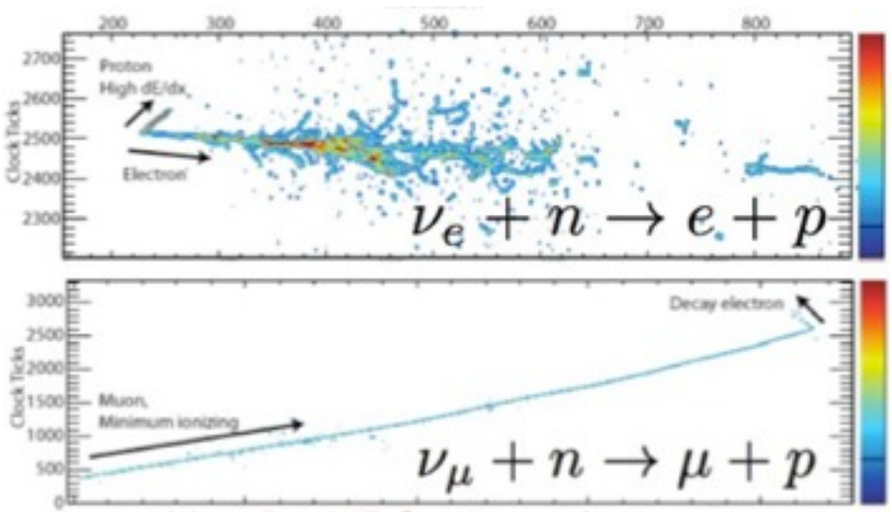
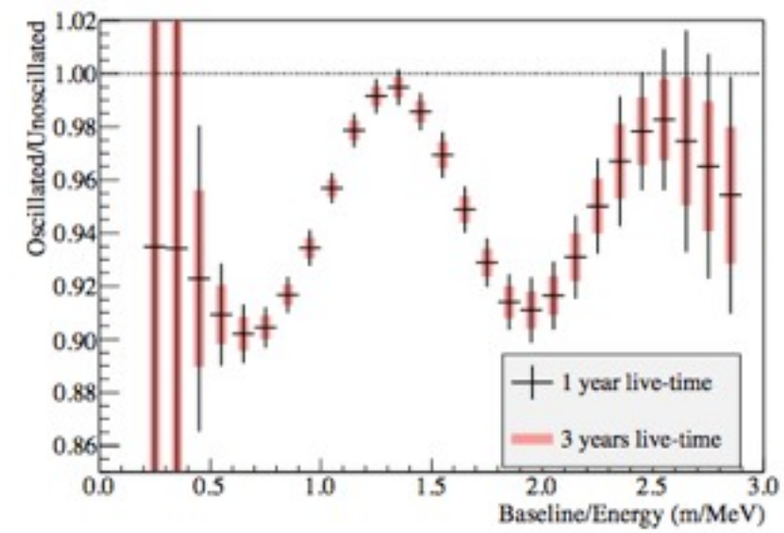
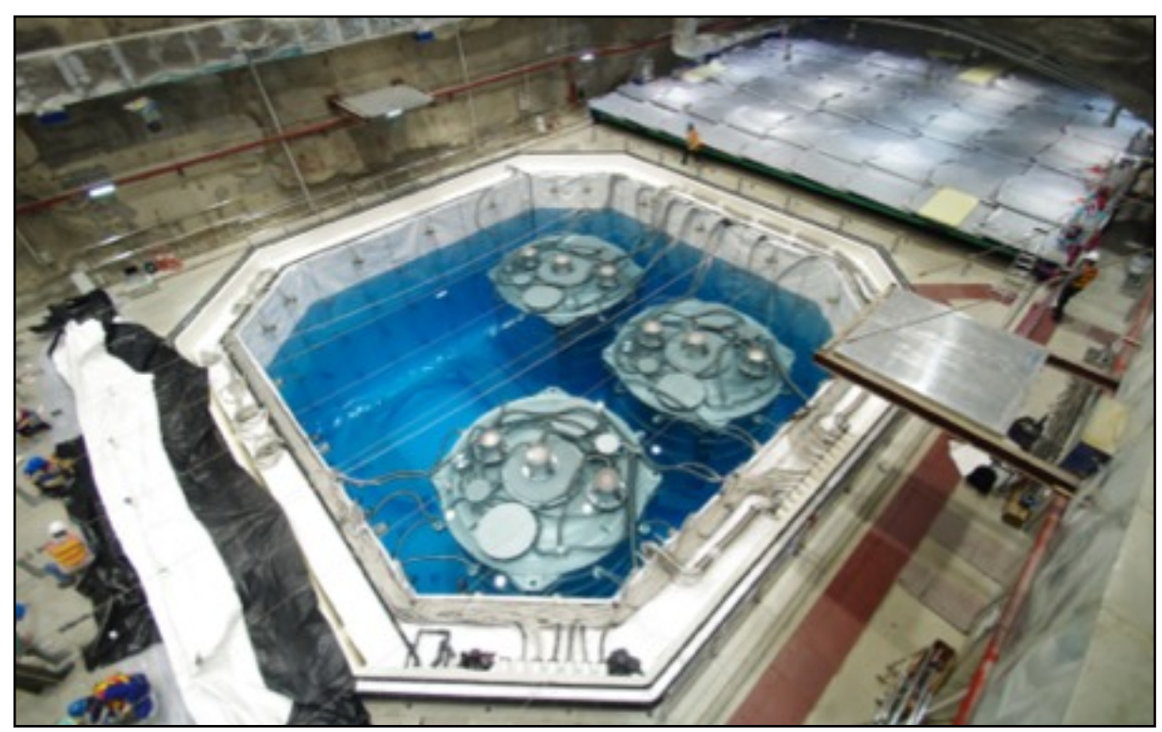
Probing Mysteries in Particle Physics With Neutrino Oscillations



Bryce Littlejohn
University of Cincinnati

February 20, 2014



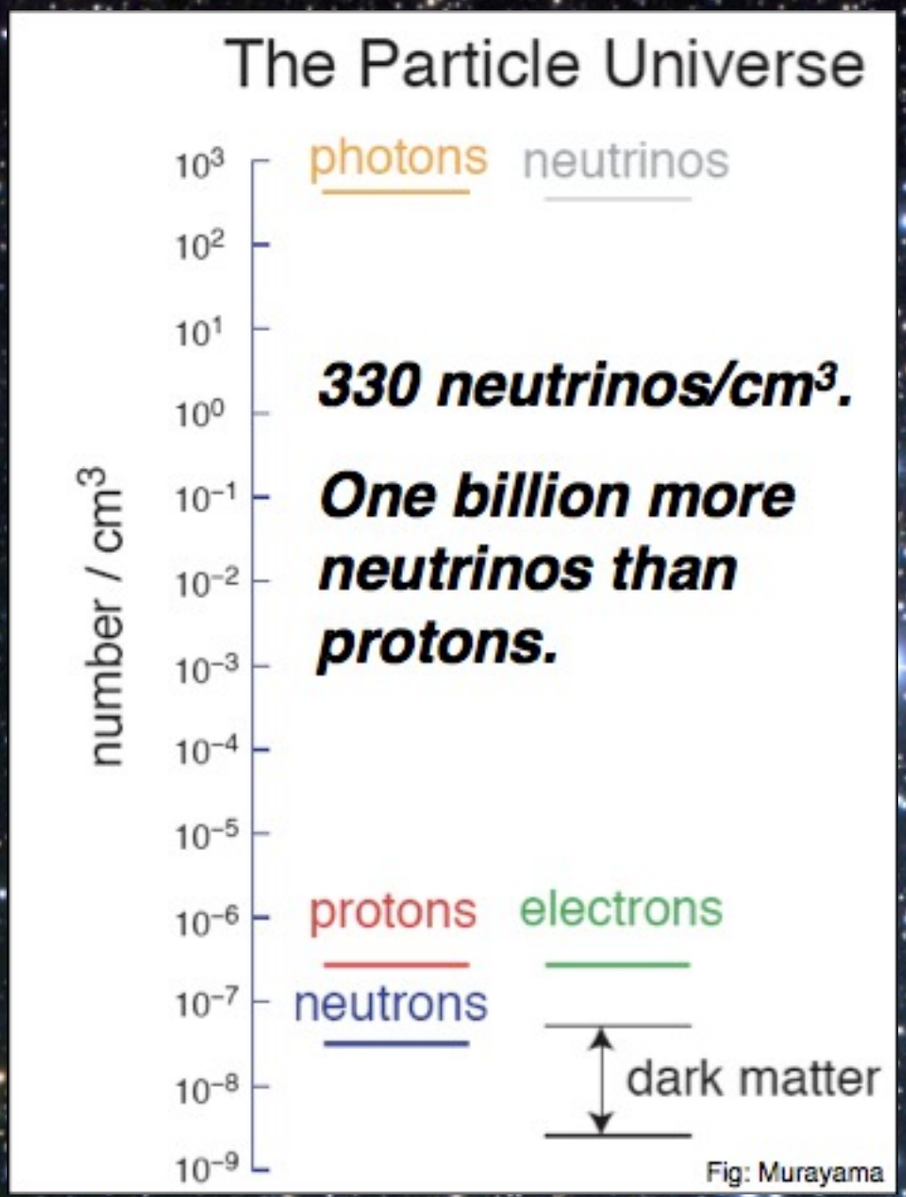


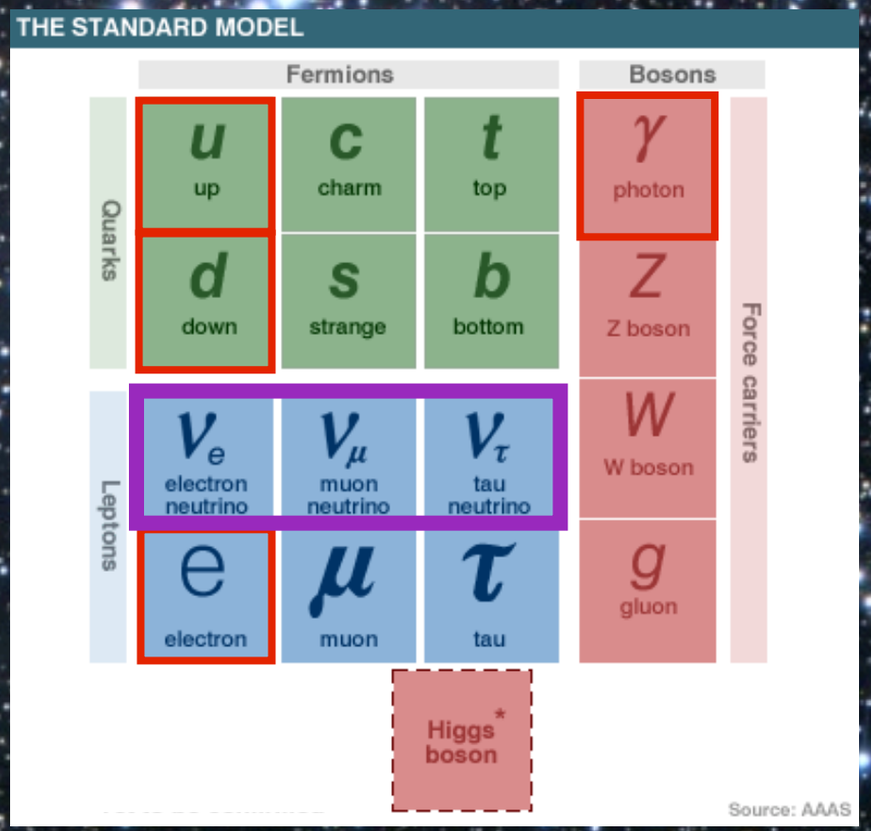
Outline

- Introduction to neutrinos
- Some solved and unsolved mysteries of particle physics
- Investigating current mysteries using neutrino oscillations
  - Daya Bay experiment
  - MicroBooNE experiment
  - PROSPECT experiment

Neutrinos

The Universe's most common particle, after photons!





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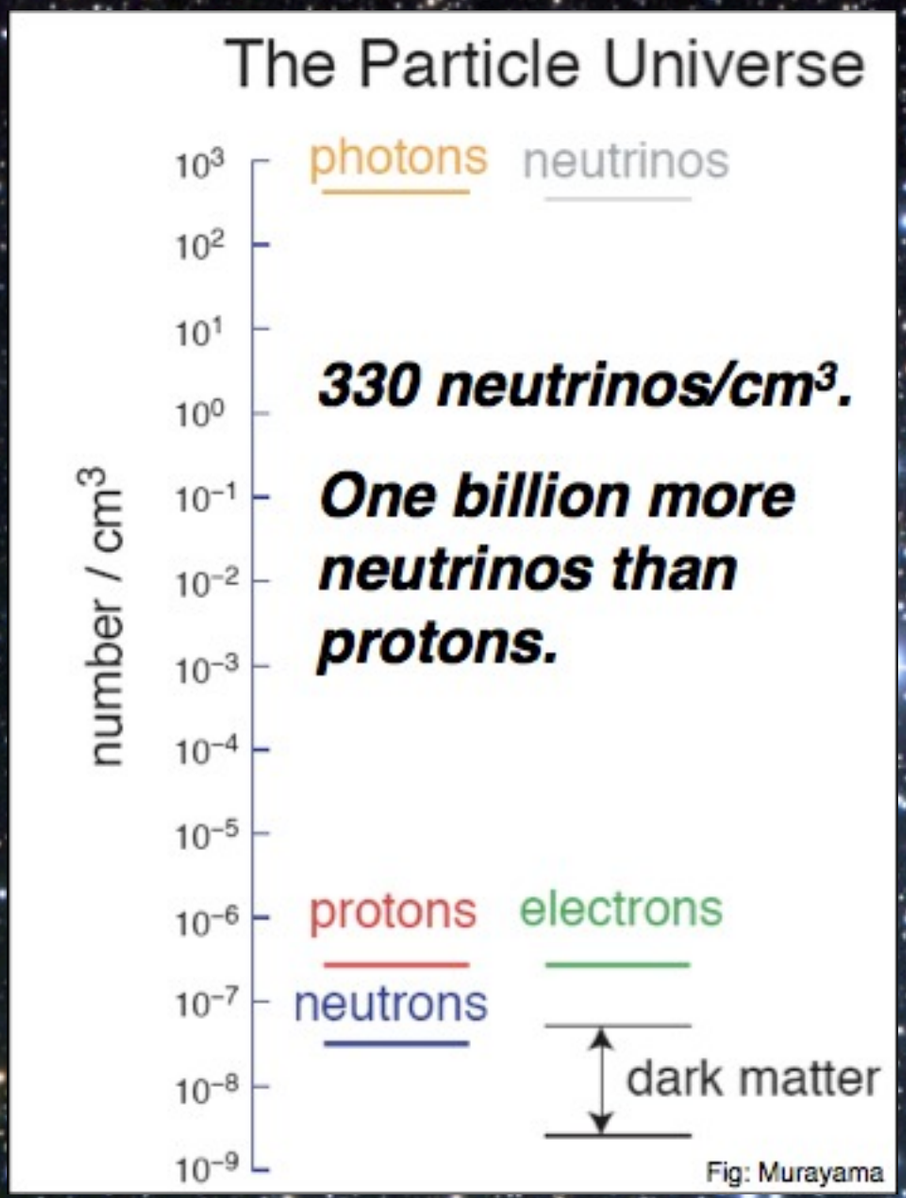
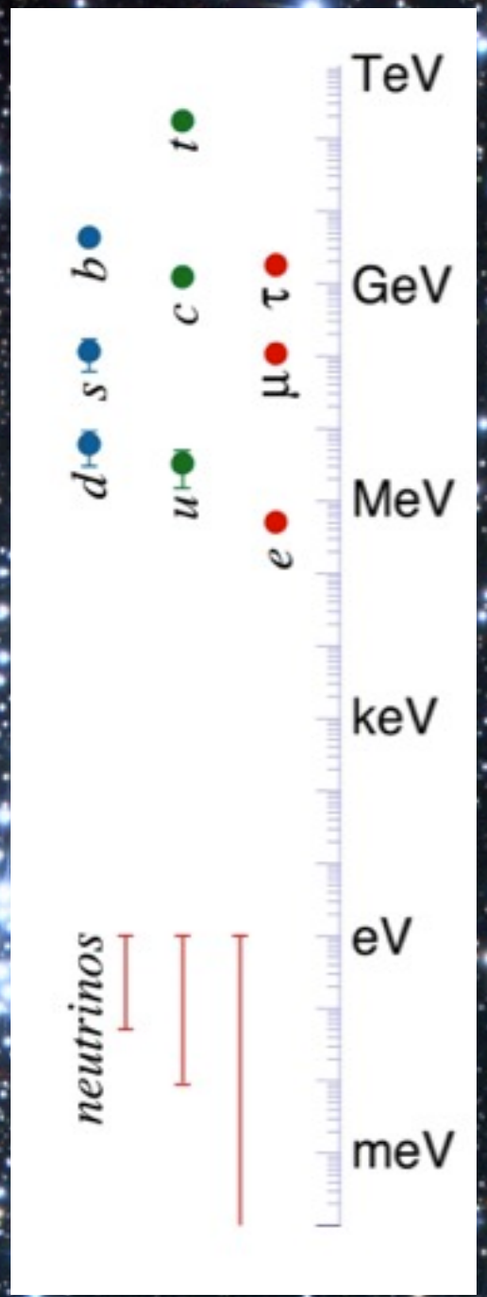
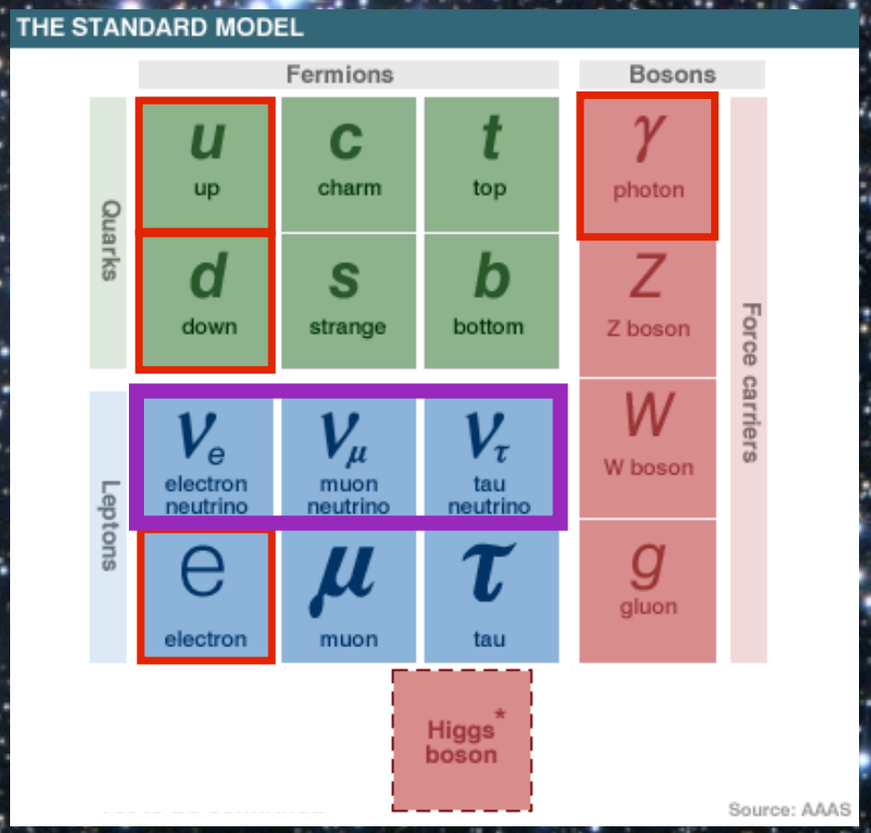






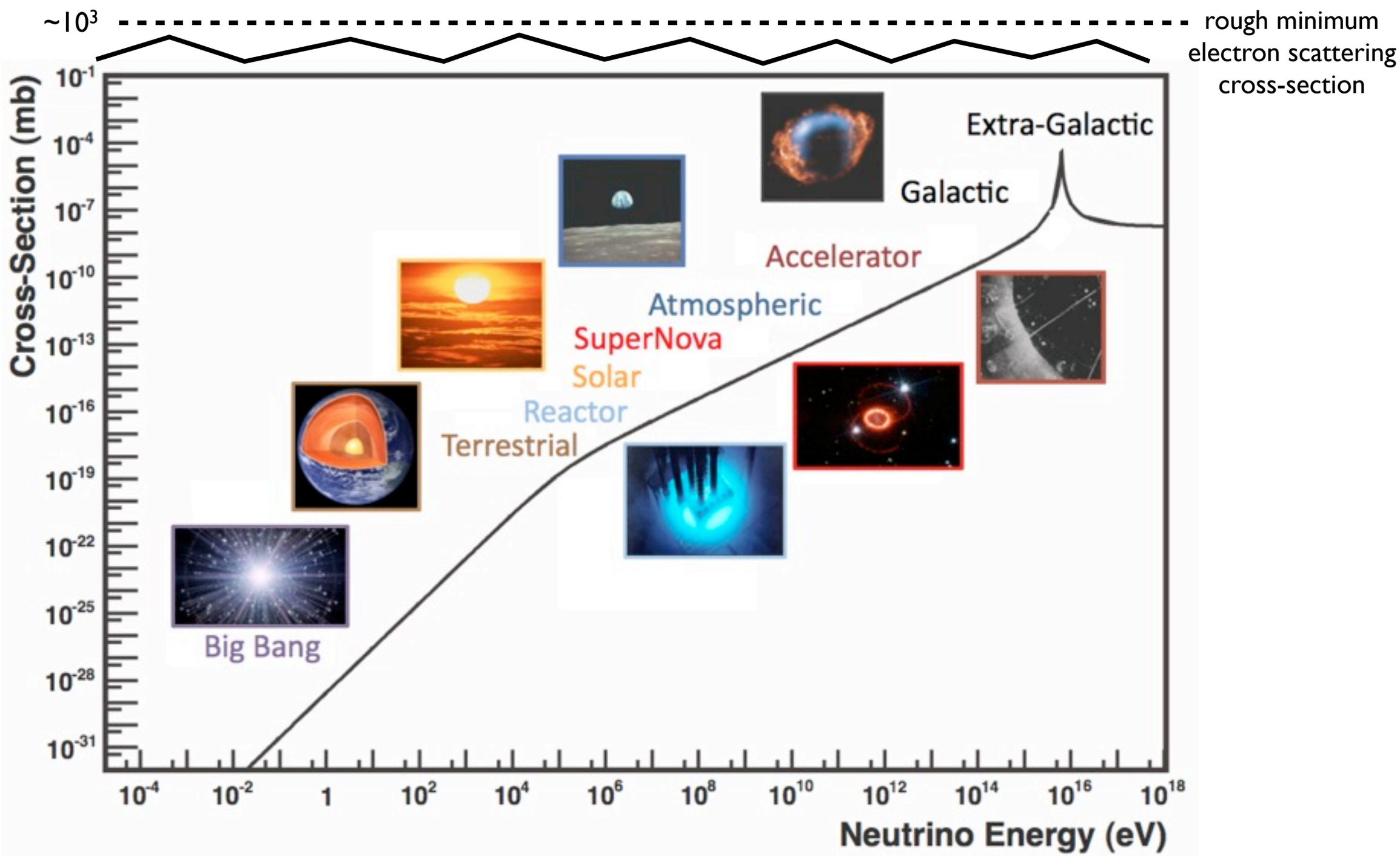
Far less massive than all other fermions

Also, no electric charge

Note: 1 eV ~1.6×10^{-19} J ~ 2×10^{-36} kg ($E=mc^2$)

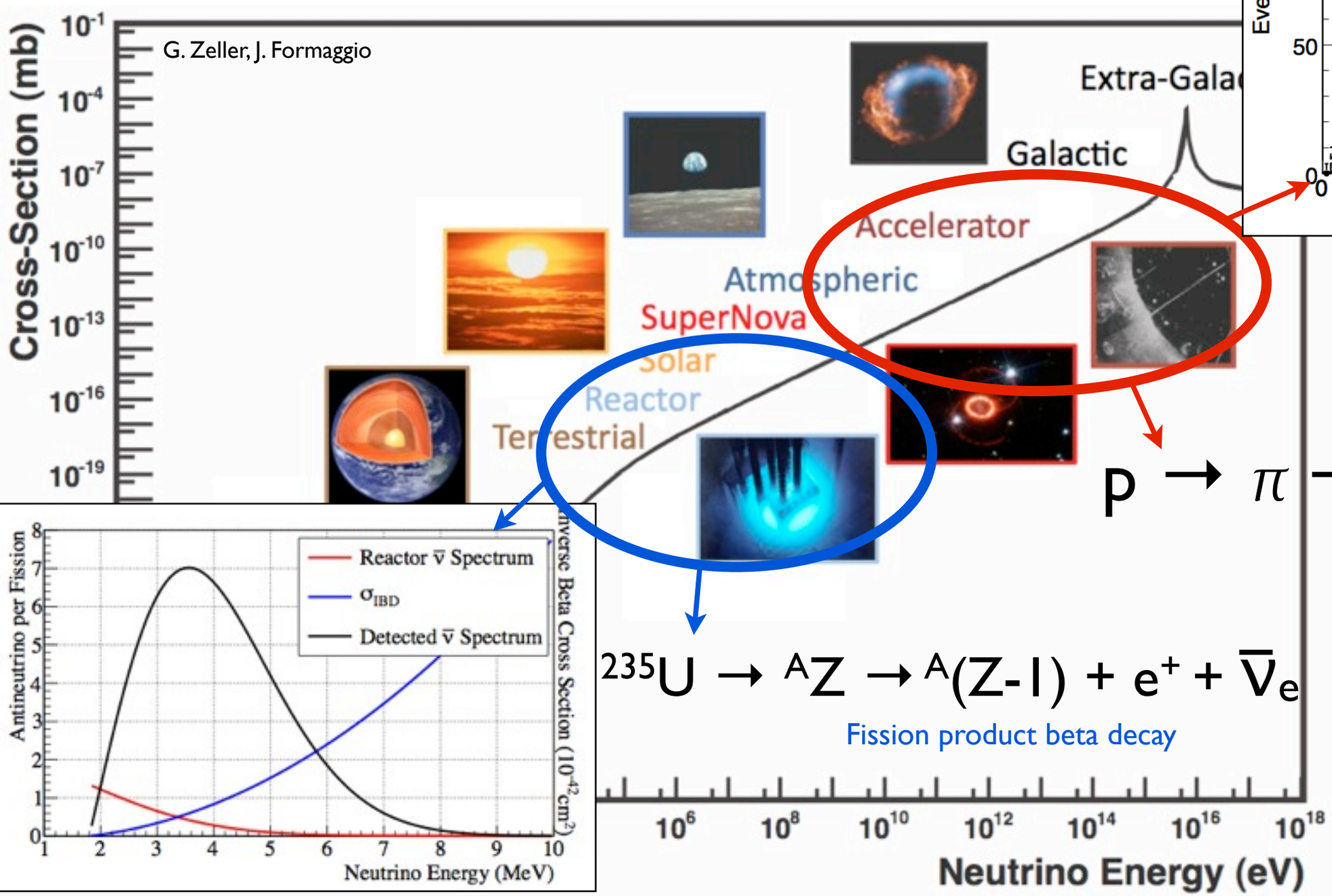
Neutrino Varietals

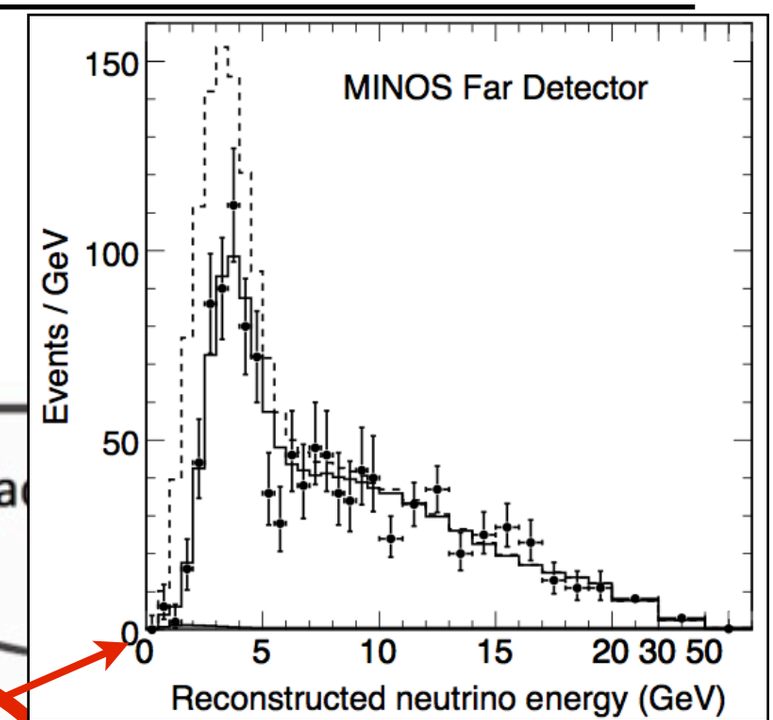
- Many neutrino sources and energies, interacting via weak force



Neutrino Varietals

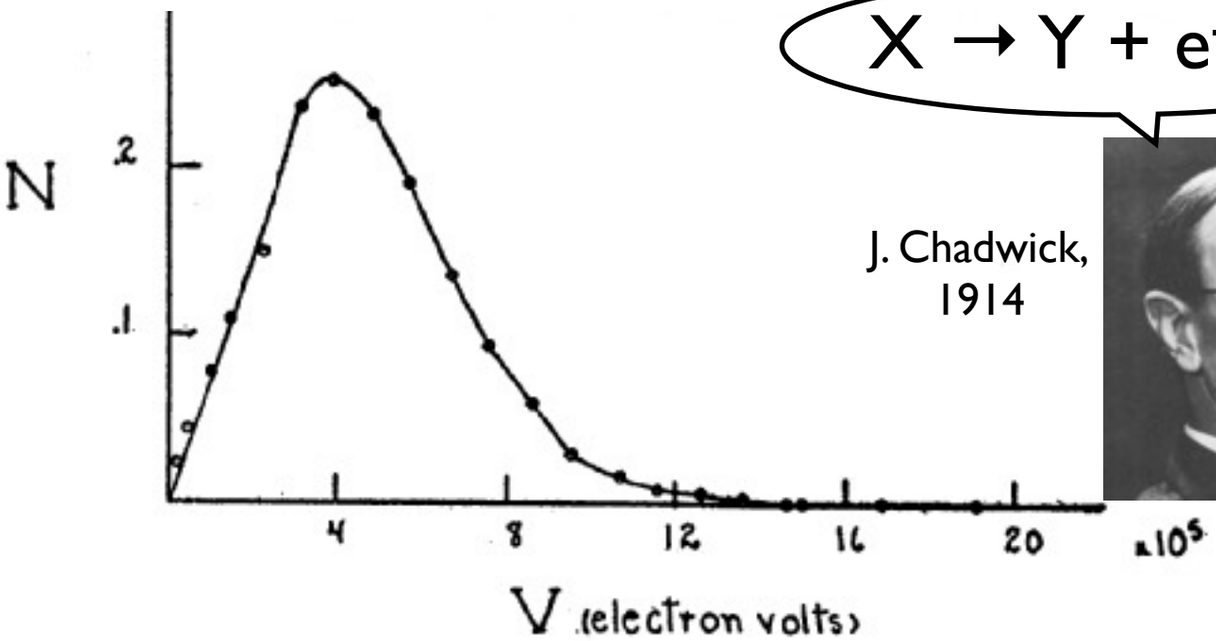
- Two particularly interesting sources:
  - Accelerators: ~0.1-10 GeV
  - Reactors: ~1-10 MeV



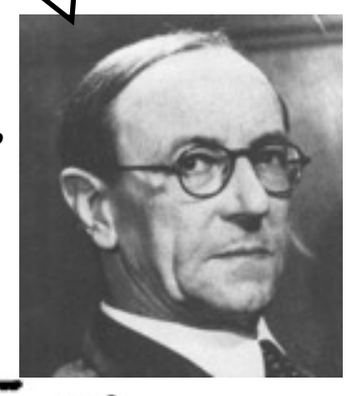


Neutrinos: A Desperate (But Correct) Remedy

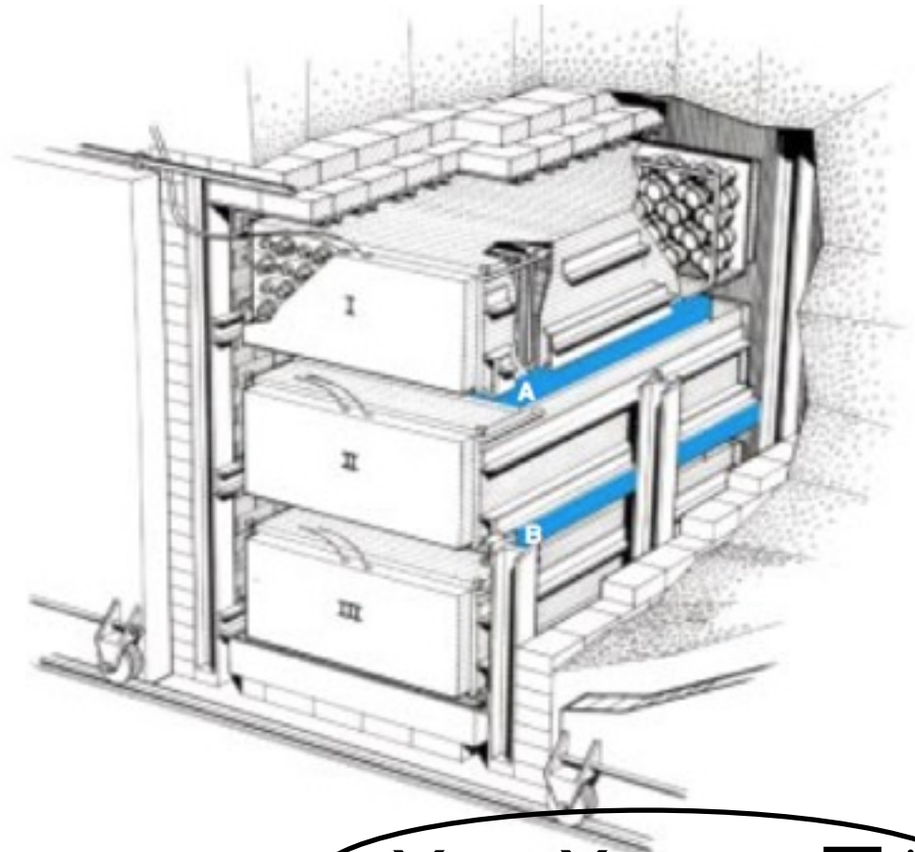
- An energy conservation mystery solved... with neutrinos



$X \rightarrow Y + e^-$...???



J. Chadwick, 1914



$X \rightarrow Y + e^- + \nu$...???

W. Pauli, 1930

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

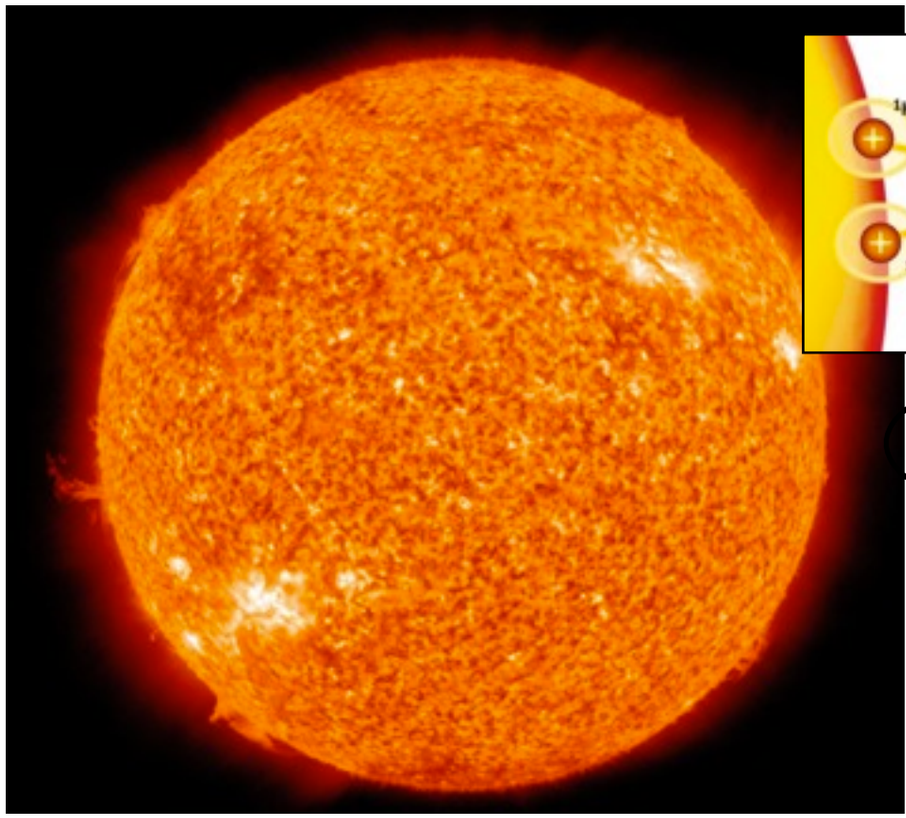
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und

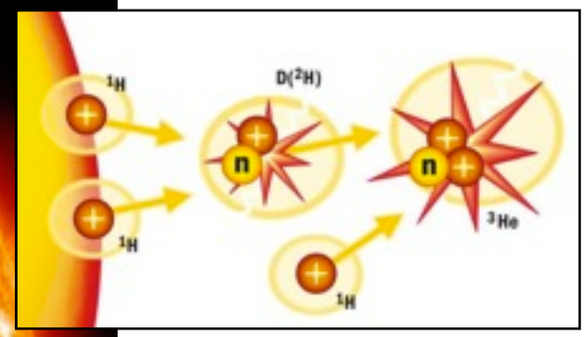
$X \rightarrow Y + e^- + \bar{\nu}_e$!

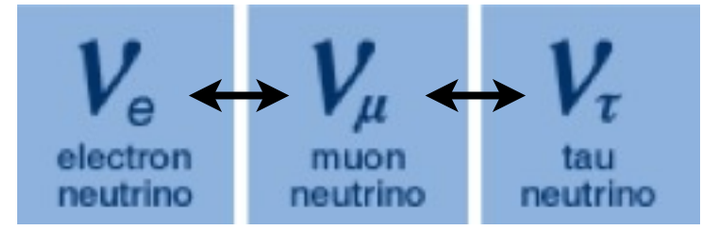
F. Reines, 1956

Neutrinos: A Desperate (But Correct) Remedy

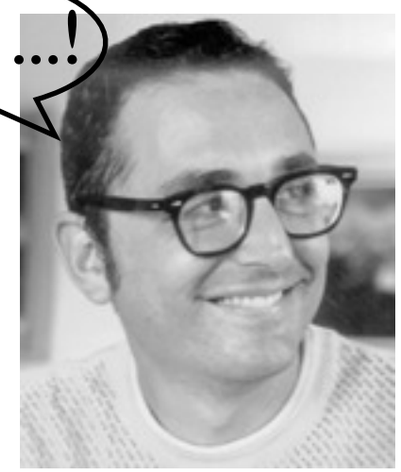
- A solar model mystery solved... with neutrino **oscillations**





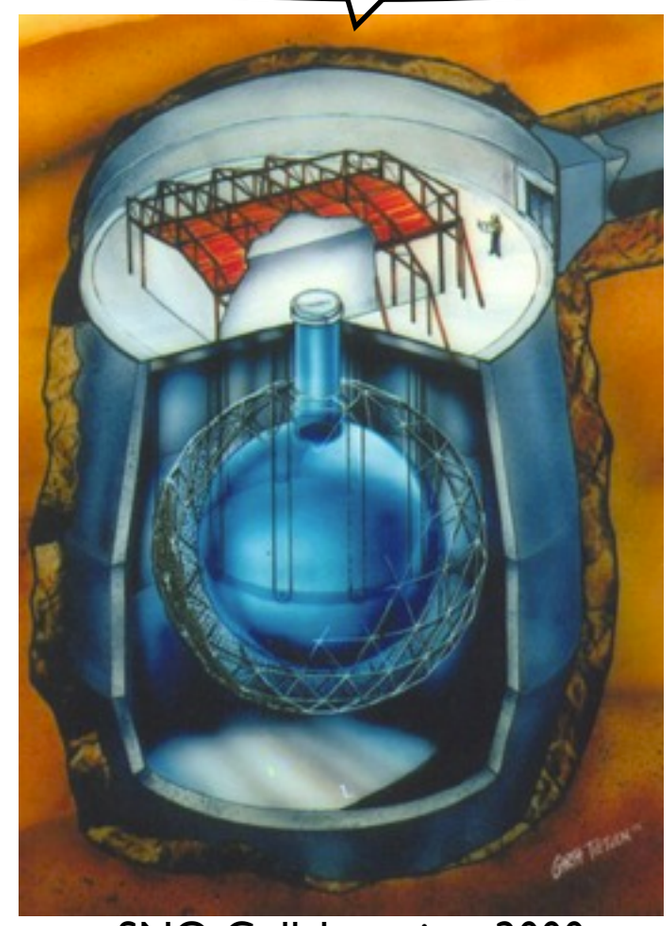


ν_{pred} ...!

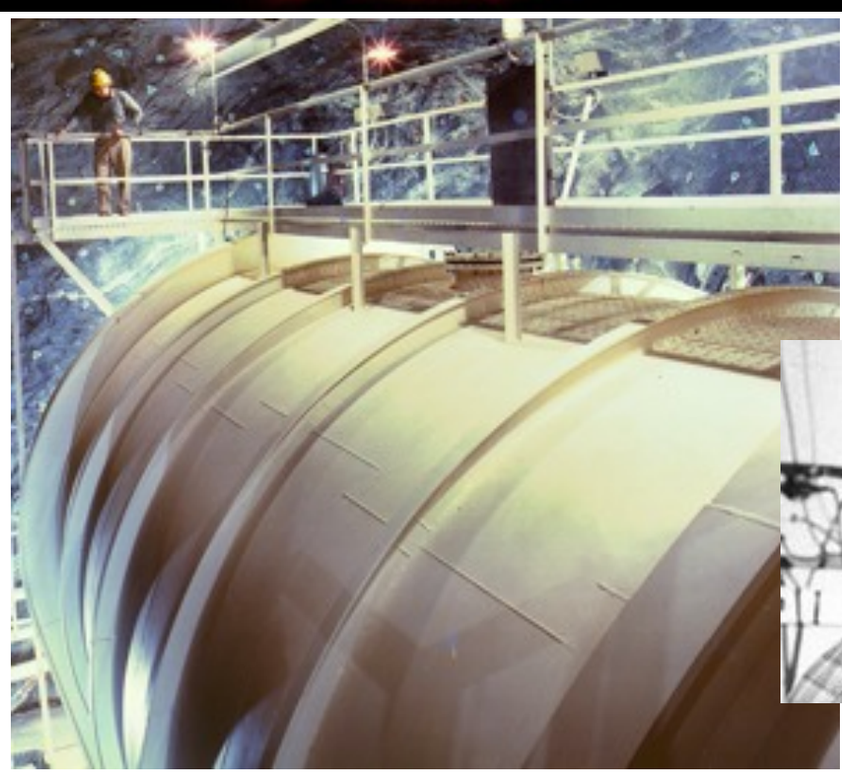


J. Bahcall, 1960s

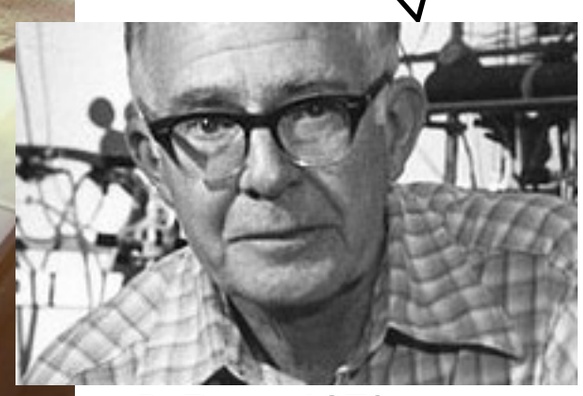
$\nu_e + \nu_\mu + \nu_{tau} = \nu_{pred}$!



SNO Collaboration, 2000



$\nu_e \ll \nu_{pred}$!?



