BROOKHAVEN NATIONAL LABORATORY

Daya Bay θ_{13}

APS DIVISION OF PARTICLES & FIELDS

Northeastern University

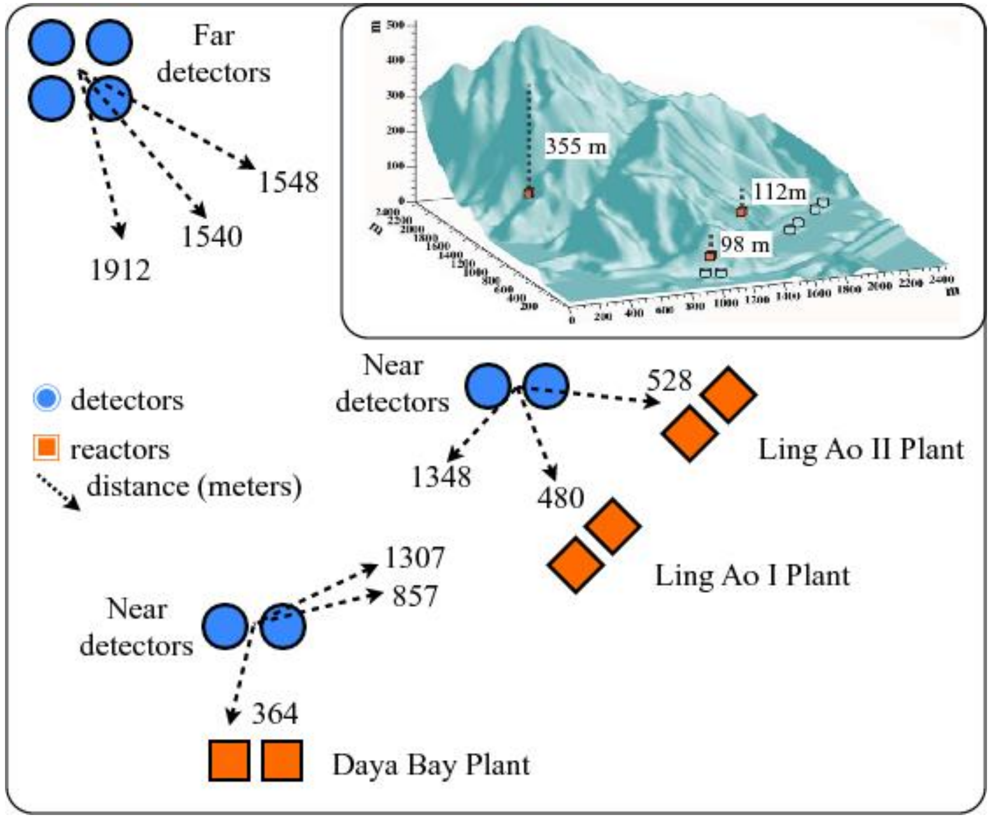
Reactor antineutrino flux and spectrum measurement from Daya Bay

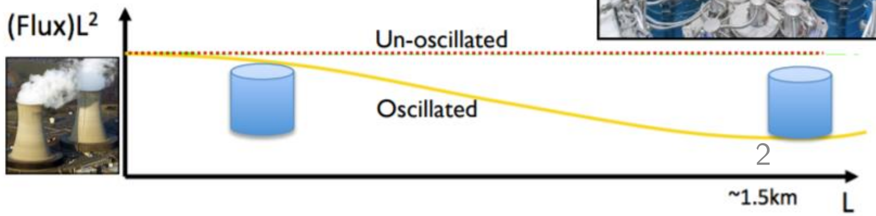
Wenqiang Gu

On behalf of the **Daya Bay** Collaboration

Daya Bay: the hunt of θ_{13}

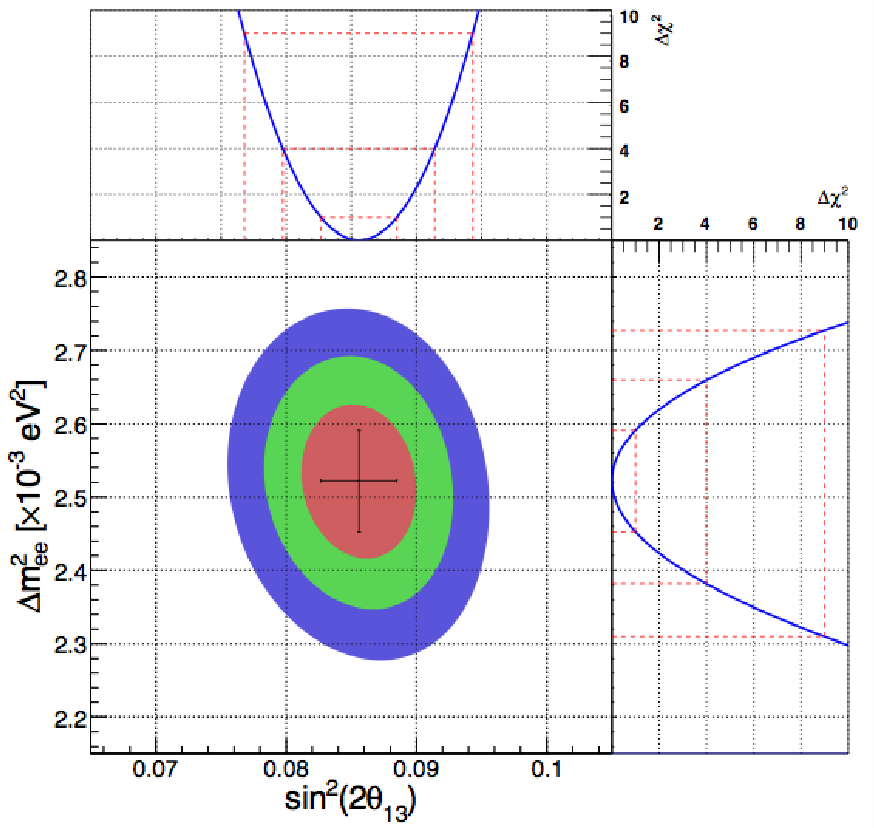
- Daya Bay reactor complex
  - Shenzhen, southern China
- Features
  - Large reactor power (6* 2.9GWth)
  - Large target mass (8* 20ton)
  - Multiple detector configuration: **near/far relative measurement**
    - ~90% reduction of reactor uncertainty for θ_{13} hunt
    - Reduction of detector systematics
  - Ample cosmic shielding from mountains



