From Daya Bay to JUNO: a brief review

王为 (Wei Wang)

School of Physics &

Sino-French Institute of Nuclear Engineering & Technology

中山大学 (Sun Yat-sen University)

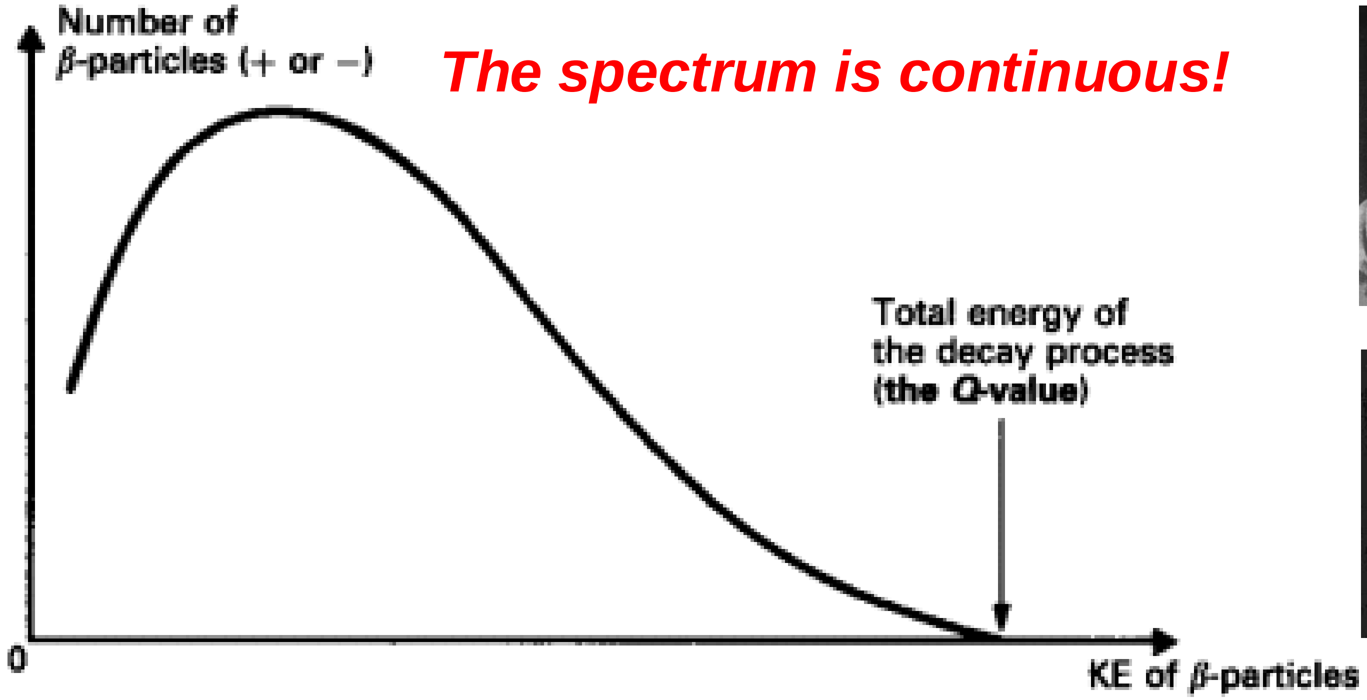
Seminar @ Kings College London, Apr 4, 2025

SYSU has 5 Campuses in 3 Major Cities
School of Physics is on the South Campus in Guangzhou
IFCEN is on the Zhuhai Campus

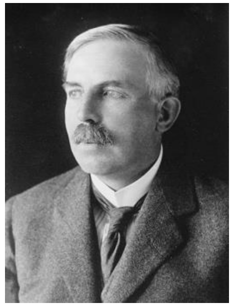
Outline

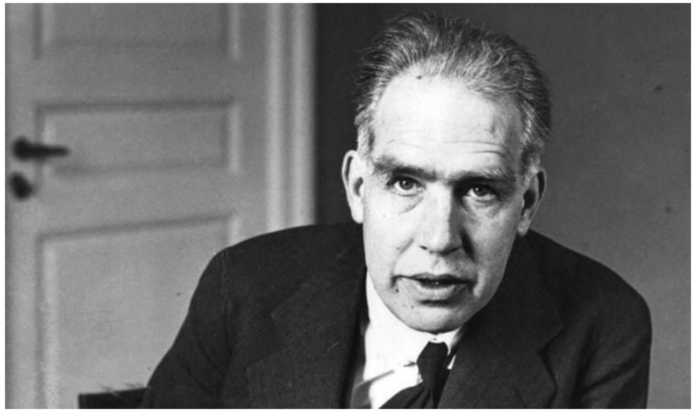
- Introduction of Neutrino and Discovery of Neutrino Oscillation
- Daya Bay Reactor Neutrino Experiment (brief)
- Jiangmen Underground Neutrino Observatory
- Summary and Future Perspectives

The "Crisis" of the beta-Spectrum in 1920s



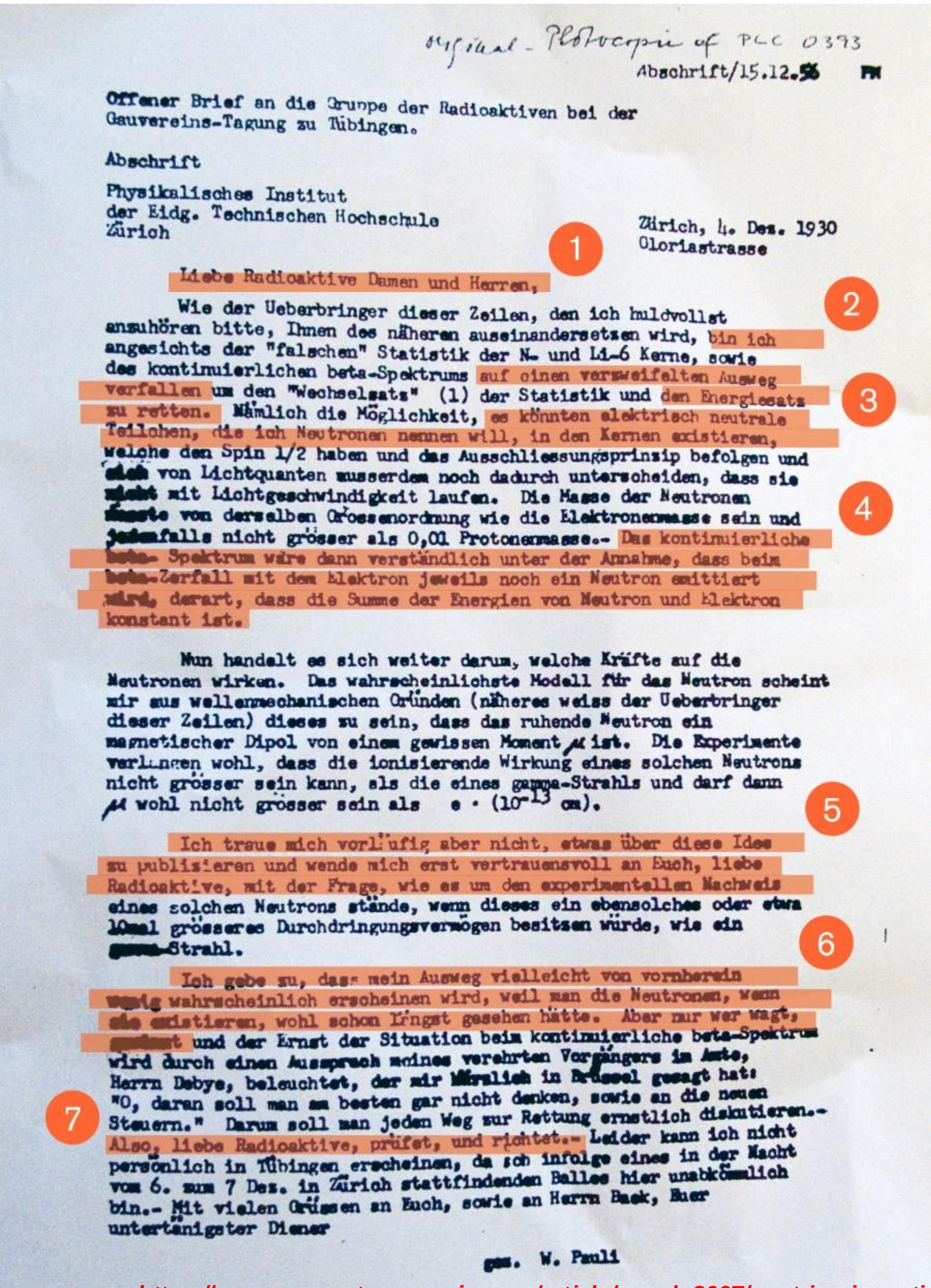
The spectrum is continuous!





- Bohr: "The energy in microworld was conserved not on an event-by-event basis, only on average"

- Pauli thought of another idea ……


original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

https://www.symmetrymagazine.org/article/march-2007/neutrino-invention

① Dear Radioactive Ladies and Gentlemen!

② I have hit upon a desperate remedy to save…the law of conservation of energy.

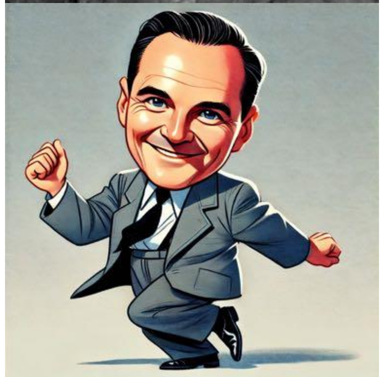
③ …there could exist electrically neutral particles, which I will call neutrons, in the nuclei…

④ The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, **a *neutron* is emitted such that the sum of the energies of *neutron* and electron is constant**

⑤ But so far **I do not dare to publish anything about this idea**, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron…

⑥ I admit that my remedy may seem almost improbable **because one probably would have seen those *neutrons*, if they exist, for a long time**. But nothing ventured, nothing gained…

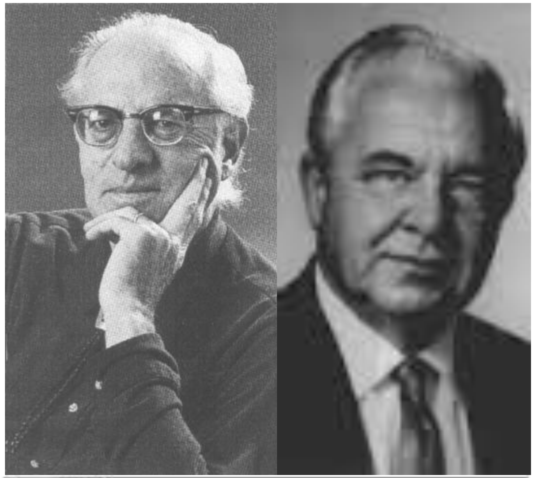
⑦ Thus, dear radioactive ones, scrutinize and judge.

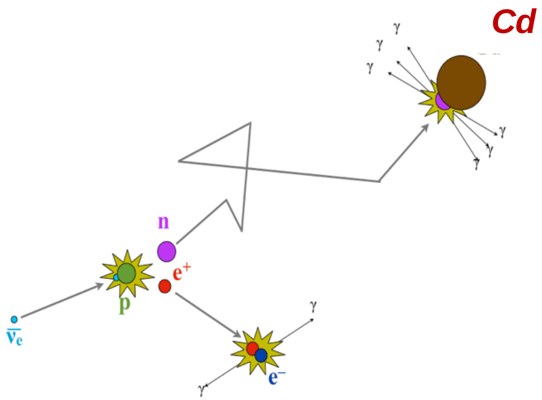


"I have done a terrible thing, I have postulated a particle that cannot be detected."

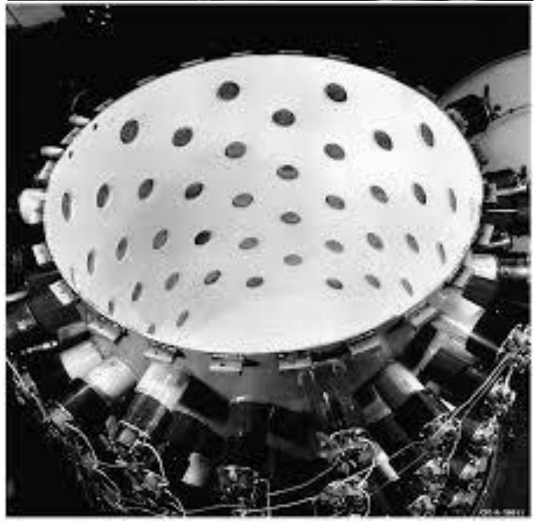
From Reines&Cowan in 1956 to Daya Bay in Earlier 2000’s

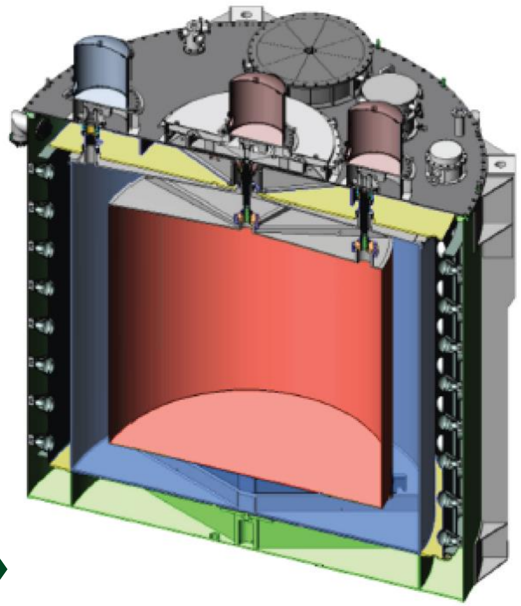
- Cowan and Reines at the Savannah River Power Plant (1956-1959)

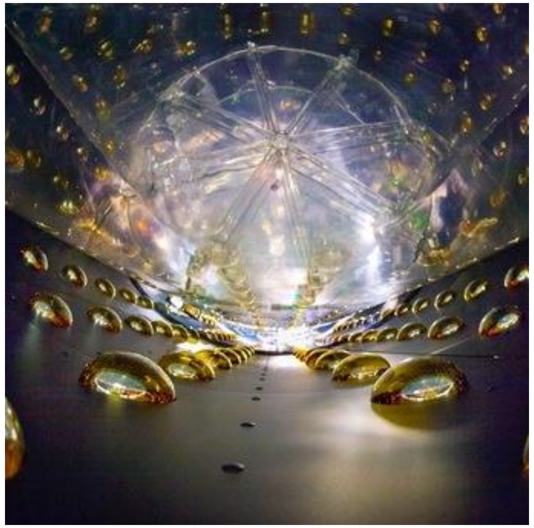




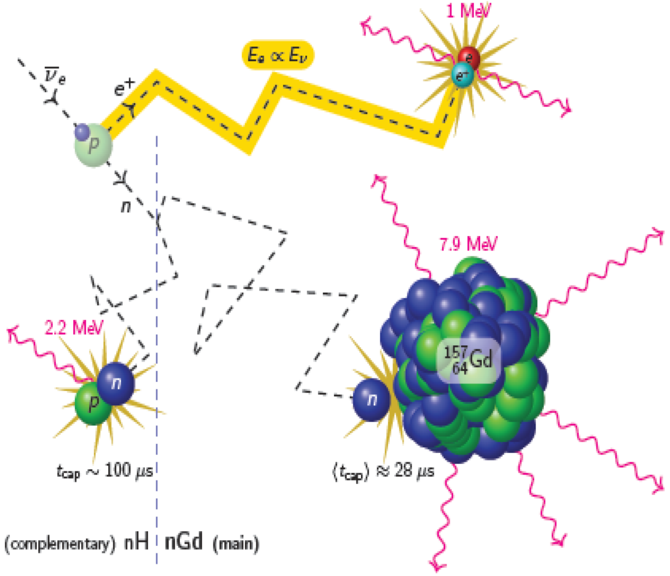
$$p+ v \longrightarrow e^{+} + n$$





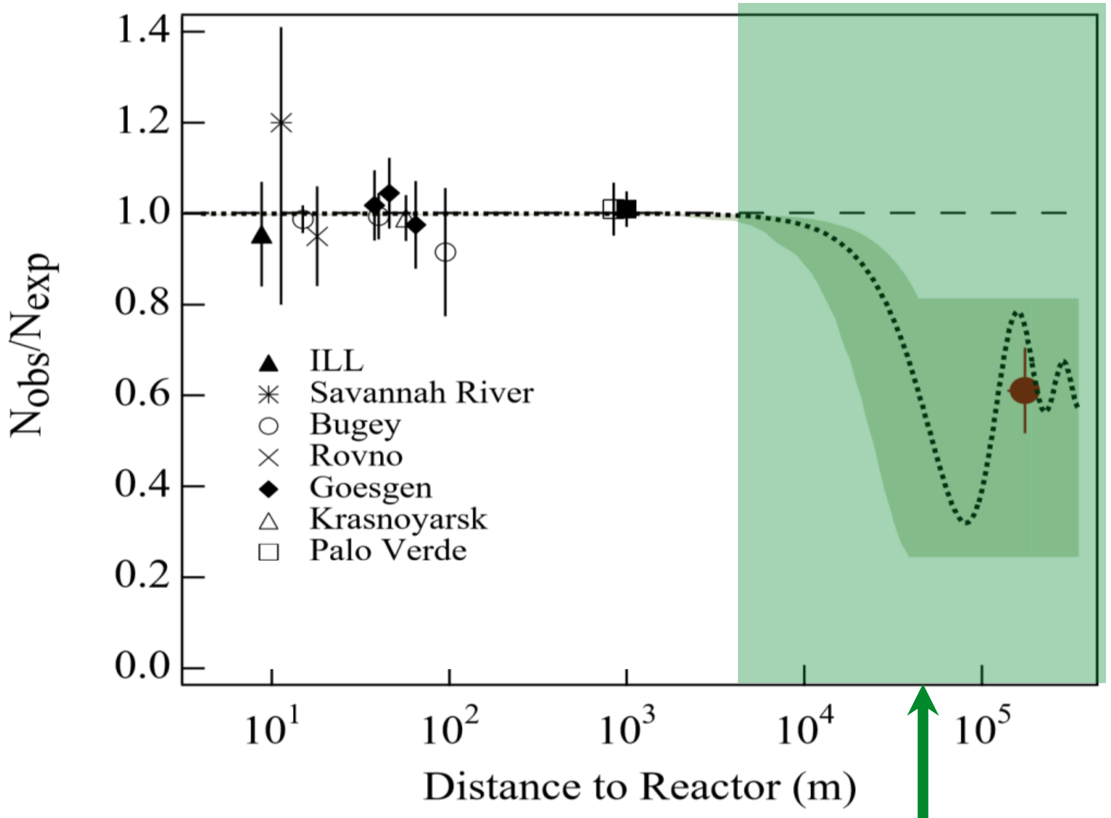


3-zone antineutrino detector (AD):		
Inner zone	20 t	Gd-doped LS
Middle zone	20 t	LS
Outer zone	40 t	Mineral oil



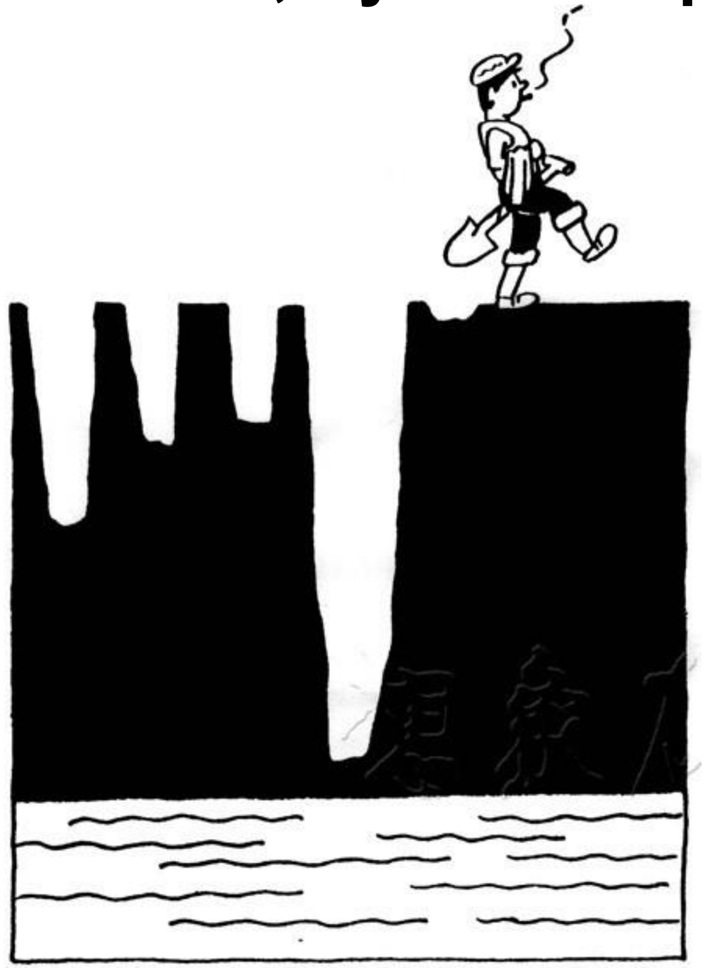
- Correlation is a VERY powerful tool!

One Page History of Discovering Reactor Neutrino Oscillation



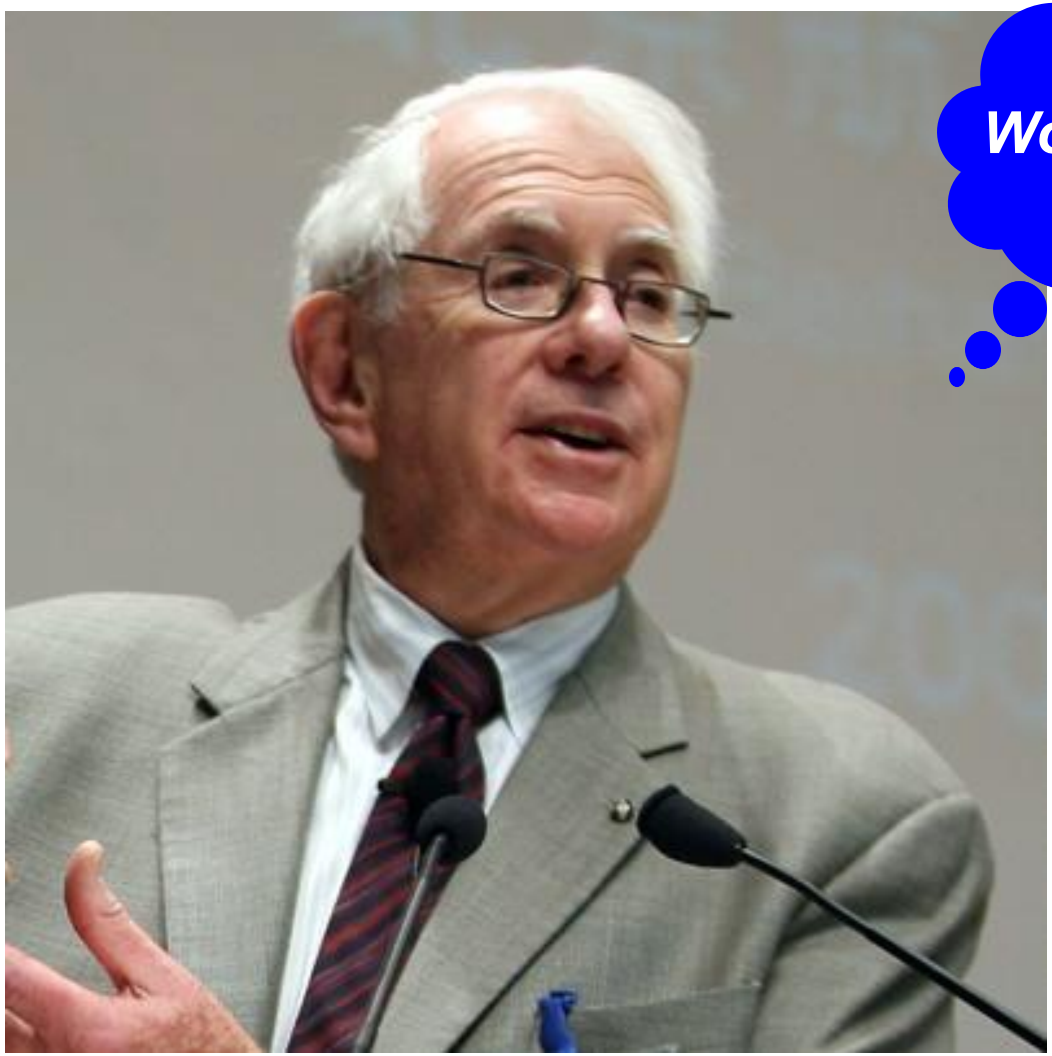
θ_{12} **Driven**

"No water here, try another place"

