Neutrino Physics

Exploring Experimental Anomalies in Accelerator and Reactor Neutrino Experiments.

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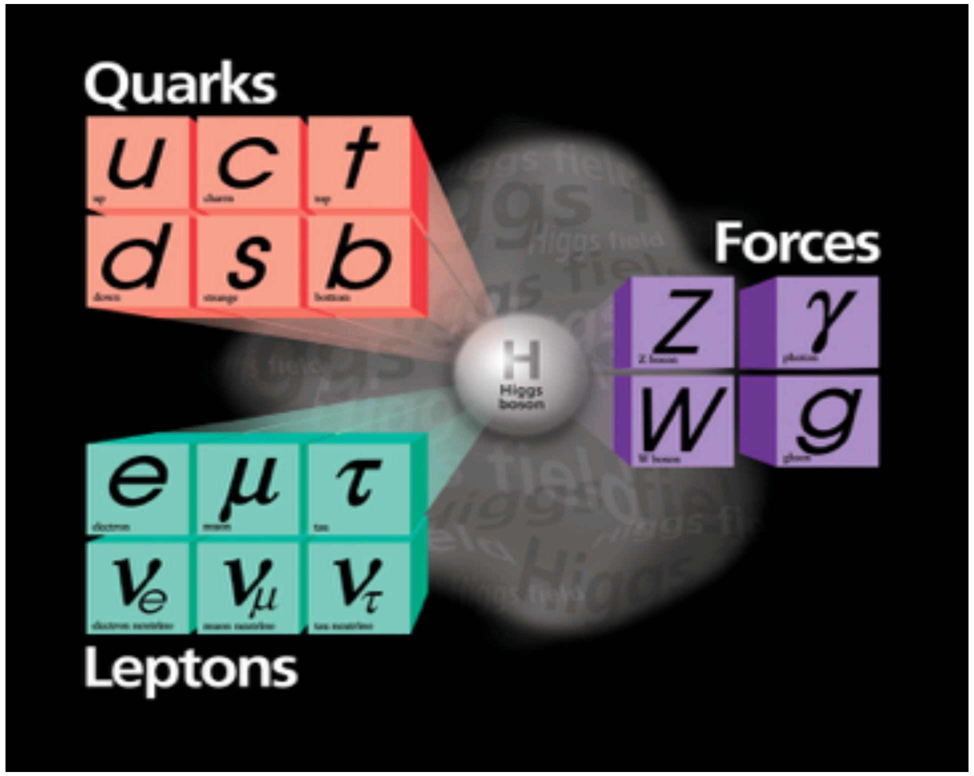
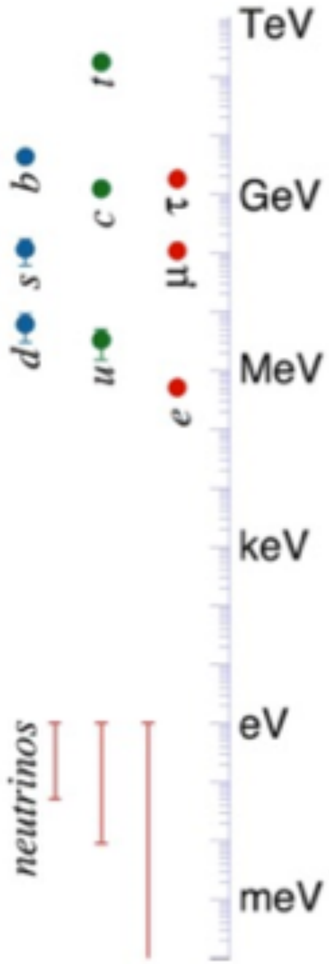
Outline

- Introduction to neutrinos
- Experimental anomalies
- Investigating anomalies :)
  - Reactor Neutrino Experiments
  - Short Baseline Neutrino program at Fermilab
  - Quick view: Deep Underground Neutrino Experiment

Neutrinos

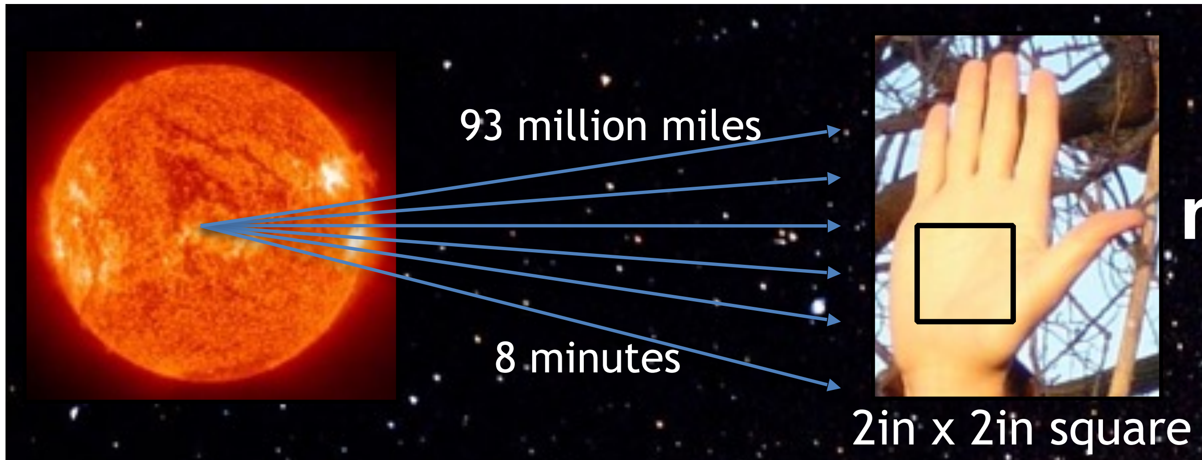
- Neutrinos are everywhere
  - The universe is filled with neutrinos
  - Apart from photons, there are more neutrinos than any other particle
- Neutrinos only feel the weak force
- Example: To stop 1 MeV particle
  - For an electron require 10mm of lead (Electromagnetic interaction)
  - For a proton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

Neutrinos



In fact, every star is an incredible neutrino factory throughout its lifetime, including our star, the Sun!

How many neutrinos in 10 seconds?

0 sec.	0
2 sec.	3,400,000,000,000
4 sec.	6,800,000,000,000
6 sec.	10,200,000,000,000
8 sec.	13,600,000,000,000
10 sec.	17,000,000,000,000

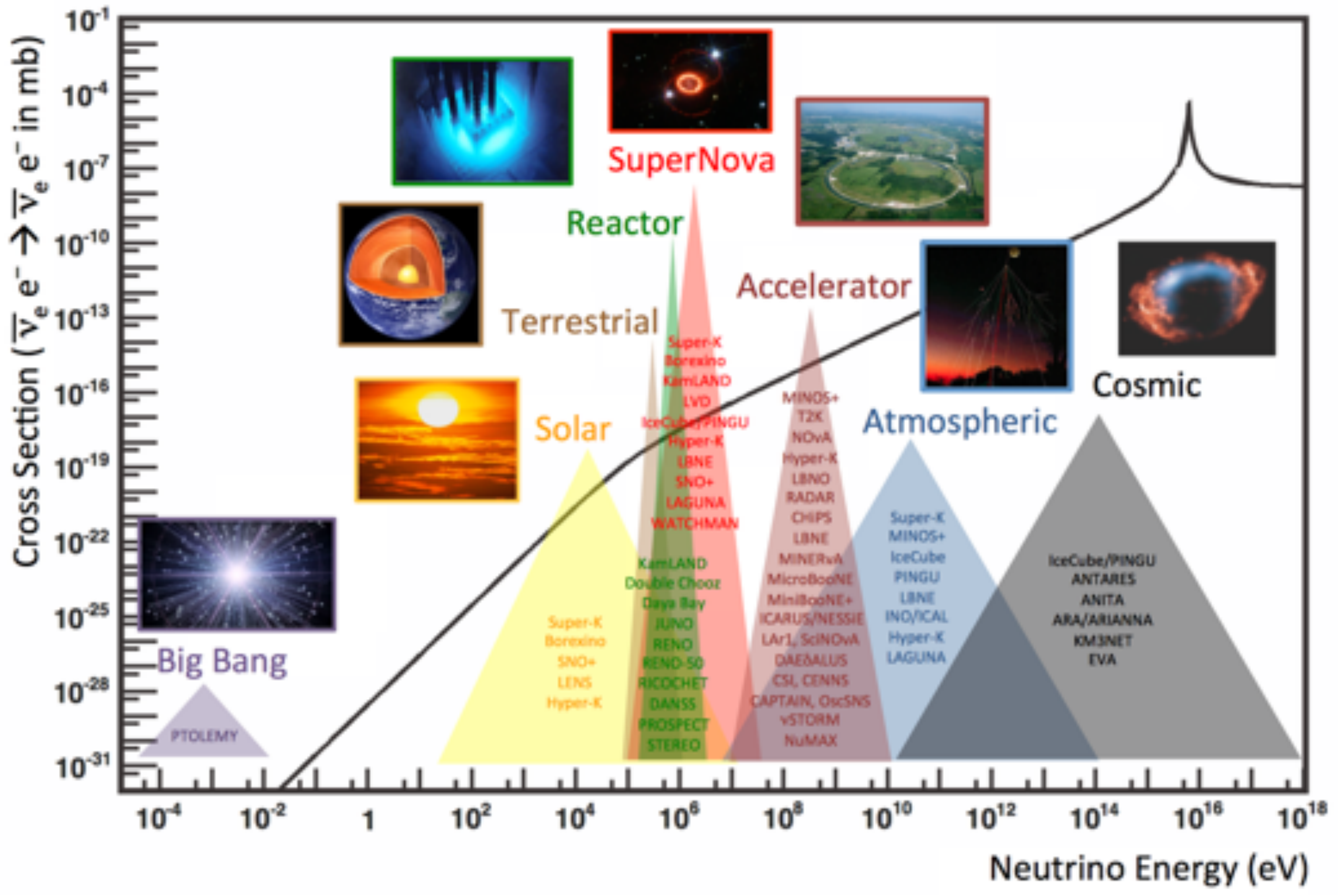
Neutrino Sources

- Many neutrino sources and energies, interacting via weak force

- Focus: Two interesting sources

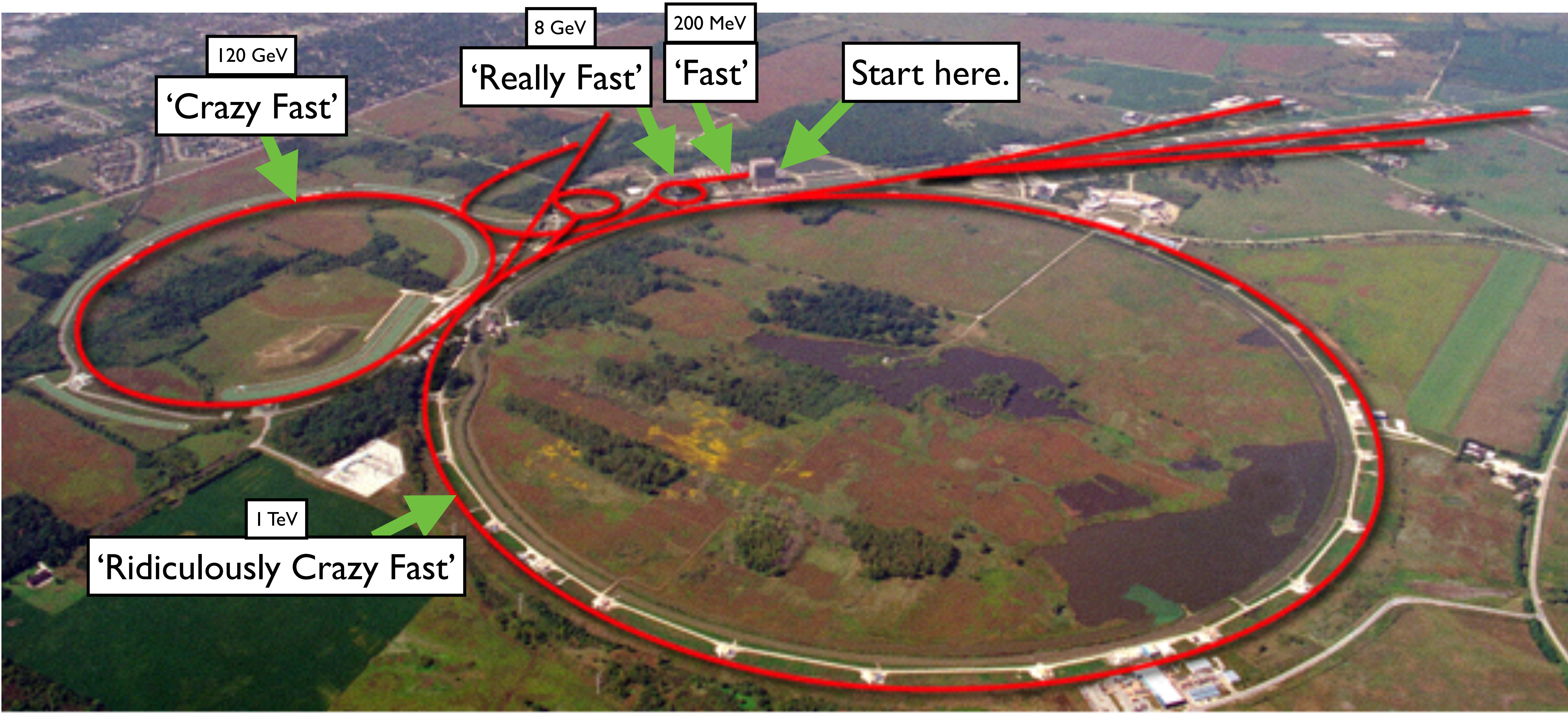
  - Reactors: 1-10 MeV

  - Accelerators: 0.1 - 10 GeV



Neutrino Sources: Accelerators

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



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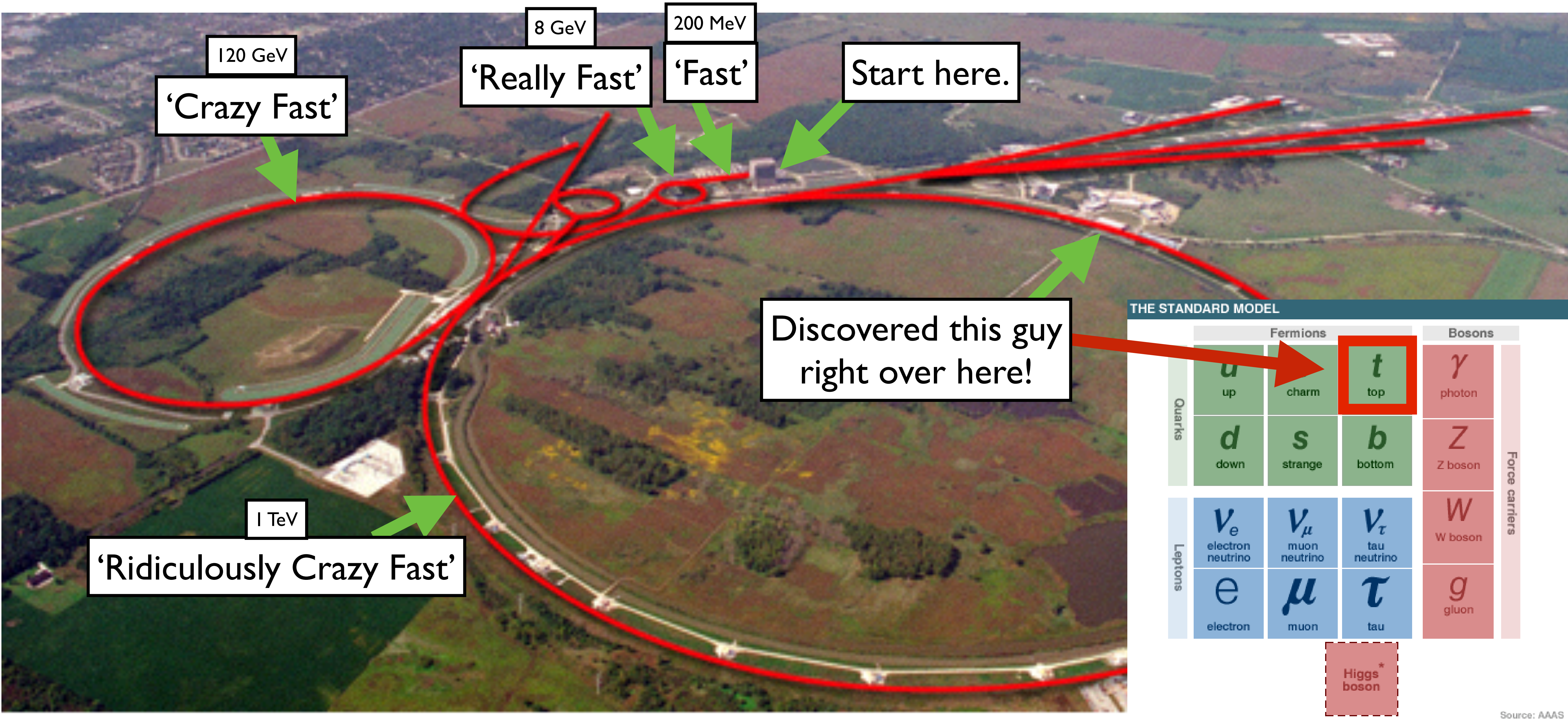


120 GeV
'Crazy Fast'

8 GeV
'Really Fast'

200 MeV
'Fast'

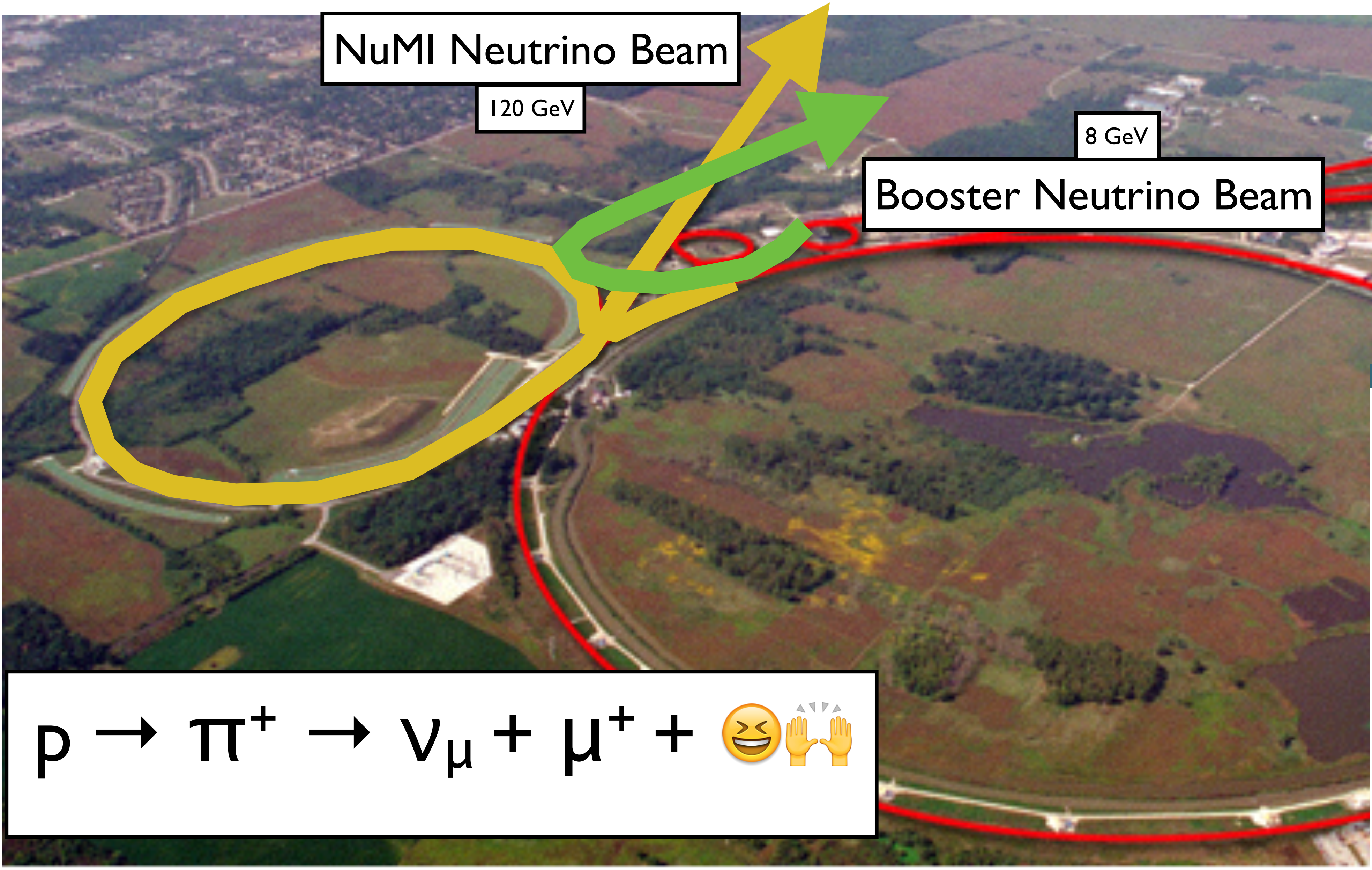
Start here.

Discovered this guy right over here!

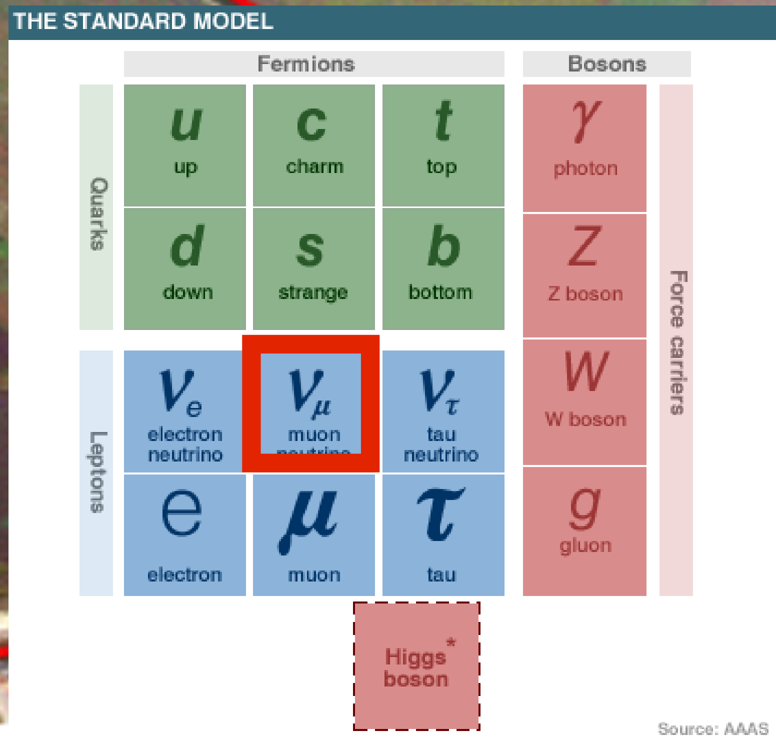
1 TeV
'Ridiculously Crazy Fast'

Neutrino Sources: Accelerators

- Fermilab: Masters of Proton Beams!
  - 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



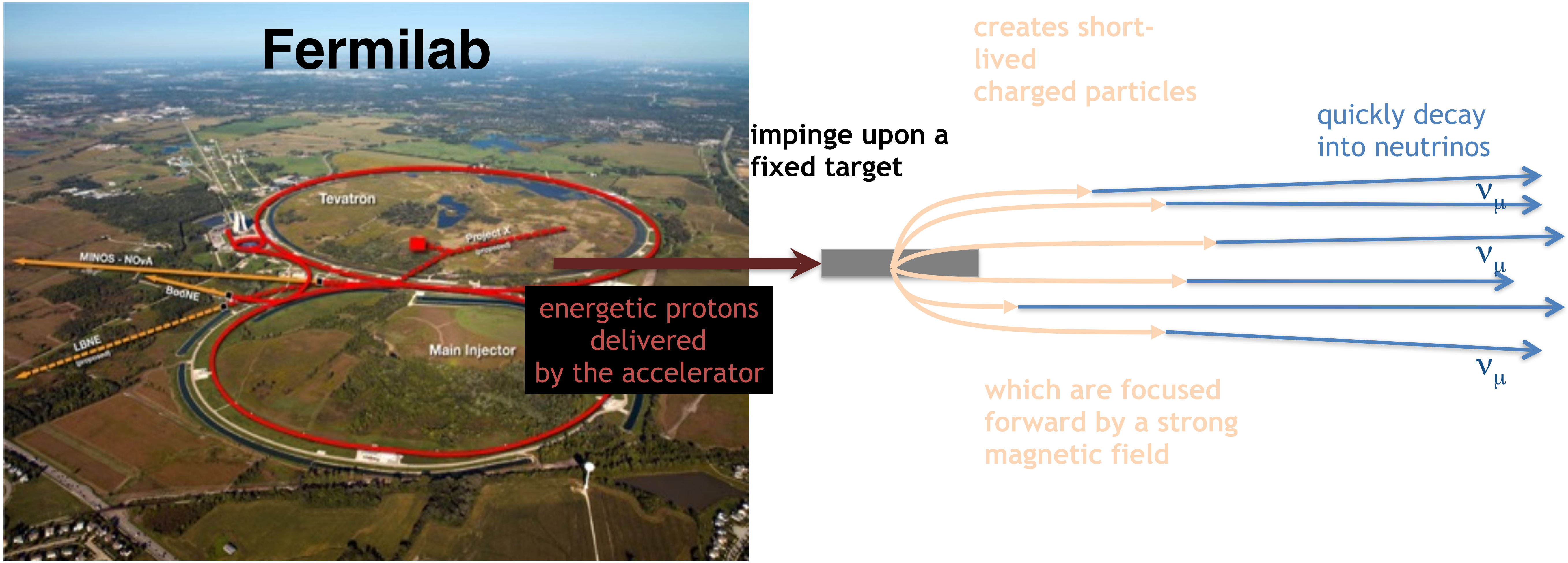
$p \rightarrow \pi^{+} \rightarrow \nu_{\mu} + \mu^{+} +$ 😆🙌



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

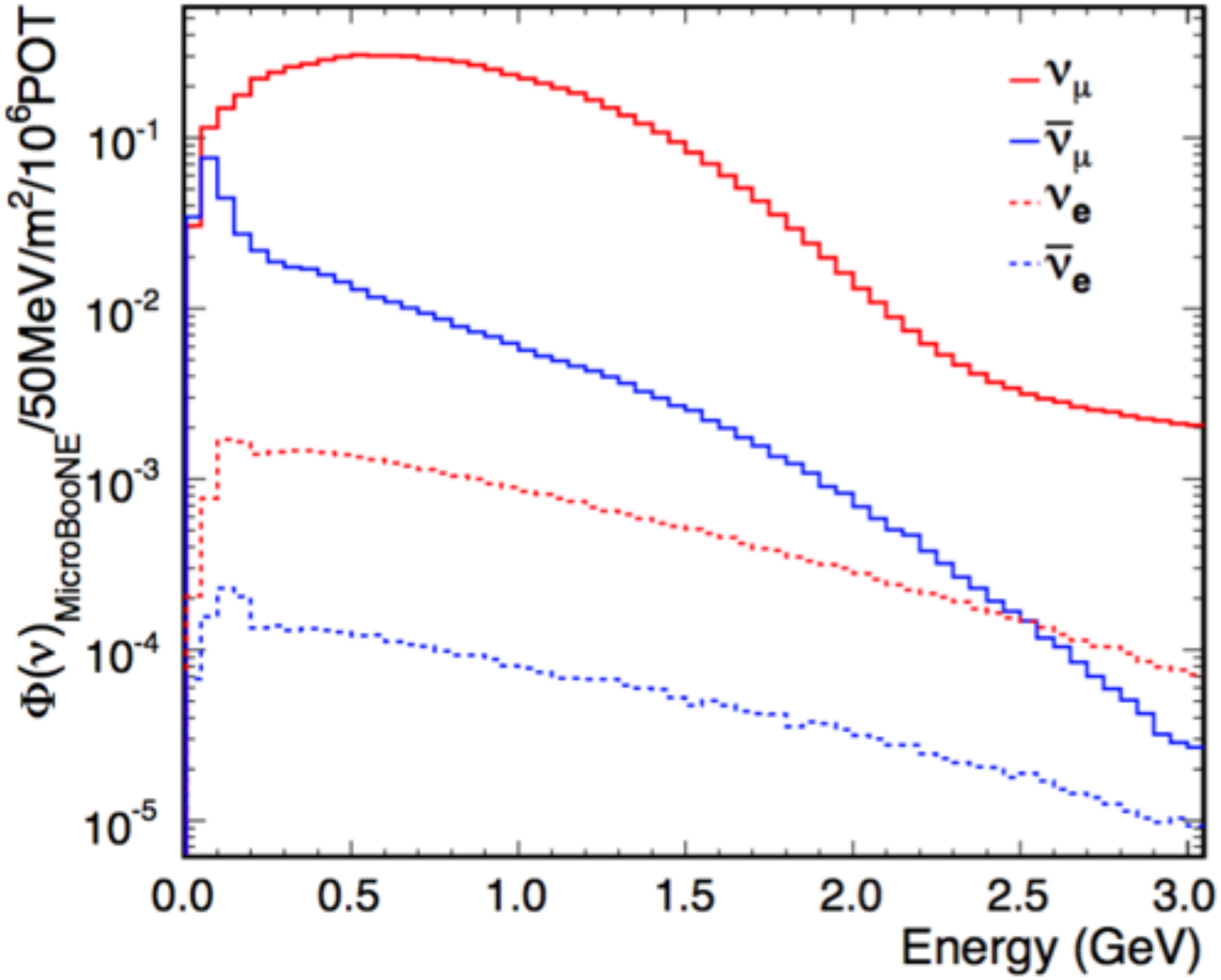
creates short-lived charged particles

which are focused forward by a strong magnetic field

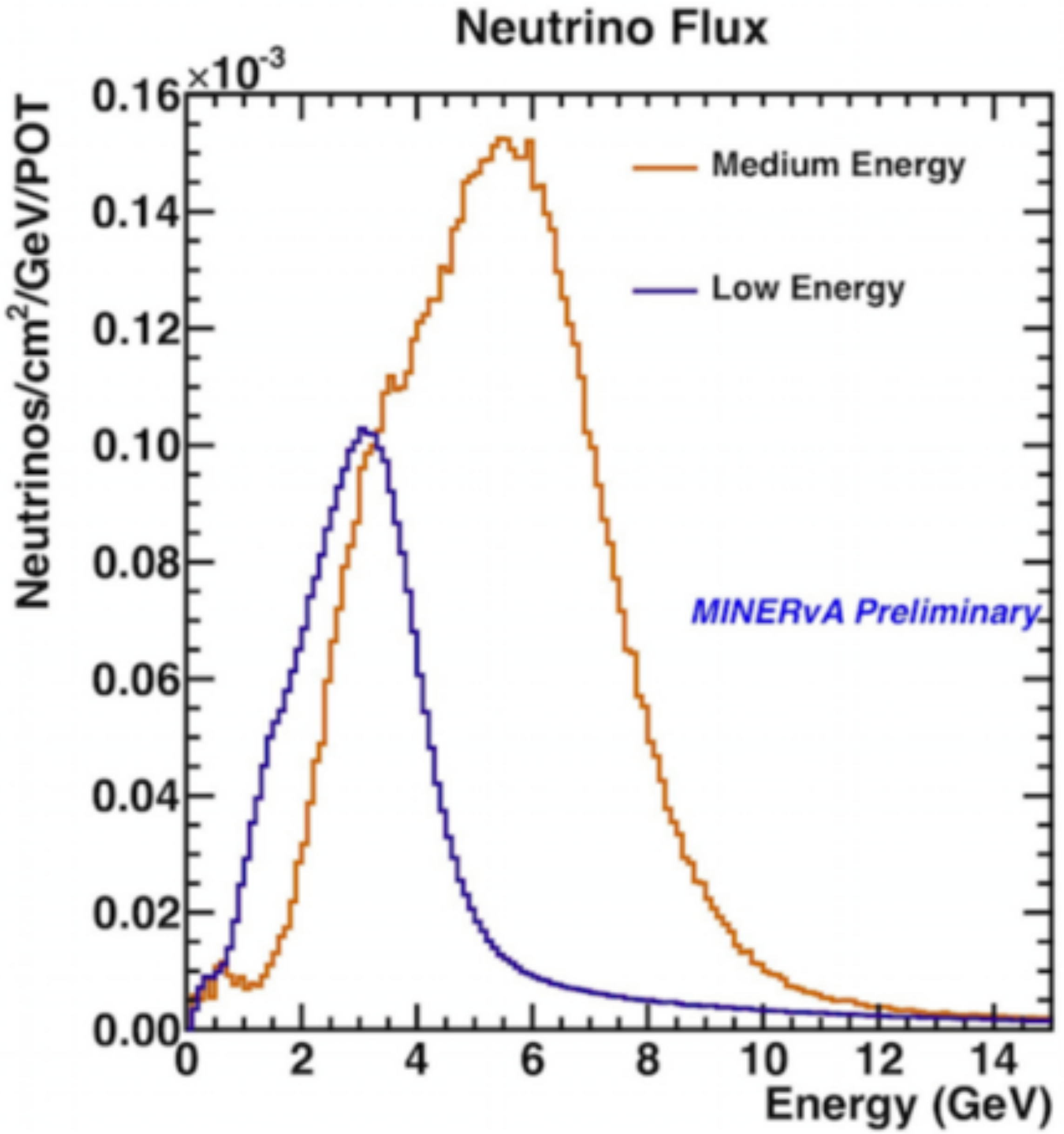
quickly decay into neutrinos

Neutrino Sources: Accelerators

Booster Neutrino Energy Spectrum



NuMI Neutrino Energy Spectrum



~0.5 - 10 GeV Neutrino Energies

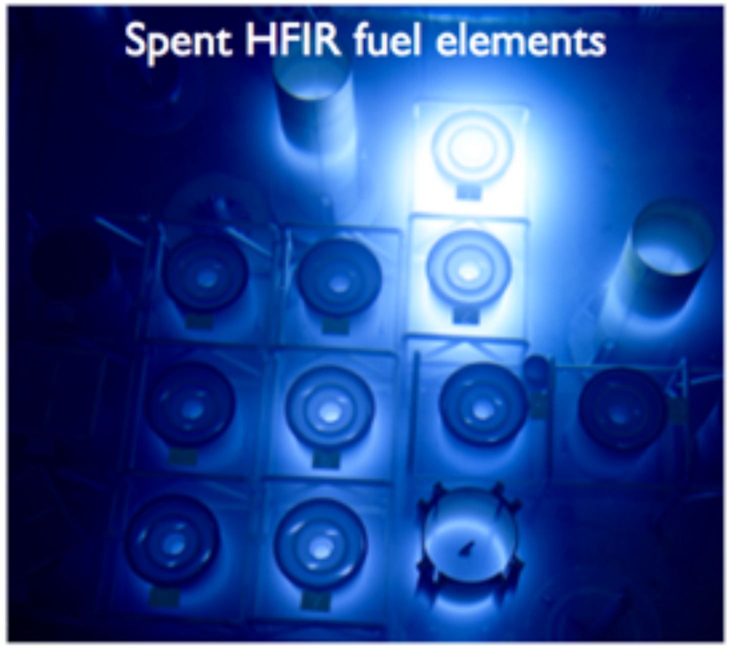
Neutrino Sources: Reactors

- 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)

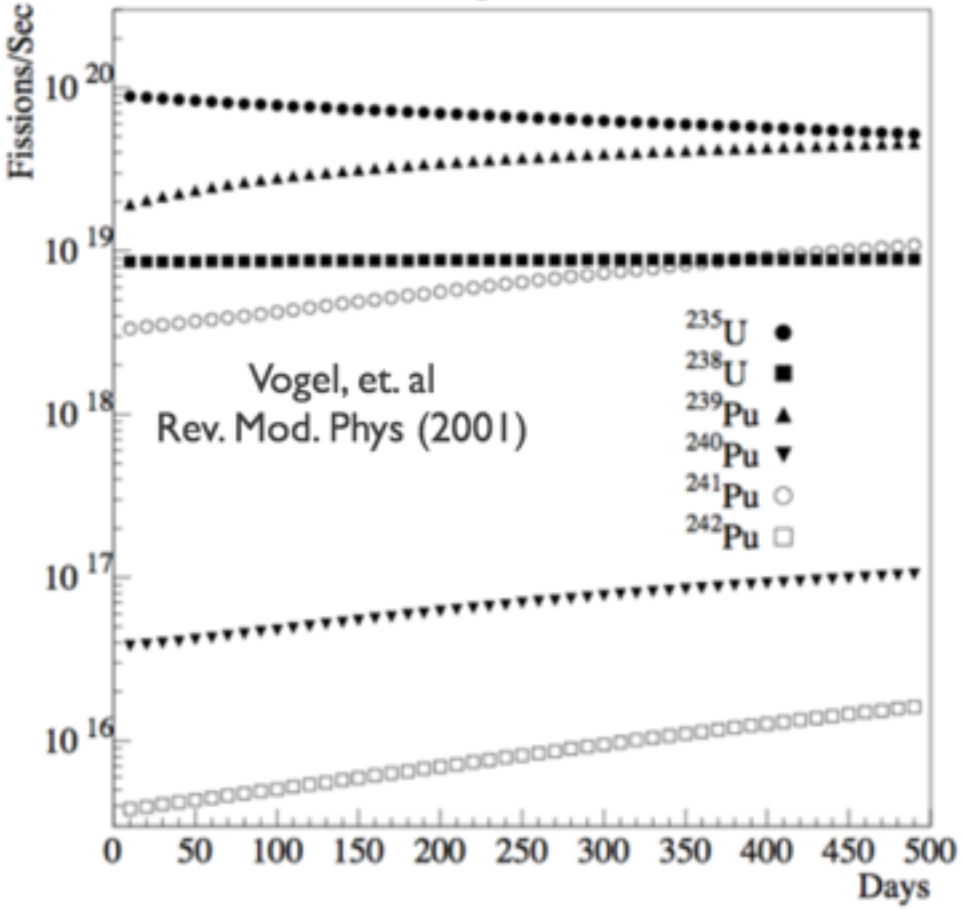
$$n \to p + e^- + \bar{\nu}_e$$

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

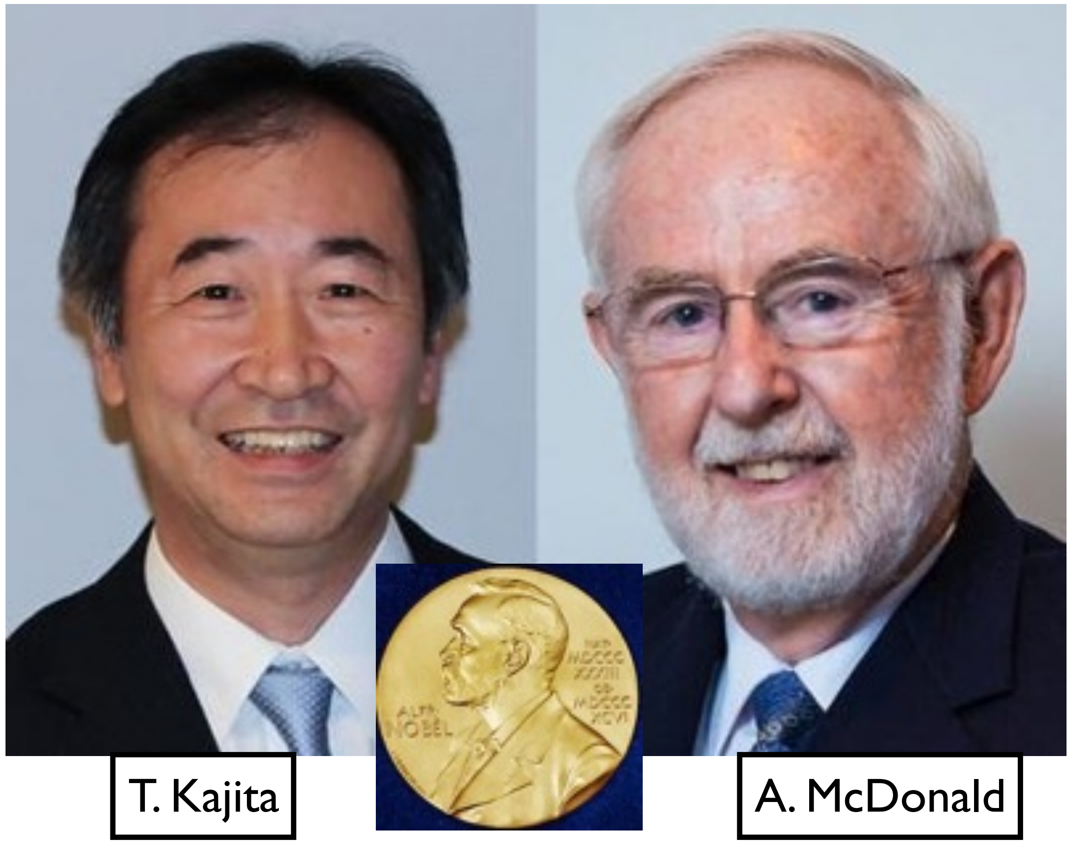


LEU Fission Fragment Contributors



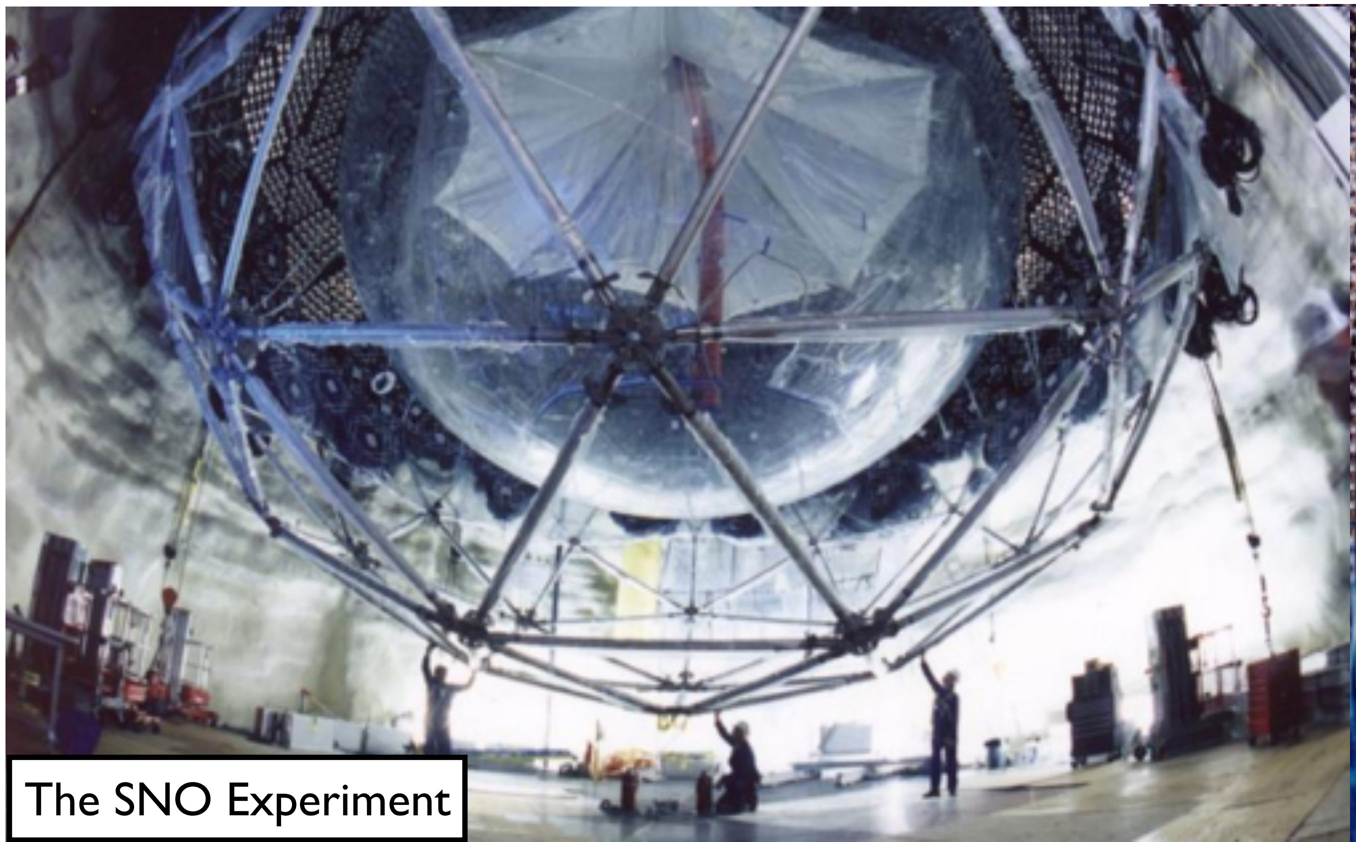
Why neutrinos?

