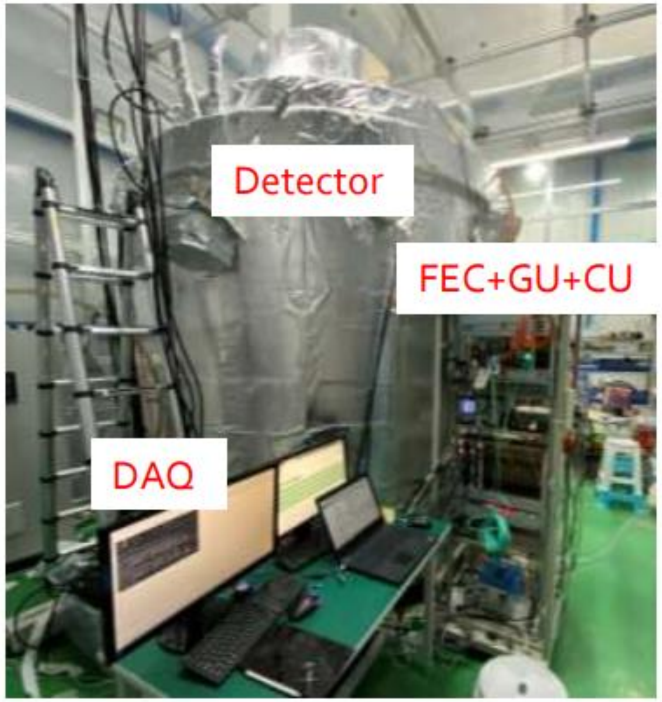
JUNO-TAO

- Main goal: **Measure the reactor neutrino spectrum** (as a reference to JUNO)
  - Better resolution to reduce fine structure effects and spectrum uncertainties
  - Improve nuclear database

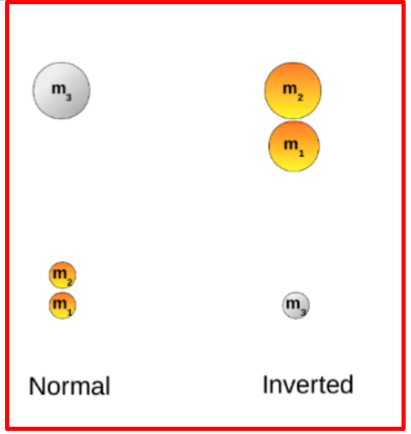
- 10 m^2 SiPM + 2.8 ton Gd-loaded LS @-50℃
  - 700k/year@44 m from the core (4.6 GW), ~10% bkg
  - Energy resolution: <2%/√E, 4500 p.e./MeV

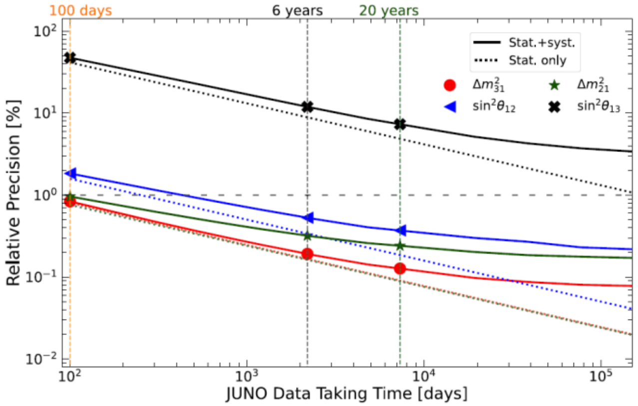
- **Installation in the Taishan Nuclear Power Plant started this week.**