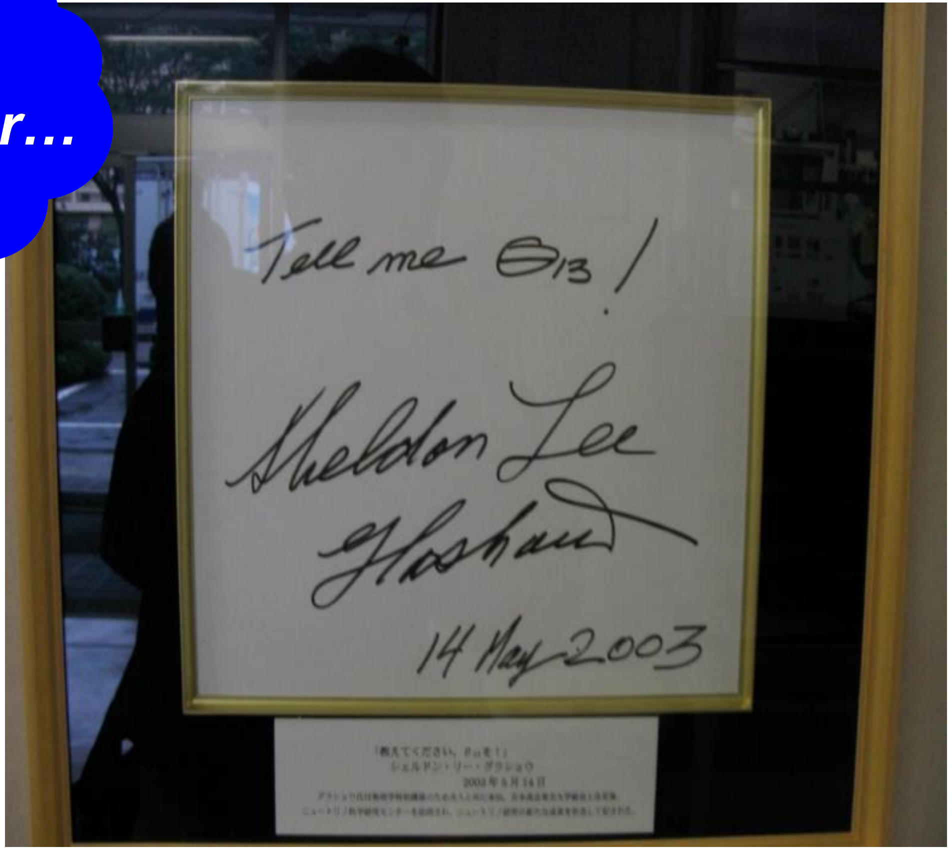


一这下面没有水，再换个地方挖 张新华画

Physicists Were All Very Very Very Desperate



Work Harder…



One of the Funders of the SM, Glashow, called for the measurement of θ_{13}

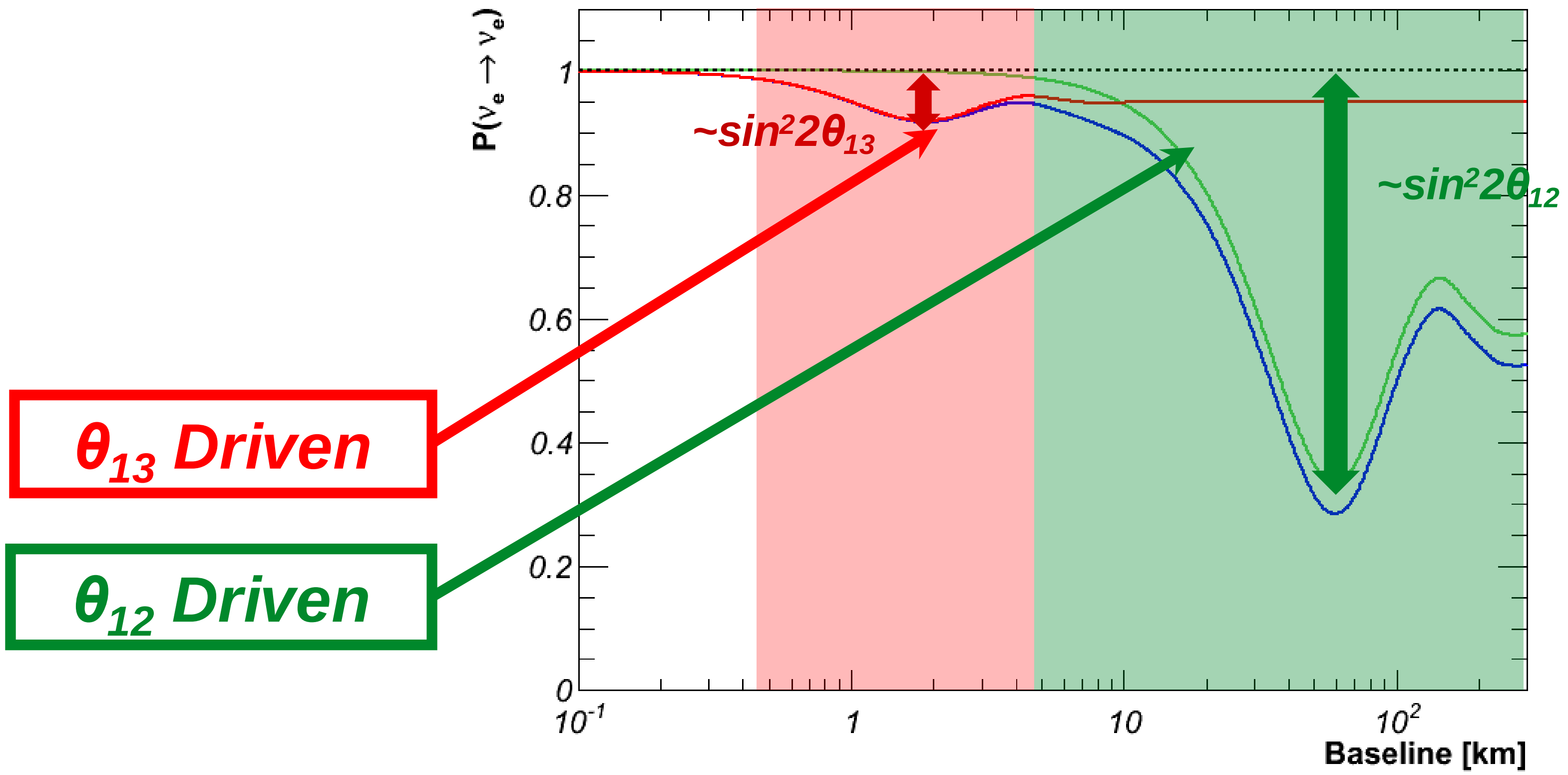
Photo by Kam-Biu Luk

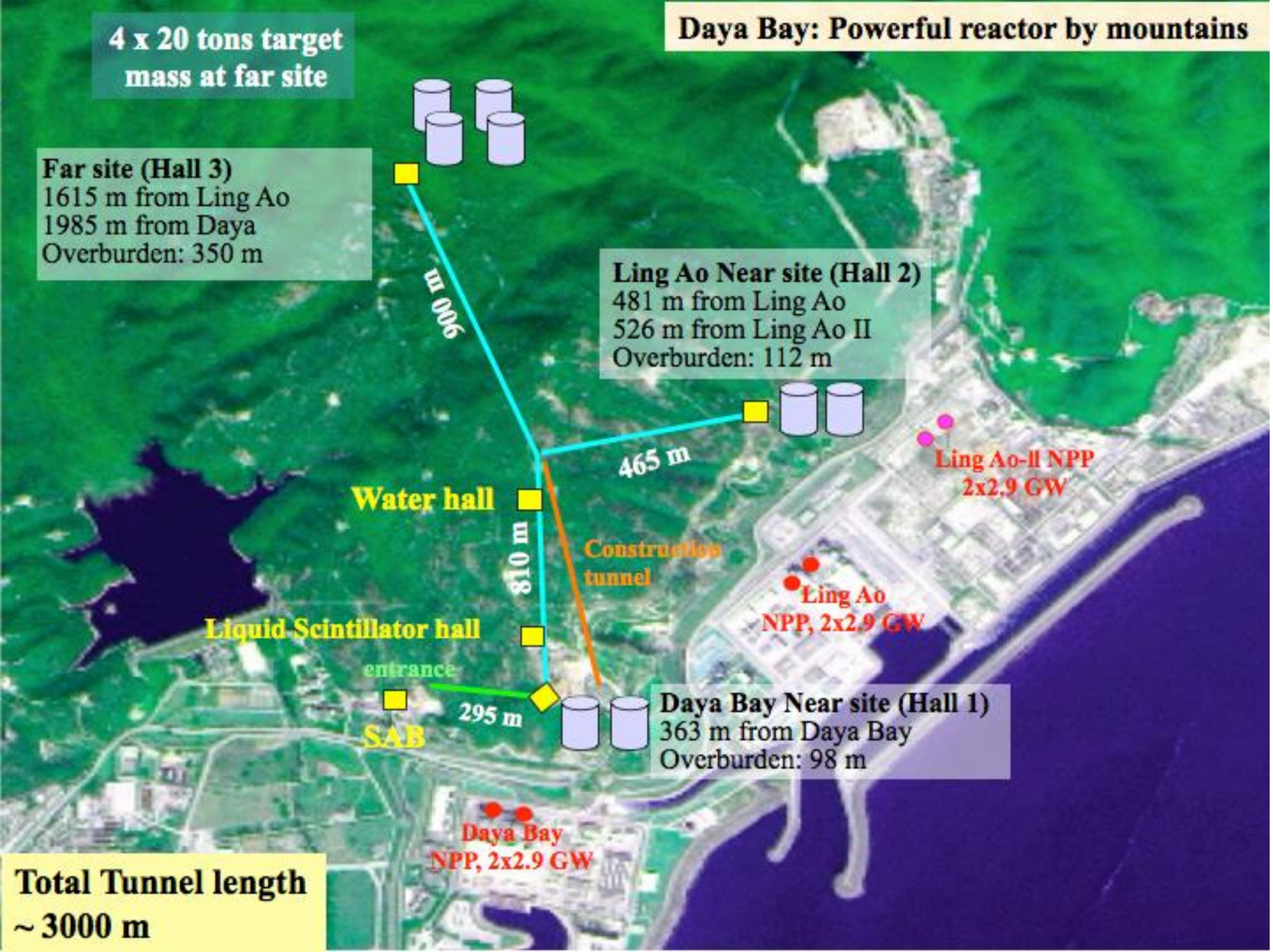
Which Mixings Drive Which Reactor Neutrino Oscillations?

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

- At different distances, the survival rate is dominated by different mixing angles
- To measure θ_{13}, a baseline of ~2 km is optimal





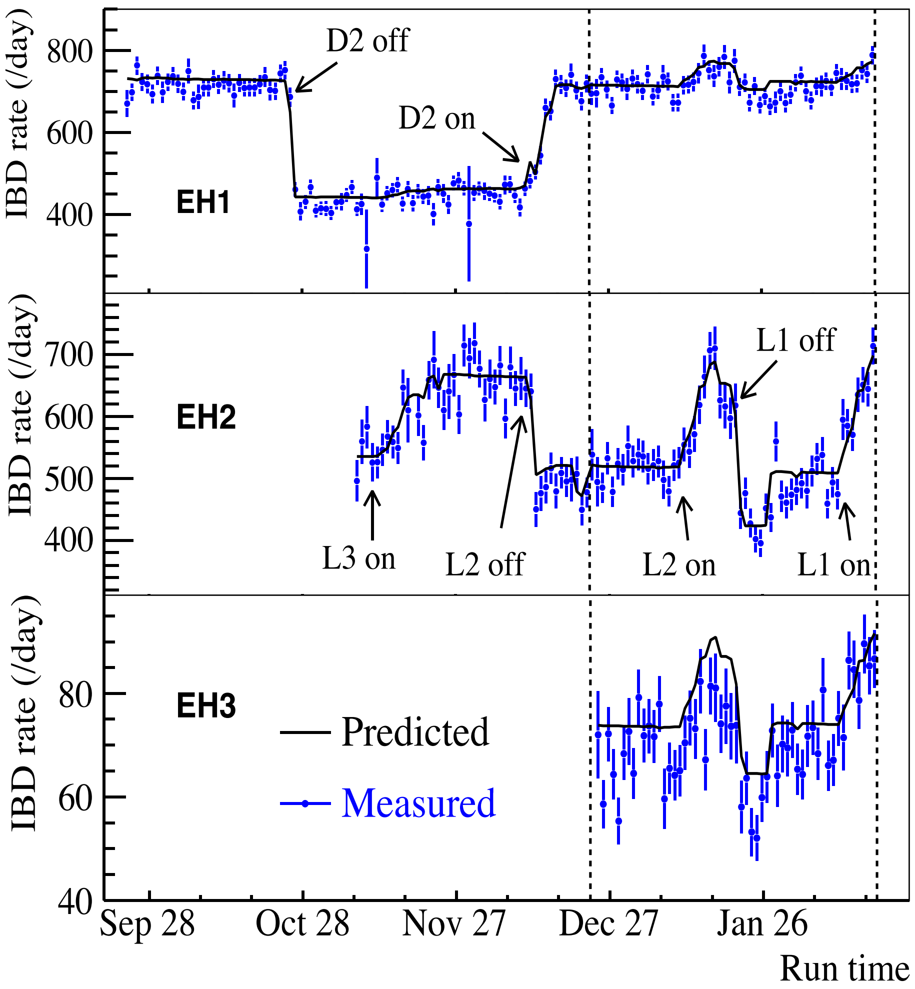
Mikaelyan LA, Sinev VV. , Phys. At. Nucl. 63:1002 2000.

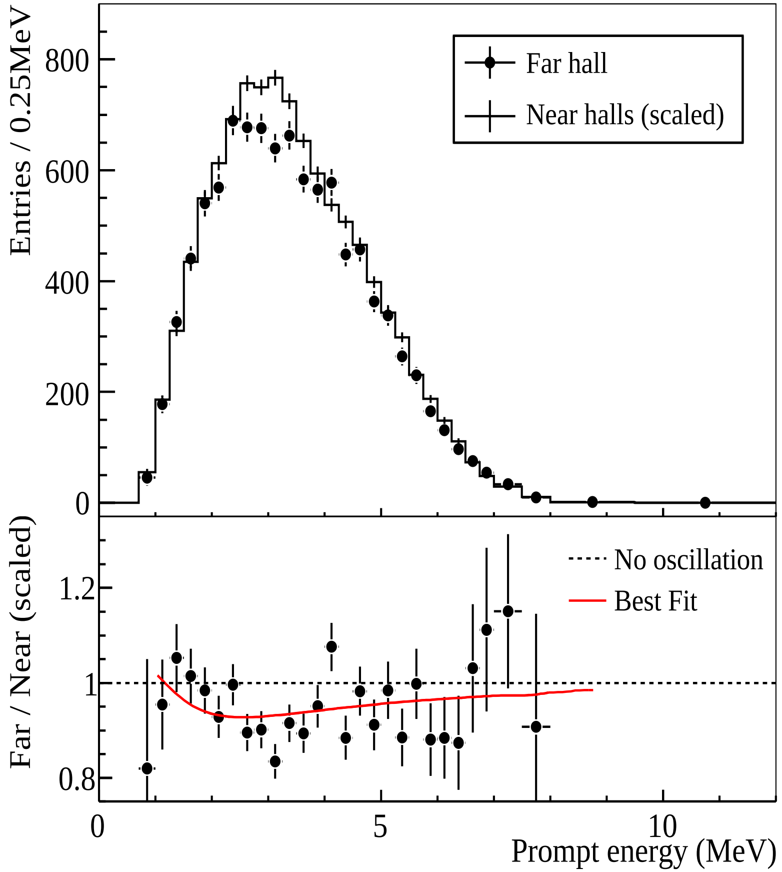
“Two identical liquid scintillation spectrometers stationed at the Krasno-yarsk underground site (600 MWE) at distances R1 = 1100 m and R2 = 250 m from the reactor source simultaneously detect (e+,n) pairs”

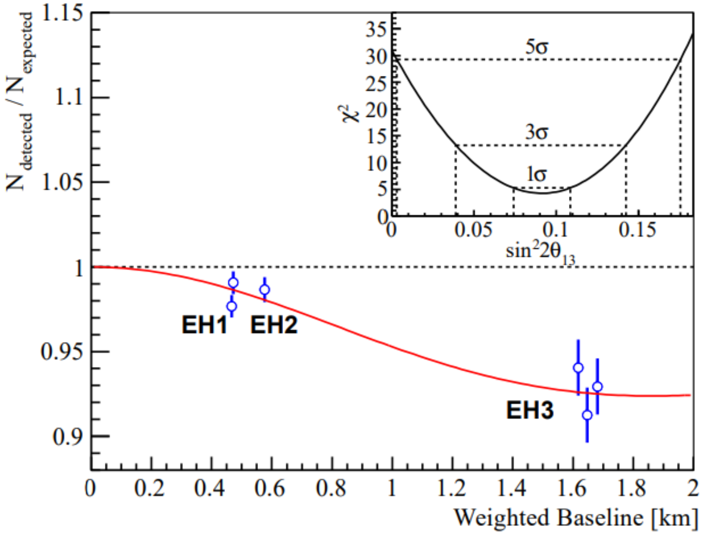
A Small Big Science Project

A Small Big Science Project

First Daya Bay Oscillation Results with 1958 Days







Daya Bay *Phys.Rev.Lett.* 108 (2012) 171803

- We see a deficit through the near-far ratio: 0.94+/-0.011(stat) +/-0.004(syst) at the far site
- **$\sin^2 2\theta_{13}$=0.092 ± 0.016(stat)± 0.005(syst)**
- **A 5-sigma discovery!**

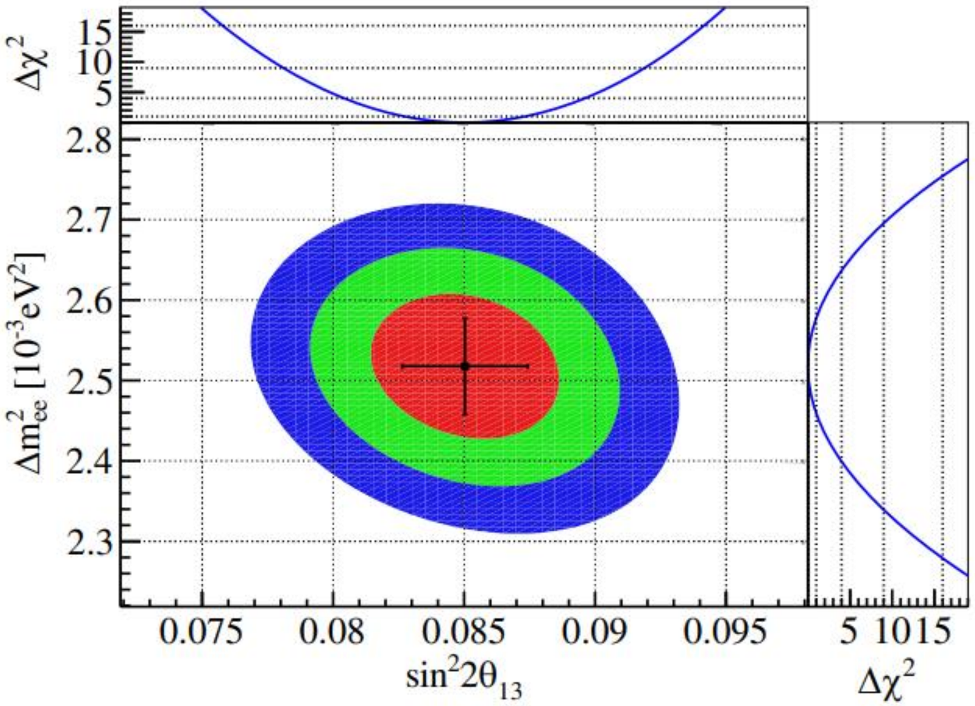
Daya Bay Full Data Set (Neutrino 2024)

Daya Bay reported the precision measurement with 3158-days full dataset in 2022

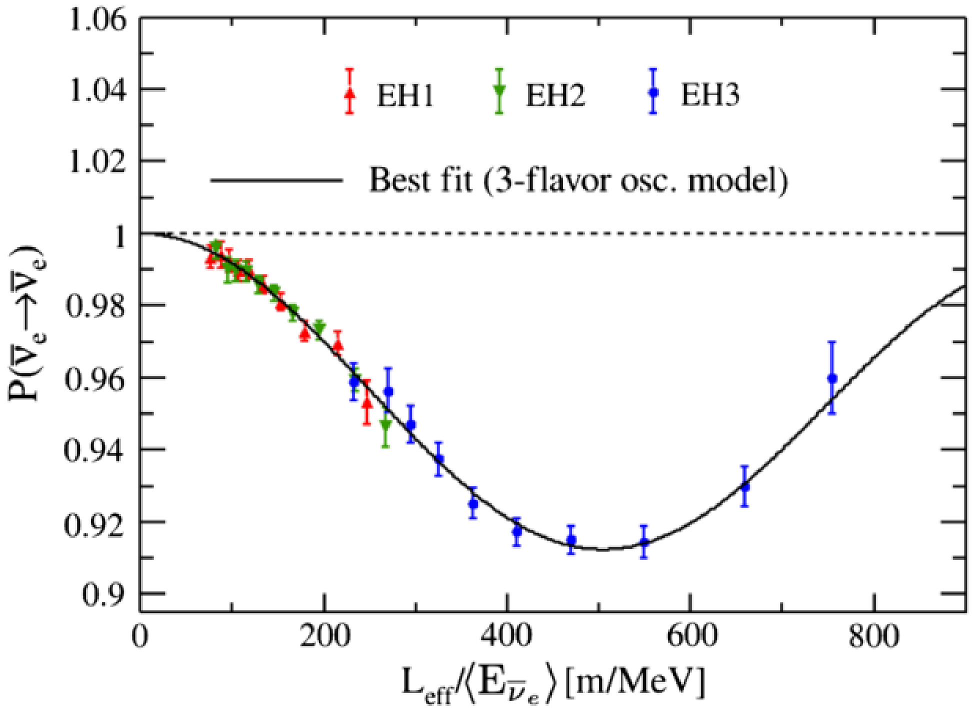
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ precision 2.8% → ***the Best in the world***

$\Delta m^2_{32} = 2.466 \pm 0.060\ (-2.571 \pm 0.060) \times 10^{-3}\ eV^2$ precision 2.4% → ***one of the Best in the world***

Systematics, mainly detector differences, contributed about 50% in the total error



PhysRevLett. 130 161802



DYB Pinned Down θ_{13} but ν Mass Hierarchy Still Unknown

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (with Majorana CP phases),

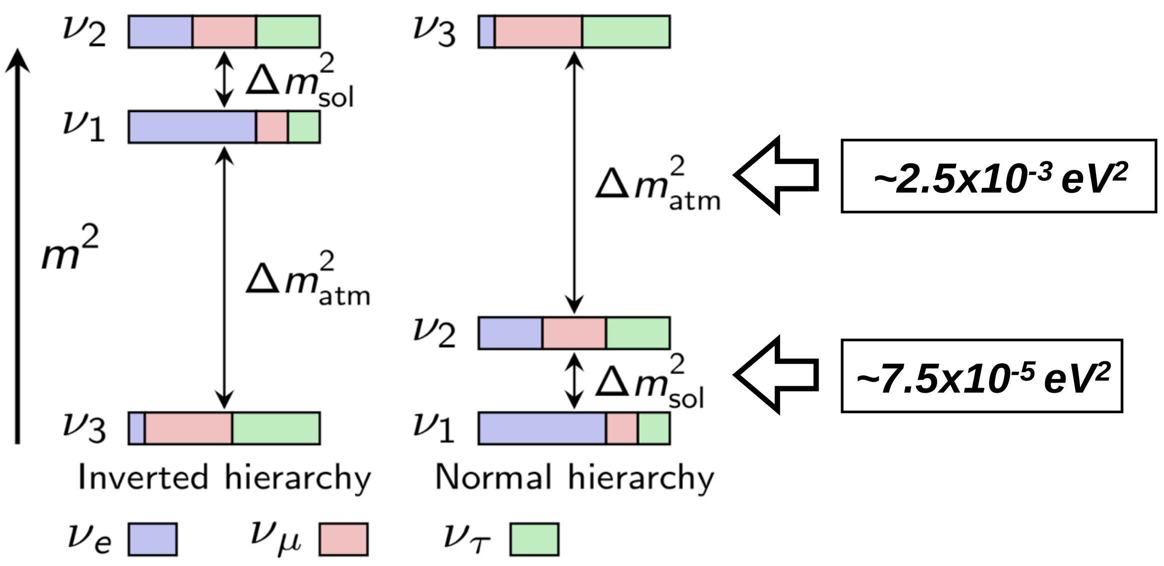
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Rightarrow$ Neutrino Oscillation Probability:

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4 \sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

Amplitude $\propto \sin^2 2\theta$ **Frequency $\propto \Delta m^2 L/E$**



Global Efforts Resolving ν Mass Hierarchy

Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Super-K, Hyper-K, IceCube PINGU, ICAL/INO, ORCA, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO + Atm/Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, 0νββ

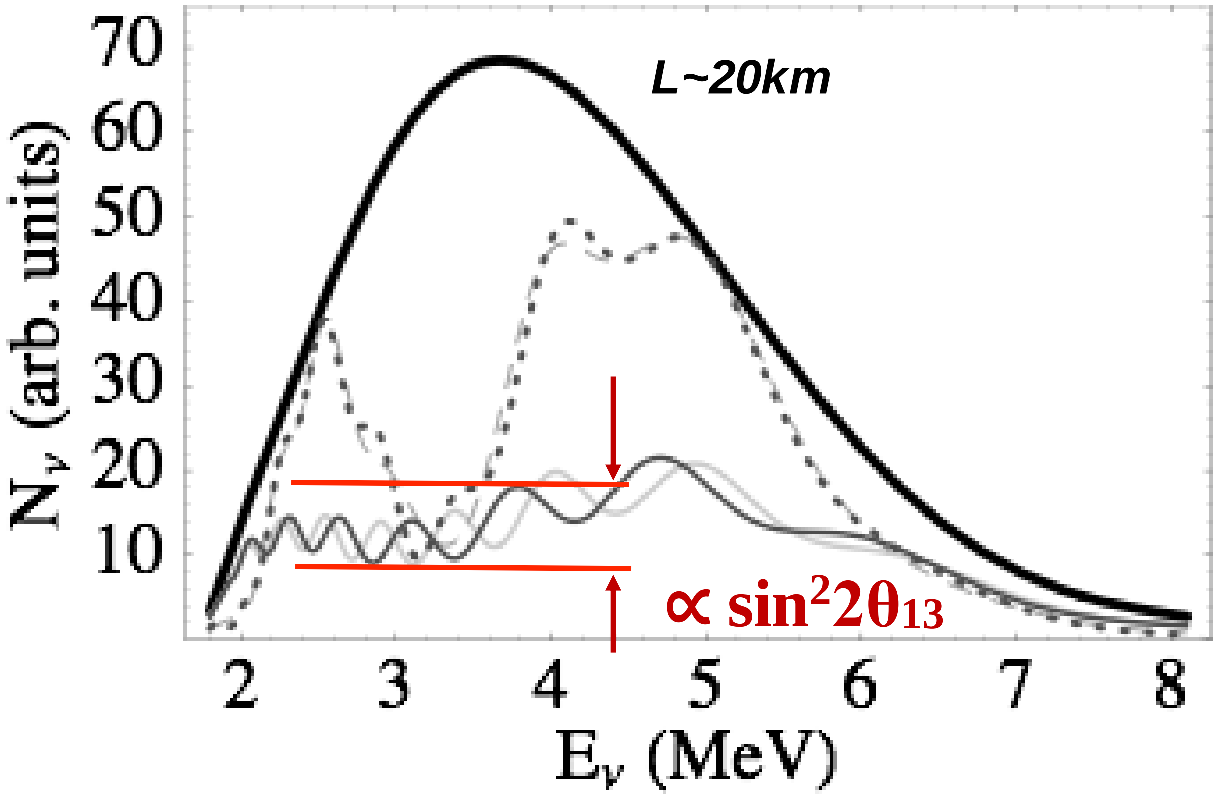
Known θ13 Enables Neutrino Mass Hierarchy at Reactors

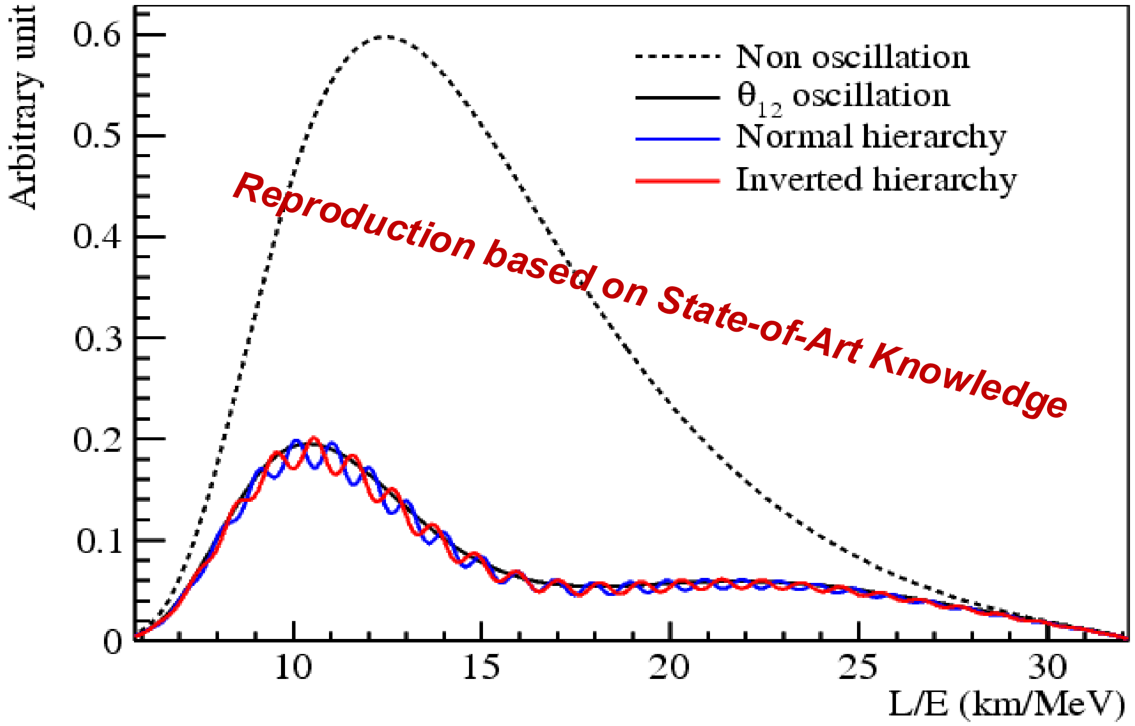
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

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

√Mass hierarchy reflected in the spectrum

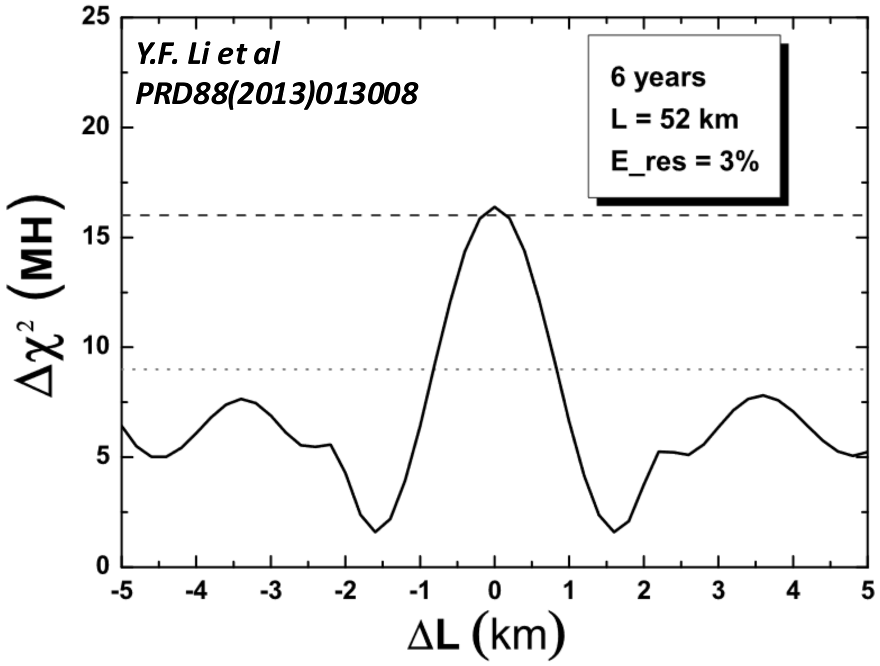
√Independent of the unknown CP phase

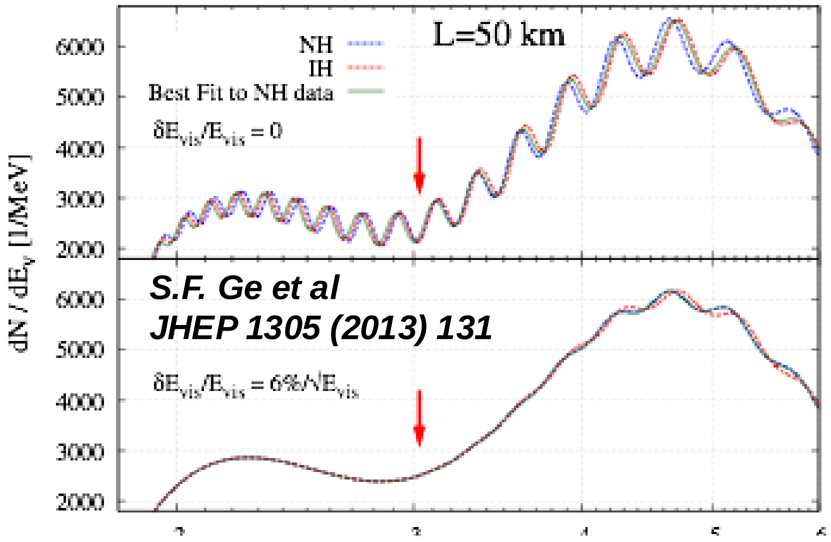


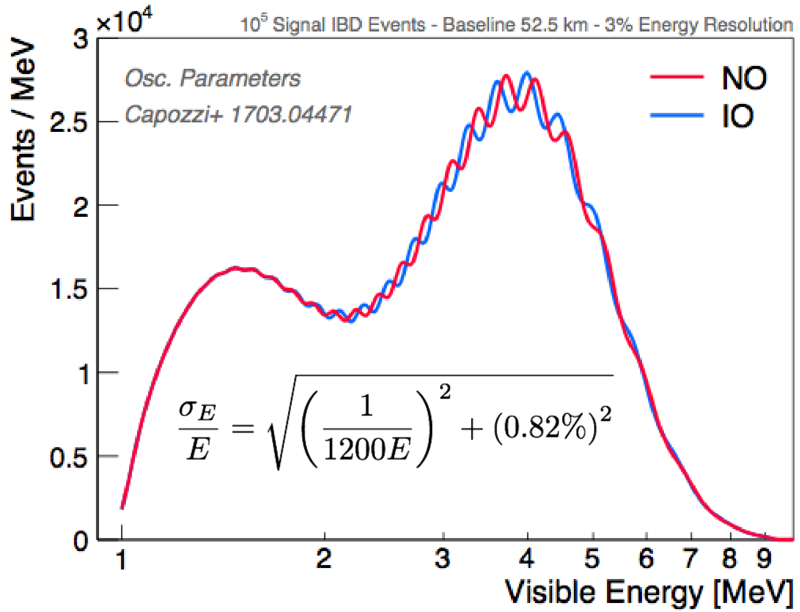


Challenges in Resolving MH using Reactors

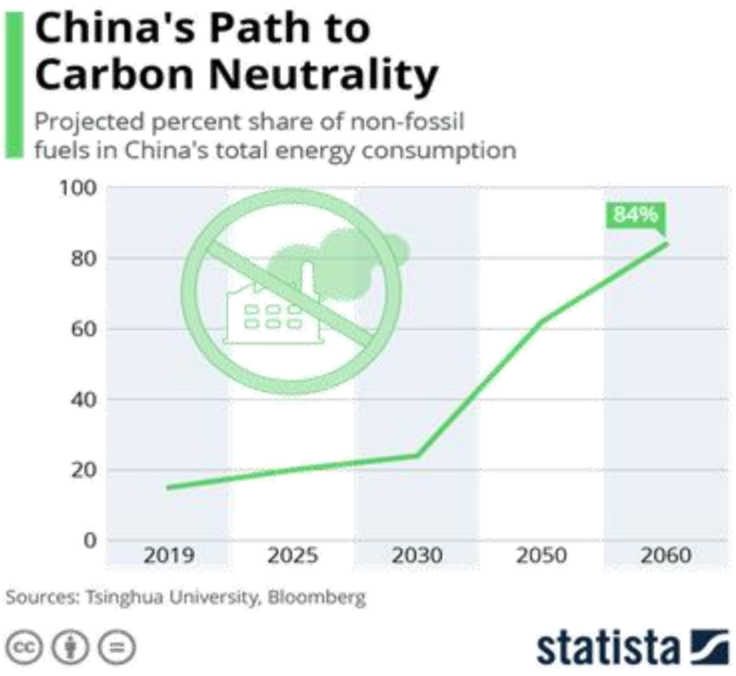
- Energy resolution: ~3%/sqrt(E)
- Energy scale uncertainty: <1%
- Statistics (the more the better)
- Reactor distribution: <~0.5km

