JUNO status and its prospective neutrino scattering physics

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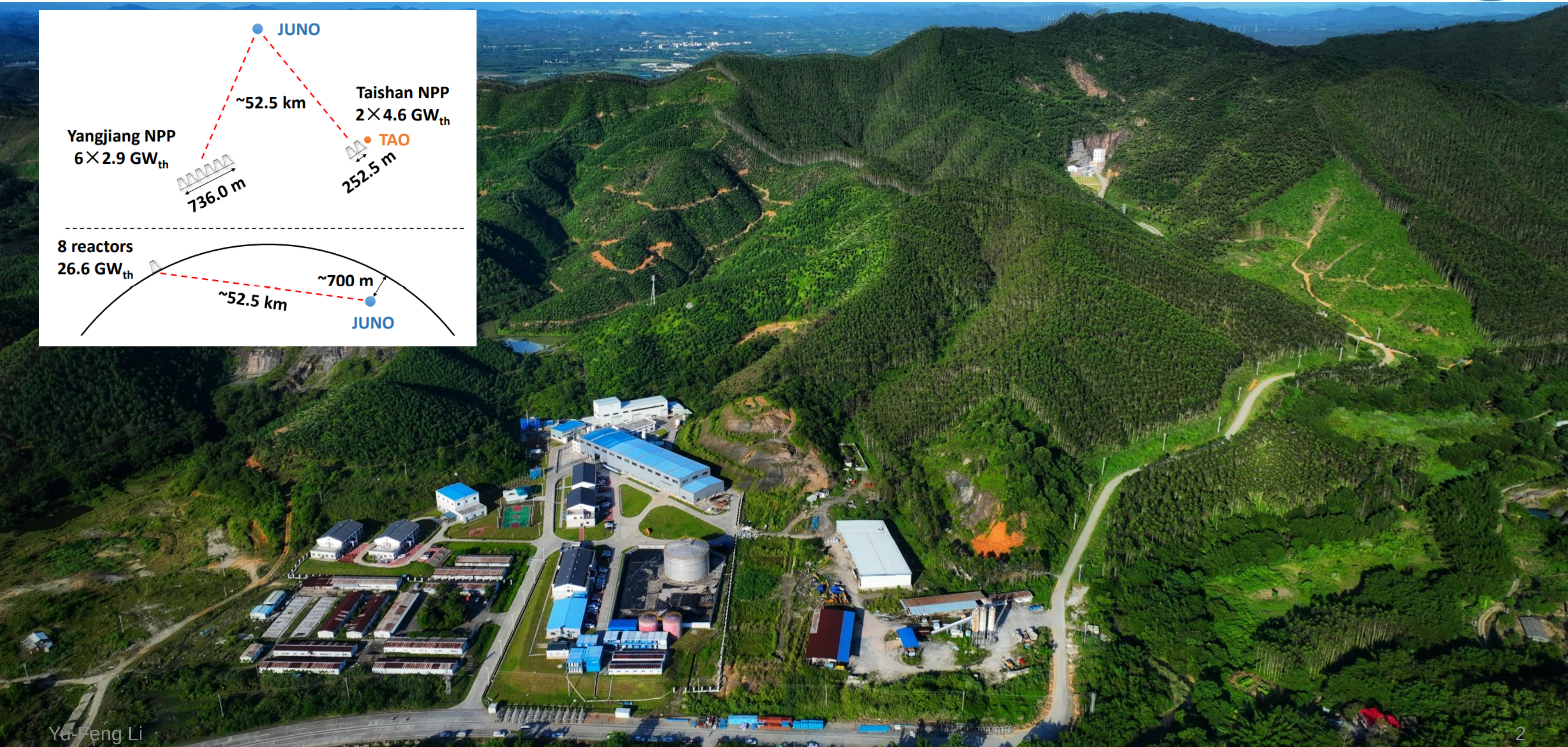
vSTEP 2025@Beijing
2025/10/25

Jiangmen Underground Neutrino Observatory



Jiangmen Underground Neutrino Observatory

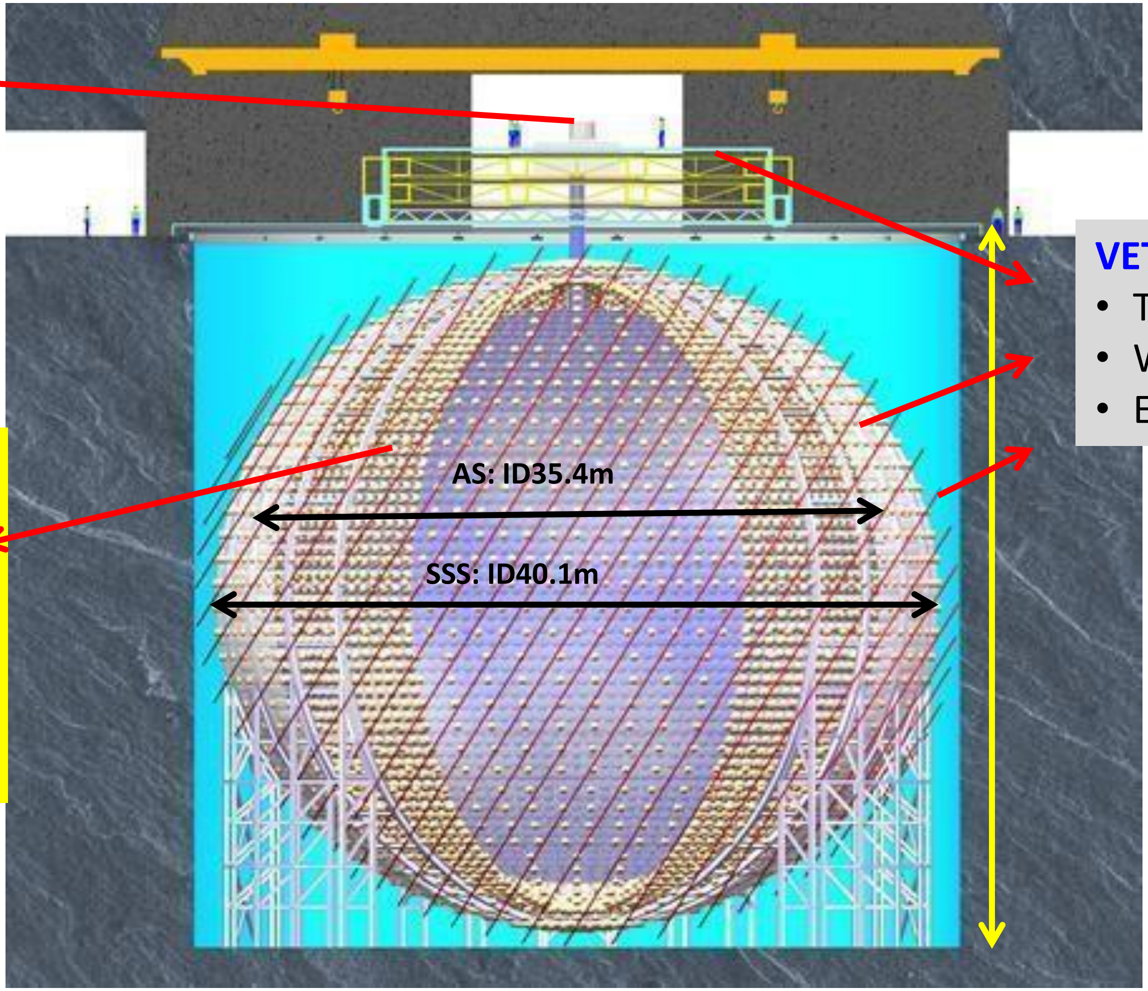
Civil construction finished in Dec, 2021
Detector construction finished in Dec, 2024

JUNO detector design

- **Two-layers structure for simplicity and cost: stainless steel frame + Acrylic tank**
- **Water as VETO and Buffer(instead of oil) → radiopurity control of water**

Calibration

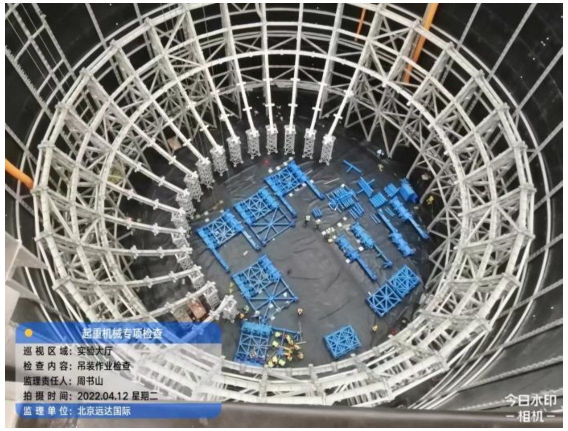
Central detector
- Steel structure
- Acrylic sphere + 20kt Liquid scintillator
- 17612 20" PMT
- 25600 3'' PMT

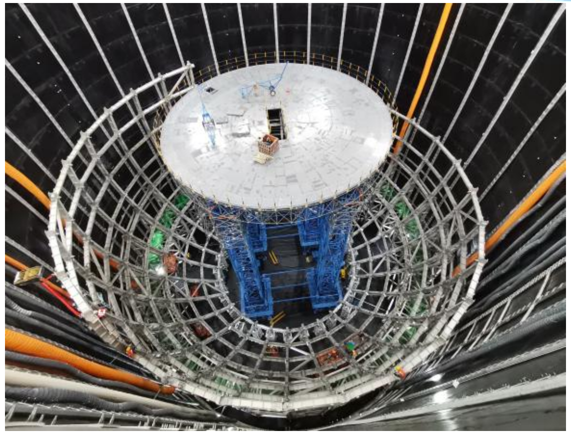


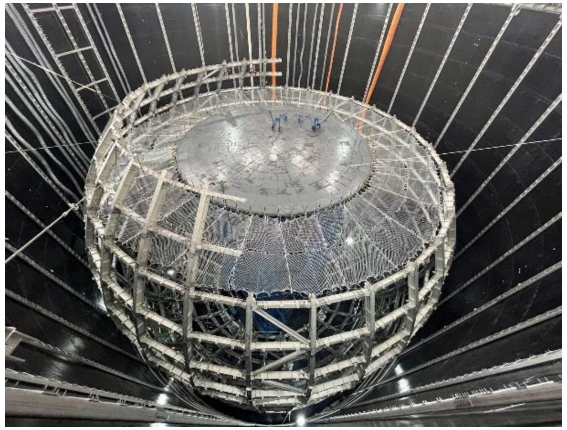
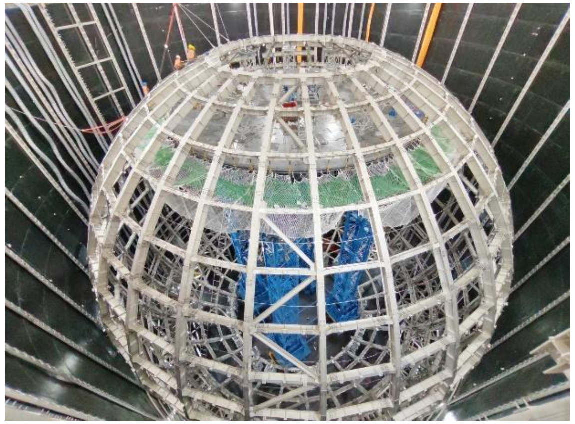
VETO system (for cosmic muon detection)
- Top Tracker: plastic scintillator
- Water + 2400 20'' PMT
- Earth Magnetic Field shielding coils

Central detector (SS structure)







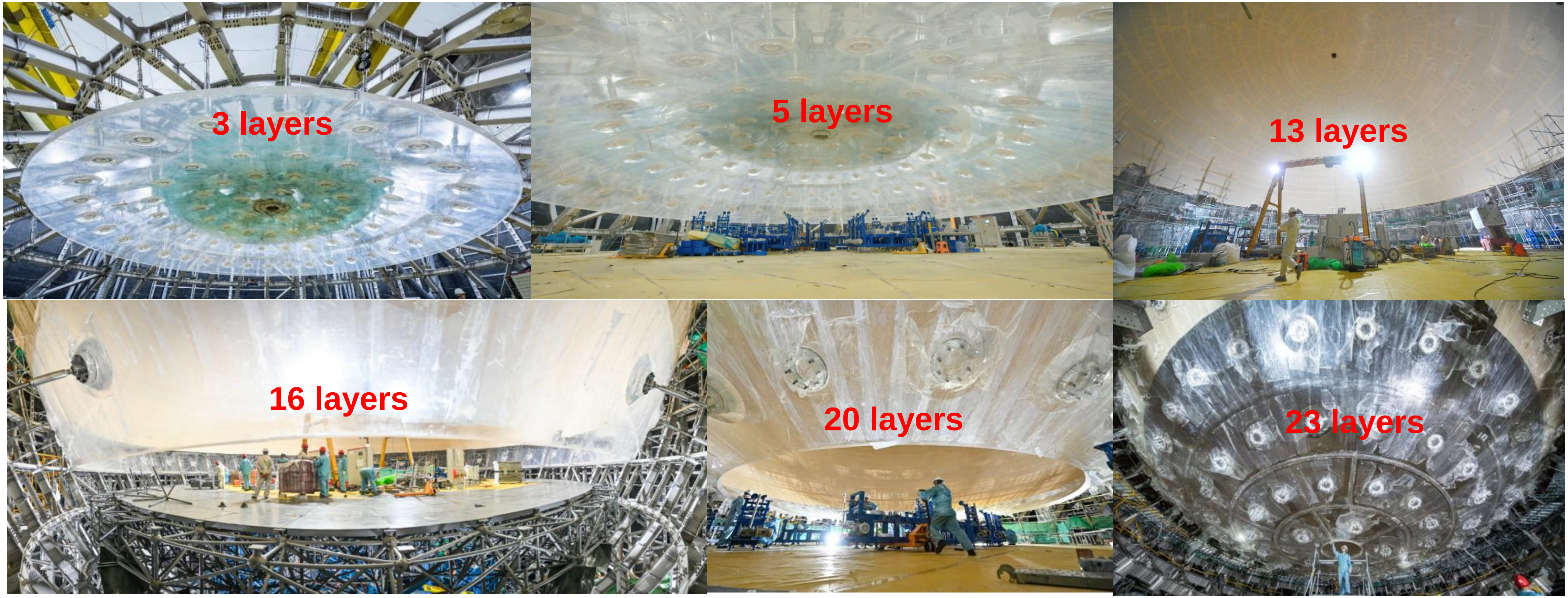

Acrylic tank is supported by D = 40.1 m stainless steel structure via 590 Connecting Bars

Assembly precision: < 3 mm for each grid. The final radius deviation -13 mm (0.06%)

Connected by 120,000 sets of special rivet bolts: high strength, high consistency, no welding.

2022.1~2022.6, pillar and shell most finished. 2024.11, bottom 4 layers of SS shell finished.

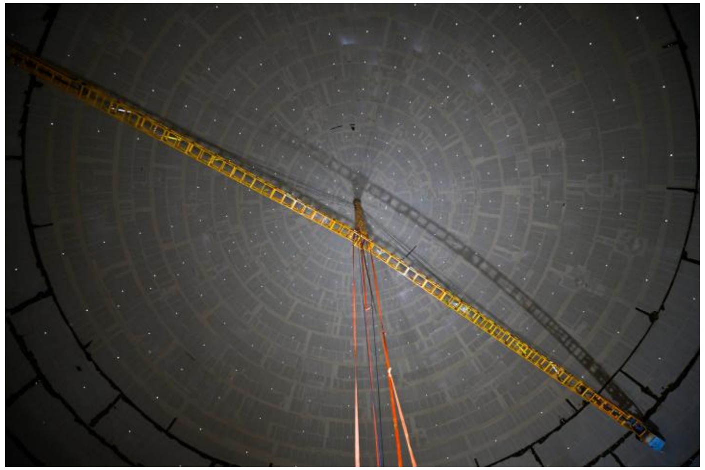
Central detector (acrylic tank)



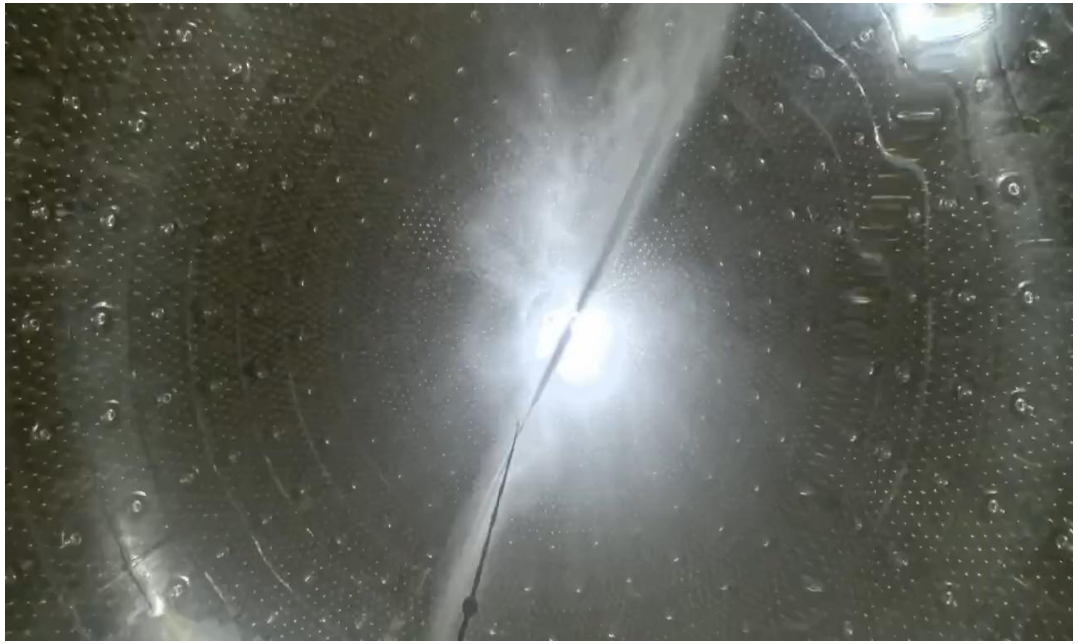
23 layers/263 spherical panels + top and bottom chimneys were bonded onsite (finished in Oct. 2024).

