國立臺灣大學
National Taiwan University

The physics prospects and current status of JUNO

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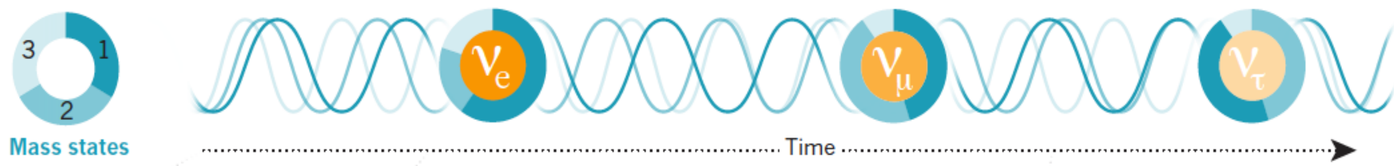
On behalf of JUNO colaboration

Jinji town, Kaipin, Jiangmen

Neutrino Oscillation

Pontecorvo

1957



- A neutrino with flavor α can be expressed as a combination of mass states: $|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$
- PMNS matrix:

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Reactor}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}} \underbrace{\begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Majorana}}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

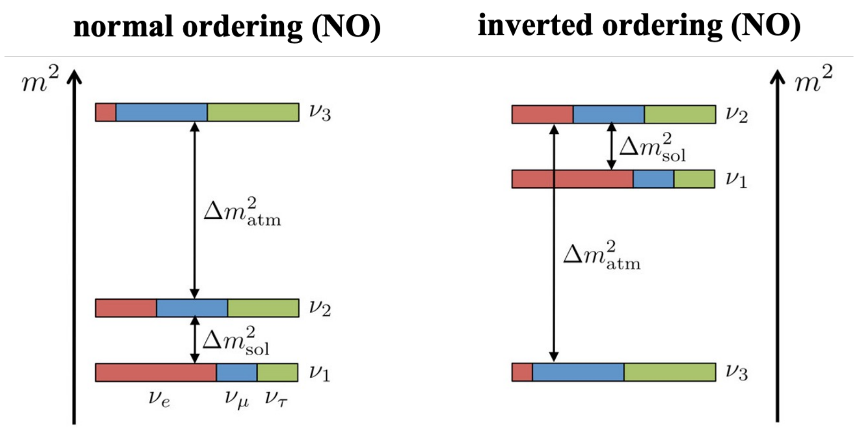
[PDG 2020]

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{23}$	δ_{cp}
Precision (%)	4.2	2.4	3.2	1.3	3.7	15

Open Questions

- Solving the Mass Hierarchy problem is a key for the open questions in neutrino physics:
  - ➢ Roadmap for 0νββ experiments
  - ➢ Understanding the mass origin and neutrino mixing in theory
  - ➢ Nucleosynthesis in supernova, neutrino mass scale, δ_{CP}, … …

Mass Hierarchy



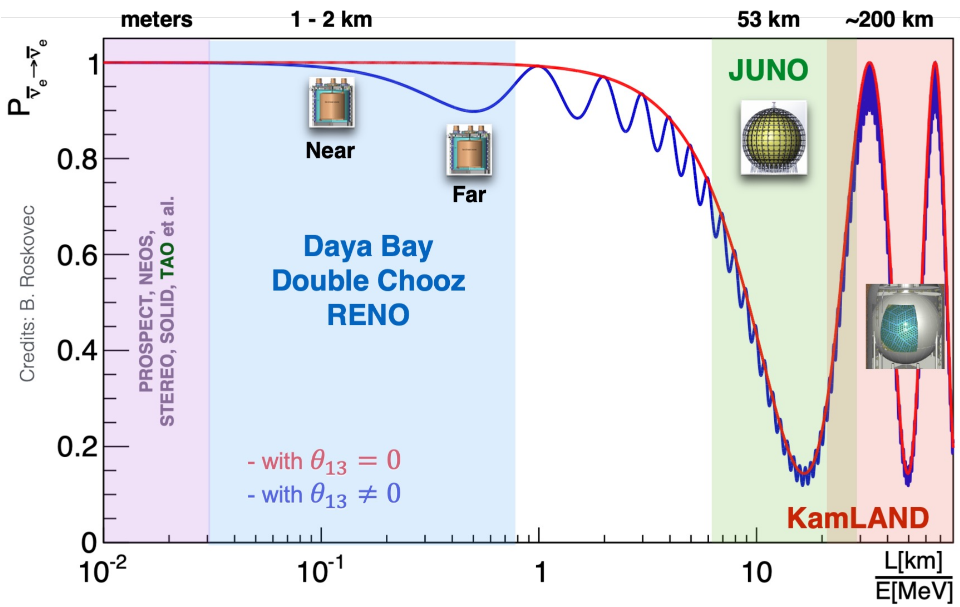
$$\text{NO:} \quad |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$

$$\text{IO:} \quad |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

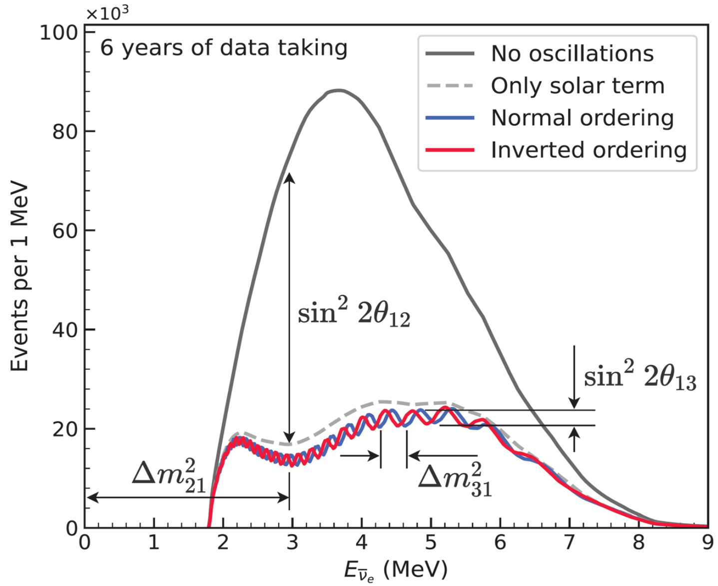
Neutrino Oscillation

$\overline{\nu}_e$ survival probability:

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



arXiv:2204.13249

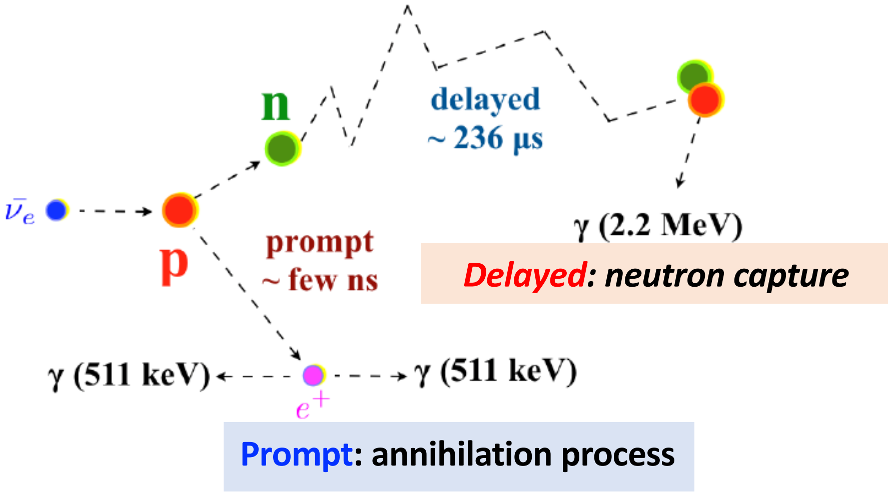


(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)

- ❖ **Neutrino Mass ordering** determined by the fine oscillation pattern in reactor neutrino spectrum
- ❖ First experiment to observe solar and atmospheric neutrino oscillation modes simultaneously

