Recent Results from Reactor Antineutrino Experiments

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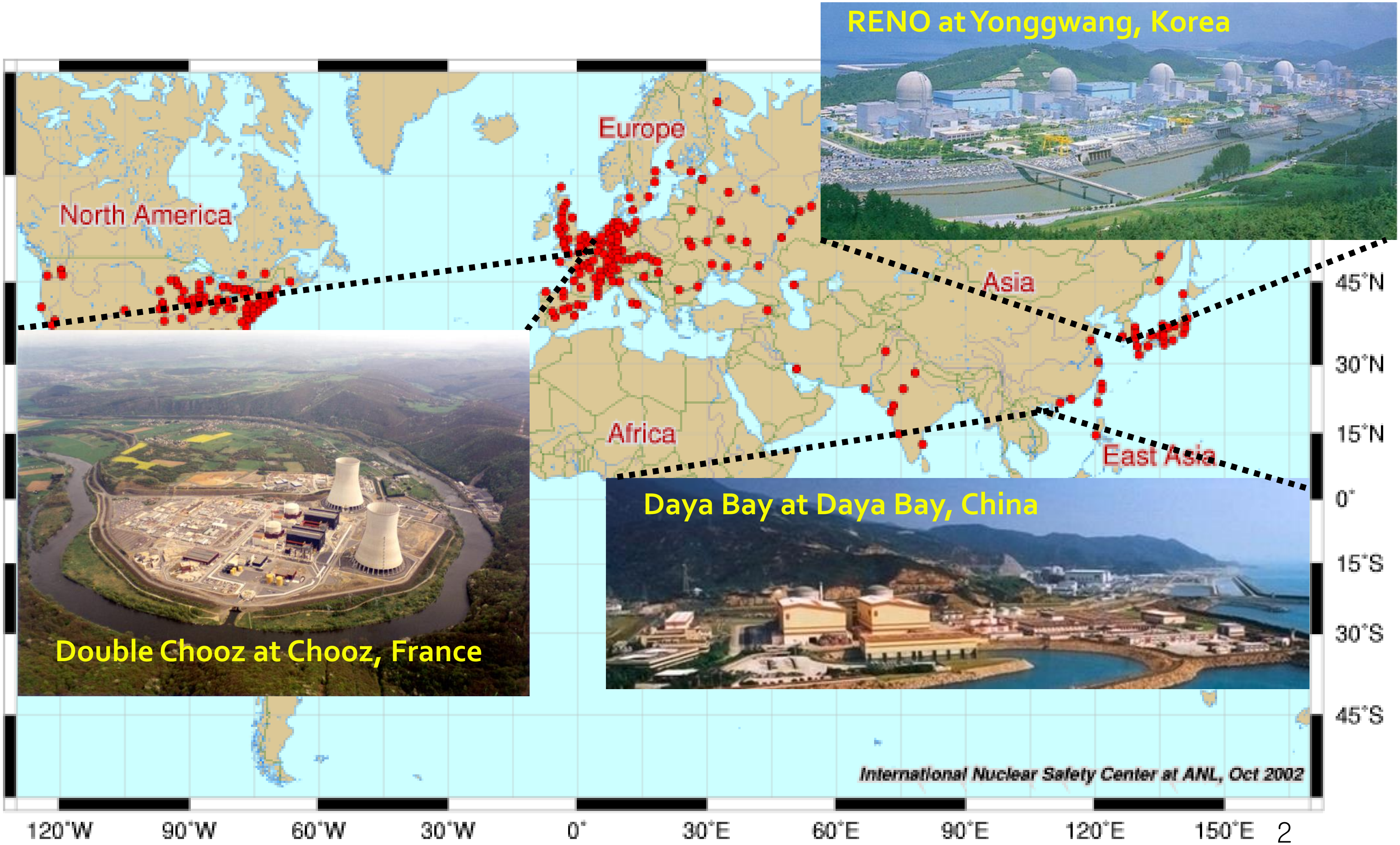
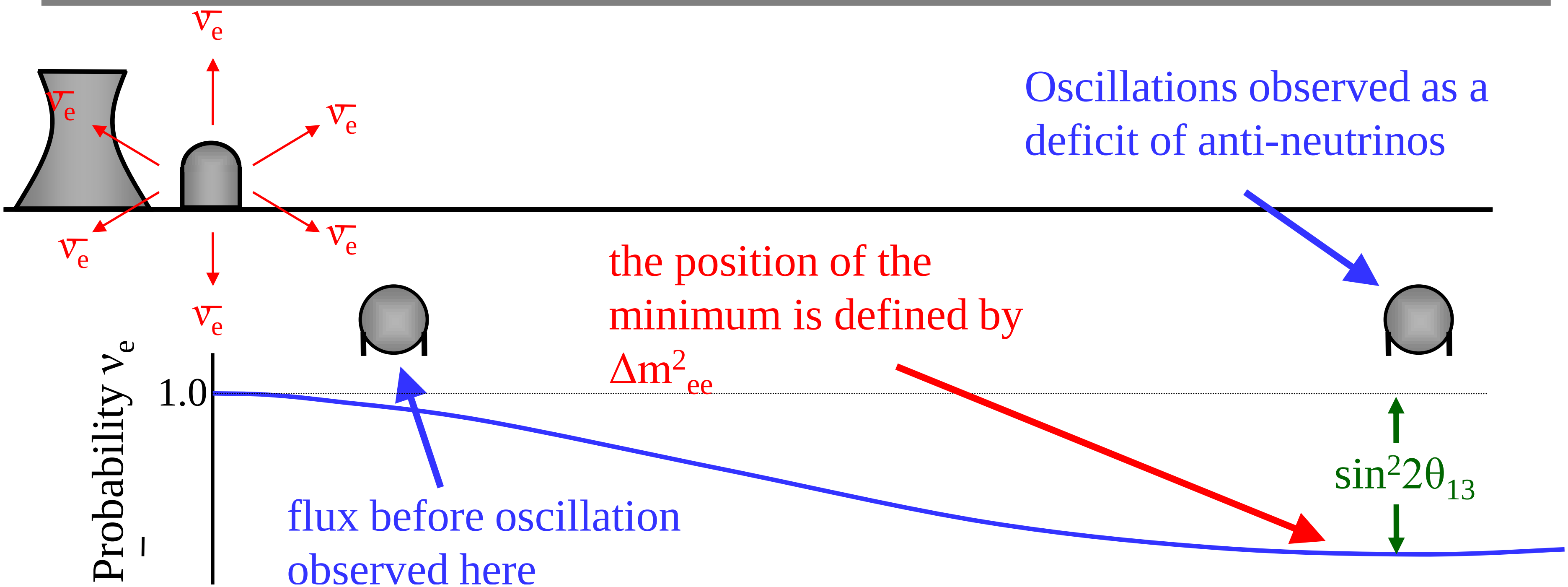
Reactor θ_{13} Experiments



Reactor Neutrino Oscillations



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

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

$$\Delta_{ij} \equiv 1.267\Delta m^2_{ij}L/E$$

Distance

1200 to 1800 meters

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

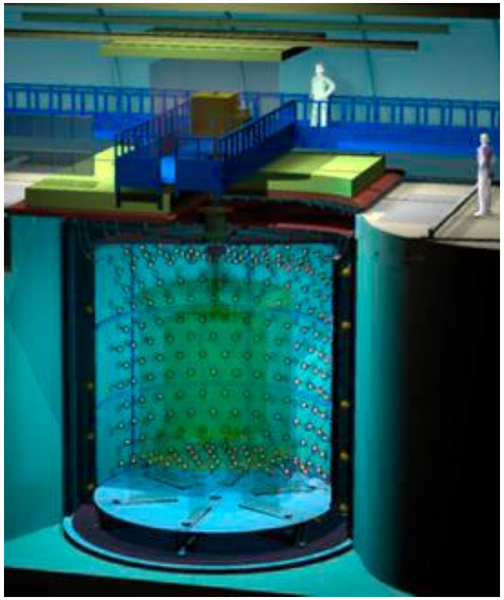
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\text{eV}^2$$

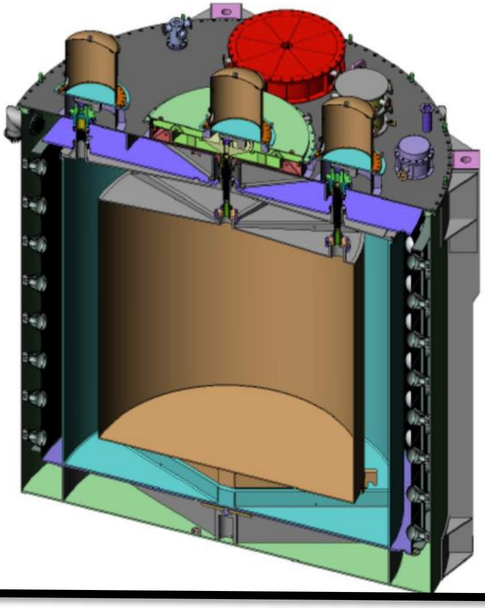
$\cos^2\theta_{12}|\Delta m^2_{21}|$

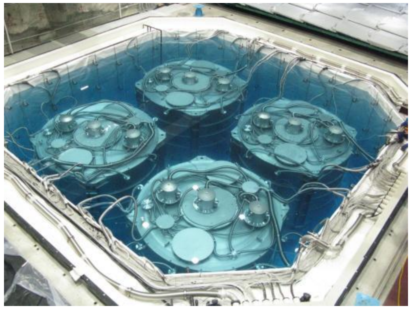
+: Normal Hierarchy
−: Inverted Hierarchy

