
Photo taken
at the end of October 2023

Status and Prospects of the JUNO Experiment

Matthias Raphael Stock

on behalf of the JUNO Collaboration

The 17th International Workshop

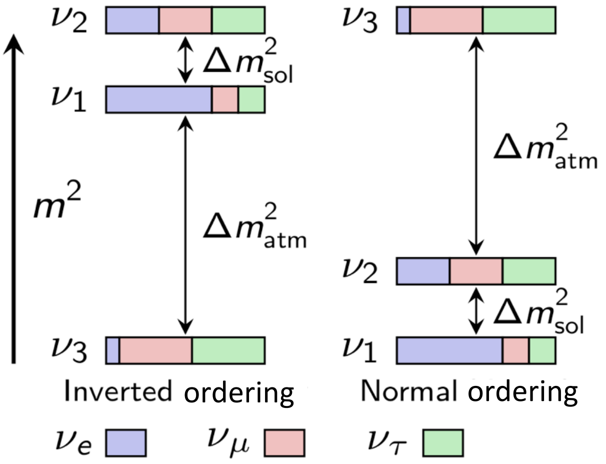
on Tau Lepton Physics (TAU2023),

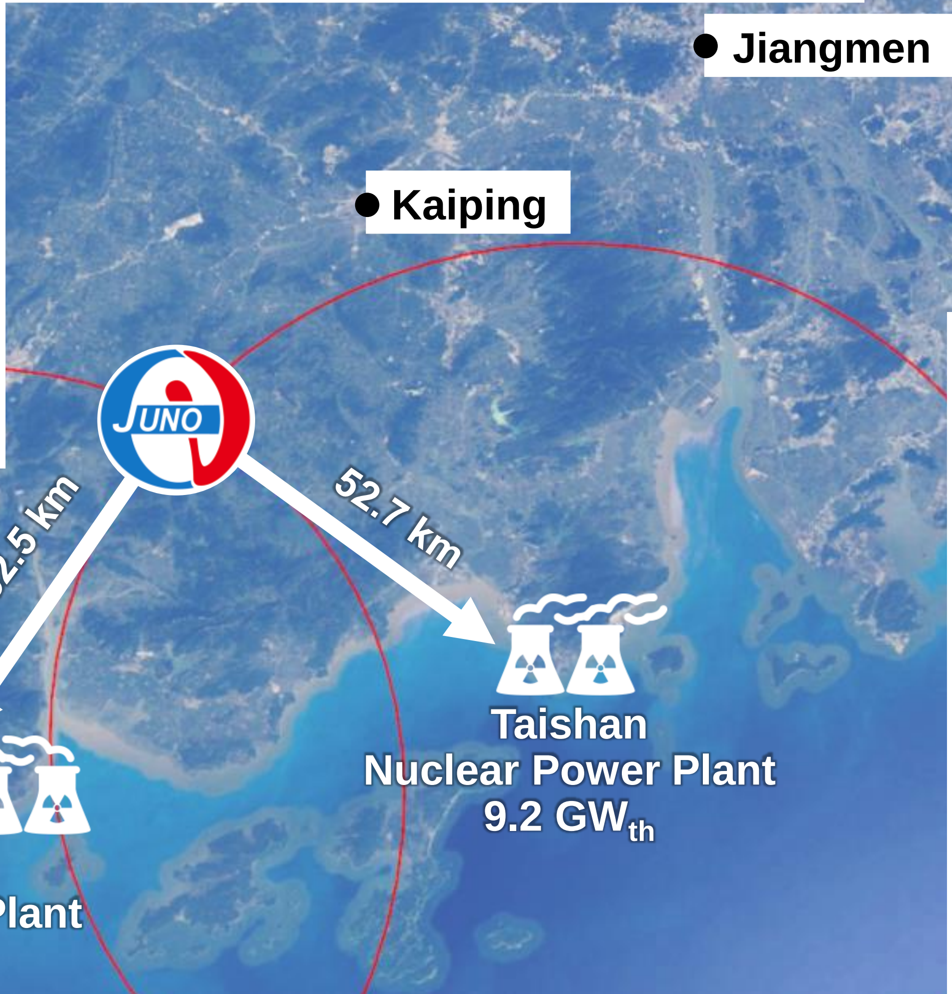
Louisville, 12/07/2023

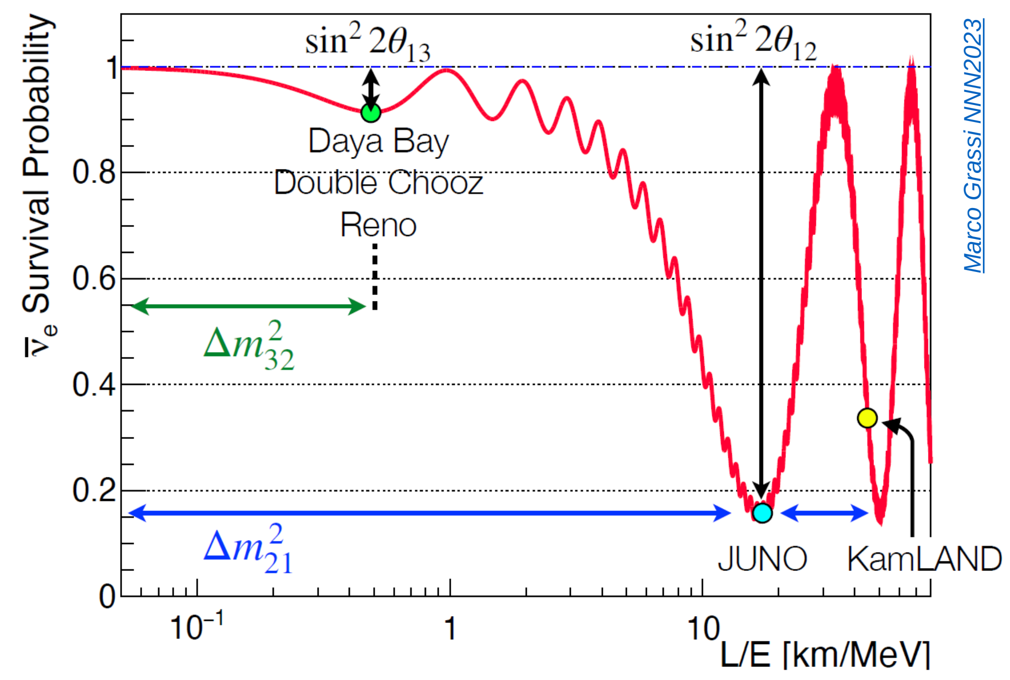
Technical University of Munich
TUM School of Natural Sciences
Physics Department

Jiangmen Underground Neutrino Observatory

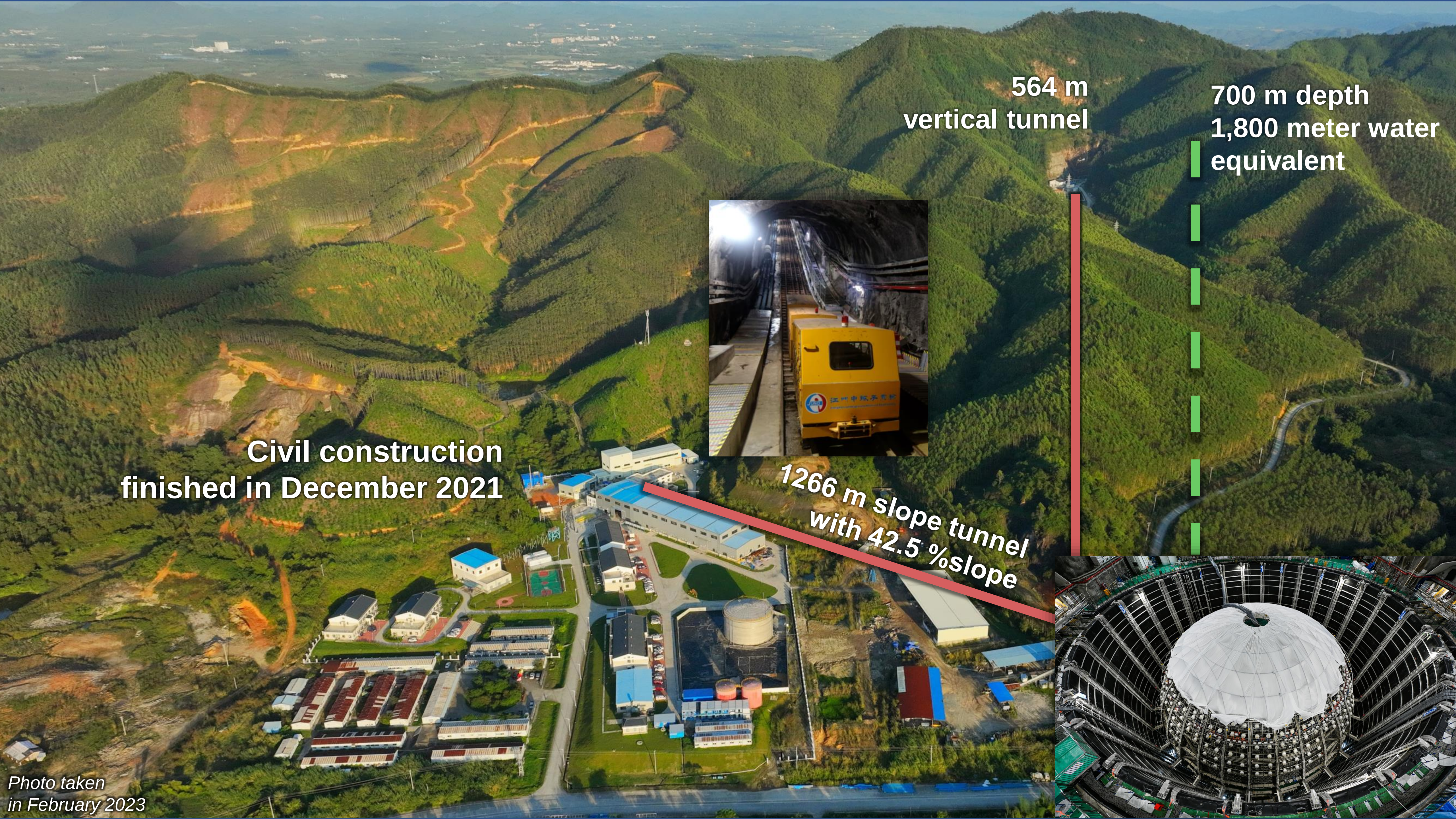
- Multi-purpose experiment currently under construction in **South China**
- Main goal is the **determination of the neutrino mass ordering** at 3 σ after 6 years data taking by measuring the oscillated electron antineutrino energy spectrum from nuclear reactors







Marco Grassi NNN2023



564 m
vertical tunnel

700 m depth
1,800 meter water
equivalent

Civil construction
finished in December 2021

1266 m slope tunnel
with 42.5 %slope

Photo taken
in February 2023

Overview of the JUNO Detector

Central Detector

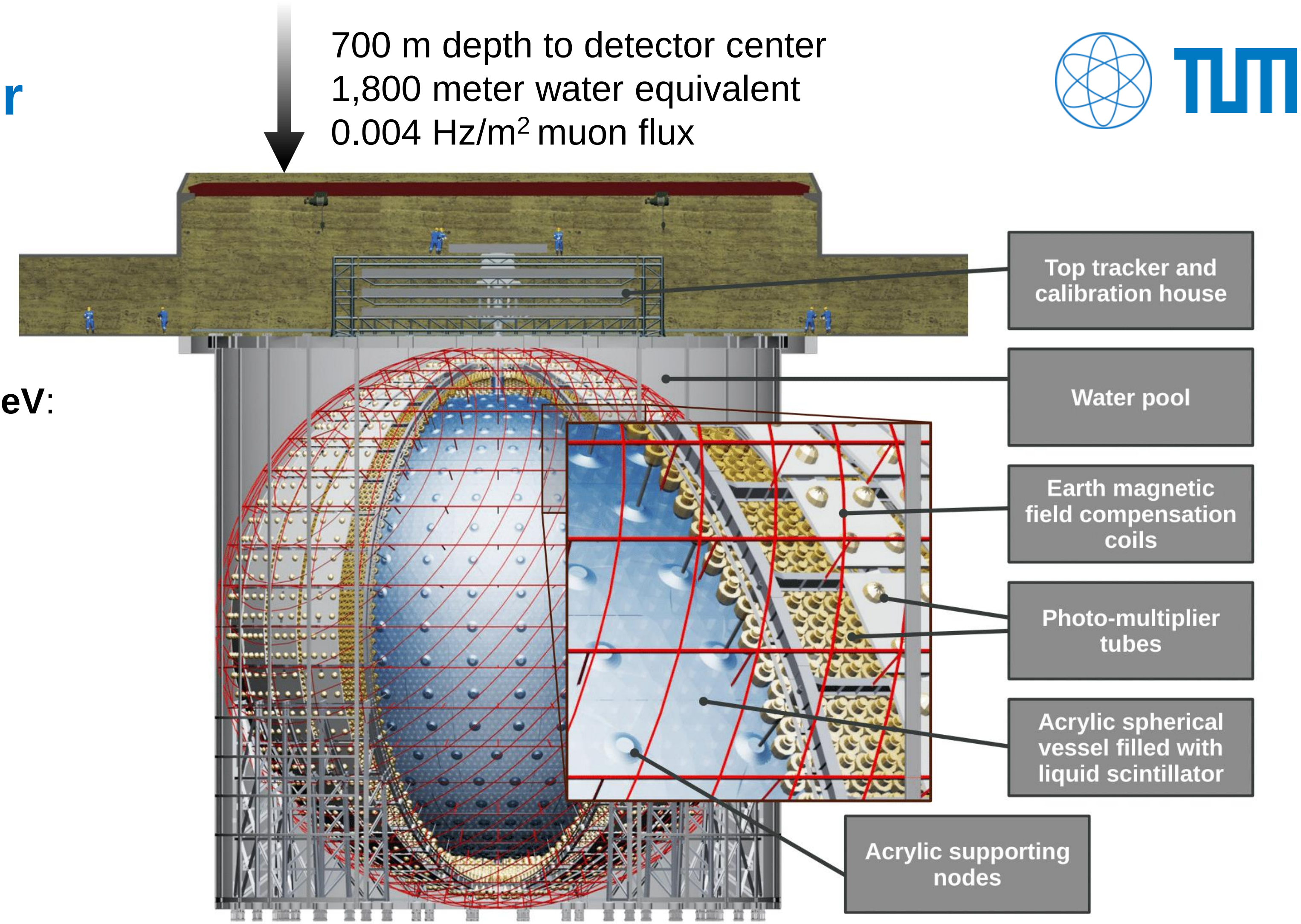
- 20,000 tons of liquid scintillator (LS) in 35.4 m in diameter acrylic sphere, largest in the world

Unprecedented energy resolution of **3 % at 1 MeV**:

- High light yield of LS:
  ~ **10,000 photons per MeV** expected
- High transparency of LS:
  ~ **20 m** attenuation length at 430 nm
- High photocoverage of ~ **78 %**:
  17,612 large PMTs (20-inch) and
  25,600 small PMTs (3-inch)

Water Cherenkov Detector

- 35,000 tons of ultra-pure water in cylinder of 43.5 m in diameter and 44 m in height
- 2,400 large PMTs (20-inch)
- Veto and shielding surrounding radioactivity

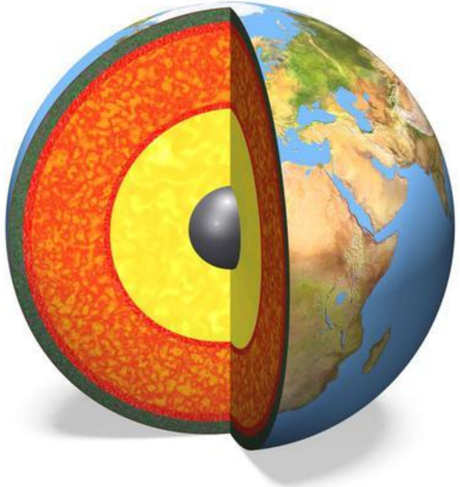


Top Tracker

- Combined with CD or WCD, well reconstructed muon sample with **> 99 %** purity → used to calibrate & tune algorithms to improve reconstruction algorithms for CD and WCD of atmospheric muons & veto affected regions

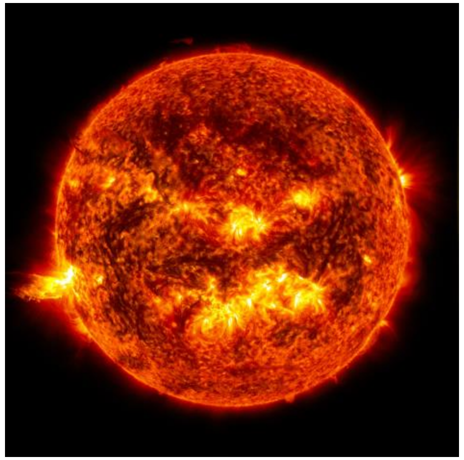
JUNO is a multi-purpose observatory with a broad physics program.