- ✓ A total of 21 cyclic operations for the construction, each lasting 20-30 days, with a total bonding length reaching 2 km.
- ✓ Developed large-volume injection, polymerization and annealing technology. The final fitting result of the diameter deviation: -23mm (0.06%)

Central detector (acrylic tank)

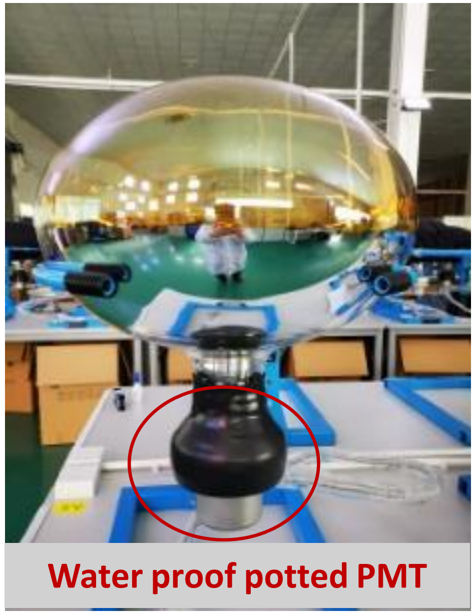


- Final checks of the acrylic tank inside and outside.
- **Moisture spray over two days** reduced dust levels inside CD air **from ~10,000 to ~100**.
- **Two weeks high pressure water jet** to **remove the protection film and clean the inner acrylic surface** by 3D rotating nozzle. Check water cleanness until satisfactory.

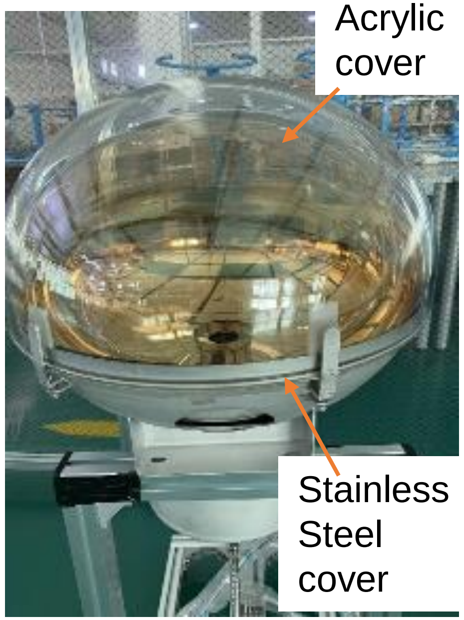


PMT testing

All PMTs were produced, tested, and instrumented with waterproof potting



Water proof potted PMT

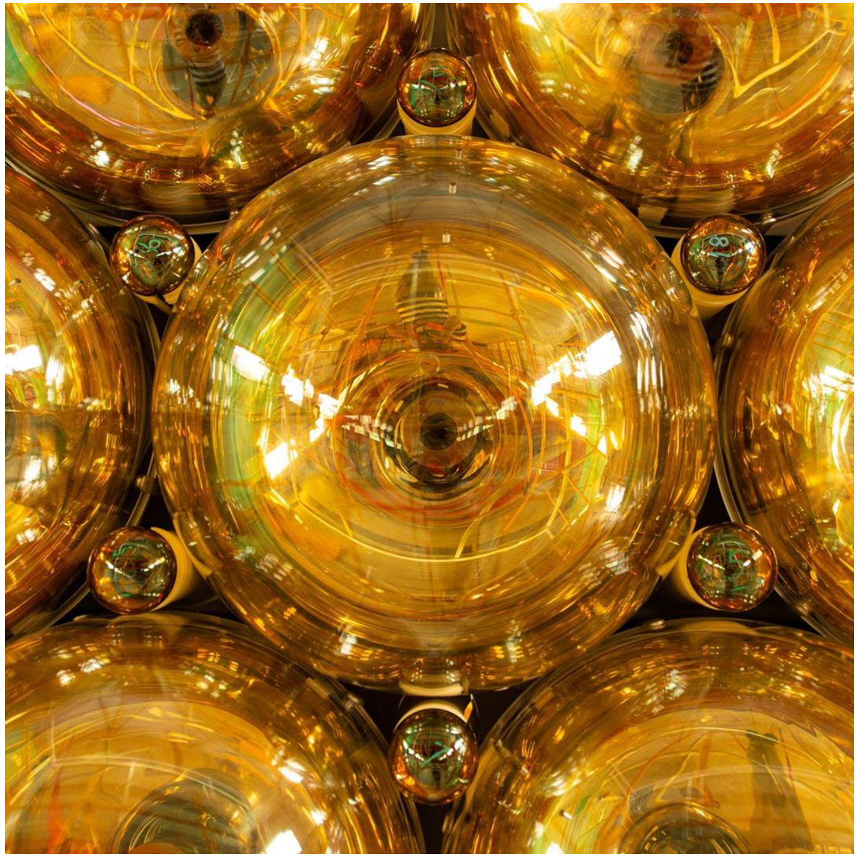


potting		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		EPJC 82 (2022) 12, 1168		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.

PMT installation

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



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

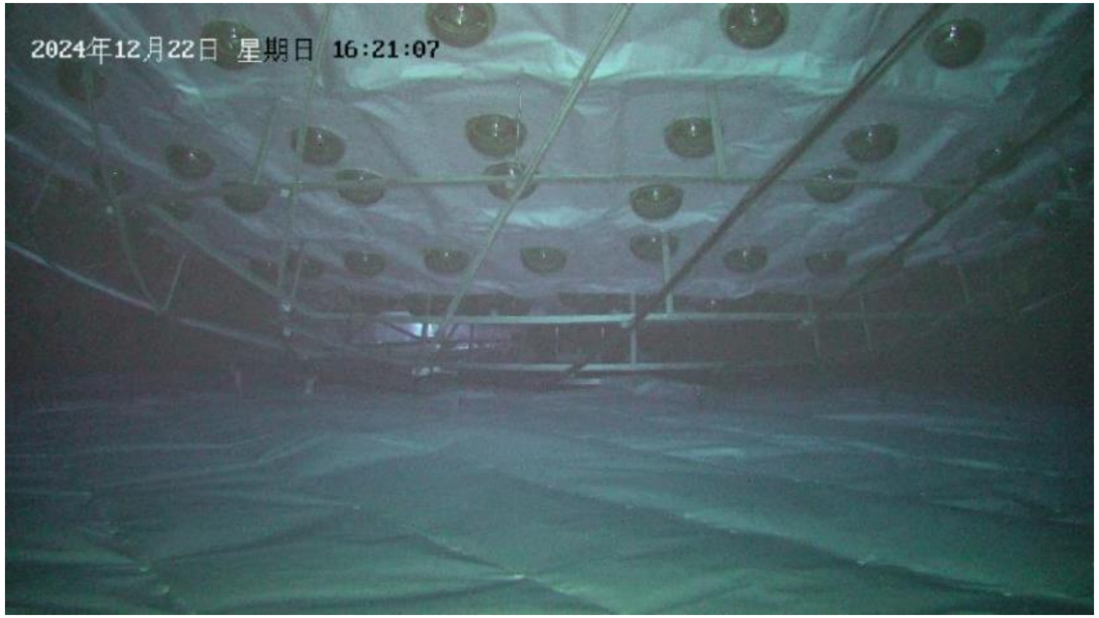
17612-16 LPMTs installed for CD, 2400-1 LPMTs installed for VETO, 25600-13 sPMT installed for CD

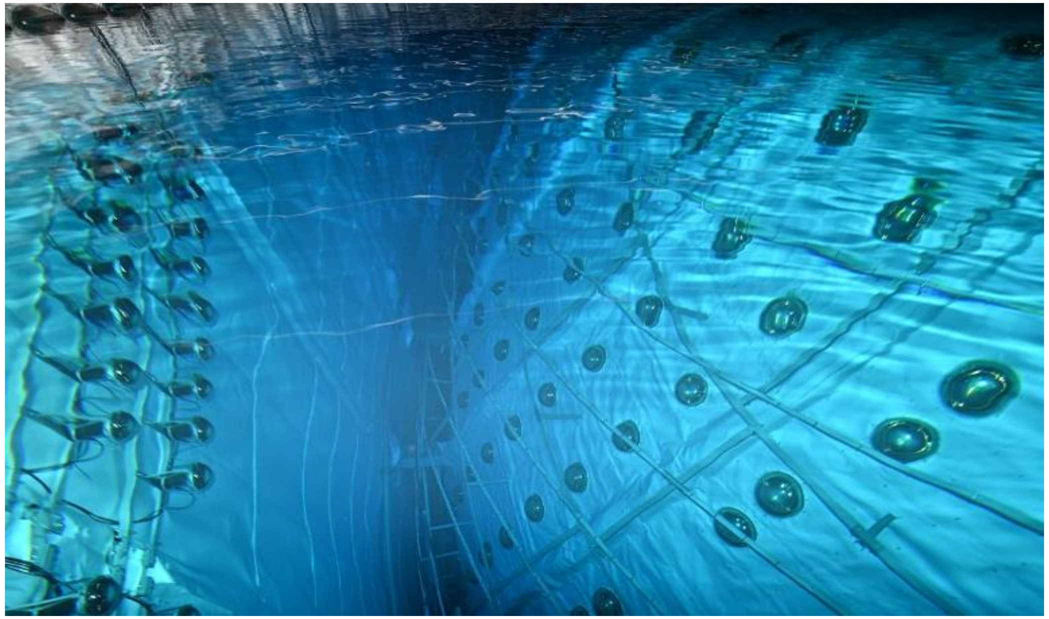
External perspective

Internal perspective

Filling the detector with water

Simultaneous filling of ultrapure water inside and outside the sphere → totally filled 60 kt





- ✓ **Filling started on Dec. 18, 2024, and finished in 45 days. No light and gas leak.** Keep the temperature uniformity **21.1℃±0.5℃**
- ✓ Liquid and air pressure were kept the same between the inside and outside of the acrylic tank. Water pipes and acrylic tank "breath" with N_2
- ✓ Stress of the detector structure closely monitored, in good agreement with expectations

	Muon rate [Hz]	Efficiency [%]	Attenuation length [m]	U/Th [10^{-15} g/g]	^{222}Rn [mBq/m^3]	^{226}Ra [mBq/m^3]
Design	~4	99.5	30-40	10	<10	<1
Reached	5	99.99	>60	<0.4	<5	<0.01

Liquid scintillator (20 kton)

Four purification plants + LS Mixing + QA/QC + high purity N_2 and water production plant to guarantee radio-purity and transparency

NIM.A 908 (2021) 164823

Recipe: LAB + 2.5g/L PPO + 3 mg/L bis-MSB


5000 m^3 LAB tank

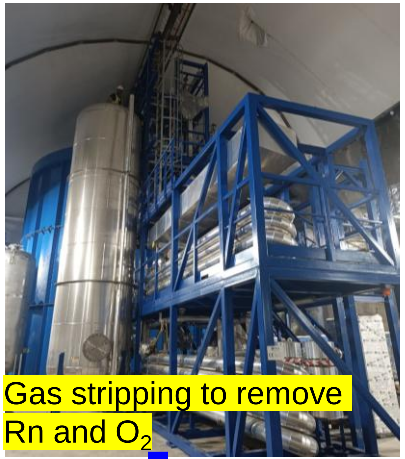

Al_2O_3 to remove particles

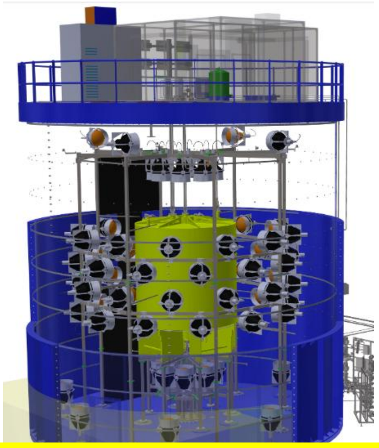

Distillation to remove radioactive impurities

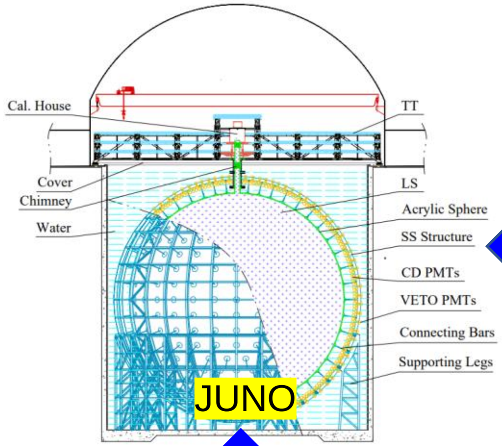

Add 2.5 g/L PPO and 3 mg/L bis-MSB

SS pipes to underground


Water extraction to remove radioactive impurities


Gas stripping to remove Rn and O_2


OSIRIS for LS qualification



JUNO

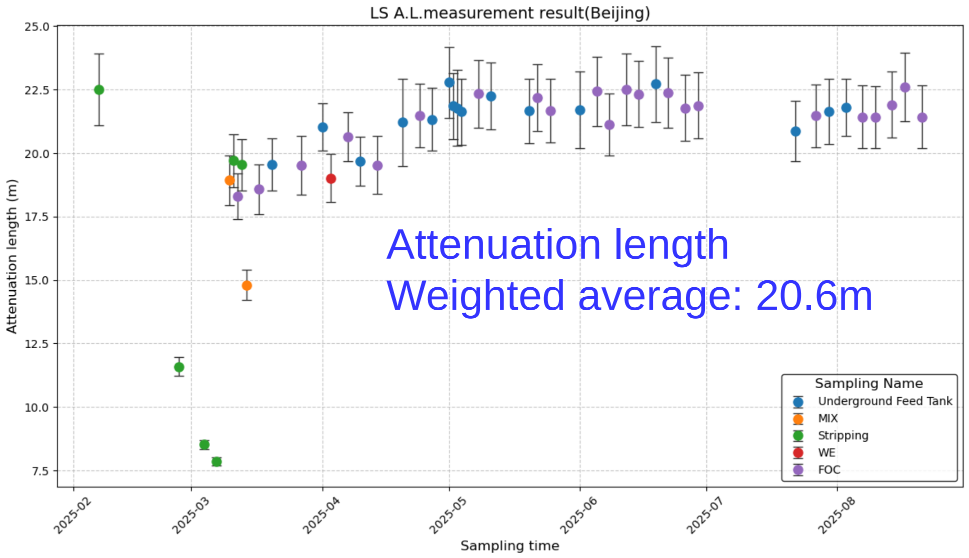
Samples tested by ICP-MS every week for radiopurity, verified by NAA and other methods

Liquid scintillator filling

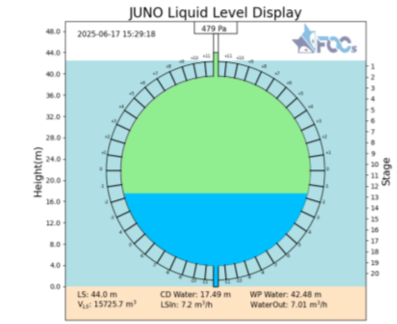
Simultaneous water extraction and LS filling

Comprehensive QC/QA program for LS production, measured for batches:

- ✓ Radiopurity by ICP-MS every week: U/Th < 1×10^{-16} g/g
- ✓ ^{222}Rn in fresh LS, monitored by CD: <1 mBq/m^3
- ✓ ^{222}Rn leak < 0.5 mBq/h
- ✓ Frequent radiopurity monitoring for N_2 and water
- ✓ Weighted average attenuation length > 20m



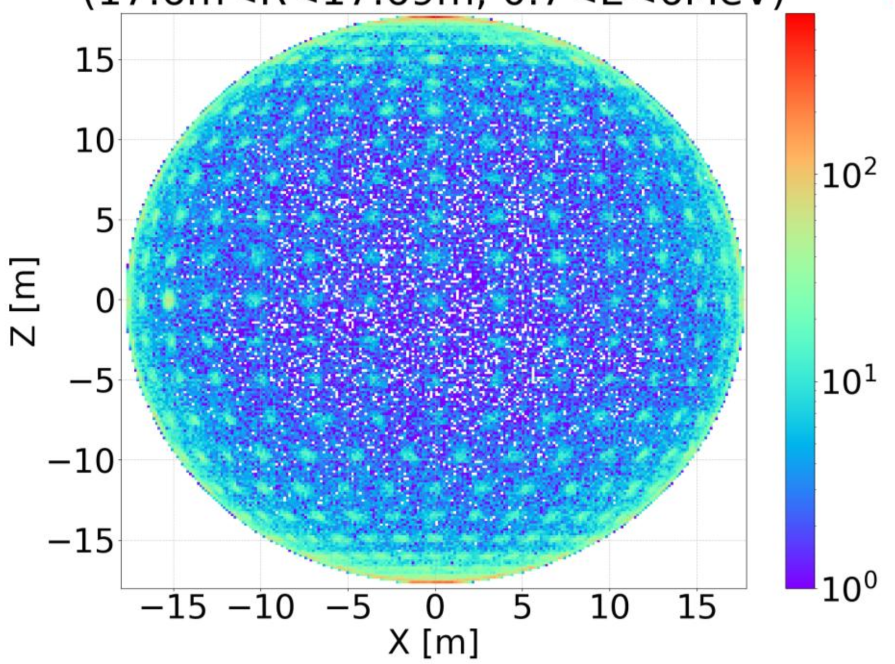
- 2024, Dec 18 — Start of Water Filling
- 2025, Feb 1 — End of Water Filling
- Water Phase
- 2025, Feb 8 — Start of LS Filling
- Mixed Phase



- 2025, Aug 22 — End of LS Filling
- 2025, Aug 23 — Replace 100 t old LS
- Full detector calibration
- 2025, Aug 26 08:00 — Start of Data Taking

A clean detector

- **VETO Water:**
  - U/Th<0.4×10^{-15} g/g, ^{222}Rn<10 mBq/m^3, ^{226}Ra<1 mBq/m^3
- **Acrylic, water, PMTs, steel and LS are clean and water shielding works :**
  - Single rate <7 Hz for R<17.2m & E>0.7MeV (design 7.2Hz)
  - Good enough for reactor neutrinos
- **LS cleanness is very close to other solar neutrino experiments**
  - ^{238}U < 3×10^{-17} g/g (low radon area in a small fiducial volume)
    < 1×10^{-16} g/g (fitted plateau from full detector radon decay)
  - ^{232}Th < 1×10^{-16} g/g (R<13m)
  - ^{210}Po < 1×10^5 [cpd/kt]



Radiopurity control of raw material:

- ✓ Meticulous Monte Carlo Simulation for proper distribution of radioactivity budget
- ✓ Careful material screening
- ✓ Accurate detector production handling

Better than spec. by 15% !

