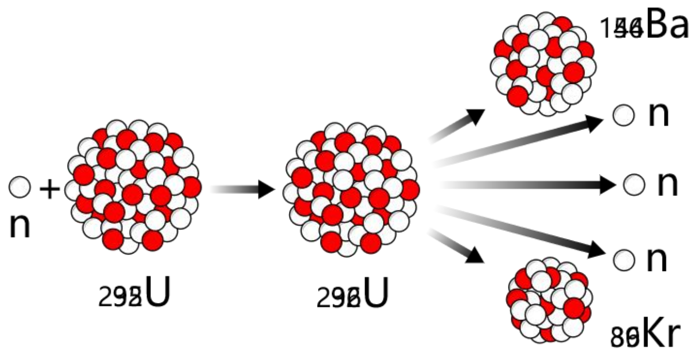
From Daya Bay to JUNO:
the quest for neutrino mass ordering

Wei Wang, Sun Yat-sen University
for Daya Bay and JUNO Collaborations

- *Neutrino Oscillation: A Brief Review*
- *Daya Bay Reactor Neutrino Experiment*
- *Jiangmen Underground Neutrino Observatory*
- *Summary and Conclusion*

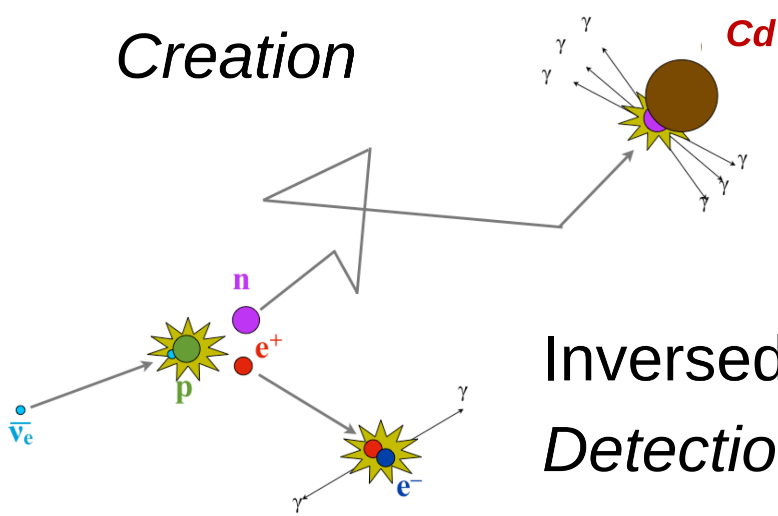
Reines&Cowan Detected Neutrinos in 1956

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



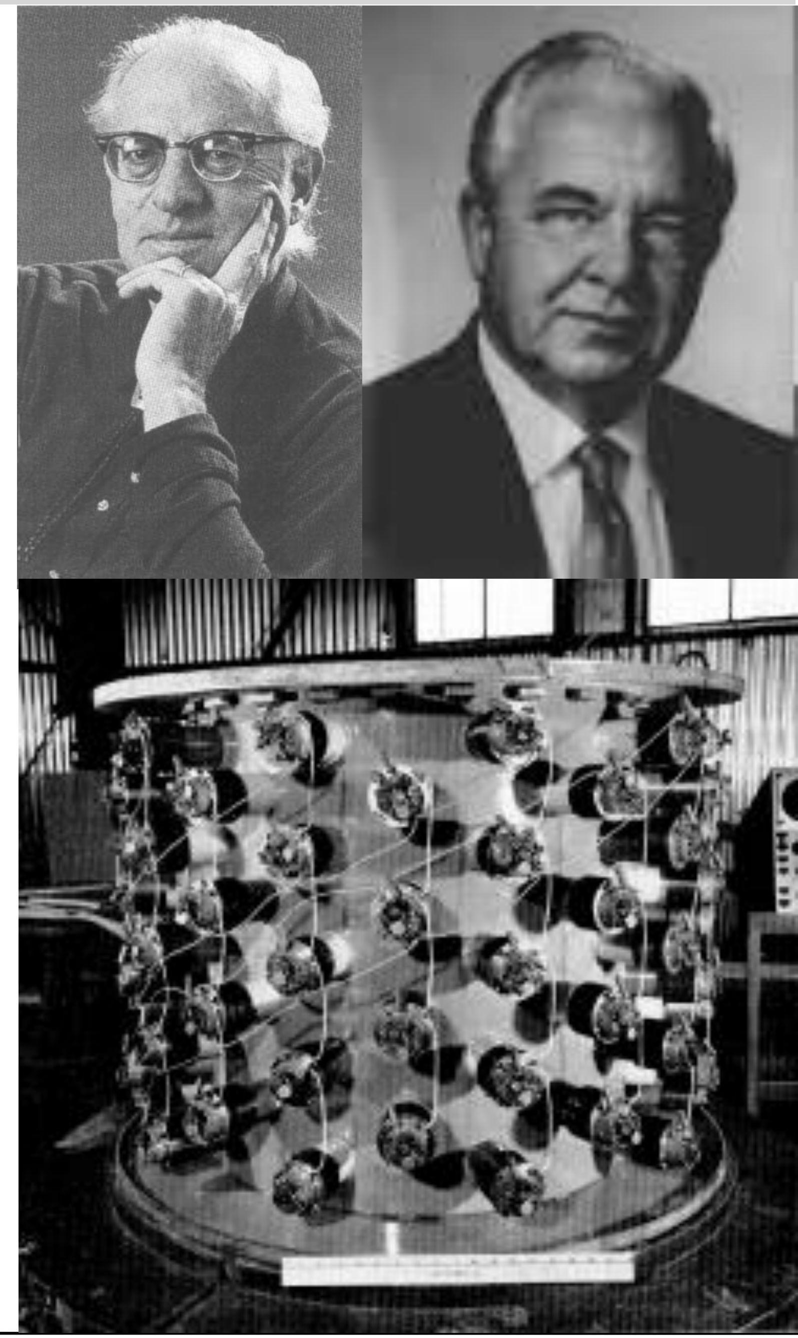
β decay: $N \rightarrow N' + e + \nu$

Creation

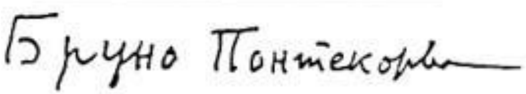


Inversed β decay

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



Neutrino Mixing & Oscillation Proposed



- Bruno Pontecorvo in 1957:

  Interaction Eigenstates ≠ Mass Eigenstates
  → Neutrino Mixing and Oscillation

Courtesy of Sakata Memorial Archival Library

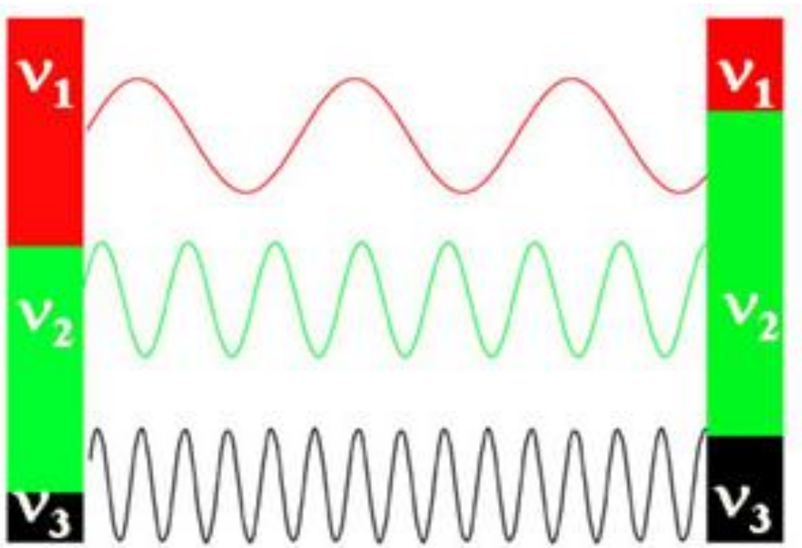
S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

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

Neutrino Mixing & Oscillation

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

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



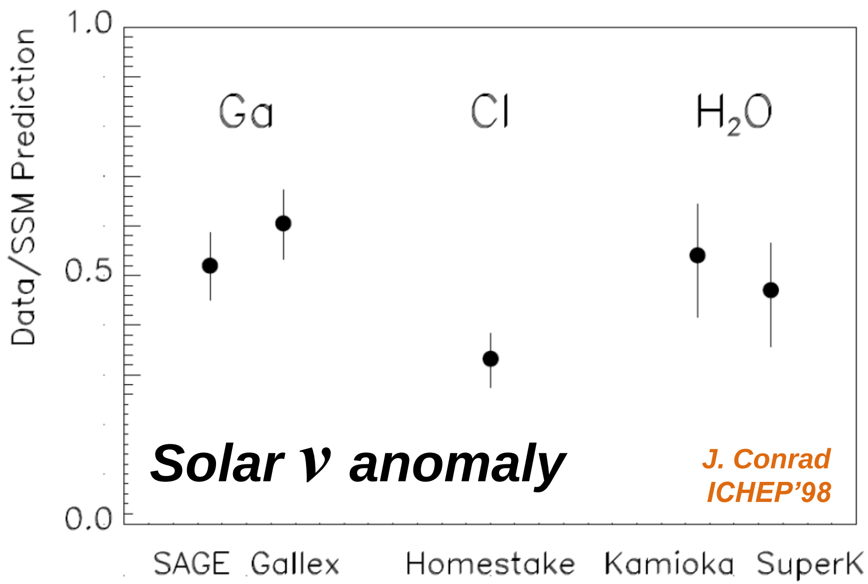
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

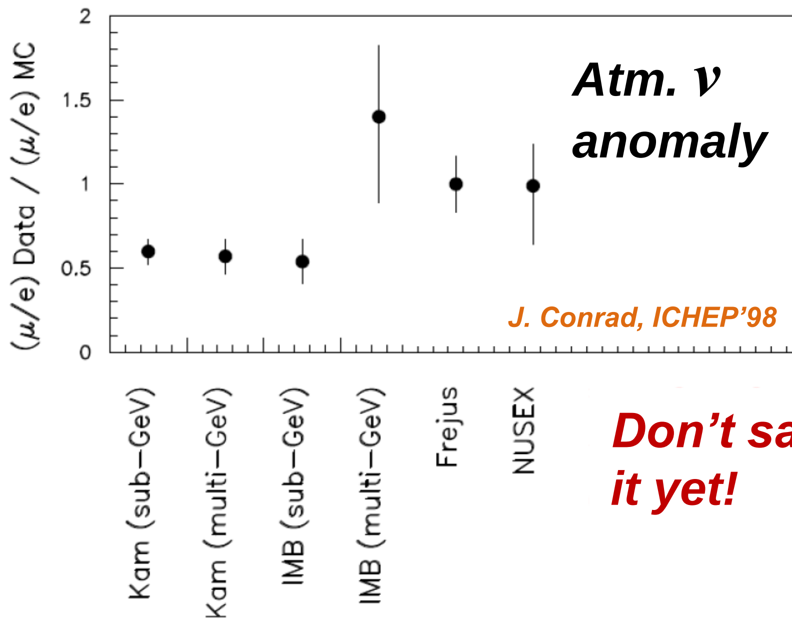
⇒ Oscillation Probability:

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

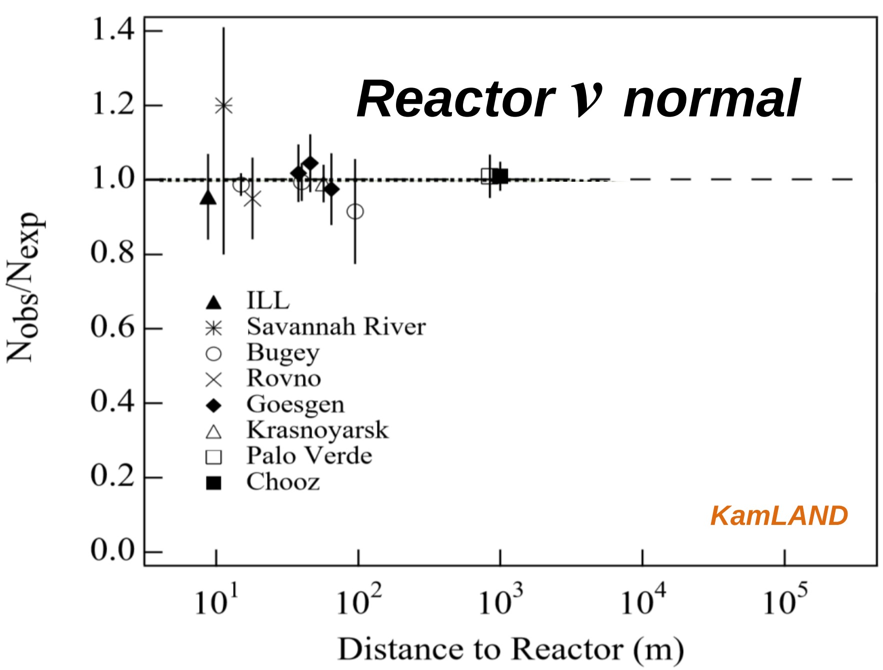
Amplitude $\propto \sin^2 2\theta$ **Frequency $\propto \Delta m^2 L/E$**

The Search for Neutrino Oscillation 1957-1997



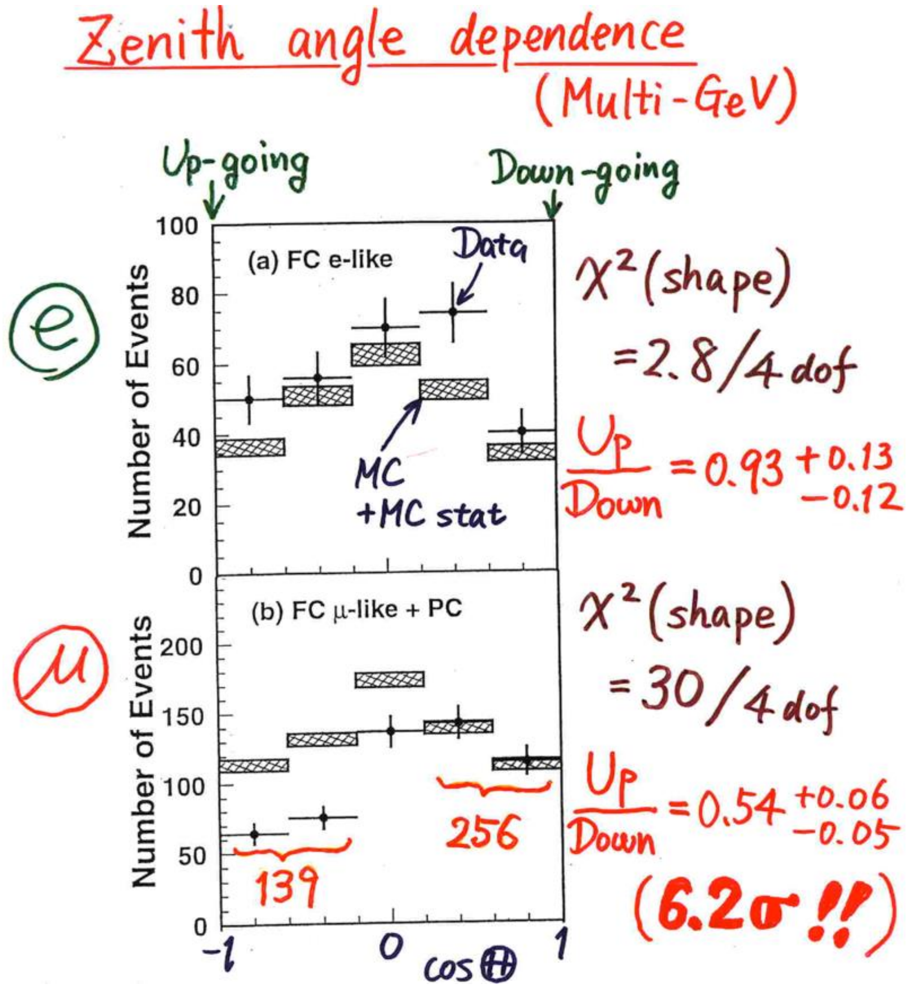


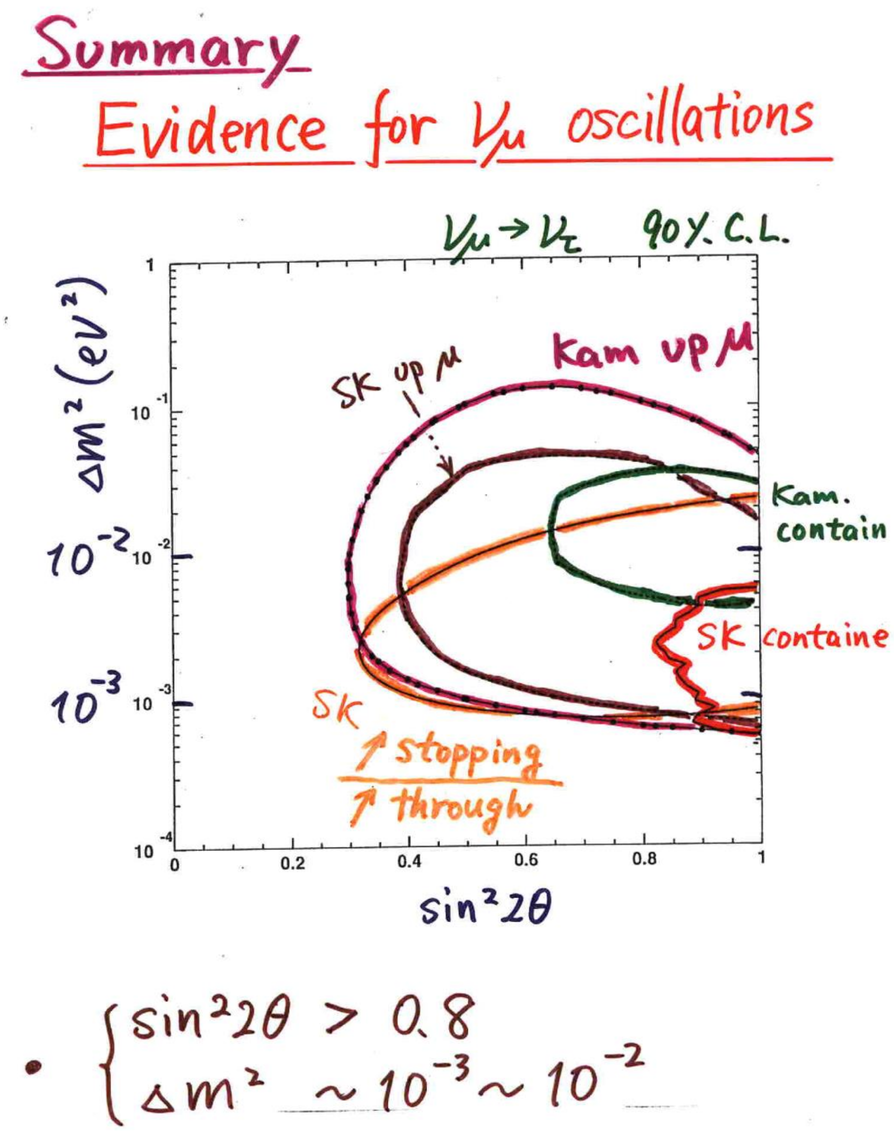
Don't say it yet!



- ***The search for neutrino oscillation lasted decades but nothing conclusive***

