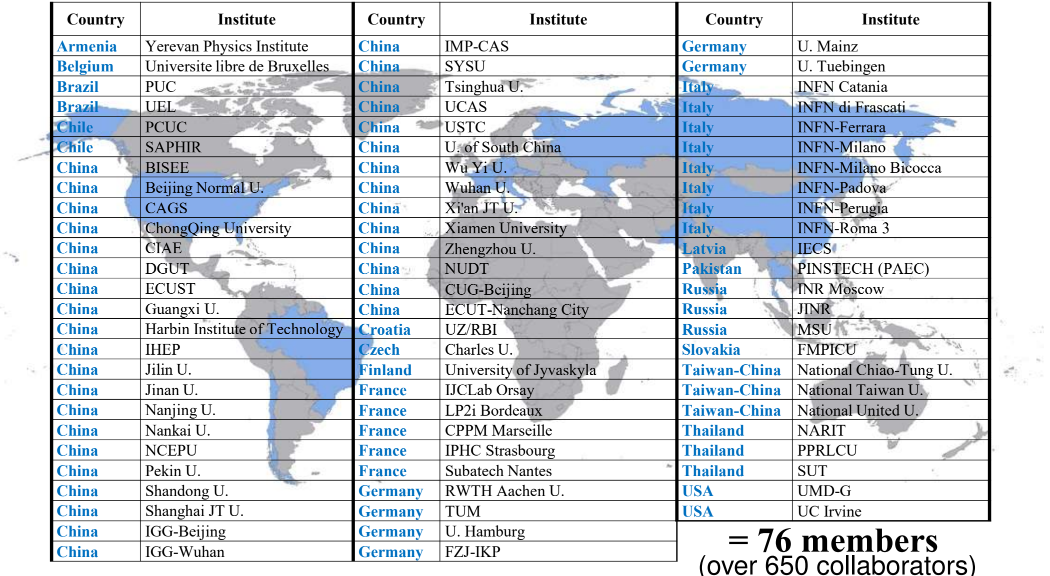
JUNO Status & Prospects

João Pedro Athayde Marcondes de André
for the JUNO Collaboration

IPHC/IN2P3/CNRS

The JUNO Collaboration



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

= 76 members

(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 physics

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

Presented by Rebin
@ last IRN meeting

- Neutrino Mass Ordering (NMO)
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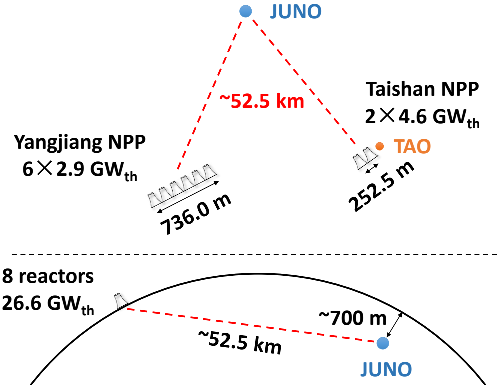
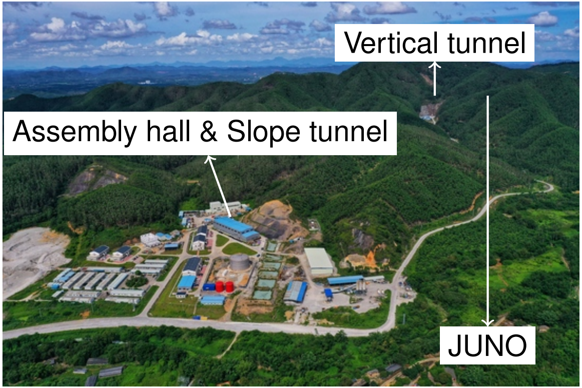
JUNO requirements

- Large statistics
  - Large target mass
  - Powerful nuclear power plants (NPPs)
    - Particularly for NMO and precision measurement of oscillations
- Good energy resolution
  - Very high PMT coverage
  - High transparency of LS
  - High PMT efficiency
- Low background
  - $\sim$1800 m.w.e. 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 → JUNO-TAO

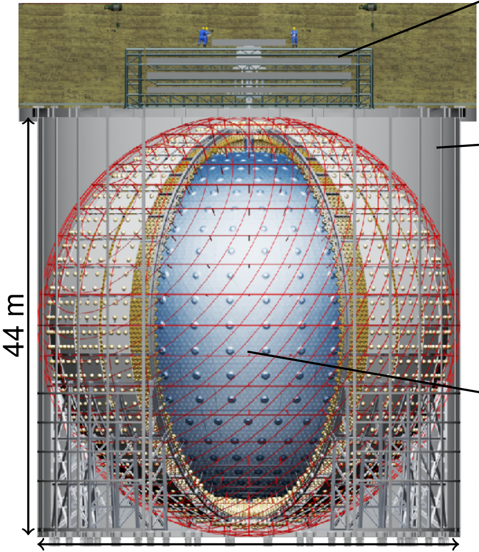
JUNO site





- Civil construction finished: 12/2021

The JUNO detector



43.5 m (Acrylic Sphere: $\varnothing$=35.4 m)

Top Tracker (TT)

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

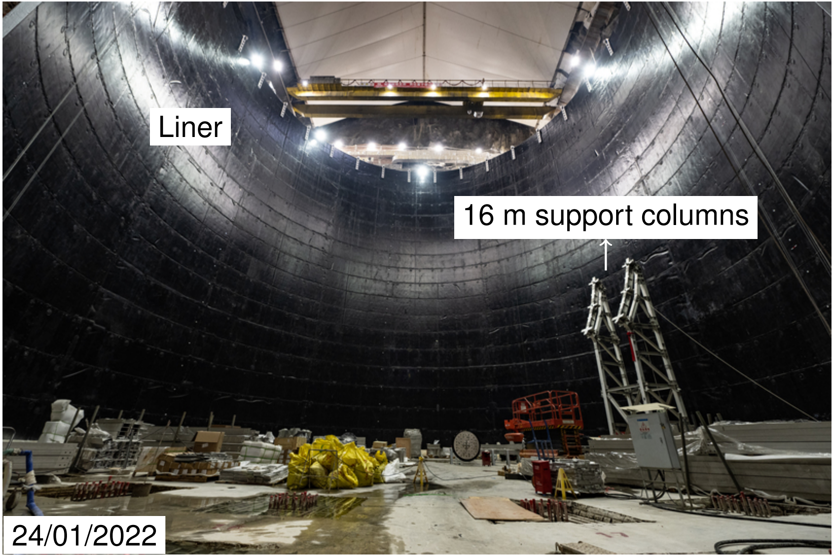
Water Cherenkov Detector (WCD)

