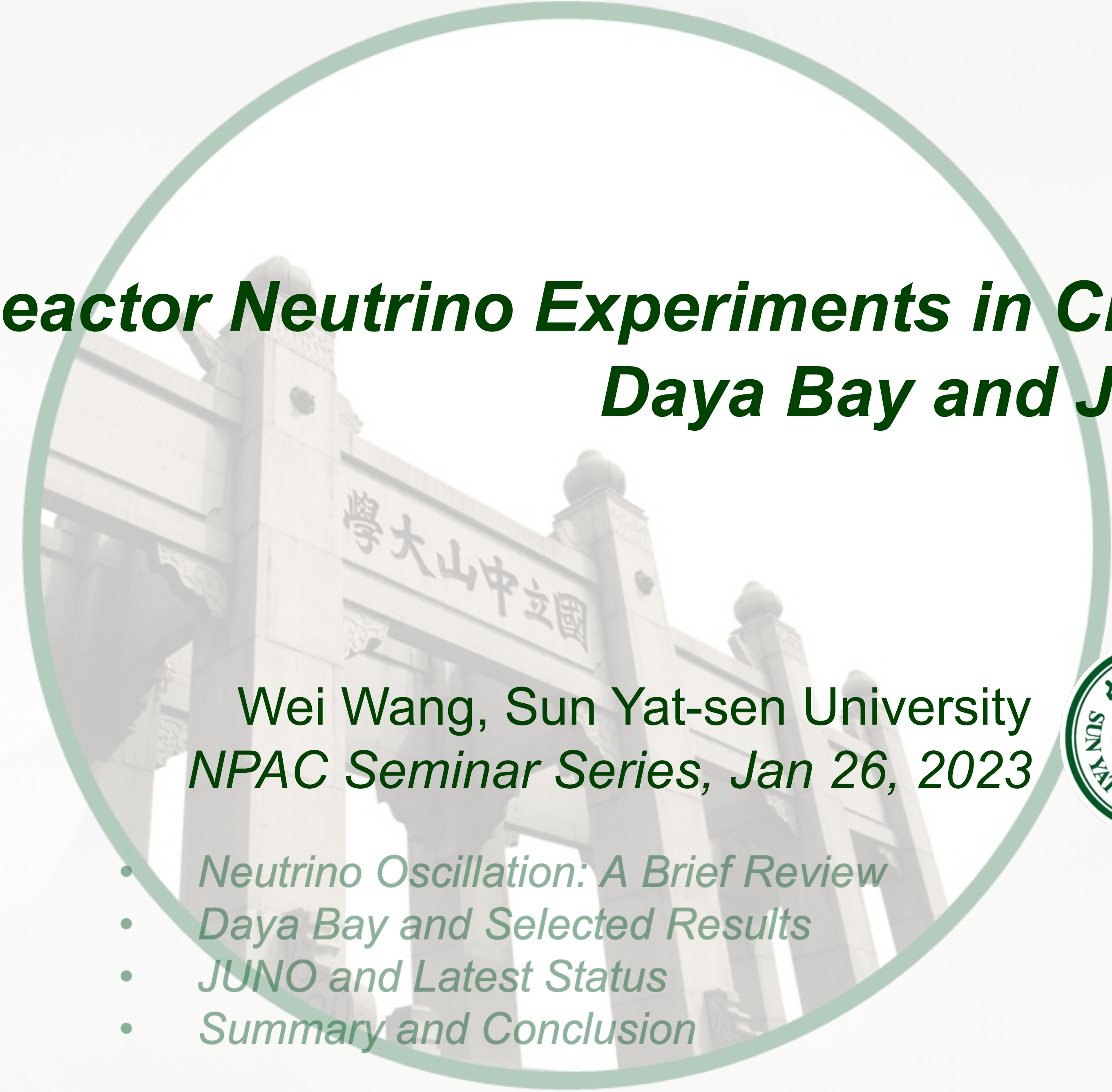
Reactor Neutrino Experiments in China: Daya Bay and JUNO



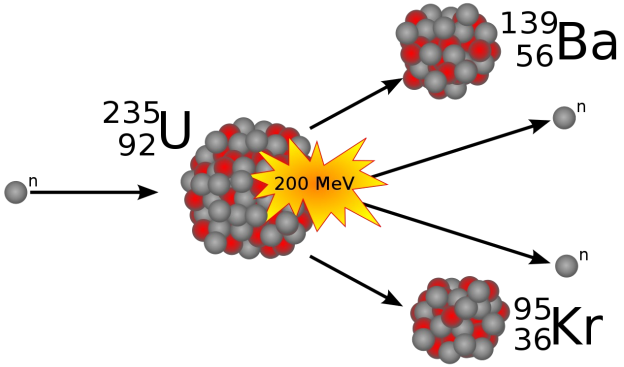
Wei Wang, Sun Yat-sen University

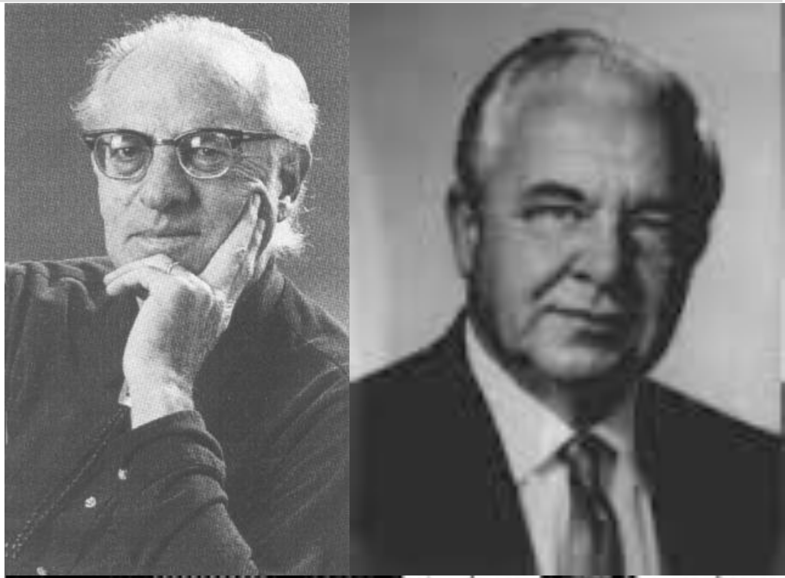
NPAC Seminar Series, Jan 26, 2023

- *Neutrino Oscillation: A Brief Review*
- *Daya Bay and Selected Results*
- *JUNO and Latest Status*
- *Summary and Conclusion*

Reines&Cowan Detected Reactor Neutrinos in 1956

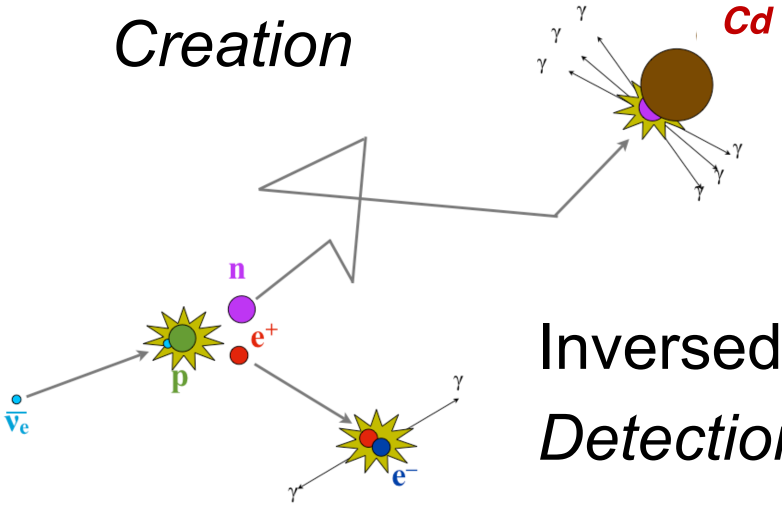
- Cowan and Reines at the Savannah River Power Plant (1956-1959)





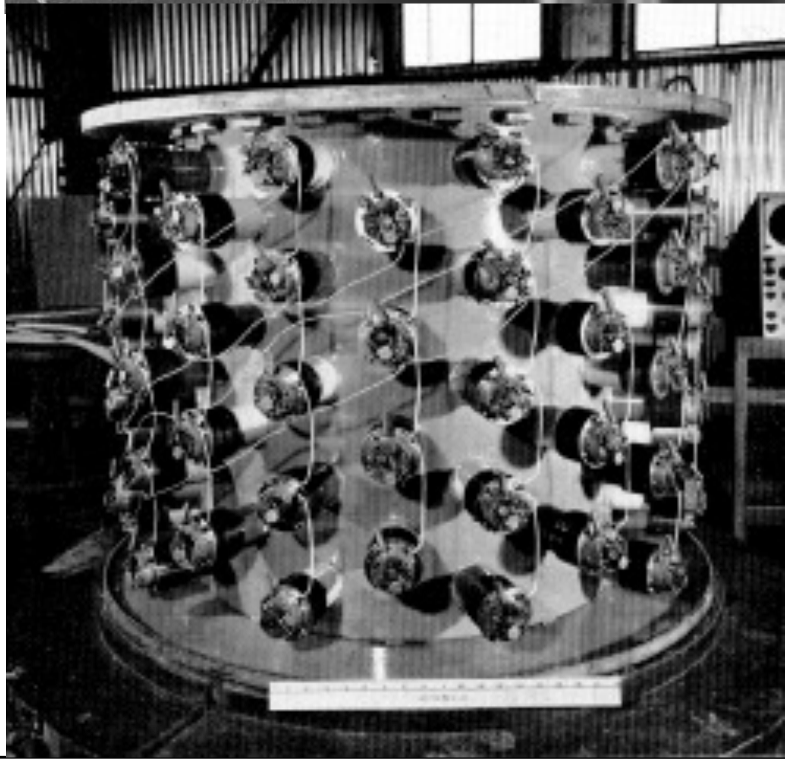
β decay :N → N′ + e + ν

Creation



Inversed β decay

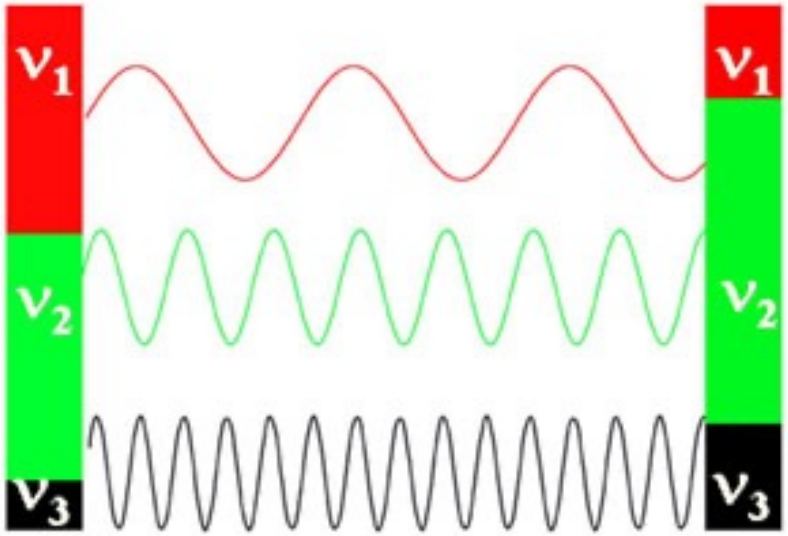
Detection: p+ ν ⟶ e^+ + n



Neutrino Mixing & Oscillation

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

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



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

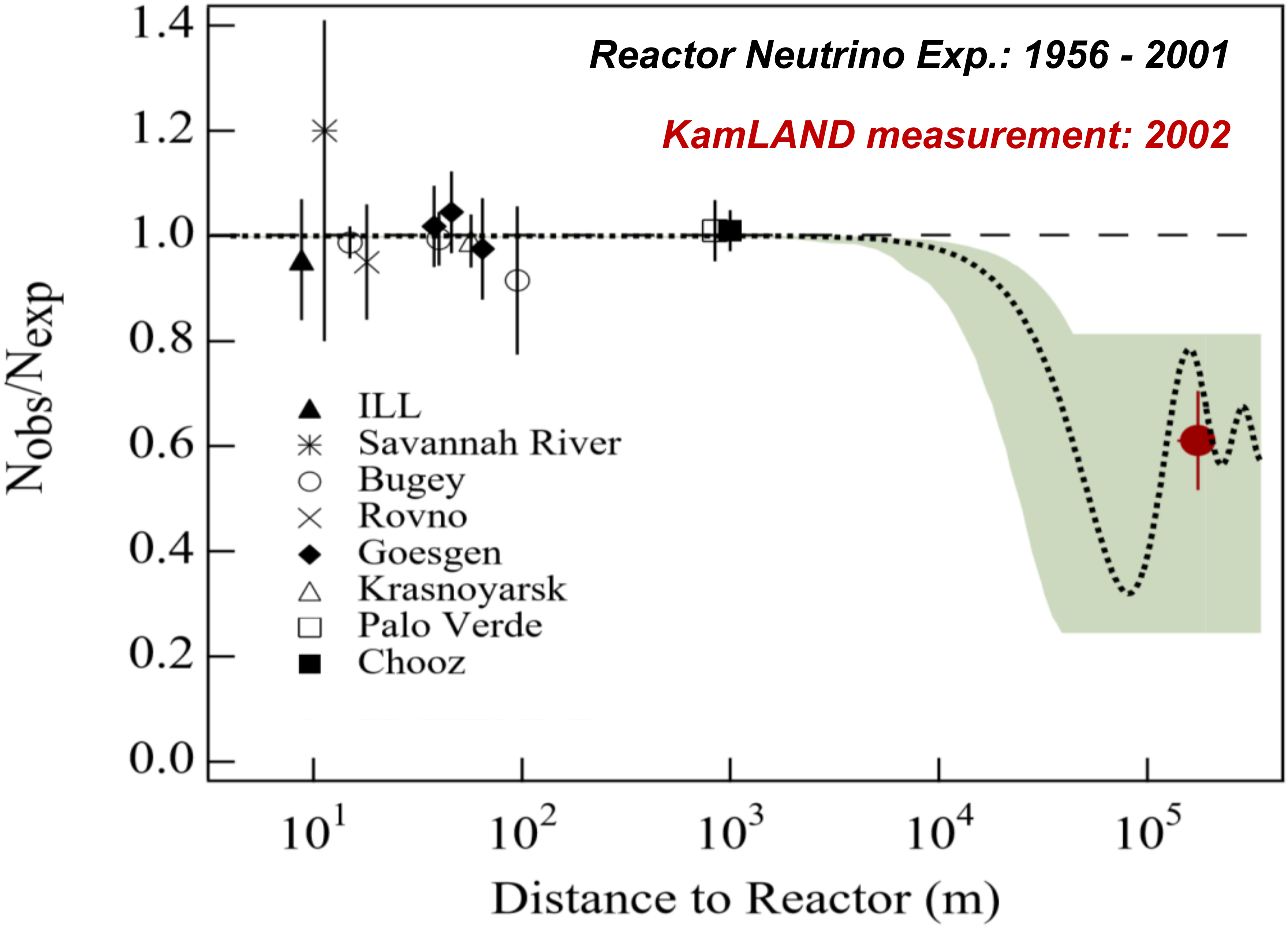
⇒ Oscillation Probability:

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

Amplitude $\propto \sin^2 2\theta$

Frequency $\propto \Delta m^2 L/E$

Search for Neutrino Oscillations @ Reactors



Reactor Neutrino Exp.: 1956 - 2001

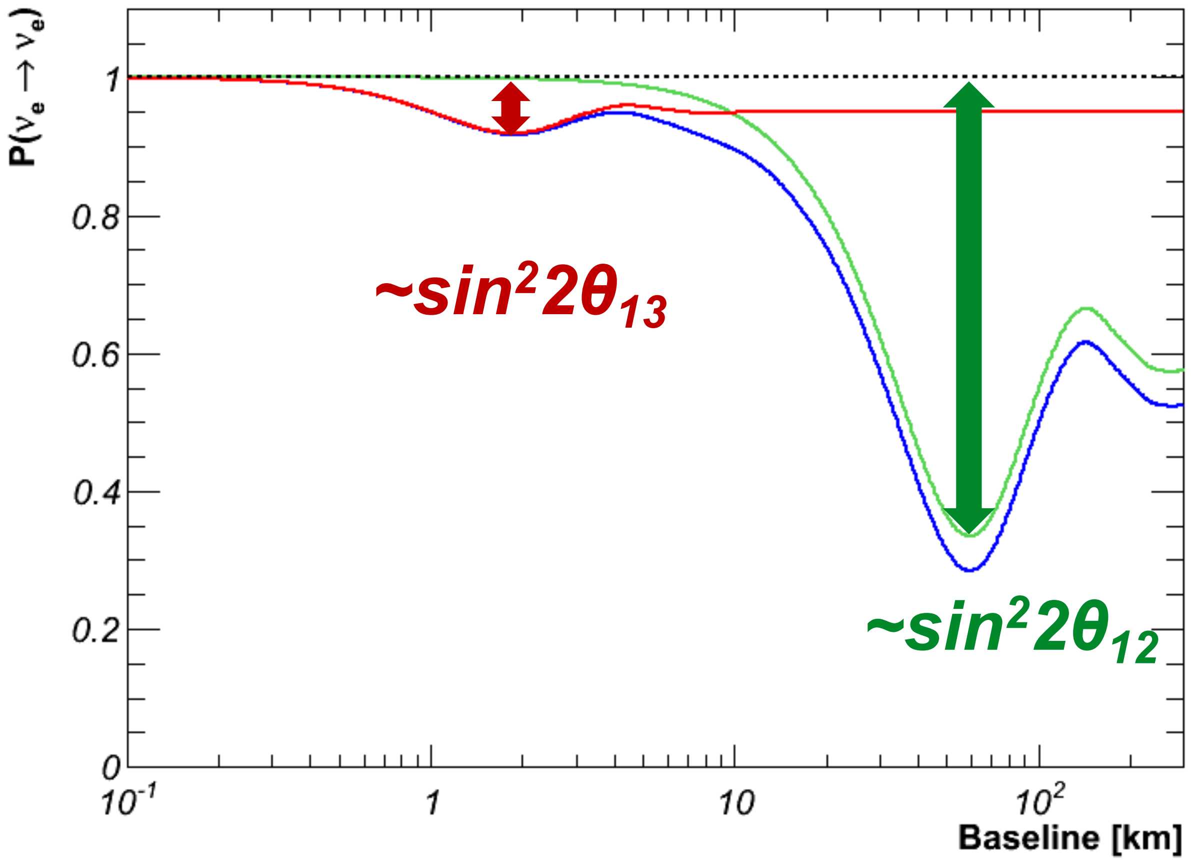
KamLAND measurement: 2002

What Reactor Neutrinos Can Measure

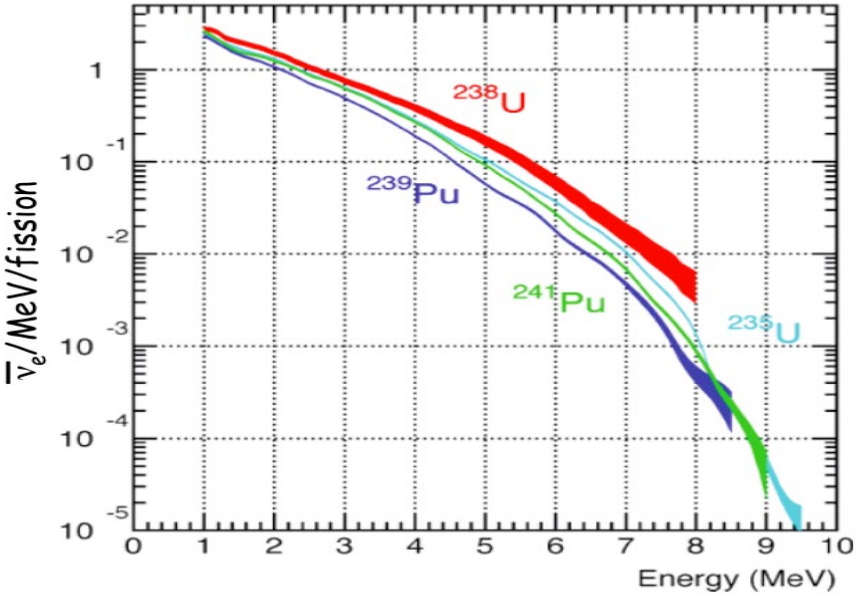
$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_e\right) \approx 1 - \boxed{\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)} - \boxed{\cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)}$$

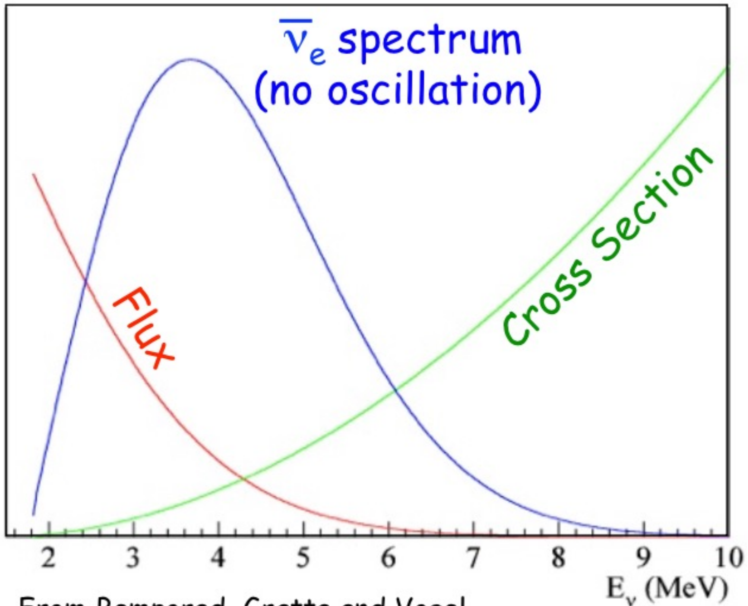
$$\sin^2\left(\Delta m^2_{ee} \tfrac{L}{4E}\right) \equiv \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \tfrac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \tfrac{L}{4E}\right)$$

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



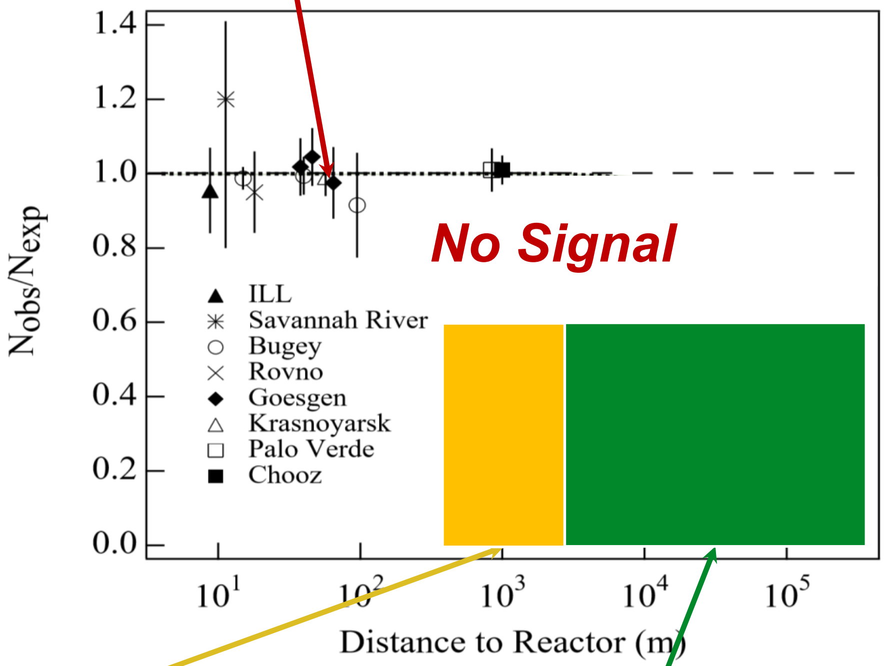
Reactor Neutrinos for Theta13: Challenges





From Bemporad, Gratta and Vogel

Six antineutrinos/fission: ~2-8MeV, ~5% accuracy



No Signal

θ_{13} Dominated

θ_{12} Dominated

Daya Bay: A Powerful Neutrino Source at an Ideal Location

Mountains shield detectors from cosmic ray background

Daya Bay NPP
$2 \times 2.9\,\mathrm{GW_{th}}$

Ling Ao I NPP
$2 \times 2.9\,\mathrm{GW_{th}}$

Ling Ao II NPP
$2 \times 2.9\,\mathrm{GW_{th}}$

Entrance to Daya Bay experiment tunnels

Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 $\mathrm{GW_{th}}$ power, 35×10^{20} neutrinos per second