Reactor antineutrino detection

Inverse Beta Decay (IBD) reaction

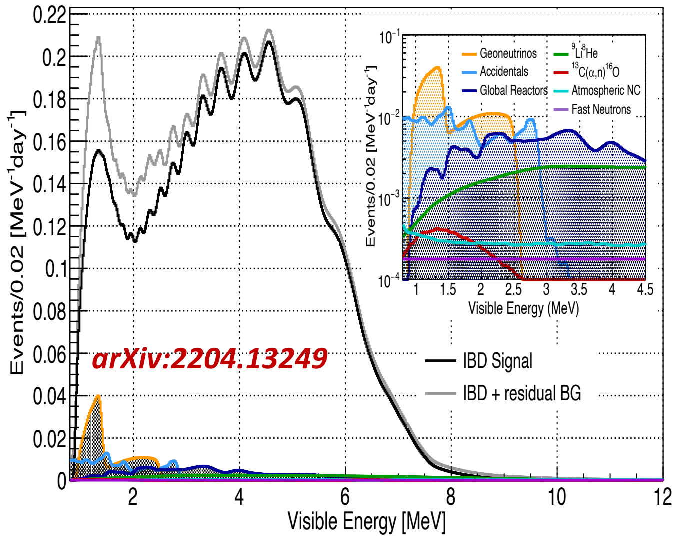


Major IBD event cuts:

- Energy threshold: $E_{vis} > 0.7\ MeV$
- Fiducial volume cut: $\mathrm{R_{LS}} < 17.2\ m$
- Timing cut: $\Delta T_{p-d} < 1\ ms$
- Spatial cut: $R_{p-d} < 1.5\ m$
- Cosmic muon veto cuts

JUNO expected spectrum:

Visible energy spectrum of the survival reactor $\overline{\nu_e}$



Background contribution from 7 types of sources

Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
$^{9}\mathrm{Li}/^{8}\mathrm{He}$	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
$^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$	0.05

- Accidentals are mainly coming from radiogenic elements such as $^{238}U/^{232}Th/^{40}K$ → material screening strategy achieved
  for details, see JHEP 11 (2021) 102

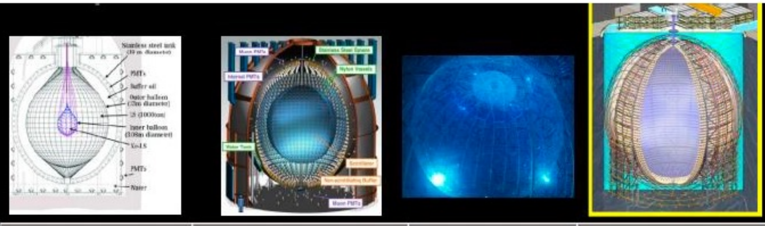
- ~47 $\overline{\nu_e}$ evt/day (assuming ~82% efficiency) and ~4.1 bckg evt/day

Reactor antineutrino detection

Requirements for precision

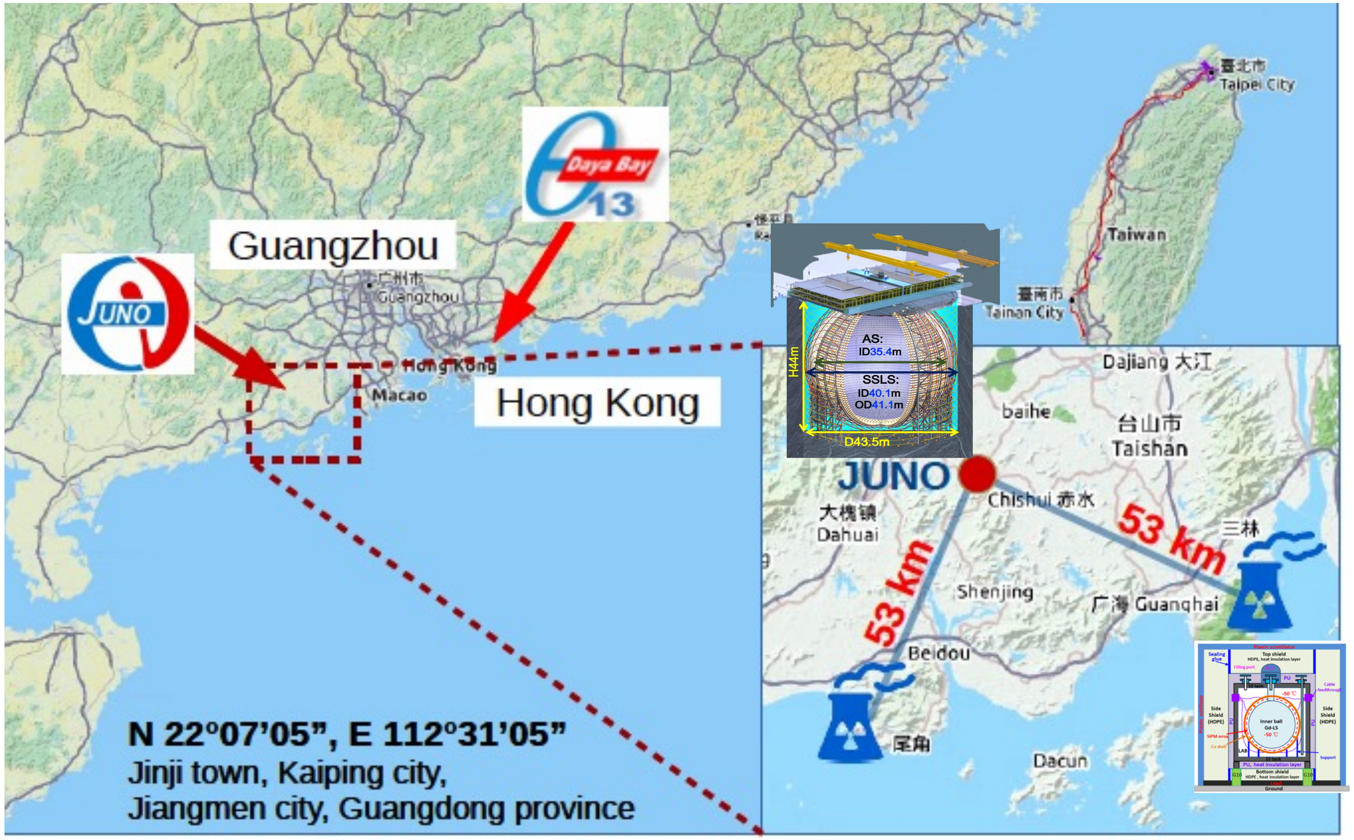
- **Large statistics**
  - ✓ Large target mass (20 kton LS)
  - ✓ Powerful reactor source (26.6 GW_{th})
- **High energy resolution**
  - ✓ Large PMT coverage (78%)
  - ✓ Highly efficient PMTs (PDE ~30%)
  - ✓ High photon yield, highly transparent LS
- **Small shape/scale uncertainties**
  - ✓ TAO satellite detector
  - ✓ Redundant calibration system
- **Low background**
  - ✓ Good overburden (~650 m)
  - ✓ Highly efficient veto system (>99.5%)
  - ✓ High sensitivity material screening
  - ✓ Careful control of installation cleanliness

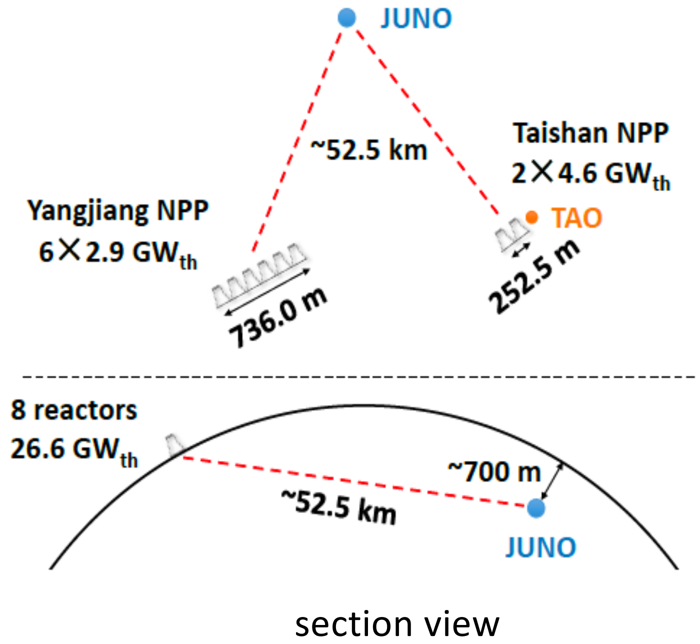
JUNO:
Energy Resolution
3% @ 1MeV



	KamLAND [2]	Borexino [3]	SNO+ [4]	JUNO
Target Mass [kilotons]	1	0.3	0.78	20
Number of PMTs	1900	2200	10,000	18,000 + 26,000
PMT Coverage	~34%	~30%	~50%	~80%
Light Collection [photoelectrons/MeV]	~250	~450	~520	>1300