JHEP 11 (2021) 102

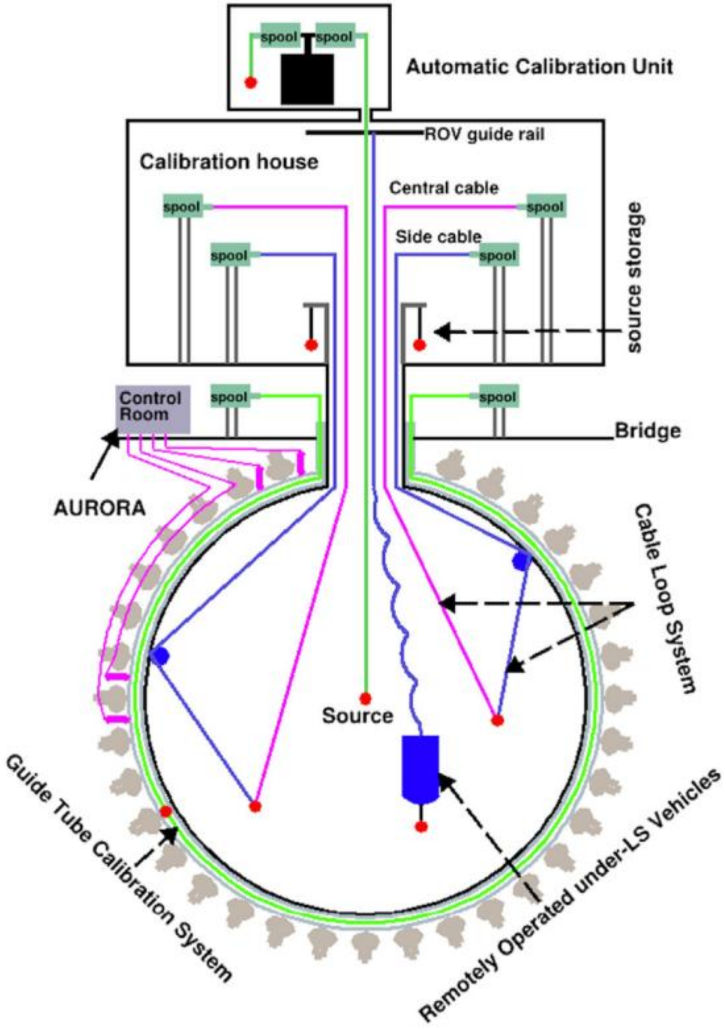
Radiopurity control during installation :

- Leak check of all joints (each < 10^{-8} mbar·L/s) for ^{222}Rn and ^{85}Kr √
- Cleaning and washing of all pipes & vessels to remove dust (by check water/LAB cleanness) √
- Clean room environment during installation √
- Acrylic Surface treatment and protection(Rn daughters) √
- LS filling scheme: water replacement and water washing √

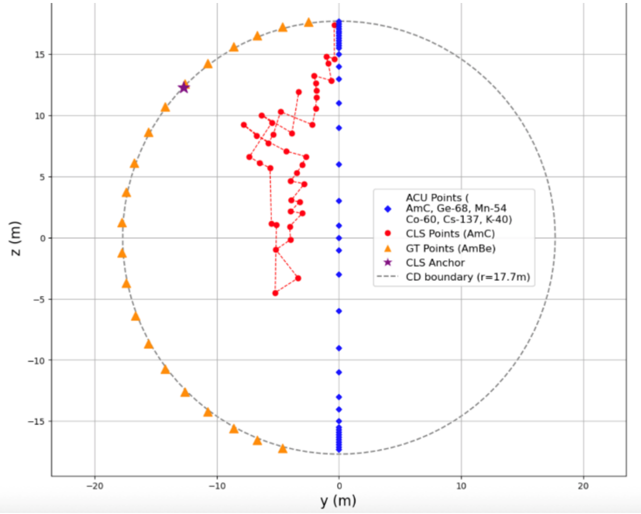
Recirculation probably impossible, unlike Borexino, KamLAND, SNO+,…

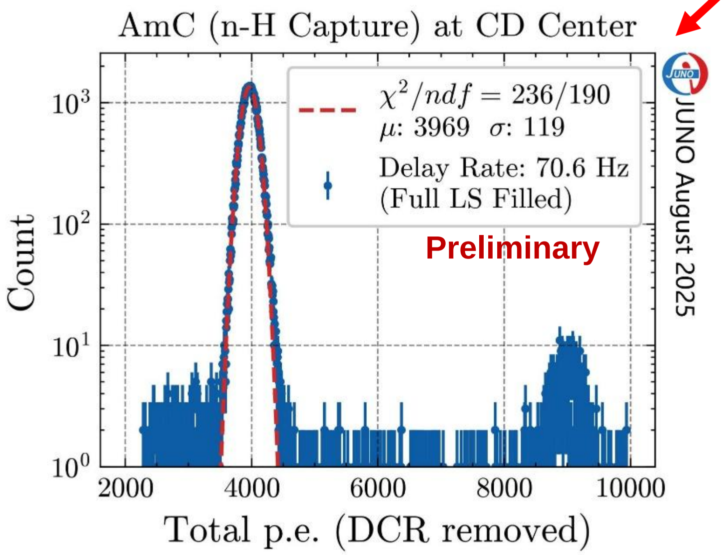
Calibration

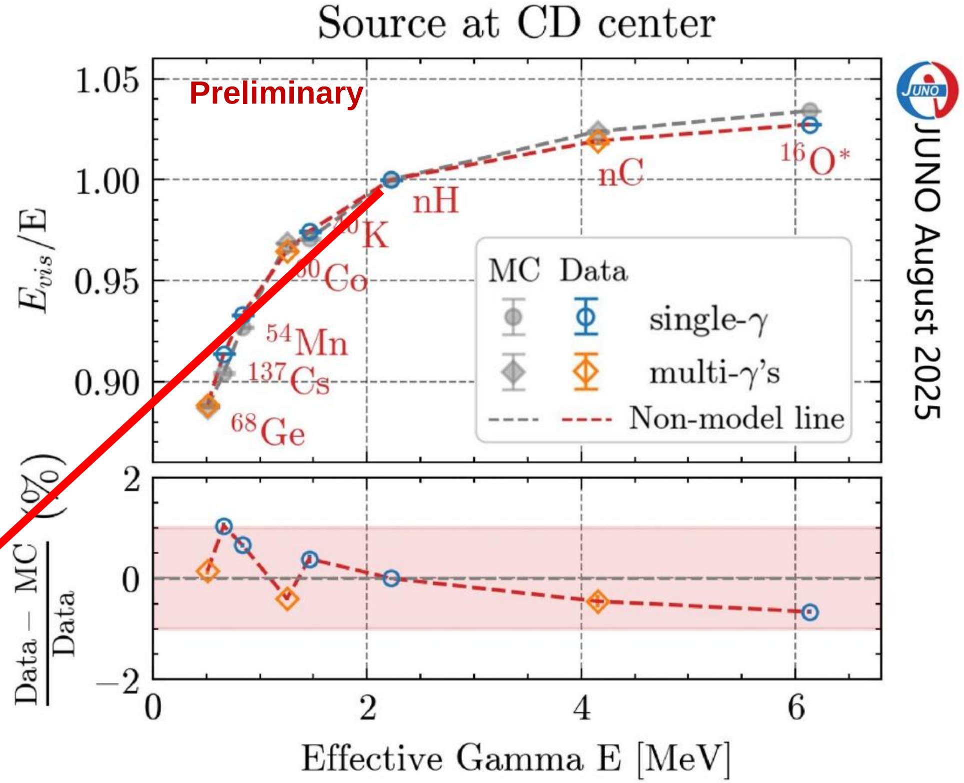
1D, 2D, 3D scan systems using laser/e⁺/γ/n sources + n/α background events



Calibration position performed







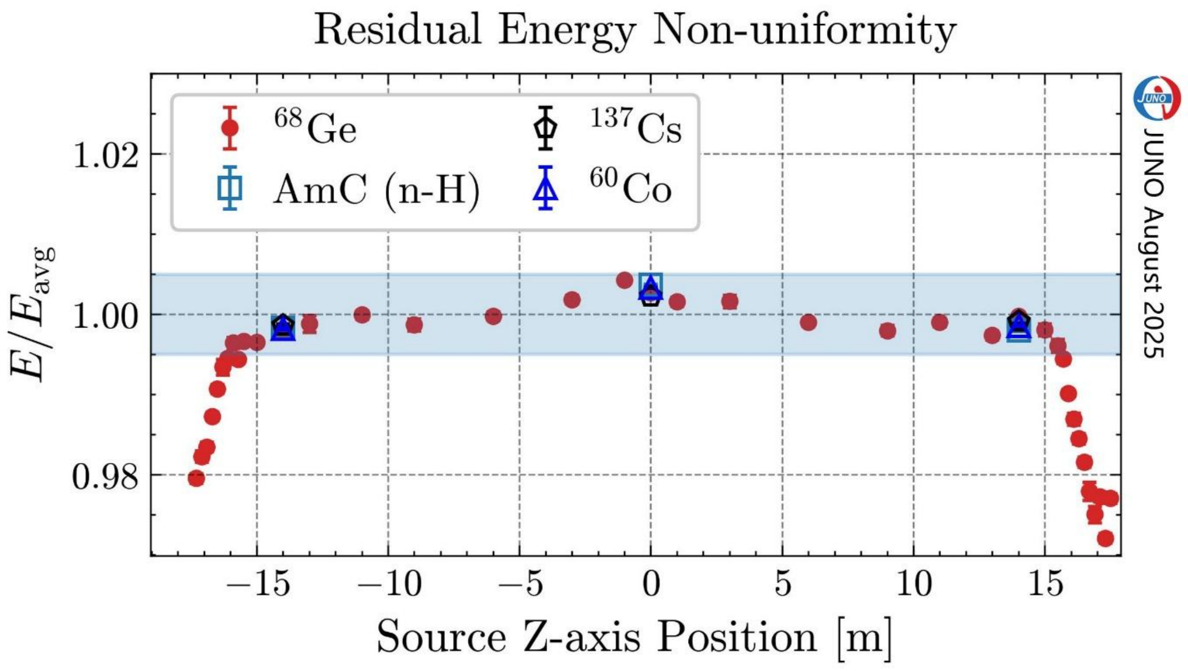
(E_{vis}: scaled from total charge)

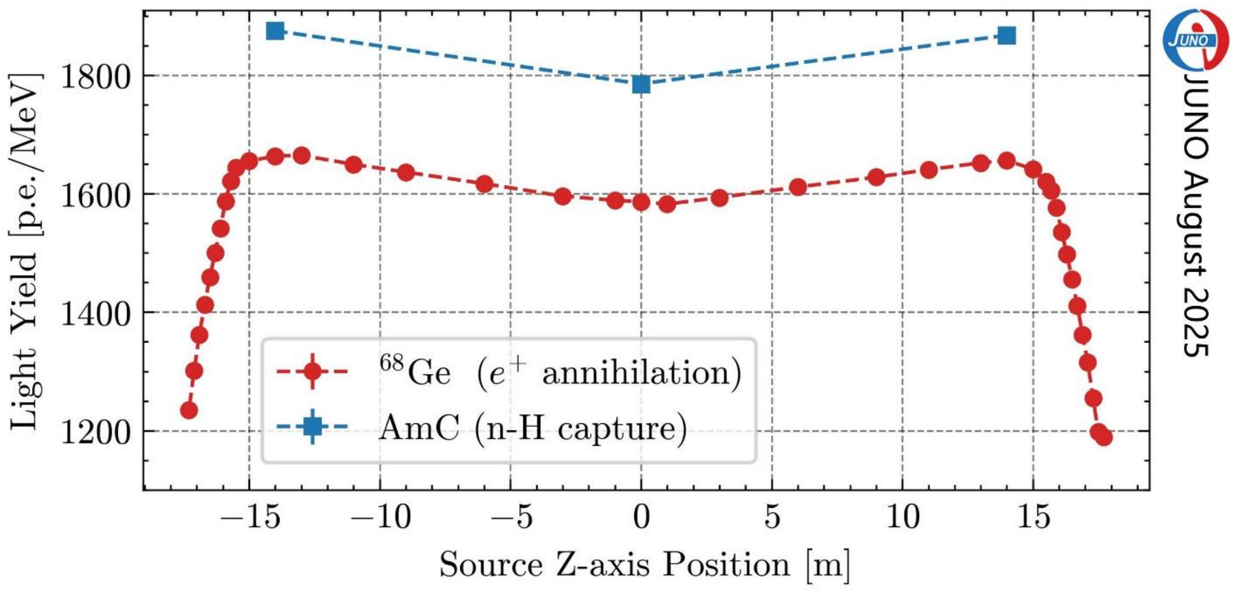
Energy Non-linearity is known to < 1% !