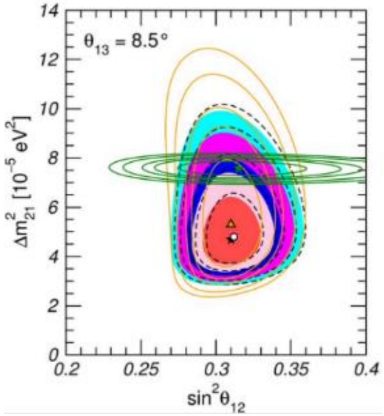
JUNO physics





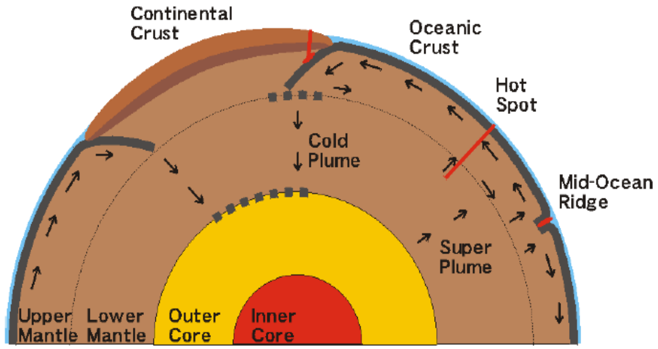
测量振荡参数到1%精度

3年



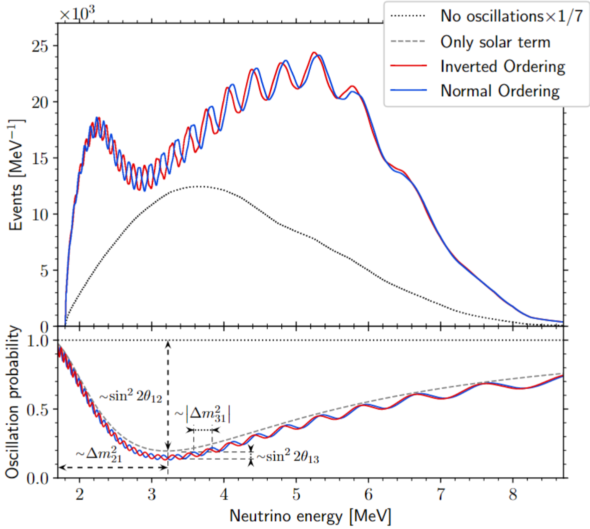
太阳中微子

3-5年



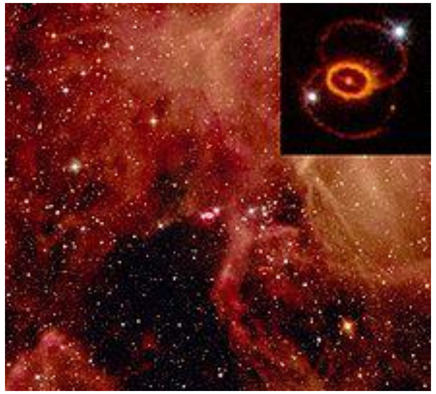
确定地球物理模型

6-10年



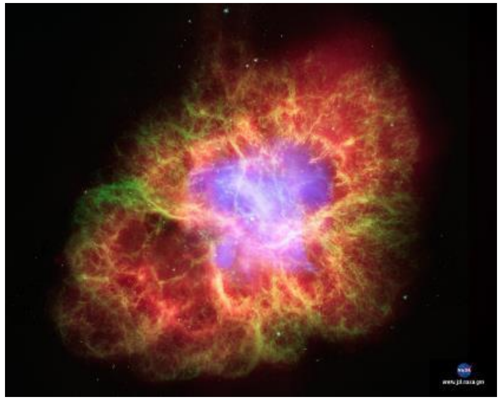
中微子质量顺序

~6年



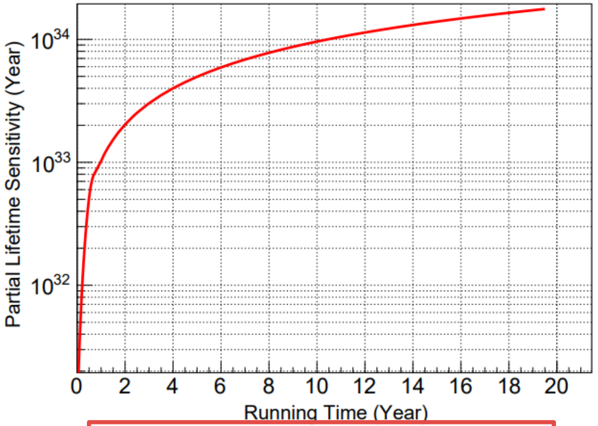
超新星背景中微子

6-10年



等待超新星爆发

2-3次/100年

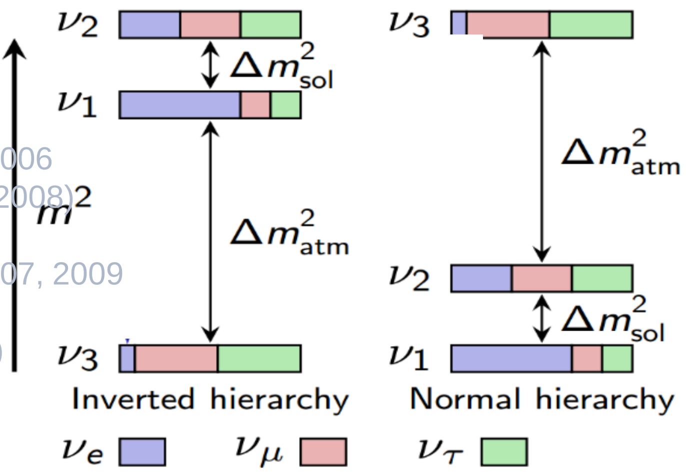


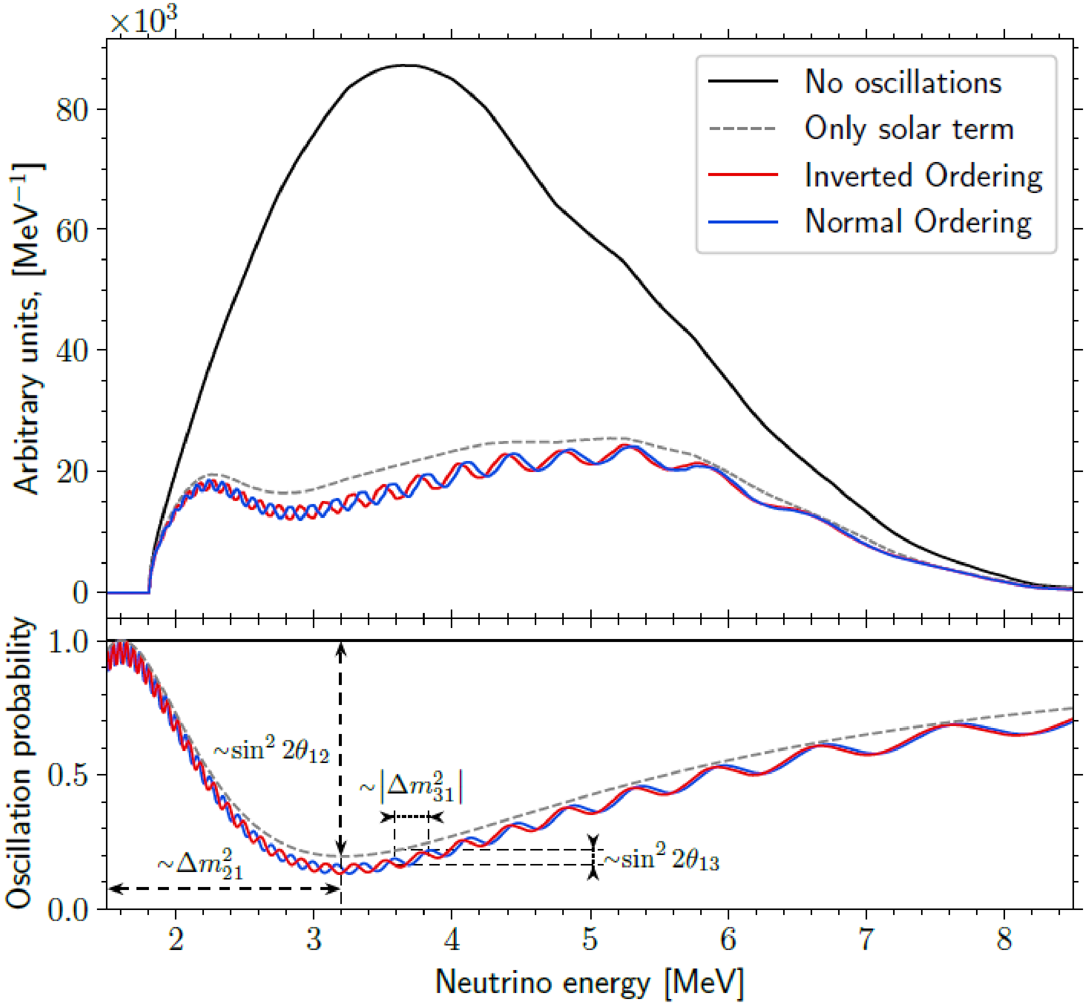
探索核子衰变

10年

Neutrino mass ordering

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
Y.F Li et al, PRD 88, 013008 (2013)