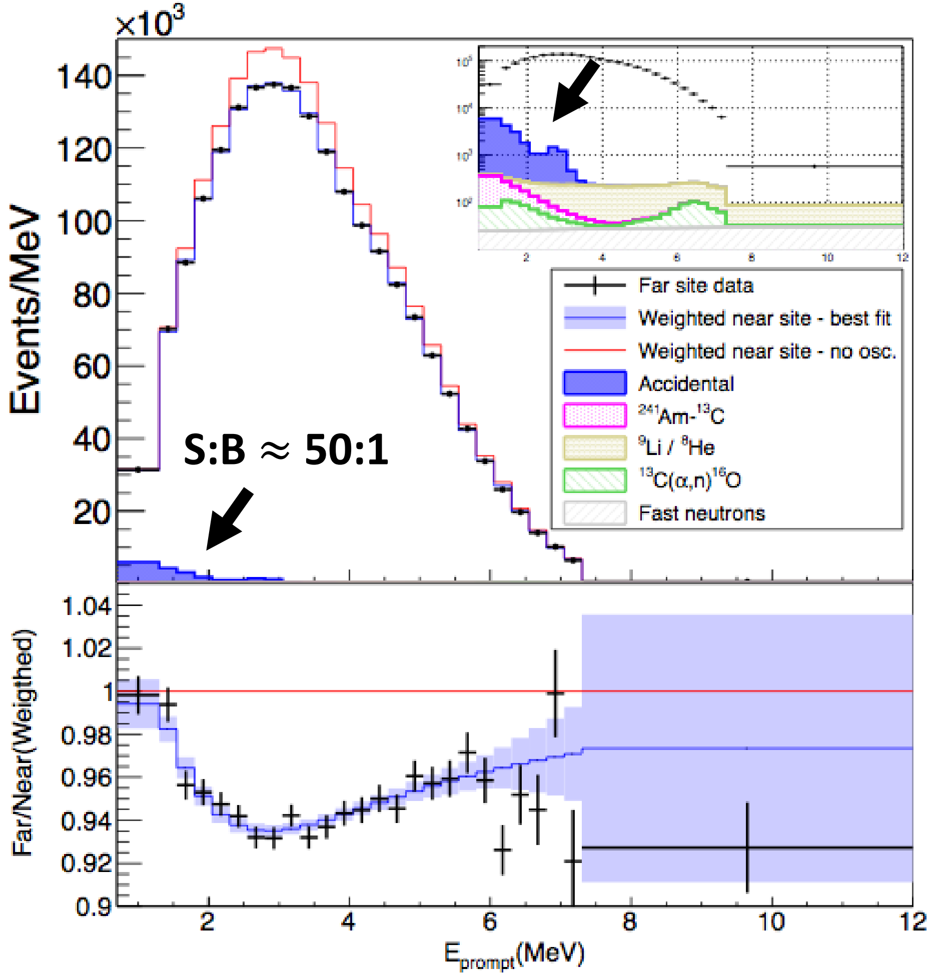


Phys. Rev. Lett. ***121***, *241805*

θ_{13} oscillation



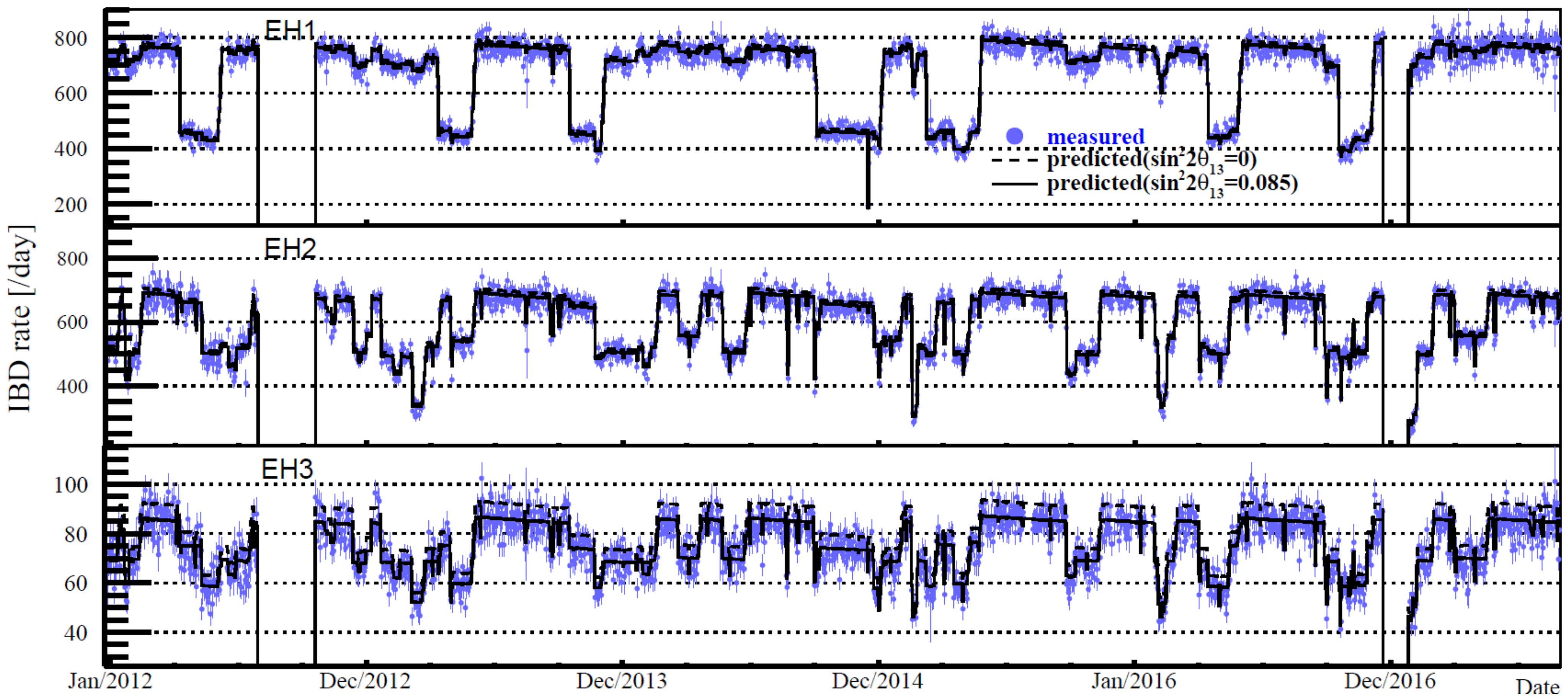
$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$
$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}$ eV^2



World leading precision in θ_{13} and $|\Delta m^2_{ee}|$

Unprecedented reactor $\bar{\nu}_e$ dataset

- 3.9 million inverse-β decay (IBD) interactions (0.5M at far site)



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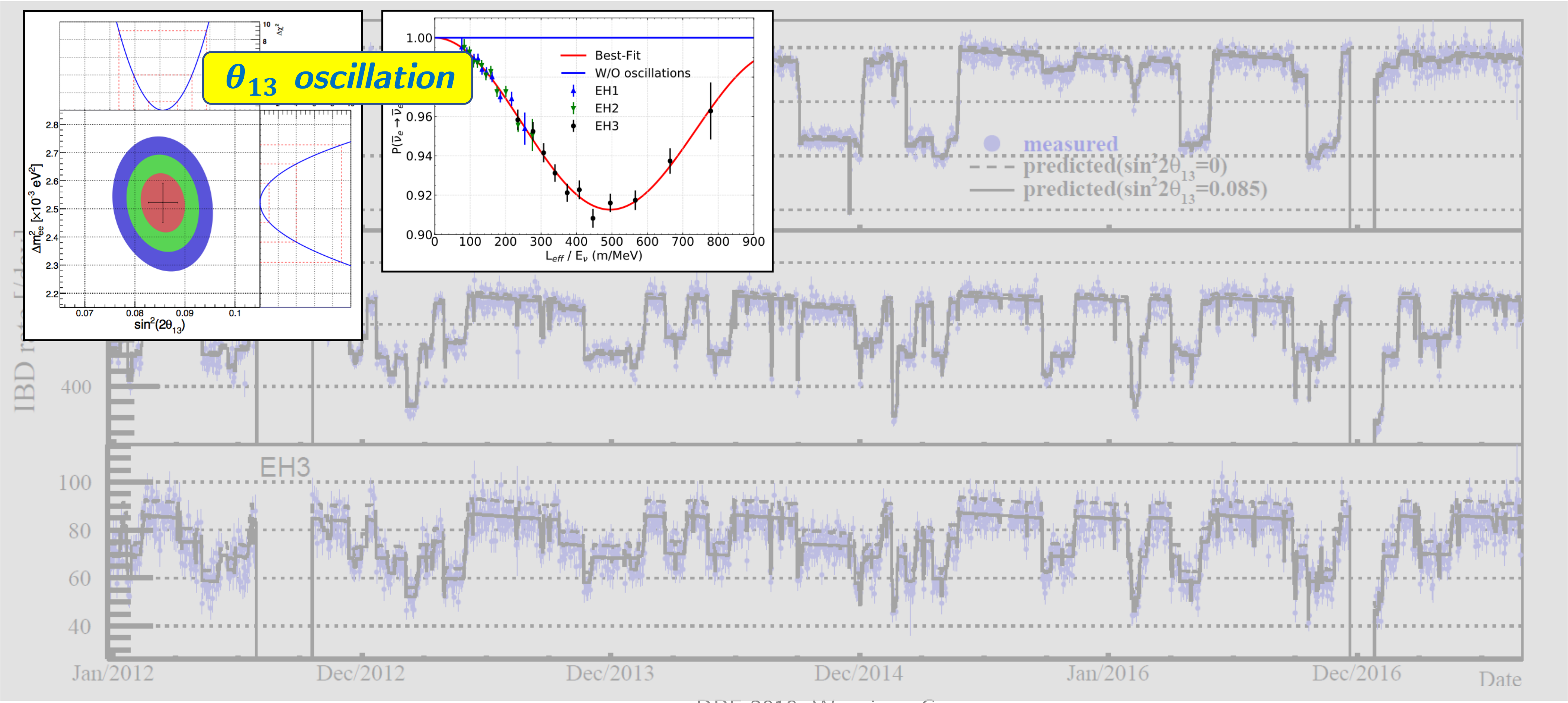