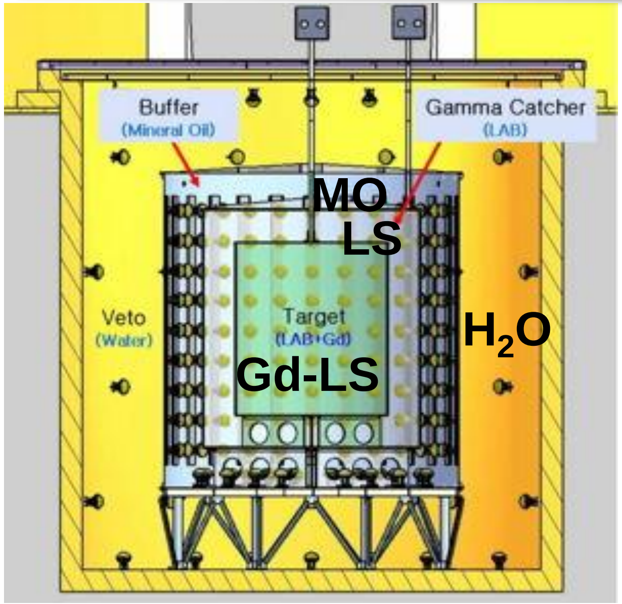
H. Nunokawa et al, PRD72 013009 (2005)

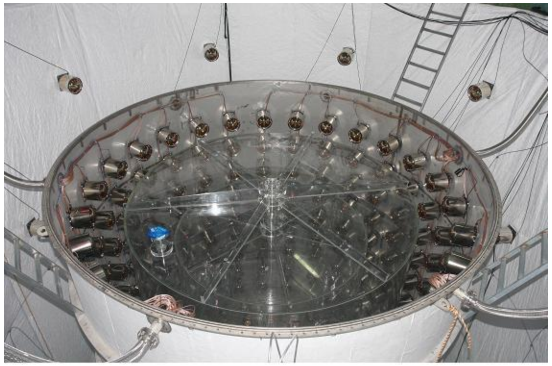
θ_{13} Reactor Neutrino Detectors





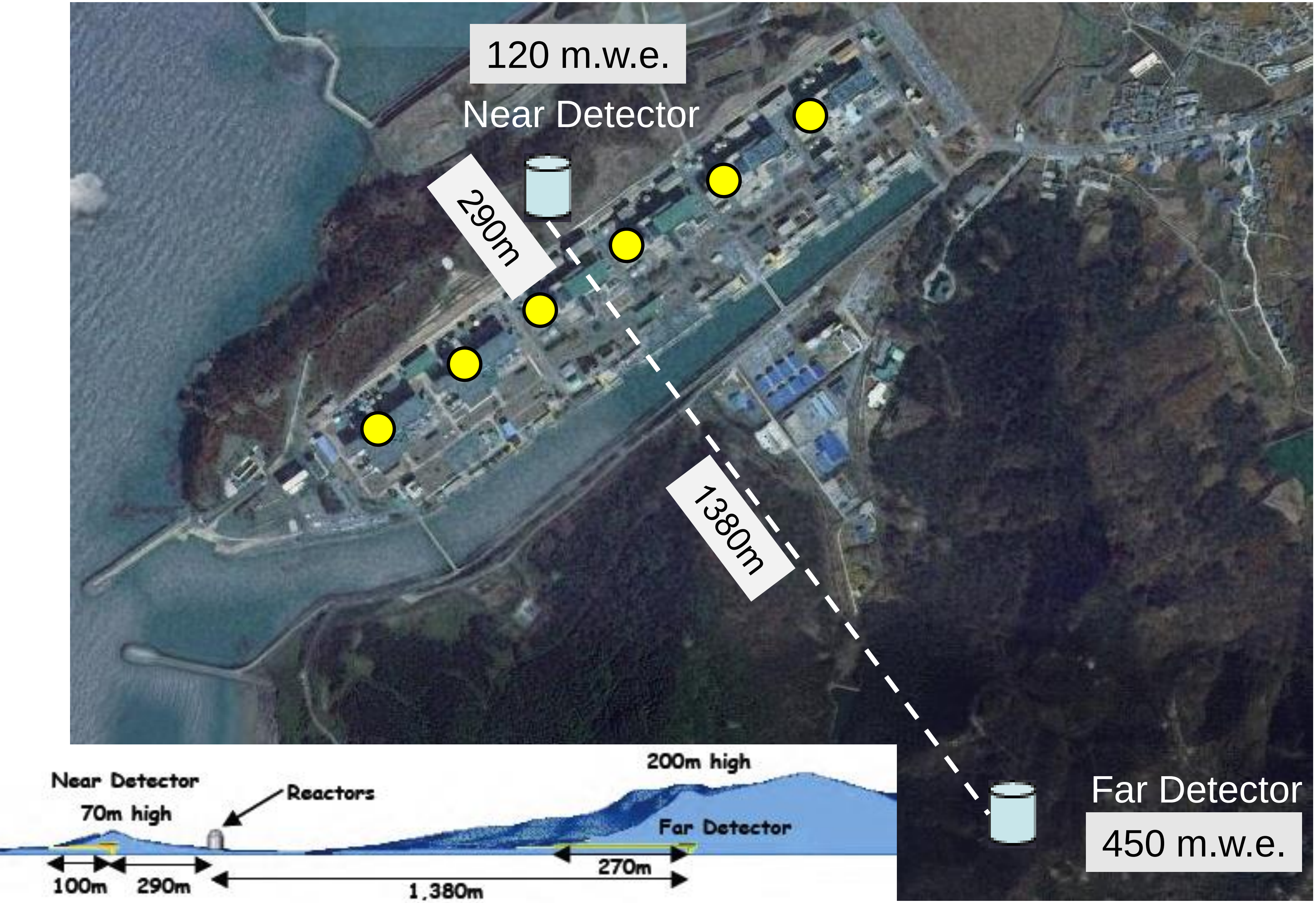




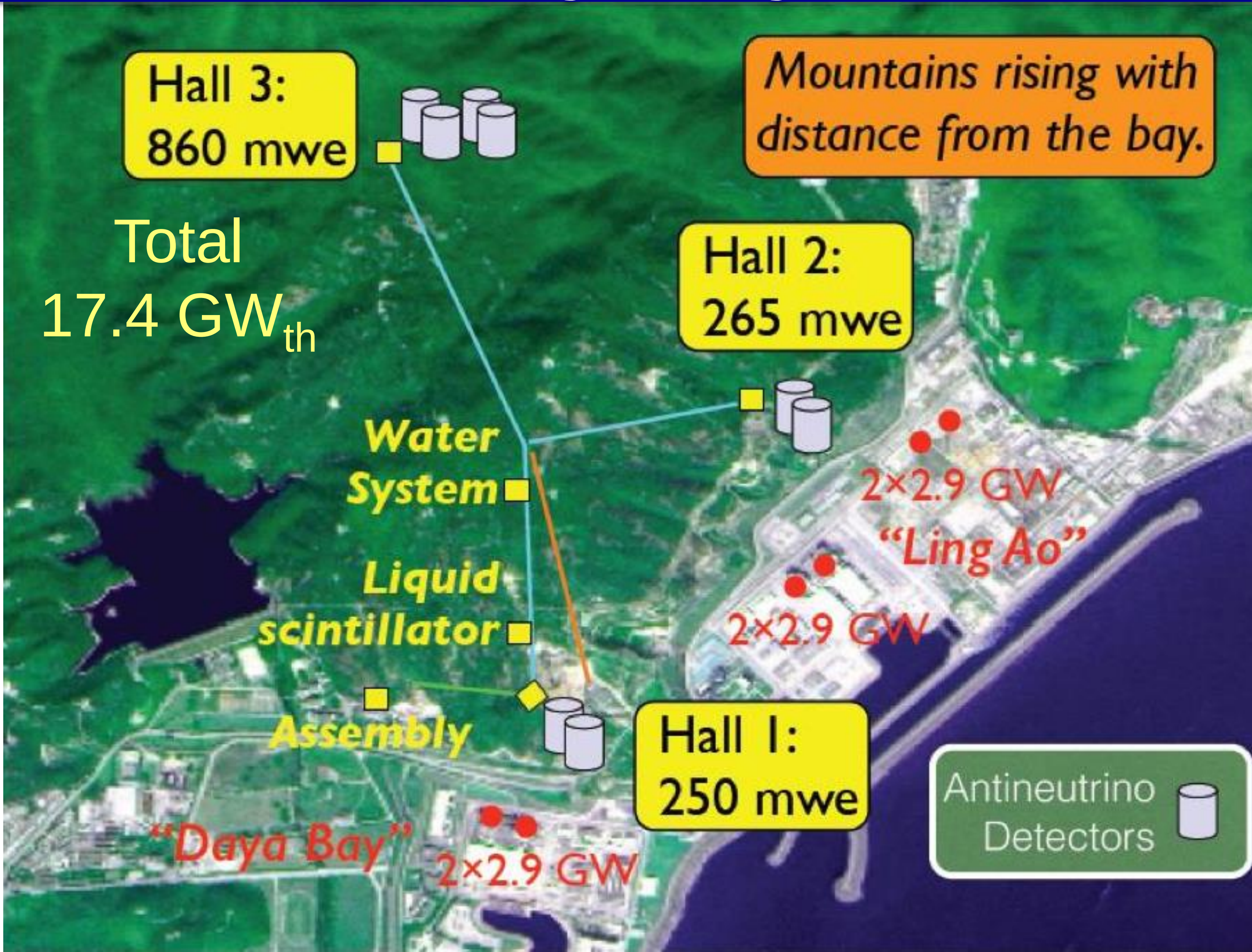


1. **Cylindrical structure (four layers)**
2. **Neutrino Target: liquid scintillator with 0.1 % Gd doping**