- 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

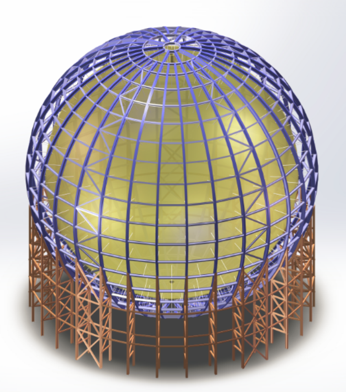
The JUNO detector – inside Water Cherenkov Detector



- 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 @ $(21 \pm 1)^\circ$C

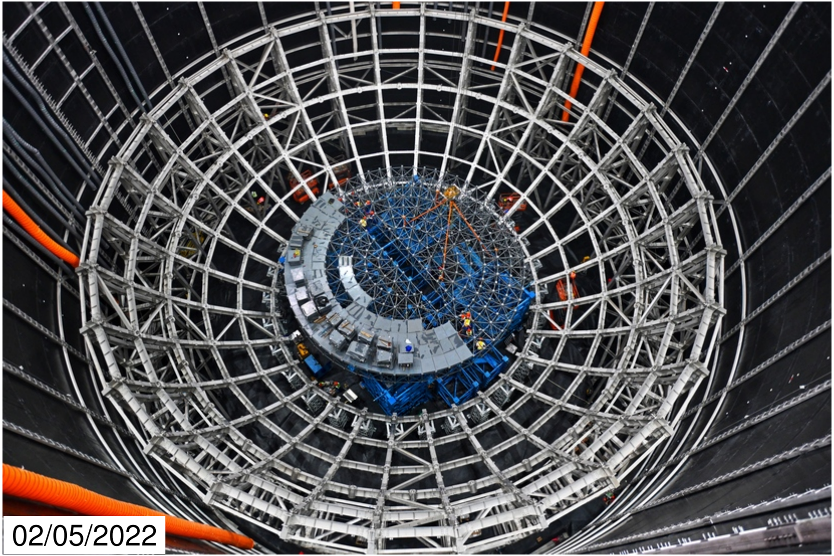
The JUNO detector – CD Support Structure

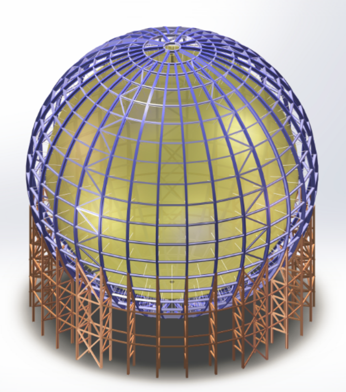

04/03/2022



- Acrylic Sphere supported by 590 connecting bars

The JUNO detector – CD Support Structure and Lift Platform


02/05/2022



- 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

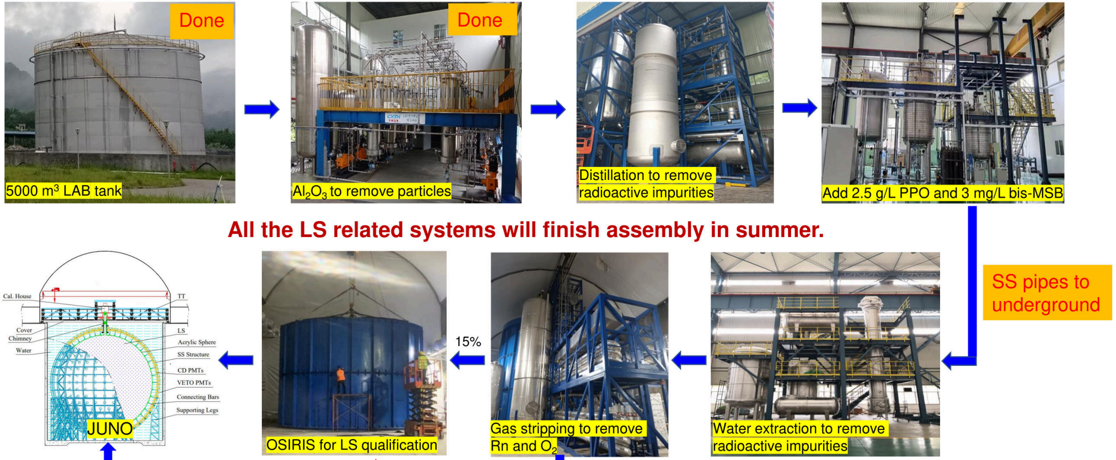
The JUNO detector – Acrylic Sphere


Assembly test in factory

- 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.



Done

$5000\ m^3$ LAB tank

Done

Al_2O_3 to remove particles

Distillation to remove radioactive impurities

Add 2.5 g/L PPO and 3 mg/L bis-MSB

SS pipes to underground

All the LS related systems will finish assembly in summer.