Unprecedented reactor $\bar{\nu}_e$ dataset

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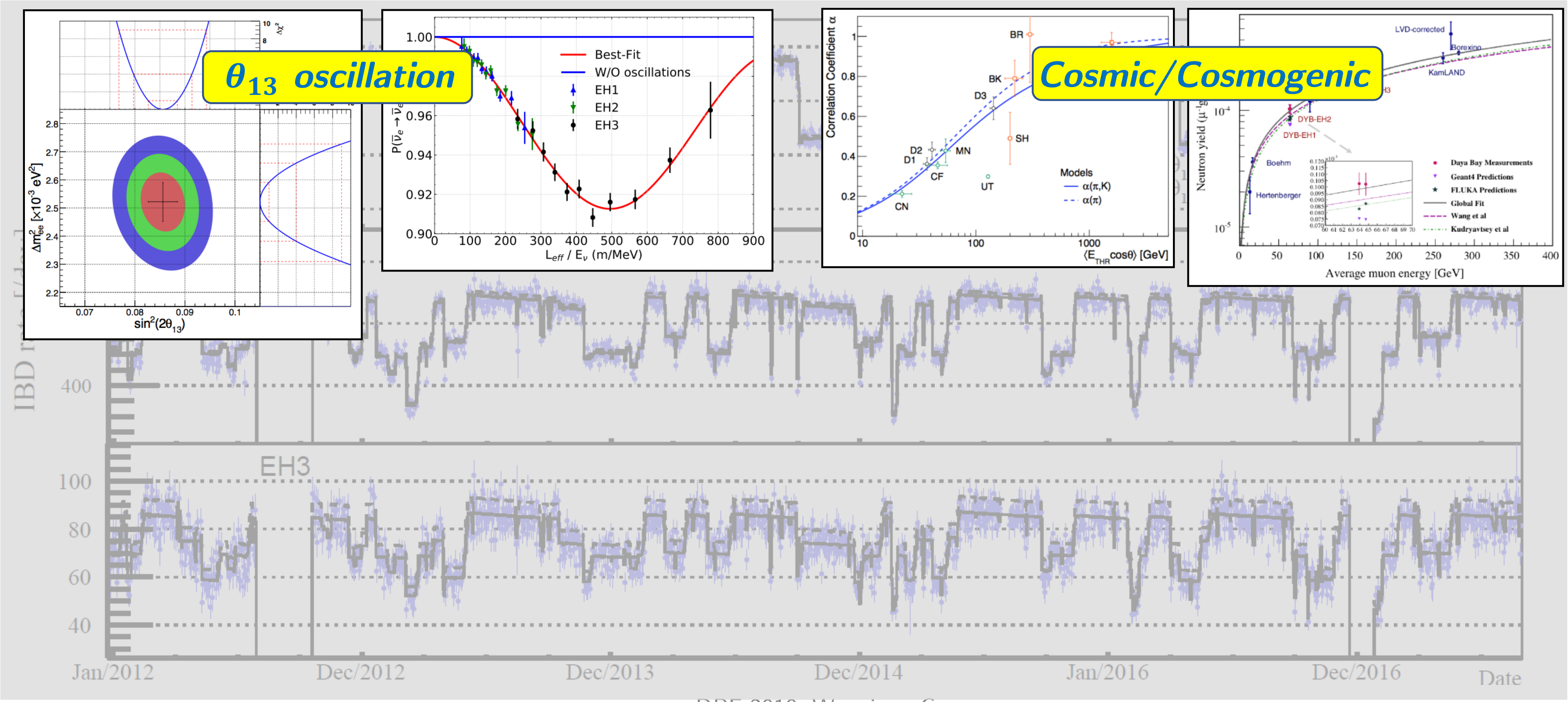

Unprecedented reactor $\bar{\nu}_e$ dataset

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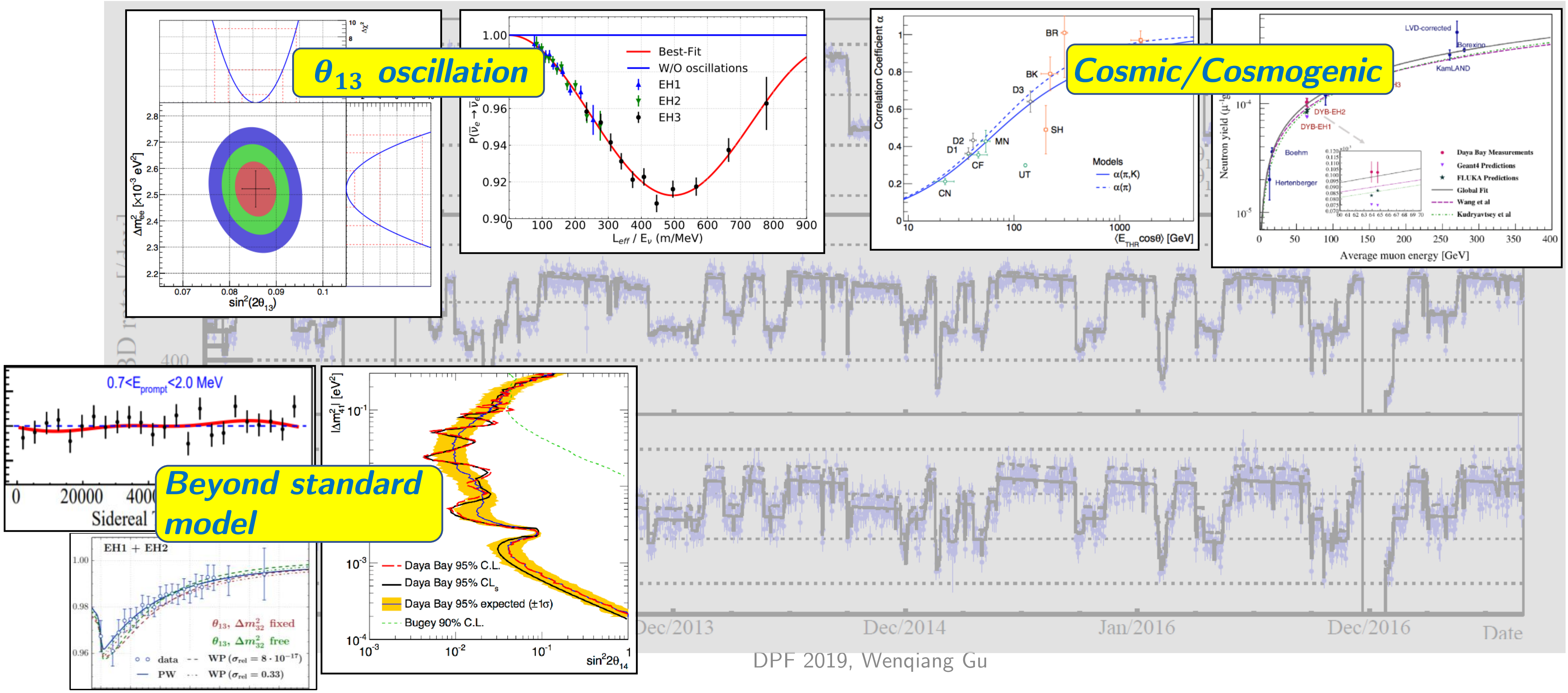