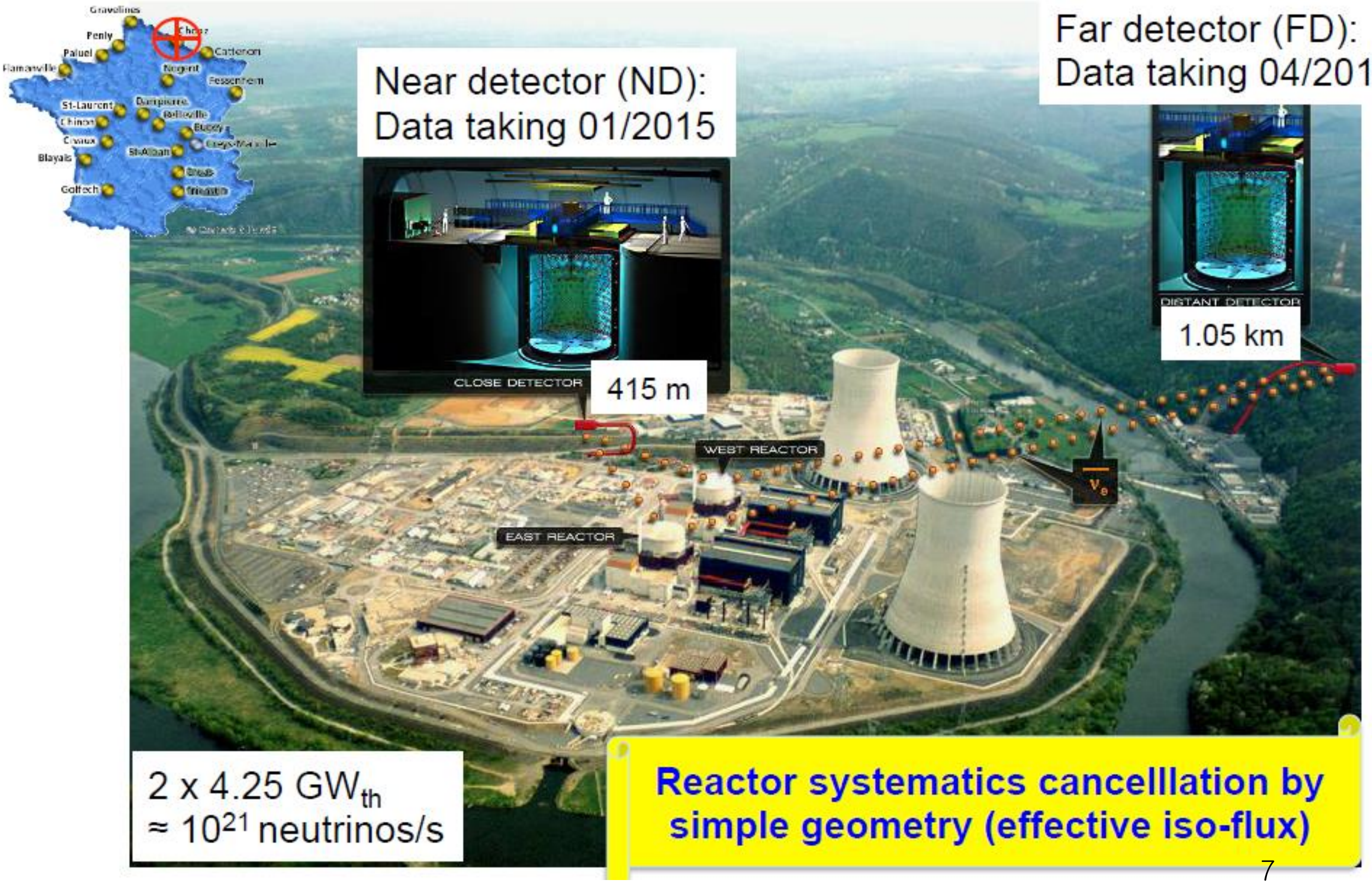
RENO Experimental Set-up



Daya Bay


Hall 3:
860 mwe
Mountains rising with
distance from the bay.
Total
17.4 GW$_{th}$
Hall 2:
265 mwe
Water
System
Liquid
scintillator
Assembly
2×2.9 GW
"Ling Ao"
2×2.9 GW
Hall 1:
250 mwe
"Daya Bay"
2×2.9 GW
Antineutrino
Detectors

Double Chooz



Outline of recent results from reactor antineutrino experiments

■ Precise measurements of $|\Delta m_{ee}^2|$ and θ_{13}

- **RENO : 2200 days, Daya Bay : 1958 days**
  n-Gd delayed signals
- **Double Chooz : 818(far) / 258(near) days**
  n-Gd/n-H/n-C delayed signals

■ Measurement of absolute reactor neutrino flux

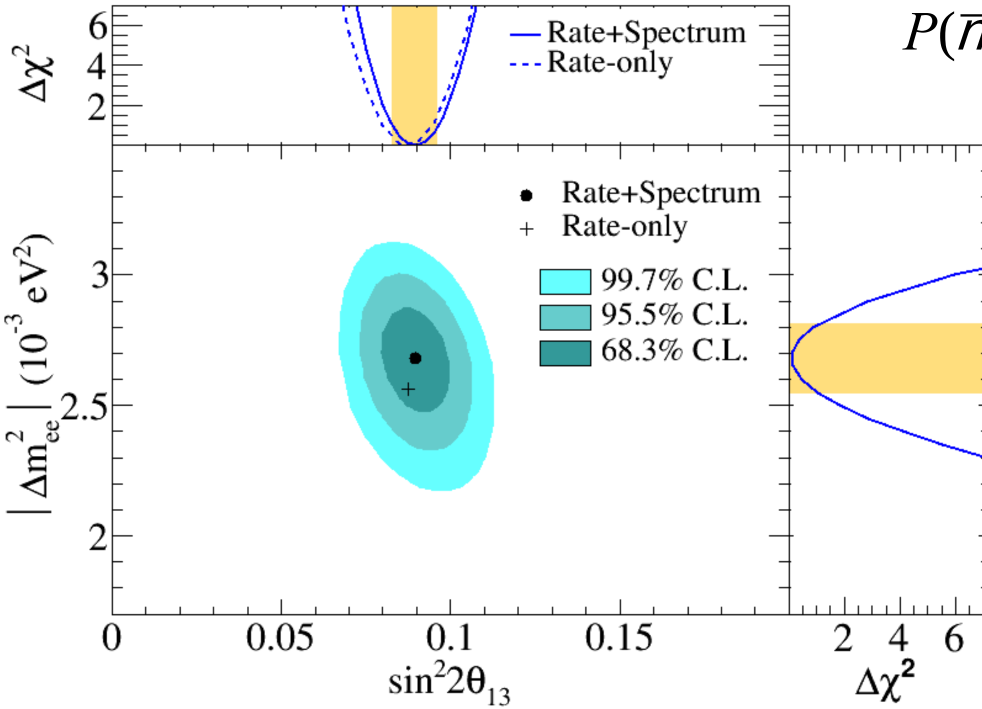
■ Fuel-composition dependent reactor antineutrino yield

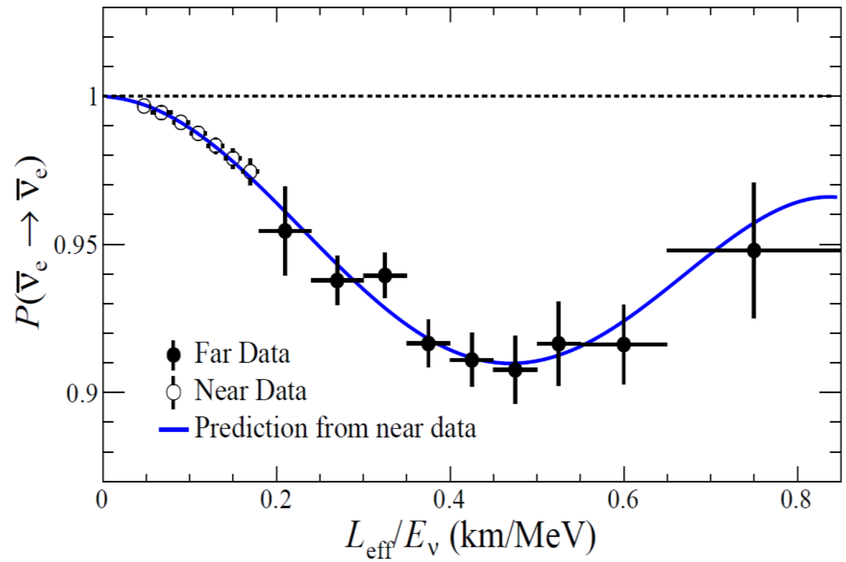
■ A model-independent reactor antineutrino spectrum

θ_{13} and $|\Delta m^2_{ee}|$ in RENO

submitted to PRL (arXiv:1806.00248)   RENO 2200 days

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$





$\sin^2 2\theta_{13}$ = 0.0896 ± 0.0068 (7.6 %)

0.0896 ± 0.0048(stat.) ± 0.0047(syst.)