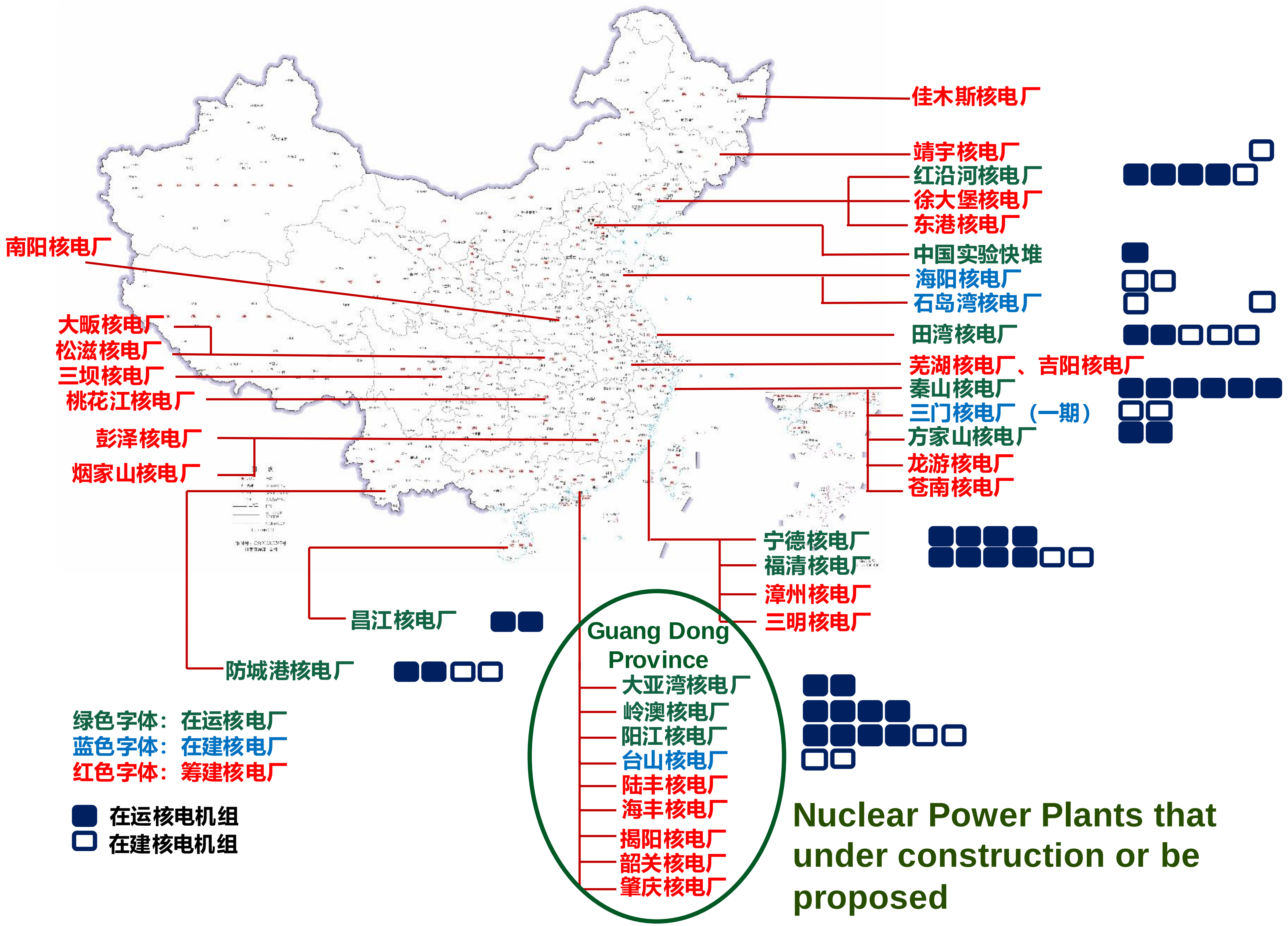






Suitable Nuclear Power Plants (very easy now) in China



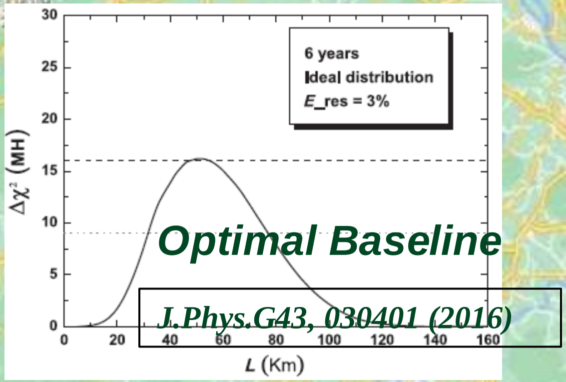


Nuclear Power Plants that under construction or be proposed

- China builds 6-8 new reactors a year
- Each reactor needs an average of 800 professional workers

Jiangmen Underground Neutrino Observatory (JUNO)

- Proposed as a reactor neutrino experiment for mass ordering in 2008 (PRD78:111103,2008; PRD79:073007,2009)
  - **driving the design specifications: location, 20 kton LS, 3% energy resolution, 700 m underground**
- Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches
- Approved in 2013. Construction in 2015-2024



70+ institutions, ~650 collaborators

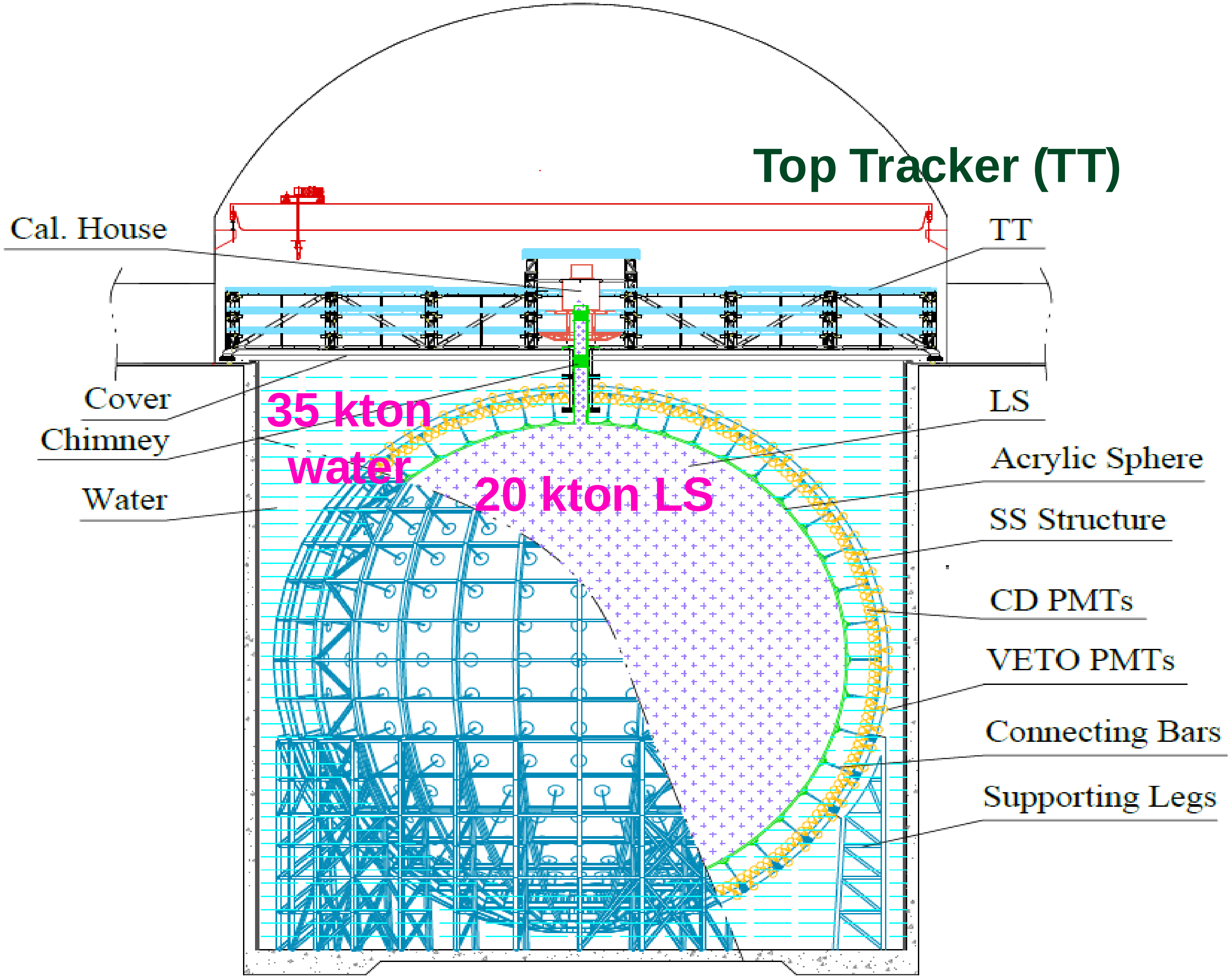
Asia: China (34), Taiwan,China (3) Thailand (3), Pakistan, Armenia
Europe: Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Latvia, Slovakia, UK
America: Brazil (2), Chile (2), USA (2)

Jiangmen Underground Neutrino Observatory

Surface Buildings

- Office/Dorm/Computation
- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Power station
- Cable train

The JUNO Central 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 (a); Photon statistics (b); Noise (~background) (c)

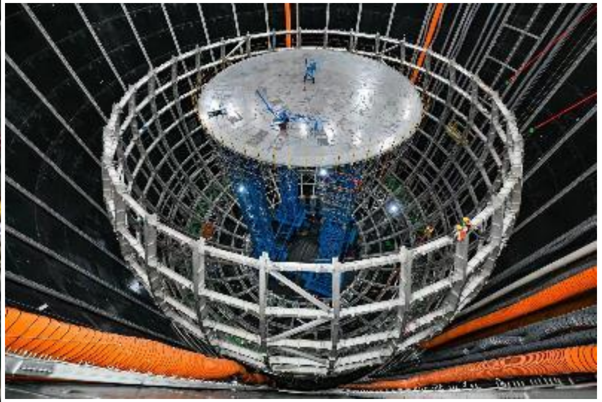
The Detector Performance Goals

	KamLAND	Daya Bay	PROSPECT	JUNO
Target Mass	**~1kt**	20t	~4t	**~20kt**
Photocathode Coverage	~34%	~12% (Effective)	ESR + PMTs	**~80%**
PE Collection	~250 PE/MeV	~160 PE/MeV	**~850 PE/MeV**	**~1200 PE/MeV**
Energy Resolution	~6%/√E	~7.5%/√E	**~4.5%/√E**	**3%/√E**
Energy Calibration	~2%	**1.5%→ 0.5%**	~1%	**<1%**

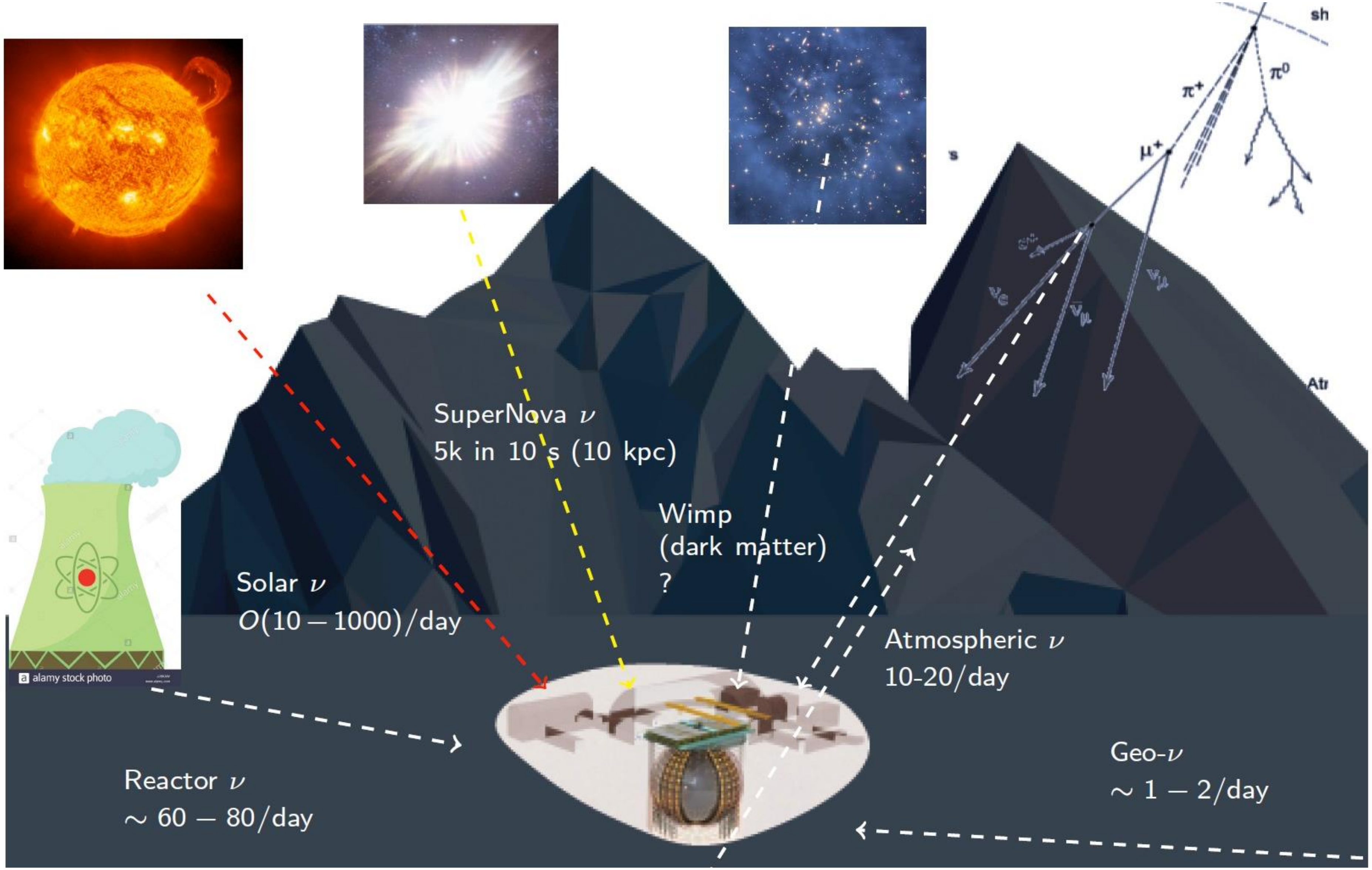
An extremely demanding detector and a challenging job

JUNO Detector and Tightly Packed PMTs

arXiv: 2311.17314 (2023)



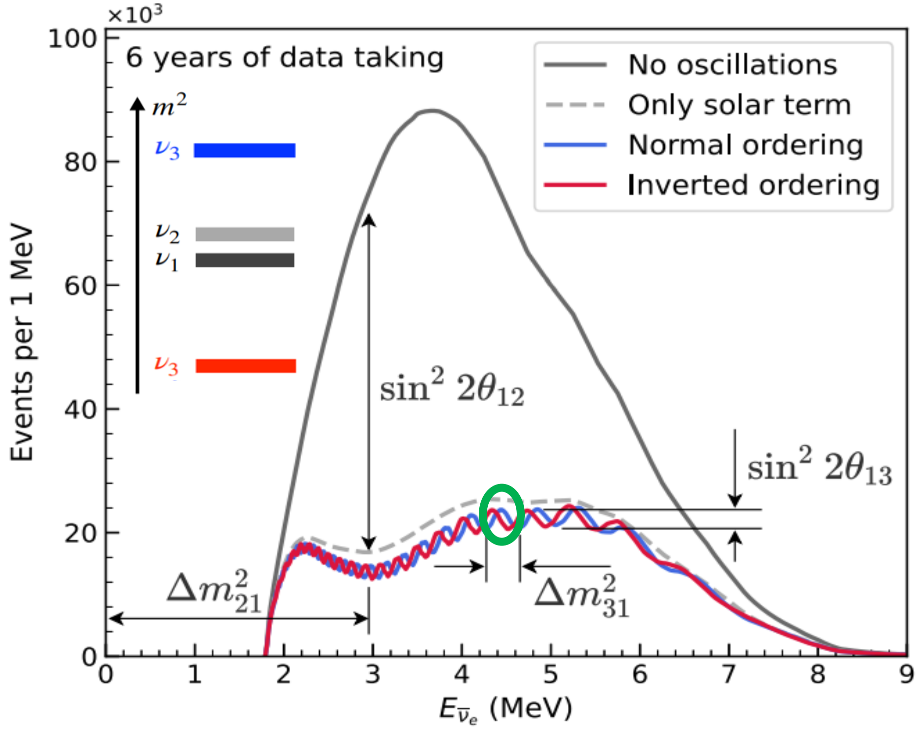
JUNO is a Multi-Physics Experiment



Systematic Controls for the Detector Performance

Primary goals:

neutrino mass ordering and oscillation parameters using reactor antineutrinos at 52.5km



Nucl.Instrum.Meth.A 1042 (2022) 167435

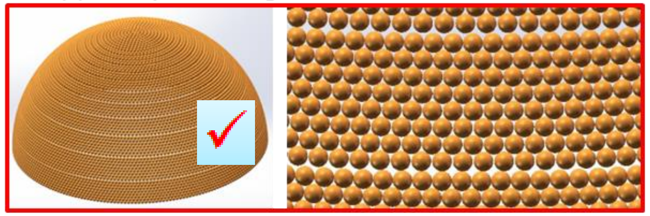
Detector Performance

- **Statistics**
  - Large target mass (20 kton LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- **Energy resolution**
  - Very high PMT coverage (78%)
  - Highly efficient PMTs (PDE~30%)
  - LS with Good Transparency
- **Shape uncertainty**
  - Satellite detector (TAO)
- **Background**
  - Overburden (~650 m)
  - Veto System (>99.5%)
  - Material Screening
  - Clean Installation

Packing PMTs as Tight as Possible and Keep Them Safe

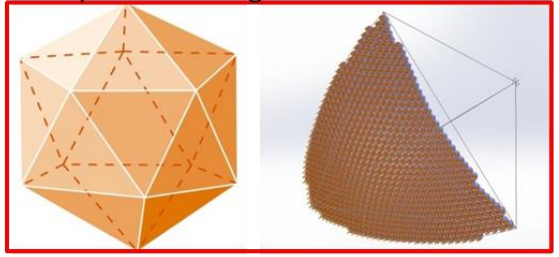
Supper layer arrangement method 77.8%

1



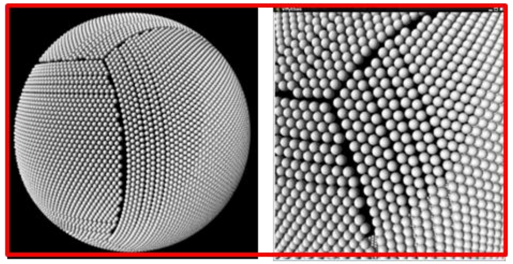
Spherical triangle method 72%

2



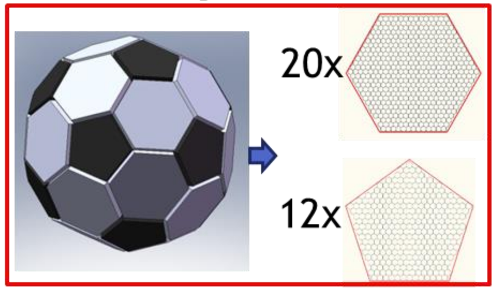
Volleyball arrangement method 75.96%

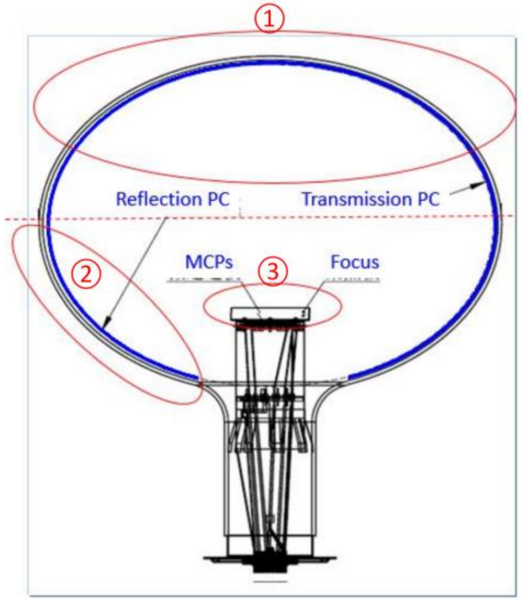
3



Football arrangement method 74.08%

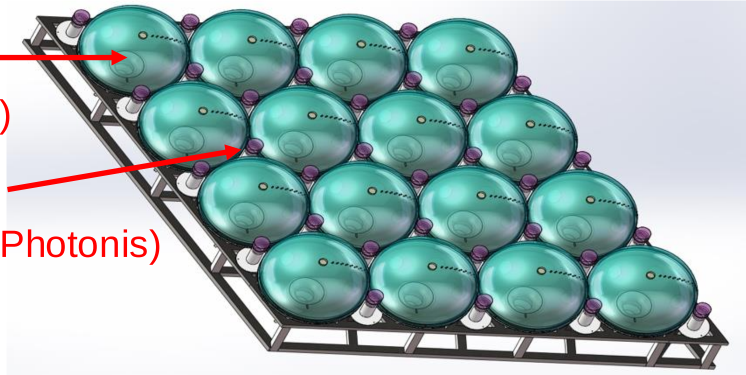
4

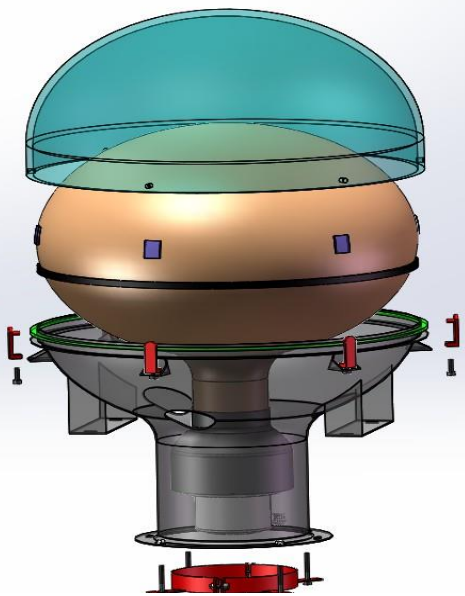




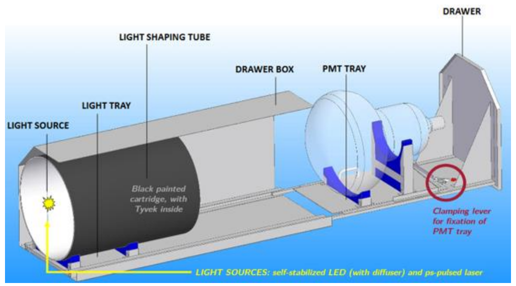
20" PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

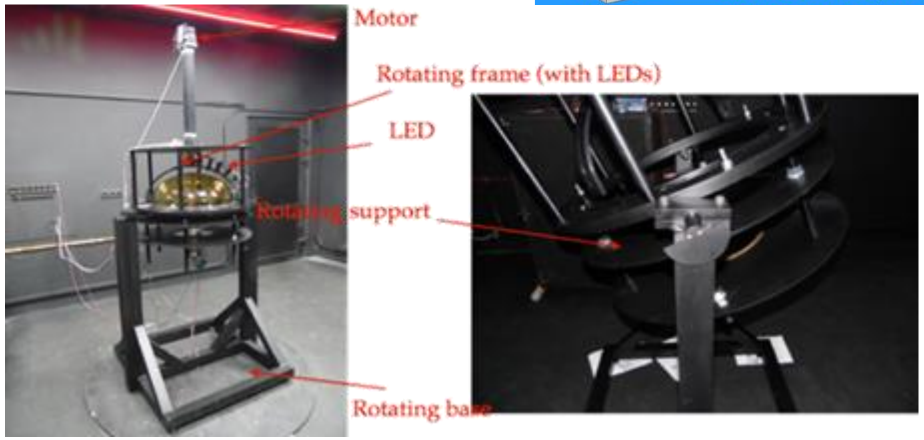
3"sPMT(~25K)
HZC XP72B22 (Photonis)

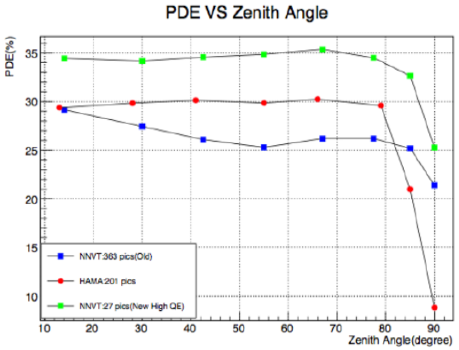


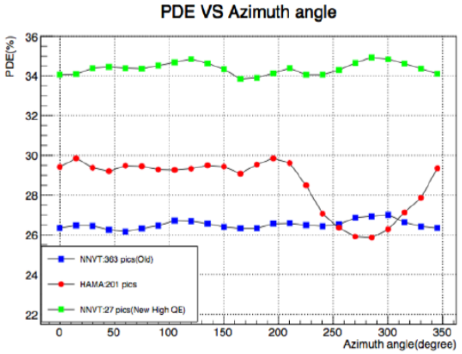


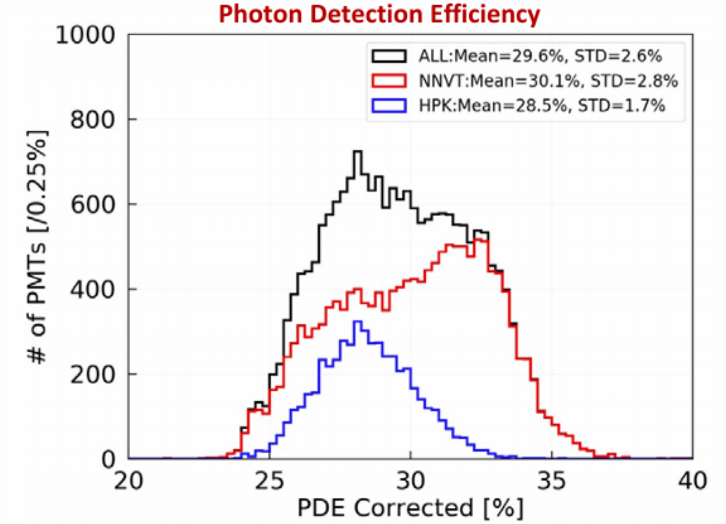
Characterizing/Testing Every Single PMT with Great Care

