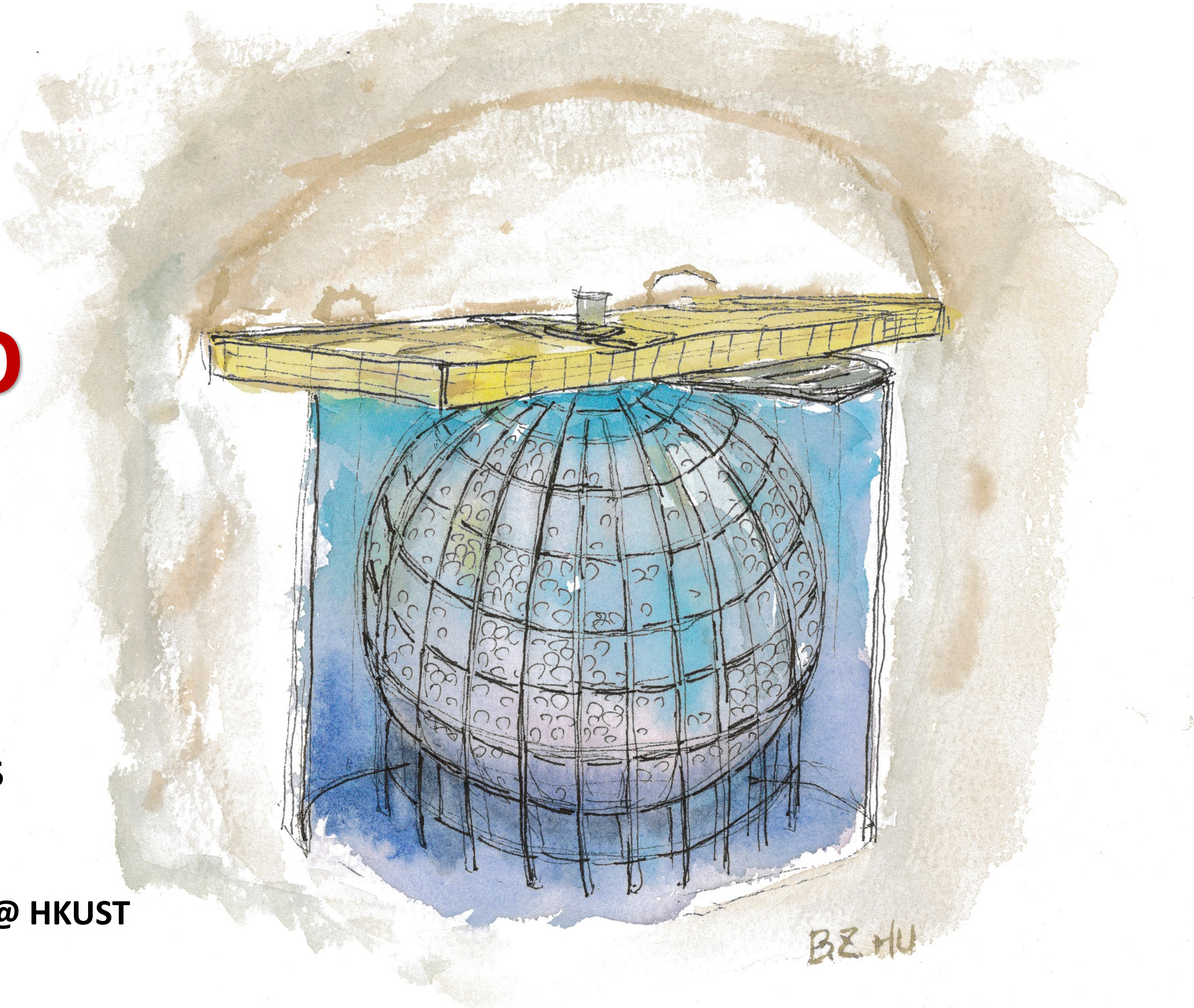
Overview on JUNO



Liangjian Wen

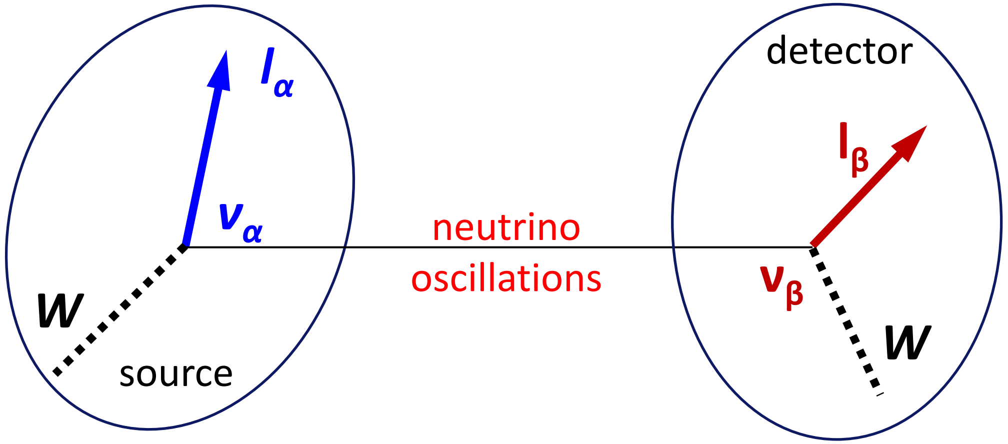
Institute of High Energy Physics, CAS

2024.01.24

IAS Program on High Energy Physics (HEP 2024) @ HKUST

Neutrino Oscillations

- It proved that neutrinos have non-zero masses ➔ huge impact on particle physics & cosmology
- Neutrinos are the possible source of CP violation, which may explain the matter-antimatter asymmetry in the Universe

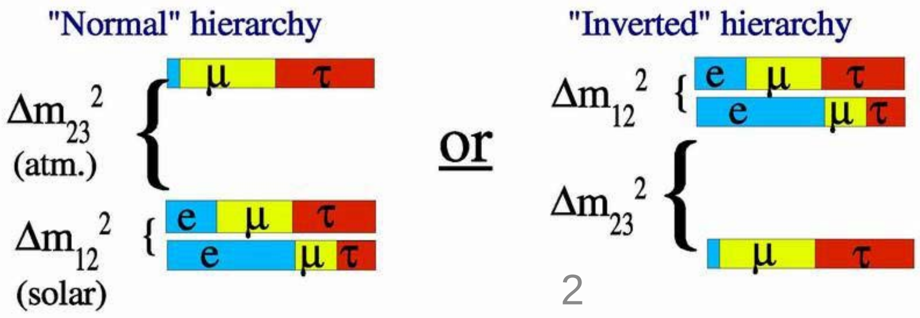


ν prod. & detection: $W^\pm$ weak interaction → identify *flavor*
ν propagation: *mass eigenstates (!= flavor eigenstates)*

- After 25 years of ν oscillations discovery, still unknow
  - **Mass ordering** ($\Delta m^2_{32}>0$?)
  - Leptonic CP phase (δ_{CP})
  - θ_{23} Octant
  - **Very precise knowledge of oscillation parameters**
  - New Physics? (sterile, ..)

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

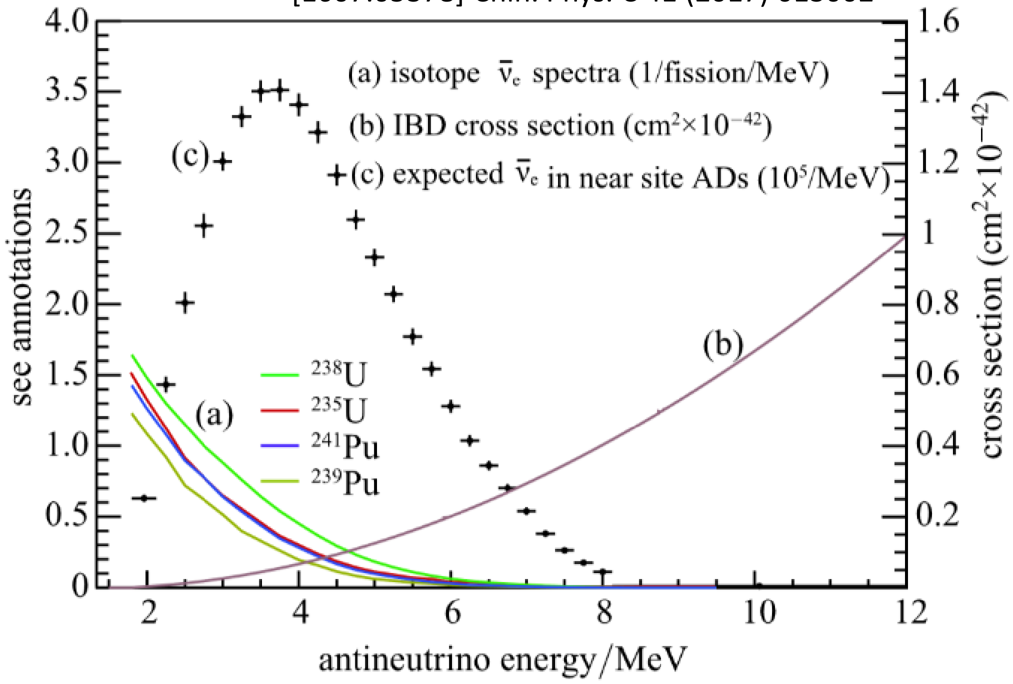
θ_{23} & Δm^2_{32}	θ_{13} & δ_{CP}	θ_{12} & Δm^2_{21}	Majorana phases
Atmospheric, Accelerator	***Reactor***, *Accelerator*	***Reactor***, *Solar*	*Double beta decays*

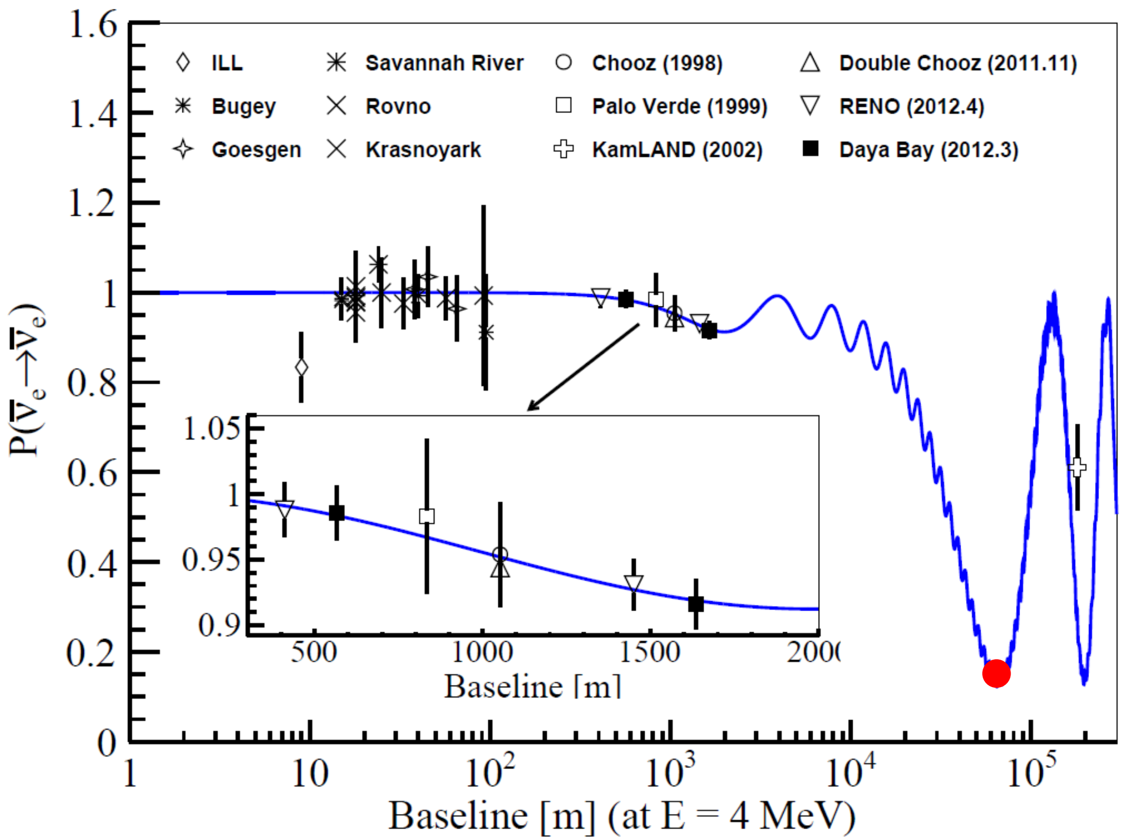


Reactor Neutrinos Experiments will continue to play a critical role in solving the unknowns

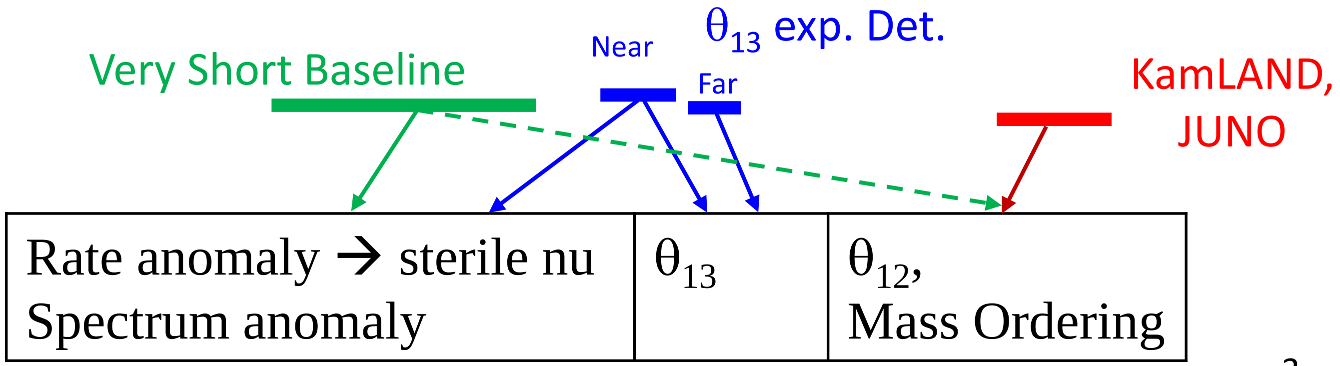
Reactor Neutrinos

[1607.05378] Chin. Phys. C 41 (2017) 013002





- Reactor antineutrino: $\bar{\nu}_e$ emitted as fission products decay
- Commercial reactor (LEU) ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu; Research HEU (^{235}U)
- Usually detected via Inverse Beta Decay (IBD)




江門中微子實驗
Jiangmen Underground Neutrino Observatory
Bei Zhen Hu.
2022.12.22 @JUNO

$\Delta m^2_{32} > 0$?

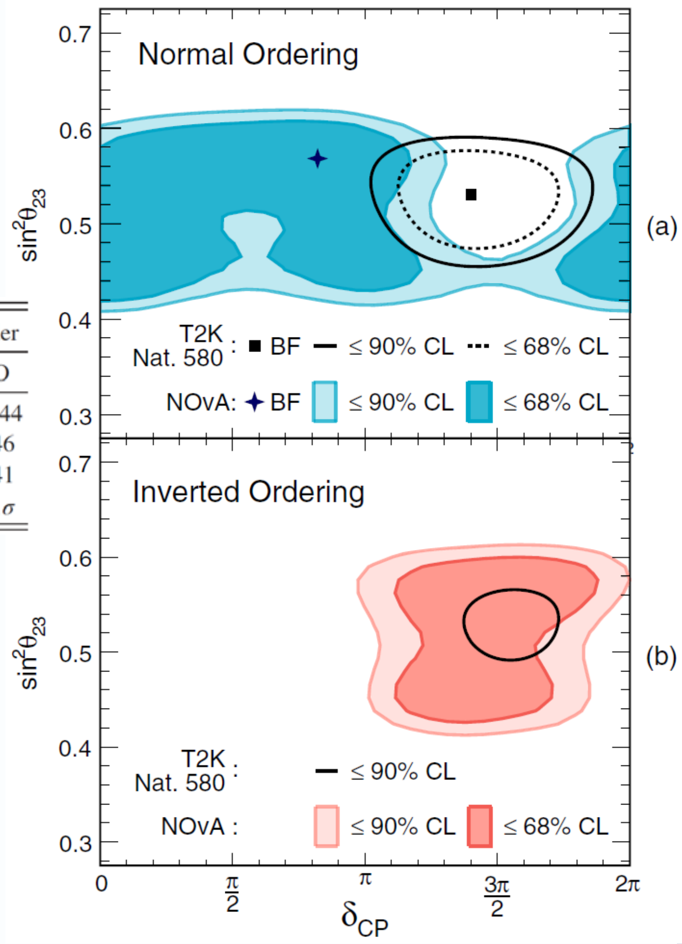
Current NMO sensitivity from Accelerators

NOvA

PRD 106, 032004 (2022)

Parameter	Normal order UO	Normal order LO	Inverted order UO	Inverted order LO
$\Delta m^2_{32} (10^{-3}\ \mathrm{eV}^2)$	$+2.41 \pm 0.07$	$+2.39$	-2.45	-2.44
$\sin^2\theta_{23}$	$0.57^{+0.03}_{-0.04}$	0.46	0.56	0.46
$\delta_{CP}(\pi)$	$0.82^{+0.27}_{-0.87}$	0.07	1.52	1.41
Rejection significance	–	1.1σ	0.9σ	1.1σ

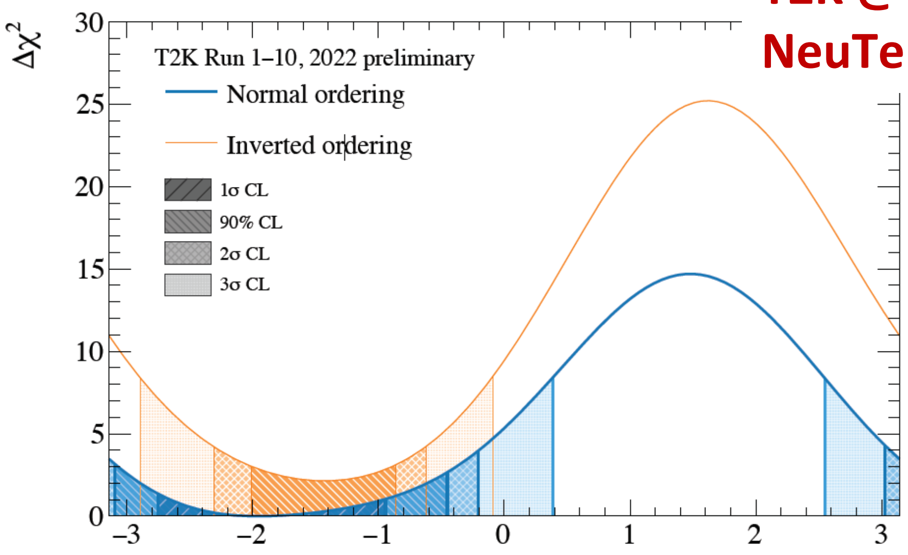
- **IH:** the vicinity of δ=π/2 excluded at >3σ
- **NH:** δ=3π/2 disfavored at 2σ level



Results on the CP phase measurement

- Large region **excluded at 3σ**
- CP-conservation values ($\sin\delta_{CP} = 0$) **excluded at 90% C.L.**
- Weak preference of **normal ordering**

T2K @ NeuTel2023



Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.75, -0.94]$	
90%	$[-3.10, -0.45]$	$[-2.01, -0.86]$
2σ	$[-\pi, -0.21] \cup [3.02, \pi]$	$[-2.31, -0.62]$
3σ	$[-\pi, 0.39] \cup [2.55, \pi]$	$[-2.89, -0.09]$

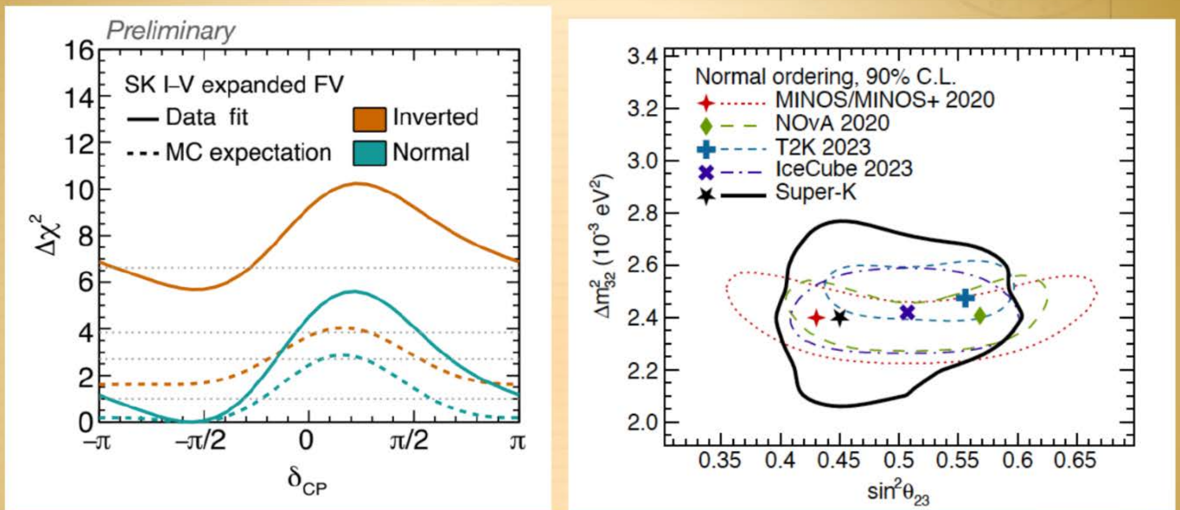
T2K Run 1-10, preliminary

Joint analysis between NOvA and T2K ongoing

Current NMO sensitivity from Atmospheric ν

SK atmospheric ν results

With $\sin^2\theta_{13}$ constrained
$\sin^2\theta_{13} = 0.0220 \pm 0.0007$
[PTEP 2022, 083C01 (2022)]



SK 2023 best fit results: Normal ordering, $\delta_{CP} \simeq -\pi/2$, $\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3}\text{eV}^2$, $\sin^2\theta_{23} \simeq 0.45$

Mass ordering: $\Delta\chi^2_{I.O-N.O} \simeq 5.7$

This analysis prefers NO over the IO at the 92.3% confidence level.