R. Davis, 1970s

Trevor Pinch, *Confronting Nature: The Sociology of Solar Neutrino Detection (1986)*

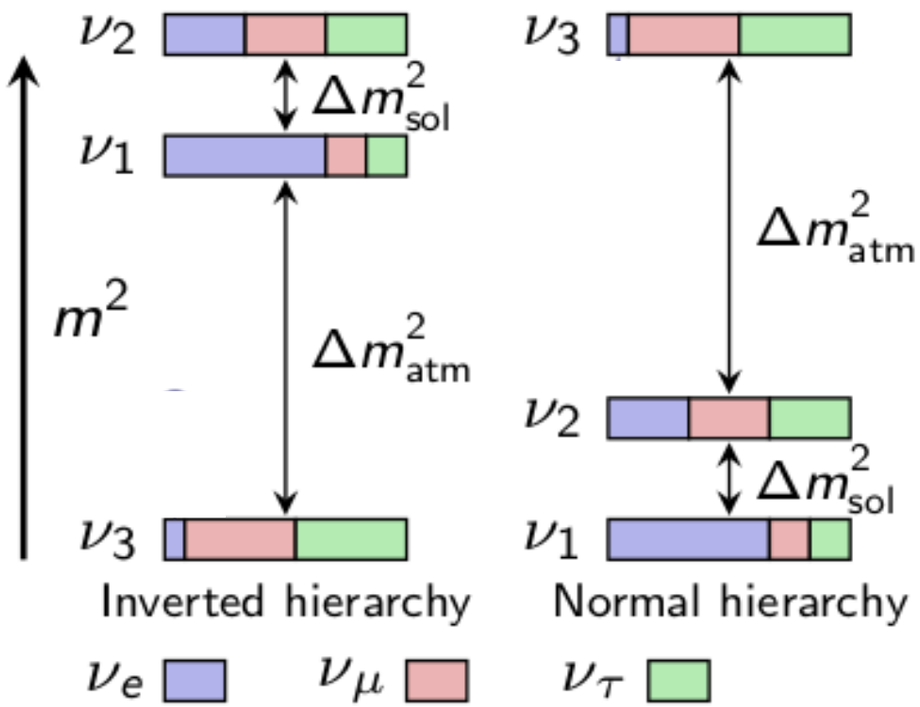
Neutrino Oscillations

Weak and mass eigenstates need not correspond:

1. How they interact
2. How they propagate

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} \, |\nu_i\rangle$$

Neutrino Oscillations



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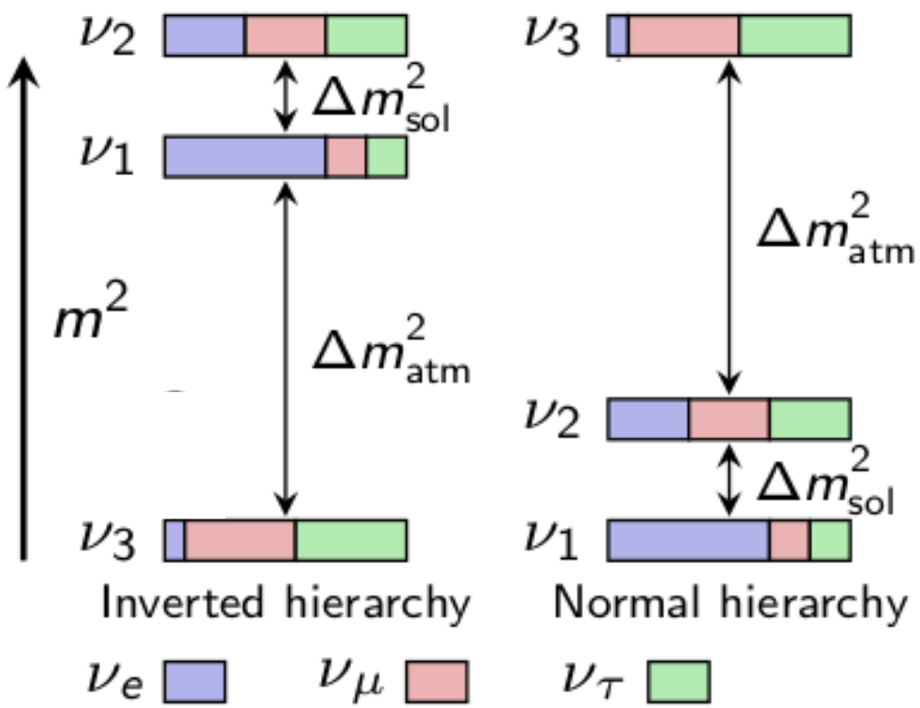
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} \, |\nu_i\rangle$$

$|\Delta m^2_{atm}| = \sim 0.0025 \text{ eV}^2$

$\Delta m^2_{sol} = \sim 0.00008 \text{ eV}^2$

Neutrino Oscillations



Weak and mass eigenstates need not correspond:

1. How they interact
2. How they propagate

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i}\,|\nu_i\rangle$$

Neutrino flavor changing determined by mixing angles θ and mass splittings Δm^2

$|\Delta m^2_{atm}| = \sim 0.0025\ eV^2$
$\Delta m^2_{sol} = \sim 0.00008\ eV^2$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric/Accelerators: $\theta_{23}\sim 45°$

Solar/KamLAND: $\theta_{12}\sim 23°$

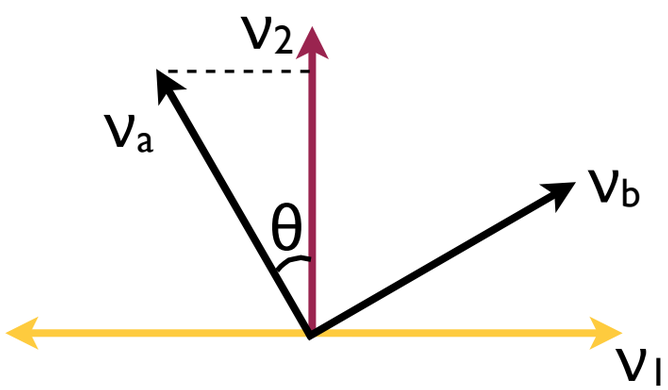
θ_{13} recently well-established!

Extra CP-violating phase

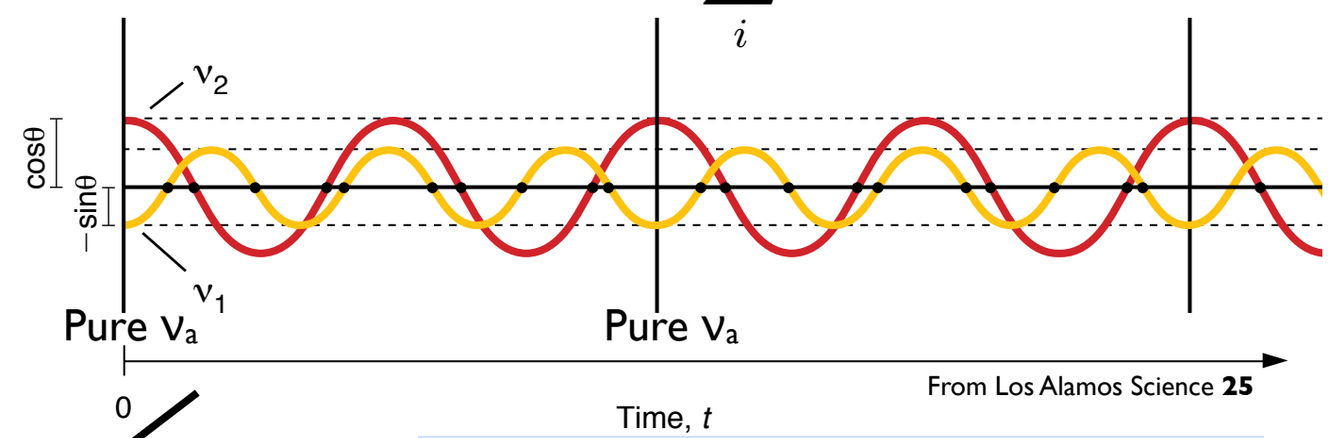
Neutrino Oscillations

- Two neutrino case:

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



$$\Psi_{\nu_a}(x,t) = f(x,t)\sum_i U_{ai}e^{-i(m_i t/2E)}$$



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

- Important quantities:
  - θ: Oscillation amplitude
  - Δm^2: Oscillation frequency
  - L/E: Experimental parameter

- Example L/E, reactor experiments: $\bar{\nu}_e$ 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: $\nu_\mu \to \nu_e$
- Can we use neutrino oscillations to solve <u>today's</u> big mysteries?

A Desperate Remedy... To Current Ills?

A Desperate Remedy... To Current Ills?

What about leptonic CP-violation?

It allows leptons and antileptons to transition differently!

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}$$

Could this asymmetry allow preferential transition of antimatter to unobservable types?

Can try to measure difference in oscillation effect between accelerator $\bar{\nu}$ and ν:

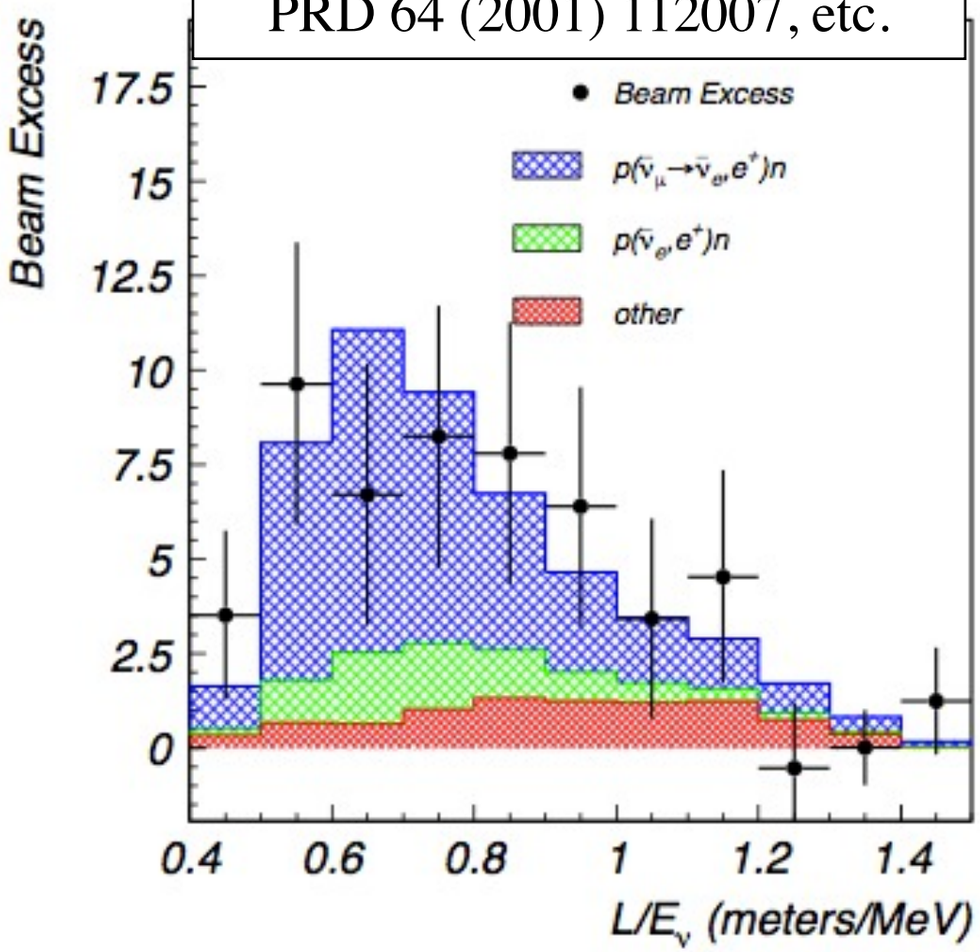
$$\begin{aligned} P(\bar{\nu}_\mu \to \bar{\nu}_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\ &+ 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31} [\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta] \sin\Delta_{21} + \ldots \end{aligned}$$

Very important to know the size of θ_{13} first...

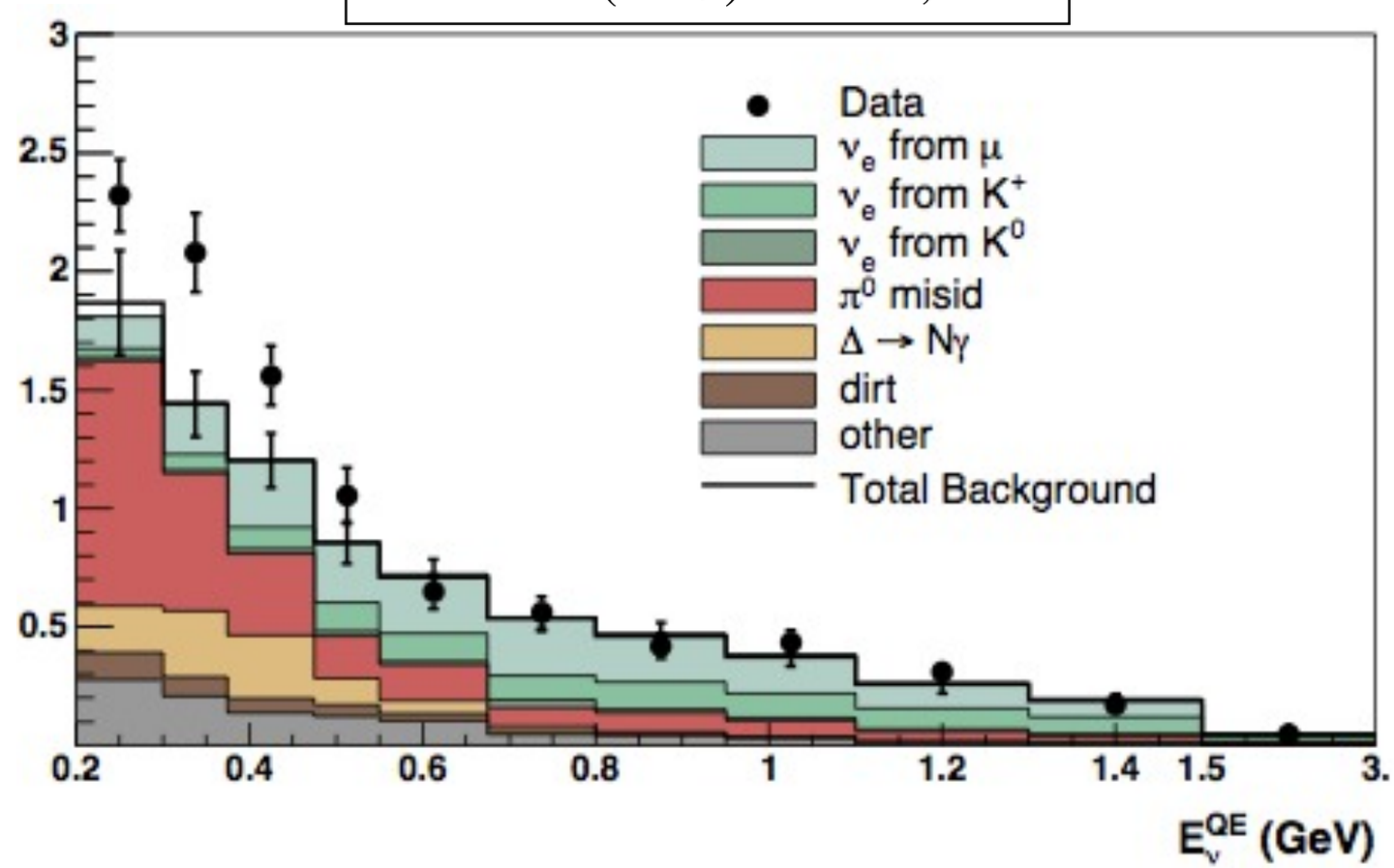
A Desperate Remedy... To Current Ills?

- Hints of beyond-the-Standard-Model neutrinos?
  - Hints at accelerators of ν_e-like events appearing at L/E ~ 1m/MeV (~1eV^2)
  - Doesn't line up with any existing mass splitting....
  - Fourth sterile neutrino could allow new mass splitting and match collider data

LSND anomaly
PRD 64 (2001) 112007, etc.

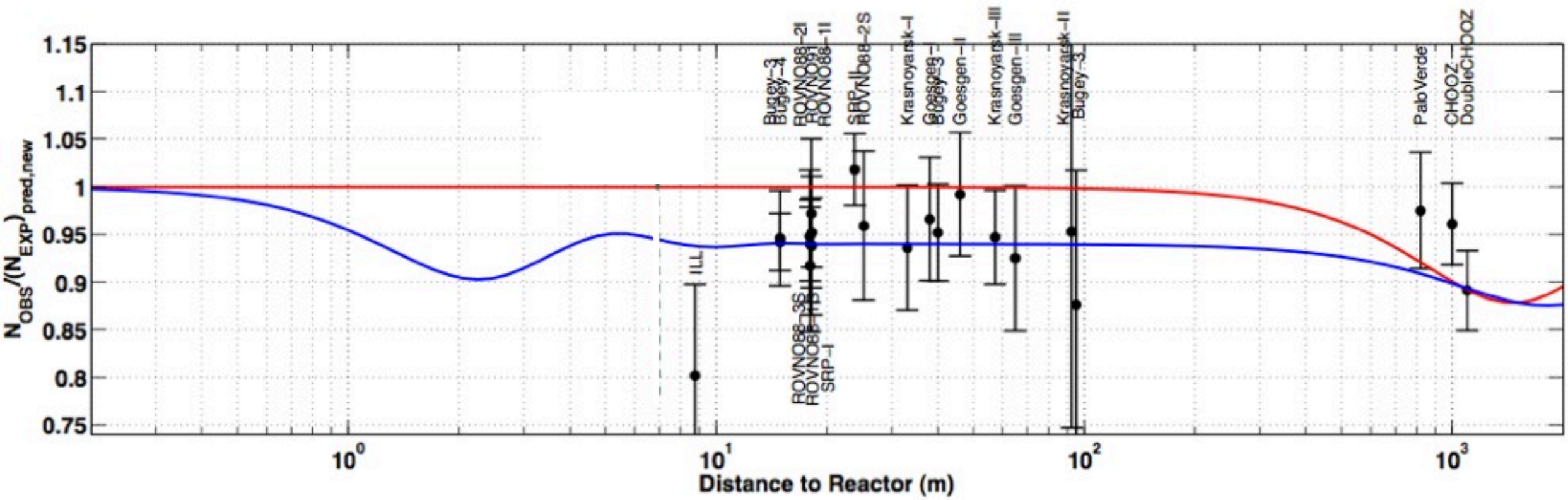


MiniBooNE anomaly
PRL 102 (2009) 101802, etc.



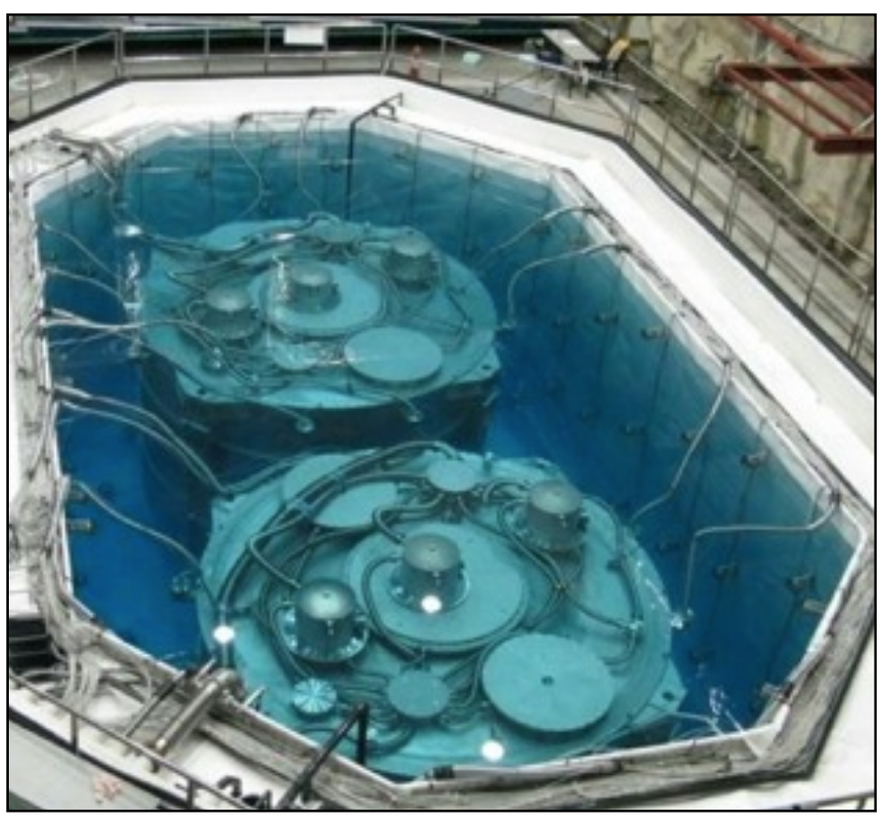
A Desperate Remedy... To Current Ills?

- Hints of beyond-the-Standard-Model neutrinos?
  - Deficit of neutrinos at short distances from nuclear reactors
  - Could result from a high-frequency (~1 m/MeV) oscillation
  - Same mass splitting as accelerator anomaly
- New oscillation experiments could provide compelling experimental proof of physics beyond the standard model



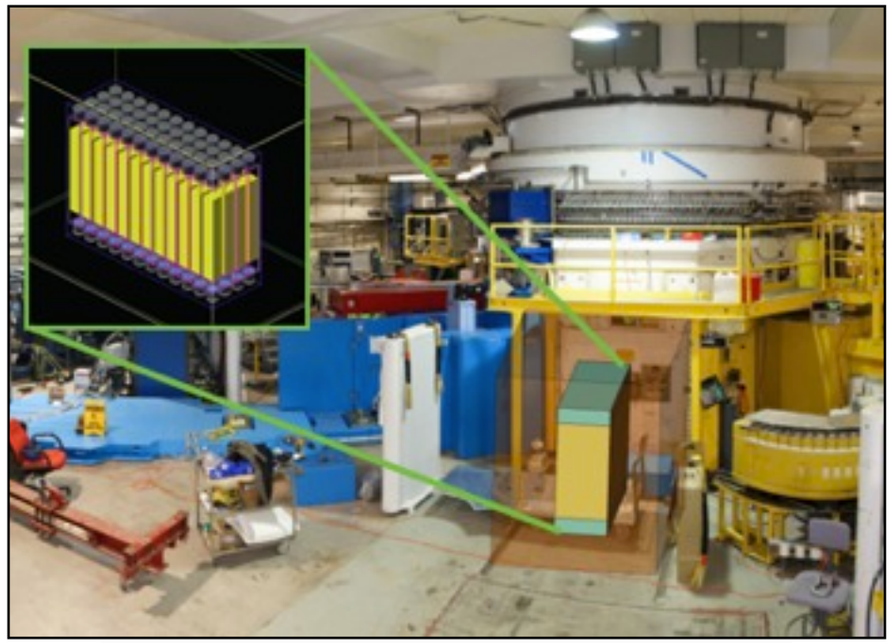
Probing Big Mysteries With Oscillations

- Pursuing the matter-antimatter asymmetry mystery
  - Precision measurement of θ_{13} at Daya Bay
- Attacking the sterile ν mystery from three orthogonal directions
  - Testing appearance of accelerator ν_e with MicroBooNE
  - Looking for disappearance of reactor $\overline{\nu}_e$ with PROSPECT
  - Measuring the reactor neutrino deficit at Daya Bay



Analyzing Data with the Daya Bay Detectors

Constructing the MicroBooNE Experiment



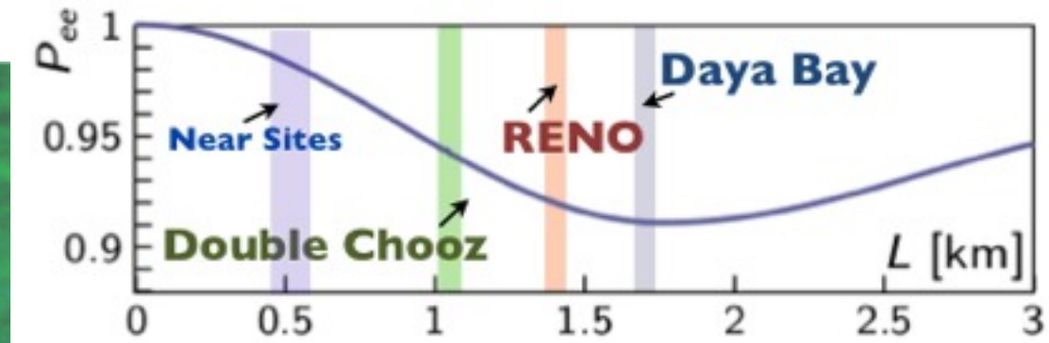
PROSPECT Design at NIST Reactor

A Powerful Neutrino Source at an Ideal Location:
The Daya Bay Experiment

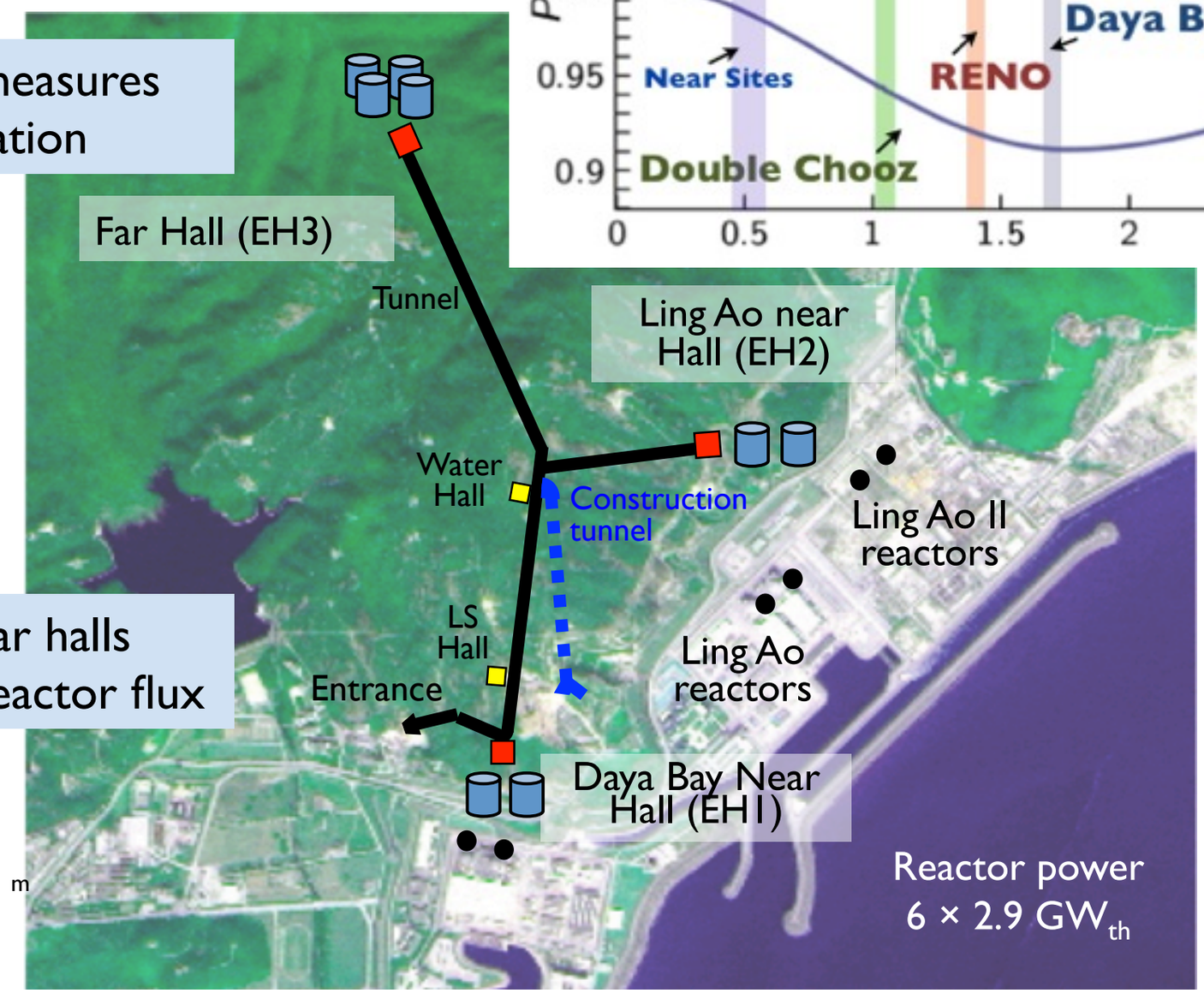
Mountains shield detectors from cosmic ray background

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

The Daya Bay Layout and Strategy



Far hall measures oscillation



Two near halls constrain reactor flux

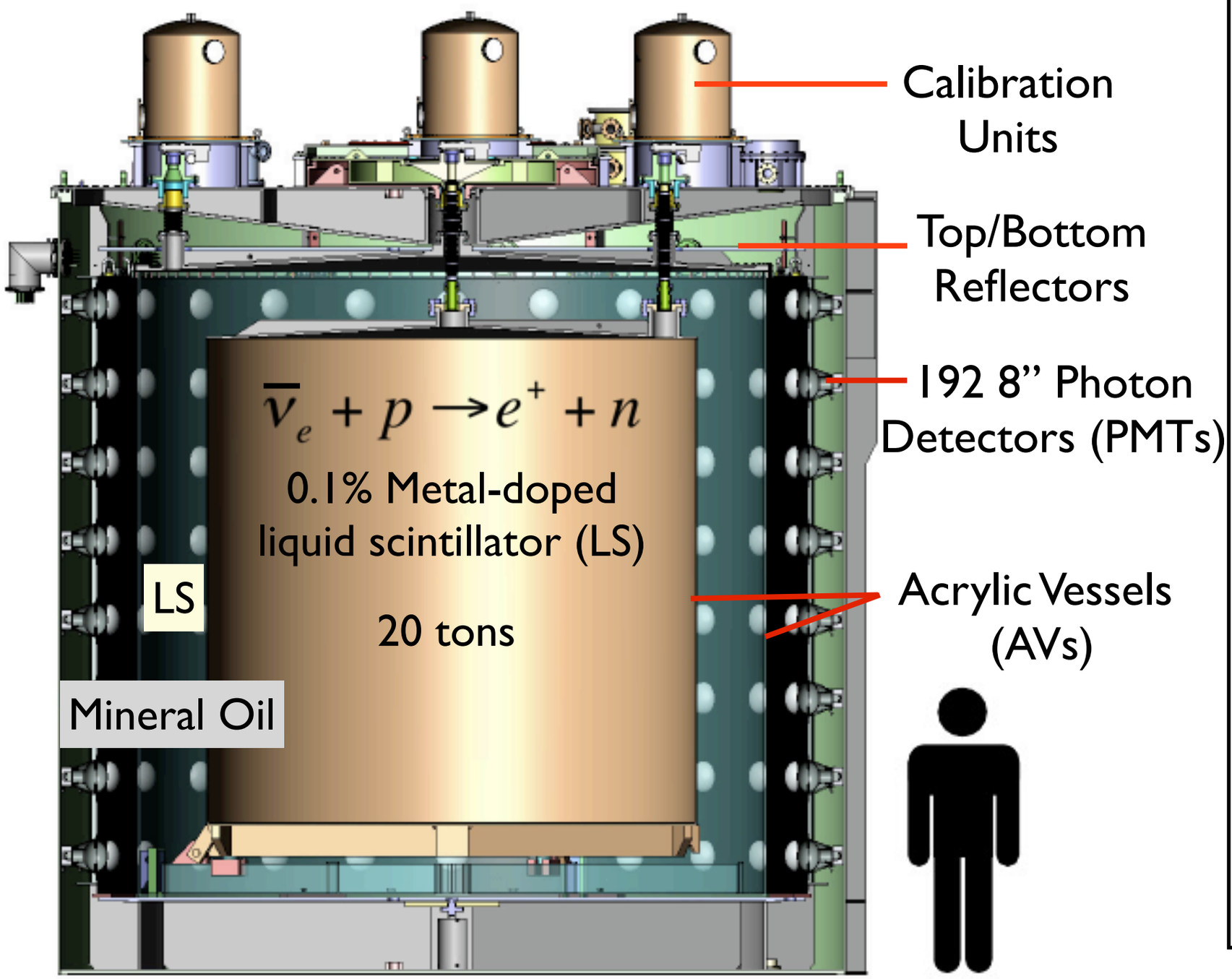
Relative measurement with 8 functionally identical detectors

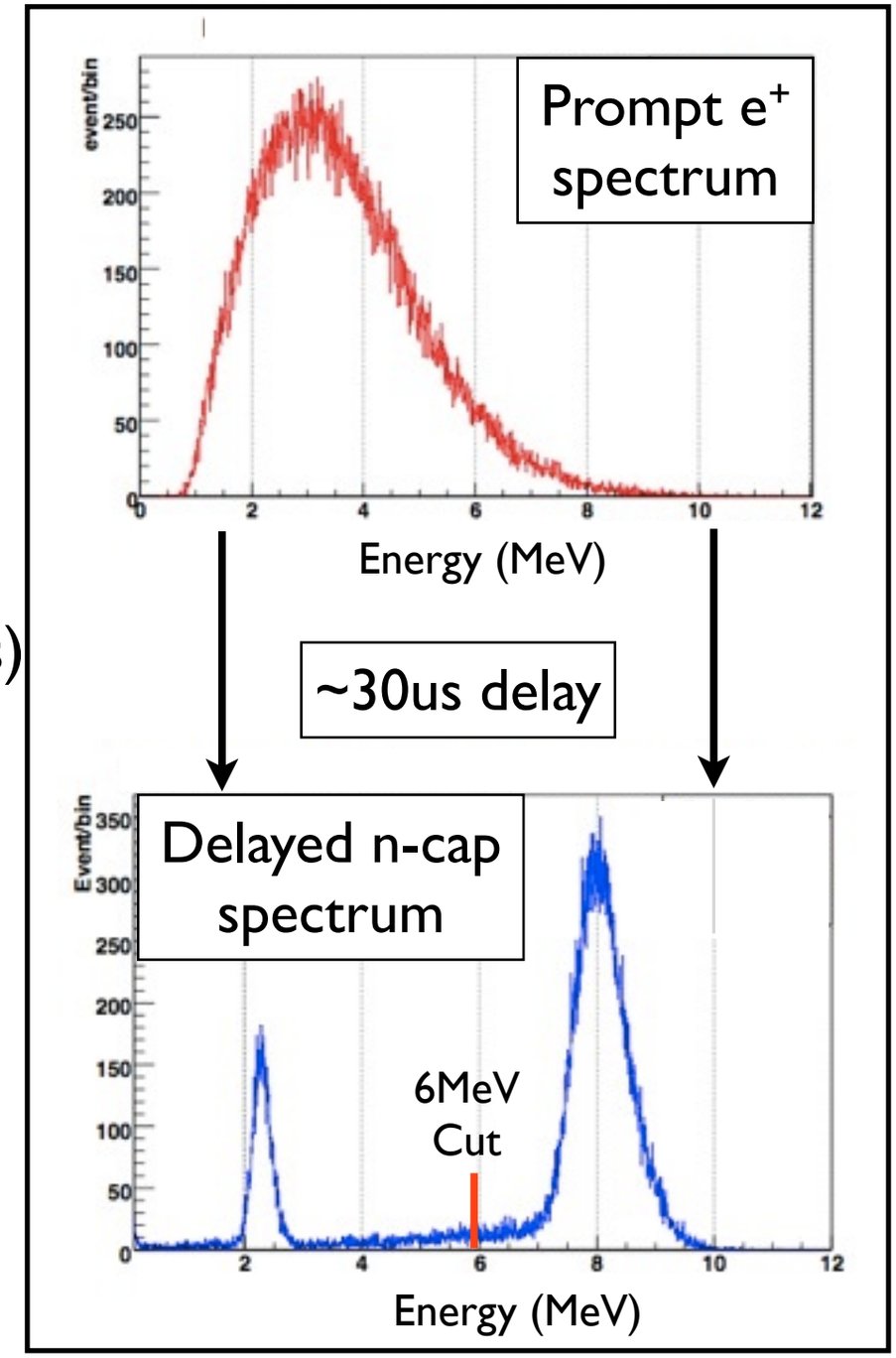
- Absolute reactor flux single largest uncertainty in previous measurements

Cancels in near/far ratio: $$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right)$$

Daya Bay $\overline{\nu}_e$ Detectors (ADs)

- A Daya Bay AD: three-zone liquid scintillator detector





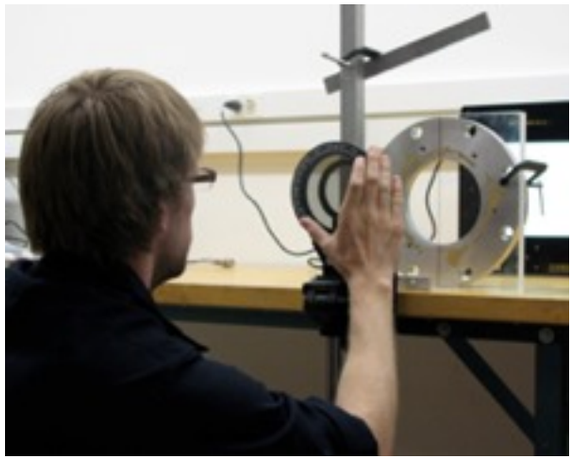
Daya Bay Monte Carlo Data

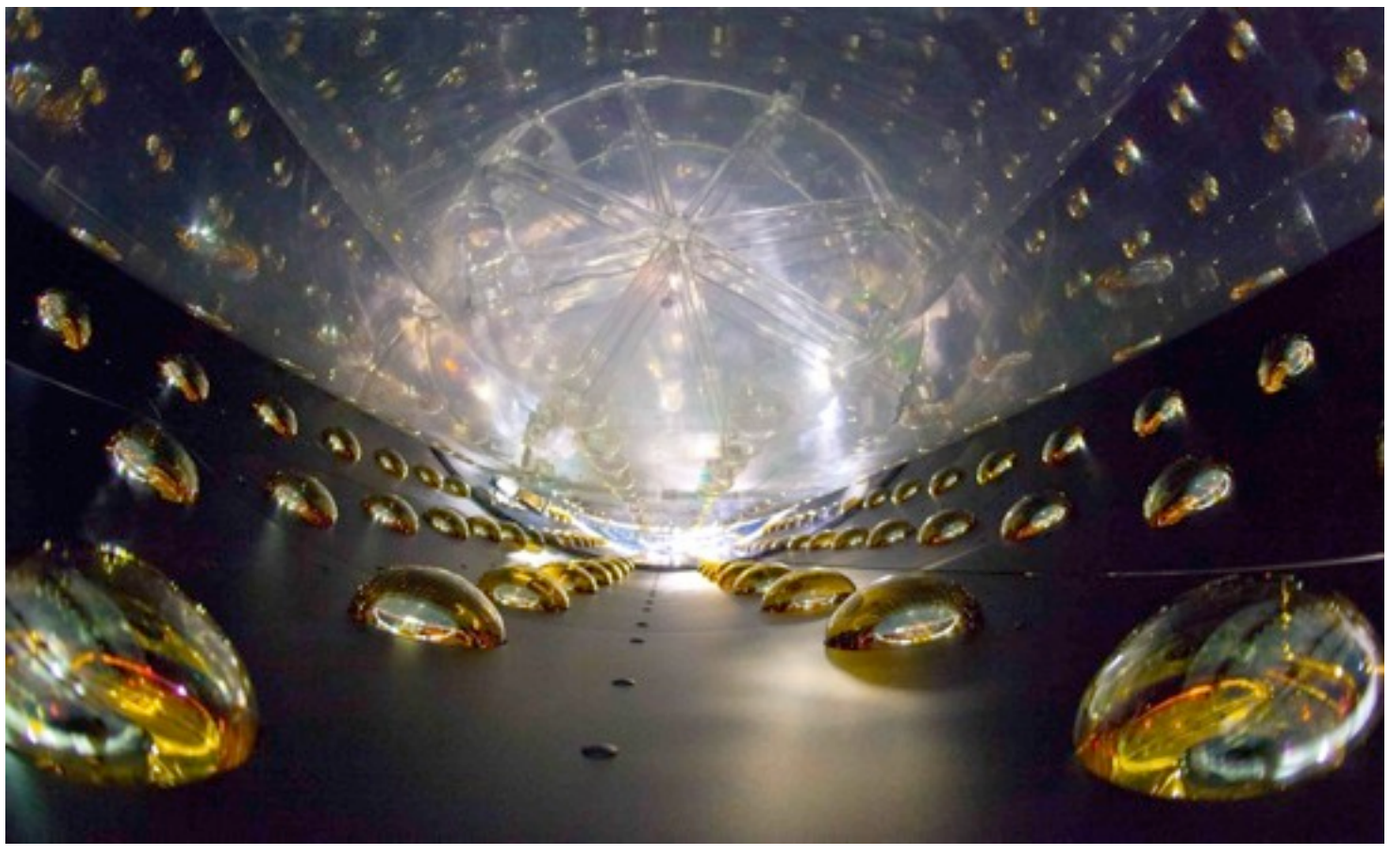
Detector Construction

- Detectors constructed, filled at Daya Bay surface facility, underground filling hall
- Led aspects of acrylic target vessel design, characterization, cleaning, and installation

B. R. Littlejohn, et. al:

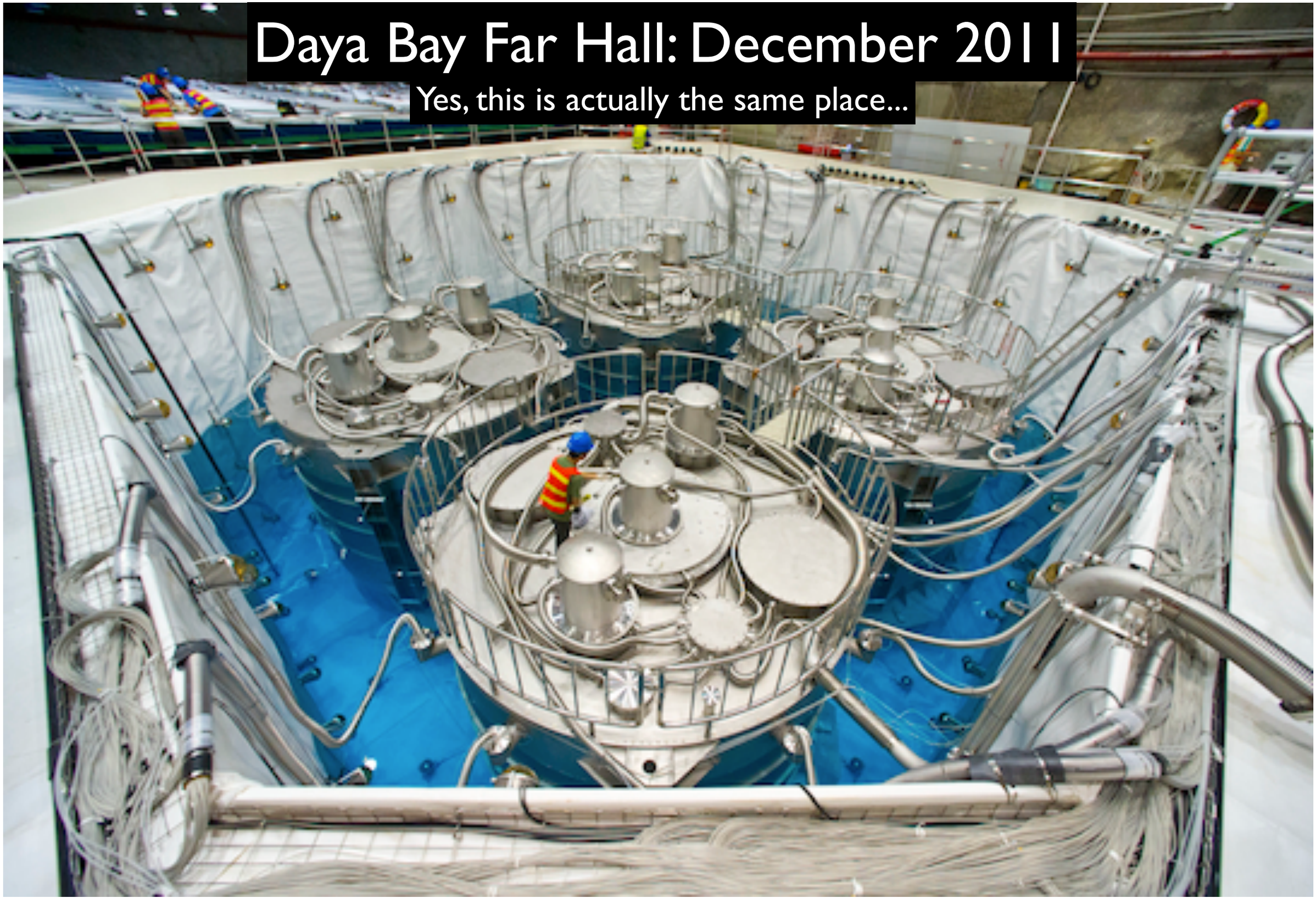
JINST 8 (2013) T11006
JINST 7 (2012) P06004
JINST 7 (2012) T08001
JINST 4 (2009) T09001