T. Kajita, Neutrino'98

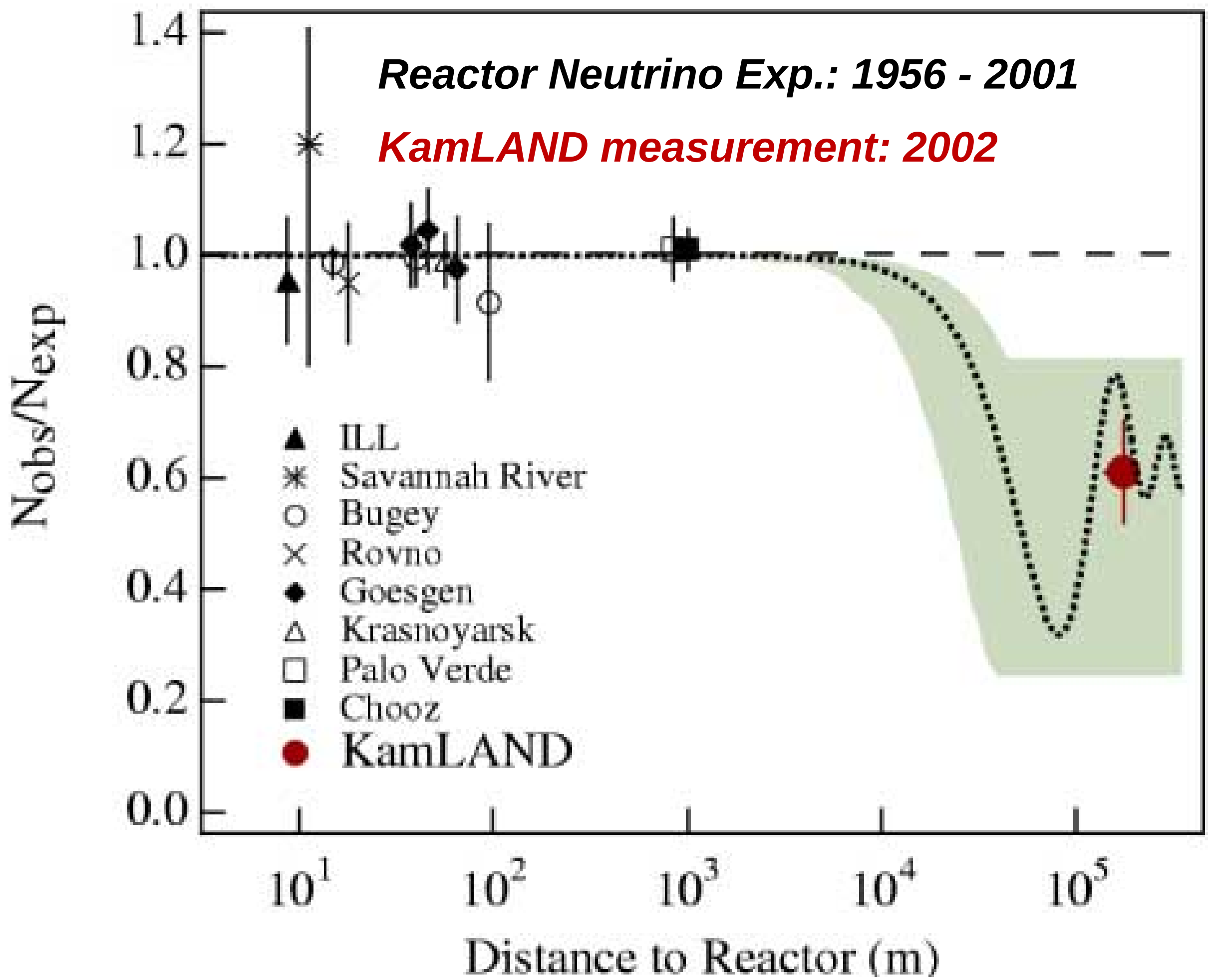




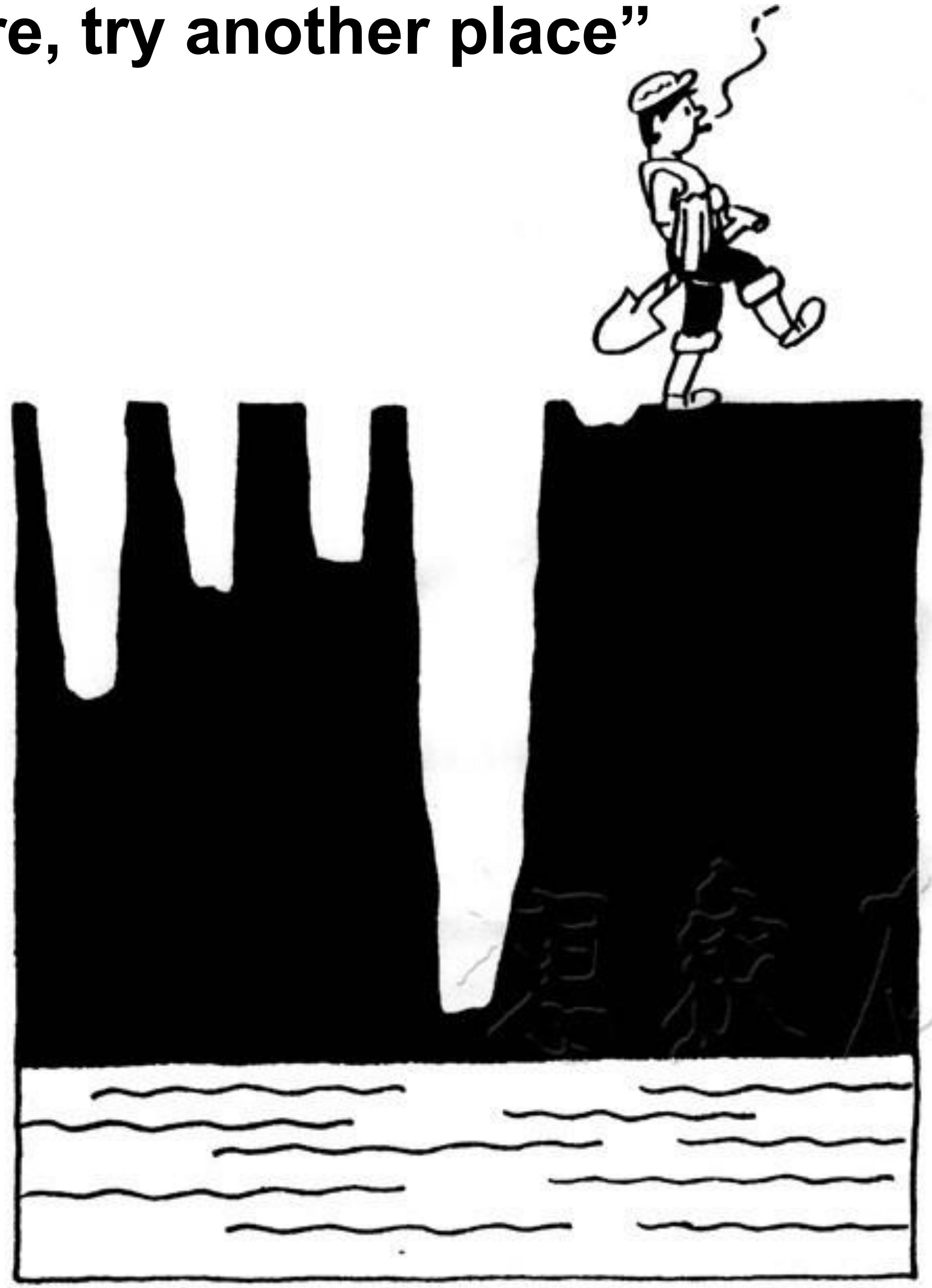
Year 2002: Reactor Neutrinos Oscillate Too!

Sometimes, we just need to push it a bit further, and more

from ~10m to over 100,000m



“No water here, try another place”



一这下面没有水，再换个地方挖　　张新华画

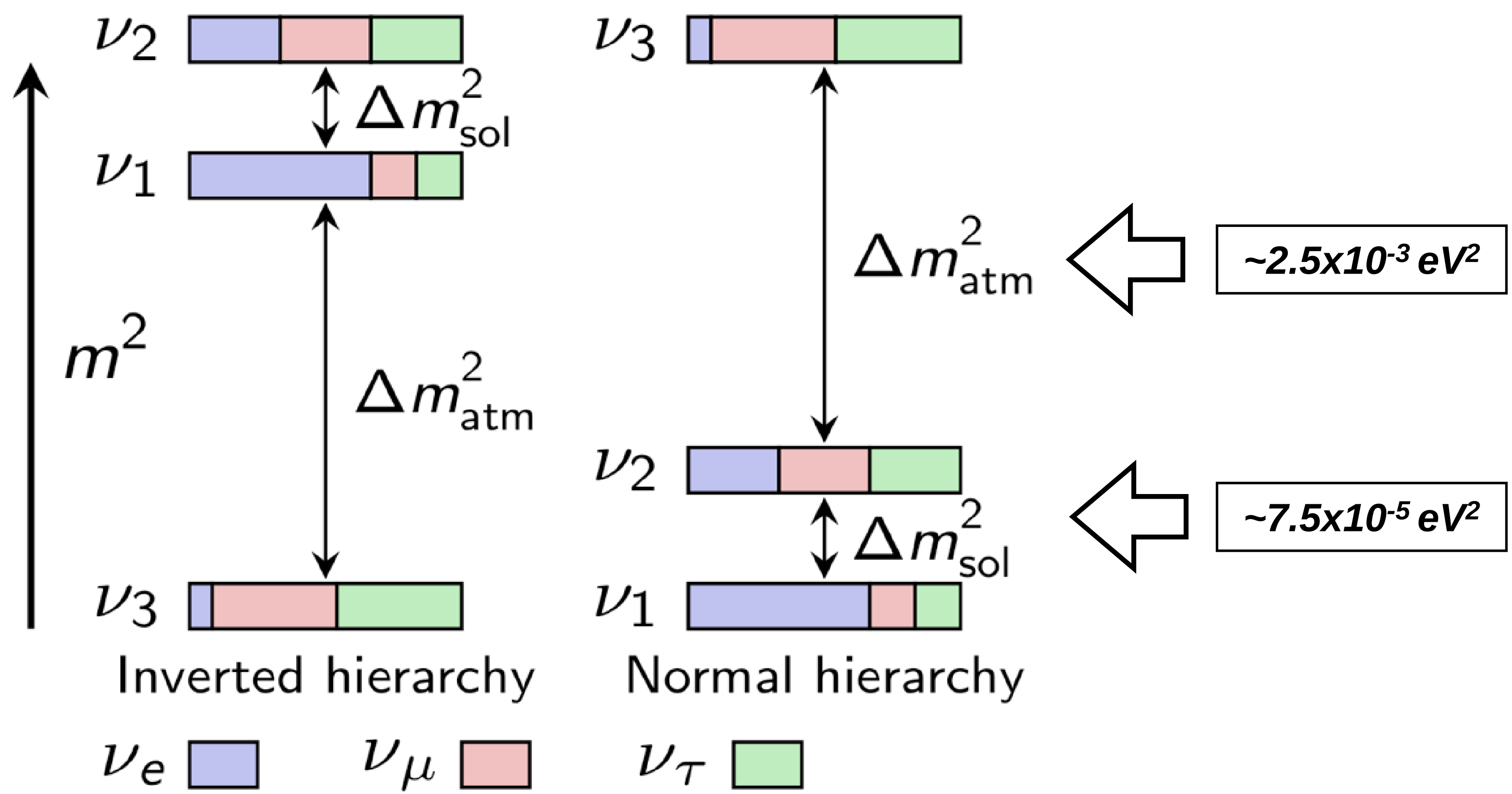
Hunt of θ$_{13}$ for a Decade (2002-2012)

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

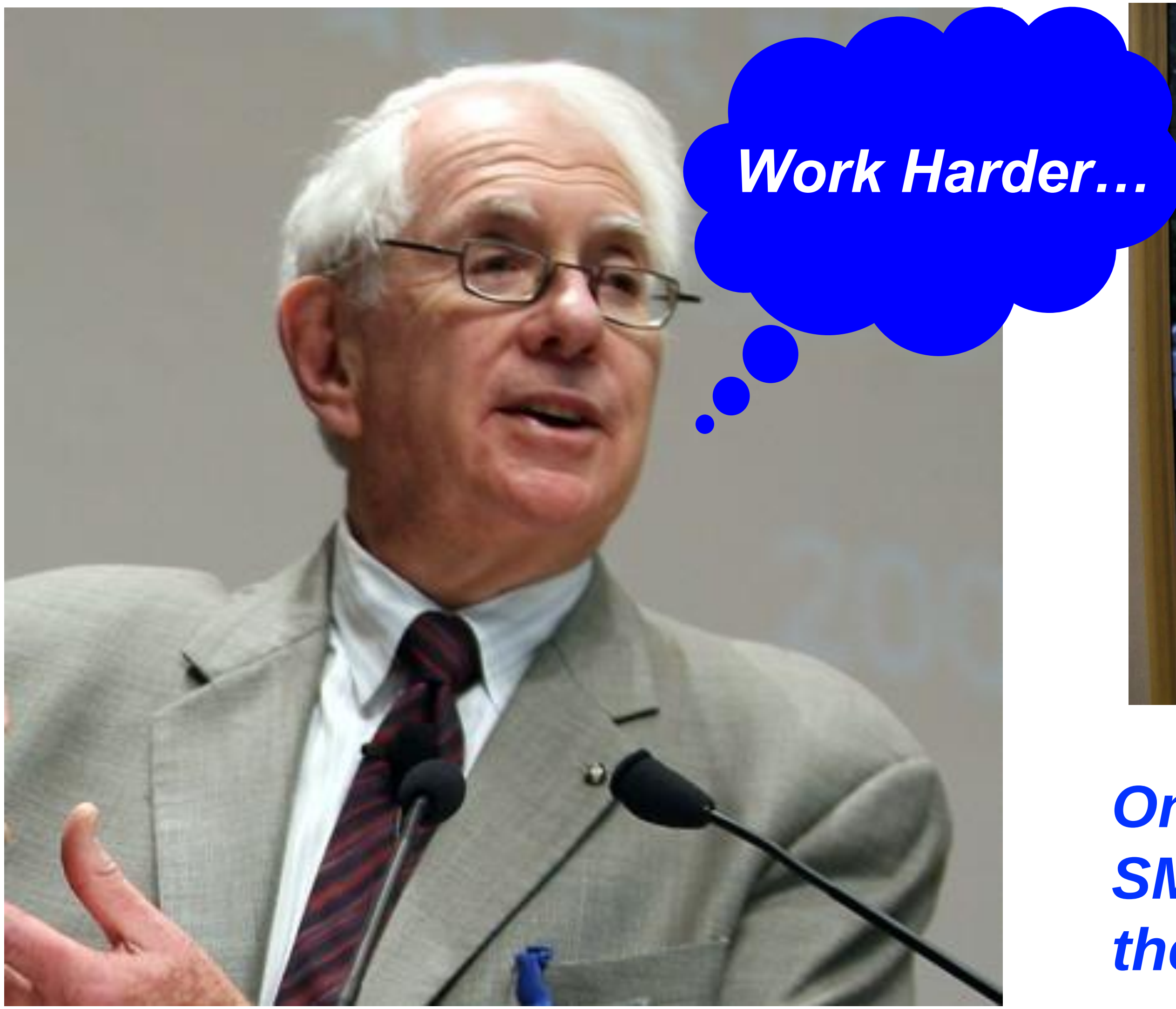
?

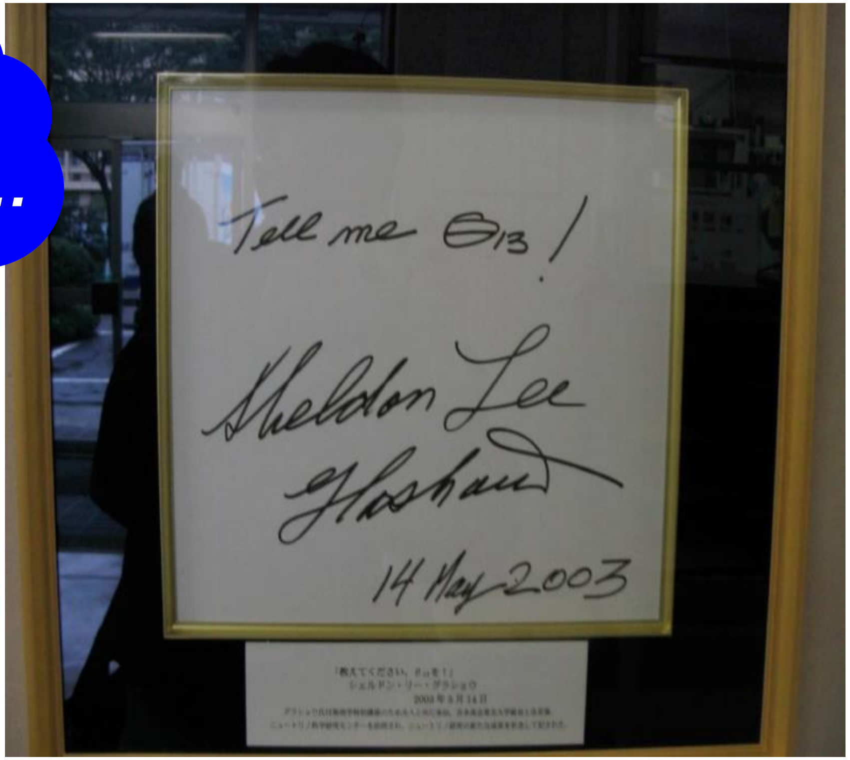
Atmospheric Sector:
SK, K2K, T2K, MINOS, etc

Solar Sector:
SNO, SK, KamLAND etc



We Were All Very Very Very **Desperate**

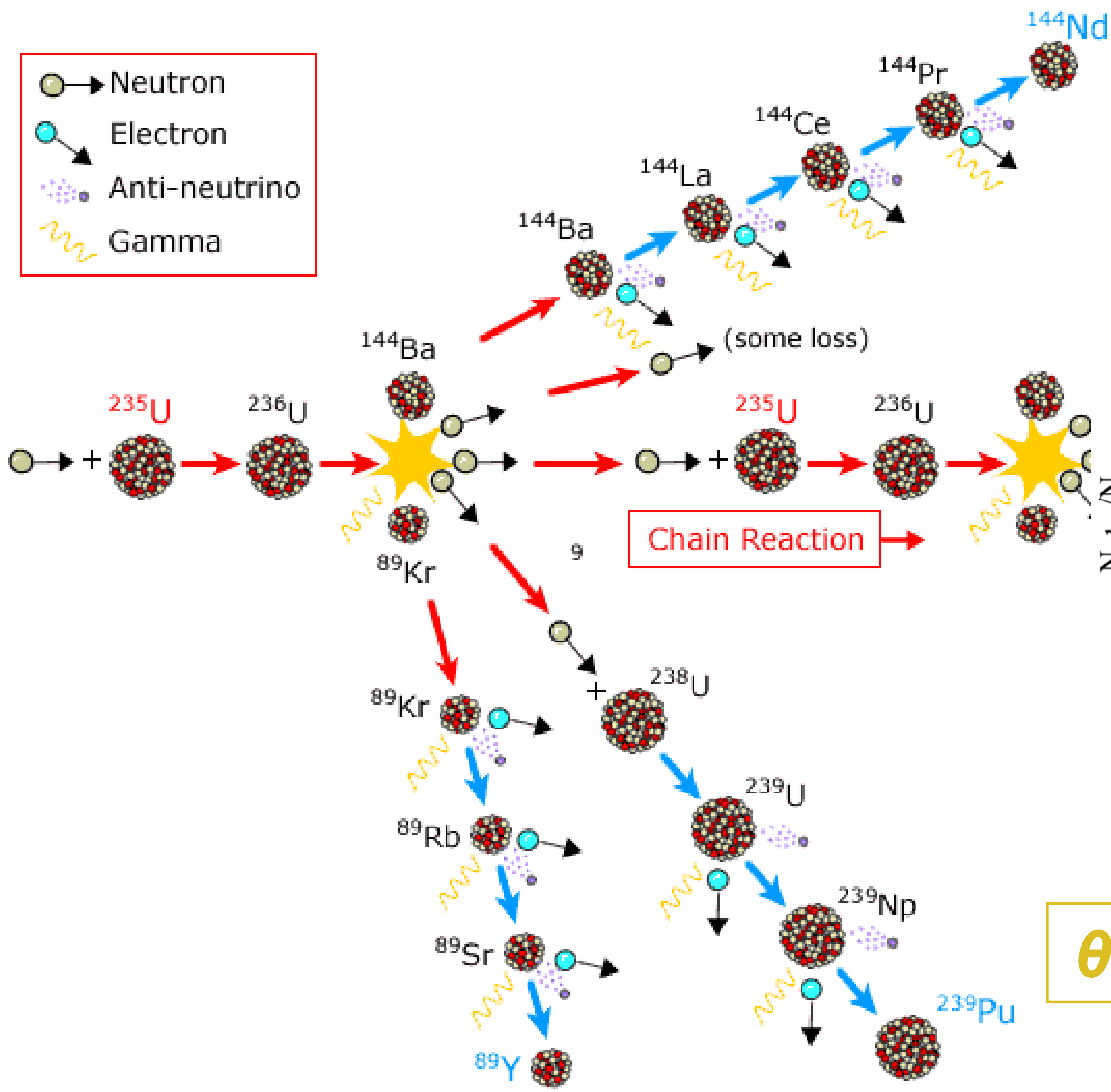




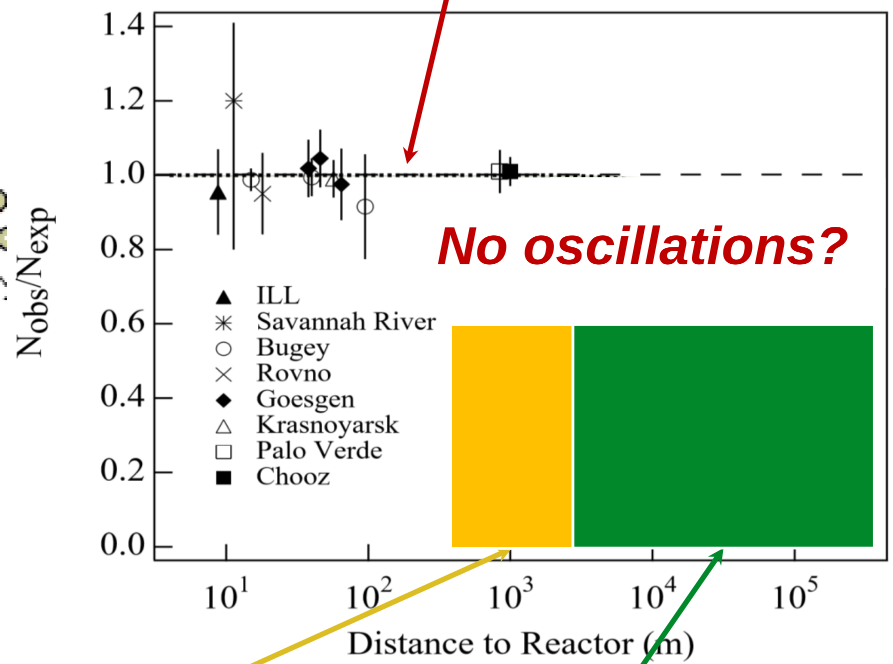
One of the Funders of the SM, Glashow, called for the measurement of θ_{13}

Photo by Kam-Biu Luk

Reactor Neutrinos for Theta13



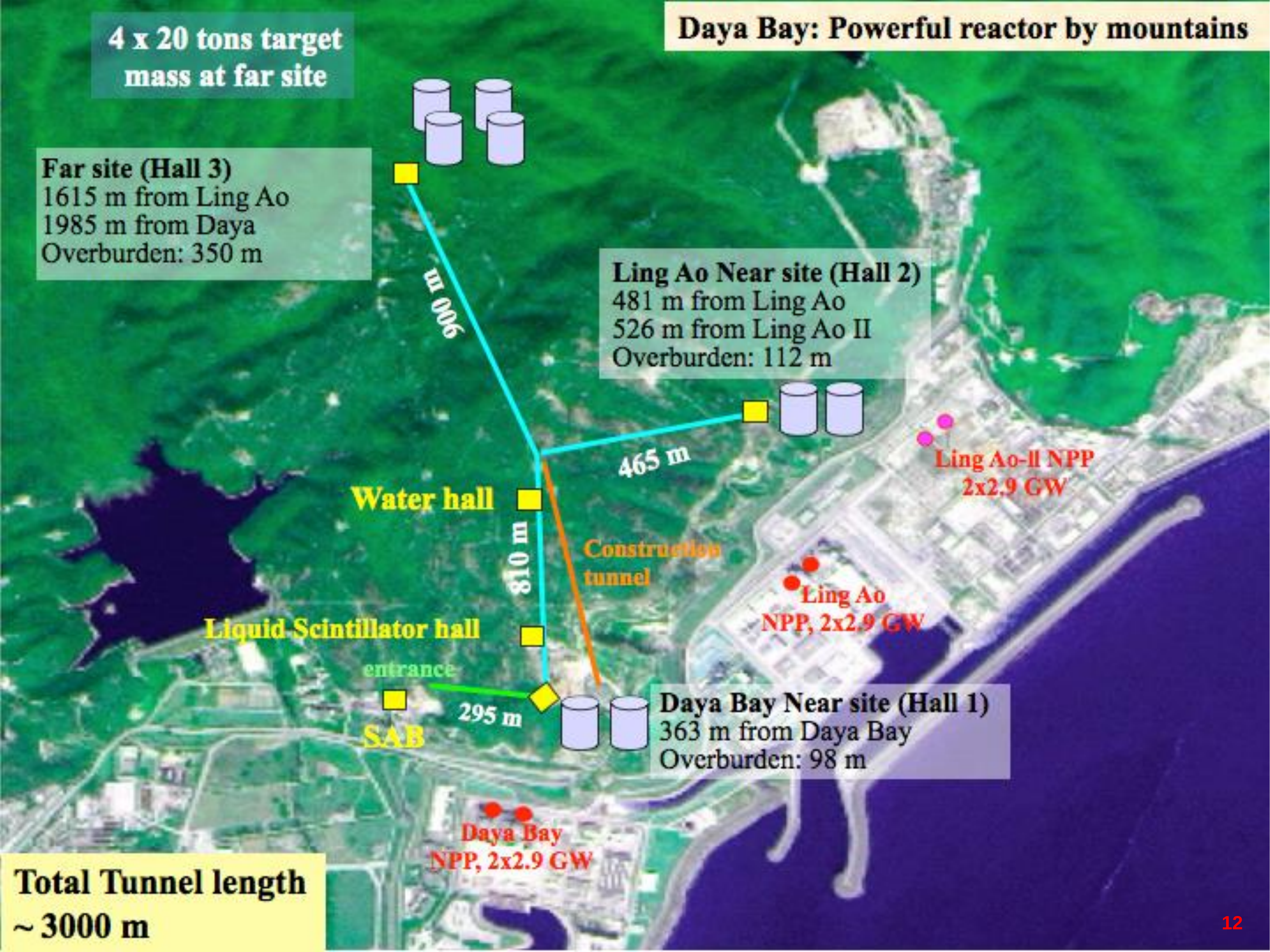
Six antineutrinos/fission: ~2-8MeV, ~5% accuracy