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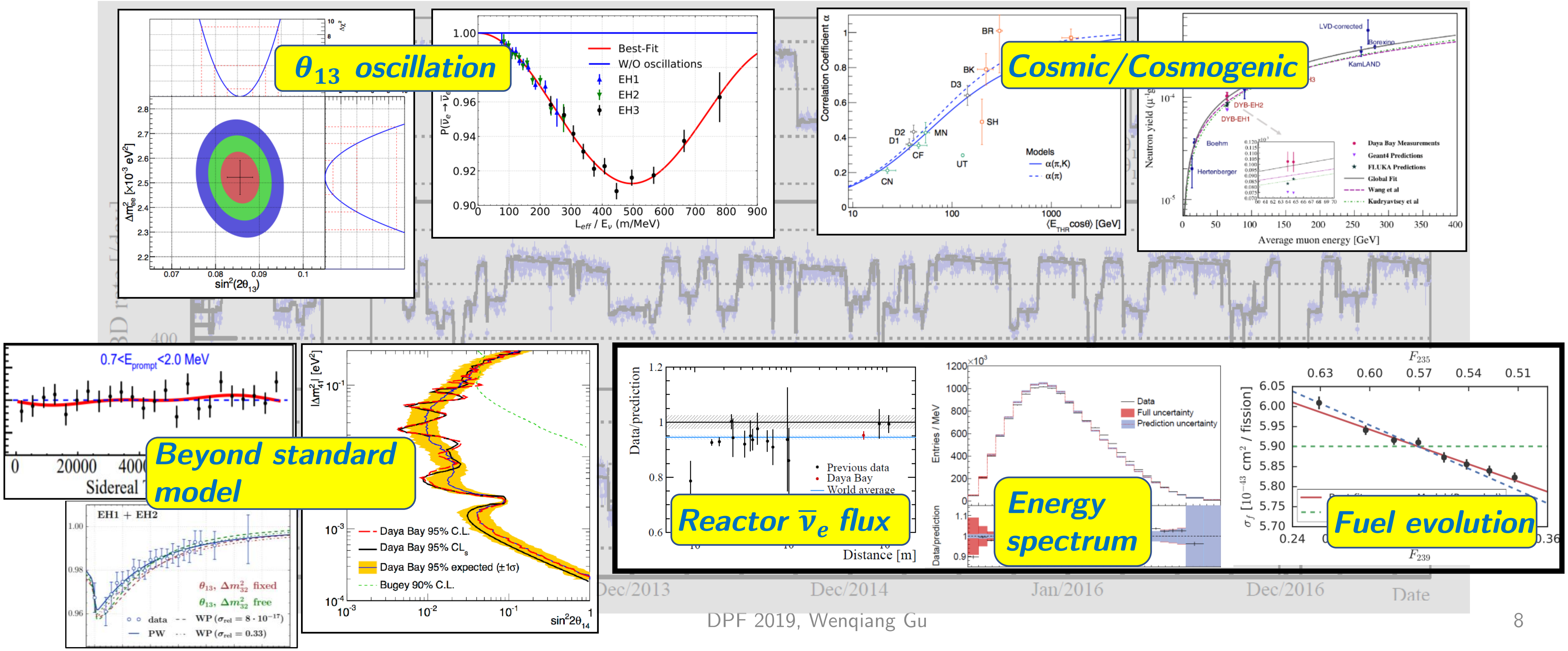


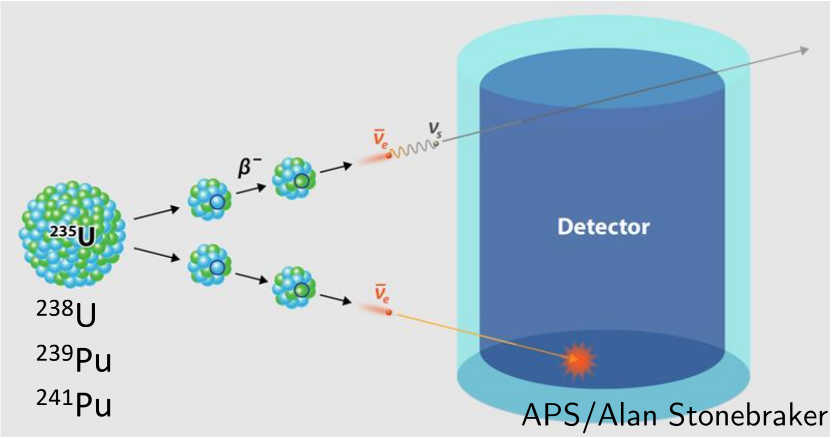
Why reactor $\bar{\nu}_e$ flux & spectrum?

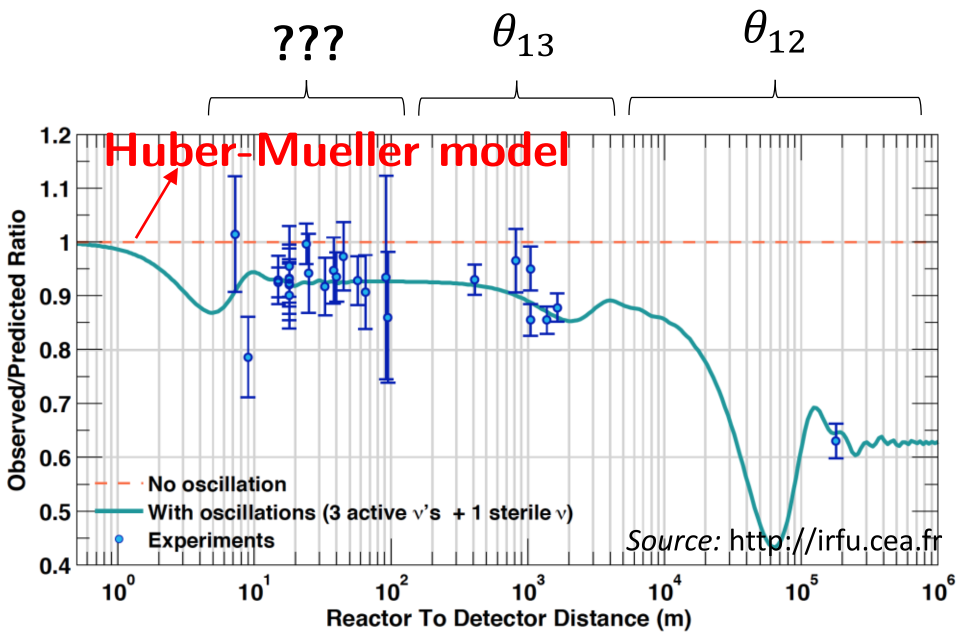
- Reactor antineutrino anomaly (RAA)
  - G. Mention *et al.*, Phys.Rev. D**83** (2011) 073006

¶ P. Huber, *Phys. Rev. C***84***:024617*
¶ Th. A. Mueller *et al.*, *Phys. Rev. C***83***:054615*

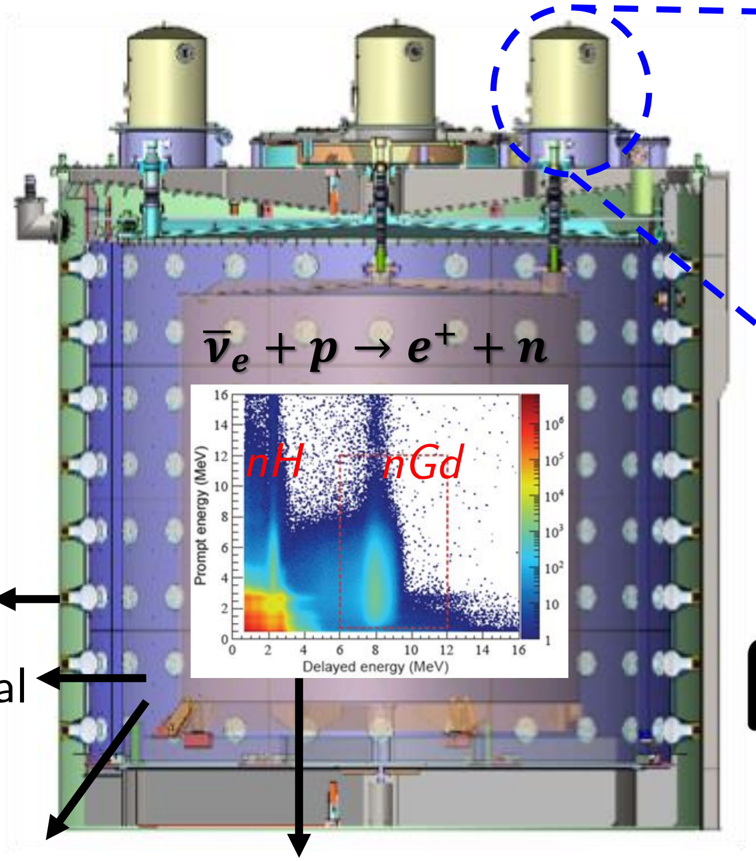
- Light sterile neutrino?
- Underestimated uncertainties in model prediction?