- 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!

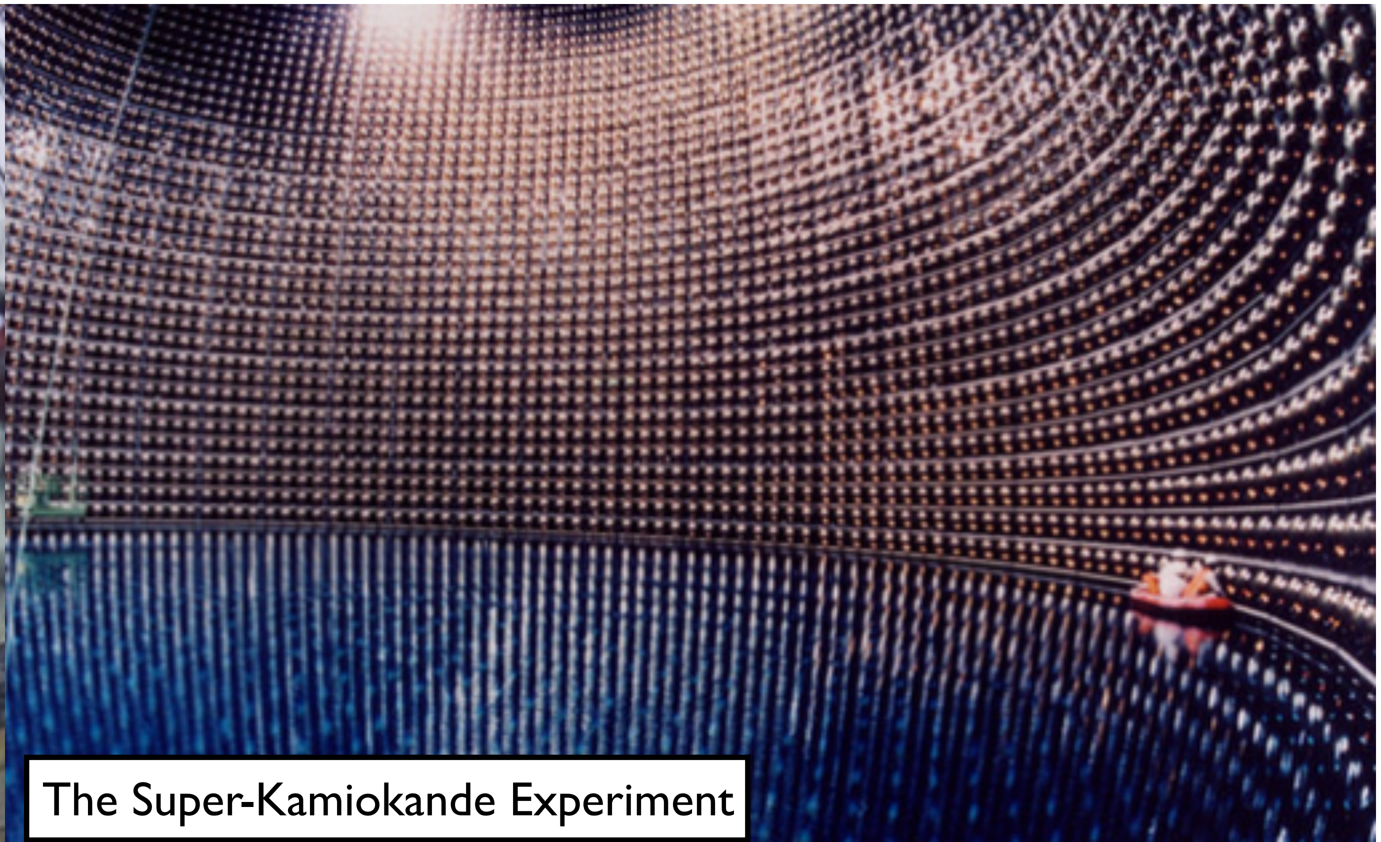


T. Kajita

A. McDonald



The SNO Experiment

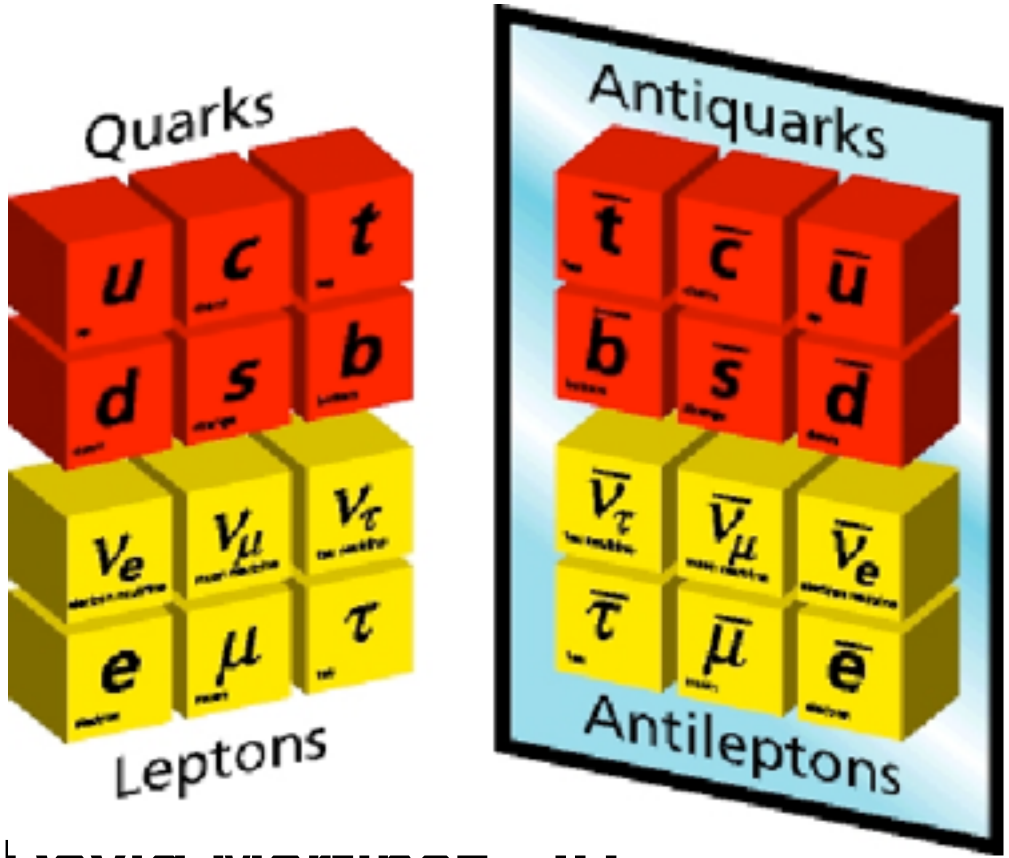


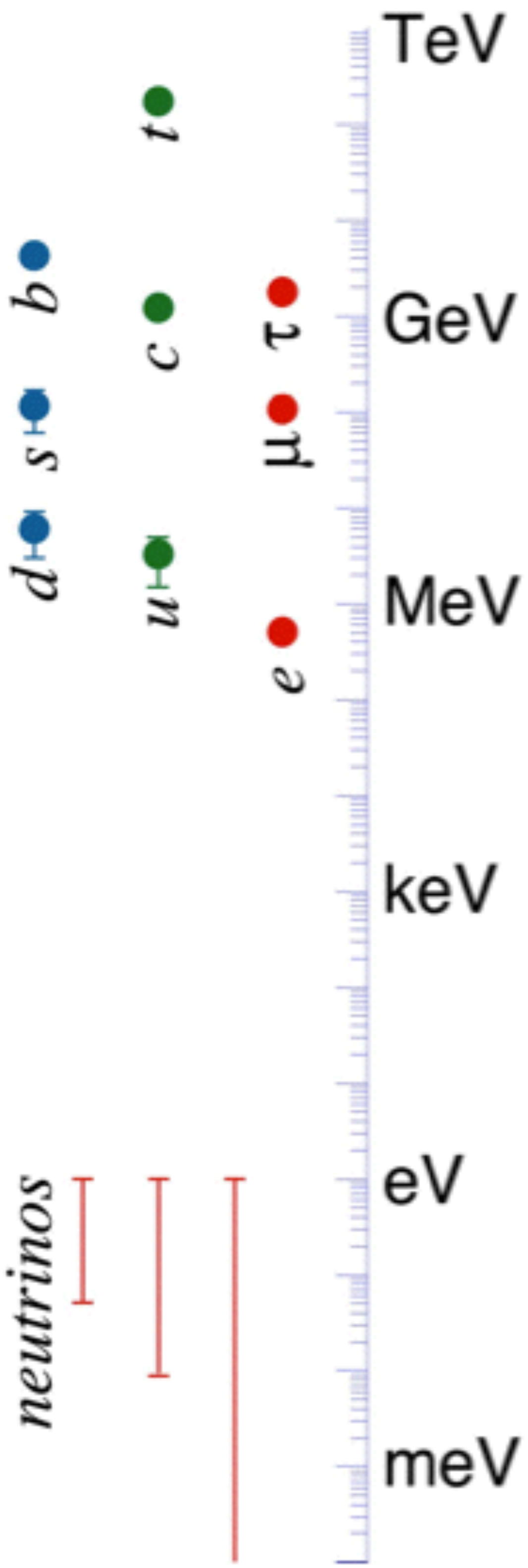
The Super-Kamiokande Experiment

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?

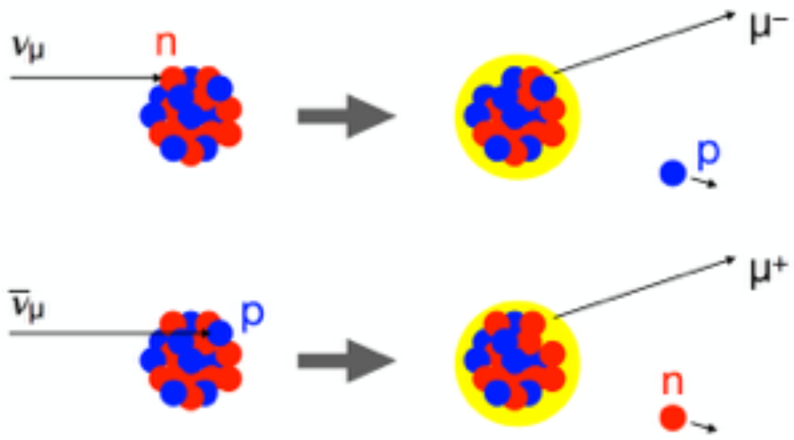
http://particlezoo.net: Go buy one!!!!

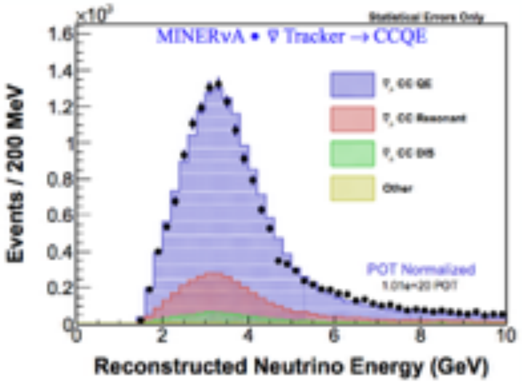




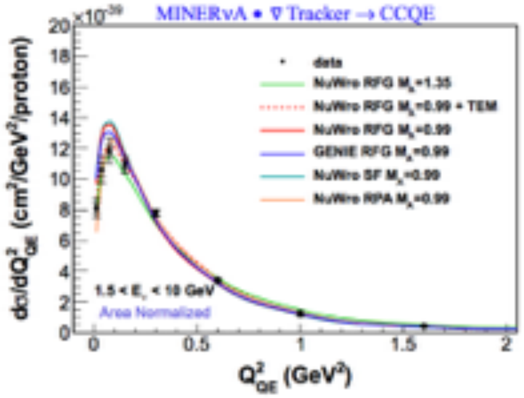
Neutrinos: Cross Sections

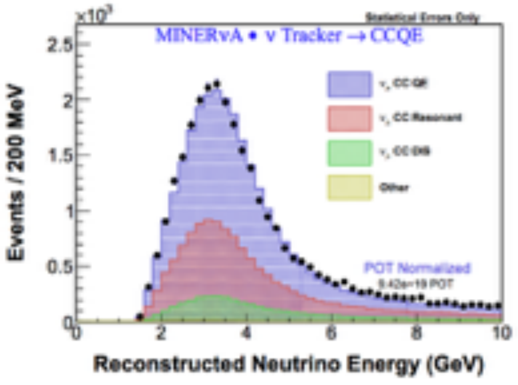
- **Message**: We detect neutrinos based on their interactions
- Targets should be massive amounts of complex materials
- Beams are mainly muon neutrinos and antineutrinos, so we expect to observe the lepton associated with the incoming neutrino (for this particular case muons)
- There are primary two kinds of high energy reactions
  - Quasi-elastic scattering (nucleons in nuclei)
  - Deep Inelastic Scattering (quarks in nucleons)



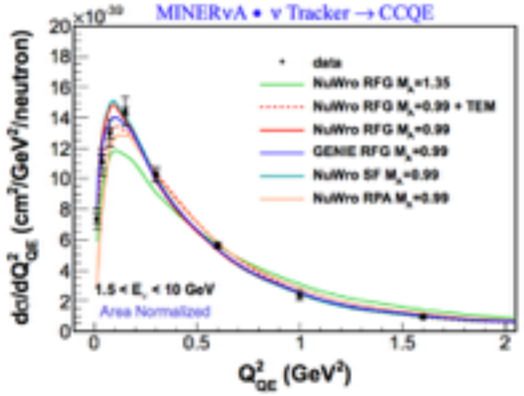


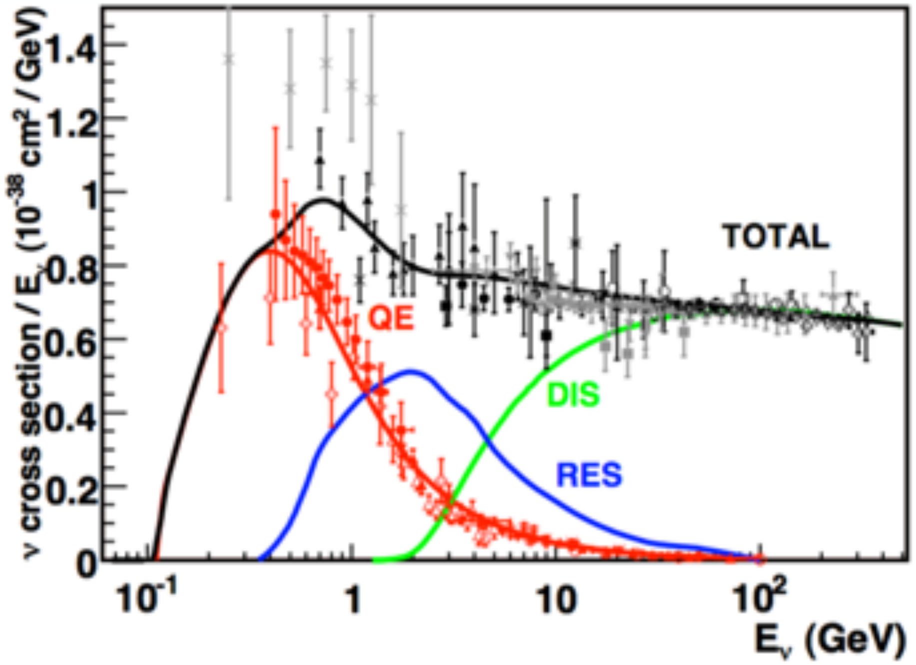
Neutrinos





Anti-Neutrinos

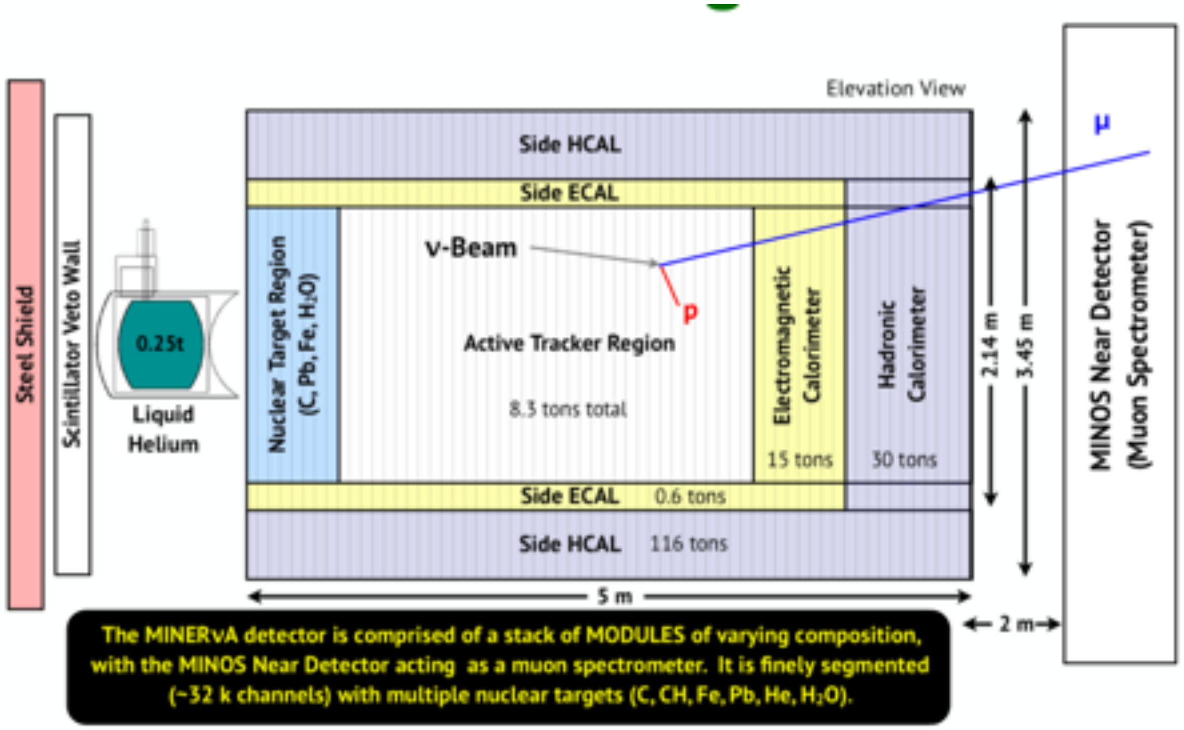




Phys.Rev.Lett. 111, 022502

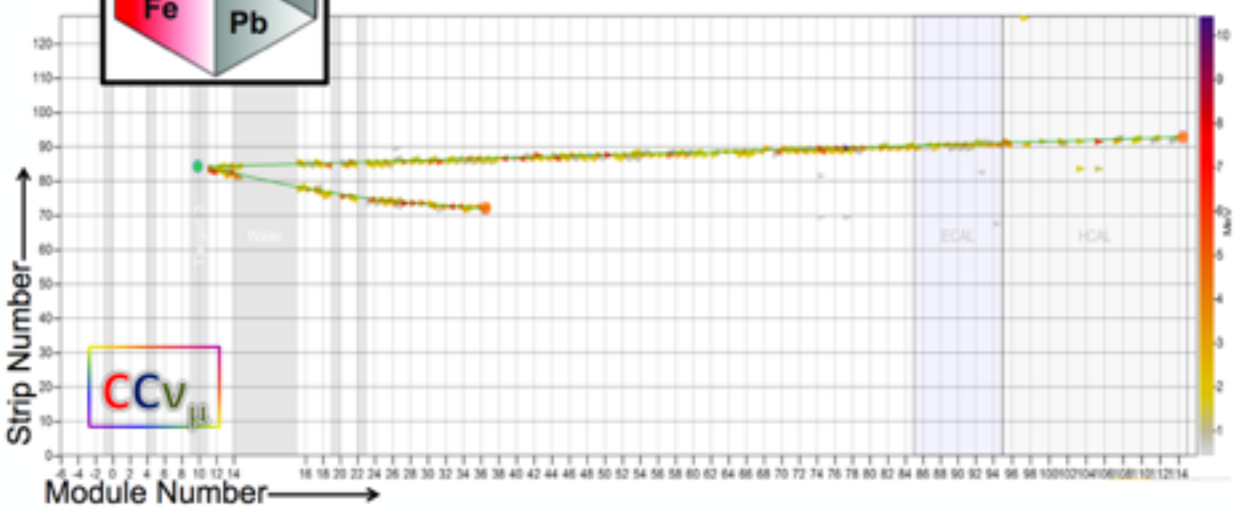
Neutrinos: Cross Sections

- **Exercise**: Find the event rate in per one tonne of target and a neutrino flux of 10^6/cm^2/sec (i.e MINERvA neutrino scattering experiment)
- First: Calculate the number of targets
  - Ntargets = (10^6g)(6.023*10^23/g) ~ 10^30
  - Rate = Ntargets X Flux X Cross Section
  - Rate = 10^30 X 10^6 X 10^-37
  - Rate = 0.1/sec!!!
- **Messages**:
  - Neutrino detectors
    - Must be huge!!
    - Must be able to discriminate different particles
  - Neutrino Fluxes
    - Must be intense



The MINERvA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H2O).

Candidate event for
$\nu_\mu + {}^{12}C \rightarrow \mu^- + p + {}^{11}C^*$



Neutrinos: Oscillations

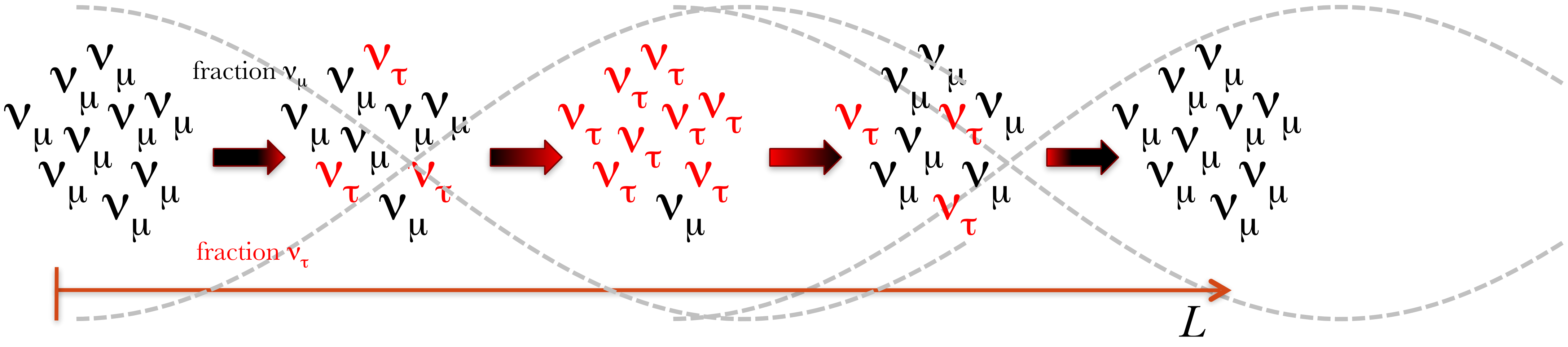
- Neutrino oscillations occur because the flavor (weak) eigenstates do not coincide with the mass eigenstates.

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

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

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

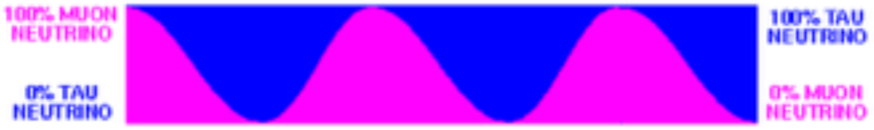
- Over a distance L, changes in the relative phases of the mass states (1,2,3) may induce neutrino flavor change.



Neutrinos: Oscillations

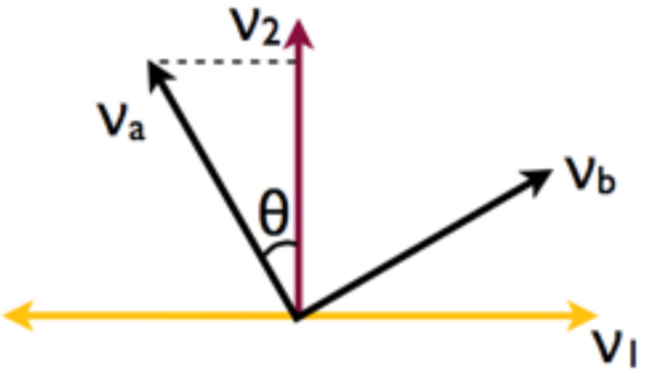
- In the two flavor case the mixing and survival probability are

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



- 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:

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

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:
3 flavor oscillations

- Everything carries through the same as for two flavors but uses the 3X3 PMNS (Pontecorvo-Maki-Nakawa-Sakata) matrix, instead of the 2X2

- BUT, there is mathematical distinction that fundamentally affects the physics and has implications for the UNIVERSE LOL!

- Whereas the 2X2 matrix has one free parameter i.e theta, the 3X3 matrix has four free parameters theta12, theta23, theta13, delta

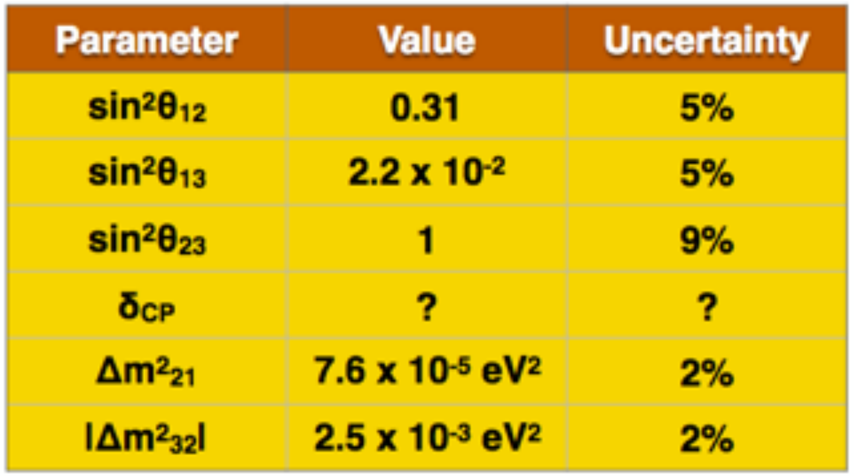
- With 3 flavors of neutrinos, there are two independent mass-squared differences

$$\Delta m^2_{21} \equiv \Delta m^2_{sol} \sim 7.6 \times 10^{-5}\ eV^2$$

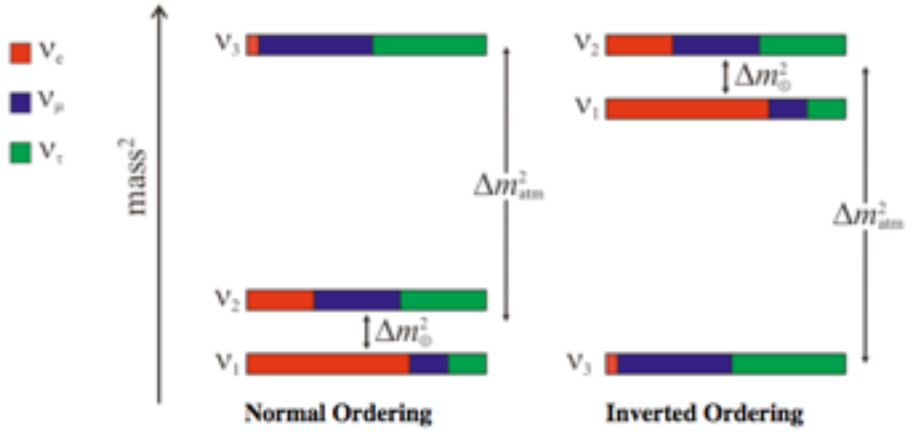
$$\Delta m^2_{32} \approx \Delta m^2_{31} \equiv \Delta m^2_{atm} \sim 2.5 \times 10^{-3}\ eV^2$$

- If the parameter delta is non-zero, then neutrinos can exhibit CP violation. That is, neutrino reactions have different cross sections than antineutrino reactions

- Question: Could be this the basis of the so-called “matter-antimatter asymmetry” of the Universe?



Parameter	Value	Uncertainty
$\sin^2\theta_{12}$	0.31	5%
$\sin^2\theta_{13}$	2.2×10^{-2}	5%
$\sin^2\theta_{23}$	1	9%
δ_{CP}	?	?
Δm^2_{21}	7.6×10^{-5} eV^2	2%
$\|\Delta m^2_{32}\|$	2.5×10^{-3} eV^2	2%

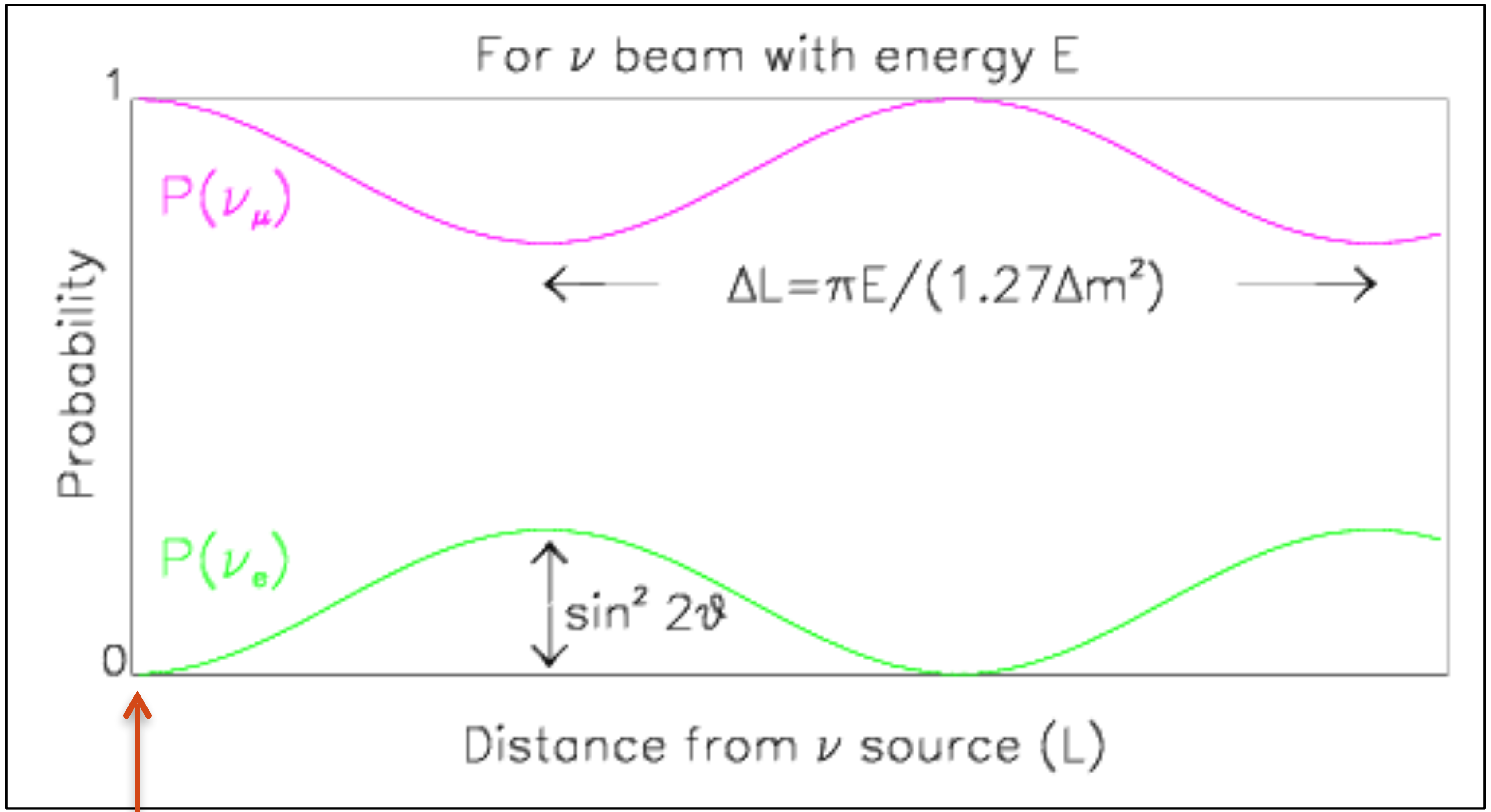


Great progress last two decades!
We still do not know:
The sign of Δm_{32}
is δ_{cp} non zero?
is U unitary?

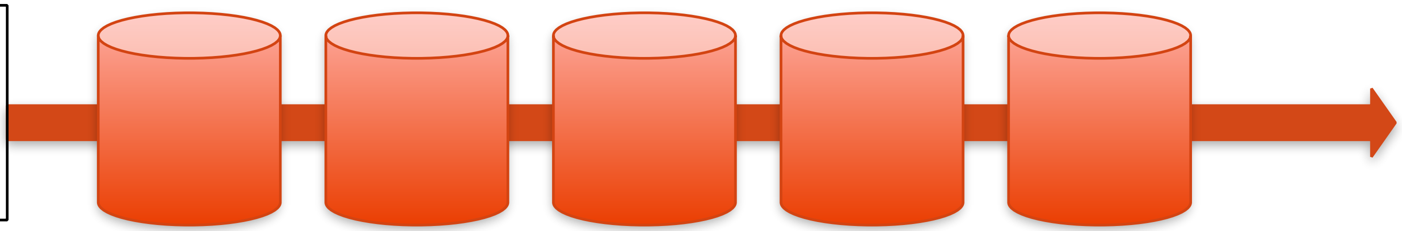
Neutrinos: Oscillations

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

Fixed energy E
Variable L



Begin with mono-energetic ν_α



Many detectors and measure the content ν_α / ν_β

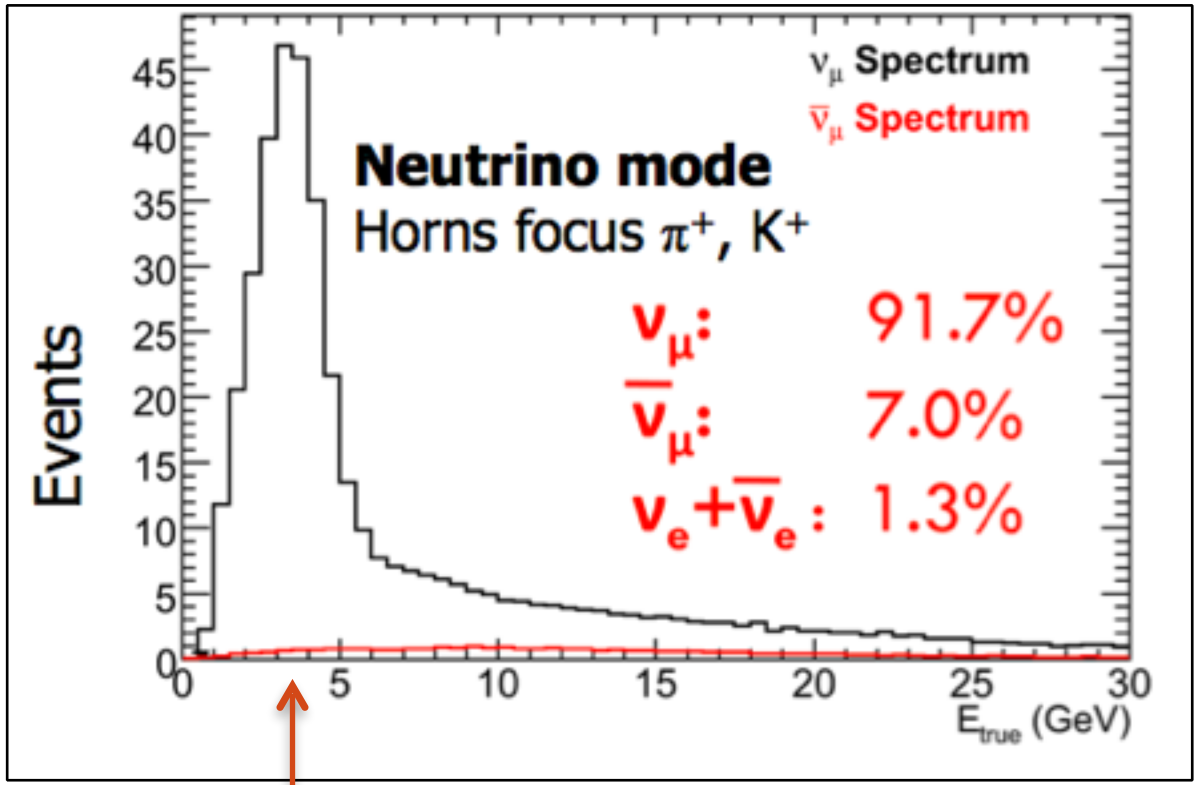
Message:

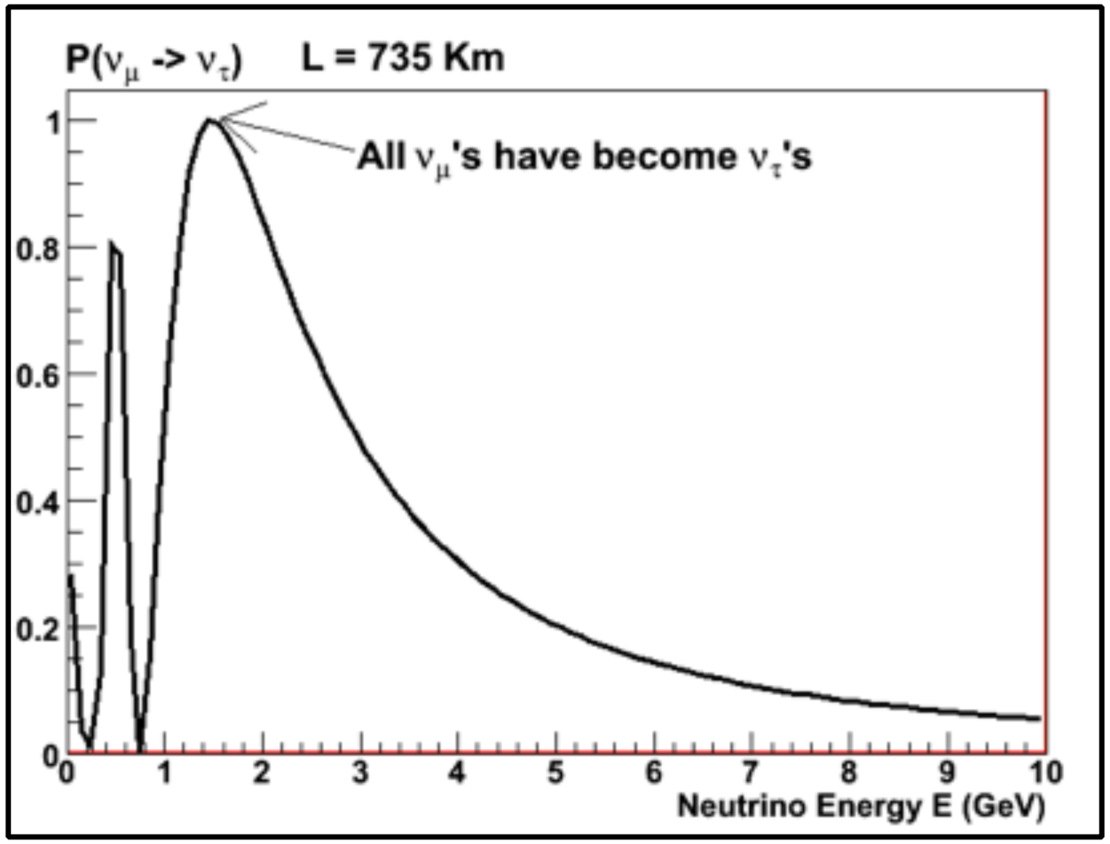
Nice idea but $$$

Neutrinos: Oscillations

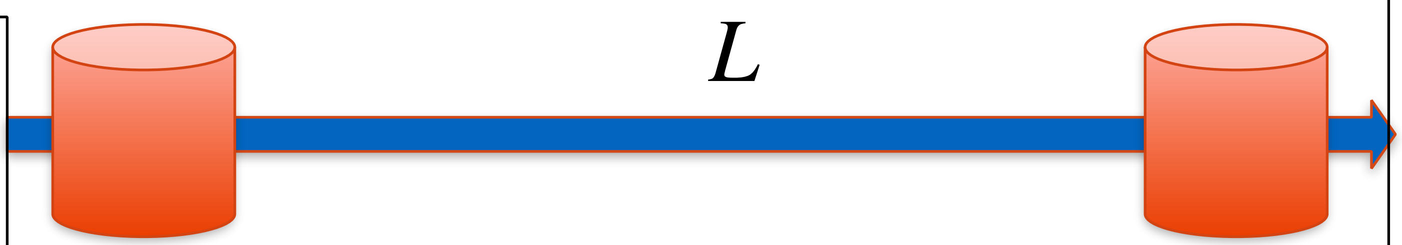
$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

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

Experimental Anomalies

Experimental anomalies: LSND

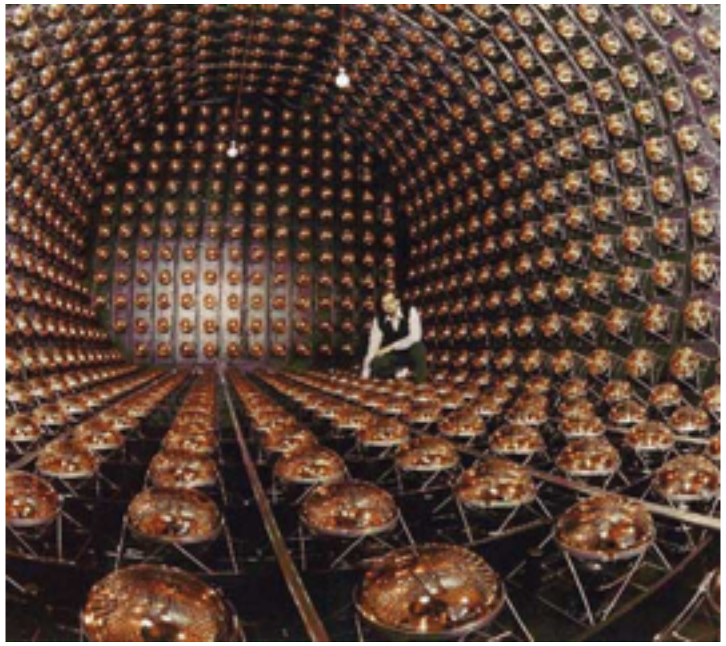
LSND used neutrinos from stopped pions to search for neutrino oscillations with $\Delta m^2 \sim 1\text{eV}^2$.

