Reactor Neutrinos

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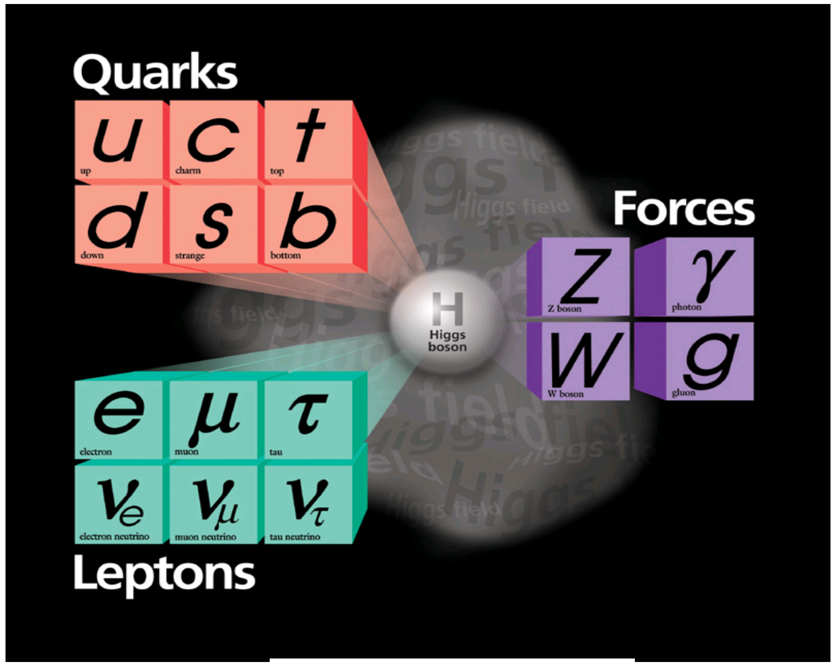
Outline

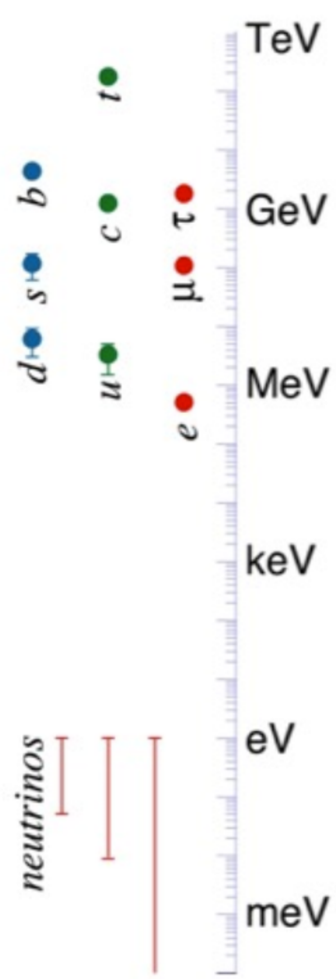
- Introduction to neutrinos
- Reactor neutrino experiments: Spectrum and Flux Anomaly studies
  - **Daya Bay**
  - PROSPECT
  - STEREO
  - RENO
  - DANNS
- Summary

Introduction to neutrinos

Neutrinos

- Neutrinos are everywhere
  - The universe is filled with neutrinos
  - Apart from photons, there are more neutrinos than any other particle
- Neutrinos only feel the weak force
- Example: To stop 1 MeV particle
  - For an electron require 10mm of lead (Electromagnetic interaction)
  - For a proton require 0.1 mm of lead (strong interaction)
  - For a neutrino we need 10 light years of lead (weak interaction)



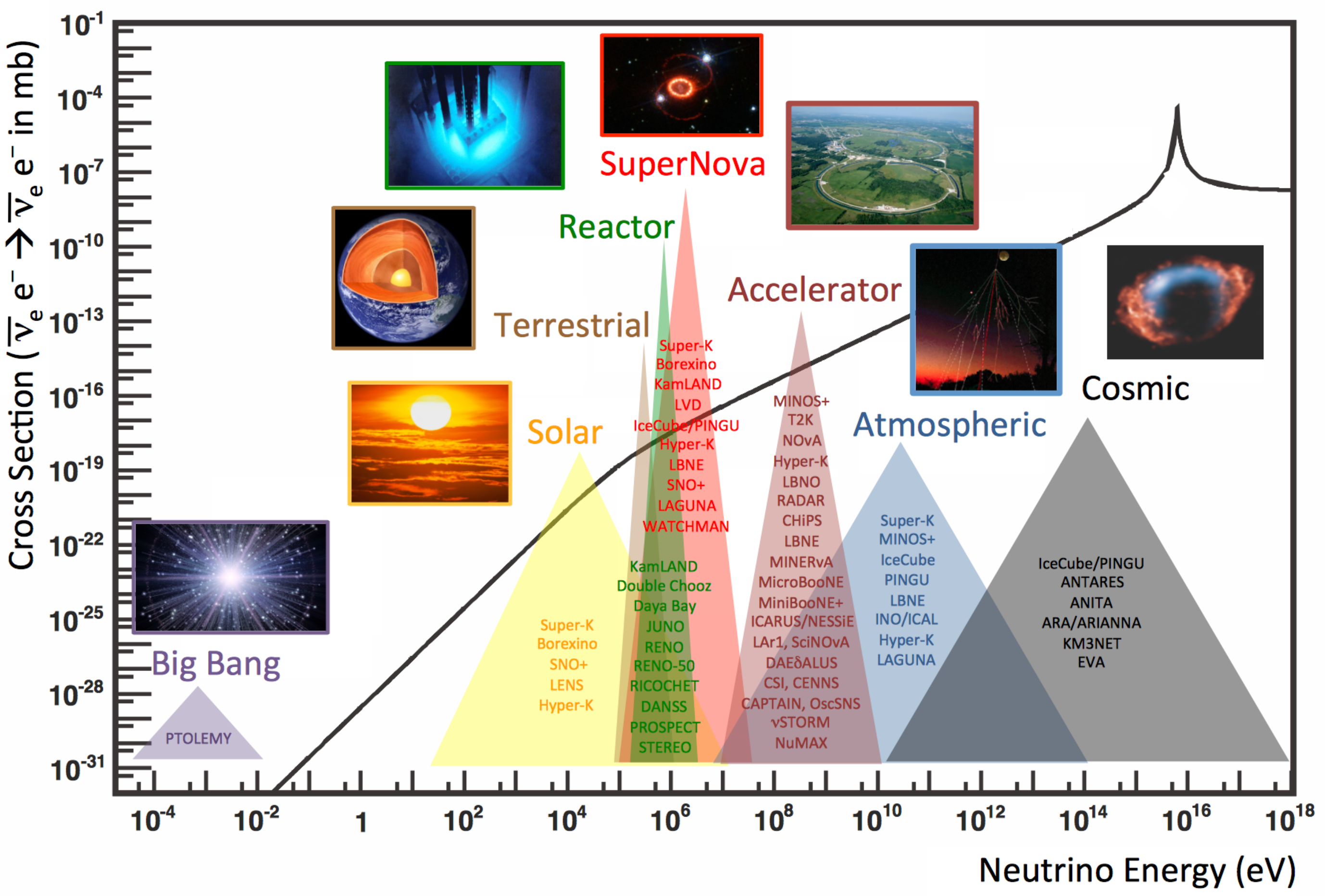


Info: 1eV ~1.6X 10^-19J ~2X10^-36 Kg

Neutrino Sources

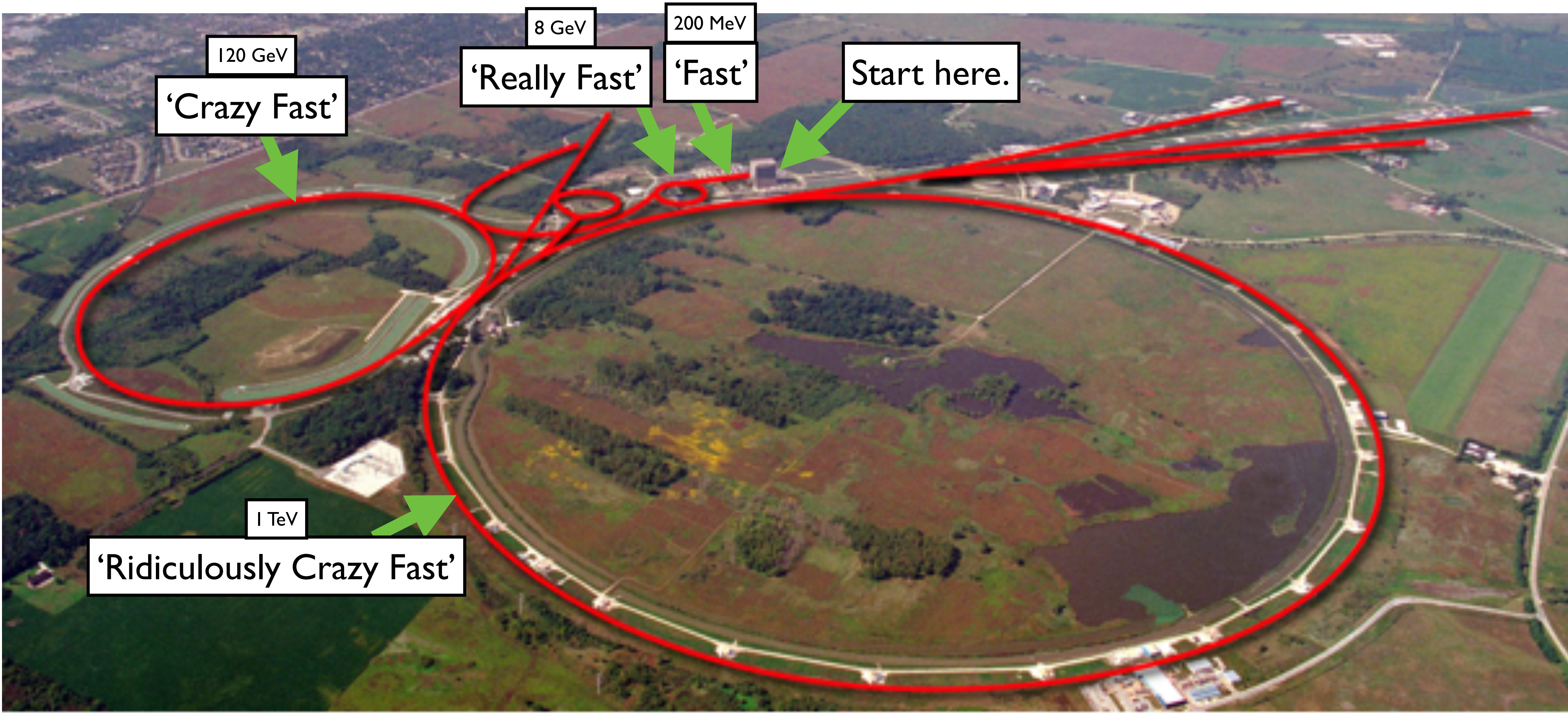
- Many neutrino sources and energies, interacting via weak force

- Focus: Two interesting sources
    - Reactors: 1-10 MeV
    - Accelerators: 0.1 - 10 GeV (See talk from Deywis)



Neutrino Sources: Accelerators

- Fermilab: Example of Proton Beam
  - Accelerate protons (hydrogen nuclei) from 0 to 99.999% the speed of light in four steps



Neutrino Sources: Accelerators

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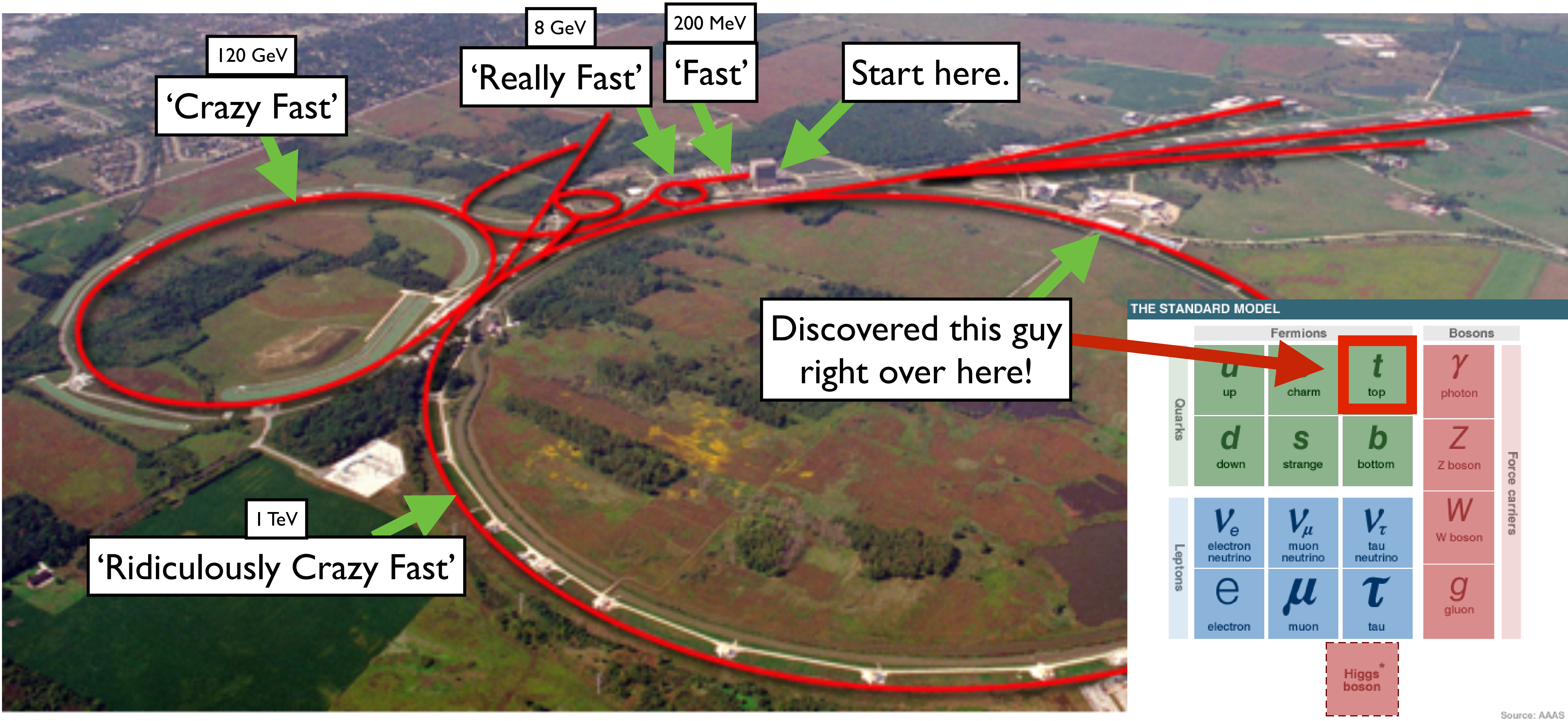


120 GeV
'Crazy Fast'

8 GeV
'Really Fast'

200 MeV
'Fast'

Start here.

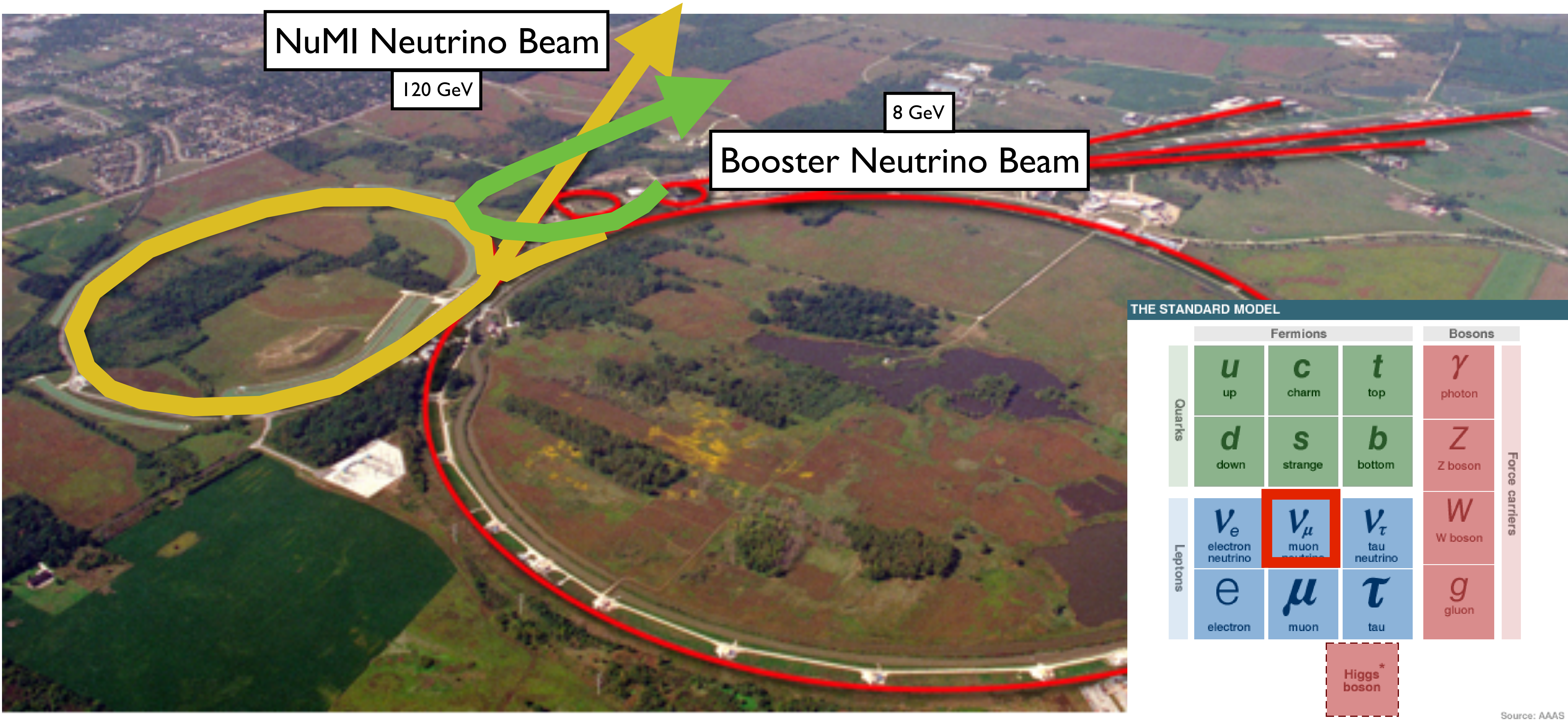
Discovered this guy right over here!

1 TeV
'Ridiculously Crazy Fast'

Source: AAAS

Neutrino Sources: Accelerators

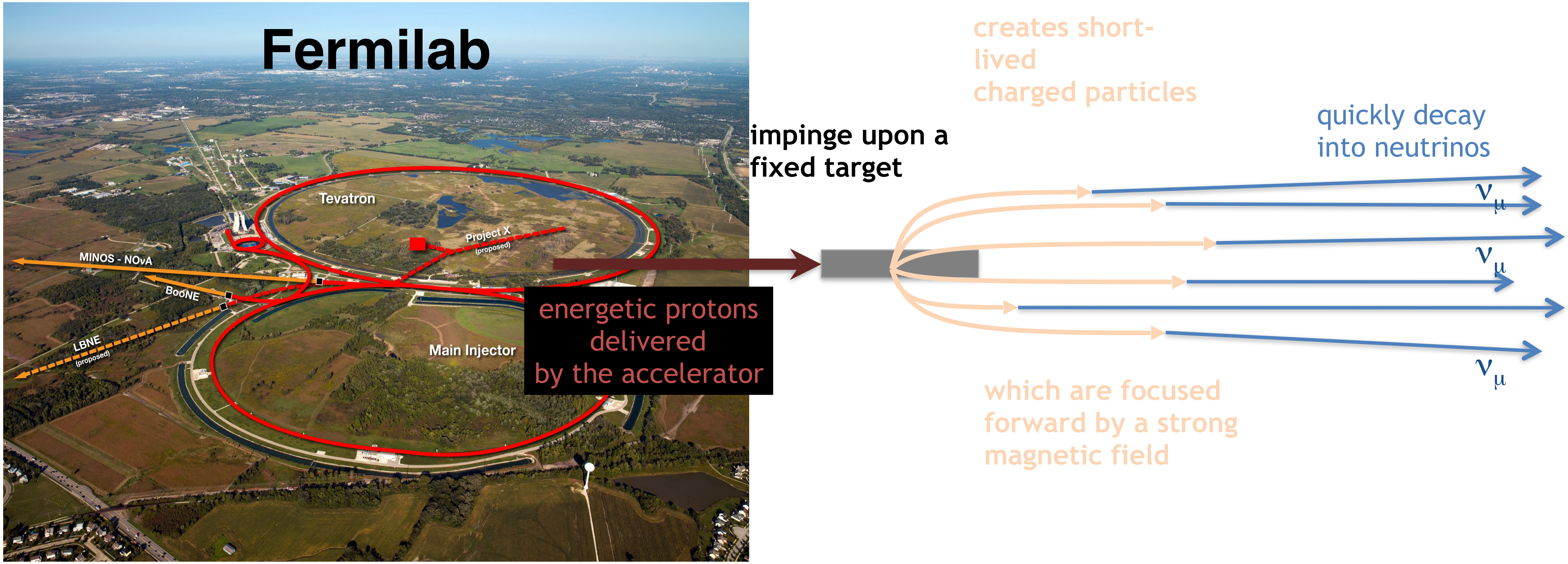
- Fermilab: Example of Proton Beam
  - Accelerate protons (hydrogen nuclei) from 0 to 99.999% the speed of light in four steps
- Use proton beams to make beams muon-type neutrinos



Source: AAAS

Neutrino Sources: Accelerators

We can use an intense beam of protons to create an intense beam of neutrinos



energetic protons delivered by the accelerator

impinge upon a fixed target

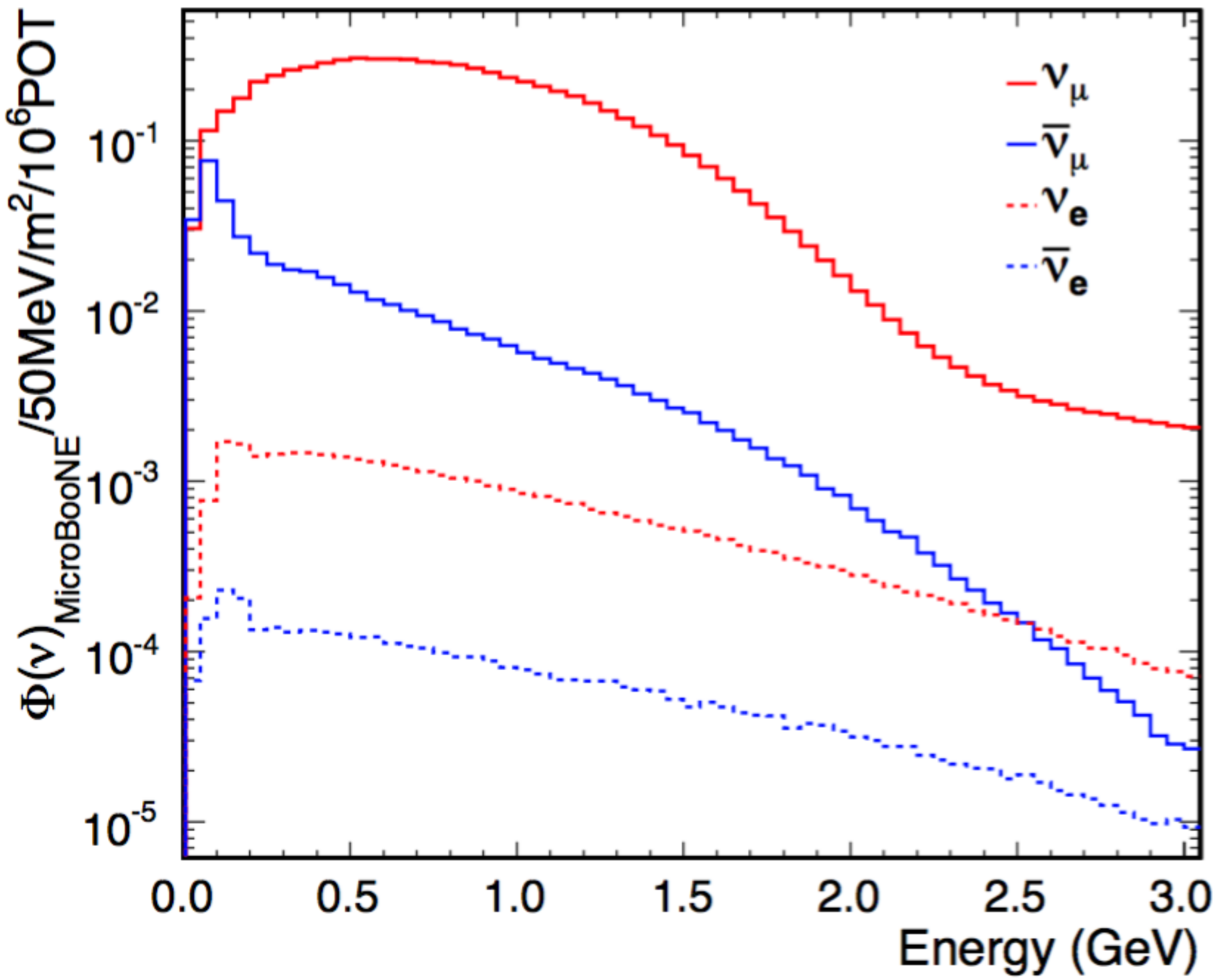
creates short-lived charged particles

which are focused forward by a strong magnetic field

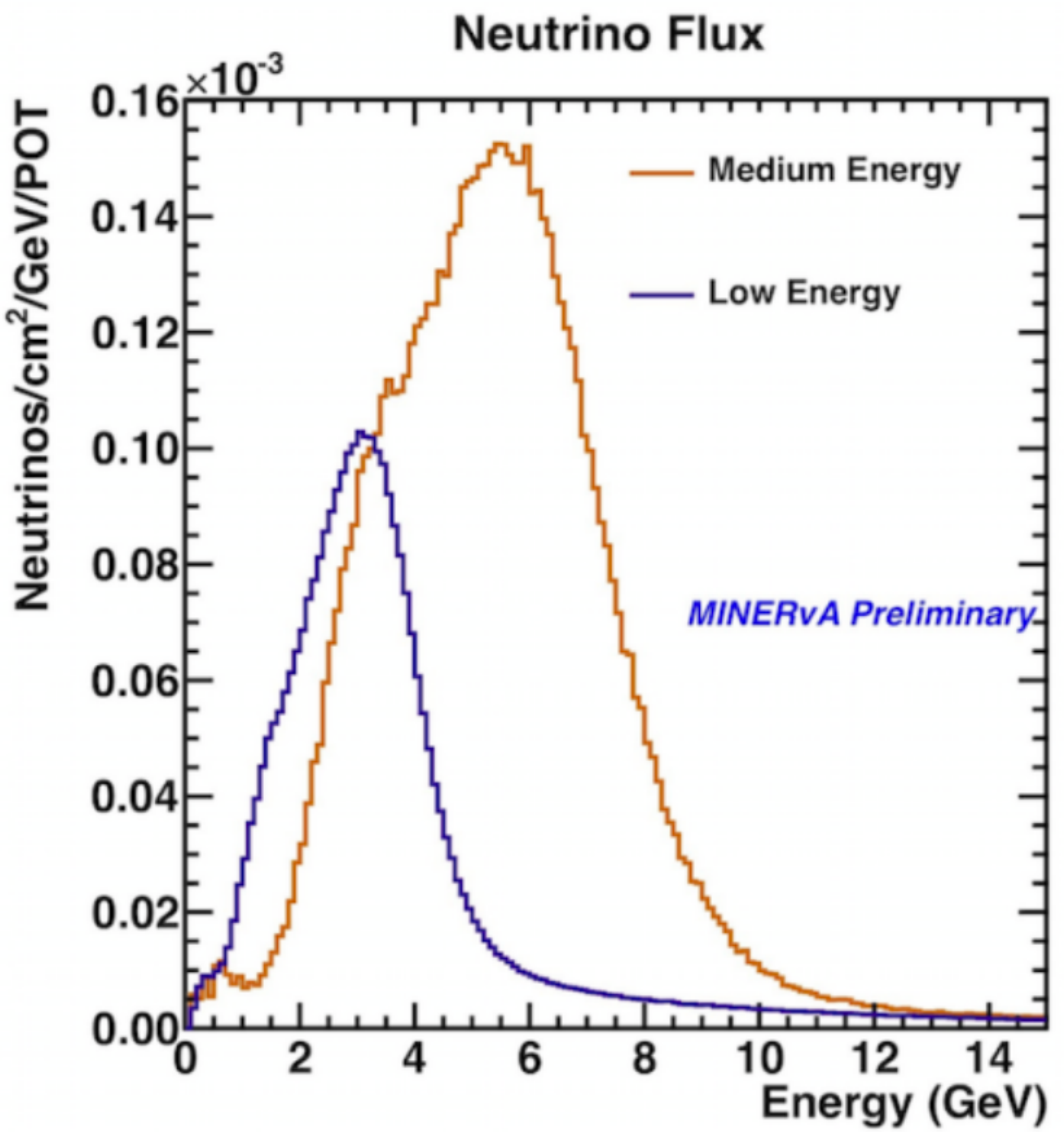
quickly decay into neutrinos

Neutrino Sources: Accelerators

Booster Neutrino Energy Spectrum



NuMI Neutrino Energy Spectrum



~0.5 - 10 GeV Neutrino Energies

Neutrino Sources: Reactors

- Reactor $\overline{\nu}_e$: produced in decay of product beta branches

- More than 99 % of $\overline{\nu}_e$ are the fission products

  of ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U.

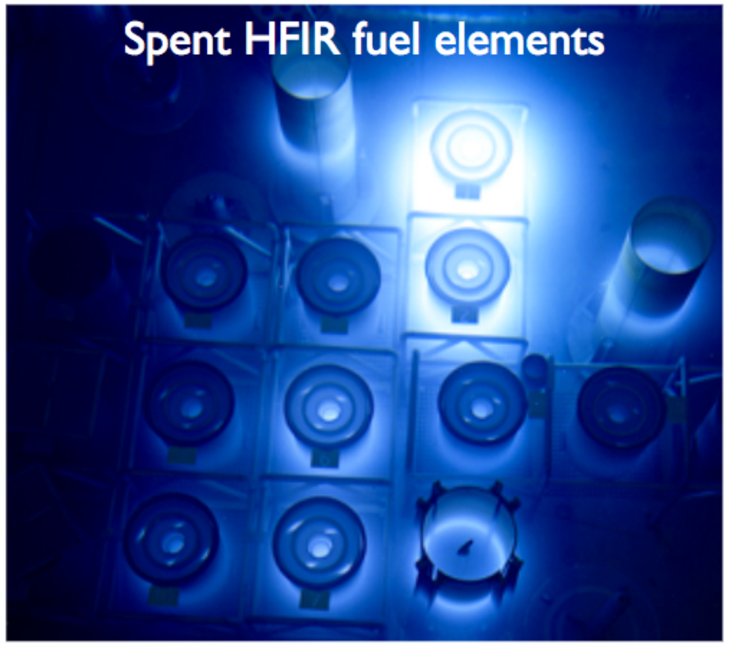
- 2×10^{20} fission/second per GWth (~6 $\overline{\nu}_e$ per fission)

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

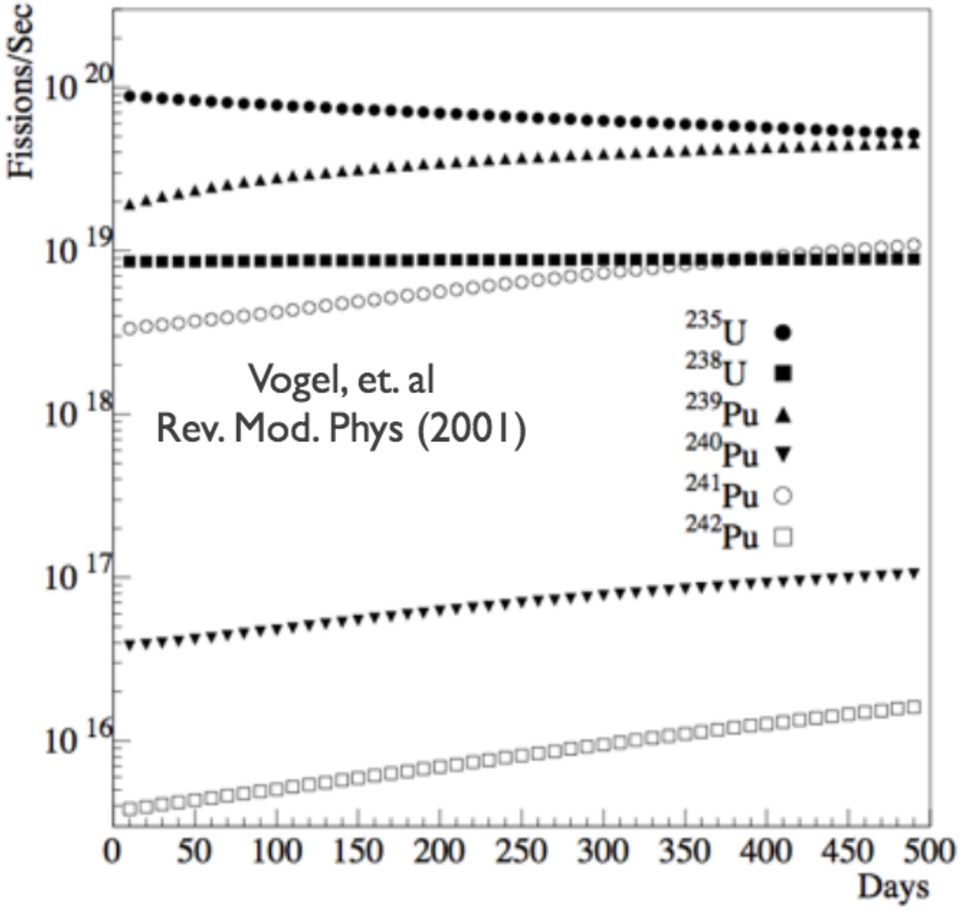
Neutrino Sources: Reactors

- Beta branches produced when fission isotopes fission
  - Low enriched (LEU): Many fission isotopes
  - High enriched (HEU): U-235 fission only
- Overall fission rate described largely by reactor thermal power


HFIR Core/Containment


Spent HFIR fuel elements

LEU Fission Fragment Contributors



Vogel, et. al
Rev. Mod. Phys (2001)

Neutrinos: Oscillations

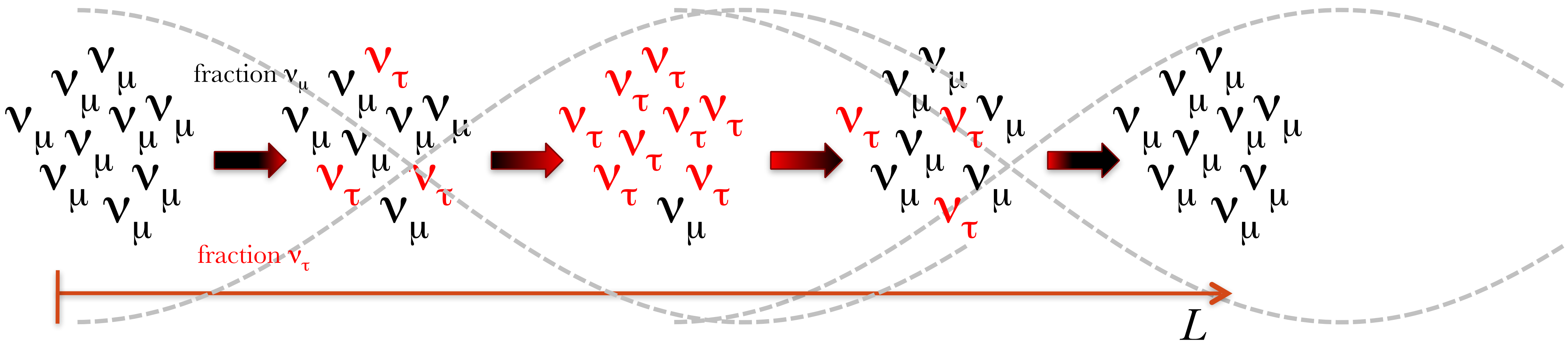
- Neutrino oscillations occur because the flavor (weak) eigenstates do not coincide with the mass eigenstates.

