Overview of reactor neutrinos

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International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN17)

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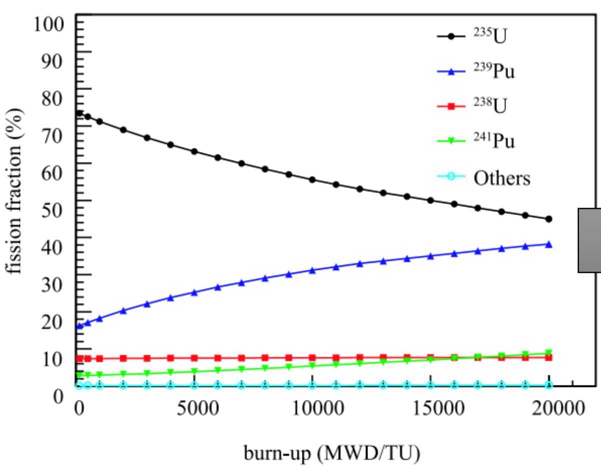
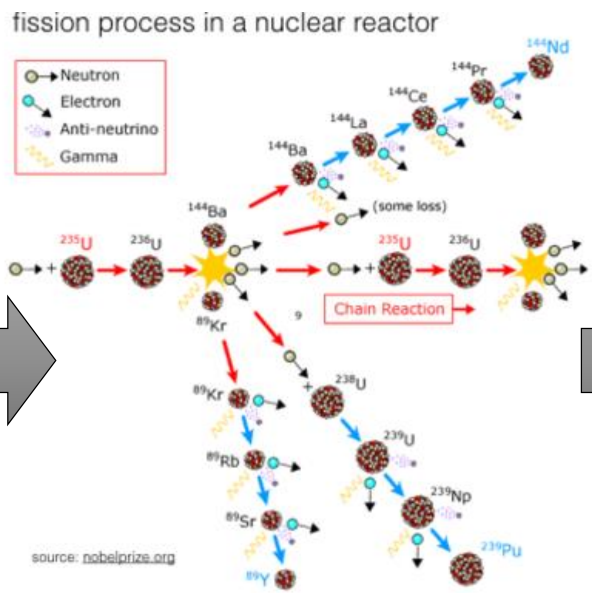
WARWICK

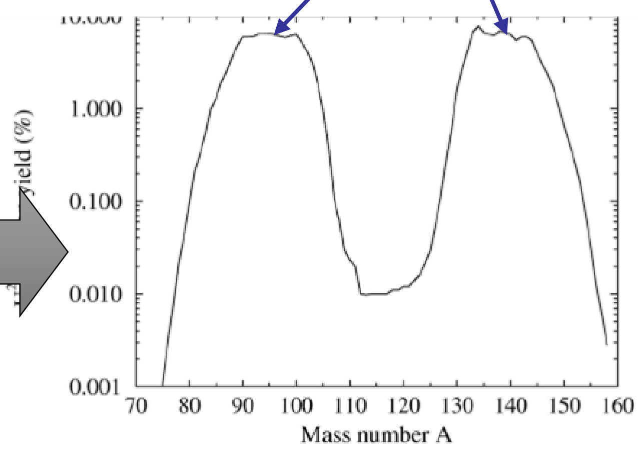
Reactor neutrinos

- Largely produced in nuclear power plants
  - Averaged 6 $\bar{\nu}_e$ per fission
  - 6×10^{20} $\bar{\nu}_e$/sec/3GW$_{th}$





$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



Detection of reactor neutrinos

- Commonly detected by inverse beta decay (IBD) with a pair of coincidence signals

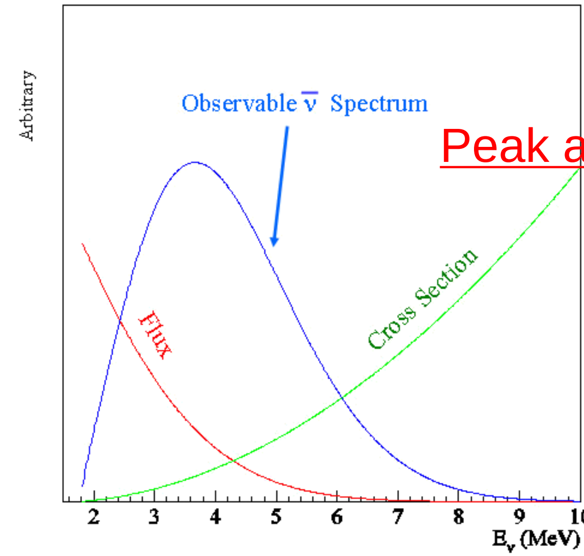
Prompt signal

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

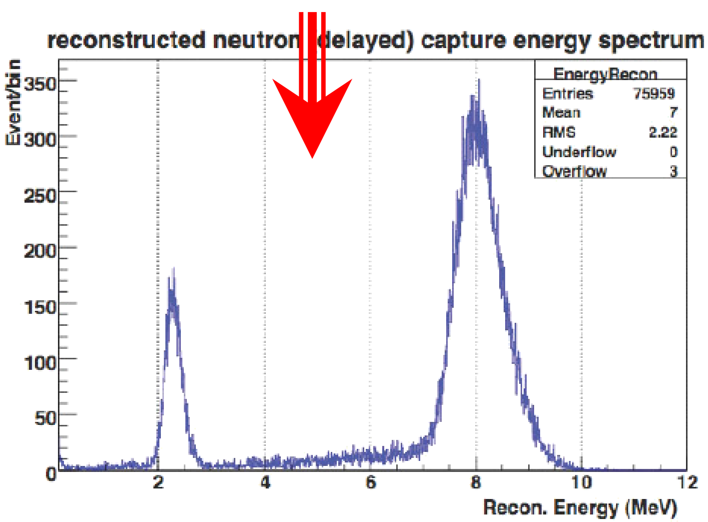
$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