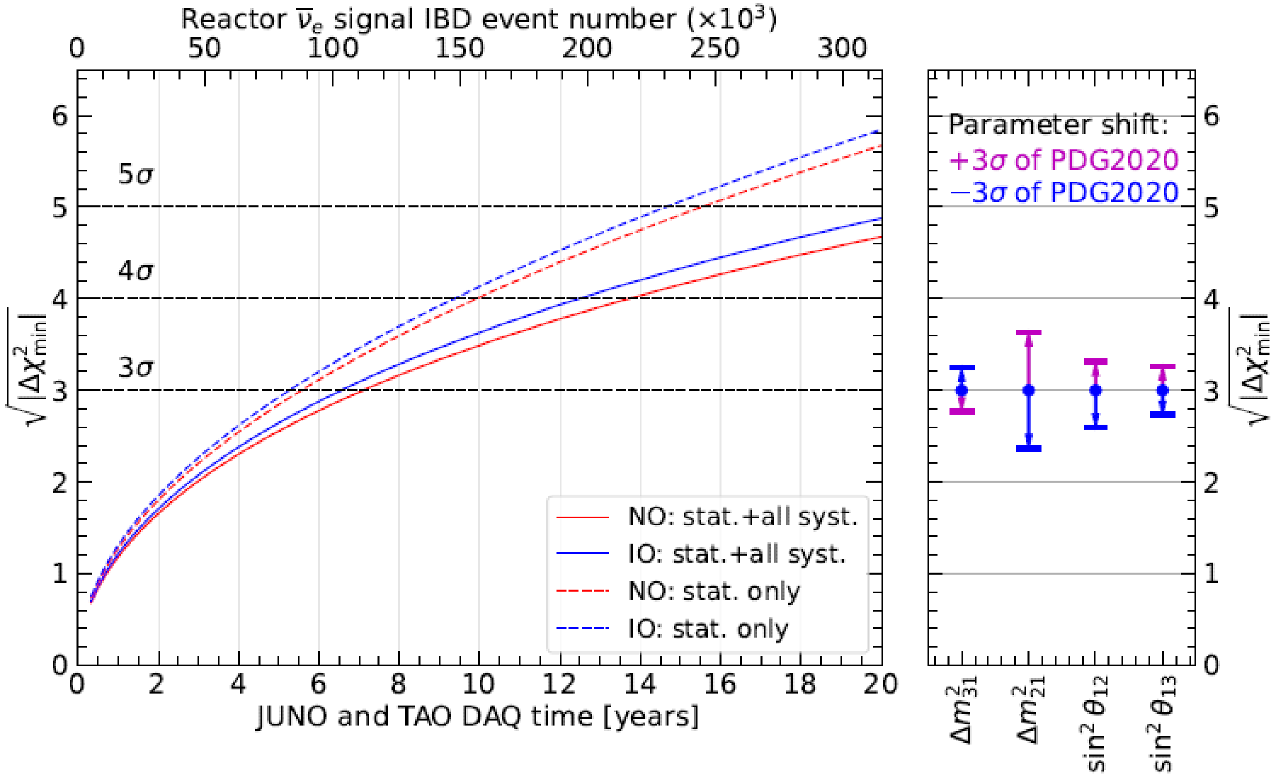


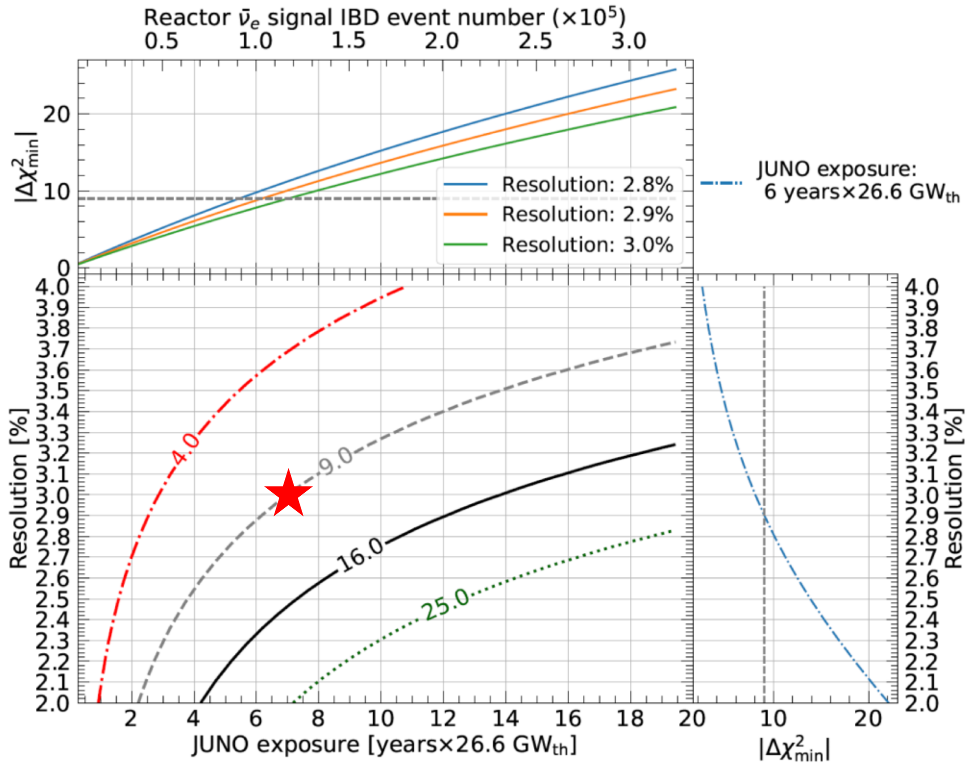
- A fundamental property of nature
- Disappearance of reactor electron antineutrinos at 50-60 km: interference between Δm^2_{31} and Δm^2_{32}
- Very unique approach, independent on θ_{23} and CP phase

Expected antineutrino spectra in JUNO

Mass ordering sensitivity

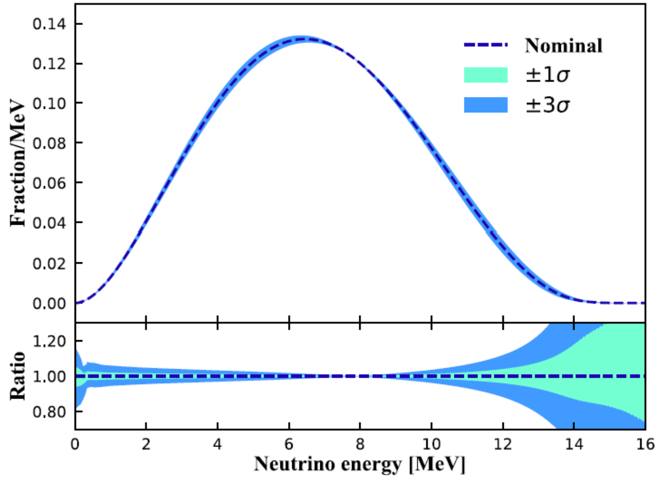
- **JUNO NMO median sensitivity:**
  3σ (reactors only) @ ~6 yrs × 26.6 GW_{th} exposure
- **Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity**





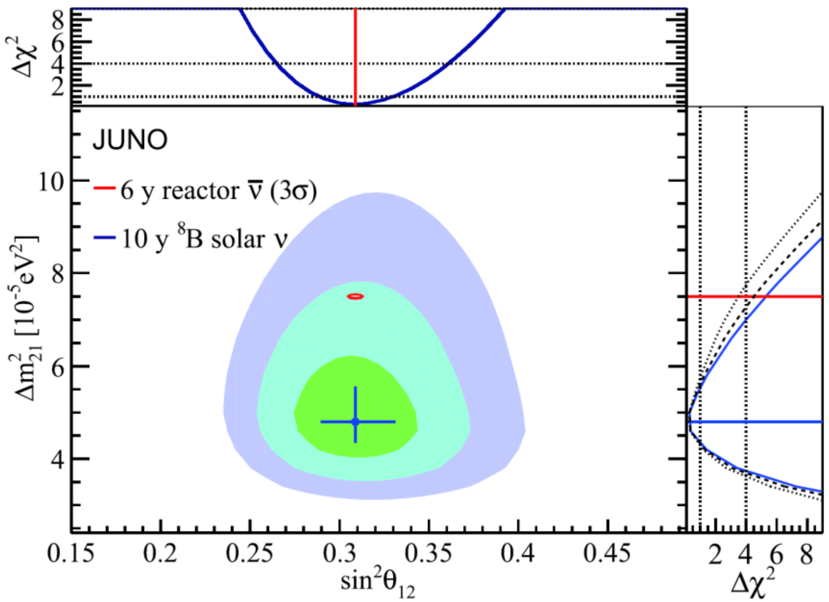
Solar neutrinos: ^{8}B

- JUNO is able to detect neutrinos from nuclear fusion in the sun

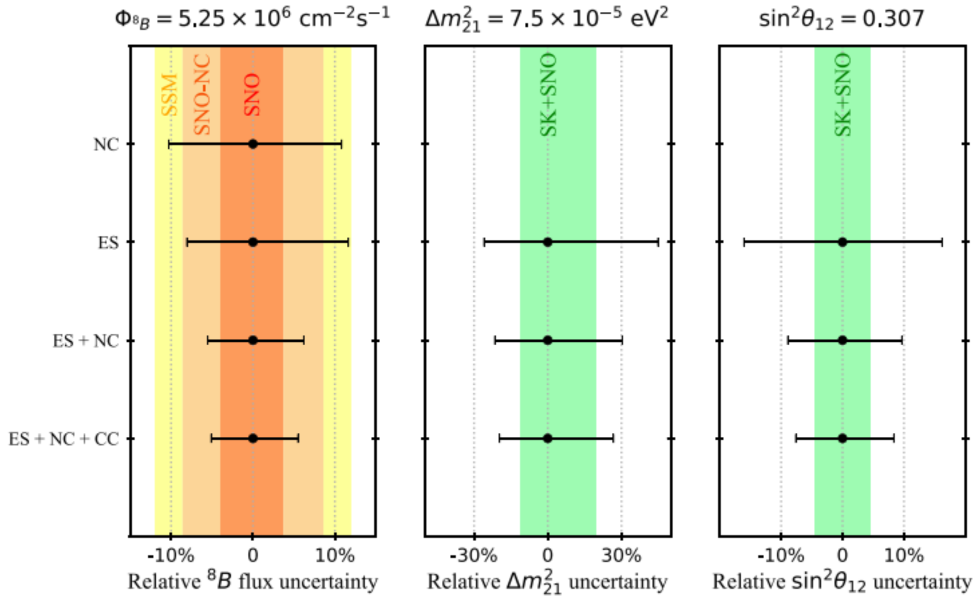


Energy spectrum of ^{8}B neutrinos

CPC 45, 023004 (2021)



