Reactor Neutrino Flux and Spectrum

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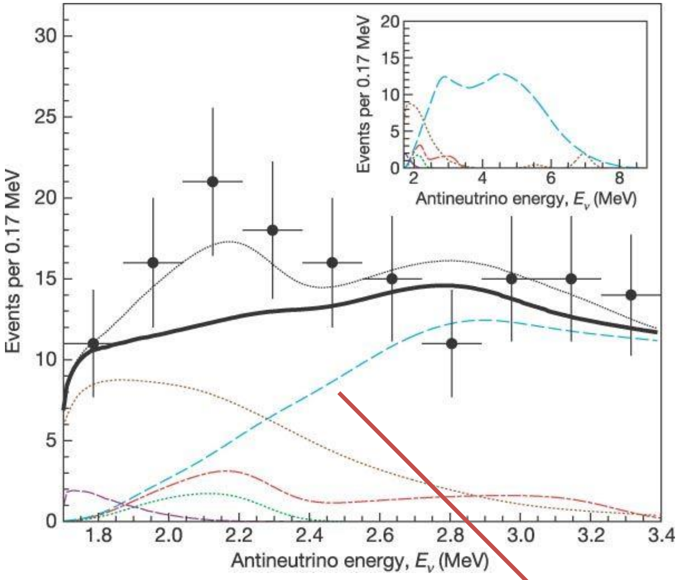
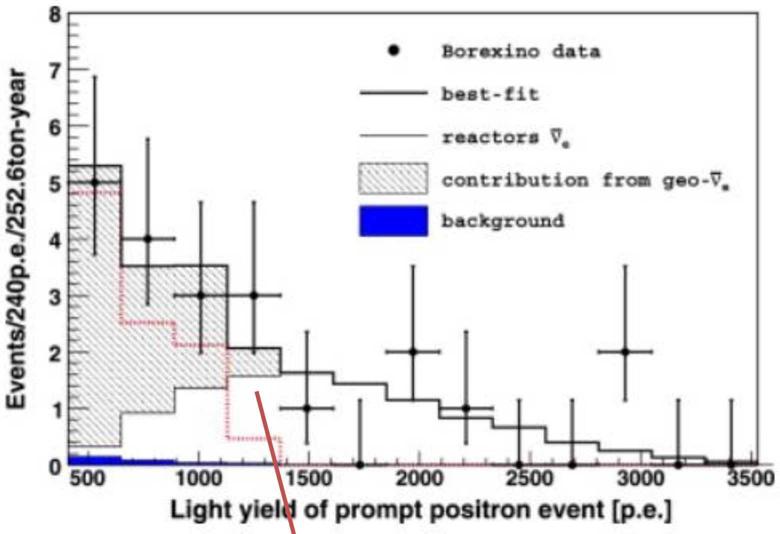
On behalf of the Daya Bay Collaboration

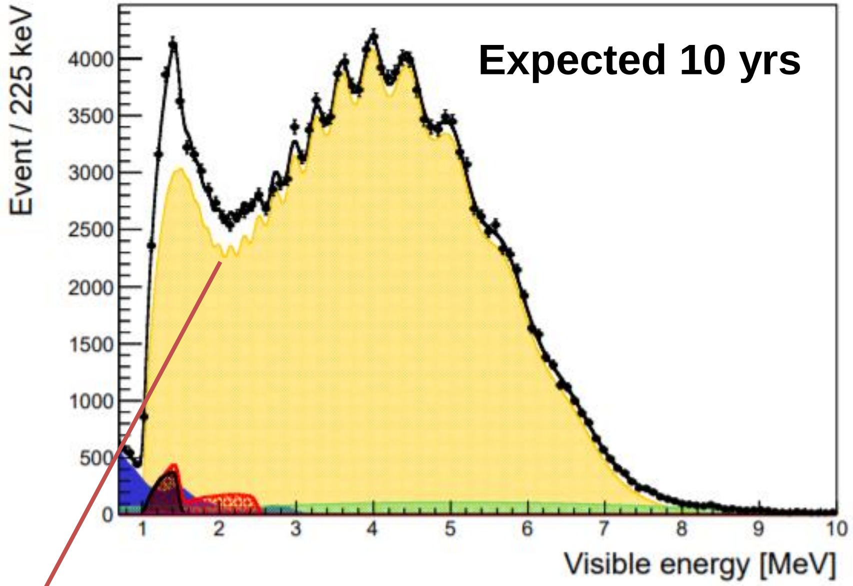
Reactor Neutrino: Largest Background to Geoneutrino



KamLAND, *Nature* **436**, 499 (2005)



Borexino, *Phys Lett B* ***687***, 299 (2010)



JUNO, *J. Phys. G* **43**, 030401 (2016)

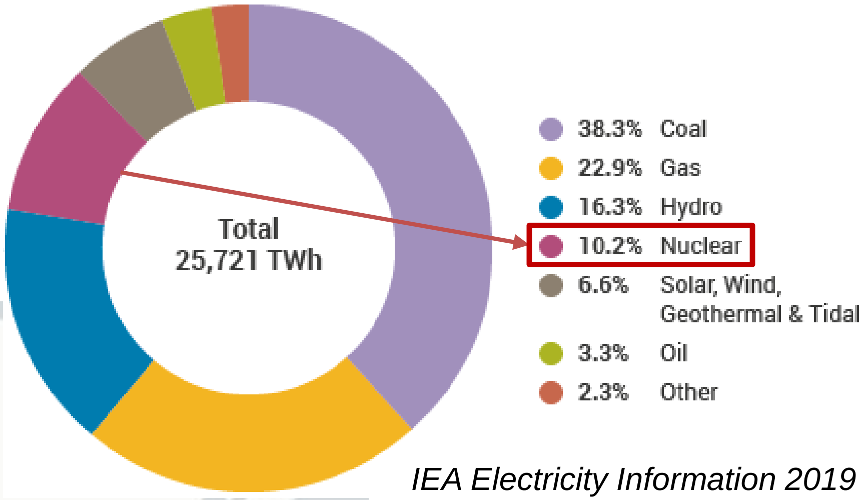
Reactor Neutrinos!

Calculate yourself: how much reactor neutrino background does my geoneutrino experiment have?

https://geoneutrinos.org/reactors/

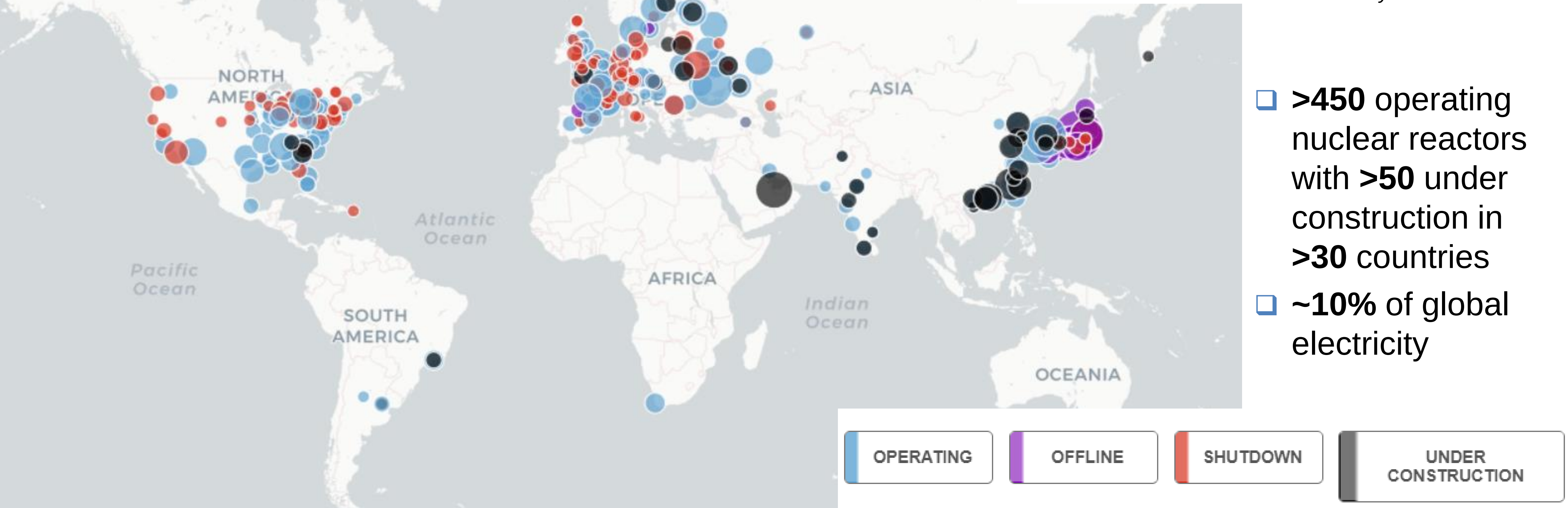
Barna, A.M. and Dye, S.T., "Web Application for Modeling Global Antineutrinos," arXiv:1510.05633 (2015).

Global Nuclear Reactor Distribution



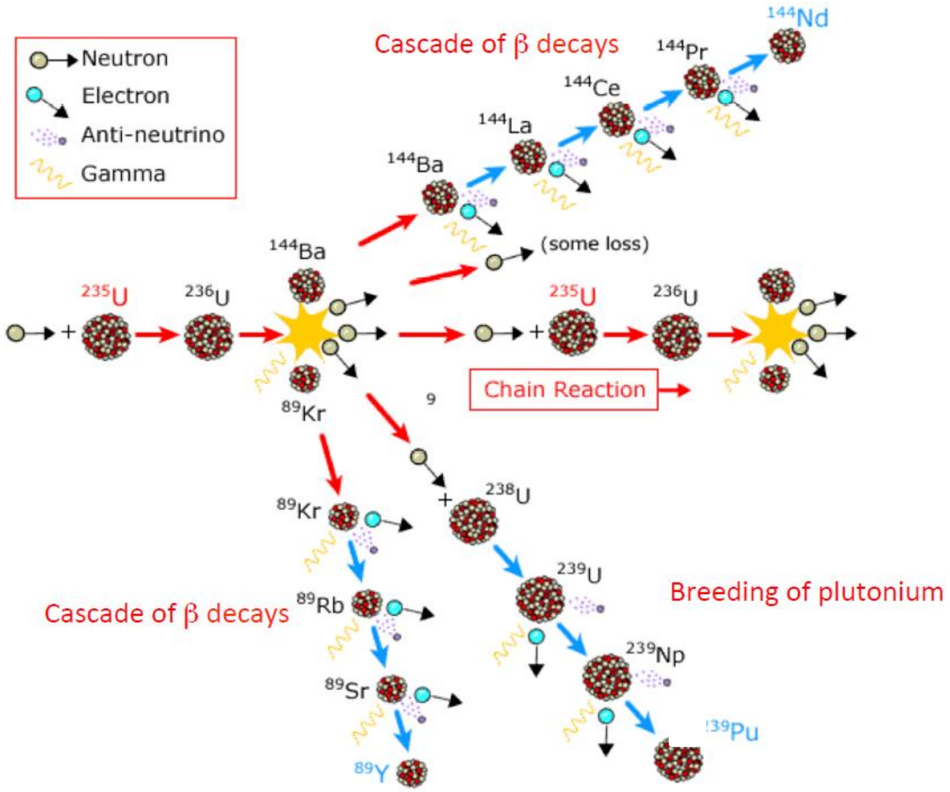
IEA Electricity Information 2019

https://www.carbonbrief.org/mapped-the-worlds-nuclear-power-plants

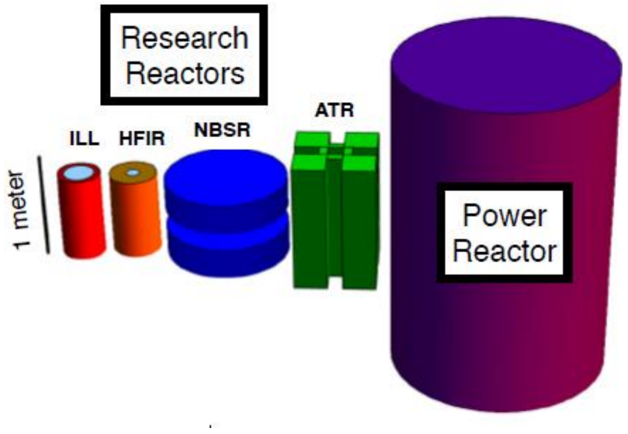


- ❑ **>450** operating nuclear reactors with **>50** under construction in **>30** countries
- ❑ **~10%** of global electricity