Magdalena Posiadala-Zezula, XX International Workshop on Neutrino Telescopes, Venice 23-27 Oct 2023

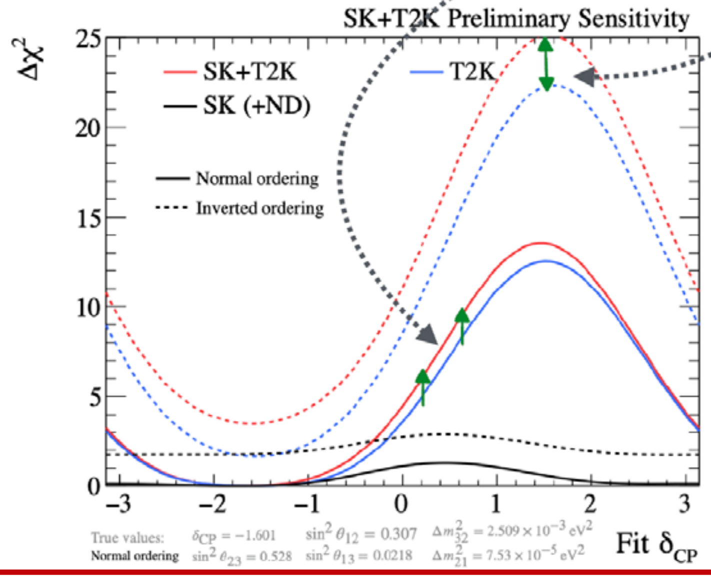
Super-K + T2K Dataset, samples and systematics

T2K Run 1-10 (from the previous analysis EPJC)
5 beam samples

SK IV atmospherics (from PTEP 2019 (2019) 5, 053F01)
18 atmospheric samples

Preliminary sensitivity results

- Asimov sensitivities at true $\sin^2\theta_{23} = 0.528$, $\delta_{CP} = -1.601$, Normal Ordering
- Δm^2_{32} & θ_{23} constraint is dominated by T2K
- Main benefit of joint fit is that both experiments are sensitive to MO
- Noticeable sensitivity boost for δ_{CP} in the ~0 region



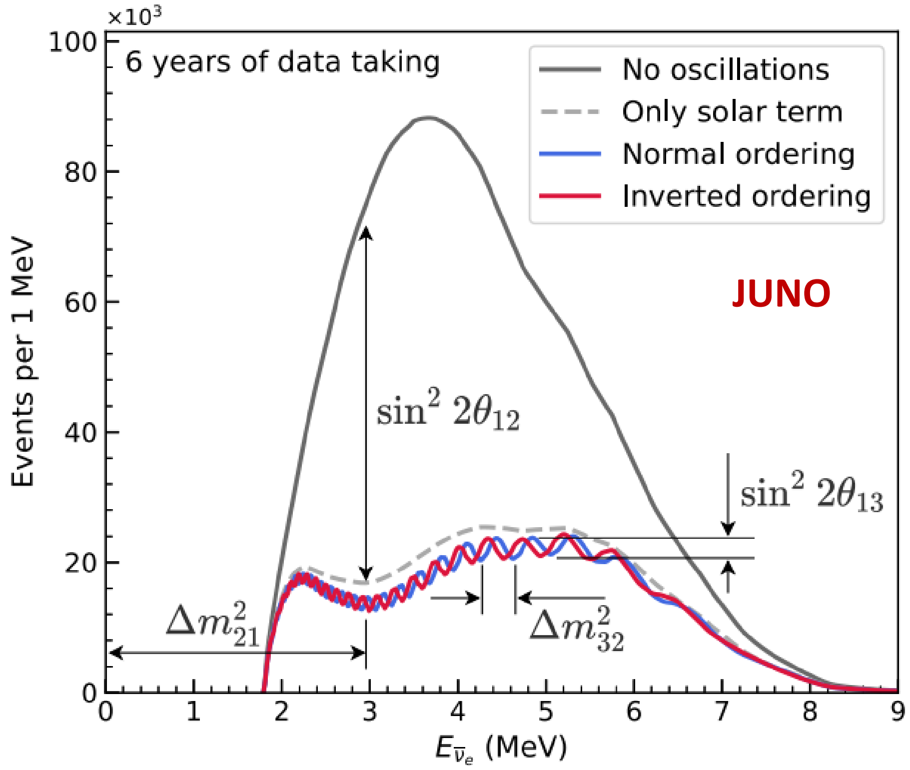
T2K @ NeuTel2023

Mass Ordering w/ reactors

- ‘Vacuum oscillation’ with reactor neutrinos → unique and complementary with accelerator/atmospheric experiments to determine neutrino mass ordering

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

- Precision measurements of θ_{12} , Δm^2_{21} , Δm^2_{32}
- Require huge mass and high energy resolution



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

Δm^2_{31} and Δm^2_{32} interplay	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

Reactor

Atmospheric

Accelerator

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta\,\sin\theta_{13}\,\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}(\cos 2\theta_{12} - \cos\delta\,\sin\theta_{13}\,\sin 2\theta_{12}\tan\theta_{23})$$


Guangzhou
广州市
Dongguan
东莞市
Huizhou
惠州市
Shenzhen
深圳市
DYB
Daya Bay
NPP
Hong Kong
Macao
Jiangmen
Zhongshan
中山市
JUNO
53 km
53 km
JUNO-TAO
Taishan NPP
Yangjiang NPP
Jiangmen Underground Neutrino Observatory
Vertical tunnel:
563 m
Overburden
~650 m (1800
m.w.e.)
Slope tunnel: 1265 m
@ slope of 42%
© 刘悦湘
Civil construction finished in Dec, 2021

Challenges…

50 m x 70 m
Exp. Hall

35.4 m
acrylic sphere,
vs. 13 m@ SNO

20 kton
Liquid scintillator,
Borexino X40,
KamLAND X20
λ>20 m,
U/Th<10^{-17} g/g

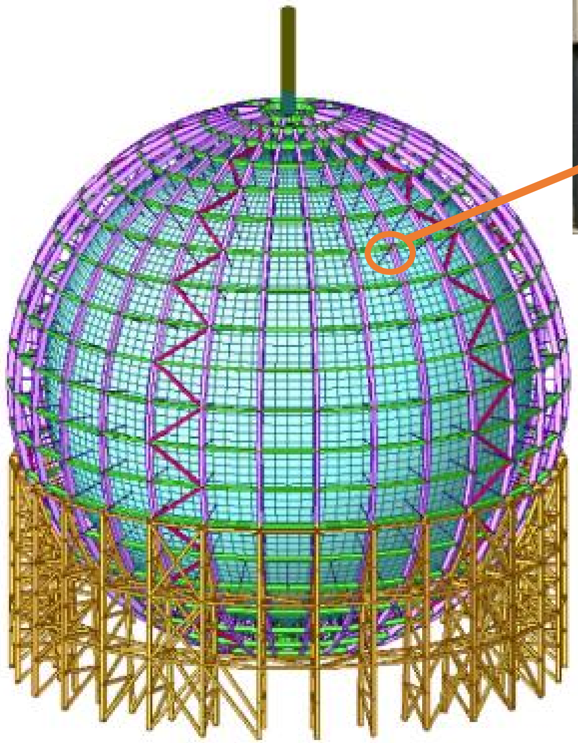
20,000
20-in PMT, ε~30%

Best Light yield
Borexino X2,
KamLAND X5

Central Detector (SS structure)

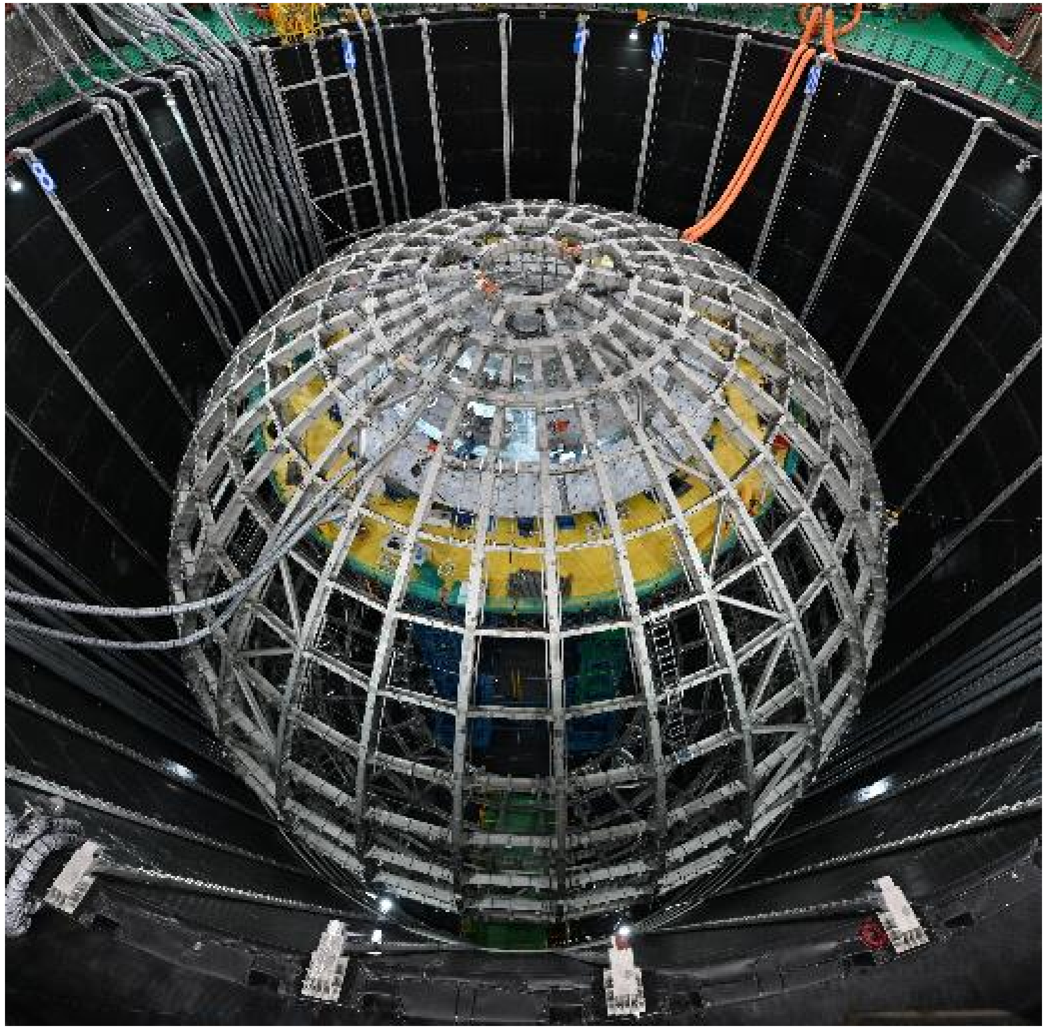
Acrylic vessel is supported by D = 40.1 m stainless steel structure via 590 Connecting Bars

Assembly precision: < 3 mm for each grid



an all-bolted stainless steel structure, using 120,000 sets of high-strength SS short-tail grooved rivets

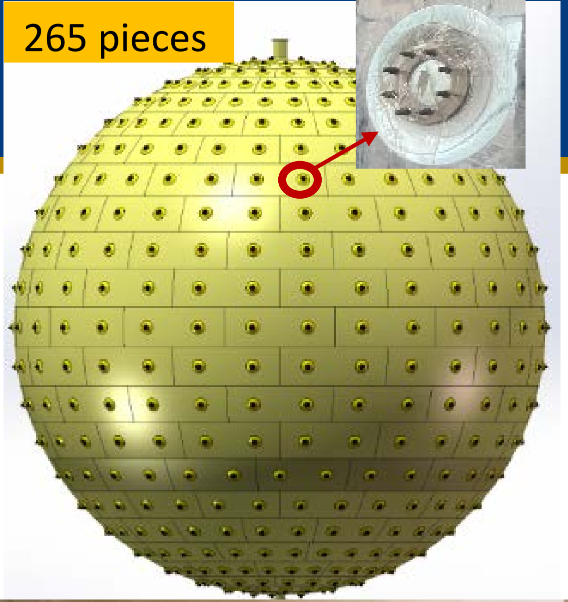
overall deformation ~20 mm
spherical center deviation: (-2, 6, -11) mm



The platform to install the acrylic vessel

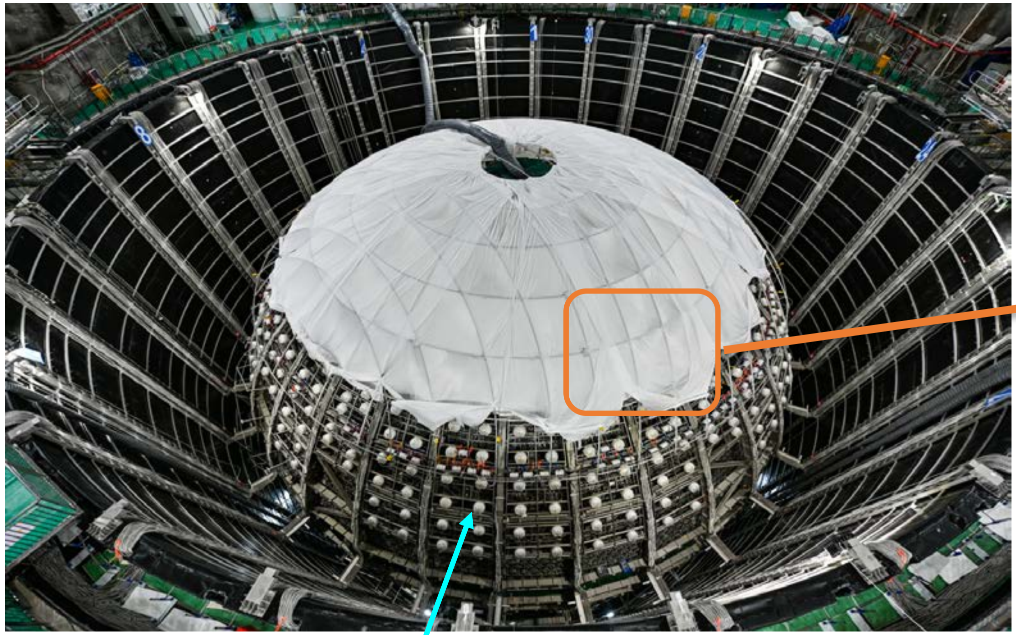
Central Detector (Acrylic Vessel)

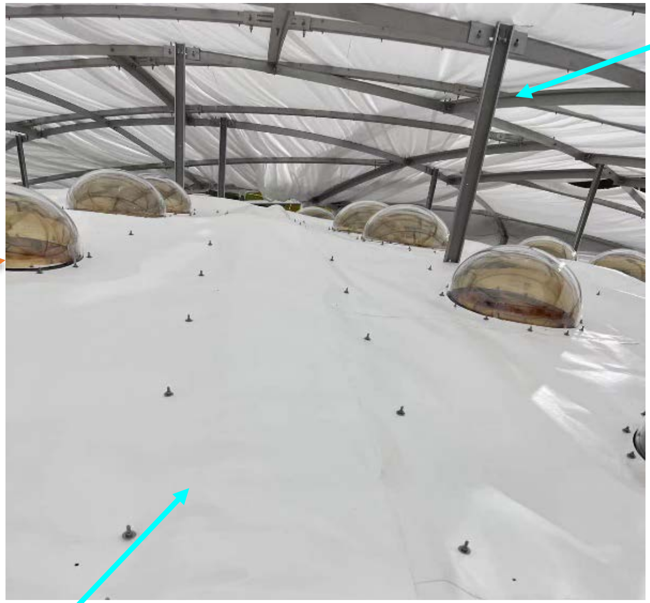
- World-largest acrylic vessel (Φ 35.4 m, 124±4 mm thickness)
- Ultra-clean production of 265 panels
  - Curved w/ high precision & Transparency > 96%
  - Ultra-low U/Th: < 1 ppt
- Developed new bonding technology to simultaneously bond all panels in one circle



	Φ	Weight	Bonding	Thickness
JUNO	35.4 m	600 t	2 km	120 mm
SNO	12 m	30 t	500 m	56 mm

Veto Detector (water Cherenkov)





Earth magnetic shielding coils installation:

20 coils installed (32 coils in total)

Veto PMTs installed(~24% of PMT)

Tyvek reflective film installation (~500 m^2)

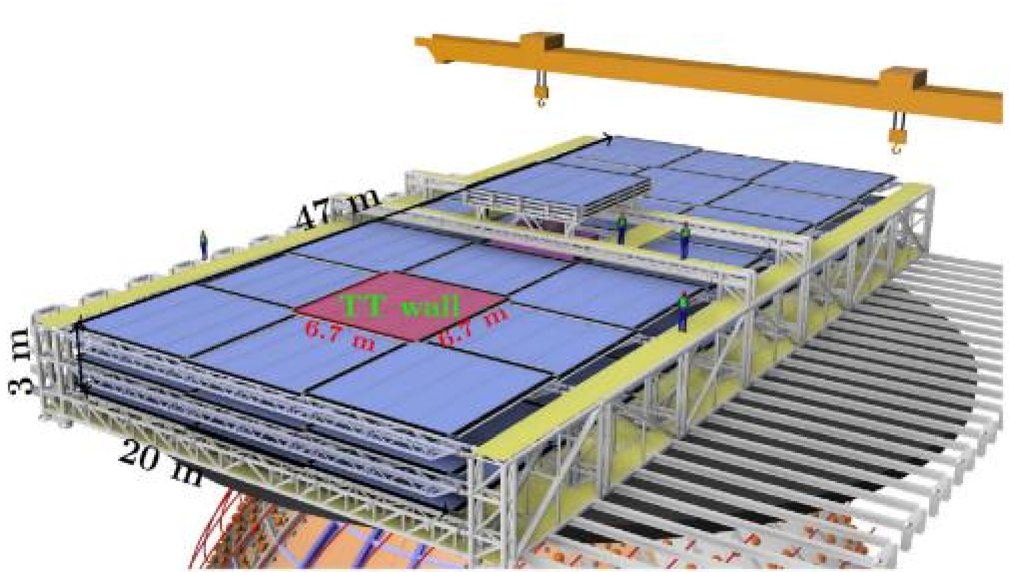
Water system is almost ready for commissioning

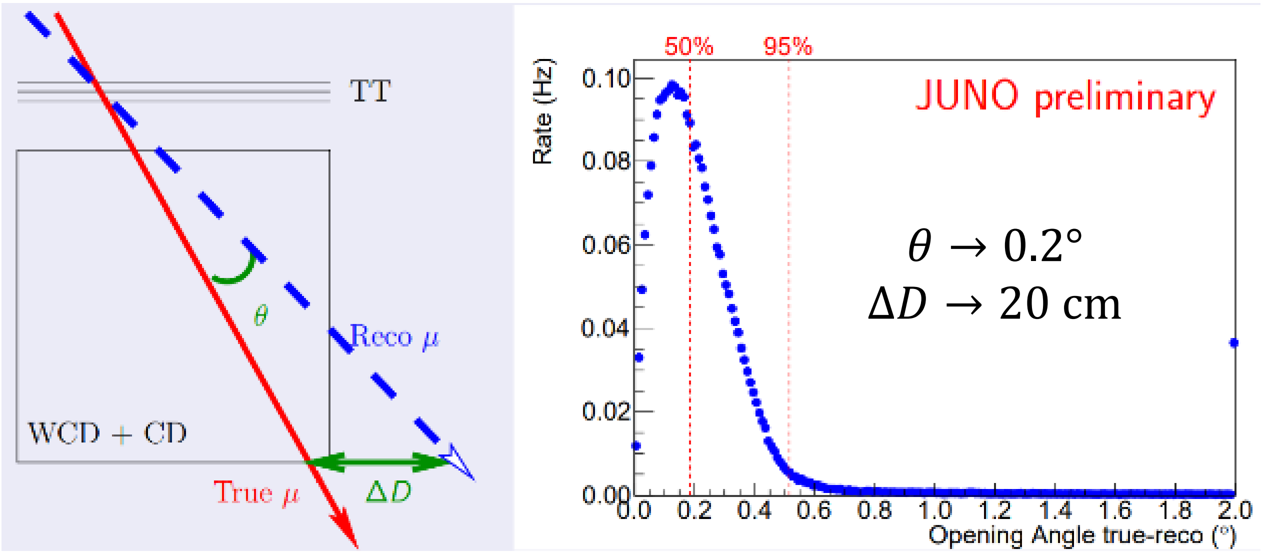
35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

