JUNO physics prospects and status

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for the JUNO Collaboration

IPHC/IN2P3/CNRS

The JUNO Collaboration

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	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	China	CDUT-Chengdu	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine

75 institutes, over 650 collaborators

JUNO physics

"Neutrino Physics with JUNO," J. Phys. G **43** (2016) no.3, 030401
"JUNO Physics and Detector," Prog. Part. Nucl. Phys. **123** (2022), 103927

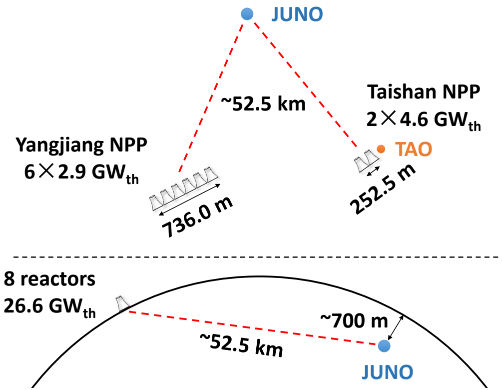
- Neutrino Mass Ordering (NMO)
- Precision measurement of oscillation parameters
- Atmospheric neutrinos
- Geoneutrinos
- Supernova (SN) neutrinos
- Diffuse SN neutrino background
- Solar neutrinos
- Nucleon decay & Exotic searches

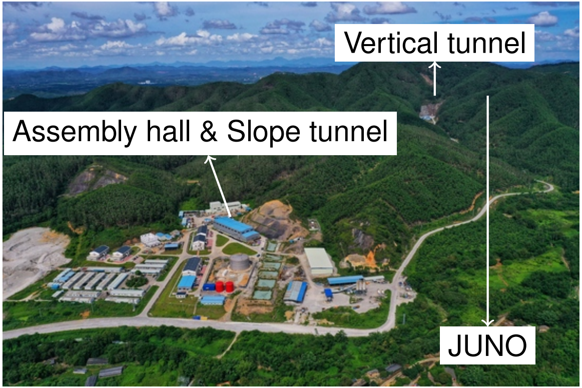
Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	60 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc 2300 elastic scattering	0–80 MeV	Negligible
DSNB (w/o PSD)	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Solar neutrino	hundreds per year for ^{8}B	0–16 MeV	Radioactivity
Atmospheric neutrino	hundreds per year	0.1–100 GeV	Negligible
Geoneutrino	$\sim$ 400 per year	0–3 MeV	Reactor ν

JUNO requirements

- Large statistics
  - Large target mass
  - Powerful nuclear power plants (NPPs)
    - Particularly for NMO and precision measurement of oscillations
- Very good energy resolution
  - Very high PMT coverage
  - High transparency of LS
  - High PMT efficiency
- Low background
  - $\sim$700 m rock overburden
  - Veto system with >99.5% efficiency
  - Material screening
  - Attention to installation procedure & clean environment
    - For solar ν tighter radiopurity requirement
- Precise reference spectra of NPPs
  - Particularly for NMO and precision measurement of oscillations
  - Satellite detector $\rightarrow$ JUNO-TAO

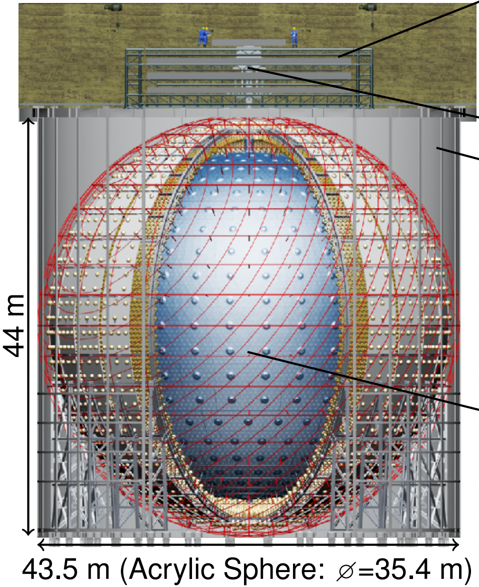
JUNO site





- Civil construction finished: 12/2021

The JUNO detector



Top Tracker (TT)

- Precise μ tracker
- 3 layers of plastic scintillator
- $\sim$ 60% of area above WCD

Calibration House

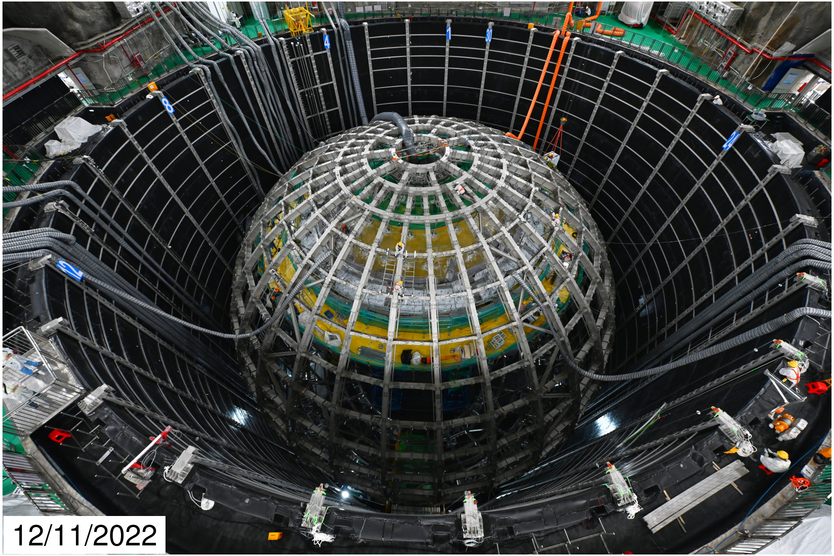
Water Cherenkov Detector (WCD)

- 35 kton ultra-pure water
- 2.4k 20” PMTs
- High μ detection efficiency
- Protects CD from external radioactivity & neutrons from cosmic-rays

Central Detector (CD) – $\bar{\nu}$ target

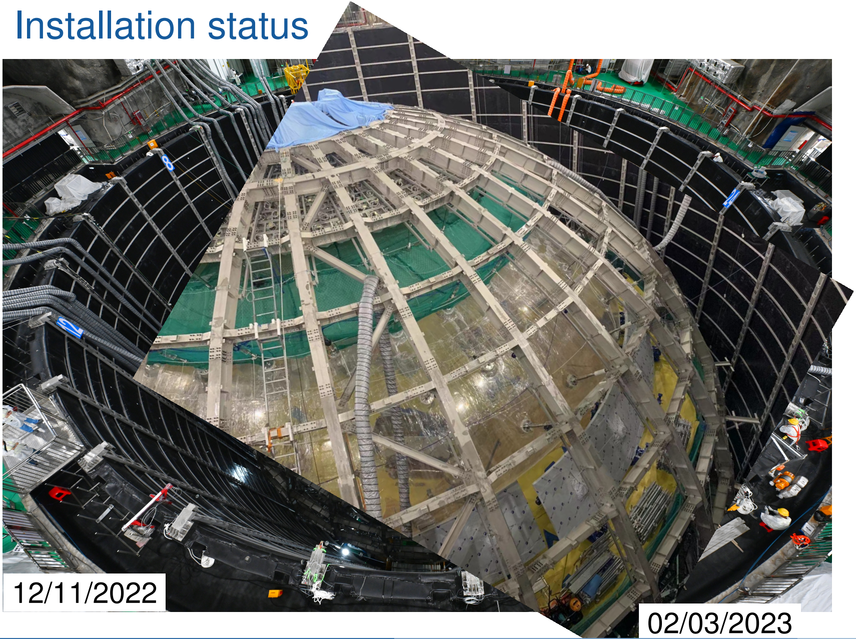
- Acrylic sphere with 20 kton liquid scint.
- 17.6k 20” PMTs + 25.6k 3” PMTs
- 3% energy resolution @ 1 MeV

Installation status



- Water pool liner: installed
- Supporting structure: installed
- Acrylic panels: being installed!