Reactor neutrinos
~ 45 IBDs per day

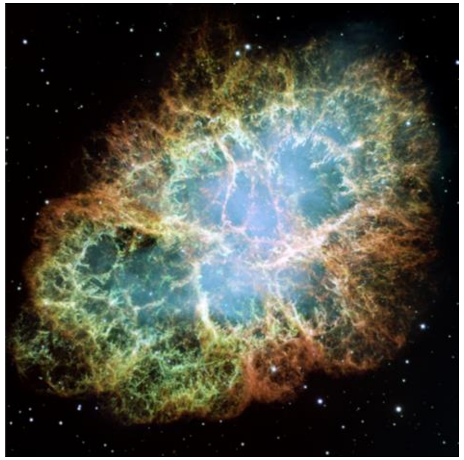


Geoneutrinos
few IBDs per day

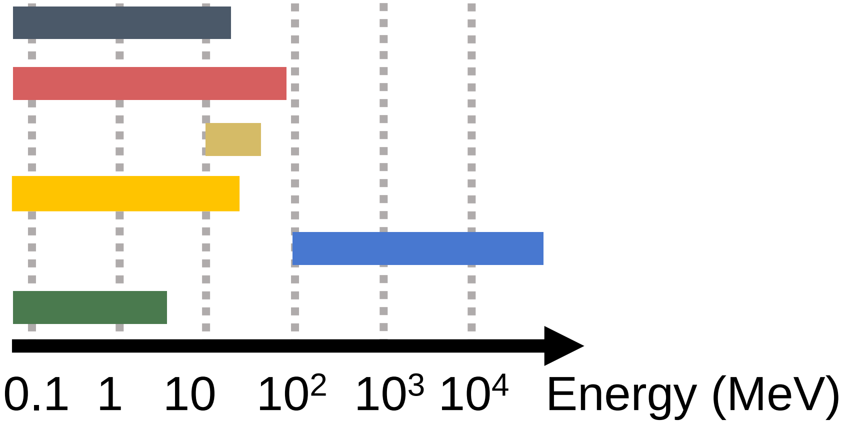
Atmospheric neutrinos
several per day



Solar neutrinos
^{8}B ~ 50 per day
^{7}Be ~ 10^4 per day
CNO ~ 10^3 per day



Supernova neutrinos
~ 10^4 for CCSN
at 10 kpc



Diffuse supernova neutrinos
~ 2 to 4 IBDs per year

**proton decay, dark matter,
sterile neutrinos, nucleon decay …**

List of Members of the JUNO Collaboration

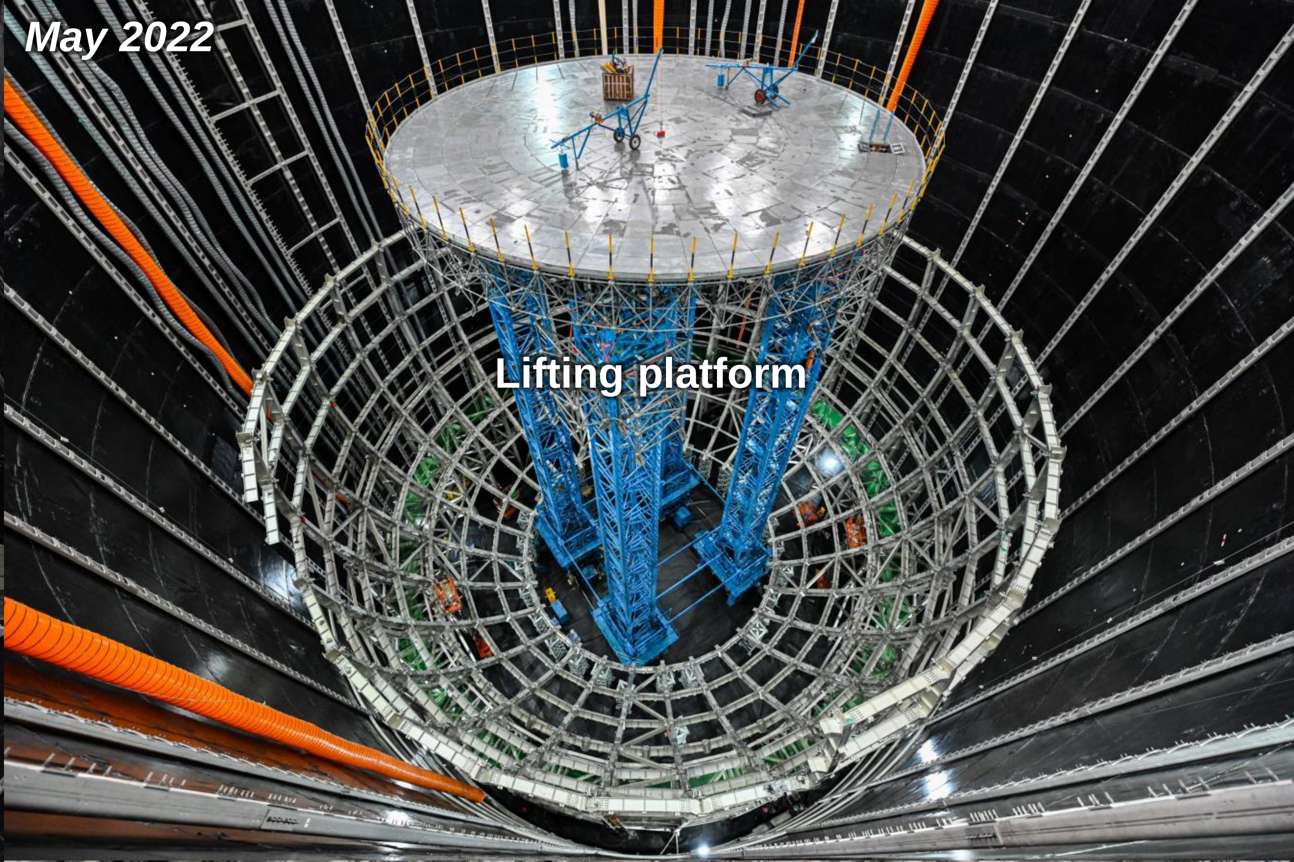
Country	Institute
Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Brazil	PUC
	UEL
Chile	PCUC
	SAPHIR
	UNAB
China	BISEE
	Beijing Normal University
	CAGS
	Chongqing University
	CIAE
	DGUT
	Guangxi University
	Harbin Institute of Technology
	IHEP
	Jilin U.
	Jinan U.
	Nanjing U.
	Nankai U.
	NCEPU
	Peking U.
	Shandong U.
	Shanghai JT U.
	IGG-Beijing
China	SYSU
	Tsinghua U.
	UCAS
	USTC
	U. of South China
	Wu Yi U.
	Wuhan U.
	Xi'an JT U.
	Xiamen University
	Zhengzhou U.
	NUDT
	CUG-Beijing
	ECUT-Nanchang City
	CDUT-Chengdu
Czech	Charles University
Finland	University of Jyvaskyla
France	IJCLab Orsay
	LP2i Bordeaux
	CPPM Marseille
	IPHC Strasbourg
	Subatech Nantes
Germany	RWTH Aachen U.
	TUM
	U. Hamburg
	FZJ-IKP
Germany	U. Mainz
	U. Tübingen
Italy	INFN Catania
	INFN di Frascati
	INFN-Ferrara
	INFN-Milano
	INFN-Milano Bicocca
	INFN-Padova
	INFN-Perugia
	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
	JINR
	MSU
Slovakia	FMPICU
Taiwan-China	National Chiao-Tung U.
	National Taiwan U.
	National United U.
Thailand	NARIT
	PPRLCU
	SUT
U.K.	U. Warwick
USA	UMD-G
	UC Irvine

+ Observers: University of Liverpool

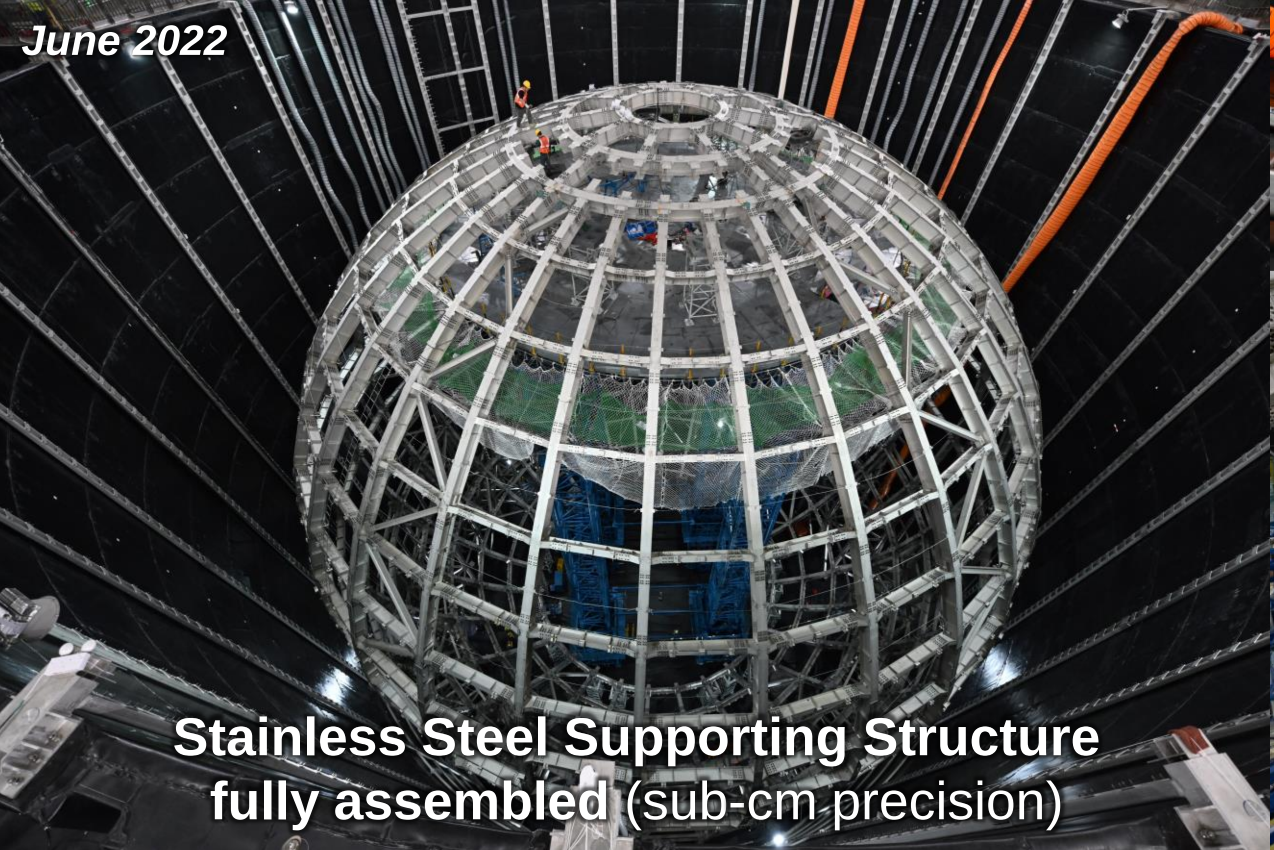
74 institutes
in 17 countries/regions
~700 collaborators

Detector Design and Status

January 2022

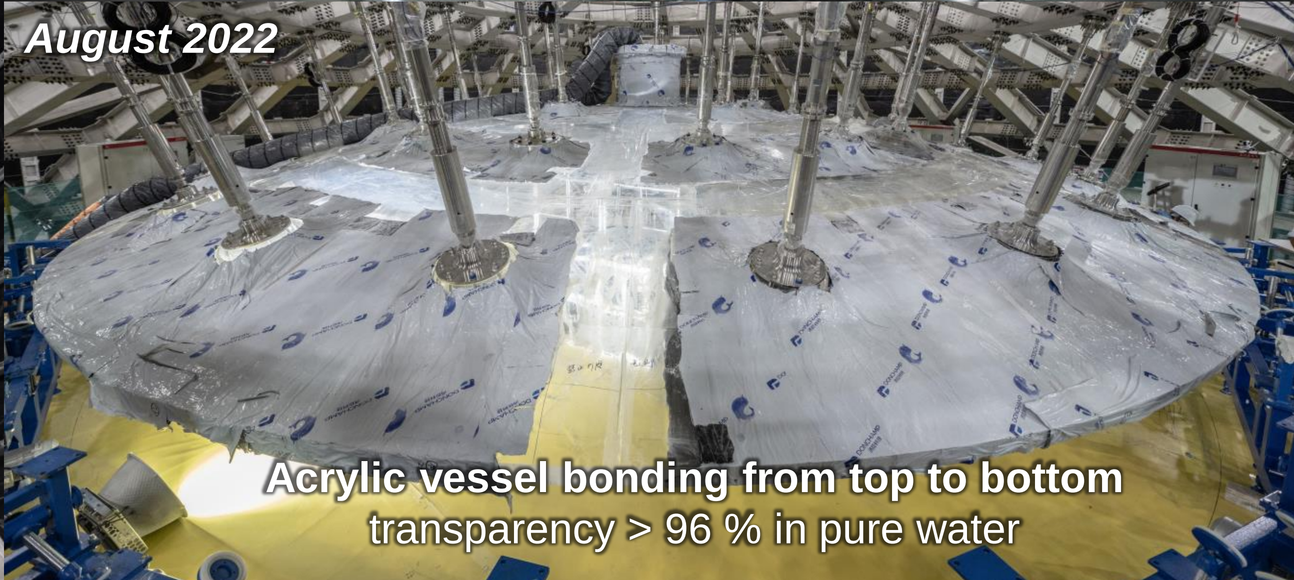


May 2022



June 2022

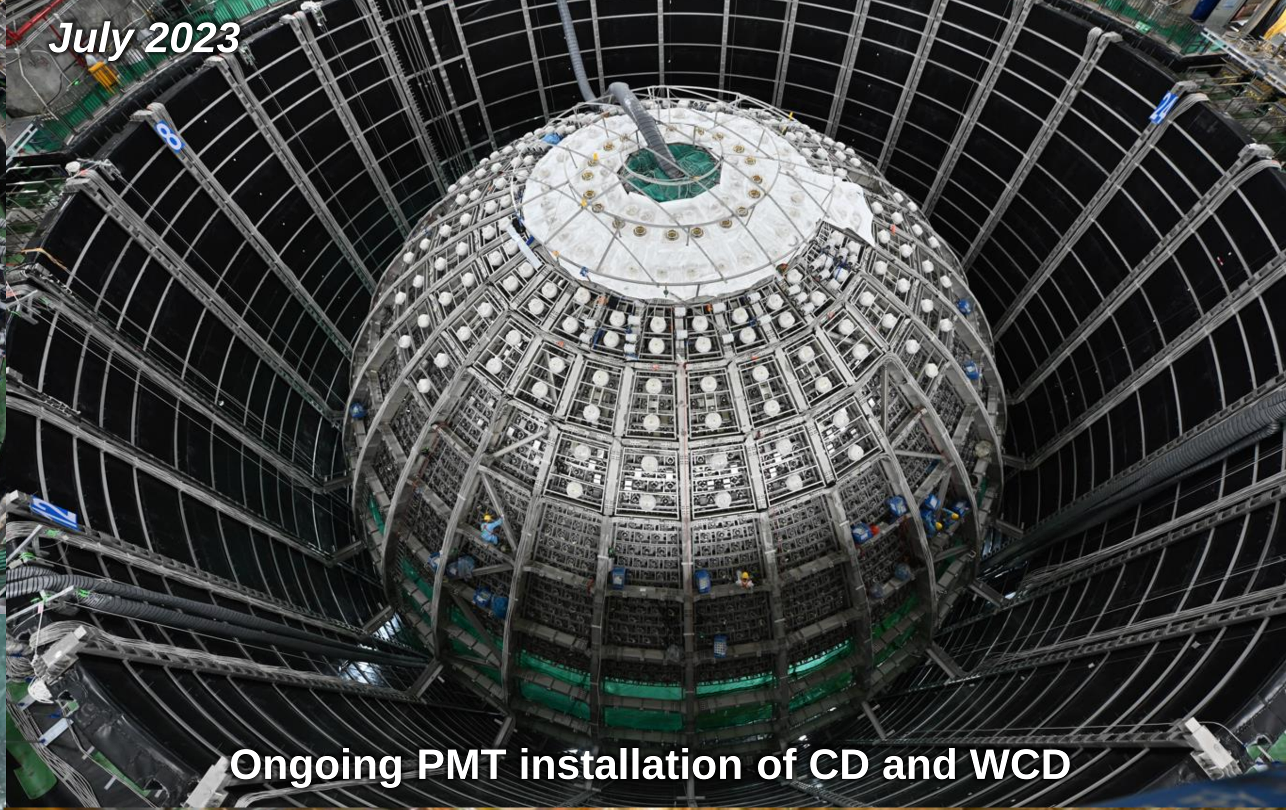
Stainless Steel Supporting Structure fully assembled (sub-cm precision)



August 2022

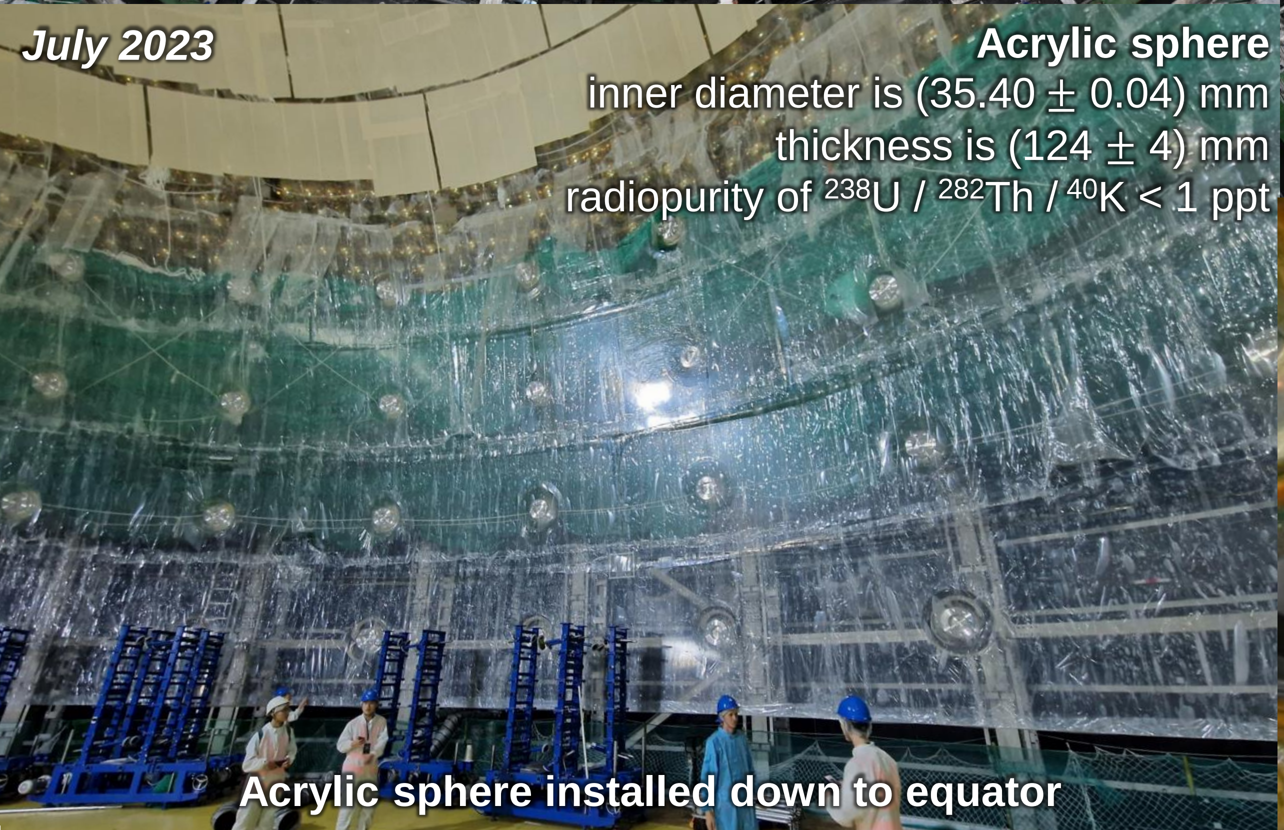
Acrylic vessel bonding from top to bottom
transparency > 96 % in pure water

December 2022



July 2023

Ongoing PMT installation of CD and WCD



July 2023

Acrylic sphere

inner diameter is (35.40 ± 0.04) mm

thickness is (124 ± 4) mm

radiopurity of ^{238}U / ^{282}Th / ^{40}K < 1 ppt

Acrylic sphere installed down to equator

Large Photomultiplier Tubes

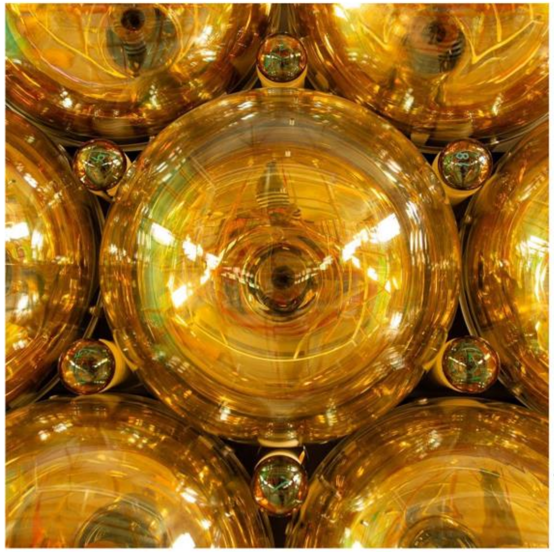
Performance testing of more than 20,000 PMTs concerning gain-voltage dependency, dark count rate, peak-to-valley, timing characteristics, pre-/afterpulses…

- 5,000 x 20-inch dynode PMTs
  from Hamamatsu, Japan

Mass testing and characterization of 20-inch PMTs for JUNO
Eur. Phys. J. C 82, 1168 (2022)

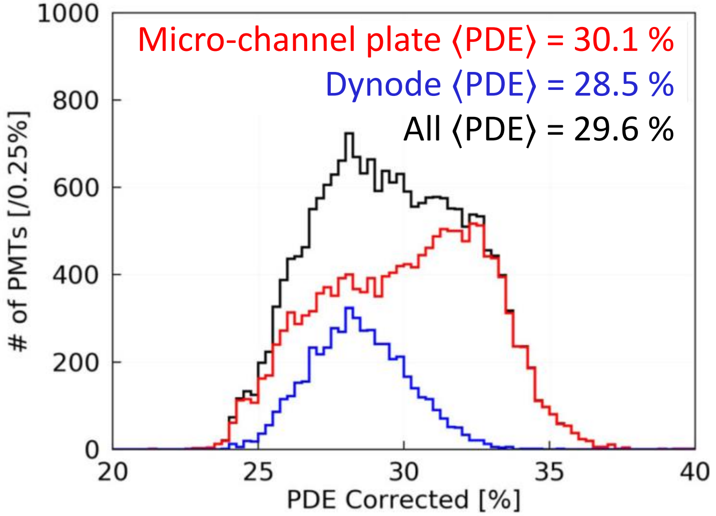
- 12,612 x 20-inch Micro-channel plate (MCP) PMTs for CD and 2,400 MCP-PMTs for WCD
  from North Night Vision Technology (NNVT), China

Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity

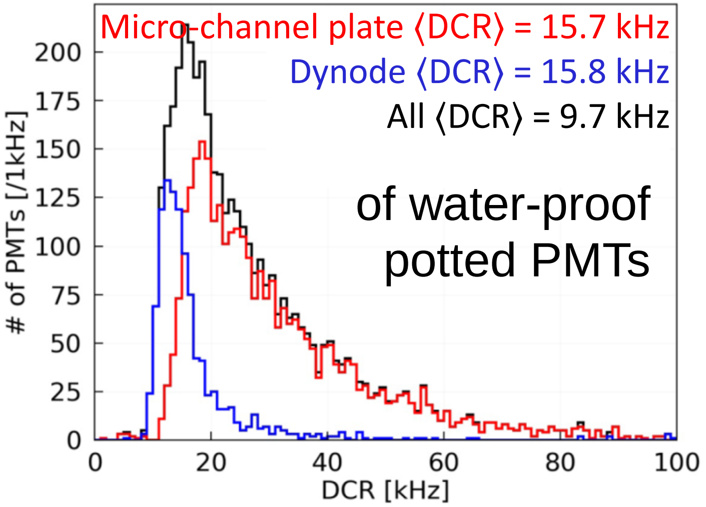


Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm**

Photo detection efficiency (PDE)

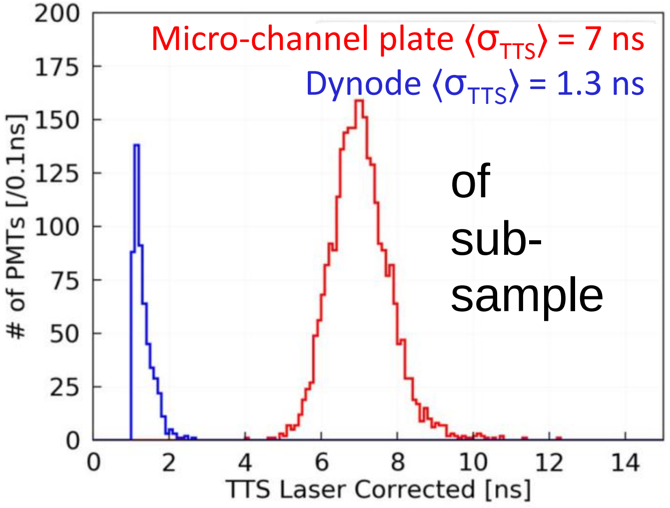


Dark count rate (DCR)



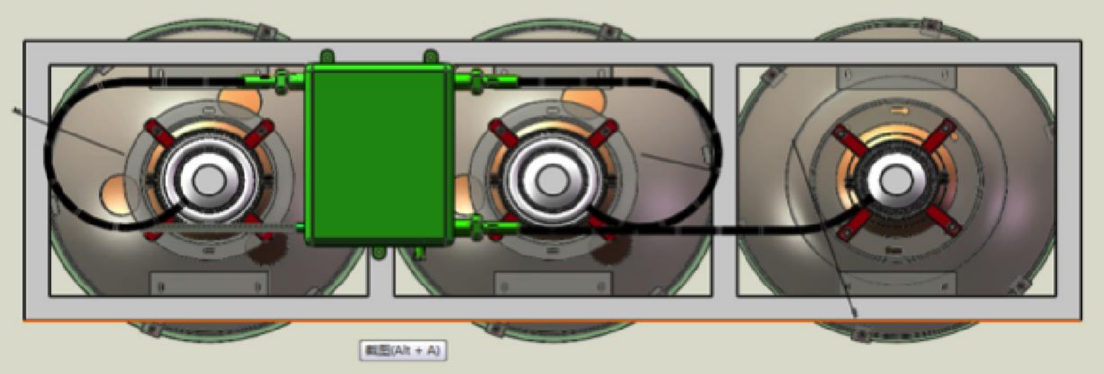
of water-proof potted PMTs

Transit time spread (TTS)



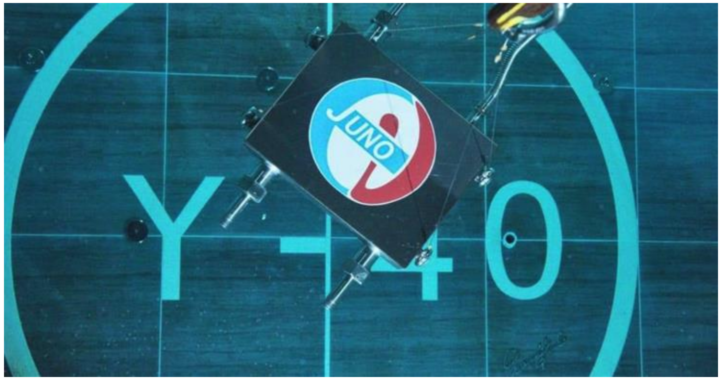
of sub-sample

Large Photomultiplier Tube Electronics Readout Scheme

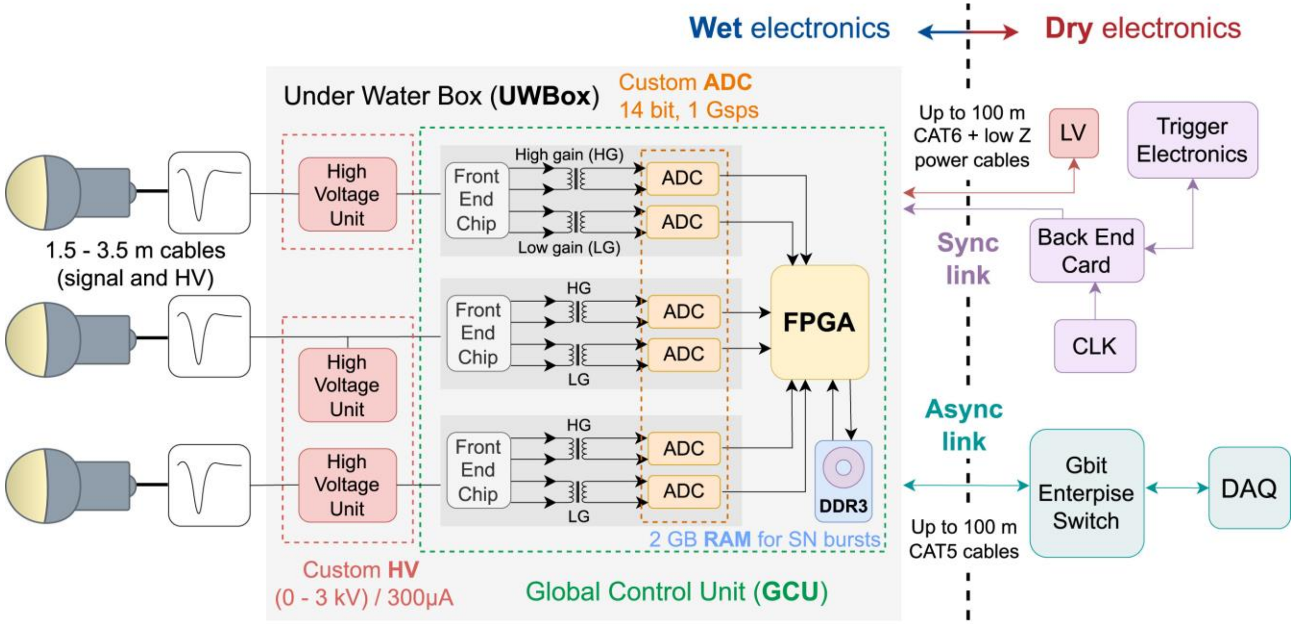


Large PMT Installation Module (Green: Under water box)

Diver with under water box in 40 m depth



Test in the Y-40 pool of the Montegrotto thermal spa in Italy



Full waveform digitization

- High speed: 1 Gsample/s
- High resolution: 14 bits

Validation and integration tests of the JUNO 20-inch PMT readout electronics
NIM A 1053, 2023, 168322

Two Flash ADC converters

- Low-gain stream: from 1 PE to 100 PE with 1 PE resolution
- High-gain stream: from 100 PE to 1,000 PE with 0.1 PE resolution

- Single PMT trigger at 50 kHz - 100 kHz single trigger rate
- Stand high rates for very short times (up to 1 MHz for 1 s)

For supernova burst

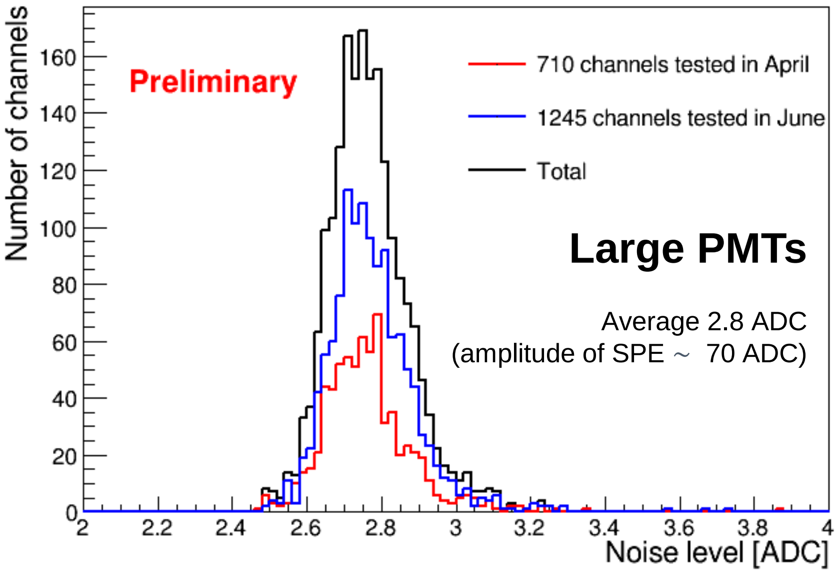
- All triggerless data stored using 2 GB RAM shared by 3 PMTs

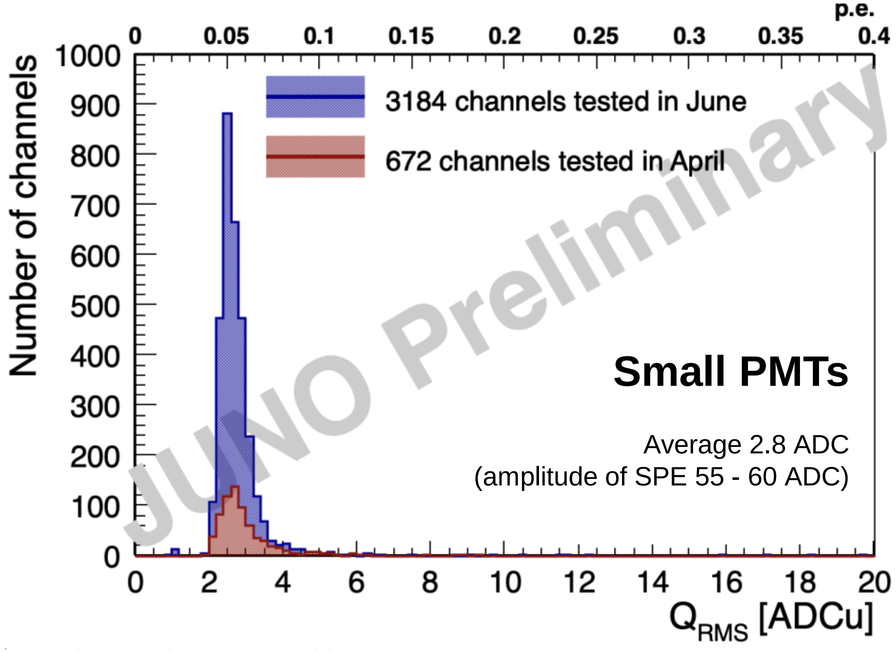
Commissioning of Large PMTs and Small PMTs

- Regular light-off/light-on tests during detector assembly started
  - **Light off tests:** full data taking and processing chain with PMT HV on
  - **Light on tests:** joint elec./trigger/DAQ/DCS test with PMT HV off

- Very good electronics, shielding and grounding
  - Electronics noise of large PMTs is **2.8 ADC** counts, **4 % of SPE**
    ➔ Much better than the design of 10 %
  - Electronics noise of small PMTs is **2.8 ADC** counts, ~ **5 % of SPE**
    ➔ Much lower than the trigger threshold of 1/3 p.e.

- All tested PMTs (710 large PMTs and 3,184 small PMTs) are working well
- More tests will continue being made as installation progresses



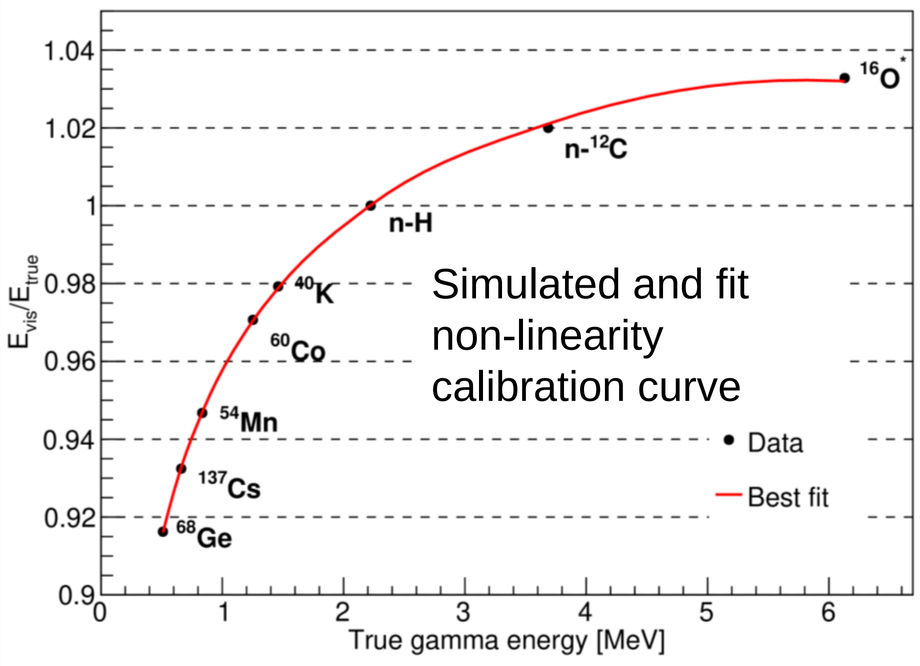


Energy Scale Calibration

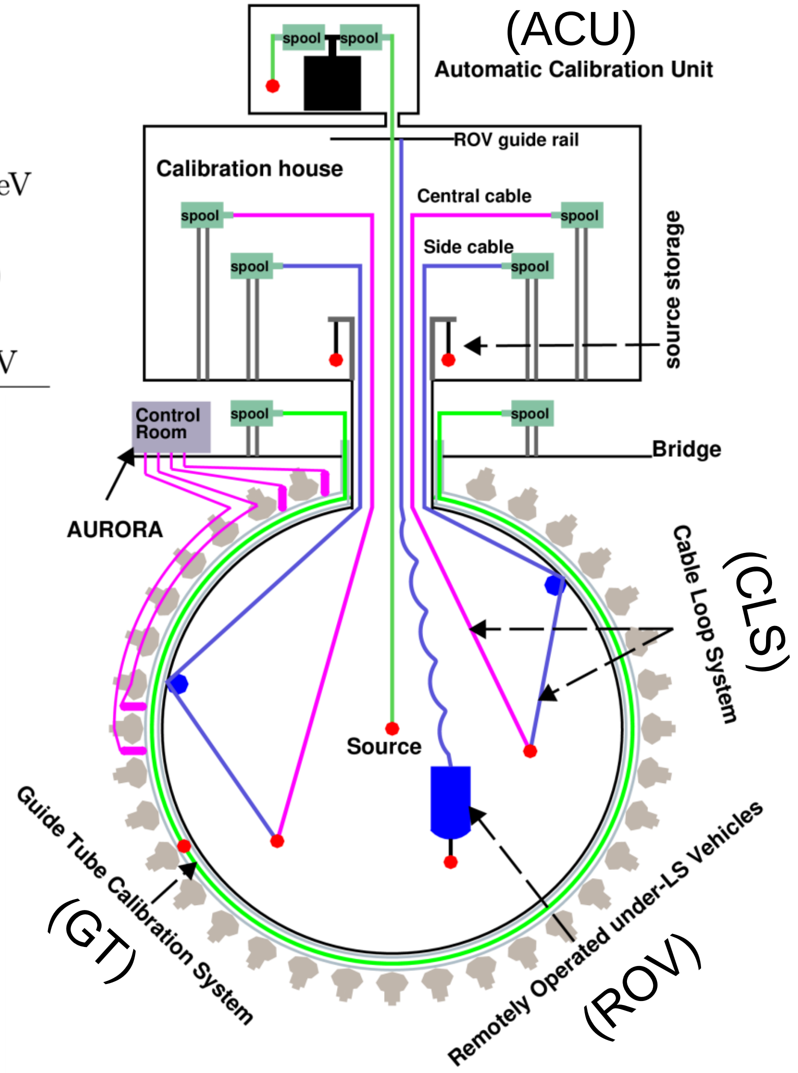
Calibration strategy of the JUNO experiment
J. High Energ. Phys. 2021, 4

- Requirement for NMO:
  < 1 % energy linearity and
  3 % effective energy resolution
- Regular calibration using radioactive sources
  + pulsed UV laser source
  by several calibration systems
- 26,500 small (3-inch) PMTs are complementary system
  to validate large (20-inch) PMTs calibration

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV



Simulated and fit non-linearity calibration curve

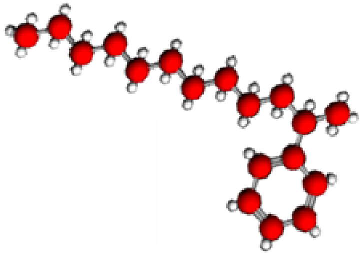


Organic Liquid Scintillator of JUNO

- Composition studied for maximal light yield in a pilot plant at Daya Bay

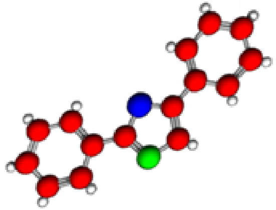
Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector
[NIM 988, 2021, 164823]

A complete optical model for liquid-scintillator detectors
[NIM A 967, 2020, 163860]



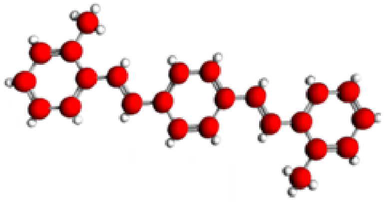
Solvent
LAB
(linear alkylbenzene)

+

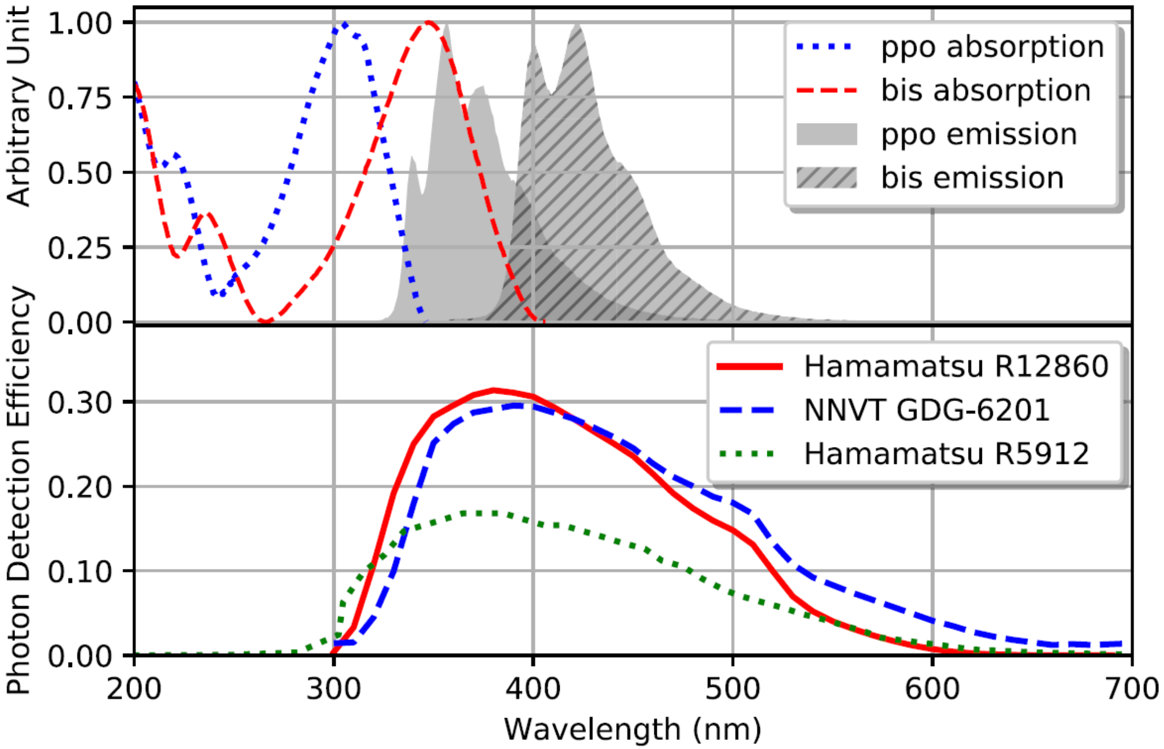


Fluor
2.5 g/L PPO
(2,5-diphenyloxazole)