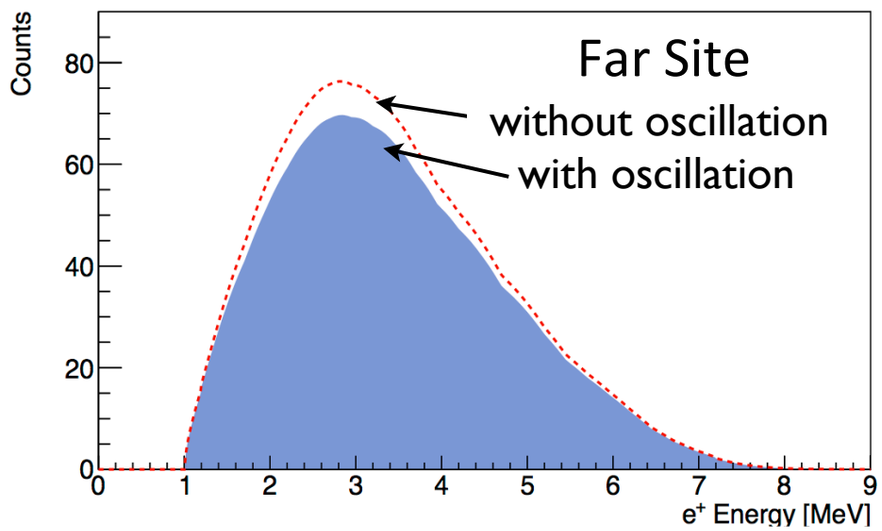


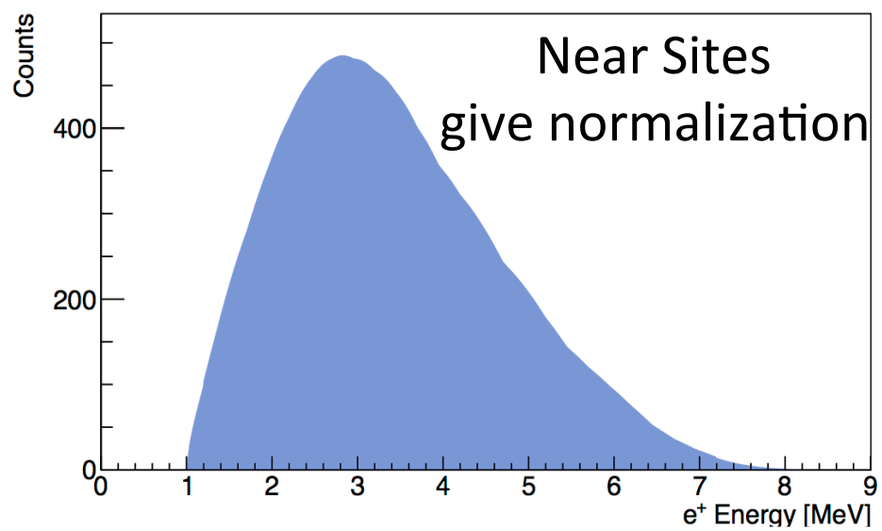
Underground Construction: Before

Underground Construction: After



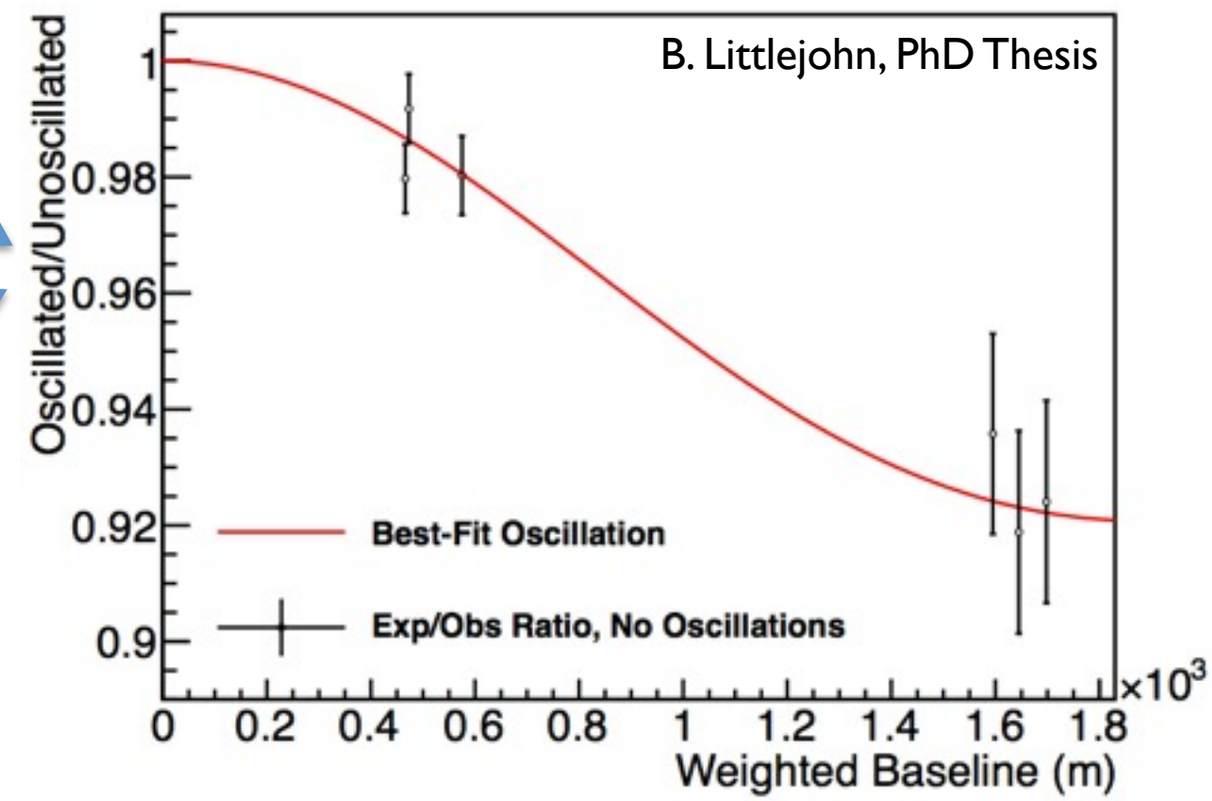
Initial Analysis: Rate-only





Compare total rate at near and far sites to look for relative rate deficit at far site

Integrate all energies



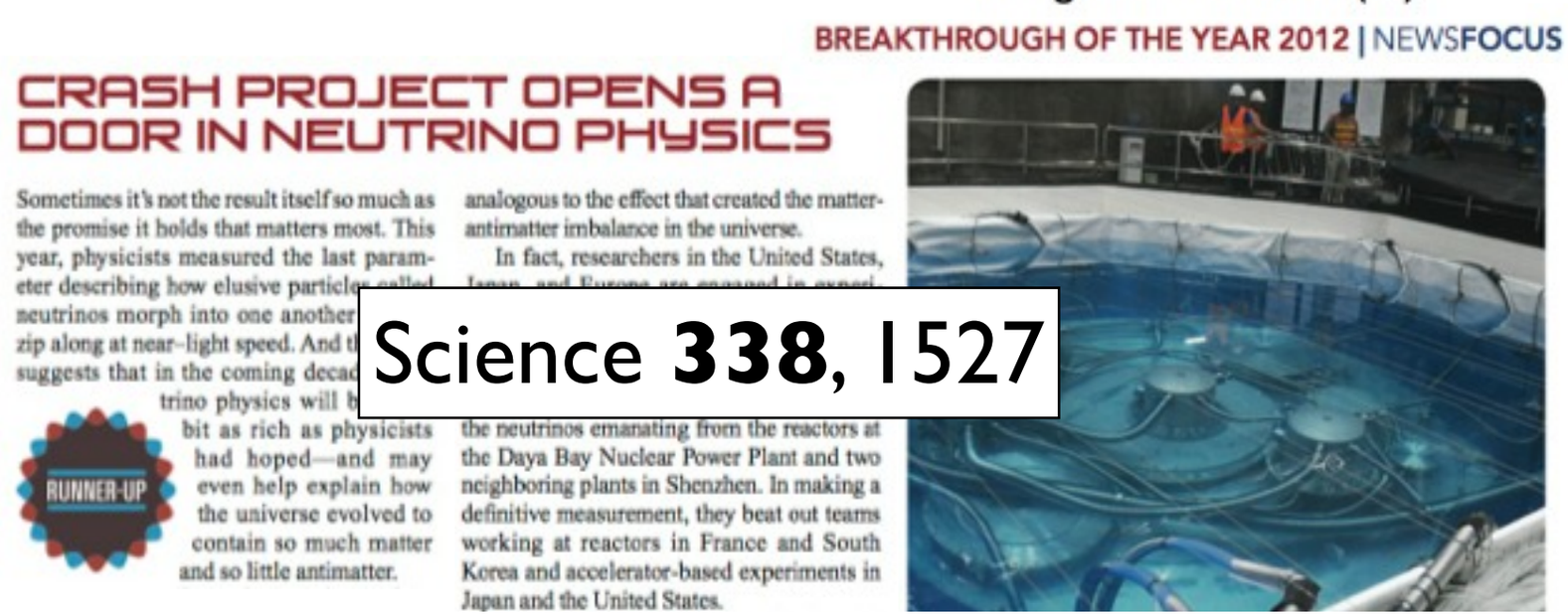
$\sin^2 2\theta_{13} = 0.089 \pm 0.011$

First unambiguous measurement of a non-zero θ_{13}

B. Littlejohn, PhD Thesis (2012)

PRL **108** (2012), 171803

CPC **37** (2013), 011001


BREAKTHROUGH OF THE YEAR 2012 | NEWSFOCUS

CRASH PROJECT OPENS A DOOR IN NEUTRINO PHYSICS

Sometimes it's not the result itself so much as the promise it holds that matters most. This year, physicists measured the last parameter describing how elusive particles called neutrinos morph into one another as they zip along at near–light speed. And t[illegible] suggests that in the coming decad[illegible] trino physics will b[illegible] bit as rich as physicists had hoped—and may even help explain how the universe evolved to contain so much matter and so little antimatter.

RUNNER-UP

analogous to the effect that created the matter-antimatter imbalance in the universe.

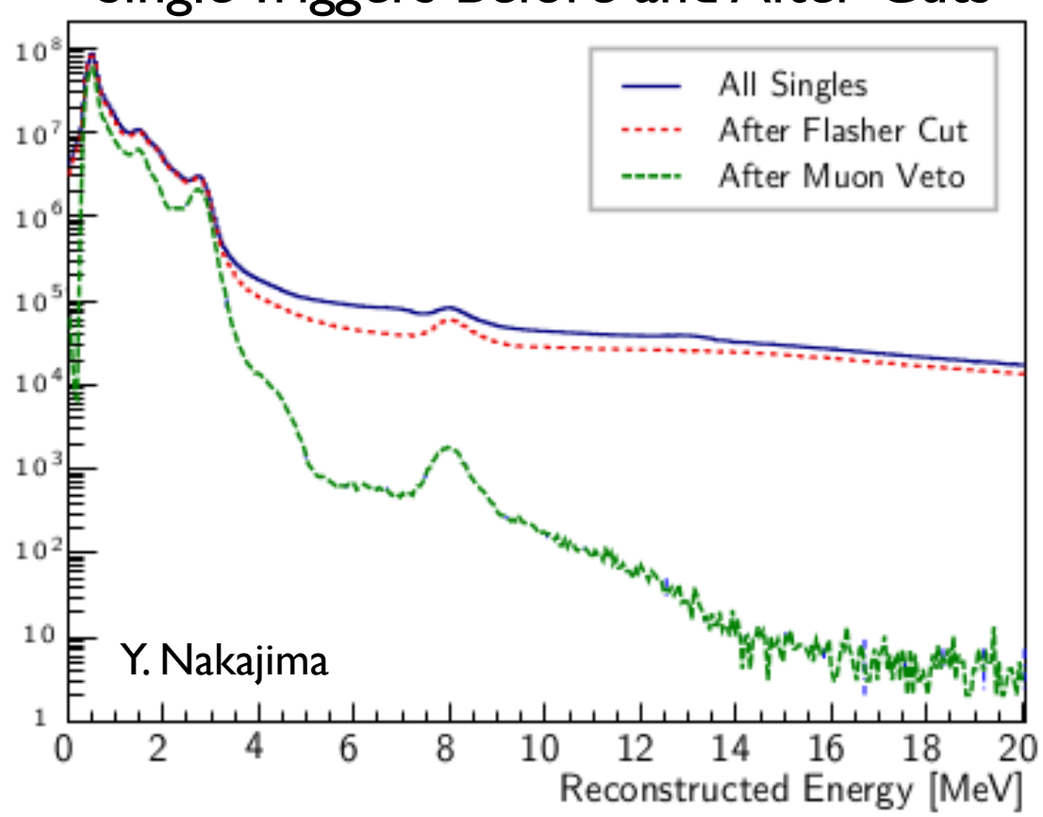
In fact, researchers in the United States, Japan, and Europe are engaged in experi[illegible] the neutrinos emanating from the reactors at the Daya Bay Nuclear Power Plant and two neighboring plants in Shenzhen. In making a definitive measurement, they beat out teams working at reactors in France and South Korea and accelerator-based experiments in Japan and the United States.

Science **338**, 1527

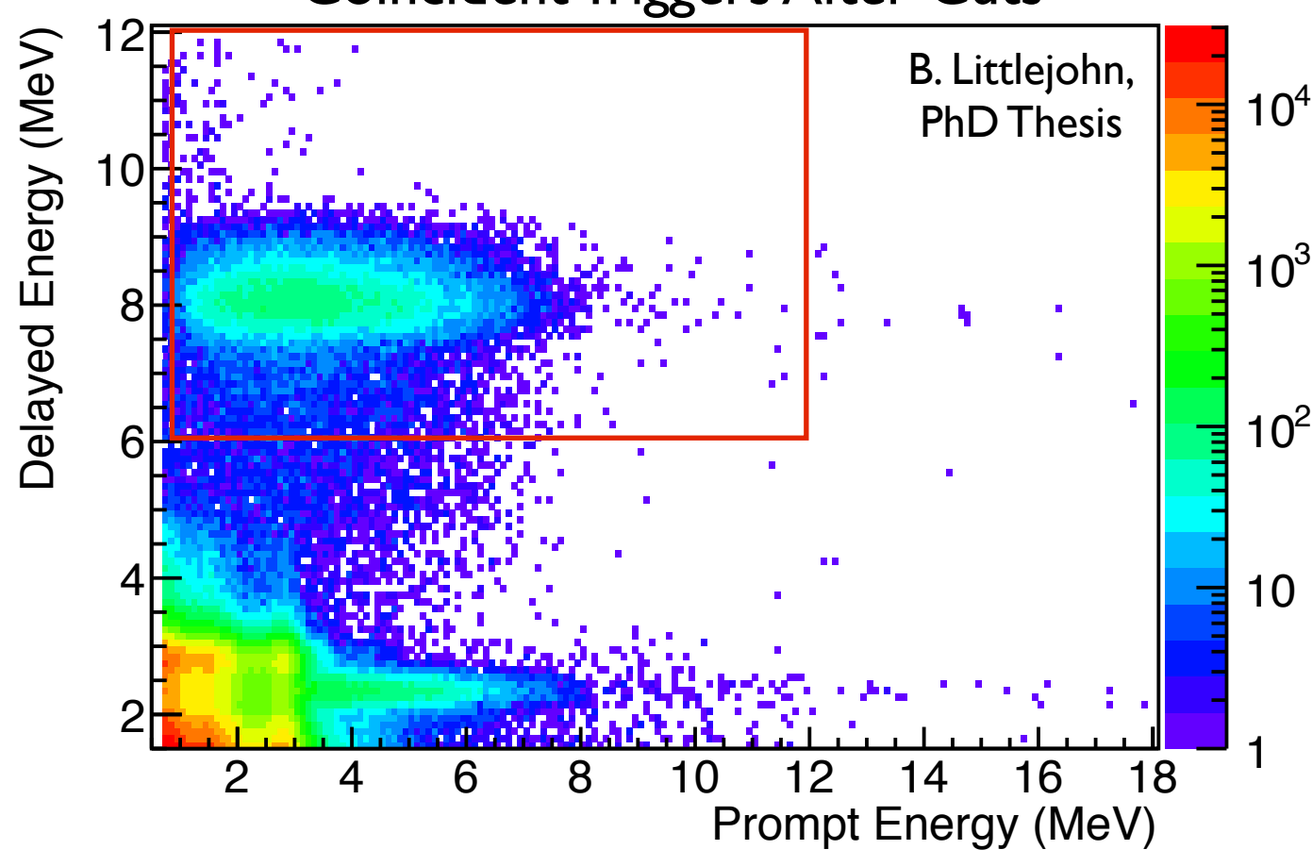
Antineutrino Selection

- Led one of four cross-checking $\bar{\nu}_e$ disappearance analyses for the first Daya Bay θ_{13} result
- Remove instrumental and muon-correlated triggers
- Apply time coincidence and energy cuts to remaining events
- After selection, a few well-understood backgrounds remain

Single Triggers Before and After Cuts

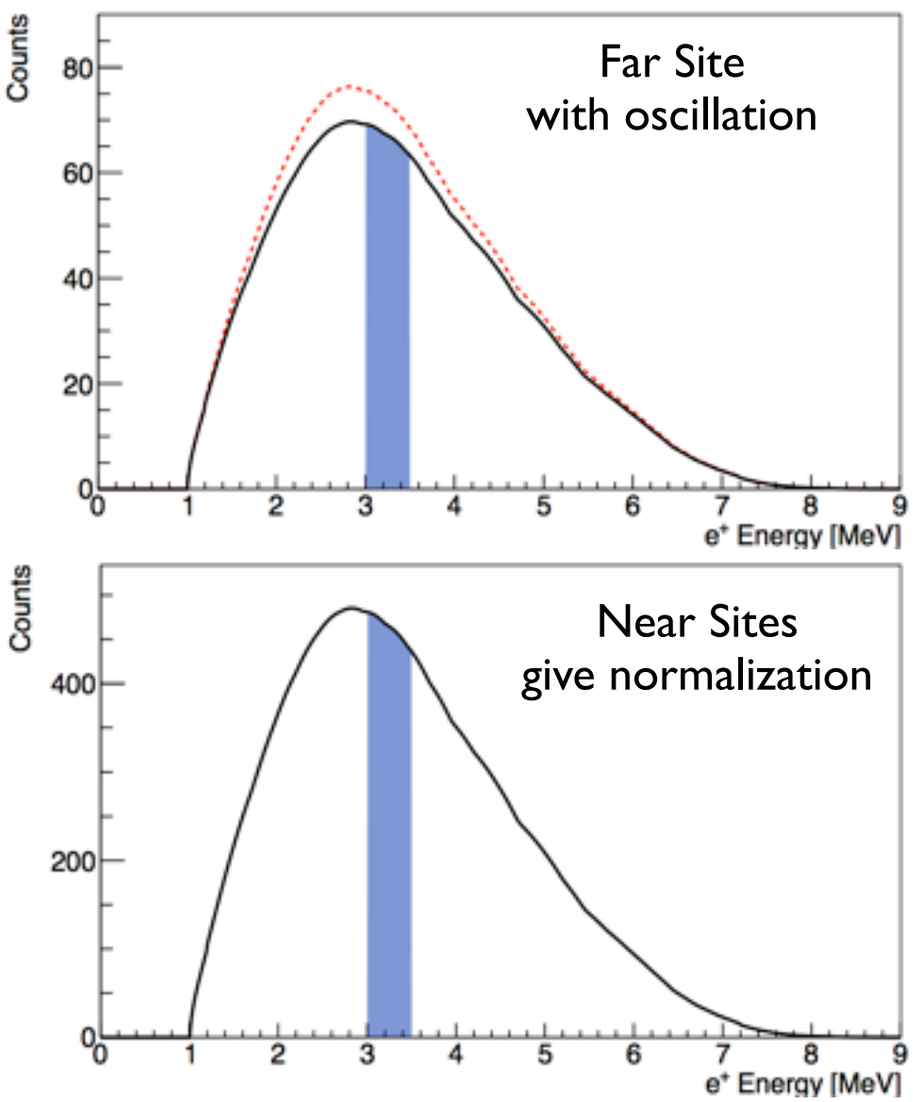


Coincident Triggers After Cuts

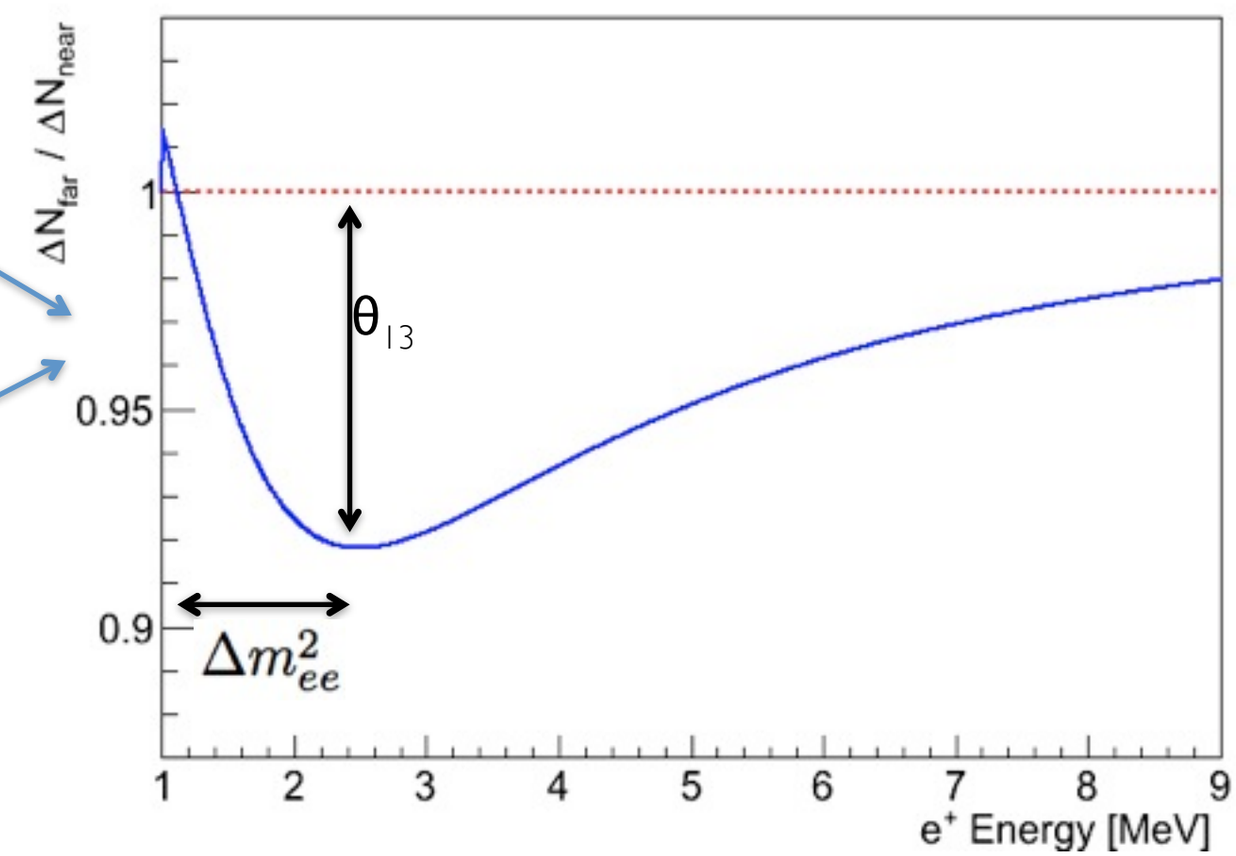


New Rate+Shape Analysis

Compare rates in each energy bin between near and far detectors



Compare each energy

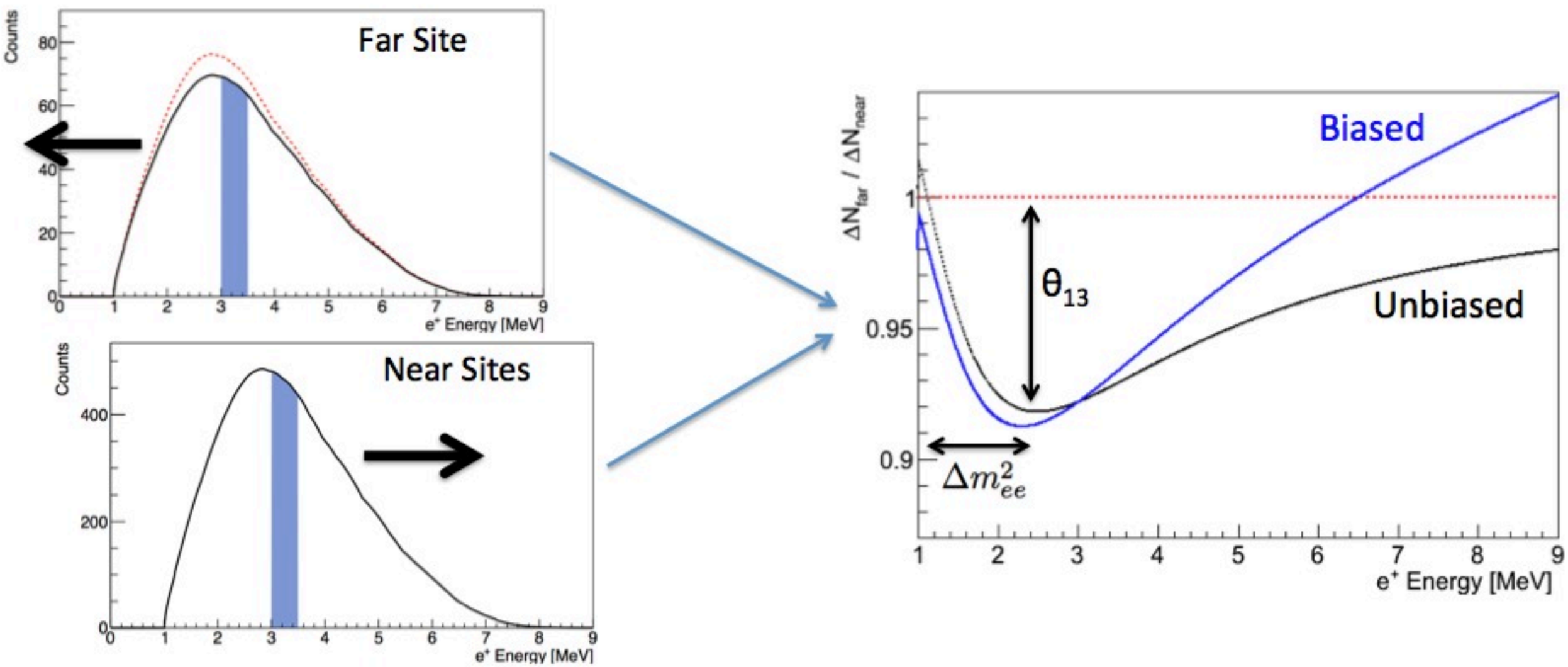


PRL **112** (2014), 061801

- Better measurement of θ_{13}
- First measurement of Δm^2_{31} at a reactor!
- Need detailed energy response model to predict entire energy spectrum, instead of just rates

Energy Response: Relative Calibration

Relative shift in energy between detectors can bias oscillation



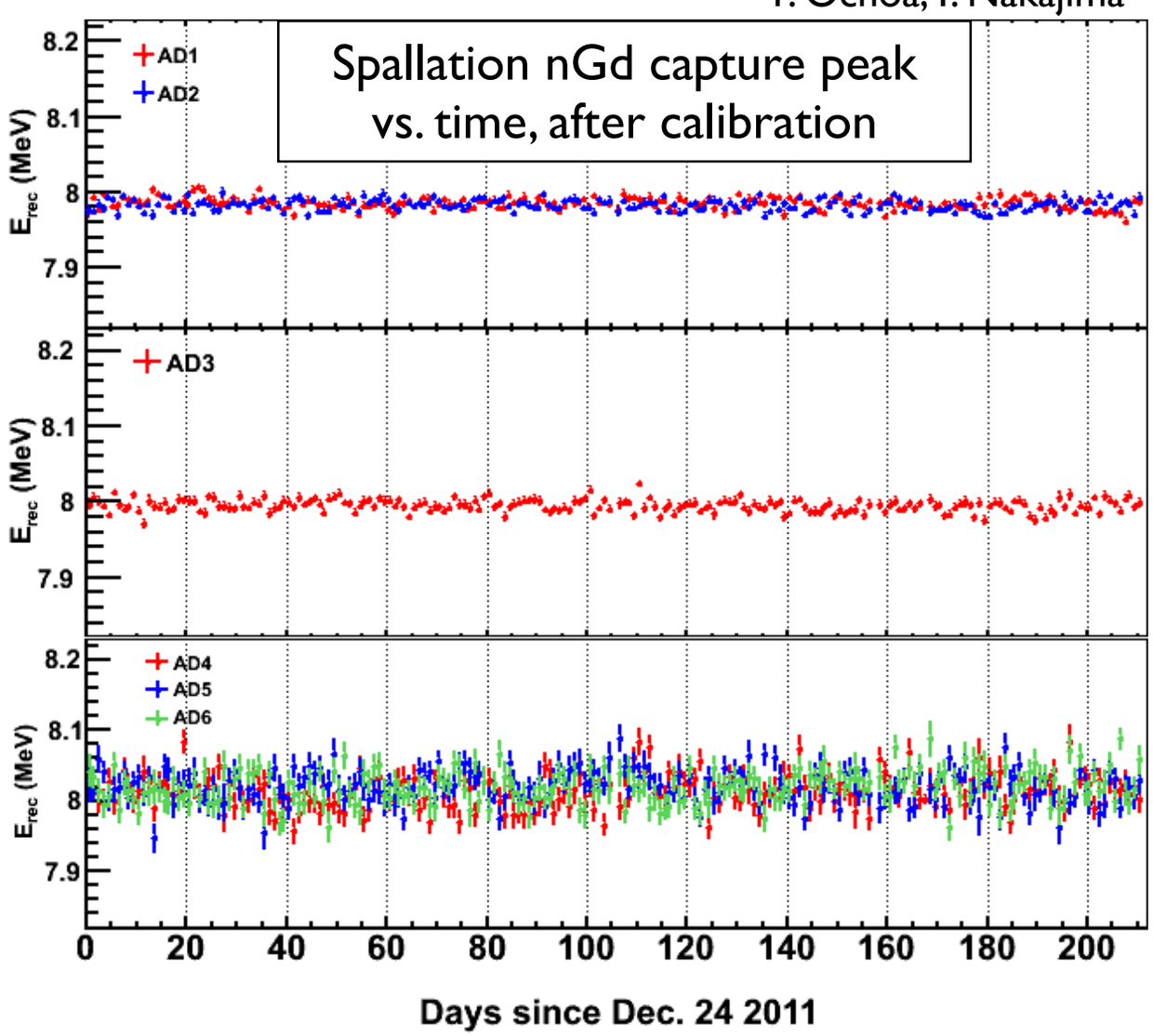
Requires careful detector calibration

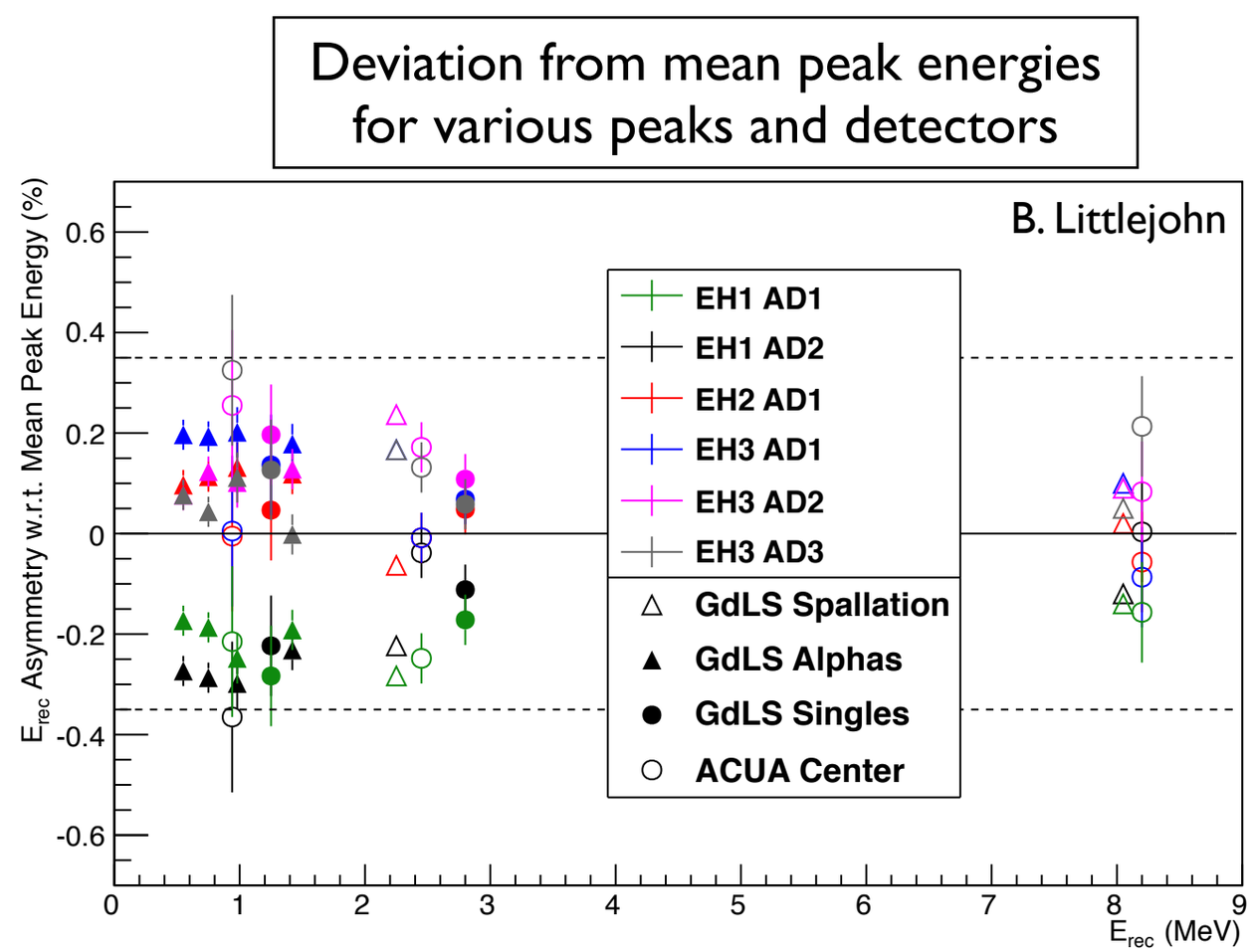
Expected to be largest detector systematic; a major focus of Cincinnati's Daya Bay efforts

Energy Response: Relative Calibration

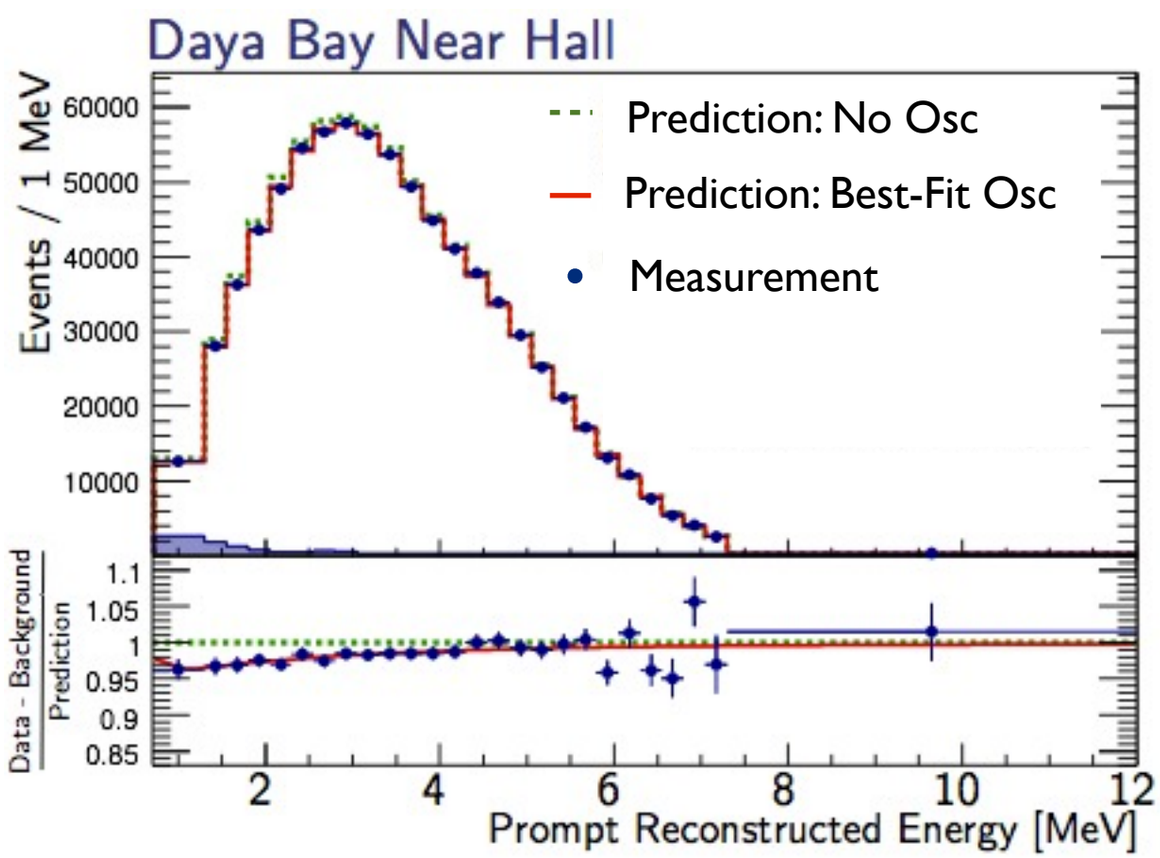
- Obtain a stable energy response consistent between detectors
  - Use spallation neutron nGd peak to benchmark energy scale
  - Stability of better than 0.1% in all detectors with time
  - Energy scales consistent for all measured energies and particles to 0.35%

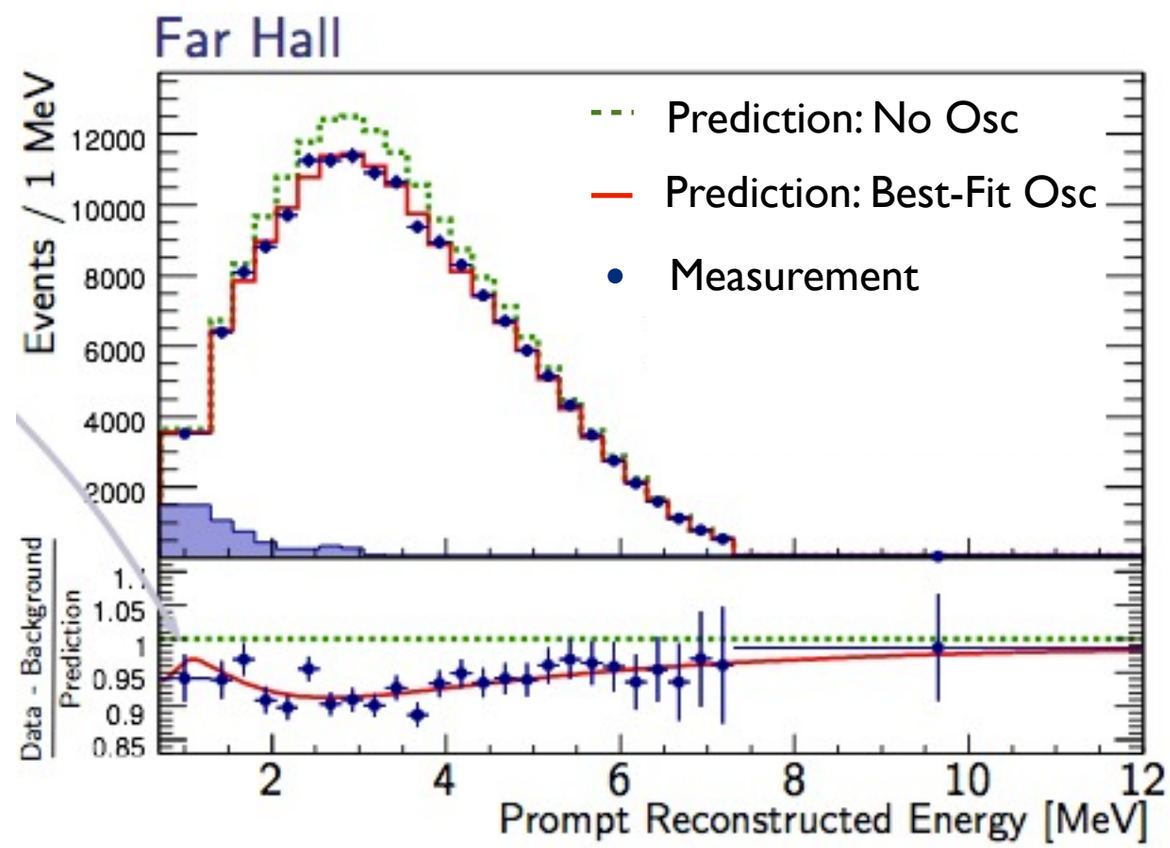
P. Ochoa, Y. Nakajima





Rate+Shape Results: Spectra and Rates





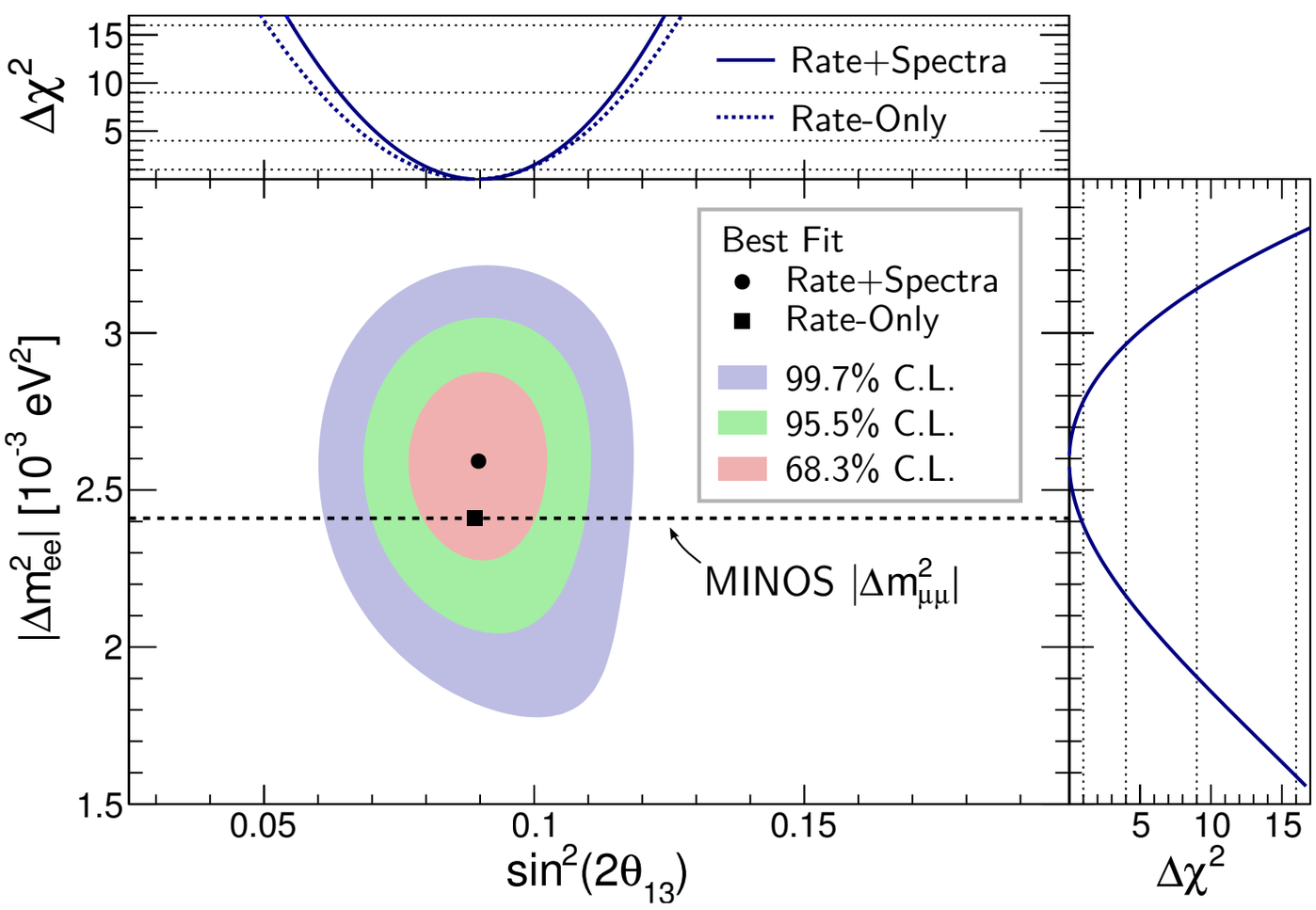
- Over 350k detected $\bar{\nu}_e$ in 217 days
  - Most neutrino detections ever recorded by a single experiment!
- Far site statistical uncertainty (~0.5%) still dominates background (~0.2%), reactor, and detector (~0.2%) systematics