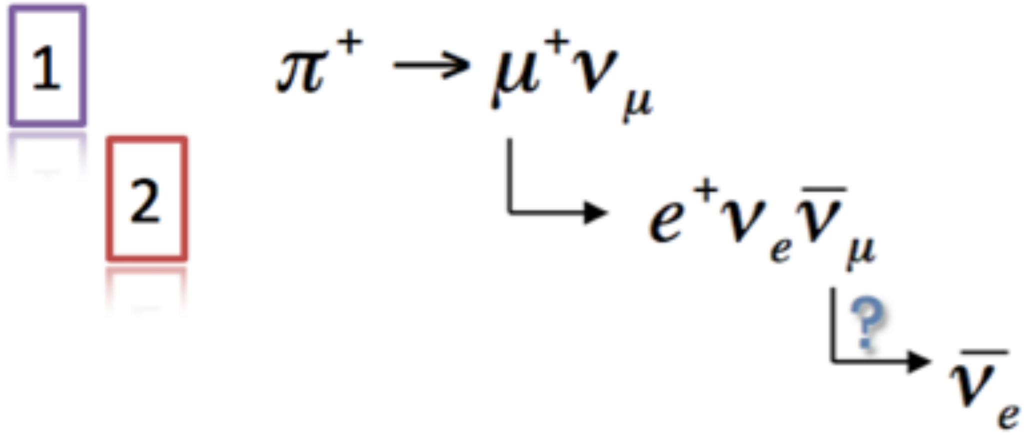
For two-state mixing:

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

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

800 MeV proton beam produces π^+ that produce neutrinos





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

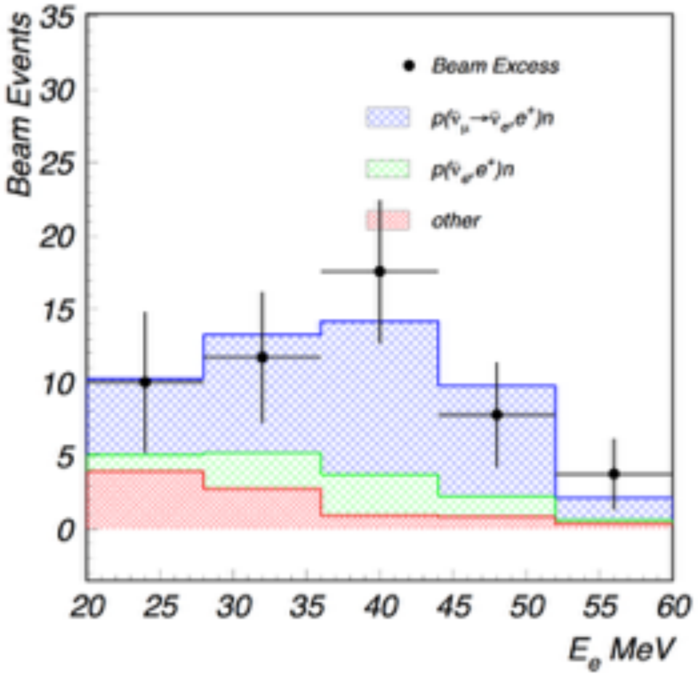
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

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

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

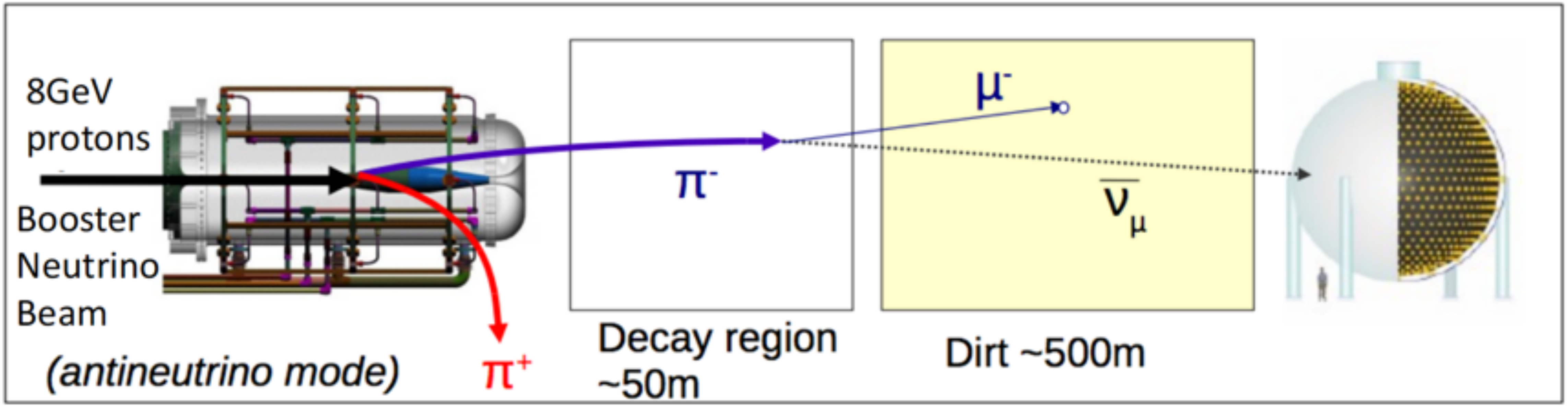
via Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$

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



LSND anomaly
PRD 64 (2001) 112007

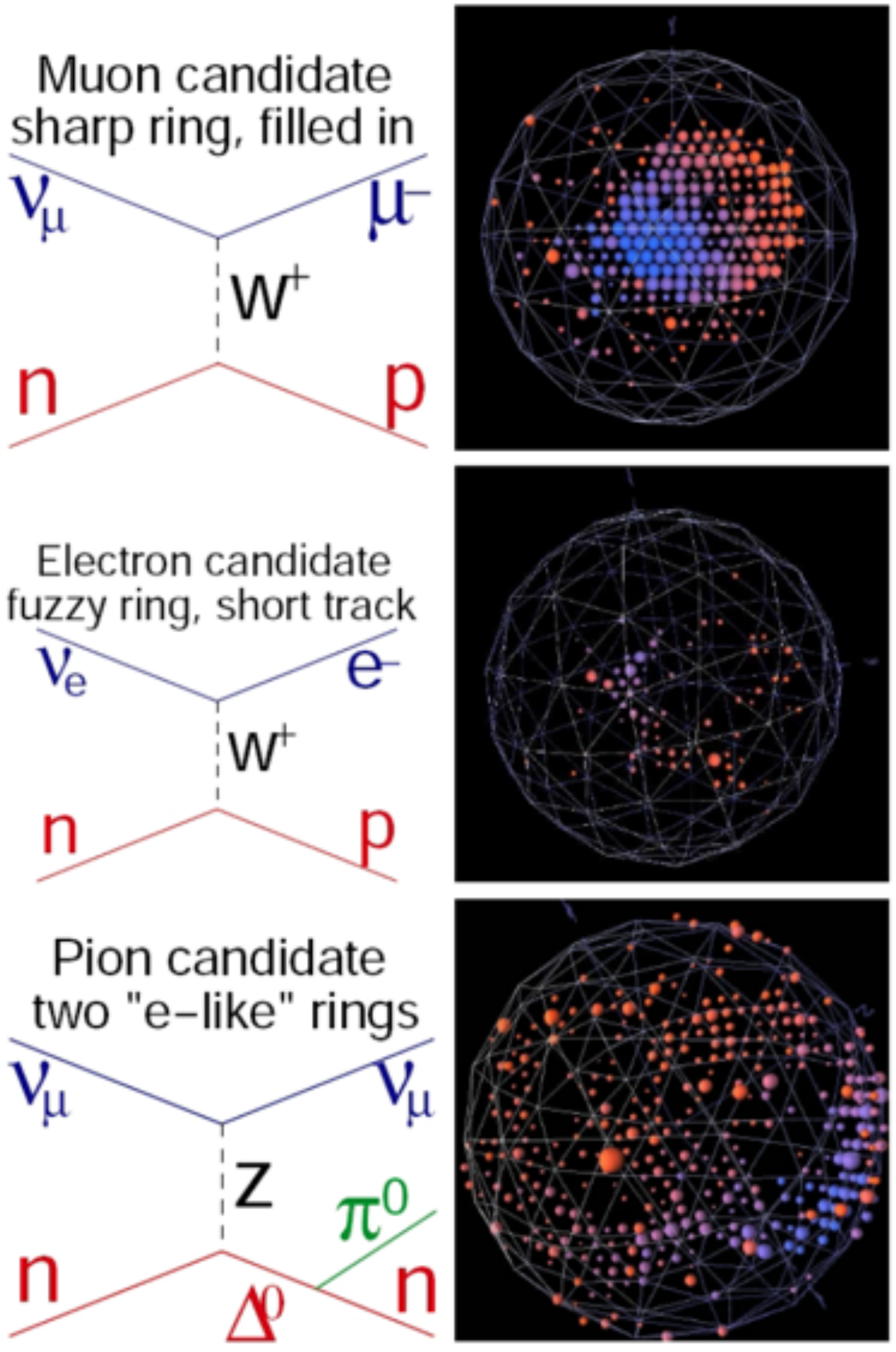
Experimental anomalies: MiniBooNE



- 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

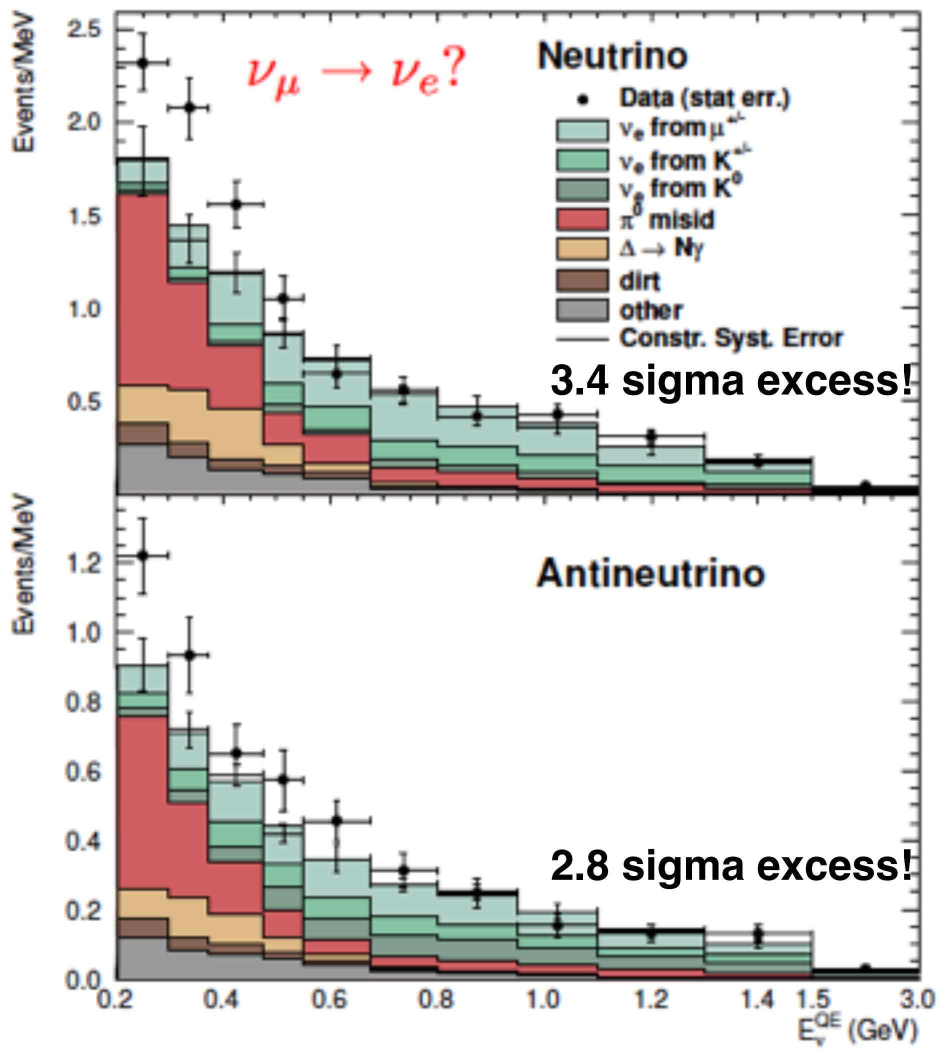


Experimental anomalies: MiniBooNE

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

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

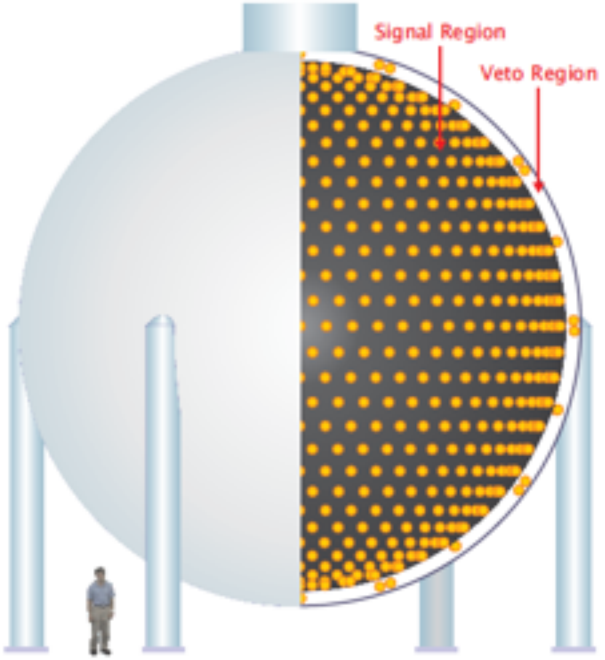
Searched for: $\nu_\mu \to \nu_e$ (or $\bar{\nu}_\mu \to \bar{\nu}_e$)



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 1eV^2 scale

Experimental anomalies: New MiniBooNE Results

arXiv:1805.12028

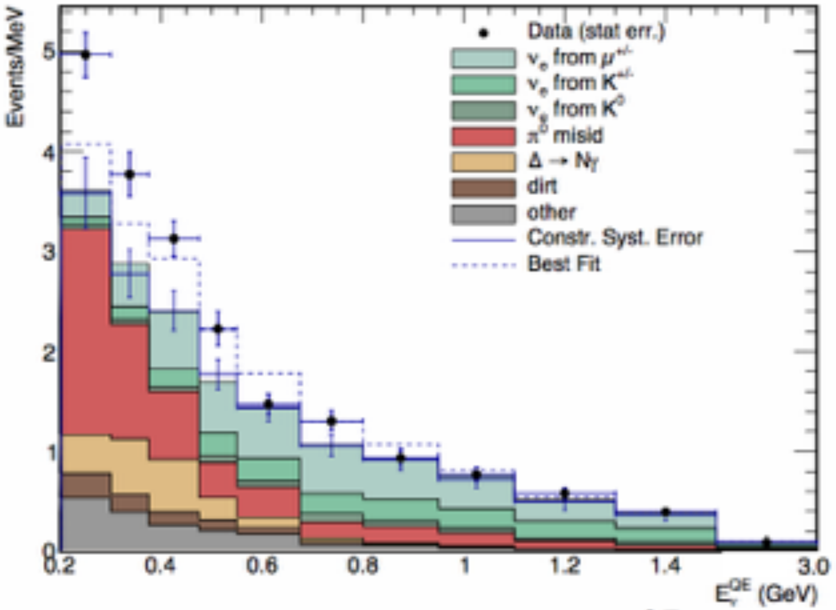


FIG. 1: The MiniBooNE neutrino mode E_ν^{QE} distributions, corresponding to the total 12.84×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and background (histogram with systematic errors). The dashed curve shows the best fit to the neutrino-mode data assuming standard two-neutrino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

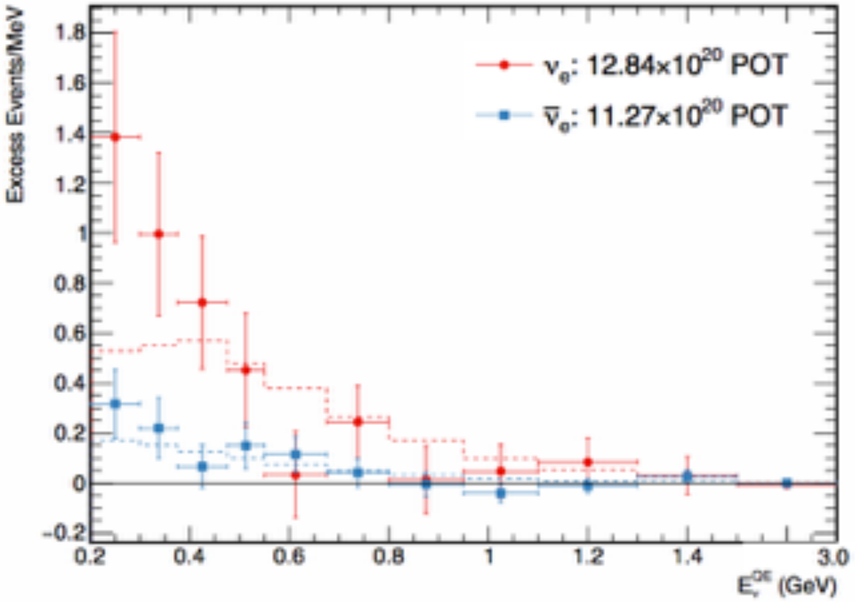


FIG. 2: The MiniBooNE total event excesses as a function of E_ν^{QE} in both neutrino mode and antineutrino mode, corresponding to 12.84×10^{20} POT and 11.27×10^{20} POT, respectively. (Error bars include both statistical and correlated systematic uncertainties.) The dashed curves show the best fits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

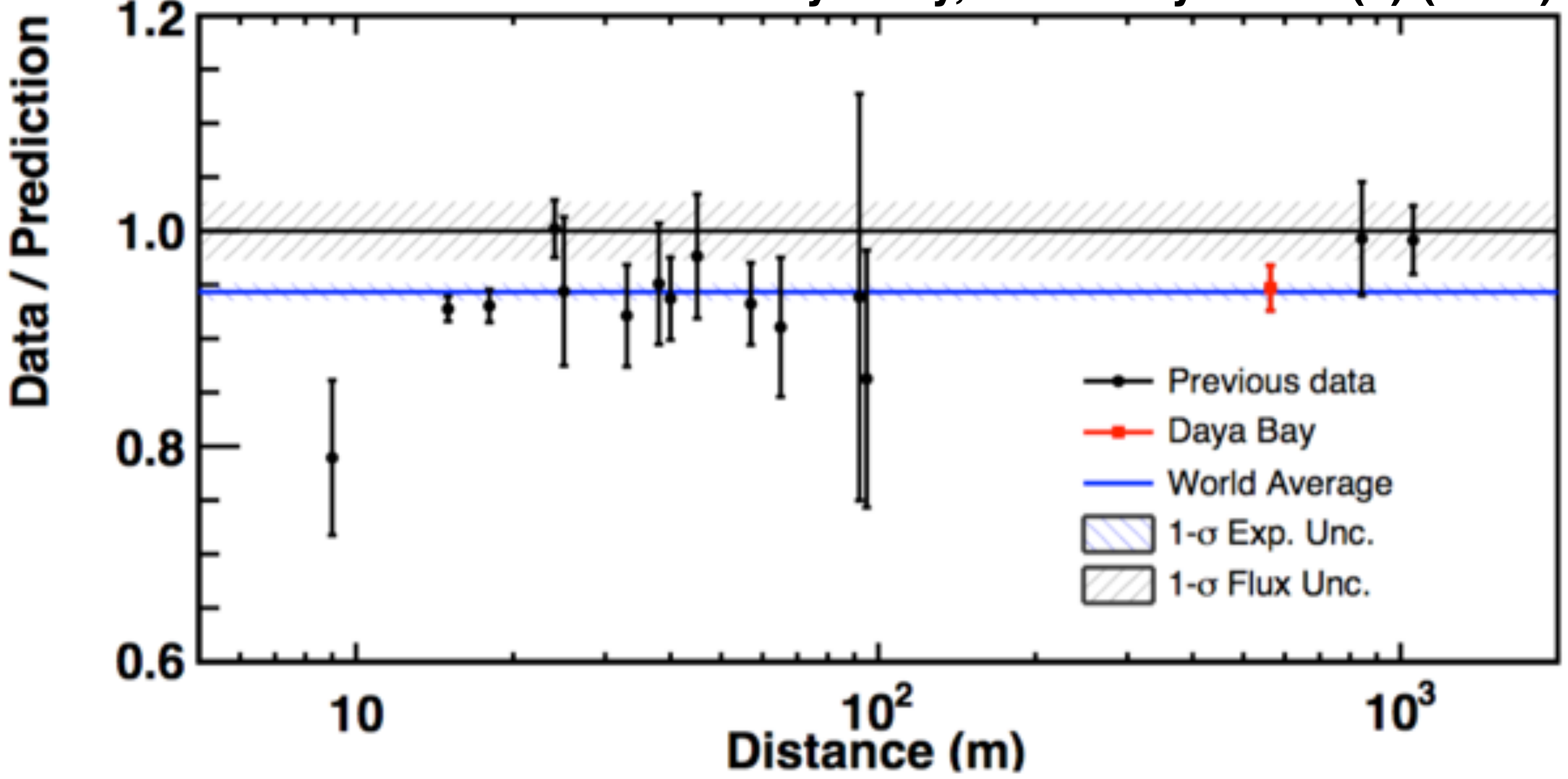
	ν mode 12.84×10^{20} POT	$\bar{\nu}$ mode 11.27×10^{20} POT	Combined
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 95.8 4.8σ

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!

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



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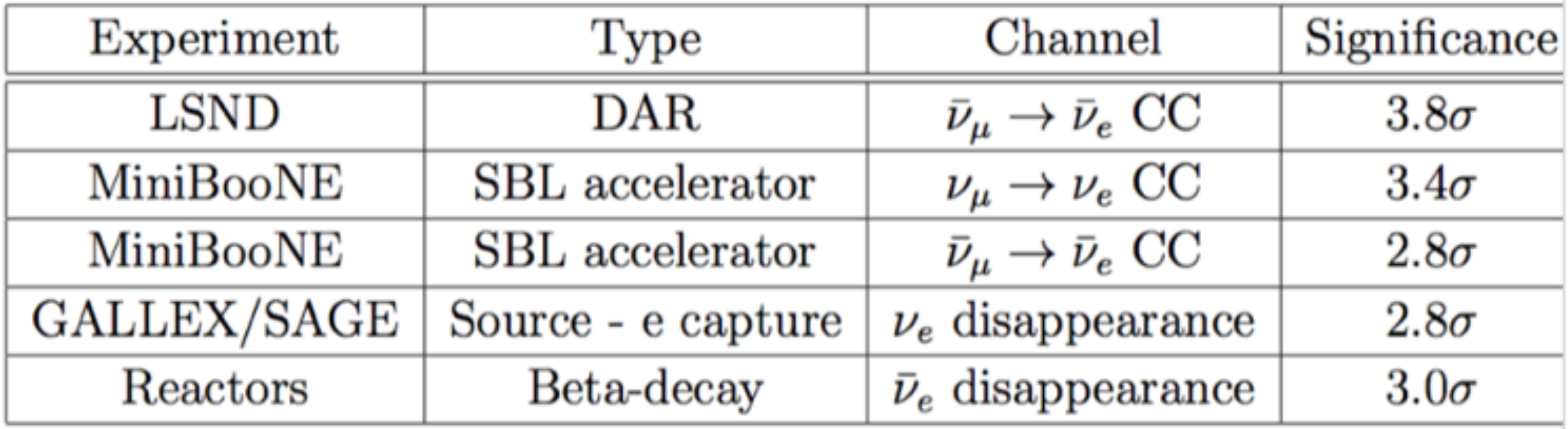
Anomalies in neutrino physics at Short Baseline experiments

- 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!



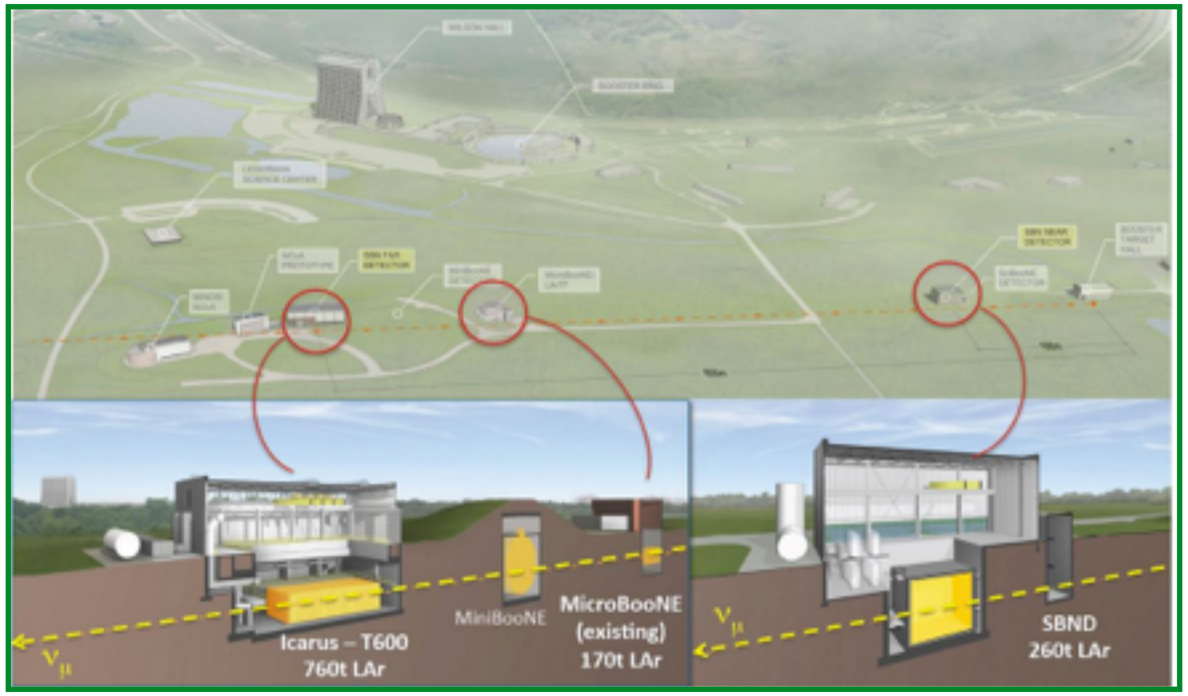
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance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

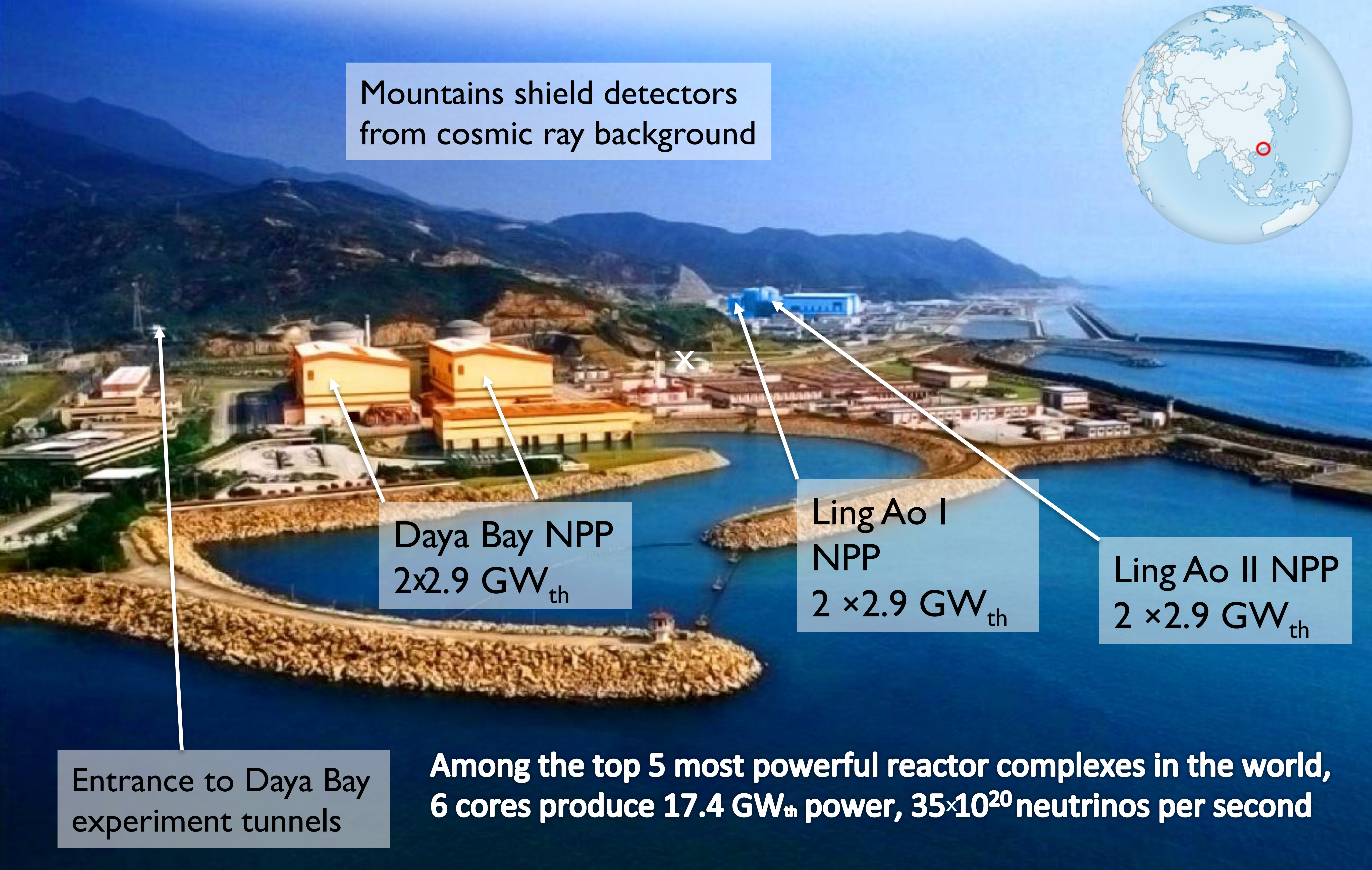
Experimental anomalies

- 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**



Reactor Neutrino Experiments
Main focus: Daya Bay

A Powerful Neutrino Source at an Ideal Location



Mountains shield detectors from cosmic ray background

Daya Bay NPP
2×2.9 GW_{th}

Ling Ao I NPP
2×2.9 GW_{th}

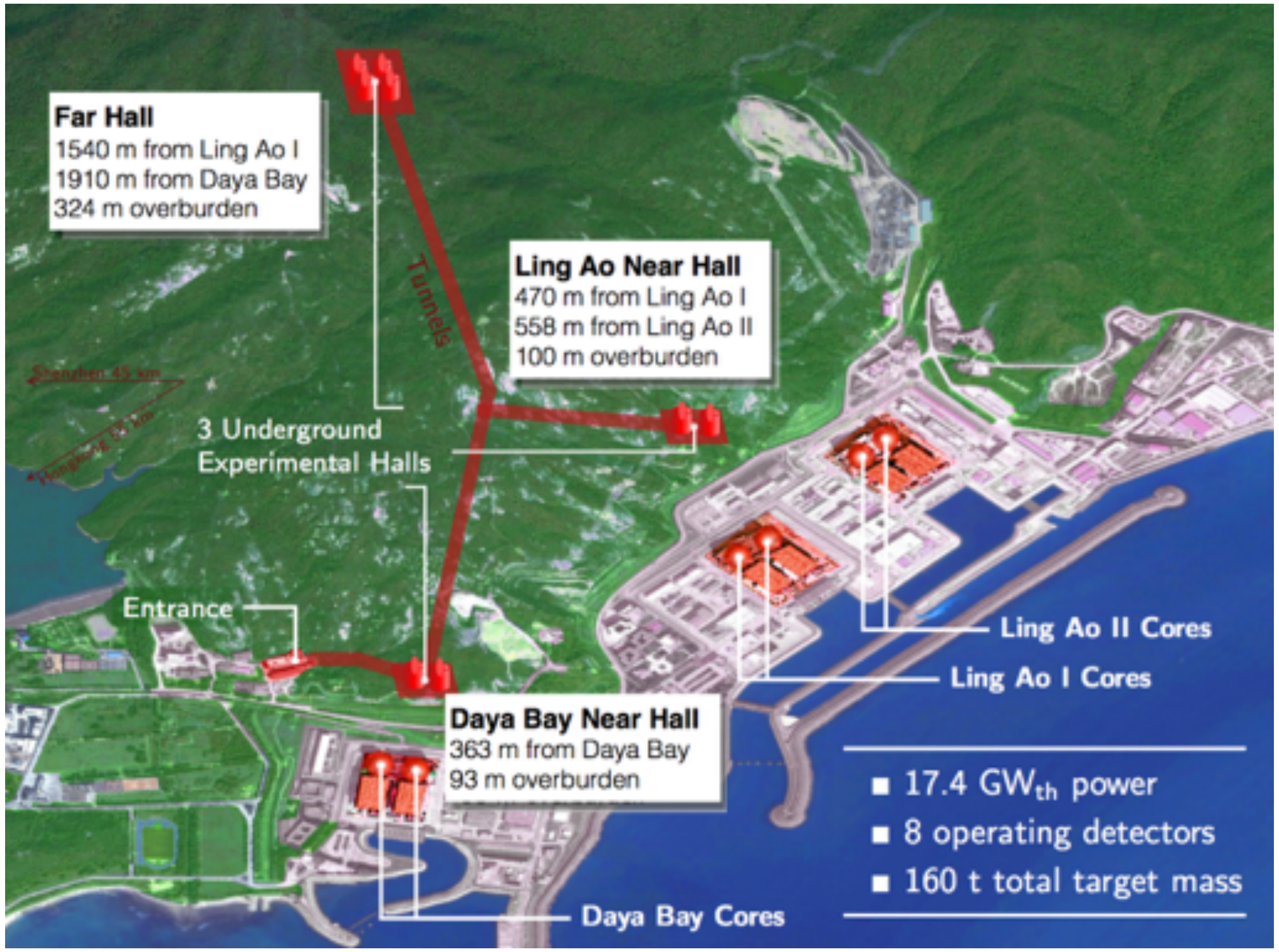
Ling Ao II NPP
2×2.9 GW_{th}

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!



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

	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

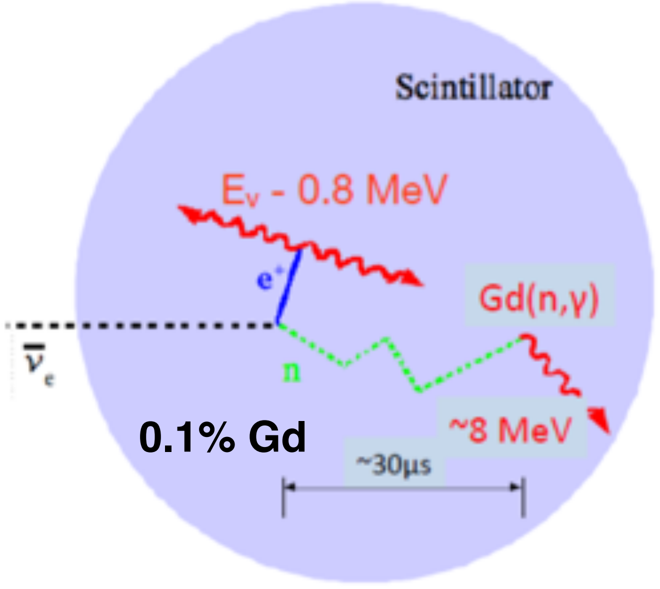
Large Signal

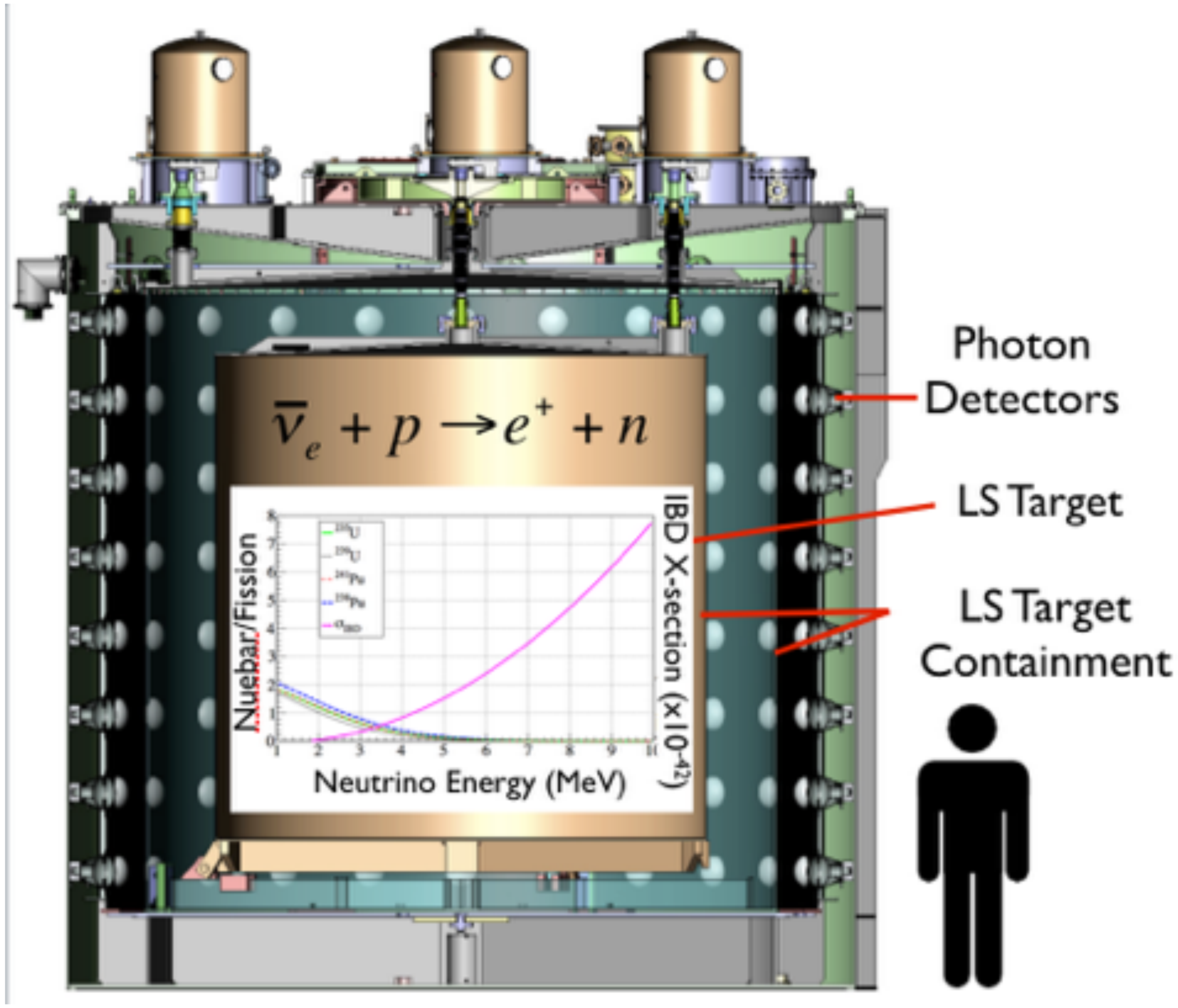
Low Background

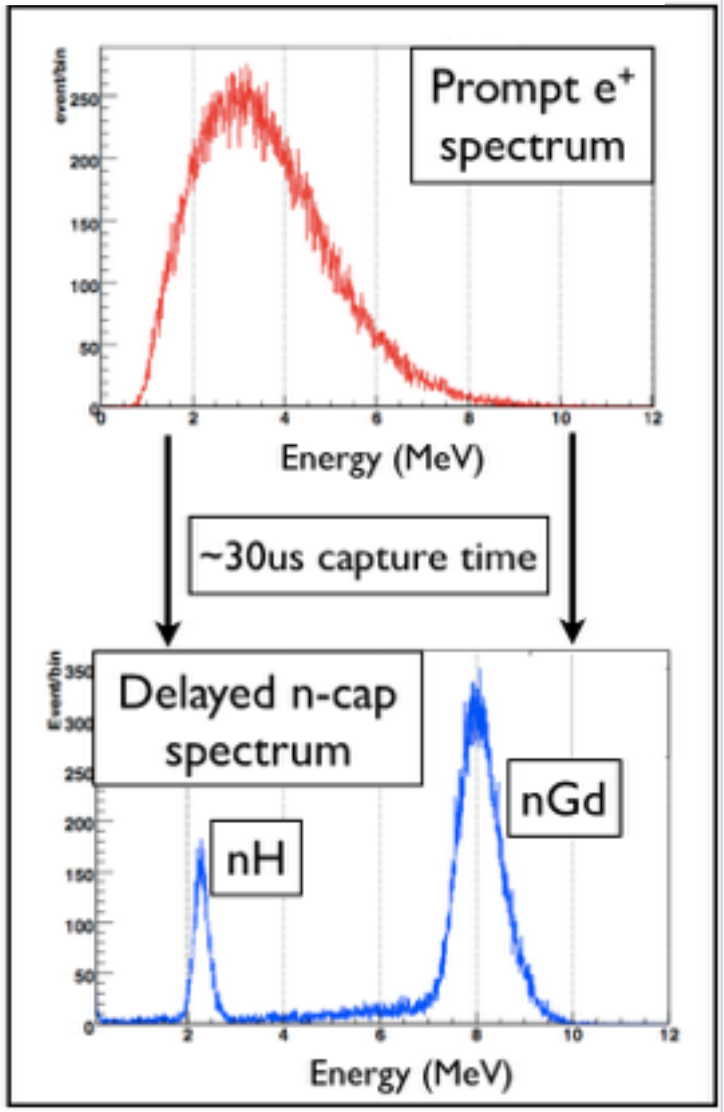
The Daya Bay antineutrino detector

- Detect inverse beta decay (IBD) with liquid scintillator.
- 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