Astrophys. J. 965.2: 122 (2024)

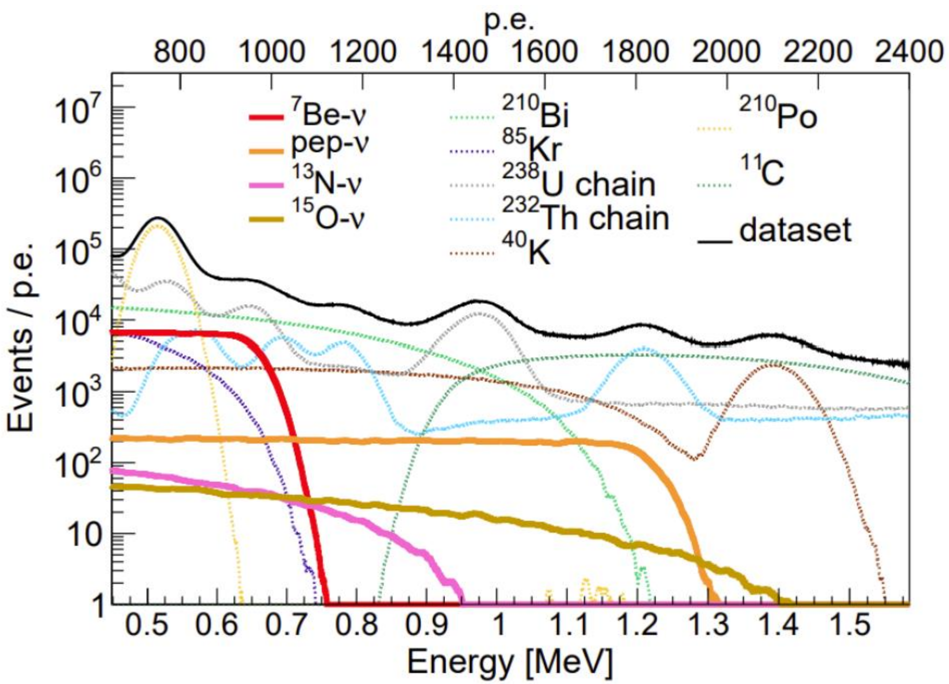


- 60,000 ES and 600 NC/CC on ^{13}C
- The largest ^{13}C ES+NC+CC sample, ^{8}B flux can be model-independently measured to 5% in 10 years (SNO 3%)
- Independent measurement of $\sin^2 2\theta_{12}$, Δm^2_{21}

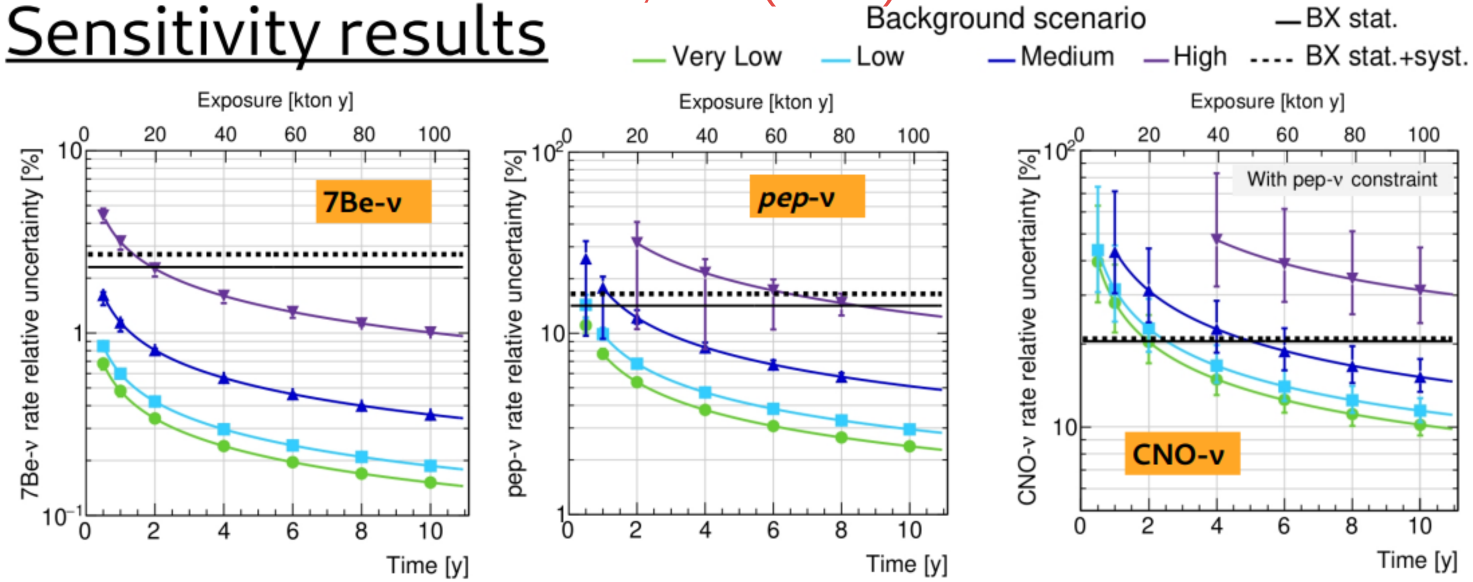
Solar neutrinos: ^{7}Be, pep, CNO

JCAP 10, 022 (2023)

- Medium energy (~1 MeV)
- Detection largely replies on the radiopurity of the liquid scintillator



Sensitivity results



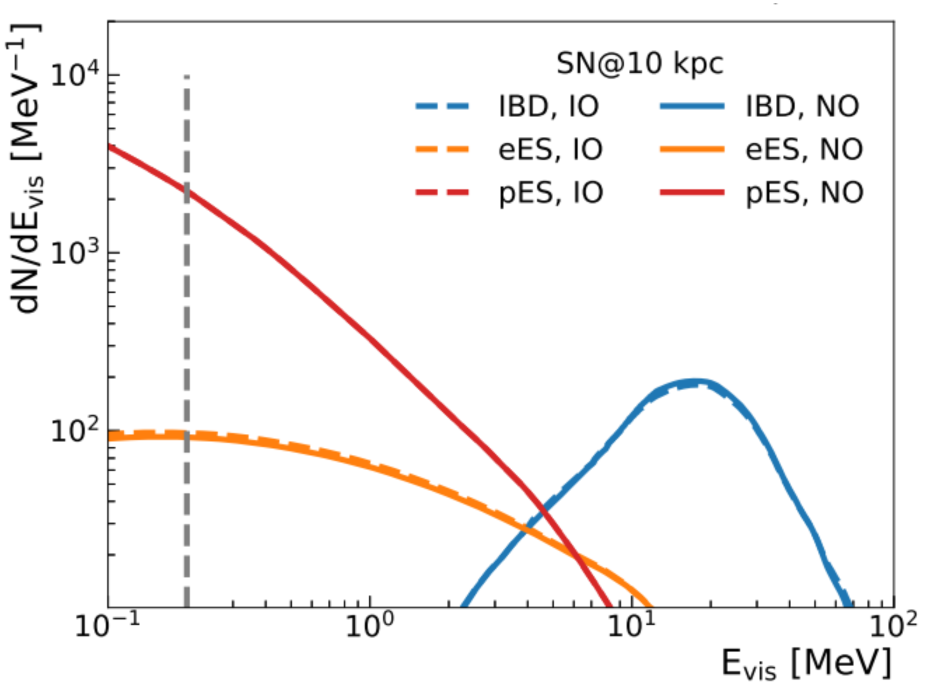
Sensitivity study with different bkg. assumptions