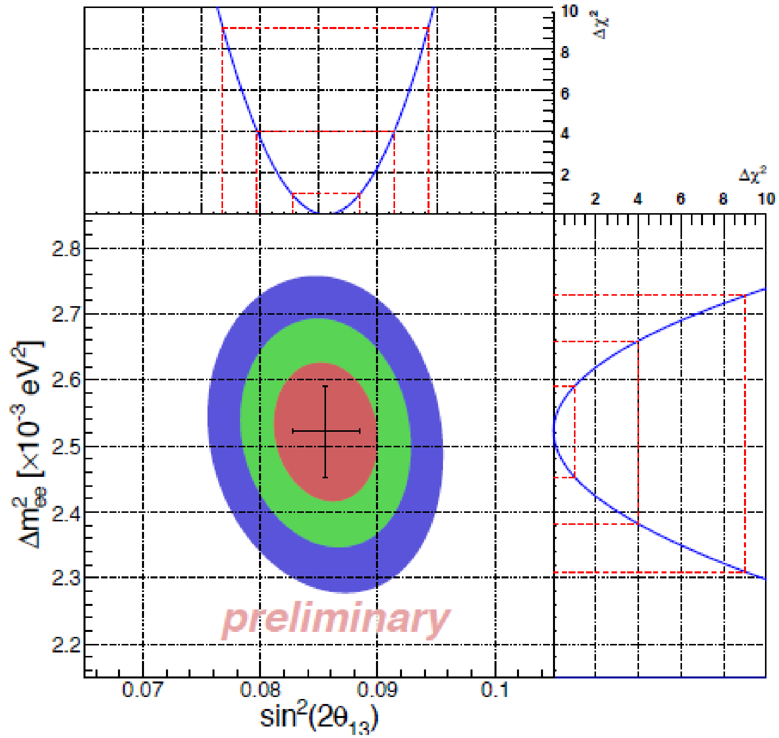
$|\Delta m_{ee}^2|$ = 2.68 ± 0.14 ($\times 10^{-3}$ eV^2) (5.2 %)

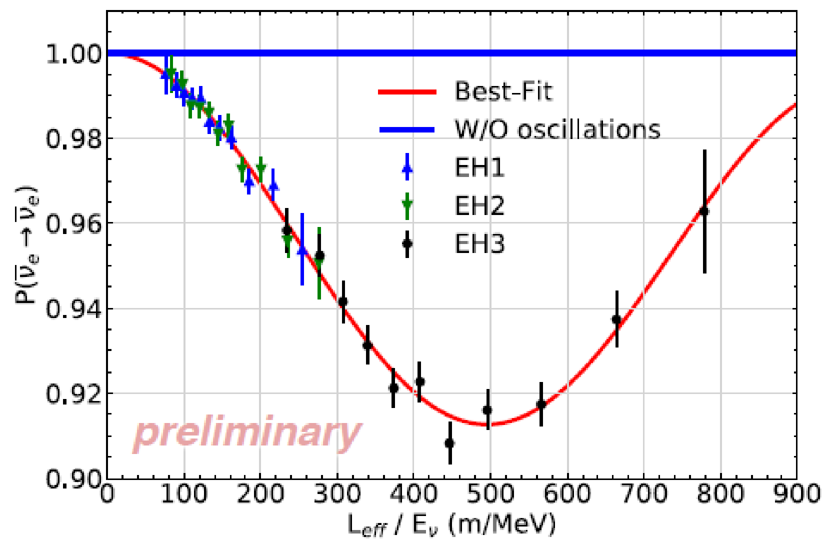
2.68 ± 0.12(stat.) ± 0.07(syst.)

θ_{13} & $|\Delta m^2_{ee}|$ in Daya Bay

Neutrino 2018 Daya Bay 1958 days

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$





$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (3.4 %)

$|\triangle m_{ee}^2| = 2.52 \pm 0.07$ ($\times 10^{-3}$ eV^2) (2.8 %)

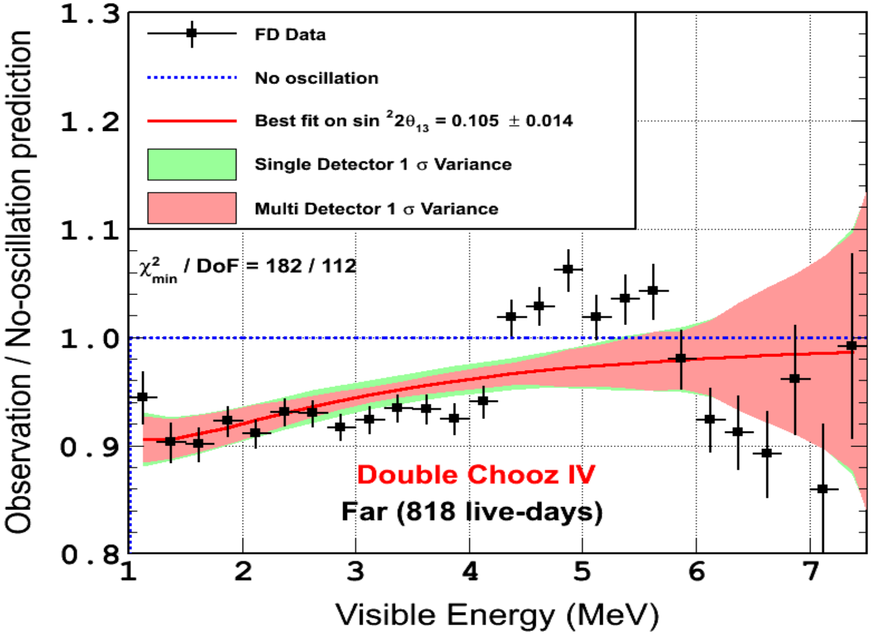
- Statistical uncertainty contribute 60% for $\sin^2 2\theta_{13}$ and 50% for $|\triangle m_{ee}^2|$