Installation status

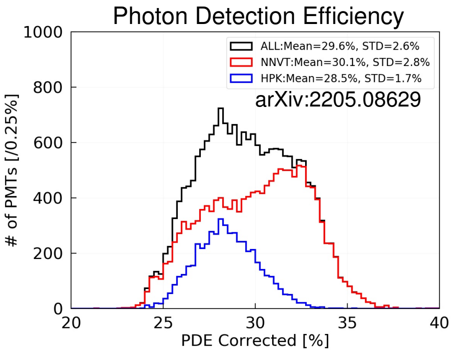


- Water pool liner: installed
- Supporting structure: installed
- Acrylic panels: being installed!
- PMTs: being installed!

The JUNO detector – CD & WCD PMTs

- 17612 (CD) + 2400 (Veto) 20” PMT
  - 5k Hamamatsu (HPK) PMTs, 15k NNVT PMTs
  - worst NNVT PMTs used in Veto
- 25600 3” PMT
- All PMTs produced & tested & waterproofed
- Electronics assembly ongoing

3 mm clearance between PMTs

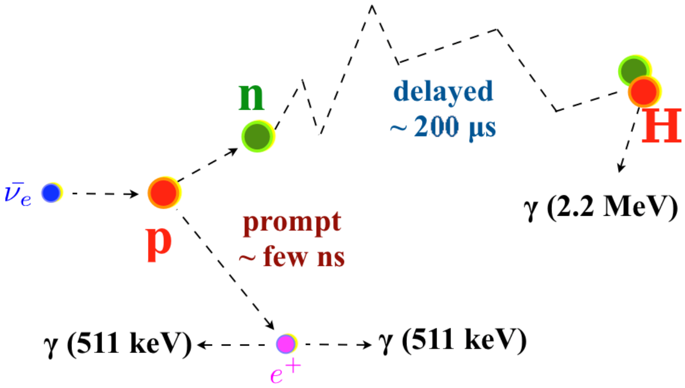


- NNVT PDE requirement: 27%
- NNVT PDE measured: 30%
  - 11% more photons detected!

NNVT: North Night Vision Technology

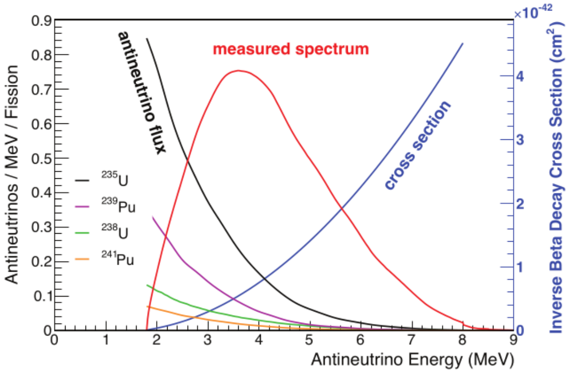
Measuring reactor $\bar{\nu}_e$: Inverse Beta Decay (IBD)

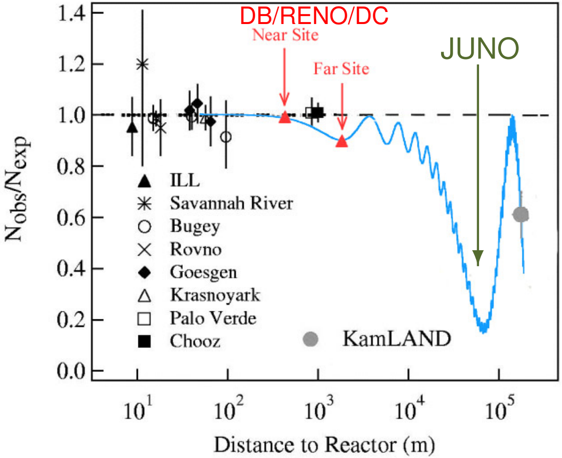
- Detected via IBD: $\bar{\nu}_e + p \rightarrow n + e^+$
  - IBD used since discovery of $\bar{\nu}$
  - Prompt+delayed signal $\Rightarrow$ large background suppression



- $E_{vis}(e^+) \simeq E(\bar{\nu}) - 0.8$ MeV ← used to as proxy for antineutrino energy

Neutrino oscillations with Reactor Antineutrinos

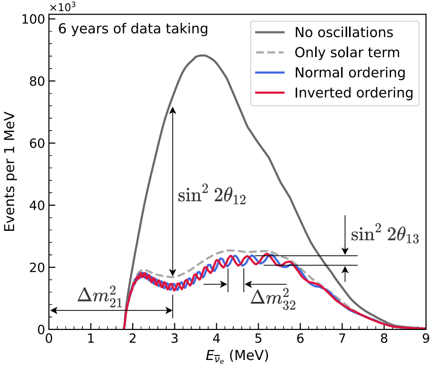


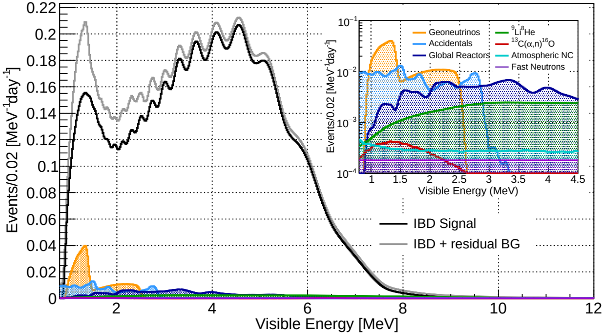


- Detected $\bar{\nu}_e$ energy 2–8 MeV
  - Only sensitive to $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- Distance: selects "oscillation regime"
  - JUNO at maximum $\bar{\nu}_e$ disappearance
  - First experiment to see both Δm^2

Expected reactor $\bar{\nu}_e$ spectrum in JUNO

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001





- Energy resolution smears low energy oscillations
  - critical importance of energy resolution

