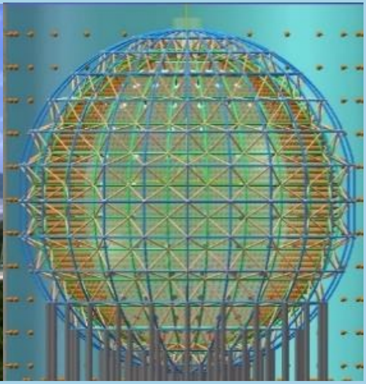


Reactor Neutrino Experiments and Anomalies

Jun Cao

Institute of High Energy Physics

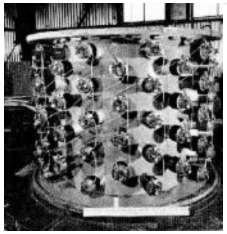
WIN2017, UC Irvine, June 19-24, 2017

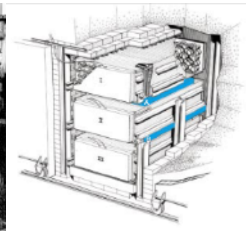
Content

- Reactor neutrino flux and spectrum
  - Rate anomaly
  - Spectrum anomaly
  - More?
- Measuring θ_{13} and Δm^2_{ee}
  - Daya Bay, Double Chooz, RENO
- JUNO status
  - Mass hierarchy & precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31} with reactor

Reactor Neutrinos

Discovery of ν



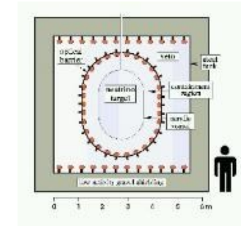


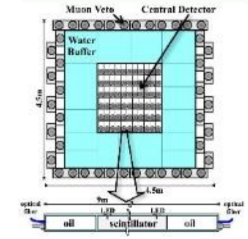
1953, Hanford, 0.3 ton
1956, Savannah River, 4.2 ton

Early searches for oscillation

1980 Savannah, **YES**
1980 ILL, **NO**
1984 Bugey, **YES**
1986 Gosgen, **NO**
1995 Bugey-3, **NO**

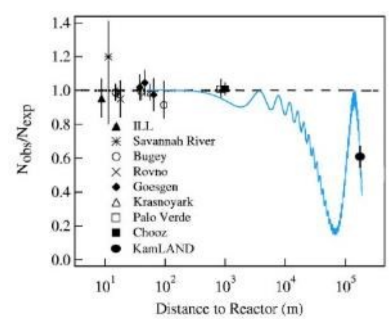
Reactor ν spectra ~2%

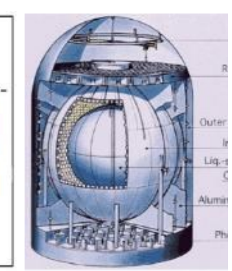




1997, CHOOZ, 8 ton
2000, Palo Verde, 12 ton

$\sin^2 2\theta_{13} < 0.15$

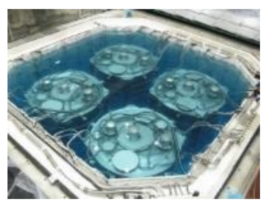


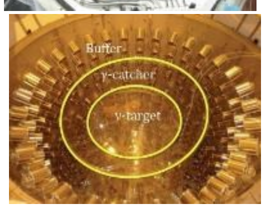


2002, KamLAND, **1000 ton**

Reactor ν oscillation (θ_{12})

2012,
Daya Bay, 160 ton
Double Chooz, 16 ton
RENO, 32 ton

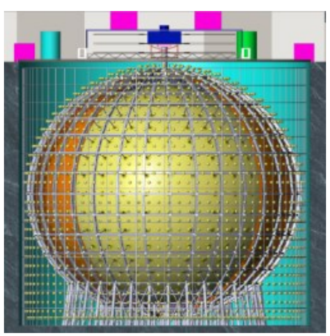




Non-zero θ_{13}

Mass Hierarchy,
Precision meas.

2020, JUNO, **20 000 ton**



Very short baseline exp. for sterile ν

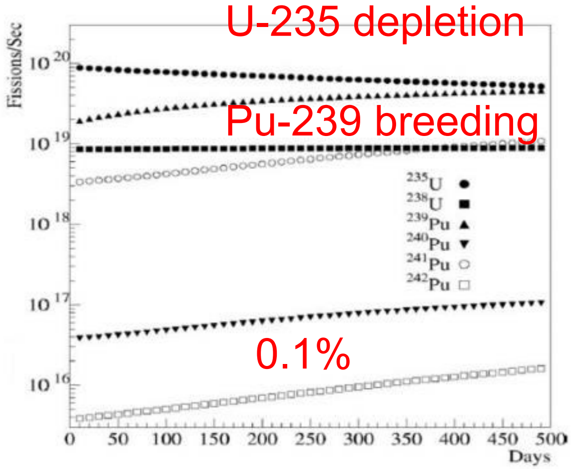
Reactor Neutrino Flux

- **Neutrinos from subsequent β-decays of fission fragments.**
- **PWR (Pressurized Water Reactor) as example.**
  (3-5)% U-235 enrichment. Other is U-238.

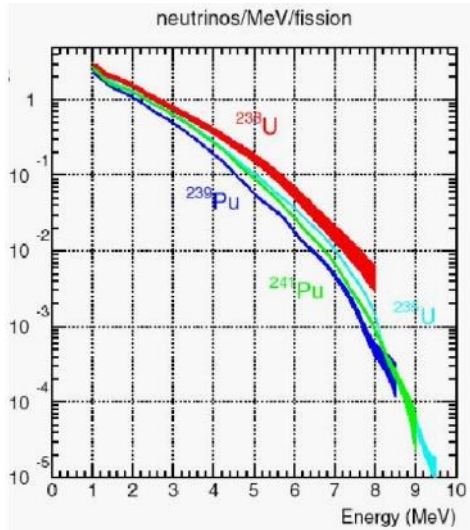
$$S(E_\nu) = \sum_{i}^{isotopes} f_i S_i(E_\nu)$$

