Status and (Astro)Physics of JUNO

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On behalf of the JUNO collaboration

Symposium on Frontiers of Underground Physics
Chengdu, China

Jiangmen Underground Neutrino Observatory

Jiangmen Underground Neutrino Observatory (JUNO)

Approved in Feb. 2013. Ground-breaking in 2015.
Construction to be completed in 2023.

JUNO Physics and Detector,
arXiv:2104.02565

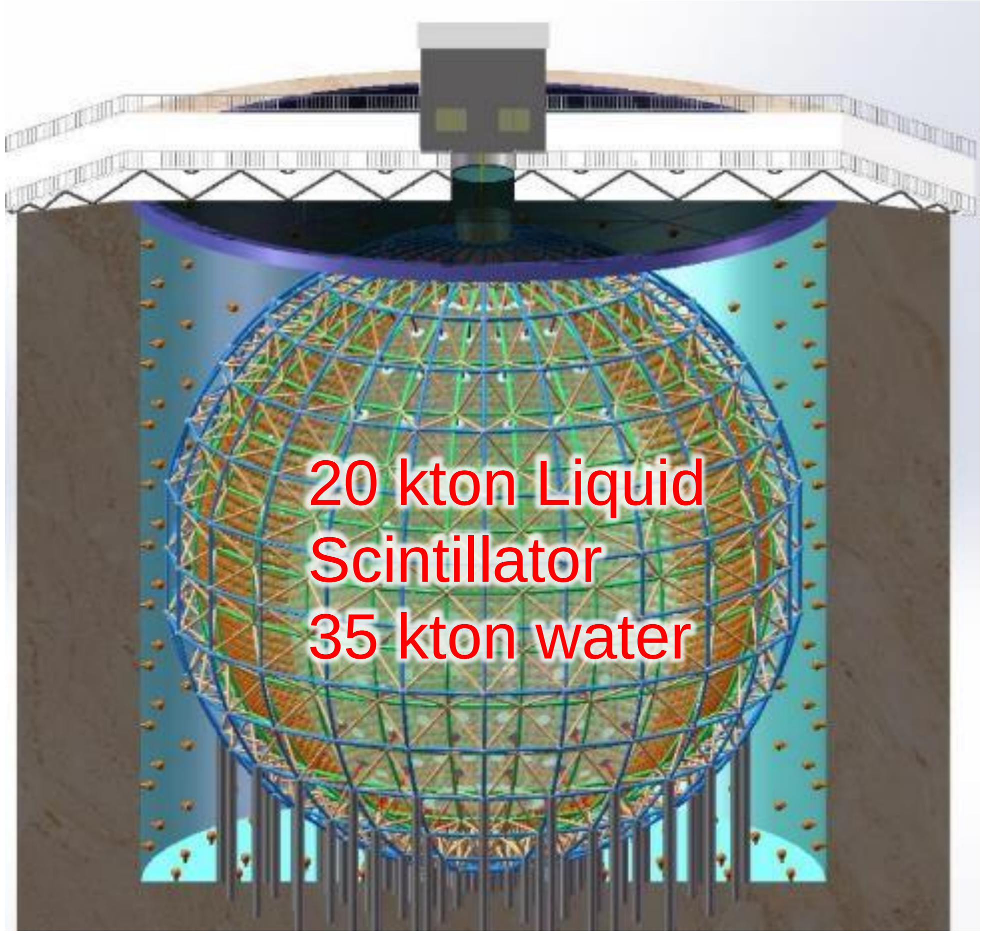
A multiple-purpose neutrino experiment with rich physics programs:

- **Reactor ν:** Oscillation, spectrum
- **Atmospheric ν**
- **Solar ν**
- **CCSN**
- **DSNB** (aka supernova relic ν)
- **Dark matter**
- **geo-ν** (backup)
- **Nucleon decay** (backup)
- **0νββ potential** (future upgrade, **Gaosong's talk**)

Acrylic Sphere:
ID: 35.4m
Thickness:12cm

SS Lattice:
ID: 40.1m
OD: 41.1m
17612 20-in PMTs
25600 3-in PMTs

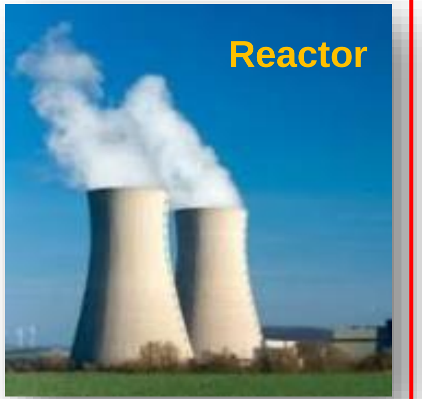
Water pool:
ID: 43.5m
Height: 44m
Depth: 43.5m
2400 20-in PMTs



Jiangmen Underground Neutrino Observatory

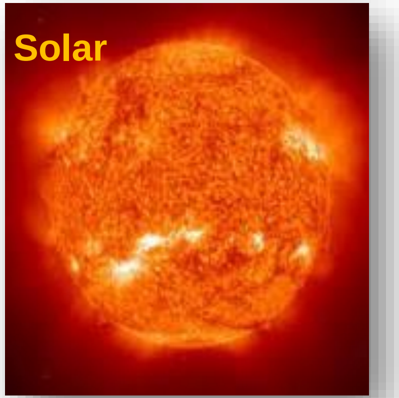
A multi-purpose observatory

Mass Ordering



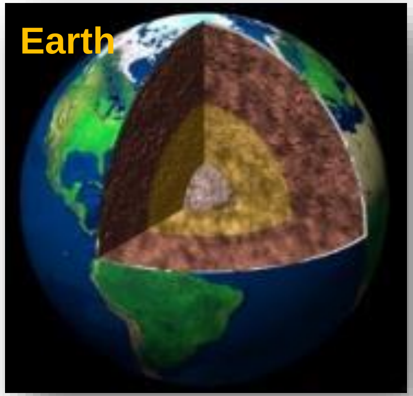
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

JUNO Collaboration

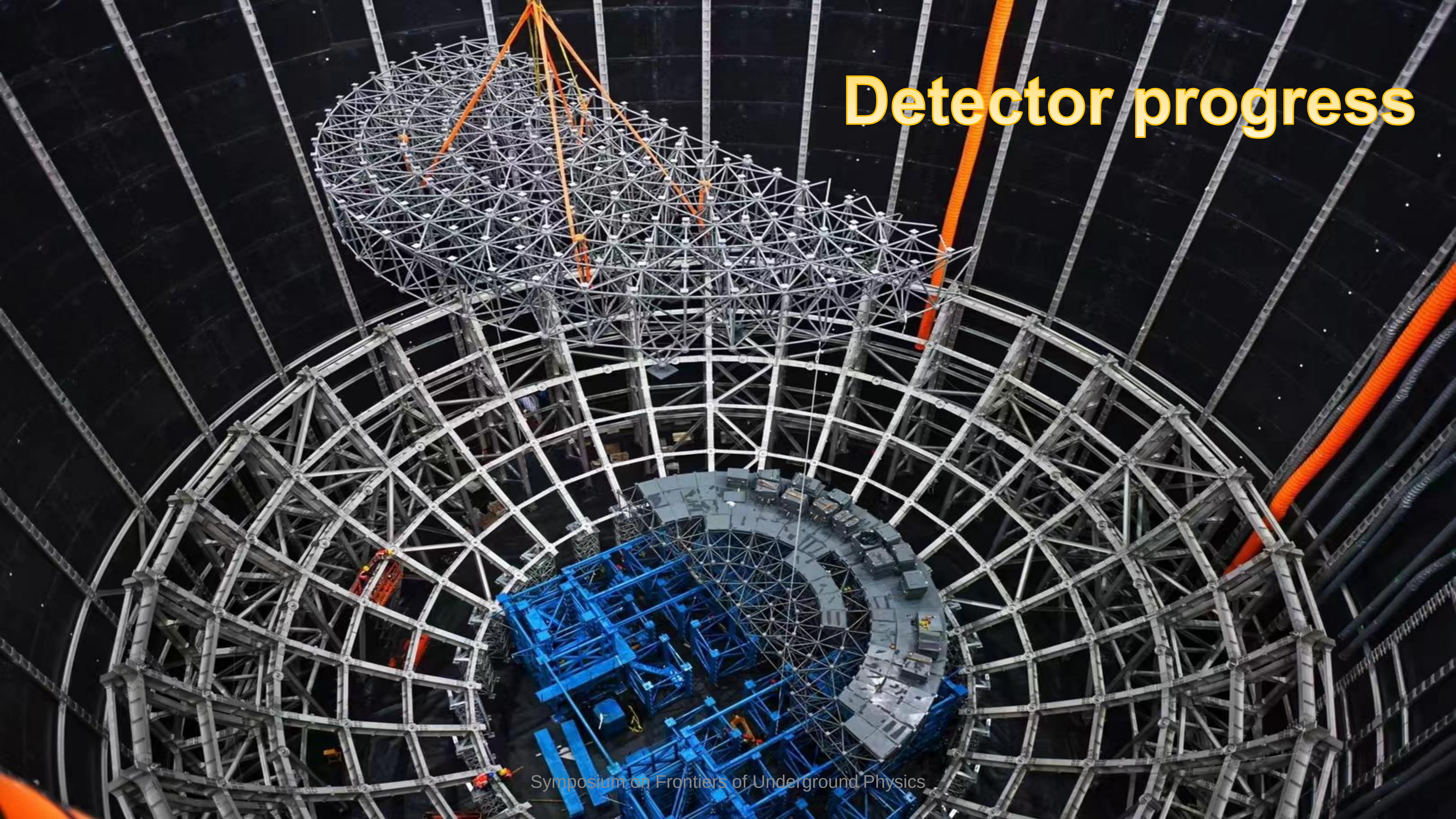
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of 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	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		

= 74 institutes

> 700 collaborators

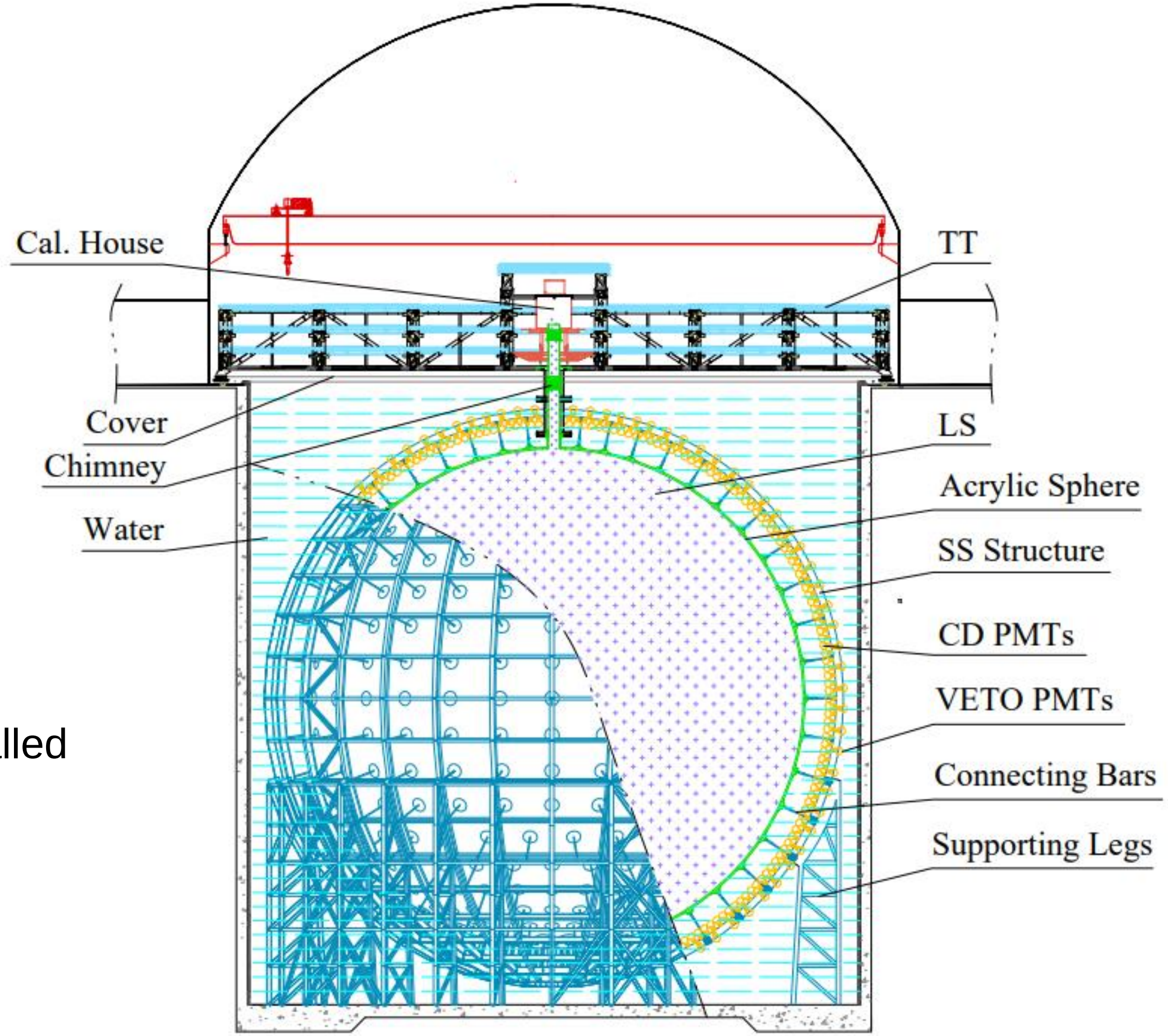
+Observers: University of Liverpool

Detector progress



Detector construction status

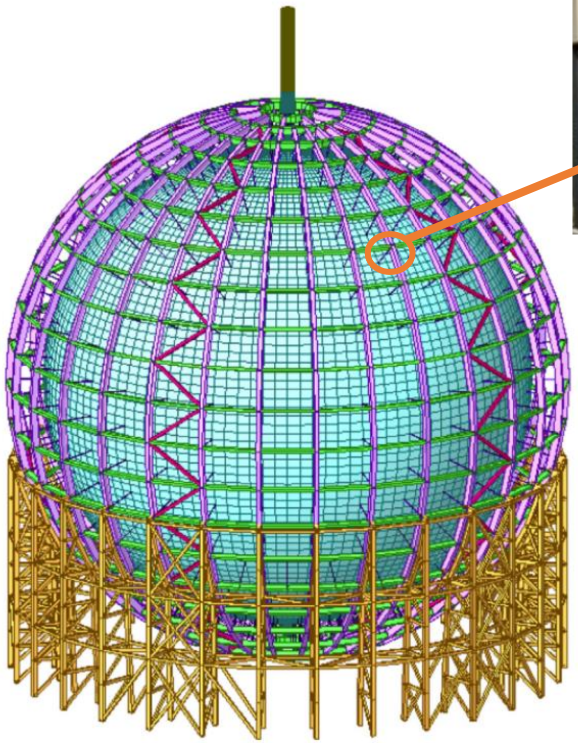
- **Acrylic panels**
  - All the panels are ready for shipping
  - More than half sphere is finished
- **Stainless Steel structure**
  - Finished in June 2022
- **20012 20'' PMTs + 25600 3'' PMTs**
  - Production and performance test done
  - ~6000 LPMT and ~6000 SPMT have been installed
- **Liquid scintillator (20 kt)**
  - Purification plants finished onsite construction
  - Under commissioning now

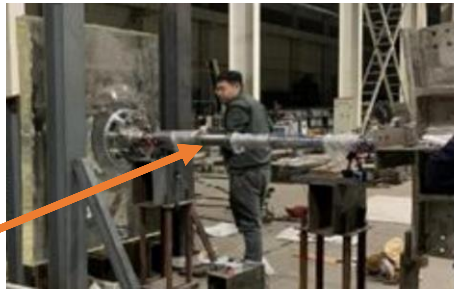


Central detector (SS structure)

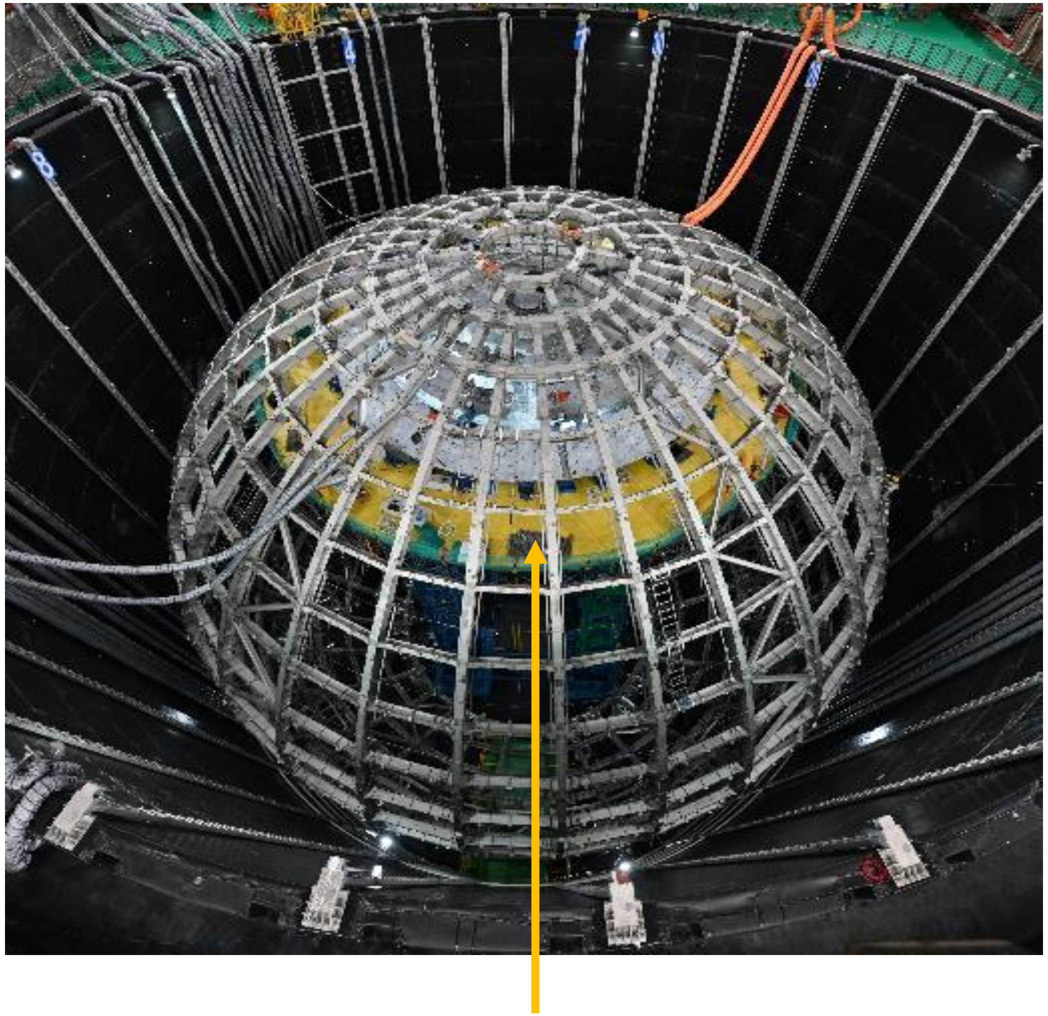
Acrylic vessel is supported by D = 40.1 m stainless steel structure via 590 Connecting Bars

Assembly precision: < 3 mm for each grid





The SS structure has been finished in June 2022



The platform to install the acrylic vessel

Central detector (acrylic vessel)

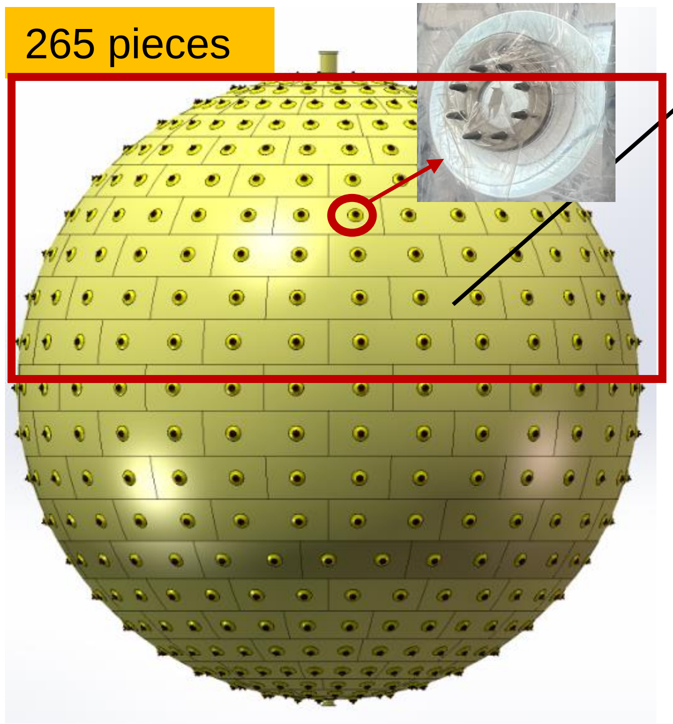
LS container:

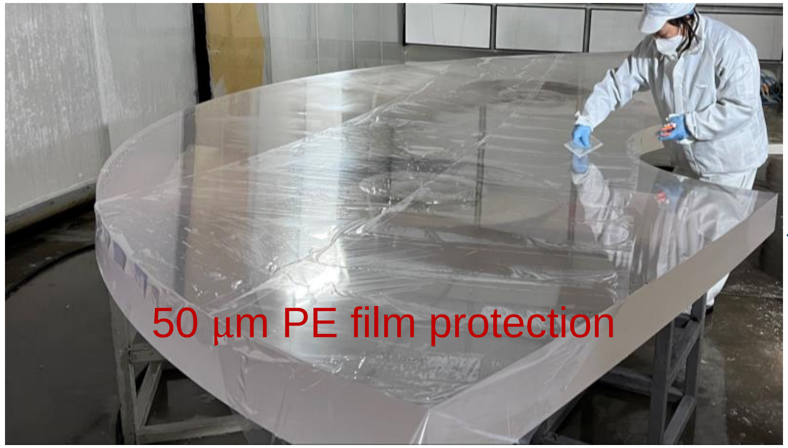
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ water

Radiopurity: U/Th/K < 1 ppt





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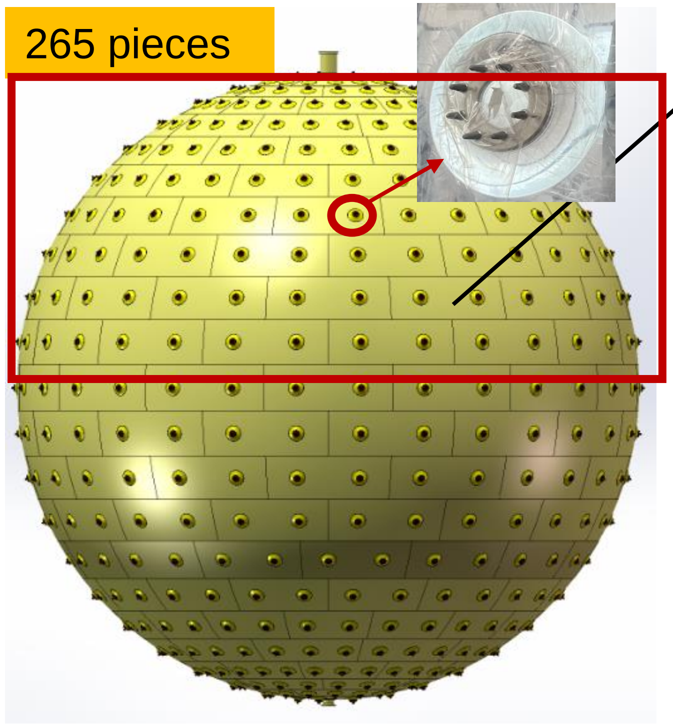
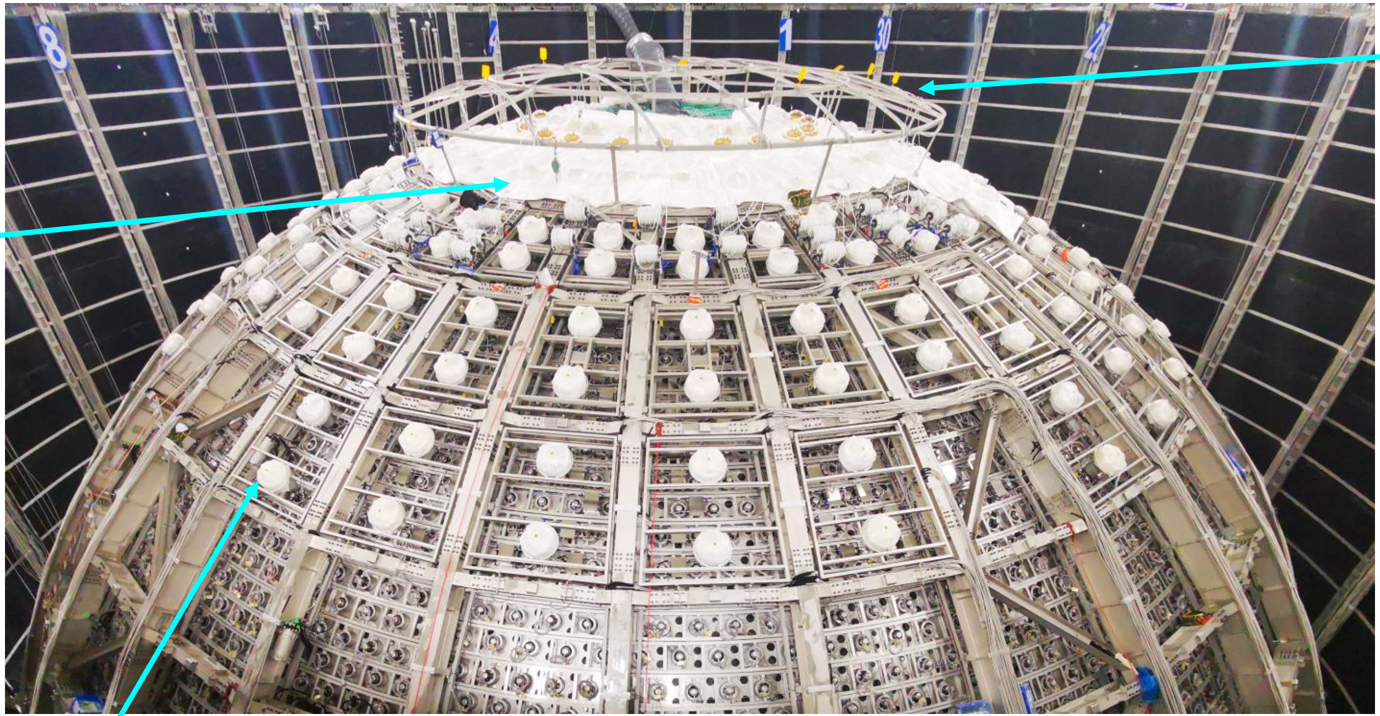


More than half acrylic sphere was finished!

Veto detector (Water Cherenkov)

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

Tyvek reflective film installation started



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

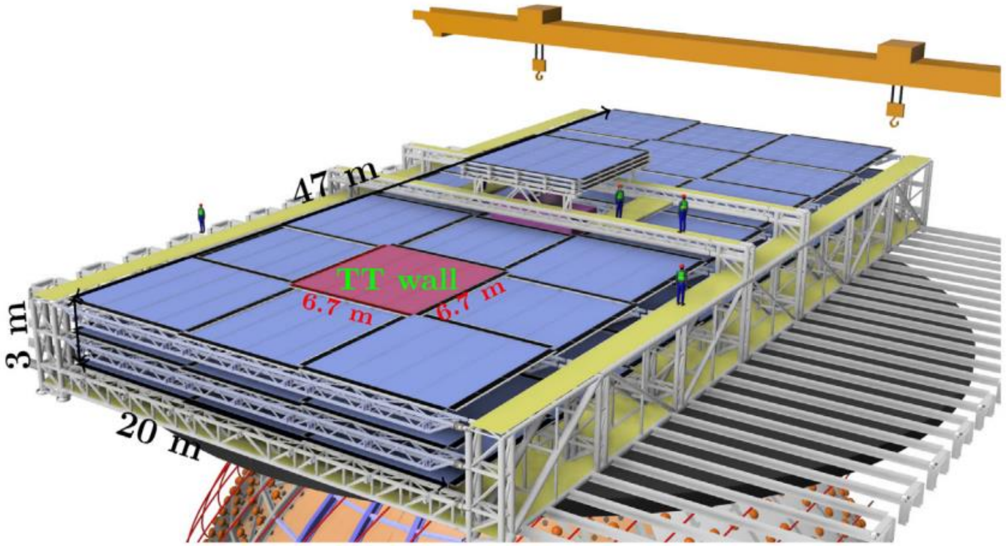
200 veto PMTs installed (~10% of PMT)

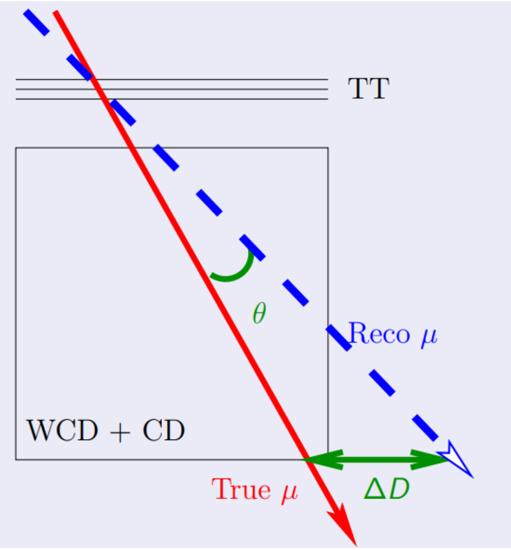
Water system almost ready for commissioning

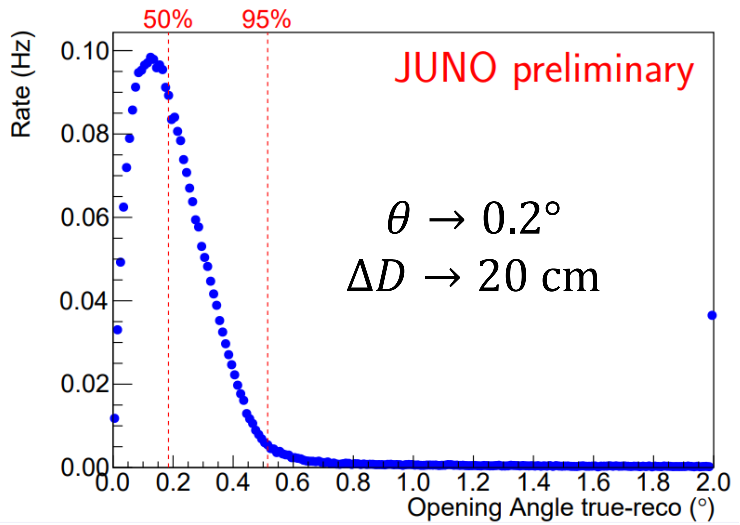
35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

- ✓ 2400 20-inch MCP PMTs, detection efficiency of cosmic muons larger than 99.5%
- ✓ Keep the temperature uniformity 21℃±1℃
- ✓ Quality: ^{222}Rn < 10 mBq/m^3, attenuation length 30~40 m

Veto detector (Top Tracker)







Plastic scintillator from the OPERA experiment *(NIM.A 1057 (2023) 168680)*

- About 50% coverage on the top, three layers to reduce accidental coincidence
- All scintillator panels arrived on site in 2019
- Provide control muon samples to validate the track reconstruction and study cosmogenic backgrounds

Status:

- The TT scintillator detector is onsite.
- The TT support bridge is ready for production.

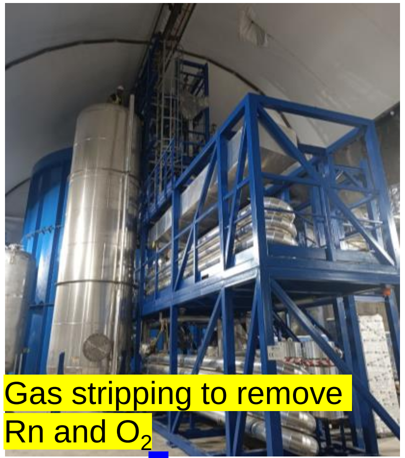
Liquid scintillator (20 kton)

NIM.A 908 (2021) 164823

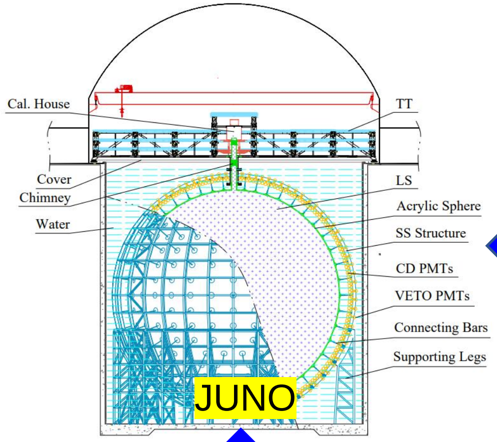
Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

All LS related systems finished assembly, commissioning ongoing

SS pipes to underground



15%



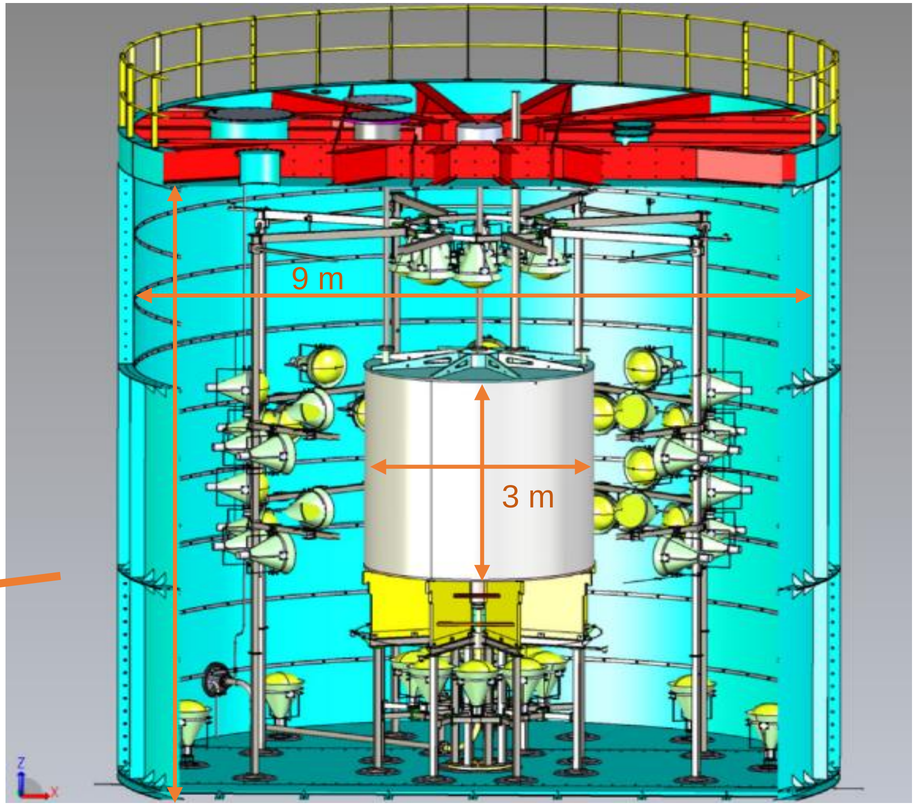
85%

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

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

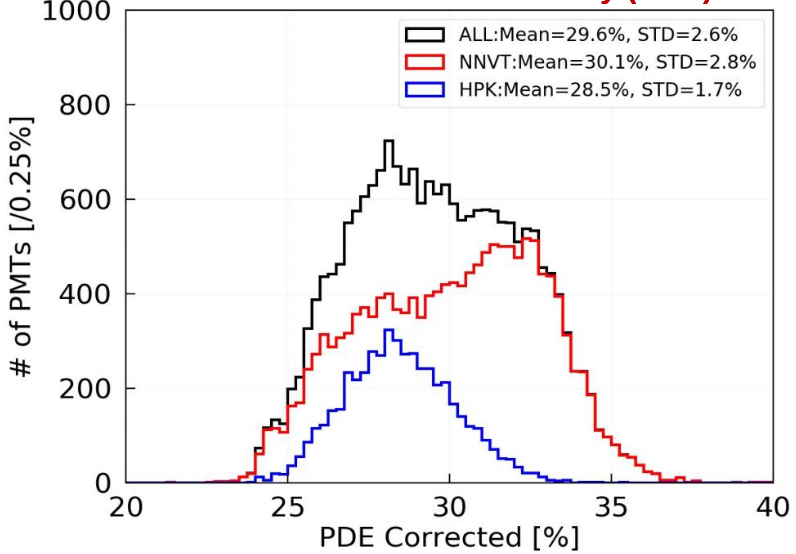


Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *arXiv: 2109.10782*

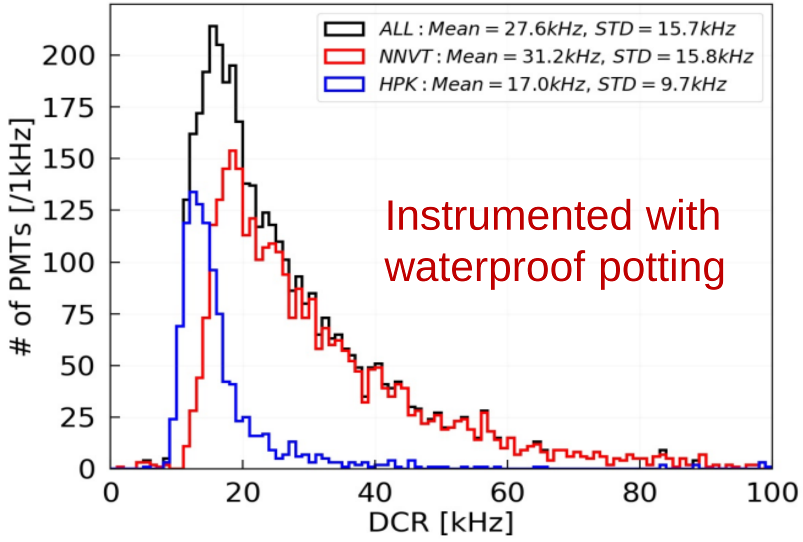
- ✓ A precision measurement of the flux of solar *pp* neutrinos on the few-percent level

Photomultiplier Tubes

Photon Detection Efficiency (PDE)



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.

Photomultiplier Tubes

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

Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm** **w/ protection cover** (JINST 18 (2023) 02, P02013)

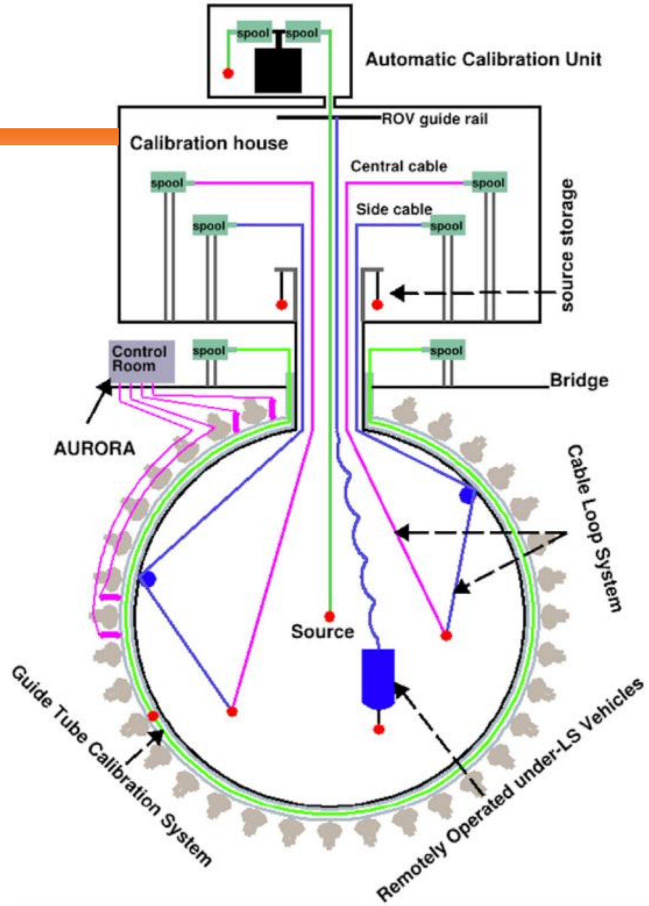
Eur.Phys.J.C 82 (2022) 12

~5800 (CD) + ~200 (veto) LPMT and ~6000 SPMT have been installed

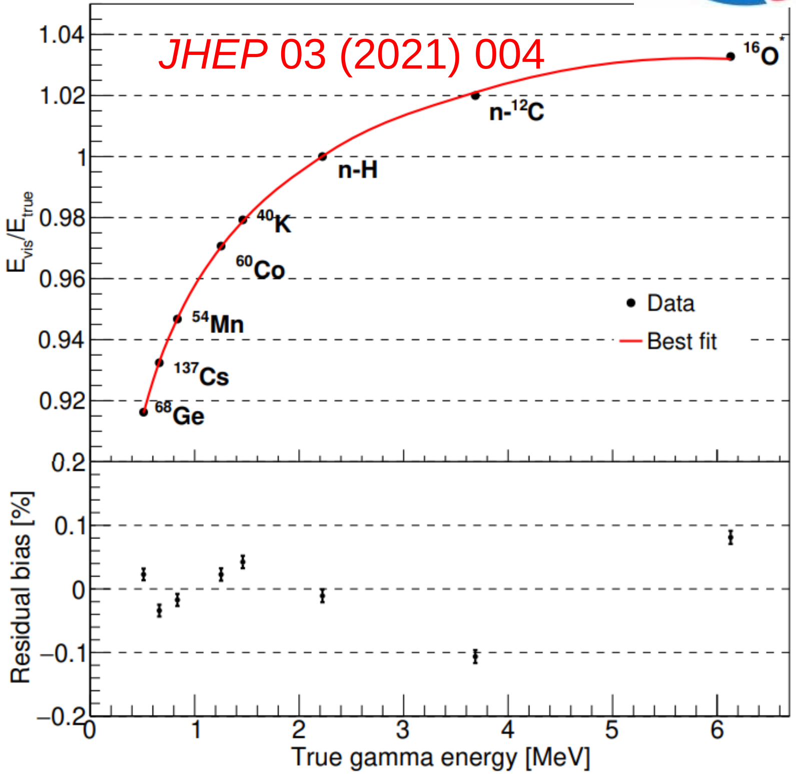
Calibration

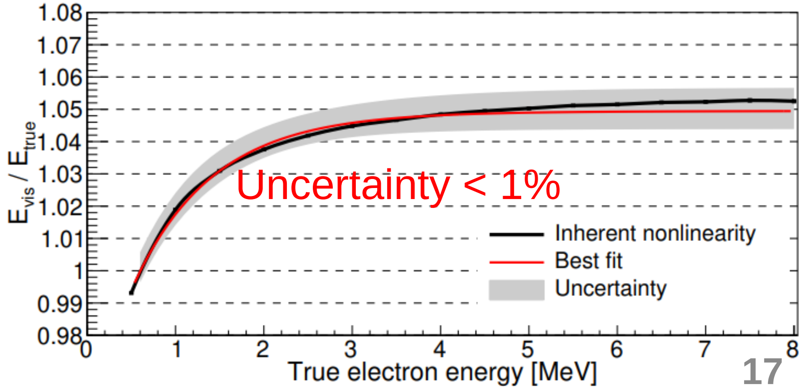
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system finished prototype test