Nuclear Reactor as Antineutrino Source

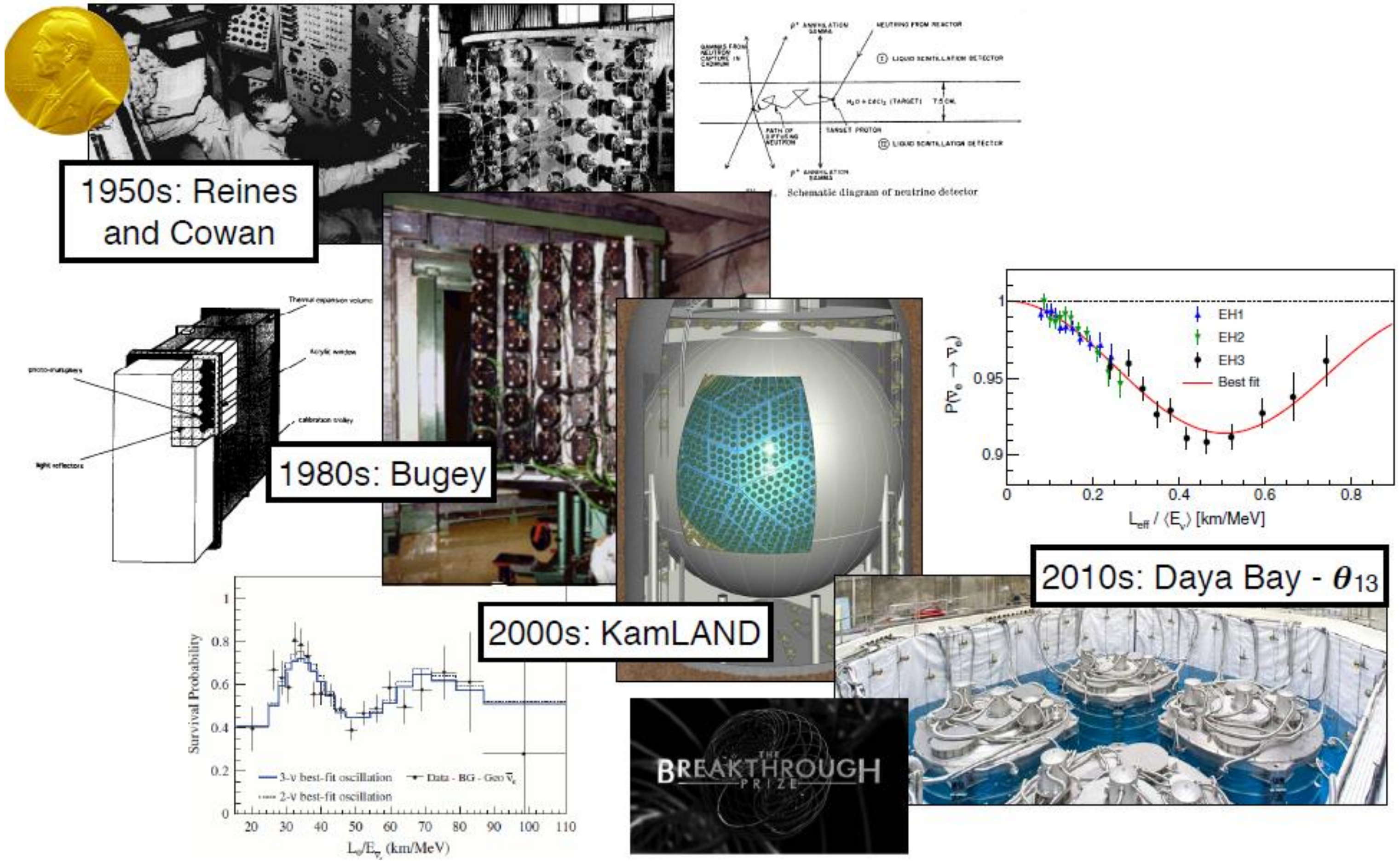


- ❑ Nuclear reactors produce pure $\overline{\nu}_e$ from beta decays of fission daughters
  - Low energy: < 10 MeV
- ❑ ~6 $\overline{\nu}_e$ / fission
- ❑ 2 x 10^{20} $\overline{\nu}_e$ / sec per GW_{th} (free for physicists)



- ❑ Commercial reactors in Nuclear Power Plants have low-enriched uranium (LEU) cores
  - Mixture of fissions: ^{235}U (~55%), ^{239}Pu (~30%), ^{238}U (~10%), ^{241}Pu (~5%)
  - Large power: ~3 GW_{th}
- ❑ Research reactors have highly-enriched uranium (HEU) cores
  - ^{235}U fission fraction ~99%
  - Lower power, few tens of MW_{th}
  - compact size

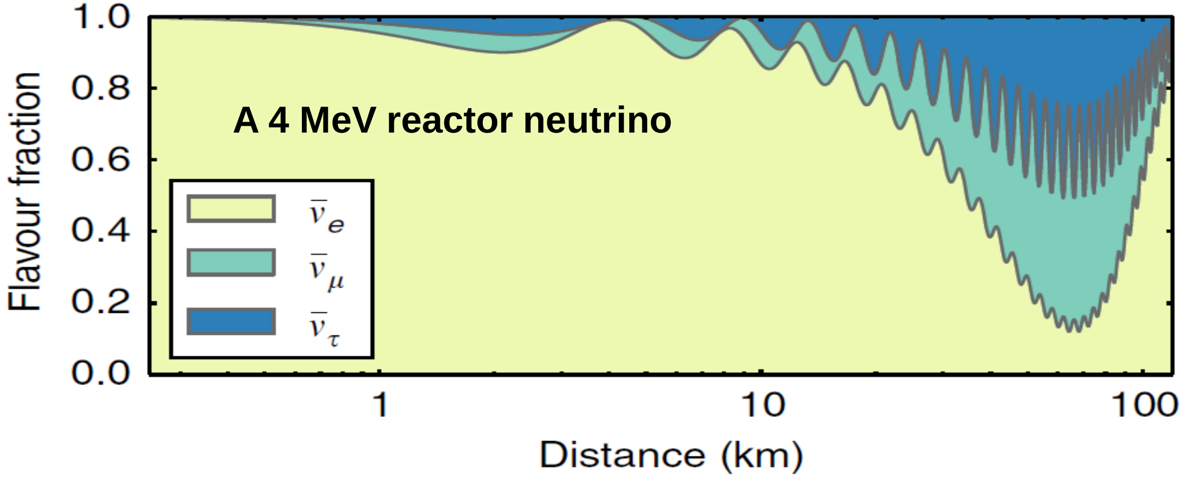
History of Reactor Neutrino Experiments



- Discovery of ν
- Solving solar ν problem on Earth
- Discovery of smallest oscillation angle θ_{13}
- Currently hold the best precision of
  - Δm^2_{21} (KamLAND)
  - θ_{13} (Daya Bay)
- Comparable precision to accelerator-based experiments
  - $|\Delta m^2_{32}|$ (Daya Bay)

Neutrino Oscillations

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - 4 s_{13}^2 c_{13}^2 \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32} \right) - 4 c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}$$



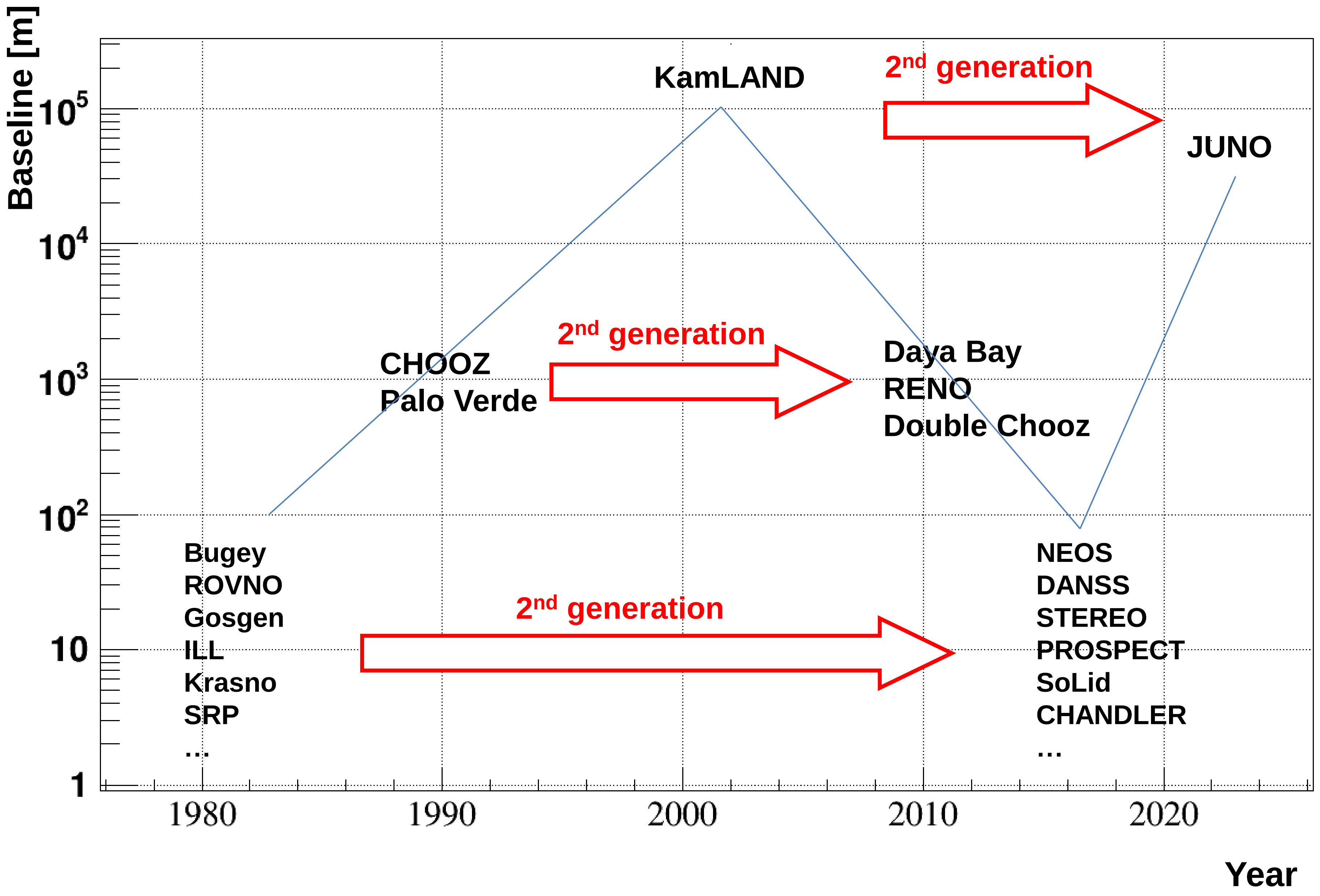
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\downarrow$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{pmatrix}$$

Atmospheric / Long baseline accelerator	Short baseline reactor / Long baseline accelerator	Solar / Long baseline reactor	Neutrinoless double beta decay