U-235
Pu-239
U-238
Pu-241

Isotope evolution

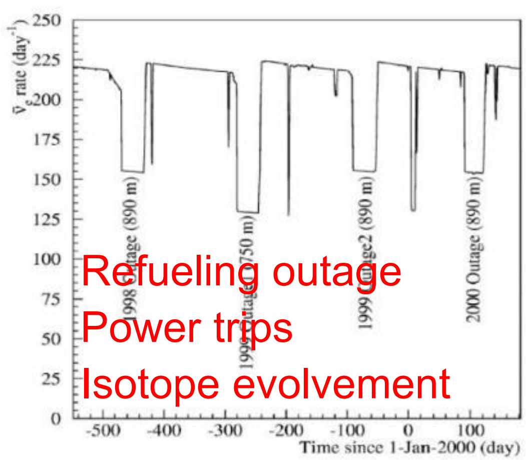


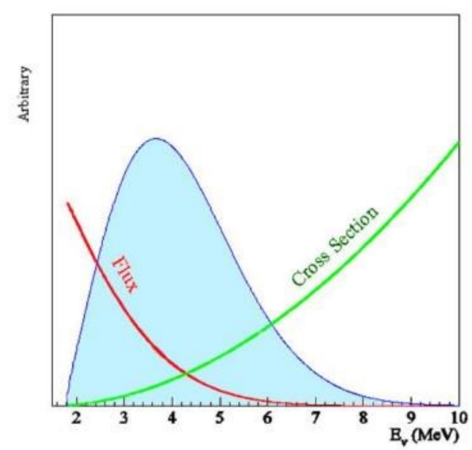
X



Neutrino spectra, ILL

More neutrinos from a U-235 fission than Pu-239

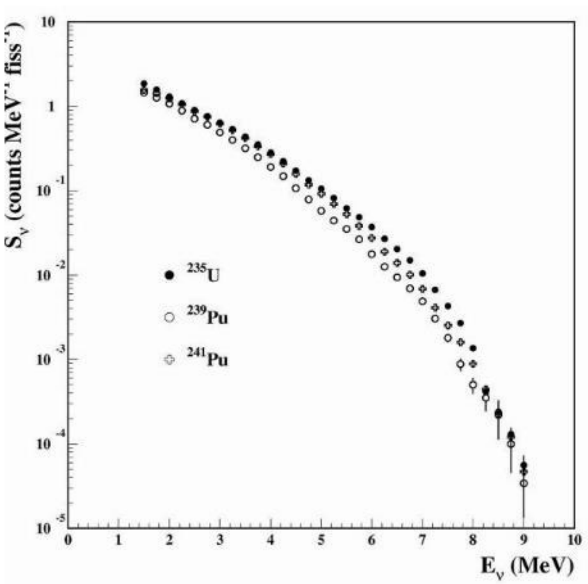




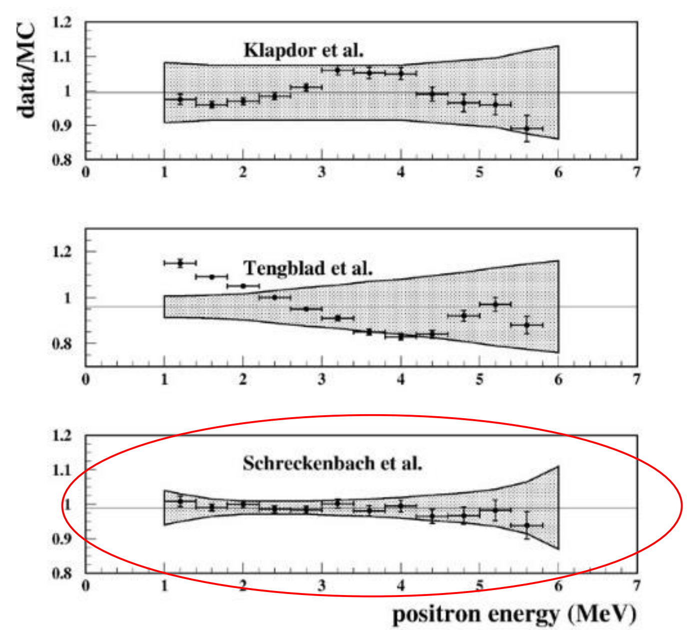
Visible spectrum,

Spectra of Isotopes

- **Ab initio: Nuclear database, Σ fragments, Σ chains, Σ branches → 10% uncertainty** (e.g. Vogel et al., PRC24, 1543 (1981)).
- **Conversion: ILL measured the β-spectra → convert to neutrino spectra**
  - ⇨ **ILL spectra: Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)**
  - ⇨ **Mueller: 90% ab initio + 10% fit → rate anomaly**
  - ⇨ **Huber: fit w/ improved nuclear effects (Huber-Mueller spectra)**



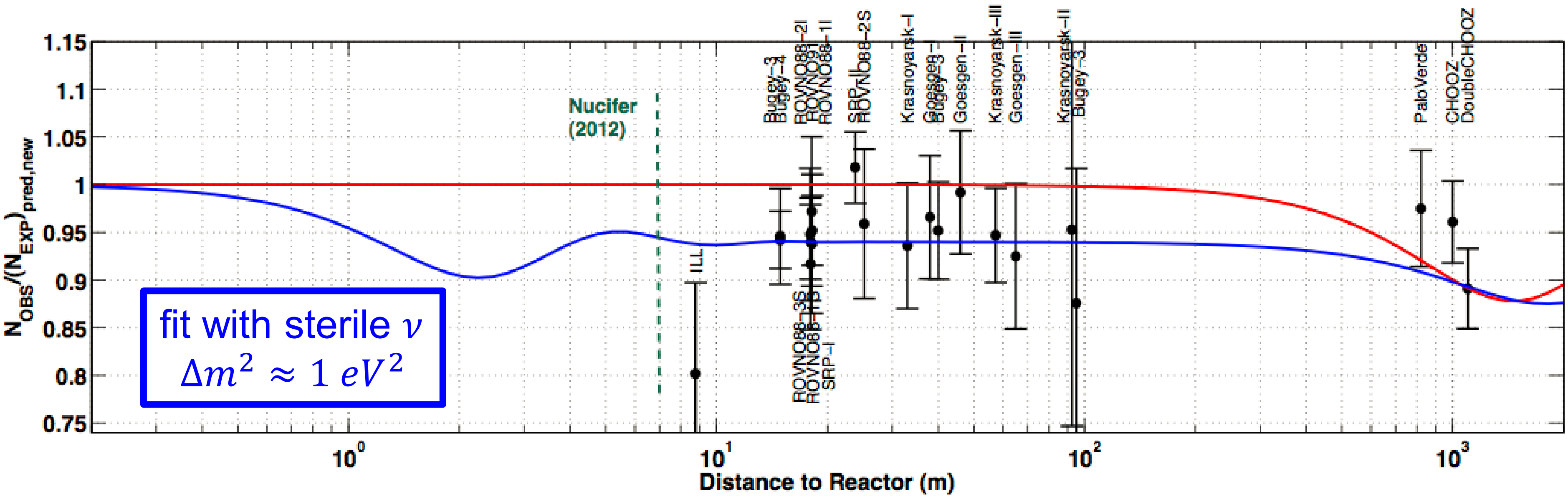
K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1985)



Shape verified by Bugey-3 data
Normalization by Bugey-4, 1.6%

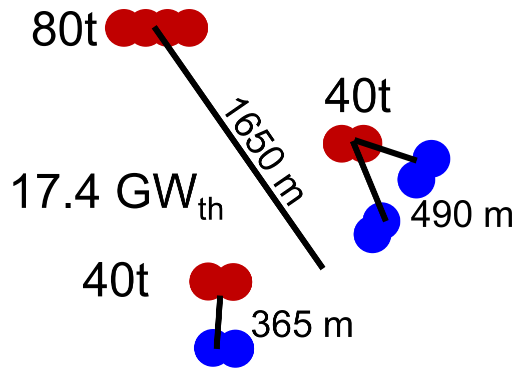
Reactor Anomaly (Rate)

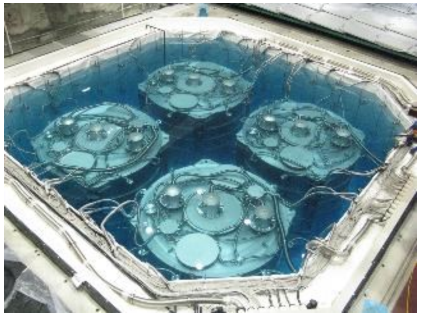
- ILL spectra agree w/ data
- 2011, Huber-Mueller spectra higher than data by 6%
- Sterile neutrino?

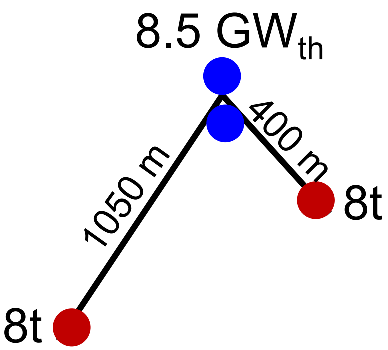


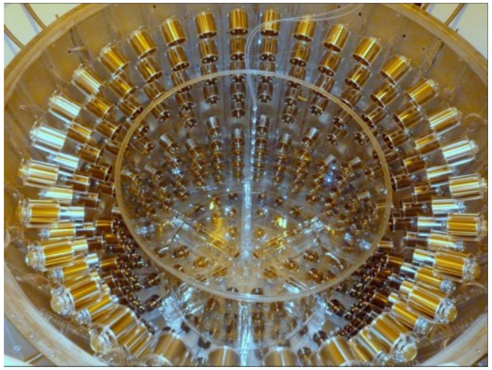
G. Mention et al.
Phys.Rev. D83 (2011) 073006

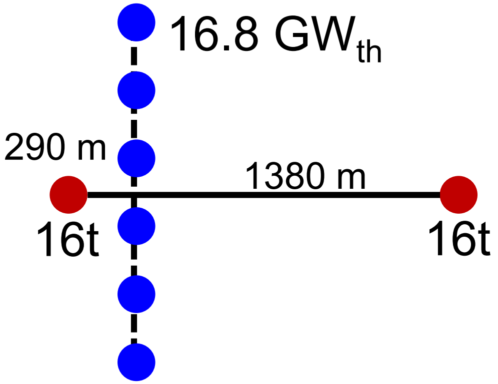
Daya Bay, Double Chooz, RENO for θ_{13}





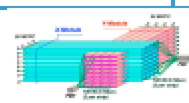
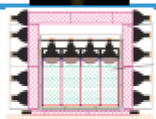
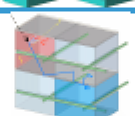
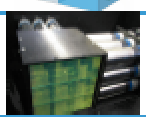






Very Short Baseline Exps.

- Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)
- Most have sensitivity 0.02~0.03 @Δm~1eV^2 @90%CL

Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Detecting Reactor Antineutrino

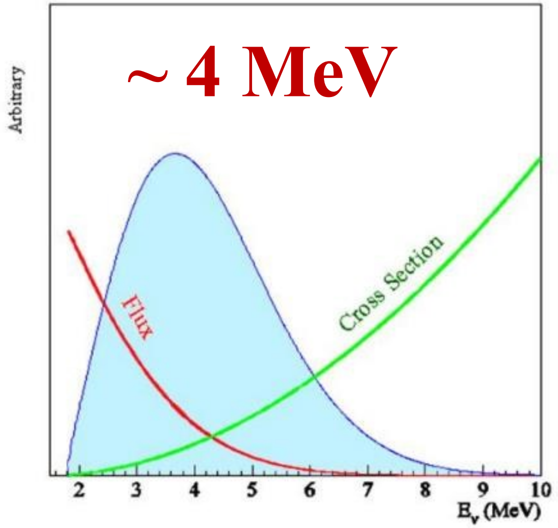
- ν-e scattering
- Inverse beta decay (IBD)

Prompt signal

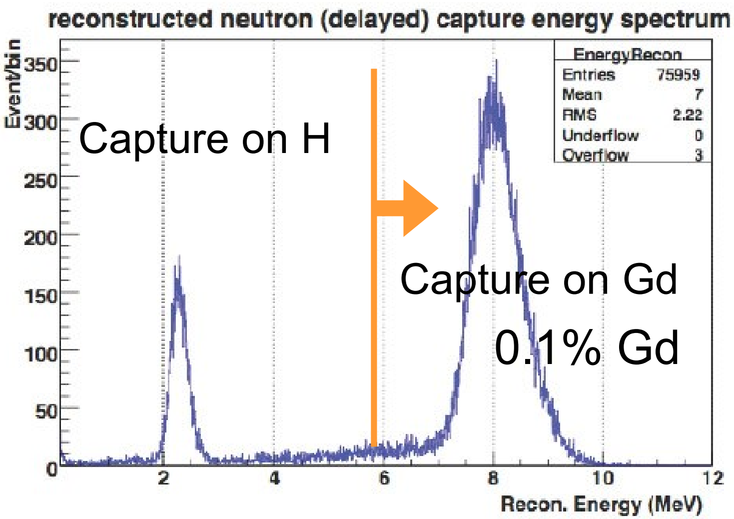
$$e^+ + e^- \rightarrow 2\gamma$$

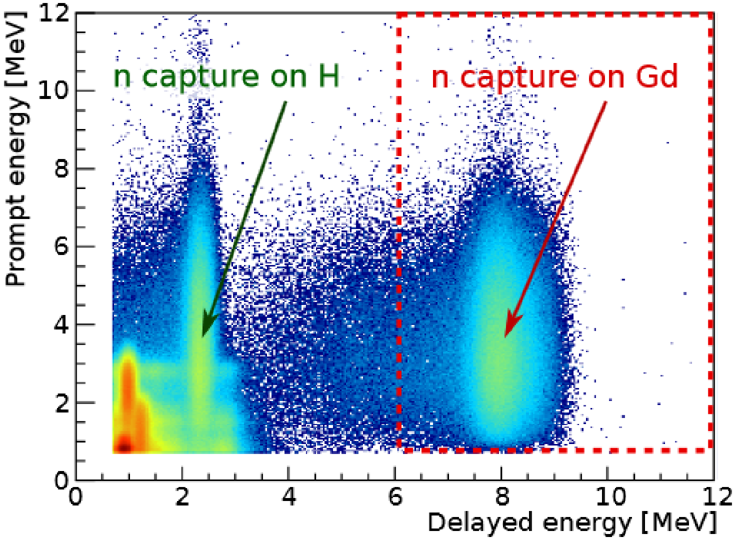
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Delayed signal, Capture on H (2.2 MeV, ~180μs) or Gd (8 MeV, ~30μs)

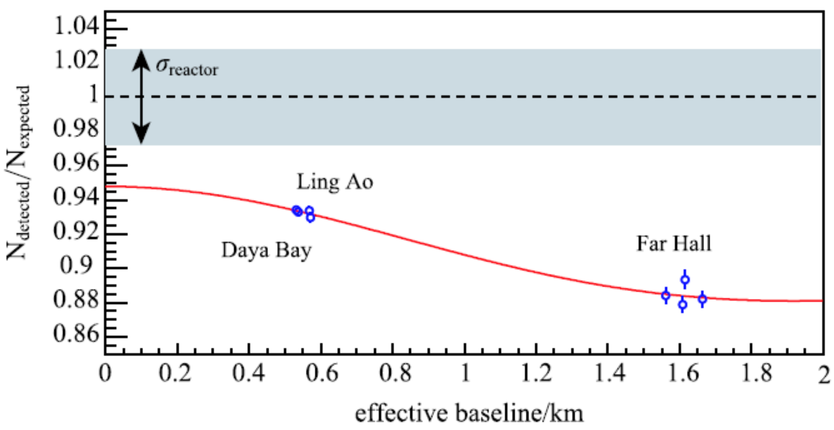


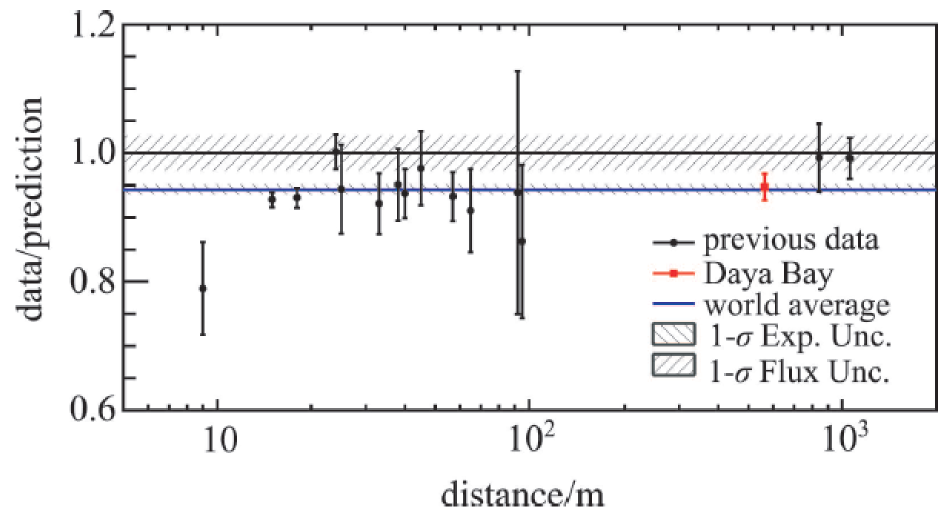
$$E(\bar{\nu}_e) = E_{\text{prompt}} + Q - m_e$$
$$\sim E_{\text{prompt}} + 0.8 \text{ MeV}$$





Daya Bay Absolute Rate Measurement





Chin. Phys. C41, 013002 (2017)

- ⇨ **Data/(Huber+Mueller):** **0.946±0.020**
- ⇨ **Past global average:** **0.942±0.009**
- ⇨ **Data/(ILL+Vogel):** **0.992±0.021**

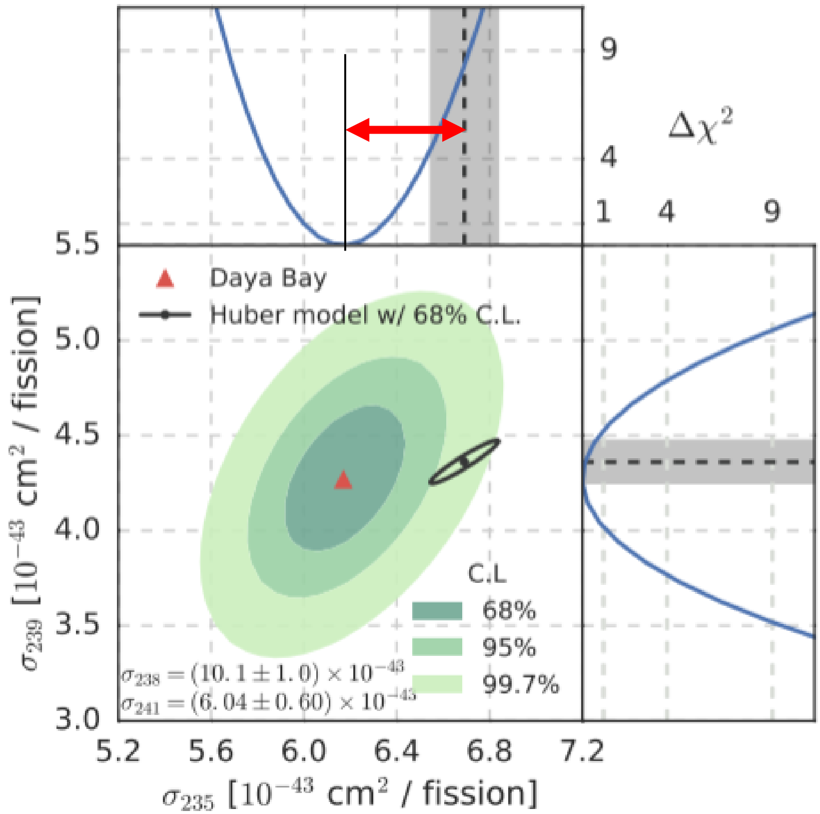
contribution	uncertainty
statistics	0.1%
oscillation	0.1%
reactor	0.9%
detection efficiency	$\boxed{1.93\%}$
total	2.1%