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

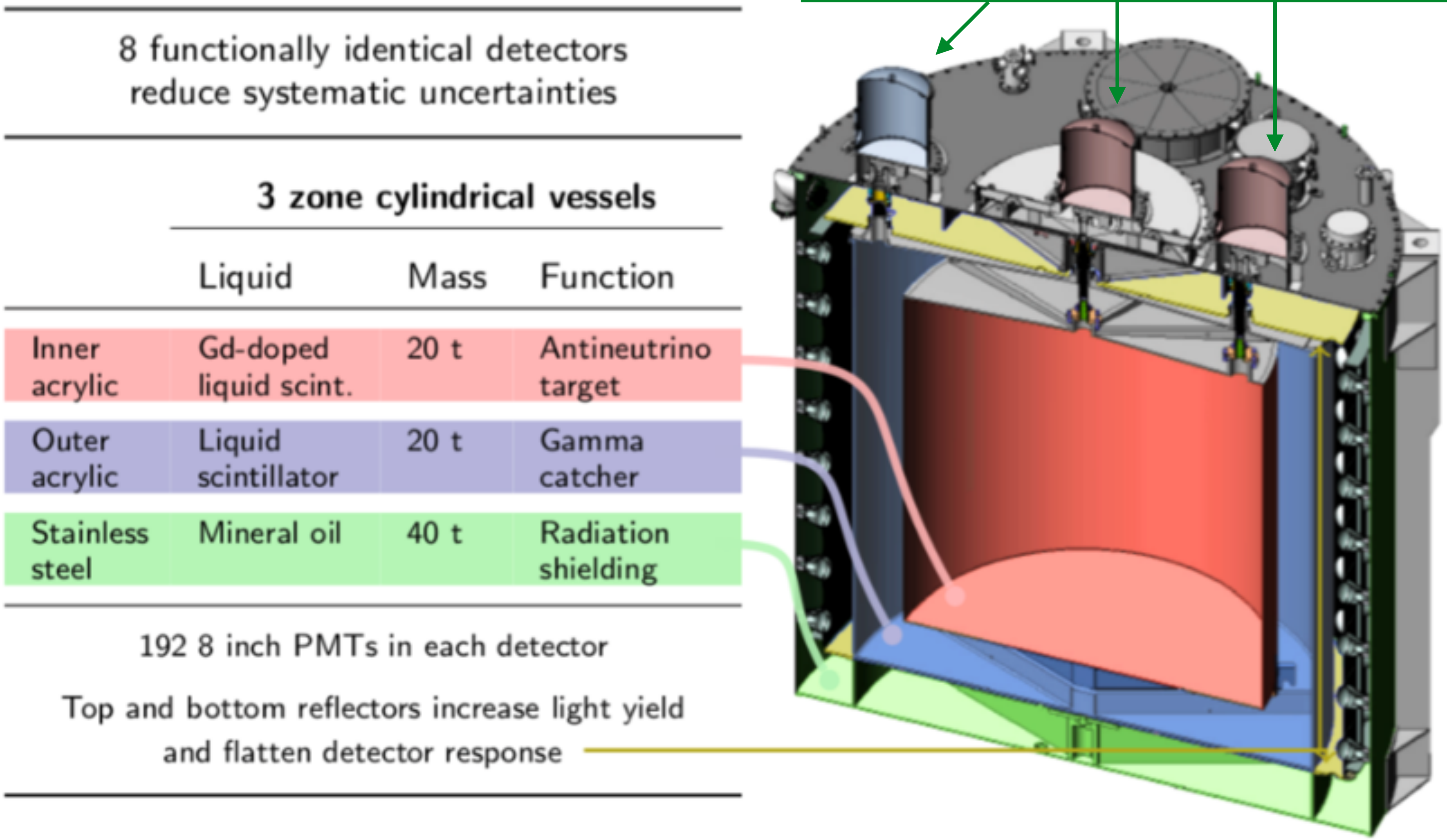






The Daya Bay antineutrino detector

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

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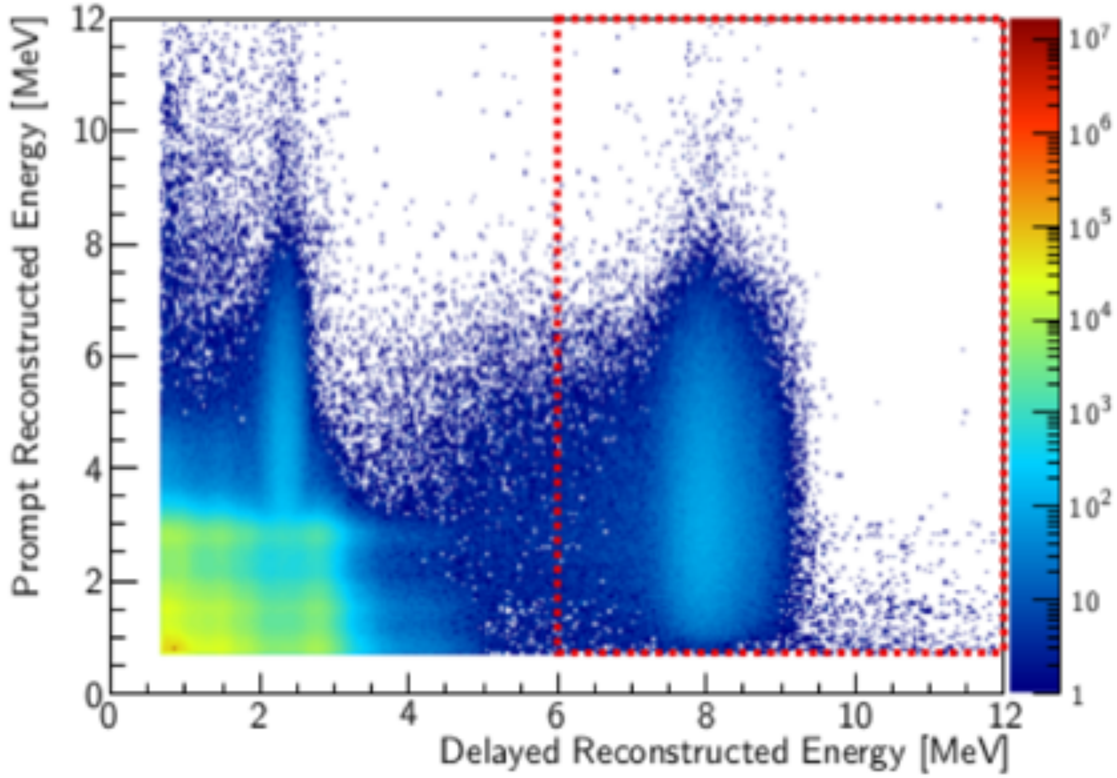
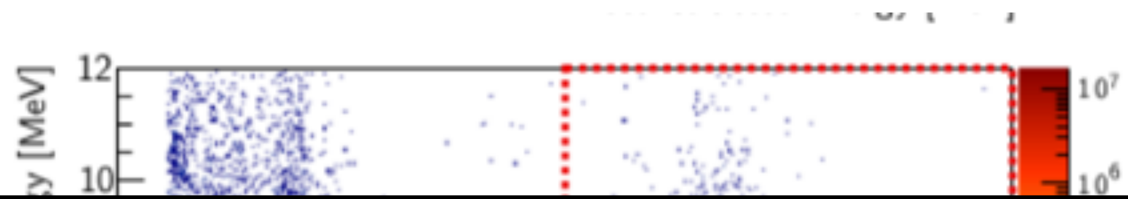
IBD Selection

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



IBD Selection



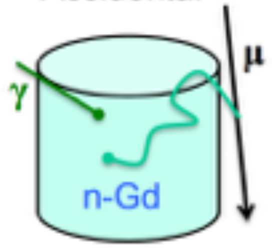
After this selection on 1230 days of data, we get 2.5 million candidates; 2.2 million from 4 Near Site detectors.

Backgrounds

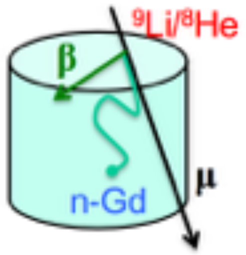
- Backgrounds make up <2% of Near Site IBD candidates
- Primary background: accidentally coincident triggers
    - 1.3% of near-site signal;
    - Other backgrounds ~0.5%.

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

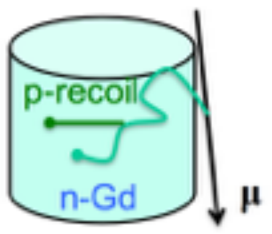
Accidental



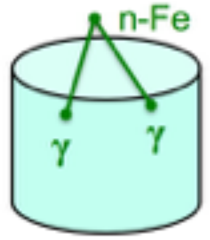
β-n isotope



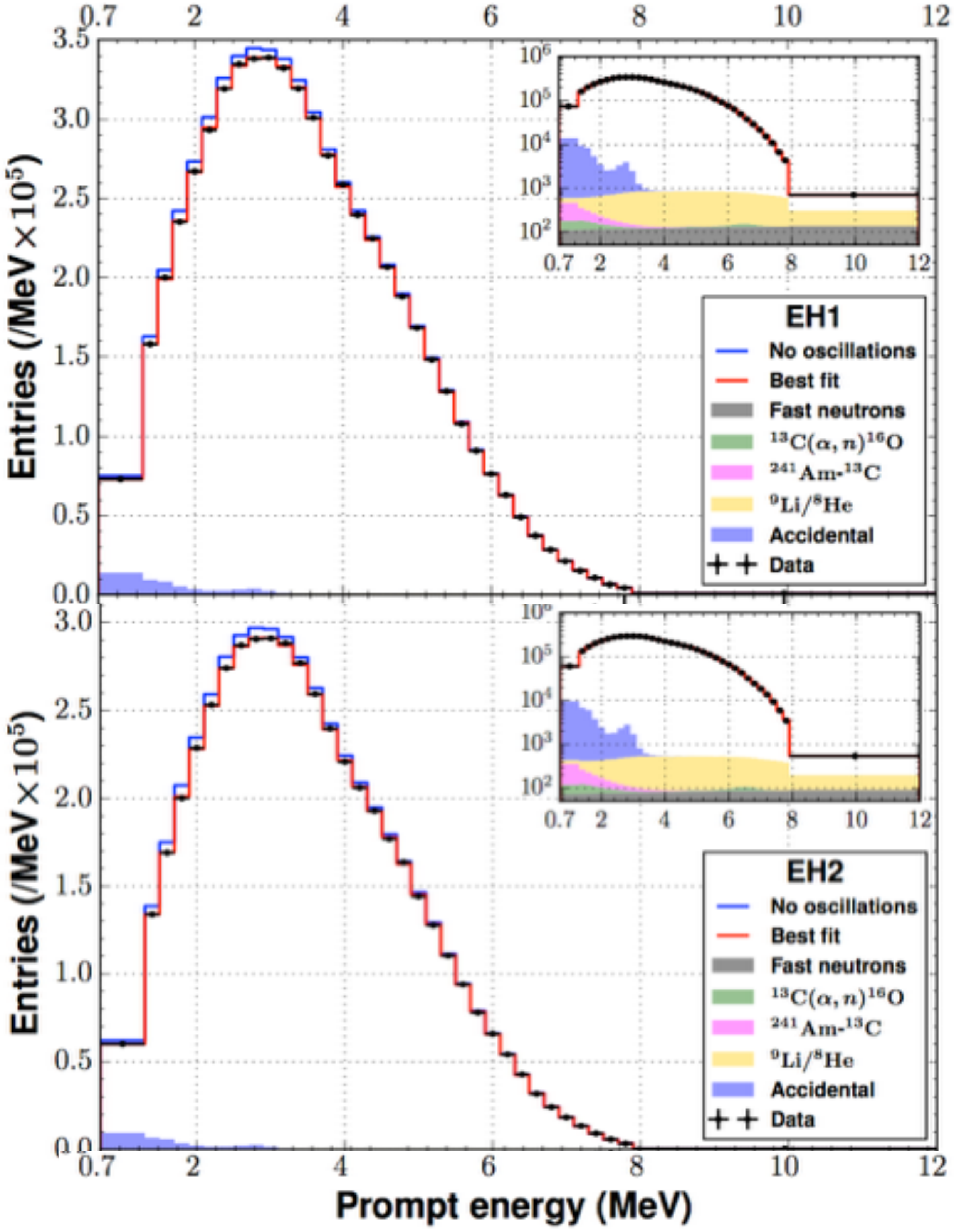
Fast neutron



neutron source



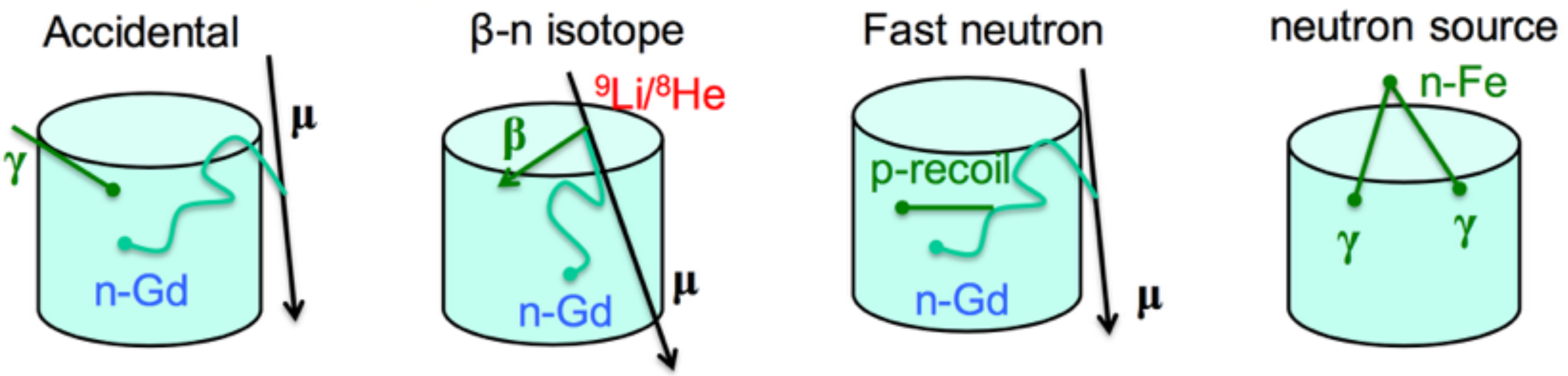
Daya Bay, PRD 95 (2017)



Daya Bay, PRD 95 (2017)

Backgrounds

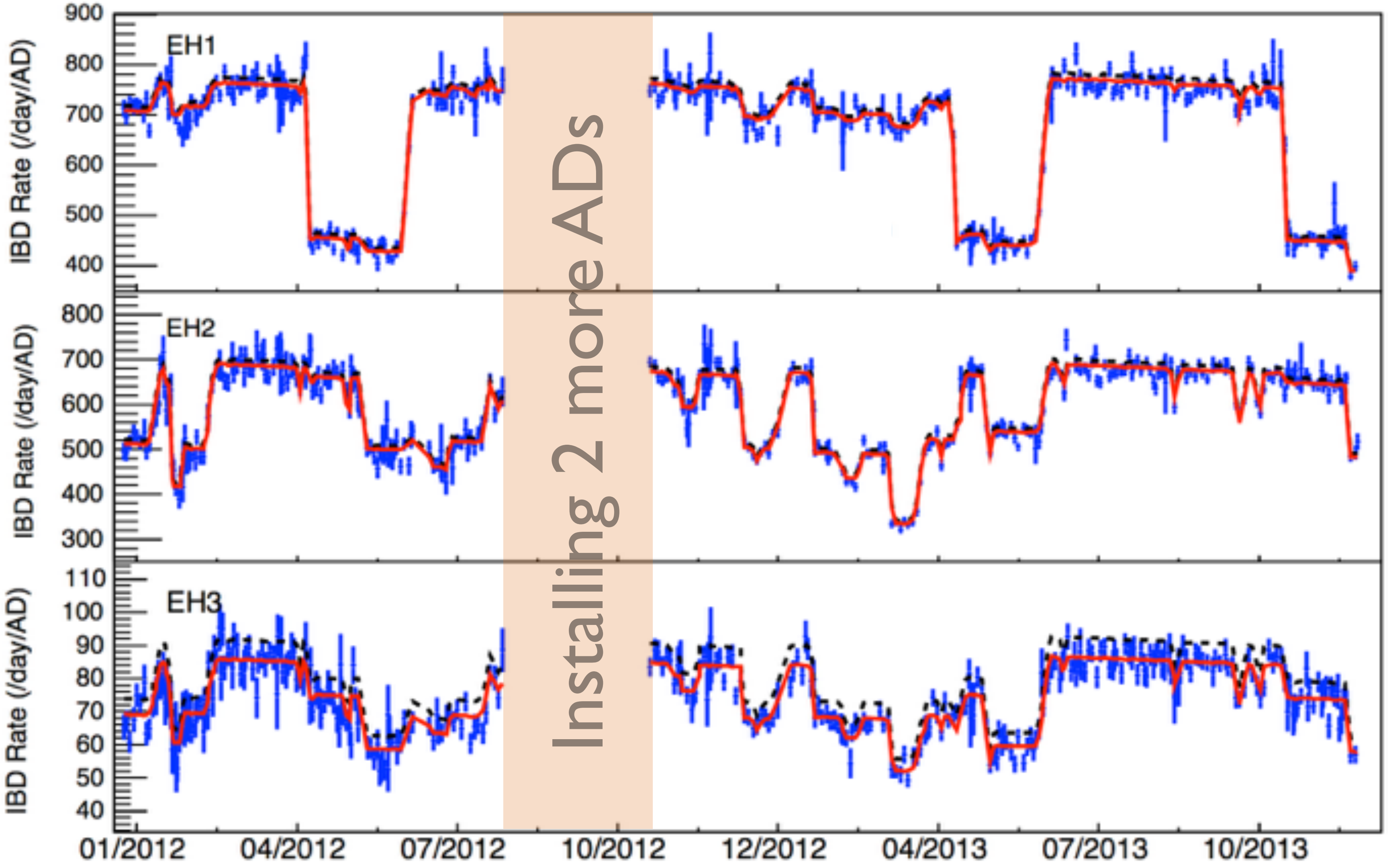
- Accidental coincidence between prompt and delayed signals ~1%
- During detector operation it was found that neutrons from the 241 Am-13 C calibration sources within the ACUs occasionally introduced several γ rays, correlated in time, to the detector. Contamination from this background was estimated 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%



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

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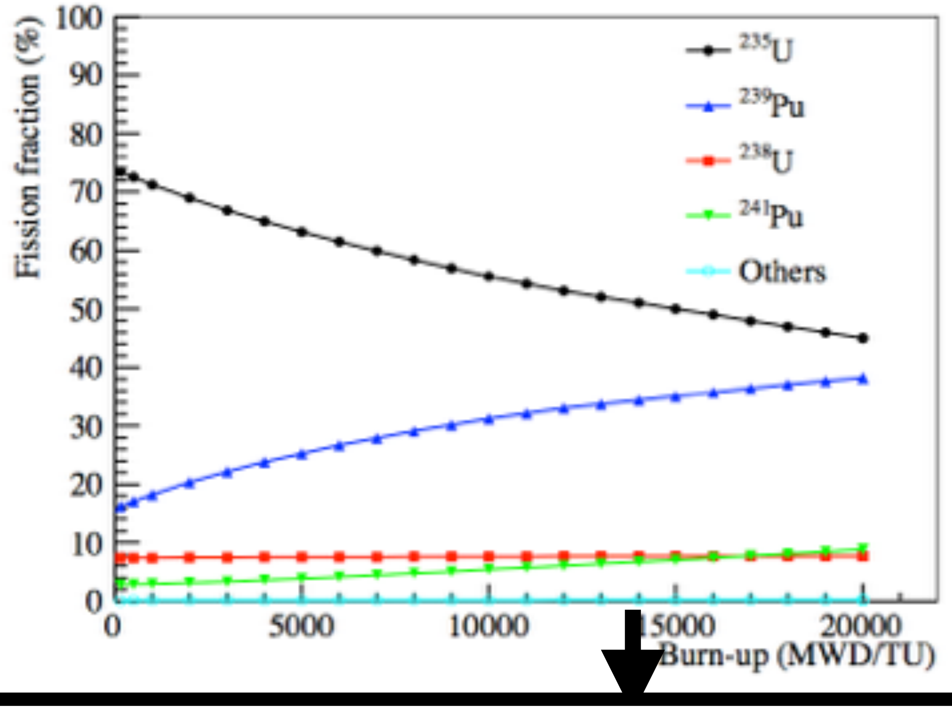
Daya Bay: Fuel evolution analysis

- 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:

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

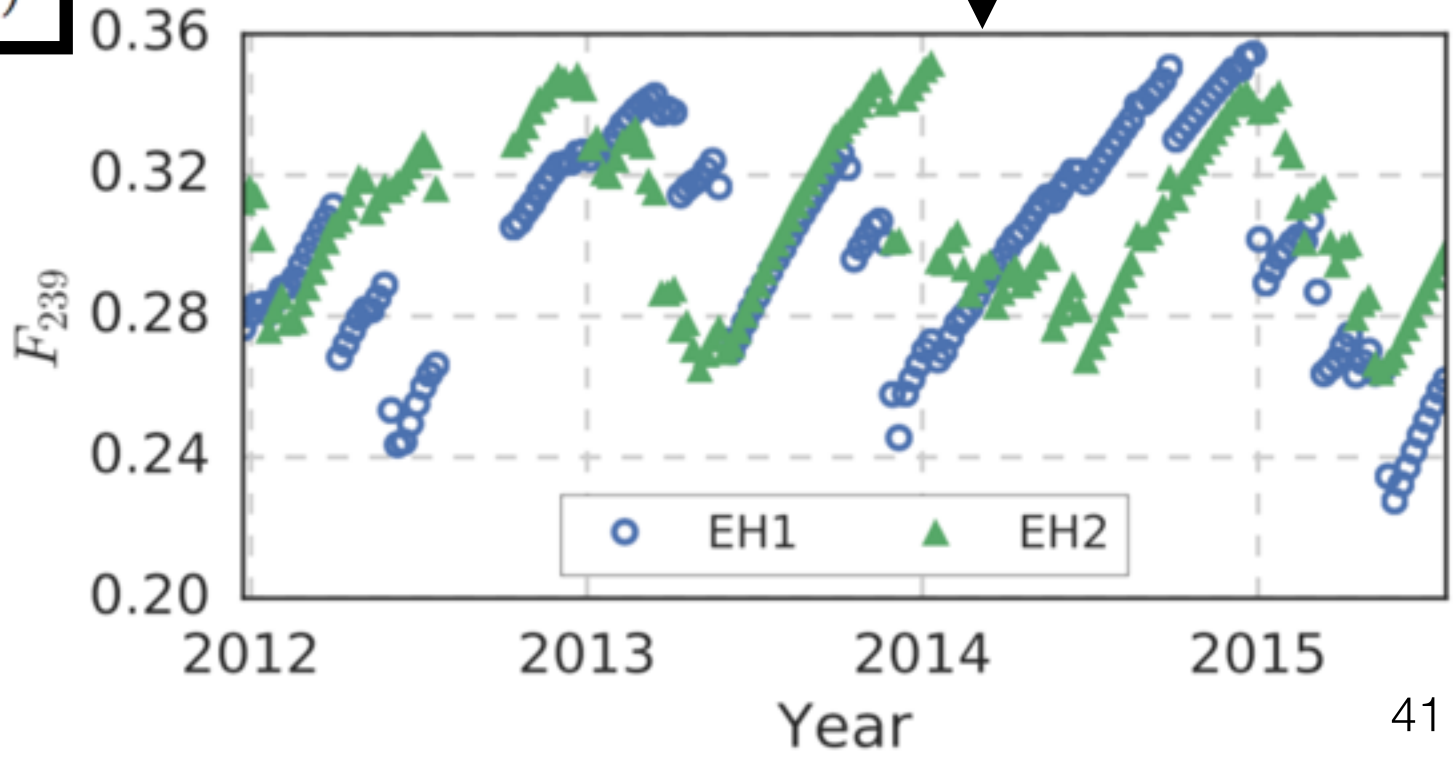
- Basically weight's each reactor's fission fraction by distance, power, and oscillation

Simulation of a complete refueling cycle



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

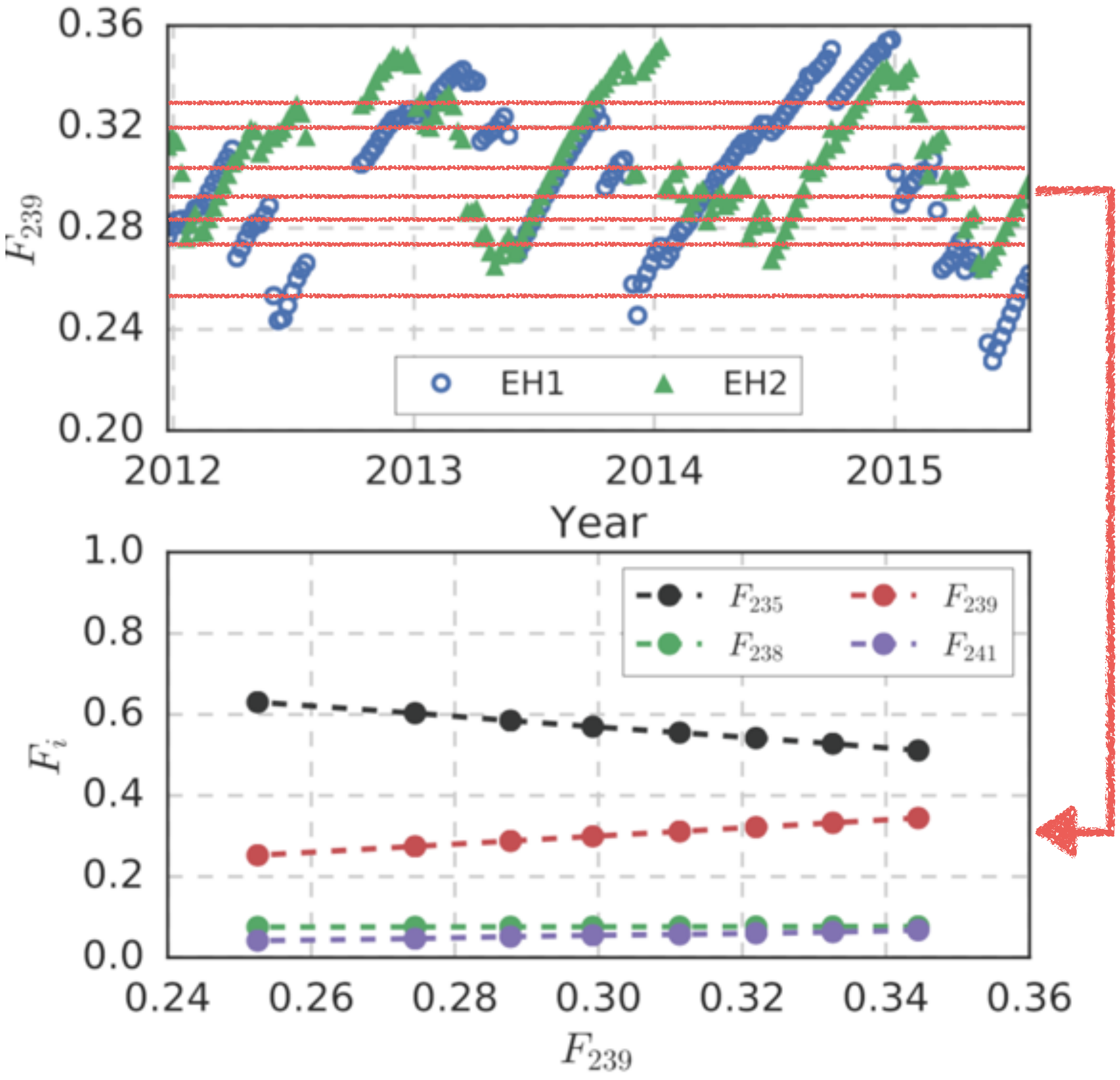
Weight for each of the 6 reactor cores



David

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

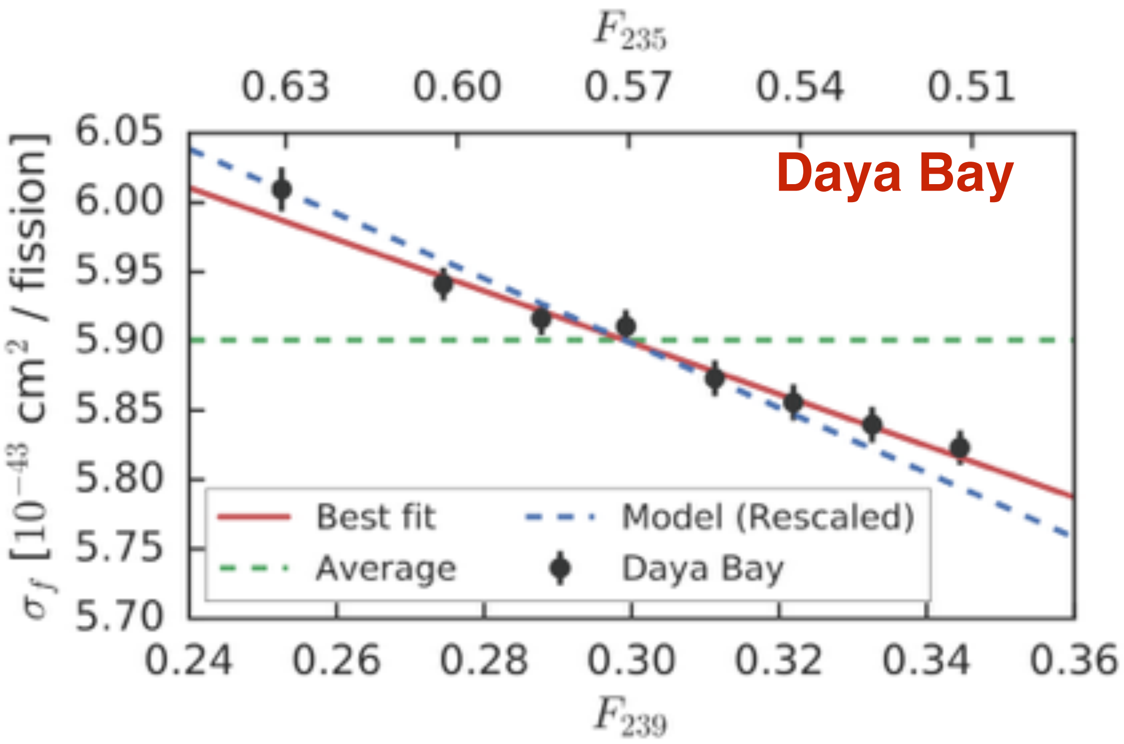
$$\boxed{\sigma_f = \sum_i F_i \sigma_i}$$

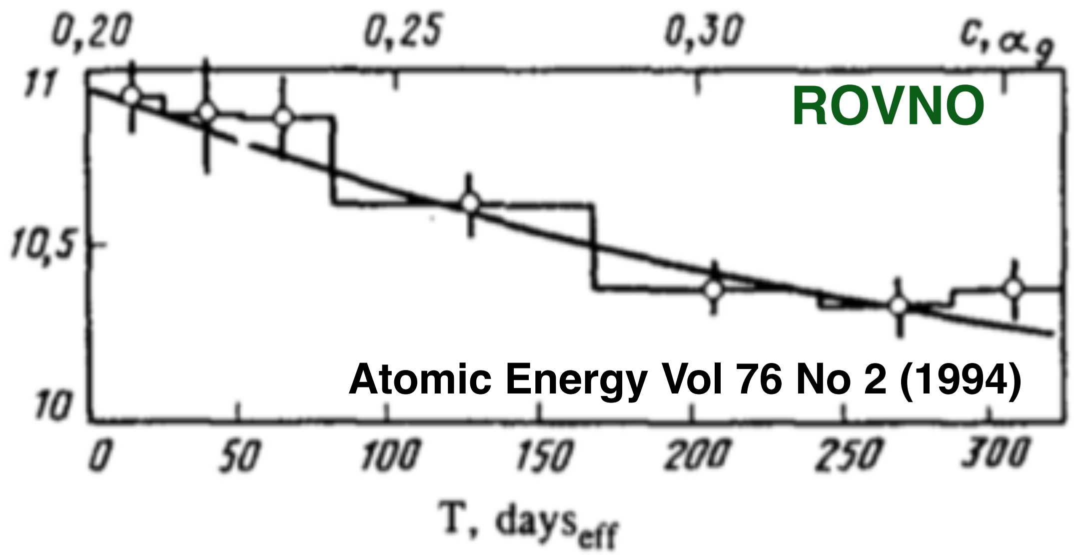
F_i : Effective fission fraction for each isotope

σ_i : IBD yield from each isotope

Results: Flux Evolution

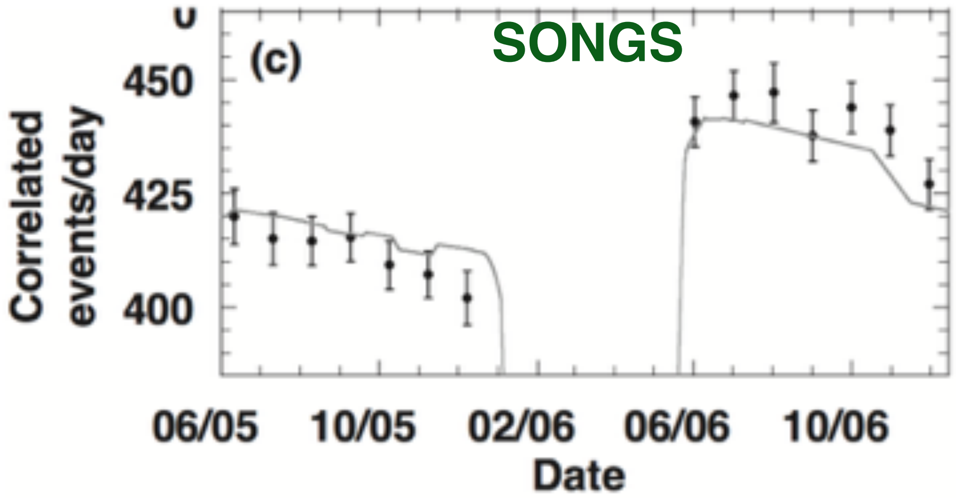
- **When plotting IBD/fission versus F_{239}, we see a slope in data**
- Very clear that flux is changing with changing fission fraction.
- Not too surprising; models predict ^{239}Pu makes fewer $\overline{\nu}_e$
  - Seen before in previous experiments: **Rovno (90's); SONGS (00's)**

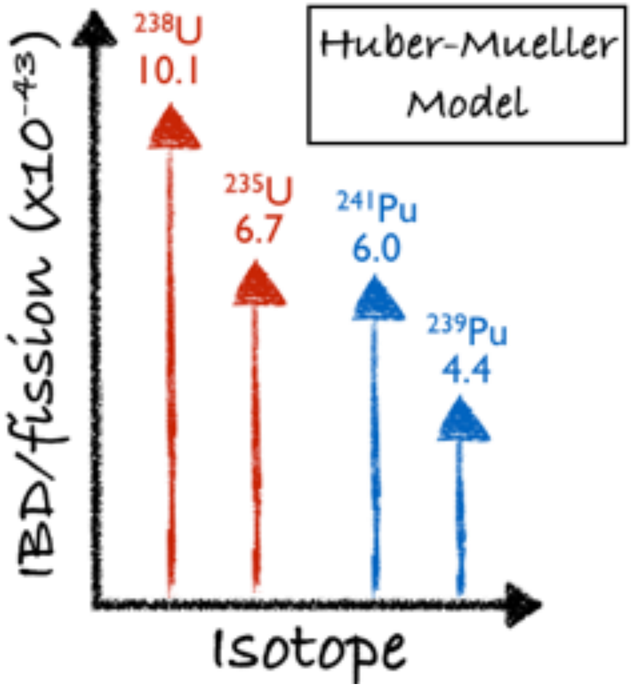




Atomic Energy Vol 76 No 2 (1994)