- 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

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

Veto Detector (Top Tracker)





Plastic scintillator from the OPERA experiment

- About 60% 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 (LS)

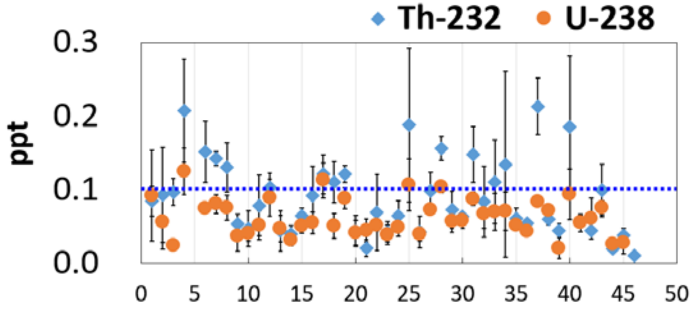
- **Challenges for 20 kton LS**
  - Most transparent LS: **attn. >20 m**
  - Ultra-low radioactivity: **U/Th<10^{-17} g/g (< 10 mg dust)**

Need be achieved in the first place, otherwise online circulation is difficult

- **The most complex system designed and built, using four purification technologies**
  - Al_2O_3 filtration
  - Distillation
  - Gas tripping
  - Water extraction

  Joint commissioning ongoing

- **Raw material control**
  (LS recipe: LAB + 2.5 g/L PPO + 3 mg/L bis-MSB)
  - Highly transparent LAB: **λ_{attn} ~ 22-23 m**
  - Ultra-low radioactivity PPO: **U/Th<0.1 ppt**
  - Ultra-pure water for liquid-liquid extraction: **<10^{-16} g/g**



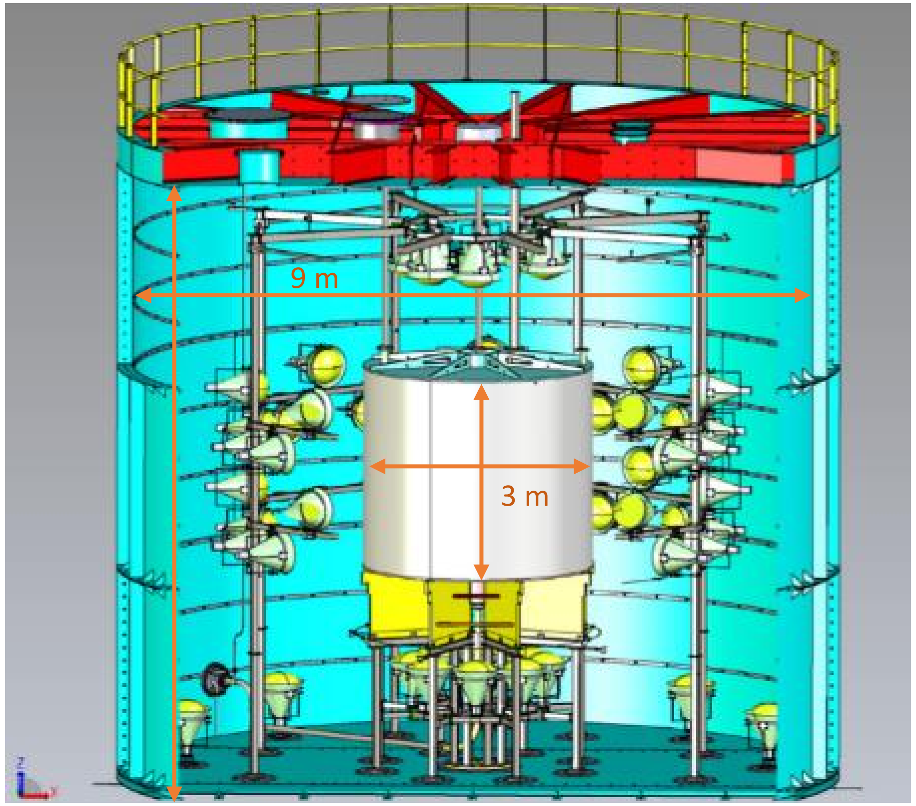
Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

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

Commissioning ongoing

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

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

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

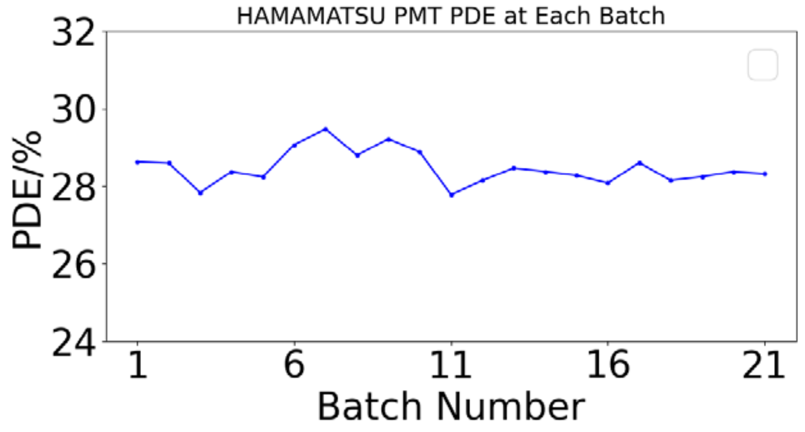
w/ protection cover (JINST 18 (2023) 02, P02013)

~7200 LPMT and ~9300 SPMT have been installed

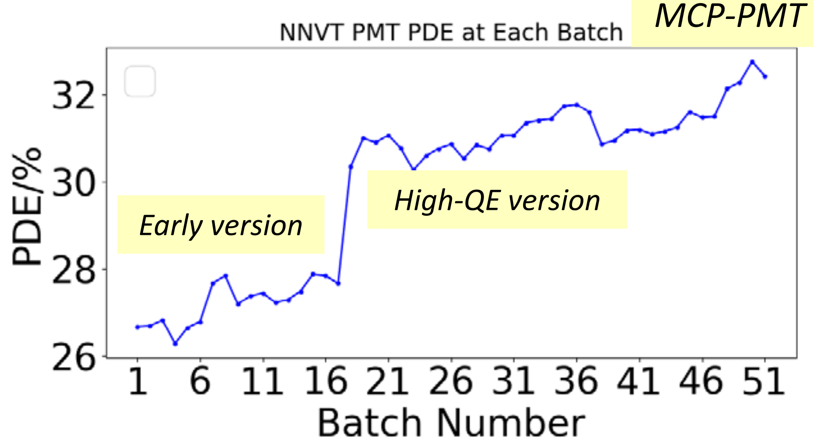
Eur. Phys. J. C 82 (2022) 12

Photomultiplier Tubes

Dynode-PMT



MCP-PMT



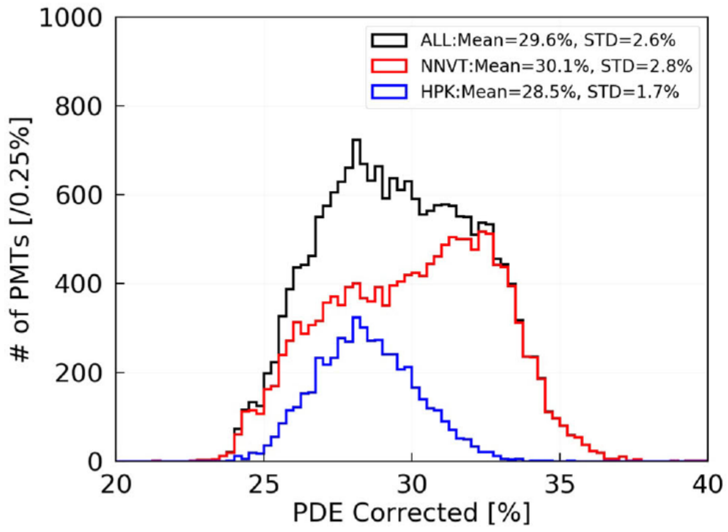
An innovative PMT optical model: Eur. Phys. J. C (2022) 82:329

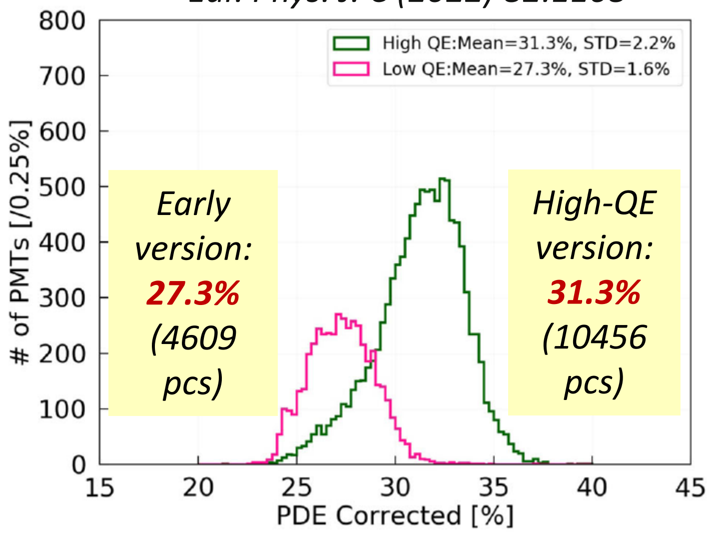
All PMTs produced, tested, and instrumented with waterproof potting

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

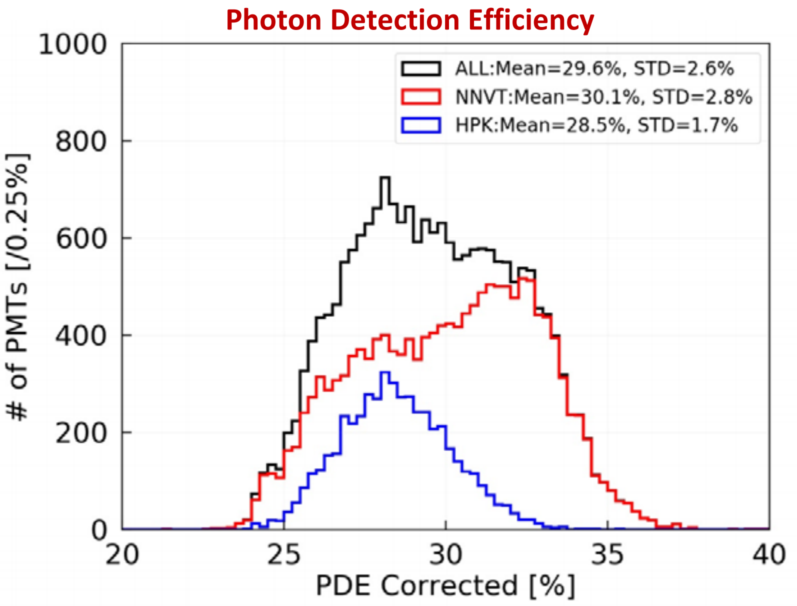
	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Charge Collection	Dynode	MCP	Dynode
Photon Detection Efficiency	**28.5%**	**30.1%**	25%

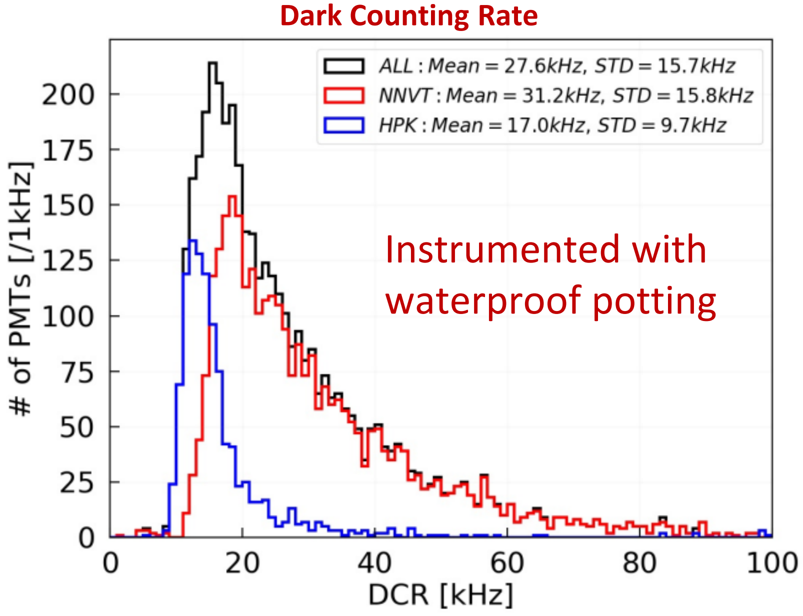
Eur. Phys. J. C (2022) 82:1168





Photomultiplier Tubes





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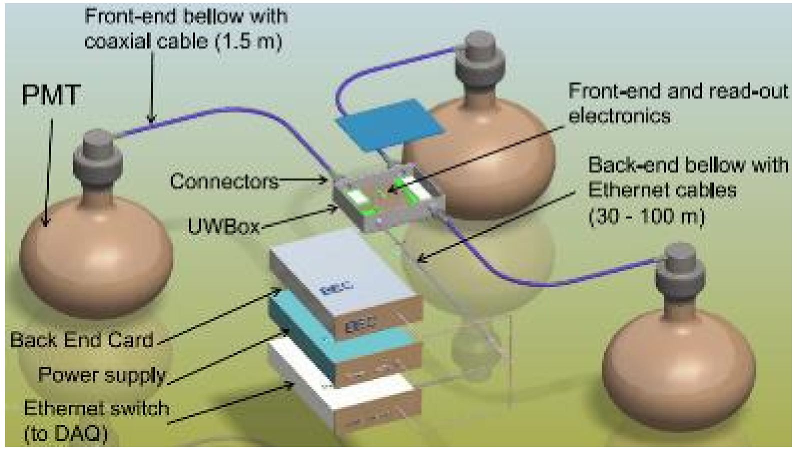
12.6k NNVT PMTs with highest PDE are selected for light collection from LS and the rest are used in the Water Cherenkov detector.

		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

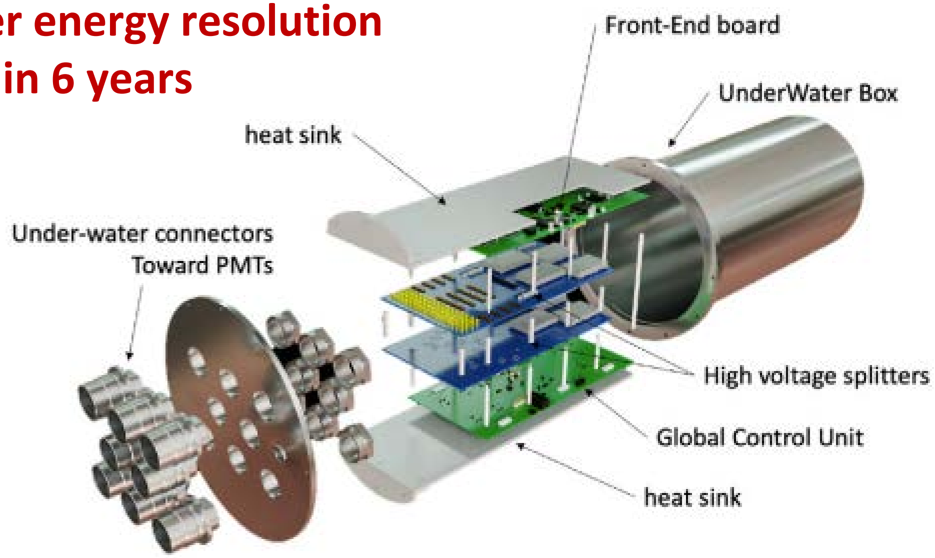
Failure rate requirement: <0.5% in 6 yrs, while same for underwater Elec.

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

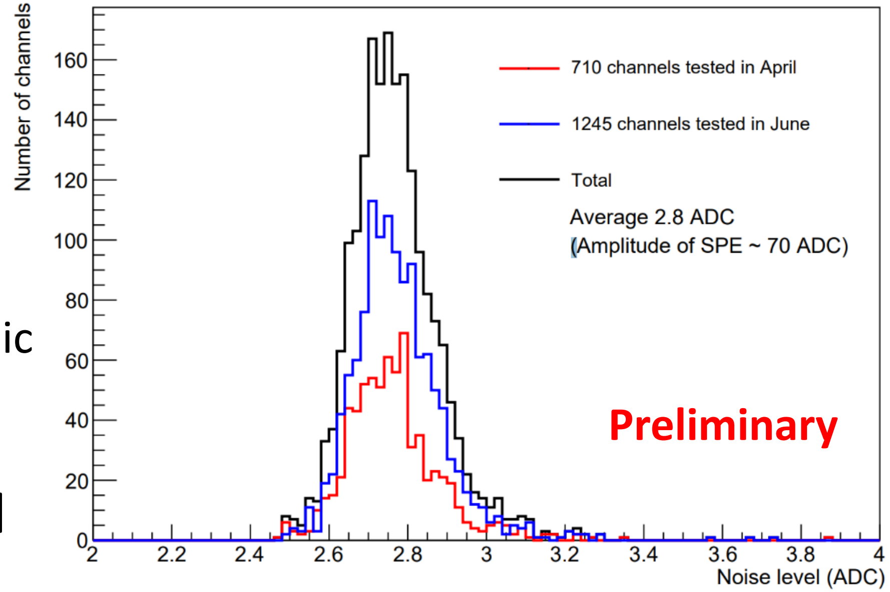


3 20-inch PMTs connected to one underwater box



128 3-inch PMTs connected to one underwater box

Electronic Noise Level [LPMT]

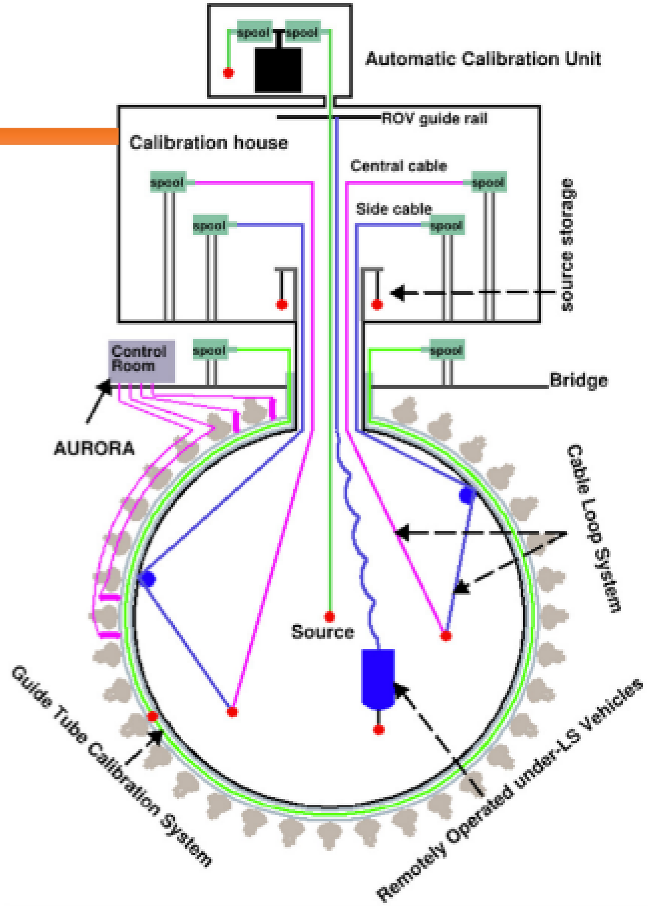


- 6862 boards produced and tested before installation
- Ongoing test campaign during installation
- Careful design & excellent grounding: noise level: 4% at 1 photoelectron better than specs: 10% at 1 p.e.

