Recent Progress on Chinese Neutrino Experiments

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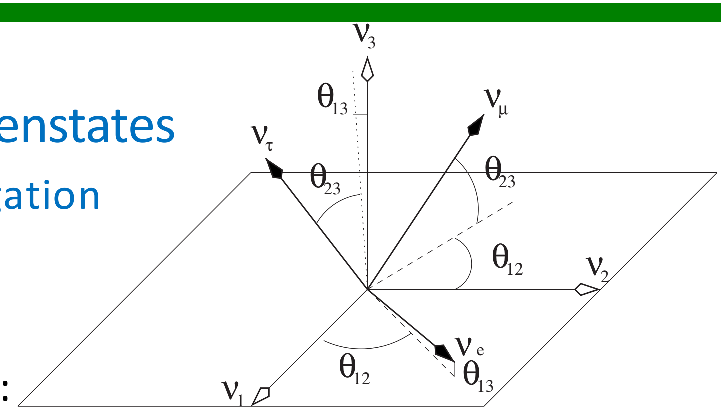
Neutrino mixing

flavor eigenstates
- Production
- Detection

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U^* \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

mass eigenstates
- Propagation



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

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij} \qquad s_{ij} \equiv \sin\theta_{ij}$$

Atmospheric — Reactor + Accelerator — Solar — Majorana

Known:
- **θ_{23}~45°** (Super-K, MINOS, T2K, NoνA)
- **θ_{12}~34°** (SNO)
- **θ_{13}~8°** (Daya Bay, RENO, Double-Chooz)

Unknown:
- Dirac or Majorana?
- 1 Dirac CP Phase δ (Accelerator)
- 2 Majorana phases α_1 and α_2 ($0\nu\beta\beta$)

Neutrino mass

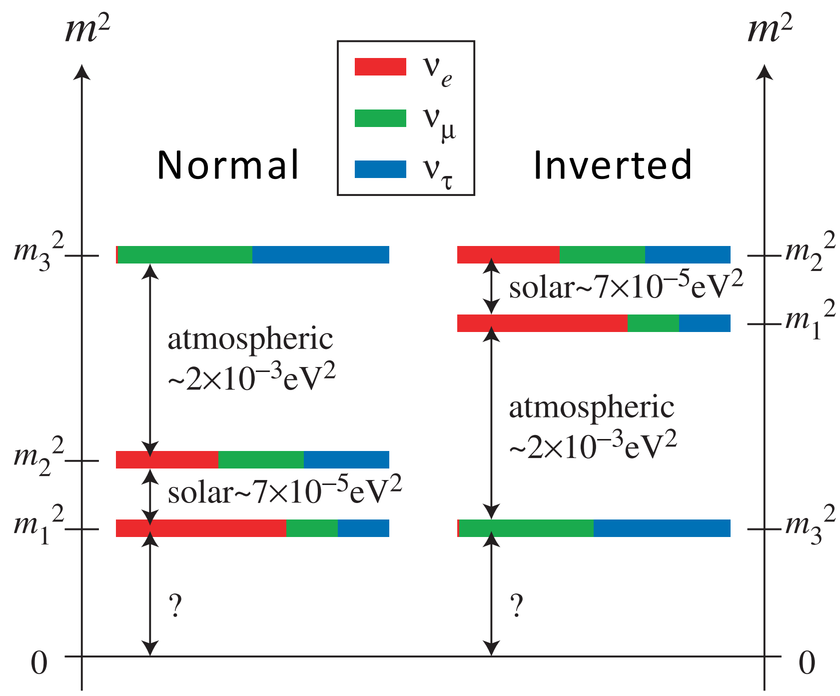
Known:

- 2 independent mass squared difference from Oscillation experiments:
    - $\Delta m^2_{sol} = \Delta m^2_{21} \sim 7.6\times10^{-5} eV^2$ (KamLAND)
    - $\Delta m^2_{atm} \sim |\Delta m^2_{31}| \sim |\Delta m^2_{32}| \sim 2.4\times10^{-3} eV^2$ (Super-K, MINOS, T2K, NOνA， IceCube)

- Upper limits for neutrinos mass
    - $\sum m_\nu < 0.2\ eV$ (cosmology)
    - $\langle m_\beta \rangle < 2eV$ (tritium decay)

Unknown:

- Mass ordering:
    - $m_1 < m_2 < m_3$?
    - $m_3 < m_1 < m_2$?
- Absolute neutrino mass: m_ν=?
- Neutrino mass mechanism
    - See-saw ?
    - Weak Yukawa coupling with Higgs?
    - Others ?



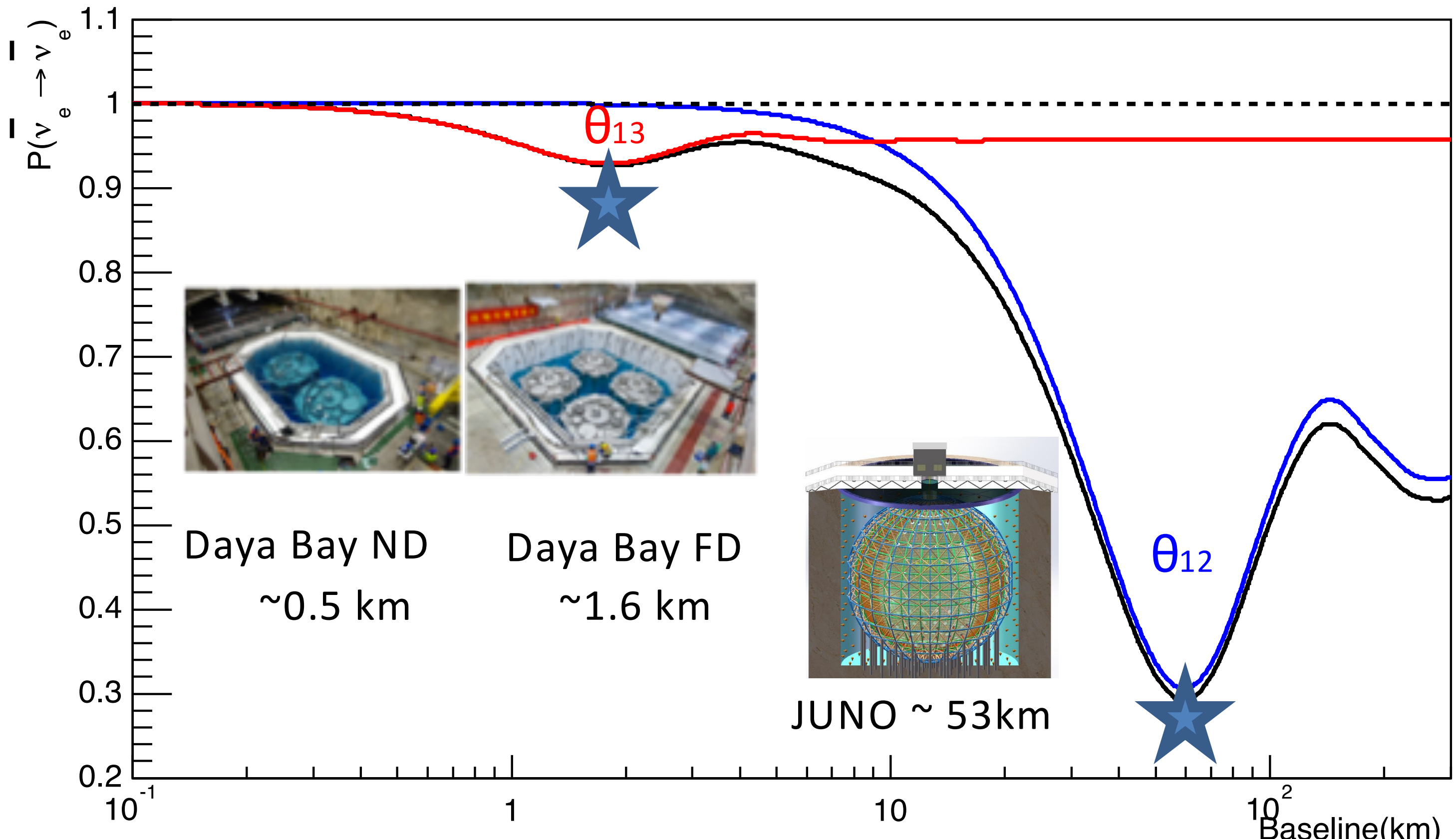
Reactor antineutrino oscillation

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

$$\approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

Insensitive to CP violation and matter effect



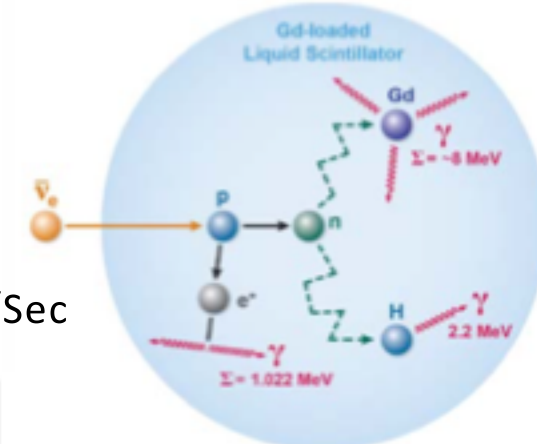
Reactor $\bar{\nu}_e$ production and detection

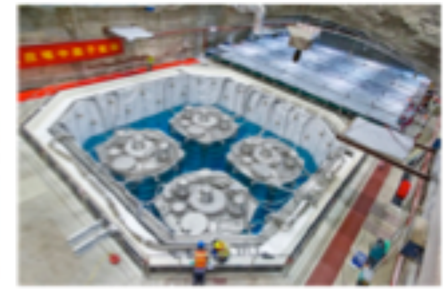
Source: Pure ν_e

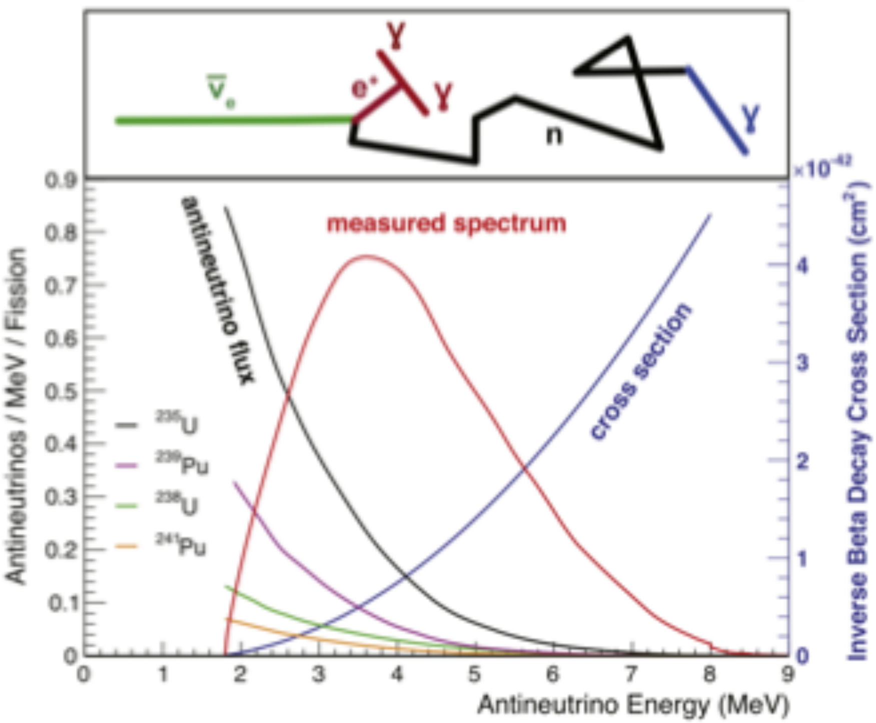
~ 200 MeV / fission

~ 6 ν_e / fission

~ 2 x 10^{20} ν_e/GWth/Sec







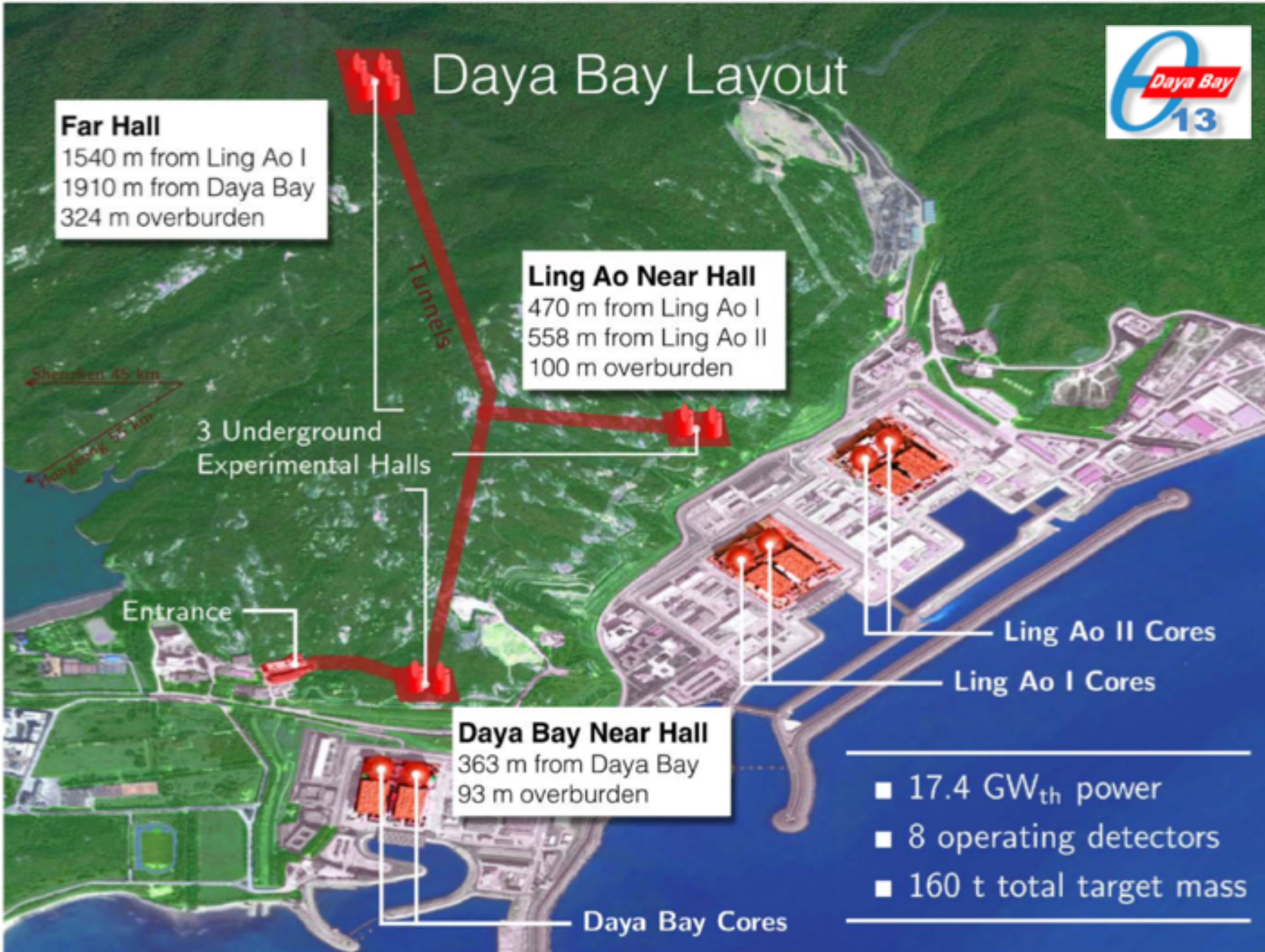
$$S(E_\nu) \approx c \cdot \sum_i f_i \cdot S_i(E_\nu) \cdot \sigma(E_\nu)$$

Observed ν_e spectrum	Isotope fission fraction	Isotope neutrino spectra	IBD Xsec

Detection: Inverse β decay (IBD)