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \qquad (\alpha = e, \mu, \tau)$$

- The neutrinos interacts as a flavor state, but propagate as a superposition of the three mass states

$$U_{PMNS} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

- Over a distance L, changes in the relative phases of the mass states (1,2,3) may induce neutrino flavor change.



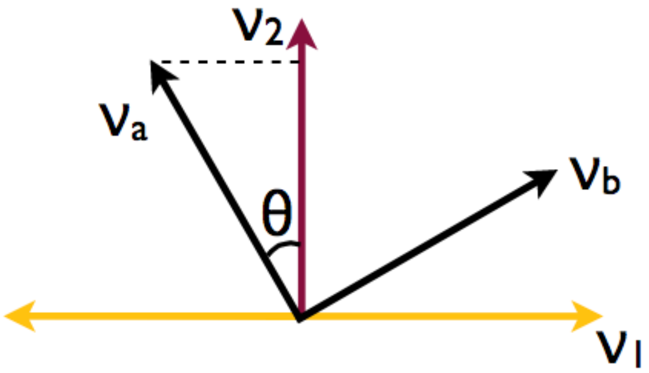
Neutrinos: Oscillations

- In the two flavor case the mixing and survival probability are

$$P(\nu_a \rightarrow \nu_b) = \sin^2 \boxed{2\theta} \sin^2 \left[1.27 \boxed{\Delta m^2} (eV^2) \boxed{\frac{L}{E_\nu}} \frac{(km)}{(GeV)}\right]$$

- In this case, oscillations are described by one mixing angle θ and one mass squared difference (mass splitting)

$$\begin{pmatrix} \nu_b \\ \nu_a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- The neutrino energy **E** and propagation length **L** are experimental parameters

- For the 3 flavor case, we have the 3X3 PMNS mixing matrix:

$$U_{PMNS} = \begin{bmatrix} 1 & \\ & \boxed{\begin{matrix} c_{23} & -s_{23} \\ s_{23} & c_{23} \end{matrix}} \end{bmatrix} \begin{bmatrix} \boxed{c_{13}} & & \boxed{-s_{13}e^{-i\delta_{CP}}} \\ & 1 & \\ \boxed{s_{13}e^{-i\delta_{CP}}} & & \boxed{c_{13}} \end{bmatrix} \begin{bmatrix} \boxed{\begin{matrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{matrix}} & \\ & 1 \end{bmatrix}$$

δ_{CP} Unknown

$\delta_{CP} \neq 0 ? => P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e)$

$c_{lk} = \cos\theta_{lk}$

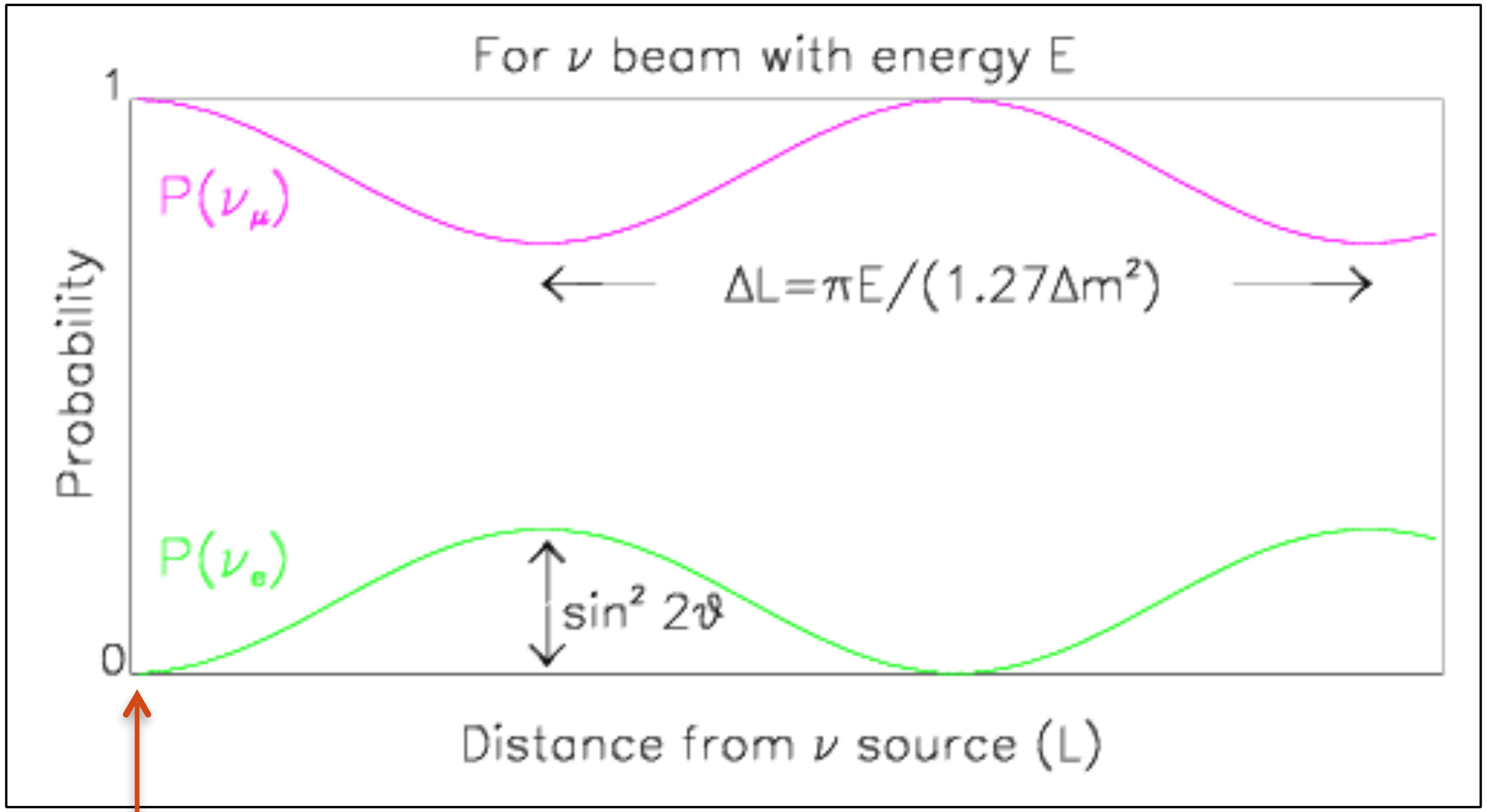
$s_{lk} = \sin\theta_{lk}$

- **Measured by atmospheric and accelerator experiments (\theta_23 ~ 45)**
- **Measured by reactors and accelerators experiments (\theta_13 ~ 9)**
- **Measured by solar experiment (\theta_12 ~ 34)**

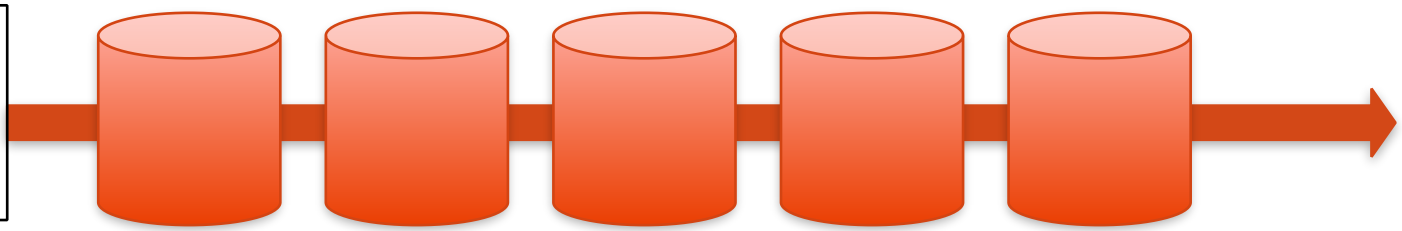
Neutrinos: Oscillations

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Fixed energy E
Variable L



Begin with mono-energetic ν_α



Many detectors and measure the content ν_α / ν_β

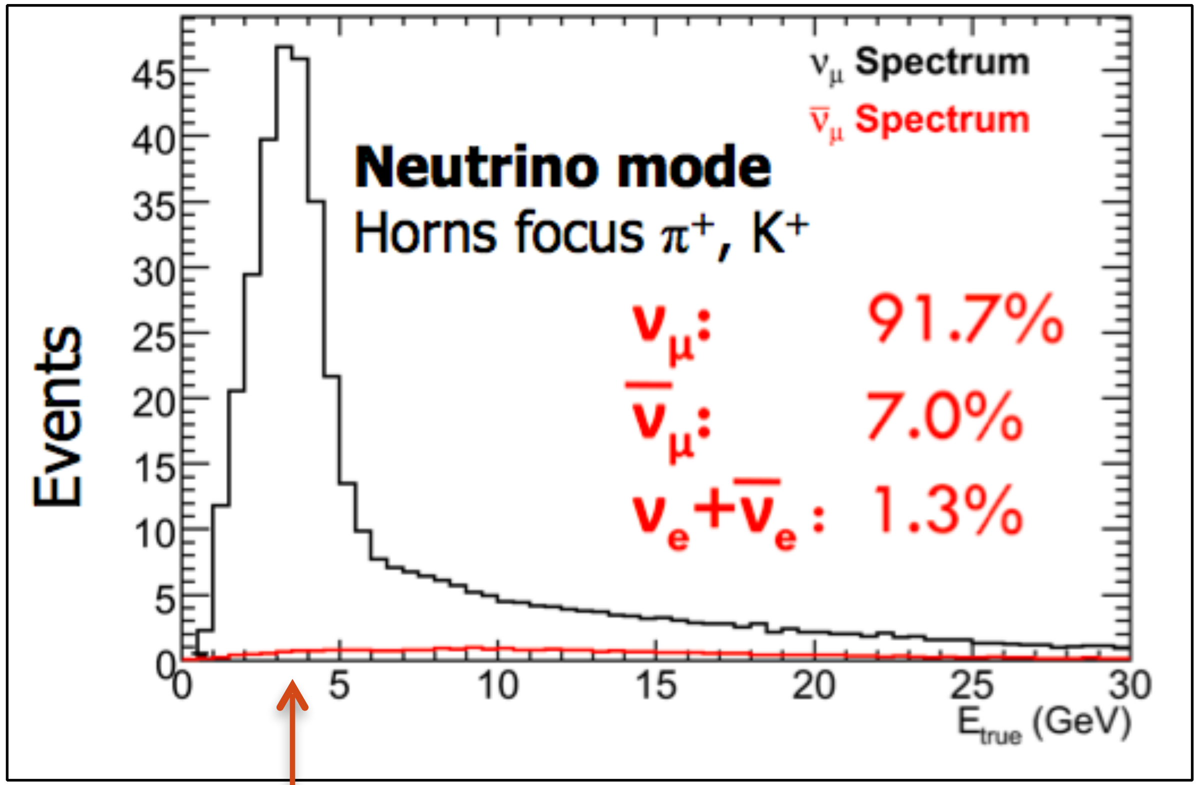
Message:

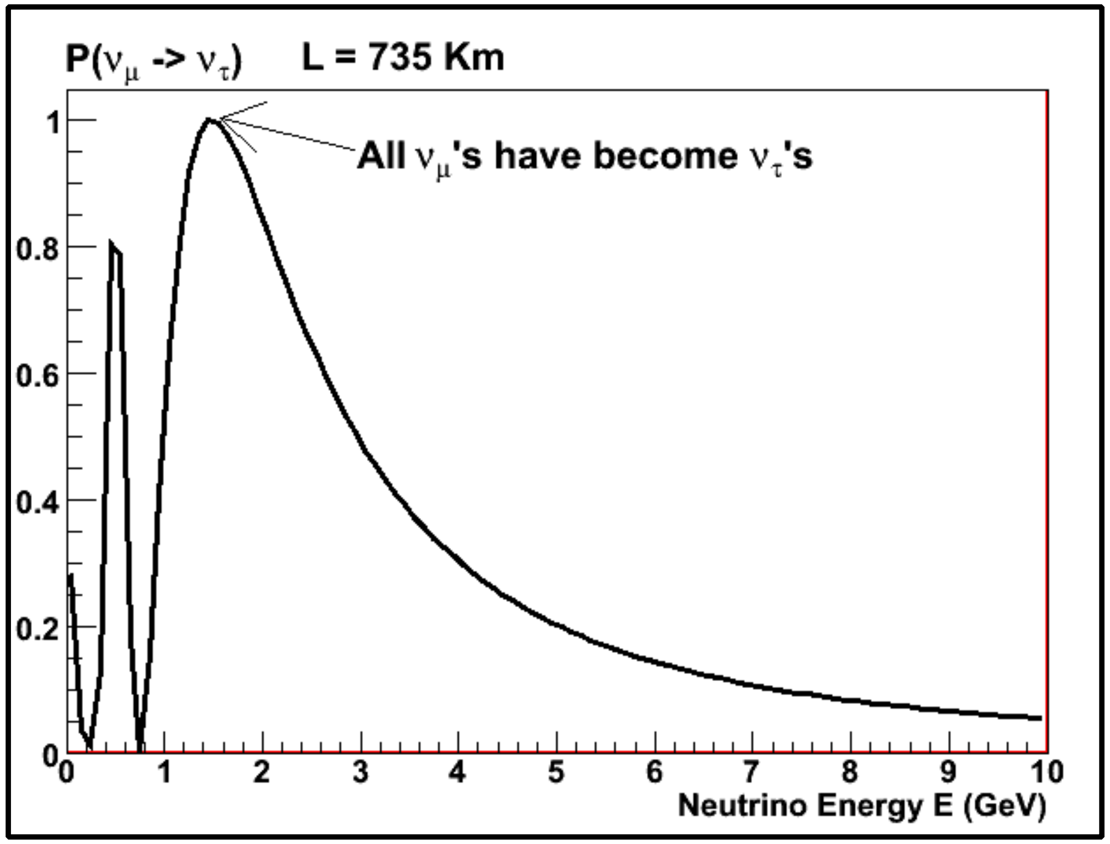
Nice idea but $$$

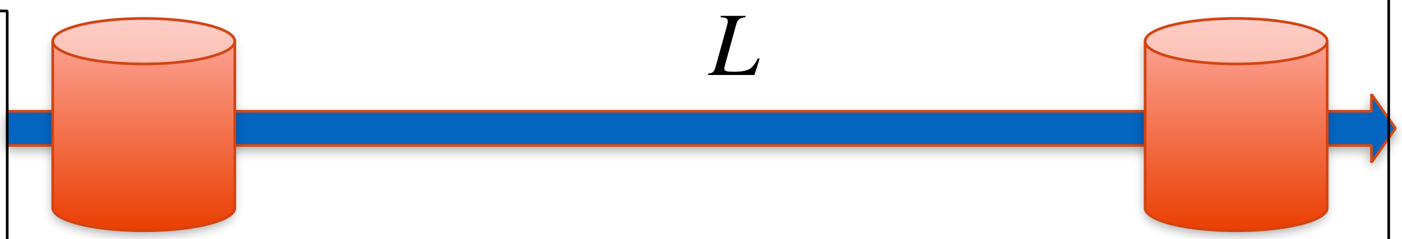
Neutrinos: Oscillations

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Fixed L
Energy
variable E





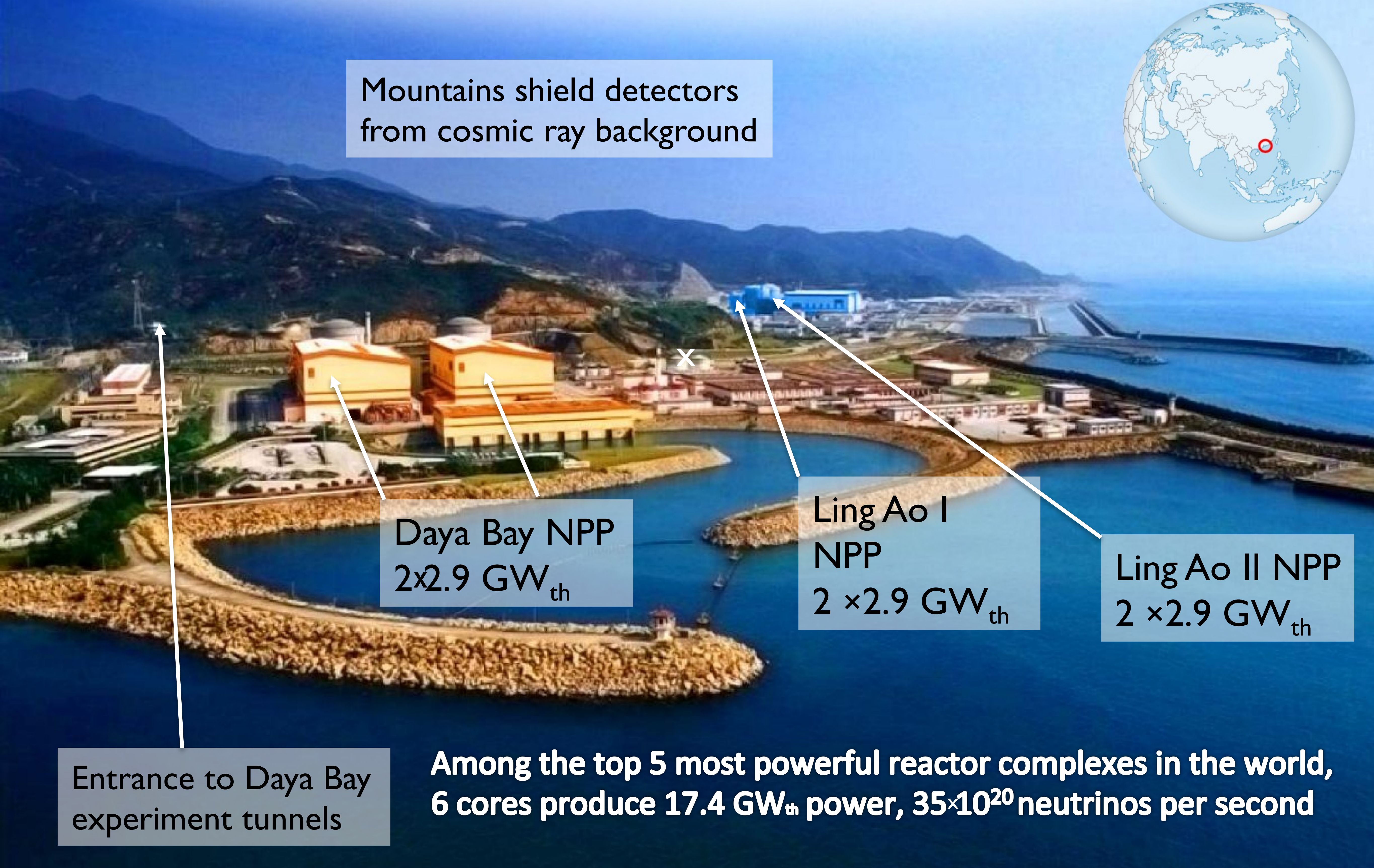


Begin with broad energy spectrum beam of ν_α

Measure ν_α / ν_β energy spectrum at origin and again after traveling a distance L

Reactor Neutrino Experiments: Daya Bay

A Powerful Neutrino Source at an Ideal Location



Mountains shield detectors from cosmic ray background

Daya Bay NPP
2x2.9 GW_{th}

Ling Ao I
NPP
2 ×2.9 GW_{th}

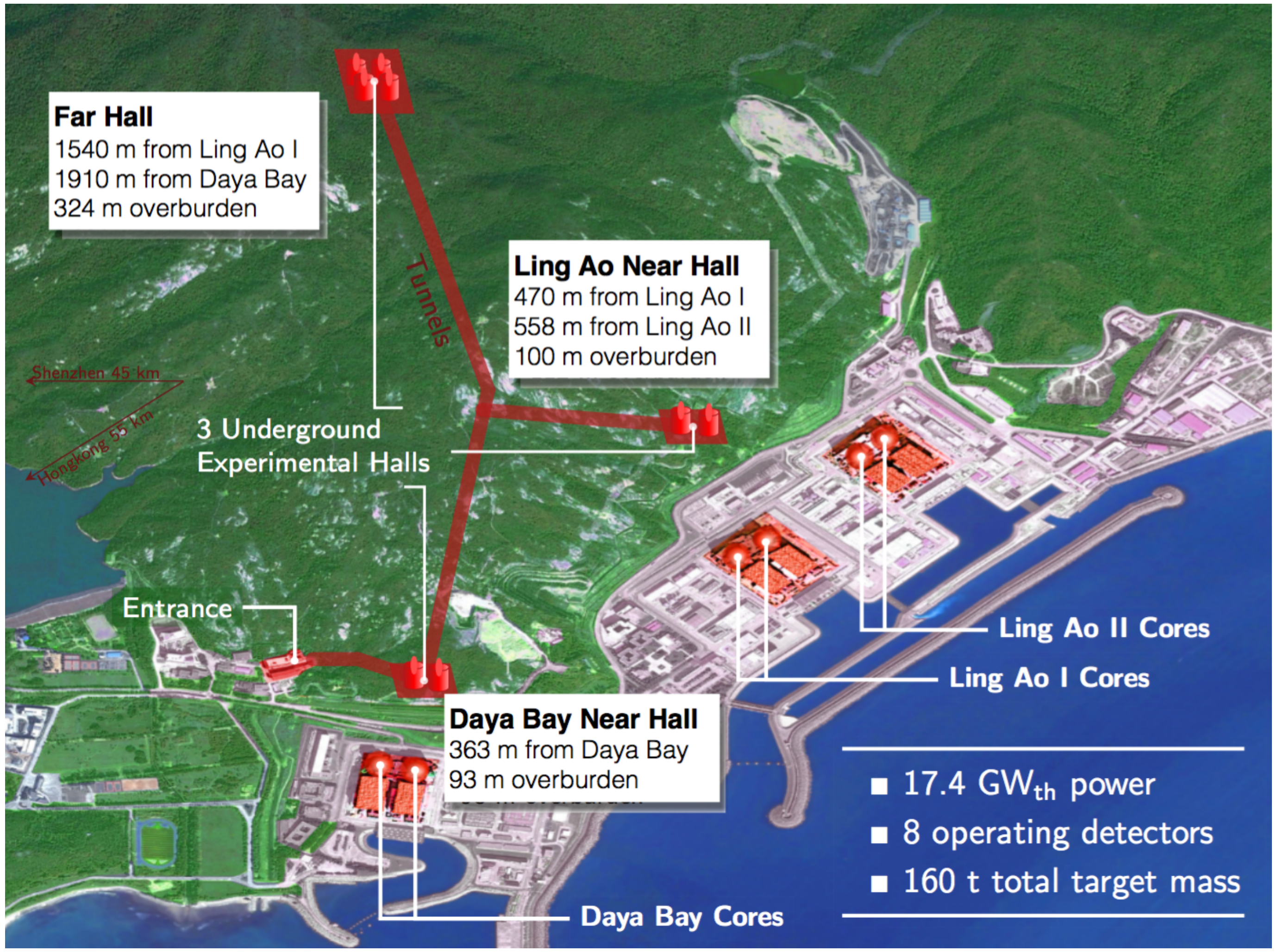
Ling Ao II NPP
2 ×2.9 GW_{th}

Entrance to Daya Bay experiment tunnels

Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW_{th} power, 35×10^{20} neutrinos per second

Daya Bay Layout

- Original concept with 8 ‘identical’ detectors:
  - Near detectors constrain flux.
  - Far detectors see if any neutrinos have disappeared.
- Daya Bay has ideal features for doing this!

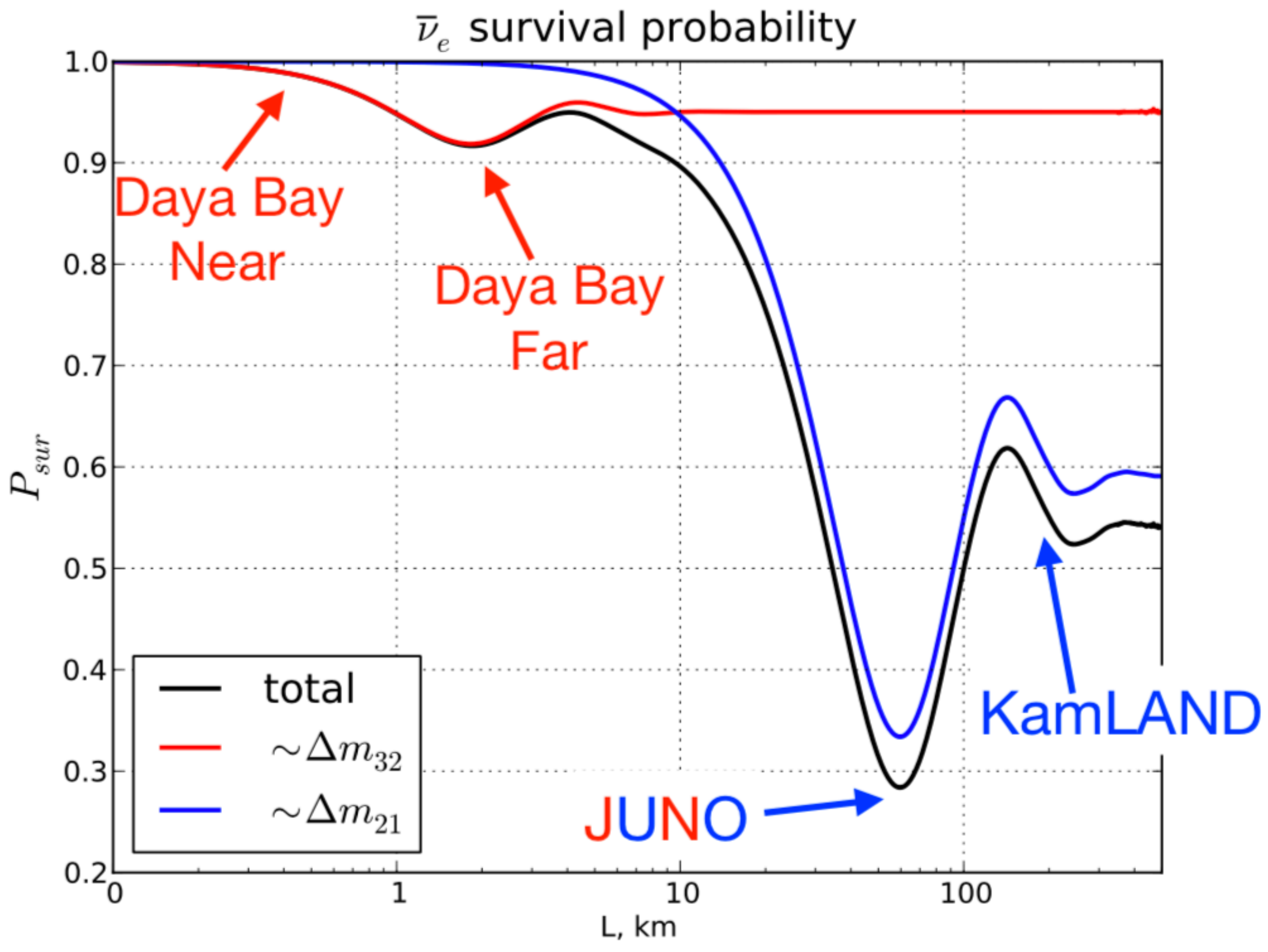


	Reactor [GW$_{th}$]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

Daya Bay Motivation

- Daya Bay was designed to measure θ_{13}
- Measurement of θ_{13} required:
  - High statistics
  - Suppression/Understanding of backgrounds
  - Clear understanding of major source of systematics
    - Construct detectors as similar as possible
    - Relative near/far measurements

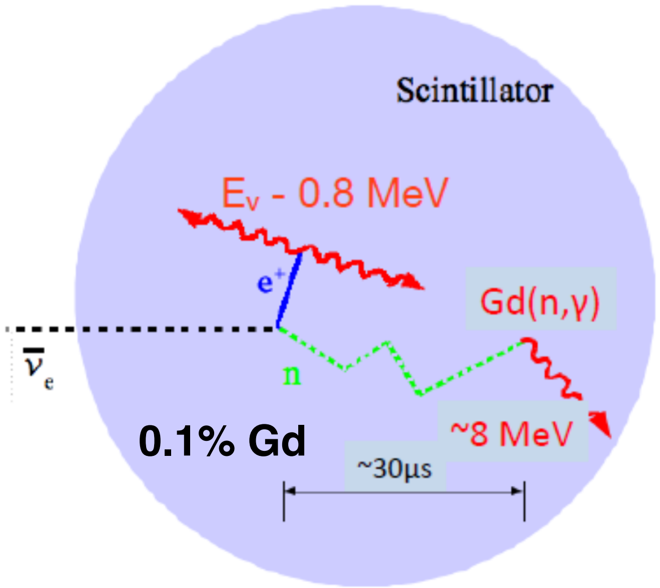
$$\begin{aligned} P &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\ &\simeq 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}} \\ &\quad - \boxed{\sin^2 2\theta_{13}\sin^2\Delta_{ee},} \end{aligned}$$

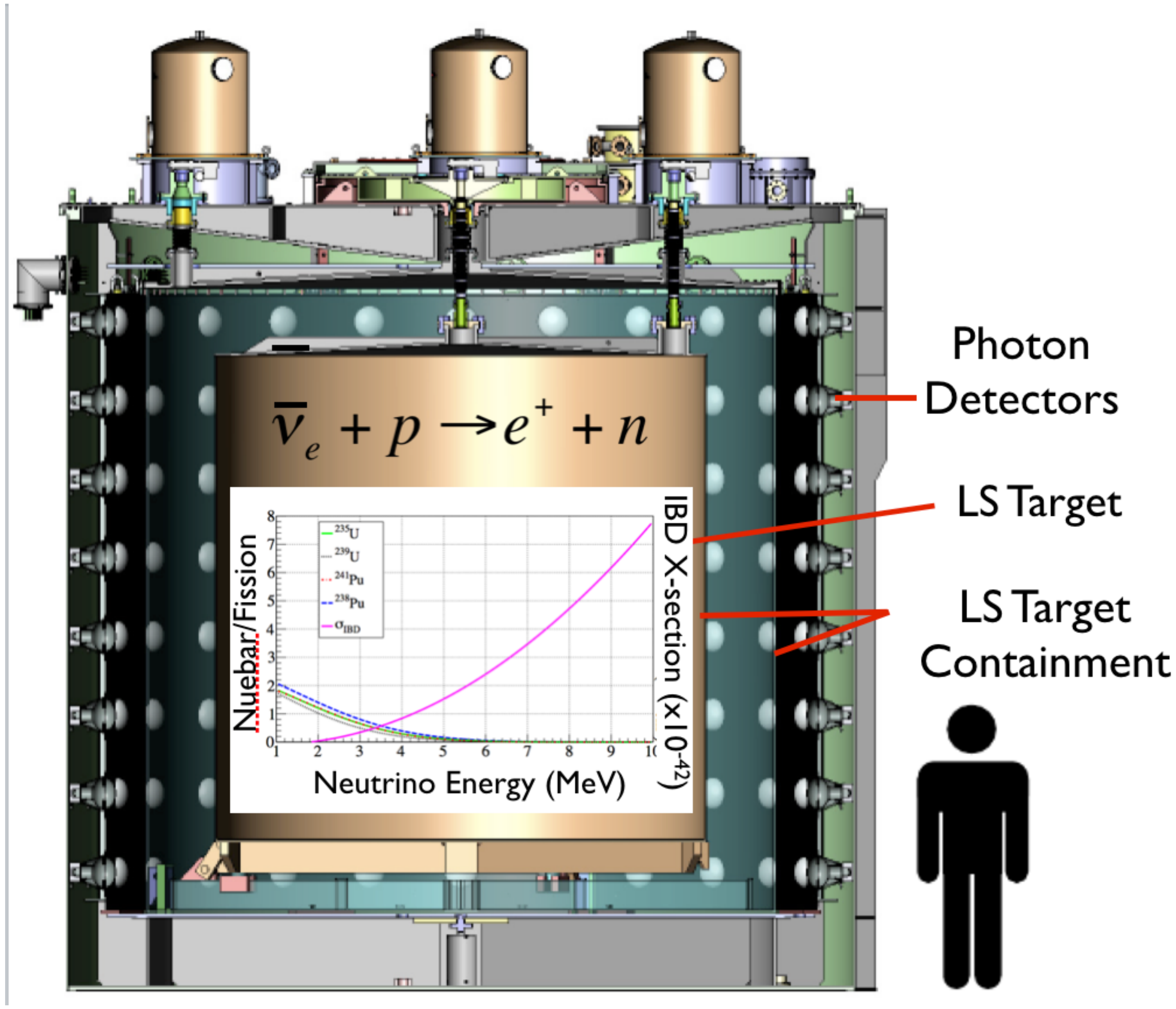


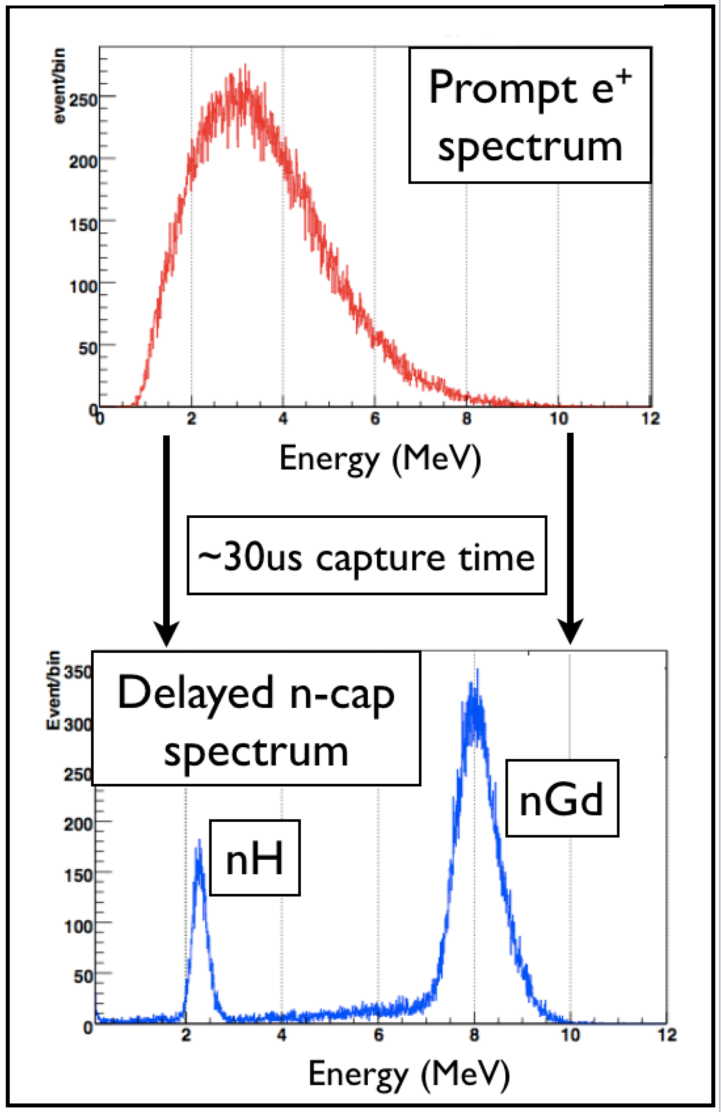
The Daya Bay antineutrino detector

$$\overline{\nu}_e + p \to \underline{e^+} + \underline{n}$$

- Detect inverse beta decay (IBD) with liquid scintillato
- Coincidence of the prompt scintillation from the positron and the delayed neutron capture on Gadolinium provides a distinctive ν_e signature.
- IBD positron is direct proxy for antineutrino energy