 JHEP 03 (2021) 004

Uniformity and light yield

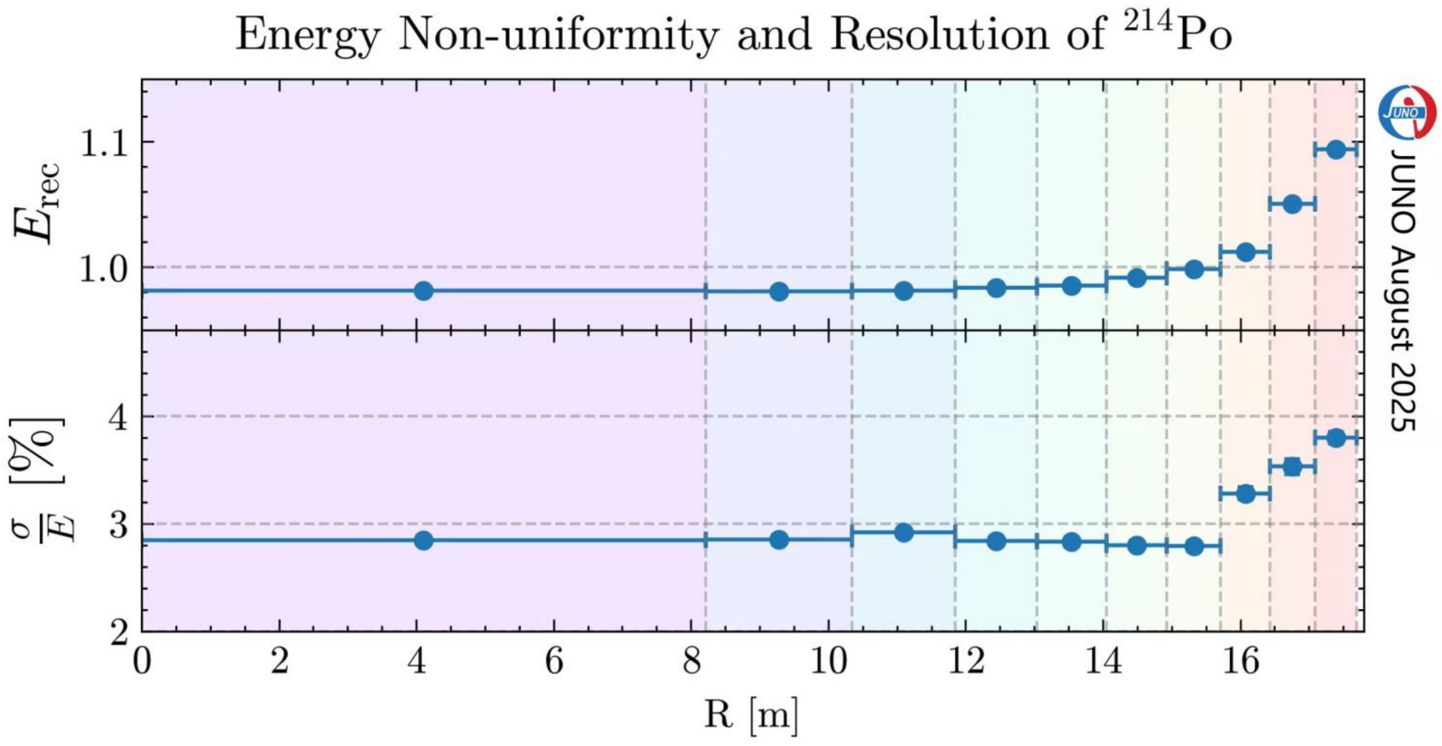
- For R<16m, residual energy non-uniformity scanned along the Z-axis is <0.5%
- Light yield is >1600 PE/MeV for ^{68}Ge, >1800 PE/MeV for neutron, better than expectations (difference due to non-linearity, *Chinese Phys. C 49 (2025) 013003*)
- Edge effects still exist, more calibration data and software work needed

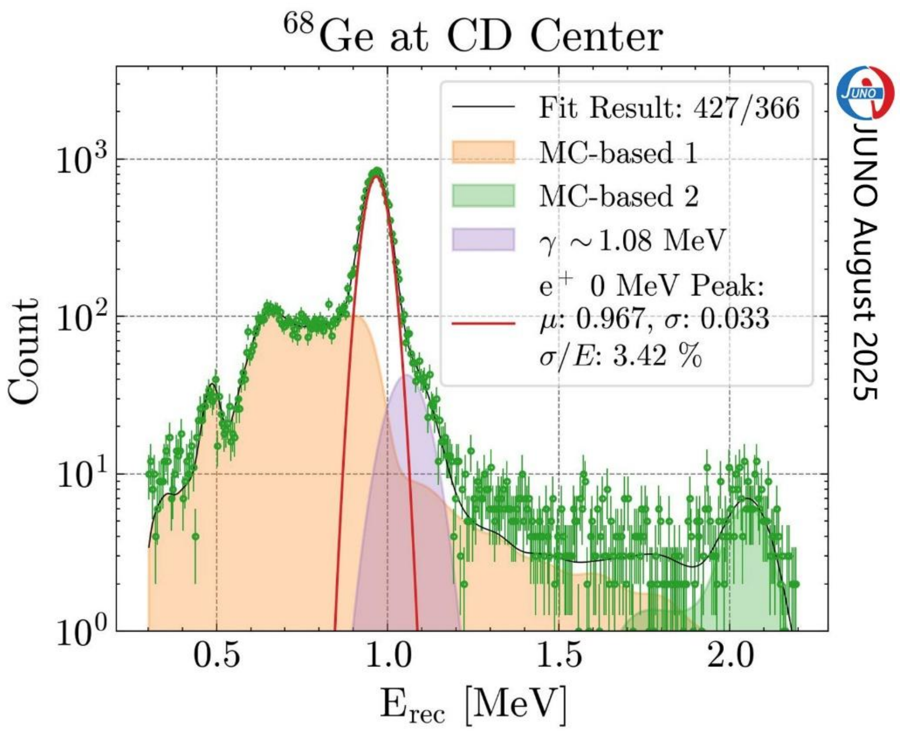




Energy Resolution

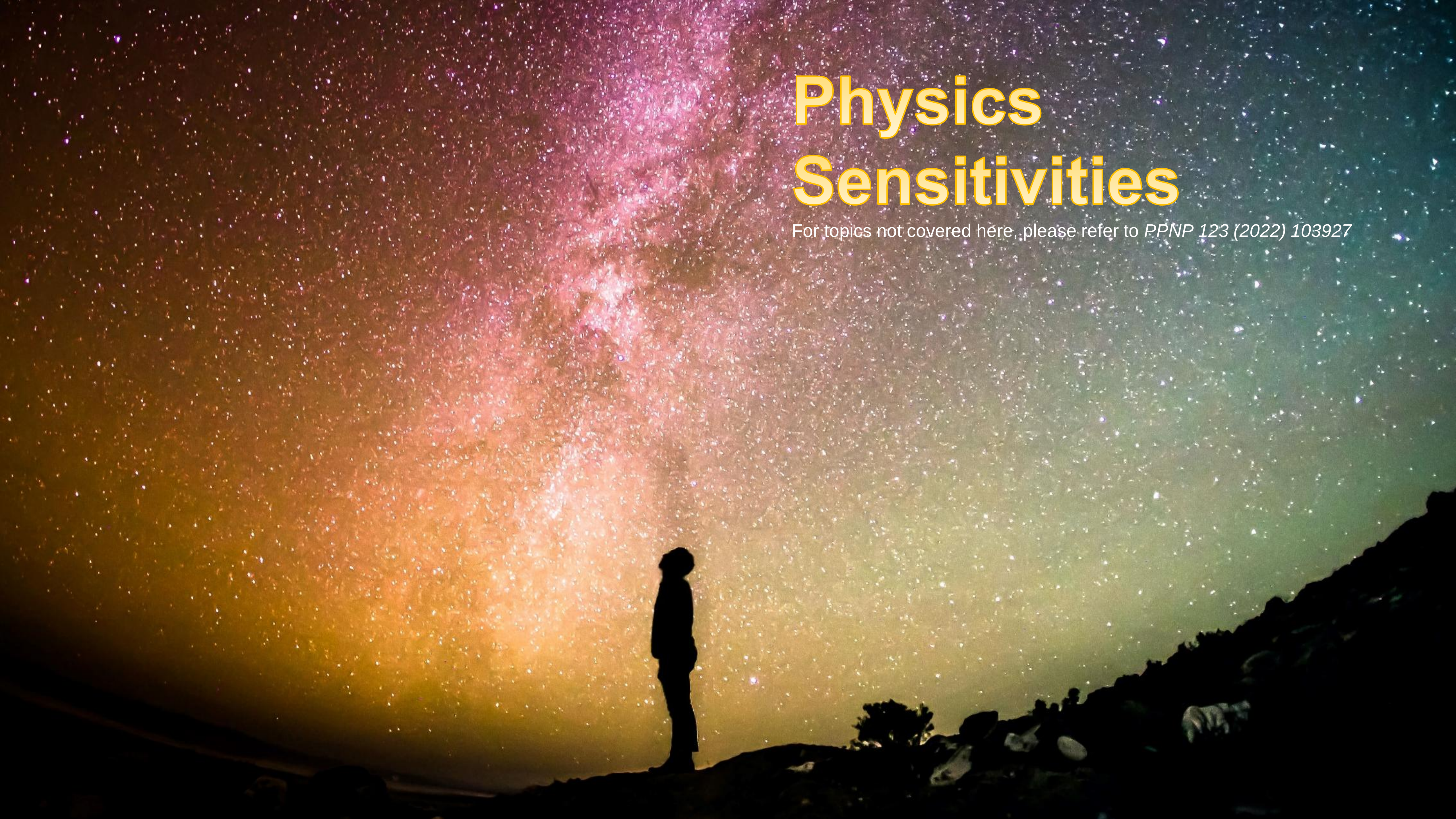
- Energy resolution for alpha from ^{214}Po is ~3% @0.92MeV
- Energy resolution for ^{68}Ge is ~3.4% @ 2× 0.511 MeV, already close to but slightly worse than the expectation of 3.1%
- Further improvement are coming: more calibration data, noise/flasher removal, reconstruction and fit, …



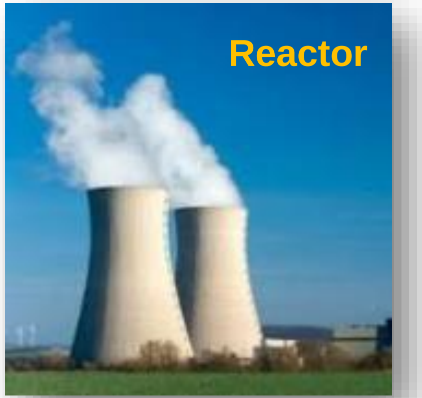


Physics Sensitivities

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

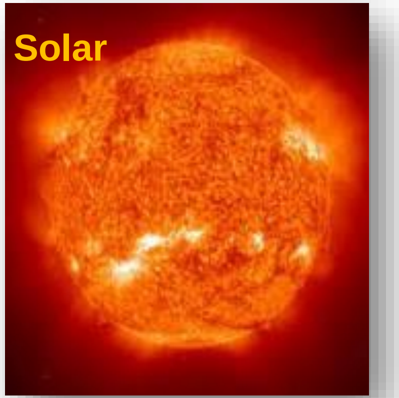


A multi-purpose observatory



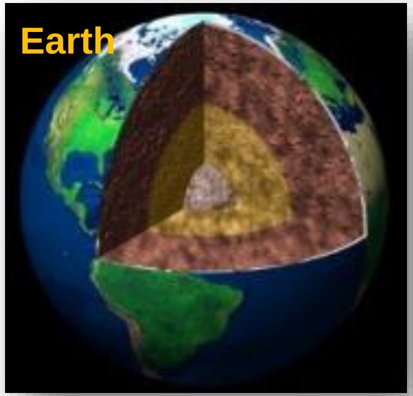
~60 IBDs per day

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

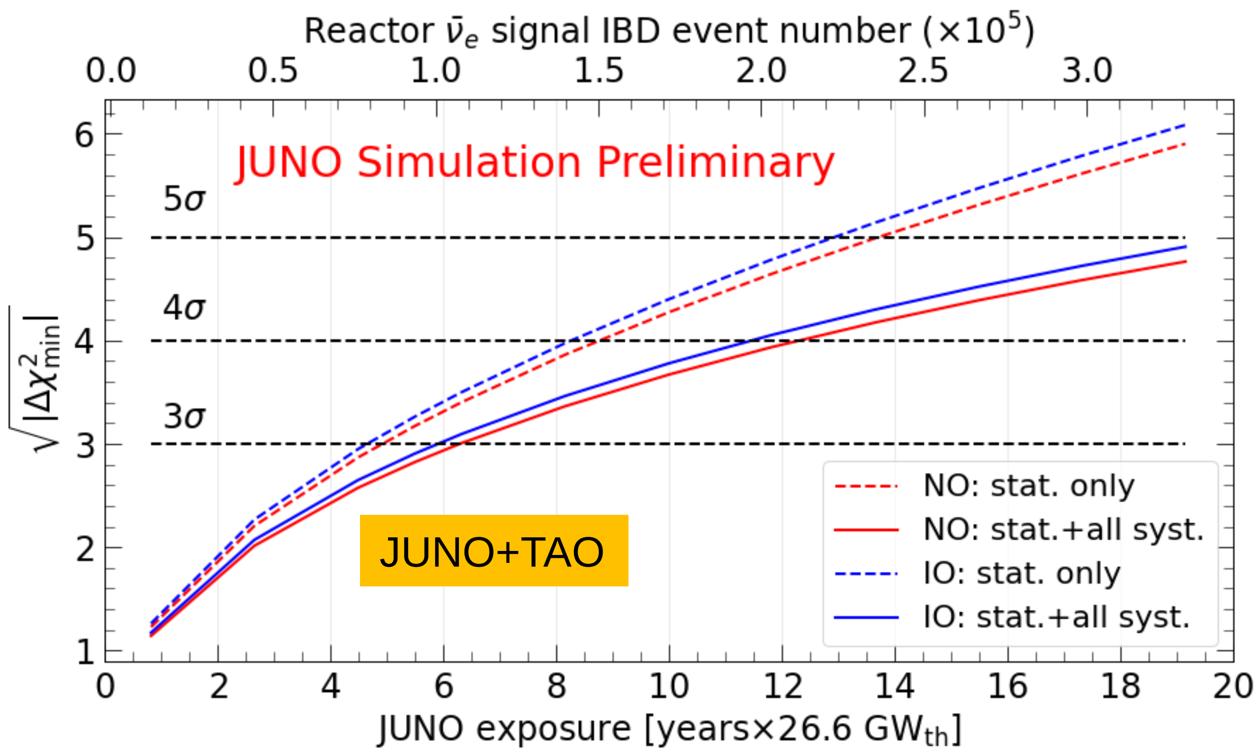
IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

Neutrino Mass Ordering

Inverse beta decay reaction

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



	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**

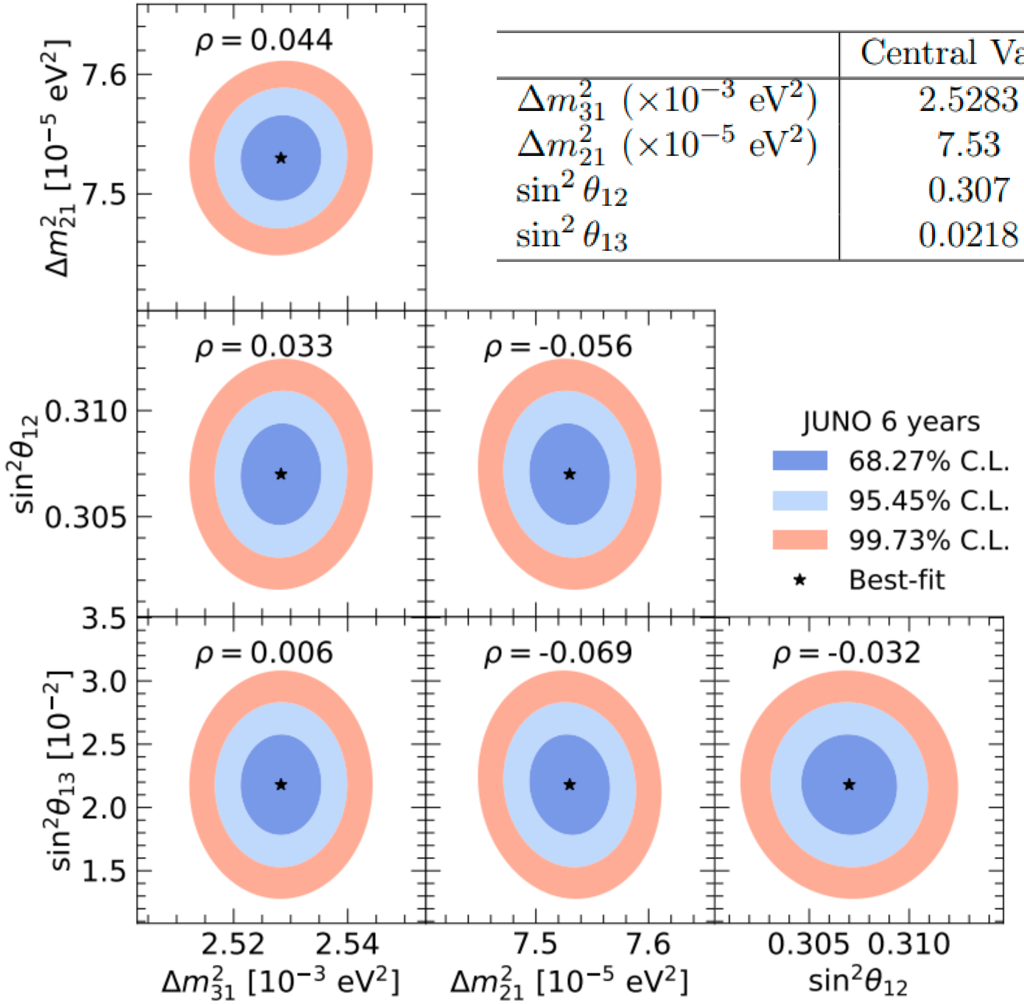
Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity

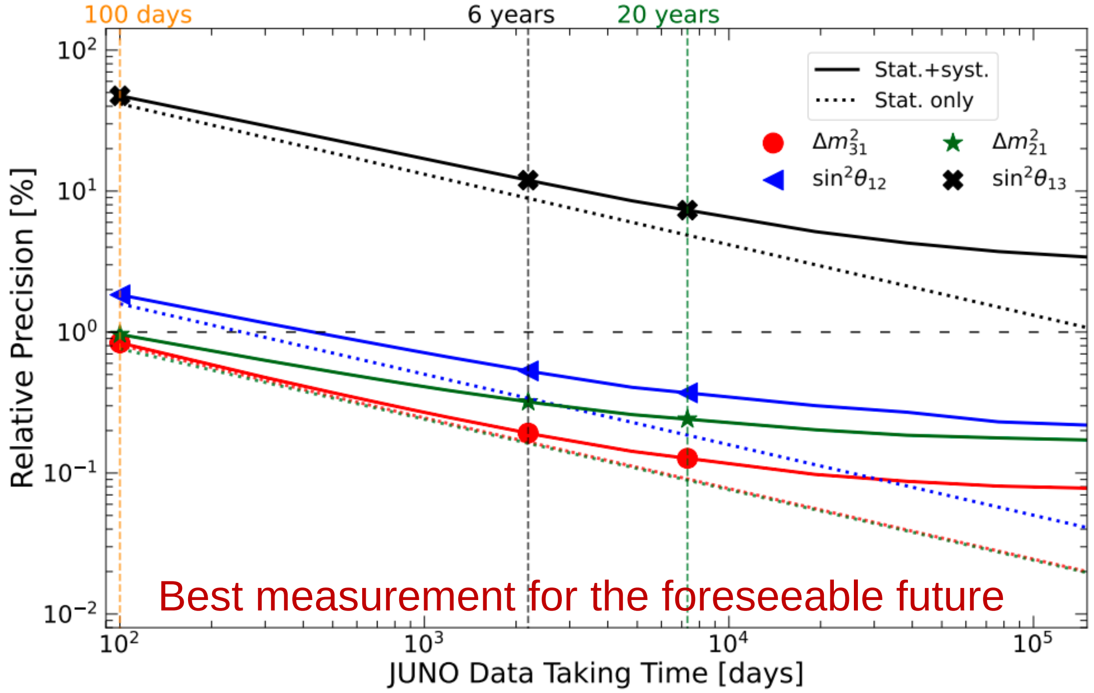
Neutrino oscillation parameters

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

A: Inverse Beta Decay

$$\nu_\ell + n \to p + \ell^- \qquad n \to p + e^- + \bar{\nu}_e$$

$$\bar{\nu}_\ell + p \to n + \ell^+$$

- **Famous inverse beta decay on free proton (in Hydrogen rich detectors)**
- **Hadron weak current: induced currents**

$$\overline{u_u}(p_u)\,\gamma^\rho\,(1-\gamma^5)\,u_d(p_d) \to \langle p(p_p)|h^\rho_W(0)|n(p_n)\rangle$$