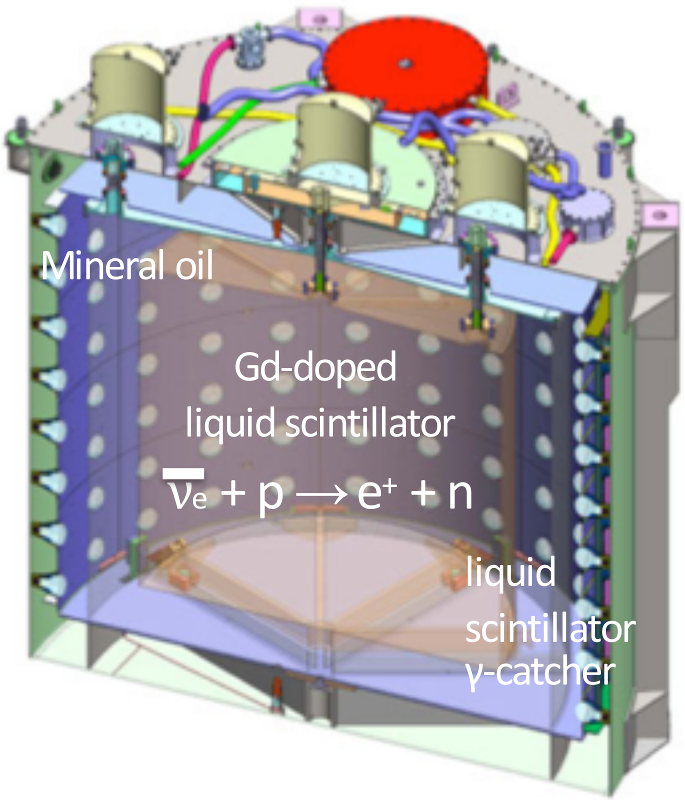
Coincidence signals to suppress background:

- Prompt: e+ $E_p \approx E_\nu - 0.8\ MeV$
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)



Daya Bay Layout
Daya Bay
13
Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden
Tunnels
Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
93 m overburden
17.4 GW$_{th}$ power
8 operating detectors
160 t total target mass
Daya Bay Cores

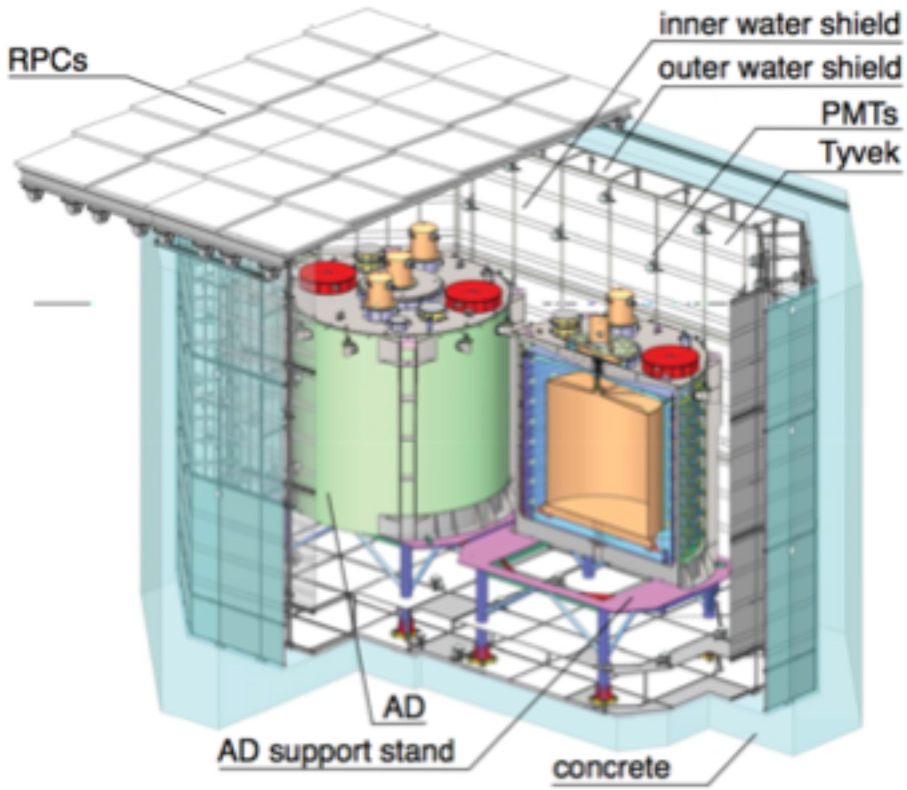
Three-zone antineutrino detectors (AD)



Relative Measurement:

- 8 "identical", 3-zone detectors

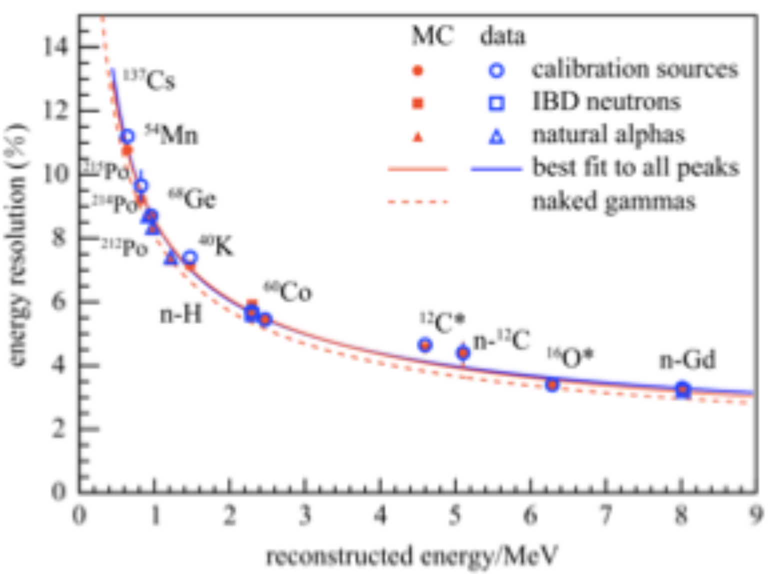
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E_\nu, L_f)}{P_{sur}(E_\nu, L_n)}\right]$$

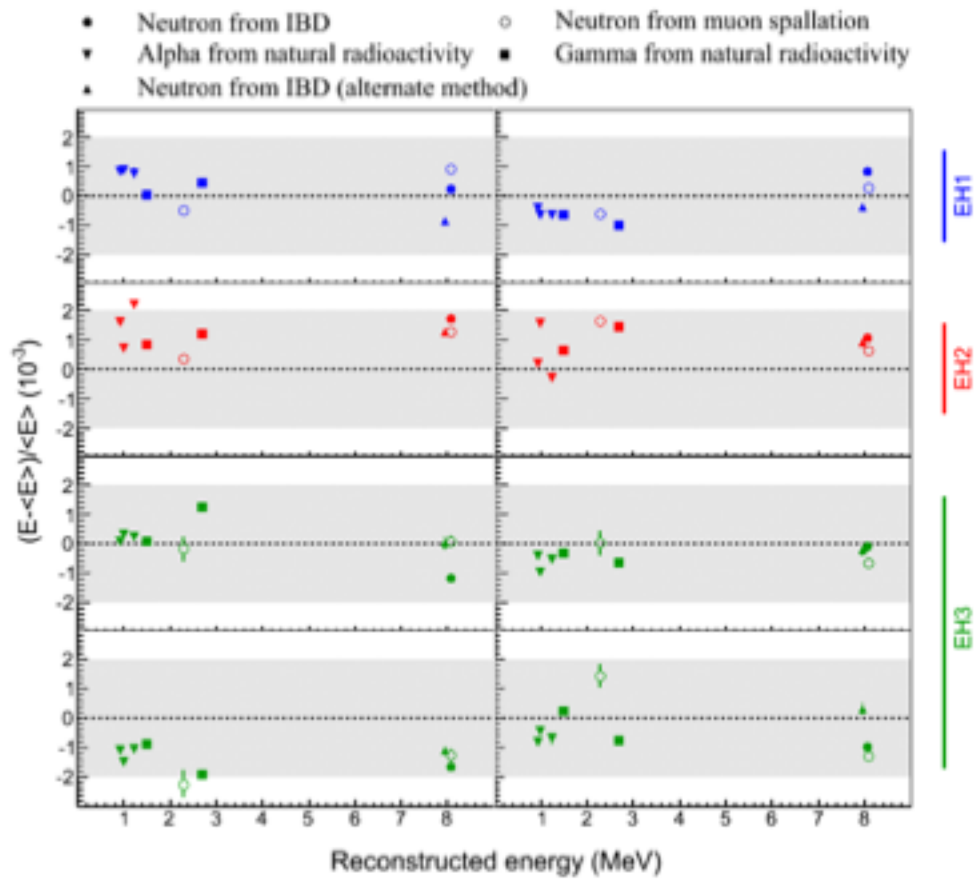


target mass: 20 ton Gd-LS
other masses: 22 ton LS + 40 ton MO
photo sensors: 192 8" PMTs

Detector Energy Response

- Weekly calibration
  - ^{68}Ge, $^{241}Am^{13}C$, ^{60}Co
  - LED diffuser ball
- Special calibration campaign
  - ^{137}Cs, ^{54}Mn, $^{241}Am^{9}Be$, $^{239}Pu^{13}C$
- Spallation neutrons
- Natural radioactivity
- Manual 4π calibration

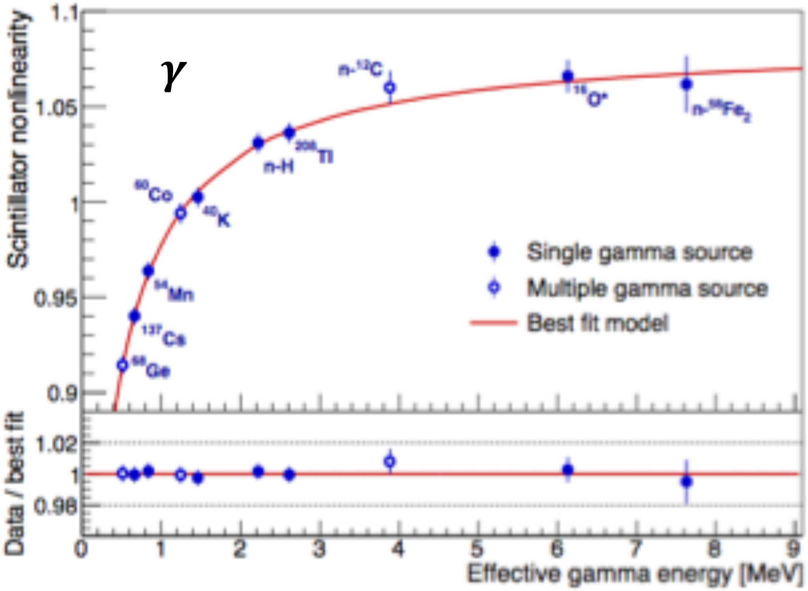


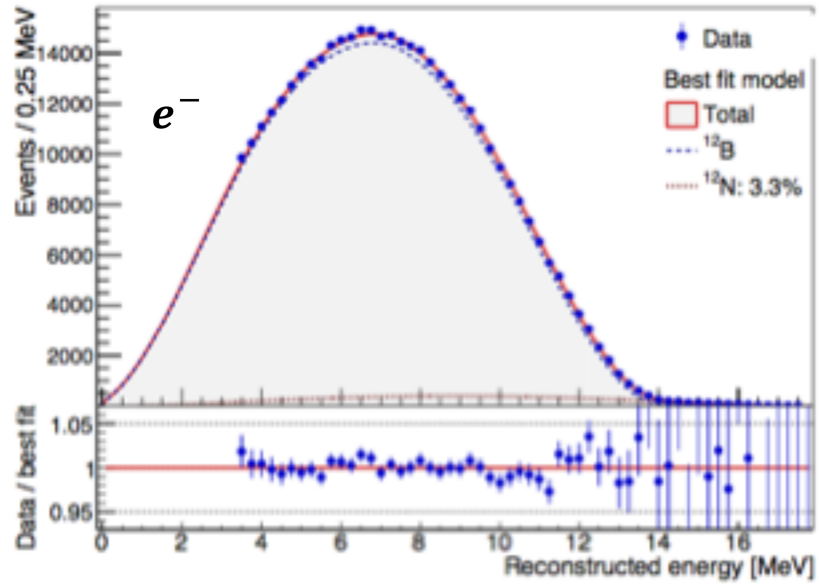


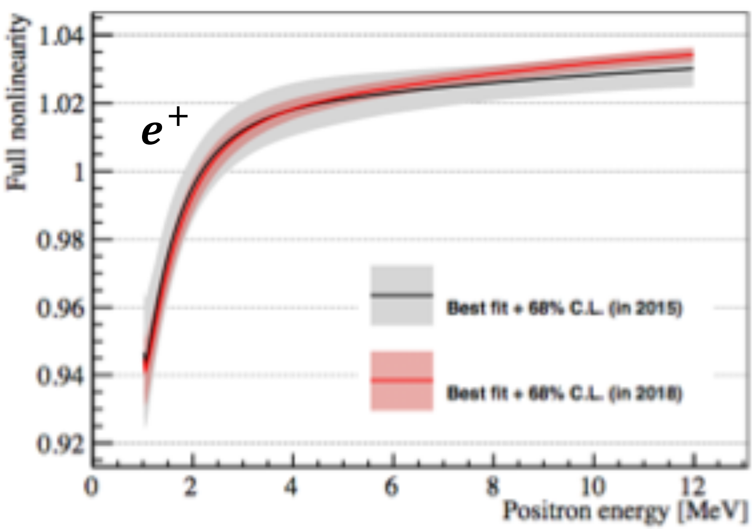
Relative detector energy scale < 0.2%

（0.13% relative detection efficiency）

Energy non-linearity calibration







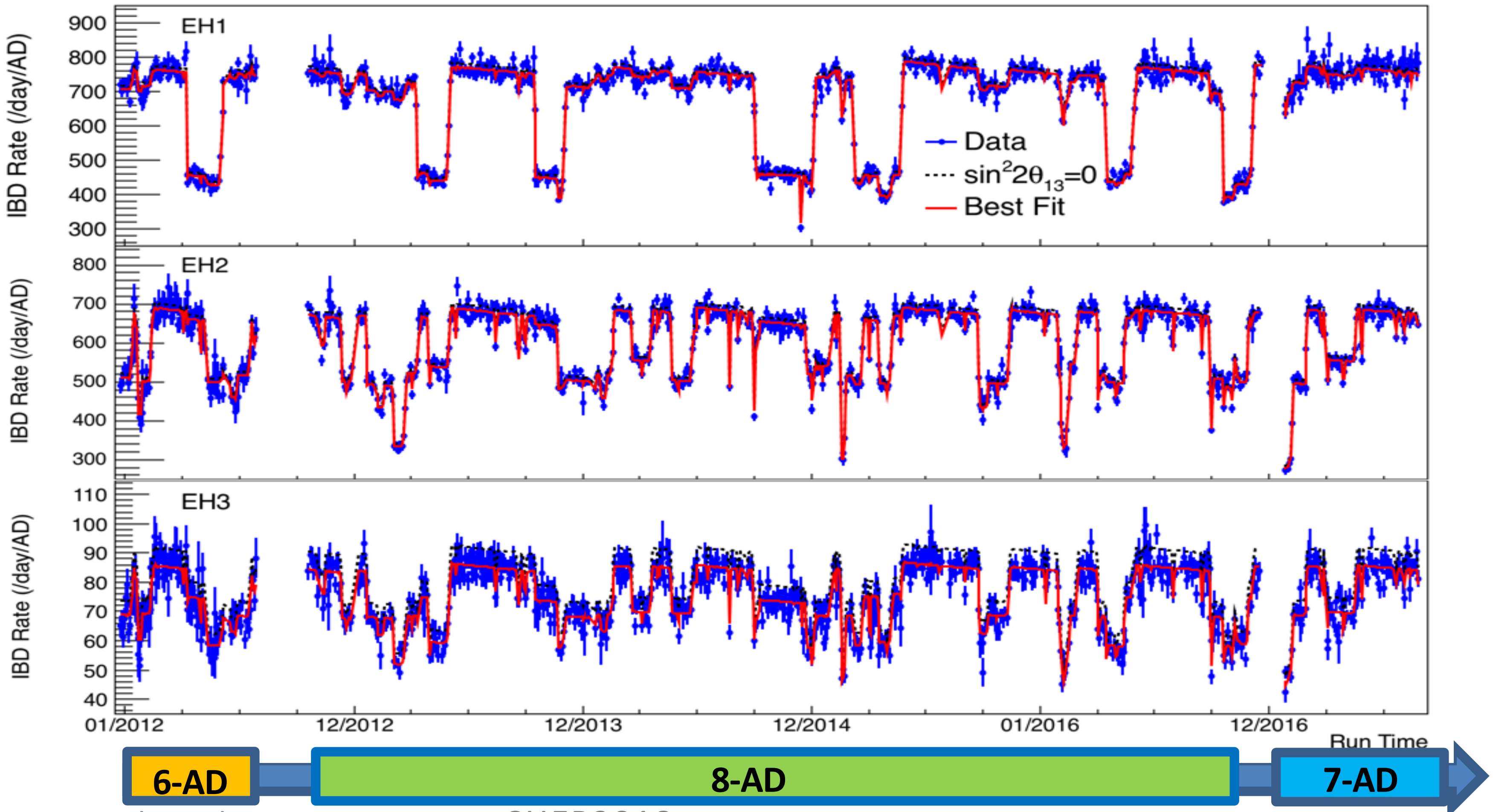
- Two major sources of non-linearity:
  - Scintillator response (Birks + Cerenkov)
  - Readout electronics (FADC correction)
- Energy model for positron is derived from measured gamma and electron responses using simulation.