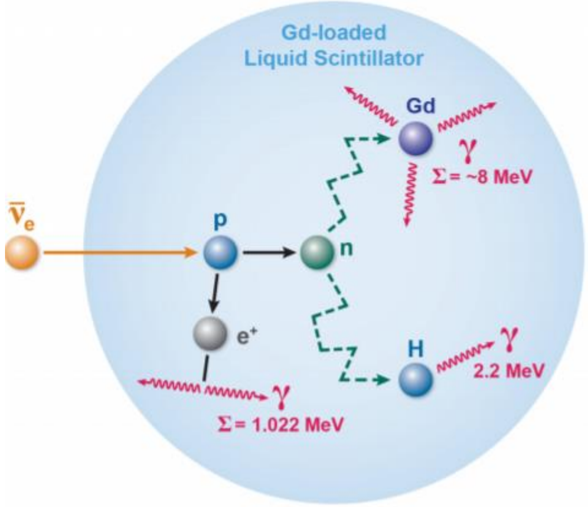
- ❑ Fundamental properties of neutrinos due to quantum mixture of mass eigenstates
- ❑ For geoneutrino: important to correctly predict reactor neutrino flux at distances



New generation of reactor neutrino experiments

- ☐ Precision measurement of neutrino oscillation parameters
- ☐ Search for new oscillation from sterile neutrinos
- ☐ Precision measurement of reactor neutrino flux and spectrum

Measure Reactor Antineutrino Spectrum



Inverse Beta Decay (IBD)

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

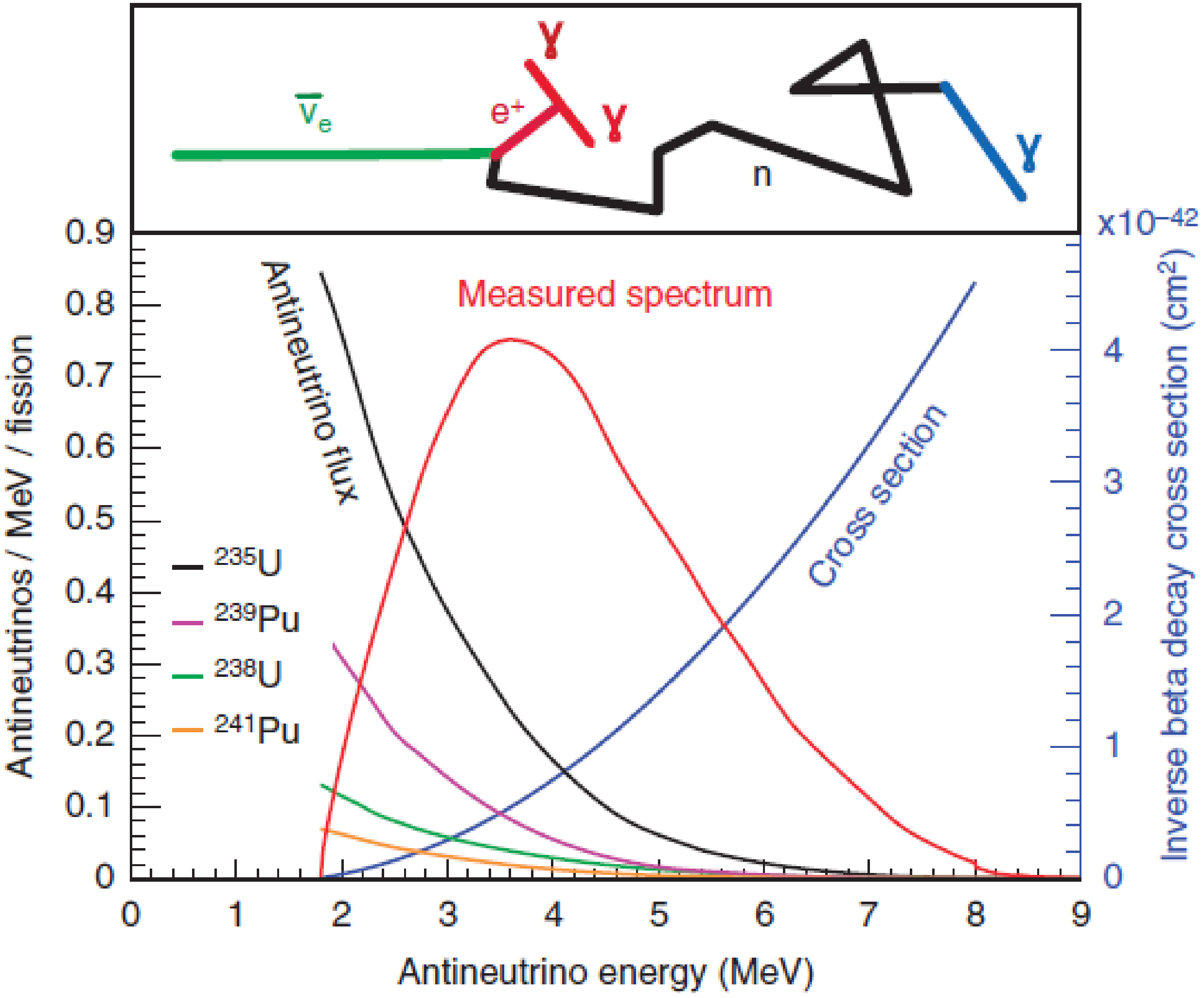
$$n + p \rightarrow D + \gamma$$ 2.2 MeV

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s$$ 8/8.5 MeV 30 μs

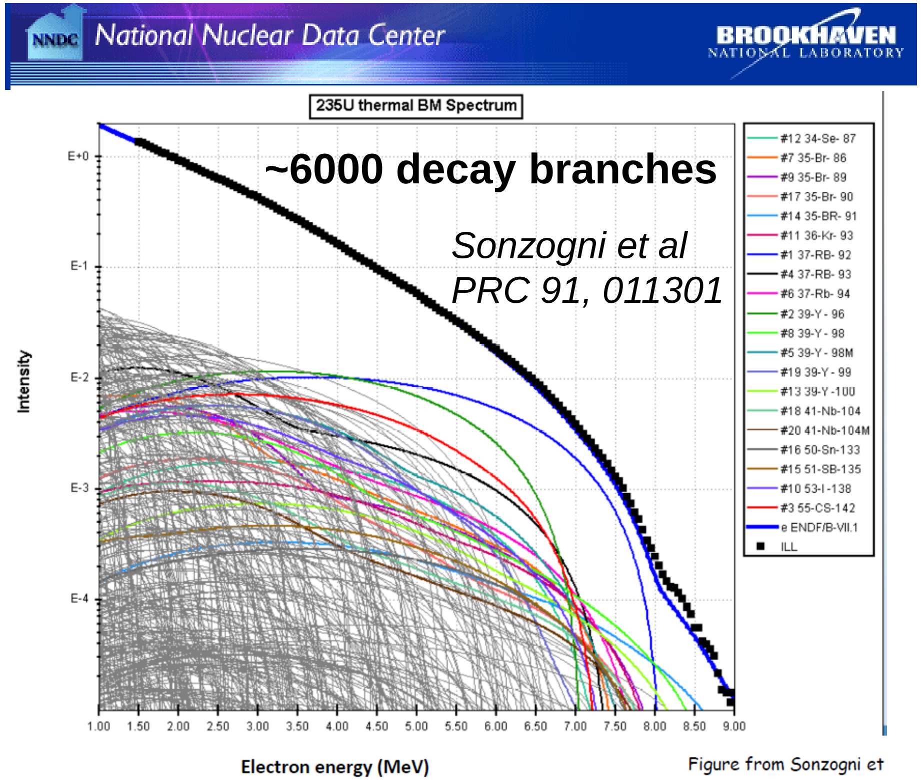
$$\mathbf{S(E_\nu) = c \cdot \sum_i f_i \cdot s_i\,(E_\nu) \cdot \sigma(E_\nu)}$$

- c: reactor thermal power, energy released per fission, baseline, target protons, detection efficiency, oscillation, etc.
- f_i: isotope fission fraction
- $s_i(E_\nu)$: isotope neutrino spectra
- $\sigma(E_\nu)$: IBD cross section

Nature Communications 6, 6935 (2015)



Reactor Models



~6000 decay branches

Sonzogni et al PRC 91, 011301

Figure from Sonzogni et

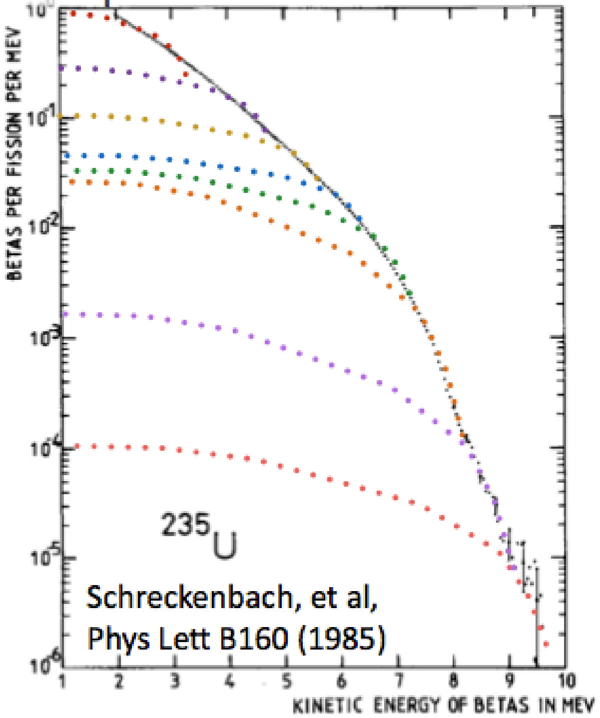
❑ Summation (*ab initio*) method

- Calculate the spectrum of each beta-decay branch using **nuclear databases**: <u>fission yields</u>, <u>decay schemes</u>
- ~10% uncertainty

❑ Conversion Method

- Measure total outgoing beta-decay electron energy spectra. (*Experiments done for ^{235}U, ^{239}Pu, ^{241}Pu at ILL in the 1980s*)
- Predict corresponding anti-neutrino spectra with >30 virtual branches
- Default model by most reactor neutrino experiments
  - Considered to be more precise: ~2.5% uncertainty

Example: Fit virtual beta branches

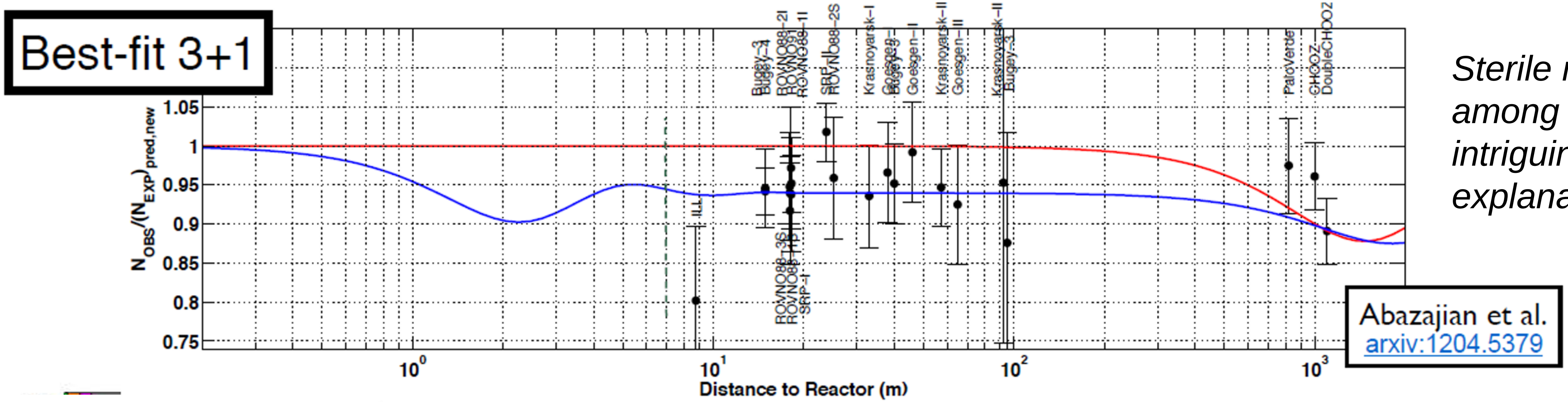


Schreckenbach, et al, Phys Lett B160 (1985)