The Daya Bay antineutrino detector

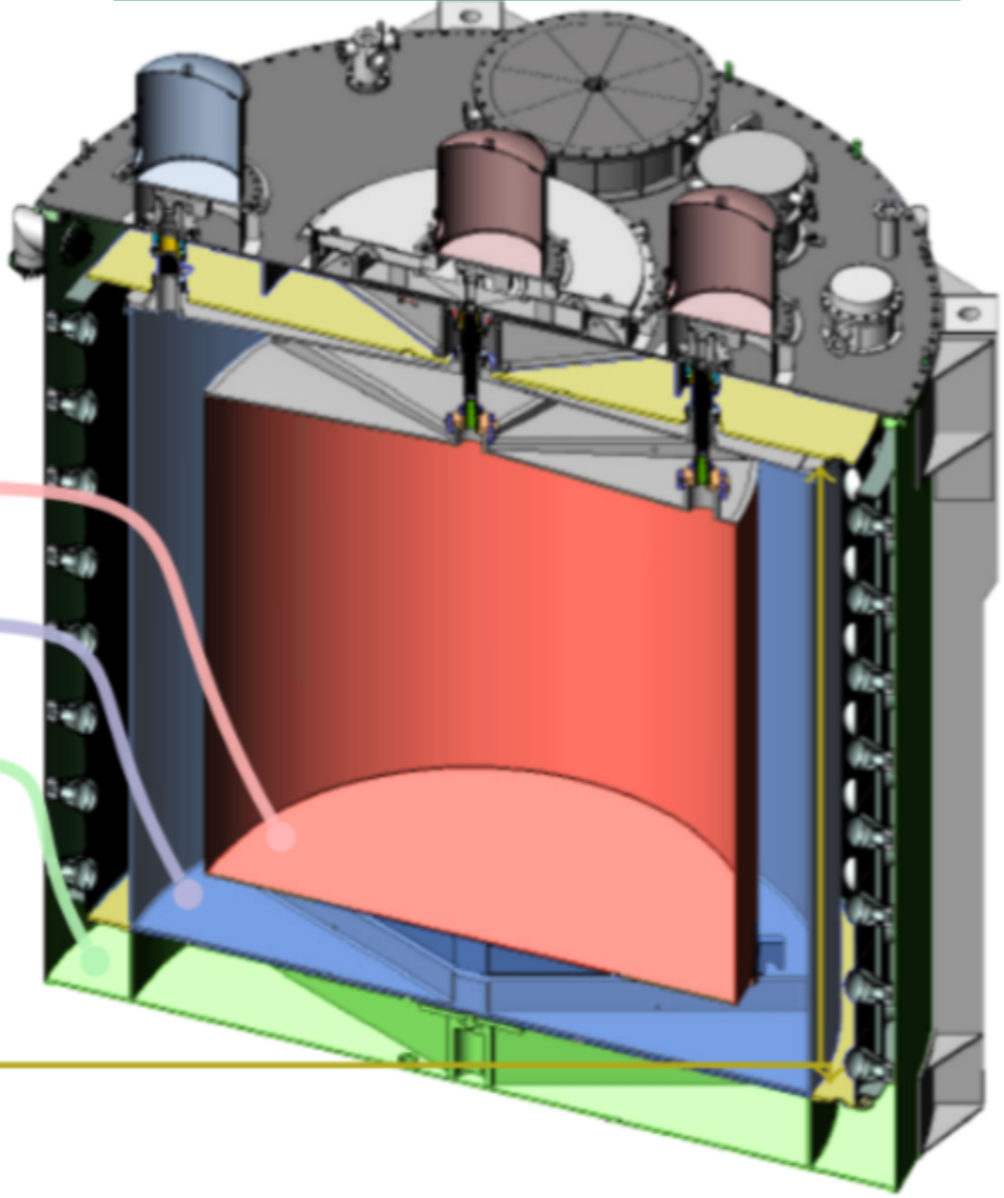
3 calibration units per detector.
3 sources per unit:
Ge68 (1.02 MeV)
Co60 (2.5 MeV)
Am241-C13(8 MeV)

8 functionally identical detectors
reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

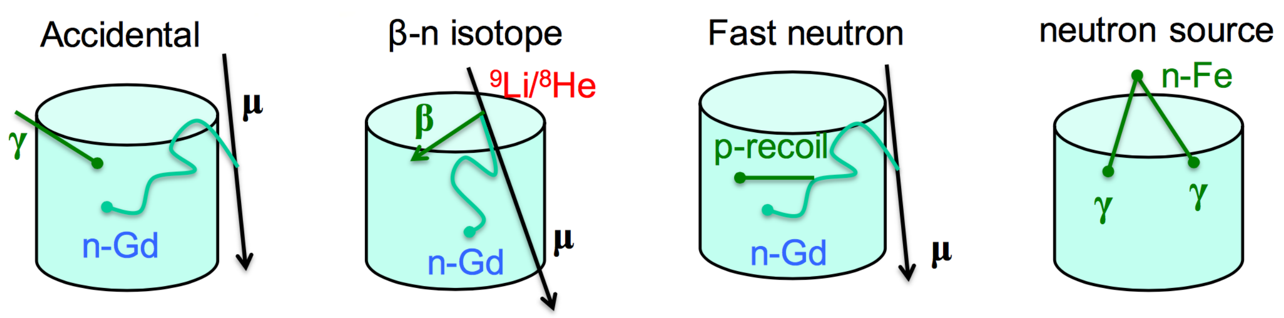
Top and bottom reflectors increase light yield
and flatten detector response



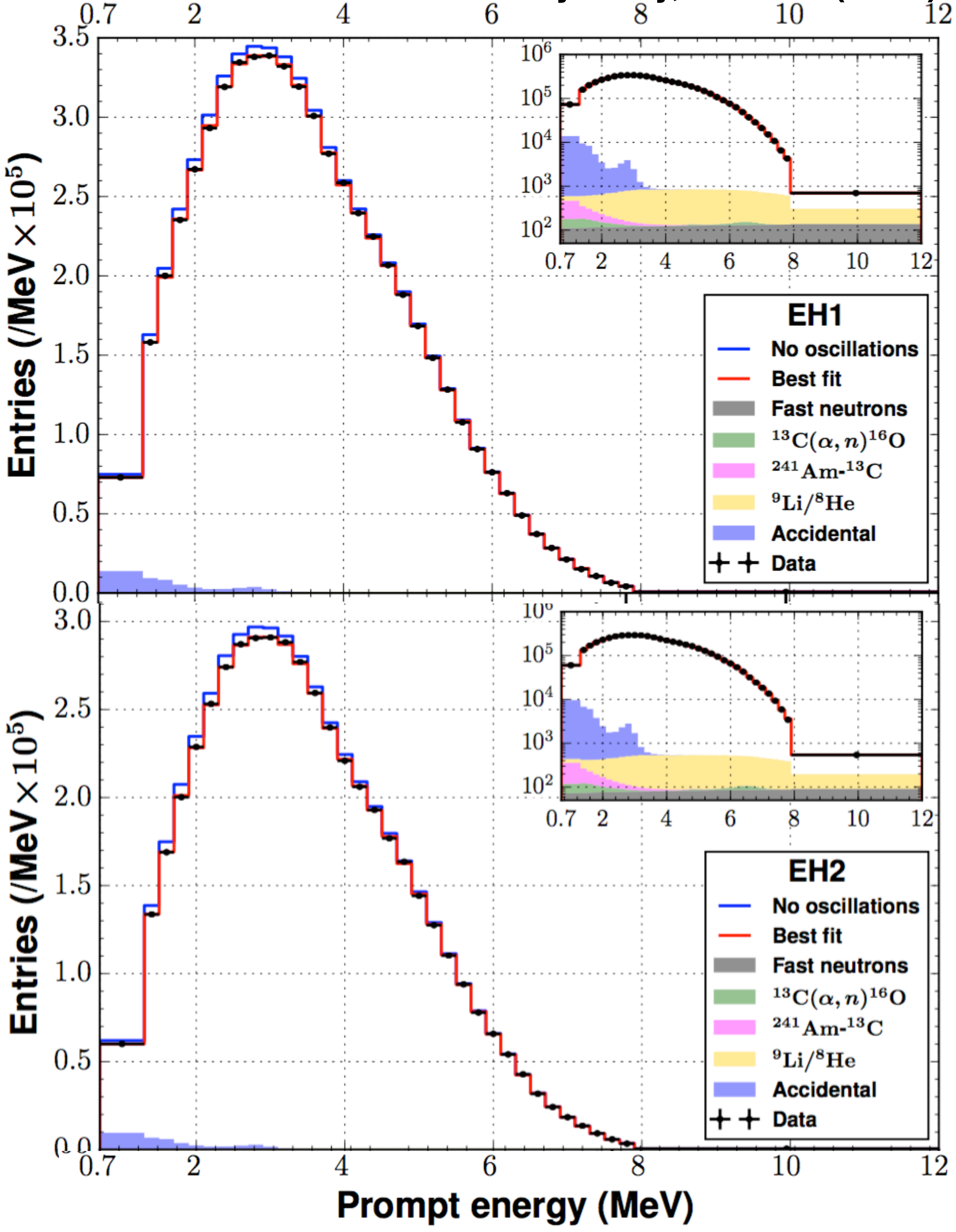
Backgrounds

- Backgrounds make up <2% of Near Site IBD candidates
- Primary background: accidentally coincident triggers
  - 1.3% of near-site signal;
  - Other backgrounds ~0.5%.

Sites	B/S ratio	Background uncertainty
Daya Bay	1.8%	0.2%
Ling Ao	1.5%	0.15%



Daya Bay, PRD 95 (2017)

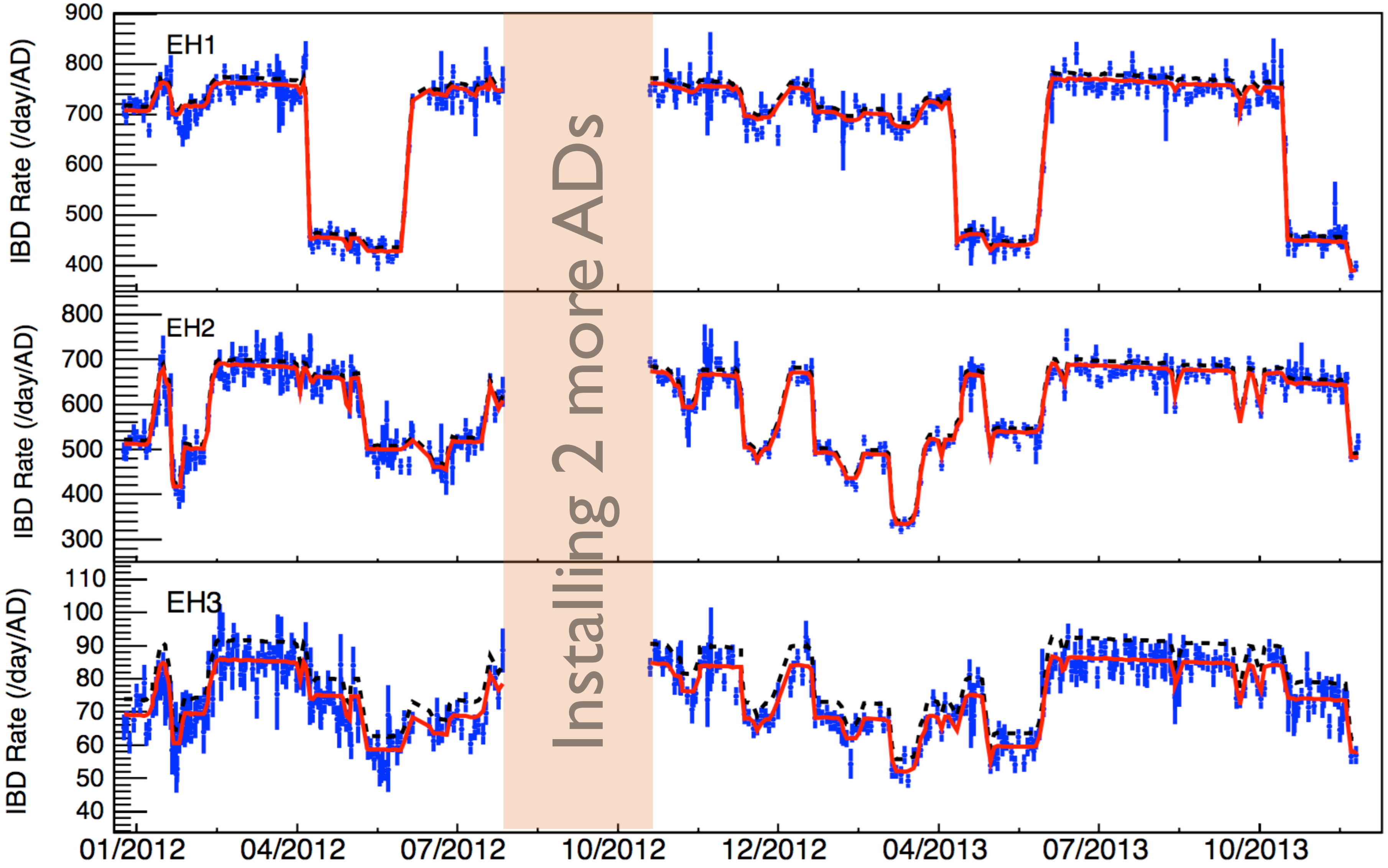


Daya Bay, PRD 95 (2017)

IBD candidate rates

- ~ 400-800 IBDs in each near site antineutrino detector per day (x4 ADs)
- Can see when reactors are turned on and off

Daya Bay, Chin. Phys. C 41(1) (2017)

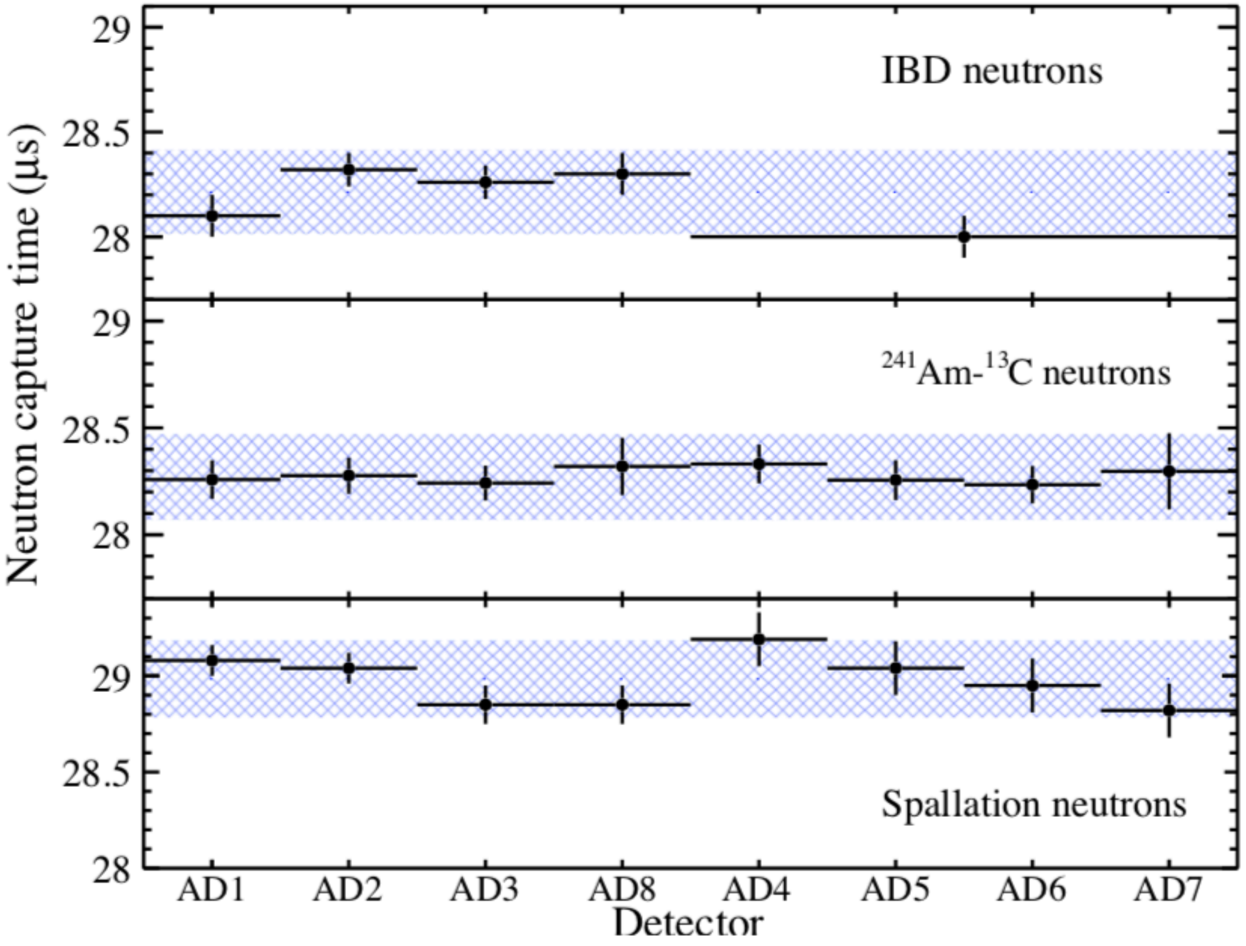


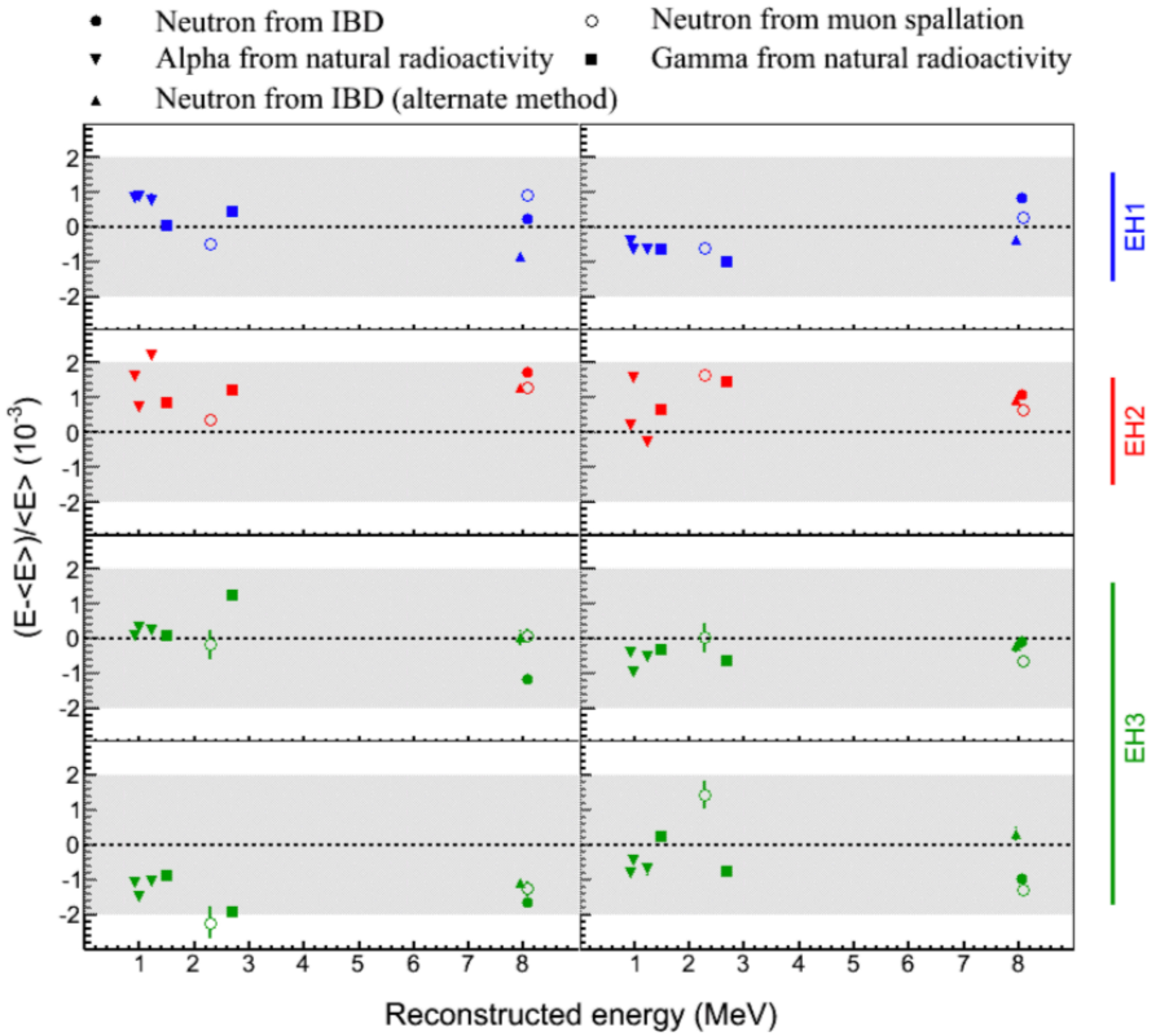
Info:
1230-day dataset
goes to July 2015

David Martinez Caicedo - SDSMT

Systematics:Relative Detection Efficiency

- Relative energy scale uncertainty and relative detection efficiency uncertainty are the dominant systematics for Δm^2_{ee} and $sin^2 2\theta_{13}$
- Achieved a relative detection efficiency uncertainty of 0.13%





Relative Gd capture fraction uncertainty < 0.10%

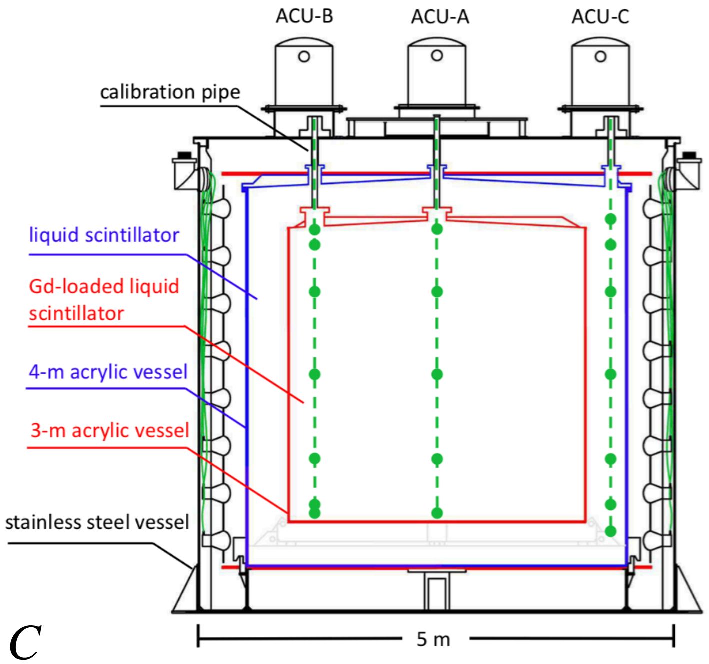
Relative energy scale uncertainty <0.2%

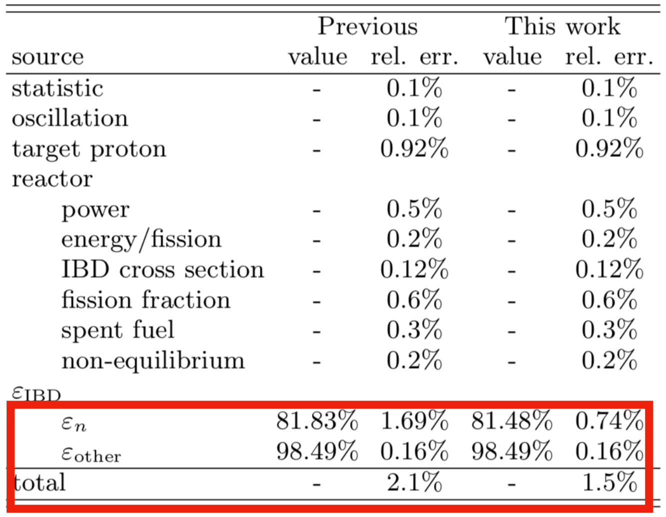
Systematics: Neutron Detection Efficiency

- **Uncertainty on neutron detection efficiency was reduced 56%**
  - New neutron calibration data (Calibration campaign late 2016/ early 207)
  - Deployed two neutron sources ($^{241}Am -^{13}C$ and $^{241}Am -^{9}Be$ along 3 vertical calibration axis)
- Confirmed reactor flux anomaly: ~5% deficit in Data/Prediction (Huber-Mueller)
- Data/Prediction is consistent with previous short baseline experiments

$$R_{\text{data/pred}} = 0.952 \pm 0.014(\text{exp.}) \pm 0.023(\text{model})$$

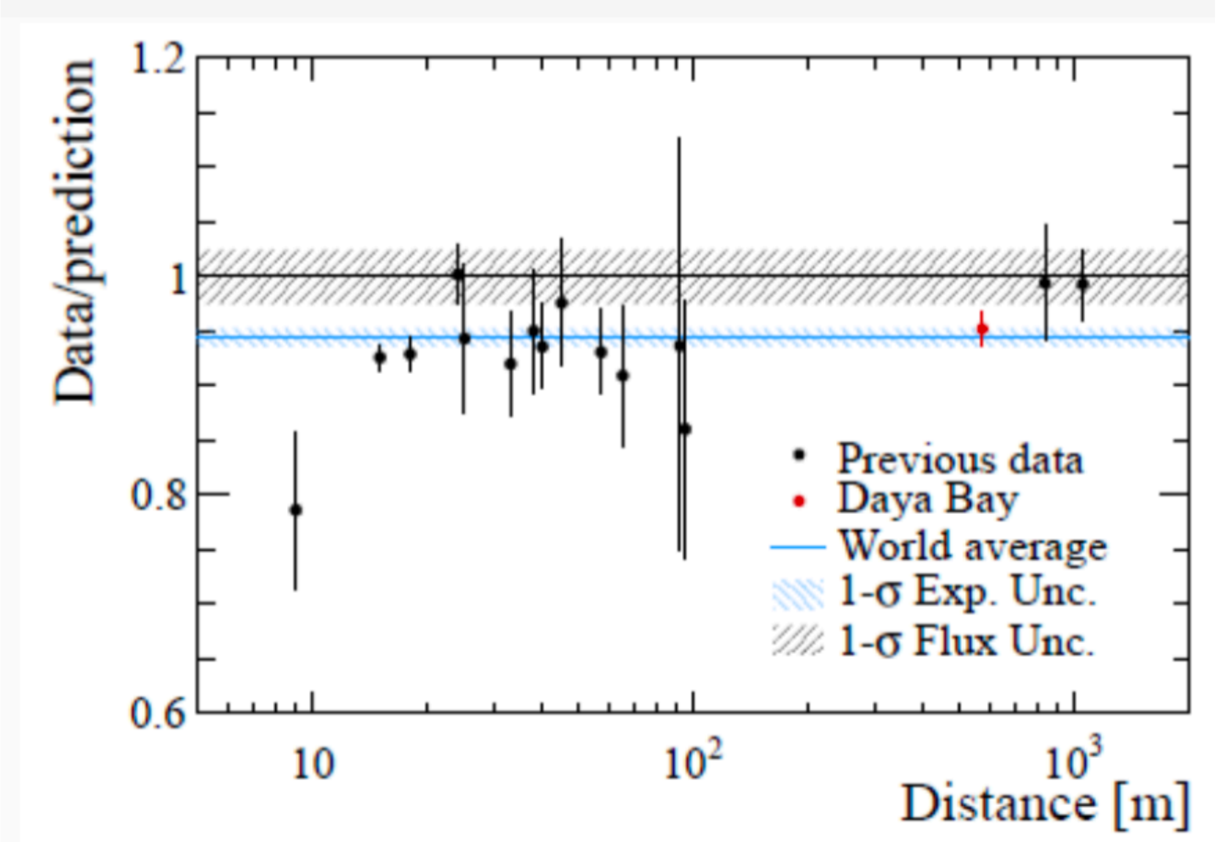
$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43} \text{ cm}^2/\text{ fission}$$



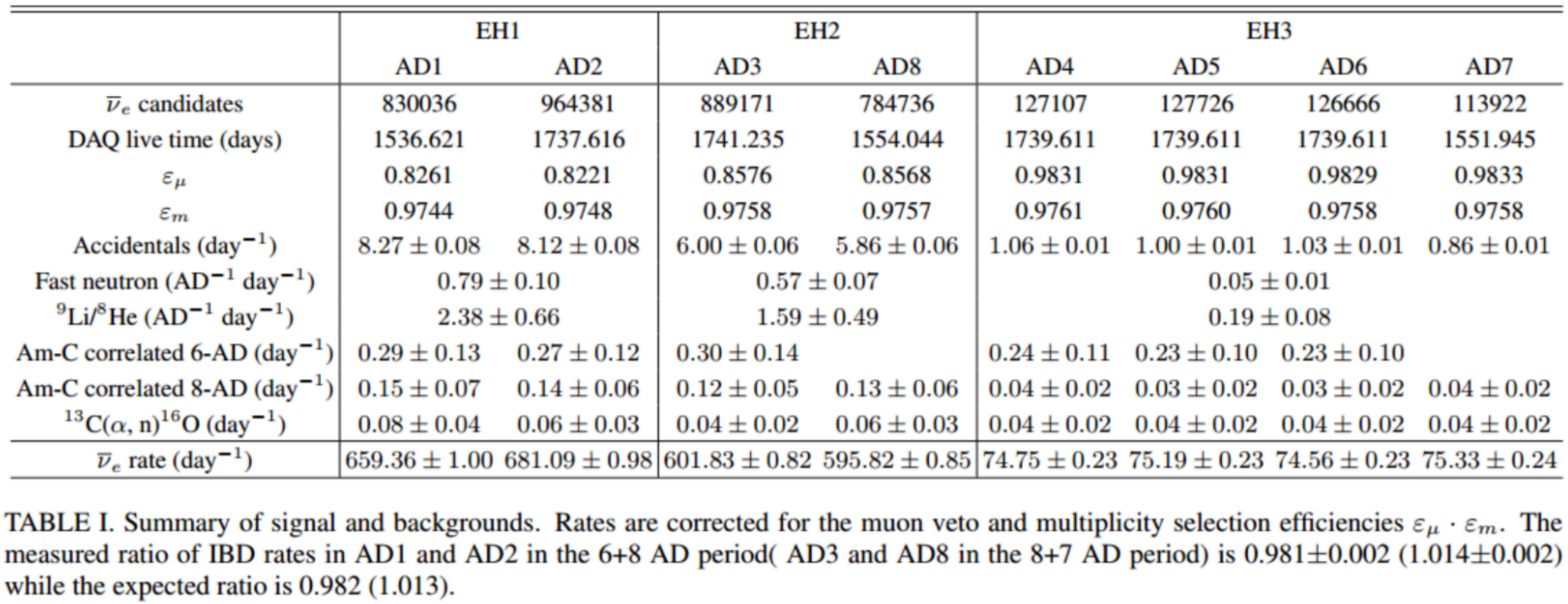


source	Previous value	Previous rel. err.	This work value	This work rel. err.
statistic	-	0.1%	-	0.1%
oscillation	-	0.1%	-	0.1%
target proton	-	0.92%	-	0.92%
reactor				
power	-	0.5%	-	0.5%
energy/fission	-	0.2%	-	0.2%
IBD cross section	-	0.12%	-	0.12%
fission fraction	-	0.6%	-	0.6%
spent fuel	-	0.3%	-	0.3%
non-equilibrium	-	0.2%	-	0.2%
ε_{IBD}				
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\text{other}}$	98.49%	0.16%	98.49%	0.16%
total	-	2.1%	-	1.5%

- Phys. Rev. D **100**, 052004 (2019)



Dataset: 1958 days of data sample



	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
ε_μ	0.8261	0.8221	0.8576	0.8568	0.9831	0.9831	0.9829	0.9833
ε_m	0.9744	0.9748	0.9758	0.9757	0.9761	0.9760	0.9758	0.9758
Accidentals (day^{-1})	8.27 ± 0.08	8.12 ± 0.08	6.00 ± 0.06	5.86 ± 0.06	1.06 ± 0.01	1.00 ± 0.01	1.03 ± 0.01	0.86 ± 0.01
Fast neutron (AD^{-1} day^{-1})	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li/^{8}He (AD^{-1} day^{-1})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated 6-AD (day^{-1})	0.29 ± 0.13	0.27 ± 0.12	0.30 ± 0.14		0.24 ± 0.11	0.23 ± 0.10	0.23 ± 0.10	
Am-C correlated 8-AD (day^{-1})	0.15 ± 0.07	0.14 ± 0.06	0.12 ± 0.05	0.13 ± 0.06	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
^{13}C(α, n)^{16}O (day^{-1})	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
$\overline{\nu}_e$ rate (day^{-1})	659.36 ± 1.00	681.09 ± 0.98	601.83 ± 0.82	595.82 ± 0.85	74.75 ± 0.23	75.19 ± 0.23	74.56 ± 0.23	75.33 ± 0.24

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of IBD rates in AD1 and AD2 in the 6+8 AD period(AD3 and AD8 in the 8+7 AD period) is 0.981±0.002 (1.014±0.002) while the expected ratio is 0.982 (1.013).