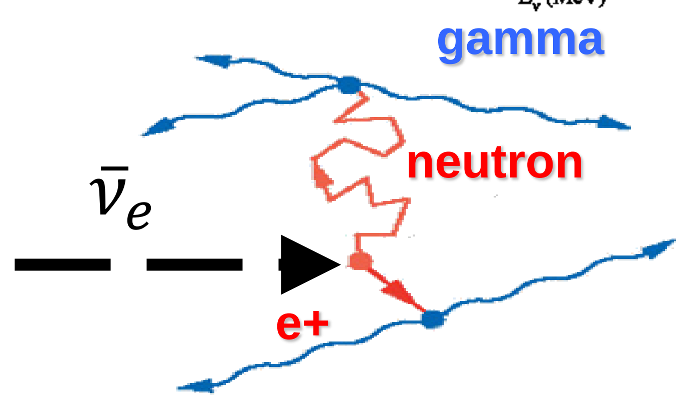
Capture on H or Gd,

Delayed signal, 2.2 or 8 MeV



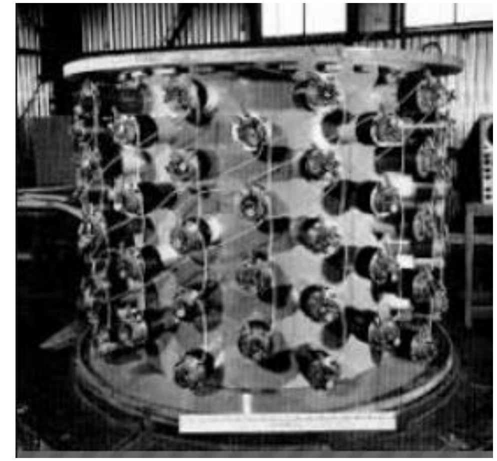
Peak at ~4 MeV

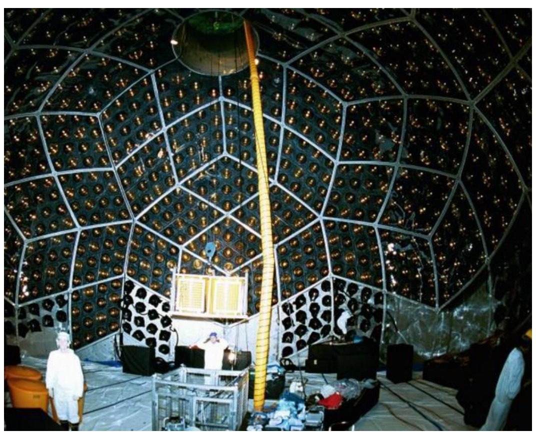


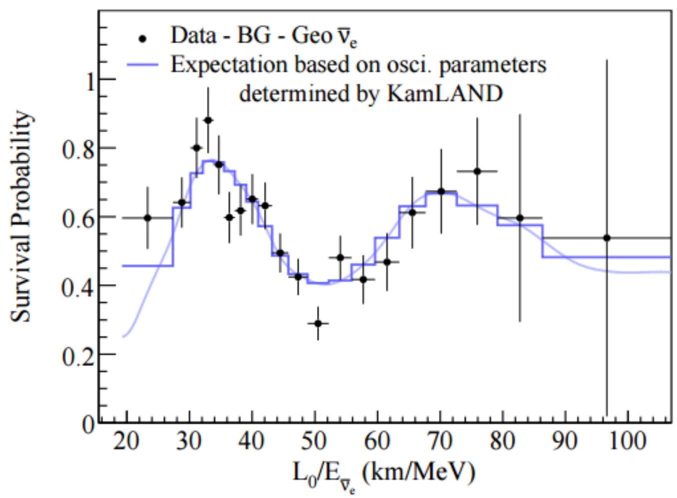


Glorious history

- First discovery of neutrinos by Clyde L. Cowan and Frederick Reines in 1956







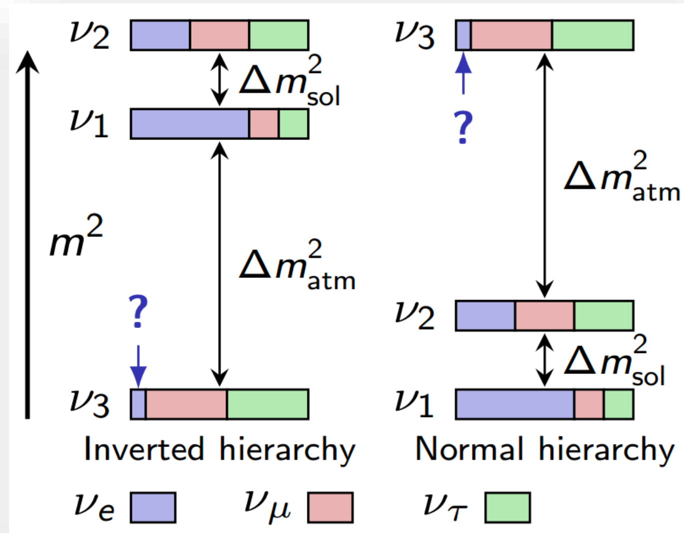
- First confirmation of solar neutrino oscillation by KamLAND in 2002

- Bugey, CHOOZ, Palo Verde …

Neutrino oscillation and θ$_{13}$

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha,i}\,|\nu_i\rangle$$

- PMNS matrix
- Mass eigenstates
- Weak eigenstates



- Known
  - $\theta_{12}, \theta_{23}, \boldsymbol{\theta_{13}}, \Delta m^2_{21}, |\Delta m^2_{32}|$
- Unknown
  - CP phase, mass hierarchy, $m_1/m_2/m_3$, δ_1/δ_2

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\delta_1} & 0 & 0 \\ 0 & e^{-i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23}~45° by atmospheric neutrinos (1998)	θ_{13}~9° by reactor and accelerator neutrinos (2012)	θ_{12}~34° by solar neutrinos (2001)	neutrino-less double beta decay

θ_{13} in reactor experiments

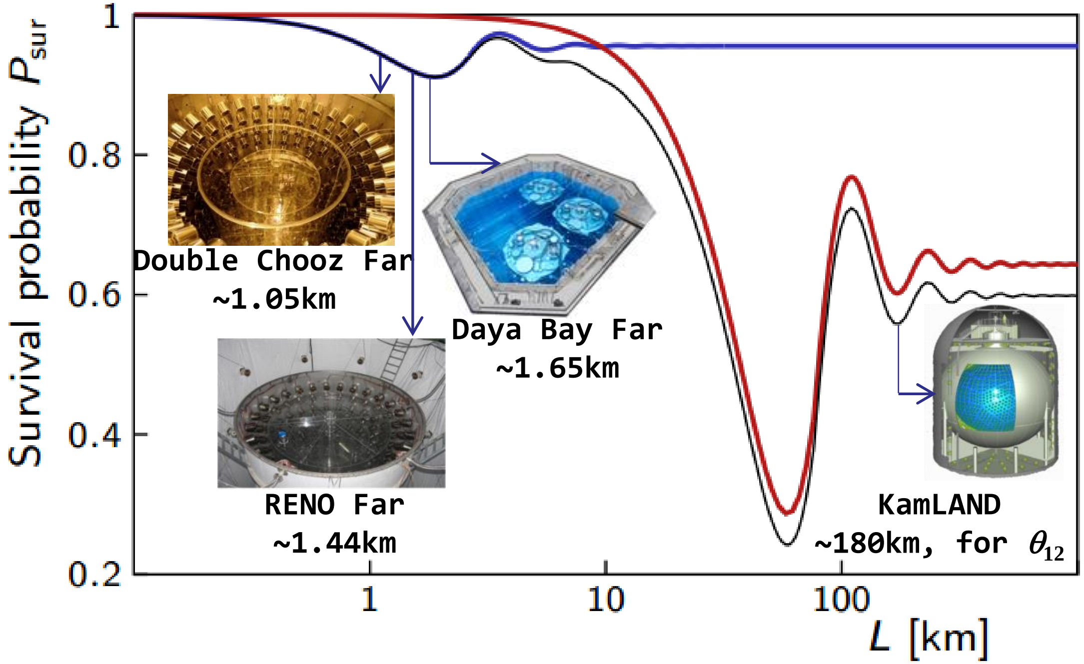
"Disappearance" experiments: $\bar{\nu}_e \to \bar{\nu}_e$

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

An unambiguous measurement of θ_{13}, no interference with CP violation phase or matter effects.

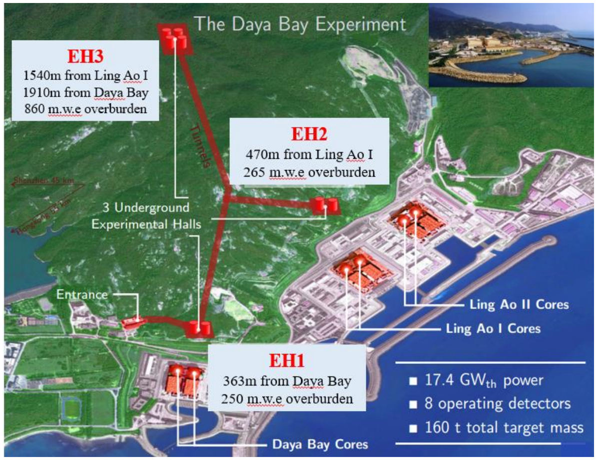
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right)$$

Far-near relative measurement reduces systematics of reactor flux, target mass and detection efficiency from percent to sub-percent level.



Ongoing reactor experiments

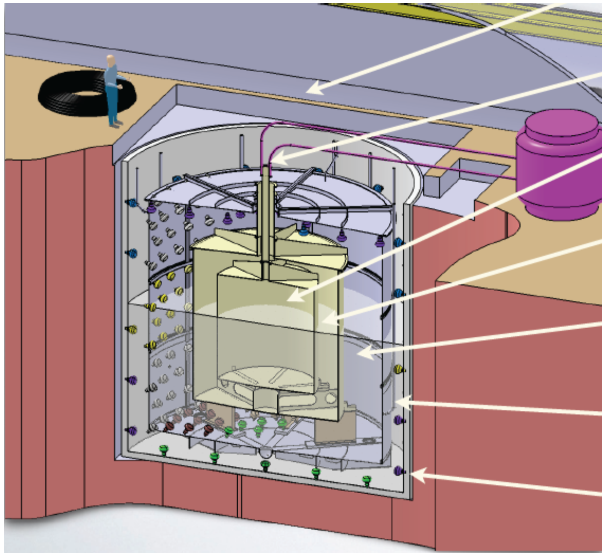
Daya Bay (China) | Double Chooz (France) | RENO (South Korea)



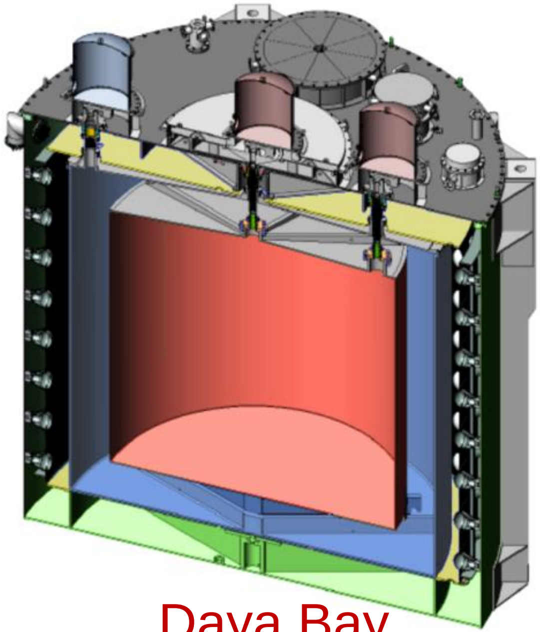
	Reactor power (GW_{th})	Overburden near/far (m.w.e.)	nGd target mass at far site (tons)	Status of data taking
Daya Bay	17.4	270/950	80	2011-2020
Double Chooz	8.6	80/300	8.3	2011-2017
RENO	16.4	90/440	15.4	2011-2021 (?)

