Evolution of the Antineutrino Flux and Spectrum, and Search for Light Sterile Neutrinos at Daya Bay

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on behalf of the Daya Bay Collaboration

ILLINOIS INSTITUTE OF TECHNOLOGY

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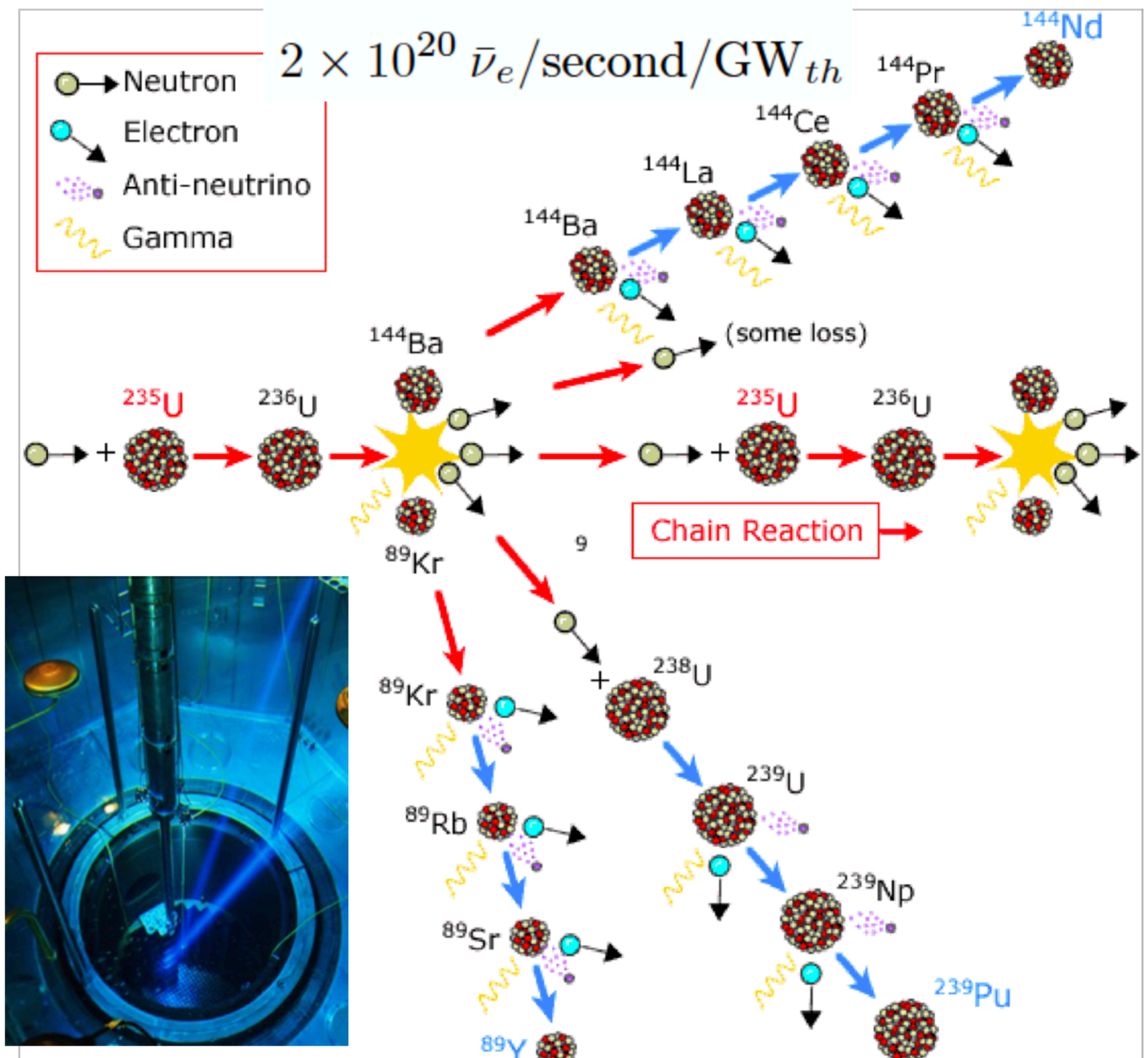
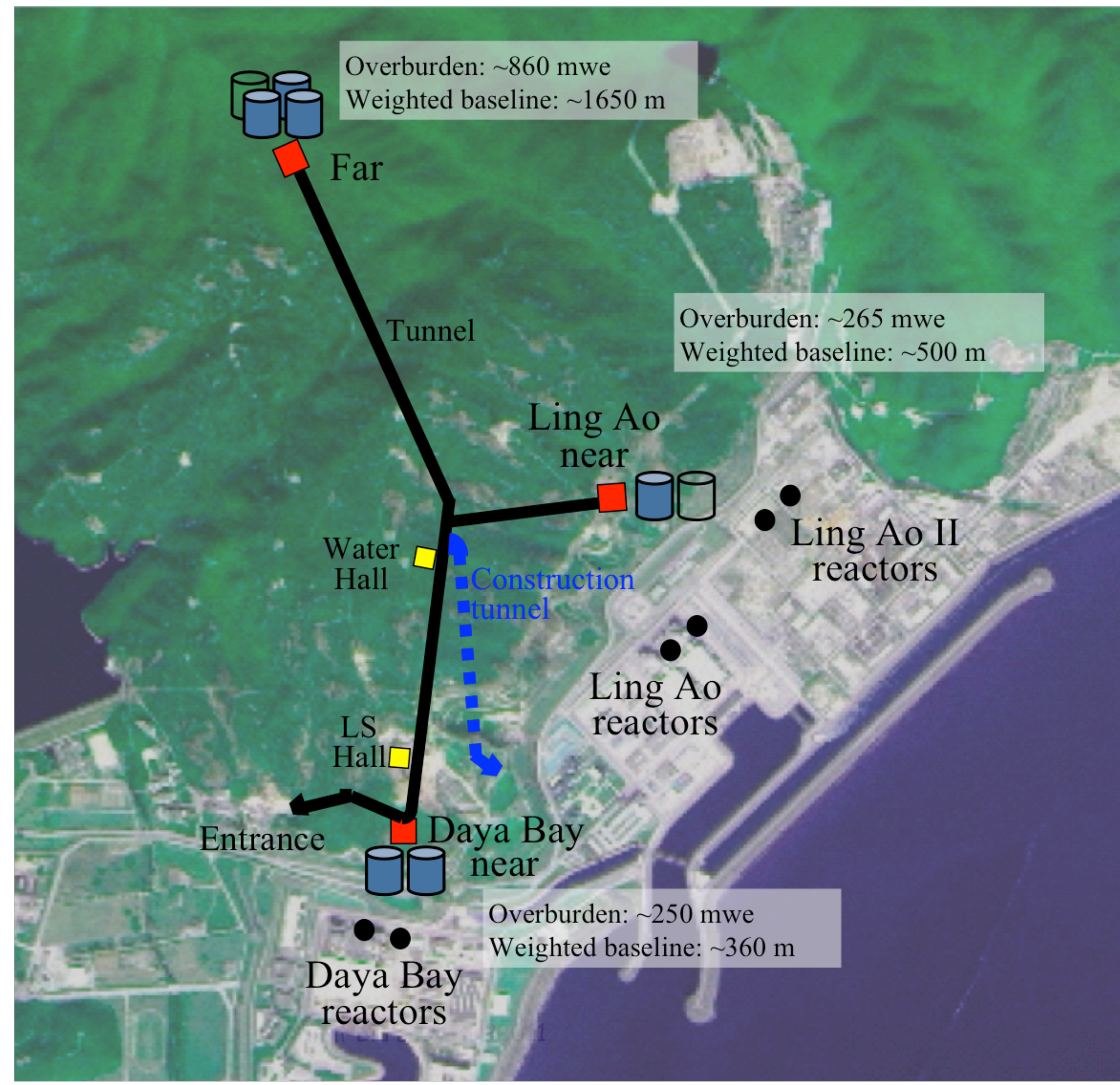
Reactor Anti-Neutrinos Measurements