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

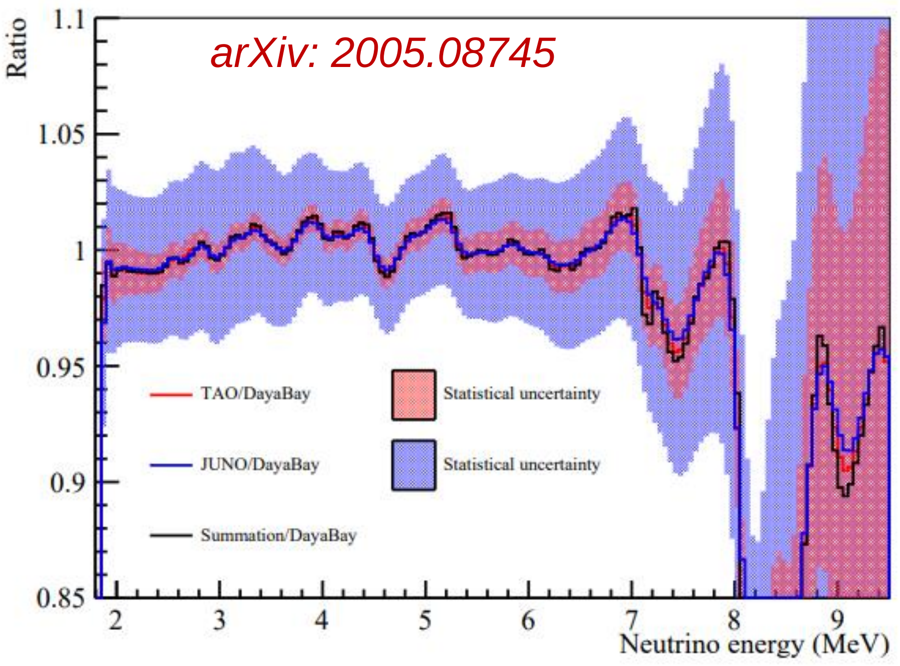




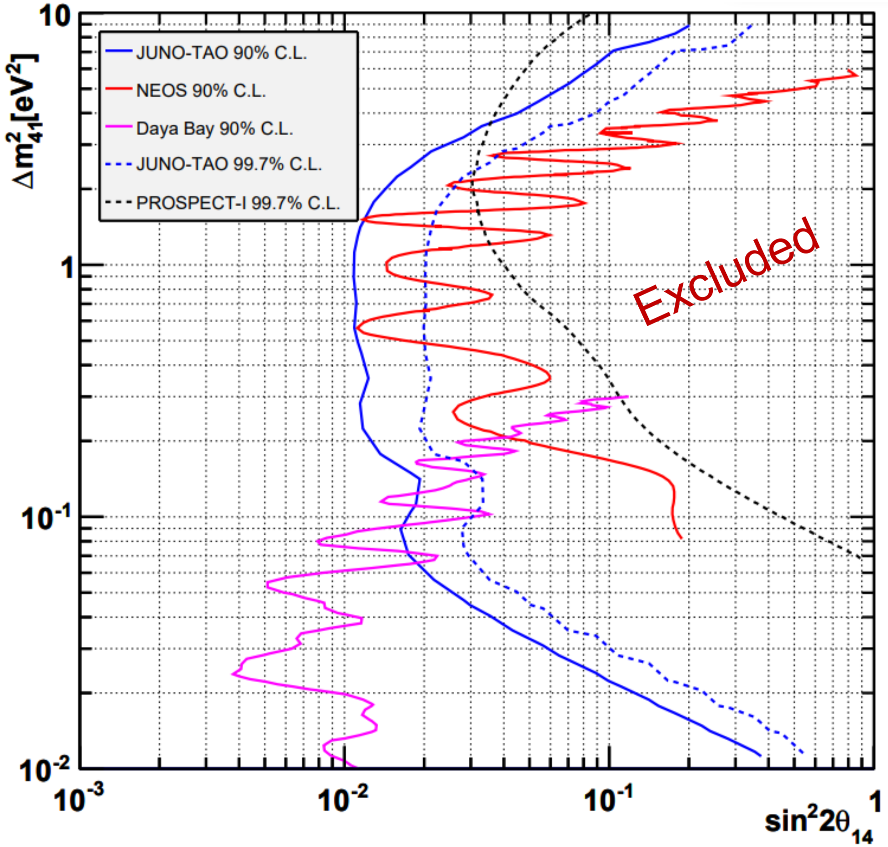
Taishan Antineutrino Observatory (TAO)

Goals:

1. Measure the reactor antineutrino spectrum with unprecedented energy resolution and see its fine structure for the first time.
2. Provide a reference spectrum for JUNO, other experiments, and nuclear databases
3. Search for light sterile neutrinos
4. Make improved measurements of isotopic yields & spectra



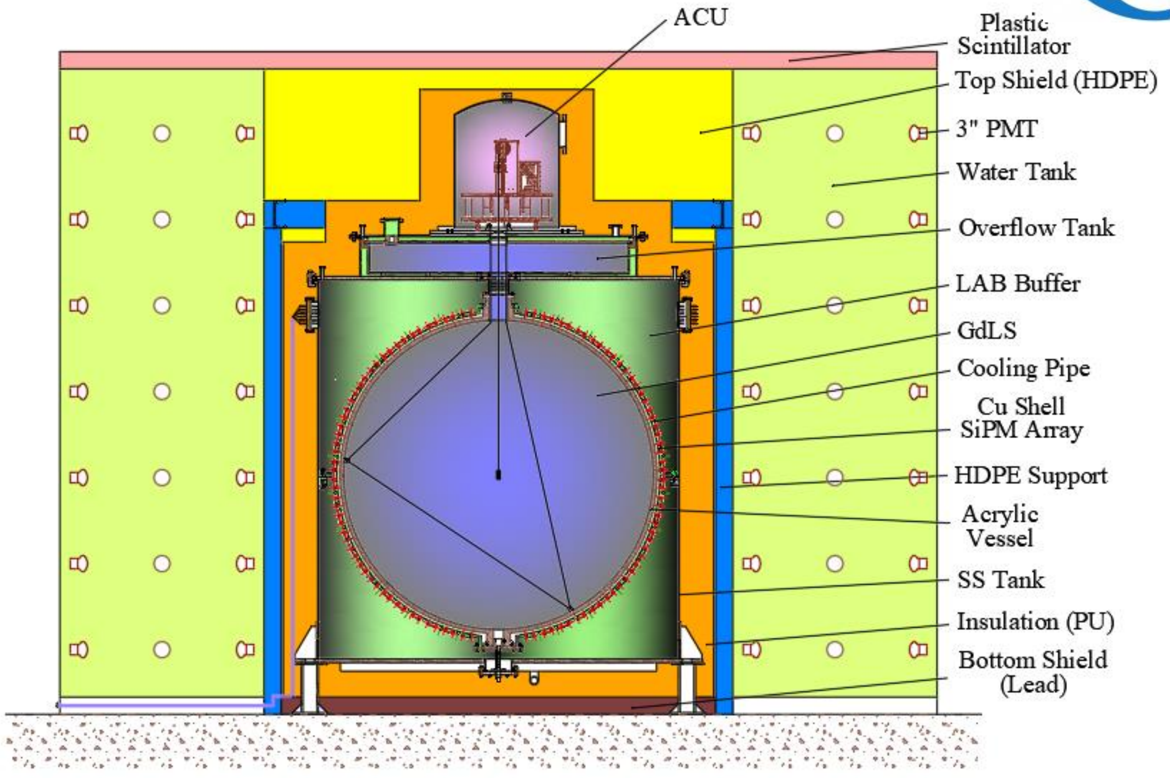
Constrain the fine structure in [2.5,6] MeV to < 1%



TAO sensitive in region 10^{-2} eV^2 < Δm^2_{41} < 10eV^2

Taishan Antineutrino Observatory (TAO)

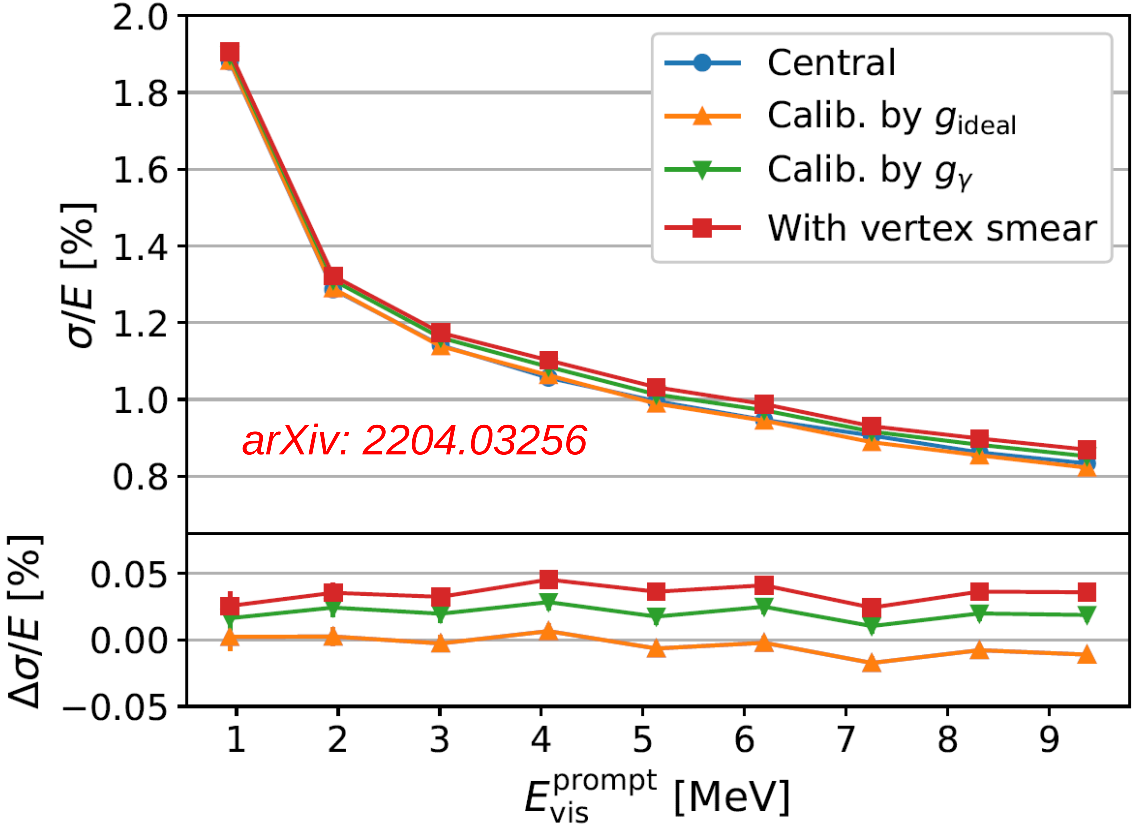
2.8 ton GdLS detector	*arXiv: 2005.08745*
Baseline	~30 m
Reactor Thermal Power	4.6 GW
Light Collection	SiPM
Photon Detection Efficiency	>50%
Working Temperature	-50 ℃
Dark Count Rate [Hz/mm^2]	~100
Coverage	~94%
Detected Light Level [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV

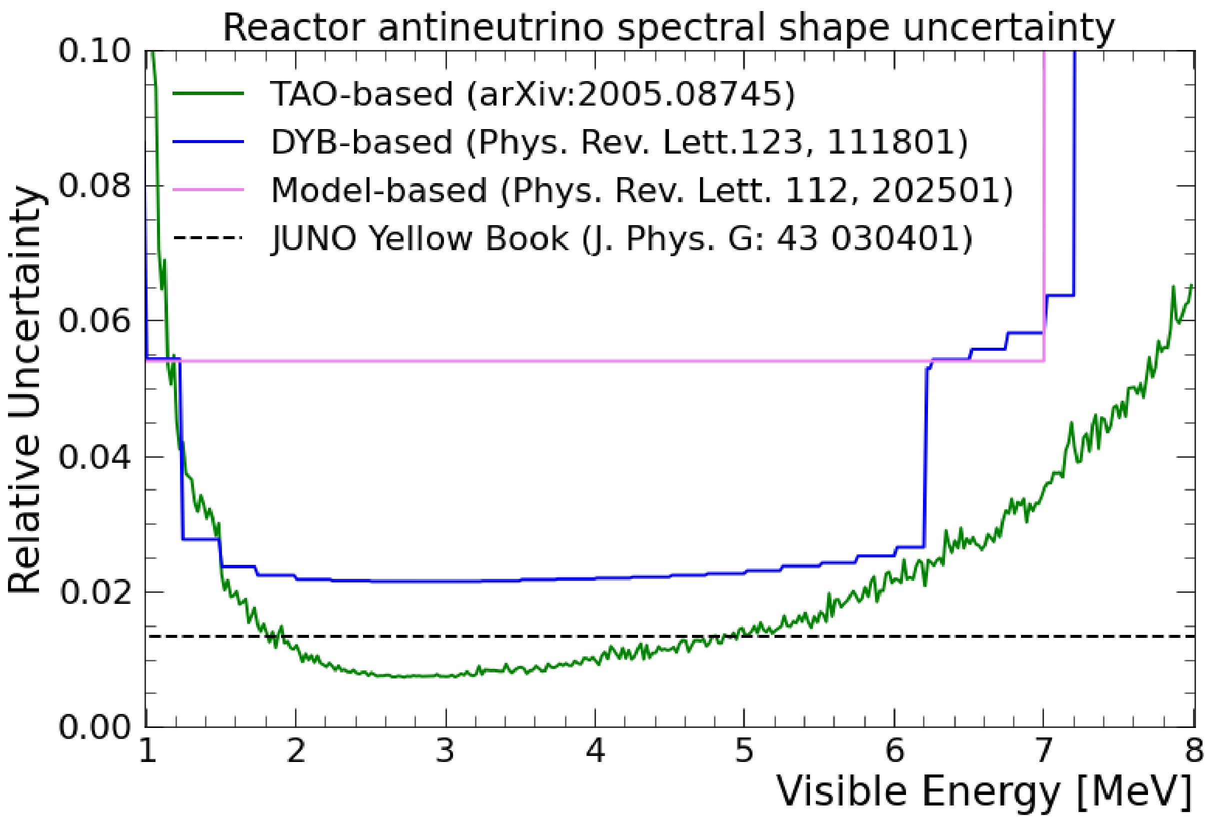


- ✓ SiPM is used to achieve high light yield with ~94% coverage
  → 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

➢ **1:1 Prototype ongoing at IHEP**
➢ **Data-taking by 2024**

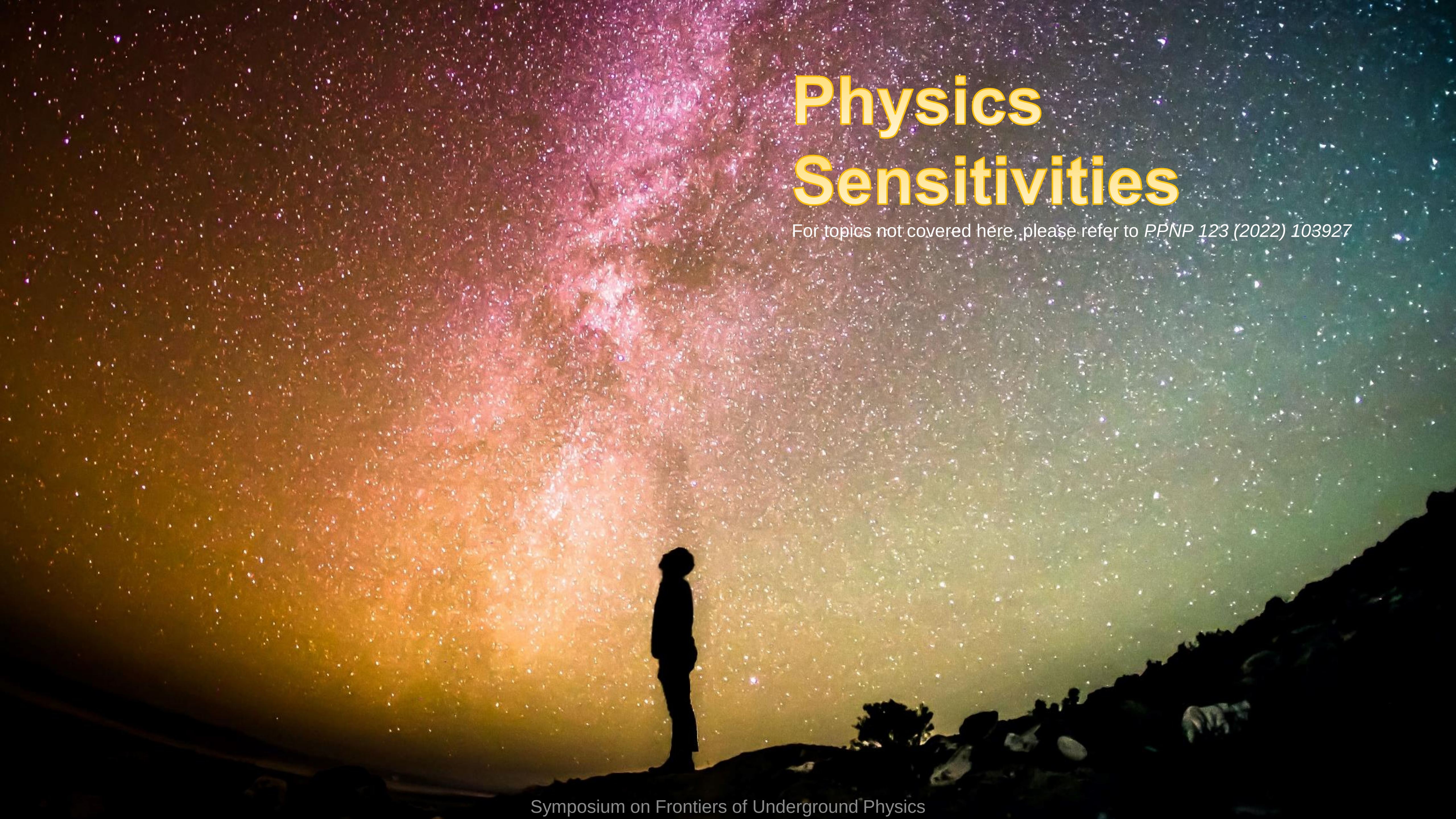
Reactor Antineutrino Spectrum from TAO





1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, absorption of scintillation very small
3. Gd-LS works at -50℃, increase the photon yield

- ✓ Unprecedented energy resolution < 2% @ 1 MeV
- ✓ Shape uncertainty close to the assumption in the JUNO Physics Book (*J. Phys. G43:030401 (2016)*)



