JUNO BEGINS:
OPENING A NEW WINDOW INTO NEUTRINO PHYSICS

LIVIA LUDHOVA

GSI DARMSTADT

& JGU MAINZ UNIVERSITY, GERMANY

SEPTEMBER 15-16, 2025, FRAUENINSEL, GERMANY

SUMMER SCHOOL - MAINZ PHYSICS ACADEMY

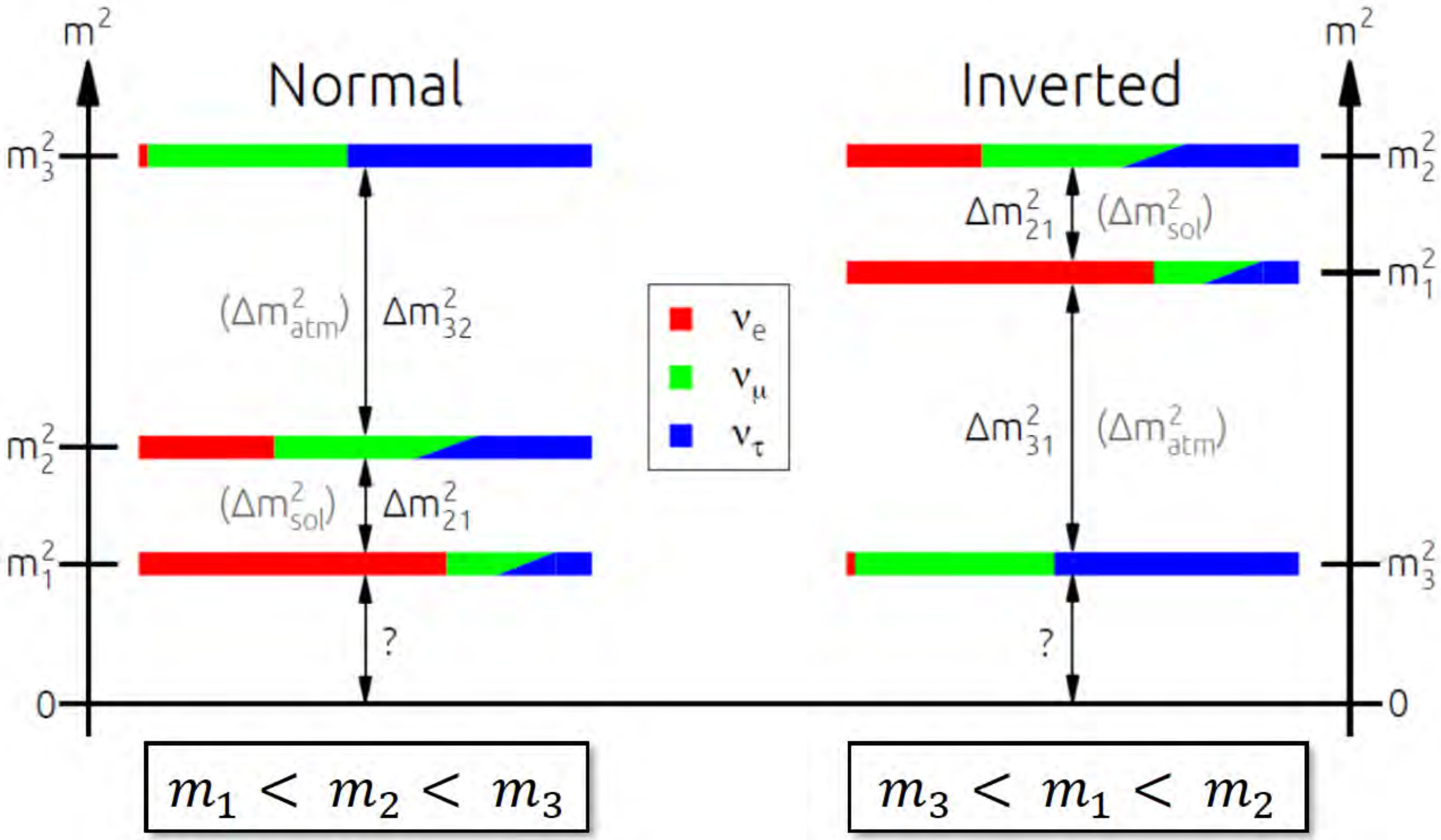
Mitglied der Helmholtz-Gemeinschaft

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JUNO

20 kton LS detector in China designed for Neutrino Mass Ordeiring (NMO) detemination with reactor (anti)-neutrinos

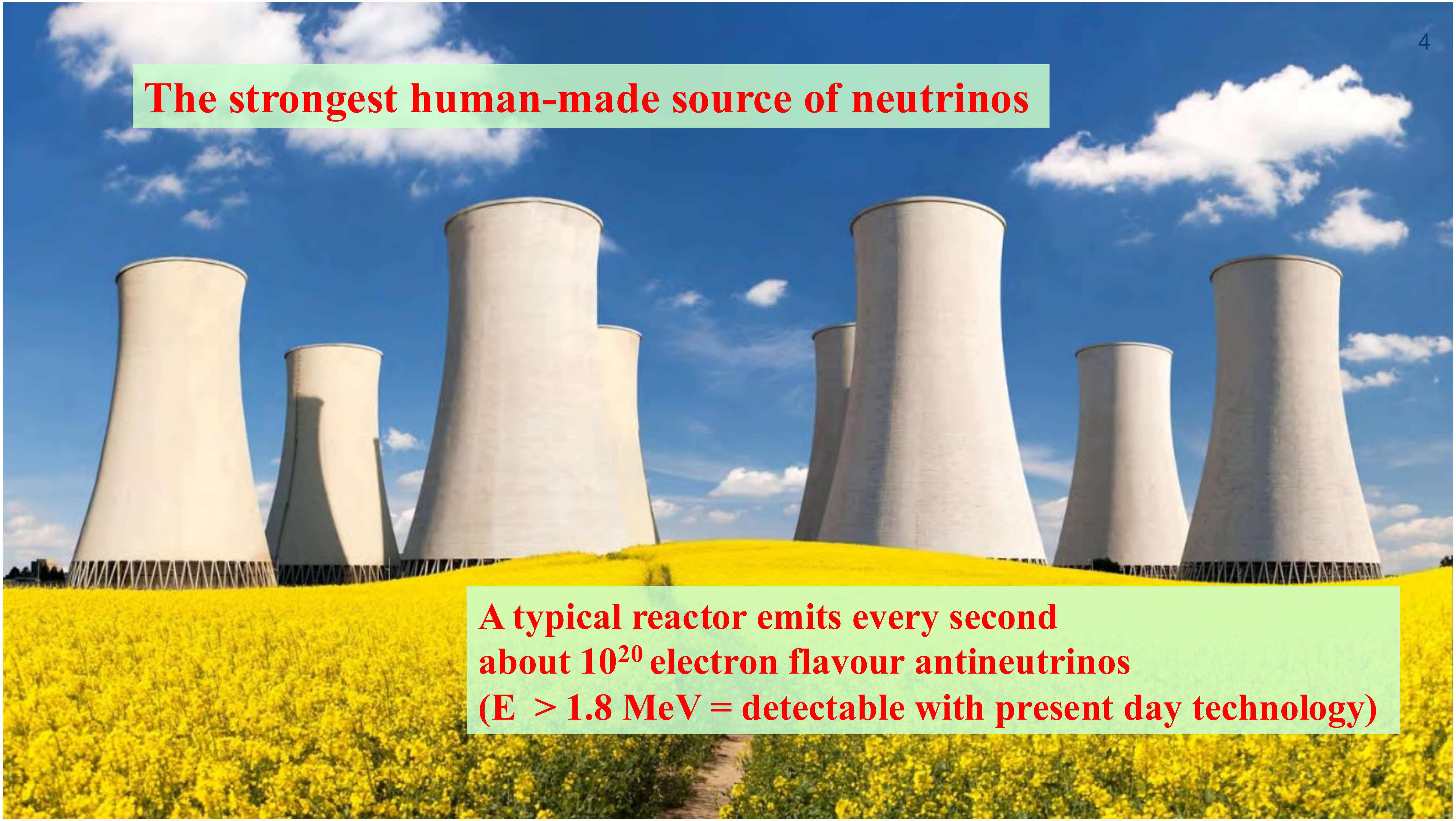
NEUTRINO MASS ORDERING



$\Delta m^2_{31,\text{normal}} > \Delta m^2_{31,\text{inverted}}$

Δm^2_{31} = has opposite signs in the two hierarchies!

The strongest human-made source of neutrinos

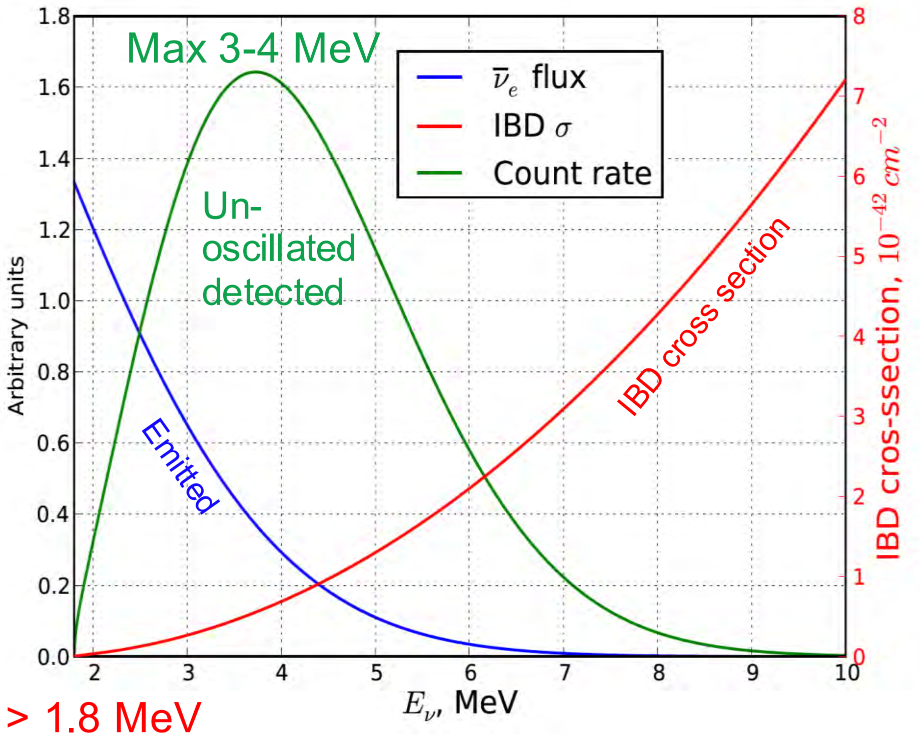


A typical reactor emits every second
about 10^{20} electron flavour antineutrinos
(E $>$ 1.8 MeV = detectable with present day technology)

DETECTION OF REACTOR ANTI-NEUTRINOS

In liquid scintillator target:

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



- **<u>Inverse beta decay (IBD)</u>** reaction on a free proton.
- Charge current reaction sensitive to only electron flavor.

Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm^2

(~100 x more than scattering)

$E_{prompt} = E_{visible}$

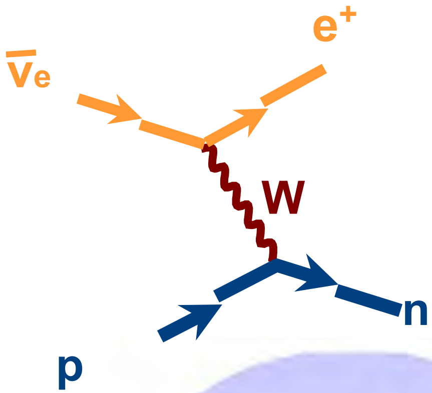
$= T_{e+} + 2 \times 511$ keV

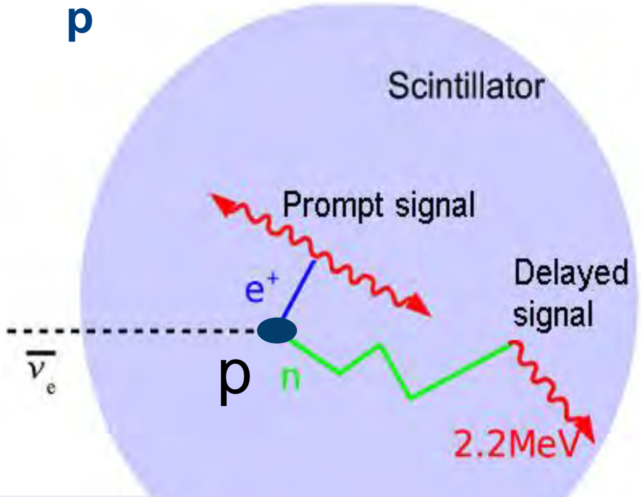
$\sim E_{antinu} - 0.784$ MeV

<u>Prompt</u> + **<u>delayed</u>** (~200 μs)

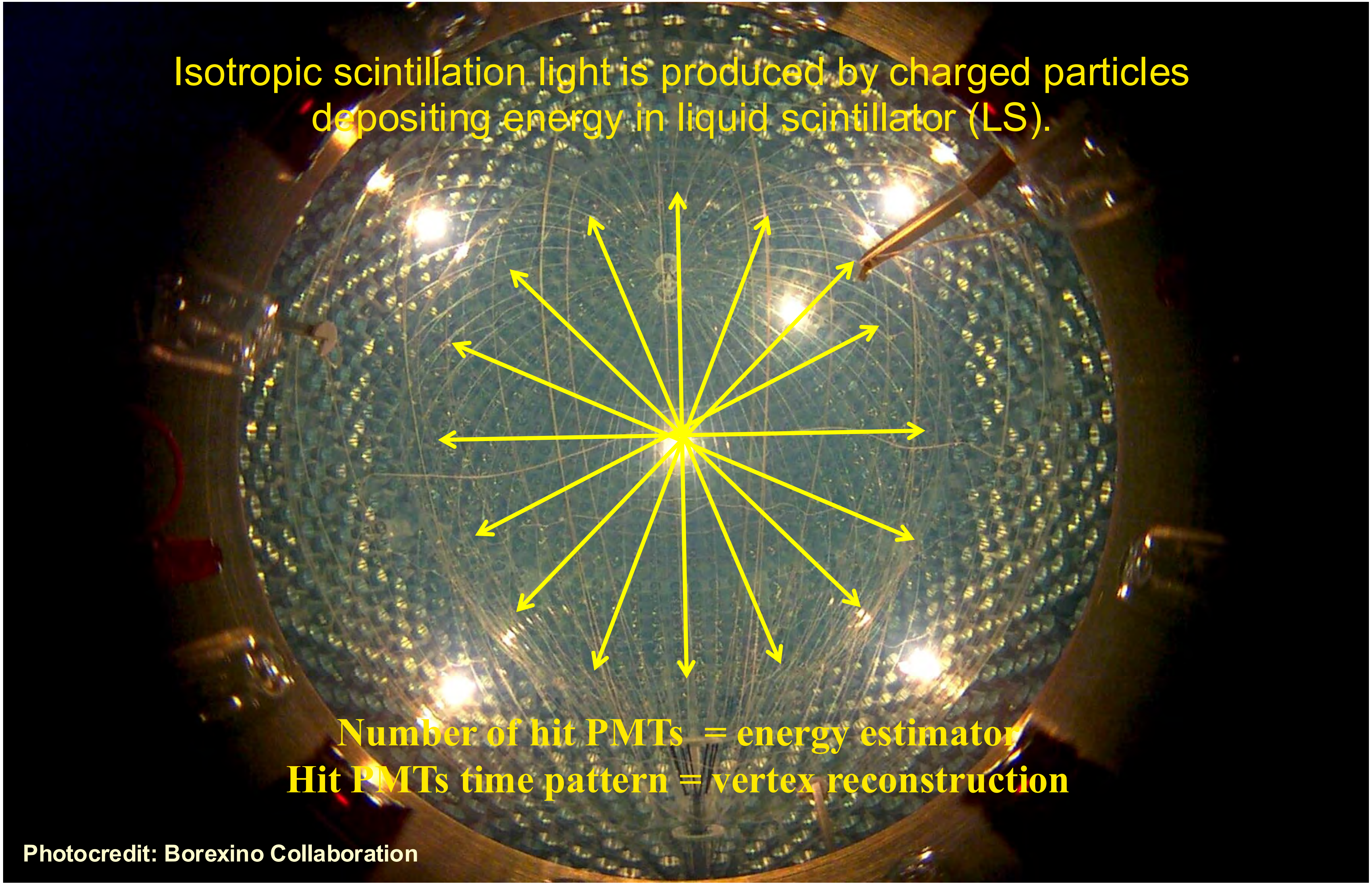
space & time coincidence

is an exceptional **background suppressing tool!**





MeV gammas deposit energy mostly via multiple Compton scatterings.