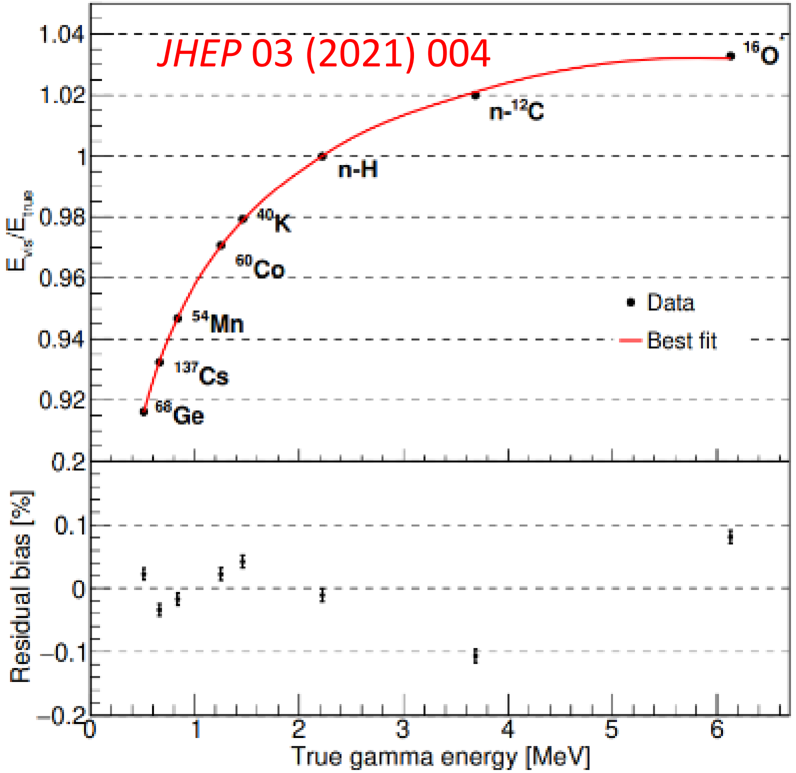
Calibration

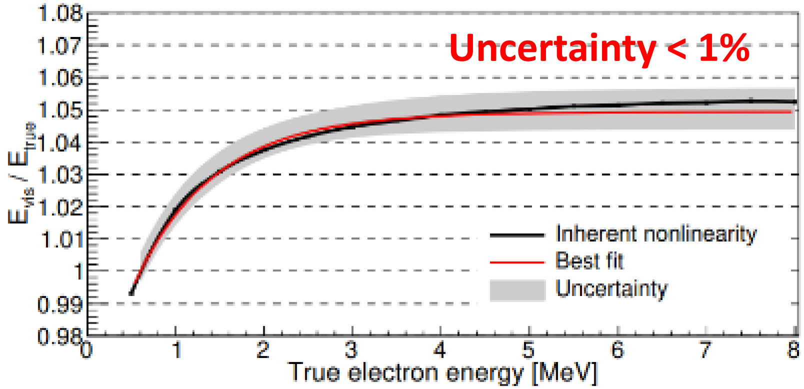
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system prototype



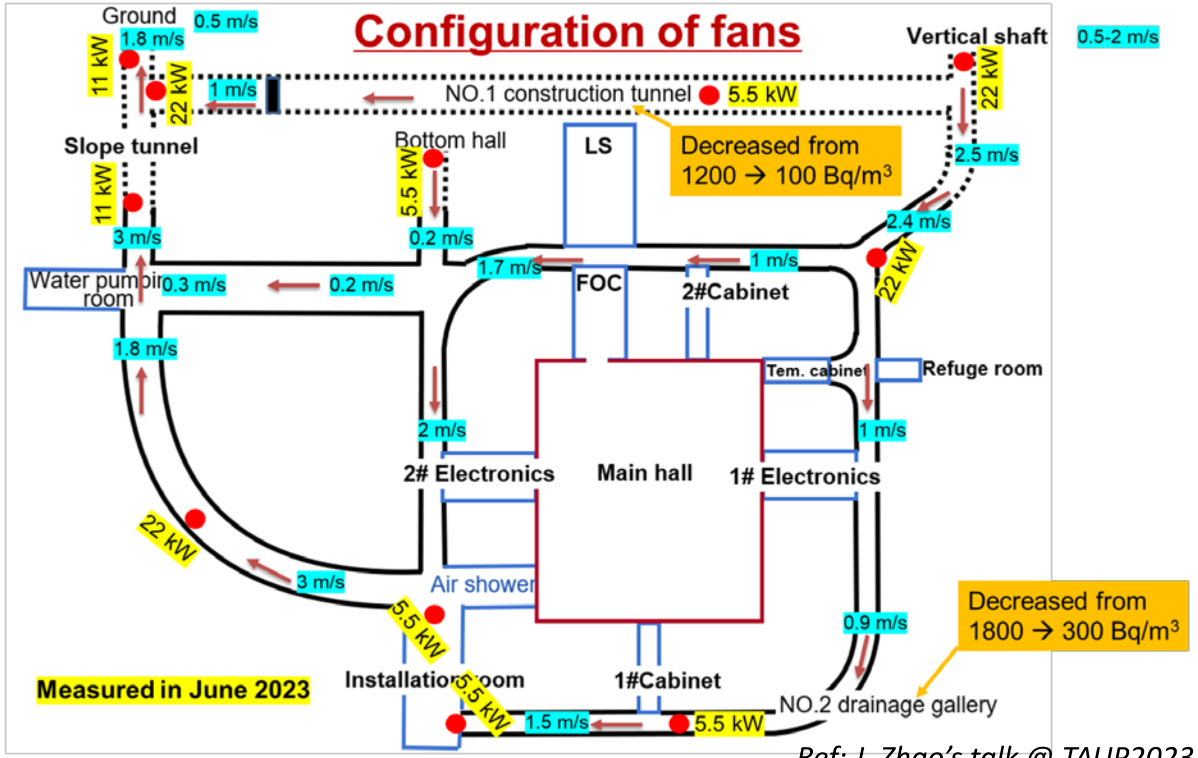
Shadowing effect uncertainty from Teflon capsule of radioactive sources: < 0.15%



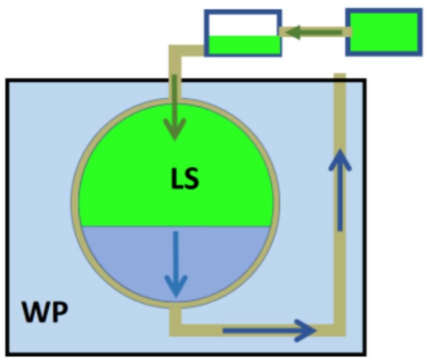


Background Control

- **Environmental Radon control**
  - Large amount of underground water at JUNO site: **450 m³ /h with 120,000 Bq/m³ radon in water** → underground water is a large radon source
  - Continuous improvement of ventilation → radon in Exp-Hall reduce to **100-200 Bq/m³**
- **Materials control & cleanness → <7.2 Hz in FV (spec: 10 Hz)**
  - LS (LAB, PPO, bisMSB)
  - Acrylic
  - PMT glass
  - SS Struss
  - PMT readout Electronics
  - Ultra-pure water (micro-bubbling tech.)
- **Cleanness control during installation & Filling**



Ref: J. Zhao's talk @ TAUP2023



Physics sensitivities

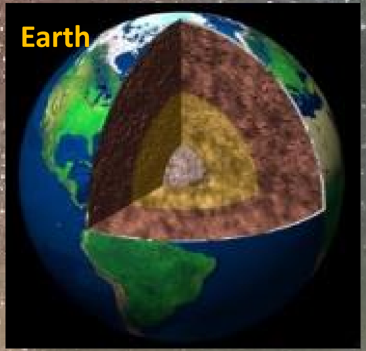
For topics not covered here, please refer to *PPNP 123 (2022) 103927*

~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

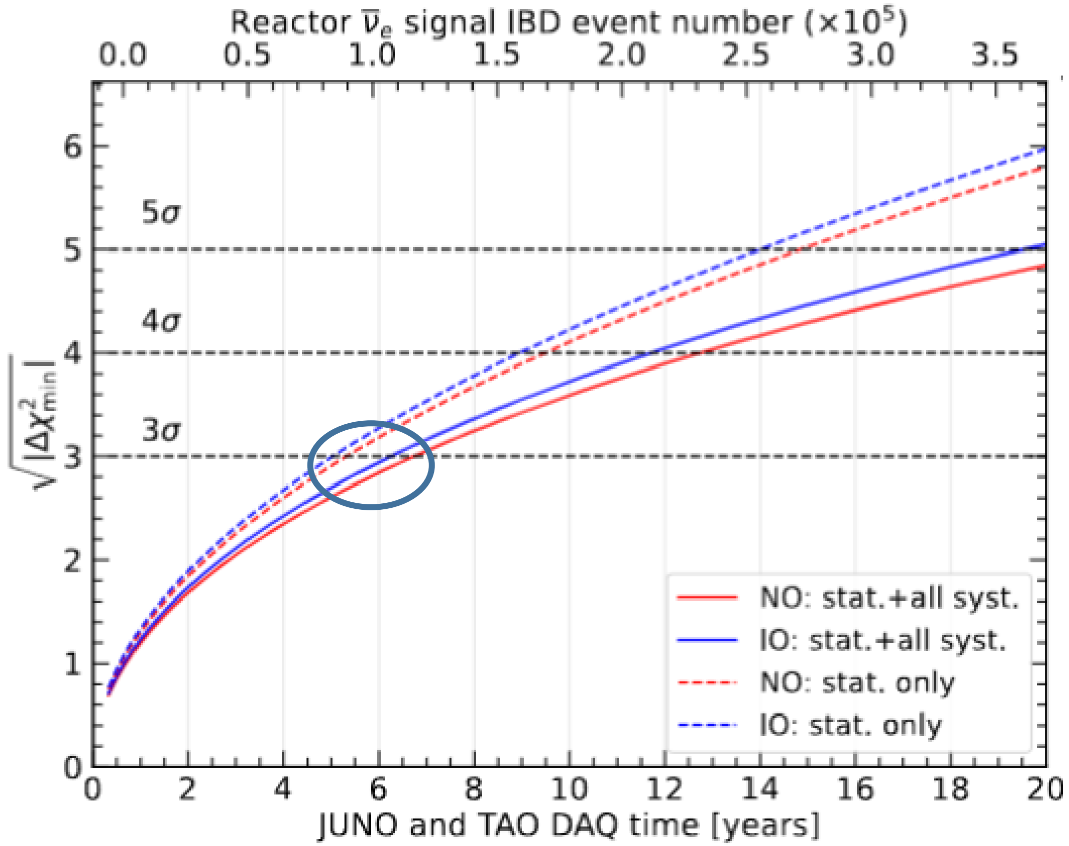
\+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay
CCSN: core-collapse supernova
DSNB: Diffused Supernova Neutrino Background

Neutrino Mass Ordering w/ reactors

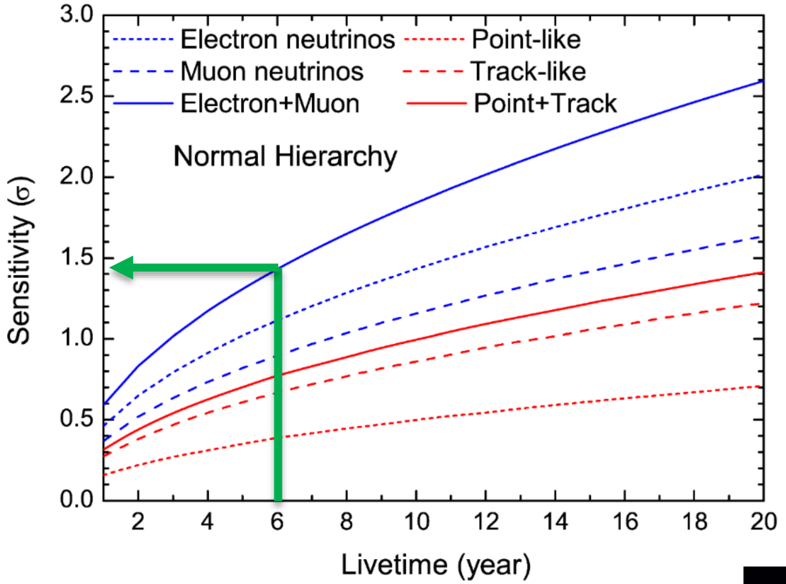


	Design *	Now
Thermal Power	36 GW_{th}	26.6 GW_{th} (26%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Signal rate	60 /day	47.1 /day (22%↓)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3% @ 1 MeV	2.95% @ 1 MeV
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. exposure	**< 6 yrs × 35.8 GW_{th}**	**~ 6 yrs × 26.6 GW_{th}**

* J. Phys. G 43:030401 (2016)

- JUNO NMO sensitivity: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**
- Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity

NMO synergy at JUNO

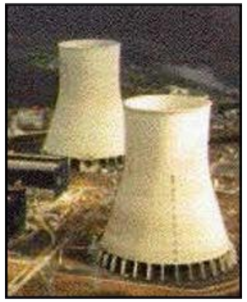


Conservative 6 yrs sensitivity on NMO:

0.8~1.4 σ (atmospheric only)

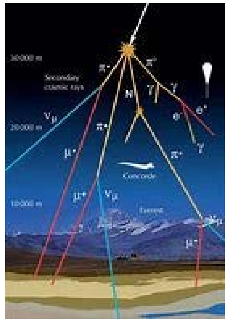
J. Phys. G43:030401 (2016)

Ongoing efforts to improve the reconstruction (e.g., 2310.06281) & Particle ID of atmospheric neutrinos



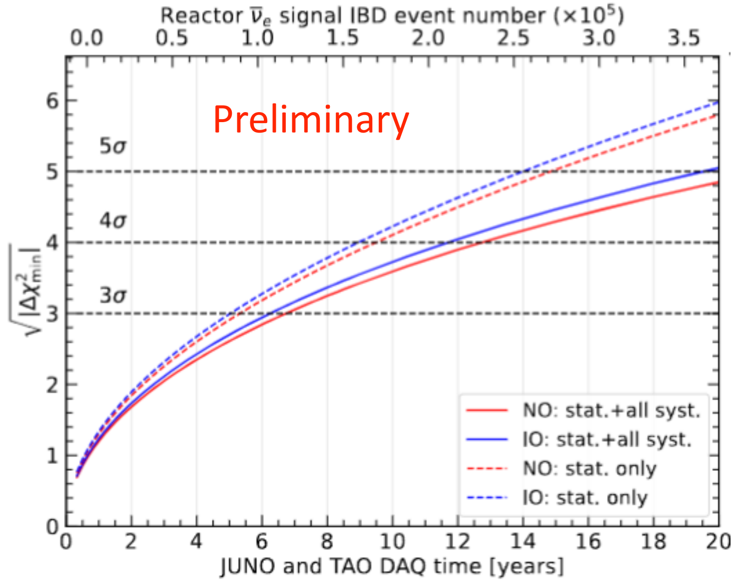
reactor ν
MeV

Neutrino Mass Ordering

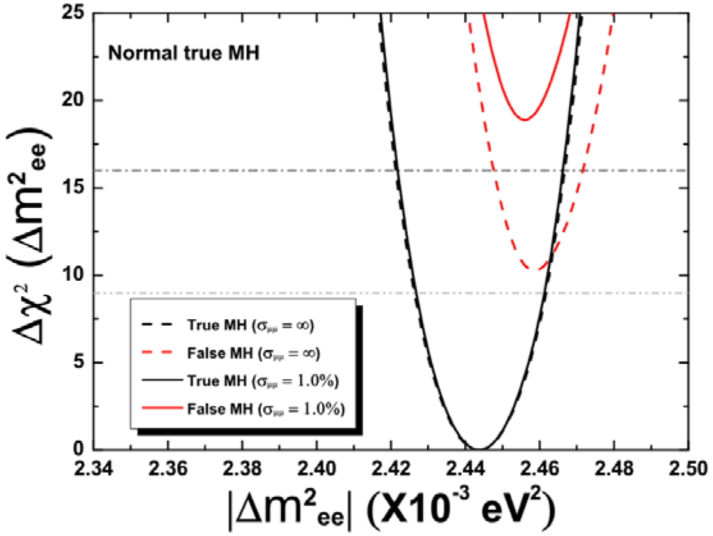


atm.ν
GeV

$|\Delta m^2_{\alpha\alpha}|$



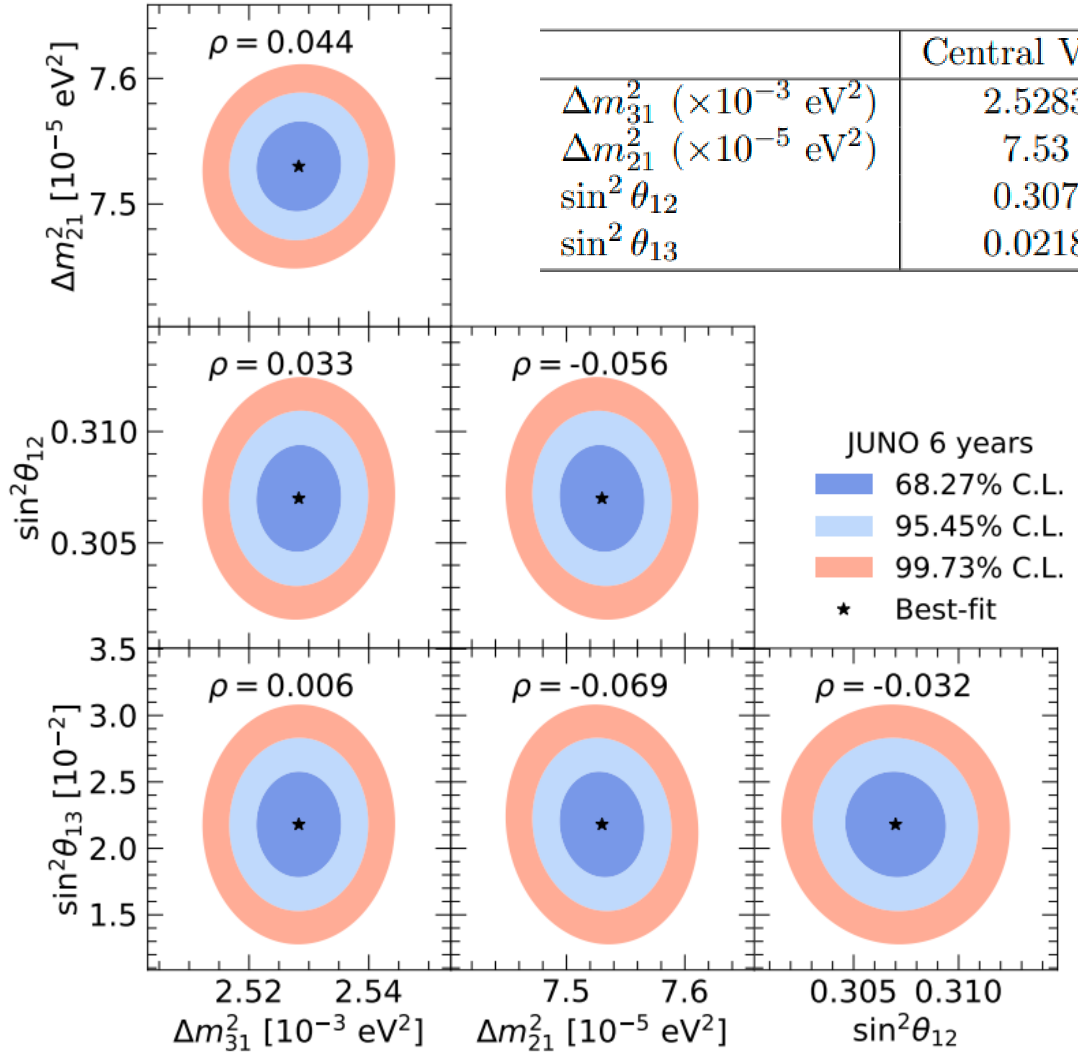
Phys. Rev. D 88 (2013) 013008



Ref: W. Luo's talk @ LeptonPhoton2023

Neutrino oscillation parameters w/ reactors

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



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

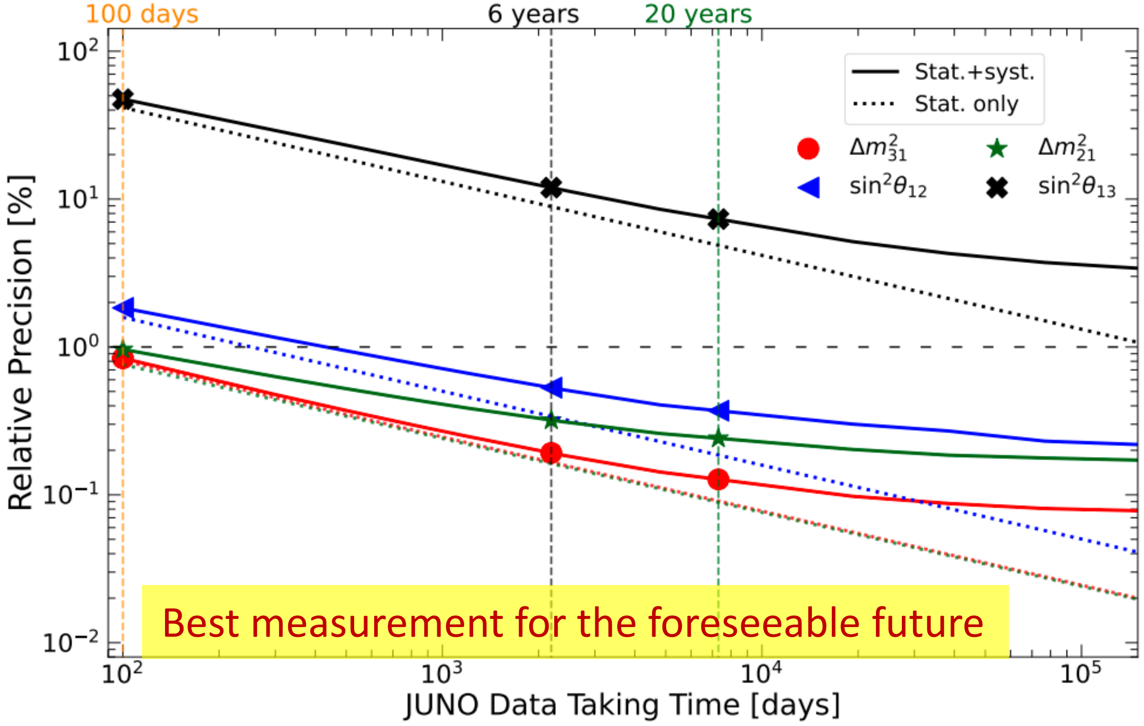
	Central Value	PDG2020	100 days	6 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)
$\sin^2\theta_{13}$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

Direct Measurement

2.3% ($|\mathbf{\Delta m^2_{32}}|$, DYB)

2.5% (KamLAND)