Water extraction to remove radioactive impurities

Gas stripping to remove Rn and O_2

15%

OSIRIS for LS qualification

85%

Jie Zhao

Neutrino2022

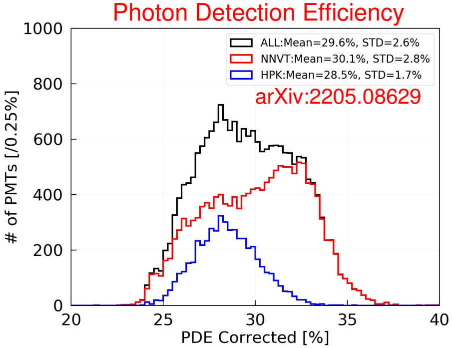
NIM.A 908 (2021) 164823

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

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

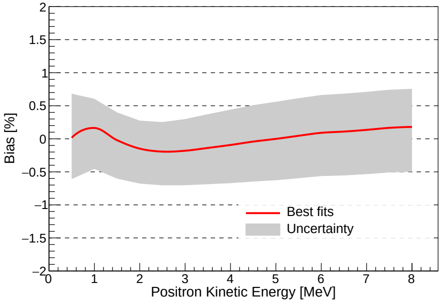


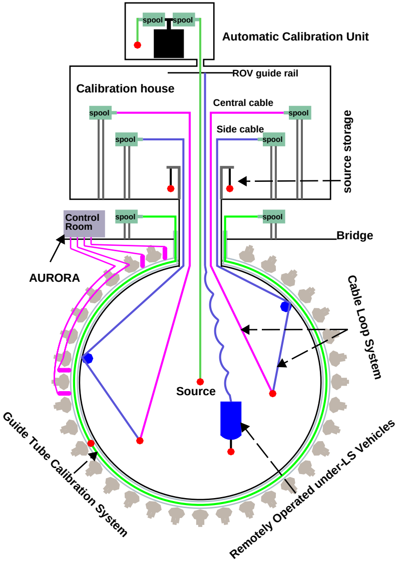
- NNVT PDE requirement: 27%
- NNVT PDE measured: 30%
  - 11% more photons detected!

Calibration strategy

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

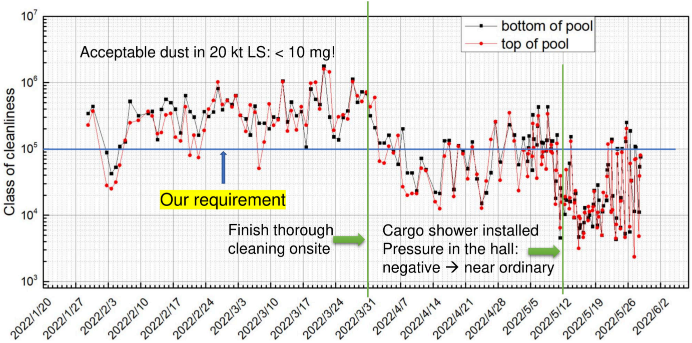
- Requirement: control energy scale, detector response non-uniformity and energy non-linearity
- 1D, 2D and 3D scan systems
- Many radioactive sources used
- 3” PMTs: correct any intrinsic 20” PMT non-linearity



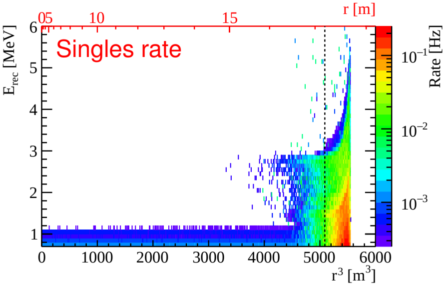


Radiopurity control

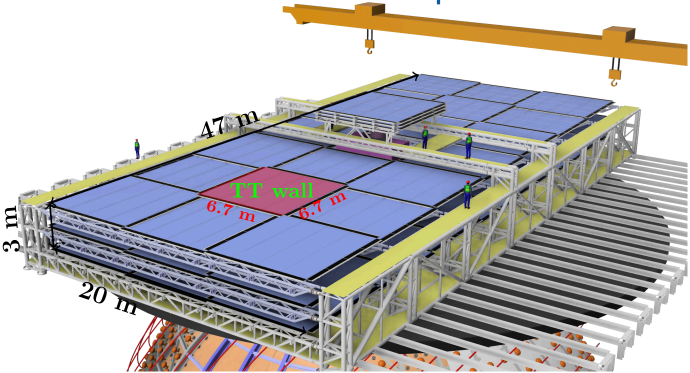
- LS recirculation impossible
  - Need to reach target radiopurity from start!
- Clean evironment during installation
  - Class 100k in WCD
  - Class 1k inside Acrylic Sphere!

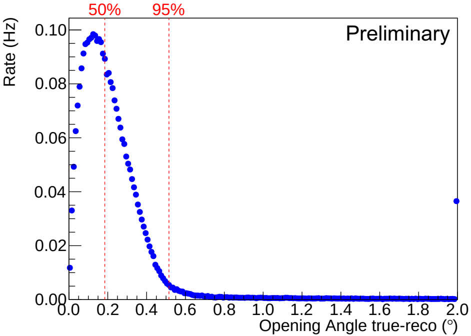


- Careful screening & handling of all materials
  - Overall 15% noise reduction from design
  - “Radioactivity control strategy for the JUNO detector,” JHEP **11** (2021), 102



The JUNO detector – Top Tracker





- Refurbished from OPERA experiment
- All plastic scintillator modules already in China
- New supporting structure designed
- Finishing up electronics development/firmware

- 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
- Study cosmogenic backgrounds

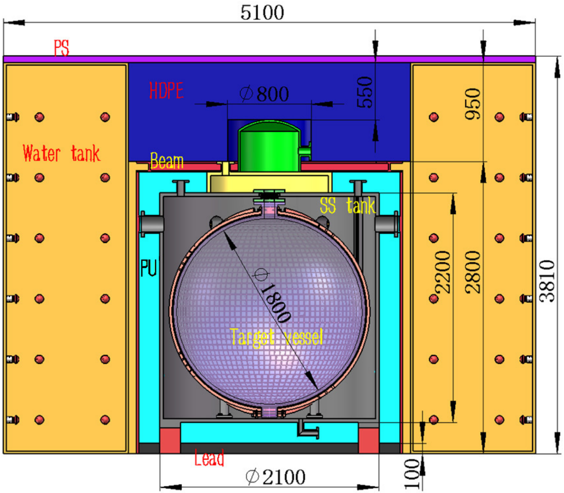
JUNO-TAO

"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:

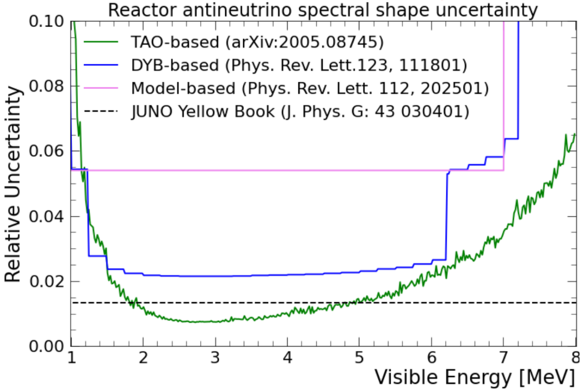
- 1 ton fiducial volume Gd-LS detector
  - 30 m from one of Taishan's 4.6 $\mathrm{GW_{th}}$ reactor core
  - 30$\times$ JUNO event rate
- 10 m^2 SiPM of 50% photon detection efficiency (PDE) operated at -50°C
  - >95% photo-coverage



JUNO-TAO – Physics potential

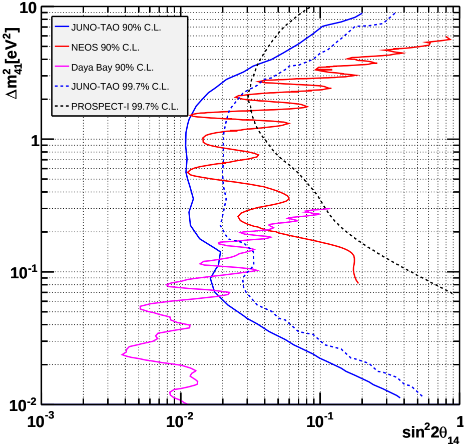
"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

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



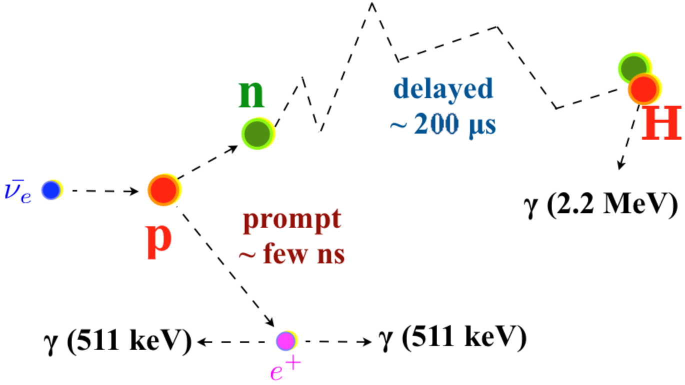
- TAO energy resolution <2% @ 1 MeV

Sterile Neutrino searches



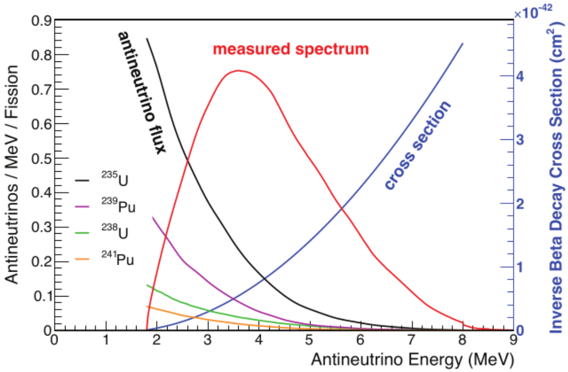
Measuring reactor $\bar{\nu}_e$: Inverse Beta Decay (IBD)

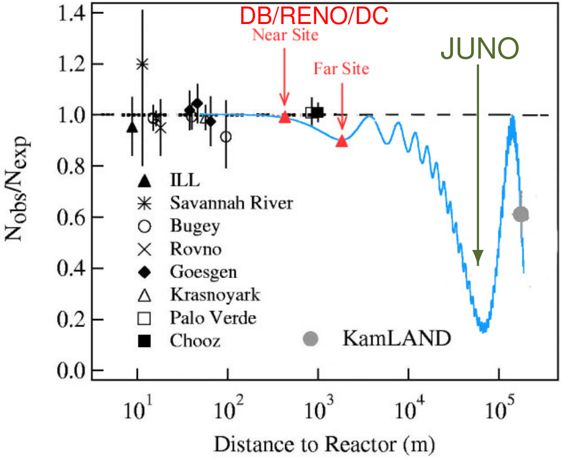
- Detected via IBD: $\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$
  - IBD used since discovery of $\bar{\nu}$
  - Prompt+delayed signal ⇒ large background suppression



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

Neutrino oscillations with Reactor Antineutrinos



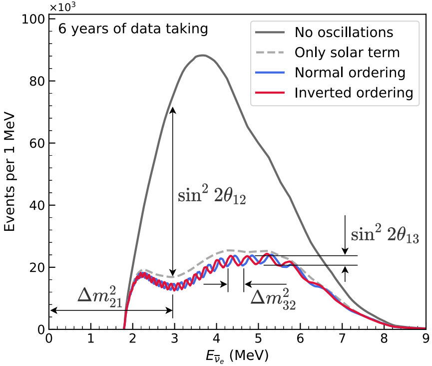


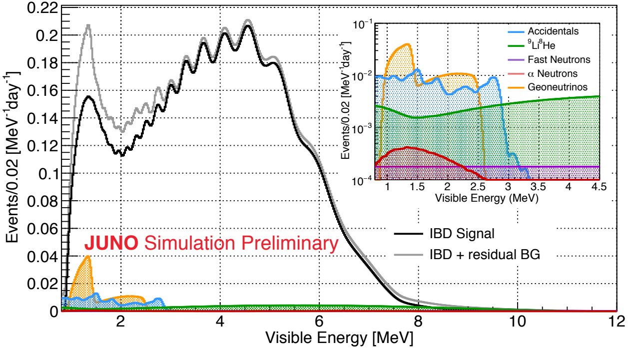
- Detected $\bar{\nu}_e$ energy 2–8 MeV
  - Only sensitive to $\bar{\nu}_e \to \bar{\nu}_e$