θ_{13} : Double Chooz

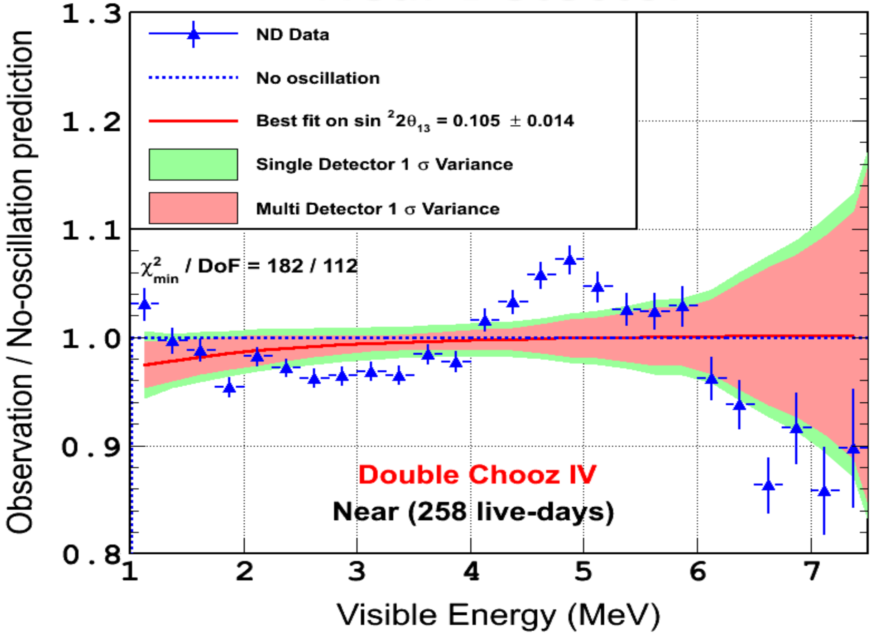
Neutrino 2018

Double Chooz : far 818 days + near 258 days

Far Detector

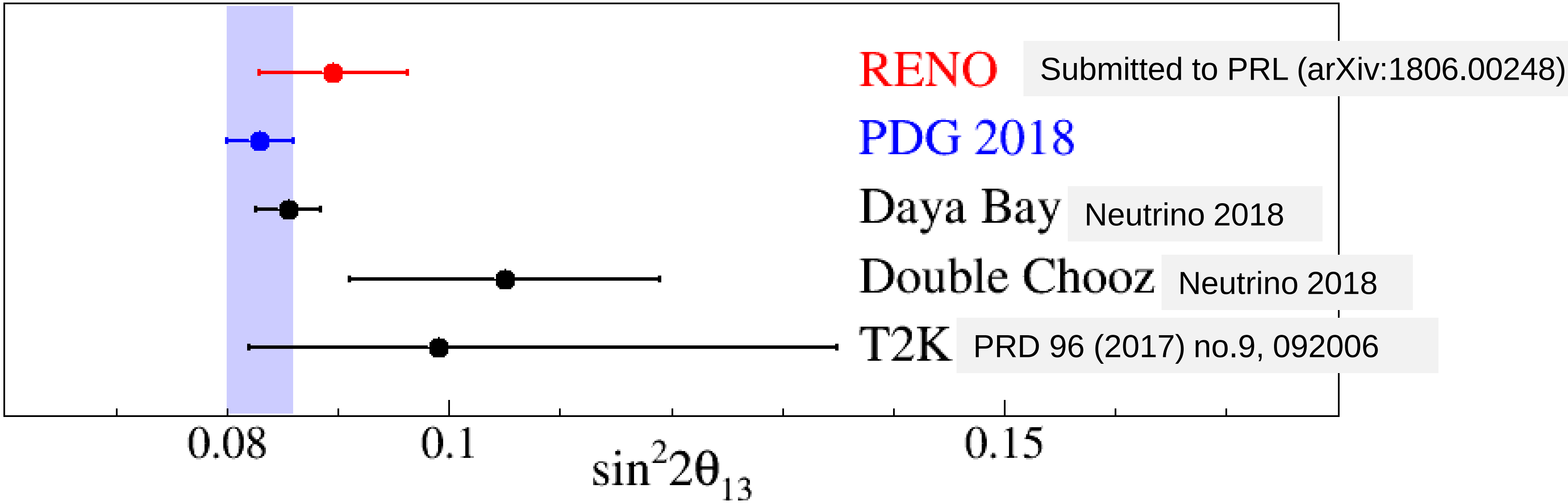


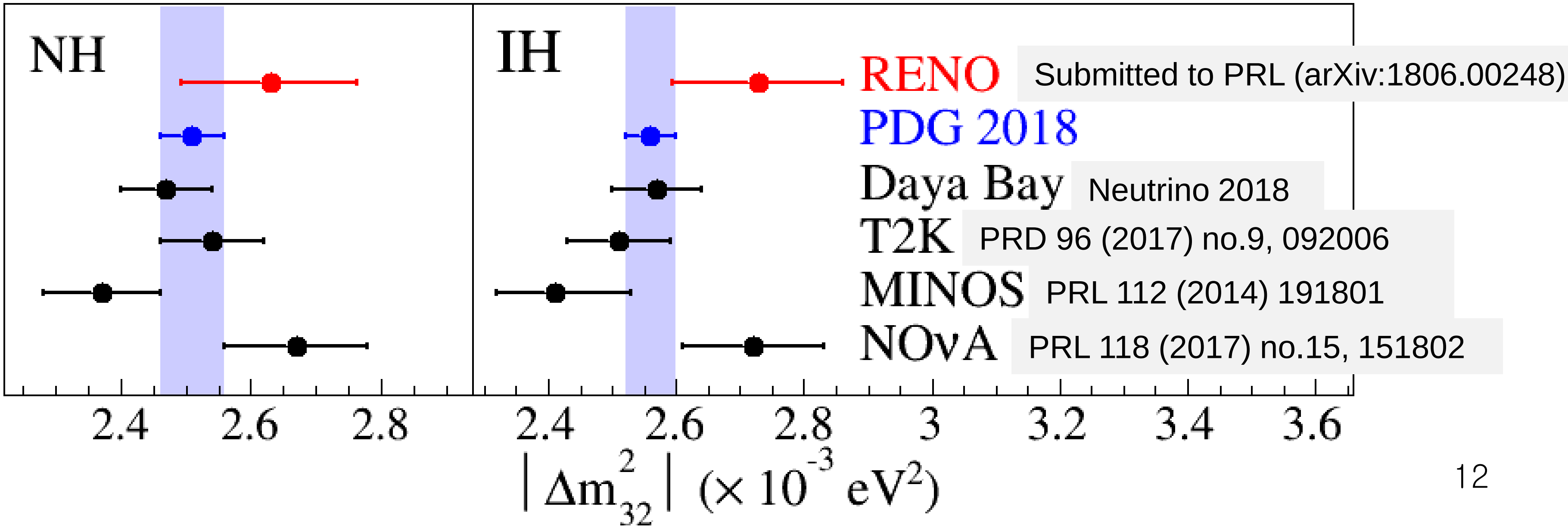
Near Detector



$\sin^2 2\theta_{13} = 0.105 \pm 0.014$ (13 %)

Comparison of θ_{13} and $|\Delta m^2_{ee}|$

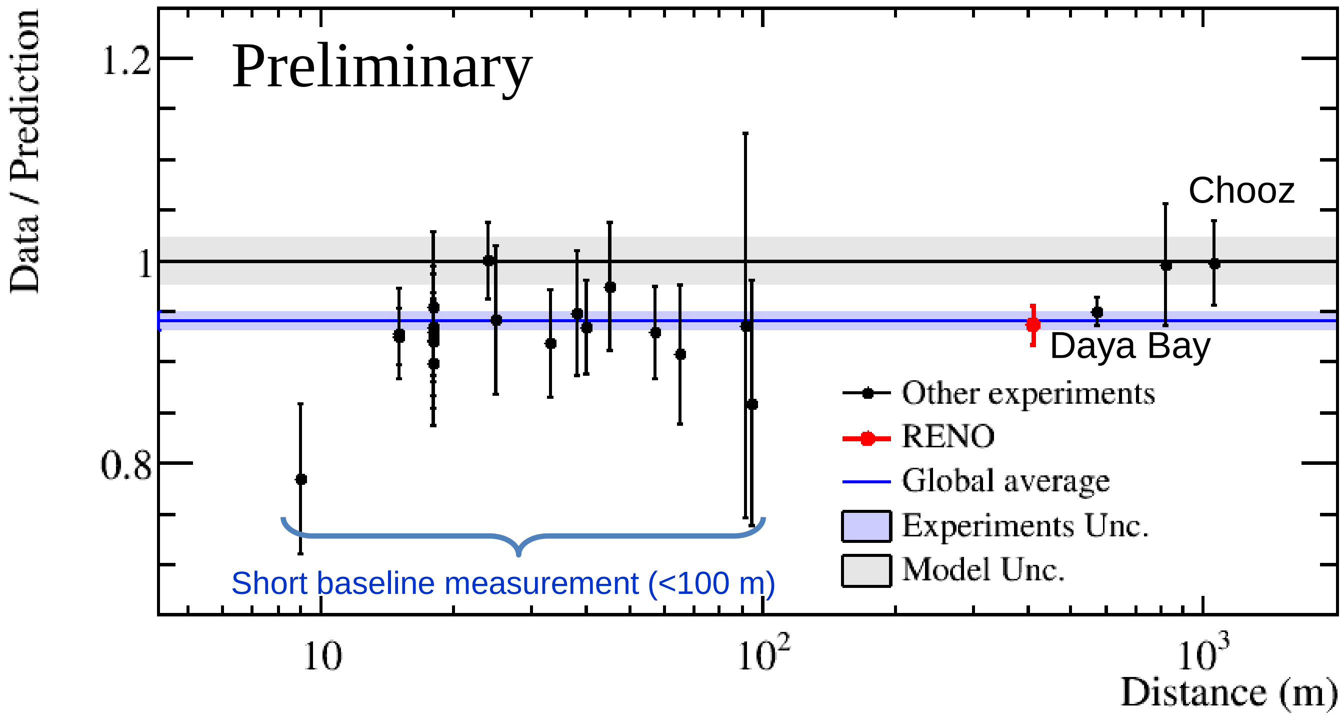




Measurement of Absolute Reactor Neutrino Flux

	Data / Prediction (Huber + Mueller)	Flux weighted baseline at near
RENO (2200 days)	0.937 ± 0.020 (exp.)	411 m
Daya Bay (1230 days)	0.952 ± 0.014 (exp.)	573 m

*Prediction is corrected for three flavor neutrino oscillation

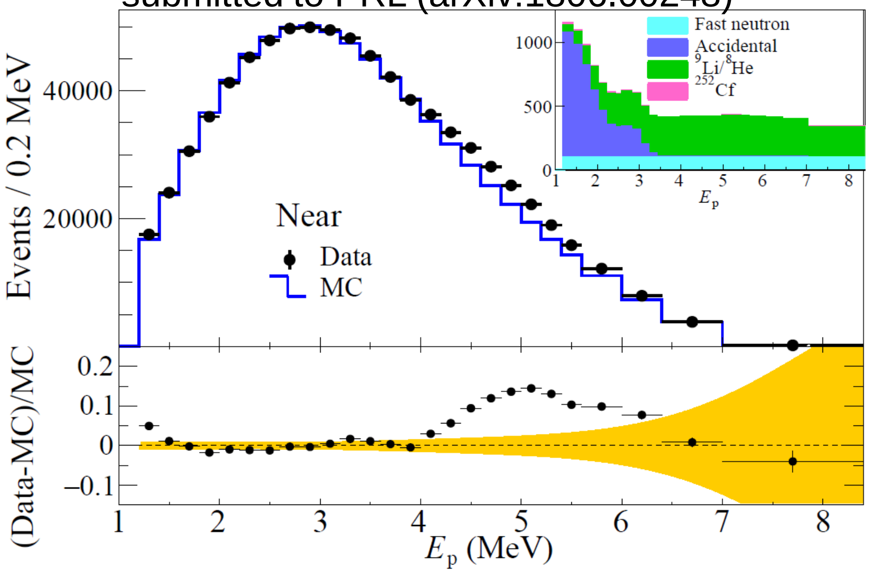


Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos

Observation of an excess at 5 MeV

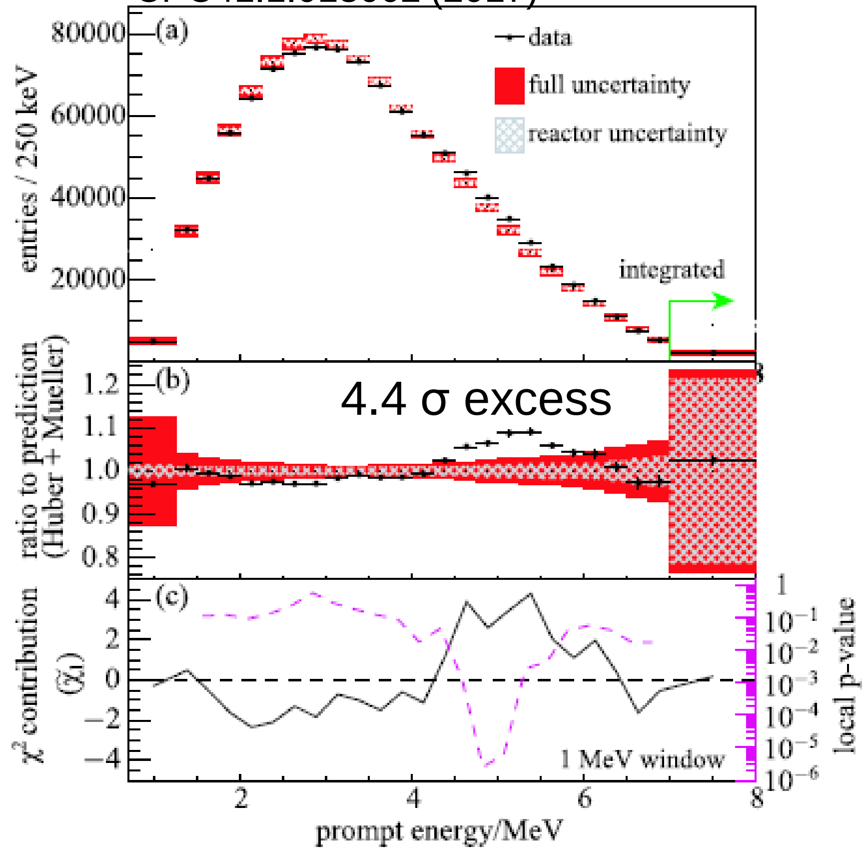
RENO 2200 days (spectral comparison)

submitted to PRL (arXiv:1806.00248)