Detector concept

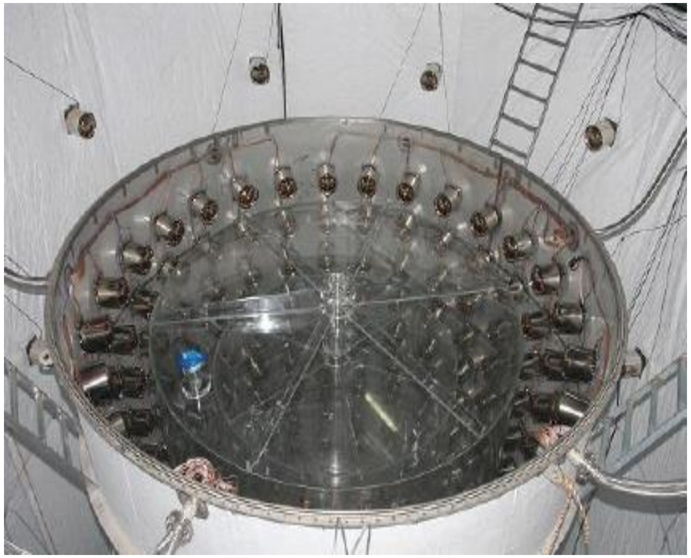
- ν-target: gadolinium-doped liquid scintillator (GdLS)
- γ-catcher: liquid scintillator (LS)
- Buffer: mineral oil
- Veto: water / scintillator / resistive plate chambers



Double Chooz



Daya Bay

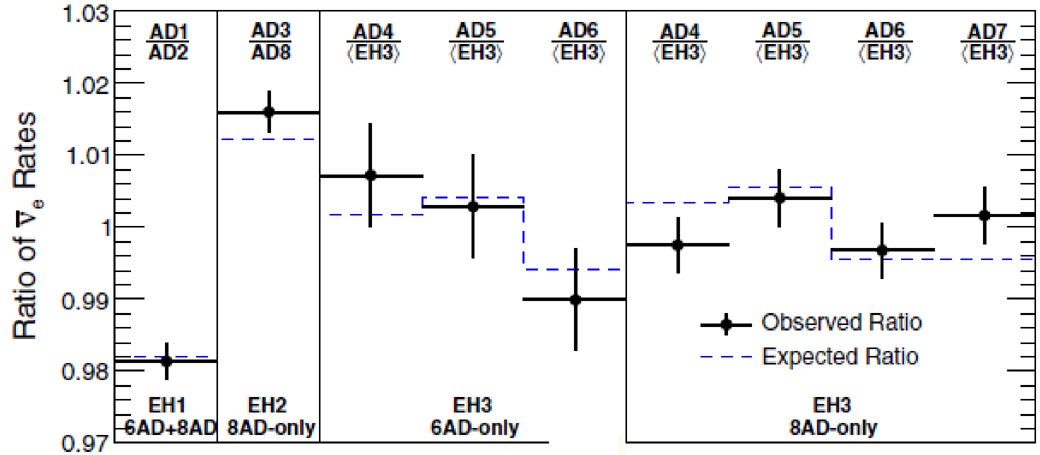


RENO

Functional identical detectors

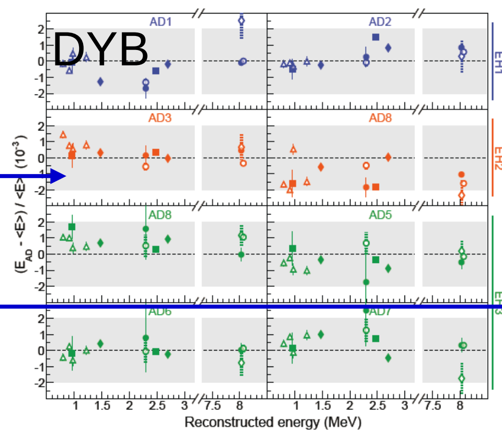
- Relative measurement reduces systematics
- State-of-the-art experiment gives 0.13% uncorrelated uncertainty
- Multi-modules in the same exp. hall allows directly validation on systematics

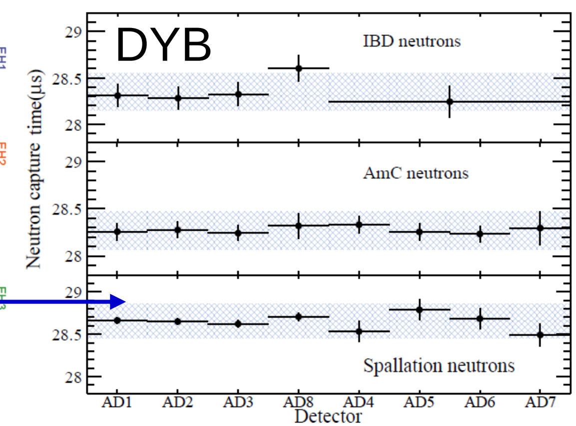
DYB: PHYSICAL REVIEW D 95, 072006 (2017)



Error bar: stat. ⊗ 0.13% syst.

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill in	104.9%	1.00%	0.02%
Live time	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%





Rel. energy scale: 0.2% **Rel. nGd time: 0.2μs**

Minimum reactor-model dependence

- Near detectors' data constrains reactor flux and spectrum
- Taking Daya Bay as an example
  - Analysis 1: extrapolate near detectors ν spectrum to far detectors

Far data   Near data   Extrapolation factor

$$\chi^2 = \sum_{i,j} (N_j^f - w_j N_j^n)(V^{-1})_{ij}(N_i^f - w_i N_i^n)$$

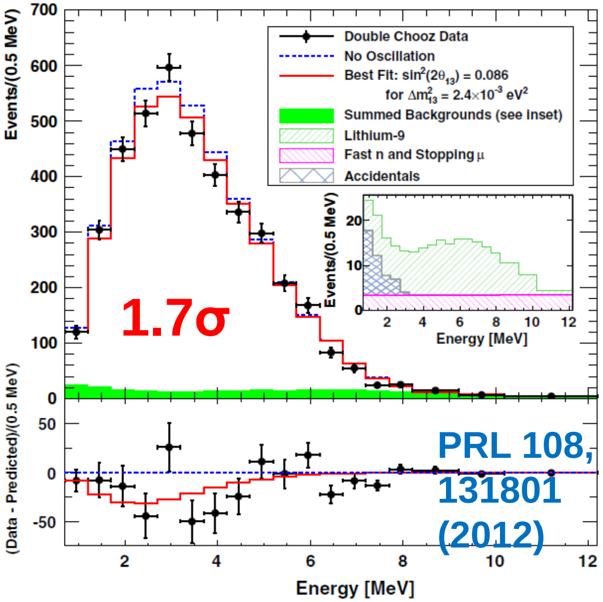
  - Analysis 2: completely remove constraints to the predicted spectrum

Free parameter for *i*th energy bin

$$\chi^2 = \sum_{d,i} \frac{\left[M_d^i - T_d^i(1 + \varepsilon_d + \varepsilon_i + \cdots)\right]^2}{(\sigma_d^i)^2} + \cancel{\left(\frac{\varepsilon_i}{\sigma_i}\right)^2} + \cdots$$

Discovery of non-zero θ_{13}

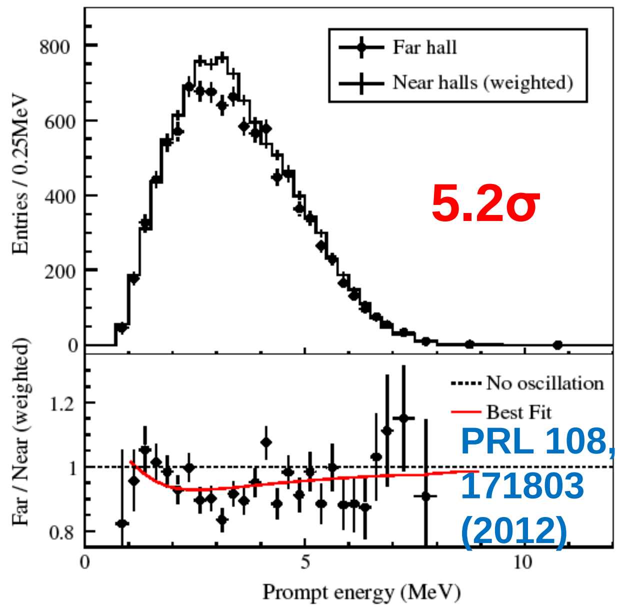
Double Chooz
with only a far detector
(Nov. 2011)



Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$$

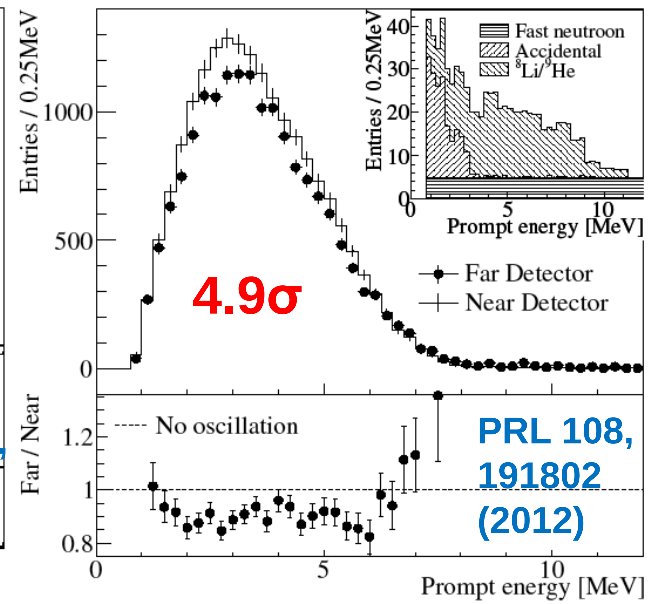
Daya Bay
(March 2012)



Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

RENO
(April 2012)

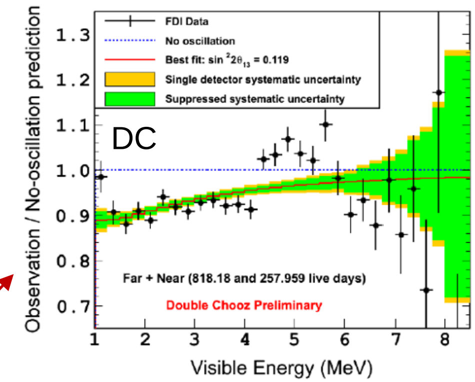


Rate only

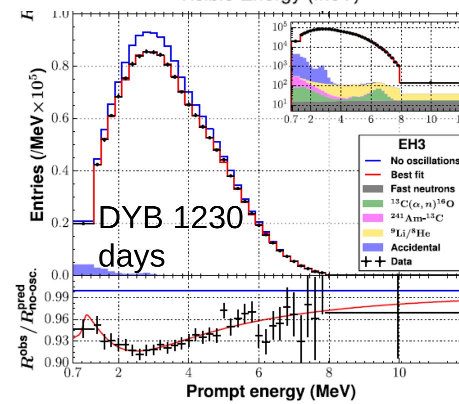
$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

