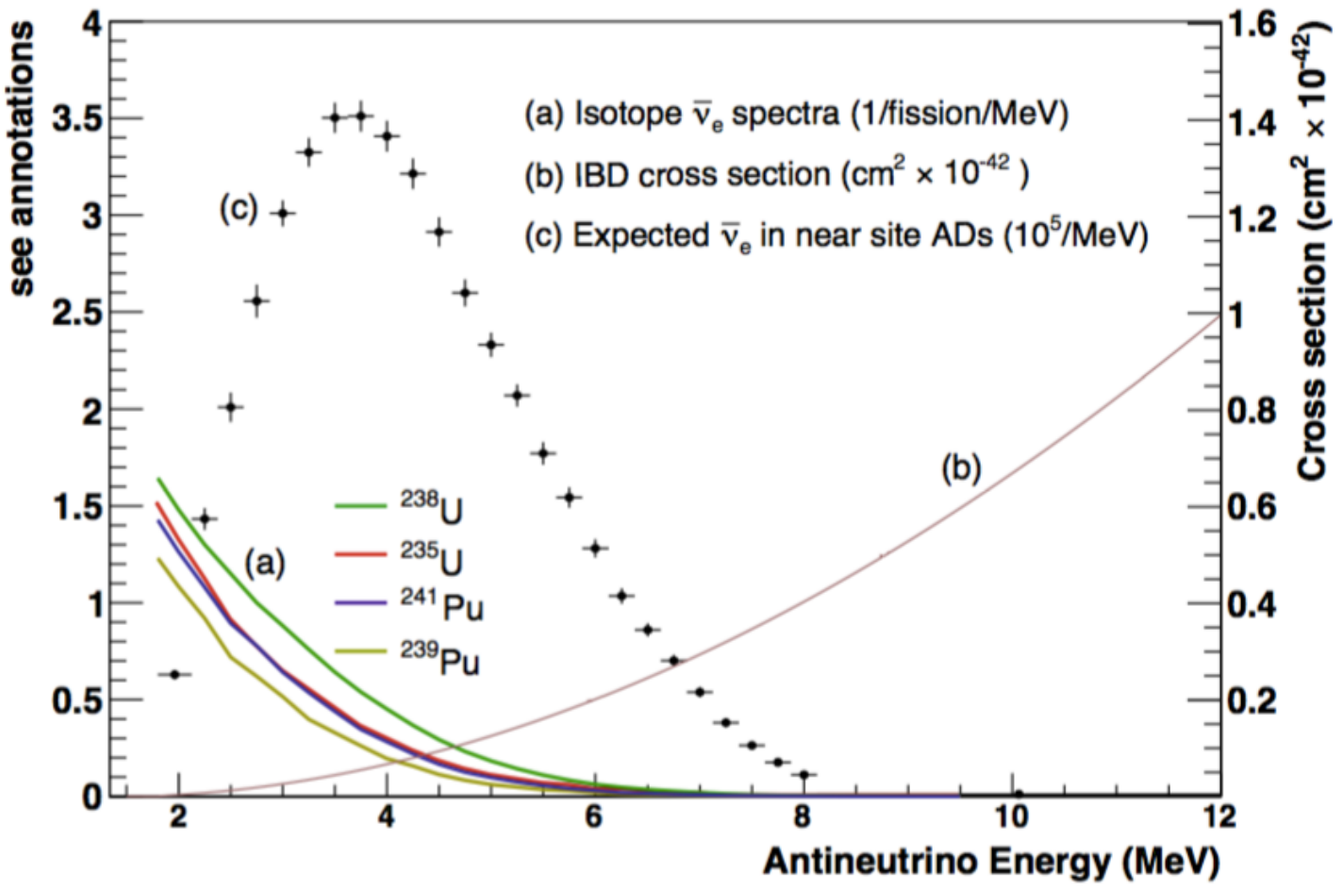
Phys. Rev. Lett. **118**, 251801

Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay

Patrick K.V. Tsang (SLAC)

EPS 2017

Reactor Antineutrino



>99.9% antineutrinos are the fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

