

JUNO and Its First Physics Results

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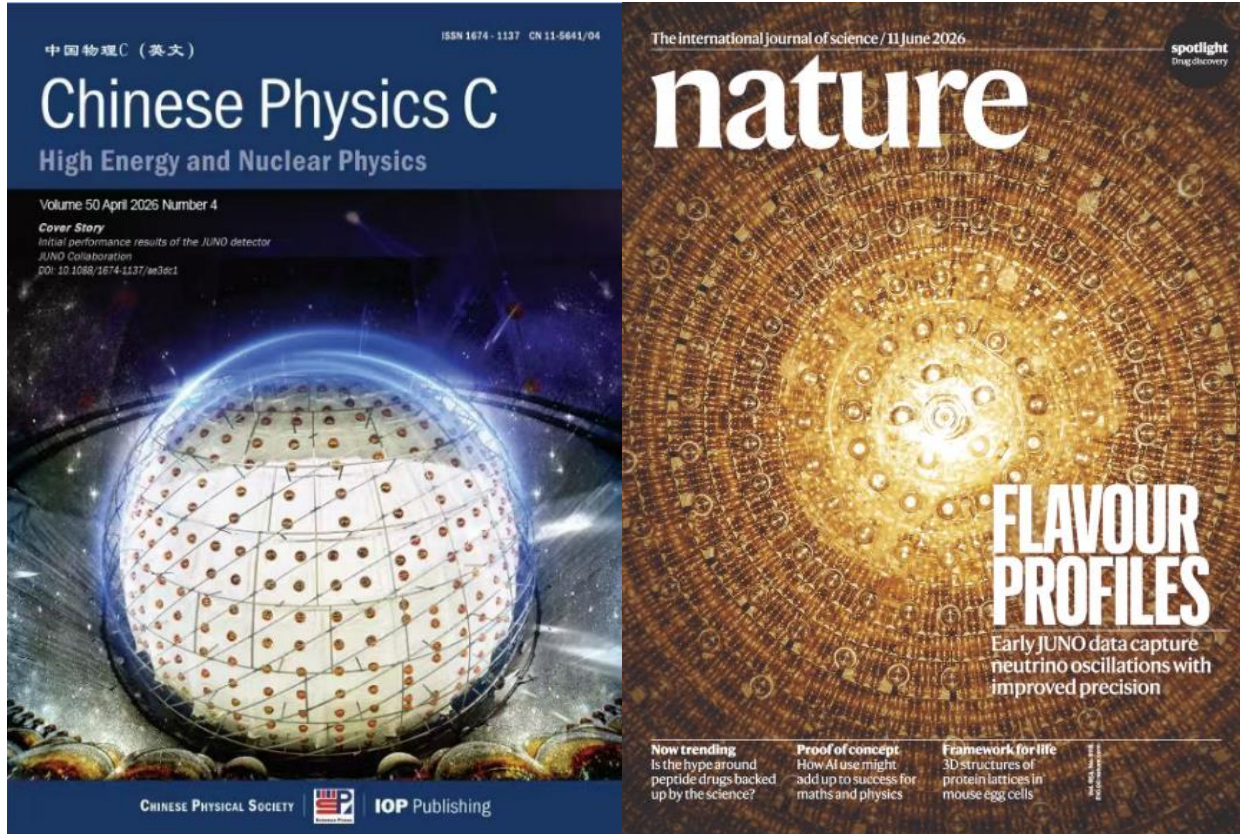


江門中微子實驗

Jiangmen Underground Neutrino Observatory

IceCube (a Nobel Prize Experiment) Particle Astrophysics Symposium, Oct 14-16, 2026

The First Physics Results from JUNO (Nov 2025 & Jun 2026)

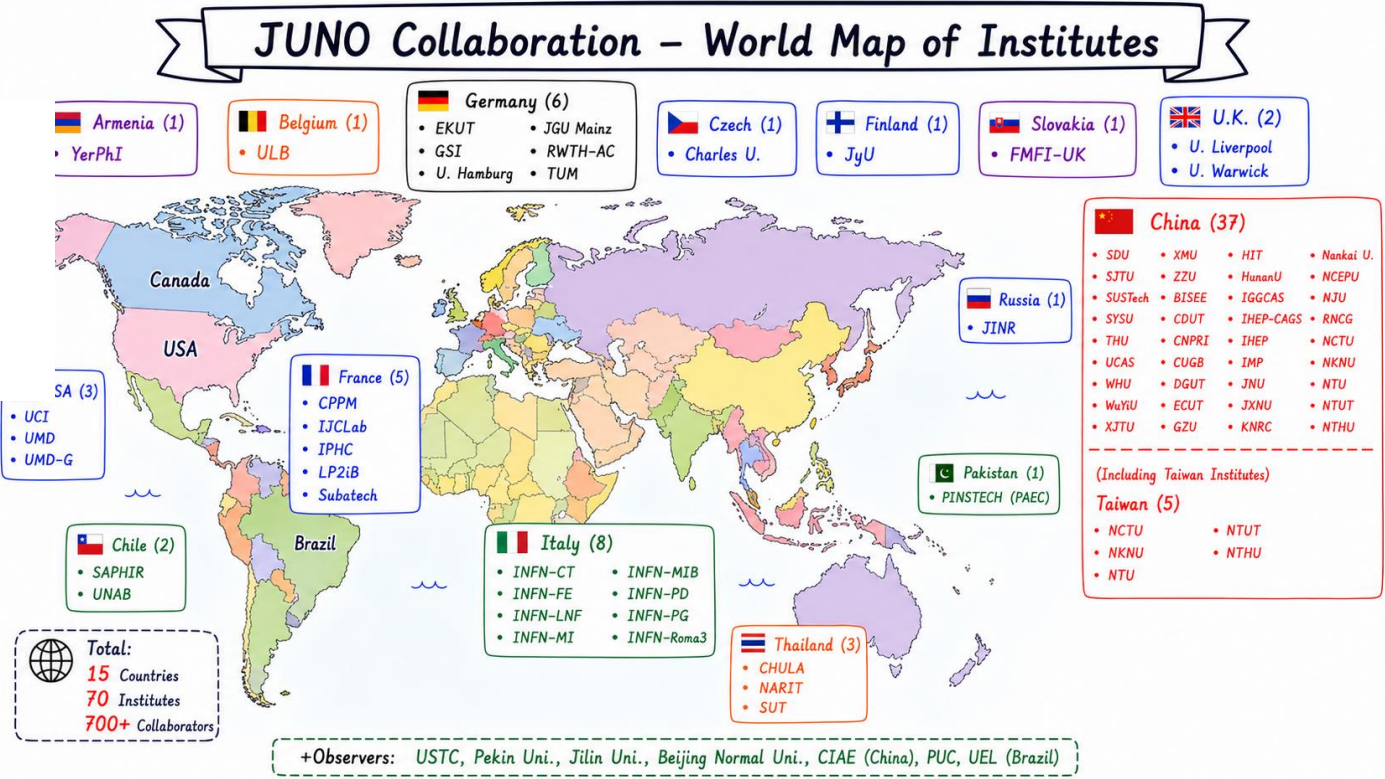
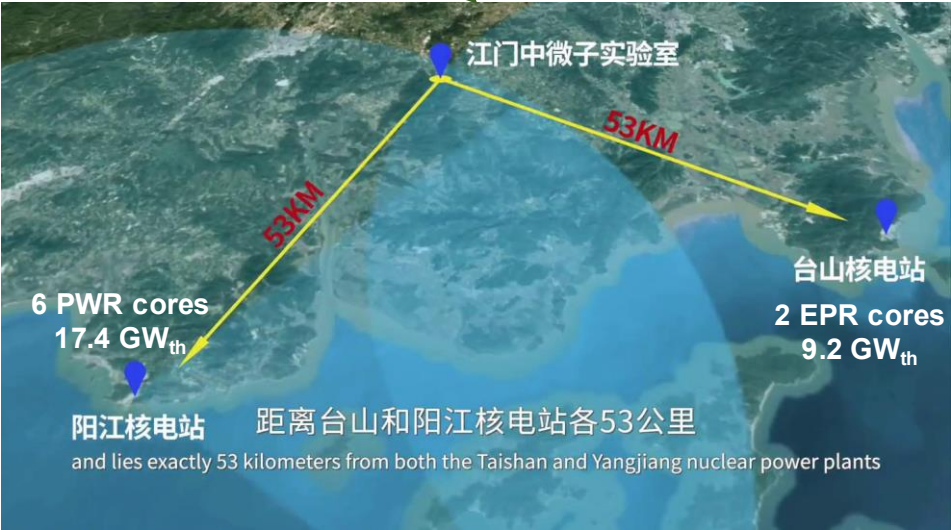
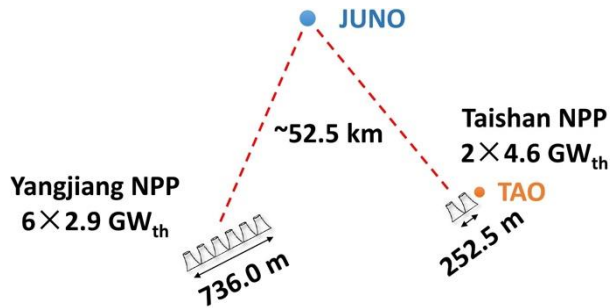


First results using 59 days of data already published, Nov 2025 – Jun 2026

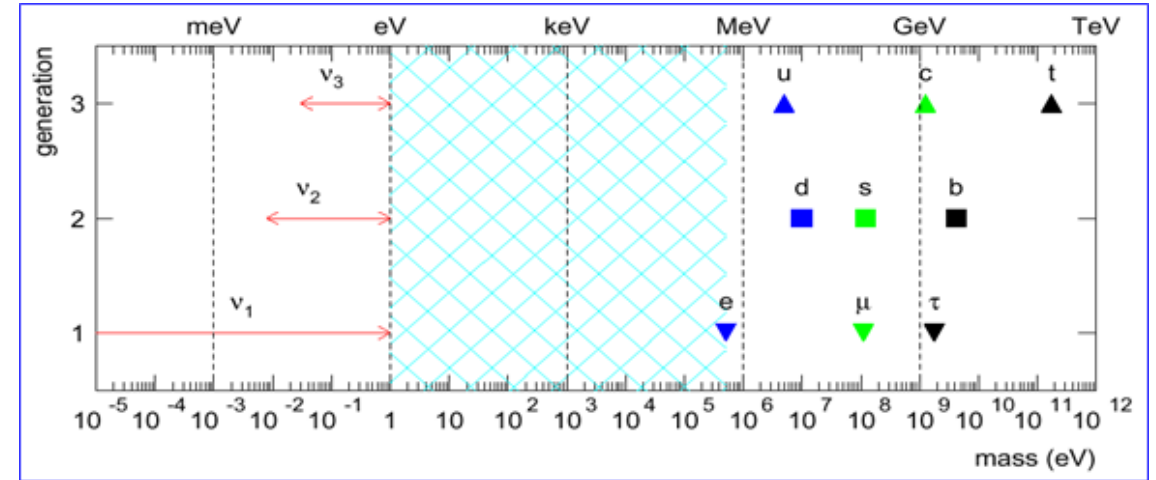
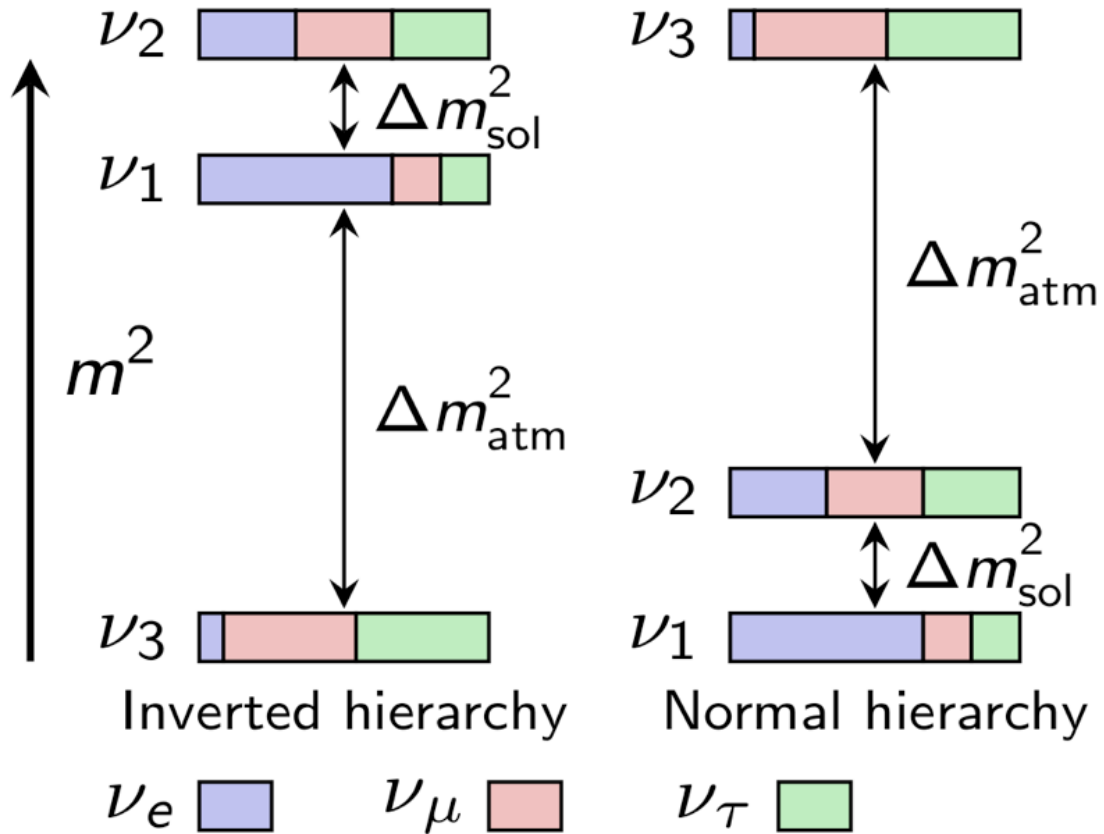


**First Neutrino Mass Ordering
207 days of data @ v'26**

The JUNO Experiment the International Collaboration



The Quest to Neutrino Mass Ordering



- ❖ Mass ordering of charged fermions are “normal” --- roughly even on log-scale
- ❖ Absolute neutrino masses are UNKNOWN
- Oscillations tell Neutrino Mass Ordering

Experimental Efforts Resolving ν Mass Ordering



Source / Principle	Matter Effect	Interference of Solar&Atm Osc.	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Hyper-K, IceCube-DeepCore, ORCA			
Beam ν_μ	T2K, NOvA, DUNE			
Reactor ν_e		JUNO		
Supernova Burst ν			Massive Detectors with Good E Resolution	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, $0\nu\beta\beta$

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors

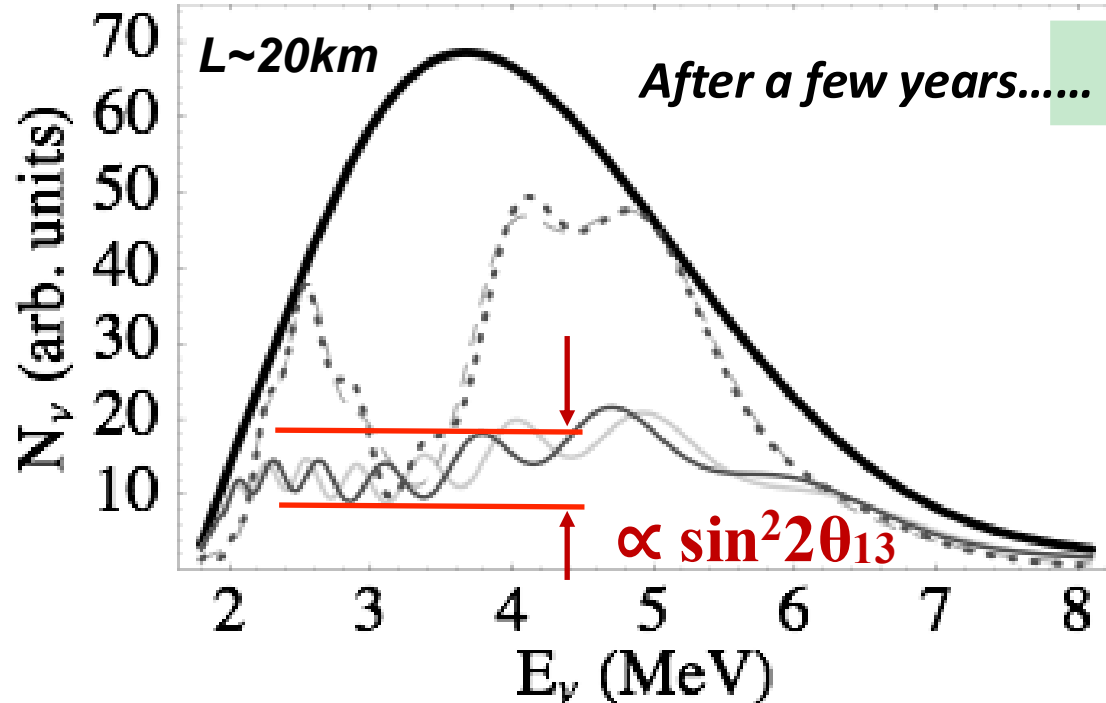


$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

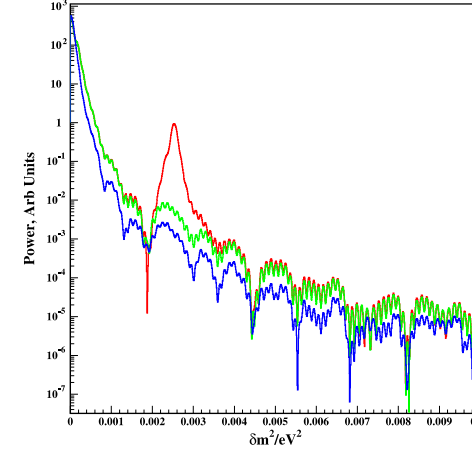
✓ Mass hierarchy reflected in the spectrum

✓ Independent of the unknown CP phase

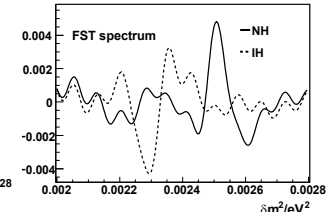
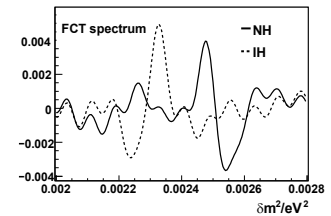
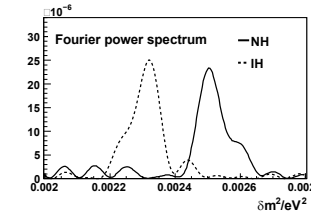
Petcov&Piai, Phys. Lett. B533 (2002) 94-106