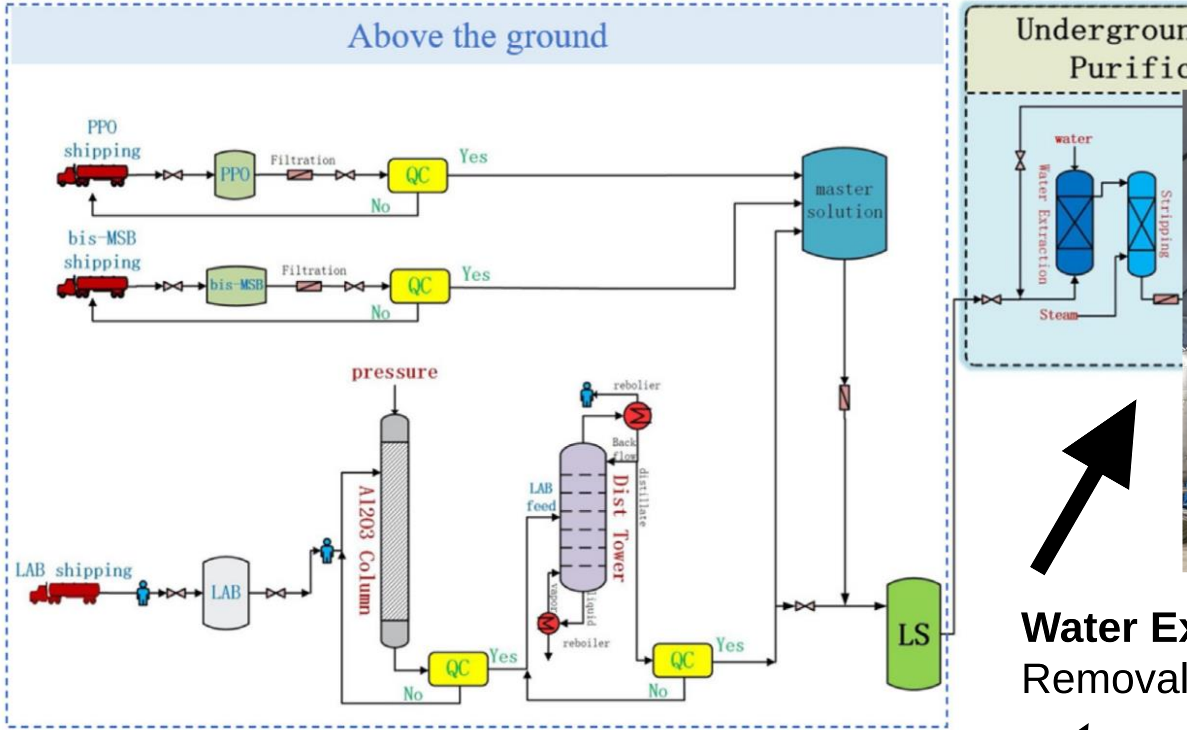
+



Wavelength-shifter
3 mg/L bis-MSB
(1,4-bis(2-methylstyryl)benzene



Before filling JUNO, the liquid scintillator goes through a purification chain.



Removal of gaseous impurities such as ^{222}Rn , ^{85}Kr , ^{39}Ar with water steam and/or N_2

Distillation and stripping pilot plants for the JUNO neutrino detector: Design, operations and reliability
NIM A 925, 2019, 6-17

Water Extraction
Removal of ^{238}U, ^{232}Th and ^{40}K

Aluminum (Al_2O_3) filtration plant
Improvement of optical properties

Removal of heavy and high-boiling radioactive metals such as ^{238}U, ^{232}Th and ^{40}K

Improvement of radio-purity and optical properties such as more transparency, less absorbance

Radiopurity during filling of JUNO will be validated by the pre-detector OSIRIS – Online Scintillator Internal Radioactivity Investigation System

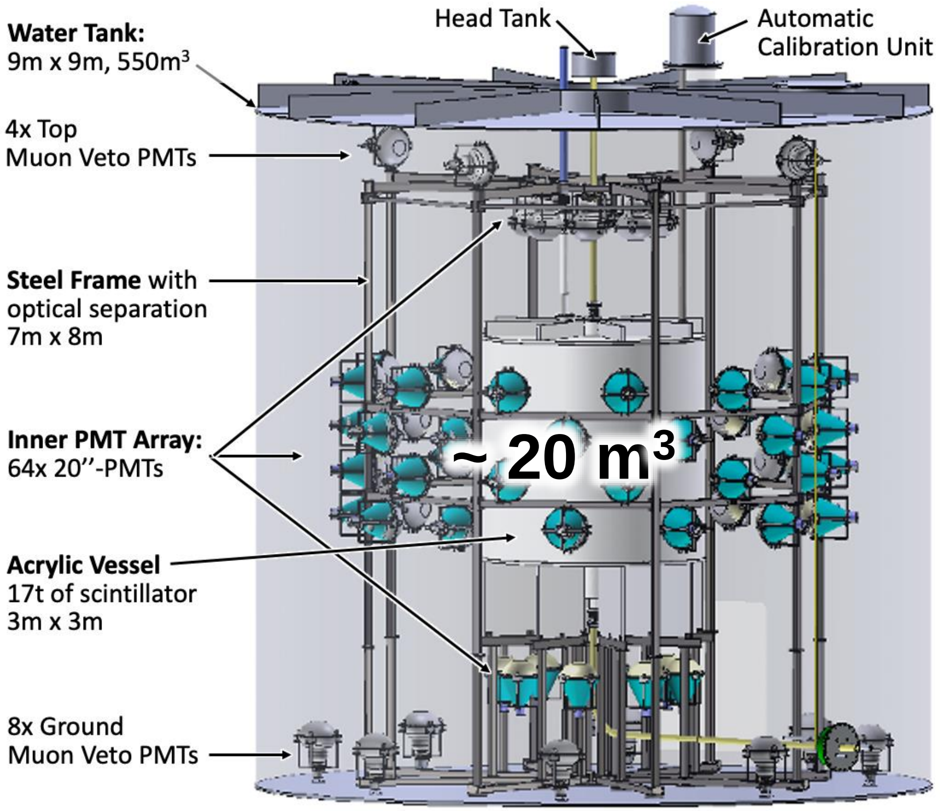
For IBD-based physics program $\leq 10^{-15}\,\mathrm{g/g}$ few days

of ^{238}U and ^{232}Th of screening time

For solar neutrino measurements $\leq 10^{-16}\,\mathrm{g/g}$ few weeks

The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS
Eur. Phys. J. C 81, 973 *(2021)*

by measuring coincidence decays of $^{214}\mathrm{Bi}\text{-}^{214}\mathrm{Po}\ (\tau \sim 164\ \mu\mathrm{s})$ $^{212}\mathrm{Bi}\text{-}^{212}\mathrm{Po}\ (\tau \sim 0.43\ \mu\mathrm{s})$



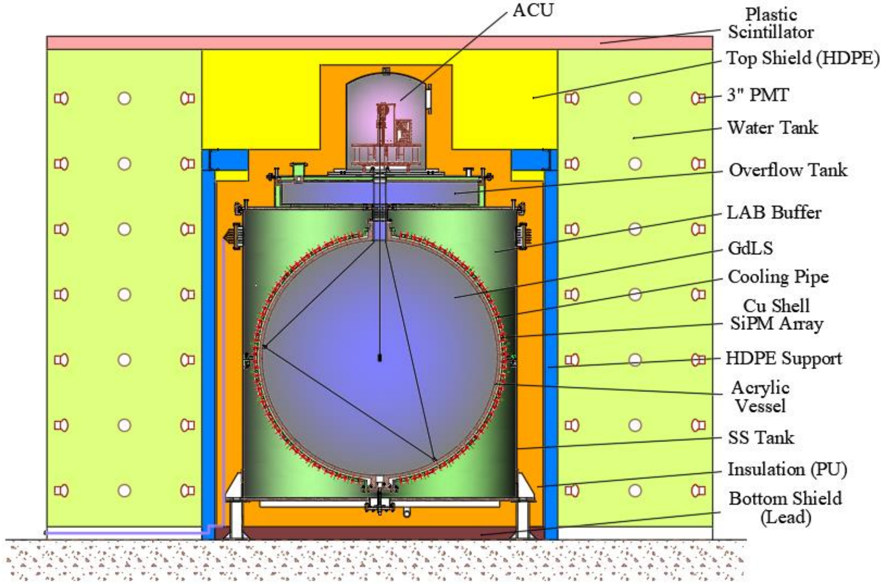

OSIRIS detector assembled

OSIRIS raises alert within hours if too unpure for IBD measurements

Potential for a precision measurement of solar pp neutrinos in the Serappis experiment
Eur. Phys. J. C 82, 779 *(2022)*

JUNO-TAO - Taishan Antineutrino Observatory

TAO Conceptual Design Report (2020)
arXiv:2005.08745v1

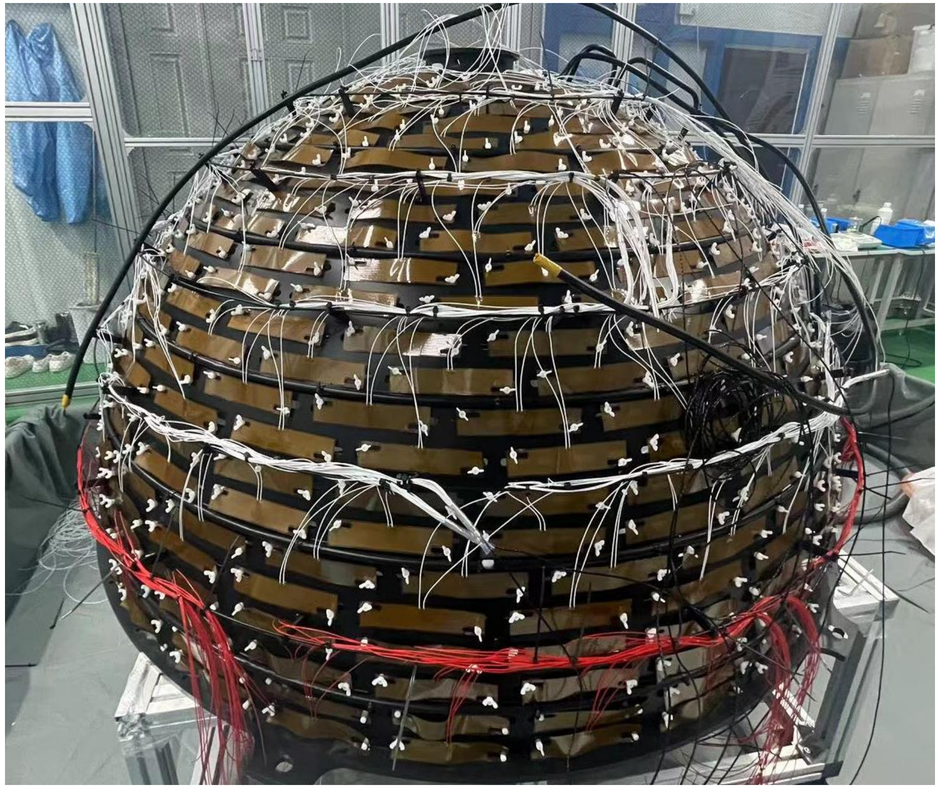


Satellite detector of JUNO at ~ 44 m from Taishan reactor core 1

- High-precision measurement of the unoscillated reactor antineutrino energy spectrum, ~ 1,500 IBD events per day
- Providing model-independent reference spectrum for the determination of the neutrino mass ordering in JUNO
- Benchmark measurement to test nuclear databases
- **Energy resolution < 2 % at 1 MeV (4,500 P.E. / MeV)**
- 2.8 ton detector using gadolinium-loaded liquid scintillator at – 50°C, 1.8 m in diameter acrylic sphere
- ~ 10 m^2 SiPMs used to achieve ~ 100 % coverage,
  > 50 % photon detection efficiency
  → cooled down to -50°C to further lower dark noise

Calibration strategy of the JUNO-TAO experiment
Eur. Phys. J. C 82, 1112 (2022)

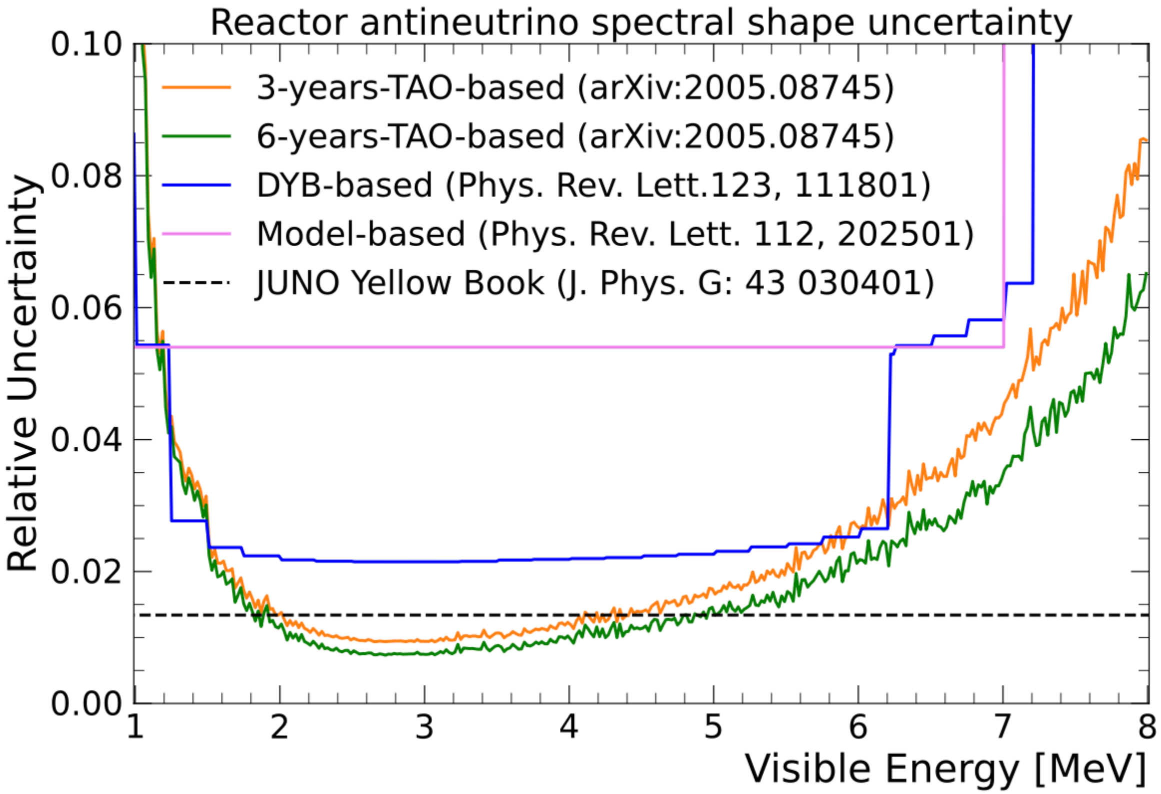
JUNO-TAO - Taishan Antineutrino Observatory



TAO built and tested at IHEP

to be transferred to Taishan power plant

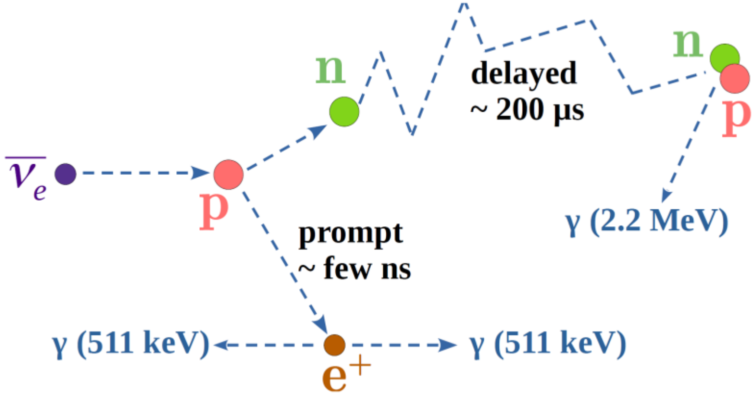
Expected performance



Physics Prospects

JUNO will detect reactor electron antineutrinos via inverse beta decay (IBD)

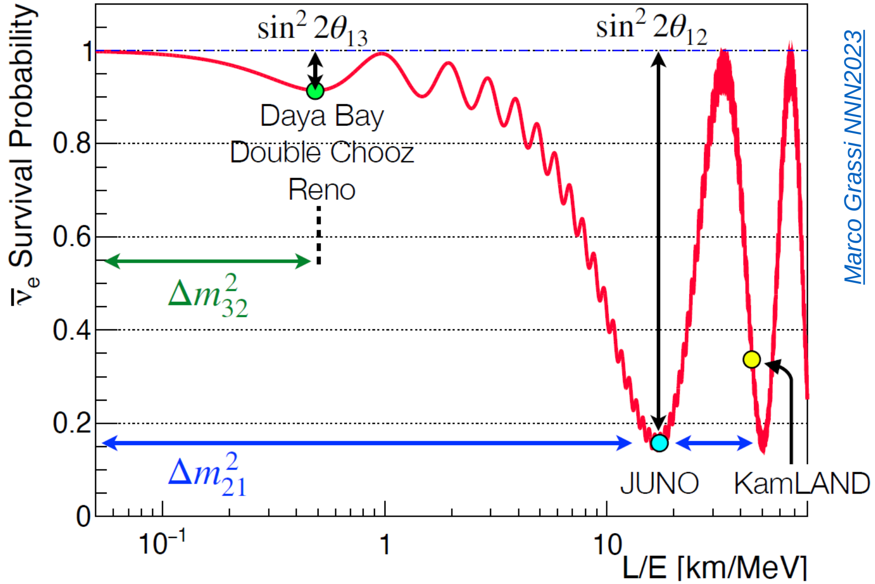
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



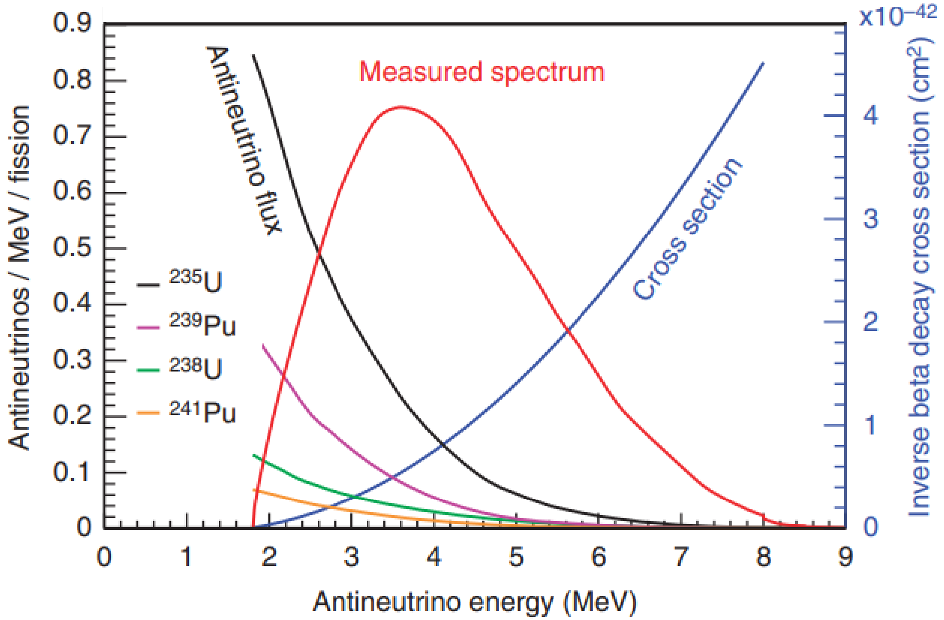
- Prompt + delayed signal:

  large background suppression
- Reaction threshold: 1.8 MeV
- Proxy for antineutrino energy:

$$E_{\mathrm{vis}}(e^+) \simeq E(\overline{\nu}) - 0.8\,\mathrm{MeV}$$

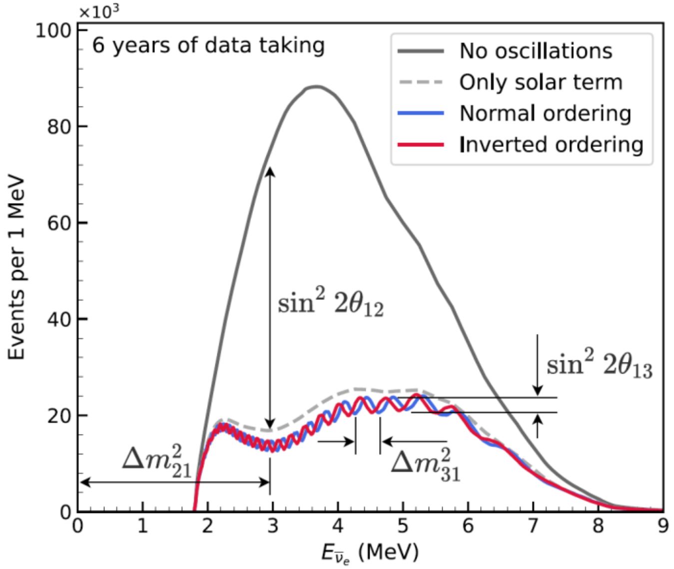


Marco Grassi NNN2023



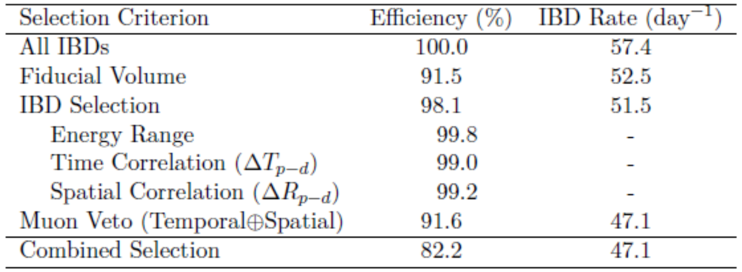
JUNO will determine the neutrino mass ordering at 3 σ after 6 years data taking.