~0.5% uncertainty (correlated among detectors)

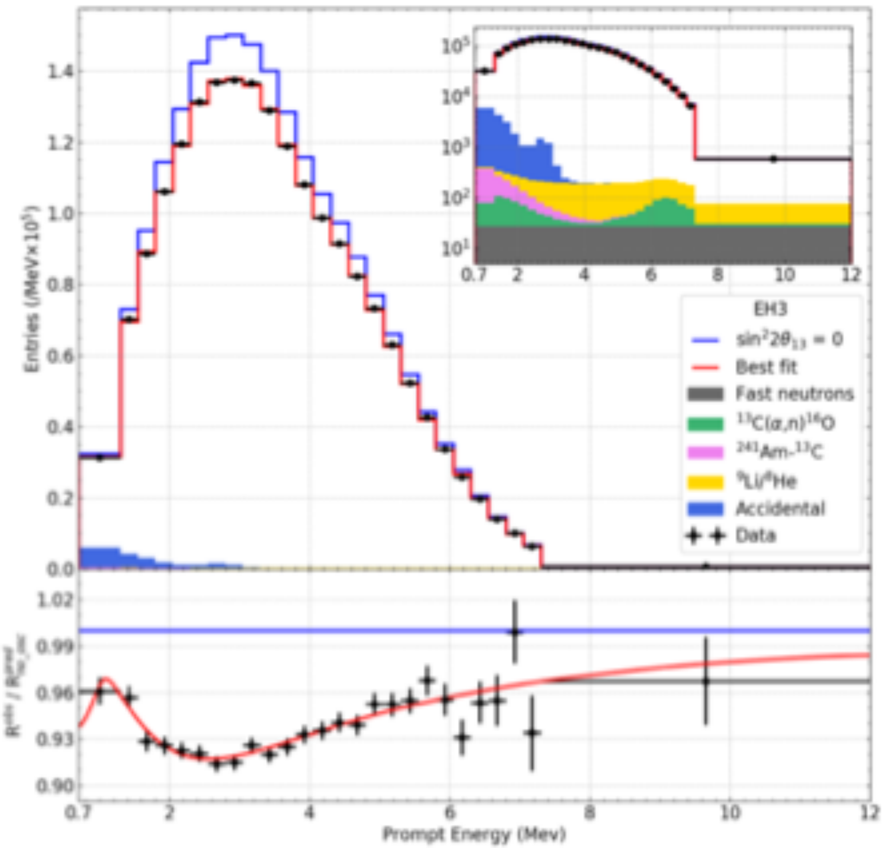
~ 4 million IBD candidates

2011/12/24 – 2017/08/30 (1958 days)

Site	EH1 (Near)	EH2 (Near)	EH3 (Far)
IBD candidates	1,794,417	1,673,907	495,421



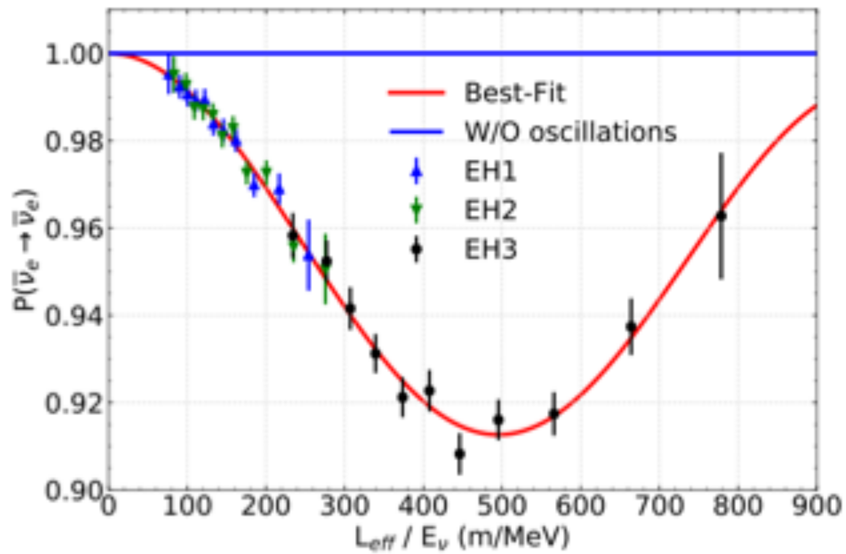
Rate + shape oscillation analysis



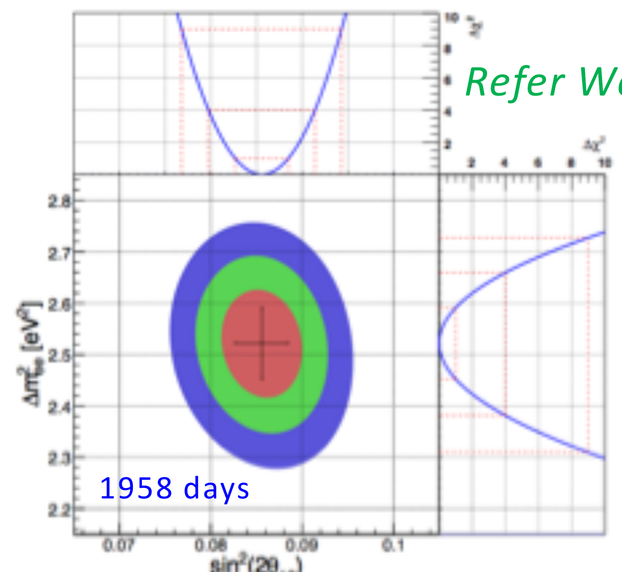
$$sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

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

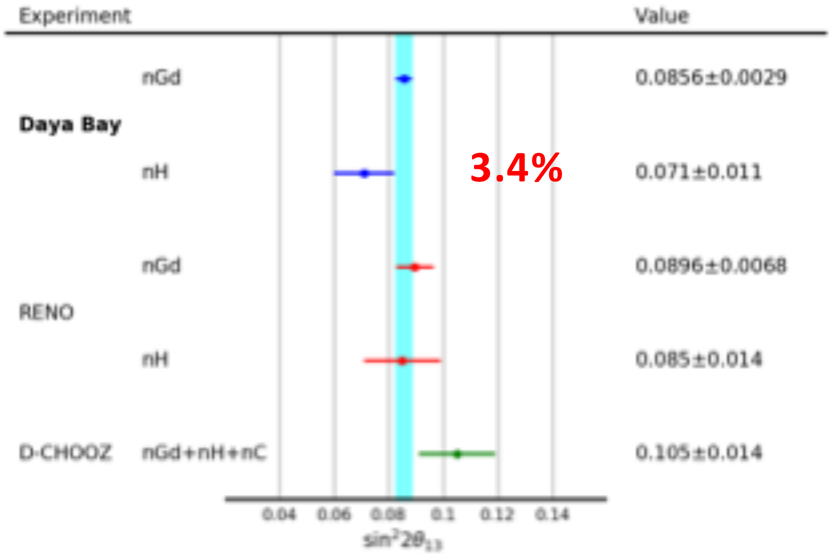
Consistent with 3-ν oscillation

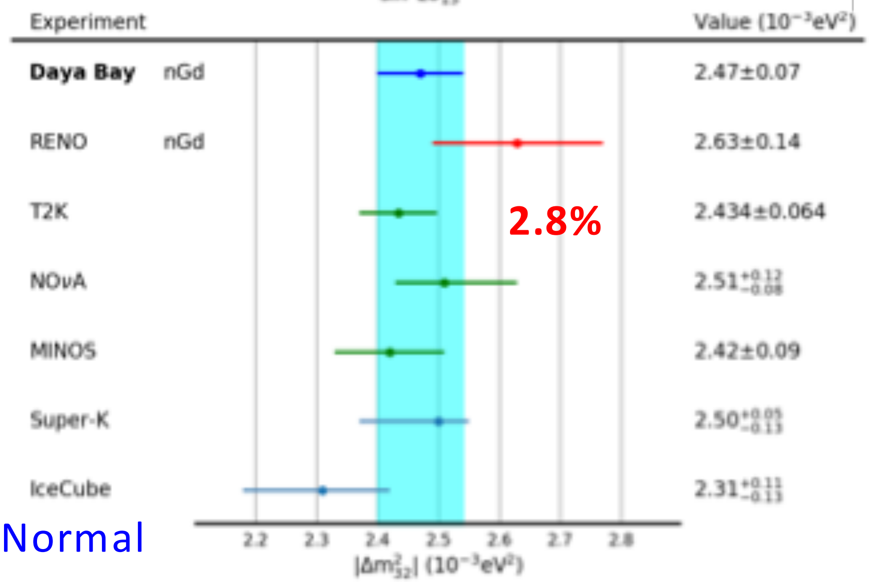


Refer Wenjie Wu's talk

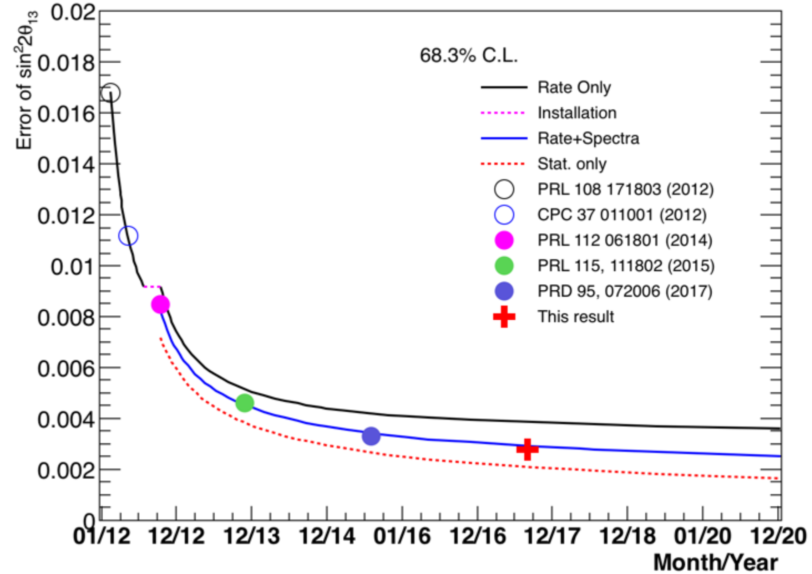


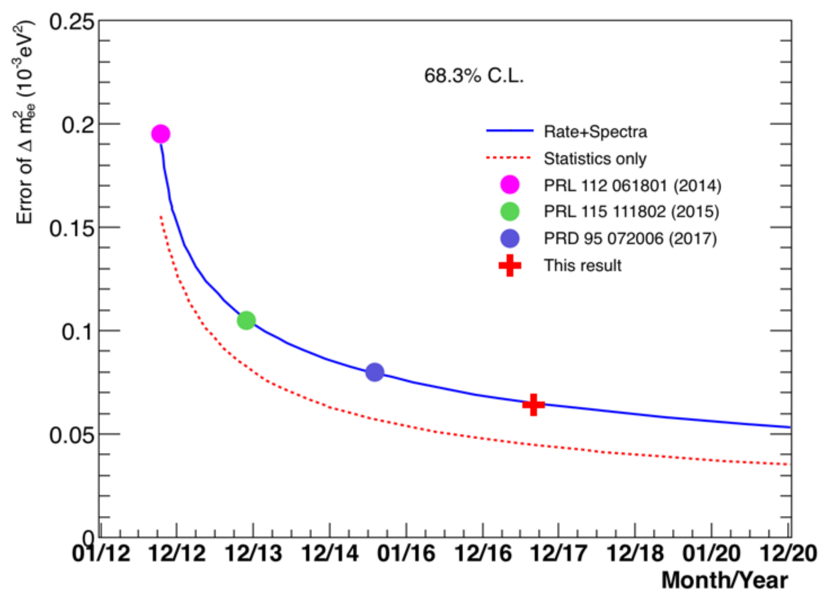
Global comparison



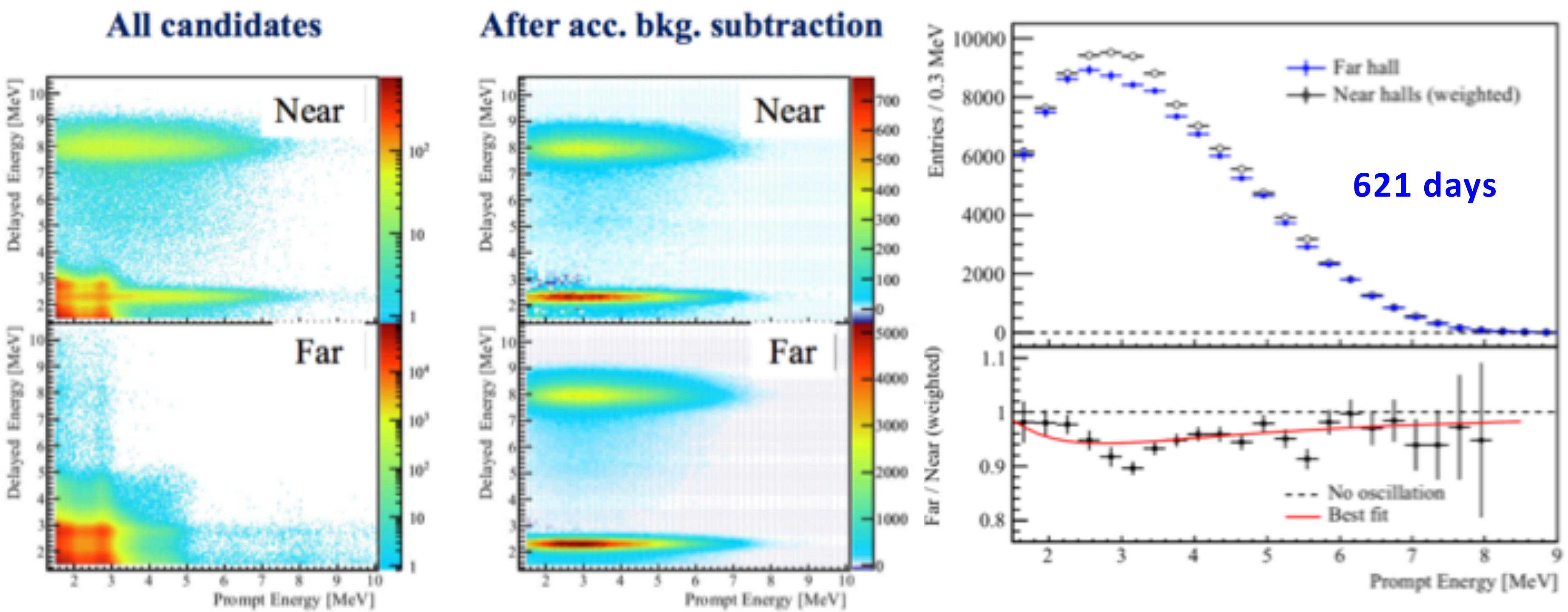


Normal





$\sin^2 2\theta_{13}$ from nH-Captured Analysis



Phys. Rev. D 93, 072011 (2016)