θ_{13} Driven

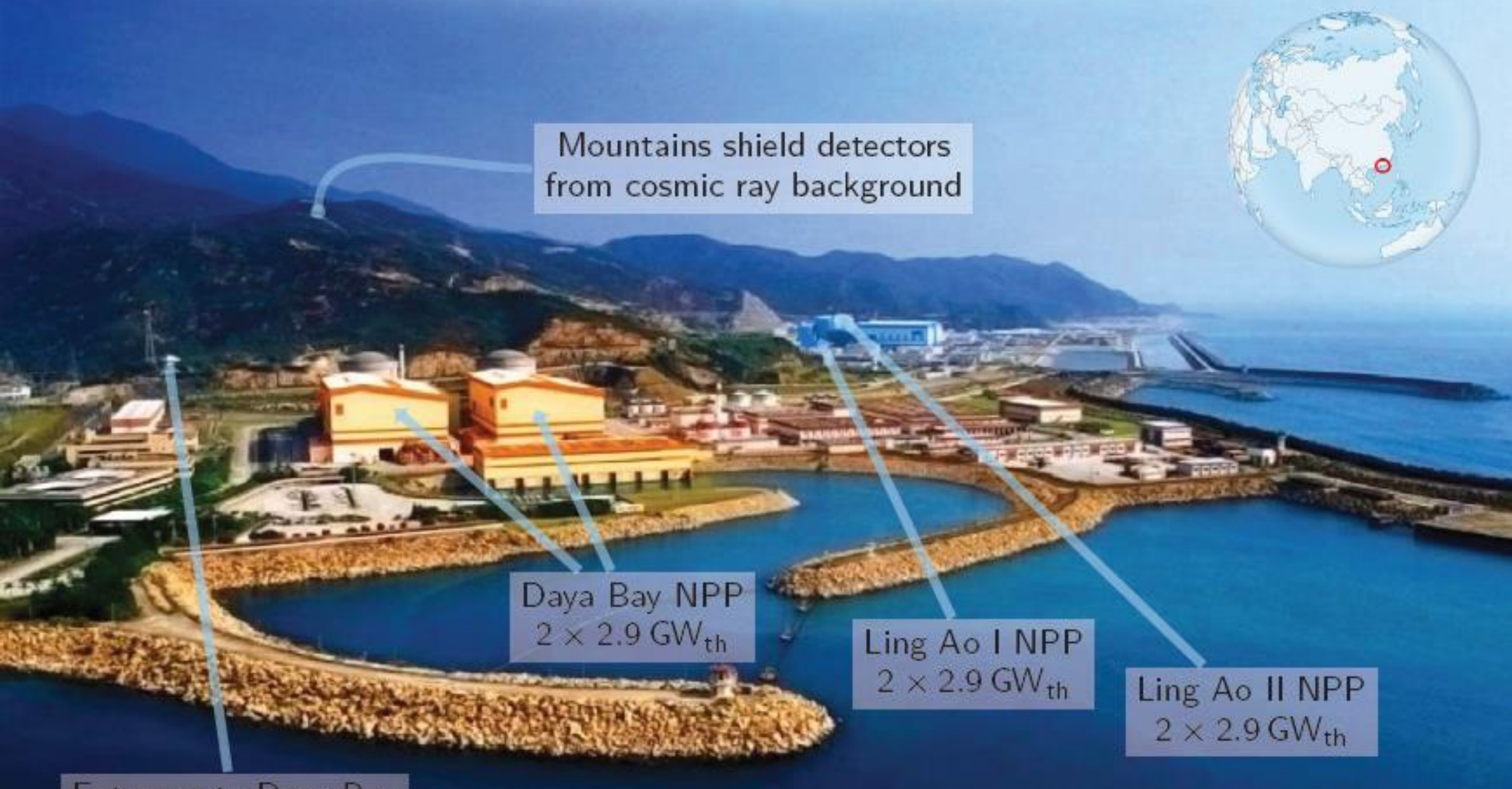
θ_{12} Driven

Daya Bay: Powerful reactor by mountains



Total Tunnel length ~ 3000 m

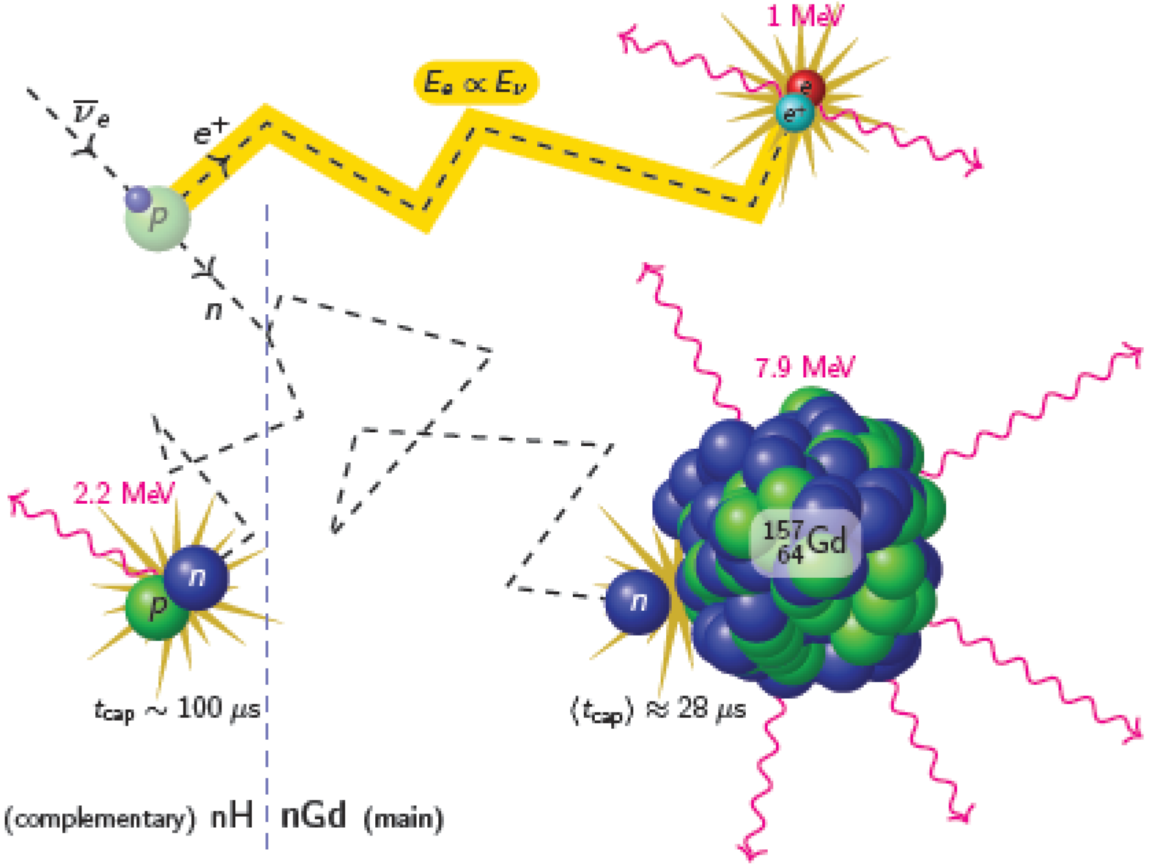
Daya Bay: A Powerful Neutrino Source at an Ideal Location

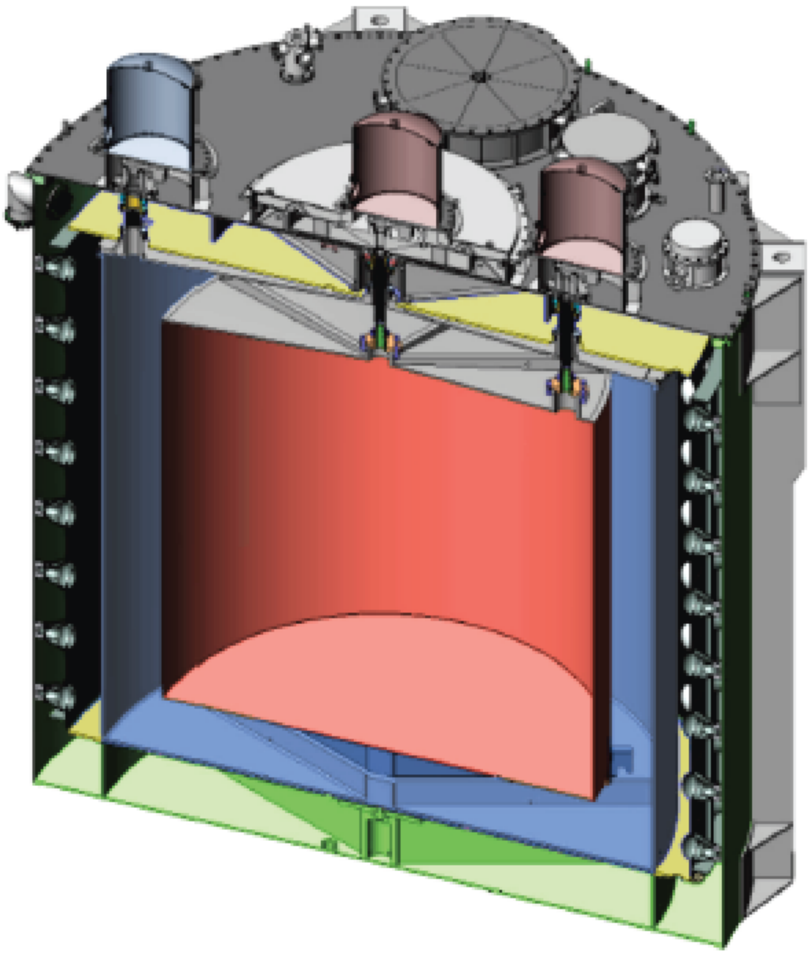


Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW$_{th}$ power, 35×10^{20} neutrinos per second

The Daya Bay Anti-neutrino Detector 2010's

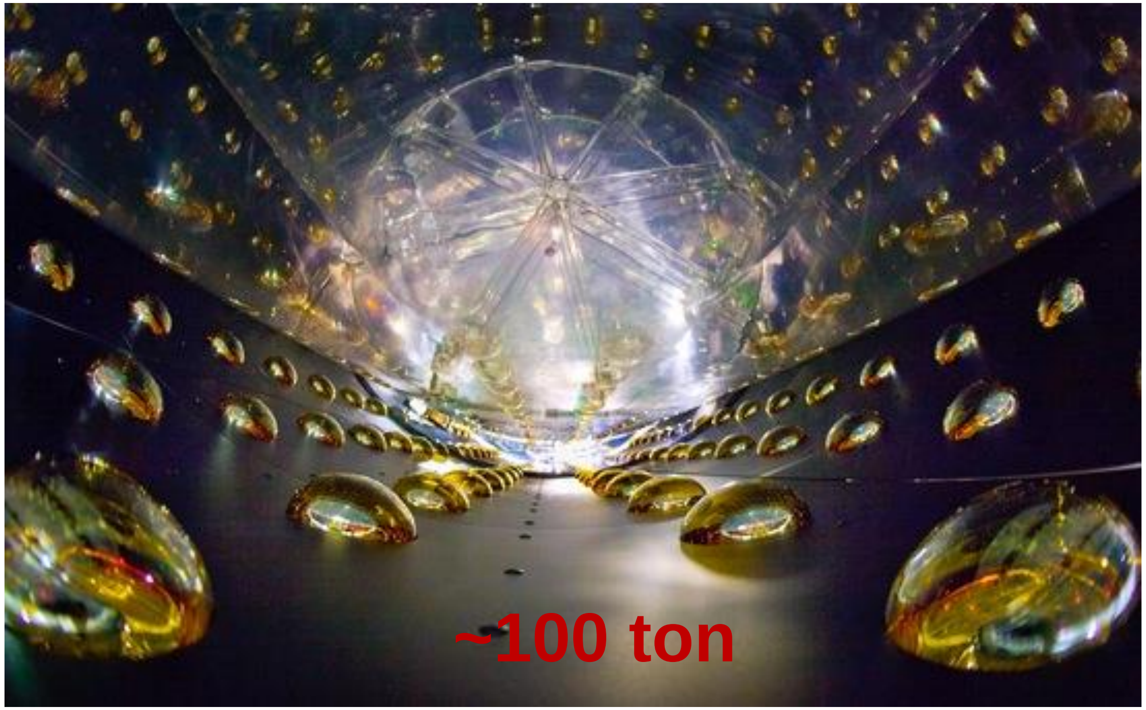
3-zone antineutrino detector (AD):		
Inner zone	20 t	Gd-doped LS
Middle zone	20 t	LS
Outer zone	40 t	Mineral oil



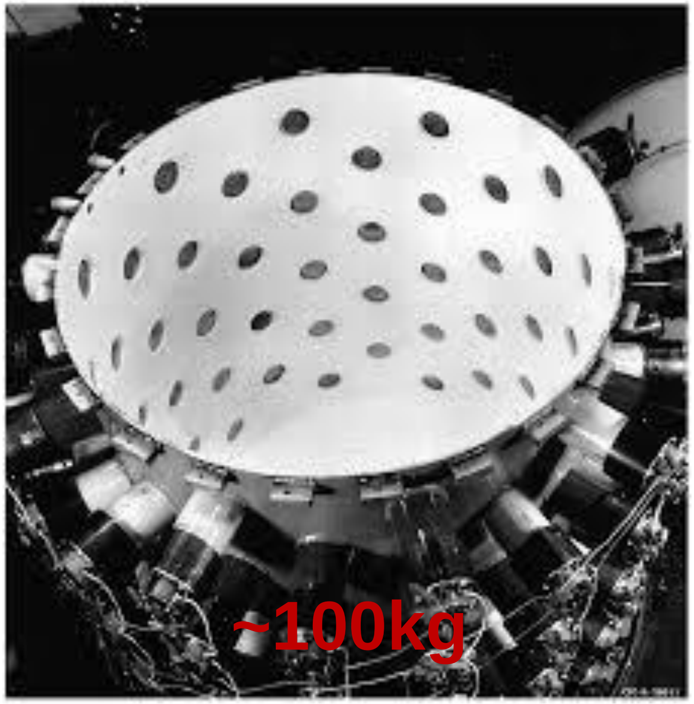


UW-Madison physics and PSL played very important roles in Daya Bay, especially in detector design, construction and operation

The Daya Bay Detector and the Reines&Cowan Design



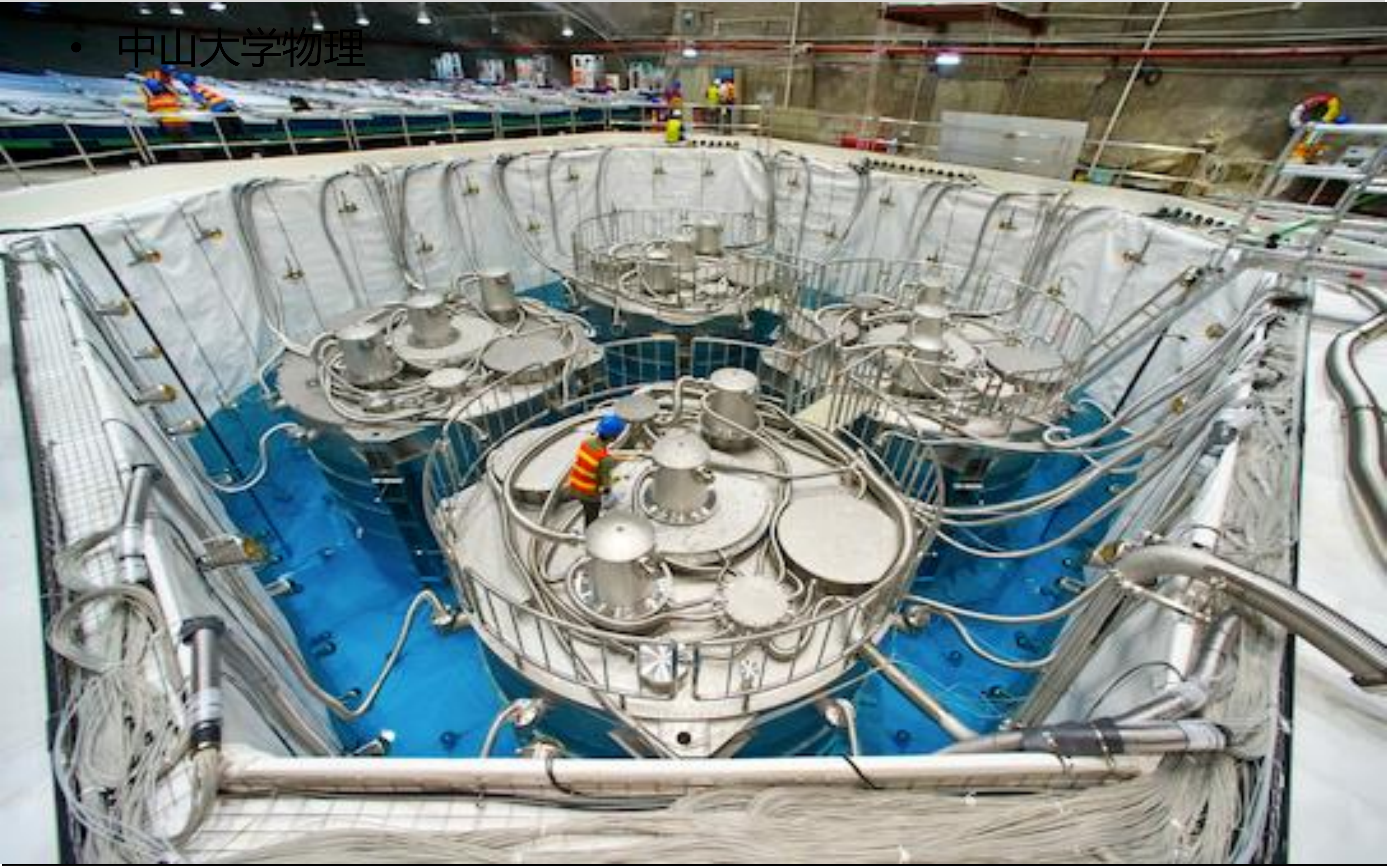
"Standing on the shoulder of giants"