- > 3.9 M of antineutrino interactions
- Statical error in antineutrino rates
  - ~0.11% in EH1, EH2
  - ~0.29% in EH3
- Background uncertainty antineutrino rates ~0.12% (all antineutrino detectors)

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

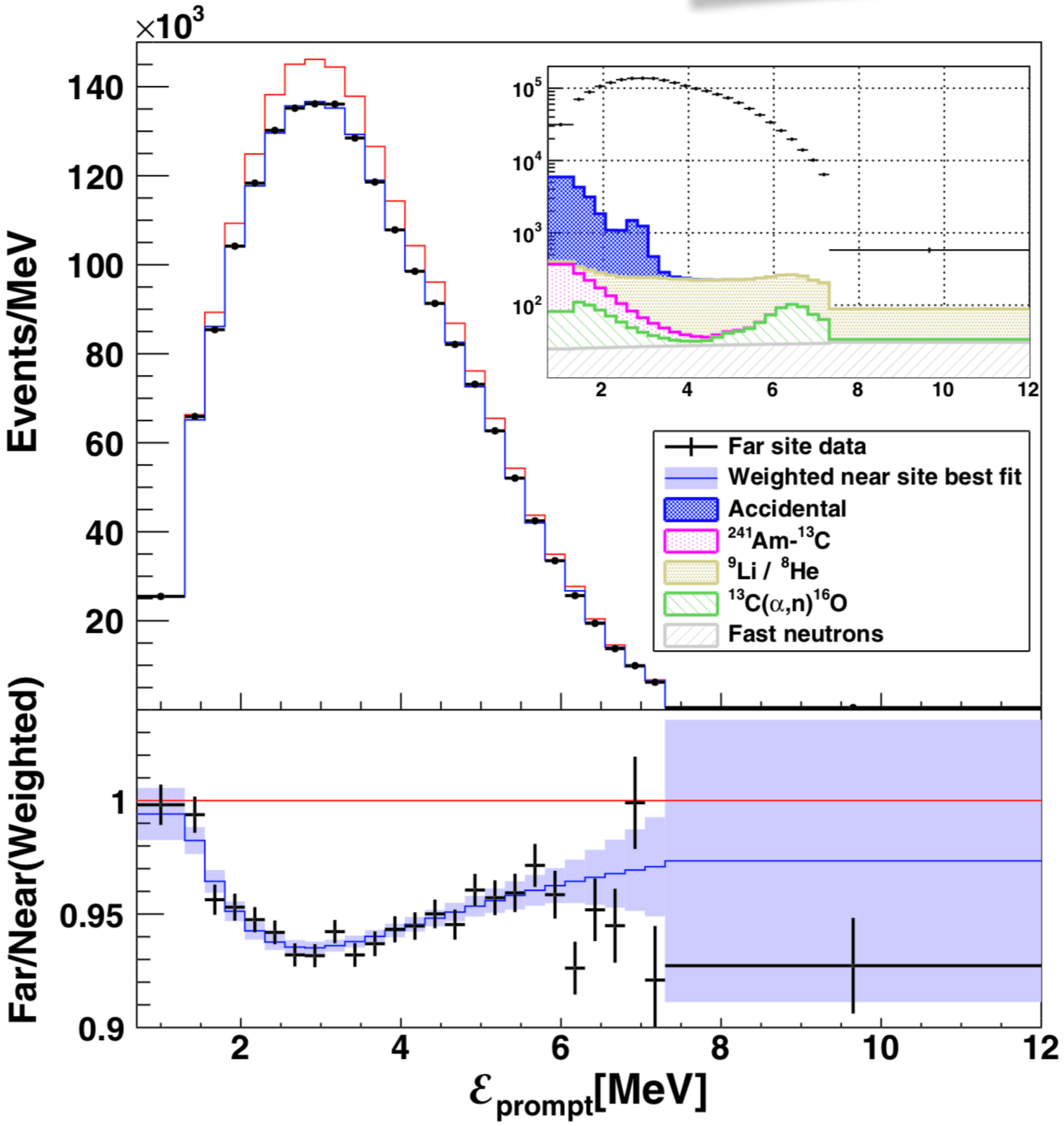
Daya Bay: Oscillation Results with 1958 Days

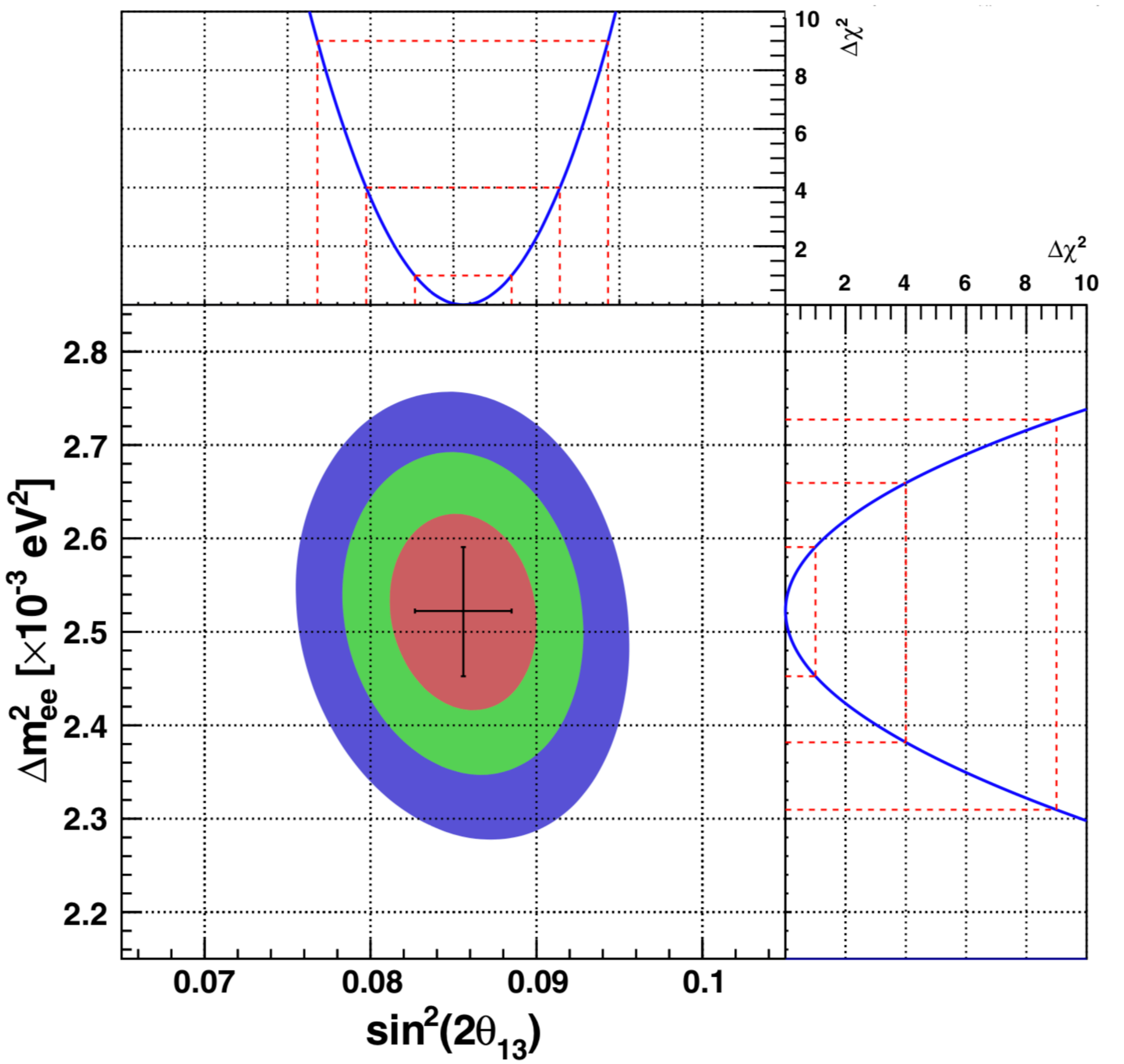
- $sin^2 2\theta_{13}$ uncertainty is 3.4% and Δm^2_{ee} uncertainty is 2.8%
- Statistical uncertainty contributes 60% for $sin^2 2\theta_{13}$ and 50% for Δm^2_{ee}
- Results were cross-checked with different independent analysis

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

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





Reactor Fuel evolution measurements
1230 days of data

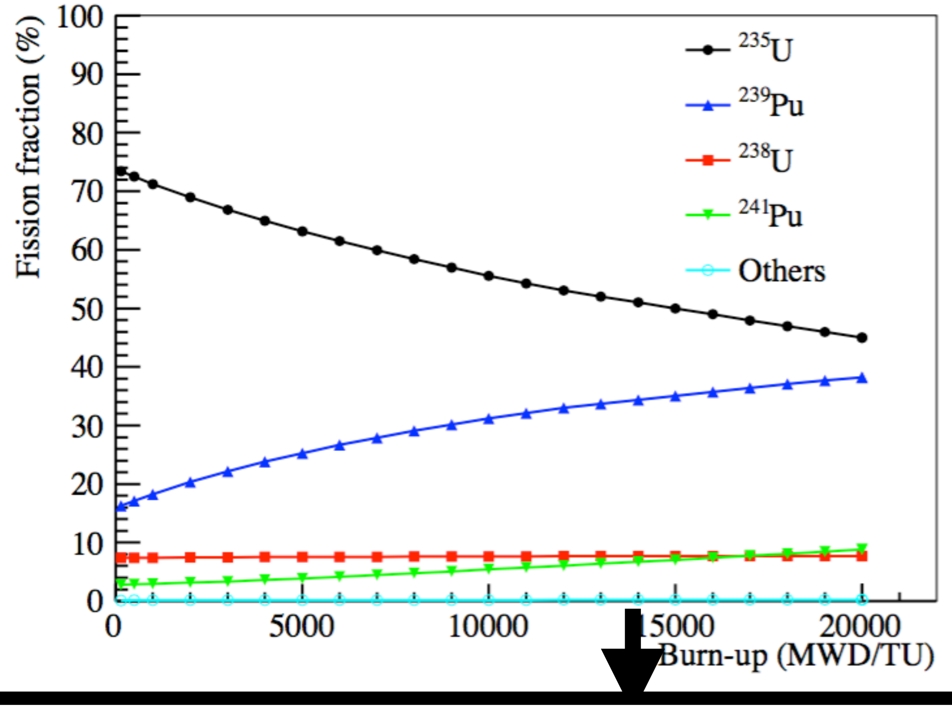
Daya Bay: Fuel evolution analysis

- DO NOT time integrate: instead, look at reactors' fission fractions
    - % of fissions from ^{235}U ^{239}Pu, ^{238}U, ^{241}Pu
- Calculate 'effective fission fraction' observed by each detector:

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

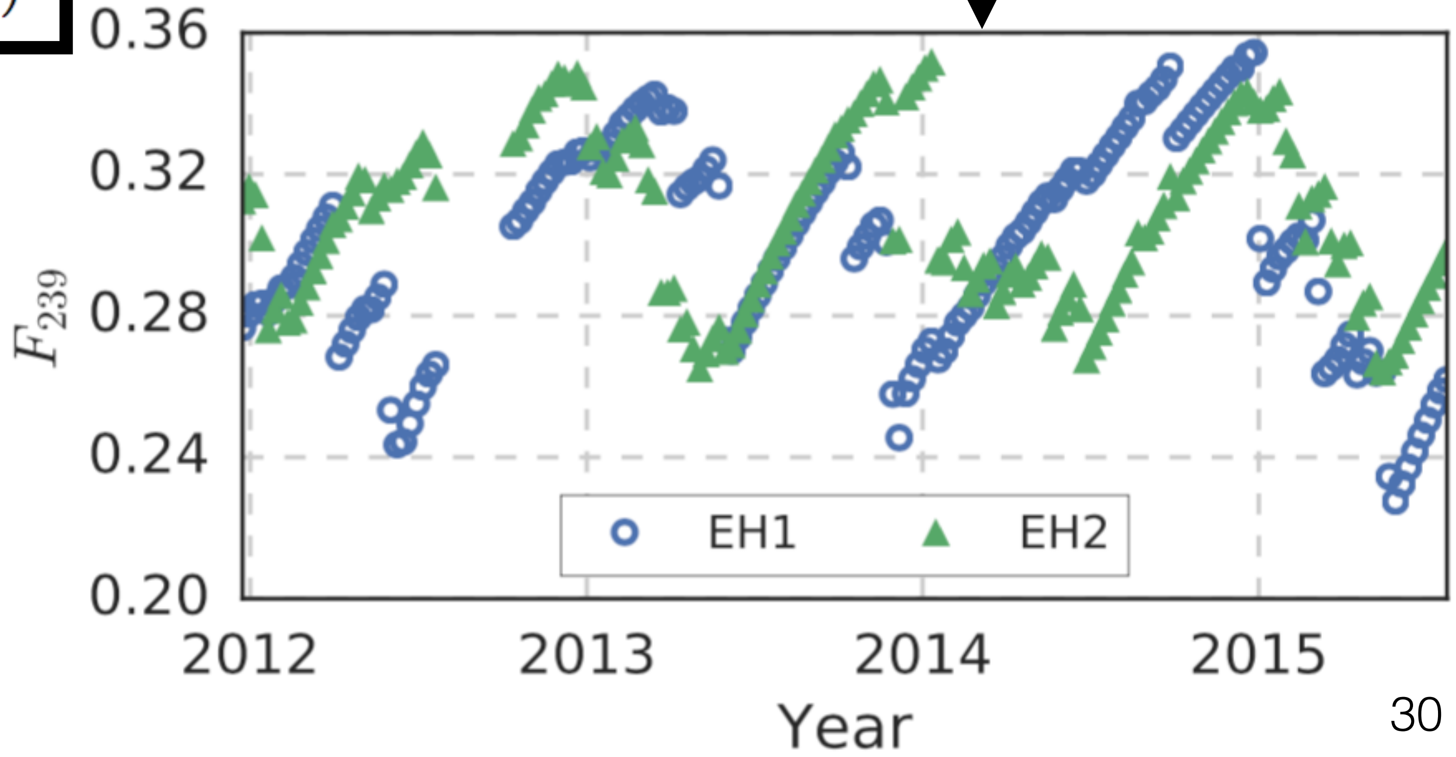
- Basically weight's each reactor's fission fraction by distance, power, and oscillation

Simulation of a complete refueling cycle



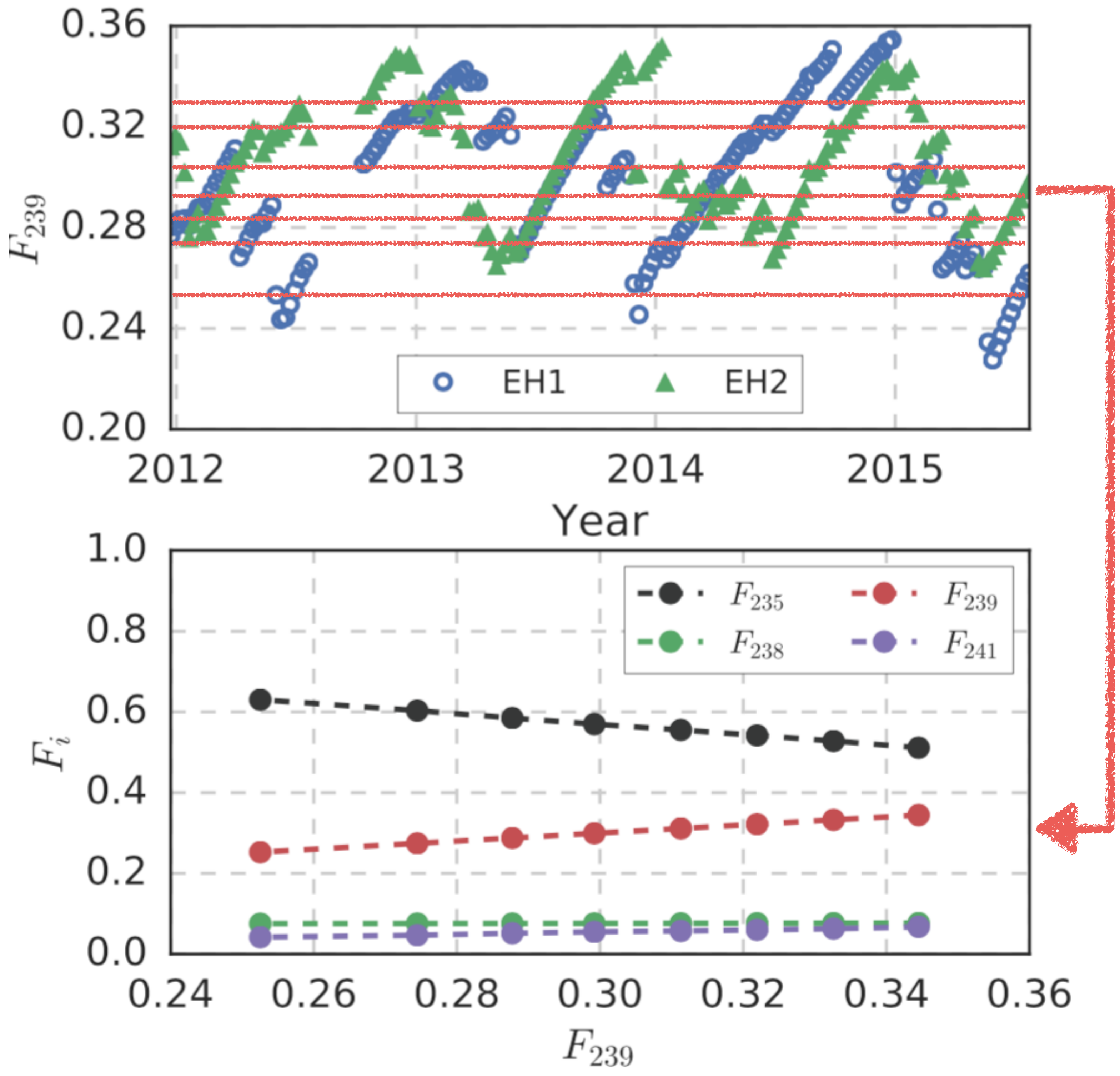
Daya Bay, Chin. Phys. C 41(1) (2017)

Weight for each of the 6 reactor cores



Daya Bay: Fuel evolution analysis

- We have fission fractions and IBDs versus time
- Let’s compare IBDs from periods of differing effective fission fractions!
- Doing this by combining periods of common fission fraction.
    - We choose 8 bins in ^{239}Pu effective fission fraction, F_{239}



From IBD/day to IBD/fission σ_f

- IBD/day depends on many time-dependent quantities:
    - Reactor status and thermal power
    - Power released per fission
    - Detector livetime
- Show final results in terms of IBD/fission
    - Basically take IBD/day and divide out all these variable quantities on a week-by-week basis

$$\boxed{\sigma_f = \sum_i F_i \sigma_i}$$

F_i : Effective fission fraction for each isotope

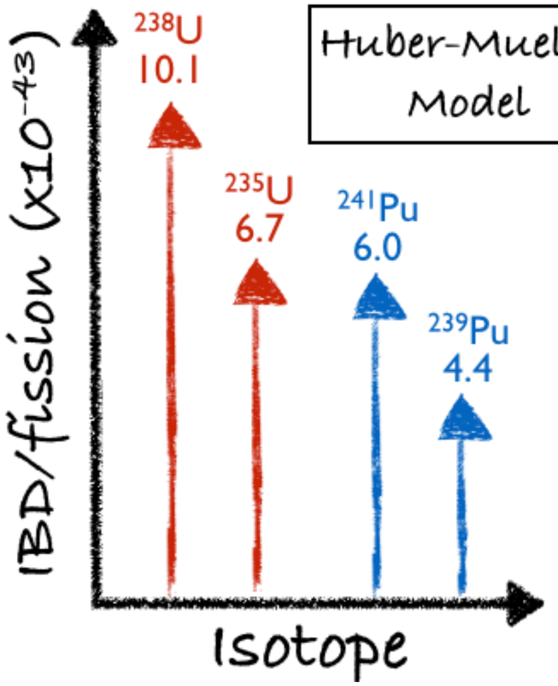
σ_i : IBD yield from each isotope

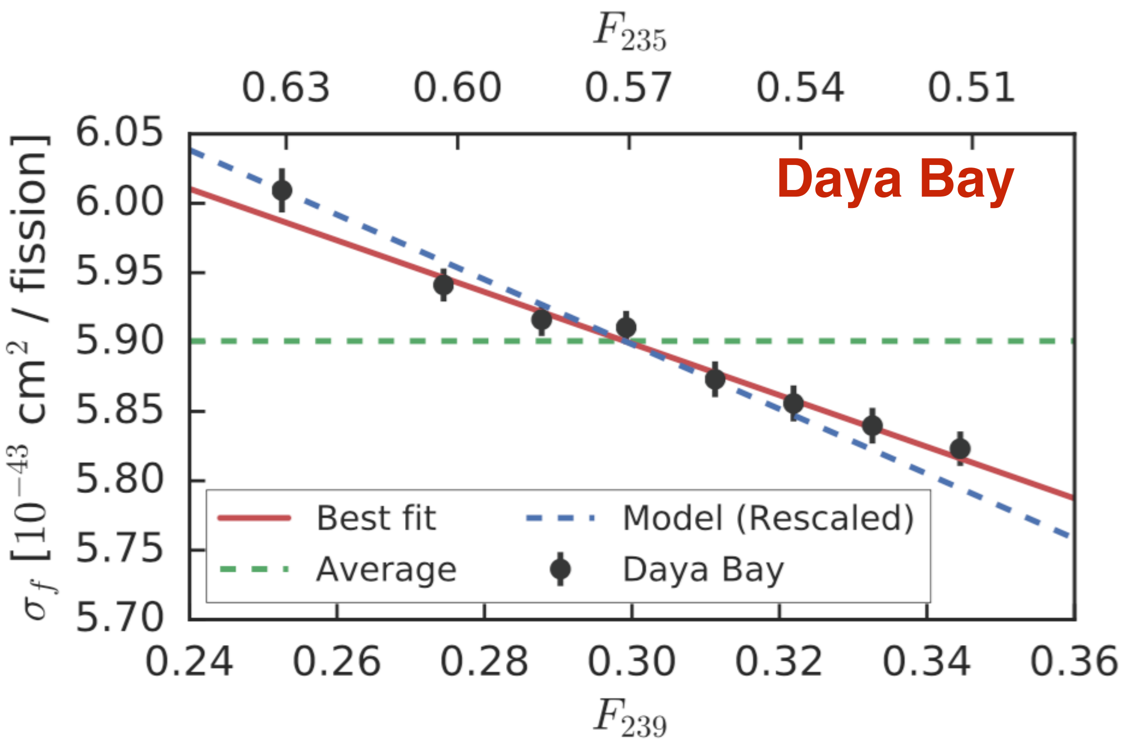
Results: Flux Evolution

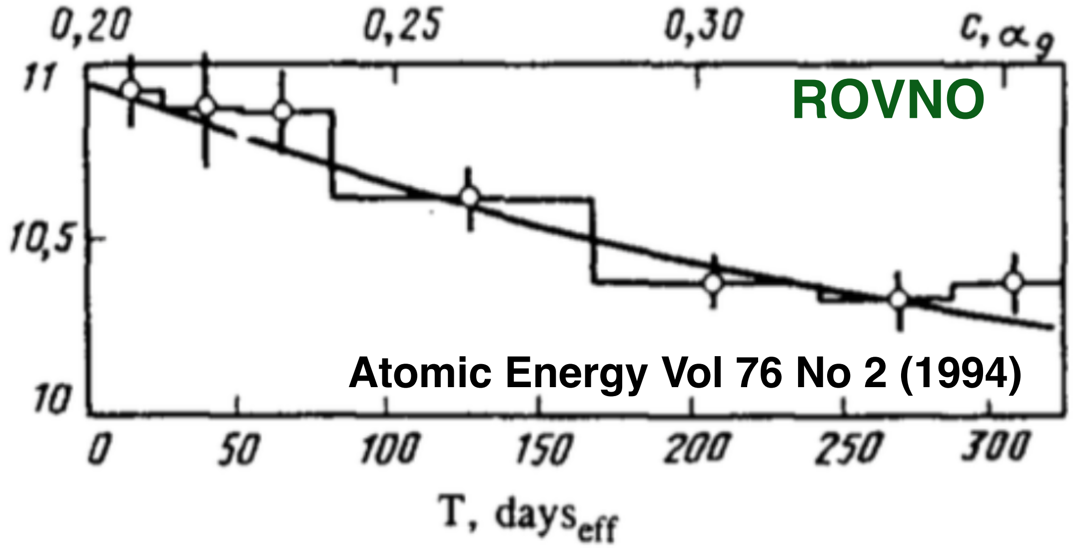
- **When plotting IBD/fission versus F_{239}, we see a slope in data**

- Very clear that flux is changing with changing fission fraction.

- Not too surprising; models predict ^{239}Pu makes fewer $\bar{\nu}_e$
  - Seen before in previous experiments: **Rovno (90's); SONGS (00's)**

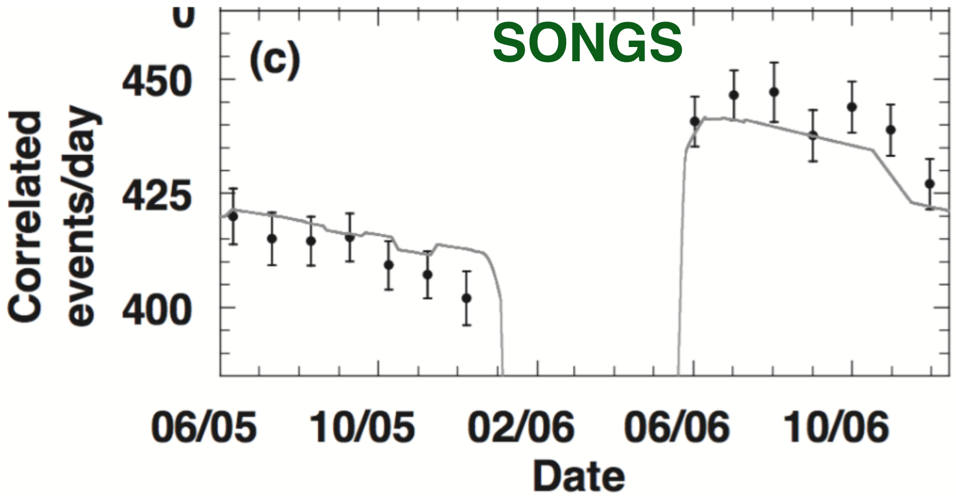






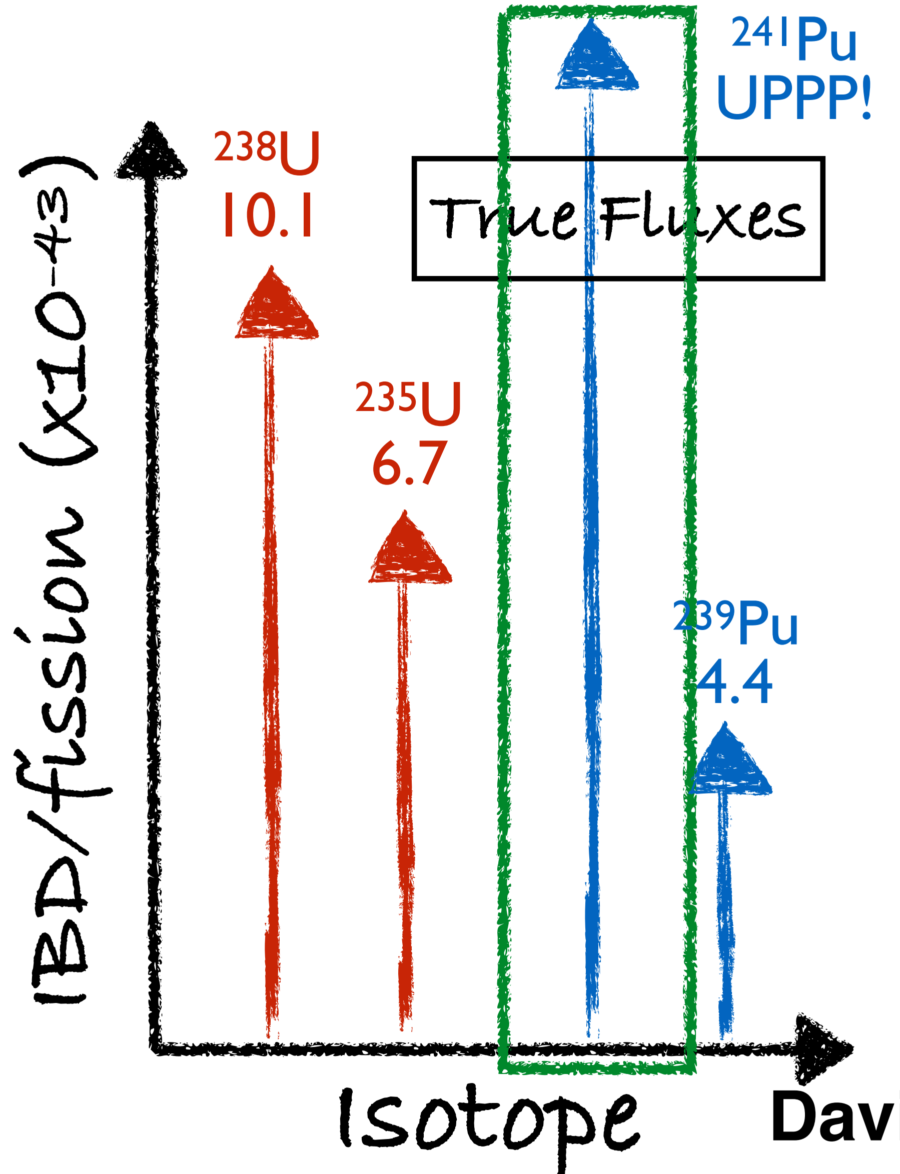
Atomic Energy Vol 76 No 2 (1994)

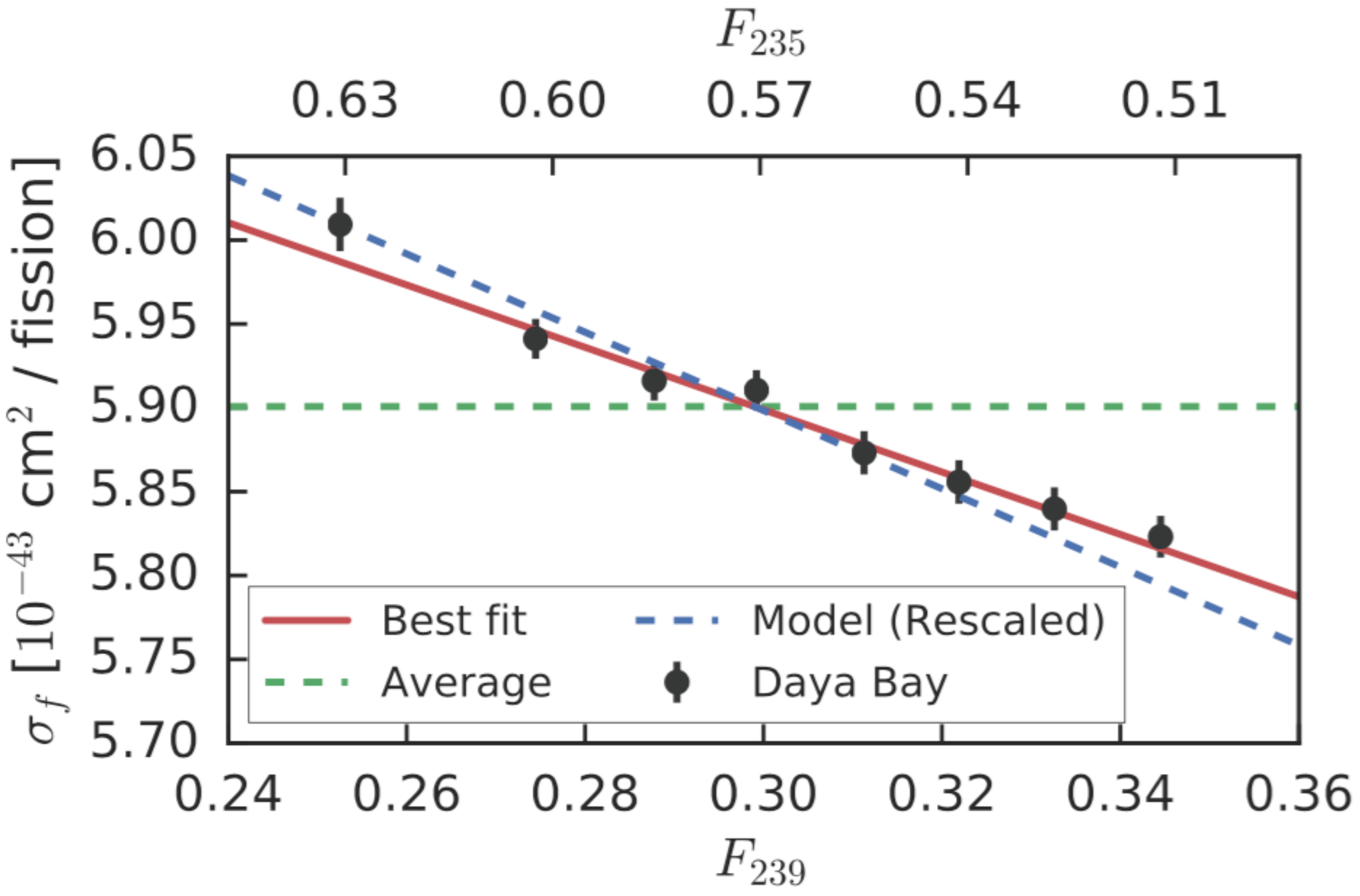
J. Appl. Phys. 105 064902



Result: Flux evolution

- **Measured slope is different than model prediction by 3.1 σ**
- Could mean a couple things:
  - ^{239}Pu prediction is too low
  - ^{235}U prediction is too high
  - Something is WAY off with ^{238}U, ^{241}Pu





Result: Flux evolution

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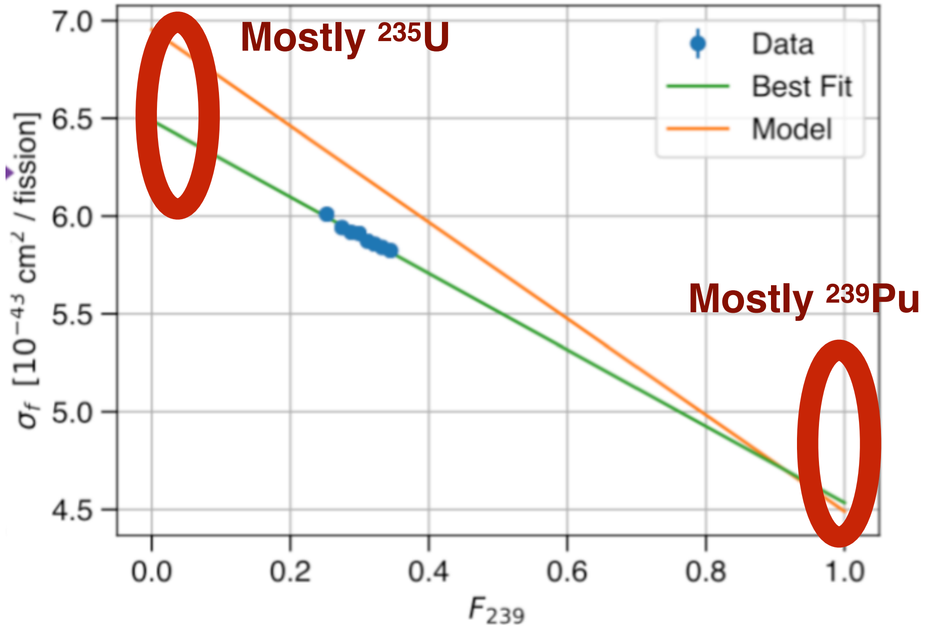
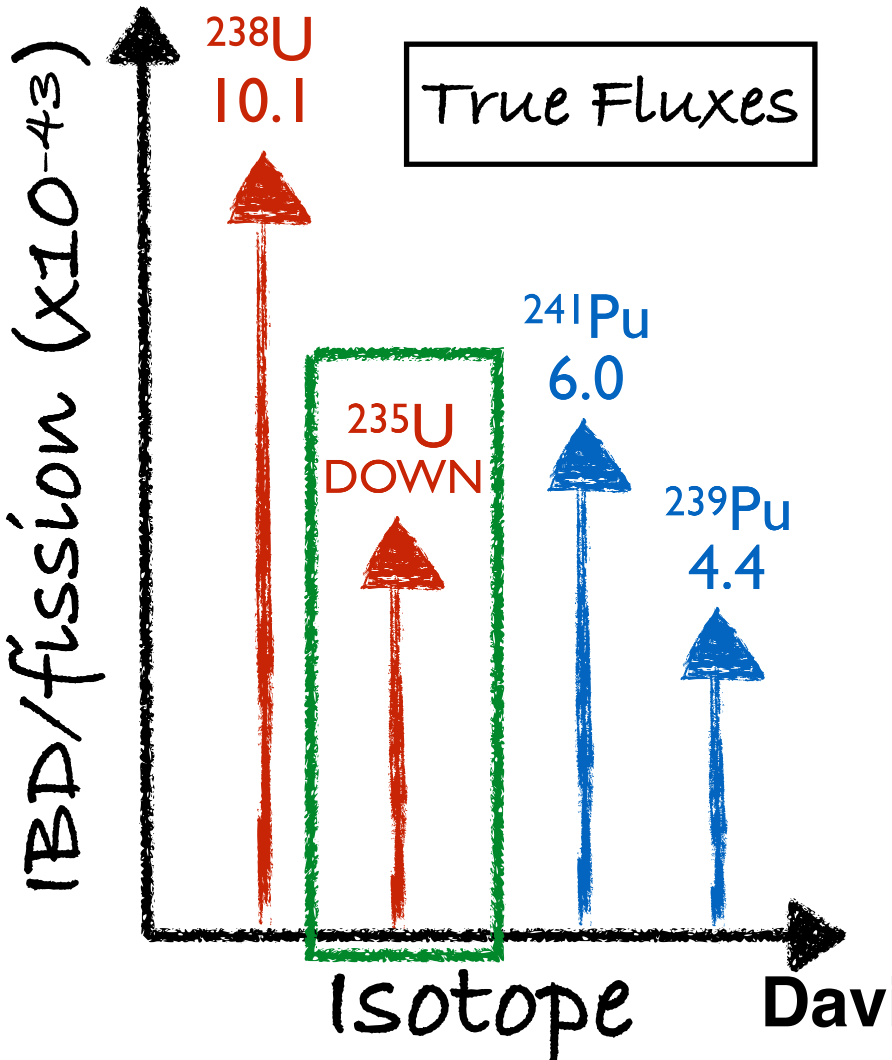
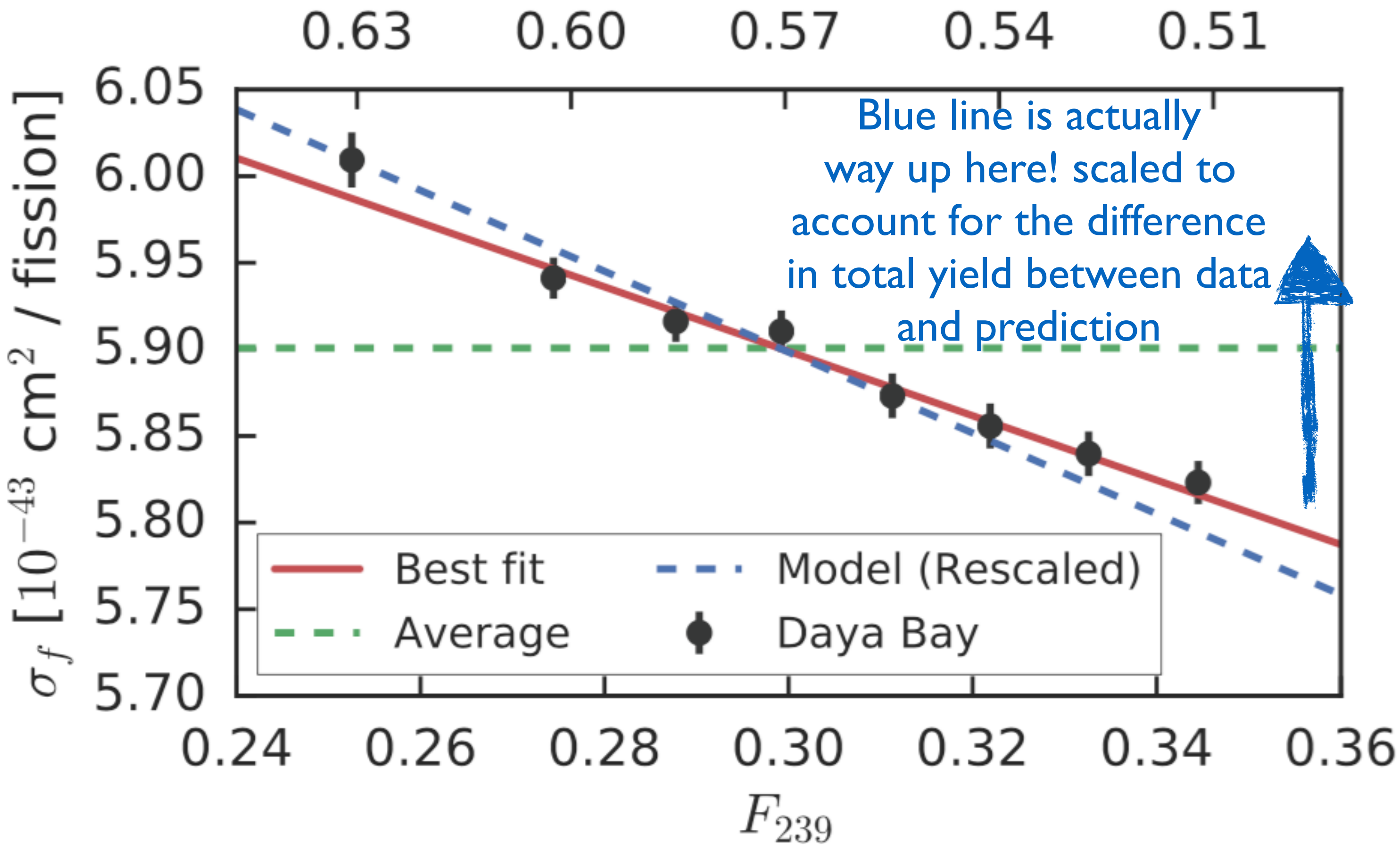