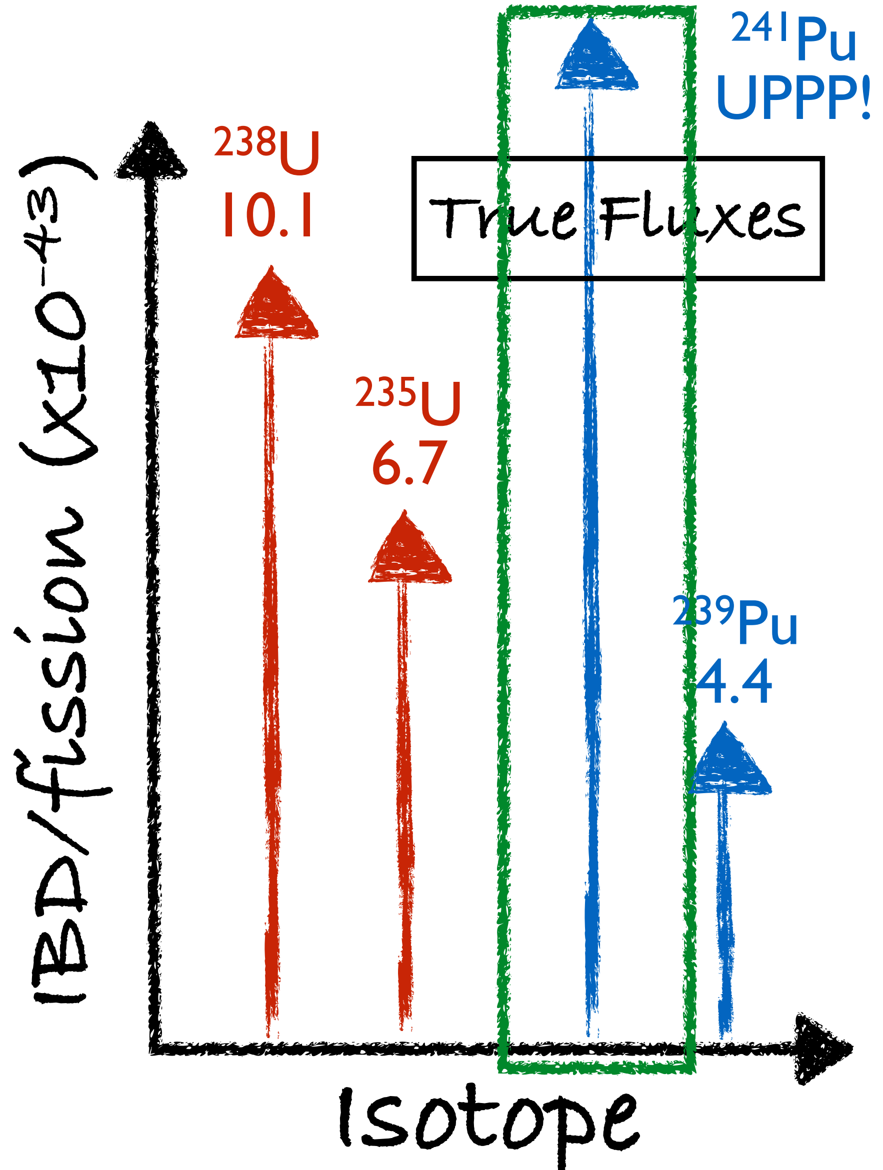
J. Appl. Phys. 105 064902

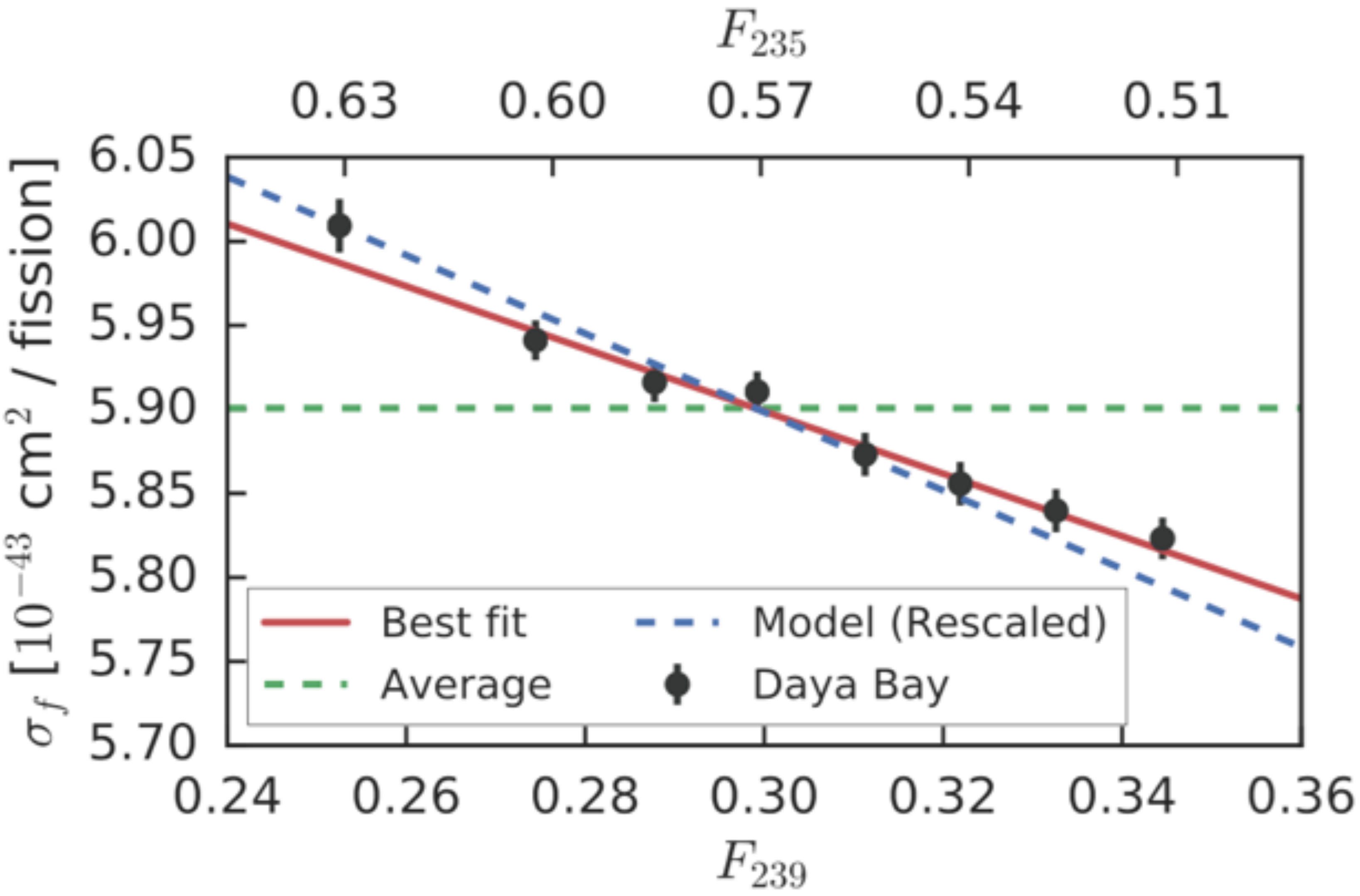




Result: Flux evolution

- **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





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Result: Flux evolution

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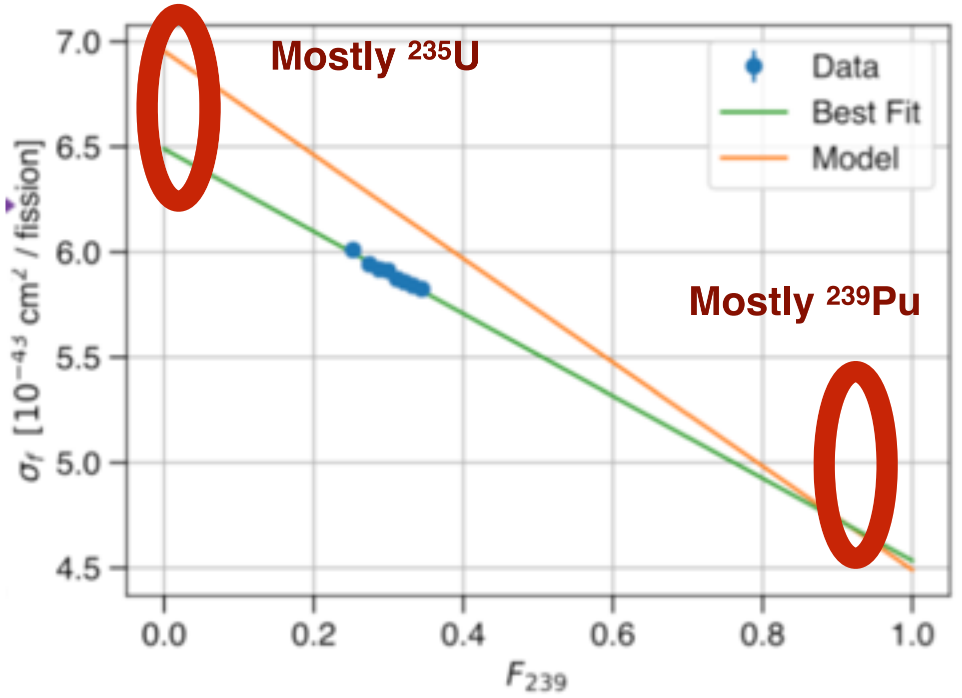
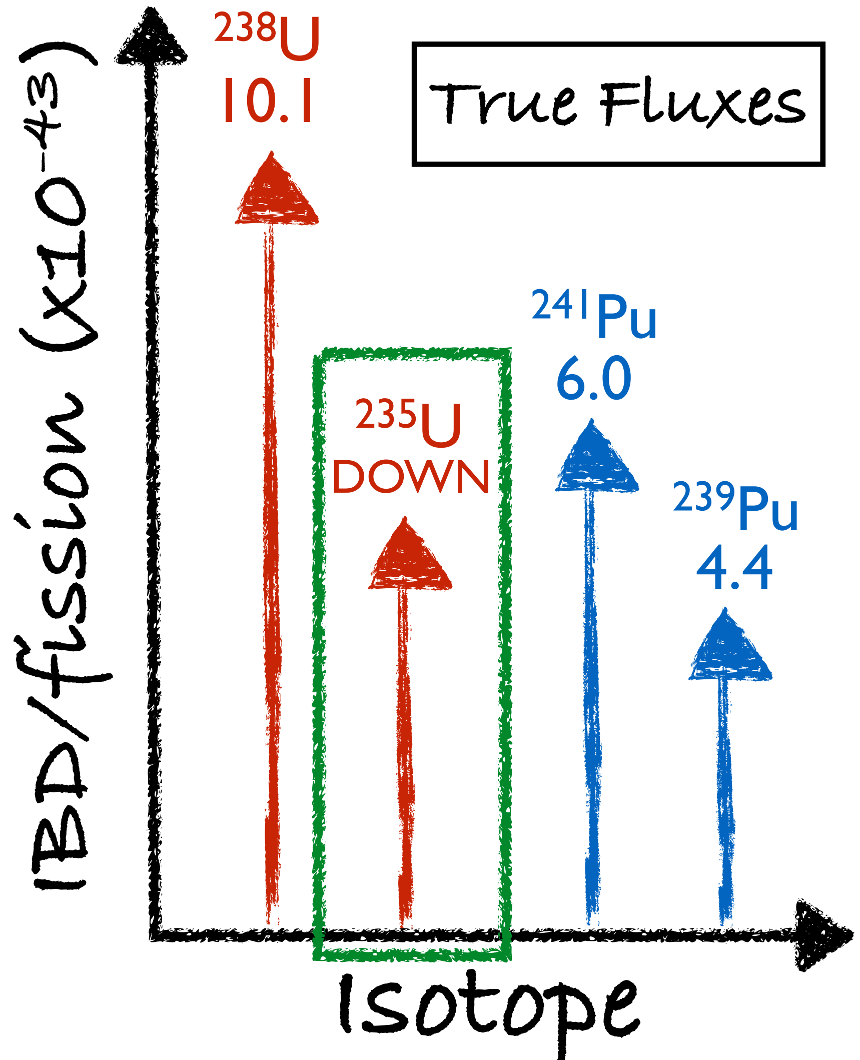
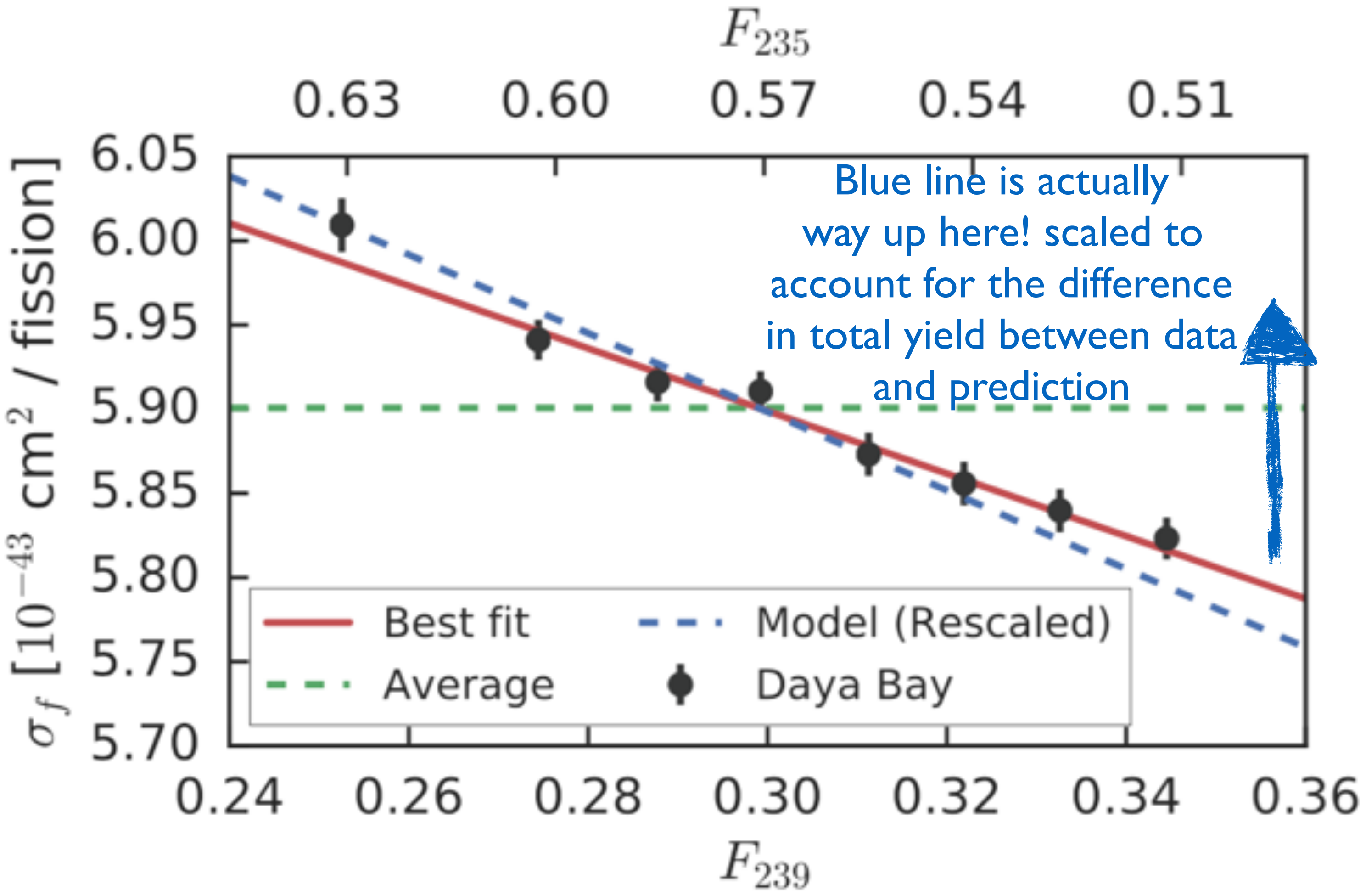
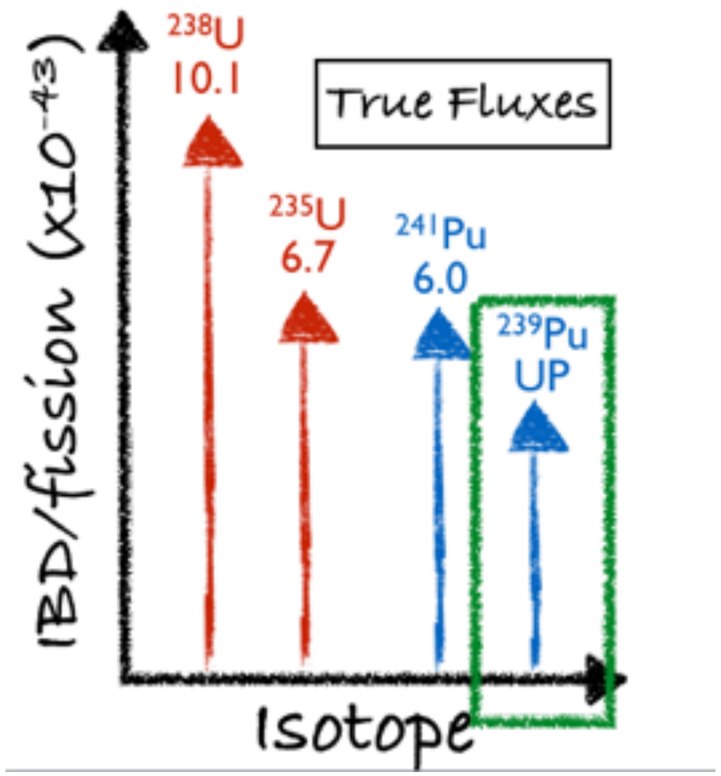


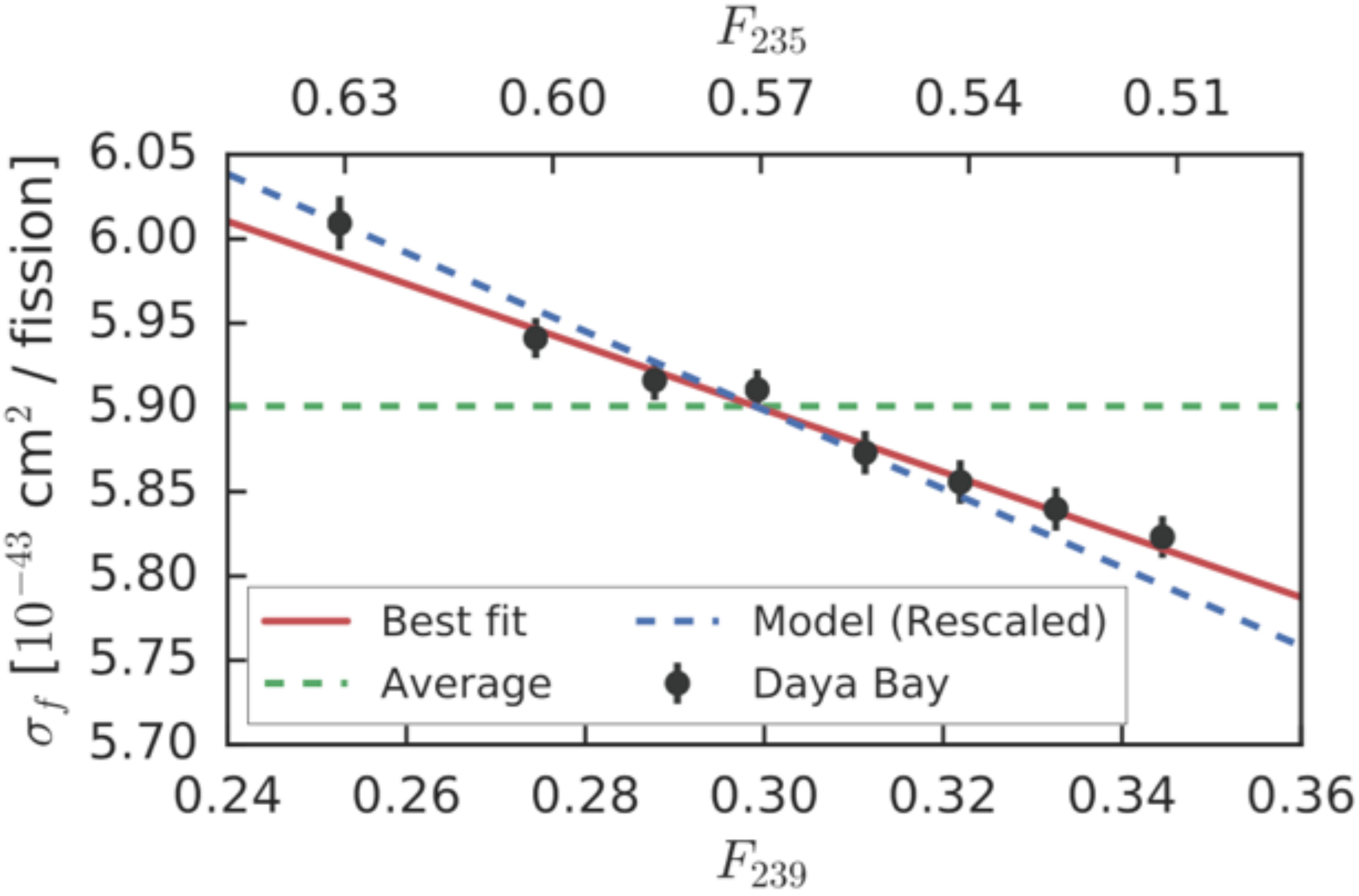



Blue line is actually way up here! scaled to account for the difference in total yield between data and prediction

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.





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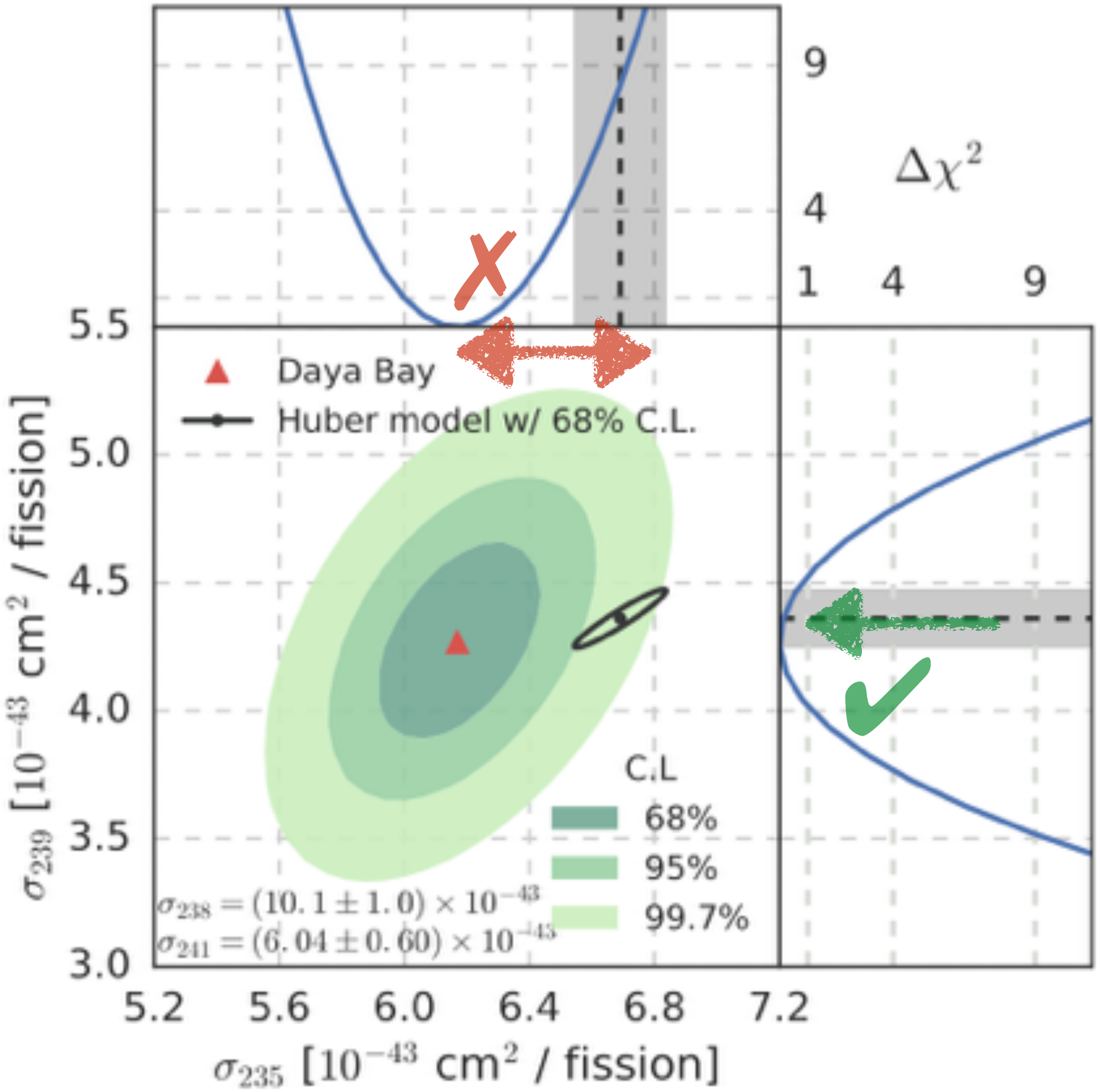
Result: Fitting For Individual Isotopes

- 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.

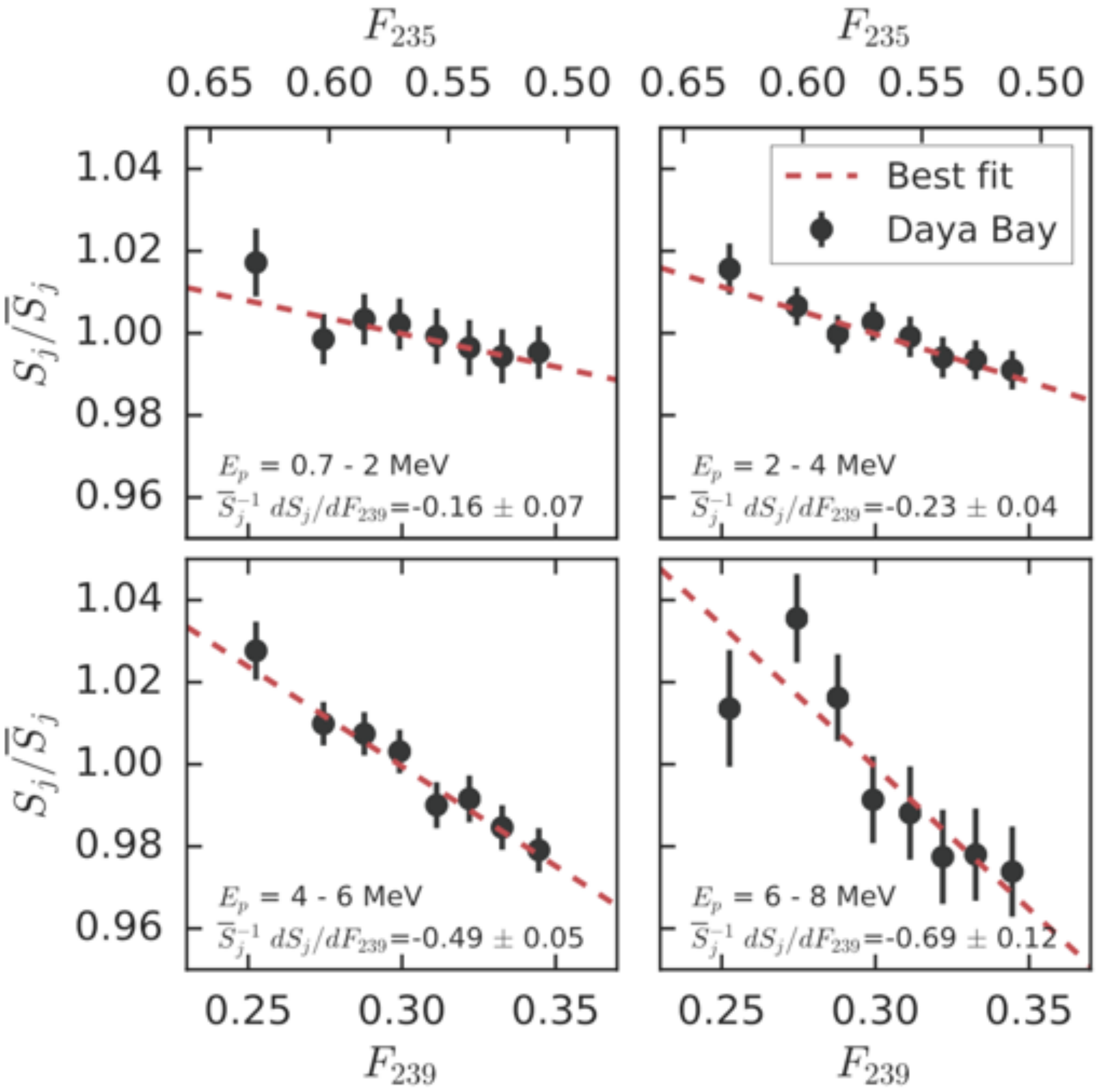


Results suggests that 235U being the main contributor of the Reactor Antineutrino Anomaly.

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

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**



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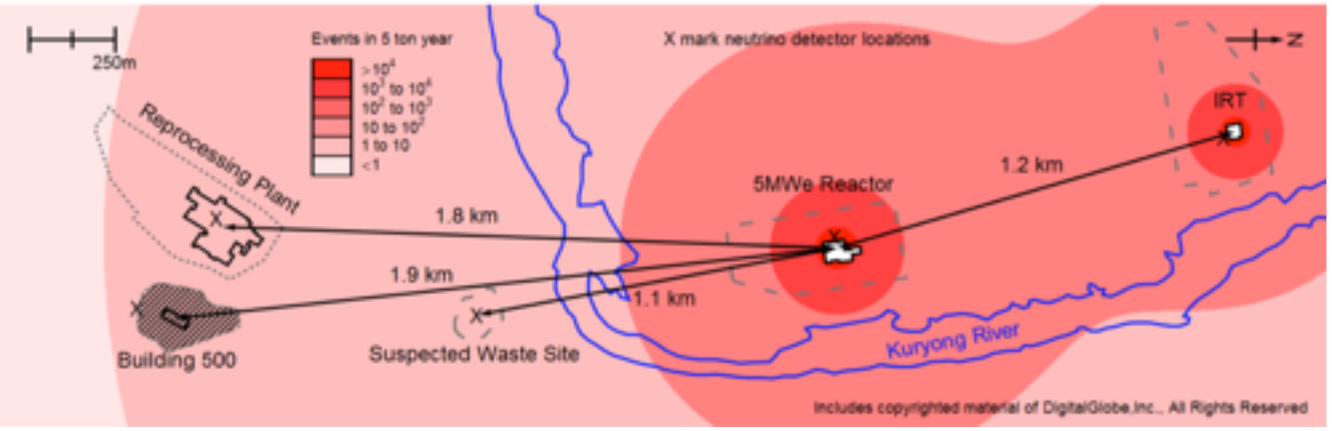
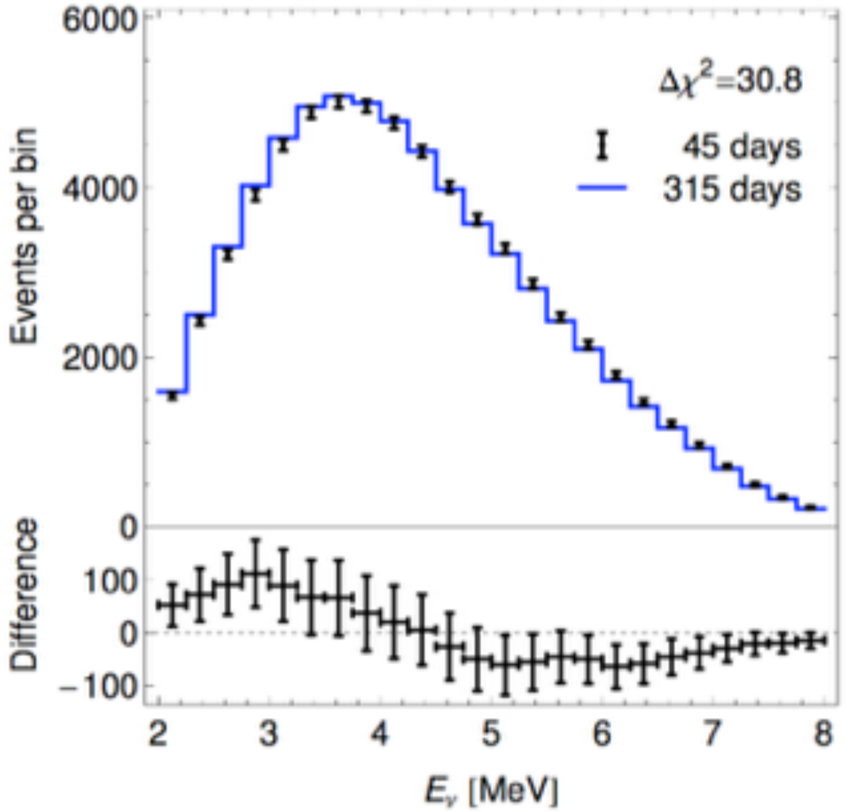
Results: Spectrum Evolution

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 :)

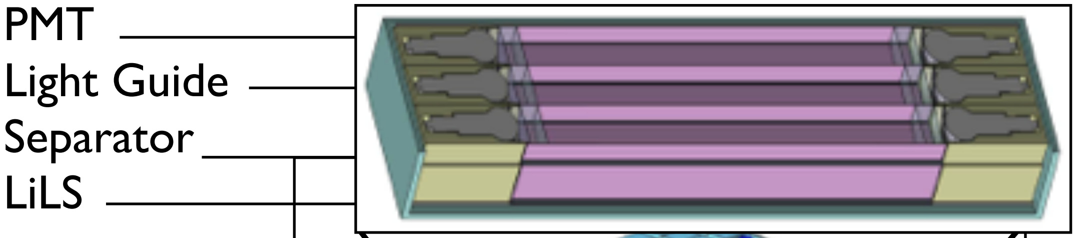


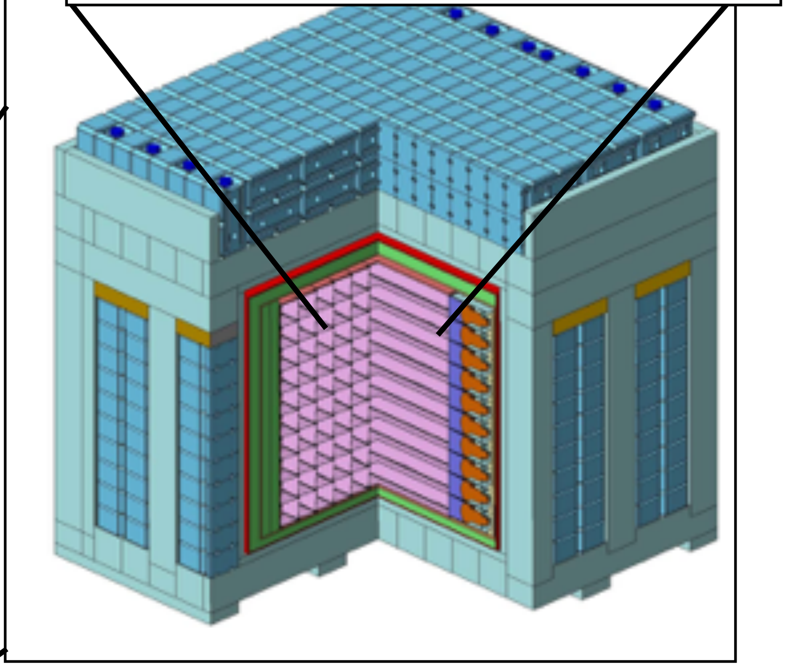
P.Huber et al, Phys. Rev. Lett. 113, 042503

PROSPECT Experimental Layout

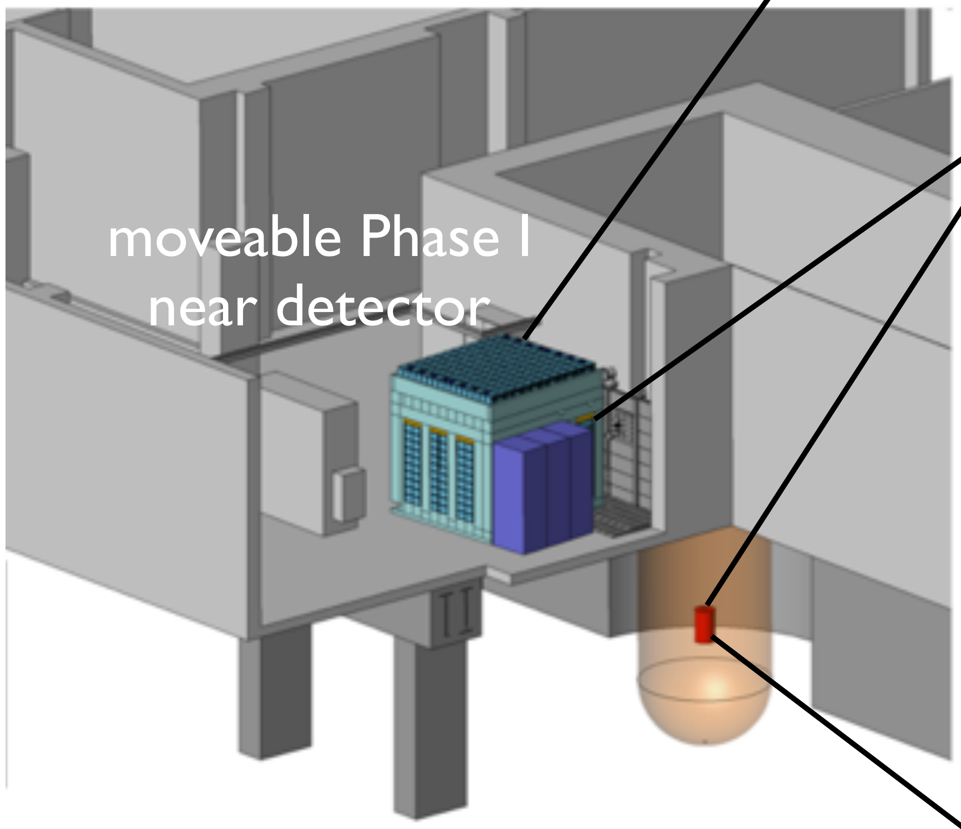
- HEU Reactor: HFIR 85 MW
- Segmented liquid scintillator target region: ~4 tons for near detector (Phase I)
- 154 segments, 119 cm X 15 cm X 15 cm
- Moveable: 7-12 m baselines
- Measure ^{235}U spectrum while directly probing sterile oscillations independent of reactor models

Sub-cell conceptual design

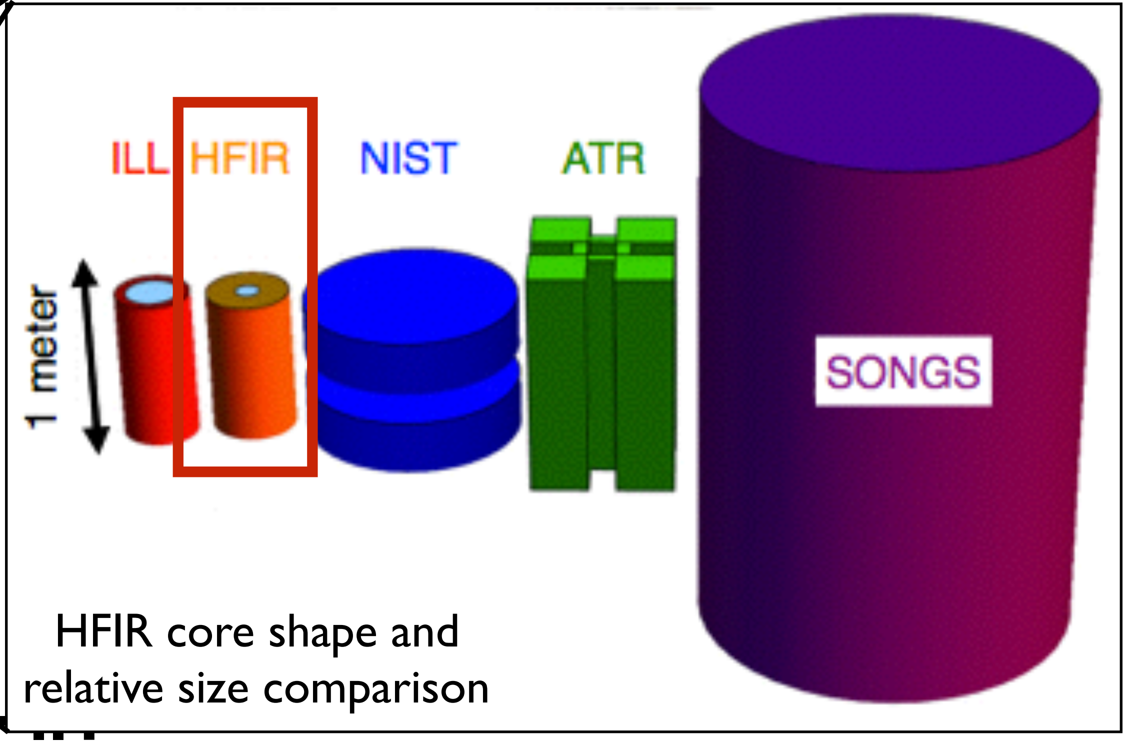




Near detector conceptual design



PROSPECT deployment at HFIR



HFIR core shape and relative size comparison

PROSPECT Experimental Layout

inner AD build

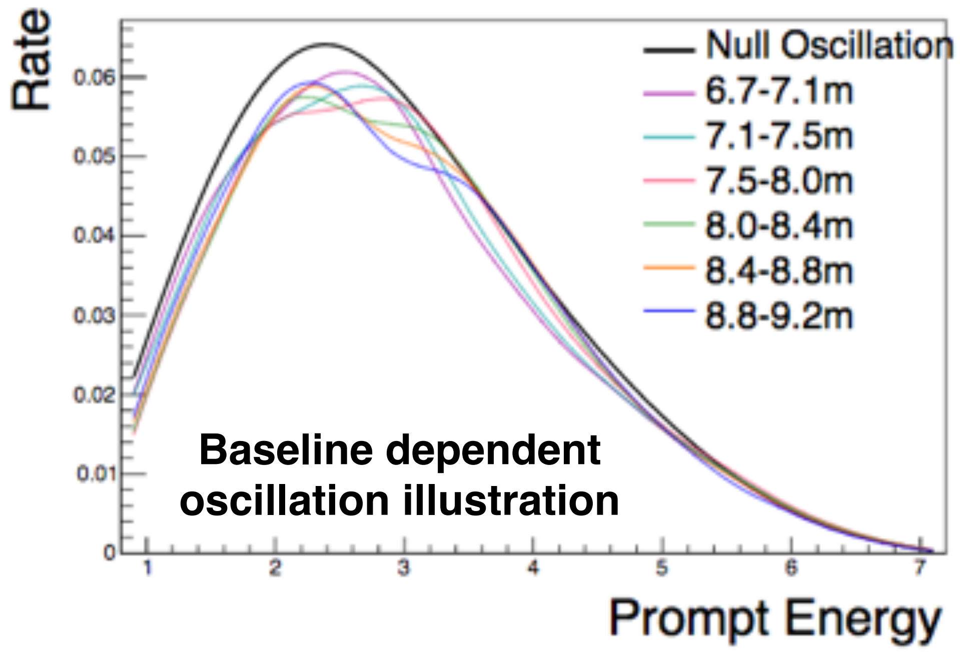
side wall lift

in Al tank

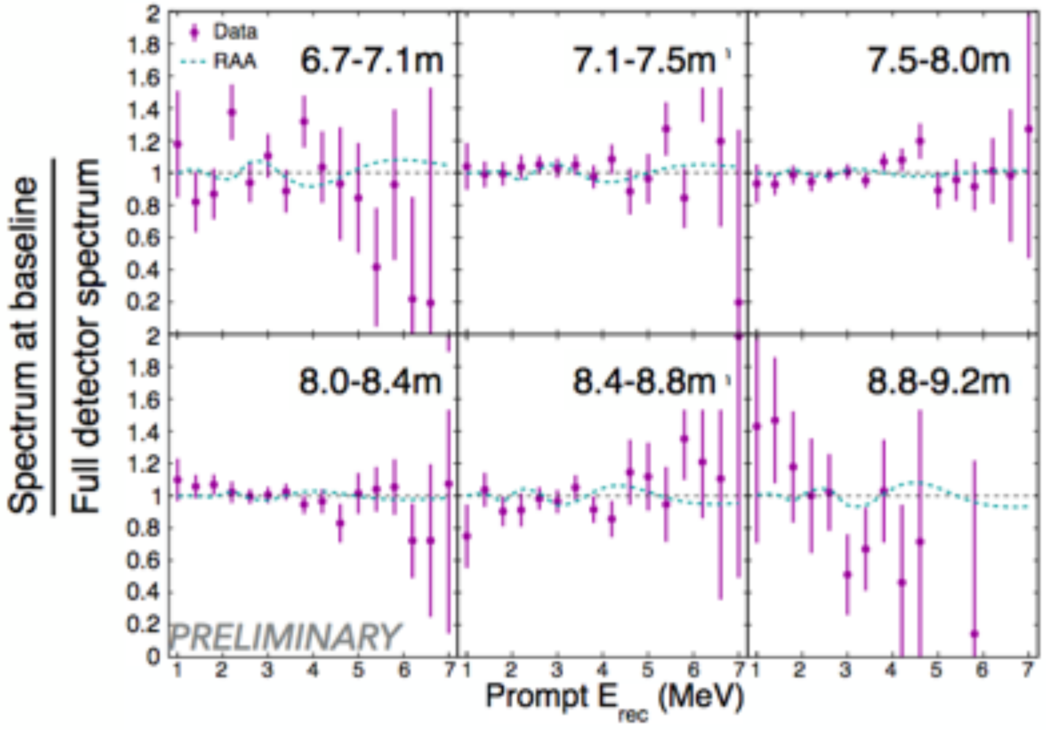
AHHHHH!

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



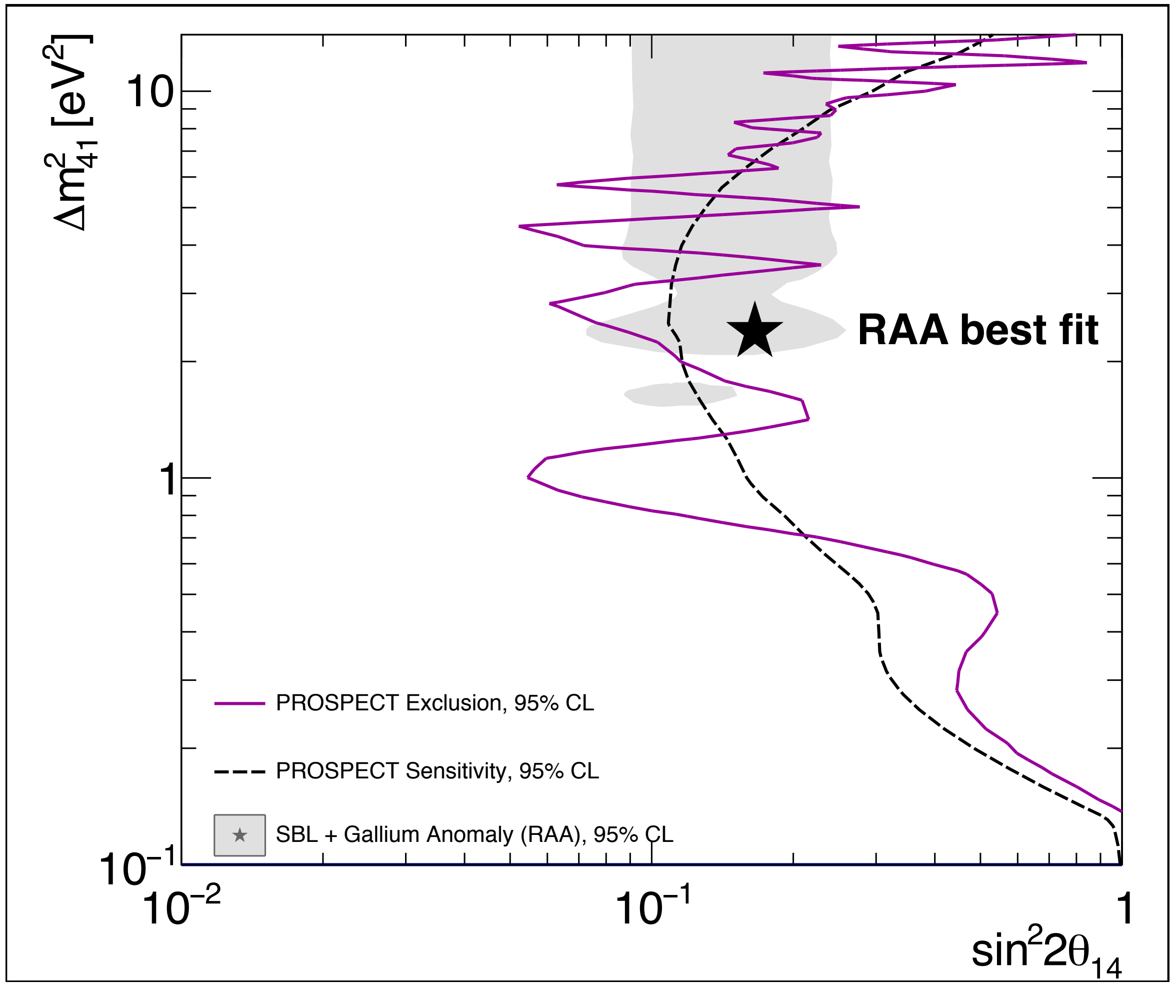
Baseline dependent oscillation illustration



arxiv: 1806.02784

PROSPECT: Results

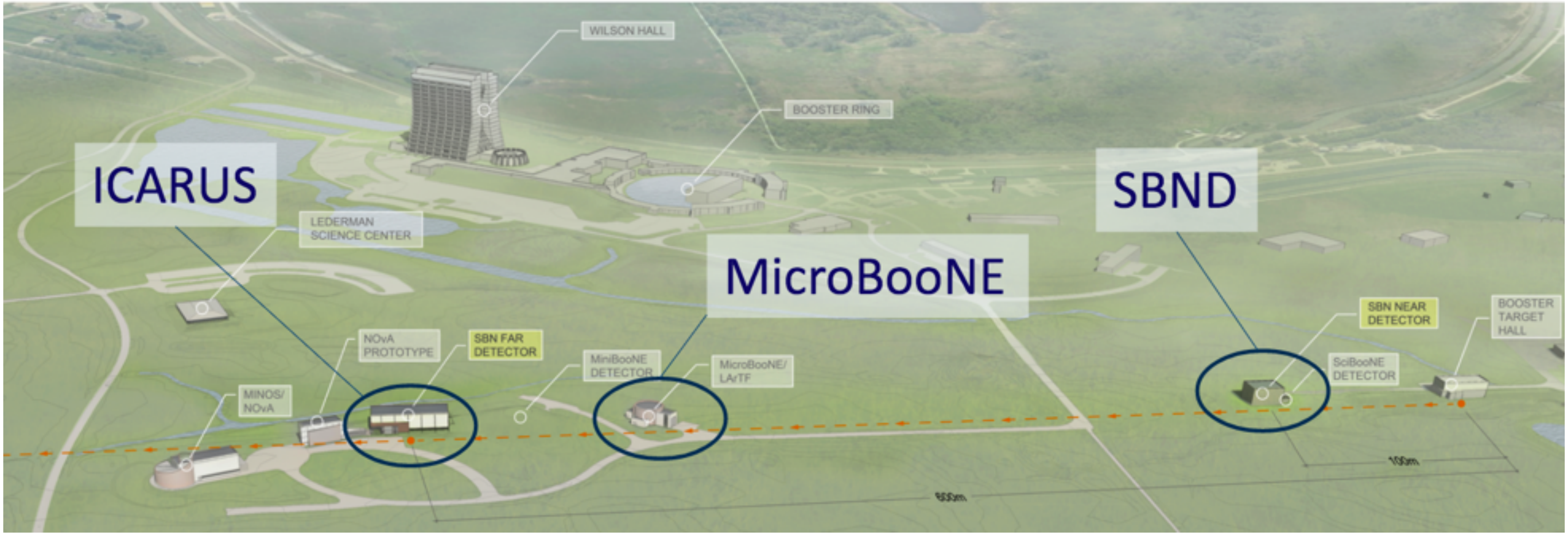
- Covariance matrices captures all uncertainties and energy/baseline correlations
- 95% exclusion curve based on 33 days of data
- First oscillation analysis on data disfavor the Reactor Antineutrino Anomaly (RAA) best fit at 2.3 sigma!