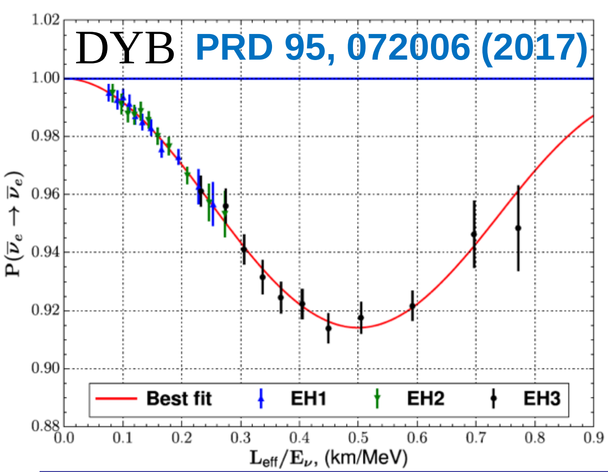
Latest result

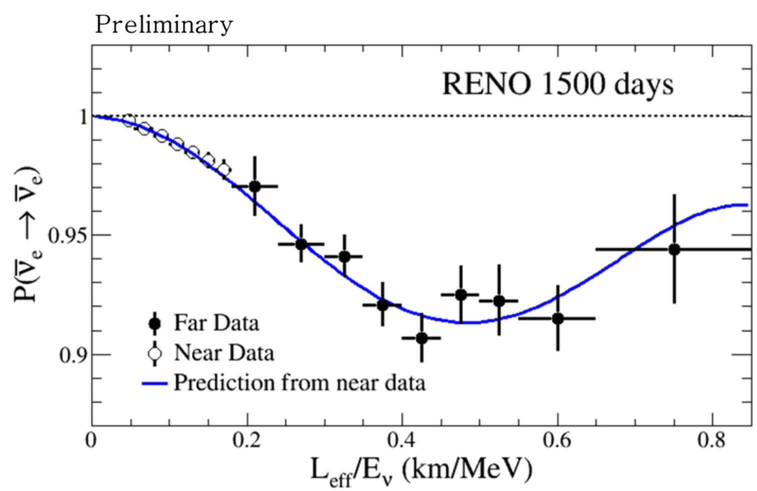
- Near far relative analysis
- Rate deficit + spectrum distortion
- DYB and RENO measured $|\Delta m^2_{ee}|$
- Clear L/E dependence

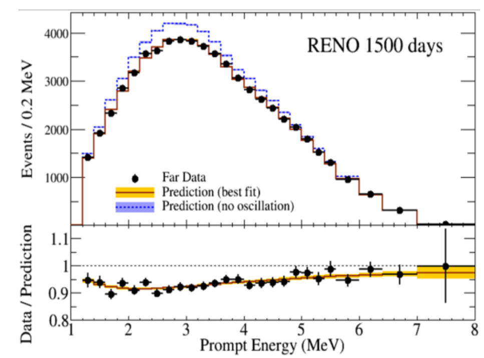


Plenary talk: *Jaime Dawson*,
Latest Results From Double Chooz



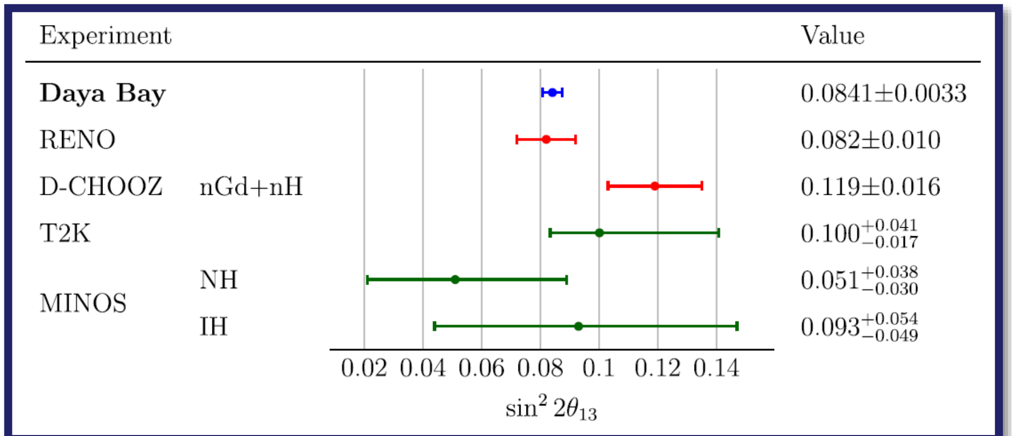


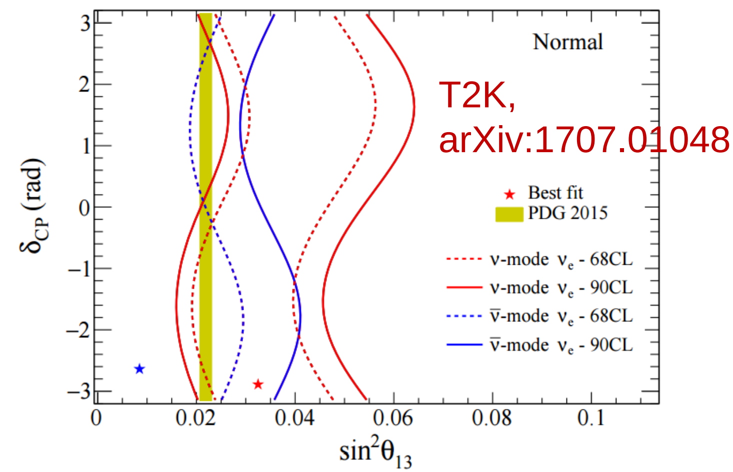


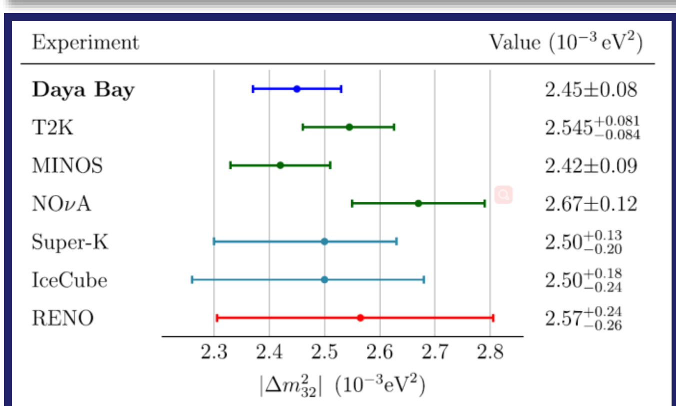


Global comparison

- Most precision θ_{13} comes from reactor experiments
- Improve δ_{CP} measurement for accelerator experiments
- ~2σ tension between DC and DYB/RENO



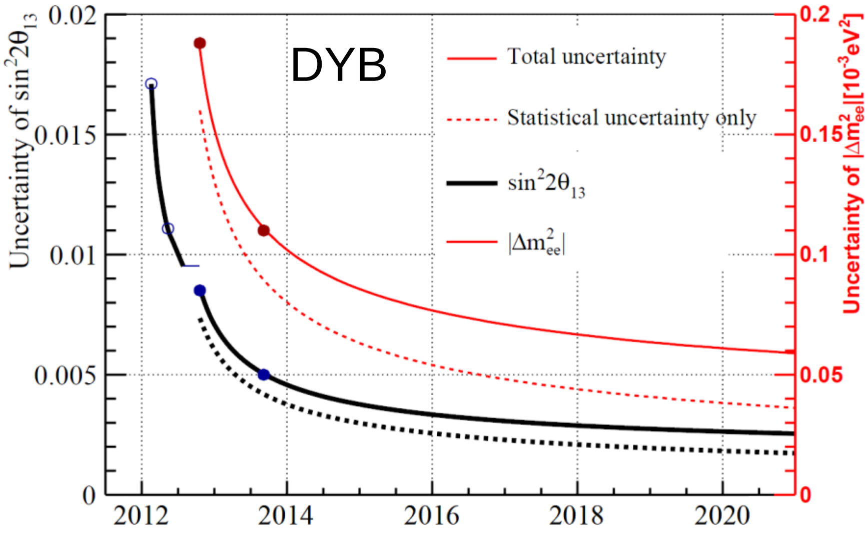


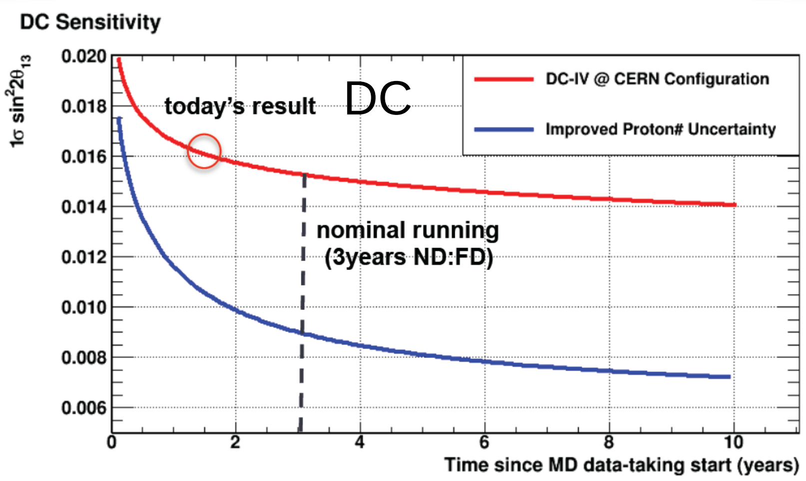


- Consistent $|\Delta m^2_{32}|$ between reactor, acc. and atm. experiments
- DYB's precision is comparable with acc.