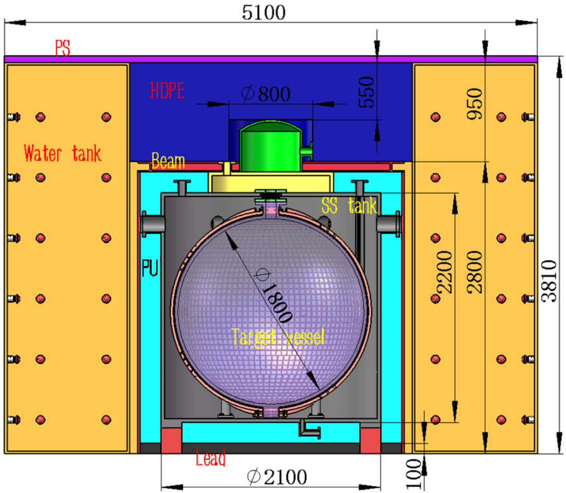
JUNO-TAO

"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

- JUNO-TAO provides reference for reactor spectrum
- Better energy resolution than JUNO (4500 PE/MeV)

JUNO-TAO detector:

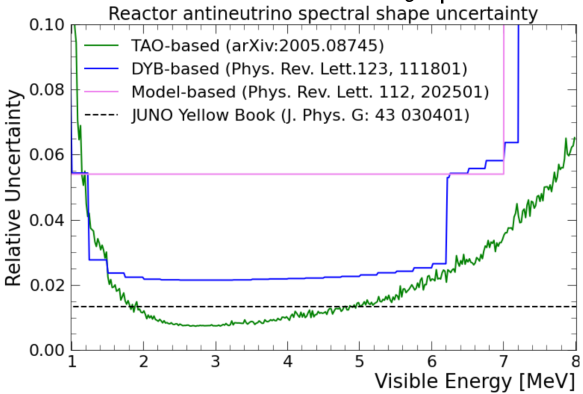
- 1 ton fiducial volume Gd-LS detector
  - 30 m from one of Taishan's 4.6 GW_{th} reactor core
  - 30$\times$ JUNO event rate
- 10 m^2 SiPM of 50% photon detection efficiency (PDE) operated at $-50°C$
  - >95% photo-coverage



JUNO-TAO – Physics potential

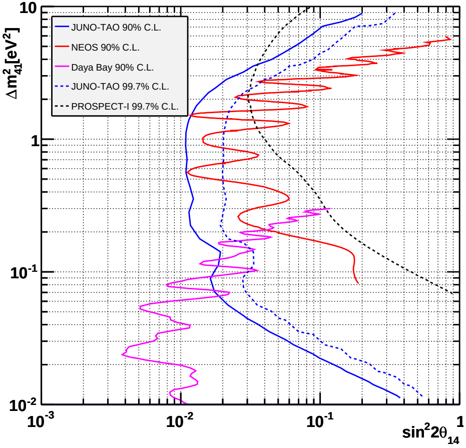
"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

Precise measurement of $\bar{\nu}_e$ spectra



- TAO energy resolution <2% @ 1 MeV

Sterile Neutrino searches



Updates to reactor $\bar{\nu}_e$ analysis

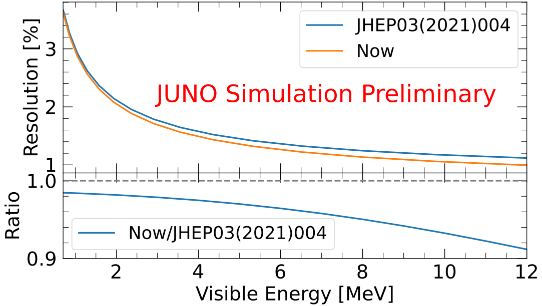
- Several updates since 2016
  - better PMT detection efficiency
  - lower radioactive background
  - 2 less reactor cores at Taishan
  - overburden reduced by ∼50 m
  - improved algorithms for veto strategy
  - $\bar{\nu}_e$ spectrum from JUNO-TAO
  - ...

Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → **47**	-	-
Geo-ν's	1.1 → **1.2**	30%	5%
Accidental signals	0.9 → **0.8**	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 → **0.8**	20%	10%
$^{13}C(\alpha,n)^{16}O$	0.05	50%	50%
Global reactors	0 → **1.0**	**2%**	**5%**
Atmospheric ν's	0 → **0.16**	**50%**	**50%**

J. Phys. G 43:030401 (2016) → **this update**

Energy resolution update

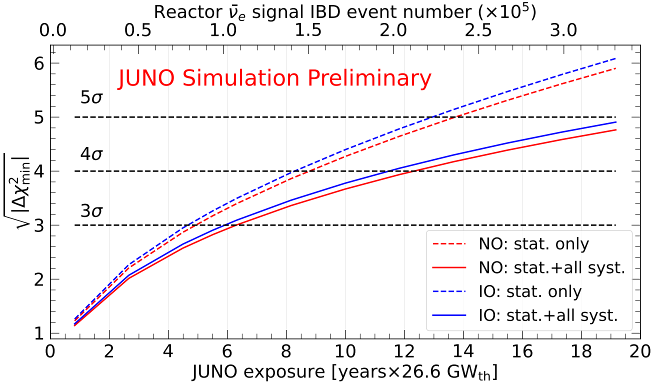
JUNO Simulation Preliminary	Resolution	Ref. poster @ Neutrino 2022
Estimated with PE yield	3.0%	JHEP03(2021)004
20-inch PMT PDE (27%→30.1%)	-	Mass testing data
More realistic optical model	-	10.5281/zenodo.6785356
New detector geometries	-	10.5281/zenodo.6805544
Now	2.9%	10.5281/zenodo.6804557



Note: not all analyses using new numbers yet!

Neutrino Mass Ordering

See poster 10.5281/zenodo.6775075 from Neutrino 2022, paper in preparation



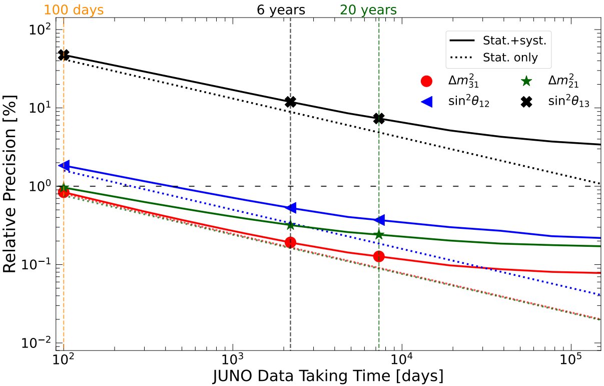
6 years	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

JUNO Simulation Preliminary

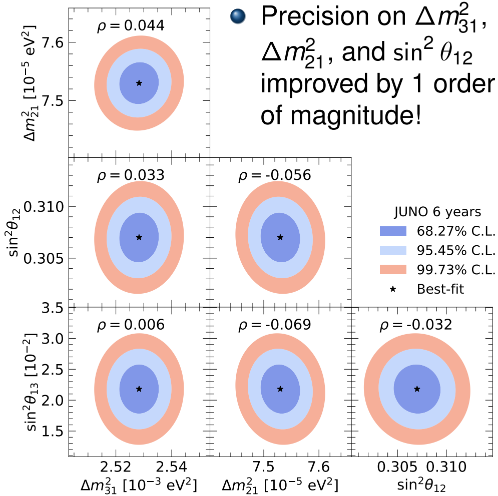
- Reactor only: 3σ in $\sim$6 years $\times$ 26.6 GW_{th} exposure
- Working into possibility to combine with JUNO Atmospheric result
- Complementary to other experiments!