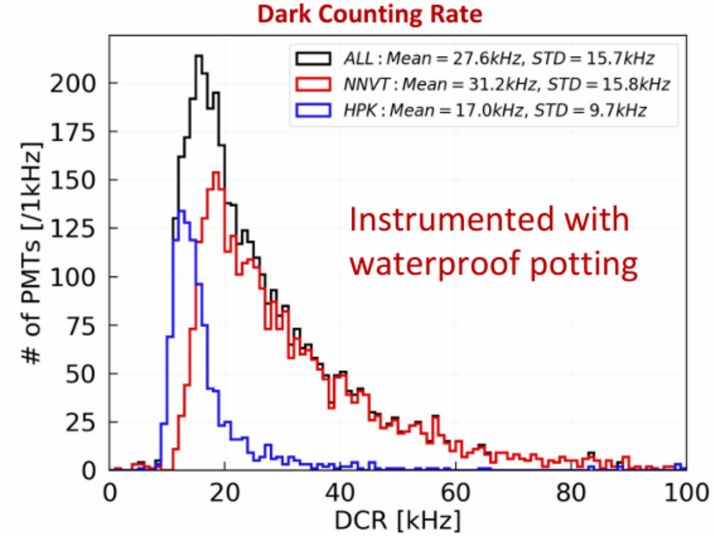


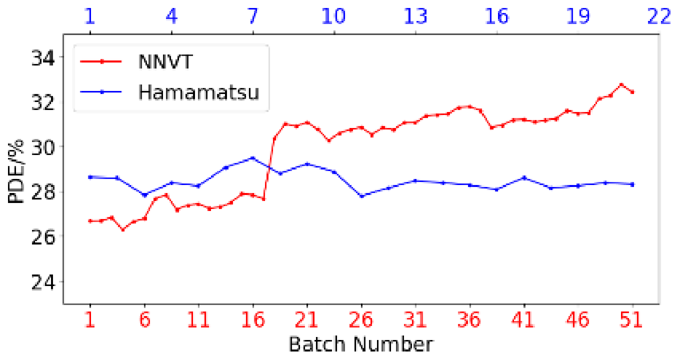


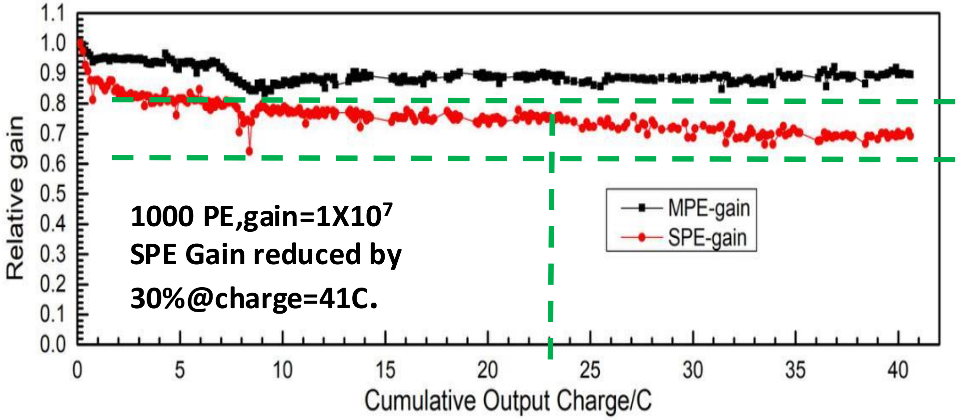








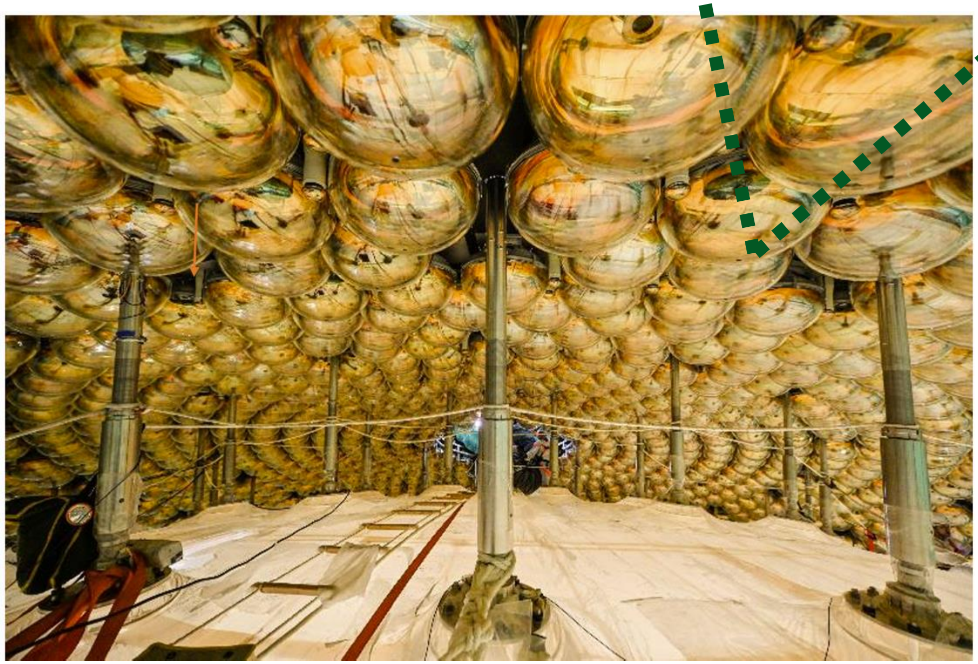




PMT System Summary

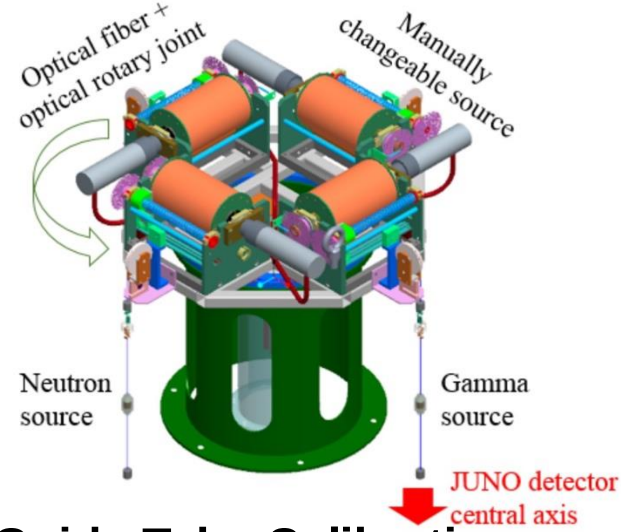
- 20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu HPK)
  3.1-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
  - All PMTs delivered and their performance tested OK
- Water proof potting done: failure rate < 0.5%/6 years
- Implosion protection: acrylic top & SS bottom (JINST 18 (2023), P02013)
  - Mass production completed

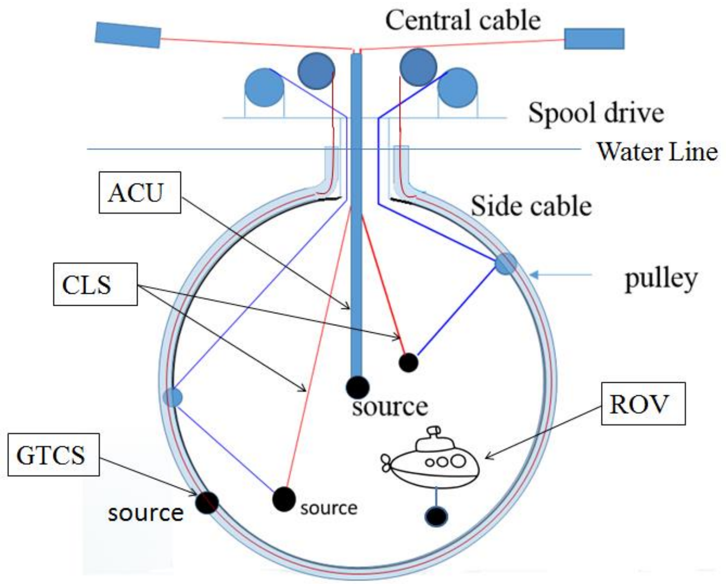
	LPMT (20-in)		SPMT (3-in)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Charge Collection	Dynode	MCP	Dynode
Photon Det. Eff.	28.5%	30.1%	25%
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347



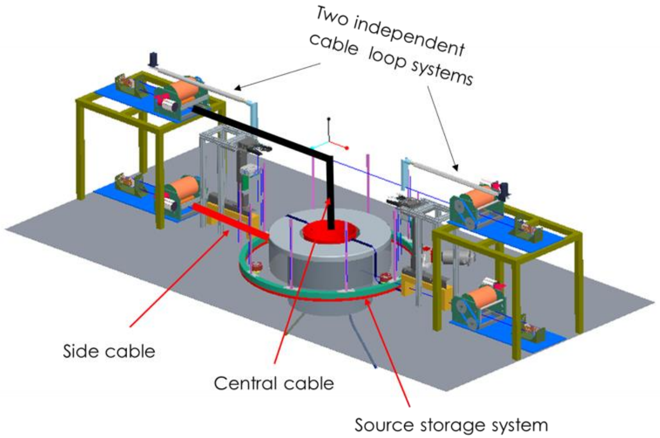
A Comprehensive Calibration System

Automatic Calibration Unit (ACU)

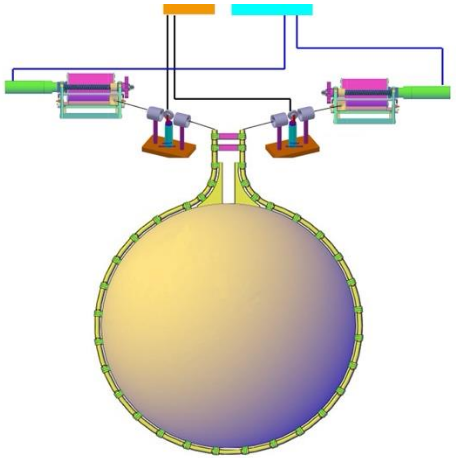




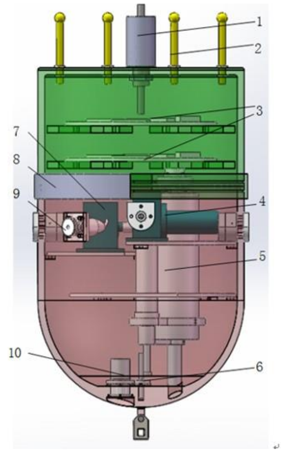
Cable Loop System (CLS)



Guide Tube Calibration System(GTCS)



Remotely Operated under-liquid-scintillator Vehicles (ROV)



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

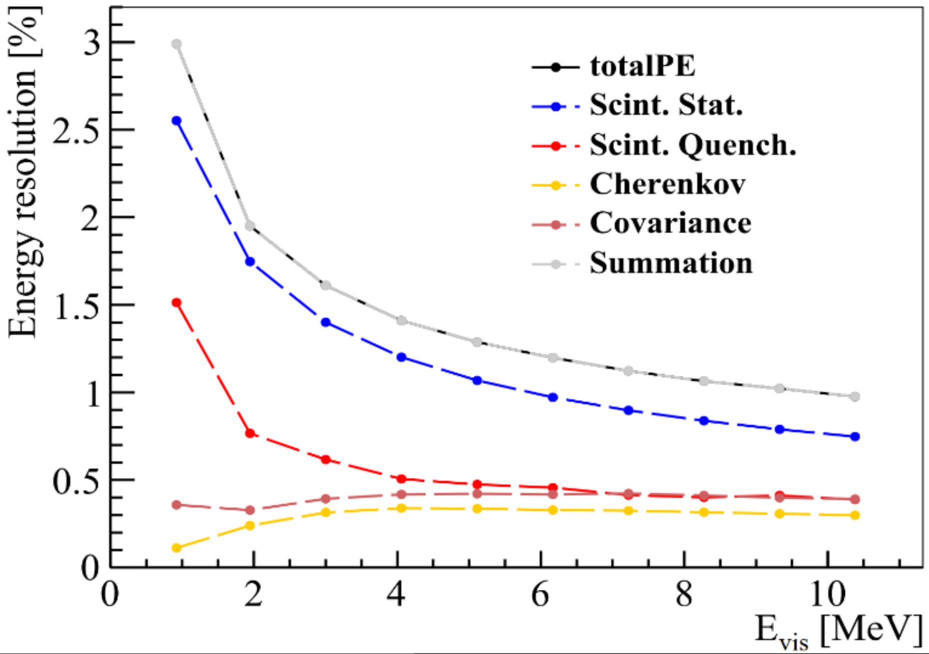
Calibration and Expected Energy Resolution

- Four systems for 1D, 2D, 3D scan with multiple sources
- Energy scale and non-linearity will be calibrated to <1% using γ peaks and cosmogenic ^{12}B beta spectrum

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

Photon statistics | Constant term | Dark noise, Annihilation-induced γs

Expected energy resolution: **2.95% @1MeV**

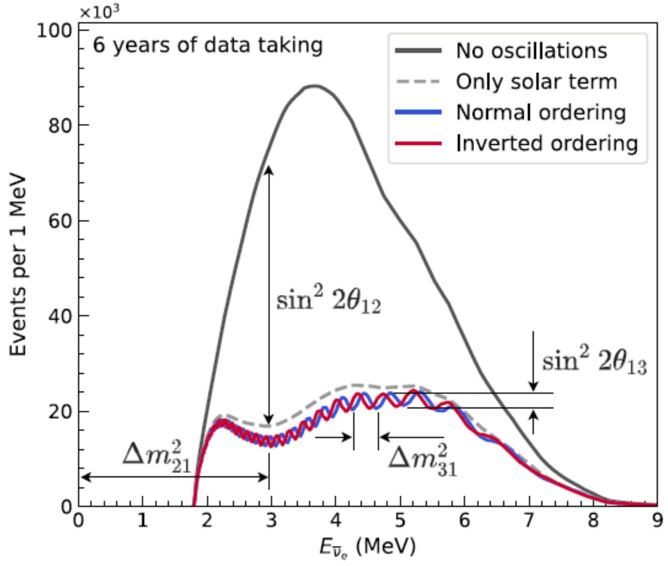


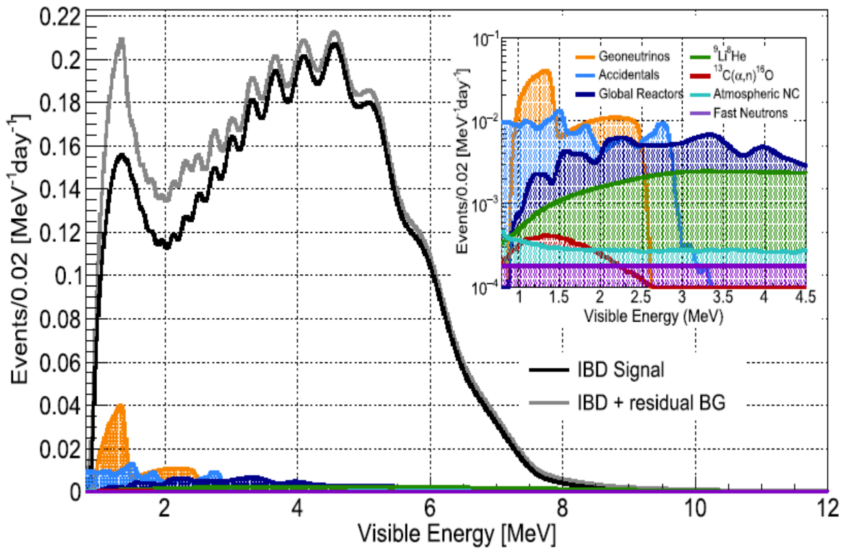
JHEP 03 (2021) 004	arXiv:2405.17860 (2024)

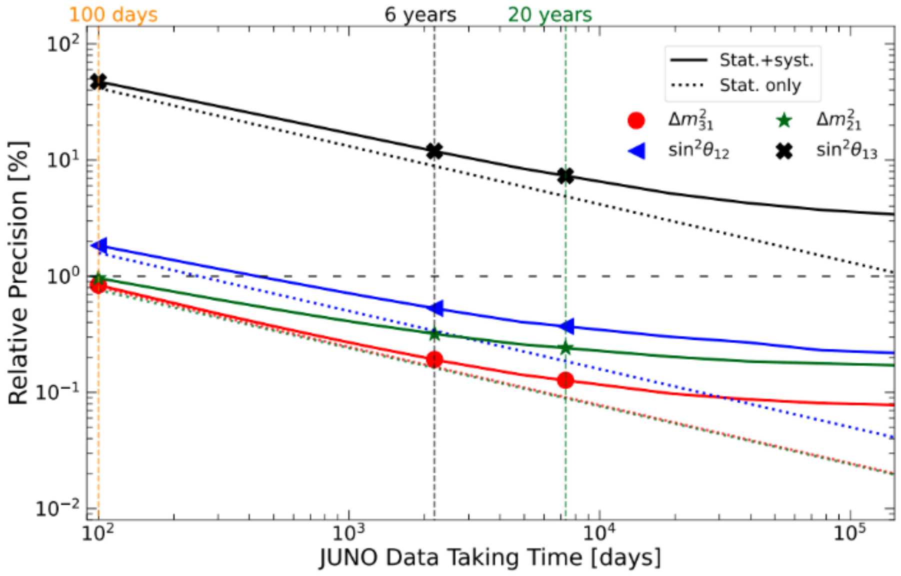
Precision Measurement of oscillation parameters

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

Chin. Phys. C46 (2022) 12, 123001

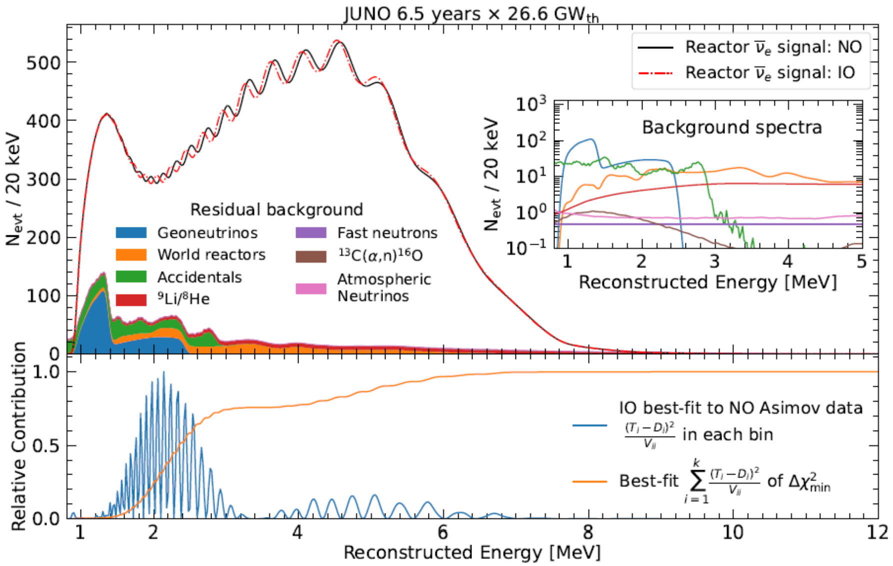




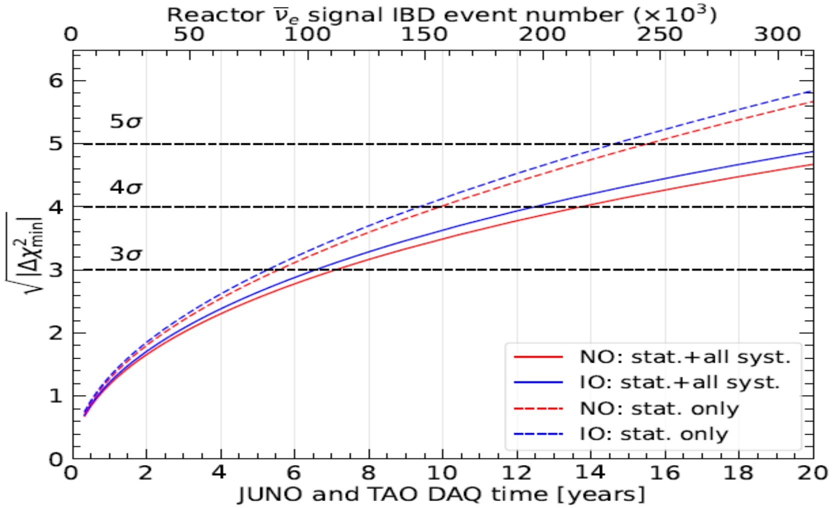


	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016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

Neutrino Mass Ordering



Sensitivity mostly from 1.5-3 MeV



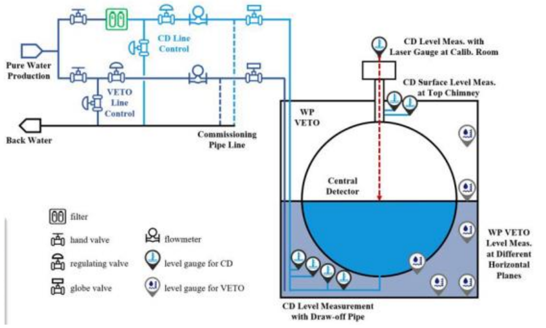
	Design	Now
Thermal Power	36 GW$_{th}$	26.6 GW$_{th}$ (**26%↓**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (**33%↑**)
Muon veto efficiency	83%	91.6% (**11%↑**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (**2%↑**)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

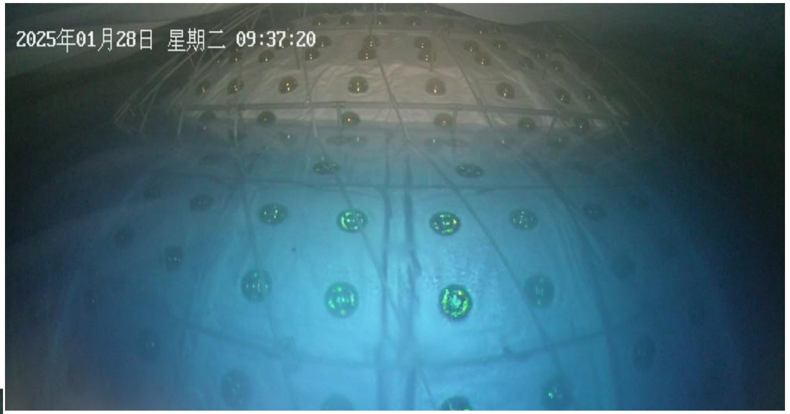
- JUNO NMO median sensitivity:
  3σ (reactors only) @ ~6 yrs * 26.6 GW$_{th}$ exposure
- Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity

arXiv:2405.18008 (2024)

Current Status of JUNO: Water Filling

- Dec 1, 2024, Installation finished
- Dec 18, 2024, water filling started
- Feb 2, 2025, water filling completed





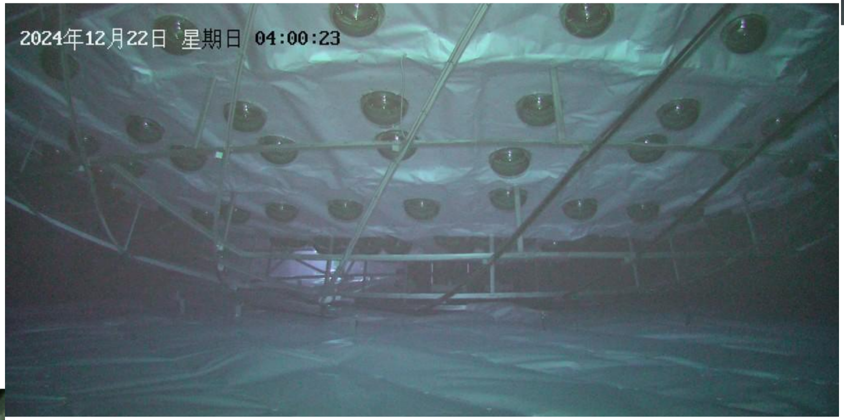
out pure water filling

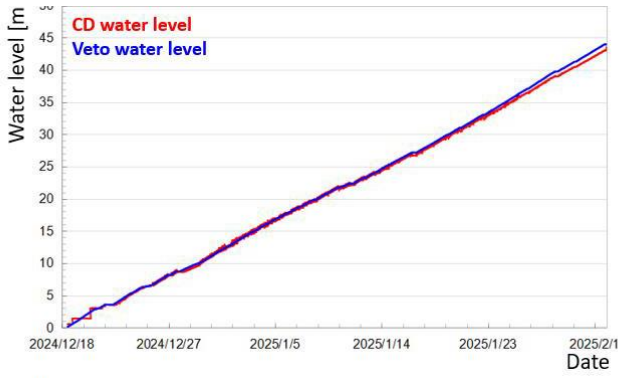
ynchronize pure water filling of CD and WP.

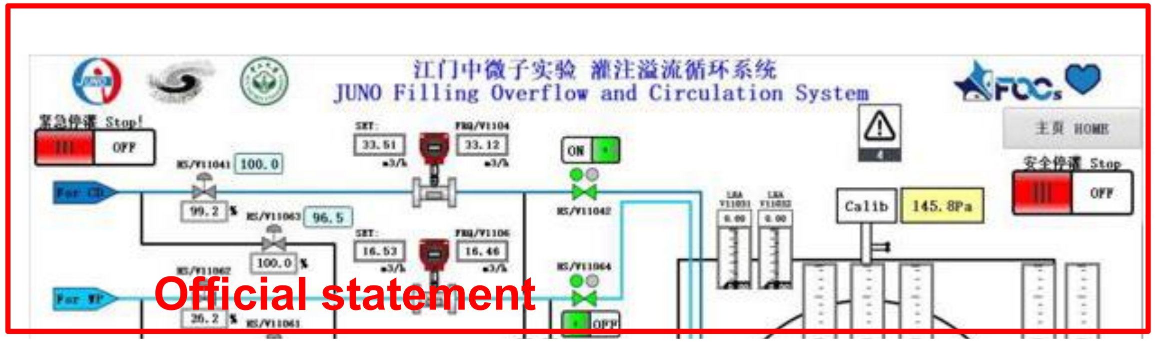
'ure water production for FOC ~90 m^3/h.

urther purification of CD line.

Jse regulating valves to regulate flow
ntering CD or WP for liquid level balance.