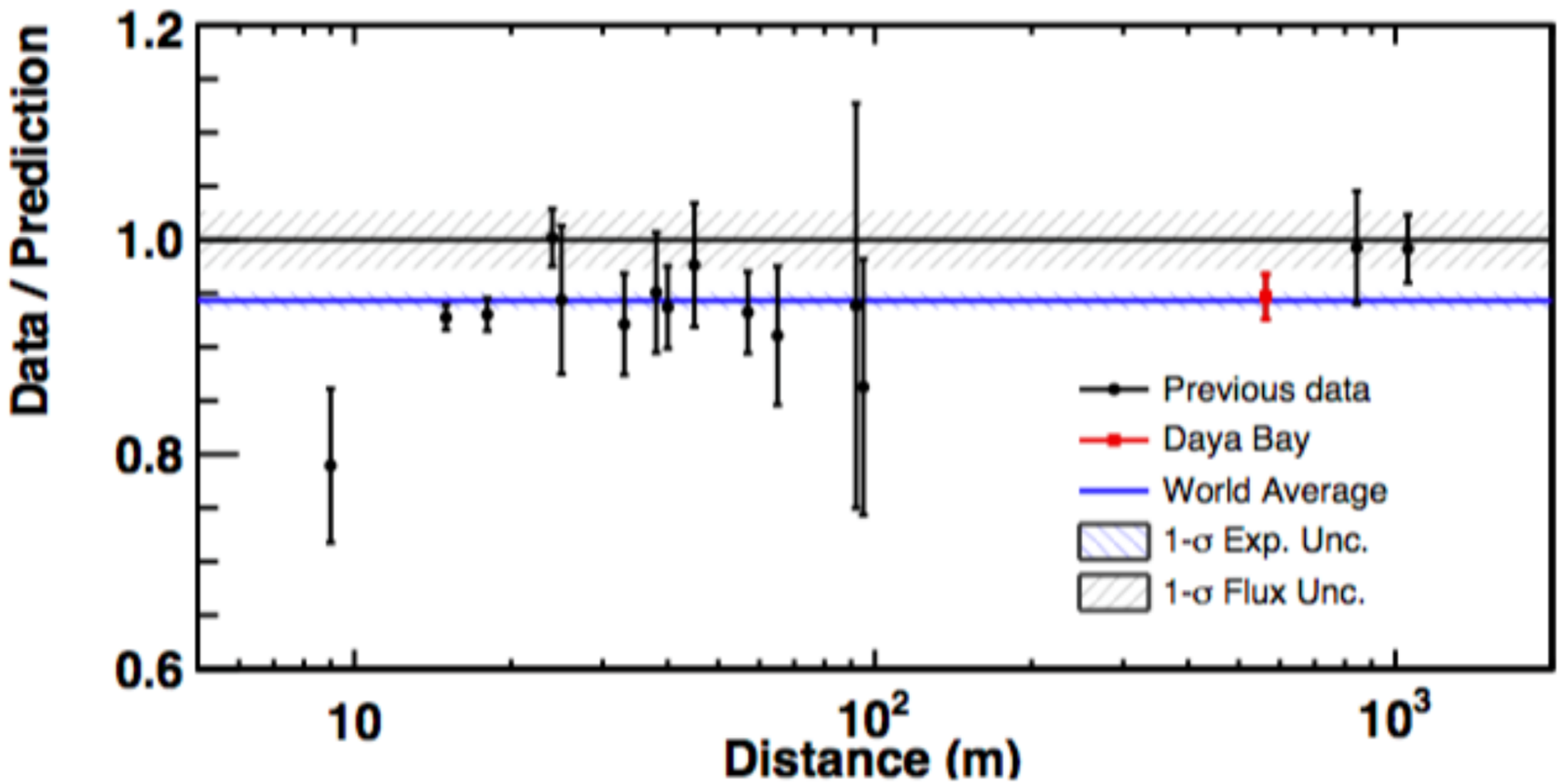
O(10^{20}) fissions / second

~6 antineutrinos / fission

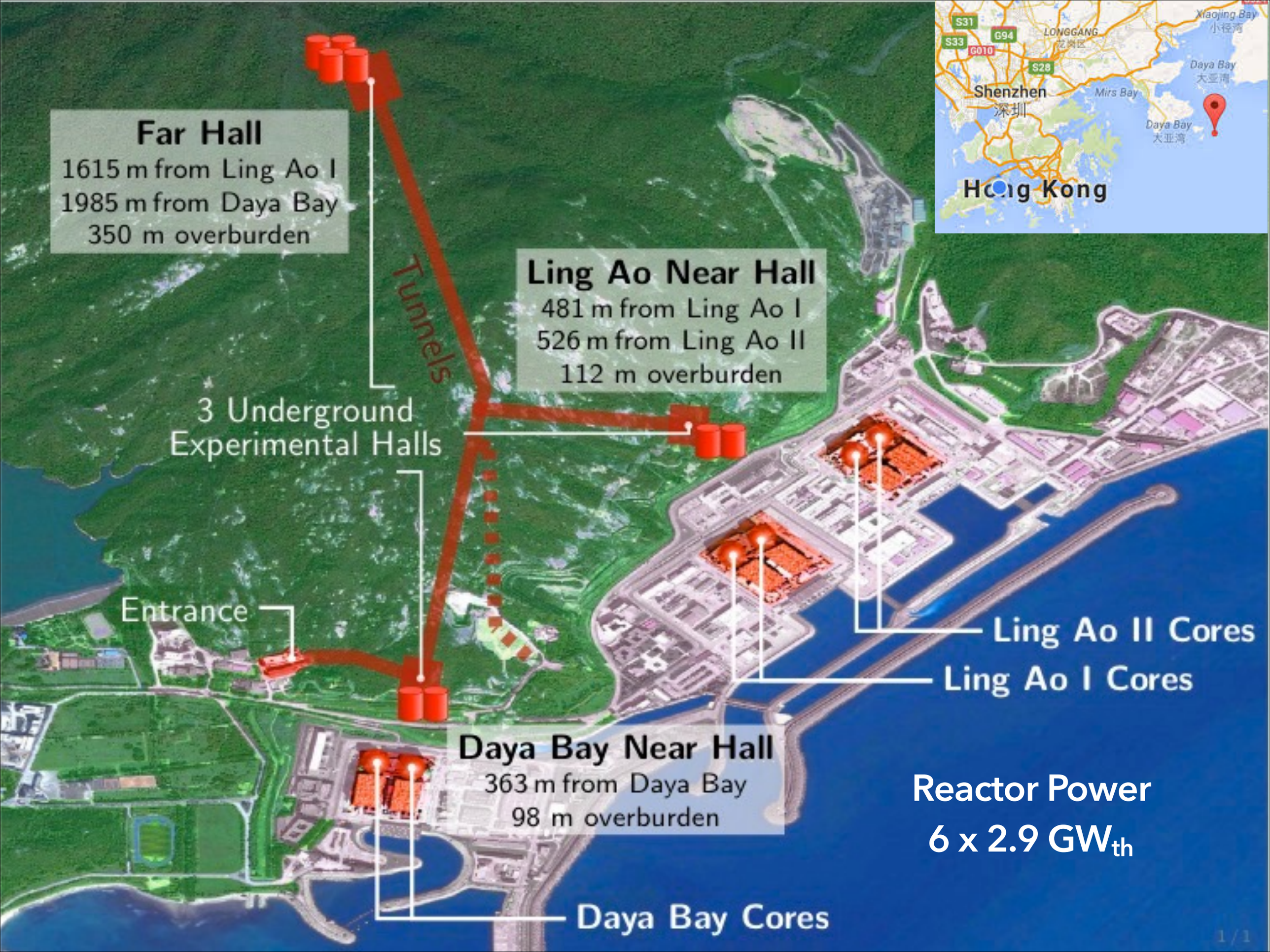
Most powerful man-made neutrino source

Reactor Antineutrino Anomaly
Missing Reactor Antineutrinos?

R_{DYB} = 0.946 ± 0.020 (exp.)
R_{ALL} = 0.943 ± 0.08 (exp.) ±0.023 (model)



Daya Bay is consistent with past reactor anti-nu experiments.
Huber-Mueller model over-estimated the flux by **~6%**


Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
Tunnels
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
Daya Bay Cores
Reactor Power
6 x 2.9 GW$_{th}$
S31
S33
G94
G010
S28
LONGGANG
Shenzhen
深圳
Mirs Bay
Daya Bay
大亚湾
Xiaojing Bay
小径湾
Hong Kong

Antineutrino Detectors (ADs)

