Overview of the JUNO Experiment

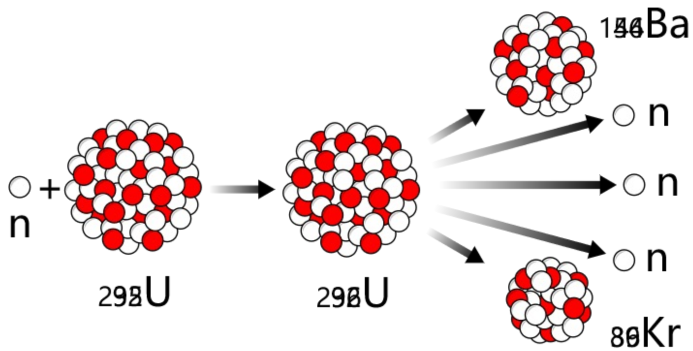
Wei Wang, Sun Yat-sen University

Lomonosov Conference, Aug 25, 2023

- *Neutrino Oscillation: A Brief Review*
- *Neutrino Mass Ordering Resolution*
- *JUNO Design and Latest Status*
- *Summary and Conclusion*

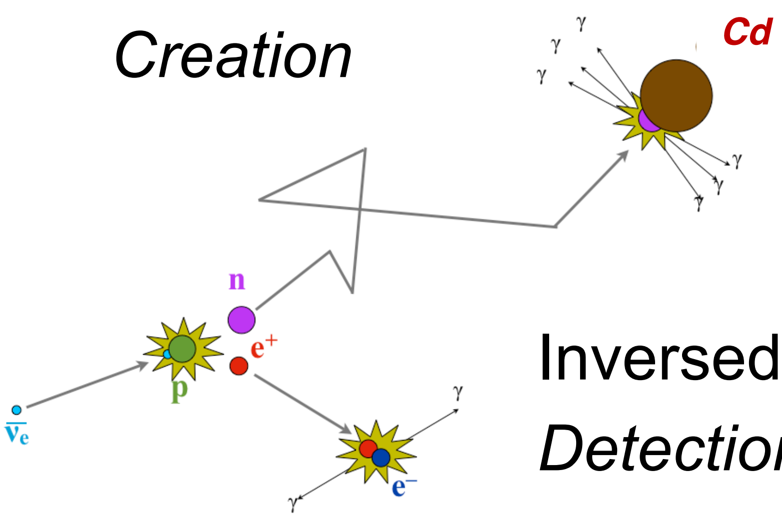
Reines&Cowan Detected Neutrinos in 1956

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



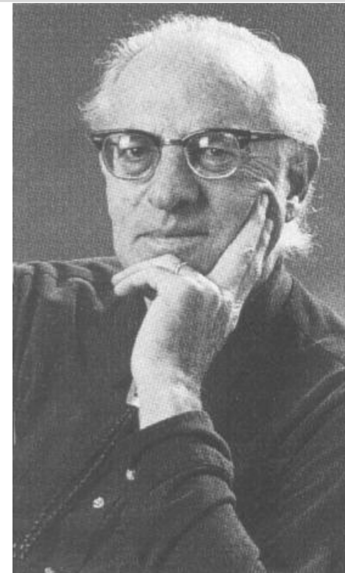
β decay: N ⟶ N′ + e + ν

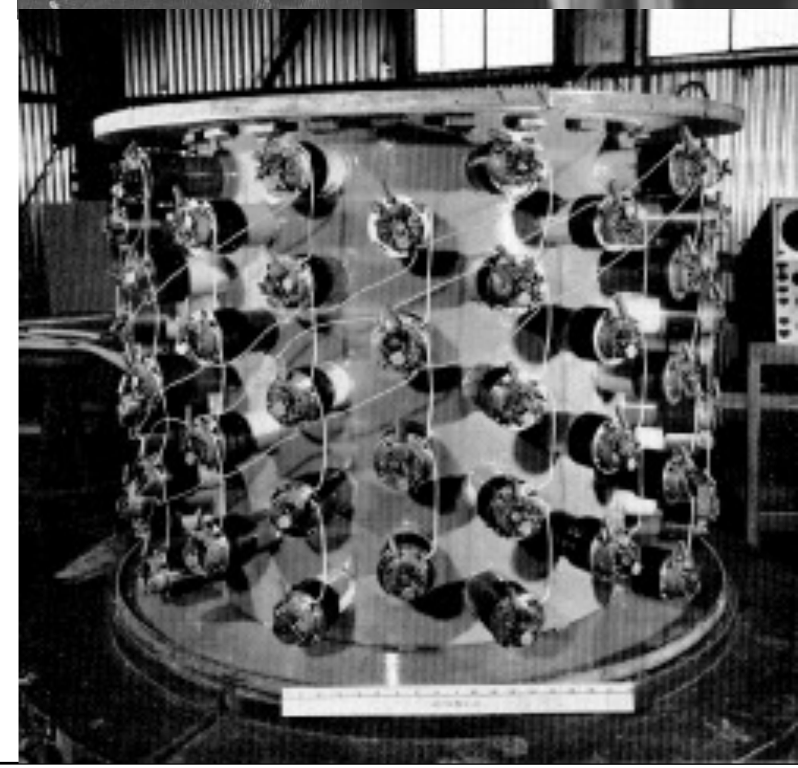
Creation



Inversed β decay

Detection: $p + \nu \longrightarrow e^+ + n$





Neutrino Mixing & Oscillation Proposed

- Bruno Pontecorvo in 1957:

  Interaction Eigenstates ≠ Mass Eigenstates
  → Neutrino Mixing and Oscillation

➢ Extended to 3 flavor mixing by Maki, Nakagawa and Sakata, after muon neutrino was discovered at BNL in 1962

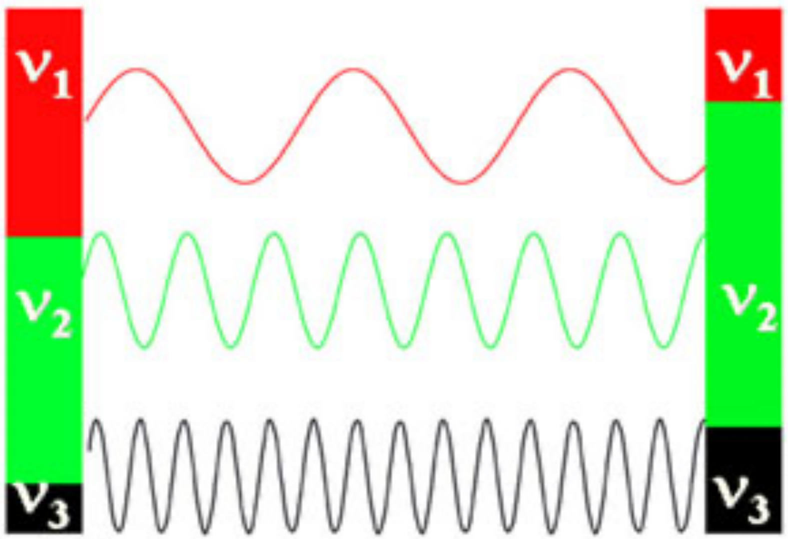
Courtesy of Sakata Memorial Archival Library

S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

Neutrino Mixing & Oscillation

➢ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix,

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



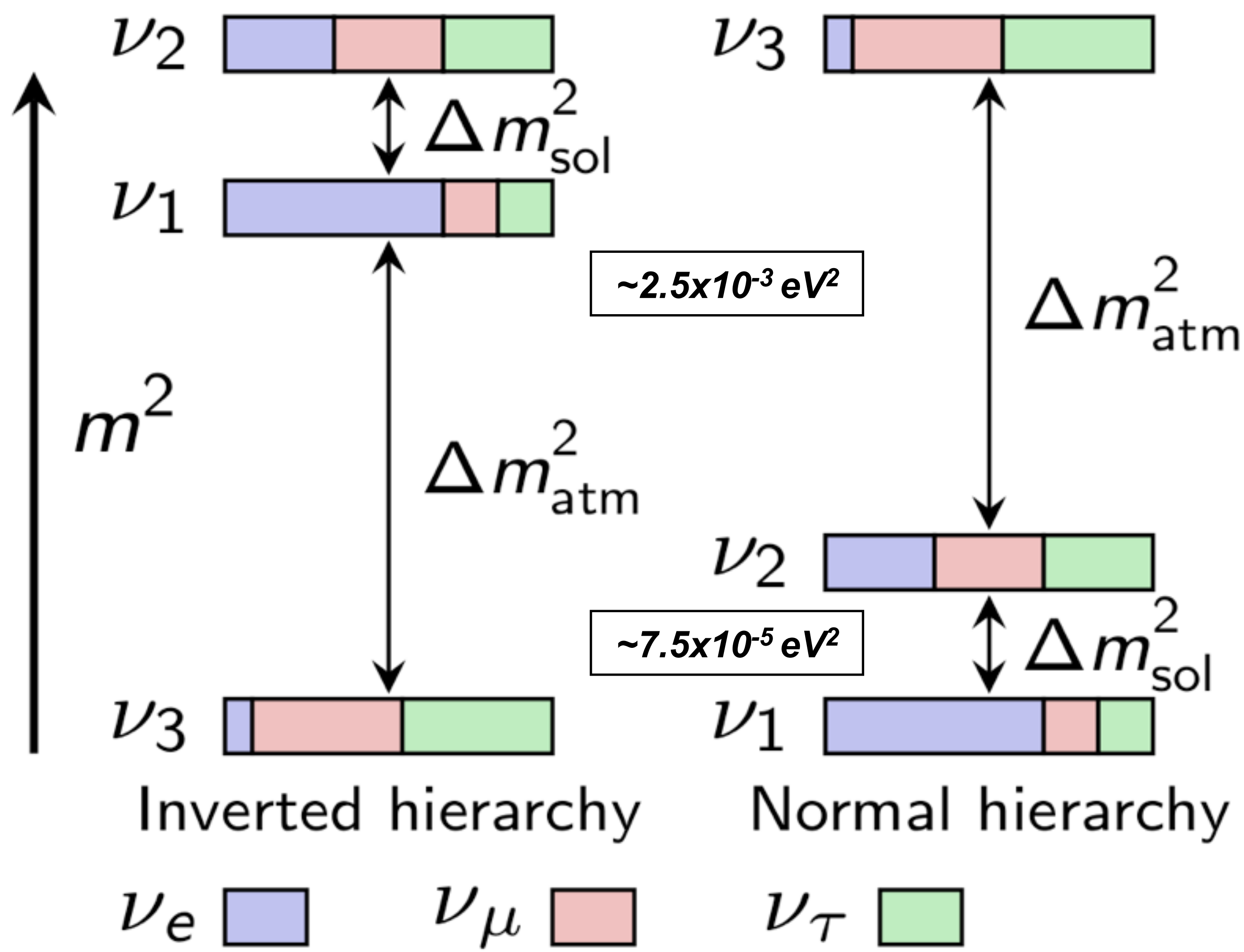
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

⇒ 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 ∝ $\sin^2 2\theta$ **Frequency ∝ $\Delta m^2 L/E$**