Background	Rate, day^{-1}	Rate Uncertainty, %	Shape Uncertainty, %
Geoneutrinos	1.2	30	5
Global reactors	1.0	2	5
Accidentals	0.8	1	negligible
^{9}Li/^{8}He	0.8	20	10
^{13}C(α,n)^{16}O	0.05	50	50
Atmospheric neutrinos	0.16	50	50
Fast neutrons	0.1	100	20



Measuring the energy spectrum in unprecedented resolution of

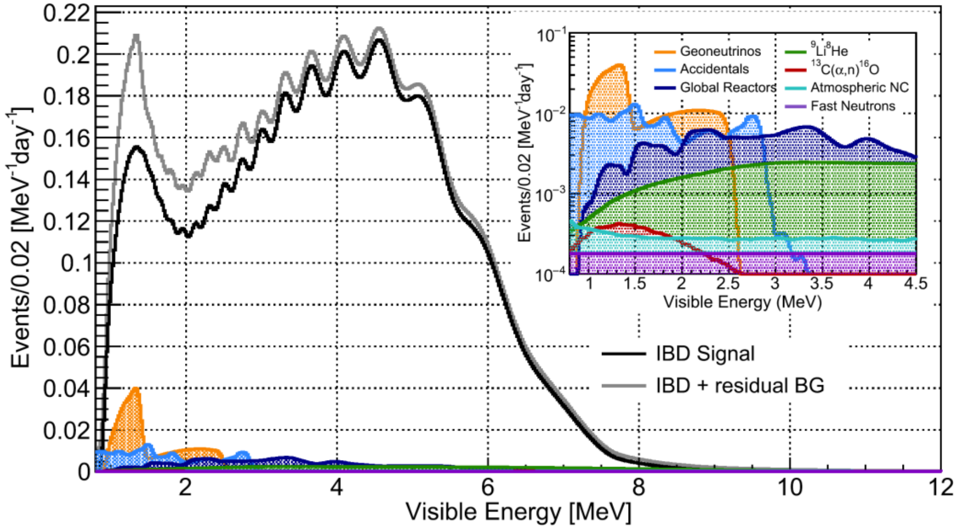
3 % at 1 MeV and < 1 % energy linearity



Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1

Reactor neutrino signal: 47.1 day^{-1} ± 1.5% (syst.)

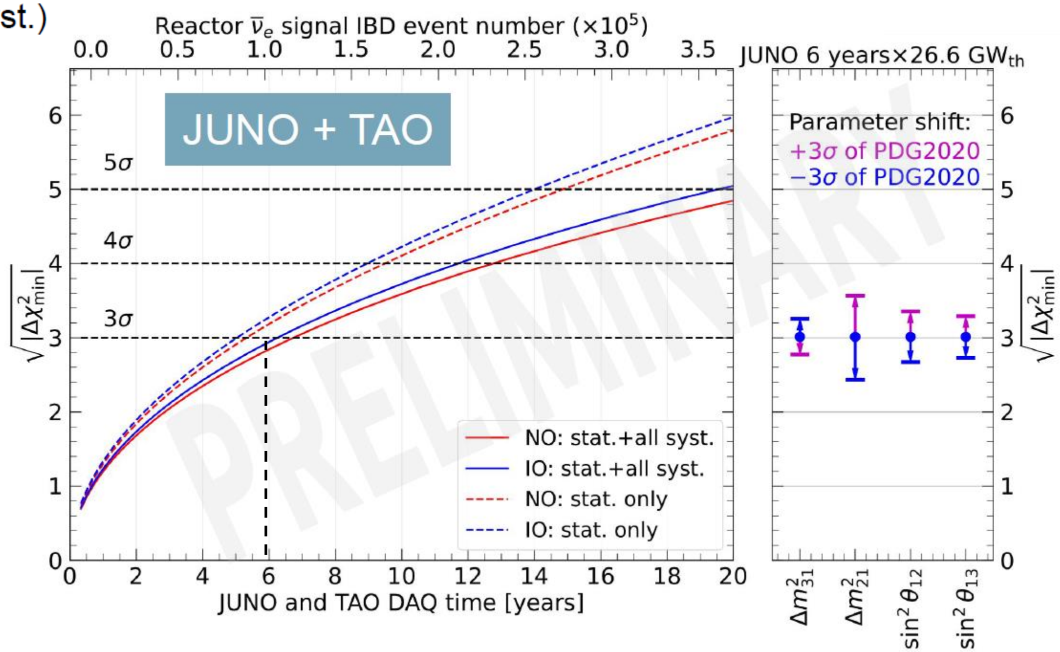
(Yangjiang + Taishan + Daya Bay NPPs, no duty cycle)



Chinese Phys. C 46 123001 (2022)

Fit spectrum with both normal ordering and inverted ordering hypotheses and compare:

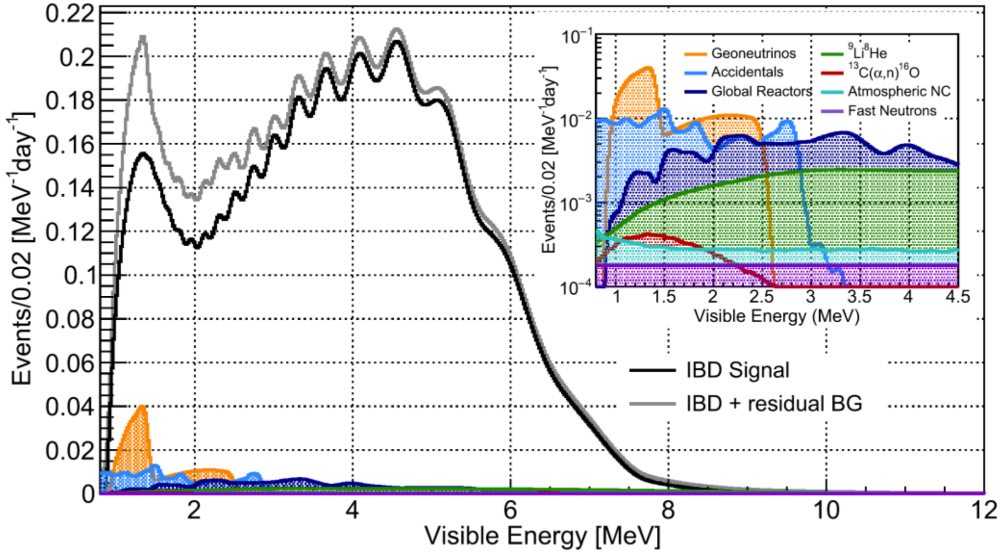
$$\Delta\chi^2_{\rm MO} = |\chi^2_{\rm min}({\rm NO}) - \chi^2_{\rm min}({\rm IO})|$$



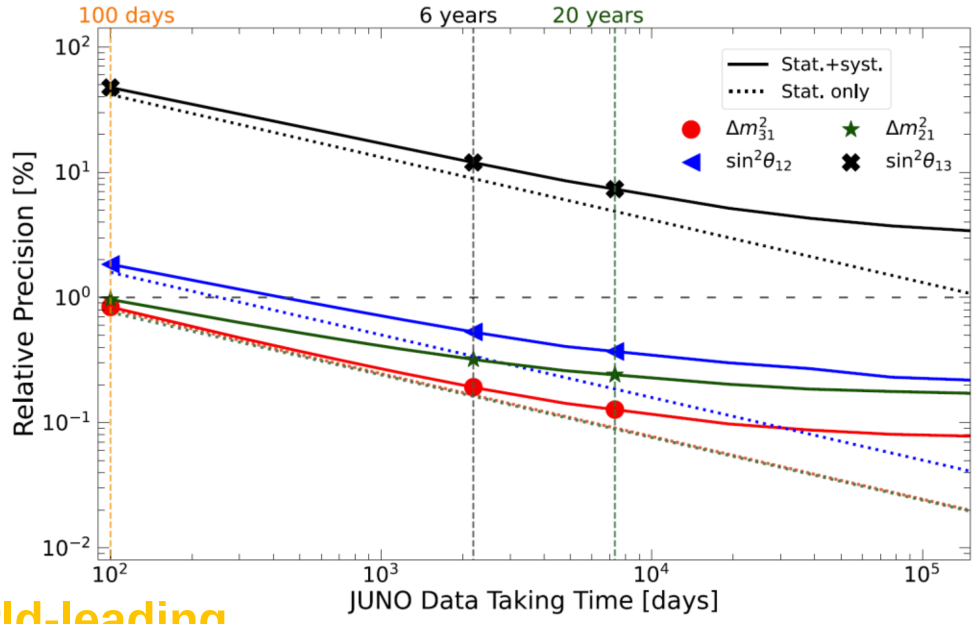
Sub-percent Precision Measurement of Neutrino Oscillation Parameters

- Simultaneous measurement of solar and atmospheric oscillation modes for the first time

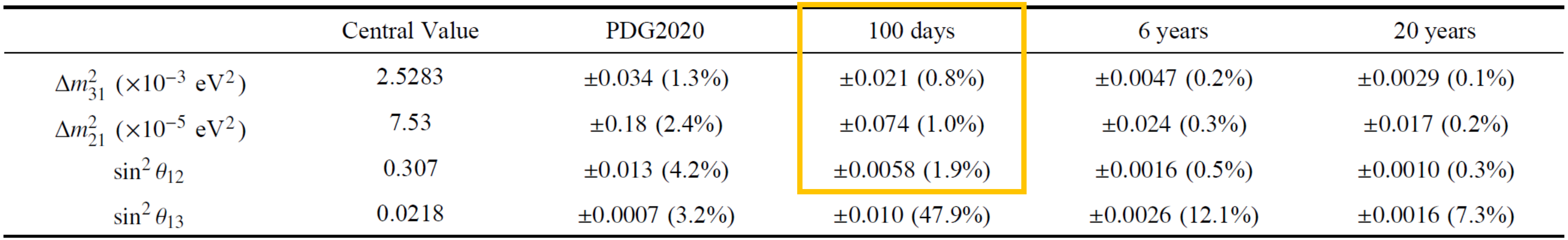
- Unitarity test of PMNS matrix possible



[Chinese Phys. C 46 123001](https://doi.org/) *(2022)*



world-leading



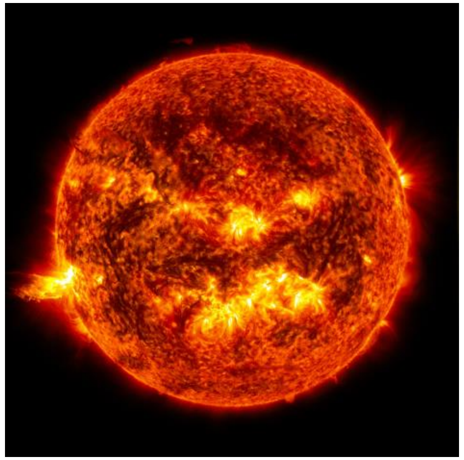
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (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%)

Further Physics Topics

Atmospheric neutrinos
several per day

Enhancing NMO sensitivity
> 3 σ after 6 years

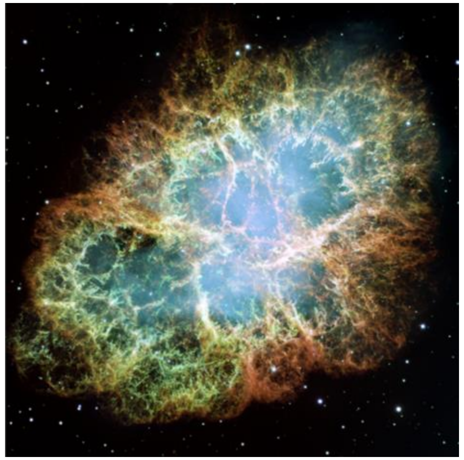
JUNO sensitivity to low energy atmospheric neutrino spectra
Eur. Phys. J. C 81, 887 (2021)



Solar neutrinos
^{8}B ~ 50 per day
^{7}Be ~ 10^4 per day
CNO ~ 10^3 per day

JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos
JCAP10(2023)022 (2023)

Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO
*Chinese Phys. C **45** 023004 (2021)*



Supernova neutrinos
~ 10^4 for CCSN
at 10 kpc

Real-time Monitoring for the Next Core-Collapse Supernova in JUNO
arXiv.2309.07109 (2023), accepted by JCAP

Neutrino physics with JUNO
J. Phys. G: Nucl. Part. Phys. 43 030401 (2016)

JUNO physics and detector
Prog. in Part. and Nucl. Phys. 123 (2022) 103927

Summary

- JUNO will be the largest liquid scintillator detector in the world with unprecedented energy resolution.
- JUNO will determine the neutrino mass ordering with 3σ after 6 years of data taking using reactor antineutrinos.
- JUNO will be an observatory for geoneutrinos, atmospheric neutrinos, solar neutrinos, supernova neutrinos, proton decay, and other exotic new physics.

2013 Project approved

2014 Collaboration formed

2015 - 2021 Civil construction

2016 Start of PMT production & Central detector parts

2017 Start of acrylic sphere production

2022 **2023** Detector construction, installation and comissioning

2024 **2025** Liquid scintillator filling, detector completion and start of data taking

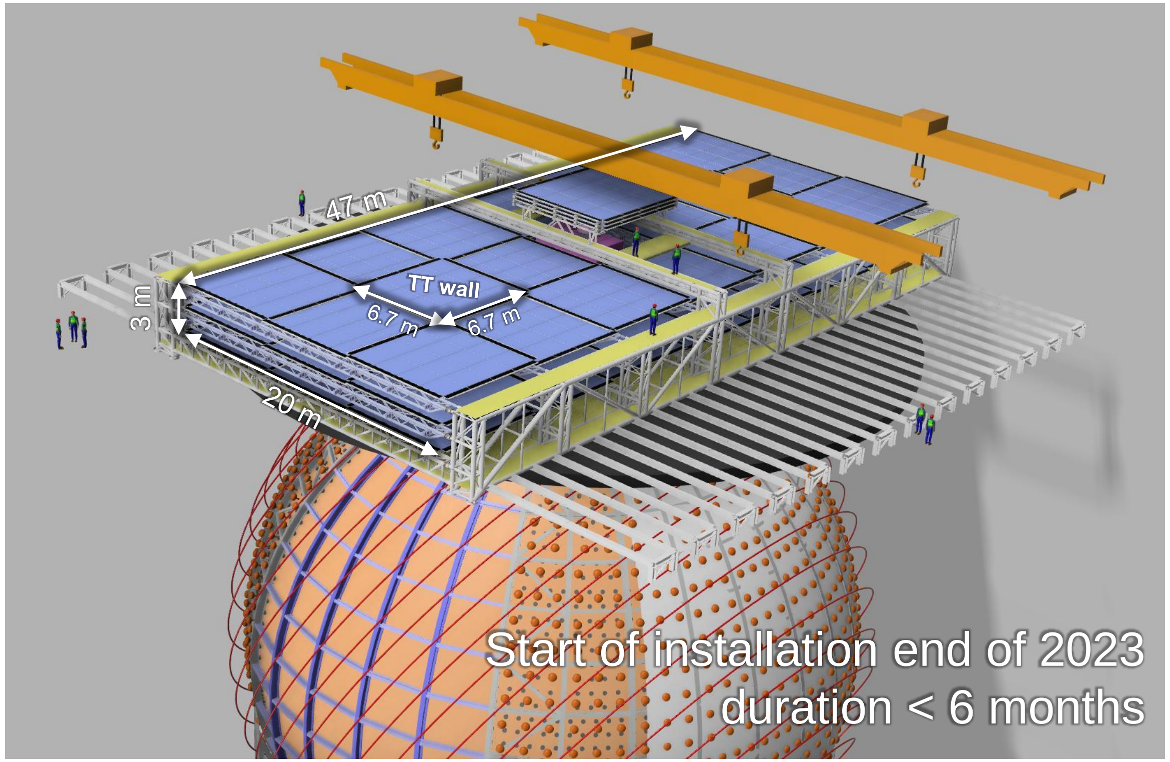
Thank you for your attention!