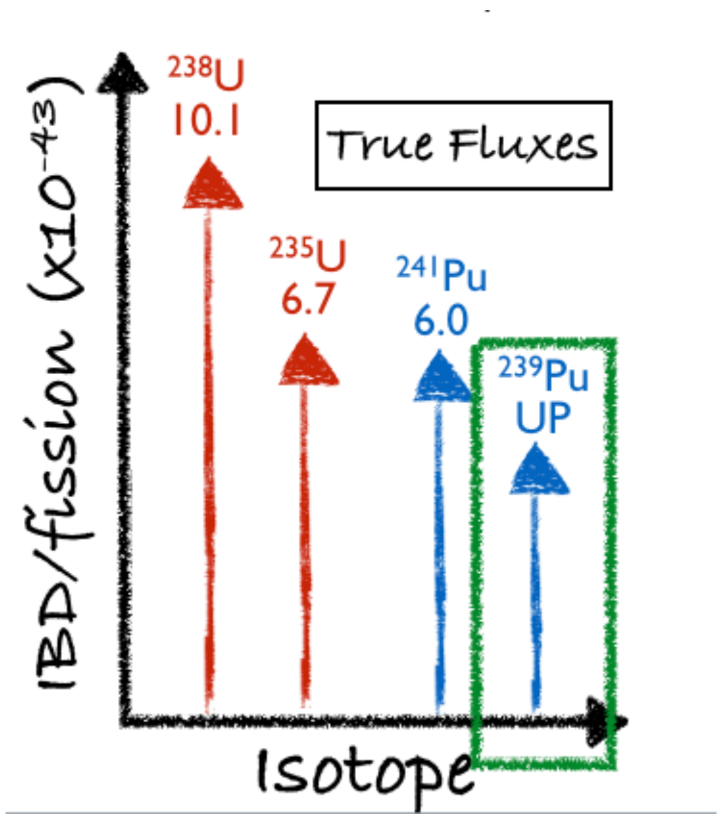


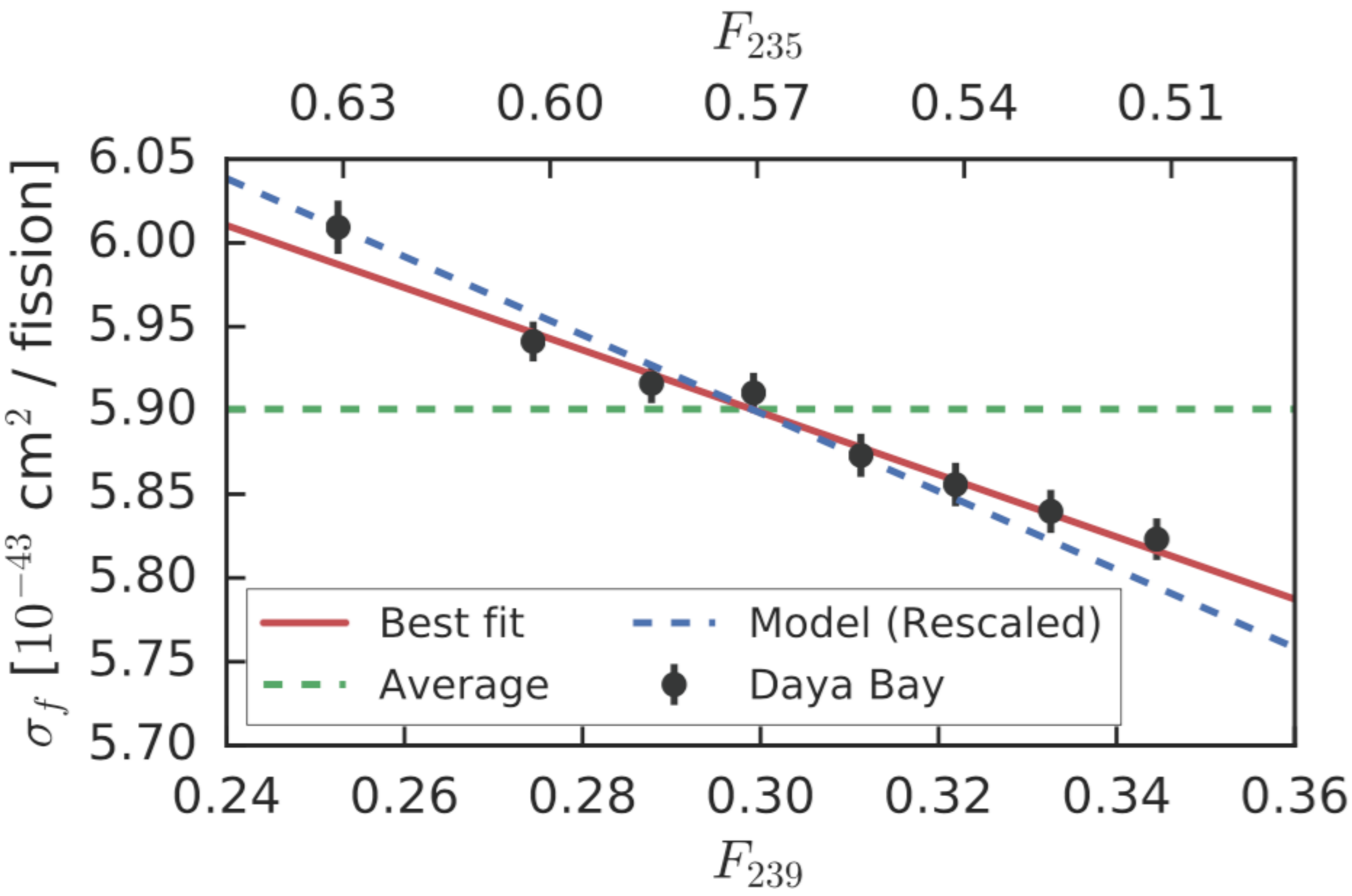
Blue line is actually way up here! scaled to account for the difference in total yield between data and prediction

Results: Flux Evolution

- More complicated scenarios still allowed: ^{239}Pu UP + sterile neutrino.
  - **Giunti et al. JHEP10(2017)143**

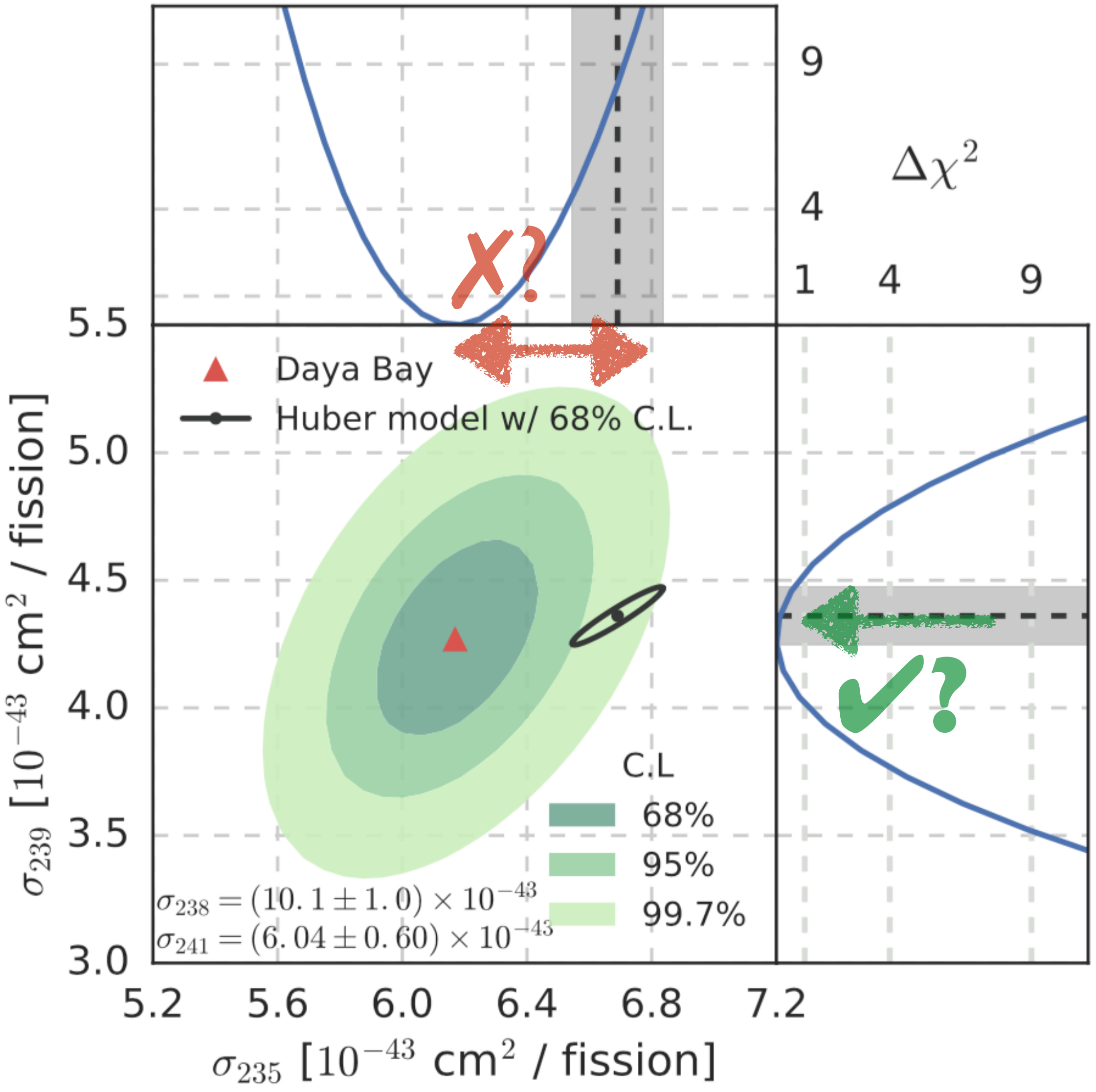
- Whatever the case reactor flux models must be wrong in some way.
- To truly rule out sterile neutrinos, direct tests of L/E with SBL reactor experiments are required.





Result: Fitting For Individual Isotopes

- Use this data to explicitly fit IBD/fission for ^{235}U, ^{239}Pu
  - Assume loose (10%) uncertainties on sub-dominant ^{238}U, ^{241}Pu
- Dominant uncertainties:
  - Statistics
  - IBD absolute detection efficiency
- The explanation of ^{235}U only being wrong fits the data well.
  - ^{239}Pu also matches model well.
- Future Highly Enriched Uranium (HEU) and Daya Bay measurements will be necessary for improvements.

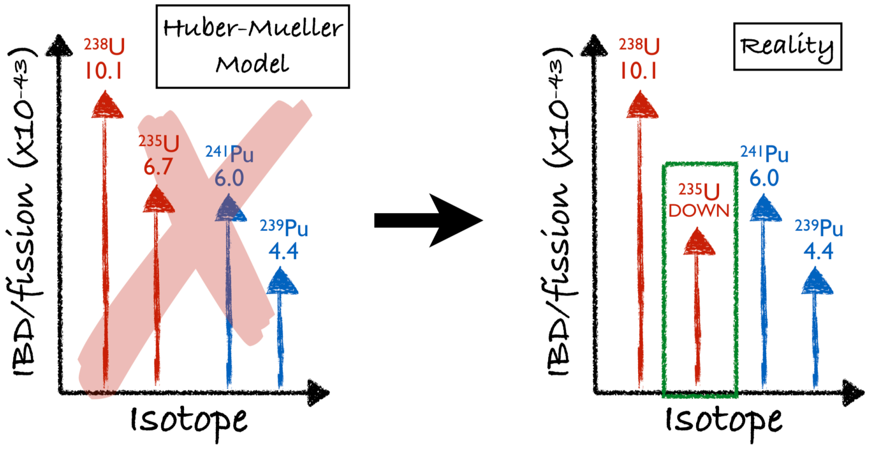


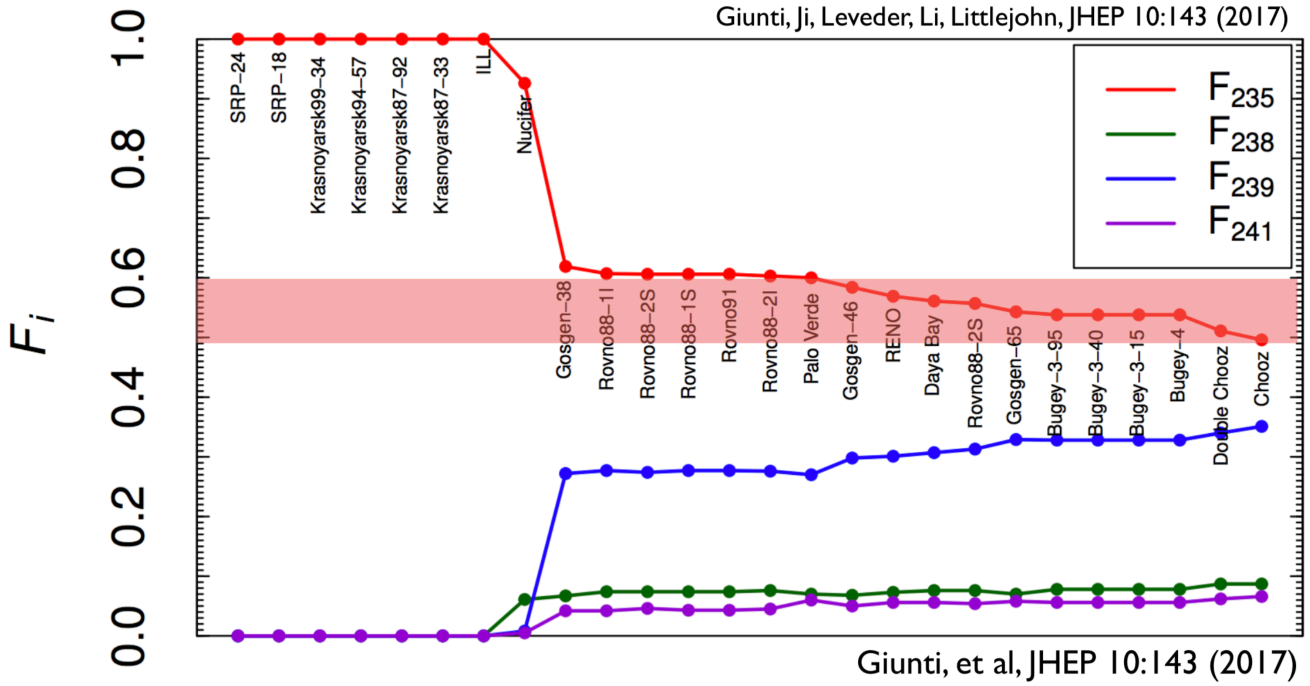
Results suggests that 235U being the main contributor of the Reactor Antineutrino Anomaly.

PRL. 118, 251801
Editor's Suggestions
and Physics Viewpoint

What about reactor flux predictions?

- Theorists have come with multiple reasons why predictions could be not so good…
- Could be one isotope, or could be all isotopes, or a mixture …
- Deficit could be fuel - content dependent
- What about compare flux measurements between different reactor types? Compare between different time periods in one experiment :)



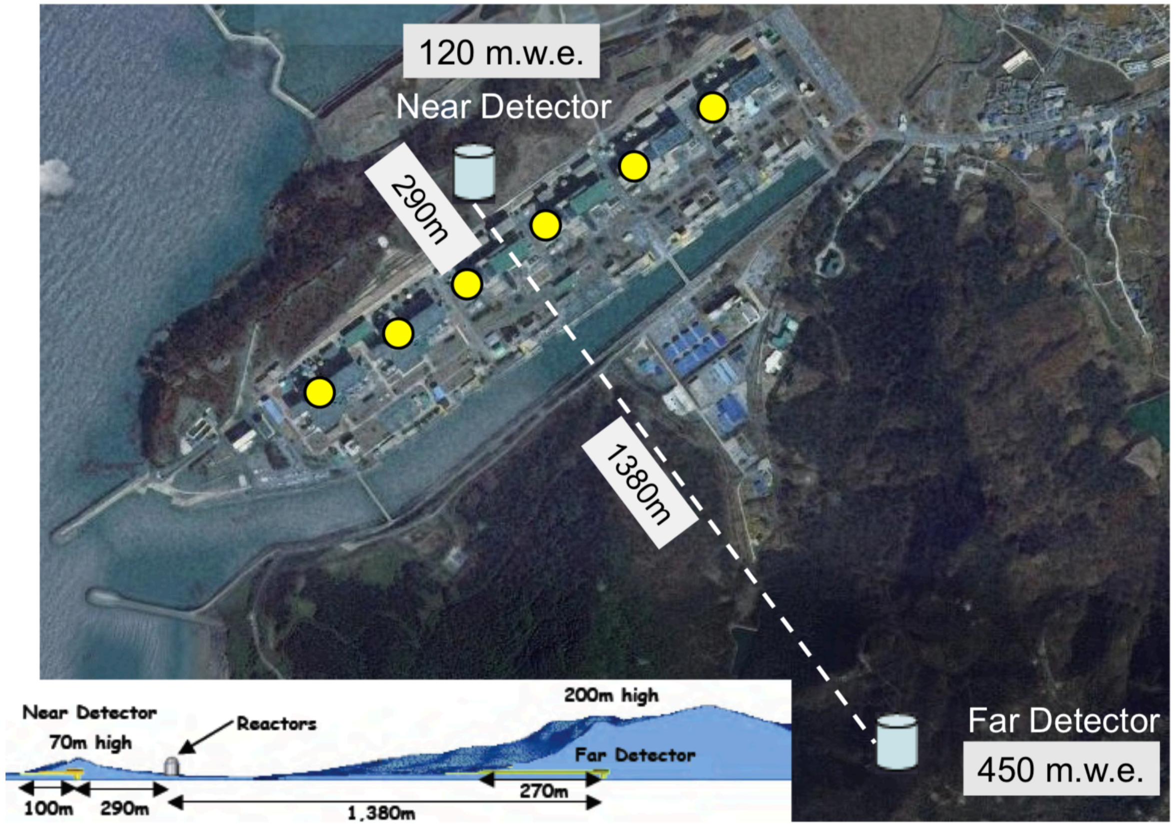


Giunti, et al, JHEP 10:143 (2017)

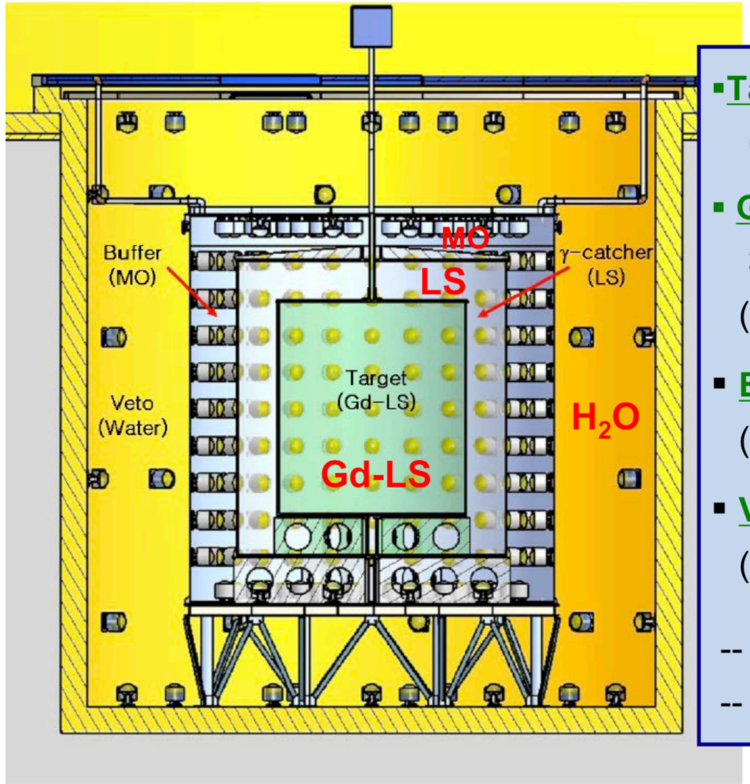
Daya Bay's observed Range over time

Other Reactor Neutrino Experiments RENO, PROSPECT, STEREO, DANNS

RENO



- Six 2.8 GWth reactors
- 850666 electron neutrino candidates
- 1807 live days
- Results from: Phys. Rev. Lett. 122, 232501 (2019)

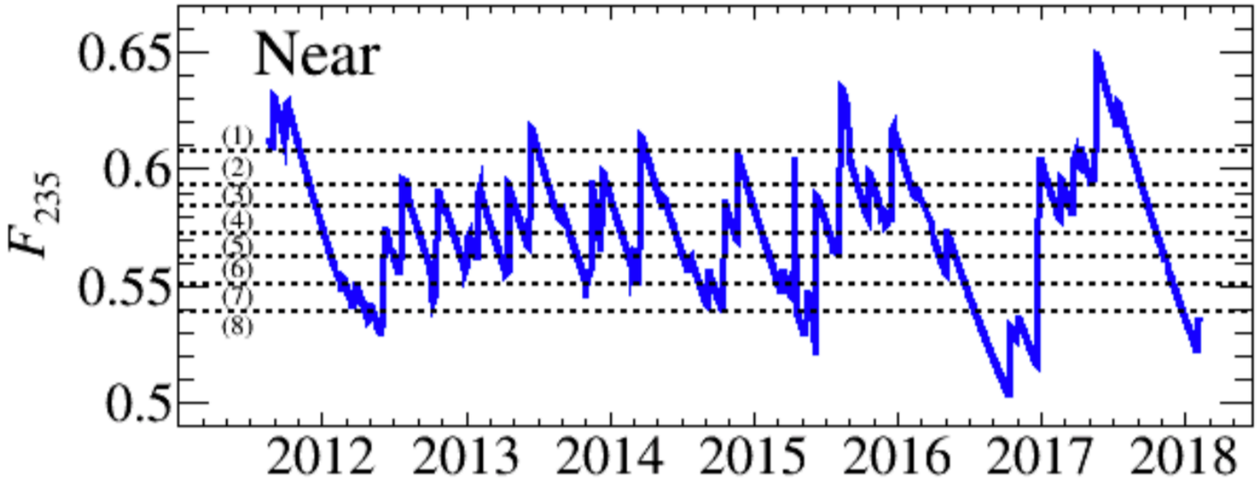


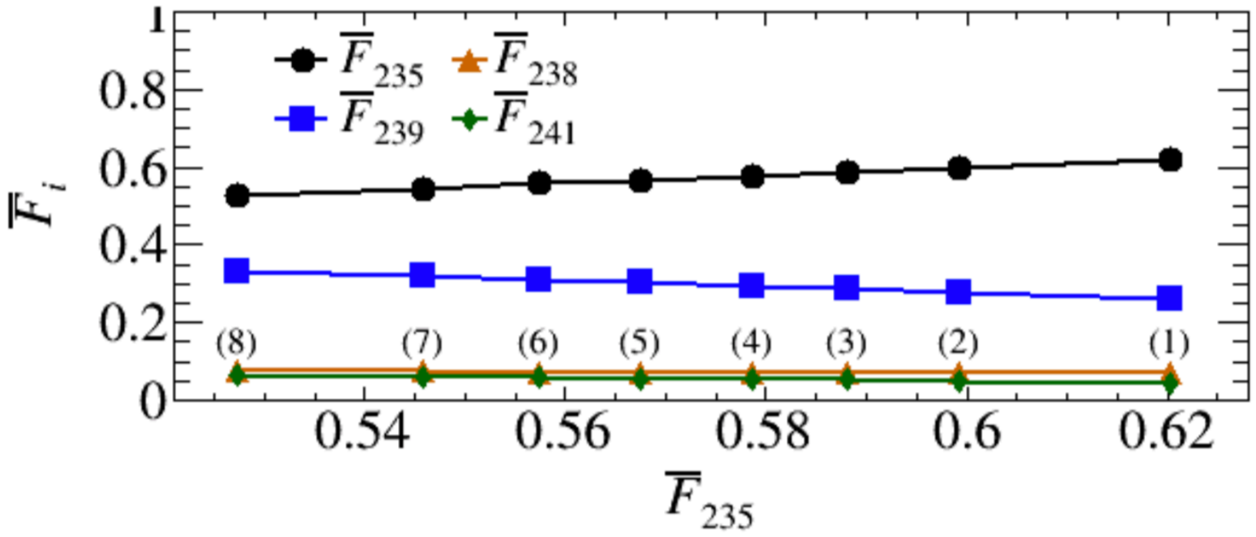
- **Target : 16.5 ton Gd-LS**
  (R=1.4m, H=3.2m)
- **Gamma Catcher** :
  30 ton **LS**
  (R=2.0m, H=4.4m)
- **Buffer** : 65 ton **mineral oil**
  (R=2.7m, H=5.8m)
- **Veto** : 350 ton **water**
  (R=4.2m, H=8.8m)

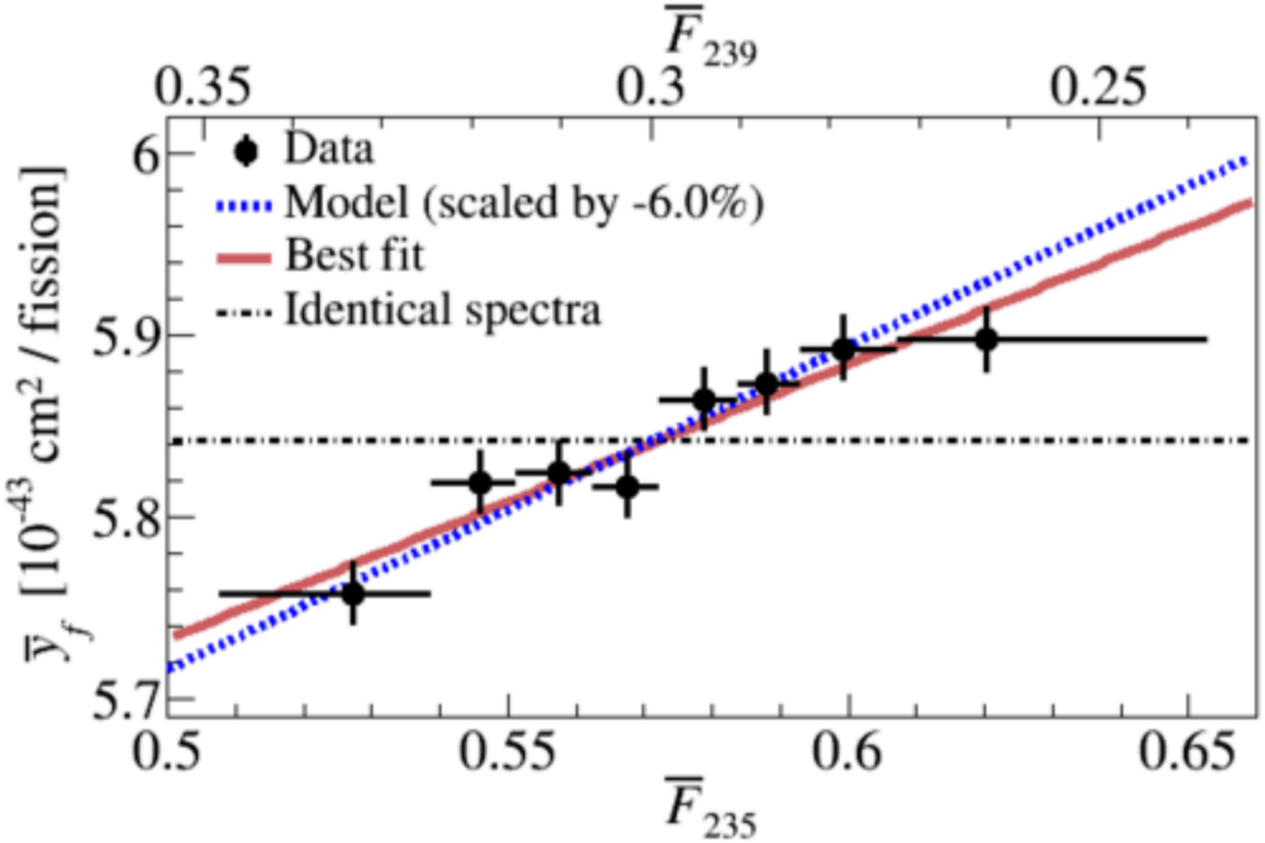
-- 354 ID 10 " PMTs
-- 67 OD 10" PMTs

Neutrino Seminar Fermilab, Soo-Bong Kim, Sep 2018

Fuel evolution analysis
Phys. Rev. Lett. 122, 232501 (2019)







The best-fit value of y_{235} :

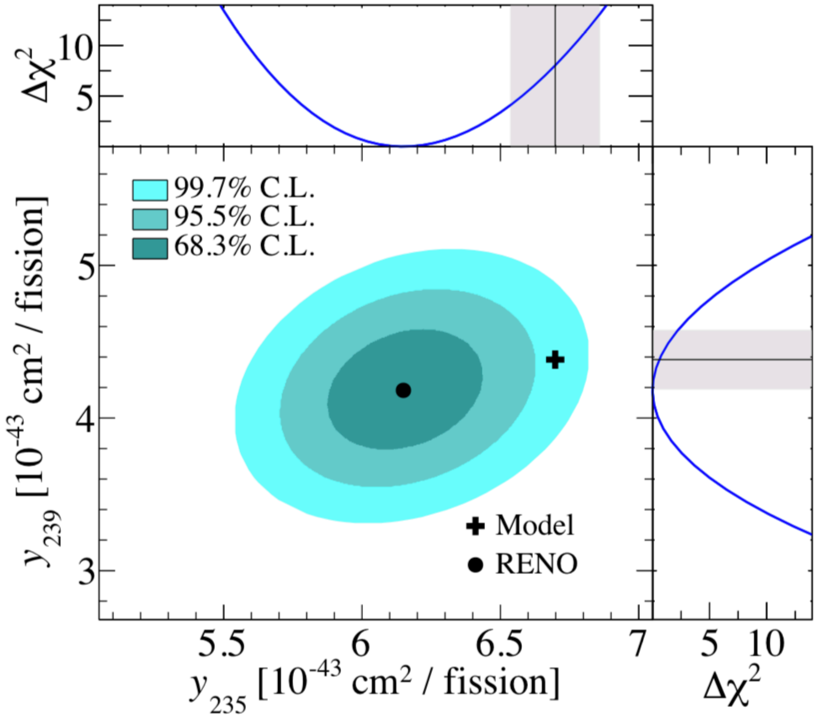
3.0 σ deficit

6.15 ± 0.19/6.70 ± 0.16

The best-fit value of y_{239} :

0.8 σ deficit

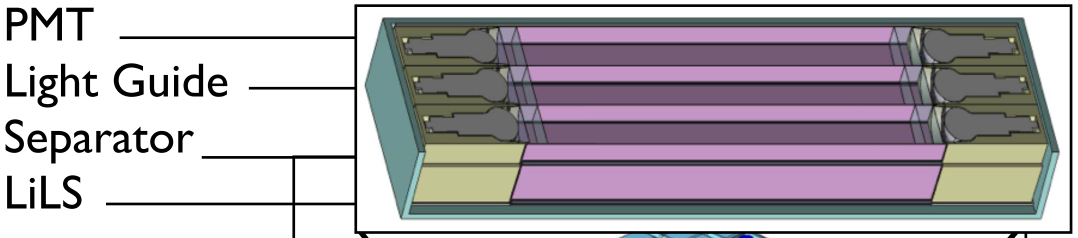
4.18 ± 0.26/4.38 ± 0.19

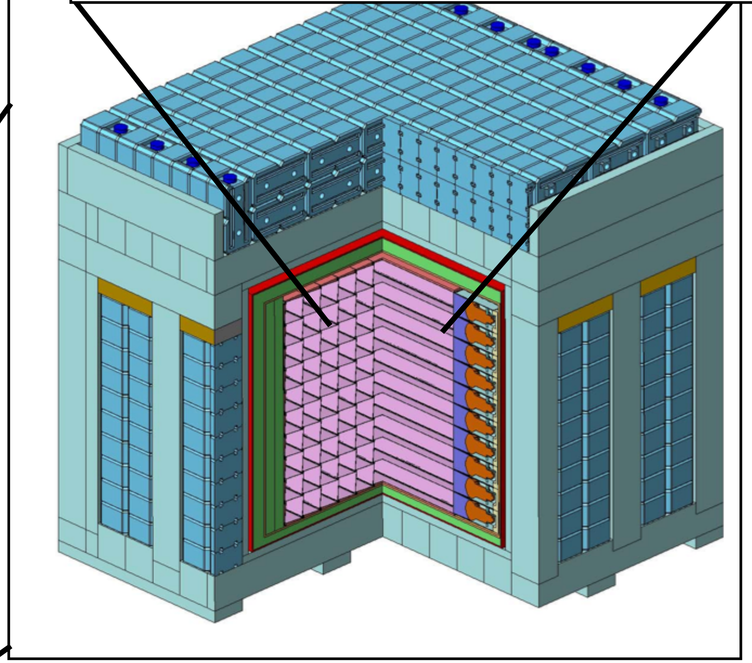


PROSPECT Experimental Layout

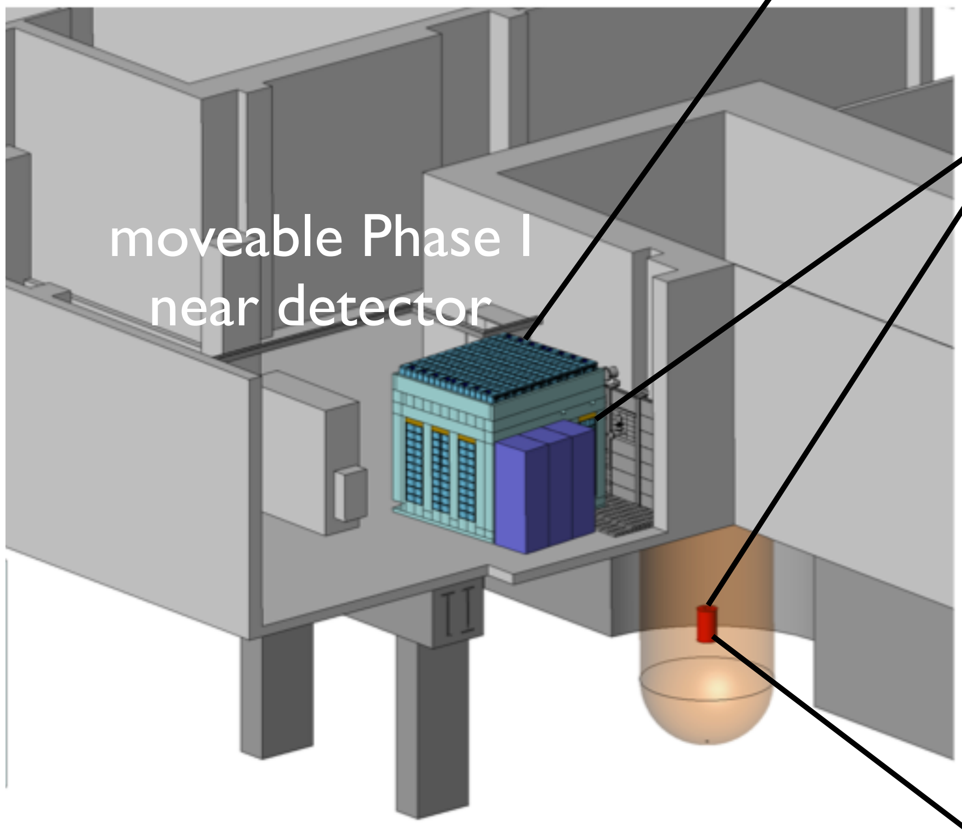
- HEU Reactor: HFIR 85 MW
- Segmented liquid scintillator target region: ~4 tons for near detector (Phase I)
- 154 segments, 119 cm X 15 cm X 15 cm
- Moveable: 7-12 m baselines
- Measure ^{235}U spectrum while directly probing sterile oscillations independent of reactor models

