Reactor neutrino results and prospects

Zeyuan Yu

Institute of High Energy Physics

Sep. 26, 2017

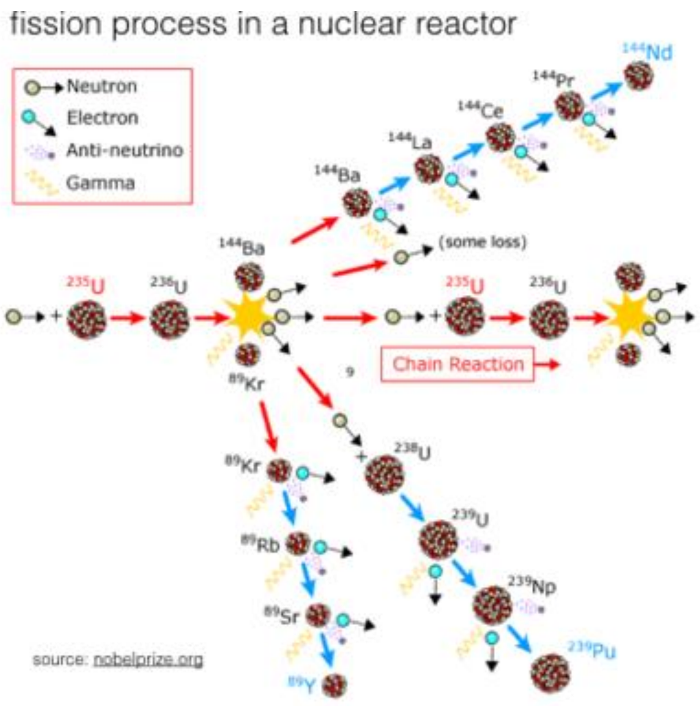
NUFACT 2017, 25 - 30 September, Uppsala University

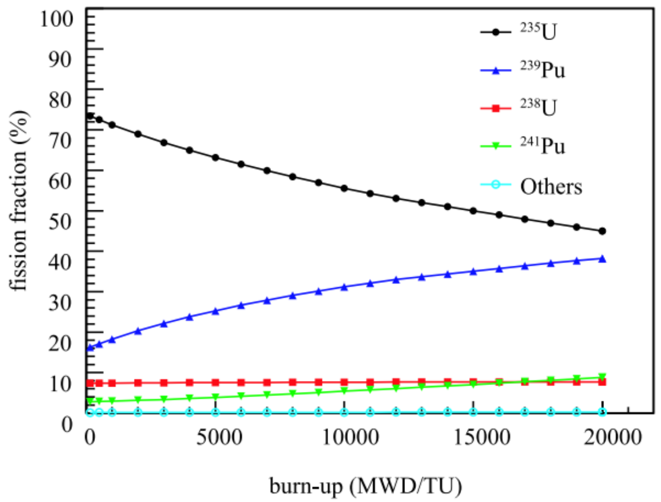
Contents

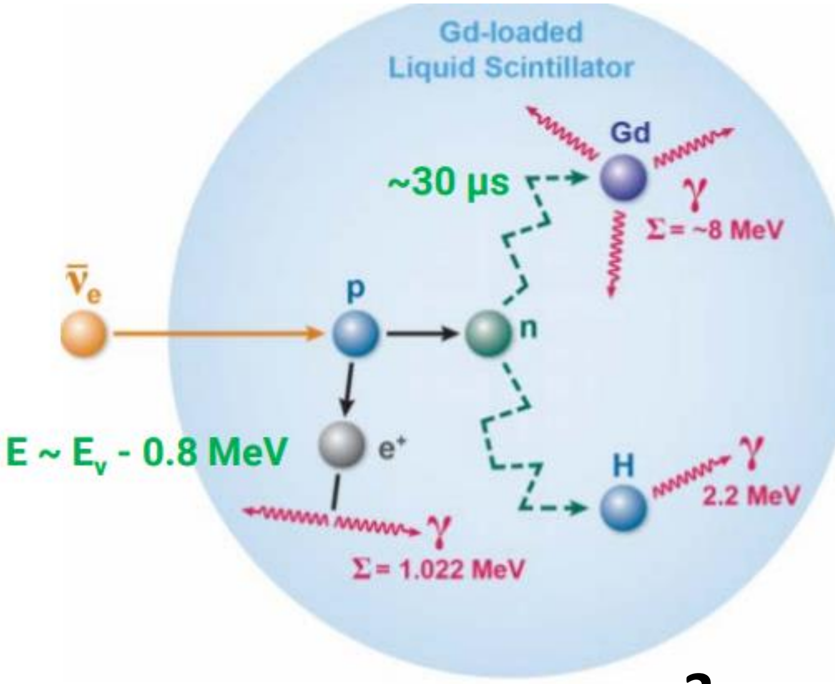
- Reactor neutrino
- Ongoing experiments
- Anomalies
- The future
- Summary

Reactor: a powerful $\bar{\nu}_e$ source

- **Pure and powerful $\bar{\nu}_e$ source**
  - Averaged 6 $\bar{\nu}_e$ per fission
  - 6×10^{20} $\bar{\nu}_e$ /sec/3GW$_{th}$
- **Major detection method**
  - **I**nverse **B**eta **D**ecay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Distinctive coincidence signature



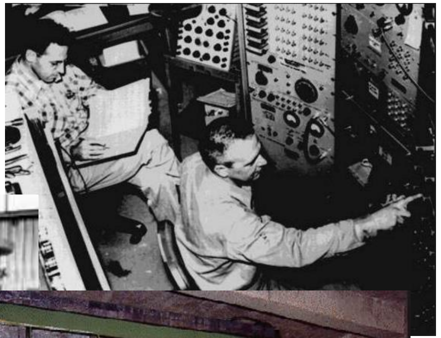


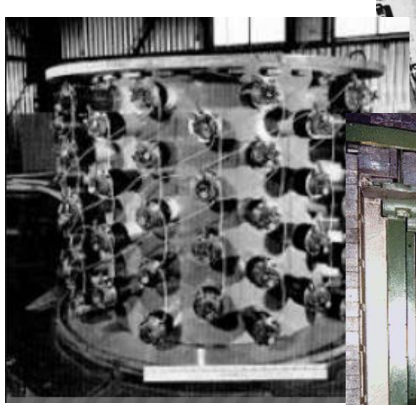


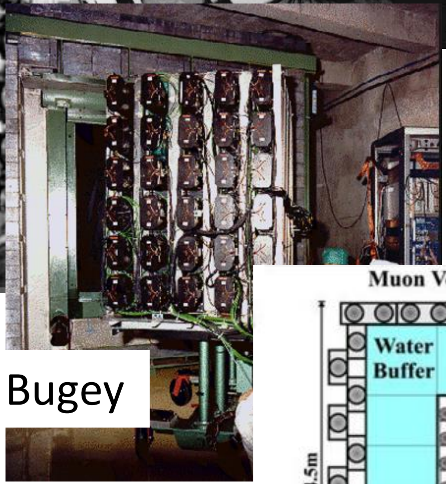
Rich physics results

- **Similar detection methods**
  - Inverse Beta Decay
  - Liquid scintillator + Photomultiplier Tubes

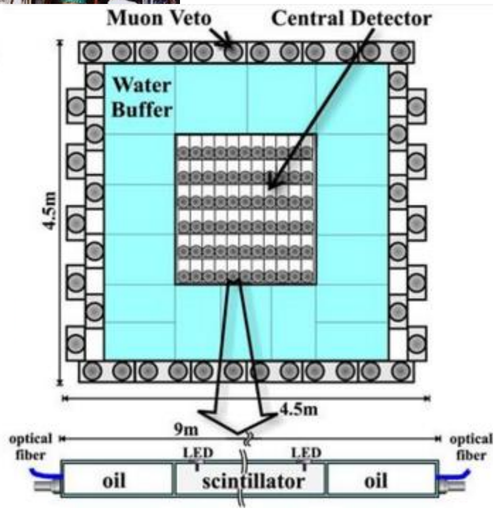
1950s: Reines and Cowan, discovery of neutrino



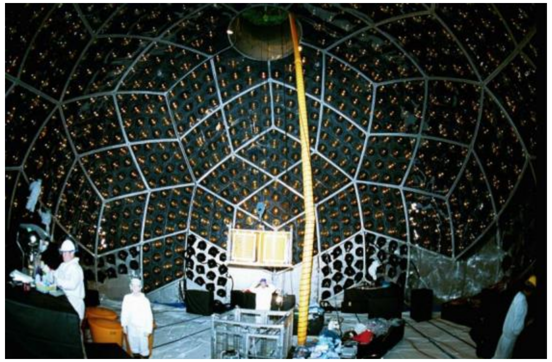




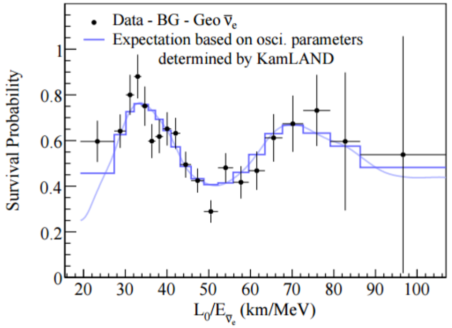
1980s: Bugey

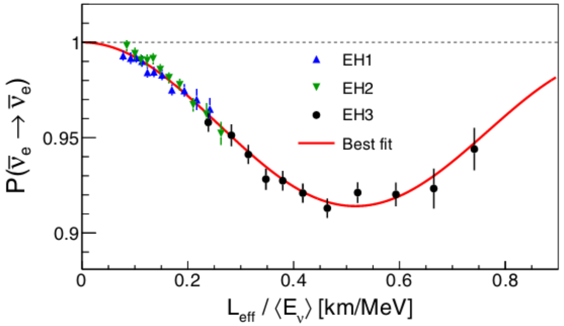


1990s: Palo Verde, CHOOZ

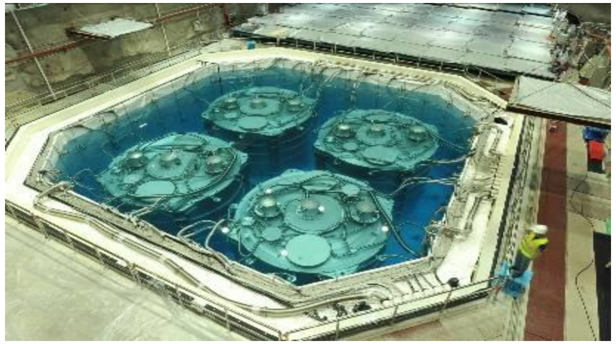


2000s: KamLAND θ_{12}, δm^2





2010s: Daya Bay, etc. θ_{13}



Neutrino oscillation

- Neutrinos are **produced and detected** by weak interactions as **flavor eigenstates**, but **propagate** in vacuum as **mass eigenstates**