Top Tracker (TT)

The JUNO experiment Top Tracker
NIM A 1057, 168680 (2023)

- Constituted by decomissioned 496 OPERA modules
- Covers ~ **60 %** of the Central Detector (CD) & Water Cherenkov Detector (WCD)
- 30 % of all atmospheric muons passing through the CD pass through all 3 layers of the TT
  → Veto, especially at chimney region
  → Remaining WCD and CD
- TT wall: two planes of plastic scintillator strips, one per transverse direction (63 TT walls)
- New electronics due to high rate produced by high rock radioactivity, threshold 1/3 P.E.: full detector rate ~ **8 MHz** time coincidence in single TT wall & in 3 aligned walls of different layers → ~ **2 kHz** compared to
  ~ **4 Hz** of atmospheric muons
- Offline 3D reconstruction of muon track → **few Hz**
- 93 % trigger efficiency & 0.2° median angular resolution (20 cm at bottom of WCD)

700 m depth to detector center
1,800 meter water equivalent
15 per hour per m^2 muon flux



Start of installation end of 2023
duration < 6 months

- Combined with CD or WCD, TT provides well reconstructed muon sample with **> 99 %** purity
  → used to calibrate & tune algorithms to improve reconstruction algorithms for CD and WCD of atmospheric muons & veto affected regions

Δχ² Constributions from Different Energies

$\Delta\square^2 = \square^2_{\text{false}} - \square^2_{\text{true}}$

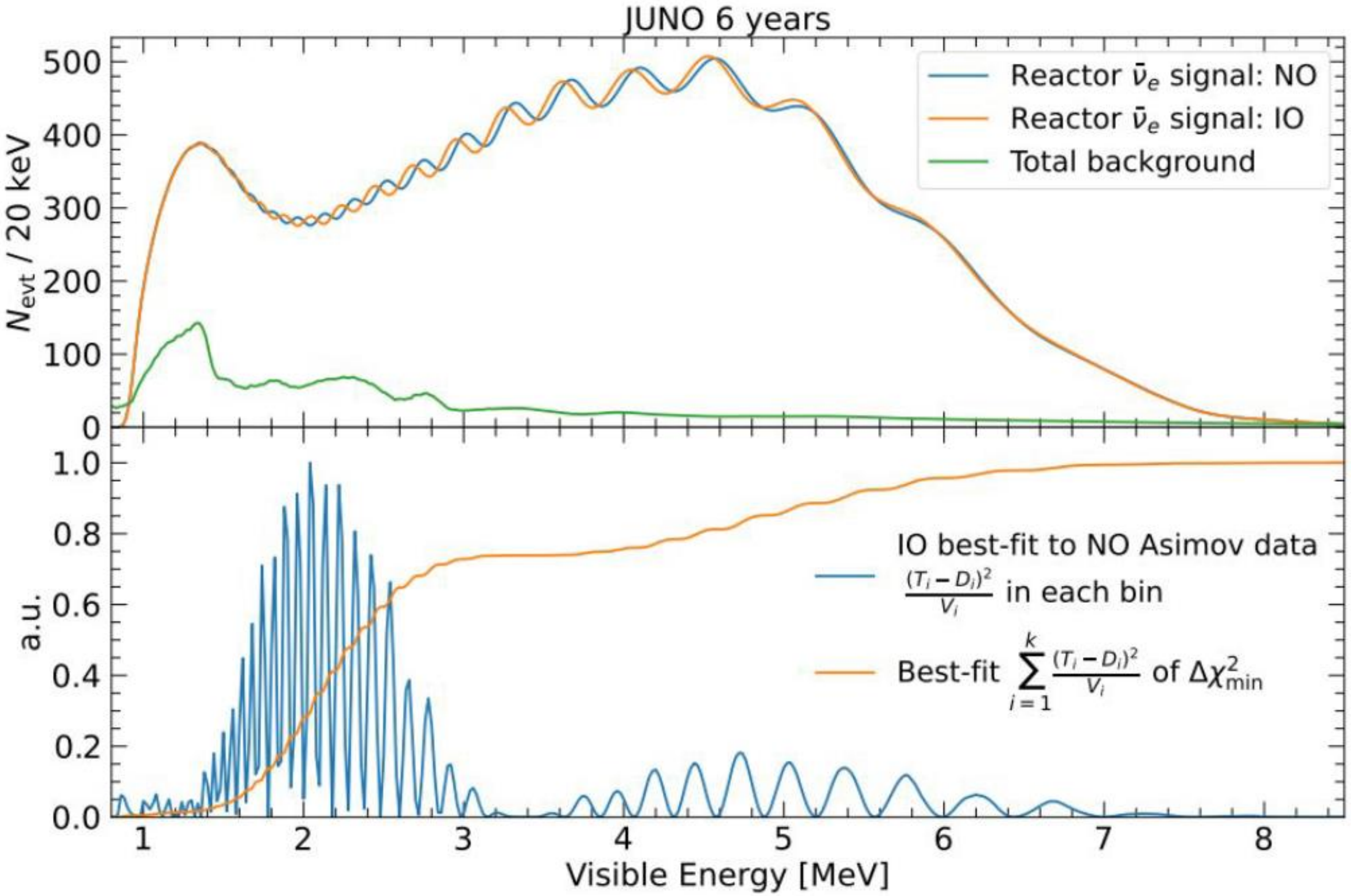
– two independent fits for two NMO assumptions

PMNS parameters free in the fit:

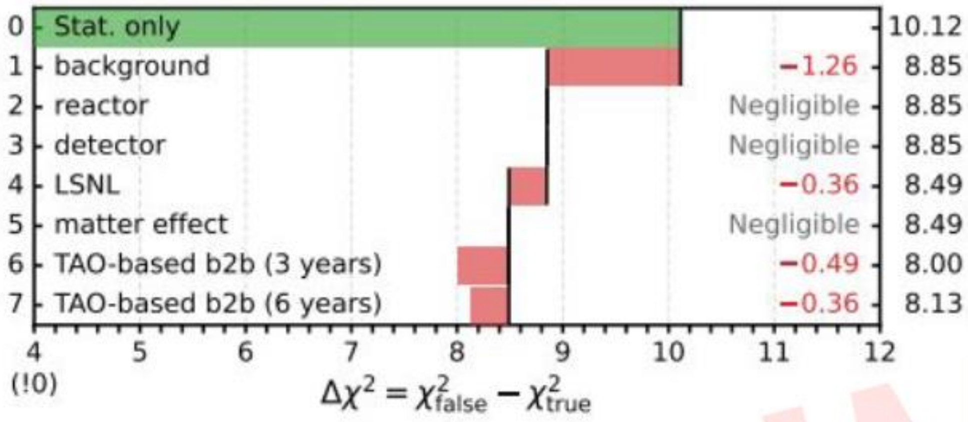
Δm^2_{21}, $\sin^2\theta_{12}$, Δm^2_{31}, $\sin^2\theta_{13}$

Nuisance parameters (for JUNO and TAO):

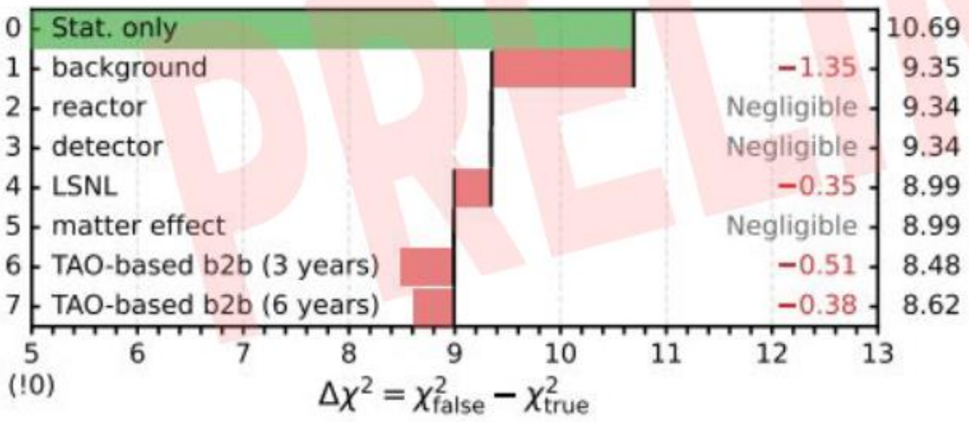
- Normalization
- Background rates
- Energy resolution
- Detector response non-linearities
- …



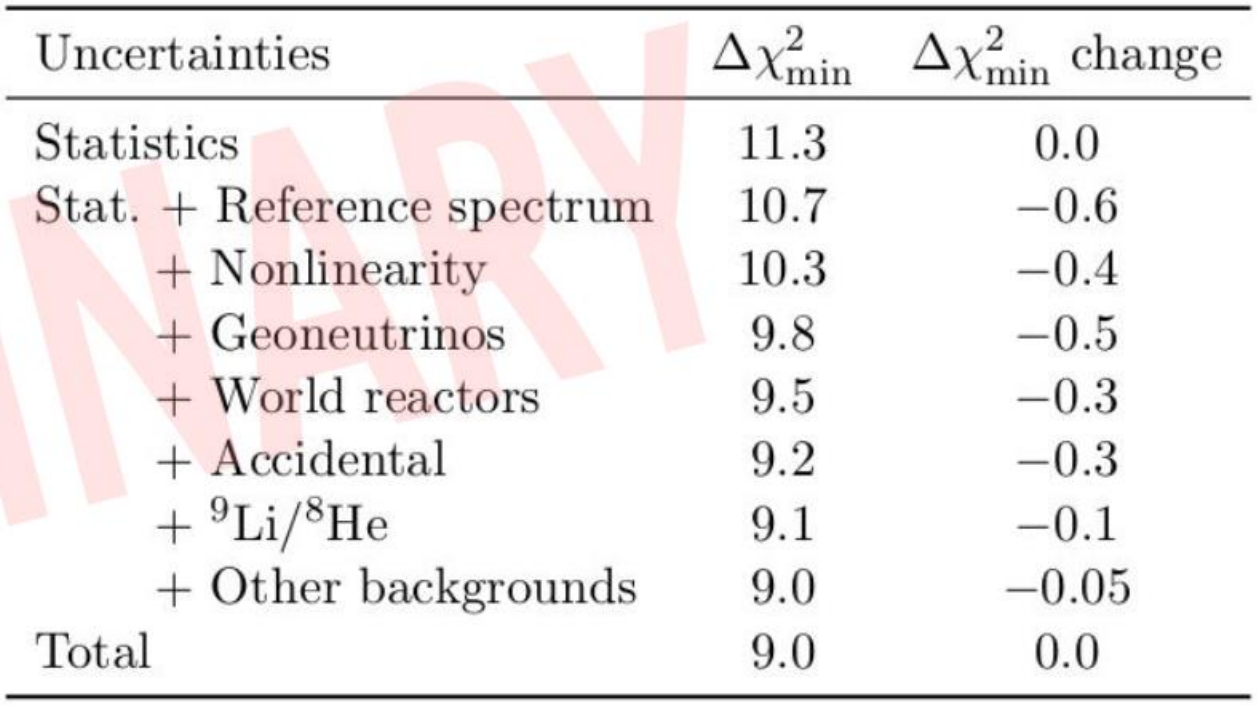
Breakdown of Systematics Effects for Δχ²



(a) true NO



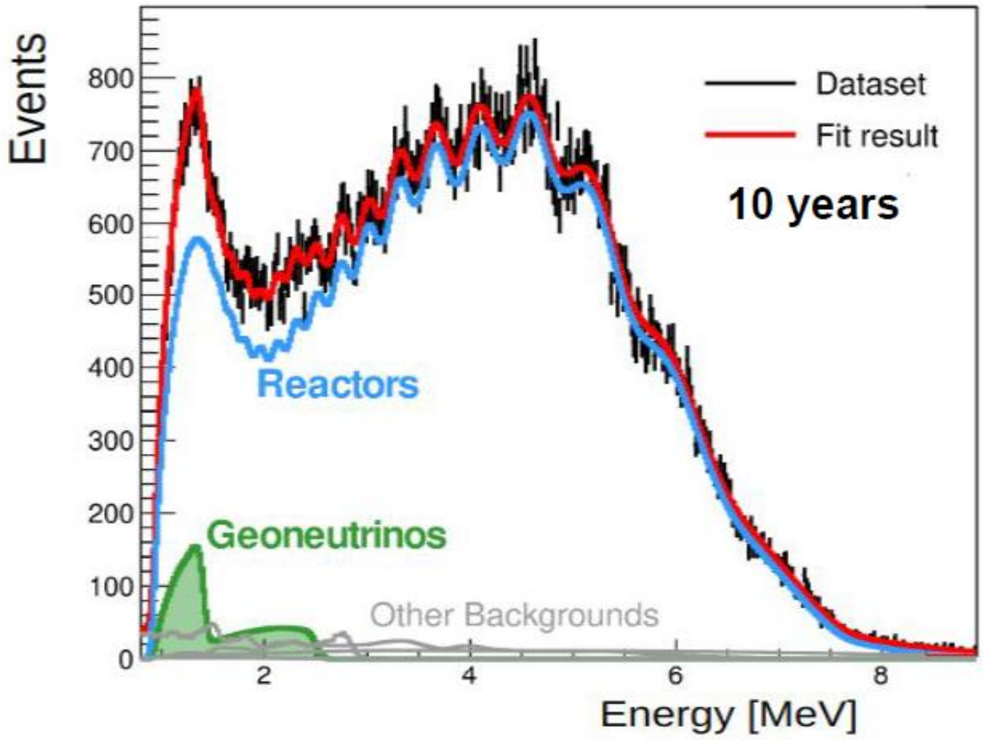
(b) true IO



Uncertainties	$\Delta\chi^2_{\text{min}}$	$\Delta\chi^2_{\text{min}}$ change
Statistics	11.3	0.0
Stat. + Reference spectrum	10.7	−0.6
+ Nonlinearity	10.3	−0.4
+ Geoneutrinos	9.8	−0.5
+ World reactors	9.5	−0.3
+ Accidental	9.2	−0.3
+ ^{9}Li/^{8}He	9.1	−0.1
+ Other backgrounds	9.0	−0.05
Total	9.0	0.0

Geoneutrinos

- Originate from β-decays of radioactive elements in the interior of the Earth
- Only ^{238}U and ^{232}Th component can be detected via IBD due to the 1.8 MeV reaction threshold
- Reactor neutrinos constitute the largest background



Expected results:

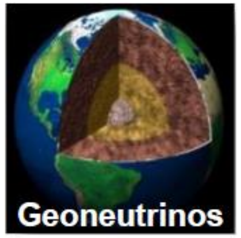
JUNO will collect the largest dataset of geoneutrinos in about 1 year (1–2 events / day)

- Precision of total geoneutrino signal with Th/U mass ratio fixed to 3.9:
  ~8% in 10 years
- **Precision of U and Th components in 10 years:**

^{232}Th	**~35%**
^{238}U	**~30%**
^{232}Th+^{238}U	**~15%**
^{232}Th/^{238}U	**~55%**

- Separation of crust and mantle signal

Existing measurements:
Borexino: 17% [PRD 2020]
KamLAND: 15% [GRL 2022]

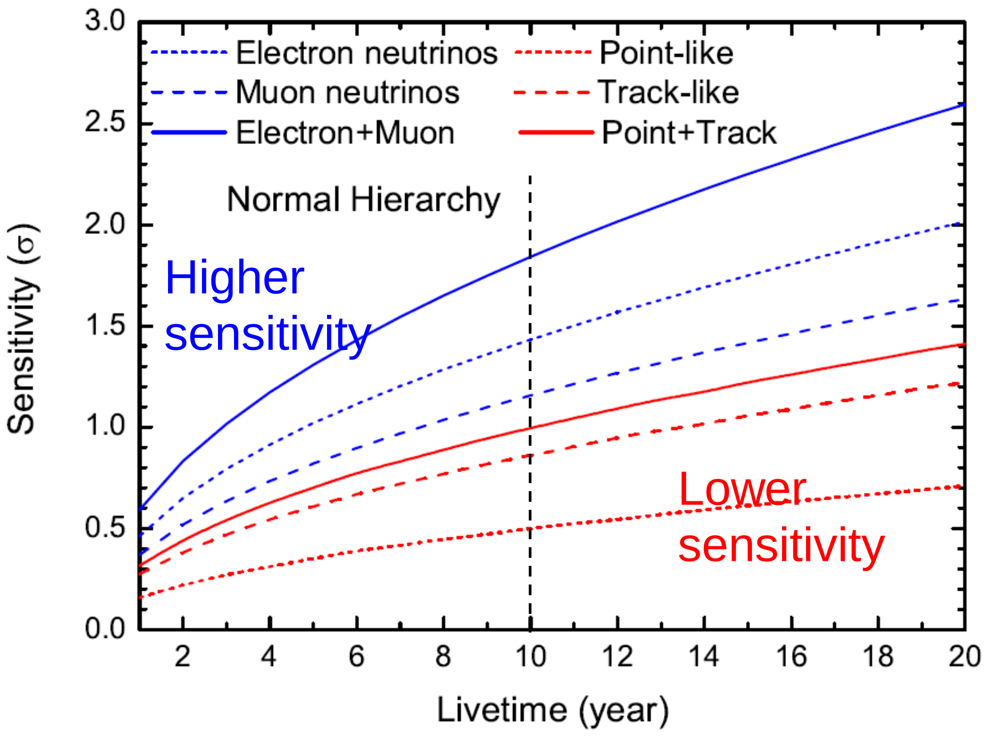


Atmospheric Neutrinos

JUNO sensitivity to low energy atmospheric neutrino spectra
[Eur. Phys. J. C 81, 887 (2021)]

- Neutrino oscillations and NMO can be studied using atmospheric neutrinos complementary to reactor neutrinos
- > 3 σ after 6 years
- Additional measurement of $\sin^2\theta_{23}$

- Flavor - dependent energy spectrum can be measured in 0.1 GeV - 10 GeV energy range

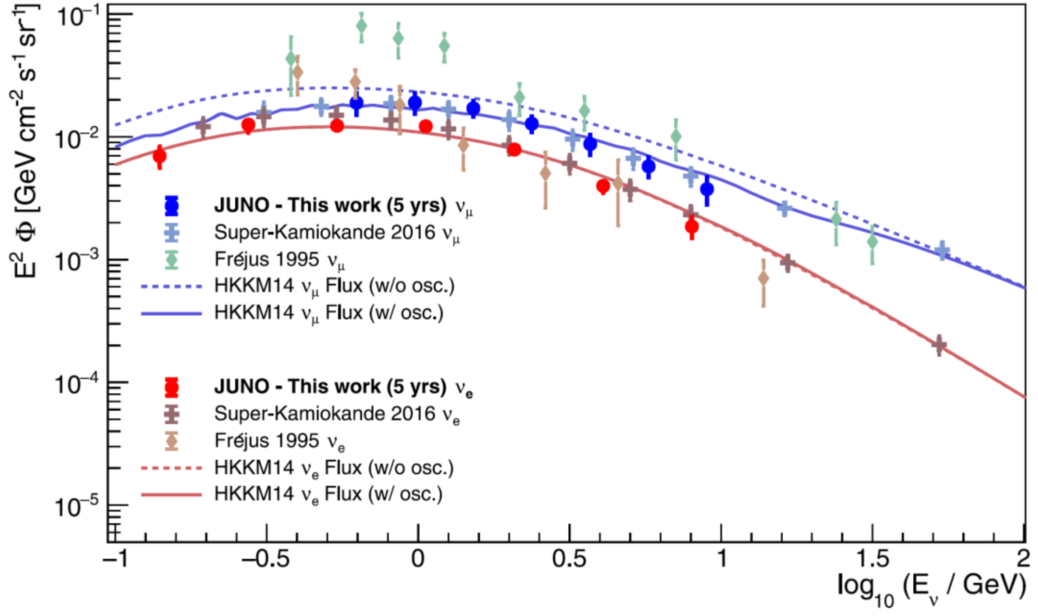


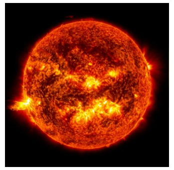
Higher sensitivity

Lower sensitivity

Neutrino physics with JUNO
[J. Phys. G: Nucl. Part. Phys. 43 030401] (2016)

JUNO physics and detector
[Prog. in Part. and Nucl. Phys. 123 (2022) 103927]