Special calibration in Jan. 2017

Stay tuned

Daya Bay Fuel Evolution

- Combined fit for major fission isotopes ^{235}U and ^{239}Pu
- σ235 is 7.8% lower than Huber-Mueller model (2.7% meas. uncertainty)
- σ239 is consistent with the prediction (6% meas. uncertainty)
- 2.8σ disfavor equal deficit (H-M model & sterile hypothesis)

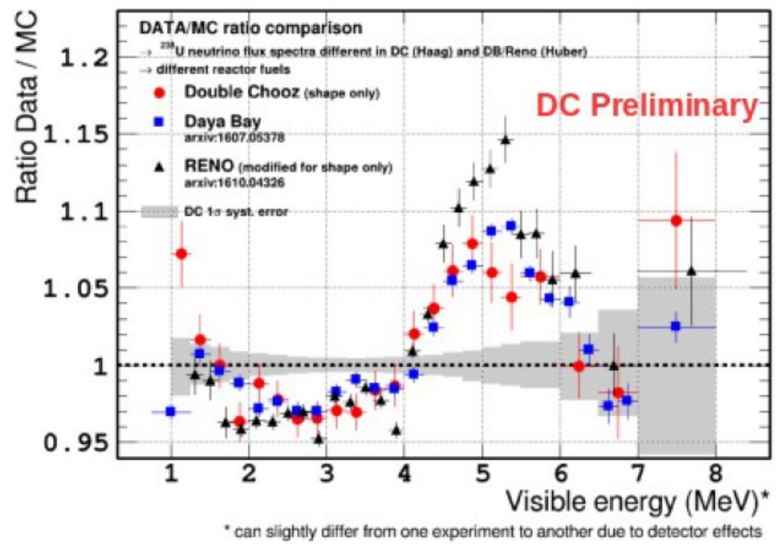


PRL118, 251801 (2017)
Published June 19, 2017

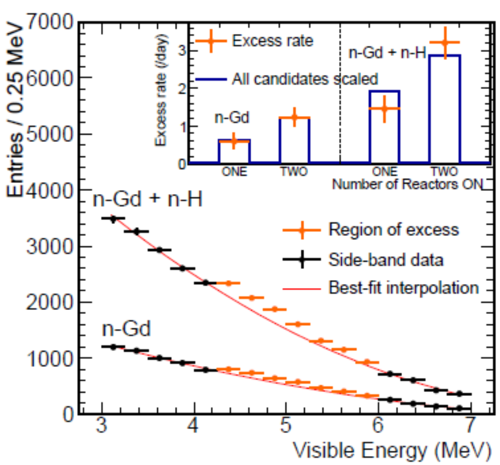
Talk by David Martinez in Neutrino session

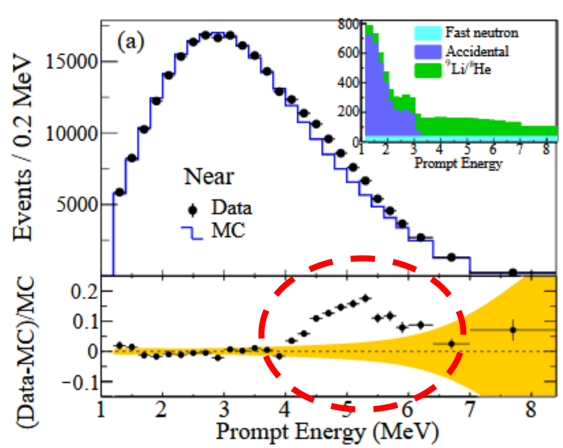
Reactor Anomaly (Spectrum)

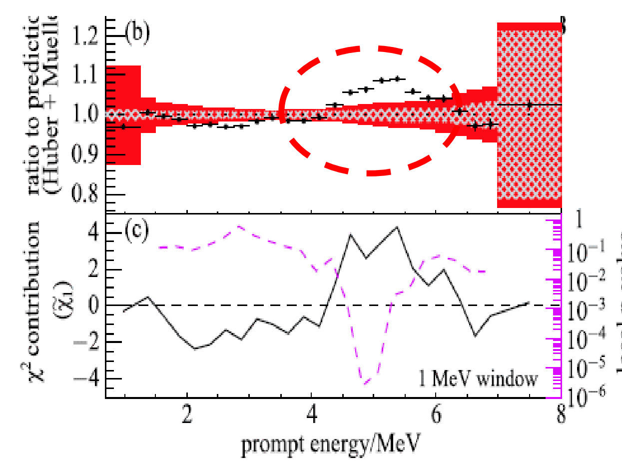
- 5 MeV Bump
- Not due to energy non-linearity
- Not due to sterile ν
- Possibly due to forbidden decays (PRL112: 2021501; PRL114:012502)



Talk by T. Sogo-Bezerra in neutrino session



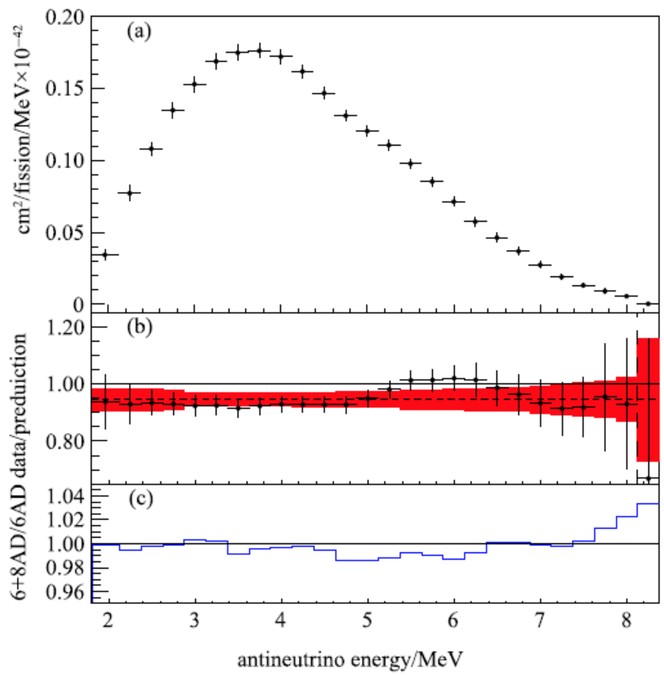


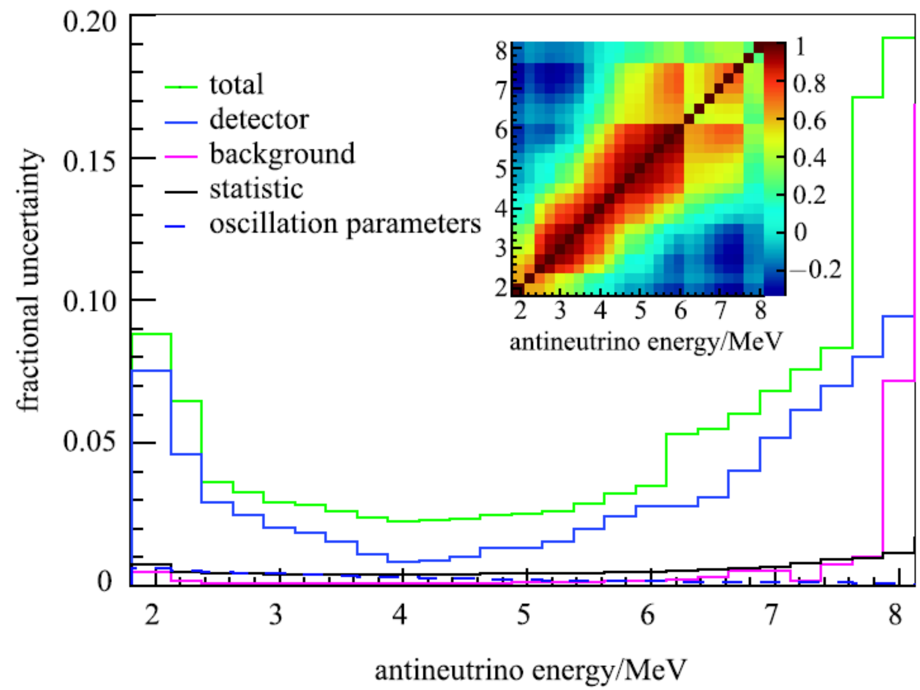


DC, JHEP 1410 (2014) 086 RENO:arXiv:1610.04326 Chin. Phys. C41, 013002 (2017)

Measuring the spectrum

- **Unfolding the reactor neutrino spectrum**
  - ⇨ Between 1.5 and 7MeV: 1.0% at 3.5 MeV, 6.7% at 7 MeV
  - ⇨ Above 7 MeV it is larger than 10%.