flavor eigenstate ⟷ ***neutrino mixing*** ⟷ ***mass eigenstate***

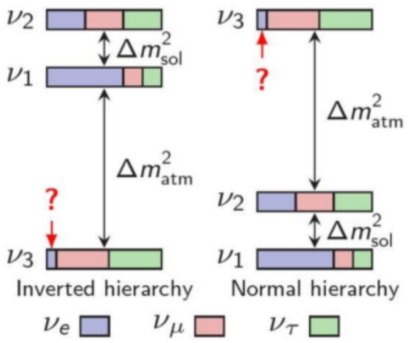
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23} ~ 45°
Atmospheric
Accelerator

θ_{13} :The smallest and the last one to be determined
Reactor
Accelerator

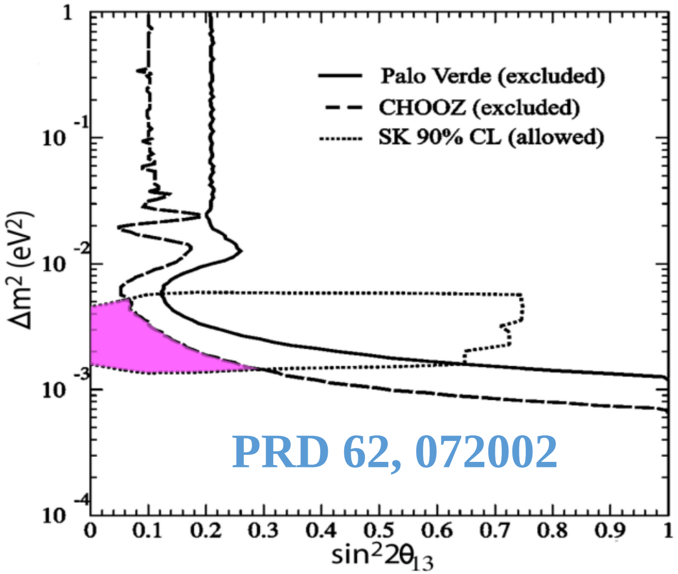
θ_{12} ~ 34°
Solar
Reactor



$$\mathrm{NH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| > |\Delta m^2_{32}|$$

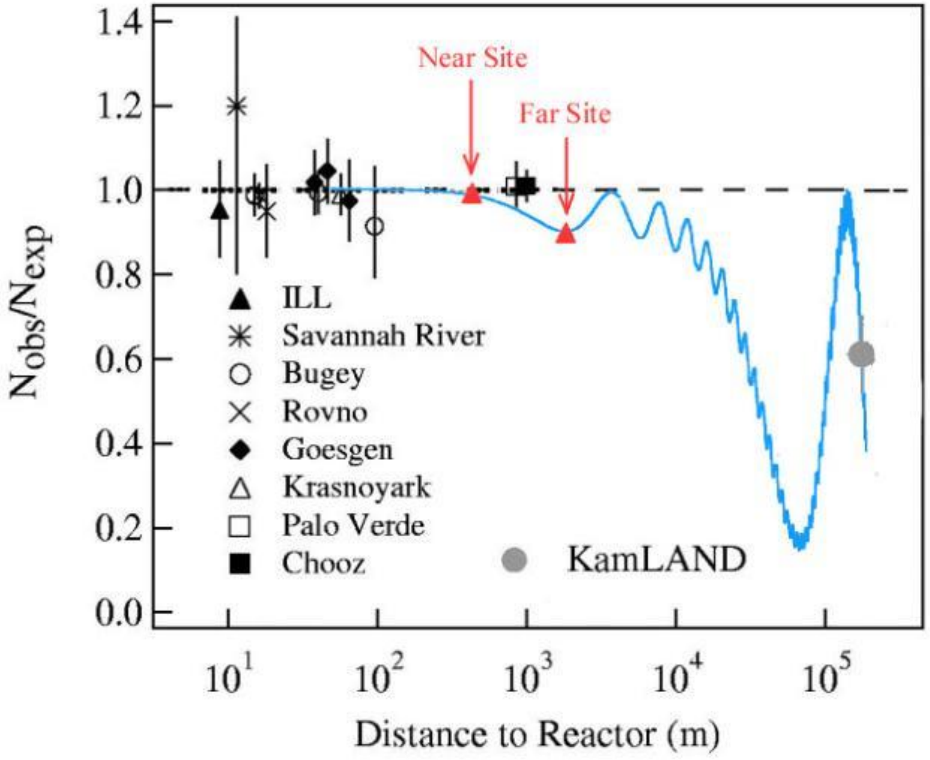
$$\mathrm{IH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| < |\Delta m^2_{32}|$$

- Only an upper limit for $\sin^2 2\theta_{13}$ around 2003
  - θ_{13} is linked to the possibility of observing CP violation at lepton sector
- **"Tell me θ_{13}!"** – S. Glashow



How to measure θ_{13}

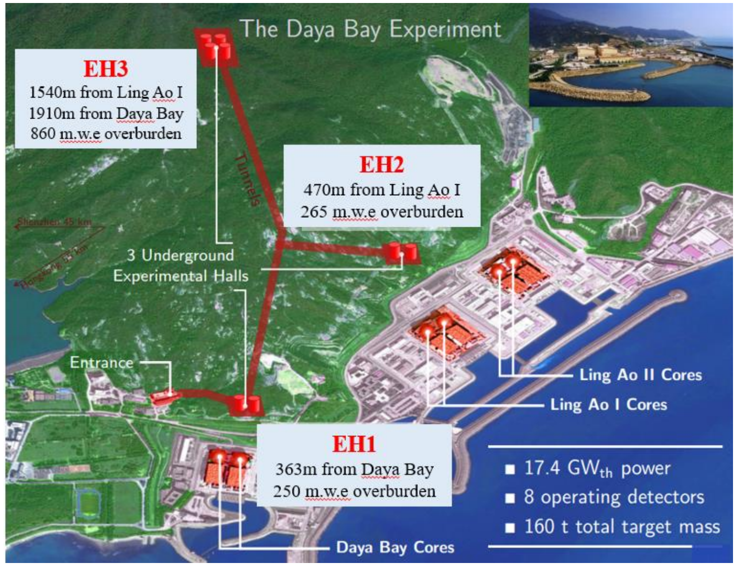
- Look for reactor $\bar{\nu}_e$ disappearance at short baselines (~ 1 to 2 km)
- **Clean in physics**
  - Only related to θ_{13}.
  - No relation with δ_{CP} and matter effect compared to accelerator experiments
- **Relative measurement**
  - Compare $\bar{\nu}_e$ flux and spectrum at near and far locations
  - Cancel most of the detector and reactor related systematics



$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m_{31}^2 L / 4E\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m_{21}^2 L / 4E\right)$$

Ongoing reactor experiments

Daya Bay (China)



Double Chooz (France)

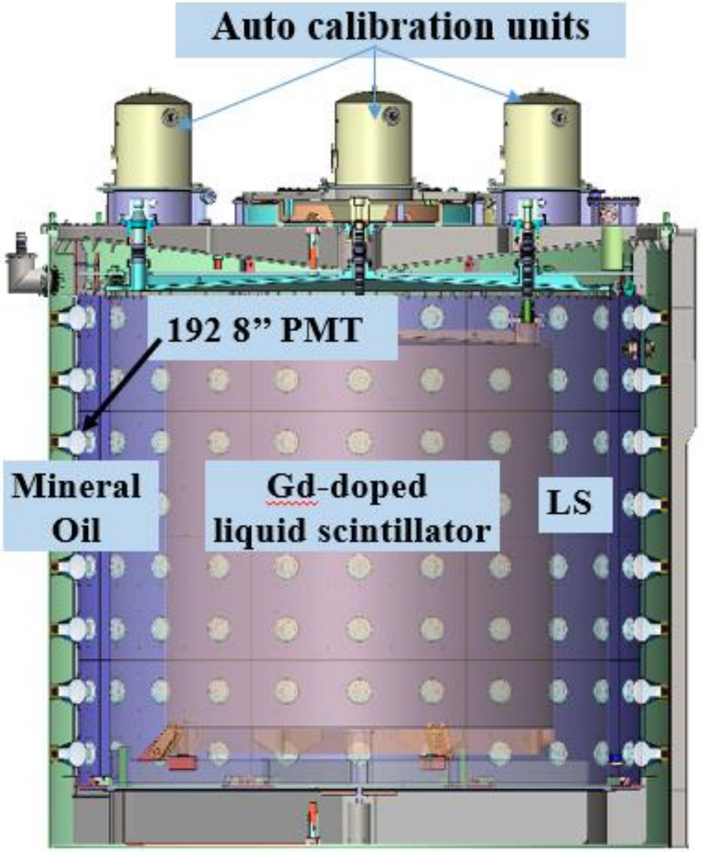
RENO (South Korea)