Site	Events/Day	Signal/Bkg (%)
EH1	1300	3.0 ± 0.1
EH2	580	3.0 ± 0.1
EH3	220	3.0 ± 0.2

PRL **112** (2014), 061801

Rate+Shape Result: Best-Fit Parameters

- Conduct X^2 fit between all measurements and predictions
- Vary θ_{13} and Δm^2 in prediction to find minimum X^2
  - Systematics taken into account by also minimizing over constrained nuisance parameters
- Clear measurement of θ_{13} and Δm^2 provides strong confirmation of three-flavor neutrino oscillation picture
  - Good agreement with earlier indications and current results, like Double Chooz



Factor of 2 more precise than any other existing θ_{13} measurement

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

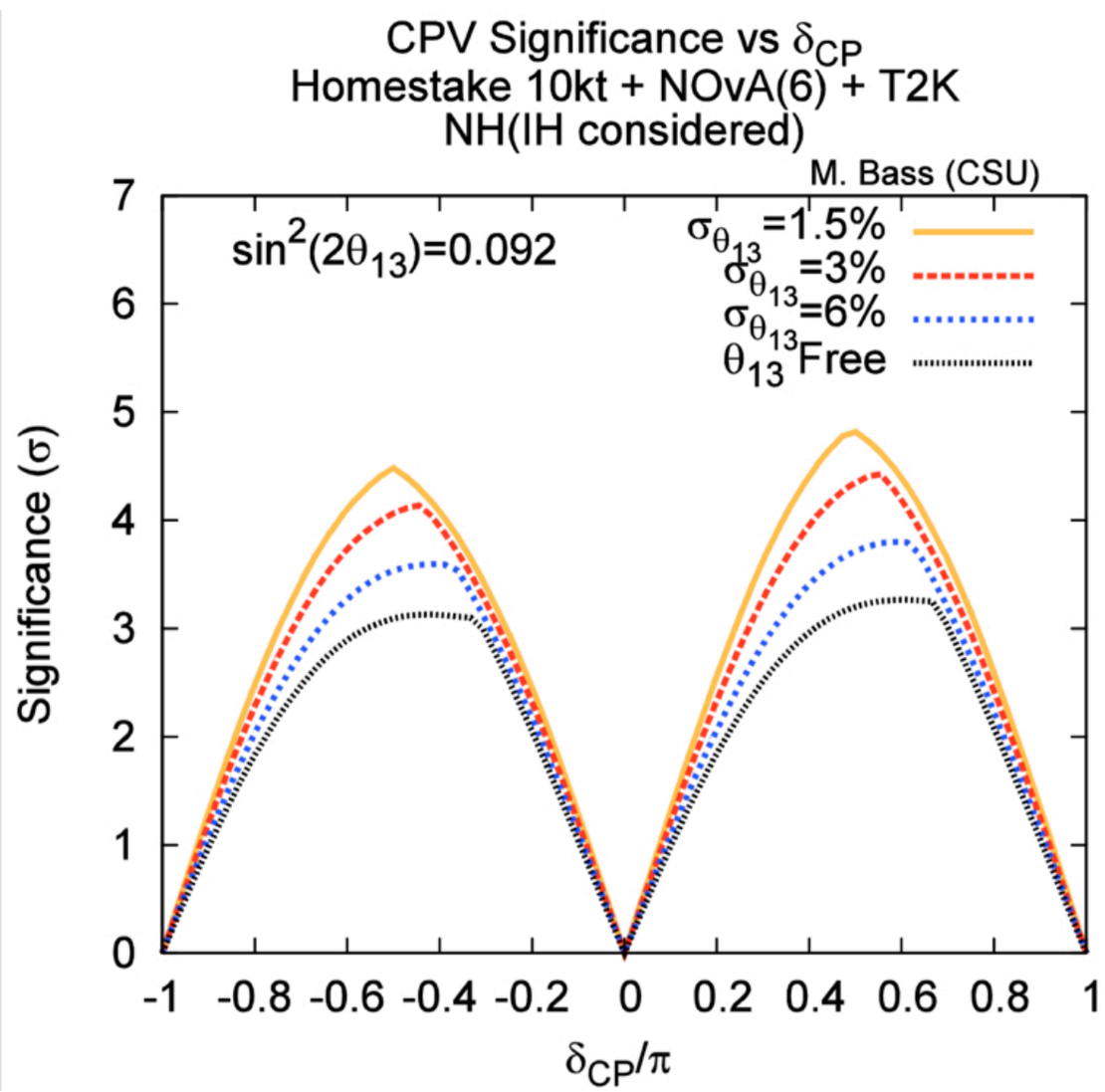
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\,\mathrm{eV}^2$$

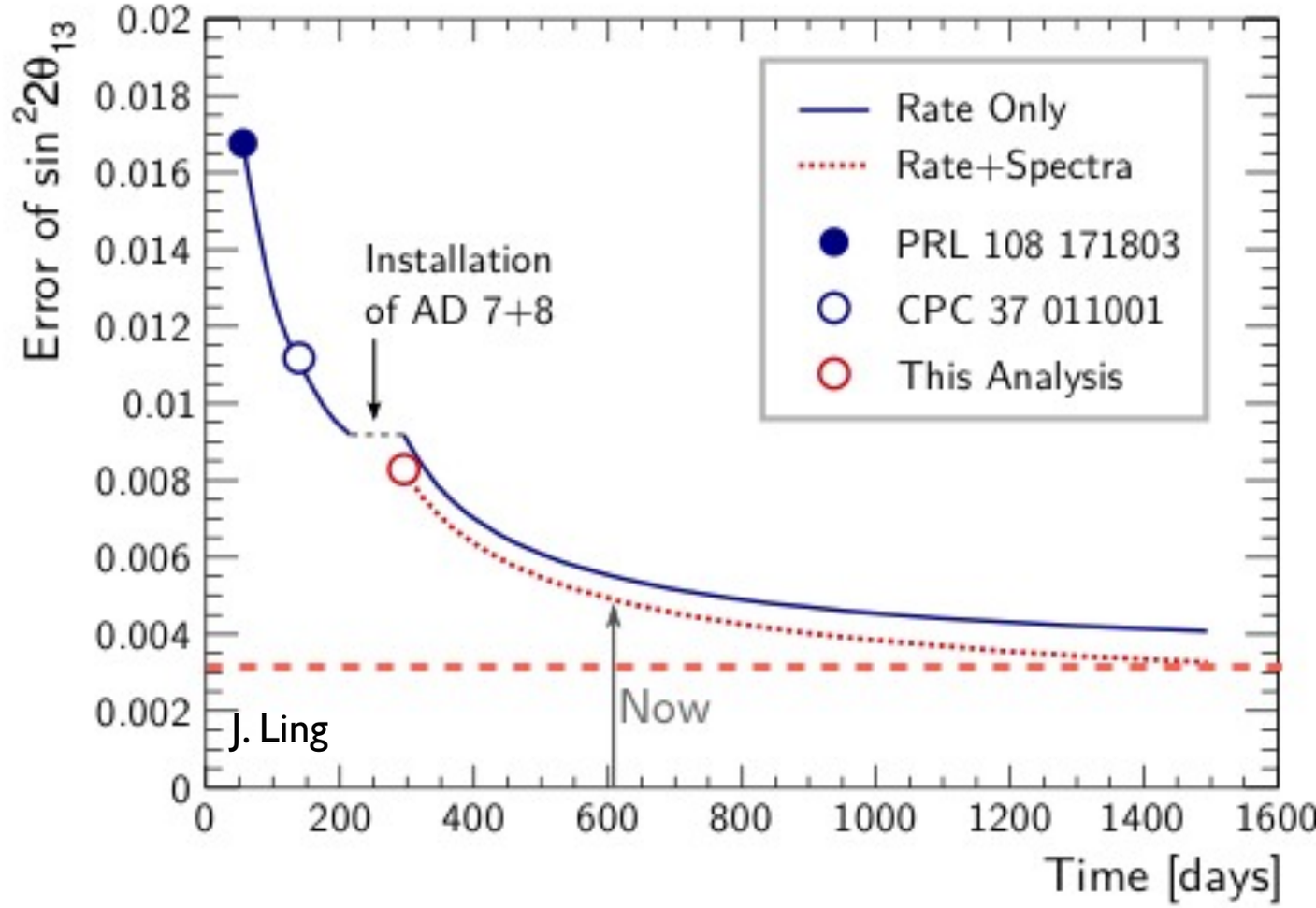
$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$

PRL **112** (2014), 061801

Closer to Addressing Asymmetry Mystery

- Prospects for measuring CP-violation much better after measuring θ_{13}
  - θ_{13} is quite large, so CP-violating effect has potential to be larger, too
  - Also true for neutrino mass hierarchy
- Precise Daya Bay result can improve global CP-violation significance
  - Expect precision to improve further with more statistics, improved uncertainty estimates

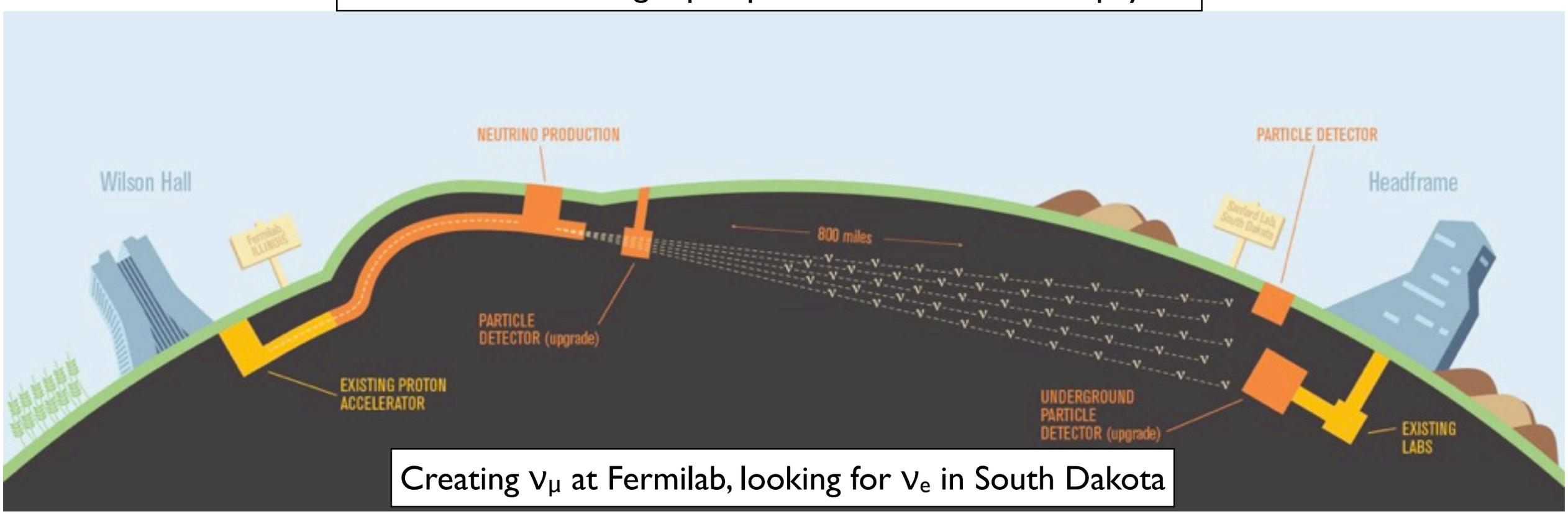




Asymmetry Mystery: Next Steps

- Next step: measure CP-violation with long-baseline accelerator ν
  - Proof that leptons and anti-leptons behave differently
  - Plan to ramp up participation in LBNE as current research efforts are completed
- Could validate a mode for creating matter-antimatter asymmetry, but exact mechanism for universe's asymmetry would need further theoretical, experimental study

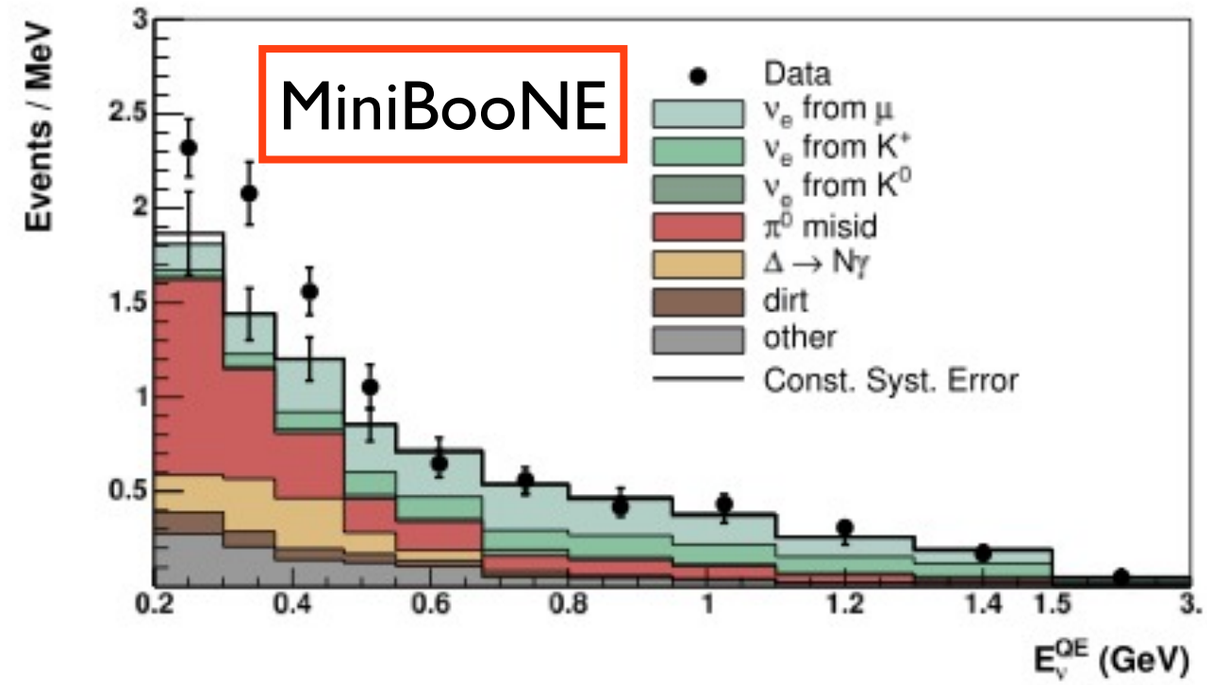
LBNE : The future flagship experiment in US neutrino physics

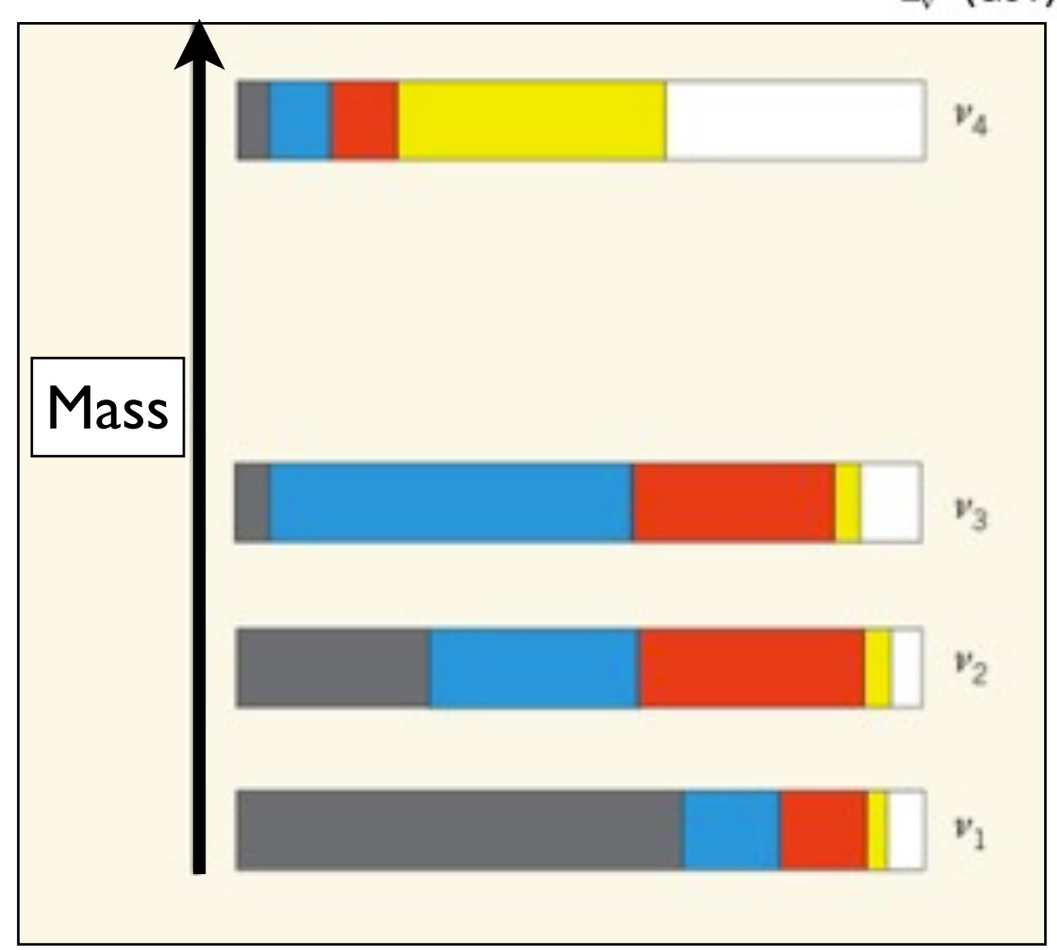


Creating ν_μ at Fermilab, looking for ν_e in South Dakota

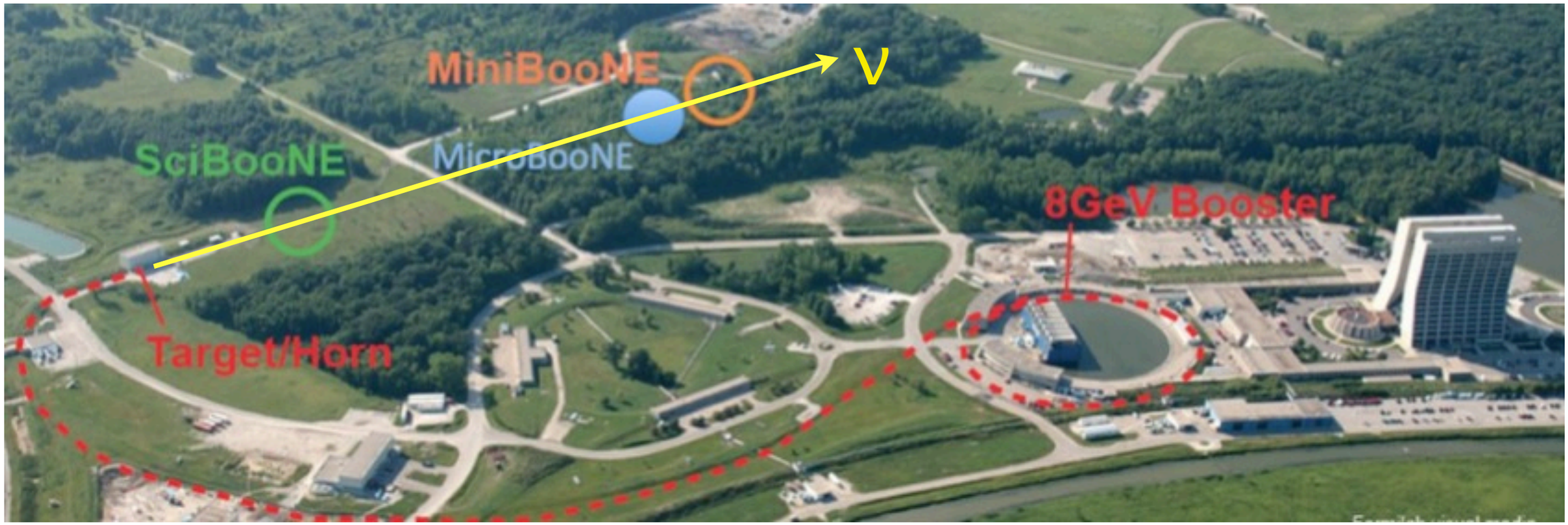
Sterile Neutrino Mystery

- Hints of appearance and disappearance of ν at an L/E of 1 m/MeV
- Have measured mass splittings of active neutrino flavors
- Possible explanation: a fourth 'sterile' neutrino
- To solve this mystery, pursuing definitive proof of oscillations from multiple new experimental angles





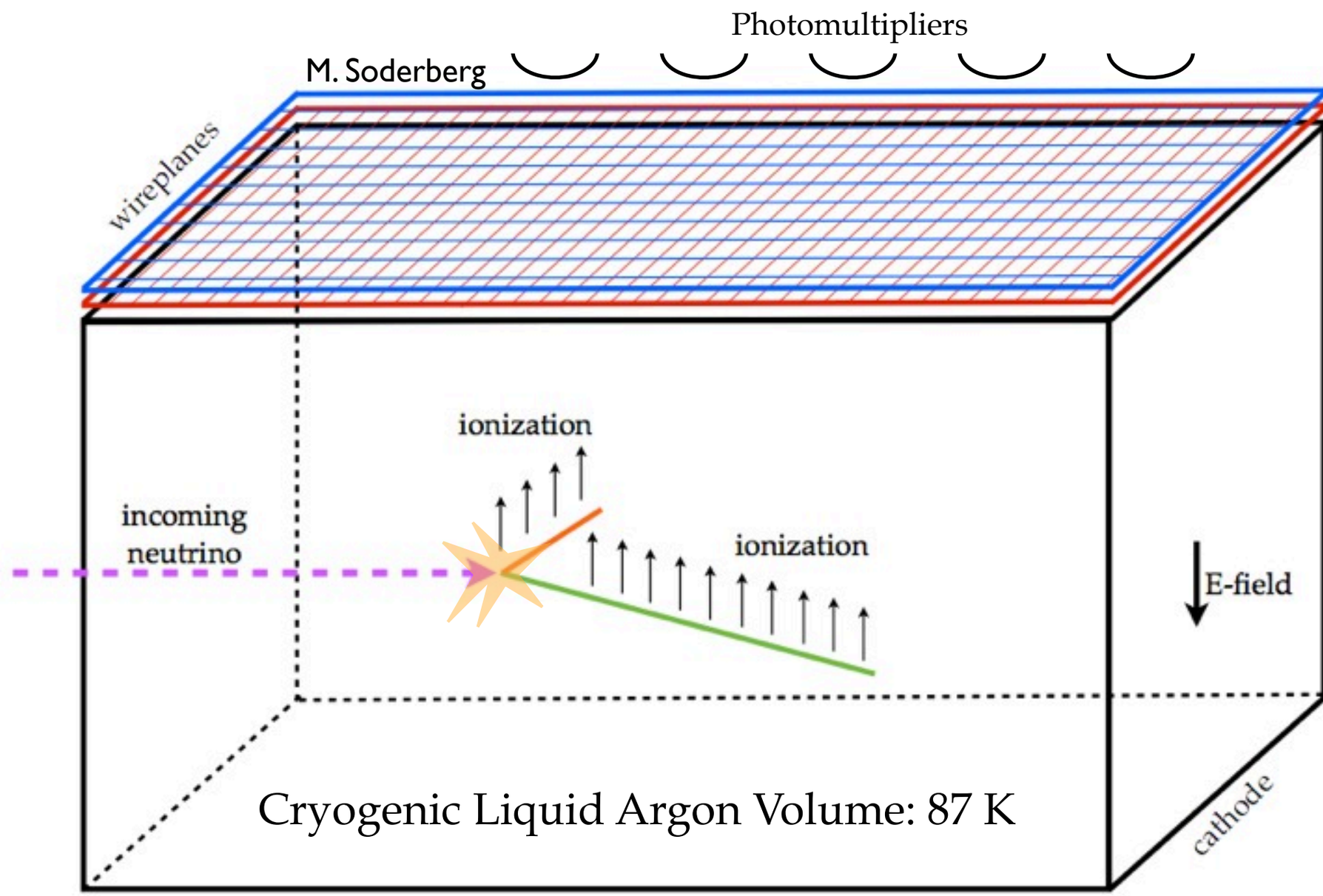
Sterile ν Mystery at MicroBooNE

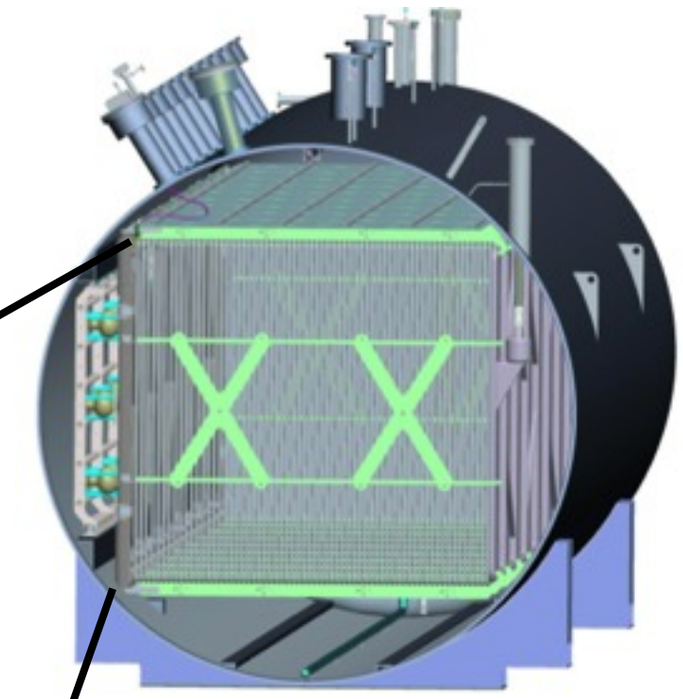


- Use a liquid argon time projection chamber (LArTPC) to directly address the MiniBooNE ν_e excess
- Same beam (BNB) at Fermilab
- Almost the same baseline
- Vastly improved detector technology!

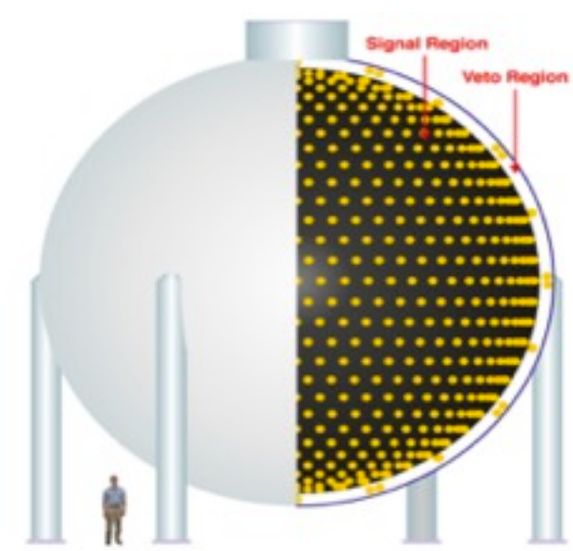
MicroBooNE: LArTPC Technology

- Dense 170 ton liquid argon target provides excellent ν interaction medium
- Ionization drifted meters along uniform E-field to finely spaced wire planes
- Constant drift speed, fast scintillation light provide position in drift direction





MiniBooNE: Spherical Oil Cerenkov Detector



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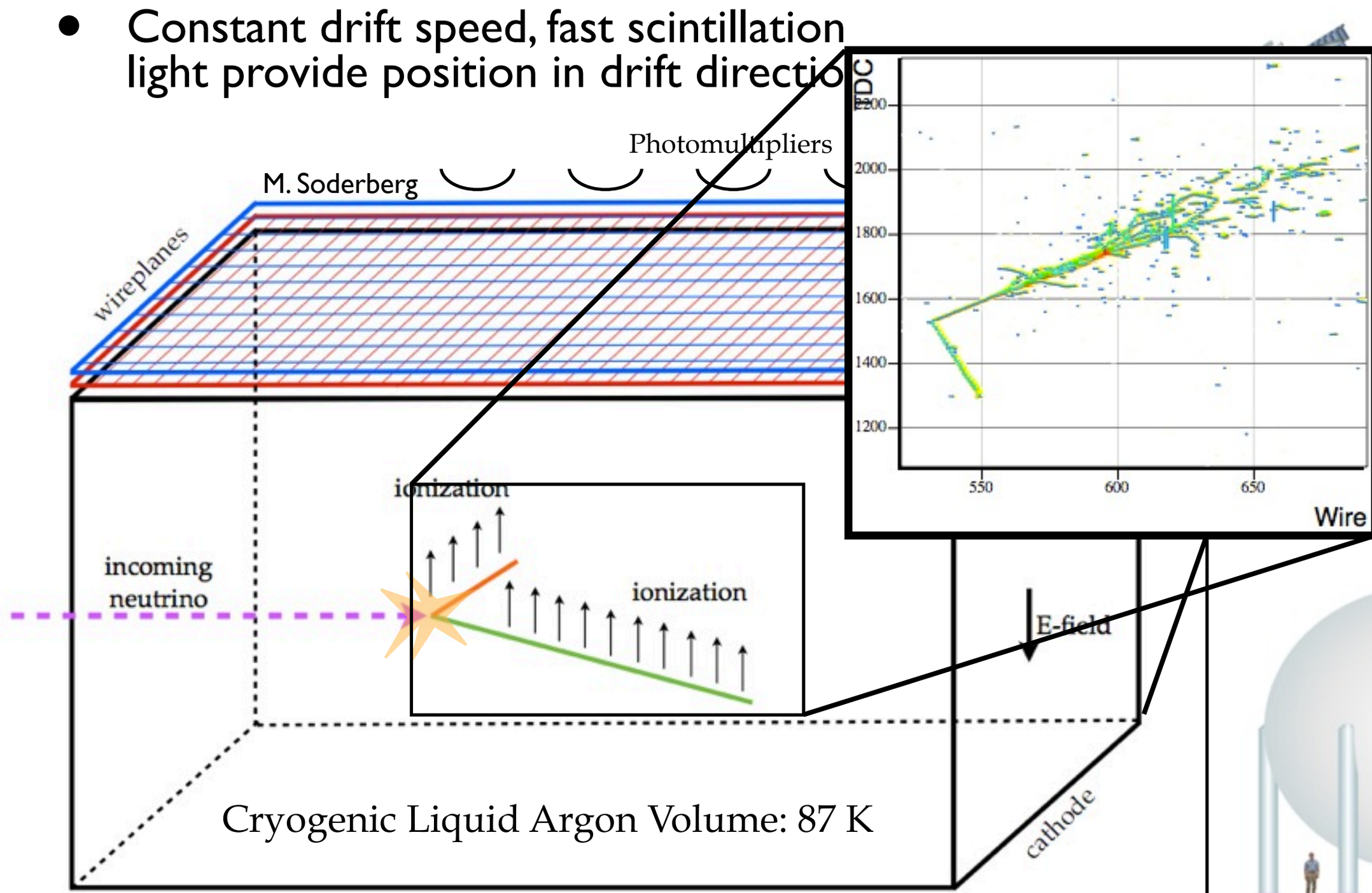
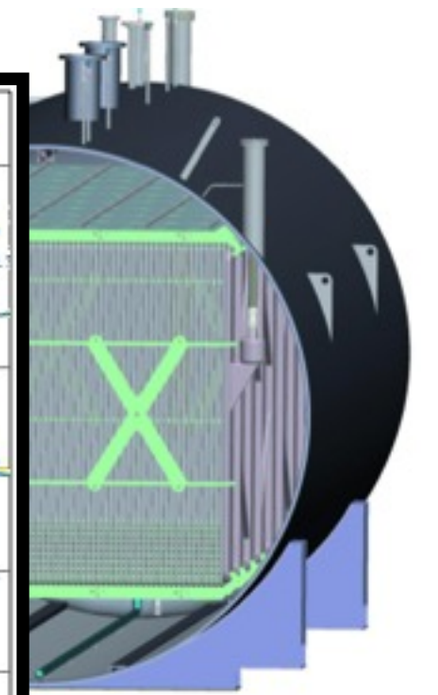
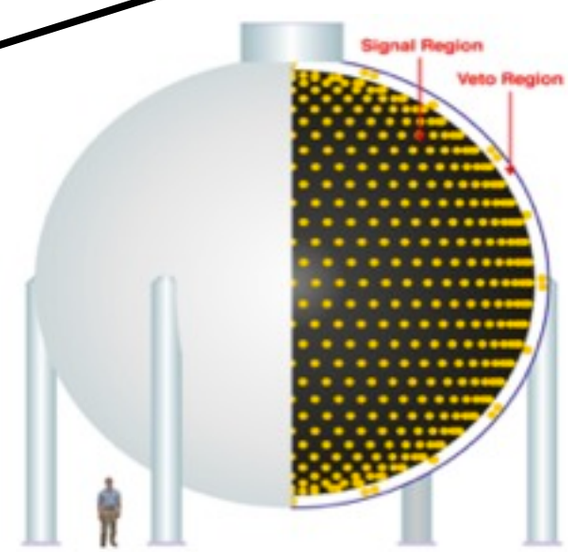
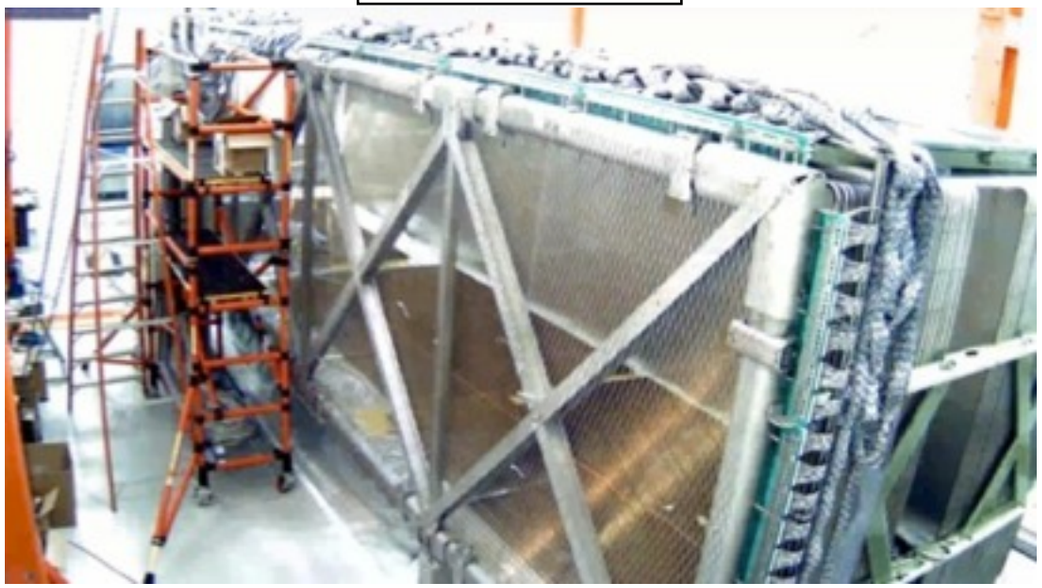


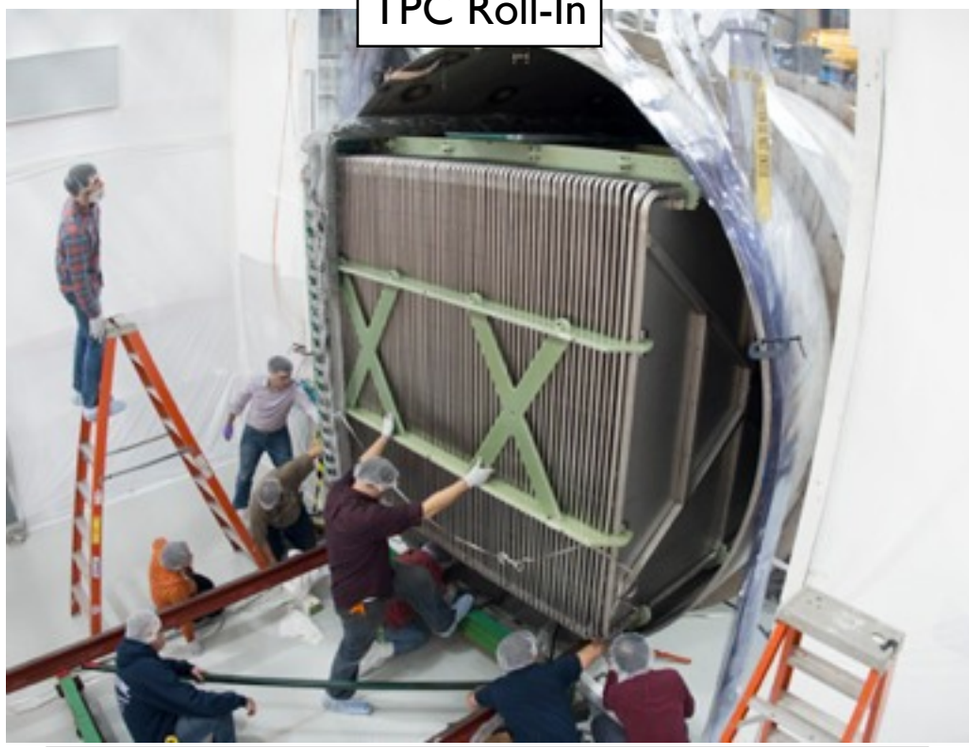


oNE: Spherical
enkov Detector



MicroBooNE: LArTPC Construction



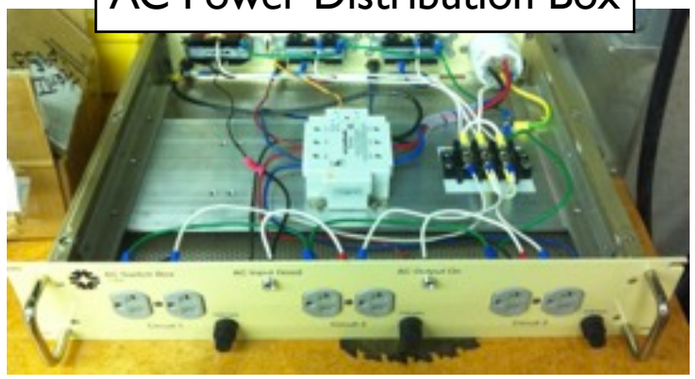


Install at experimental hall in Summer 2014!