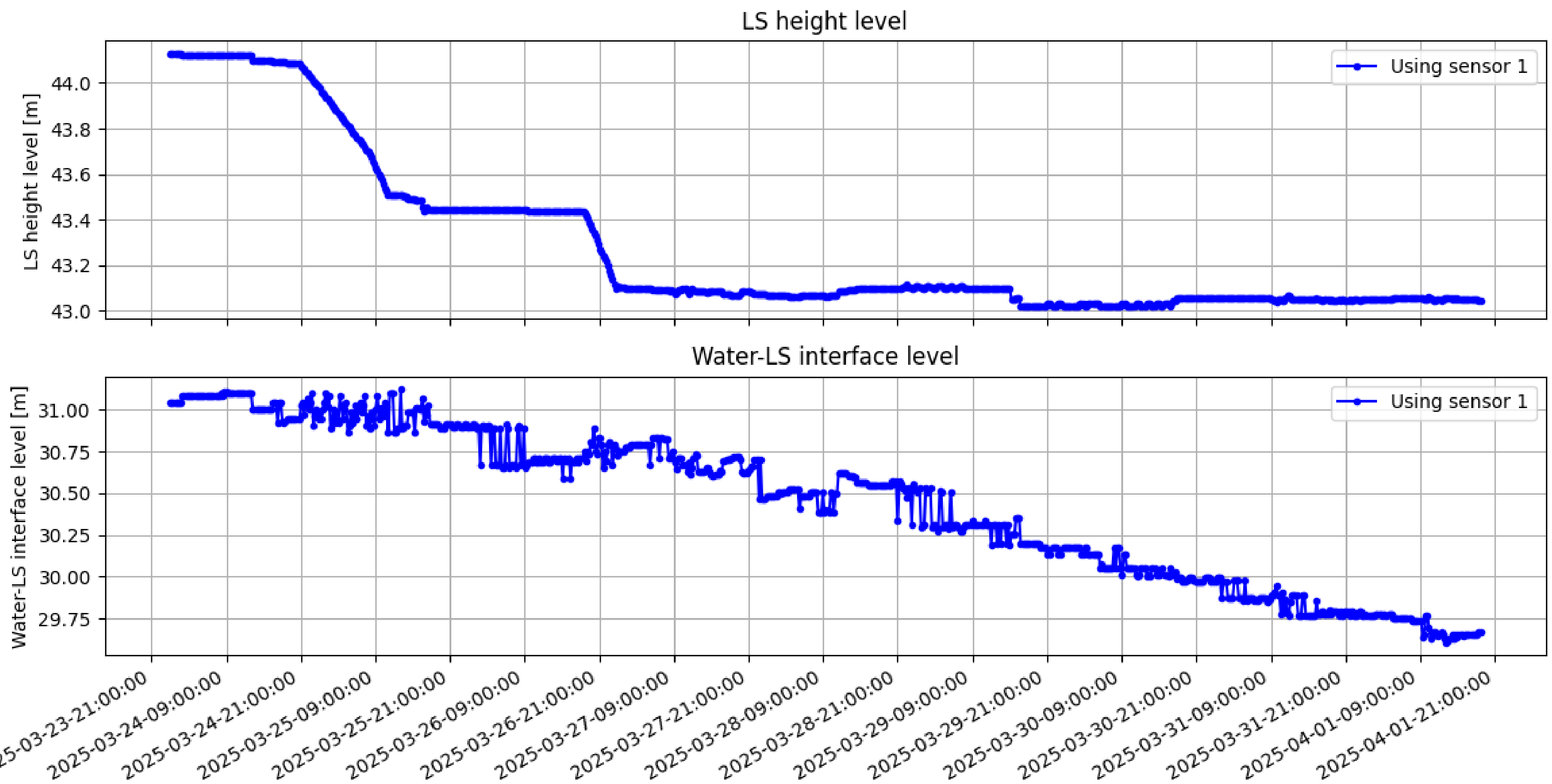


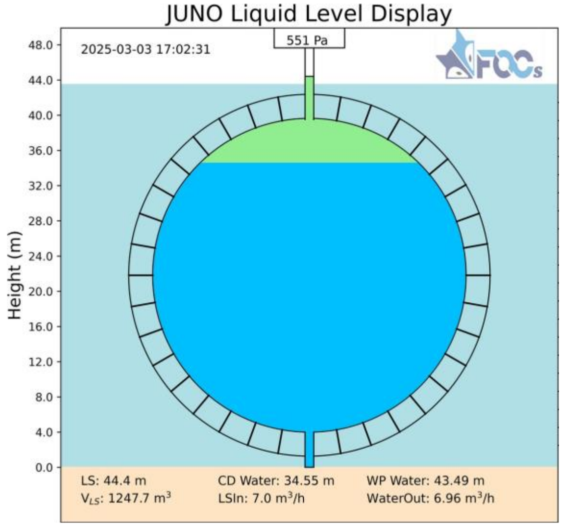




Current Status of JUNO: Water Filling

- Feb 8, 2024, LS replacing/filling started

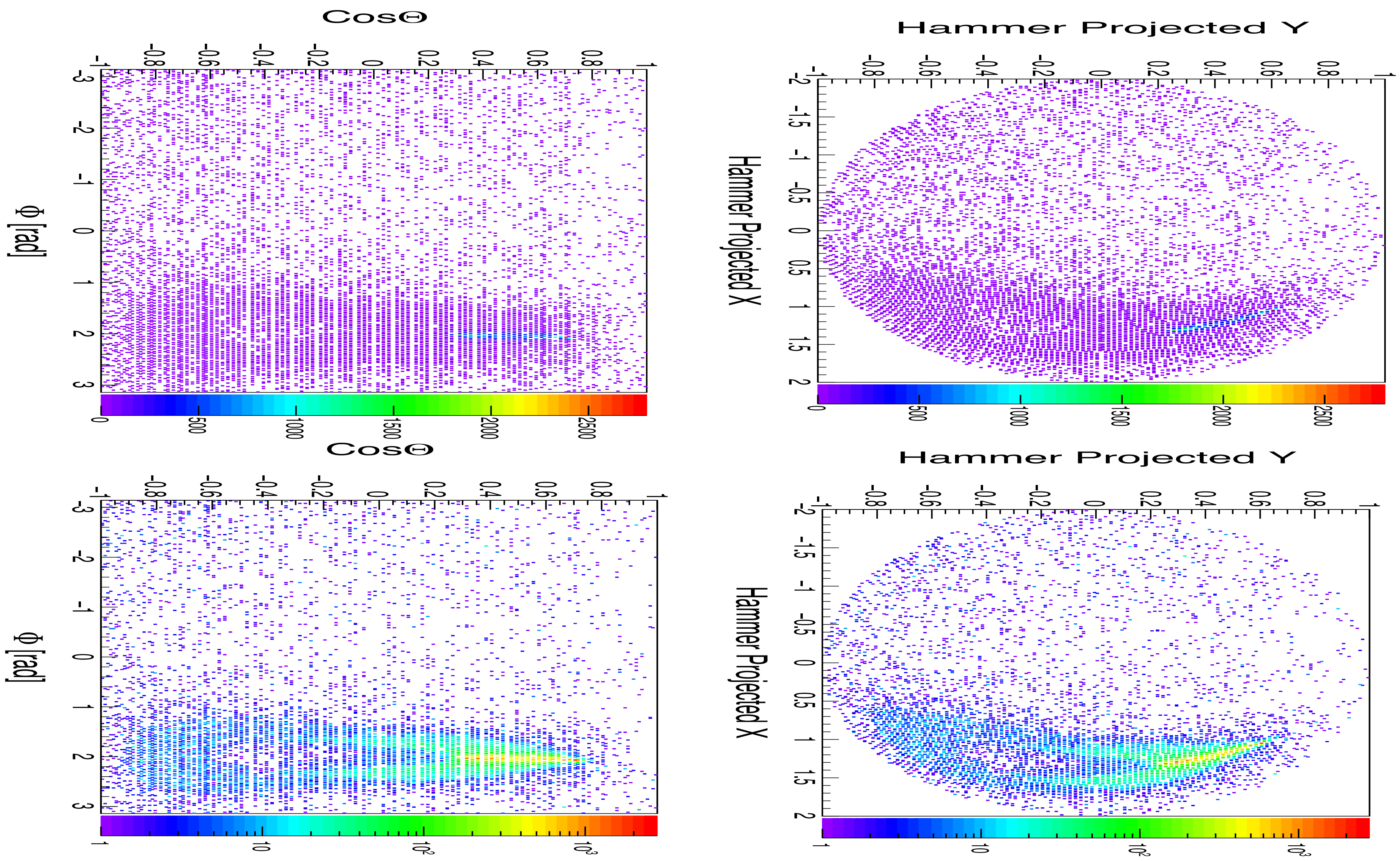




LS radiopurity better than 10^{-15} mBq/m^3 (ICP-MS)

- Apr 1, 2025, total LS in: ~4,248 m^3

Let's See Some Event/Photons!



Achievements:

- Calibration of the large PMTs using laser data
- Small failure channels : ~7/17k (~0.04% loss at installation)
- Calibration sources working as expected (Am-Be and Am-C)
- We have seen some muon candidates

JUNO Milestones

Project Approved and Funded!

2013

Civil Started

2015

2017

NNVT PMTs Delivered

Civil completed

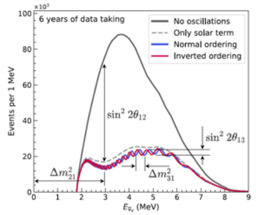
2021

Detector Const. Started

2022

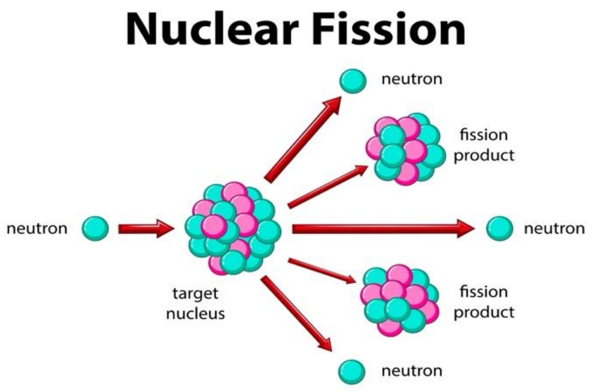
2023-2024-2025

Detector completing, Filling starting



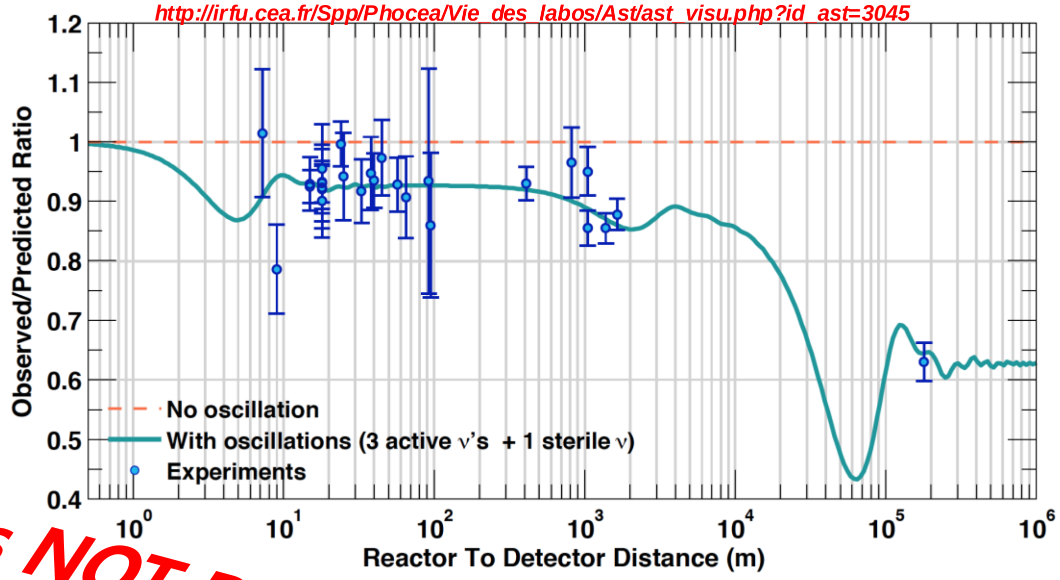
Summer 2025: Data Taking!

Reactor Antineutrino Anomaly (RAA)

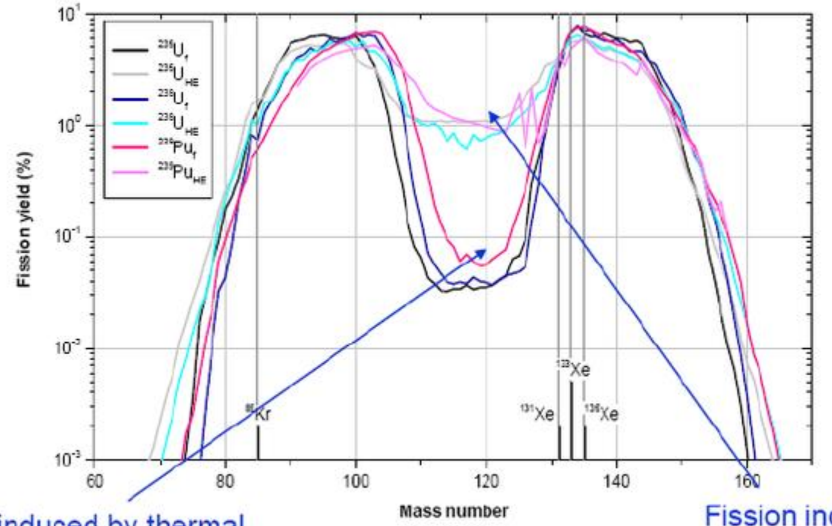


- *T. A. Mueller et al., PRC83, 054615 (2011)*
- *P. Huber, Phys. Rev.C84, 024617 (2011)*
- *Daya Bay, PRL116(2016), PRL123(2019)*
- *RENO, PRL121(2018)*
- *NEOS, PRL118(2017)*
- *Double Chooz, Nature Physics 16(2020)*

Reactor Neutrinos NOT Perfect

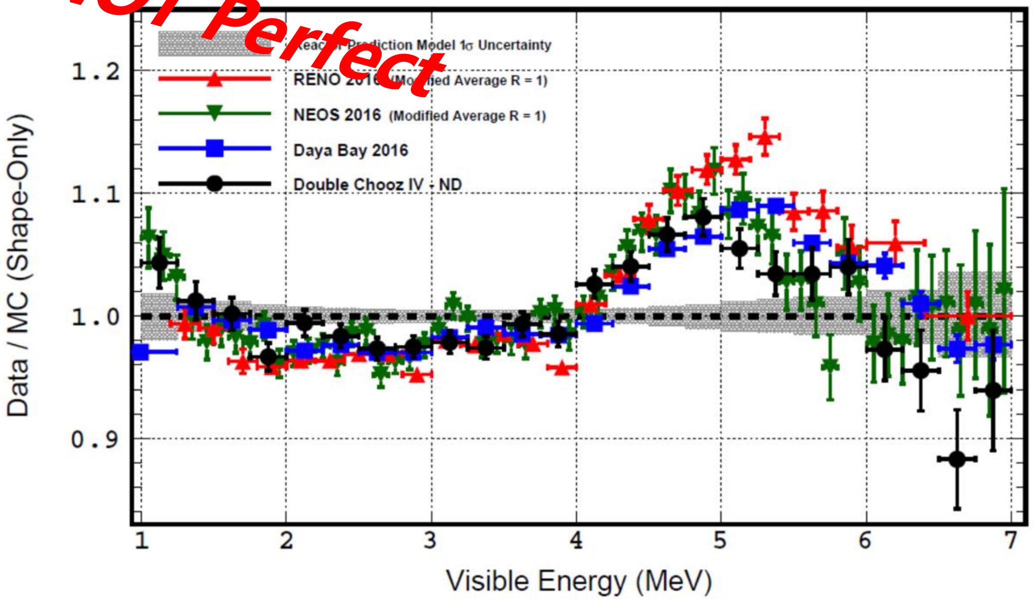


(Fission yield is a function of the fissioning nuclide and the incident neutron energy)



Fission induced by thermal (fission spectrum) neutrons

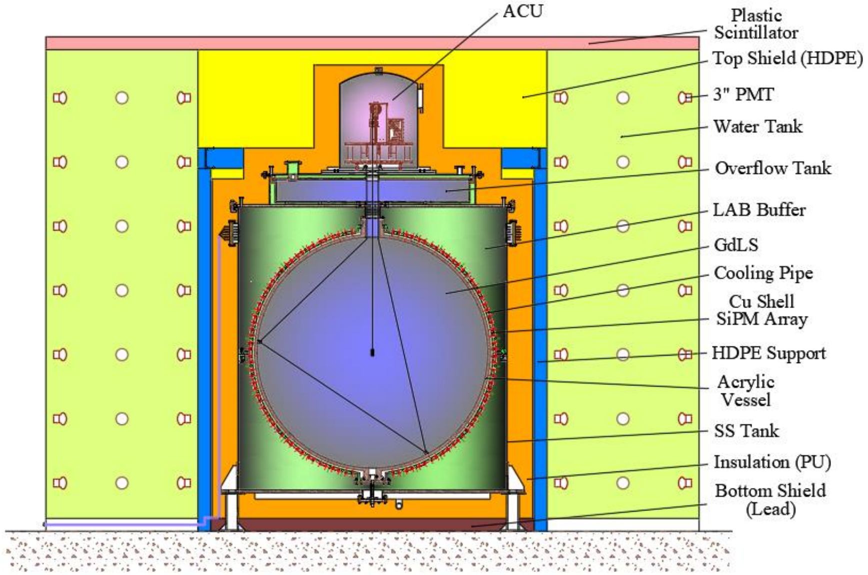
Fission induced by high energy neutrons (14.7 MeV)

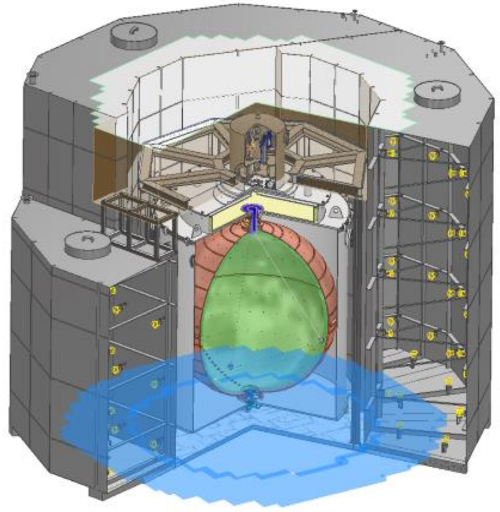


JUNO-TAO: another unprecedented reactor detector

arXiv: 2005.08745

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



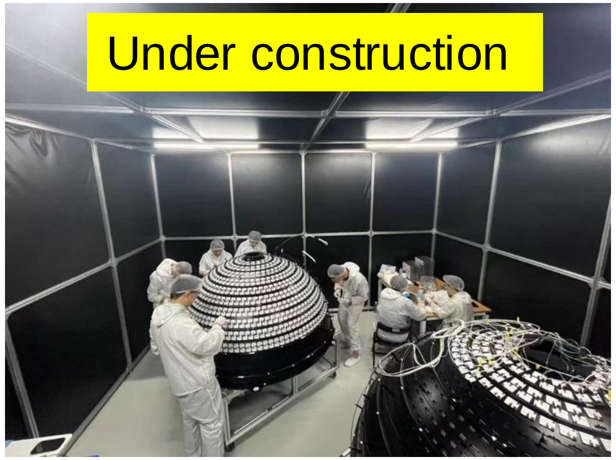


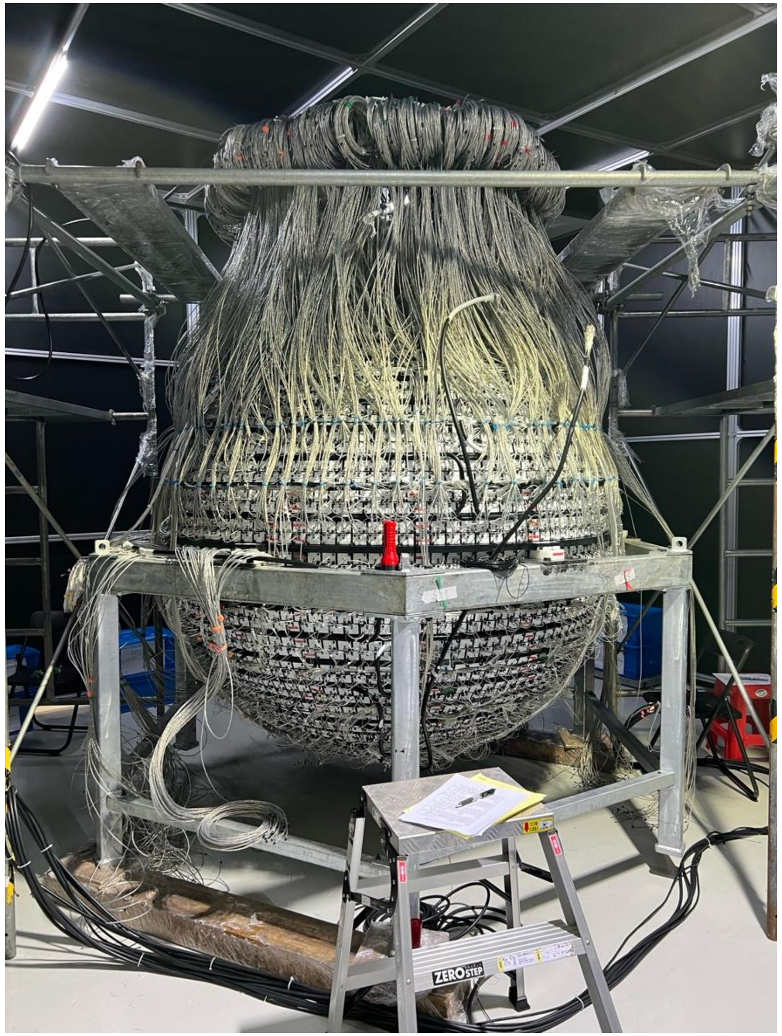
- ✓ SiPMs to achieve high light yield with ~94% coverage
  - ➢ 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

Start construction in Taishan Laboratory since Nov. 2024 and expected to be completed in Summer 2025.

The TAO Detector Installation

arXiv: 2005.08745



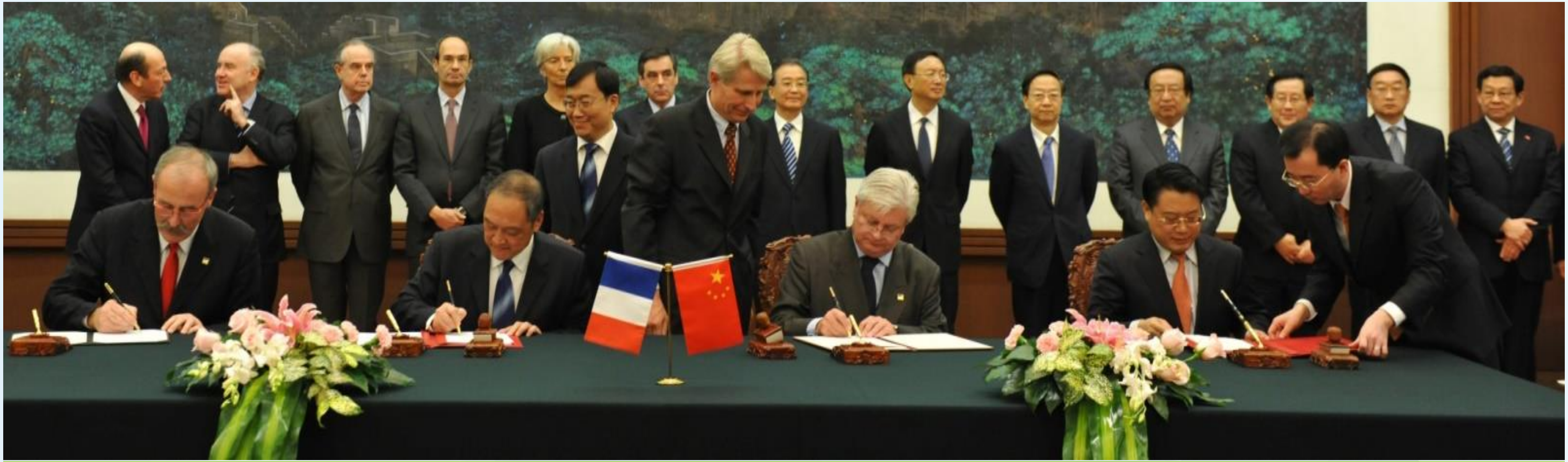


Summary and Future Perspectives

- ❖ Neutrino physics has provided the first new physics beyond the SM and it is now entering the precision phase → **Reactor Neutrinos have been playing essential roles**;
- ❖ JUNO's neutrino physics highlights: neutrino mass ordering 3-4σ in 6 years (reactor neutrino alone); sub-percentage precision oscillation parameter measurements
- ❖ JUNO construction is completed → **Detector filling & Commissioning in parallel: both water and LS quality good**
- ❖ We have been using reactor neutrinos for free --- it is payback time to the nuclear energy industry → **JUNO-TAO has great potential in reactor physics and nuclear data**

➢ ***Stay tuned for our data taking in July 2025!***

2009: IFCEN was jointly built by SYSU and FINUCI, an alliance formed by 5 French partners



SYSU and FINUCI signed the first phase of cooperation (witnessed by the then prime ministers of the two countries at the Great Hall of the People)

GRENOBLE INP UGA
cea instn
Chimie Paris ParisTech
IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom
enscm CHIMIE Montpellier

Academic Path 学术型人才培养；接收推免、硕博连读

全国招生、含推免
Nation Wide Admission

学术型硕士（三年制）
3-Year Academic Master

学术型博士
PHD

学术生源
Academia source

Hoff Class

本科（四年制）
4-Year Bachelor

Curie Class

专业型硕士（中法三年制）
（CTI认证，中英文教学）
3-Year Engineering Master
(Chinese/English Instruction, CTI Accredited)

工程博士
Engineering PHD

业界生源
Industry source

全国招生、含推免
Nation Wide Admission

Professional Path 工程型人才培养；接收推免

核科学与技术
Nuclear Science & Technology

核燃料循环与材料
Nuclear Fuel Cycle & Materials

- 核工程材料与力学
  Nuclear Materials and Mechanics
- 核化学与放射化学
  Nuclear chemistry and radiochemistry

核能科学与工程
Nuclear Energy Science & Engineering

- 核仿真与安全
  Nuclear energy simulation and safety
- 反应堆热工水力
  Nuclear reactor thermal hydraulis
- 先进核能系统
  Advanced Nuclear Energy Systems

核物理
Nuclear Physics

中低能核物理、天体物理、核数据
Low- and medium-energy nuclear physics, astrophysics, nuclear data

核数据科学与应用
Nuclear Data

辐射防护与环境保护
Radiation & Environmental Protection

- 核环境辐射监测与应急
  Nuclear environmental radiation monitoring and emergency response
- 辐射防护与安全
  Radiation protection and safety

核技术及应用
Nuclear Technology & Applications

- 辐射探测
  radiation detection
- 等离子体技术
  plasma technology
- 放射治疗及核医药
  Radiotherapy and nuclear medicine

粒子物理
Particle Physics

粒子物理、新型探测器、中微子应用
Particle physics, novel detectors, neutrino applications

SUN YAT-SEN UNIVERSITY 中山大學

IFCEN just moved into a new building on Zhuhai Campus

We are actively reaching out for new partners in both education and research!

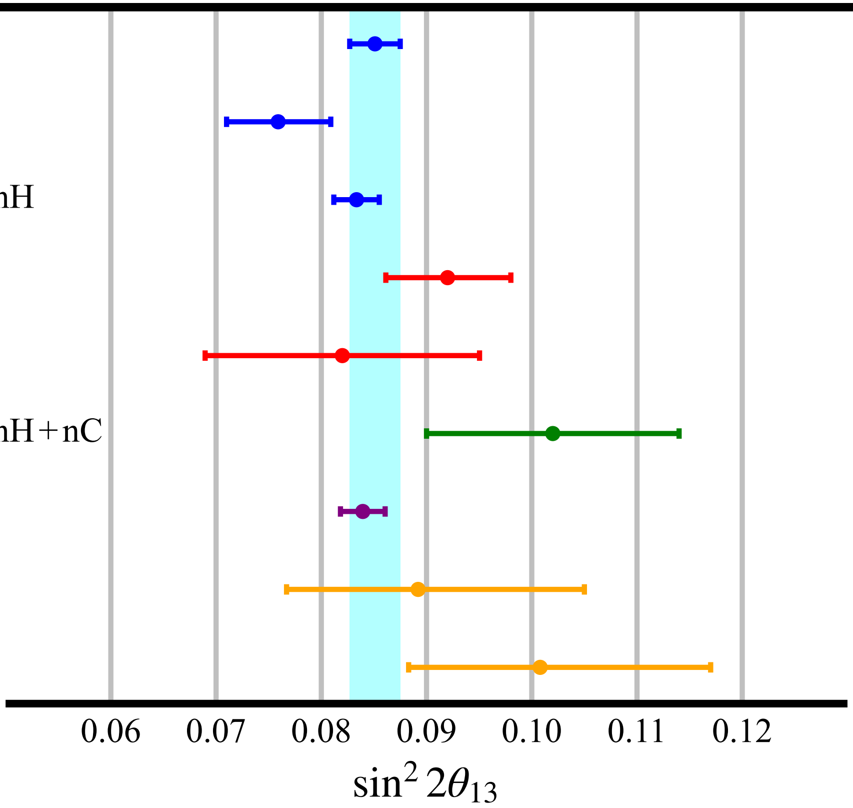
Global comparison θ_{13}

Daya Bay leads the precision measurement, nGd+nH gives 2.6% precision

By combining all reactor results, ultimate precision of $\sin^2 2\theta_{13}$: 2.5%

Consistent results from reactor and accelerator experiments

Experiment		Value	
Daya Bay	**nGd**	**0.0851** $\pm$**0.0024**	2.8%
	nH	0.0759 $^{+0.0050}_{-0.0049}$	6.5%
	nGd+nH	0.0833 $\pm$0.0022	2.6%
RENO	nGd	0.0920 $^{+0.0060}_{-0.0059}$	6.5%
	nH	0.082 $\pm$0.013	15.9%
Double Chooz	nGd+nH+nC	0.102 $\pm$0.012	11.8%
Reactor Average		0.0839 $\pm$0.0021	2.5%
T2K + NOνA	NO	0.0892 $^{+0.0158}_{-0.0125}$	15.9%
	IO	0.1008 $^{+0.0162}_{-0.0125}$	14.2%



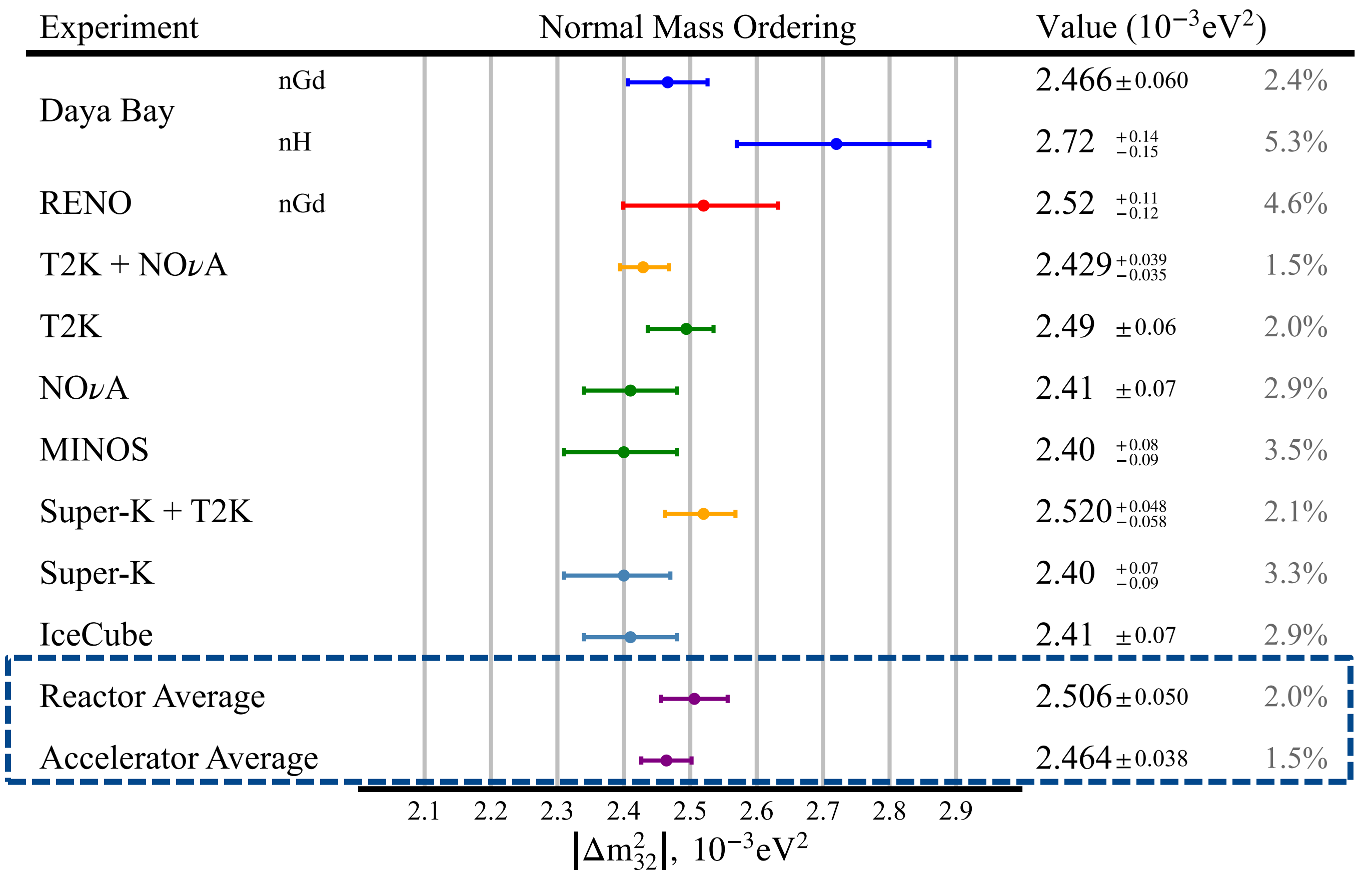
Note: average is error weighted average assuming no correlation