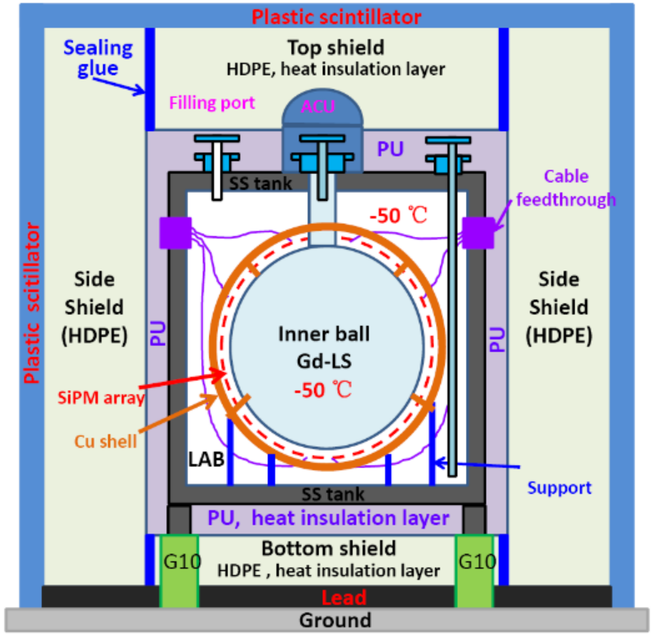
5% (SNO)



The improvement in precision over existing constraints will be about one order of magnitude except for θ_{13}

Fine Structures in the Spectrum (JUNO-TAO)

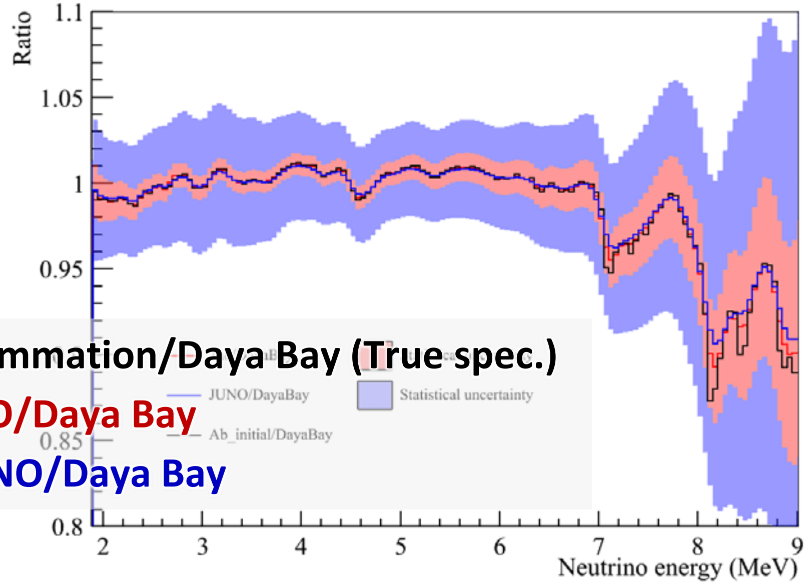
- **Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the 4.6 GW_{th} core, a satellite exp. of JUNO.**
- **Measure reactor neutrino spectrum w/ high E resolution.**
  - **Model-independent reference spectrum for JUNO**
  - **A benchmark for testing the nuclear database**



CDR: 2005.08745

Calibration strategy: 2204.03256

- **Detector Features**
  - 2.8 ton Gd-LS, 10 m^2 SiPM (84.6% photocathode coverage) w/ PDE > 50%
  - Operate at -50 ℃ (suppress SiPM dark noise)
  - 4500 p.e./MeV, <2% resolution @ 1MeV
- **Expected online in 2024**



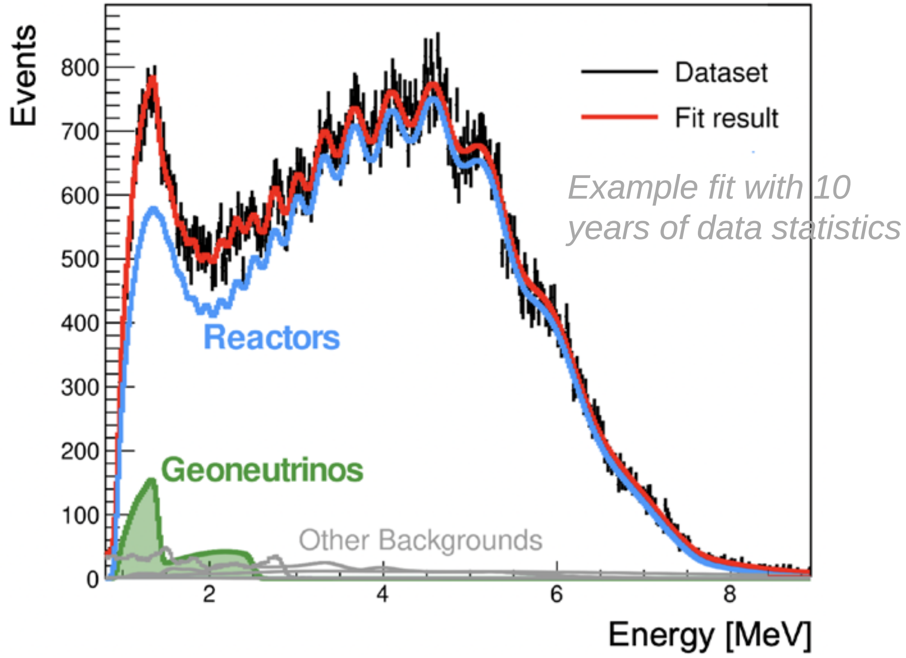
Solid: Summation/Daya Bay (True spec.)
RED: TAO/Daya Bay
Blue: JUNO/Daya Bay

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

2111.10112

Geo-neutrino sensitivity

- ~400 geo-ν/year (based on GLOBAL model)
- Significant updates since YB & PPNP 123, 103927 (2022)
  - Same updates as for NMO and precision measurement
  - Updated geo-ν model, e.g., JULOC(-I) predict ~30% more ν
  - Updated detector inputs, spectrum uncertainties
- Expected precision for U+Th, U, Th, Th/U ratio and mantle obtained
- Mantle discovery potential is under ongoing
  - Mantle = Total Geonu Measurement – Lithosphere Prediction



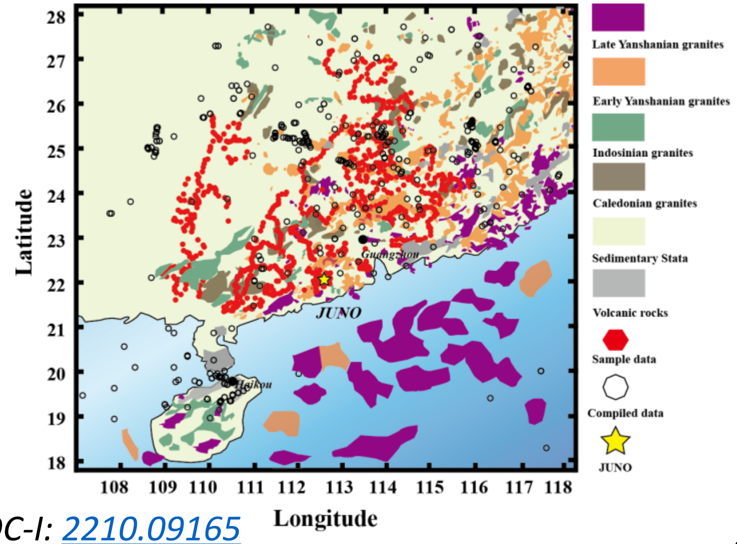
Expected geoneutrino precision
(assuming Th/U mass ratio fixed to 3.9)

1 year	~22%
6 years	~10%
10 years	~8%

PRELIMINARY

	6 years	10 years
^{232}Th:	~40%	~35%
^{238}U:	~35%	~30%
^{232}Th+^{238}U:	~18%	~15%
^{232}Th/^{238}U ratio:	~70%	~55%

PRELIMINARY

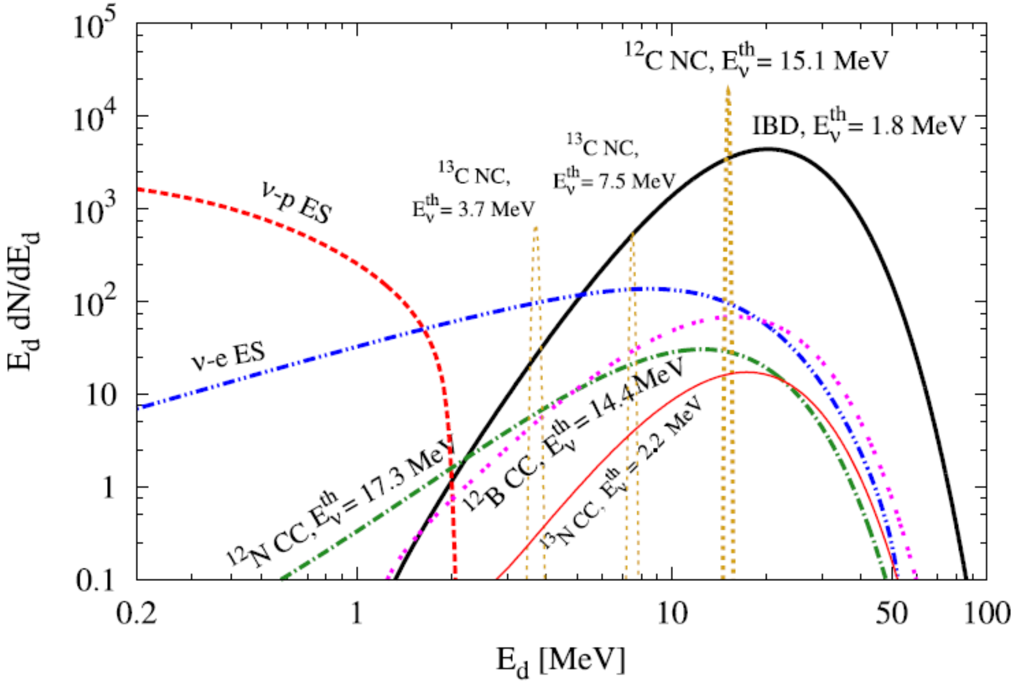


JULOC: 1903.11871, JULOC-I: 2210.09165

Core-collapse Supernova Neutrinos (CCSN)

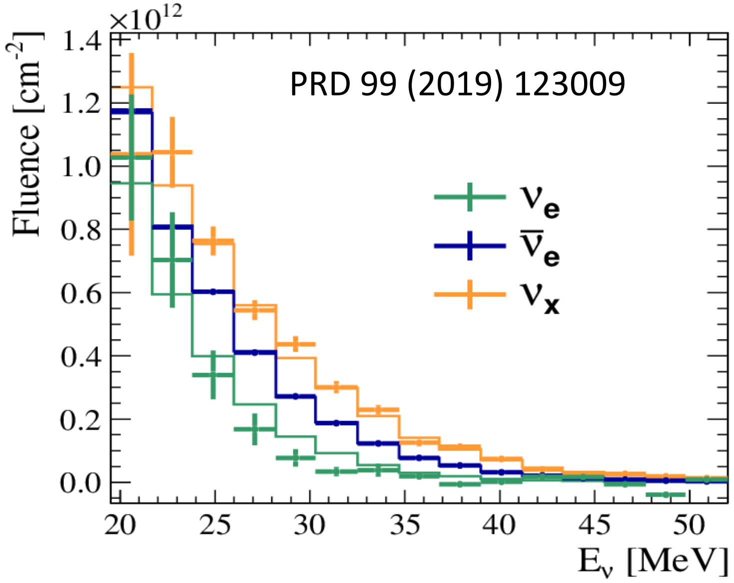
Multi-channel detection, all flavors of CCSN:

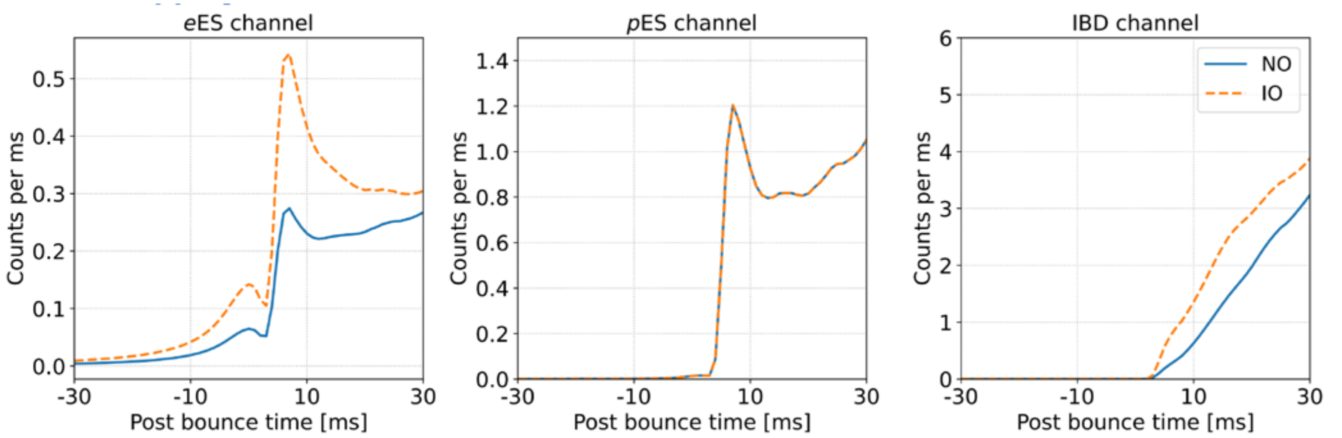
~5000 IBD, ~300 eES, ~2000 pES， ~200 ^{12}C CC, ~300 ^{12}C NC @10 kpc



Allow model-independent reconstruction of the energy spectra of $\bar{\nu}_e, \nu_e, \nu_x$ via unfolding approach ➔

Full chain Monte Carlo analysis ongoing





Garching group, 1D simulation, LS220 EoS , 27 solar mass

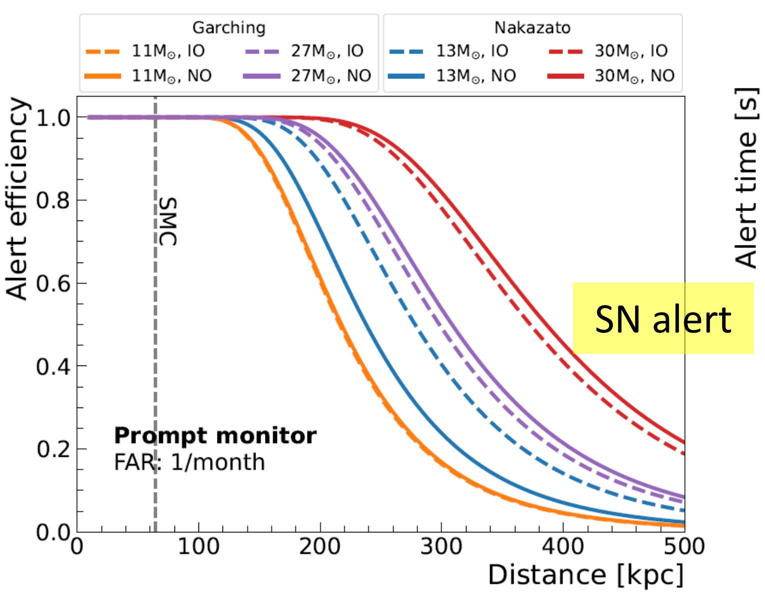
Other physics Potentials

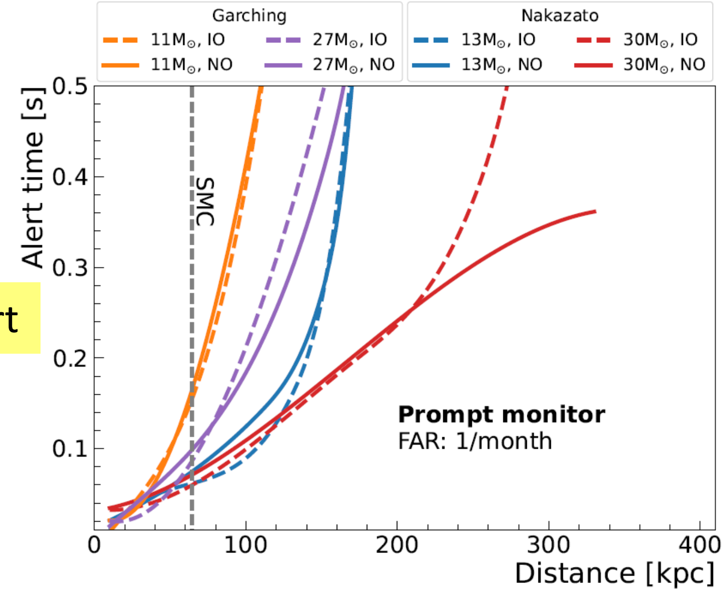
- Neutrino mass ordering : using MSW matter effect, pES channel to anchor the bounce time
- Absolute neutrino masses: probing the mass of ν_x (rather than ν_e) with pES channel, or absolute masses from black hole forming CCSNe

Important effects: Model dependency and Threshold

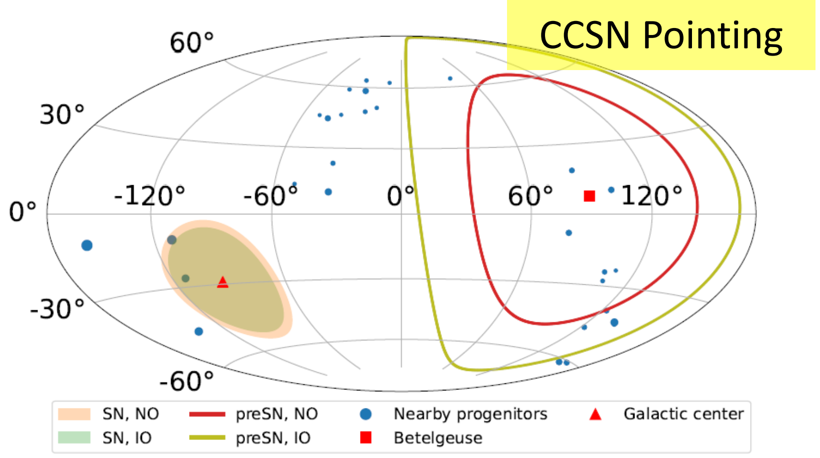
Core-collapse Supernova Neutrinos (CCSN)

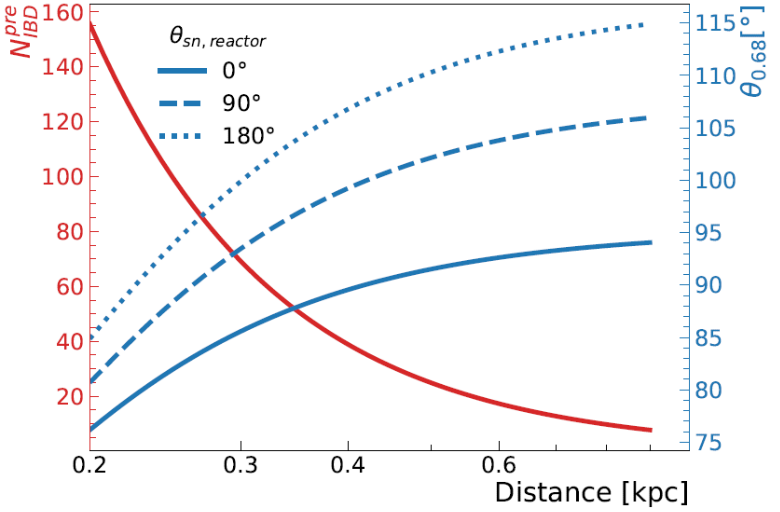
- Excellent capability of early warning
- CCSN
  - reach 220 ~ 400 kpc w/ 50% prob.
  - alert in 10 ~ 30 ms for typical 10 kpc
- pre-SN:
  - reach 0.6 ~ 1.7 kpc w/ 50% prob.
  - >~ 100 hr in advance if 0.2 kpc

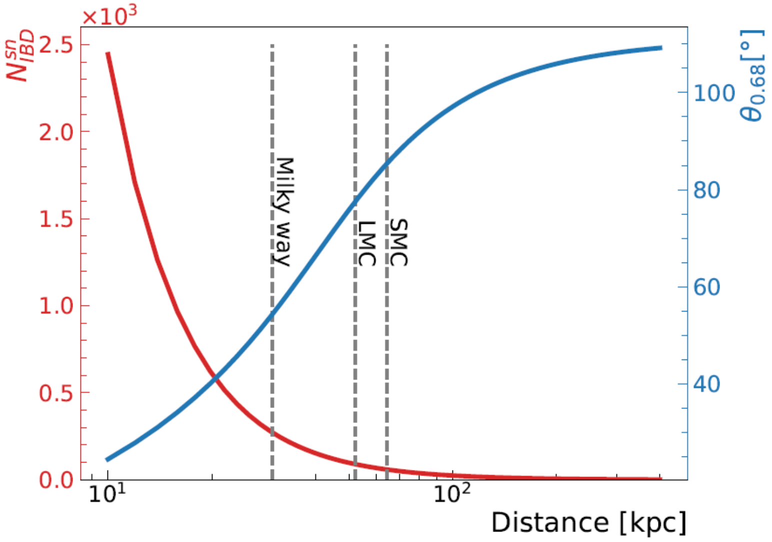




[2309.07109], accepted by JCAP







Diffused Supernova Neutrino Background (DSNB)