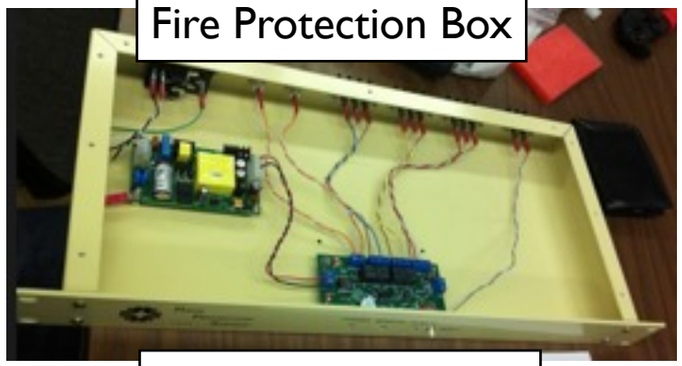
Experiment Electronics Infrastructure

- Managing implementation of electronics infrastructure
  - Build up experiment electronics racks, support structure
  - Oversee design, install of experiment cabling scheme
  - Roles in pre-commissioning many key subsystems
    - Cold readout electronics
    - TPC drift high voltage system
    - DAQ and trigger test stands

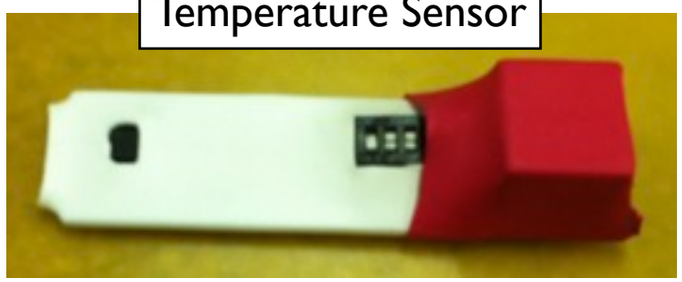
AC Power Distribution Box

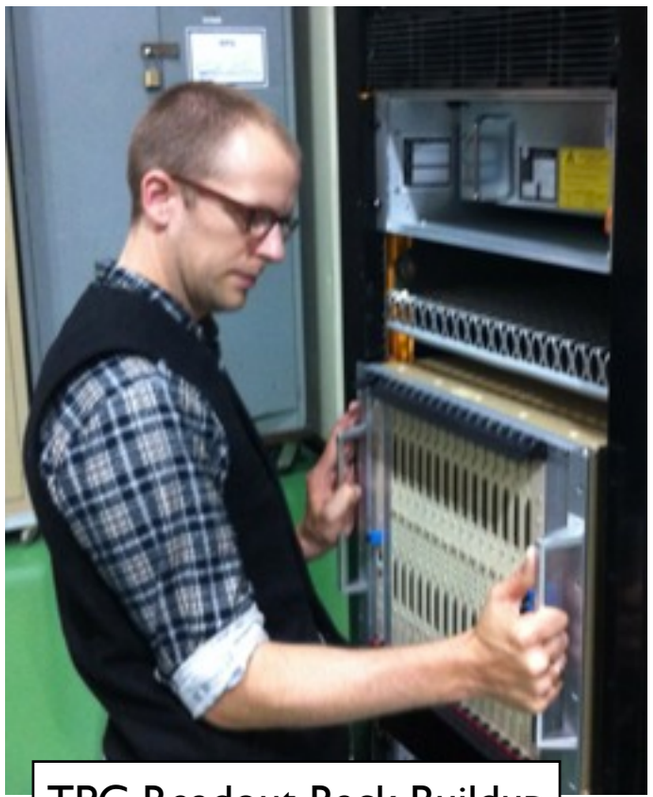


Fire Protection Box

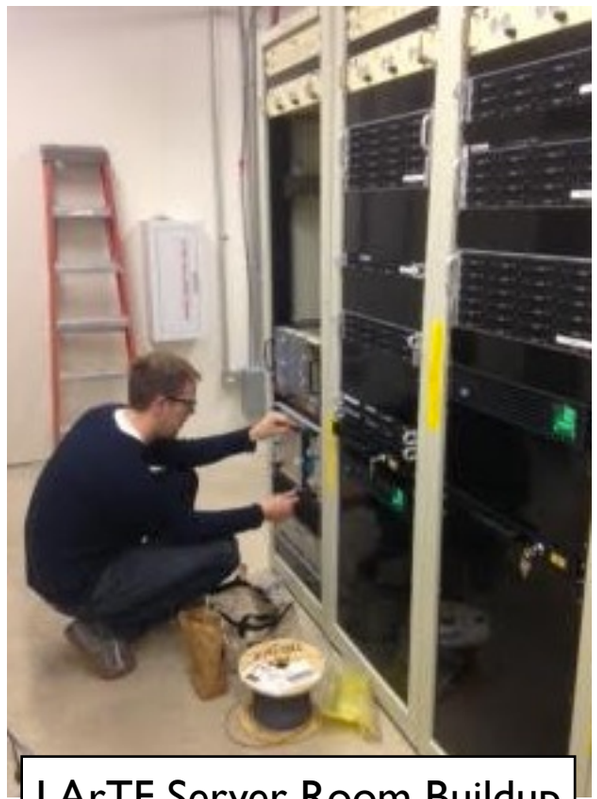


Temperature Sensor

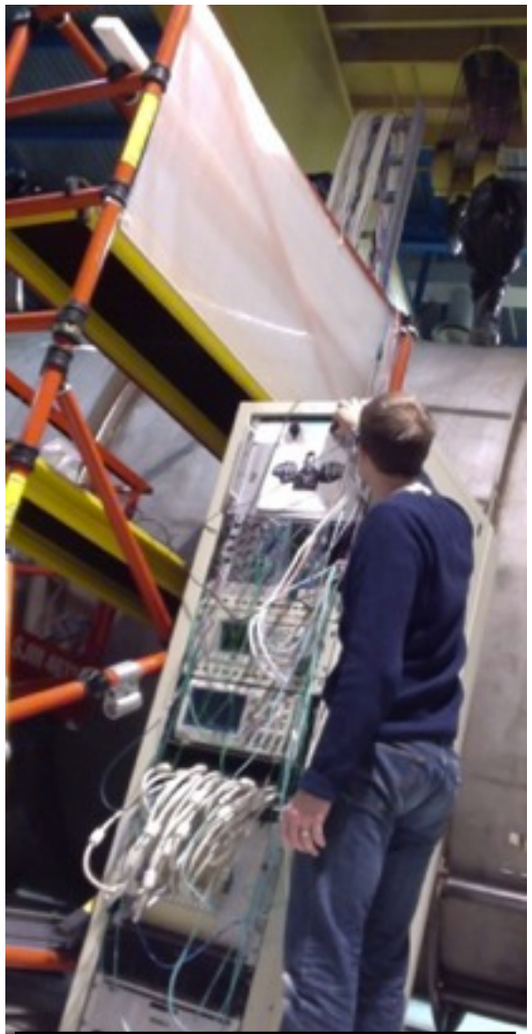




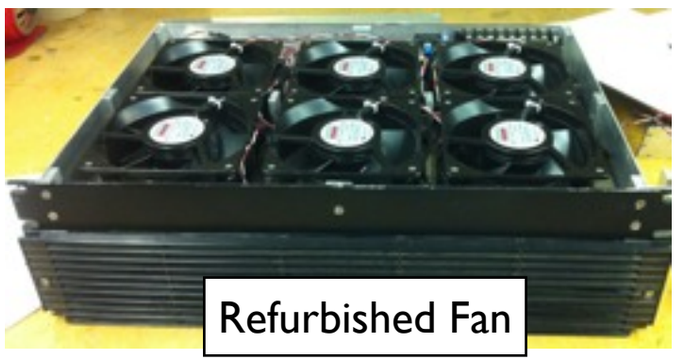
TPC Readout Rack Buildup



LArTF Server Room Buildup



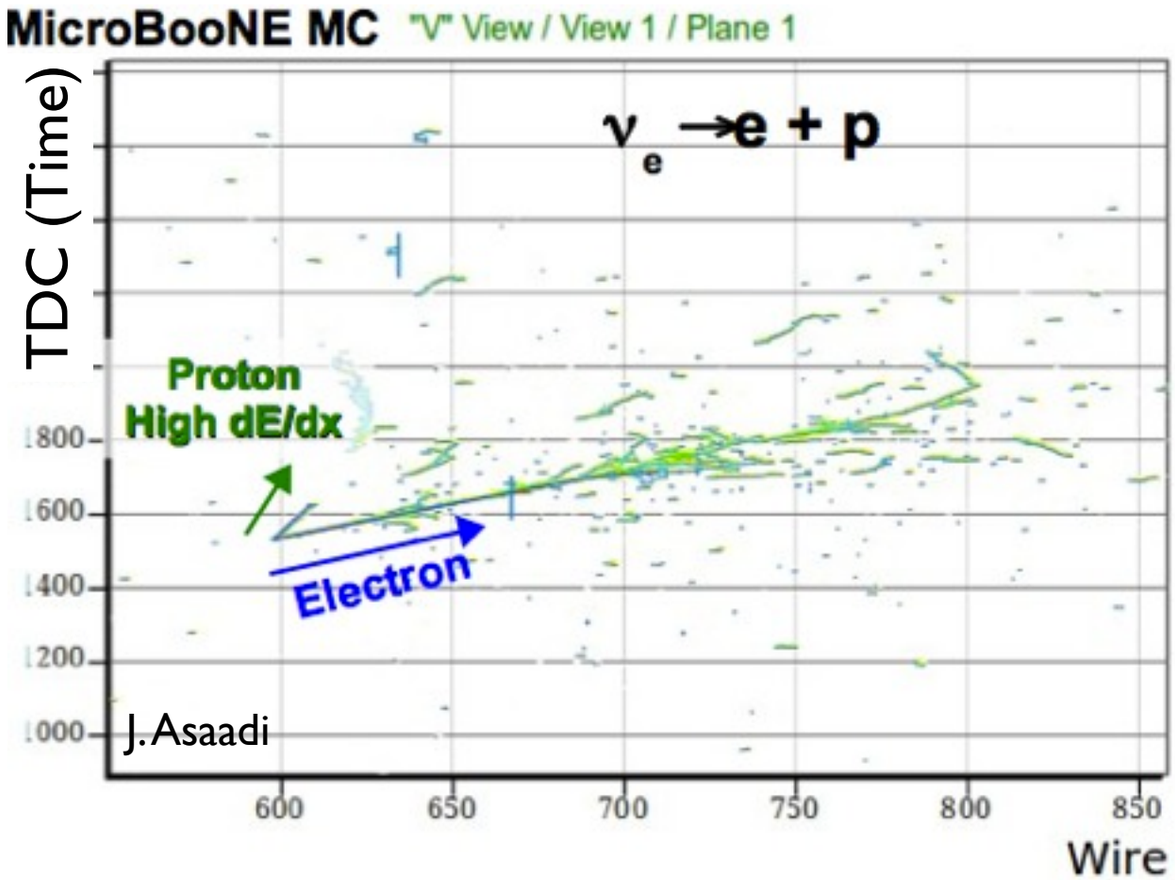
Mr. T: TPC Electronics Pre-Commissioning Stand

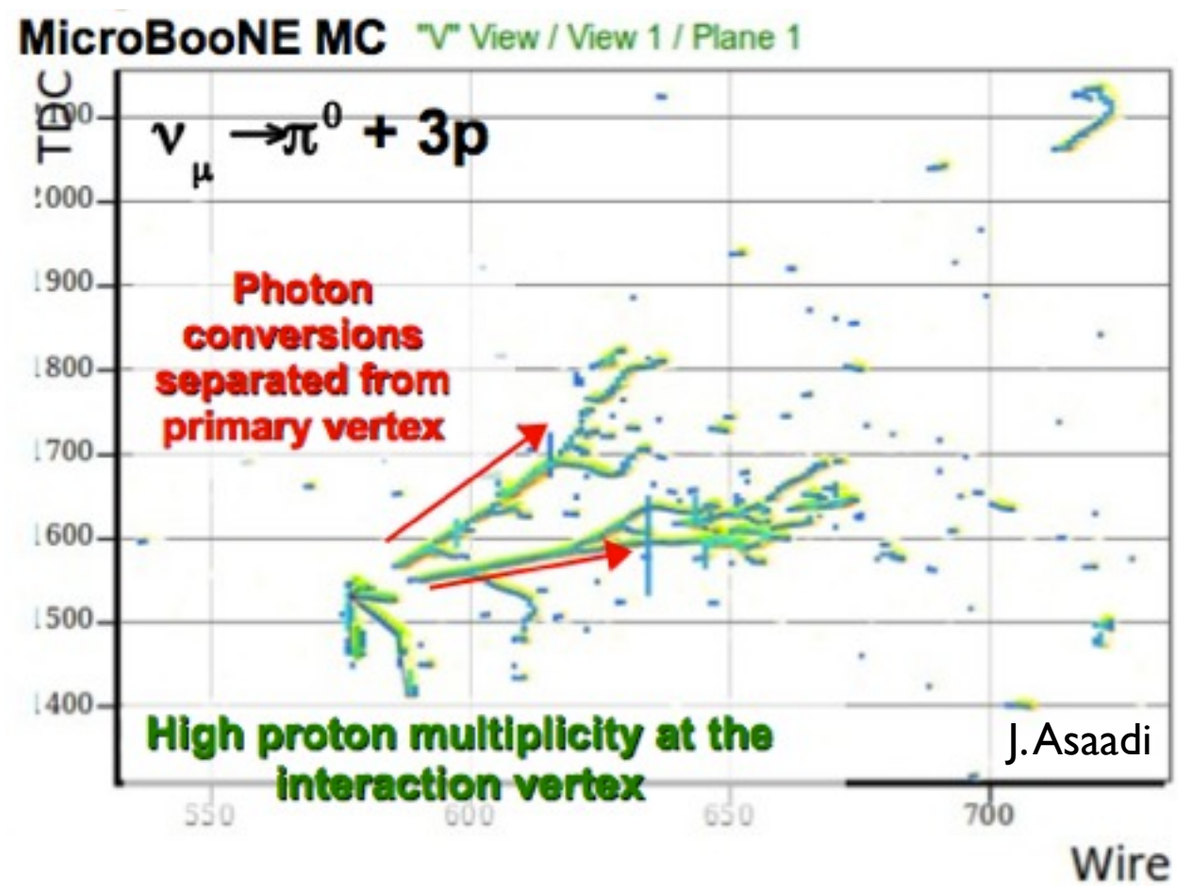


Refurbished Fan

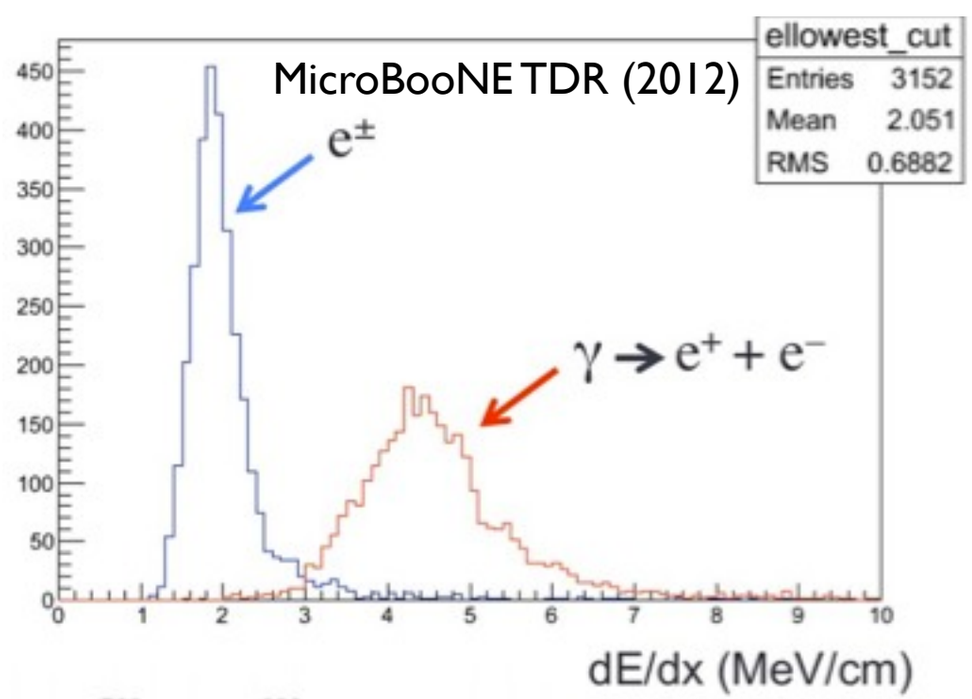
MicroBooNE: LArTPC Detection

- LArTPC provides mm-scale precision 3D projection of ν interaction vertex

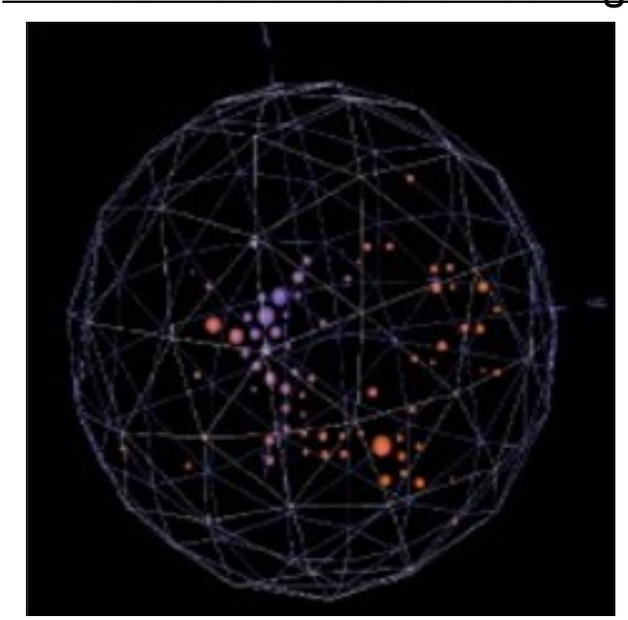




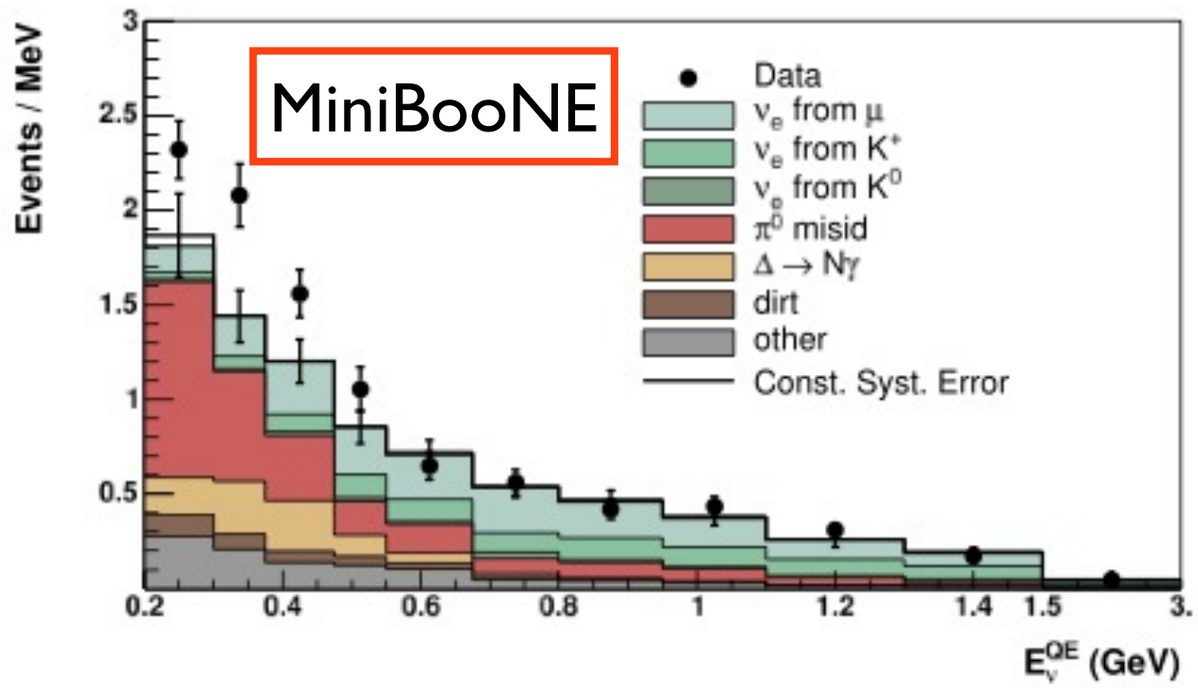
- Topological separation of γ and e^-
- Further discrimination of γ and e^- using deposited energy density near event vertex!

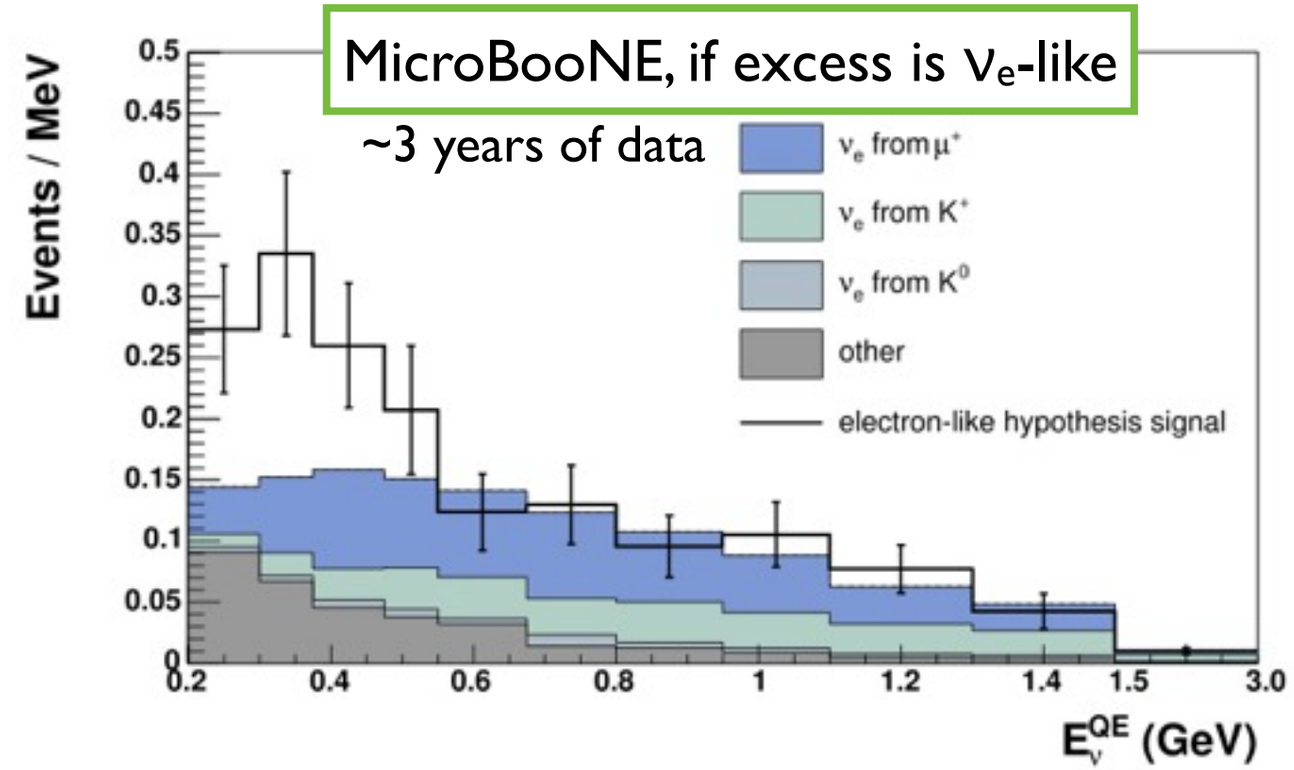


MiniBooNE: Utilize Cerenkov rings

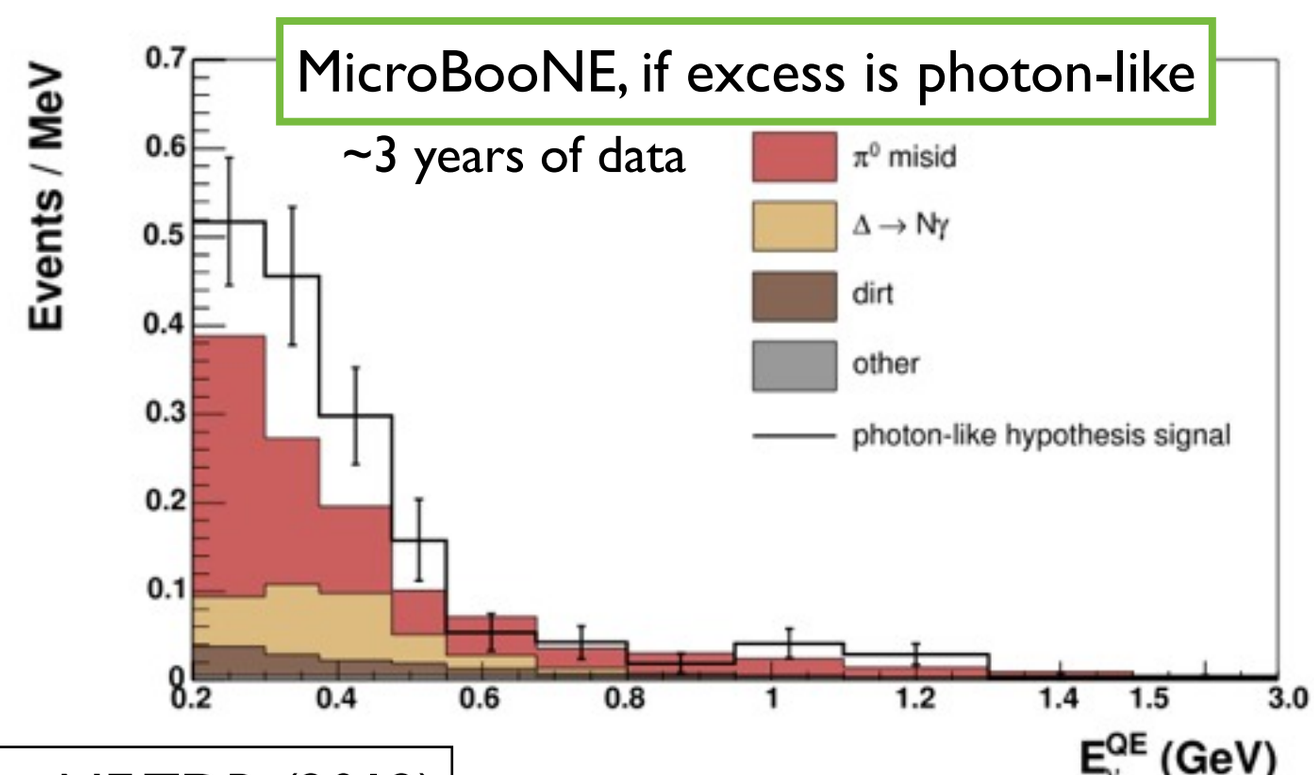


Oscillation Physics Potential





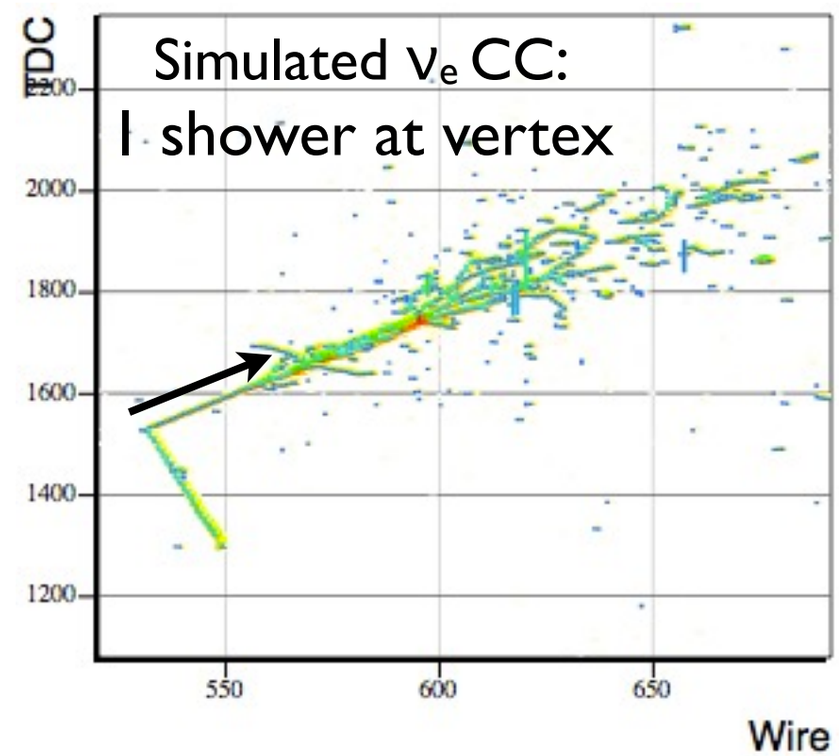
- MicroBooNE event topology and e/γ info will reduce backgrounds regardless of the source of MiniBooNE excess
- If ν_e-like, sensitivity to oscillations significantly improved

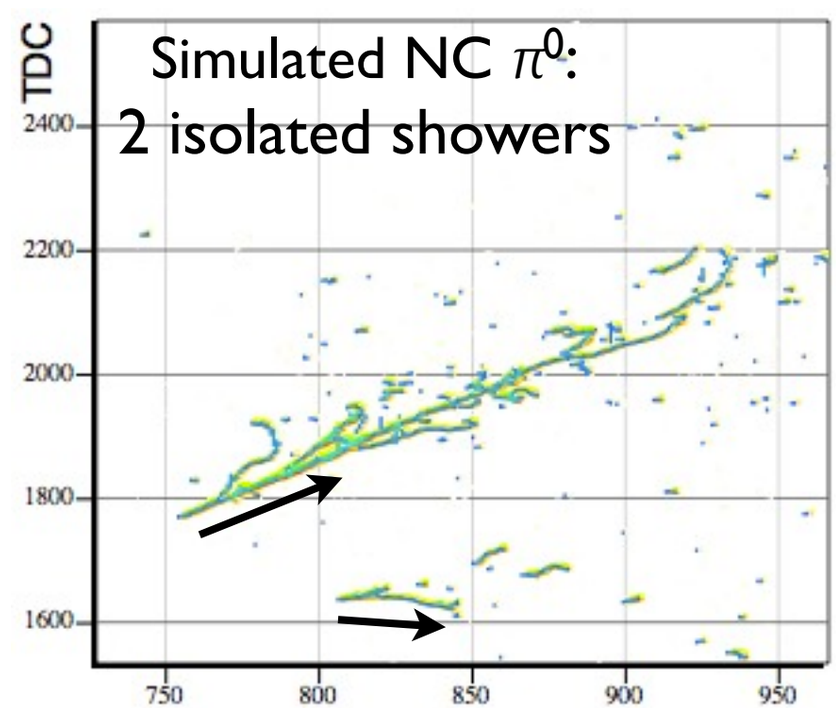


MicroBooNE TDR (2012)

MicroBooNE Oscillation Working Group

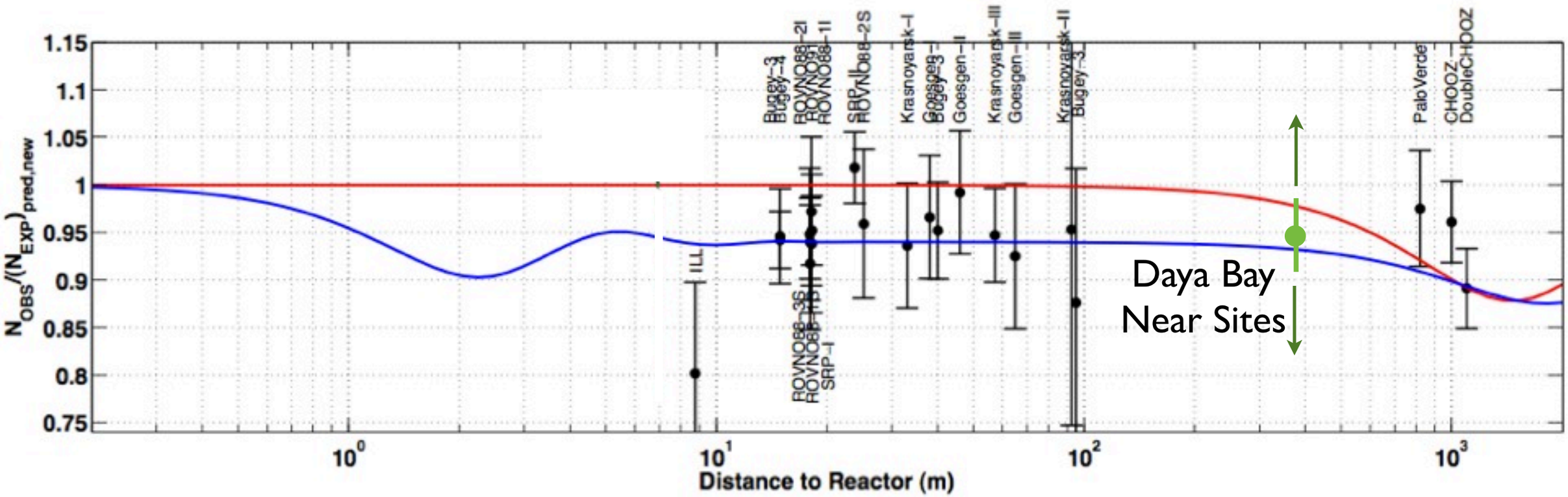
- Currently convening MicroBooNE Oscillation Working Group
- Search for sterile neutrinos will wait for 3 full years of data
- Deliverables in the near term to set this up:
  - Automatically identify showers in simulated data
  - Show that showers look the same with simulation and data
  - Show that we can separate e/γ events in real data
- Lots of data quickly available to reach these goals
  - For example: ν_μ NC π^0: > 2,000/year





Sterile ν Mystery at Daya Bay

- First 'post-anomaly' check on reactor flux normalization



- Key input: absolute detection efficiency
- Currently leading this analysis
  - Results coming soon!

Detector

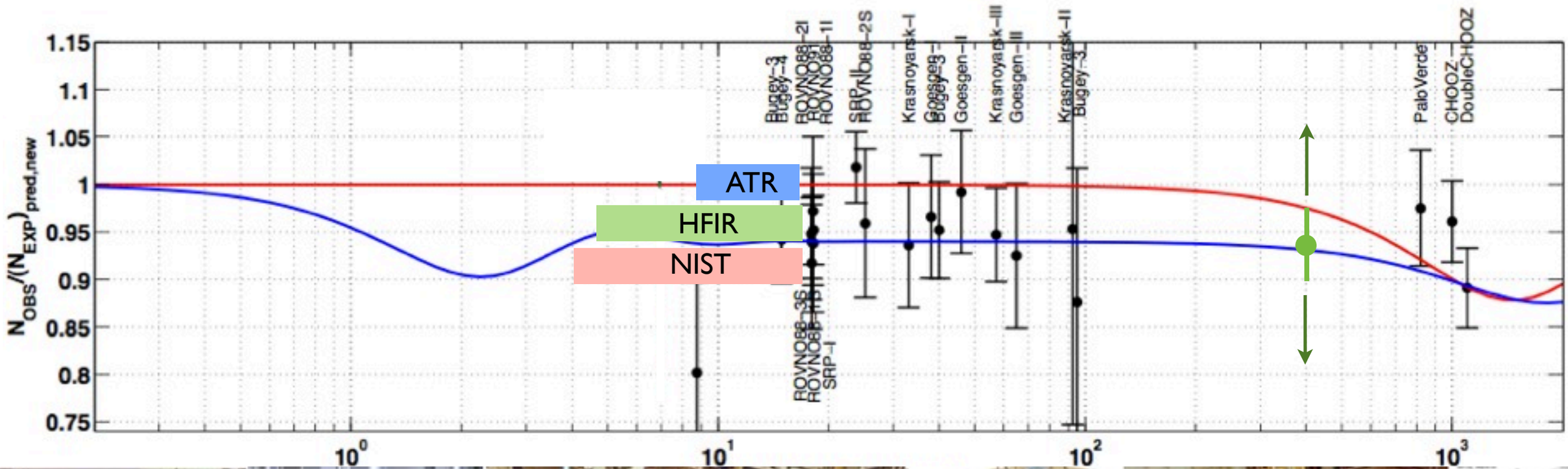
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.9%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

PRL 108 (2012), 171803

Need New Data-Driven Estimates!!

Sterile ν Mystery at PROSPECT

- Daya Bay L/E not right to see reactor spectral distortion
- US research reactors provide a venue for oscillation searches at shortest-ever reactor baselines (highest-ever reactor L/E)

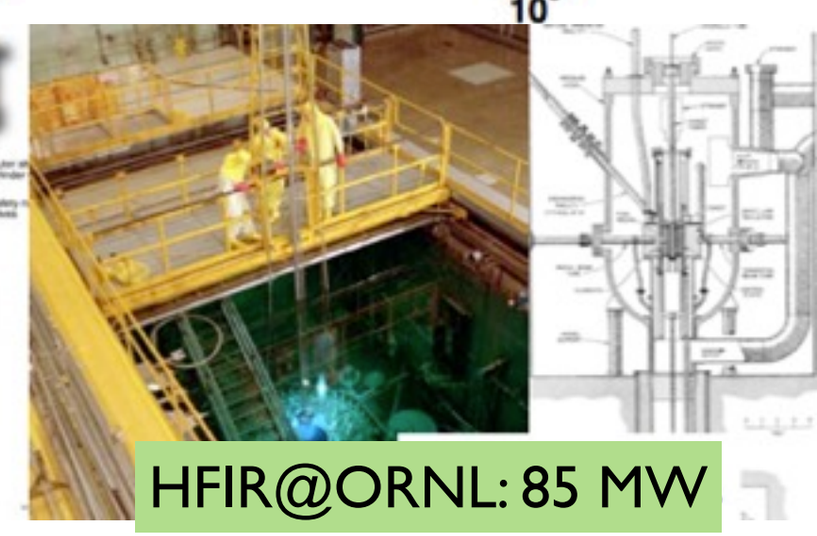


NBSR@NIST: 20 MW

Gaithersburg, MD

ATR@INL: 110 MW

Idaho Falls, ID



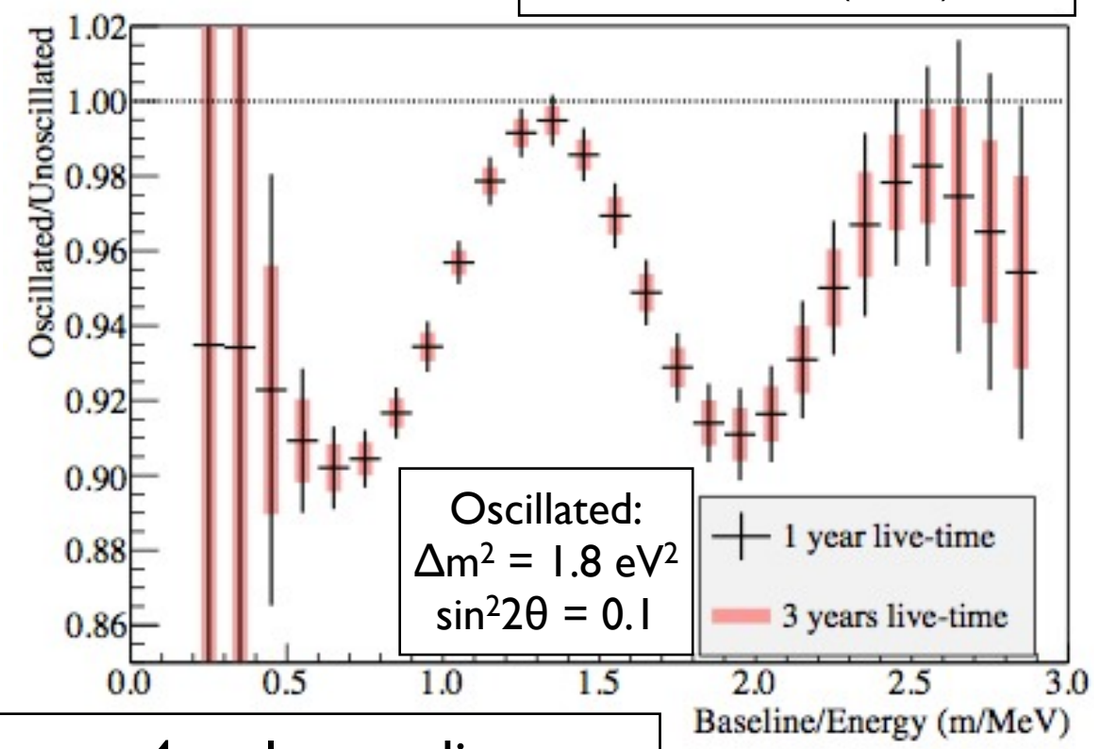
HFIR@ORNL: 85 MW

Oak Ridge, TN

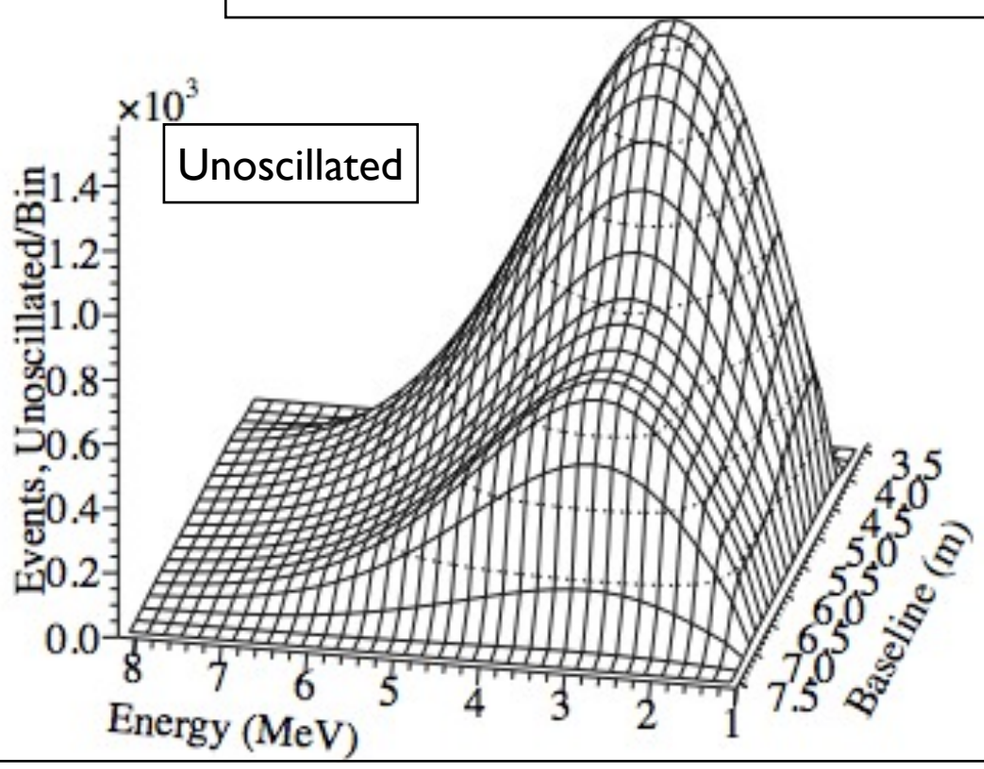
Short-Baseline Reactor Signal

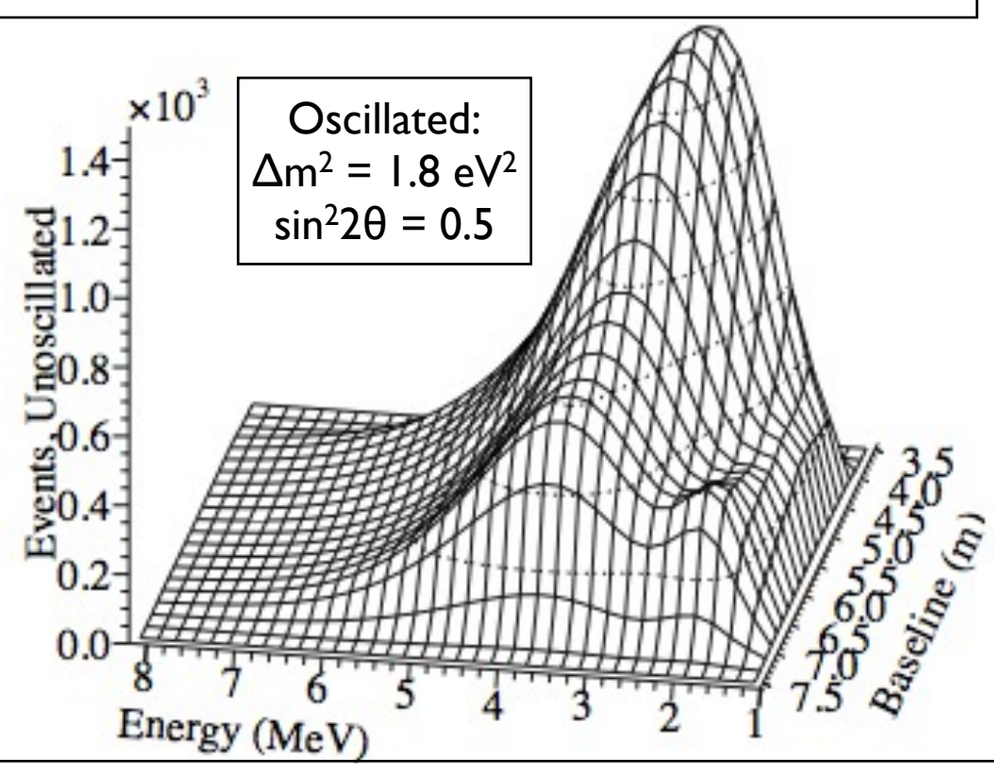
- Detect reactor neutrinos via inverse beta decay interaction in scintillating detector
- Look for spectral distortions in position, energy
- Segmented detector necessary for sufficient position resolution

Heeger, Mumm, Tobin, BRL
PRD D**87** (2013)



One 3x1x1 m^3 detector, 1m^3 20 MW HEU core, 4m closest distance





30% Efficiency

15cm position resolution

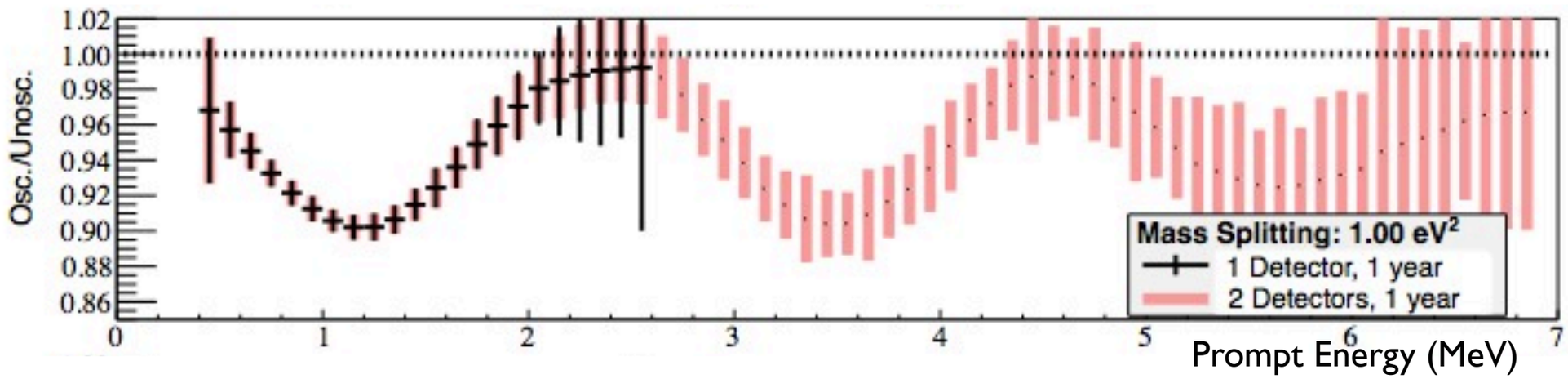
10%/Sqrt(E) Energy Resolution

Multiple Segmented Detectors

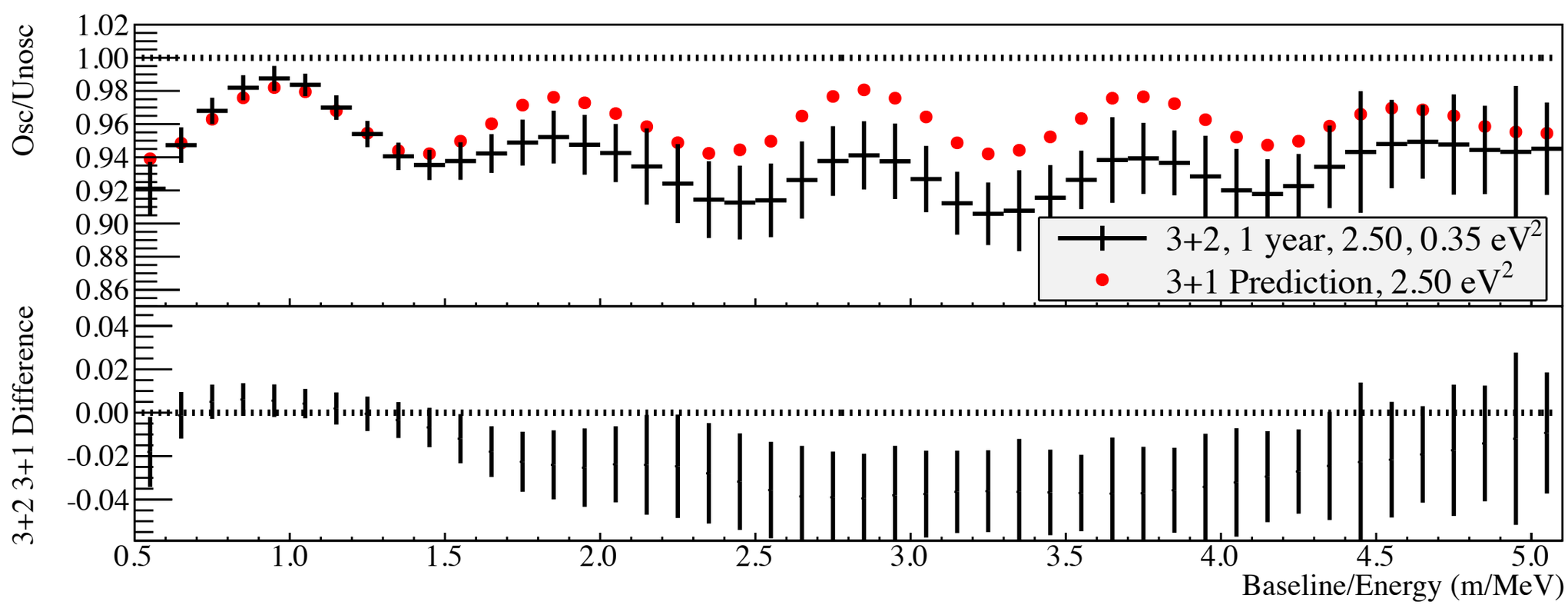
- Multiple detectors give better L/E coverage

Heeger, Mumm, BRL
arXiv:1307.2859 (2013)

  - Example: 2m long detectors at 4 and 15 m closest distances to a 20 MW reactor

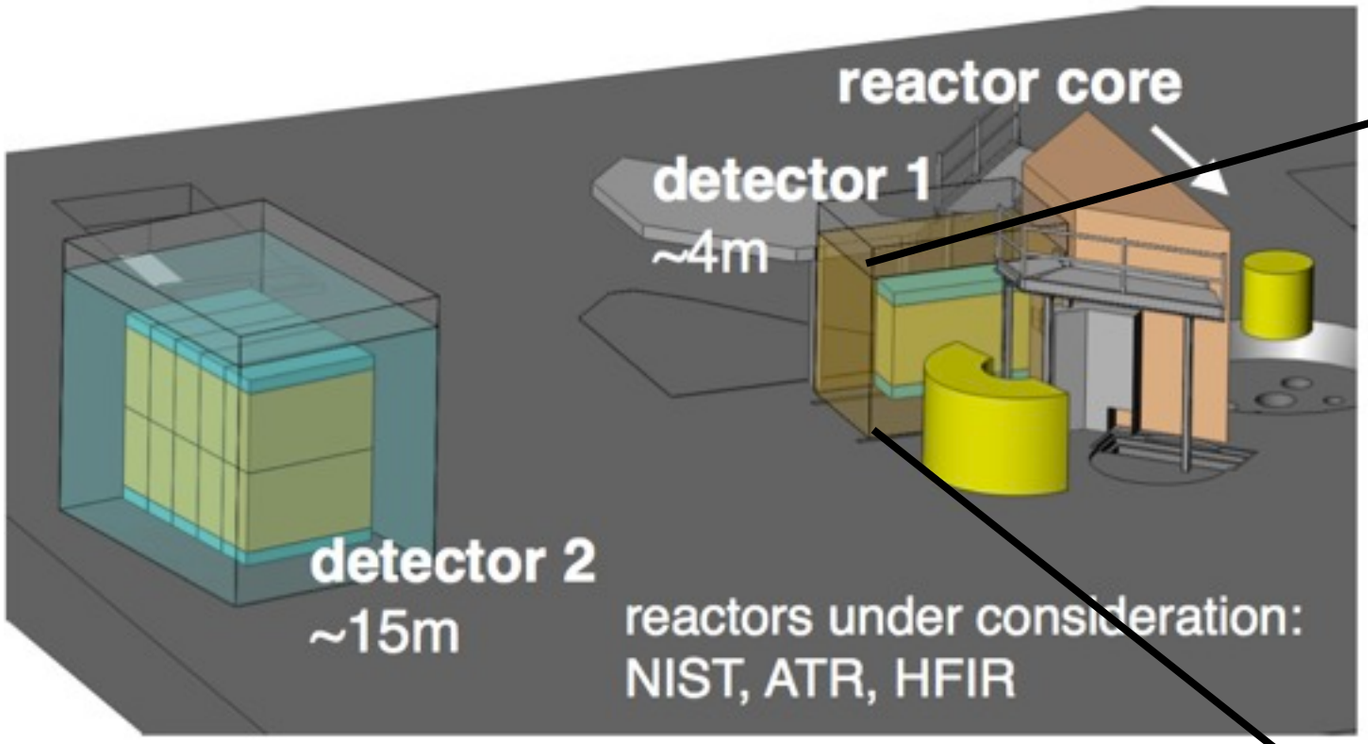


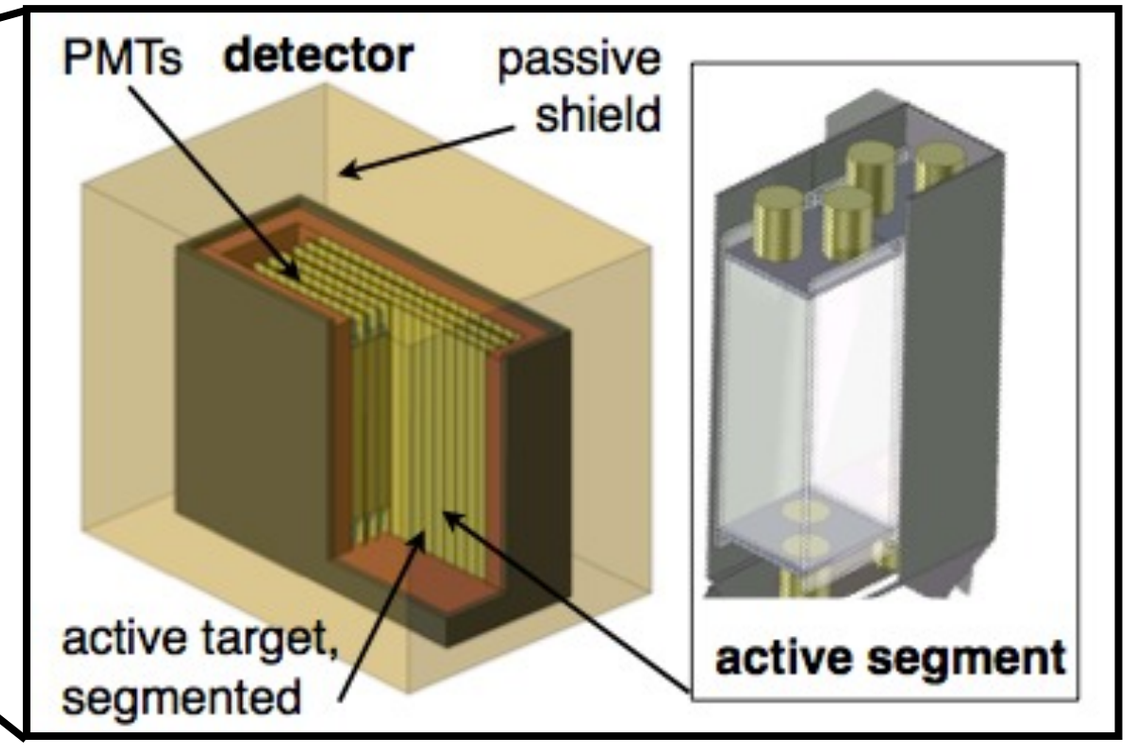
- Ability to distinguish existence of multiple sterile ν!