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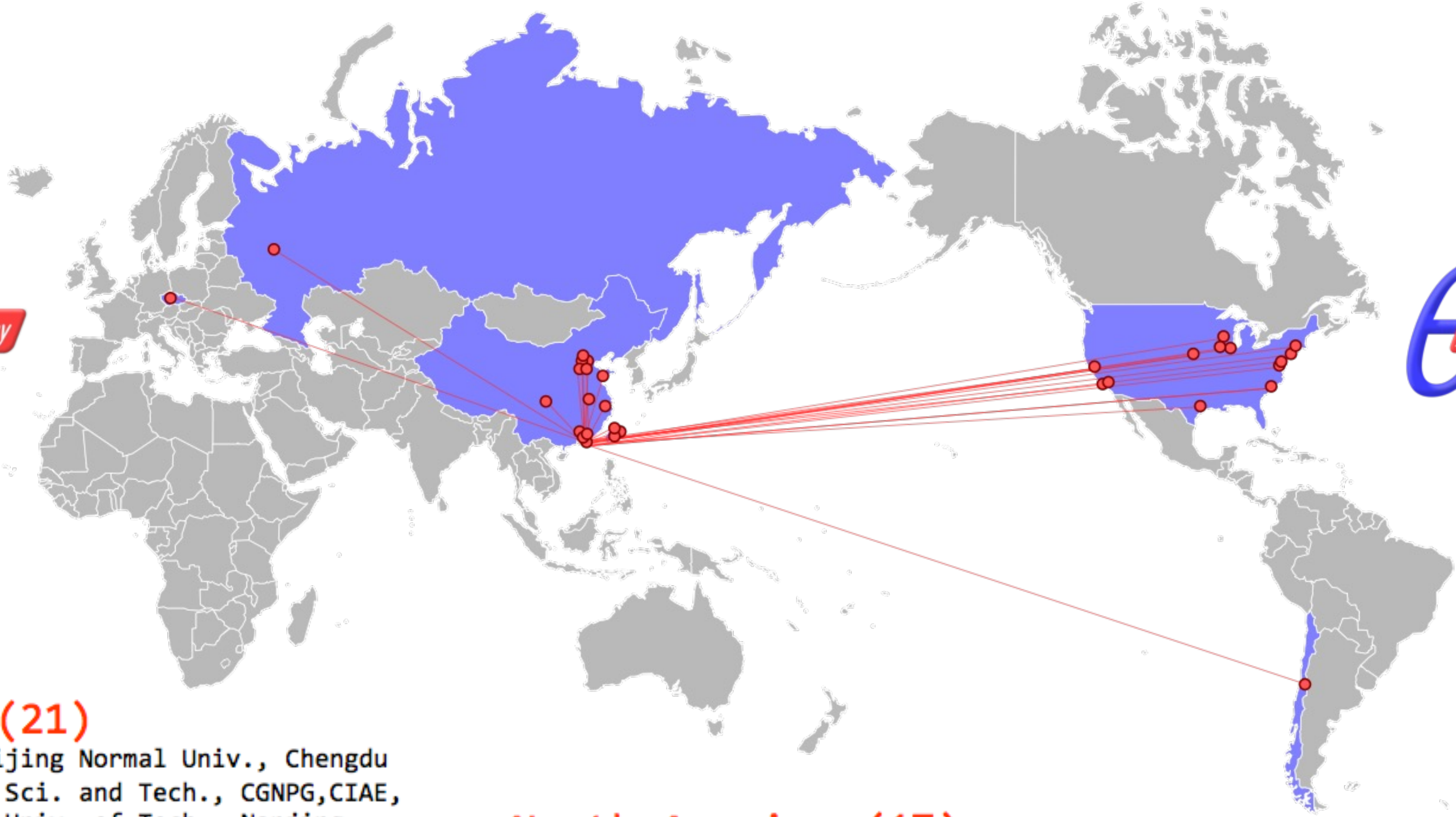
The Daya Bay International Collaboration



Asia (21)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG,CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., **Sun Yat-sen Univ,** Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)

BNL, **LBNL, Iowa State Univ., RPI,** Illinois Inst. Tech., Princeton, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena, Temple Univ, Yale

Europe (2)

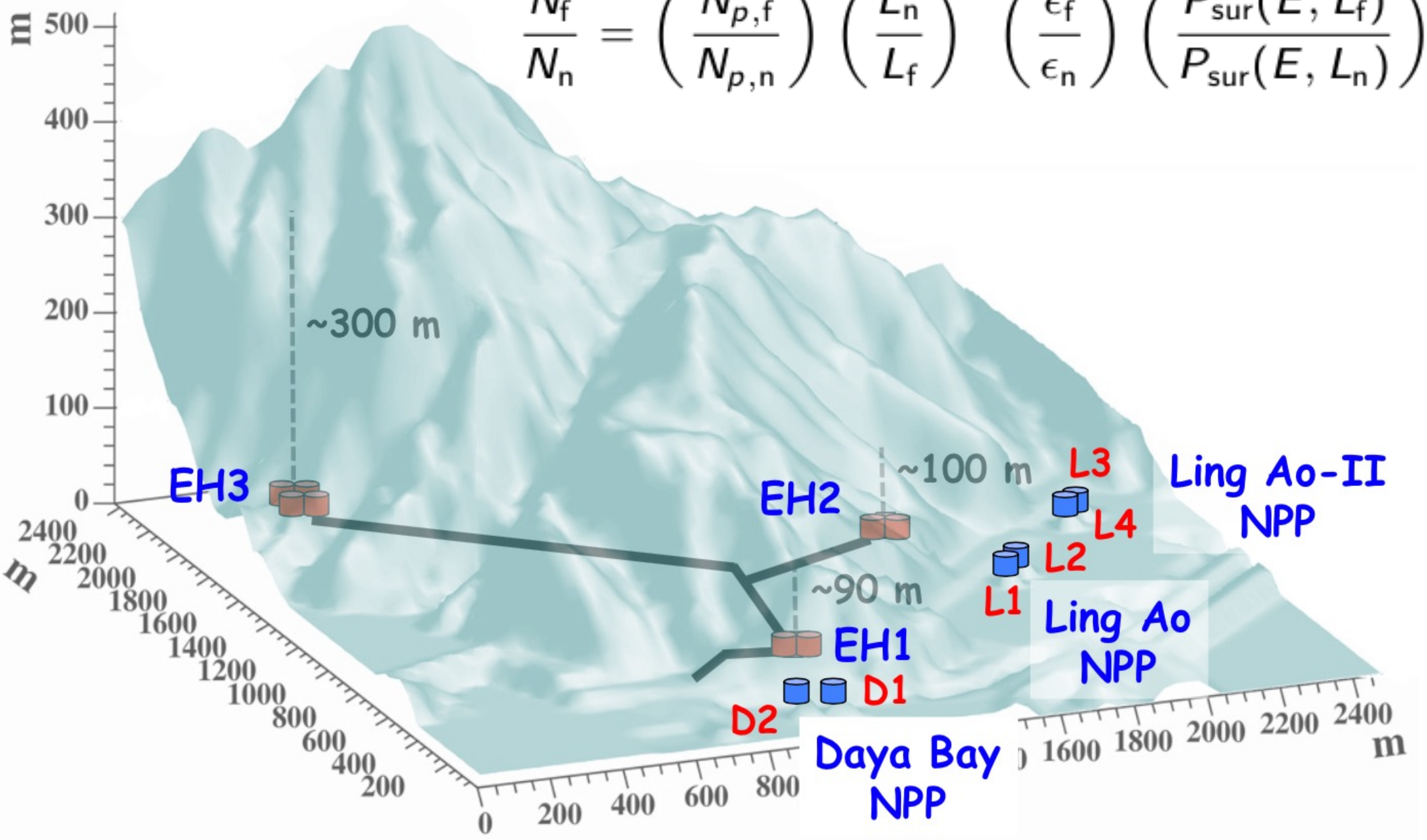
JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)

Catholic Univ. of Chile (2014-2019)

Multi-Baseline and Multi-Detector Design of Daya Bay

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right)$$



The Daya Bay Antineutrino Detector (AD)

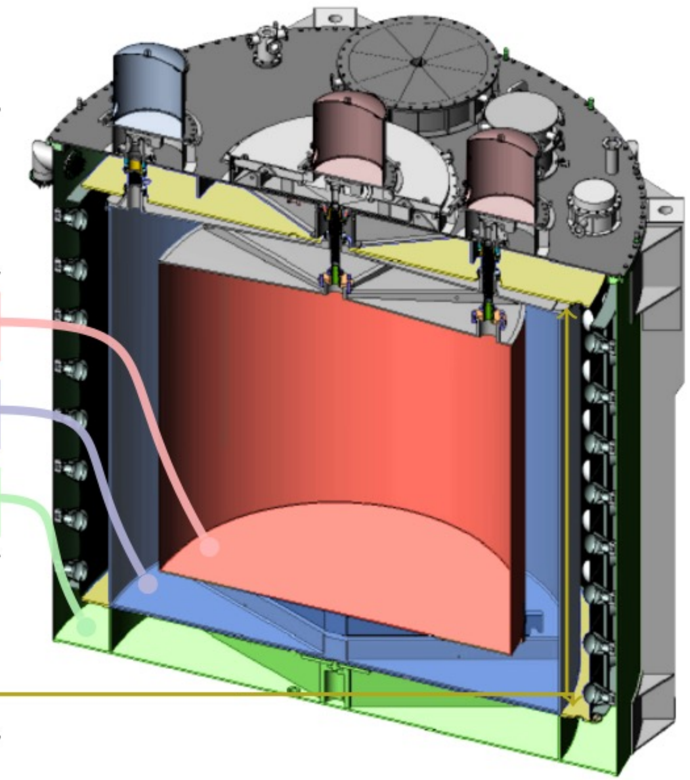
8 functionally identical detectors reduce systematic uncertainties

3 zone cylindrical vessels

	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield and flatten detector response



$\overline{\nu}_e + p \to e^+ + n$ (prompt signal)

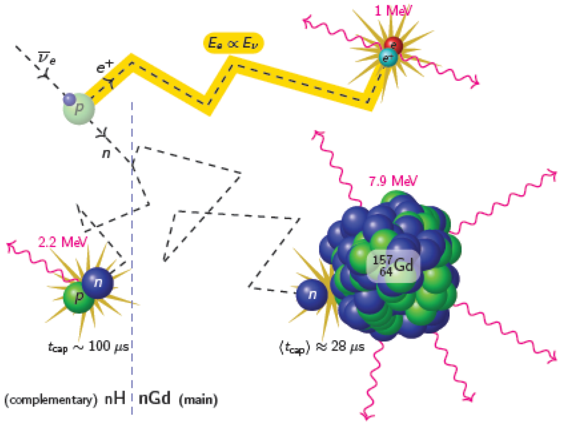
~180μs

$\to + p \to D + \gamma$ (2.2 MeV) (delayed signal)

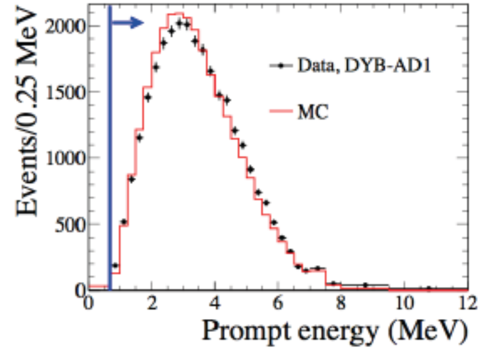
$\to + Gd \to Gd^*$

~30μs for 0.1% Gd

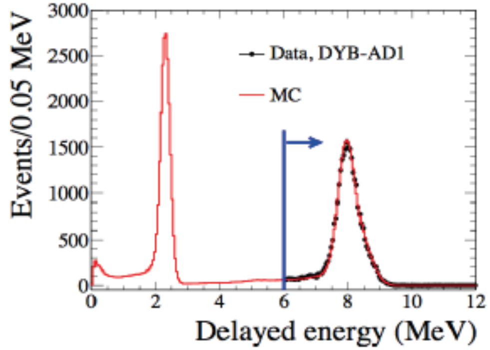
$\to Gd + \gamma$'s (8 MeV) (delayed signal)



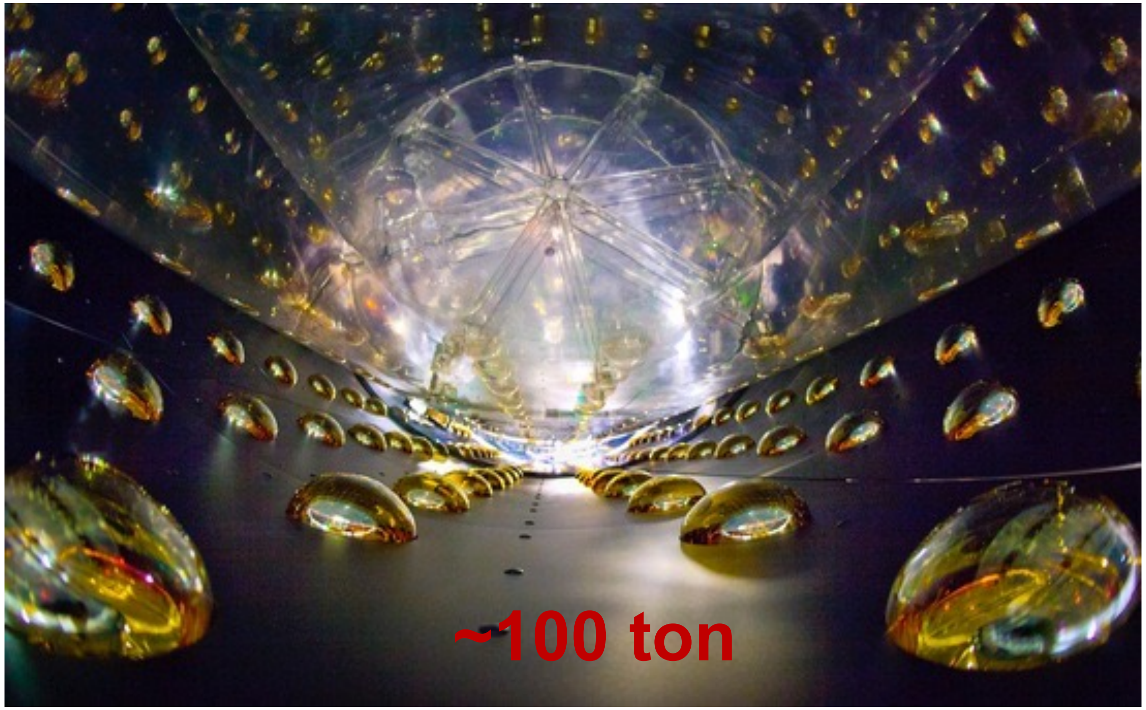
Prompt Energy Signal



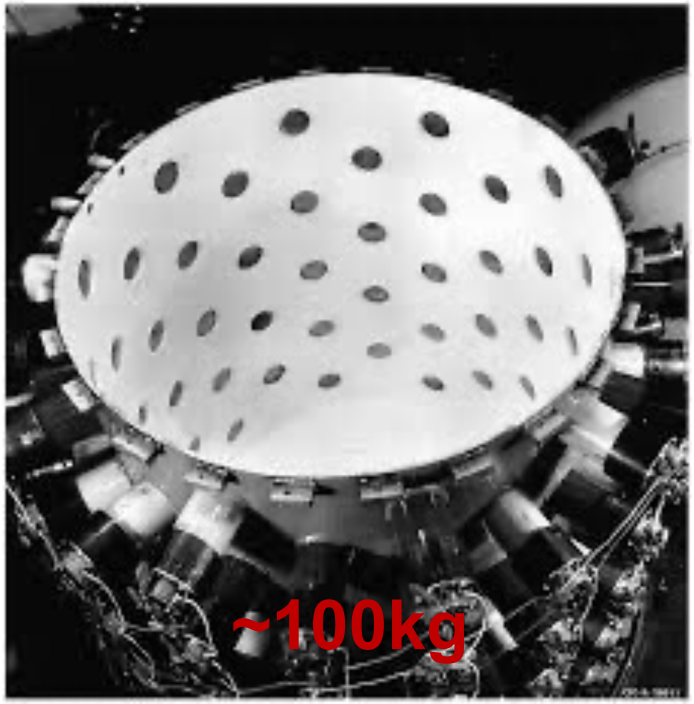
Delayed Energy Signal



The Daya Bay Detector and the Reines&Cowan Design

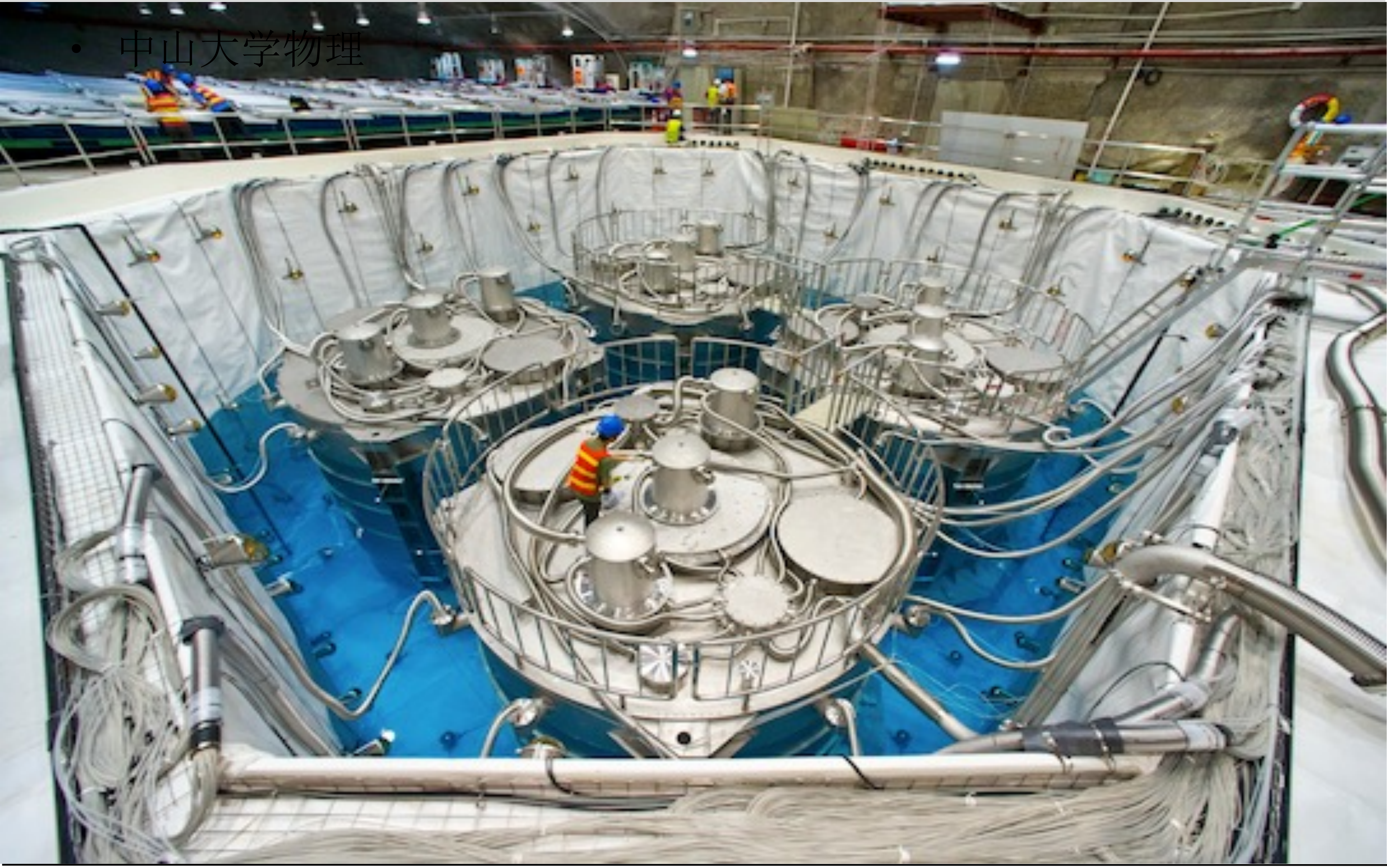


“Standing on the shoulder of giants”



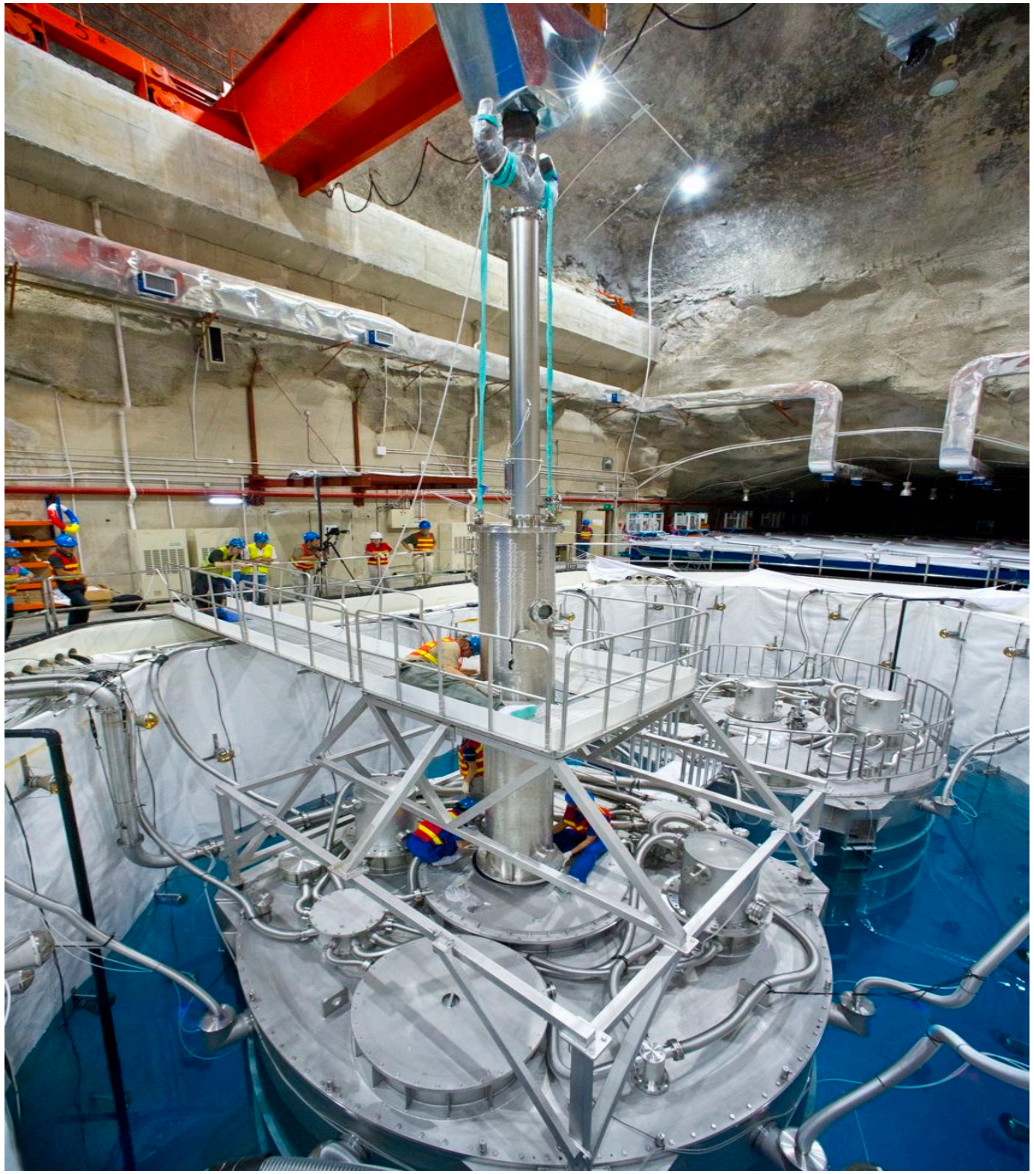
A Small Big Science Project

A Small Big Science Project



- 中山大学物理

Daya Bay Calibration Systems



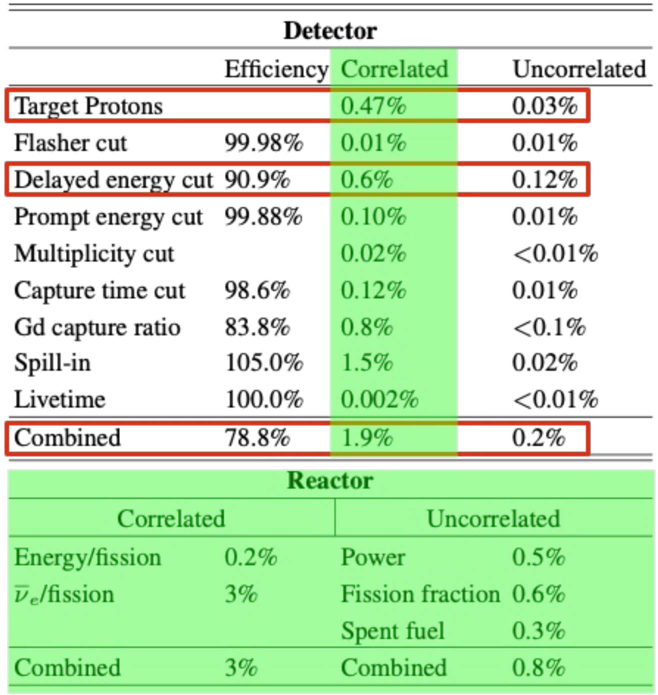
- Automatic Calibration Units (ACUs)
- Manual calibration by CIAE

The Daya Bay Running & Data Taking

Date	Operation	Duration
Dec 24, 2011	**Data taking with 6 ADs** EH1: 2 ADs EH2: 1 AD EH3: 3 ADs	217 Days
Jul 28 – Oct 19, 2012	Special calibration runs; Installation of the last 2 ADs	
Oct 19, 2012	**Data taking with 8 ADs**	1,524 Days
Dec 20, 2016 – Jan 26, 2017	Special calibration runs **EH1 AD1 used for JUNO LS studies**	
Jan 26, 2017	**Data taking with 7 ADs** EH1: 1 ADs EH2: 2 AD EH3: 4 ADs	1,417 Days
Dec 12, 2020	**Shutdown; Decommissioning started**	/