❑ Recent re-analyses in 2011 increased prediction by ~5%

- Conversion +3%
- Neutron lifetime +1%
- Non-equilibrium isotopes +1%

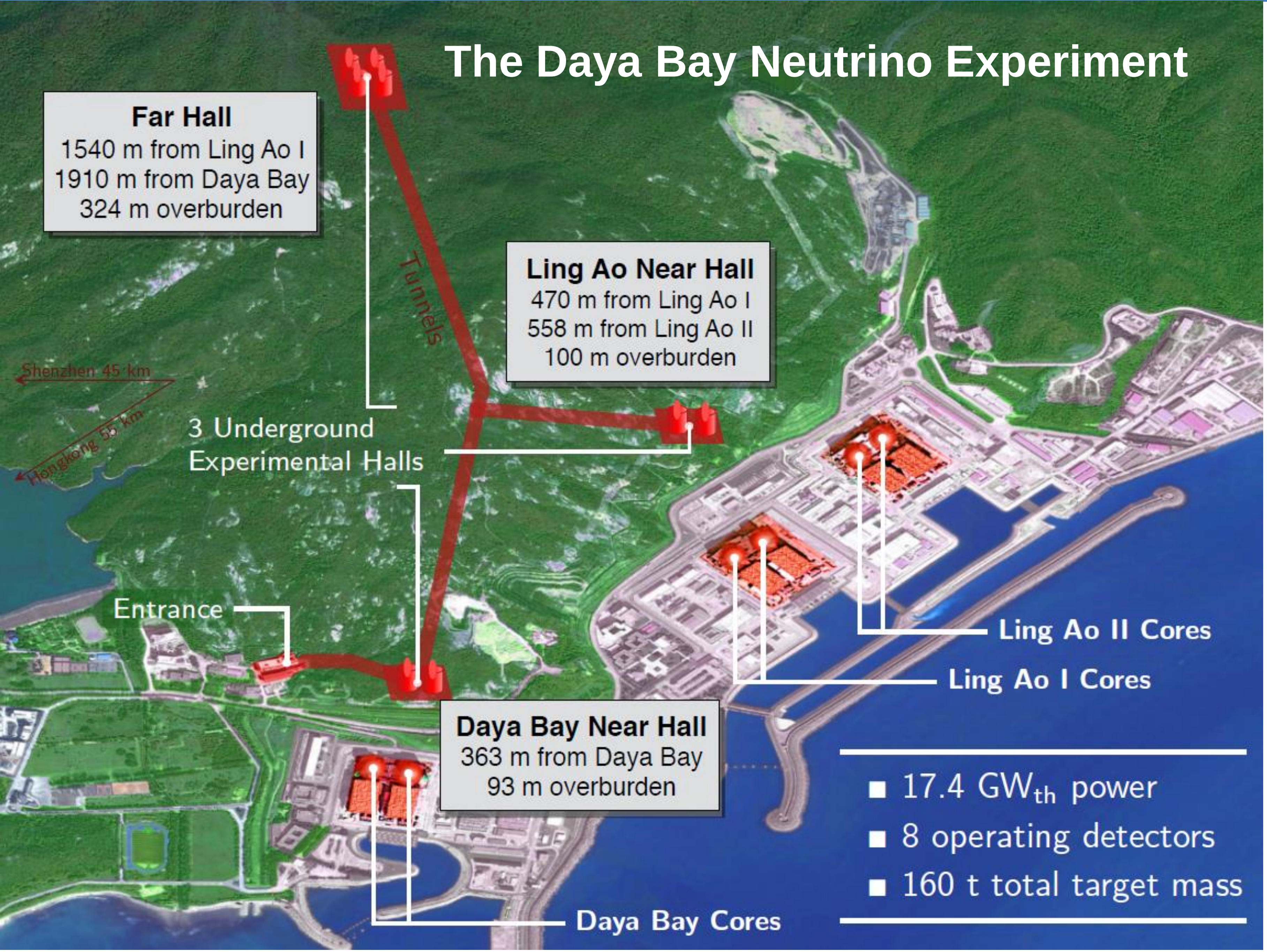
Model vs. Measurements: Disagreement



Abazajian et al.
arxiv:1204.5379

Sterile neutrino is among the most intriguing explanations of RAA

- Recent reactor neutrino experiments have revealed at least three disagreements with model predictions
  - Integrated flux deficit: often called “Reactor Antineutrino Anomaly (RAA)”
  - Spectral shape difference: often called “5 MeV bump”
  - Individual isotope spectra: through the study of “fuel evolution”
- Daya Bay is leading these flux and spectrum measurements due to its largest statistics and best control of systematic uncertainties
  - also measured by RENO, Double Chooz, and other short-baseline (SBL) experiments

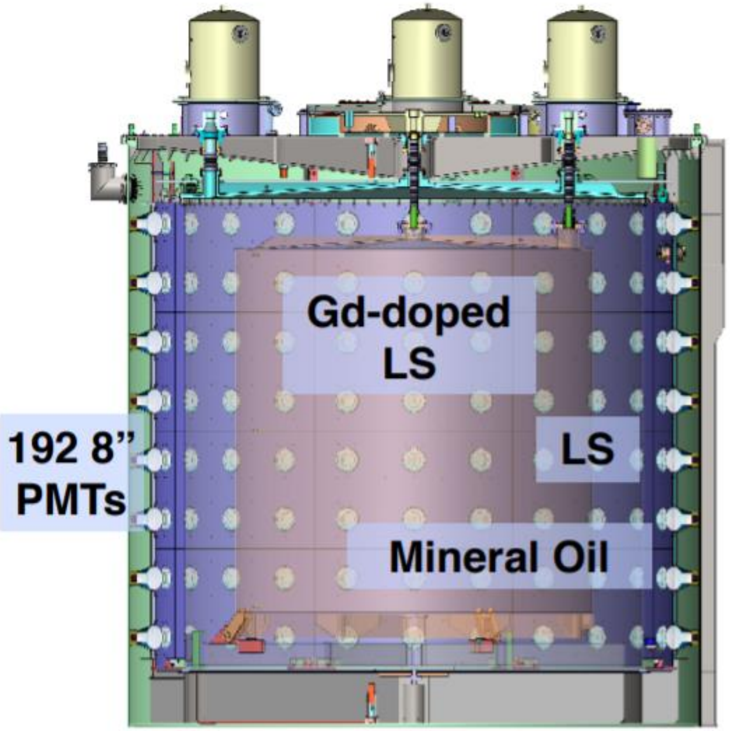


- 17.4 $\mathrm{GW_{th}}$ power
- 8 operating detectors
- 160 t total target mass

Timeline

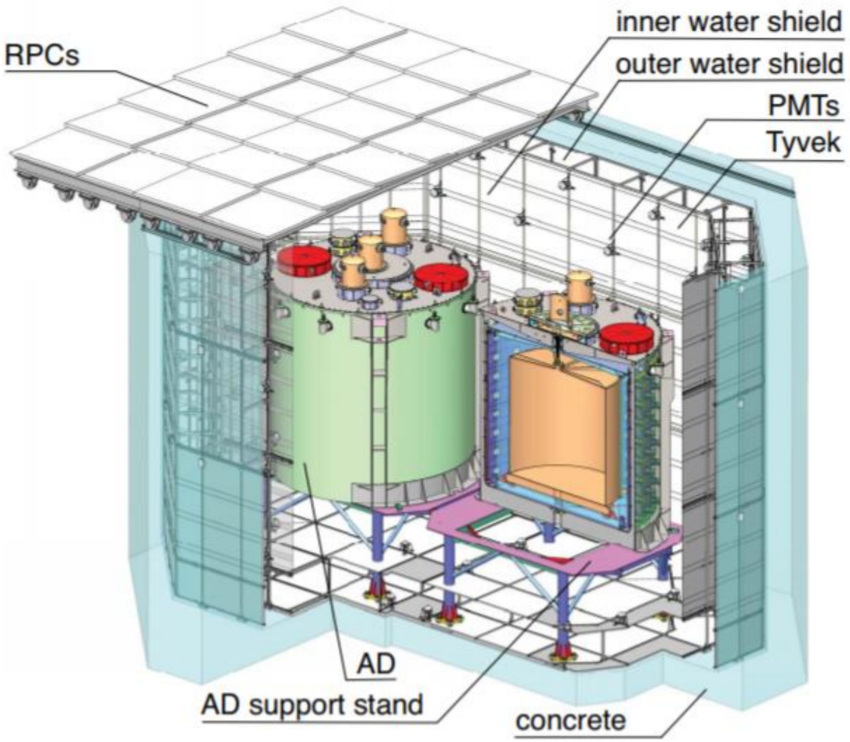
- ❑ 2003: Experiment proposed
- ❑ 2006: Collaboration Established
- ❑ 2011.8: First near hall data taking
- ❑ 2011.12: 3-hall data taking
- ❑ 2012.3: Discovery of non-zero θ_{13}
- ❑ Latest data set: 2011.12 – 2017.9 (1958 days)

Daya Bay Detectors



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E}$(MeV)

NIM A811, 133 (2016)

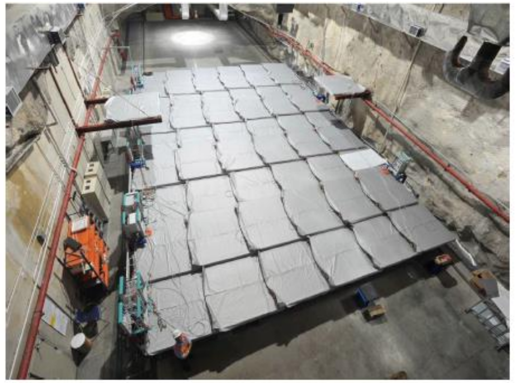


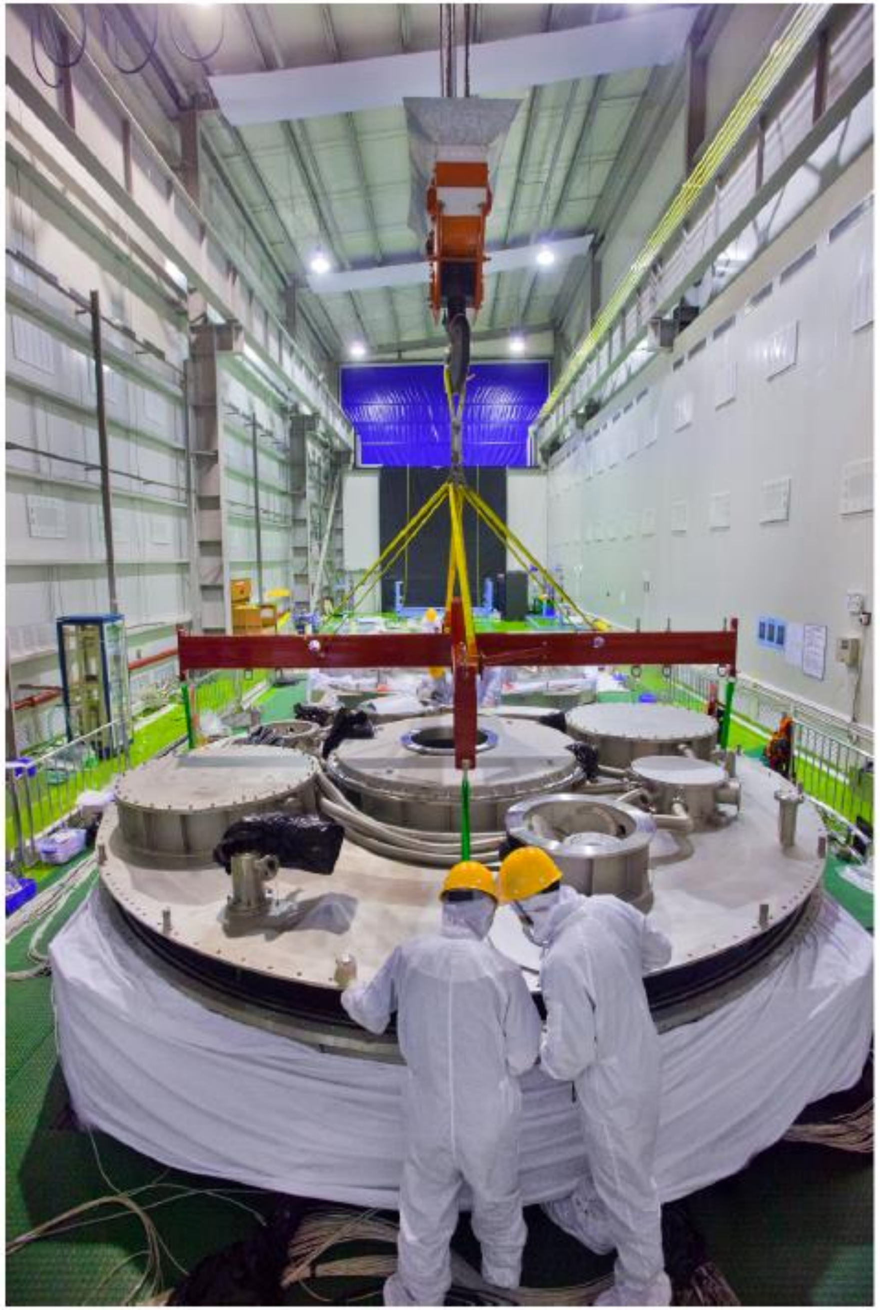
Double purpose: shield the ADs and veto cosmic ray muons