Neutrino Mass Ordering Still Unknown



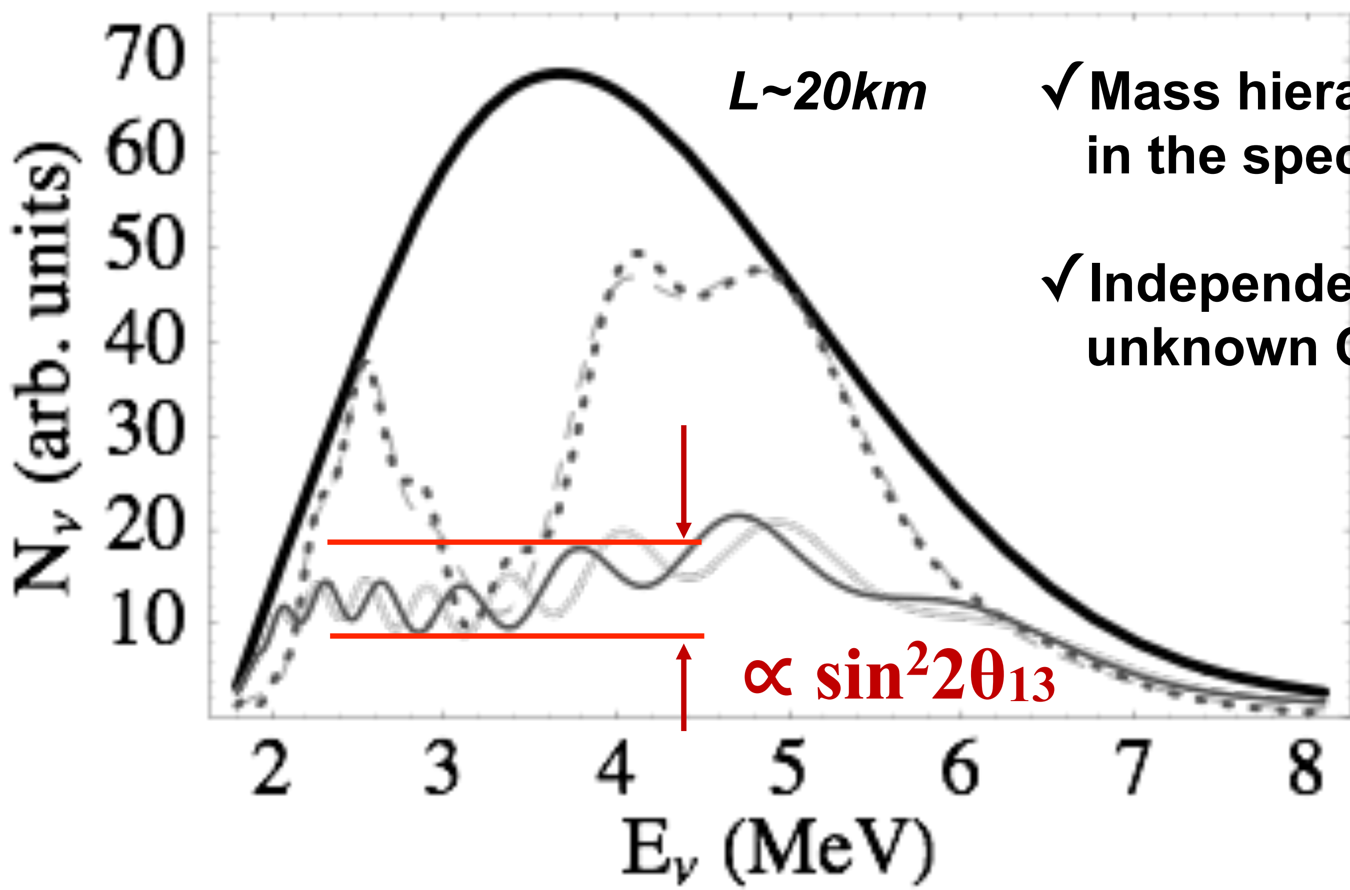
~2.5x10^{-3} eV^2

~7.5x10^{-5} eV^2

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

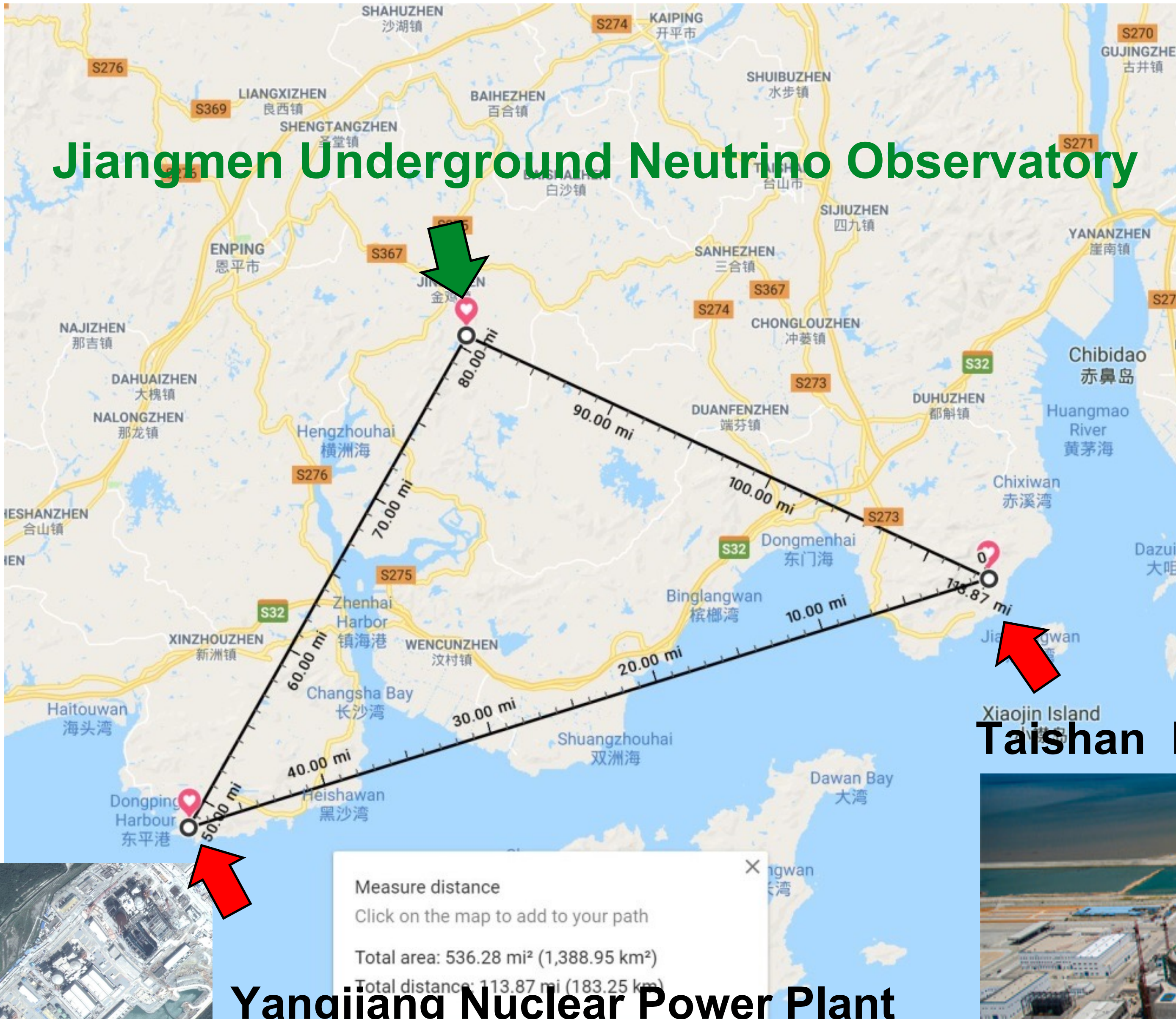


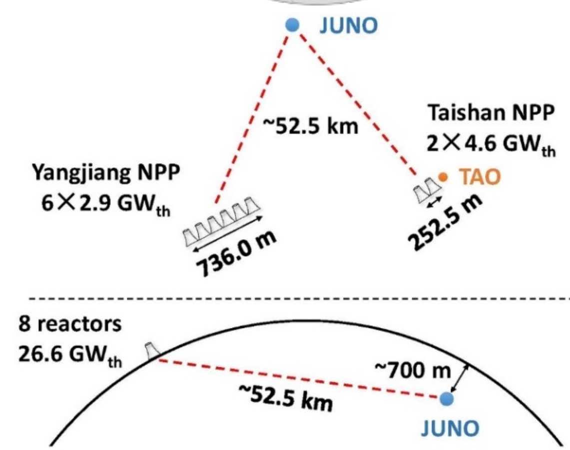
- √ **Mass hierarchy reflected in the spectrum**
- √ **Independent of the unknown CP phase**

Various Methods Resolving ν Mass Ordering

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+Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, 0νββ