- **Isospin symmetry**
- **Correlated with free neutron decay**

$$\langle p(p_p)|v^\rho_W(0)|n(p_n)\rangle = \overline{u_p}(p_p)\left[\gamma^\rho F_1(Q^2) + \frac{i\,\sigma^{\rho\eta}q_\eta}{2m_N}F_2(Q^2) + \frac{q^\rho}{m_N}F_3(Q^2)\right]u_n(p_n)$$

$$\langle p(p_p)|a^\rho_W(0)|n(p_n)\rangle = \overline{u_p}(p_p)\left[\gamma^\rho\gamma^5 G_A(Q^2) + \frac{q^\rho}{m_N}\gamma^5 G_P(Q^2) + \frac{p^\rho_p + p^\rho_n}{m_N}\gamma^5 G_3(Q^2)\right]u_n(p_n)\,.$$

$$e^+ + e^- \to 2\gamma$$

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

Capture on H or Gd,
Delayed signal, 2.2, 8 MeV

Dedicated calculations in :
Vogel & Beacom, 1999
Strumia & Vissani, 2003
Ricciardi, Vignaroli, Vissani, 2022

Radiative correction:
Kurylov, Ramsey-Musolf, Vogel, 2003

Uncertainty as small as ~0.2%

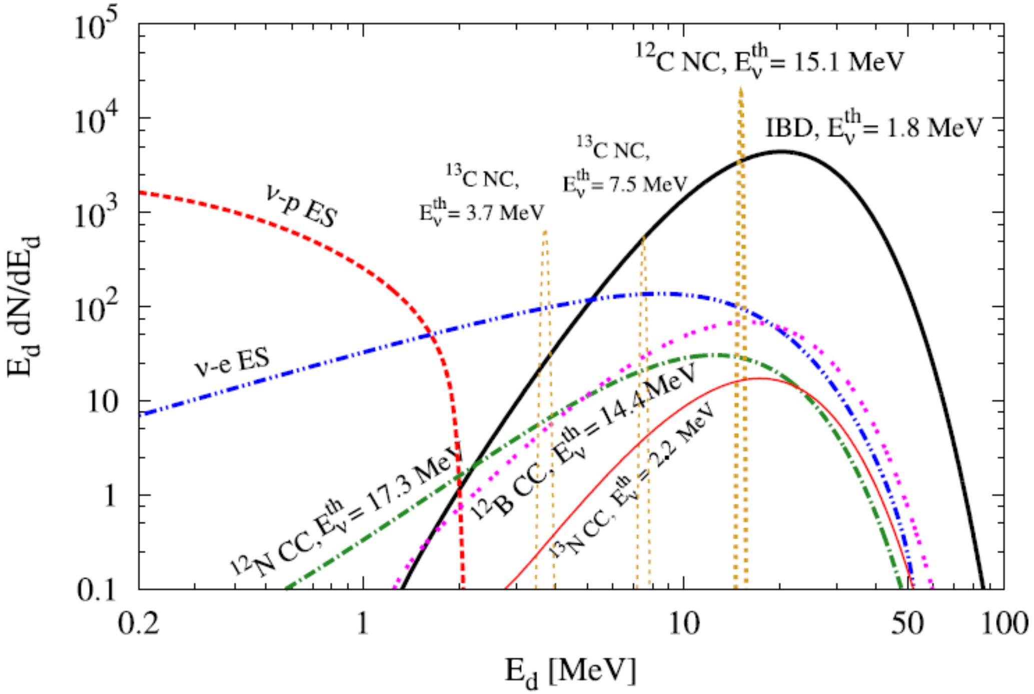
Excellent opportunity for new physics searches!

CCSN potential at JUNO

Multi-channel detection, all flavors

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

- Early warning
- CCSN Characteristics
  - Time evolution & Energy spectra
  - Total energy, luminosity,
- Neutrino properties
  - Mass ordering
  - Absolute mass
  - New physics



Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

JUNO: Feasibility (high energy)

[Chin. Phys. C 45 023004 (](#)
[Ap. J. 965 (2024) 122](#)

Interaction channels of ^{8}B-ν:

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

- No threshold
- All flavours & $\sigma(\nu_{\mu,\tau}) / \sigma(\nu_e) = 1/6$
- Single events - continuous spectrum

CC: $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$

- $E_{thr} = 2.2$ MeV
- Possible only with ν_e
- Prompt: e^-; Delayed: ^{13}N decay

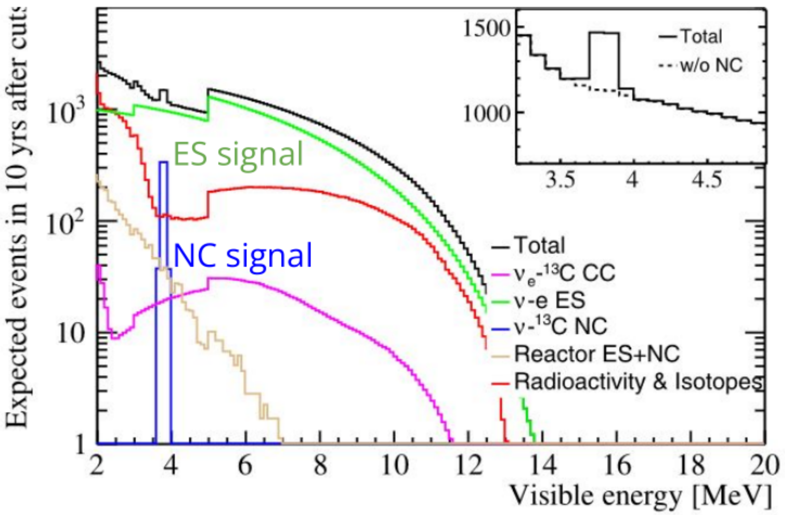
NC: $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C^*$

- $E_{thr} = 3.685$ MeV
- All flavors & equal σ
- Single events - monochromatic γ

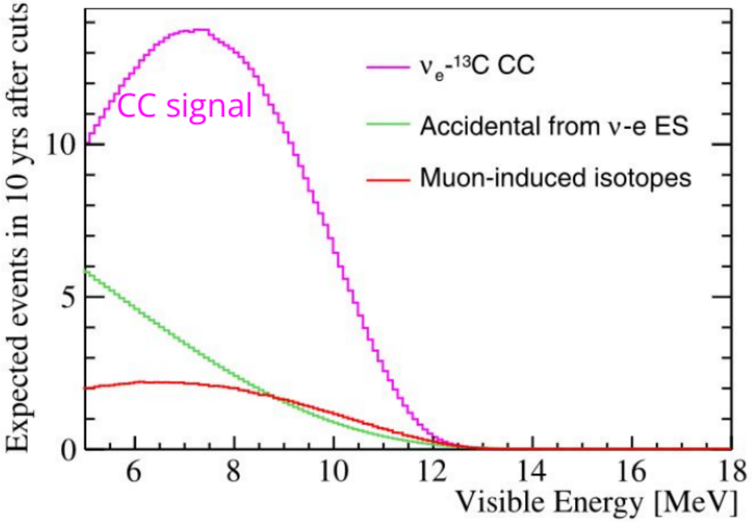
Backgrounds:

- **Externals**: can be neglected after FV cuts
- **Internals**: unstable nuclei in ^{232}Th and ^{238}U chains with high Q values
- **Cosmogenics**: can be reduced after Three-Fold Coincidences cuts
- **Accidental** coincidences (specific for CC)

10 years, single events after cuts



10 years, correlated prompt events after cuts



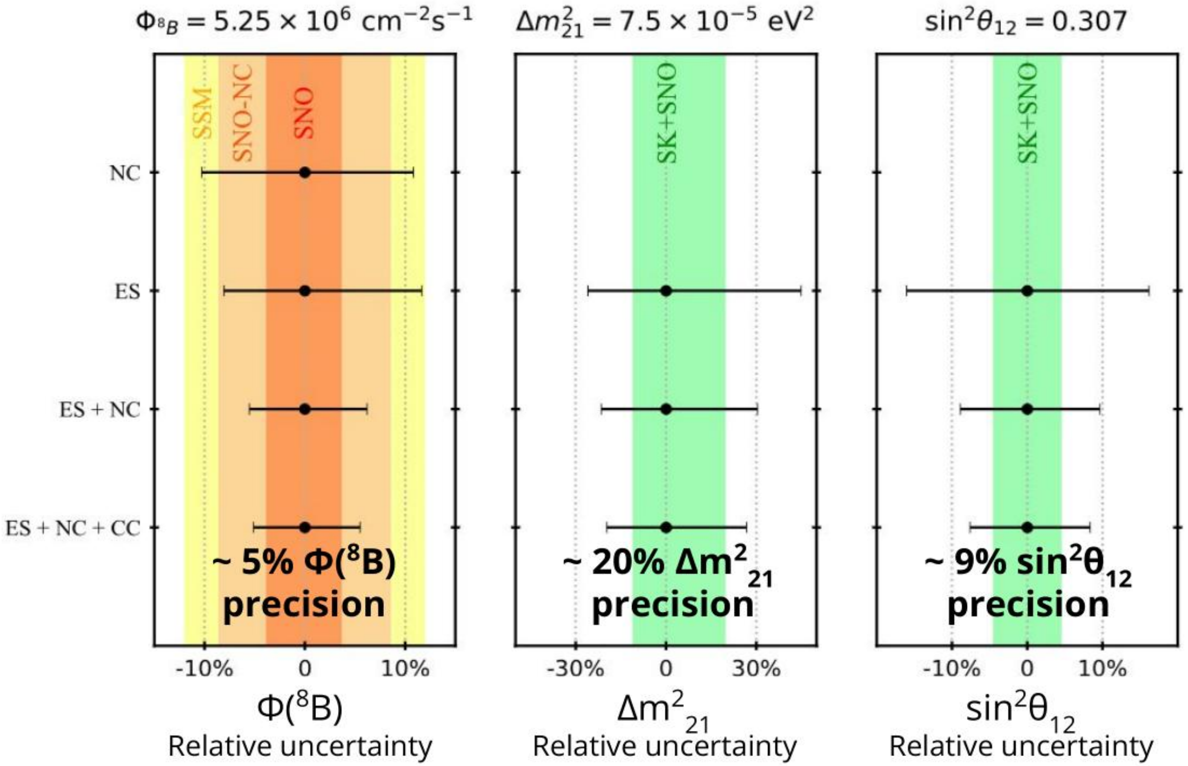
Neutrinos from Sun (B8)

CC & ES: their event **rate** depends on the neutrino flux and on the ν_e **survival probability** model
NC: it will allow a **model independent measurement** of **Φ(^{8}B)**, first after SNO

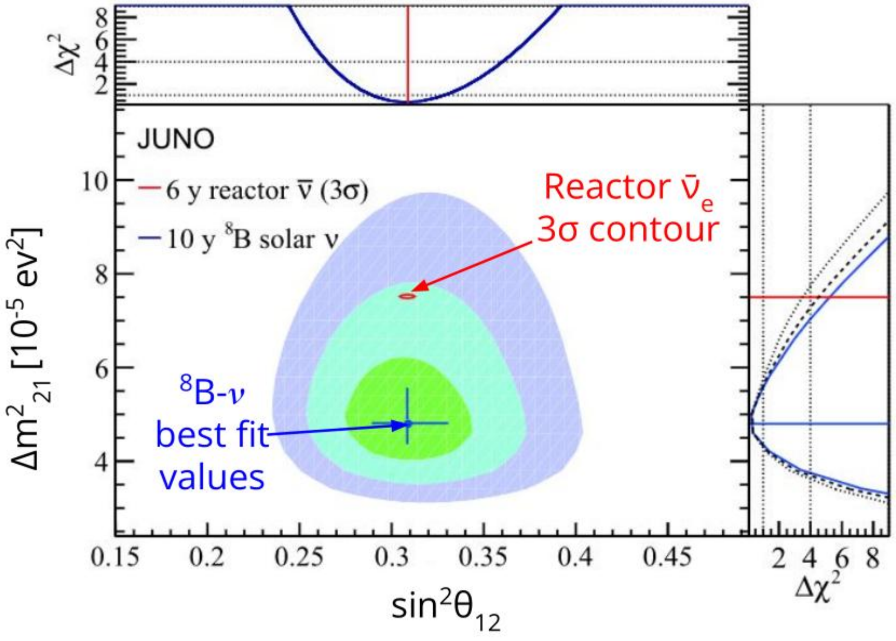
→ **Simultaneous measurement** of **Φ(^{8}B), Δm^2_{21}, and $\sin^2\theta_{12}$**

Chin. Phys. C 45 023004 (2021) 1
Ap. J. 965 (2024) 122

JUNO results with 10 years of data-taking

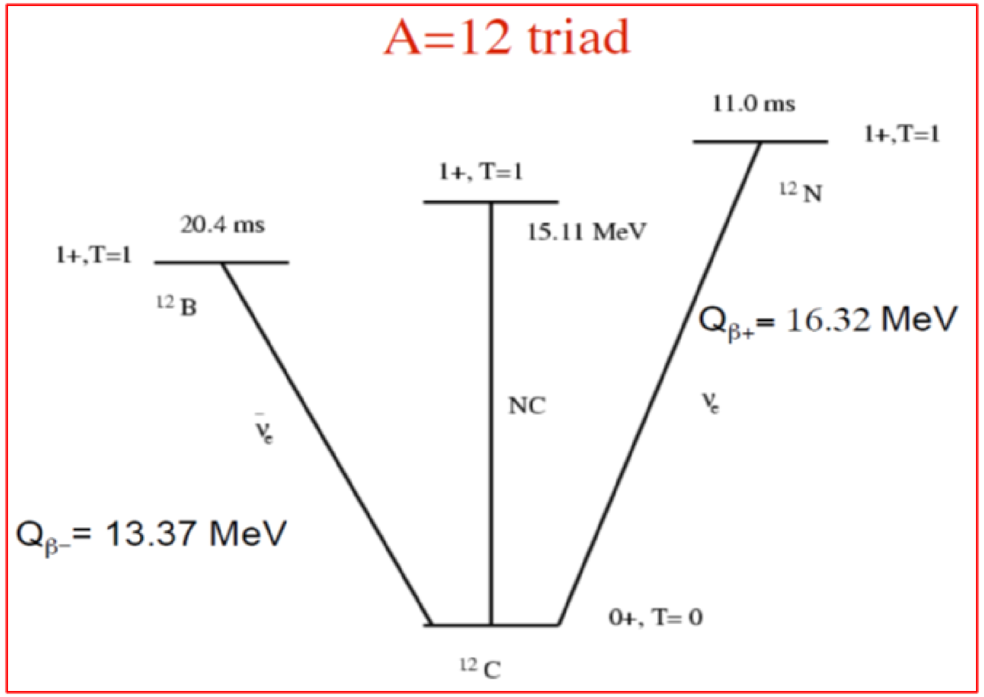


Δm^2_{21} and **$\sin^2\theta_{12}$** with **^{8}B-ν & reactor $\bar{\nu}_e$**



Potential to search for possible discrepancies

B: Low Energy Scattering on Carbon



Nuclear structure effects:

- **beta (M1) decay calibration**
- **ν-energy ~ nuclear excitation energy: shell model**
- **giant resonance: CRPA or shell model**
- **>100 MeV, fermi Gas models or spectral function method**
- **DIS region: parton,**

From Vogel, NPA 777 (2006) 340-355

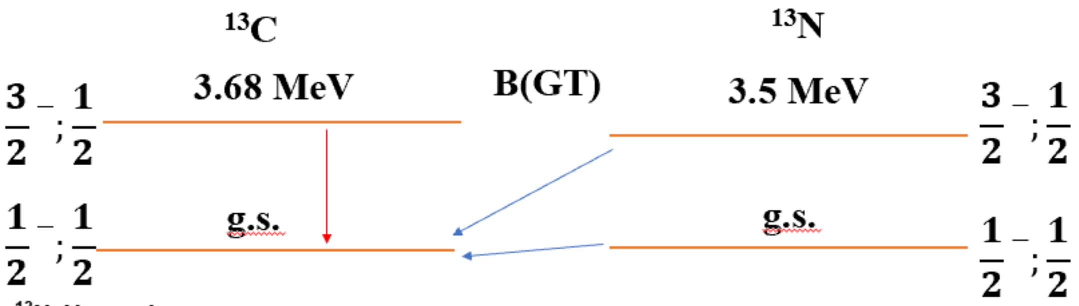
	$^{12}C(\nu_e, e^-)^{12}N_{gs}$ decay at rest	$^{12}C(\nu_\mu, \mu^-)^{12}N_{gs}$ decay in flight	$^{12}C(\nu_e, e^-)^{12}C(15.11)$ decay at rest
Experiment [31]	9.4±0.5±0.8	–	11 ± 0.85 ± 1.0
Experiment [32]	9.1±0.4±0.9	66 ± 10 ± 10	–
Experiment [33]	10.5±1.0±1.0	–	–
Shell model [36]	9.1	63.5	9.8
CRPA [34,35]	8.9	63.0	10.5
EPT [37]	9.2	59	9.9