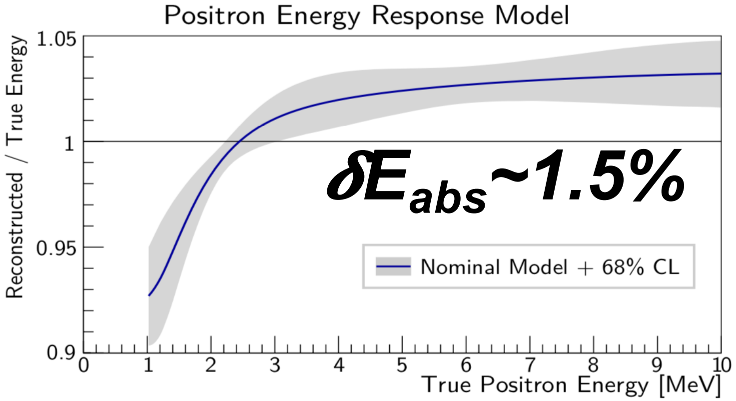
Understanding the Detector *to Extreme*

2012



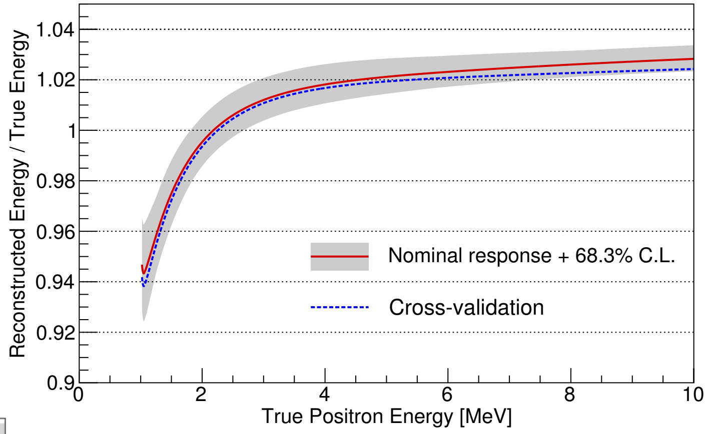
Detector	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\bar{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%



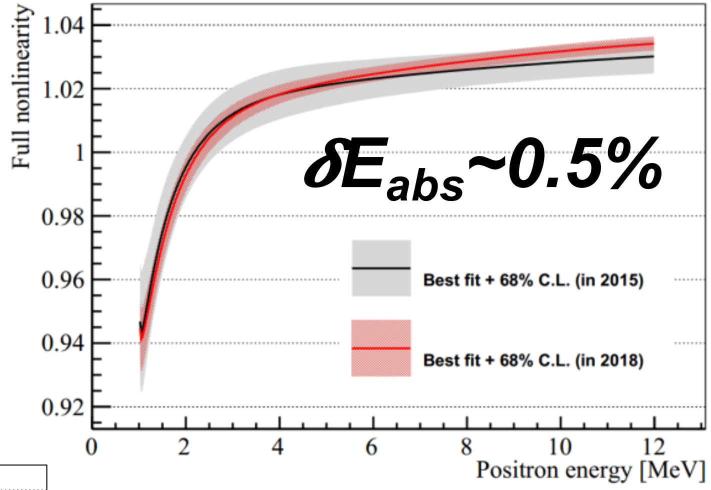
δE_{abs}~1.5%

2015

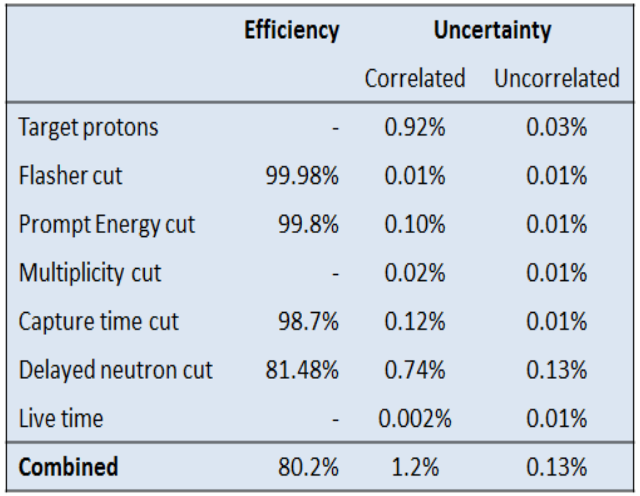


δE_{abs}~1%

2018



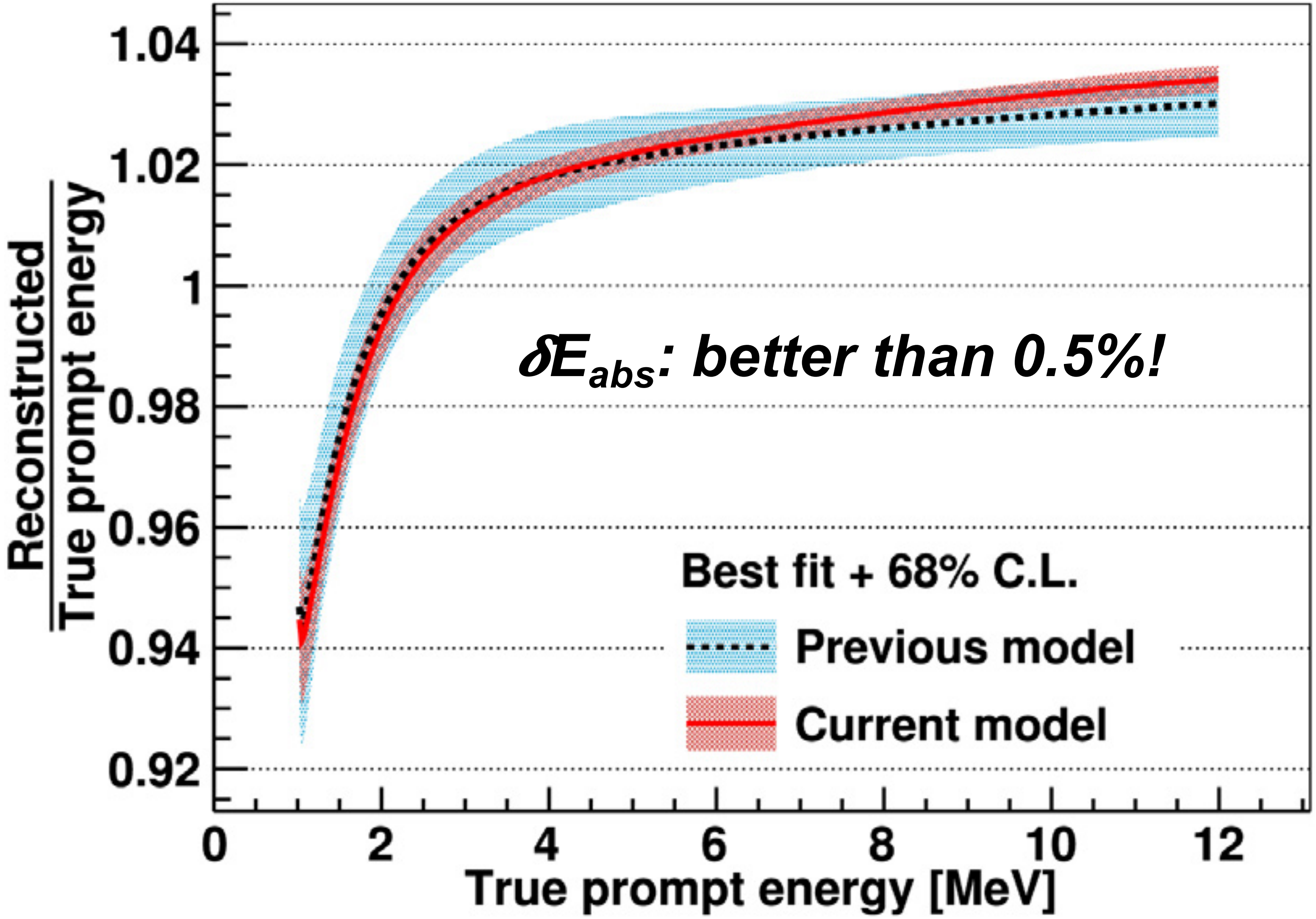
δE_{abs}~0.5%



	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Prompt Energy cut	99.8%	0.10%	0.01%
Multiplicity cut	-	0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Delayed neutron cut	81.48%	0.74%	0.13%
Live time	-	0.002%	0.01%
Combined	80.2%	1.2%	0.13%

The Best Understood LS Reactor Neutrino Detector

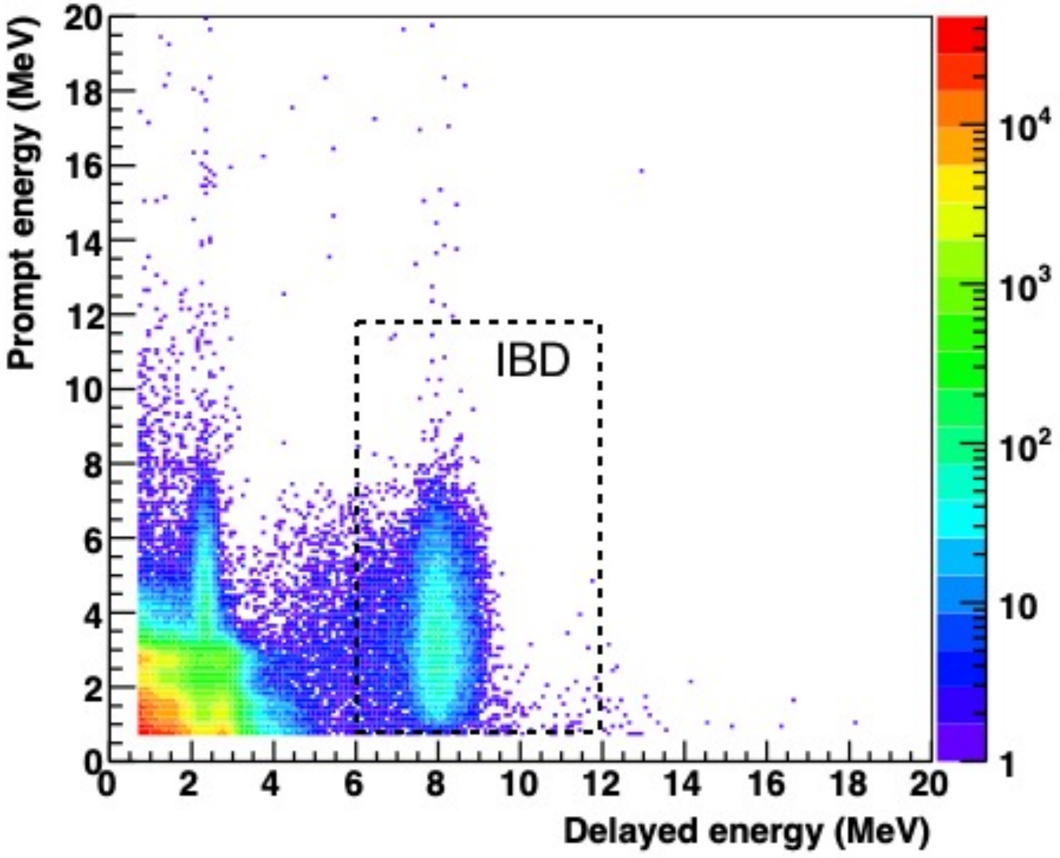
2019



δE_{abs}: better than 0.5%!

For Details, see Nuclear Inst. and Methods in Physics Research, A 940 (2019) 230–242

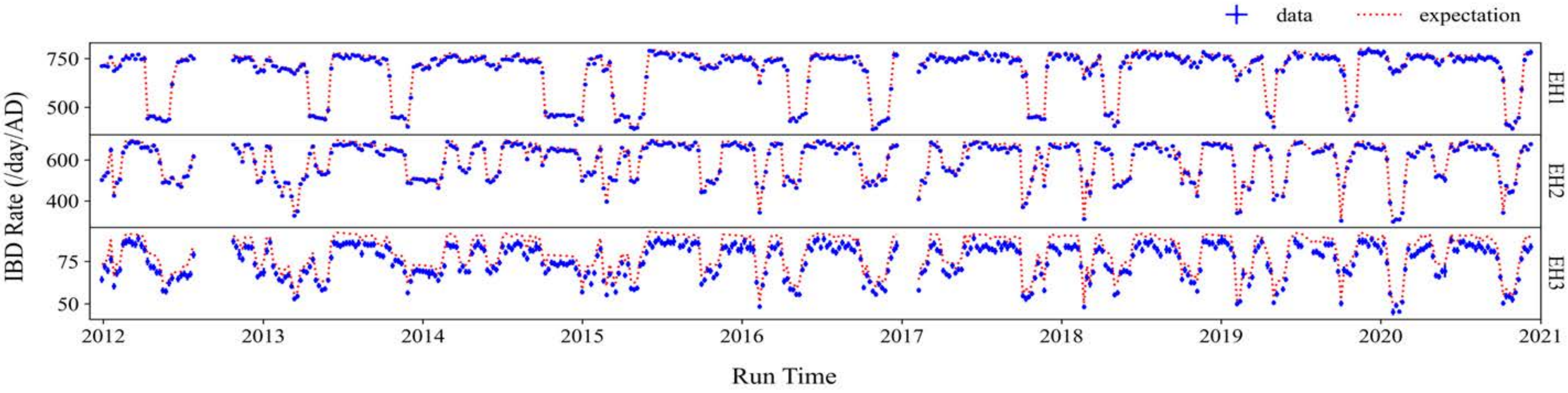
How to Select Antineutrino Events

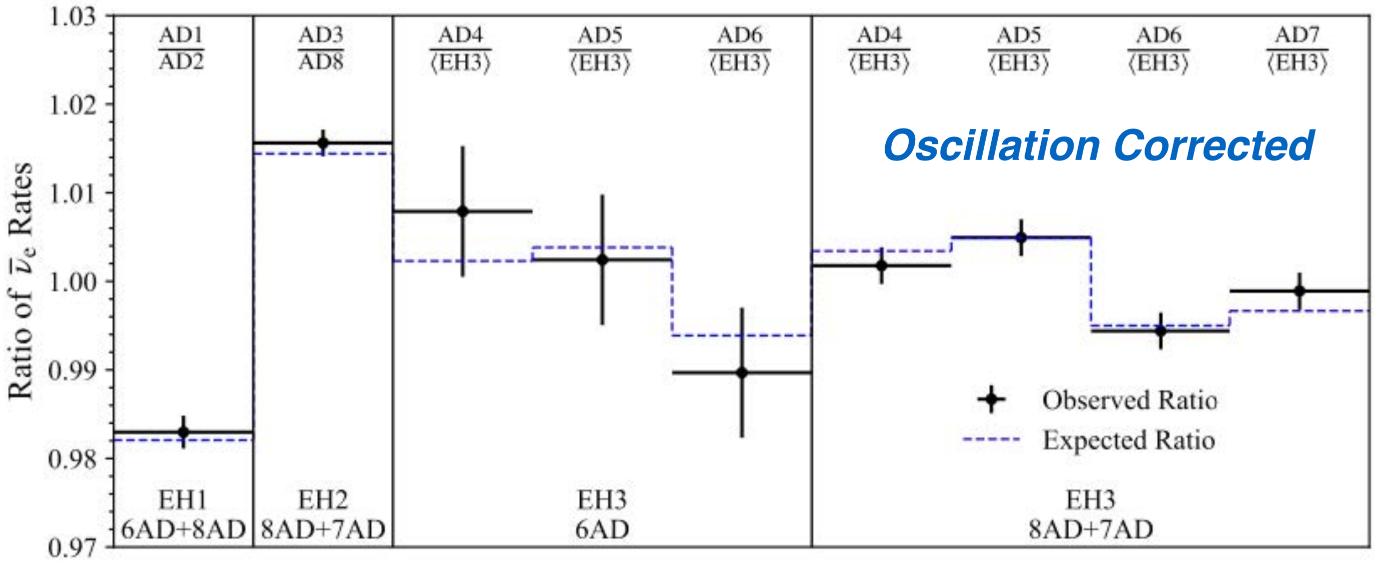


For details, see PRD95 (2017) 072006

- First apply flasher cuts to clean up the data
- Muon veto to get rid of cosmogenic products
- IBD cuts
    - Prompt energy cut: (0.7, 12) MeV
    - **Delayed energy cut: (6, 12) MeV**
    - **Time correlation (Multiplicity)** cut to pick up IBD pairs
    - Bkgs at ~1% level

Event Rates at Daya Bay Detectors

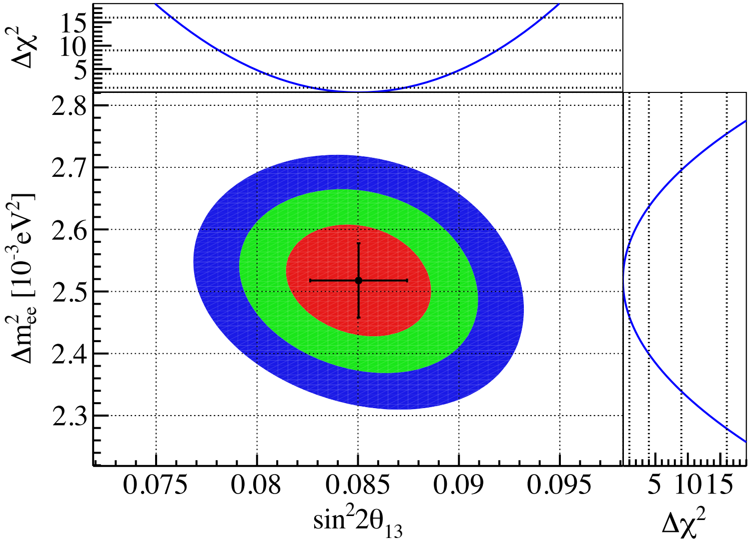




Oscillation Corrected

- Daya Bay uses a combined Huber-Muller model to predict reactor neutrino fluxes --- the HM model

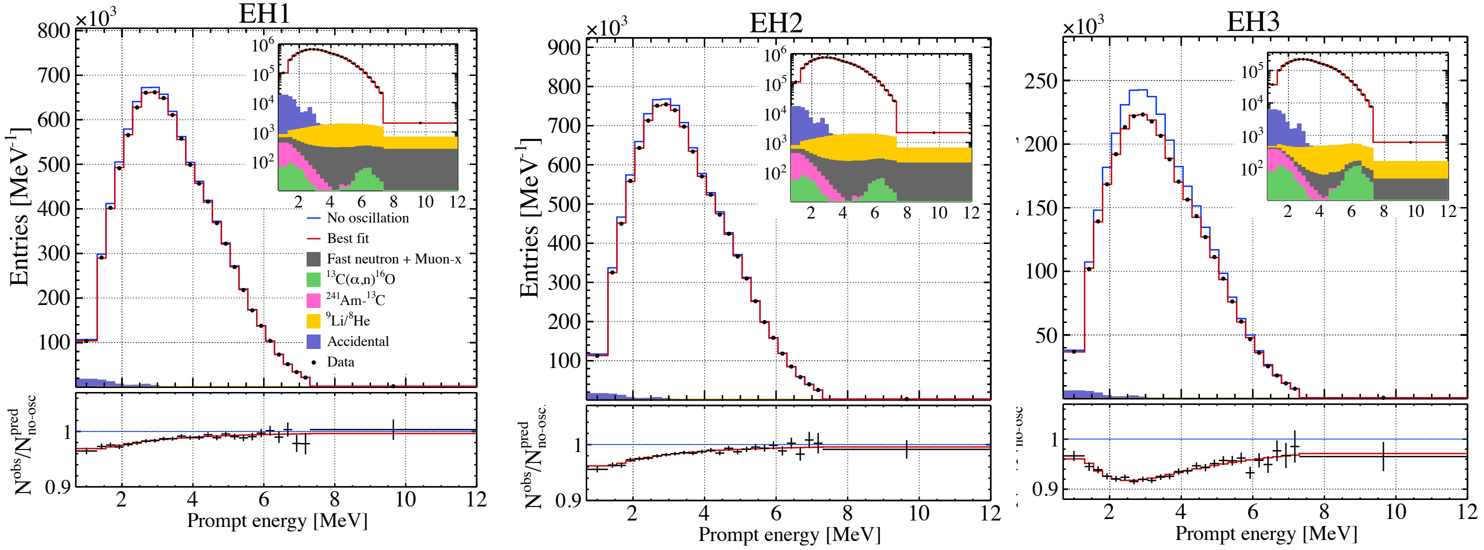
The Latest Daya Bay Oscillation Results

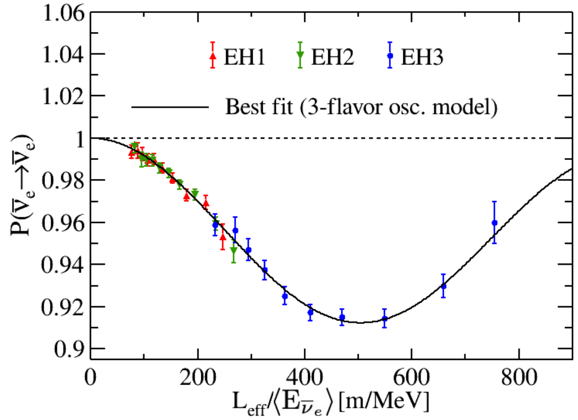


$$\sin^2 2\theta_{13} = 0.0852 \pm 0.0024$$
$$|\Delta m^2_{ee}| = (2.519 \pm 0.060) \times 10^{-3}\ eV^2$$

$$\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3}\ \text{eV}^2$$
$$\Delta m^2_{32} = -(2.571 \pm 0.060) \times 10^{-3}\ \text{eV}^2$$

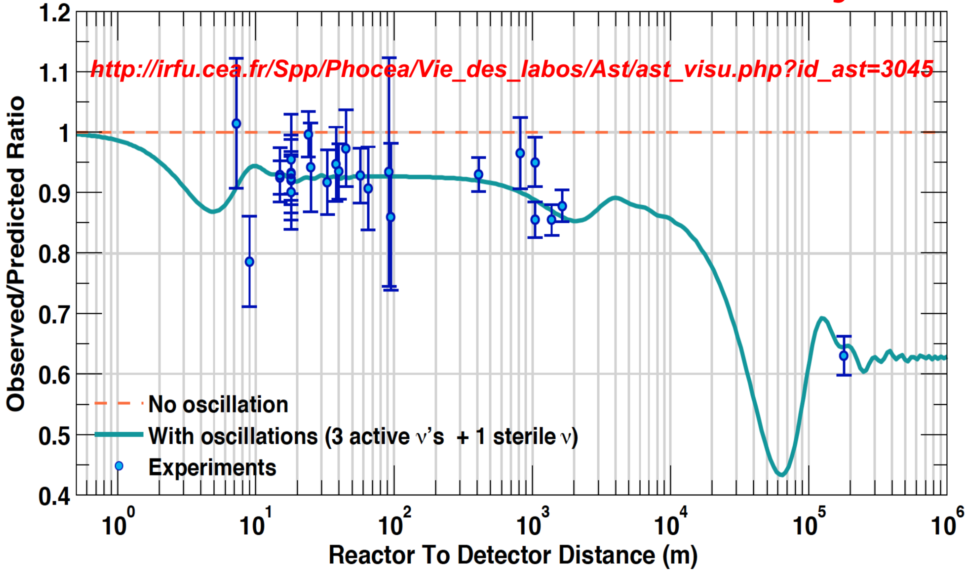
- **θ_{13} measured to a precision of 2.8%, currently the best known mixing angle**
- **Also the most precise Δm^2_{atm}**

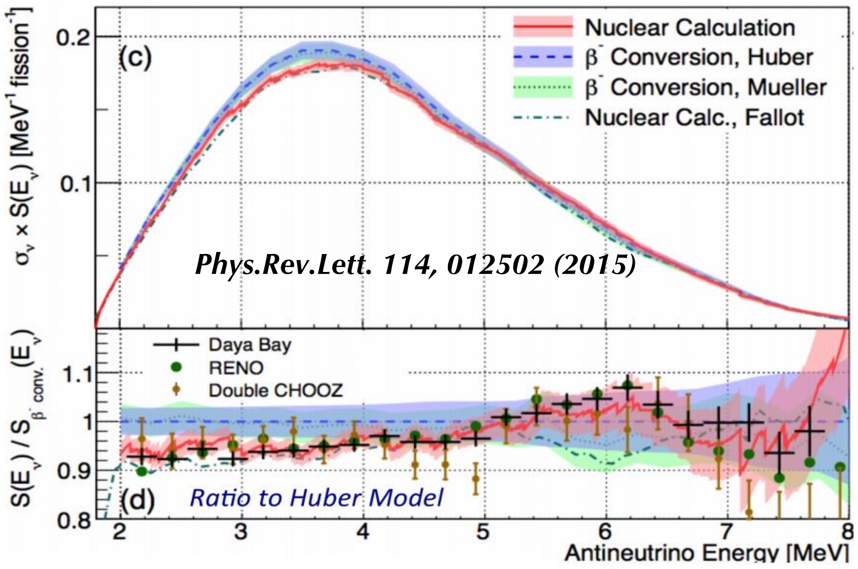




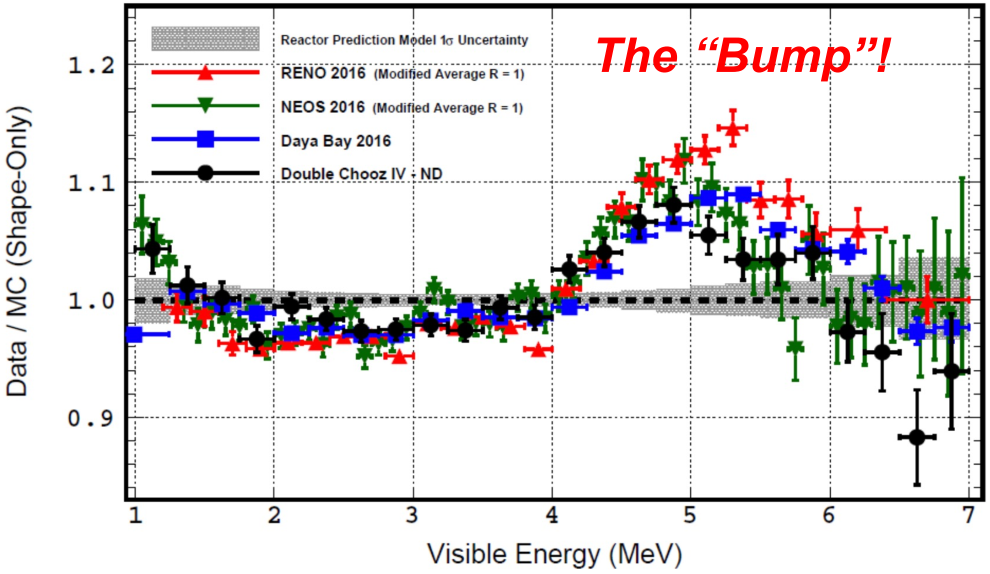
Reactor Neutrinos *NOT* Perfect: RAA and a “Bump”

The Reactor Antineutrino Anomaly



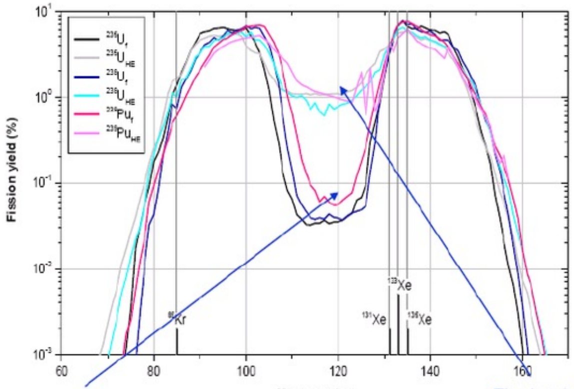


Phys.Rev.Lett. 114, 012502 (2015)



The “Bump”!