Physics Sensitivities

For topics not covered here, please refer to *PPNP 123 (2022) 103927*

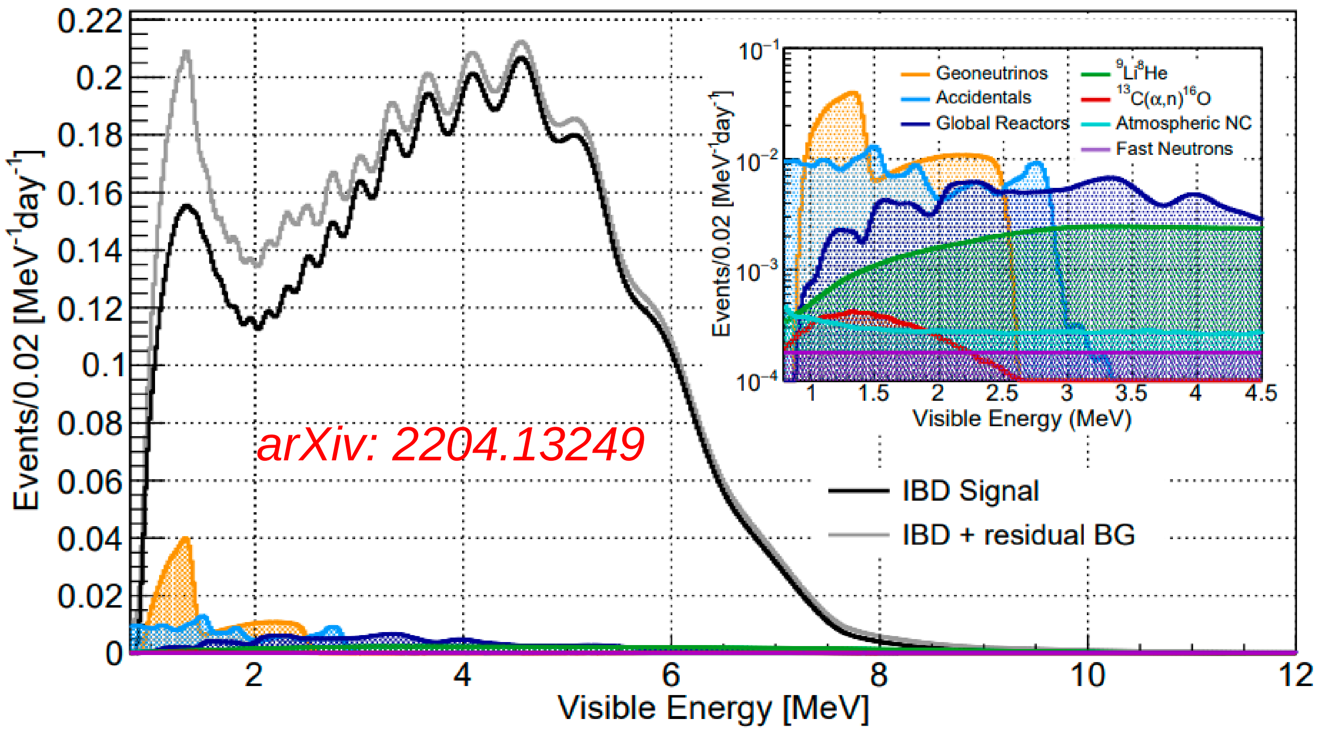
Reactor Antineutrino Oscillation & Detection

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

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

Inverse beta decay reaction

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



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%**

JUNO physics book *(J. Phys. G43:030401(2016))* ➔ **updated values**

- ☹ 2 fewer reactor cores in Taishan
- ☺ Better muon veto strategy
- ☺ Improved energy resolution: 3.0% @1MeV ➔ 2.9% @1MeV
- ☺ Signal and backgrounds now assessed with full JUNO simulation
- ☹ Slight less overburden
- ☺ Lower radioactivity background based on latest measurements on material radiopurities

Update of energy resolution

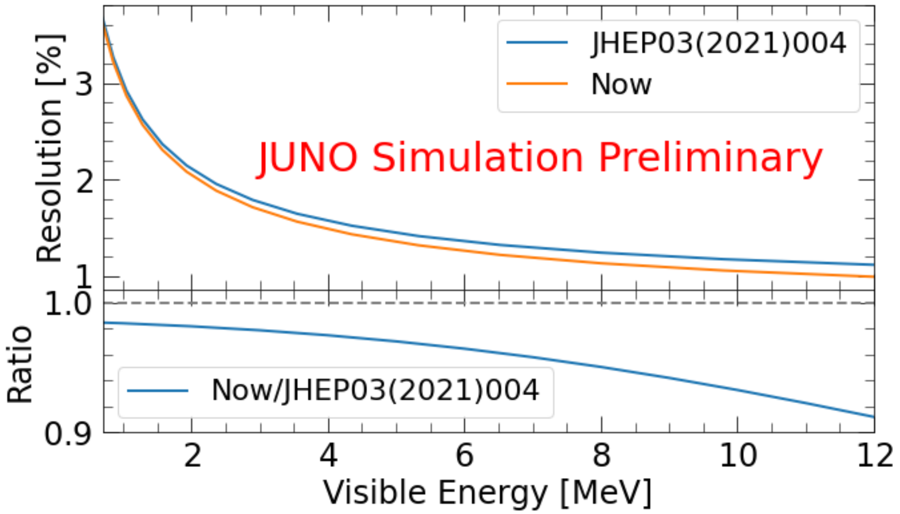
Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	JHEP03(2021)004
Photon Detection Efficiency (**27%→30%**)	**+11%↑**	**2.9% @ 1MeV**	arXiv: 2205.08629
New Central Detector Geometries	**+3%↑**		
New PMT Optical Model	**+8%↑**		EPJC 82 329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

Positron energy resolution is understood:

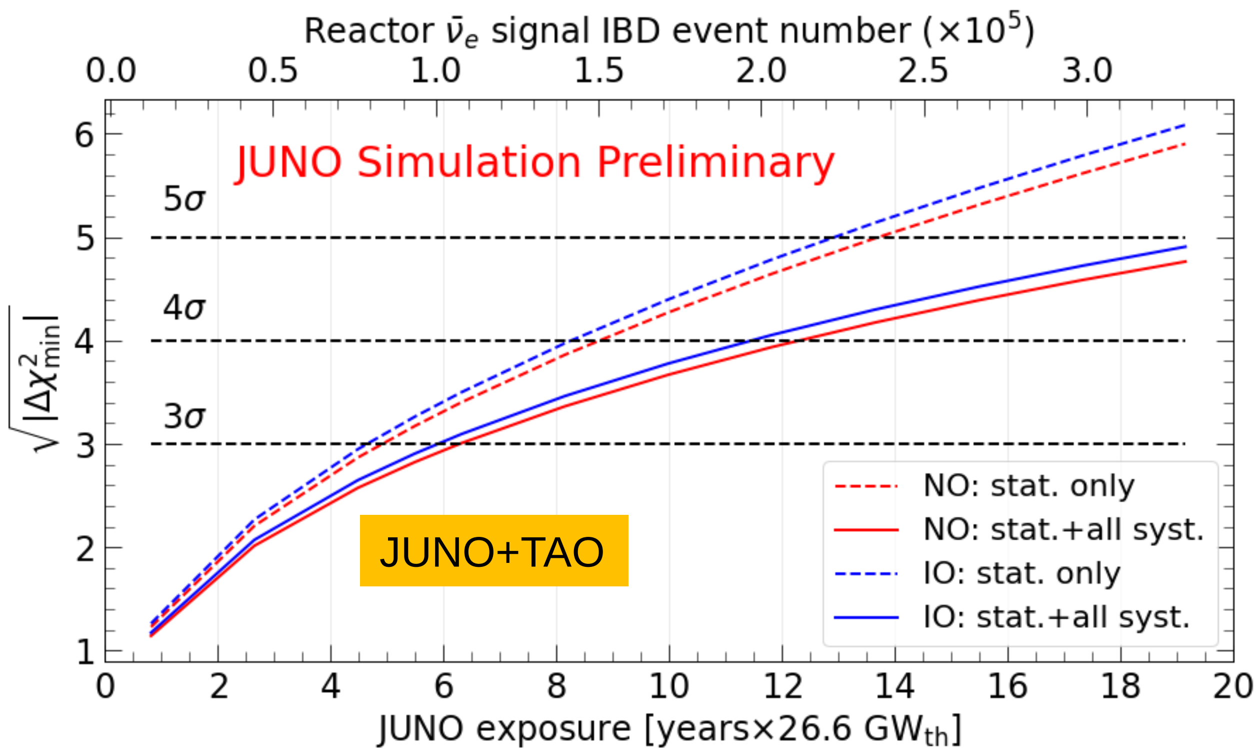
$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}$$

- **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**



Neutrino Mass Ordering



	Design (J. Phys. G 43:030401 (2016))	Now (2022)
Thermal Power	36 GW_{th}	**26.6 GW_{th} (26%↓)**
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	**4 Hz (33%↑)**
Muon veto efficiency	83%	**93% (12%↑)**
Signal rate	60 /day	**47.1 /day (22%↓)**
Backgrounds	3.75 /day	**4.11 /day (10%↑)**
Energy resolution	3% @ 1 MeV	**2.9% @ 1 MeV (3%↑)**
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

JUNO sensitivity on NMO: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

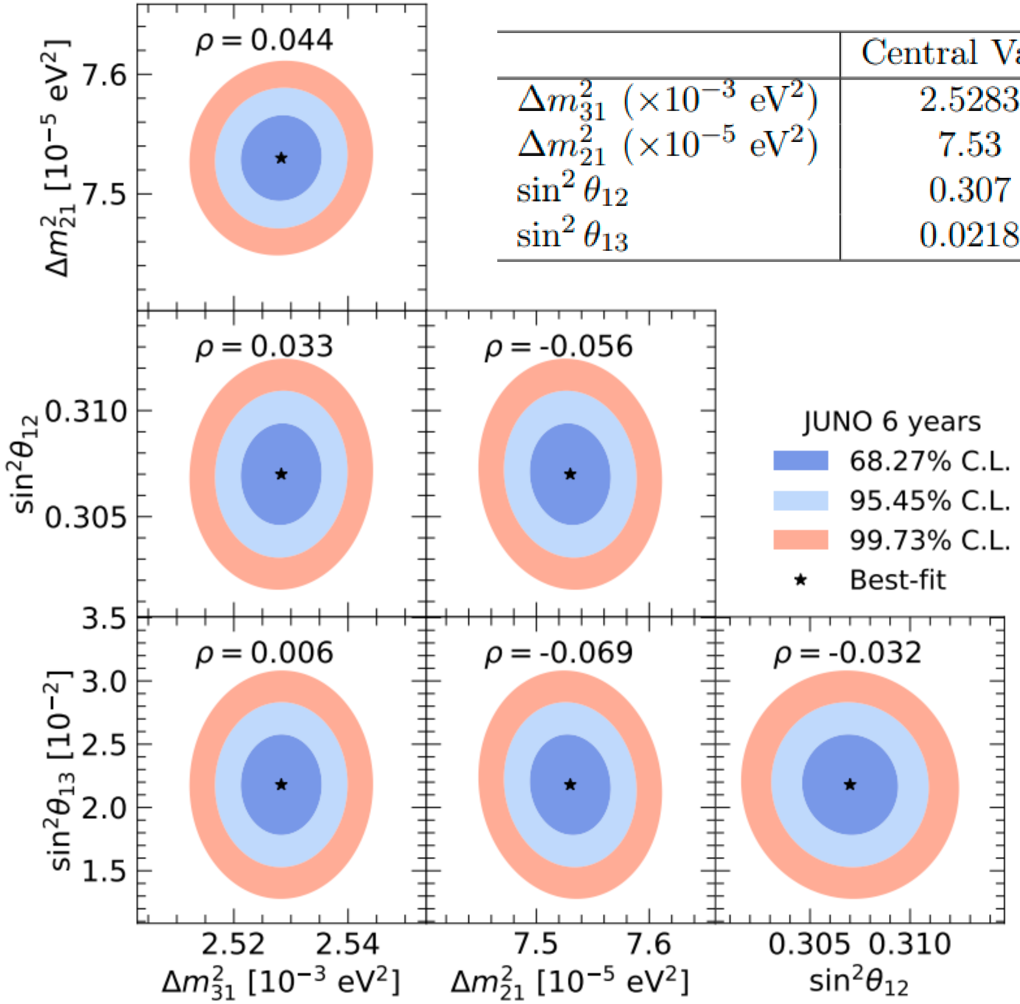
Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity

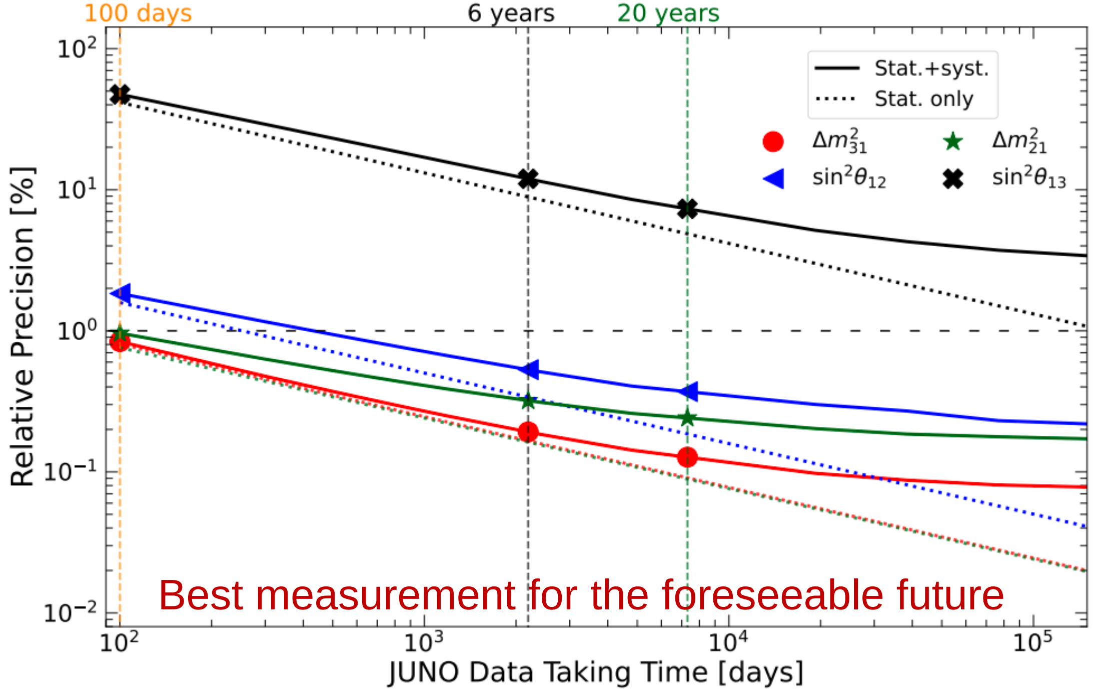
Neutrino oscillation parameters

arXiv:2204.13249, Chin. Phys. C 46 (2022) 123001

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

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





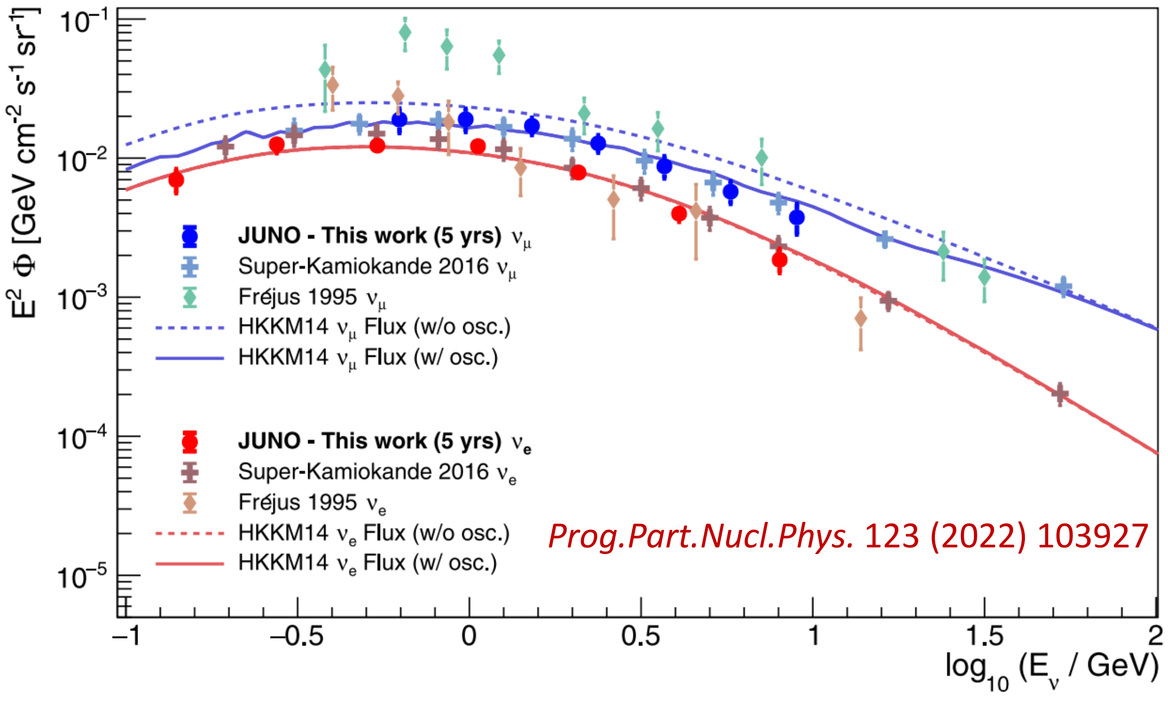
The improvement in precision over existing constraints will be about one order of magnitude

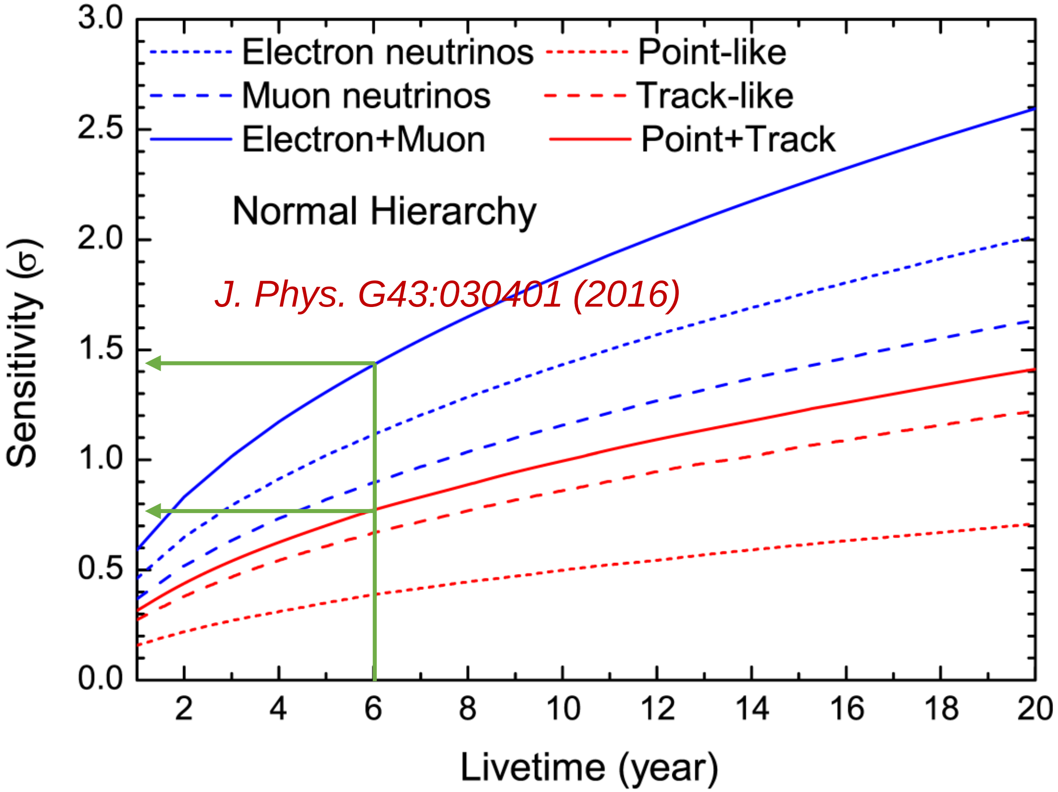
Atmospheric neutrinos

Precision measurement of low energy atmospheric neutrino fluxes

MSW effect → Neutrino Mass Ordering (NMO) → Independent measurement from reactor antineutrinos

Critical techniques: **energy and angular resolutions, flavor and $\nu/\bar{\nu}$ identifications**





ν_e/ν_μ discrimination thanks to PMT hit pattern

JUNO sensitivity on NMO: **0.7~1.4 σ (atmospheric only) @ ~6 yrs exposure**

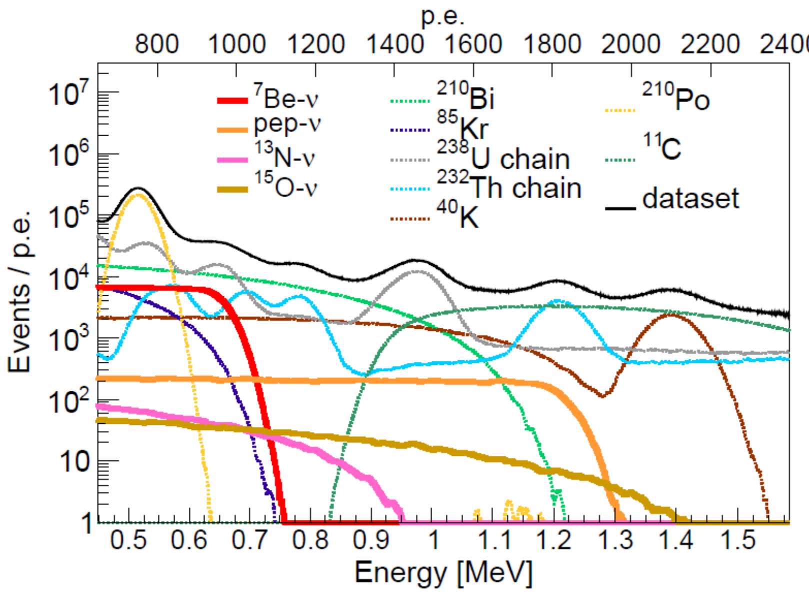
Updated sensitivity based on ML-based reconstruction and PID performance