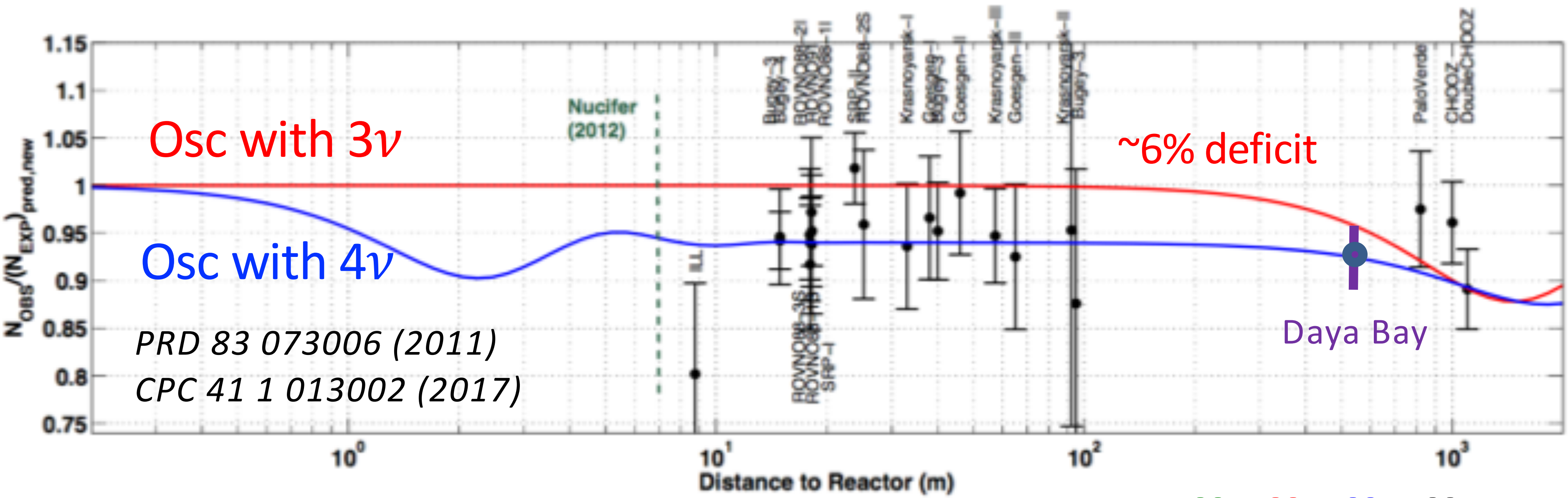
- Independent $\sin^2 2\theta_{13}$ measurement
- Challenging: 12% (54%) accidental background at near (far) site

Rate Only analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.011$

Update results from rate + shape analysis is coming!

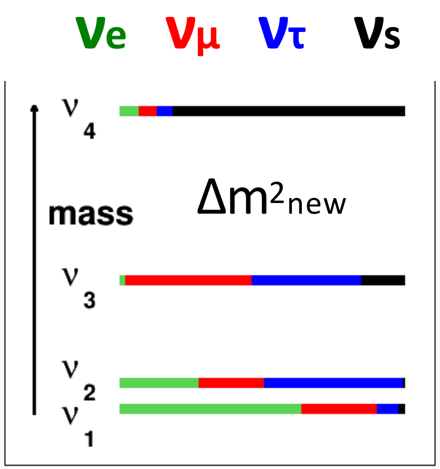
Refer Chao Li's talk

Reactor Antineutrino Anomaly (RAA)



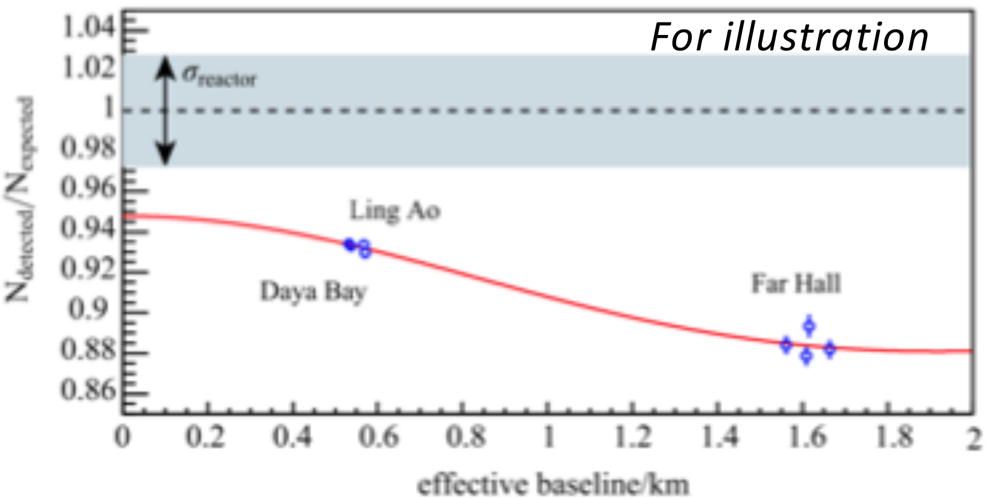
The measured ν_e flux at 10-100 m from reactor cores is ~6% below the theoretical calculation

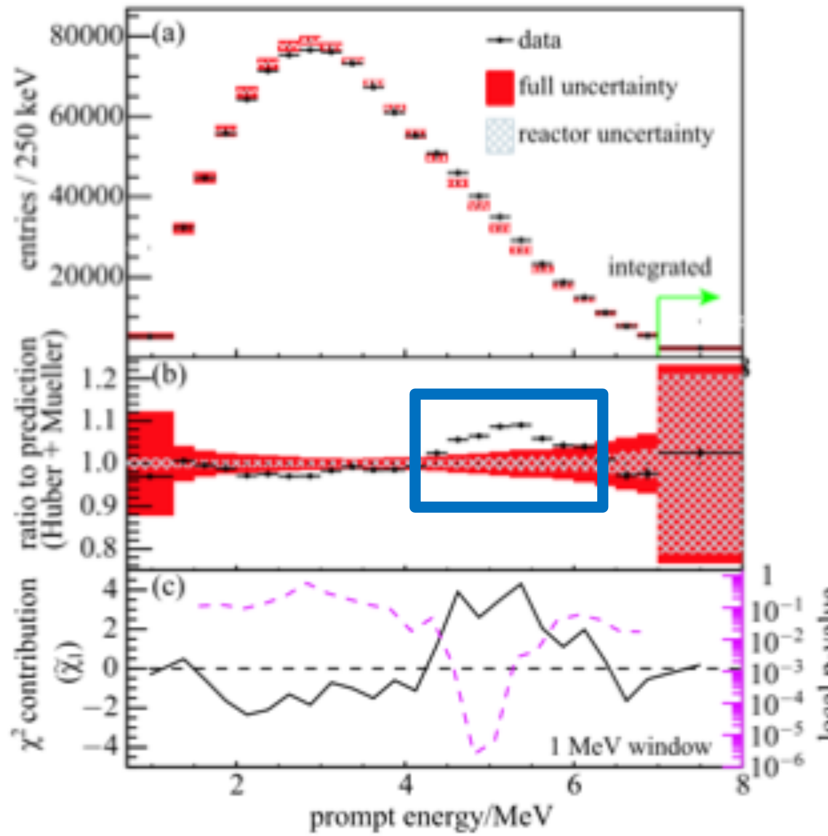
- Theoretical reactor ν_e flux modelling?
  - Systematic uncertainty underestimation (2%→5%) A. Hayes. *PRL.112, 202501 (2014)*
- Sterile neutrinos ($\nu_e \rightarrow \nu_s$)?
  - High frequency oscillation (Δm^2_{new}~ 1-10 eV^2) at baseline of few meters



3 (active)+1(sterile)-υ model

$\bar{\nu}_e$ Flux and spectrum measurement





$$R = \frac{data}{Model\ (Huber + Mueller)}$$

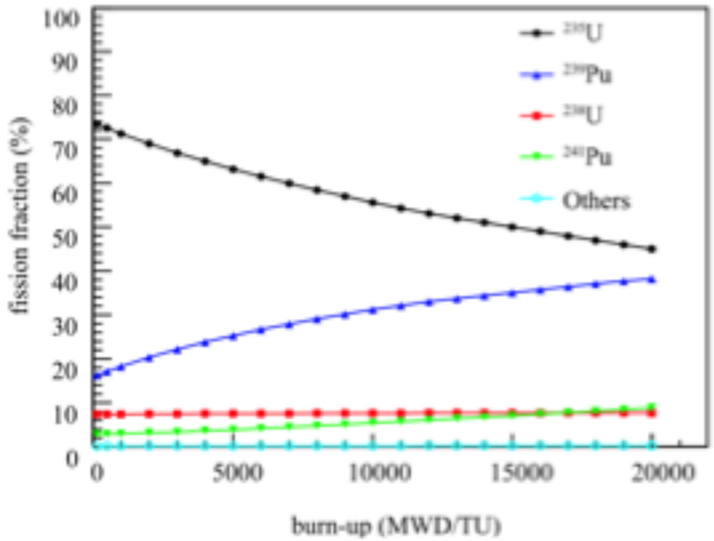
$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

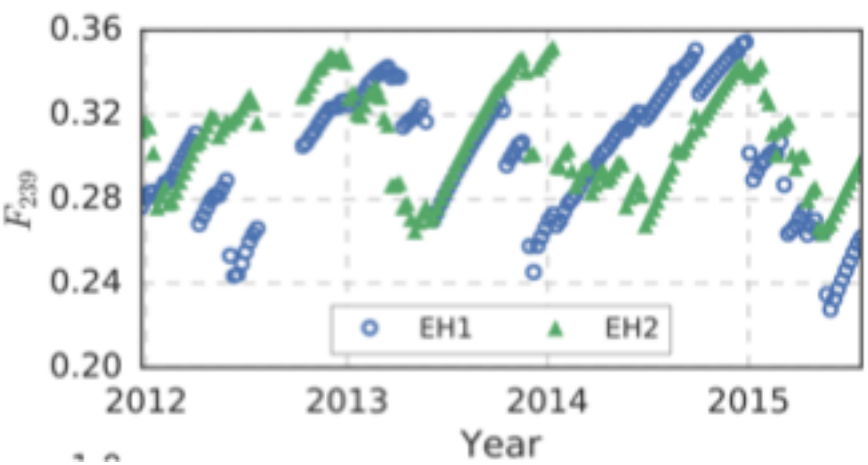
- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total 3σ deviation, especially significant deviation at 4-6 MeV region
- No effect on θ_{13} for far/near relative measurement

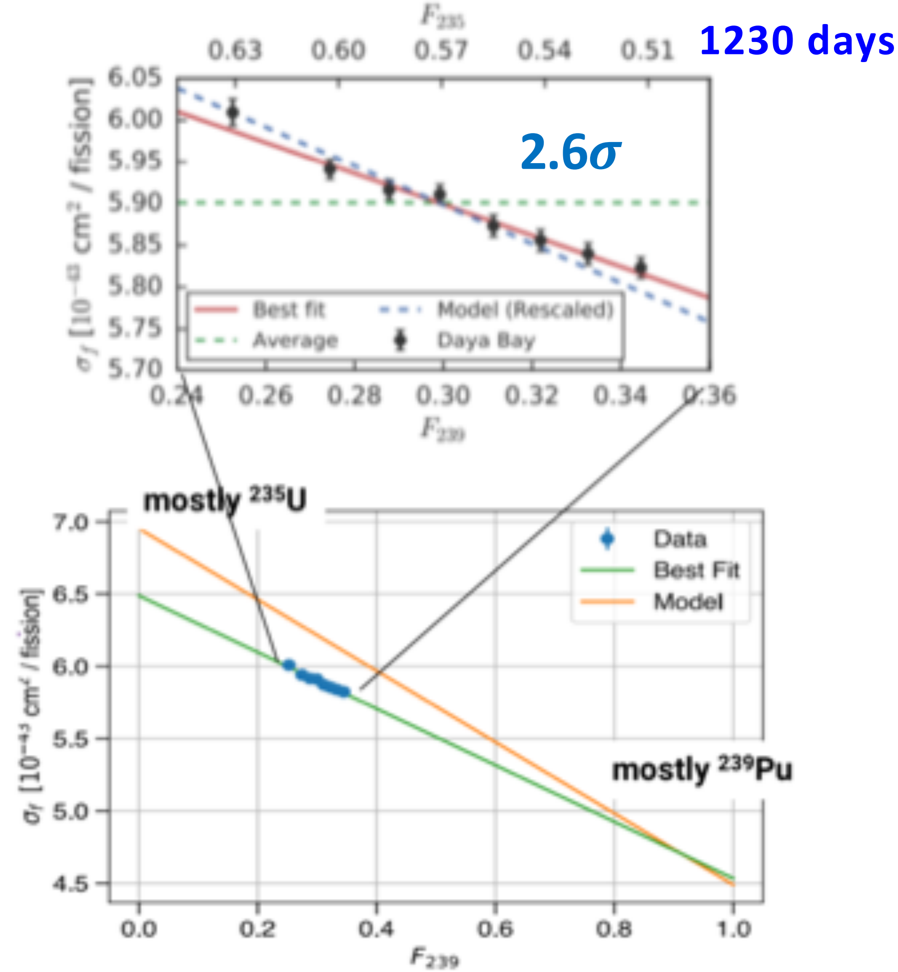
CPC 41.1.013002 (2017)

Reactor Fuel Evolution

Phys. Rev. Lett. 118, 251801 (2017)







- Clear fuel-dependent evolution
- Evolution slope deviates from model: disfavors sterile neutrino only hypothesis

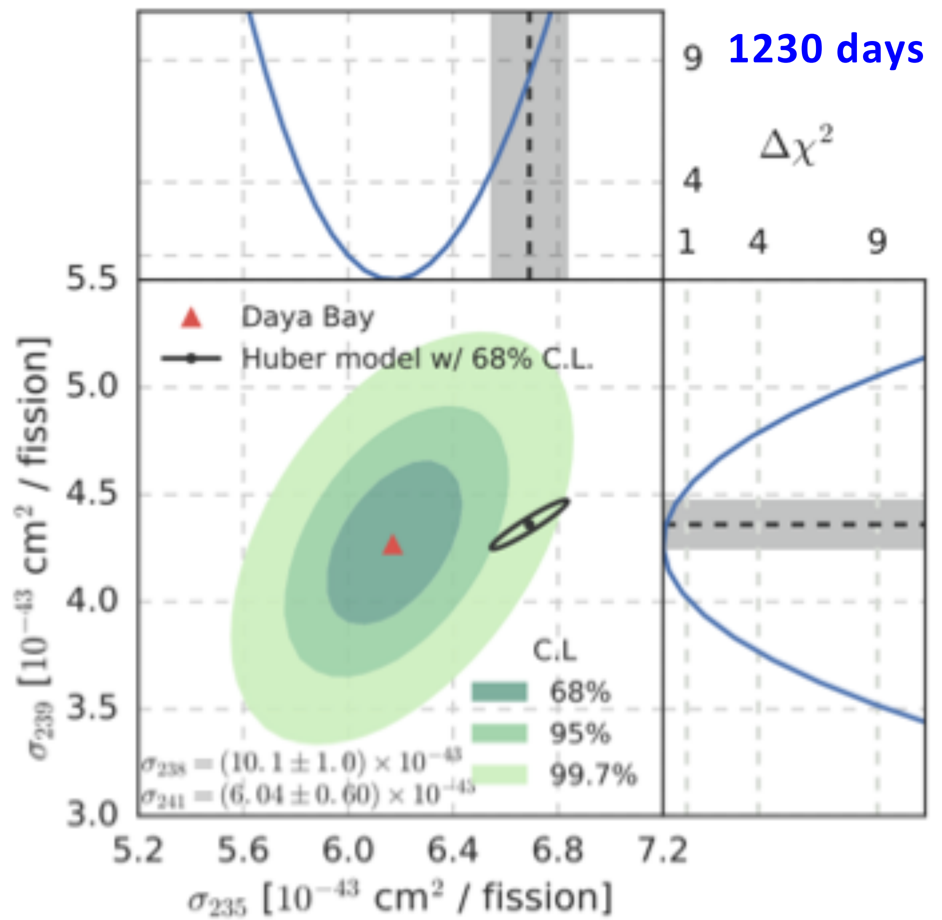
Reactor Isotope $\bar{\nu}_e$ Yield Measurement