Photocredit: Borexino Collaboration

Jiangmen Underground Neutrino Observatory

The first multi-kton liquid scintillator detector ever built.

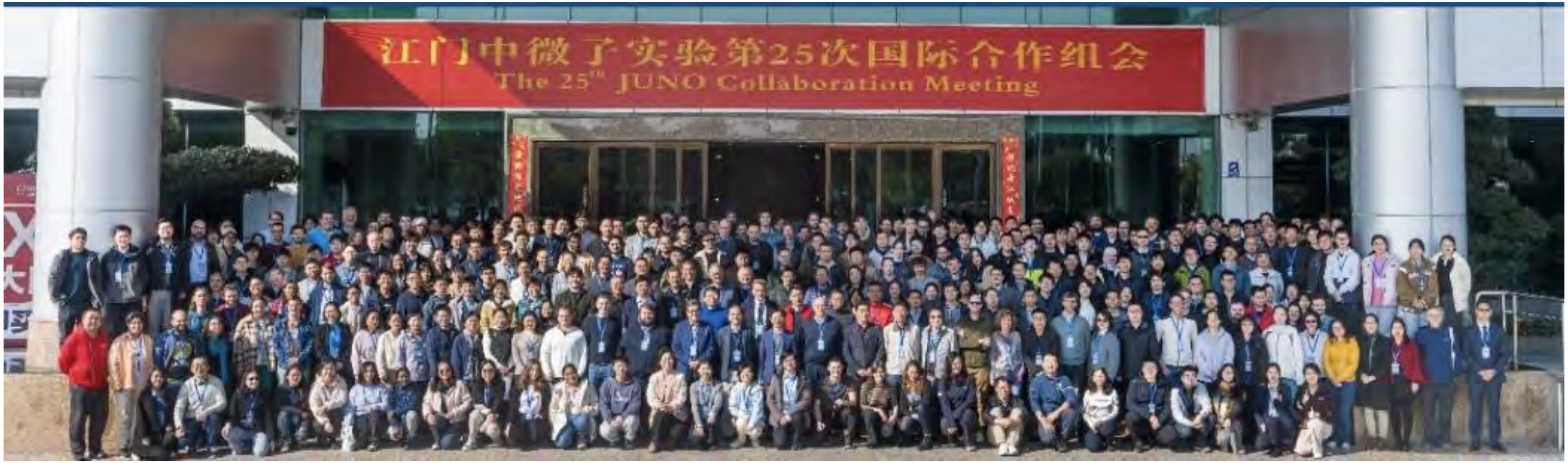
Neutrino Mass Ordering (NMO): 3σ in ~6 years with reactor neutrinos
Many other goals: neutrino properties & astrophysics.

Train in the slope tunnel, Jan 24, 2022

JUNO COLLABORATION

- established in 2014
- 72 institutions
- 750 collaborators
- 17 countries and regions

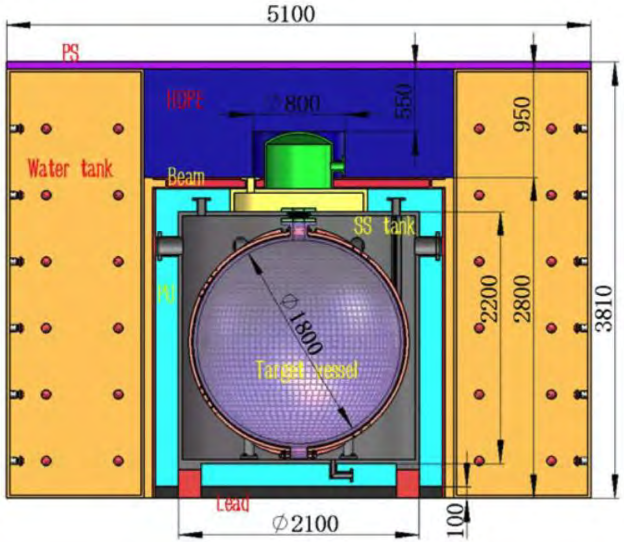
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC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



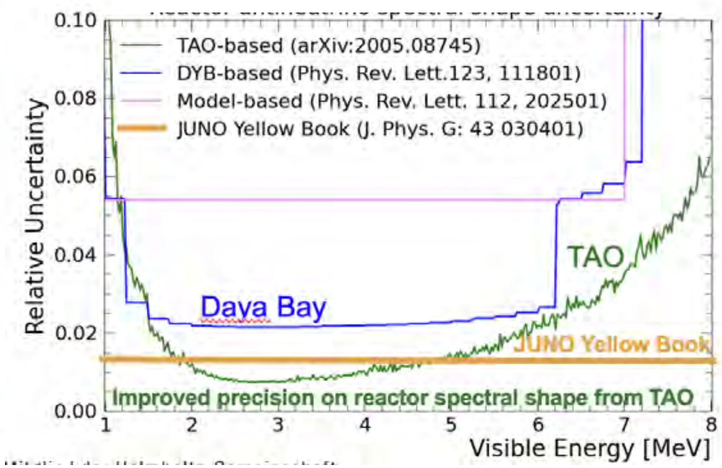
JUNO AS A REACTOR ANTINEUTRINO EXPERIMENT

Baseline difference for all cores should be < 500 m.

JUNO – **TAO** satellite detector
Taishan Antineutrino Observatory



Reactor antineutrino
spectral shape uncertainty.



Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
	Yangjian						Taishan			
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

TAO

- **To measure the reactor neutrino spectrum as a reference to JUNO**
  - ✓ Better resolution to constrain fine structure and spectral shape.
- **Improve nuclear databases, search for sterile neutrinos.**
- **Novel technology: Gd-loaded LS @ -50°C + SiPM**
  - ✓ **30 m from** 4.6 GW$_{th}$ Taishan 1 core – **unoscillated spectrum**
  - ✓ Energy resolution: ~1.5%/√E, 4500 p.e./MeV
  - ✓ 2.8 t (1ton fiducial volume)
- ***Construction and installation basically completed, data taking soon.***

JUNO CIVIL CONSTRUCTION FINISHED IN 12/2021

NEUTRINO MIXING AND OSCILLATIONS

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

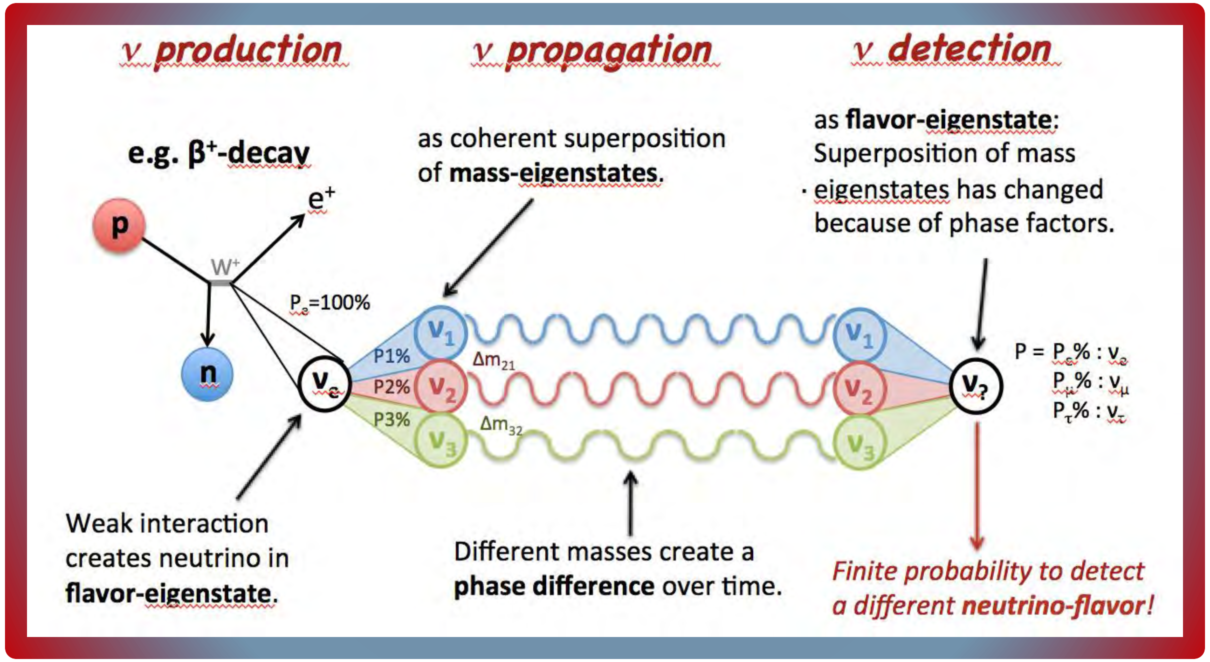
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric	Reactor	Solar	Majorana

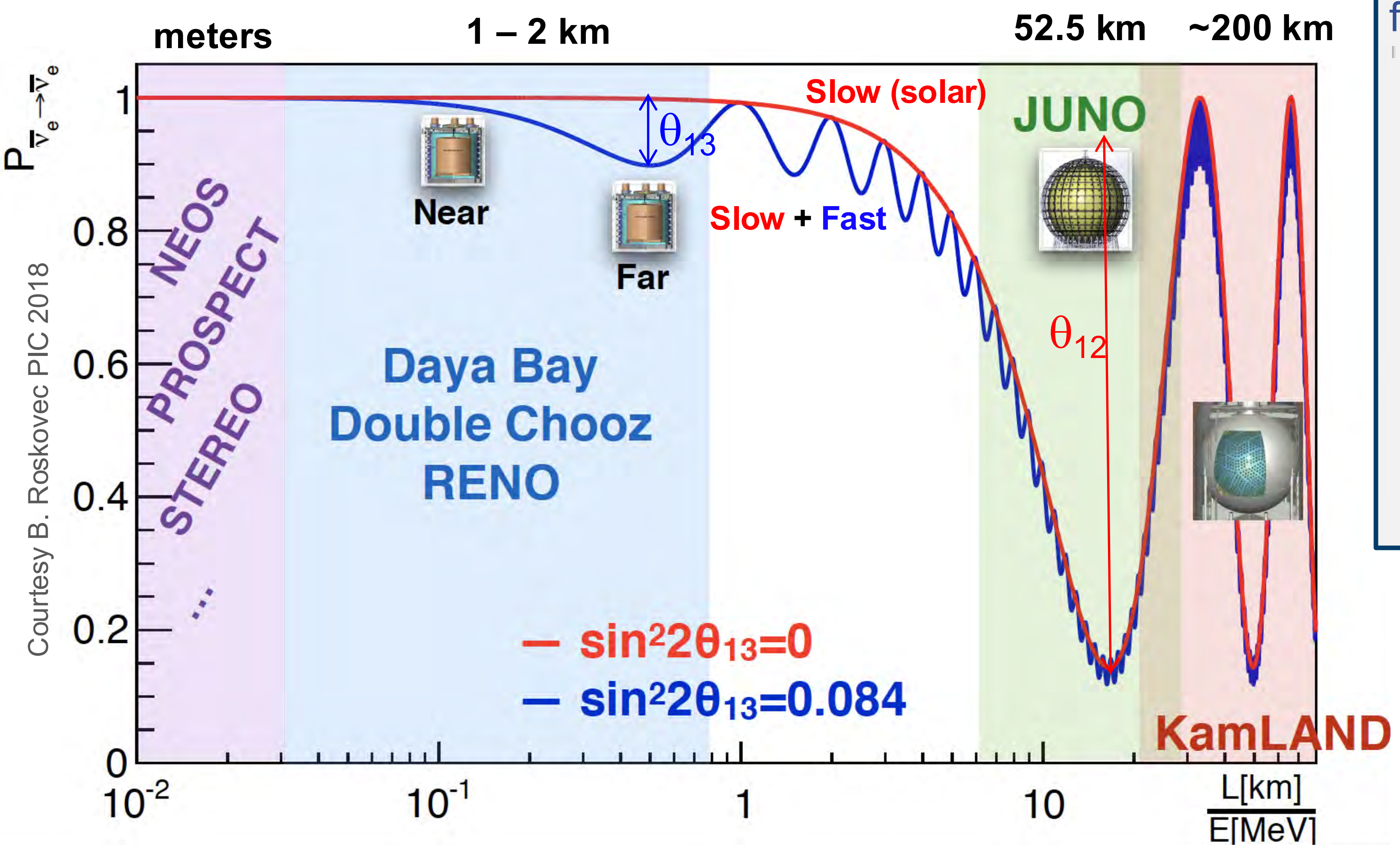
Courtesy M. Wurm



- **3 mixing angles θ_{ij}:**
  - $\theta_{23} \sim 45°$ (which quadrant?)
  - $\theta_{13} \sim 9°$ (non-0 value confirmed in 2012)
  - $\theta_{12} \sim 33°$
- **Majorana phases α1 , α2** and **CP-violating phase δ** unknown.

- **Neutrino oscillations**
  - Non-0 rest mass (Nobel prize 2015).
  - Survival probability of a certain flavour = f(baseline L, E_ν).
  - Different combination (L, E_ν) => sensitivity to different (θ_{ij}, Δm_{ij}^2).
  - Appearance/disappearance experiments.
  - Oscillations in matter -> effective (θ_{ij}, Δm_{ij}^2) parameters = f(e^- density N_e, E_ν).

JUNO AMONG REACTOR NEUTRINO EXPERIMENTS AT DIFFERENT BASELINES



Electron survival probability for reactor antineutrinos:

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

Slow (solar)

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Fast (atm.)