Relative Measurements versus Absolute Measurements

$\sim 6 \ \bar{\nu}_e$ per fission

$2 \times 10^{20} \ \bar{\nu}_e/\text{second}/\text{GW}_{th}$

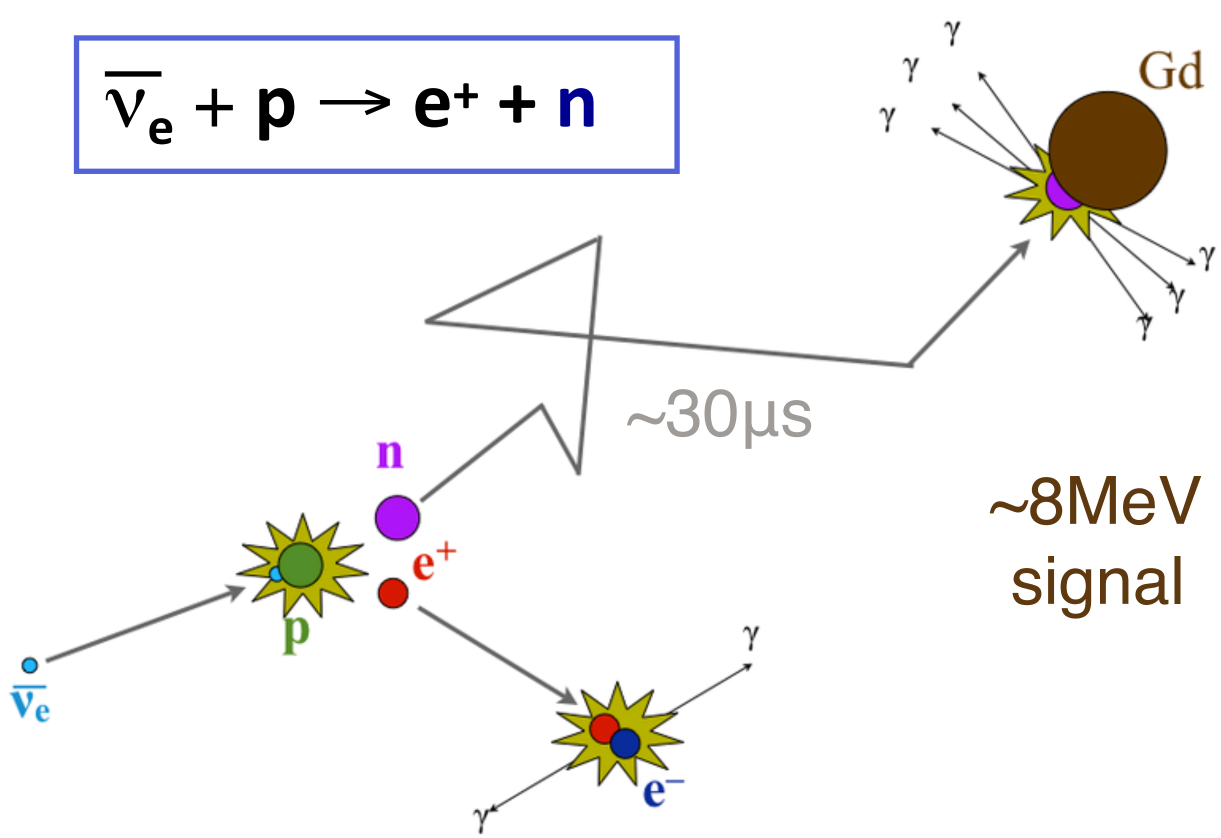


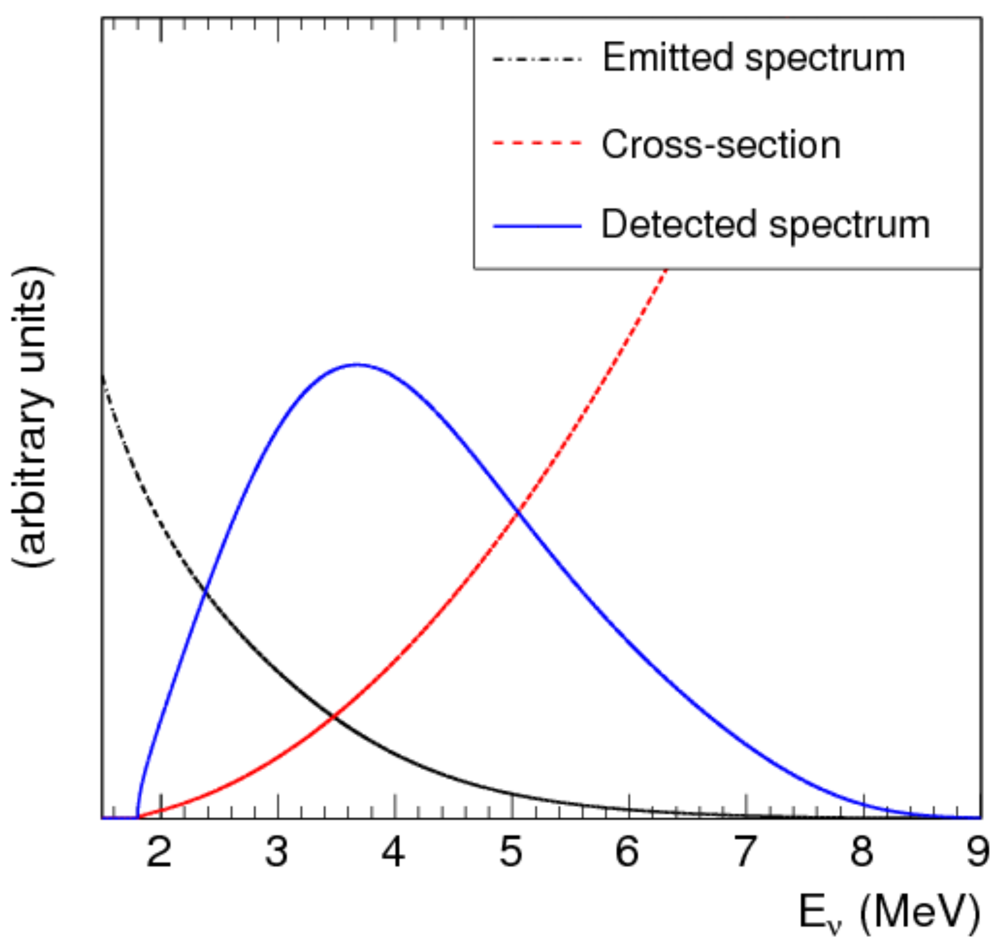


Antineutrino Detection

- Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction:

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





  - Coincidence between positron and neutron signals allows for **powerful background rejection**
  - Energy of positron preserves information about energy of incoming $\bar{\nu}_e$

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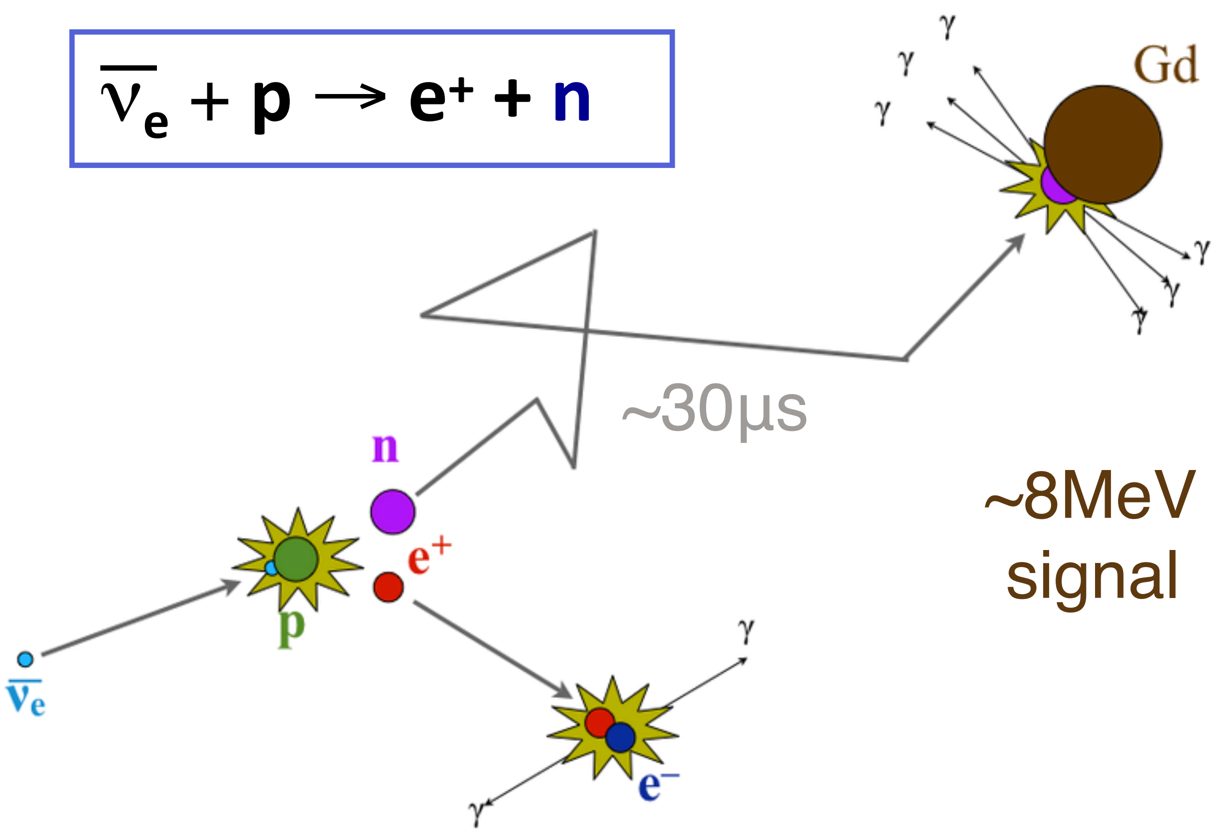

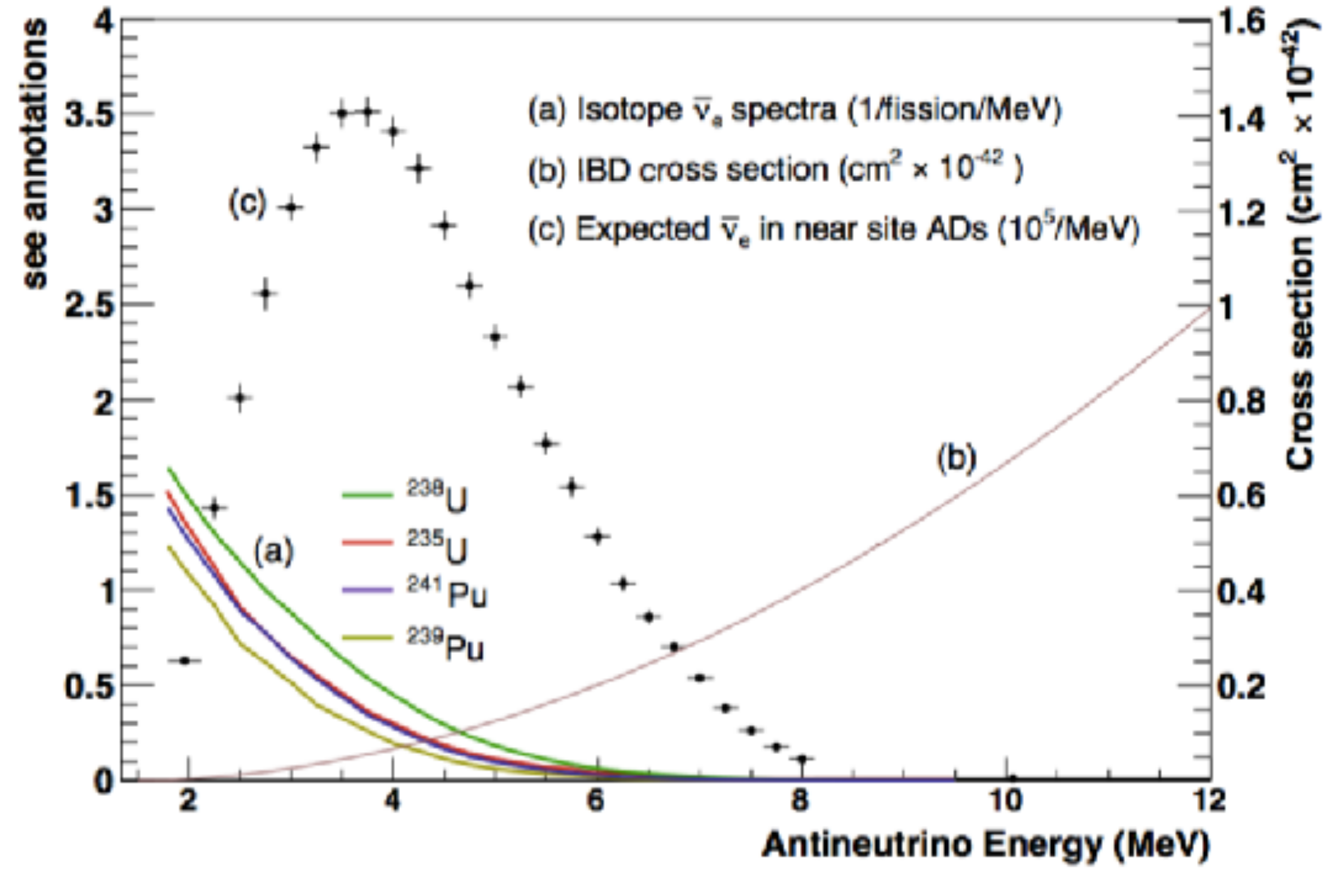

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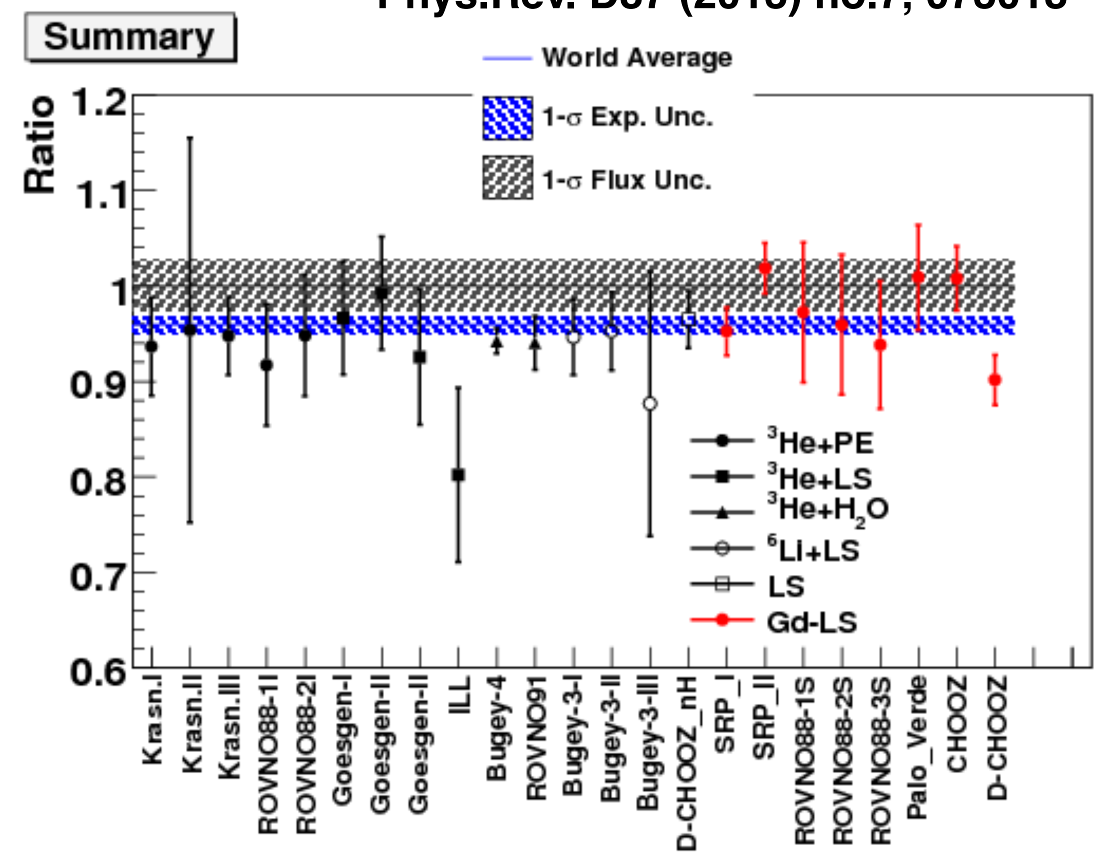
Reactor Antineutrino Anomaly