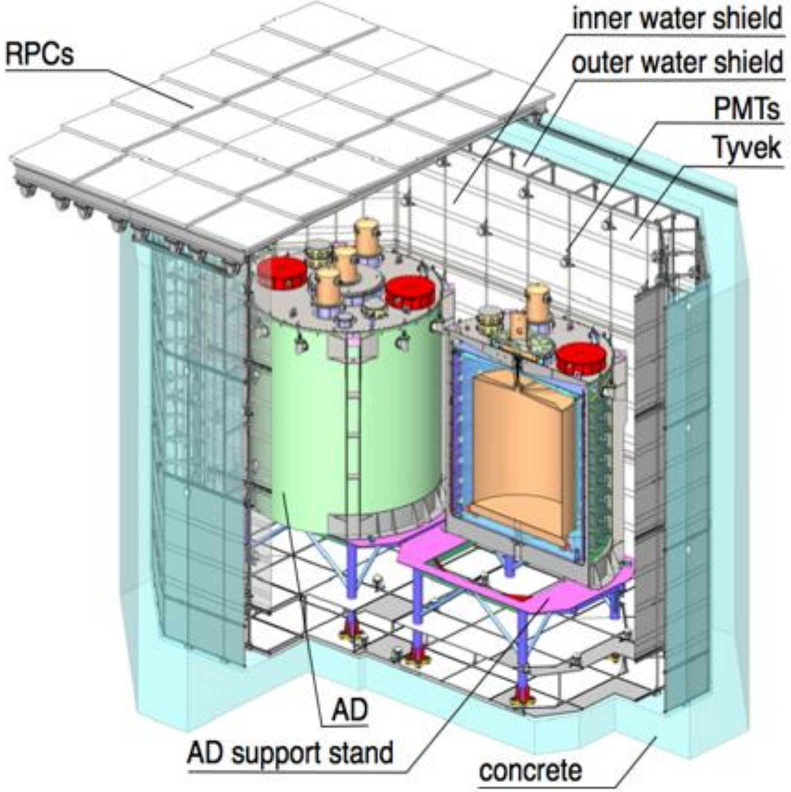
	Reactor power (GW_{th})	Overburden near/far (m.w.e.)	nGd target mass at far site (tons)	Status of data taking
Daya Bay	17.4	270/950	80	2011-2020
Double Chooz	8.6	80/300	8.3	2011-2017
RENO	16.4	90/440	15.4	2011-2021 (?)

Detectors

Similar detection technologies

- Three-zone $\overline{\nu}_e$ detectors
- Surrounded by water Cherenkov detectors
  - Veto muons
  - Shield natural radioactivity and neutrons



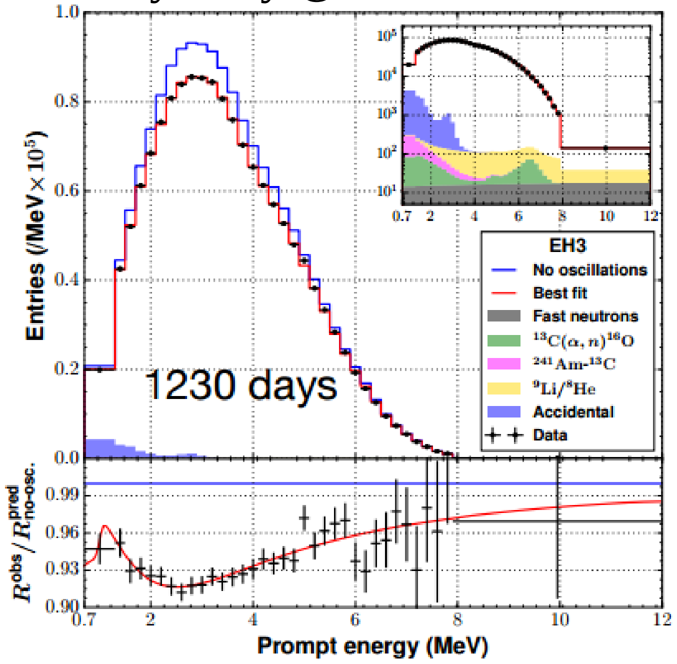


Daya Bay

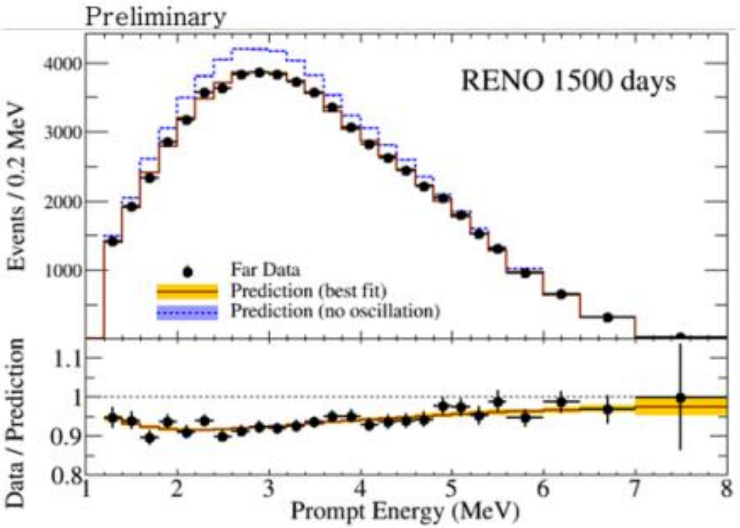
θ_{13} is large

- 2011: T2K, MINOS and Double Chooz saw indications of non-zero θ_{13}
- 2012: Daya Bay obtained unambiguous evidence of non-zero θ_{13} (> 5σ). RENO confirmed
- Now: θ_{13} has been the best known angle in the PMNS matrix
- **All experiments see clear disappearance signature, consistent with standard oscillation**