- 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

Figures from arXiv:2204.13249





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

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

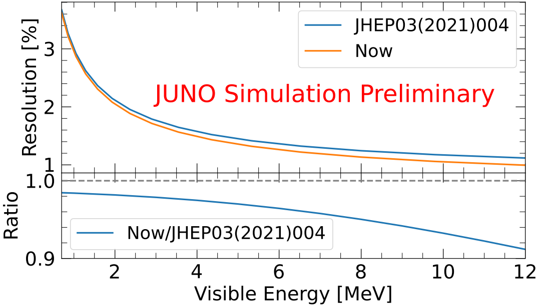
- Several updates since 2016
  - better PMT detection efficiency
  - lower radioactive background
  - 2 less reactor cores at Taishan
  - overburden reduced by ~50 m
  - improved algorithms for WCD
  - $\bar{\nu}_e$ spectrum from JUNO-TAO
  - . . .

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(α,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

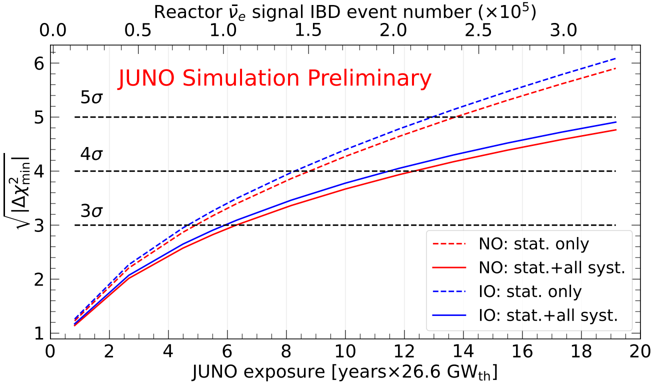
JUNO Simulation Preliminary	Resolution	Ref. / poster #: Neutrino 2022
Estimated with PE yield	3.0%	JHEP03(2021)004
20-inch PMT PDE (27%→30.1%)	-	Mass testing data
More realistic optical model	-	Poster #815 by Y. Wang
New detector geometries	-	Poster #184 by Z. Wu
Now	2.9%	Poster #519 by G. Huang



Note: not all analyses using new numbers yet!

Neutrino Mass Ordering

paper in preparation



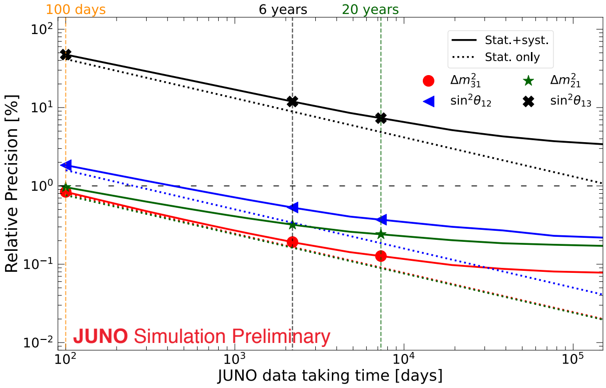
6 years	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

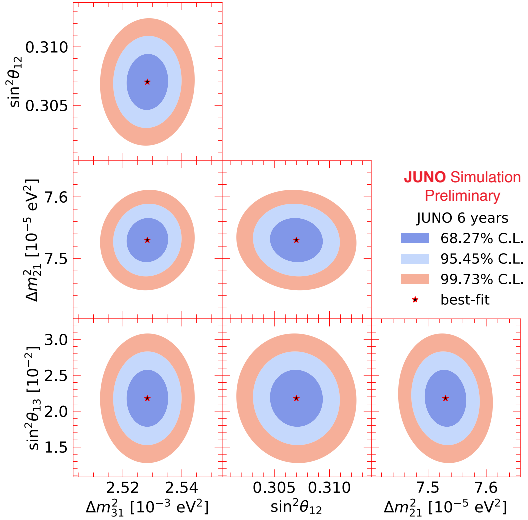
JUNO Simulation Preliminary

- reactor only: 3σ in $\sim$6 years × 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,” arXiv:2204.13249

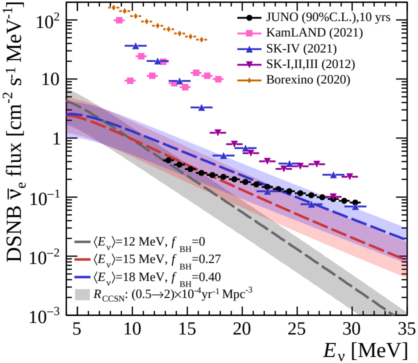


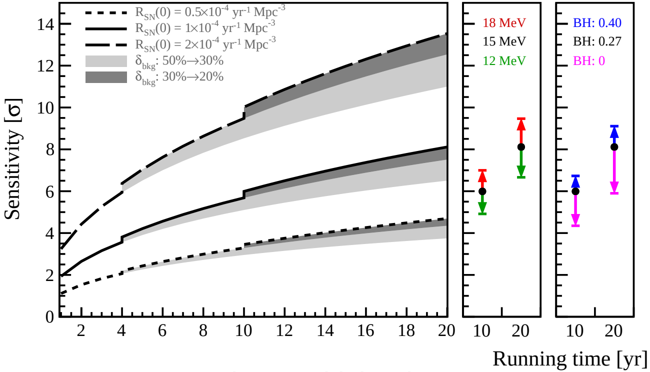


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

Diffuse Supernova Neutrino Background

“Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO,” arXiv:2205.08830



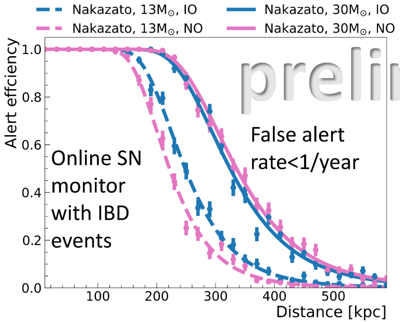


- For reference model:
  - @ 3 years → 3 σ sensitivity
  - @ 10 years → 5 σ sensitivity