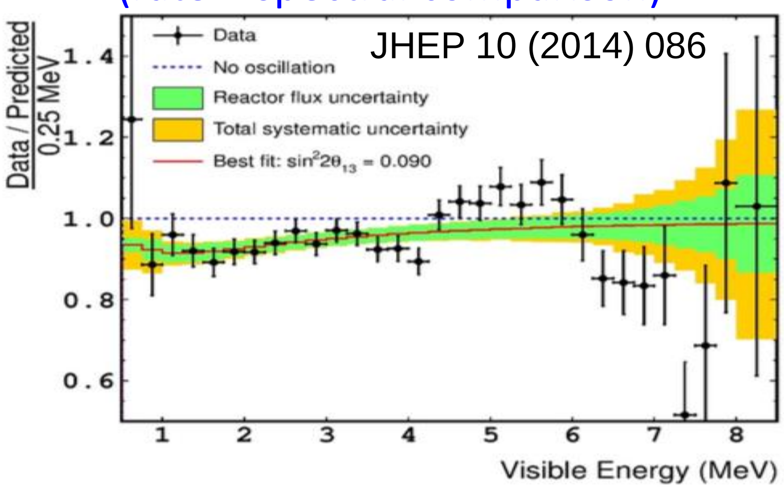
Daya Bay (rate + spectral comparison)

CPC41.1.013002 (2017)



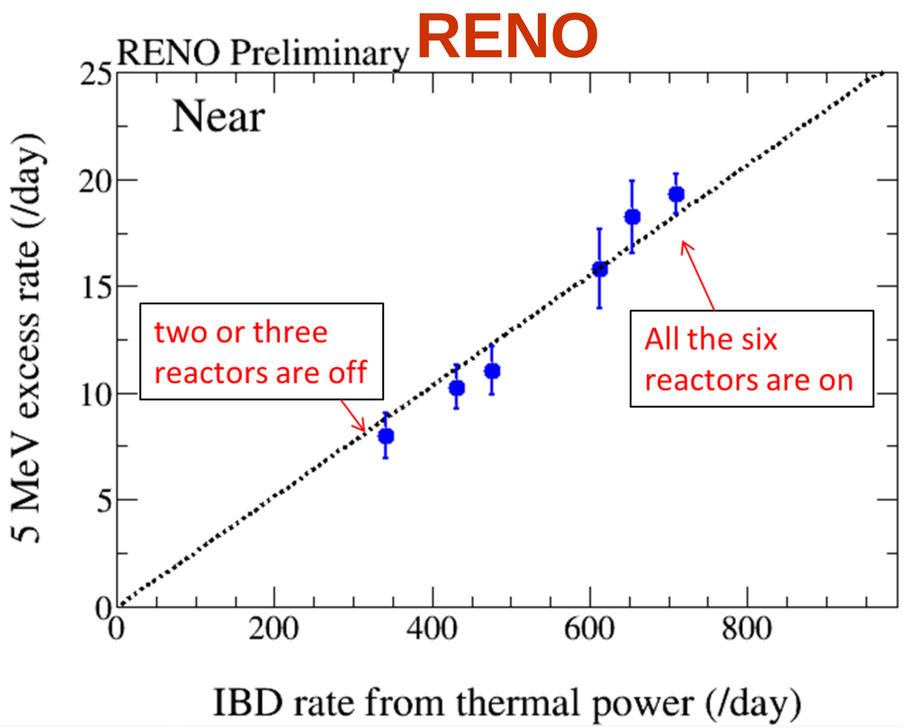
Double Chooz

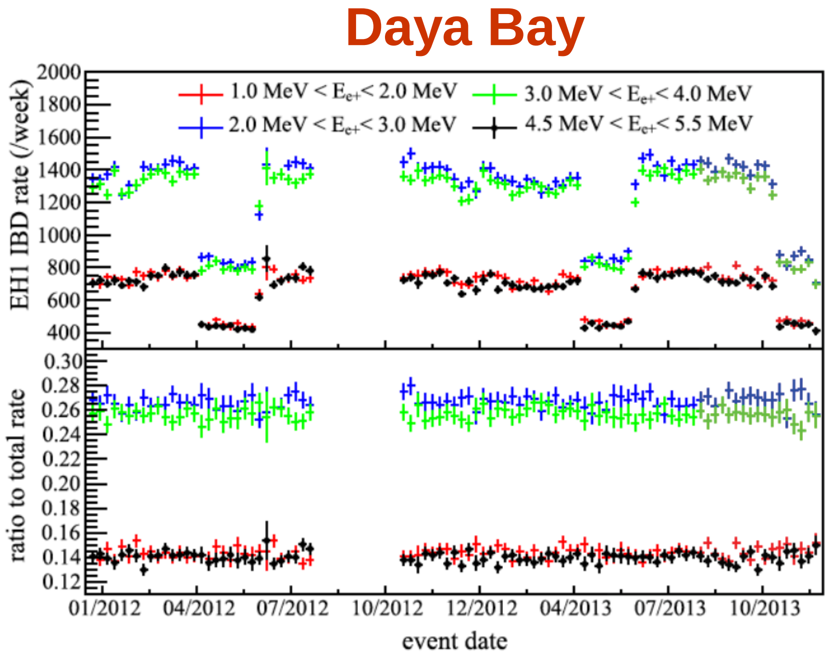
(rate + spectral comparison)



Clear excess at 5 MeV

Correlation of 5 MeV Excess with Reactor Power

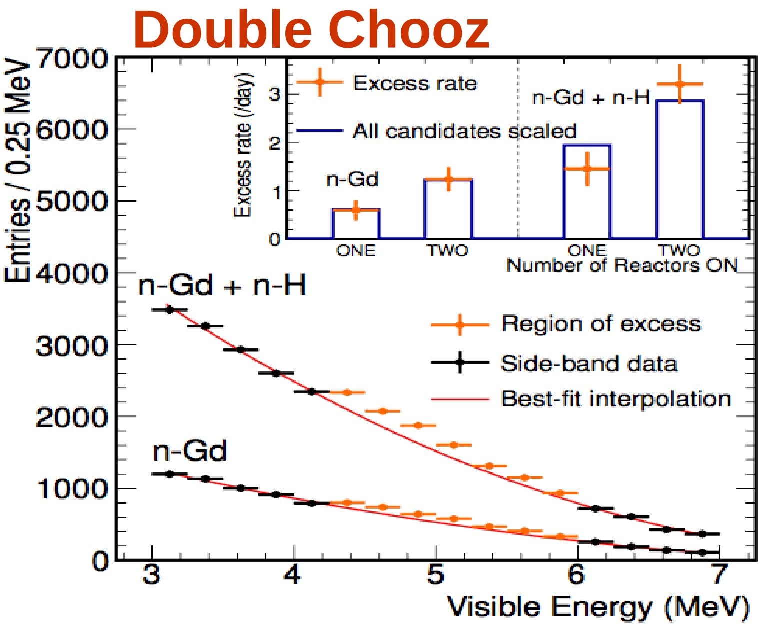




Clear correlation with reactor thermal power

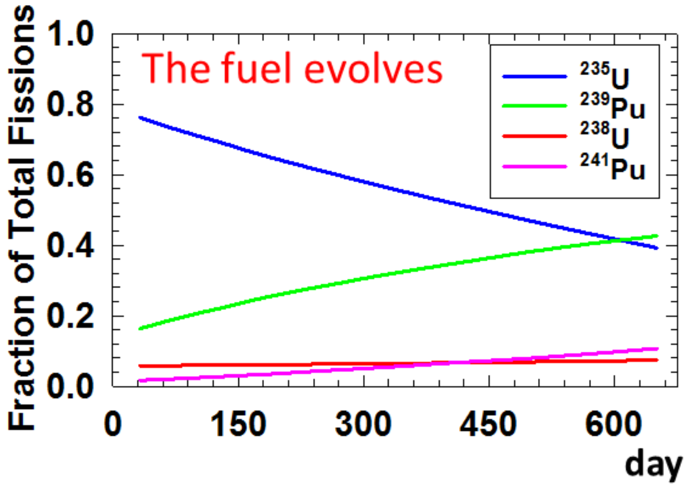
⇩

The 5 MeV excess comes from reactors!