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



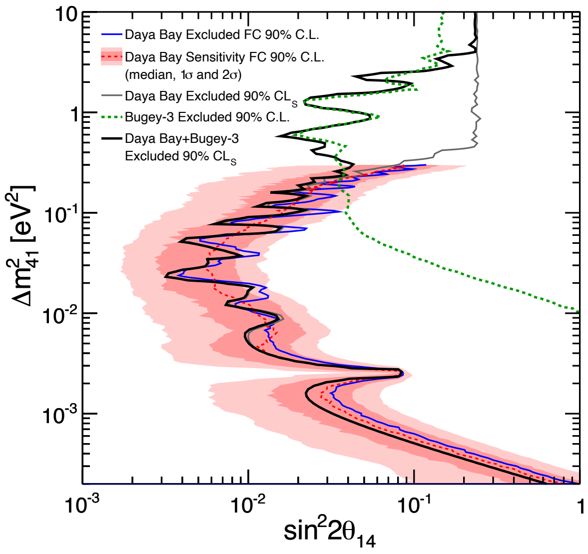
Fission induced by thermal (fission spectrum) neutrons

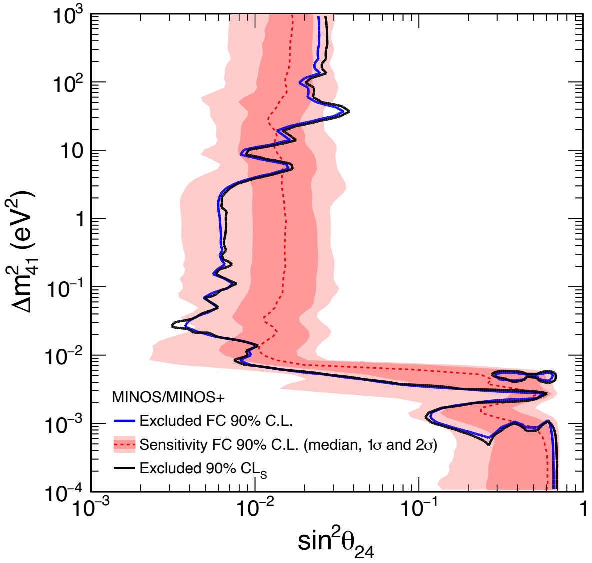
Fission induced by high energy neutrons (14.7 MeV)

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)*

Sterile Neutrino Searches at Daya Bay (and Combined with MINOS/MINOS+ & Bugey-3)





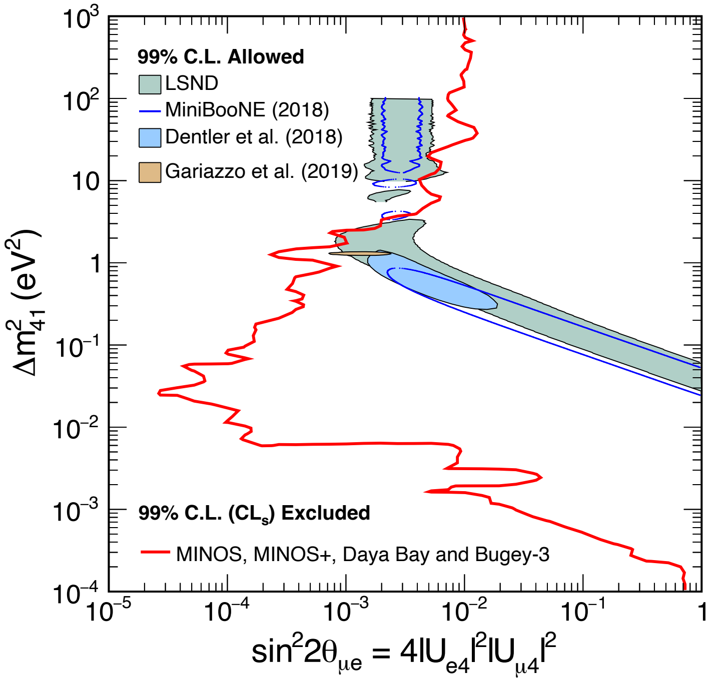
- Daya Bay has multiple baselines
- Daya Bay and MINOS are sensitive to ~0.1 eV^2 but different flavors
- Together, better sensitivity to the LSND result

Appearance probability:

$$4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

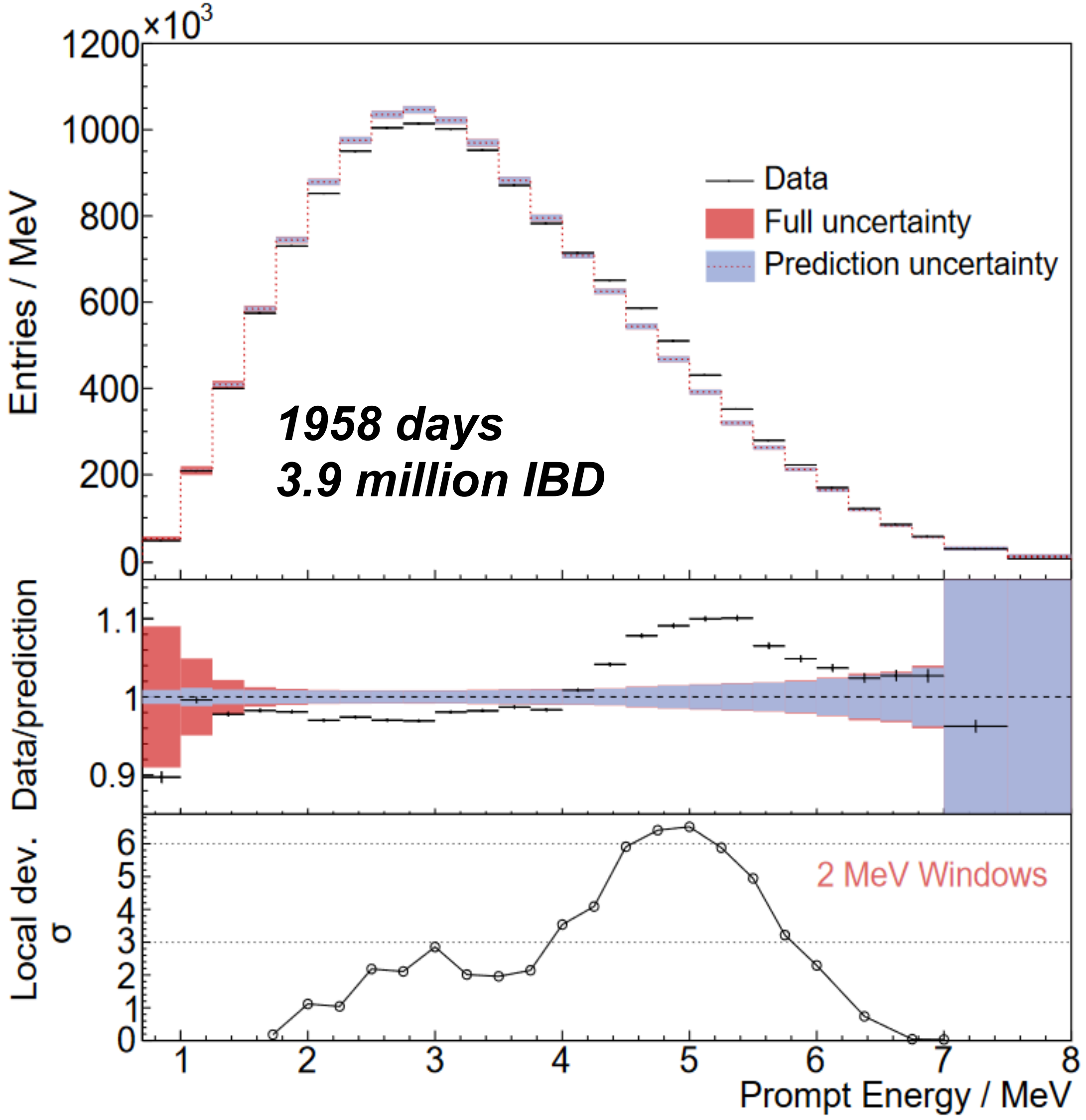
Where:

$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$



For details, see Daya Bay, PRL125 (2020) 7, 071801
PRL113 (2014) 141802, PRL117 (2016), PRL117 (2016) 15, 151801

Measuring the Reactor Antineutrinos Spectrum



- With 1958 days of data, Daya Bay has confirmed the discrepancy between 4-6 MeV (visible energy) with a ~6σ significance

- This discrepancy, the “Bump”, is not correlated with burn-up, i.e. the operation of reactors, or the operations of the Daya Bay detectors

- *For details, see PRL 123 (2019) 111801, PRL 116 (2016) 061801*

Fuel Evolution and Responsible Fuel Components

- *See PRL 118 (2017) no.25, 251801 and CPC, 2017, 41(1) for details*

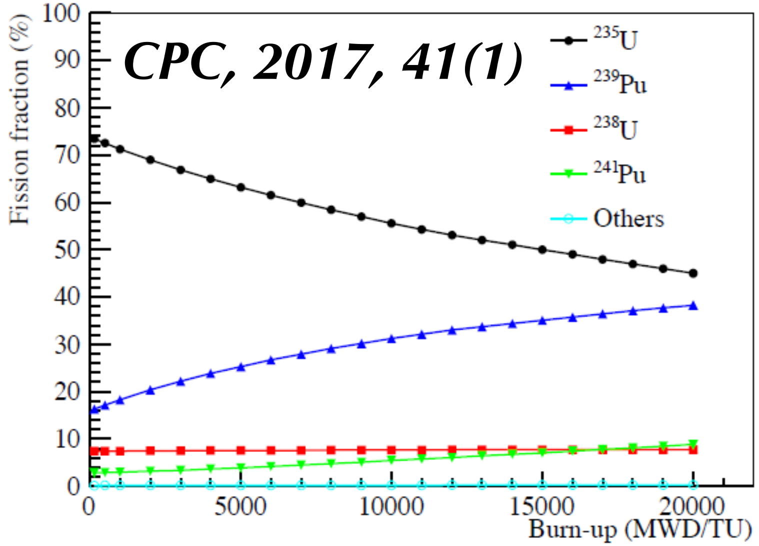
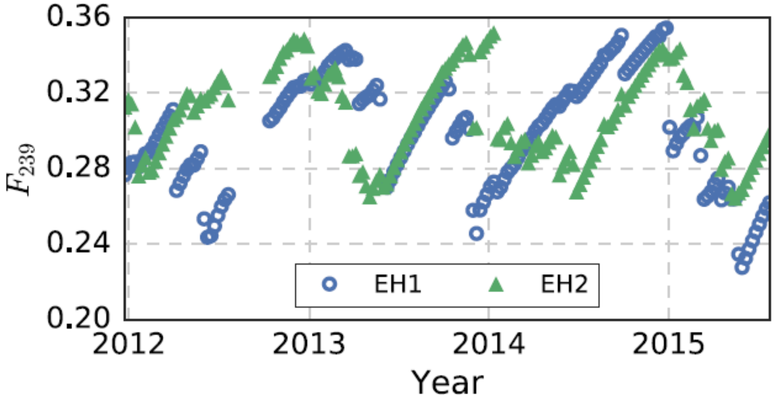
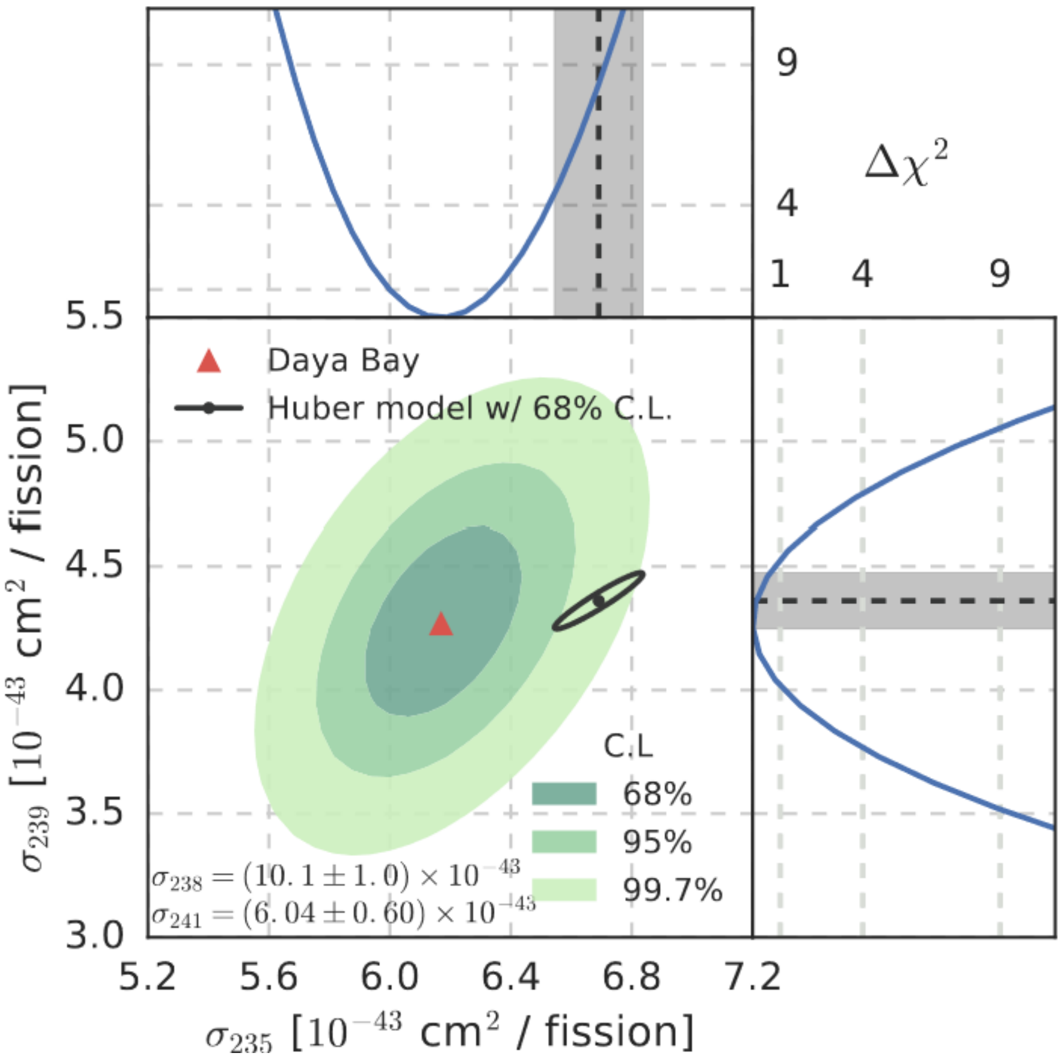

CPC, 2017, 41(1)

Fig. 4. Fission fractions of isotopes in reactor core D1 as a function of cycle burn-up from a simulation of a complete refueling cycle. Other isotopes contribute less than 0.3%.

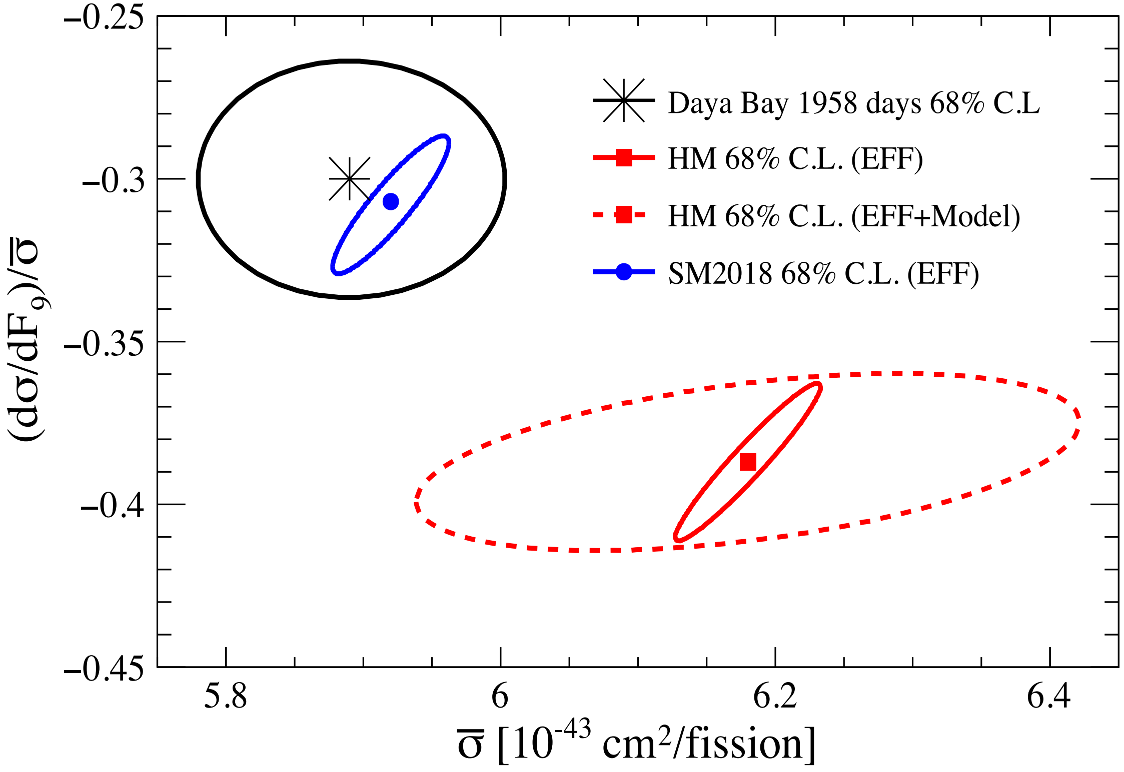


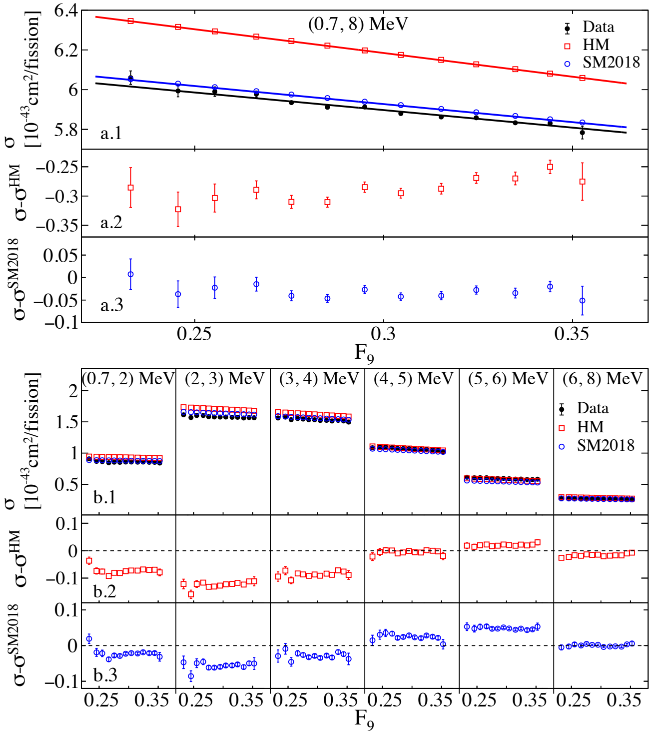


PRL 118 (2017) no.25, 251801

The Lates Fuel Evolution Analysis

- *An improved analysis on fuel evolution by the Daya Bay Collaboration just released, see arXiv:2210.01068*

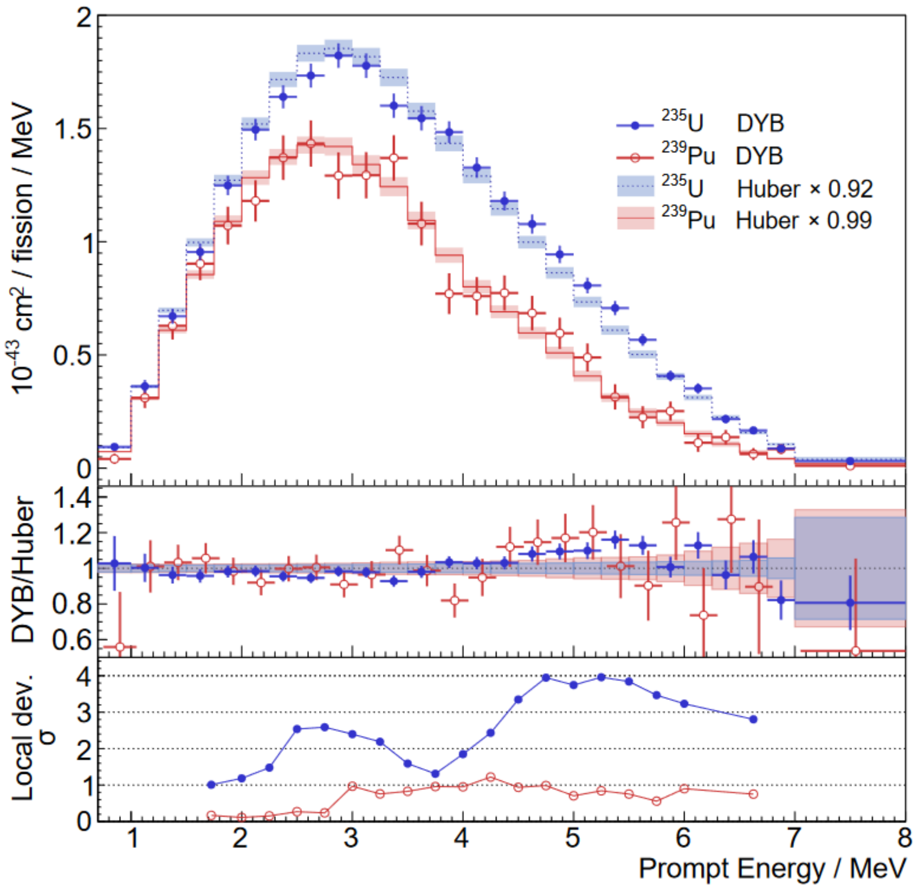




Analysis Improvements besides more statistics (1230 days → 1958 days)

- SM2018: a new summation method by M. Estienne *et al.*, PRL123, 022502 (2019)
- Better correlated and uncorrelated detector uncertainties
- Improved reactor related uncertainties
- Checking two characteristic variables: average neutrino yields and their evolution slope wrt. F_9, the ^{239}Pu fraction bred within the reactor