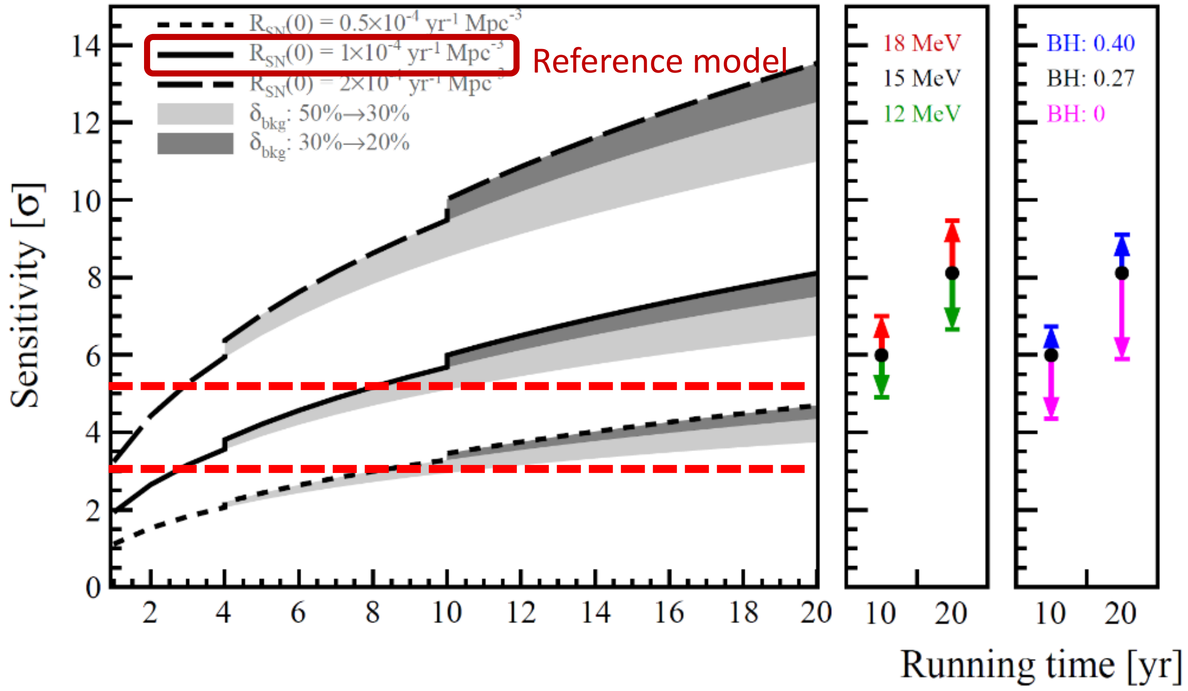
High bkg.	10^{-15} g/g
Medium bkg.	10^{-16} g/g
Low bkg.	10^{-17} g/g
Very low bkg.	10^{-19} g/g

- With <10^{-16} U/Th
  - Pep and ^{7}Be better than Borexino in ~2y
  - CNO better than Borexino in ~6y

Supernova neutrinos

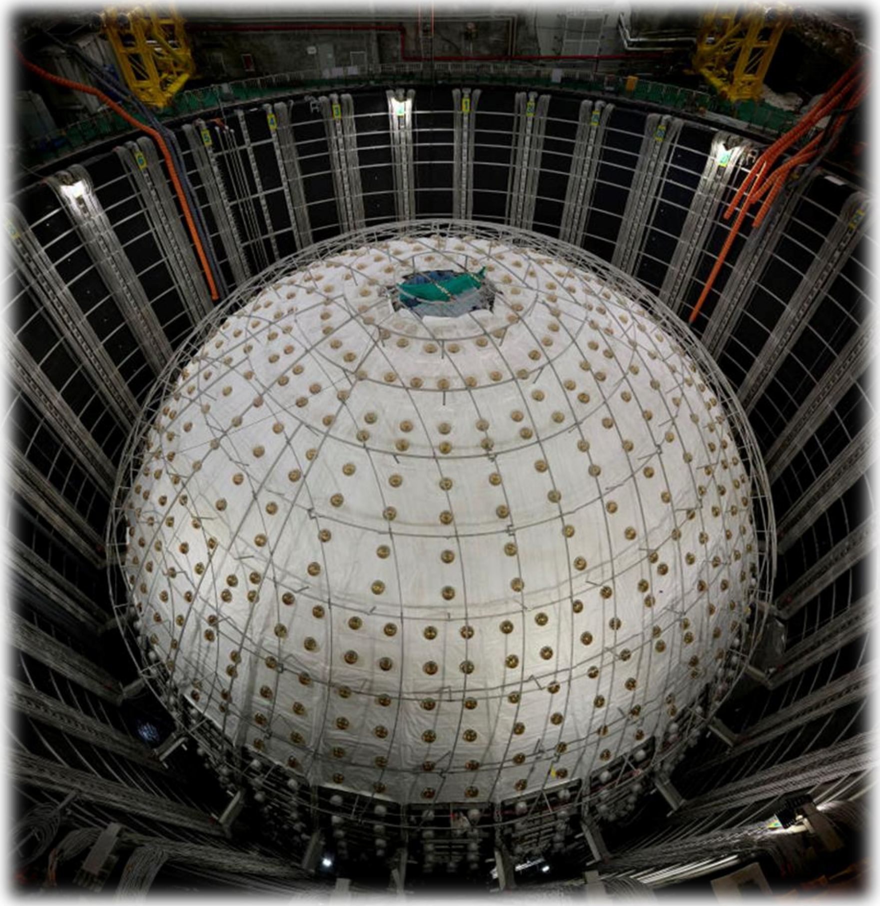
- 3 detection channels sensitive to all flavors
- Excellent capability for early warning
  - 220~400 kpc with 50% probability
  - **pre-SN** 1.6 (0.9) kpc
  - 10~30 ms for typical 10 kpc
- Diffuse Supernova Neutrino Background
  S/B ratio improved from 2 to 3.5 with Pulse Shape Discrimination
- Using the reference model:
  3σ in 3 years and >5σ in 10 years





Summary

- JUNO is building the largest (20 kton) liquid scintillator detector in the world.
- Detector installation to be finished in 2024 and data taken starts in 2025 after 2 months of water filling and 6 months of liquid scintillator filling.
- Precision measurement of neutrino oscillation parameters followed by mass ordering determination through reactor antineutrinos.
- Rich physics potentials with solar, geo-, supernova, atmospheric neutrinos and nucleon decays.