Neutrinos from Sun (Be7, pep and CNO)

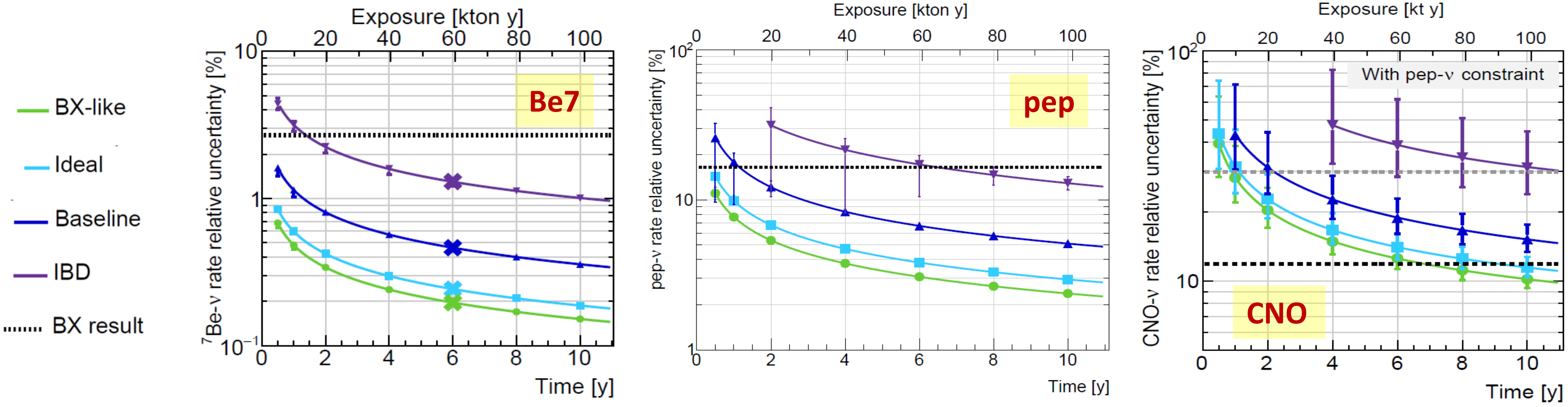
Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	$c\ [\frac{g}{g}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R\ [\frac{cpd}{kt}]$	2289	5000	3508	15047	12031	12211
Baseline	$c\ [\frac{g}{g}]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	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	$c\ [\frac{g}{g}]$	-	-	$<5.7\times10^{-19}$	$<9.4\times10^{-20}$	-	-
	$R\ [\frac{cpd}{kt}]$	4.2	100	1.4	2	115	446.9

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

No detector systematics is included



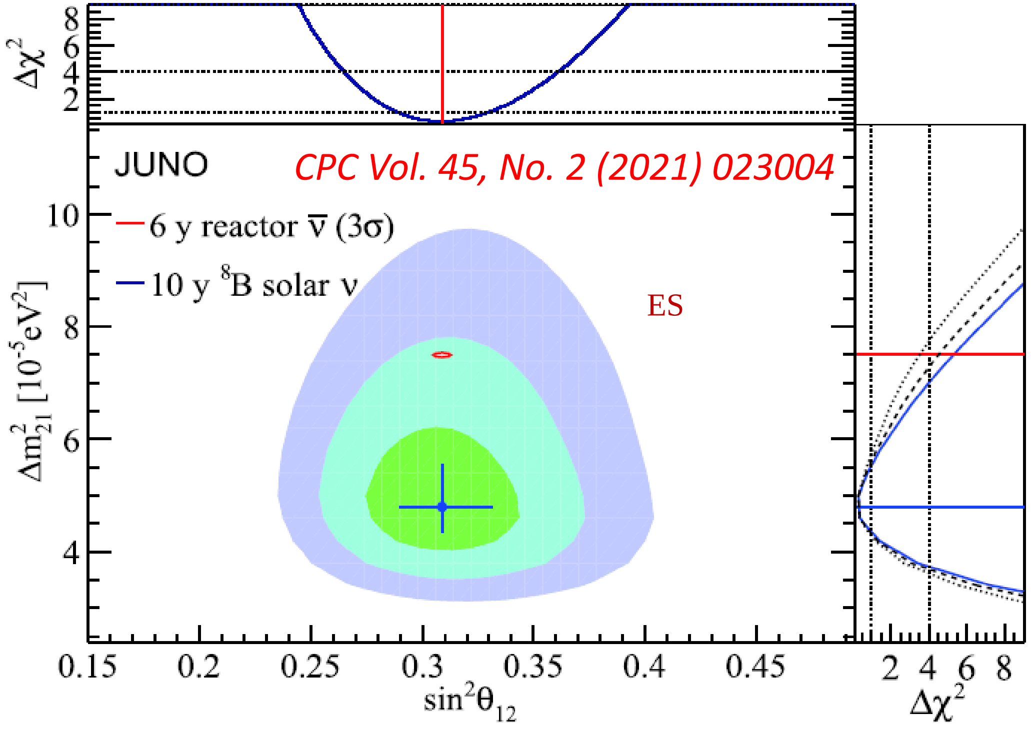
arxiv:2303.03910, JCAP 10 (2023) 022



Neutrinos from Sun (B8)

Low visible energy threshold: E_{th} ~ 2 MeV
Day-Night-Asy precision: 0.9% in 10 years

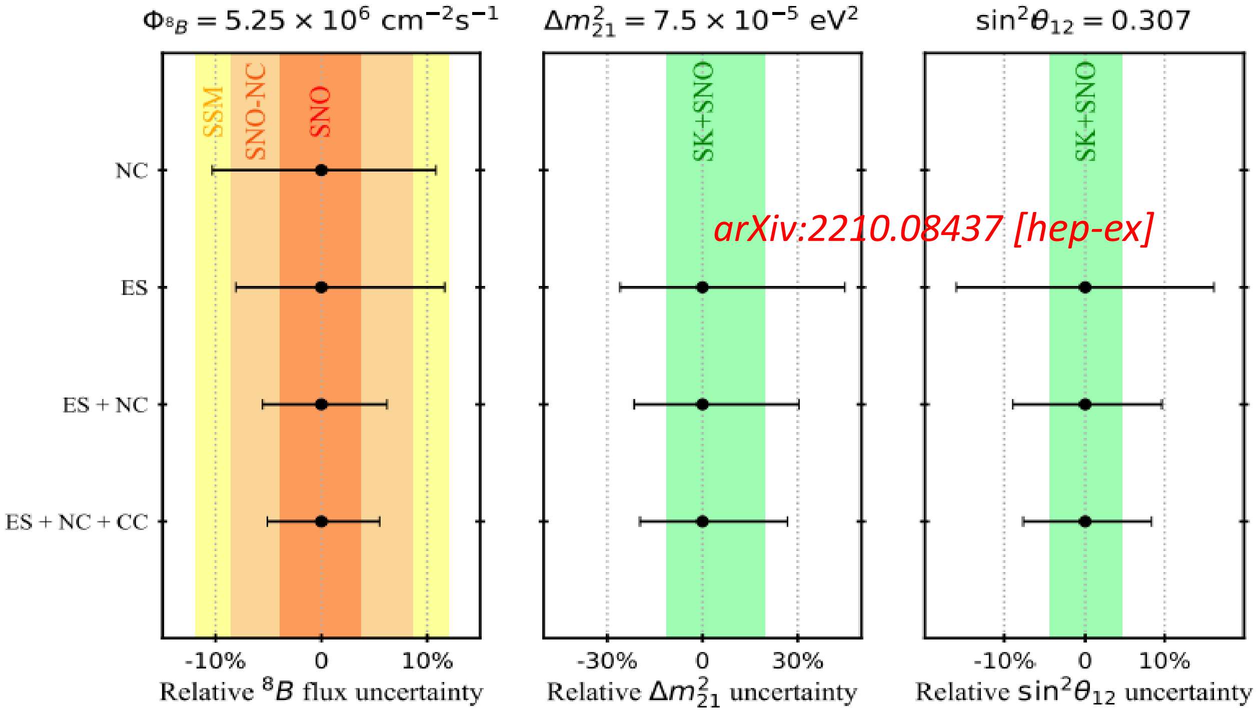
Solar & reactor measurement in Δm^2_{21} with one single detector



Model independent measurement of ^{8}B-ν flux (~5%) and solar oscillation parameters

	Channels	Threshold [MeV]	Signal
CC	$\nu_e + ^{13}\mathrm{C} \to e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + ^{13}$N decay
NC	$\nu_x + ^{13}\mathrm{C} \to \nu_x + ^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ
ES	$\nu_x + e \to \nu_x + e$	0	e^-

Correlated (CC); Single (NC, ES)



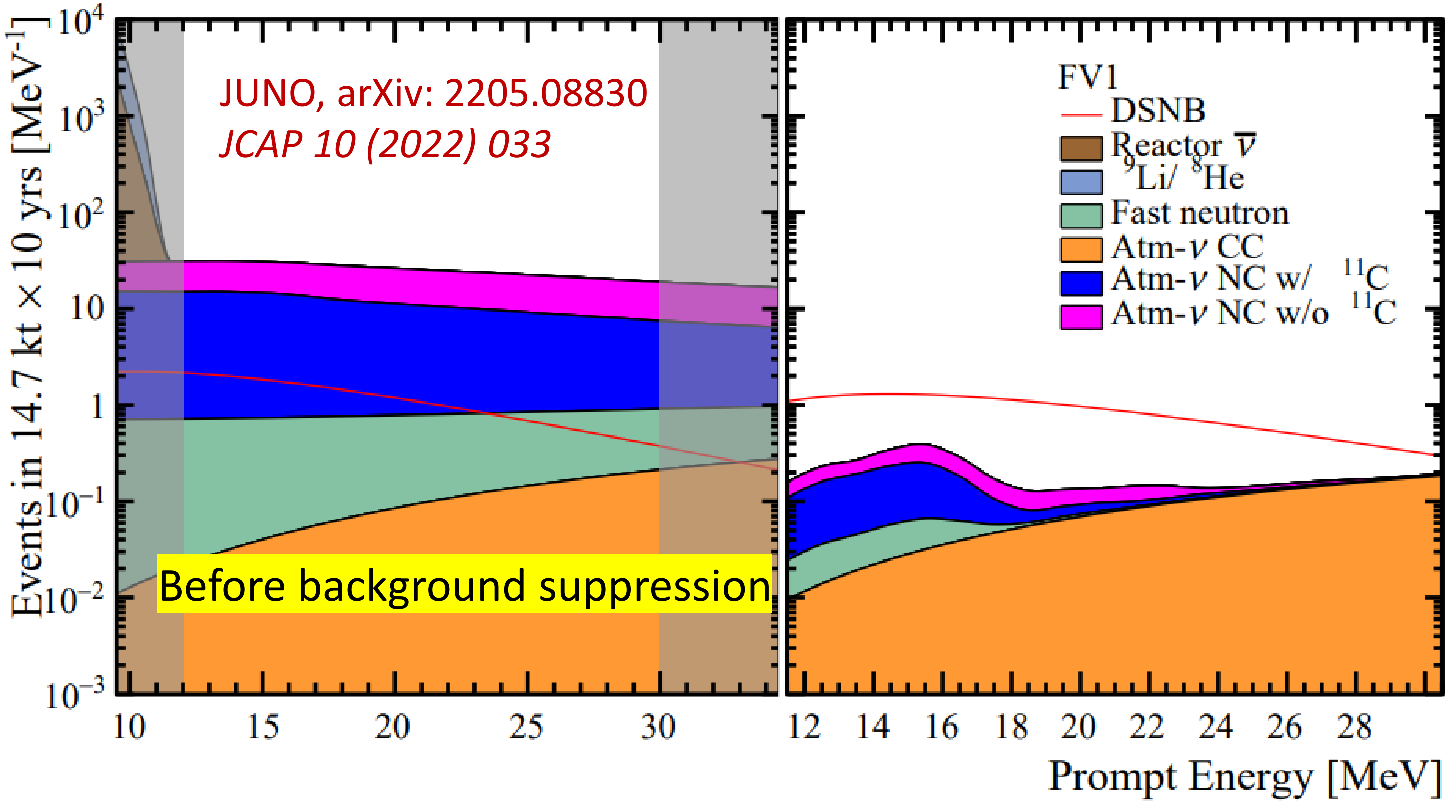
Diffuse Supernova Neutrino Background (DSNB)

- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

Holding:
- Supernova (SN) rate ($R_{SN}(0)$)
- Average energy of SN neutrinos ($\langle E_\nu \rangle$)
- Fraction of black hole (f_{BH})

- Dominant background (above 12 MeV):
  - ✓ Atm-ν NC interactions

- Highlights on background suppression
  - ✓ Muon veto
  - ✓ Pulse shape discrimination (PSD) technique
  - ✓ Triple coincidence (^{11}C delayed decay)



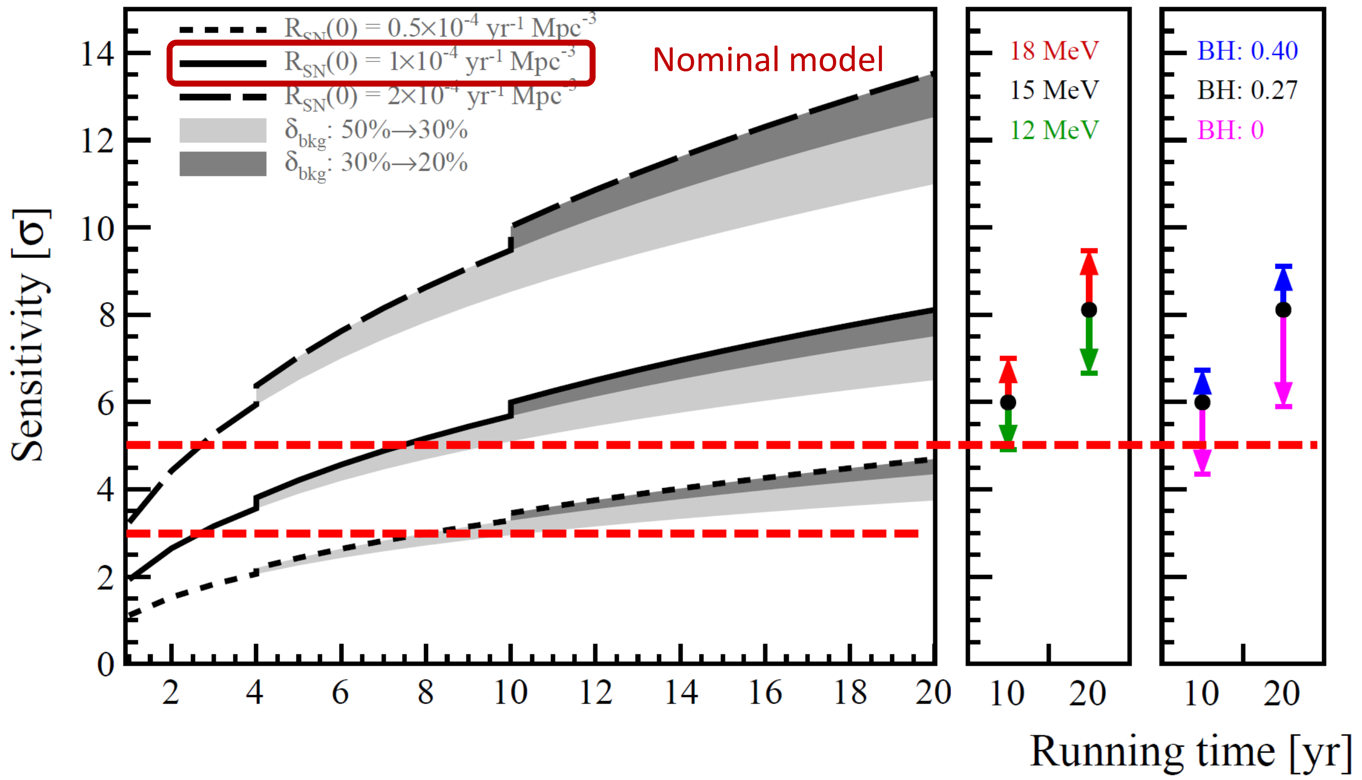
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* :

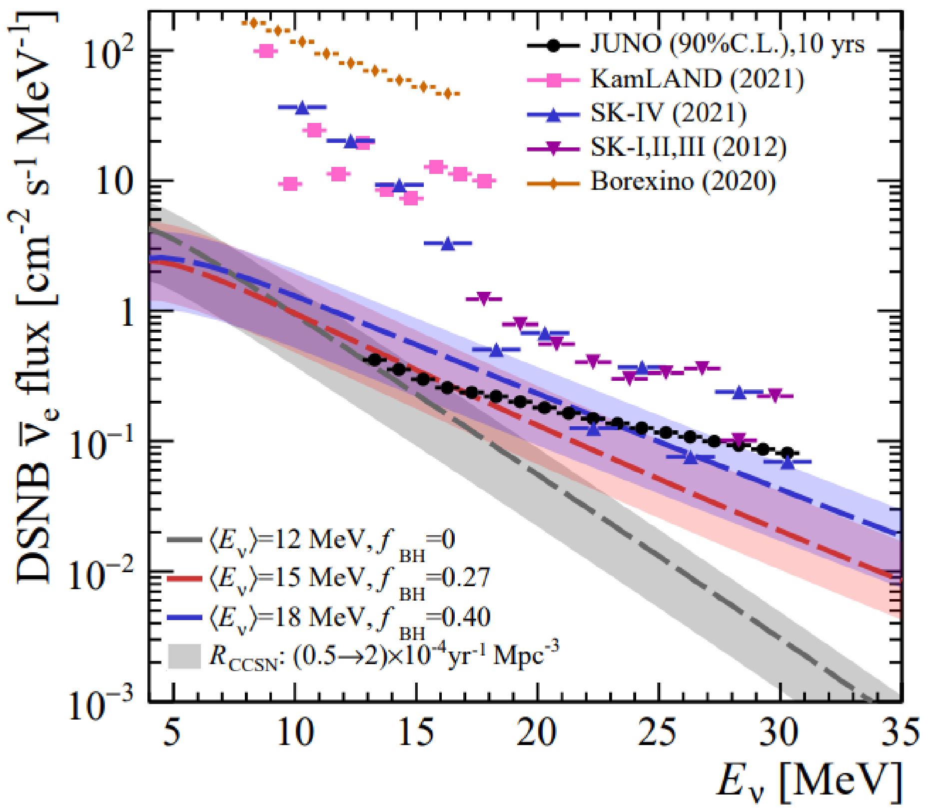
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

➡ S/B improved from **2 to 3.5**

Diffuse Supernova Neutrino Background (DSNB)

arXiv: 2205.08830, JCAP 10 (2022) 033





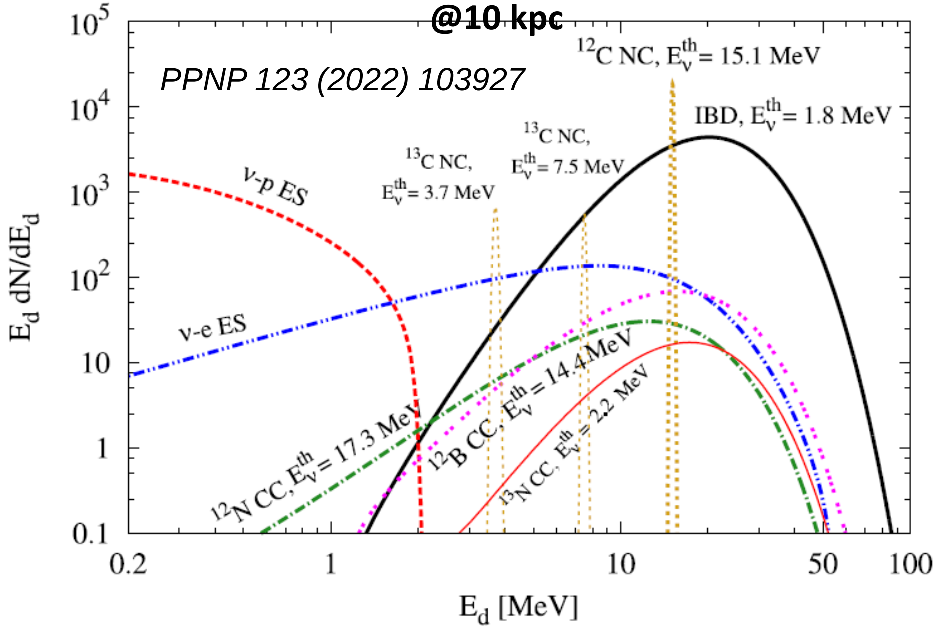
- **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**
- **With the nominal model (black solid curve (left plot)): 3σ (3 yrs) and 6σ (10 yrs)**

