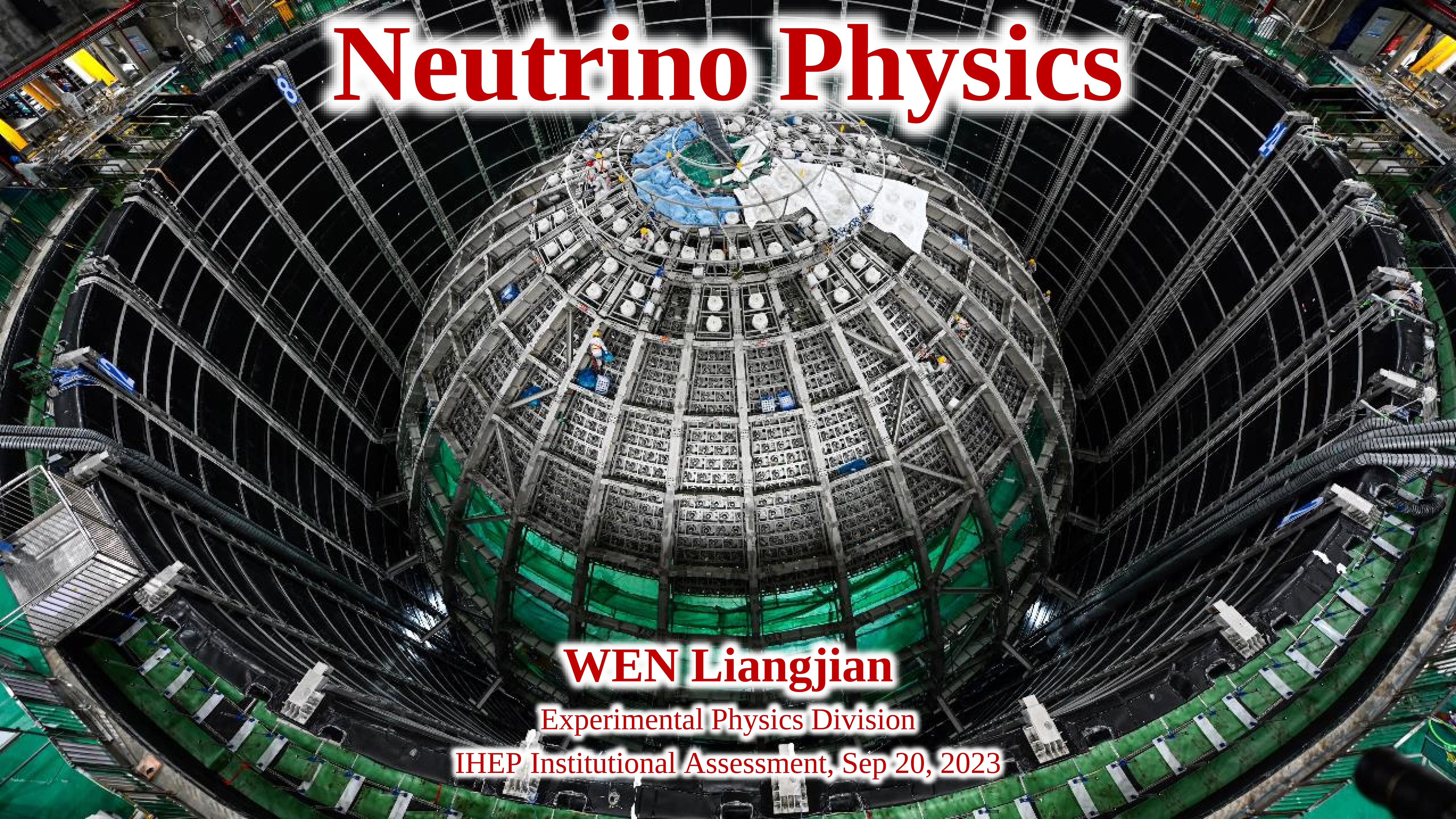
Neutrino Physics



WEN Liangjian

Experimental Physics Division

IHEP Institutional Assessment, Sep 20, 2023

Neutrino Researches at EPD

Aim to be a world-leading center for neutrino physics and neutrino astronomy

Frontiers & Targeted problems

- **Neutrino oscillation**
  - CP violation phase
  - Mass ordering
  - Precision measurements
- **Neutrino properties**
  - Direct measurement of mass
  - Neutrinoless double beta decay
  - Exotic searches: sterile, magnetic moment, NSI, …
- **Neutrino astronomy**
  - High energy cosmic neutrinos
  - Supernovas, diffuse SN background
  - Solar neutrinos
  - Geo-neutrinos

Neutrino Projects at IHEP

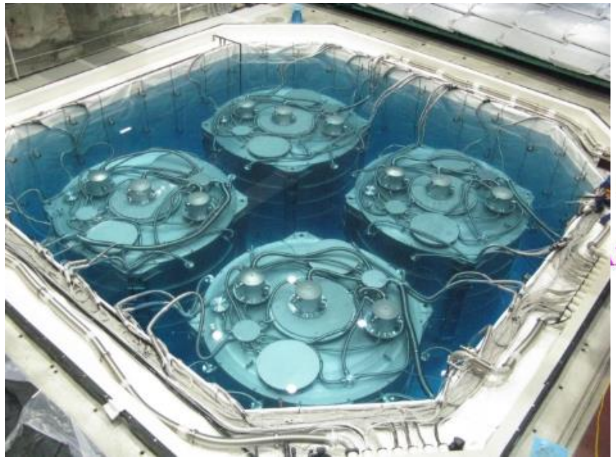
- **Over the last 5 years:**
  - **Daya Bay** operation completed in Dec. 2020
  - **JUNO** (including satellite experiment **TAO**) construction and physics prospects
  - Participation in R&D of **nEXO**, **Darkside, COMET**
  - R&D on GasTPC, **JUNO-0νββ**
- **Work plan for next 5 years:**
  - **Complete** JUNO and TAO construction and **obtain 1st results**
  - Intl collaboration: EXO/nEXO, Darkside
  - R&D on JUNO-0νββ, …

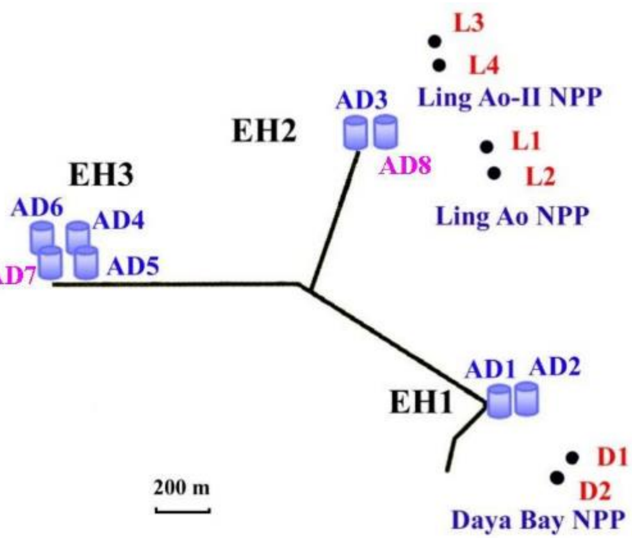
Daya Bay

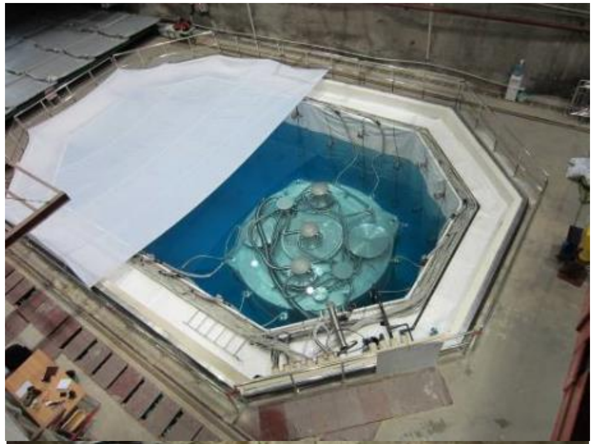
Daya Bay Reactor Neutrino Experiment for θ_{13}. Proposed in 2003, started in 2011, finished in 2020, and decommissioned in 2021

- IHEP: Civil construction + ~1/2 detector
- US: ~1/2 detector.
- Russia, Czech, Hong Kong, and Taiwan: ~1 M$ each

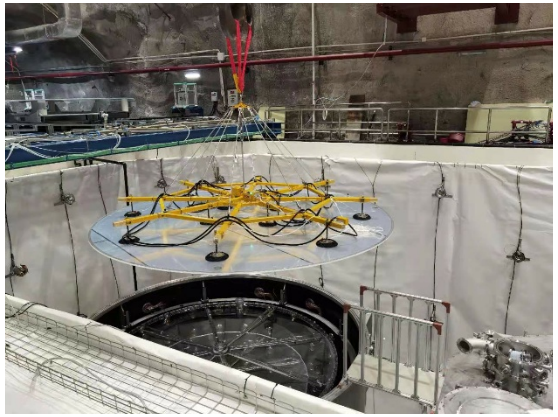
Continuous important scientific outcomes in 2018 to 2023 (7 PRL, 2 featured in physics)







Aug. 15, 2011



Decommissioning in 2021

Collaboration

- 41 institutions, 193 collaborators
- China (22), US (16), Europe (2), Chile
- IHEP: 47 (~80 in 2011)