Global comparison Δm^2

Consistent results from reactor and accelerator experiments

Reactor weighted average 2% dominated by Daya Bay

Accelerator weighted average 1.5% (SK+T2K) + NOvA + MINOS + IceCube

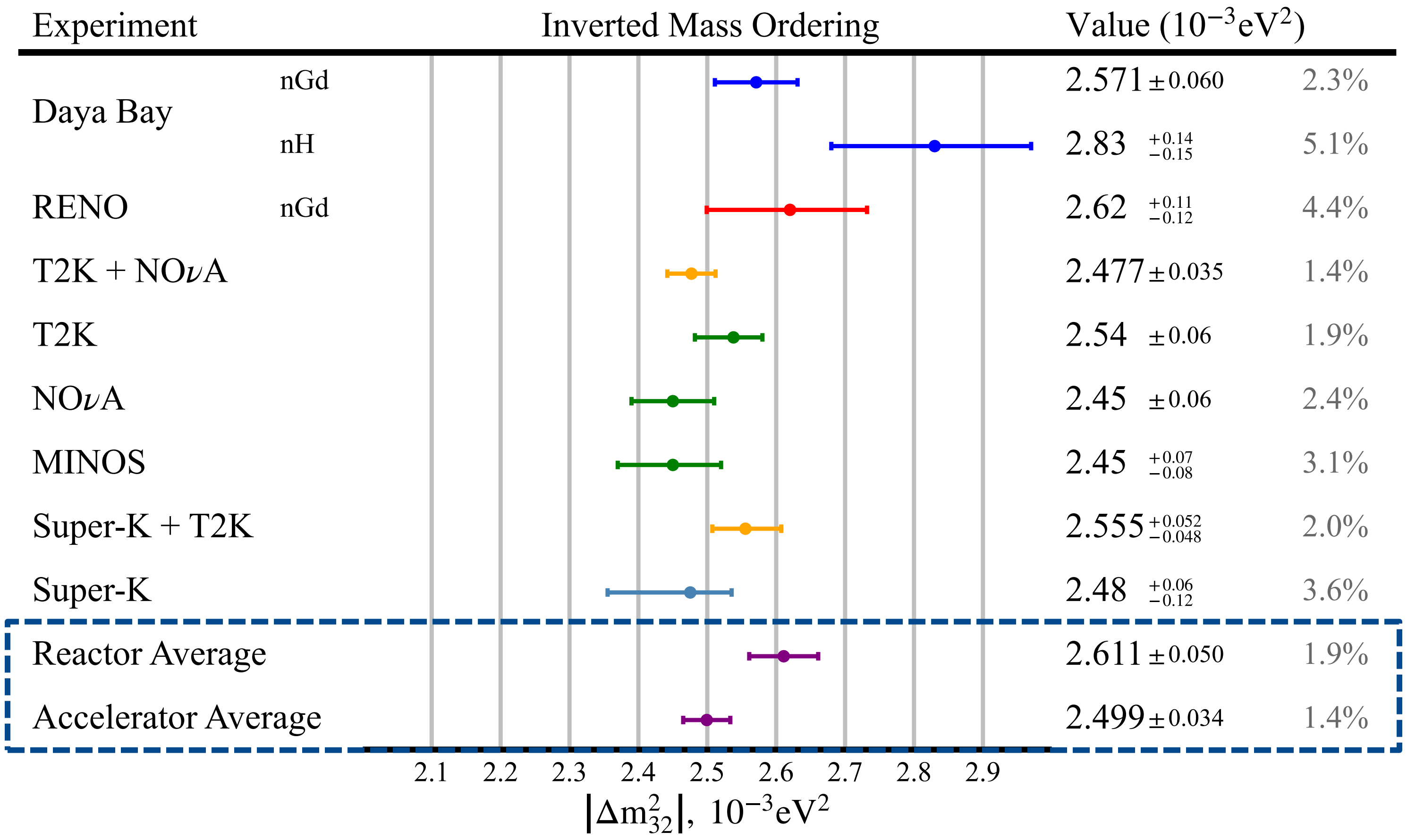


Note: average is error weighted average assuming no correlation

Global comparison Δm²

Consistent results from reactor and accelerator experiments

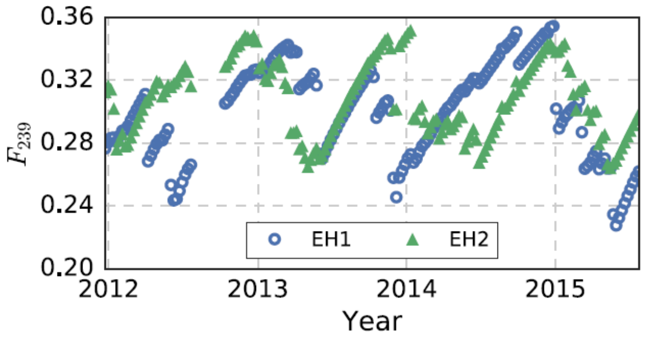
Normal Ordering slightly preferred (<2σ) from reactor/accelerator averages

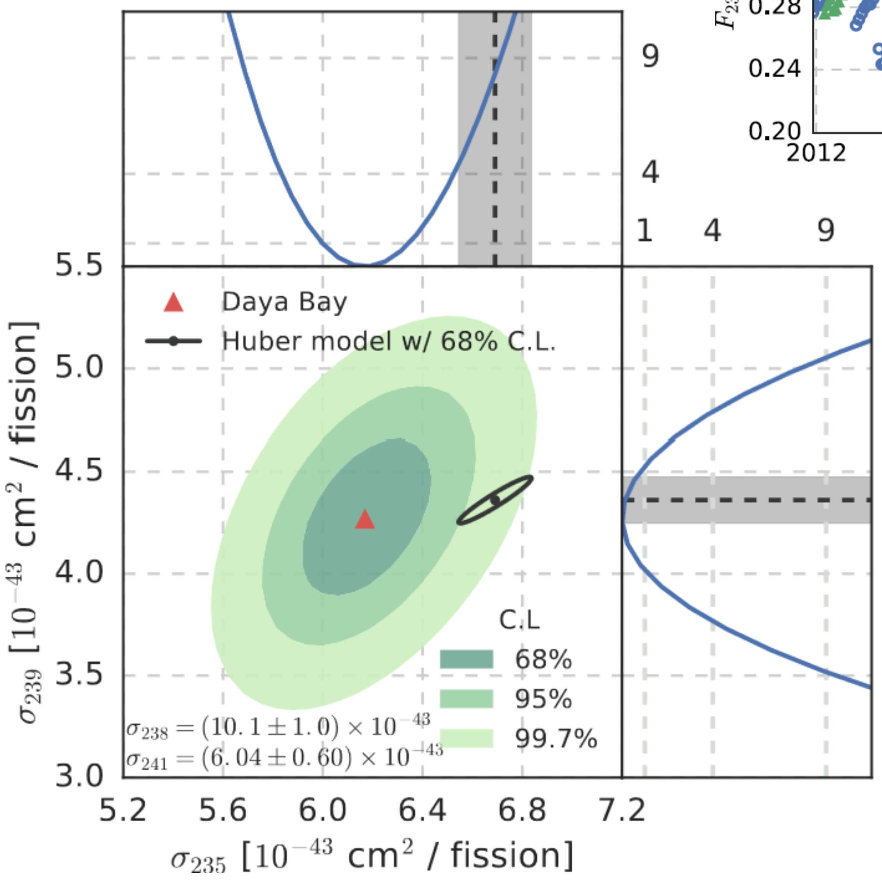


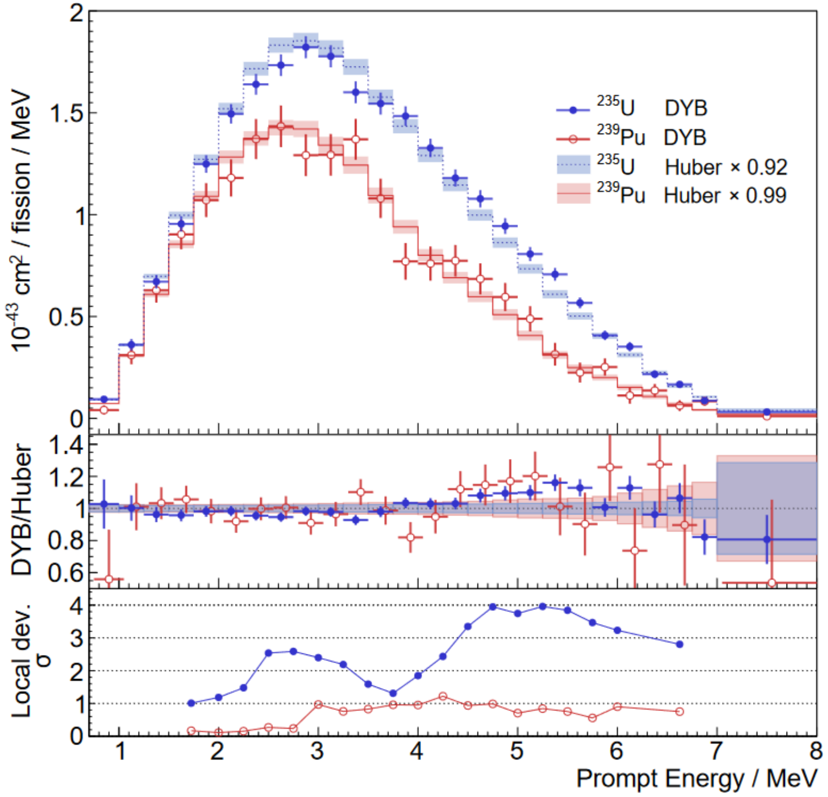
Note: average is error weighted average assuming no correlation

Understanding Reactor Antineutrinos: Fuel Evolution

- ***Fuel evolution: Phys.Rev.Lett. 118 (2017) no.25, 251801***
- **Isotope decomposition**, *PRL 123 (2019) no.11, 111801*





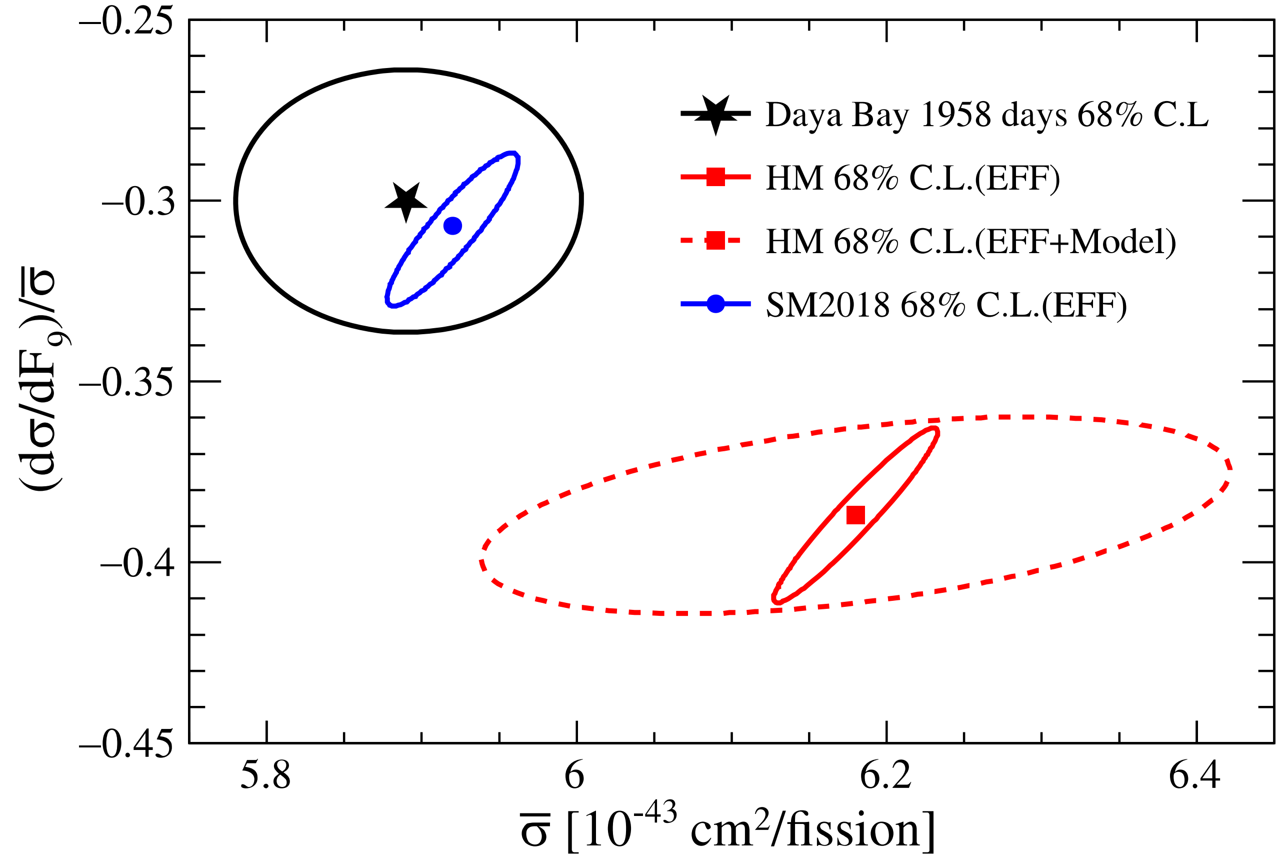


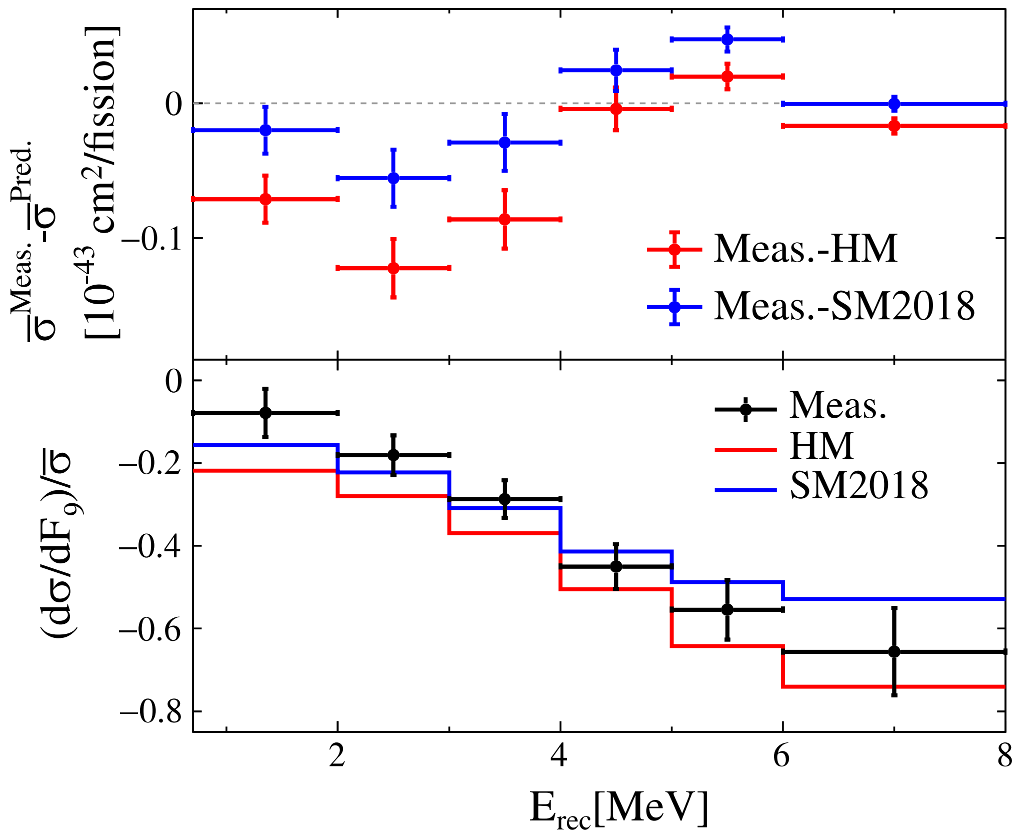
^{235}U: 4-sigma effect

^{235}Pu: 1.2-sigma effect

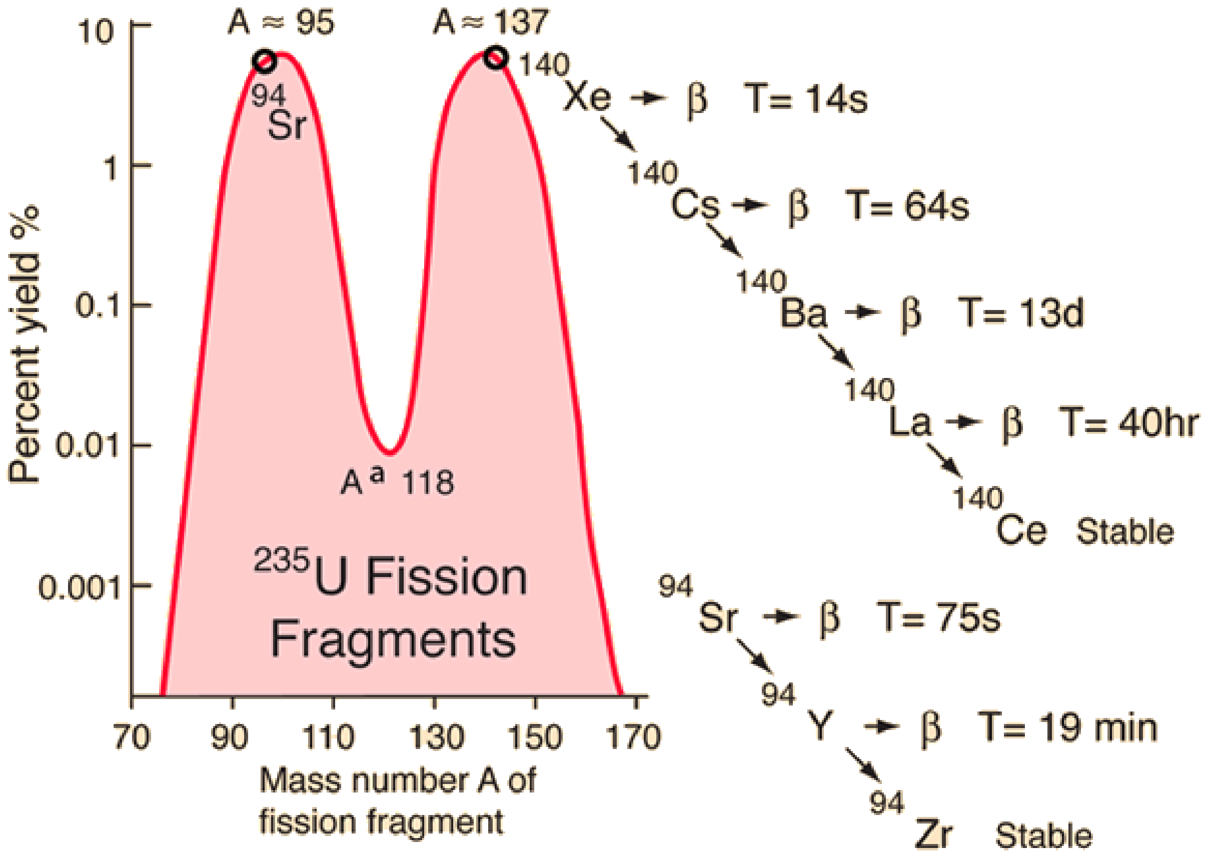
Understanding Reactor Antineutrinos: Improved Systematics

- ***Improved Fuel evolution: Phys.Rev.Lett. 130 (2023) no.21, 211801***

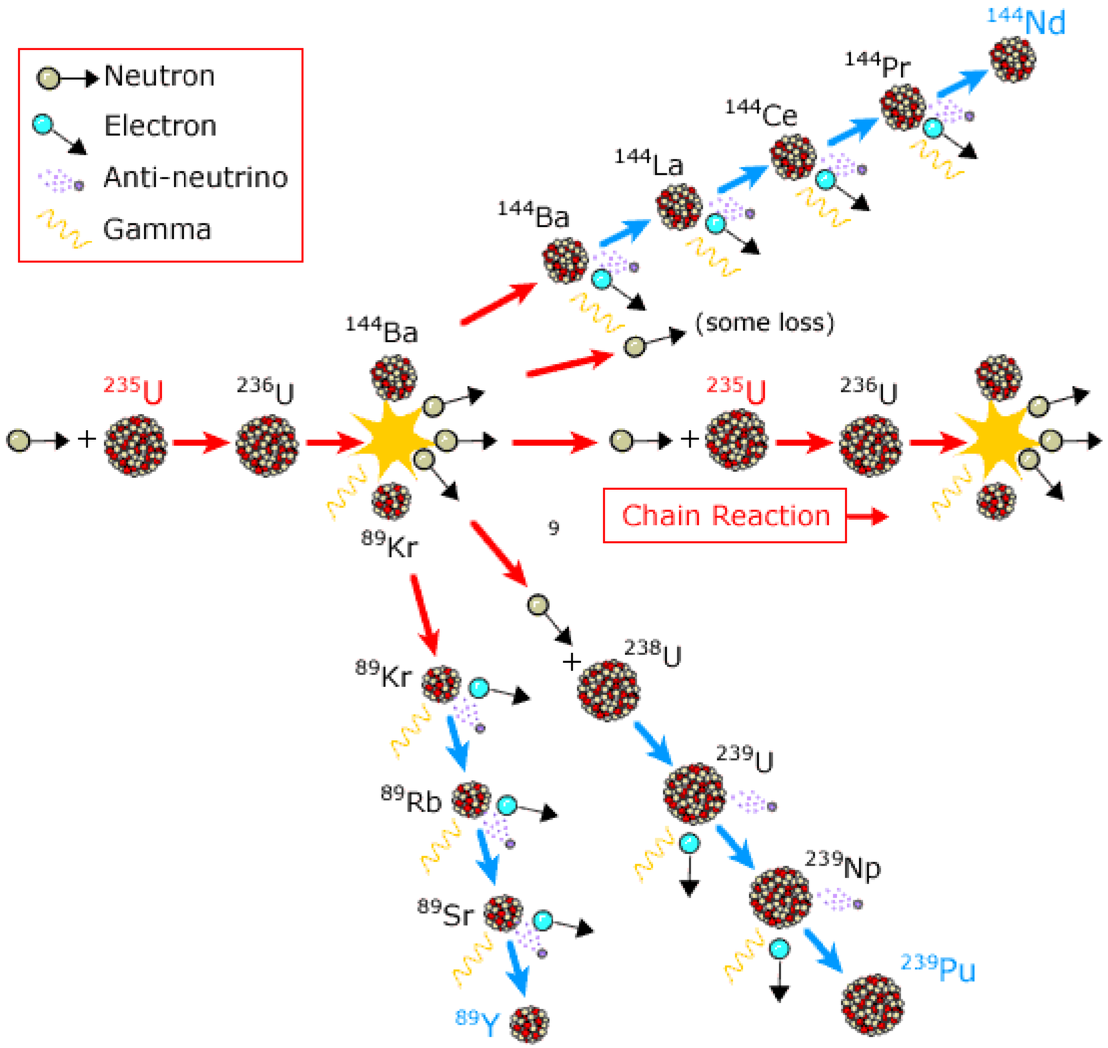




How Reactor Neutrinos are Produced



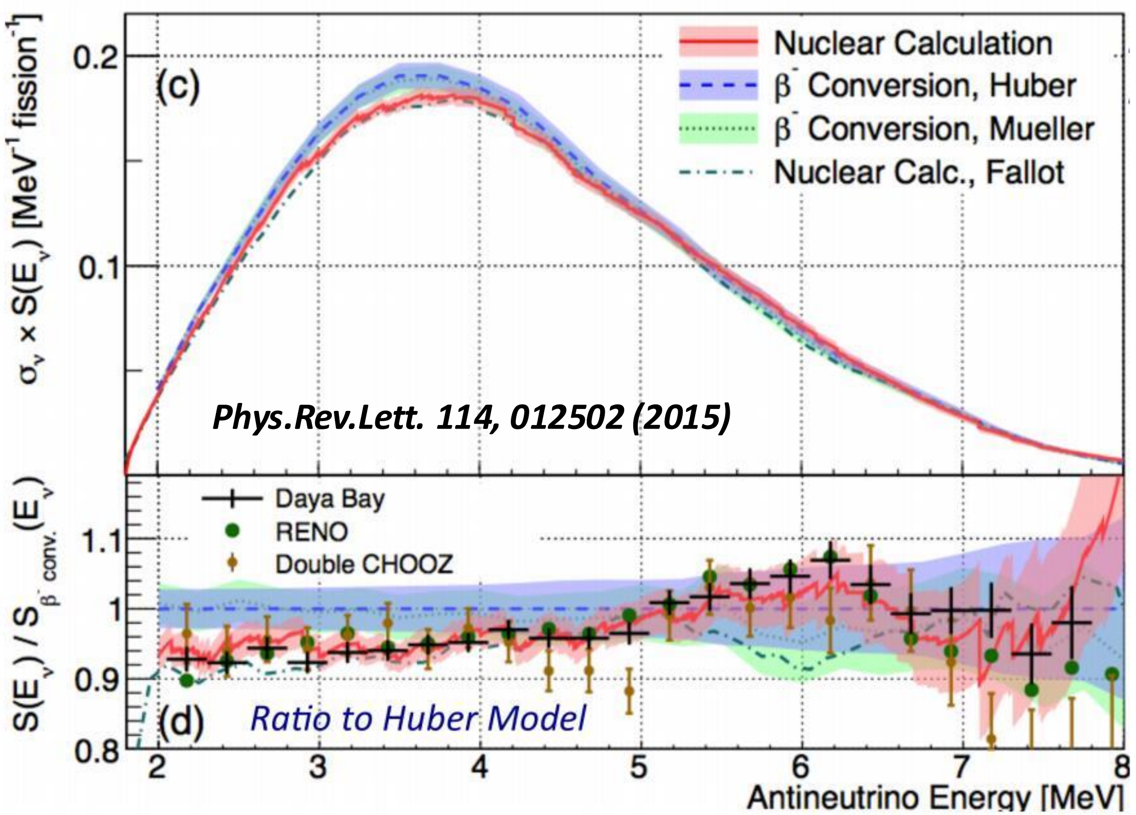
❖ *Six antineutrinos/fission up to ~10MeV*



The "*ab initio*" (summation) Method

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\bar{\nu}})$$

f_{ij} — the branching fraction of isotope i decaying to the energy level j of daughter isotope



R_i — the equilibrium decay rate of isotope i

$$R_i \cong \sum_{p=0}^{P} R_p^f Y_{pi}^c$$

- ✓ R_p^f — the fission rate of the parent *isotope* p
- ✓ Y_{pi}^c — the cumulative yield of isotope i

The 5 MeV bump was predicted with **a large uncertainty** from summation calculation.

Additionally, the **saw-tooth structures** were also predicted in the summation spectrum.

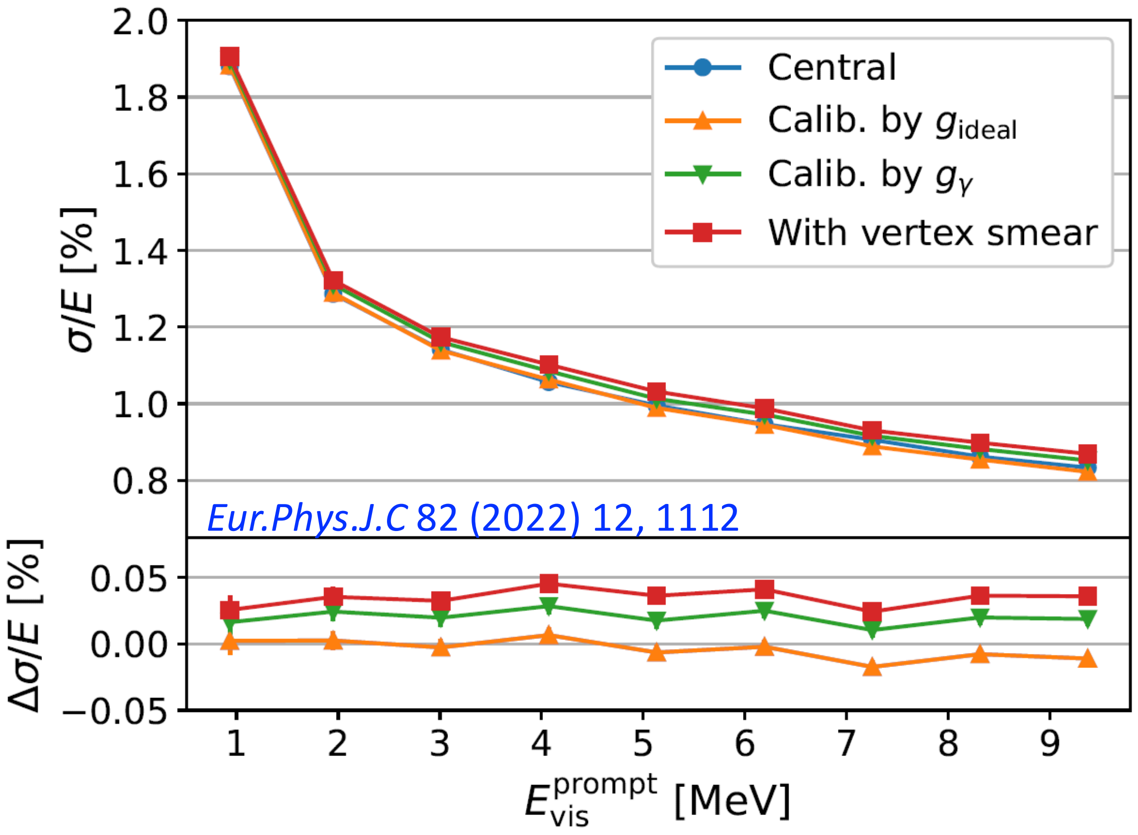
The Tao Site

- Taishan Nuclear Power Plant has two cores currently in operation (other two cores might be built later)
- Both reactors are European Pressurized Reactor (EPR) with 4.6 GWth thermal power
- Taishan-1 reached first criticality and was connected to the grid in June 2018
  - the first running EPR in the world!