NIM A773, 8 (2015)

❑ Antineutrino Detector (AD)
  - Inner: 20-ton GdLS (target volume)
  - Mid: 20-ton LS (gamma catcher)
  - Outer: 40-ton mineral oil (buffer)

❑ Muon Veto System
  - Water Cherenkov: optically separated inner/outer region
  - RPC: independent tagging

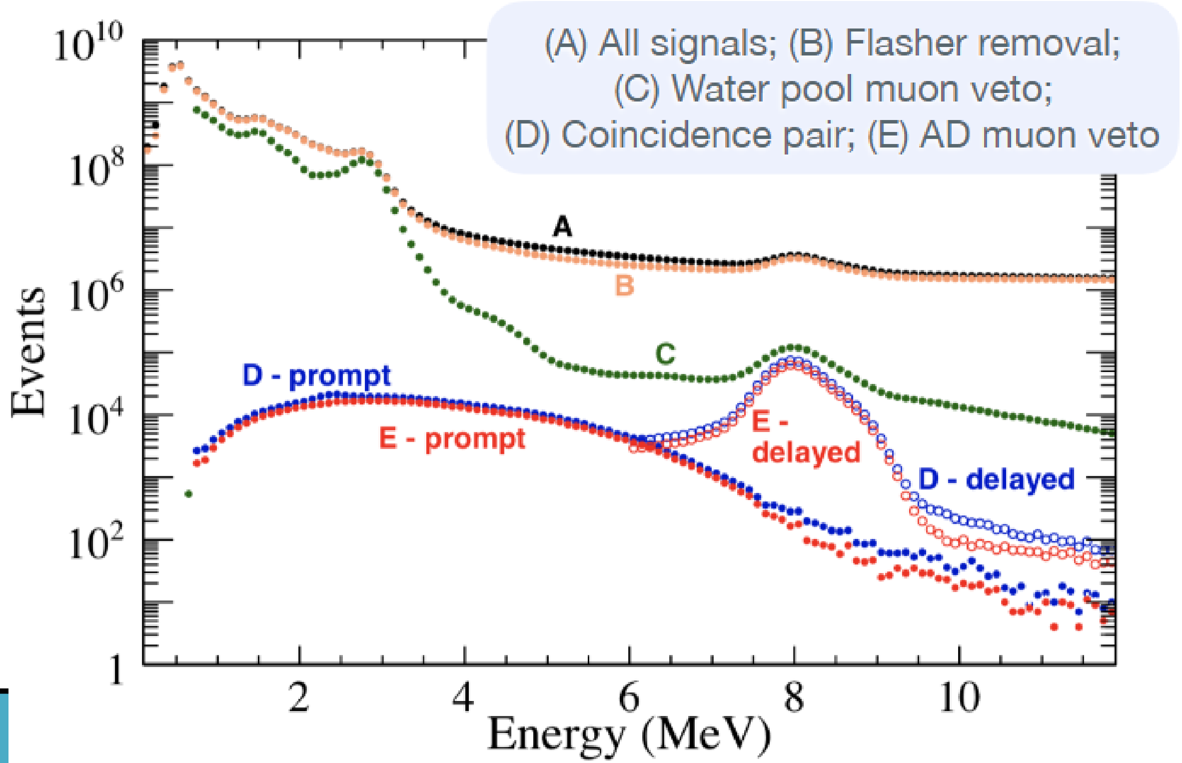


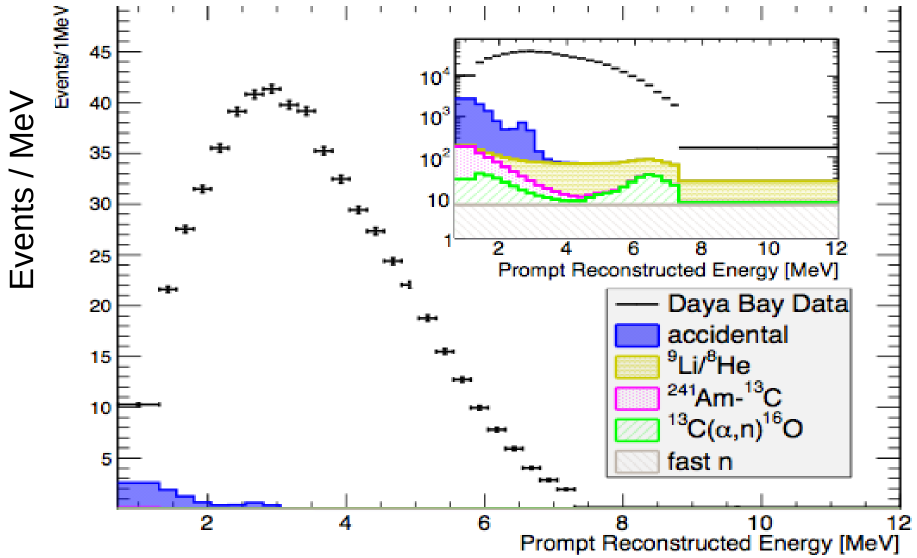


A Low Background Experiment

- ❑IBD Events
  - Near site: ~600 /day
  - Far site: ~75 /day
- ❑Accidental background to signal: ~2%
- ❑Correlated background to signal: ~0.5%

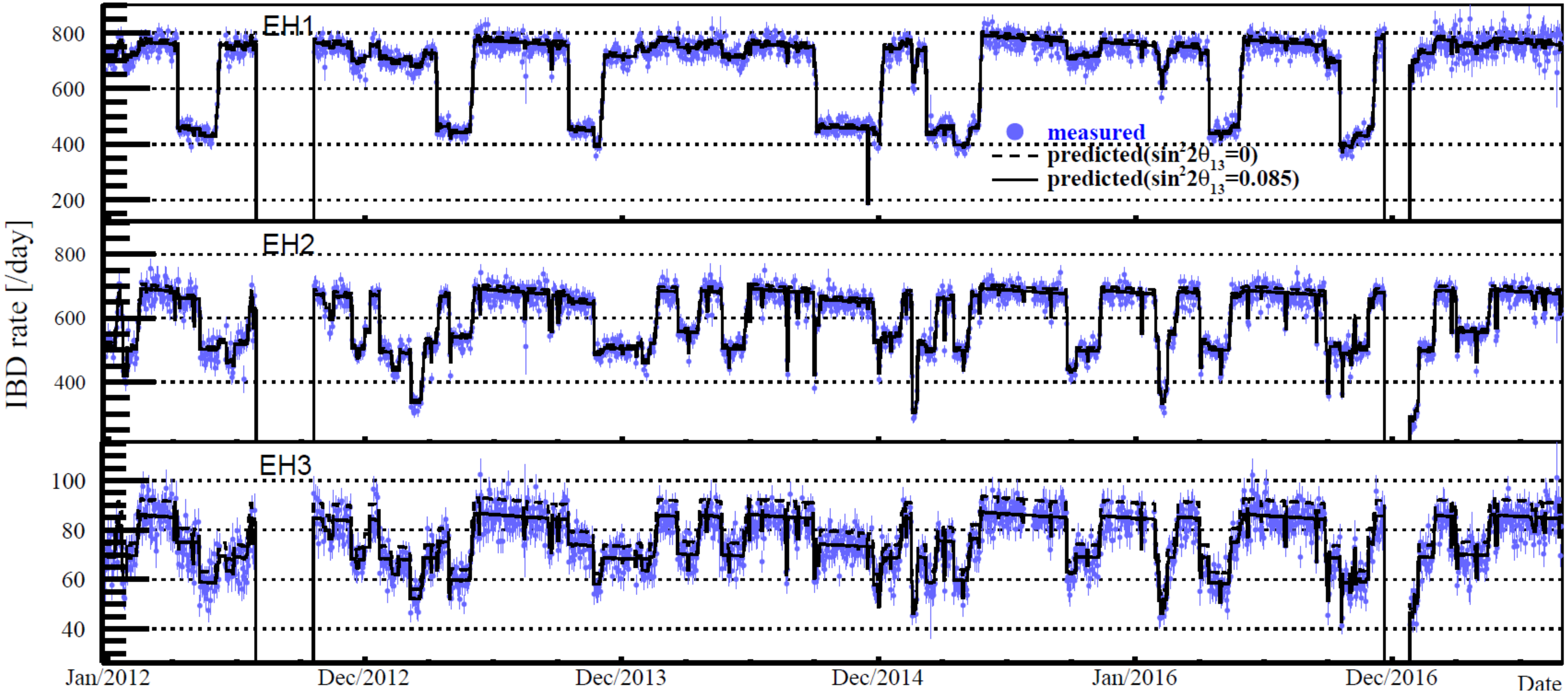
Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	negligible	statistically calculated from uncorrelated singles
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source
Li-9 / He-8	0.4%	0.4%	~30%	measured with after-muon events
Fast neutron	0.1%	0.1%	~30%	measured from AD/water/RPC tagged muon events
Alpha-n	0.01%	0.1%	~50%	calculated from measured radioactivity


(A) All signals; (B) Flasher removal; (C) Water pool muon veto; (D) Coincidence pair; (E) AD muon veto



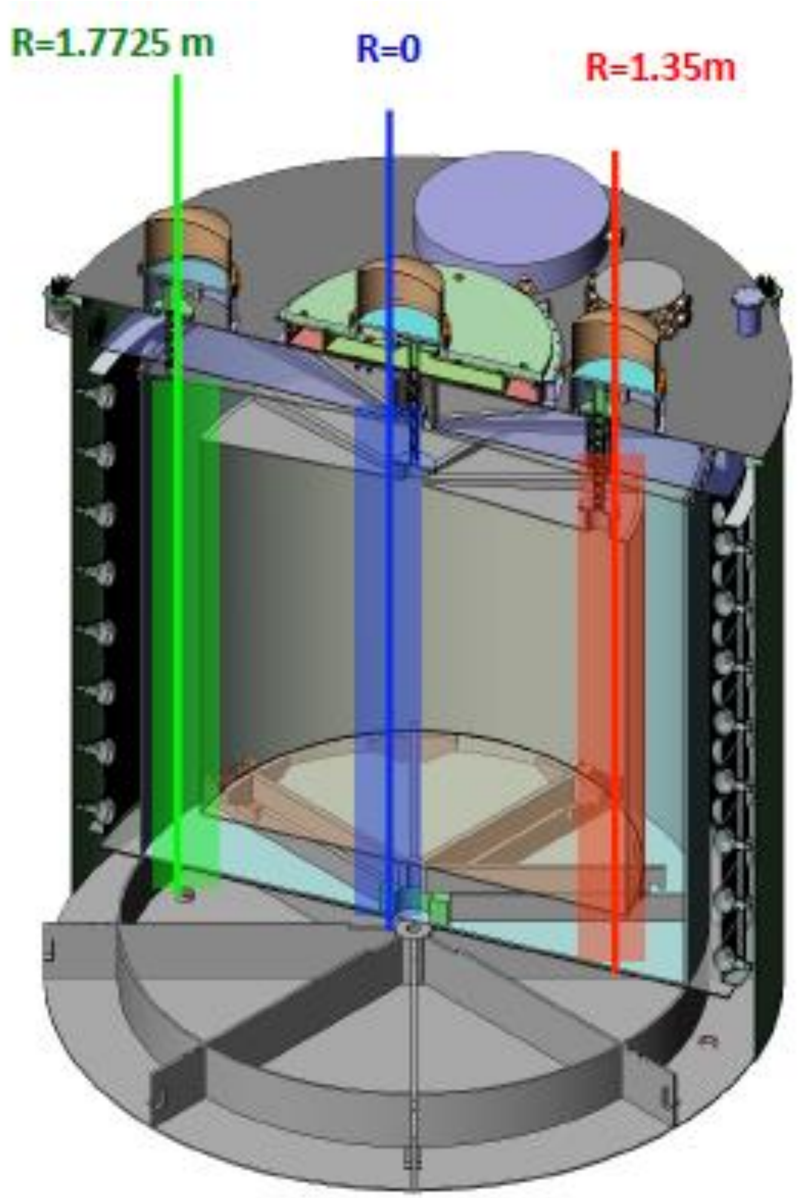
Unprecedented Reactor Antineutrino Sample