Jiangmen Underground Neutrino Observatory

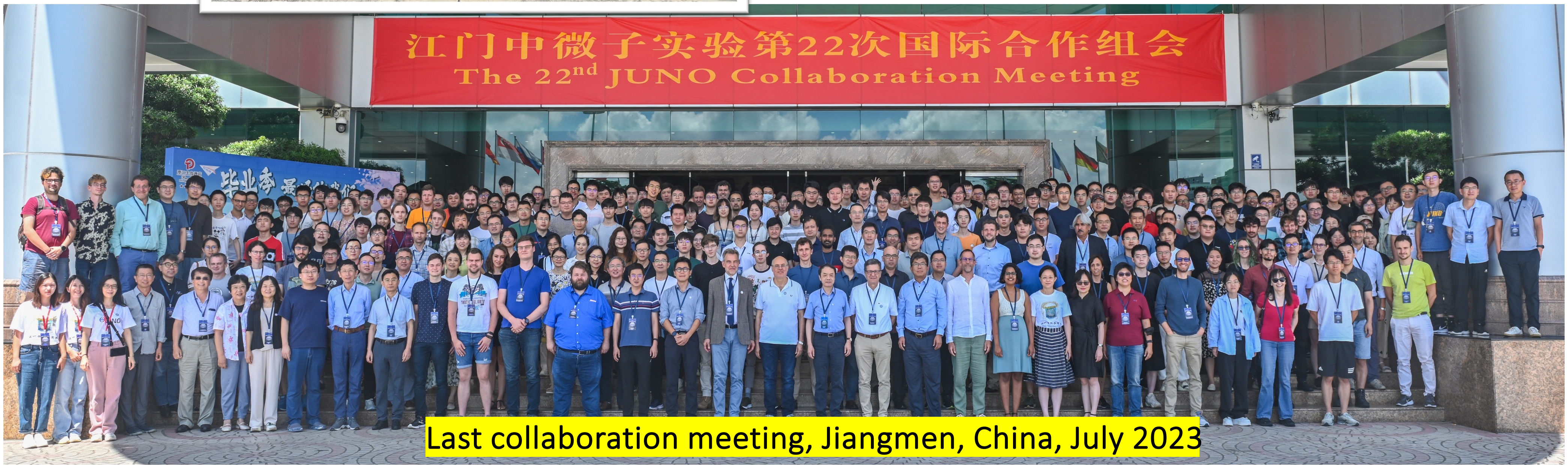




The JUNO Collaboration

= 74 institutes   > 700 collaborators

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

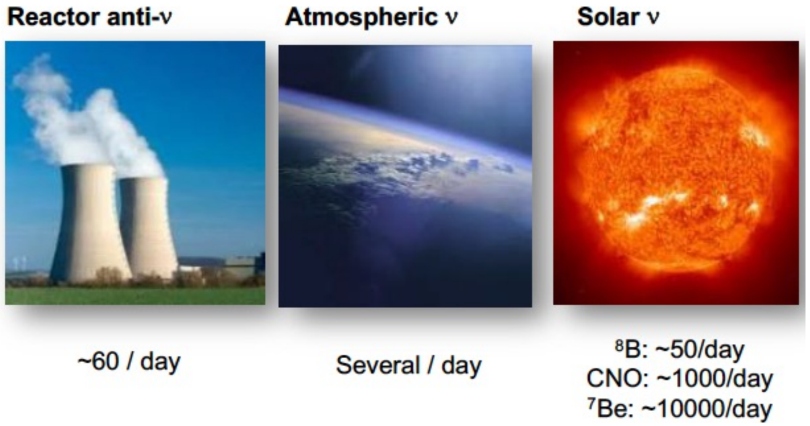


Last collaboration meeting, Jiangmen, China, July 2023

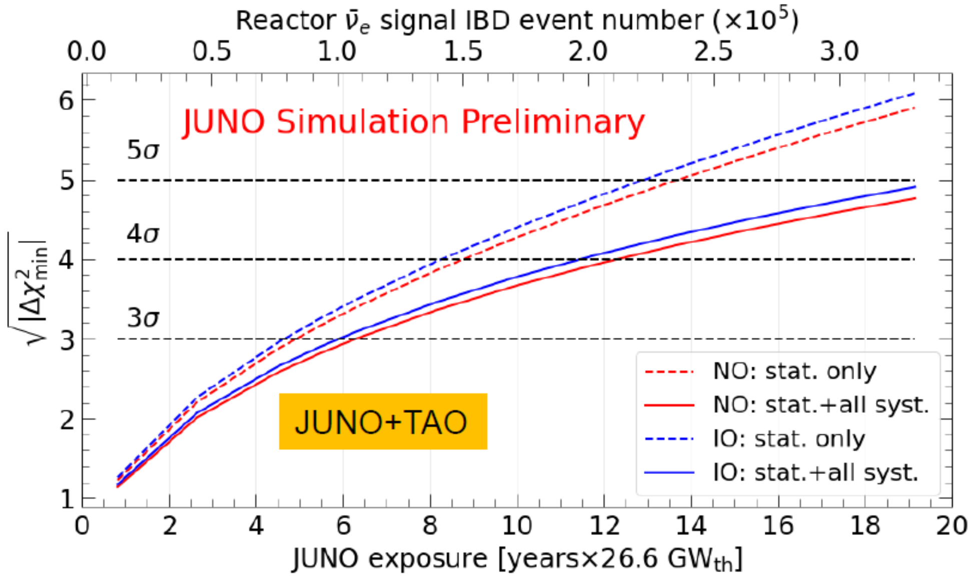

The tunnel to reveal mystery

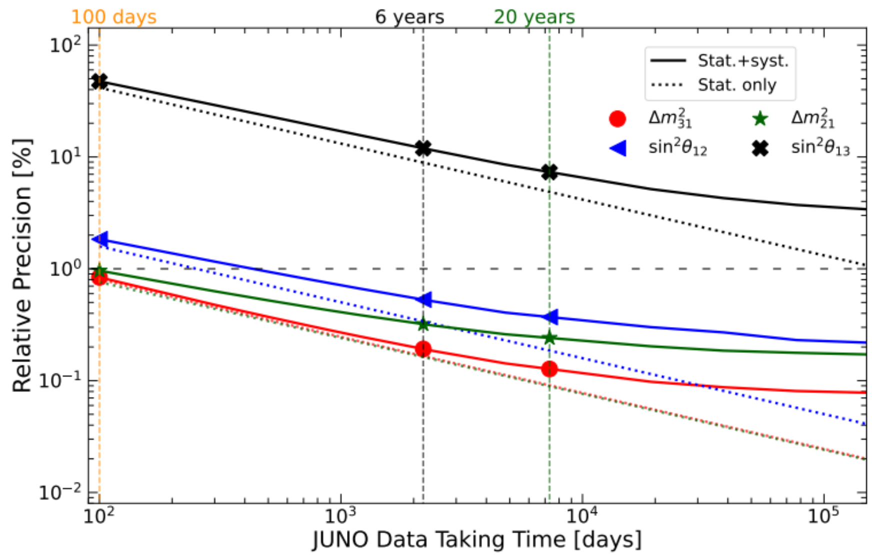
JUNO: a neutrino observatory

Reactor neutrino oscillation Chin.Phys.C 46 (2022) 12, 123001
Solar neutrino oscillation Chin.Phys.C 45 (2021) 2, 023004
Atmospheric neutrino flux Eur.Phys.J.C 81 (2021) 10
Diffuse supernova neutrinos JCAP 10 (2022) 033
Proton Decay arXiv: 2212.08502 and others



- **In 6 years:**
  - **Determine neutrino mass ordering at 3σ**
  - **Precision of $\sin^2\vartheta_{12}$, Δm^2_{31}, Δm^2_{21} < 0.5%**

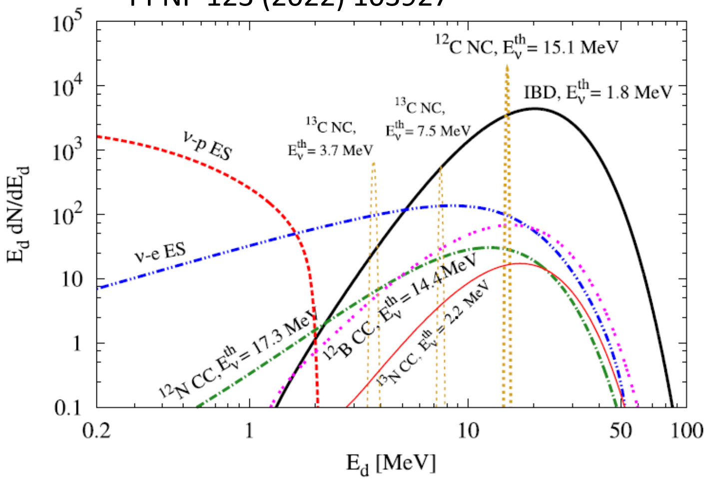




Precision of $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs

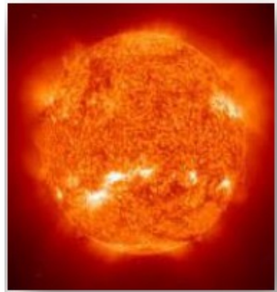
JUNO: a neutrino observatory

PPNP 123 (2022) 103927



10kpc Supernova: ~5000 IBD, ~300 eES, ~2000 pES, ~200 ^{12}C CC, ~300 ^{12}C NC

Solar ν



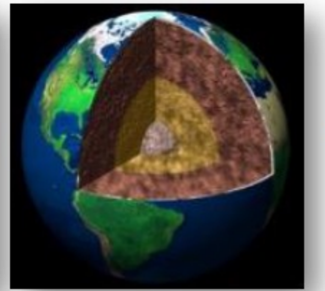
^{8}B: ~50/day
CNO: ~1000/day
^{7}Be: ~10000/day

Supernovae (SN) ν

Core Collapse SN @ 10 kpc: thousands in few sec.