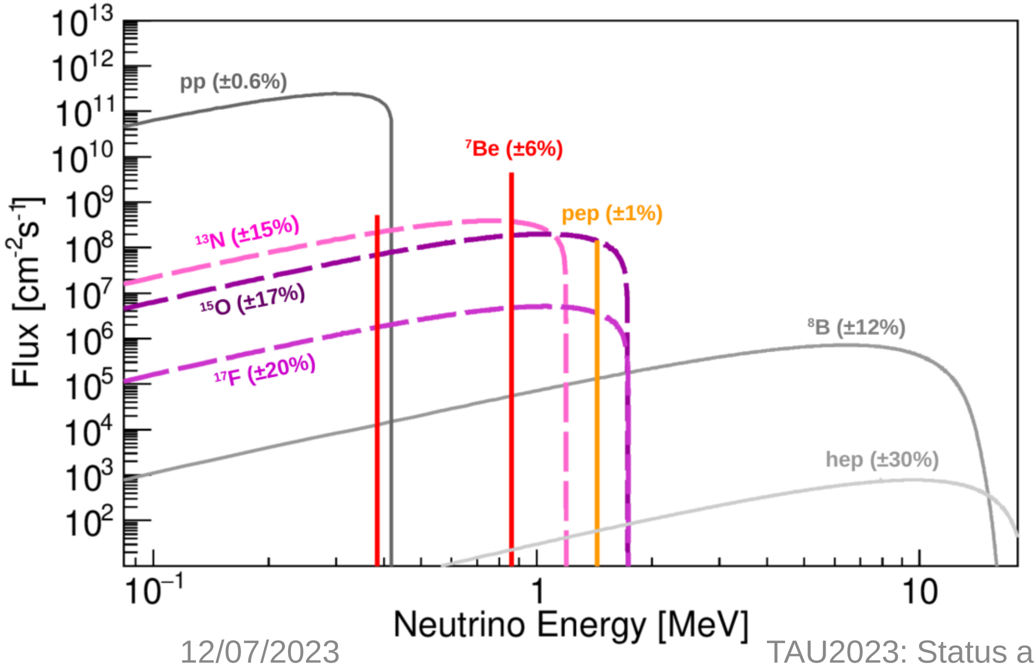


Solar Neutrinos

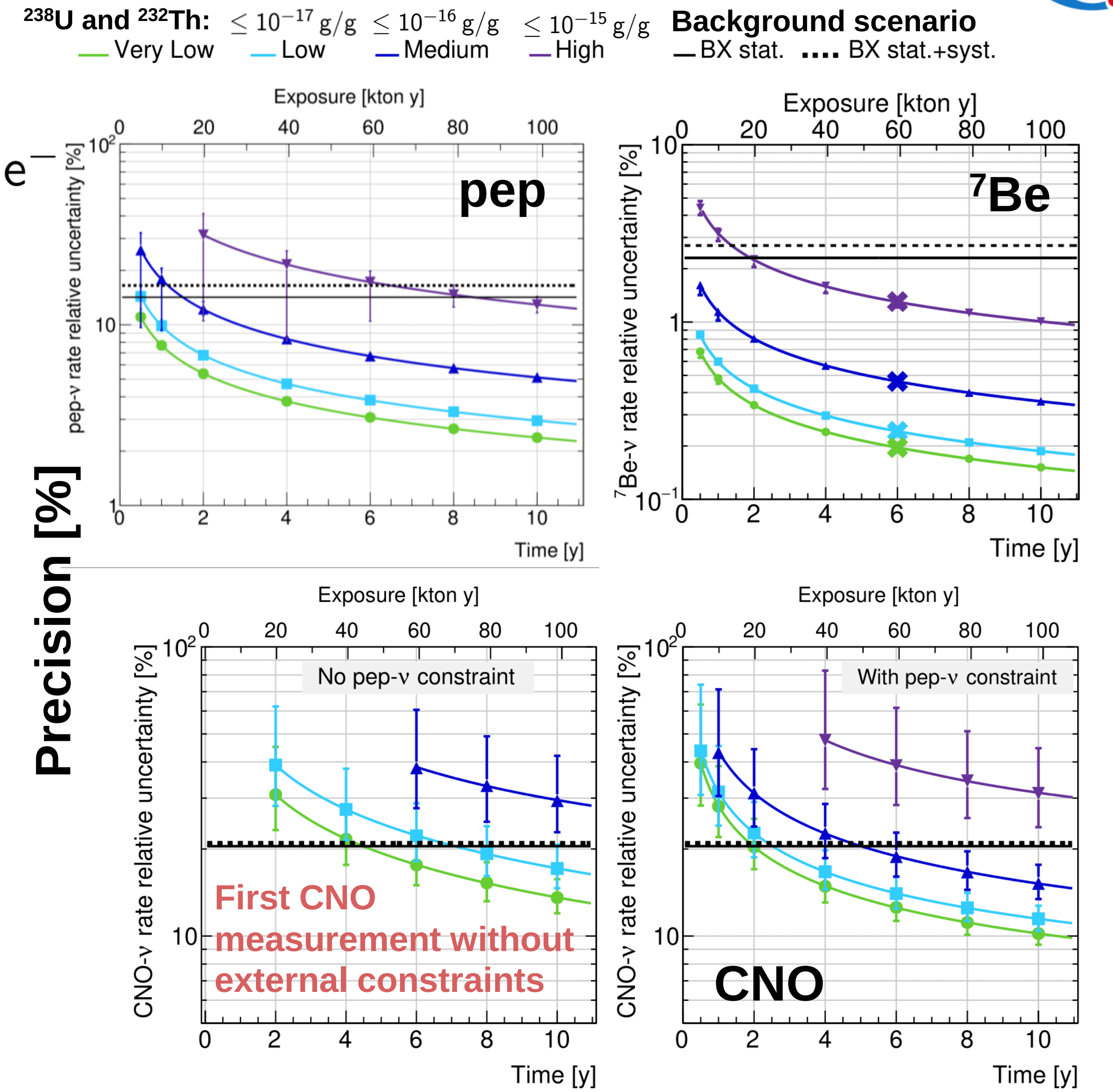
JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos
JCAP10(2023)022 (2023)

- Nuclear fusion in Sun produces ν_e
- Probe solar metallicity
- Elastic scattering detection channel: $\nu + e^- \rightarrow \nu + e^-$

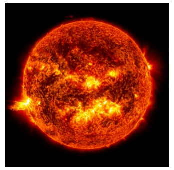
- cosmogenic background (muons)
  → triple-fold coincidence techniques, e.g. for ^{11}C
- external (detector) backgrounds→ fiducial volume
- internal backgrounds (radioactivity)
  → pure scintillator, spectral fit



- Minimal requirement for JUNO NMO
- Best radiopurity reached by **Borexino (BX)**



First CNO measurement without external constraints



Solar Neutrinos

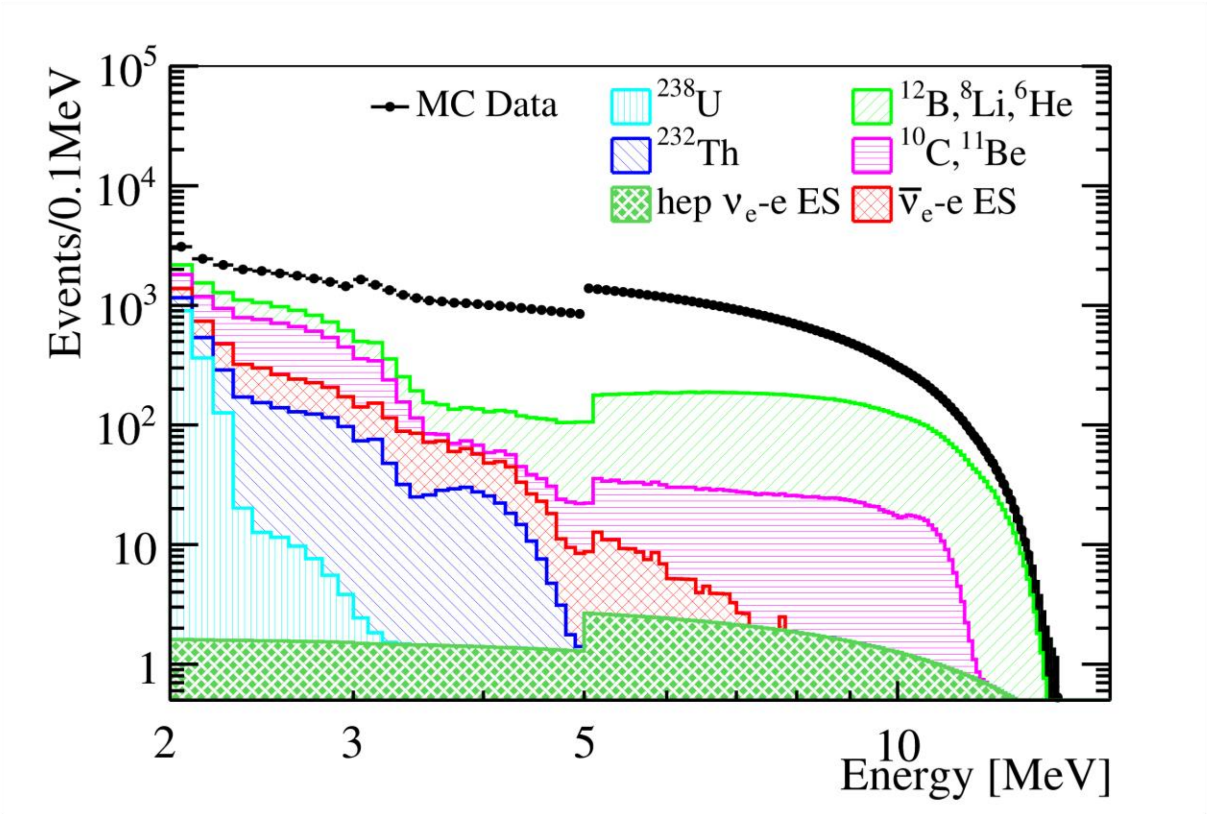
Elastic scattering detection channel:

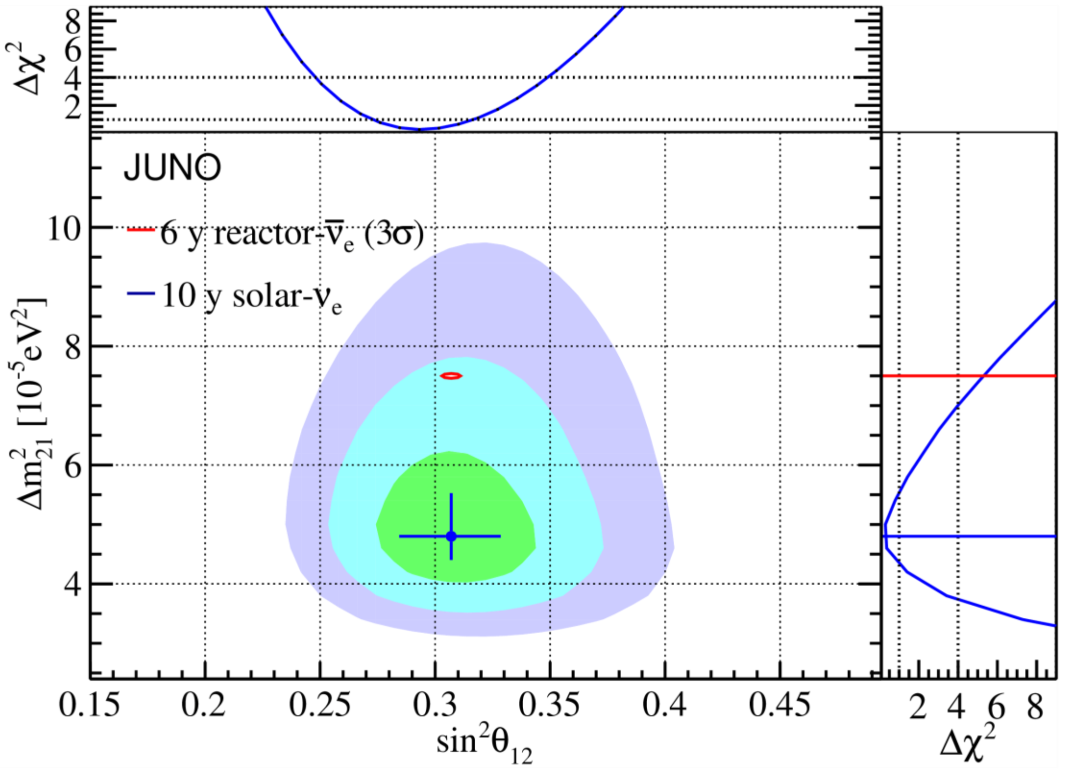
$$\nu + e^- \rightarrow \nu + e^-$$

Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO
*[Chinese Phys. C **45** 023004](#) (2021)*

High energy ^{8}B neutrinos

- Possibility to use CC and NC interactions on ^{13}C
- Unprecedented detection threshold at 2 MeV
- More precision: contribute to solve metallicity puzzle
- Spectral shape: study day/night asymmetry + other NSI





Core Collapse Supernova Burst Neutrinos

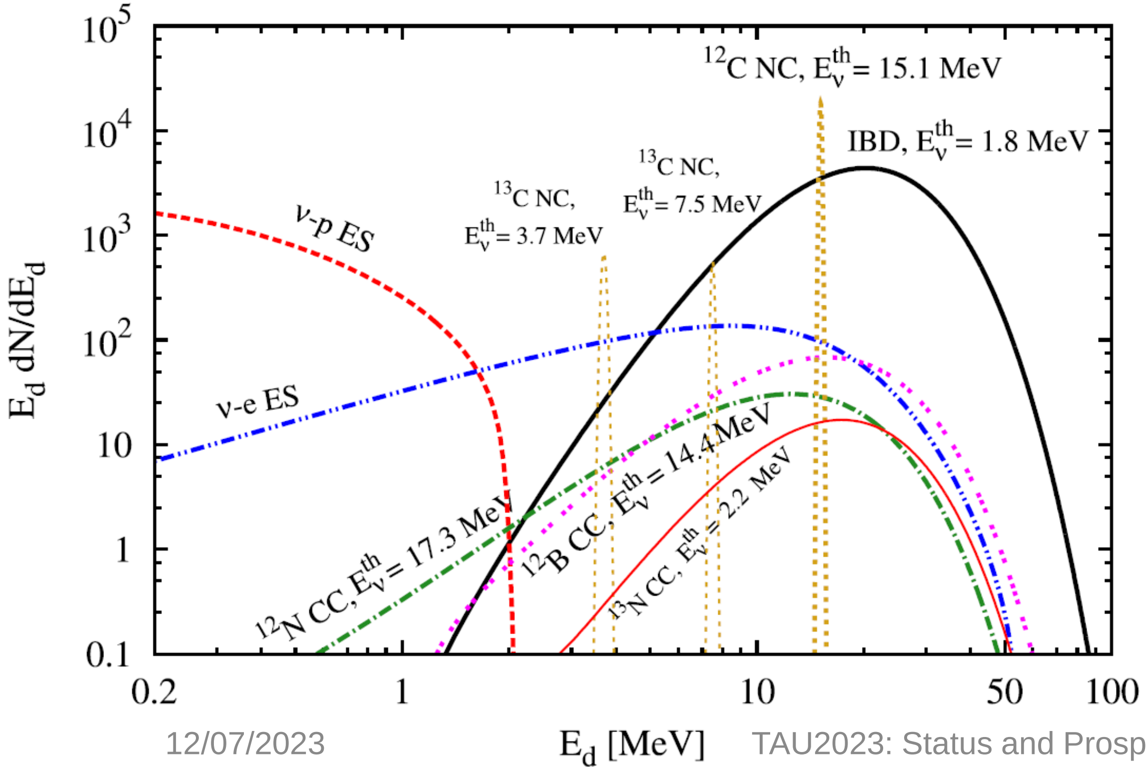
Real-time Monitoring for the Next Core-Collapse Supernova in JUNO
arXiv.2309.07109 (2023), accepted by JCAP

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$ ~ 5,000 events

Elastic neutrino-electron scattering: $\nu + e^- \rightarrow \nu + e^-$ ~ 300 events

Elastic neutrino-proton scattering: $\nu + p \rightarrow \nu + p$ ~ 2,000 events

CCSN flux from all neutrino flavors with high statistics
→ constrain CCSN physics



Multi-messenger Astronomy

- Multi-messenger (MM) trigger:
  - Lower energy threshold (~ O(10 keV))
  - Increase signal statistics
  - All triggerless data stored using 2 GB RAM shared by 3 PMTs

- JUNO as powerful neutrino telescope for transient MM observations
- Major player in the next-generation Supernova Early Warning System (SNEWS 2.0)

JUNO physics and detector
Prog. in Part. and Nucl. Phys. 123 (2022) 103927

Diffuse Supernova Neutrino Background

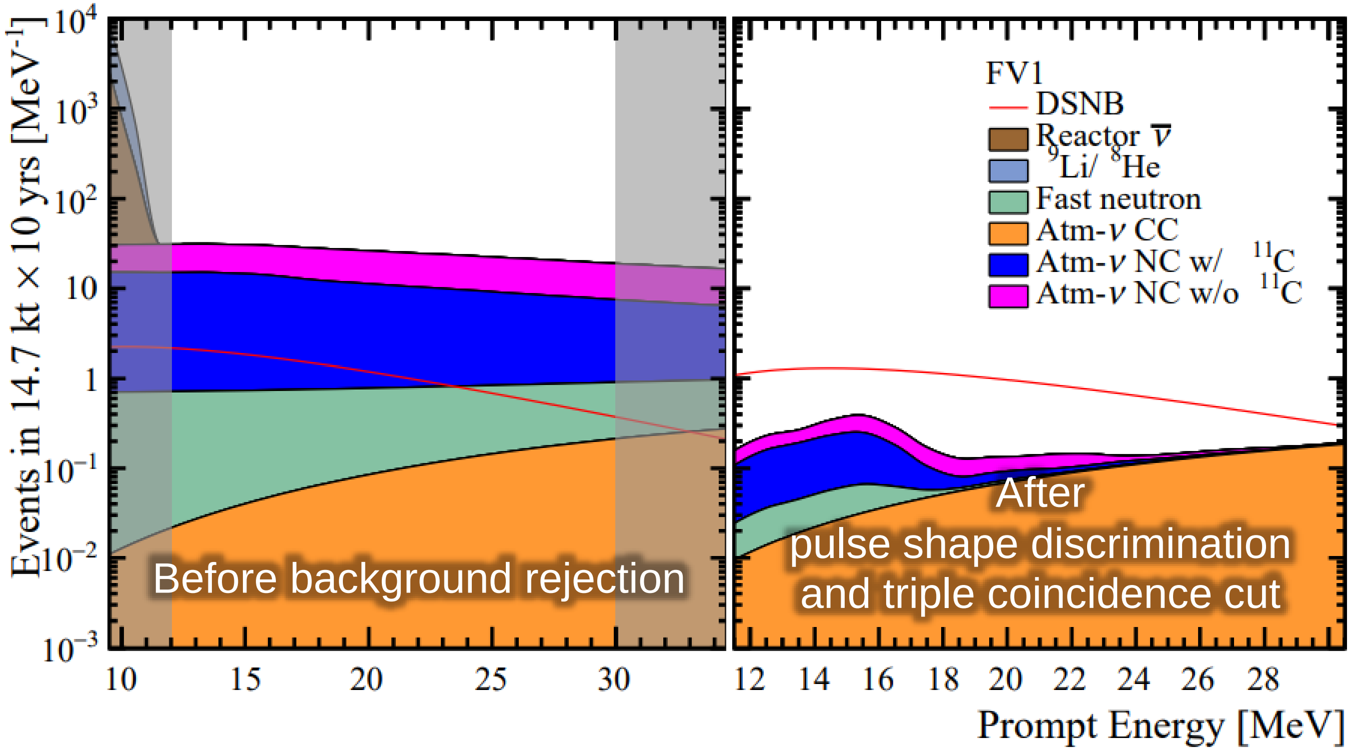
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

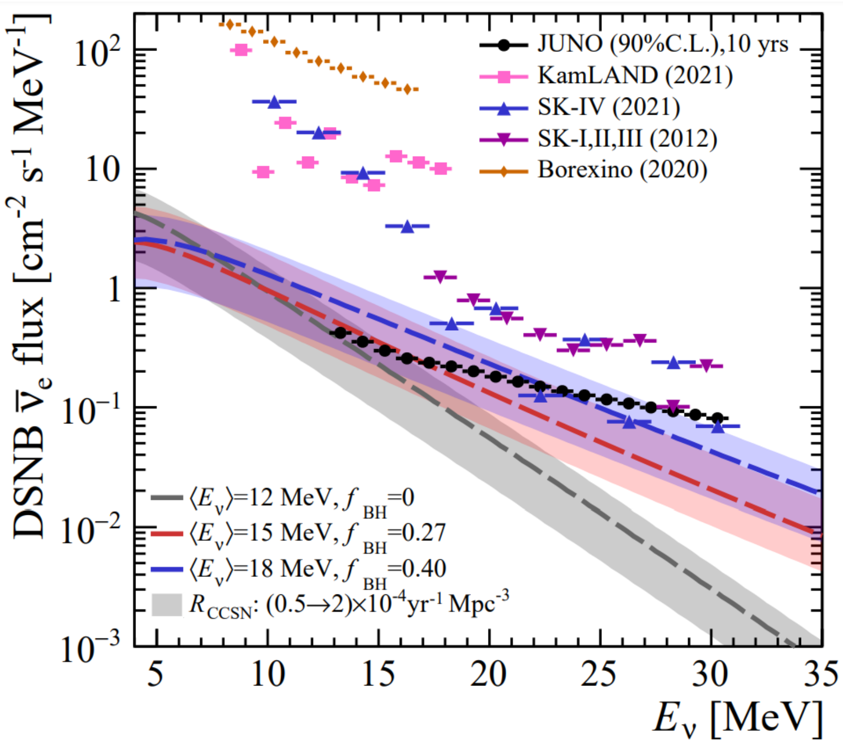
- Integrated neutrino signal from all supernovae (SNe) explosions in the Universe
- Encodes average core-collapse SN neutrino spectrum, cosmic star formation rate, fraction of failed black hole forming SNe