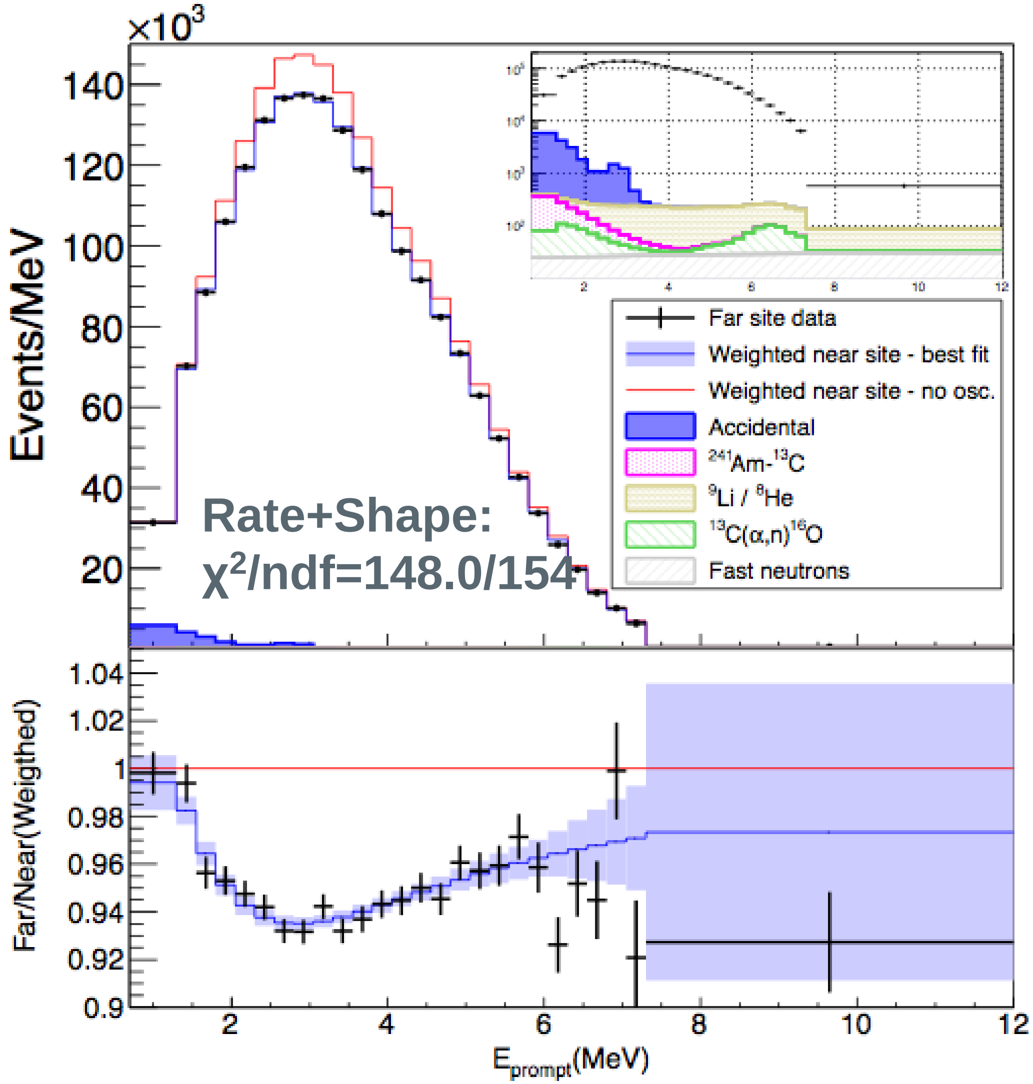
A Small Big Science Project

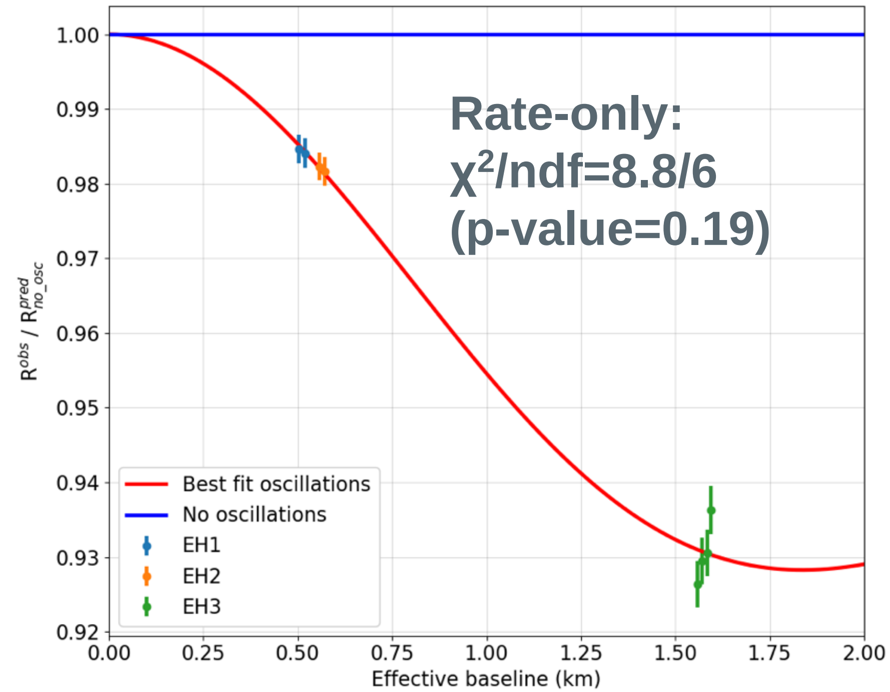
A Small Big Science Project

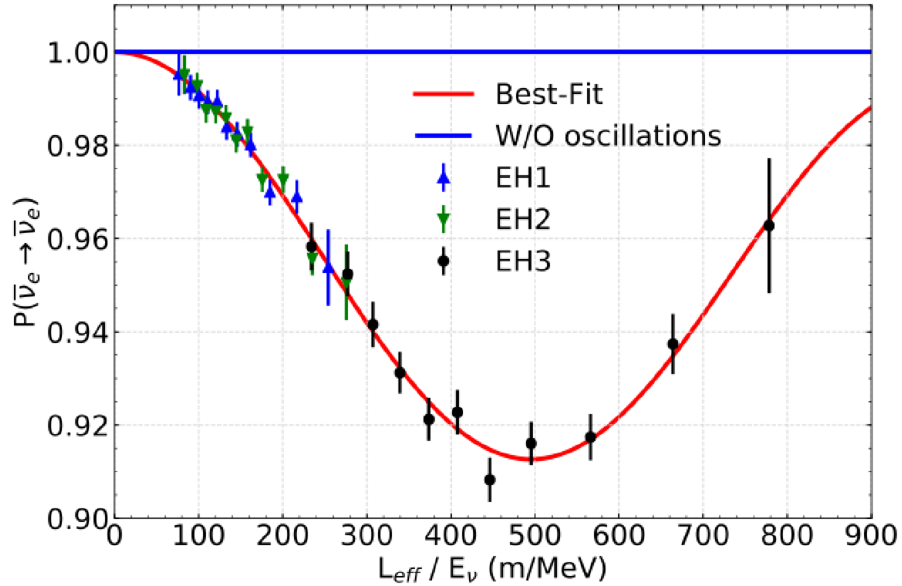
- 中山大学物理



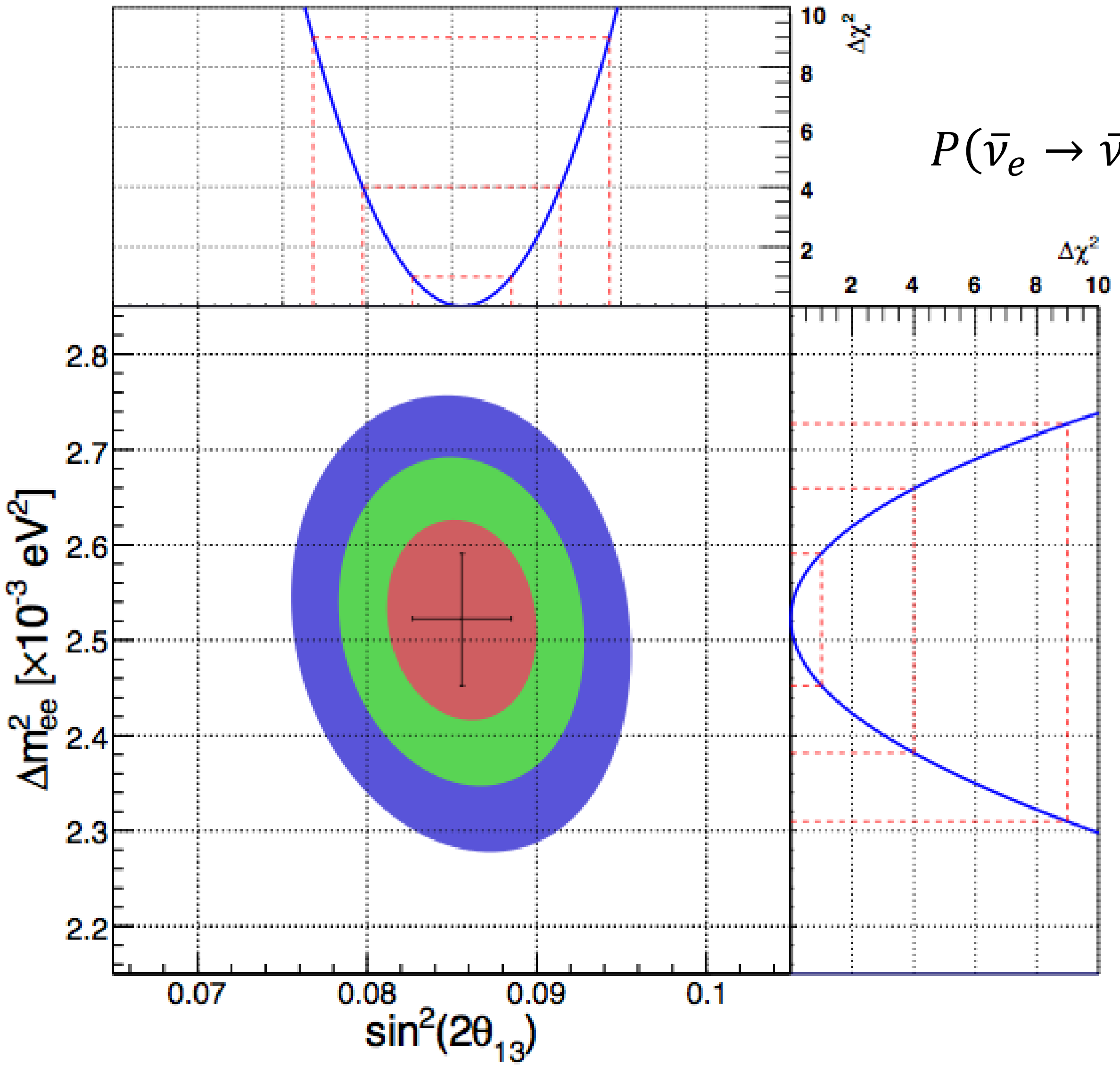
Oscillation Results with 1958 Days







Oscillation Results with 1958 Days



$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E}$$

effective mass splitting

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ eV^2$$

Statistical Uncertainty Portion:

~60% (50%) for θ_{13} (Δm^2_{ee})

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

The Neutrino Decades (1996-2016) Rewarded

LAUREATES

Breakthrough Prize   Special Breakthrough Prize   New Horizons Prize   Physics Frontiers Prize

2016   2015   2014   2013   2012


Kam-Biu Luk and the Daya Bay Collaboration


Yifang Wang and the Daya Bay Collaboration


Koichiro Nishikawa and the K2K and T2K Collaboration


Atsuto Suzuki and the KamLAND Collaboration

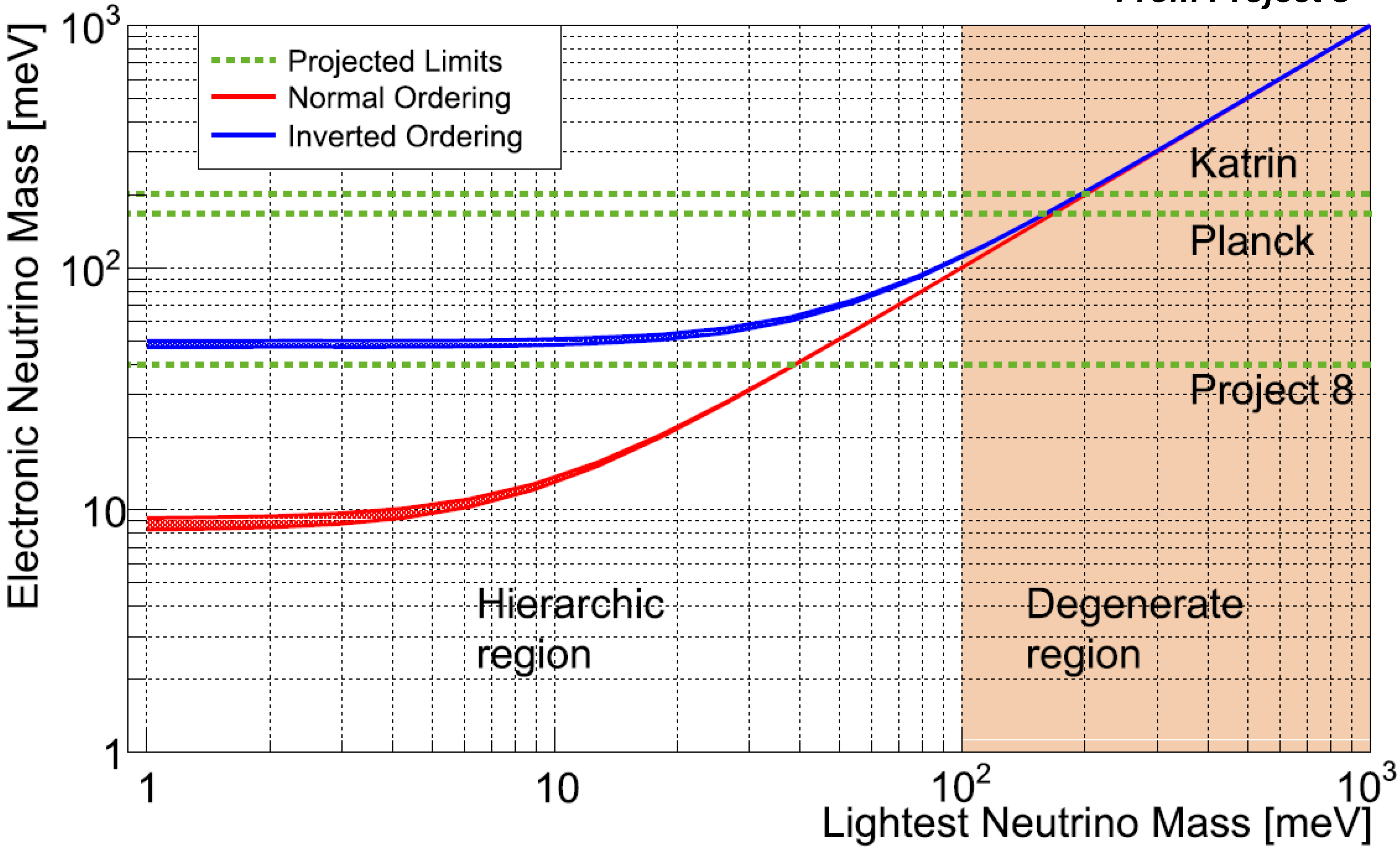

Arthur B. McDonald and the SNO Collaboration


Takaaki Kajita and the Super K Collaboration


Yoichiro Suzuki and the Super K Collaboration

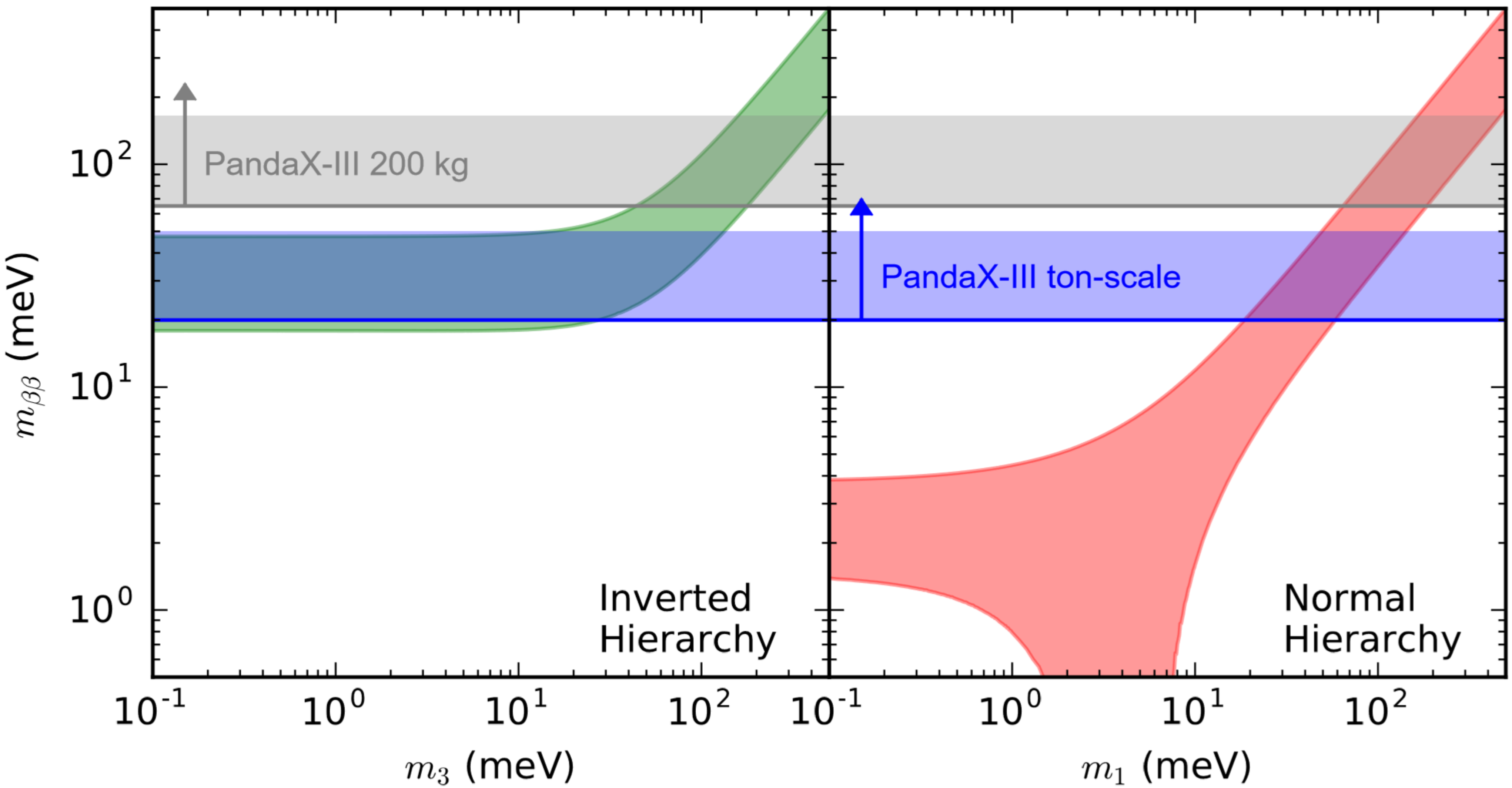
Mass Ordering via Mass Measurements

From Project 8



Mass Ordering via Mass Measurements

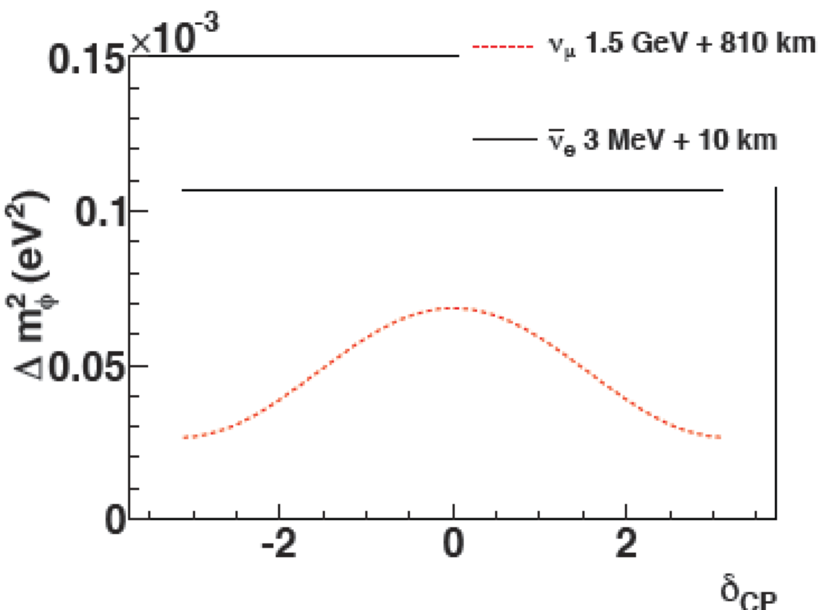
From PandaX-III



e- / μ-Flavor Feels Mass Ordering Differently

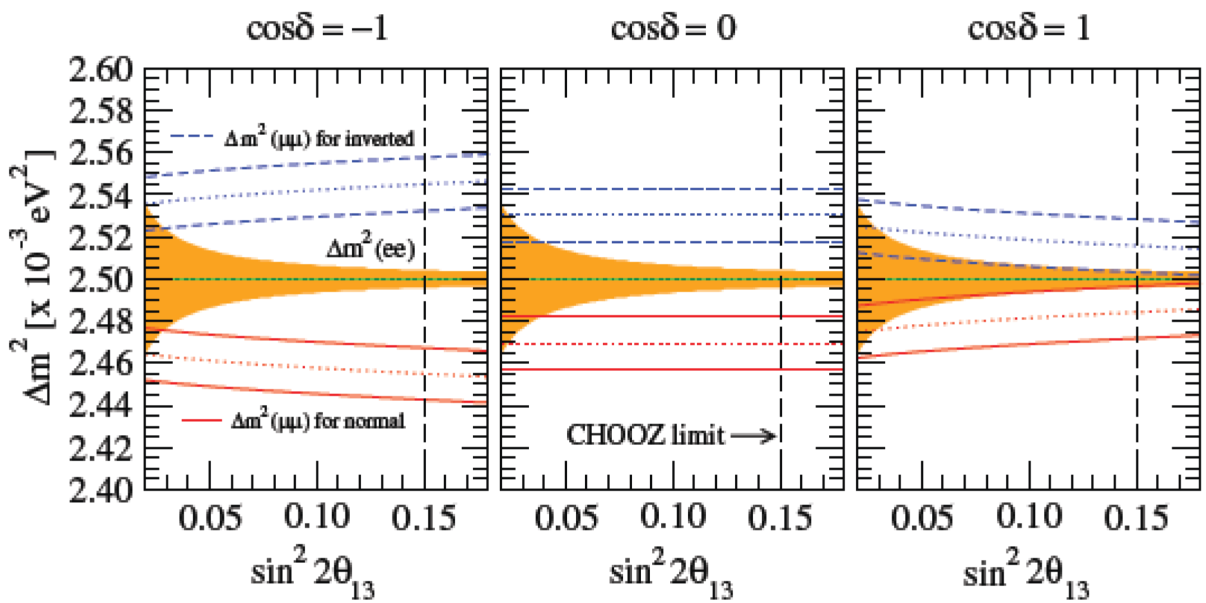
A fair question to ask: Why care $|\Delta m^2_{ee}|$ from reactor experiments?

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



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

Impractical: Need 1% accuracy!

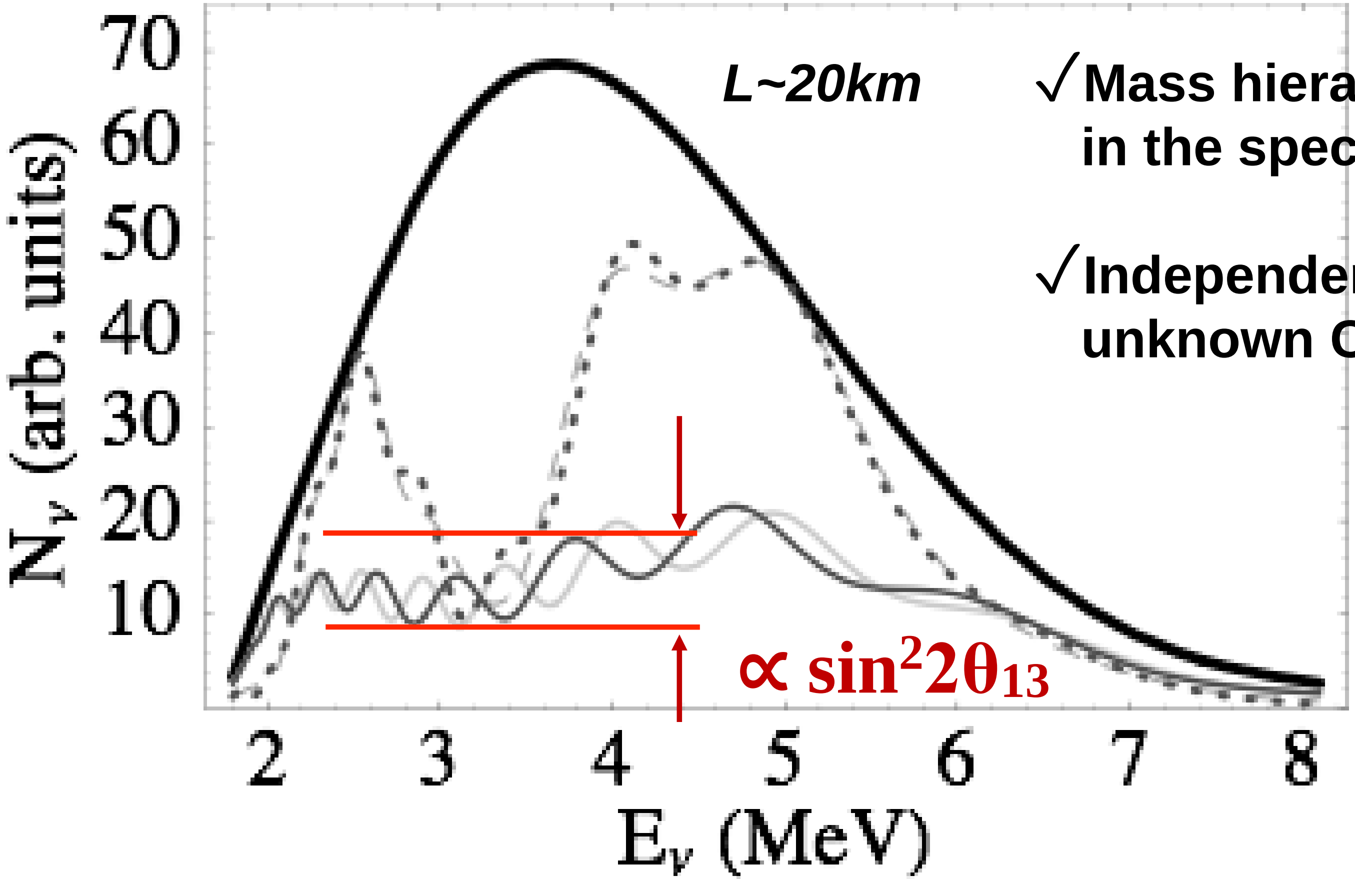
Global Efforts Resolving ν Mass Hierarchy