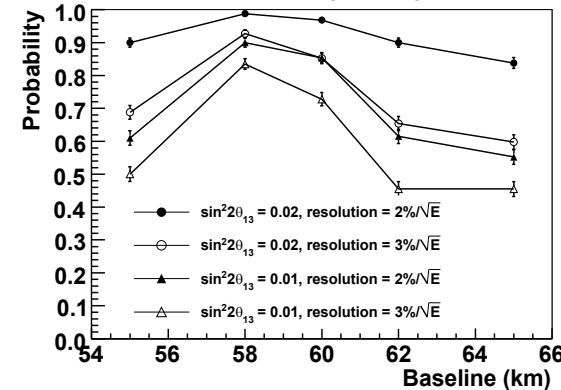
Learned et al, PRD78(2008)071302(R)



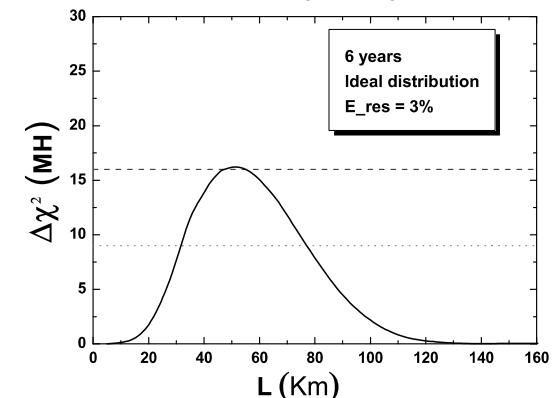
Zhan et al,
PRD78 (2008)
111103



Zhan et al, PRD79 (2009) 073007

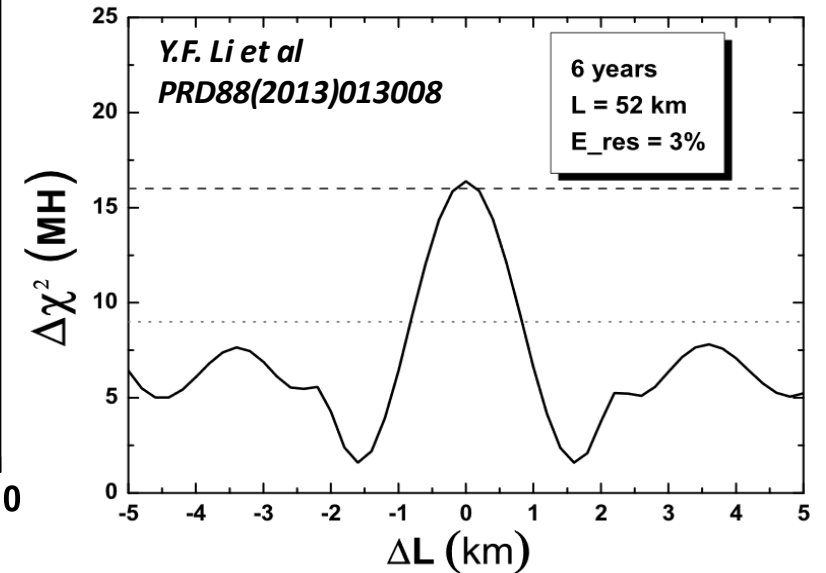
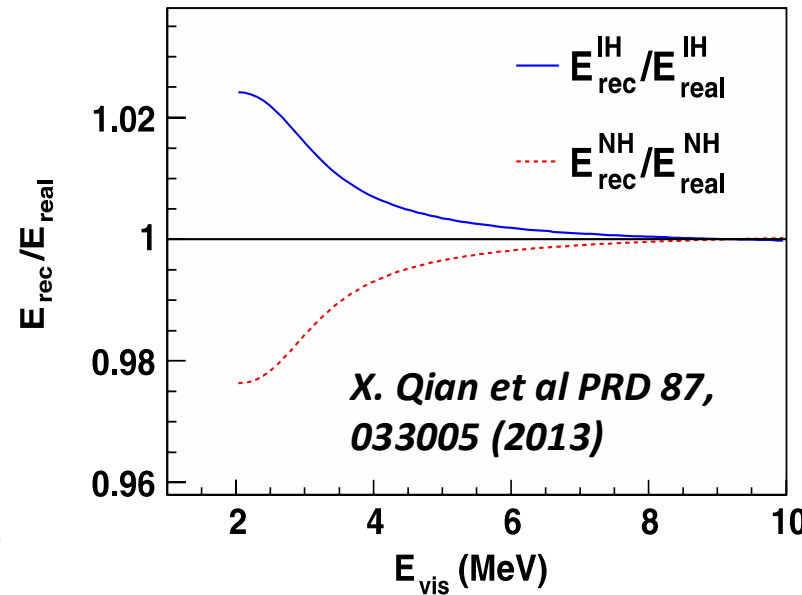
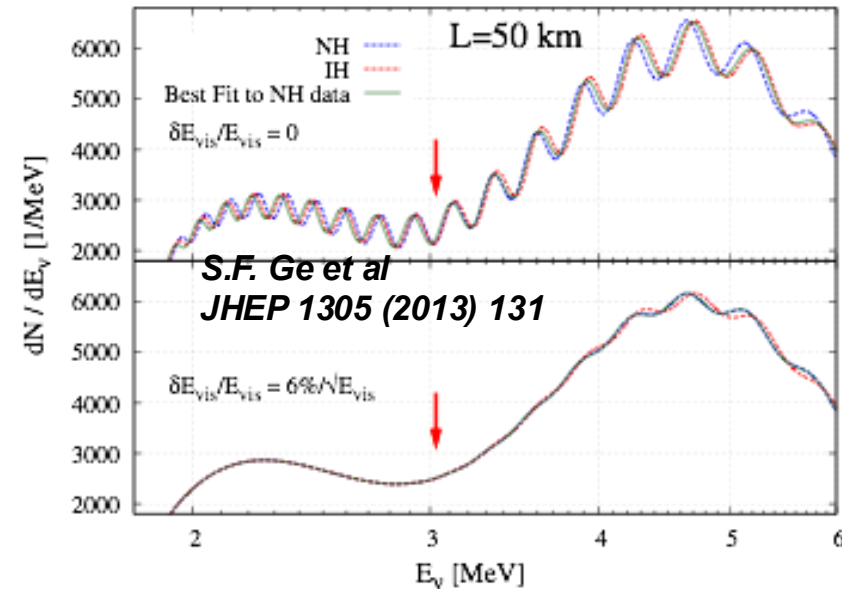
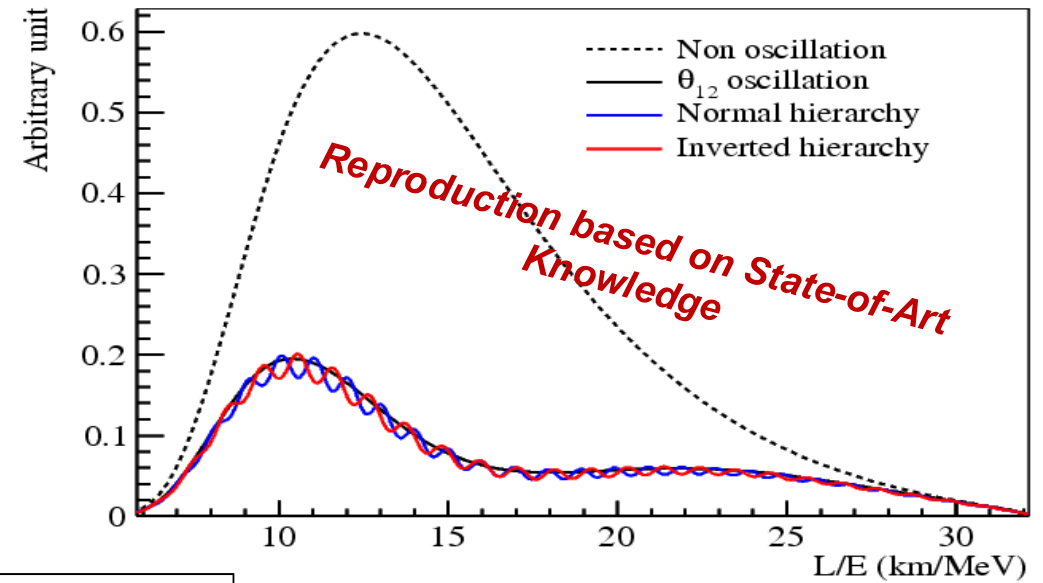


Li et al, PRD 88 (2013) 013008

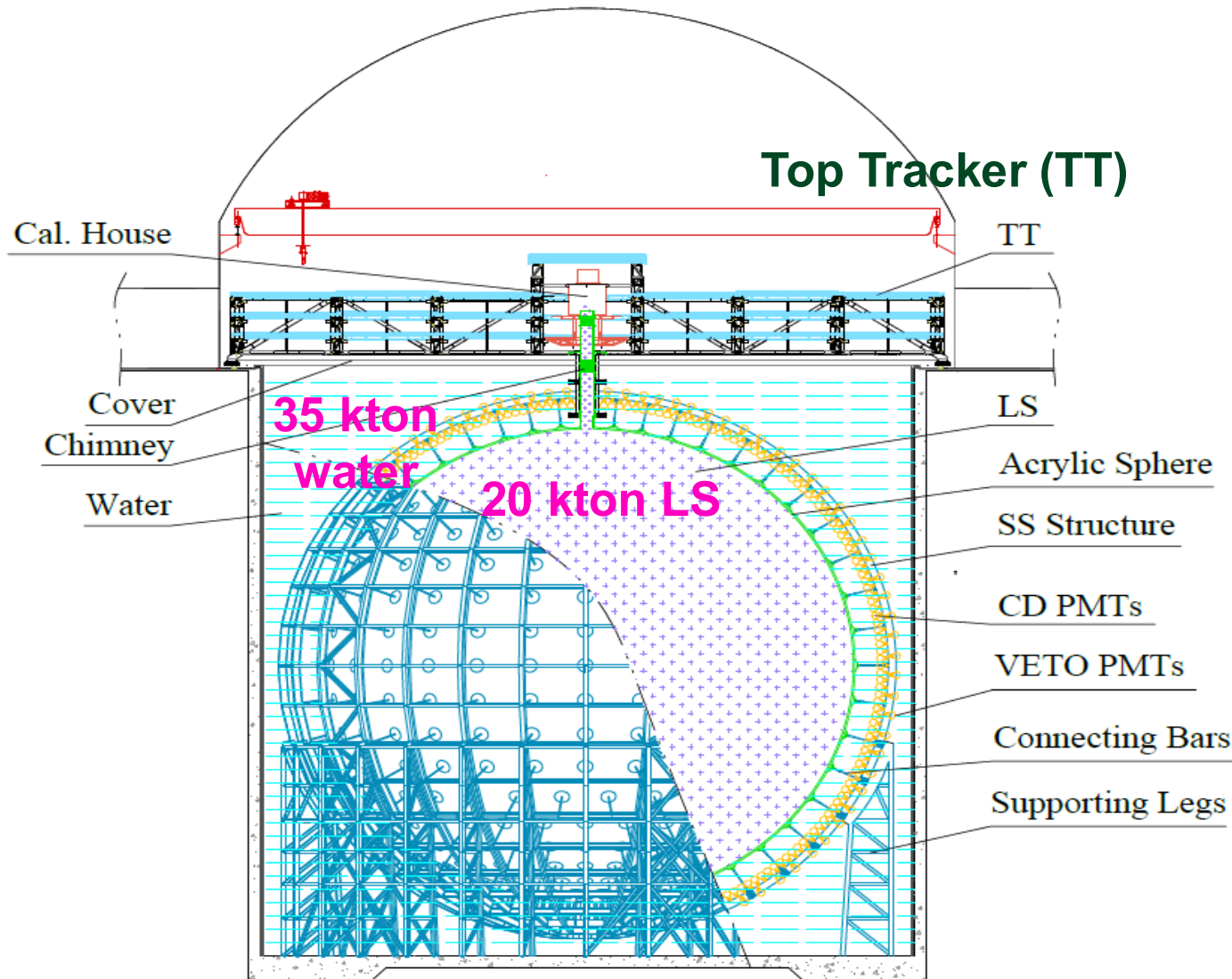


Challenges in Resolving NMO using Reactors

- Energy resolution: $\sim 3\%/\sqrt{E}$
- Energy scale uncertainty: $< 1\%$
- Statistics (the more the better)
- Reactor distribution: $< \sim 0.5\text{km}$



The Conceptual Design of the JUNO Detector



Acrylic Sphere:

Inner Diameter (ID): 35.4 m

Thickness: 12 cm

Stainless Steel (SS) Structure:

ID: 40.1 m, Outer Diameter (OD): 41.1 m

17612 20-inch PMTs, **25600** 3-inch PMTs

Water pool:

ID: 43.5 m, Height: 44 m, Depth: 43.5 m

2400 20-inch PMTs

$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage &
non-uniformity

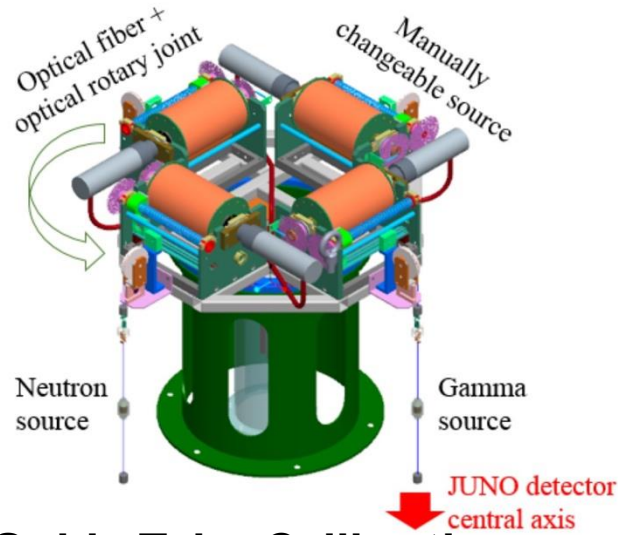
Photon
statistics

Noise
(~background)

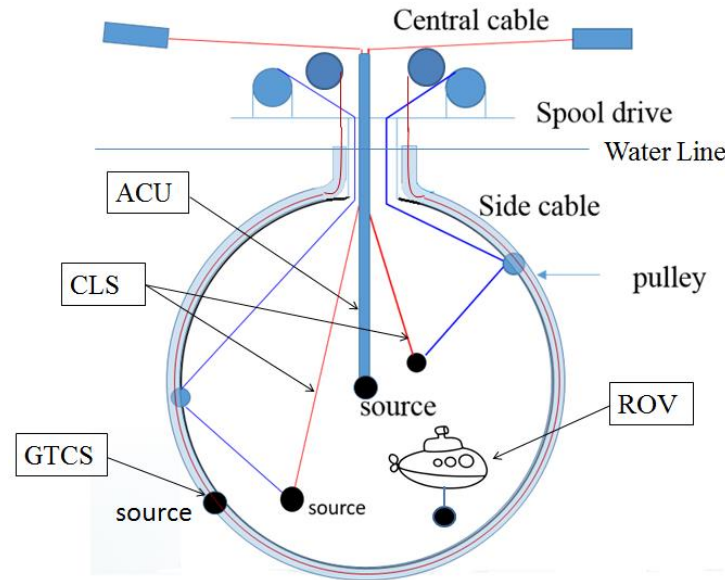
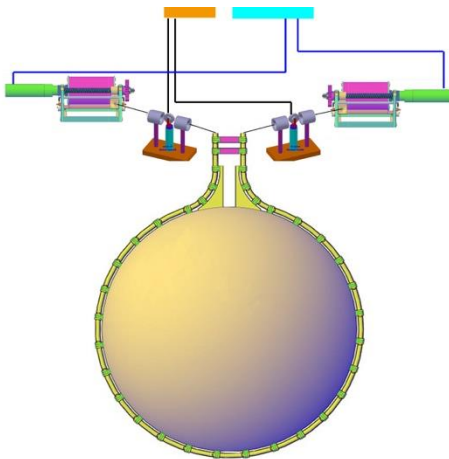
A Comprehensive Calibration System



Automatic Calibration Unit (ACU)

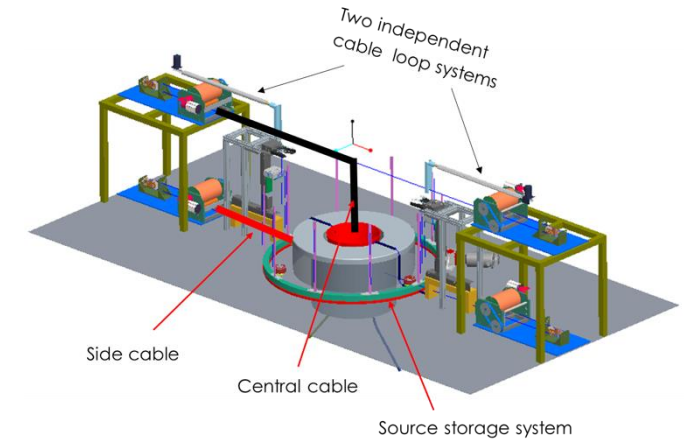


Guide Tube Calibration System (GTCS)

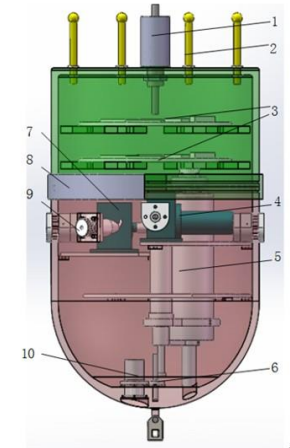


□ Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

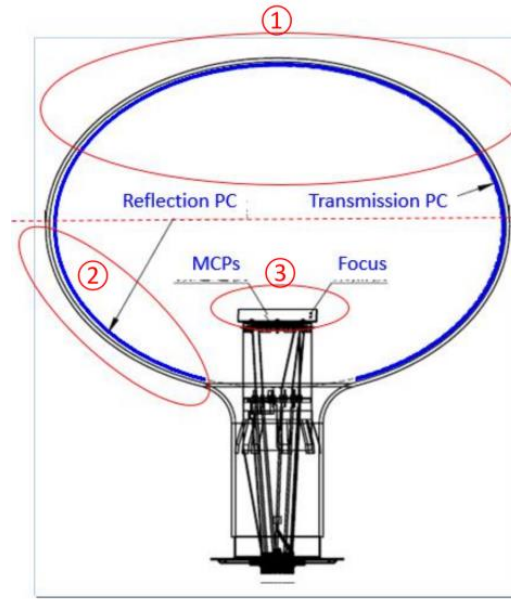
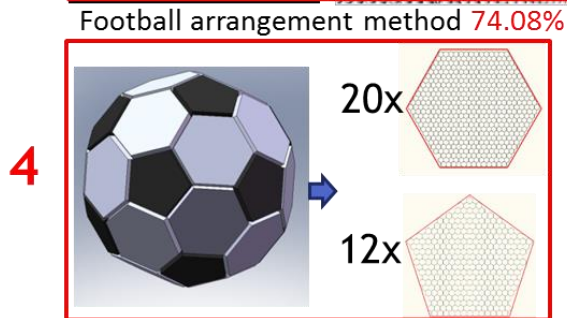
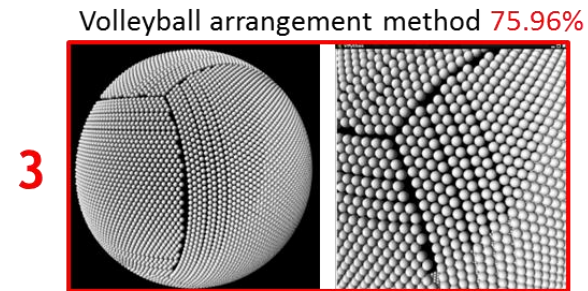
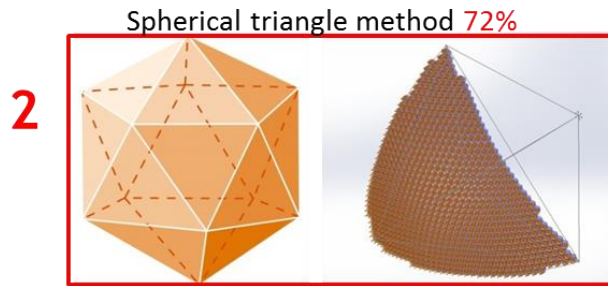
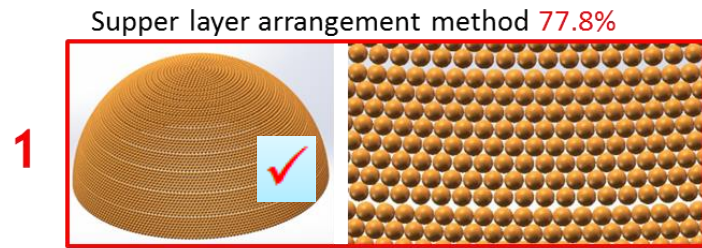
Cable Loop System (CLS)