Prospect of θ_{13}

- **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 of systematics and LS technical studies
- **RENO**
  - Plan to 2018 with possible extension to 2021

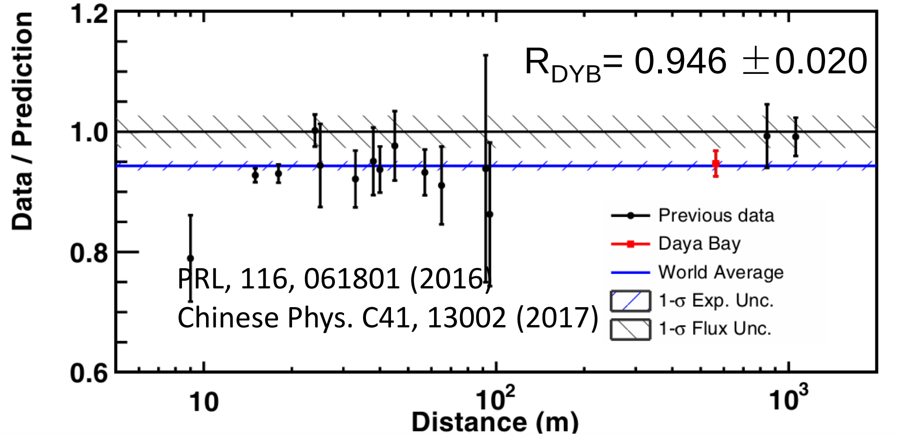




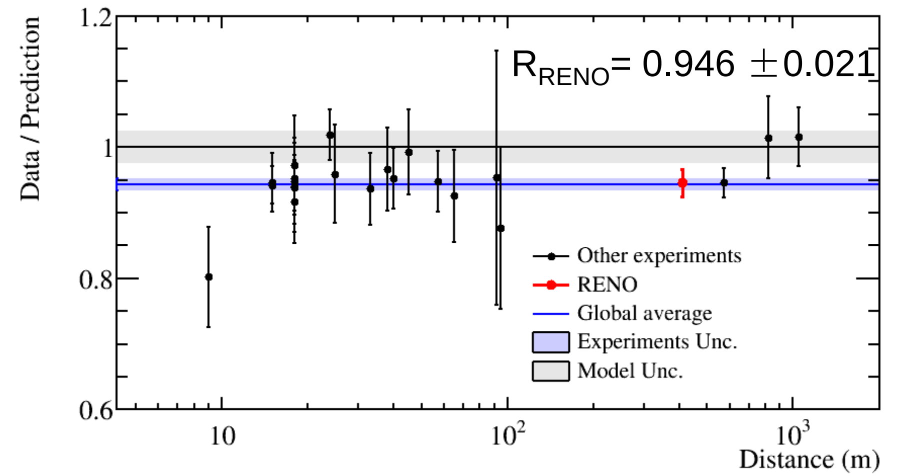
Reactor flux anomaly

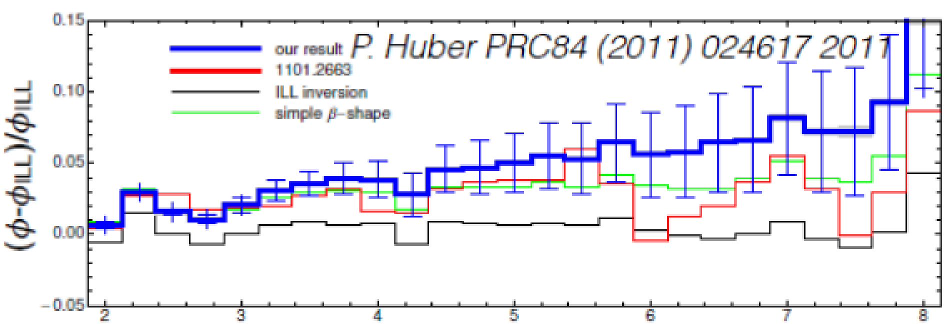
- Huber + Mueller's prediction of reactor neutrino flux (~2.4% uncertainty) by re-analysis of ILL's beta spectra: ~5% higher than short baseline experiments
- DYB and RENO: consistent with previous experiments
- ~2% uncertainty, dominated by detection efficiency

Daya Bay/(Huber+Mueller)



RENO/(Huber+Mueller)

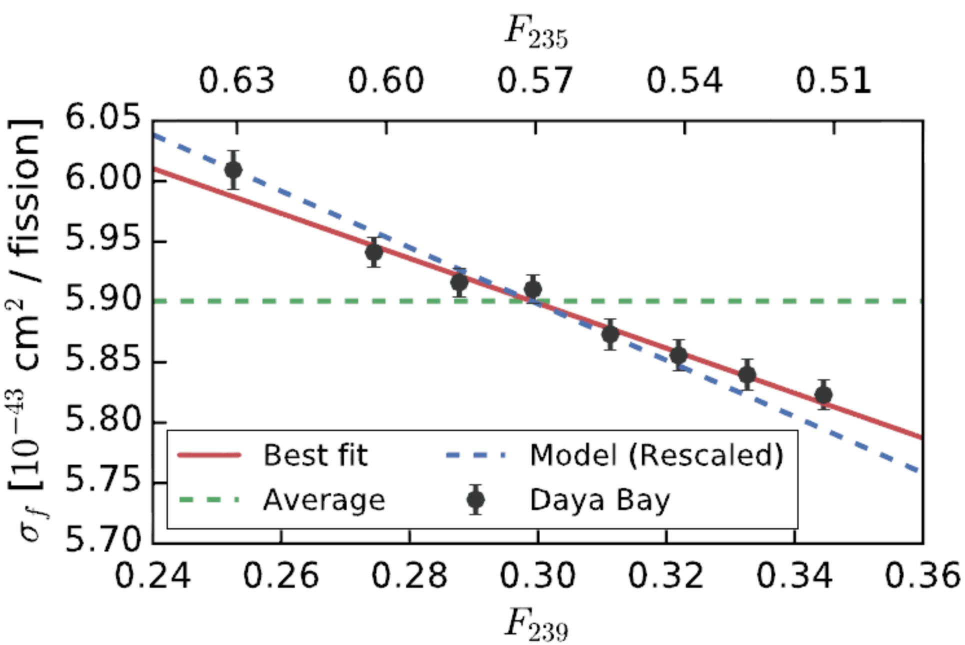


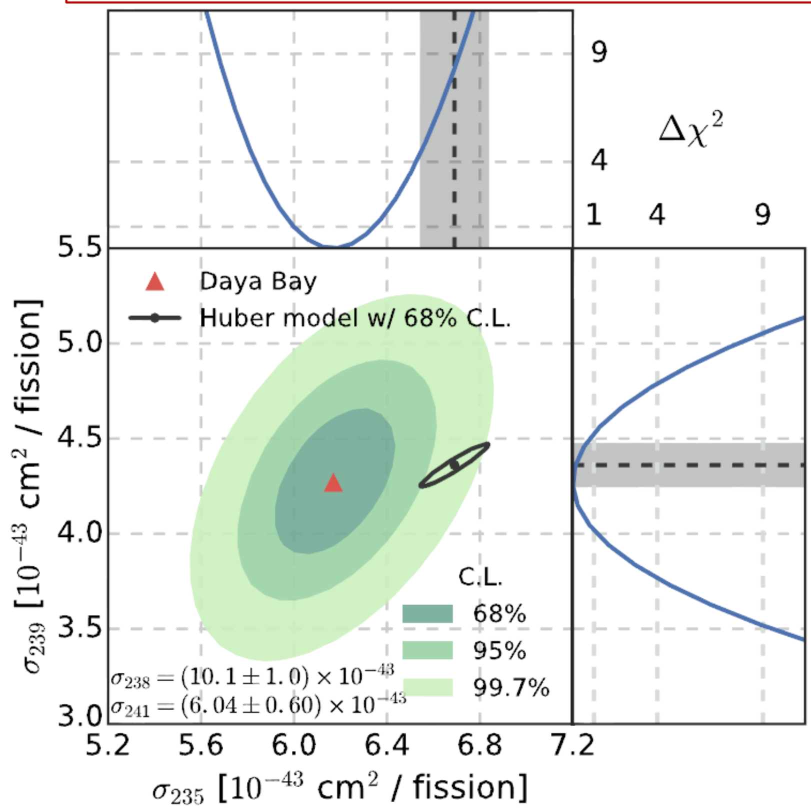


Reactor fuel evolution

- Study of the neutrino flux and shape changing with reactor fuel evolution by Daya Bay
- ^{235}U appears to be the main contributor to the Reactor Antineutrino Flux Anomaly
- Sterile neutrino as the sole cause of RAA is disfavored by 2.8σ