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

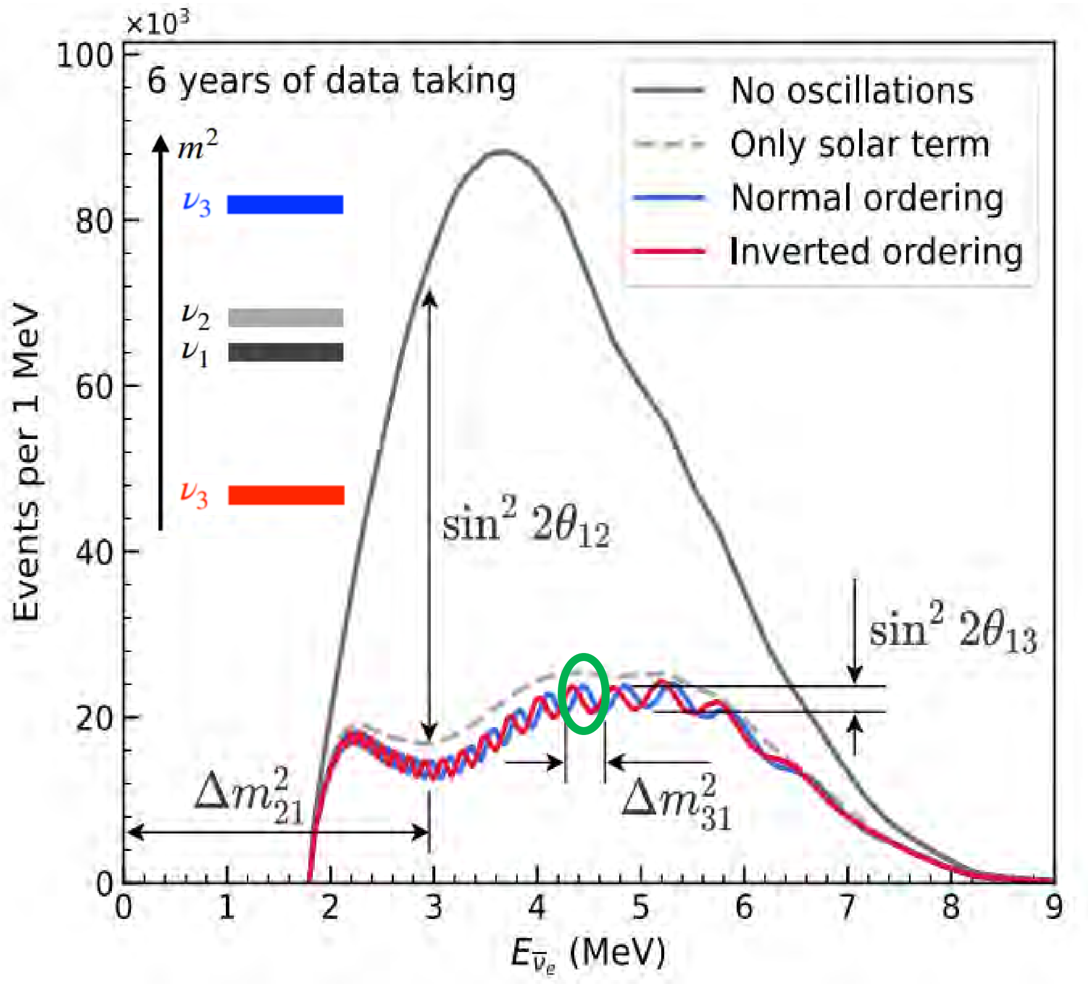
Normal ordering: $\Delta m^2_{31} > 0$

Inverted ordering: $\Delta m^2_{31} < 0$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

- 52.5 km baseline used only by JUNO.
- Fast oscillation pattern of reactor antineutrinos at this baseline.
- **Pattern dependent on NMO (sign of $\Delta m^2_{31/2}$)**
- **Independent from δ_{CP} and θ_{23}.**

REACTOR ANTINEUTRINO SPECTRUM @ JUNO



- Method for the **Neutrino Mass Ordering** with reactors antineutrinos suggested by Petcov and Piai, PLB 553 (2002) 94.
- **Complementarity** to the method based on matter effects on long baseline oscillations of atmospheric and accelerator neutrinos that depend also on δ_{CP} and θ_{23}.
- High sensitivity to the **oscillation parameters**
  - solar mixing angle θ_{12}
  - solar mass splitting Δm^2_{21}
  - atmospheric mass splitting Δm^2_{31}

JUNO PHYSICS CHALLENGES

- Resolving signature wiggles of the fast oscillation in the energy spectrum:
  - excellent **energy resolution ~3% @ 1 MeV,**
  - better than **1% understanding of the intrinsically non-linear energy scale of the liquid scintillator (LS),**
  - **possible micro-structures in the reactor spectrum under control** *(PRL 114 (2015) 012502).*
- Large antineutrino statistics O(100k) @ 52.5 km baseline: **powerful reactors (26.6 GW_{th}) & large target mass (20 kton)**
- **Backgrounds:**
  - cosmogenic background: rock overburden of 650 m,
  - radio-purity of all materials: < 10^{-15} / 10^{-17} g of U/Th /g of LS for NMO/solar physics *(JHEP 11 (2021) 102).*
- **Time stability** over several years.

Stochastic terms in the energy resolution (photon statistics):

- **High light yield** (LY ~10^4 photons/MeV).
- **LS transparency:** λ_{att} > 20 m @ 430 nm.
- **PMT geometrical coverage: 78%.**
- **PMT collection efficiency x quantum efficiency:** ~30%.

Systematic effects in the energy scale / spectra:

- **Calibration** (JHEP 03 (2021) 004)
  - ✓ $\alpha/\beta/\gamma$ sources, light pulses, UV-laser
  - ✓ 5 complementary systems
- **Double calorimetry concept**
  - ✓ large 20'' and small 3'' PMTs
- **TAO** – Taishan Antineutrino Observatory with an excellent energy resolution <2% (stat) @ 1MeV *(arXiv:2005.08745, 2020)*

JUNO DETECTOR

Top Tracker

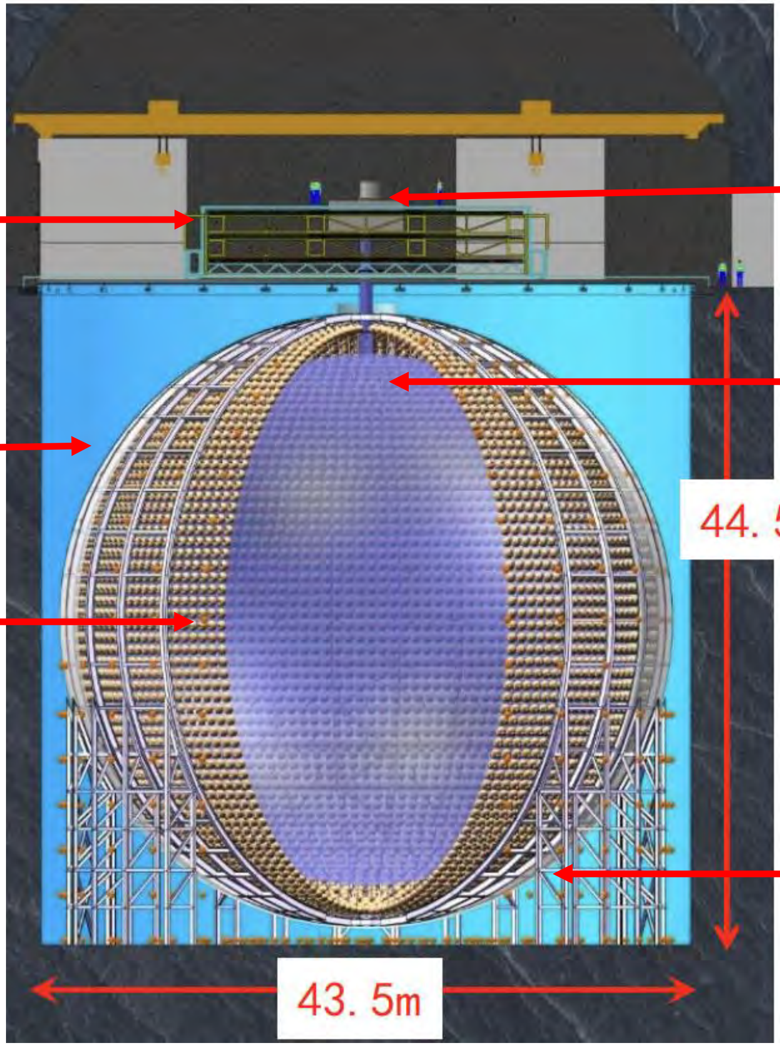
Calibration house

Water Pool
Water Cherenkov μ veto
2400 20" PMTs

Acryllic Sphere
Diameter = 35.4 m

Central Detector
20 kton of LS
Linear Alkali Benzene (LAB) + PPO + bis-MSB + BHT
17612 20" PMTs +
25600 3" PMTs

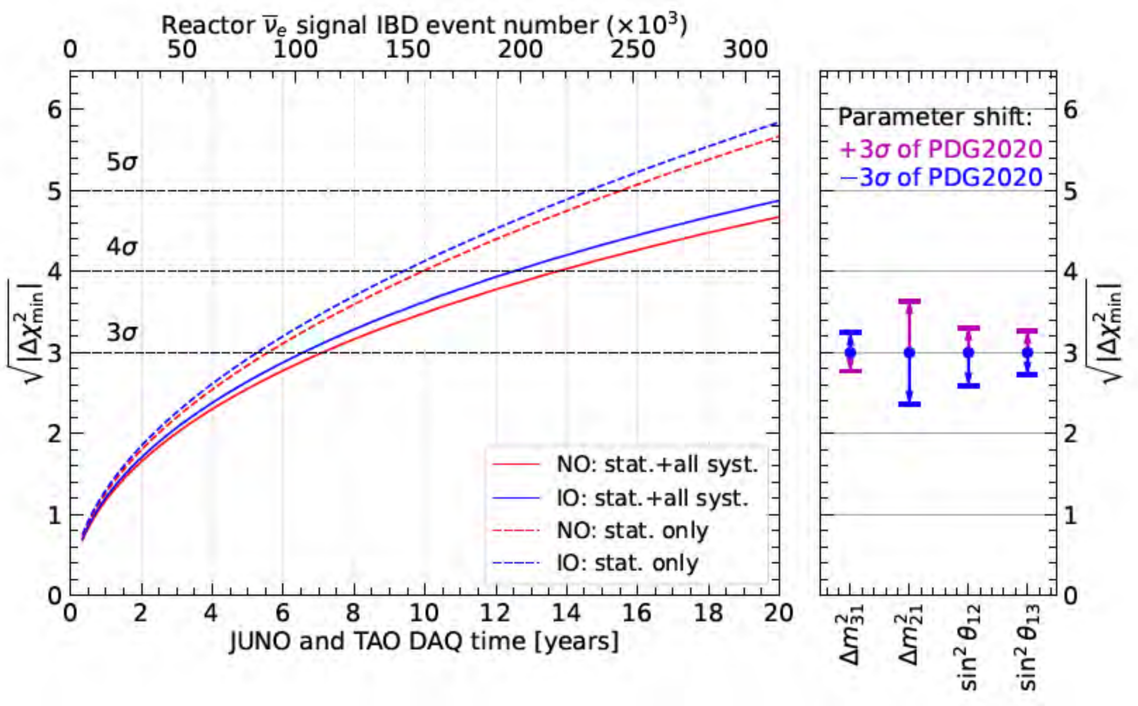
Stainless steel
Latticed Shell



Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	8x 20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	78%
Energy resolution	8.5% / √E MeV	~5%/√E MeV	~6%/√E MeV	~3%/√E MeV
Eff. Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~1600 p.e./MeV

JUNO & REACTOR NEUTRINO OSCILLATION PHYSICS

NEUTRINO MASS ORDERING

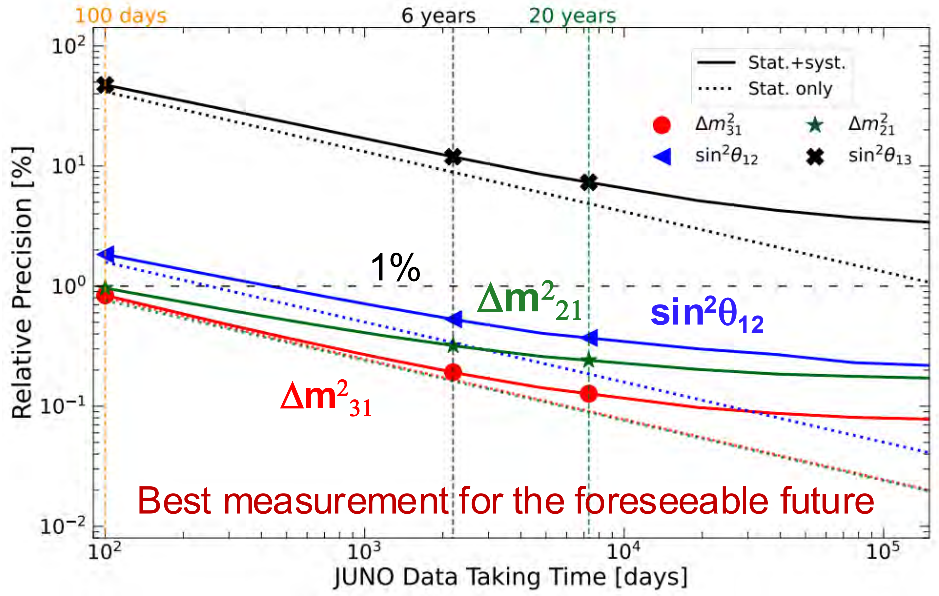


3σ (reactors only) @ ~6 years * 26.6 GWth exposure

Combined reactor + atmospheric neutrino analysis in progress: further improvement of the NMO sensitivity.

Chin. Phys. C 49 (2024) 033104.

OSCILLATION PARAMETERS



- Precision of $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31} **< 0.5% in 6 years.**
- Measurement of $\sin^2\theta_{12}$($^{+9\%}$ / $_{-8\%}$) and Δm^2_{21} ($^{+27\%}$ / $_{-17\%}$) also with ^8B solar neutrinos.
- Unique: solar neutrino oscillation parameters with neutrinos and antineutrinos in one detector.

Chin. Phys. C 46 (2022) 123001.

JUNO: A MULTI-PURPOSE OBSERVATORY

Reactor anti-ν

~60 / day

Atmospheric ν

Several / day

Solar ν

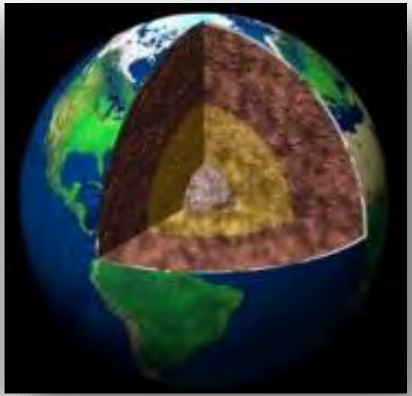
^{8}B: ~50/day
CNO: ~1000/day
^{7}Be: ~10000/day

Supernovae (SN) ν

Core Collapse SN
@ 10 kpc:
thousands in few sec.