JUNO for Neutrino Mass Ordering

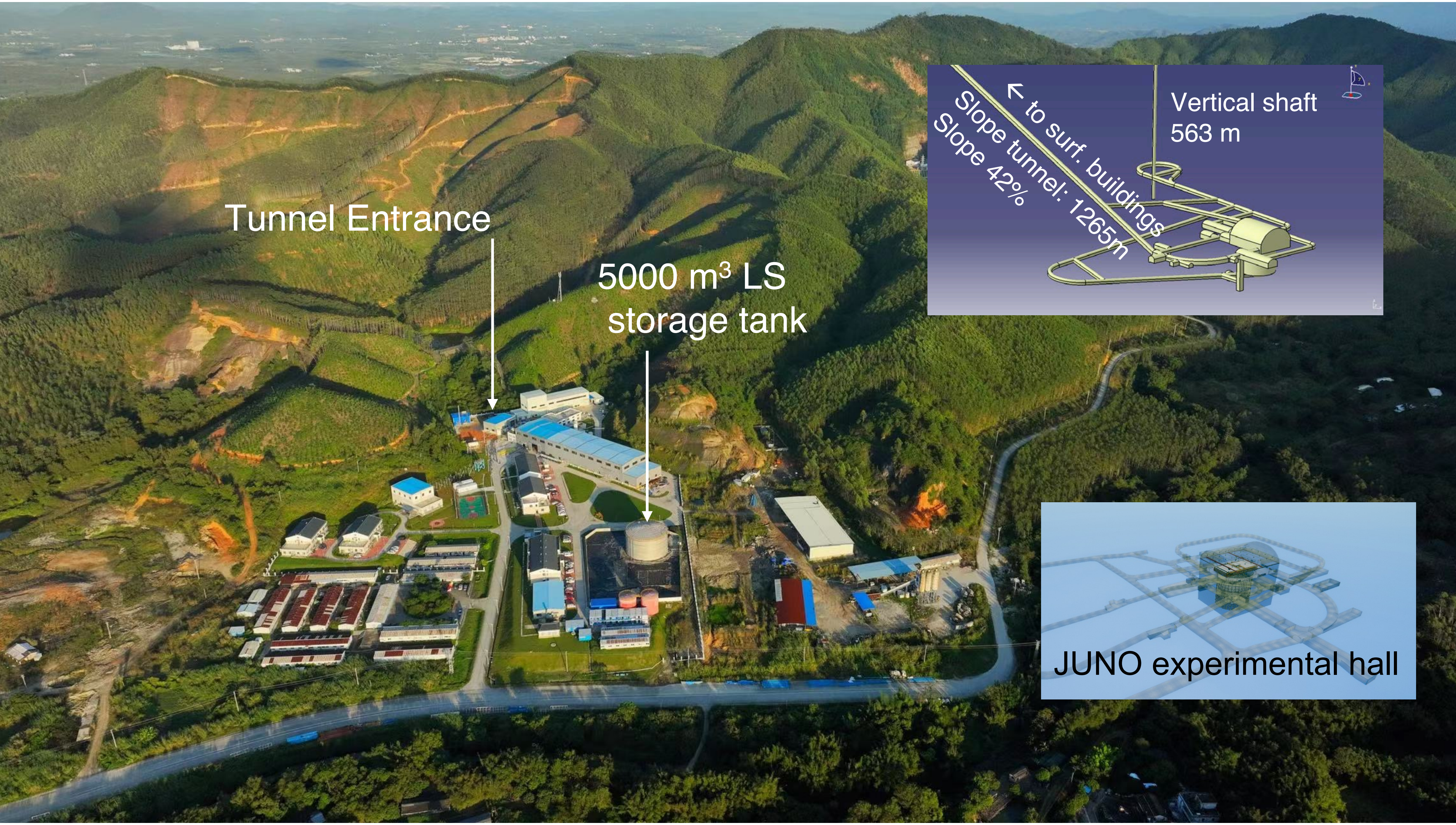




Taishan Nuclear Power Plant

Yangjiang Nuclear Power Plant

The JUNO Experimental Site



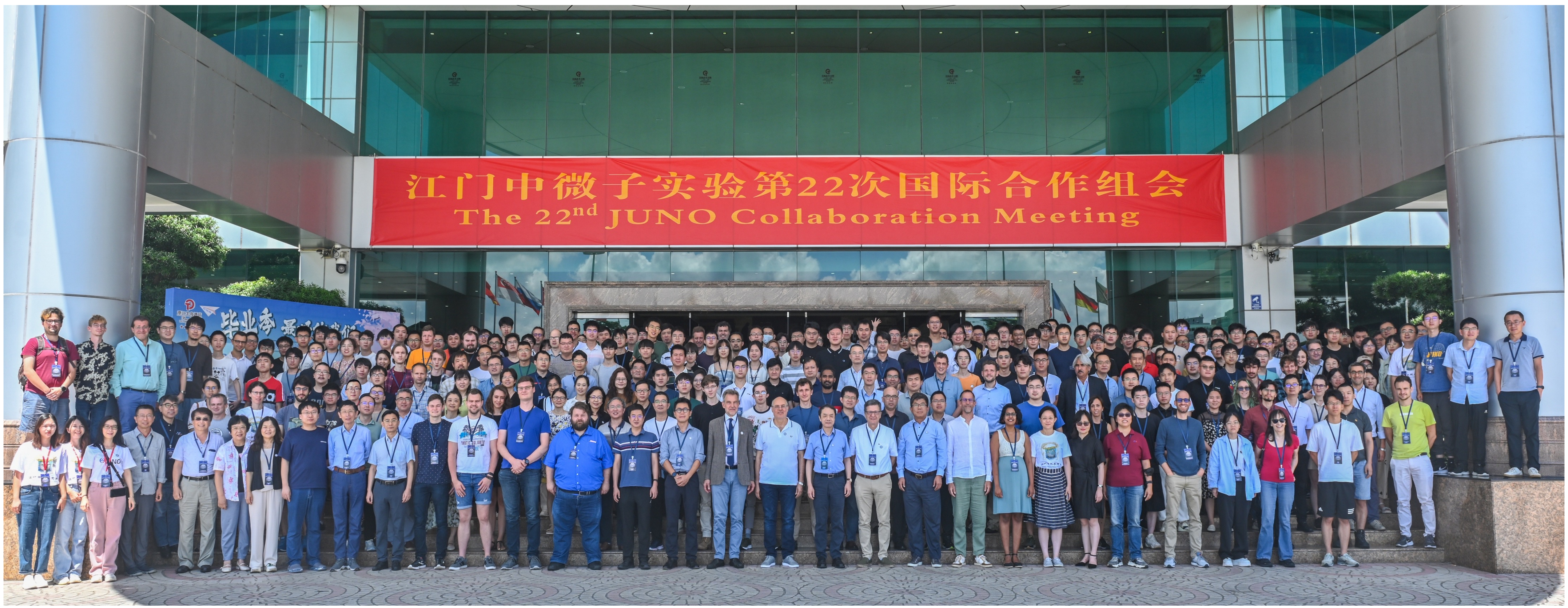
The JUNO Collaboration

17 countries，74 institutions，~670 members

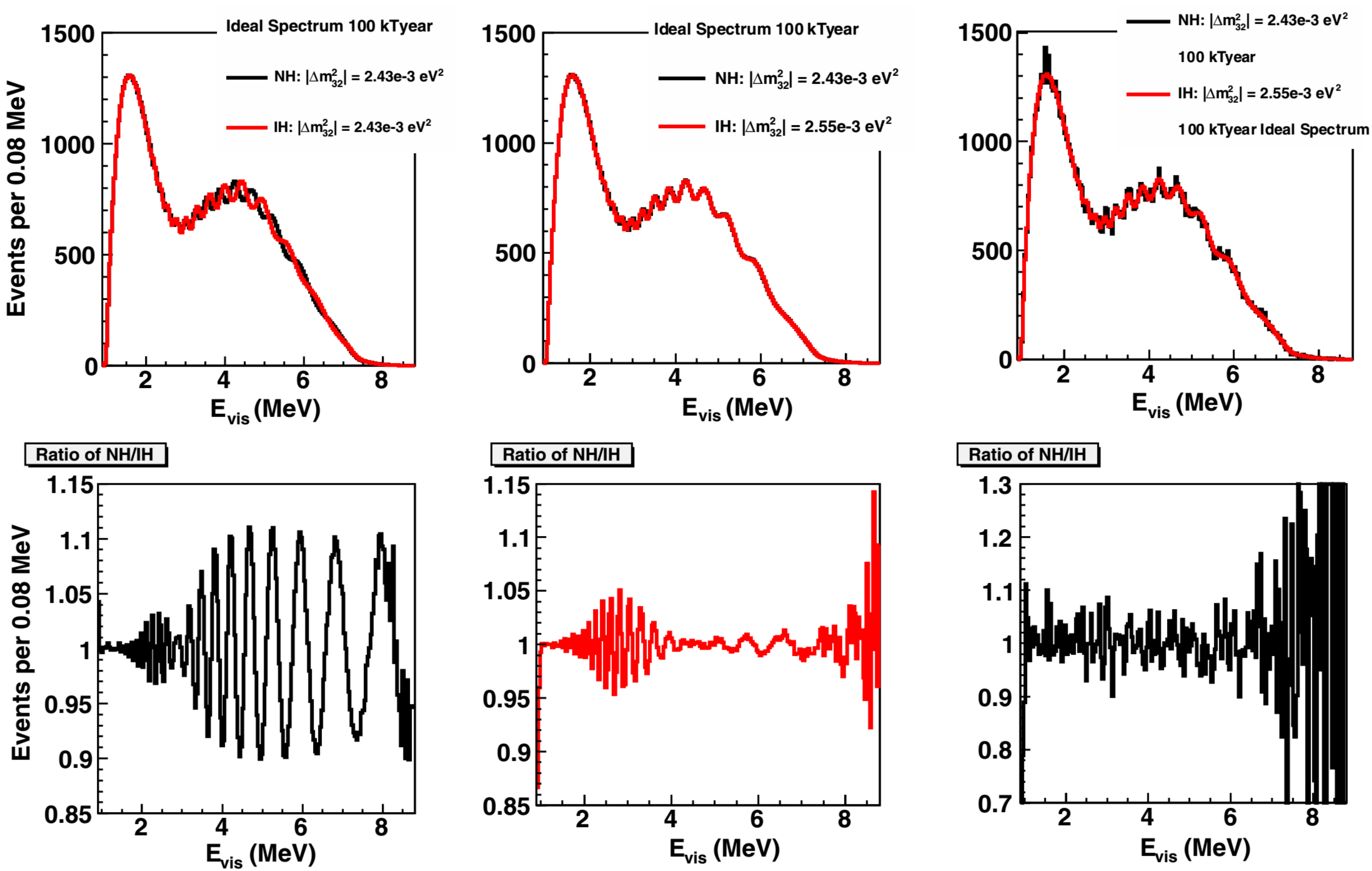
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of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