- ❑ 3.9 million inverse beta decay (IBD) interactions (0.5M at far site)
- ❑ Observed rate highly correlated with reactor operations



Calibration System

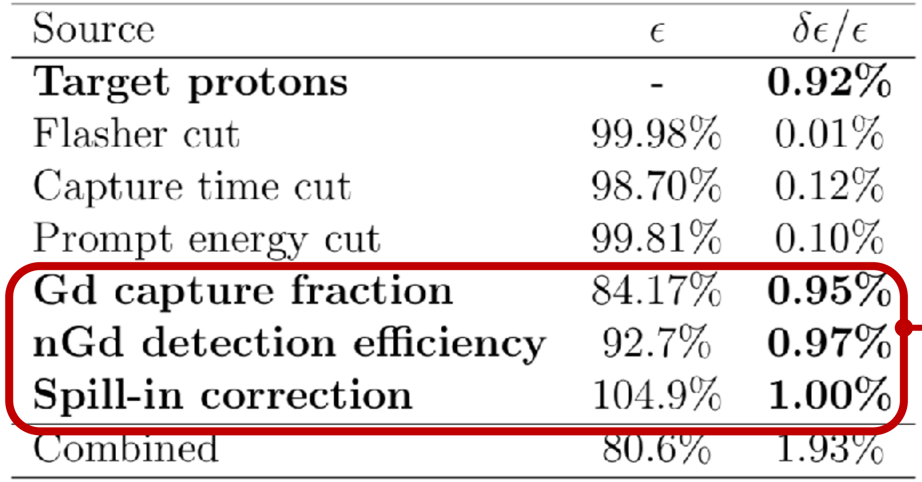
- ❑ Three fully Automated Calibration Units (ACUs) per detector, weekly calibration
  - 3 sources for each z axis on a turn-table
    - ^{68}Ge (2 x 0.511 MeV γ)
    - ^{60}Co (1.173 + 1.332 MeV γ) + ^{241}Am^{13}C (neutron)
    - LED for PMT gain and timing
- ❑ Special calibration campaign with temporary sources for energy and efficiency study
  - ^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- ❑ One-time 4-π manual calibration system in one AD for position dependence study
- ❑ In-situ calibration
  - PMT gain: dark noise
  - Energy scale: spallation neutrons



Antineutrino Detection efficiency

Phys. Rev. D 100, 052004 (2019)

Previous IBD efficiency values

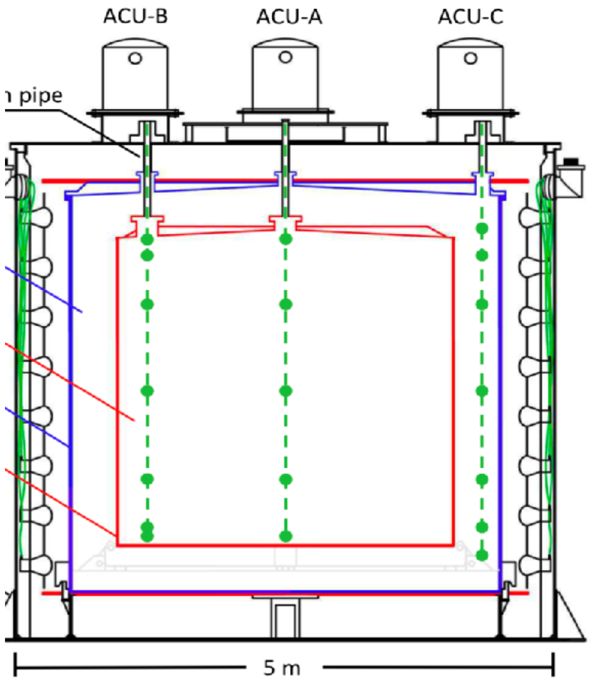


Source	ϵ	$\delta\epsilon/\epsilon$
Target protons	-	**0.92%**
Flasher cut	99.98%	0.01%
Capture time cut	98.70%	0.12%
Prompt energy cut	99.81%	0.10%
Gd capture fraction	84.17%	**0.95%**
nGd detection efficiency	92.7%	**0.97%**
Spill-in correction	104.9%	**1.00%**
Combined	80.6%	1.93%

Uncertainty improved x2

$\epsilon_n = 81.48\ (1 \pm 0.74)\%$

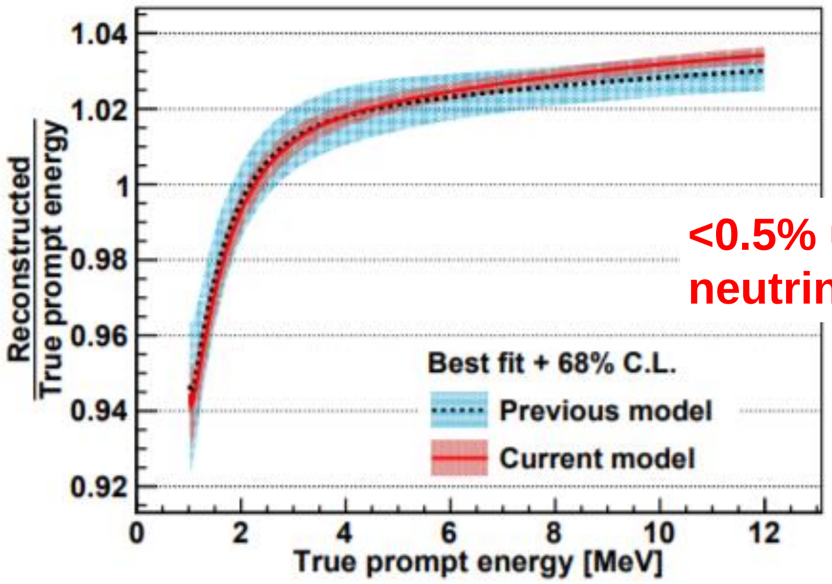
$\epsilon_{total} = 80.24\ (1 \pm 1.50)\ \%$



- ❑ Gd capture fraction: neutron capture on other target (e.g. hydrogen) or outside GdLS region (spill out)
- ❑ nGd detection efficiency: low energy tail from capture gammas escaping GdLS+LS
- ❑ Spill in: IBD interaction outside of GdLS but neutron capture inside GdLS

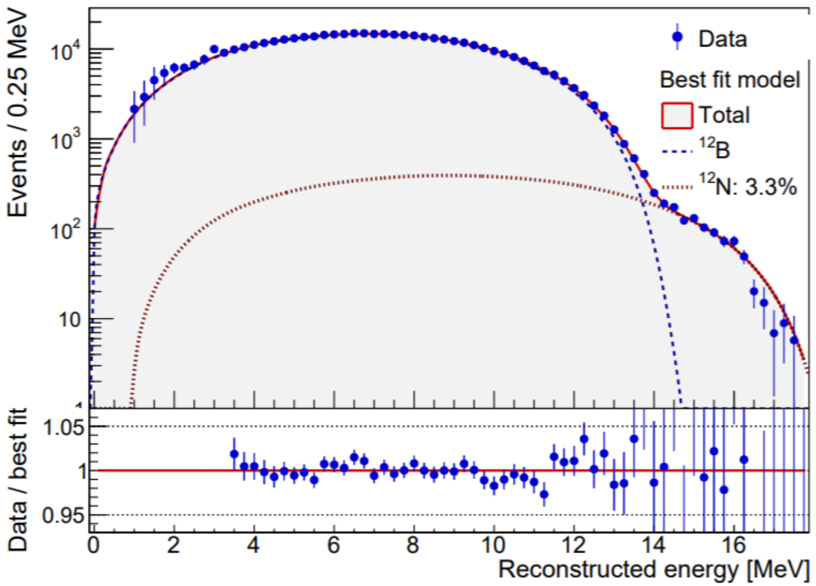
- ❑ Special calibration in 2016 with neutron sources (^{241}Am-^{13}C and ^{241}Am-^{9}Be)
- ❑ Systematic Monte-Carlo study with different models to constrain neutron detection efficiency

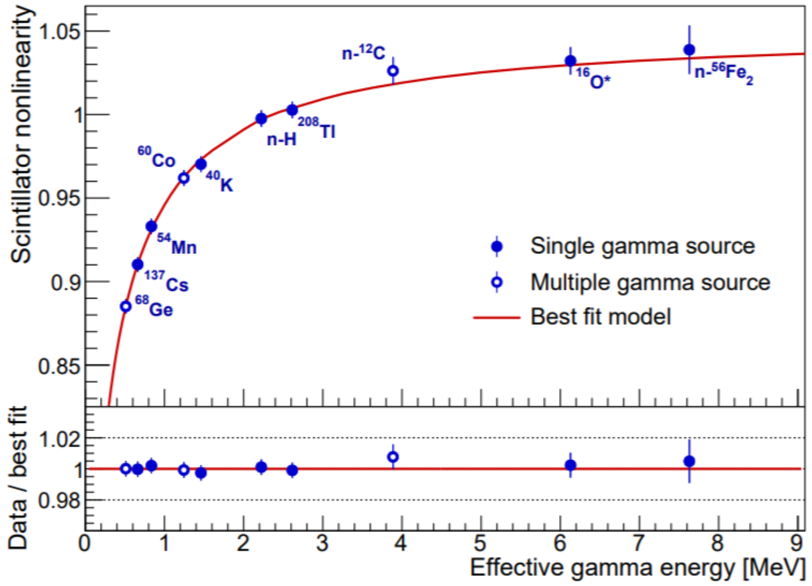
Energy Nonlinearity Calibration



<0.5% uncertainty in the reactor neutrino energy range

NIMA 940, 230 (2019)





- Scintillator response: modeled by Birks formula and Cherenkov contribution
- Electronics response: measured by dedicated FADC system in one AD
- Nominal model determined by combined fit to mono-energetic gamma peaks and ^{12}B beta-decay spectrum
  - Cross-validated by: ^{212}Bi, ^{214}Bi, ^{208}Tl beta-decay spectrum, Michel electron spectrum, and standalone bench-top Compton scattering measurement.