- Combined fit of two major fission isotopes ^{235}U and ^{239}Pu

$$\chi^2 = (\sigma_f - F\sigma)^T V^{-1} (\sigma_f - F\sigma) + \sum_{^{238}U,^{241}Pu} \frac{(\sigma_i - \sigma_i)^2}{\varepsilon_i^2}$$

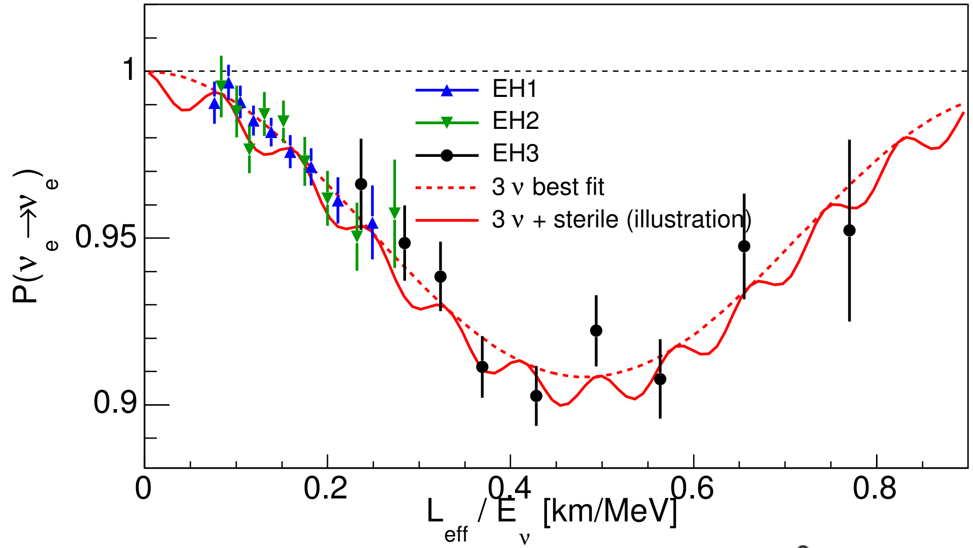
  - The yields of ^{238}U and ^{241}Pu are from model and errors enlarged to 10%
- Sterile neutrino oscillation requires equal deficit for all isotopes
- Sterile neutrino as the sole cause of RAA is disfavored at 2.8σ
- Daya Bay data prefer ^{235}U to be mainly responsible for the RAA

Phys. Rev. Lett. 118, 251801 (2017)

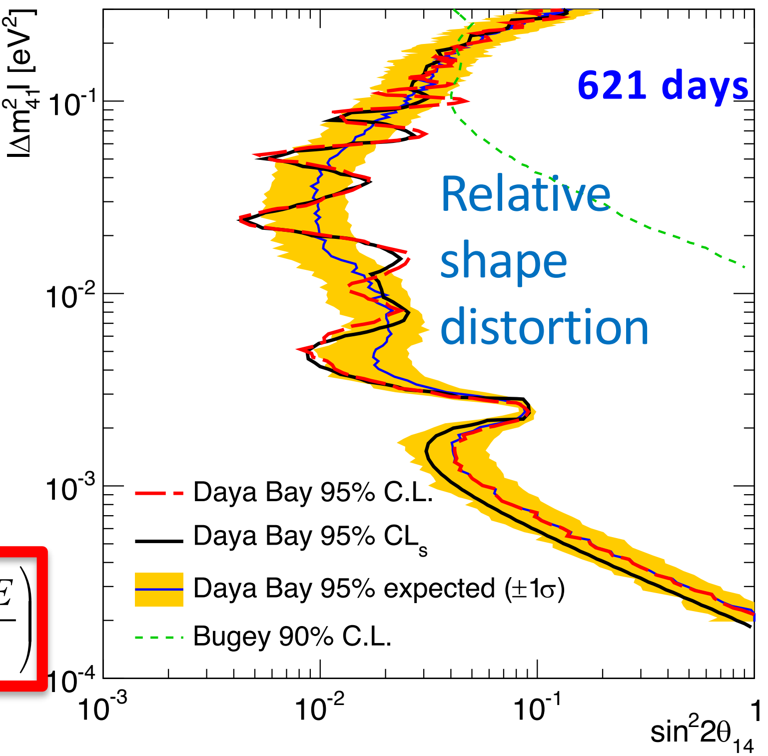


HEU data are important for understanding this issue

Light sterile neutrino search



PRL 117, 151802 (2016)



$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41} E}{4E_\nu}\right)$$

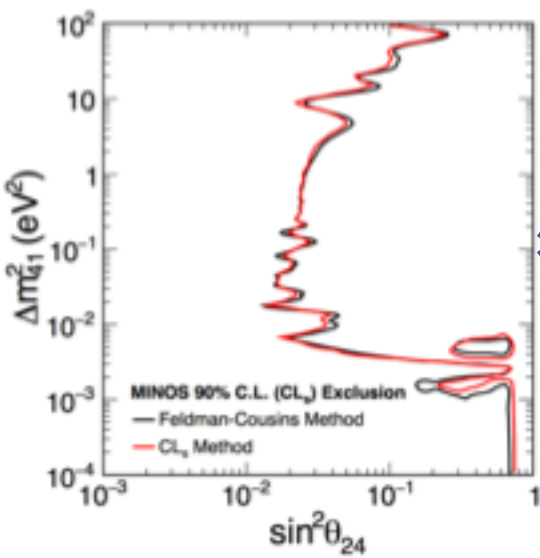
- A minimum extension of the 3-ν model: 3(active) + 1(sterile)-ν model
- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{ee}|$

No light sterile neutrino ($\Delta m^2 < 0.2$ eV^2) signal was found

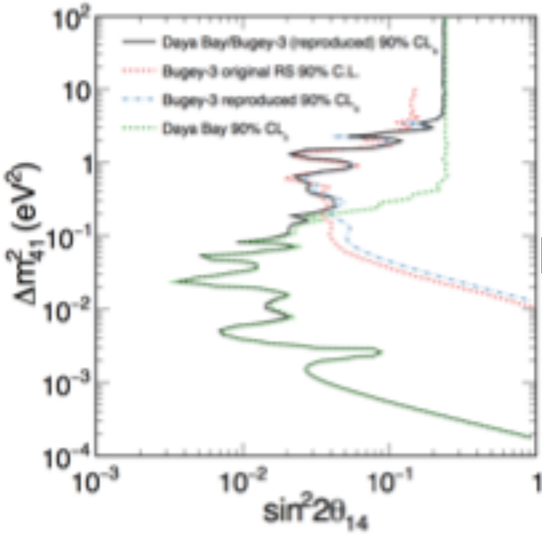
Joint Analysis

PRL 117, 151803 (2016)

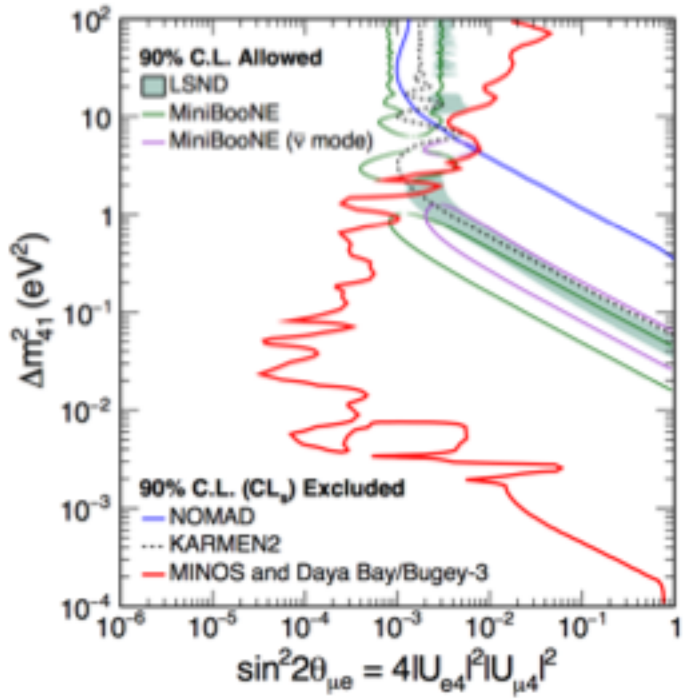
MINOS



Daya Bay + Bugey-3



PRL 117, 151801 (2016)

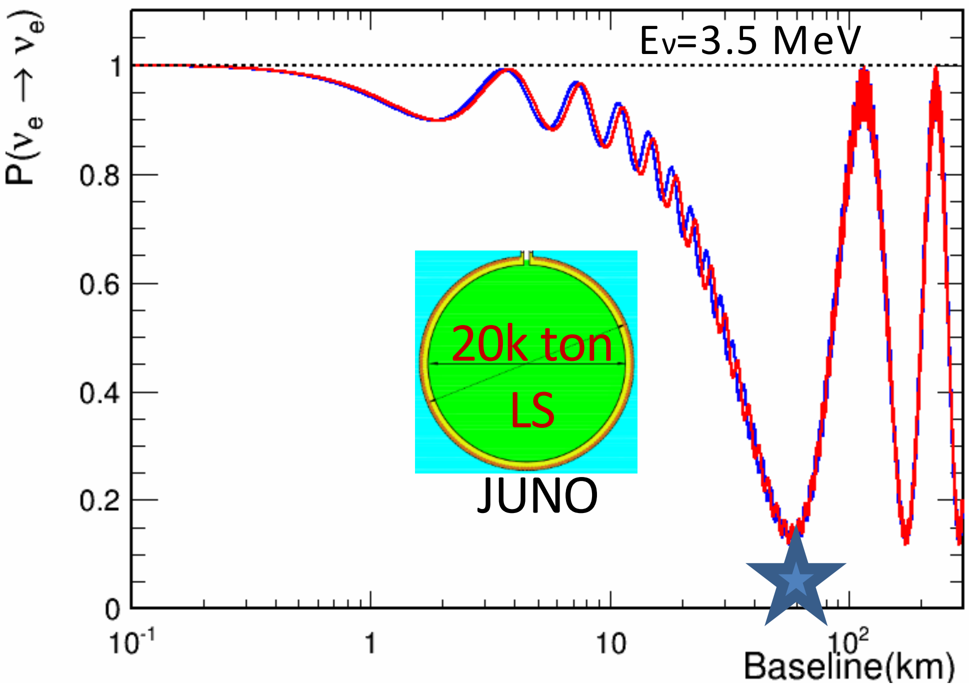


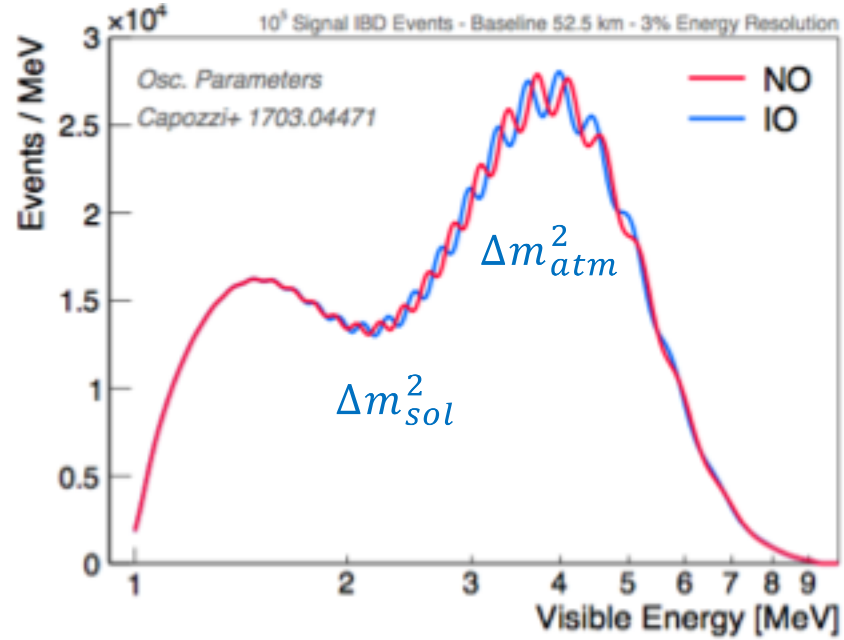
- The combined results can largely exclude the LSND and MiniBooNE region assuming 3+1 neutrino model
- Update results are expected in the near future

The JUNO collaboration

72 institutes from 17 countries, 580 collaborators

Neutrino mass ordering (MO)



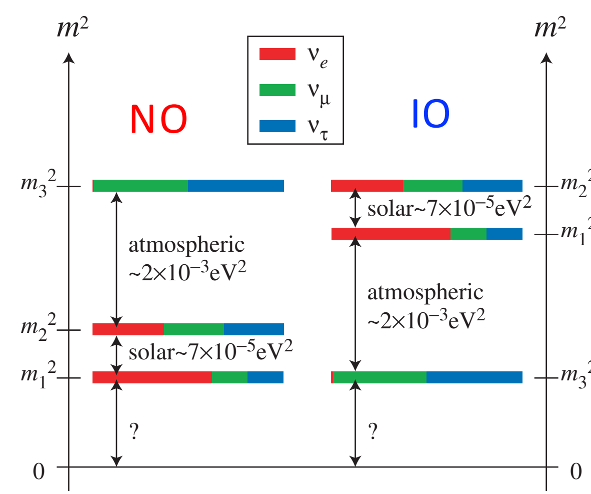


$$P(\nu_e \to \nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

NO : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

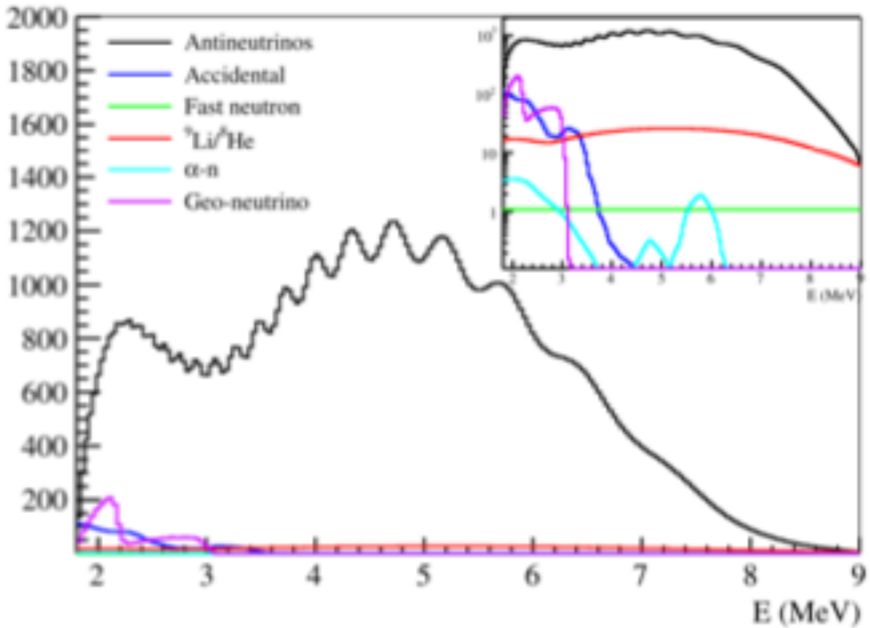
IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

Independent MO determination W/O CP phase

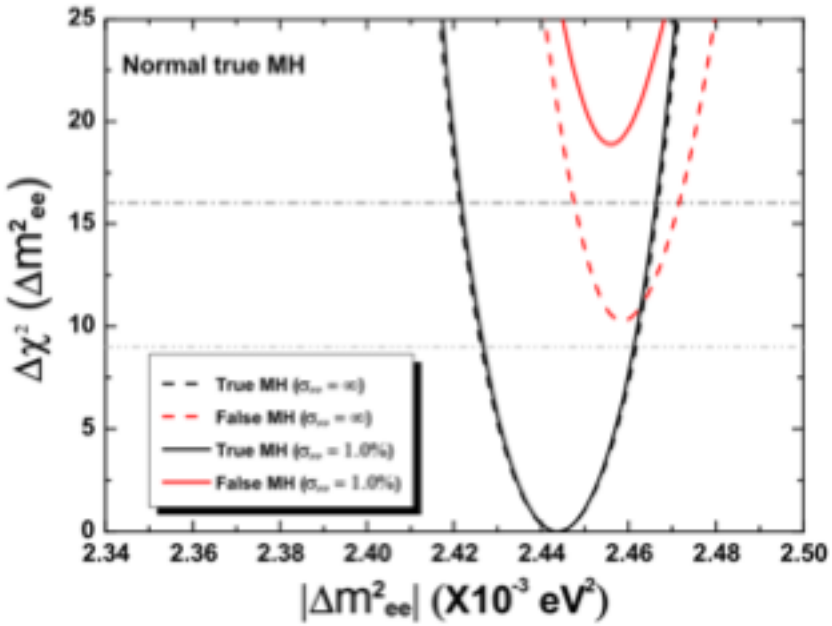


Neutrino mass ordering sensitivity

J. Phys. G 43(2016) 030401



Y-F. Li, Phys. Rev. D 88, 013008 (2013)