The JUNO Collaboration

Last collaboration meeting, Jiangmen, China, July 2023

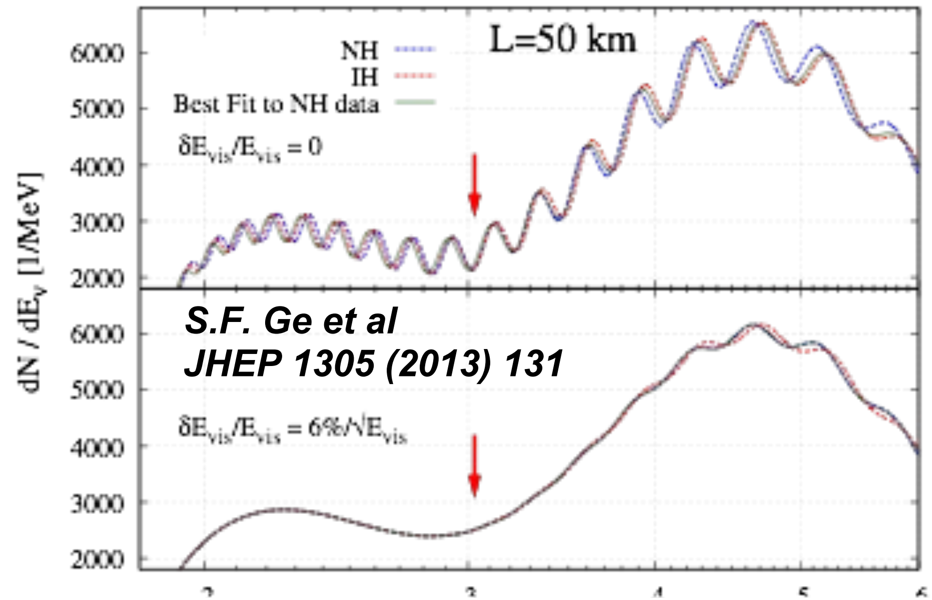


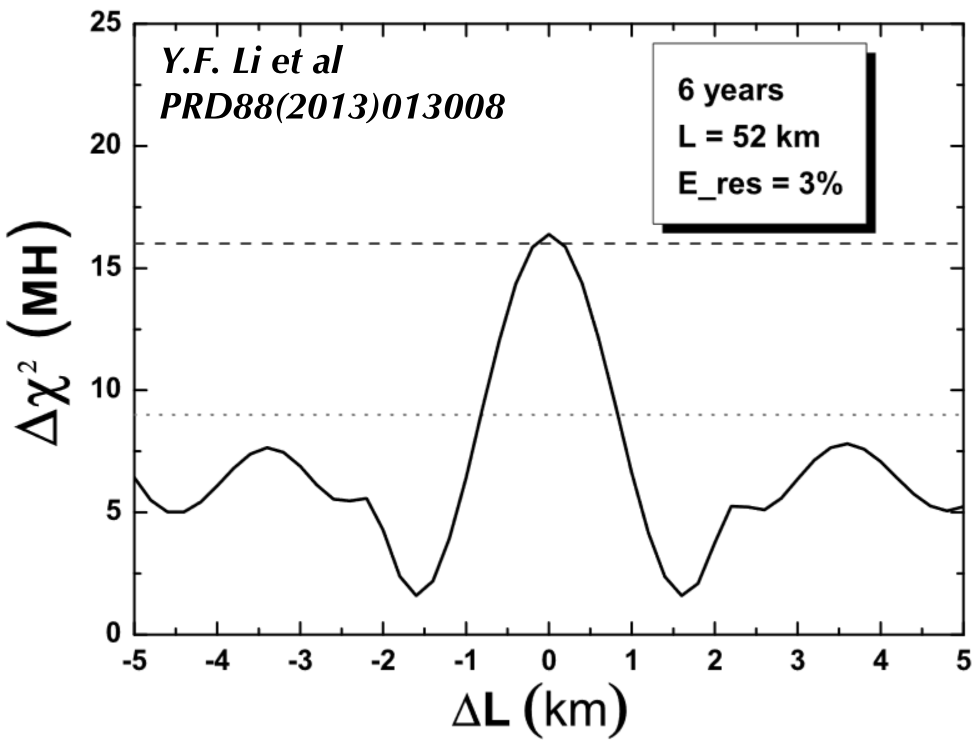
Challenges in Resolving MH using Reactors

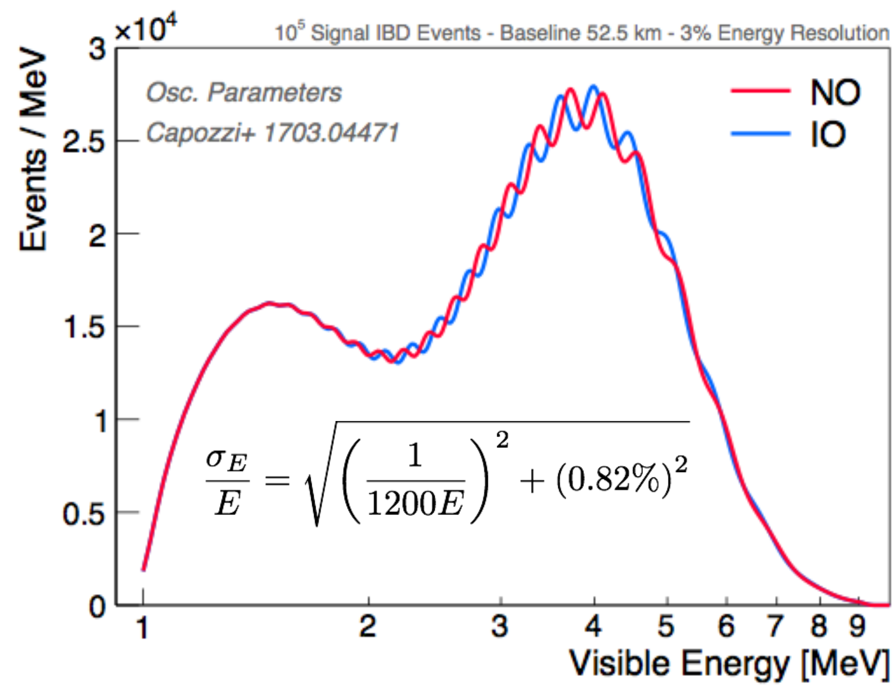


Challenges in Resolving MH using Reactors

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

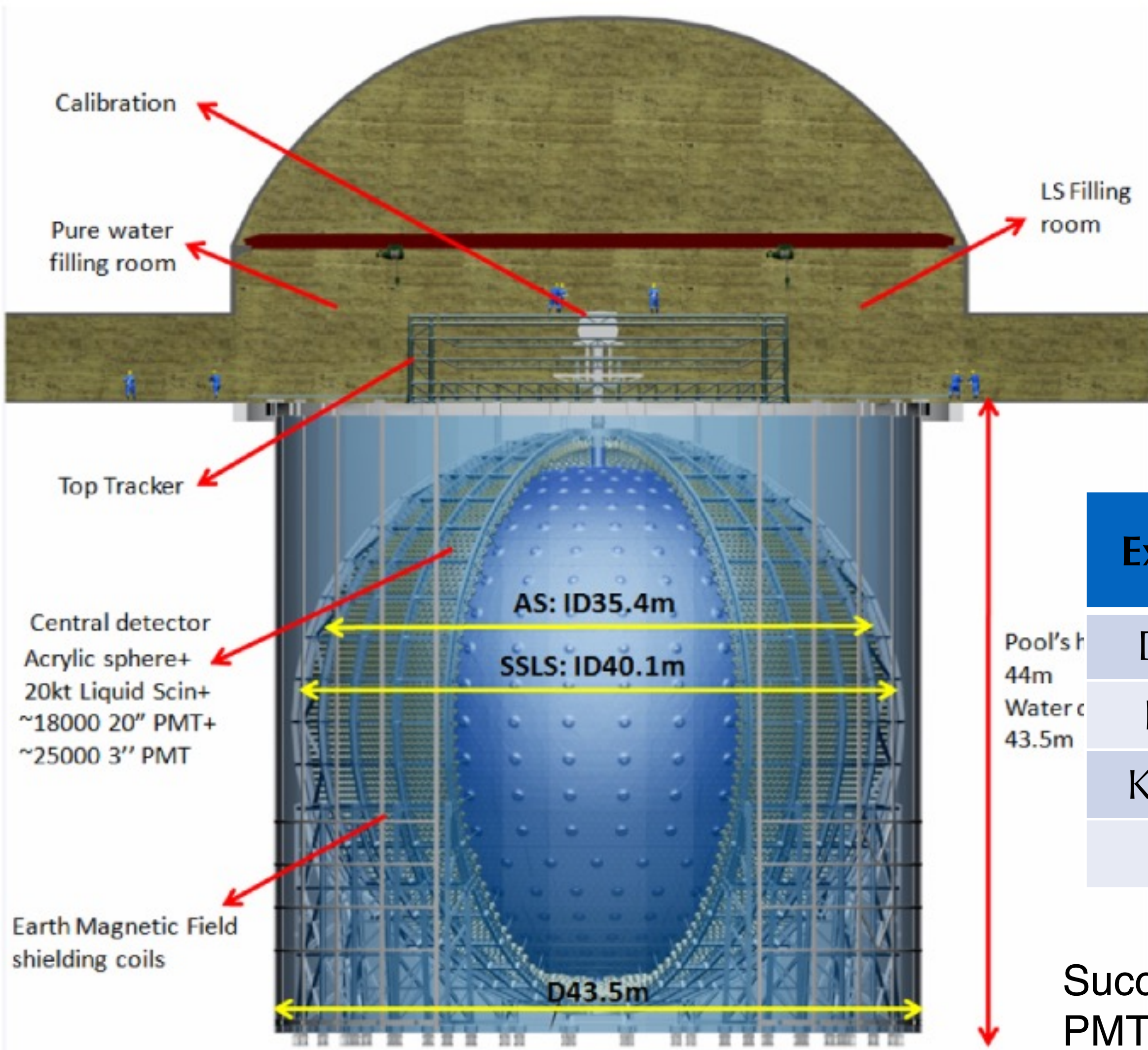






The Central Detector of JUNO

- A 20kt liquid scintillator detector → the biggest LS detector ever!



AS: Acrylic sphere; SSLS: stainless steel latticed shell

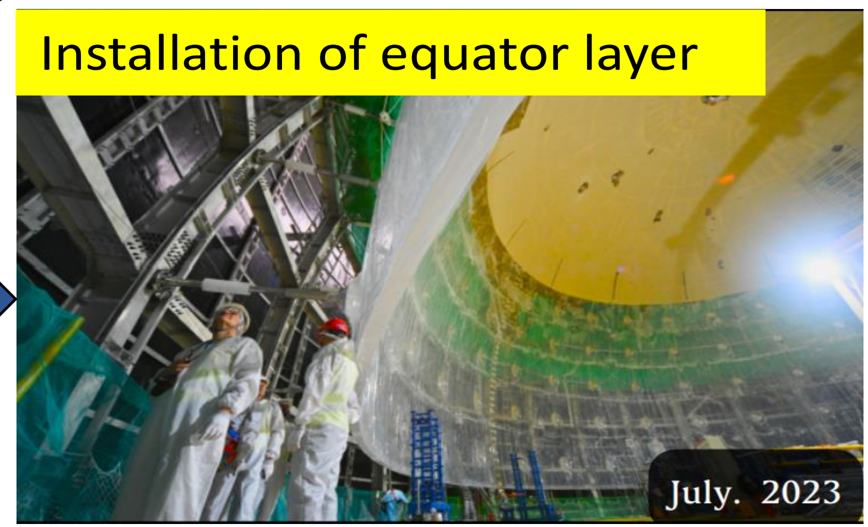
- An acrylic sphere of 35.4m diameter immersed in a cylindrical water pool

Experiment	Mass (tons)	Energy resolution at 1 MeV (σ)
Daya Bay	20	~7.5%
Borexino	~300	~5%
KamLAND	~1,000	~6%
JUNO	**~20,000**	**~3%**

Successful R&D program on LS transparency, PMT performances and calibration system

Nucl. Instrum. Meth. A 988 (2021) 164823
Prog. Part. Nucl. Phys. 123 (2022) 103927
JHEP 03 (2021) 004

Progresses&Status of the Central Detector



- Totoally, 265 spherical panels
- Thickness:120mm; weight: ~600 tons

- Transparency > 96% in pure water
- Radiopurity: U/Th/K < 1 ppt

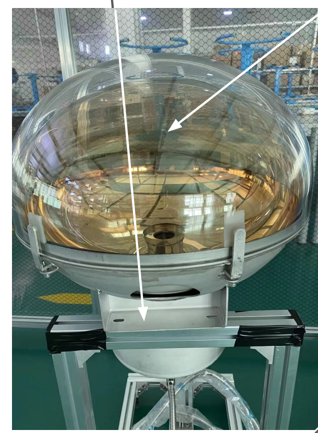
The JUNO PMT System

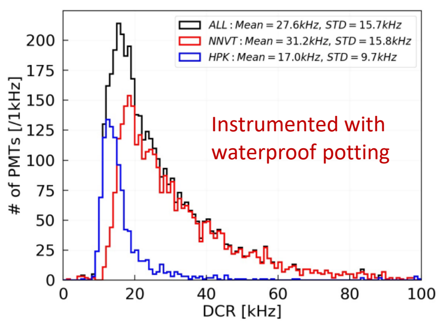
Photomultiplier Tubes (PMTs)