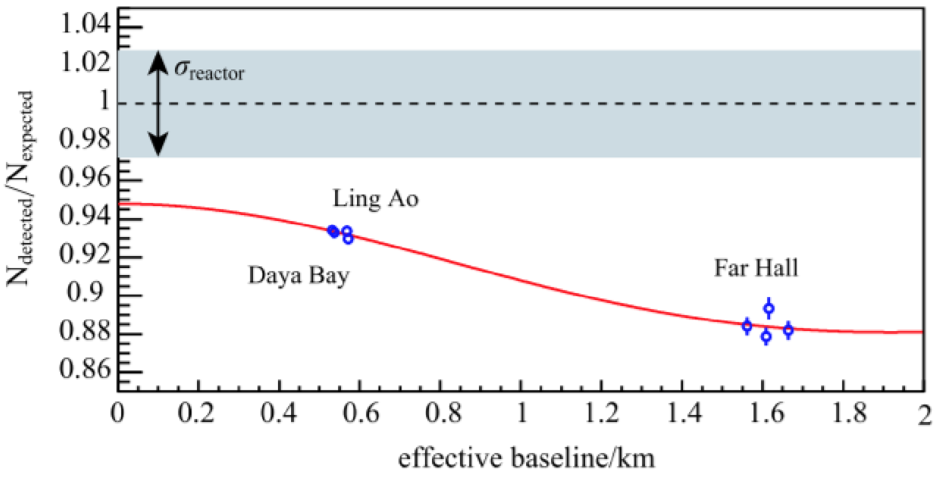
Reactor Antineutrino Flux

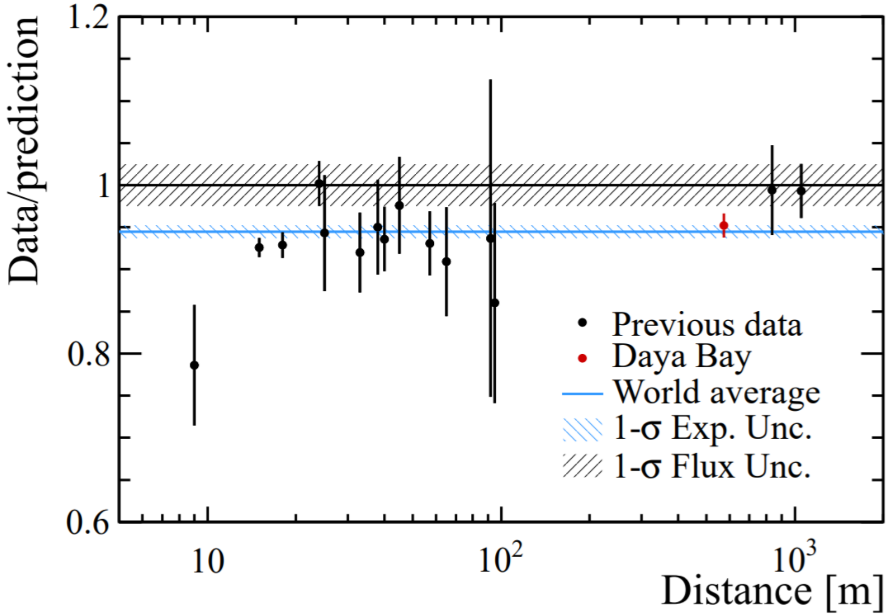
Phys. Rev. D 100, 052004 (2019)

- Daya Bay's measured absolute flux $\sigma_f = (5.91 \pm 0.09) \times 10^{-43}$ cm^2 /fission
- 4.8% deficit compared with the most recent Huber (^{235}U, ^{239}Pu, ^{241}Pu) plus Muller (^{238}U) model

$$\frac{Data}{Model\ (\mathrm{Huber + Muller})} = 0.952 \pm 0.014\,(exp.) \pm 0.023\,(model.)$$

- Consistent with previous short baseline reactor experiments in the 80-90s
  - ~2σ deficit could come from issues in the reactor model and/or eV-scale sterile neutrino oscillation

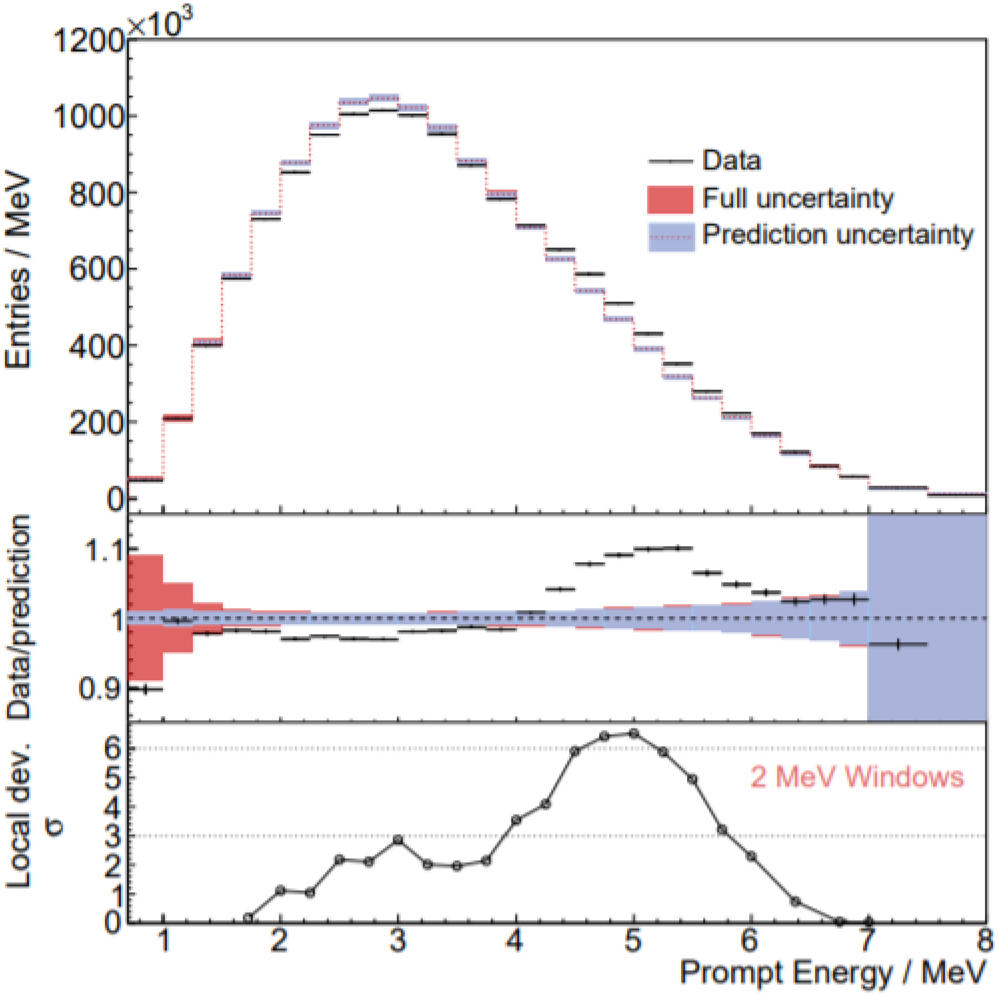




Reactor Antineutrino Spectral Shape

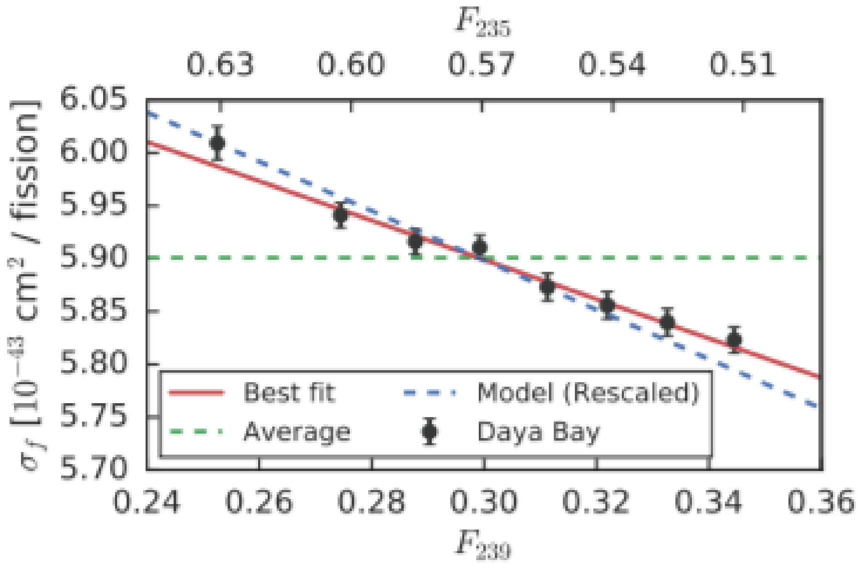
- ❑5.3σ discrepancy with Huber-Muller model overall (0.7 – 8 MeV)
- ❑6.3σ discrepancy in the 4 – 6 MeV region (often referred to as the "bump")
  - Bump events have all the IBD characteristics and are correlated with reactor power
  - Bump does not appear in ^{12}B or other beta-decay spectra (cannot be explained by detector effects)
- ❑This shape anomaly cannot be explained by sterile neutrino mixing

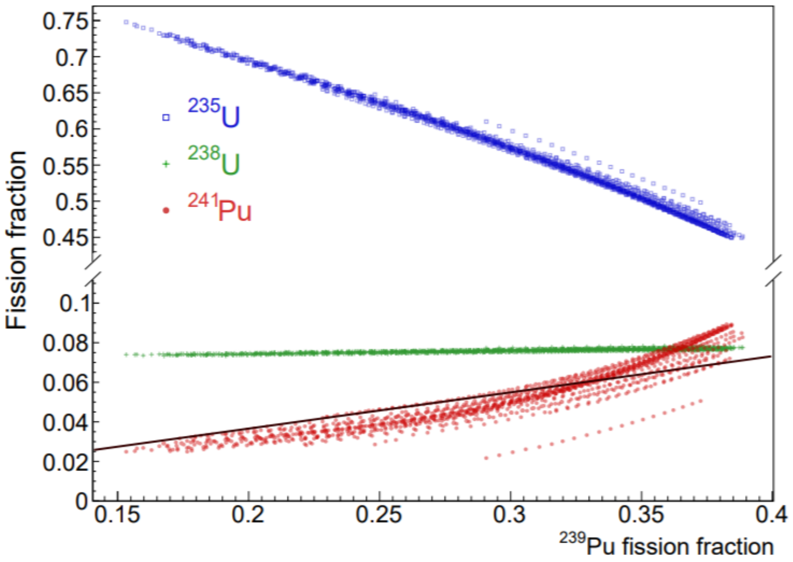
Phys. Rev. Lett. 123, 111801 (2019)



Evolution with Fuel Composition

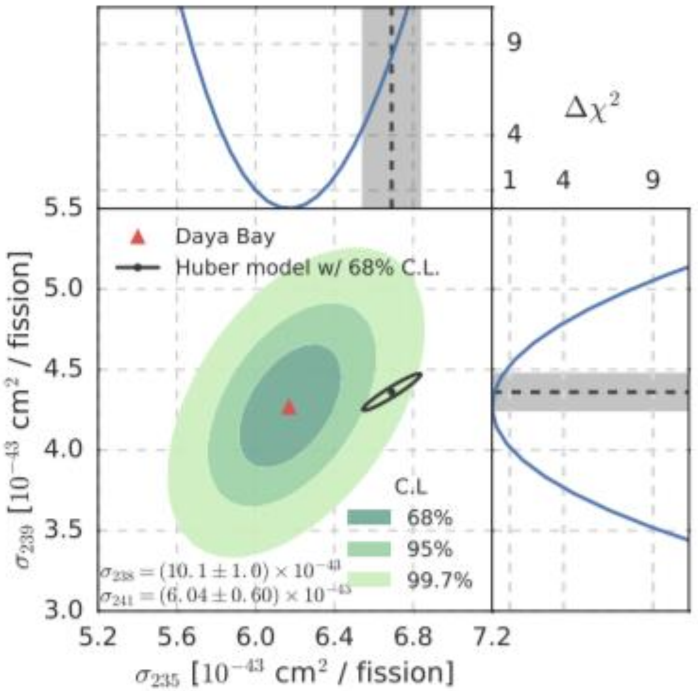
- Question: can these anomalies be traced to a particular isotope?
  - Study of how the total flux changes with fuel composition allowed to extract the individual antineutrino yield of ^{235}U and ^{239}Pu





PRL 118, 251801 (2017)