Remotely Operated under-liquid-scintillator Vehicles (ROV)

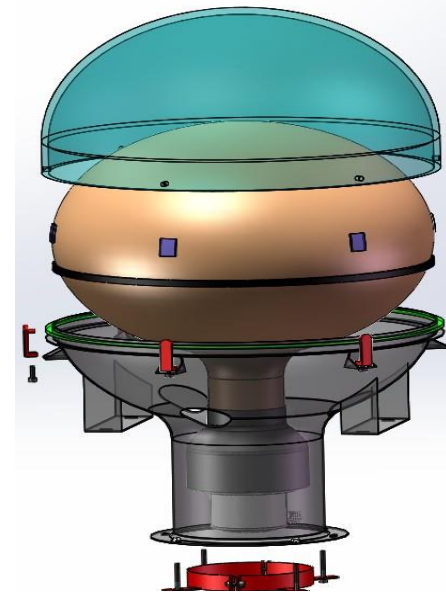
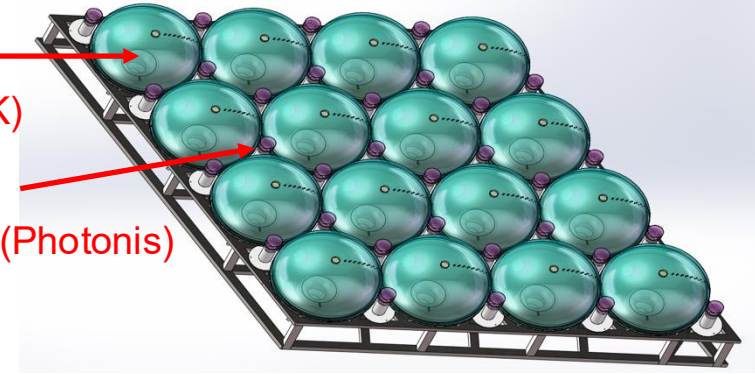


Packing PMTs as Tight as Possible and Keep Them Safe

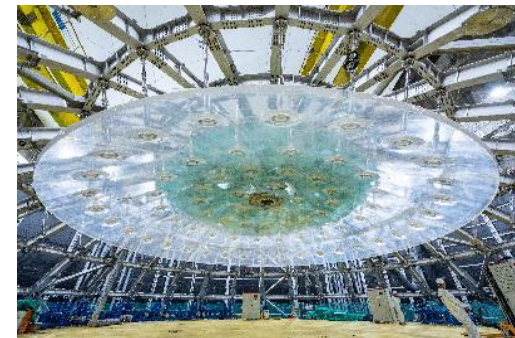
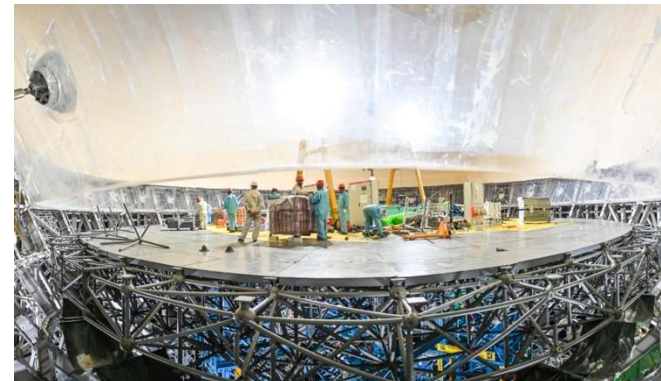
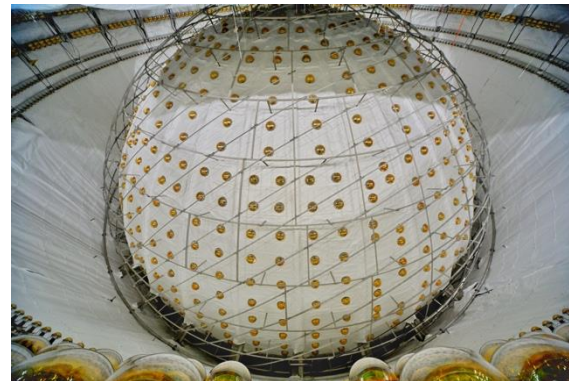
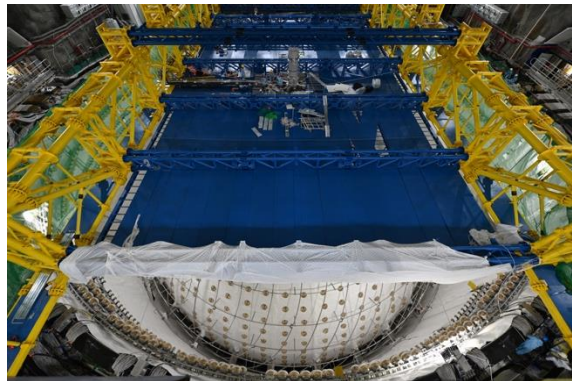
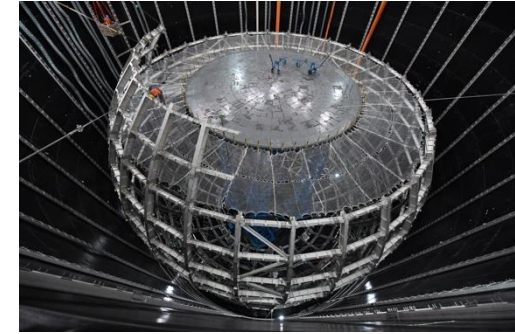


20" PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

3"sPMT(~25K)
HZE XP72B22 (Photonis)



The Construction of the Central Detector of JUNO



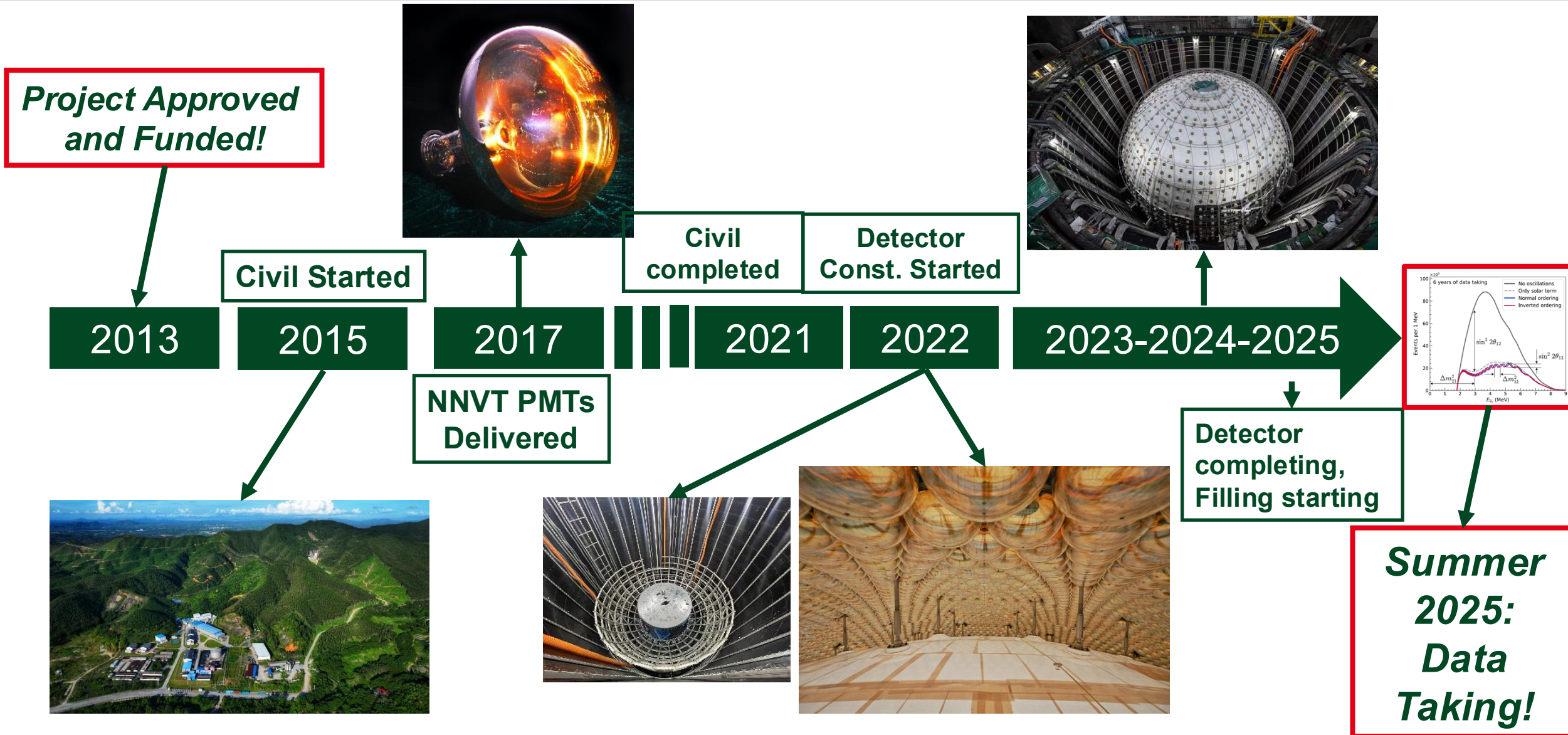
Views from Inside of the Central Detector



	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Coverage	75%		3%
Reference	Eur.Phys.J.C 82(2022) 12, 1168		NIM.A 1005 (2021) 165347



Major Milestones of the JUNO Experiment



The Evolution of Large Volume LS Detectors: 1956-2025

From 200+ kg to 20kt over 70 years



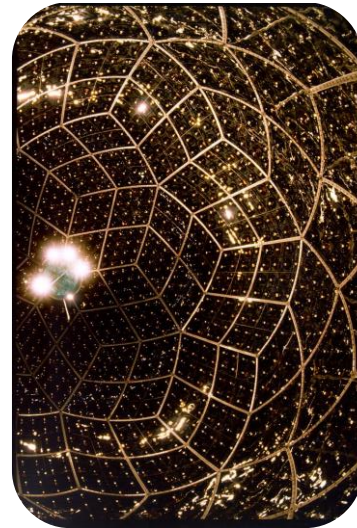
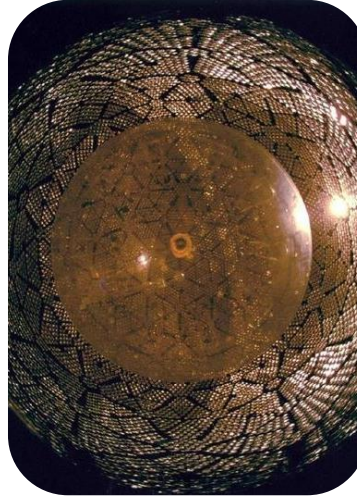
300 L



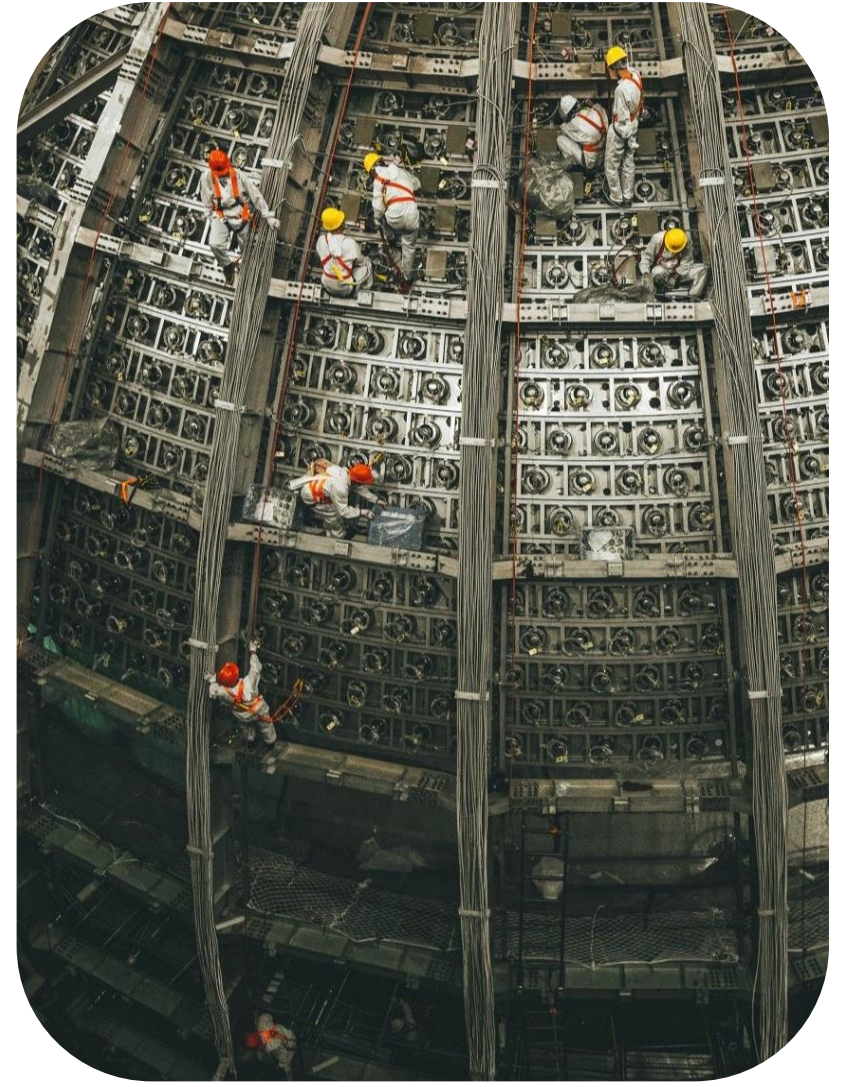
8 x 20 tons



300 t

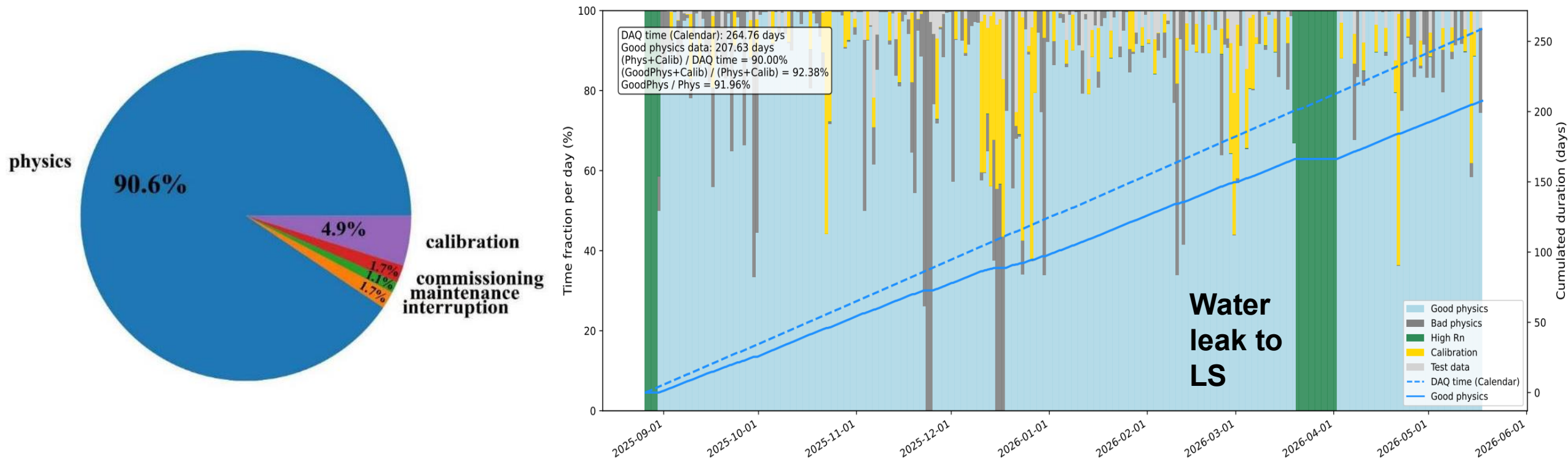


1000 t



20,000 t

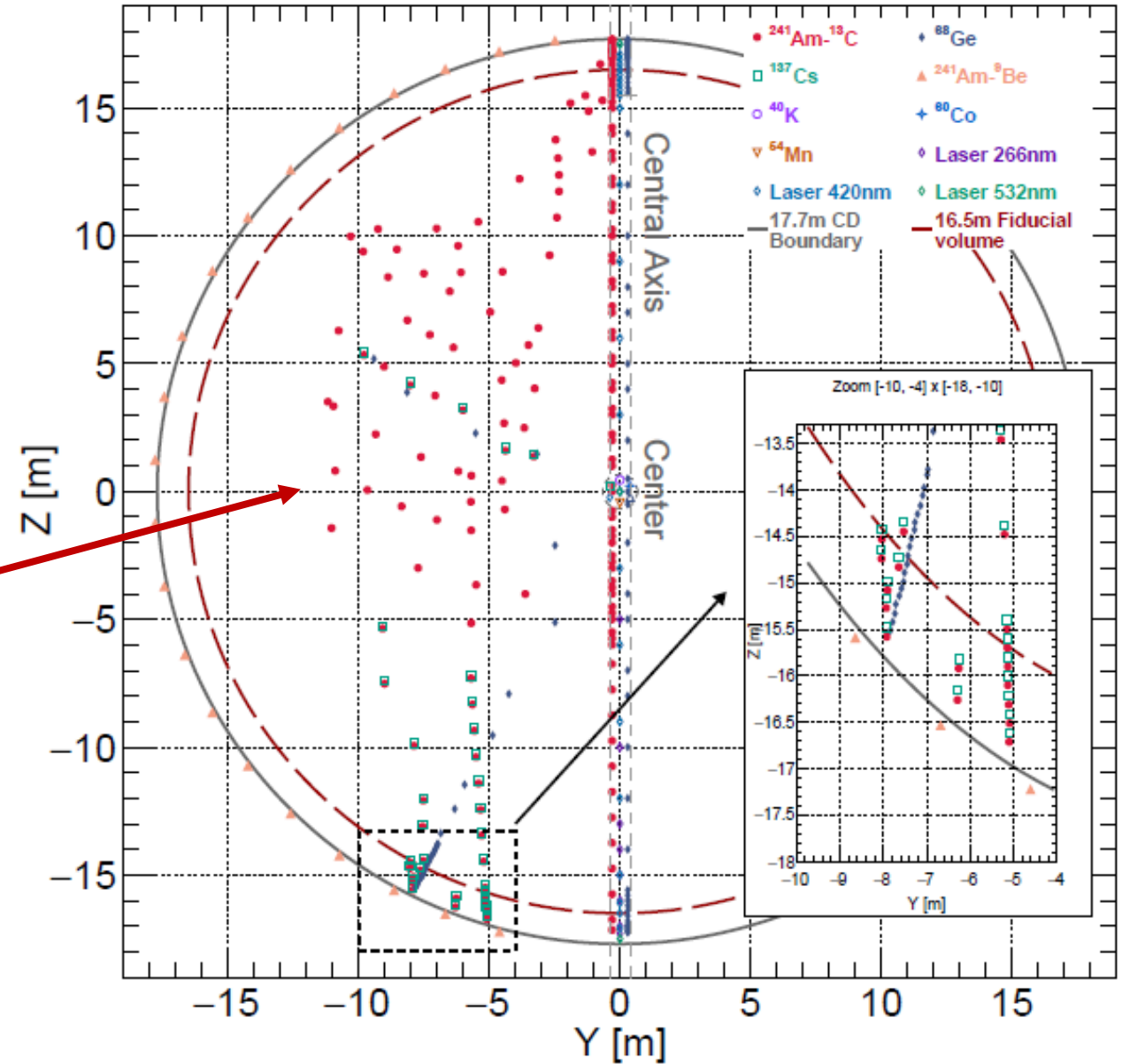
- Data taking period for this analysis: 2025.08.30-2026.05.18
- Golden data are selected for physics analysis