Daya Bay: precision era

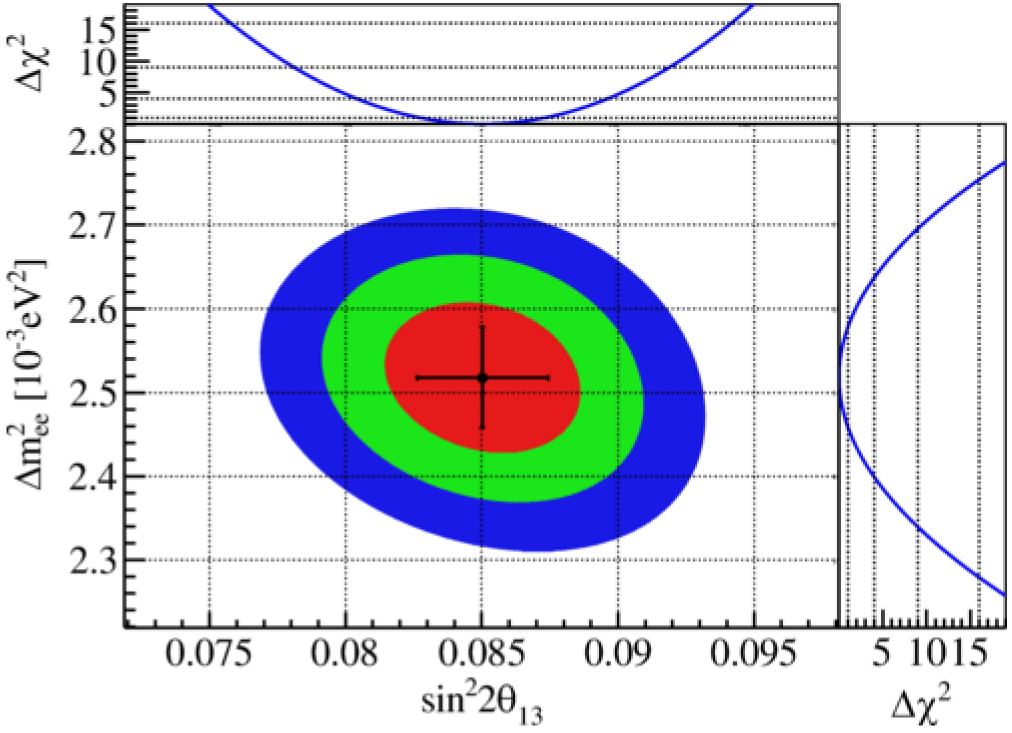
- **Most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$ with the full dataset**

Featured in Physics | Editors' Suggestion | Open Access | Access by University c

Precision Measurement of Reactor Antineutrino Oscillation at Kilometer-Scale Baselines by Daya Bay

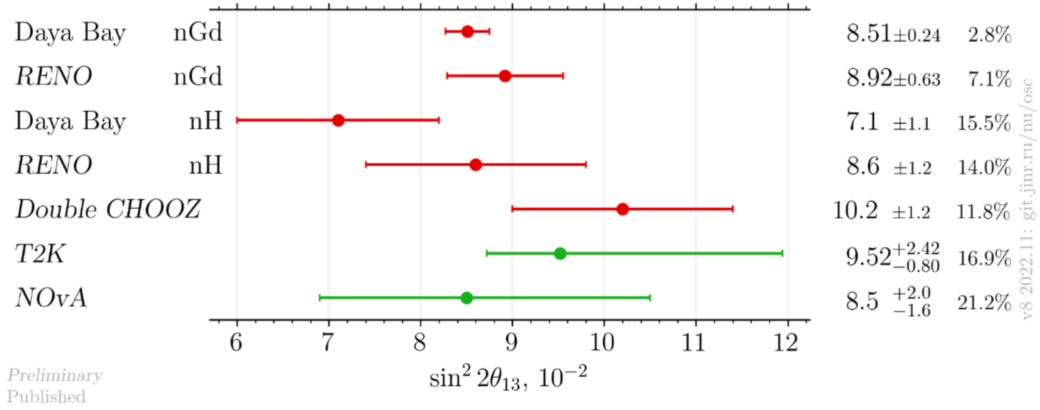
F. P. An *et al.* (Daya Bay Collaboration)
Phys. Rev. Lett. **130**, 161802 – Published 21 April 2023

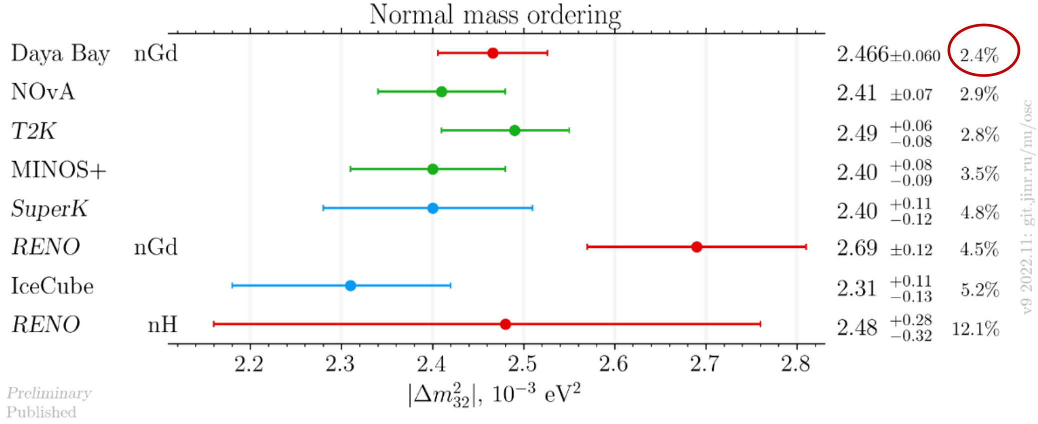
Physics See synopsis: Daya Bay's Final Measurement



Precision of $\sin^2 2\theta_{13}$ reached 2.8%

Likely be the best result in future 20 years.



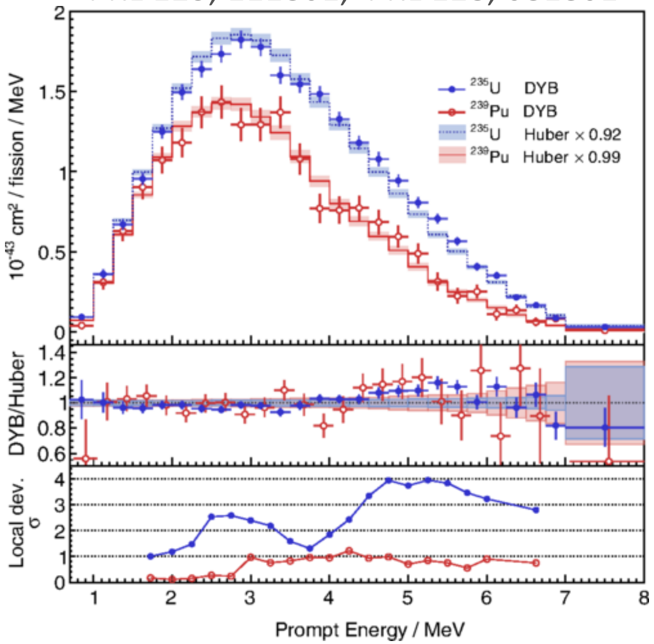


Daya Bay: reactor ν spectrum & sterile ν

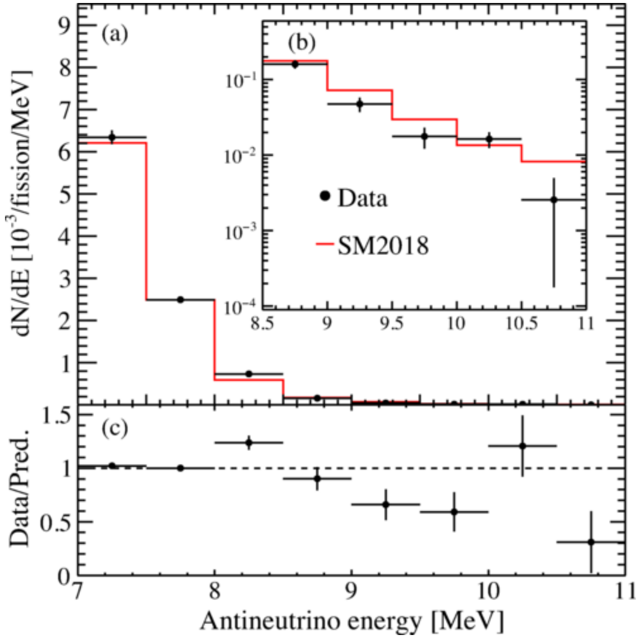
- **Precision measurement on reactor ν flux and spectra**, compared to theoretical prediction
  - **Flux deficit:** only **^{235}U has deficit**, NOT ^{239}Pu
  - **Spectrum anomaly: 5.3 σ** (overall), **6.3 σ** (in 4-6 MeV bump), similar shape in ^{235}U and ^{239}Pu
- **First, likely the only, observation of reactor neutrinos with E>10 MeV**

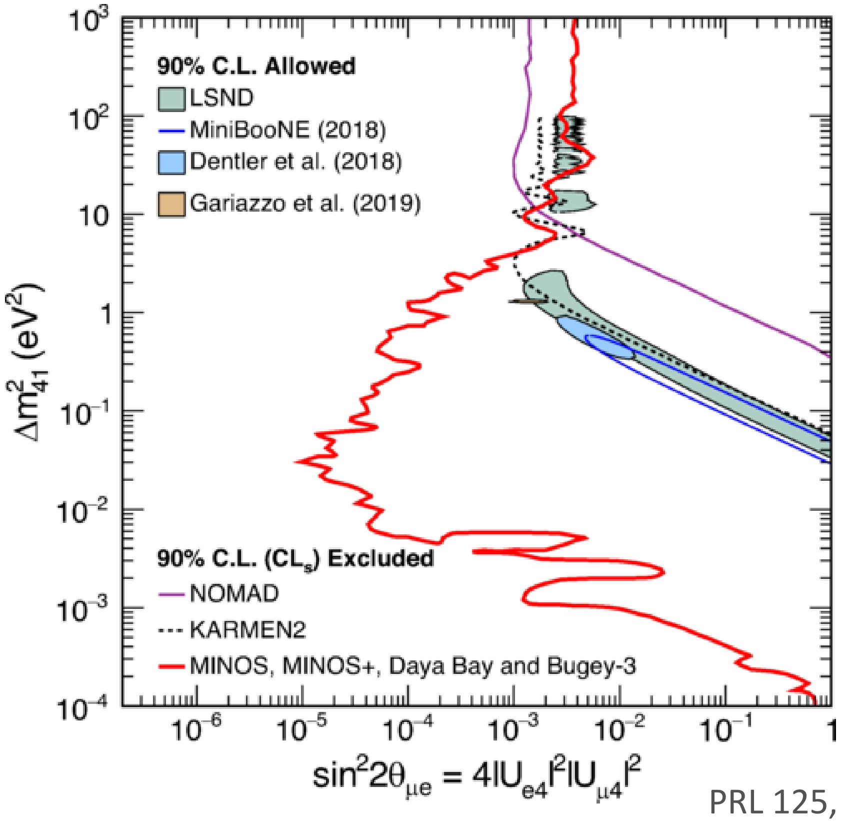
- **Daya Bay puts the most stringent upper limit for light sterile neutrinos (Δm^2_{41} < 0.2 eV^2)**
- **Joint Daya Bay, MINOS+, and BUGEY-3 results exclude the LSND and MiniBooNE signal region (at Δm^2_{41} < 5 eV^2 at 90% C.L.)**