PROSPECT Conceptual Design

PROSPECT, arXiv:1309.7647 (2014)



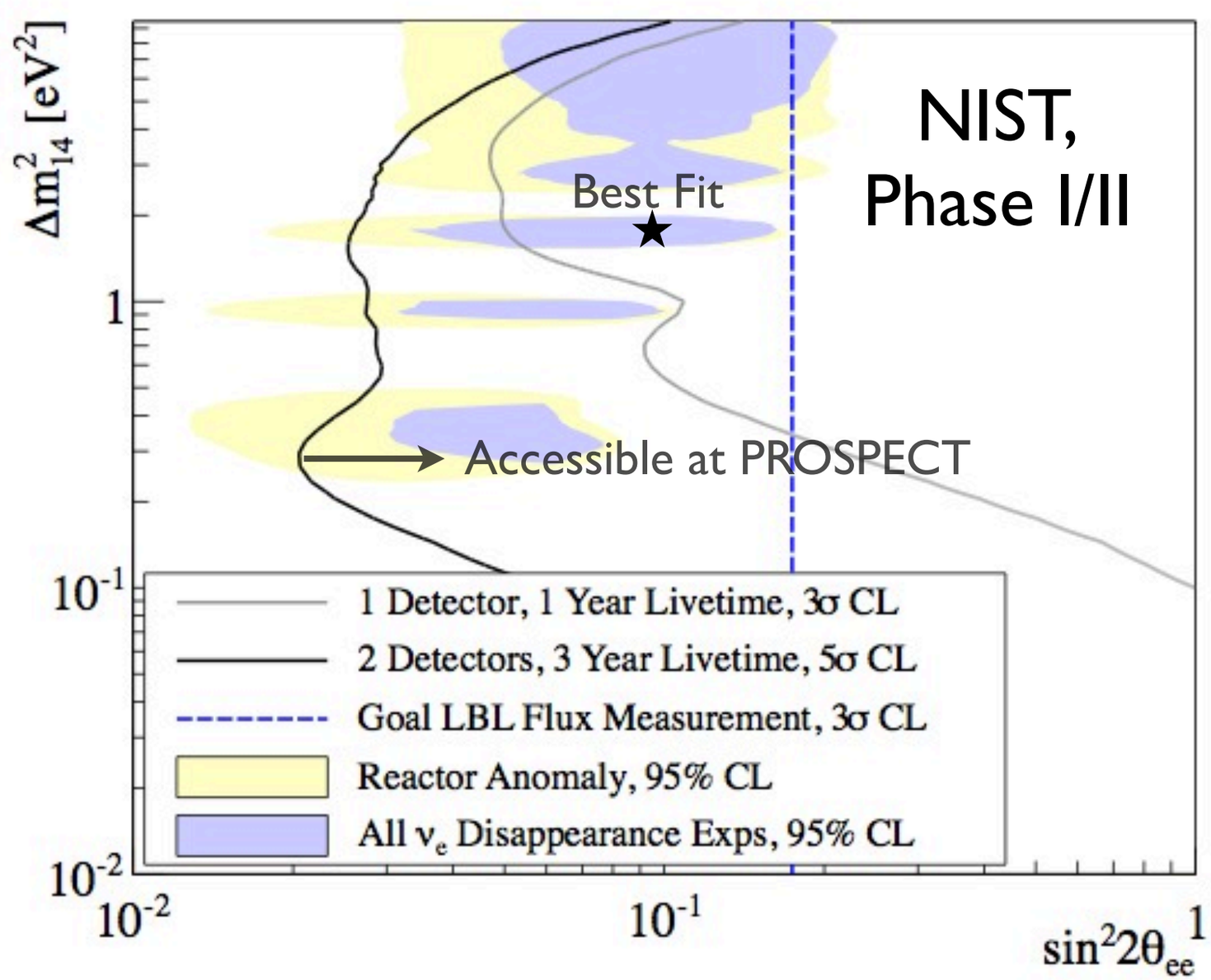


- Two segmented detectors
  - Pursuing plastic, liquid scintillator options: MC being run, with test cells operating soon
  - Cincinnati leading development of detector calibration options
- Can be built in phased approach
  - Phase I: Smaller near detector (~1.6 m^3 target) deployed on a shorter timescale
  - Phase II: Near + Far detector (~16 m^3 target) deployed on a longer timescale
  - Relatively cost effective: small detectors, no civil construction, free ν_e!
- Near and far locations identified at each reactor site
  - CAD, engineering design models already being developed; backgrounds are measured

PROSPECT Oscillation Physics Potential

PROSPECT, arXiv:1309.7647 (2014)

- Excellent discovery potential
  - If new sterile neutrino is where previous experiments suggest, it's very likely we'll see it!
  - Comparable potential for discovery at all three reactor sites
- Competitive in international context in timing and sensitivity



<u>Assumptions</u>

Detection Efficiency: 30%

20cm/10% position/energy resolution

1:1 Signal:Background

1 year Phase I running

3 year Phase II running

Outlook

- Daya Bay: Taking Data
  - Test sterile neutrino hint at reactors by measuring absolute flux (2014)
  - Continue to improve θ_{13} sensitivity through 2015 (or 2017?)*
- MicroBooNE: In Construction
  - Detector will begin taking data in 2014
  - Precise search for ν_e appearance 3 years of data*
- PROSPECT: In Development Phase
  - Aim to start running near detector in next few years
  - Two-detector multiple-year dataset to definitively search for sterile ν *
- A decade of exciting physics, coming right up!

* : PhD Theses!

Other Physics Opportunities

- MicroBooNE
  - Cross-section physics: Does Standard Model predict right ν interaction rates? *
  - Nuclear structure: Do nucleons stick together in pairs? *
- PROSPECT
  - Absolute reactor spectrum: what neutrinos are created in a reactor? *
  - Nuclear non-proliferation: can we precisely monitor operation of nuclear reactors with on-surface detectors? *

* : PhD Theses!

Conclusions

- Neutrinos and their flavor oscillations have proved to be fascinating remedies to puzzling mysteries in particle physics
- Using oscillation to address today's big puzzles at Daya Bay, MicroBooNE, and PROSPECT
- Many diverse and exciting results to look forward to over the next decade!

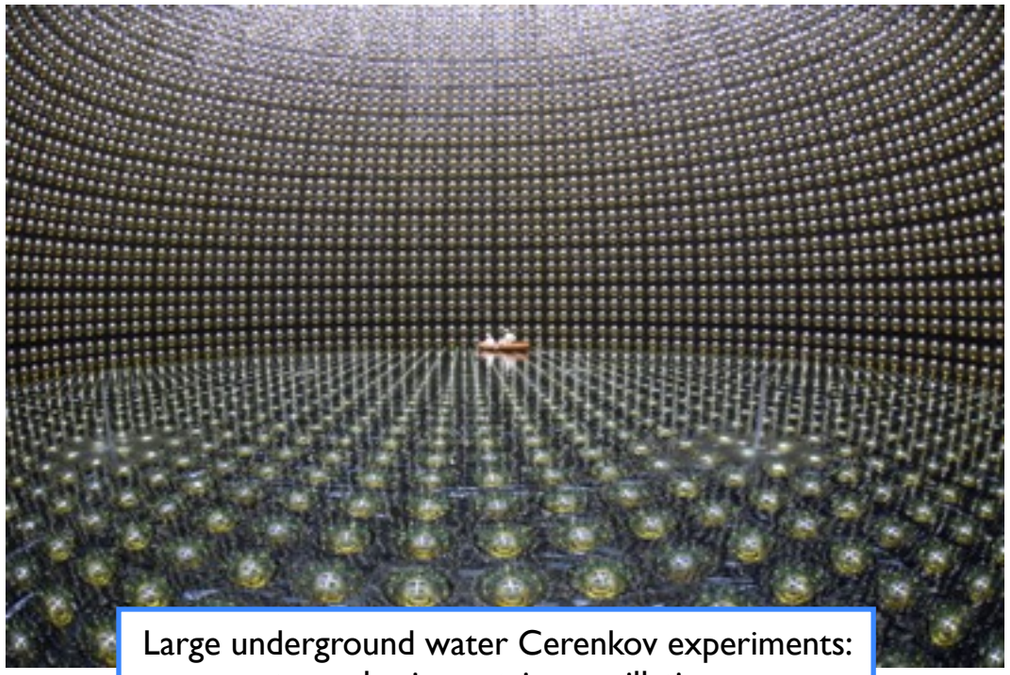
Thanks for your attention!

BACKUP

PhD Theses

- Daya Bay
  - θ_{13} rate+shape measurement with full Daya Bay dataset
  - Absolute spectrum measurement with full Daya Bay dataset
  - Absolute flux measurement with full Daya Bay dataset
  - Time evolution of reactor spectrum with full Daya Bay dataset
- MicroBooNE
  - Precise ν_e appearance test with 3 years of data from BNB beam
  - ν_μ disappearance search with full 3 year dataset
  - Sterile search via neutral current interaction deficit: In combo with LAr1?
- PROSPECT
  - Oscillation search with full Phase I dataset
  - Oscillation search with partial and full Phase II datasets
  - Absolute spectral measurement with PROSPECT
  - At-surface reactor monitoring with the PROSPECT detector
  - First detection of spent fuel neutrinos for nuclear non-proliferation

20+ Years of Neutrino Oscillations



Large underground water Cerenkov experiments: atmospheric neutrino oscillations

K2K, MINOS, T2K, NOvA; Long-Baseline Oscillations

The Hunt For θ_{13}:, Double Chooz, Daya Bay, RENO, etc.

1980s

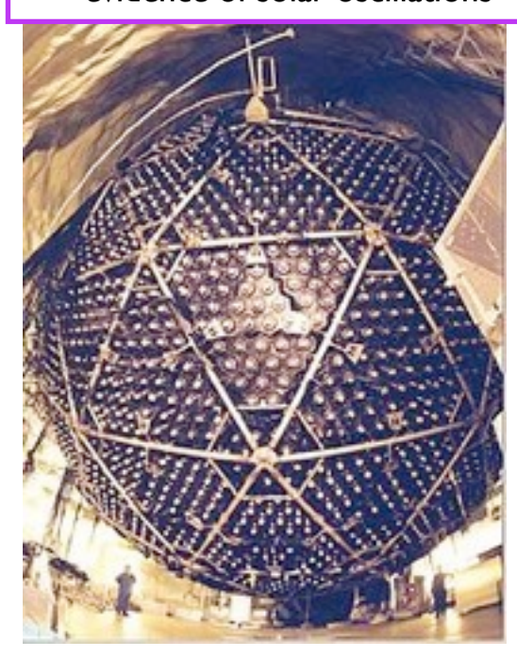
1990s

2000s

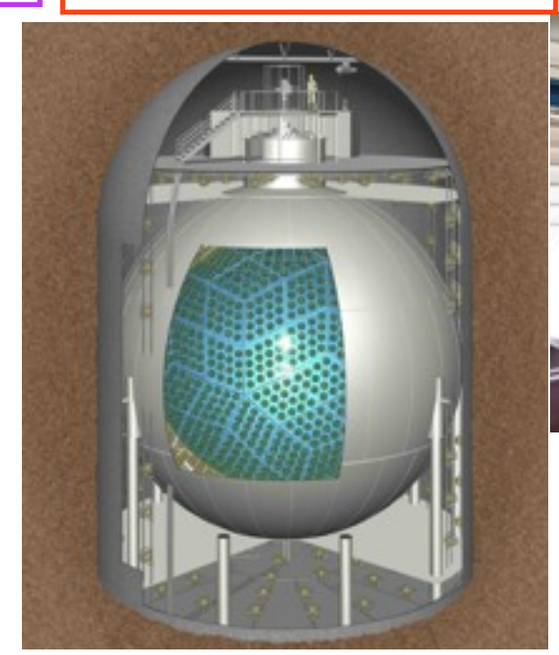
2010s

Large-Δm^2 Mixing: LSND and MiniBooNE

SNO: Solves solar neutrino problem, evidence of solar oscillations



KamLAND: First reactor neutrino oscillations



LAr@Fermilab: MicroBoone, LBNE

Can we use neutrino oscillations to solve today's big mysteries?

Formulas for Energy Reconstruction

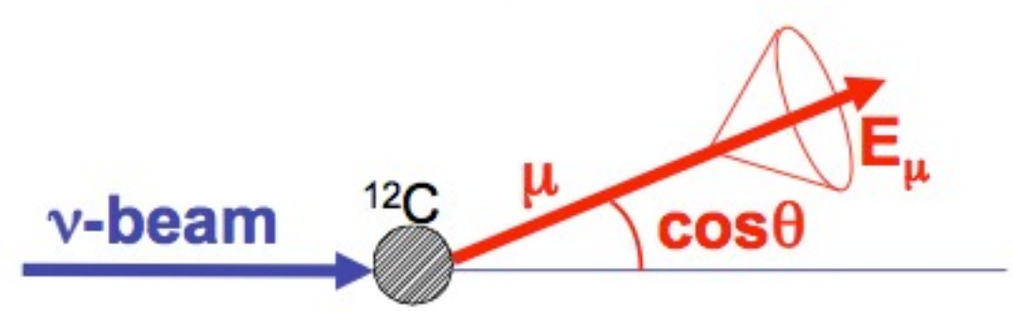
- Daya Bay
  - Minimum energy of 1.8 MeV needed to make neutron and positron
  - Momentum conservation means positron gets almost all kinetic energy

$$E_{prompt} = E_{\overline{\nu}_e} + (m_n - m_p) + m_{e^-}$$

- MicroBooNE
  - Not such a simple picture at higher energy; both target an lepton get significant amounts of momentum
  - In addition, interacting proton is bound in a nucleus
  - Need to measure lepton energy AND angle to get neutrino energy

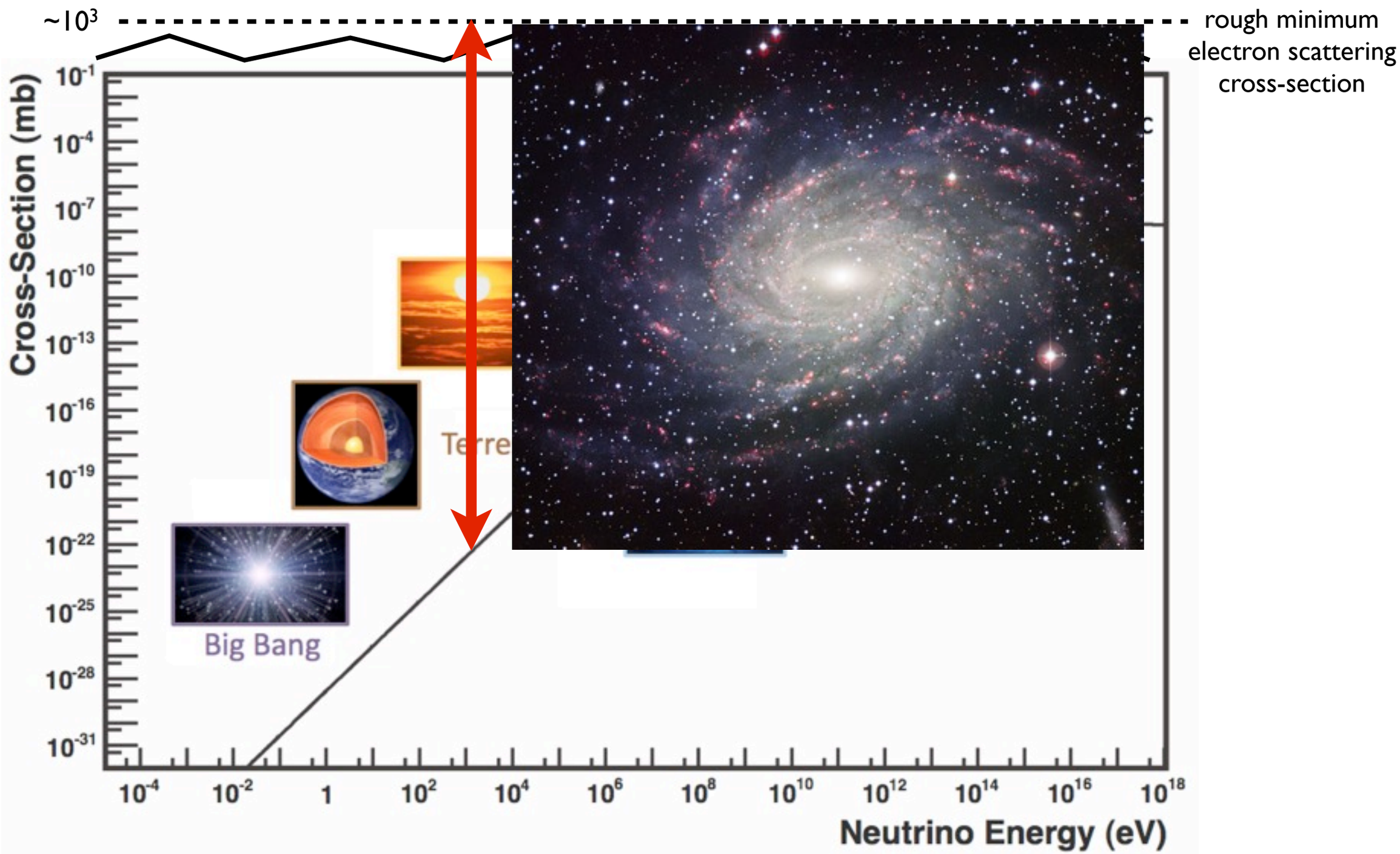
$$E_\nu^{QE} = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$



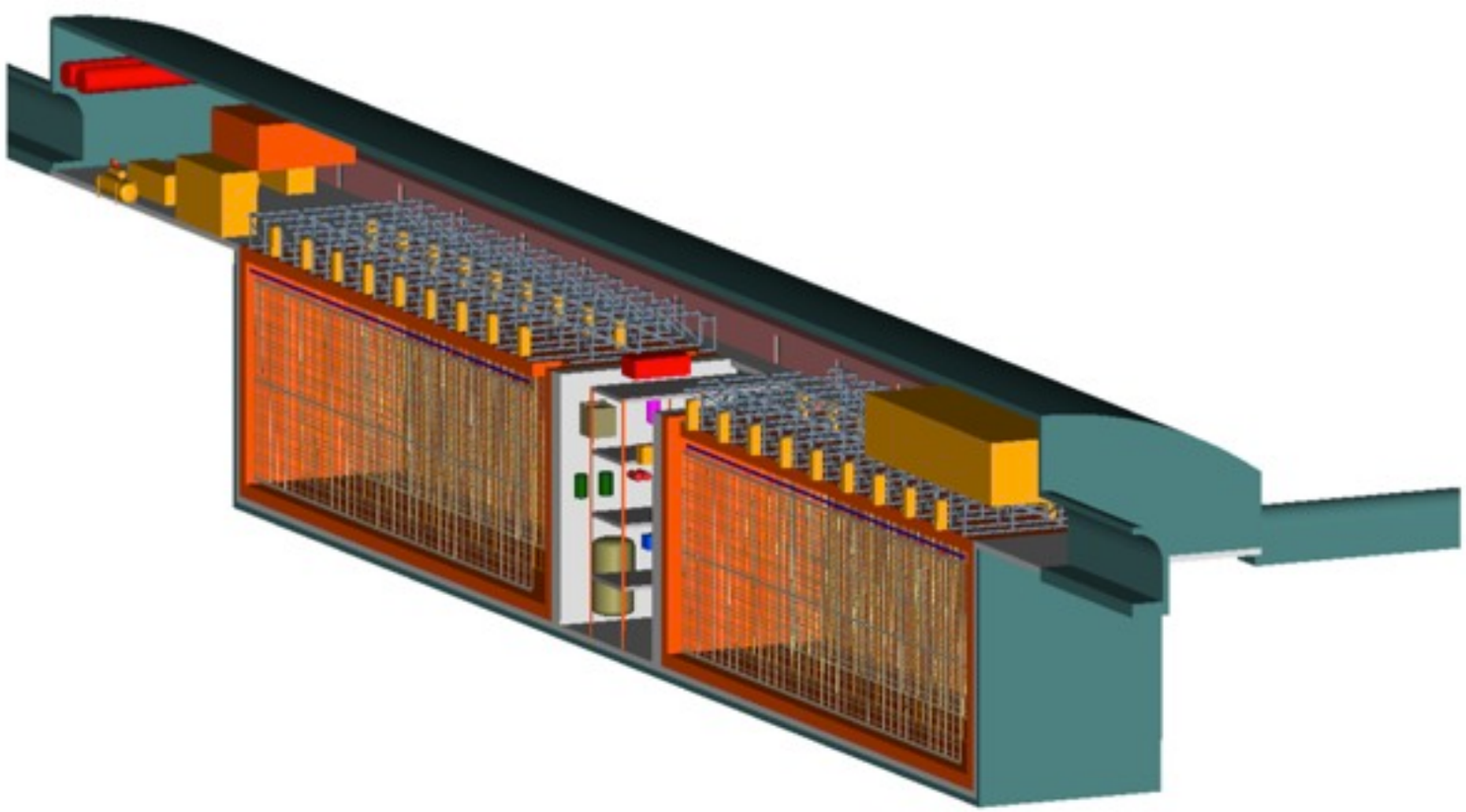
Neutrino Varietals

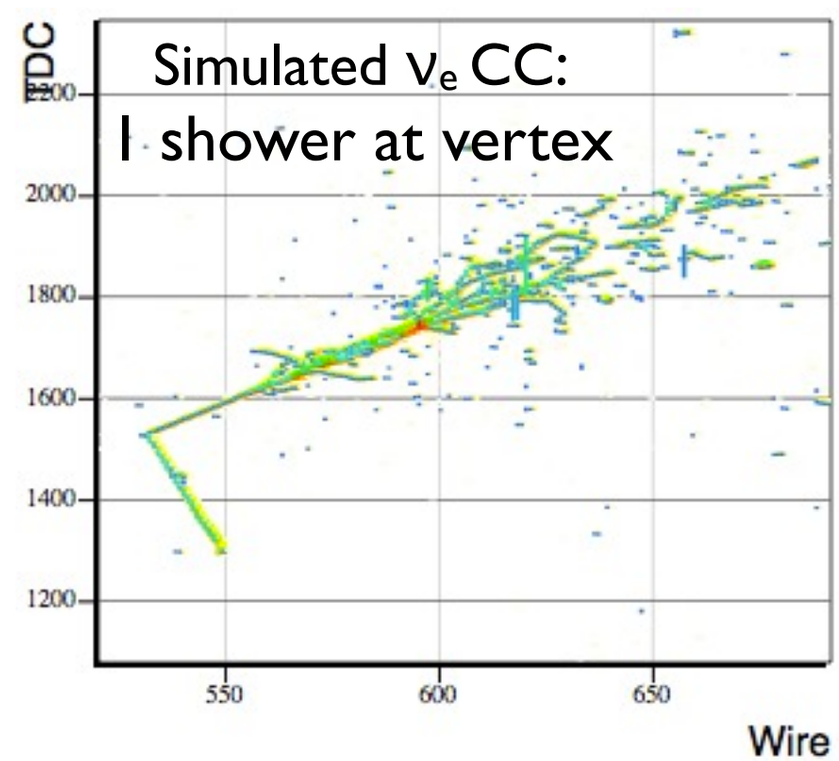
- Many neutrino sources and energies, interacting via weak force
  - ~1 paper sheet stops a <1 MeV electron; 10^{25} sheets to stop 1 MeV ν!



LBNE

- LBNE will be LArTPC, building on MicroBooNE design
  - 34 kiloton -- 200 times larger than MicroBooNE!!!
- LBNE will look for ν_e appearance, just like MicroBooNE
  - At L/E closer to 500 m/MeV, looking for Δm^2_{31}-mediated mixing
  - Appearance at these L/E is dependent on CP-violating phase δ
- 10 years to build, 20 years of taking data

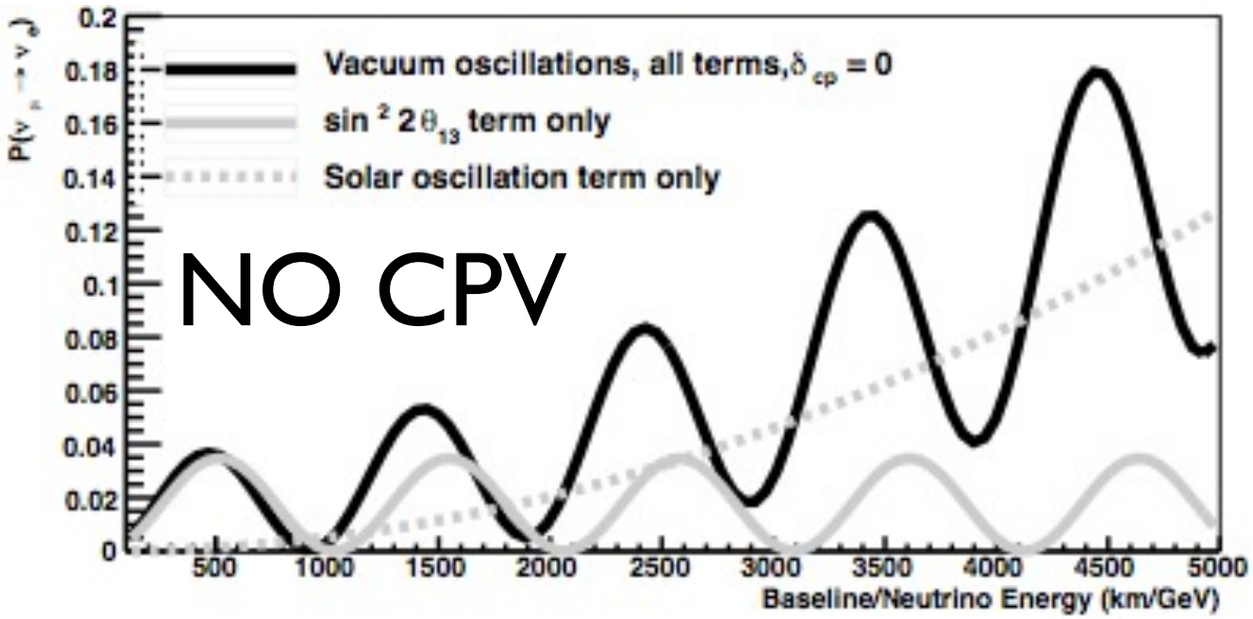


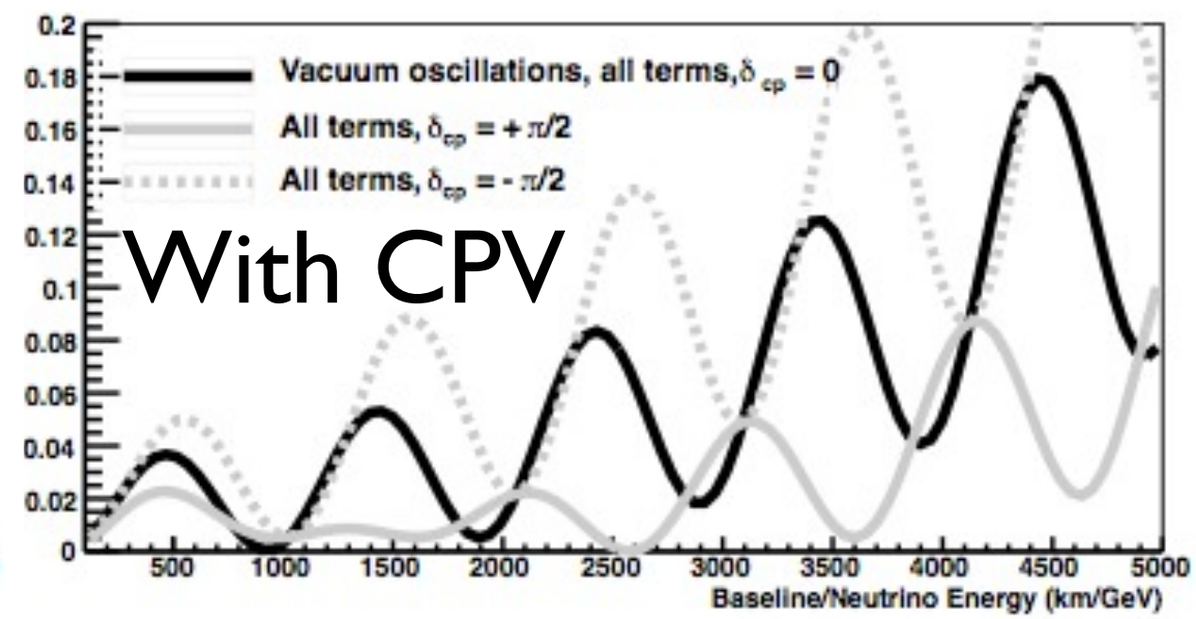


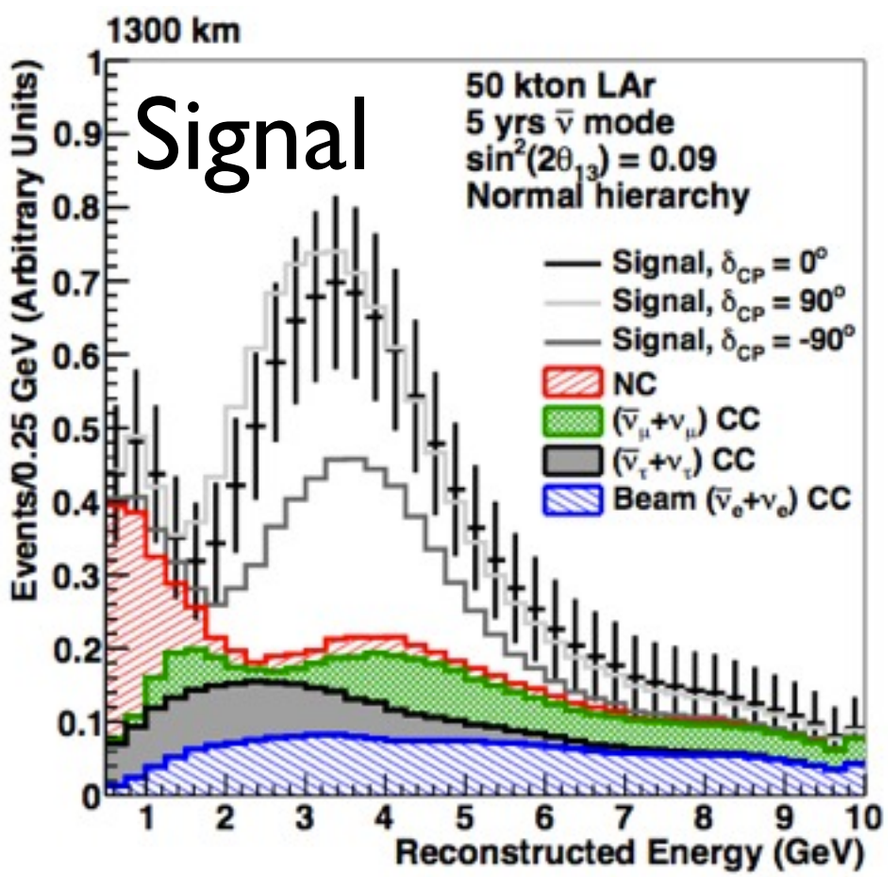
LBNE Oscillation Physics

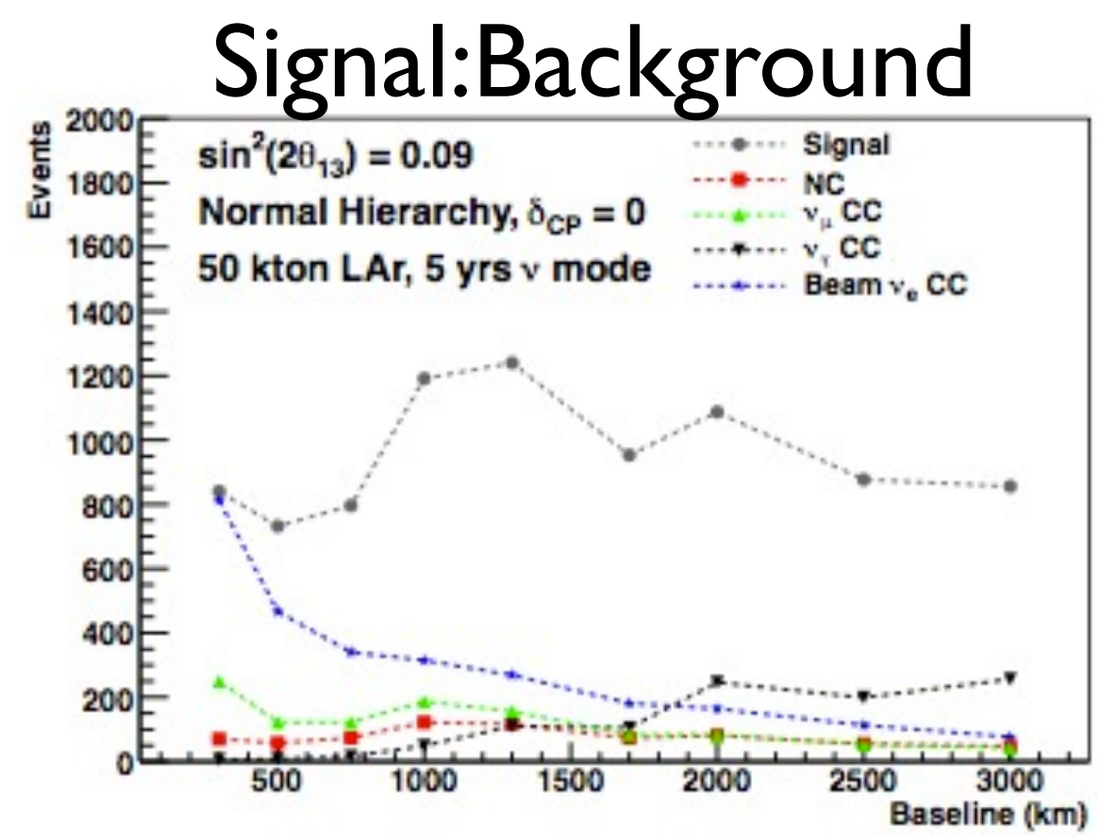
- Looking for ν_μ to ν_e, affected by CPV phase

arXiv:1311.0212









Reactor Flux Models

Antineutrino flux S(E) from each reactor used to predict IBDs at each detector

	^{235}U	^{238}U	^{239}Pu	^{241}Pu
AD 1	63.3	12.2	19.5	4.8
AD 2	63.3	12.2	19.5	4.8
AD 3	61.0	12.5	21.5	4.9
AD 4	61.5	12.4	21.1	4.9
AD 5	61.5	12.4	21.1	4.9
AD 6	61.5	12.4	21.1	4.9

Approximate percentage of IBDs from each fission isotope at each detector

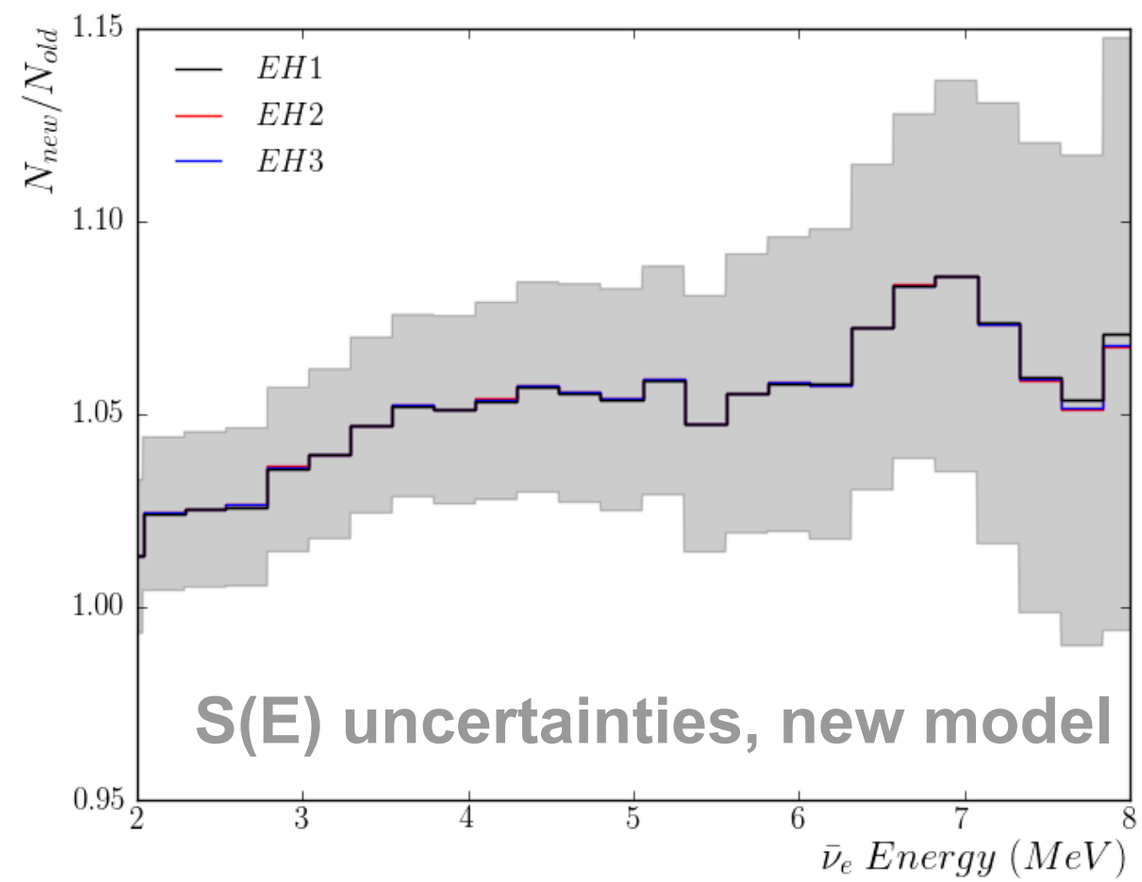
New model:

P. Huber, Phys. Rev. C84, 024617 (2011),
T. Mueller et al., Phys. Rev. C83, 054615 (2011)

Old model:

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys Rev Lett. B218, 365 (1989)
P. Vogel et al. Phys. Rev. C24, 1543 (1981)