- **New prediction besides *ab initio* method and conversion method**
- **W/ the direct measurement, spectra uncertainty comes mainly from energy non-linearity uncertainty (do not double counting): 1% energy scale → 10% uncertainty in spectrum.**
- **Aim at 1% for JUNO → next page**

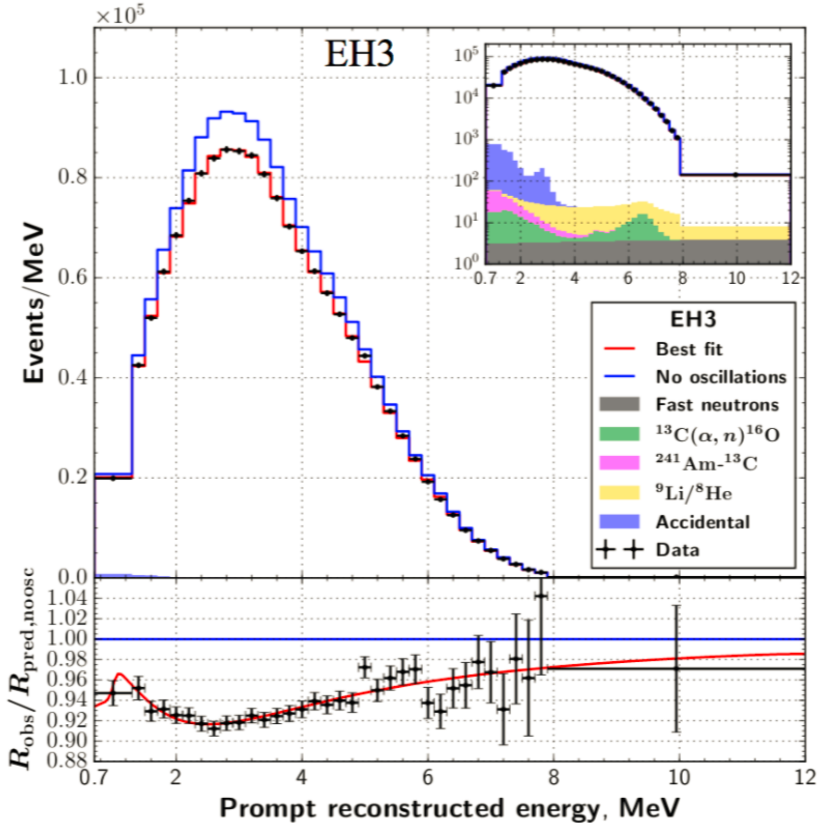
Precision Spectrum with Gas TPC

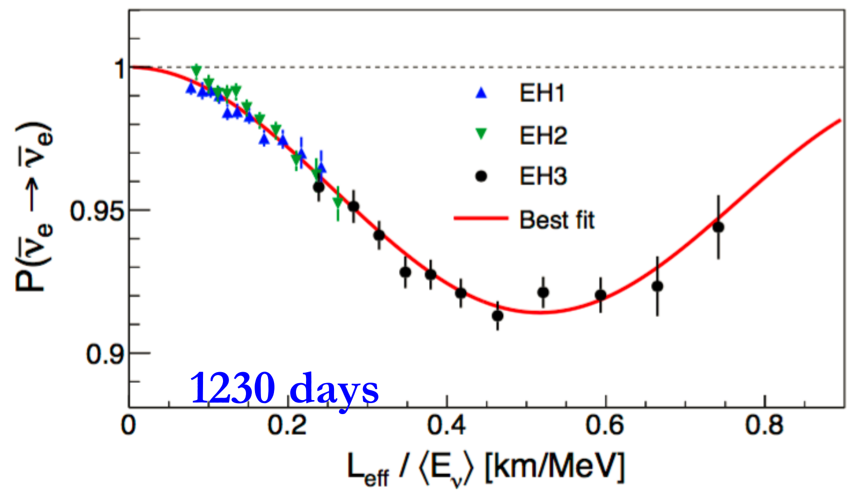
- **How to reach 1% spectrum uncertainty?**
- **Improving Daya Bay (Stay tuned)**
  - **Electronics non-linearity**
    - 192 channels Flash ADC for AD1. Data taking completed.
  - **Liquid scintillator non-linearity**
    - Replaced LS in AD1 for JUNO R&D

      → Consequence: Daya Bay from 8 AD to 7 AD since Dec. 2016
    - Testing detector responses with 13 different LS configurations (PPO from 0.5g/L to 4g/L, bis-MSB from 0.1-15 mg/L)

      → Building precision Monte Carlo
  - **Relative meas. to cancel non-linearity btwn Daya Bay and JUNO**
- **Other experiments, like PROSPECT (4.5% energy resolution)**
- **Gas TPC detector at ~20 m from a reactor (Prototyping at IHEP)**
  - **ν-e scattering**
  - **High energy resolution (1%/sqrt(E), Daya Bay 8%, JUNO 3%)**
  - **Other motivations: θw, abnormal magnetic moment (to 10^{-12})**

Precision Measurement at Daya Bay

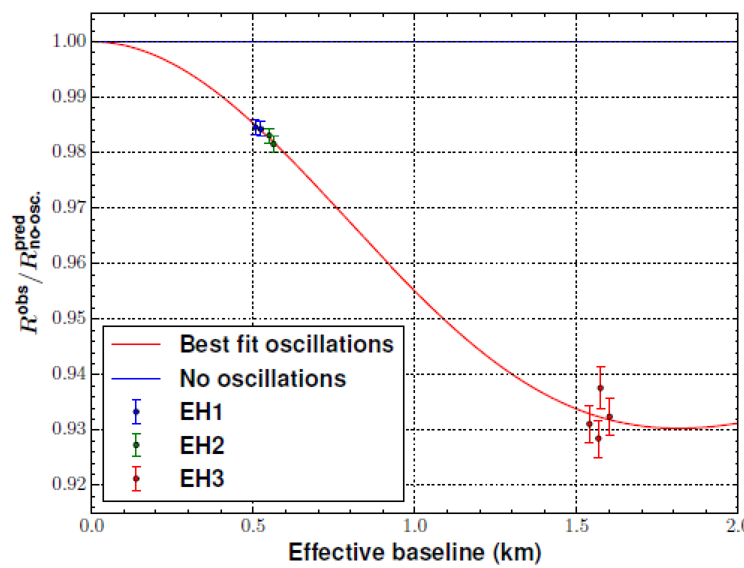




$\text{Sin}^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$

NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\ \text{eV}^2$

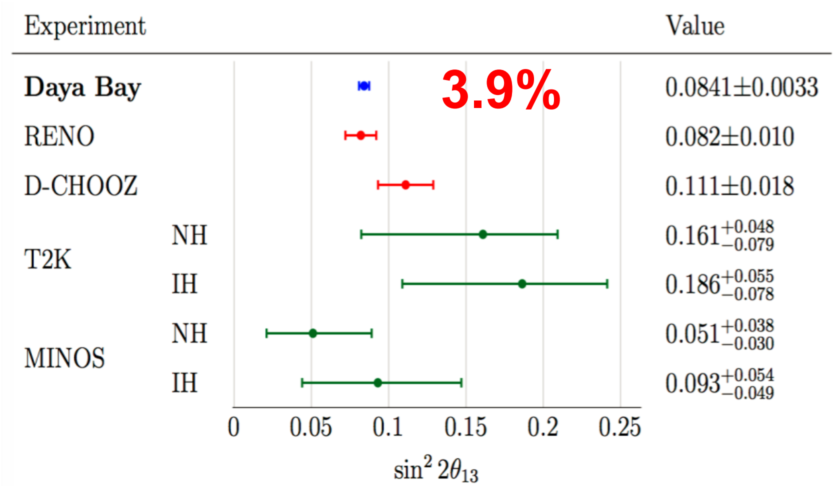
IH: $\Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\ \text{eV}^2$