- 20inch PMTs: 17612 (CD) + 2400 (Veto)
  - 15000 MCP-PMTs (NNVT)
  - 5000 Hamamatsu
- 3inch PMTs: 25600
- spacing between PMTs: 25mm
- energy resolution and charge linearity
- mass testing completed
- expected channel loss rate <1% in 6 yr

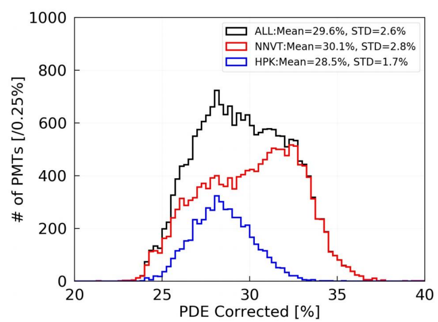
stainless steel cover

acrylic protective cover

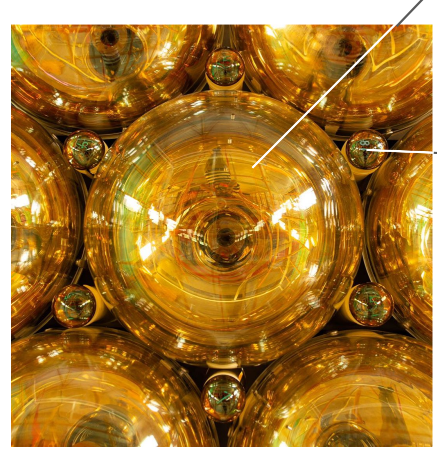




dark count rate



photon detection efficiency

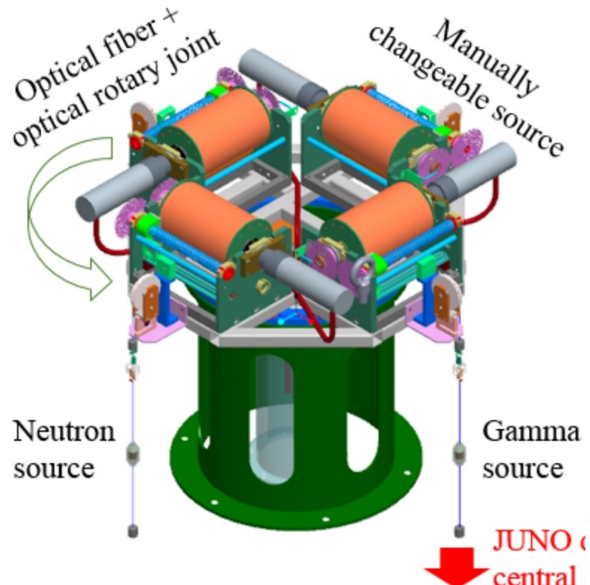


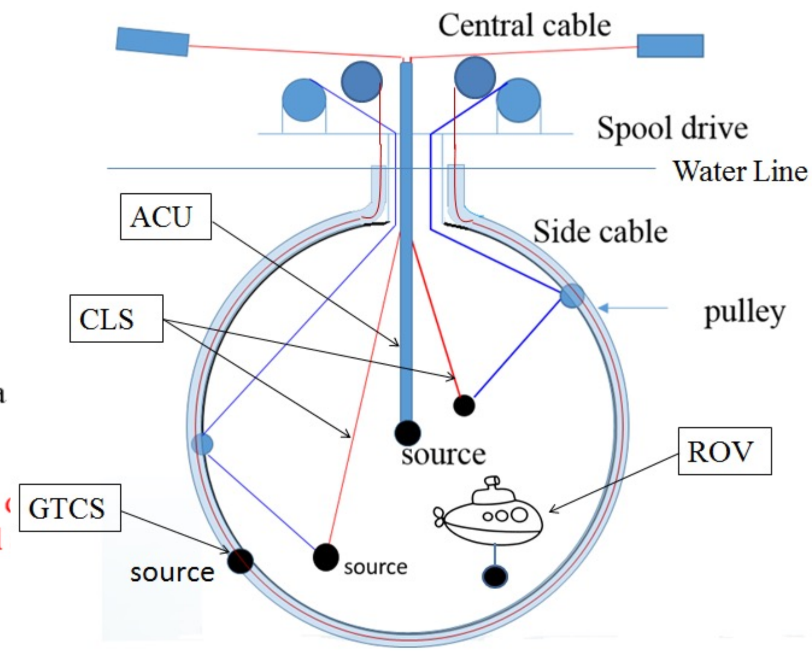
- Large PMTs get exanimated, tested, selected, characterized one by one to make sure they meet the requirements

Progresses&Status of the PMT System

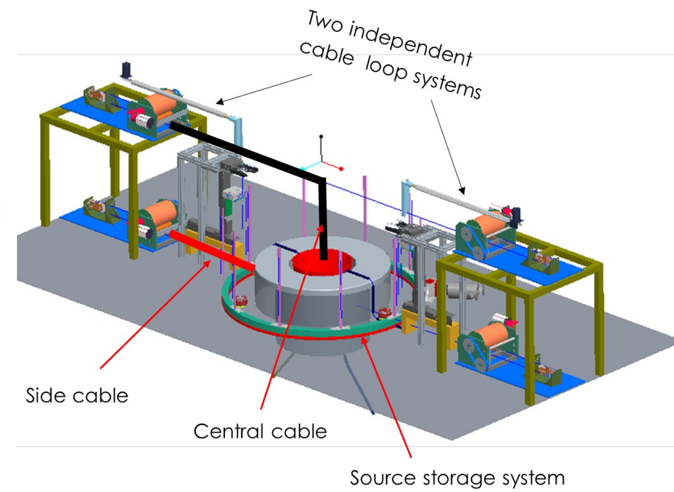
Calibration System *based on the Daya Bay experiences*

Automatic Calibration Unit (ACU)

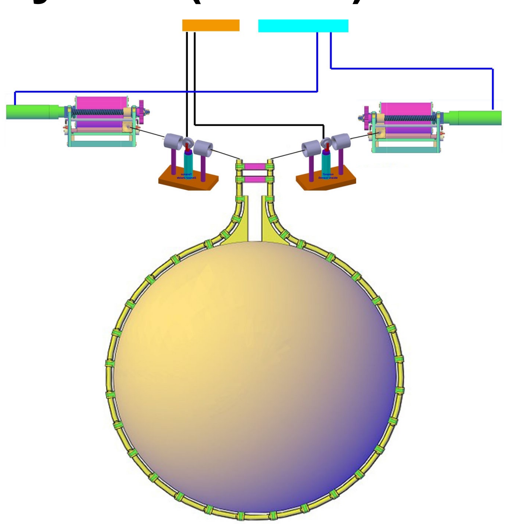




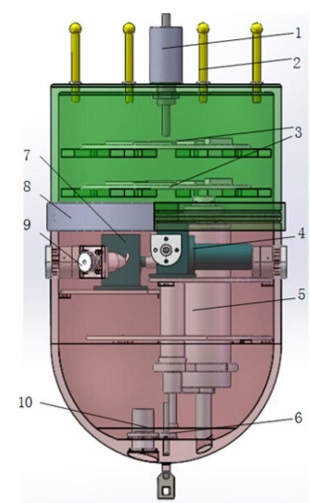
Cable Loop System (CLS)



Guide Tube Calibration System(GTCS)



Remotely Operated under-liquid-scintillator Vehicles (ROV)

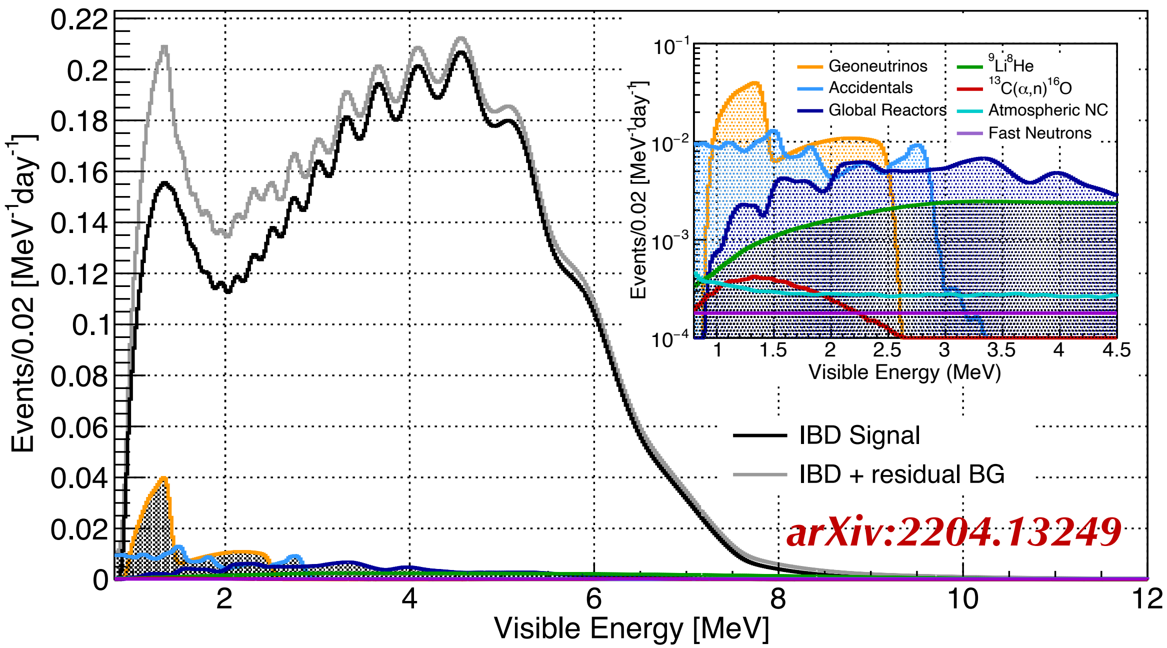


- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector
- Energy scale uncertainty < 1%

Design and Status of the LS System

- ❖ Using a recipe optimized from Daya Bay's experience, tested and changed to be more suitable for JUNO
- ❖ Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

Signal and backgrounds



- **Visible energy spectrum of the survival reactor $\overline{\nu_e}$'s**
- Background contribution from 7 types of sources
- Accidentals are mainly coming from radiogenic elements such as $^{238}U/^{232}Th/^{40}K$ → material screening strategy achieved

for details, see JHEP 11 (2021) 102

Major IBD event cuts:

- Energy threshold: $E_{vis} > 0.7\ MeV$
- Fiducial volume cut: $R_{LS} < 17.2\ m$
- Timing cut: $\Delta T_{p-d} < 1\ ms$
- Spatial cut: $R_{p-d} < 1.5\ m$
- Cosmic muon veto cuts