PRL 123, 111801, PRL 128, 081801



PRL 129, 041801





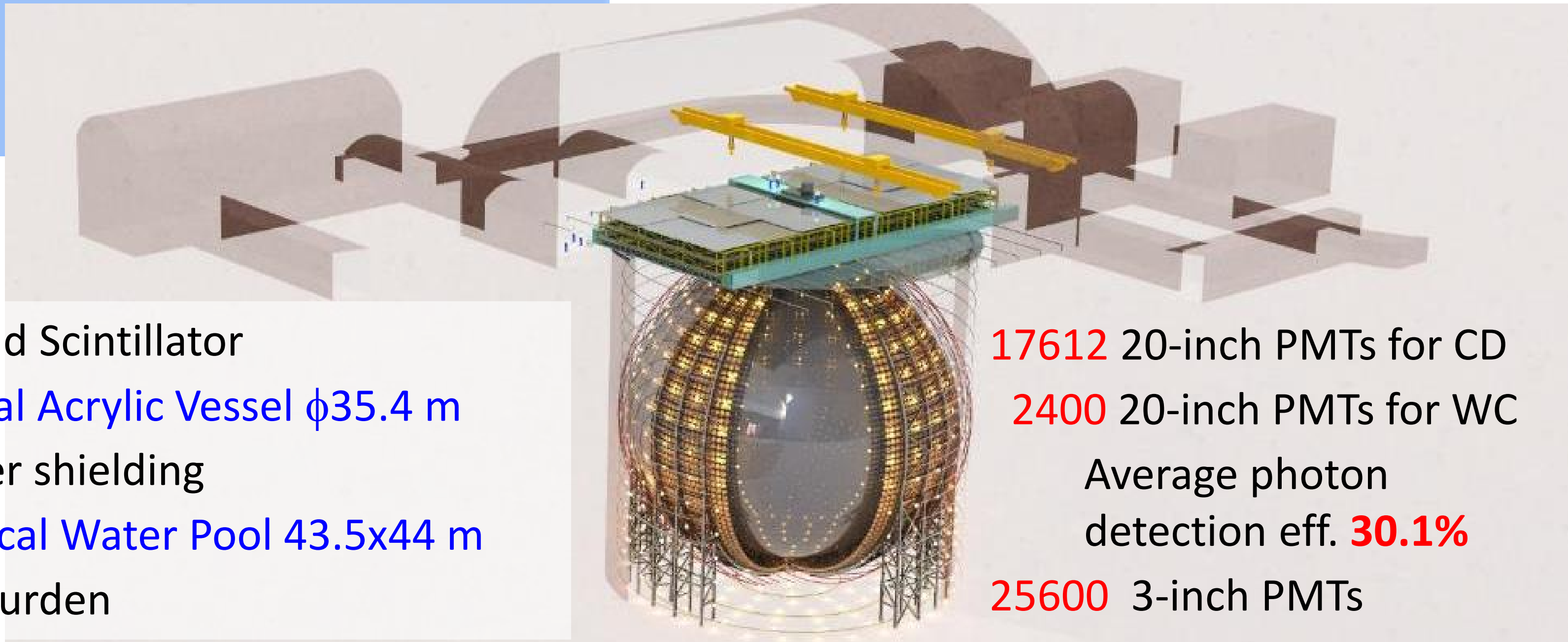
PRL 125, 071801

JUNO Jiangmen Underground Neutrino Observatory

- **Proposed in 2008 for mass ordering**
- **Approved in Feb. 2013**
- **~ 300 M$ (+ ~30 M€ international)**
- **Data taking in 2024**

JUNO collaboration: >700 collaborators (40% Intl), 74 institutions, 17 countries/regions

Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km



20 kton Liquid Scintillator

Spherical Acrylic Vessel ϕ35.4 m

35 kton water shielding

Cylindrical Water Pool 43.5x44 m

700 m overburden

17612 20-inch PMTs for CD

2400 20-inch PMTs for WC

Average photon detection eff. **30.1%**

25600 3-inch PMTs

Physics Potentials with JUNO

JUNO has great potentials on the physics topics below, although except for CP phases, θ_{23} Octant

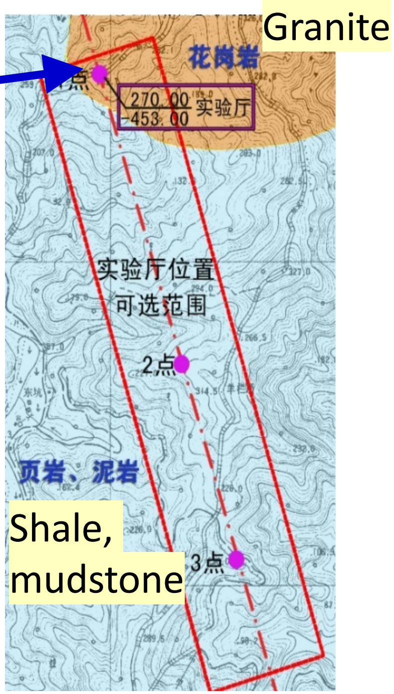
Exp.	Time	**Mass ordering**	**CP phases**	**Precision Meas.**	**CCSN burst @ 10 kpc**	**DSNB**	**Geo-ν**	**Solar**	**Proton Decay** (sensitivity@10 y)
JUNO (20 kt)	2024	**3-4 σ** *6 y*	—	**$\sin^2\theta_{12}$ (0.5%), Δm^2_{21} (0.3%), Δm^2_{31} (0.2%),** *6 y*	**all-flavor ν (IBD, eES, pES)**	**3σ**, *3 y*	**~400/y**	**^{7}Be, pep, CNO, ^{8}B**	> 9.6x10^{33} y ($\bar{\nu}K^+$)
DUNE (17 kt*4)	2030	**>5 σ** *1-3 y*	5σ (50%) *10 y*	Δm^2_{32} ~3.5%, *15 y*	**^{40}Ar CC & NC, eES**	^{40}Ar CC	—	^{8}B, hep	>8.7x10^{33} y ($e^+\pi^0$) >1.3x10^{34} y ($\bar{\nu}K^+$)
HyperK (260 kt)	2027	**3-5 σ** *10 y*	**5σ (60%)** *10 y*	Δm^2_{32} ~0.6%, *10 y*	**eES, IBD**	3σ, *6 y*	—	^{8}B, hep	**>7.8x10^{34} y ($e^+\pi^0$) >3.2x10^{34} y ($\bar{\nu}K^+$)**
ORCA (7 Mt)	Un-known	**2-4 σ** *3 y*	—	Δm^2_{32} ~2% , *3 y*	rate excess	—			
IceCube Upgrade	2026	**2-4 σ** *7 y*	—	Δm^2_{32} ~1.3% , *3 y*	rate excess	—			

eES: ν-electron scattering, pES: ν-proton scattering, IBD: inverse beta decay

JUNO Civil

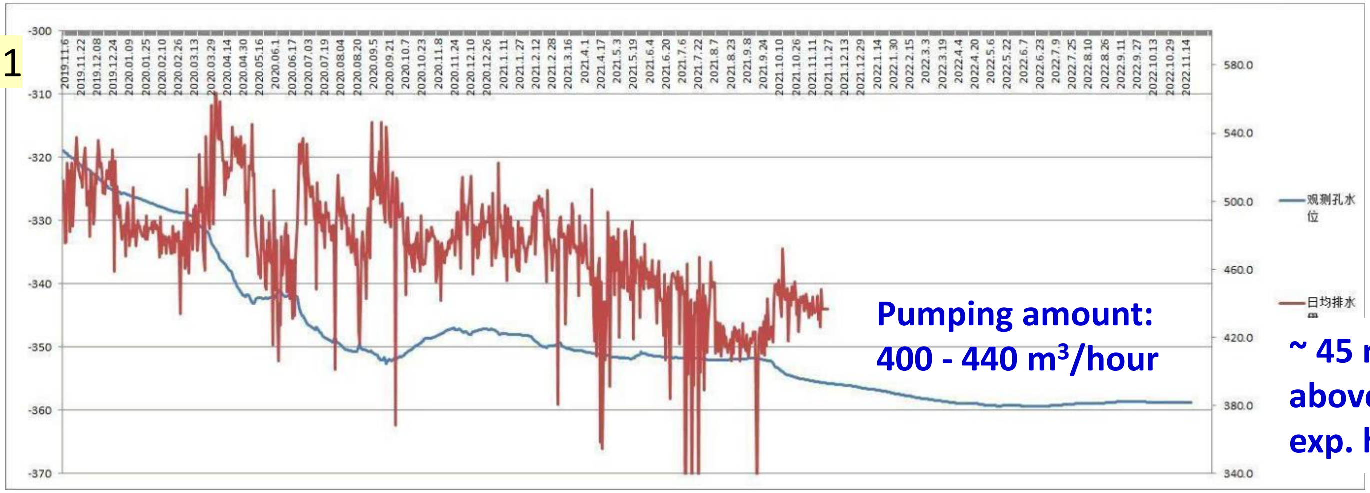
- **Excavation suffered from huge fissure water**
  - Geological survey shows that the rock resistivity is low, but it is interpreted as iron ore, proved by bore hole samples
  - Largest water flow rate seen was 600 m^3/h, prediction was 150 m^3/h.

The only possible site !