Diffuse SN signal: few / year

Geoneutrinos



~400 / year

+

New physics

Proton decay
Neutrino magnetic moment
Sterile neutrinos
Non standard interactions
Lorentz invariance

Physics	Sensitivity
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor
DSNB	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, B8 flux
Atmospheric neutrino	0.7-1.4σ for NMO in 6 yrs. Boost the reactor result
Nucleon decays ($p \to \bar{\nu} K^+$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs

See Cristobal's talk

JUNO Detector

VETO System

Top tracker

- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top of the water pool

Water Cherenkov veto pool

- 2400 20" PMTs
- 35 kton ultra-pure water
- Efficiency >99.5%
- Radon control → < 0.2 mBq/m^3

Compensation coils

- Earth magnetic field <10%
- Necessary for 20" PMTs

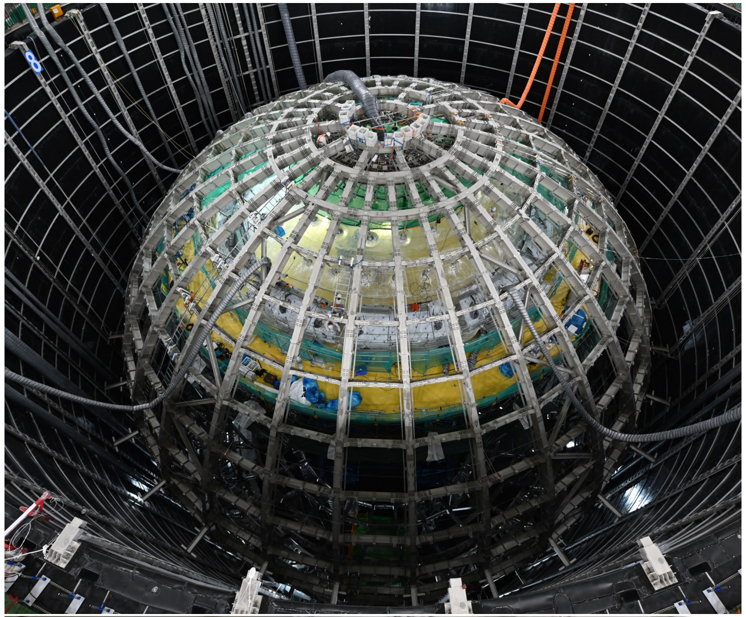
Calibration System

- Automatic Calibration Unit (ACU)
- Cable Loop System (CLS)
- Guide Tube Calibration System(GTCS)
- Remotely Operated Vehicles (ROV)

Central detector (CD)

- Optical separation: ***Acrylic sphere*** (Ø 35.4 m)
- ***Stainless Steel Latticed Shell*** (Ø 41.1 m)
- 20 kton ***Liquid Scintillator***
- ***PMTs***: 17612 20'' PMTs + 25600 3'' PMTs

Central Detector (CD)



❖**Acrylic sphere + Stainless Steel Truss support**

- **Acrylic Sphere** ID 35.4 m, thickness 120 mm, weight: ~600 tons
- 265 acrylic panels
- **SS truss** ID 40.1 m, OD 41.1 m
- Buoyancy ~ 3000 ton. 590 supporting bars to hold the acrylic. Stress of acrylic <3.5 MPa
- Acrylic transparency >96%, Radiopurity U/Th/K <1 ppt

Installation of equator layer

Status

About half acrylic sphere was finished!

Central Detector (CD) - Liquid Scintillator

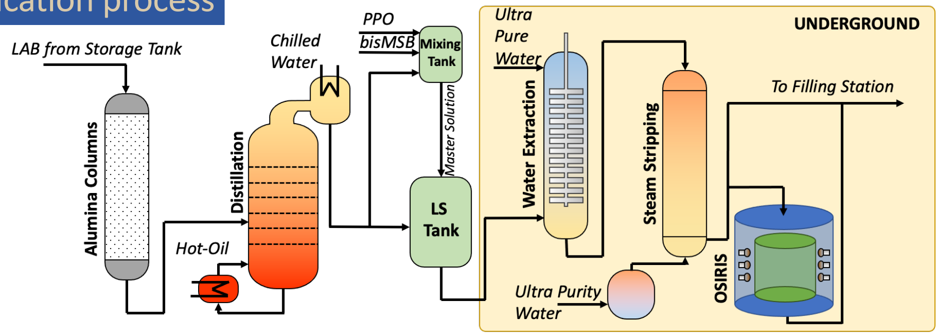
JHEP 03(2021)004

❖ **20 kt liquid scintillator: LAB** based**, PPO** as fluorescence**, bis-MSB** as wavelength shifter

- High light yield: >1345* p.e./MeV
- Long attenuation length: > 20 m @430m
- Extremely high radiopurity

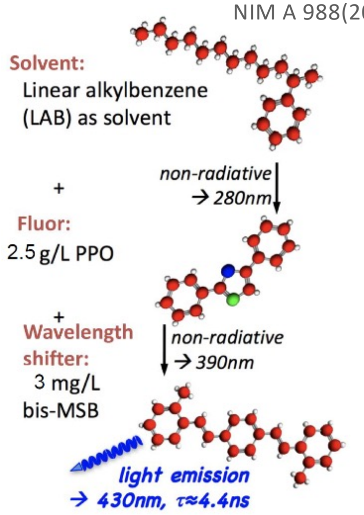
➢ Full system commissioning will start soon

an industrial scale purification process



*Linear Alkyl Benzene (**LAB**) + 2.5 g/L **PPO** + 3 mg/L **bis-MSB***

NIM A 988(2021)164823




1) Al_2O_3 for optical


2) Distillation for radiopurity


Mixing PPO and bis-MSB


3) Water extraction to remove radioactive impurities


4) Gas stripping to remove Rn and O_2


OSIRIS to monitor the LS quality

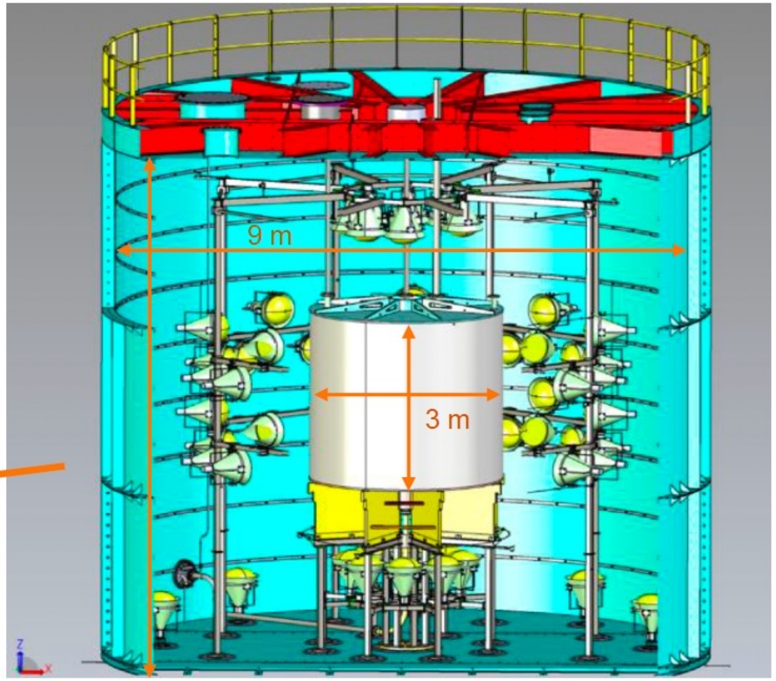
Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

A 20-t detector to monitor radiopurity of LS before and during filling to the central detector

- ✓ Few days: U/Th (Bi-Po) ~ 1×10^{-15} g/g (reactor baseline case)
- ✓ 2~3 weeks: U/Th (Bi-Po) ~ 1×10^{-17} g/g (solar ideal case)
- ✓ Other radiopurity can also be measured: ^{14}C, ^{210}Po and ^{85}Kr

Under commissioning now.