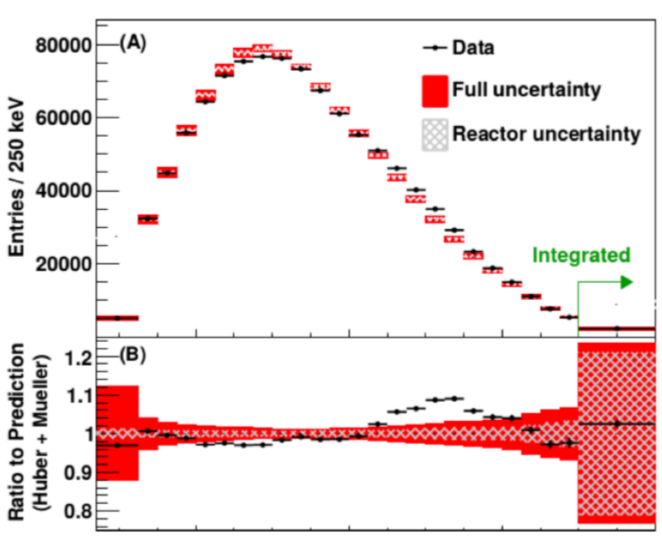
Phys.Rev. D87 (2013) no.7, 073018



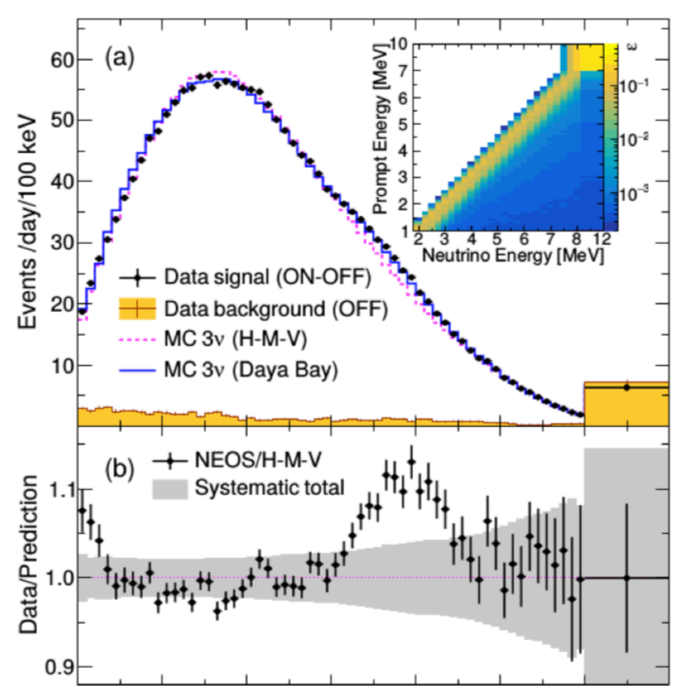
There is tension between the flux and spectrum predictions and experimental measurements

NEOS spect.

Daya Bay spect.

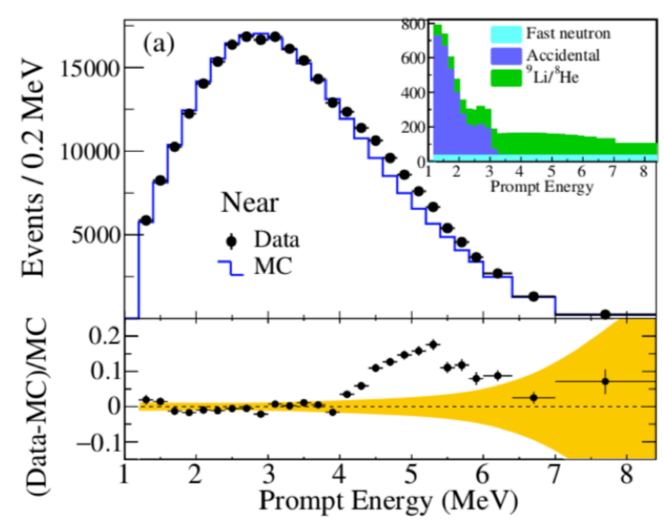


arXiv: 1607.05378



arXiv: 1610.05134

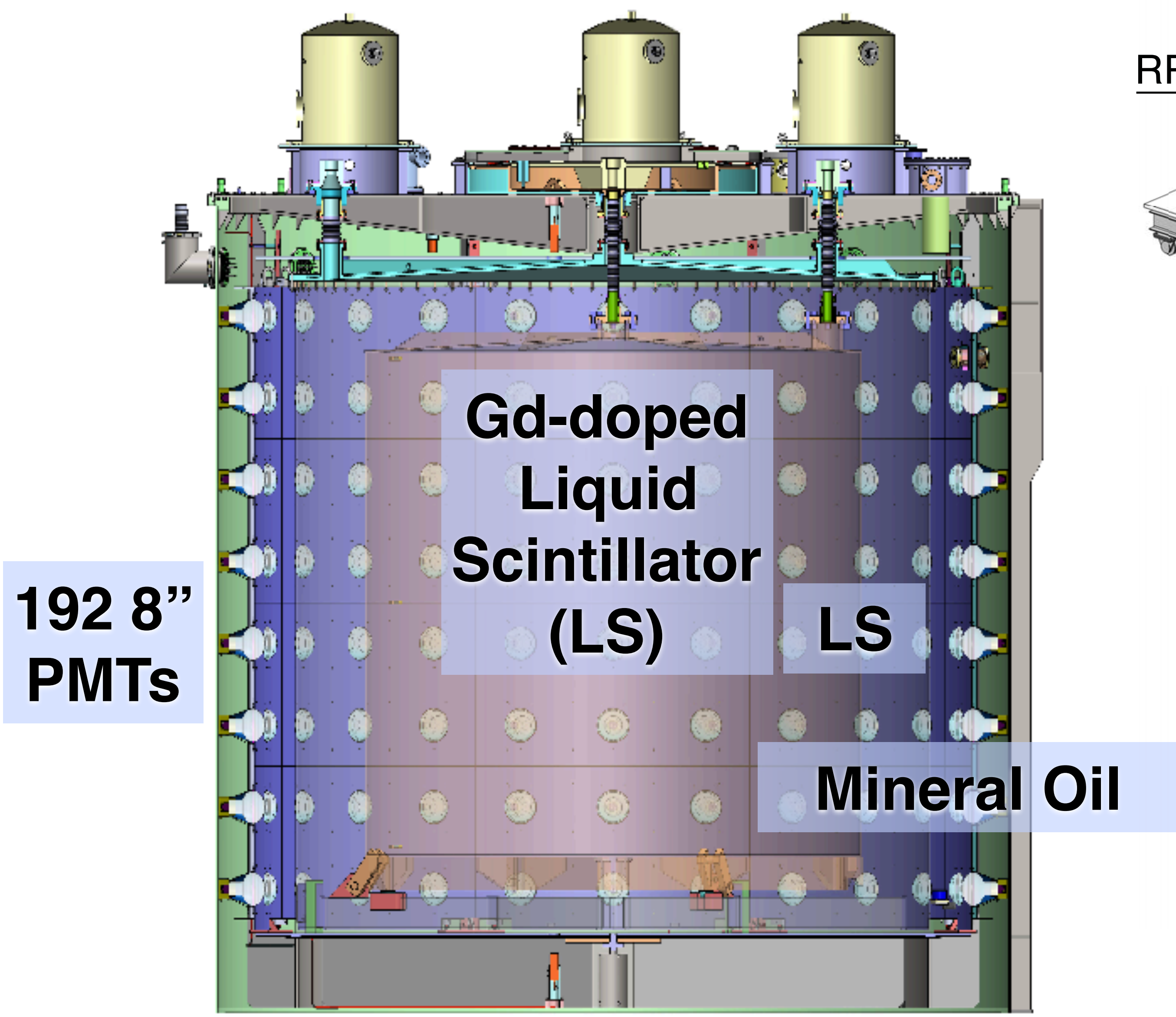
RENO spect.



arXiv: 1610.01326

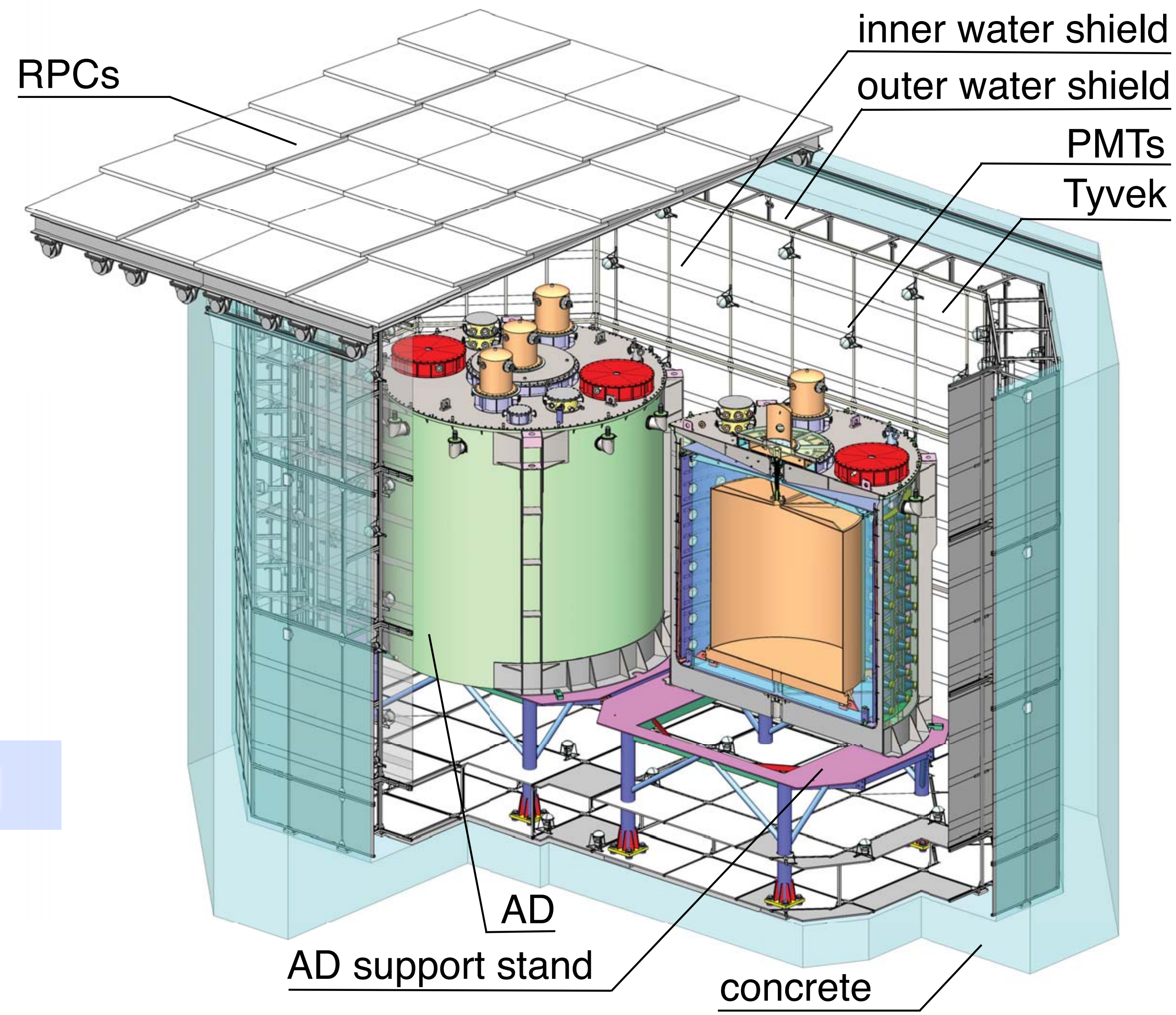
Daya Bay Detectors

- The antineutrino detectors (ADs) are "three-zone" cylindrical modules immersed in water pools:



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E[\text{MeV}]}$

NIM A 811, 133 (2016)