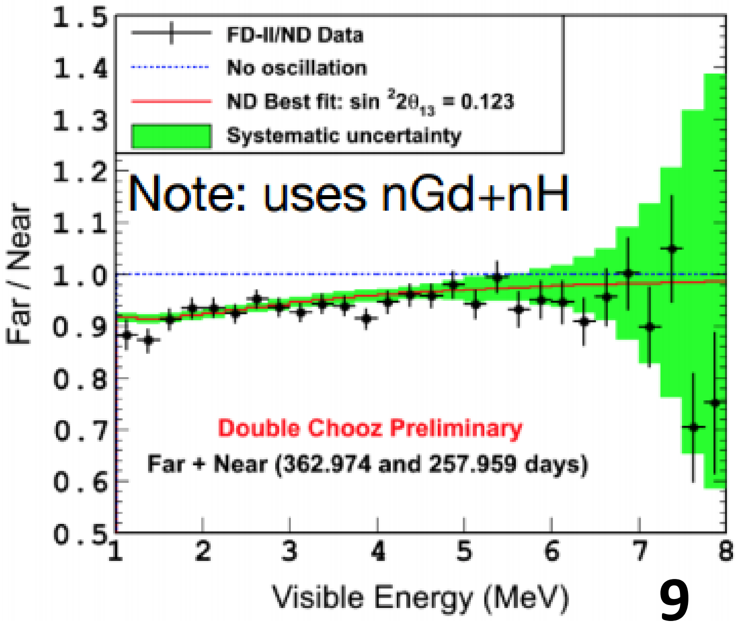
Daya Bay @ Neutrino 2016



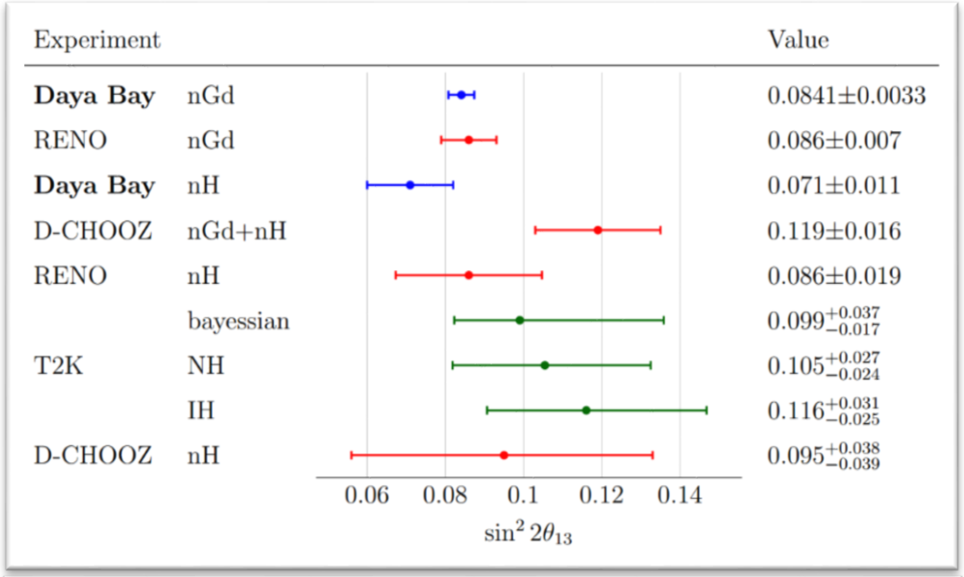
RENO @ TAUP 2017

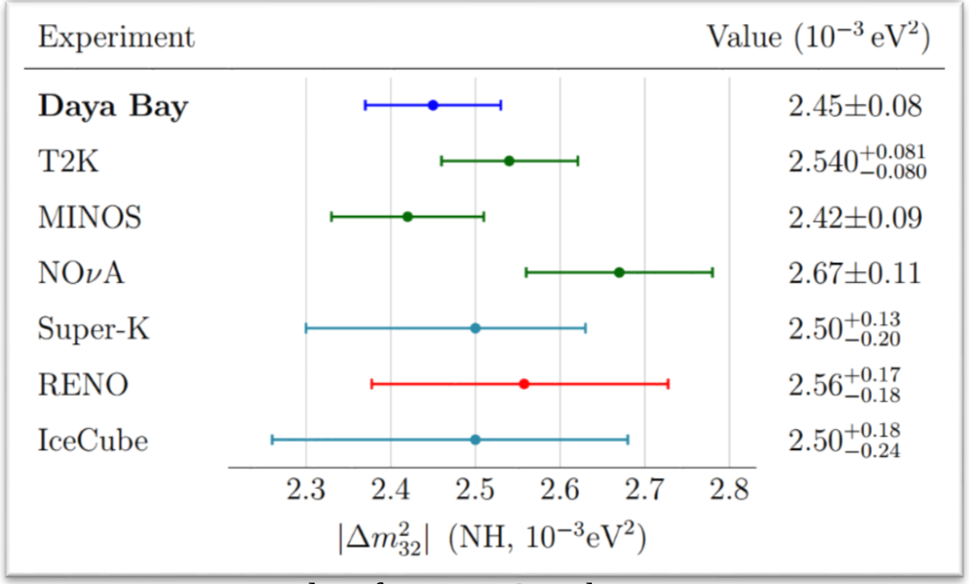


DC @ CERN seminar 2016



Latest results





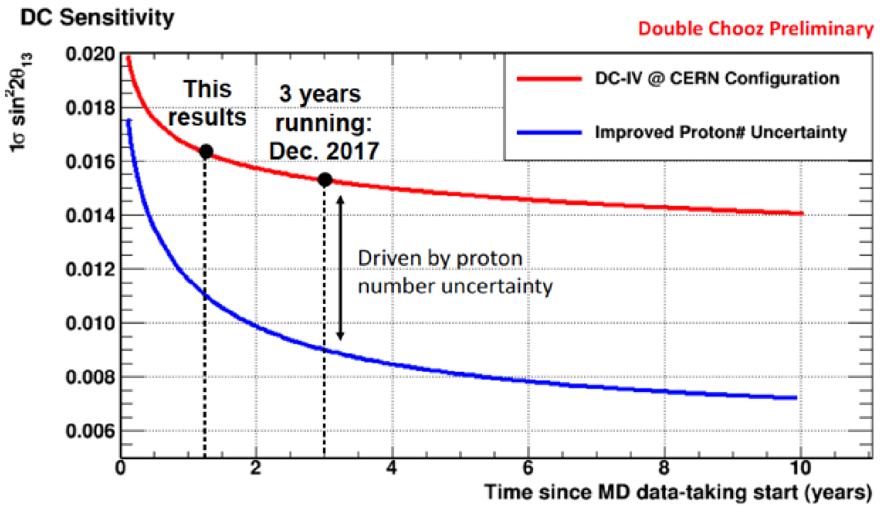
Plots from M. Gonchar

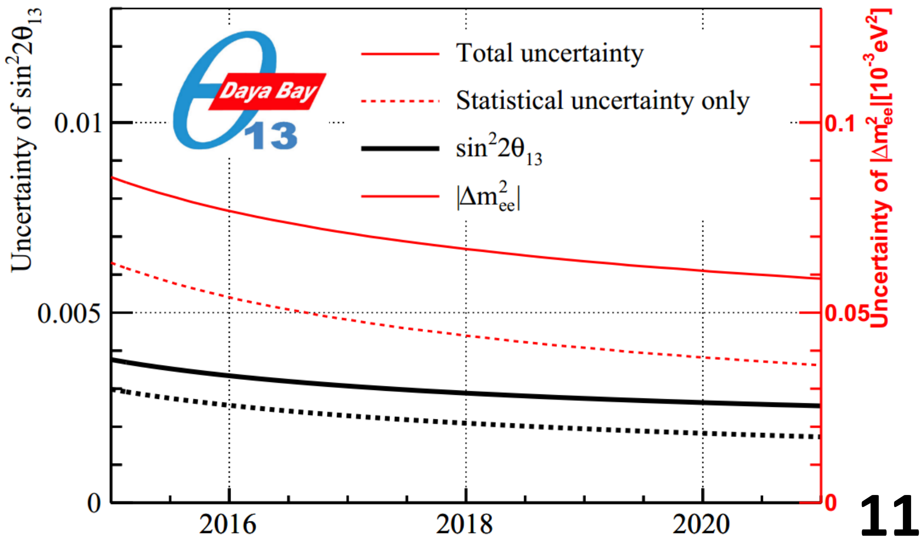
- θ_{13}: **reactor experiments give the most precise measurement**
  - Key input to the δ_{CP} determination in current generation accelerator experiments

- Δm_{32}^2: **consistent results between**
  - MeV scale reactor experiments
  - GeV scale accelerator and atmospheric ones
  - Beauty of nature

Prospects of ongoing experiments

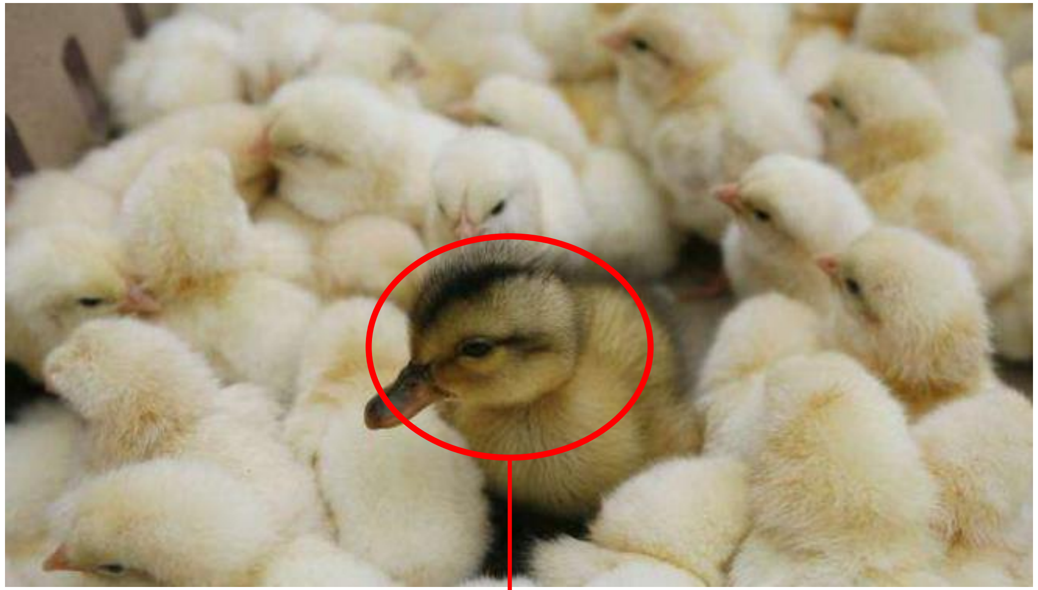
- **Double Chooz**
  - Data taking to end of 2017
  - Reduce the largest systematics: proton number
- **Daya Bay**
  - Data taking to 2020
  - Better than 3% precision of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$
  - Better understanding to systematics and LS technical studies
- **RENO**
  - Plan to 2018 with possible extension to 2021





Reactor neutrino “anomalies”

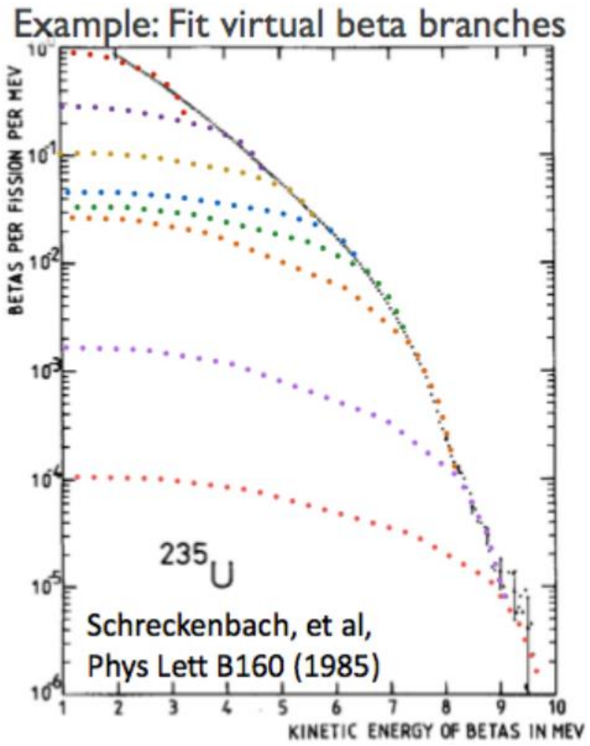
- Compare the measurements to model predictions
  - $\overline{\nu}_e$ flux anomaly
  - $\overline{\nu}_e$ spectrum bump
  - Fuel evolution

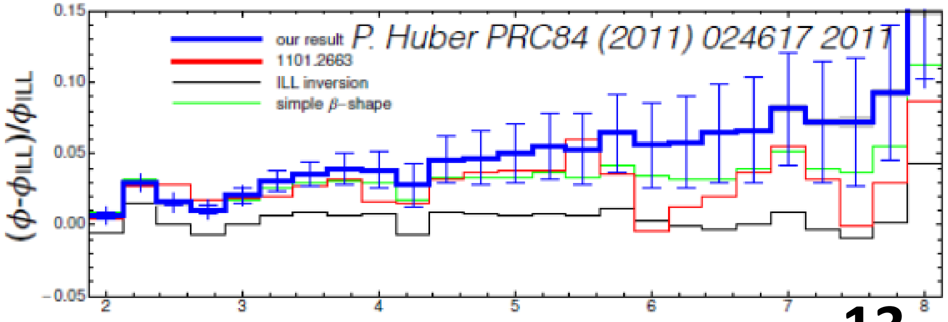


Anomaly: Who am I ?
A discovery or a mistake?