Eur.Phys.J.C 81 (2021) 11, 973



Central Detector (CD) - Photomultiplier Tubes

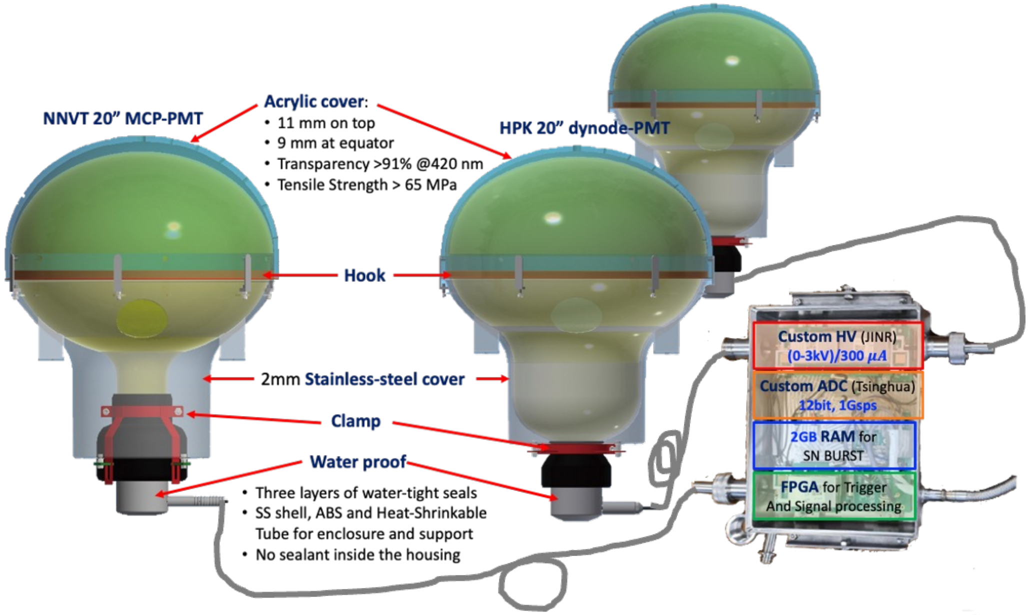
- **All has been produced, tested, and potted.**
- 20,012 **20-inch PMTs**: **15,012 MCP (2,400 for** veto) **and 5,000 dynode**
  → 17612 20” PMTs Looking inside →installed ~6000 (~34%)
- 25,600 **3-inch PMTs** →installed ~9293 (~36.3%)

		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		28.5%	30.1%	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	17.0	31.2	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

MCP: micro-channel plate

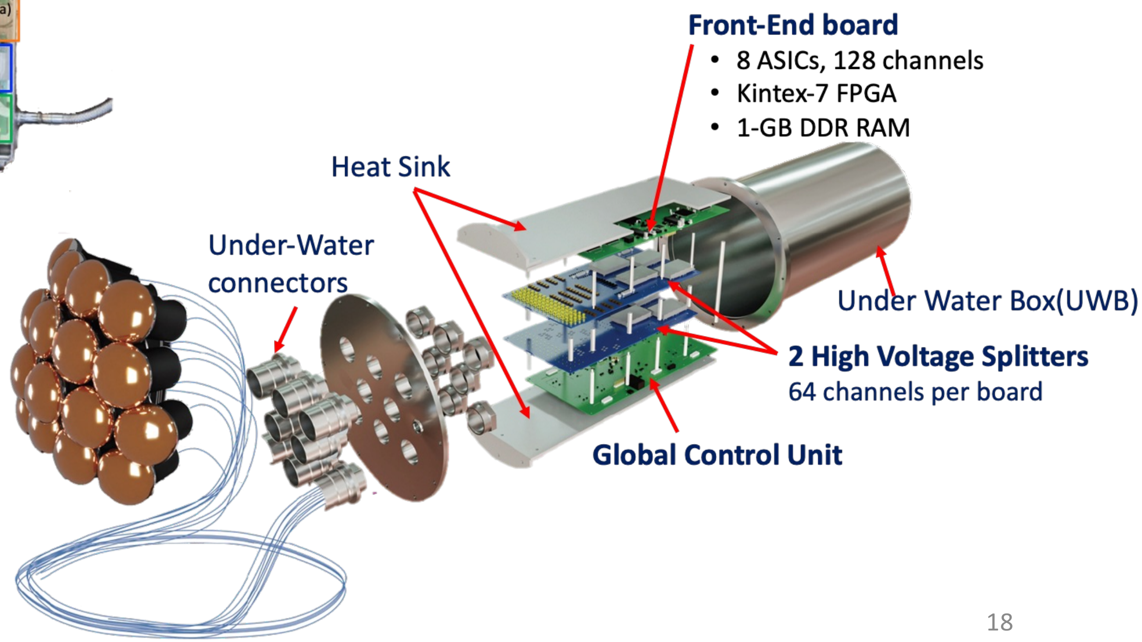
~6000 20” PMTs and 9293 3” PMTs are installed

Central Detector (CD) – PMT Instrumentation



SPMT System

- Always in ***photon counting mode*** in 1~10 MeV range
- 200 underwater electronics box in total
- 128 3-inch PMTs are connected to a UWB:
  - An UWB holds 8 receptacles
  - 16 PMTs coupled to one connector
- Same HV will be set for 16 PMTs

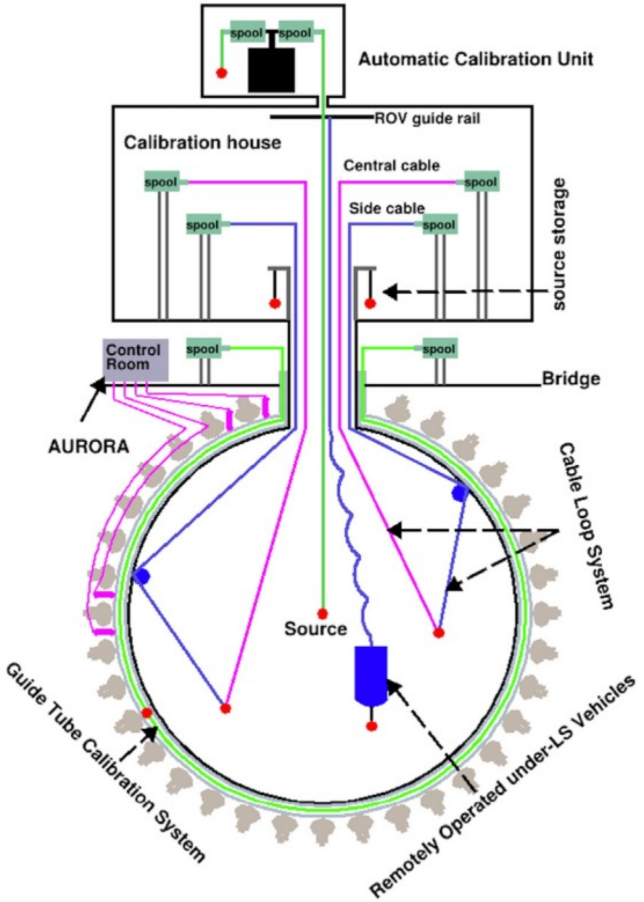


LPMT System

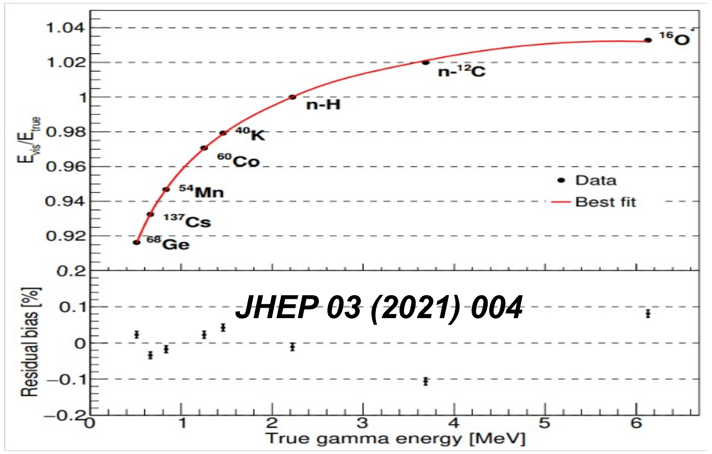
- 6886 underwater electronics box in total
- 3 20-inch PMTs are connected to a UWB
- **1F3 system**: splitter, HV FEC, ADC, GCU&FPGA
- Dry electronics:
  48 GCUs are connected to 1 BEC through the synchronous link and to 1 switch through the asynchronous link.