Diffuse SN signal:
few / year

Geoneutrinos



~400 / year

+

New physics

Proton decay

Neutrino magnetic moment

Sterile neutrinos

Non-standard interactions

Lorentz invariance violation

Neutrino oscillation & properties

Neutrinos as a probe

MODEL INDEPENDENT MEASUREMENT OF ^{8}B SOLAR NEUTRINOS

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

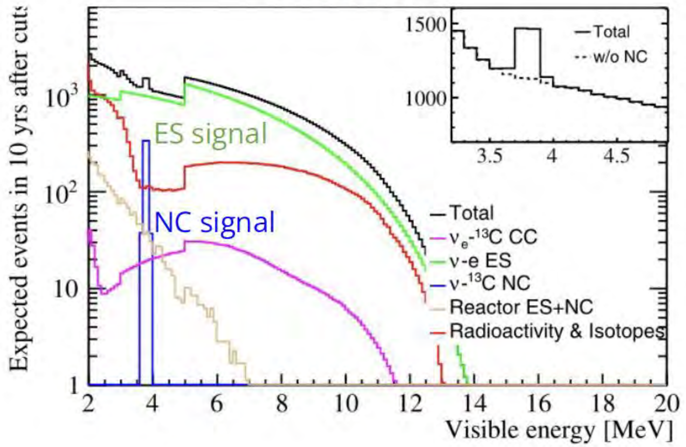
- E_{thr} = 2.2 MeV
- Possible only with ν_e
- Prompt: e^-; Delayed: ^{13}N decay

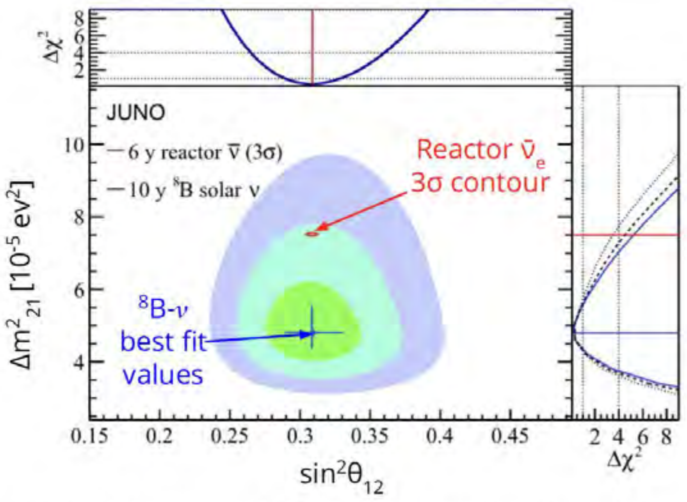
NC: $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C^*$

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

ES: Chinese Phys. C 45 (2021) 1
ES+NC+CC: Ap. J. 965 (2024) 122

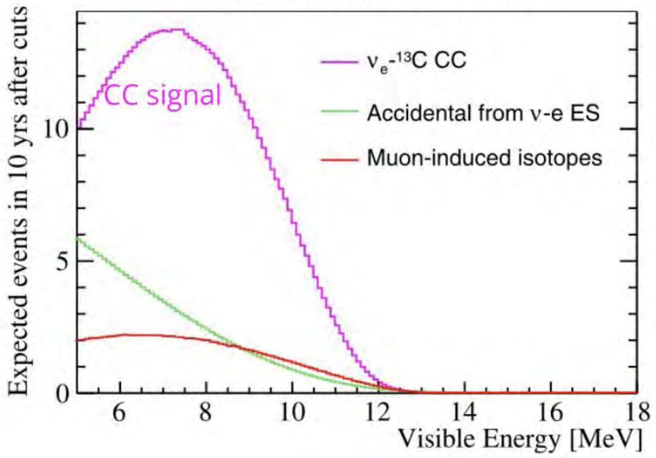
10 years, single events after cuts





Potential to search for possible discrepancies

10 years, correlated prompt events after cuts



Expected precision in 10 years:

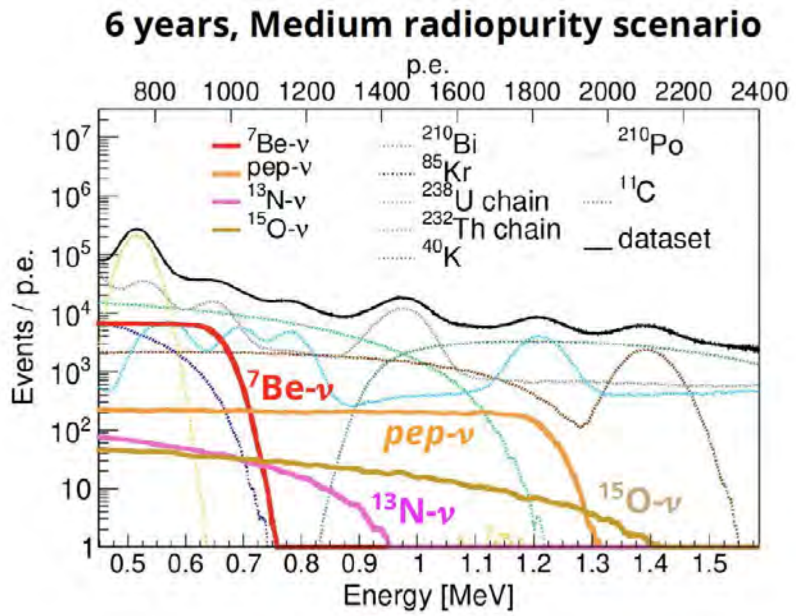
^{8}B flux: 5% JUNO & 3% JUNO + SNO

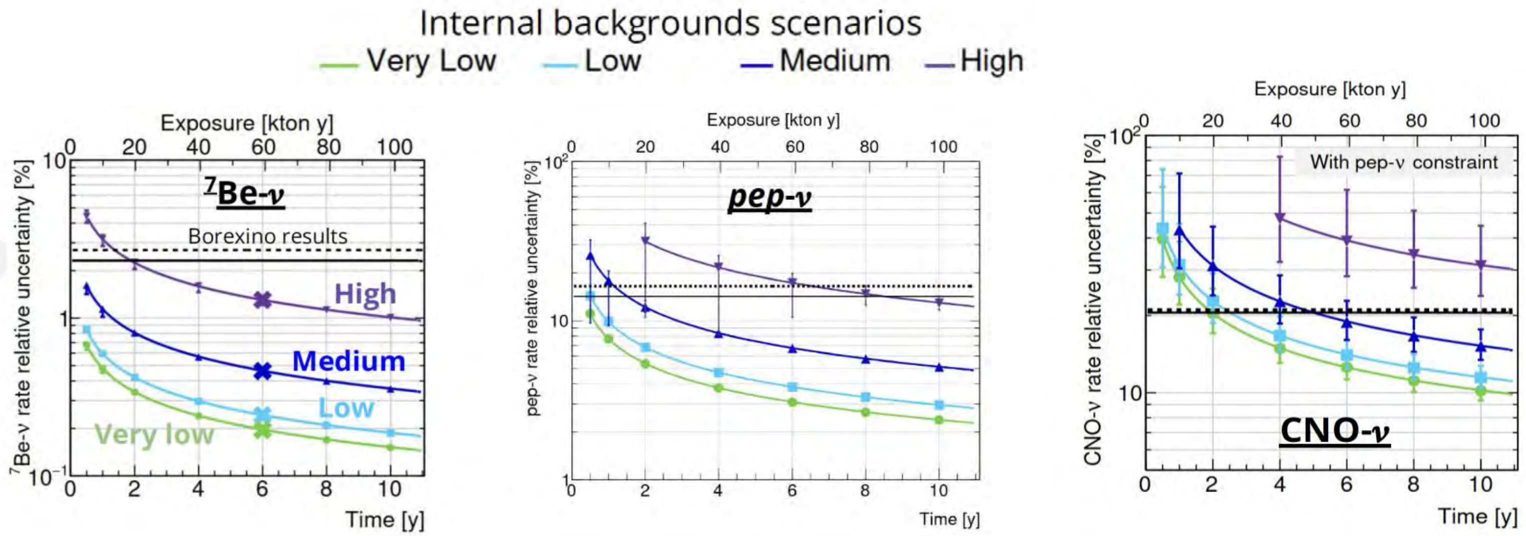
$\sin^2\theta_{12}$: +9% / -8%

Δm^2_{21}: +27% / -17%

SENSITIVITY TO ^{7}Be, pep, CNO SOLAR NEUTRINOS

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



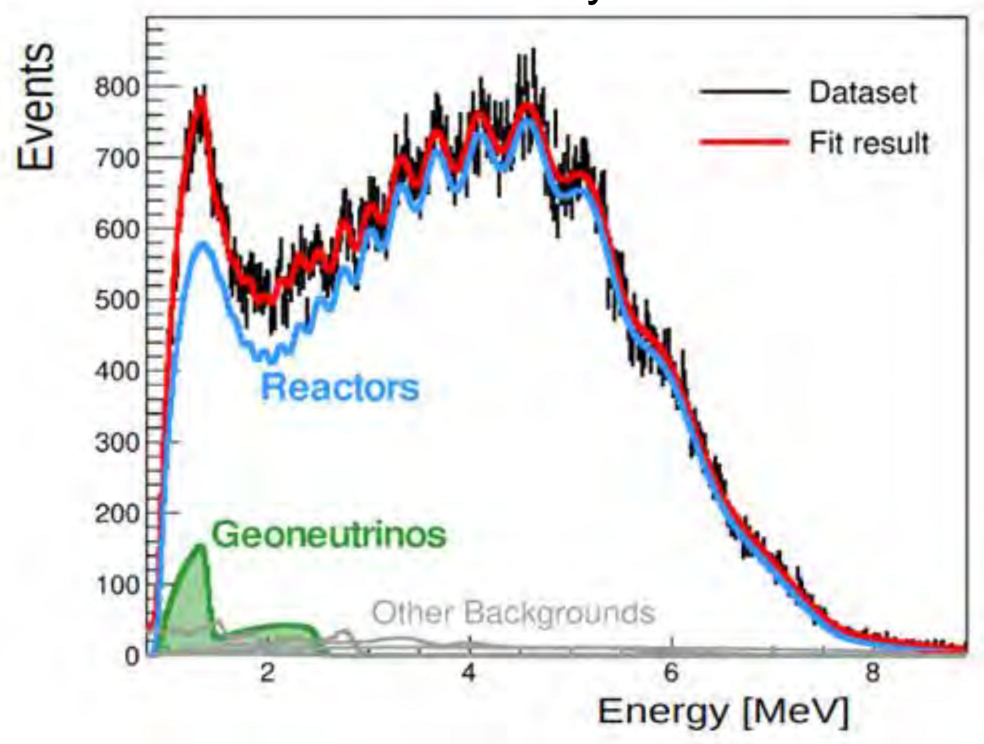


J. Cos. Astro. Phys. 10 (2023) 022.

- Several radio-purity scenarios: from the Borexino level up to the “IBD” one (minimum required for the NMO)
- JUNO has potential to improve the precision of the existing Borexino measurements
  - ^{7}Be: **in 1-2 years time < 2.7% (current Borexino precision) for all radiopurity scenarios**
  - pep: **in 1-2 years time < 17% (current Borexino precision), only in IBD scenario after more than 6 years**
  - **CNO:** constraining *pep* rate is crucial, precision of 20% possible in 2 to 4 years (except for the IBD scenario)
    - constraint of ^{210}Bi radioactive background not needed (applied in Borexino analysis *Nature* 587 (2020) 577–582)
    - Independent measurement of ^{13}N and ^{15}O might be possible for the first time.

GEONEUTRINOS IN JUNO

Simulation of 10 years of data



Big advantage:

✓ Large volume and thus high statistics: **400 geoneutrinos / year.**

Main limitation:

✓ Large **reactor neutrino background.**

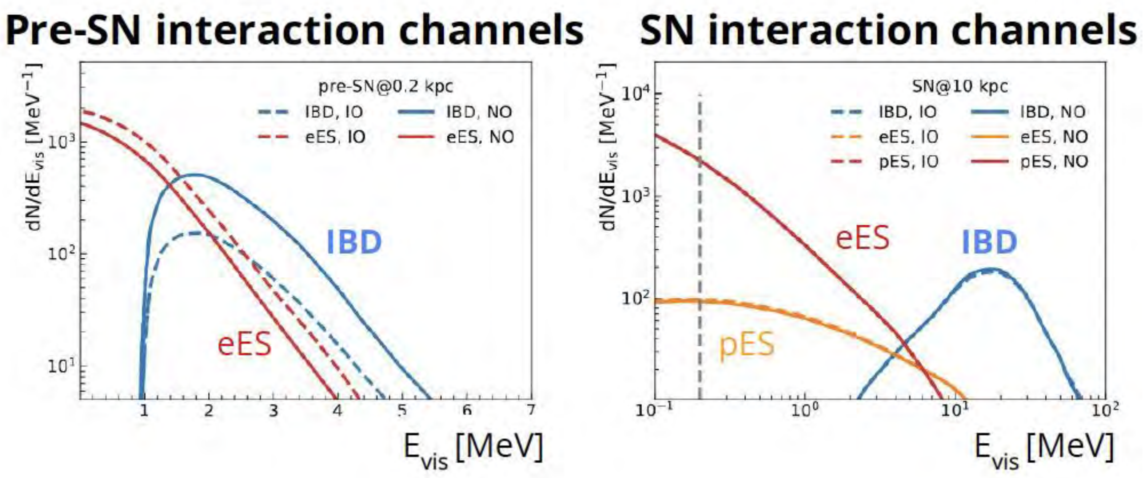
- Current (KamLAND and Borexino) precision on measured geoneutrino flux is ~16-18%.
- JUNO can reach this precision in a few years.
- JUNO will provide statistics sufficient to separate with a high statistical significance U and Th.
- **Geological study of the local crust** important in order to separate the mantle contribution and it is ongoing.

- Expected precision of the total geoneutrino signal: **~8% in 10 years** (Th/U mass ratio fixed to 3.9)
- Precision of U and Th individual components **in 10 years:**
  ^{232}Th ~35% ^{238}U ~30% ^{232}Th + ^{238}U ~15% ^{232}Th/^{238}U ~55%

PRELIMINARY

SUPERNOVAE (SN)

- **Pre-SN neutrinos:** *emitted* ***in the last hours before the collapse.*** *Never detected. Allert of SN.*
- **Core-collapse SN:** *emitted during the SN explosion,* ***burst of few tens of seconds*** *in three phases (shock breakout, accretion, cooling). Observed from SN1987A.*
- **SN rate in our Galaxy:** ~3 per century.



J. Cos. Astro. Phys. 01 (2024) 057.

Dominant detection channel: IBD

Integrated signal for a 30M⊙ progenitor:

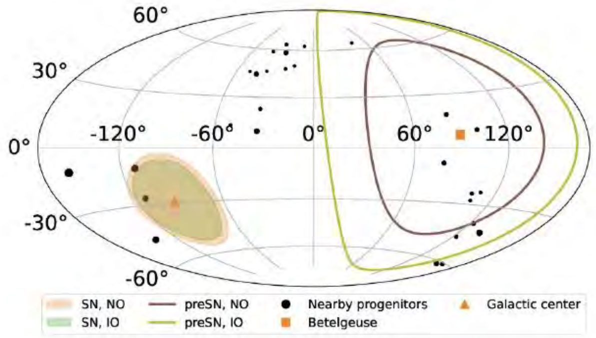
- **Pre-SN @0.2 kpc:** 400 - 1200 IBDs in a few hours
- **SN @10 kpc:** ~ 5000 IBDs in few seconds

Alert efficiency: probability to identify Pre-SN/SN neutrinos burst
Sensitivity: distance at which the alert efficiency is 50%

For an exploding star of **30M⊙** **JUNO is sensitive** to:

- **Pre-SN up to 1.6 kpc (0.9 kpc)** in case of **NO (IO)**
- **SN up to 370 kpc (360 kpc)** in case of **NO (IO)**

Directionality of **IBD** events → Possible to **point** to the **source**, crucial to help telescopes to detect early electromagnetic radiation