T. Langford
Neutrino 2018

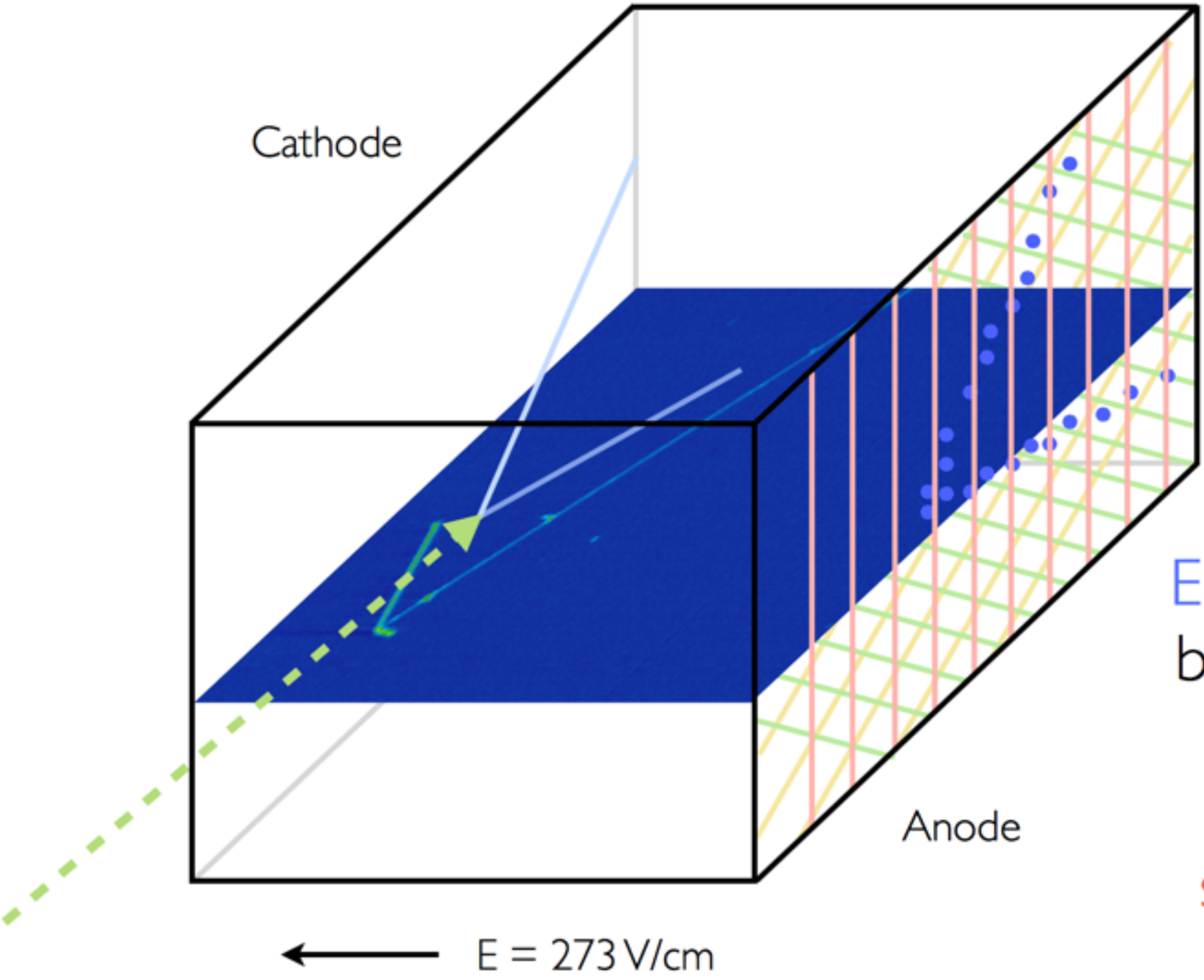
The Short Baseline Neutrino Program

The Short Baseline Neutrino (SBN) program
Liquid Argon TPC Technology



- Booster Neutrino Beam
  - Muon neutrinos produced from protons at 8 GeV on a Beryllium target
- 3 Liquid Argon Time Projection Chambers (LArTPCs): Short Baseline Near Detector (SBND), MicroBooNE, ICARUS T-600
- SBND (110 m, 112 tons), MicroBooNE (470 m, 89 tons), ICARUS (600 m, 476 tons)

Liquid Argon TPC
How it works?

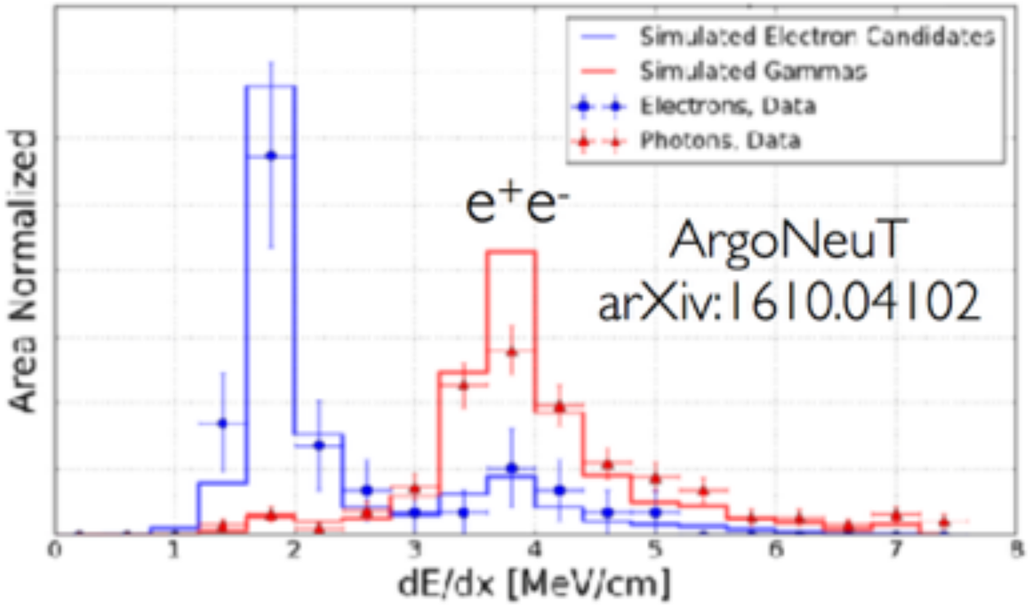


Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

SBN program: Why LArTPC?

- Why liquid argon? Large interaction rate
- Scalability: Argon is affordable (low cost :))
- High spatial resolution: able to characterize complicated events (multiplicity)
- Excellent energy resolution: electron/gamma separation

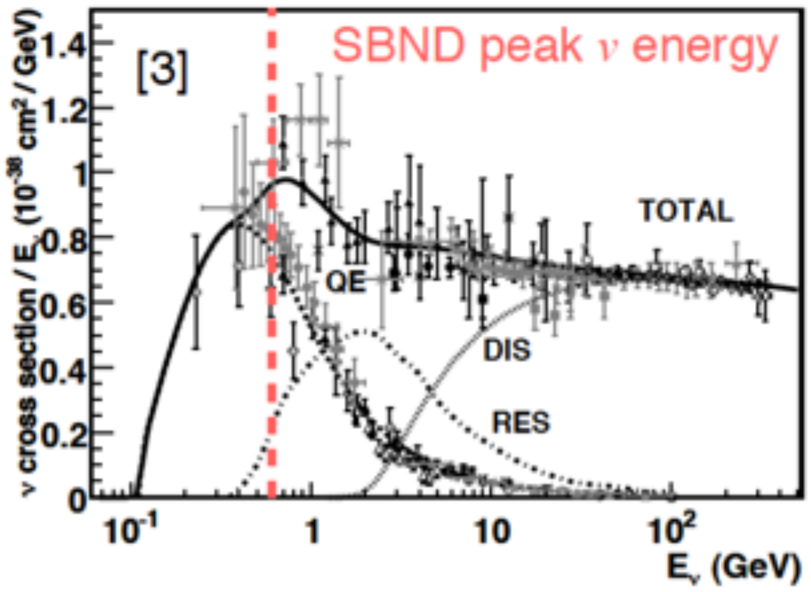
Run 3493, Event 41075, October 23rd, 2015

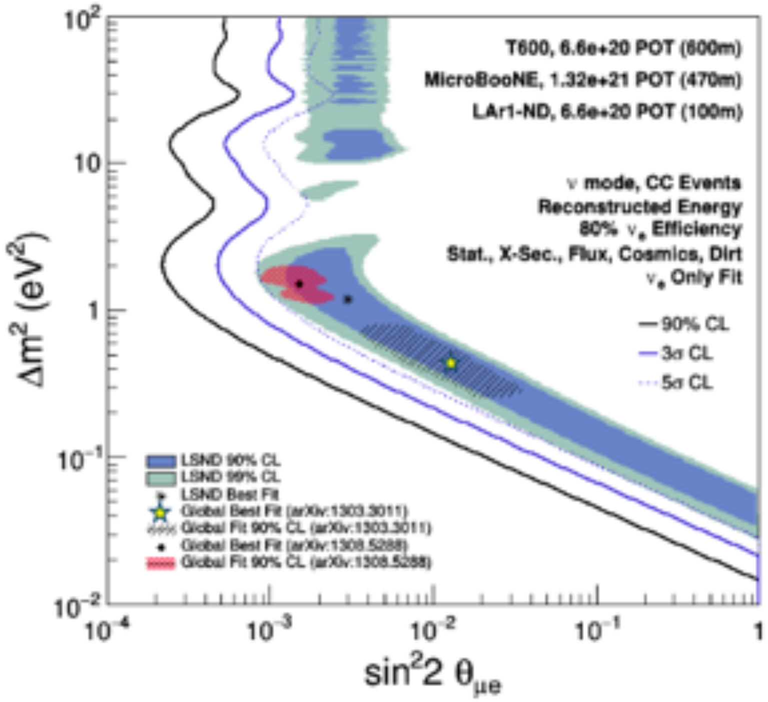


ArgoNeuT arXiv:1610.04102

SBN program: Physics goals MicroBooNE-> SBND -> SBN

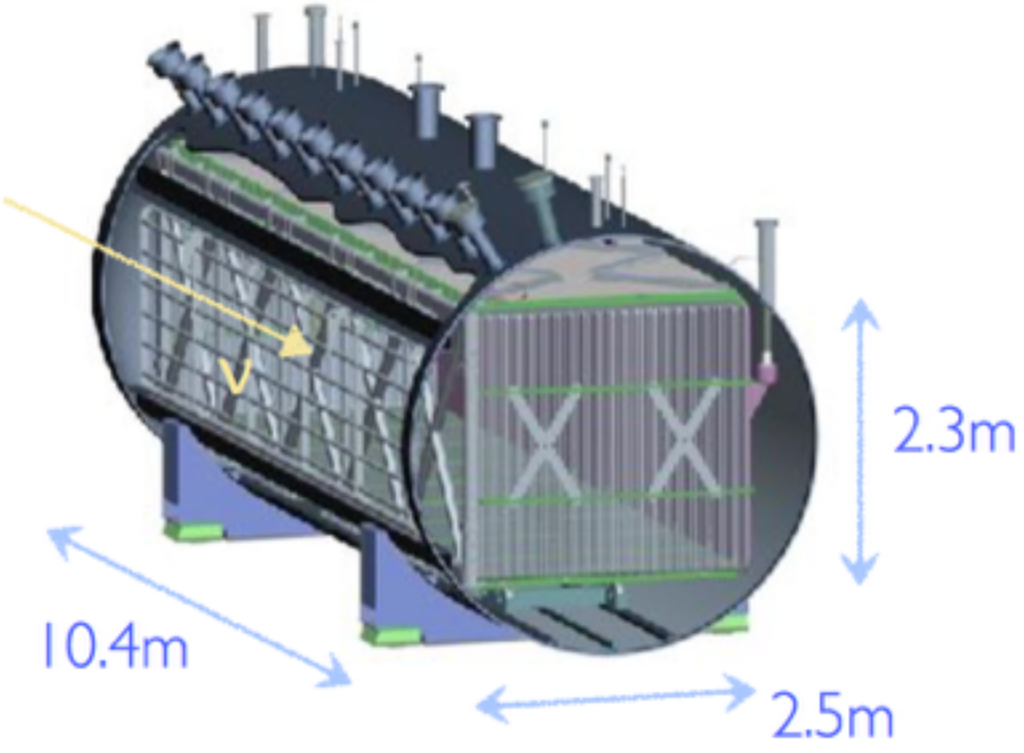
- MicroBooNE (taking data since late 2015!) and SBND data will be crucial for:
  - Measuring neutrino argon interactions with high statistics
  - nu-Ar interaction cross sections will be crucial for making neutrino oscillation measurements.
    - **Dominant systematics for Deep Underground Neutrino Experiment (DUNE)**
  - Understanding how the neutrinos interact with Argon
    - **Nuclear effects change the final state topology and kinematics**
- SBN will measure neutrino oscillations in the Booster Neutrino Beam (BNB)
- Experimental anomalies have been observed in short baseline neutrino experiments (<1 km)
  - SBN: Sensitivity to sterile neutrinos in the 1eV^2 mass region from same beam as MiniBooNE (BNB)

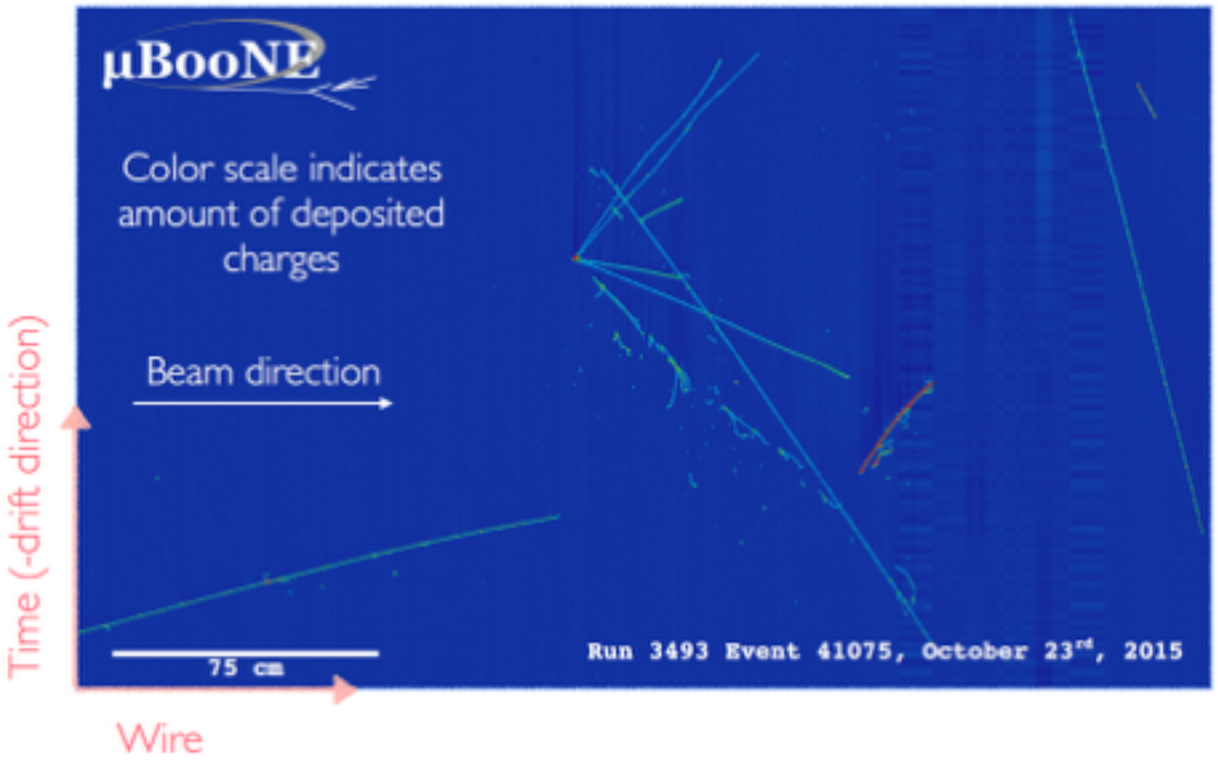


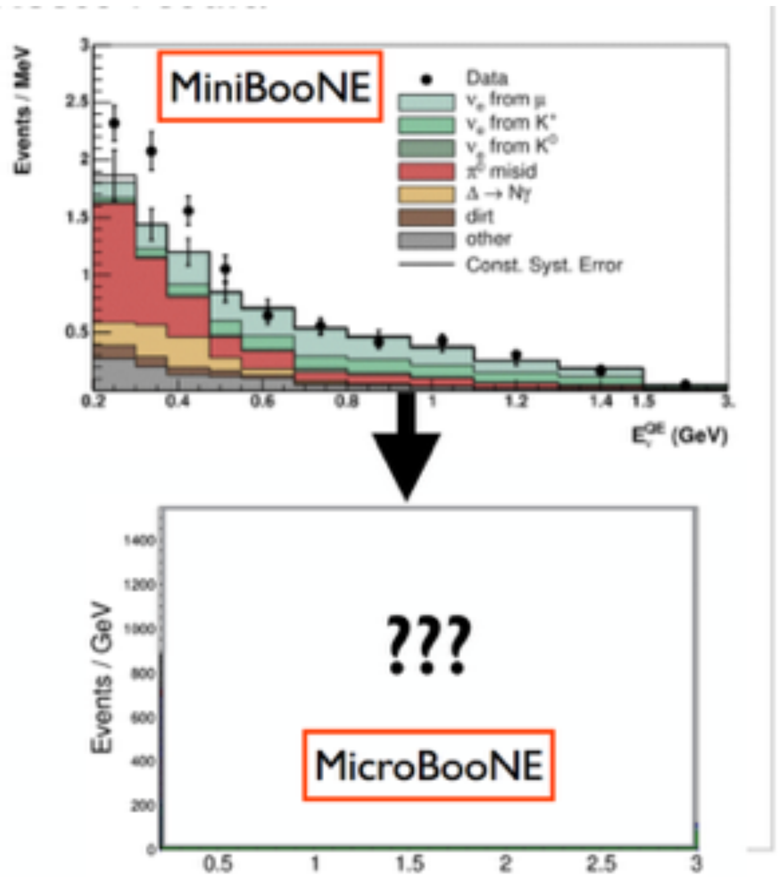


MicroBooNE experiment

- Largest operational LArTPC in US!
- Same neutrino beam and same distance (nearly) as MiniBooNE
- TPC: 2.3 m X 2.5 m X 10.4 m
  - 8192 Wires, 3 mm pitch
- Light collection system: 32 PMTs
- Cosmic Ray Tagger
- Collecting beam data since October 2015
- Identify the nature of the low energy excess (differentiate between electrons and photons)

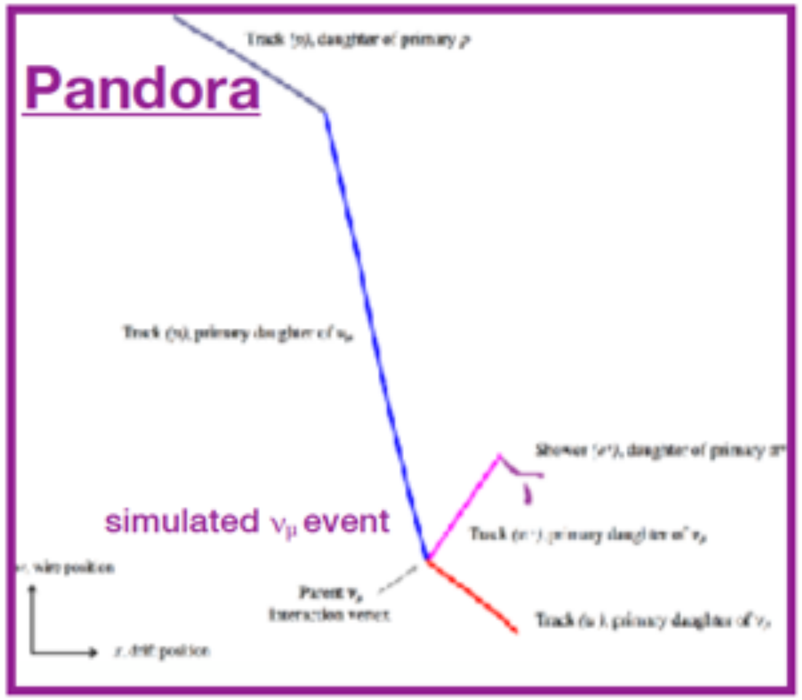






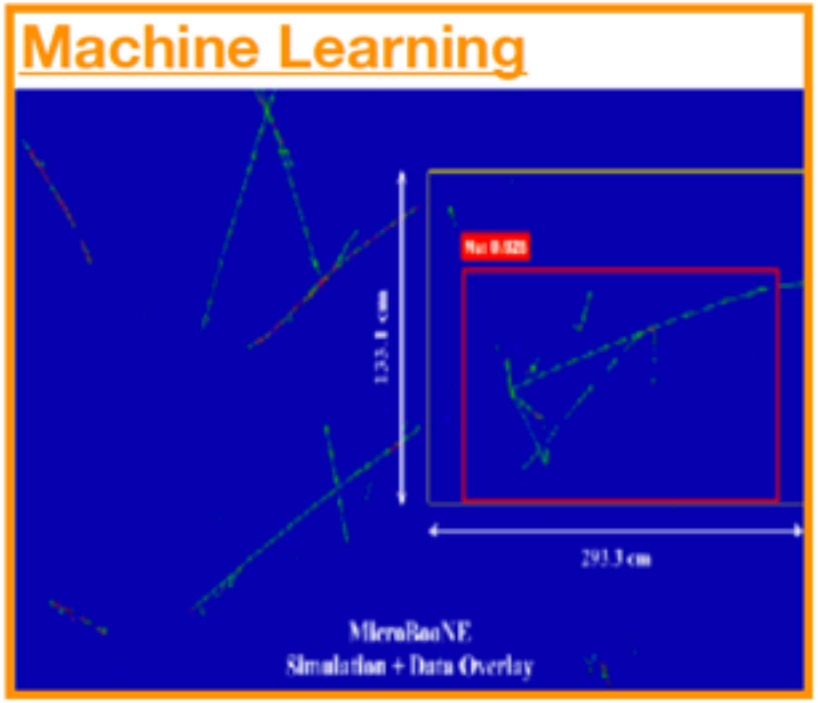
MicroBooNE experiment Event Reconstruction

- Variety of techniques developed
- Essential for SBN program and DUNE



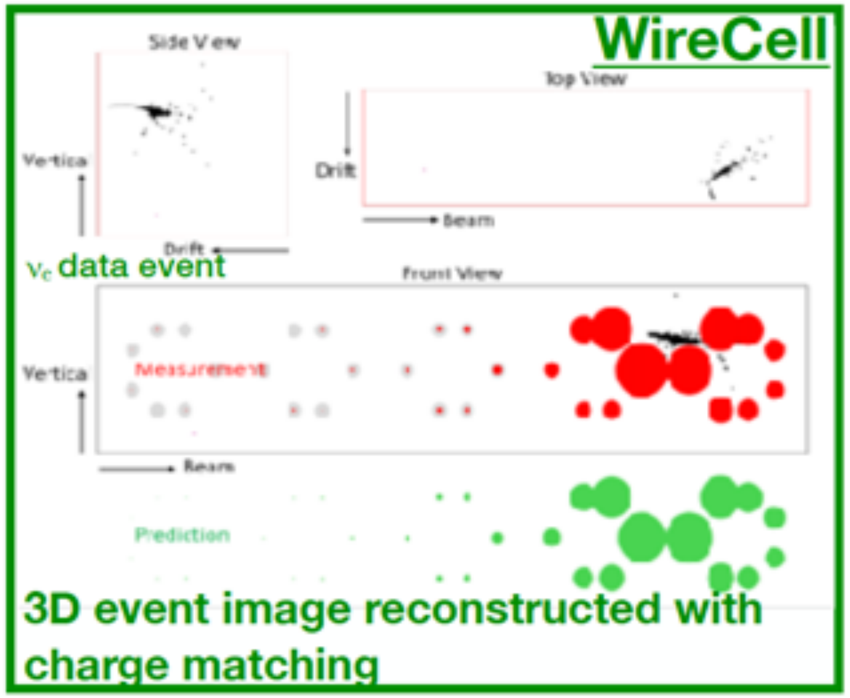
"The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", Eur. Phys. J. C78, 1, 82 (2018)"

Starts with 2D patterns to get 3D reconstruction



"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", JINST 12, P03011 (2017)

Employ recent computer vision advances

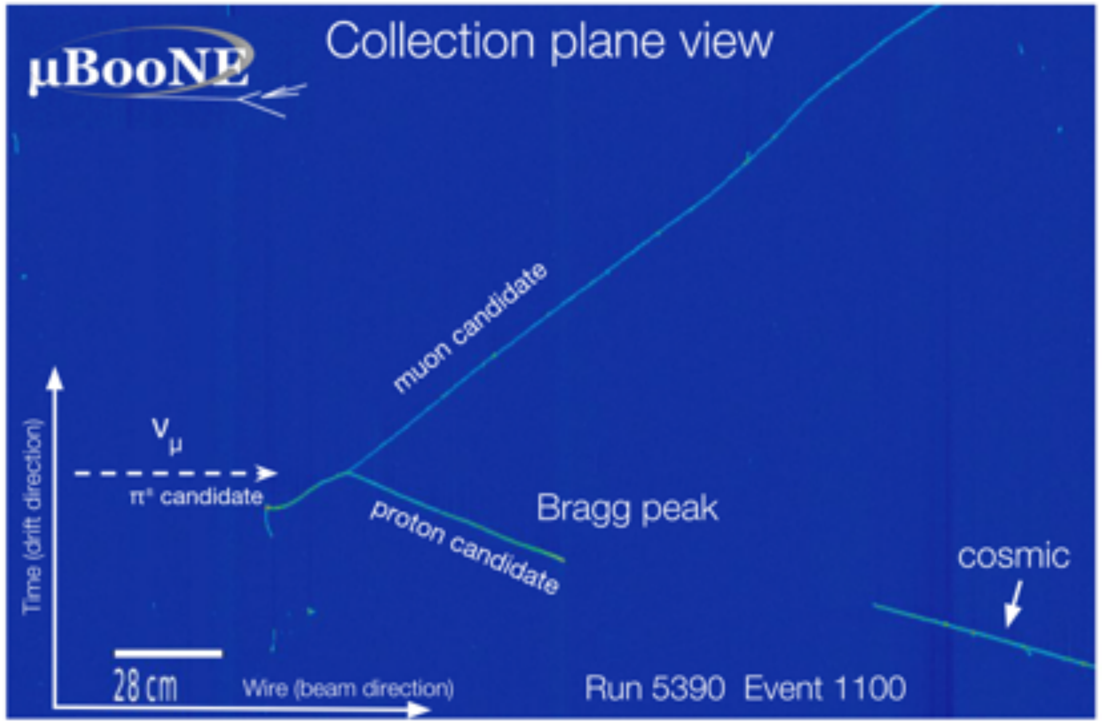


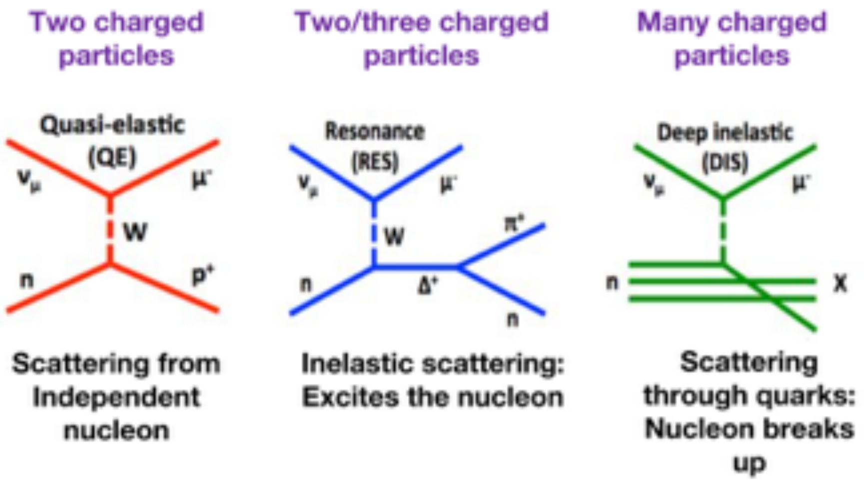
Three-dimensional imaging for large LArTPCs", JINST 13, P05032

Tomographic approach to turn 2D charge info in 3D charge.

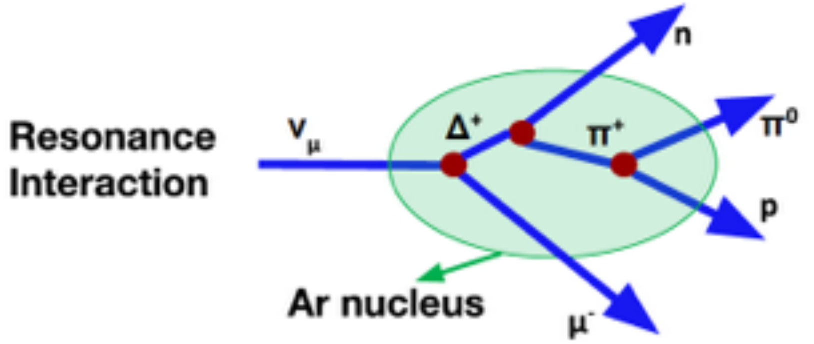
MicroBooNE experiment
Neutrino Interactions

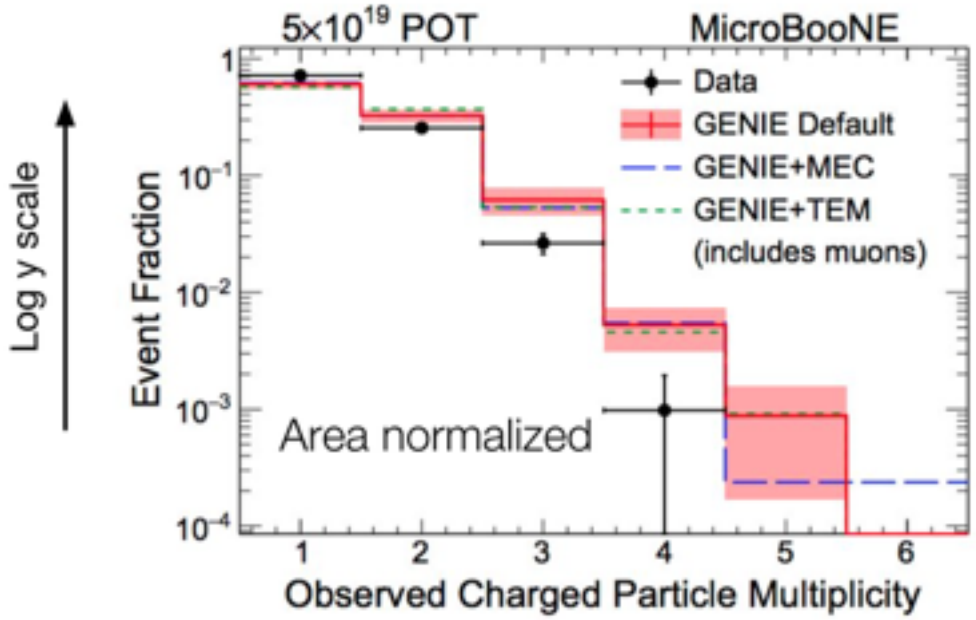
- Cross section measurements on argon are important for the flagship low energy excess analysis and future liquid argon experiments i.e DUNE
- Liquid argon TPCs are great to study final state topologies and inform theoretical models
- Study the charged particle multiplicity (CPM) in muon neutrino interactions
  - Useful to validate generators, models!





Example of neutrino interaction with CPM = 2



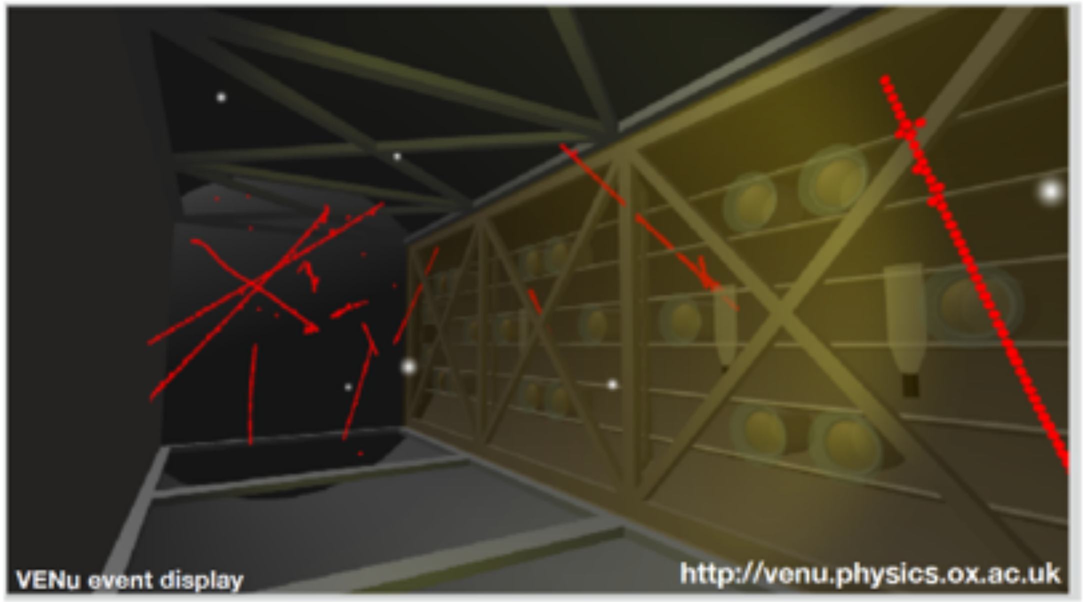


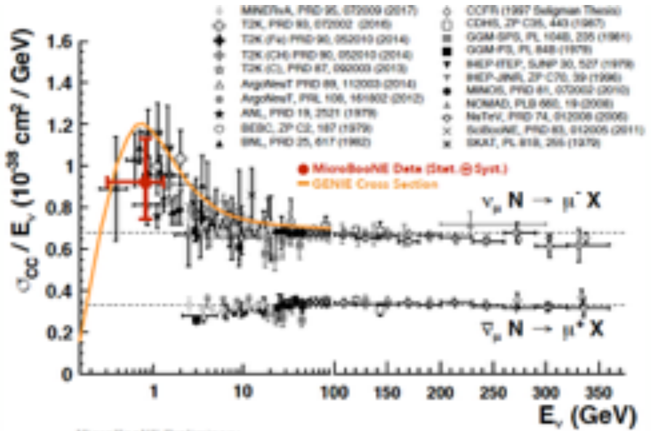
- arXiv:1805.06887, submitted to PRD (2018)
- A. Rafique W&C Seminar. Fermilab, June 2018

simulation agrees with data at 2 sigma level

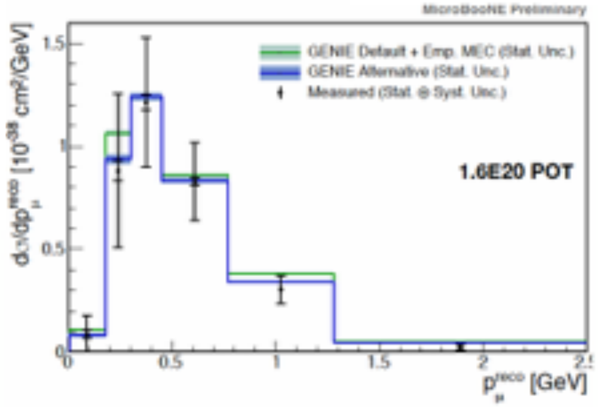
MicroBooNE experiment Neutrino Interactions

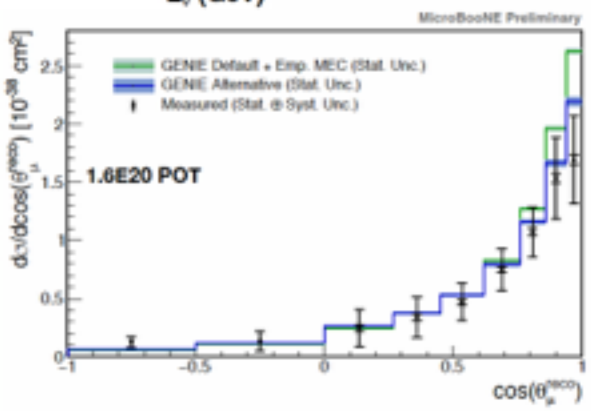
- Inclusive muon neutrino charged current interactions has been measured by other experiments, NOW we need to measure on argon!
- Comparison to GENIE with different models
- Relevant to DUNE muon neutrino charged current signal





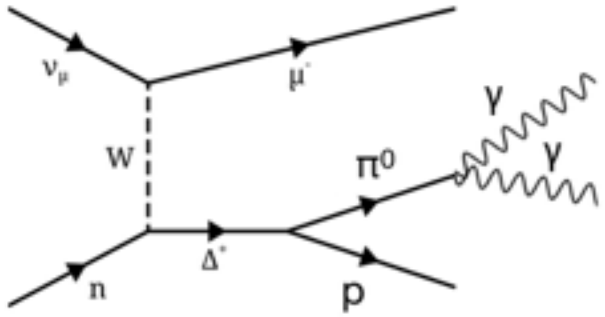
$$\sigma_i = \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bg})}{\phi_i T \epsilon_i}$$



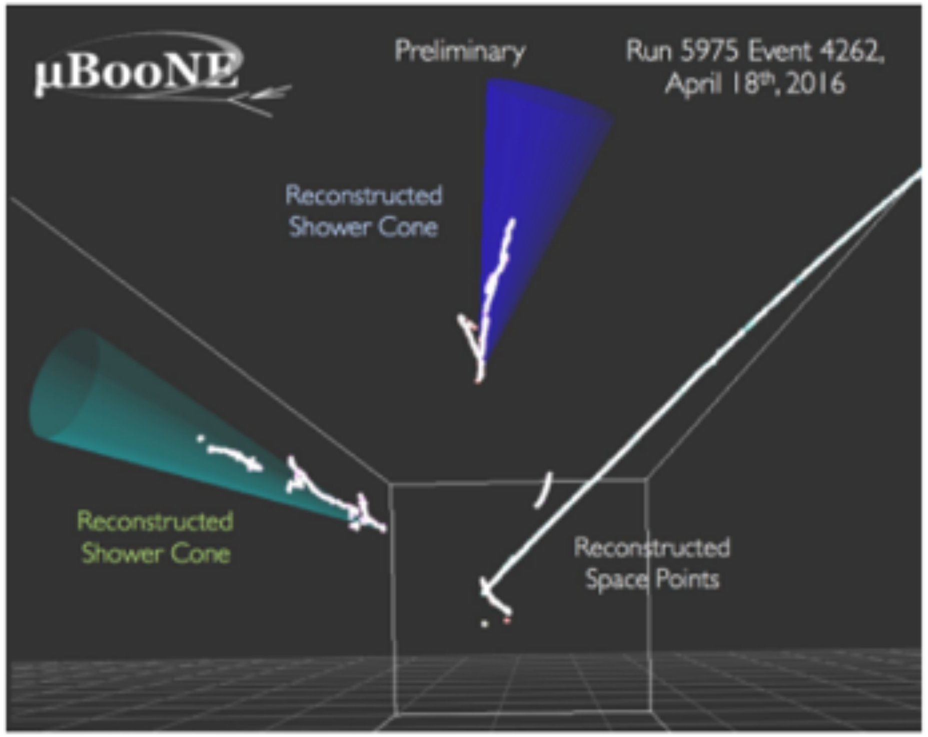


public note: MicroBooNE-NOTE-1045-PUB

MicroBooNE experiment
Neutrino Interactions

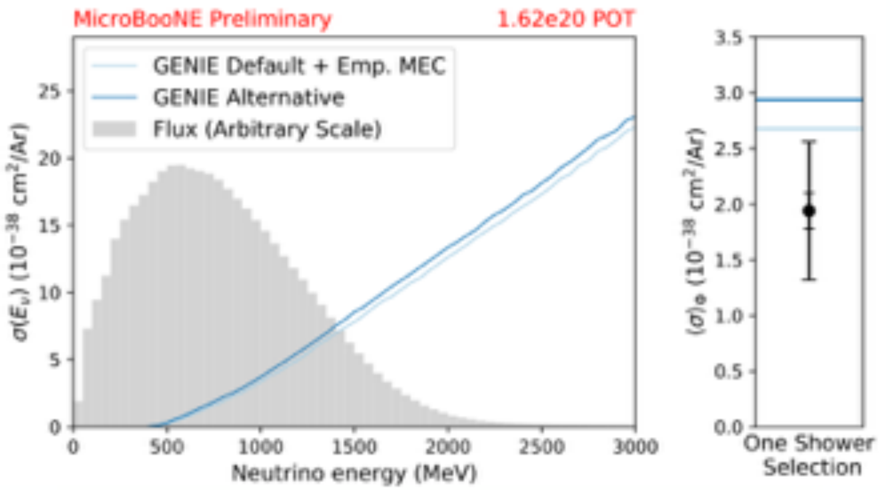


- Important for the low energy excess
  - Challenge: Require track and low energy reconstruction
  - Demonstration of shower reconstruction being used to analyze LArTPC data
- Shower reconstruction and validation of shower resolution
- First time $\nu_\mu CC1\pi^0$ measurement on Argon



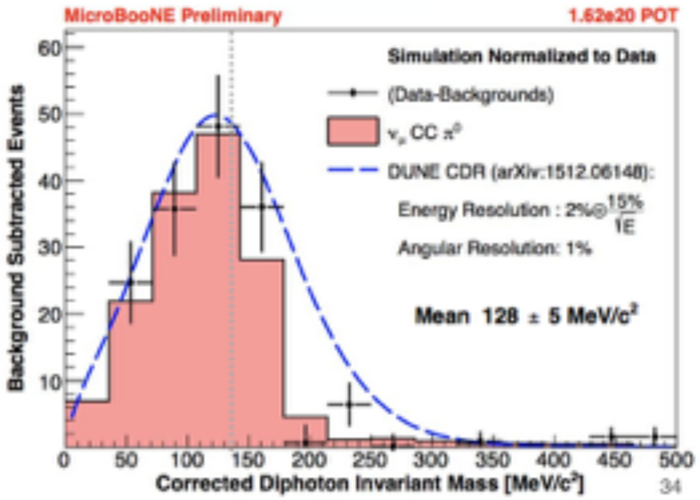
Flux integrated cross section

$$\left\langle \sigma^{\nu_\mu CC\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16[\text{stat.}] \pm 0.60\text{syst.}) \times 10^{-38} \frac{\text{cm}^2}{\text{Ar}}$$

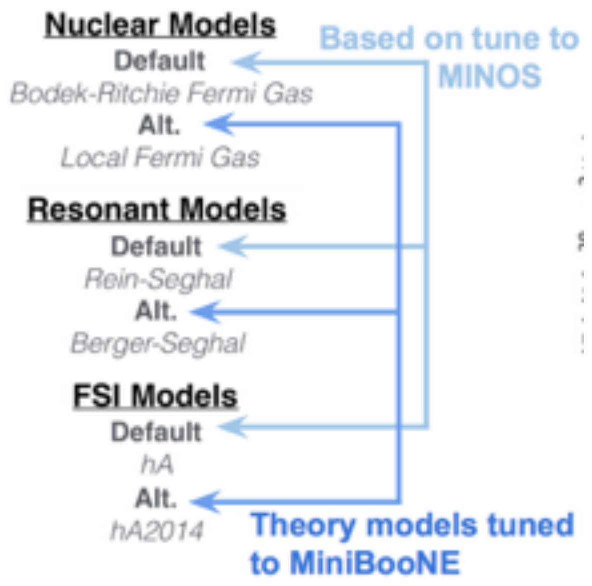


Public Note: MICROBOONE-NOTE-1032-PUB, 2018

Two-photon invariant mass



Measurement is consistent within 1.6 sigma with prediction of both models!