Inverse ß-decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

Prompt positron

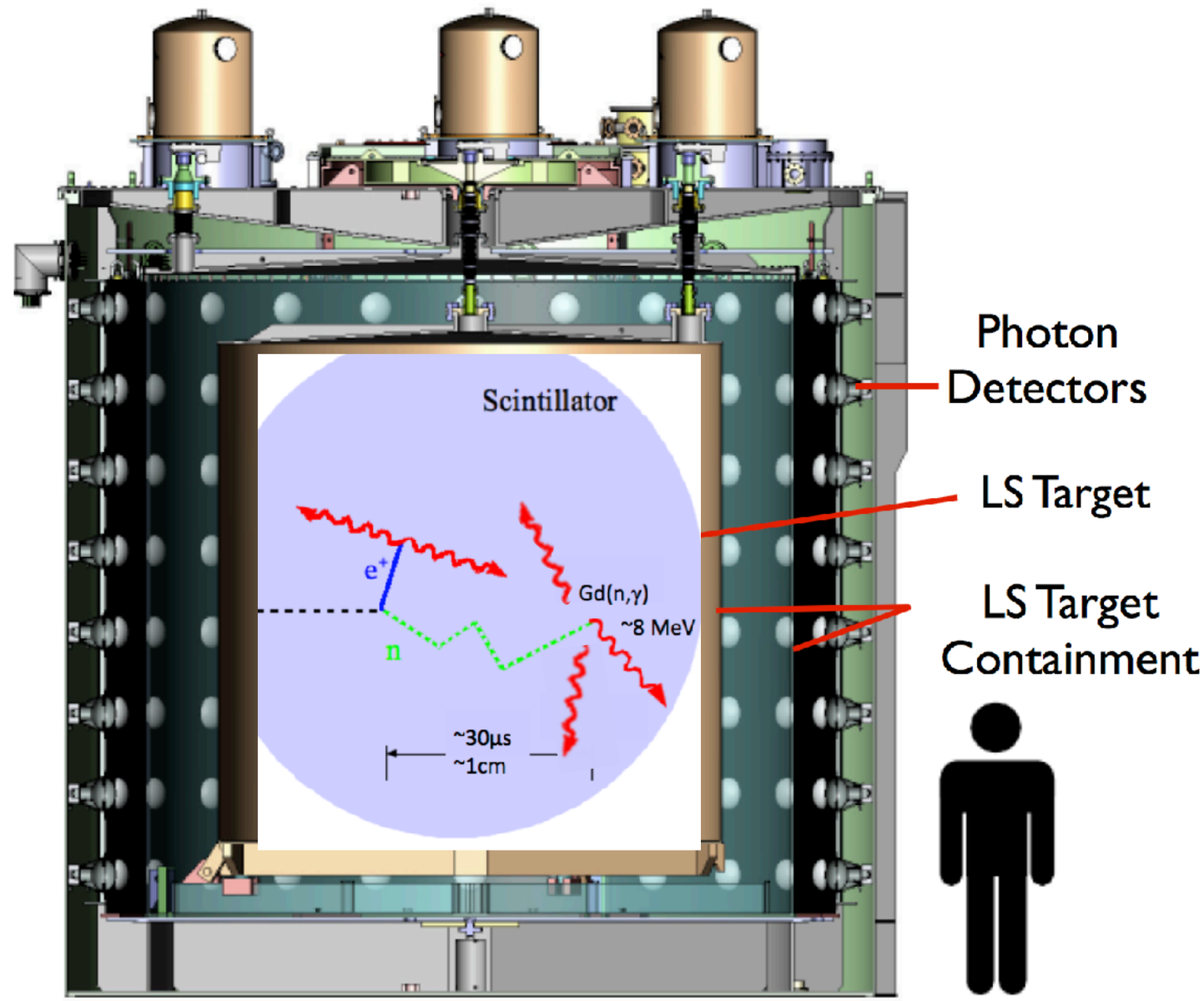
Carries antineutrino energy

$E_{e+} \approx E_{\nu}$ - 0.8 MeV

Delayed neutron capture

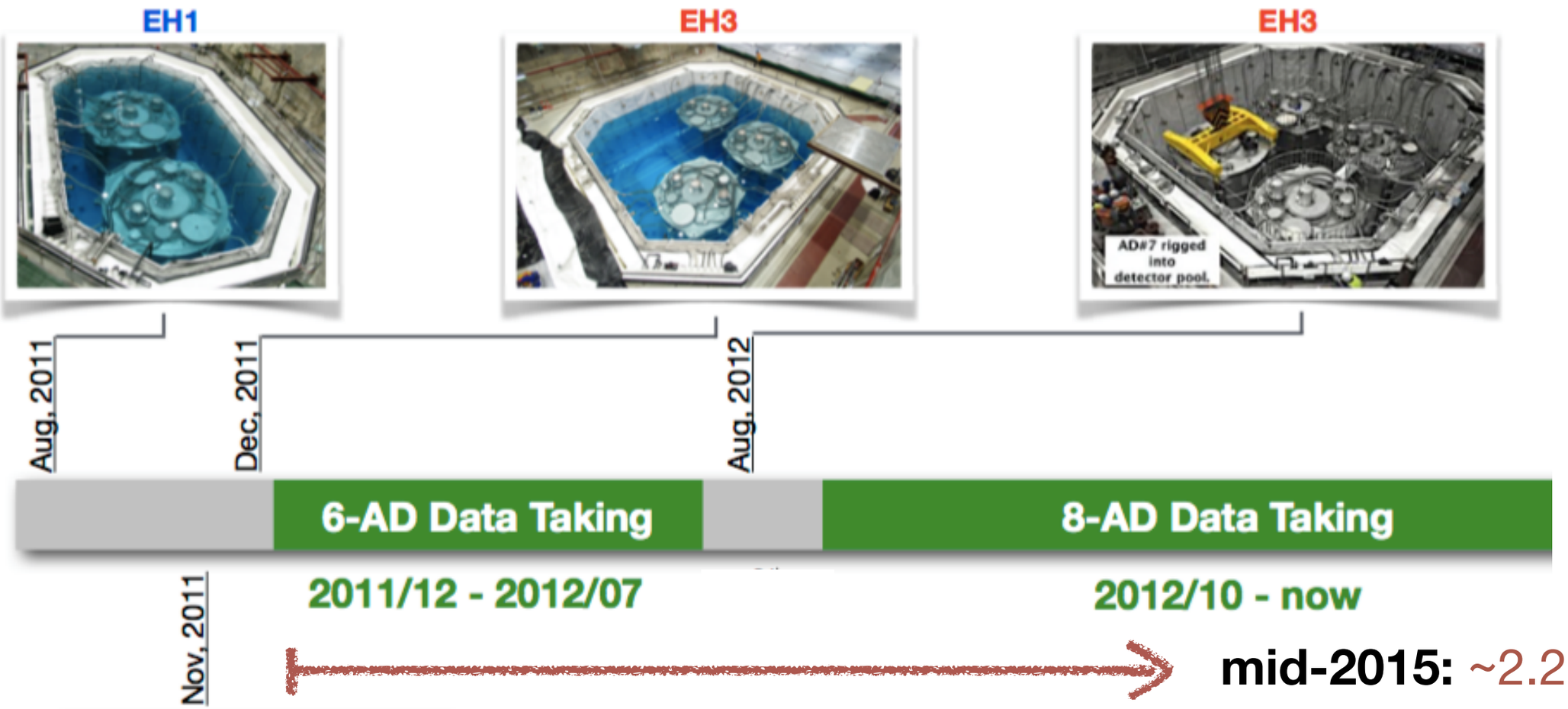
~30 μs for 0.1% Gd

Allows tagging a high purity sample of antineutrinos

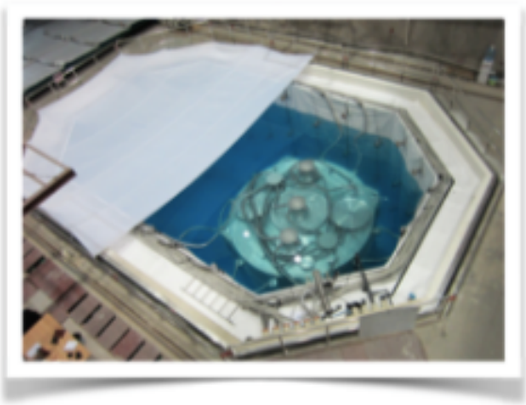


Example: Daya Bay Detector

Daya Bay: Largest Sample of $\overline{\nu}_e$ Interactions



mid-2015: ~2.2M candidates at the near sites

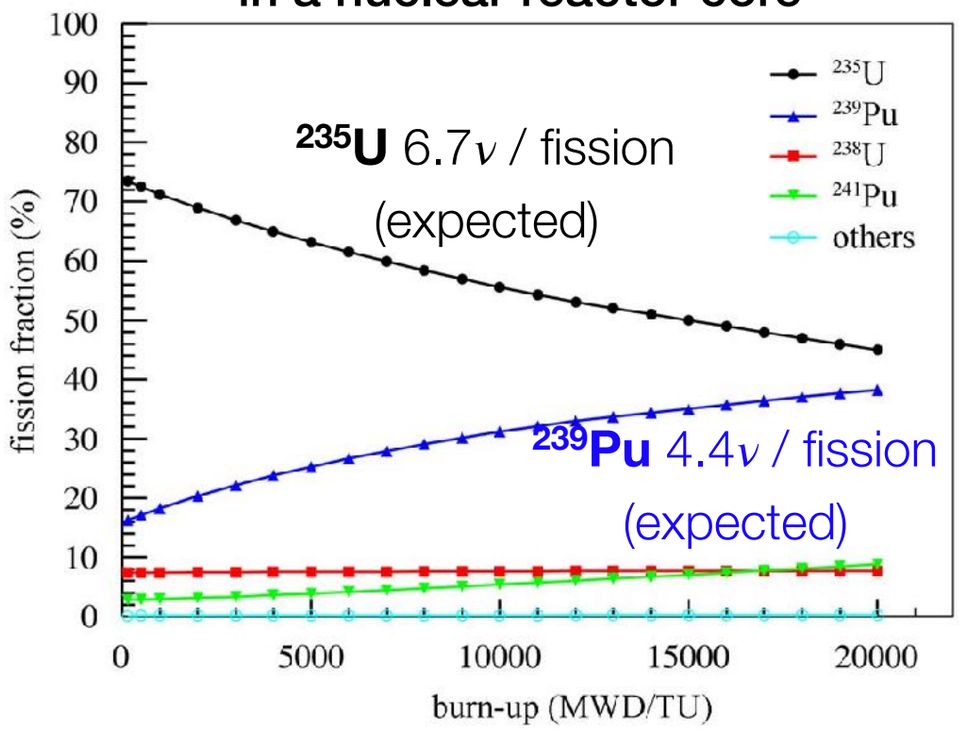


EH2

Daya Bay @ EPS 2017