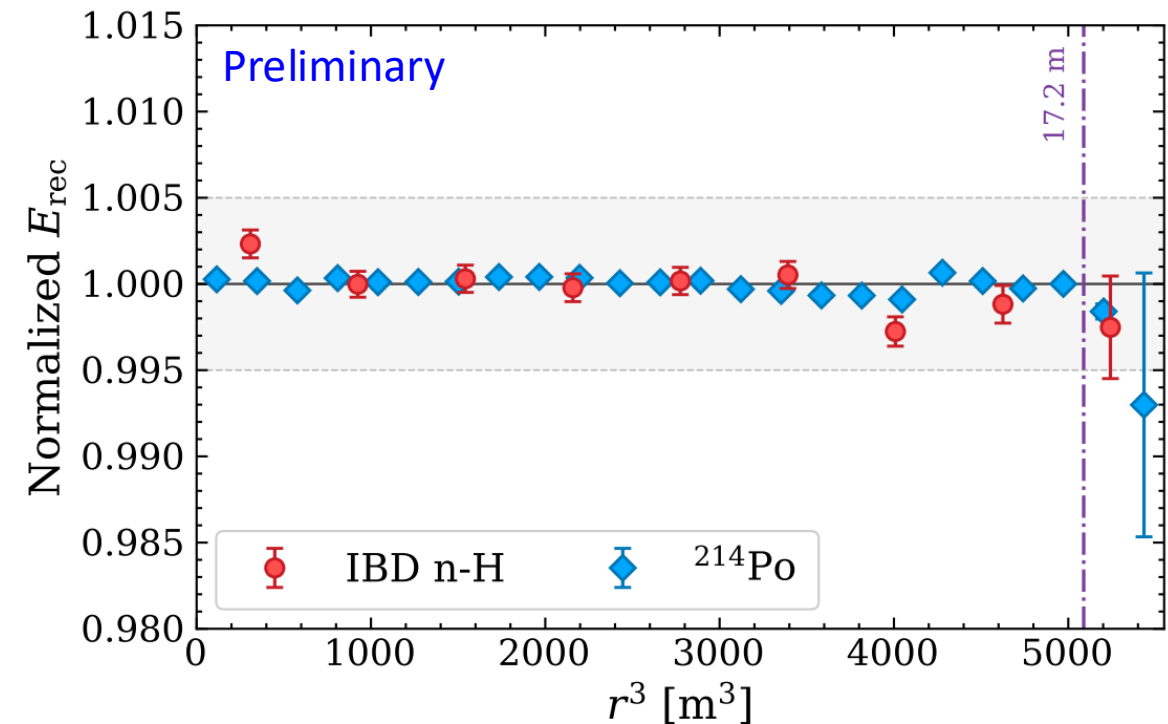
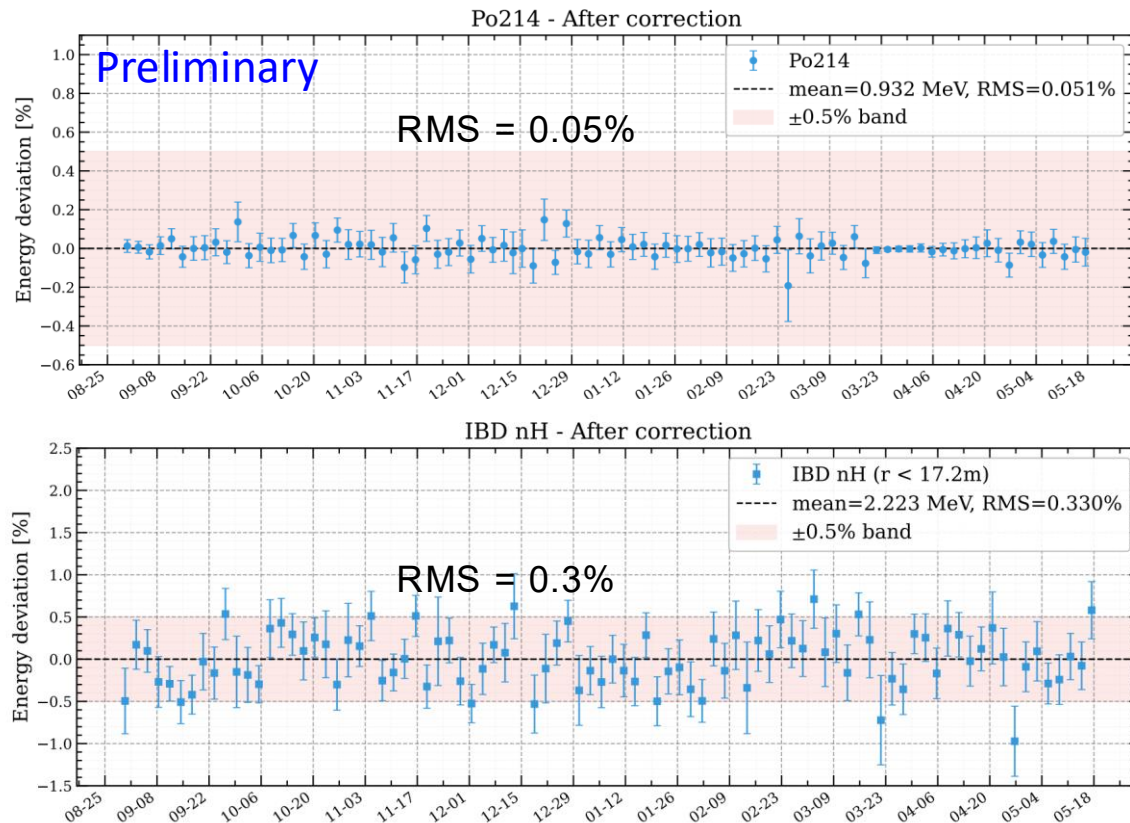
➤ Power outage due to weather is one of the main causes of interruptions

- 1D (central axis): ^{137}Cs , ^{54}Mn , ^{40}K , ^{68}Ge , ^{60}Co , Am-C, Am-Be, sensors, laser
- 2D (cable loop): Am-C, ^{68}Ge , ^{137}Cs
- 3D using cosmogenic backgrounds:
 - ⇒ Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

- Positions at which source calibration performed
- No ^{222}Rn leakage or other contaminations introduced during calibration



- Vertex and energy are determined by maximum likelihood taking into account PMT response, geometry, optical properties, verified by calib. sources
- Other reconstruction methods give similar results
- Time dependent variations corrected by Po214 in the whole volume, check by n-H from IBD
 - Residual r- θ -t dependence ($\sim 1\%$) further corrected by ^{214}Po in the whole volume
 - Energy scale anchored at nH from ^9Li +IBD
 - Final performance checked by IBD nH in $r < 17.2\text{m}$
 - Residual spatial non-uniformity RMS $\sim 0.2\%$
 - Residual time dependent variation RMS $\sim 0.3\%$



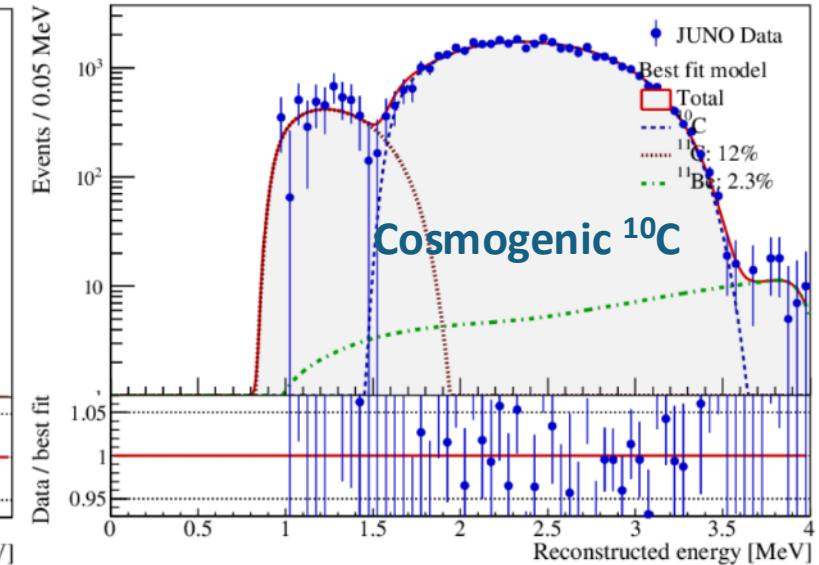
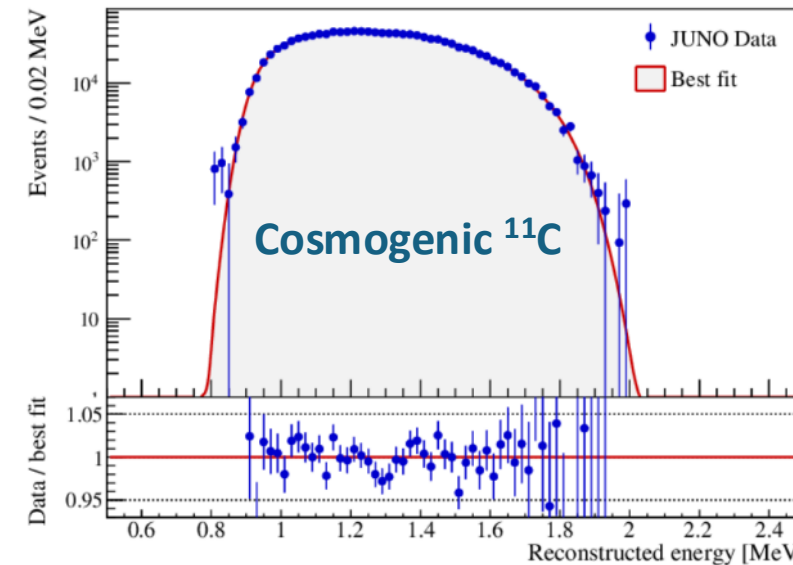
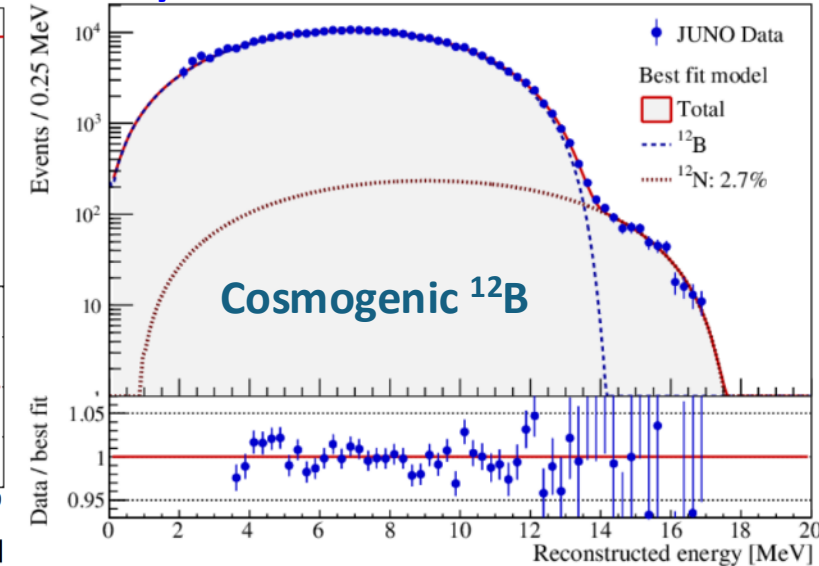
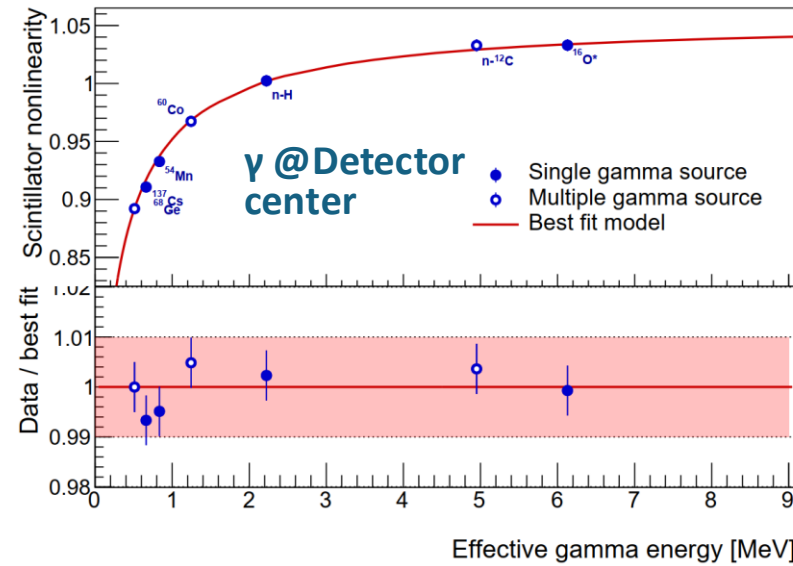
Energy Non-linearity

Yifang's Slide @ v26



- Non-linearities of LS and electronics are determined by calibration sources at the center: ^{68}Ge , ^{137}Cs , ^{54}Mn , ^{40}K , ^{60}Co , Am-C, and Am-Be
- The non-linearity model for e^+ is based on Geant4 and g-sources
- The model is constrained by cosmogenic isotopes, $^{11}\text{C}(e^+)$, $^{10}\text{C}(e^+)$, $^{12}\text{B}(e^-)$, $^8\text{Li}(e^-)$, $^8\text{B}(e^+)$, $^6\text{He}(e^-)$, etc. in the whole volume
- Using sPMTs to correct and constrain LPMT instrumental non-linearity
- **Uncertainty < 1%**