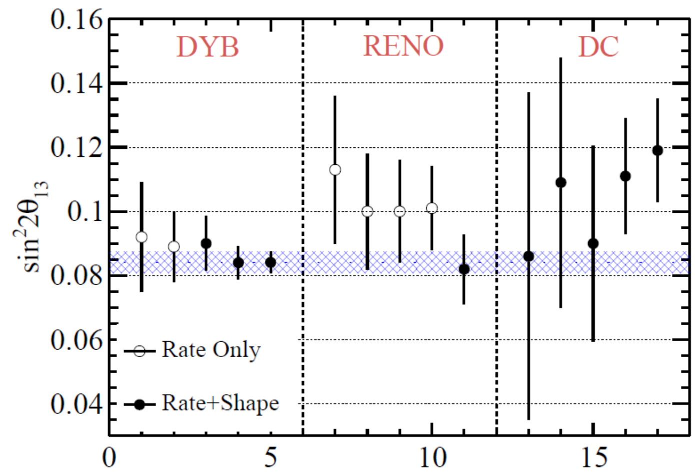


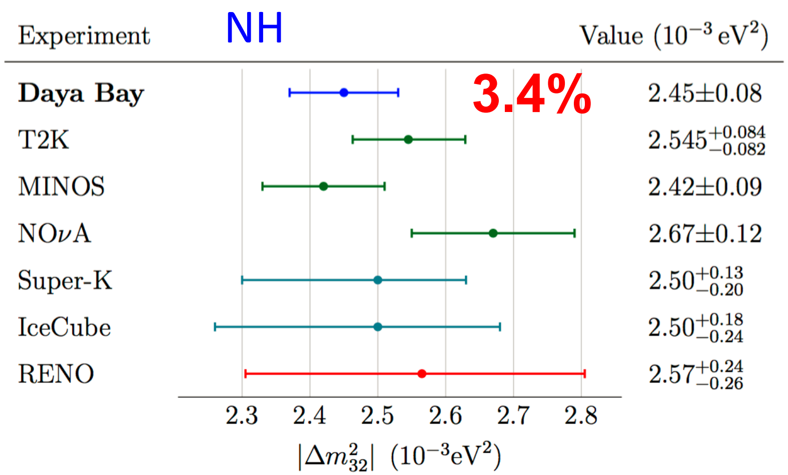
1230 days

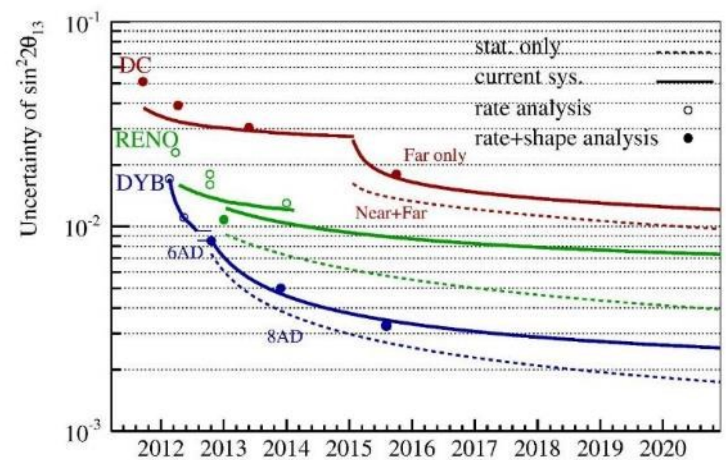
PRD 95, 072006 (2017)

Global Comparison





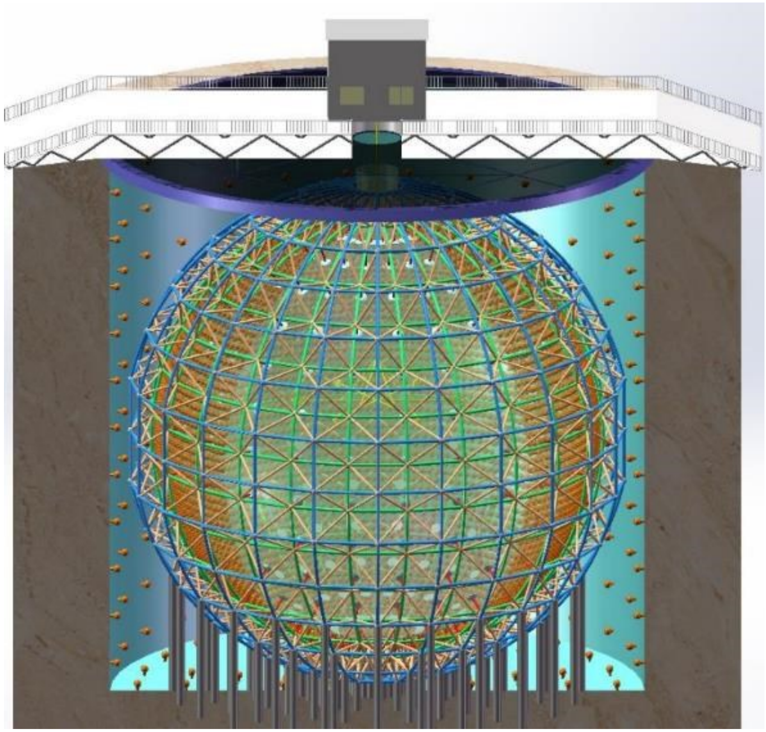




- DYB: running to 2020, 3% precision (1.5x stat. in 2018 summer)
- RENO: operation funding secured until 2019.2
- Double Chooz: at least Jan. 2018

The JUNO Experiment

- **Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$. Aiming at data taking in 2020.**

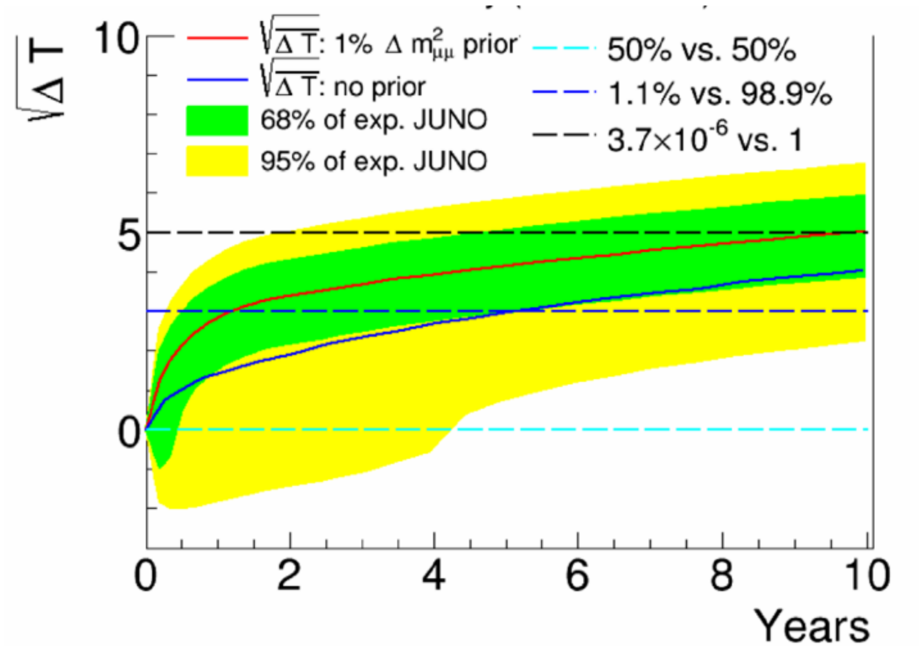


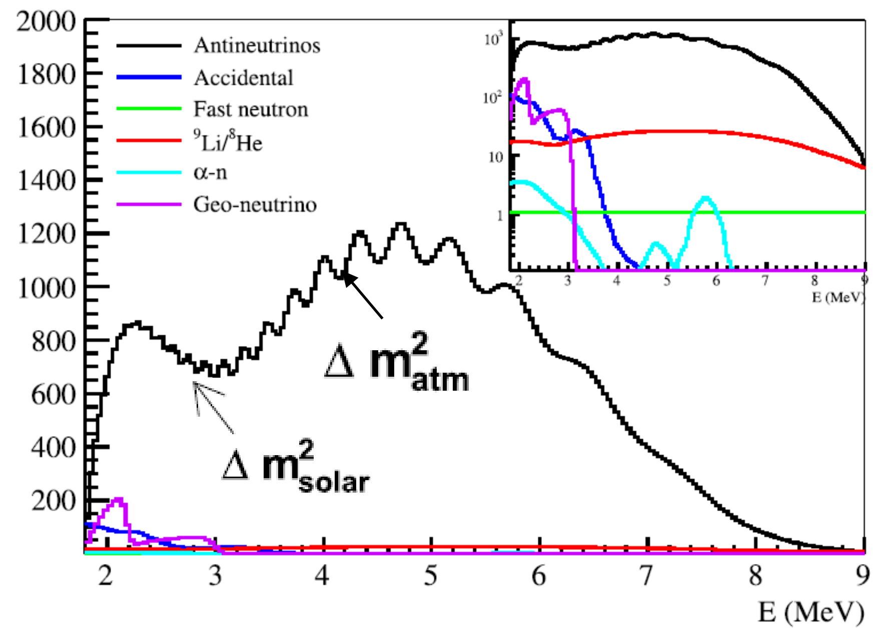
http://juno.ihep.ac.cn

Talks by A. Cabrera (general), H. Li (SN), M. Grassi (sPMT) in neutrino session.

- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - **Supernovae, DSNB**
  - **Geo-neutrino**
  - **Solar neutrino**
  - **Proton decay**
  - **Exotic searches**

Sensitivity w/ Reactor nu





	KamLAND	BOREXINO	JUNO
mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

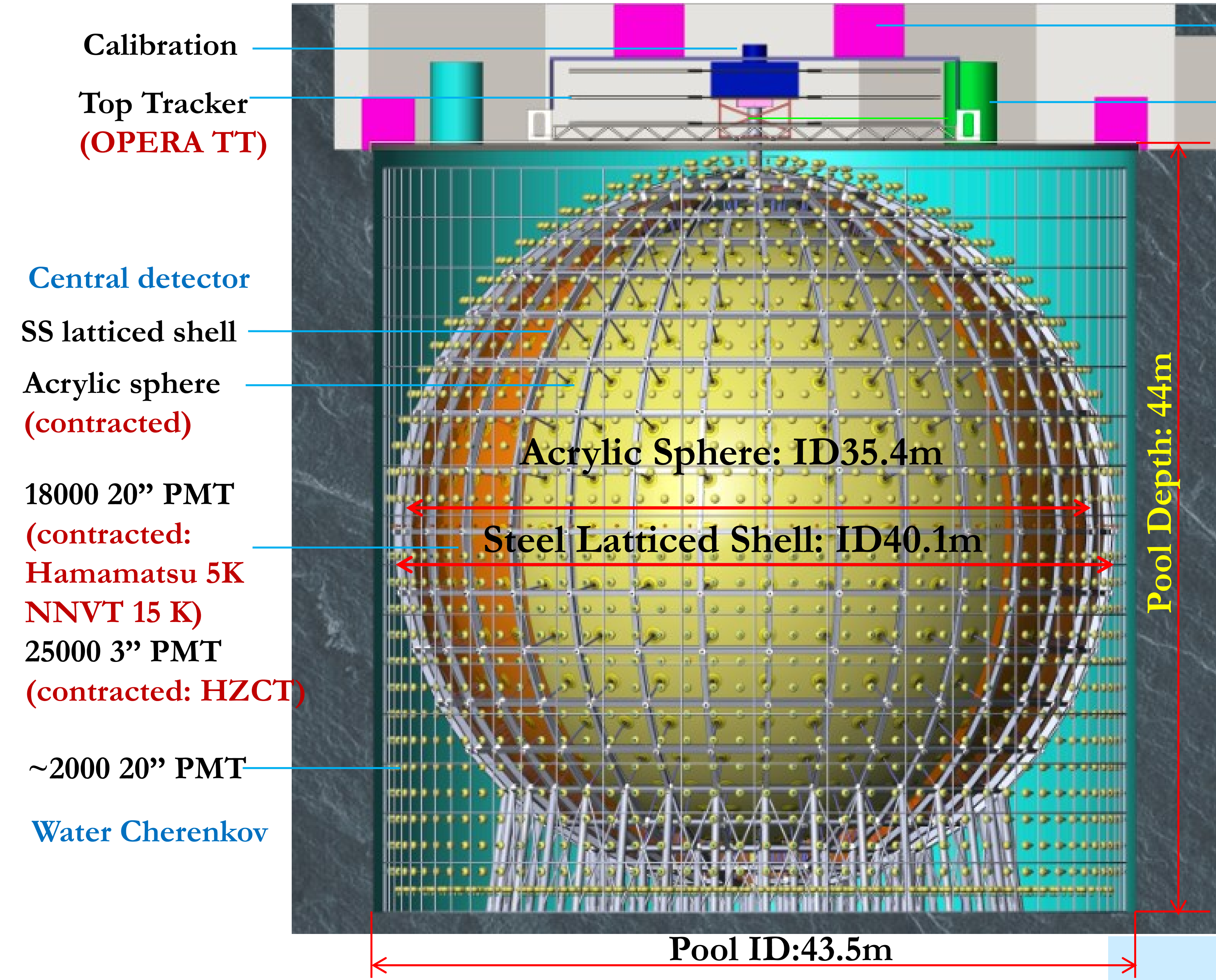
	Statistics	w/ sys.
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%

JUNO Location/Collaboration

71 Institutions, 533 collaborators

- China (32), Thailand (3), Pakistan, Armenia
- Italy (8), Germany (7), France (6), Russia (3), Belgium, Czech, Finland, Slovakia
- Brazil (2), Chile (2), USA (2)

JUNO Detector



Acrylic Sphere:
ID: 35.4m
Thickness:120mm

SSLS:
ID: 40.1m
OD: 41.1m

Water pool
ID: 43.5m
Height: 44m
Water Depth:
43.5m

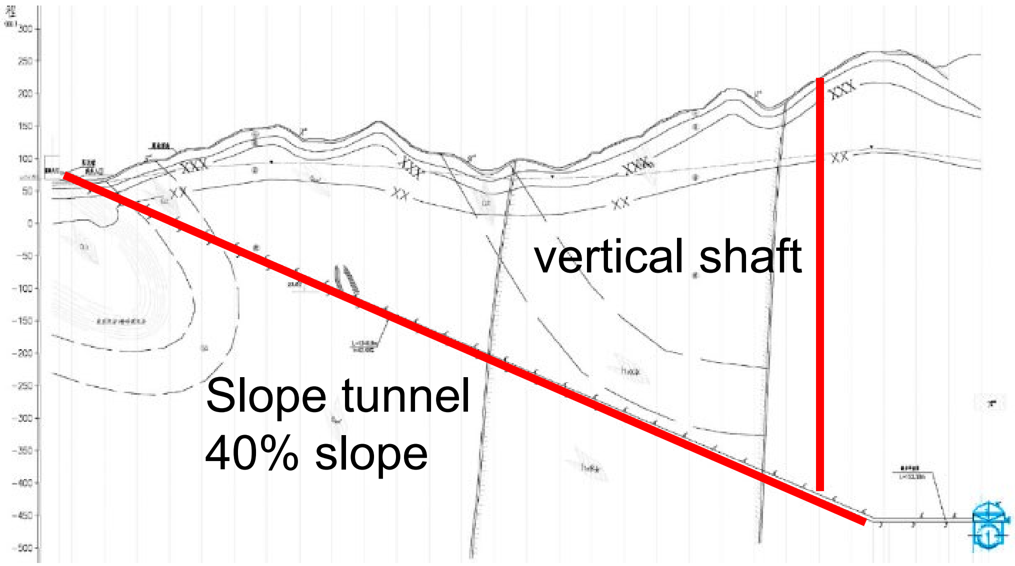
JUNO Progress and Schedule

Ground breaking in Jan. 2015

- ⇨ slope tunnel done (1265 m)
- ⇨ vertical shaft done (575 m)
- ⇨ Delayed by unexpected water

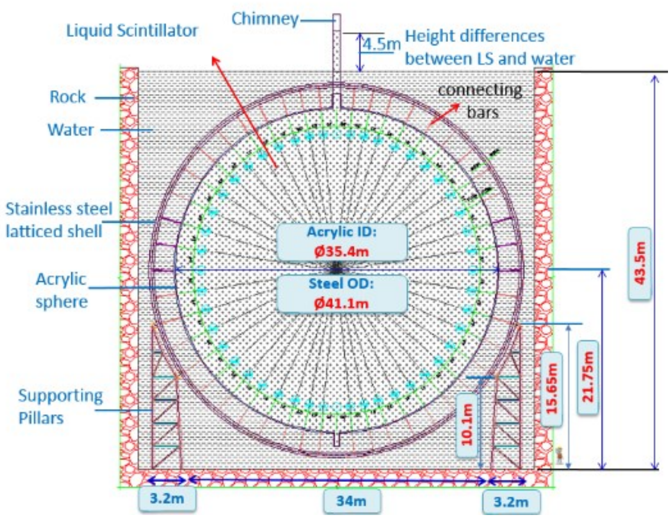
Schedule:

- ⇨ Detector assembly & installation: 2018-2019
- ⇨ Filling & data taking: 2020
- ⇨ Delayed by ~1 year

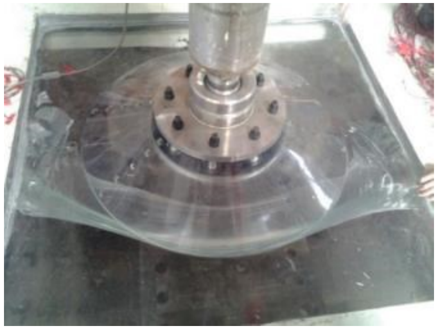


Central Detector + Muon Detector

- Acrylic sphere: ID35.4m, thickness: 120mm
  >200 pieces of panels bonded on site. 600 t
- Stainless steel: ID40.1m, OD41.1m, divided into 30 longitudes and 23 layers, 600 t

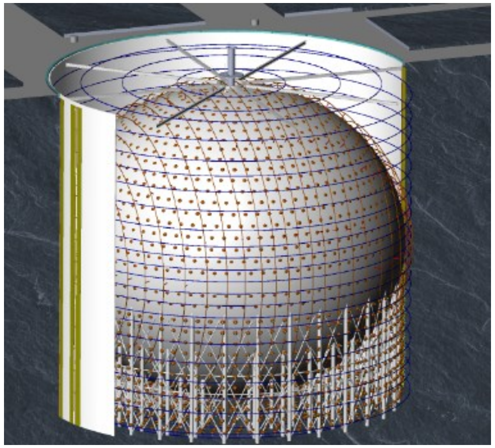


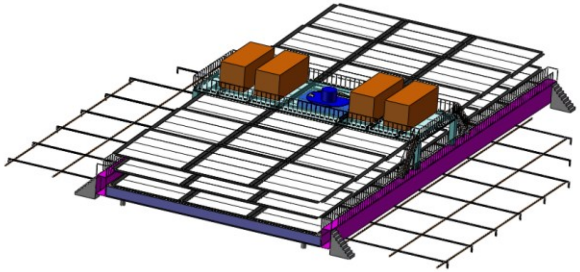
Bonding



Node test

- Water cherenkov detector
  ~2000 20" PMT
  35 kton ultrapure water
- Top tracker
  Re-using the OPERA's Target Tracker. Arrived in China