¶ A. C. Hayes *et al.*, Phys. Rev. Lett. **112**, 202501





Antineutrino detector at Daya Bay



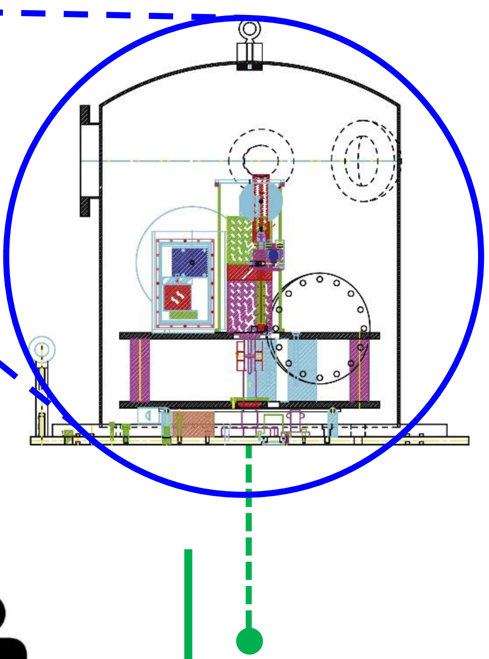
PMT

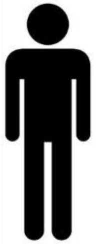
Mineral Oil

Liquid Scintillator (LS)

Gd-doped LS

NIM A 811, 133 (2016)

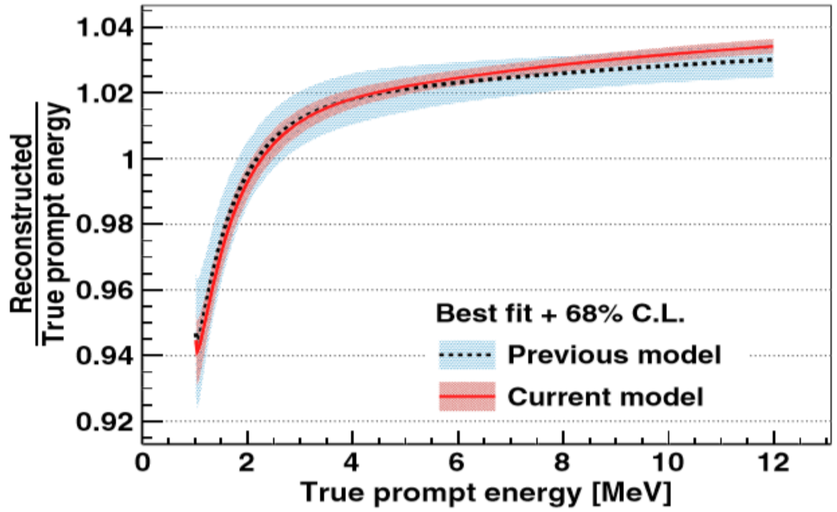




calib. source: γ, n

NIM A750, 19-37 (2014)

NIM A940 (2019) 230-242



- Positron energy uncertainty ~ 0.5%
  - γ calibration + cosmogenic ^{12}B

Integrated flux measurement: IBD yield

- IBD spectrum

$$\frac{d^2N(E_\nu,t)}{dE_\nu dt} = N_p\sigma(E_\nu)\varepsilon\sum_{r=1}^{6}\frac{P(E_\nu,L_r)}{4\pi L_r^2}\frac{d^2\phi_r(E_\nu,t)}{dE_\nu dt}$$

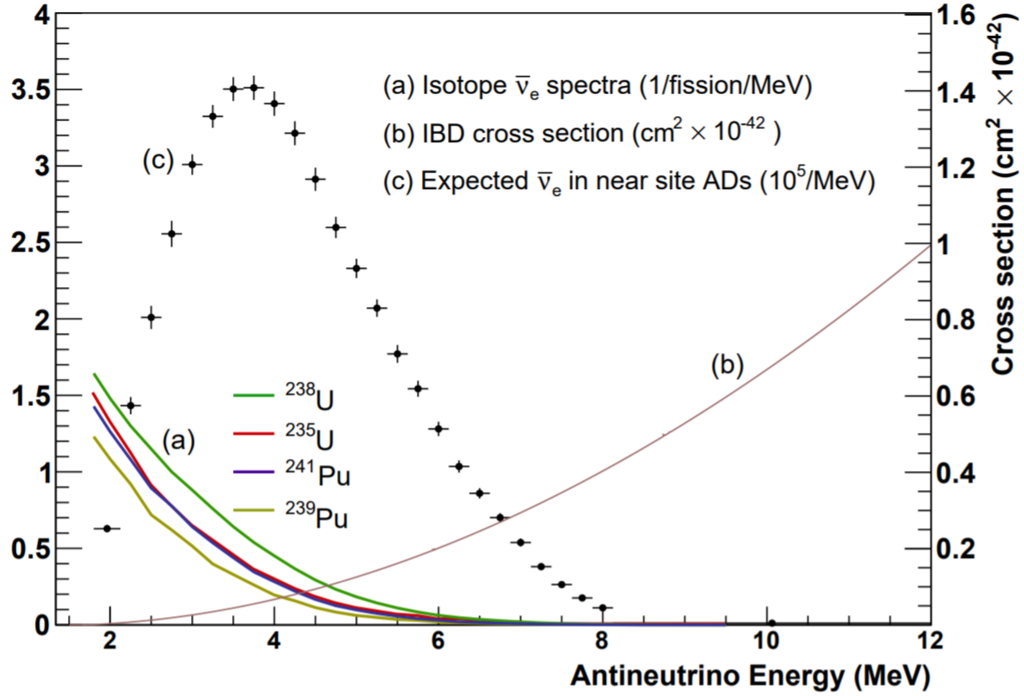
N_p: # of proton

$\sigma(E_\nu)$: IBD cross section

ε: IBD detection efficiency

$\frac{P(E_\nu,L_r)}{4\pi L_r^2}$: oscillation & propagation

$\frac{d^2\phi_r(E_\nu,t)}{dE_\nu dt}$: antineutrino spectrum from fissile isotopes



- σ_f: IBD yield per fission

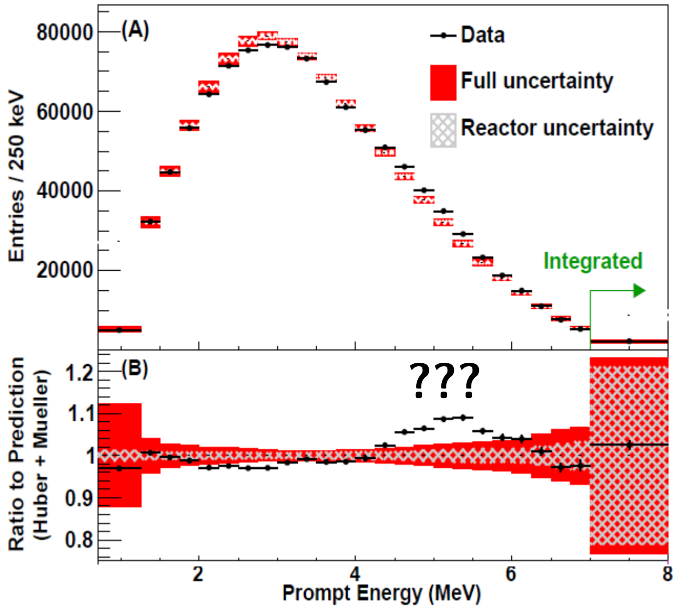
$$N_{\rm IBD}(1-c^{\rm SNF}) = \sigma_f\sum_{d=1}^{4}\sum_{r=1}^{6}\frac{N_d^P\varepsilon_{\rm IBD}P_{sur}^{rd}N_r^f}{4\pi L_{rd}^2}$$

Report σ_f for antineutrino flux

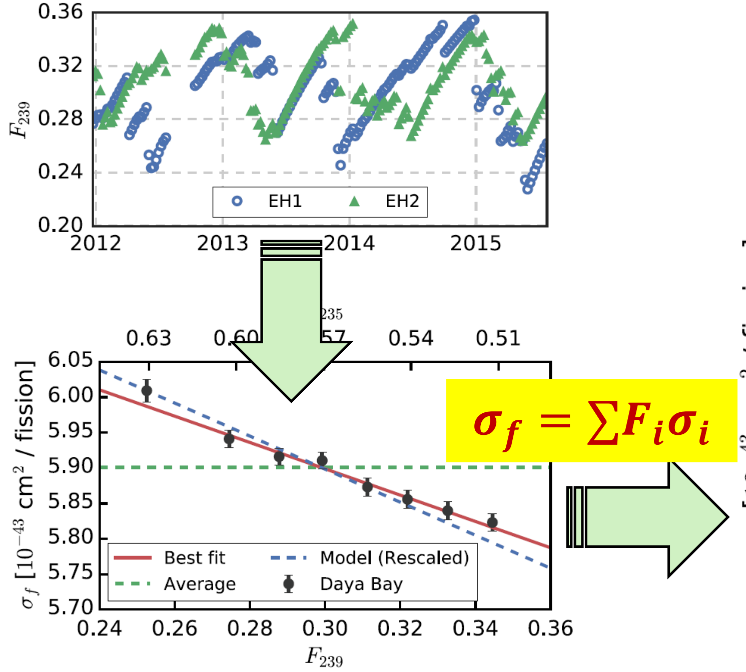
Chinese Physics C, 2017, 41(1): 13002-013002
Phys. Rev. Lett. 118.251801