Reactor neutrino predictions

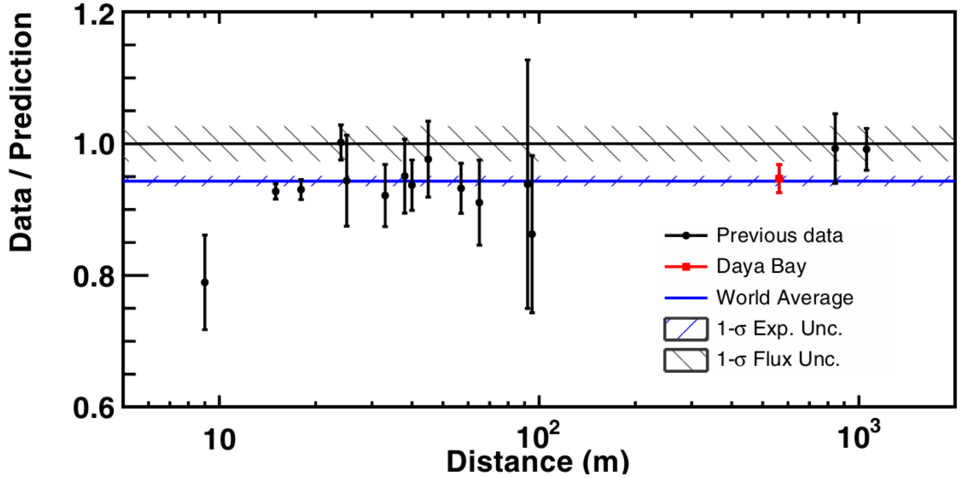
- **Summation method: 10% uncertainty**
  - Sum over the fission products' $\bar{\nu}_e$ spectra from the nuclear database
- **^{235}U, ^{239}Pu, ^{241}Pu: conversion method, ~2.7% uncertainty**
  - Convert ILL's measured beta spectra to $\bar{\nu}_e$ ones with virtual beta-decay branches
  - ILL + Vogel model since 1980s
    - Predicted flux was consistent with Bugey-3 and other short baseline experiments
  - Huber + Mueller Model
    - In 2011, two conversion re-analyses increased the predicted flux by ~5%
  - **R**eactor **A**ntineutrino **A**nomaly



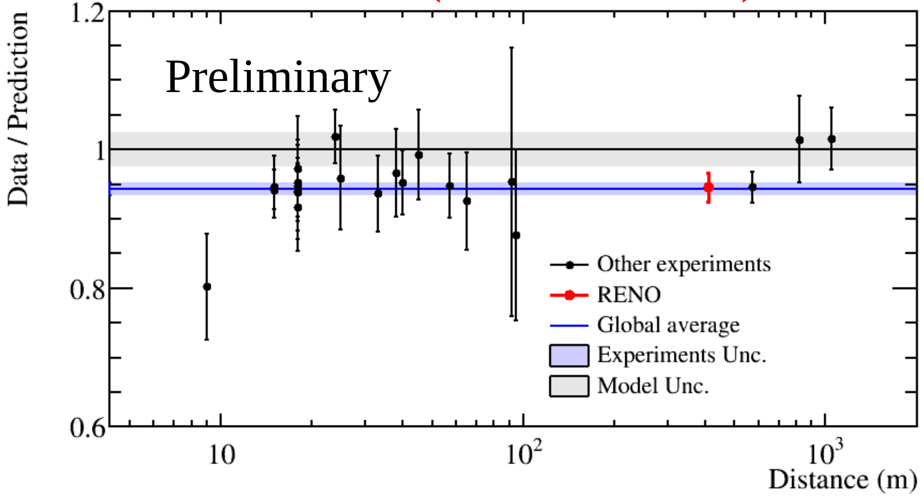


Neutrino flux anomaly

Daya Bay/(Huber+Mueller)



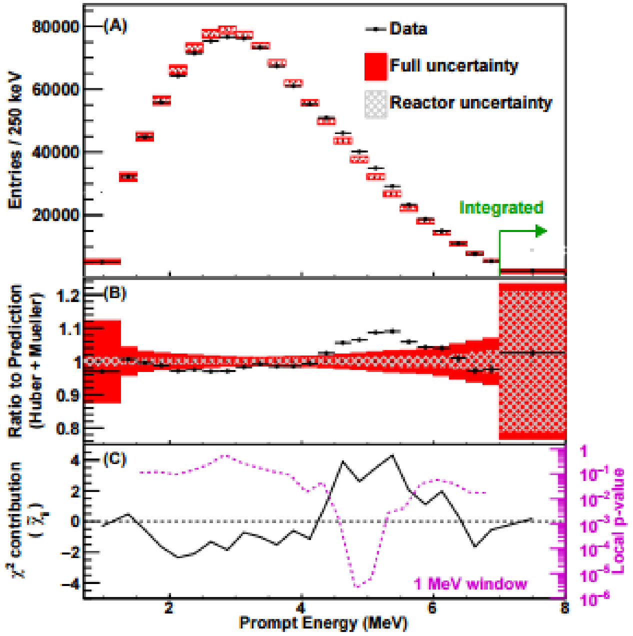
RENO/(Huber+Mueller)



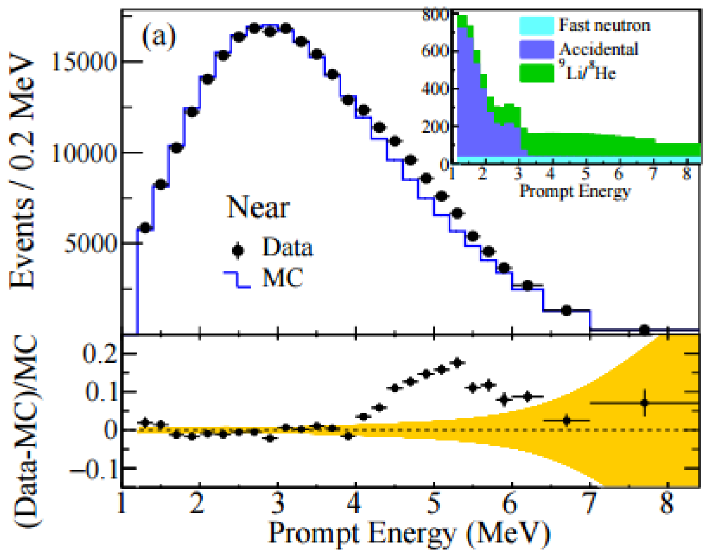
- Daya Bay and RENO obtained consistent flux results with those from previous short baseline experiments
- How to explain the anomaly?
  - Experimental systematics? (Unlikely)
  - Sterile neutrino? Problem in flux prediction?

Neutrino spectrum

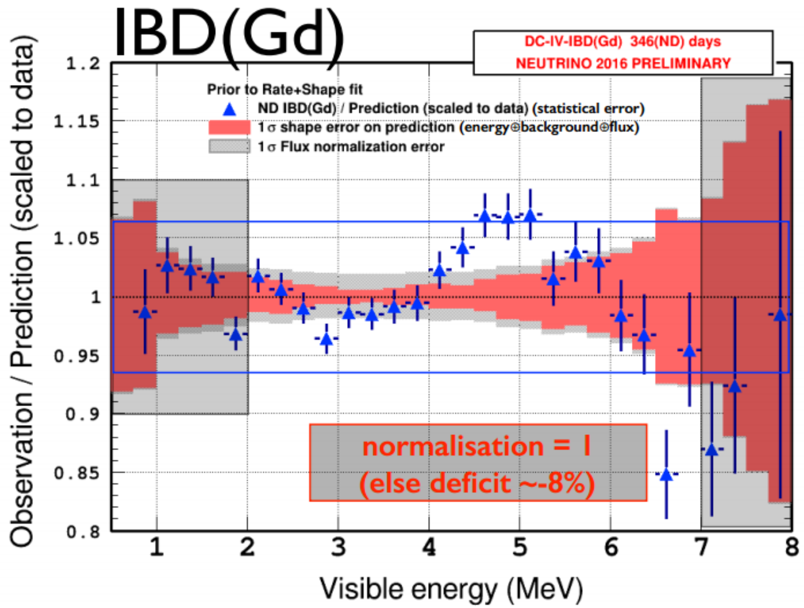
DYB @ Neutrino 2016



RENO arXiv:1610.04326



DC @ Neutrino 2016

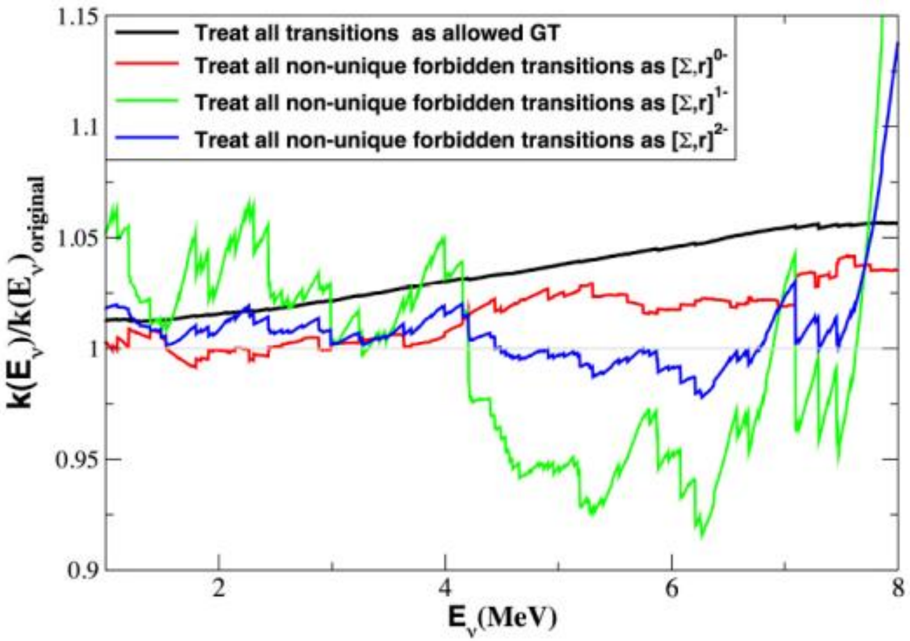


- In 2014, all three experiments saw a bump in (4 – 6 MeV) prompt energy region
  - Different reactor fuels; different ^{238}U predictions between DC and DYB/RENO
  - Can't be explained by detector response or sterile neutrino oscillation
- **Implication**: if uncertainty of the predicted shape is larger than expected, the same might be true for the flux