Decomposing Reactor Antineutrino Components



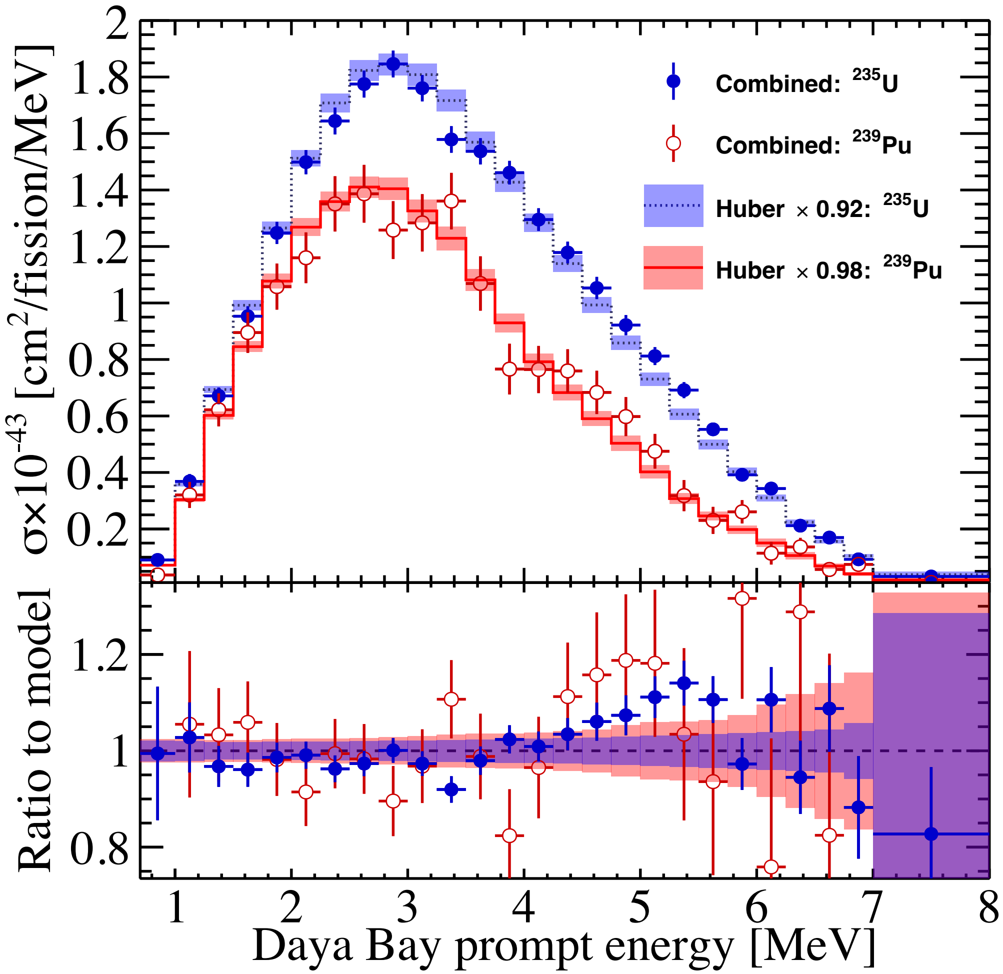
- The very first measurement of the ^{235}U and ^{239}Pu spectra at commercial reactors
- An excess, data over prediction, around 4-6 MeV for ^{235}U is more pronounced but the ^{239}Pu one is consistent with null bump

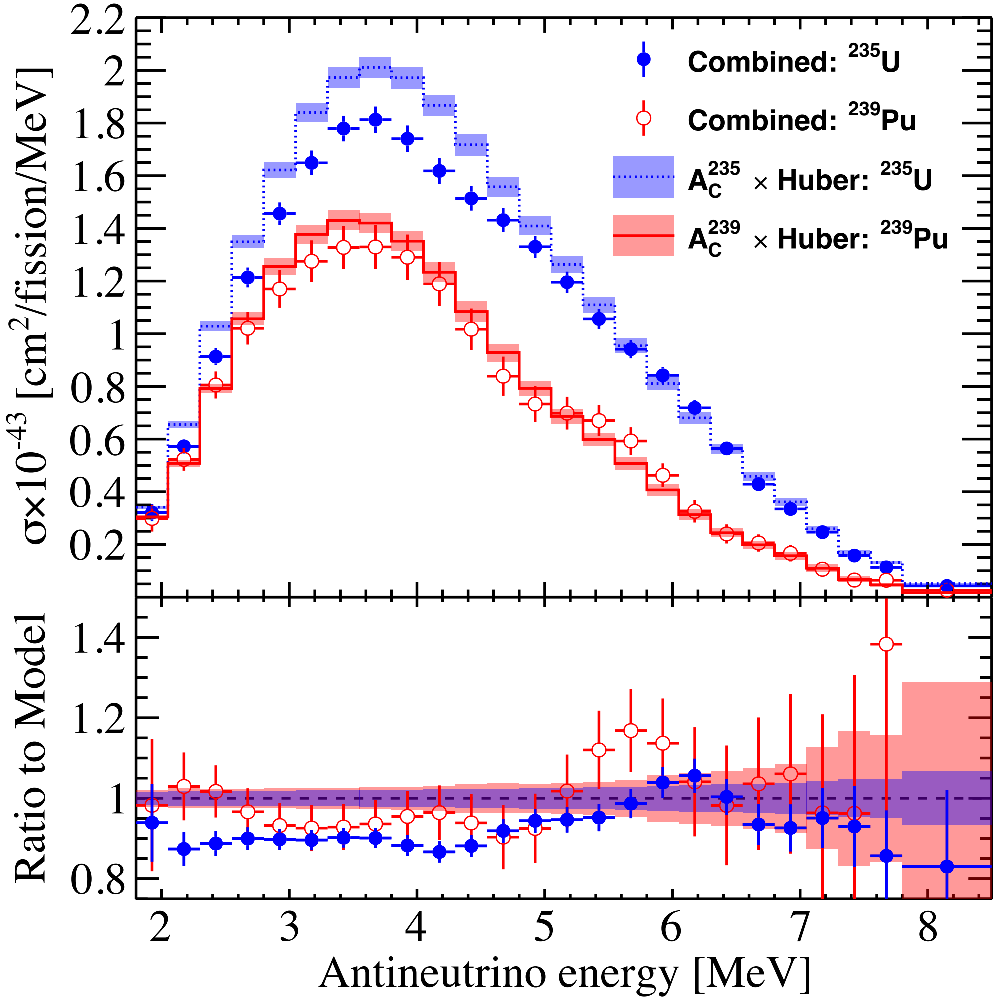
^{235}U: a 4σ effect; ^{239}Pu: a 1.2σ effect

- *For details of the isotope decomposition analysis, see PRL 123 (2019) no.11, 111801*

Combined Flux Analysis of Daya Bay and PROSPECT

- *Daya Bay + PROSPECT Collaborations, see PRL 128 (2022) 8, 081801*

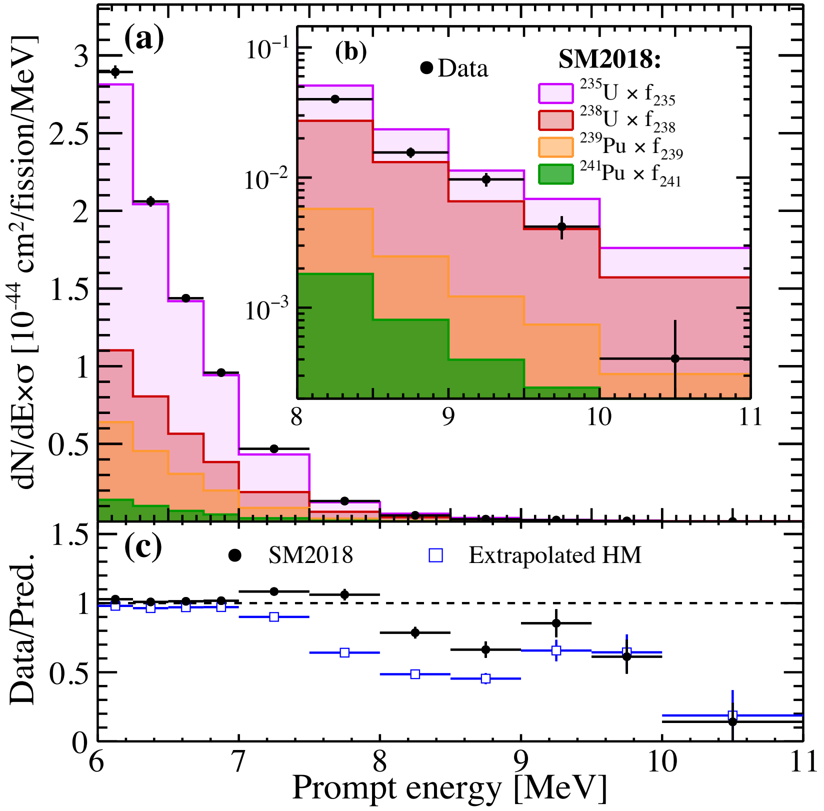


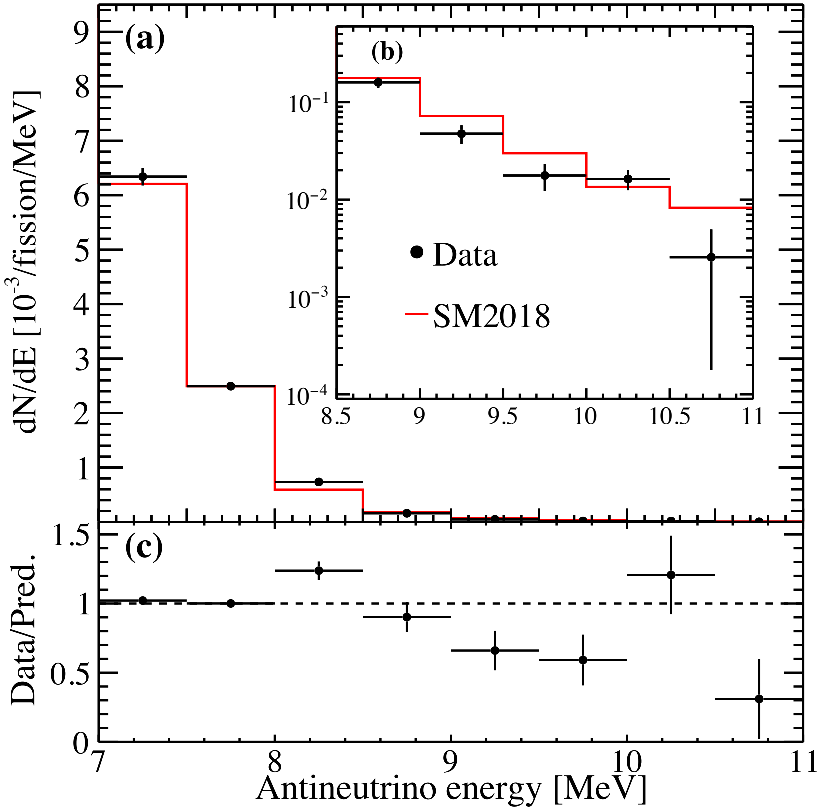


- ➢ First ever results: A HEU reactor + LEU reactors (commercial PWR reactors)
- ➢ ^{235}U flux improved to 3%; Degeneracy between U and Pu contributions reduced

First Evidence of High-Energy Reactor Neutrinos

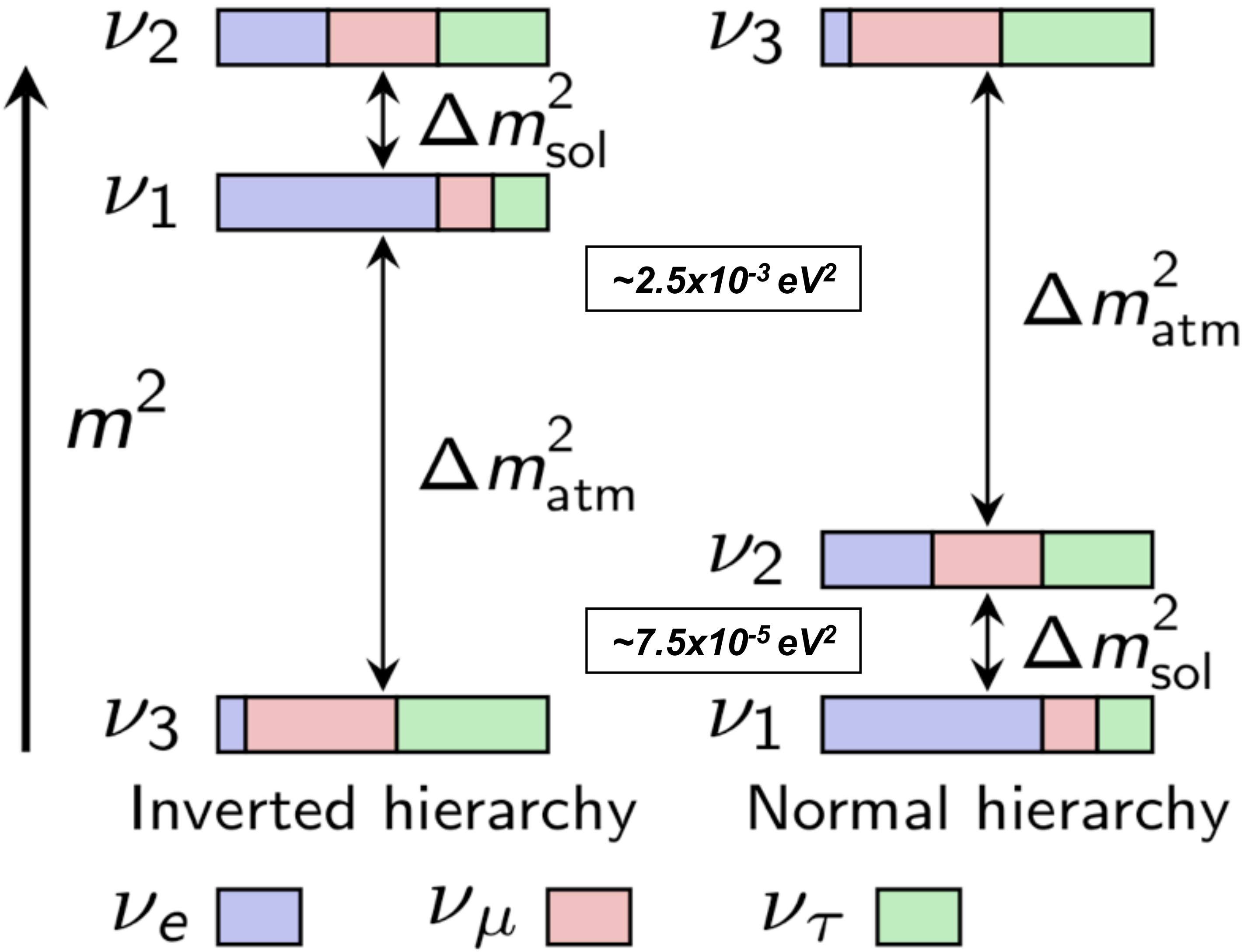
- Daya Bay discovers reactor neutrinos above 10MeV with a 6.2σ significance for the first time
- A deficit of 29% in the high-E region (8-11MeV) is observed compared with the SM2018 ab-initio prediction
- The first direct observation of antineutrinos from several high-Q_β isotopes in commercial reactors





- ***For details, see PRL 129 (2022) 4, 041801***

Neutrino Mass Ordering Still Unknown



~2.5x10^{-3} eV^2

~7.5x10^{-5} eV^2

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

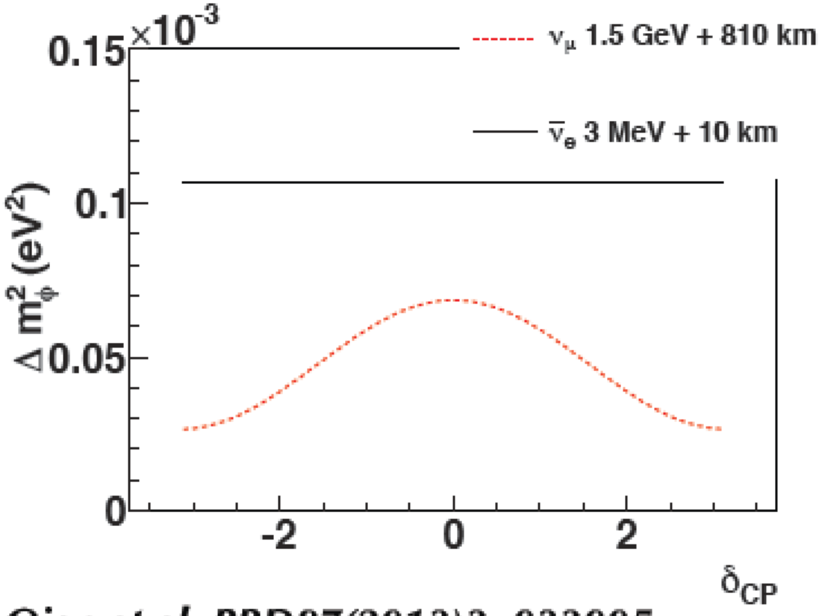
e- / μ-Flavor “Senses” Mass Ordering Differently

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

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

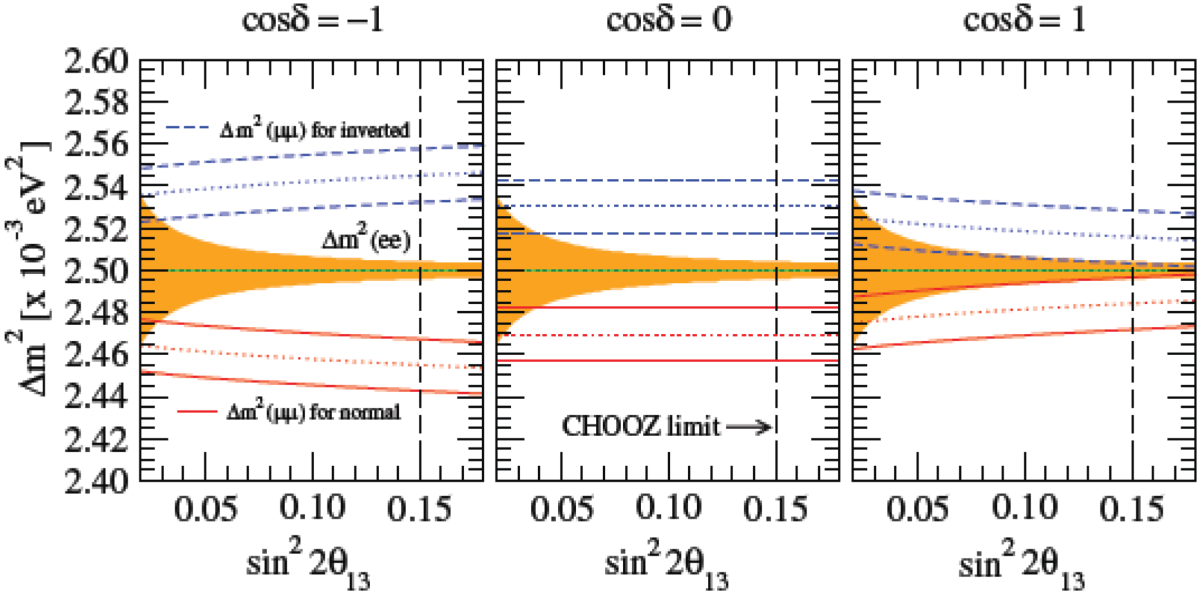
$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2}{4l}$$

Very Challenging:
Need 1% accuracy!



Qian et al, PRD87(2013)3, 033005

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



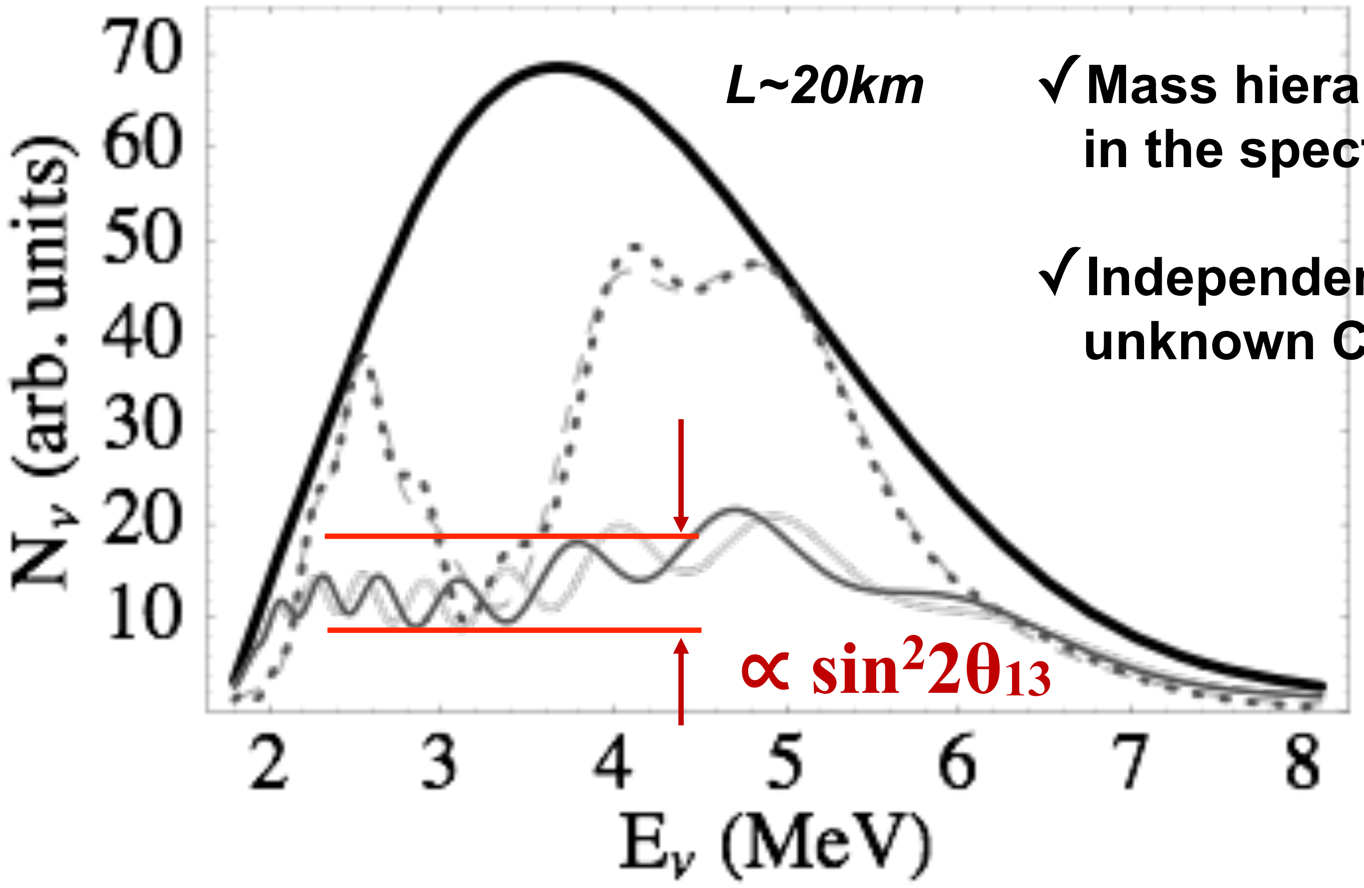
Minakata et al PRD74(2006), 053008

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

Known θ13 Enables Neutrino Mass Hierarchy at Reactors

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

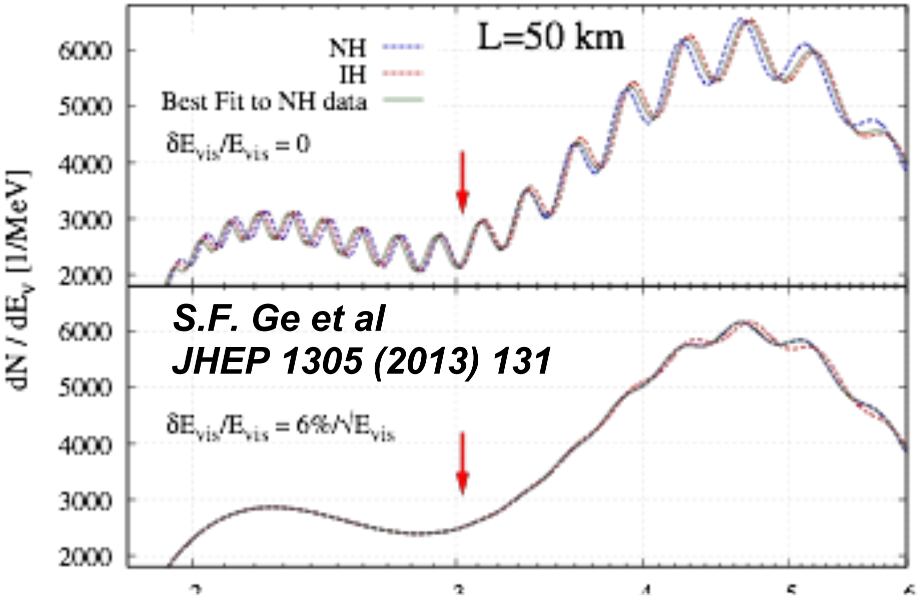
Petcov&Piai, Phys. Lett. B533 (2002) 94-106