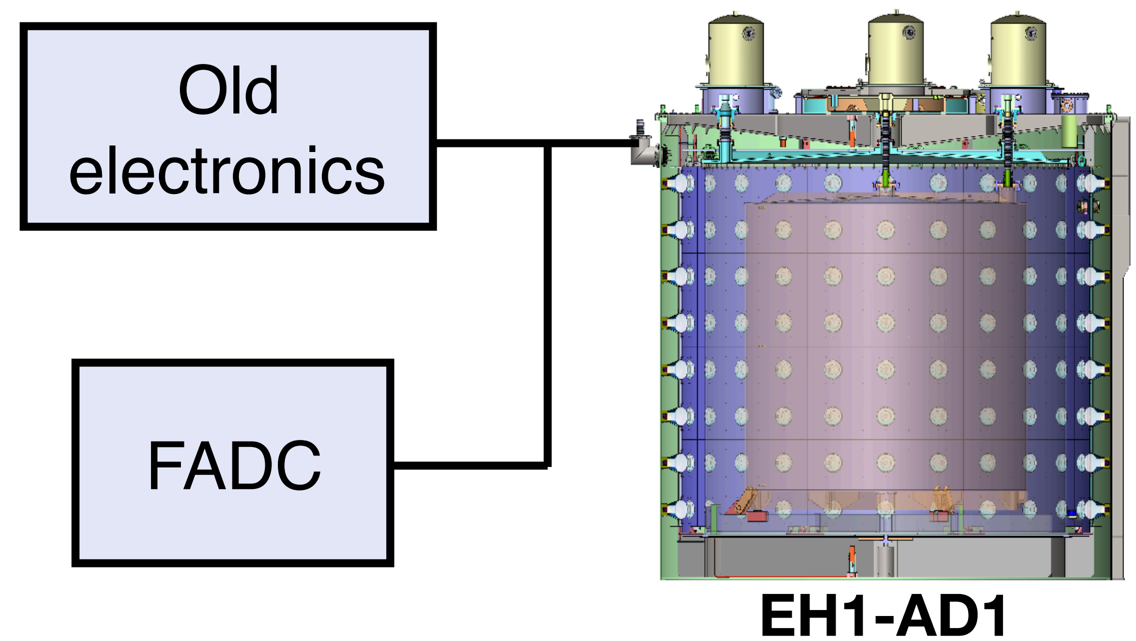
Double purpose: shield the ADs and veto cosmic ray muons

NIM A 773, 8 (2015)

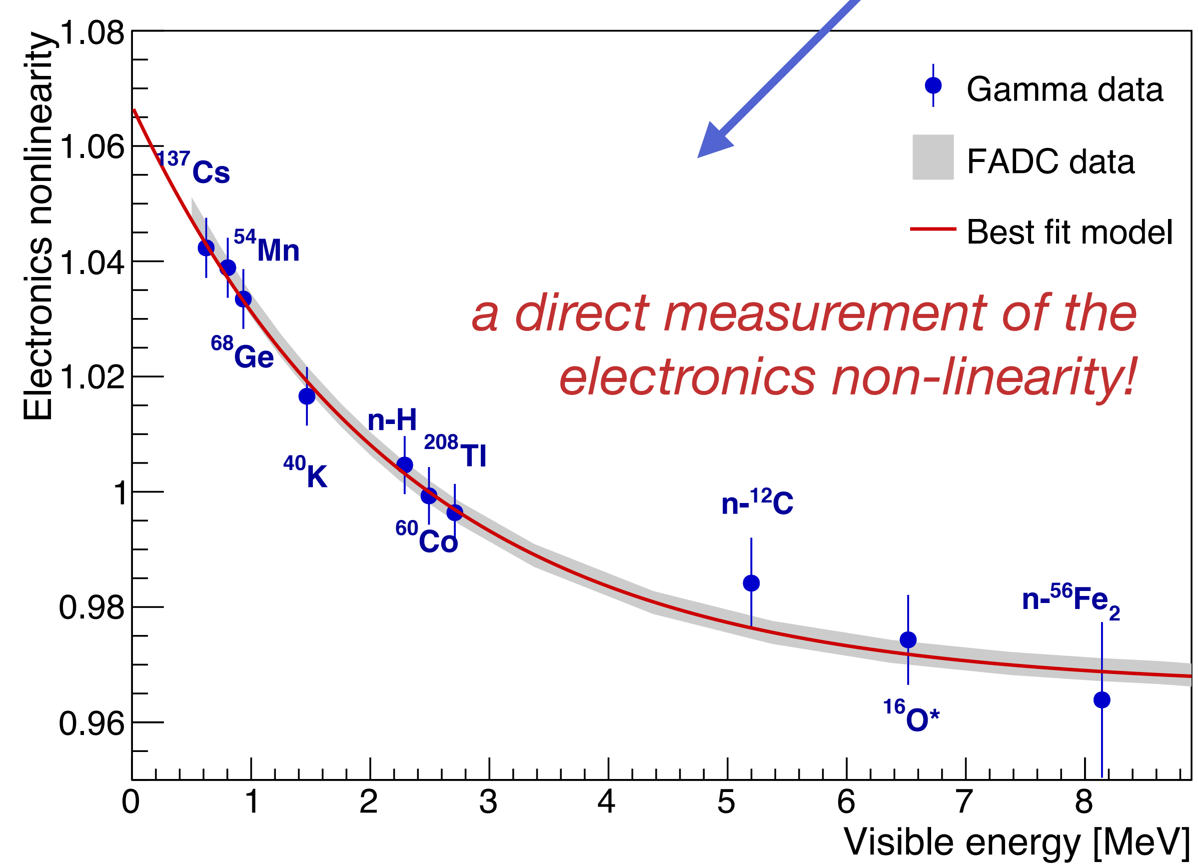
Improved Energy Response Model

- A model is needed to convert reconstructed positron energy to antineutrino energy
- Energy response is non-linear mainly due to two reasons:
  - Normal quenching + Cerenkov light in liquid scintillator
  - Response of the electronics

both in the order of 10%!

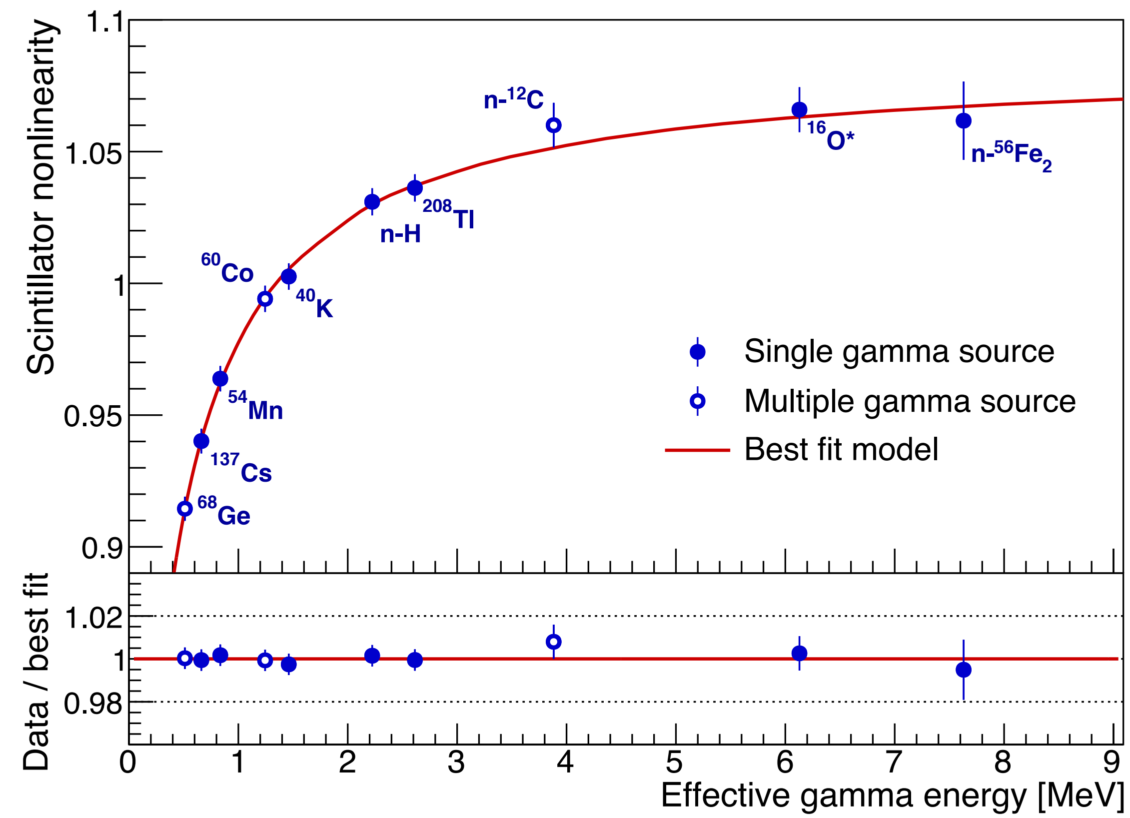


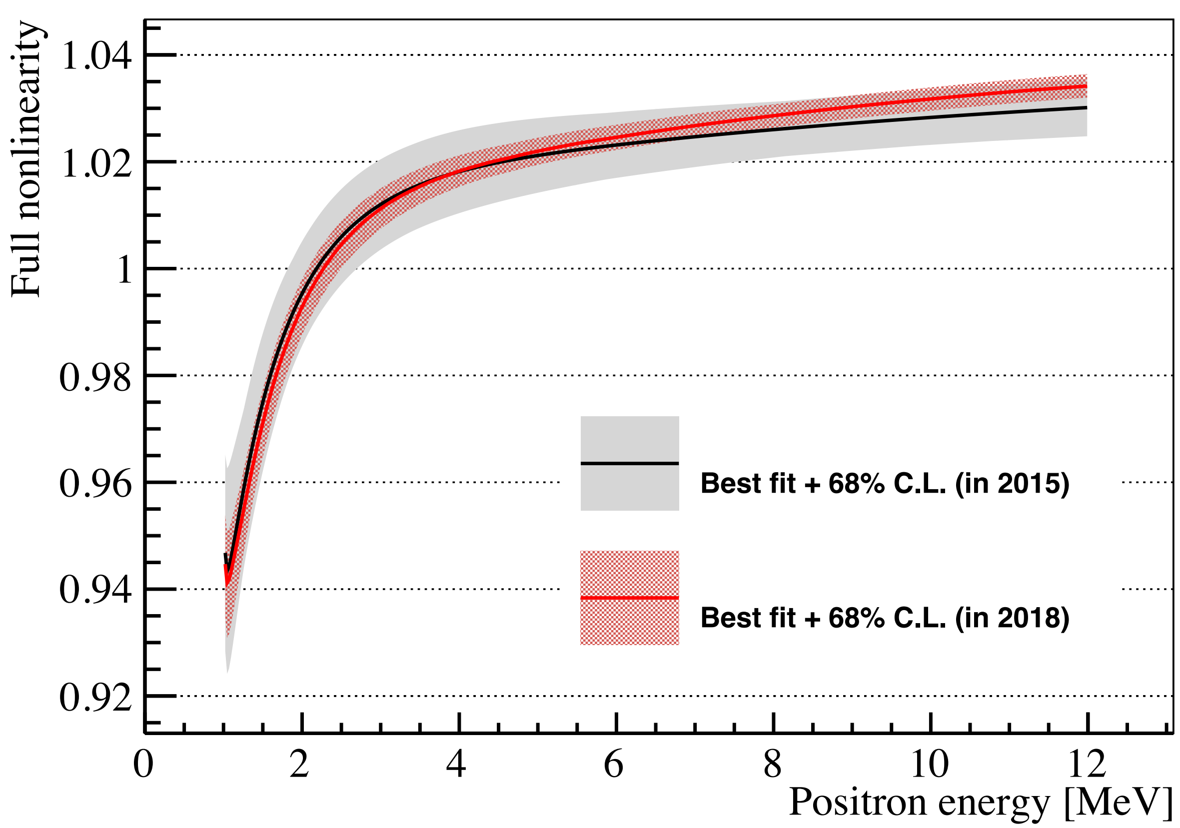
- Carried out two key measurements:
  - End of 2015: installation of a full FADC readout system in EH1-AD1, taking data simultaneously with standard electronics
  - Early 2017: deployment of ^{60}Co calibration sources with different encapsulating materials, to constrain optical shadowing effects