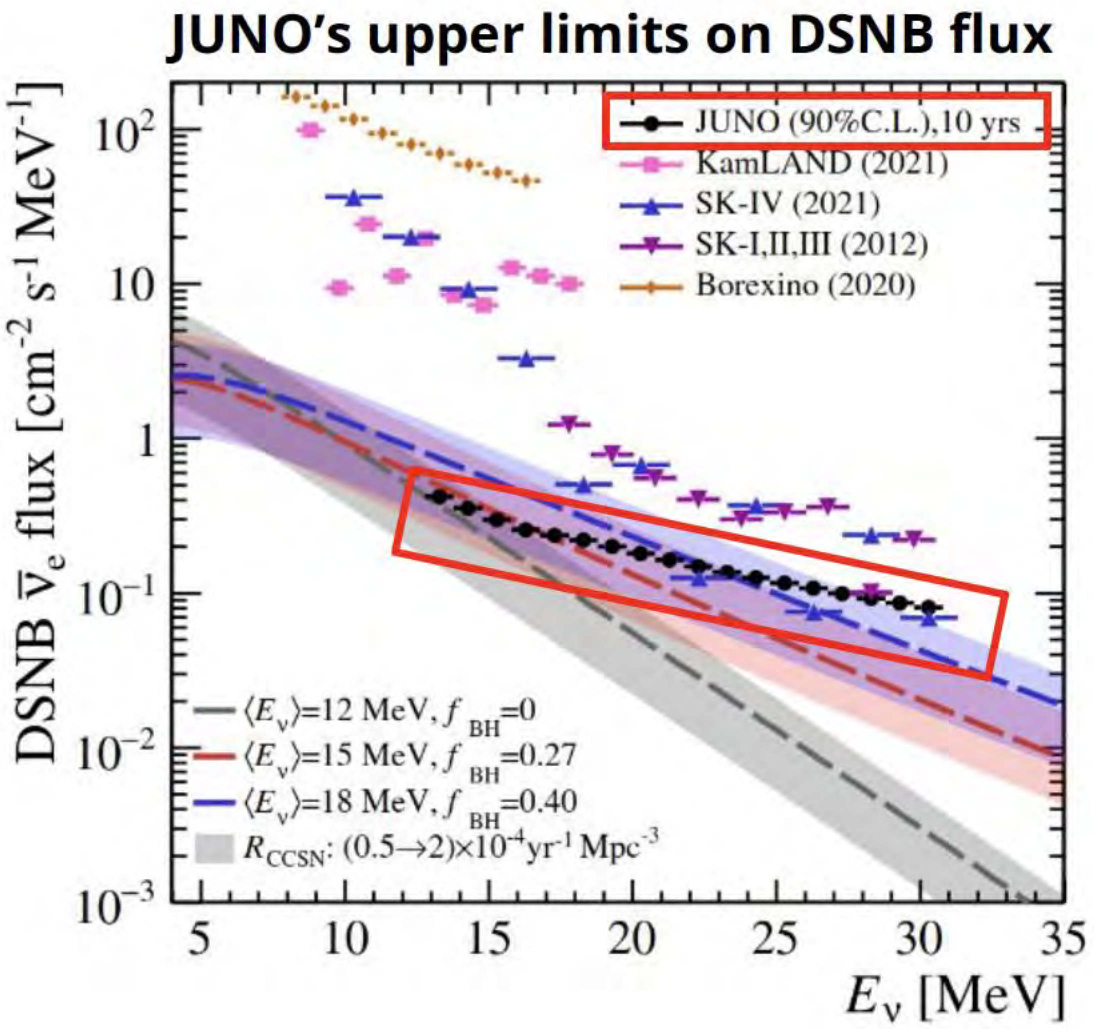
DIFFUSE SUPERNOVAE ~~BACKGROUND~~ SIGNAL (DSNB)

- Integrated neutrino flux from the past SN in the visible Universe.
- ~10 core collapse SN/s in the visible Universe.
- Info about the star formation rate.
- Expected signal: few IBD events / year.
- Main background:
  - ✓ reactor anti-ν → go above 10 MeV
  - ✓ NC atmospheric ν - pulse shape discrimination (eff 50% → 80%),

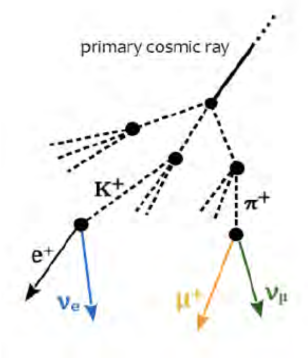
JUNO DSNB discovery potential:

3σ in 3 years with nominal models

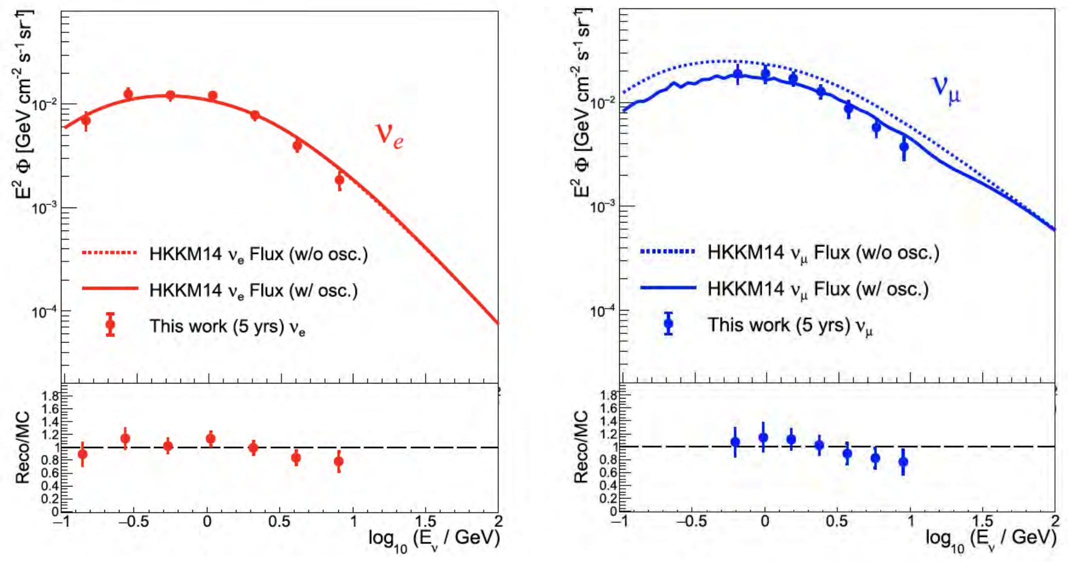
J. Cos. Astro. Phys. 10 (2022) 033.



ATMOSPHERIC NEUTRINOS



- **Expected ~10/15 events per day before the cuts.**
- Will be the first measurement with LS: can play a major role in GeV range, possibly pushing to MeV region.
- CC and NC interactions.



CC events

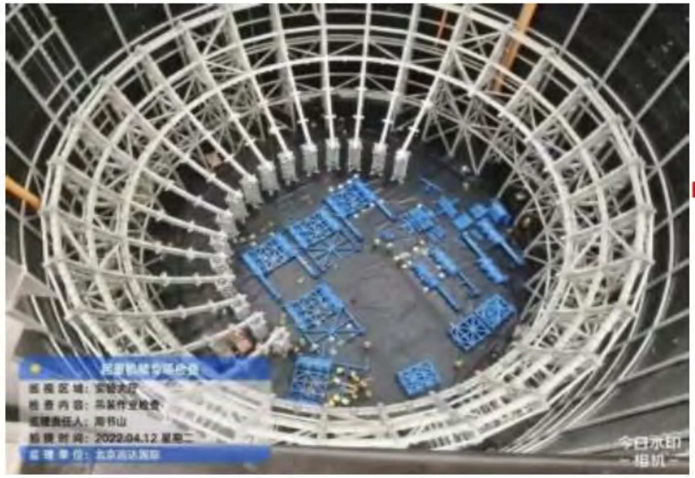
- ✓ Muon/electron flavour discrimination.
- ✓ ν_e and ν_μ energy spectra: 25% precision after 5 years
- ✓ θ_{23} with 6 degree precision.

<u>Motivation: boost the sensitivity to NMO:</u>

- *Atmospheric neutrinos provide an independent channel exploiting the Earth matter effect on oscillation of ~GeV neutrinos.*
- *Requirement of the reconstruction of neutrino*
  - *Direction* (*Phys. Rev. D 109.052005*).
  - *Energy and flavour* (Eur. Phys. J. C 81 (2021) 887).

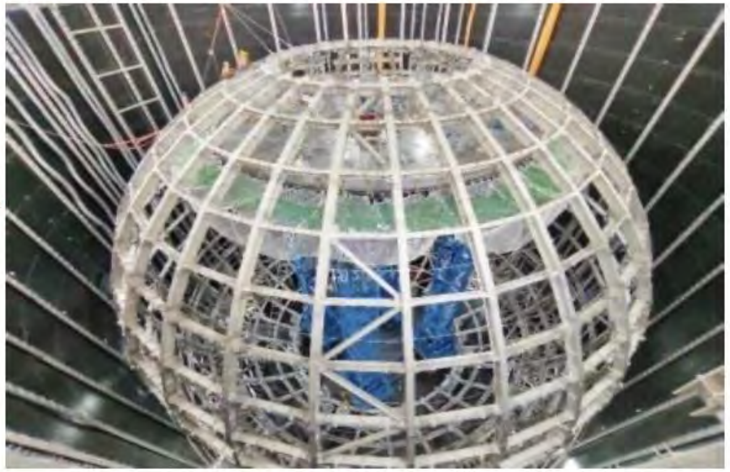
JUNO NMO sensitivity with combined reactor and atmospheric neutrinos is ongoing.