Precision Measurement of Neutrino Oscillation Parameters

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001



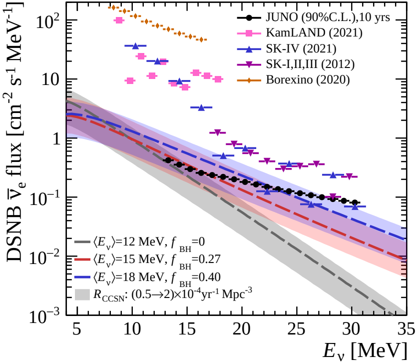
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

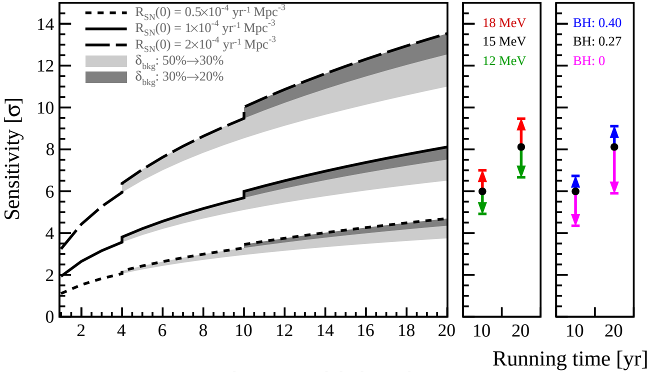


- Precision on Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ improved by 1 order of magnitude!

Diffuse Supernova Neutrino Background

"Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO," JCAP **10** (2022), 033

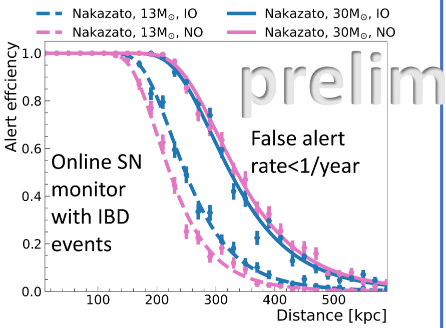




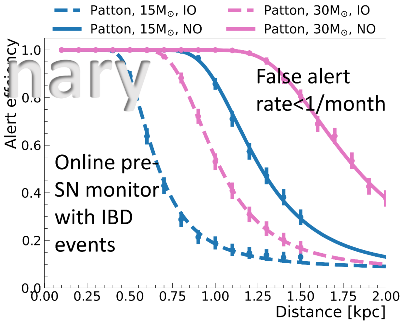
- For reference model:
  - @ 3 years → 3 σ sensitivity
  - @ 10 years → 5 σ sensitivity
- Improvements in sensitivity due to:
  - Reduced expected background
  - Increase signal efficiency (50% → 80%) w/ PSD
  - Better DSNB model

Core Collapse Supernova Neutrinos

See poster 10.5281/zenodo.6785184 from Neutrino 2022, paper in preparation



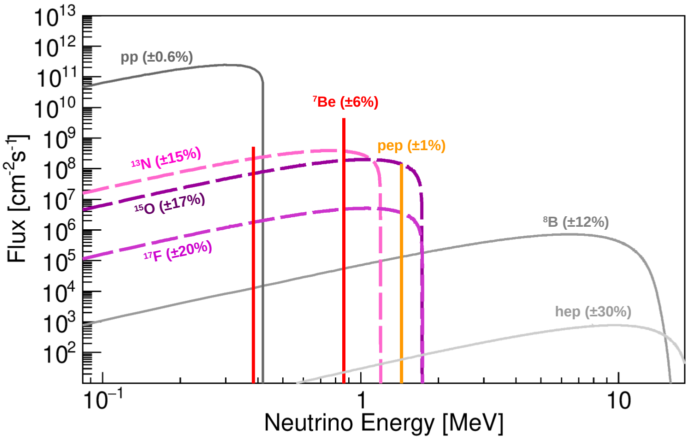
Alert efficiency for SN of online monitor. False alert rate is set to be smaller than 1/year.



Alert efficiency for pre-SN of online monitor. False alert rate is smaller than 1/month.

- Capability to detect pre-SN neutrinos from close SN-candidates
- >50% efficiency to detect CCSN up to 250–300 kpc
  - For reference: Milky Way diameter ∼30 kpc; Andromeda galaxy distance ∼ 780 kpc

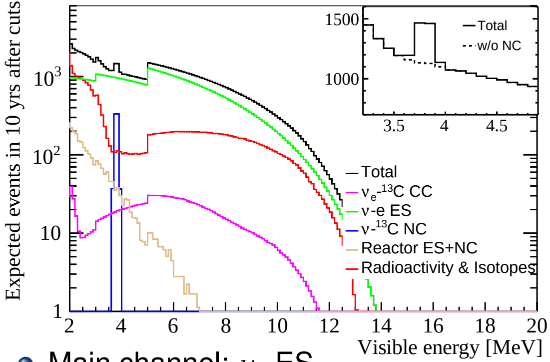
Solar Neutrinos

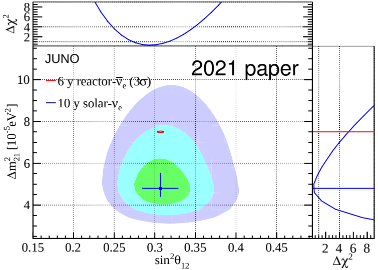


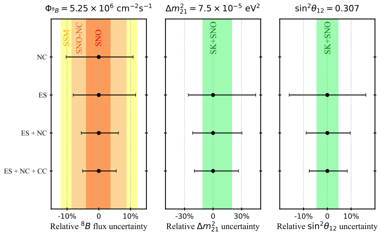
- Nuclear fusion in Sun $\Rightarrow \nu_e$
  - ν energy depends on specific reaction
  - Probe Sun composition
- JUNO expected to be able to measure ^{8}B, ^{7}Be, pep, CNO
  - Main limitation from radioactive backgrounds

Solar Neutrinos: ^{8}B @ JUNO

"Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO," Chin. Phys. C **45** (2021) no.2, 023004 and "Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program," arXiv:2210.08437