Preliminary

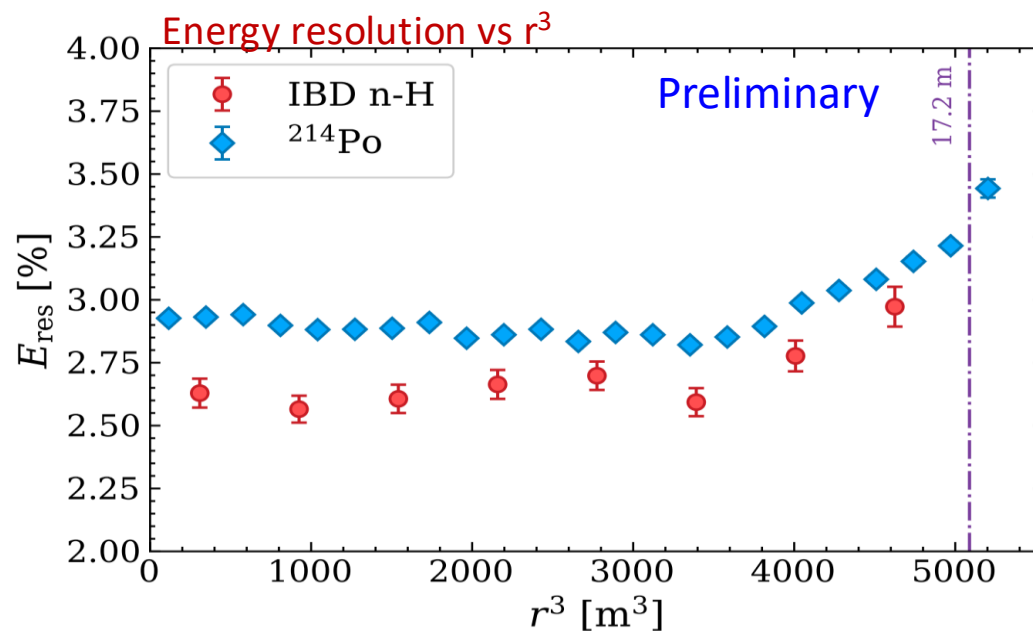
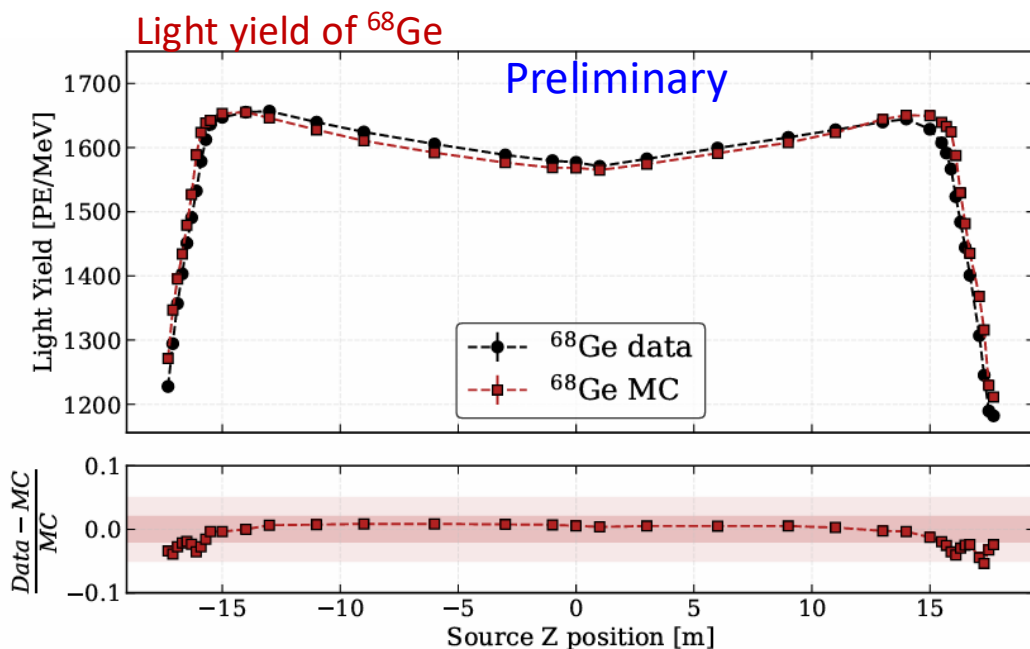
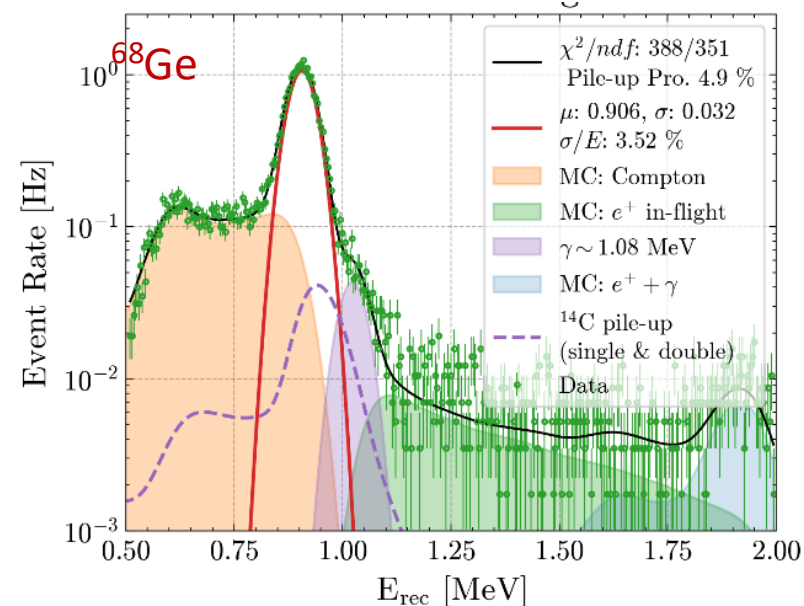


Light Yield and Energy Resolution

Yifang's Slide @ v26



- Light yield at the detector center is ~ 1600 PE/MeV for ^{68}Ge and ~ 1785 PE/MeV for neutrons, in good agreement with MC
- Energy resolution for ^{68}Ge is $\sim 3.5\%$ @ 2×0.511 MeV at the center, slightly worse than the expected 3.1%
 - ⇒ Better MC for Č process, optical boundaries, δ electrons, ...
 - ⇒ Possible improvements: ML to remove ^{14}C , more calibration, better reconstruction and fitting methods, ...
- Energy resolution for alpha from ^{214}Po is $\sim 2.9\%$ @ 0.93MeV

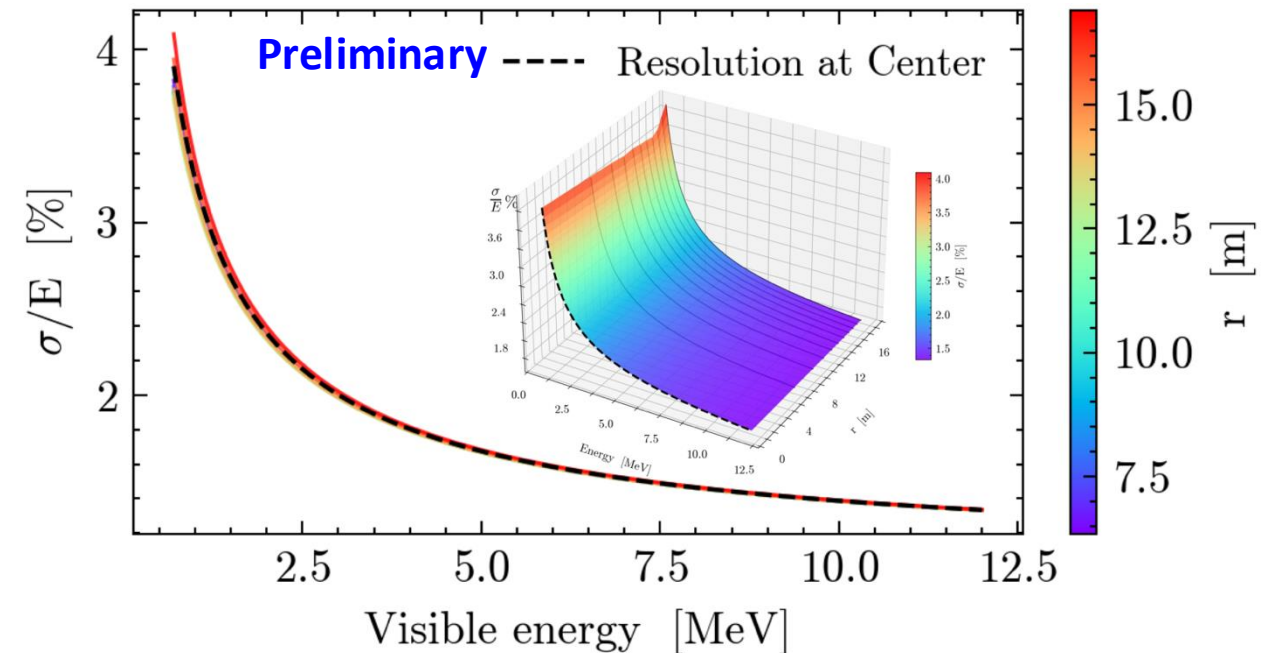
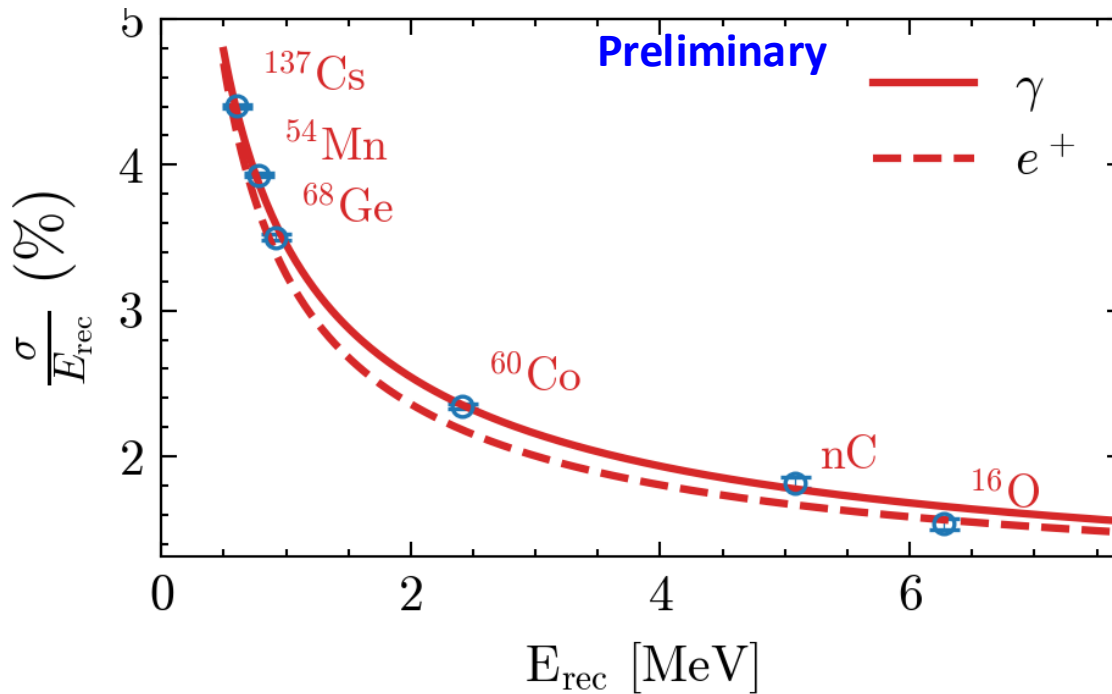


Energy Resolution Model

Yifang's Slide @ v26



- Energy resolution is particle type, energy and space dependent
- An analytical R-dependent resolution model for e^+ was built using Geant4 simulation and data from calibration sources (α , γ)
- An energy response matrix was then used for e^+ spectrum fitting after adding ^{14}C pile-up to 5% events



Reactor Neutrino Selection

Yifang's Slide @ v'26

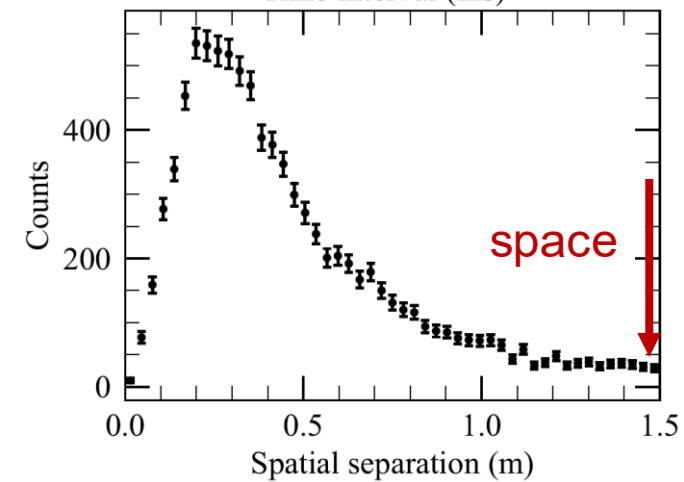
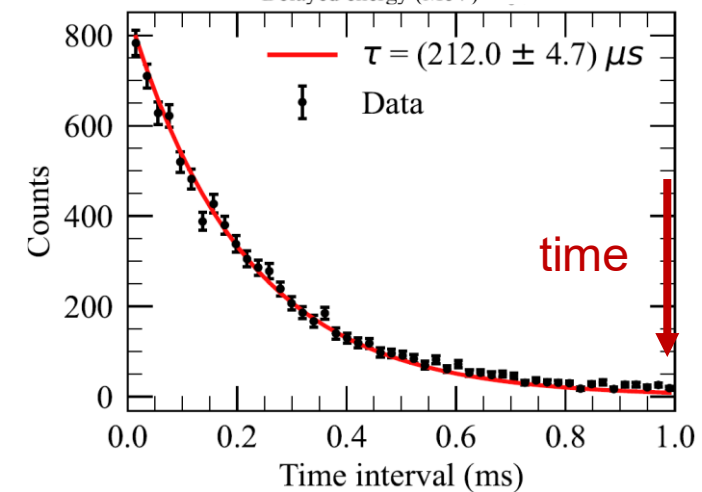
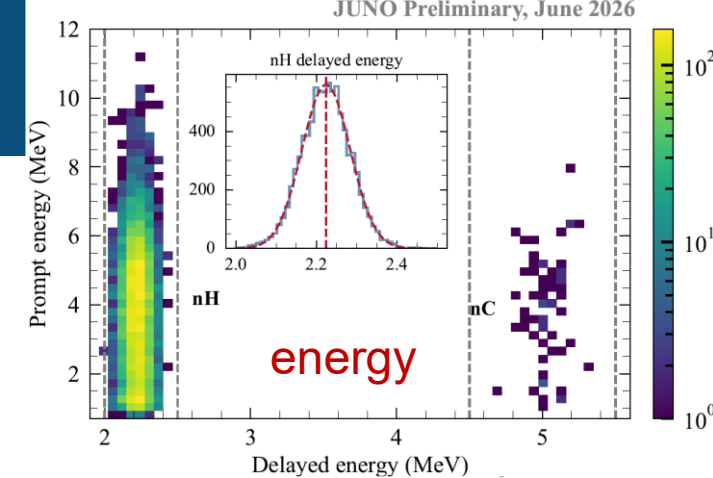
- Prompt and delayed coincidence in **time**, **space** with **energy** features

Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2$ m, $ z_p < 15.5$ m
Prompt energy	(0.7, 12) MeV
Delayed energy	$(2.0, 2.5) \cup (4.5, 5.5)$ MeV
Coincidence time	(5, 1000) μ s
Relative distance	< 1.5 m
Multiplicity cut	No other events > 0.7 MeV in the FV or (2.0, 6.0) MeV outside the FV within 2 ms before and 1 ms after the delayed event
Water pool muon veto	Veto if the delayed is within (0, 2) ms after NPE > 700 in WP
CD muon veto	Veto if the delayed is within (0, 5) ms after NPE $> 3 \times 10^4$ in CD
Spallation neutron veto	Veto if the delayed satisfies $\Delta r < 4$ m and $\Delta t < 1.2$ s after spallation neutrons with $NPE_{\text{spn}} \in (3000, 30000)$ and $T_{\text{spn}2\mu} \in (20, 2000)$ μ s
Muon track veto	Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5\text{m}} + \frac{\Delta t_{\mu d}}{0.5\text{s}} < 1$
Correlated discriminator	$\log(\text{L.R.}) > -1.26$

Similar to our
“Nature” paper

- What is new in this analysis:

- ~10% more fiducial volume (R=16.5m→17.2m)
- ~60% reduction of ^9Li bkg.
- a factor of 50 reduction of accidental bkg. using likelihood cut
- model independent estimate of the ^{214}Bi bkg.

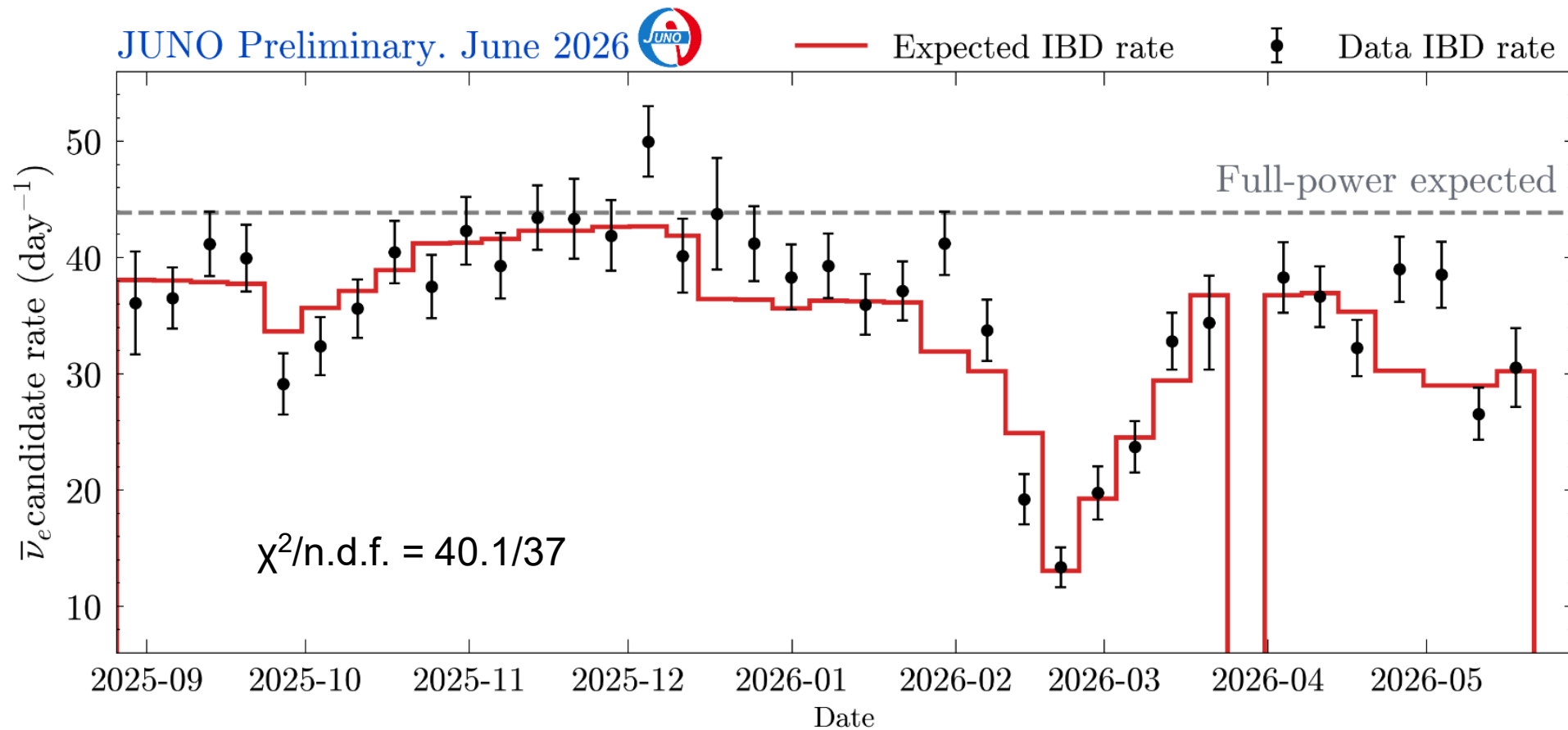


Reactor Neutrino Event Rate versus Time

Yifang's Slide @ $\nu 26$

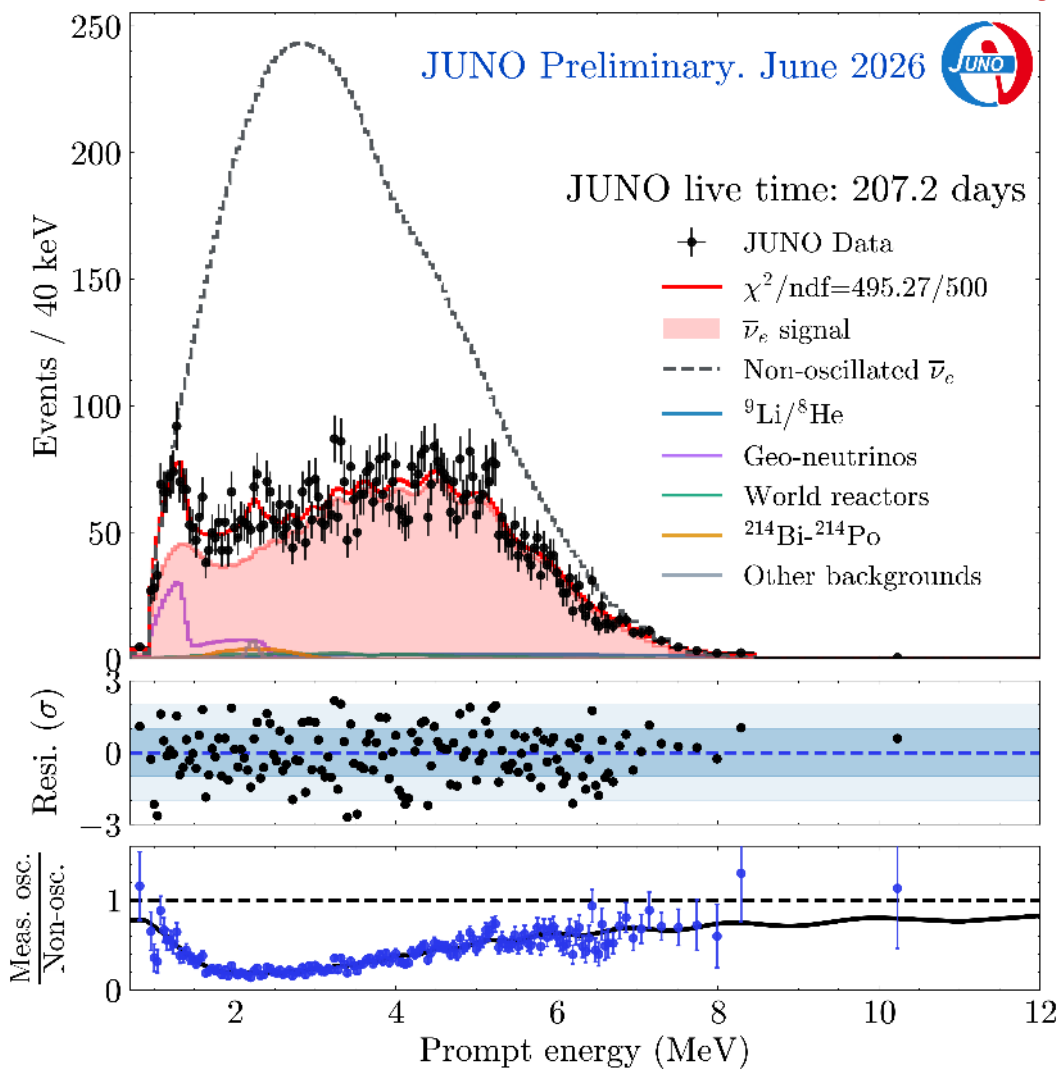


- Measured reactor neutrino event rate consistent with expectation
- Total live time is 207.2 days