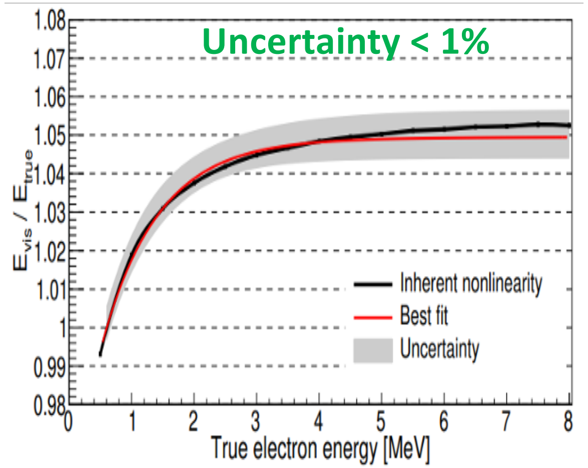
Calibration System

- Full-volume position coverage inside JUNO central detector



- Complementary for covering entire energy range of reactor neutrinos





- **Different tools deployed for detector calibration:**
  - **1D**: Automatic Calibration Unit (ACU) → central axis scan
  - **2D**: Cable Loop System (CLS) → scan vertical planes
    Guide Tube Calibration System (GTCS) → CD outer surface scan
  - **3D**: Remotely Operated under-LS Vehicle (ROV) → whole detector scan
  - **Auxiliary system**: Calibration House, Ultrasonic Sensor System (USS) CCD and a unit for researching Online LSc tRAnsparency (AURORA)

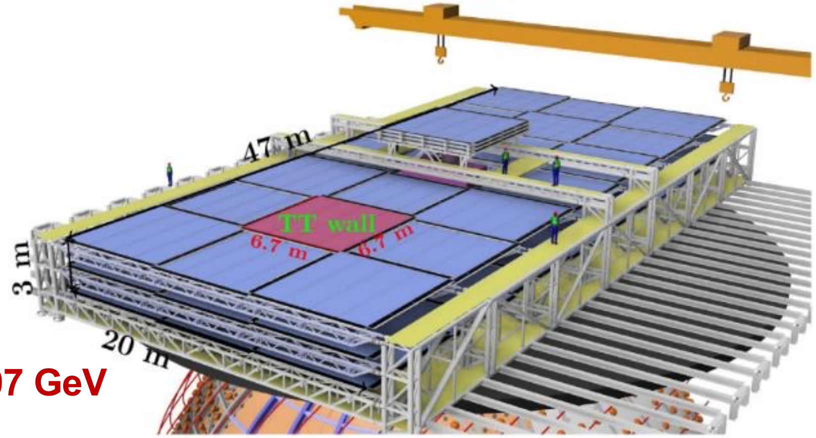
Veto System

Tasks

Shield rock-related backgrounds

Tag & reconstruct cosmic-rays tracks

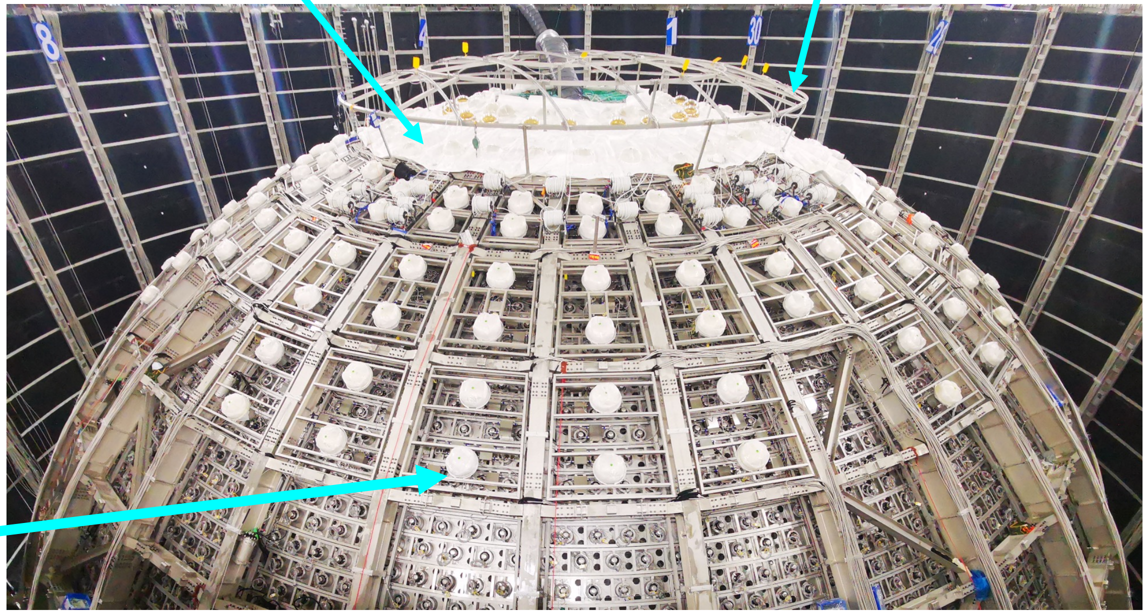
~650 m rock overburden (1800 m.w.e.) → R_μ = 4 Hz in LS, $< E_\mu >$ = 207 GeV



- **Top tracker: OPERA scintillators**
  - 3 layers, ~50% coverage on the top
- **Water Cerenkov detector**
  - 35 kton water, 2400 20-inch PMTs, detection efficiency >99.5%
  - Keep uniform temp 21℃±1℃
  - ^{222}Rn < 10 mBq/m^3 (w/ micro-bubble system)
- **Pool lining: HDPE**
- **Earth magnetic field compensation coil**

Tyvek reflective film installation started

Earth magnetic shielding coils installation: 6 coils installed (32 coils in total)

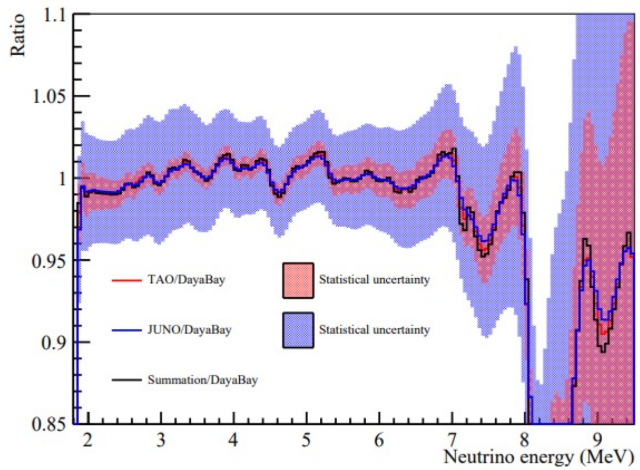


~500 veto PMTs installed

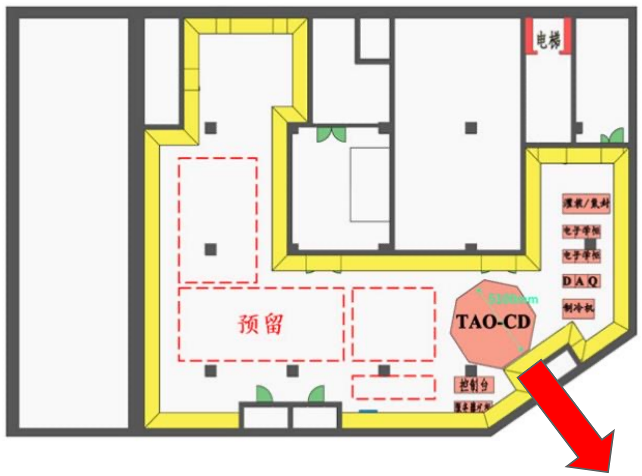
JUNO-TAO Taishan Antineutrino Observatory (TAO)