Reference: **PRL 118, 251801 (2017)**

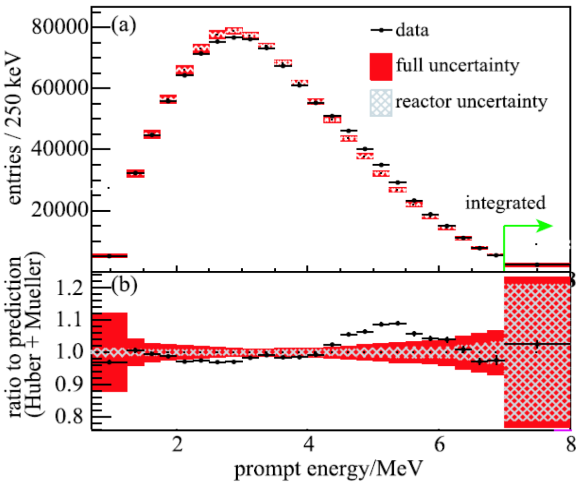




Reactor spectrum anomaly

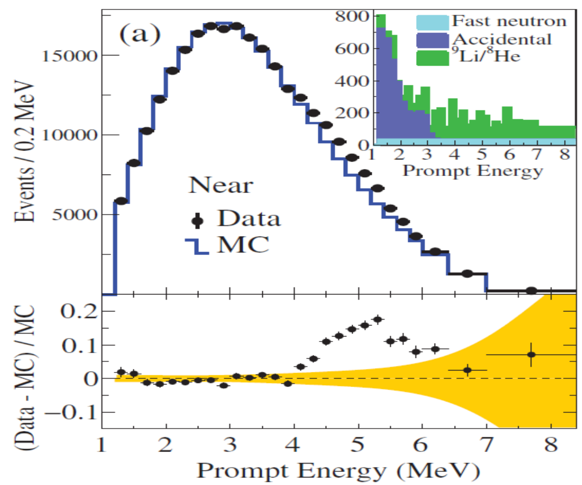
Daya Bay

CPC 41, 1 (2017) 013002



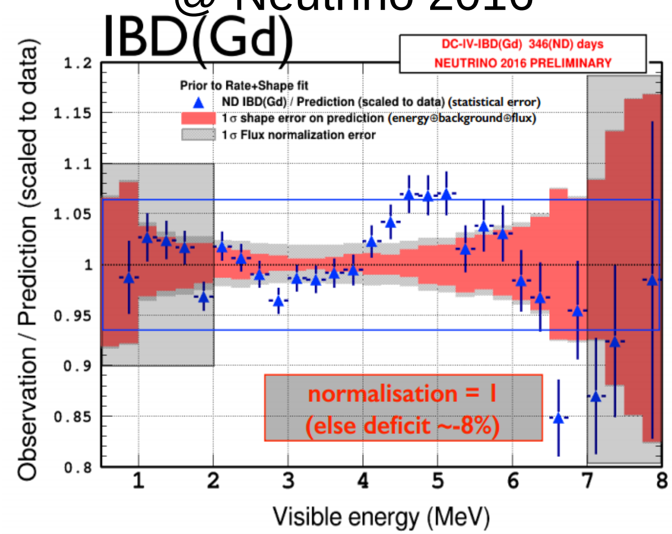
RENO

PRL 116, 211801 (2016)



Double Chooz

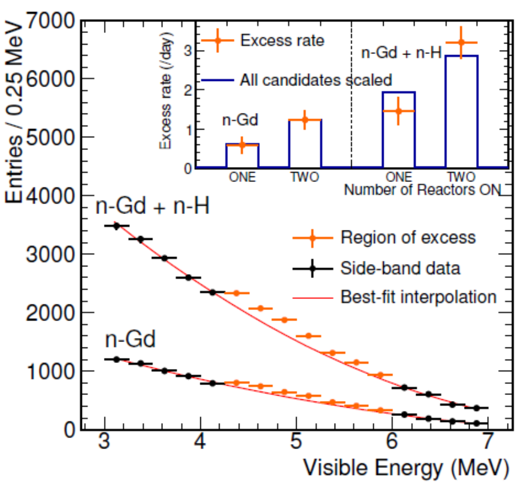
@ Neutrino 2016



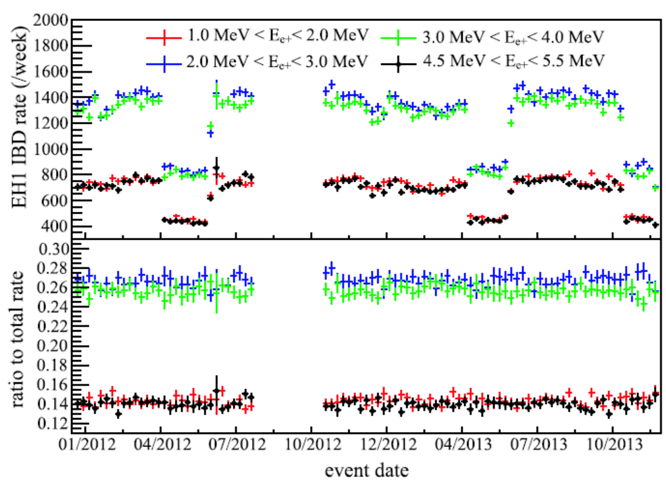
- All three experiments observed "bump" in the 4-6 MeV region of the prompt energy spectrum since 2014.

Source of 4-6MeV excess

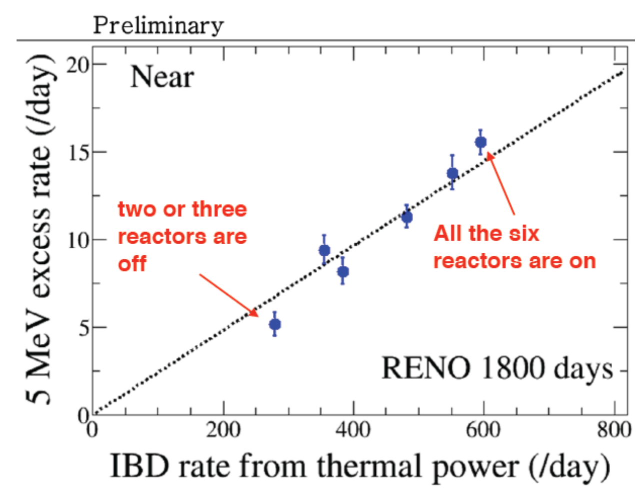
- Evidence that the 4-6 MeV excess comes from reactors
  - NOT from background, sterile neutrino, energy nonlinearity …
  - Clear correlation with reactor thermal power
- Underestimation of reactor prediction uncertainty? *A. Hayes et al.*
  - 30% of the decays are first forbidden. 5% uncertainty is more realistic



Double Chooz
JHEP10(2014)086



Daya Bay
CPC 41, 1 (2017) 013002



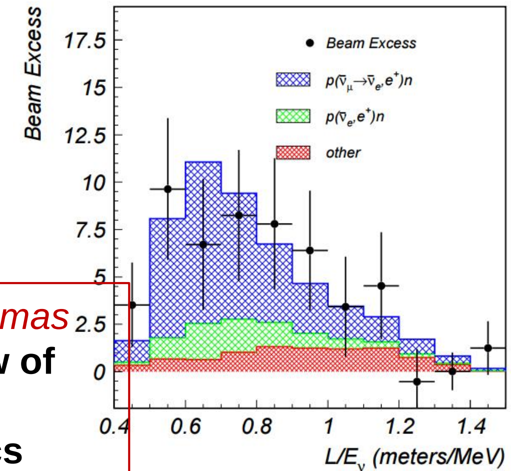
RENO
@ NUFACT17

Sterile neutrino searches

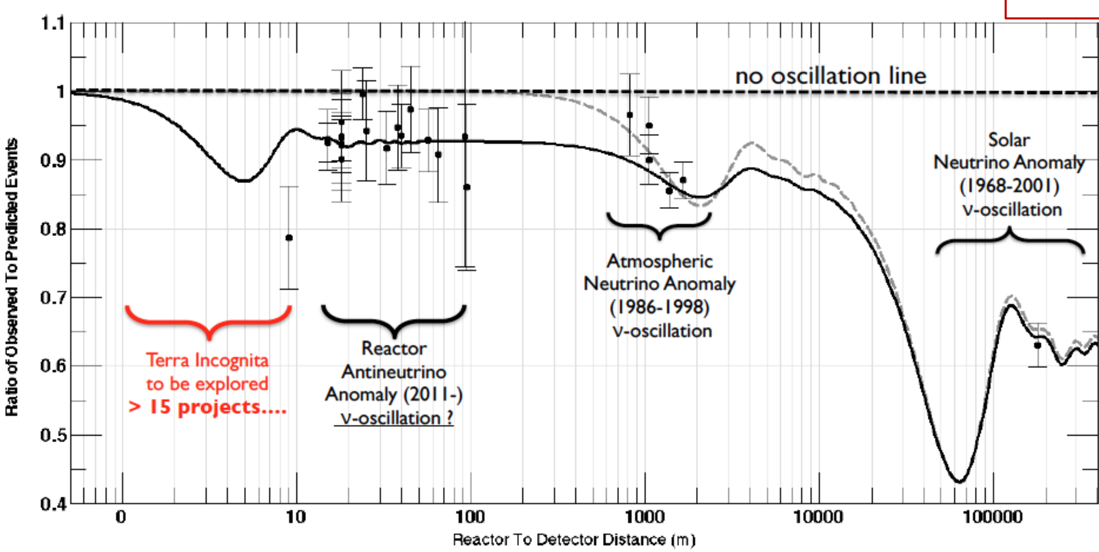
- LSND anomaly: excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam (2001), similar excess seen by MiniBooNE (2013)
- Reactor anomaly: ~5% deficit at 10-100m baselines (2011)
- Gallium anomaly: ~2.9σ deficit of ~0.8MeV ν_e at meter level (2006-2009)