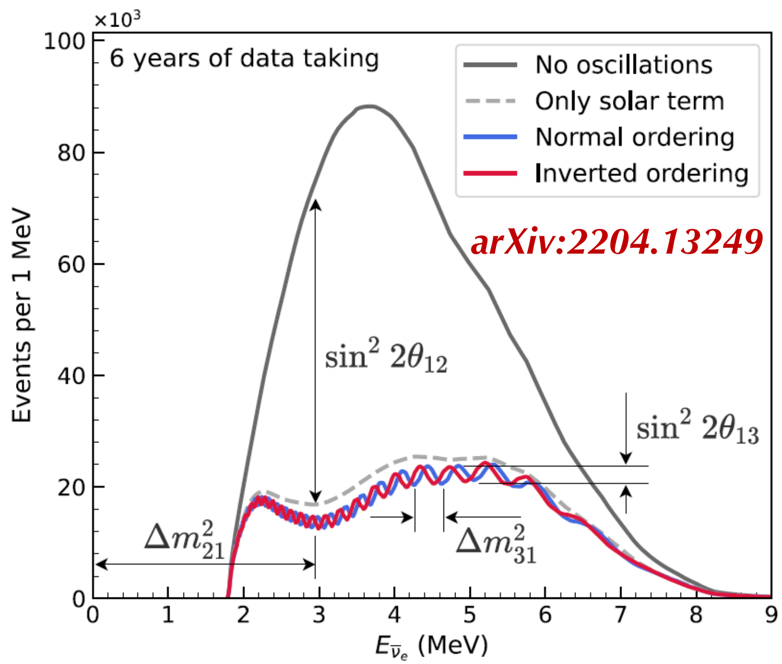
Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

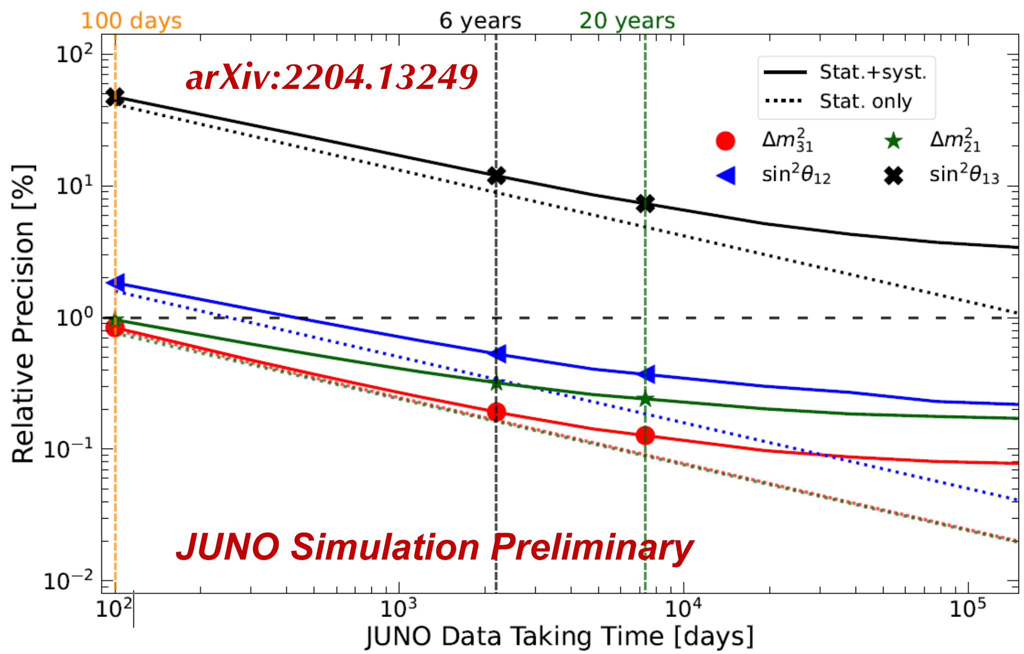
- ~47 $\bar{\nu}_e$ evt/day (assuming ~82% efficiency) and ~4.1 bckg evt/day

Neutrino oscillation studies using reactor $\overline{\nu_e}$

JUNO measures Δm^2_{21}&Δm^2_{32} oscillations on the same spectrum

❖ JUNO can determine the Mass Ordering at 3σ level (6 years)



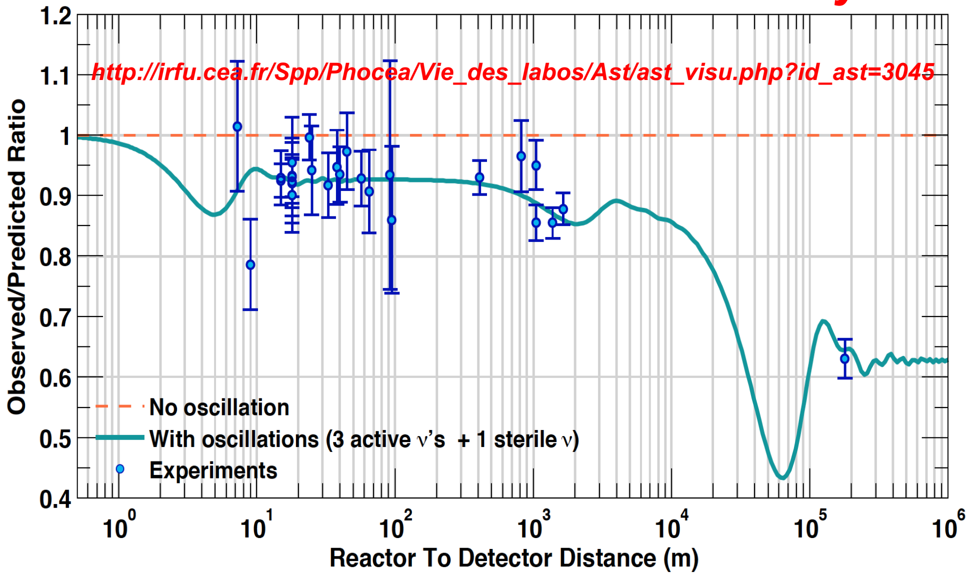


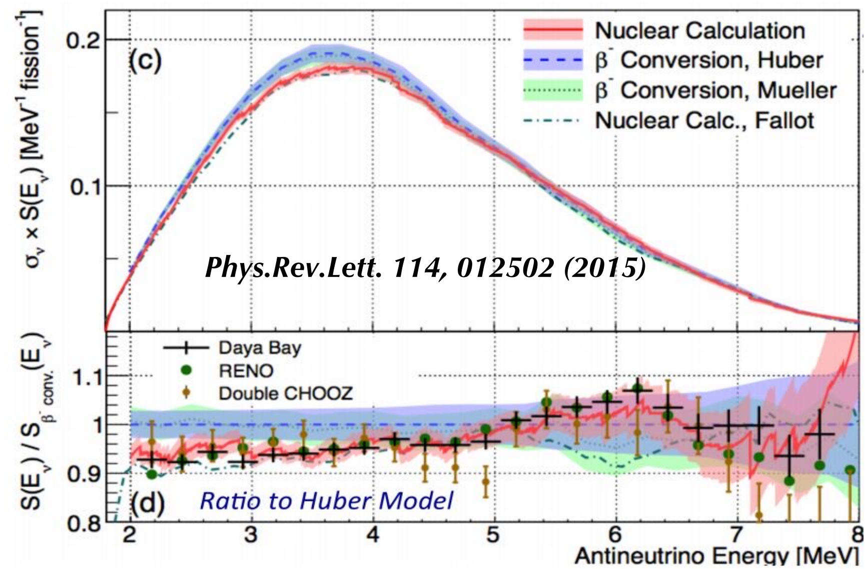
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

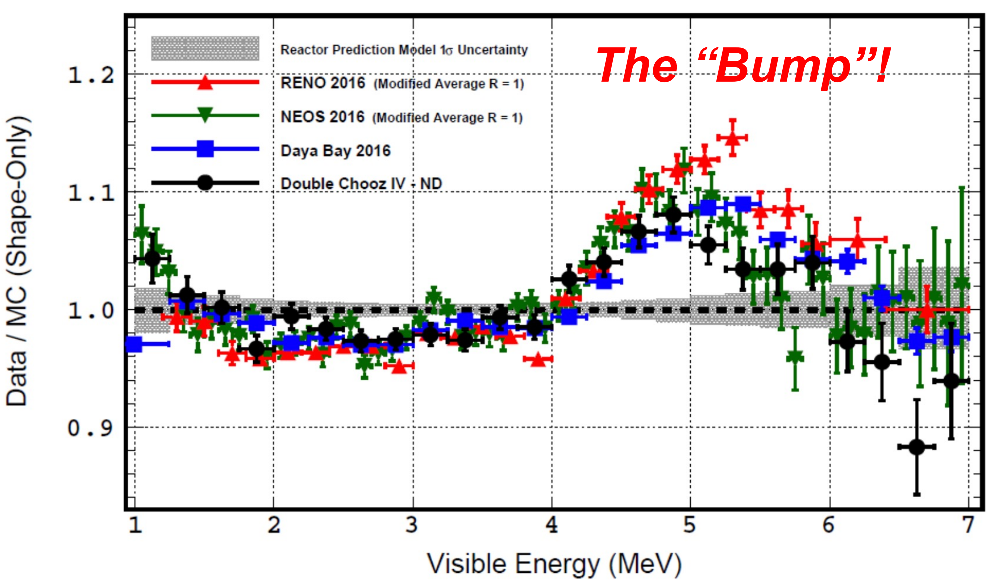
❖ Subpercent precisions for 3 oscillation parameters (JUNO only)

Reactor Neutrinos *NOT* Perfect: RAA and a "Bump"