CONSTRUCTION OF THE CENTRAL DETECTOR



Bottom structure

Platform for Acrylic assembly



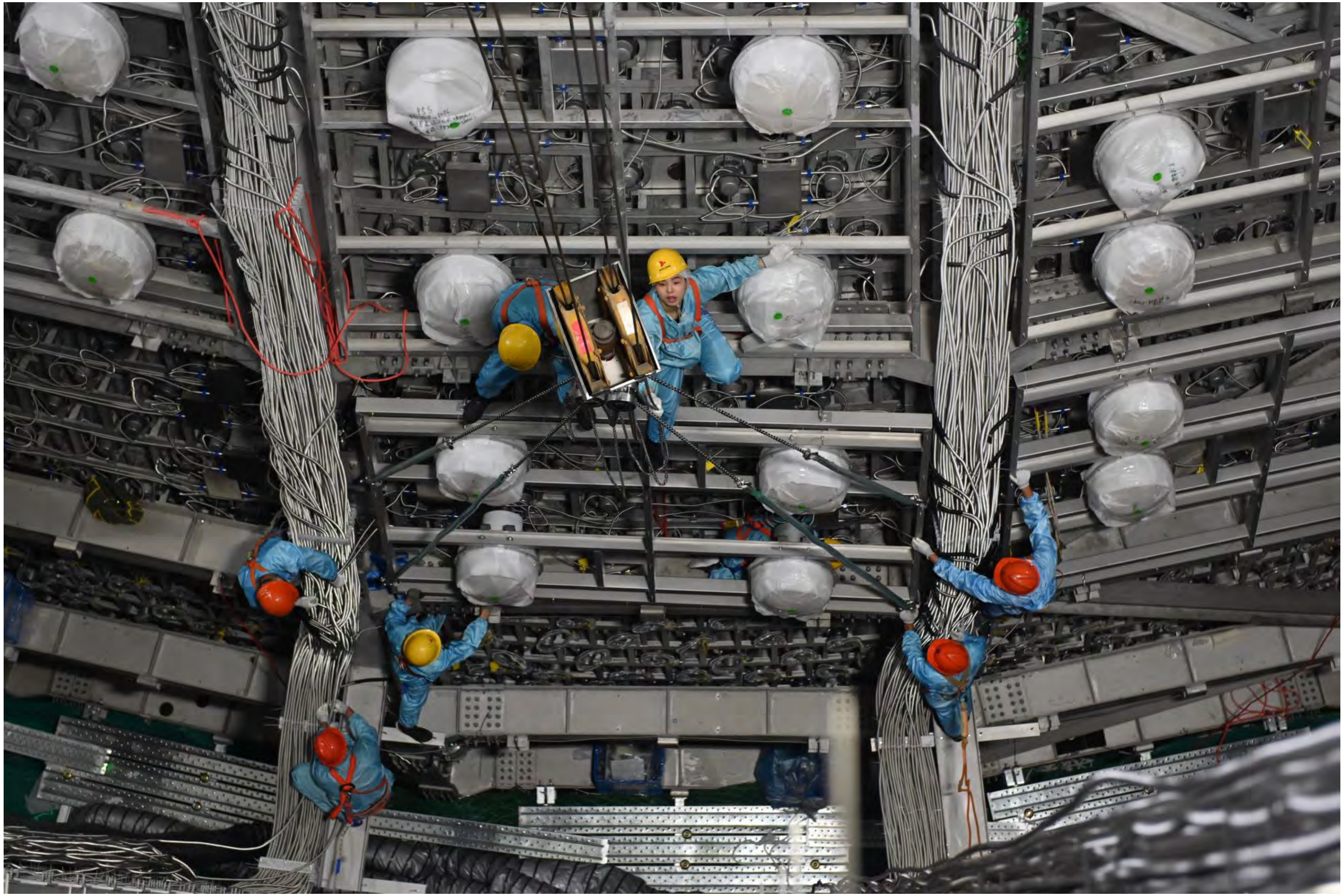
Top structure

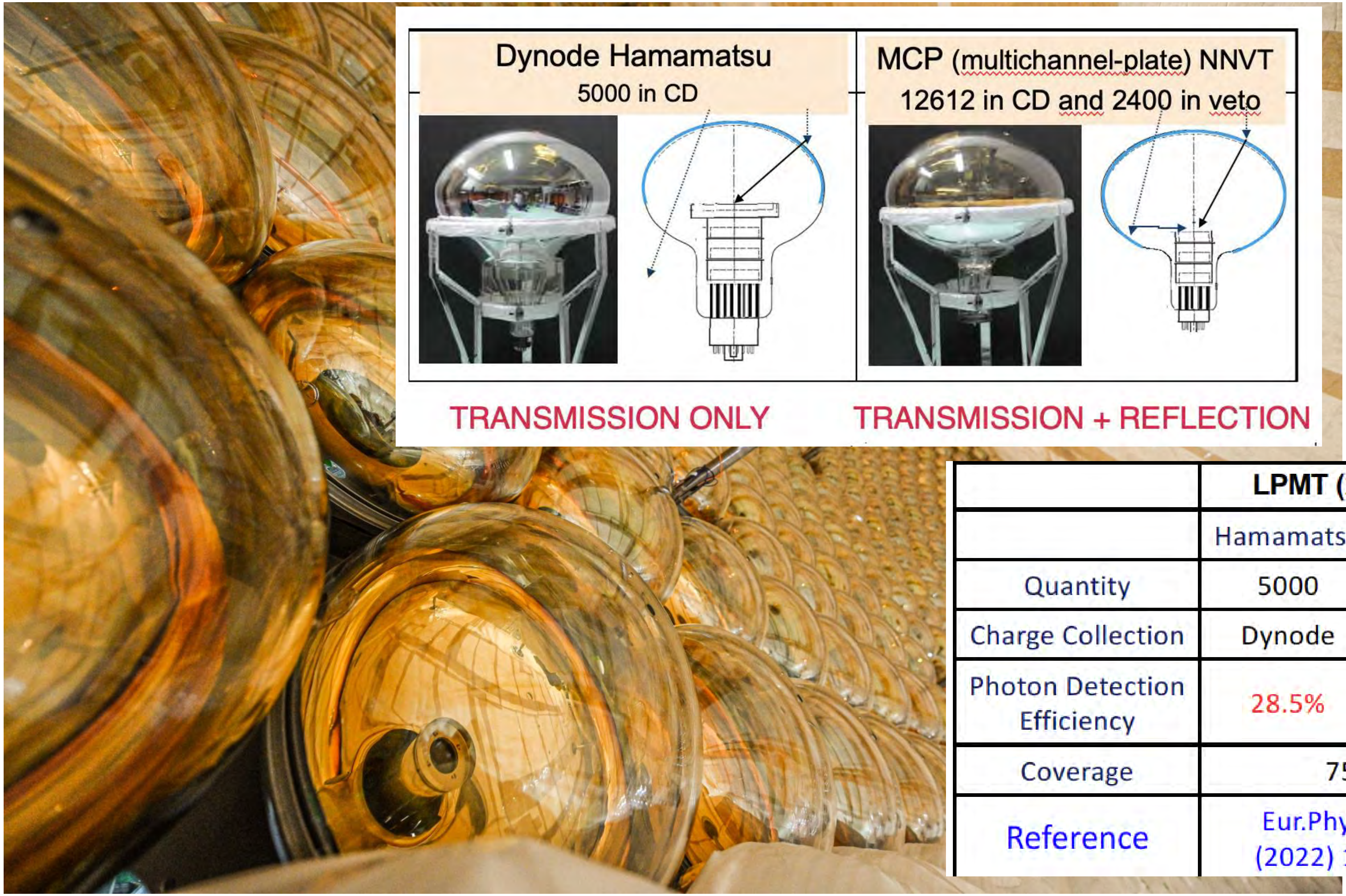
5 layers of Acrylic

20 layers of Acrylic

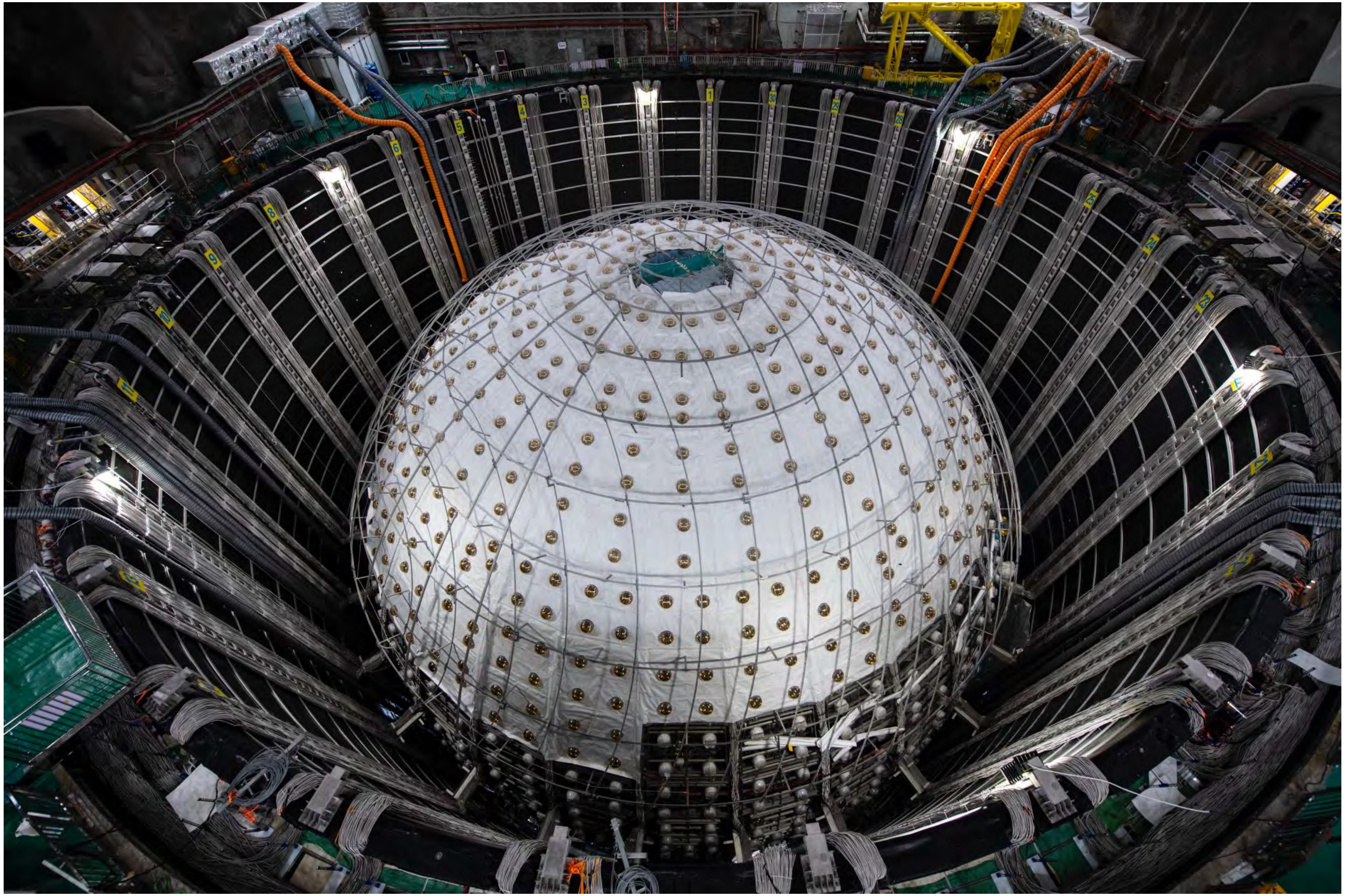
23 layers of acrylic

CONSTRUCTION OF THE CENTRAL 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%
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

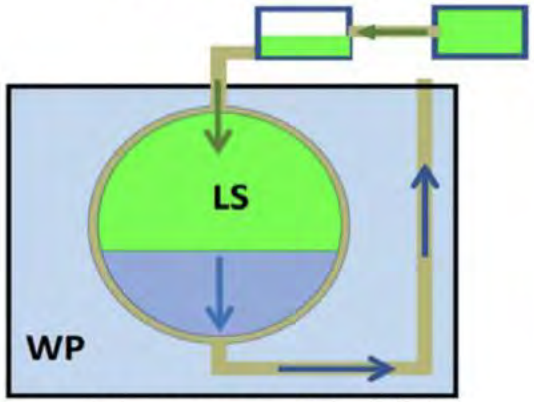


CD CLEANING AND LS FILLING SCHEME

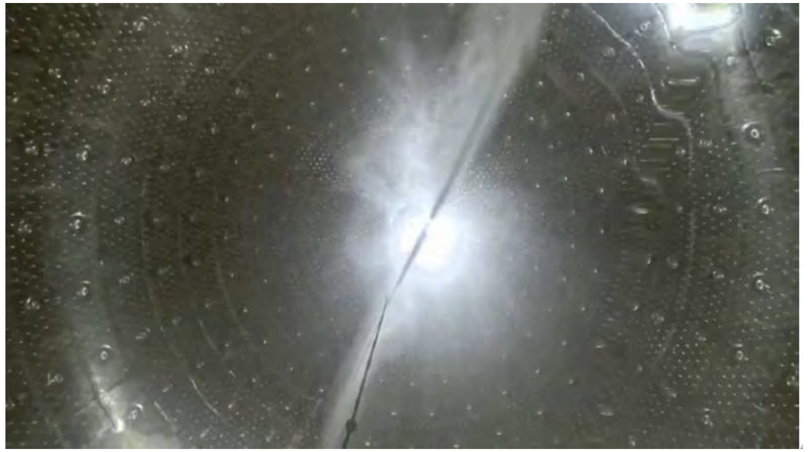
Reduce dust to class <1000, Rn by ÷10

Complete CD construction → 1 week settlement with proper moisture → Remove the protective film and wash the acrylic surface by the high pressure water spray → Fill CD and VETO by high purity water → replacing water in CD by LS

LS filling($7m^3/h$)



Drain water($7m^3/h$)



Water for CD: U/Th<10^{-15} g/g, ^{226}Ra<0.1 mBq/m^3
Water for VETO: U/Th<10^{-14} g/g

LIQUID SCINTILLATOR PLANTS ON SITE


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

Four purification plants for a radio-purity of 10^{-17} g/g (U/Th) and 20 m attenuation length @ 430 nm

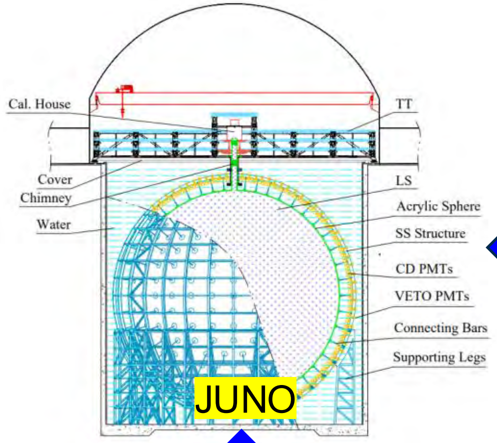
SS pipes to underground


Water extraction to remove radioactive impurities


Gas stripping to remove Rn and O_2

15%


OSIRIS for LS qualification



JUNO

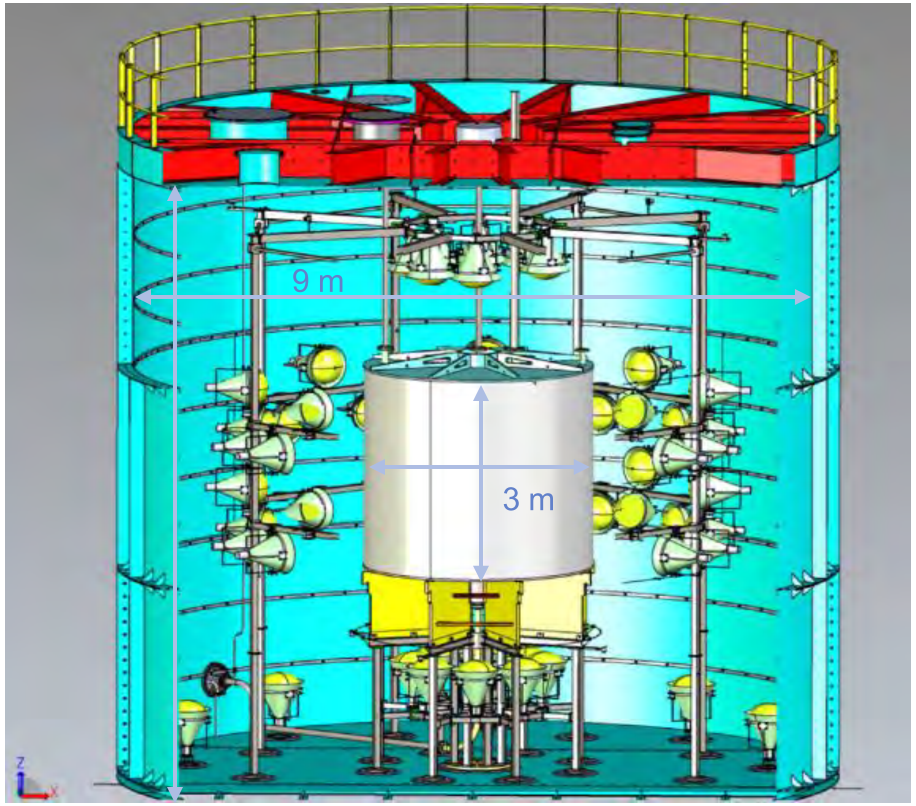
85%

ONLINE SCINTILLATOR INTERNAL RADIOACTIVITY INVESTIGATION SYSTEM (OSIRIS)

A 20-t detector to monitor radiopurity of LS before and during filling to the central detector

- ✓ RADON CONTAMINATION
- ✓ OPTICAL PROPERTIES

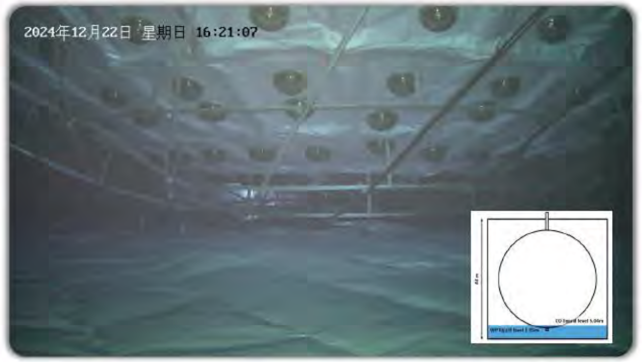
Eur.Phys.J.C 81 (2021) 11, 973.

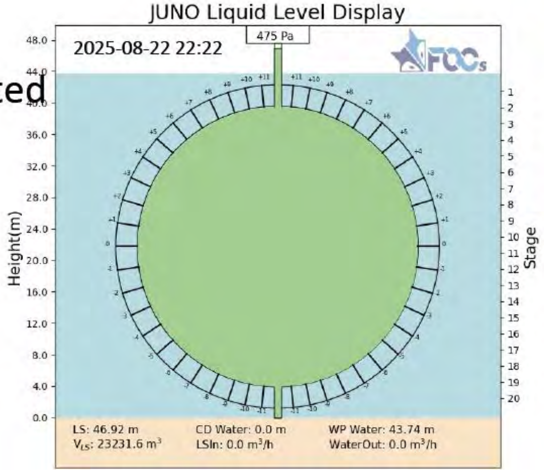


KEY CONTRIBUTION OF GERMAN GROUPS WITH LEADERSHIP BY PROF. M. WURM (JGU)

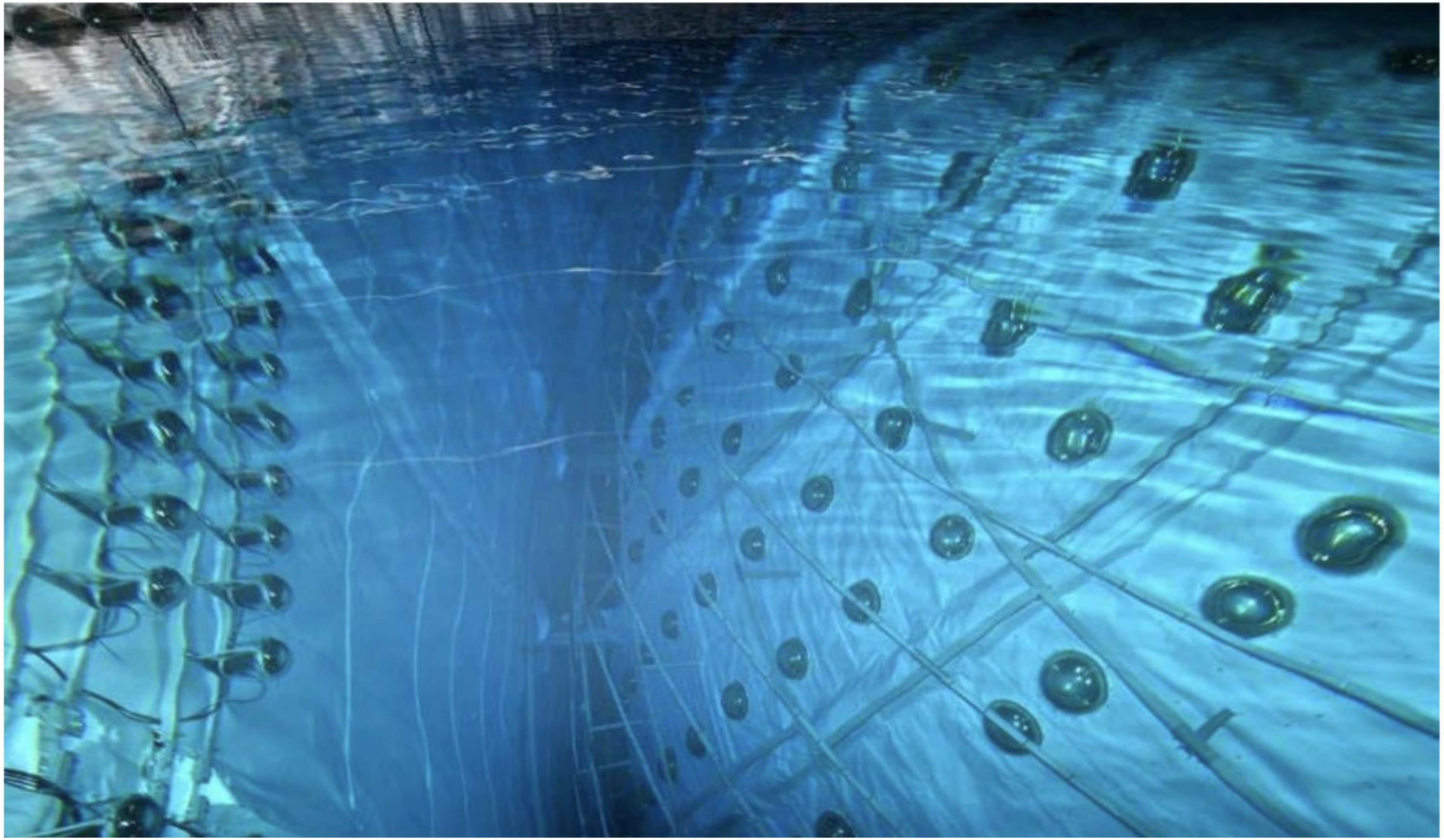
JUNO timeline

- 2024, Dec 18 — Start of Water Filling
- 2025, Jan — TT installation started
- 2025, Feb 1 — End of Water Filling
- Water Phase
- 2025, Feb 8 — Start of LS Filling
- Mixed Phase
- 2025, Jun — TT installation completed
- 2025, Aug 22 — End of LS Filling
- Full detector calibration
- 2025, Aug 26 08:00 am — Start of Data Taking