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

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors

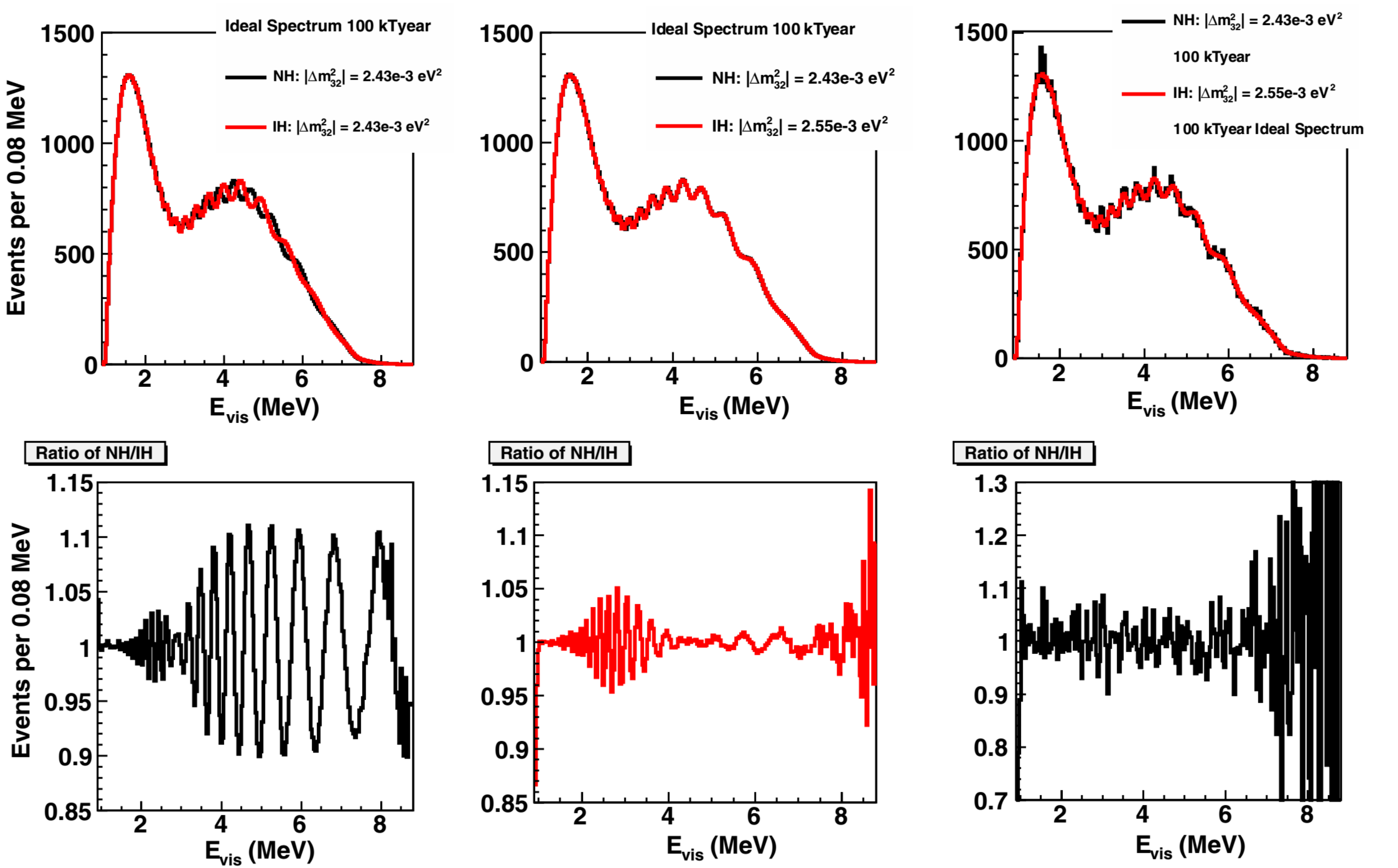
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

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



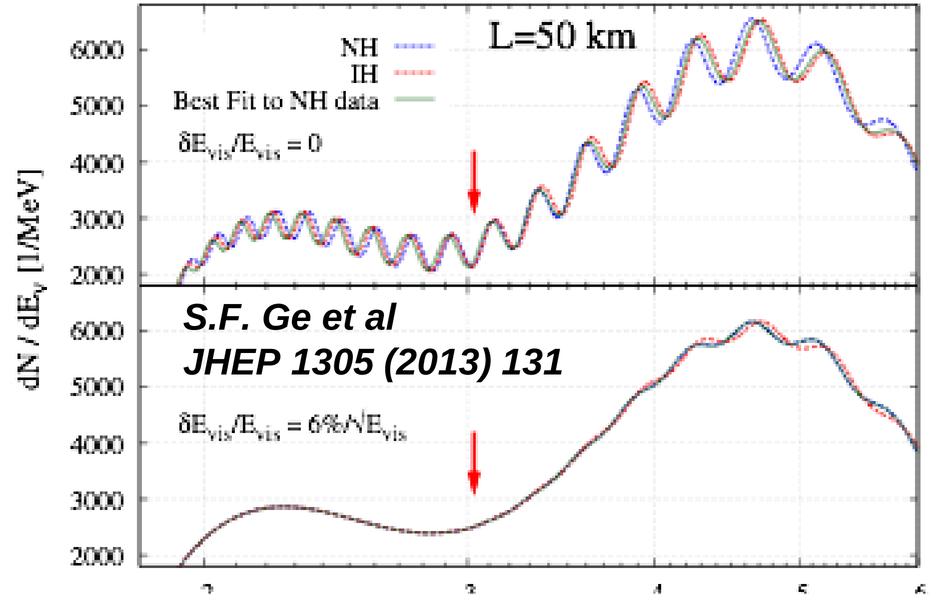
- √ **Mass hierarchy reflected in the spectrum**
- √ **Independent of the unknown CP phase**

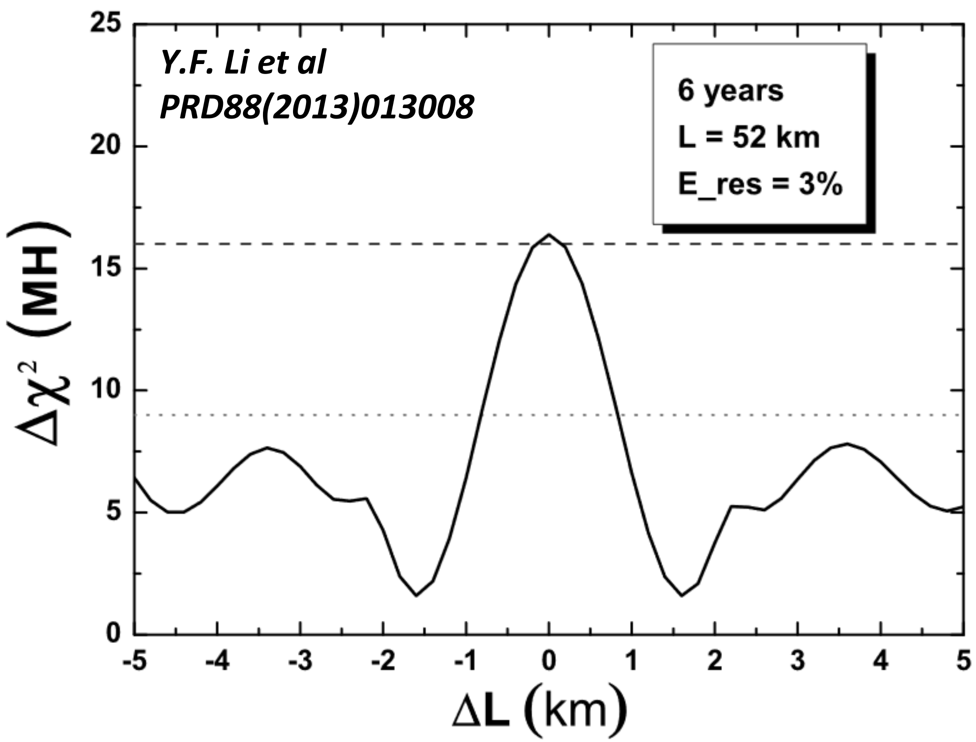
Challenges in Resolving MH using Reactor Sources

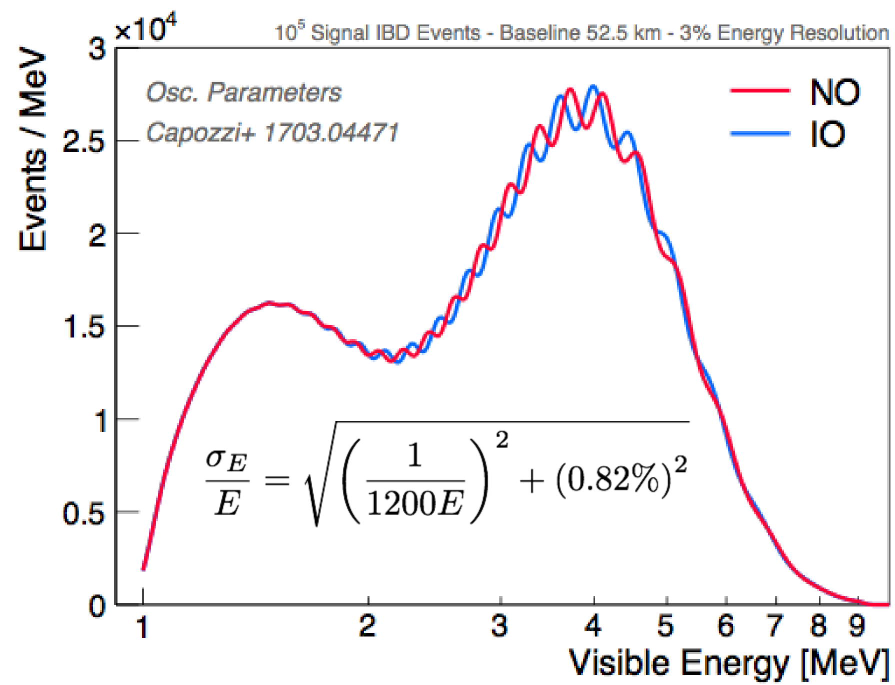


Challenges in Resolving MH using Reactors

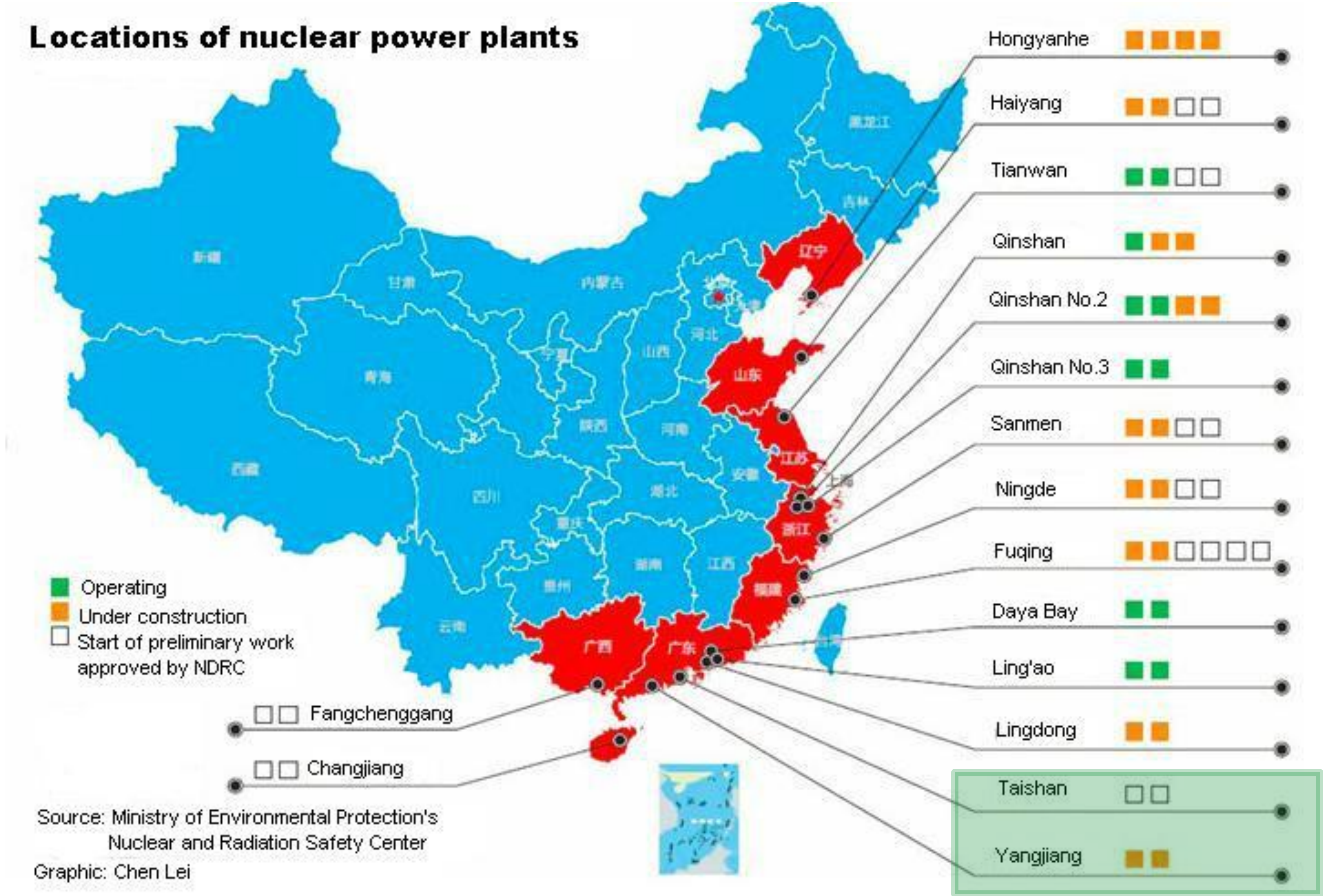
- Energy resolution: ~3%/sqrt(E)
- Energy scale uncertainty: <1%
- Statistics (the more the better)
- Reactor distribution: <~0.5km







Looking for Suitable Power Plants is Easy?

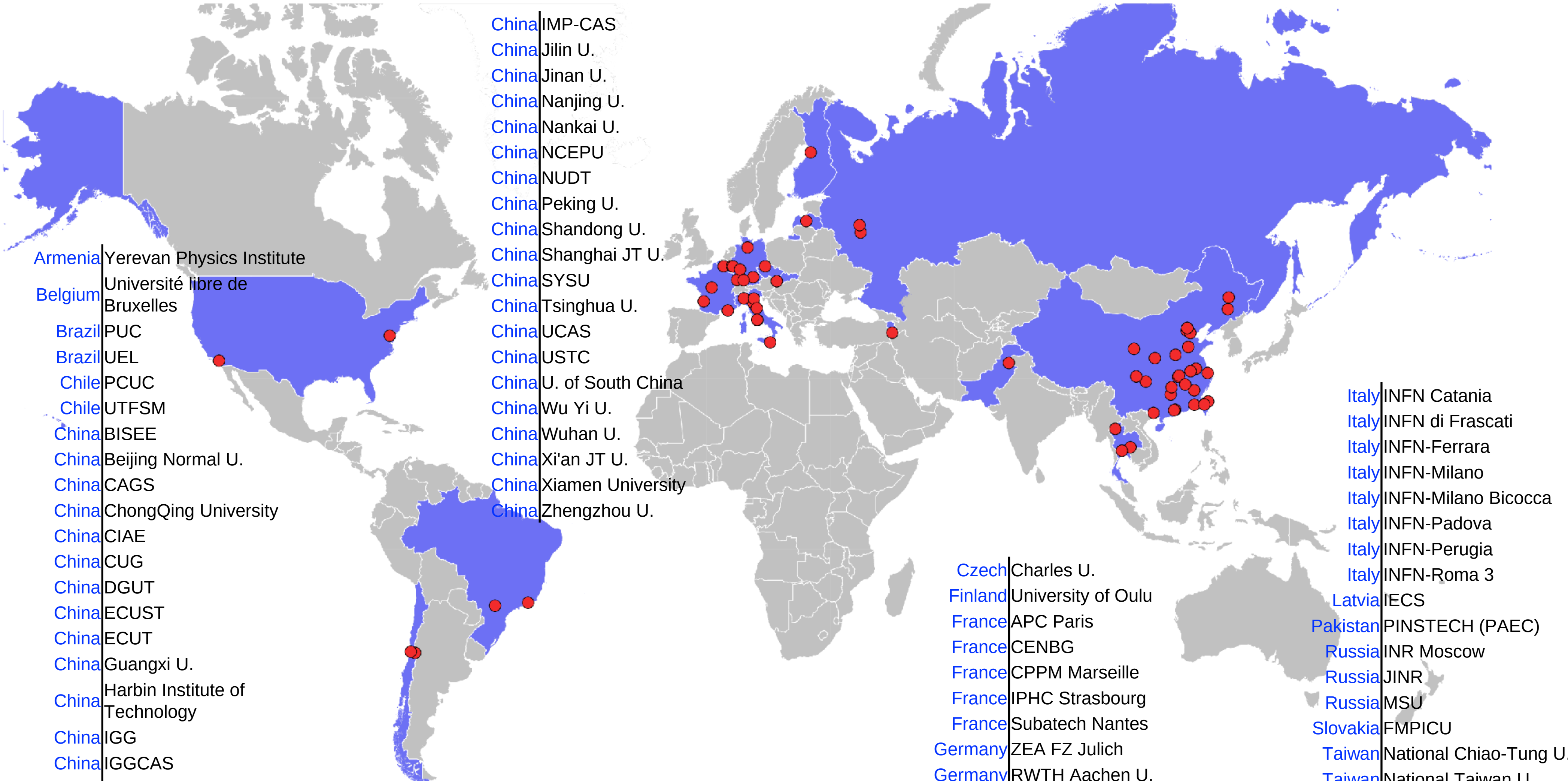


The Jiangmen Underground Neutrino Observatory

JUNO collaboration

Collaboration established on July 2014

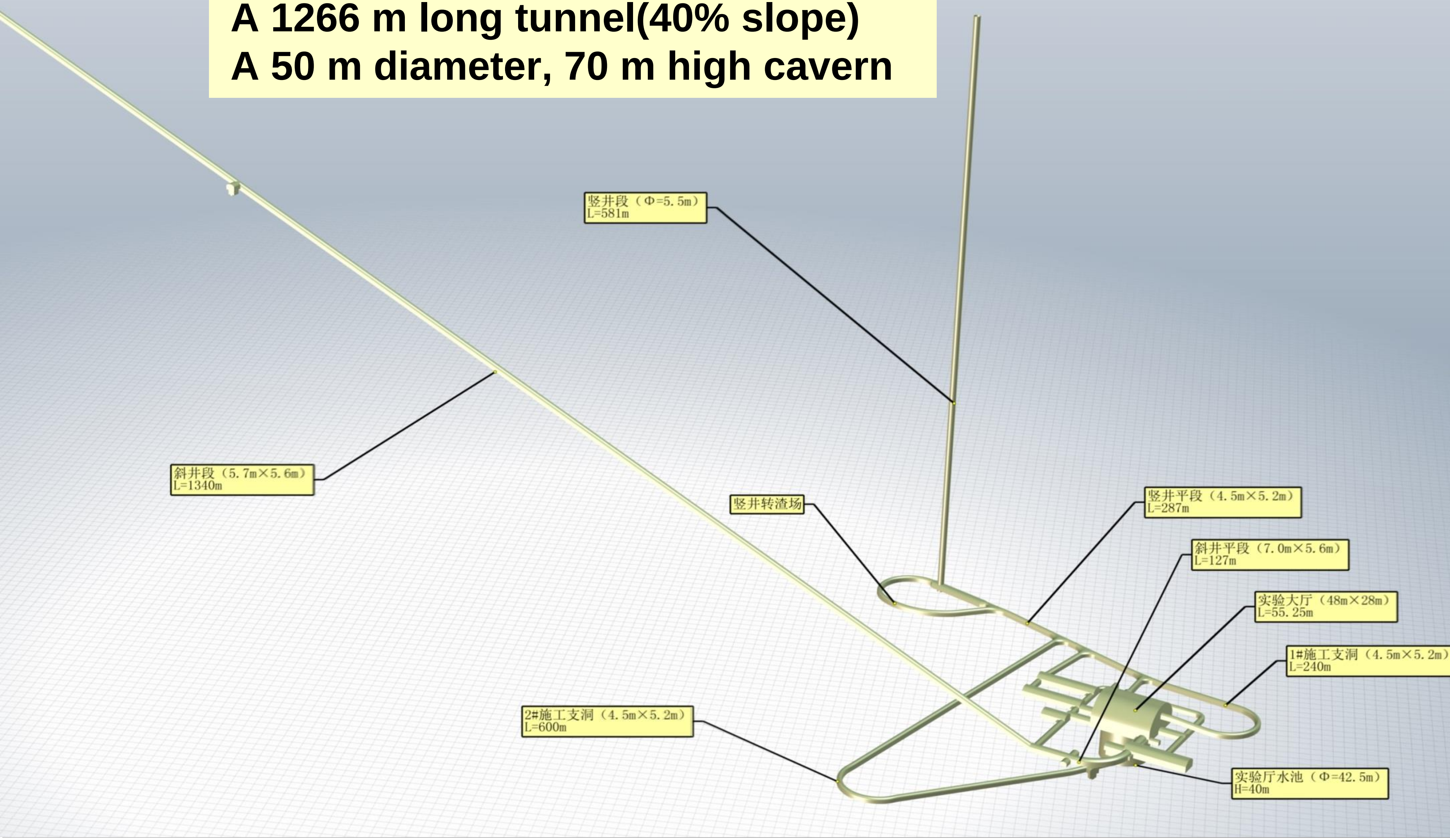
Now 77 institutions ~600 collaborators



Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of Technology
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	NUDT
China	Peking U.
China	Shandong U.
China	Shanghai JT U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	Zhengzhou U.
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CENBG
France	CPPM Marseille
France	IPHC Strasbourg
France	Subatech Nantes
Germany	ZEA FZ Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZ Jülich
Germany	U. Mainz
Germany	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

Underground Tunnel and Hall

A 564 m vertical shaft
A 1266 m long tunnel(40% slope)
A 50 m diameter, 70 m high cavern