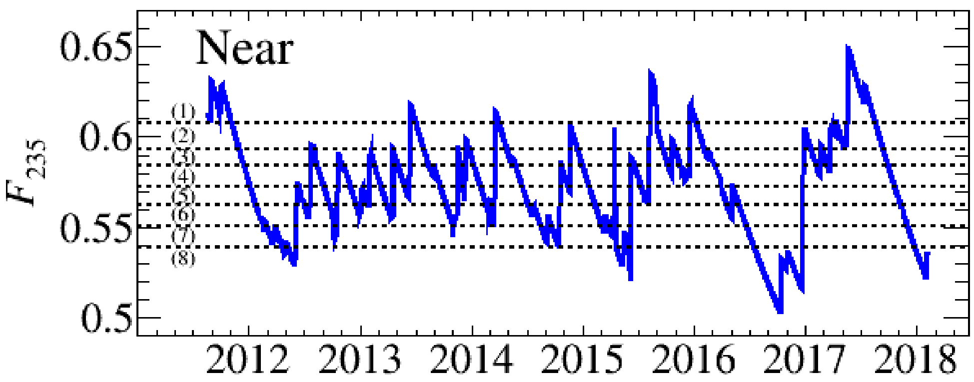
Evolution of Fuel Isotope Fraction

For single reactor core



Weighted from 6 reactors at RENO

Effective fission fraction of ^{235}U



Effective fission fraction

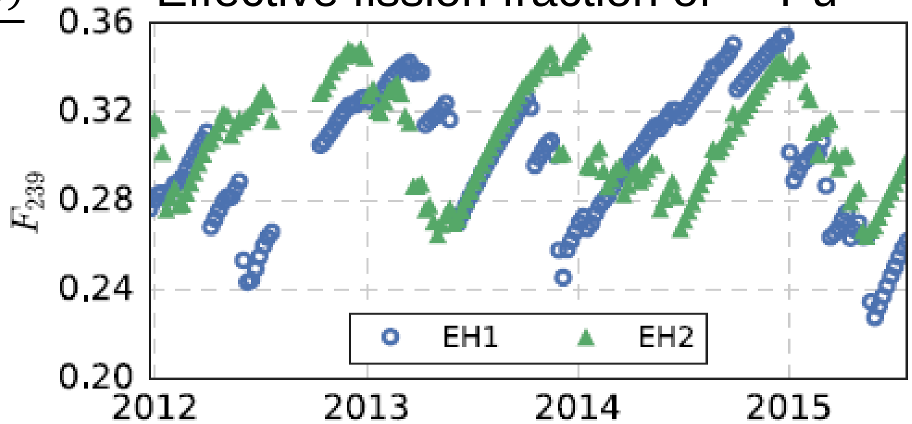
$$F_i(t) = \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r(t) f_{i,r}(t)}{L_r^2 \bar{E}_r(t)} \Big/ \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r(t)}{L_r^2 \bar{E}_r(t)}$$

weighted by thermal power (W), survival probability(p), baseline (L) over multiple reactor cores

8 groups of IBD samples with different effective fission fraction

Weighted from 6 reactors at Daya Bay

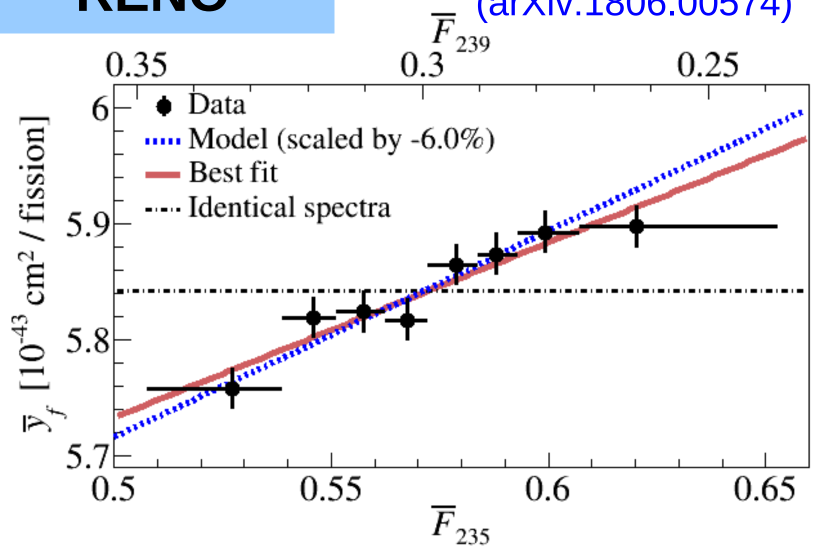
Effective fission fraction of ^{239}Pu



Fuel Composition Dependent IBD Yield

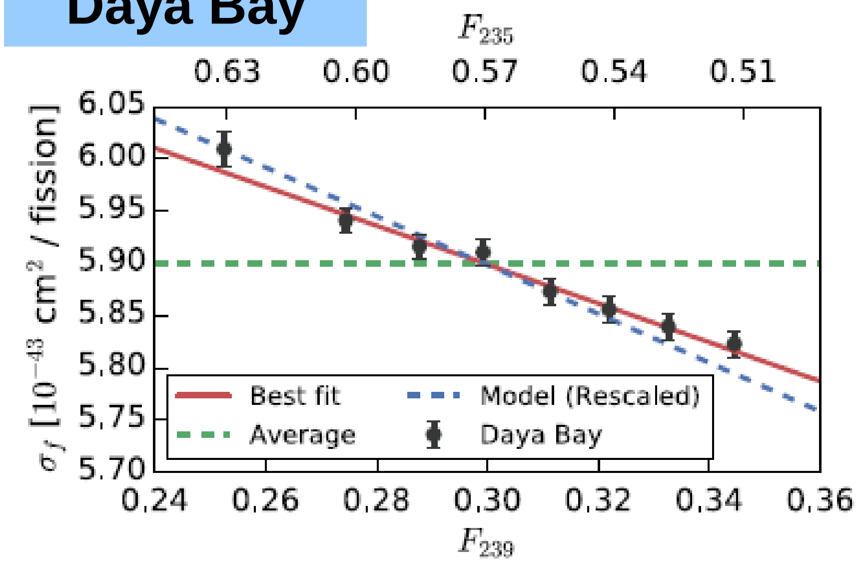
RENO

submitted to PRL (arXiv:1806.00574)



Daya Bay

PRL 118, 251801 (2017)



IBD yield per fission

$$\overline{y}_f = \sum \overline{F}_i y_i$$

where,

$$y_i = \int \sigma(E_\nu)\phi_i(E_\nu)dE_\nu$$

$\phi(E_\nu)$: energy spectrum

$\overline{F}_i$: fission fraction of isotope i

- The best fit slopes reject identical reactor antineutrino spectra hypothesis by 6.6σ (RENO) and 10σ (Daya Bay)
- Difference between best fit and Huber-Mueller slopes : 1.3σ (RENO) and 2.6σ (Daya Bay)

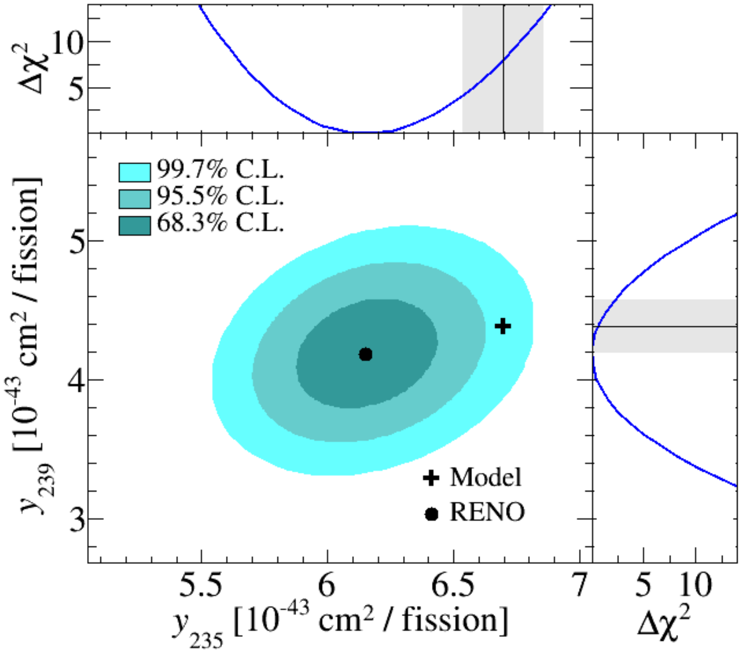
- If particular isotope contribute more to the reactor anomaly, the best fit slope may be different from the model

Reactor Antineutrino Yield per ^{235}U vs. ^{239}Pu Fission

submitted to PRL (arXiv:1806.00574)

RENO

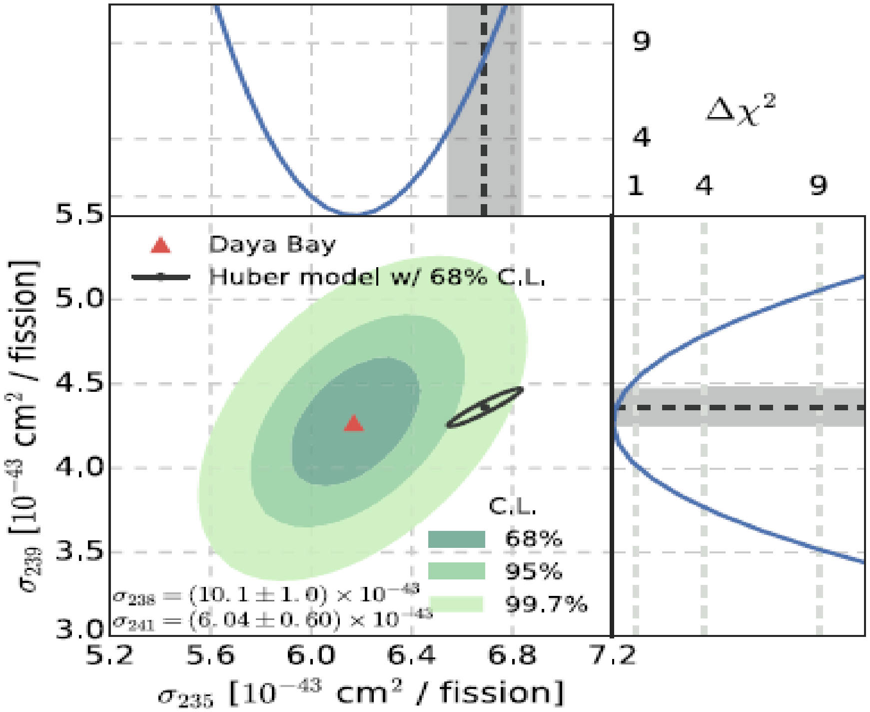
y_{235} = 6.15 +- 0.19
y_{239} = 4.18 +- 0.26