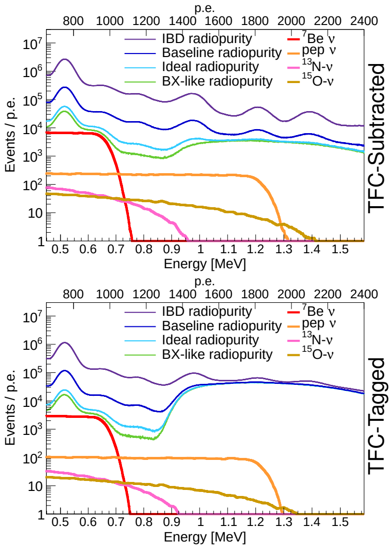
2022 paper

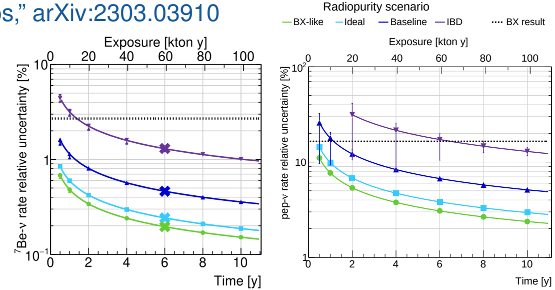
- Main channel: ν_e ES
- Also visible:
  - $\nu_x + ^{13}$C NC: 3.7 MeV γ
  - $\nu_e + ^{13}$C CC: 2.2 MeV β^+

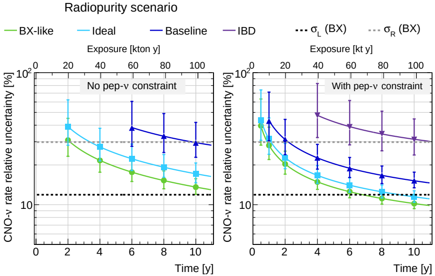
Solar Neutrinos: ^{7}Be, pep, CNO @ JUNO

*BX: Borexino

"JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos," arXiv:2303.03910

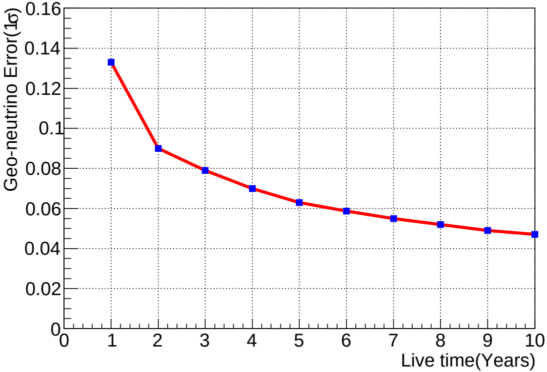






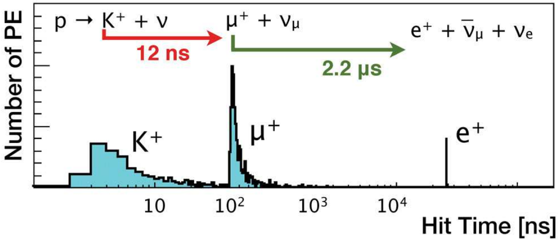
Other topics in JUNO

Geo $\bar{\nu}$



- Also potential to constrain Th/U ratio

Nucleon decay



- Triple coincidence signature from $\mathrm{p} \rightarrow \bar{\nu} + \mathrm{K}^{+}$
- Other nucleon decay modes also being investigated

Among other topics discussed in J. Phys. G **43** (2016) no.3, 030401 and Prog. Part. Nucl. Phys. **123** (2022), 103927

Conclusions

- JUNO will have unique properties: large target mass & good energy resolution
  - JUNO-TAO for reference reactor spectrum
  - Very large photo-coverage & high LS light yield
  - Comprehensive calibration strategy $\rightarrow$ clear path to 3% energy resolution
  - Strict radiopurity requirements
- Precision oscillation measurements with reactor $\bar{\nu}_e$ flux
  - First simultaneous observation of solar and atmospheric oscillations in same experiment
  - Measurement of NMO not relying on matter effects $\Rightarrow$ 3σ in $\sim$ 6 years (reactor only)
  - $<$ 0.5% precision on $\sin^2\theta_{12}$, Δm^2_{21}, and Δm^2_{32}
- Rich physics & astrophysics program beyond reactor-$\bar{\nu}$ analysis
  - DSNB discovery possible within JUNO
  - CCSN field of view extended to $\sim$300 kpc
  - Improved precision in Solar ν studies, particularly for some radiopurity scenarios
  - ...
- Detector construction progressing well $\Rightarrow$ data coming soon!

Backup

Measuring NMO with reactor neutrinos

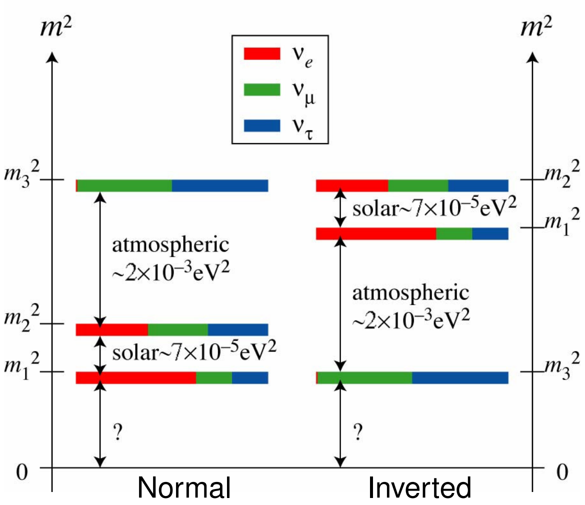
method: S. T. Petcov, M. Piai, Phys. Lett. B **533** (2002) 94; formulas: S. F. Ge, *et al*, JHEP **1305** (2013) 131

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i\frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$
$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31}) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32}),$$

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

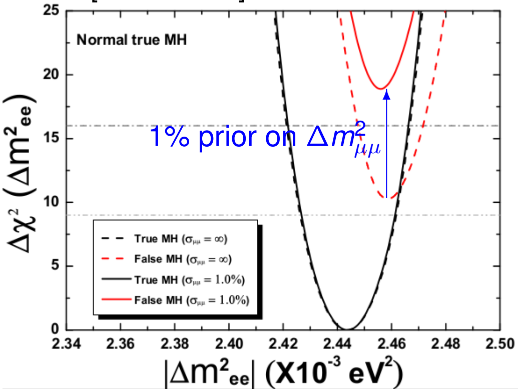
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$

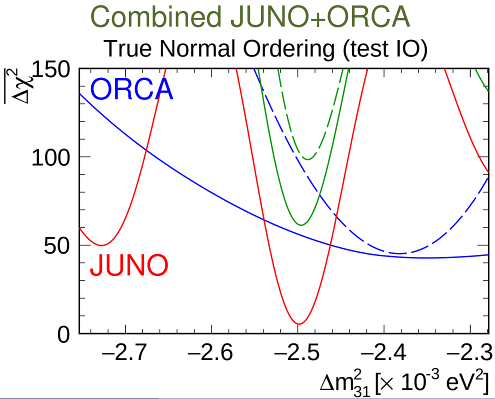
- Orderings: Normal $\rightarrow +$; Inverted $\rightarrow -$



NMO via combined fits of JUNO and other experiments

- Intrinsic differences between $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$, precise measurements of Δm^2 obtain different best-fit values for Δm^2_{31} when wrong ordering assumed
  - JUNO independent of δ_{CP}, θ_{23}, and doesn't rely on matter effects
- Dedicated studies performed with external priors and with other experiments
  - IceCube [1306.3988] & [1911.06745], accelerators [2008.11280], KM3NeT/ORCA [2108.06293]