Measured Reactor Neutrino Spectrum

Yifang's Slide @ $\nu 26$



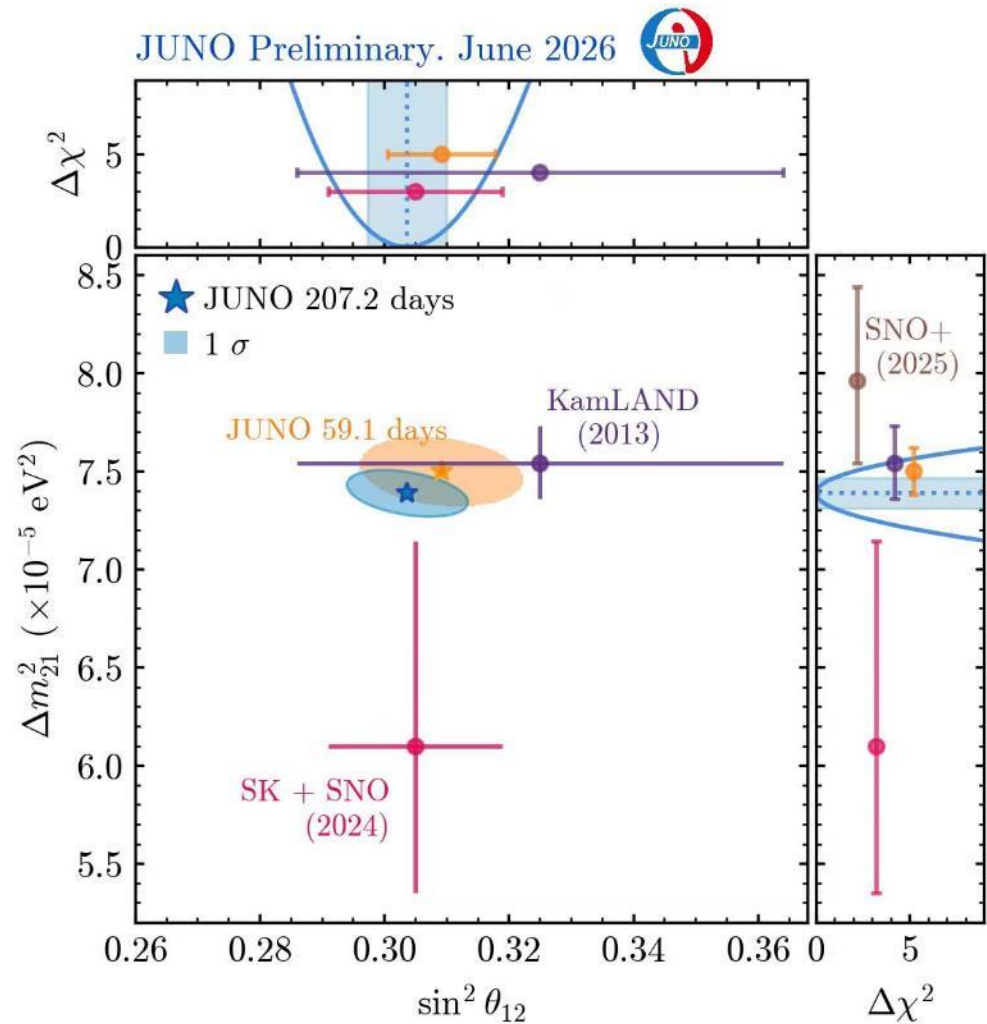
Fitting constrained
by the near detector
spectra from TAO
(talk by Yichen) and
Daya Bay (PRL
130 16, 161802)

Consistent results from three independent analyses

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ϵ	σ_{rel}
Fiducial volume	87.12%	0.96%
PMT flasher rejection	$> 99.9\%$	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency (ϵ_{tot})	74.01%	1.02%
$\bar{\nu}_e$ signal (cpd)		
w/o ϵ_{tot} corrected	36.02 ± 0.62	
w/ ϵ_{tot} corrected	48.67 ± 1.08	
Backgrounds (cpd)	Pre-fit	Best-fit
${}^9\text{Li}/{}^8\text{He}$	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 ± 0.09	0.92 ± 0.09
${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$	0.42 ± 0.31	0.57 ± 0.34
${}^{13}\text{C}(\alpha, \text{n}){}^{16}\text{O}$	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01

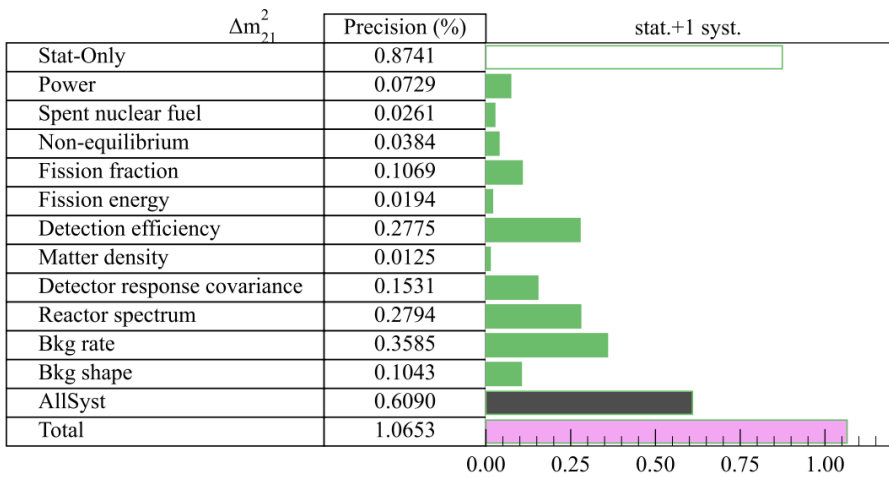
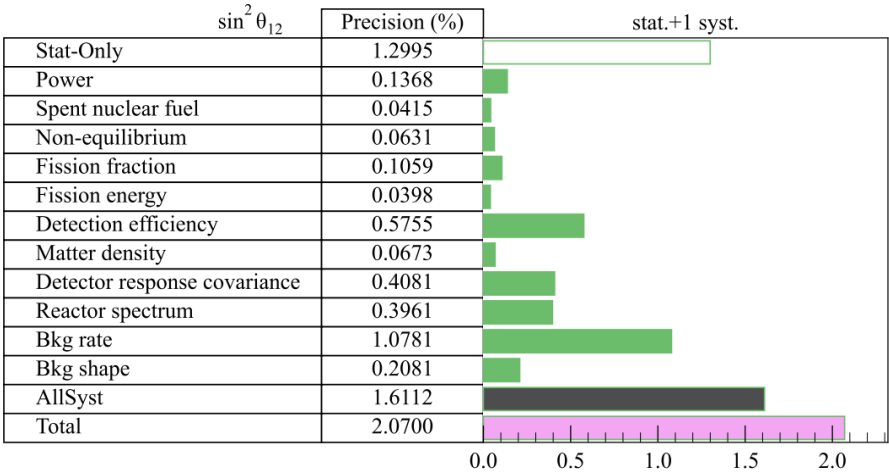
New Results of Solar Oscillation Parameters

Yifang's Slide @ V26



Δm^2_{21}	7.388 ± 0.078 (1.60% $\rightarrow$ 1.06%)
$\sin^2 \theta_{12}$	0.3036 ± 0.0064 (2.8% $\rightarrow$ 2.1%)

- Even though the statistical uncertainty is dominant, systematic errors become important:
 $\Rightarrow$ ^{214}Bi bkg. and detection eff. can be improved

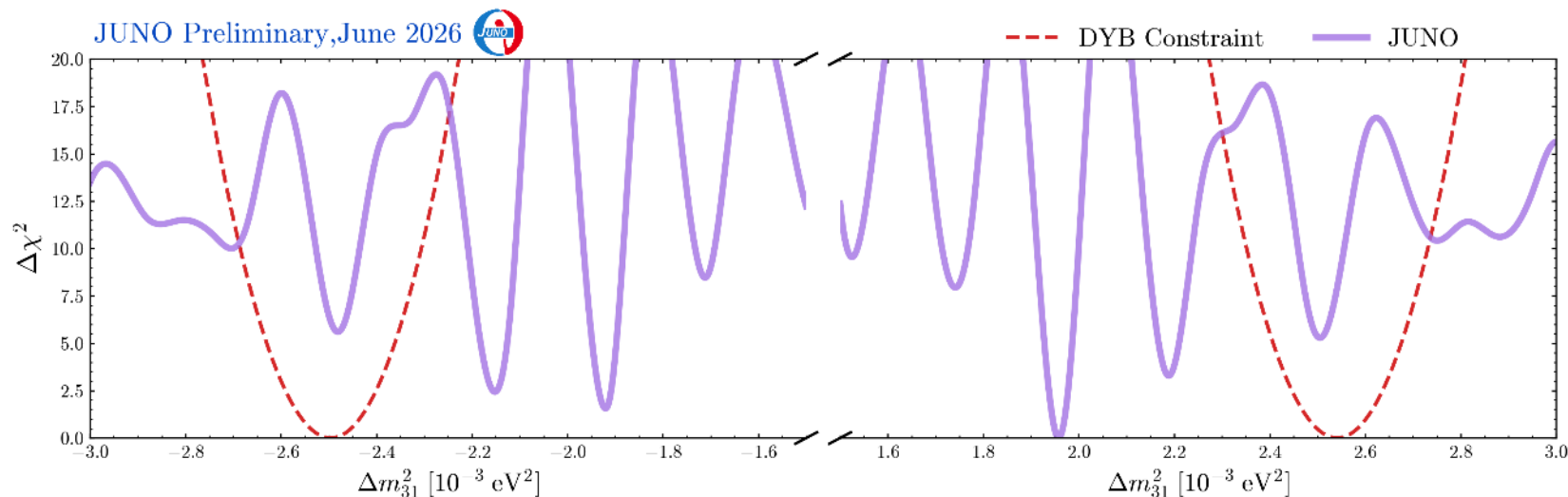


First Result of Δm_{31}^2

Yifang's Slide @ $\nu 26$

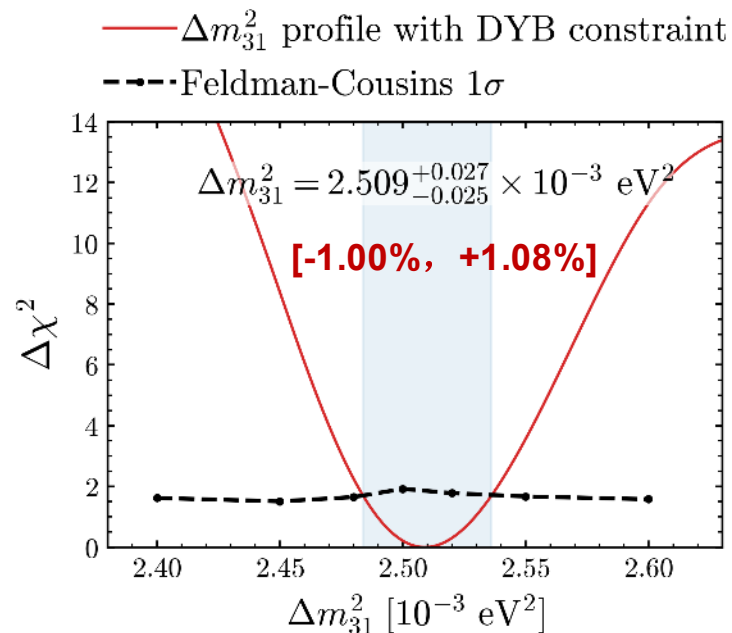
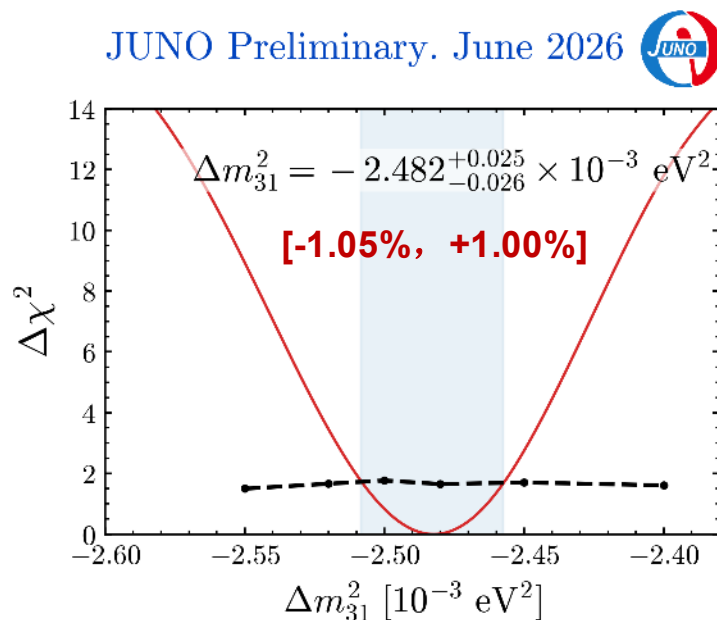


- Due to statistical fluctuations, JUNO only profiles of Δm_{31}^2 have multiple minima

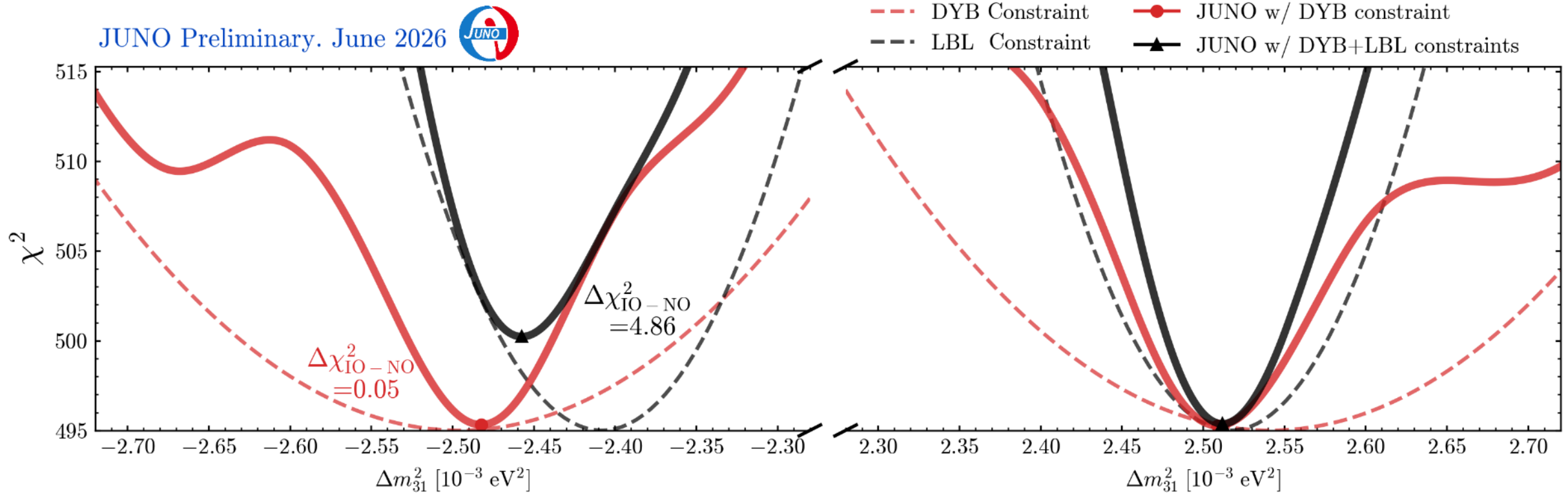


The final minimum for each mass ordering is obtained by using the Δm_{31}^2 constraint from the Daya Bay result (PRL 130 16, 161802)

Feldman-Cousins (FC) method is used to determine the 1σ range of Δm_{31}^2 :
~1% precision achieved



- ◆ Δm_{31}^2 from reactor and accelerator neutrinos should align at the right mass ordering[1]
- ◆ Adopt the NuFit-LBL results from [2]: normal mass ordering is favored at $\Delta\chi^2 = 4.86$