PRL 118, 251801 (2017)

Daya Bay

y_{235} = 6.17 +- 0.17
y_{239} = 4.27 +- 0.26



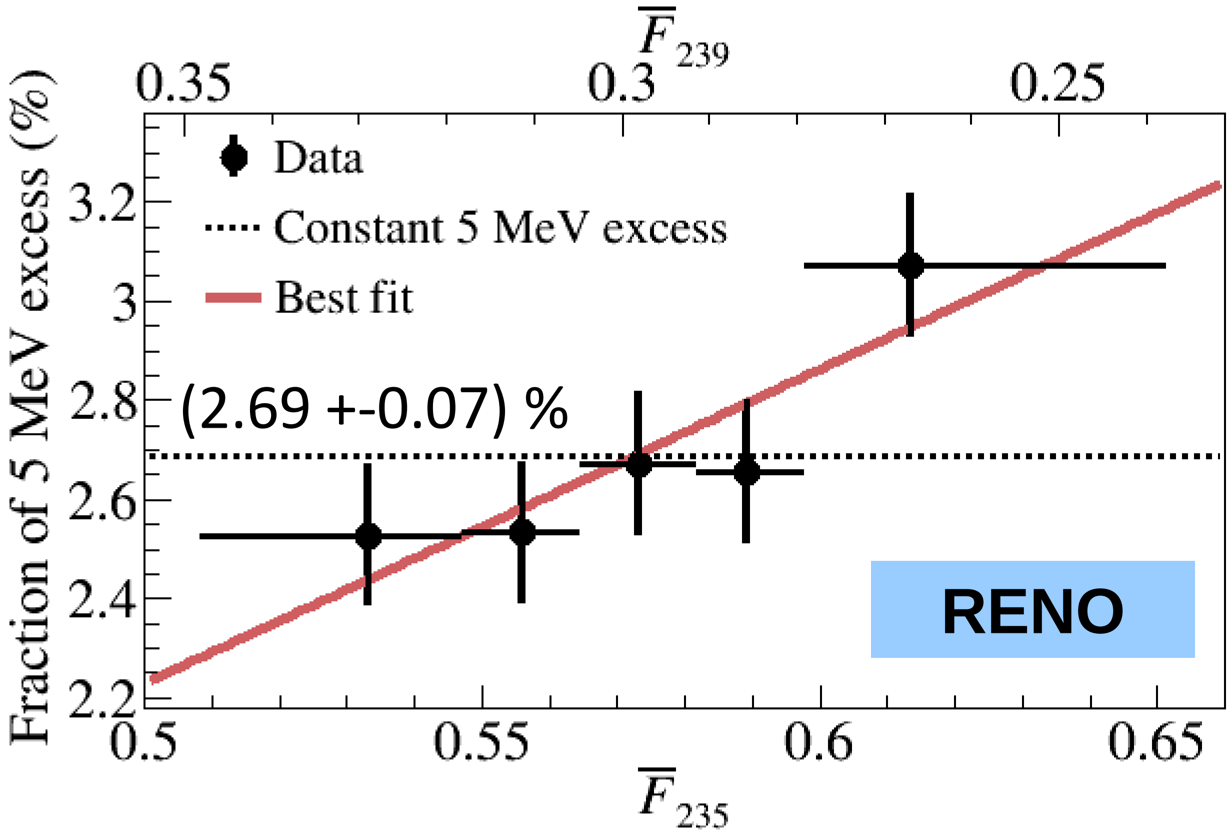
Isotope	Ratio with respect to Huber-Mueller model	
	RENO	Daya Bay
^{235}U	0.918 +- 0.036	0.922 +- 0.033
^{239}Pu	0.954 +- 0.072	0.979 +- 0.073

- Reevaluation of the 235U IBD yield may mostly solve the reactor antineutrino anomaly

Correlation of 5 MeV excess with ^{235}U isotope fraction

submitted to PRL (arXiv:1806.00574)

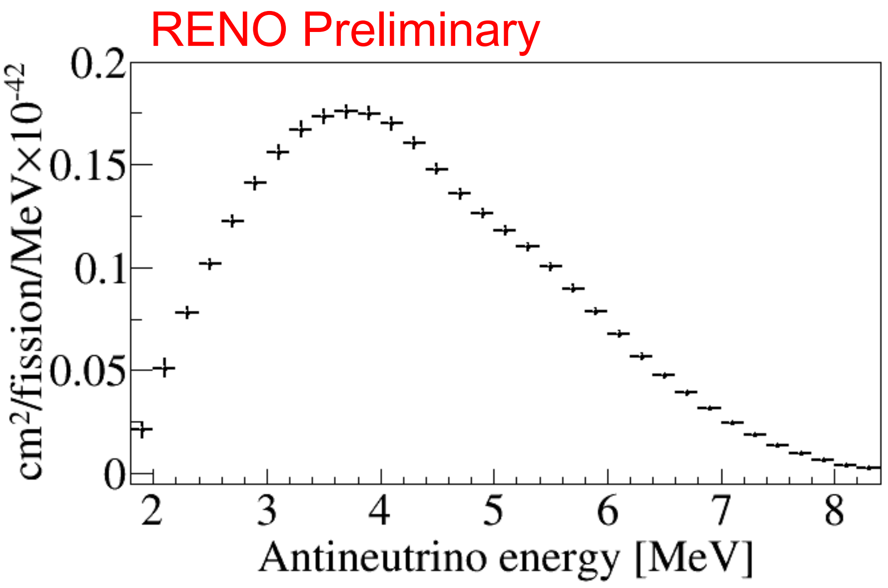
2.7σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!



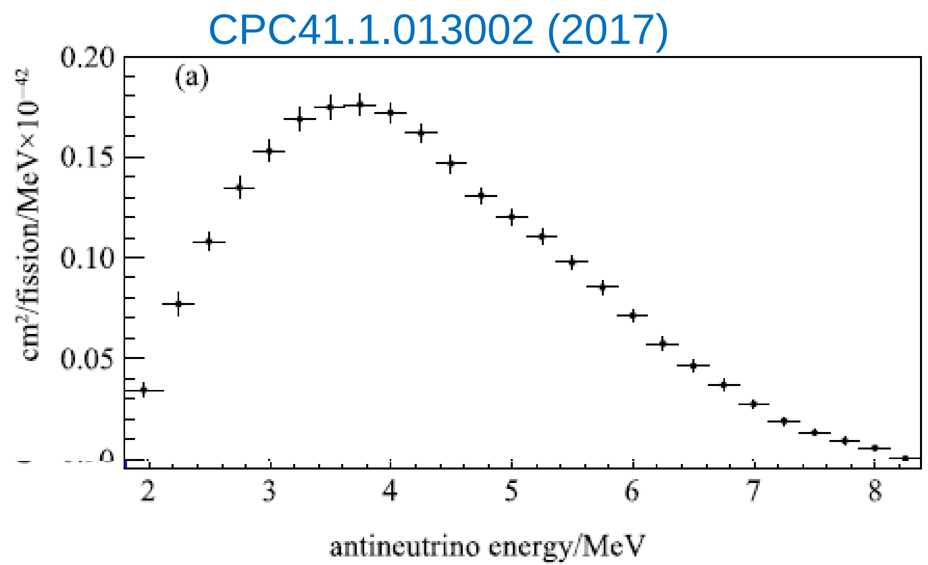
$\Delta\chi^2$ (constant – best fit) = 7.17 (2.7σ)
p-value = 0.0074

Unfolded Reactor Antineutrino Spectrum

RENO



Daya Bay



- Unfolding using singular value decomposition (SVD) method
- A model-independent spectrum is obtained with the following fission fraction

Average fission fraction

	^{235}U	^{238}U	^{239}Pu	^{241}PU
RENO	0.573	0.073	0.299	0.055
Daya Bay	0.561	0.076	0.307	0.056

Summary

- More precise θ_{13} and $|\Delta m^2_{ee}|$ measurements

θ_{13} → Daya Bay: 3.4 %, RENO: 7.6 %, Double Chooz: 13 %

$|\Delta m^2_{ee}|$ → Daya Bay: 2.8 %, RENO: 5.2 %

- The 5 MeV excess is seen by all three experiments

→ strong correlation with reactor thermal power

- Measured absolute reactor neutrino flux (wrt Huber-Mueller)

$R_{data/pred}$: 0.952±0.014 (Daya Bay), 0.937±0.020 (RENO)

- Observation of fuel composition dependent IBD yield

Rejection of identical reactor antineutrino spectra : 6.6σ (RENO), 10σ (Daya Bay)

Reevaluation of the 235U IBD yield may mostly solve the reactor antineutrino anomaly

First hint for correlation between 5 MeV excess and ^{235}U fission fraction (RENO)

- A model-independent spectrum is obtained

Thanks for your attention!