Sub-cell conceptual design

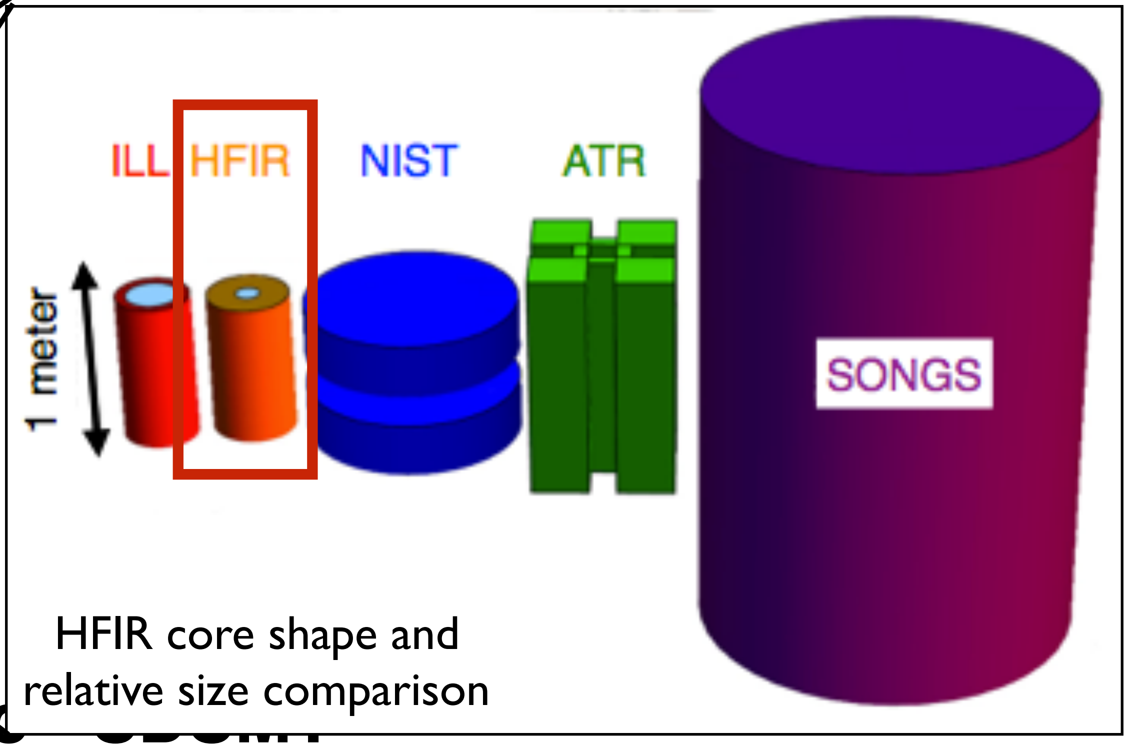




Near detector conceptual design



PROSPECT deployment at HFIR

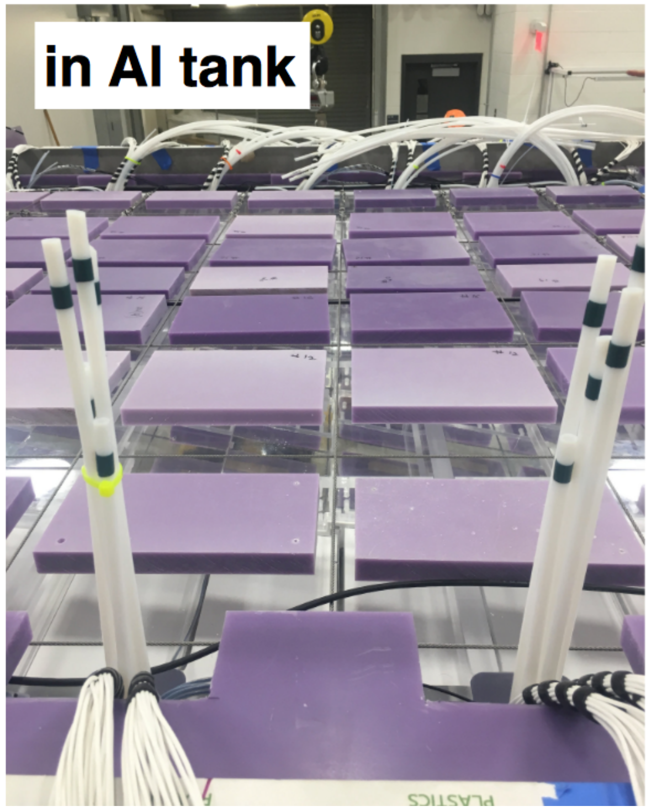


HFIR core shape and relative size comparison

PROSPECT Experimental Layout

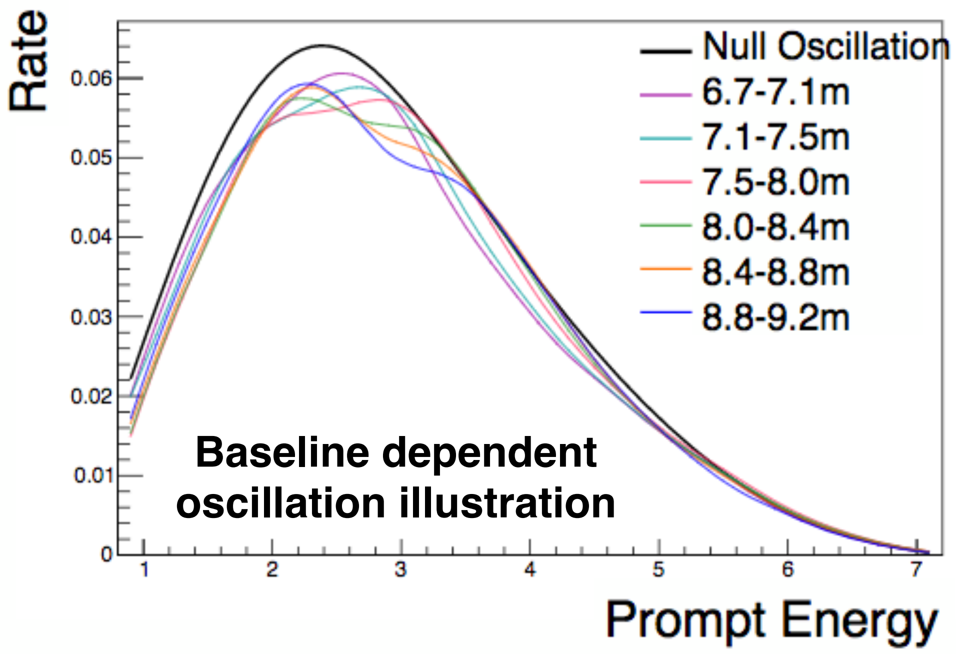

inner AD build

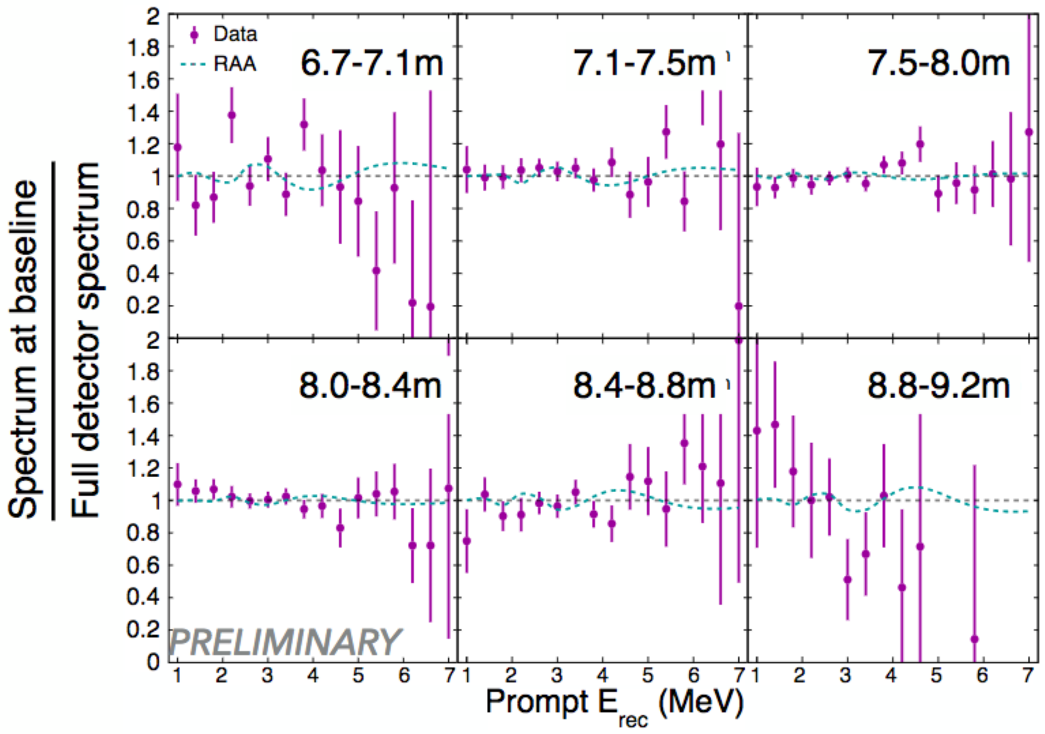
side wall lift


in Al tank

PROSPECT: Results

- 33 days of reactor on
- 28 days of reactor off
- ~24000 IBDs (750/day)
- Compare spectra from different baselines to measured full detector spectrum
- Null-oscillation will give a flat ratio for all baselines



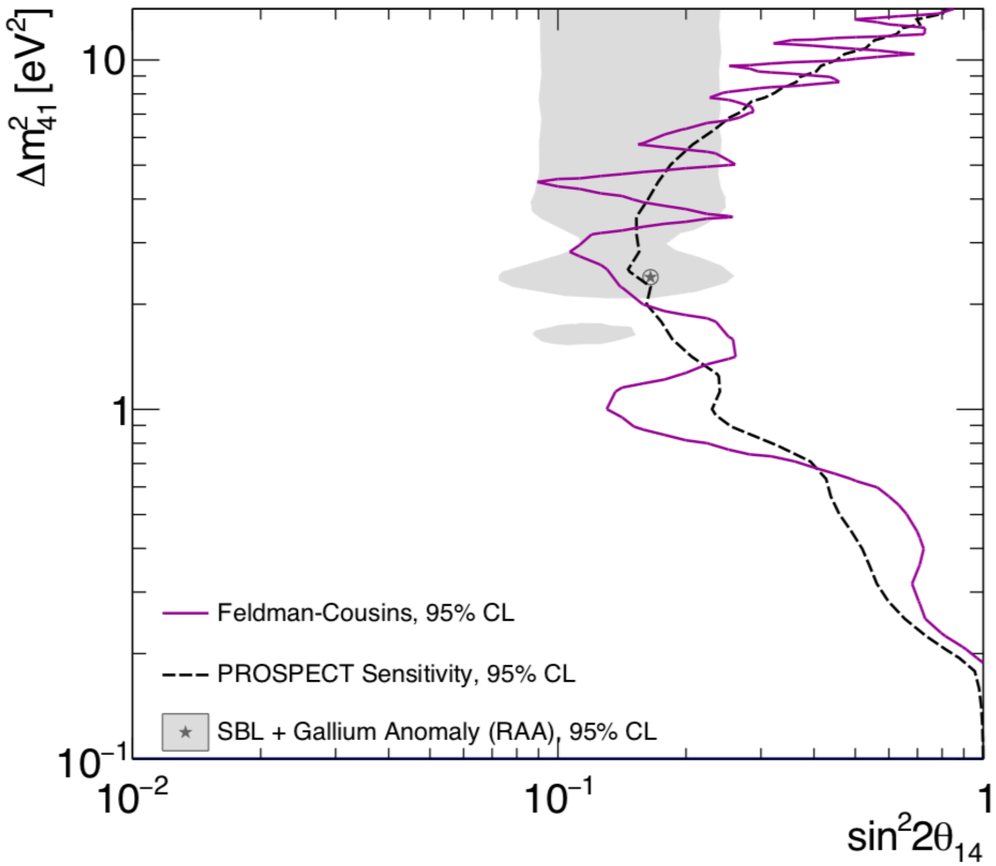


Phys. Rev. Lett. 121, 251802

PROSPECT: Results

- Covariance matrices captures all uncertainties and energy/baseline correlations
- 95% exclusion curve based on 33 days of data
- First oscillation analysis on data disfavor the Reactor Antineutrino Anomaly (RAA) best fit at 2.2 sigma!
- No evidence of steriles so far

Phys. Rev. Lett. 121, 251802

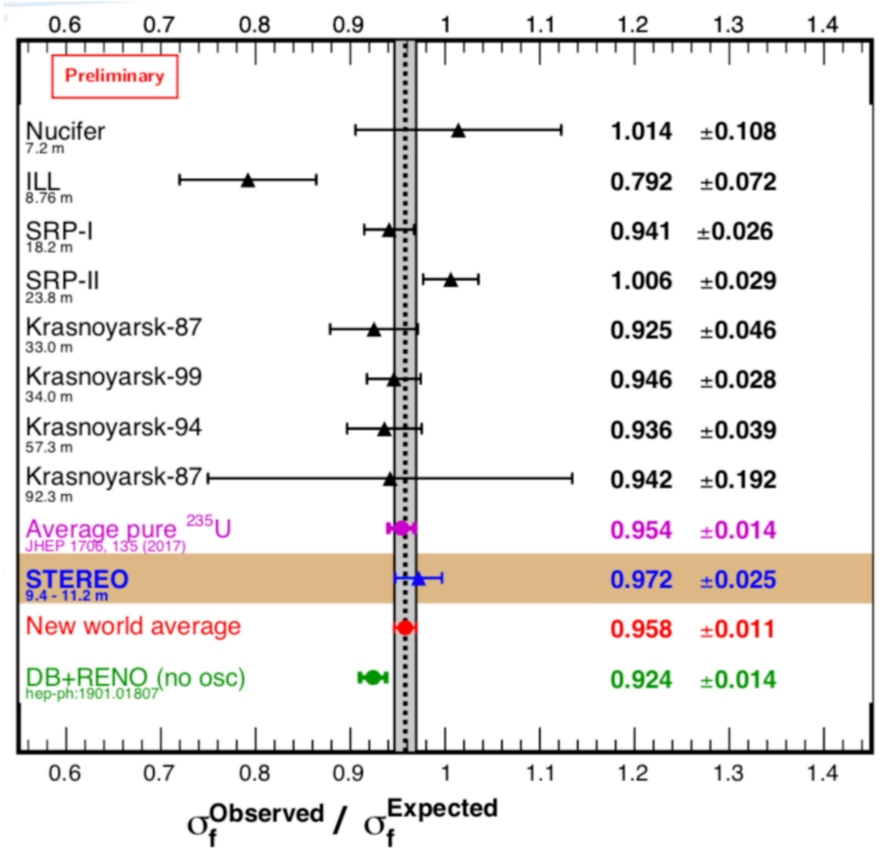


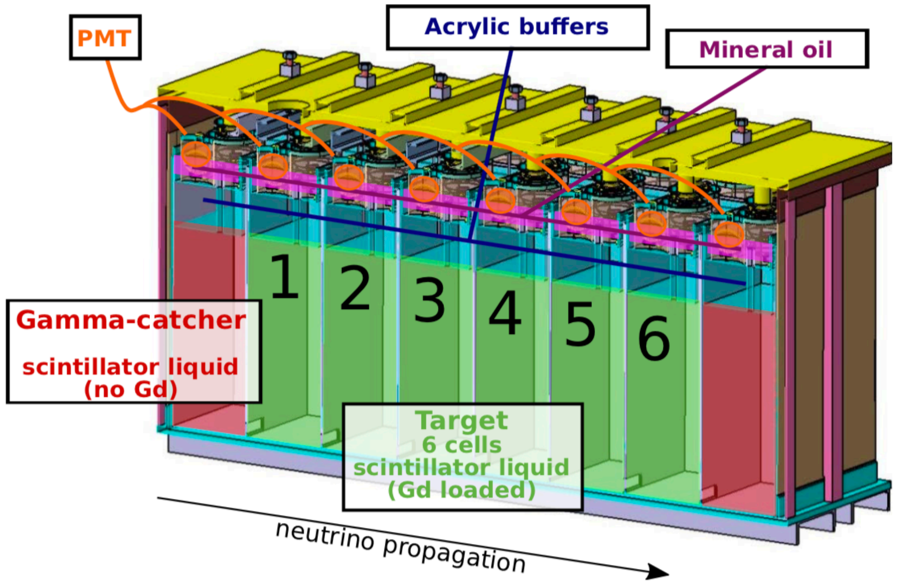
David Martinez Caicedo - SDSMT

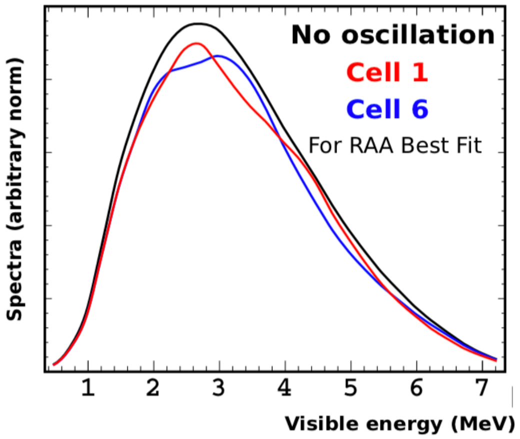
STEREO

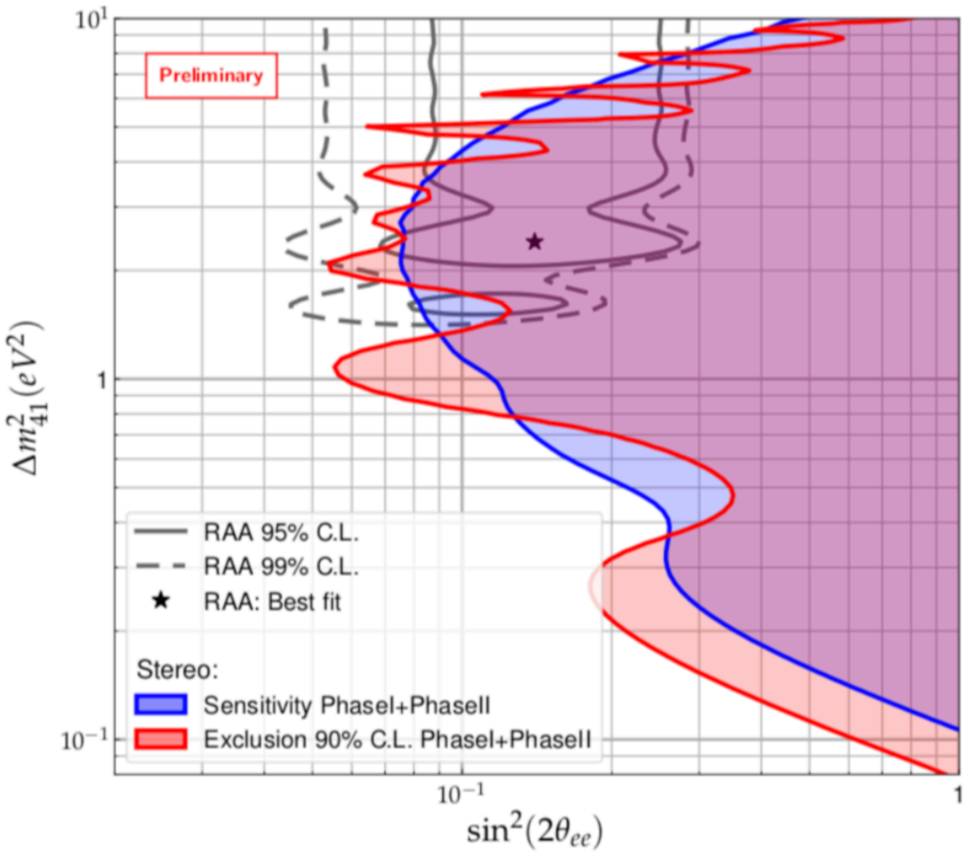
- Research reactor core 58 MWth (ILL, Grenoble, France)
- Highly Enriched Uranium (U235 ~93%)
- Short baseline measurement
    - 9.4 < Distance to core < 11.2 m
- Interesting to see (near future) comparisons with PROSPECT, global fluxes and other theta13 experiments

Reencontres de Moriond, 2019





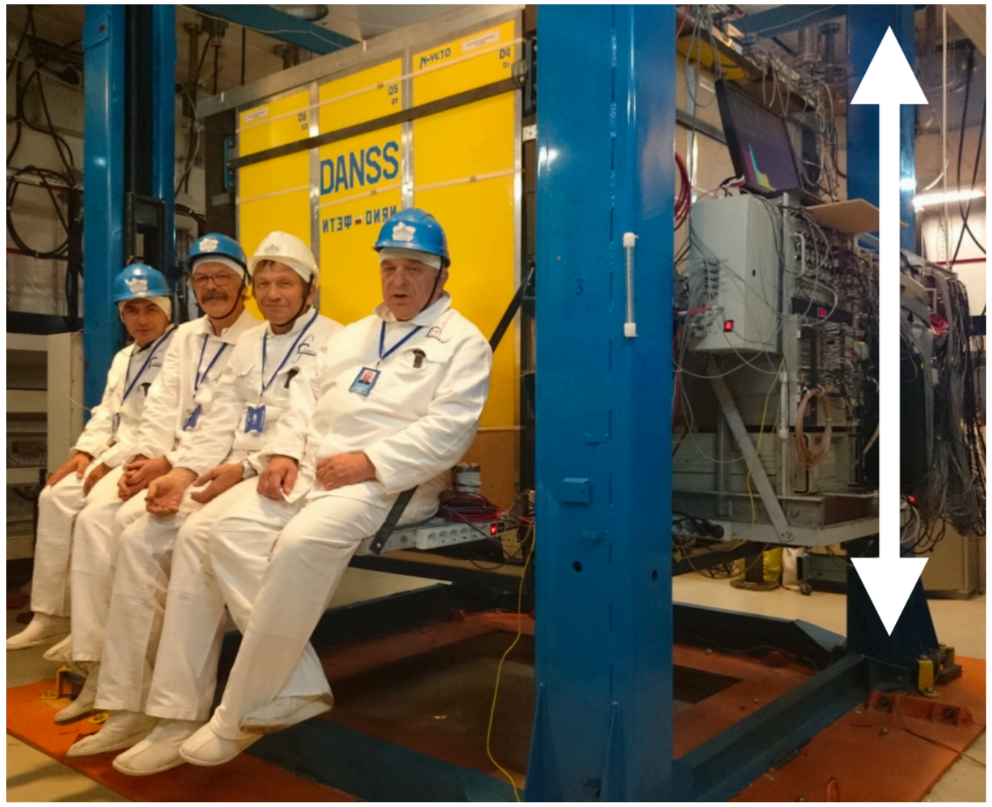


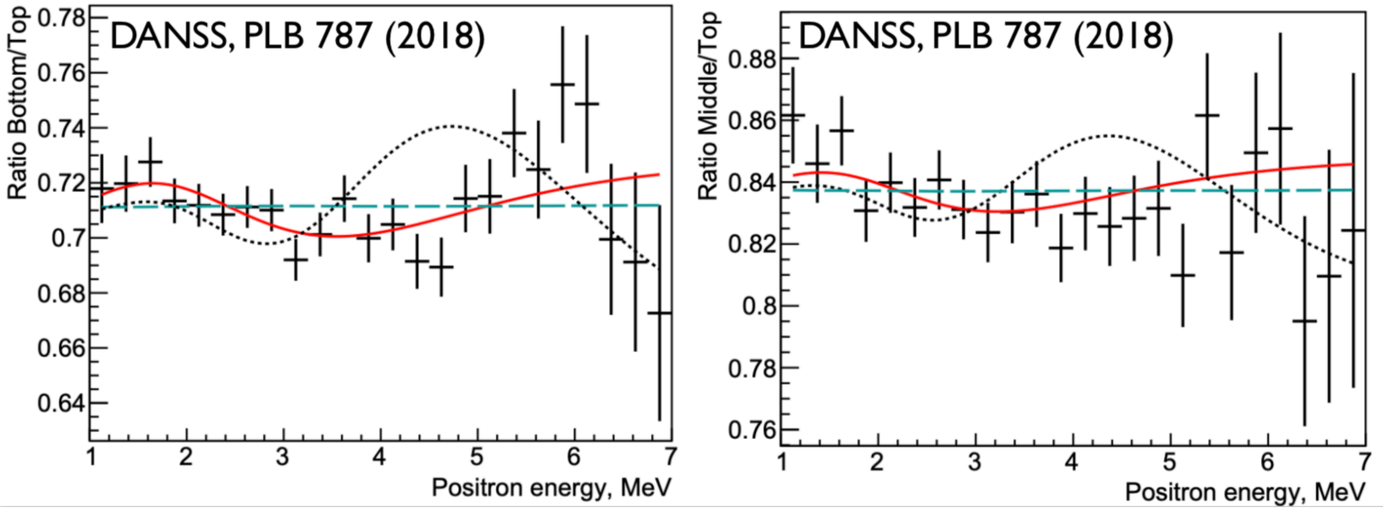


DANNS

- Compare spectra between the same detector deployed at two different baselines (10.7 m and 12.7 m)
  - Commercial reactor -> 5000 IBD events per day
  - Have presented relative spectra between locations

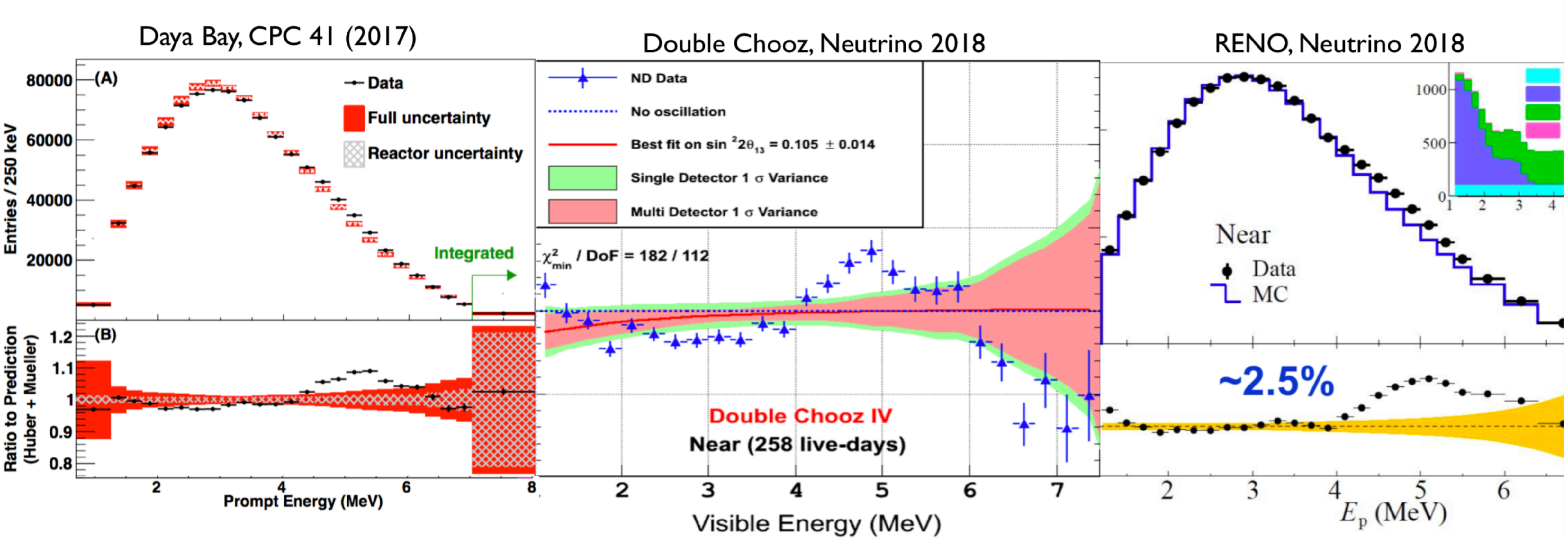
Reactor up here





Reactor Spectrum Anomaly

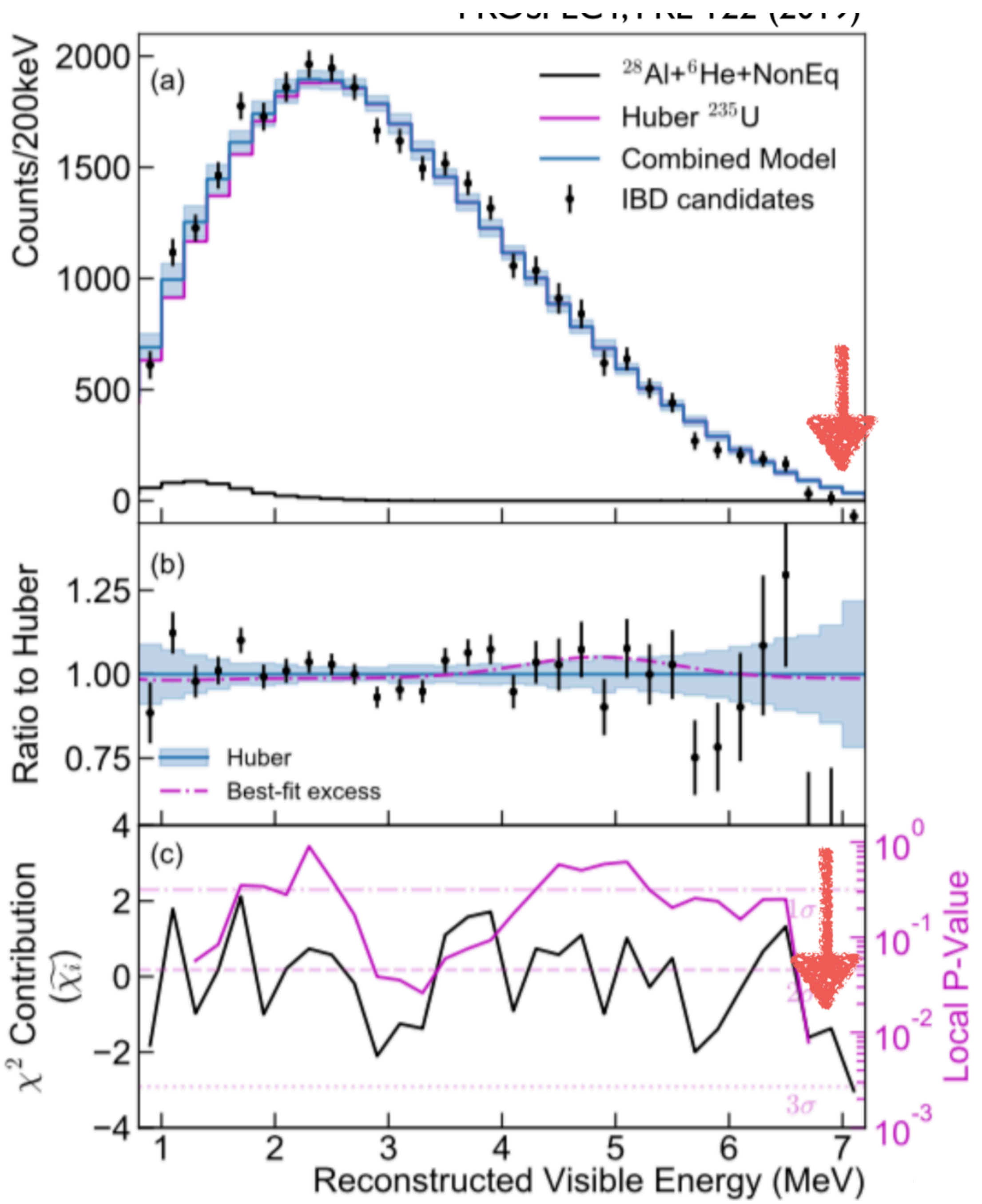
- Reactor spectrum predictions do not match the LEU data
    - Bump in the 4-6 MeV range
- Spectrum is incorrectly predicted?
    - Is one particular isotope? Could be a combination? or all the isotopes?
    - Short baseline measurements at U235 cores could give us new input :)



Reactor Spectrum Anomaly

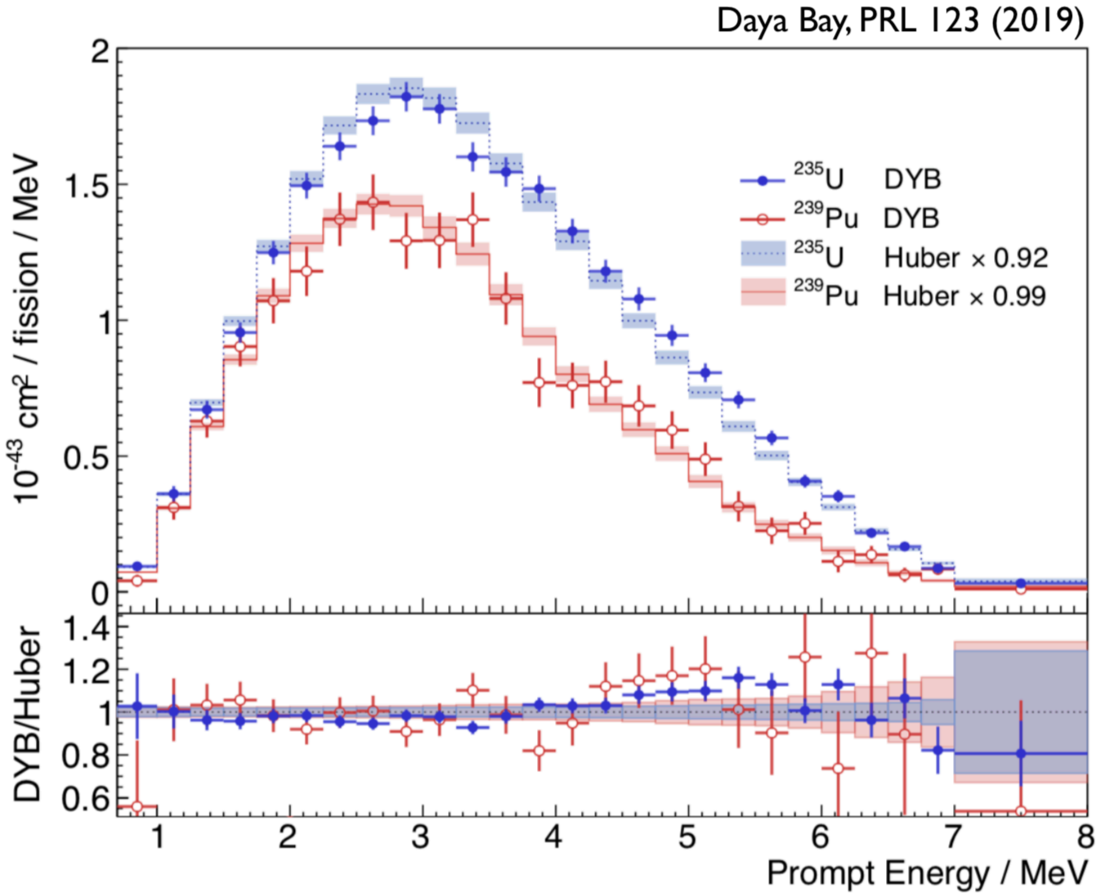
- PROSPECT: Measured spectrum at U235 HFIR reactor
- Comparing PROSPECT spectrum measurement with Huber's U235 model
  - X^2/ndf = 51.4/31
  - Huber broadly agrees with PROSPECT data (but not the best fit)
    - High energy bins -> Stats, background issue?