- **Huge efforts to seal water, delayed by ~3.5 years (completed on 2020.12.30)**
  - **Drill holes to inject cement before drilling holes for blasting**
  - Add a tunnel to release the water pressure at the top of the hall

2019.11

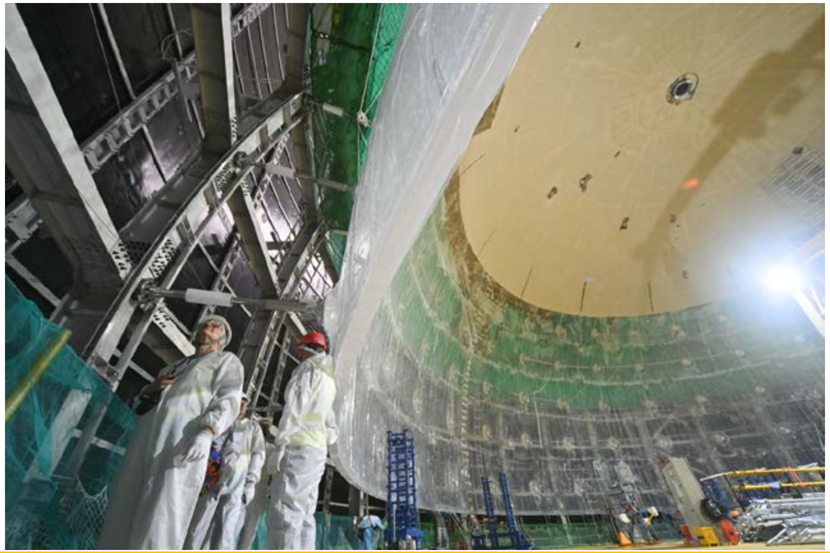


JUNO – Acrylic Sphere Vessel

- **World-largest acrylic vessel (Φ 35.4 m, 12 cm thickness)**
- **Ultra-clean production of 263 panels**
  - Curved w/ high precision & **Transparency > 96%**
  - **Ultra-low U/Th: < 1 ppt**
- **Developed new bonding technology to simultaneously bond all panels in one circle**

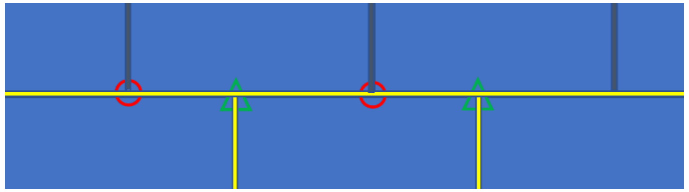
	Φ	Weight	Bonding length	Thickness	Installation
JUNO	**35.4 m**	**600 t**	**2 km**	**120 mm**	**~ 20 mon**
SNO	12 m	30 t	500 m	56 mm	~ 24 mon

- **Difficulties/Risks and Solutions**
  - **Internal stress** (higher in some bonding area)→ **Epoxy protection to the surface of bonding area**
  - **Defects** in "T" area → **Protection w/ pre-bonded acrylic cover**
  - **Radioactivity** control → **Very careful cleaning procedures & Radon control during installation and filling**



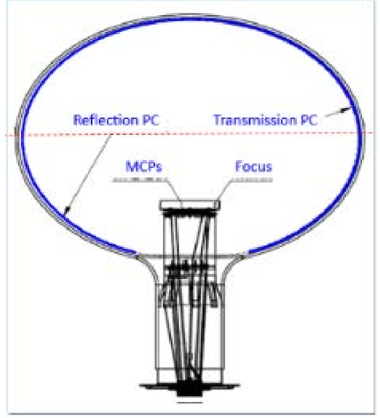
Acrylic sphere from top to equator layer (1/2 completed)

Typical defects to be repaired : holes, rectangles, bubbles.
They are mainly from the bonding lines especial the "T" area.

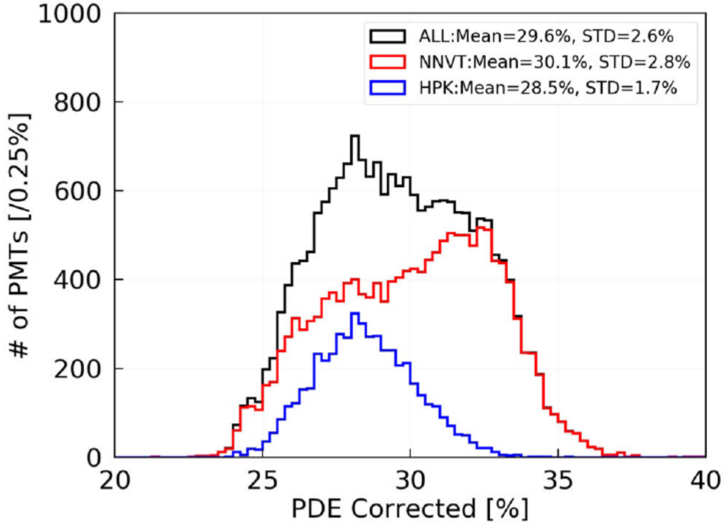


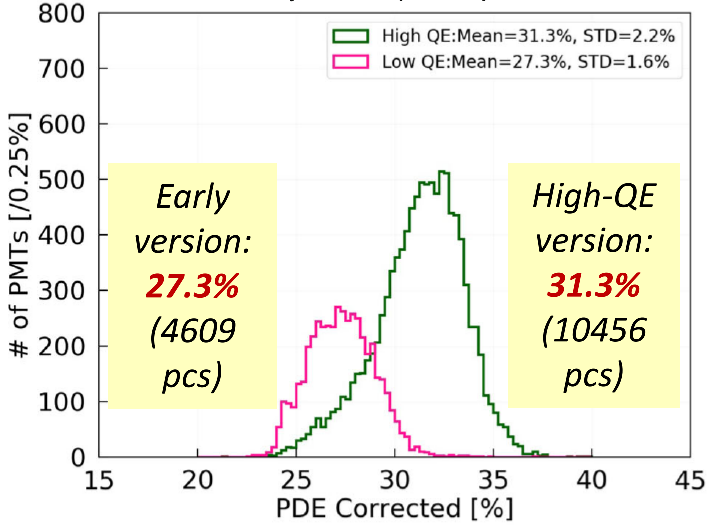
JUNO – MCP-PMT

- New type of 20-inch PMT based on MCPs
  - ⇨ Started PMT R&D in 2008, chose MCP-PMT in 2009 (Patented by Y.F.Wang, S. Qian, T.C.Zhao, J. Cao in China, US, Russia, Japan, EU)

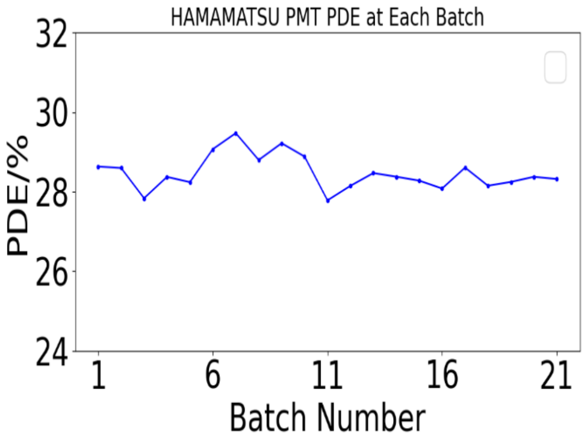


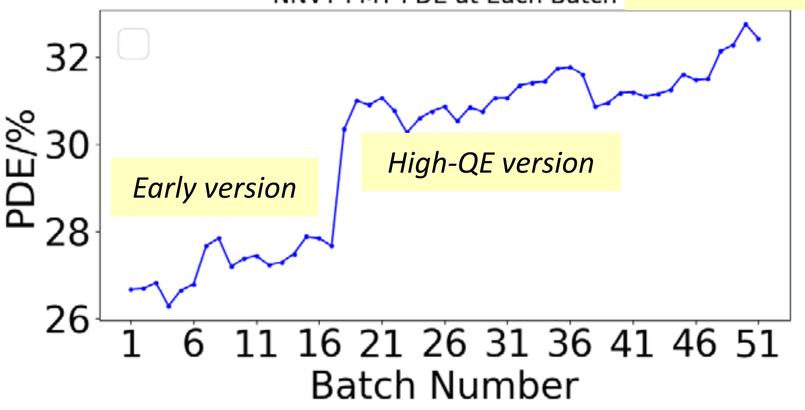
Eur. Phys. J. C (2022) 82:1168





- 2020: all 15k MCP-PMTs produced and tested
  - **Average PDE~30.1%**
  - **DCR~16KHz** (after long-term cooling down)
- 2021: all PMTs potted for waterproof
  - Failure rate <0.5% in 6 yrs, while same requirement for underwater electronics
- 2022: Installation at JUNO started
- **~35% installed now**





JUNO – Liquid Scintillator (LS)

- **Challenges for 20 kton LS**
  - Most transparent LS: **attn. >20 m**
  - Ultra-low radioactivity: **U/Th<10^{-17} g/g (< 10 mg dust)**

Need be achieved in the first place, otherwise online circulation is difficult

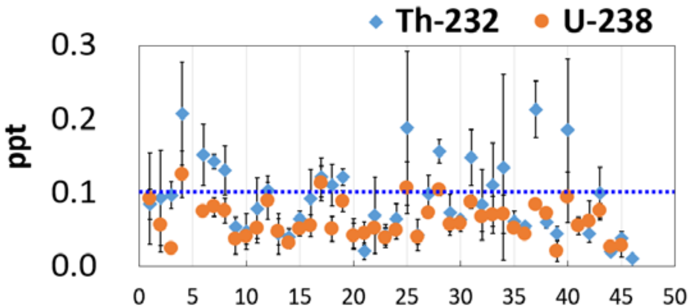
- **The most complex system designed and built, using four purification technologies**
  - **Al_2O_3 filtration**
  - Distillation (Italy)
  - Gas tripping (Italy)
  - **Water extraction**