Neutrino spectrum

- No definitive answer to the bump yet
- Uncertainty of the conversion method is probably underestimated
  - It assumes that the shapes of all beta-decays are known
  - 30% of the decays are first forbidden, thus the assumption is not justified
  - 5% uncertainty is more realistic
- Some other explanations
  - Fast neutron fission of ^{238}U? (Hayes)

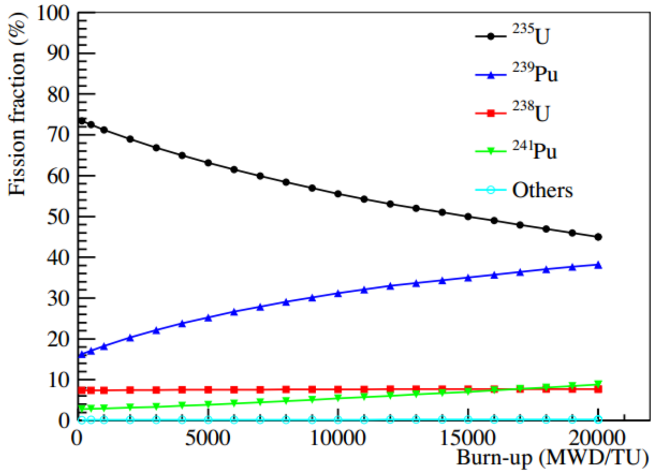
Ratio of neutrino spectrum to electron spectrum by assuming different forbidden shape factors

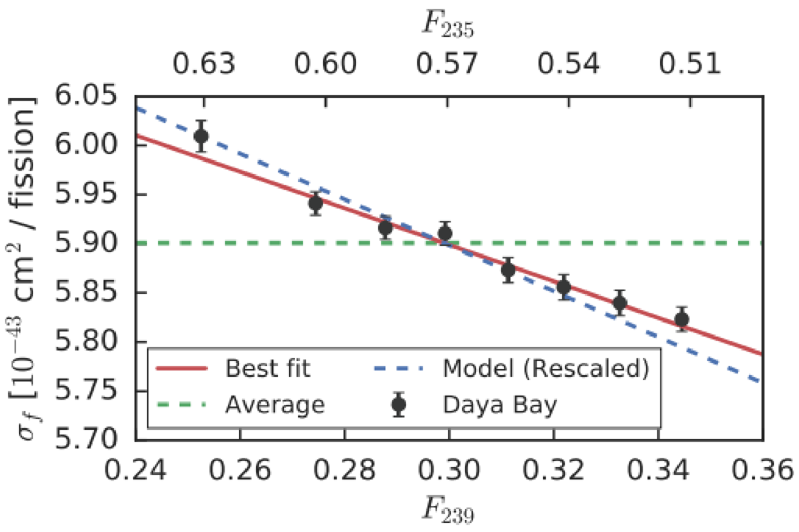


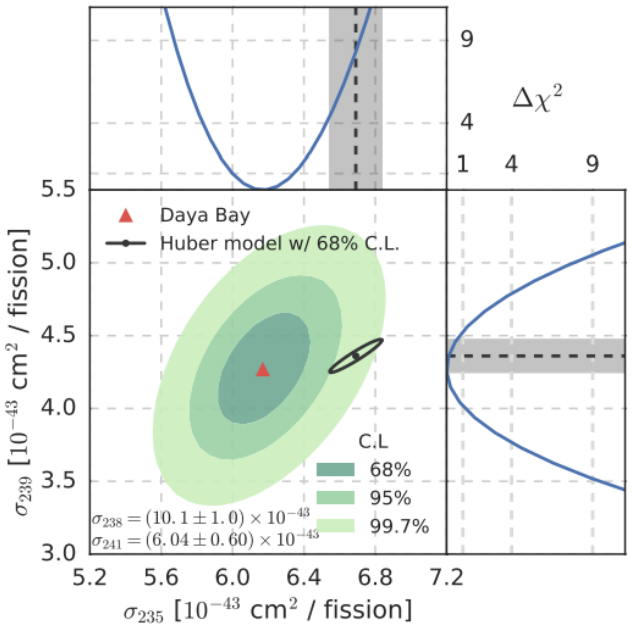
A. Hayes et al, PRL ***112****, 202501 (2014).*

Fuel evolution

- Recently, Daya Bay studied the neutrino flux and shape changes with reactor fuel evolution
- Results suggest **^{235}U is the main contributor** to the **Reactor Antineutrino Flux Anomaly**
- **Sterile neutrino as the sole cause of RAA is disfavored by 2.8σ**

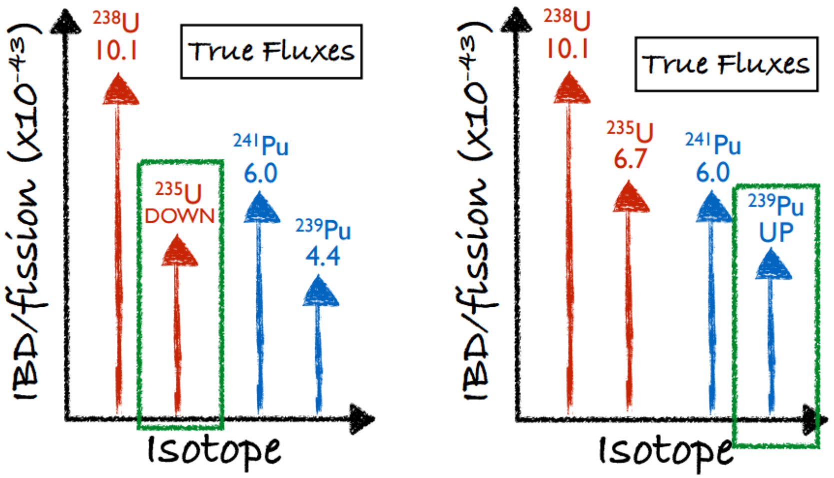






Fuel evolution

- Some complicated scenarios still allowed
  - For example, larger ^{239}Pu flux with sterile neutrino suggested by C. Giunti
  - Whatever the case, uncertainties in flux predictions are largely underestimated
- The coming HEU (more than 94% ν from ^{235}U) reactor experiments are critical for model-independent tests

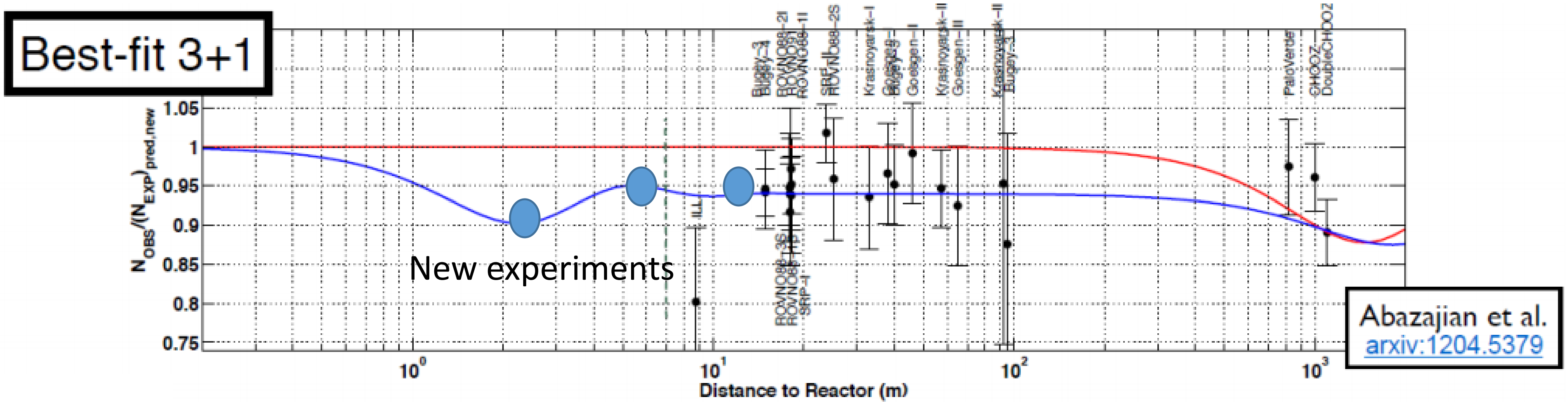


Plot from L. Bryce

Combined fit of the DYB evolution and global reactor rates, by C. Giunti et al, arXiv:1708.01133

	235	**235+239**	**OSC**	**235+OSC**	**239+OSC**
$\chi^2_{\min}$	25.3	24.8	23.0	20.2	17.5
NDF	32	31	31	30	30
GoF	79%	78%	85%	91%	100%
Δm^2_{41}	–	–	0.48	0.48	0.48
$\sin^2 2\vartheta_{ee}$	–	–	0.14	0.11	0.15
r_{235}	0.934	0.934	–	0.987	–
r_{239}	–	0.970	–	–	1.099