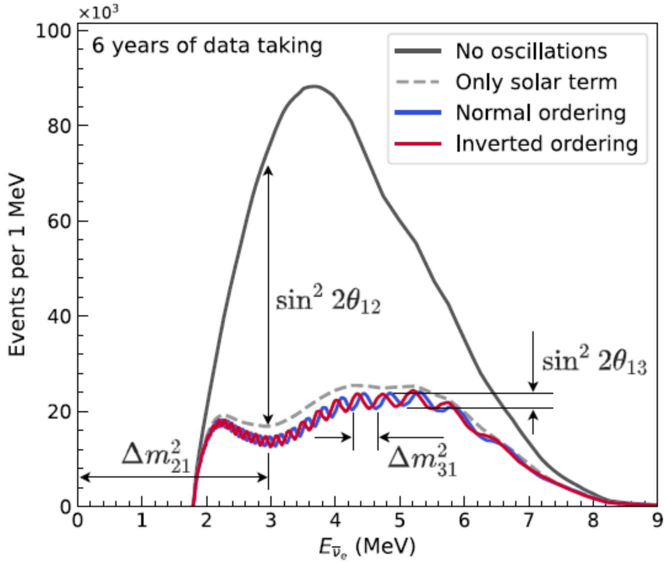


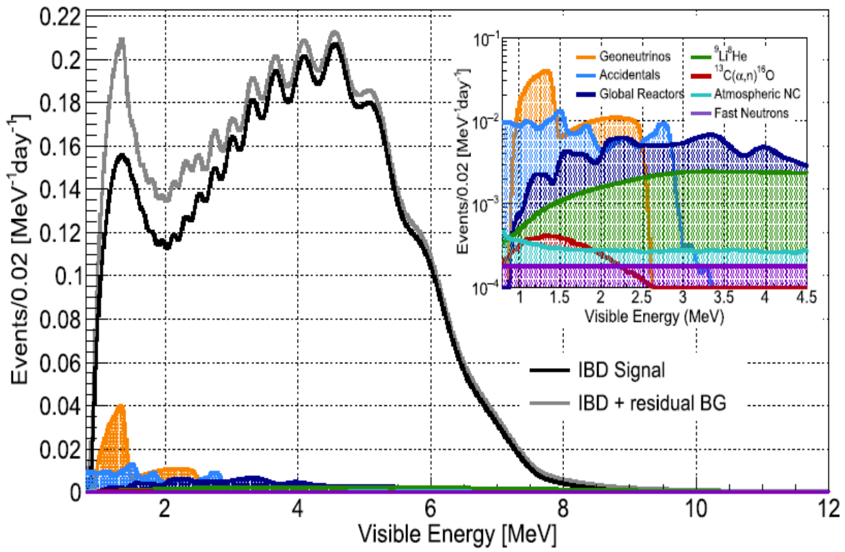
backup

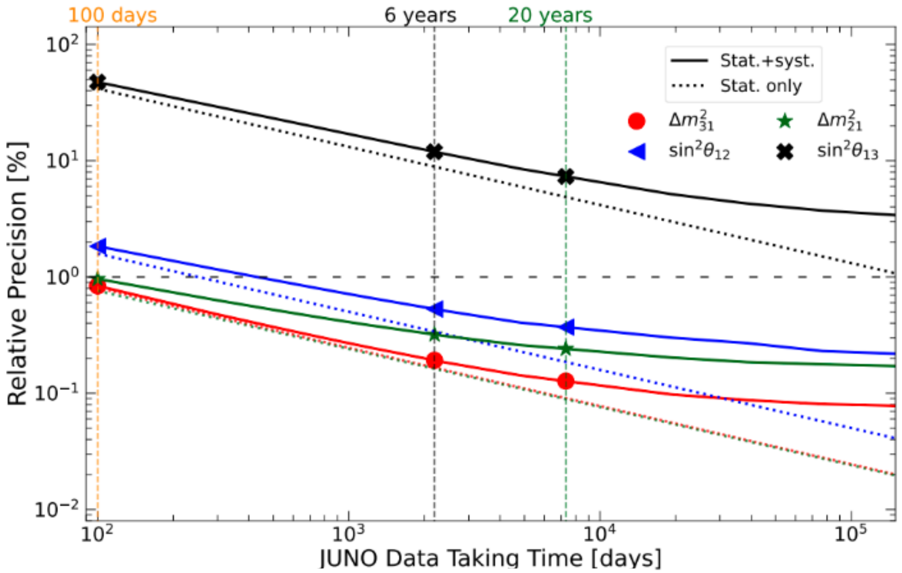
Oscillation parameters precision measurement

$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Chin. Phys. C46 (2022) 12, 123001





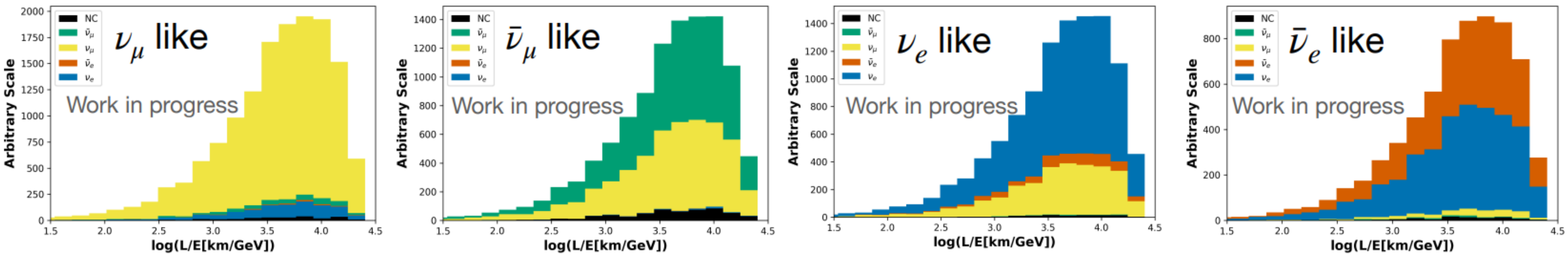


	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

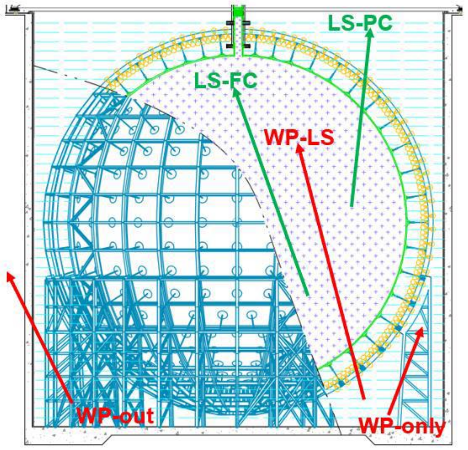
$\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$, leading measurements in 100 days; precision <0.5% in 6 years

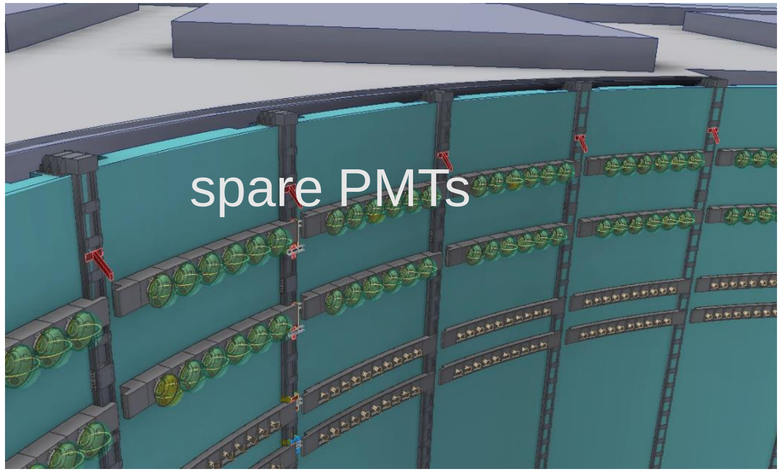
Atmospheric Neutrino

- JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator: e/μ separation, $\boldsymbol{\nu/\bar{\nu}}$ separation, ν energy (instead of lepton energy), track direction in LS