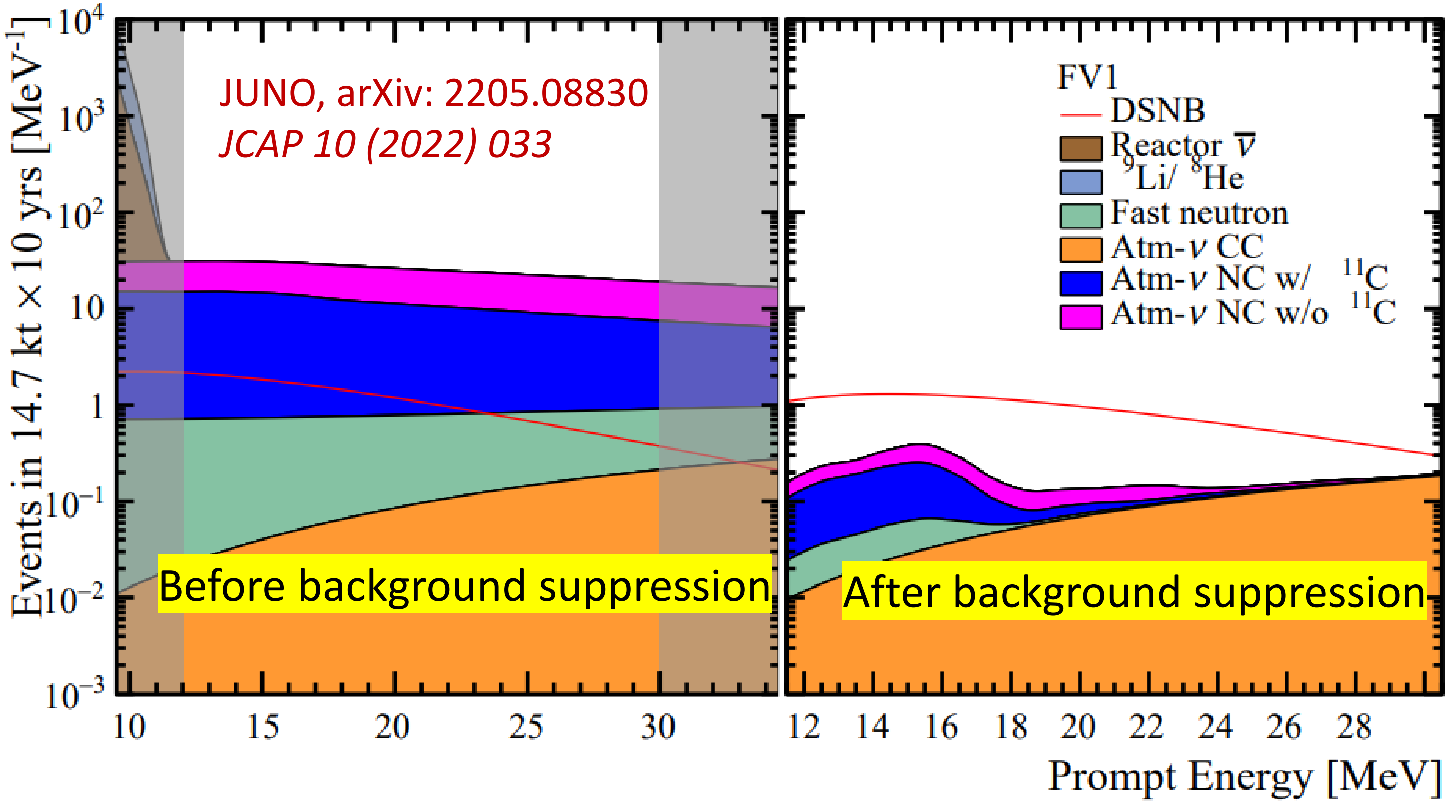
- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

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)



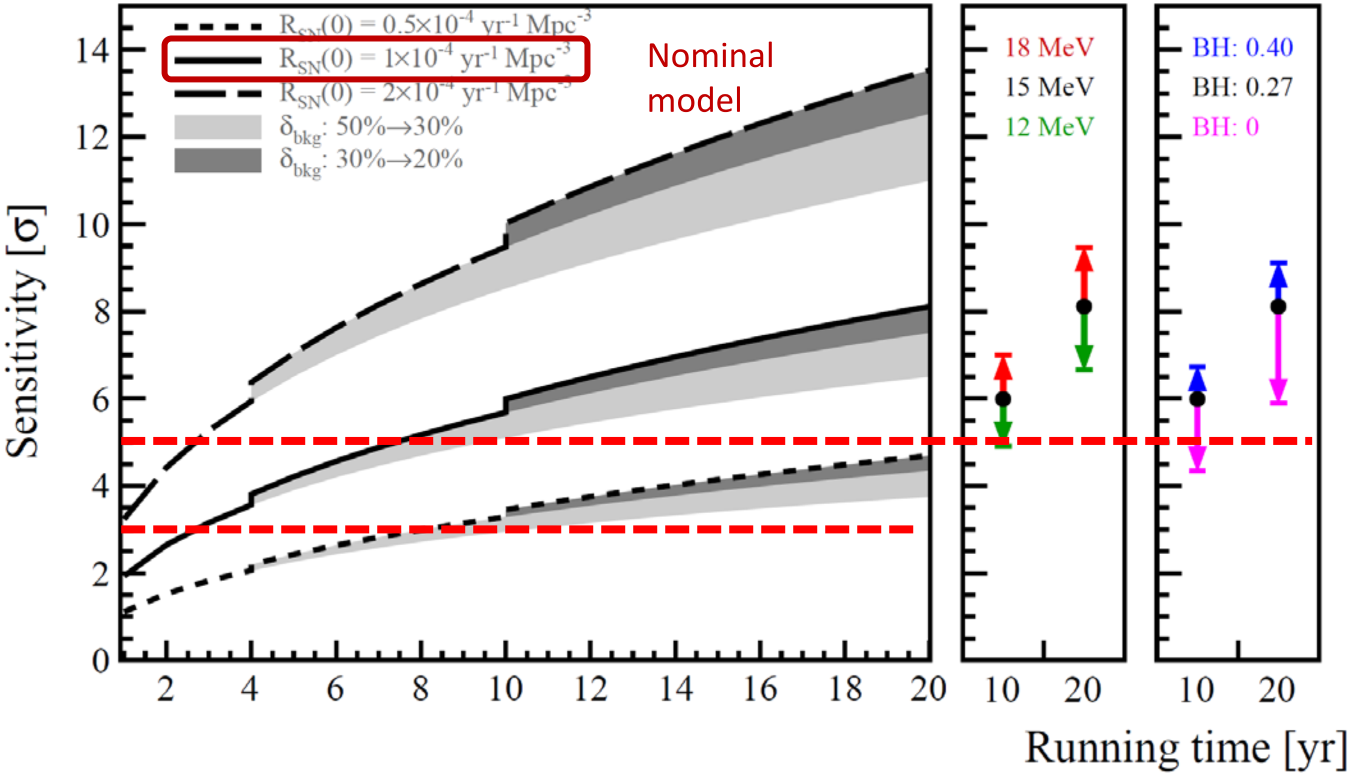
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* :

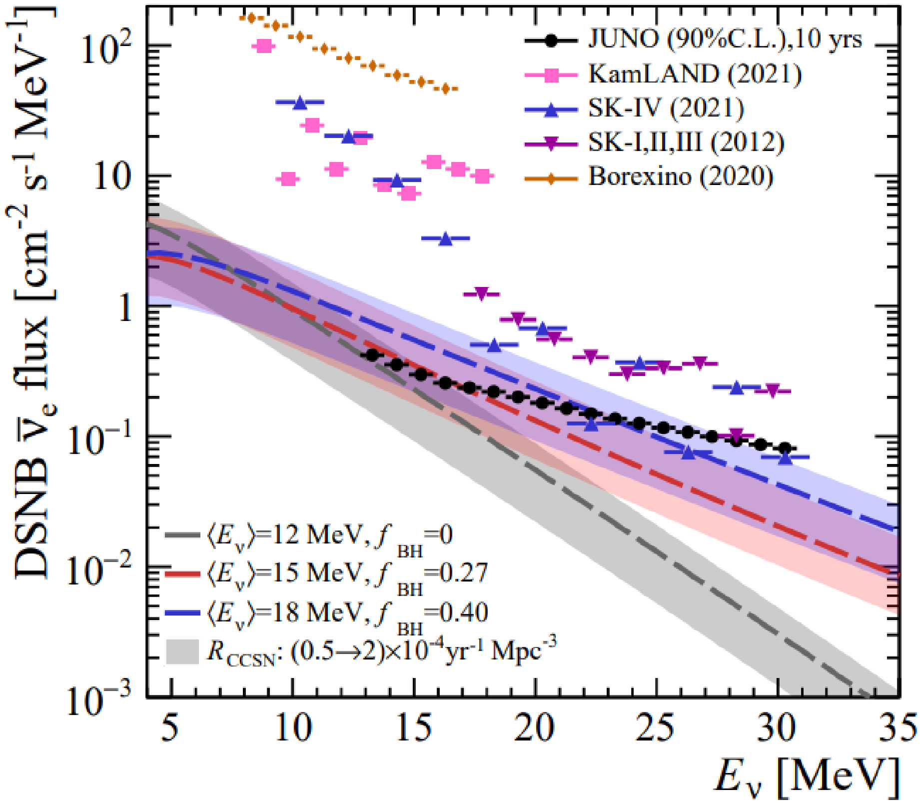
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

➡ S/B improved from **2 to 3.5**

Diffused Supernova Neutrino Background (DSNB)

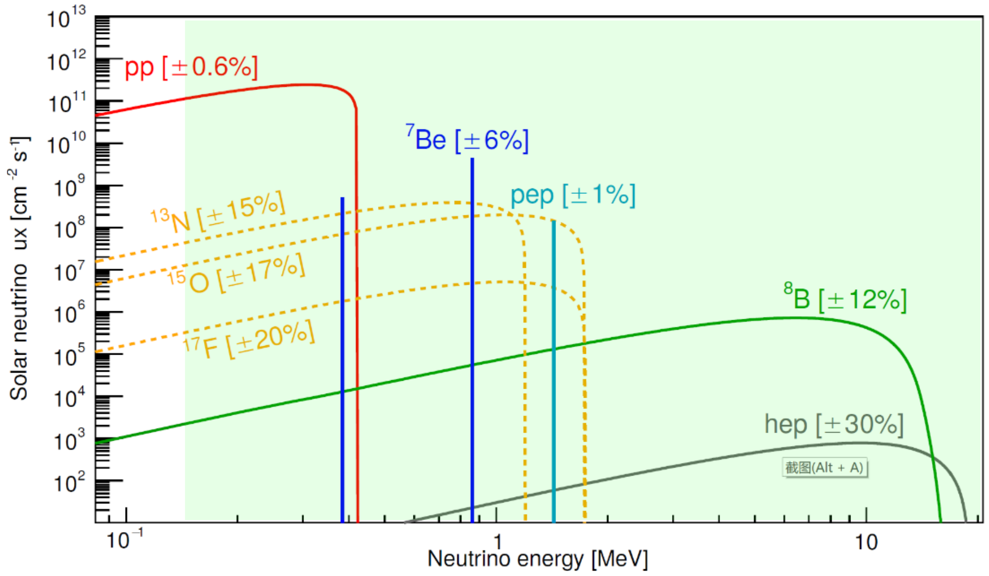
arXiv: 2205.08830, JCAP 10 (2022) 033





- **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)**

Sensitivities to Intermediate energy solar ν



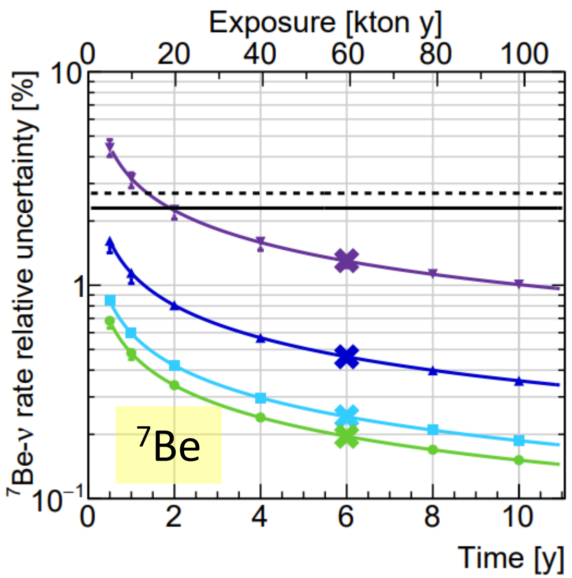
- Improving the understanding of neutrino-emitting solar processes, significant better precision on **^{7}Be, pep**
- First **CNO** measurement without external constraints

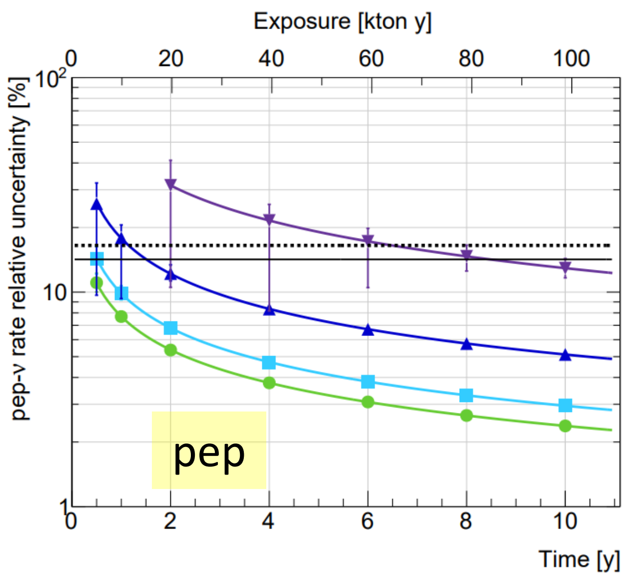
[2303.03910] JCAP 10 (2023) 022

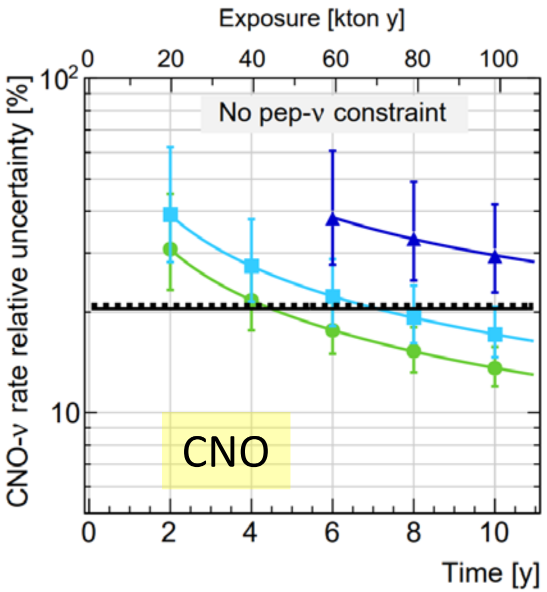
Radiopurity is the key

	^{238}U, ^{232}Th
Borexino-like	10^{-19} g/g
Ideal	10^{-17} g/g
Baseline	10^{-16} g/g
Reactor	10^{-15} g/g

— BX stat. .... BX stat.+syst.



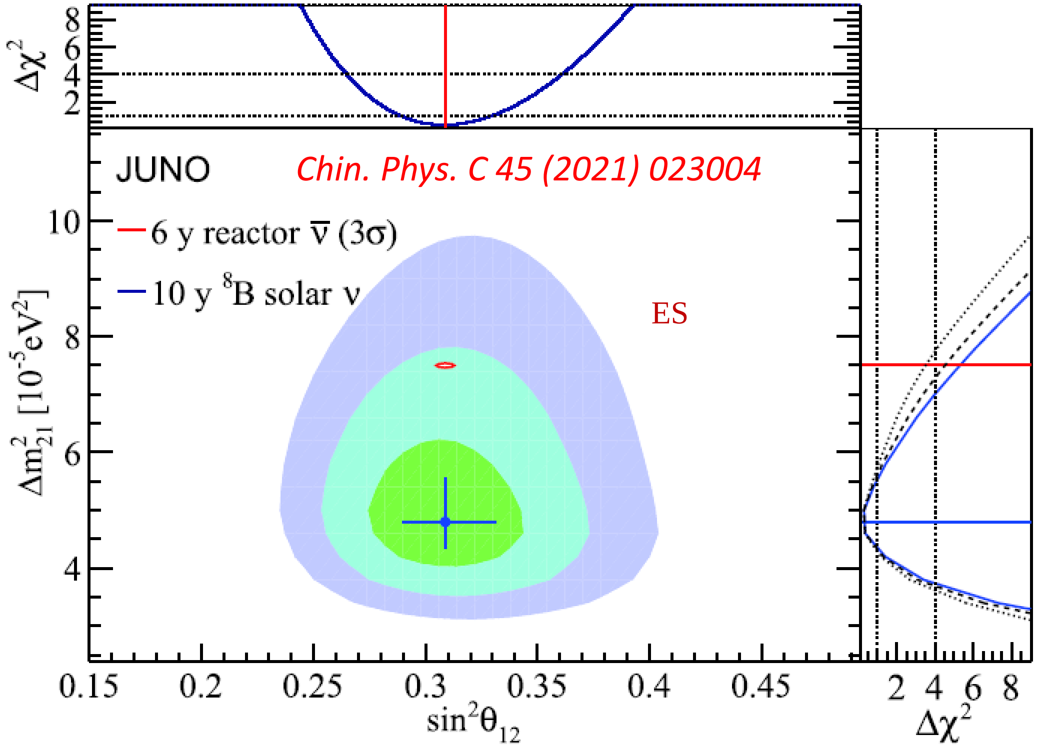




Sensitivities to ^{8}B solar ν

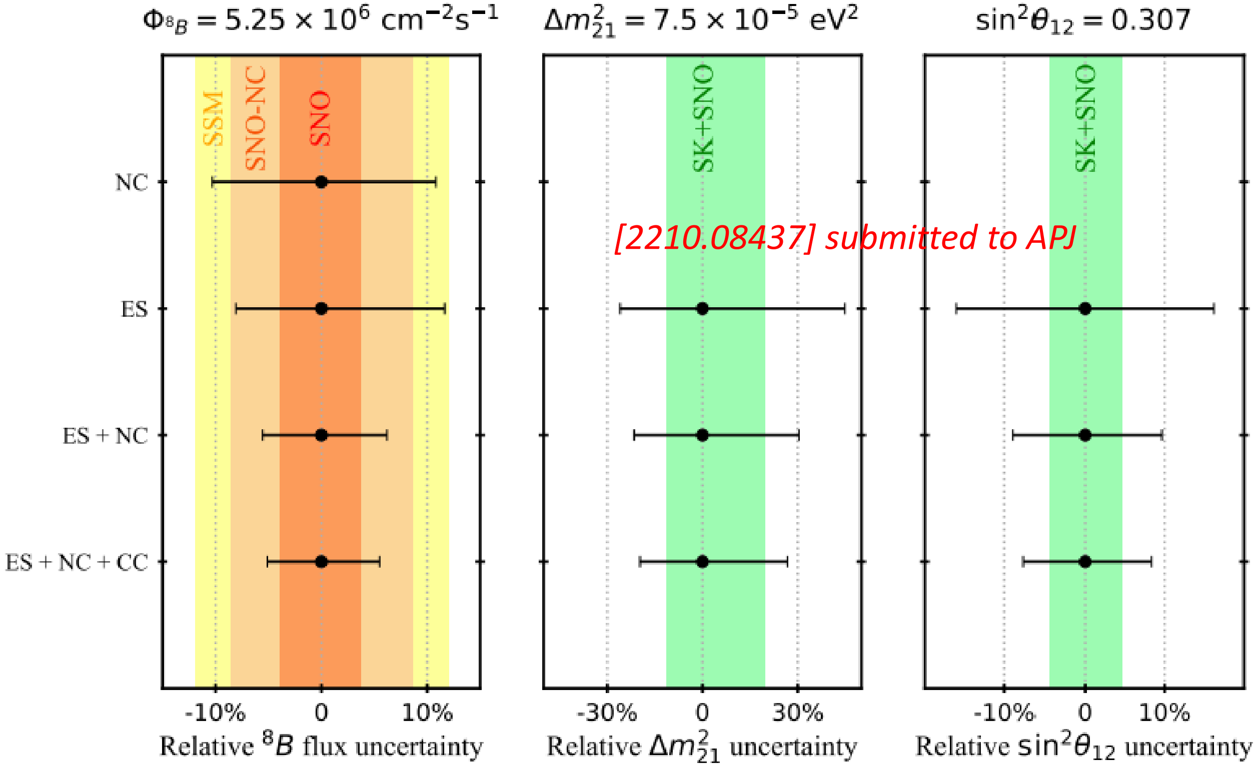
Low visible energy threshold: E_{th} ~ 2 MeV
Day-Night-Asy precision: 0.9% in 10 yr

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



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

	Channels		Threshold [MeV]	Signal
Correlated ←	CC	$\nu_e + ^{13}\mathrm{C} \to e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-; \mathrm{gnd})$	2.2 MeV	$e^- + ^{13}$N decay
Single {	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^-