⇨ eV scale sterile neutrino

LSND: 3.8σ

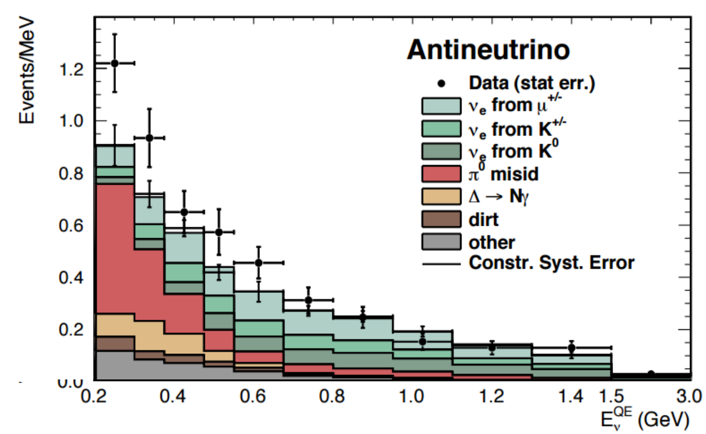


Plenary talk: *Thomas Schwetz*, **Review of eV-Scale Sterile Neutrino Physics**



lore it

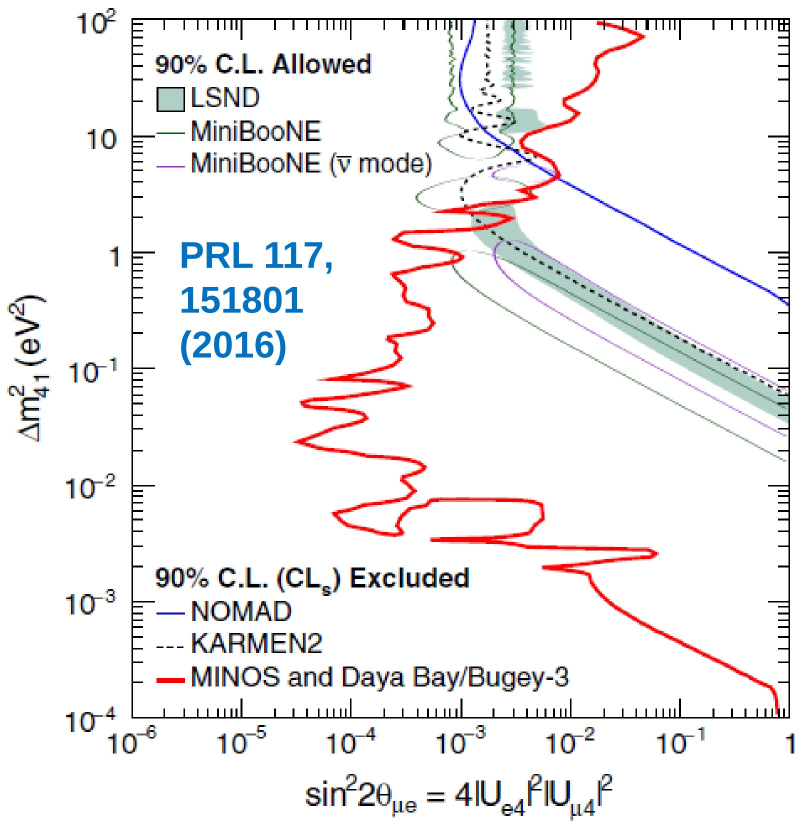
MiniBooNE: 2.8σ



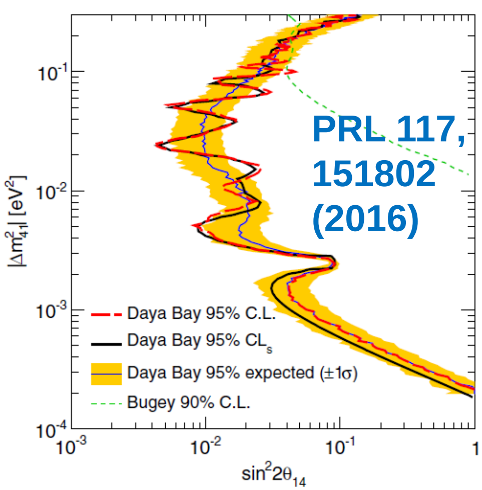
Constrain from ~km experiments

- Additional spectrum distortion with the existence of sterile neutrinos.
- Reactor disappearance experiments constrain Δm^2_{41} and $\sin^2 2\theta_{14}$.
- Combination of accelerator and reactor experiments further constrain Δm^2_{41} and $\sin^2 2\theta_{\mu e}$:
  LSND + MiniBooNE's allowed par. space excluded < 0.8 eV^2 @90% C.L

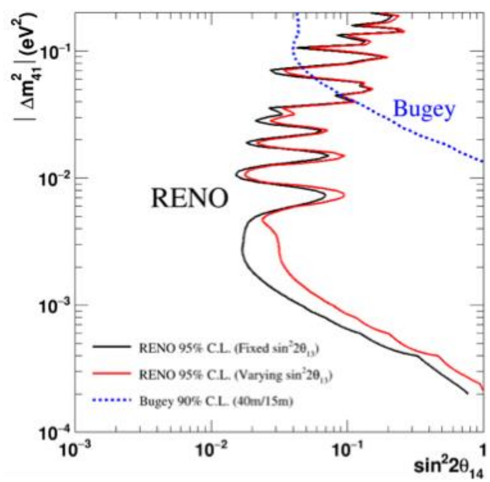
MINOS+DYB+Bugey-3:



Daya Bay

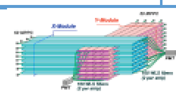
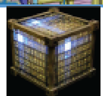
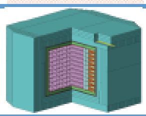
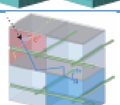


RENO preliminary



Short baseline reactor experiments

Only introduce NEOS and SoLid in this talk

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

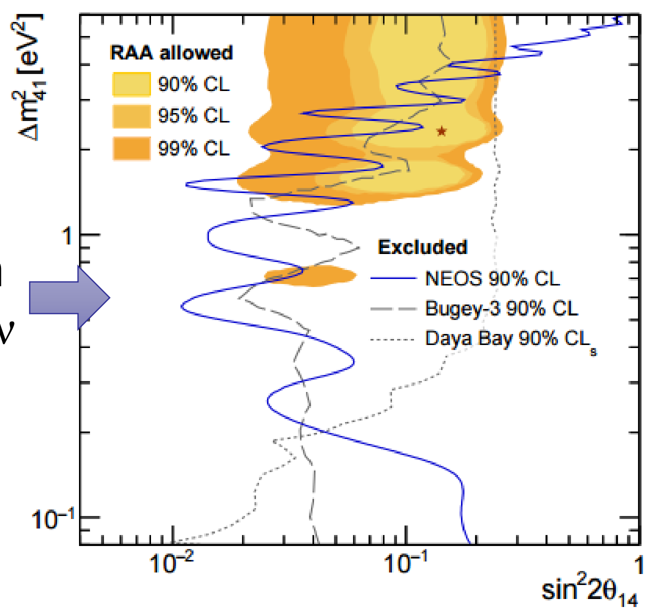
Nathaniel Bowden @ Neutrino 2016

NEOS

Reference: PRL 118, 121802 (2017)

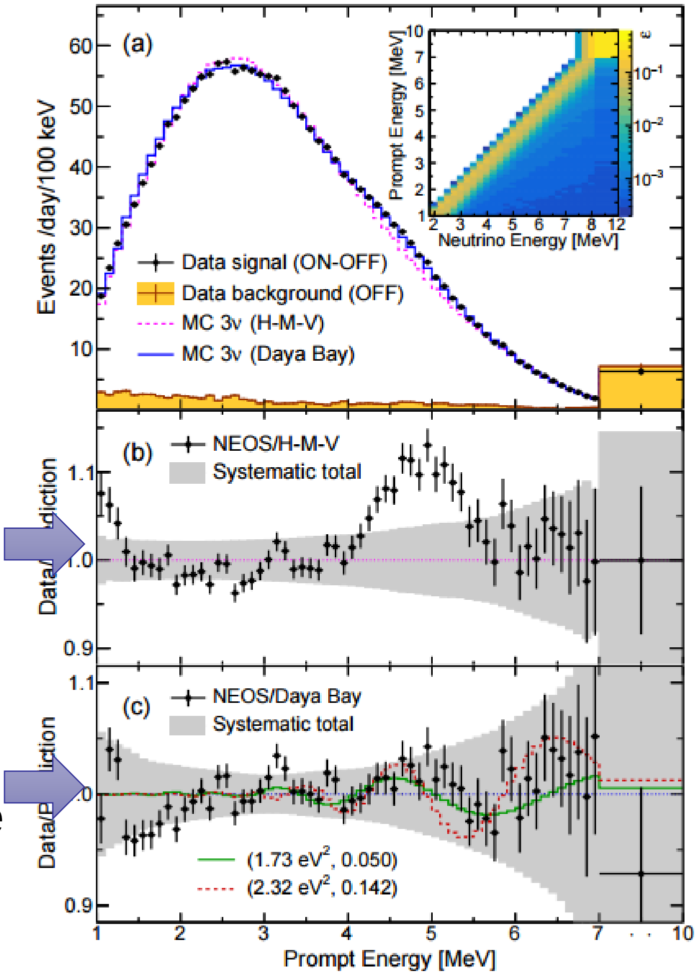
- Neutrino Experiment for Oscillation at Short baseline
  - 2.8 GW_{th} commercial reactor in Younggwang NPP, Korea
  - Low enriched uranium fuel (4.6% ^{235}U)
  - 23.7-m baseline and 20-m.w.e overburden
  - LS detector with 4.8%@1MeV energy res.
  - Single detector, need a reference model