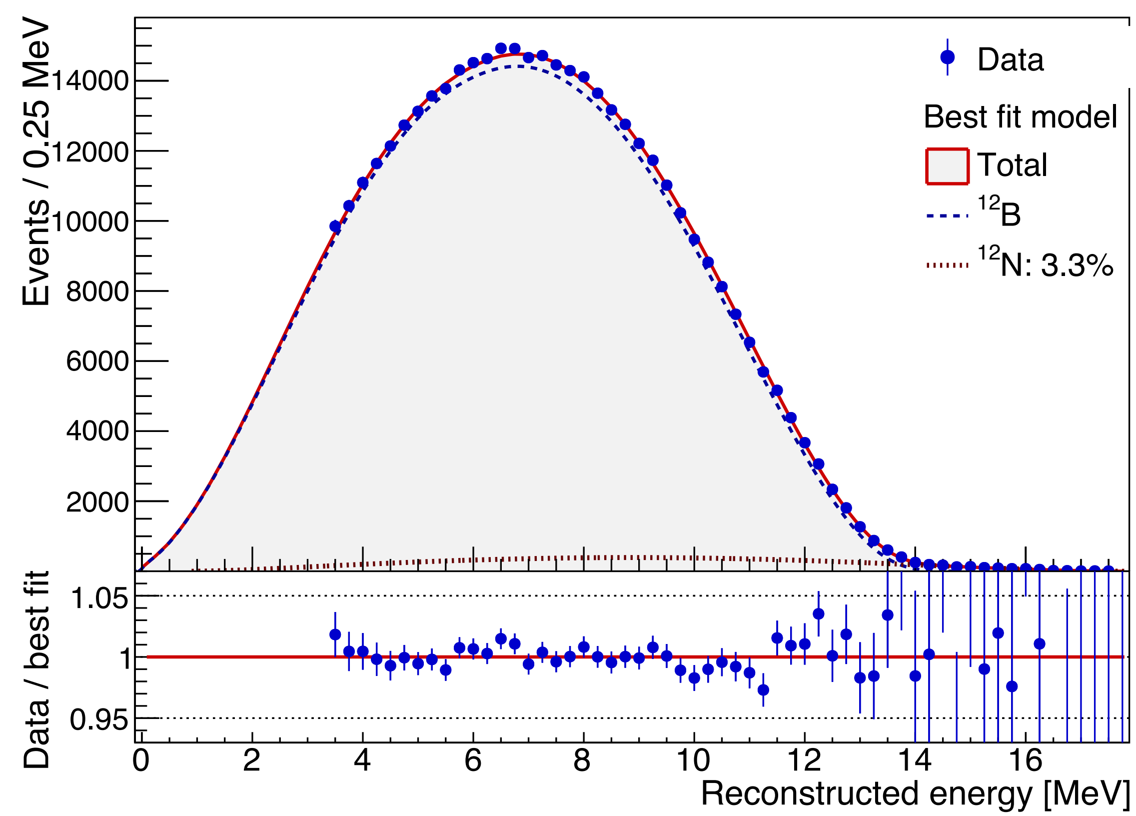


Improved Energy Response Model

- The model is built based on various gamma peaks and the continuous ^{12}B spectrum
  - Validated with low energy β+γ spectra from ^{212}Bi and ^{214}Bi
  - Halved uncertainty of absolute energy scale to **~0.5%**







Absolute Antineutrino Flux

- Previous measurement of the absolute reactor $\bar{\nu}_e$ flux compared to the Huber+Mueller expectation:

$$R_{data/pred} = 0.946 \pm 0.020 \text{ (exp.)}$$

← systematics-dominated from absolute detection efficiency

- New strategy: take new neutron calibration data and use it to constrain the "neutron detection efficiency" ε_n

previous efficiency values

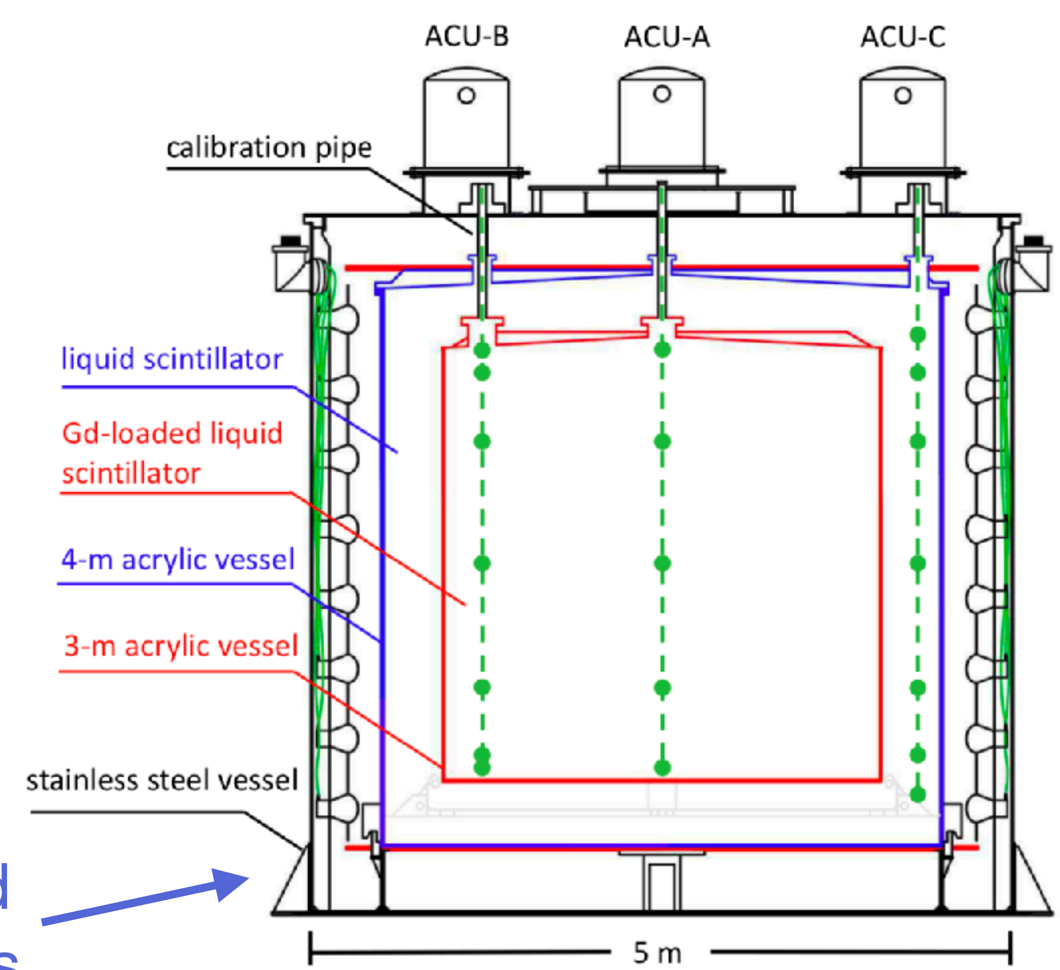
Source	ϵ	$\delta\epsilon/\epsilon$
Target protons	-	**0.92%**
Flasher cut	99.98%	0.01%
Capture time cut	98.70%	0.12%
Prompt energy cut	99.81%	0.10%
Gd capture fraction	84.17%	**0.95%**
nGd detection efficiency	92.7%	**0.97%**
Spill-in correction	104.9%	**1.00%**
Combined	80.6%	1.93%

ε_n (Gd capture fraction, nGd detection efficiency, Spill-in correction)

Carried out an extensive calibration campaign in late 2016 / early 2017

Deployed two neutron sources (^{241}Am-^{13}C and ^{241}Am-^{9}Be) along three vertical calibration axes

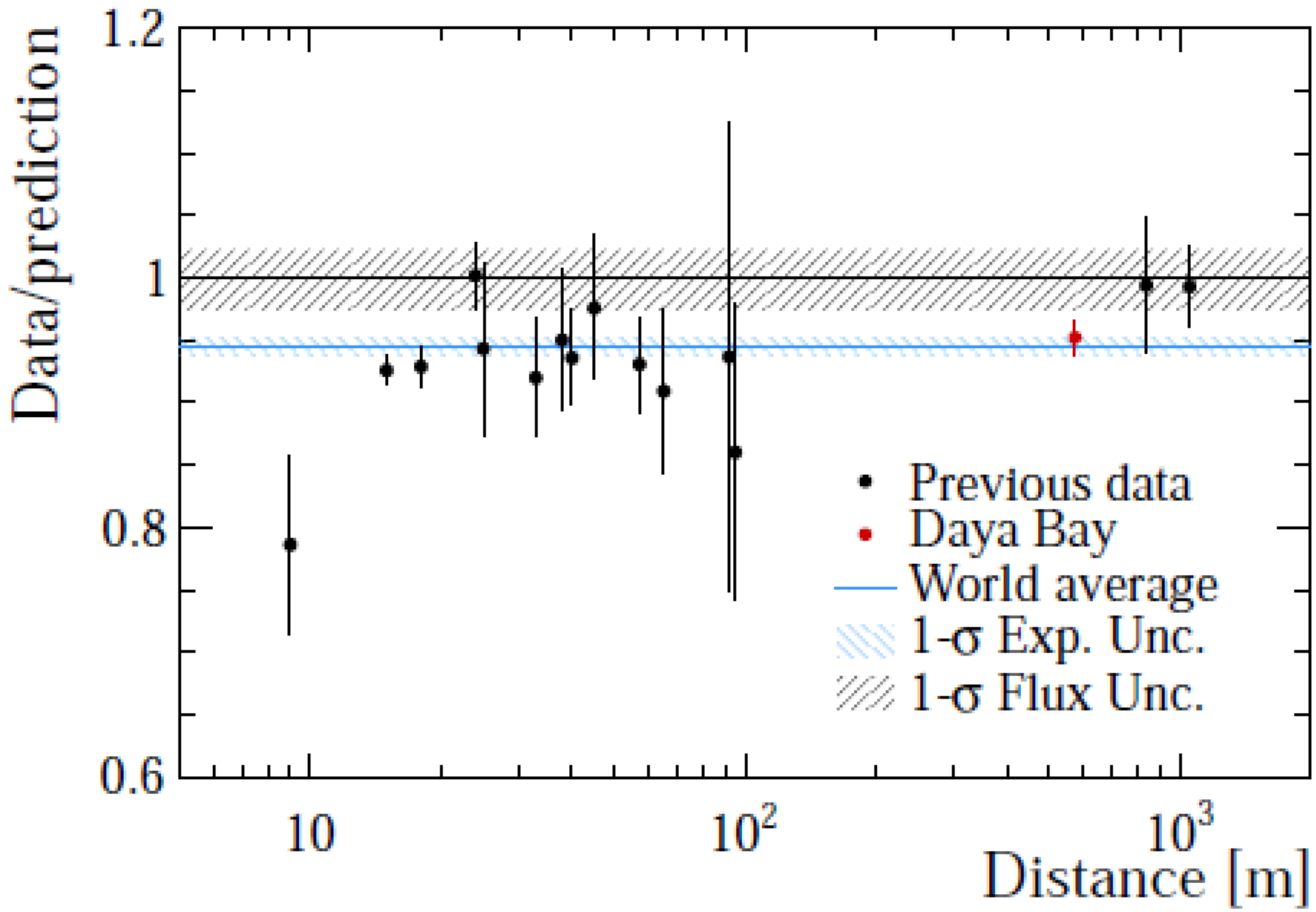
ACU=Automated Calibration Unit



Absolute Antineutrino Flux

Chinese Physics C, 2017, 41(1)

- Reactor antineutrino yield: f = (5.91+/-0.09)x10^{-43} cm^2/fission

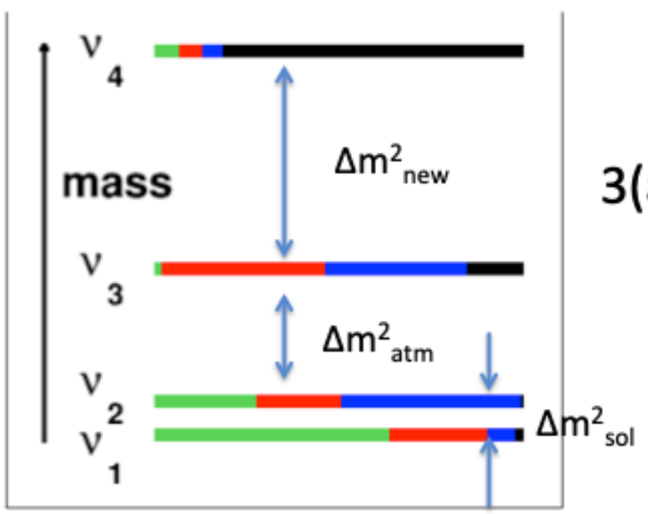


ILL+Vogel	Huber+Mueller
R = 1.001+/-0:015+/-0.0026 (exp) (model)	R = 0.952+/-0.014+/- 0.023 (exp) (model)