Precision Measurement of Neutrino Oscillation Parameters: σ

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001

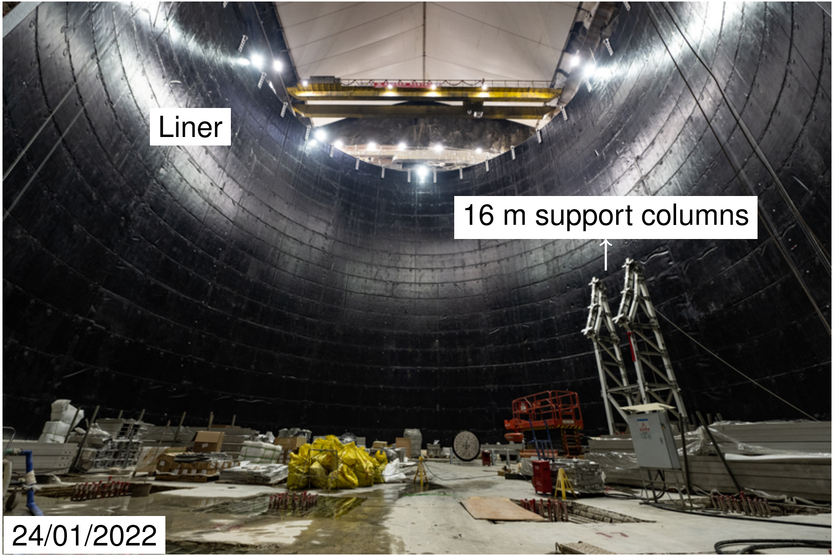
$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

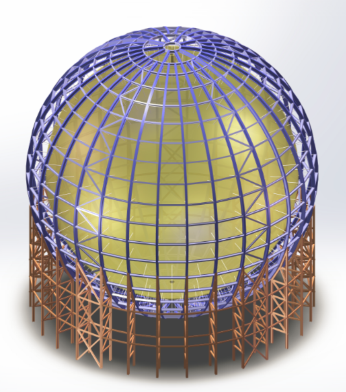
$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

The JUNO detector – inside Water Cherenkov Detector



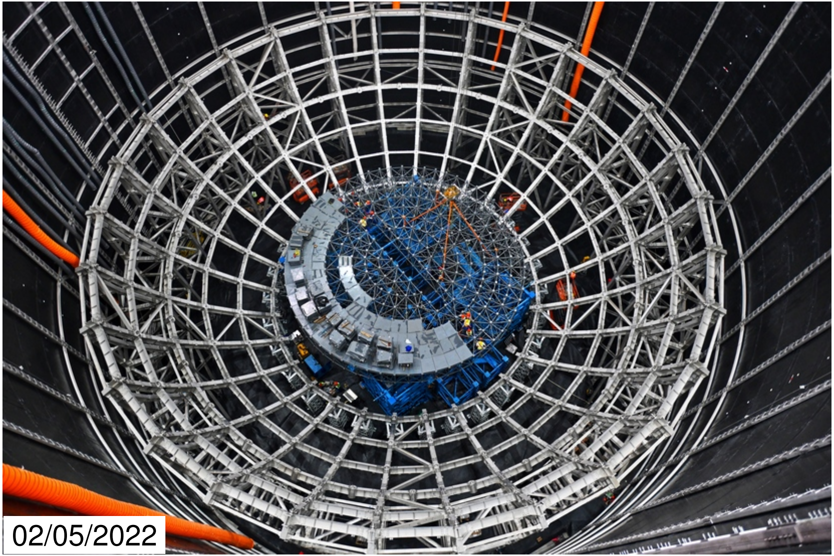
- 35 kt ultrapure water
- 2400 20” MCP PMTs
- μ det. eff. > 99.5%
- passive shield for radioactivity
- ^{222}Rn < 10 mBq/m^3
- Keep temperature @ (21 ± 1)°C

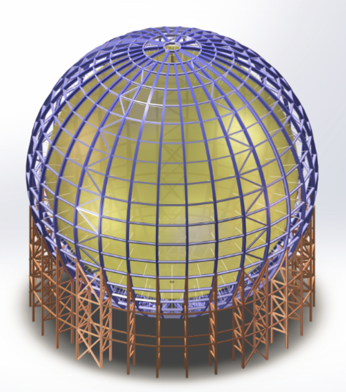
The JUNO detector – CD Support Structure



- Acrylic Sphere supported by 590 connecting bars

The JUNO detector – CD Support Structure and Lift Platform





- Acrylic Sphere supported by 590 connecting bars

The JUNO detector – CD Support Structure and Lift Platform

- Assembly of SS finished now
- Starting to install acrylic sphere

The JUNO detector – Acrylic Sphere

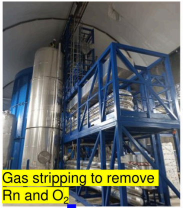
- 265 acrylic plates
- thickness: 124±4 mm
- radiopurity: U/Th/K < 1 ppt
- Each plate:
  - polished
  - cleaned
  - PE protective film added
- PE film to be removed after installation

The JUNO detector – Liquid Scintillator

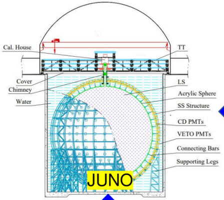
Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

All the LS related systems will finish assembly in summer.

SS pipes to underground



15%



85%

Jie Zhao

Neutrino2022

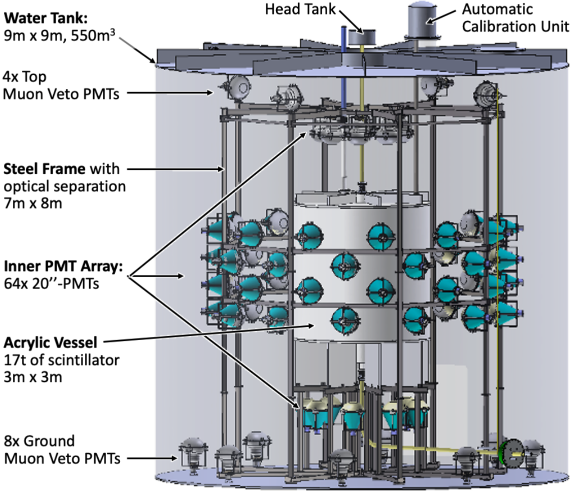
NIM.A 908 (2021) 164823

Eur. Phys. J. C **81** (2021) no.11, 973

The JUNO detector – OSIRIS

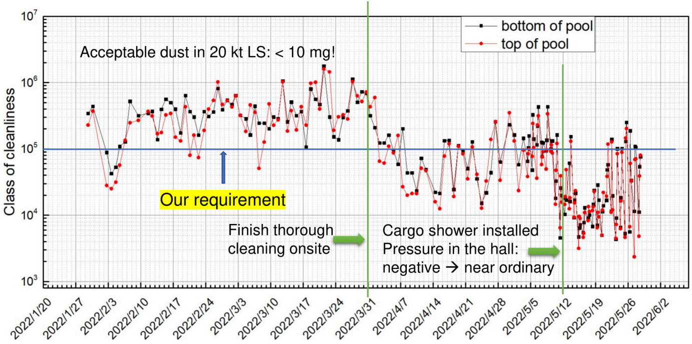
"The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS", Eur. Phys. J. C **81** (2021) no.11, 973