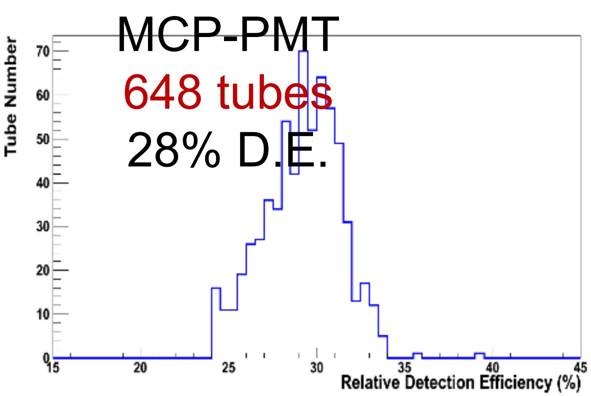
LS Pilot plant

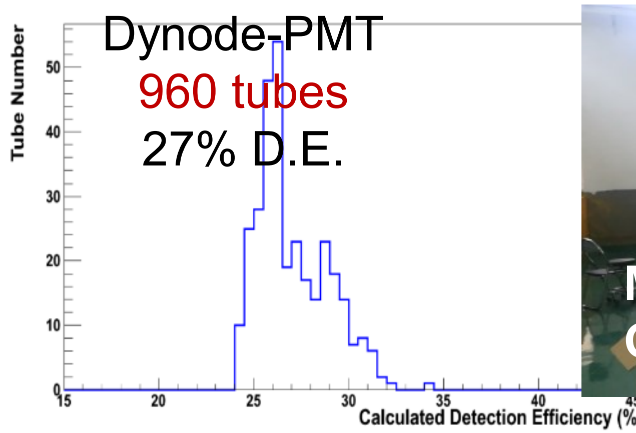
- Purified 20 ton LAB to test the overall design of the purification system at Daya Bay. Replaced the target LS in one detector
  - ⇨ **Optimization of recipe, Study of radioactivity background**
- Target:
  - ⇨ **Optical : >20m A.L @430nm**
  - ⇨ **Radio-purity: 10^{-15} g/g (U, Th)**

20-inch PMT

- **Contracts were signed in 2015**
  - ⇨ **15k MCP-PMT (75%) from NNVT**
  - ⇨ **5k Dynode (25%) from Hamamatsu**

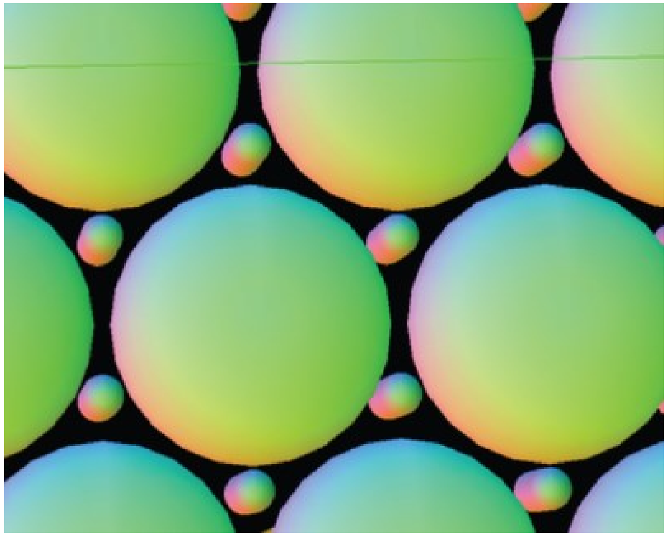
Characteristics	**unit**	**MCP-PMT （NNVT）**	**R12860 （Hamamatsu）**
Detection Efficiency (QE*CE*area)	%	**27%, > 24%**	**27%, > 24%**
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	**2.7, < 3.5**
Rise time/ Fall time	ns	R~2, F~12	R~5, F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	**1, <2**	10, < 15
Radioactivity of glass	ppb	**238U:50 232Th:50 40K: 20**	238U:400 232Th:400 40K: 40





Small PMT

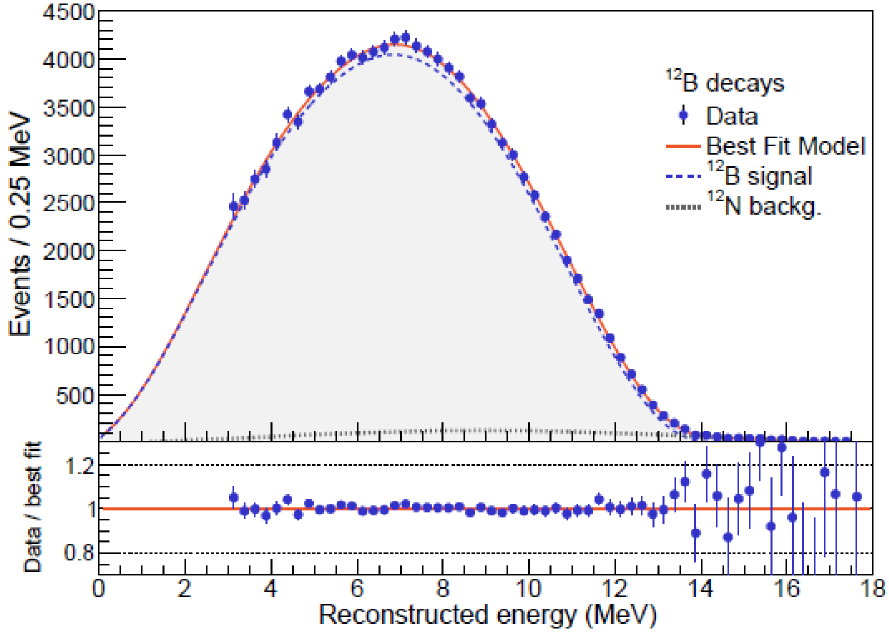
- 25,000 3-inch PMTs, contracted to HZC (China)
- Work together with the 20-in PMT as a double calorimetry
  - Increase photon statistics by 3%
  - Measure energy via "photon counting", control systematics
  - muon tracking, supernova detection …



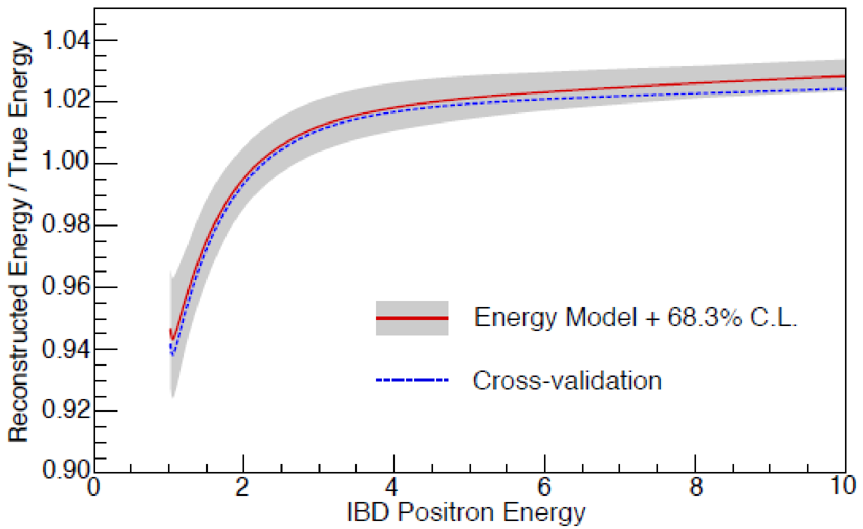
Summary

- Ultimate precision of $\sin^2 2\theta_{13}$ will reach ~3%.
- Flux and spectrum anomalies are also interesting.
  - ⇨ Fuel evolution shows deficit from U-235
- Systematics improvements of DYB expected with special calibration, FADC, LS replacement.
- Major progresses in JUNO construction
  - ⇨ 35.4-meter acrylic sphere
  - ⇨ Super-transparent liquid scintillator (>20m)
  - ⇨ High DE PMTs (27%)

Thanks !



Events / 0.25 MeV
12B decays
Data
Best Fit Model
12B signal
12N backg.
Data / best fit
Reconstructed energy (MeV)



Reconstructed Energy / True Energy
Energy Model + 68.3% C.L.
Cross-validation
IBD Positron Energy