Sterile neutrino search, X. Qian (talk)
Oscillation results, M.C. Chu (poster)
Lorentz Violation search, A. Higuera (poster)
Cosmogentic neutron production, J. Cheng (poster)

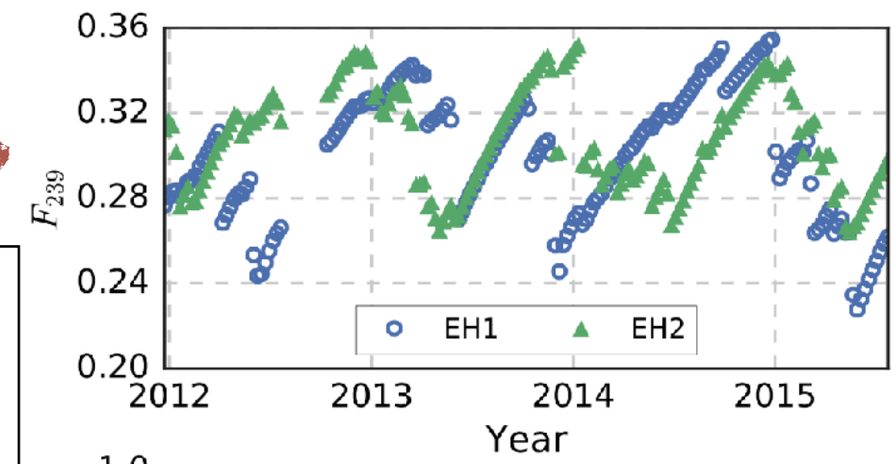
Evolution of Reactor $\overline{\nu}_e$ Flux

Evolution of fission fractions in a nuclear reactor core

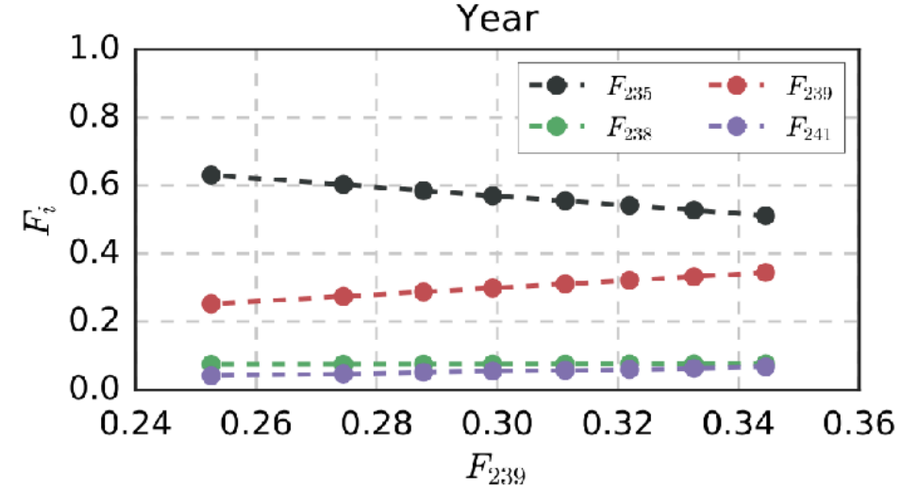


Weighted over 6 reactor cores

Effective fission fraction (Daya Bay)



Binned in 8 groups



- Fuel composition evolves over time
- Expected more anti-ν produced from ^{235}U fission chain than ^{239}Pu