Previous results from Daya Bay

621-day dataset
1.1 million IBD

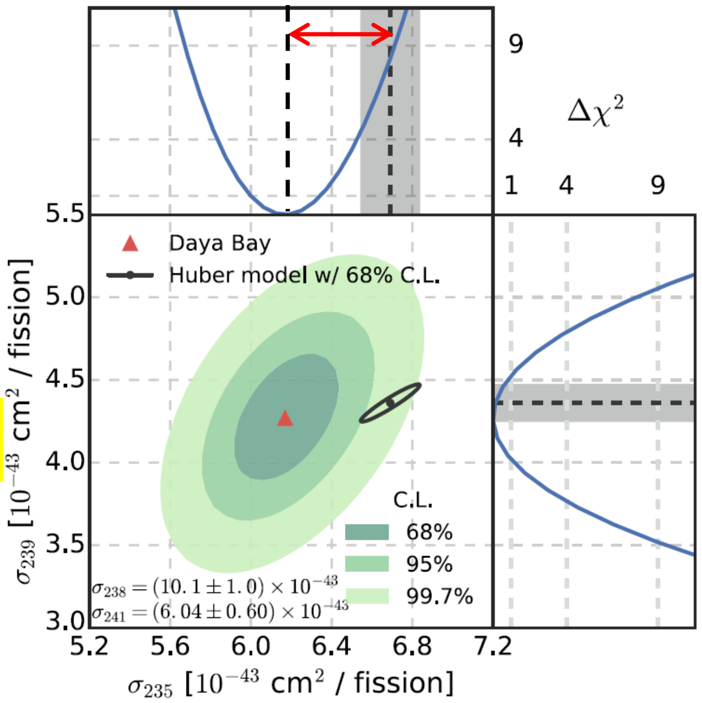


1230 days



$$\sigma_f = \sum F_i \sigma_i$$

7.8% deficit for ^{235}U



Prev. { σ_f = (5.91 ± 0.12) × 10^{-43} cm^2 / fission
R(Huber-Mueller) = 0.946 ± 0.020 (exp.)

- Fuel evolution => decomposed IBD yield of ^{235}U and ^{239}Pu
- Indicates overprediction of ^{235}U IBD yield
- Underestimated systematic uncertainty in model prediction?

Improved IBD detection efficiency

Previous IBD efficiency values

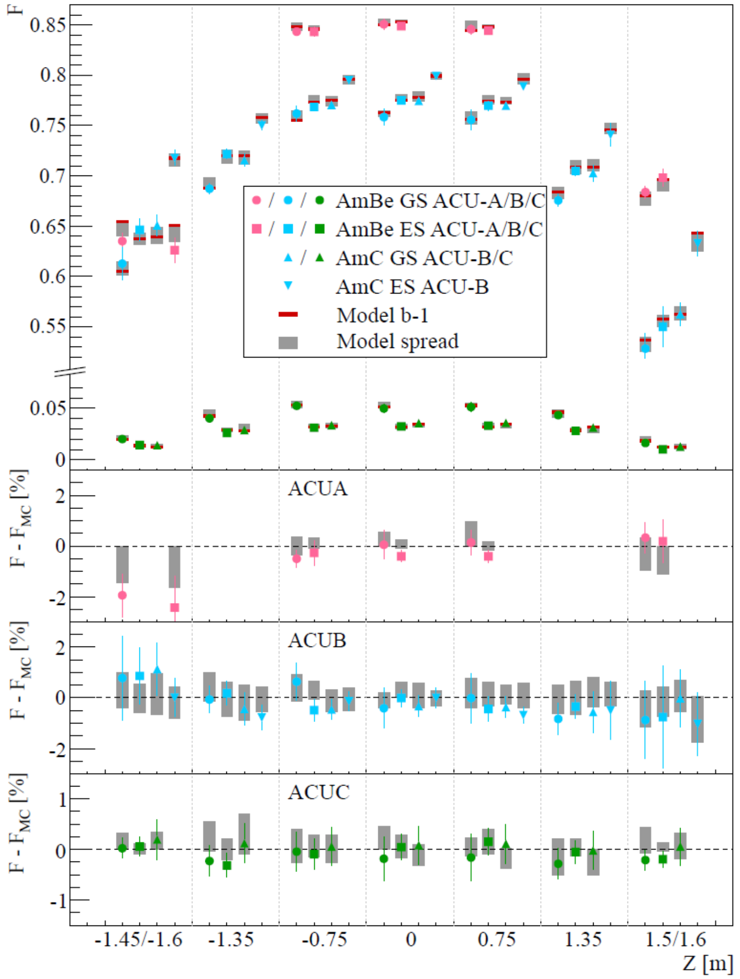
Source	ϵ	$\delta\epsilon/\epsilon$
Target protons	-	**0.92%**
Flasher cut	99.98%	0.01%
Capture time cut	98.70%	0.12%
Prompt energy cut	99.81%	0.10%
Gd capture fraction	84.17%	**0.95%**
nGd detection efficiency	92.7%	**0.97%**
Spill-in correction	104.9%	**1.00%**
Combined	80.6%	1.93%

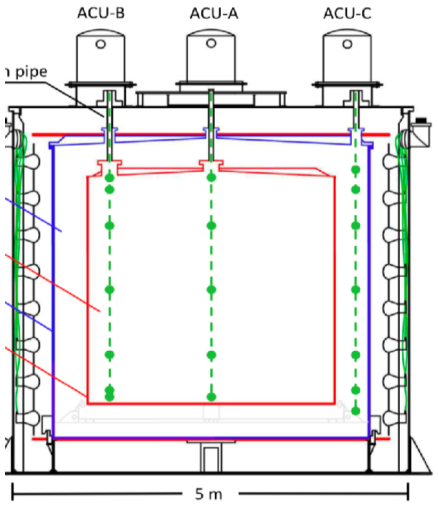
Neutron-related efficiency

$\varepsilon_n = 81.83 \pm 1.38\%$

Uncertainty improved x2

$\varepsilon_n = 81.48 \pm 0.60\%$



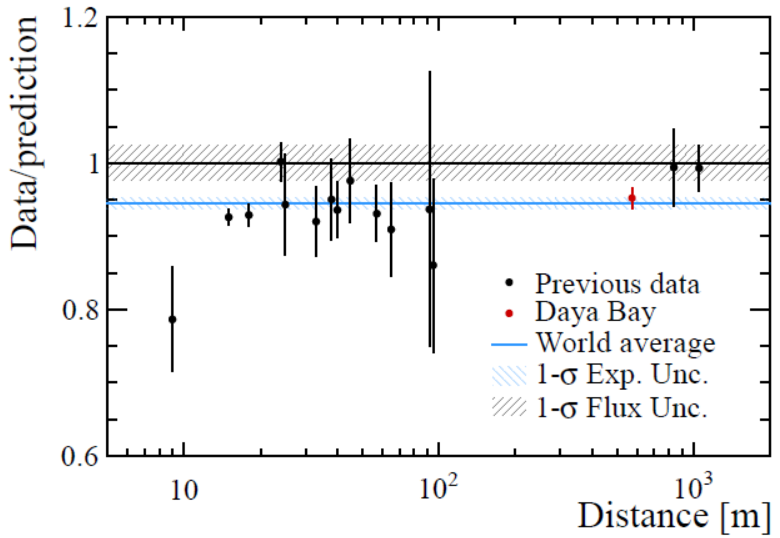


- ^{241}Am-^{13}C and ^{241}Am-^{9}Be
- Neutron calibration well constrained by model spread in MC simulation

Updated absolute $\bar{\nu}_e$ flux & spectrum

arXiv:1808.10836 [hep-ex]
arXiv:1904.07812 [hep-ex]