- **A satellite detector of JUNO**
  - at 30 m from the core(4.6 GW), in a hall at -10 m underground
- **Measure reactor neutrino spectrum**
  - model-independent reference spectrum for JUNO
  - a benchmark for investigation of the nuclear database

TAO CDR: arXiv: 2005.08745



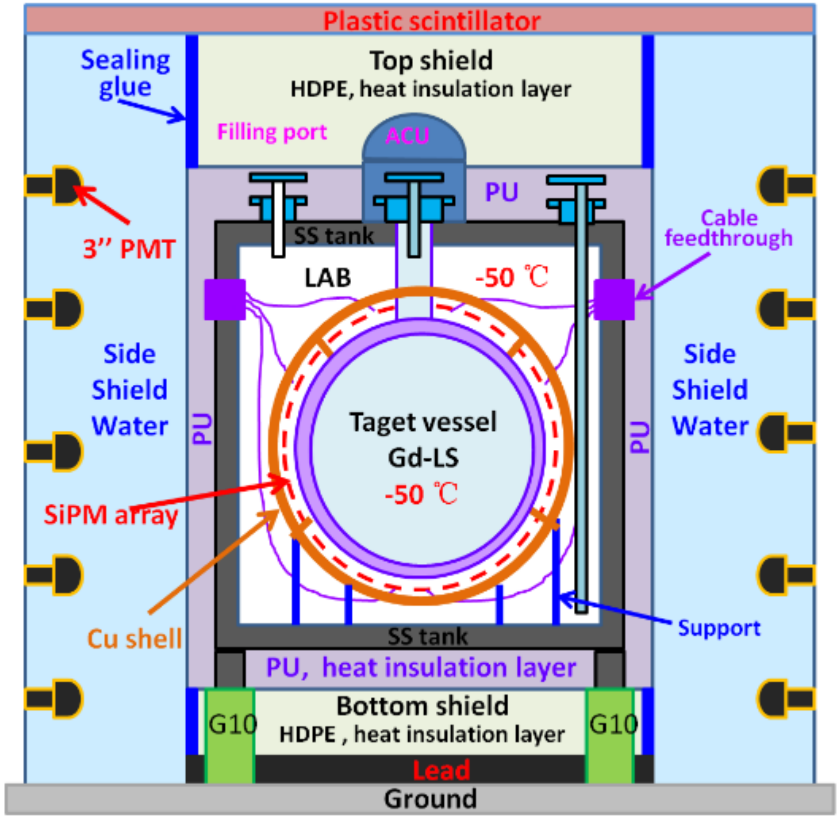
Constrain the fine structure in [2.5,6] MeV to < 1%



Core

JUNO-TAO

- 2.8 ton Gd-LS (1 ton fiducial mass), **produced**
- 94% coverage of SiPM w/ PDE > 50%, 1st batch received, under testing
- 1.8-m ID acrylic vessel, **ready**
- SS tank, **ready**
- Electronics, in production
- Operate at -50 °C (SiPM dark noise)
- To be tested at IHEP, w/ SiPM samples.
- 4500 p.e./MeV → < 2% resolution
- Neutron back-to-signal ratio ~2% (*JINST* 17 (2022) 09, P09024)



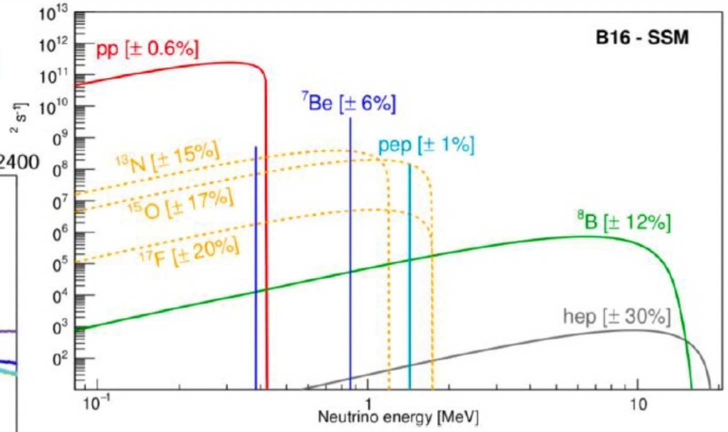
Summary

- JUNO is motivated to measure the Neutrino Mass Ordering
    - 20 kton liquid scintillator
    - 3%/sqrt(E) energy resolution
    - Advance detector technology
- Rich physics program. World-leading studies on
    - Precision measurement of oscillation parameters, Supernova ν, DSNB, Geo-ν, solar ν, proton decay, …
    - Future JUNO-0νββ
- **JUNO construction has entered its final stage. Data taking is expected in 2024!**
- Short-baseline experiment TAO
    - High energy solution measurement of reactor neutrino spectrum
    - JUNO reference spectrum and benchmark for nuclear database

Thanks!

Solar neutrinos

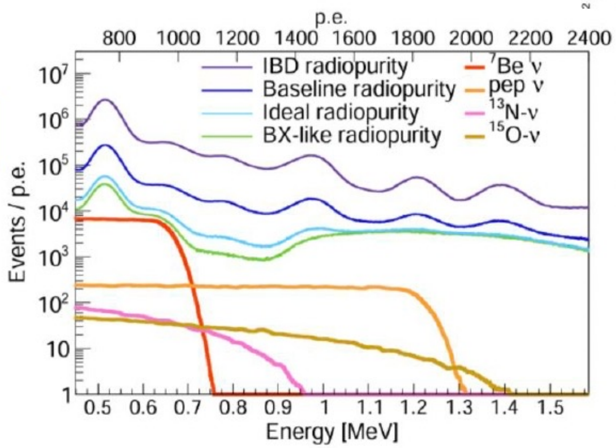
- JUNO sensitive to both high and intermediate energy solar neutrinos



- Intermediate energy solar neutrinos

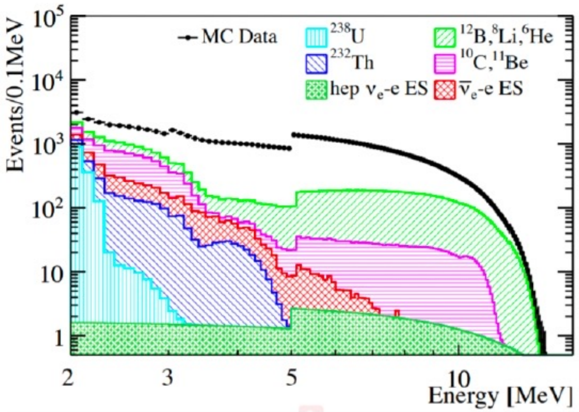
More radiopurity efforts (U/Th ~ 1×10^{-17} g/g)

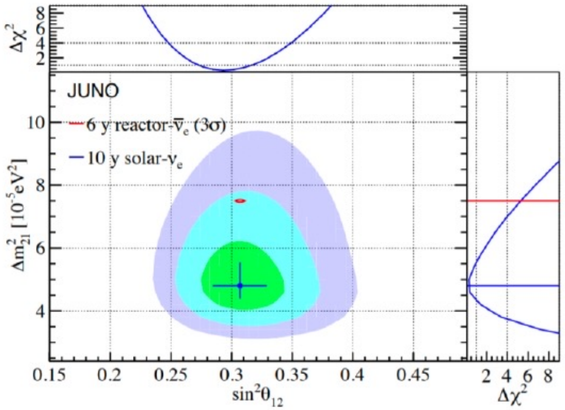
JUNO sensitivity to 7Be, pep, and CNO solar neutrinos
arXiv:2303.03910



- High energy solar neutrinos (^{8}B)

- Model independent measurement of ^{8}B solar neutrino flux (~5%) and oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}