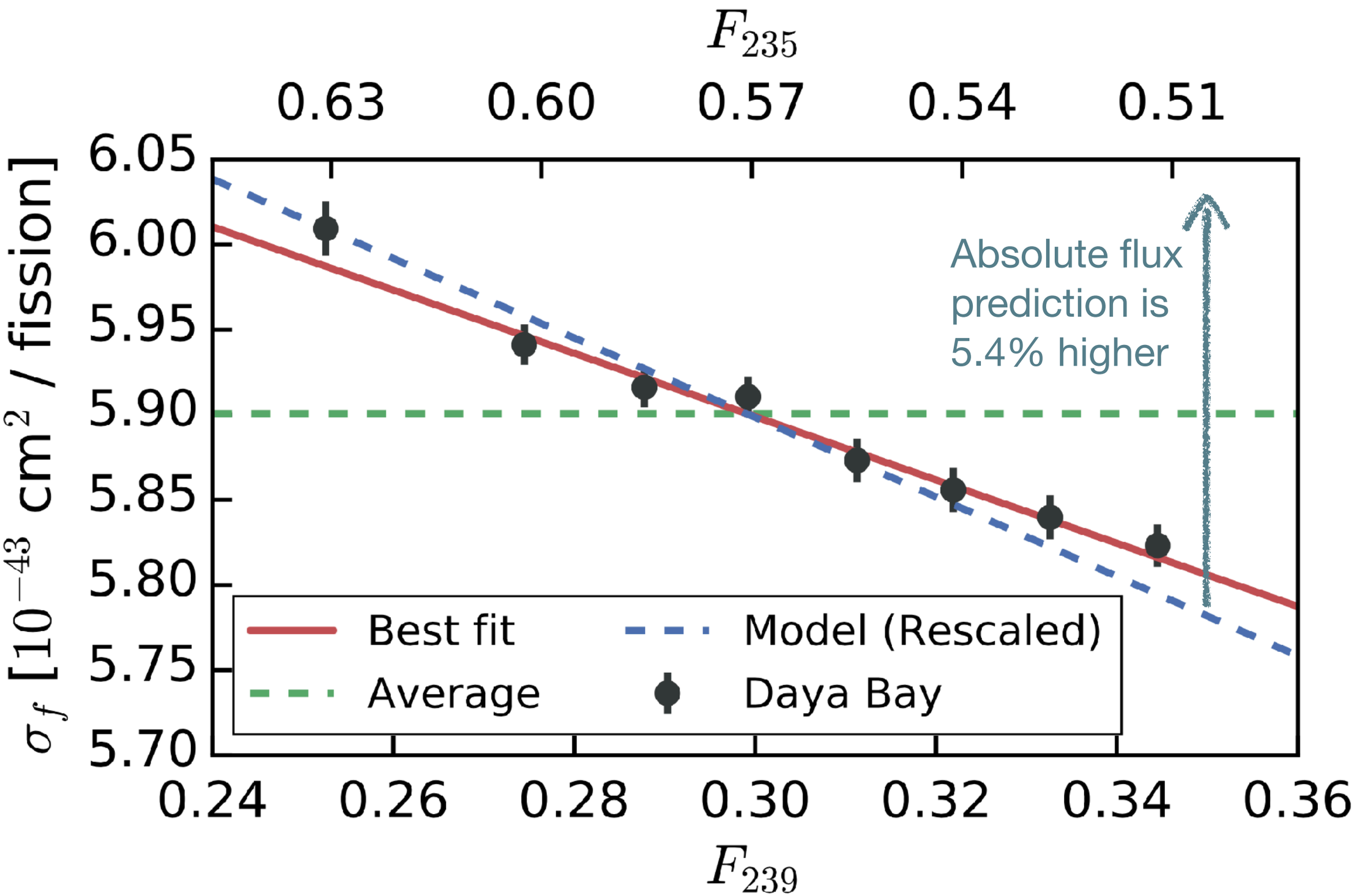
⇒ Changes in anti-*ν* flux

Effective fission fraction (F_i)

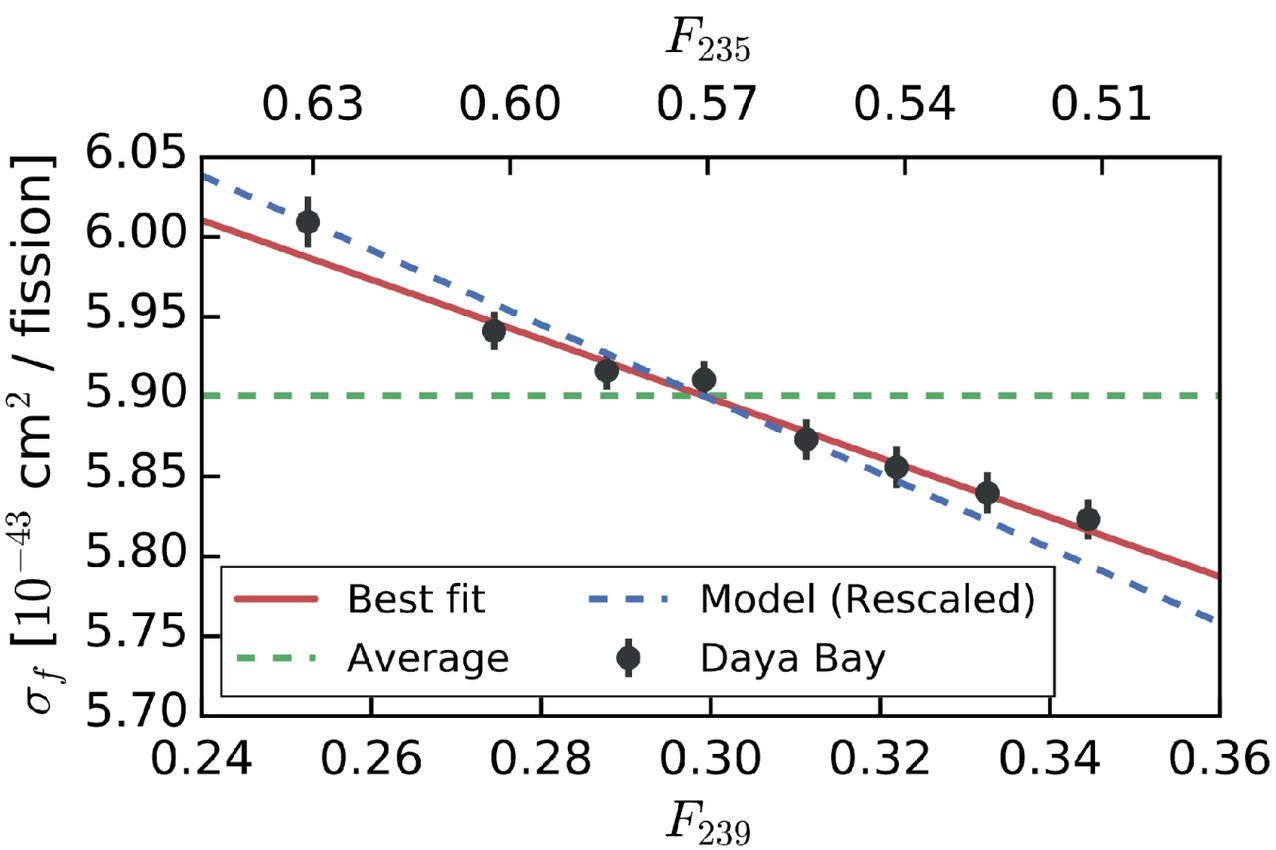
Weighted by power (*W*), survival probability (*p*), baseline (*L*) over 6 reactor cores

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

Daya Bay Results
Unambiguous Fuel-dependent Variation (at 10 s.d.)



Daya Bay Results
Flux Evolution (cont.)