- The TAO detector will be installed in a basement at 9.6 m underground, outside of the concrete containment shell of the reactor core
  - >99.99% signal from Taishan-1+Taishan-2
  - 4% signal from Taishan-2
- Muon rate and cosmogenic neutron rate are measured to be 1/3 of those on the ground

TAO Energy Resolution

	JUNO	TAO
Coverage	~ 75%	~ 94%
Photon detection efficiency	~ 30%	> 50%
Attenuation length	> 20 m (R = 17.2 m)	> 20 m (R = 0.9 m)
Photoelectron yield	~ 1665 PE/MeV	~ 4500 PE/MeV
Energy resolution	2.95% @ 1 MeV	~ 2% @ 1 MeV



Non-stochastic effects affecting energy resolution in TAO:

- at low energies, the contribution from the LS quenching effect might be quite large;
- at high energies, the smearing from neutron recoil of IBD becomes dominant.

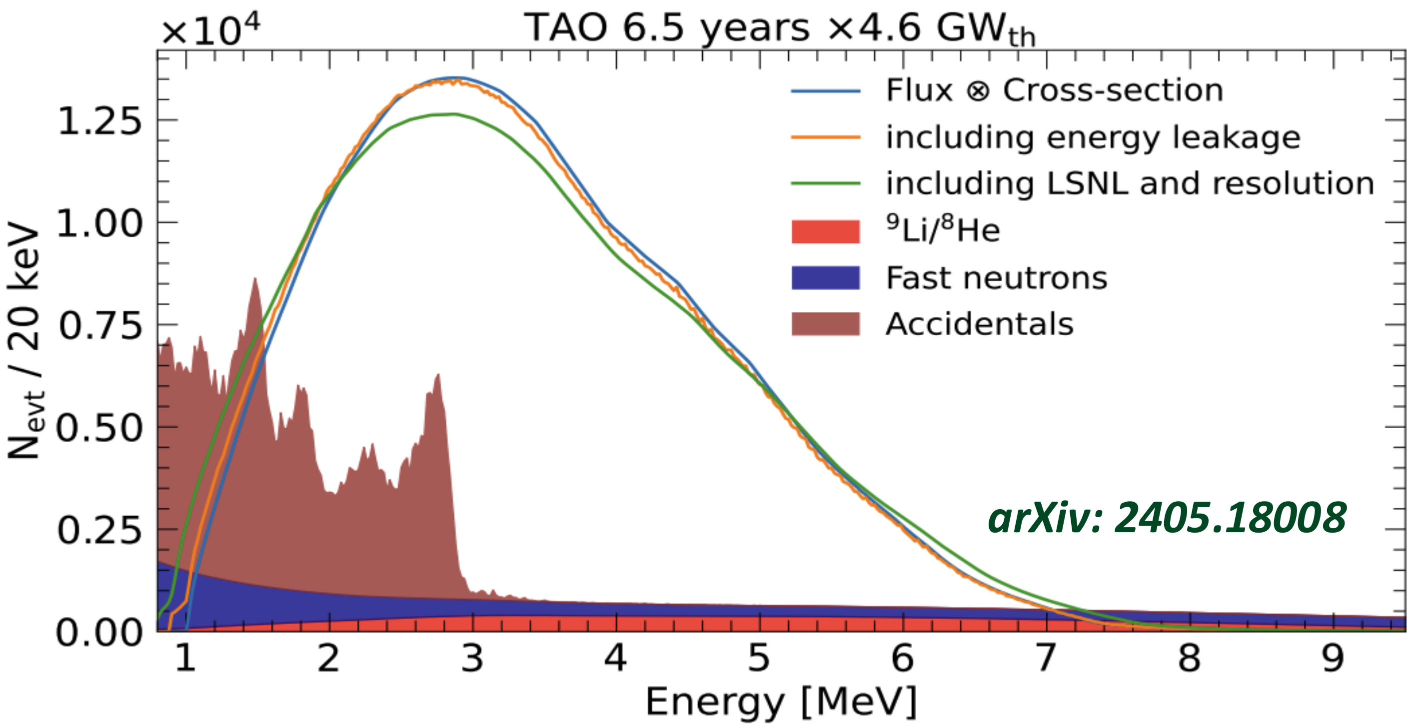
1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, $\boldsymbol{L_{absorption}}$ very small
3. Gd-LS works at -50℃, increase the photon yield

In most of the energy region of interest, the energy resolution of TAO will be sub-percent!

TAO Expected Signal and Background

- The signal spectrum is shown w/ and w/o applying energy leakage, liquid scintillator non-linearity (LSNL), and energy resolution effects.

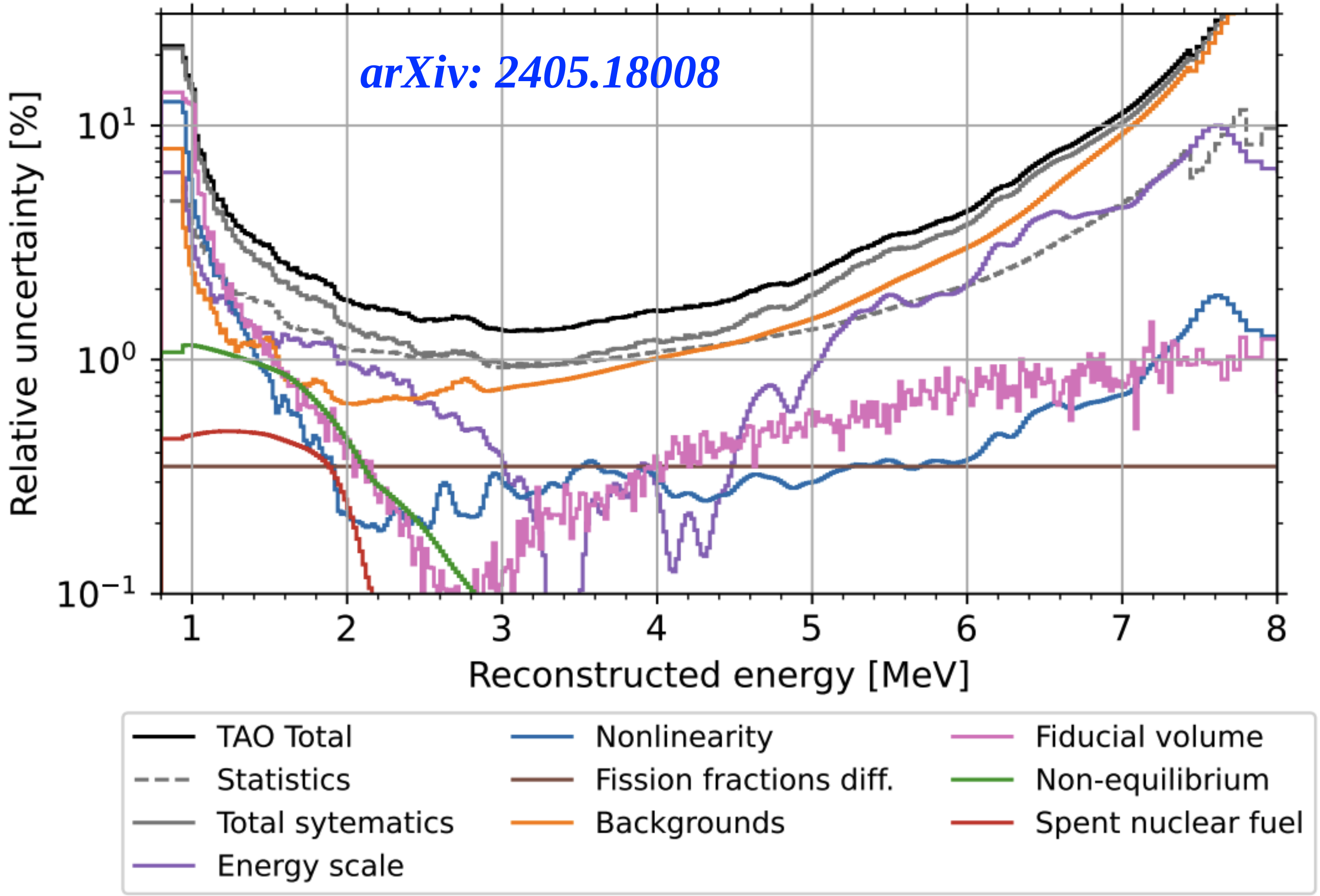
- TAO backgrounds will be directly measured exploiting the reactor-off data (about one month per year)



Type	Rate [day^{-1}]	Rate Uncert. [%]	Shape Model	Shape Uncert. [%]
Signal	1000	10	same as JUNO	FF, FV, ES
Fast neutron	86	–	TAO simulation	<10%
^{9}Li/^{8}He	54	20	same as JUNO	10%
Accidental	190	1	same as JUNO	–

Shape Uncertainty of the TAO Spectrum

- Statistical uncertainty: ~1% in the energy range 2−5 MeV (20keV bin width)
- Systematic uncertainties not negligible at low/high energies, but are ~1% in the central energy range 2−5 MeV



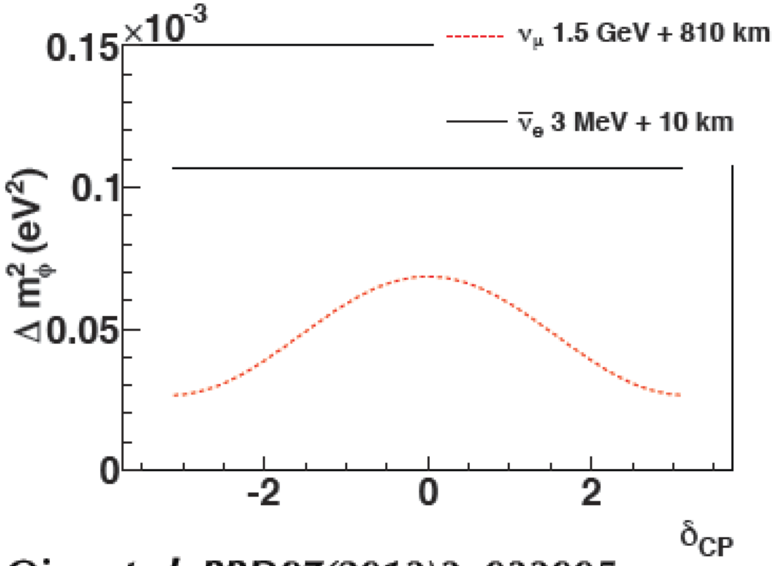
e- / μ-Flavor Feels Mass Ordering Differently

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

$$= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1 - 4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

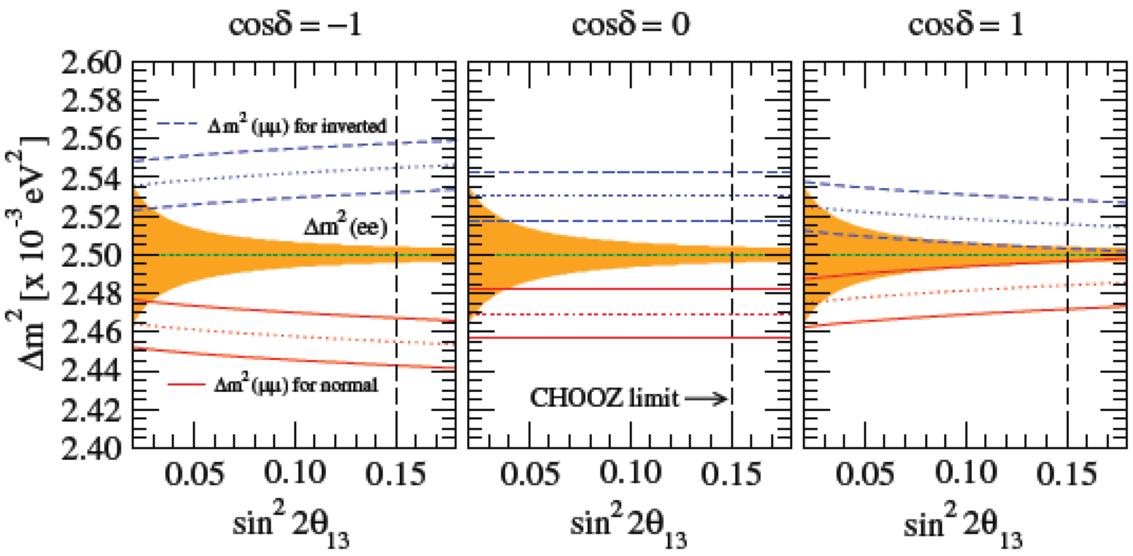
$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$

- *Both reactor and long-baseline experiment measure mass-squared splitting*
- *A natural question to ask: Is this meaningful?*



Qian et al, PRD87(2013)3, 033005

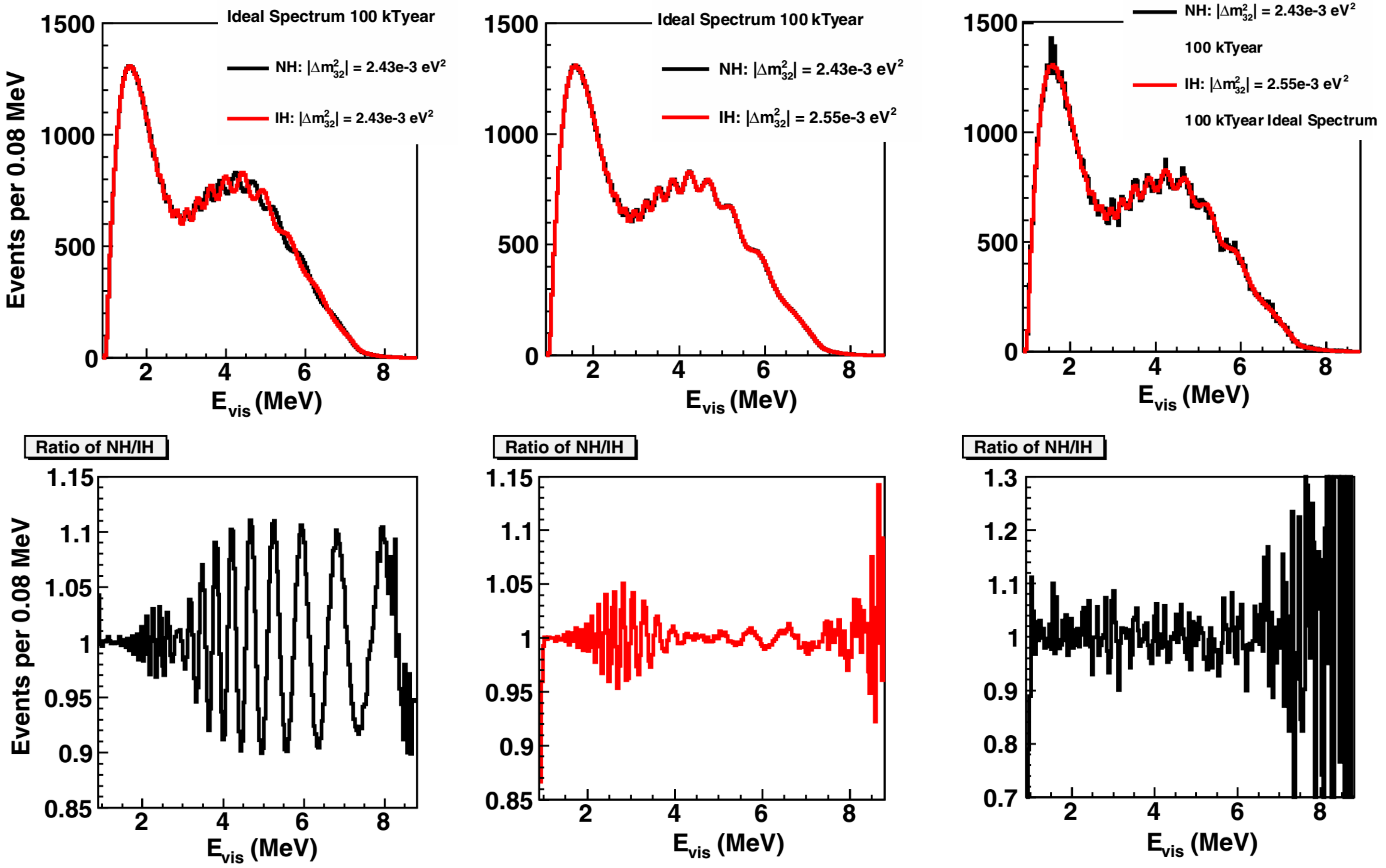
FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



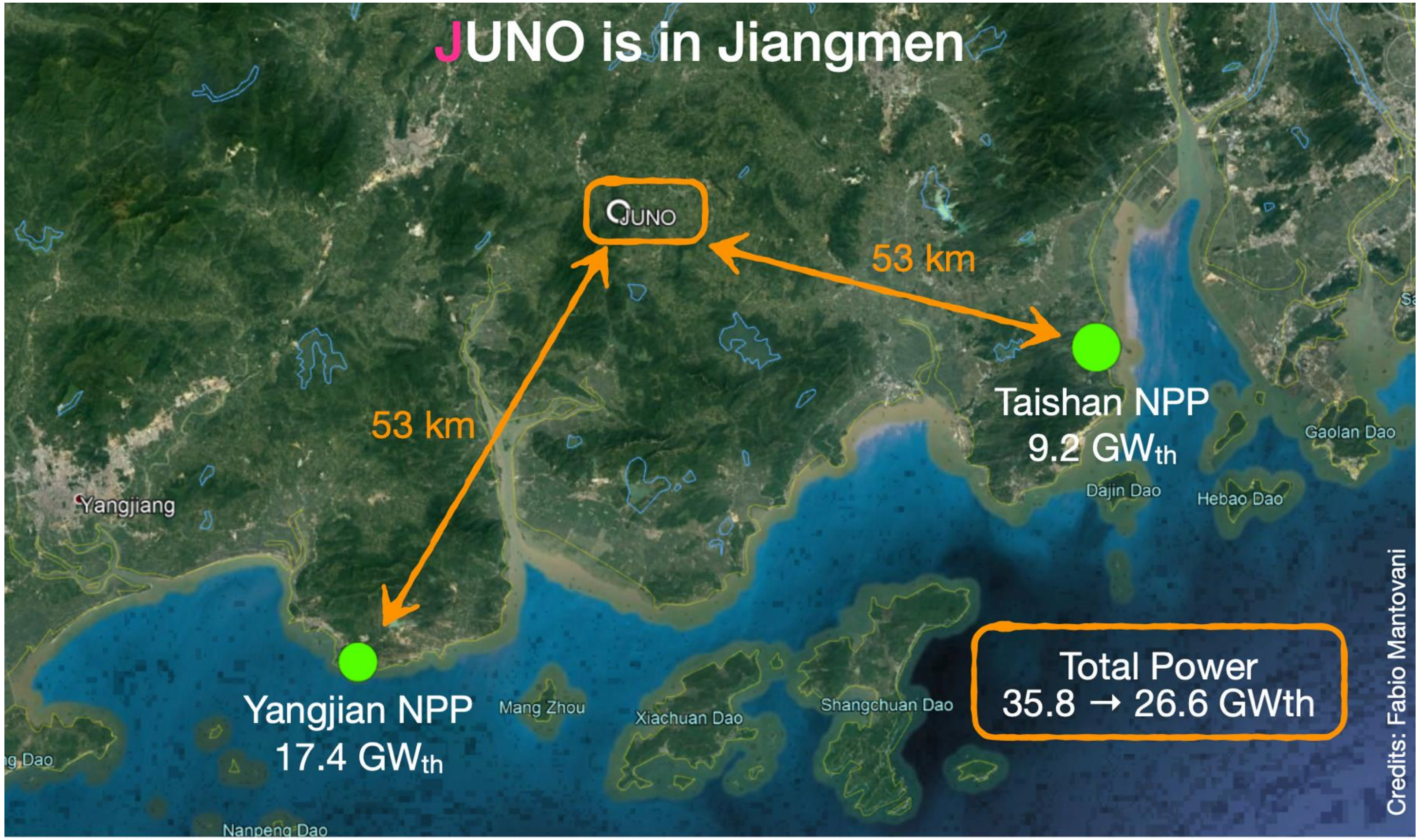
Minakata et al PRD74(2006), 053008

Also See: Zhang&Ma, arXiv:1310.4443/ Mod. Phys. Lett. A29 (2014) 1450096

Challenges in Resolving MH using Reactor Sources



The Jiangmen Underground Neutrino Observatory



Taishan Power Plant

Yangjiang Power Plant

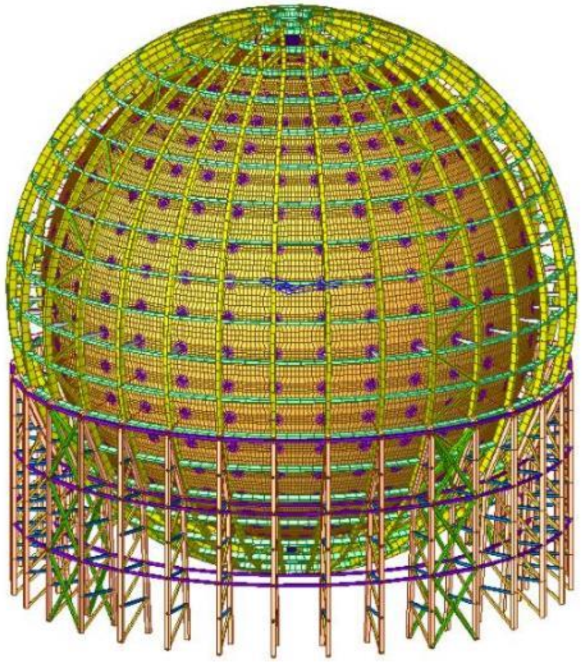
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

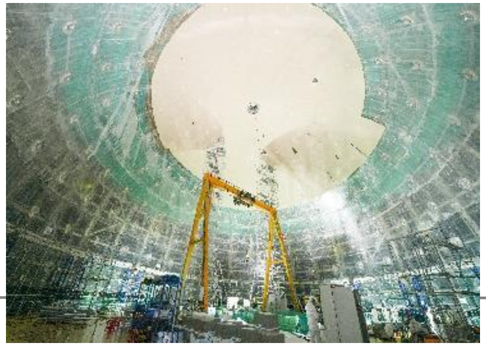
8 Reactors Operating

The Central Detector

arXiv: 2311.17314 (2023)

- **35.4 m spherical acrylic vessel, containing 20 kton LS, supported by the 41.1 m Stainless Steel structure via 590 supporting bars**
- **SS structure completed except bottom 4 layers**
- **Acrylic panel production completed**
  - A special production line for low backgrounds (< 1 ppt U/Th/K)
  - Processed while maintaining **high transparency** (>96%) and **low surface background** (<5 ppt U/Th in 50 μm thickness): Shaping, sanding/polishing, cleaning, machining, and protection of panels by PE film
- **Acrylic vessel construction on-going (critical path)**
  - SS structure built from bottom to top, then, acrylic built from the top to bottom, layer by layer, **17/23 layers finished**, defects repaired
  - SS bars connecting the acrylic and SS, sensors for stress monitoring

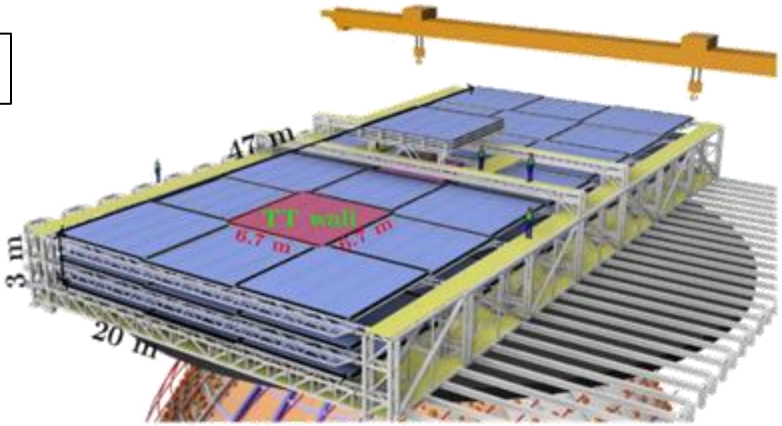


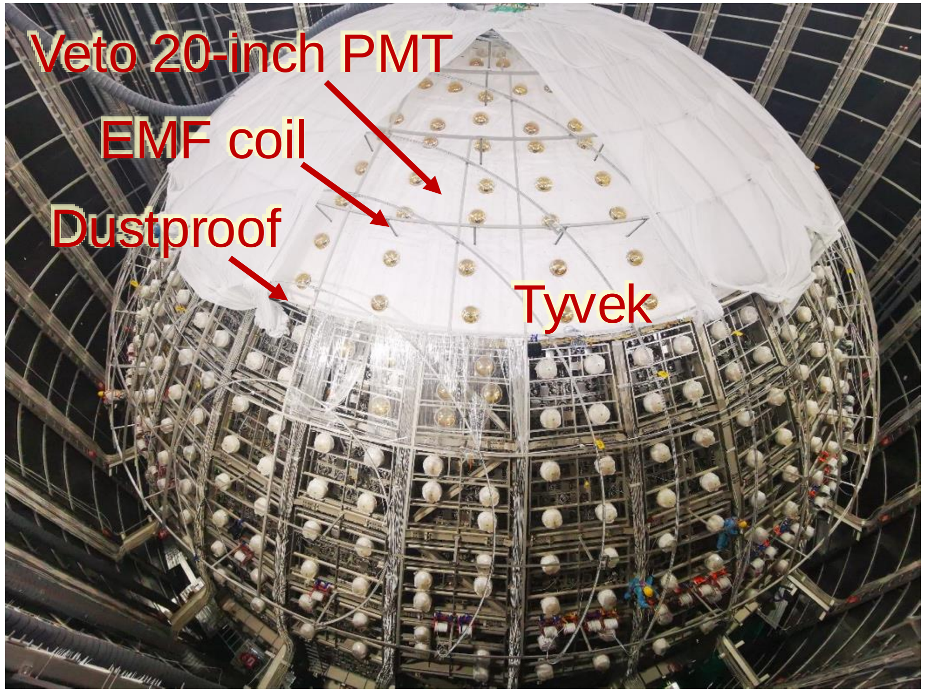


Veto Detectors

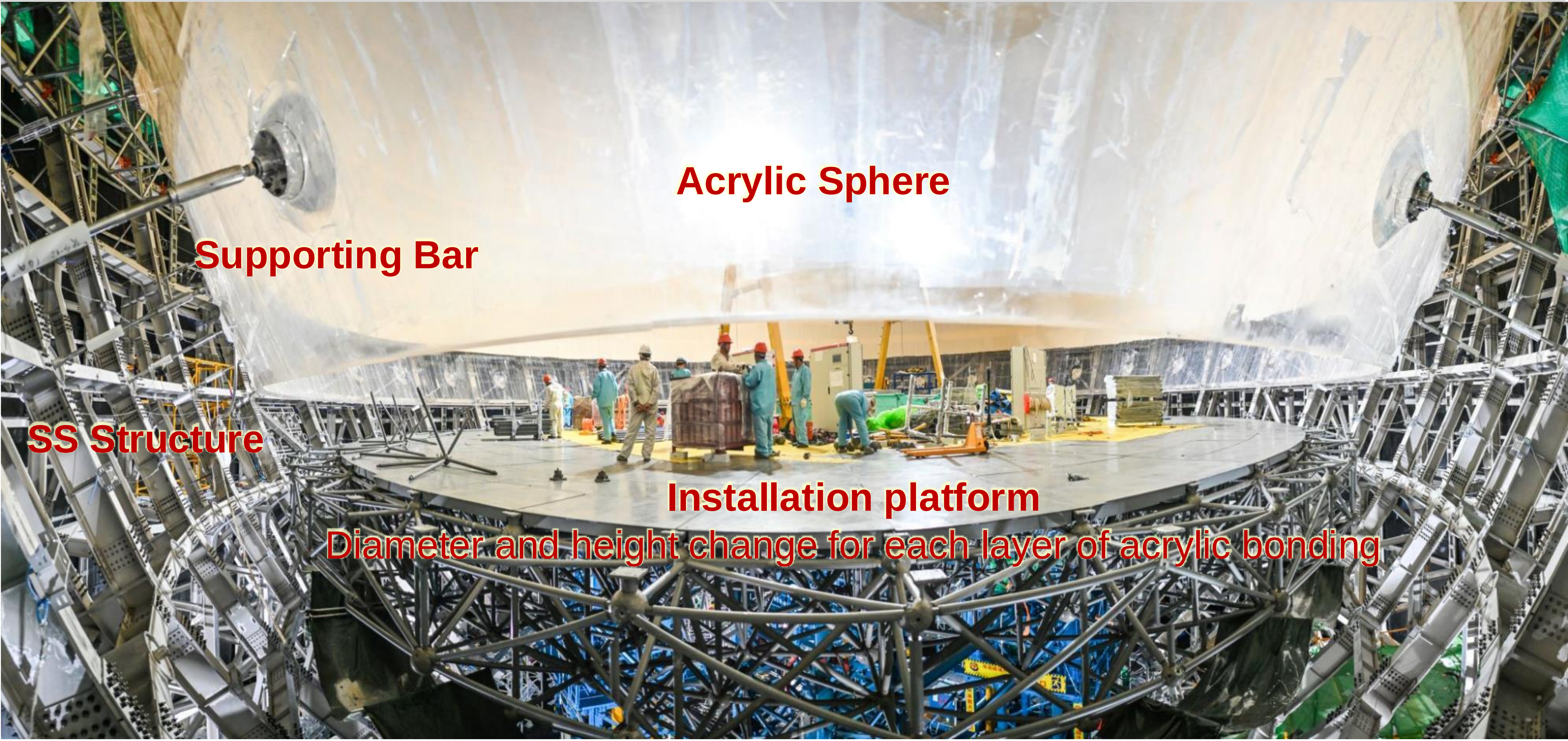
NIMA 1057 (2023) 168680

- Water Cherenkov + Top tracker
- Water Cherenkov detector
  - 35 kton water to shield backgrounds from the rock
  - Instrumented w/ 2400 20-inch PMTs on SS structure
  - Water pool lining: 5 mm HDPE (black) to keep the clean water and to stop Rn from the rock, will cover w/ tyvek
  - 100 ton/h pure water system installed. Requirement: U/Th/K<10^{-14} g/g and Rn<10 mBq/m^3, attenuation length>40 m, temperature controlled to (21±1) °C
- Top tracker (to be installed)
  - Refurbished OPERA scintillators
  - 3 layers, ~60% coverage on the top
  - $\Delta\theta \sim 0.2°$, $\Delta D \sim 20$ cm
- Earth Magnetic Field compensation coil