Joint commissioning ongoing

- **Raw material control**

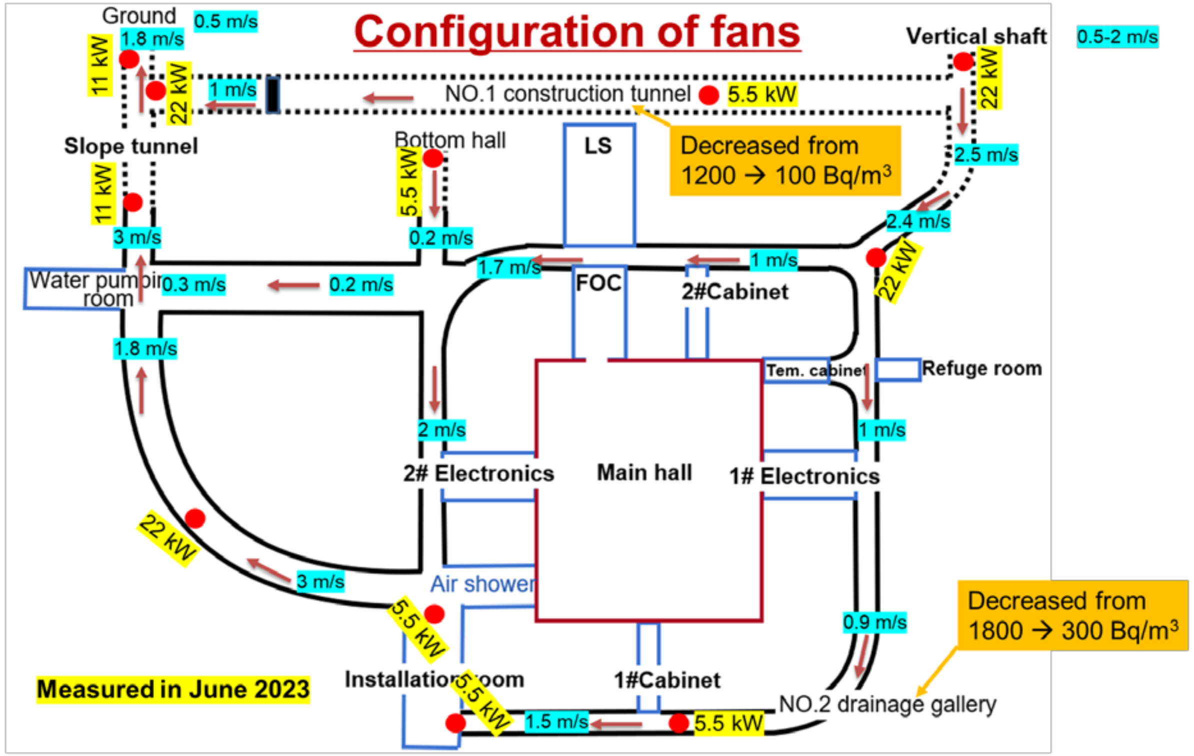
(LS recipe: LAB + 2.5 g/L PPO + 3 mg/L bis-MSB)

  - Highly transparent LAB: **λ_{attn} ~ 22-23 m**
  - Ultra-low radioactivity PPO: **U/Th<0.1 ppt**
  - Ultra-pure water for liquid-liquid extraction: **<10^{-16} g/g**

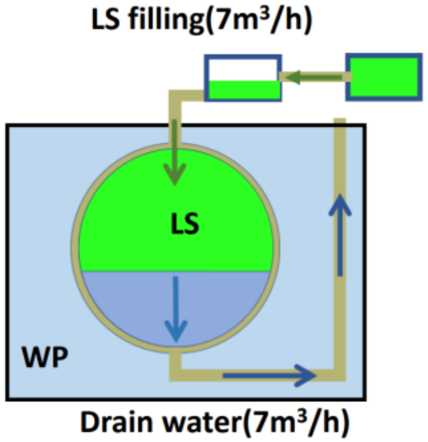


JUNO – Background Control

- **Environmental Radon control**
  - Large amount of underground water at JUNO site: **450 m³ /h with 120,000 Bq/m³ radon in water** → underground water is a large radon source
  - Continuous improvement of ventilation → radon in Exp-Hall reduce to **100-200 Bq/m³**



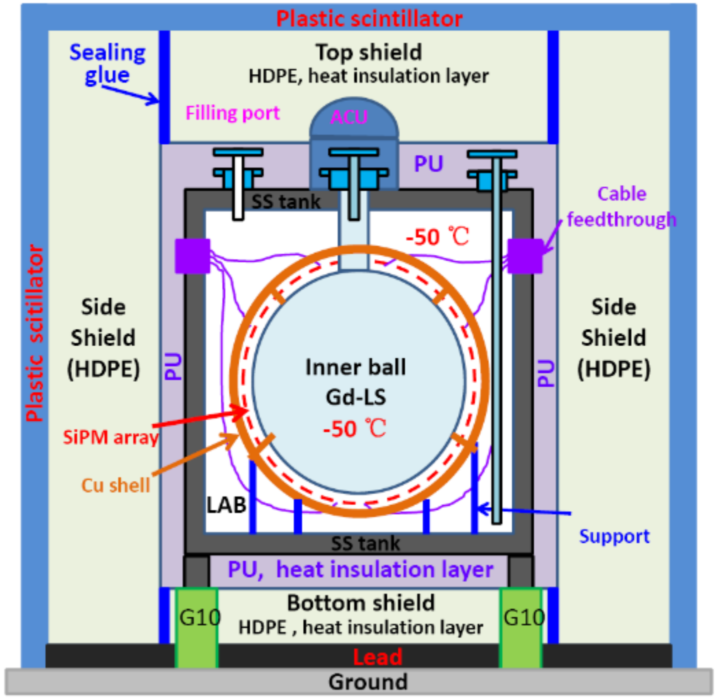
- **Materials control & cleanness → <7.2 Hz in FV (spec: 10 Hz)**
  - LS (LAB, PPO, bisMSB)
  - Acrylic
  - PMT glass
  - SS Struss
  - PMT readout Electronics
  - Ultra-pure water (micro-bubbling tech.)



- **Cleanness control during installation & Filling**

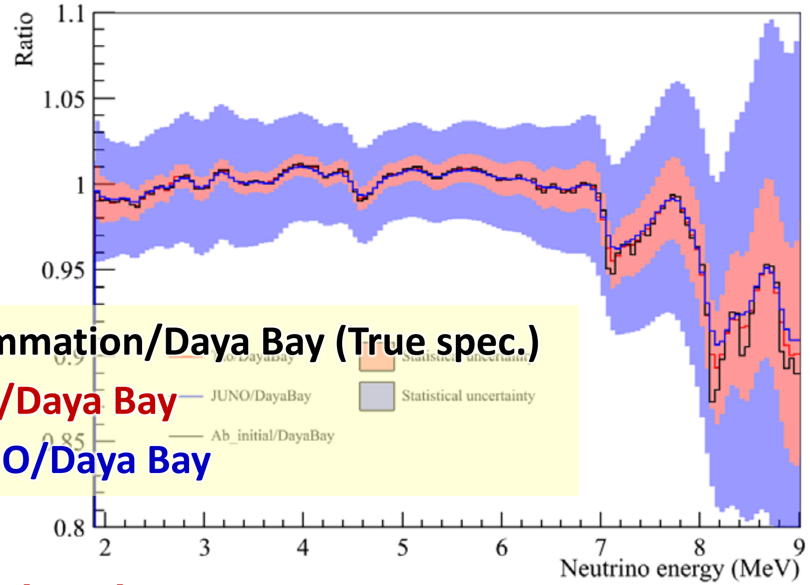
JUNO – TAO

- **Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the 4.6 GW_{th} core, a satellite exp. of JUNO.**
- **Measure reactor neutrino spectrum w/ high E resolution**
  - **Model-independent reference spectrum for JUNO**
  - **A benchmark for testing the nuclear database**
- **Detector Features**
  - 4500 p.e./MeV, <2% resolution @ 1MeV
  - 2.8 ton Gd-LS
  - full coverage (~10 m^2) of SiPM w/ PDE > 50%
  - Operate at -50 ℃ (low SiPM dark noise)
- **Expected online in 2024**



CDR: 2005.08745

Calibration strategy: 2204.03256



Solid: Summation/Daya Bay (True spec.)
RED: TAO/Daya Bay
Blue: JUNO/Daya Bay

Constrain the fine structure in [2.5, 6] MeV to < 1% 2111.10112

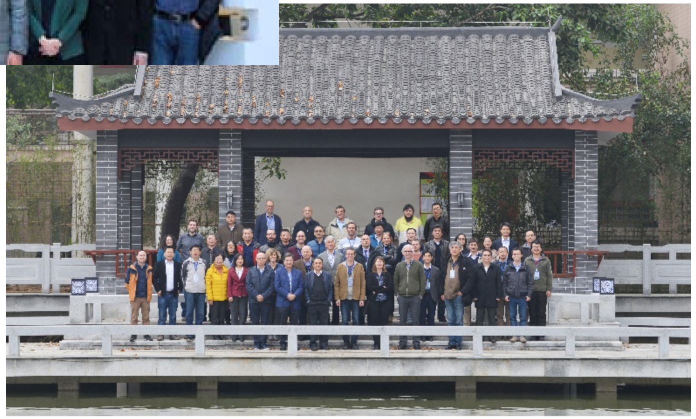
JUNO ISC

- Established International Scientific Committee (ISC) in 2019
- The collaboration annually reported to the ISC on project status & progresses, issues, management, physics, etc.
- Very positive comments, and invaluable suggestions from the ISC

"… owing to the actual value of δ_{CP}, JUNO will potentially make the first 3σ measurement (or be a major contributor to it)."