Nuclear Models
Default
Bodek-Ritchie Fermi Gas
Alt.
Local Fermi Gas

Resonant Models
Default
Rein-Seghal
Alt.
Berger-Seghal

FSI Models
Default
hA
Alt.
hA2014

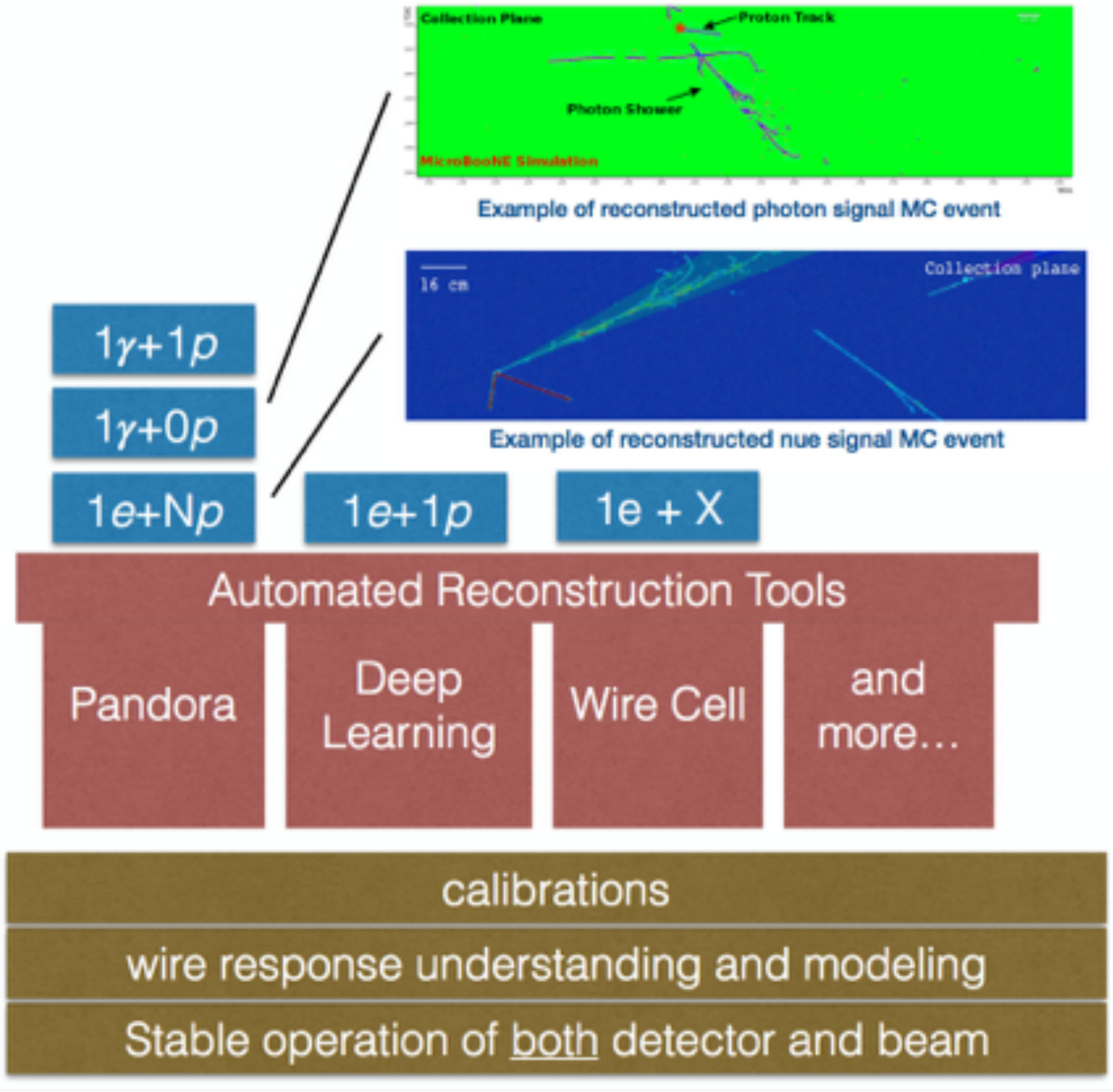
Based on tune to MINOS

Theory models tuned to MiniBooNE

MicroBooNE experiment
Towards Low Energy Excess

- Working in different channels to investigate the low energy exces

- Important: we want to test the different hypothesis of the exces
(not only sterile neutrinos :))



Example of reconstructed photon signal MC event

Example of reconstructed nue signal MC event

$1\gamma+1p$

$1\gamma+0p$

1e+Np | 1e+1p | 1e + X

Automated Reconstruction Tools

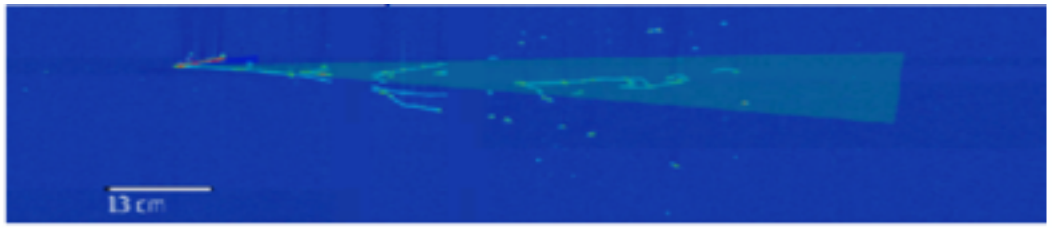
Pandora | Deep Learning | Wire Cell | and more…

calibrations

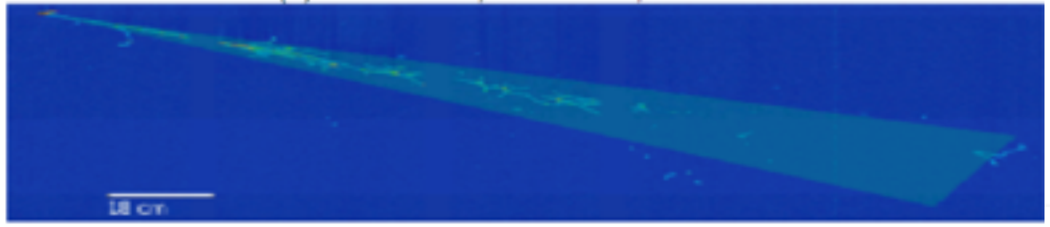
wire response understanding and modeling

Stable operation of <u>both</u> detector and beam

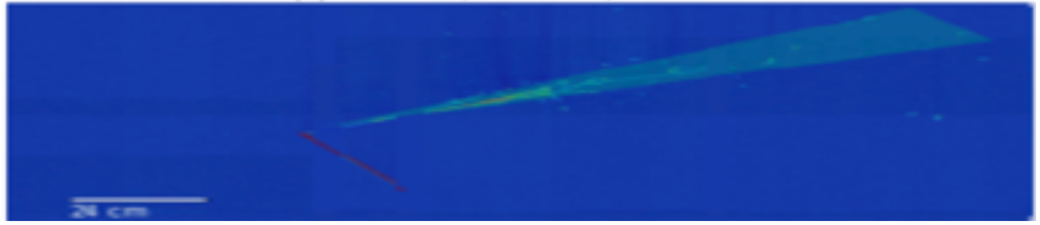
Selected
ν_e
data events



(a) Event 1515, Subrun 30, Run 5328



(b) Event 31, Subrun 0, Run 5513



T. Wongjirad
Users Meeting
Fermilab 2018

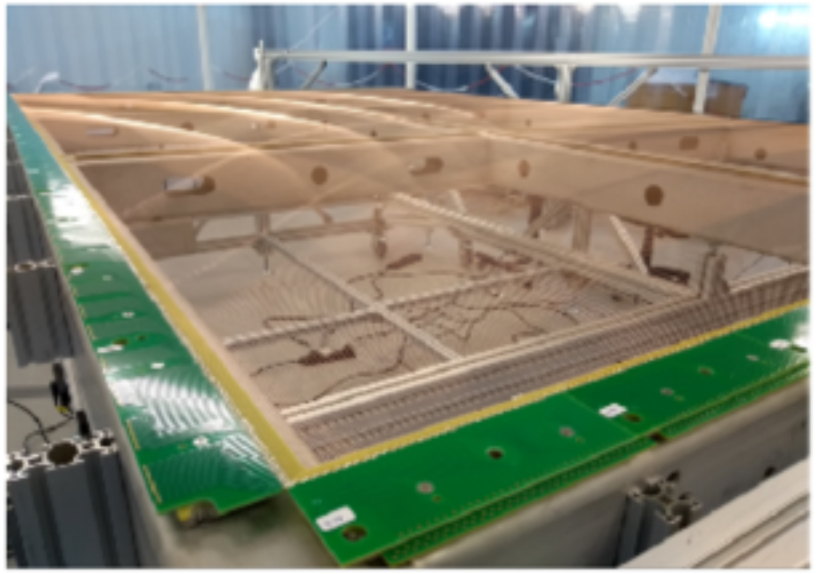
Short Baseline Neutrino Program

- Detector **installation** underway
- Planned data taking **2019**

- TPCs delivered at FNAL July 2017
- Warm vessel completed
- Cold shield under installation

- Detector **construction** underway
- Planned data taking **2020**

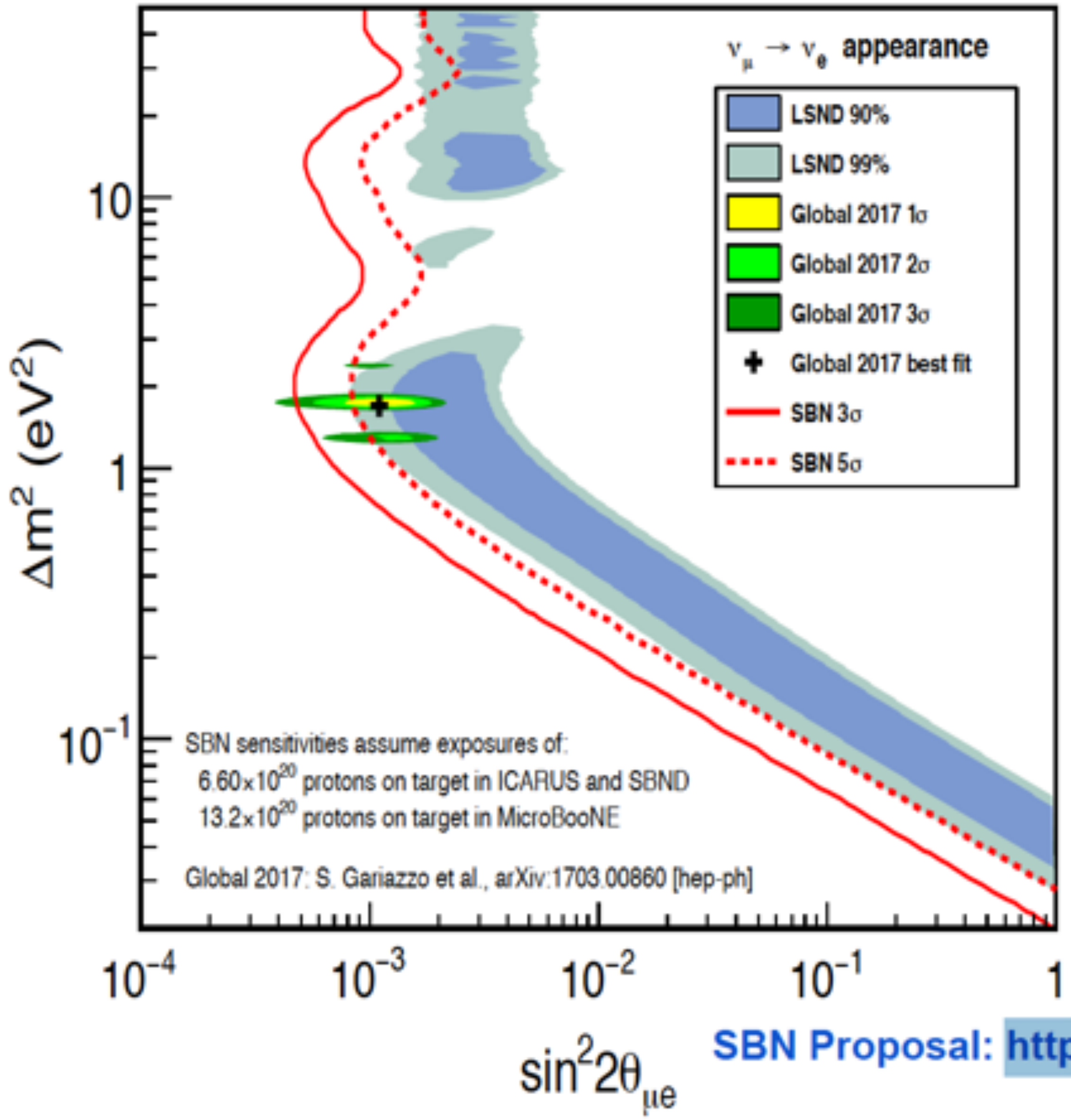
- CRT panels installed for preliminary beam data

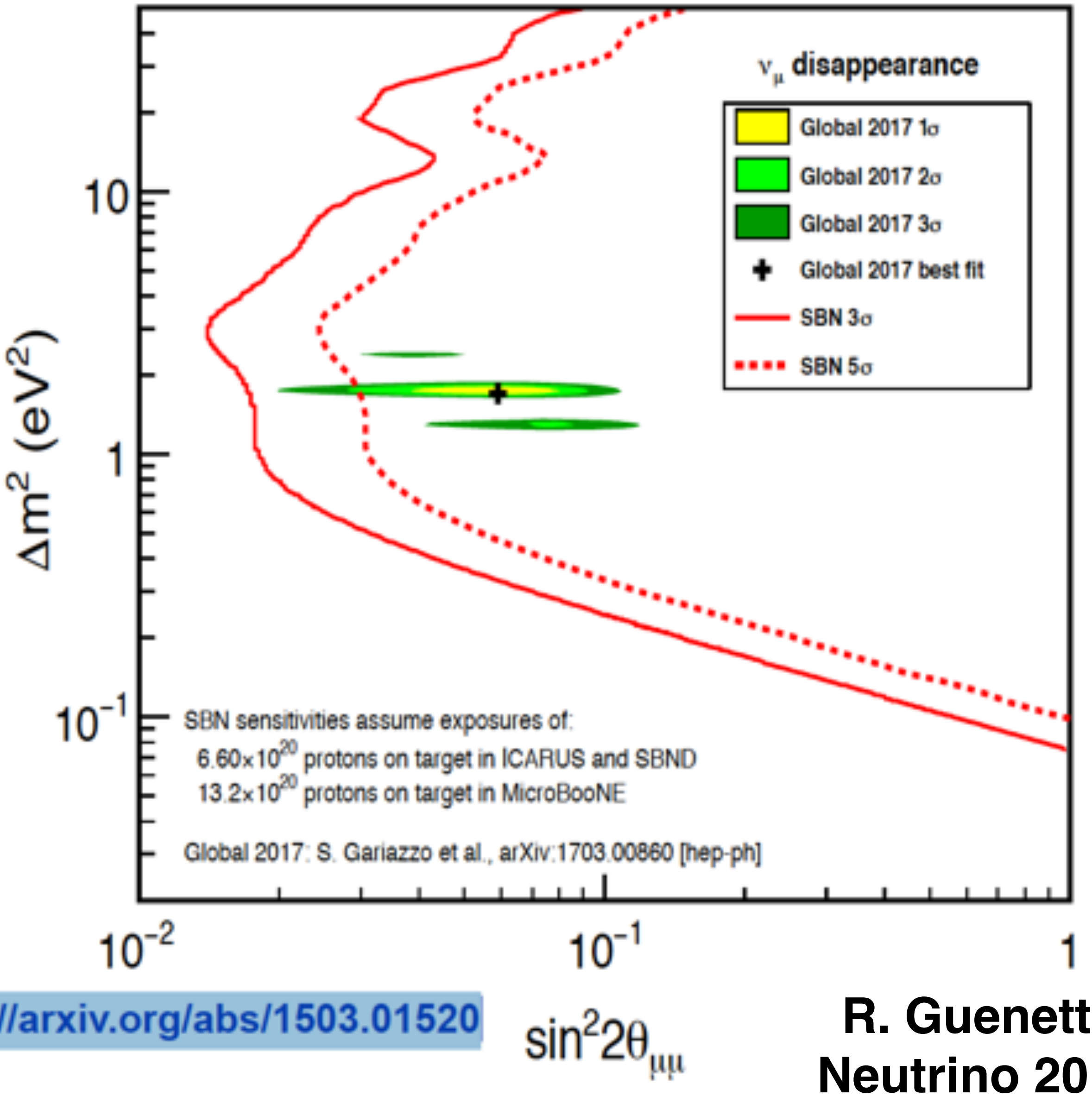


- *Anode Plane Assemblies* and other components under construction (US & UK)

Short Baseline Neutrino Program

- We expect to have an answer to the short baseline anomalies in next 5 years!





SBN Proposal: https://arxiv.org/abs/1503.01520

R. Guenette
Neutrino 2018

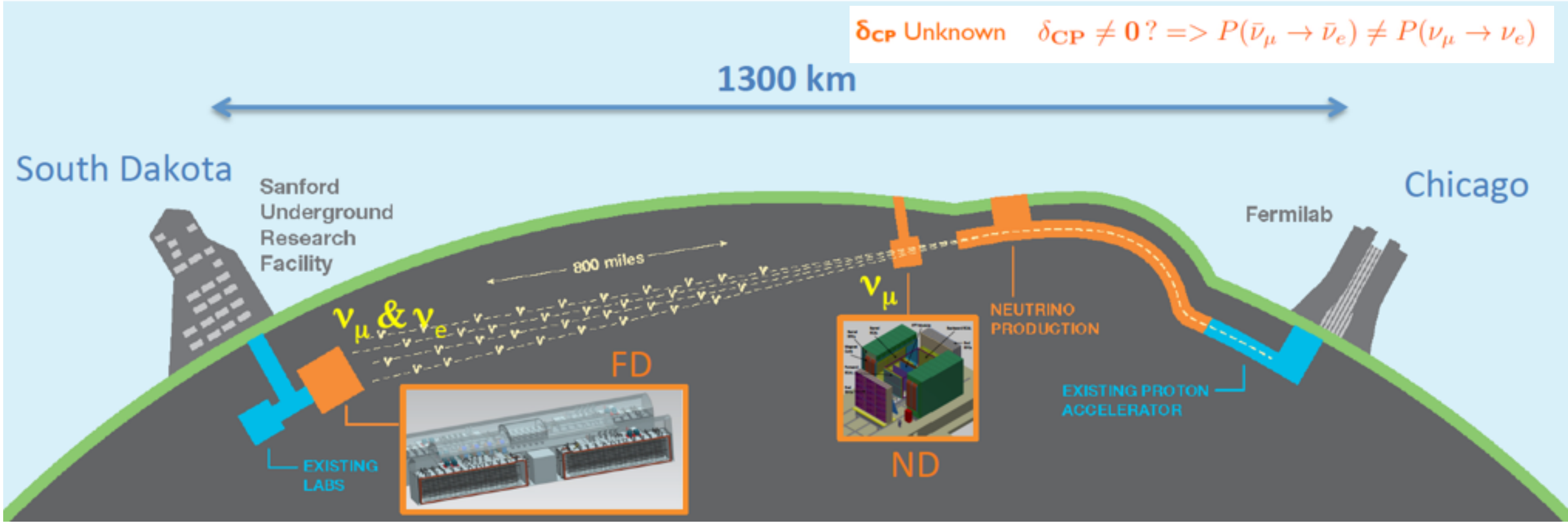
Deep Underground Neutrino Experiment
DUNE

DUNE

Video: DUNE

- Intense beam of v_{mu} or $\overline{v}_{mu}$ fired 1300 km at a large detector
  - Muon neutrinos/antineutrinos from high power proton beam ~ 1.2 MW
- Large underground (~1500 m) Liquid Argon Time Projection Cham
  - 4 X 17 kton (fiducial mass > 40 kton)
- Near detector to characterize the beam
- Maybe if we compare neutrinos and antineutrino's oscillation behavior we'll find a clue as to how the two can behave differently, and possibly lead to matter's apparent domination :)

Not an experimental anomaly, but a more UNIVERSAL anomaly: Where is the antimatter?

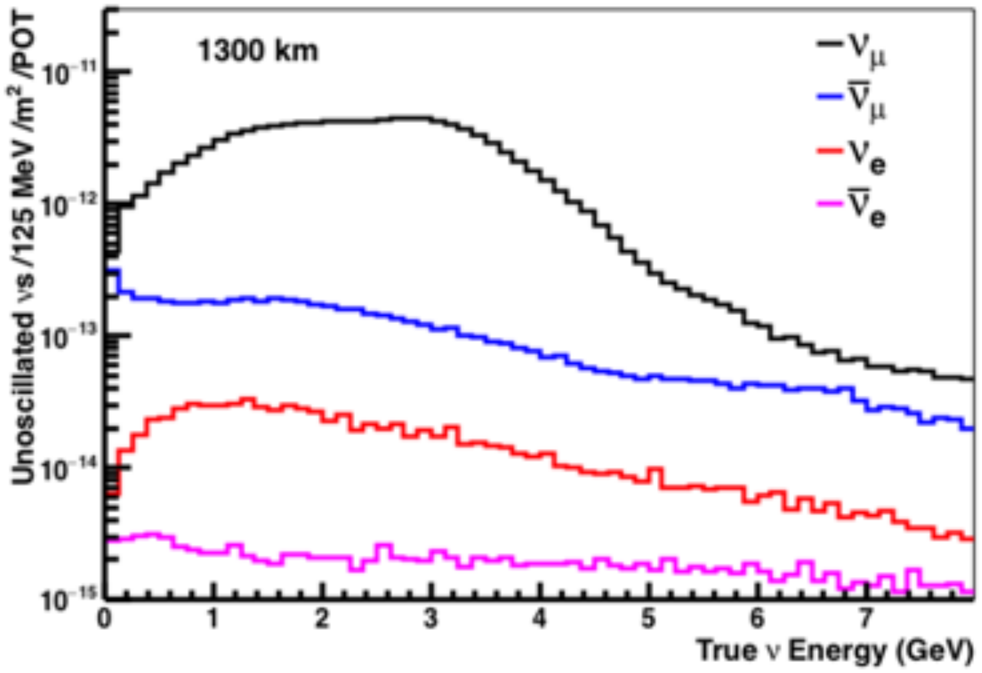


δ_{CP} Unknown $\delta_{CP} \neq 0? => P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e)$

DUNE

- LBNF Beam
  - 60-120 GeV proton beam
  - 1.2 MW upgradeable to 2.4 MW
  - Horn-focused neutrino beamline optimized for CP Violation.
- Neutrino Forward Horn Current (FHC) and antineutrino (RHC) modes

Neutrino Flux at 1300 km
(CDR Optimized Beam)

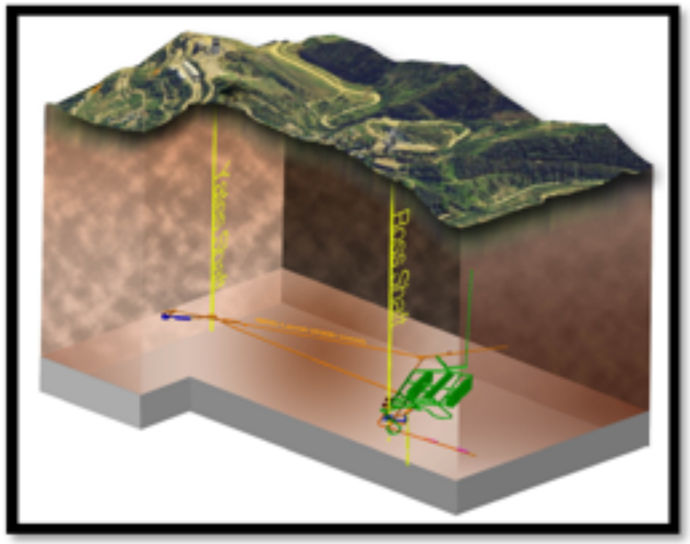


E. Worcester
Neutrino 2018

DUNE TIMELINE

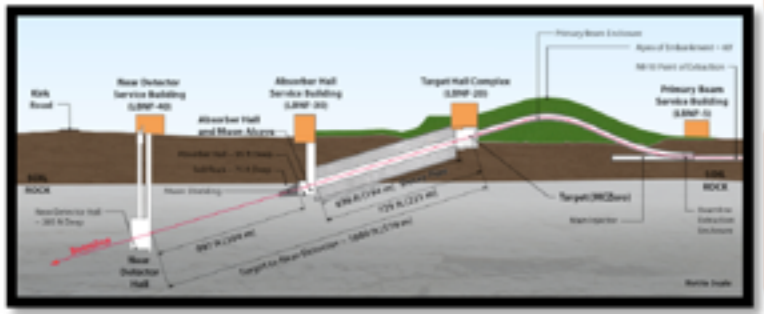
- 2018: protoDUNEs at CERN
- 2019: Technical Design Report
- 2019: Far Site Primary Excavation Begins
- 2022: First Module Installation Begins
- 2026: Neutrino Beam Available

DUNE Far Detector Interim Design Report (2018)
Will be made public soon…



Physics data as soon as 1st module complete

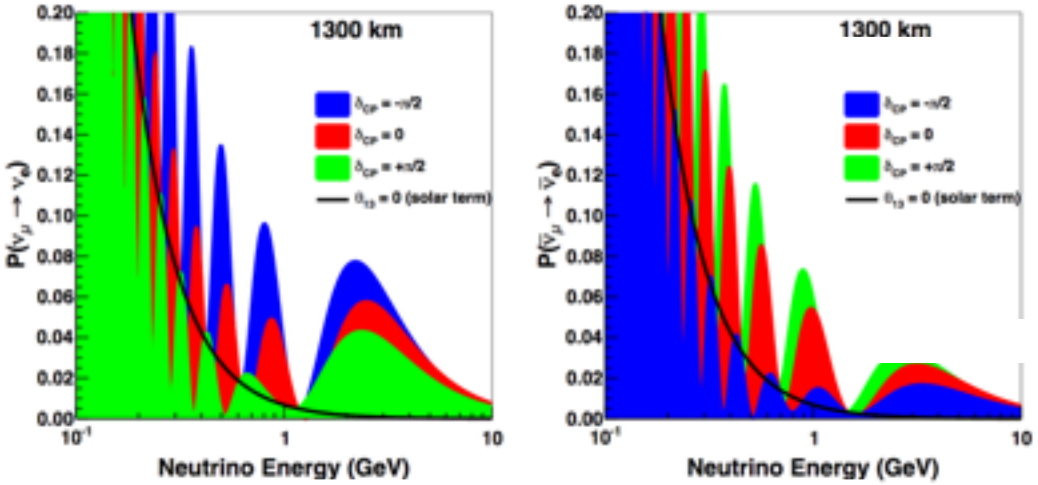
- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration



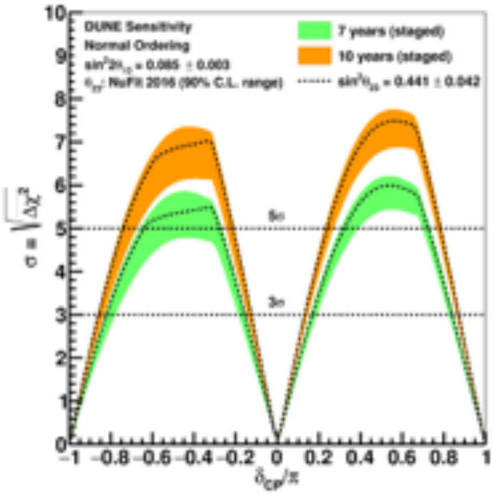
DUNE Science Goals

- Neutrino oscillation physics
    - Discover CP Violation in the leptonic sector

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

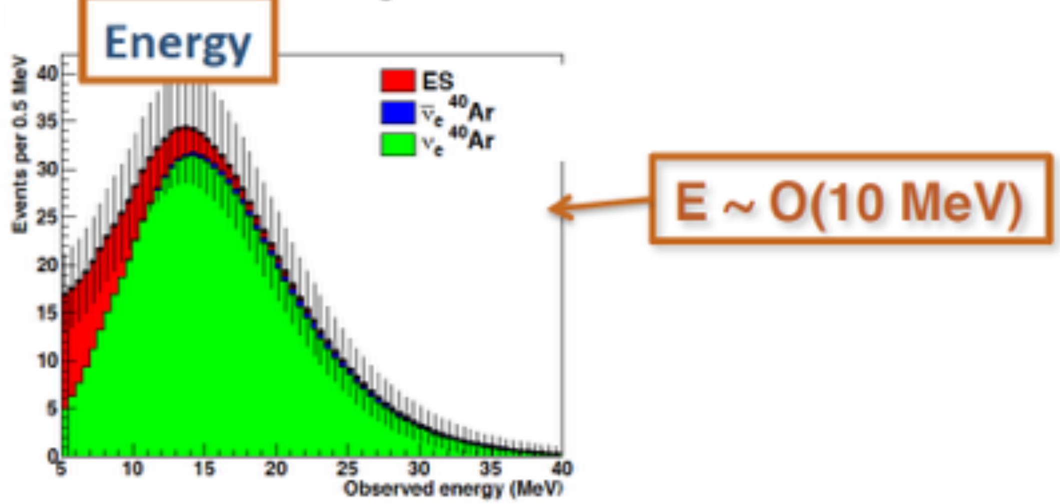


CP Violation



- Proton decay: constrain grand unified theories
- Supernova bursts physics and astrophysics
    - Galactic core collapse supernova, sensitivity to ν_e
        - In argon (uniquely) the largest sensitivity is to ν_e

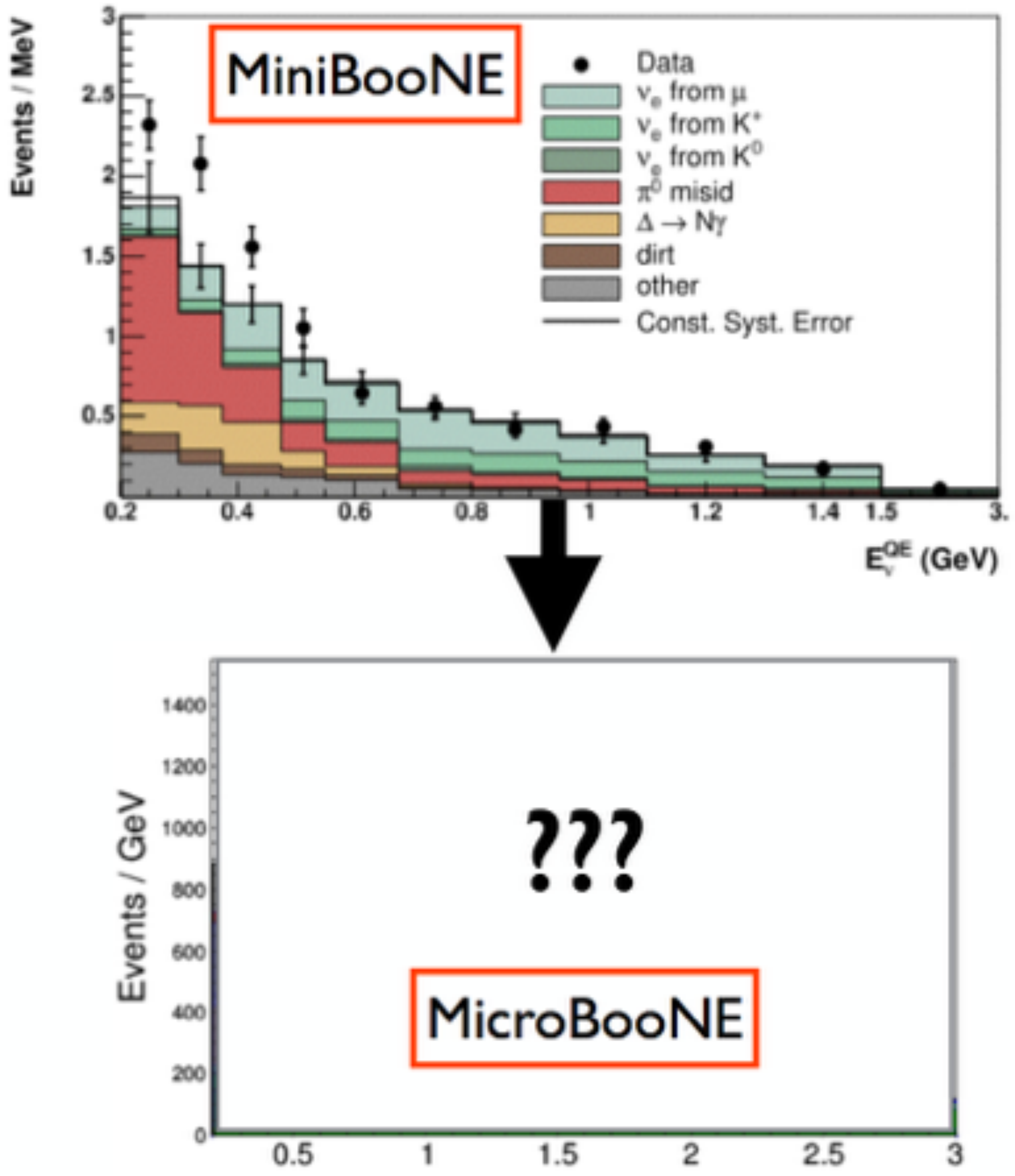
$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$$



Expected measured event spectrum using SNoWGlobes in 40 kt liquid argon detector for electron capture supernova at 10 kpC

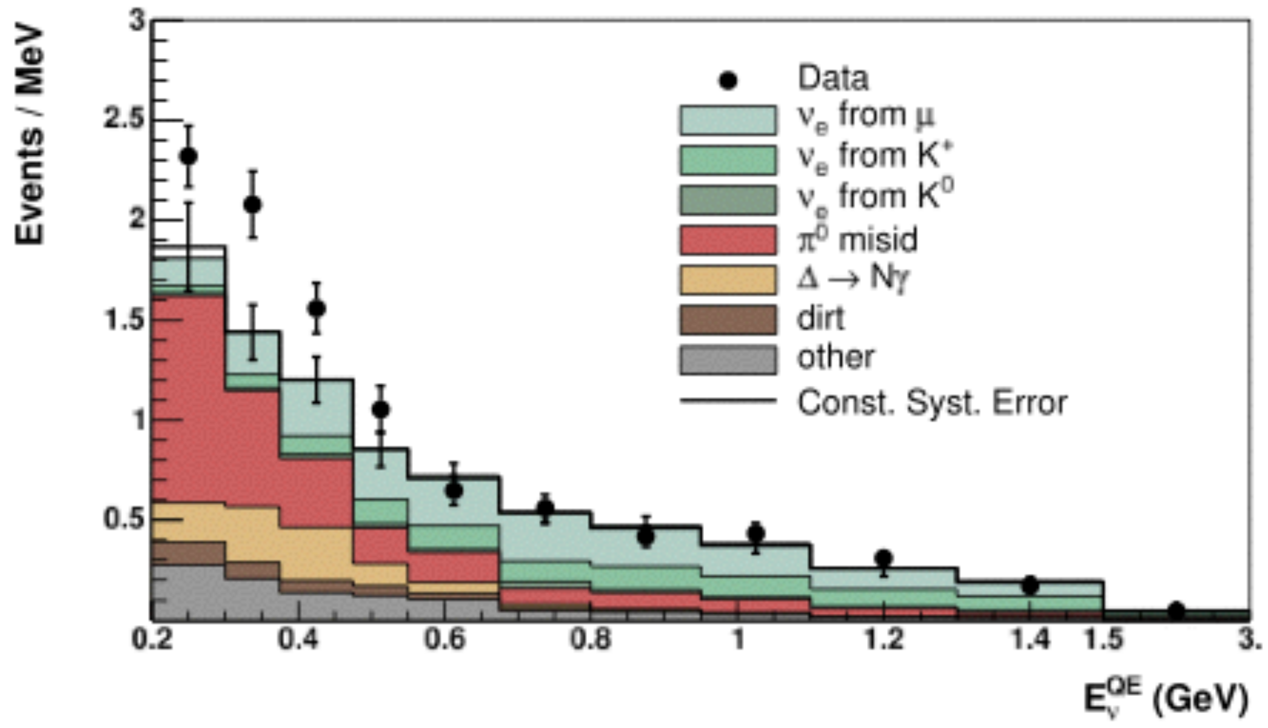
Recap:
Sterile neutrino mystery

- Lets think a bit in future, and MicroBooNE has released their low energy excess result
    - Will definitely test MiniBooNE excess by measuring the same neutrinos with a more sensitive detection technique
- What might show
    - Electron-like excess
    - Photon-like excess
    - No excess?
    - Excess in both channels?
    - ? :O ?
- Lets investigate this scenarios in detail



Electron-Like Excess: Differences

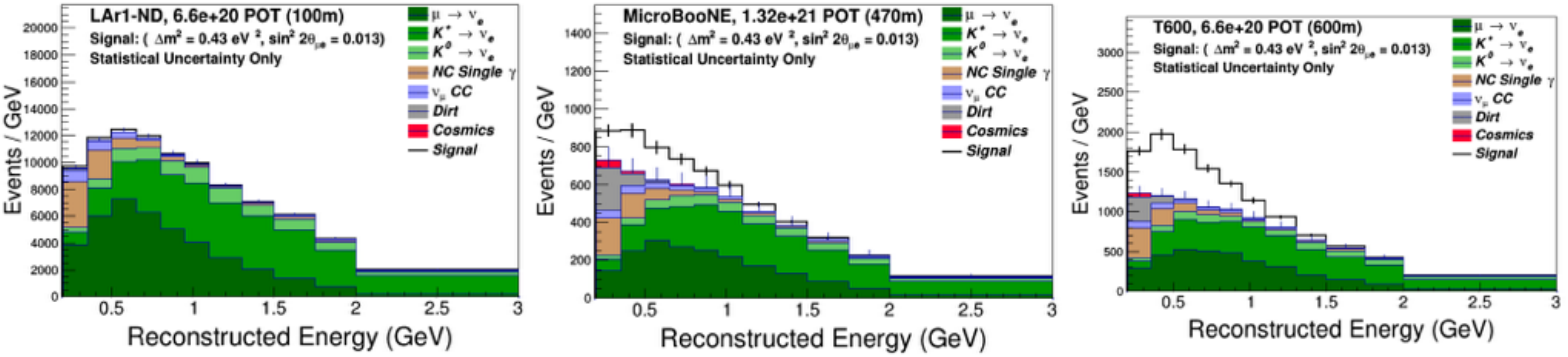
- How will the electron-like result look different than MiniBooNE?
  - **Gamma-related backgrounds should be way smaller in this stack.**
  - **TPC-external beam backgrounds might look different: more of them, but also new rejection methods.**



  - There will likely be a new (small) color in here from cosmogenic backgrounds
  - You might see a totally different x-axis metric: instead of CCQE, maybe lepton+vertex energy, or maybe something else!
  - You might also see a different range on this plot: no Cherenkov thresholds and excellent 3D position information could enable a lowered threshold.
- So more than just an improvement in e/ɣ separation.

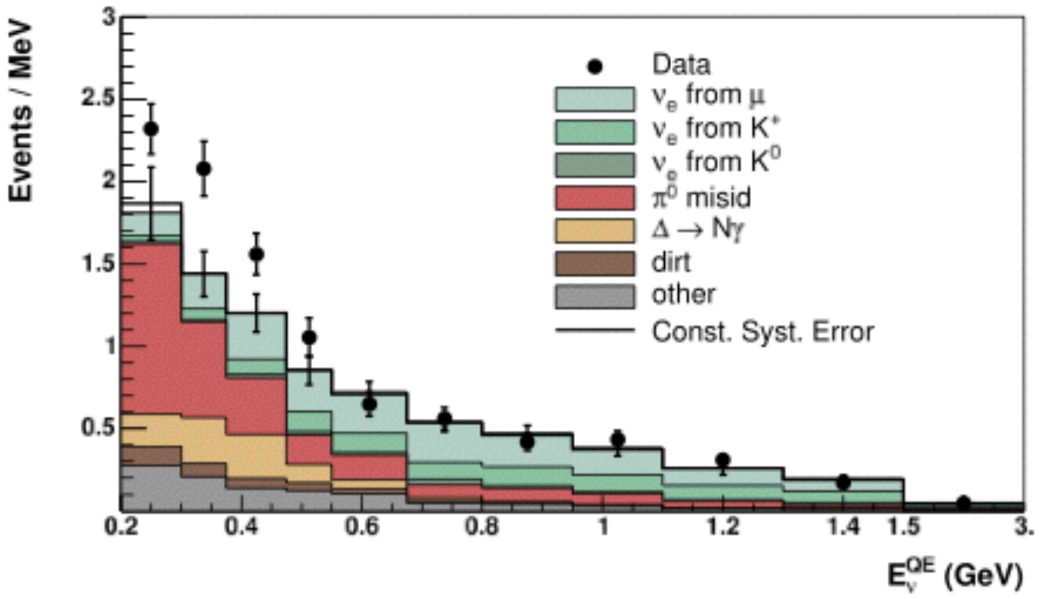
Electron-Like Excess: Scenarios

- If we see an electron-like excess, this would be AWESOME!
  - SBND would collect statistics quickly at its shorter baseline, giving very convincing confirmation of the nue appearance interpretation.
  - Full SBN would then provide the precision measurement of this oscillation.
  - Must be diligent in our proper estimation of TPC-external beam backgrounds and cosmic backgrounds.