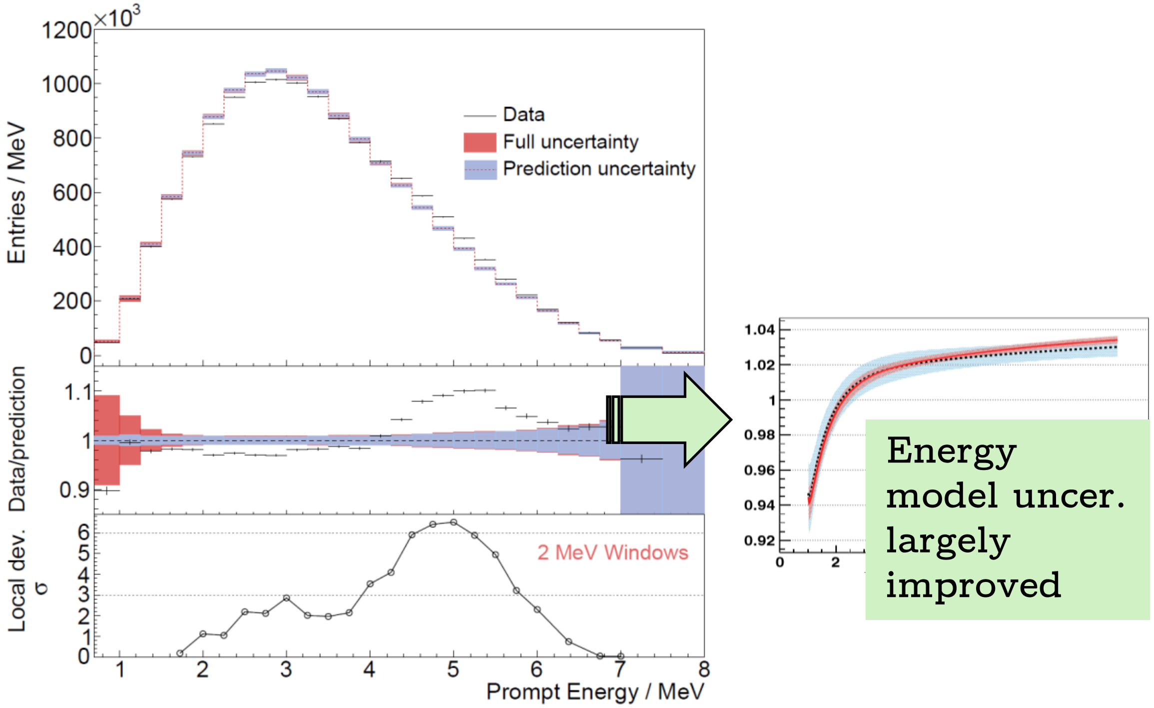
1230 days



$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}\ \mathrm{cm}^2$ / fission
R(Huber-Mueller) = 0.952 ± 0.014 (exp.)

- Consistent with previous experiments and world average

1958 days



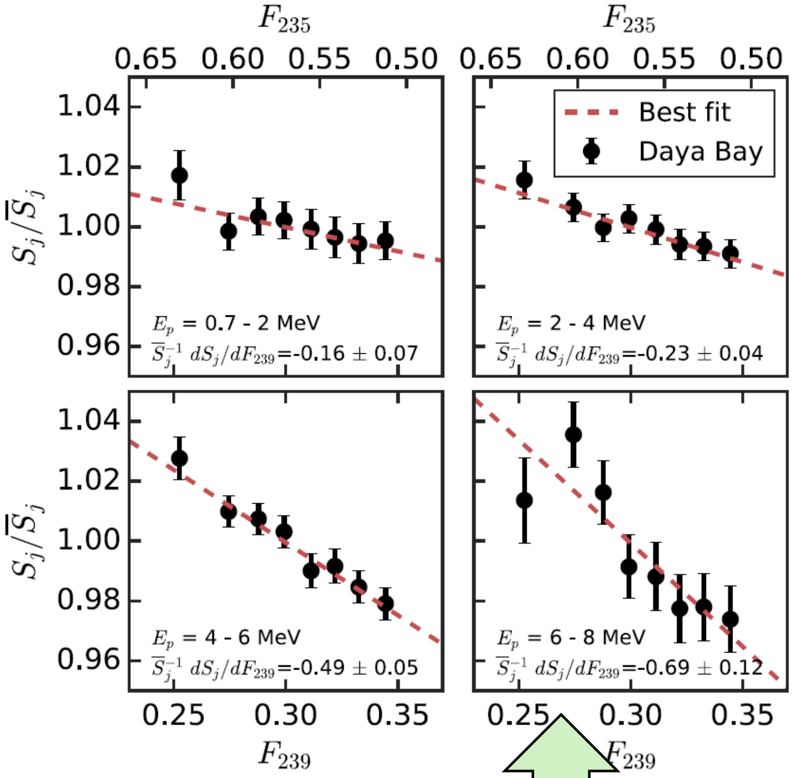
Energy model uncer. largely improved

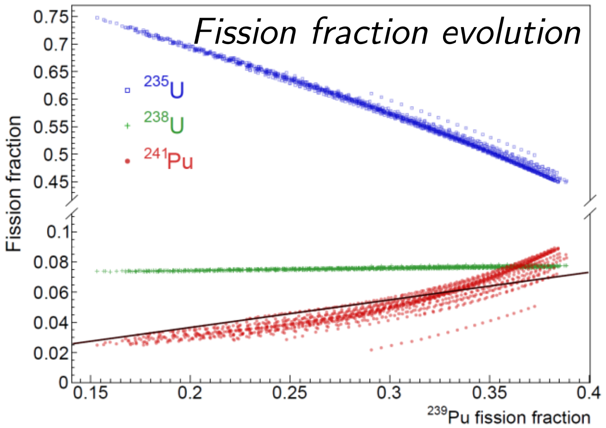
- Spectral shape (normalized) NOT consistent with model prediction
- Global discrepancy: 5.3 σ
- Local deviation in 4-6 MeV: 6.3 σ

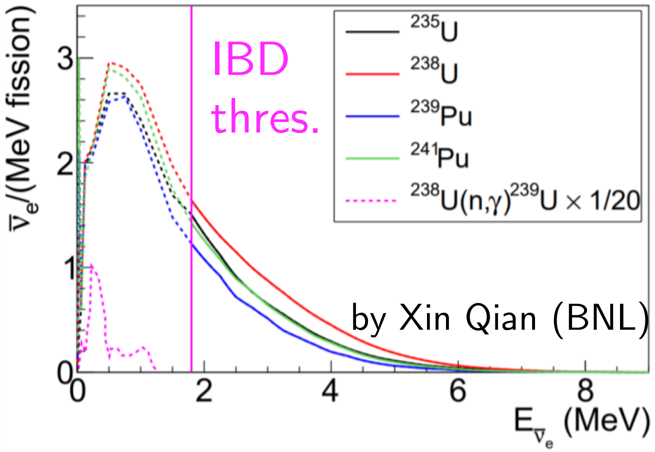
Spectral evolution & decomposition

- Spectral evolution observed in early result
  - Can decompose ^{235}U/^{239}Pu antineutrino flux
  - In a very coarse energy binning
- Given 3.5M IBDs at near sites, Daya Bay extracts ^{235}U & ^{239}Pu antineutrino spectra
  - In 26 energy bins

Phys. Rev. Lett. 118.251801







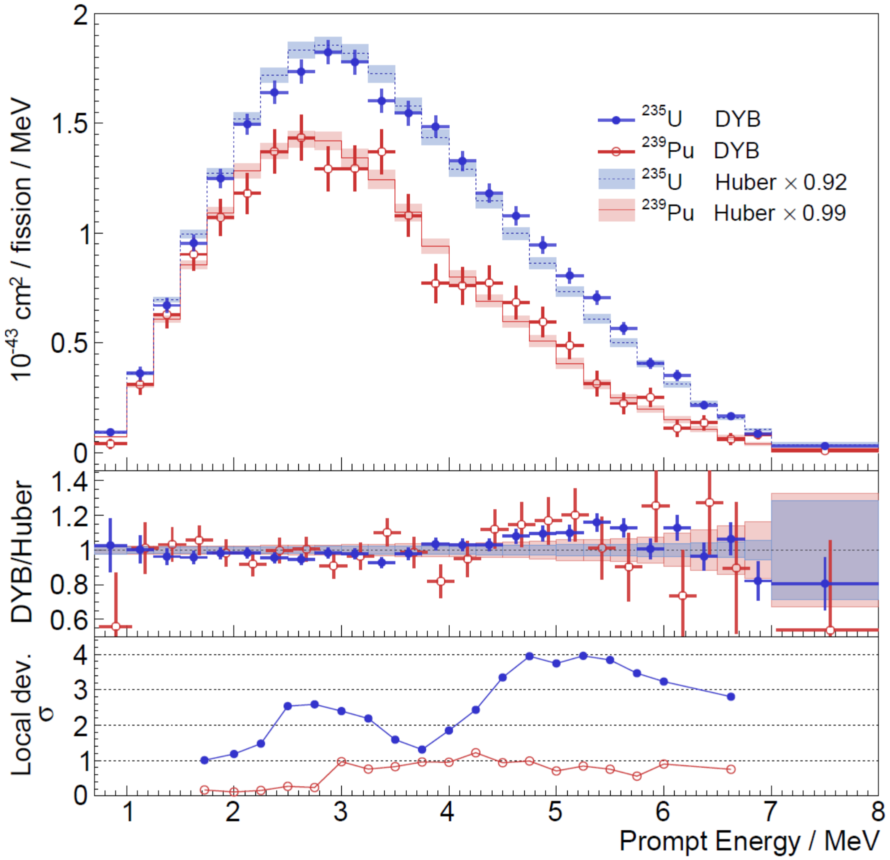
Slopes indicate enhanced contribution from ^{239}Pu at high energy

Extract ^{235}U & ^{239}Pu antineutrino spectra

- First measurement of antineutrino energy spectrum of ^{239}Pu
- First measurement of ^{235}U in a commercial reactor
- Similar deviation in 4-6MeV for ^{235}U and ^{239}Pu when normalized
- IBD yield comparison

^{235}U: data/prediction = 0.92 $\pm$0.023(exp.)