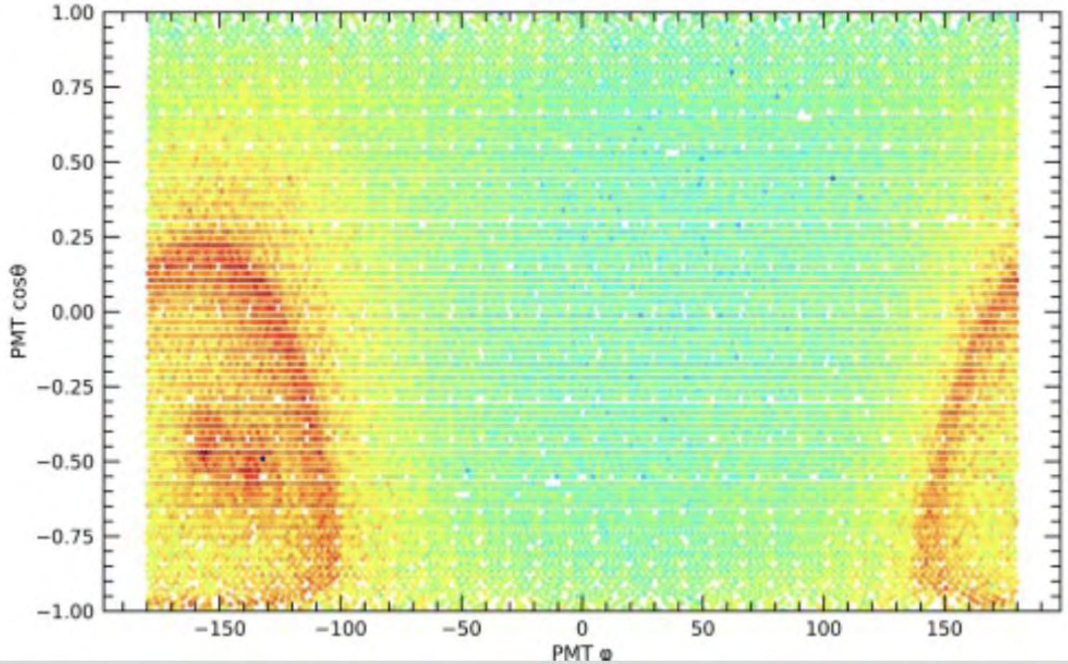


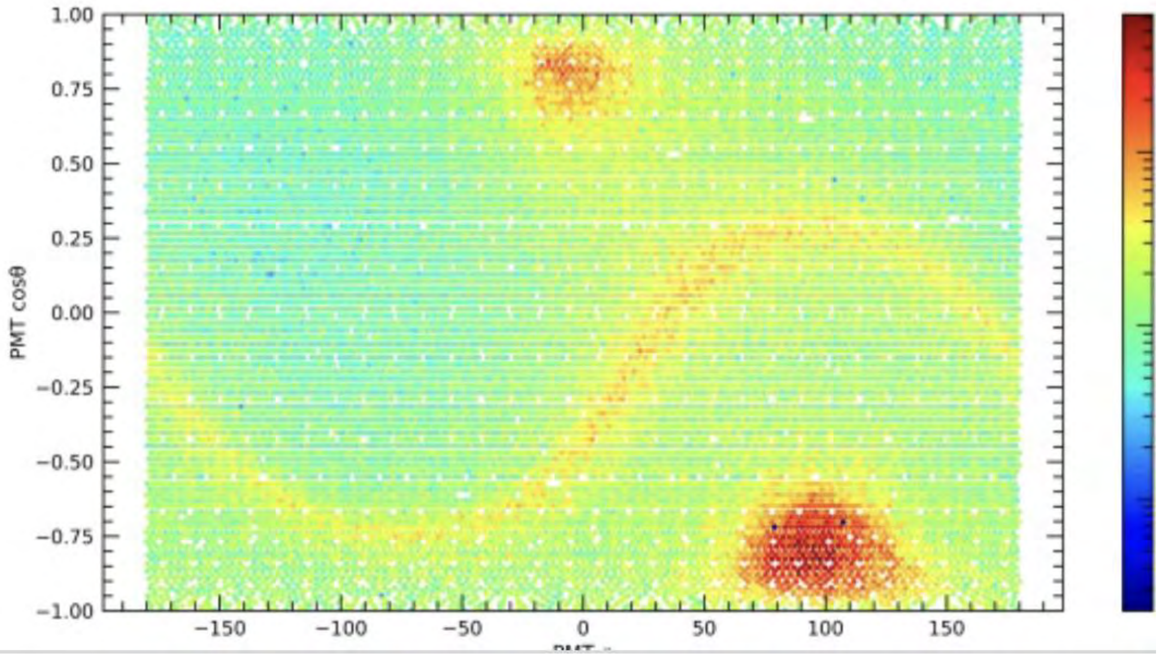


WATER POOL FILLED WITH WATER

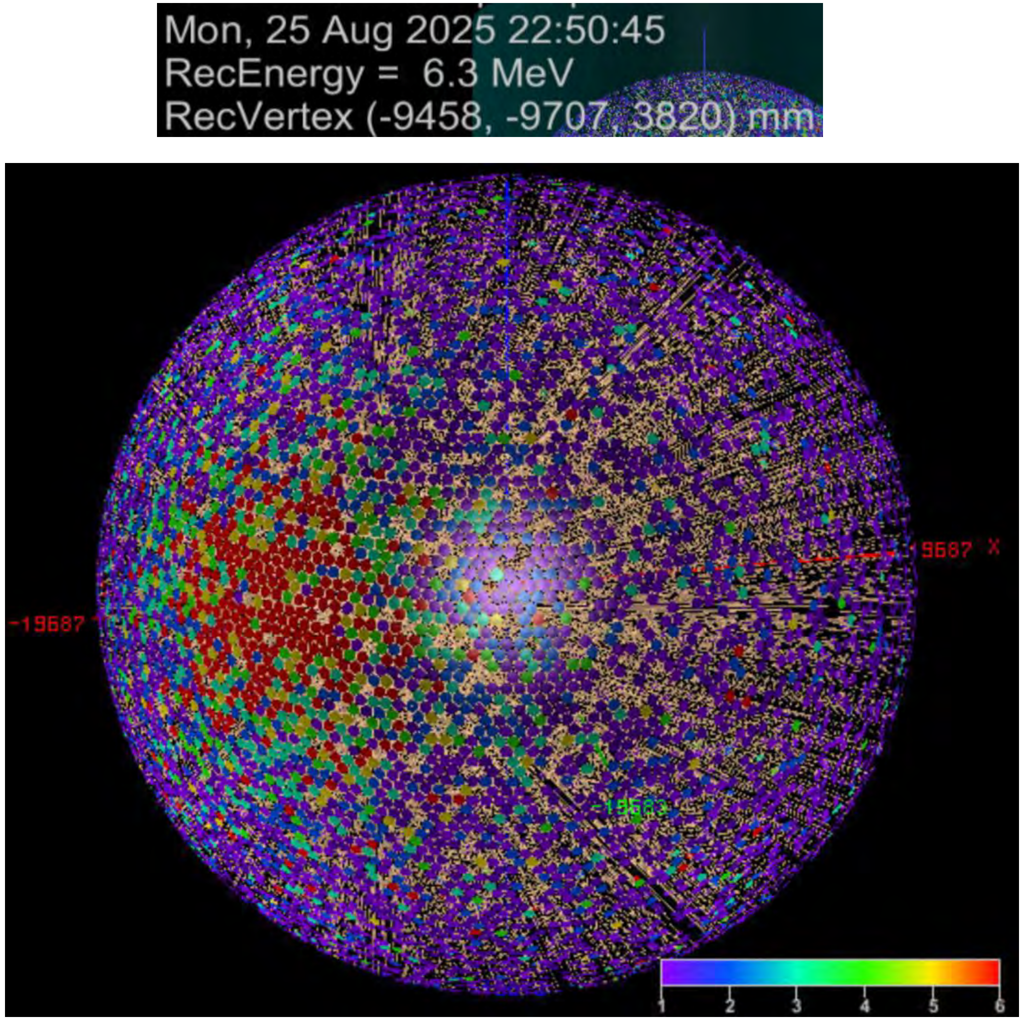


FIRST MUON EVENT IN THE WATER POOL

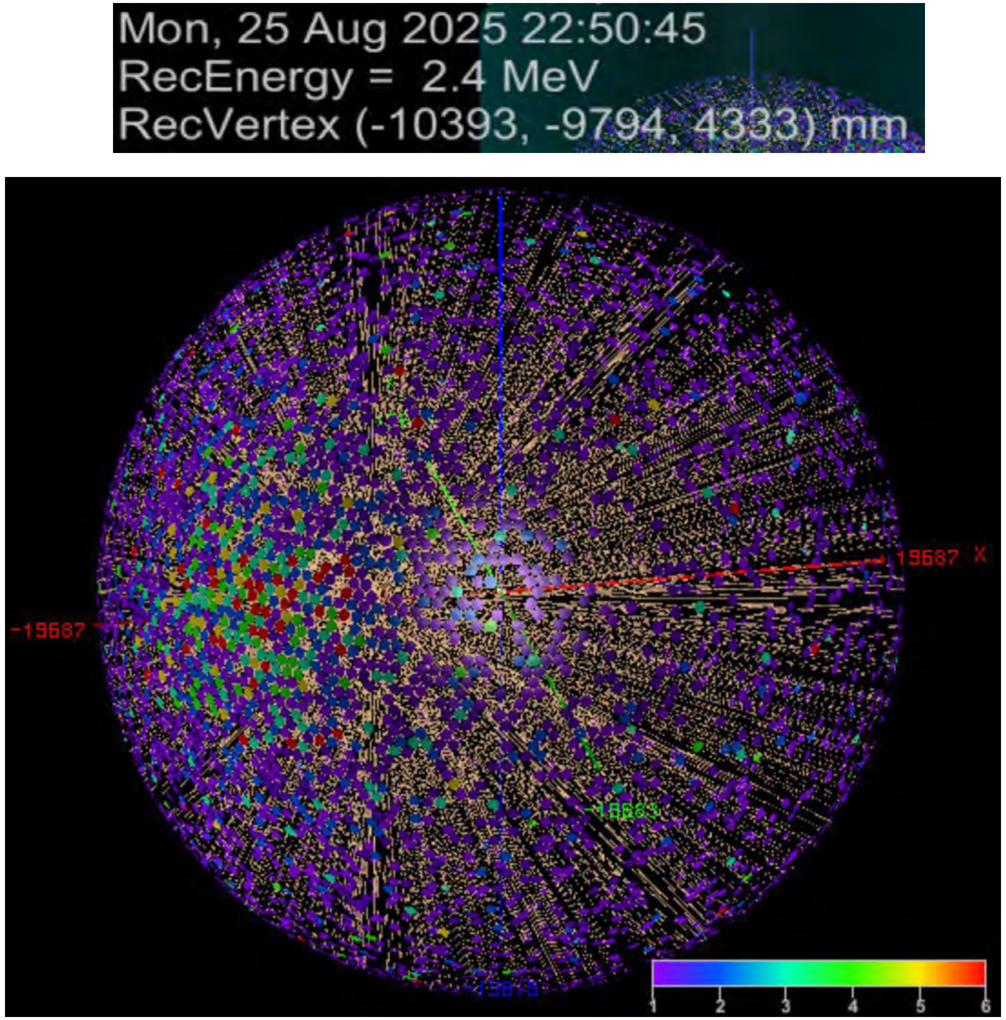




GOLDEN ANTINEUTRINO EVENT



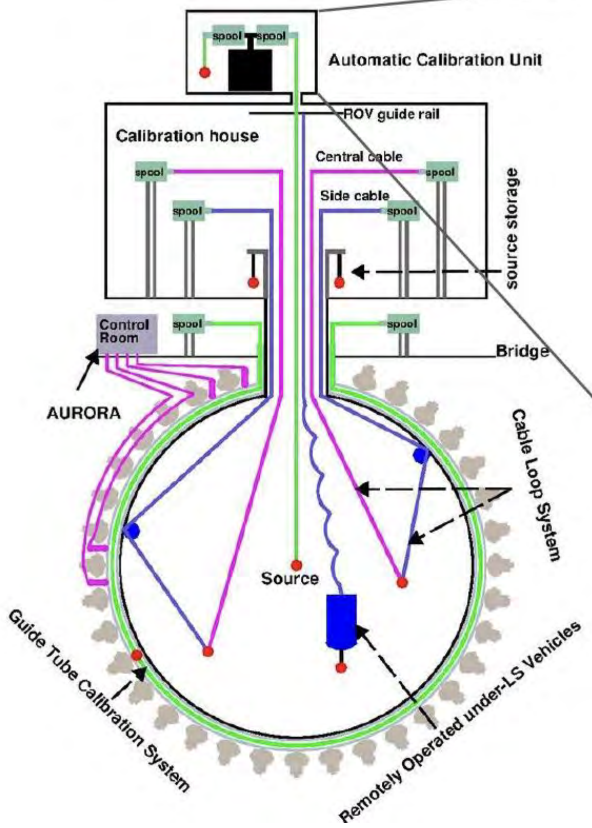
Prompt e+ signal



Delay neutron signal

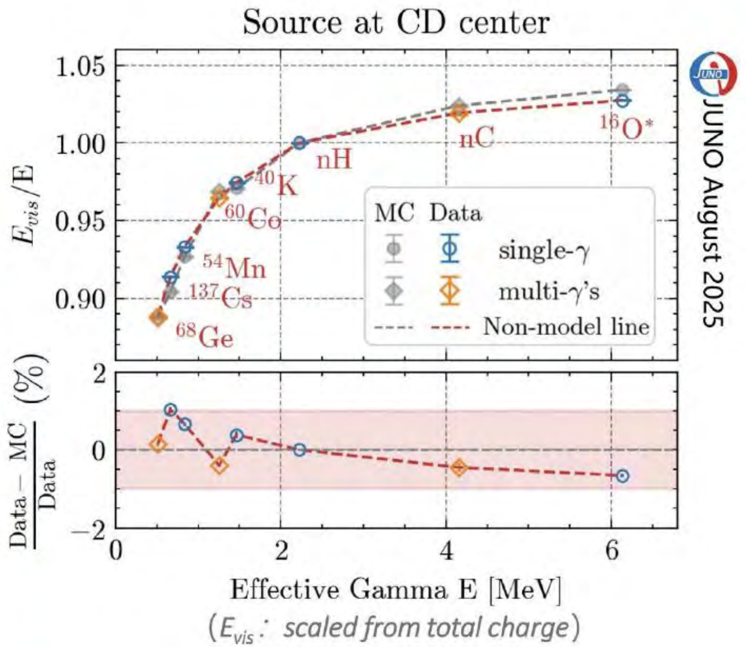
DETECTOR CALIBRATION

JUNO has multiple calibration systems:
- to cover the whole detector
- to cover the whole energy range
- to monitor detector stability