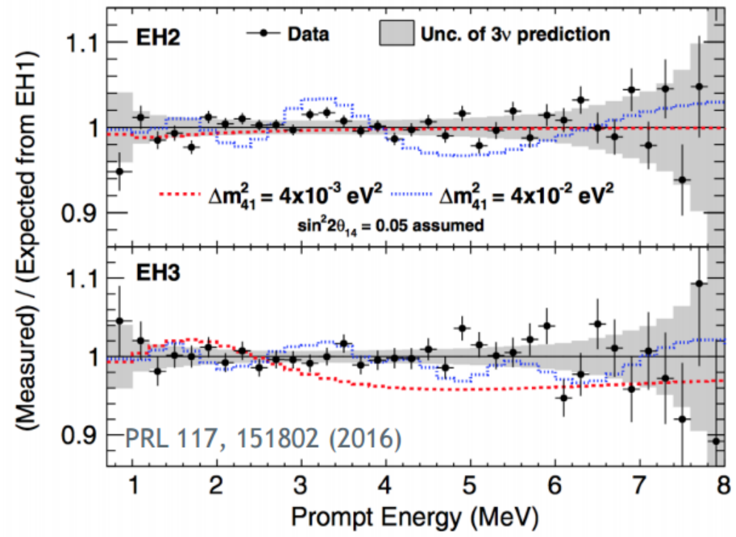
Searching for sterile neutrino

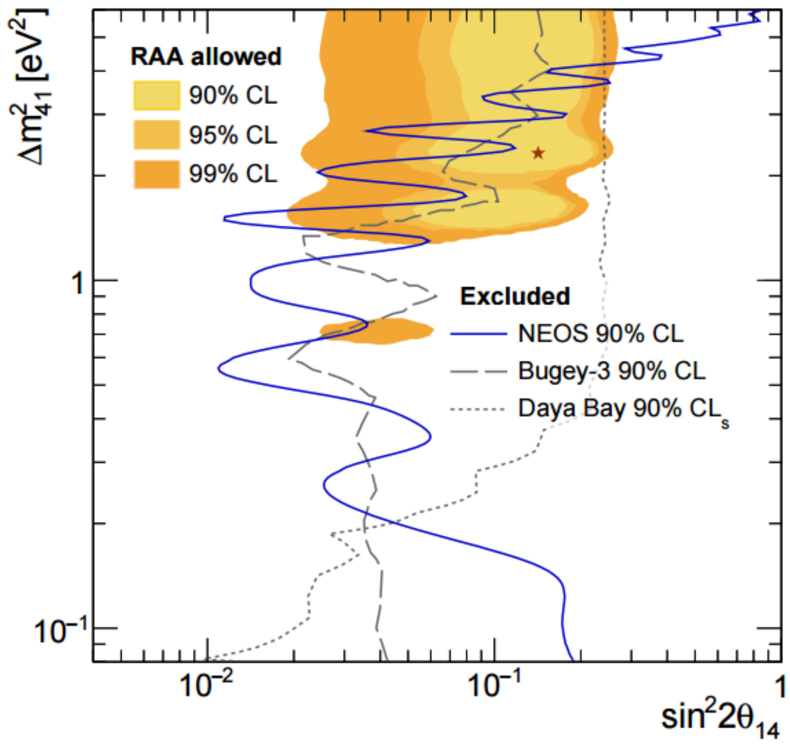


- **The Reactor Antineutrino Anomaly problem is still open**
- More inputs
  - Light sterile neutrino search at Daya Bay and RENO (sub-eV scale)
  - Very short baseline experiments (eV scale). Most of them use HEU reactors
    - PROSPECT, Solid, NEOS, etc. See Marco's talk at Sep. 28

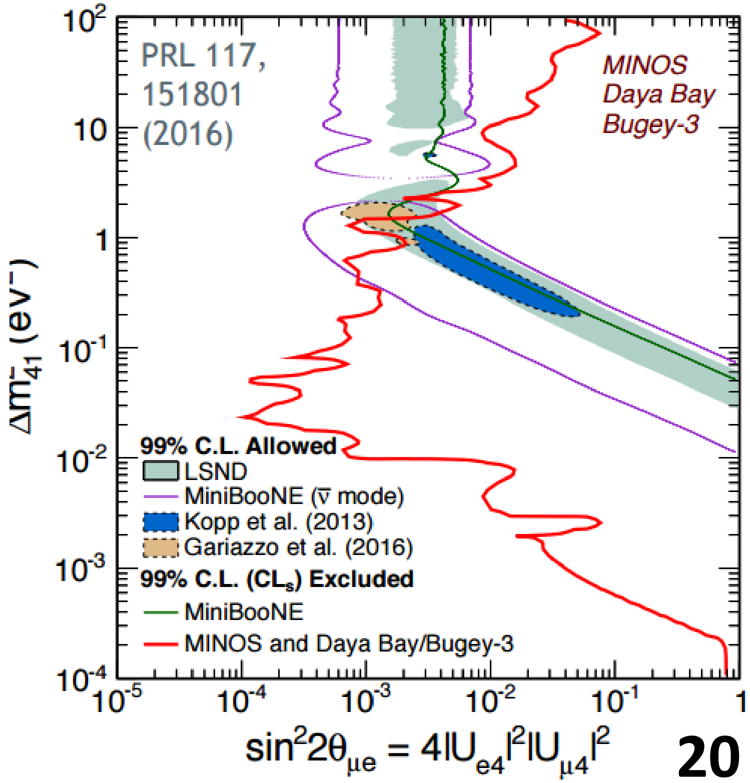
Searching for sterile neutrino

- The existence of sterile neutrino would introduce an additional spectral distortion
- Daya Bay, RENO and NEOS set limits to $\sin^2 2\theta_{14}$ at different $|\Delta m^2_{41}|$ region
- A combined analysis between DYB, MINOS and Bugey-3 excluded the MiniBooNE and LSND allowed parameter space at Δm^2_{41}<0.8 eV^2





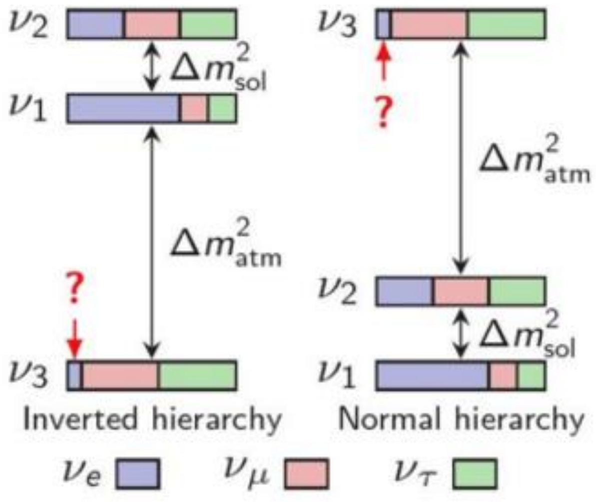
Phys. Rev. Lett. 118, 121802 (2017)



Future experiments

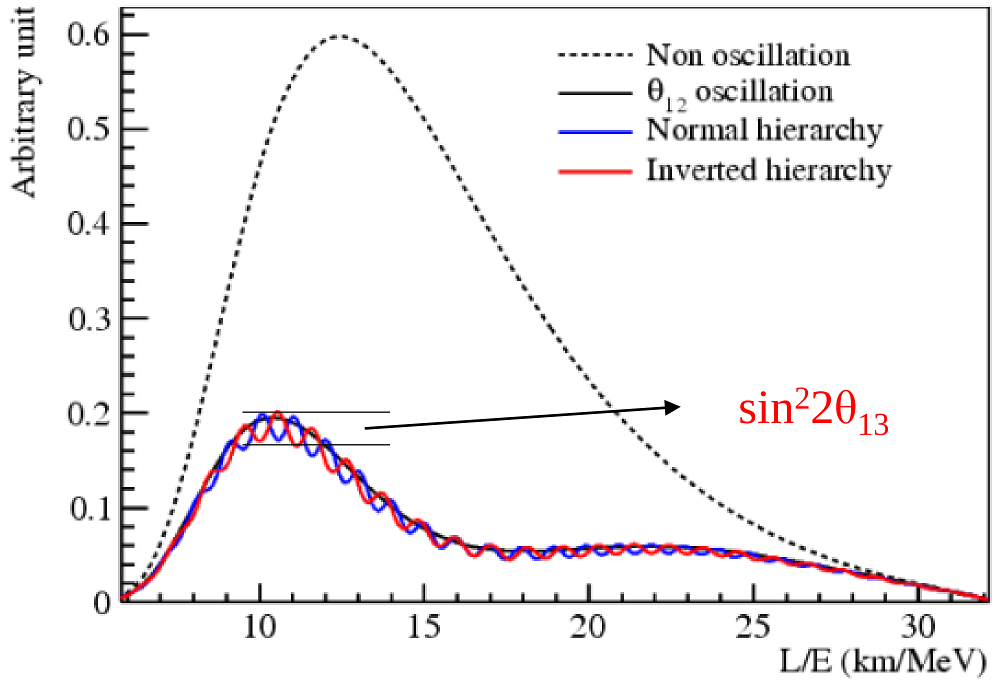
Thanks to the large θ_{13}!