- Monitor LS radiopurity during before/during filling
- Few days: U/Th $\sim 10^{-15}$ g/g (IBD requirement)
- 2–3 weeks: U/Th $\sim 10^{-17}$ g/g (solar "ideal" case)
- Can also measure ^{14}C, ^{210}Po, ^{85}Kr
- Start commissioning in July

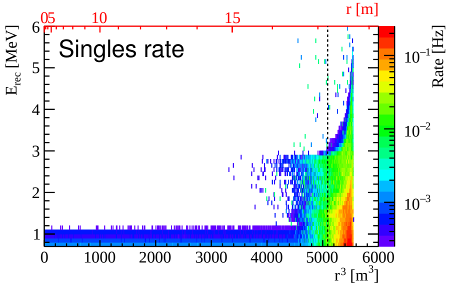


Radiopurity control

- LS recirculation impossible
  - Need to reach target radiopurity from start!
- Clean evironment during installation
  - Class 100k in WCD
  - Class 1k inside Acrylic Sphere!

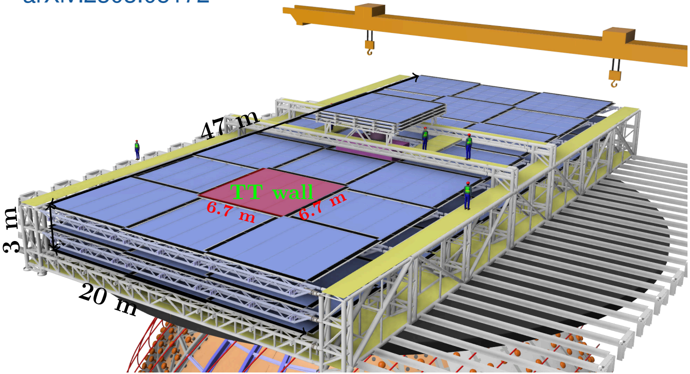


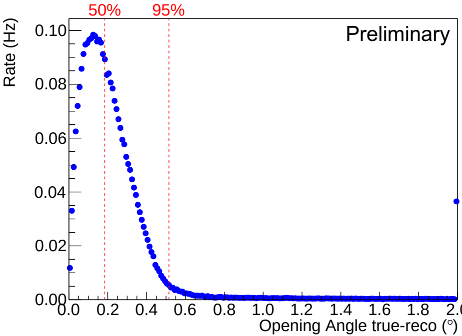
- Careful screening & handling of all materials
  - Overall 15% noise reduction from design
  - "Radioactivity control strategy for the JUNO detector," JHEP **11** (2021), 102



The JUNO detector – Top Tracker

arXiv:2303.05172





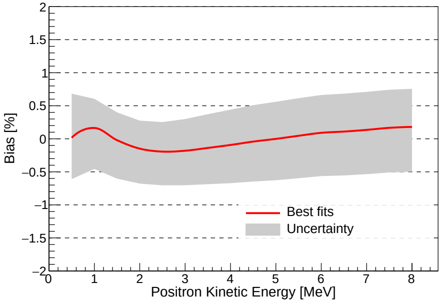
- Refurbished from OPERA experiment
- All plastic scintillator modules already in China
- New supporting structure designed

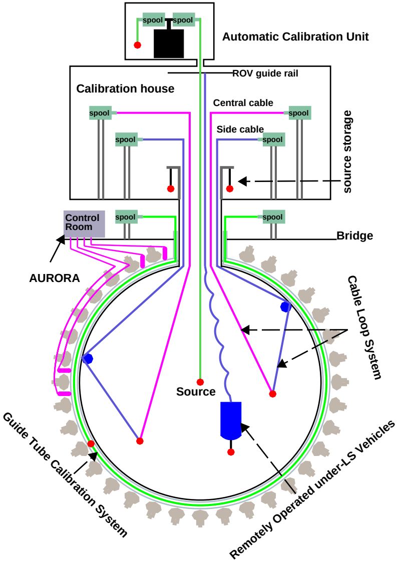
- Very precise μ tracking
  - 2.6×2.6 cm^2 XY granularity
  - 0.2° median angular resolution
- Provide well reconstructed μ sample for other systems

Calibration strategy

"Calibration Strategy of the JUNO Experiment," JHEP **03** (2021), 004

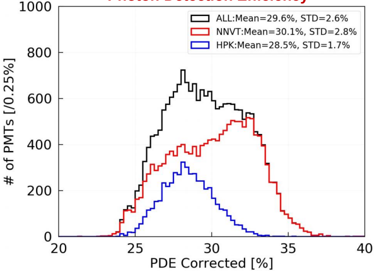
- Requirement: control energy scale, detector response non-uniformity and energy non-linearity
- 1D, 2D and 3D scan systems
- Many radioactive sources used
- 3" PMTs: correct any intrinsic 20" PMT non-linearity



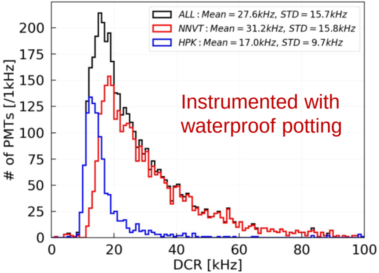


Photomultiplier Tubes

Photon Detection Efficiency



Dark Counting Rate



All PMTs produced, tested, and instrumented with waterproof potting

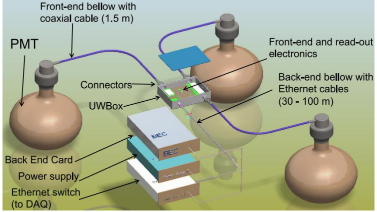
		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for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

12.6k NNVT PMTs with highest PDE are selected for light collection from LS and the rest are used in the Water Cherenkov detector.