Search for a Light Sterile Neutrino

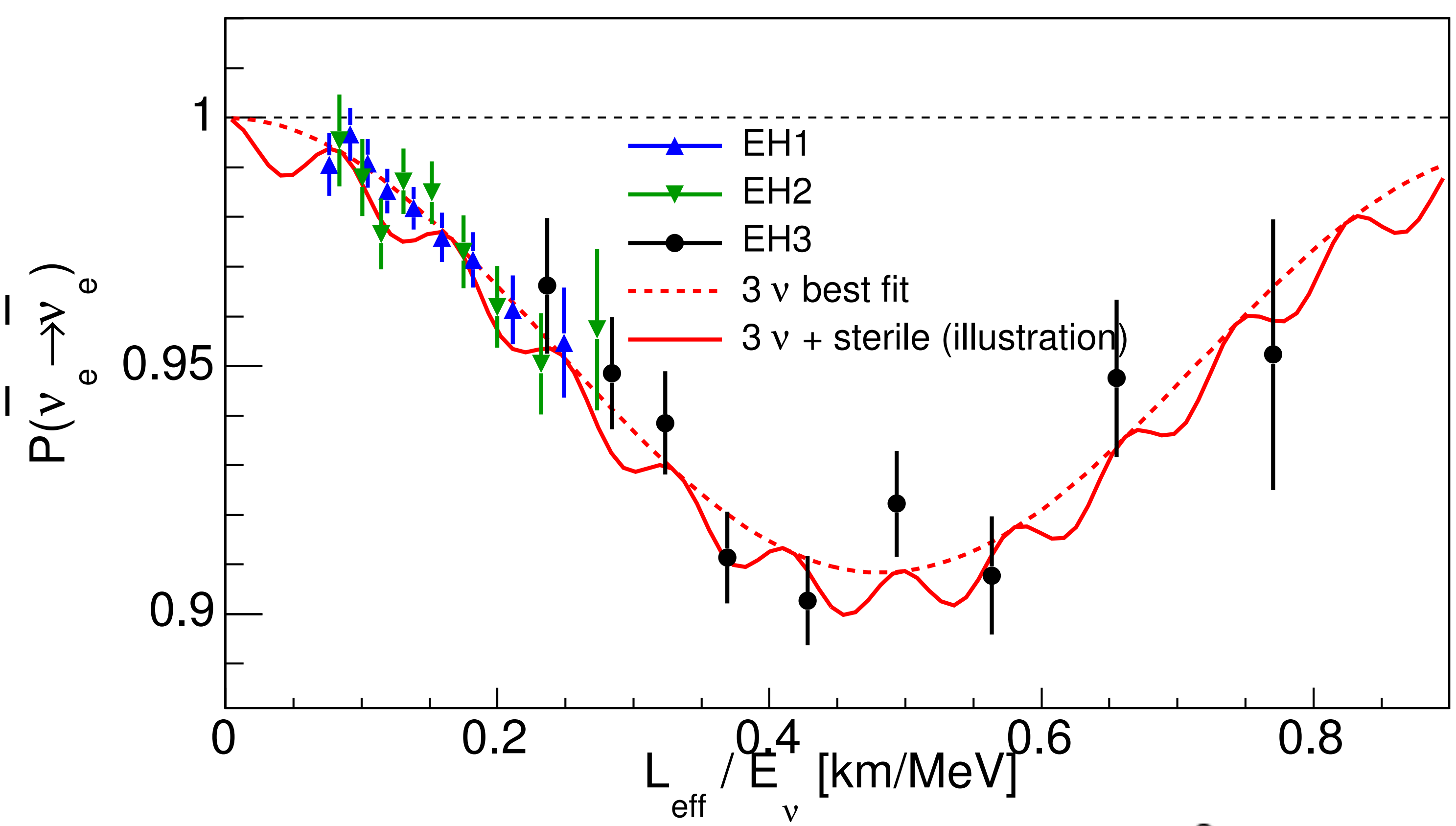
A minimal extension of the 3-ν model that includes one sterile neutrino will create a higher frequency oscillation pattern, as shown below.

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m_{41}^2 E}{4E_\nu}\right)$$