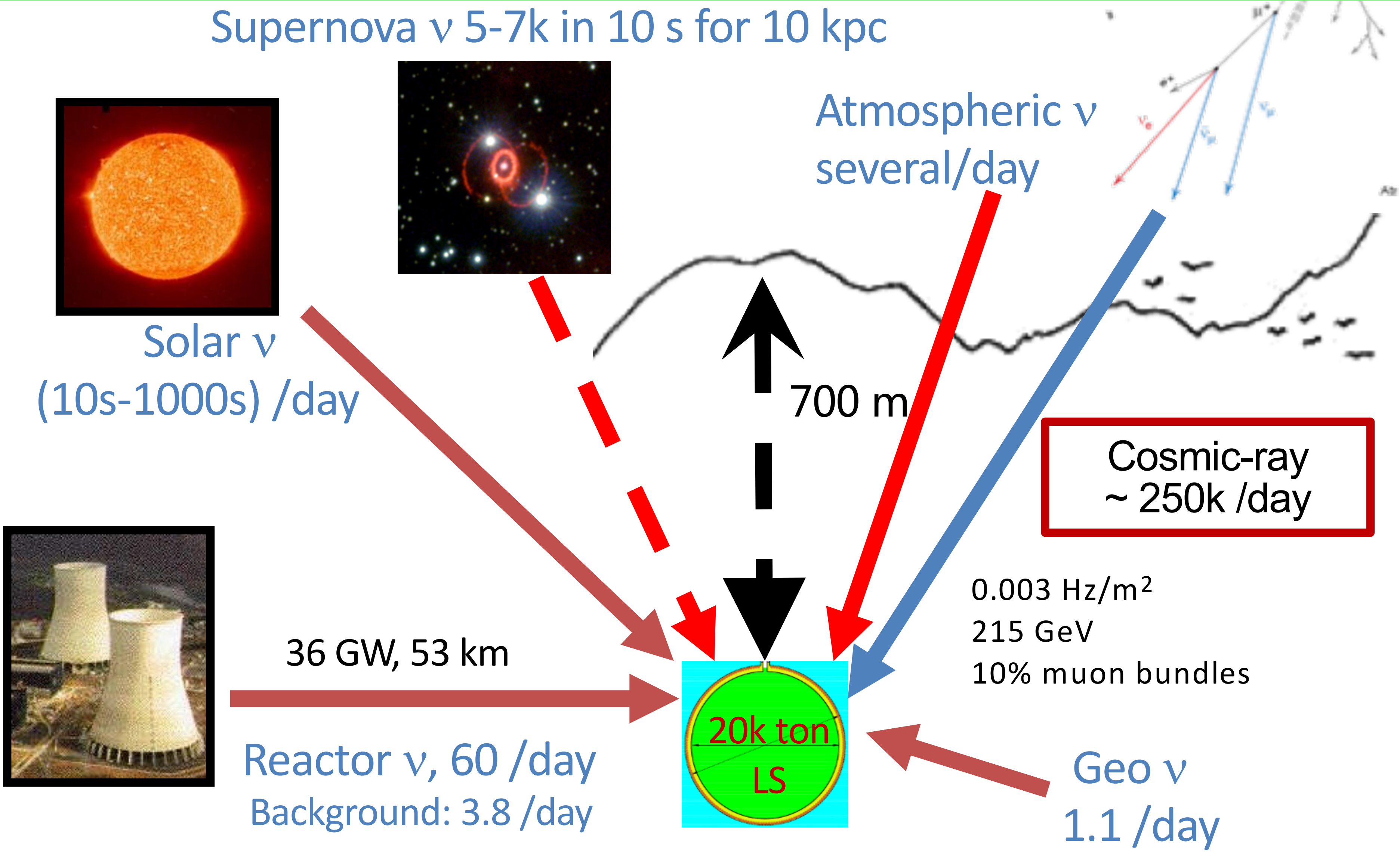


Sensitivity with 100k events (20k ton LS + 6 years with 36GWth reactor power)

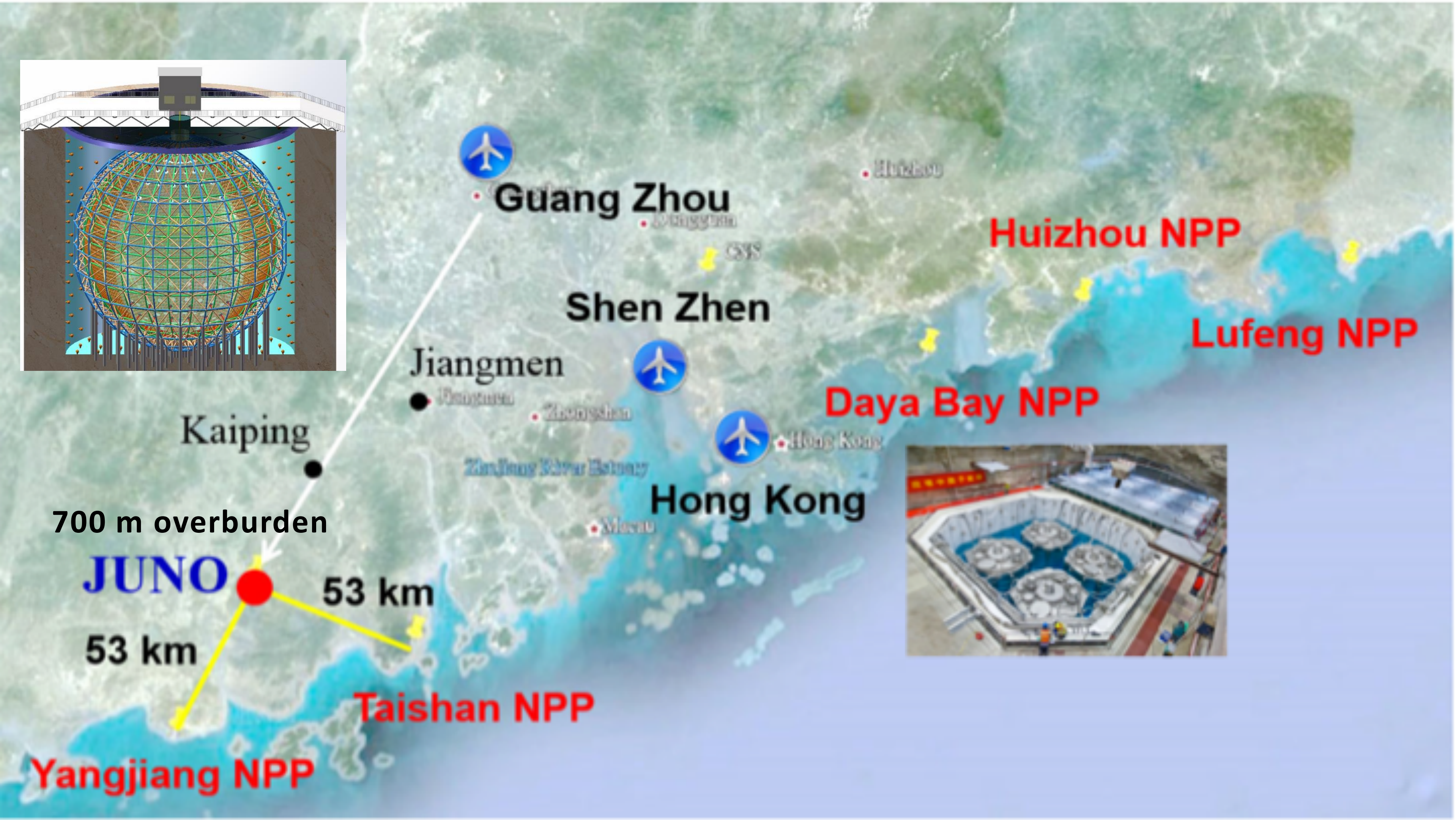
- 3% energy resolution, <1% energy calibration
- **$\overline{\Delta\chi^2} > 9$ ($\overline{\Delta\chi^2} > 16$ with external 1% $|\Delta m^2_{\mu\mu}|$ constraint)**

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}(\cos 2\theta_{12} - \sin 2\theta_{12} \sin\theta_{13} \tan\theta_{23} \cos\delta),$$

Other rich physics for JUNO



The JUNO site



JUNO detector design

	KamLAND	Borexino	Daya Bay	JUNO
LS Mass [kt]	1	0.278	~0.04 x 8	20
E resolution@ 1 MeV	6%/√E	5%/√E	8%/√E	3%/√E
Light yield [p.e/MeV]	250	500	~180	1200 P.E./MeV
Photon-coverage	34%	30%	12%	77%
E calibration	1.4%	1%	0.5%	<1%

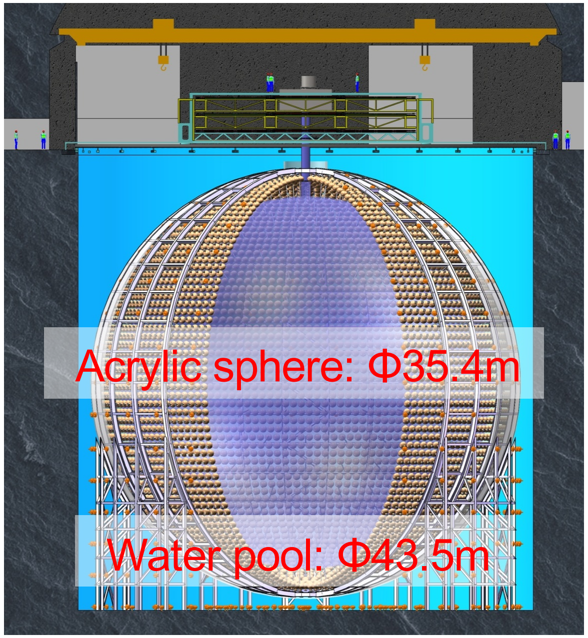
Calibration room

Central detector

SS latticed shell
Acrylic sphere

Liquid scintillator

20 kton



Top Tracker

PMT

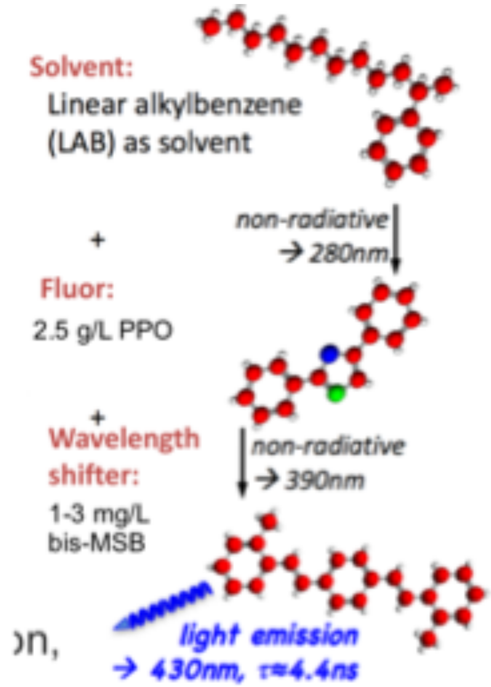
~18,000 20" PMTs +
~25,000 3" PMTs:
coverage 77%

Water Cherenkov

35 kton pure water
2,000 20" veto PMTs

Liquid scintillator

- Requirements for JUNO LS
  - Low background: $^{238}U < 10^{-15}$ g/g, $^{232}Th < 10^{-15}$ g/g, $^{40}K < 10^{-17}$ g/g
  - High light yield: 10^4 PE/MeV
  - High transparency: Attenuation length > 20m@430nm
- Purification pilot plant
  - DYB-AD1 LS replacement
  - Distillation, Al_2O_3 column purification, water extraction and gas stripping
  - Optimize LS recipe
  - Study radioactivity



Double calorimetry

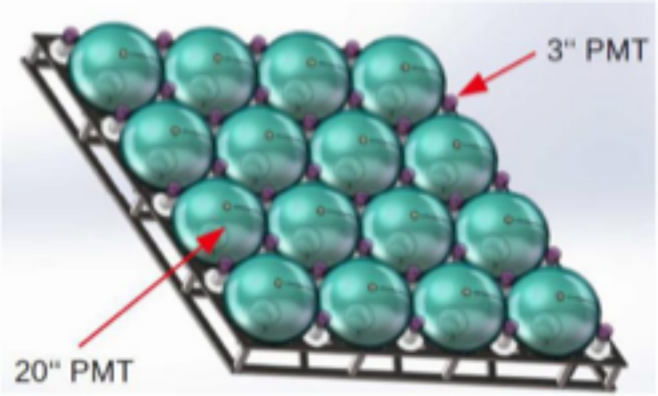
- 20” PMTs (75% photon-coverage)
  - 15,000 MCP-PMTs from NNVT (北方夜视)
  - 5,000 dynode PMTs from Hamamatsu
- 3” PMTs (2% photon-coverage)
  - 25,000 PMTs from HZC (海南展创)
  - Photon counting
  - Extend dynamic range of muon measurements

20” MCP-PMT

20” Dynode-PMT

3.1” PMT

Characteristics	unit	MCP-PMT (NNVC)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE*area)	%	27%	27%
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