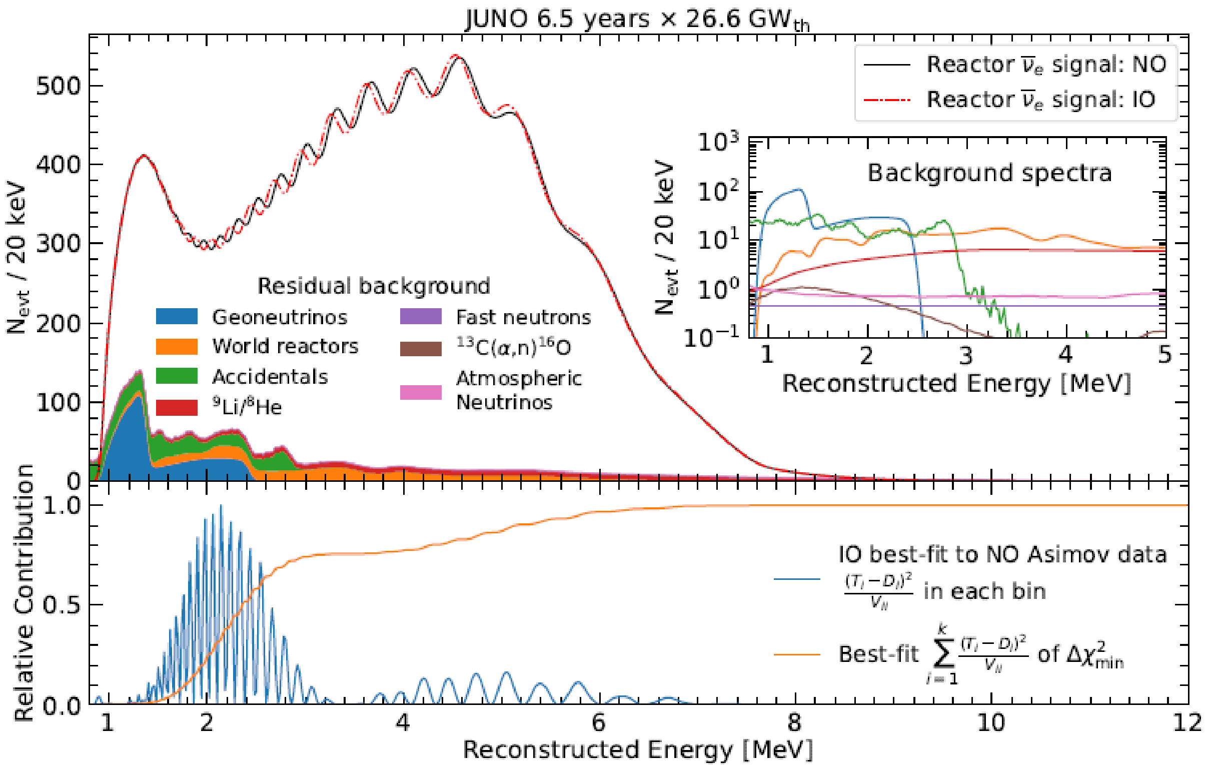
- Improving the reconstruction and PID algorithm, as well as sensitivity
- Plan to install all spare PMTs on top wall of the water pool to improve PID and direction reconstruction





Signal and backgrounds

	Design	Now
Thermal Power	36 GW_{th}	26.6 GW_{th} (**26%↓**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (**33%↑**)
Muon veto efficiency	83%	91.6% (**11%↑**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (**2%↑**)
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sens. Exposure	**<6 yrs × 35.8 GW_{th}**	**~6 yrs × 26.6 GW_{th}**

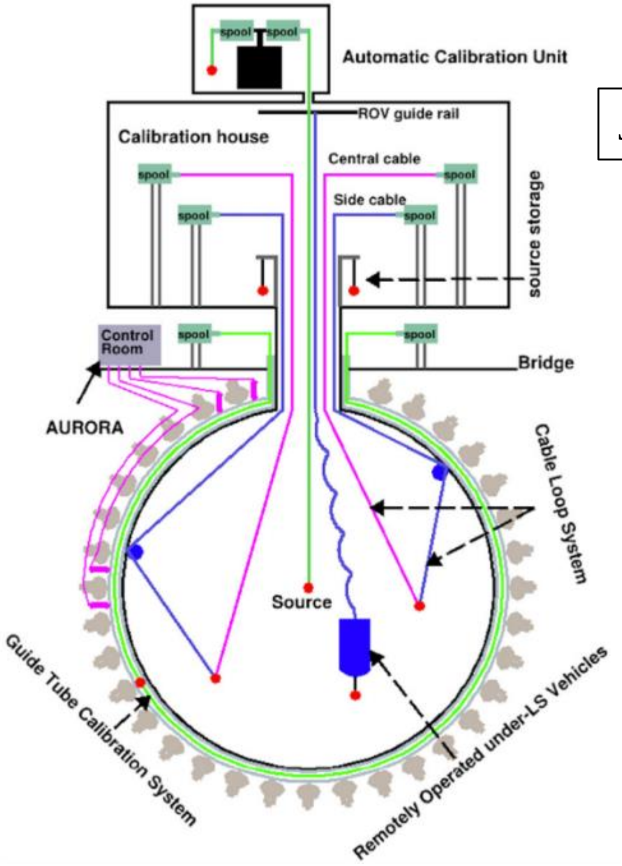


S/B=47.1/4.1

Sensitivity mostly from 1.5-3 MeV

Energy calibration and resolution

- Four systems for 1D, 2D, 3D scan with multiple sources
- Energy scale and non-linearity will be calibrated to <1% using γ peaks and cosmogenic ^{12}B beta spectrum



JHEP 03 (2021) 004

Calibration house

All systems ready for installation

arXiv:2405.17860 (2024)

For positron

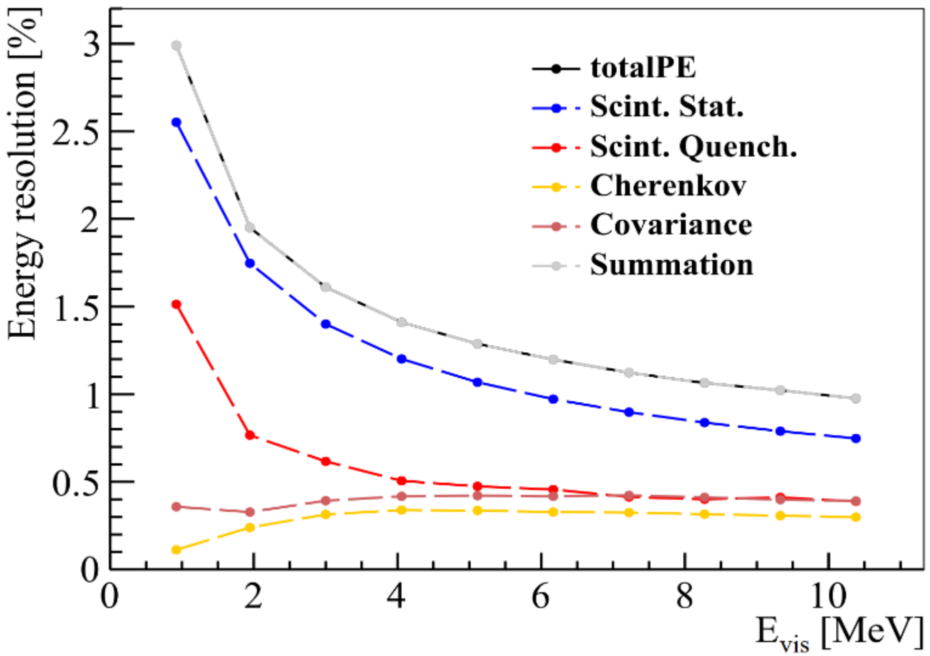
$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