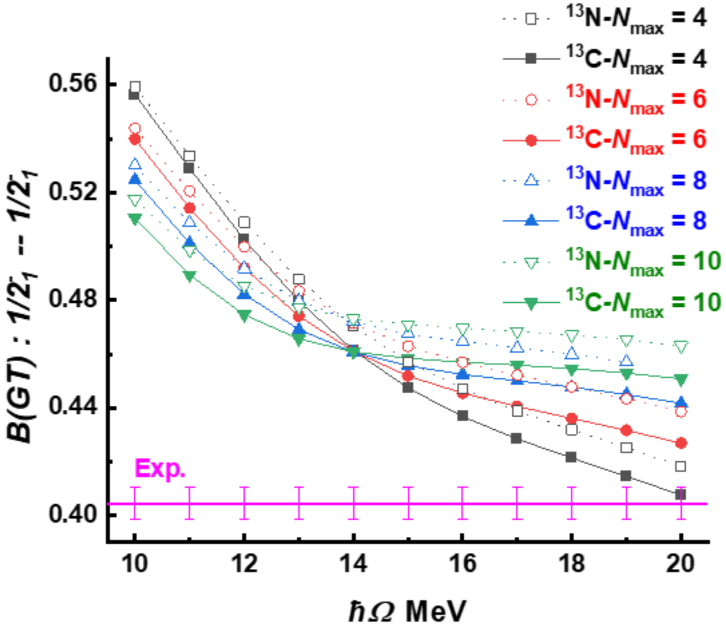
B: Low Energy Scattering on Carbon

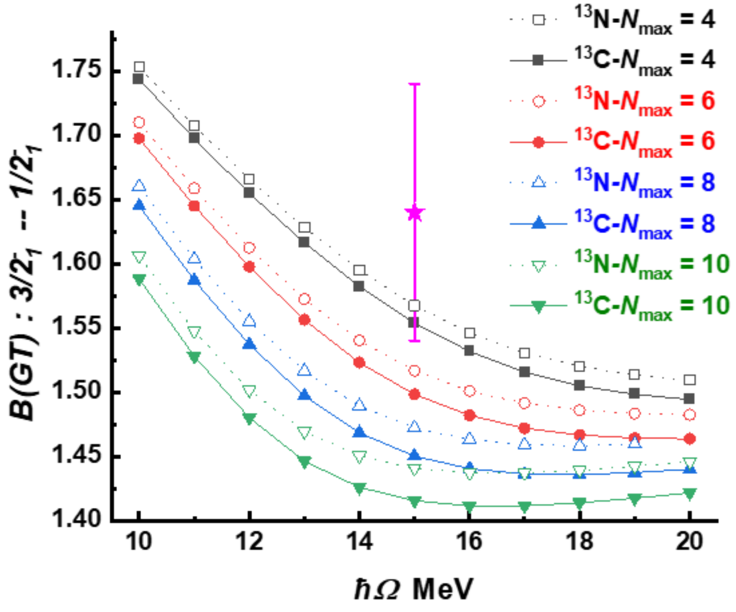
- $B(GT)$ from Daejeon16 using the wave functions from ^{13}C or ^{13}N (based on isospin symmetry)

Work in progress based on No-Core Shell Model method, by He Li, P. Yin, J Vary et al.

Also early calculations by Kajino-san et. al.







Atmospheric neutrinos

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

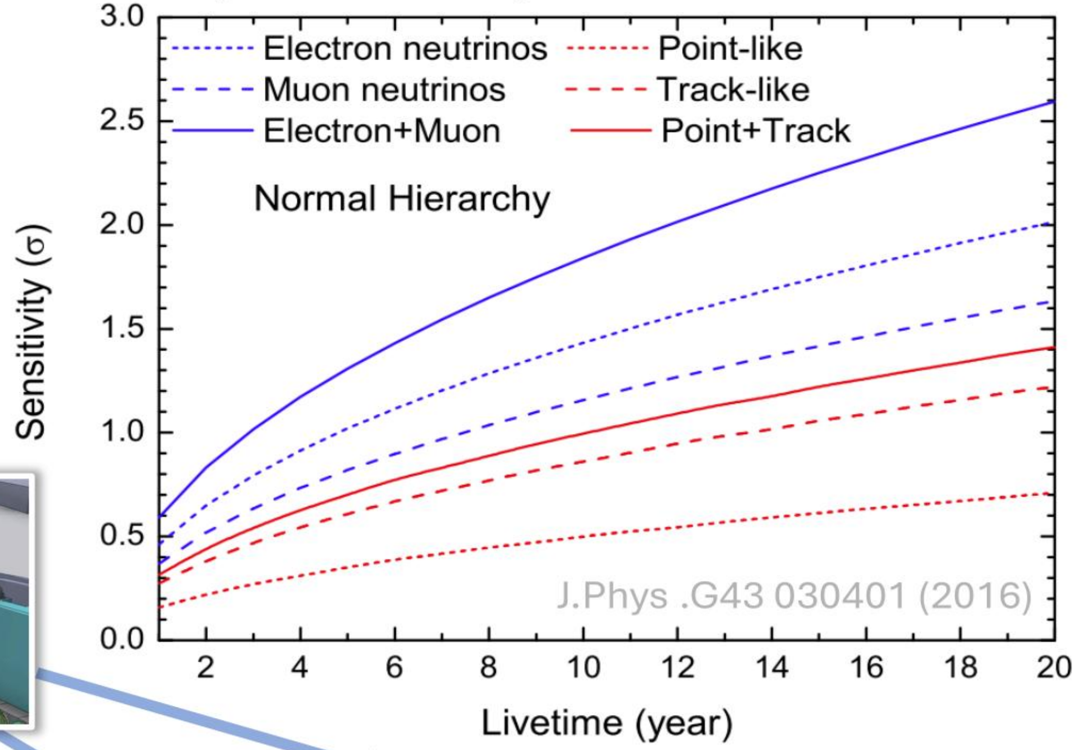
JUNO **first experiment** to study **atmospheric** neutrino oscillation with **liquid scintillator:**

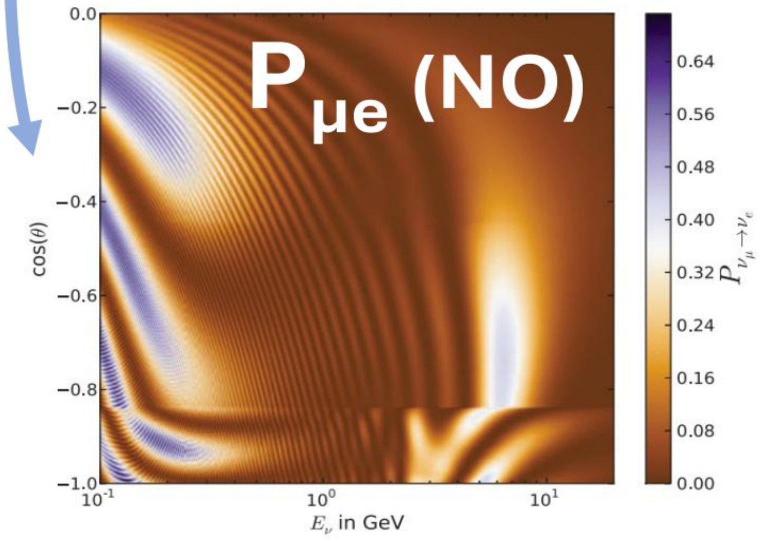
NMO via **matter effects** requirements:

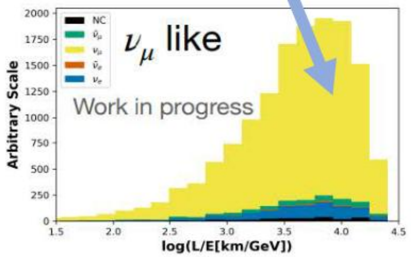
→ Good **flavor separation** (traditional + ML)

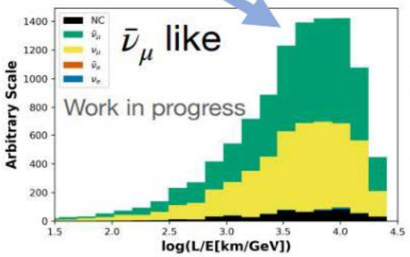
→ Good track reconstruction

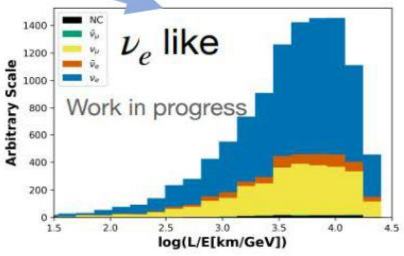
Expected > 3σ in 6 years combined with reactor

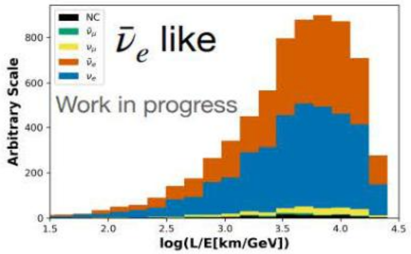












Diffuse Supernova Neutrino Background (DSNB)

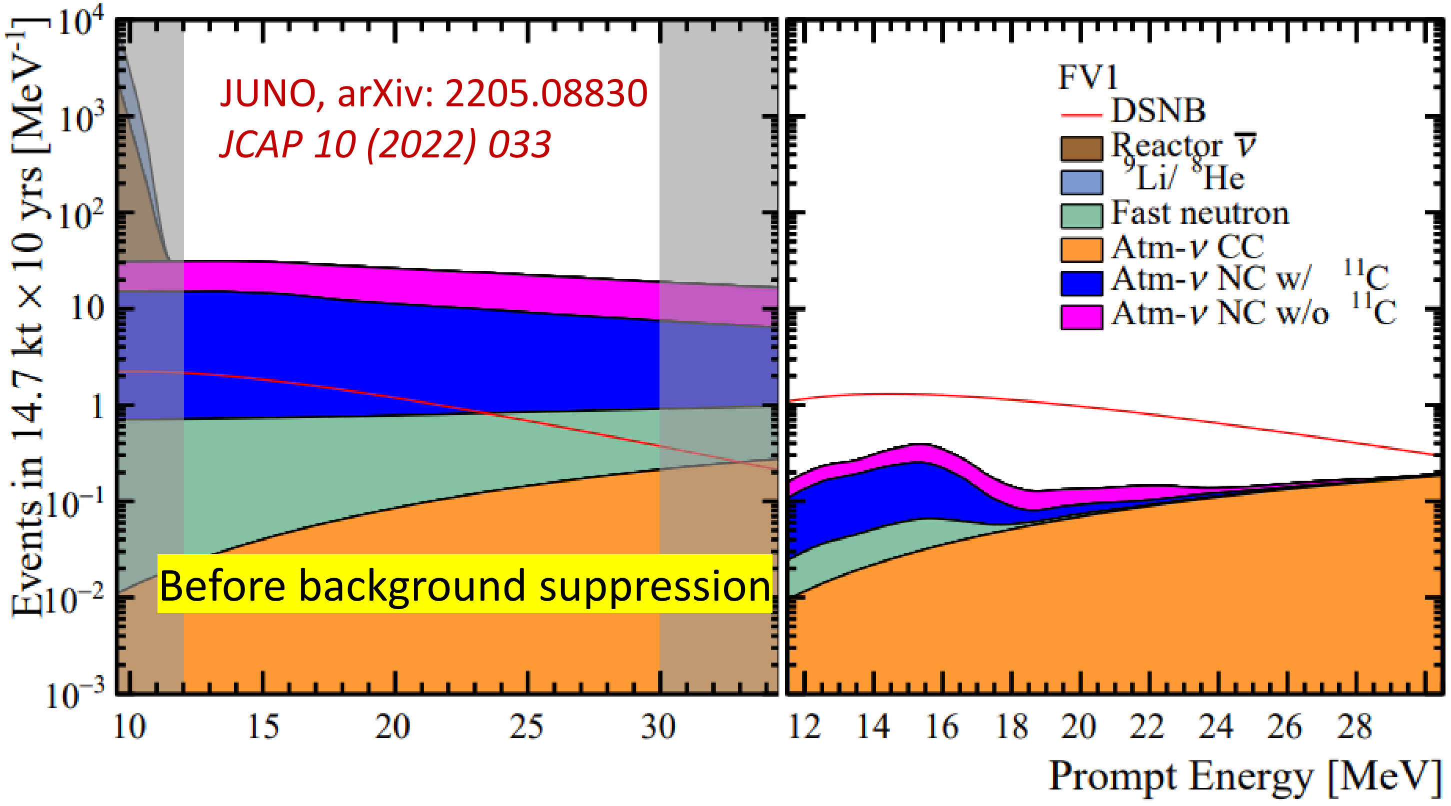
- **DSNB: 2-4 events in JUNO per year**
  - ✓ **Not detected yet**

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)



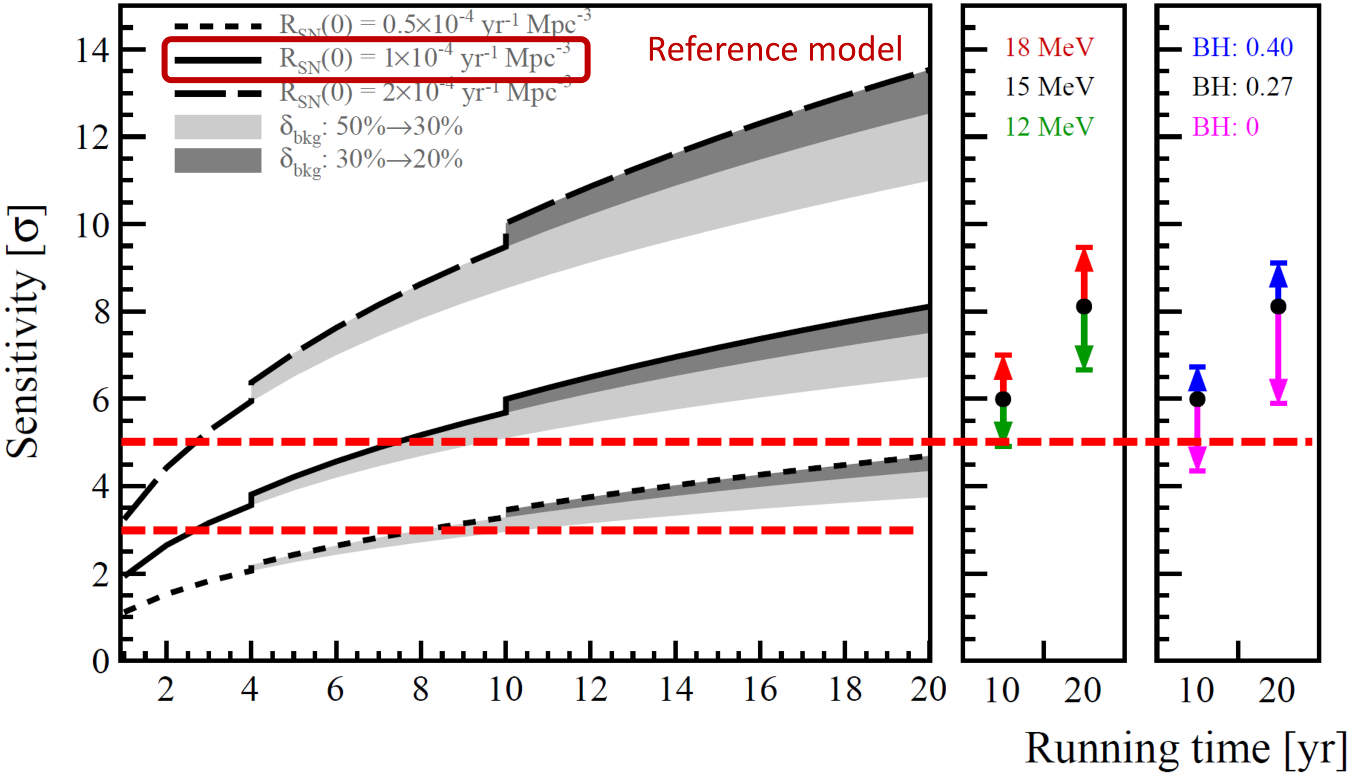
Improvements compared to JUNO physics book *J. Phys. G43:030401(2016)* **:**