Prospects for detecting the diffuse supernova neutrino background with JUNO
JCAP 10 (2022) 033 (2022)

- ~ 2 to 4 IBDs events per year
- Expected significance:
  - after 3 years → 3 σ sensitivity
  - after 10 years → 5 σ sensitivity

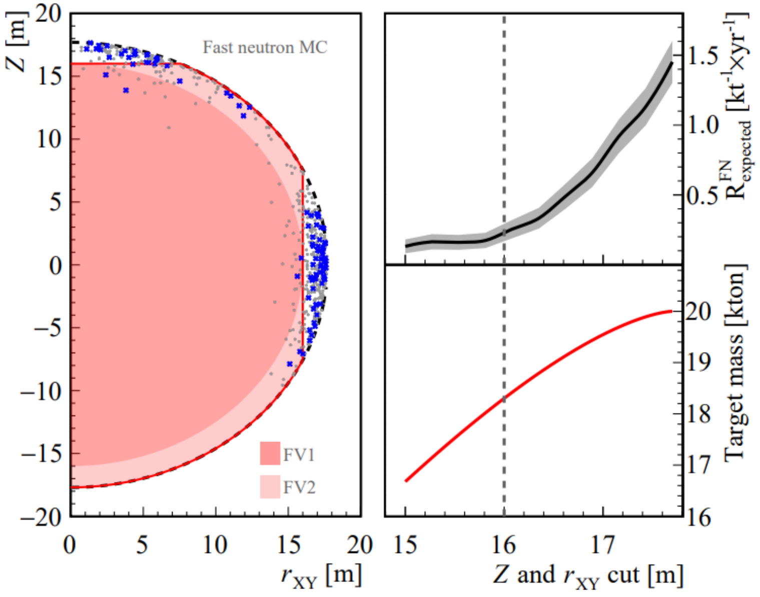
- Non-observation would still improve current best limits and exclude significant region of model parameter space

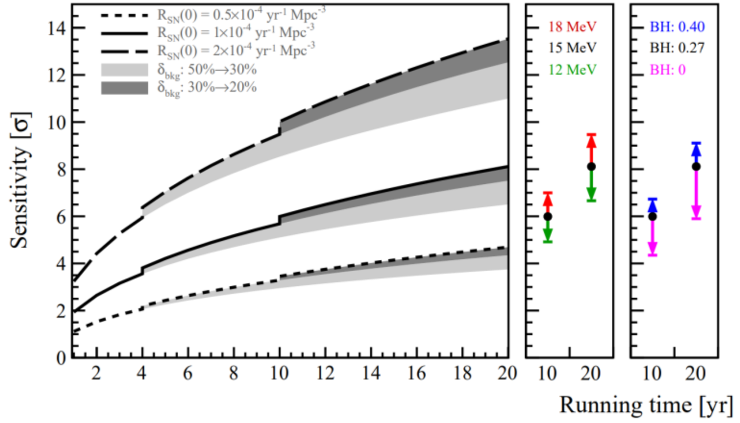




Diffuse Supernova Neutrino Background

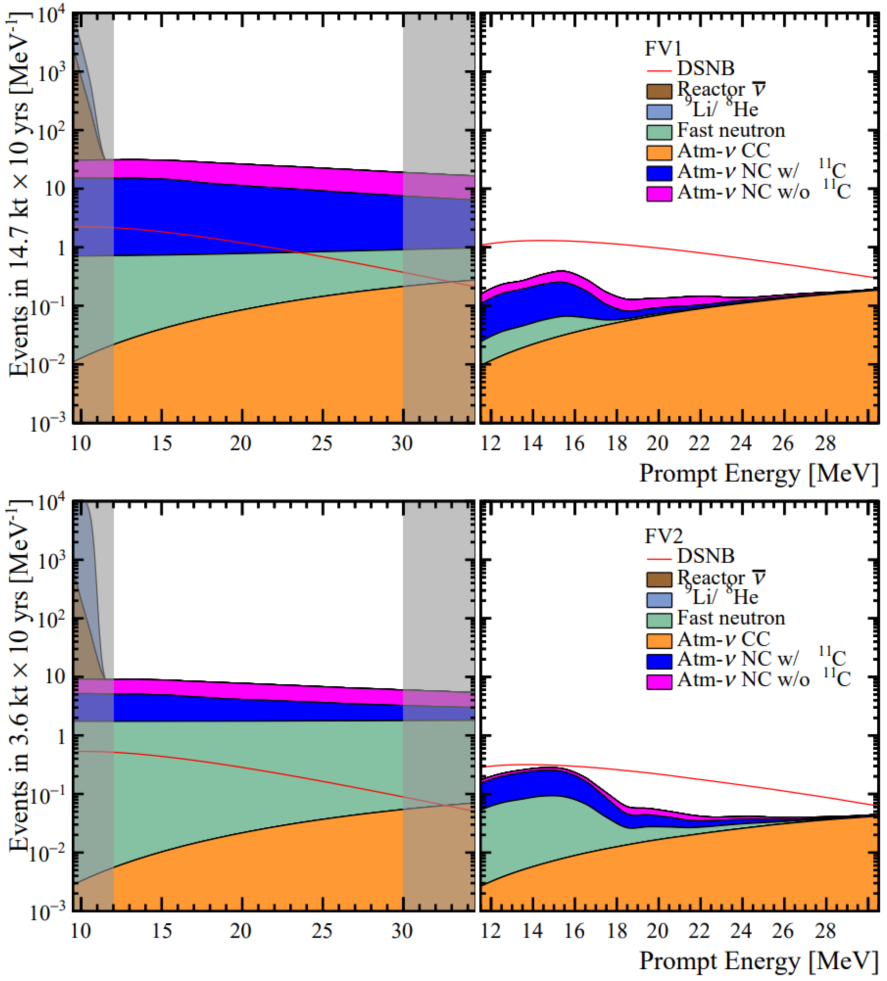
Prospects for detecting the diffuse supernova neutrino background with JUNO
JCAP 10 (2022) 033 (2022)

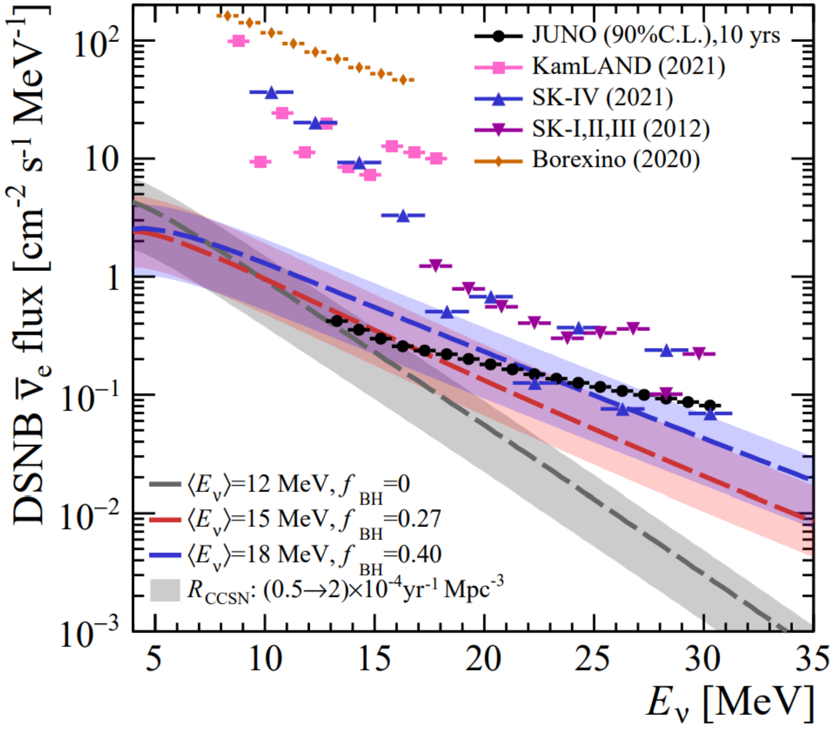




Before

After background rejection





Proton Decay

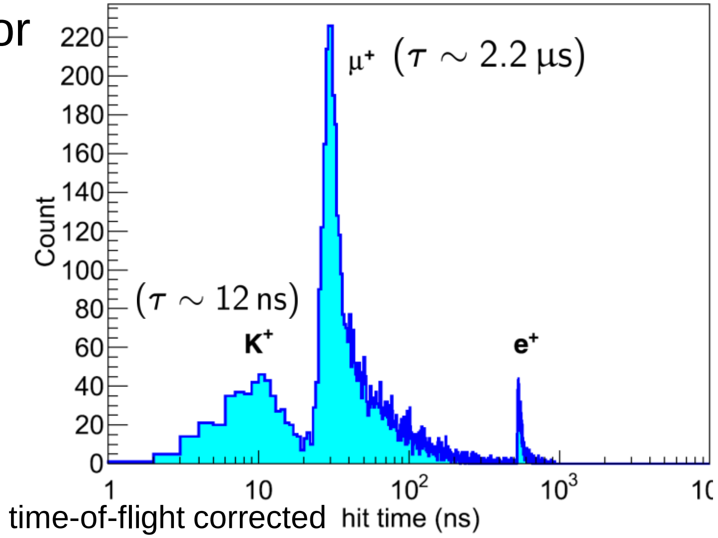
- Large number of protons in 20 kton scintillator
- SUSY-favoured decay:
  Time-correlated triple coincident signature

$$p \rightarrow \overline{\nu} + K^+$$

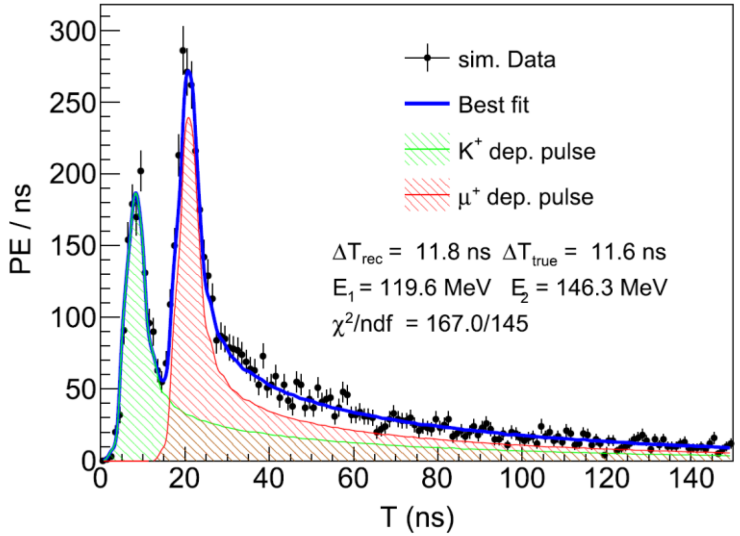
$$K^+ \rightarrow \nu_\mu + \mu^+$$

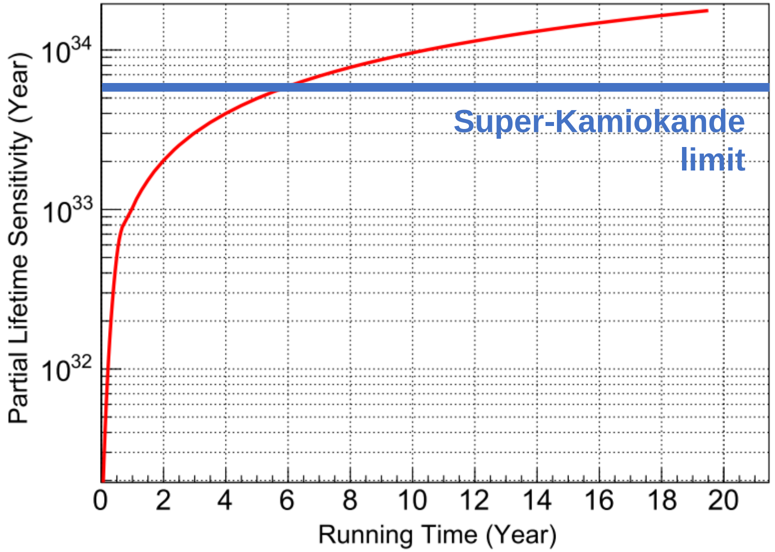
$$\mu^+ \rightarrow \nu_e + \overline{\nu}_\mu + e^+$$

- Rejecting atmospheric neutrino background



Multi-pulse fitting





Expected sensitivity of JUNO:
*Chinese Phys.C **47** 113002*
(2023)

$> 9.6 \times 10^{33}$ years
at 90 % C.L. with 200 kton × years
in 10 years of data taking

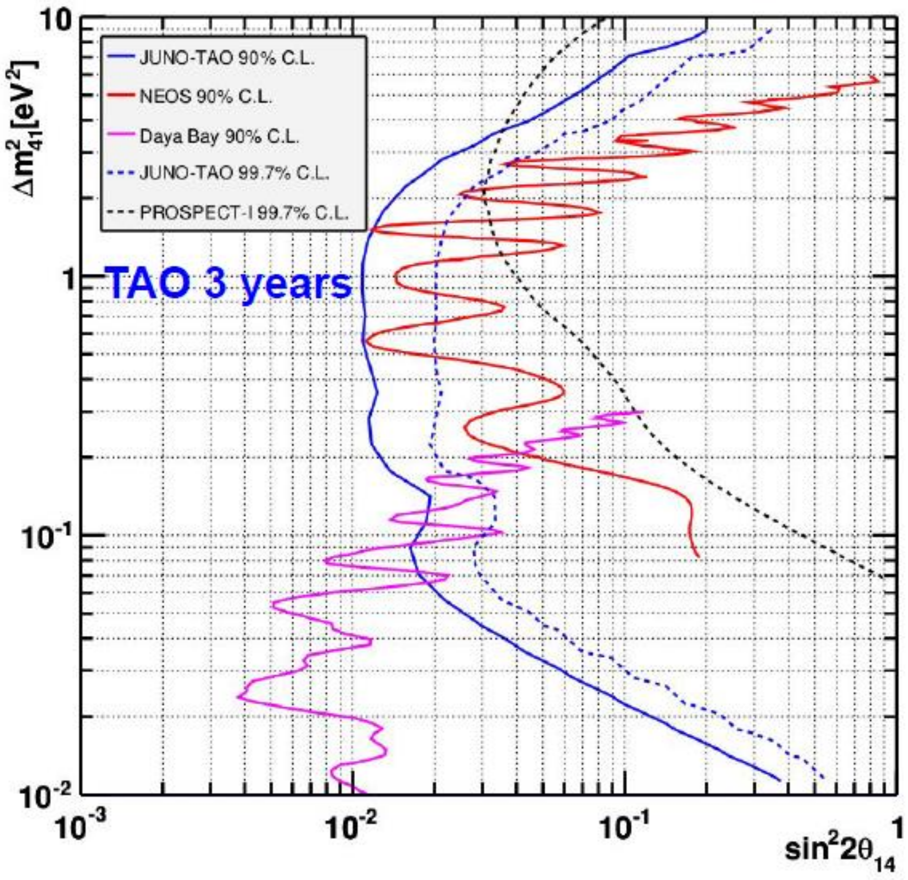
Super-Kamiokande
*Phys. Rev. D **90**, 072005*
(2014)

$> 5.9 \times 10^{33}$ years
at 90 % C.L. with 260 kton × years

Sterile Neutrinos

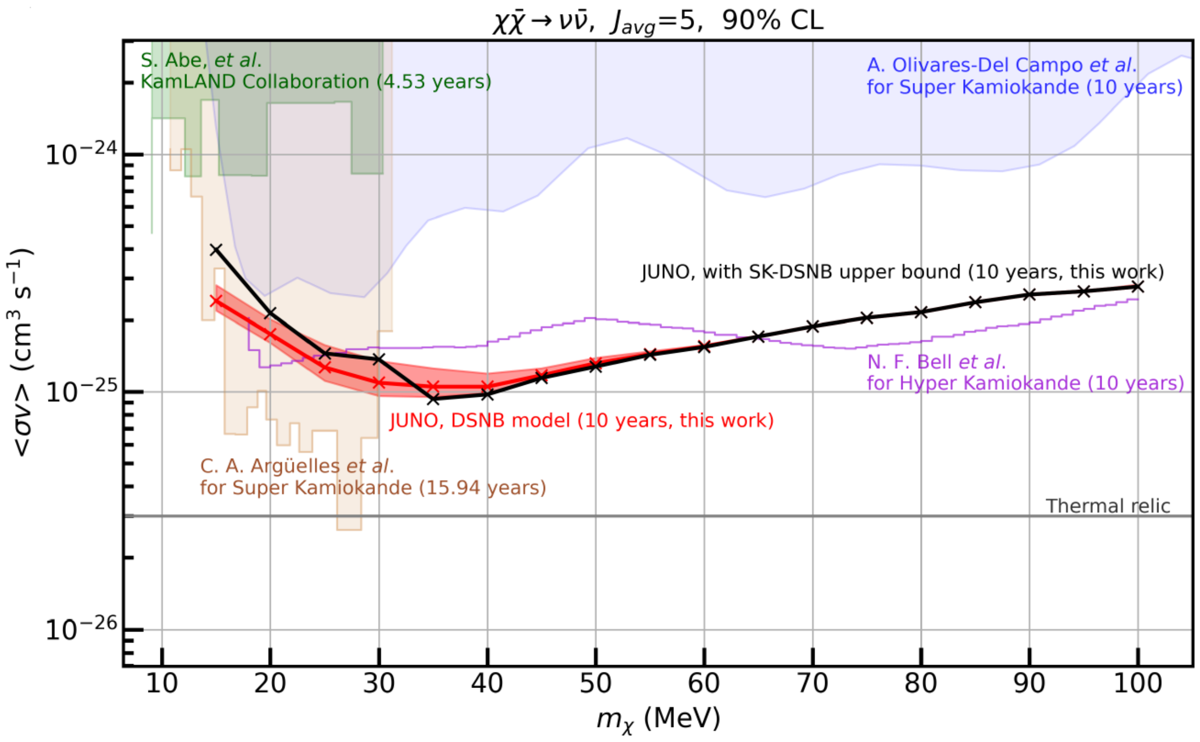
Sensitivity at the Δm^2 region of 0.05 – 1 eV^2:

complimentary to the longer baseline experiments

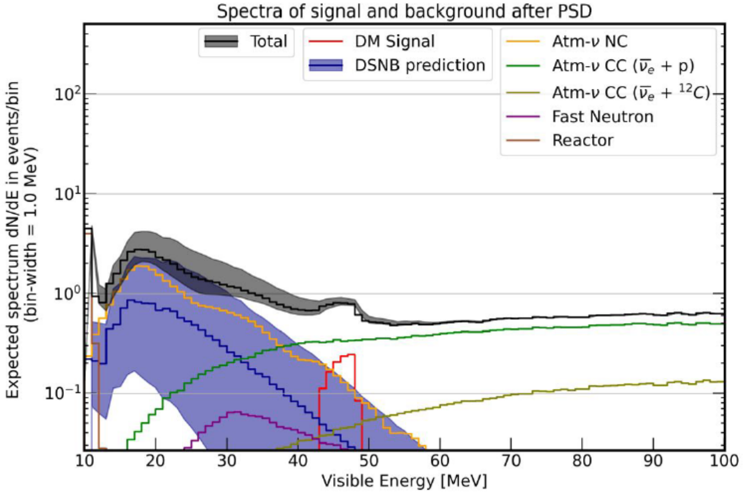


Indirect Dark Matter

- Self-annihilation of dark matter in the Milky Way
- IBD channel
- Expected limit for the range 15 - 100 MeV: 1.1×10^{-25} cm^3 s^{-1} in 10 years



JCAP09(2023)001 (2023)



Detection in the IBD channel

PSD for atmo-nu rejection

15-100 MeV range

JUNO limit in 10 years
(in terms of thermally averaged self-annihilation rate)

$$\langle \sigma v \rangle = 1.1 \times 10^{-25}\, \mathrm{cm}^3\, \mathrm{s}^{-1}$$