Exclusion of sterile ν



H-M as reference

DYB as reference

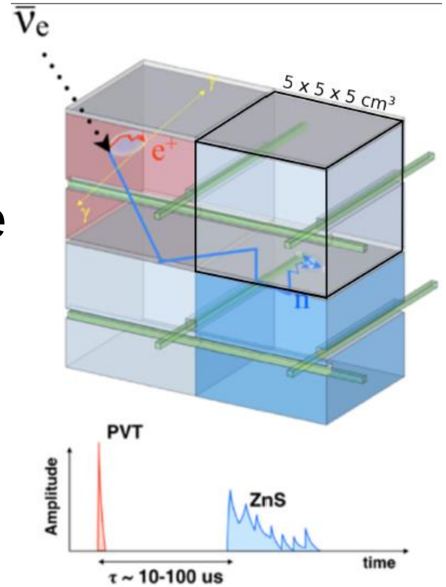


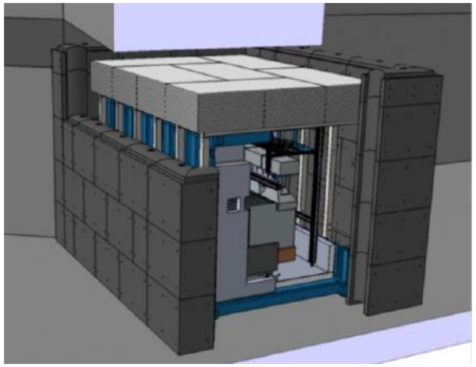
SoLid

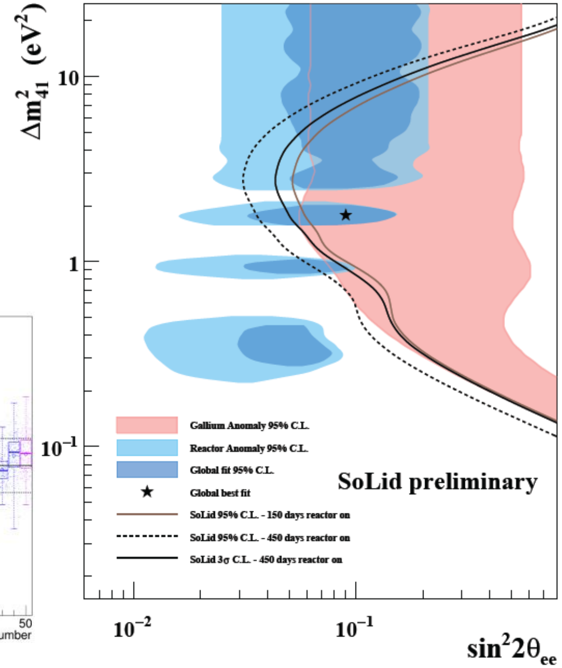
Parallel talk: *Simon Vercaemer*, **Reactor Experiment SoLid**

Many thanks to Simon V. and SoLid collaboration

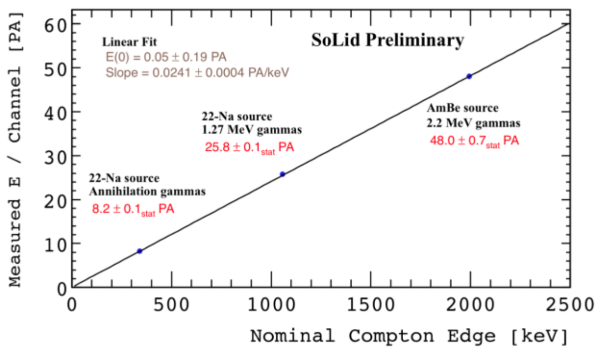
- Compact reactor BR2 at SCK-CEN (Belgium)
  - 93.5% ^{235}U, 50-80 MW, 6-9 m baseline
- 3D highly segmented composite detector (1600kg for phase 1)
  - e+ detection in PVT cubes
  - Neutron capture on Li in ZnS layer
  - n and e/γ discrimination with PSD
- First physics results in 2018

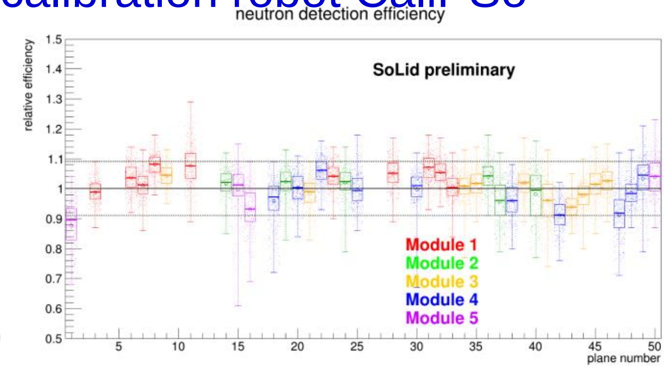






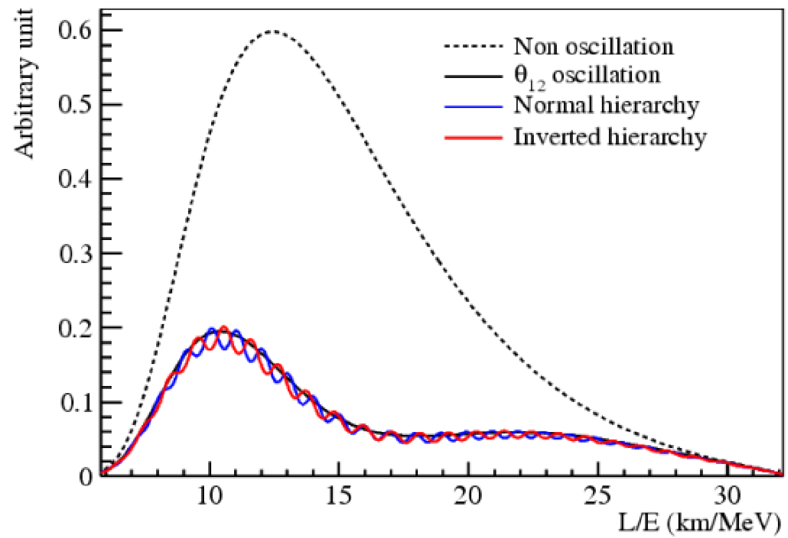
Obtained by off-site calibration robot CaliPSo

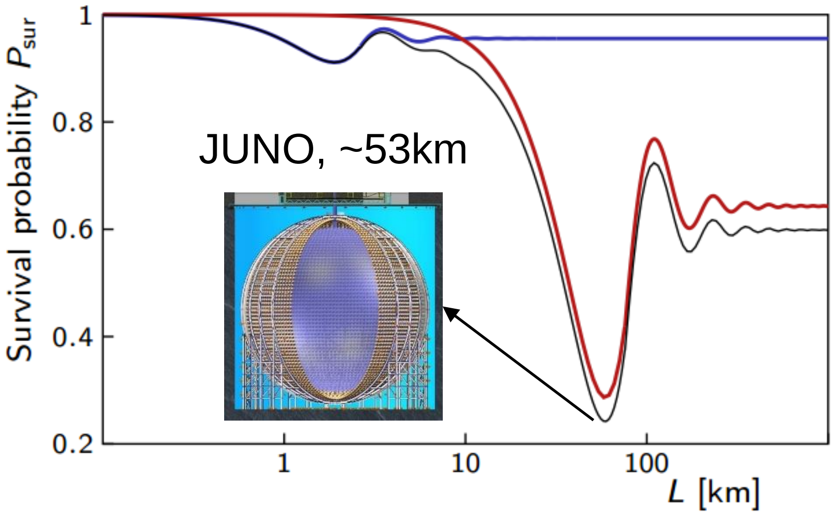




Next generation reactor experiment

- A unique way to determine mass hierarchy using reactor antineutrinos by the interference between Δm^2_{31} and Δm^2_{32}.
- Challenge: very large detector volume and unprecedent energy resolution
- JUNO: 20kton liquid scintillator, 3%@1MeV energy resolution, 700m underground





Parallel talk: *Z.H. Qin*, **JUNO: Recent Progress in Detector R&D**

Summary

- Reactor neutrinos played an important role in the history, leading to the first discovery of the neutrino, and the first confirmation of solar neutrino oscillation.
- The current generation reactor experiments, Double Chooz, Daya Bay and RENO observed the neutrino oscillation driven by the smallest mixing angle theta13, and provided the most precision measurement of theta13 to date.
- Anomalies were observed in reactor neutrino flux, spectrum, and the fuel revolution. These evidences suggest an underestimation of the reactor model uncertainty.
- Combination of Daya Bay and MINOS excluded part of the sterile neutrino parameter space allowed by LSND and MiniBooNE.
- Many short baseline reactor experiments have started or are about to start taking data in the coming year to further explore the sterile neutrinos at eV scale.