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



Reactor Spectrum Anomaly

- Measured Daya Bay spectrum variation with fuel content
- Extract U235 and Pu239 spectrum
  - Option: Both isotopes have bump with respect to prediction
    - 0.8 sigma better than the ‘U235 only’ case.
    - Result is consistent with PROSPECT
  - Active efforts pursuing future joint LEU-HEU analysis



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

Summary

- Reactor neutrino experiments will continue providing crucial input to precisely test the sterile neutrino hypothesis!
- Need to continue working on the reactor spectrum and flux anomaly
    - Increase stats, compare multiple reactor neutrino experiments, joint efforts for combined analysis (LEU+HEU)
- Nice research opportunities within the long baseline and short baseline neutrino experiments in the coming decade!

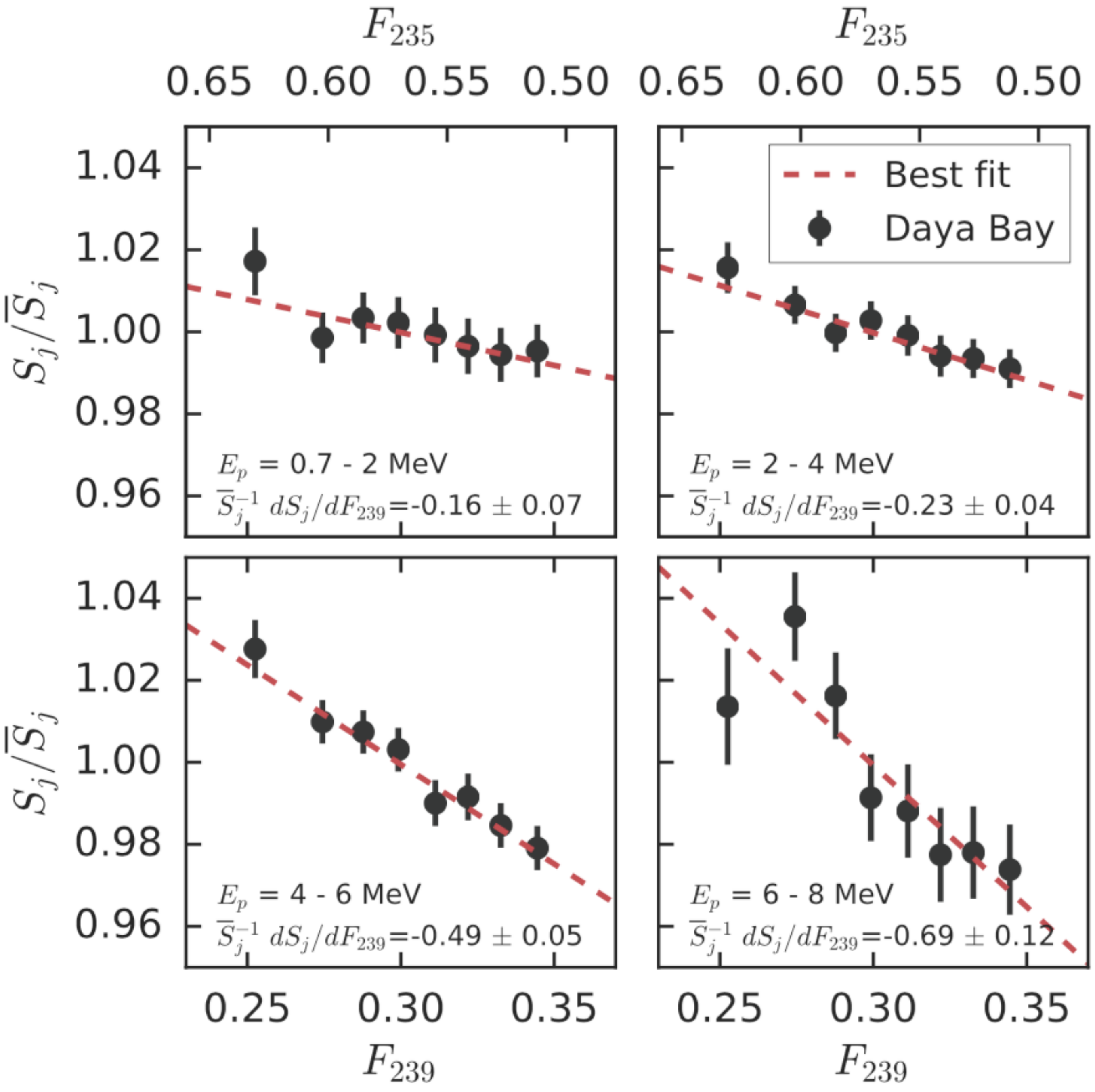

Thanks!


Gracias!

BACKUP

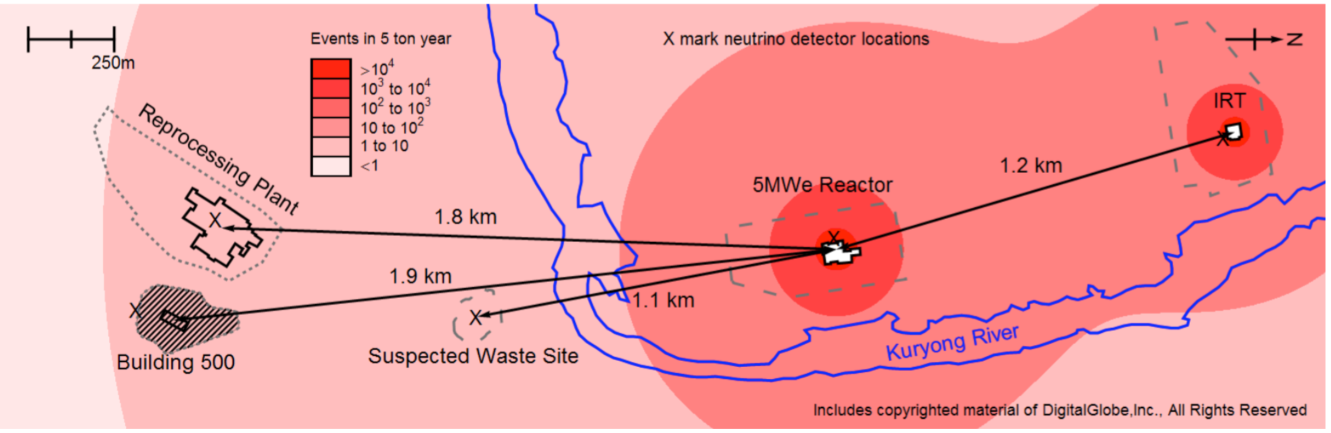
Results: Spectrum Evolution

- What if we add IBD energy into the mix?
  - Examine evolution in 4 separate energy ranges
- Slope is different for different energy ranges.
- Put another way: IBD spectrum is changing with F_{239}
  - **This is the first unambiguous measurement of this behavior**
  - **Highly relevant to ν_e based nuclear non-proliferation**

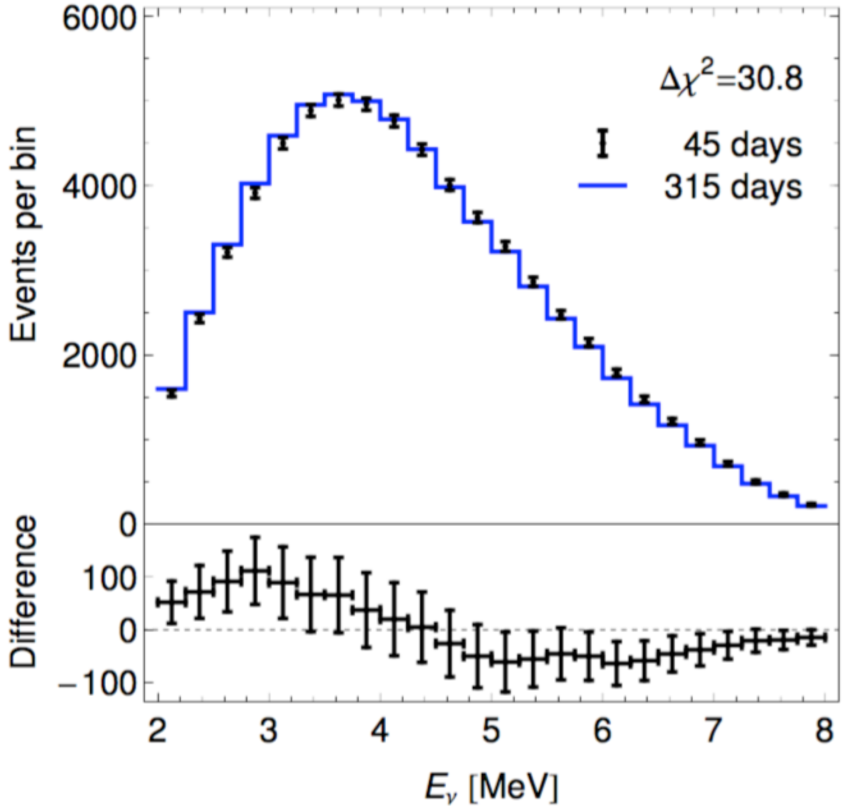


Results: Spectrum Evolution

Important: An experimental demonstration of reactor monitoring



- Theory-based case-studies of Iranian, North Korean nuclear reactors: P. Huber et al arXiv[1403.7065], arXiv[1312.1959]
- Unambiguous monitoring of reactor's ^{239}Pu content utilizing a reactor's antineutrino spectrum
- Daya Bay spectrum evolution result validate these theoretical studies. Looks like this should be possible :)

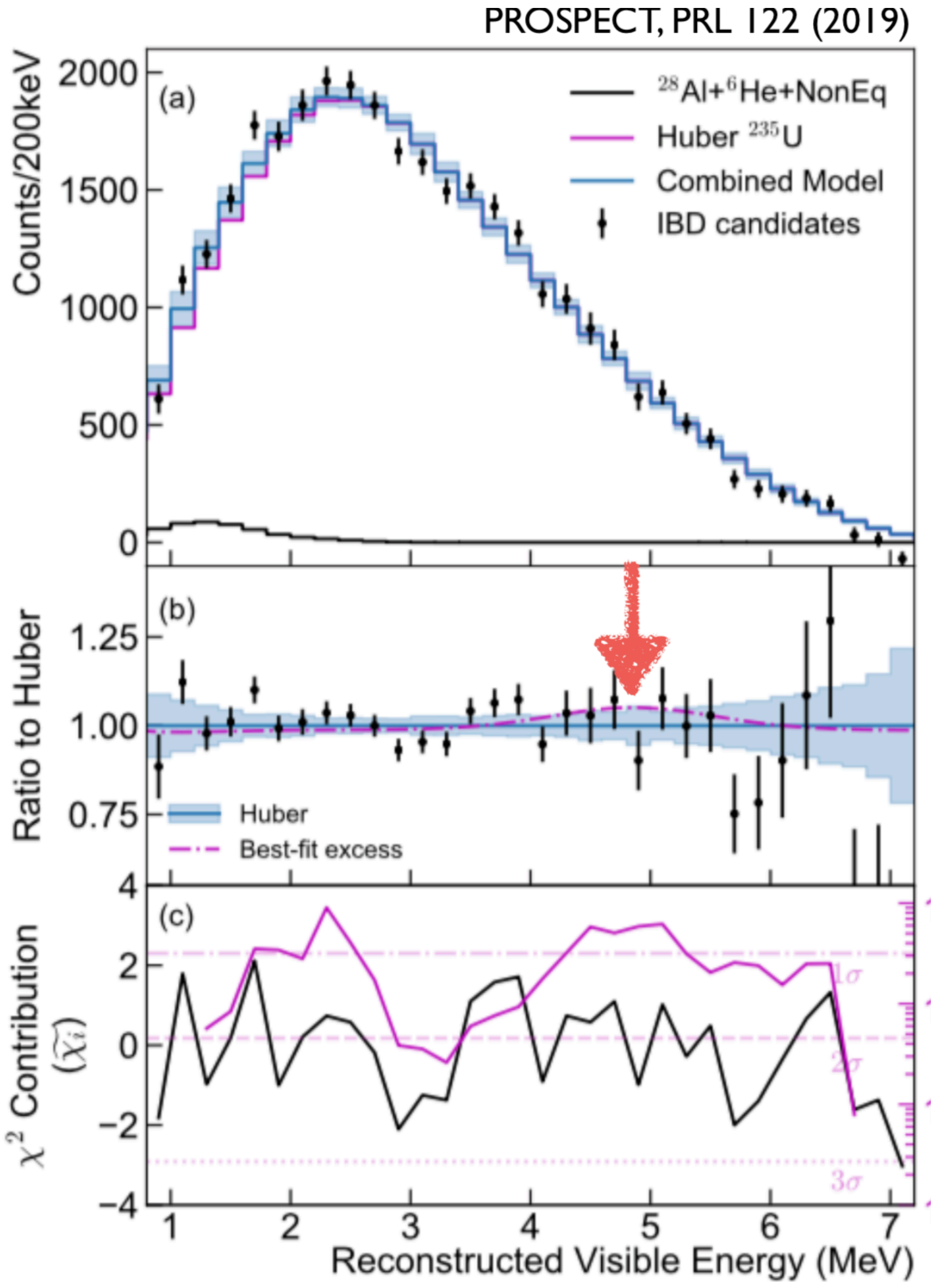


P.Huber et al, Phys. Rev. Lett. 113, 042503

Reactor Spectrum Anomaly

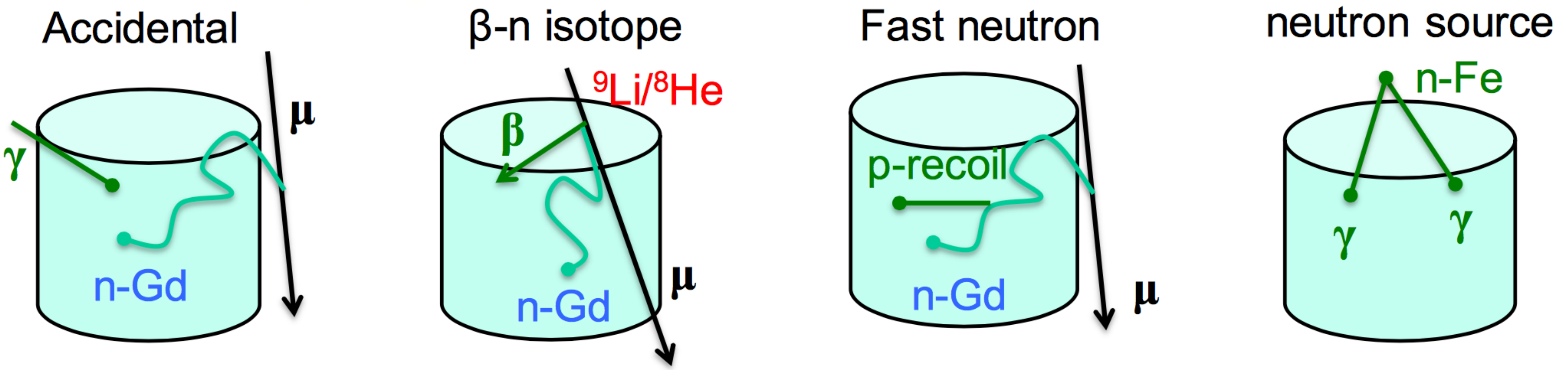
- How does PROSPECT compares to bump in other reactor neutrino experiments?
    - PROSPECT relative bump size with respect to Daya Bay 69% +/- 53%
    - Consistent with no bump (0%) and Daya Bay sized bump (100%)
    - Big bump (178%) if U235 is the sole bump contributor
        - Disfavored at 2.1 sigma

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



Backgrounds

- Accidental coincidence between prompt and delayed signals ~1%
- During detector operation it was found that neutrons from the 241 Am-13 C calibration sources within the ACUs occasionally introduced several γ rays, correlated in time, to the detector. Contamination from this background was estimated to be ≲0.1%
- Fast neutrons: Muon interactions in the environment near the detector generated energetic, or fast neutrons <0.1%
- 9Li/8He b-n followers produced by cosmic muon spallation. 0.3-0.4%

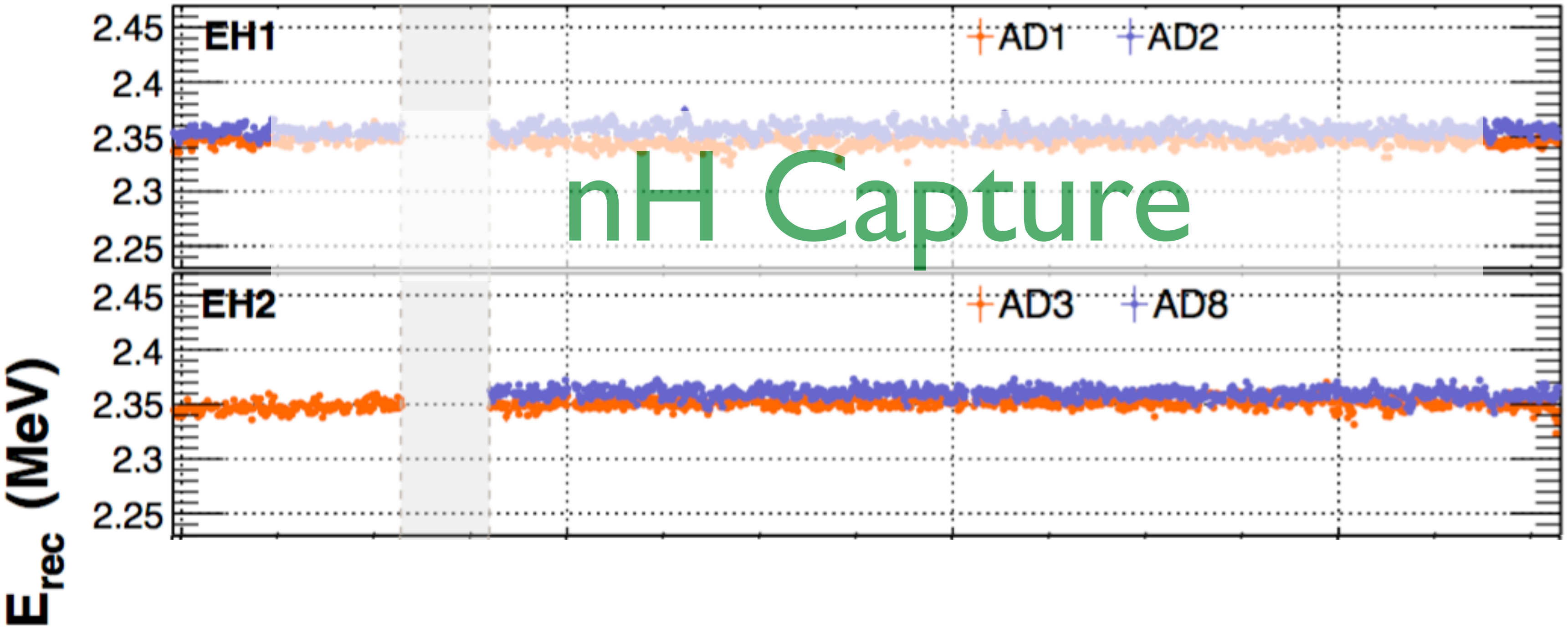


David Martinez Caicedo - SDSMT

Systematics: Detector

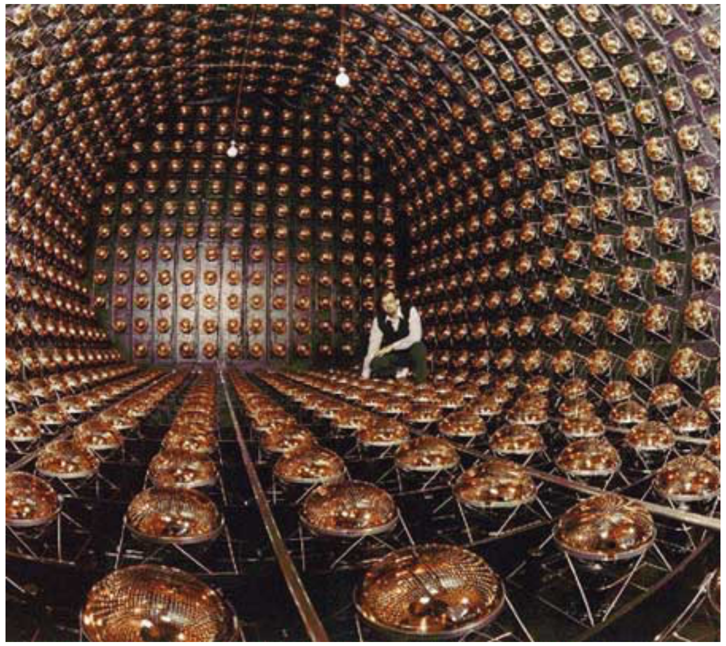
- How does a detector change over time?
  - Reconstructed energy scales are **extremely** time-stable (<0.1% variation)
  - Most inefficient IBD cuts are energy-based: also time-stable (<0.1% variation)
  - IBD Absolute detection efficiency uncertainty: 1.9%

Daya Bay, PRD 95 (2017)



Experimental Anomalies

Experimental anomalies: LSND



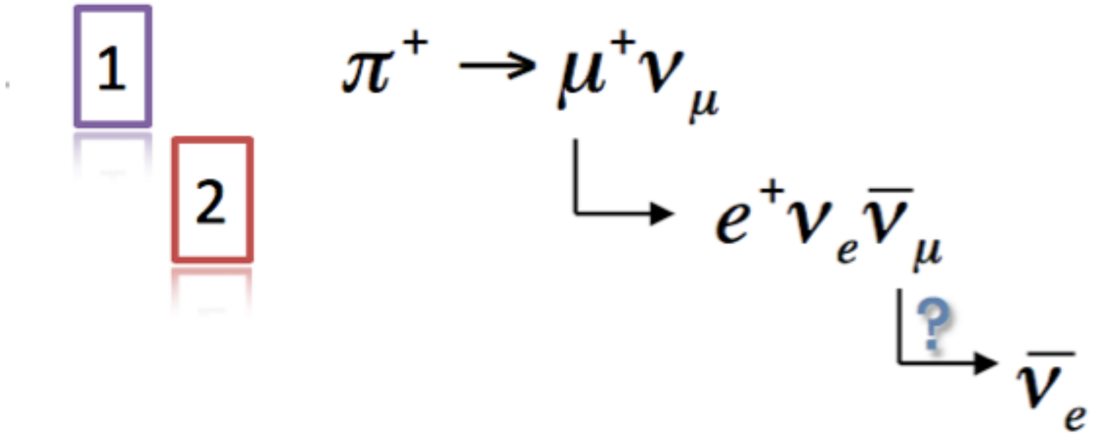
LSND used neutrinos from stopped pions to search for neutrino oscillations with $\Delta m^2 \sim 1 eV^2$.

For two-state mixing:

$$P = \sin^2 2\theta \ \sin^2(1.27\Delta m^2(L/E))$$

The detector was 30 m from the source and $<E_\nu> \sim$ 30 MeV.

800 MeV proton beam produces π^+ that produce neutrinos



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

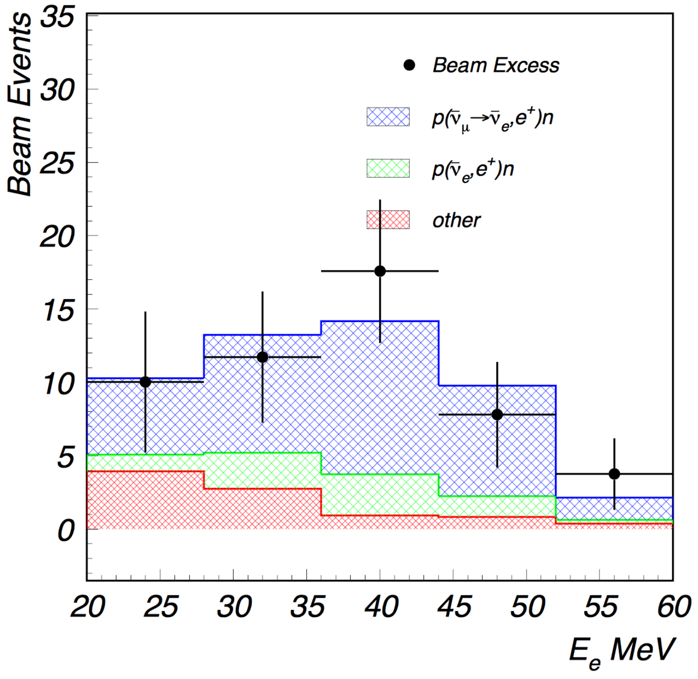
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\hookrightarrow \bar{\nu}_e$$

Searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

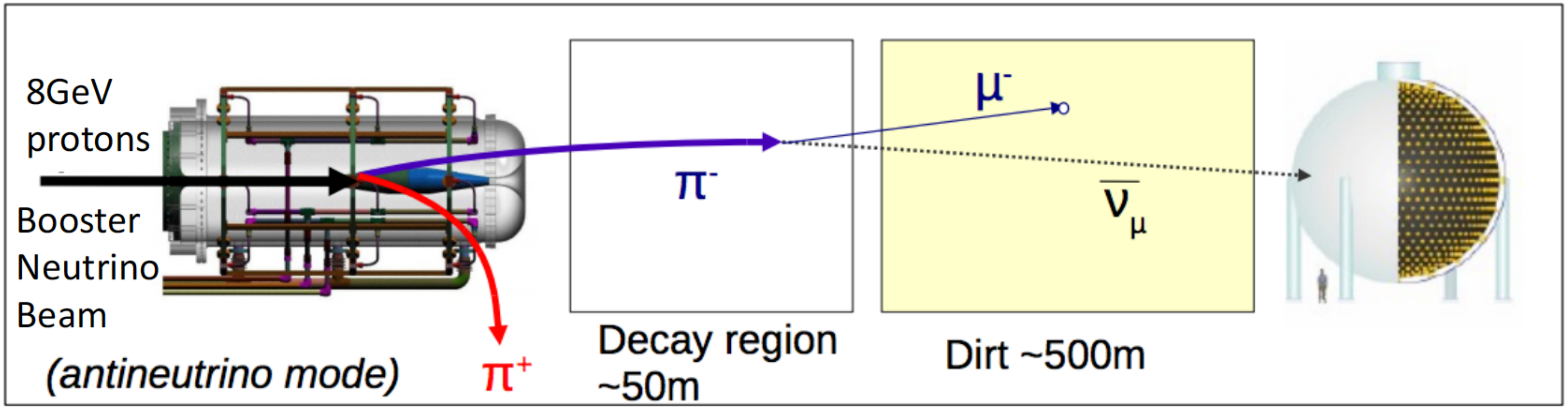
via Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$

- **LSND (at 30 m) observed an excess of 87.9+/-22.4+/-6.0 events (3.8 sigma)**



LSND anomaly
PRD 64 (2001) 112007

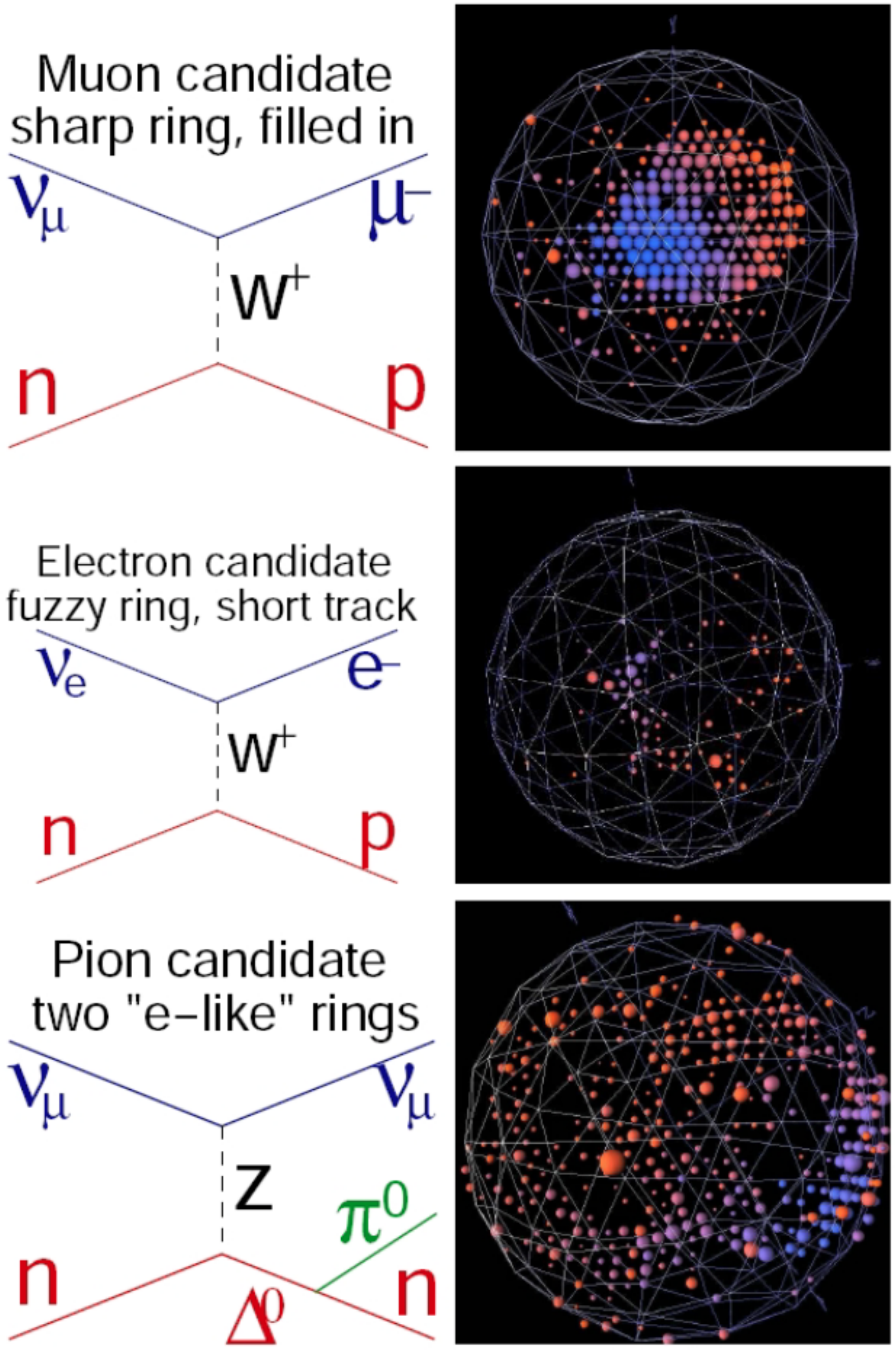
Experimental anomalies: MiniBooNE



- Similar L/E as LSND
  - MiniBooNE ~500 m / 500 MeV
  - LSND ~30m/ 30 MeV
  - Different systematics i.e. different flux, event signatures, backgrounds
- 800 ton mineral oil Cherenkov detector
- Horn polarity determine neutrino or antineutrino mode
- Great flux monitor for the short baseline neutrino program at Fermilab!

Experimental anomalies: MiniBooNE

- Cherenkov detector see Cherenkov light rings generated by charged particles
- Looking for: $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$
- Backgrounds come from small intrinsic electron neutrino rate in the beam and any muon neutrino interactions that leave a single reconstructed photon in the final state
- Cherenkov detector can not distinguish electron from single gamma

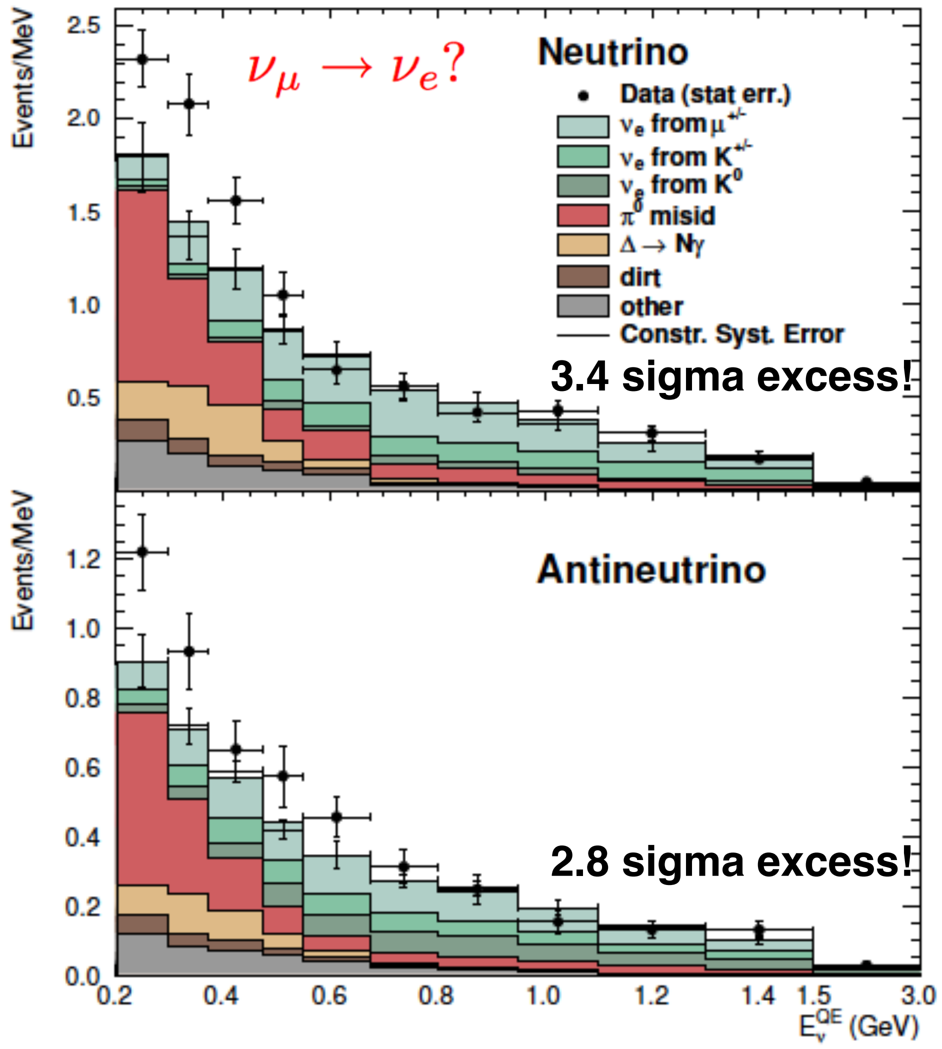


Experimental anomalies: MiniBooNE

Designed to test LSND , same L/E, but with <E>~ GeV, L=541 m

$$P = \sin^2 2\theta \;\; \sin^2(1.27\Delta m^2 (L/E))$$

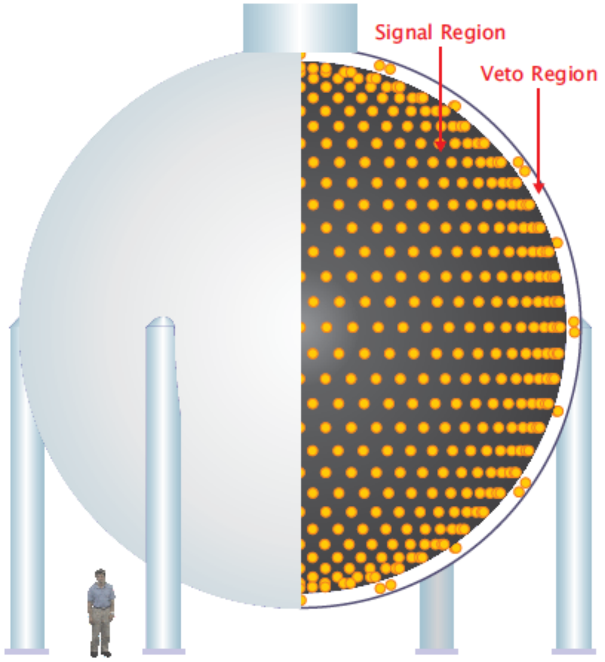
Searched for: $\nu_\mu \rightarrow \nu_e \; (\text{or } \bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



3.4 sigma excess!