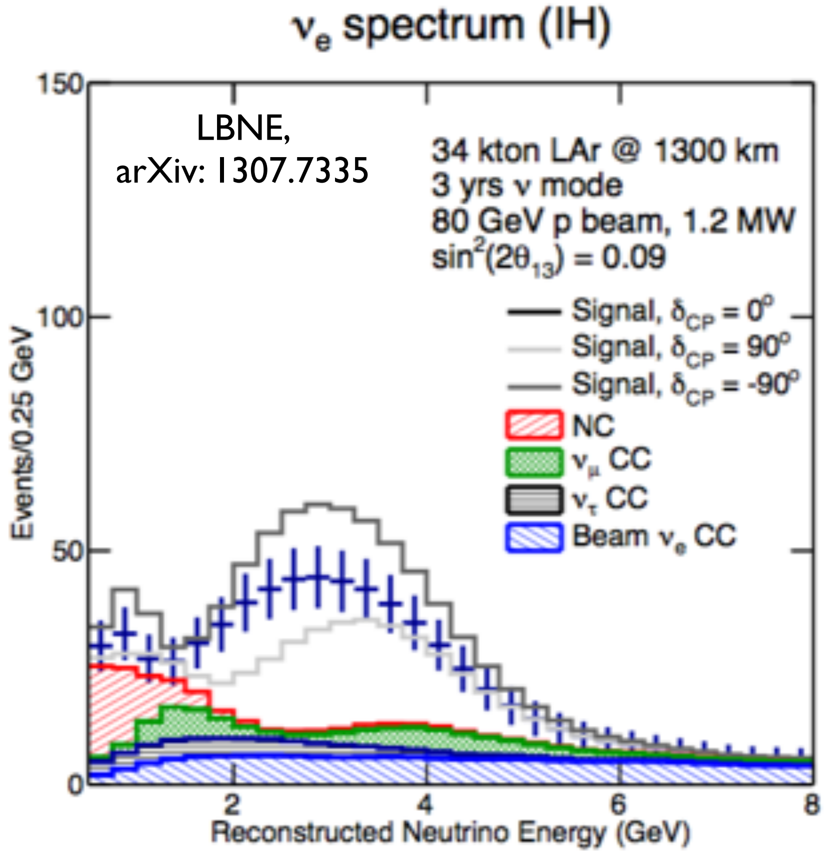
Photon-Like Excess: Scenarios

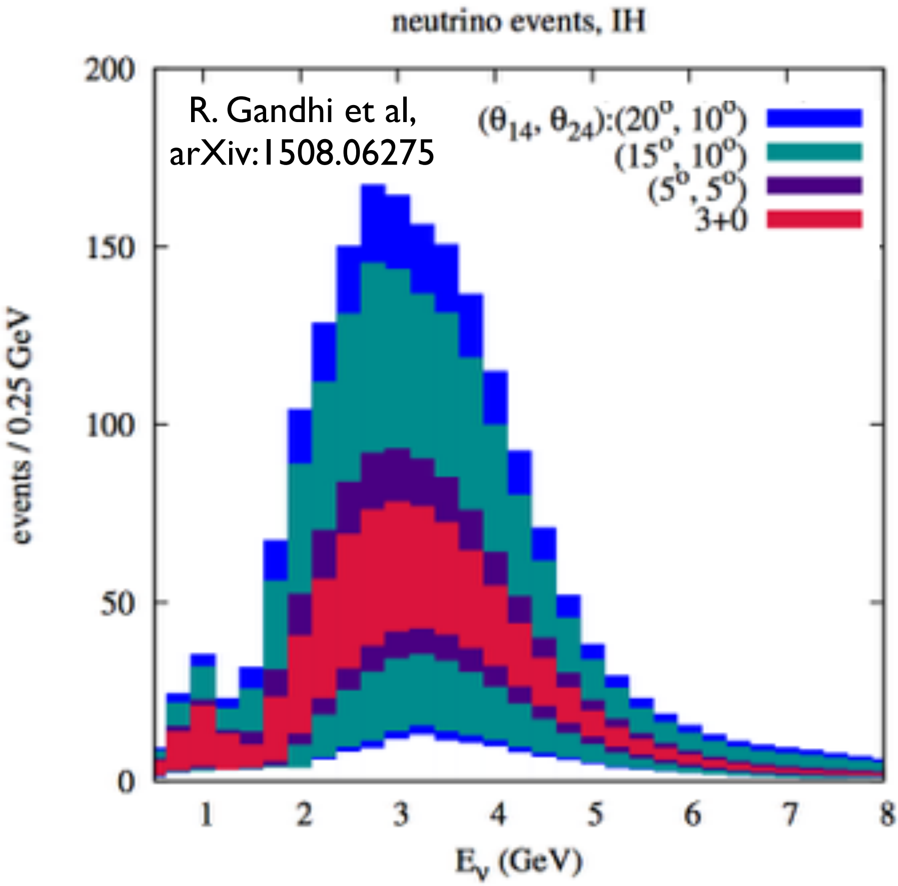
- A big question in this case: where is the excess?
  - If excess picks up at lowest energies, this could point an issue with π^0s:
    - Issues with neutrino NC π^0 mis-identification estimates?
    - Improper estimation of external single-gammas-from-π^0?
  - Excess at low-energy, but not TOO low: additional single-gamma processes…
  - Massive uptick at very low energies could come from cosmic mis-estimation.
- In all these scenarios, subsequent SBND measurement is <u>crucial</u>
  - If it's 'BITE'- or cosmic-related, SBND's signature will look totally different.
  - If it's a neutrino cross-section thing, SBND, ICARUS will provide very valuable high-statistics measurements for…



DUNE Impacts

- Crucial for DUNE that MicroBooNE (and the rest of SBN) tell us what is causing the excess.
- If electrons:
    - We must correct our predictions for the existence of a new short-baseline oscillation!
- If photons:
    - We must properly re-configure our background estimates; particularly valuable for properly understanding the 2nd oscillation maximum
- If both electron and photon excess, ditto, for same reasons as above.
- If no excess in MicroBooNE:
    - Still extremely important to address sterile phase space in full to properly interpret DUNE results — i.e. DUNE would still need SBN





Summary

- SBN neutrino program at Fermilab and reactor neutrino experiments (i.e. Daya Bay) will continue providing crucial input to precisely test the sterile neutrino hypothesis!

- Great research opportunities within the long baseline and short baseline neutrino experiments in the coming decade!

- DUNE physics program will be a game-changing in neutrino physics!

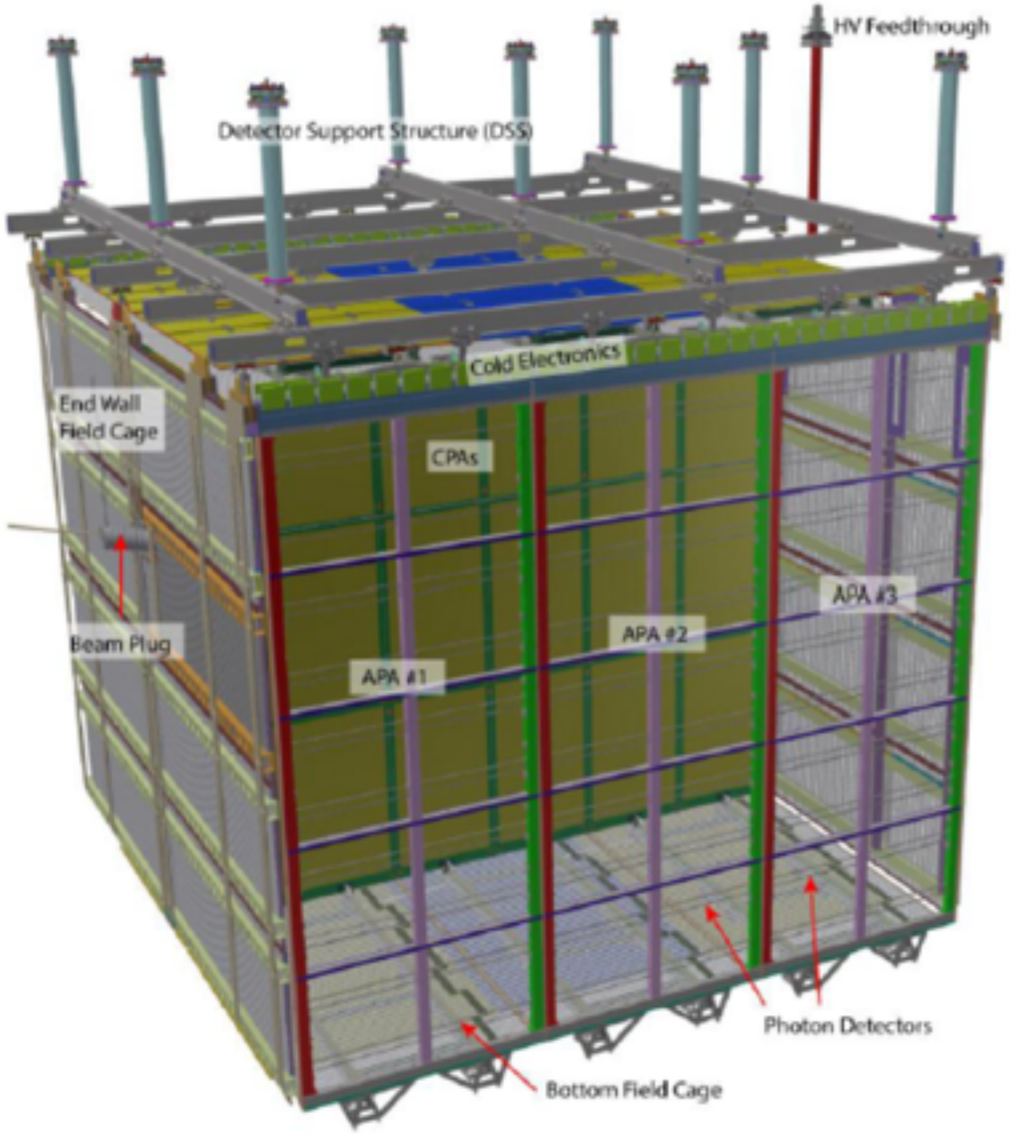
Thanks!
Gracias!

image A. Obando (http://arturobando.blogspot.com)

BACKUP

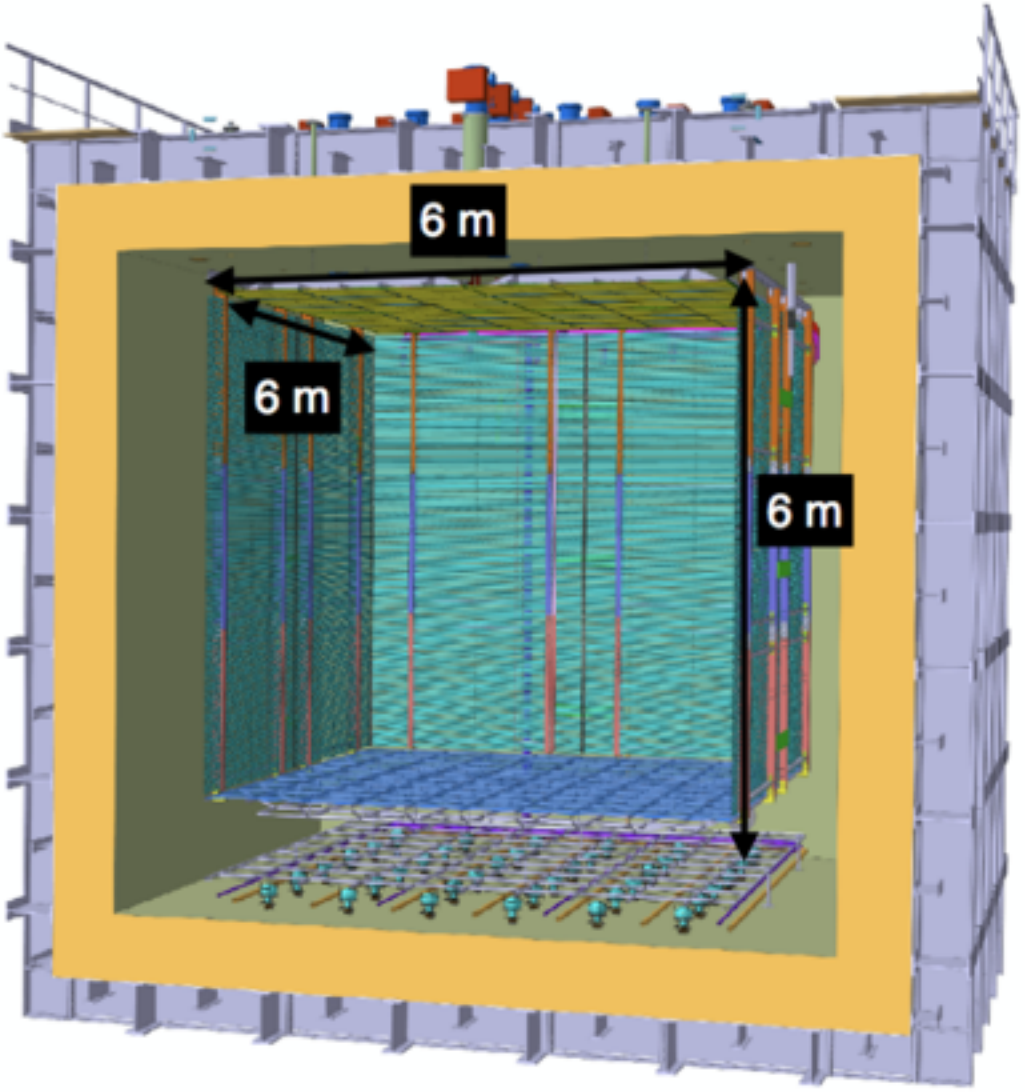
PROTODUNE

Single Phase:



Active volume 6.9 x 7.2 x 6 m^3

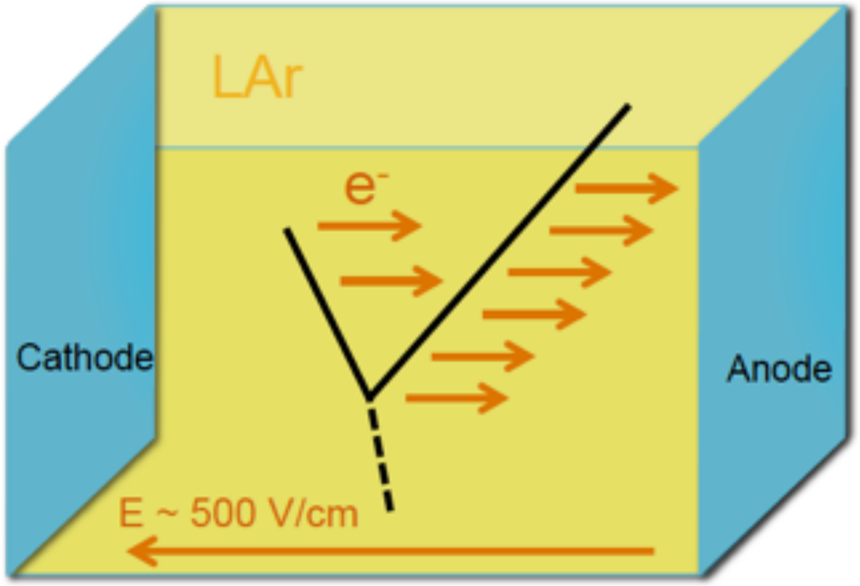
Dual Phase:



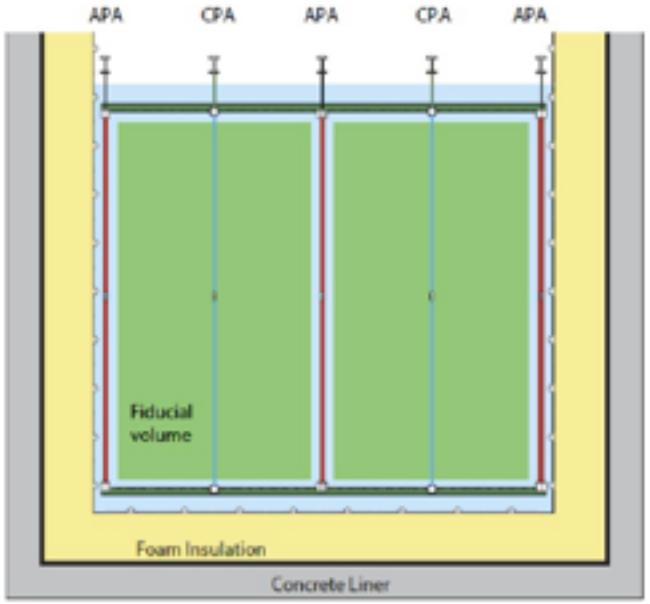
Active volume 6 x 6 x 6 m^3

Single Phase

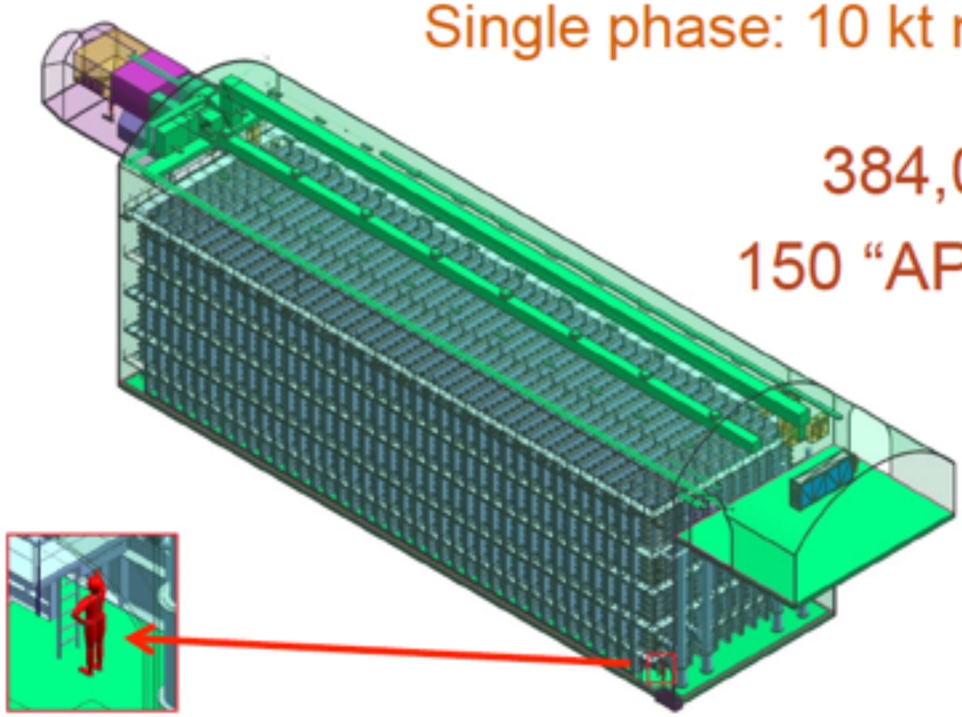
- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical



Single phase: modular wire-plane readout



Single phase: 10 kt module



384,000 readout wires

150 “APAs” (2.3 m x 6 m)

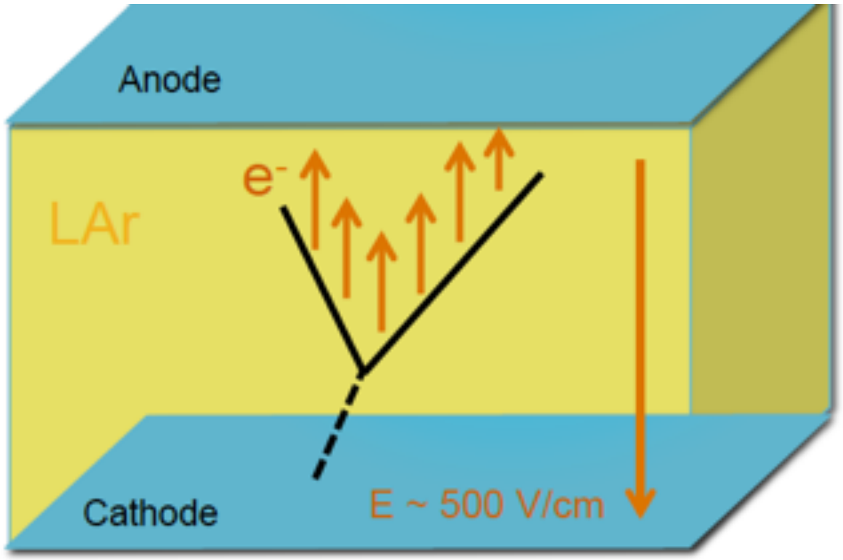
12 m high

15.5 m wide

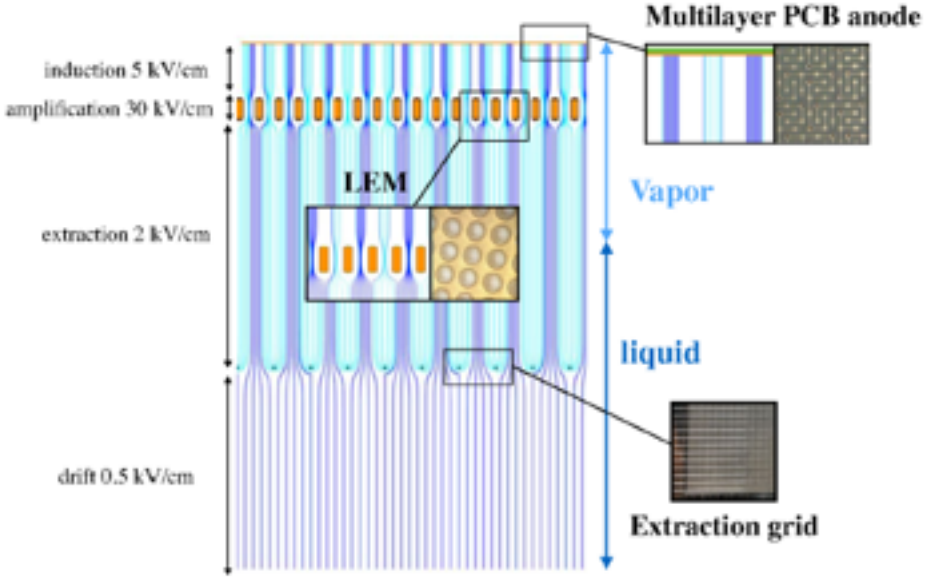
58 m long

Dual Phase

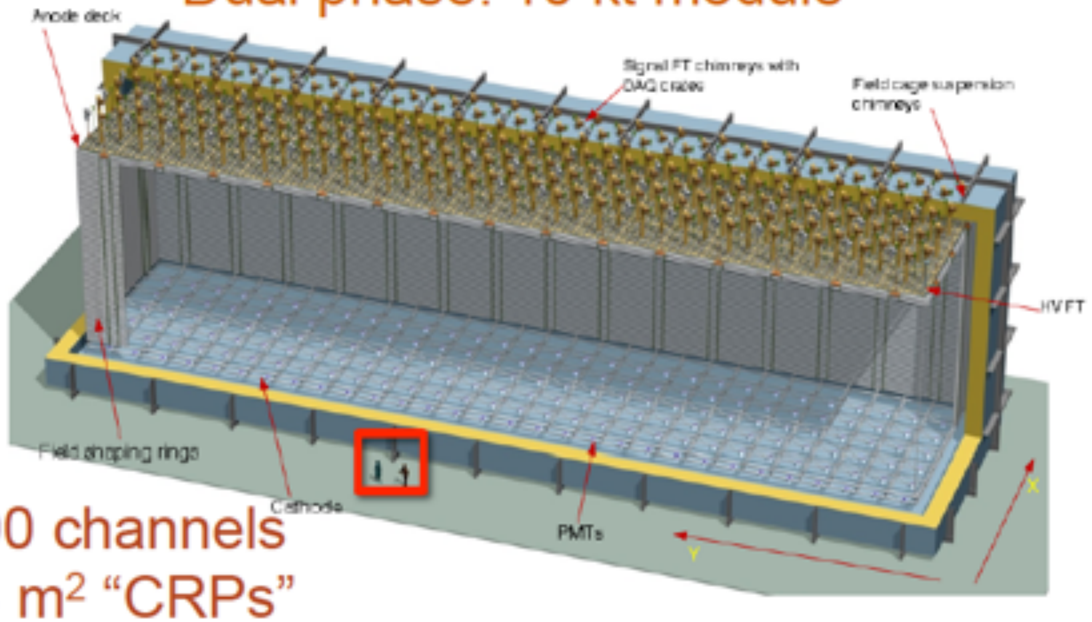
- 4 10-kt (fiducial) liquid argon TPC modules
- Single- and **dual**-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical



Dual phase: signal extracted; amplified in gas phase



Dual phase: 10 kt module



153,600 channels
80 3x3 m^2 “CRPs”
(Charge Readout Planes)

PROTODUNE

Dual phase cryostat

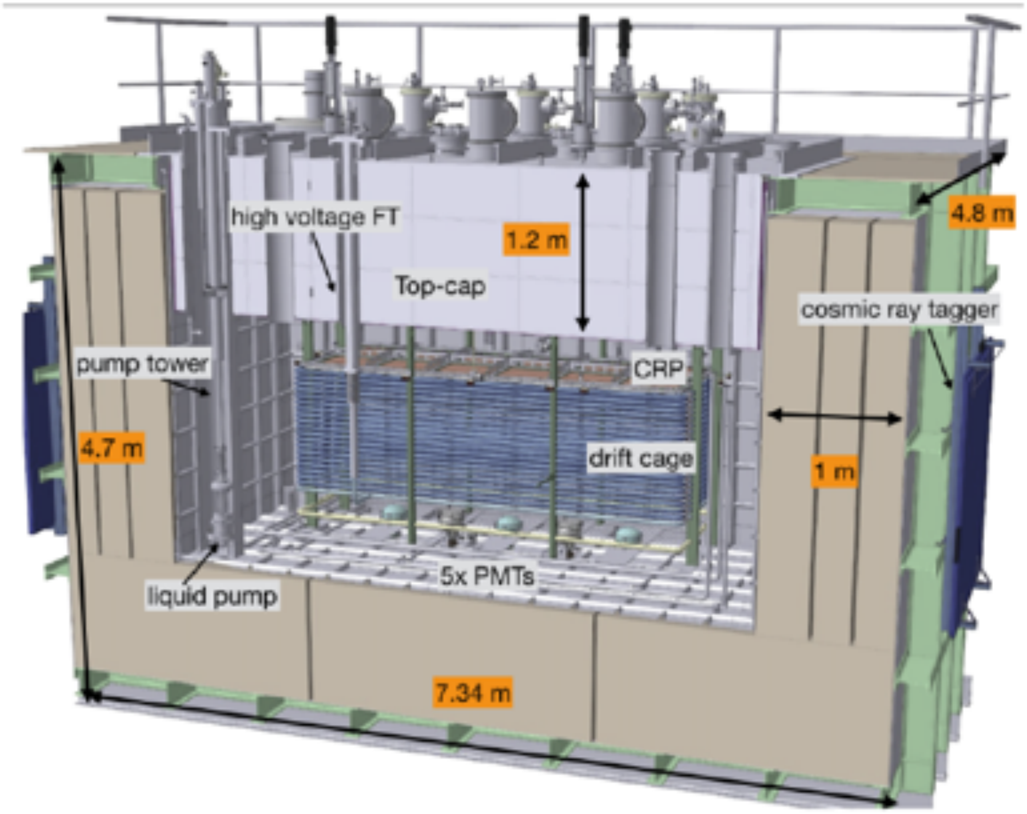
Single phase clean room and cold box

Single phase cryostat

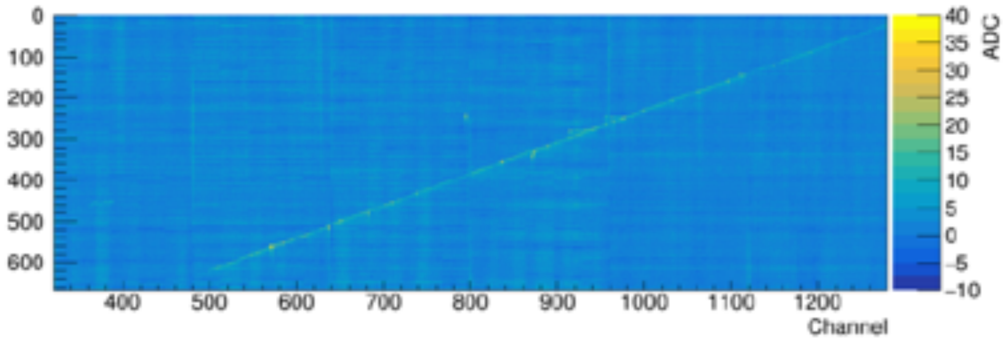
David Martinez - IIT

PROTODUNE

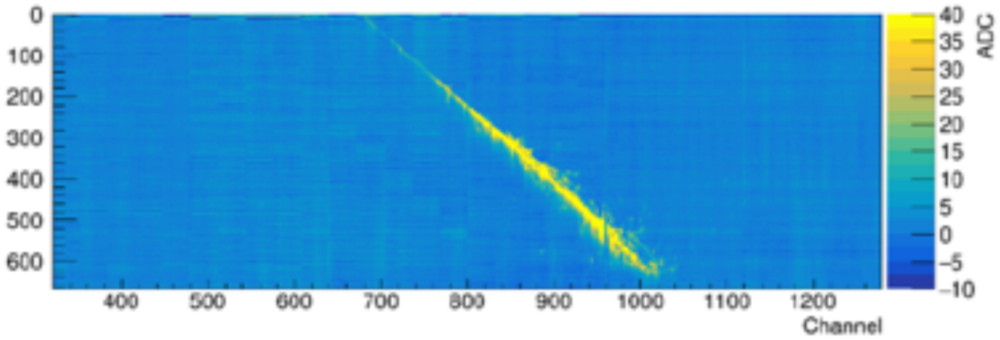
- Dual phase 3 X 3 X 1 m ^3 prototype ran from June to November 2017
- Succesful demonstration of dual phase LArTPC concept



Thru-going muon:



EM Shower:

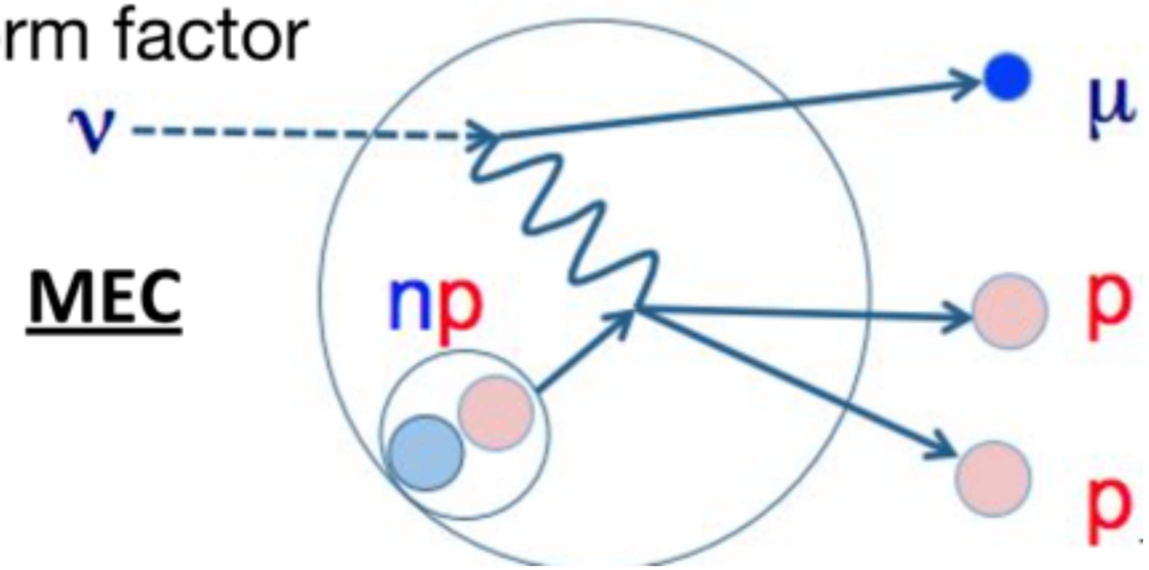


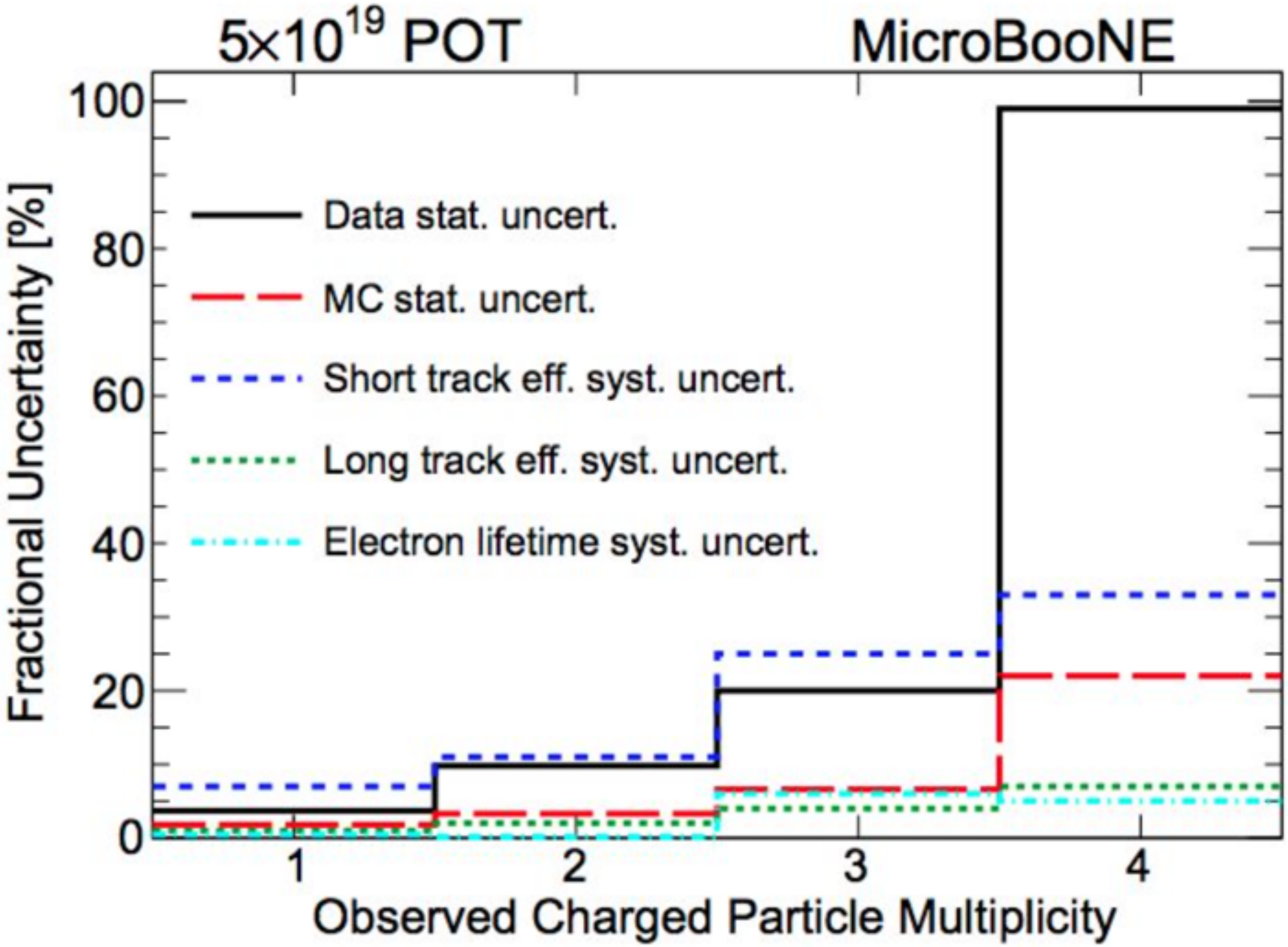
Models for these nuclear effects are largely based on electron scattering data

- Need to test if these hold up in neutrino scattering

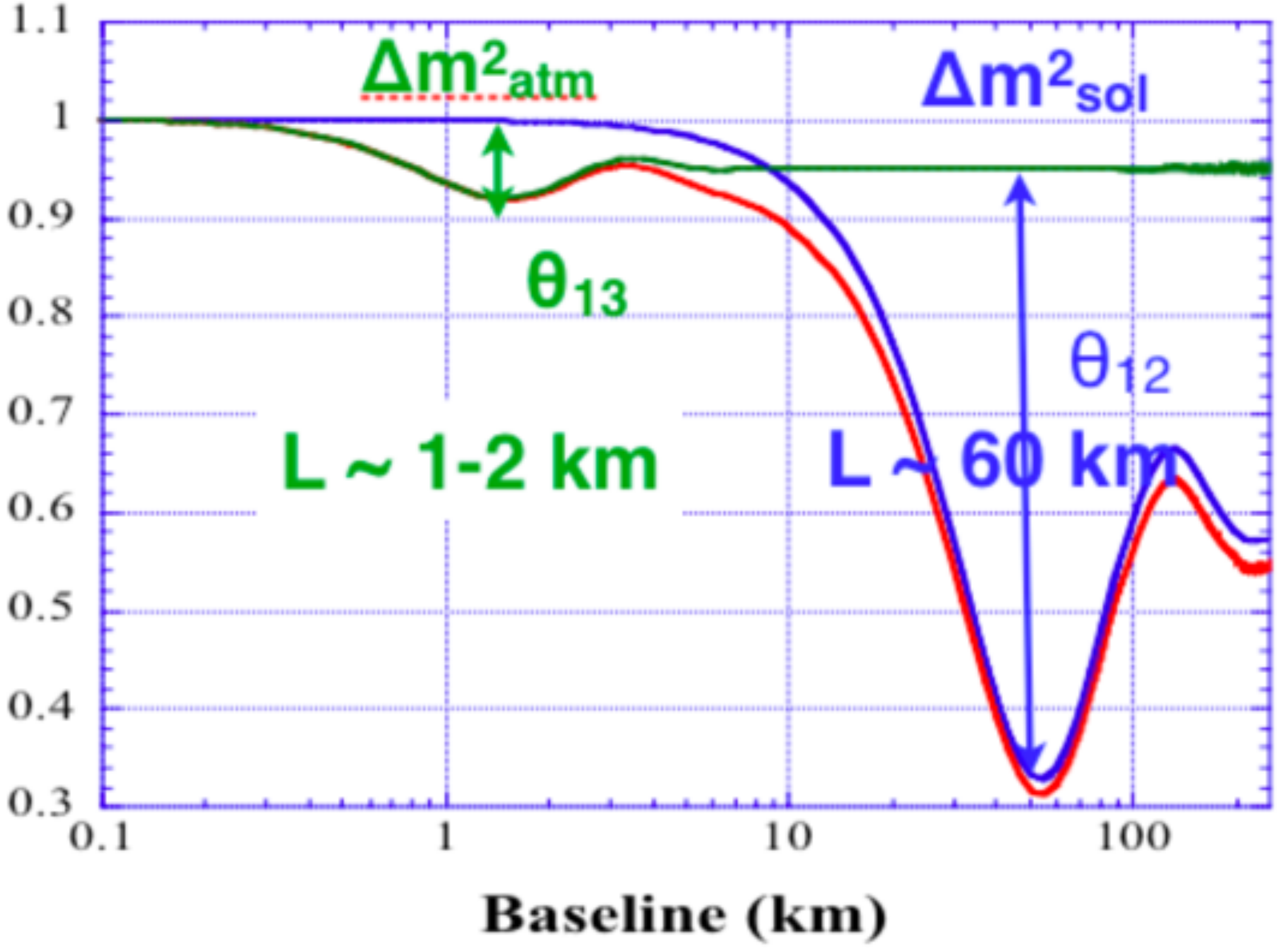
Two such models will be put to the test today using the MicroBooNE LArTPC

- Meson Exchange Current (MEC): Populates multi-nucleon final states
- Transverse Enhancement Model (TEM): Enhancement of the transverse quasi-elastic form factor




5×10^19 POT
MicroBooNE
Fractional Uncertainty [%]
100
80
60
40
20
0
Data stat. uncert.
MC stat. uncert.
Short track eff. syst. uncert.
Long track eff. syst. uncert.
Electron lifetime syst. uncert.
1
2
3
4
Observed Charged Particle Multiplicity

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$



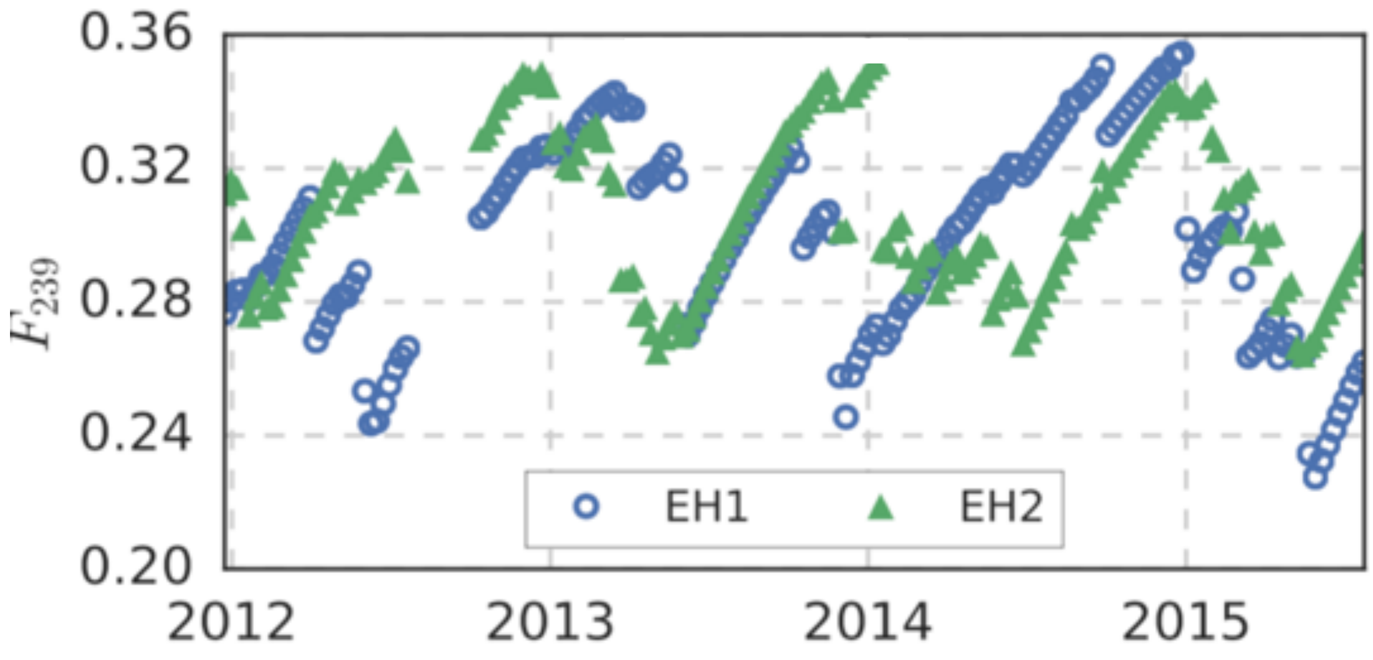
- "Long-baseline" reactor experiments (eg, KamLAND) are sensitive only to the solar mass splitting.
- "Short-baseline" reactor experiments (eg, Double Chooz, Daya Bay) are sensitive only to the atmospheric mass splitting and θ_{13}!

What about the systematics: Reactor

- Uncertainties from various inputs to our F_i definition are not too large

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

  - Reactor power:
    small (0.5%), ~ constant in time,
    reactor-uncorrelated
  - Energy per fission:
    very small, time-constant
  - oscillations, baselines:
    very small, time-constant ;)



- Example L/E, reactor experiments: $\overline{\nu}_e$ disappearance
  - Daya Bay: ~500 m/MeV (measure Δm^2_{31} mixing)
  - KamLAND: ~50,000 m/MeV (measure Δm^2_{21} mixing)
- Accelerators at 500 m/MeV: $\nu_\mu \rightarrow \nu_e$

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)