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

Daya Bay Results
Fits to Individual Isotopes ^{235}U & ^{239}Pu

Assume loose (*10%*) uncertainties on sub-dominant ^{238}U & ^{241}Pu (central values taken from Huber-Mueller model)

<u>Daya Bay</u>

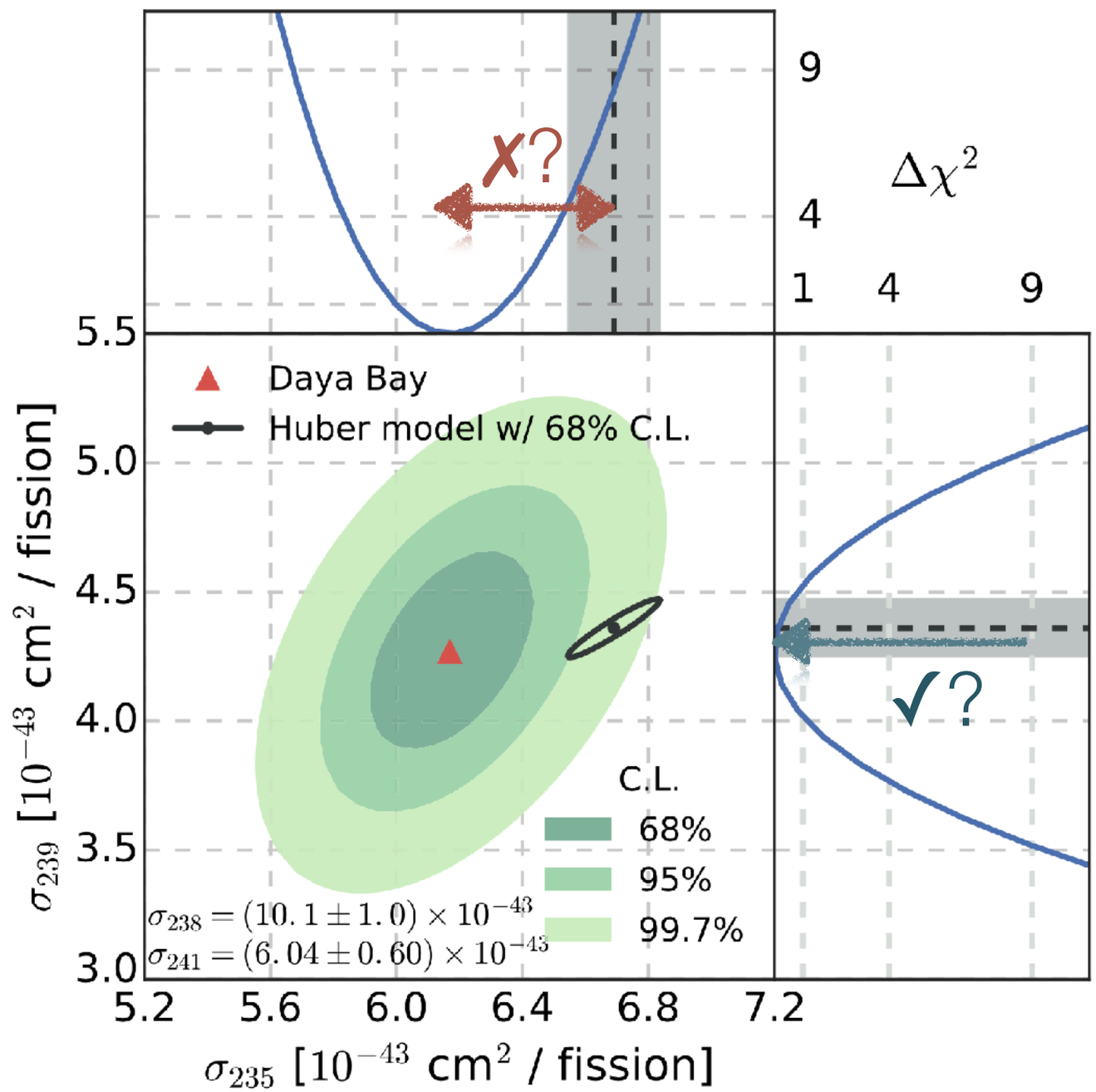
$\sigma_{235} = 6.17 \pm 0.17$

$\sigma_{239} = 4.27 \pm 0.26$

<u>Huber-Mueller model</u>

$\sigma_{235} = 6.69 \pm 0.15$

$\sigma_{239} = 4.36 \pm 0.11$



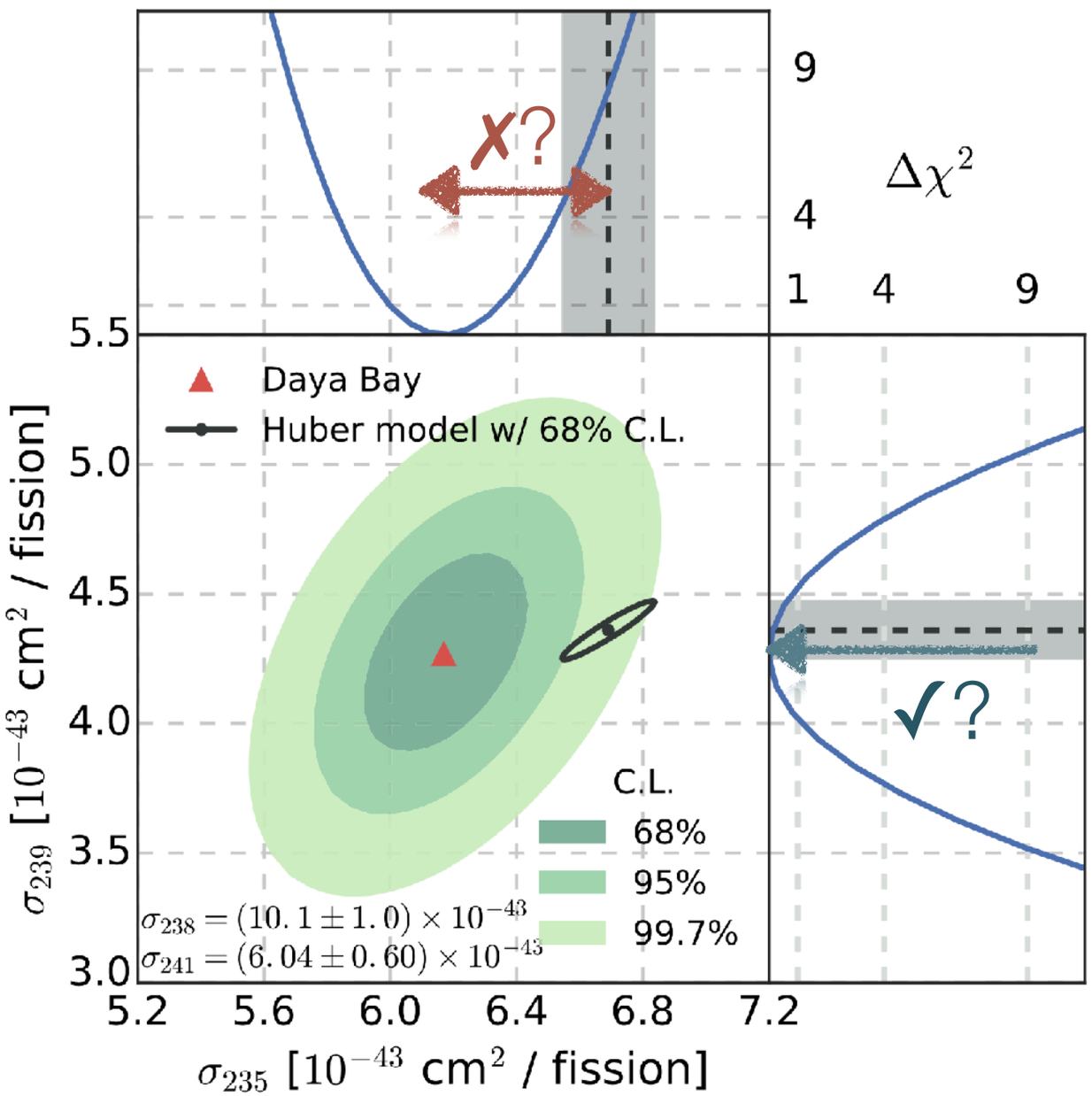
Overestimated contribution from ^{235}U?