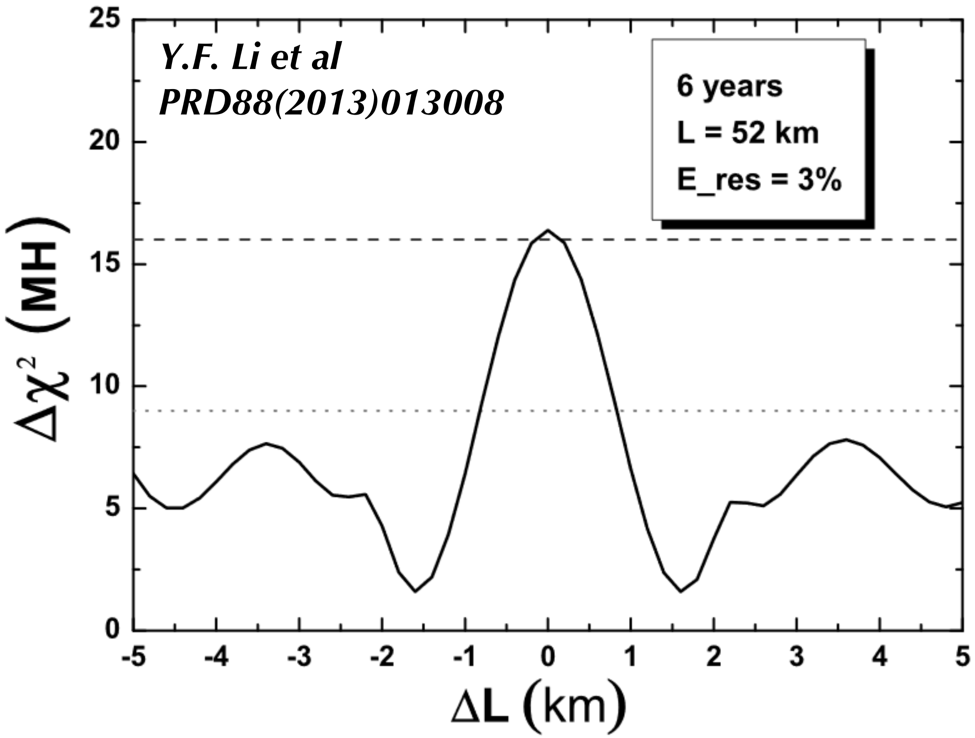
- ✓ **Mass hierarchy reflected in the spectrum**
- ✓ **Independent of the unknown CP phase**

Challenges in Resolving MH using Reactors

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

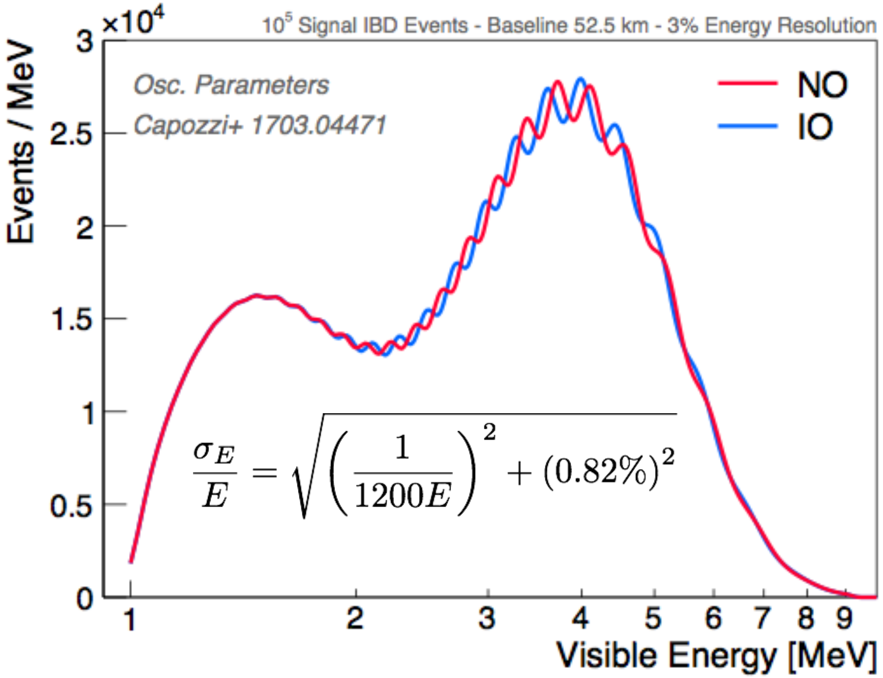


S.F. Ge et al
JHEP 1305 (2013) 131



Y.F. Li et al
PRD88(2013)013008

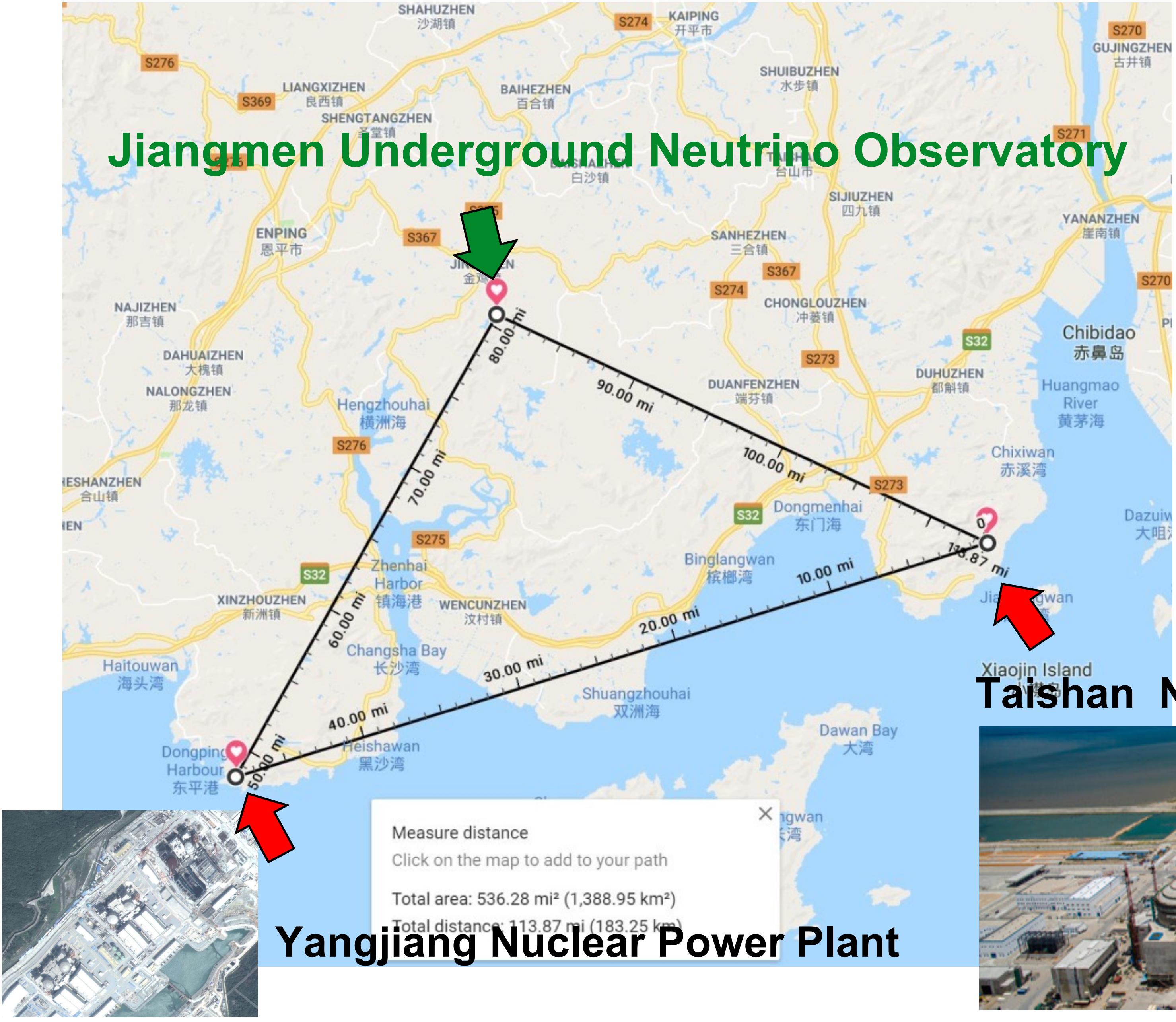
6 years
L = 52 km
E_res = 3%



$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{1}{1200E}\right)^2 + (0.82\%)^2}$$

JUNO for Neutrino Mass Ordering

Jiangmen Underground Neutrino Observatory



Measure distance

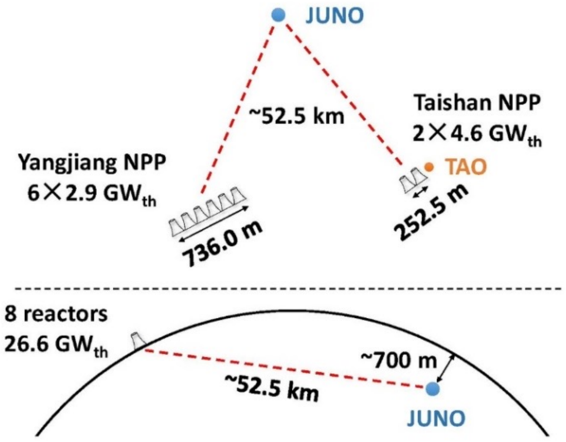
Click on the map to add to your path

Total area: 536.28 mi² (1,388.95 km²)

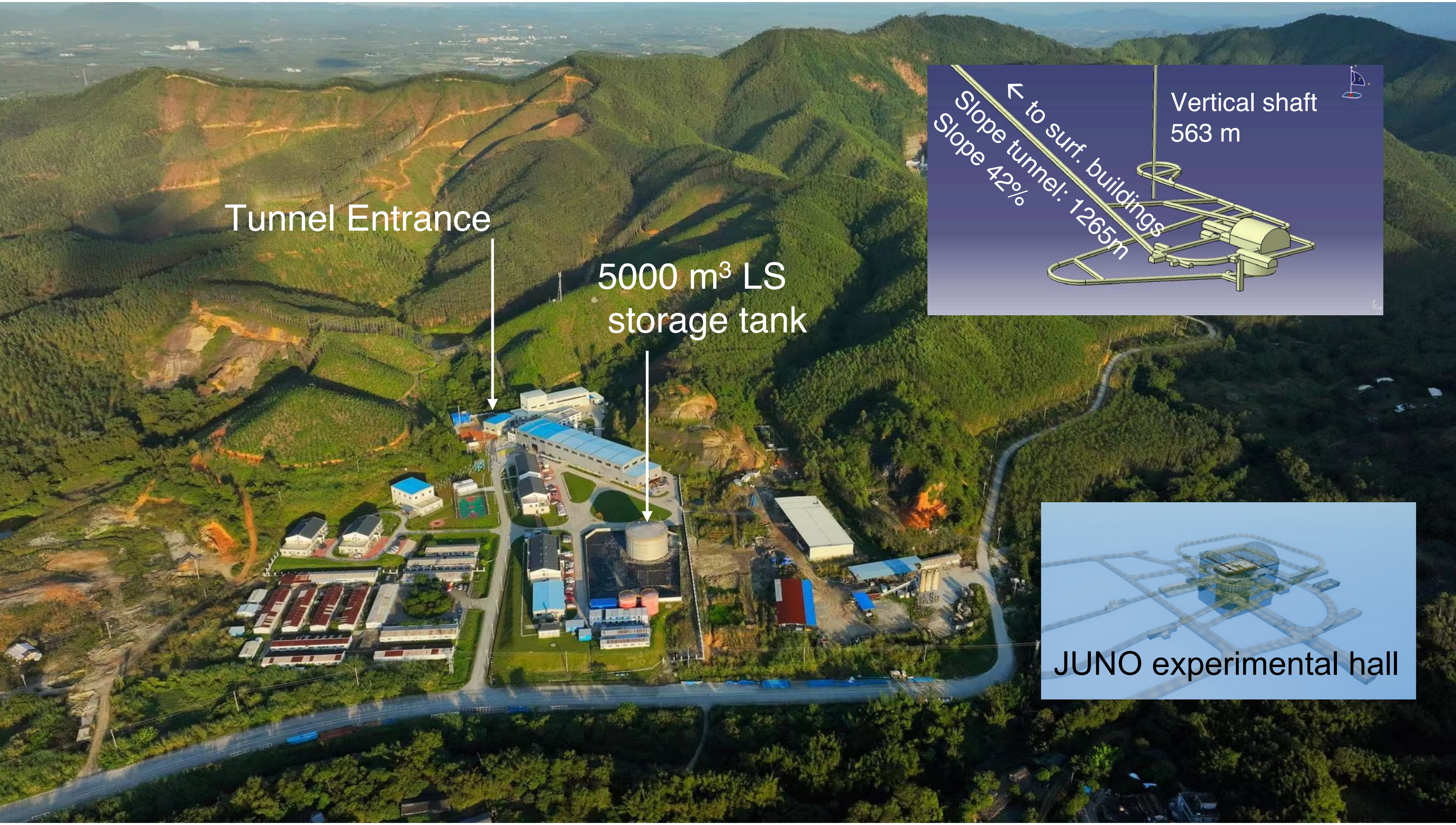
Total distance: 113.87 mi (183.25 km)

Yangjiang Nuclear Power Plant

Taishan Nuclear Power Plant

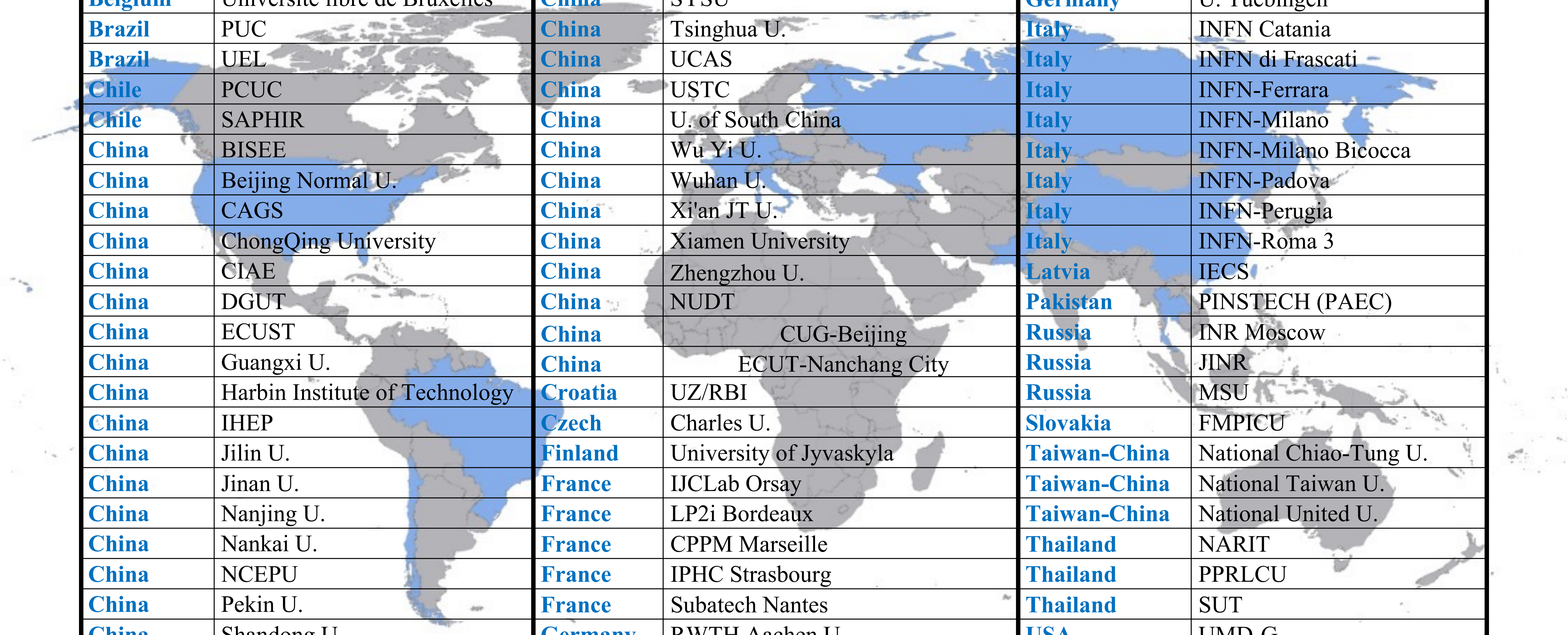


The JUNO Experimental Site



The JUNO Collaboration

77 institutions, ~650 members



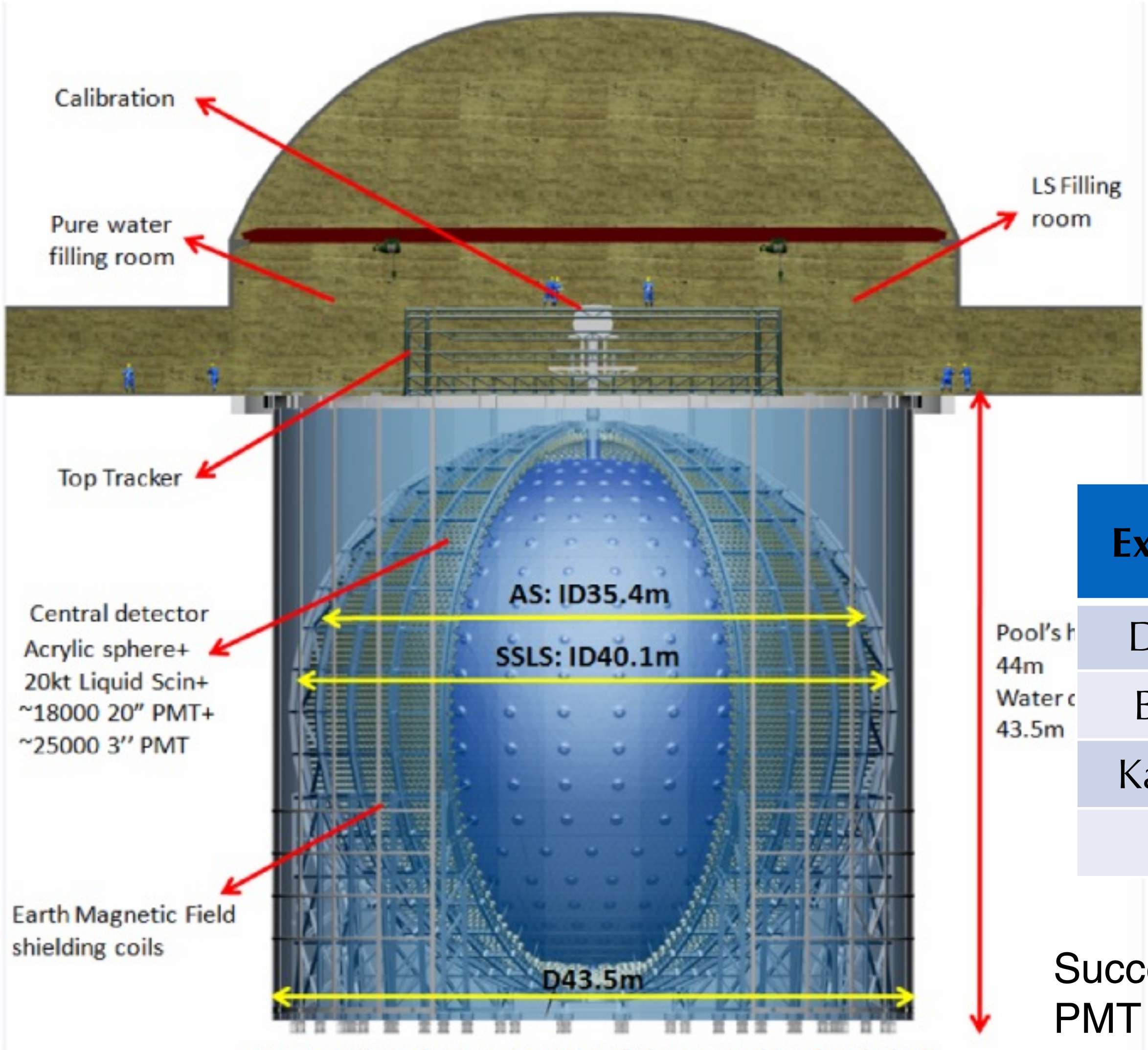
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	**China**	IMP-CAS	**Germany**	U. Mainz
Belgium	Universite libre de Bruxelles	**China**	SYSU	**Germany**	U. Tuebingen
Brazil	PUC	**China**	Tsinghua U.	**Italy**	INFN Catania
Brazil	UEL	**China**	UCAS	**Italy**	INFN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

The JUNO Collaboration

Last meeting in person in January, 2020 in Nanning, China

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

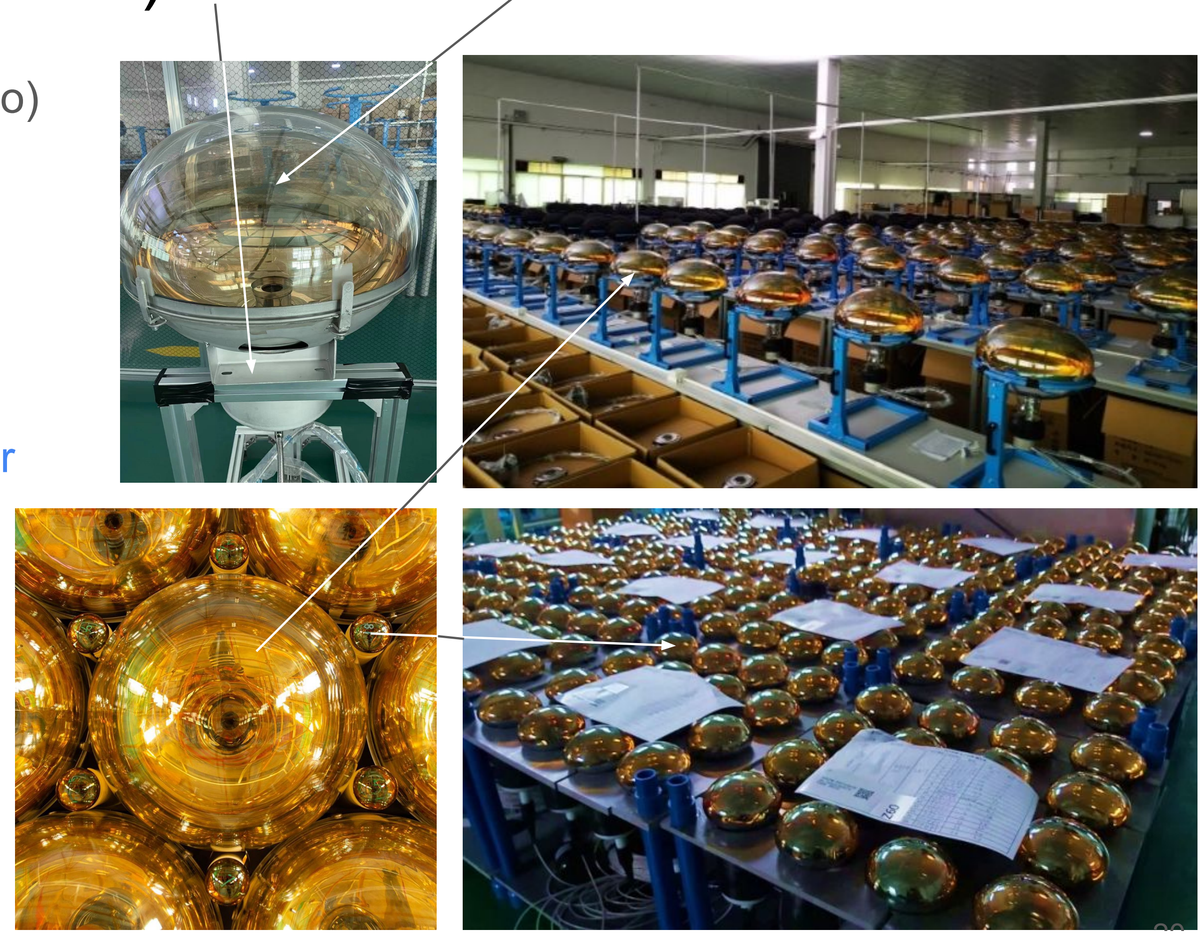
The JUNO PMT System

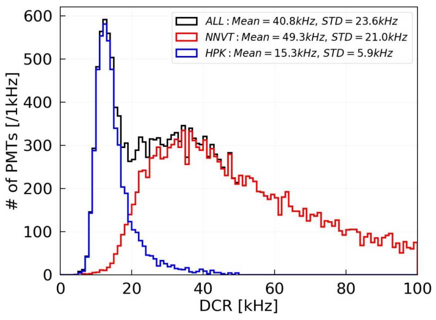
Photomultiplier Tubes (PMTs)