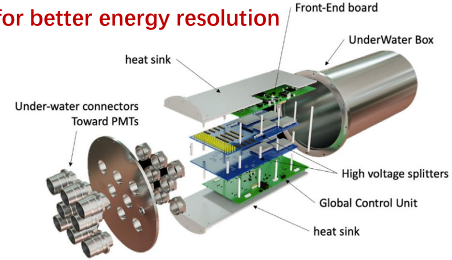
Electronics

Posters: #216, # 218, #270

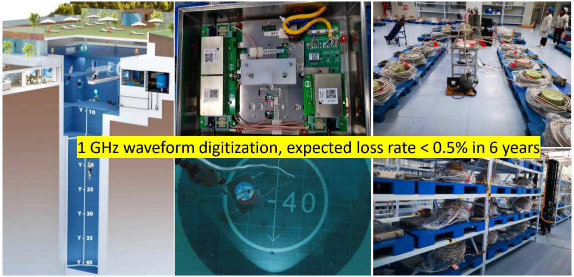
Underwater electronics to improve signal-to-noise ratio for better energy resolution



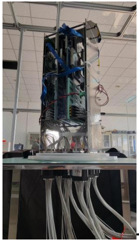
3 20-inch PMTs connected to one underwater box

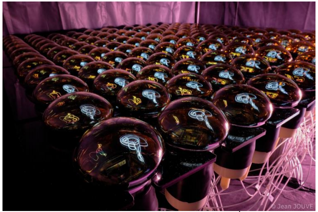


128 3-inch PMTs connected to one underwater box



1 GHz waveform digitization, expected loss rate < 0.5% in 6 years





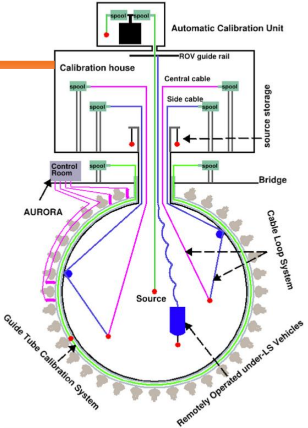
Electronics assembly ongoing

Calibration

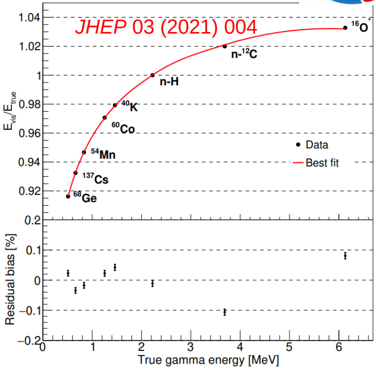
Poster: #293

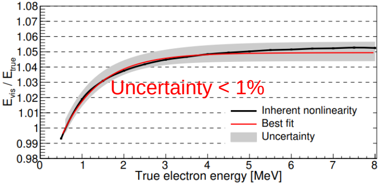
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system finished prototype test



Shadowing effect uncertainty from Teflon capsule of radioactive sources: < 0.15%





Radiopurity control

Reduced by 15% compared to the design. Ref: *JHEP* 11 (2021) 102

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	**-3.2**	10 ppt -> 1 ppt
Metal in node	0.087	**+1.0**	Copper -> SS
PMT glass	0.33	**+2.47**	Schott -> NNVT/Ham
Rock	0.98	**-0.85**	3.2 m -> 4 m
Radon in water	1.31	**-1.25**	200 mBq/m^3 -> 10 mBq/m^3
Other	0	**+0.52**	Add PMT readout, calibration sys
Total	8.5	**-1.3**	

Radiopurity control on raw material:

✓ Careful material screening

✓ Meticulous Monte Carlo Simulation

✓ Accurate detector production handling

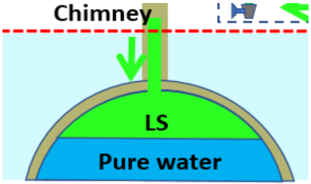
Liquid Scintillator Filling

✓ Recirculation is impossible at JUNO due to its large size

→ Target radiopurity need to be obtained from the beginning

✓ **Strategies:**

1. **Leakage** (single component < 10^{-6} mbar·L/s)
2. **Cleaning vessel** before filling
3. **Clean environment**
4. **Water/LS filling**



Update of energy resolution

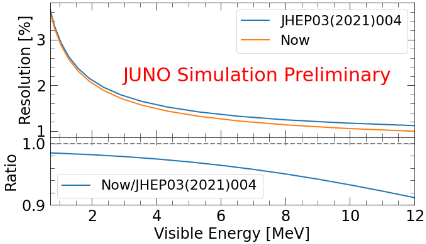
Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	*JHEP03(2021)004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV** (Poster #519)	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		Poster #184
New PMT Optical Model	+8%↑		*EPJC 82 329 (2022)* Poster #815

Positron energy resolution is understood:

$$\frac{\sigma}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}$$

- **Photon statistics**
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**

- **Annihilation-induced γs**
- **Dark noise**



Positron energy resolution

$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

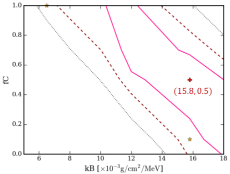
Photon statistics

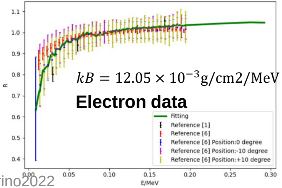
- **Annihilation-induced γs**
- **Dark noise**

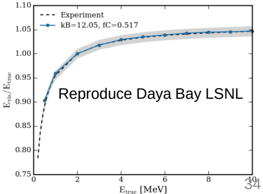
- **Scintillation quenching effect**
  - LS Birks constant **(kB)**
- **Cherenkov radiation**
  - LS refractive index
  - LS re-emission probability
  - Cherenkov yield scale factor **(fC)**
- **Detector uniformity and reconstruction**

- **kB** & **fC** are key parameters to predict energy resolution

- **Firstly attempt to constrain kB & fC with Daya Bay LS non-linearity**
  - Strong correlation between kB and fC
- **Solved by combining a series of table-top measurements on scintillation quenching effect**
  - kB of LS is determined to be 12.05×10^{-3} g/cm2/MeV
- **Re-constrain fC with Daya Bay LS non-linearity**
  - fC is determined to be 0.517



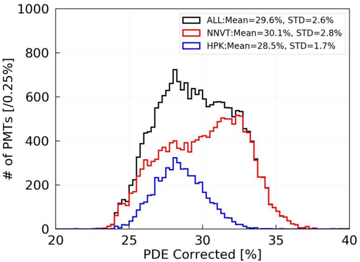




Light yield evolution

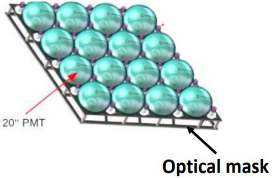
PMT PDE

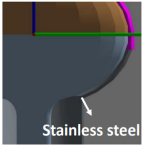
- Averaged PDE:27.0%→30.1%
- 27.0% is based on the original requirement of **QE~30%, CE~90%**
- 30.1% is the selected mean PDE, from **PMT mass testing system**

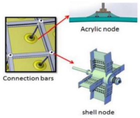


arXiv:2205.08629

New Geometries





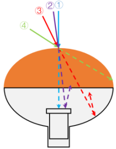


- **Reflections** on them are taken into consideration
- Yield 2.7% more photons

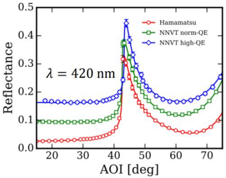
New PMT Optical Model

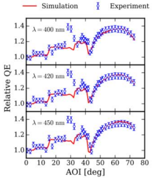
Optical Processes in PMT

- Reflection on photocathode
- PDE angular response
- Multiple reflections inside PMT



- ◆ Multilayer thin film theory
- ◆ Experimental tests
- ◆ GEANT4 simulation





Poster #815