Daya Bay Results
Fits to ^{235}U & ^{239}Pu (cont.)

Possible explanations to the reactor antineutrino anomaly:

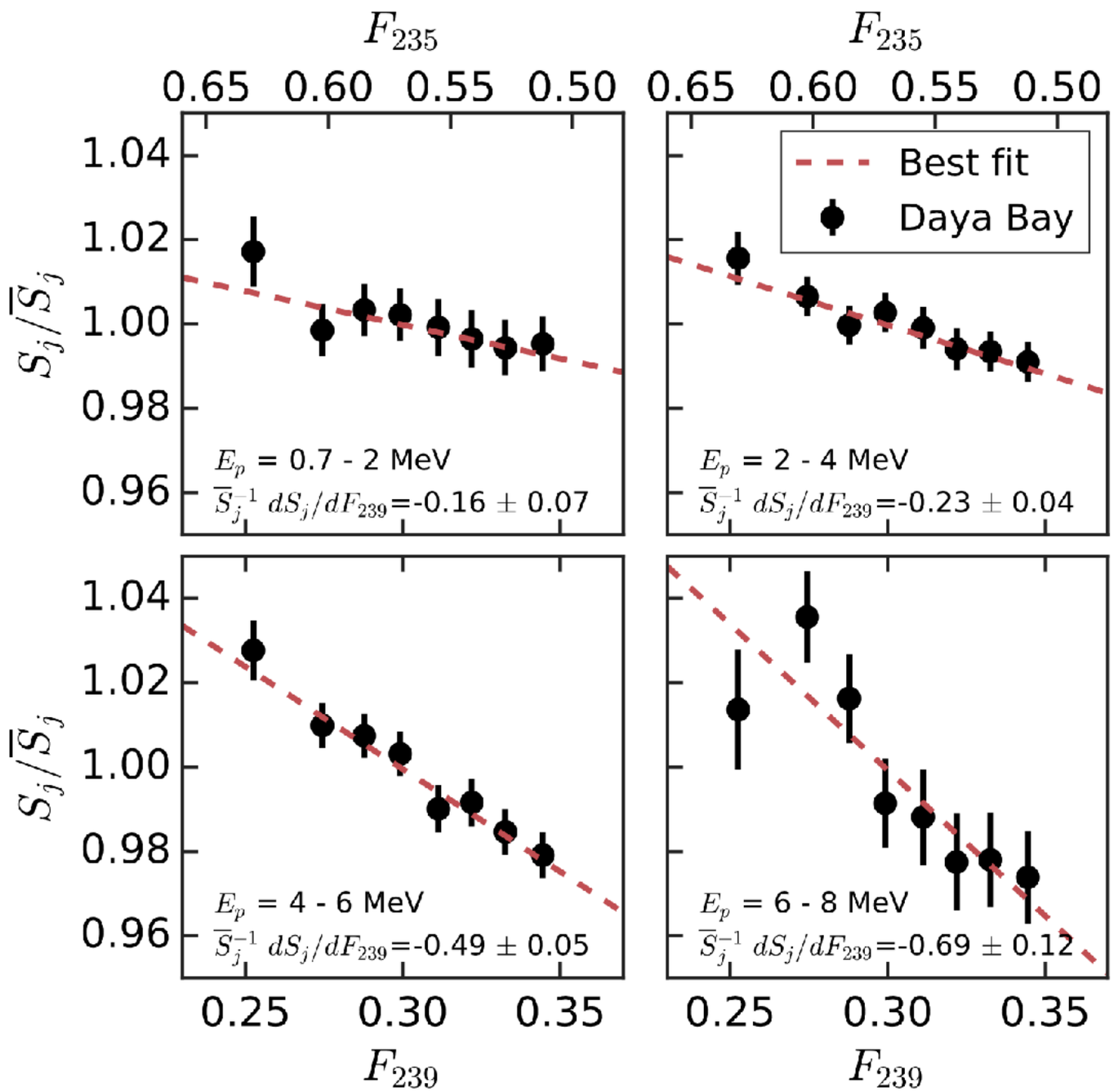
1. solely incorrect prediction on ^{235}U
   - favored by Daya Bay data with (2-side) p-value 0.68
2. solely incorrect prediction on ^{239}Pu
   - disfavored at 3.2σ C.L.
3. equal deficit on all isotopes
   - disfavored at 2.8σ C.L.