Inside the Detector



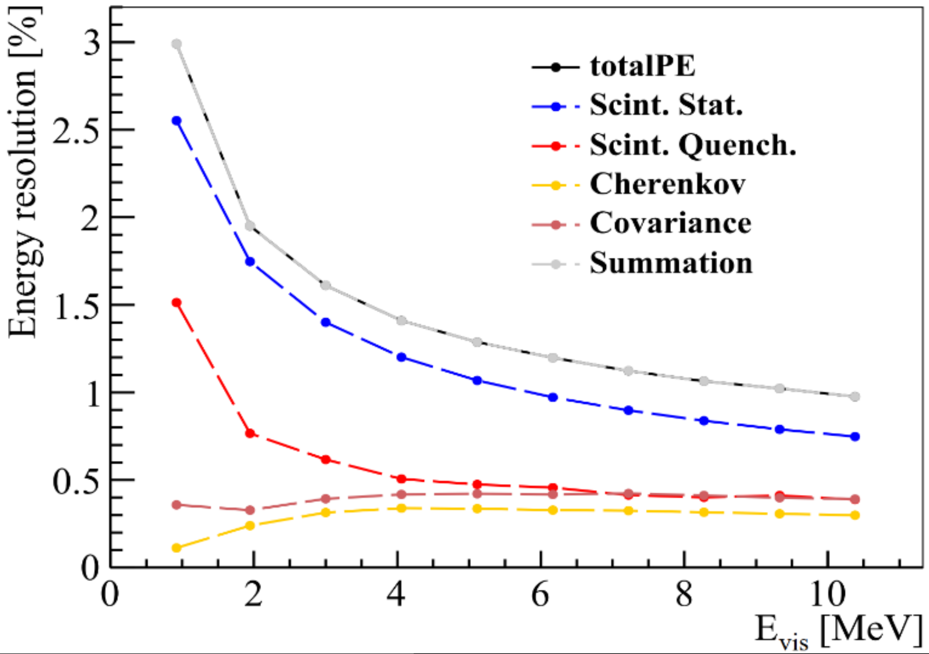
Calibration and Expected Energy Resolution

- Four systems for 1D, 2D, 3D scan with multiple sources
- Energy scale and non-linearity will be calibrated to <1% using γ peaks and cosmogenic ^{12}B beta spectrum

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

Photon statistics — Constant term — Dark noise, Annihilation -induced γs

Expected energy resolution: **2.95% @1MeV**

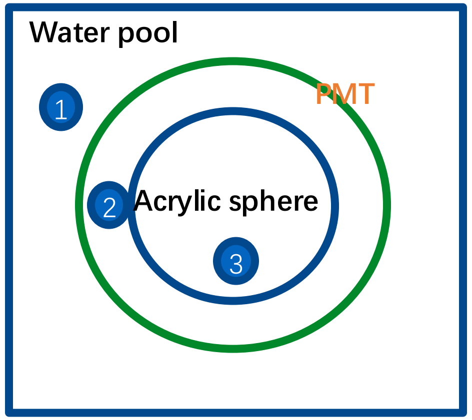


JHEP 03 (2021) 004	arXiv:2405.17860 (2024)

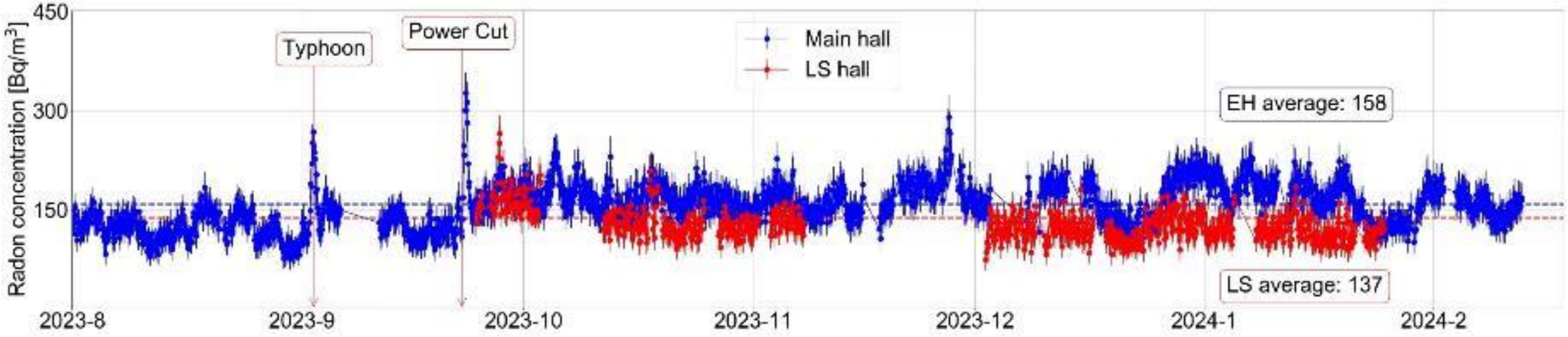
A Controlled Installation Environment for Cleanness

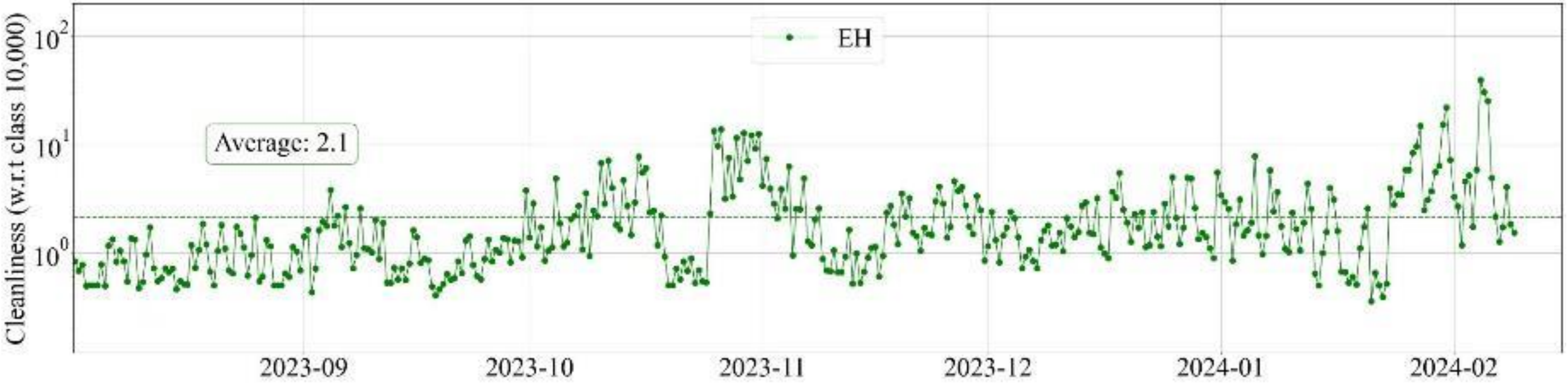
- Average radon and cleanliness:
  - Radon concentration: ~160 Bq/m^3 in the EH, ~140 Bq/m^3 in the LS hall
  - Cleanliness: class 20,000

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



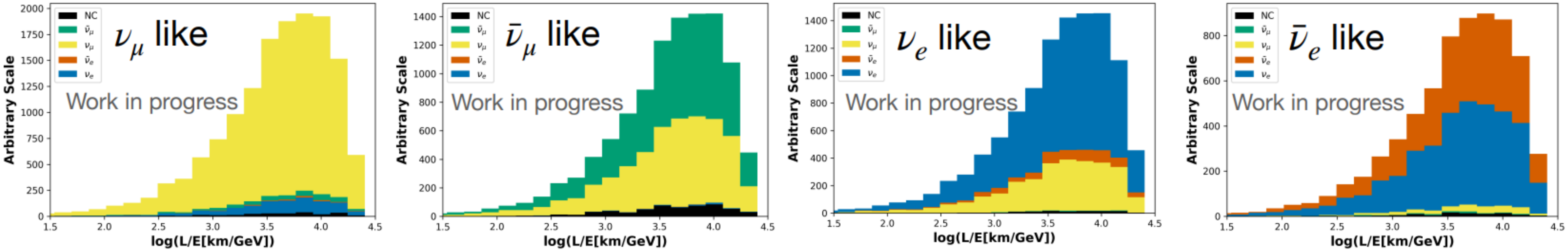
Radon concentration in air: < 200 Bq/m^3



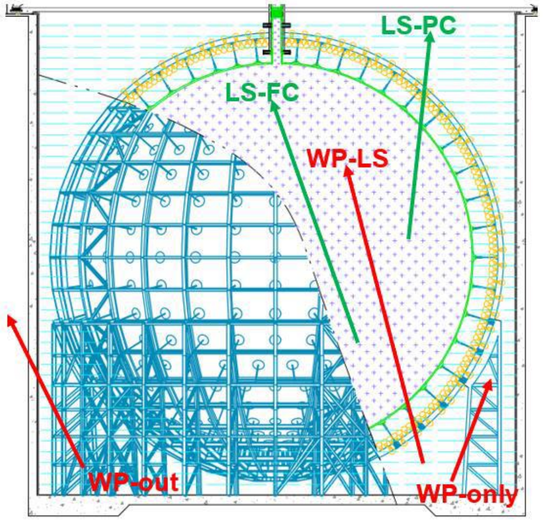


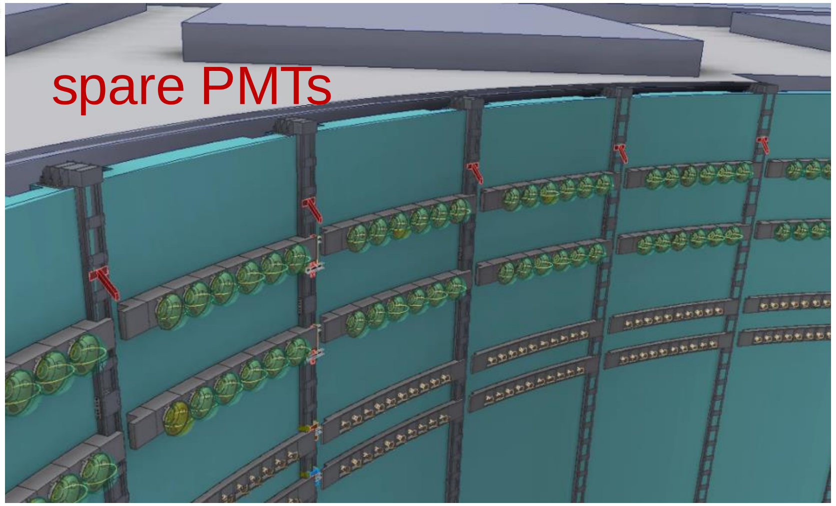
Adding Contributions from Atmospheric Neutrinos

- JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator:
  e/μ separation, $\boldsymbol{\nu}/\bar{\boldsymbol{\nu}}$ separation, ν energy (instead of lepton energy), track direction in LS



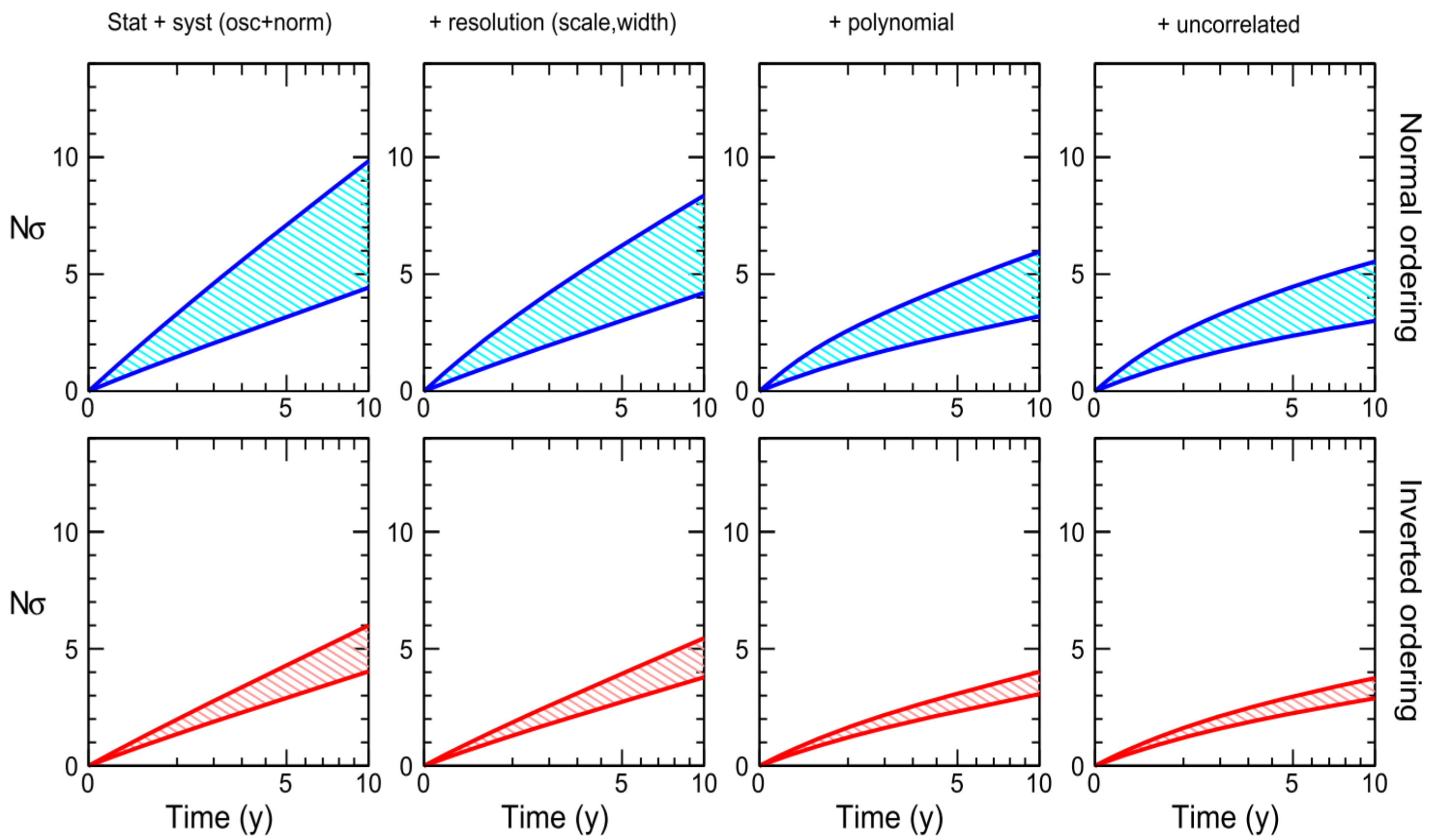
- ❖ **Improving the reconstruction and PID algorithm, as well as sensitivity**
- ❖ **Plan to install all spare PMTs on top wall of the water pool to improve PID and direction reconstruction**

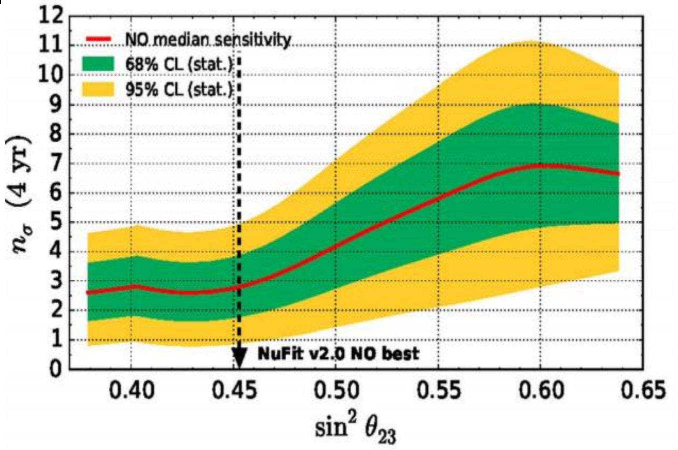


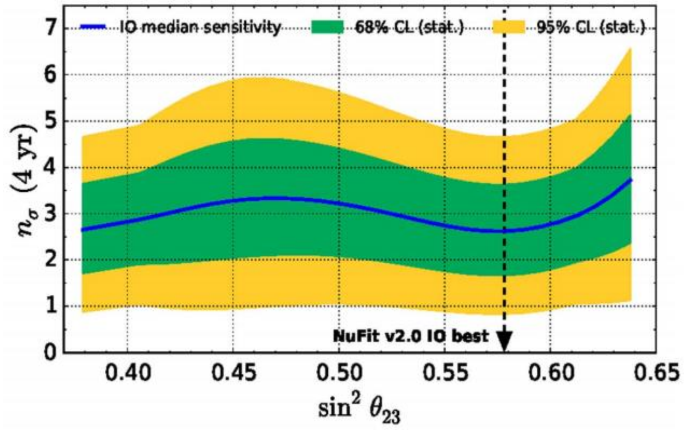


KM3NeT/ORCA and PINGU Sensitivities

- More advantageous for the normal ordering case
- Uncertain due to a different unknown parameter, the atmospheric mixing angle

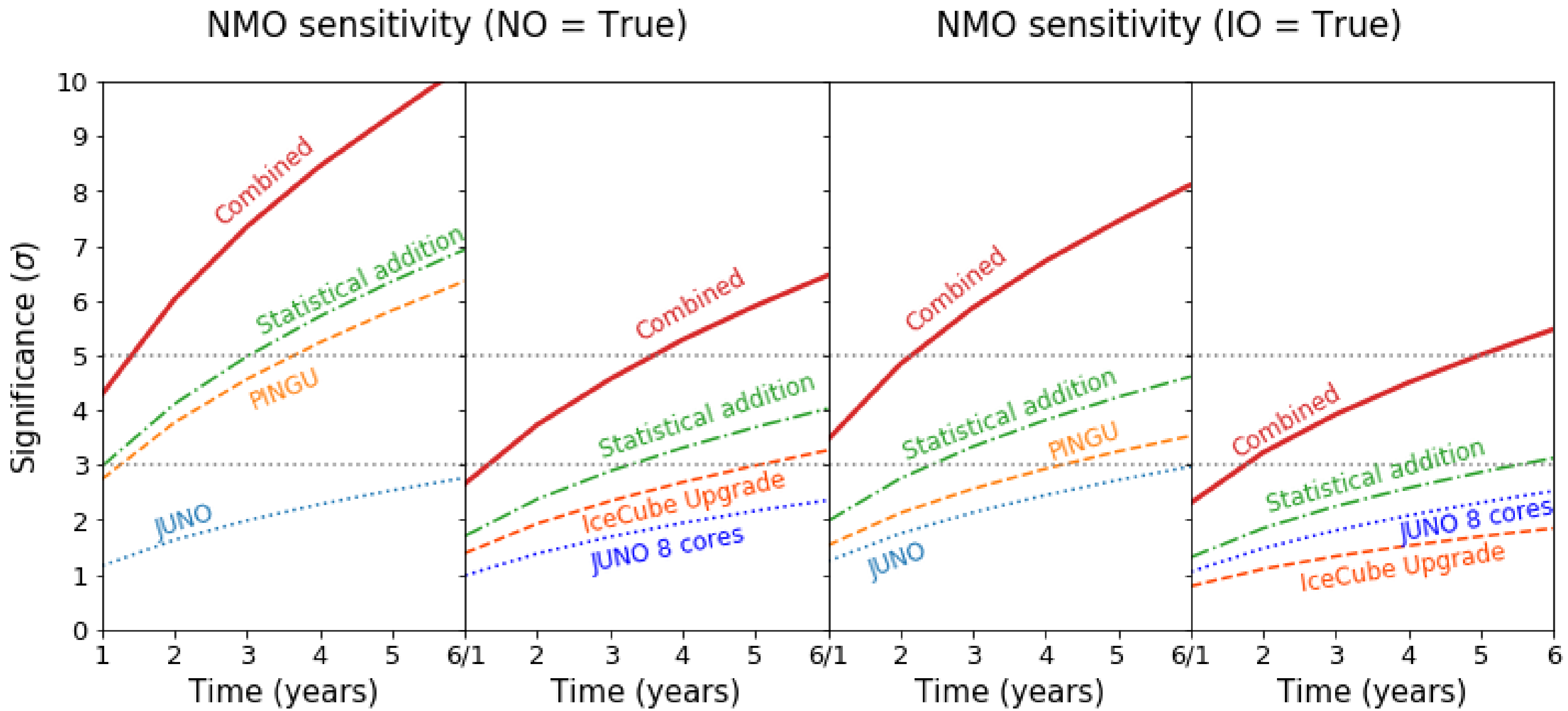






- ***F Capozzi et al for KM3NeT/ORCA, PINGU Group for PINGU***
  J. Phys. G: Nucl. Part. Phys. 45 (2018) 024003

Combining JUNO and PINGU/DeepCore *(courtesy of M. Wurm)*

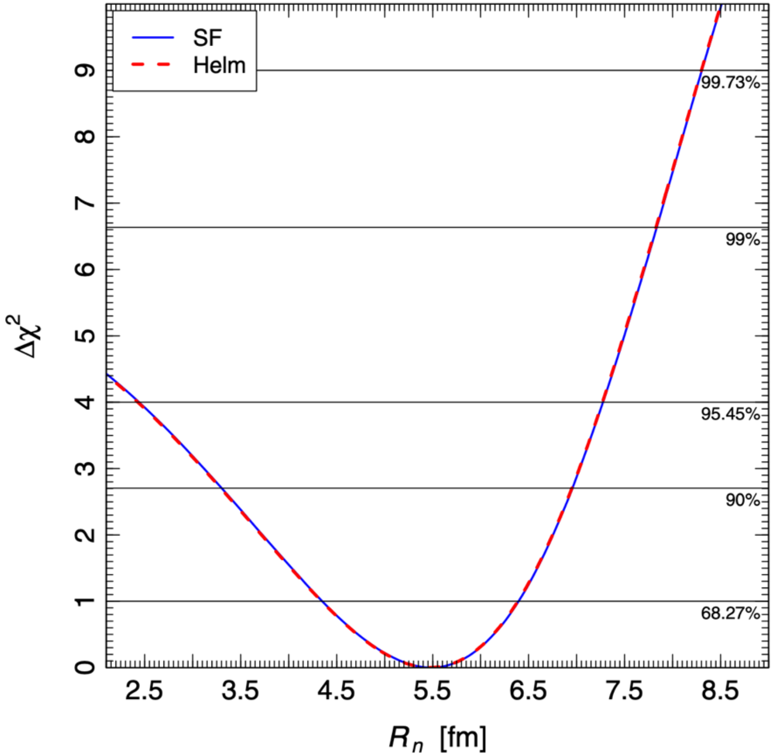


- Nominal configuration, i.e. PINGU (26 strings) + JUNO (10 cores)
- Reduced configurations, i.e. IC Upgrade (7 str) + JUNO (8 cores)

➢ **In any case, 5σ-discovery after 5 years**

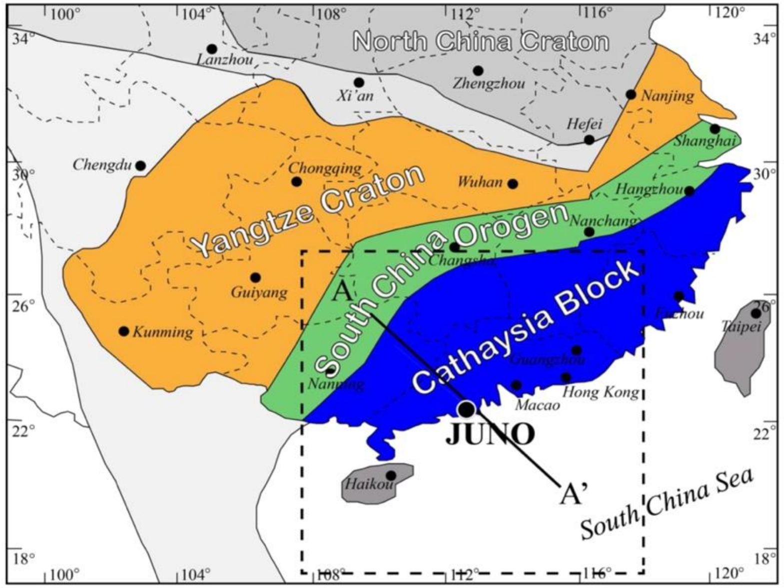
Neutrino as Probes: Nuclear and Earth Sciences

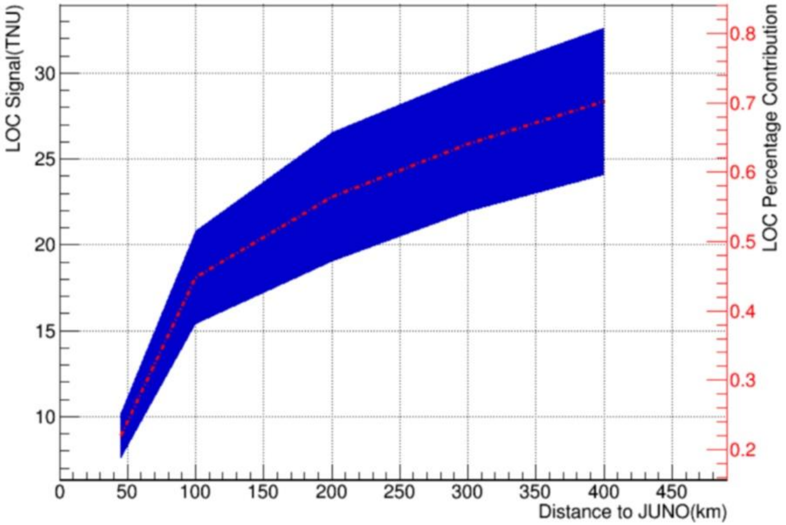
Cadeddu & Y.F. Li et al, PRL120, 072501 (2018)



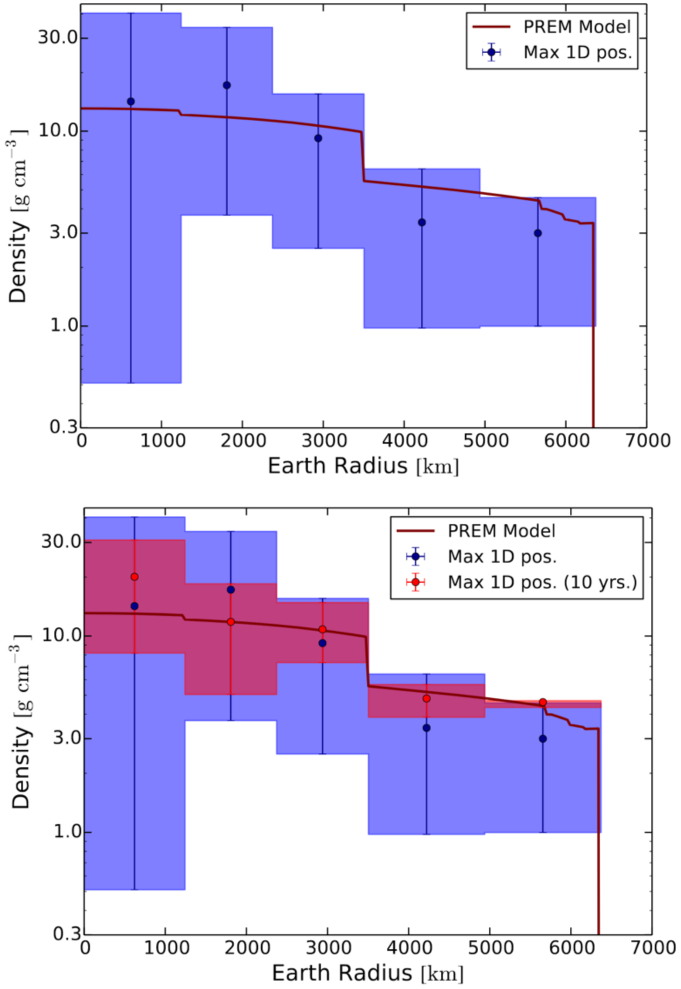
$$R_n = 5.5^{+0.9}_{-1.1} \text{ fm.}$$

First time measuring neutron radius!





A. Donini et al, Neutrino tomography of Earth, Nature Physics 2018



ν Mass Hierarchy Still Unknown