^{239}Pu: data/prediction = 0.99 $\pm$0.057(exp.)



Summary

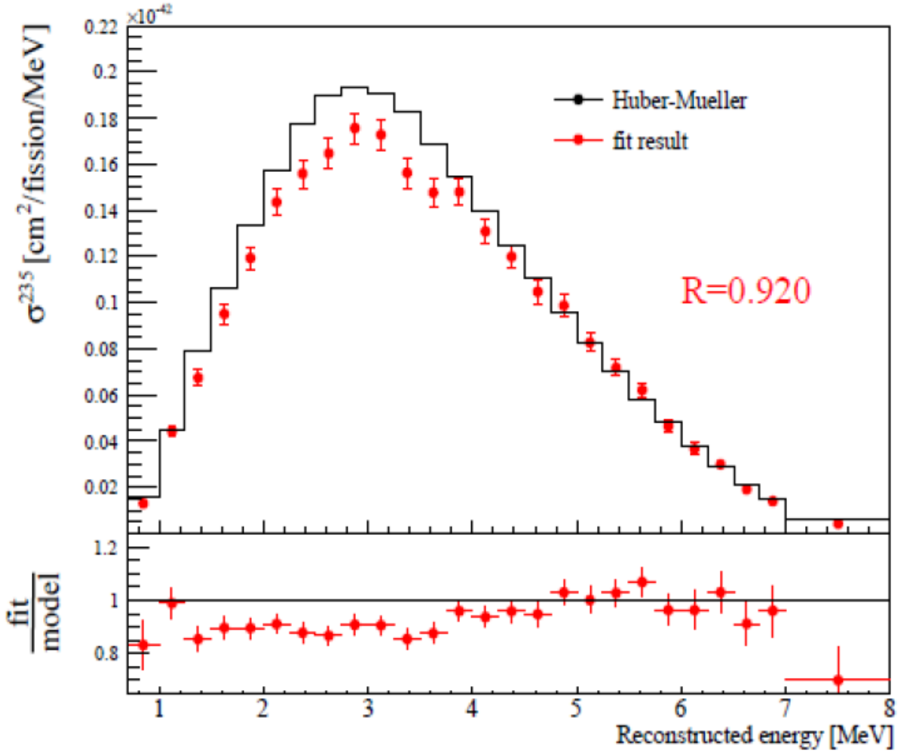
- Daya Bay has accumulated unprecedented (3.9 million) reactor antineutrino interactions
- Improved reactor antineutrino flux measurement
  - Neutron-related detection efficiency improved by a factor of 2
  - Data/prediction (Huber-Mueller) $= 0.952 \pm 0.014$ (exp.)
  - Consistent with world average
- Measurement of antineutrino energy spectra from ^{235}U and ^{239}Pu
  - ^{235}U: First time in a commercial reactor
  - ^{239}Pu: First time in the world
- Daya Bay expect to continue taking data until end of 2020

Thanks!

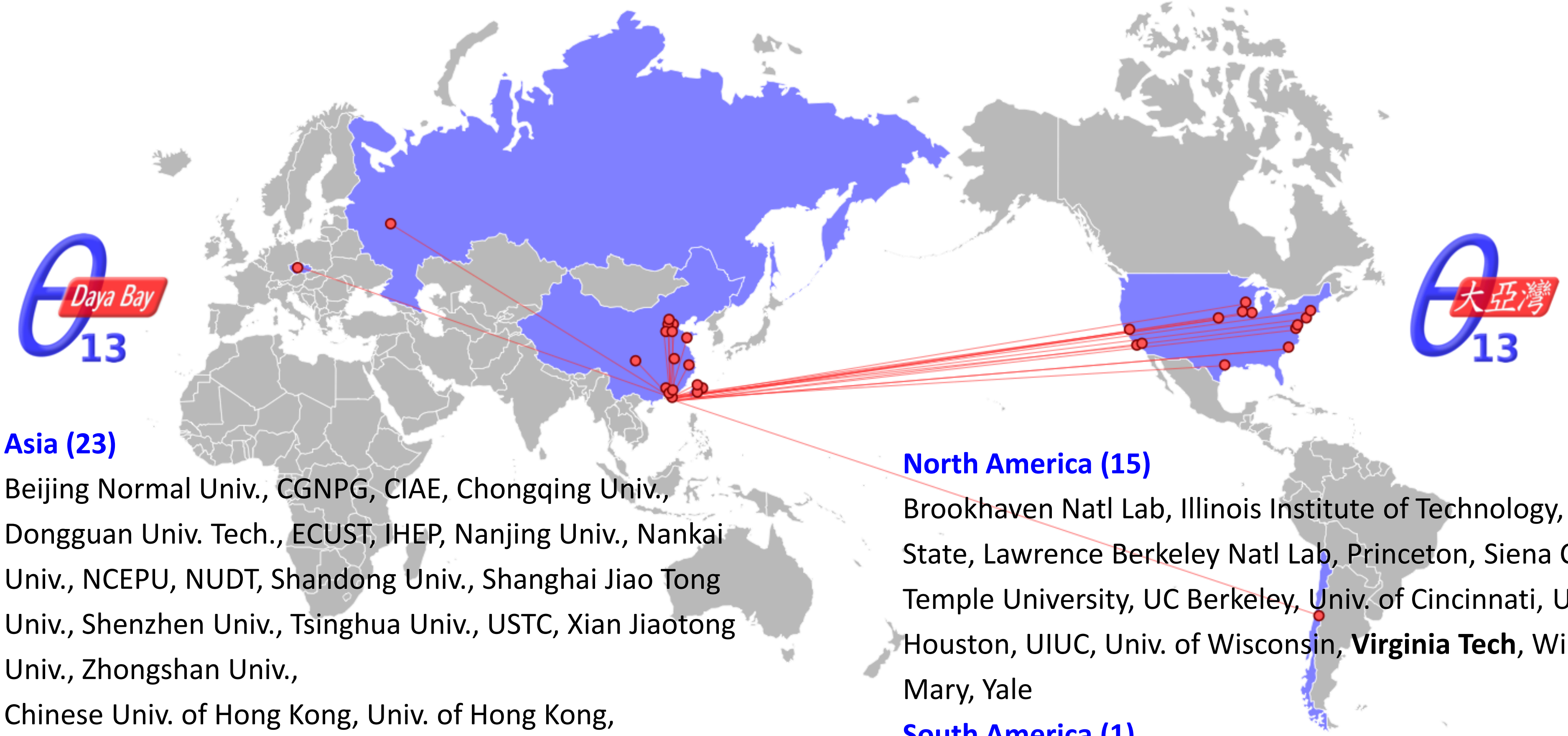
	Physics analysis published date	Detector status
2011	AD 1/2 comparison	2 EH1 ADs start data taking in Aug. 2+1+3 ADs start data taking in Dec.
2012	March, First 5σ θ_{13}, rate only, 55d	Calibration campaign in Jun. 2+2+4 ADs start data taking in Oct.
2013	Improved θ_{13} (9σ), rate only, 139d	
2014	Spectral analysis (θ_{13} and Δm^2), 217d nH rate analysis, 217d Sterile neutrino, 217d	
2015	Full 8AD oscillation analysis, 621d	AD1 Flash-ADC upgrade in Dec.
2016	Reactor flux & spectrum, 217d Improved nH, 621d Improved sterile nu, 621d Combined sterile with MINOS, 621d	
2017	Long reactor paper, 621d Long osc. paper, 1230d Fuel evolution, 1230d	Calibration campaign in Jan. AD1 taken out for LS study in Jan.
2018	Muon flux variation Cosmogenic neutron production Long osc. Paper, 1958d New reactor flux, 1230d Time-varying antineutrino signal Individual antineutrino spectra, 1958d	

Absolute spectrum for ^{235}U

- Compare with the model prediction without normalization
  - 8% deficit in the entire range
  - 11% deficit below 4MeV



The Daya Bay collaboration



Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Chongqing 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