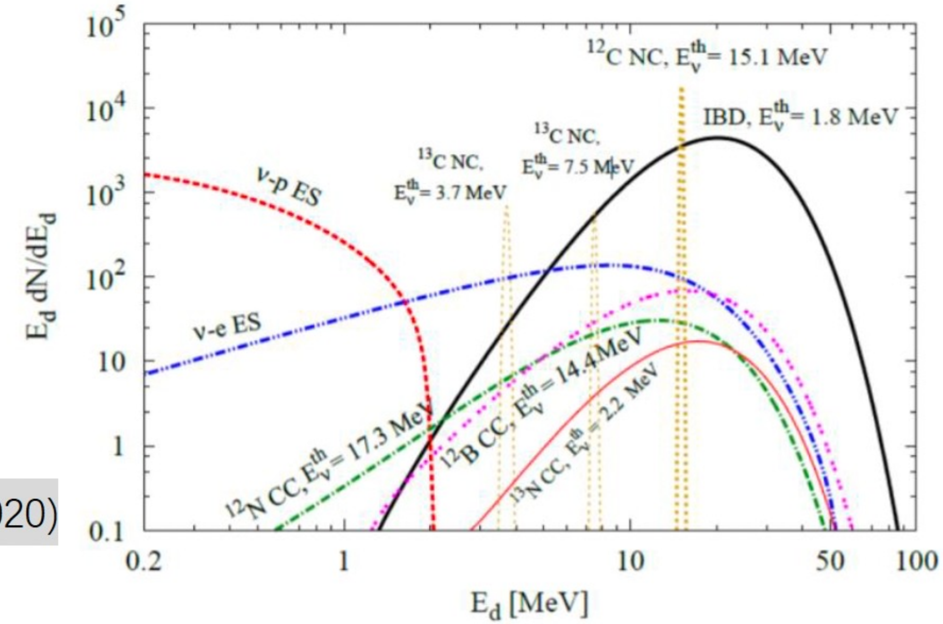


Chin. Phys. C 45 (2021) 2, 023004

Supernova neutrinos(SN)

- A high-statistics detection of neutrinos from a galactic SN will provide us with precious information about the explosion mechanism and intrinsic properties of neutrinos themselves.
- JUNO has excellent capability of detecting all flavors of the O(10 MeV) postshock neutrinos.
- Determination of the time evolution, energy spectra and flavor contents of SN neutrinos
- Main detection channel: IBD, ν-p ES, and ν-e ES
- Real-time detection of ~5000 IBD, ~1000 ν-p ES and ~4000 ν-e ES events for a SN @10kpc, assuming 0.2 MeV threshold and with special triggers design

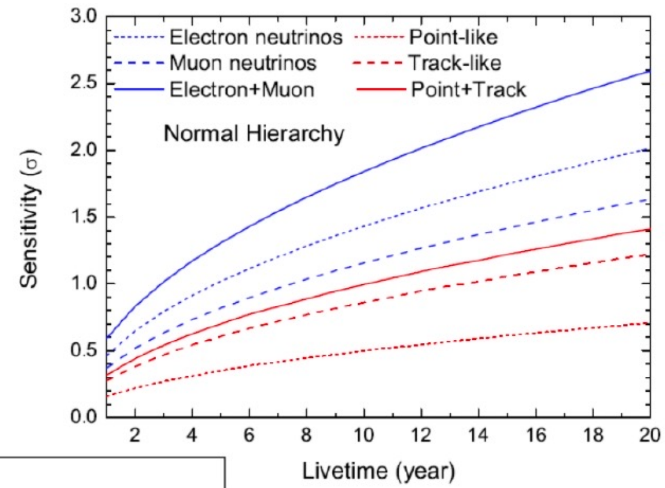
JCAP 05 049 (2020)



Atmospheric neutrino

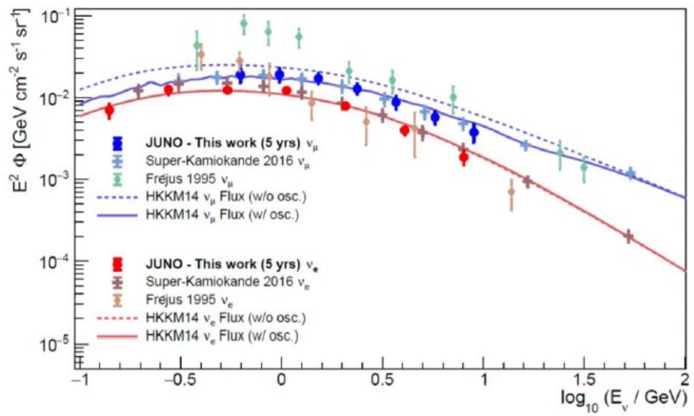
- JUNO NMO sensitivity from atmospheric neutrinos is complementary to that from the reactor neutrino results.
- Exploit matter effects for neutrinos crossing the Earth.
- Contributions to the sensitivity of NMO, θ_{23} and δ_{CP}.

J. Phys. G: Nucl. Part. Phys. 43 030401 (2016)



- Promising potential towards the low energy range.
  - ✓ Atmospheric ν spectrum measurement.

Eur. Phys. J. C (2021) 81:887



Diffuse Supernova Neutrino Background (DSNB)

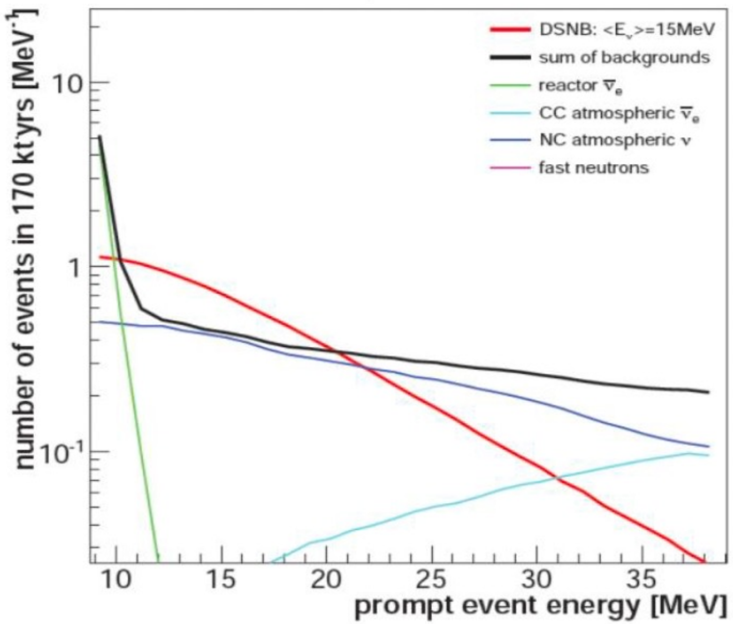
- The integrated neutrino flux from all past core-collapse events in the visible universe forms the diffuse supernova neutrino background (DSNB)
- Provide information: the red-shift dependent supernova rate, average SN neutrino energy spectrum and the fraction of black hole formation in core-collapse SNe
- Detection channel: IBD
- Background
  - ✓ $\overline{\nu}_e$ from reactor and atmospheric neutrino

    ➡ Visible energy range (10 , 30) MeV
  - ✓ atmospheric neutrino NC

    ➡ PSD helps to suppress
  - ✓ cosmogenic isotopes/fast neutron

    ➡ Muon veto

J. Phys. G43:030401 (2016)

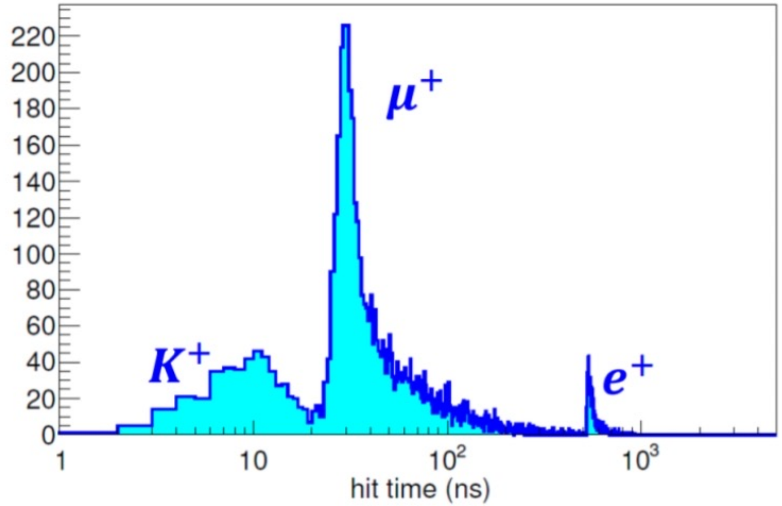


Exotic process

Proton decay

- Main search channel: $p \rightarrow \bar{\nu} K^+$
- Clear signature from 3–fold coincidence in JUNO

K^+ ionization $\rightarrow \mu^+$ ionization from K^+ decay $\rightarrow e^+$ from μ^+ decay



- Background:
  - Muon → muon veto
  - Atmospheric neutrino → energy , Michel electron, neutron, time character
- Expected sensitivity: 8.34 x 10^{33} years (90% CL) in 10 years data-taking

J. Phys. G43:030401 (2016)
JCAP01 039 (2016)
Chinese Phys. C 40 033003 (2016)

Other new physics

- ✓ Indirect dark matter search
- ✓ Light sterile neutrino searches
- ✓ Lorentz Invariance Violation
- ✓ Majorana neutrinos (Phase 2, upgraded JUNO)