Nucleon Decay

$p \to K^+ + \bar{\nu}$

Prompt pulse

$K^+ \to \nu_\mu + \mu^+$ ($\tau = 12.4\text{ns}$)

Delayed pulse

$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$K^+ \to \pi^+ + \pi^0$

$\pi^0 \xrightarrow{8.4\times10^{-8}\text{ns}} 2\gamma$

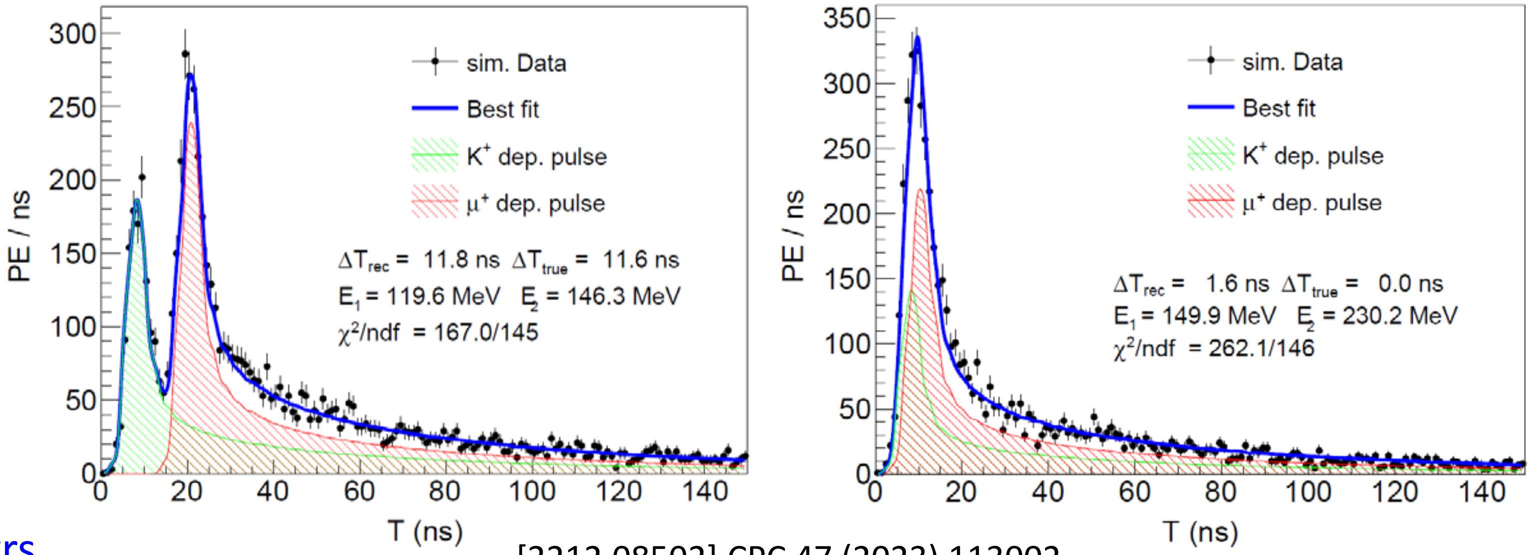
$\pi^+ \to \nu_\mu + \mu^+$ ($\tau = 26\text{ns}$)

- **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	$\nu + n \to \nu + n$ $\nu + p \to \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \to n + l^+$ $\nu_l + n \to p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \to l^- + p + \pi^+$ $\nu + p \to \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \to l^- + \Lambda + K^+$ $\nu_l + p \to l^- + p + K^+$	Double Pulse

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

- **Expect sensitivity:** 9.6×10^{33} years (90% C.L.) for 193 kton*yrs fiducial exposure



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

[2212.08502] CPC 47 (2023) 113002

Physics Potentials with JUNO

JUNO has great potentials on the physics topics below, although except for CP phases, θ_{23} Octant

Exp.	Time	Mass ordering	CP phases	Precision Meas.	CCSN burst @ 10 kpc	DSNB	Geo-ν	Solar	Proton Decay (sensitivity@10 y)
JUNO (20 kt)	2024	**3-4 σ** *6 y*	—	**$\sin^2\theta_{12}$ (0.5%), Δm^2_{21} (0.3%), Δm^2_{31} (0.2%),** *6 y*	**all-flavor ν (IBD, eES, pES)**	**3σ**, *3 y*	**~400/y**	**^{7}Be, pep, CNO, ^{8}B**	> 9.6x10^{33} y ($\bar{\nu}K^+$)
DUNE (17 kt*4)	2030	**>5 σ** *1-3 y*	5σ (50%) *10 y*	Δm^2_{32} ~0.4%, $\sin^2\theta_{23}$~*1.1% *, 15 y*	**^{40}Ar CC & NC, eES**	^{40}Ar CC	—	^{8}B, hep	>8.7x10^{33} y ($e^+\pi^0$) >1.3x10^{34} y ($\bar{\nu}K^+$)
HyperK (260 kt)	2027	**3-5 σ** *10 y*	**5σ (60%)** *10 y*	Δm^2_{32} ~0.6%, $\sin^2\theta_{23}$~*1.6% *, 10 y*	**eES, IBD**	*3σ, 6 y*	—	^{8}B, hep	**>7.8x10^{34} y ($e^+\pi^0$) >3.2x10^{34} y ($\bar{\nu}K^+$)**
ORCA (7 Mt)	Un-known	**2-4 σ** *3 y*	—	Δm^2_{32} ~2% , *3 y*	rate excess	—			
IceCube Upgrade	2026	**2-4 σ** *7 y*	—	Δm^2_{32} ~1.3% , *3 y*	rate excess	—			

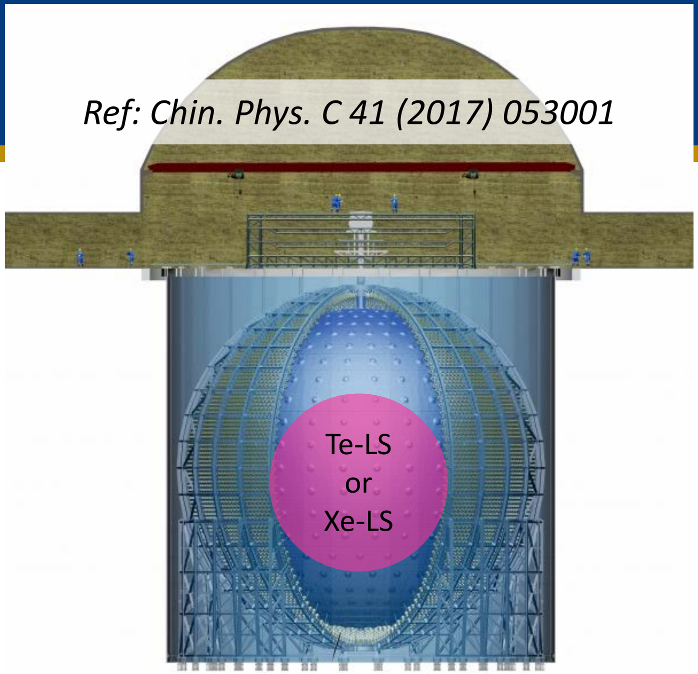
** Upper octant assumption*

eES: ν-electron scattering, pES: ν-proton scattering, IBD: inverse beta decay

JUNO's future update

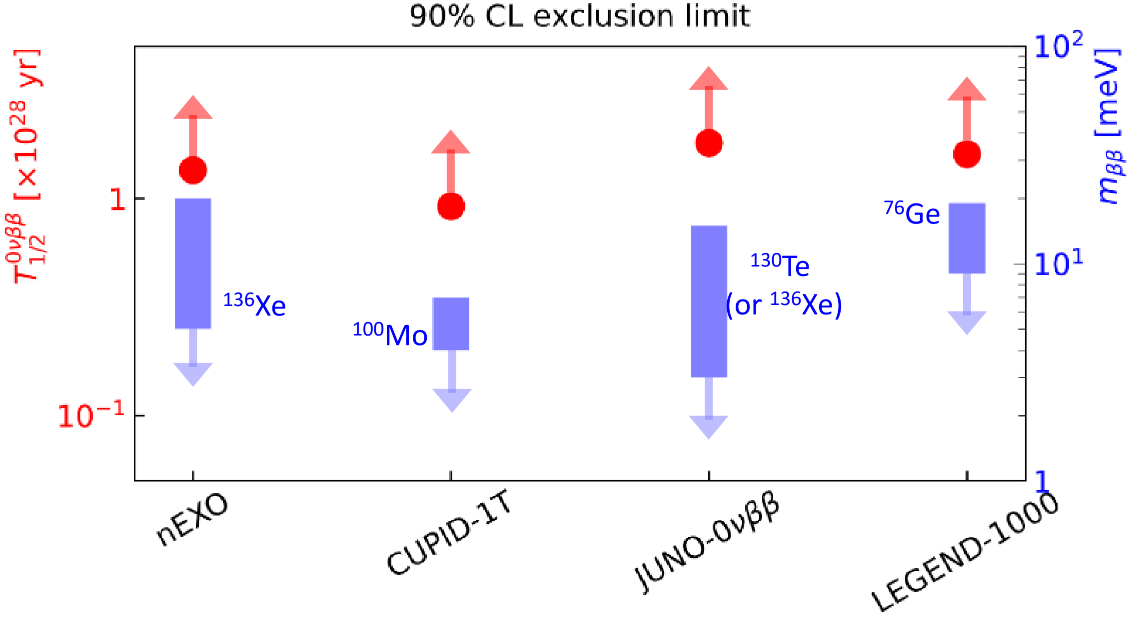
- JUNO offers an unique opportunity to search for 0νββ after completion of mass ordering measurements (~2030)
  - Large target mass: 20 kton LS → **100-ton scale isotope loading** (e.g., Tellurium, no enrichment, cost effective)
  - Excellent clean LS shielding → **Low background**
  - Energy resolution < 3% @ 1 MeV

  → Potential to explore normal mass ordering parameter space of Majorana neutrino mass. Snowmass2021 LOI



Concept of the experiment

- Critical R&D in progress
  - **Te-loaded LS** (requirements: high light yield, transparency and solubility and stability)
  - **Background rejection** (^{8}B solar neutrinos, Te muon-spallation products)
  - **Xenon enrichment** w/ a company, aiming at 200 kg/yr



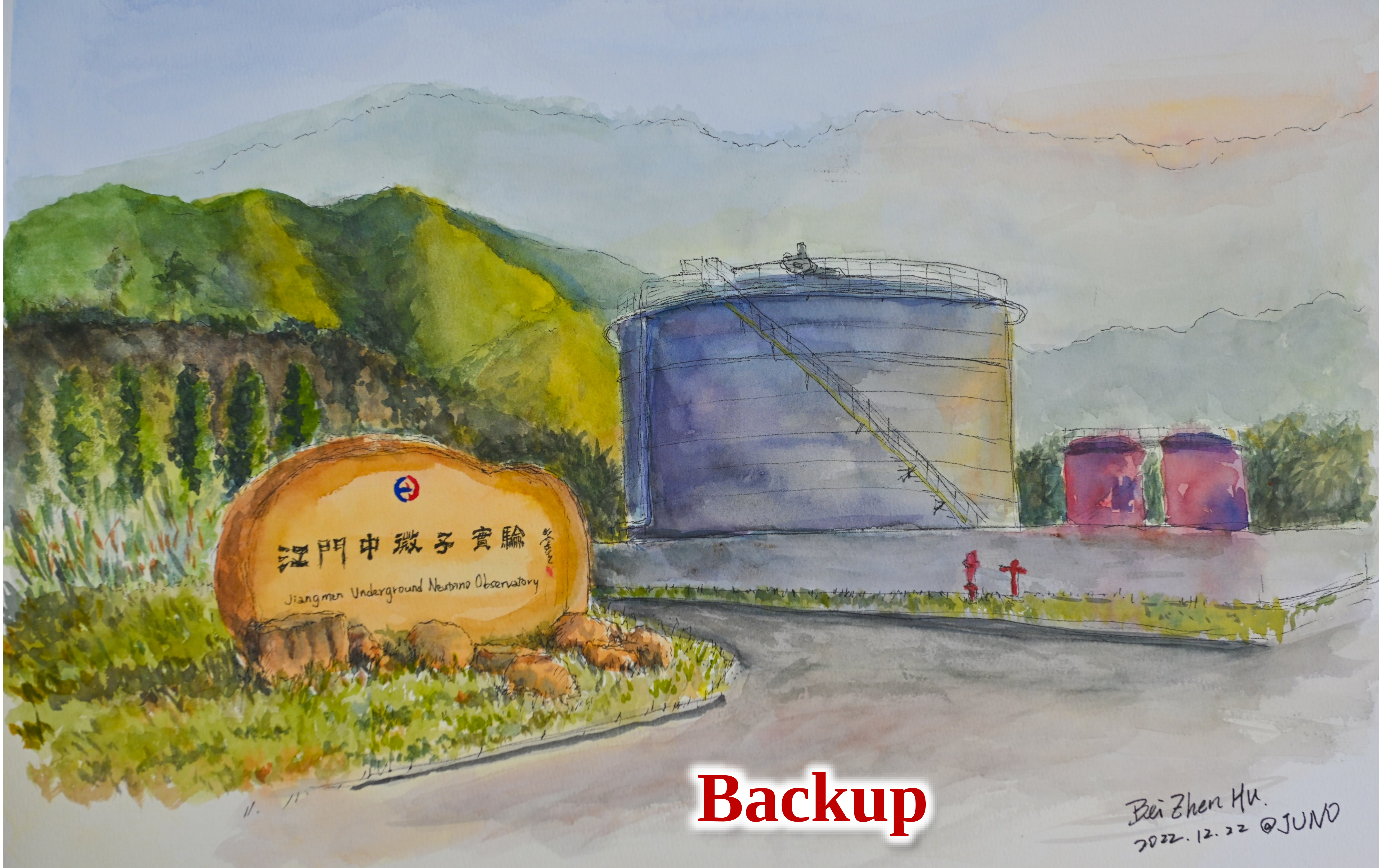
Summary

- Revealing the mysteries of neutrinos are extremely important for understanding the two infinities: particle physics and cosmology
- Neutrino oscillation studies entered a precision era, and there are still many unknowns about fundamental properties of neutrinos (mass ordering, Majorana nature, absolute mass, CP-violating phases, etc)
- JUNO has great potential on solving some of the problems. Its construction going on well. Expect first data in 2024.
- Stay tuned!

Thank you!

Courtesy: S. Blyth, T. Lin, Y. X. Hu
Opticks : GPU Optical Photon Simulation

Backup


江門中微子實驗
Jiangmen Underground Neutrino Observatory
Bei Zhen Hu.
2022.12.22 @JUNO

Reactor Antineutrino Oscillation

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$
$$- \frac{1}{2} \sin^2 2\theta_{13} \left[\sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \frac{\Delta m^2_{32} L}{4E} \right]$$
$$- \frac{1}{2} \cos 2\theta_{12} \sin^2 2\theta_{13} \sin \frac{\Delta m^2_{21} L}{4E} \sin \frac{(\Delta m^2_{31} + \Delta m^2_{32}) L}{4E}$$

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

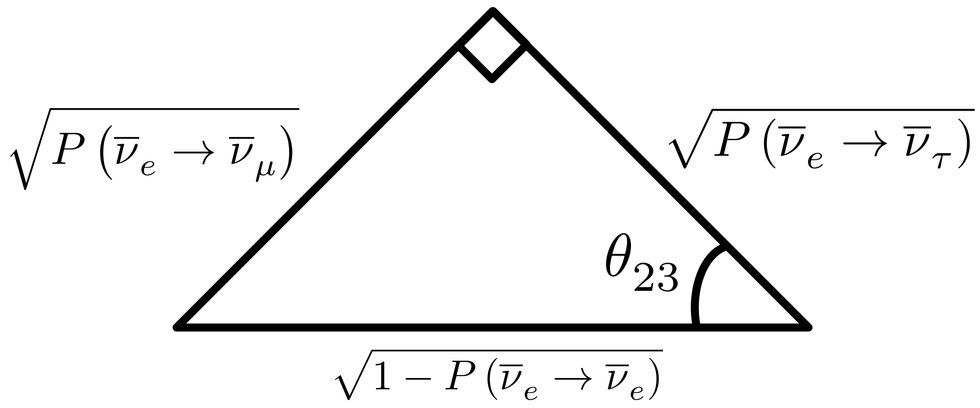
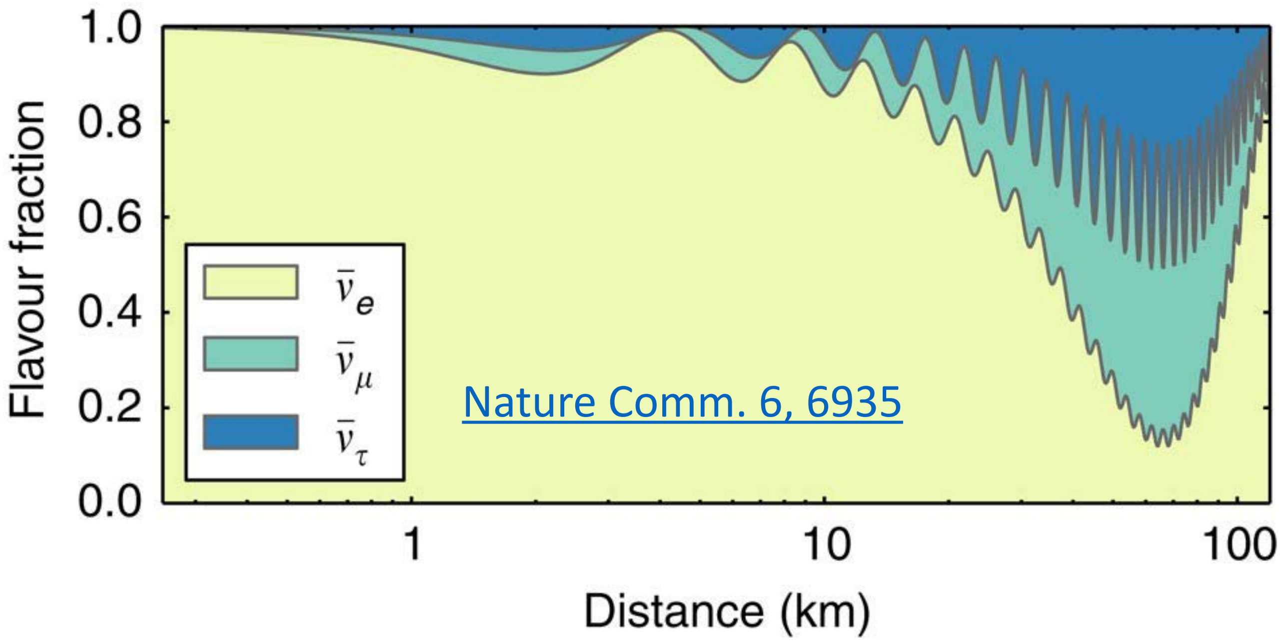