3(active) + 1(sterile)-ν

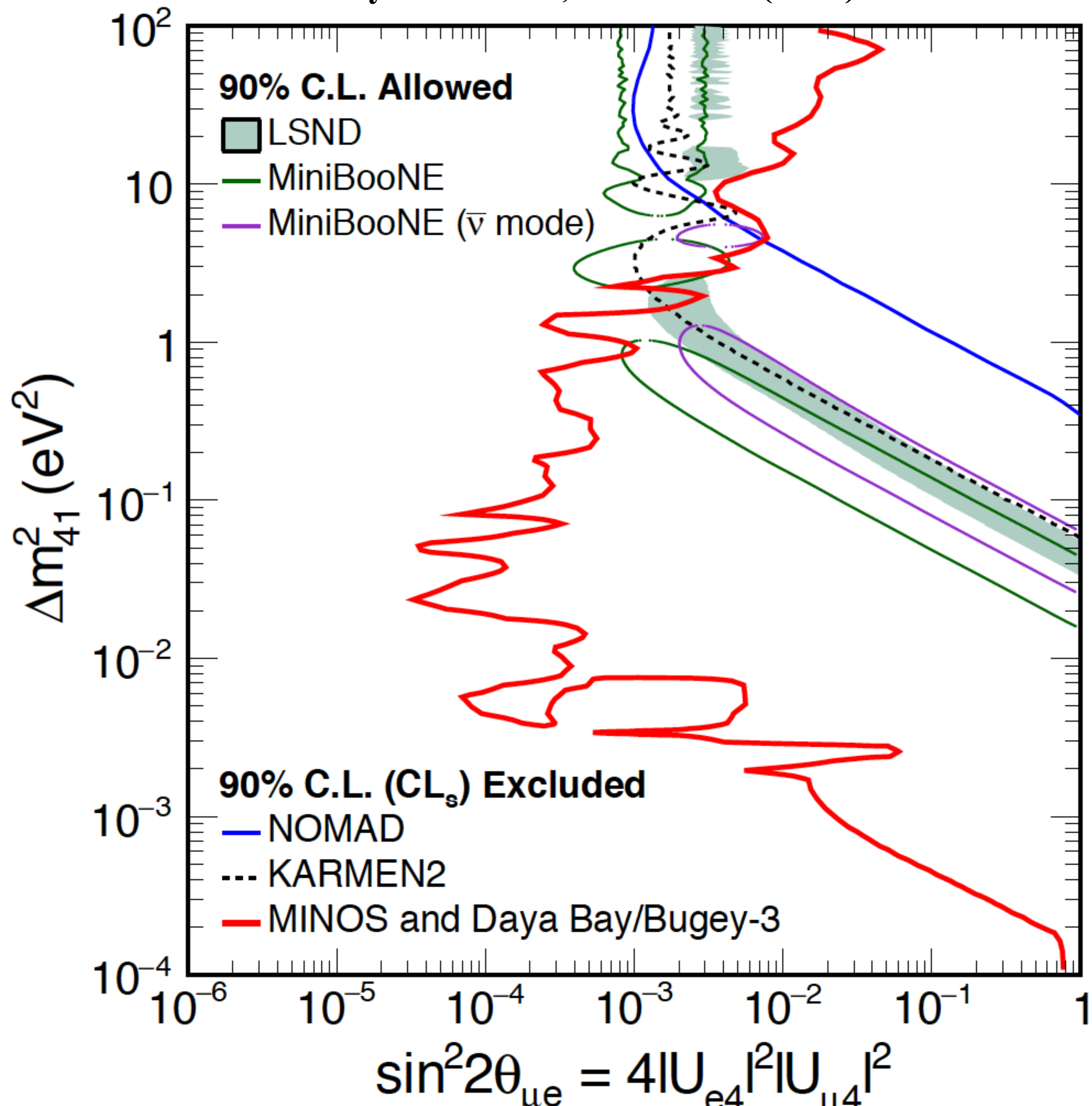
ν_e ν_μ ν_τ ν_s



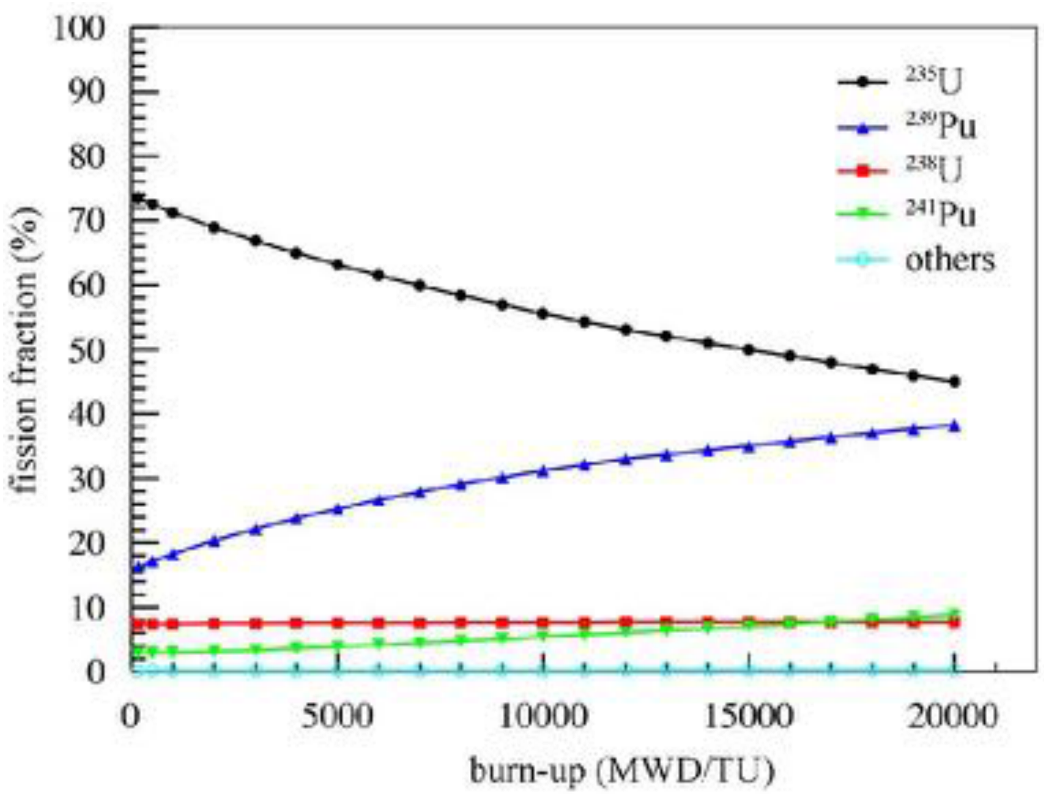
Search for a Light Sterile Neutrino

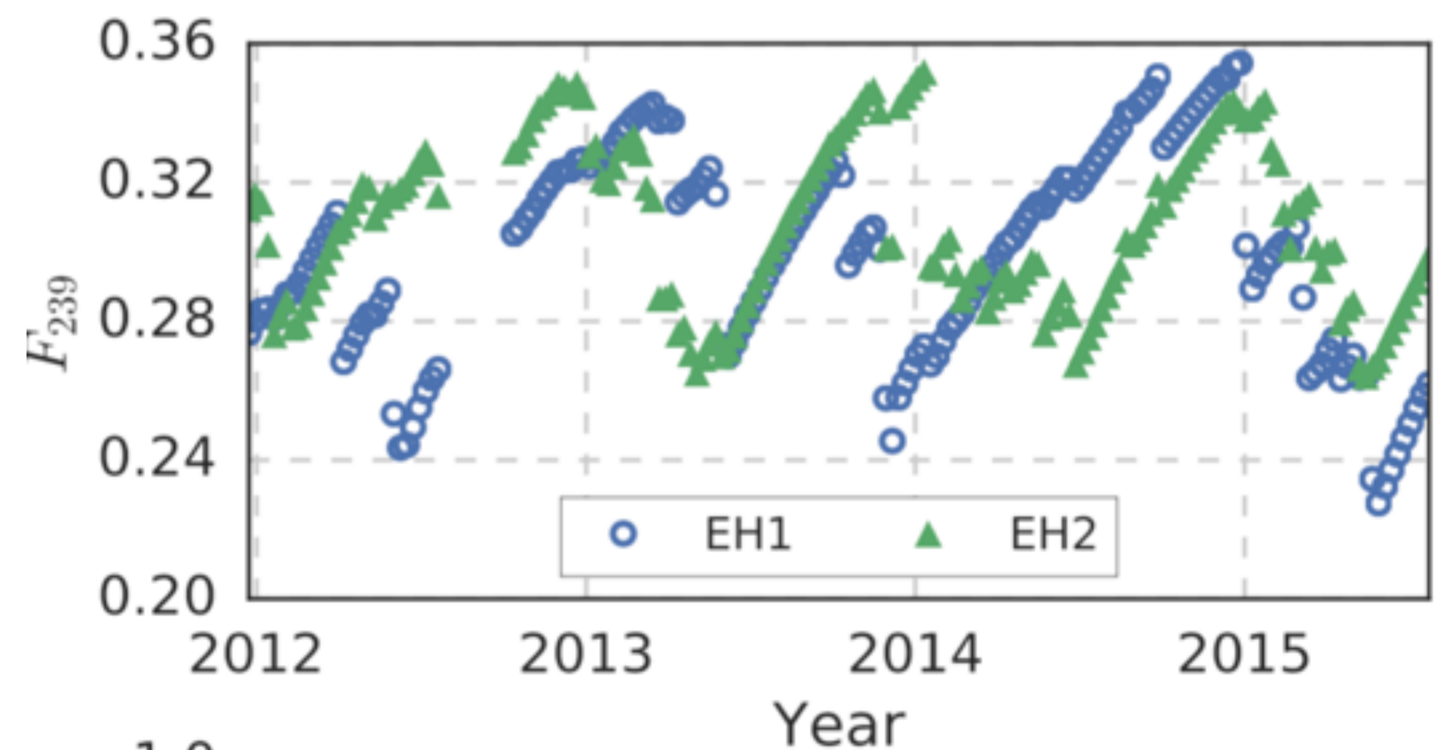
In collaboration with MINOS (Bugey-3)

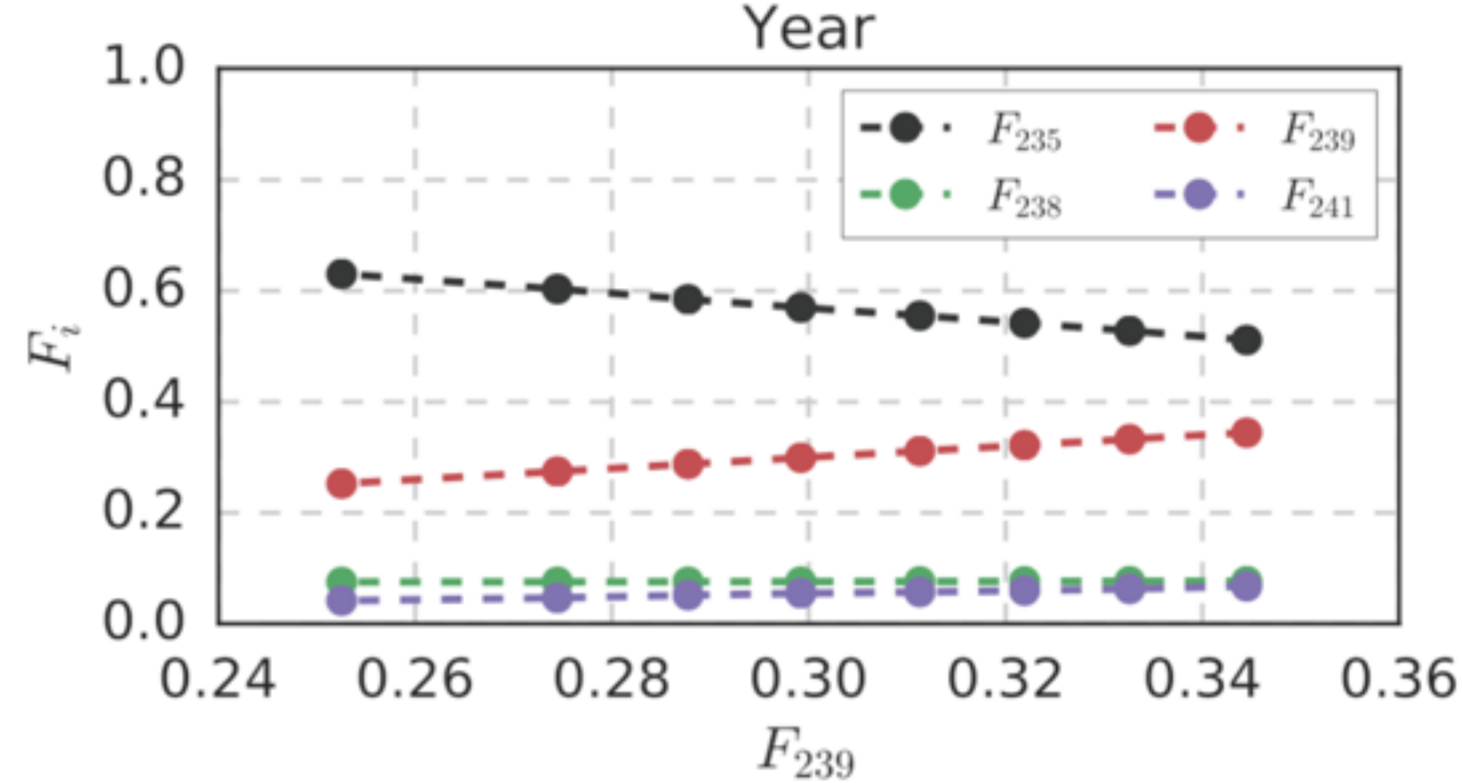
Phys. Rev. Lett, 117 151801 (2016)



Evolution of Neutrino Flux and Spectrum

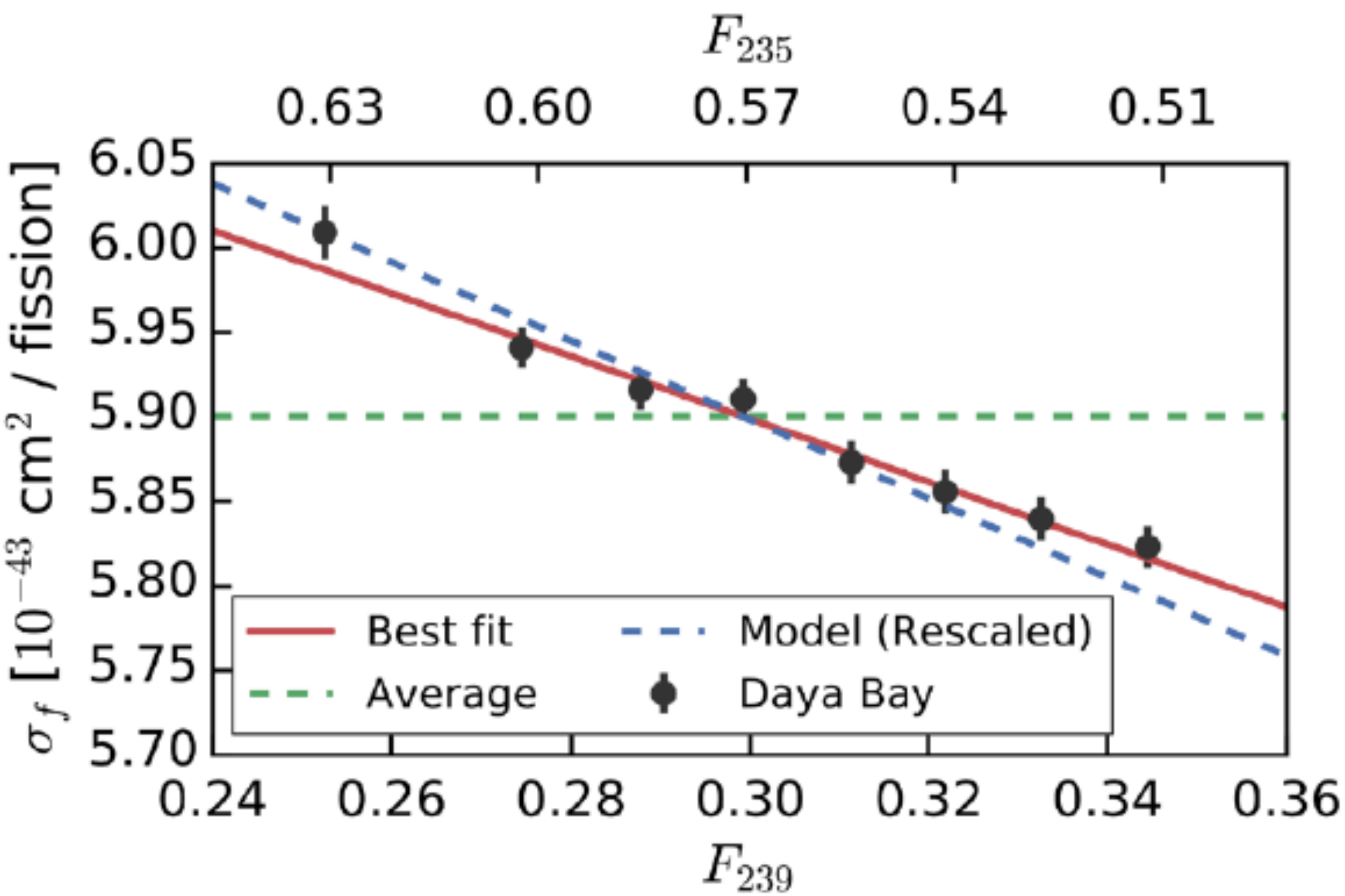






- ✦ Calculate effective fission fraction observed by each detector
- ✦ Compare IBDs from periods of differing effective fission fractions
- ✦ Doing this by combining periods of common fission fraction F_{239}

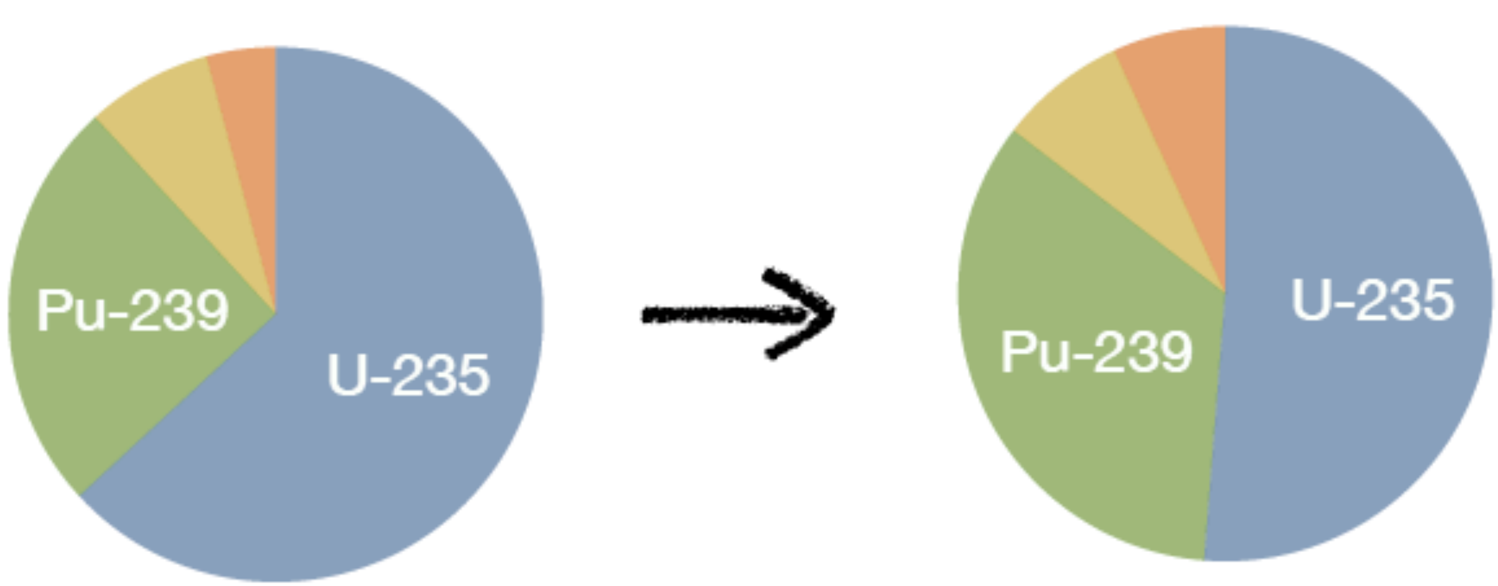
Unambiguous Observation of Fuel Evolution