"… The schedule delays so far are not devastating in the context of world-wide competition for mass ordering determination. Although this physics should remain the highest priority, the ISC advises the Collaboration to avoid any compromise on eventual detector quality resulting from unnecessarily rushing the schedule…"

2019.01, Shanghai



2020.01, Nanning

The 2nd JUNO International Scientific Committee Meeting
January 18-19, 2020, Guangxi University, Nanning

Online ISC meetings: 2021.02, 2022.02

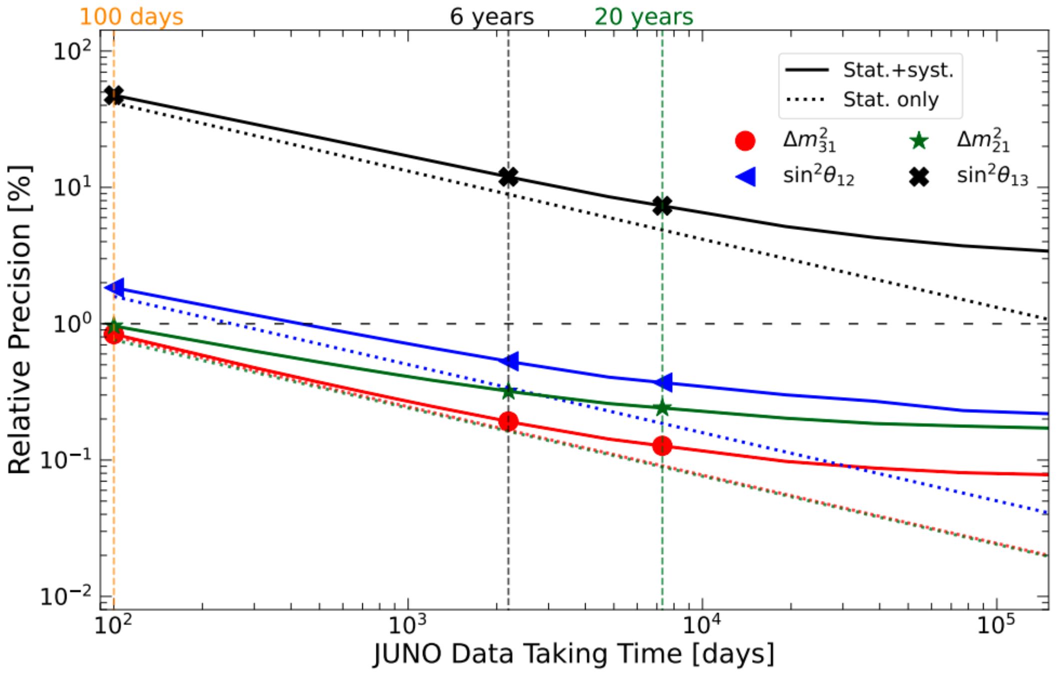
The 5th JUNO International Scientific Committee Meeting
July 29-30, 2023, Kaiping, Guangdong

2023.02, Kaiping (JUNO site)

JUNO in next 5 years

- **Towards detector completion and operation in 2024**
- **3.5-year operation:**
  - **Best $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31}, <1%**
  - **3σ mass ordering sensitivity w/ synergy of Reactor + Atmospheric oscillations**
  - **Geo-ν, 400/year versus ~150 observed in Borexino+KamLAND**
  - **Best DSNB sensitivity**
  - **Solar-ν, Nucleon decay, …**
  - **Most precise reactor spectrum w/ JUNO-TAO**

arXiv:2204.13249, Chin. Phys. C 46 (2022) 123001



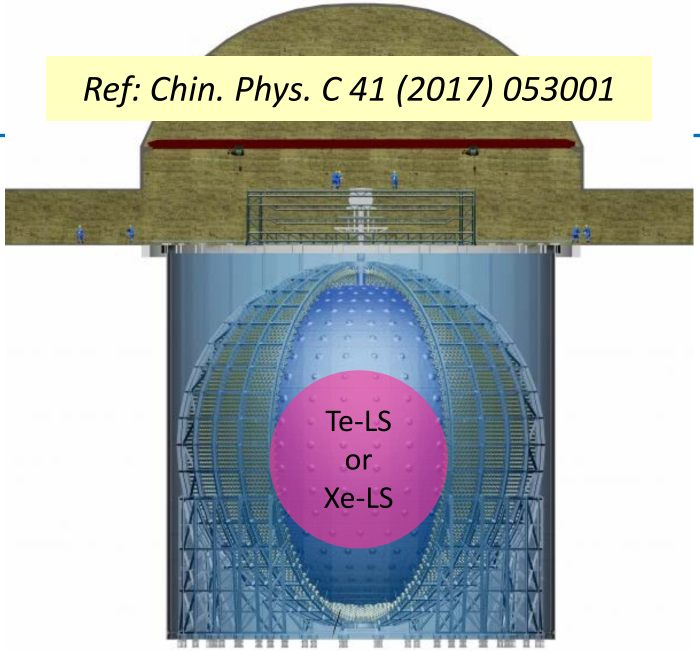
JUNO-0νββ

■ JUNO offers an unique opportunity to search for 0νββ after completion of mass ordering measurements (~2030)

- Large target mass: 20 kton LS → **100-ton scale isotope loading** (e.g., Tellurium, no enrichment, cost effective)
- Ultra-pure LS shielding → **Low background**
- Energy resolution **< 3% @ 1 MeV**

➔ Potential to explore normal mass ordering parameter space of Majorana neutrino mass (~ meV)

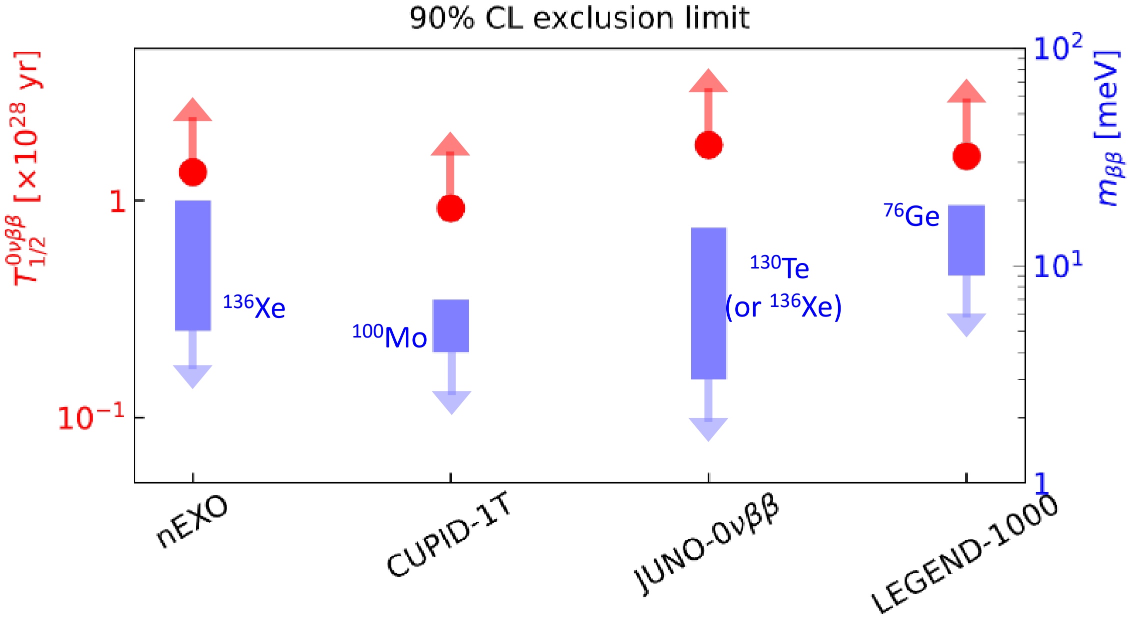
Ref: Chin. Phys. C 41 (2017) 053001



Concept of the experiment

■ Critical R&D in progress

- **Te-loaded LS** (requirements: high light yield, transparency and solubility and stability)
- **Background rejection** (^{8}B solar neutrinos, Te muon-spallation products)
- **Xenon enrichment** w/ a company, aiming at 200 kg/yr