Illustration: Daya Bay Conversion Probability

Curtesy: Jihong Huang, Zhi-zhong Xing



Updated reactor neutrino models

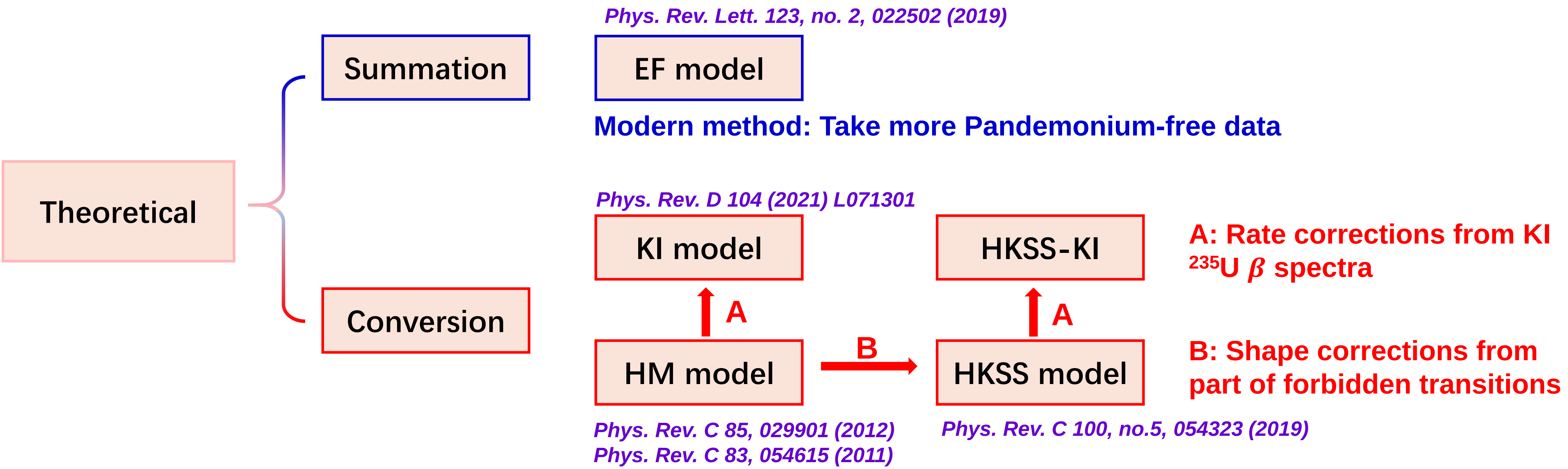


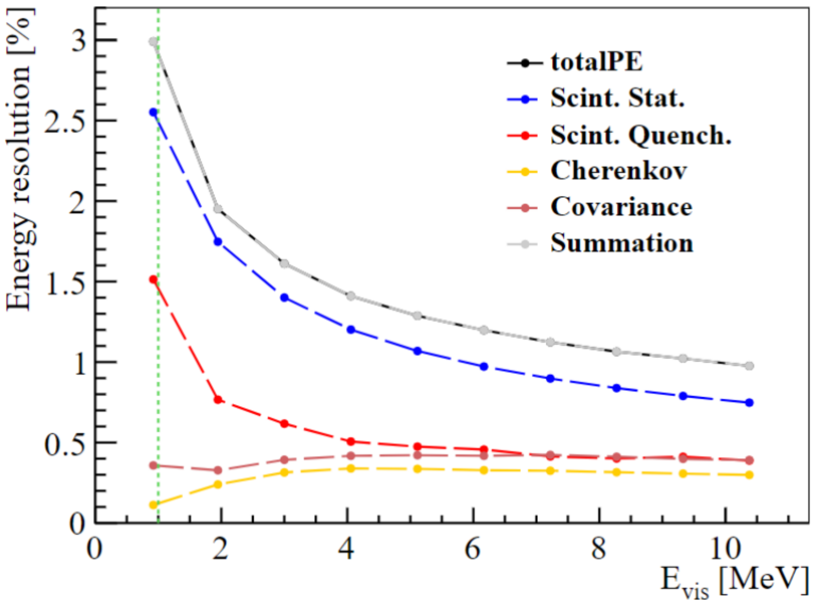
Diagram Courtesy: XIN Zhao

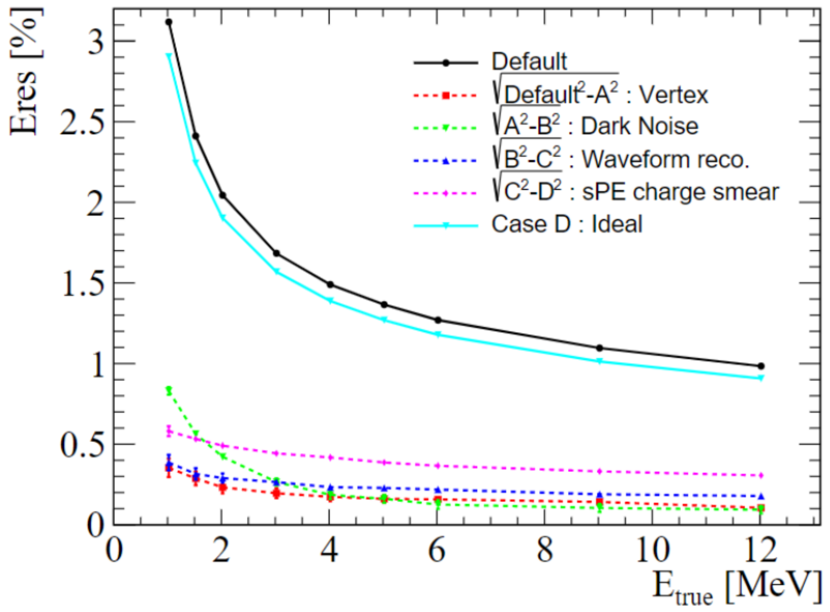
- Huber-Mueller model
- Hayen-Kostensalo-Severijns-Suhonen model
- Recent Kurchatov Institute measurements
- HM → KI model
- HKSS → HKSS-KI model
- Estienne-Fallot summation model

Energy Resolution (current understanding)

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% ↑**		arXiv: 2205.08629
New Central Detector Geometries	**+3% ↑**	**2.95% @ 1MeV**	
New PMT Optical Model	**+8% ↑**		EPJC 82 329 (2022)

- **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**

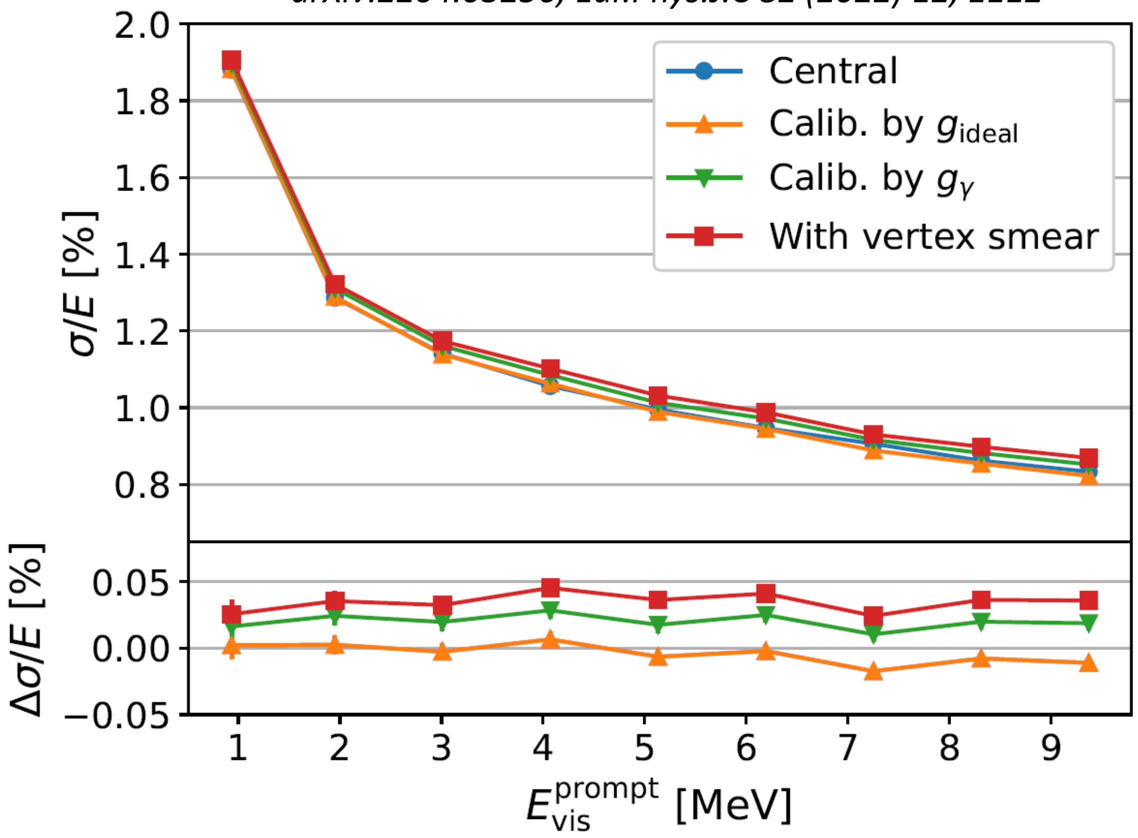


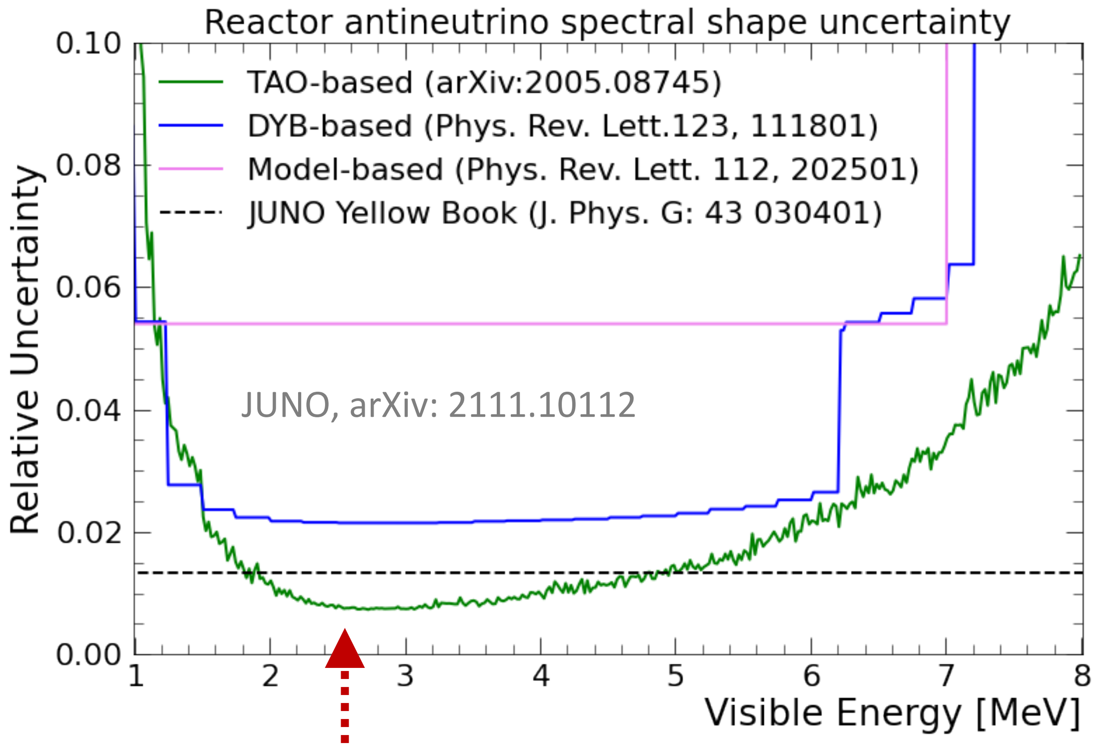


Strategy of measuring the energy resolution with calibration data is developed

Reactor Antineutrino Spectrum from TAO

arXiv:2204.03256, Eur.Phys.J.C 82 (2022) 12, 1112



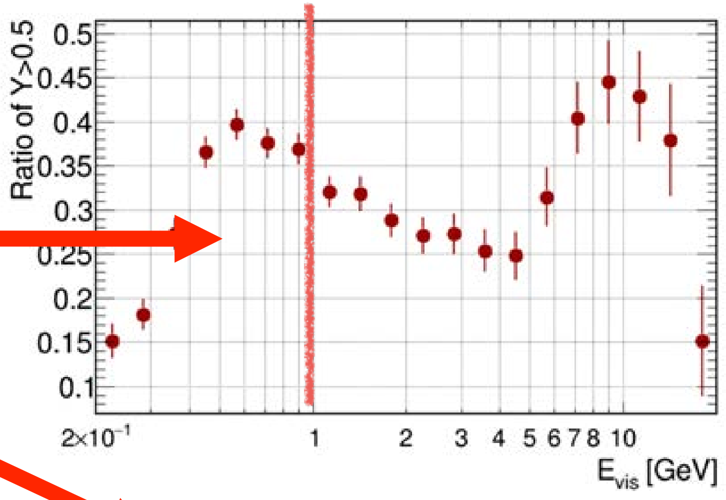


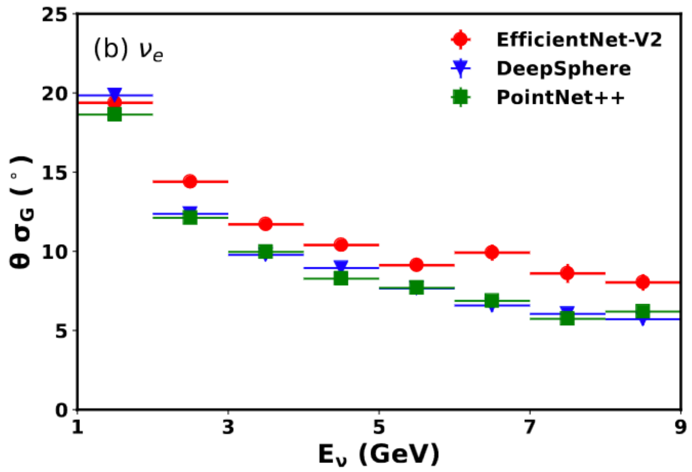
Shape uncertainty close to the assumption in the JUNO physics book *J. Phys. G43:030401(2016)*

- Precisely measure the unoscillated reactor $\bar{\nu}_e$ spectrum
- ➔ good understanding of the shape uncertainty
- ➔ model-independent combined analysis with JUNO
- Also search for sterile neutrinos and measure spectra of dominant isotopes

Improvements on atmospheric neutrino analysis

	Yellow Book assumptions	NEW developments	Potential improvement
Event Selection ν_e/ν_e	E_{vis} > 1GeV **$Y_{vis}=E_h/E_{vis}$ < 0.5**	E_{vis} > 1GeV	~30% more stats.
Directionality	$\sigma_{\theta\mu}=1^\circ$ **$\sigma_{\theta\nu}=10^\circ$**	**$\sigma_{\theta\nu}<10^\circ$** (E>3GeV)	Better resolution; E-dependent
Classification	CC-e / CC-μ / NC: **100% eff.**	CC-e / CC-μ / NC: **80%~95% eff.**	—
	ν vs $\bar{\nu}$: **simple classification with $N_{michel-e}$, Y_{vis}**	ν vs $\bar{\nu}$: **50%~80% eff.**	Better ν vs $\bar{\nu}$ separation
Energy	σ_{Evis} = 1%/√E	$\sigma_{E\nu}$	E_ν instead of E_{vis}





Invisible nucleon decay search

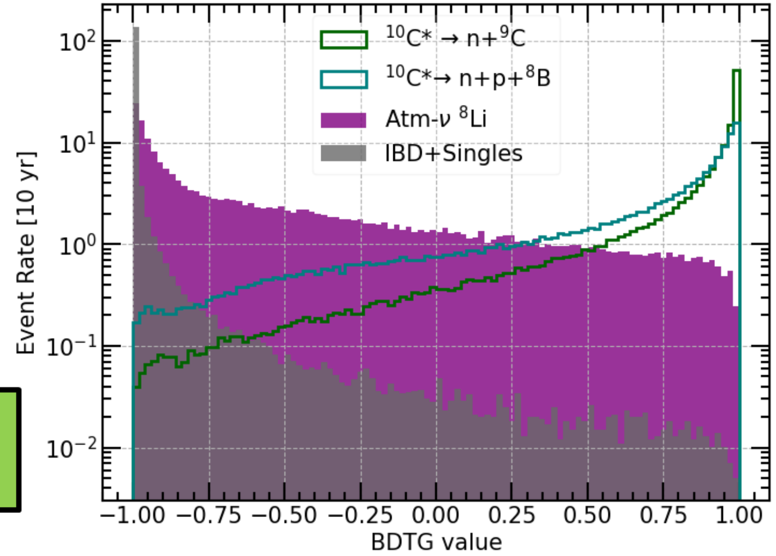
Triple-coincidence signatures from excited $^{11}C^*$, $^{10}C^*$ nuclei after **Invisible decay of bounded neutron(s) in ^{12}C**

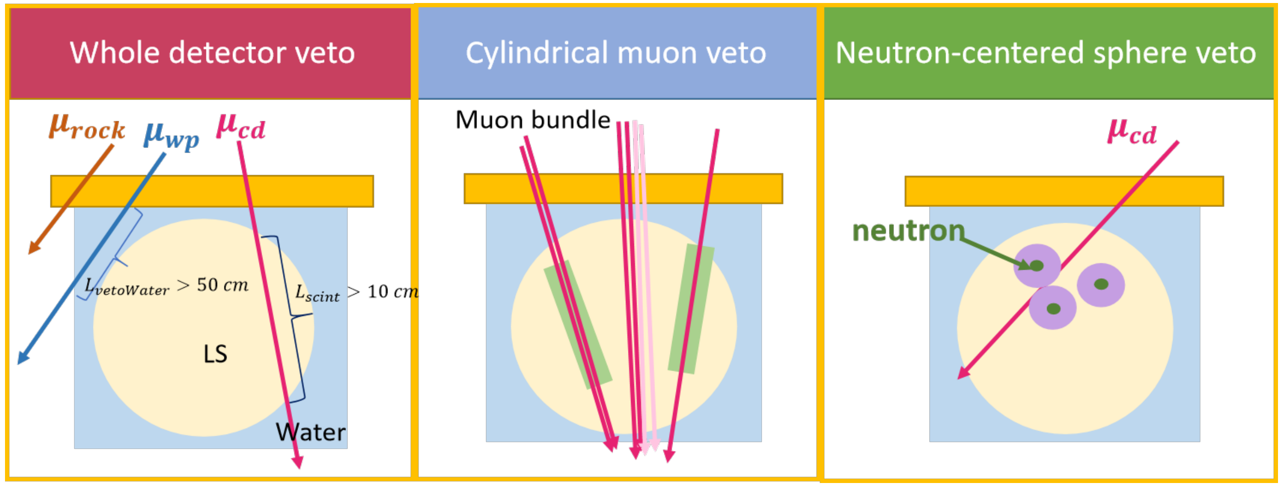
Prompt(1st)
- Proton recoil by neutron
- Neutron inelastic with ^{12}C
- γ (3.35 MeV) and proton (0.922 MeV)

Delayed(2nd)
- Neutron capture (220 μs, 2.2 MeV)

$$^{11}C^* \to n + {}^{10}C_{gs} \quad (B_{n1} = 3.0\%)$$
$$^{11}C^* \to n + \gamma + {}^{10}C_{gs} \quad (B_{n1} = 2.8\%)$$
$$^{10}C^* \to n + {}^{9}C \quad (B_{nn1} = 6.2\%)$$
$$^{10}C^* \to n + p + {}^{8}B \quad (B_{nn1} = 6.0\%)$$

Decay (3rd)
- β^+ decay of $^{10}C_{gs}$, ^{9}C, ^{8}B





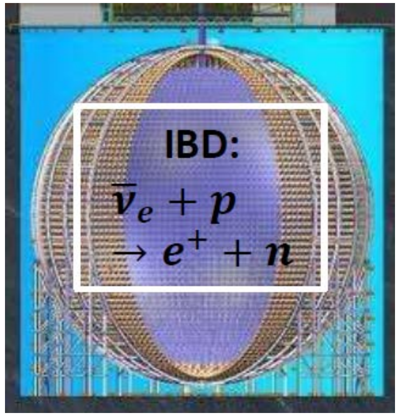
- Analyses ongoing, preliminary results show significantly better sensitivity than the current experimental limits

Decay mode	sensitivity or limit (90% CL) [yr]		
	JUNO (10 yrs)	SNO+	KamLAND
$n \to inv$	1.1×10^{31}	2.5×10^{29}	5.8×10^{29}
$nn \to inv$	1.5×10^{32}	1.3×10^{28}	1.4×10^{30}

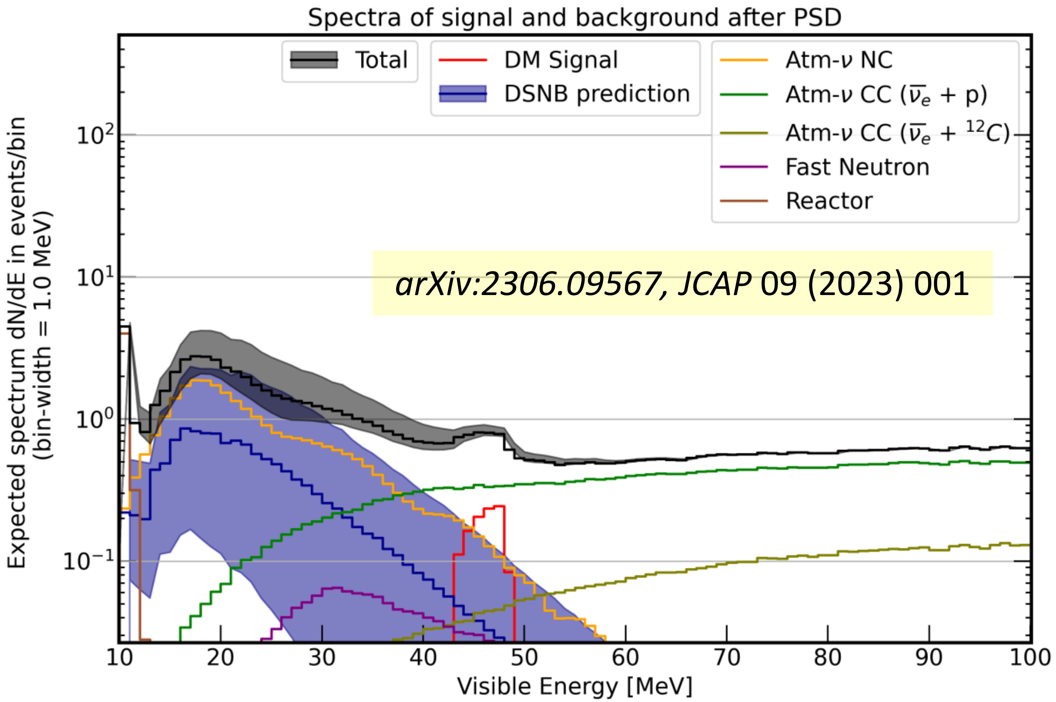
PRD99.032008 ~235 days

PhysRevLett.96.101802 ~750 days

Indirect Dark Matter Search



- DM annihilation into neutrinos in the Milky Way
- DM masses: 15 - 100 MeV
- Detection channel in JUNO: Inverse Beta Decay
- Backgrounds: **atm-ν NC/CC, DSNB,** fast neutron, reactor
  - PSD technique to suppress atm-ν NC and fast neutron



arXiv:2306.09567, JCAP 09 (2023) 001