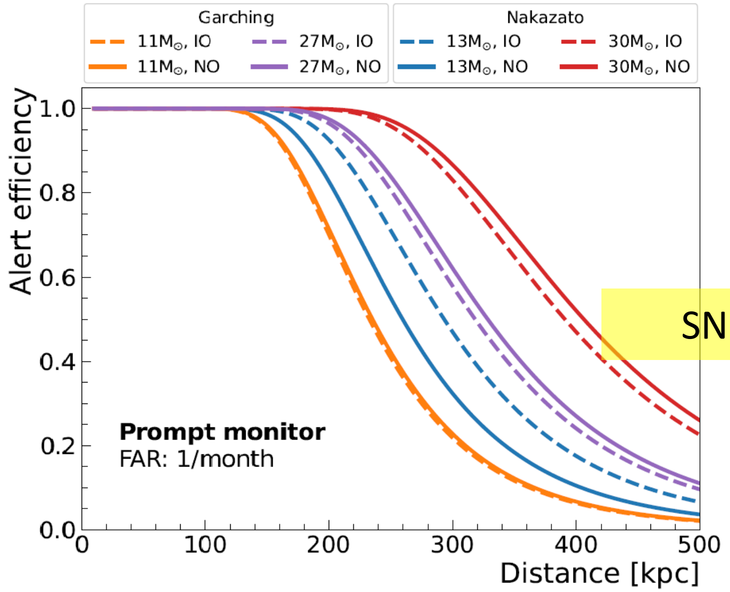
Core Collapse Supernova Neutrinos

arXiv: 2309.07109 [hep-ex]

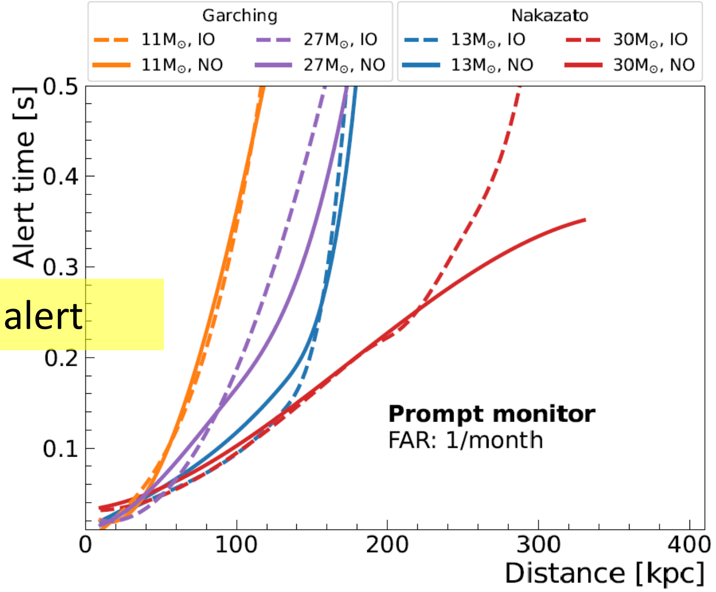
Multi-channel detection, all flavors of CCSN:

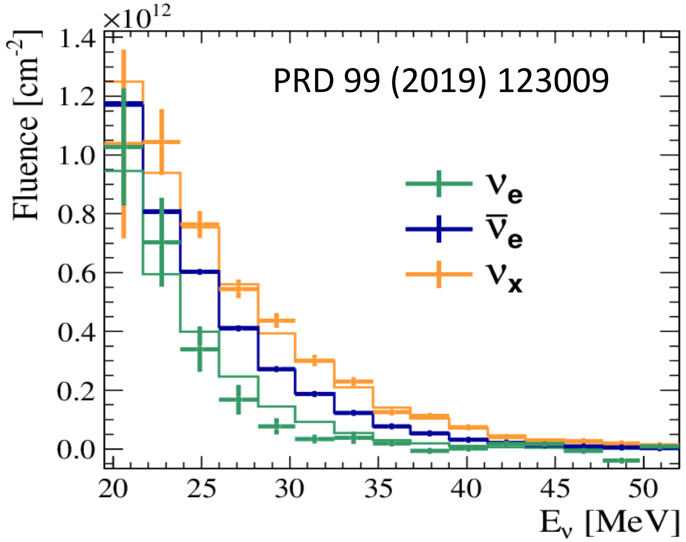
~5000 IBD, ~300 eES, ~2000 pES， ~200 ^{12}C CC, ~300 ^{12}C NC @10 kpc





SN alert





Model-independent reconstruction of the energy spectra of $\bar{\nu}_e$, ν_e, ν_x via unfolding approach

→ Allow for further physics and astrophysics studies!

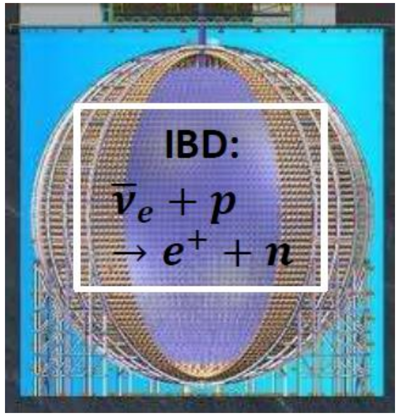
- Excellent capability of early warning
- CCSN:

  reach 240 ~ 400 kpc w/ 50% prob., alert in 10 ~ 30 ms
- pre-SN:

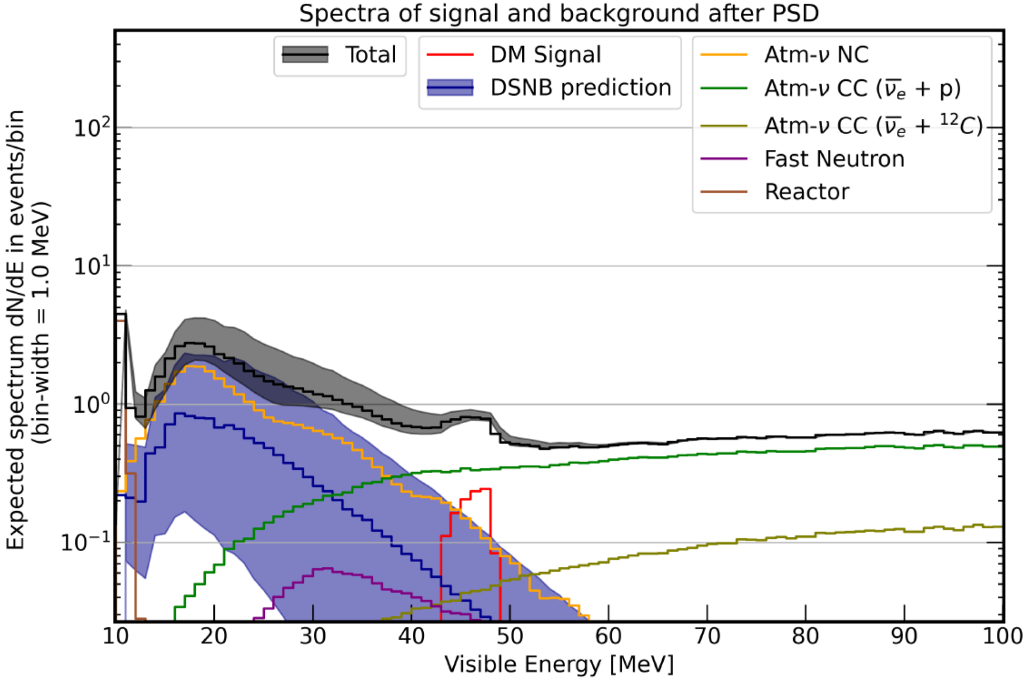
  reach 0.6 ~ 1.7 kpc w/ 50% prob., >~ 100 hr in advance if 0.2 kpc

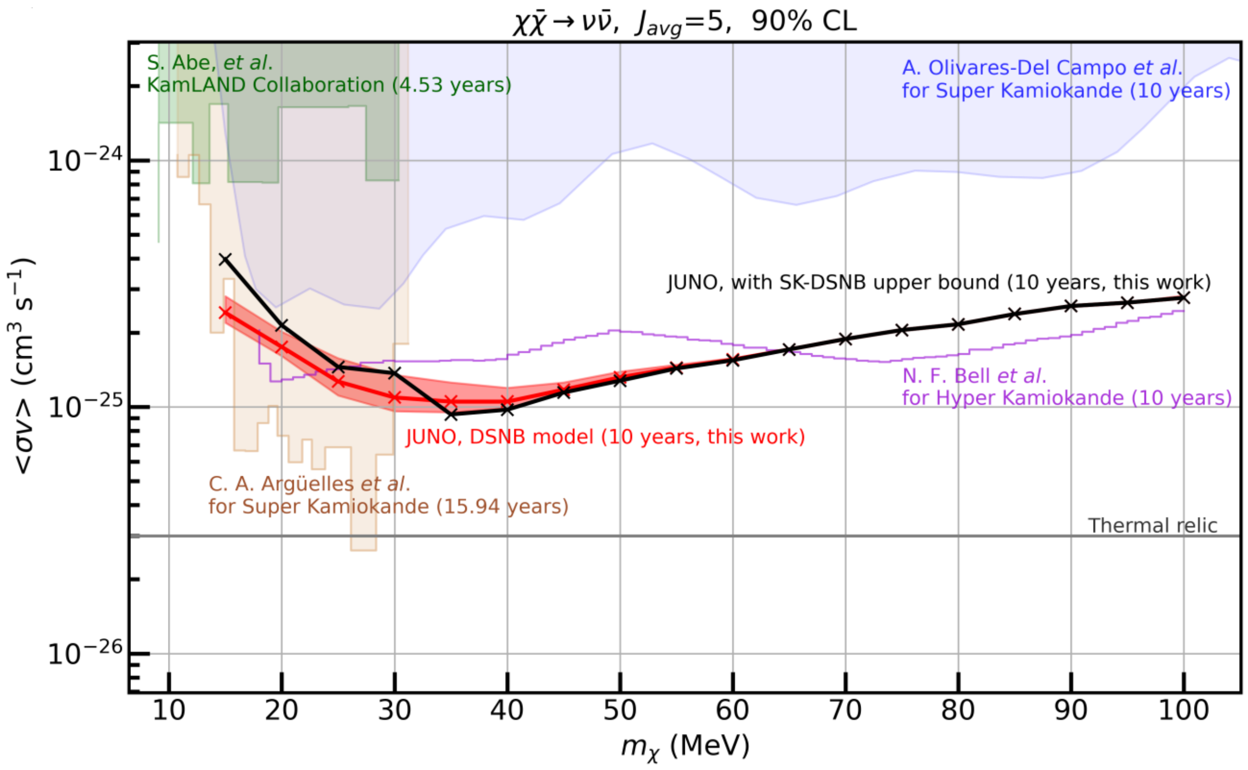
A dedicated Multi-Messenger Trigger System is on the way

Indirect Dark Matter Search



- DM annihilation into neutrinos in the Milky Way
- DM masses: 10 - 100 MeV
- Detection channel in JUNO: IBD
- Backgrounds: DSNB, atm-ν NC/CC (dominant), fast neutron, reactor
  - PSD technique to suppress atm-ν NC and fast neutron

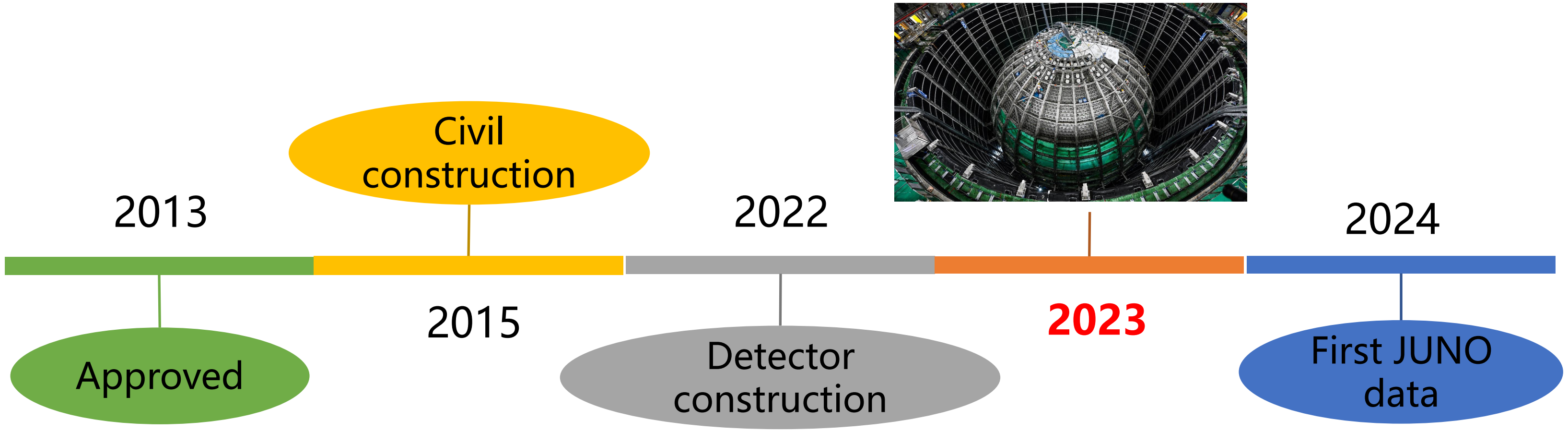




arXiv:2306.09567 [hep-ex]

Outlook

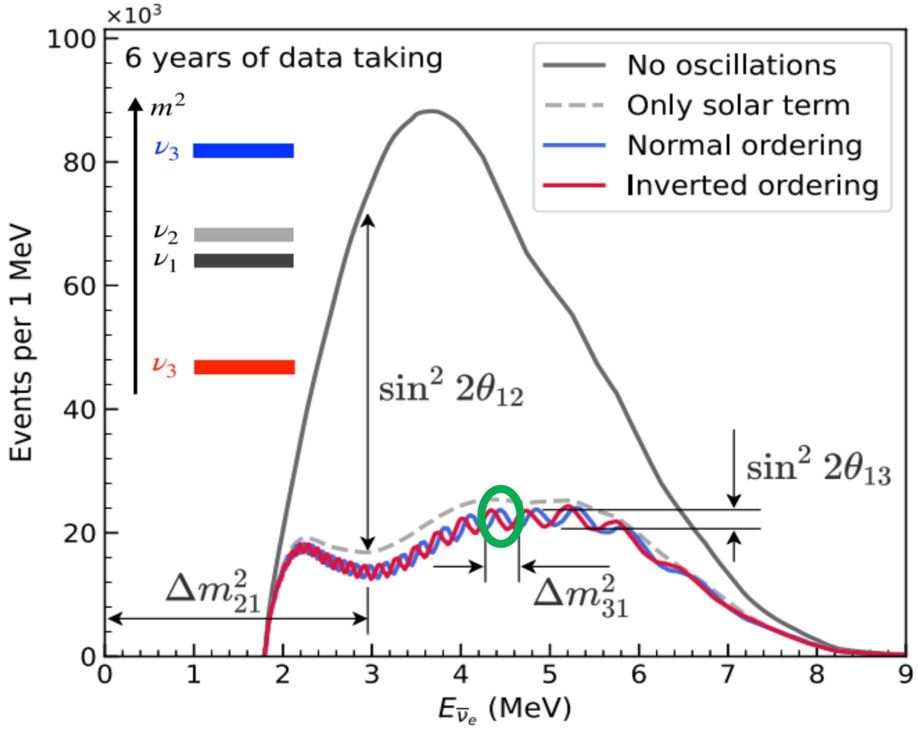
Physics	Sensitivity
Neutrino Mass Ordering	3σ in 6 yrs by reactor neutrinos. *Atmospheric ν sensitivity to be improved*
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{31}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~7300 of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar Neutrino	Measure ^{7}Be, pep, CNO simultaneously, measure ^{8}B flux independently
Nucleon Decays ($p \to \bar{\nu} K^+$)	9.6×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs



Back up

Requirement for rich physics program

Example: Precision Neutrino Oscillation Measurements



Detector properties

- **Statistics**
  - Large target mass (20 kton LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- **Energy resolution**
  - Very high PMT coverage (78%)
  - Highly transparent LS
  - Highly efficient PMTs (PDE~30%)
- **Shape uncertainty**
  - Satellite detector (TAO)
- **Background**
  - Good overburden (~650 m)
  - Highly-efficient veto system (>99.5%)
  - Material screening
  - Clean installation

For solar neutrinos: tighter requirements on Liquid Scintillator (LS) radiopurity by 1~2 orders of magnitude.

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**	

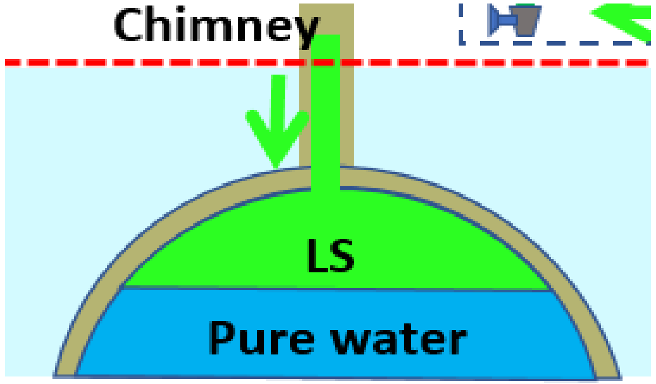
Radiopurity control on raw material:

- ✓ Careful material screening
- ✓ Meticulous Monte Carlo Simulation
- ✓ Accurate detector production handling

Liquid Scintillator Filling

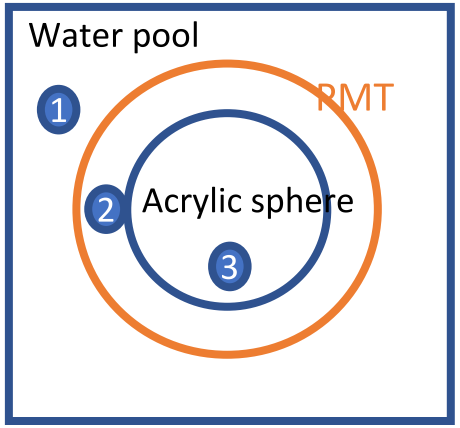
- ✓ Recirculation is impossible at JUNO due to its large size
- → Target radiopurity need to be obtained from the beginning
- ✓ **Strategies:**

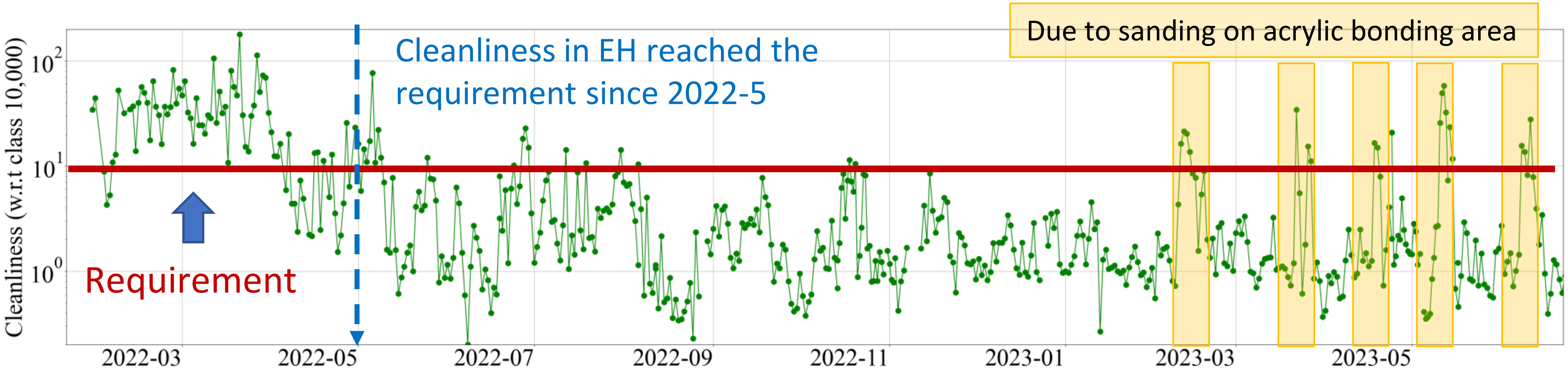
1. **Leakage** (single component < 10^{-6} mbar·L/s)
2. **Cleaning vessel** before filling
3. **Clean environment**
4. **Water/LS filling**



Radiopurity control: environment cleanliness

Acceptable dust in 20 kt LS: < 10 mg!