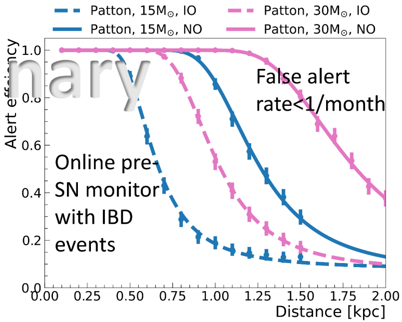
- Improvements in sensitivity due to:
  - Reduced expected background
  - Increase signal efficiency (50% → 80%) w/ PSD
  - Better DSNB model

Core Collapse Supernova Neutrinos

Seei poster #288 @ Neutrino 2022



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

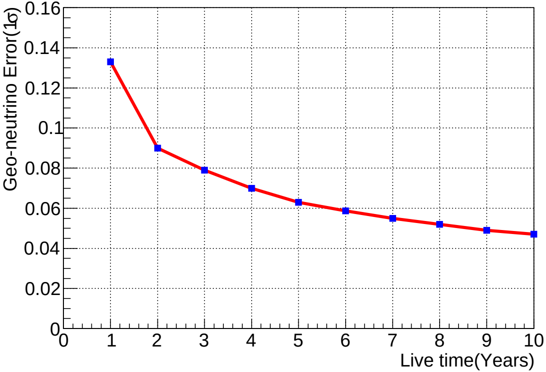


Alert efficiency for pre-SN of online monitor. False alert rate is smaller than 1/month.

- 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

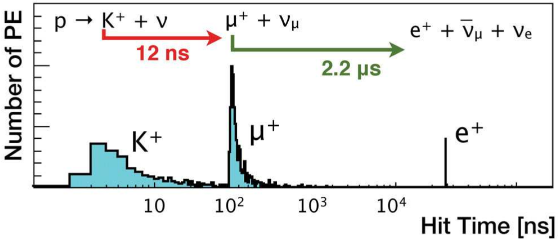
Other topics in JUNO

Geo $\bar{\nu}$



- Also potential to constrain Th/U ratio

Nucleon decay



- Triple coincidence signature from p $\rightarrow \bar{\nu} + K^{+}$
- 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 → clear path to 3% energy resolution
  - Strict radiopurity requirements

- Precision oscillation measurements with reactor $\bar{\nu}_e$ flux
  - First observation of several $\bar{\nu}_e$ oscillation peaks within single experiment
  - Measurement of NMO not relying on matter effects $\Rightarrow 3\sigma$ 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 ~300 kpc
  - ...

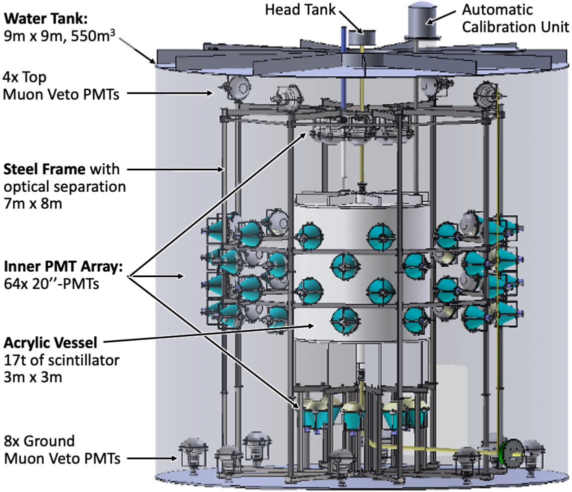
- Detector construction advancing rapidly
  - Civil construction finished in 2021
  - Detector construction to be finished in 2023 → looking forward to first data next year!

Backup

The JUNO detector – OSIRIS

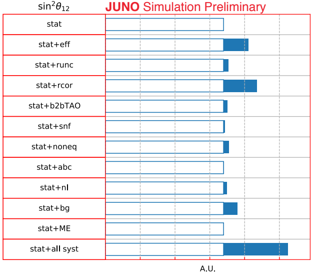
"The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS", Eur. Phys. J. C **81** (2021) no.11, 973

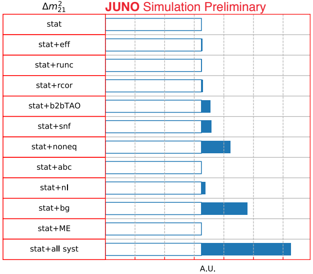
- Monitor LS radiopurity during before/during filling
- Few days: U/Th $\sim 10^{-15}$ g/g (IBD requirement)
- 2–3 weeks: U/Th $\sim 10^{-17}$ g/g (solar "ideal" case)
- Can also measure ^{14}C, ^{210}Po, ^{85}Kr
- Start commissioning in July

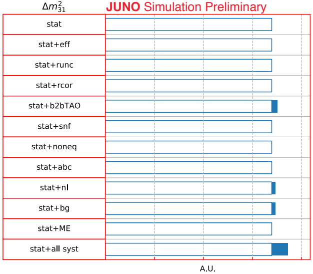


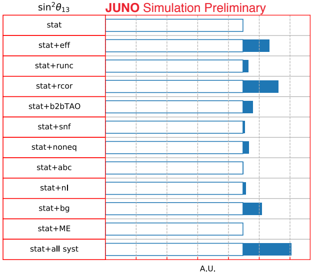
Precision Measurement of Neutrino Oscillation Parameters: σ

“Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO,” arXiv:2204.13249





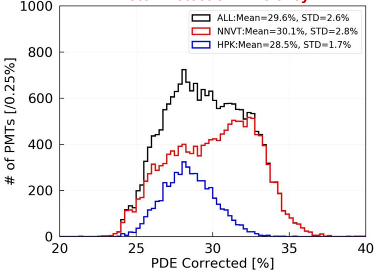




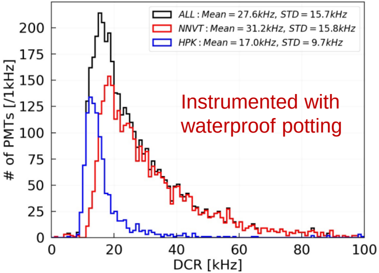
stat	Statistical (reactor $\bar{\nu}_e$ events only)
eff	Detection efficiency
runc	Reactor $\bar{\nu}_e$ flux reactor-uncorrelated
rcor	Reactor $\bar{\nu}_e$ flux reactor-correlated
b2bTAO	Reactor $\bar{\nu}_e$ spectrum shape based on TAO measurement
snf	$\bar{\nu}_e$ flux from spent nuclear fuel)
noneq	Non-equilibrium correction to reactor $\bar{\nu}_e$ flux
abc	Energy resolution (JHEP03,004(2021))
nl	Liquid scintillator non-linearity (NIMA940,230(2019))
bg	Backgrounds
ME	Earth’s matter density
all syst	All systematics above

Photomultiplier Tubes

Photon Detection Efficiency



Dark Counting Rate



Instrumented with waterproof potting

All PMTs produced, tested, and instrumented with waterproof potting

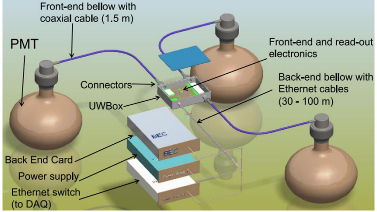
		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [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.

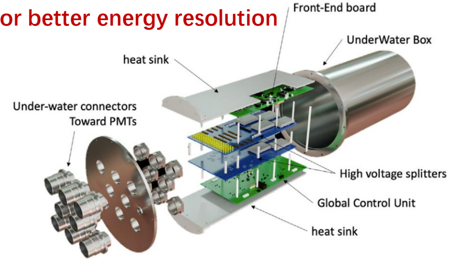
Electronics

Posters: #216, # 218, #270

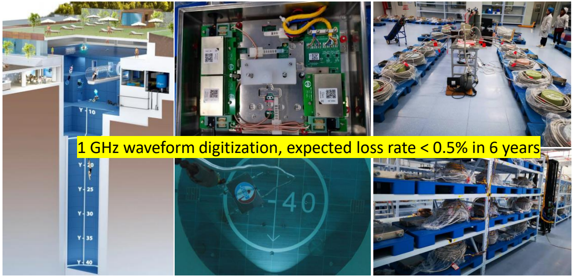
Underwater electronics to improve signal-to-noise ratio for better energy resolution



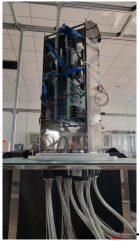
3 20-inch PMTs connected to one underwater box

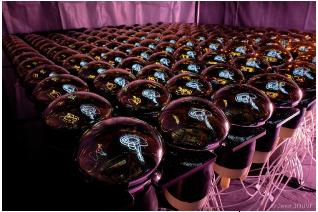


128 3-inch PMTs connected to one underwater box



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





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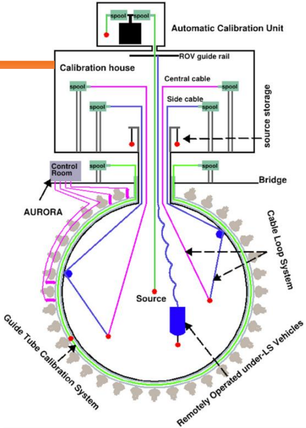
Electronics assembly ongoing

Calibration

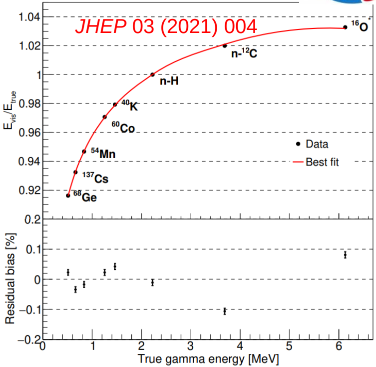
Poster: #293

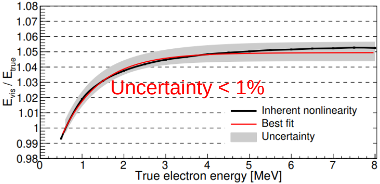
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

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

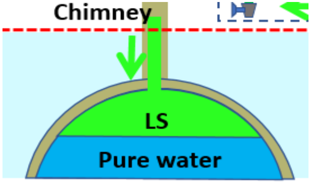
Liquid Scintillator Filling

✓ 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**

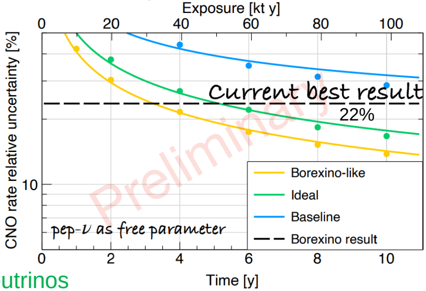


Neutrinos from Sun (E_{vis}<2MeV)