Calibration house

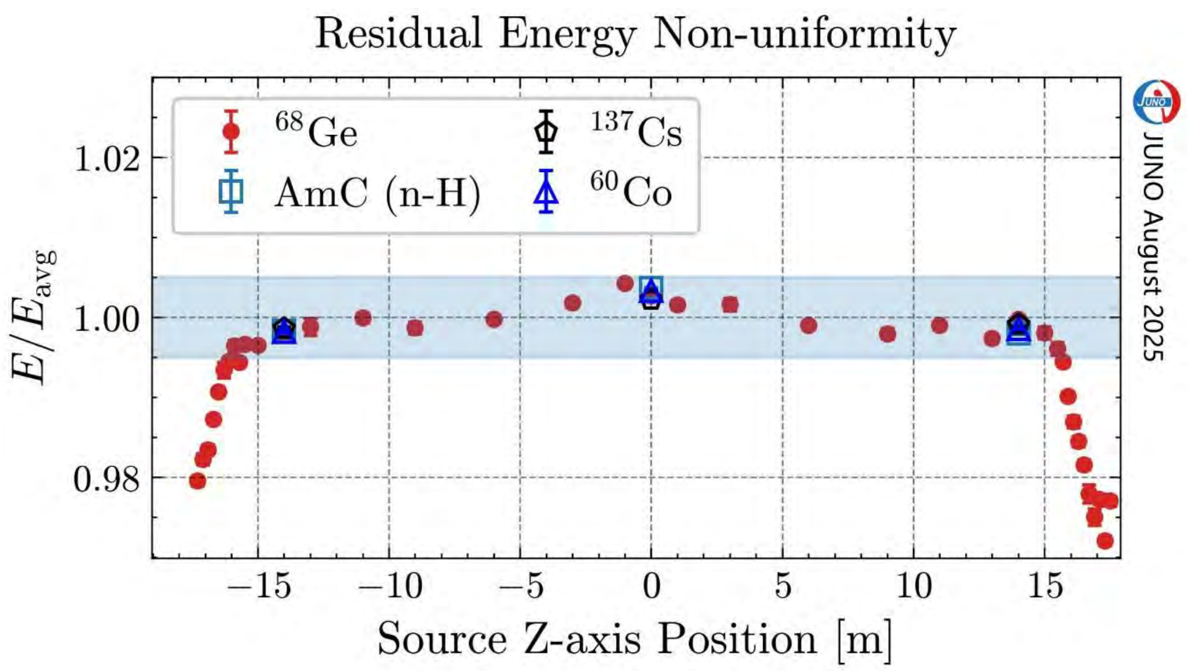
Multiple calibration sources:
^{68}Ge, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{40}K, ^{241}Am-C, and laser

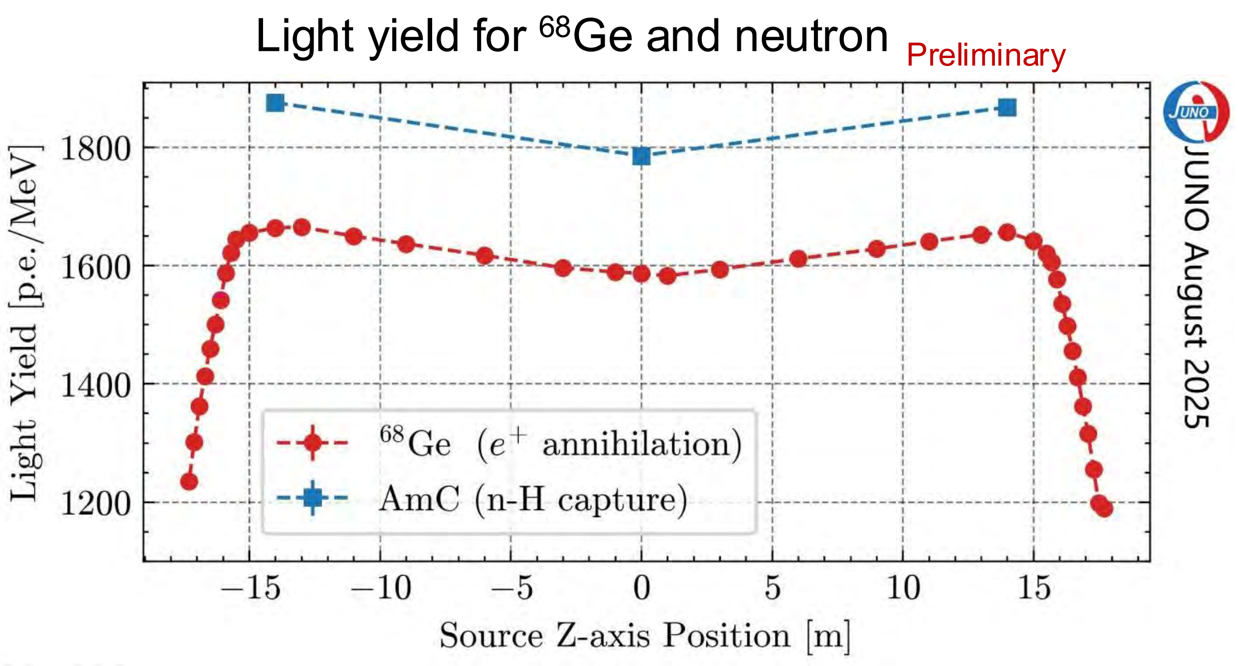


Energy non-linearity known to <1%

DETECTOR UNIFORMITY & LIGHT YIELD

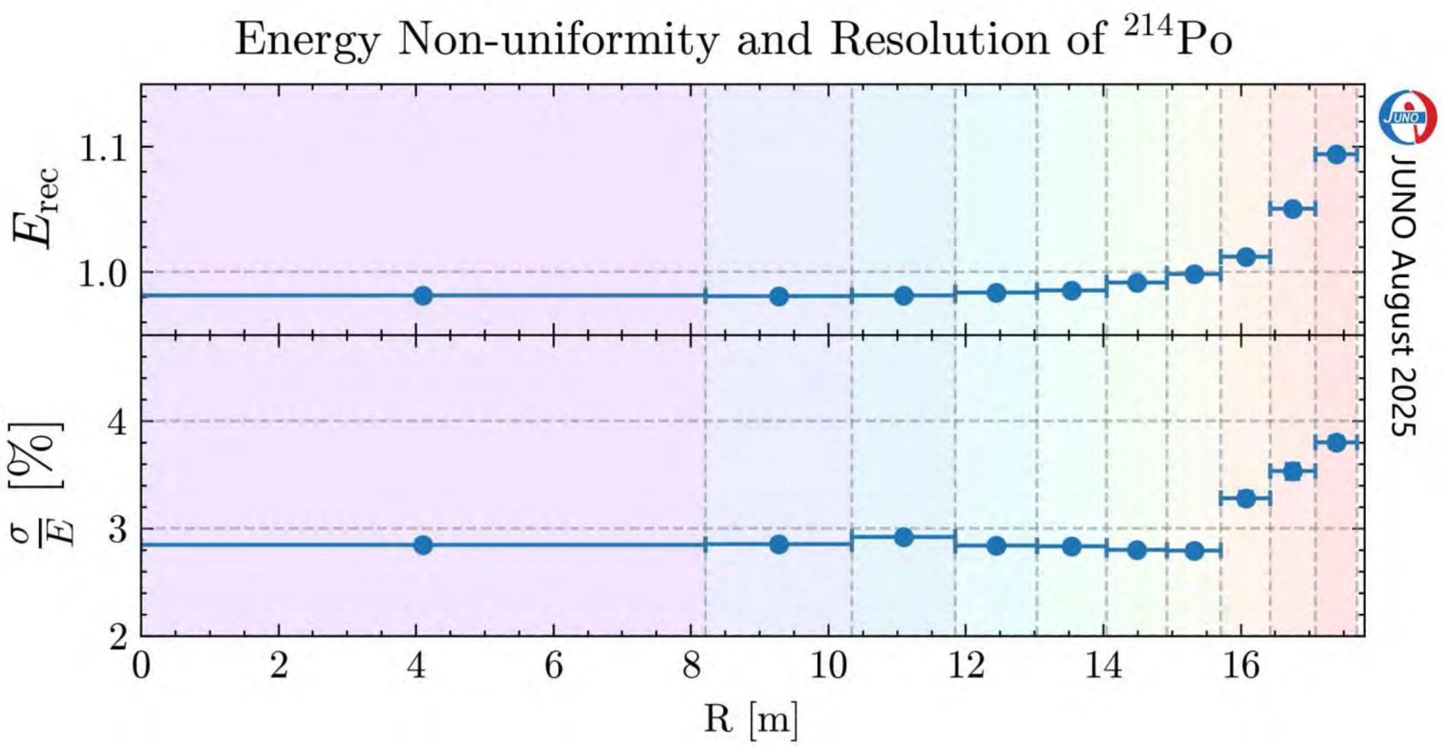
- For R<16m, residual energy non-uniformity scanned along the Z-axis is <0.5%
- Light yield is >1600 PE/MeV for ^{68}Ge, >1800 PE/MeV for neutron, better than expectations (difference due to non-linearity, Chinese Phys. C 49 (2025) 013003)
- Edge effects still exist, more calibration data and software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

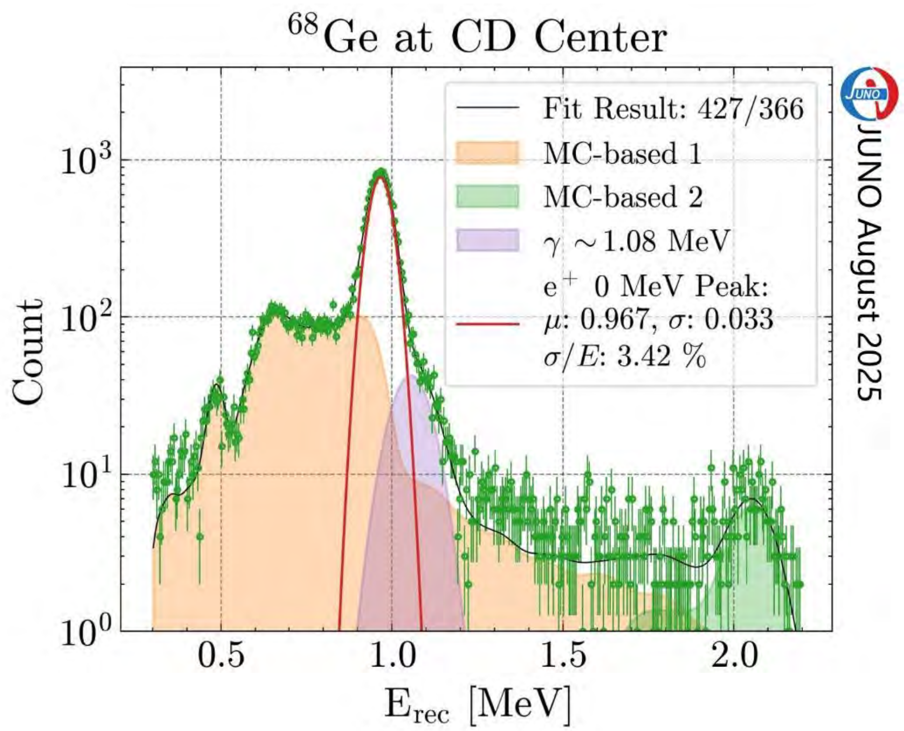




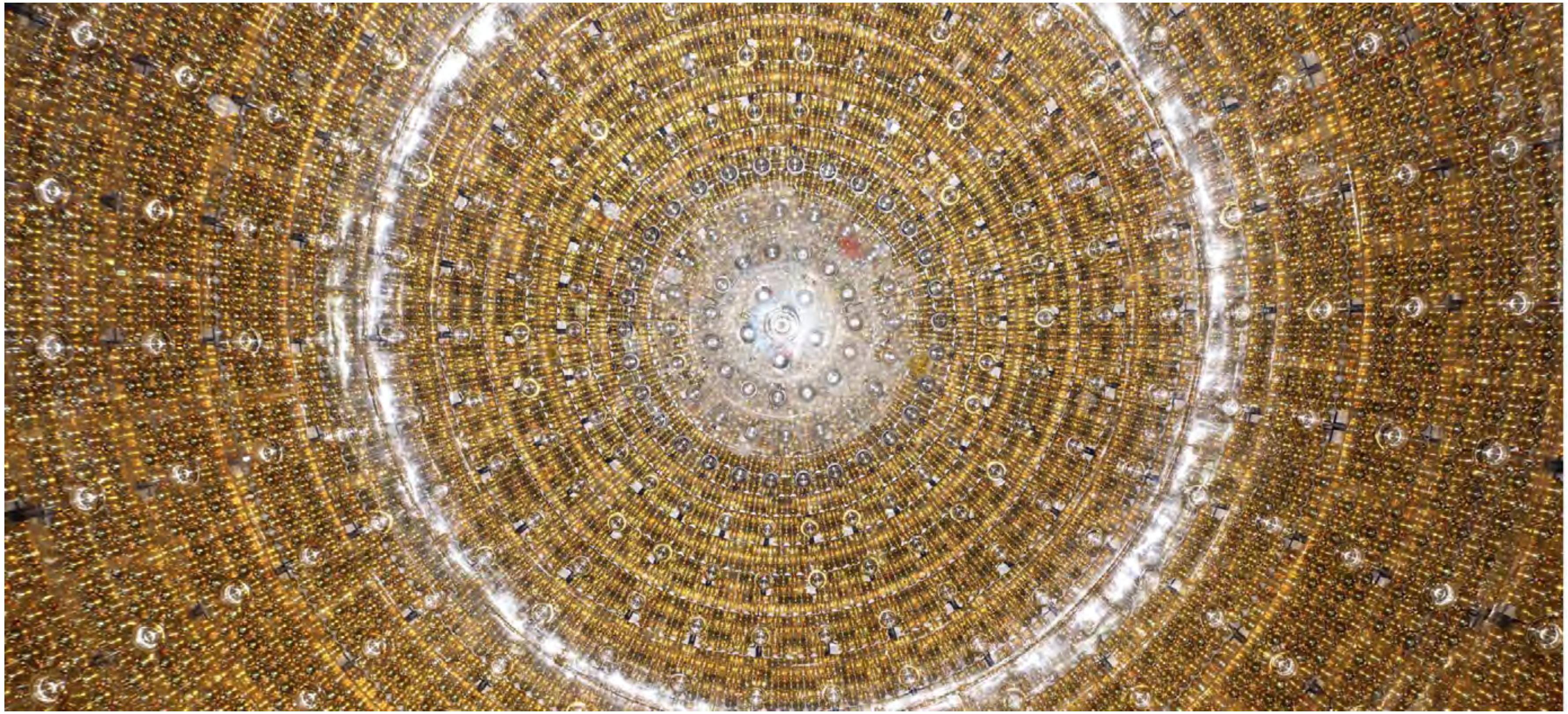
ENERGY RESOLUTION

- 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, …





SUMMARY



- After 17 years efforts, from idea to construction, JUNO detector is fully completed.
- Initial testing and performance studies show that key specifications have been mostly met.
- We are excited to have started the physics data taking:
  - Results from reactor neutrinos will come soon
  - Results on astrophysics will come later

STAY TUNED, A LOT OF ADVENTURE AHEAD OF US!

A few days ago underground with Marco and Cristobal working on JUNO commissioning.

Thank you!