- 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

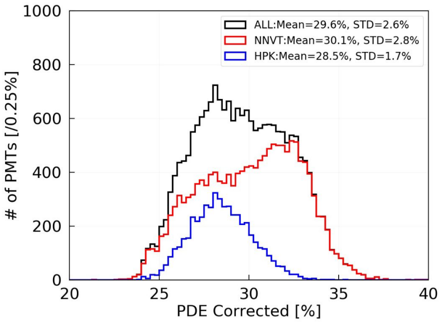
stainless steel cover

acrylic protective cover





dark count rate

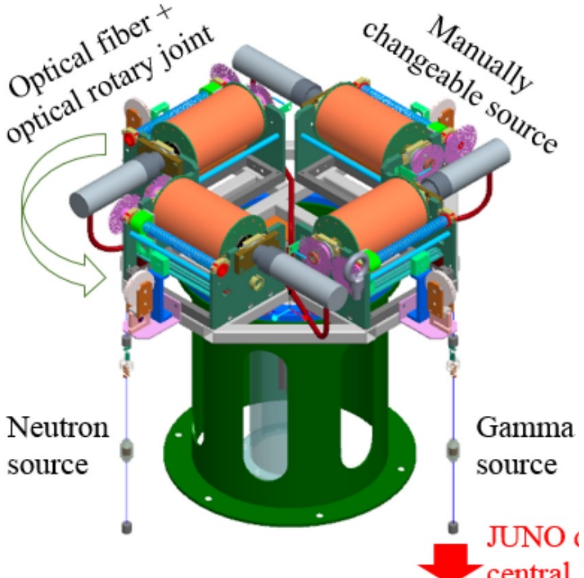


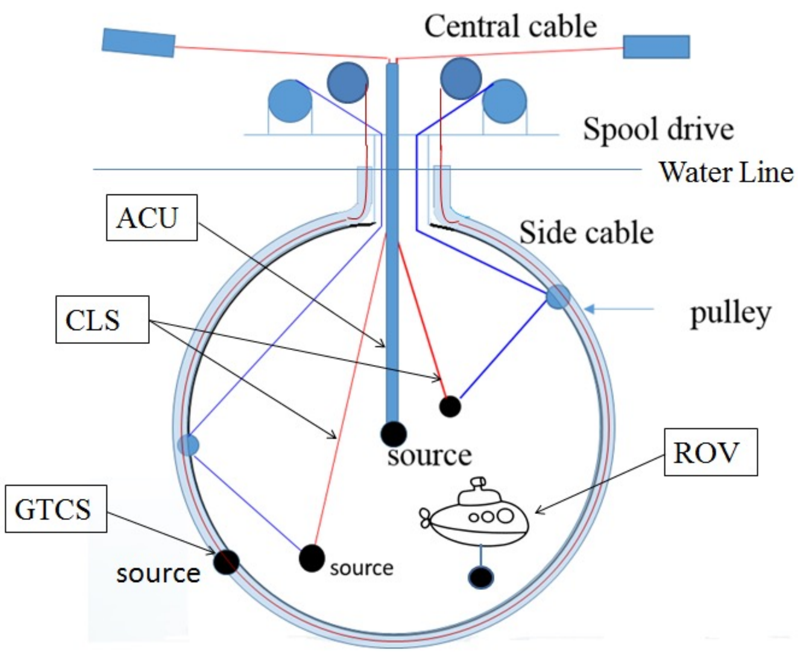
photon detection efficiency

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

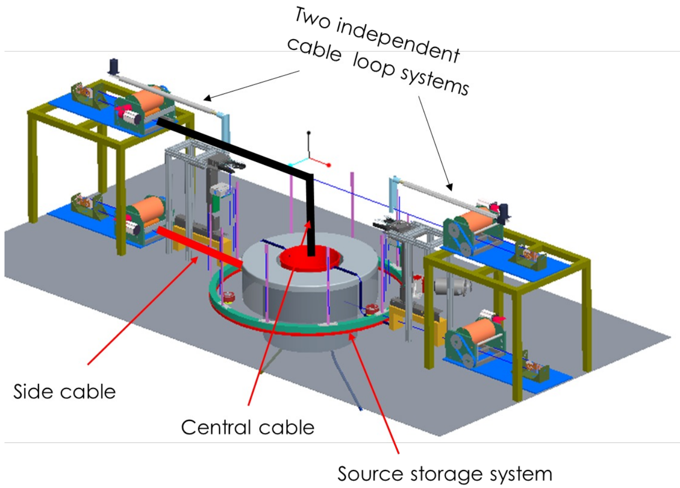
Calibration System *based on the Daya Bay experiences*

Automatic Calibration Unit (ACU)

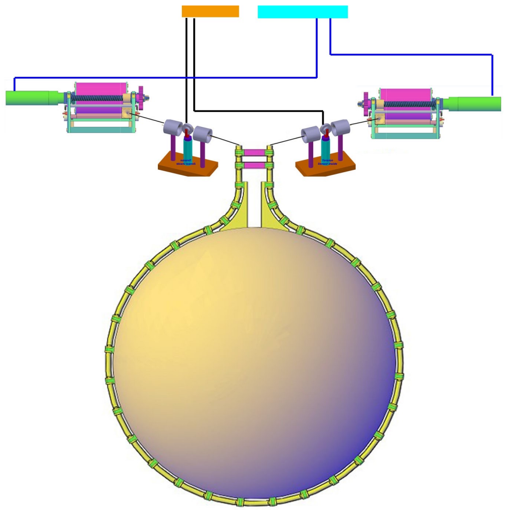




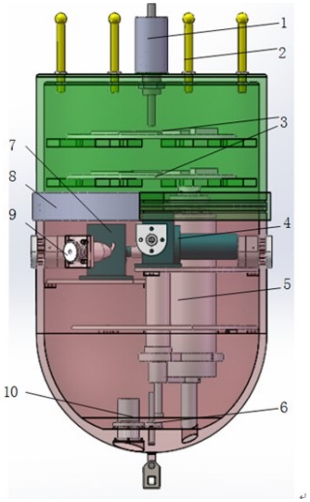
Cable Loop System (CLS)



Guide Tube Calibration System(GTCS)

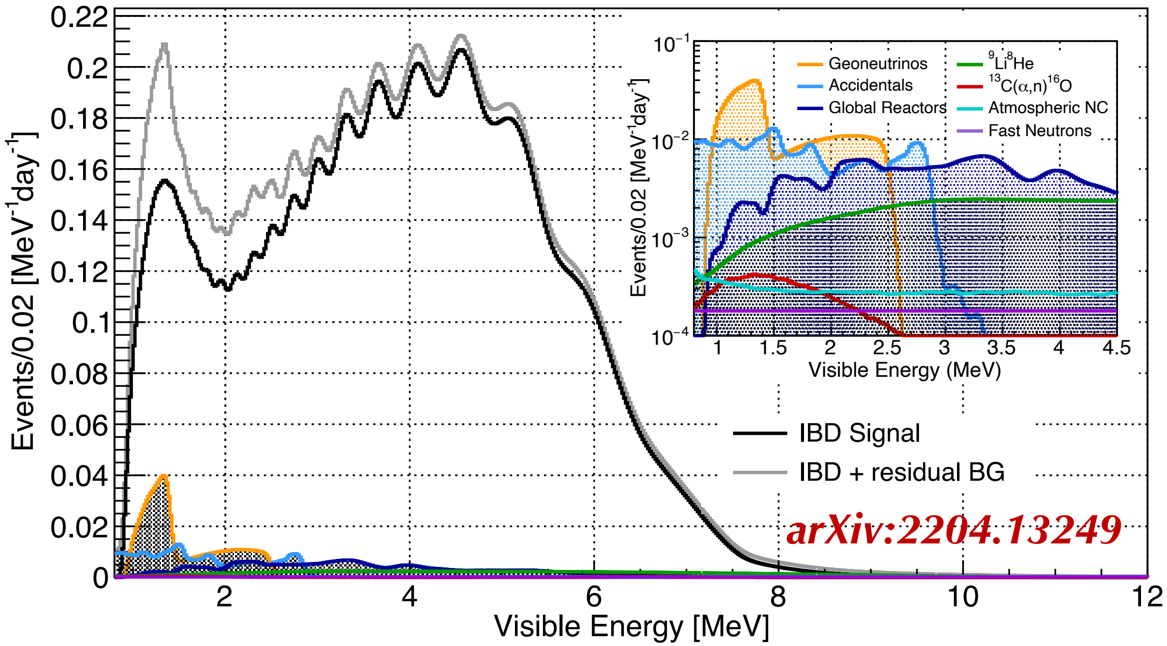


Remotely Operated under-liquid-scintillator Vehicles (ROV)



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

Signal and backgrounds



arXiv:2204.13249

- **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: $\mathrm{R_{LS}} < 17.2\ m$
- Timing cut: $\Delta T_{p-d} < 1\ ms$
- Spatial cut: $R_{p-d} < 1.5\ m$
- Cosmic muon veto cuts

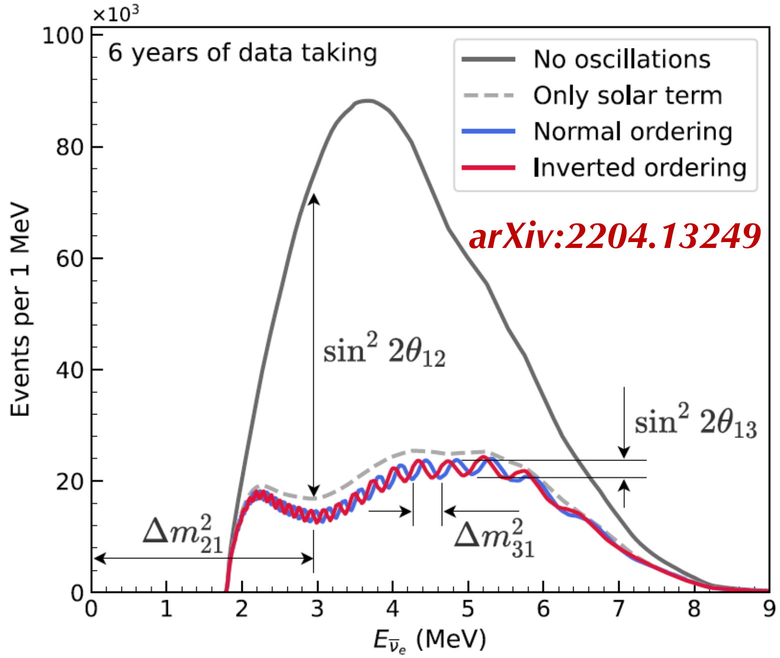
Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

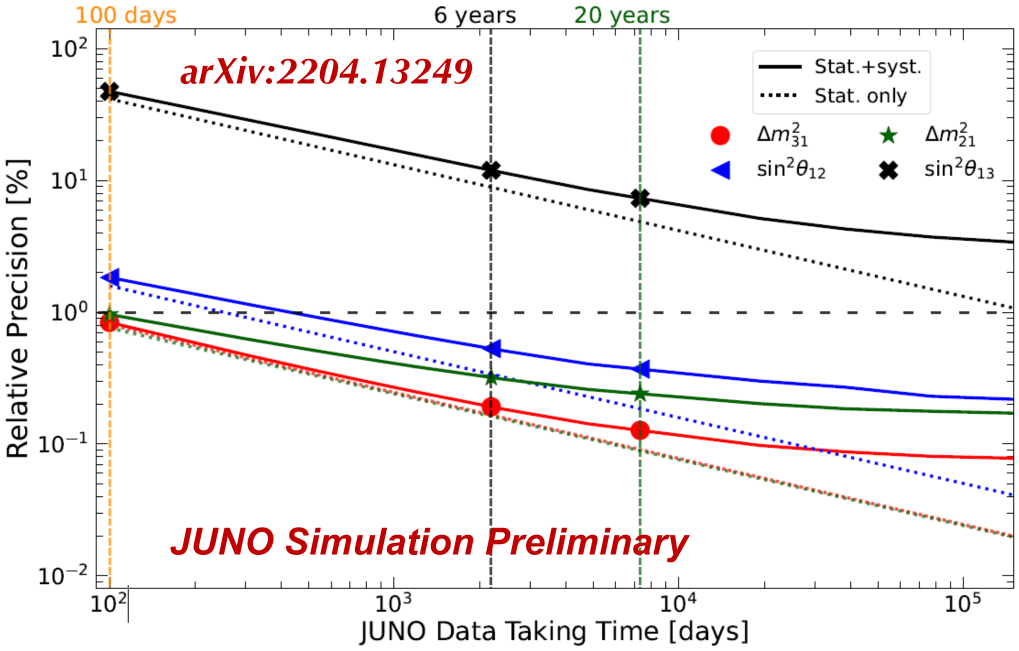
- ~47 $\bar{\nu}_e$ evt/day (assuming ~82% efficiency) and ~4.1 bckg evt/day

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)



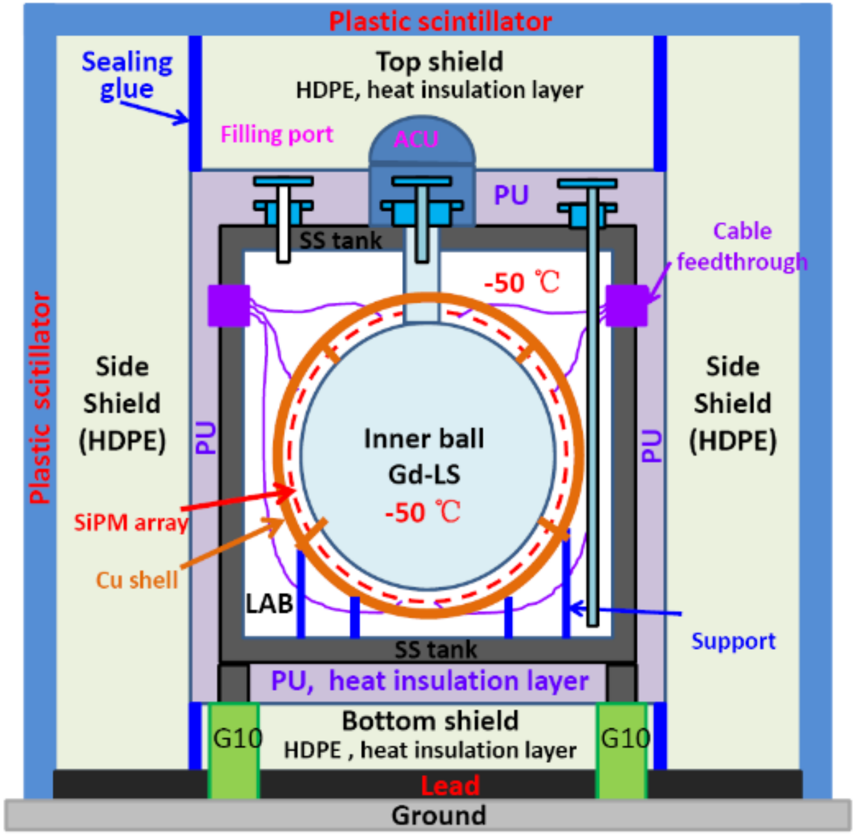


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	$\sim$0.2%	$\sim$0.3%	$\sim$0.5%	$\sim$12%
PDG2020	1.4%	2.4%	4.2%	3.2%

- ❖ Subpercent precisions for 3 oscillation parameters (JUNO only)

JUNO-TAO: A Satellite Experiment of JUNO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector, at 30-35 m from a 4.6 GW_{th} core, a satellite exp. of JUNO
- 2.6 ton GdLS | acrylic vessel | SiPM and Cu shell | Cryogenic vessel | water or HDPE



◆ TAO will be used to measure reactor neutrino spectrum

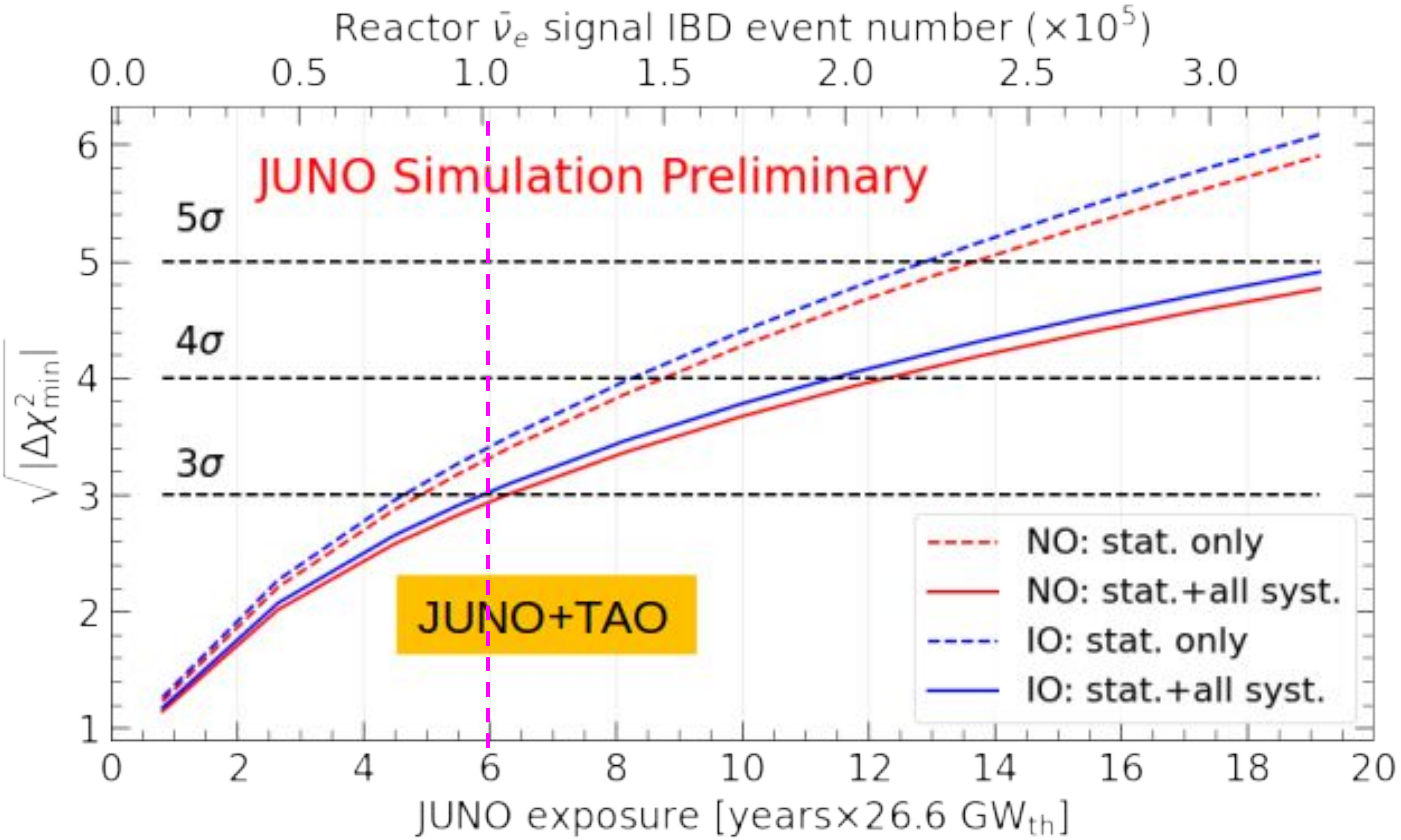
◆ Full coverage of SiPM with PDE > 50%
Operate at -50 °C (lower SiPM dark noise)

- ➢ 4500 p.e./MeV → **$1.5\%\sqrt{E(MeV)}$**

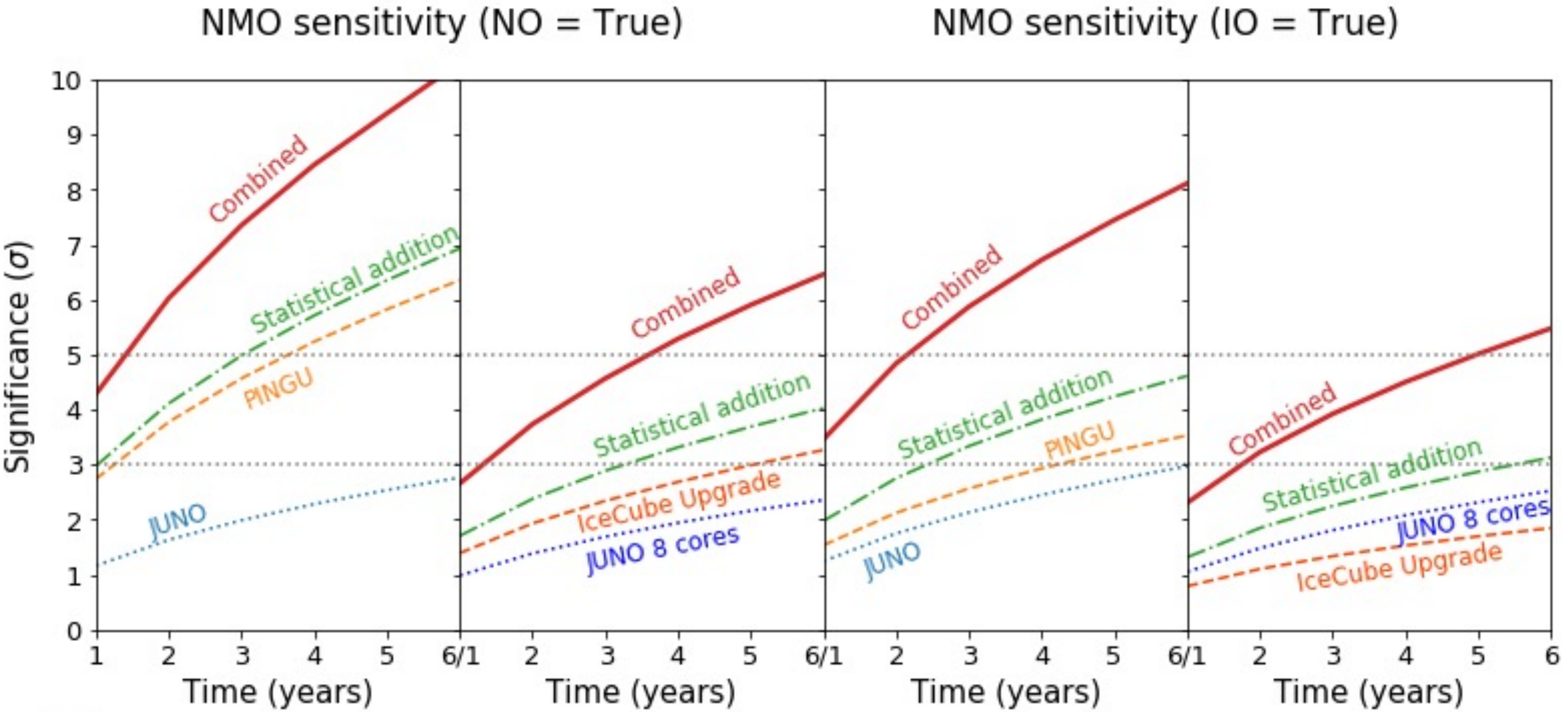
◆ Taishan Nuclear Power Plant 2000 IBD/day (4000)