2.8 sigma excess!

MiniBooNE anomaly
PRL 102 (2009) 101802



Observed an excess below 500 MeV
Observed no excess above 500 MeV
To explain both LSND and MiniBooNe by oscillations possibly suggest a fourth sterile neutrino requiring a mass on the 1eV² scale

Experimental anomalies: New MiniBooNE Results

Phys. Rev. Lett. 121, 221801

arXiv:1805.12028

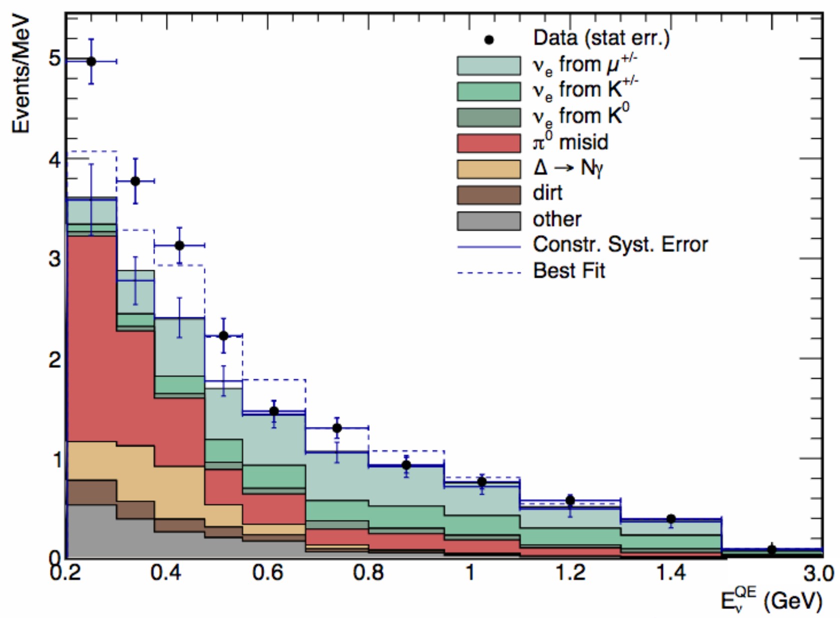


FIG. 1: The MiniBooNE neutrino mode E_ν^{QE} distributions, corresponding to the total 12.84×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and background (histogram with systematic errors). The dashed curve shows the best fit to the neutrino-mode data assuming standard two-neutrino oscillations.

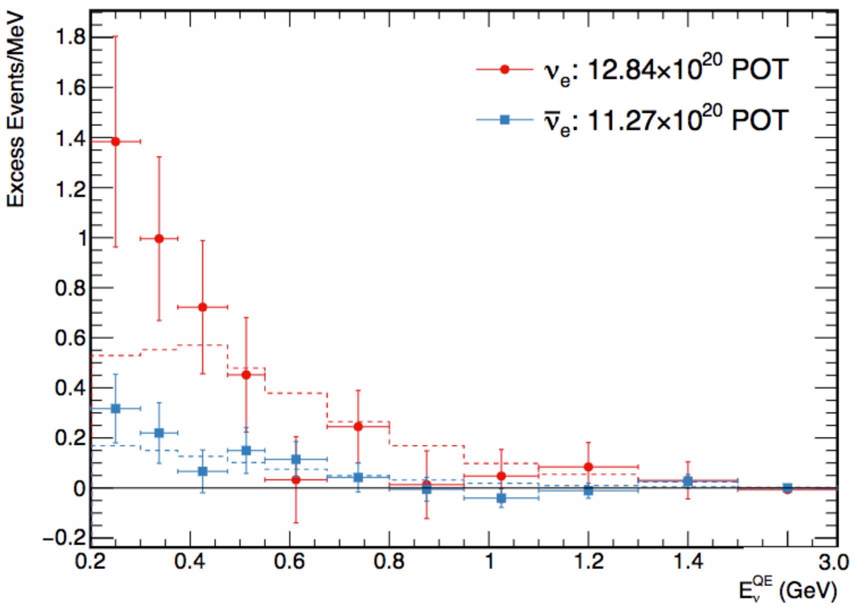


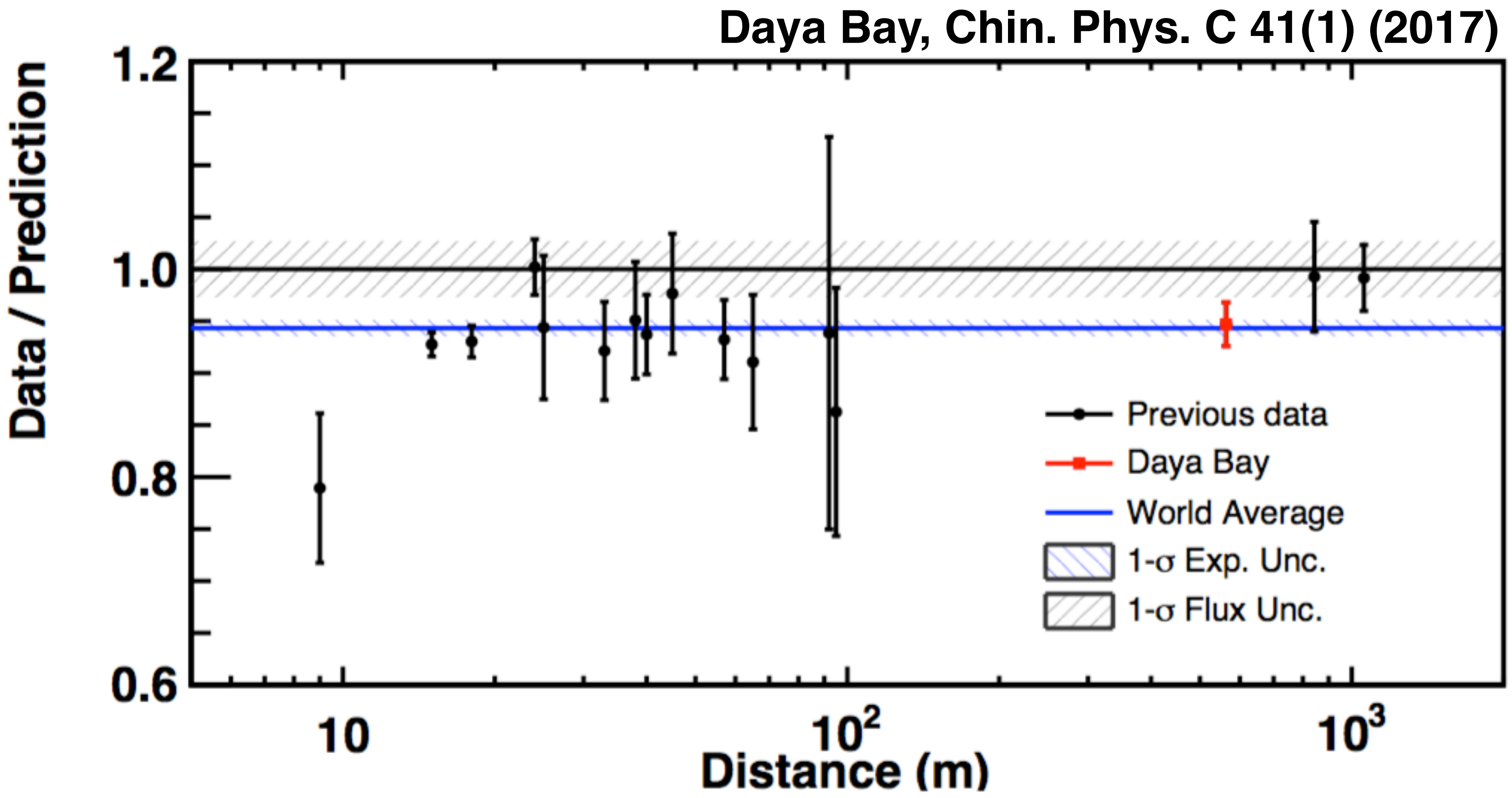
FIG. 2: The MiniBooNE total event excesses as a function of E_ν^{QE} in both neutrino mode and antineutrino mode, corresponding to 12.84×10^{20} POT and 11.27×10^{20} POT, respectively. (Error bars include both statistical and correlated systematic uncertainties.) The dashed curves show the best fits to the neutrino-mode and antineutrino-mode data assuming standard two-neutrino oscillations.

	ν mode 12.84×10^{20} POT	$\bar{\nu}$ mode 11.27×10^{20} POT	Combined
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 95.8 4.8σ

E. Chuan Huang
Neutrino 2018

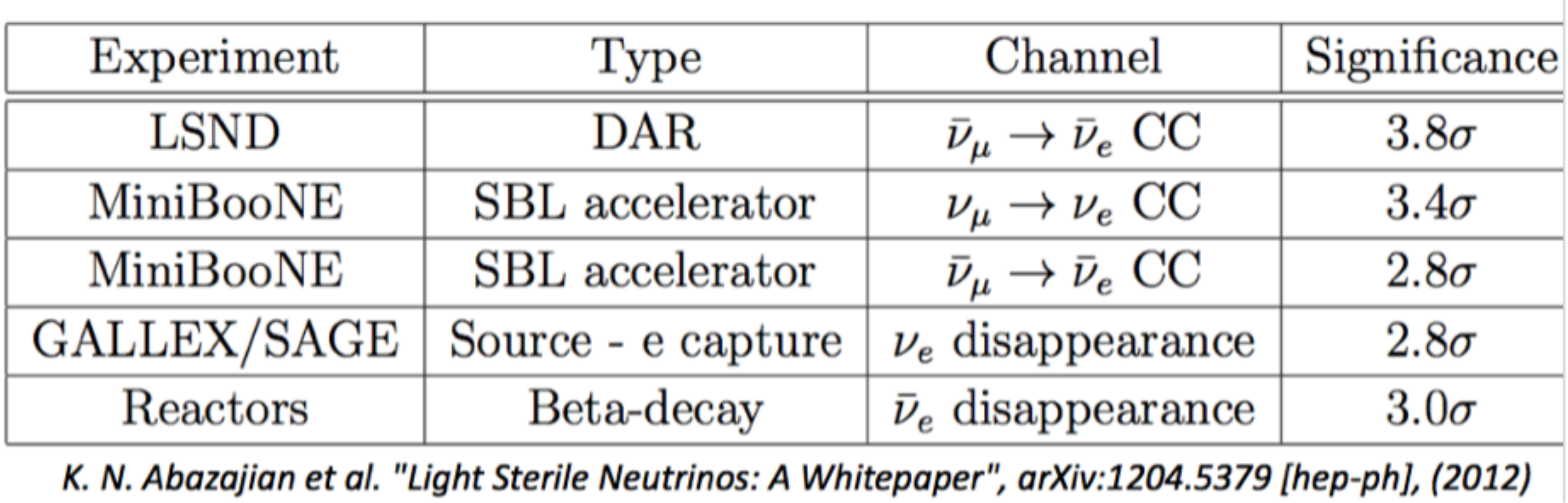
Experimental Anomalies: Reactors

- Hints of beyond standard model neutrinos?
  - Deficit of neutrinos at short distances from nuclear reactors
  - Could result from a high frequency (1 m /MeV) oscillation
- New oscillation experiments could provide compelling experimental proof of physics beyond the standard model!



Anomalies in neutrino physics at Short Baseline experiments

- Different experiments studying neutrinos on baselines less than 1 km have reported anomalies varying in significance
- Common interpretation: Could be evidence of high mass squared neutrino oscillations and the existence of one or more “sterile” neutrino states with masses ~ 1 eV
  - Tons of global fits to the data (both with signal and null results) in literature that fit the data to 3+1, 3+2, 3+3 (Conrad et al, Giunti et al, …)
- All these signals could be hinting at important new physics that requires further exploration!



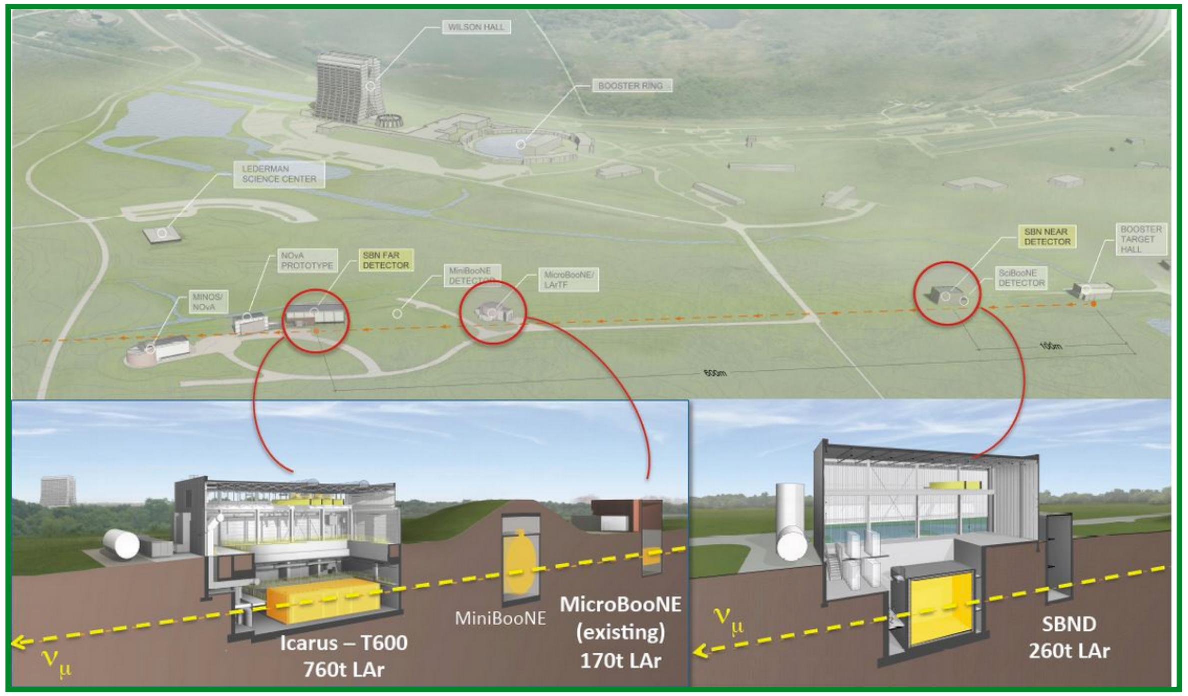
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

New MiniBooNE results 4.8 sigma (neutrino + antineutrino)

Experimental anomalies

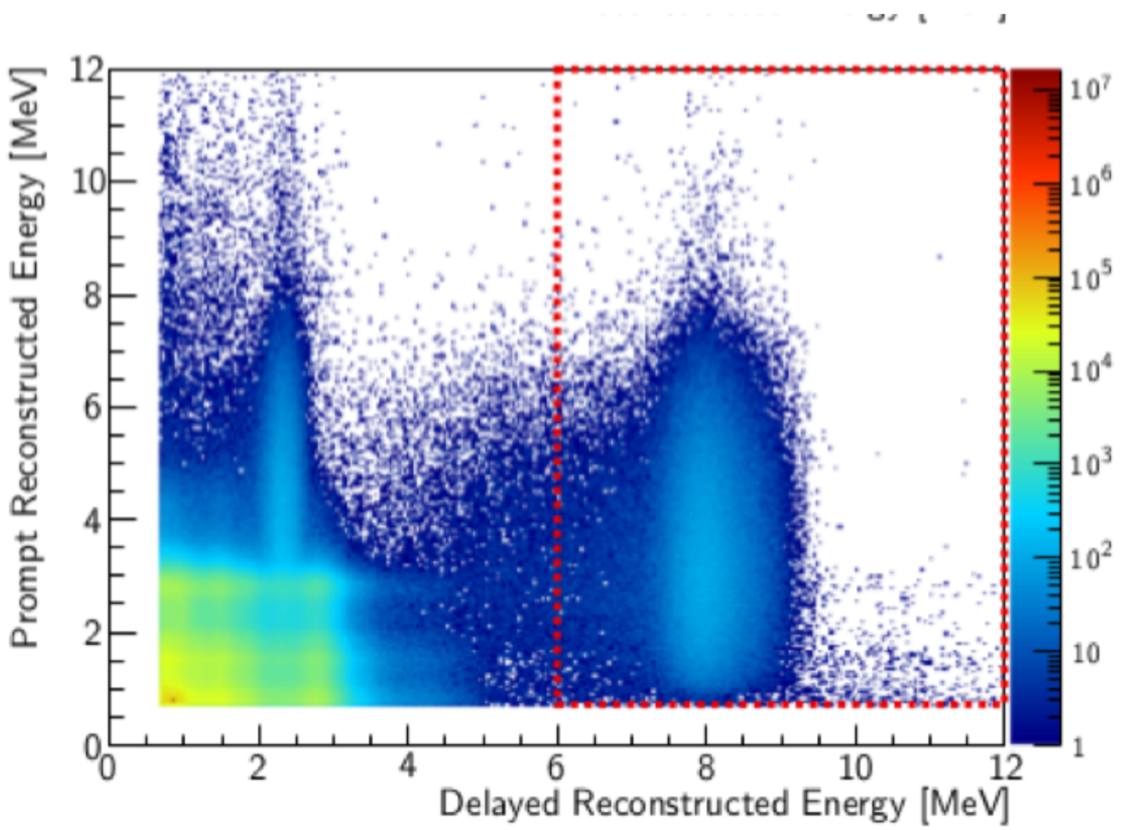
- Testing the “sterile neutrino” hypothesis by different fronts:
  - **Measuring the reactor neutrino flux evolution at Daya Bay**
  - **Testing accelerator ν_e appearance within Fermilab Short Baseline Neutrino (SBN) program**



David Martinez Caicedo - SDSMT

IBD Selection

- Muon Veto (Cosmogenic backgrounds)
- Apply time coincidence and energy cuts.
- Δ_t : time difference between the prompt and delayed signals
  - $1 < \Delta_t < 200$ us

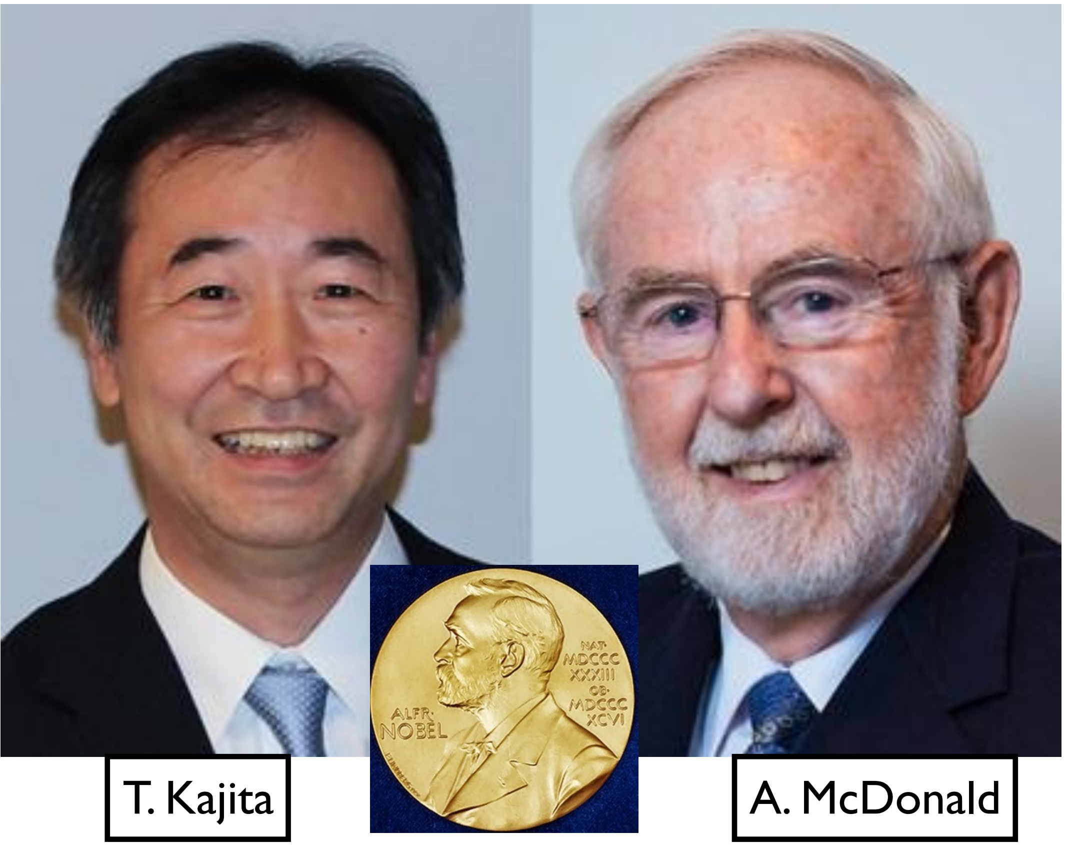


IBD Selection

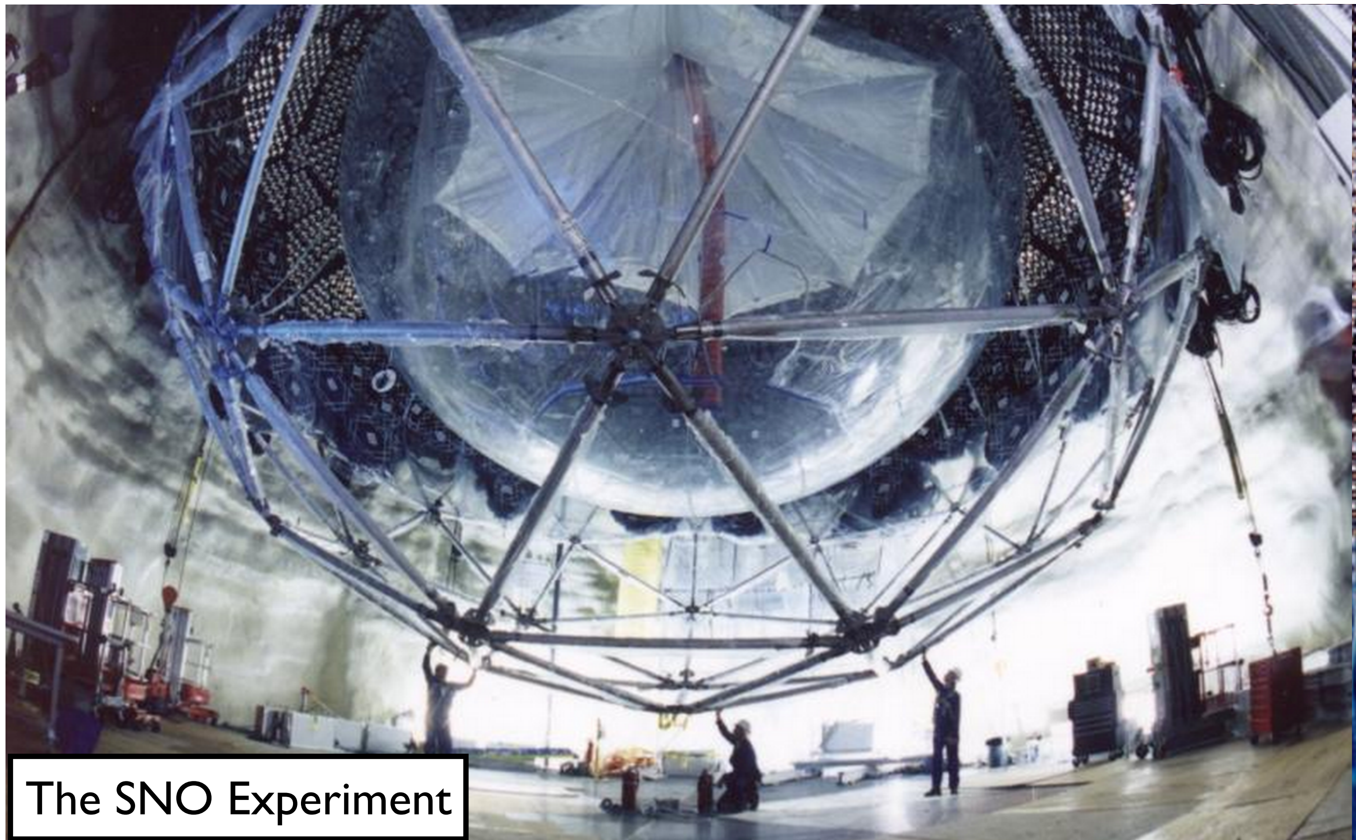
**After this selection on 1230 days of data, we get 2.5 million candidates;
2.2 million from 4 Near Site detectors.**

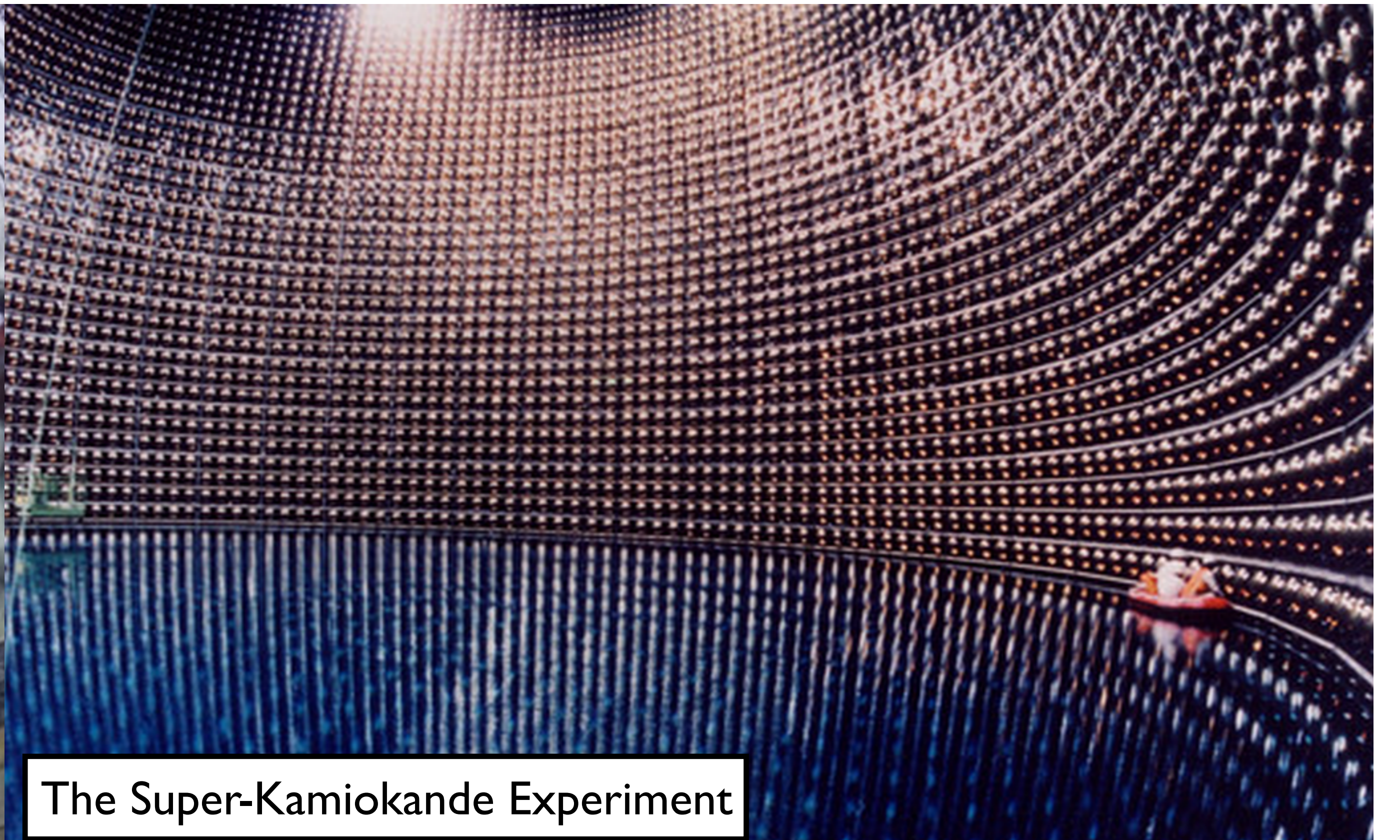
Why neutrinos?

- 2015 Physics Nobel prize: “for the discovery of neutrino oscillations, which shows that neutrinos have mass”
  - Not the only one either: 2002, 1995, 1988
- It’s a very exciting time to be studying neutrino physics!


T. Kajita

A. McDonald

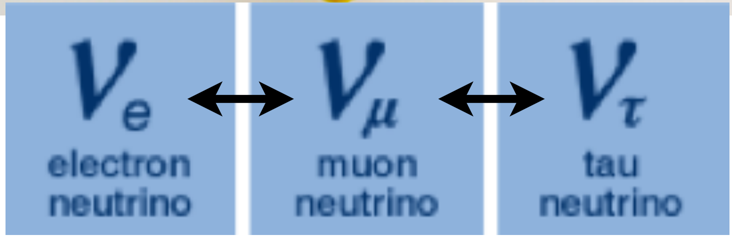

The SNO Experiment

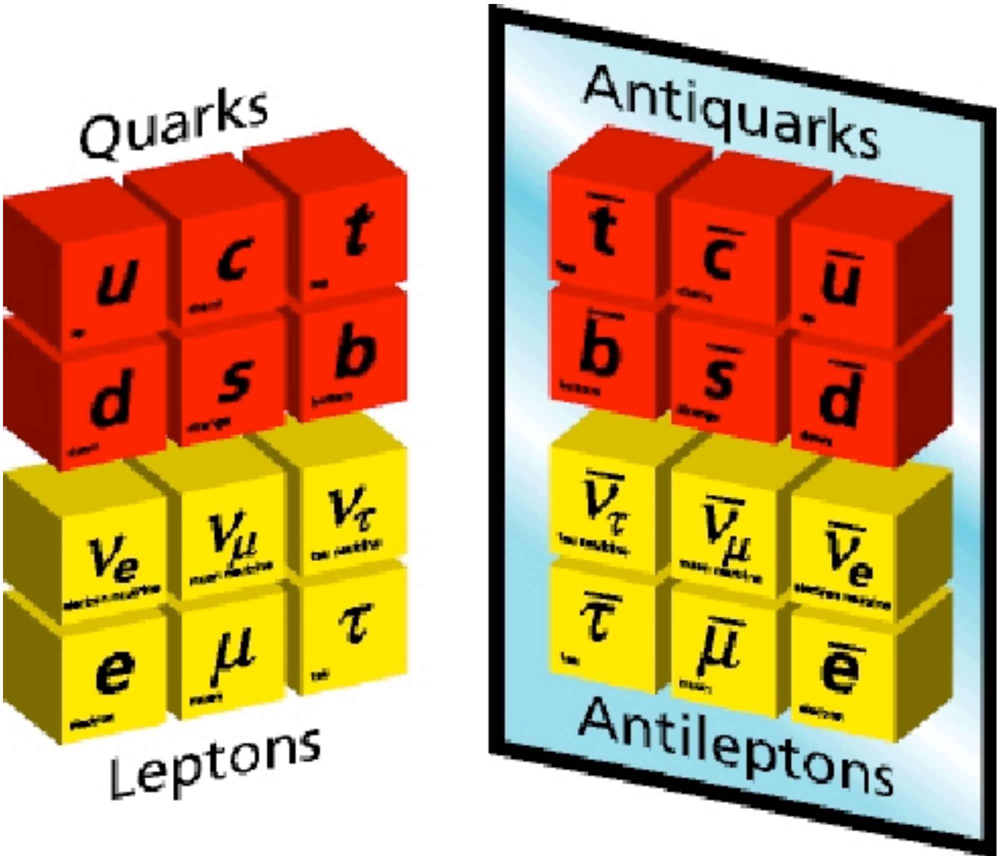

The Super-Kamiokande Experiment

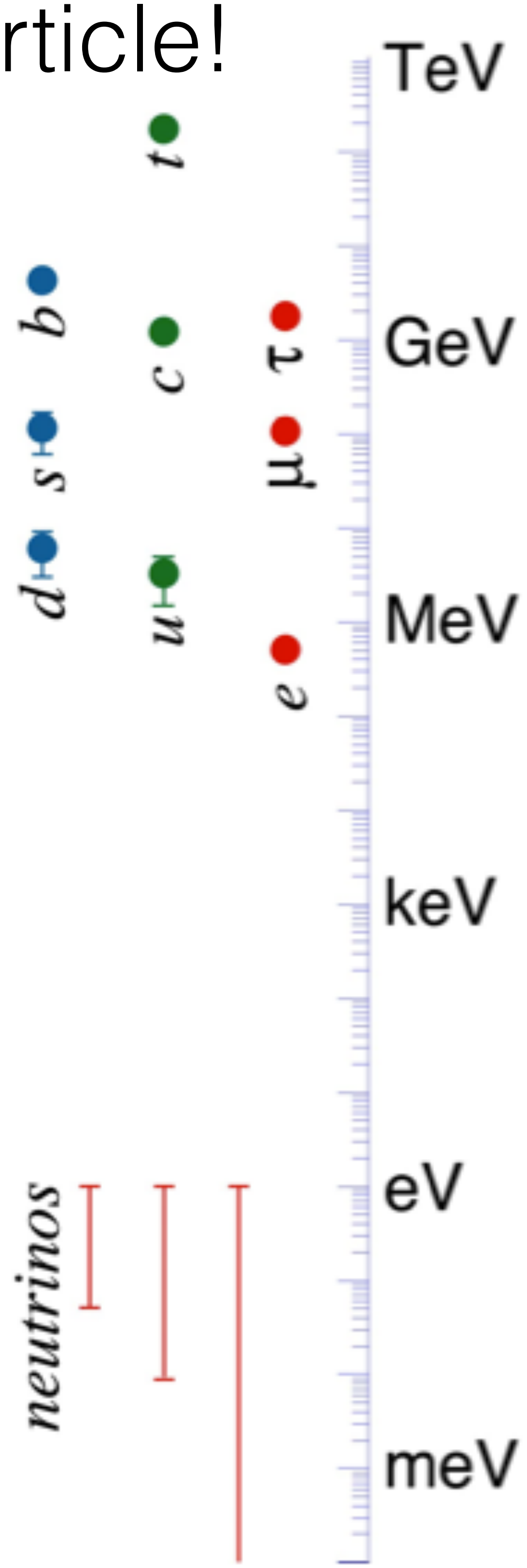
Why Neutrinos?

- Learn more about the least-well-known SM particle!
  - How they interact?
  - How much do they weigh?
  - Related: how much to they oscillate?
  - Related: do neutrinos and antineutrinos OSCILLATE differently?

http://particlezoo.net: Go buy one!!!!







Oscillation results
1958 days of data