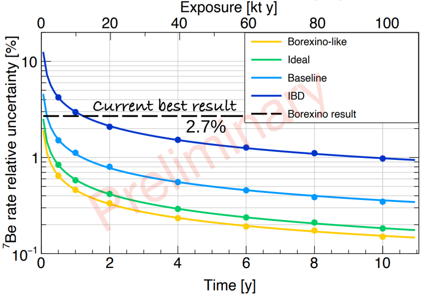
Poster: #327

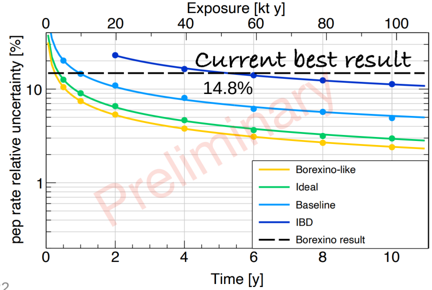
Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	$c\,[\frac{g}{g}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R\,[\frac{cpd}{kt}]$	2289	5000	3508	15047	12031	12211
Baseline	$c\,[\frac{g}{g}]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R\,[\frac{cpd}{kt}]$	229	500	351	1505	1203	1221
Ideal	$c\,[\frac{g}{g}]$	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	$R\,[\frac{cpd}{kt}]$	23	100	35	150	241	244
Borexino	$c\,[\frac{g}{g}]$	-	-	$<5.7 \times 10^{-19}$	$<9.4 \times 10^{-20}$	-	-
	$R\,[\frac{cpd}{kt}]$	4.2	100	1.4	2	115	446.9

NOTE: Contribution from pileup and reactor neutrinos found negligible in the ROI



Measure simultaneously Be7, pep and CNO solar neutrinos





Neutrinos from Sun (E_{vis}>2MeV)

Poster: #290

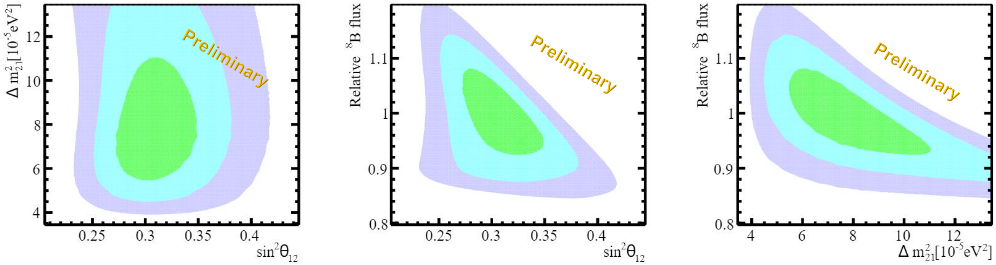
~0.2 kt ^{13}C in JUNO LS → enable observation of **B8 solar neutrino** CC and NC interactions on ^{13}C

Channels		Threshold [MeV]	Signal	Event numbers	
				[200 kt×yrs]	after cuts
CC	$\nu_e + ^{13}\mathrm{C} \rightarrow e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + ^{13}$N decay	3929	647
NC	$\nu_x + ^{13}\mathrm{C} \rightarrow \nu_x + ^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

→ Correlated events

Singles event

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



Update of energy resolution

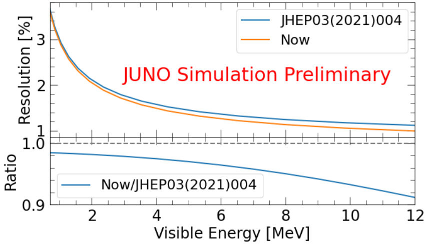
Change	**Light yield in detector center [PEs/MeV]**	**Energy resolution**	**Reference**
Previous estimation	1345	3.0% @1MeV	*JHEP03(2021)004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV** (Poster #519)	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		Poster #184
New PMT Optical Model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

Positron energy resolution is understood:

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

- **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

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

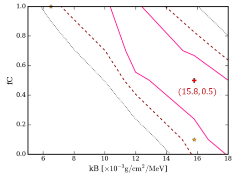
Photon statistics

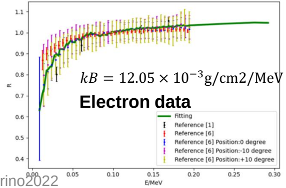
- **Annihilation-induced γs**
- **Dark noise**

- **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

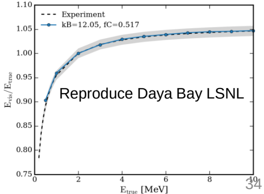
- **Firstly attempt to constrain kB & fC with Daya Bay LS non-linearity**
  - Strong correlation between kB and fC
- **Solved by combining a series of table-top measurements on scintillation quenching effect**
  - kB of LS is determined to be $12.05 \times 10^{-3}\mathrm{g/cm2/MeV}$
- **Re-constrain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





$kB = 12.05 \times 10^{-3}\mathrm{g/cm2/MeV}$

Electron data

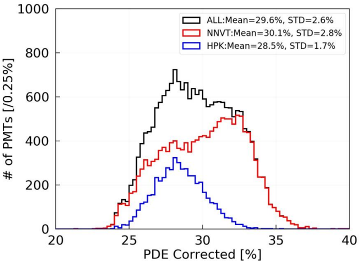


Reproduce Daya Bay LSNL

Light yield evolution

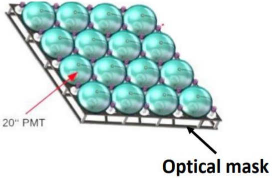
PMT PDE

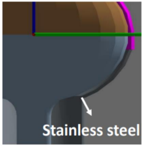
- Averaged PDE:27.0%→30.1%
- 27.0% is based on the original requirement of **QE~30%, CE~90%**
- 30.1% is the selected mean PDE, from **PMT mass testing system**

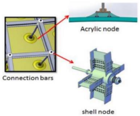


arXiv:2205.08629

New Geometries





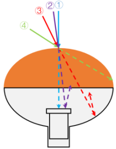


- **Reflections** on them are taken into consideration
- Yield 2.7% more photons

New PMT Optical Model

Optical Processes in PMT

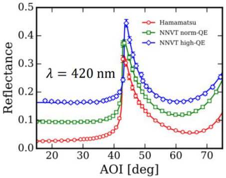
- Reflection on photocathode
- PDE angular response
- Multiple reflections inside PMT

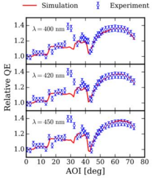


◆ Multilayer thin film theory

◆ Experimental tests

◆ GEANT4 simulation





Poster #815