For details, see CDR arXiv:2005.08745

Latest Re-Evaluations of JUNO Physics Potential



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

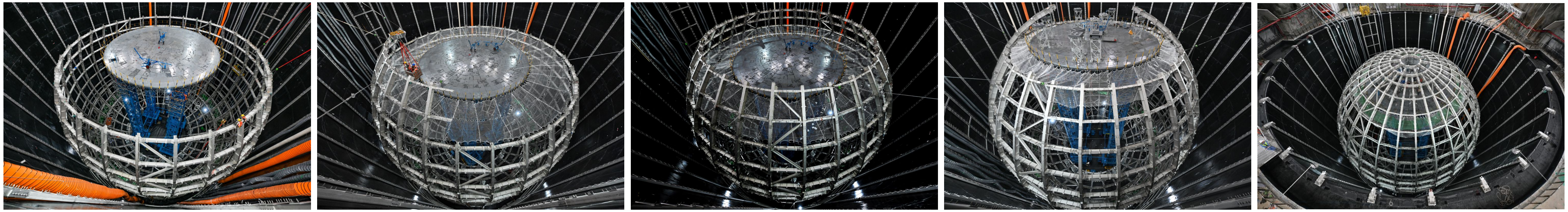


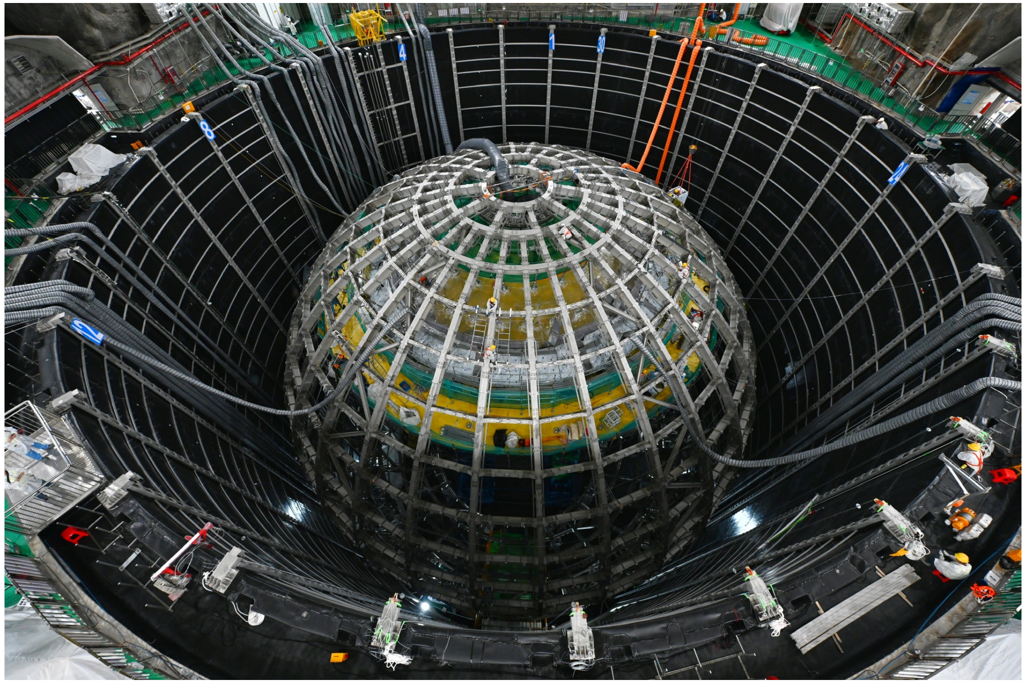
JUNGU unchained

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

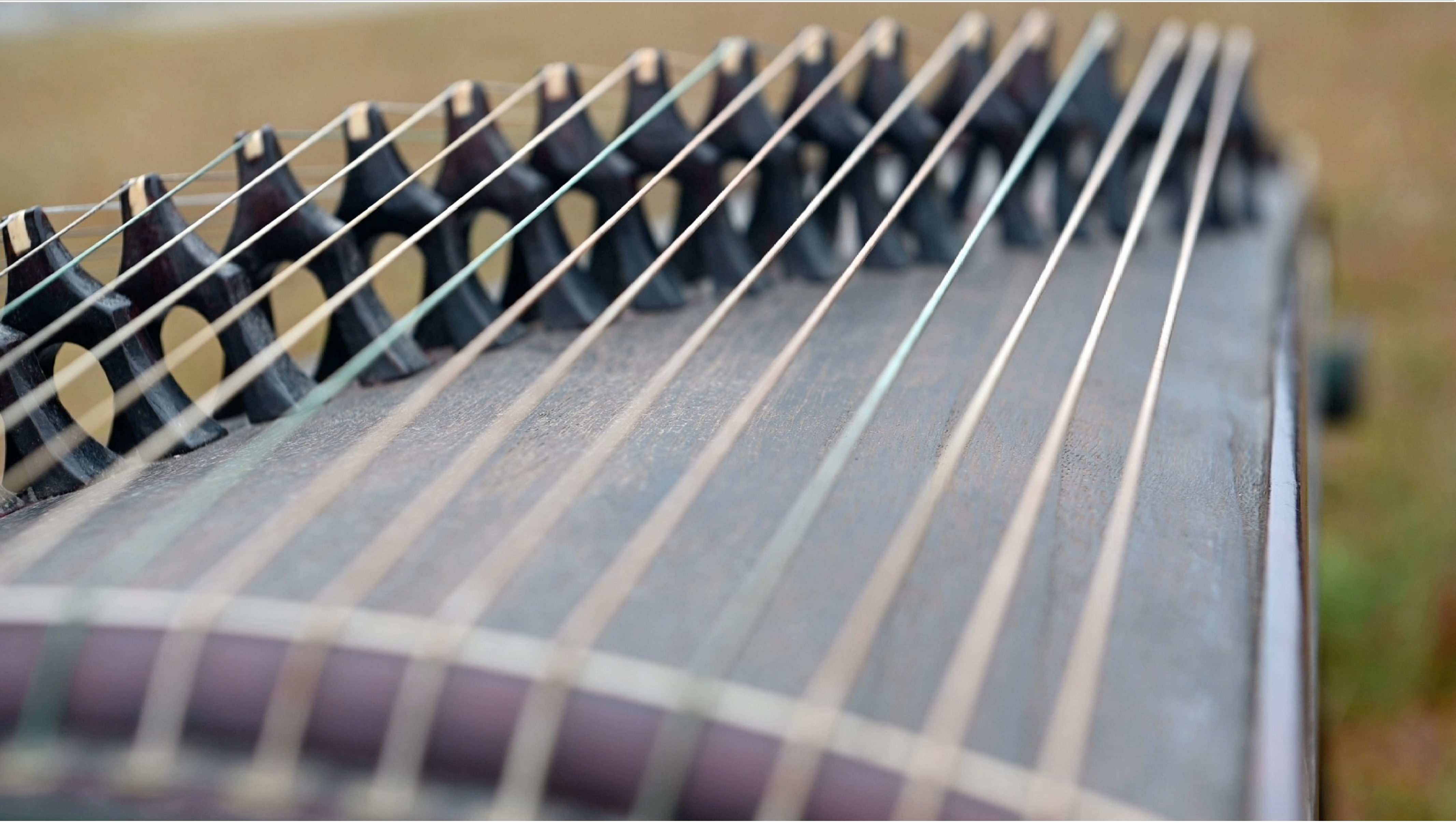
➢ **In any case, a 5σ discovery after 5 years!**

2022 Has Been A Very Exciting Year for JUNO





2022 Has Been A Very Exciting Year for JUNO



Summary and Conclusion

- **Reactor neutrino has played irreplaceable roles in neutrino studies**
- **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**
- **Daya Bay has made precise measurements of reactor antineutrino flux, its spectrum and decomposed contributions of 2 major fission isotopes**
  - **→ RAA, spectrum discrepancy, cross disciplinary fields**
  - **→ Daya Bay data will be made open: proposals welcome**
- **JUNO is the only reactor experiment for neutrino mass ordering: observing the two oscillations on the same spectrum for the first time**
- **JUNO construction has entered a very exciting phase (see the movie). Data taking is expected to start by the end of 2023!**

Thanks for your Attention!

Welcome to SYSU Zhuhai

Weak Interaction and Neutrinos 2023: July 3-8

Guangzhou South Campus

Guangzhou East Campus

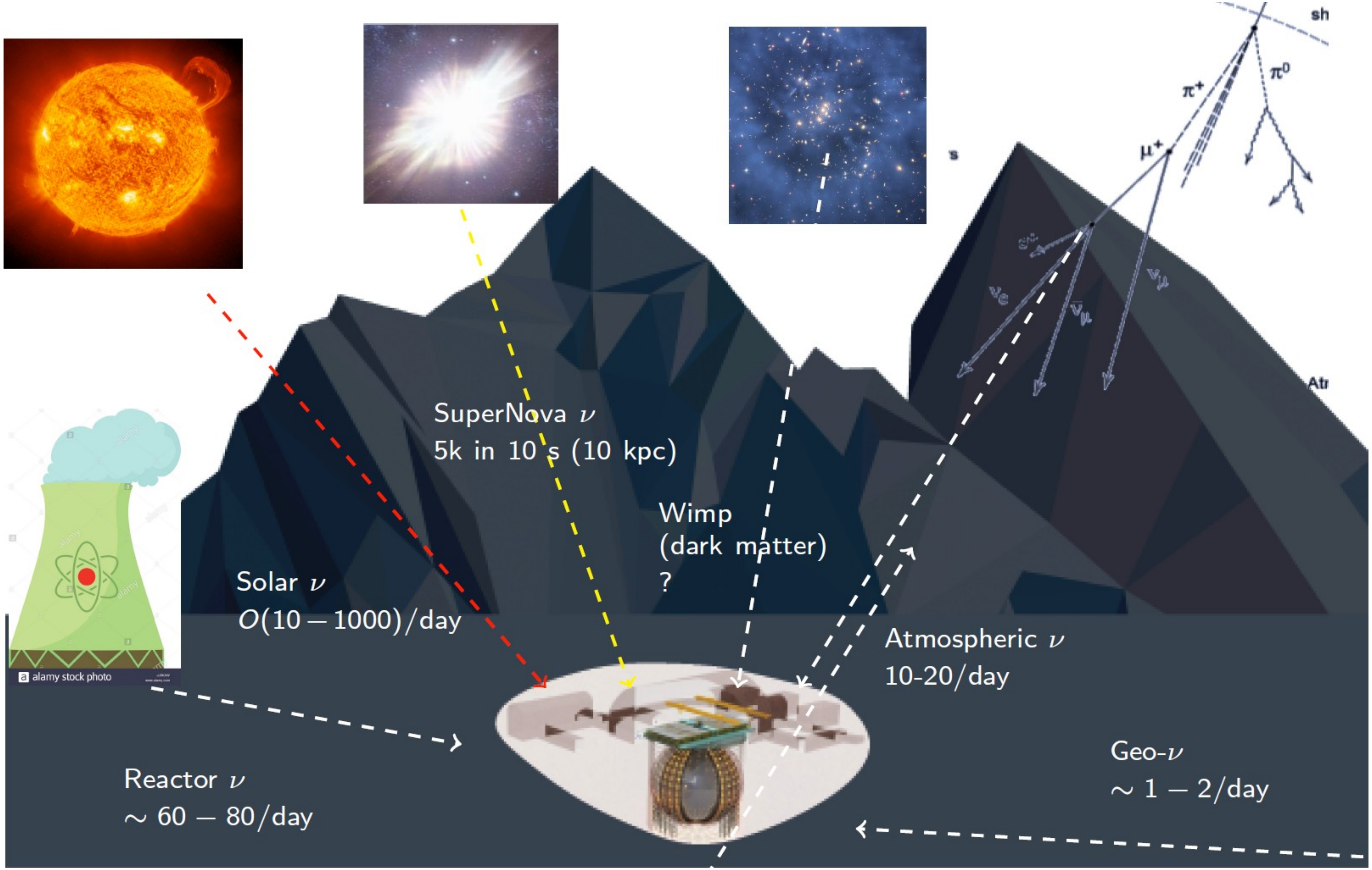
Guangzhou North Campus

Shenzhen Campus

Zhuhai Campus

Wushunde Academic Center and Multiple Auditoriums (Venue of ~300 plenary and multiple parallel sessions)

JUNO’s Multi-Physics Potential



SuperNova ν
5k in 10 s (10 kpc)

Wimp
(dark matter)
?

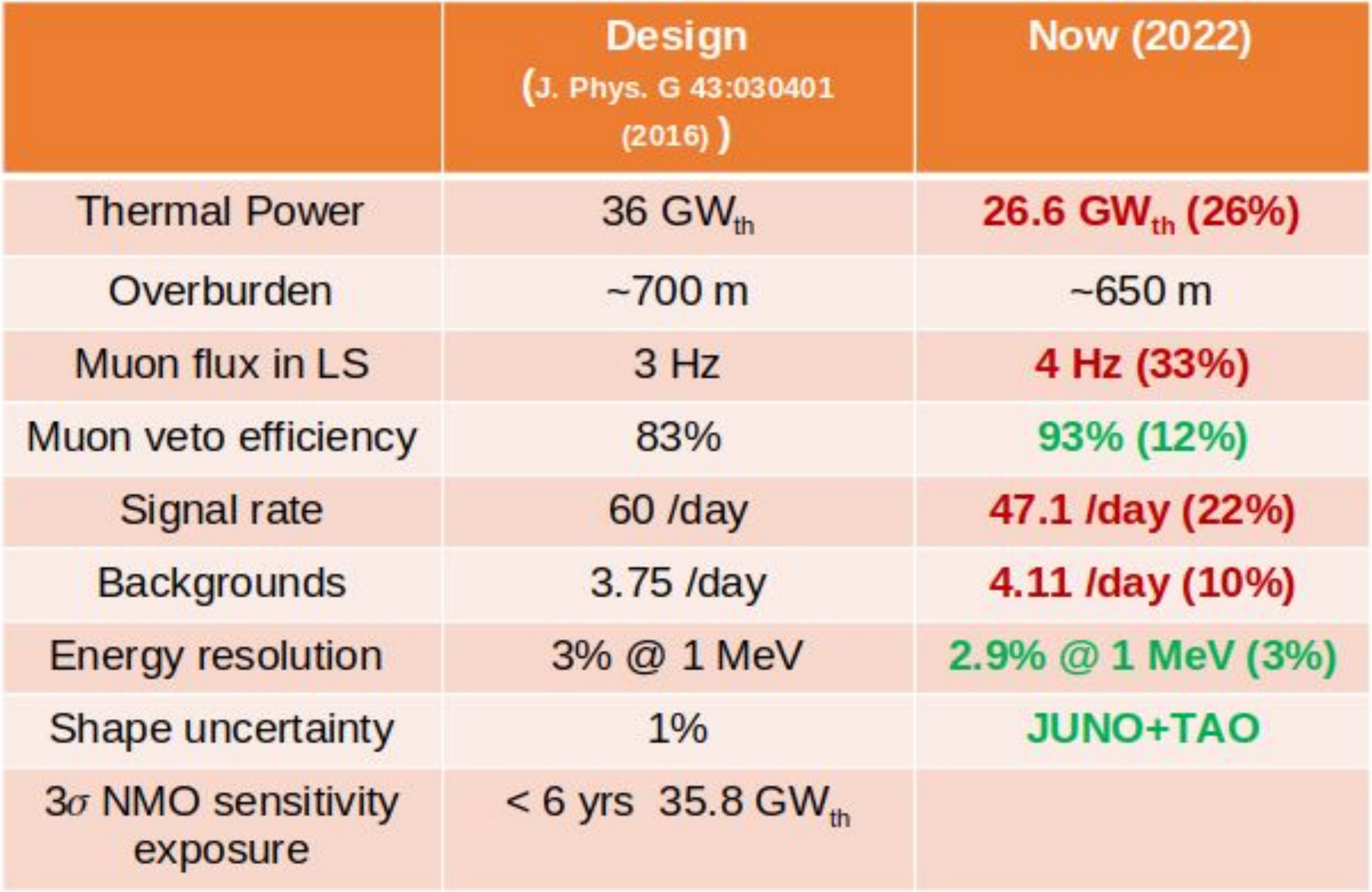
Solar ν
$O(10-1000)$/day

Atmospheric ν
10-20/day

Geo-ν
$\sim 1-2$/day

Reactor ν
$\sim 60-80$/day

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}	

The Latest Daya Bay Reactor Neutrino Data Set

- Summary of the Daya Bay data sample:

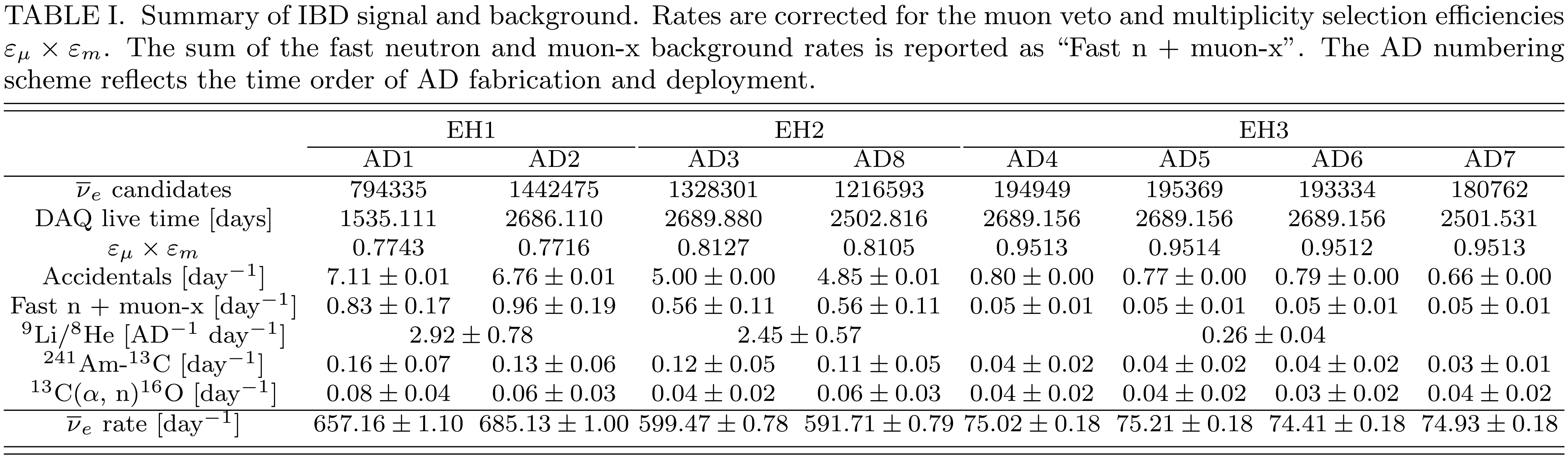


TABLE I. Summary of IBD signal and background. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \times \varepsilon_m$. The sum of the fast neutron and muon-x background rates is reported as "Fast n + muon-x". The AD numbering scheme reflects the time order of AD fabrication and deployment.

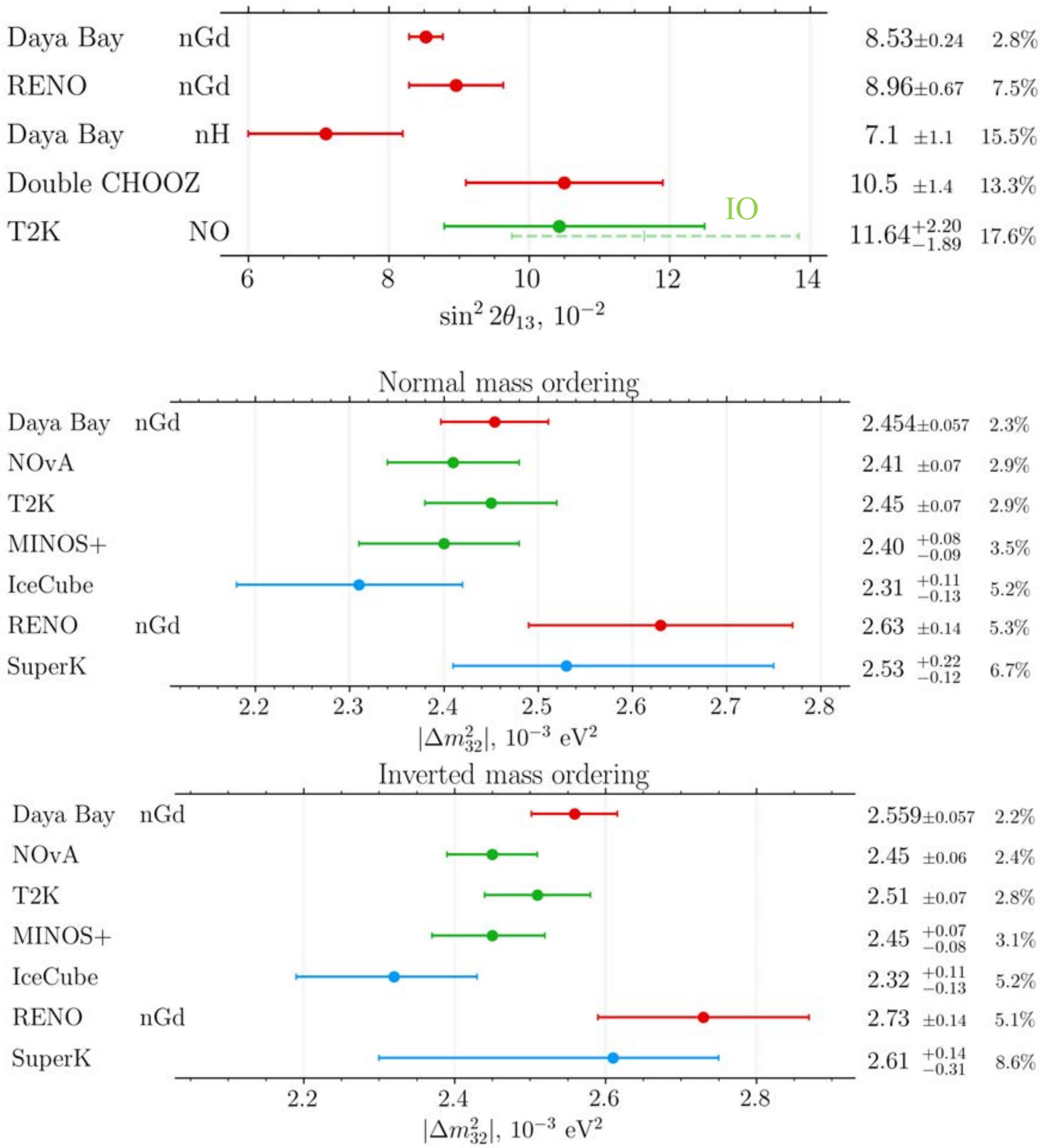
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	794335	1442475	1328301	1216593	194949	195369	193334	180762
DAQ live time [days]	1535.111	2686.110	2689.880	2502.816	2689.156	2689.156	2689.156	2501.531
$\varepsilon_\mu \times \varepsilon_m$	0.7743	0.7716	0.8127	0.8105	0.9513	0.9514	0.9512	0.9513
Accidentals [day^{-1}]	7.11 ± 0.01	6.76 ± 0.01	5.00 ± 0.00	4.85 ± 0.01	0.80 ± 0.00	0.77 ± 0.00	0.79 ± 0.00	0.66 ± 0.00
Fast n + muon-x [day^{-1}]	0.83 ± 0.17	0.96 ± 0.19	0.56 ± 0.11	0.56 ± 0.11	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
^{9}Li/^{8}He [AD^{-1} day^{-1}]	2.92 ± 0.78		2.45 ± 0.57		0.26 ± 0.04			
^{241}Am-^{13}C [day^{-1}]	0.16 ± 0.07	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.01
^{13}C(α, n)^{16}O [day^{-1}]	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
$\overline{\nu}_e$ rate [day^{-1}]	657.16 ± 1.10	685.13 ± 1.00	599.47 ± 0.78	591.71 ± 0.79	75.02 ± 0.18	75.21 ± 0.18	74.41 ± 0.18	74.93 ± 0.18

- Largest Reactor Neutrino Data Ever:
  - More than **5.5 million IBDs (~0.7 million at far site)**

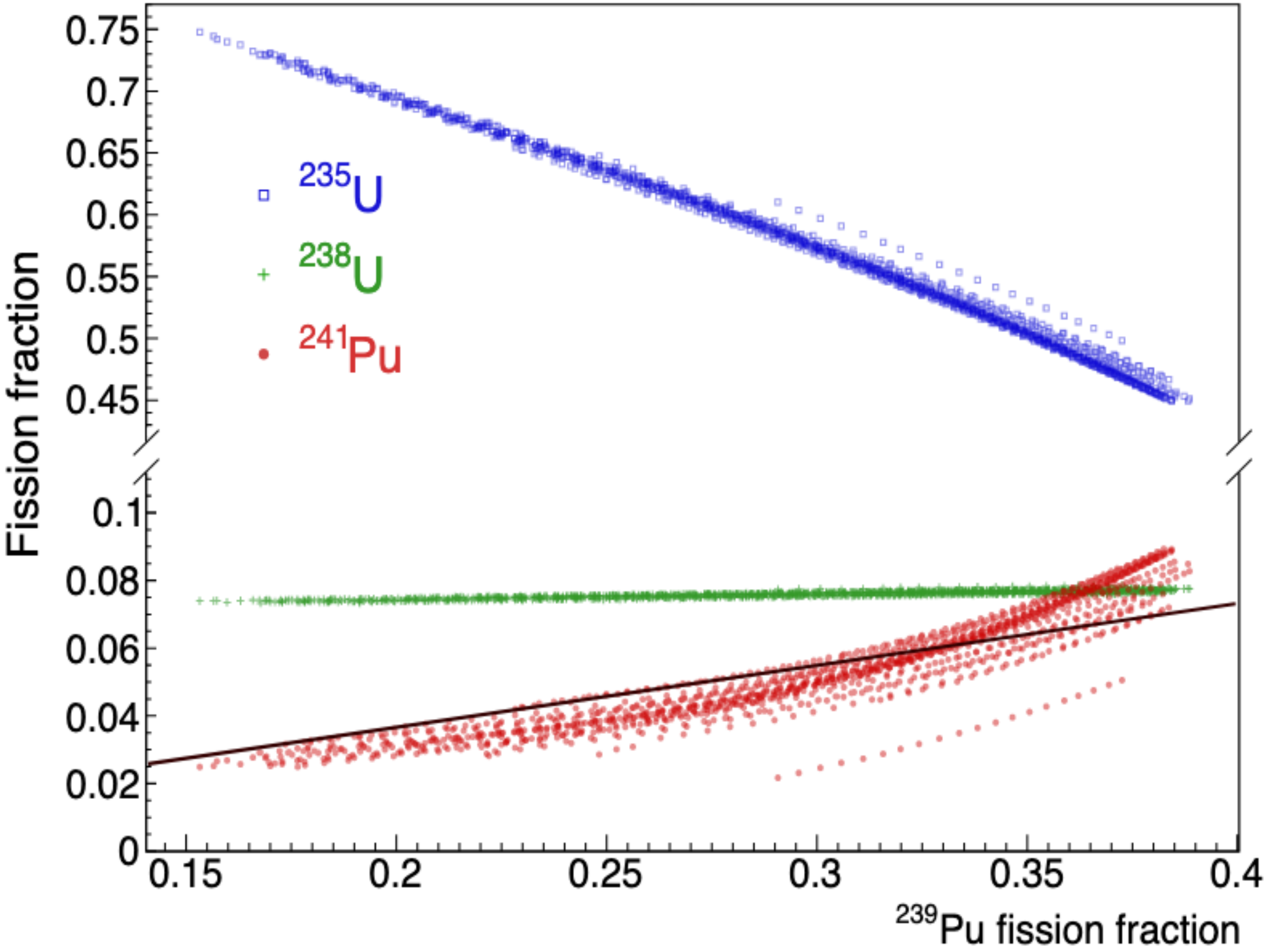
Inversed Beta Decay Like Background Events

- Uncorrelated background: accidental pairs
- Correlated backgrounds:
  - Fast neutron: cosmogenic outside → AD
  - ^{9}Li/^{8}He: cosmogenic from spallation products of cosmic-ray muons
  - ^{241}Am-^{13}C: ACU neutron calibration sources
  - $^{13}C(\alpha,n)^{16}O$: α decay of natural radioactive isotopes
  - New backgrounds: Residual PMT flasher & Muon-x

Daya Bay Oscillation Results and Global Comparison



Fission Fraction Evolution



$\sin^2 2\theta_{13}$ from nH-IBD analysis

PRD 93 072011 (2016)

- Independent $\sin^2 2\theta_{13}$ measurement
- Challenging: much more low-energy backgrounds
  - Signal to background ratio is about 1:1 at the far hall
- Rate-only analysis result: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$
- Improved measurement is coming soon