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

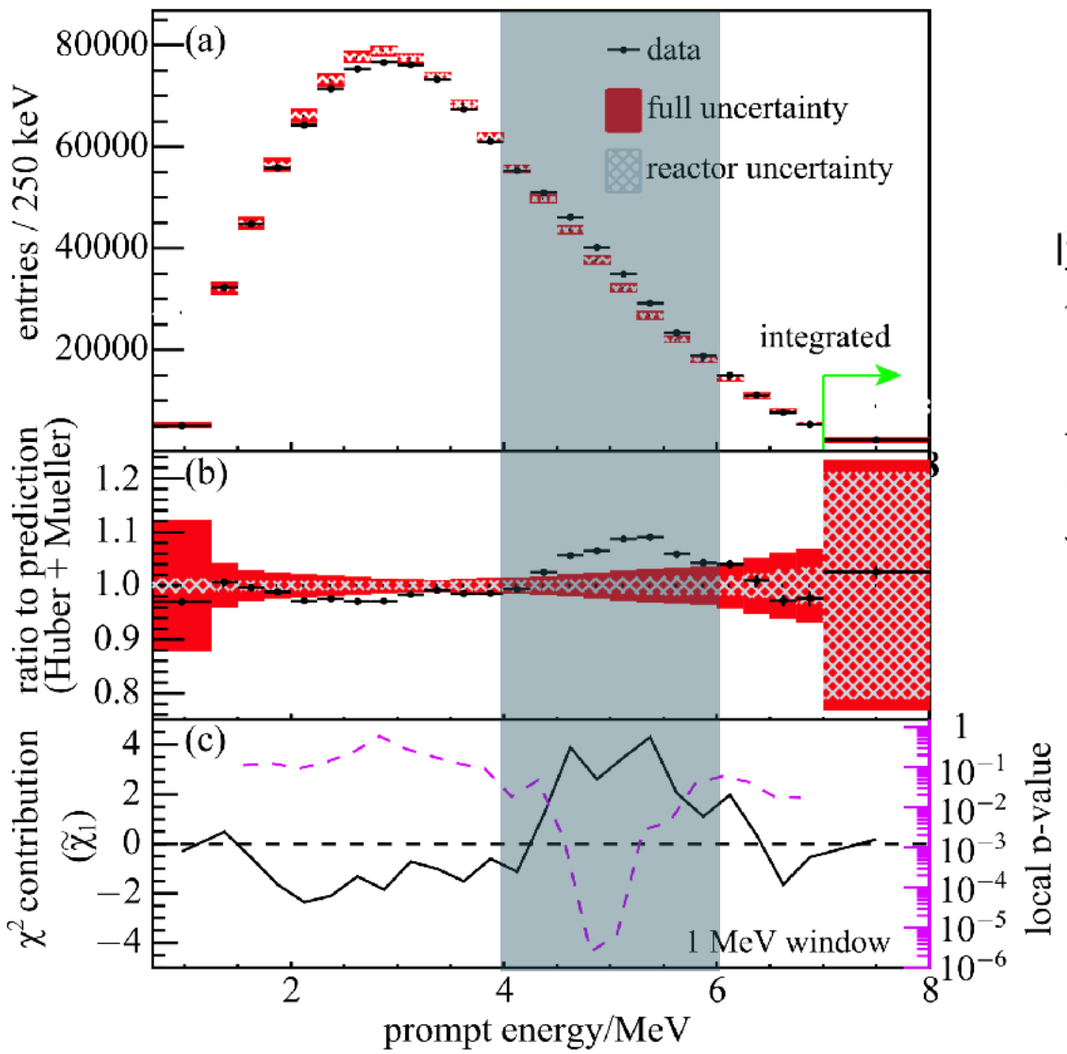


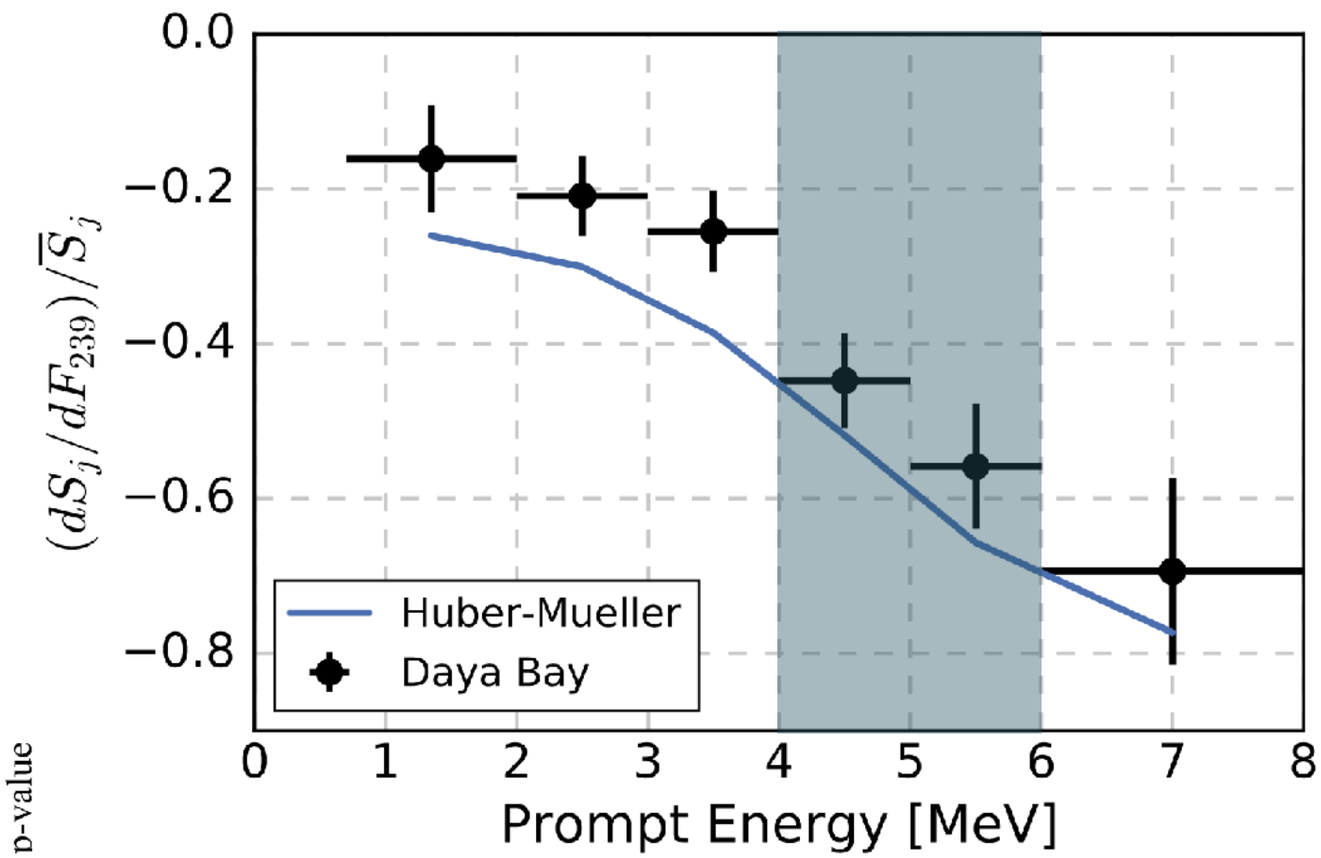
Daya Bay Results
Evolution of Energy Spectrum

- Same analysis in 4 different energy bins
- Energy-dependent evolution is observed
  - change in spectral shape as fuel composition evolves
  - first unambiguous measurements of this behavior
  - excluded no spectral change hypothesis by 5.1σ



Daya Bay Results
How about the spectral discrepancy?





No major indication that ‘bump’ data-model discrepancy comes from a particular isotope.

Conclusions

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- Daya Bay observed unambiguous flux and energy spectrum variations w.r.t. fuel composition evolution
- Daya Bay data suggests an overestimation antineutrino flux from 235U in reactor models
  - might explain the reactor antineutrino anomaly
- Improvements in systematic uncertainties (e.g. detection efficiency) and increase in statistics could further strengthen the claim