[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

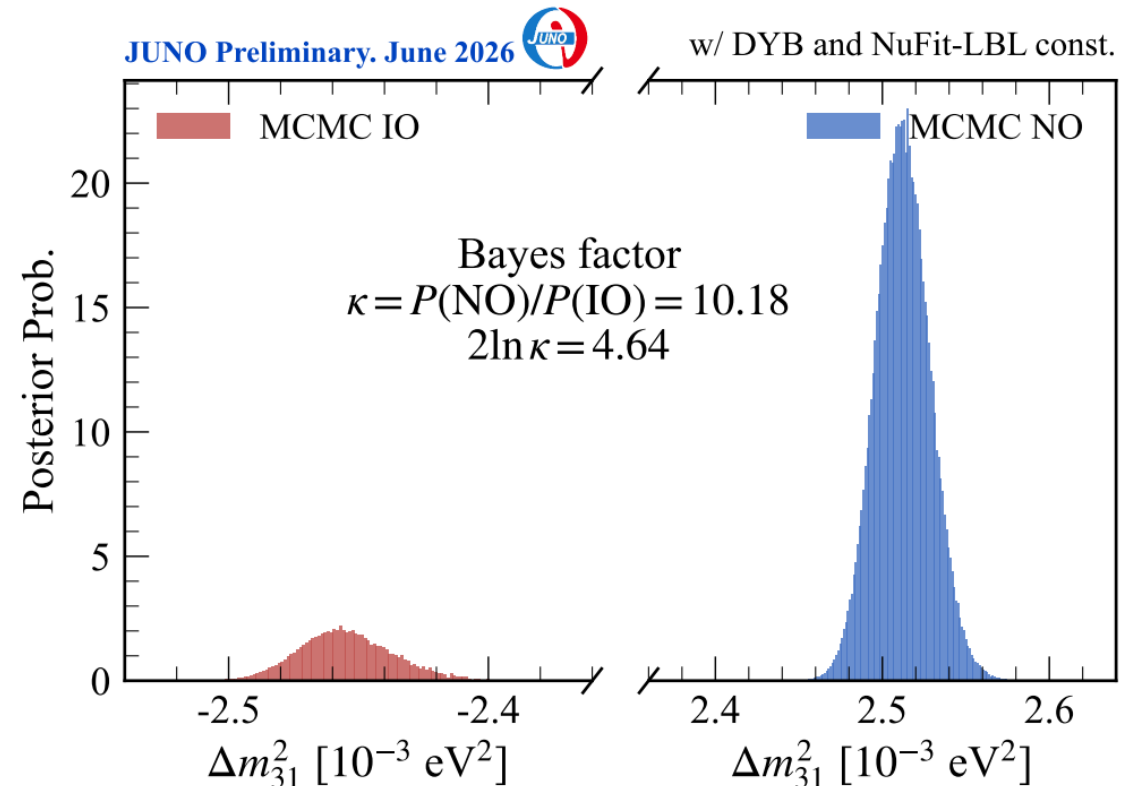
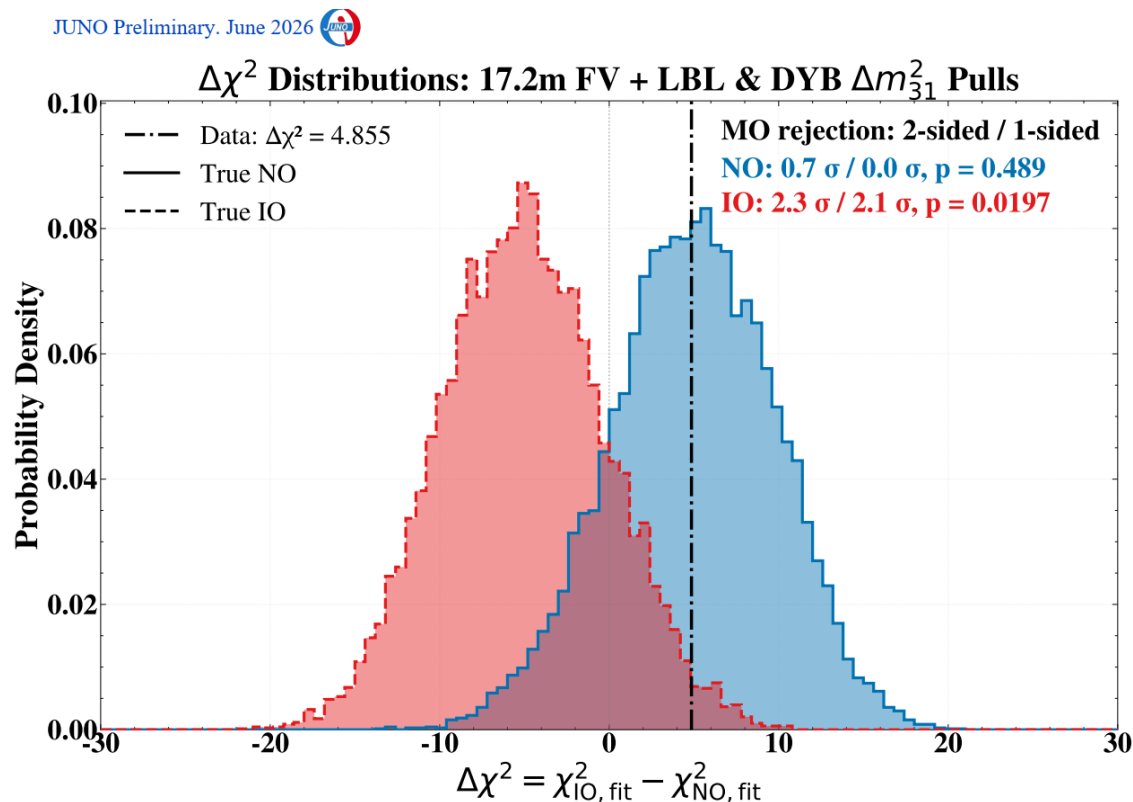
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Neutrino Mass Ordering Significance

Yifang's Slide @ $\nu 26$

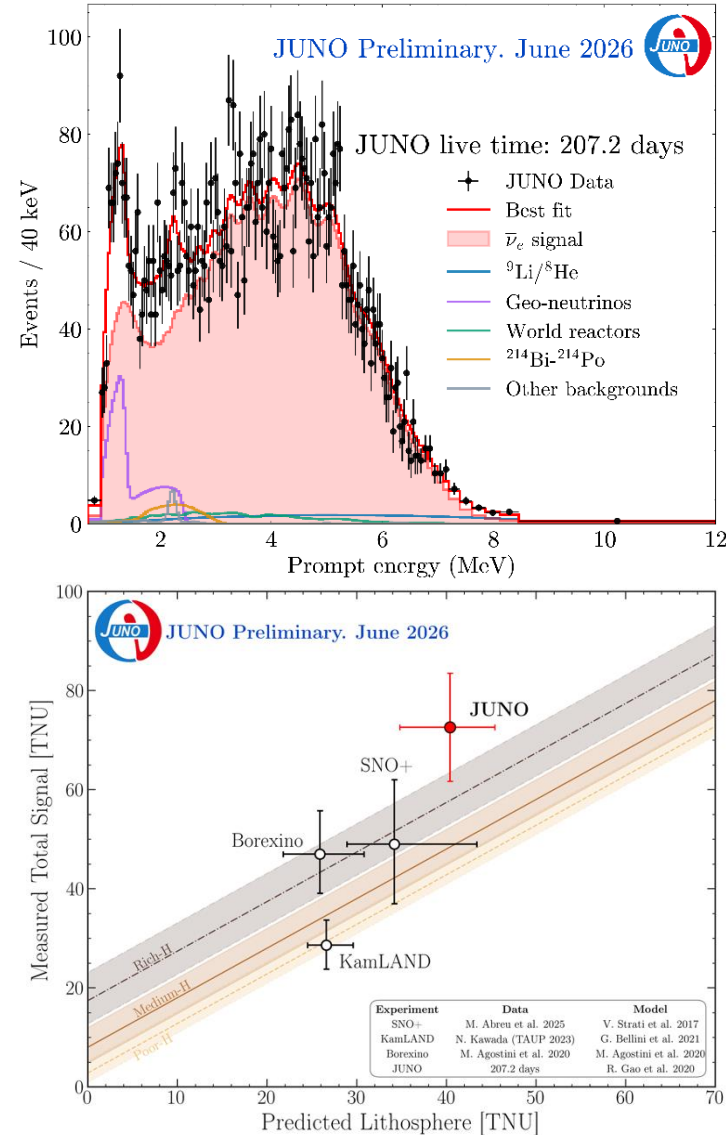


- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
 - Influence of δ_{CP} considered (scanned)
 - Normal Ordering is favored at **2.3 σ**
- Bayesian approach using Markov Chain Monte Carlo(MCMC) method
 - Normal Ordering is favored with a Bayes factor of **10.18** $\rightarrow 2\ln \kappa = 4.64$
- $\Rightarrow$ Consistent with the frequentist $\Delta\chi^2$



Results on Geo-neutrinos

- Fits are performed w/o constraint on geo-neutrino flux, but with $3.4(\pm 10\%)$ U/Th ratio
- Clear geo-nu signals at 1-3 MeV, giving a flux of 73 ± 11 TNU (the largest and most precise)
- JUNO result is higher than expectation from existing models, but not statistically significant;
- Need more JUNO data and more refined geological model predictions



NG2026

Neutrino Geoscience 2026

NEUTRINO PHYSICS / EARTH INTERIOR / GEOSCIENCE

FALL SCHOOL NOV 11-14

WORKSHOP NOV 16-19

Fall School on neutrino geoscience

Neutrino Geoscience Workshop 2026

ZHUHAI, CHINA

Sun Yat-sen University, Zhuhai Campus

ORGANIZERS

The Institute of High Energy Physics (IHEP)
China University of Geosciences, Beijing (CUGB)
North China Electric Power University (NCEPU)
Sun Yat-sen University (SYSU)

CONTACT nugeoscience@mail.sysu.edu.cn

WEBSITE <https://icen.sysu.edu.cn/nu-geoscience2026/>

REGISTER <https://indico.ihep.ac.cn/event/28857/>

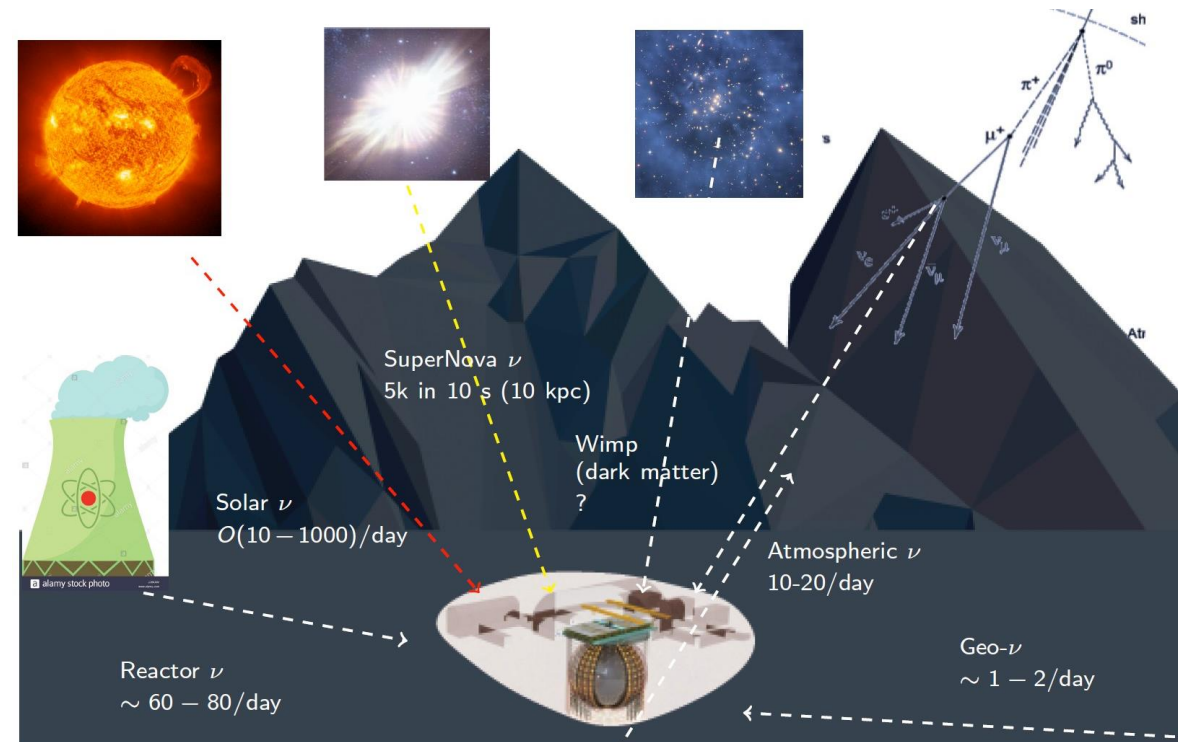
Scan to join us!




Summary --- *This is Just the Beginning!*

- The JUNO detector and TAO are successfully built and operating smoothly
- Initial performance shows that the detector works well as designed
- Solar oscillation parameters further improved by a factor of 1.3-1.5
- First measurement on Δm^2_{31} , a precision of $\sim 1\%$
- With external constraint, **Normal Mass Ordering** is favored at $\sim 2.3\sigma$

NOTE: Many physics results not covered

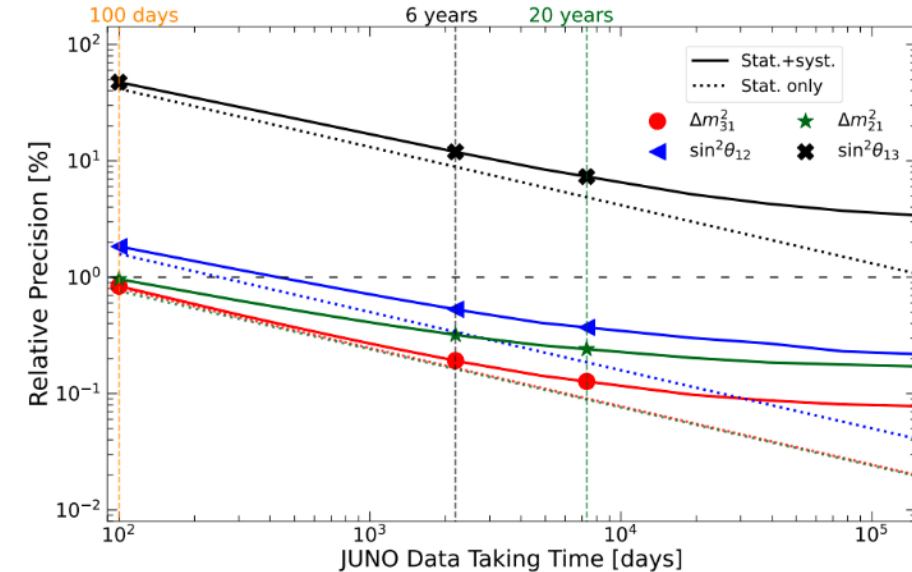
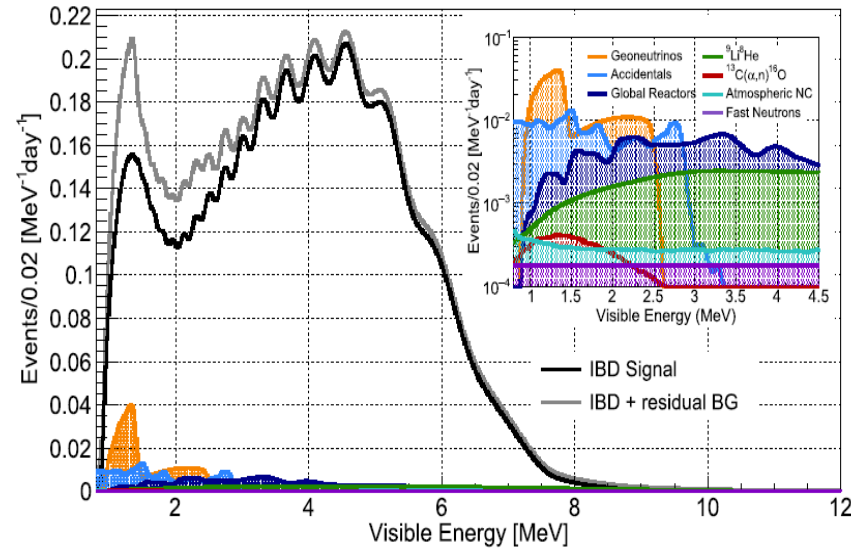
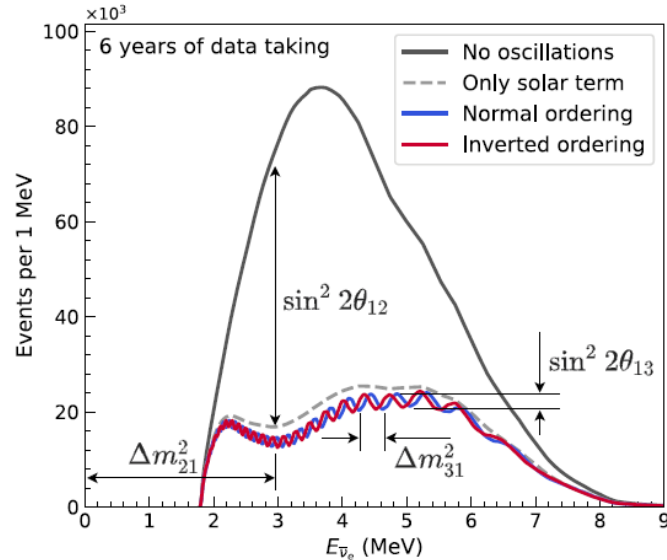


Future Prospects in Precision Measurements



$\sin^2 2\theta_{12}$, Δm_{21}^2 , $|\Delta m_{32}^2|$, leading measurements in 100 days; precision <0.5% in 6 years