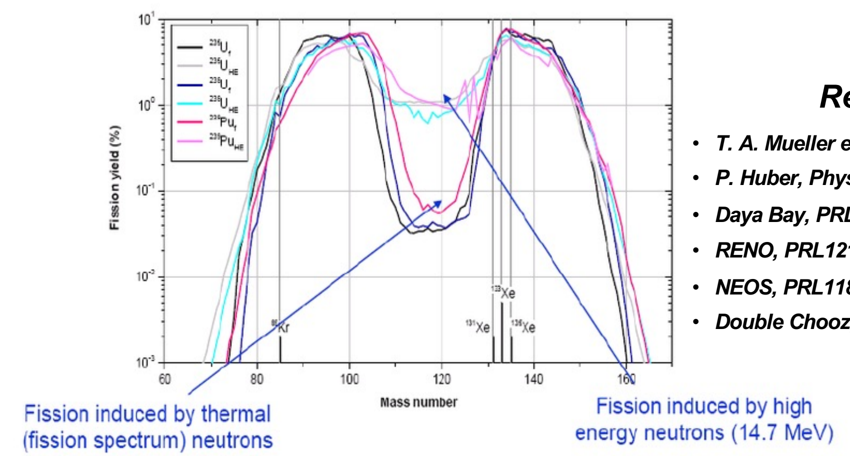
The Reactor Antineutrino Anomaly







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



References

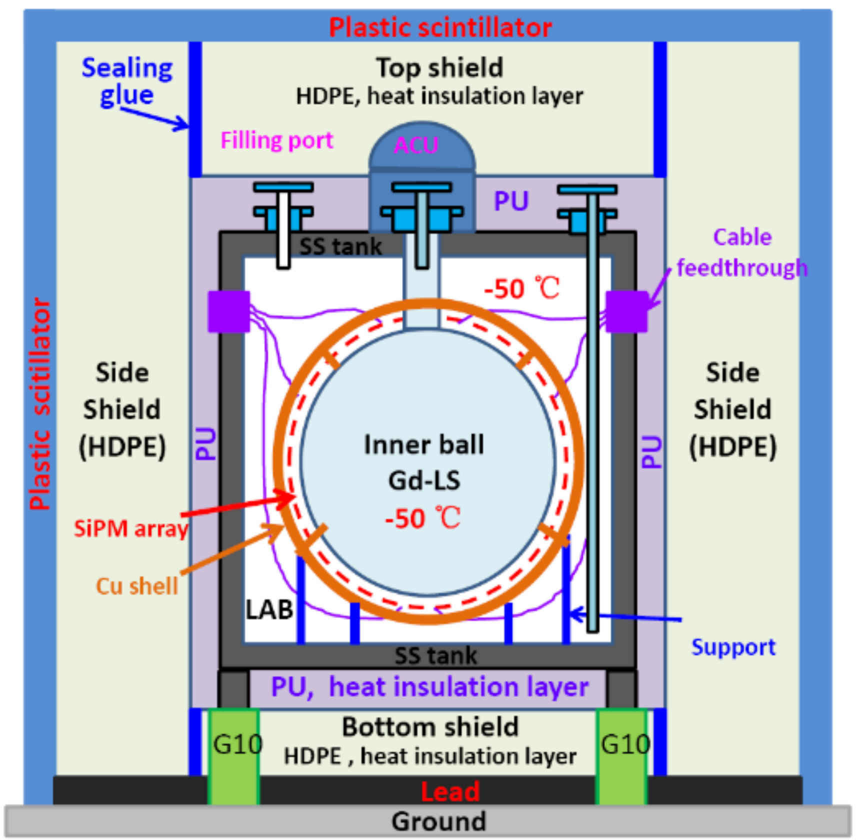
- ***T. A. Mueller et al., PRC83, 054615 (2011)***
- ***P. Huber, Phys. Rev.C84, 024617 (2011)***
- ***Daya Bay, PRL116(2016), PRL123(2019)***
- ***RENO, PRL121(2018)***
- ***NEOS, PRL118(2017)***
- ***Double Chooz, Nature Physics 16(2020)***

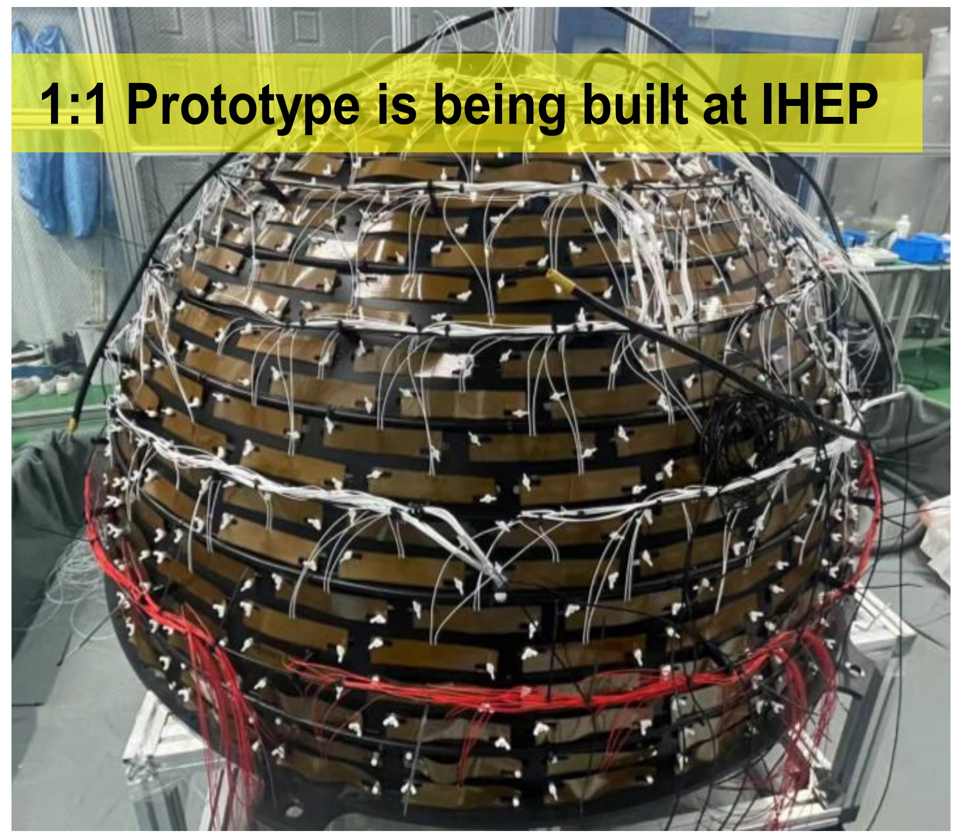
JUNO-TAO: A Satellite Experiment of JUNO

- Taishan Antineutrino Observatory (TAO), a ton-scale (2.6 ton GdLS in FV), at ~40m from a 4.6 GW_{th} core

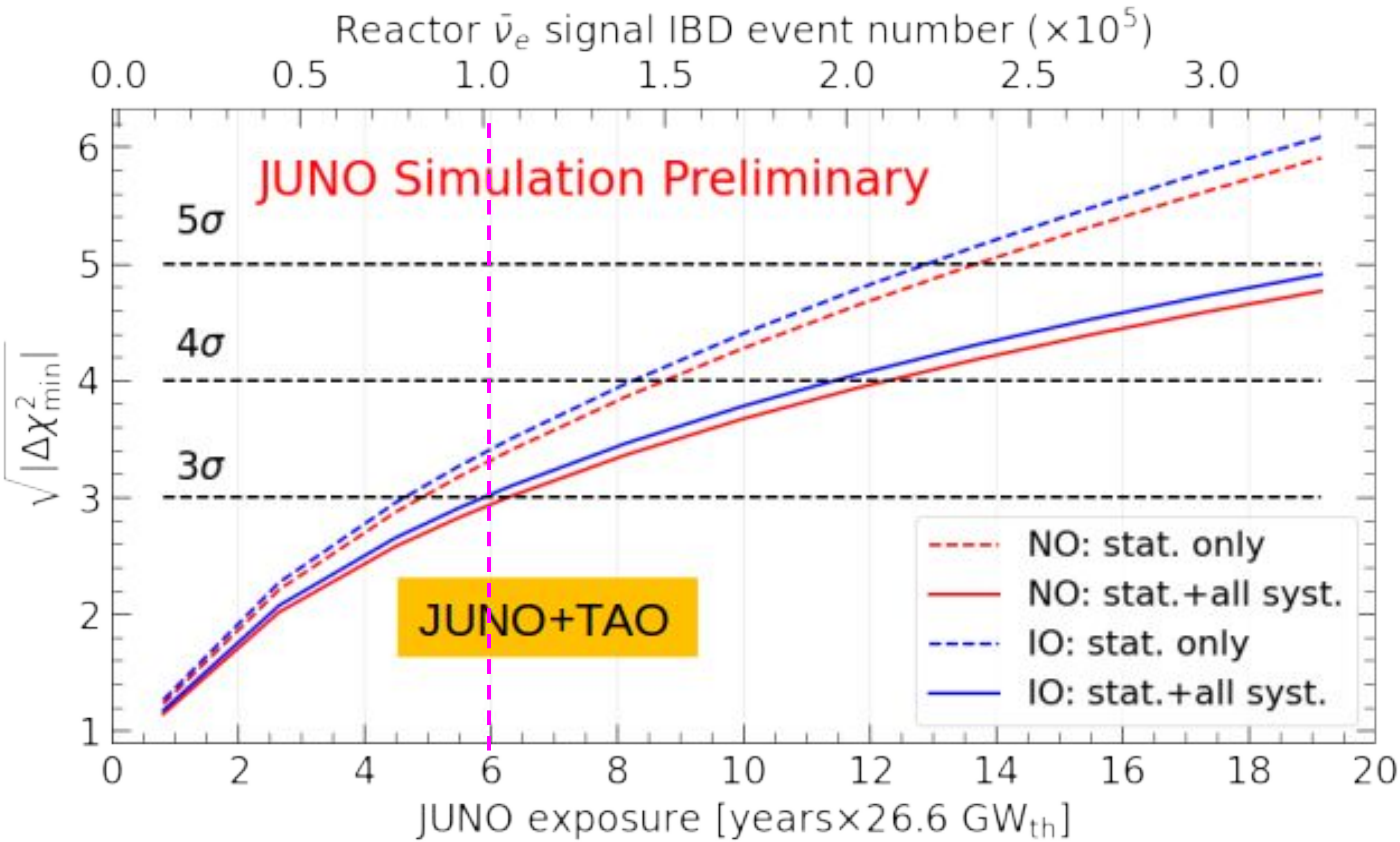
- Full coverage of SiPM with PDE > 50% Operate at -50 ℃ (lower SiPM dark noise): 4500 p.e./MeV → **1.5%$\sqrt{E(MeV)}$**

For details, see CDR arXiv:2005.08745

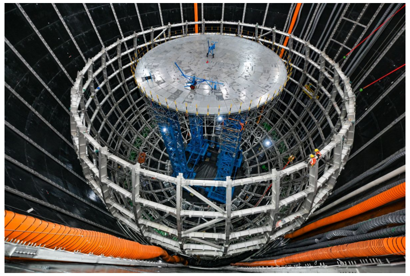
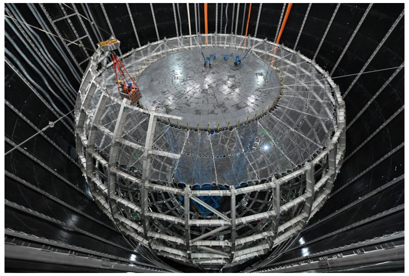
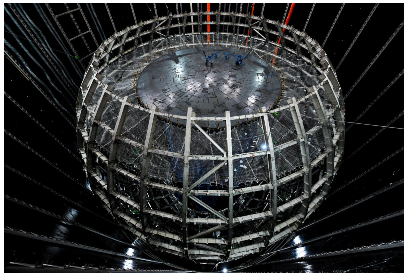
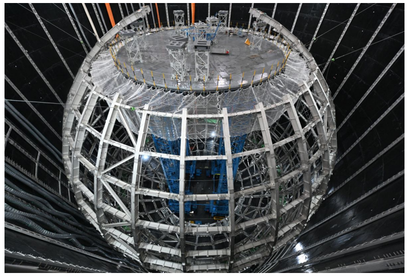