3” HZC-PMT

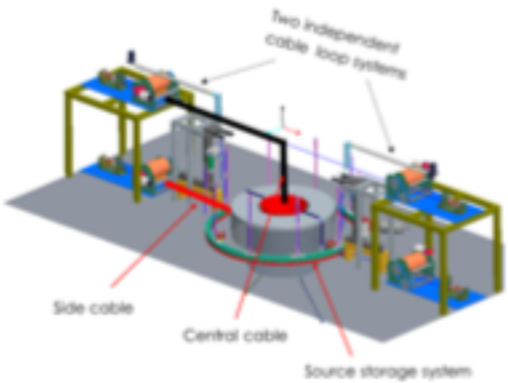
JUNO custom design: XP72B22

QE 24%, P/V 3.0, SPE resolution 30%, TTS 2-5 ns

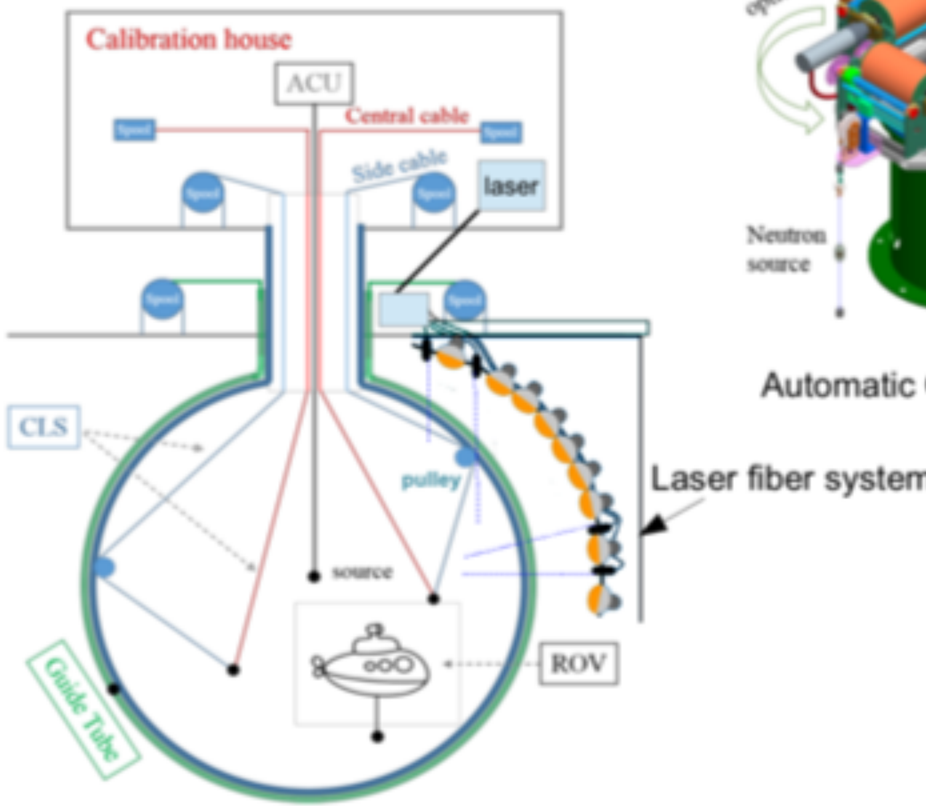
Refer Sen Qian’s talk

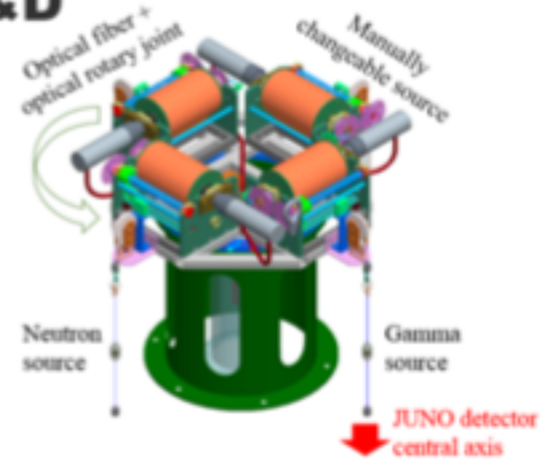
Energy calibration

- **Five complementary systems under R&D**

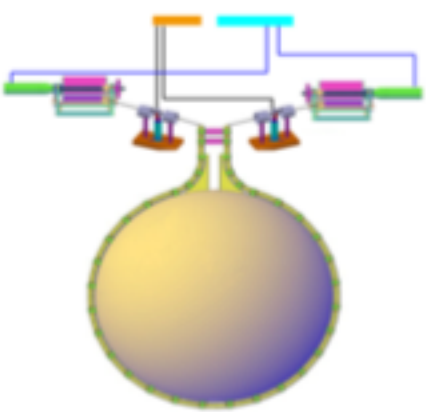


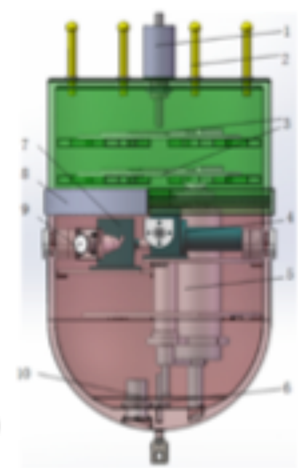
Cable Loop System (CLS)





Automatic Calibration Unit (ACU)


Guide tube system


Remotely Operated Vehicle (ROV)

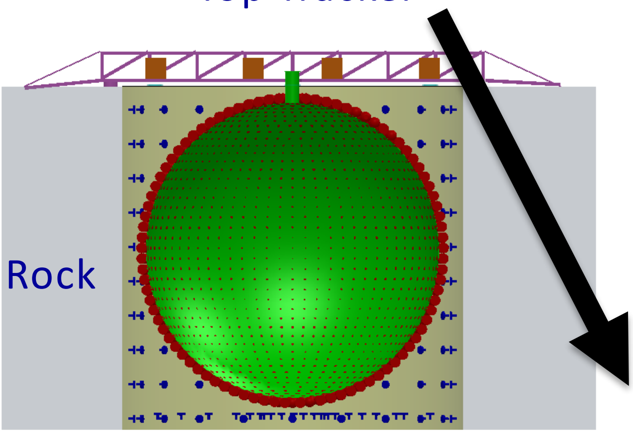
Muon veto

Goal of muon veto

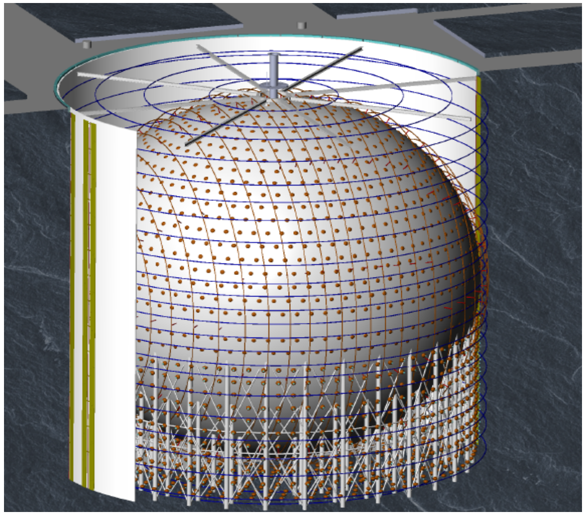
- Active and passive shielding
- Muon tracking and cosmogenic isotope study
- Earth magnetic field shielding for 20" PMTs

- Water Cerenkov detector
  - ~2000 20" PMTs inside EMF veto
  - 35 kton ultrapure water with circulation
  - Muon detection efficiency > 95%
  - Radon control < 0.2 Bq/m^3
  - Fast neutron background ~0.1 /day

- Top tracker
  - Reuse OPERA's target tracker
  - Cover half of the top area

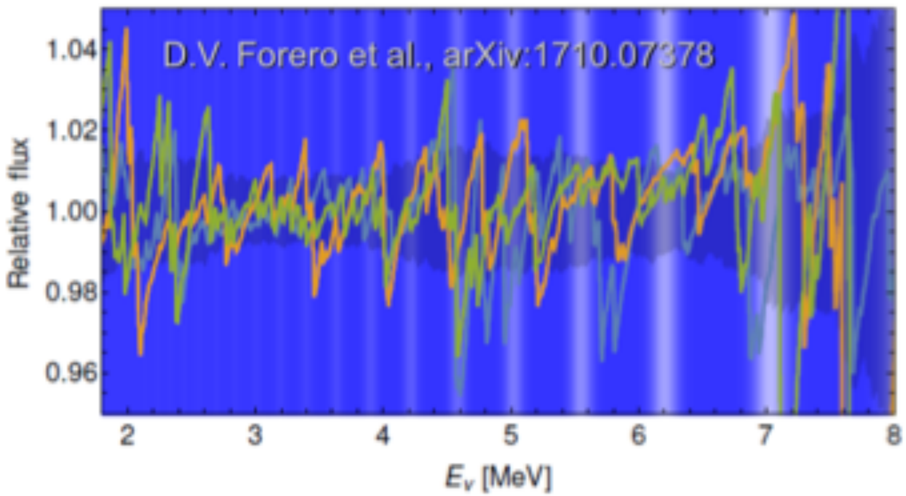


Water Cerenkov detector



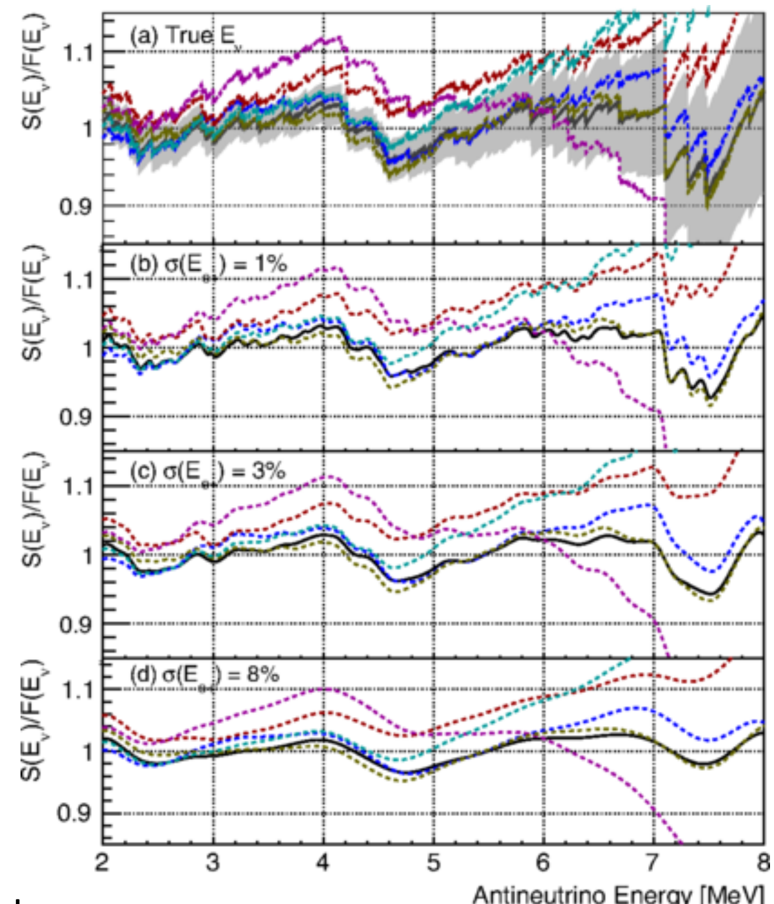
EMF coil shielding

JUNO near detector design



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)

D. Dwyer Phys. Rev. Lett. 114, 012502 (2014)



- 2.9 ton Gd-LS in spherical vessel
- Outer buffer oil in stainless steel vessel
- Central detector size: ~ 2 m × 2 m × 2 m
- @35m to reactor: 10 × JUNO statistics
- Two photon sensor options:
  - SiPM@ -50 ℃ → 1.7% energy resolution
  - 2300 3.5” PMTs → 2.5% energy resolution

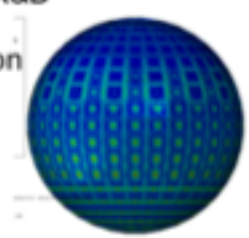
JUNO schedule

2014:

- International collaboration established

2015:

- PMT production line setup
- CD parts R&D
- Start civil construction



2016:

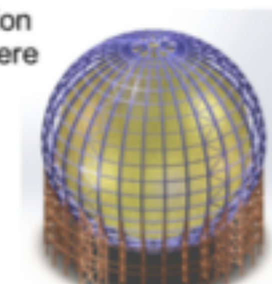
- Start PMT production
- Start CD parts production

2017:

- Start PMT testing
- TT arrived

2018:

- PMT potting starts
- Delivery of surface buildings
- Start production of acrylic sphere

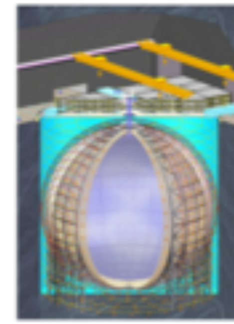


2019-2020:

- Electronics production starts
- Civil work and lab preparation completed;
- Detector constructing

2021:

- Detector ready
- Data taking!



Summary

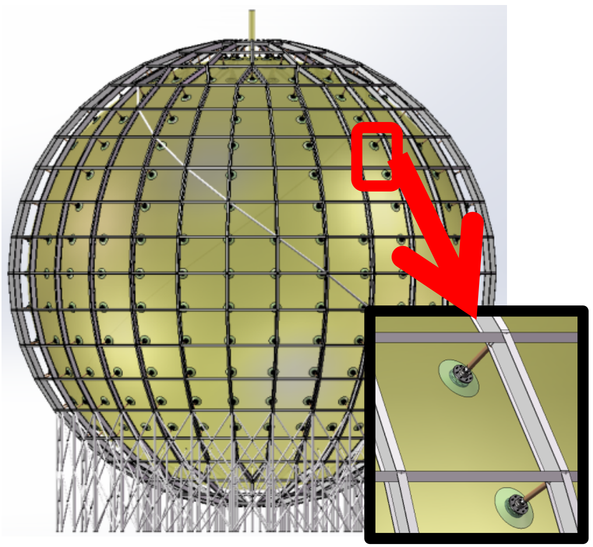
- Neutrino physics has entered the precision era.
- Daya Bay has made the most precise measurements on
  - $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$
  - $|\Delta m^2_{ee}| = [2.52 \pm 0.07] \times 10^{-3}\ \mathrm{eV}^2$
  - Expected to < 3% by 2020.
- JUNO can have independent determination of neutrino mass hierarchy at 3-4σ.
- JUNO will largely advance the reactor neutrino physics and liquid scintillator technology.

backup

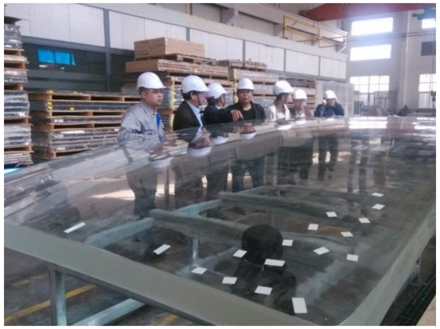
Future prospect of DYB

- Daya Bay will run until 2020
- Will achieve < 3% precision in $sin^2 2\theta_{13}$and $|\Delta m^2_{ee}|$
- EH1-AD1 was taken down and its Gd-LS is replaced with JUNO LS
  - Optimize LS recipes
  - Evaluate purification methods
- Work on improving other analysis
  - Single channel NL correction
  - nH rate + shape
  - Sterile neutrino
  - Fuel evolution
  - Reactor ν flux / spectrum
  - Other new physics topics

Central detector

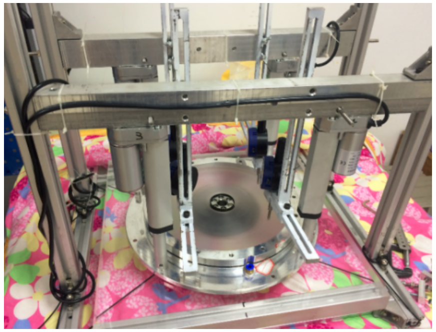


- Acrylic sphere: ID 35.4m, thickness: 120 mm
  - 265 pieces of 3 m×8 m panels
- Stainless steel: ID 40.1 m, OD 41.1 m
  - 30 longitudes and 23 layers
- Weight: ~600 t (acrylic) + ~590 t (stainless steel)
- No. of connecting nodes: 590
- Production company: Donchamp acrylic (汤臣新材料)

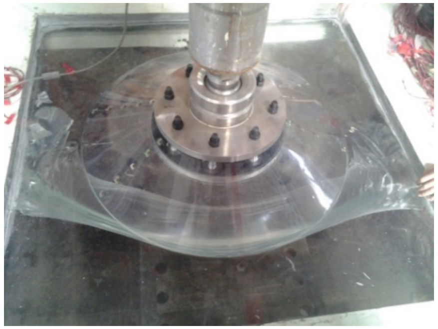


Acrylic panel

Onsite assembly

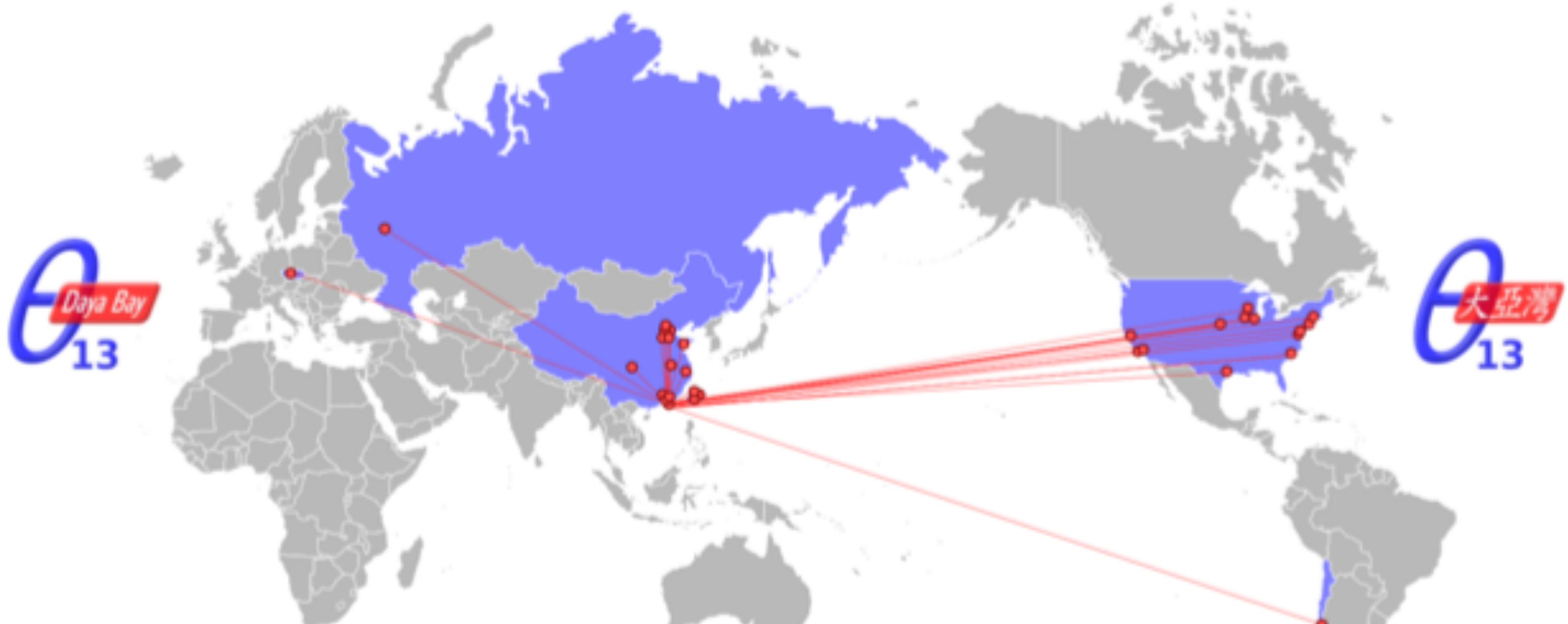


Bonding machine



Node test

The Daya Bay collaboration



Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (15)