- The next generation of reactor experiments aims to solve the neutrino mass hierarchy problem
  - An unprecedentedly large and precise detector to distinguish relative shape difference from different MH

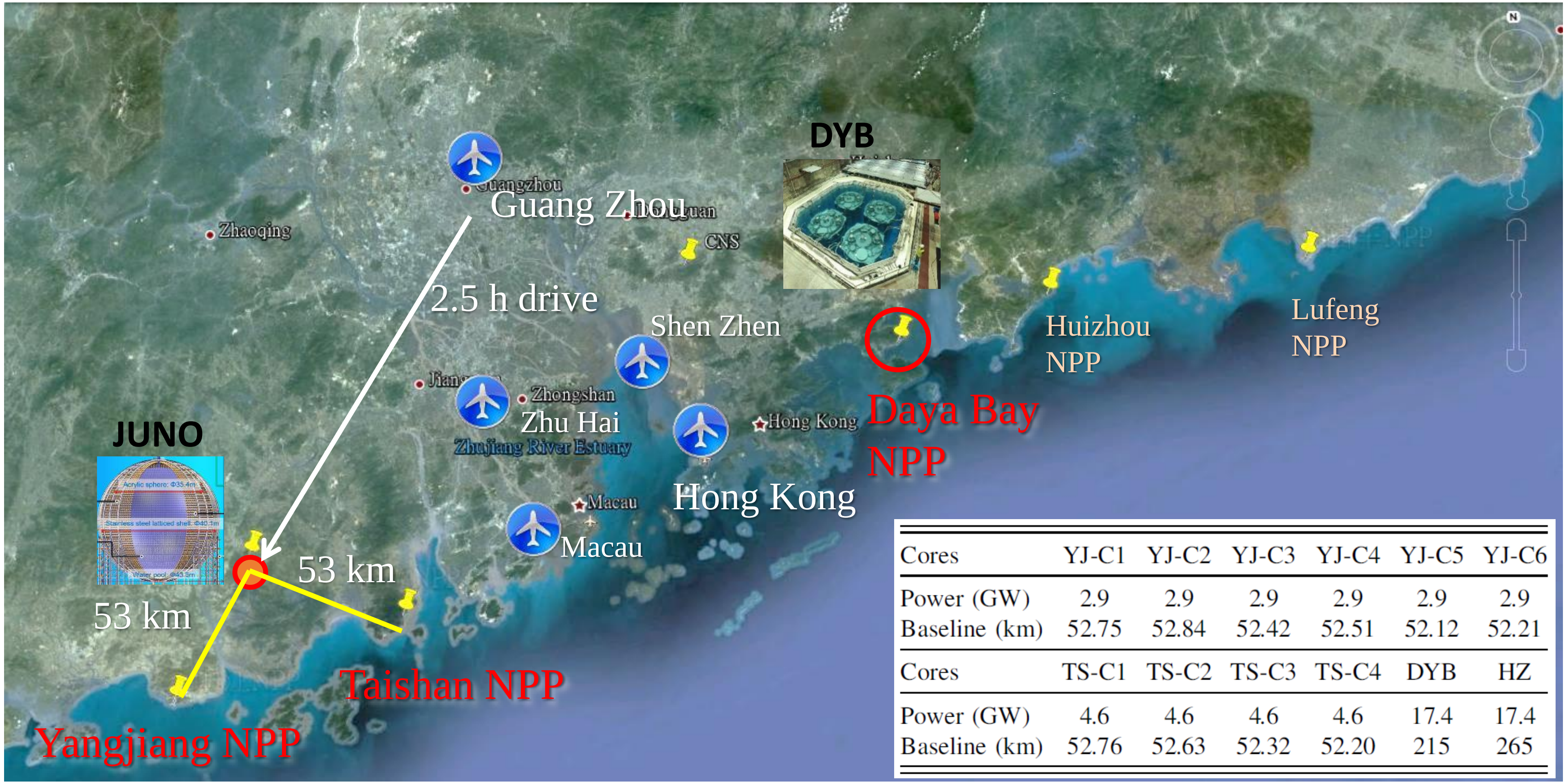


$$\mathrm{NH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| > |\Delta m^2_{32}|$$

$$\mathrm{IH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| < |\Delta m^2_{32}|$$



JUNO

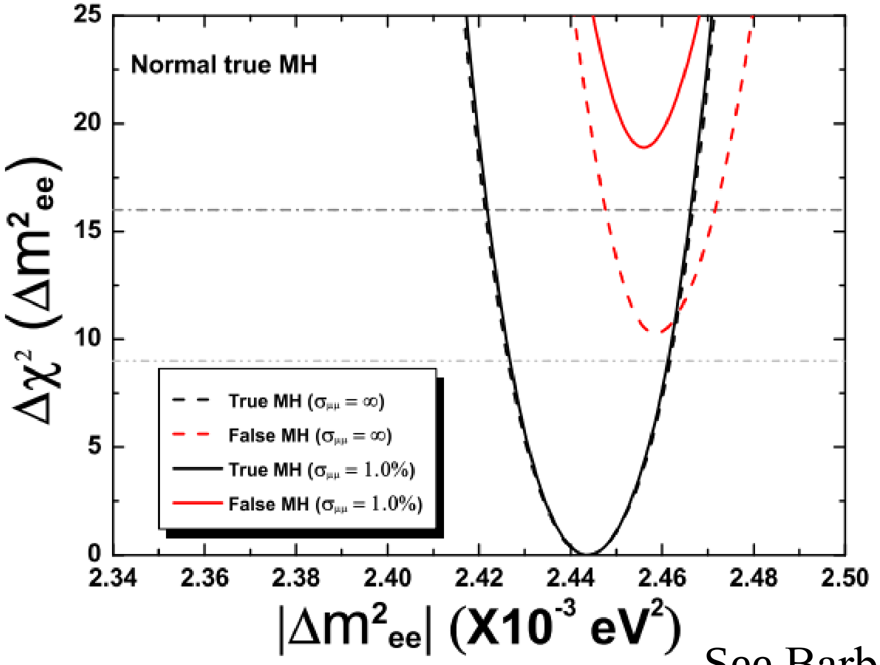


Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

A similar proposal RENO-50 at Korea has been abandoned

JUNO physics

- Achieve sensitivity to MH at 3σ with a six years running
  - Larger than 4σ with 1% precision $|\Delta m^2_{\mu\mu}|$ input
- A multi-purpose detector with rich physics potentials
  - Precise measurements of $\sin\theta_{12}$ and Δm^2_{21}, geo-neutrino, supernova neutrino, etc.



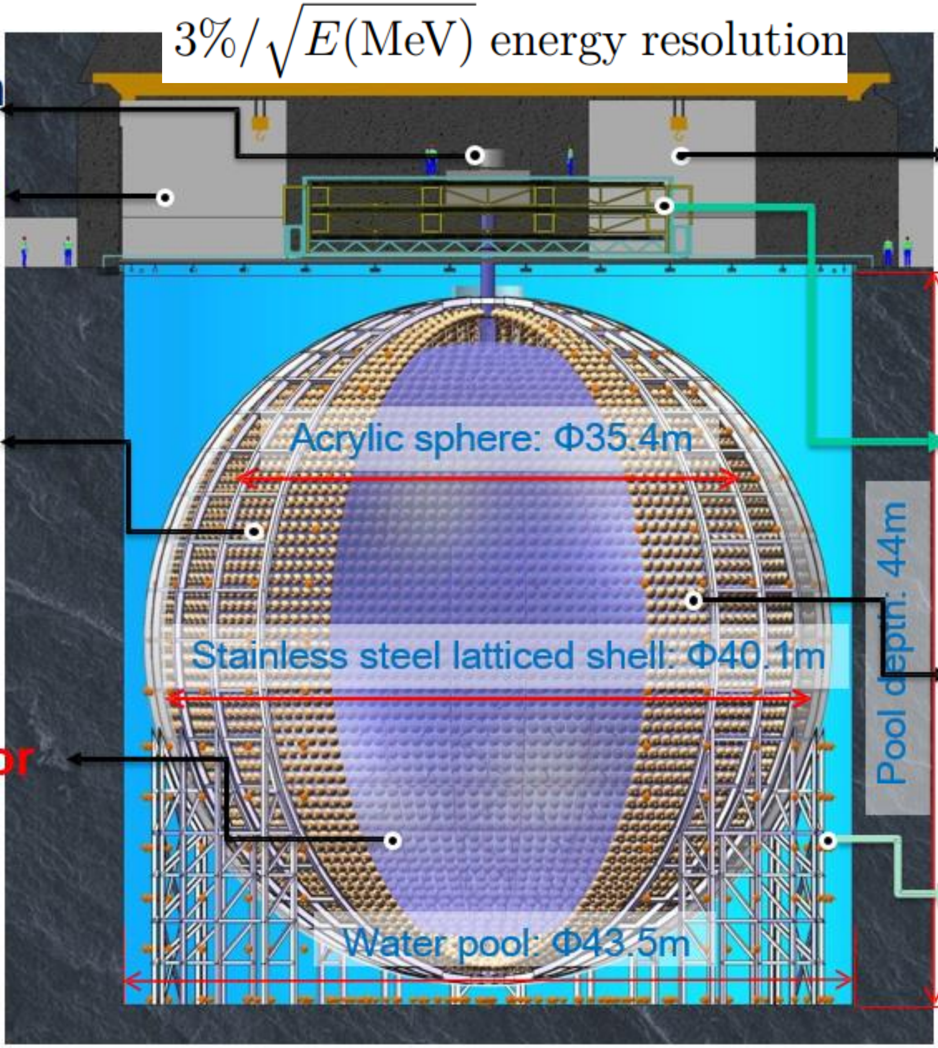
Registered events for a supernova at 10 kpc

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
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

See Barbara's talk at Sep. 25 for details

JUNO detector

$3\%/\sqrt{E(\mathrm{MeV})}$ energy resolution



Till now, received 3k 20" PMTs. Under mass testing.

Replaced the GdLS in DYB AD1 with JUNO LS for light yield and radio-purity test.

See Pedro's talk at Sep. 25 for details

JUNO schedule

Complete conceptual design. Complete civil design and bidding

PMT production line manufacturing

Complete civil construction. Start detector construction and assembly

Complete detector assembly, installation and LS filling

2013 ▶ 2014 ▶ 2015 ▶ 2016 ▶ 2017 ▶ 2018 ▶ 2019 ▶ 2020

Start civil construction. Complete prototyping (PMT & detector). International collaboration established

Start PMT production. Start detector production or bidding

Start LS production

Start data taking

expect to run for over two decades

Summary

- **Reactor plays an important role in the neutrino physics**
  - From the discovery of neutrino to the precise determination of θ_{13}
- **Anomalies of reactor neutrinos require better predictions**
  - Current data suggest the anomalies are probably due to predictions
  - Very short baseline experiments are critical
- **The next generation experiment, JUNO, has a decent probability of solving the mass hierarchy problem in the next 10 years**

Thanks for your attention!