Chin. Phys. C46 (2022) 12, 123001

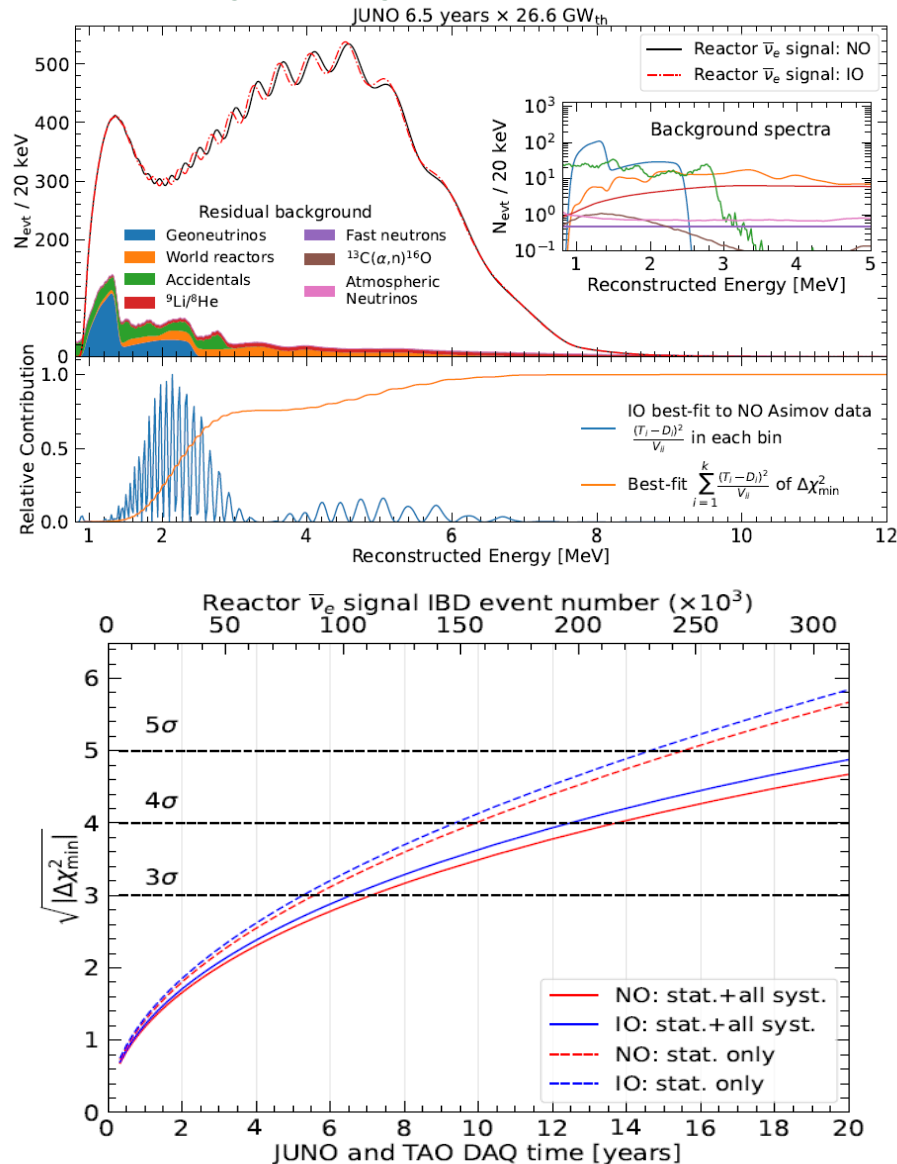


	Central Value	PDG2020	100 days	6 years	20 years
Δm_{31}^2 ($\times 10^{-3}$ eV ²)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm_{21}^2 ($\times 10^{-5}$ eV ²)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2 \theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 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%)

Future Prospects in Mass Ordering Sensitivity



Sensitivity mostly from 1.5-3 MeV

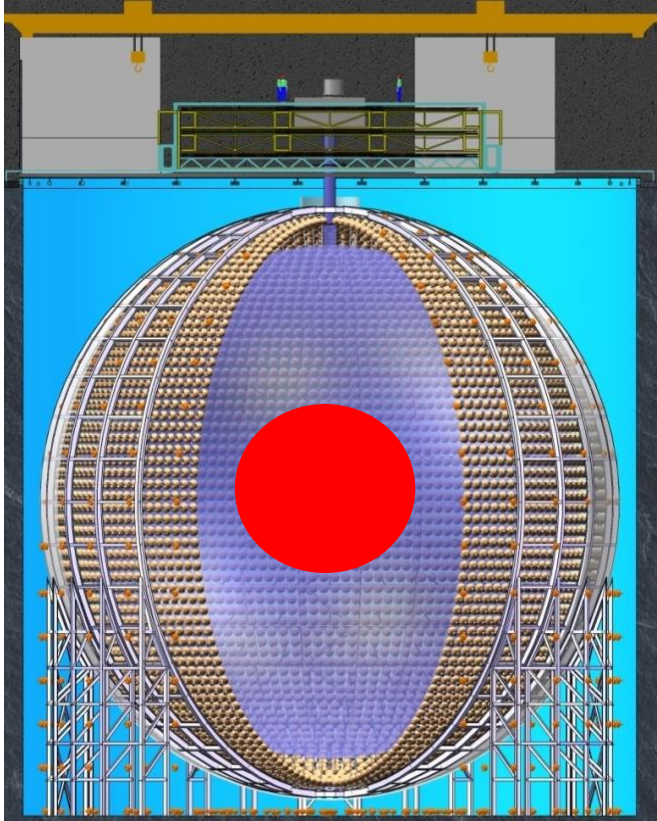


	Design	Now
Thermal Power	36 GW _{th}	26.6 GW _{th} (26%↓)
Signal rate	60 /day	47.1 /day (22%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (2%↑)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. Exposure	<6 yrs $\times$ 35.8 GW_{th}	~6 yrs $\times$ 26.6 GW_{th}

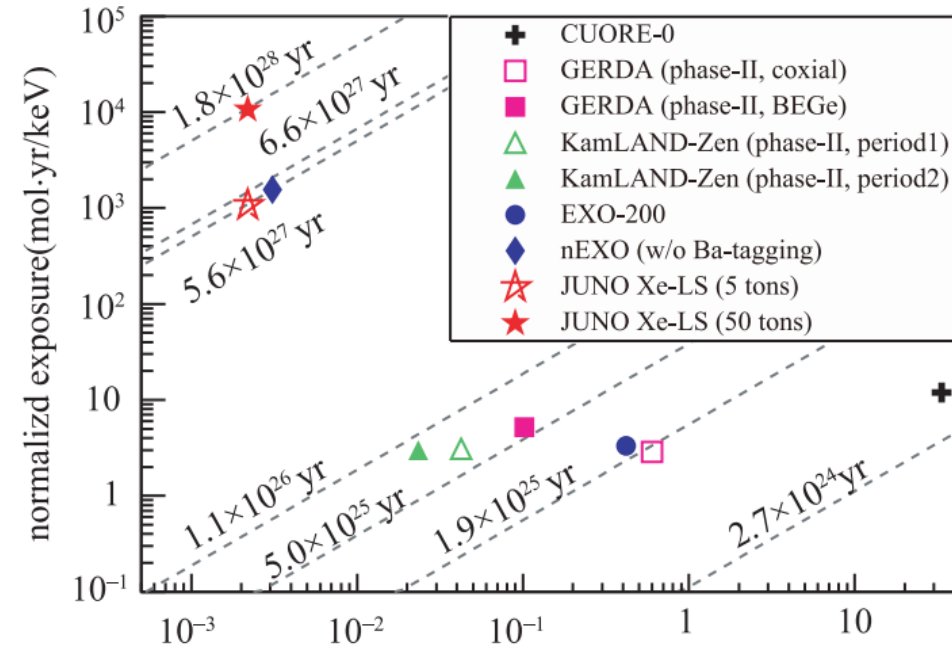
- ◆ JUNO NMO median sensitivity:
3 σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure
- ◆ Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity

arXiv:2405.18008 (2024)

JUNO Future: JUNO- $\beta\beta$



Insert a balloon/Directly filled with ^{136}Xe -loaded LS(or ^{130}Te) into the JUNO detector



- Once mass ordering is determined (~ 2030), JUNO will be upgraded for $\beta\beta$ -decays, in addition to existing capabilities;
- $^{130}\text{Te}/^{136}\text{Xe}$ will be loaded into the LS;
- R&D about the Te/Xe-LS is undergoing

Cracks on the Acrylic Tank

- A LS leak to water on Mar 21, 2025:
 - ✓ Abnormal trigger rate observed and confirmed by under water robot;
 - ✓ Leak was stopped within 1 week using epoxy and tape by divers;
 - ✓ Further repair by epoxy and acrylic plate to reduce the stress (pulling open the crack) by 50%
- A water leak to LS on Mar 19, 2026:
 - ✓ Experienced divers were stopped the leak within 2 days;
 - ✓ Further repair in the following two days ;
 - ✓ A total of $\sim 1\text{Bq } ^{222}\text{Rn}$ went into LS, 13 days of data loss;
 - ✓ No other increase of radioactive backgrounds in LS



❖ **Main structure is safe, stress within expectations**

PMT Characterization, Potting and Assembly in a Warehouse



Unloading PMTs



Shelves



Visual check station



Checking



Container systems



Container inside



Scanning stations



Rotating frame



Potting station

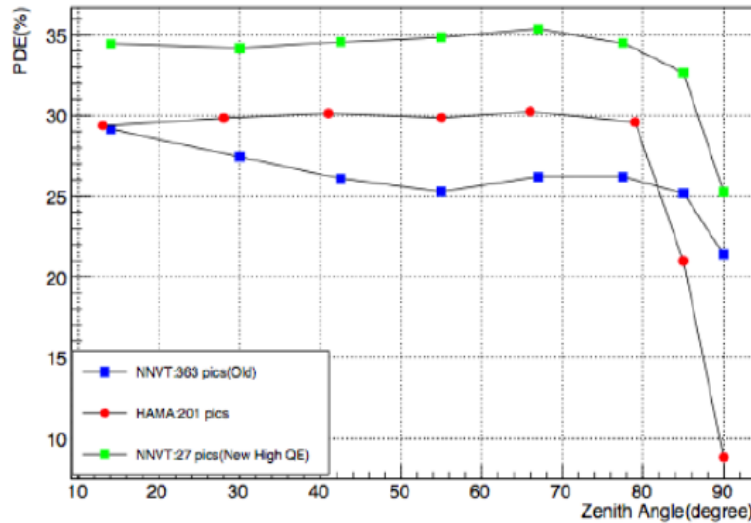


Butyl tape wrapping

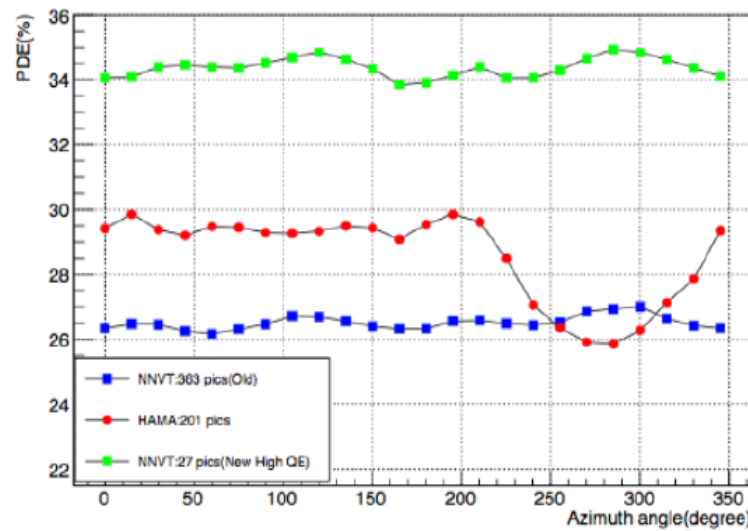
Characterizing/Testing Every Single PMT with Great Care



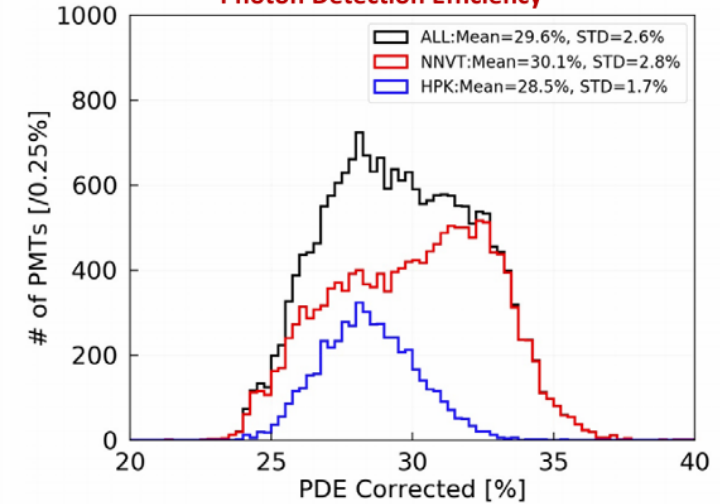
PDE VS Zenith Angle



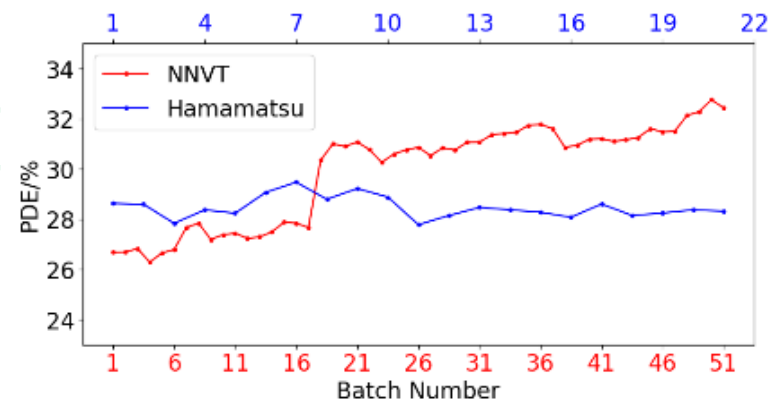
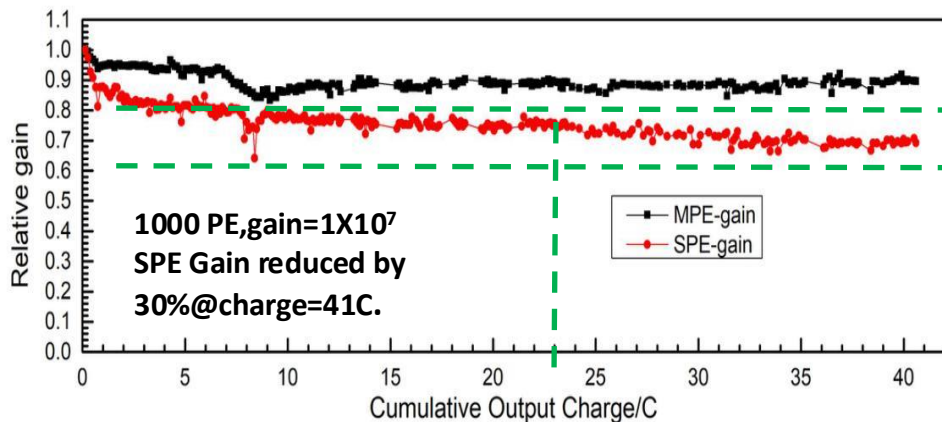
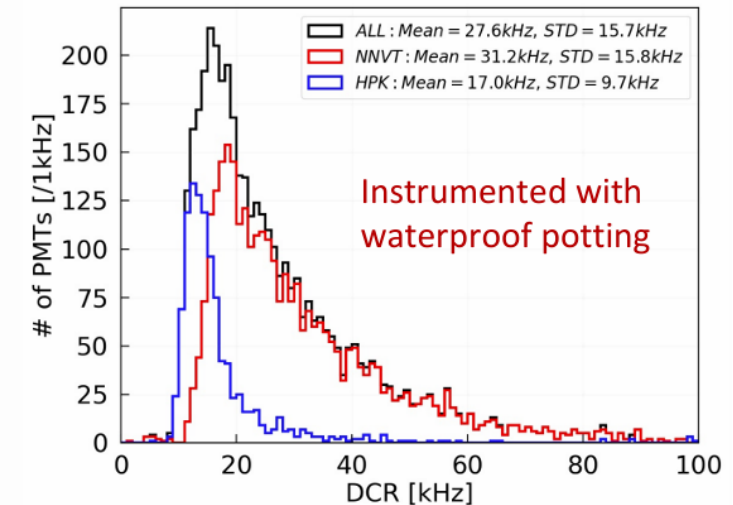
PDE VS Azimuth angle



Photon Detection Efficiency



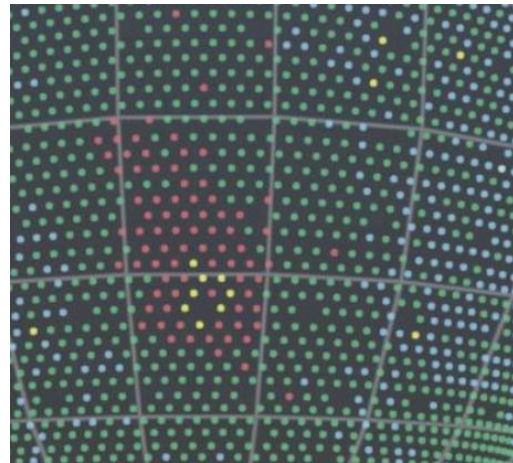
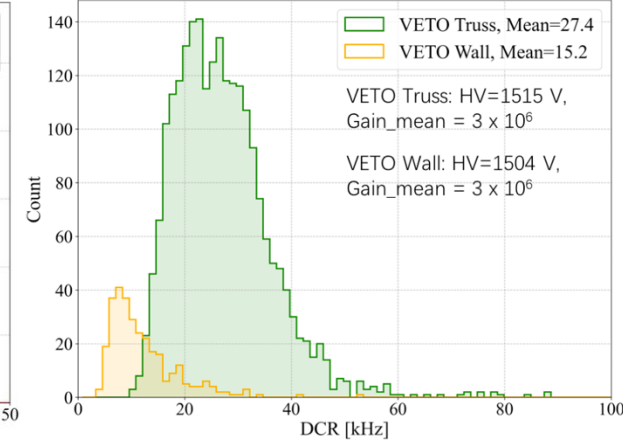
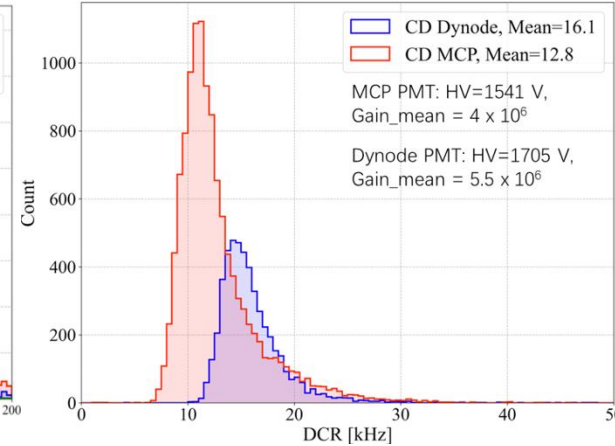
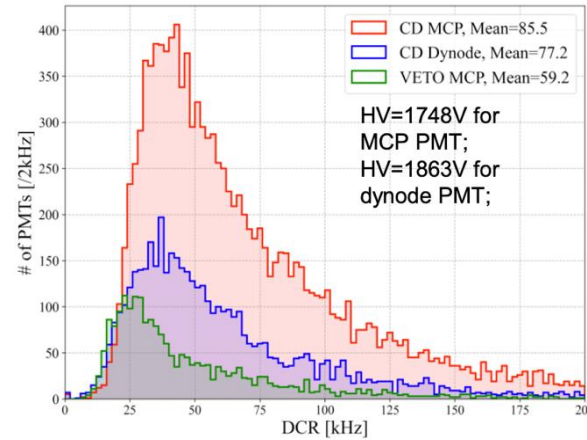
Dark Counting Rate



Operation Status since Detector Filling and Operation



- PMT DCR gradually decreased; DCR of MCP PMTs in CD is now ~13 kHz (acceptance test: 31 kHz); DCR of dynode PMT is ~16 kHz
- ~40 channels (PMTs + electronics) dead since water filling (Dec, 2024)
- Extensive efforts have been done to mitigate PMT flashing, including HV reduction, periodic PMT restarts, and automatic shutdown of PMTs with high DCRs, ~600 PMTs
- Fluctuations of DCR due to HV, T and light conditions observed



A Flashing Event