The JUNO Detector System Details

Calibration

Top Tracker

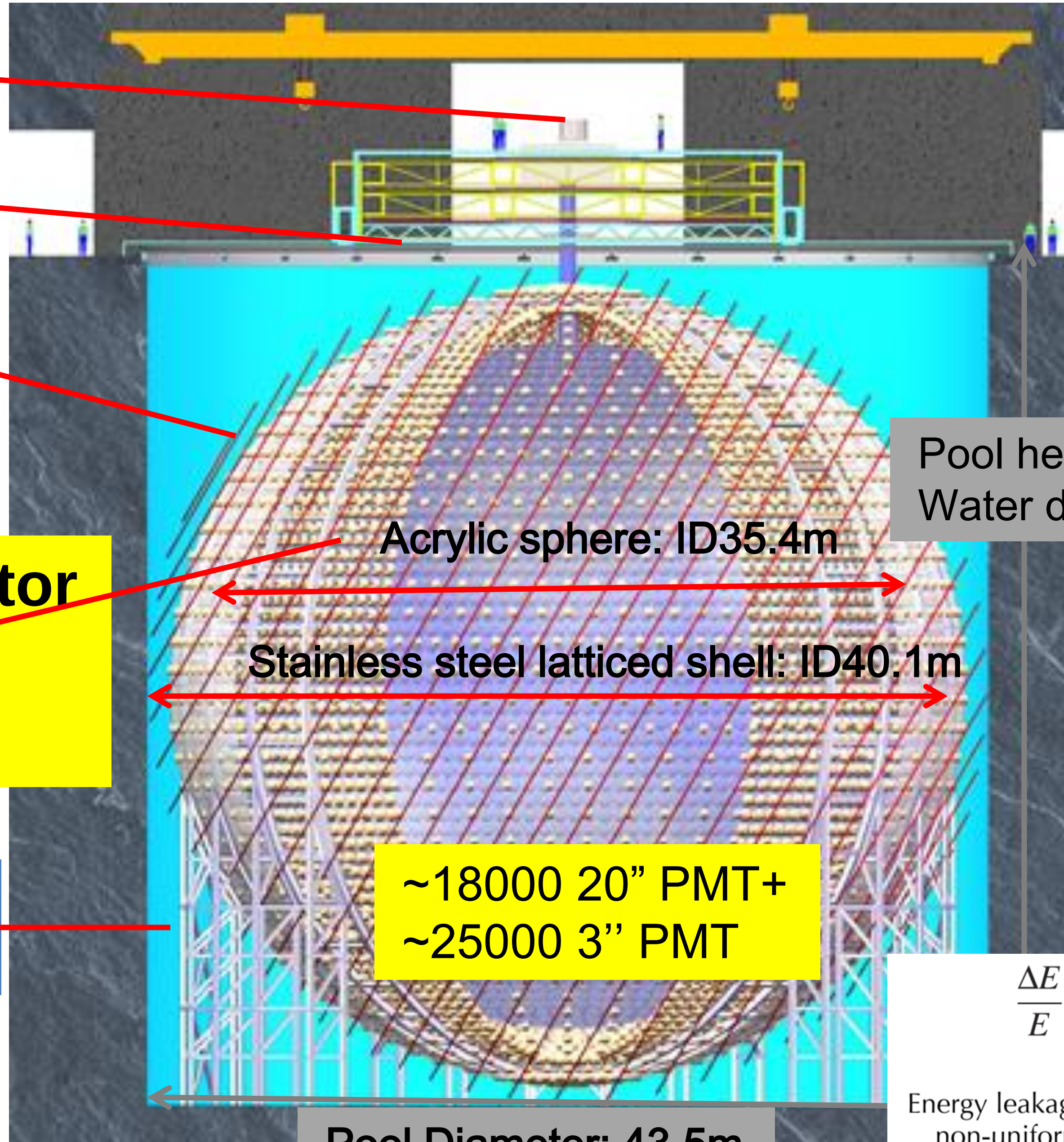
Earth Magnetic Field compensation coils

Central Detector
Steel Structure +
Acrylic sphere +
20kt Liquid Scin

Water Cherenkov
~2400 20'' PMT

LS/Water Filling room

Pool height 44m
Water depth 43.5m



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

Energy leakage & non-uniformity | Photon statistics | Noise (~background)

The Detector Performance Goals

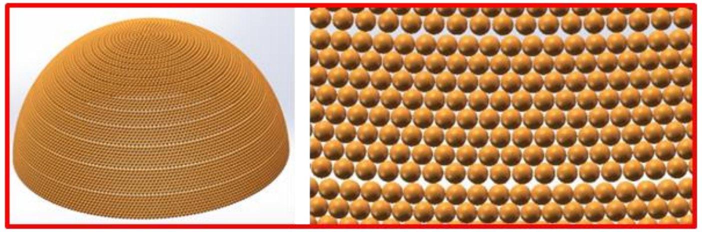
	KamLAND	Daya Bay	PROSPECT	JUNO
Target Mass	**~1kt**	20t	~4t	**~20kt**
Photocathode Coverage	~34%	~12% (Effective)	ESR + PMTs	**~80%**
PE Collection	~250 PE/MeV	~160 PE/MeV	**~850 PE/MeV**	**~1200 PE/MeV**
Energy Resolution	~6%/√E	~7.5%/√E	**~4.5%/√E**	**3%/√E**
Energy Calibration	~2%	**1.5%→ 0.5%**	?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

→ **An extremely demanding detector and a challenging job**

Packing PMTs as Tight as Possible

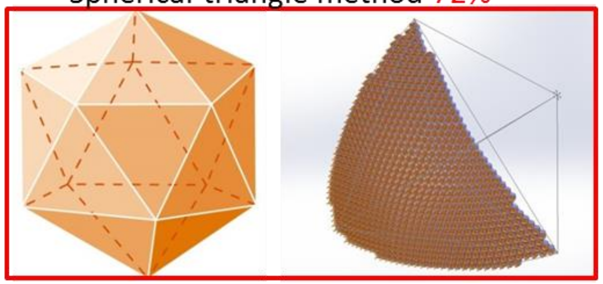
Supper layer arrangement method 77.8%

✓



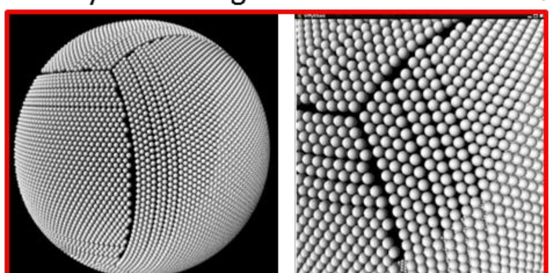
Spherical triangle method 72%

2



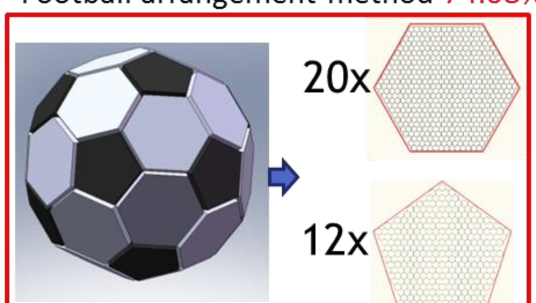
Volleyball arrangement method 75.96%

3



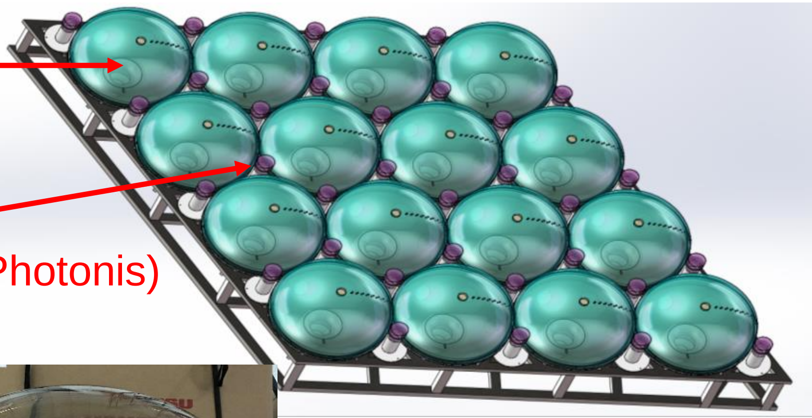
Football arrangement method 74.08%

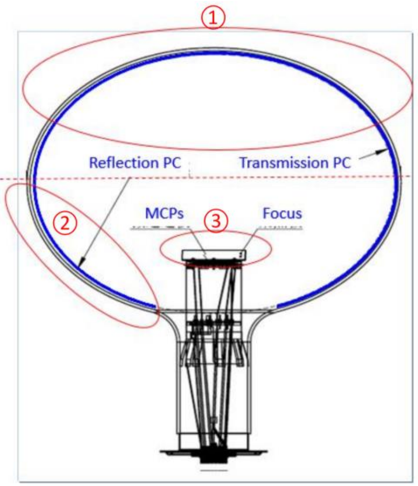
4

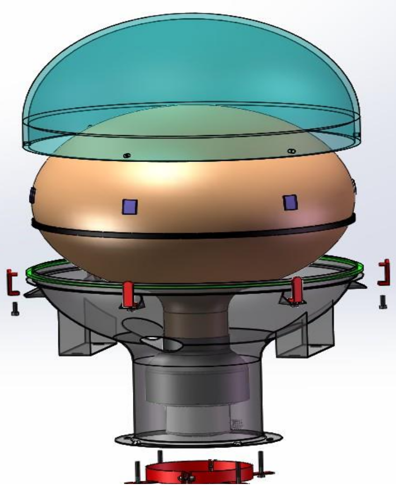


20” PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

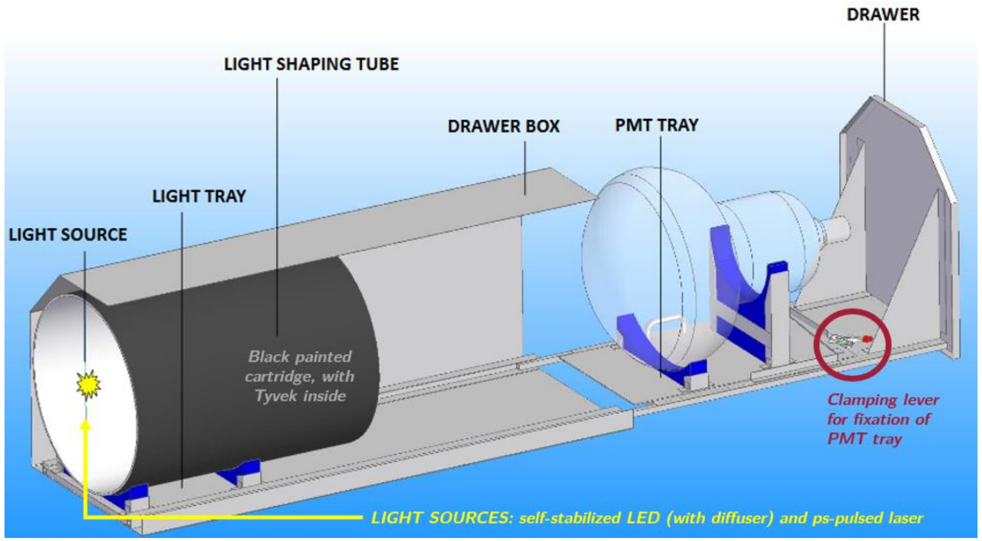
3”sPMT(~25K)
HZC XP72B22 (Photonis)

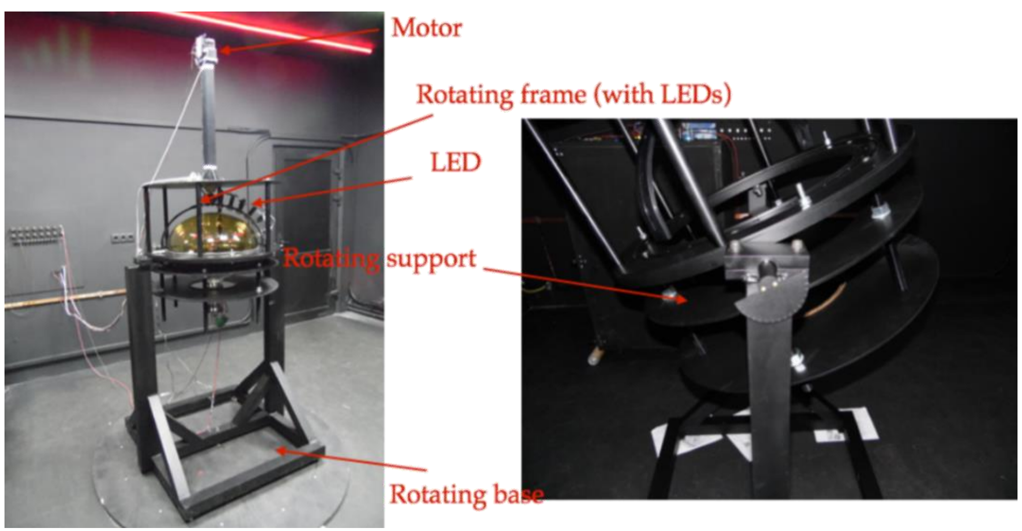


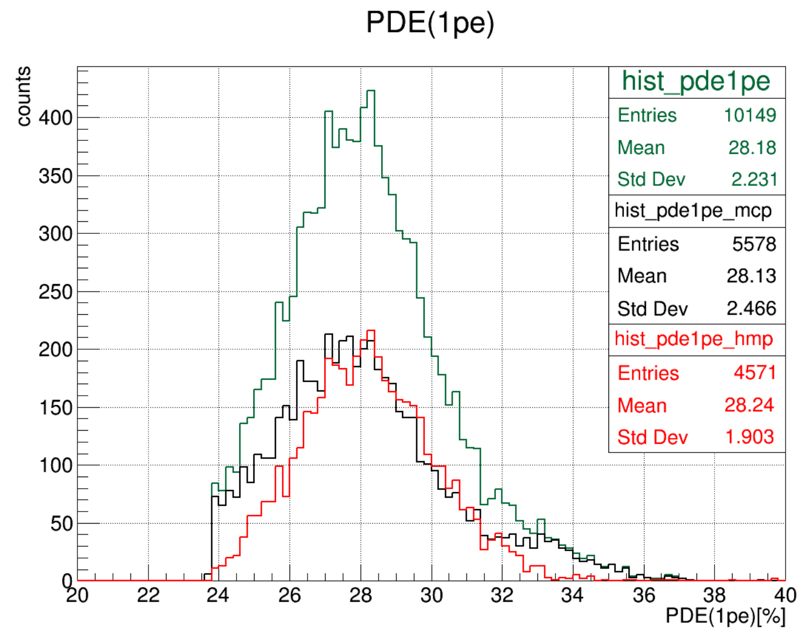


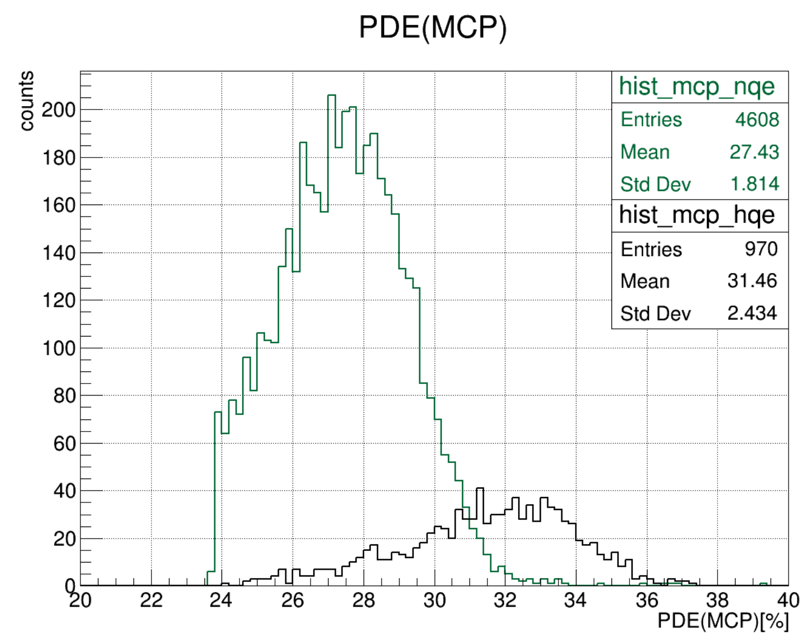


Characterizing Every Single PMT with Great Care



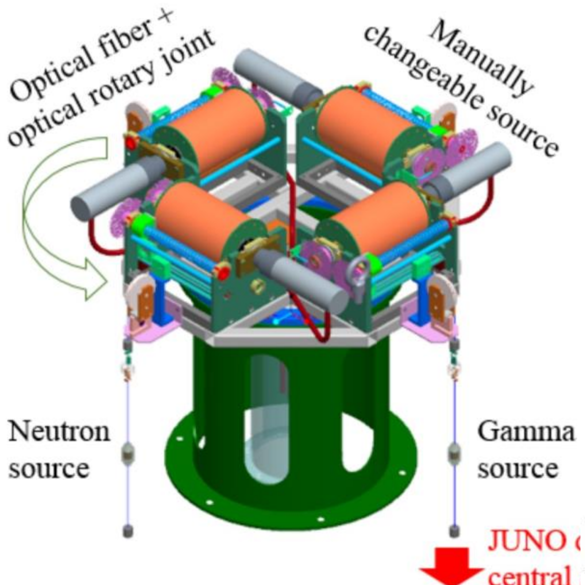




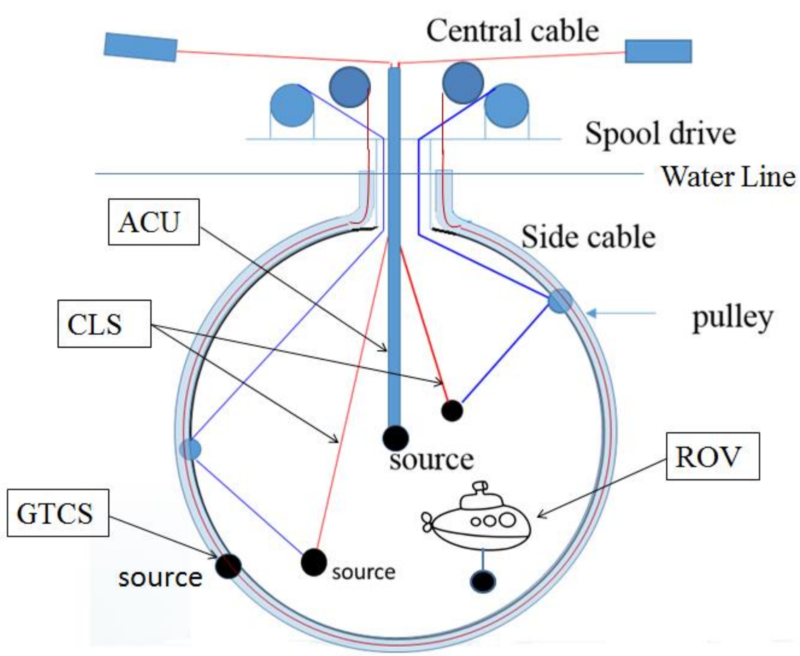


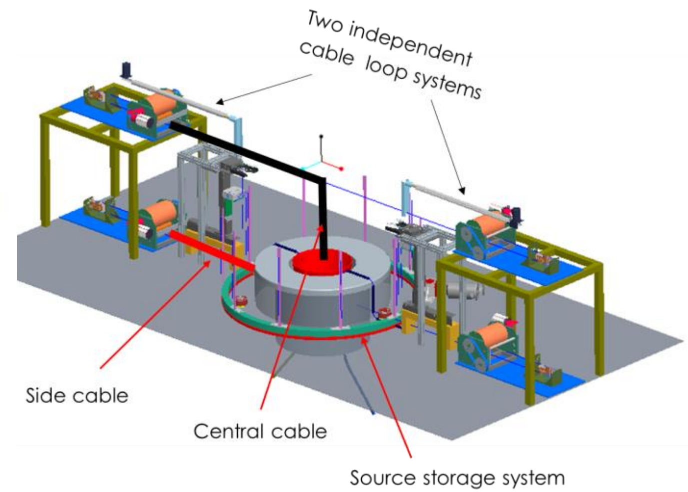
Calibration System *based on the Daya Bay experiences*

Automatic Calibration Unit (ACU)

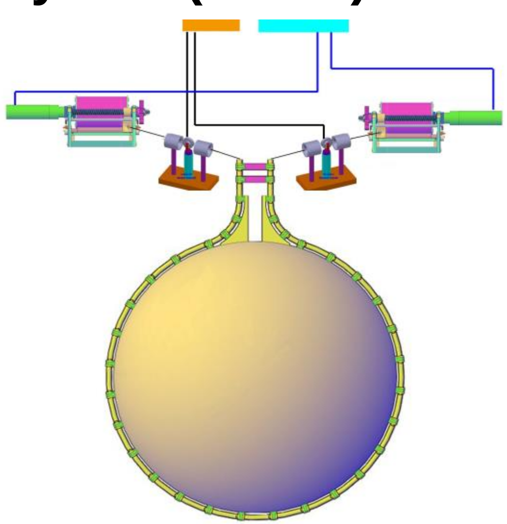


Cable Loop System (CLS)

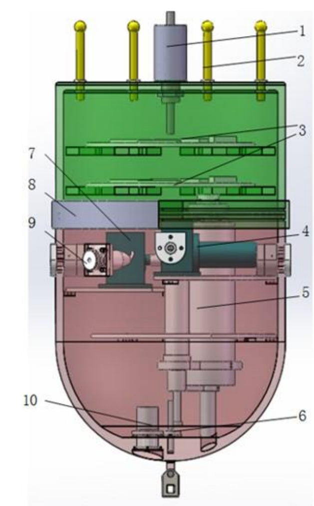




Guide Tube Calibration System(GTCS)

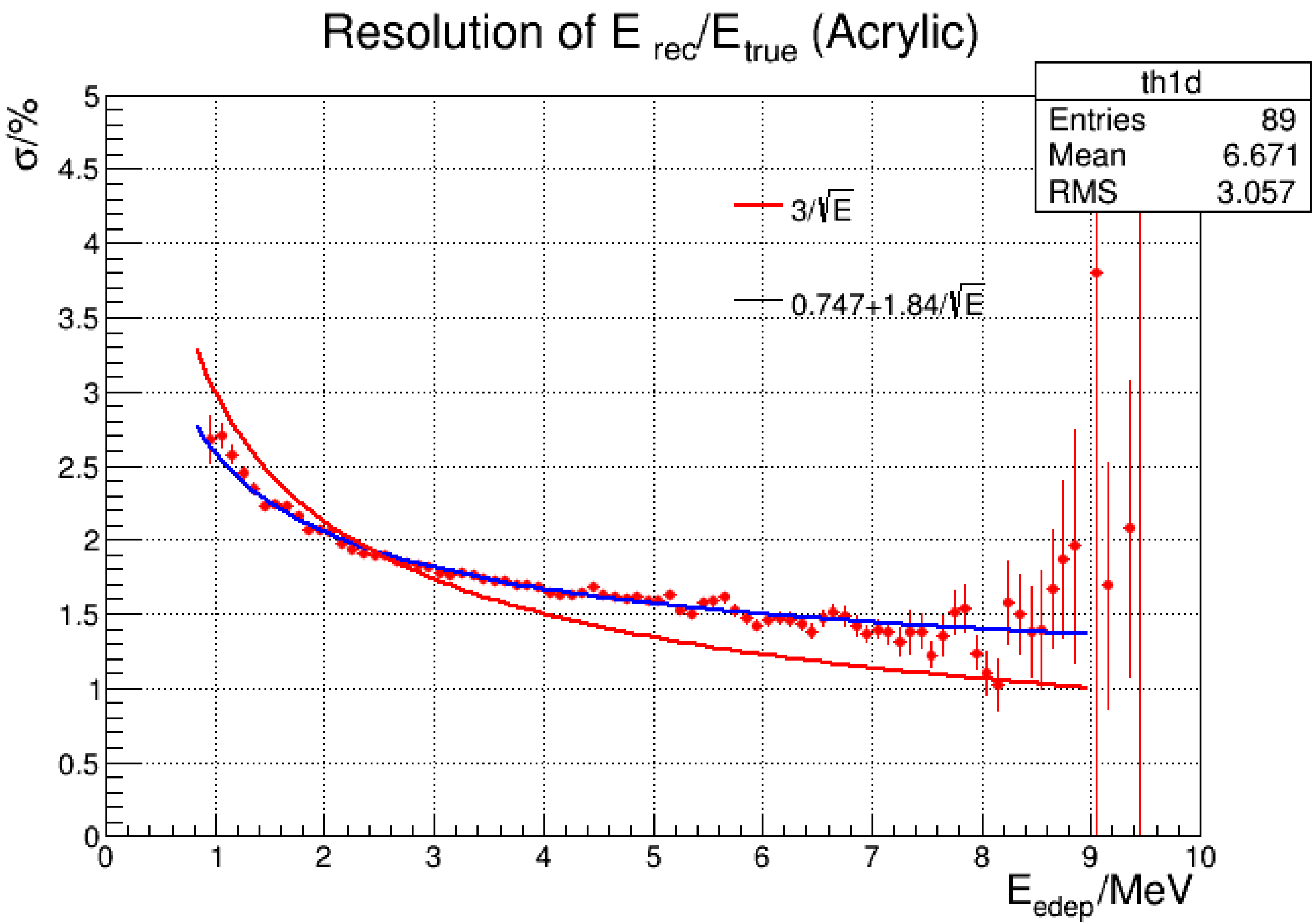


Remotely Operated under-liquid-scintillator Vehicles (ROV)