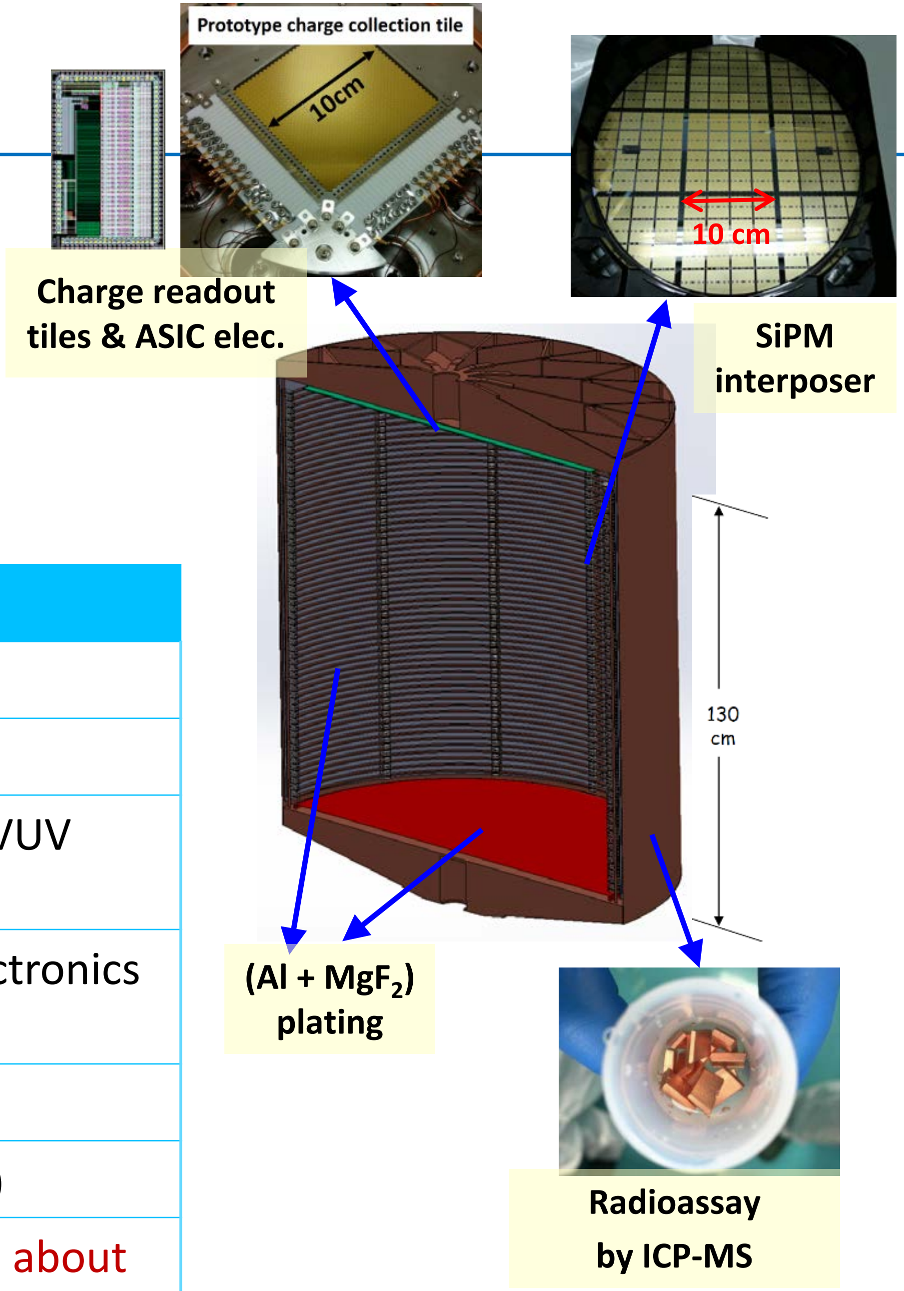


EXO-200/nEXO

- **Management Roles**
  - Physics coordinator: Liangjian Wen (2015-2016), Gaosong Li (2017-2022)
  - 1.04.02 L3 (Photon Detector - photon detector specification) : Guofu Cao
  - 1.03.04 L3 (TPC - Charge Detection & Anode) : Liangjian Wen

- **Major activities in nEXO R&D**

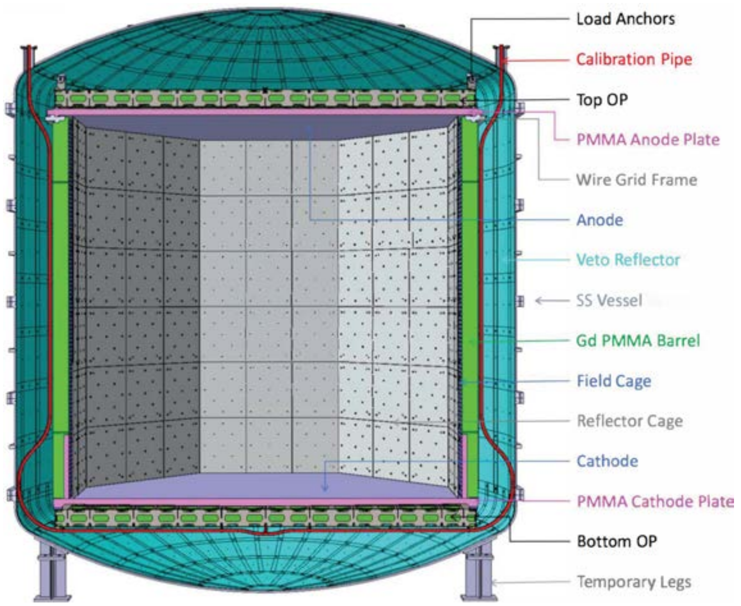
L2 systems	WBS tasks
TPC System	Anode charge tiles (full size ~1.3 m^2)
Photon Detector	Si-interposer (full size ~ 5 m^2) for SiPM readout
	($Al+MgF_2$) coating on cathode & shaping rings to reflect VUV photons
Electronics (charge readout)	Analog multiplexing ASIC (cold) + under-water FADC electronics based on JUNO experience
Radioactivity Control	Radio-assay via ICP-MS at IHEP
Veto system	~500 water-proof 8-in. PMTs + Elec. (in-kind from Daya Bay)
Xenon	Pursue a domestic solution for Xe-136 enrichment (up to about ~ 1 ton ^{enr}Xe)



* Planned Hardware contribution from IHEP, not including manpower & overhead. Presented at 0νββ international summit at SNOLAB, Apr 2023

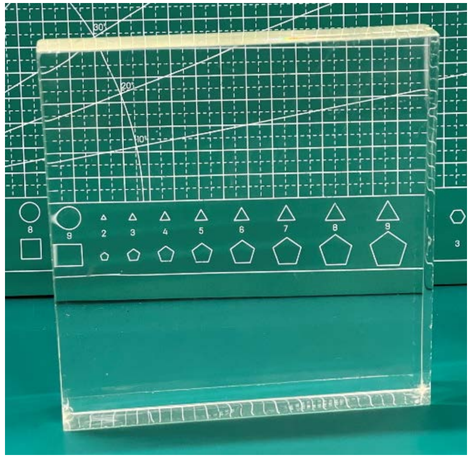
Darkside-50 / Darkside-20k

- **IHEP-Darkside team, since 2011**
  - Current PI: Yi Wang (EB, IB, Finance board, resource review board)



- **Significant contributions to world-leading low-mass WIMP searches at DarkSide-50**
  - Innovative ionization-only analysis achieved 3 e- threshold
  - Precise low recoil energy calibration with Ar-37

- **Leading activities on Darkside-20k**
  - Inner detector baseline design
  - Development of Gd-PMMA (JUNO technology), critical to facilitate "background-free" WIMP searches by prefect neutron tagging

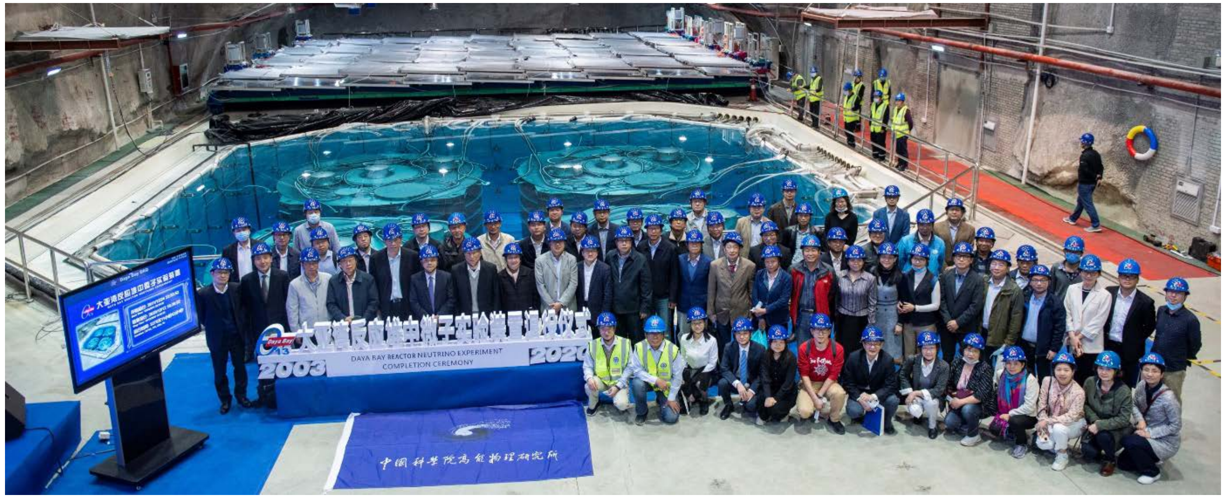


IHEP Neutrino Team

- **Starting from a few scientists in 2003, IHEP has built a strong team. ~80 scientists involved in Daya Bay, ~100 in JUNO.**

Division	JUNO coll.
Experimental Phys. Div.	87
Computing Center	10
Theory Div.	3
Multidisciplinary Div.	1

FTE	Full Prof.	All Staff	Postdocs & Students
Daya Bay	1.1	2	7.3
JUNO	14.8	55.1	21.8
EXO	0.45	1.1	2.2
Darkside	0	1.2	3



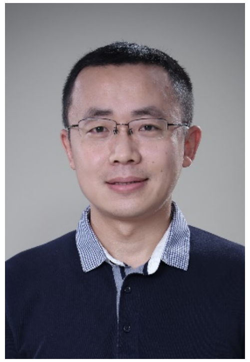
Leading & Young Scientist

Leading Scientists

Yifang Wang (60)

Jun Cao (50)

Liangjian Wen (40)



He Miao (42)

Selected Young Talents

Homegrown

Liang Zhan (41)

Zeyuan Yu (33)

Guofu Cao (43)

Yufeng Li (42)

Jie Zhao (35)

Haoqi Lu (40)

Oversea Young Talent Program

Wuming Luo (38)

Gaosong Li (34)

Yichen Li (35)

Yi Wang (33)

Xuefeng Ding (34)

International Visibility

- **Many plenary talks by young members on Daya Bay, JUNO, overviews of reactor neutrinos and detectors at major conferences like ICHEP, Lepton-Photon, Neutrino, NeuTel, TIPP, WIN, TAUP, FPCP, CHEP etc.**

- **Young members served as**
  - IUPAP-C11 Commission: Liangjian Wen
  - IAC of Lepton Photon: Shun Zhou, IAC of TIPP: Liangjian Wen
  - SPC of NuFact: Miao He, Conveners of ICHEP, NuFact, NNN, Applied Nu Workshop: Yufeng Li, Zhimin Wang, Liangjian Wen

- **Awards**

Domestic (3) International (1)	Awardee	Date
EPS-HEPP Prize	Y.F. Wang (Daya Bay)	2023.4
XPLORER Prize	L.J. Wen	2021.9
CAS International Partnership Prize for Young Scientists	M. He, J. Pedro Ochoa-Ricoux	2021
CAS Young Scientist Award	L.J. Wen	2020.1

Summary

- Daya Bay completed in Dec 2020, and has continued its impact in the last 5 years
  - $\sin^2 2\theta_{13}$: 2.8%, Δm^2_{ee} : 2.4%, best in foreseen future
    - $\sin^2 2\theta_{13}$ may achieve 2.6% if nGd+nH combined analysis
  - Precision reactor ν spectrum, exotic searches
- JUNO construction going well, making breakthroughs in key technology such as MCP-PMTs, acrylic vessel, liquid scintillator, etc, aiming at data taking in 2024
- R&D on JUNO-0νββ, nEXO, etc.