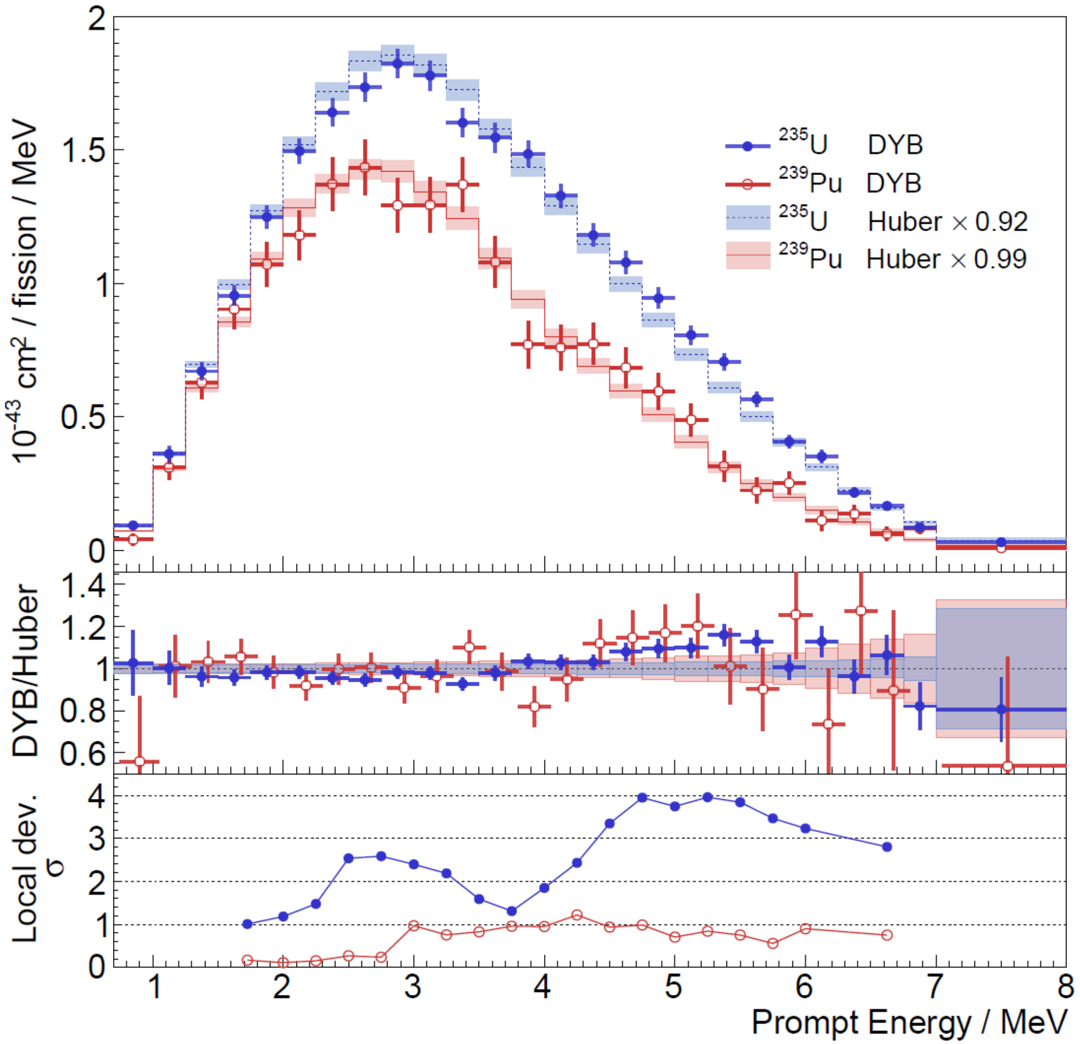
Daya Bay data suggest ^{235}U is the primary contributor to the flux anomaly



Extraction of Individual ^{235}U and ^{239}Pu Spectra

- Similarly, the individual ^{235}U and ^{239}Pu spectra can be simultaneously extracted from the evolution of the spectrum with fuel composition
- Similar bump excess seen with both ^{235}U and ^{239}Pu. Local deviations:
  - 4σ for ^{235}U
  - 1.2σ for ^{239}Pu (larger uncertainty)
- ~ 4% uncertainty for ^{235}U and 9% for ^{239}Pu at 3 MeV

This is the first measurement of the individual ^{235}U and ^{239}Pu spectra with commercial reactors

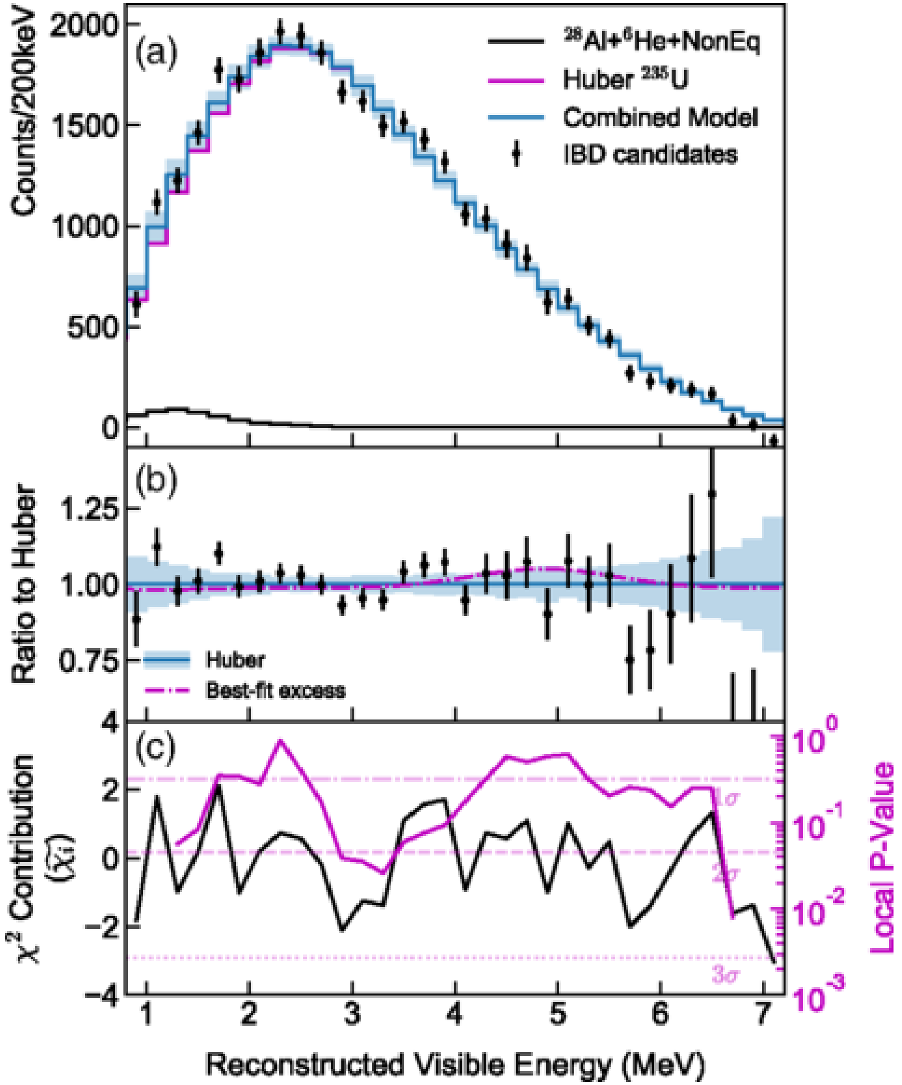


Phys. Rev. Lett. 123, 111801 (2019)

Future Improvement

- Daya Bay will continue taking data until end of 2020
  - Larger statistics will help the extraction of individual isotope spectrum
- ^{235}U-only spectrum measurement from short baseline experiments with HEU research reactors
  - PROSPECT, STEREO, SoLid, etc.
  - Combined analysis with Daya Bay and other commercial reactor experiments will help the extraction of ^{239}Pu spectrum
- Future high-resolution experiments
  - JUNO, JUNO-TAO, etc.

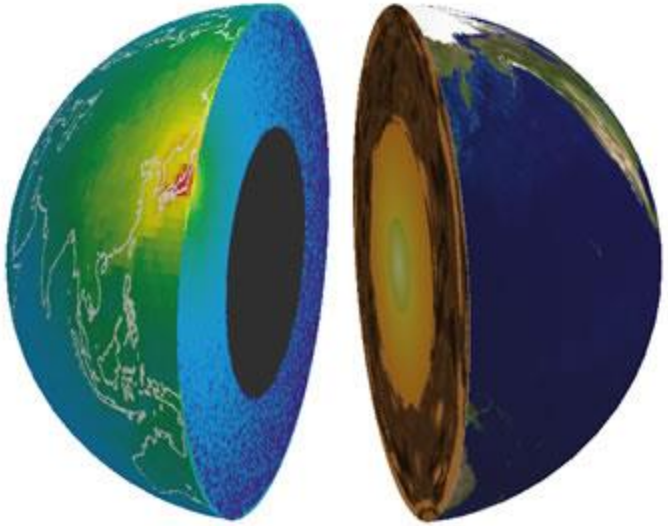
Phys. Rev. Lett. 122, 251801 (2019)



Summary

- ❑ Reactor neutrino is one of the largest backgrounds for geoneutrino detection
- ❑ At present, reactor neutrino models still have relatively large uncertainties
- ❑ However, reactor neutrino flux and spectrum have been precisely measured by recent experiments, in particular by Daya Bay to ~1.5% for flux and 0.5-4% for spectral shape
  - Individual spectra from ^{235}U and ^{239}Pu were also extracted
- ❑ These precision measurements are important inputs to future geoneutrino experiments

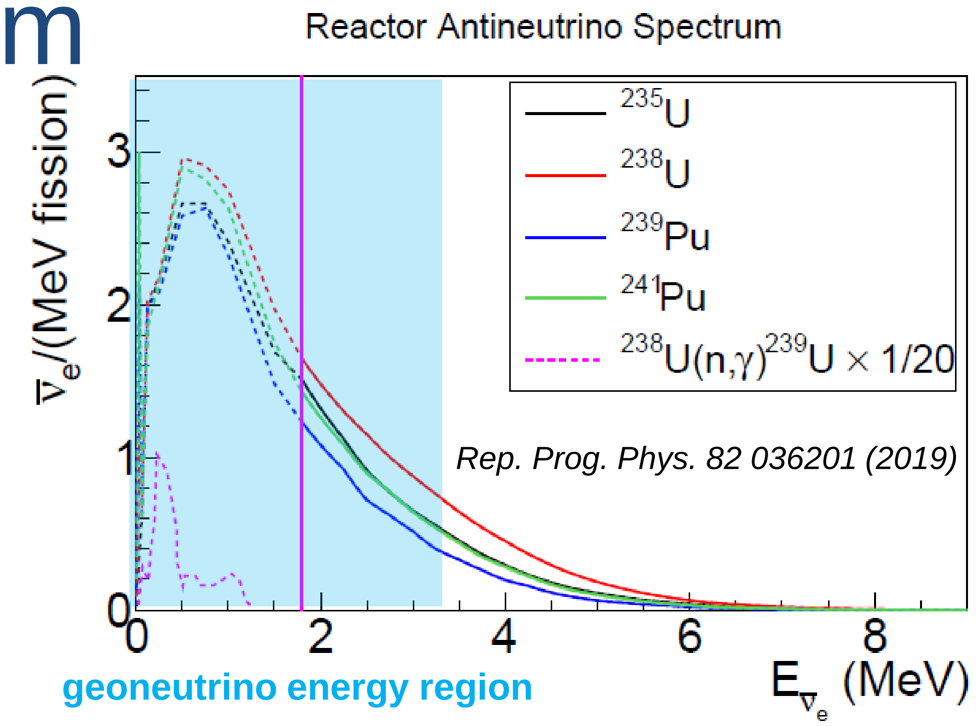

Berkeley Lab - Roy Kaltschmidt, photographer



Backup Slides

Low Energy (<1.8 MeV) Spectrum

- **Inverse Beta Decay (IBD)** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Relatively large cross section
  - Distinctive coincidence signature
  - 2/3 of reactor flux are below the 1.8 MeV threshold
- **Neutrino-electron Elastic Scattering (ES)** $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$
  - No threshold
  - Reasonable event rate: smaller cross section but larger flux and more targets
  - Background challenge: a single electron recoil event



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geoneutrino energy region