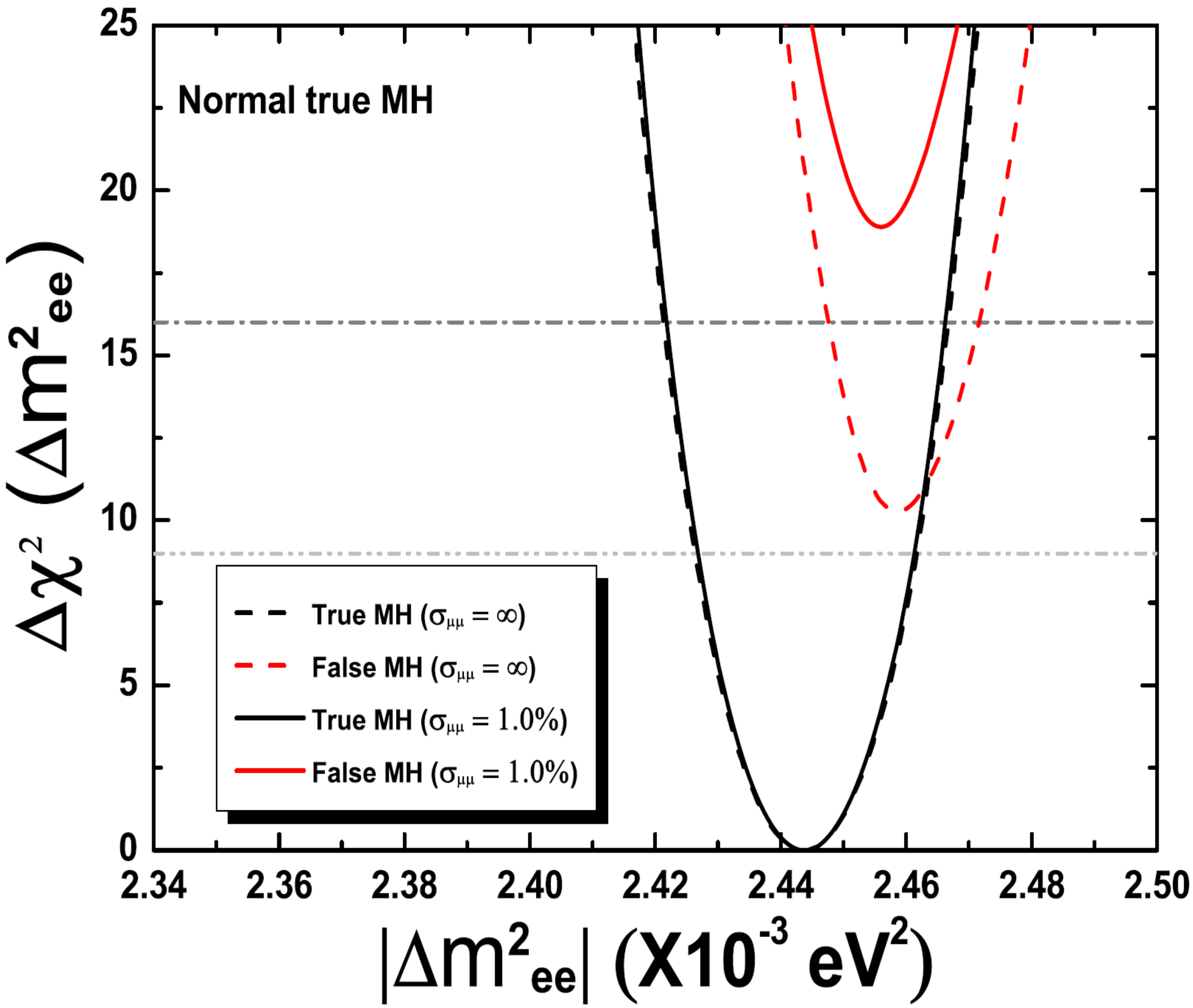


- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

Putting Everything Together (Simulation)



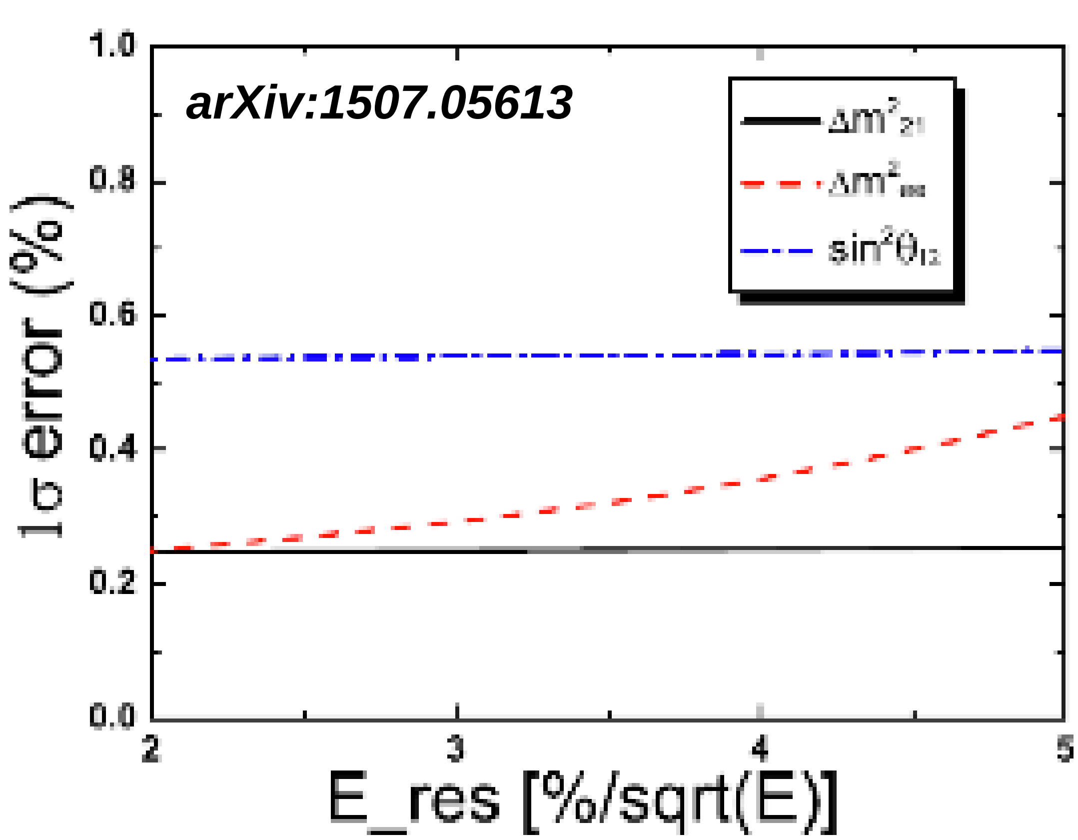
Expected Significance to Mass Hierarchy

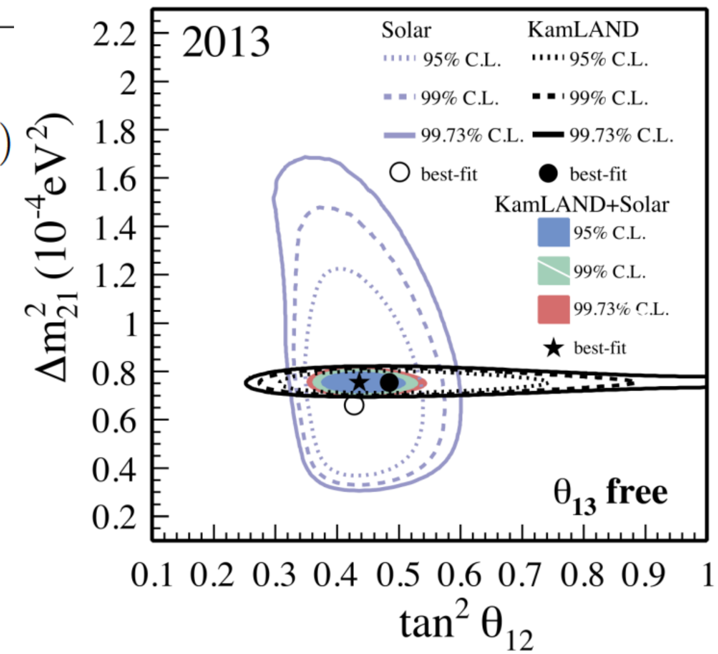


JUNO Precision Measurements Warranted

PDG 2017

Parameter	best-fit		3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	**~2.3%**	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	**~1.6%**	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	**~5.8%**	0.250 – 0.354





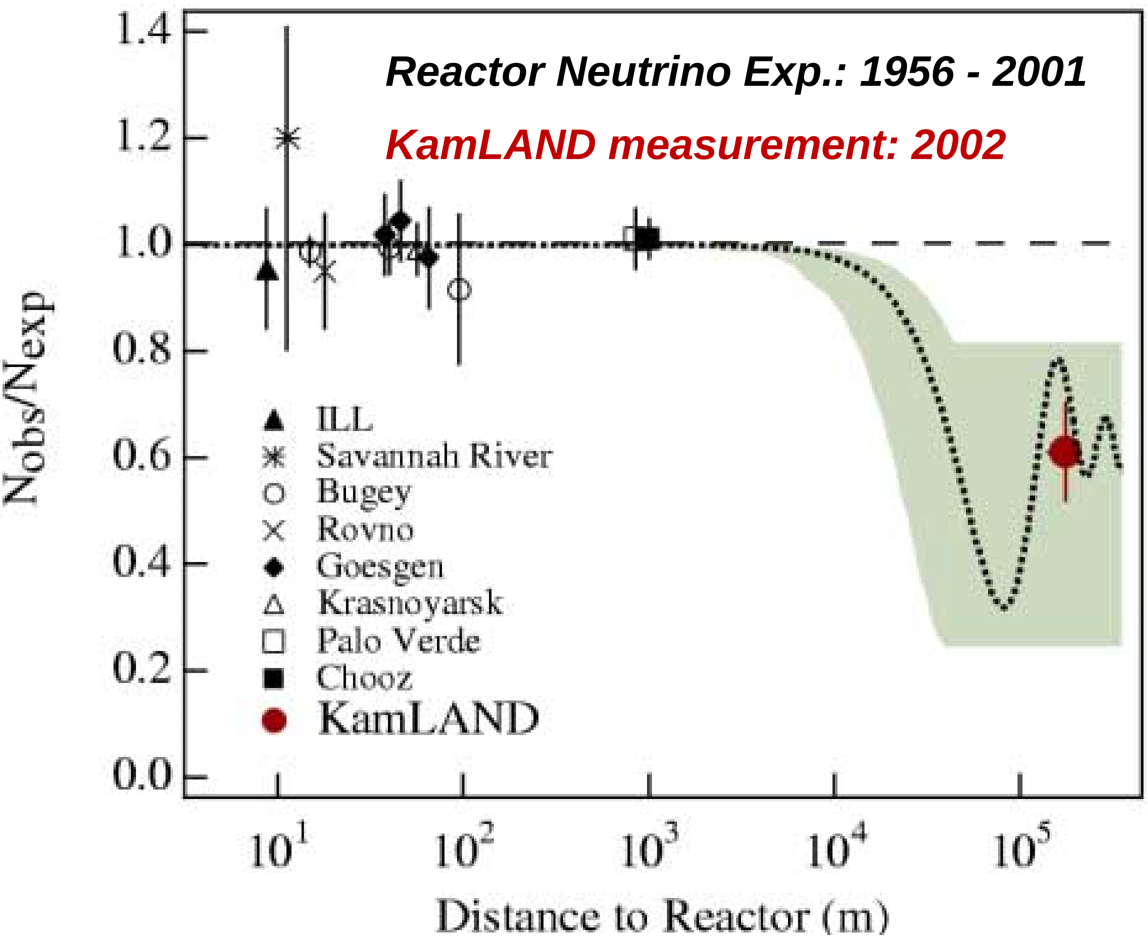
- **Precision <1% measurements are warranted in a experiment like JUNO**
  - **Enable a future ~1% level PMNS unitarity test**

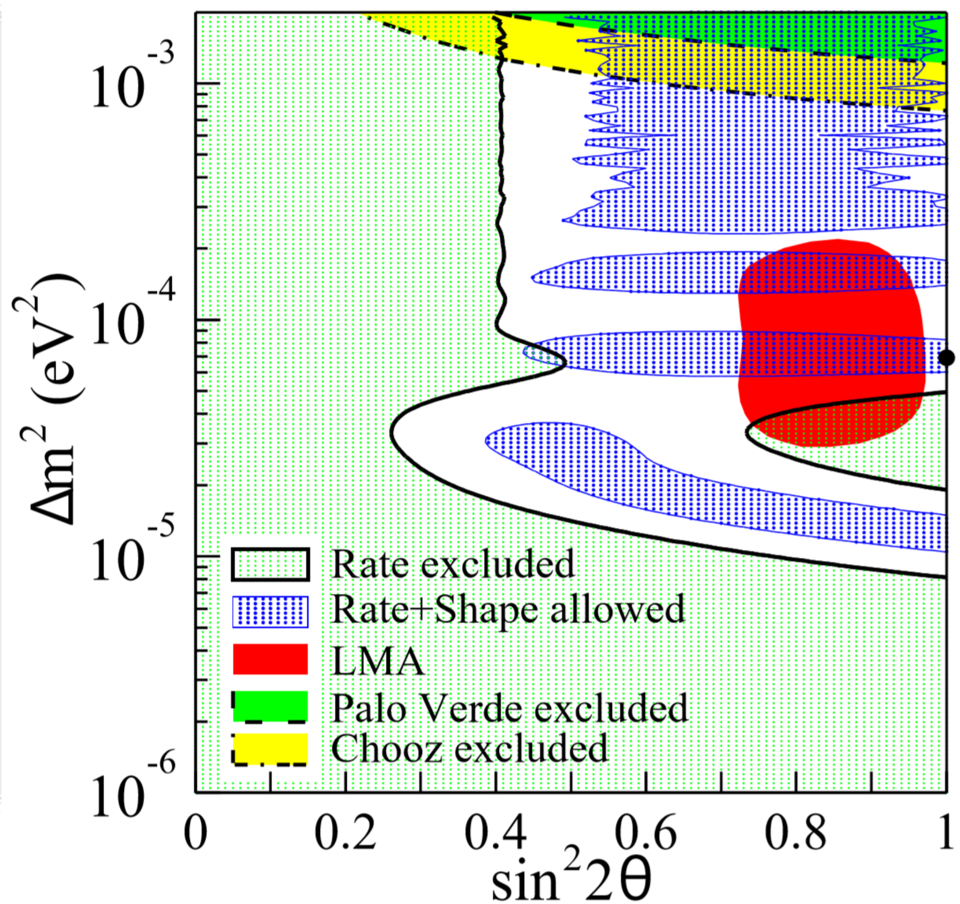
Conclusion

- **Neutrino oscillation tells us that neutrinos have non-zero mass --- the only new physics beyond the SM**
- **Neutrino mass ordering must be resolved using oscillation experiments**
- **Daya Bay measurement has made the mass ordering resolution possible using reactor neutrinos**
- **JUNO is the only experiment taking the advantage of copious free reactor antineutrinos**
- **Global complementary efforts in parallel for neutrino mass ordering, for science and beyond**

Year 2002: Reactor Neutrinos Oscillate Too!

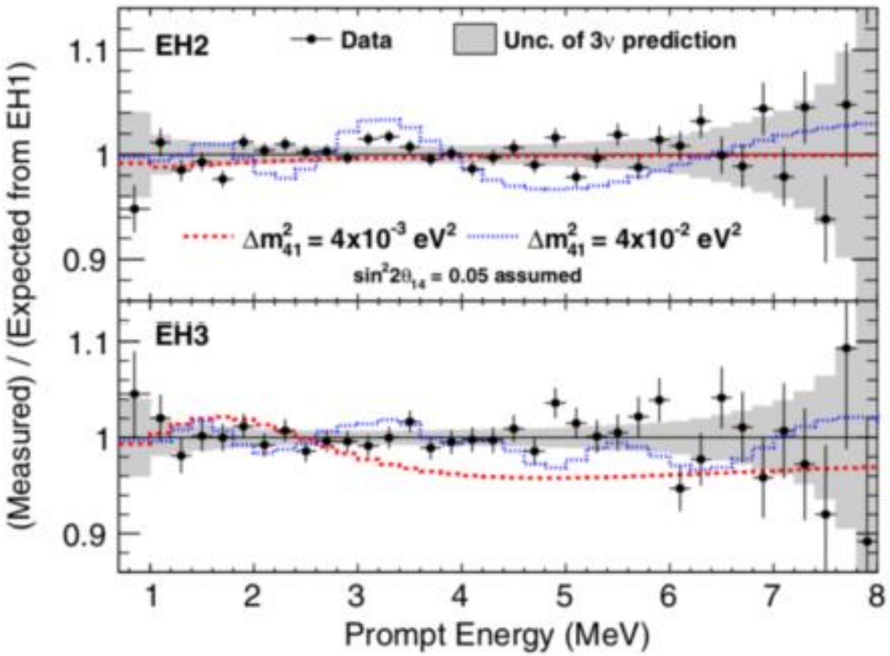
Sometimes, we just need to push it a bit further, and more





KamLAND data added: $\Delta m^2_{\mathrm{LM}A} \sim 7 \times 10^{-5}\ \mathrm{eV}^2$

Sterile Neutrino Search



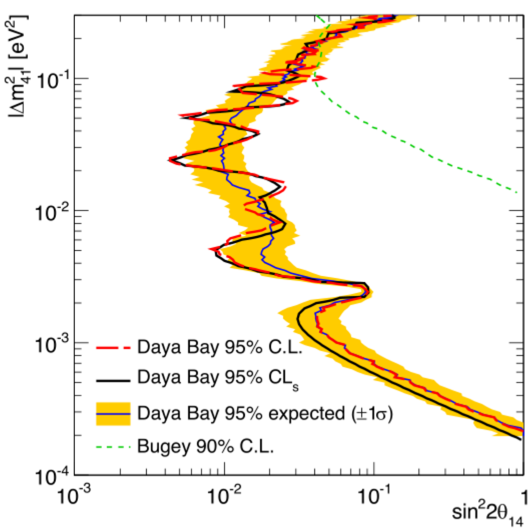
- Unique multi-baseline opportunity

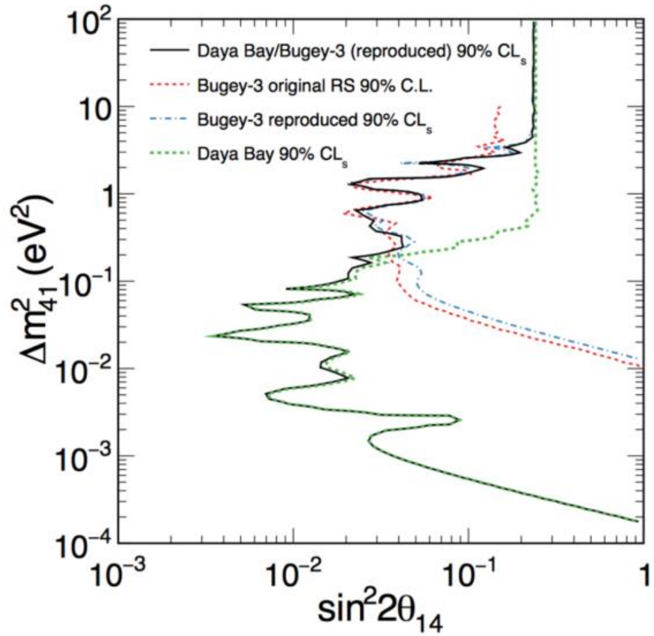
Exclusion Contours

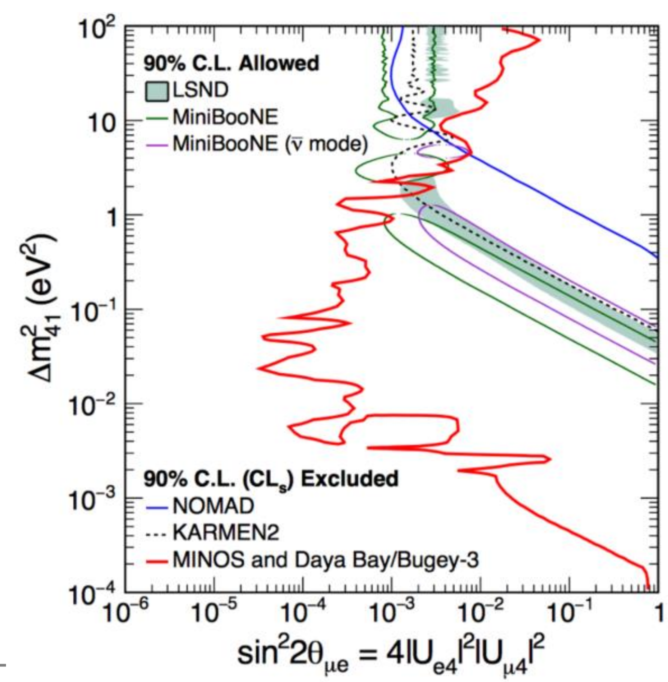
- Two-hypothesis test for 3ν and 3+1-ν
- Gaussian CLs[4] approach to set exclusion contour

$$\mathrm{CL}_s = \frac{1 - p_1}{1 - p_0},$$

p_0: 3ν p_1: 3+1-ν

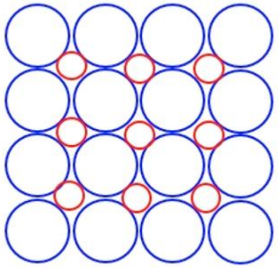




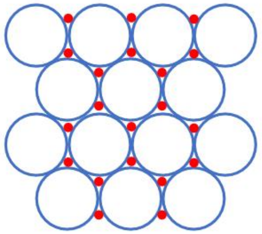


Packing PMTs as Tight as Possible

2012	2014	2016	2018
		Approval by the collaboration **SPMT consortium**	Beginning of production