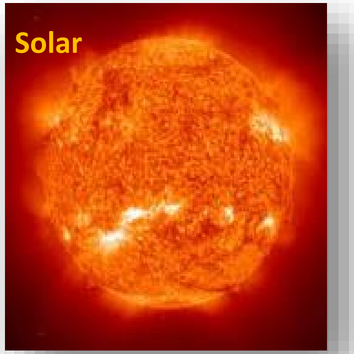
- IHEP aims to be a world-leading neutrino research center. After 20 years' effort, a strong team has been built for reactor neutrinos and 0νββ. Expertise expands to neutrino astronomy.
- Led by IHEP, the neutrino community in China is growing.
  Broad international cooperation has been established.

Thank you!

Physics Potentials with JUNO

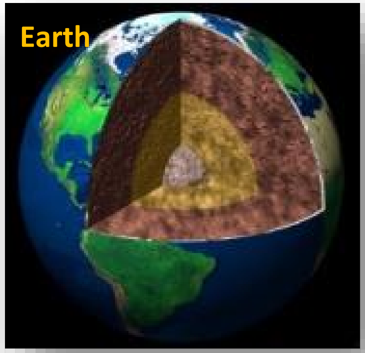
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

\+ New physics

Prog. Part. Nucl. Phys. 123, 103927 (2022)

IBD: inverse beta decay
CCSN: core-collapse supernova
DSNB: Diffused Supernova Neutrino Background

Neutrino oscillation & properties

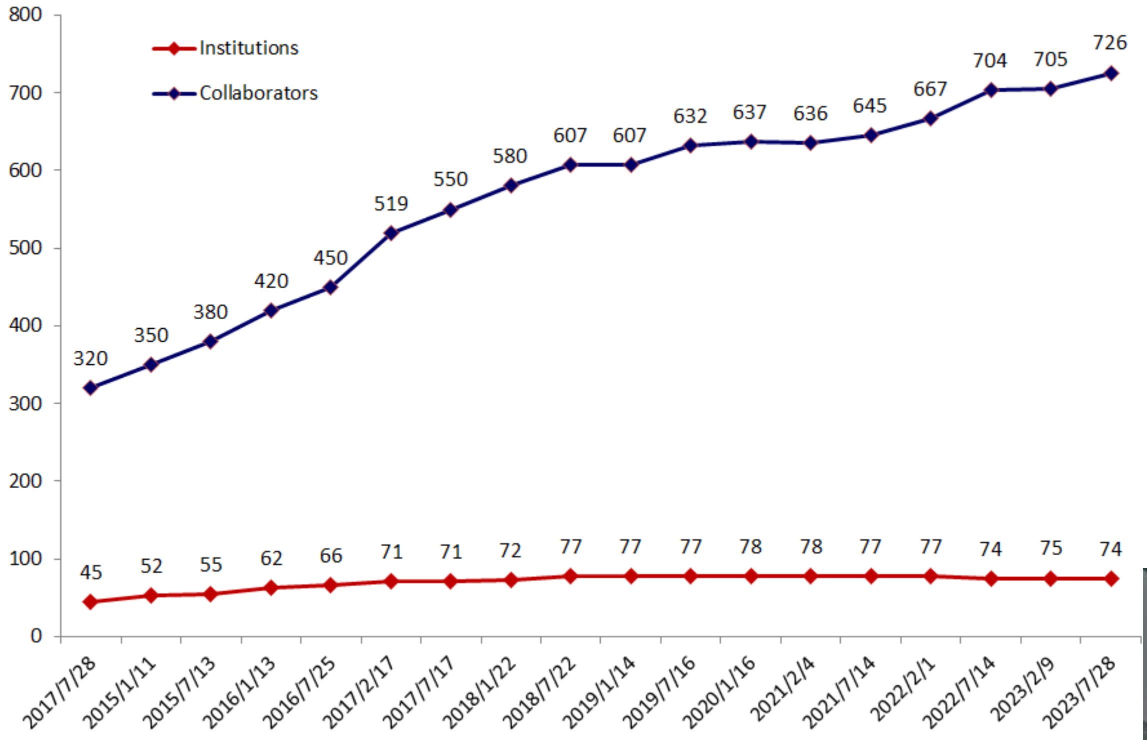
Neutrinos as a probe

- Energy resolution **2.95%** @ 1MeV w/ full simulation
- **ν mass ordering: 3σ (reactor only)** @ ~6 yrs (*Neutrino 2022*), atmospheric ν oscillation being improved
- **ν oscillation parameters:** precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ **< 0.5%** in 6 yrs (2204.13249)

- **Supernova** ν: ~7300 of all-flavor neutrinos @ 10 kpc
- **DSNB**: **3σ** in 3 yrs (2205.08830)
- **Solar** ν:
  - ^{7}Be, pep, CNO (2303.03910)
  - ^{8}B (2006.11760, 2210.08437)
- **Geo** ν: ~400 per year, 8% measurement in 10 yrs

- **Nucleon Decays**: $p \to \bar{\nu} K^+$ 9.6×10^{33} yrs (90% C.L.) in 10 yrs (2212.08502), neutron invisible decay (ongoing)
- **Indirect DM search:** ~good sensitivity in 15-100 MeV region (2306.09567)
- **Future upgrade (2030s) : searching for 0νββ**

JUNO Collaboration

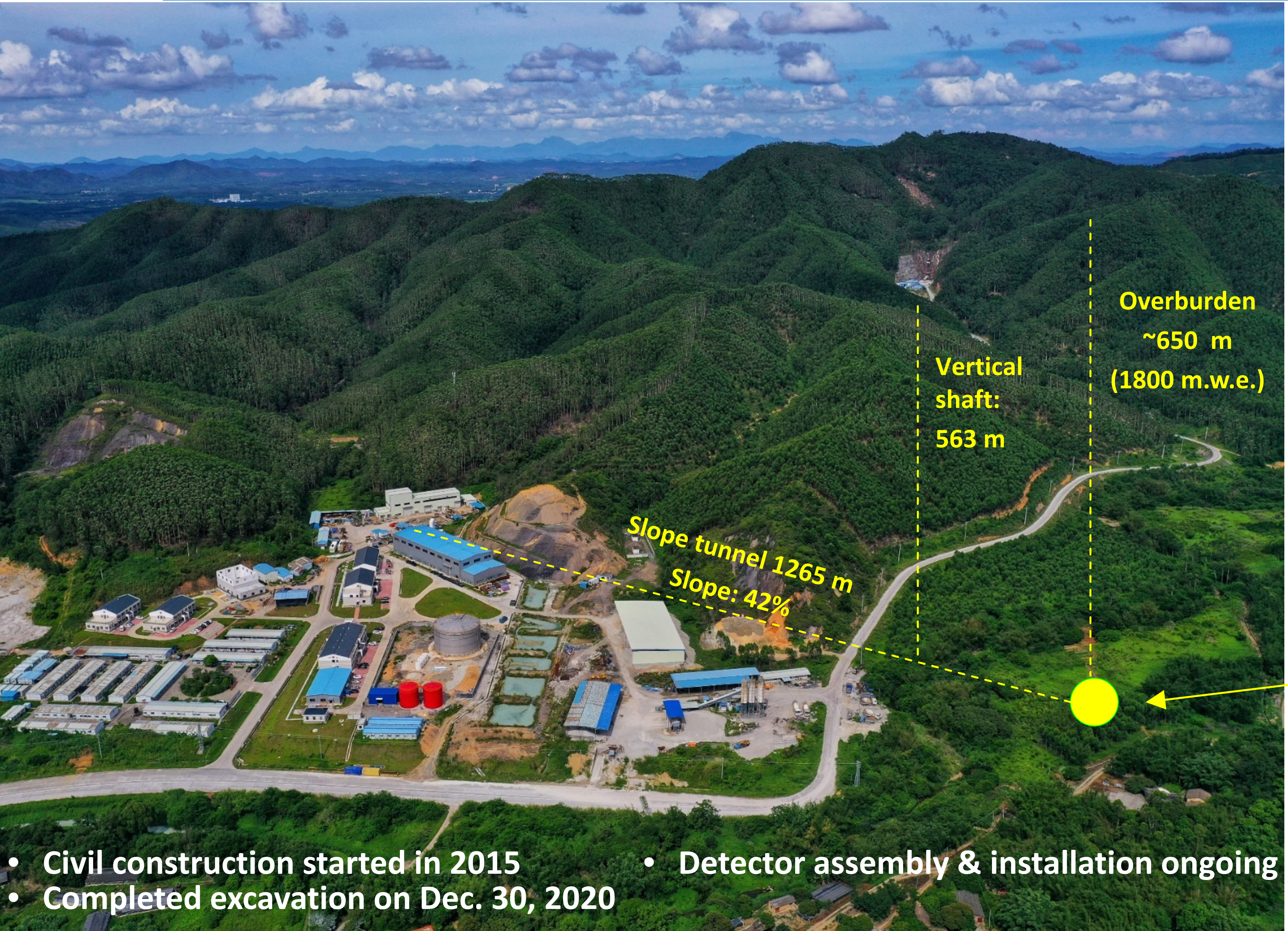


- China (33), China-Taiwan (3), Thailand (3), Pakistan, Armenia
- Italy (8), Germany (6), France (5), Russia (3), Belgium, Czech, Finland, Slovakia, UK
- Brazil (2), Chile (3), USA (2)

Jul 24-28, 2023, Kaiping

Spokesperson: Yifang Wang
Deputy-spokesperson: Jun Cao, Gioacchino Ranucci
IB Chair: Marcos Darcos

JUNO Campus



- Civil construction started in 2015
- Completed excavation on Dec. 30, 2020
- Detector assembly & installation ongoing

Funding

- **Daya Bay operation funding: 12 MCNY/year, stopped since 2021**
  - Daya Bay analysis supported by MoST
- **JUNO construction: 747 MCNY before 2018, 1323 MCNY to 2024**

			Total (MCNY)	IHEP (MCNY)
MoST	2018-2022	Daya Bay Physics & JUNO Physics	18	5.8
MoST	2022-2027	Reactor antineutrino monitor and physics	18	12.6
MoST	2023-2028	JUNO Reactor Antineutrino Physics (Applying)	20	7.6
		Sum	56	26

- **22 individual grants: > 70 MCNY**