Photon statistics

Constant term

Dark noise, Annihilation -induced γs

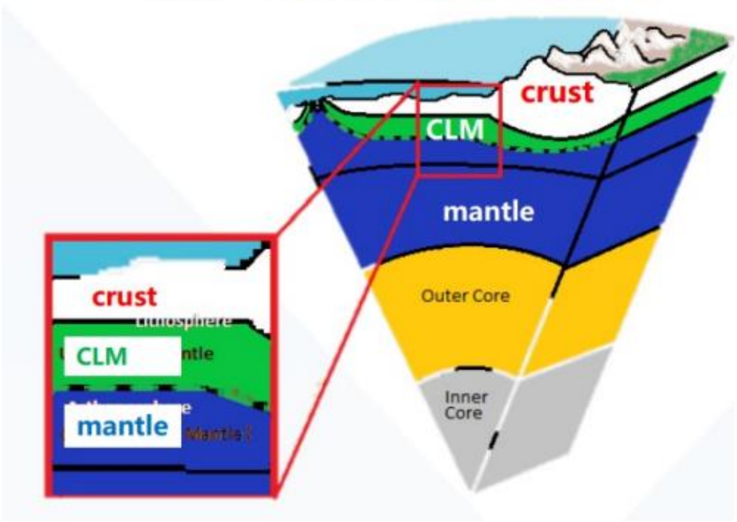
Expected energy resolution: 2.95% @1MeV



Geoneutrinos

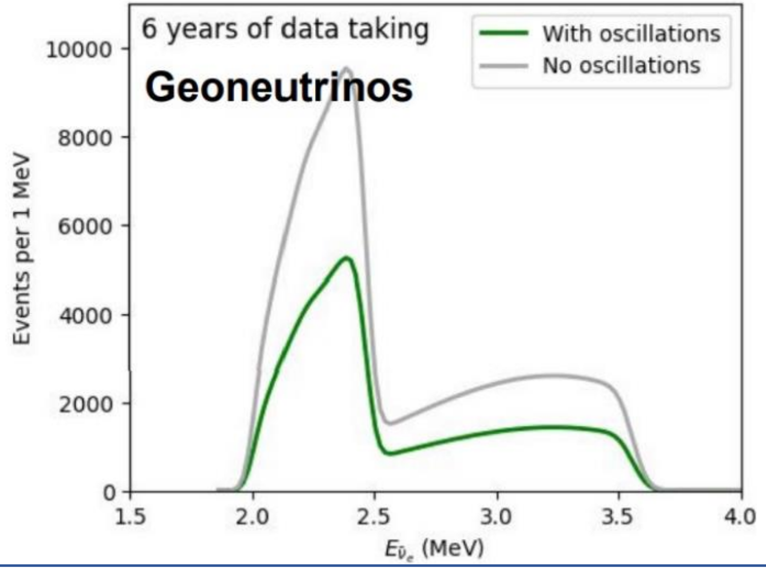
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\beta^- + 6\bar{\nu}_e$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\beta^- + 4\bar{\nu}_e$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \beta^- + \bar{\nu}_e$$

$$S_{\mathrm{Total}} = S_{\mathrm{Crust}} + S_{\mathrm{CLM}} + S_{\mathrm{Mantle}}$$



- Crust: high U & Th
- CLM (Continental Lithospheric Mantle): relatively low U & Th
- Mantle: very low U & Th, large volume

- **400 evts**/year largest detection rate
- Unprecedented precision ~**8%** in 10y
- U/Th separation and crust/mantle separation possible



Expected geoneutrino precision*
(assuming Th/U mass ratio fixed to 3.9)

1 year	**~22%**
6 years	**~10%**
10 years	**~8%**

PRELIMINARY

Phys. Rev. D 101, 012009
Borexino 17% with 8.9 years

KamLAND 15% with 14.3 years
Phys. Rev. C, 80, 015807

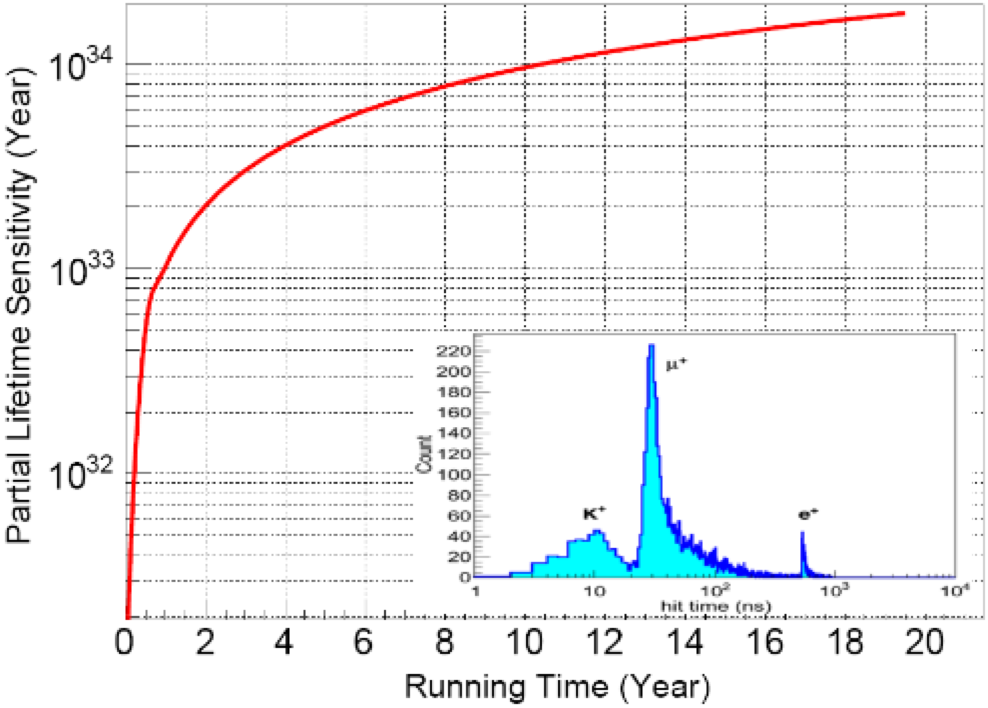
	6 years	10 years
^{232}Th:	**~40%**	**~35%**
^{238}U:	**~35%**	**~30%**
^{232}Th+^{238}U:	**~18%**	**~15%**
^{232}Th/^{238}U ratio:	**~70%**	**~55%**

PRELIMINARY

Nucleon decays

Target mass: 20 kton LS → 1.45×10^{33} free protons, 5.30×10^{33} bound protons/neutrons

$p \to \overline{\nu} K^{+}$ **triple coincidence**



$\tau/B(p \to \overline{\nu} K^{+}) > 9.6 \times 10^{33}$ **yrs / 10 yrs**

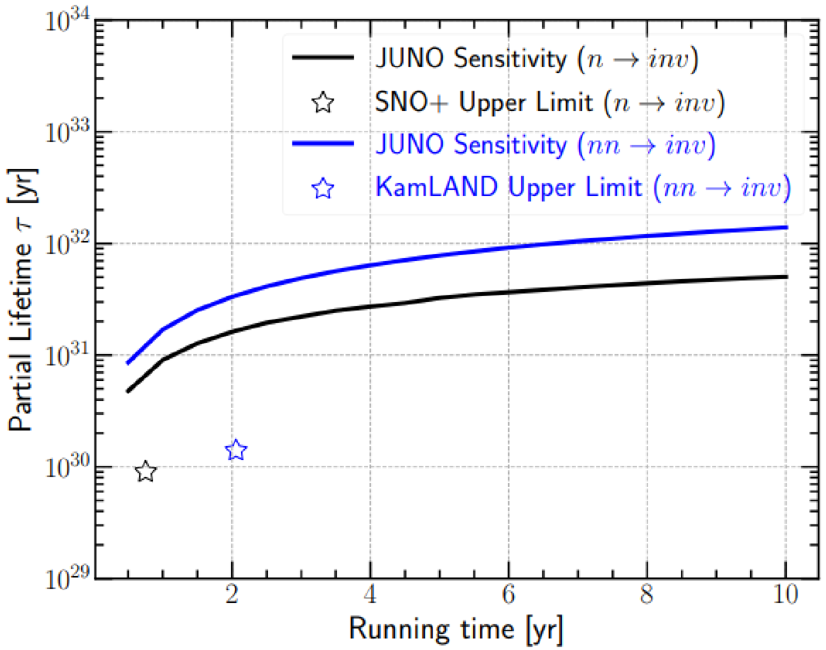
Best limit: 5.9×10^{33} **yrs from Super-K**

CPC 47, 113002 (2023)

Neutron invisible decays

$n \to inv \; (^{12}C \to {}^{11}C^{*})$

$nn \to inv \; (^{12}C \to {}^{10}C^{*})$



An order of magnitude improvement to the current best limits in 2 years data taking

arXiv: 2405.17792