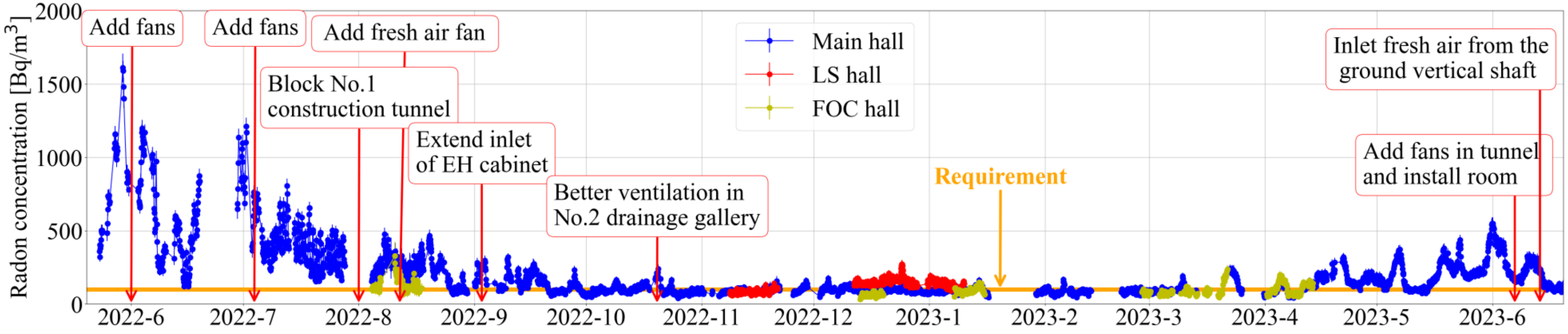


- Cleanliness Class calculation: total dust volume divide Class 10,000 particles volume

Region	Level
1	Class 100,000
2	Class 10,000
3	Class 1000

Temperature: 21℃±1℃

Radon in air: 100 Bq/m^3

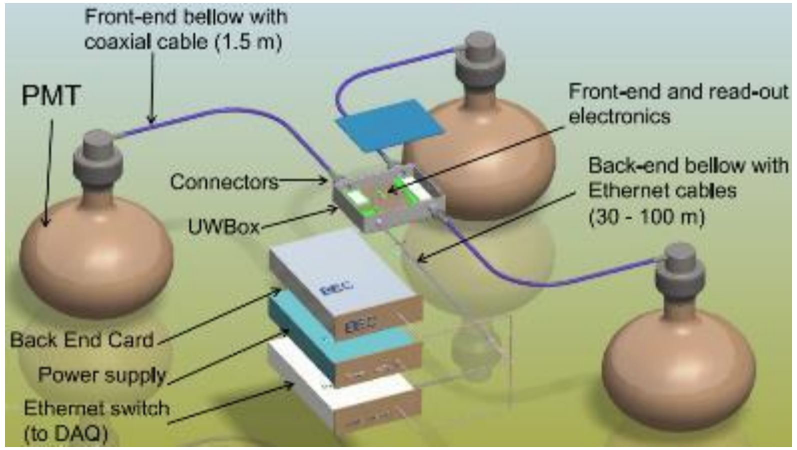


With great efforts on onsite cleanliness control and ventilation optimization, both the radon and the cleanliness in the hall reached our requirement

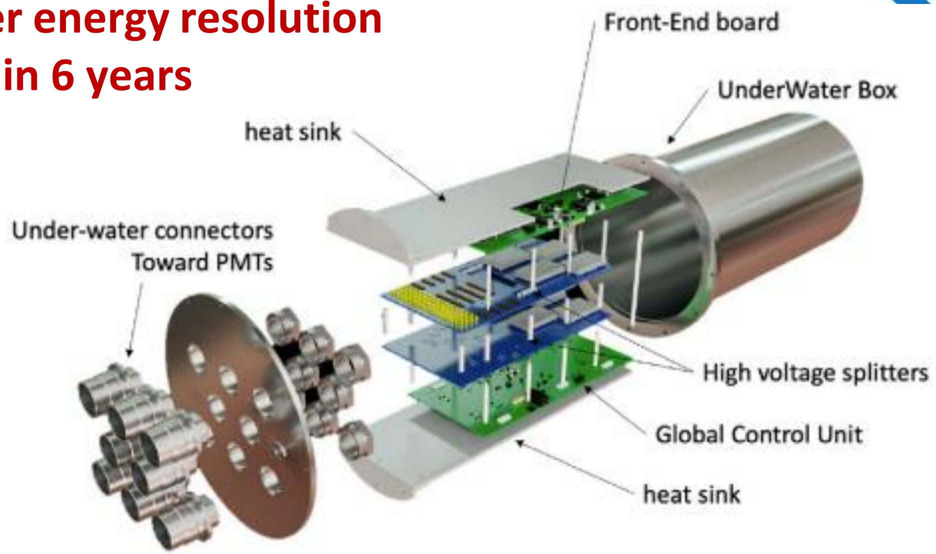
Electronics

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

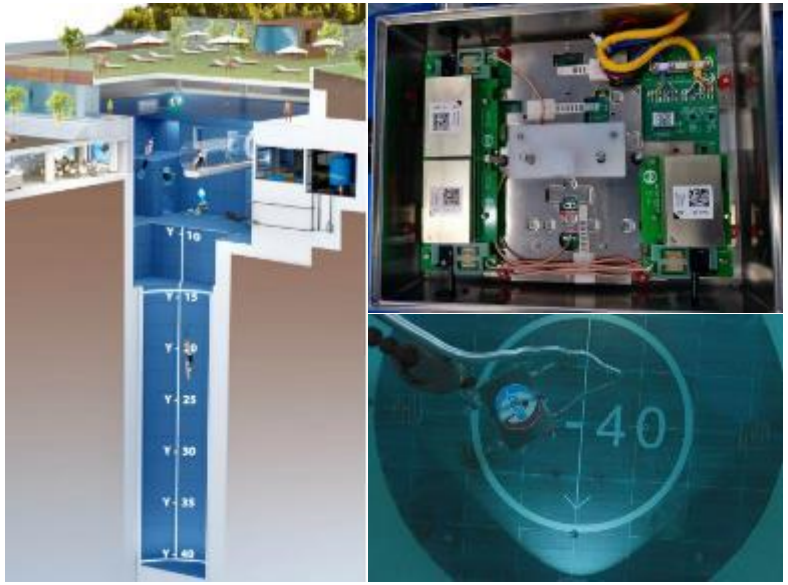
1 GHz waveform digitization, expected loss rate < 0.5% in 6 years

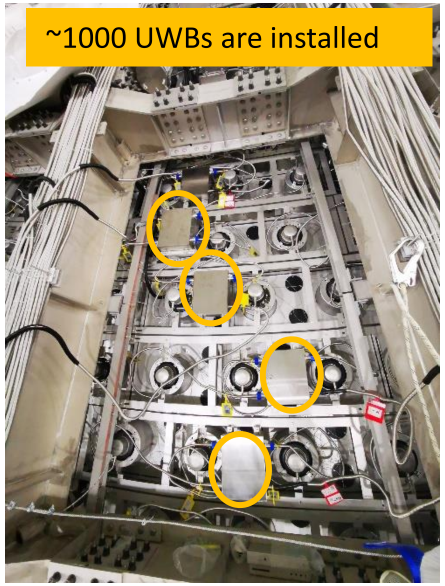


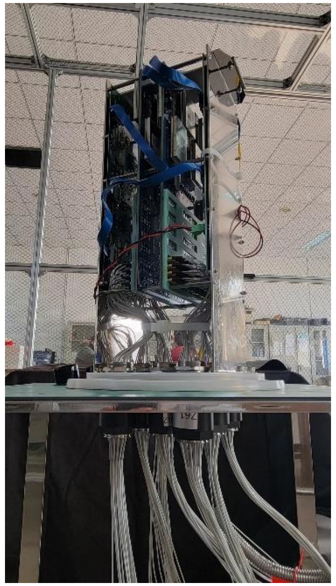
3 20-inch PMTs connected to one underwater box (UWB)



128 3-inch PMTs connected to one underwater box







Positron energy resolution

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

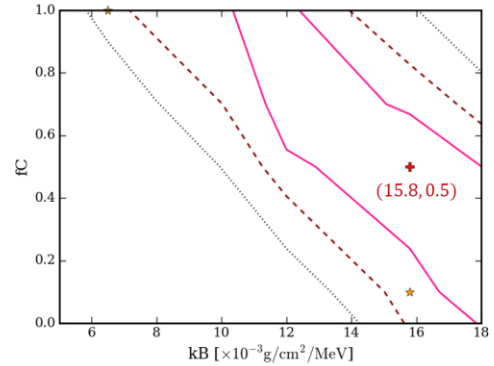
Photon statistics

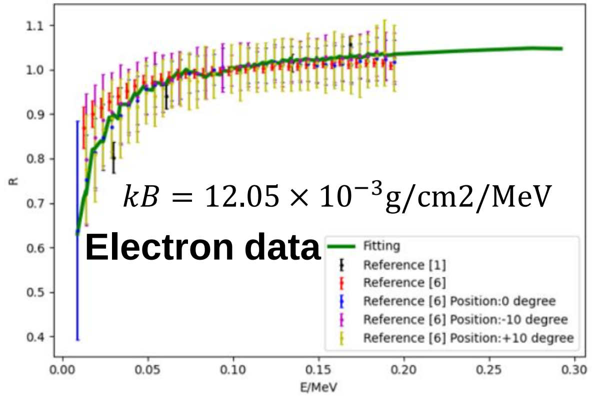
- **Annihilation-induced γs**
- **Dark noise**

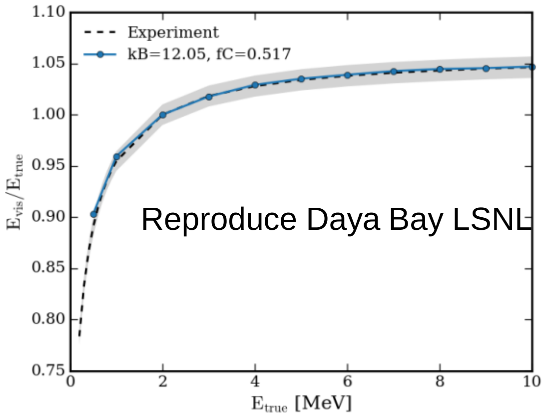
- **Scintillation quenching effect**
  - LS Birks constant **(kB)**
- **Cherenkov radiation**
  - LS refractive index
  - LS re-emission probability
  - Cherenkov yield scale factor **(fC)**
- **Detector uniformity and reconstruction**

- **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



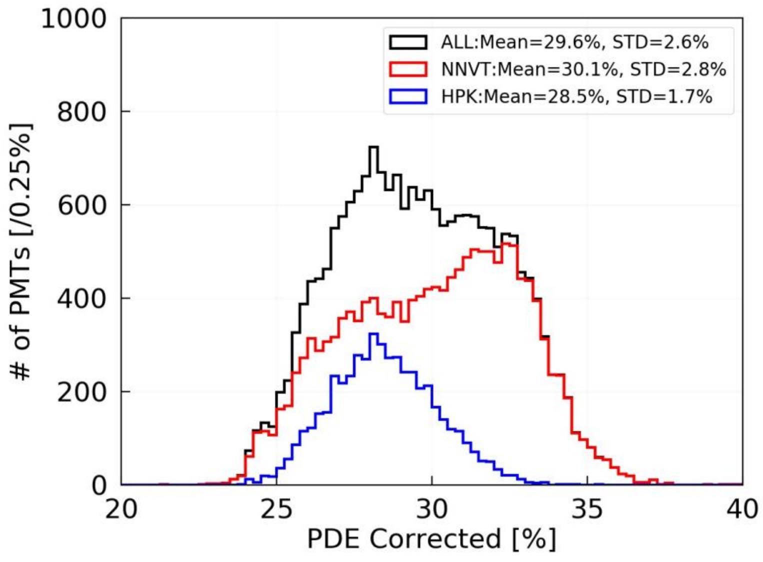




Light yield evolution

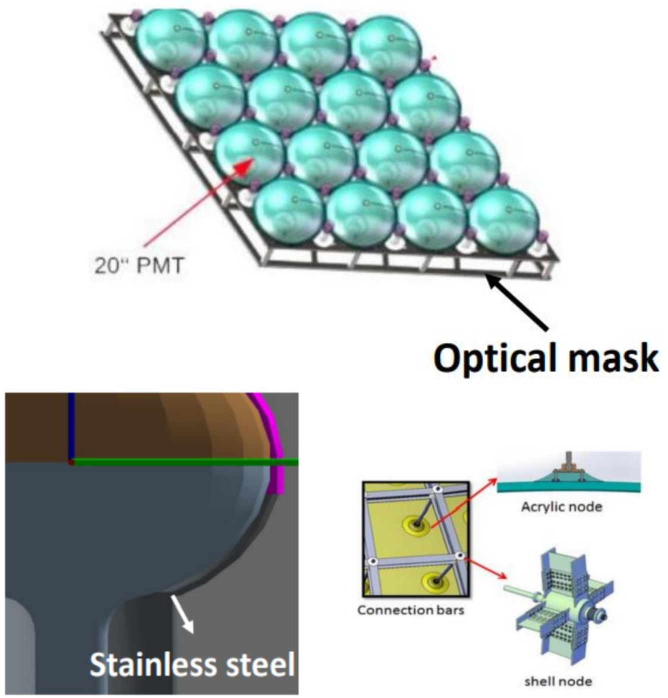
PMT PDE

- 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

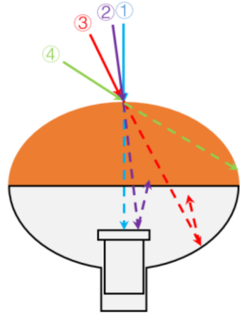


- **Reflections** on them are taken into consideration
- Yield 2.7% more photons

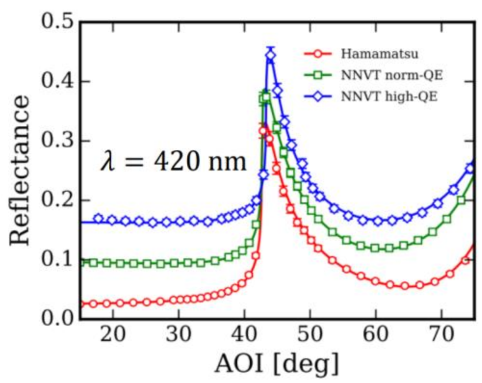
New PMT Optical Model

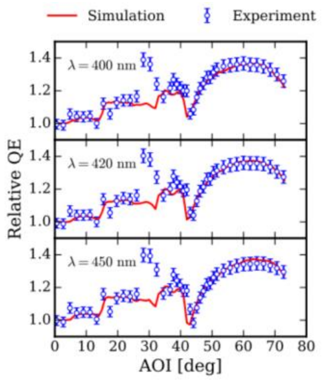
Optical Processes in PMT

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



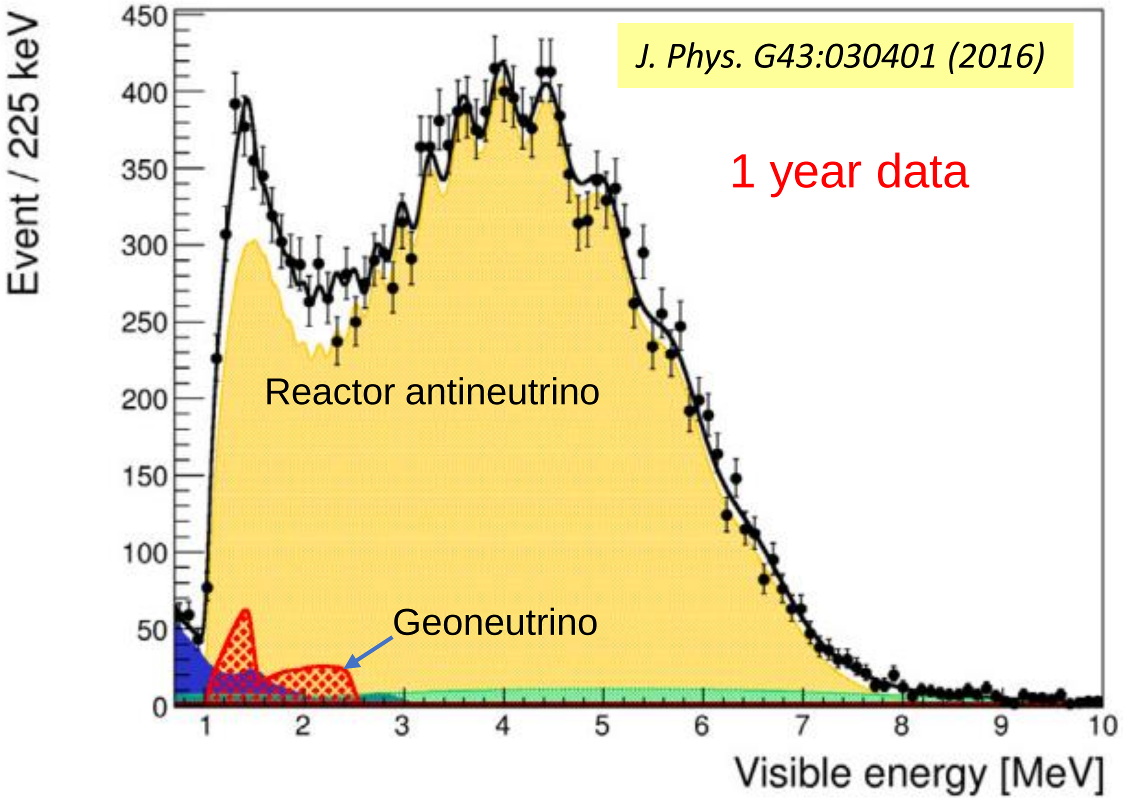
- ◆ Multilayer thin film theory
- ◆ Experimental tests
- ◆ GEANT4 simulation

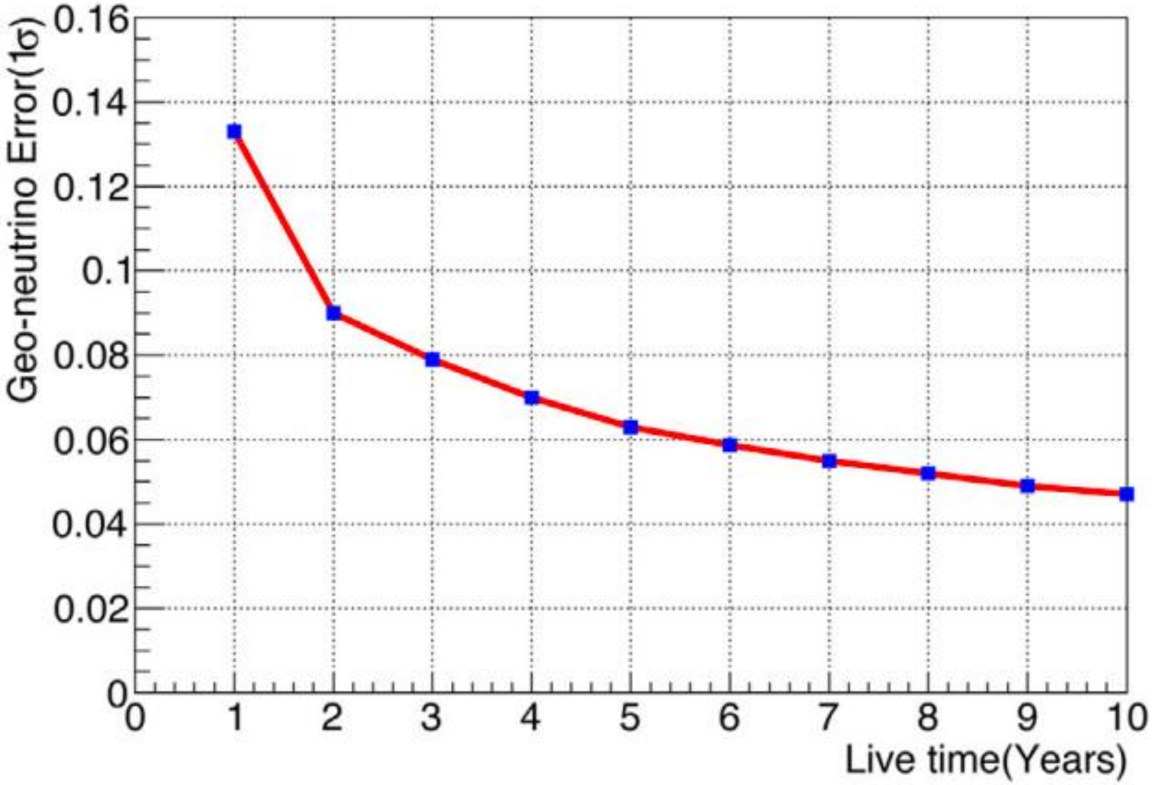




Neutrinos from earth

$\bar{\nu}_e$ from ^{238}U and ^{232}Th decay chains in earth



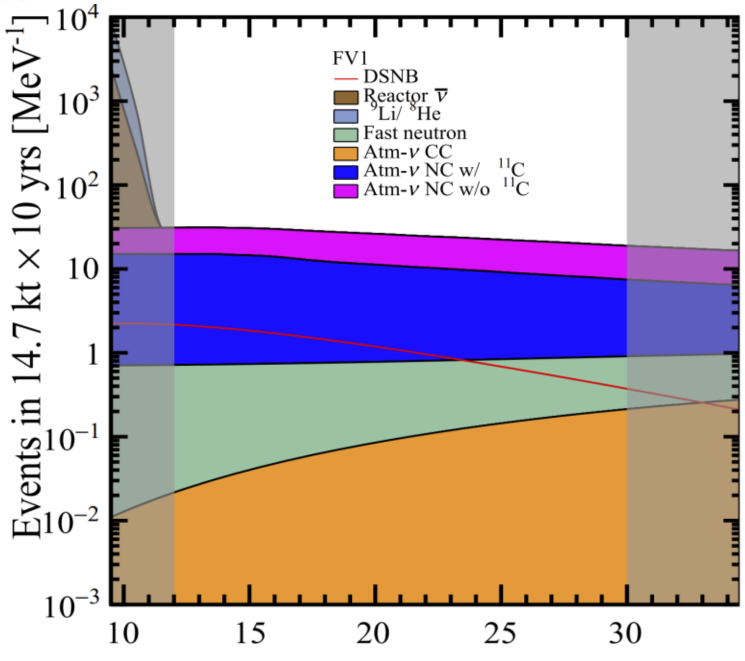


Signal in JUNO (CRUST1.0): 39.7 +6.5 −5.2 TNU (~400 geo-νs per year), 5% measurement in 10 years.