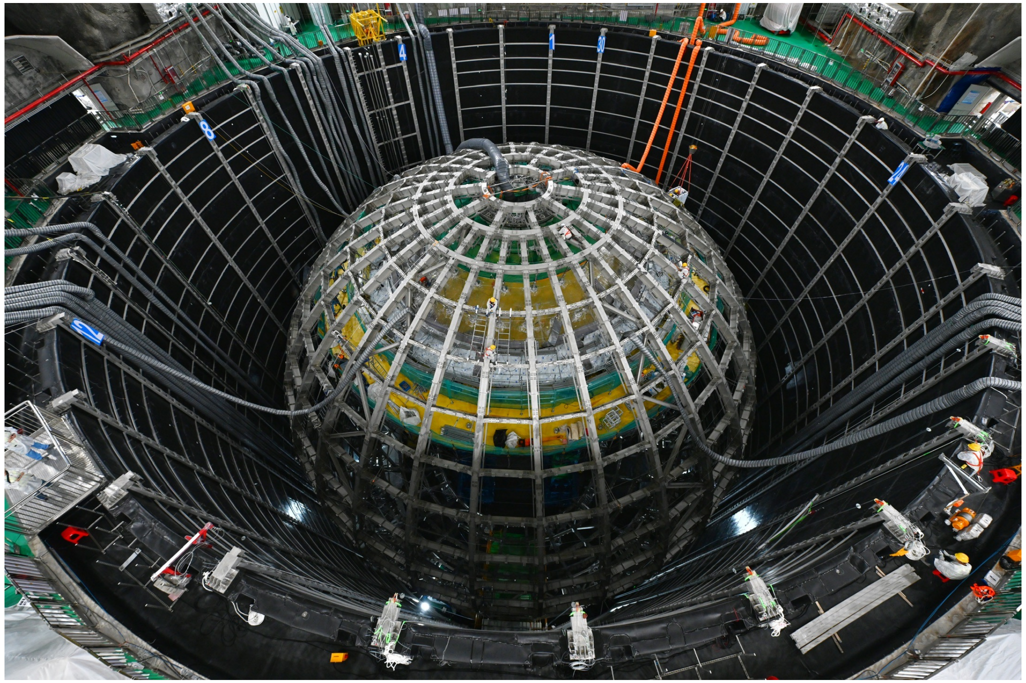
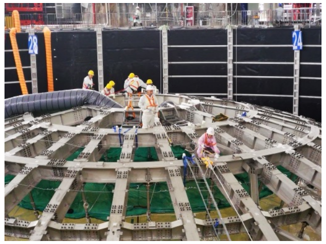
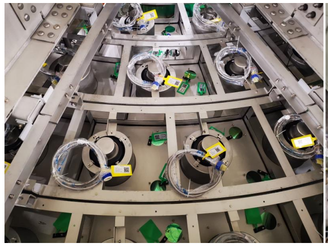
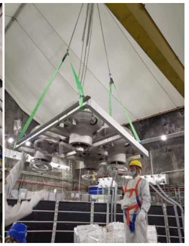
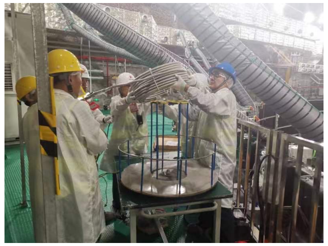


Latest Re-Evaluations of JUNO Physics Potential



An Exciting Phase for JUNO

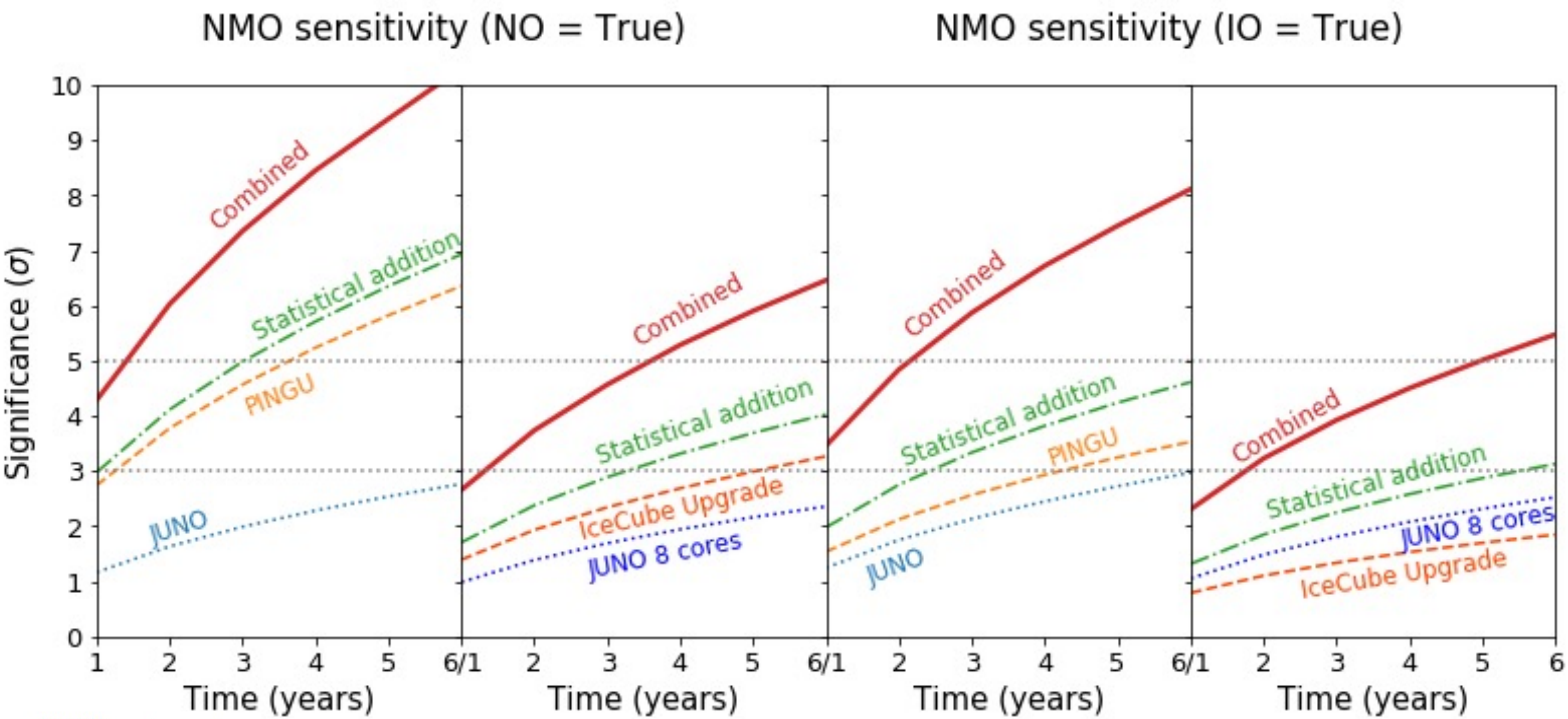
Summary and Conclusion

- **Reactor neutrino has played irreplaceable roles in neutrino studies and Daya Bay has made the most precise measurement of $\sin^2 2\theta_{13}$, which makes mass ordering resolution possible using reactor antineutrinos → JUNO has been a continuous effort based on the Daya Bay success**
- **JUNO is the only reactor experiment for neutrino mass ordering: observing the two oscillations on the same spectrum for the first time**
- **JUNO will also make subpercentage measurements of multiple oscillation parameters**
- **JUNO construction has entered its final stage. Data taking is expected in 2024!**

Thanks for your Attention!

Come visit us!

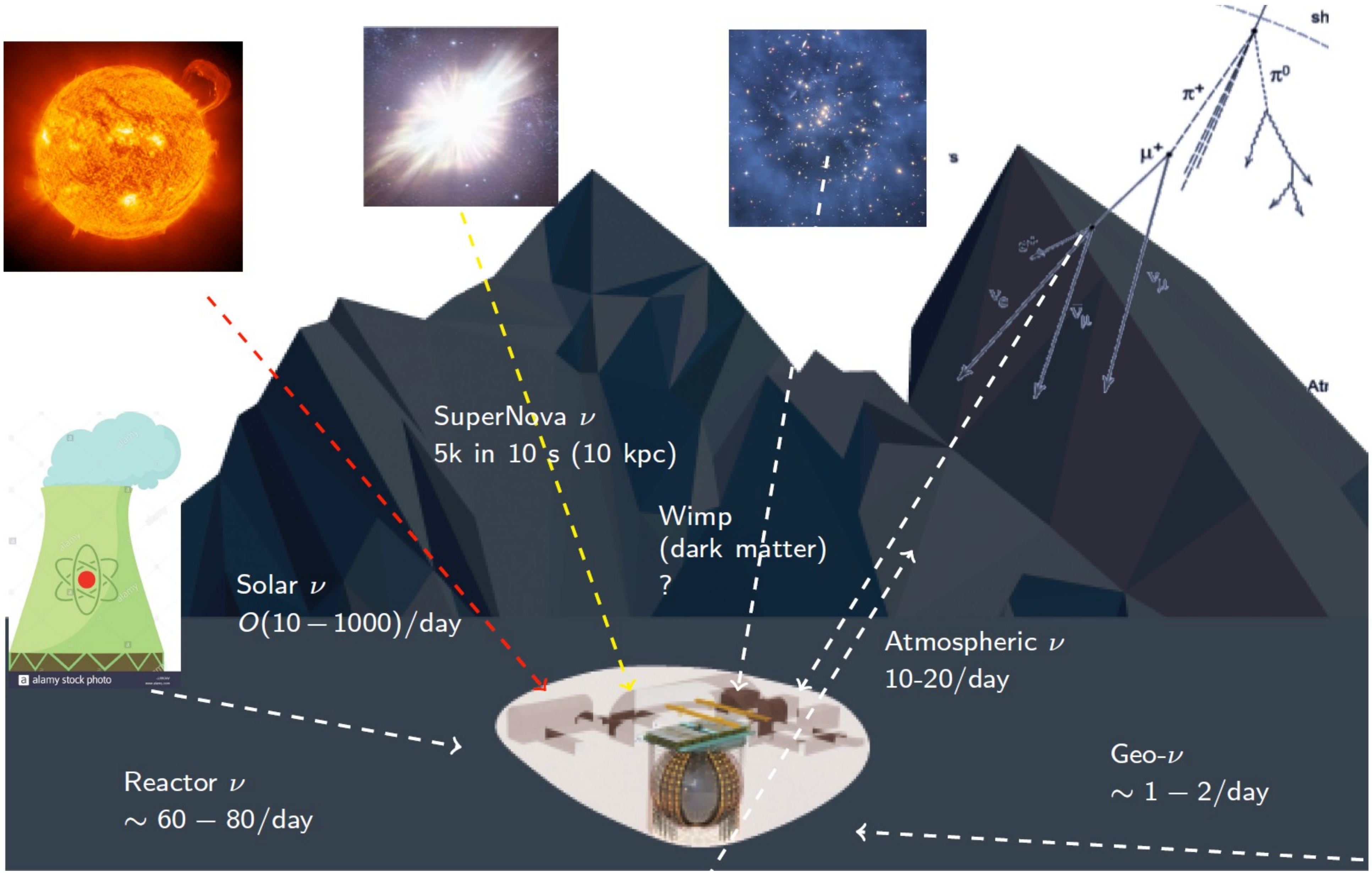
Combining JUNO and PINGU *(courtesy of M. Wurm)*



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

➢ **In any case, a 5σ discovery after 5 years!**

JUNO's Multi-Physics Potential



Updated Performance of JUNO

	Design (J. Phys. G 43:030401 (2016))	Now (2022)
Thermal Power	36 GW_{th}	26.6 GW_{th} (26%)
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	4 Hz (33%)
Muon veto efficiency	83%	93% (12%)
Signal rate	60 /day	47.1 /day (22%)
Backgrounds	3.75 /day	4.11 /day (10%)
Energy resolution	3% @ 1 MeV	2.9% @ 1 MeV (3%)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sensitivity exposure	< 6 yrs 35.8 GW_{th}	