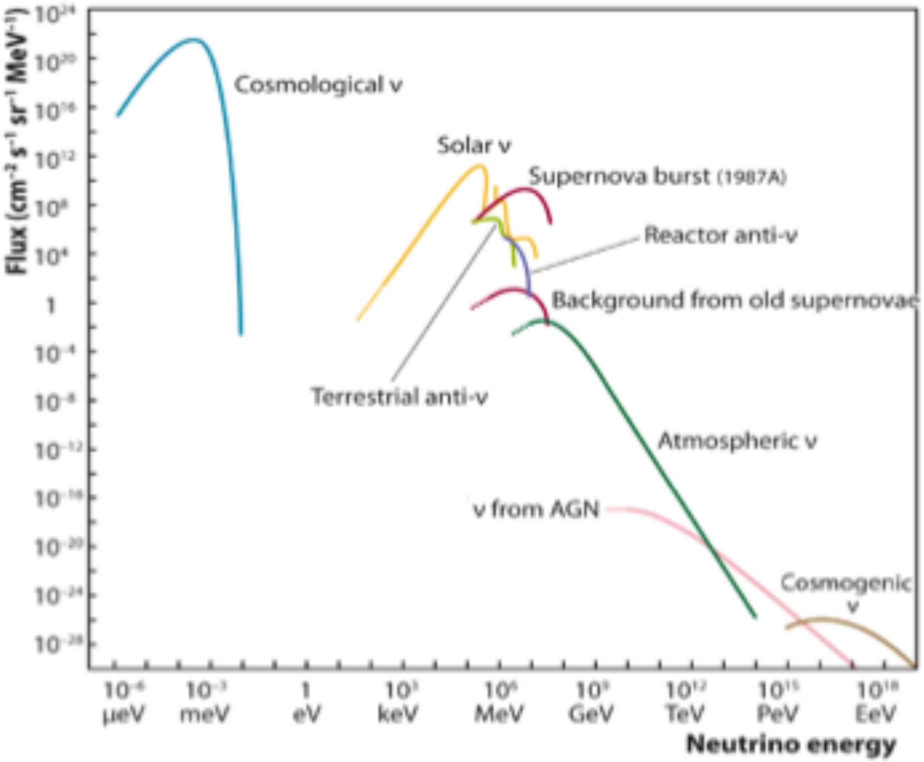
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

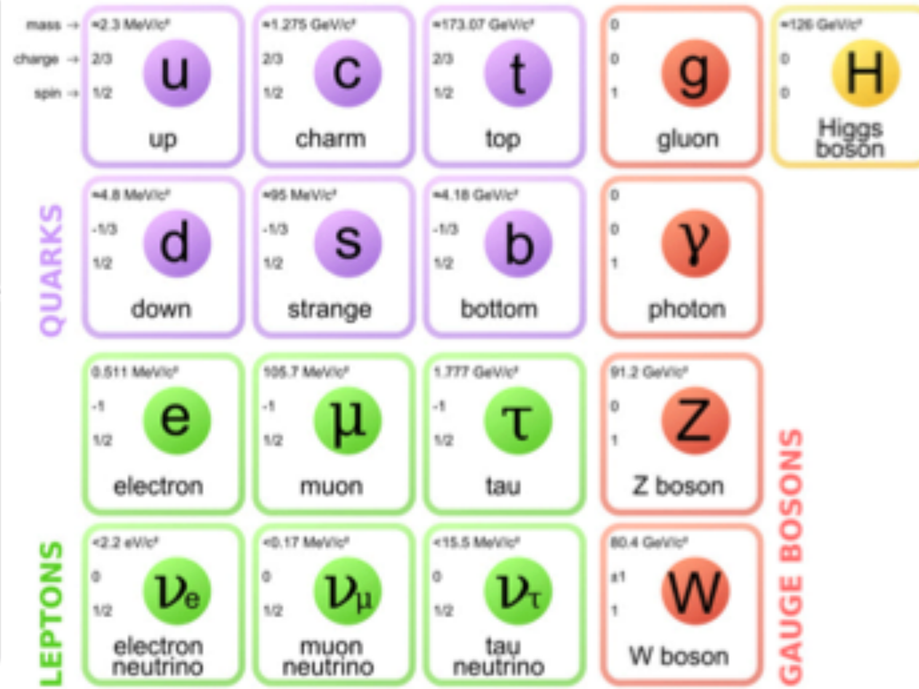
South America (1)

Catholic University of Chile

~200 collaborators

Neutrinos: elementary particles of the universe





Neutrinos in the Standard Model:

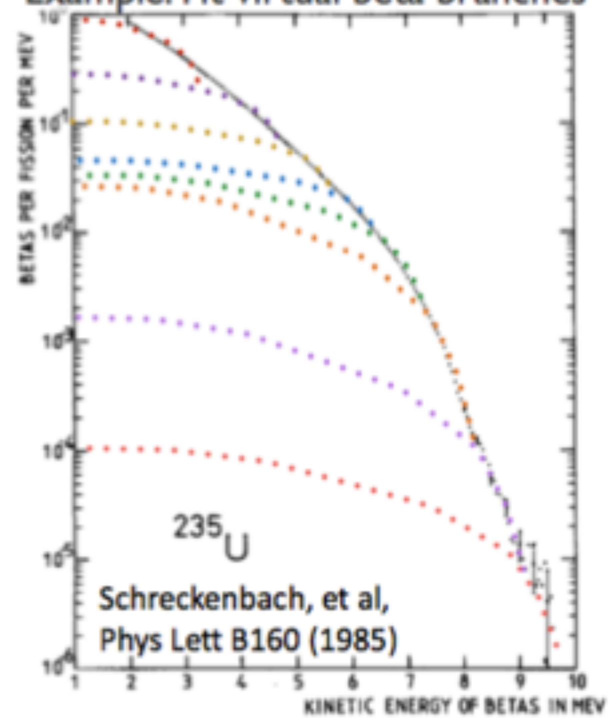
- Three generation of neutrinos and antineutrinos ν_e, ν_μ, ν_τ
- $s = \frac{1}{2}, e = 0, m = 0, v = c$ Only participate EW interactions

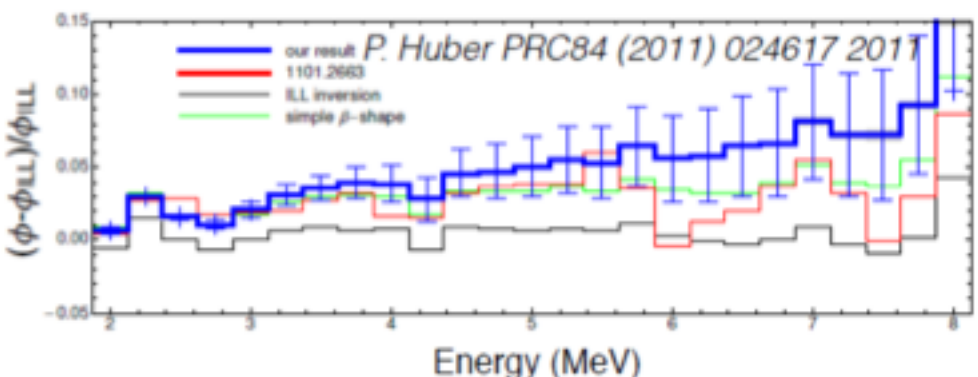
The discovery of neutrino oscillations shows neutrinos have mass (Nobel Prize in 2015)

Reactor $\bar{\nu}_e$ Flux Prediction

- Summation (ab initio) method
  - > 6000 decay branches
  - Missing data in the nuclear database
  - ~30% forbidden decays
  - ~ 10% uncertainty
- Conversion method
  - Convert ILL measured ^{235}U, ^{239}Pu and ^{241}Pu β spectra to υ_e with >30 virtual β-decay branches
  - Old: ILL + Vogel (^{238}U) model (1980s)
  - New: Huber + Mueller (^{238}U) model (2011)
  - ~ 2.4% uncertainty

Example: Fit virtual beta branches

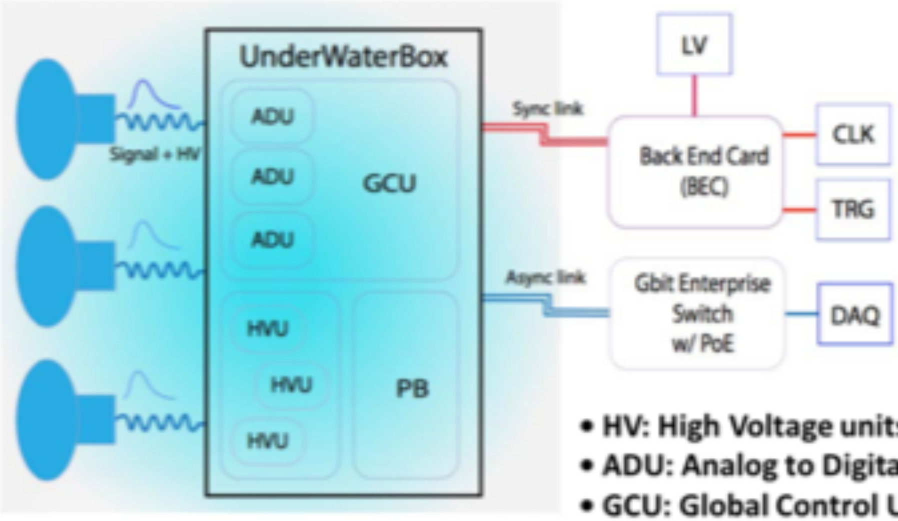




Readout electronics

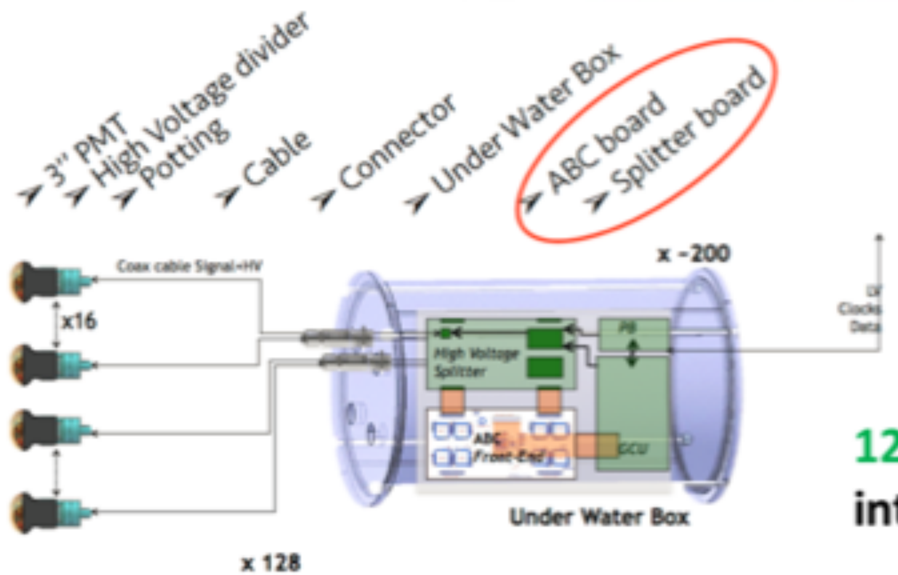
THREE 20'' PMTs' signals go into ONE underwater box.

1GHz 14bit-FADC in very front of each 20'' PMT



- **HV: High Voltage units**
- **ADU: Analog to Digital Unit**
- **GCU: Global Control Unit**
- **CAT cable: Category 5e cable**
- **High reliability needed**

Severe constraints by power consumption



128 3'' PMTs' signals go into ONE underwater box

6

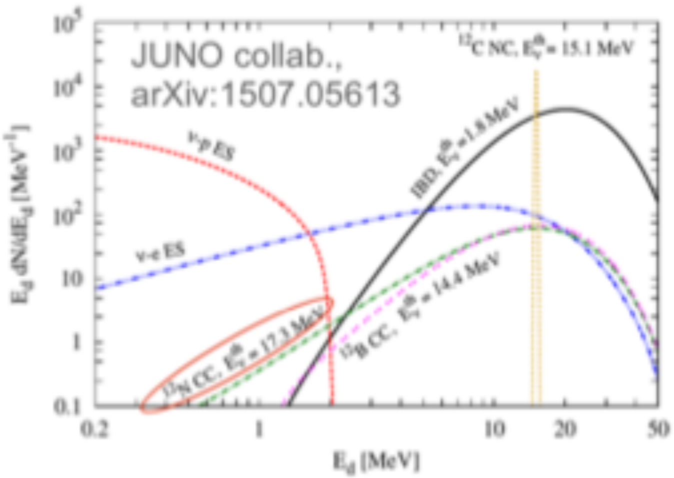
Supernova Neutrinos in JUNO

- **Core-collapse SN at 10kpc**
- **Opens new physics window:**
  - Test SN models
  - Information about MH
  - Multi-messenger astronomy
  - ...

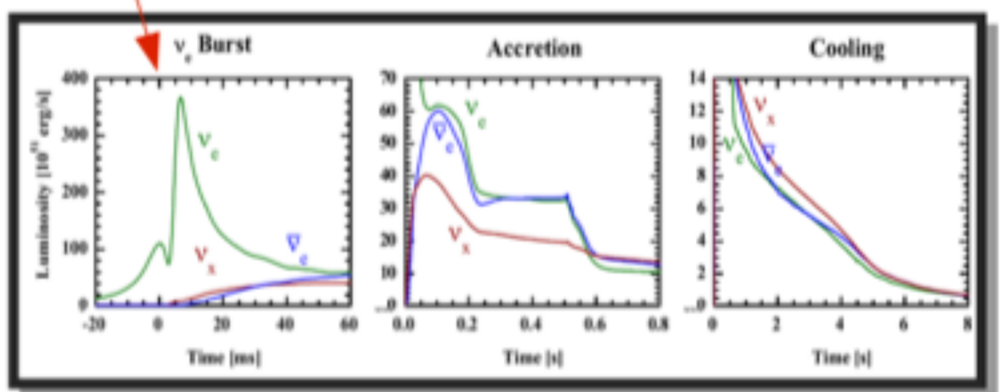
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

JUNO collab., arXiv:1507.05613

Huge statistics + Flavour information



Energy spectrum



JUNO collab.,arXiv:1507.05613, based on: L. Hüdepohl, PhD Thesis, TU Munich (2013), A. Mirizzi et. al., arXiv:1508.00785

Time evolution

Geo-neutrinos

- **Exploring origin and thermal evolution of the Earth**
- **Uncertainty on flux:** 17% (1 yr) / 6% (10 yr) U/TH ratio fixed
- **For comparison:**
  - KamLAND 14.3±4.4 evts PLB 722 (2013) 295
  - Borexino 116+28-27 evts PRD 88 (2013) 033001

- **Uncertainty for U/TH flux:**
  - U: 11% (JUNO 10 yr)
  - Th: 24% (JUNO 10yr)