JUNO can observe as much geo-ν as Borexino and KamLAND for the whole time combined in 1 yr.

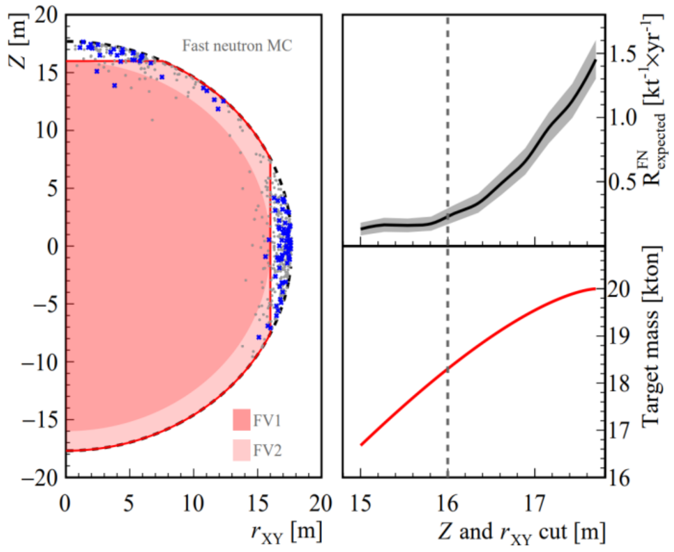
With new Local Refined Crust model (*PEPI,* 299 (2020) 106409), the geo-ν signal is ~30% larger, updated sensitivity is on-going.

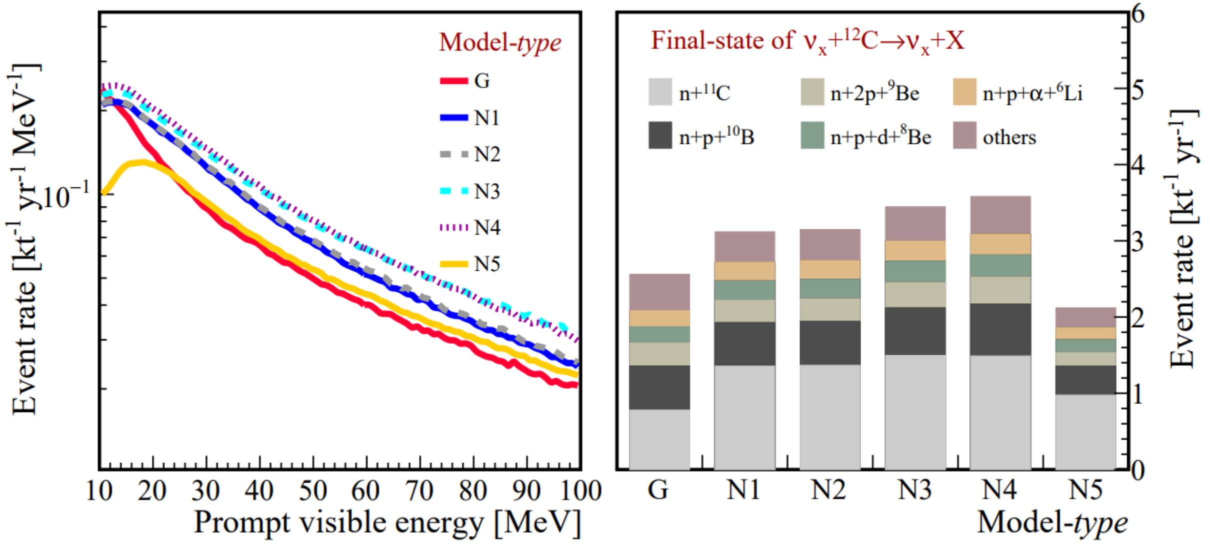
Diffuse Supernova Neutrino Background



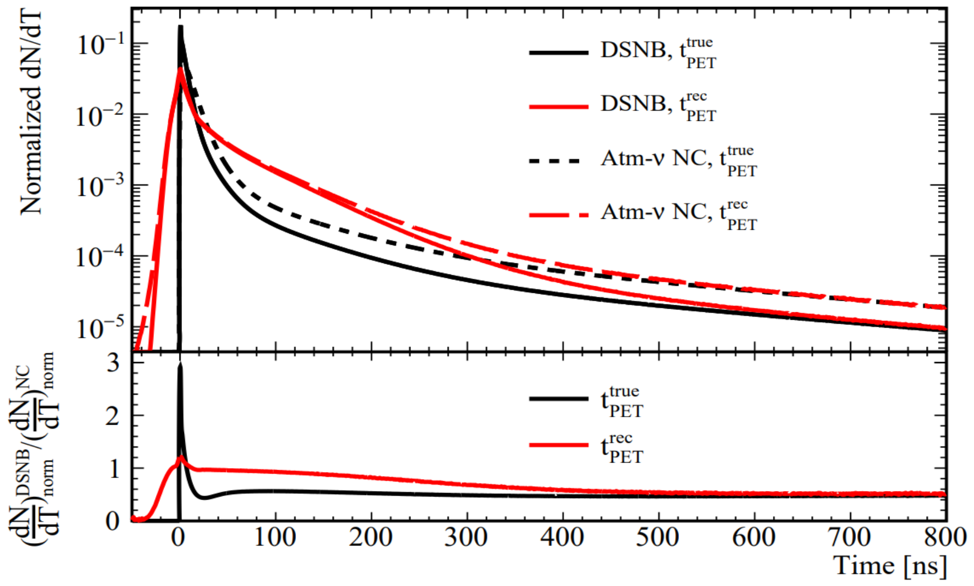
Major backgrounds (above 12 MeV):

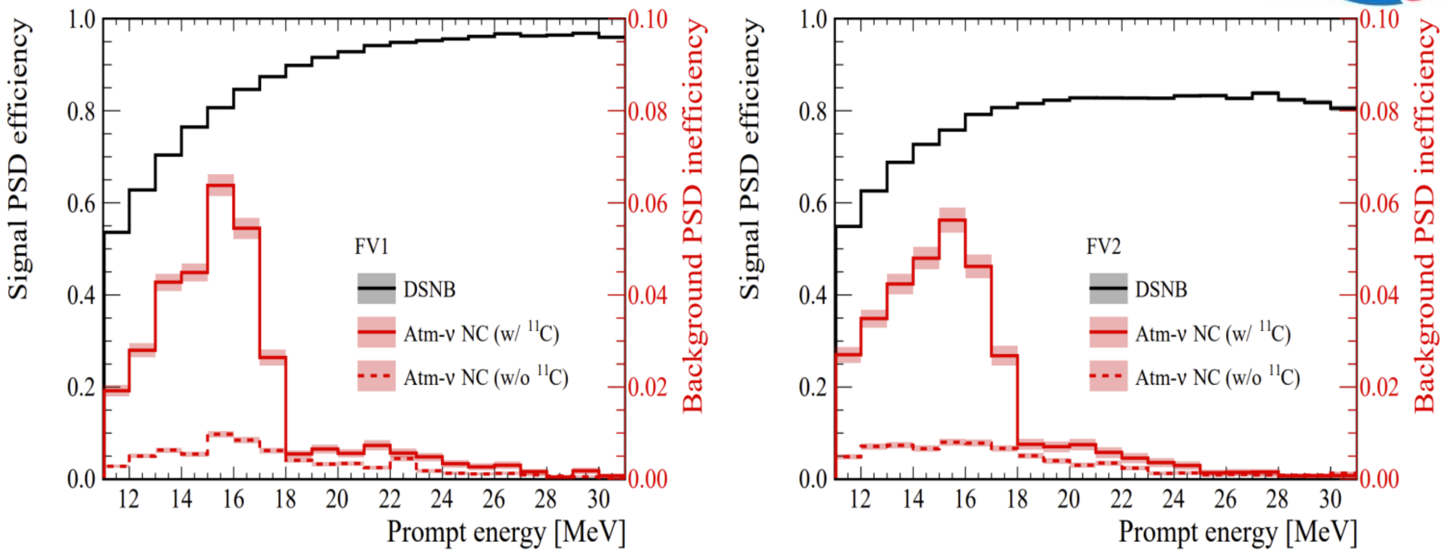
- Fast neutron ➔ Two fiducial volumes
- Atmospheric neutrino CC interactions (intrinsic IBDs)
- Atmospheric neutrino NC interactions
  - Prediction ➔ ν-N interactions (GENIE, NuWro) + TALYS (de-excitation)
    method Ref: Phys.Rev.D 103 (2021) 5, 053001
  - Uncertainty ➔ Future *in situ* meas. (~15% after ten years)
    method Ref: Phys.Rev.D 103 (2021) 5, 053002
  - Discrimination ➔ PSD technique & Triple coincidence (^{11}C delayed decay)





Diffuse Supernova Neutrino Background

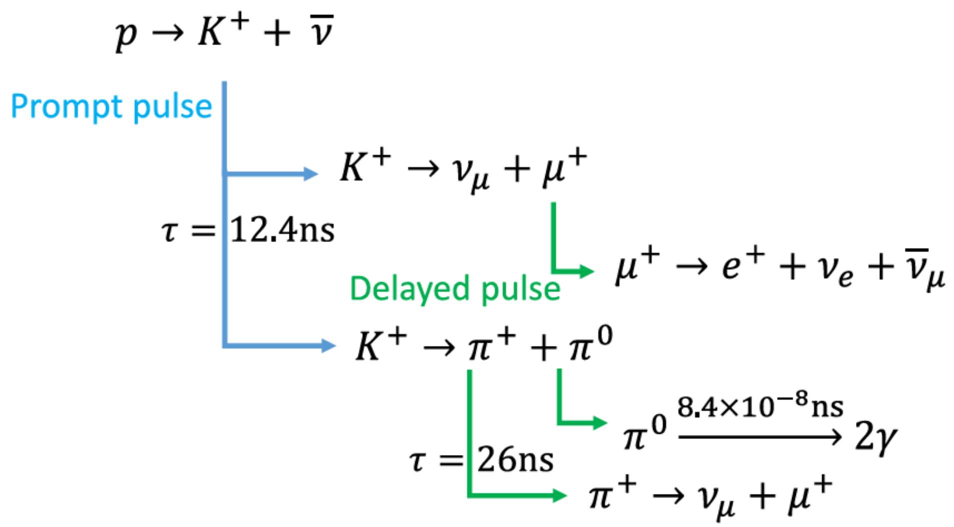




- Different time profiles of signal and background lay the foundation of pulse shape discrimination
- Machine-learning based PSD analysis
  - TMVA (baseline), Scikit-learn (cross check)

> - Final PSD efficiency at 1% residual background
>   - FV1 (84%), FV2 (77%) versus 50% in JUNO (2015)
> - Energy dependent feature of PSD in DSNB analysis (first time found in LS detectors)
>   - Energetic neutron below 18 MeV in LS: the inelastic reaction channel of ^{12}C with gamma production becomes dominate

Nucleon decays



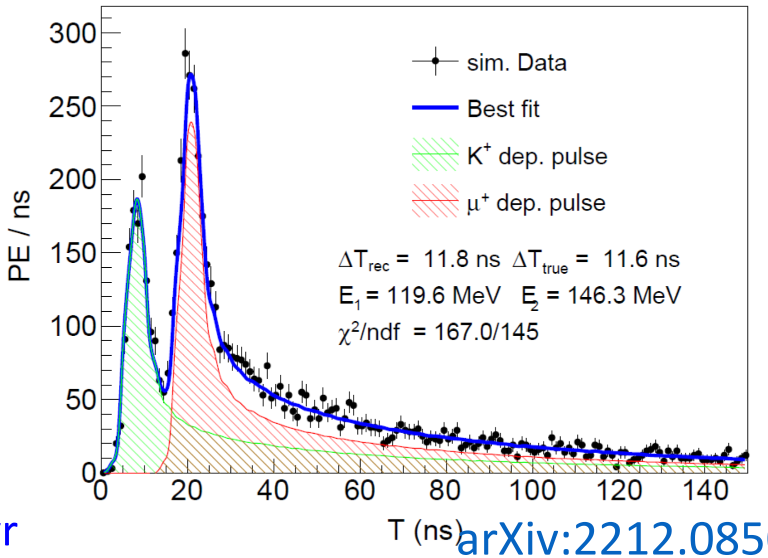
- **Signature:** three-fold coincidence
- **Dominant background:** atmospheric neutrino interactions

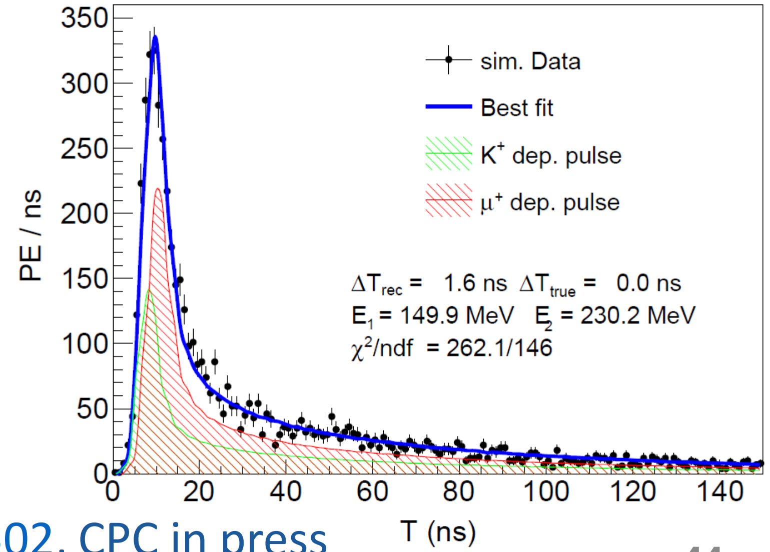
Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \rightarrow \nu + n$ $\nu + p \rightarrow \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \rightarrow n + l^+$ $\nu_l + n \rightarrow p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \rightarrow l^- + p + \pi^+$ $\nu + p \rightarrow \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \rightarrow l^- + \Lambda + K^+$ $\nu_l + p \rightarrow l^- + p + K^+$	Double Pulse

- Disentangle pile-up of signals with 3-inch PMTs
- Multiplicity, spatial distribution of Michel e- and neutrons in the FSI

- **Expect sensitivity:** 9.6×10^{33} years (90% C.L.) for 200 kton*yrs exposure

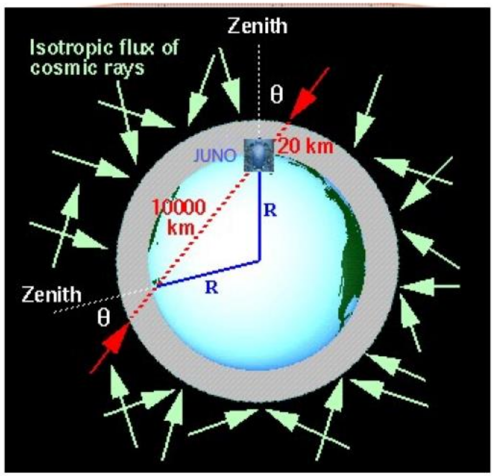
Super-K (2014): >5.9×10^{33} yrs @ 260 kton·yr

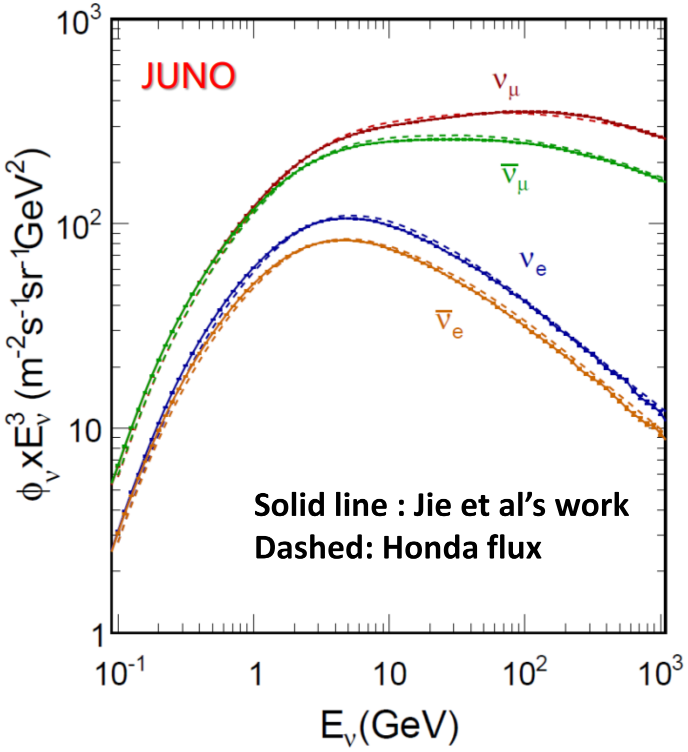


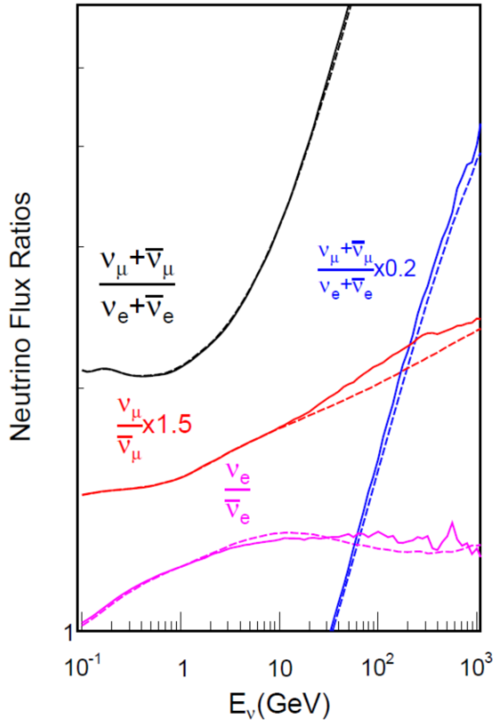


arXiv:2212.08502, CPC in press

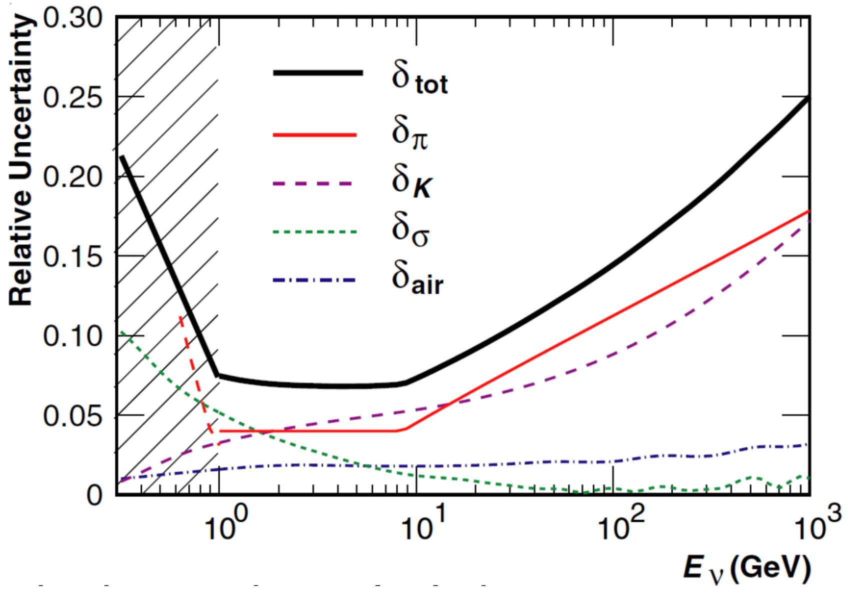
Atmospheric Neutrinos







PHYSICAL REVIEW D **75,** 043006 (2007)



3D atm-ν flux calculation based on:

- Primary cosmic ray flux
- Rigidity cut, depends on geomagnetic field and rigidity of cosmic ray particle
- Hadronic interaction model, air profile and meson-muon decay

Evaluation of GeV ν interaction models

- GENIE, GiBUU, NuWro, etc

On-going improvement at <100 MeV:

- Propagation of muon inside the earth
- Local info: mountain profile, atmospheric density, geomagnetic field