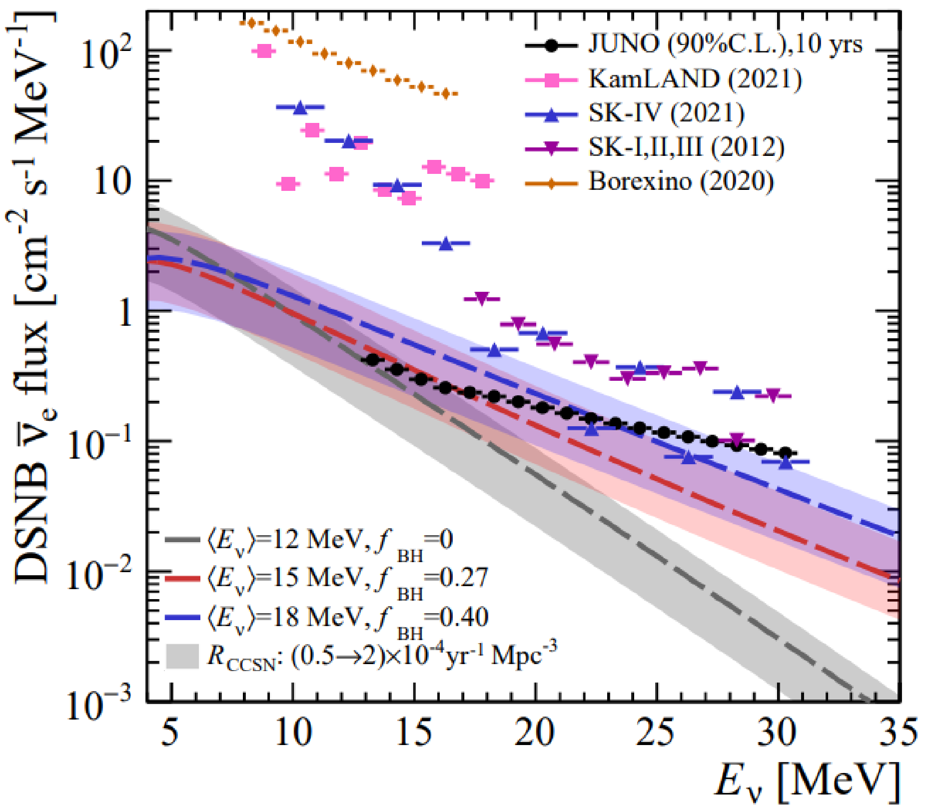
- ✓ **Background evaluation:** 0.7 per year → **0.54** per year
- ✓ **PSD:** signal efficiency 50% → **80%** (1% residual background)
- ✓ **Realistic DSNB signal model: non-zero fraction of failed Supernova**

➡ S/B improved from **2 to 3.5**

Diffuse Supernova Neutrino Background (DSNB)

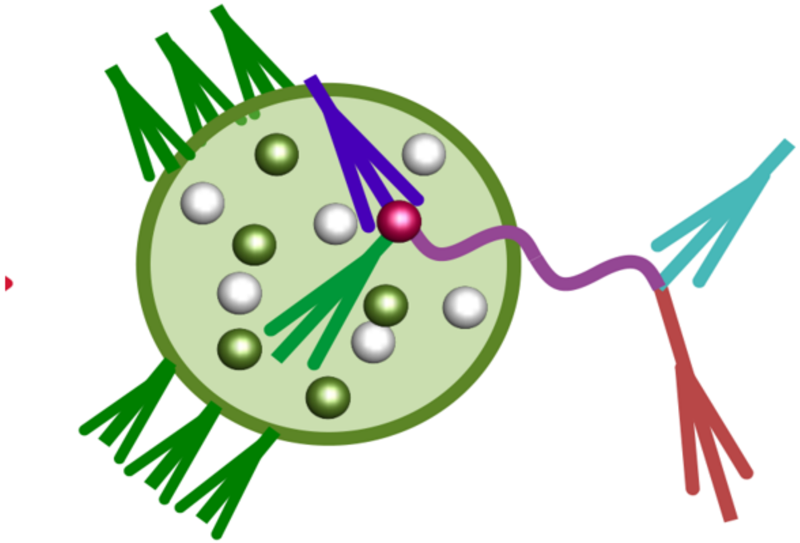
arXiv: 2205.08830, JCAP 10 (2022) 033

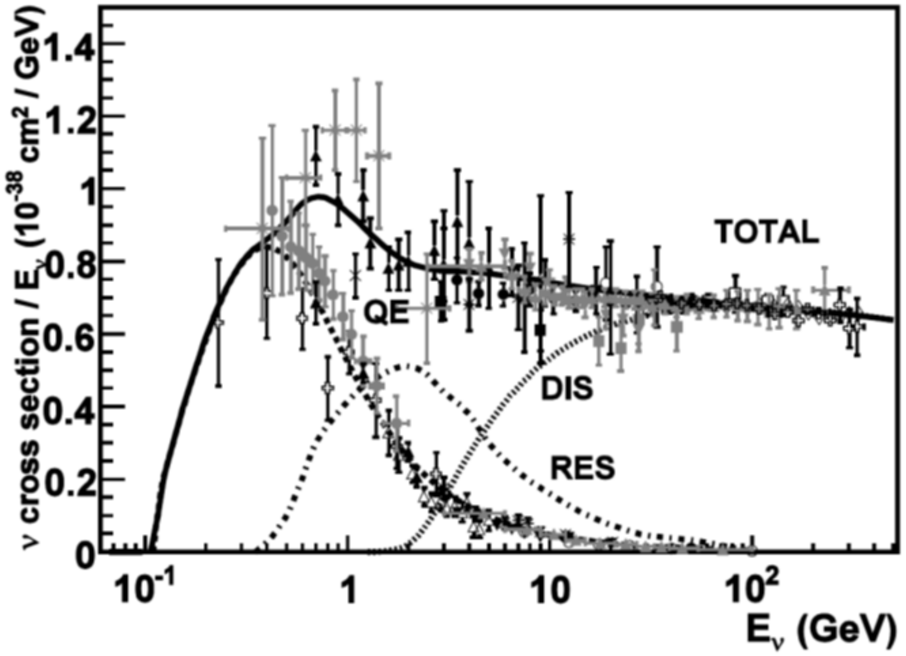




- **If no positive observation, JUNO can set the world-leading best limits of DSNB flux**
- **With the nominal model (black solid curve (left plot)): 3σ (3 yrs) and 6σ (10 yrs)**

C: GeV neutrino-nucleus interactions





quasielastic scattering	resonance production	deep-inelastic scattering
$\nu_l + n \rightarrow l^- + p$ $\bar{\nu}_l + p \rightarrow l^+ + n$	$\nu_l + n \rightarrow l^- + \Delta^+$ $\nu_l + p \rightarrow l^- + \Delta^{++}$ $\bar{\nu}_l + n \rightarrow l^+ + \Delta^-$ $\bar{\nu}_l + p \rightarrow l^+ + \Delta^0$	$\nu_l + N \rightarrow l^- + N' + n\pi$ $\bar{\nu}_l + N \rightarrow l^- + N' + n\pi$
Fermi motion, binding energy, M_A, 2p2h, … …	**Hardon production, FSI**	**Parton Model, FSI**

C: Generators in the Market

Marco Roda @ NUINT24

Status overview

- Well established generator
  - Used by many experiments around the world
    - Main new addition is JUNO
  - Main generator for all the LAr experiments
- Two main efforts
  - Model development
  - Tuning
- Contacts, details and code are all available from our website: www.genie-mc.org/
- Latest release: version 3.04.02, released in April 2024
  - Previous release was 3.04.00, released in March 2023
  - http://releases.genie-mc.org/
- Recent publications
  - Neutrino-nucleon cross-section model tuning in GENIE v3 - Phys.Rev.D 104 (2021) 7, 072009
  - Hadronization model tuning in genie v3 - Phys.Rev.D 105 (2022) 1, 012009

Genie — UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GiBUU

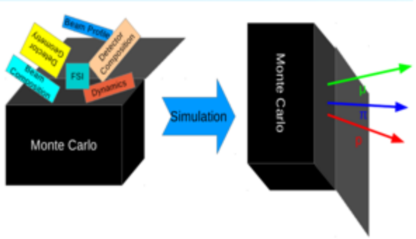
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Ulrich Mosel and Kai Gallmeister @ NUINT24

- GiBUU is presently used to describe
  1. Dilepton and pion production in heavy-ion collisions (HADES experiment at GSI)
  2. Inelastic electron scattering at JLAB (and SLAC, MAMI)
  3. Neutrino-nucleus reactions at Fermilab, T2K and FASER
- All with the same theory input and code!
- We provide the code for download from gibuu.hepforge.org,

NuWro - general information (1)

Jan T. Sobczyk @ NUINT24



- Monte Carlo generator of neutrino interactions
- Beginning ~ 2005 at the University of Wrocław
- Optimized for ~1 GeV
- Can handle all kind of targets, neutrino fluxes, equipped with detector interface
- Written in C++
- Output files in the ROOT format
- PYTHIA6 used for hadronization in DIS
- Open source code, repository: https://github.com/NuWro/nuwro

NuWro — Wrocław Neutrino Event Generator

3

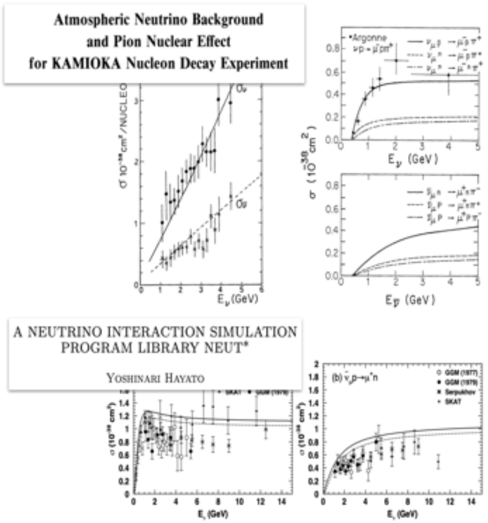
NEUT

Patrick Stowell @ NUINT24

The NEUT neutrino interaction simulation program library

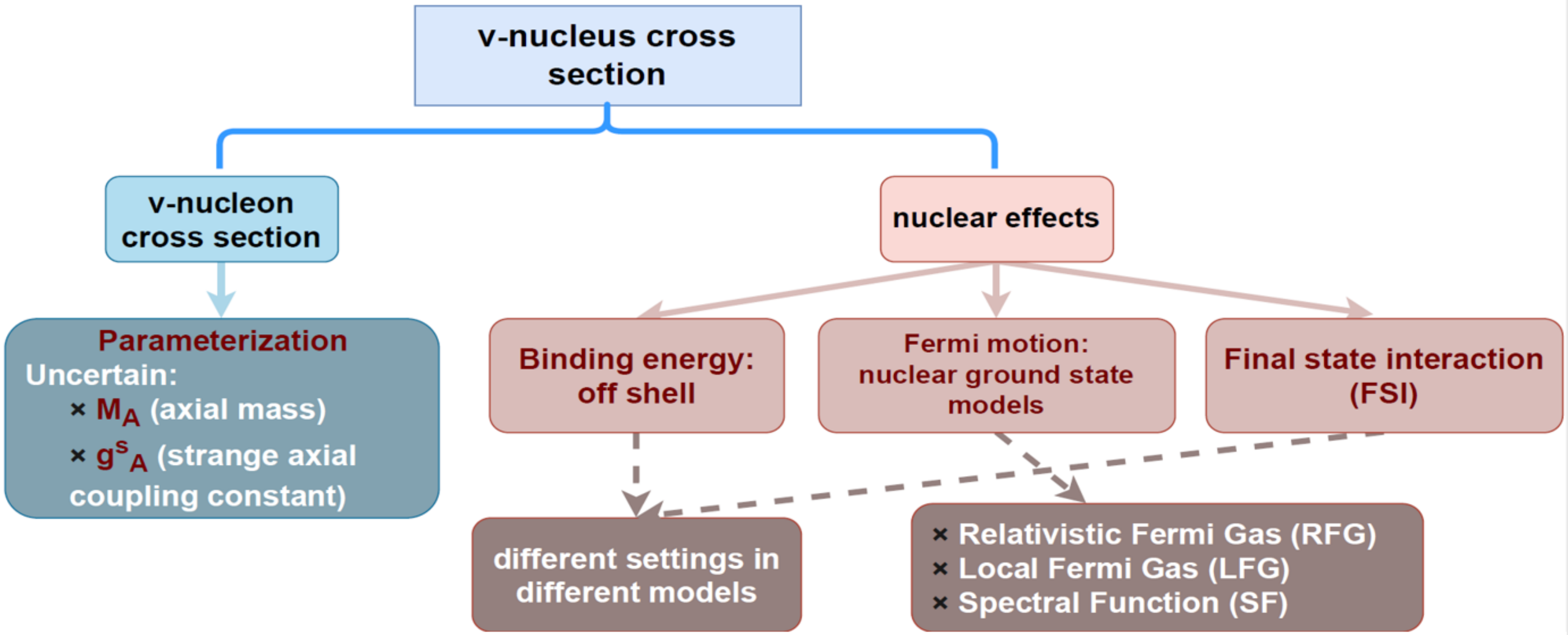
Yoshinari Hayato and Luke Pickering — The European Physical Journal Special Topics volume 230, pages 4469–4481 (2021)

- MeV to TeV scale neutrino interaction generator originally created in the 70s to support neutrino backgrounds at Kamioka.
- Long history of development driven by evolving requirements of KamiokaNDE, Super-KamiokaNDE, and T2K.
- Currently the primary interaction generator for SK and T2K, used in all oscillation/cross-section analyses.
  - See Laura, Stephen, Ulyesse, and Cesar's talks this NuINT!



C: General components in generators

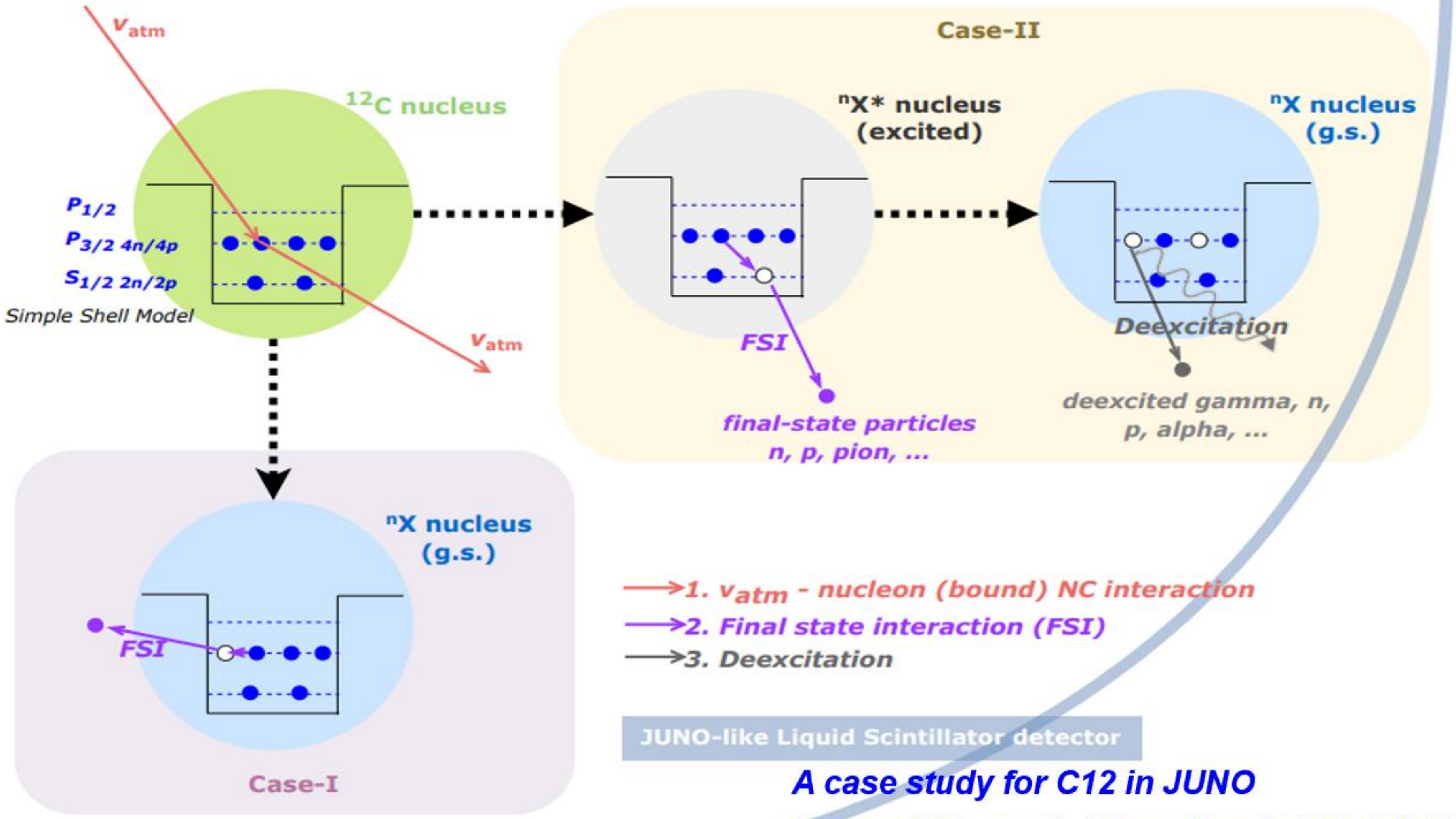
Brief summary of GeV neutrino interaction models



$$\frac{d\sigma^{\mathrm{IA}}_{\ell A}}{d\omega\, d\Omega} = \sum_N \int d^3p\, dE\, P^N_{\mathrm{hole}}(\mathbf{p}, E)\, \frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\mathrm{elem}}_{\ell N}}{d\omega\, d\Omega}\, P^N_{\mathrm{part}}(\mathbf{p}', \mathcal{T}')$$

average over the initial nucleon state | nucleon cross section | final-state interactions