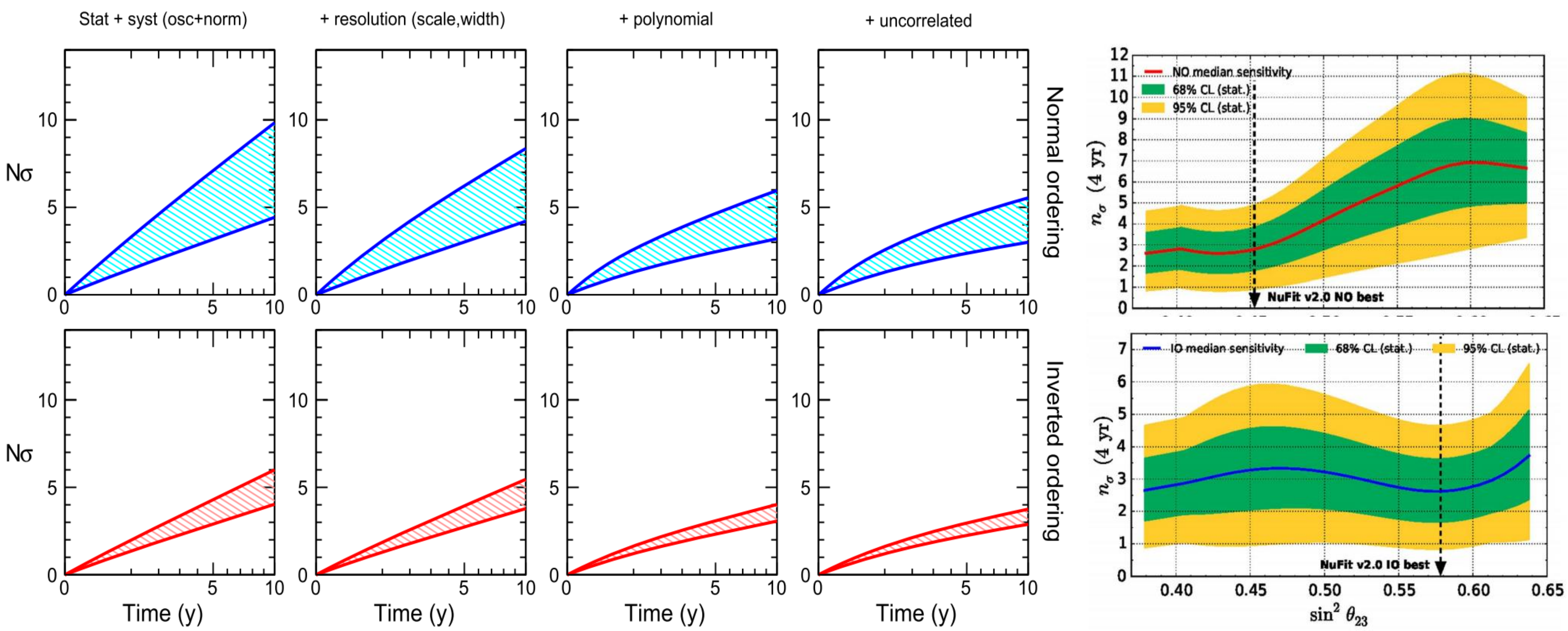
20''+8'' *M.He*



20''+3'' *A.Cabrera*

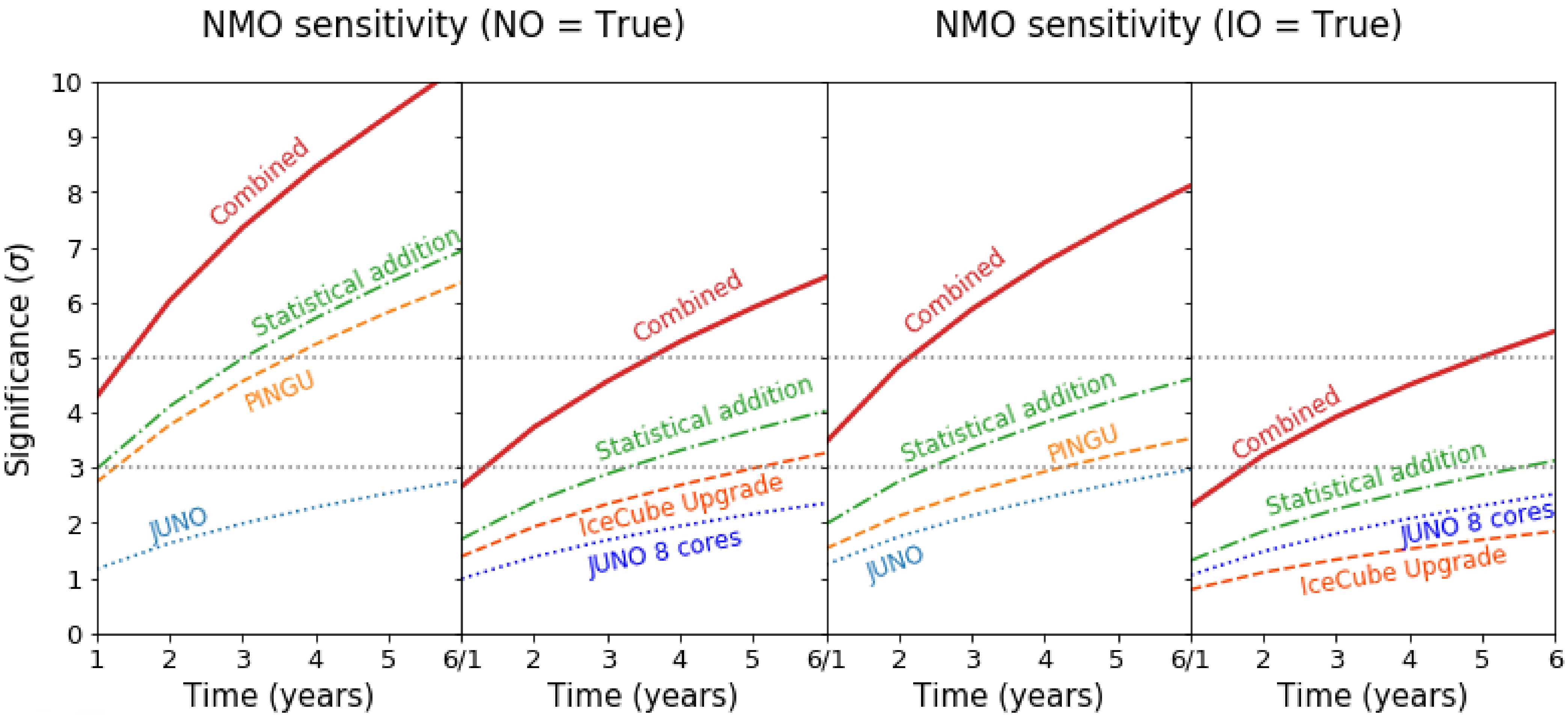
KM3NeT/ORCA and PINGU Sensitivities

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



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

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



JUNGU unchained

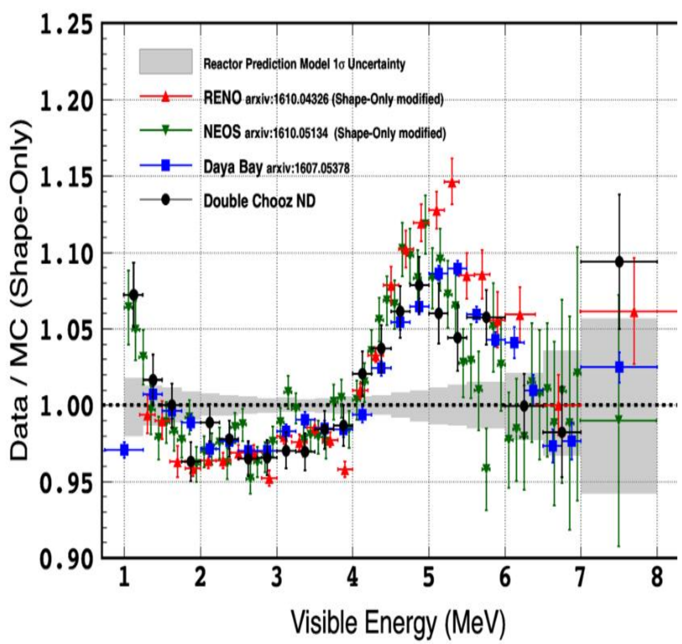
- Nominal configuration, i.e. PINGU (26 strings) + JUNO (10 cores)
- Neduced configurations, i.e. IC Upgrade (7 str) + JUNO (8 cores)

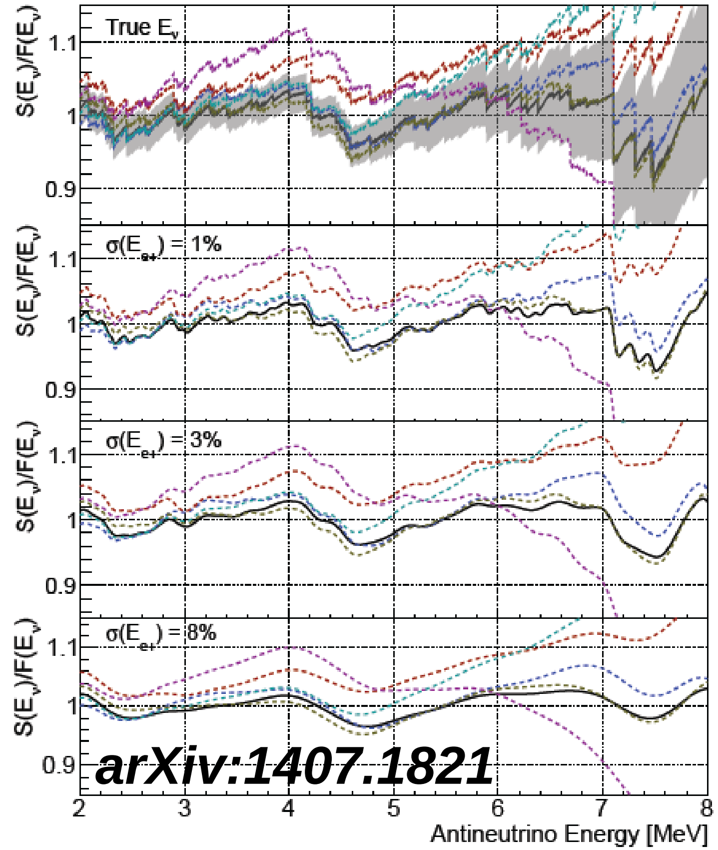
➢ **In any case, 5σ-discovery after 5 years**

Motivation of the JUNO Near Detector

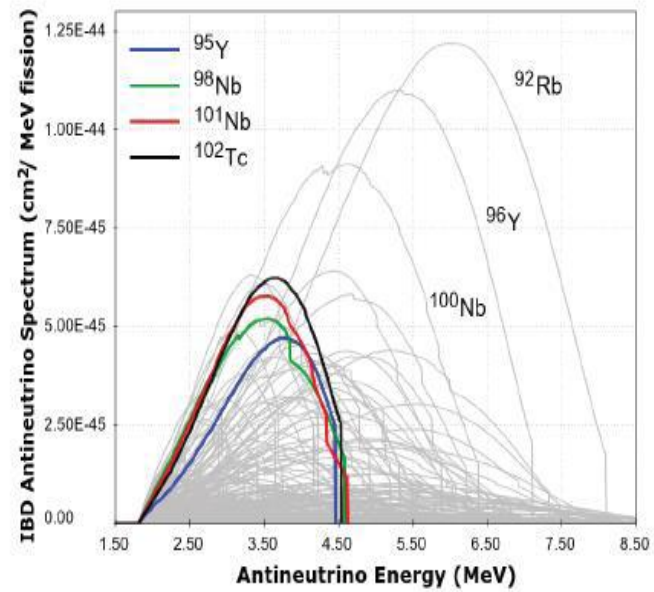
- *Danielson, Hayes and Garvey,* ***Reactor Neutrino Spectral Distortions Play Little Role in Mass Hierarchy Experiments,*** *arxiv.1808.03276:*

Current measurements



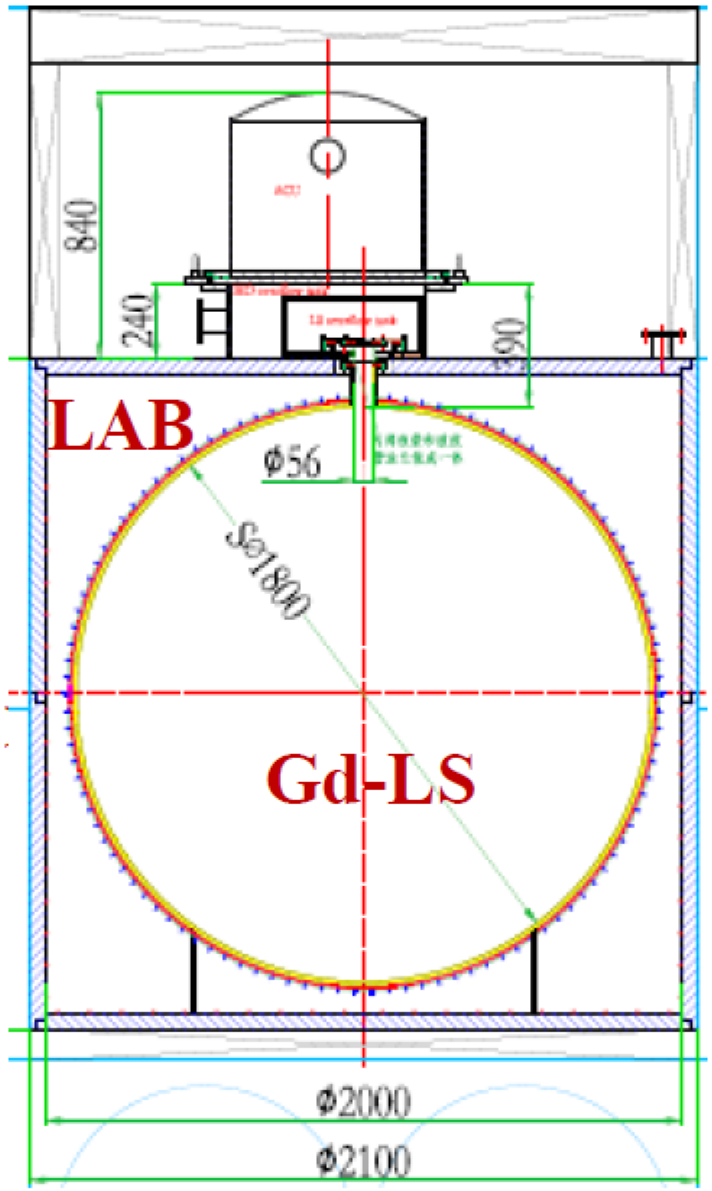


arXiv:1710.00092



	Stat.	Core dist.	DYB and HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Table 2	Table 2%	1%	6.3%	0.4%	1%
$\Delta\chi^2_{\rm MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

A Conceptual Design as of Summer 2018

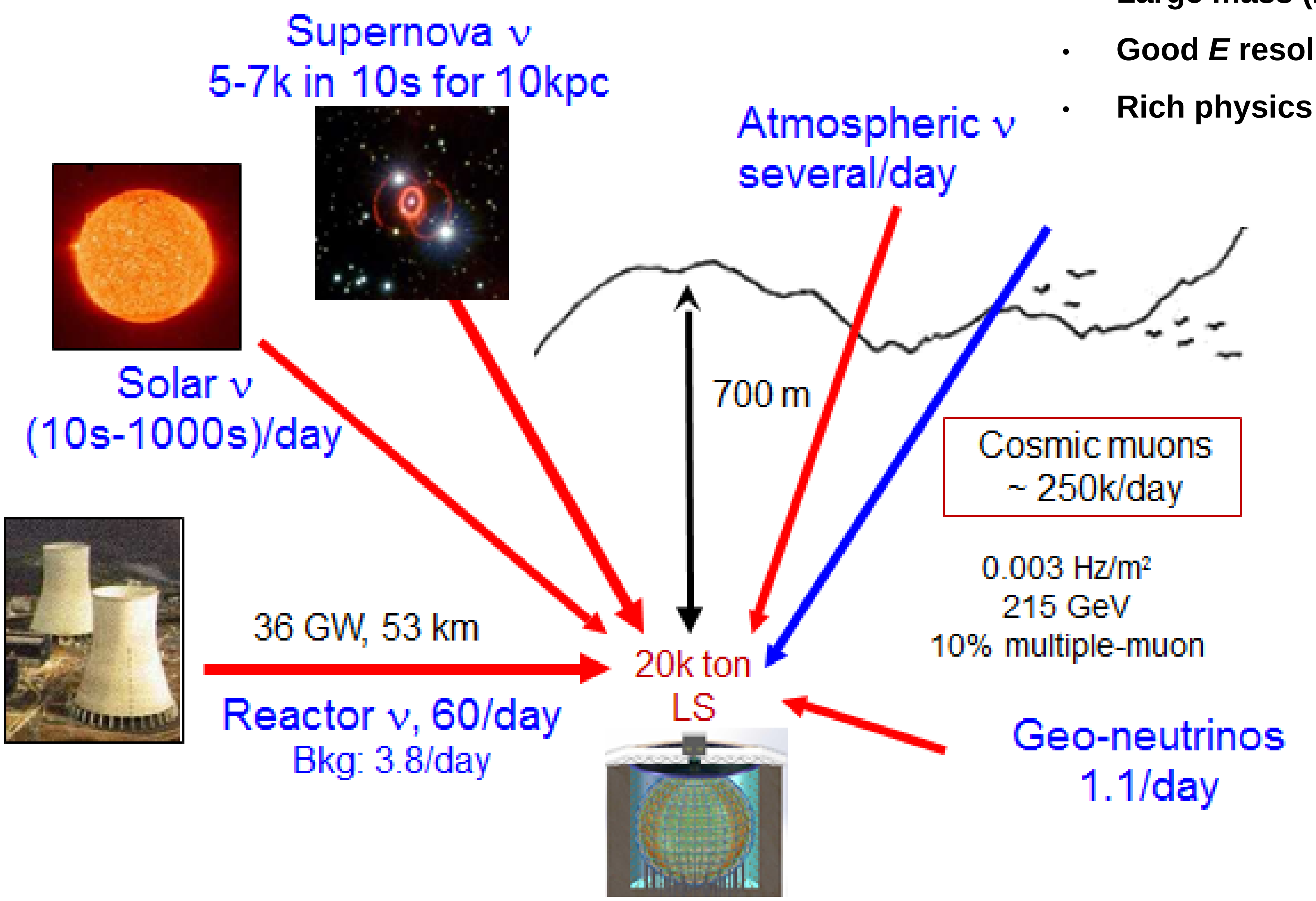


- Gd-LS in diameter of 1.8m
  - Surface 10.2 m^2; V = 3.05 m^3, or 2.63 ton; 1 ton fiducial volume w/ a 25cm cut
  - ~30 m from the core, Event rate 30 times of JUNO
  - **Resolution better than 1.7%**
- Nylon bag w/ acrylic support (JUNO backup option)
- 10 m^2 SiPM of 50% PDE, at -50
- LAB+quencher as buffer cryogenic vessel
- DYB Automatic Calibration Unit

Underground Construction Status

JUNO Has a Rich Physics Program

- **Large mass (20 kt)**
- **Good *E* resolution (3%)**
- **Rich physics potentials**

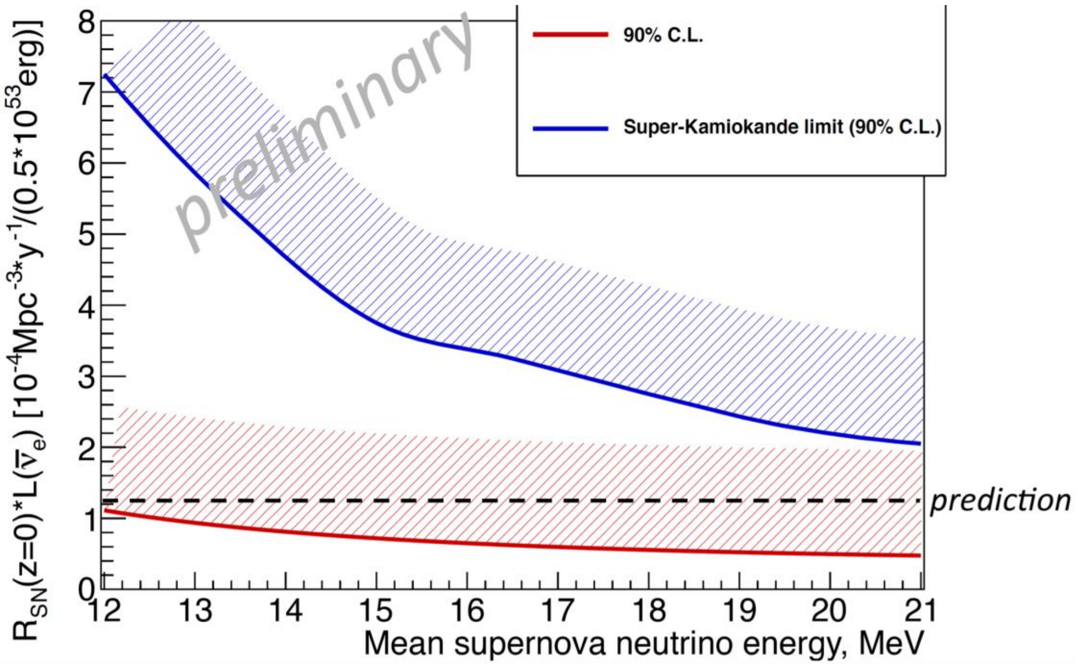


Other Physics Potential of JUNO

- Supernova neutrinos
- Diffused supernova neutrinos
- Proton decay: $P \rightarrow K^{+} + \bar{\nu}$

  $\tau > 1.9 \times 10^{34}$ yr (90% C.L.)
- Geoneutrinos
  - KamLAND: 30±7 TNU [PRD 88 (2013) 033001]
  - BOREXINO: 38.8±12.0 TNU [PLB 722 (2013) 295]
  - JUNO (preliminarily projected): 37±10%(stat)±10%(syst)TNU
- Dark matter indirect searches

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\text{C} \rightarrow \nu + {}^{12}\text{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\text{C} \rightarrow e^+ + {}^{12}\text{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2



- Solar neutrinos: high demand on the radioactive background purity.
- Atmospheric neutrinos: could potentially aid the MH