Daya Bay
$d\sigma / dF_{239} = -1.86 \pm 0.18$

Huber-Mueller Model
$d\sigma / dF_{239} = -2.46 \pm 0.06$

[units: 10^{-43} cm^2 / fission]



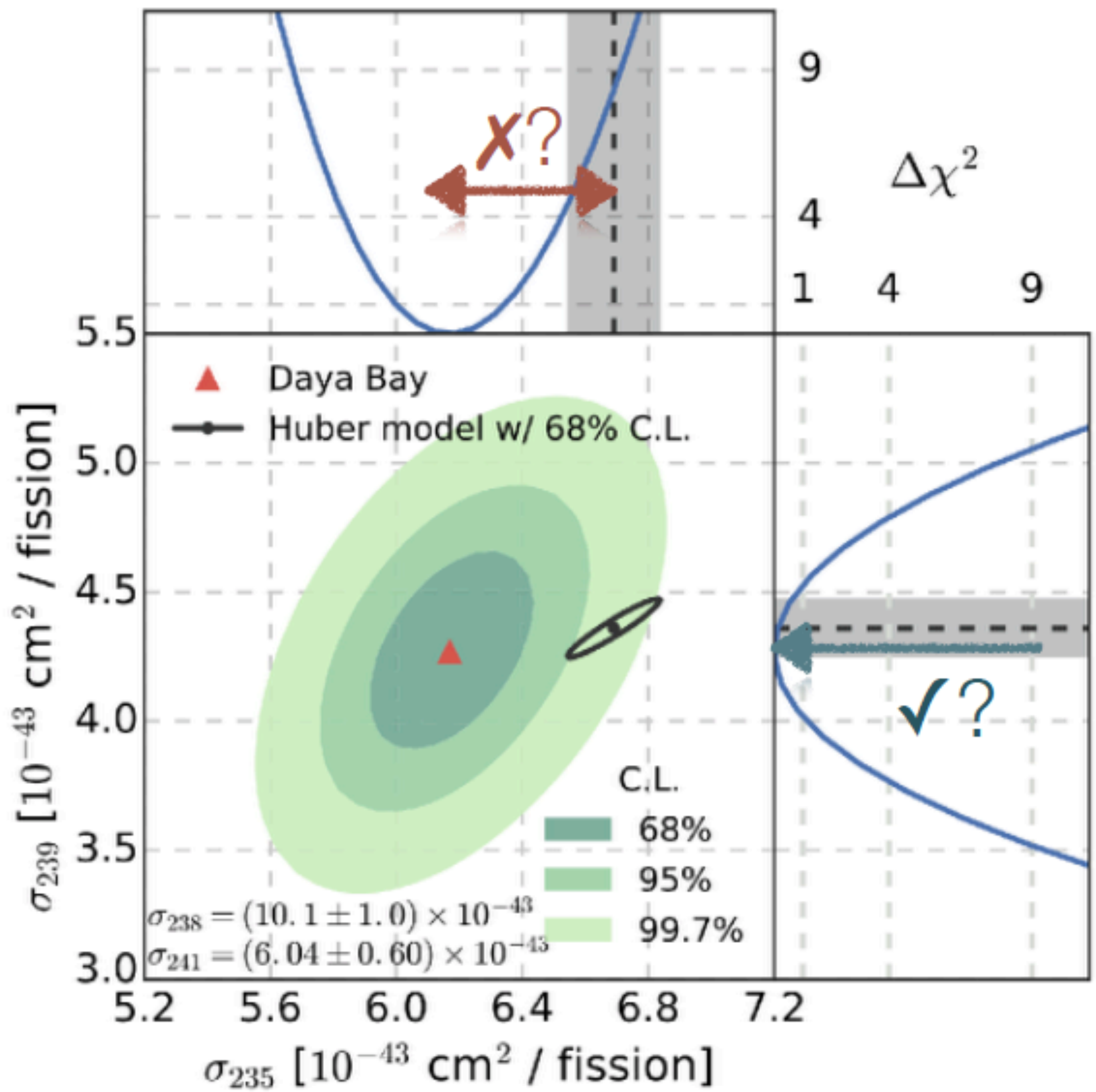
- total flux prediction is *5.4% higher*
- predicted magnitude of feul-dependent variation is *7.8% higher* too

Unambiguous Observation of Fuel Evolution

Possible explanations to the reactor antineutrino anomaly:

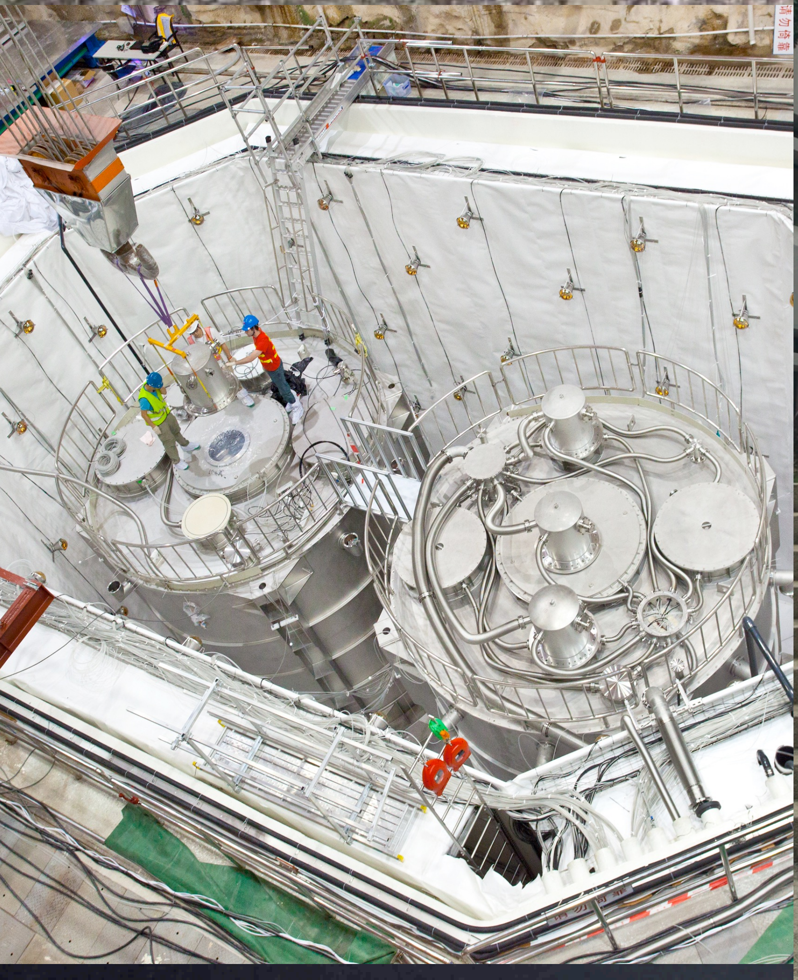
1. solely incorrect prediction on ^{235}U
   - favored by Daya Bay data with (2-side) p-value 0.68
2. solely incorrect prediction on ^{239}Pu
   - disfavored at 3.2σ C.L.
3. equal deficit on all isotopes
   - disfavored at 2.8σ C.L.

Daya Bay results suggest an overestimation of antineutrino flux from ^{235}U in reactor models.



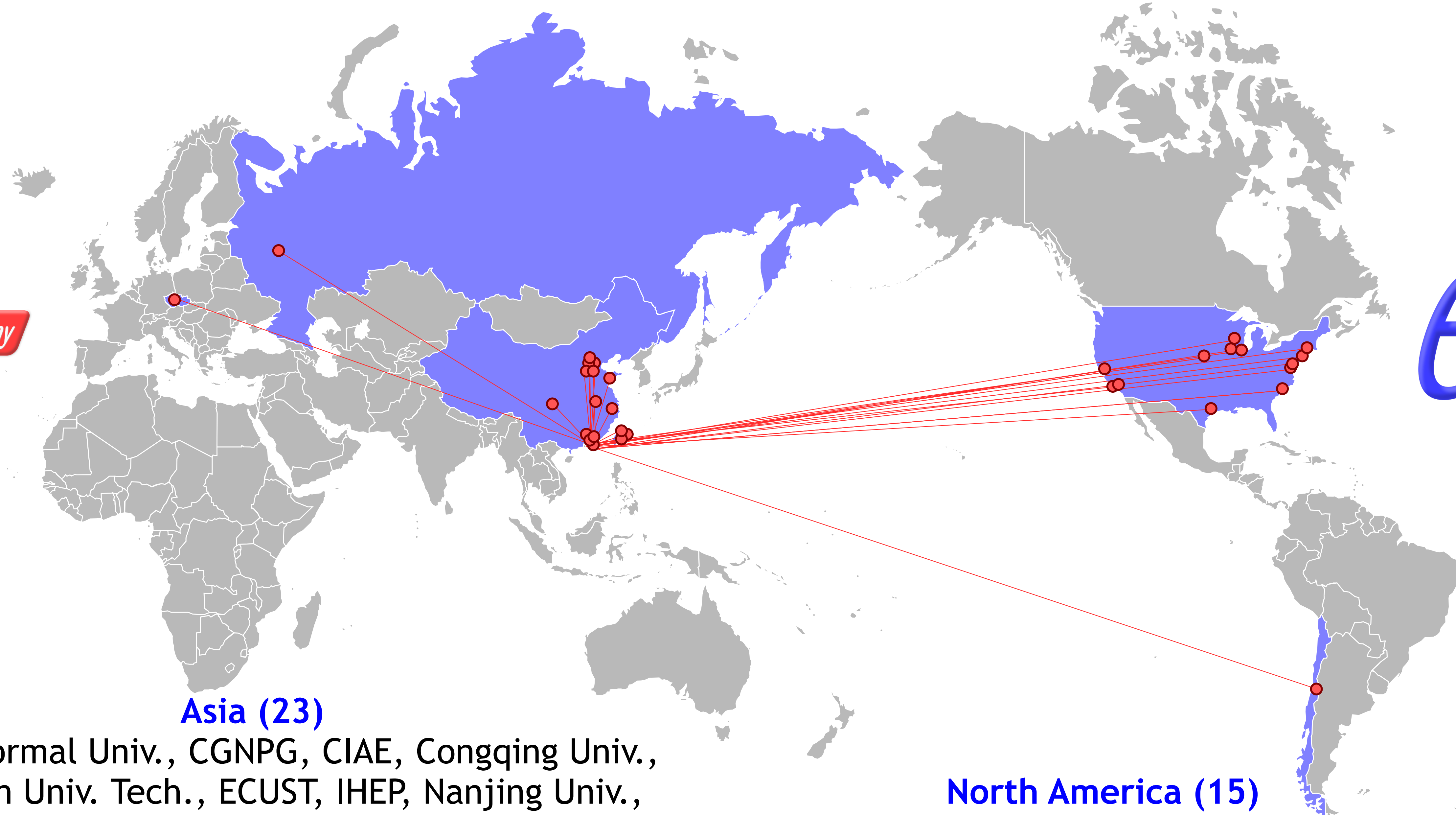

大亚湾反应堆中微子实验奠基
Daya Bay Reactor Neutrino Experiment Foundation Stone

Thank You




Daya Bay Neutrino Oscillation Experiment
Collaboration Meeting
June 7 - 13, 2009
Institute of Theoretical Physics and Department of Physics
The Chinese University of Hong Kong
Supported by
Lee Hysan Foundation
Department of Physics, CUHK

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

~230 Collaborators