C: New component: adding deexcitation



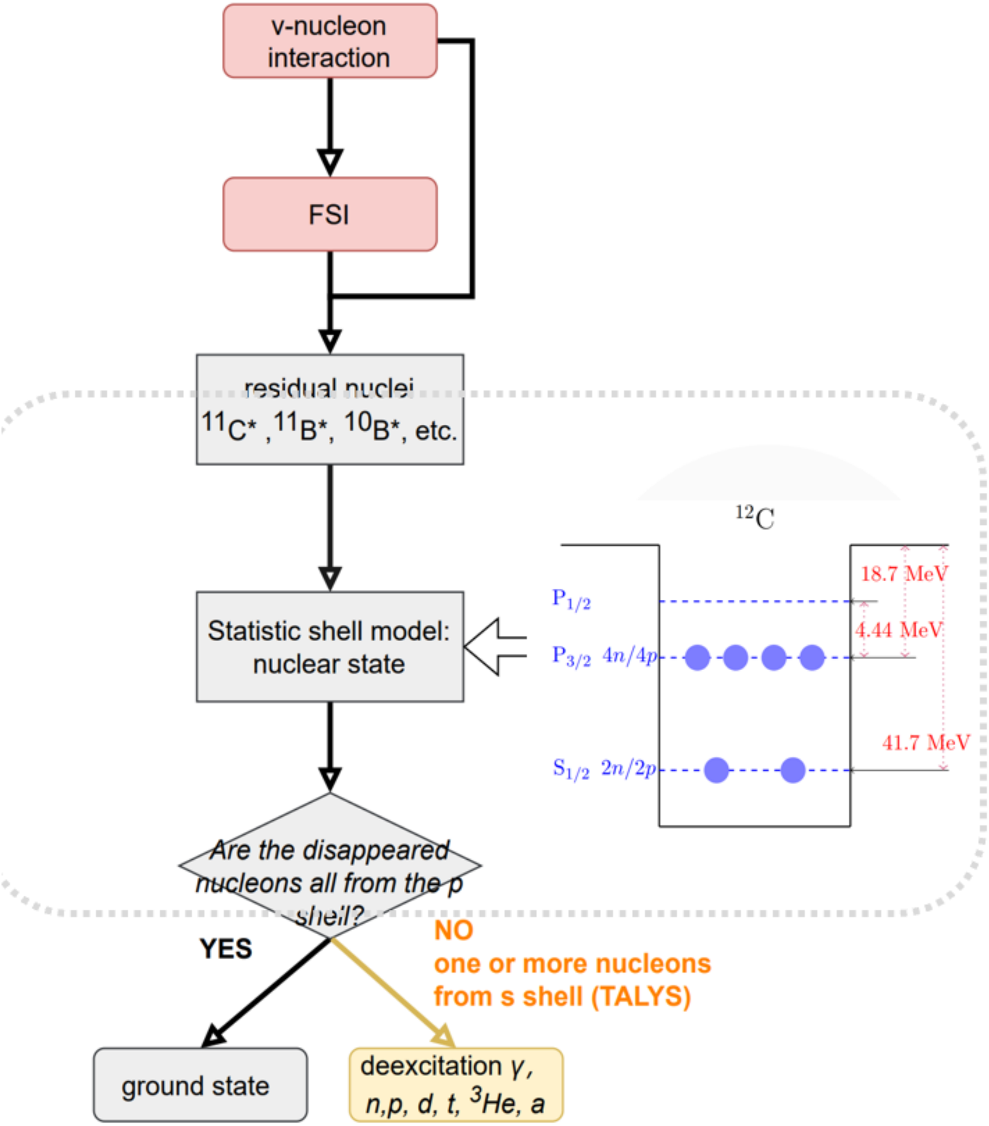
A case study for C12 in JUNO

Cheng, YFL, et al., Phys. Rev. D 103, 05001 (2021)

Cheng, YFL, et al., Phys.Rev.D 103, 053002 (2021)

Cheng, Li,YFL, et al, Eur.Phys.J.C 85, 295 (2025)

C: TALYS-based Deexcitation



Simple shell model → Status of the residual nuclei

- All residual nuclei with A>5 have been considered
- Taking 11C*, 11B*, 10C*, 10Be* and 10B* for example

Daughter Nuclei	Shell Hole	Configuration Probability	Excitation Energy
$^{11}C^*$ or $^{11}B^*$	$s_{1/2}$	1/3	$E^* = 23$ MeV
	$p_{3/2}$	2/3	$E^* = 0$ MeV
$^{10}C^*$ or $^{10}Be^*$	$s_{1/2}$	1/15	$E^* = 46$ MeV
	$p_{3/2}$	6/15	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	8/15	$E^* = 23$ MeV
$^{10}B^*$	$s_{1/2}$	1/9	$E^* = 46$ MeV
	$p_{3/2}$	4/9	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	4/9	$E^* = 23$ MeV

Triggered a variety of research interest in the neutrino interaction community:

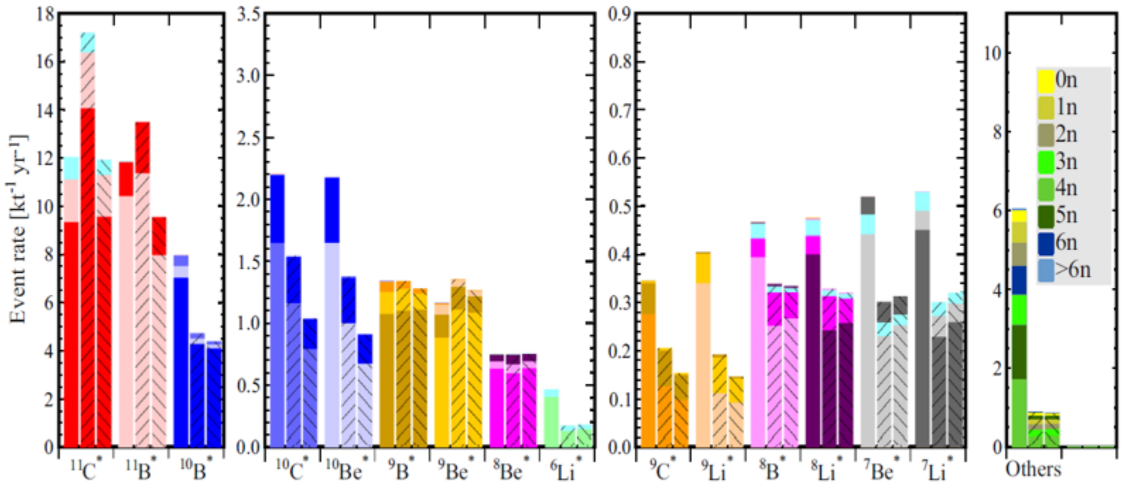
Abe, PRD (2024), 2508.04040, etc.

Guo et al, PLB (2022), PLB (2025) etc.

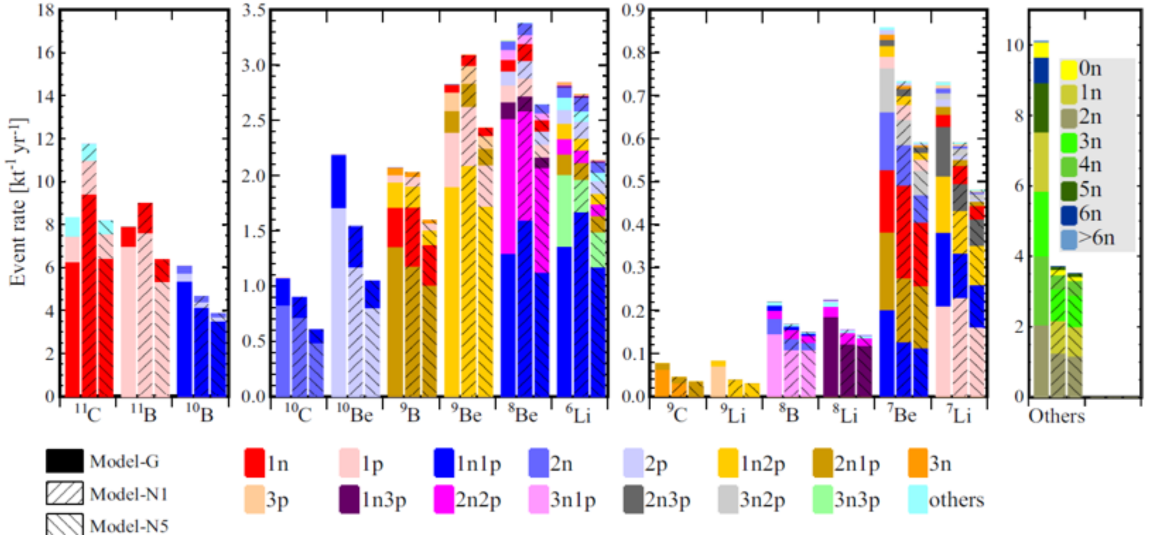
Gardiner, MARLEY, etc.

C: Impact on exclusive cross sections

Before deexcitation



After deexcitation



- **^{11}C, ^{11}B, ^{10}B reduced, and lighter nuclei increased; neutron multiplicity redistributed.**

- **Exclusive final-state information, such as neutron multiplicity, charge pion multiplicity, unstable nuclei, is important for**

(a) Energy reconstruction

(b) Evaluate systematics

Summary and outlook

- After 17 years efforts, from idea to construction, JUNO detector is fully completed, despite numerous challenges
- Initial testing and performance studies show that key specifications have been mostly met
- We are excited to have started the physics data taking
- Many important and challenging topics on neutrino-scattering physics!

Physics	Sensitivity *PPNP 123 (2022) 103927*
Neutrino Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{32}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos
Diffuse Supernova Neutrino Background	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, measure B8 flux independently
Nucleon decays ($p \rightarrow \bar{\nu} K^+$)	9.6×10^{33} years (90% C.L.) in 10 yrs (*CPC 47, 113002 (2023)*)
Geo-neutrino	~400 per year, 8% measurement in 10 yrs

Central detector (acrylic tank)

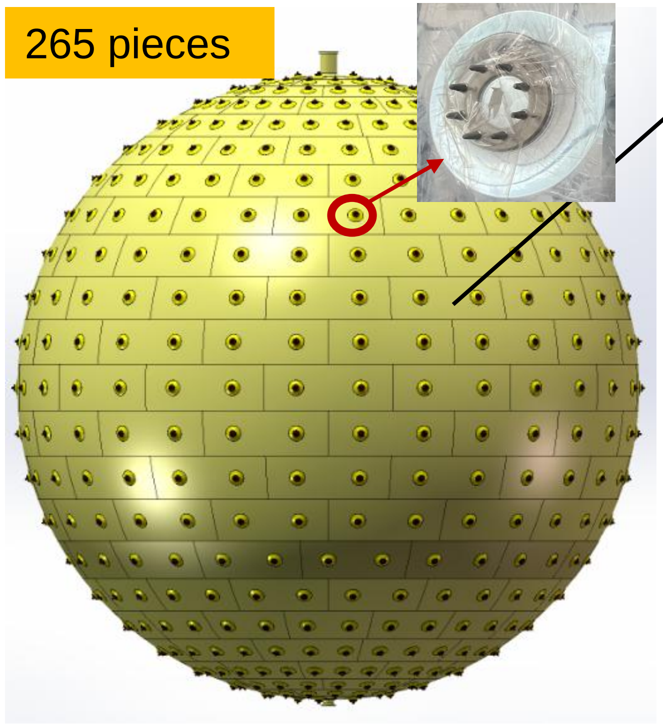
LS container:

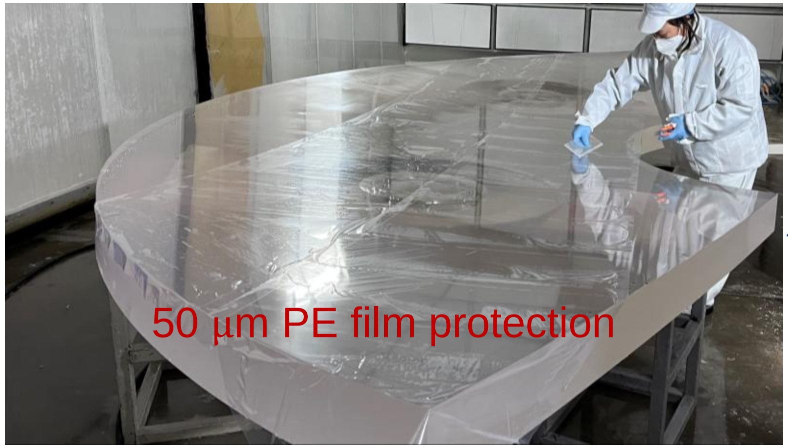
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

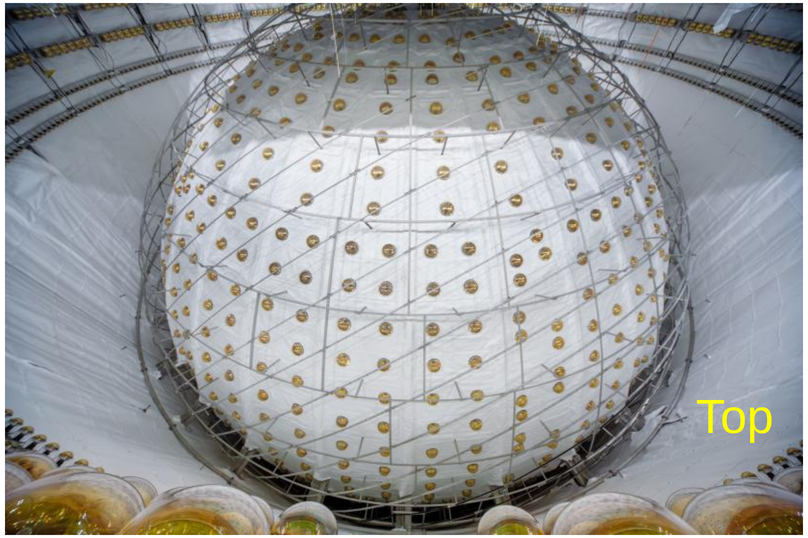
Light transparency > 96% @ LS

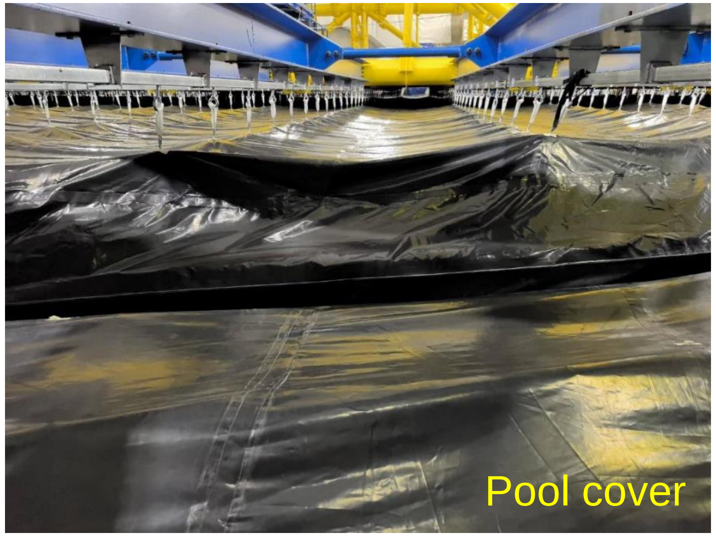
Radiopurity: U/Th/K < 1 ppt

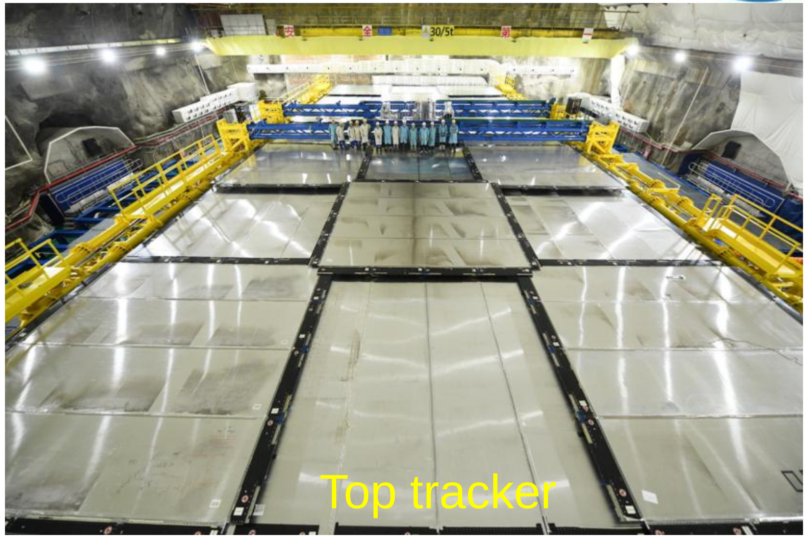




Veto detector







Water Cherenkov:

- ✓ 40 kt pure water for backgrounds shielding & tagging + 2400 20" PMTs + Tyvek for light reflection
- ✓ 100 t/h pure water production system
- ✓ Pool lining: 5 mm HDPE for clean water and Rn prevention
- ✓ Pool cover by using 0.6 mm vulcanized fabric

Top tracker: refurbished OPERA plastic scintillators

Earth magnetic field compensation coil