New/Old flux model difference in unoscillated IBD prediction by hall



Flux model has negligible impact on far vs. near oscillation measurement

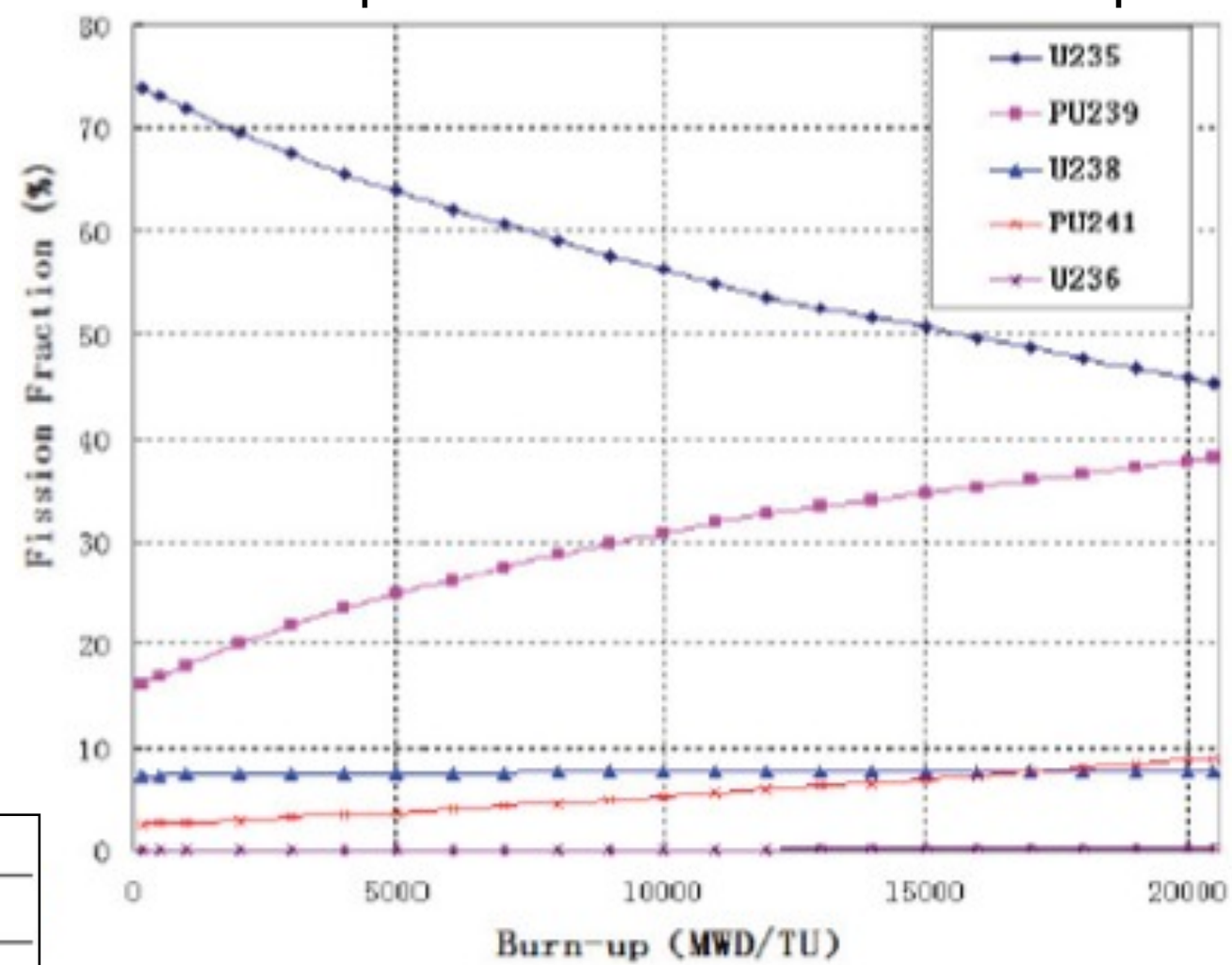
Reactor Antineutrino Flux Predictions

Reactor flux uncertainty ALMOST completely cancels.
Must estimate antineutrino flux from each reactor.

$$N_{det} = \frac{N_p}{4\pi L^2} \int \epsilon \sigma P_{sur} S dE$$

- **Inputs:**
- Reactor operators provide:
  - Thermal power: W_{th}
  - Fission fractions f_i
- Energy per fission: e_i
  - V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)
- Antineutrino spectra per fission: $S_i(E_{nu})$
  - Many varied models have negligible effect on near-far relative measurement

Isotope fission rates vs. reactor burnup



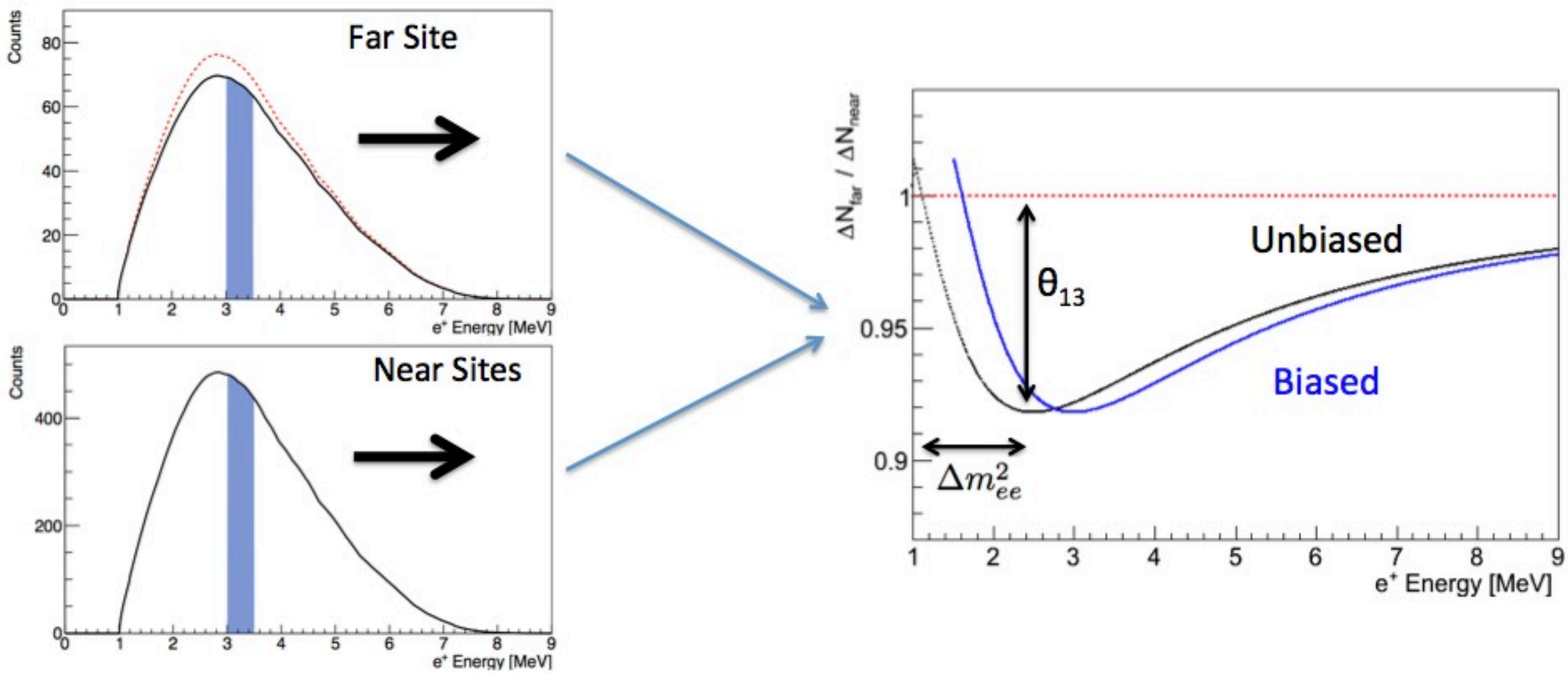
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\bar{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

TABLE III. Summary of systematic uncertainties.

Uncorrelated uncertainties are further reduced by ~1/20 for near/far measurement

Energy Response: Absolute Calibration

Absolute energy shift common between detectors can also bias measured oscillation



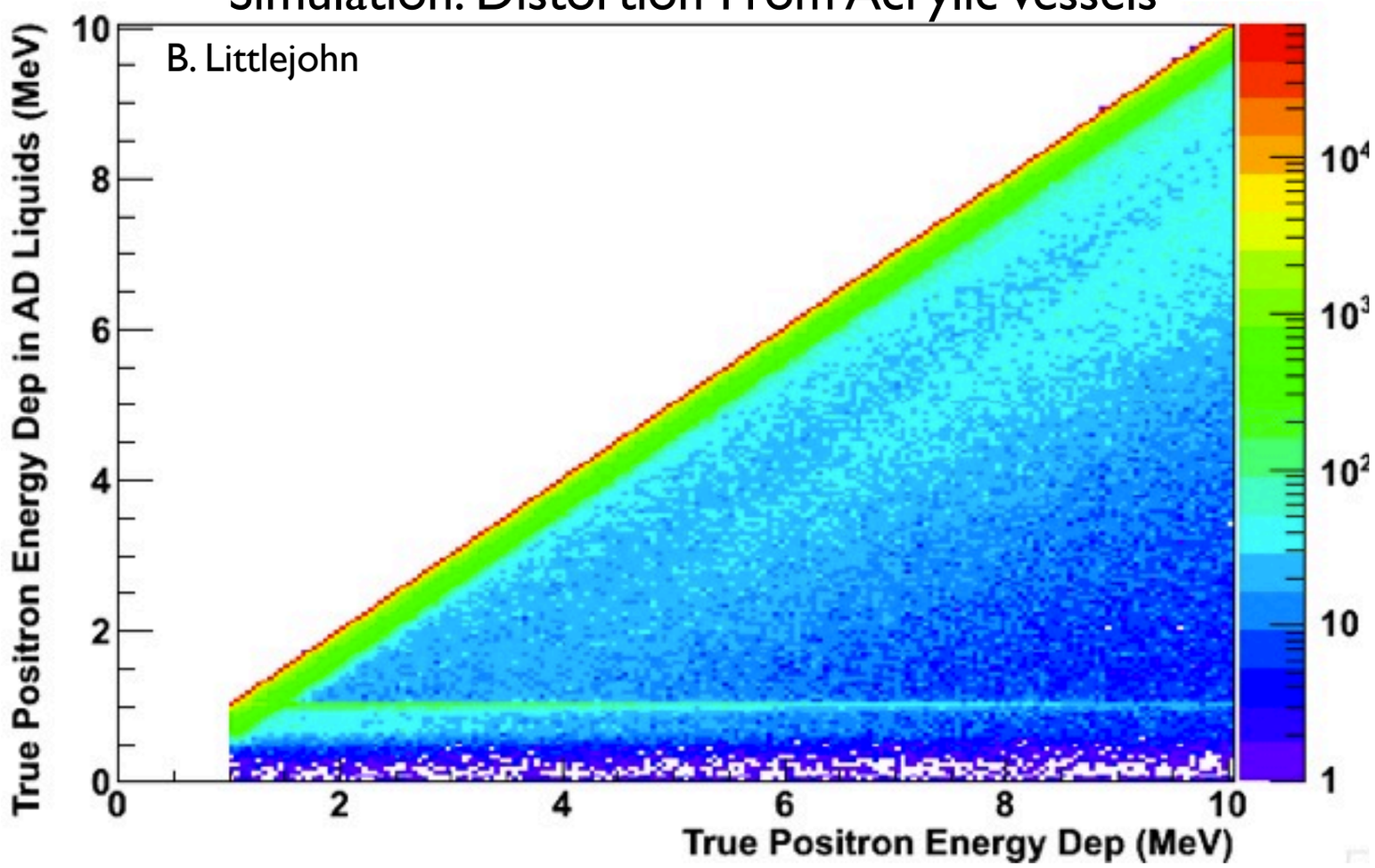
Requires detailed translation between true and detected energies

Another major focus of Cincinnati's Daya Bay efforts

Absolute Detector Response Model

- Start with predicted reactor neutrino spectrum
- Necessary corrections to get prediction of detected spectrum:
  - Distortion: missing energy deposited in non-scintillating acrylic vessels
  - Broadening: light production/collection not linear with energy
  - Smearing: energy resolution

Simulation: Distortion From Acrylic Vessels



Absolute Detector Response Model

True e^+ energy from fissions, IBD interaction

Energy Leakage Model

Deposited e^+ energy

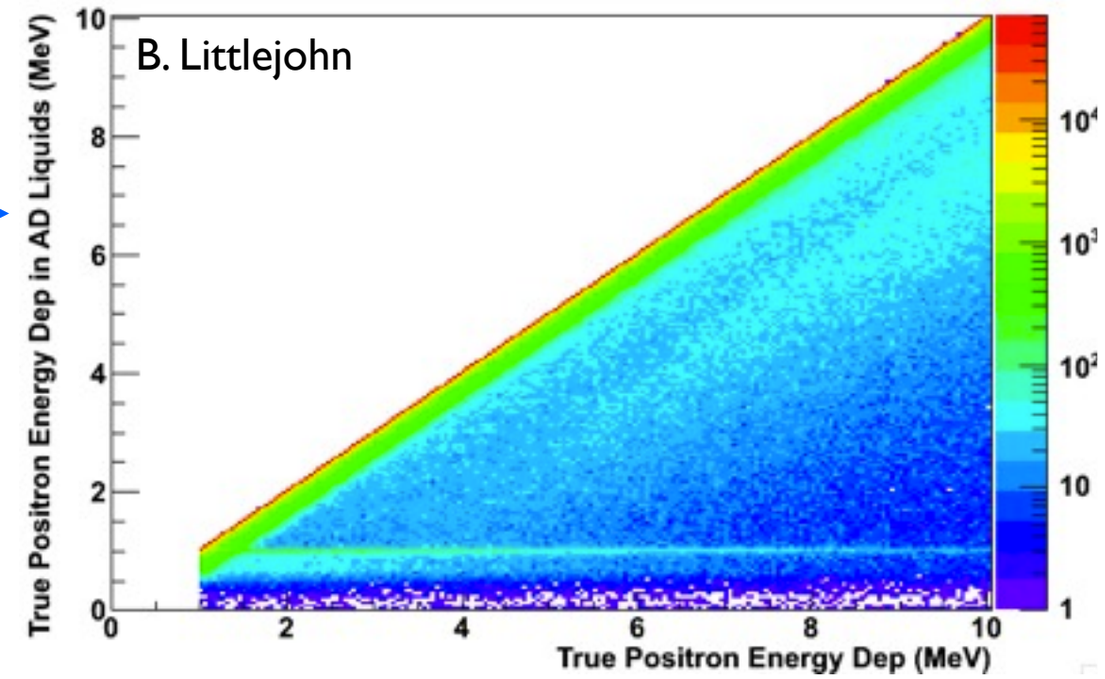
Scintillator + Electronics Non-linearity

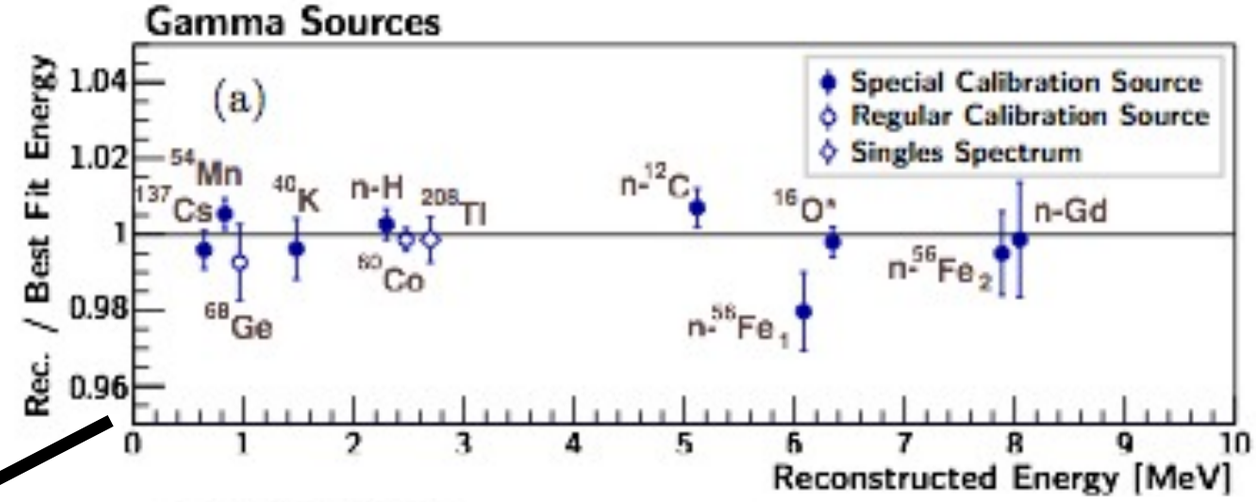
Visible e^+ energy

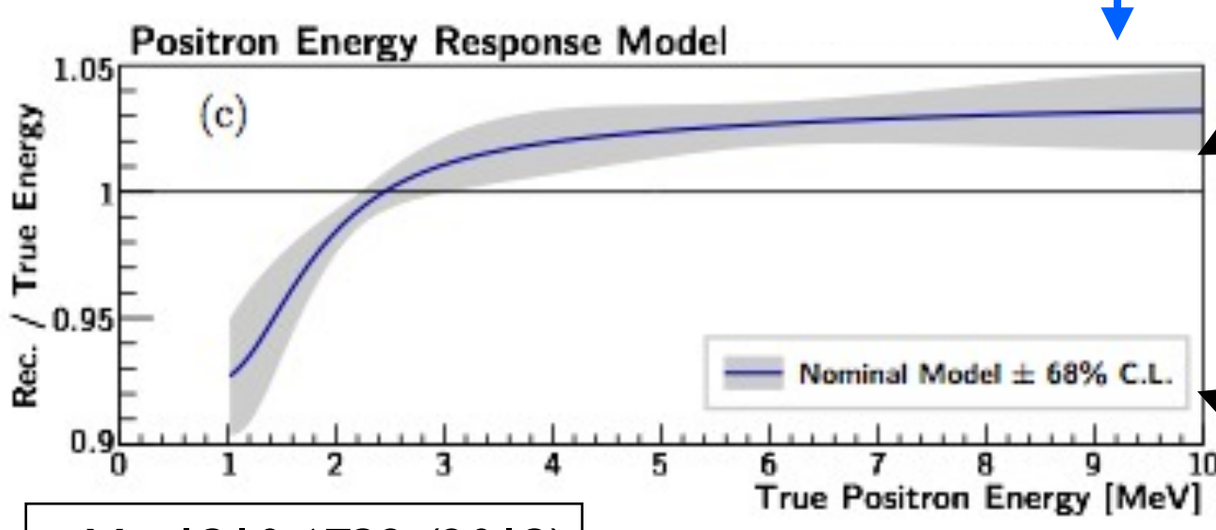
Energy Resolution

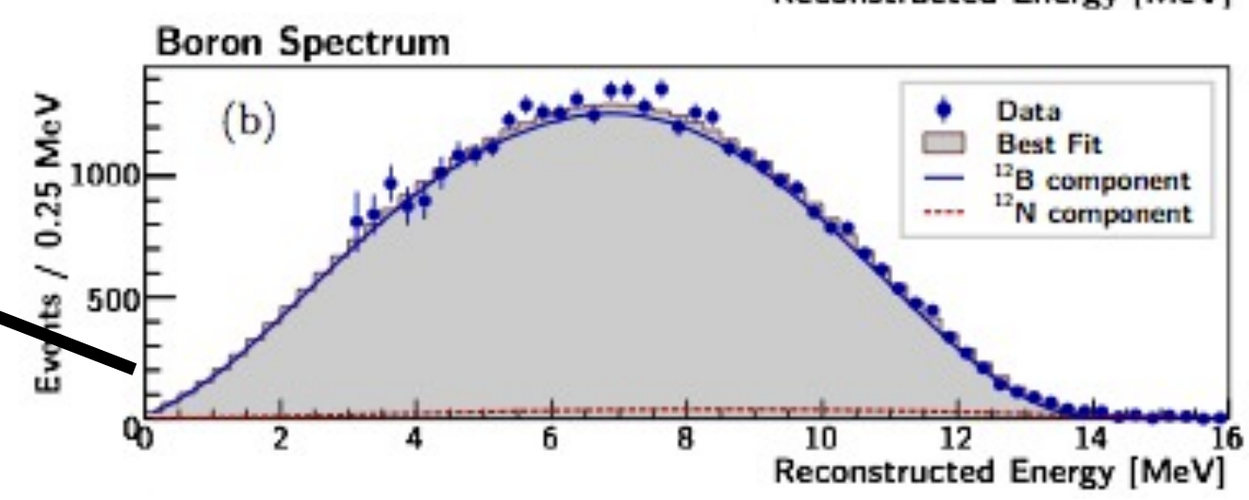
Predicted reconstructed e^+ energy

Compare to measured e^+ E_{rec} for all detectors





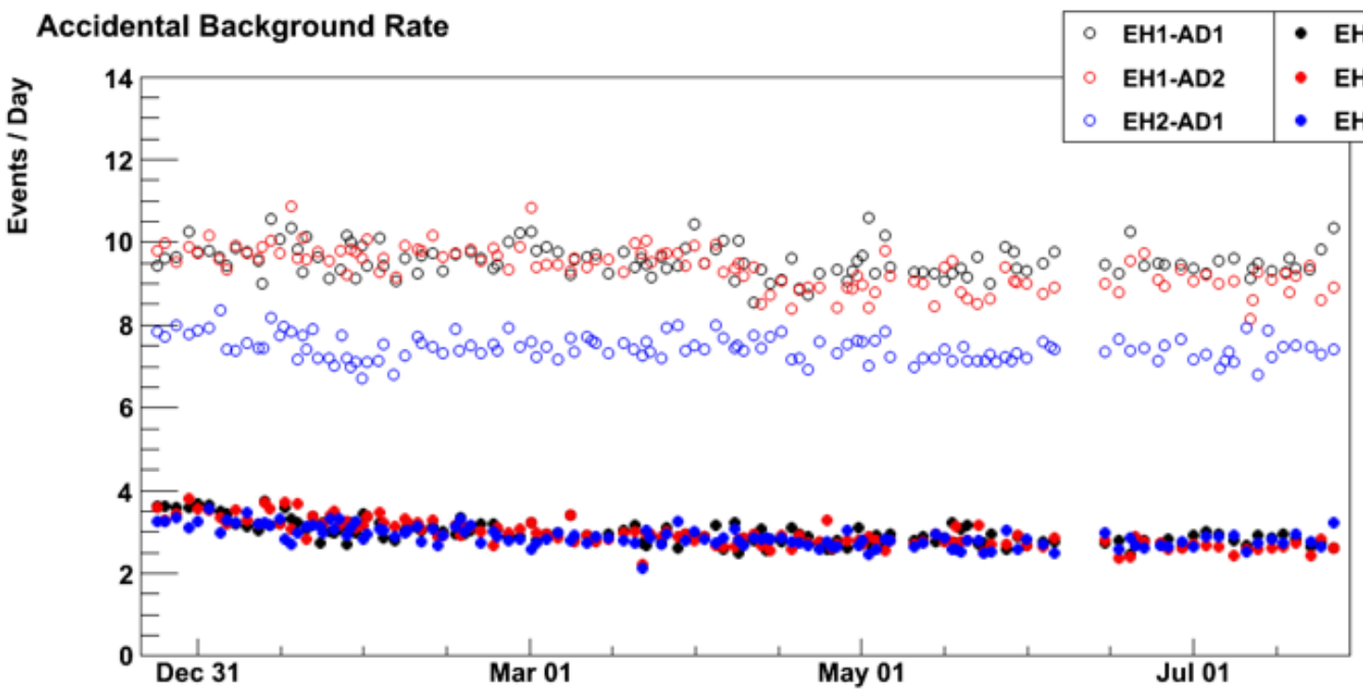


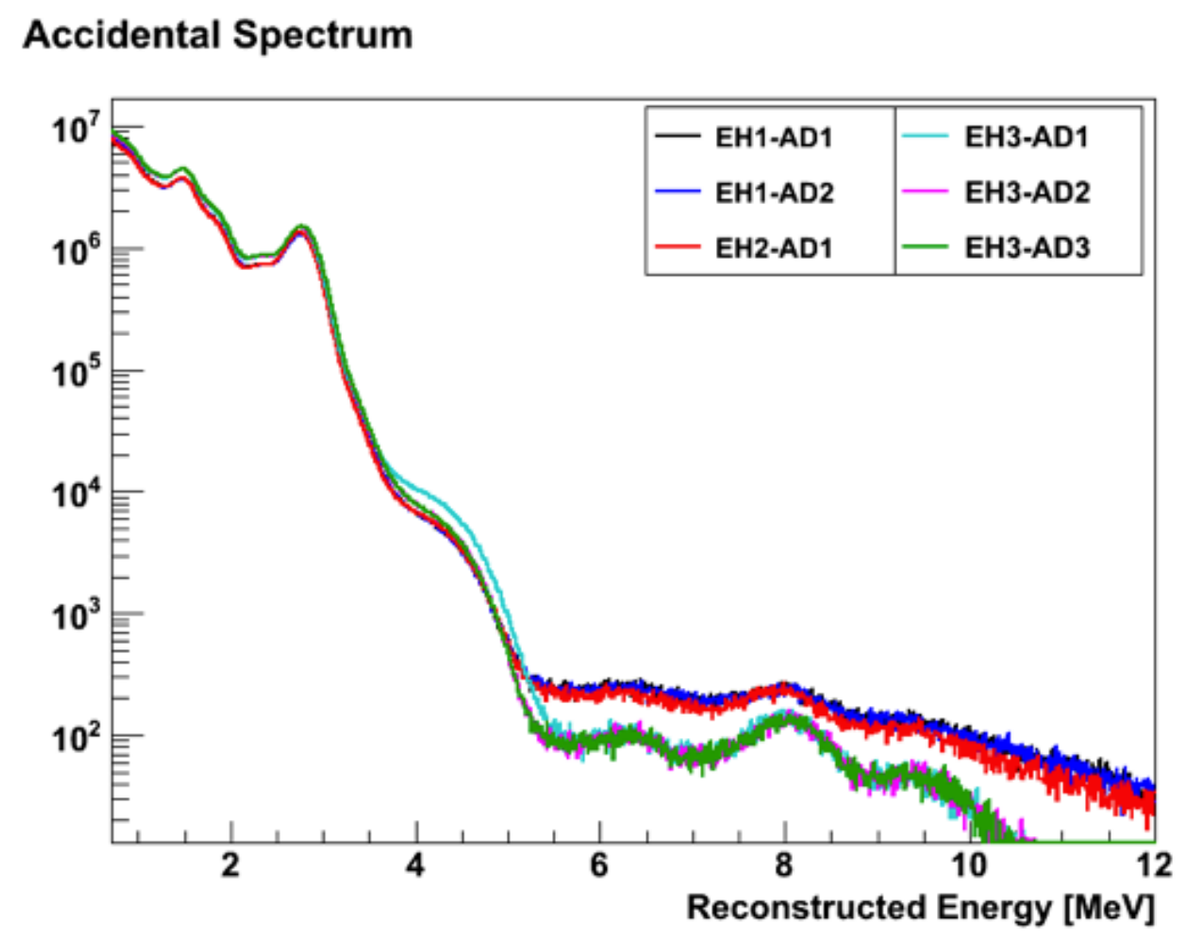


arXiv:1310.6732 (2013)

Backgrounds: Accidentals

- Largest contributor to background rates: two uncorrelated detector triggers passing all selection cuts: 4% (1%) B/S at near (far) sites

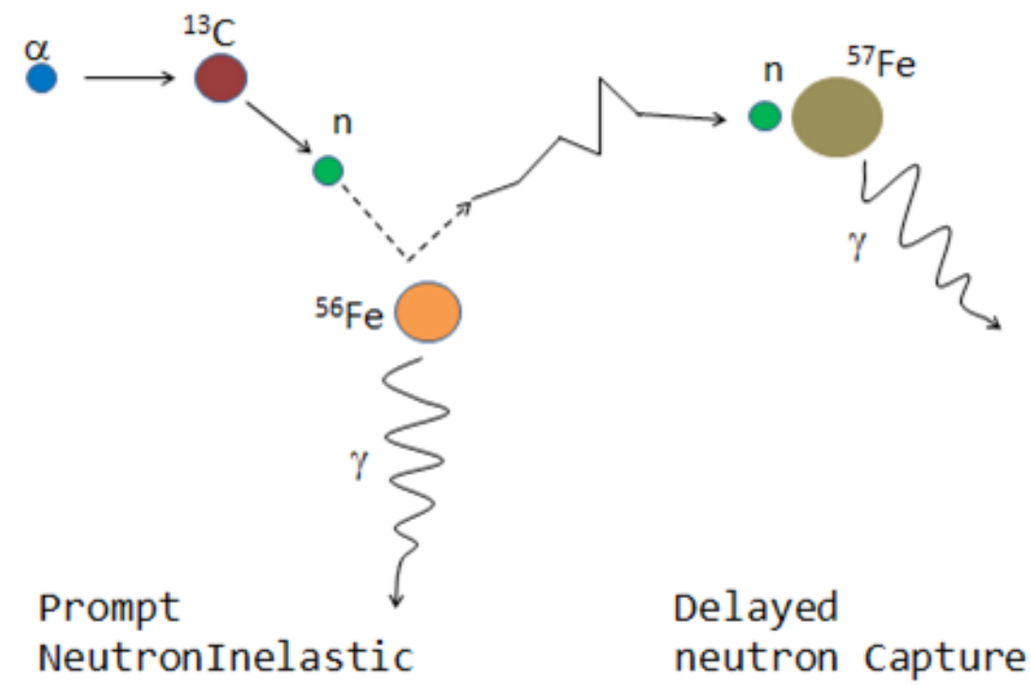


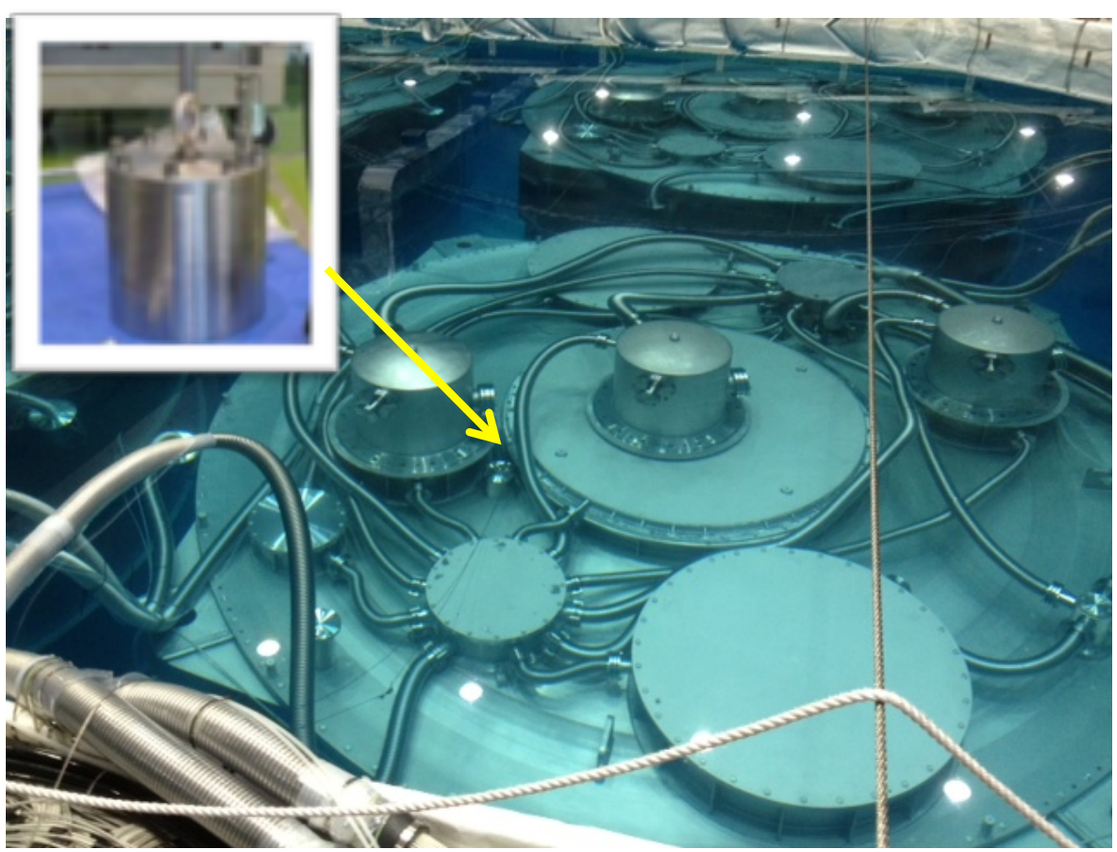


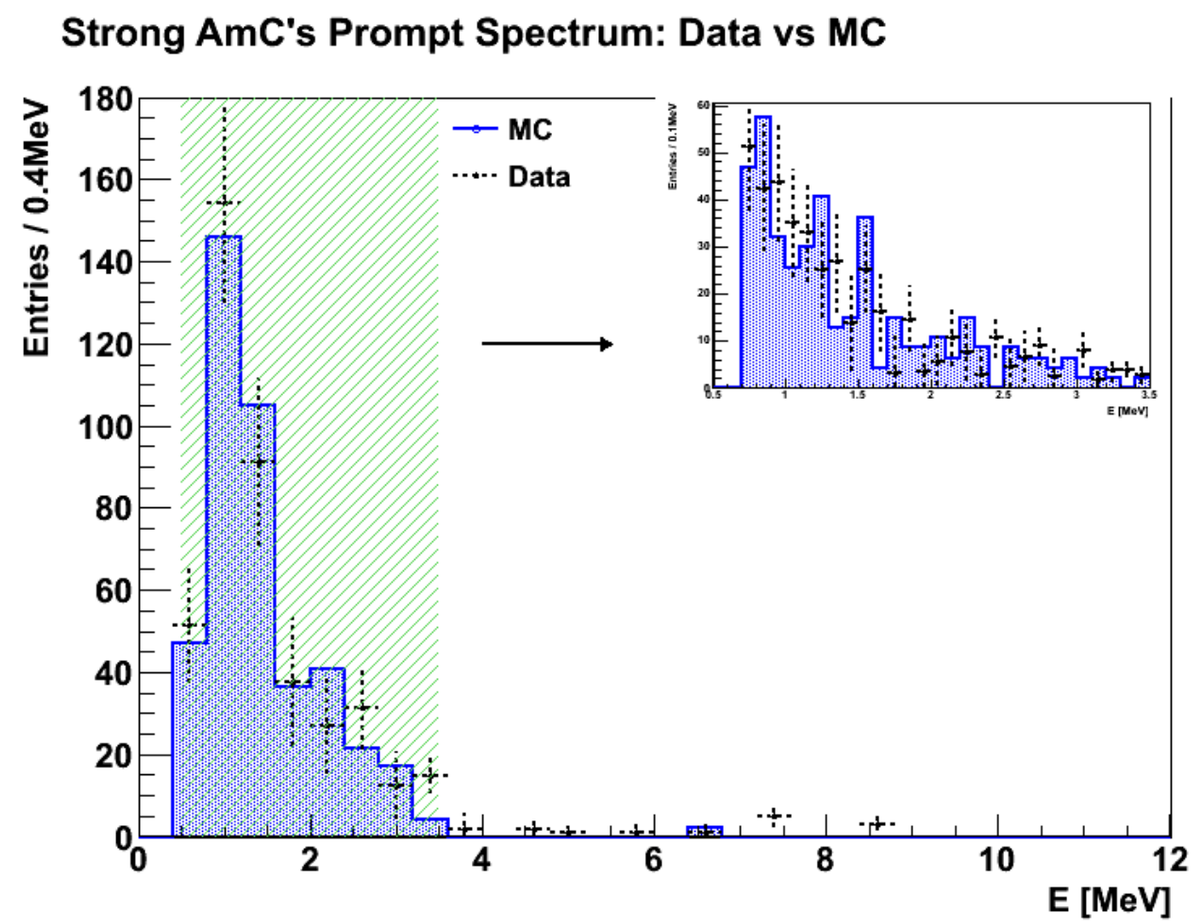
- Accidentals rate, spectrum statistically calculated with excellent precision using rate and spectrum of single triggers

Backgrounds: AmC Source

- Minor low-energy background from AmC neutron calibration sources: ~0.3% B/S
- Contribution to total rate, spectrum calculated using detector Monte Carlo
- MC benchmark: measured rate and spectrum of 80x stronger AmC source on top of AD





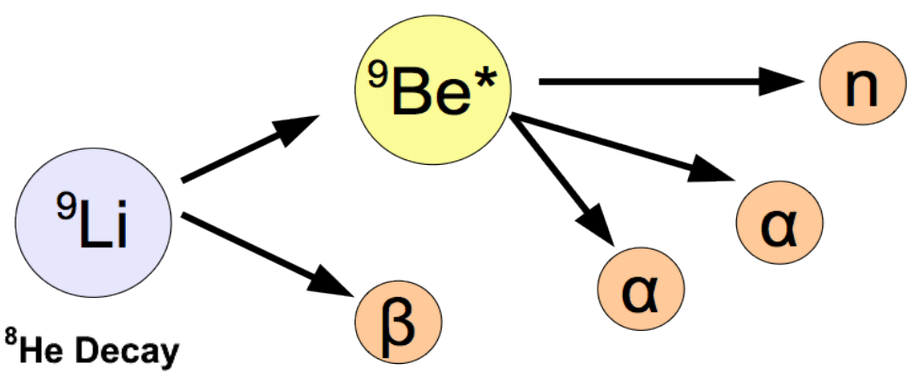


Backgrounds: High Energies

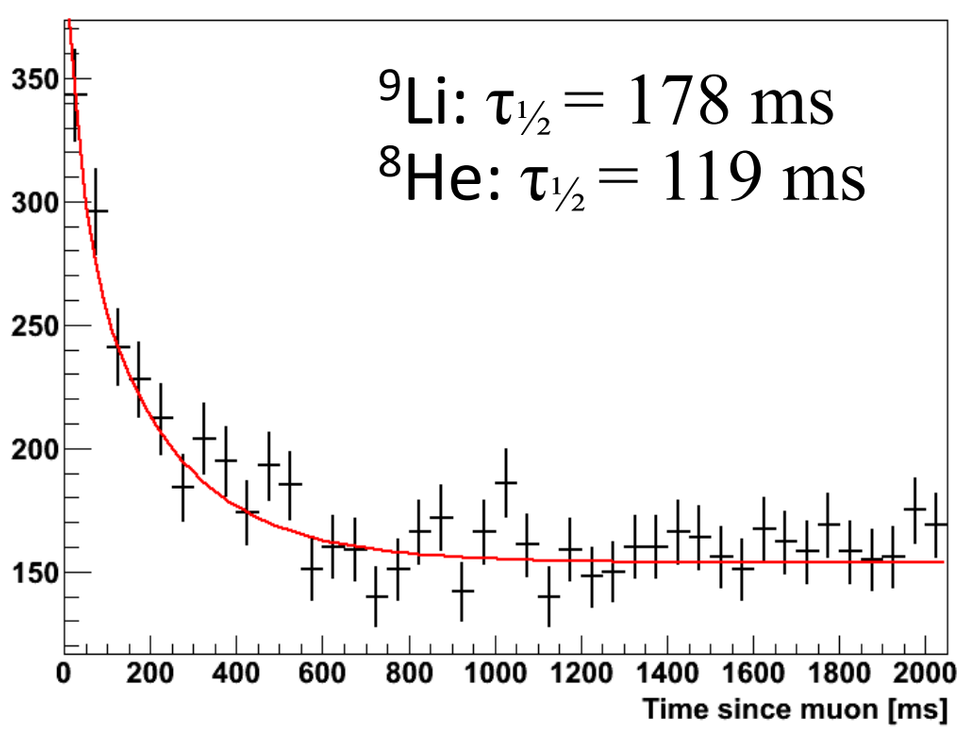
- High-energy backgrounds contributed by spallation: neutrons and beta isotopes
  - Untagged fast neutrons provide estimated 0.1% B/S, with flat spectral shape
  - Unvetoed He-8, Li-9 decays provide 0.3% B/S with spectral shape determined by combining theoretical decay product spectra with detector non-linearity model

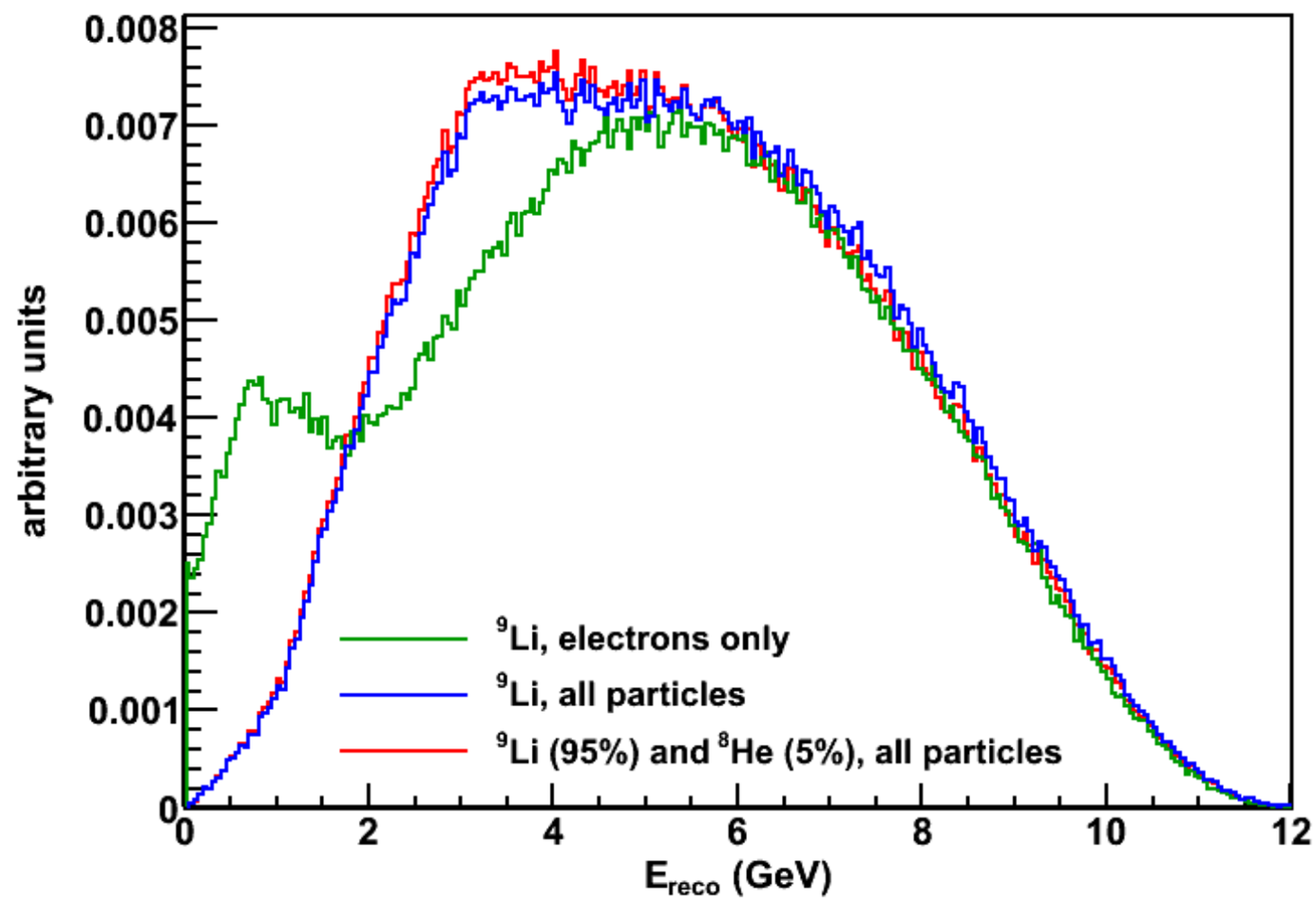
β-n decay:

- Prompt: β-decay
- Delayed: neutron capture



^{9}Li / ^{8}He Decay

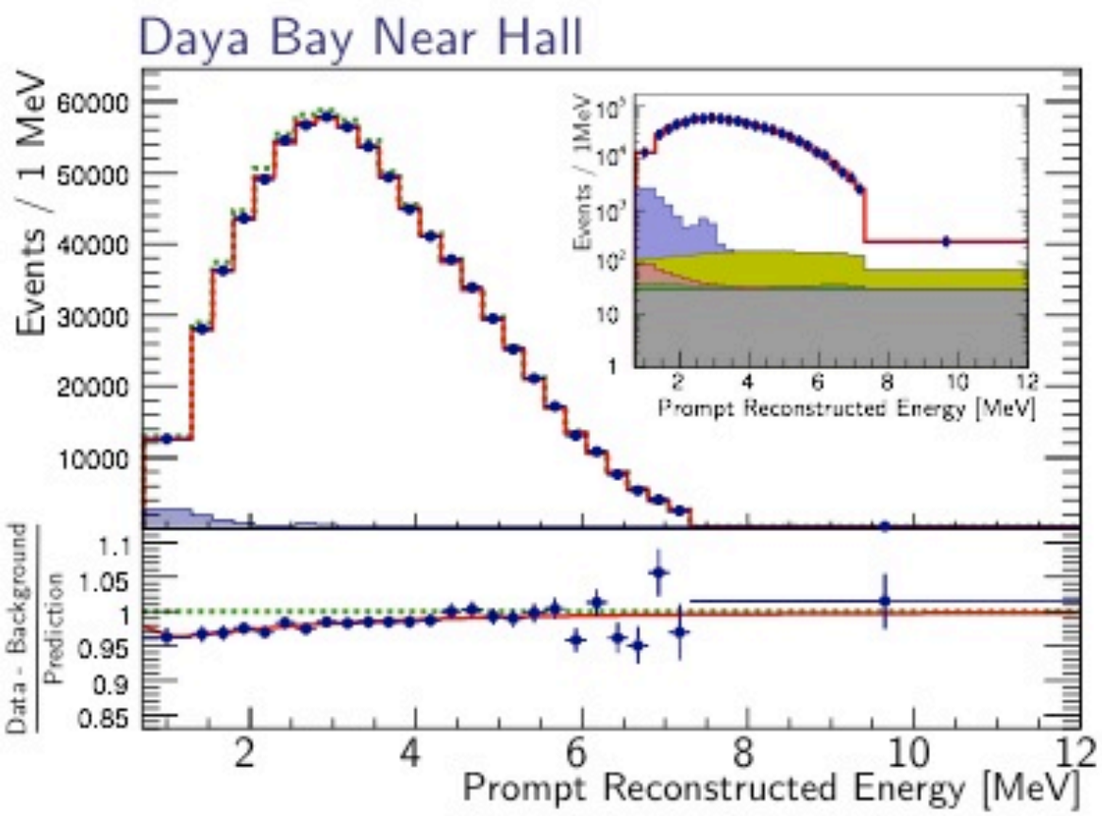


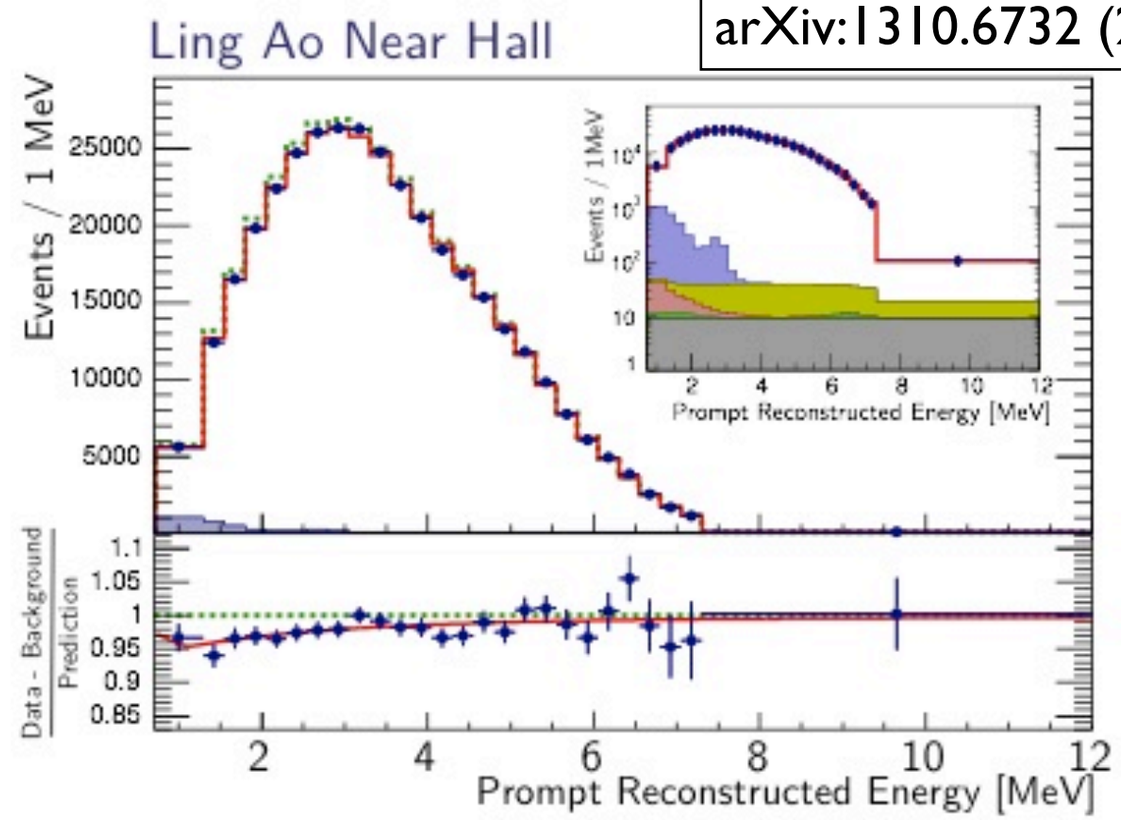


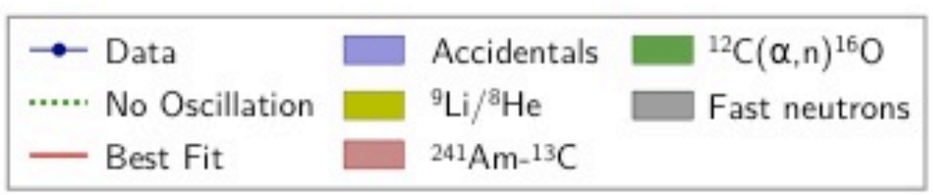
Will eventually provide spectrum of vetoed He-8/Li-9

Rate+Shape Result: Prompt Spectra

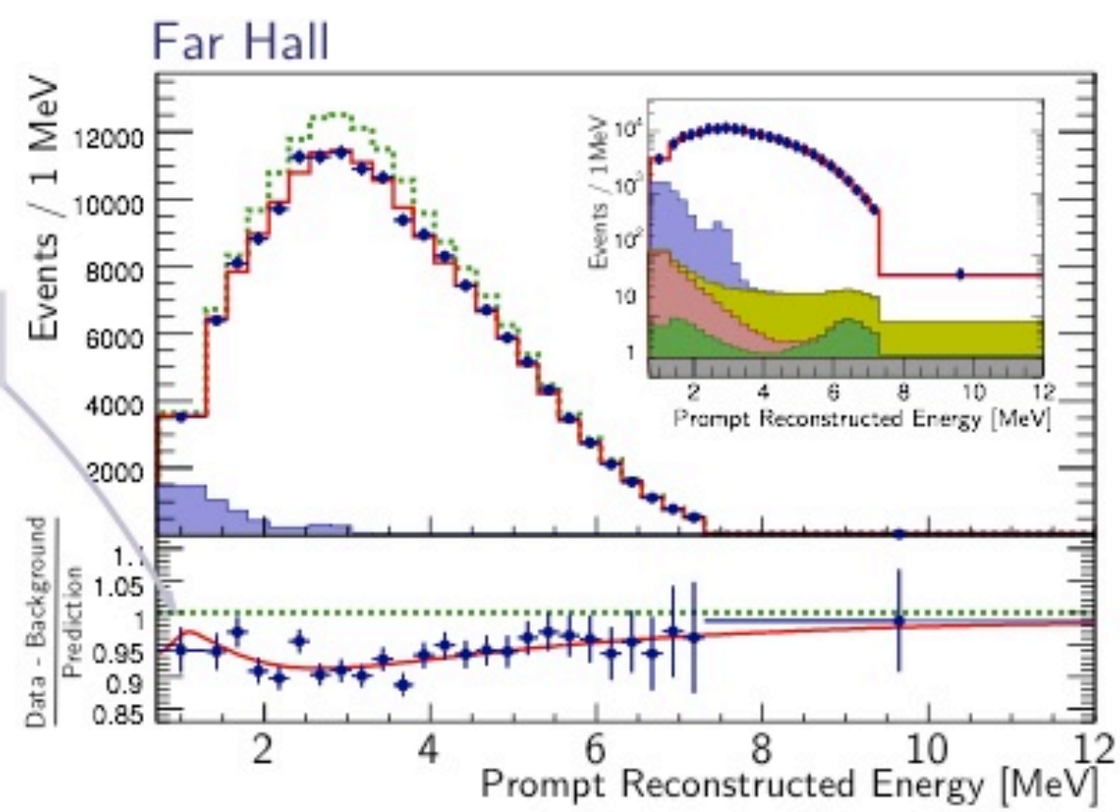
arXiv:1310.6732 (2013)







Shape distortion from energy losses in acrylic

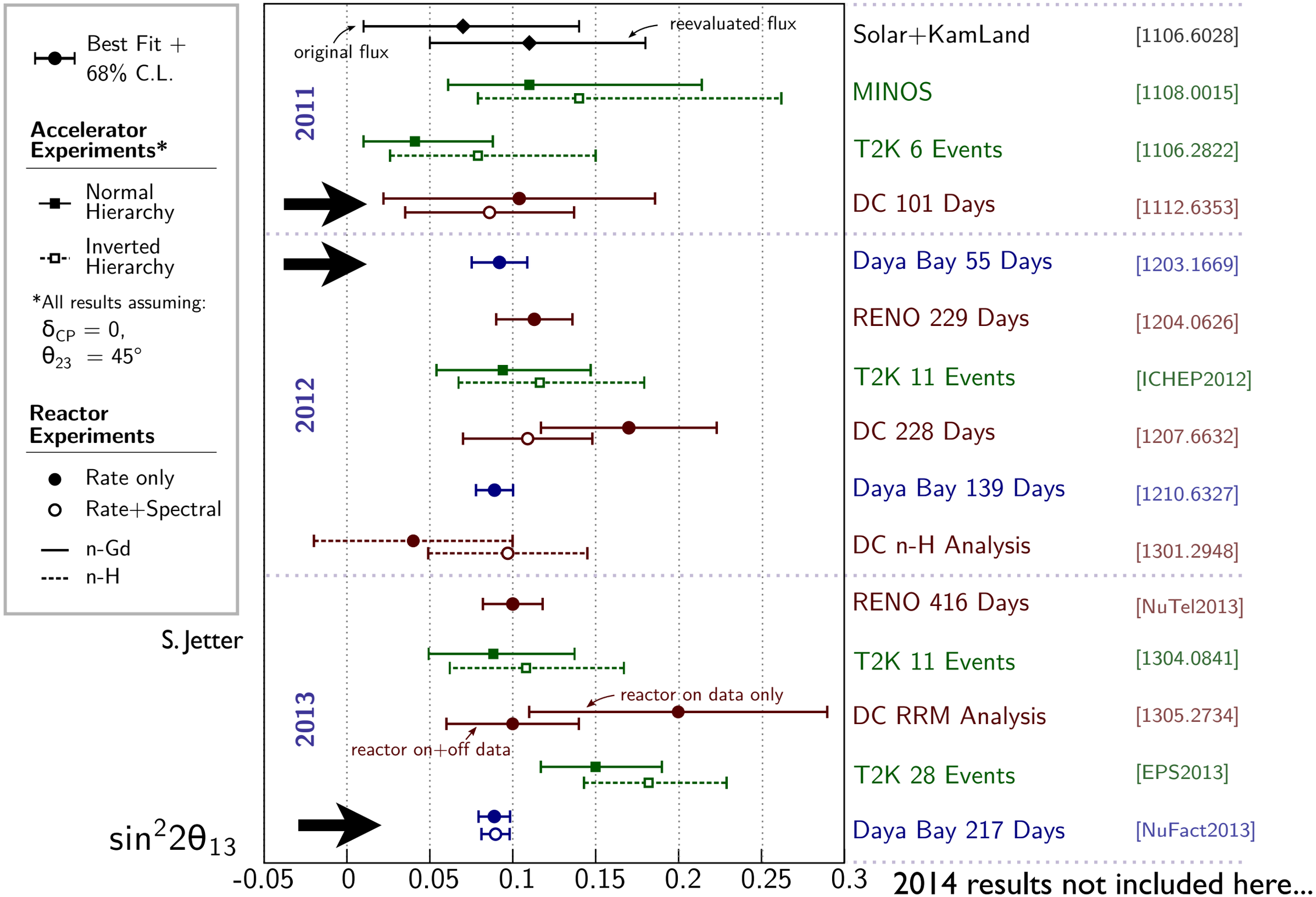


Spectral distortion consistent with oscillation

- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

θ_{13} Global Picture

Daya Bay remains the most precise of numerous largely consistent θ_{13} measurements



S. Jetter

2014 results not included here...

A Note on Mass Splitting

Short-baseline reactor experiments insensitive to neutrino mass hierarchy.

Cannot discriminate two frequencies contributing to oscillation: Δm^2_{31}, Δm^2_{32}

One effective oscillation frequency is measured:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

Result can be easily related to actual mass splitting, based on true hierarchy:

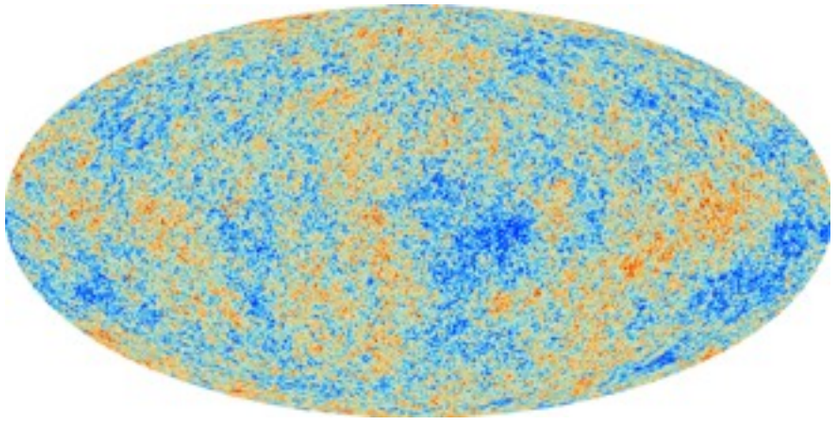
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$$

+: Normal Hierarchy
–: Inverted Hierarchy

Hierarchy discrimination requires ~2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

Other Anomalies

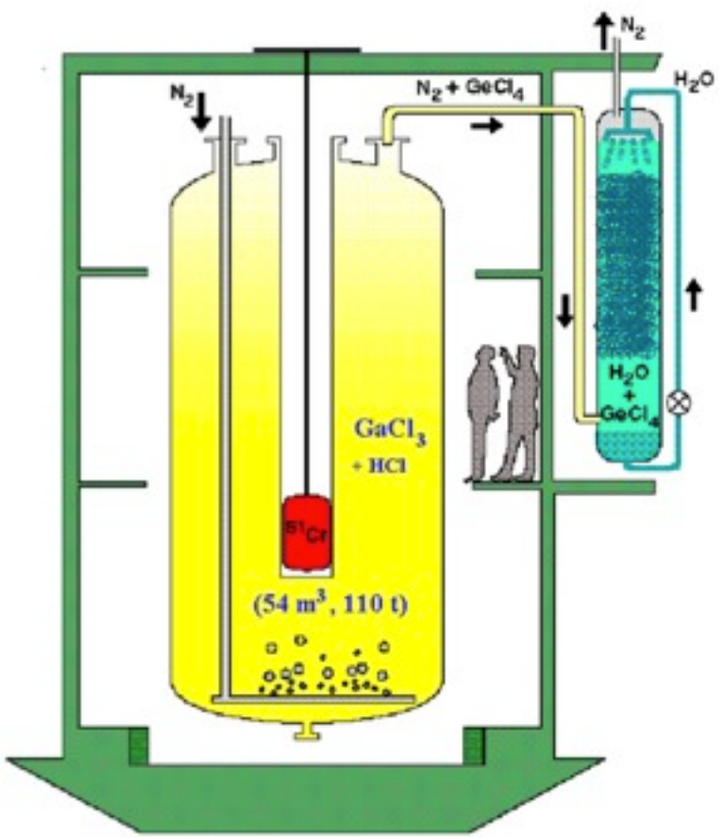
- Cosmology: Hints of additional degrees of freedom
  - Total mass of universe's neutrinos determines clustering of universe's stuff in early universe
  - Also depends on total number of neutrino flavors ('relativistic degrees of freedom')
  - Other probes exist: expansion rate of early universe depends on number of neutrinos



- Gallium Anomaly: Missing events from a neutrino calibration source
  - Kept measuring solar neutrino deficit
  - "Why don't we calibrate our detector with a radioactive source?"
  - Saw a 'small' deficit, which matches existing anomaly

arXiv:1006.3244

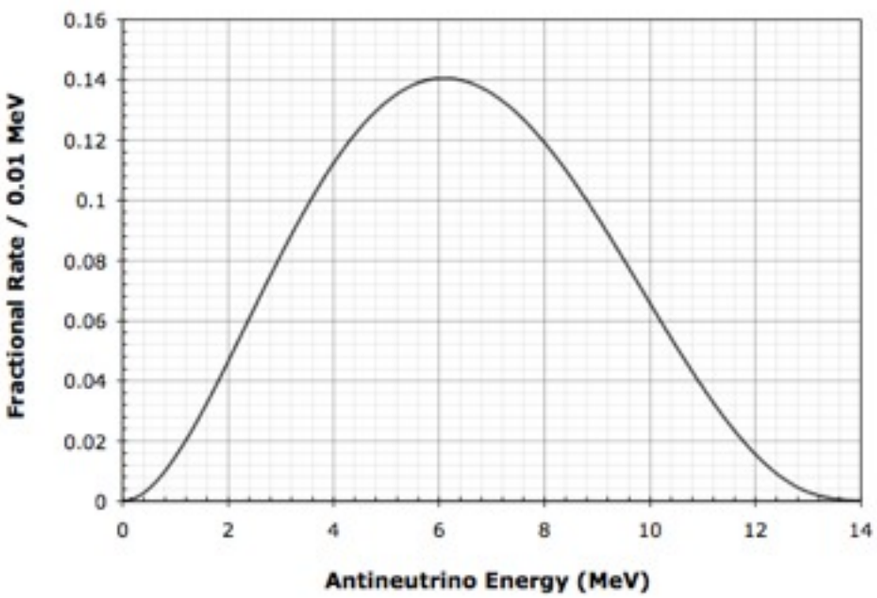
$$R = 0.86 \pm 0.05$$

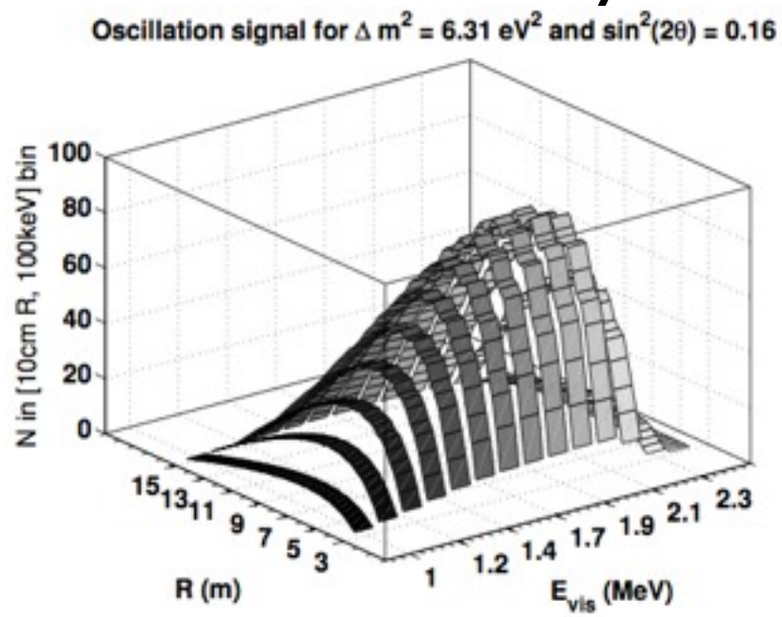


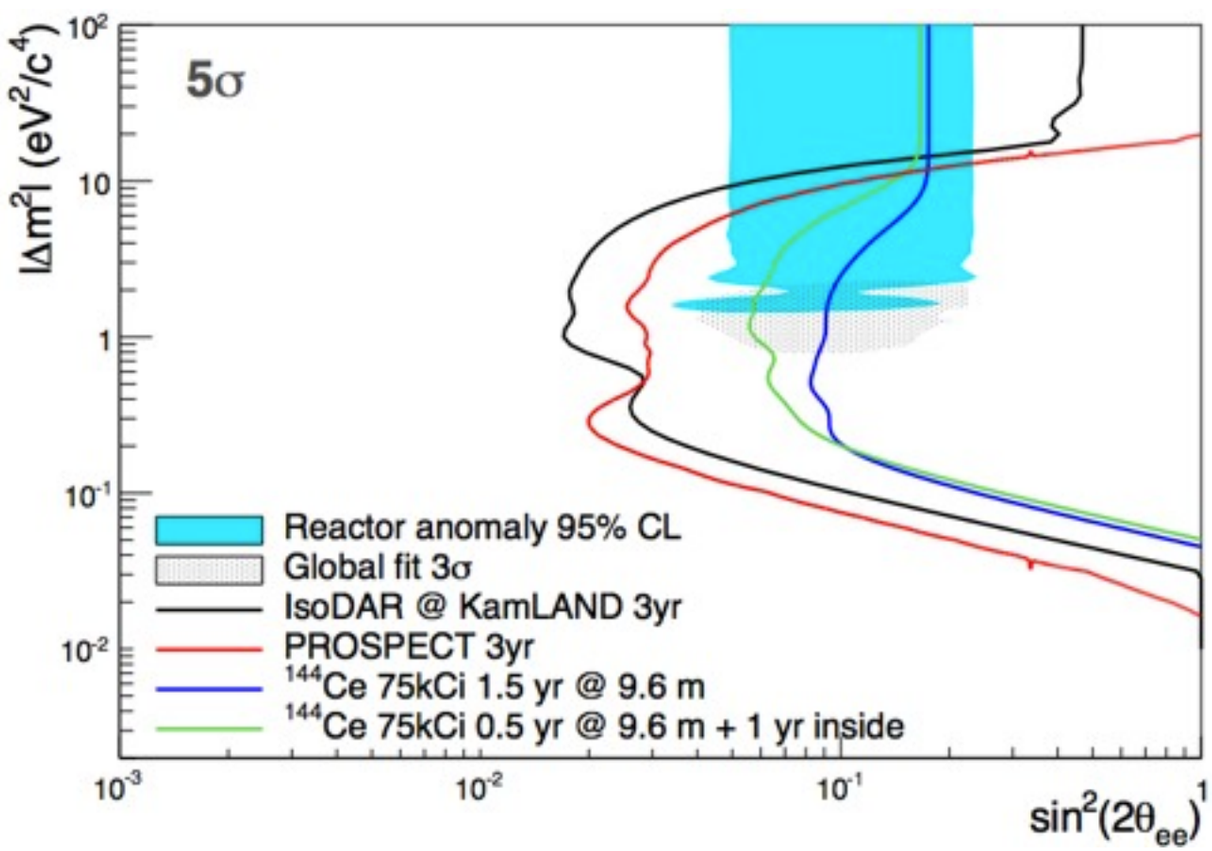
GALLEX

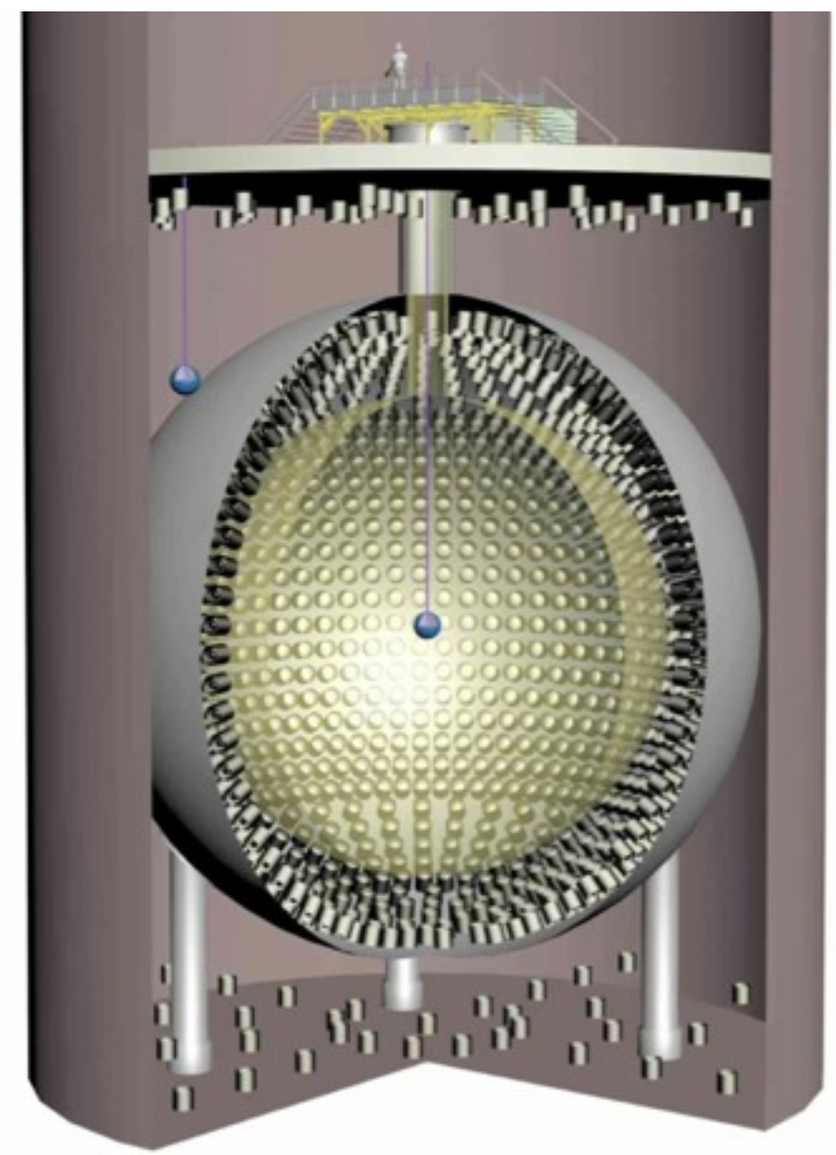
Competing Efforts

- CeLAND and SOX: Radioactive source experiments: quick-ish
- IsoDAR: Accelerator-produced beta decay source: longer timescale









arXiv:1312.0896

arXiv:1307.2949

arXiv:1304.7721

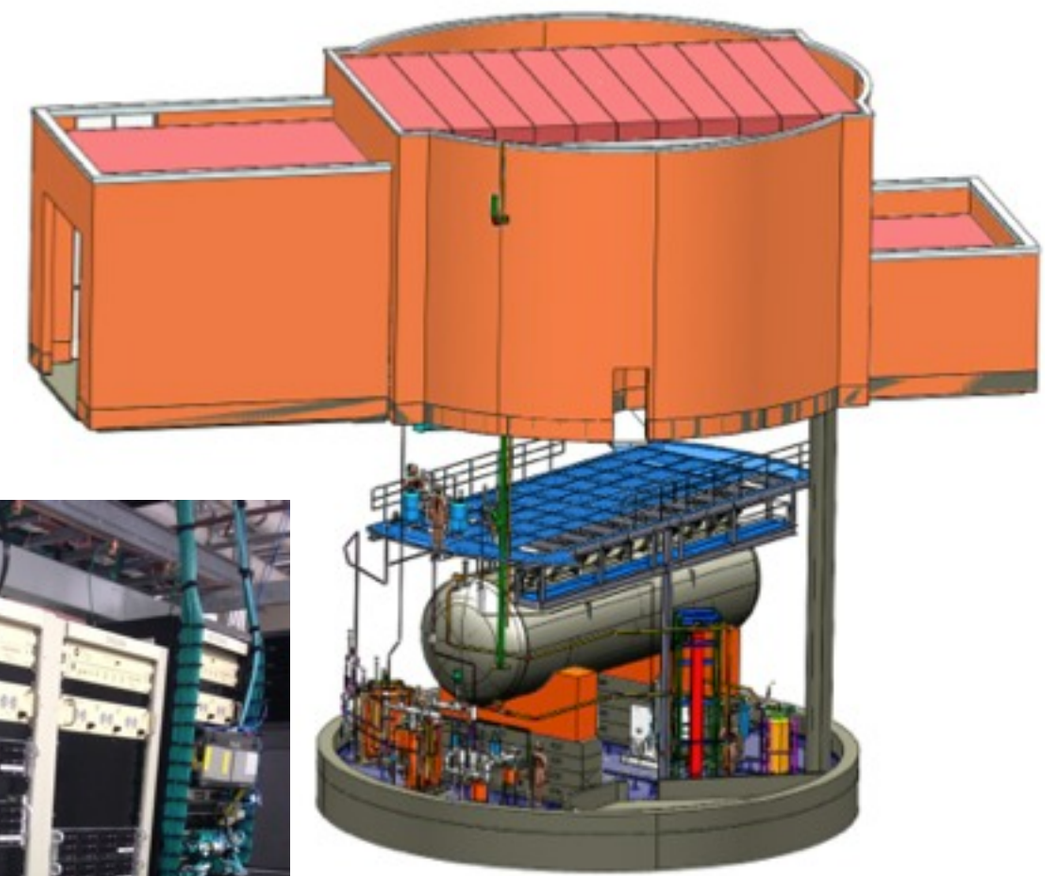
MicroBooNE: Installation

- Detector construction is nearly complete
- Detector installation at LArTF in next few months
- Data taking and commissioning beginning Summer 2014

Experimental Hall

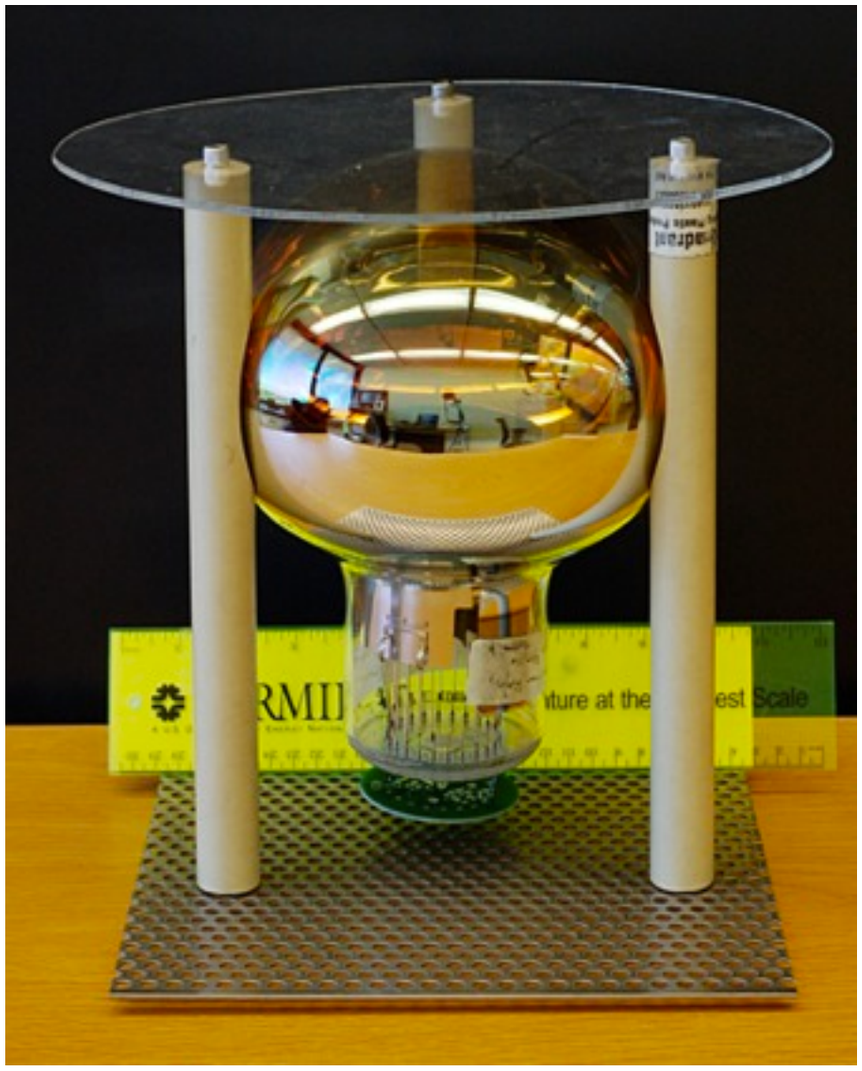
Cryo tanks

Network/Server Room


Installed Detector at LArTF

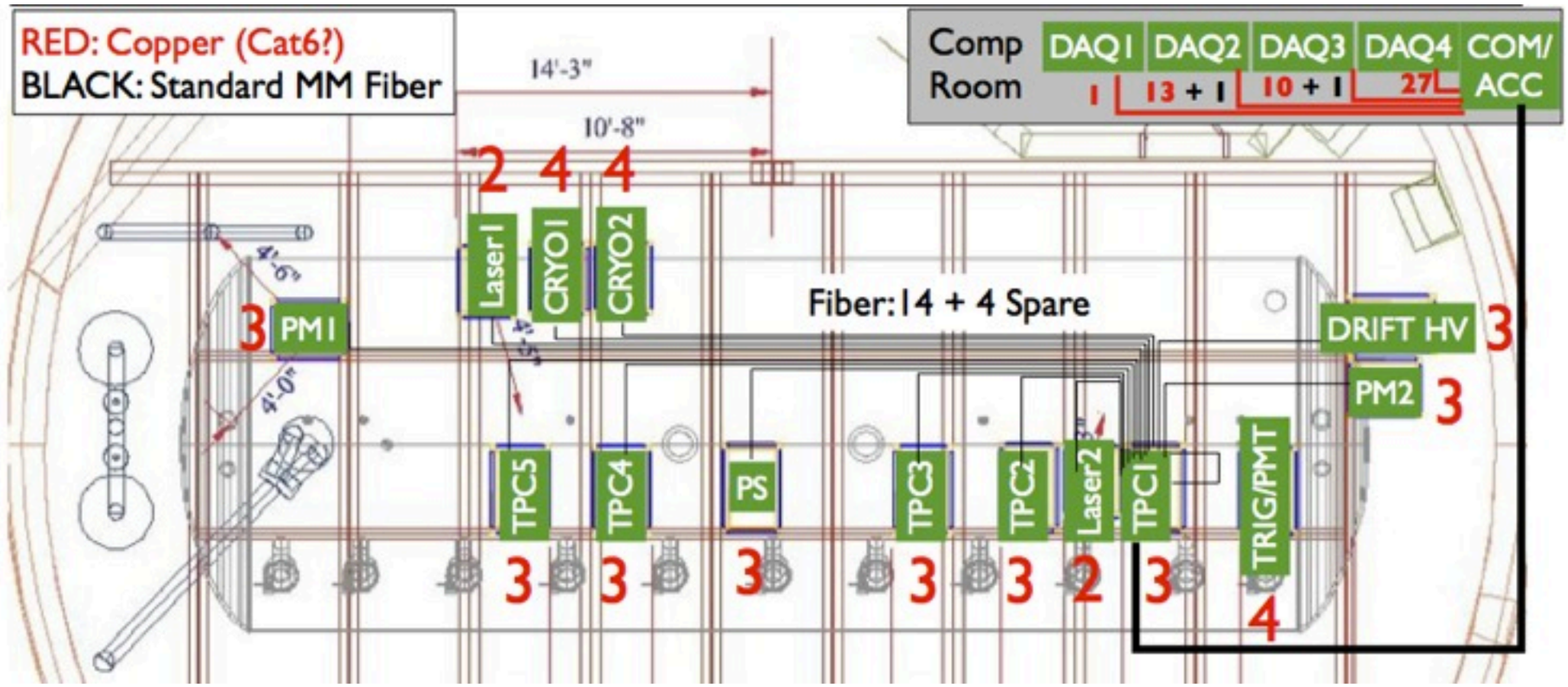
MicroBooNE PMTs

- Photomultiplier tubes detect prompt light from neutrino interactions
- Light signals collected within 100 ns of event interaction

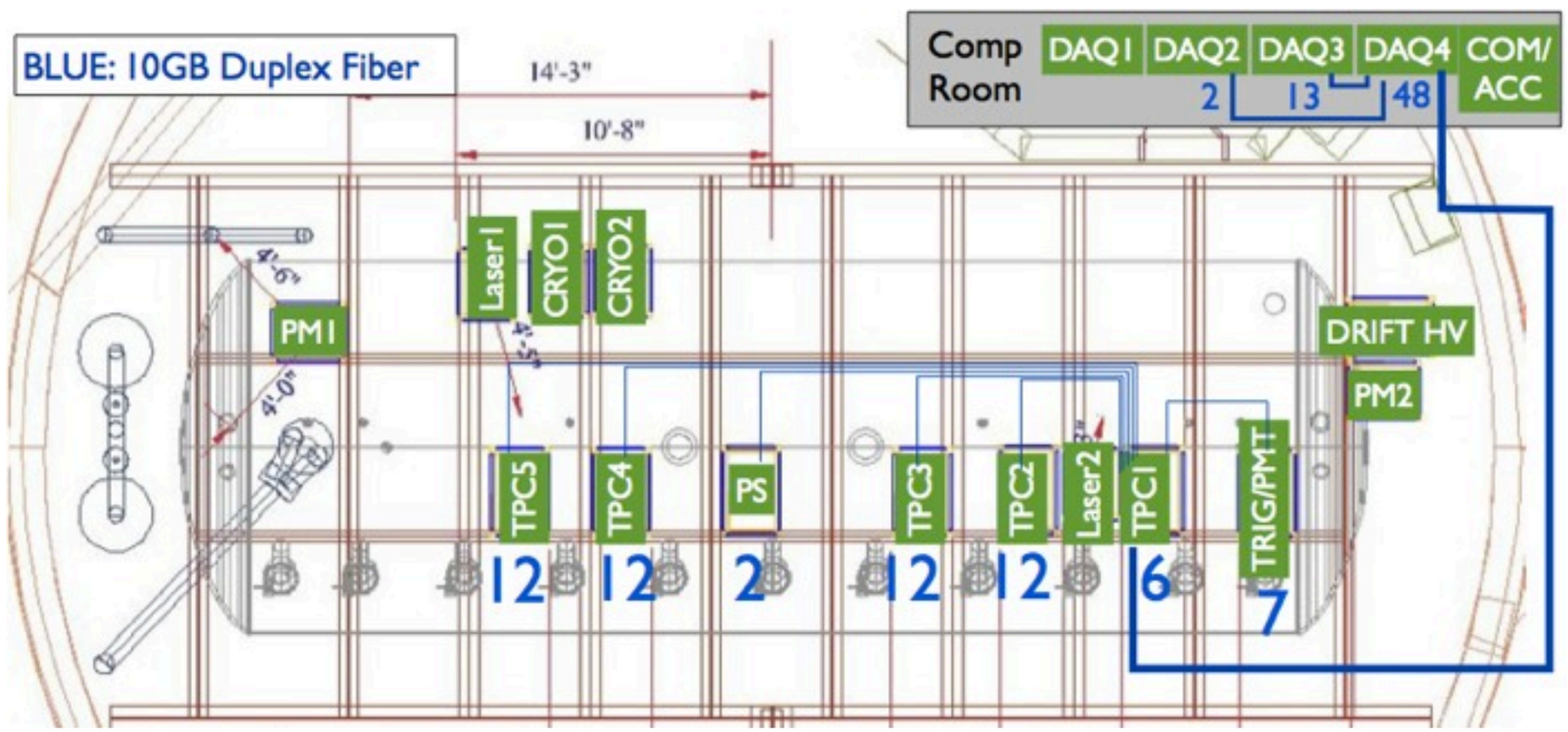


MicroBooNE Cabling Layouts

Network
Cable Plant

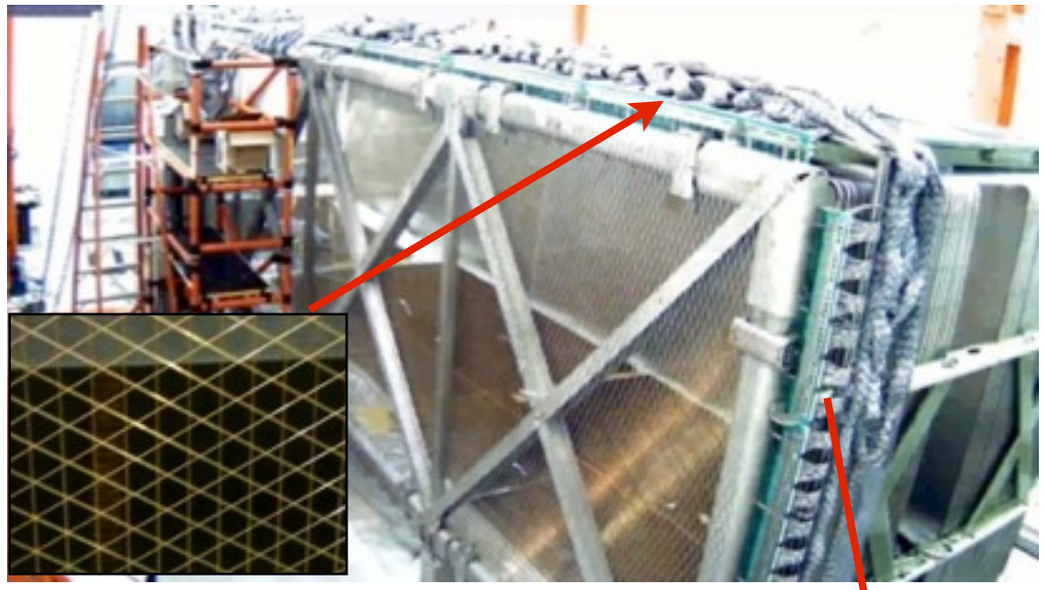


Data
Fiber Plant



Also have beam timing fibers plant

MicroBooNE Readout Scheme



Wires

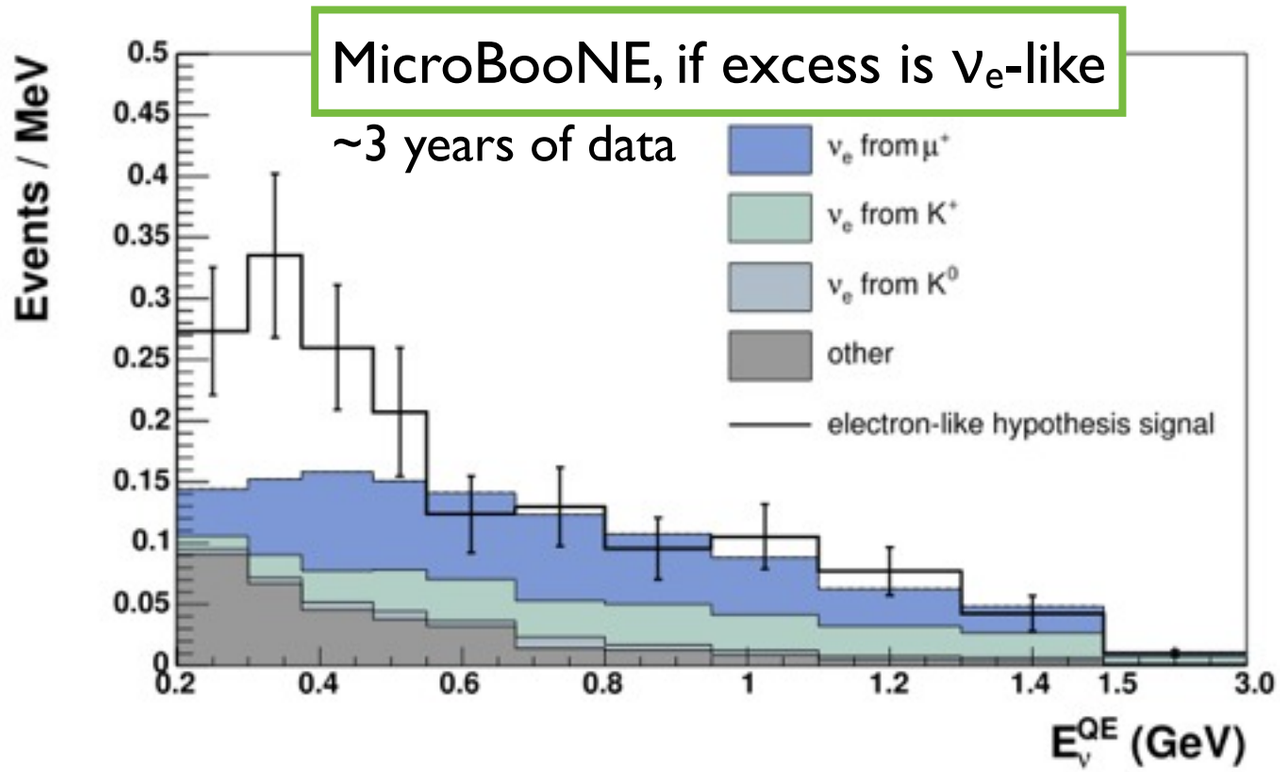
Cold Electronics:
Calibration, Amplification

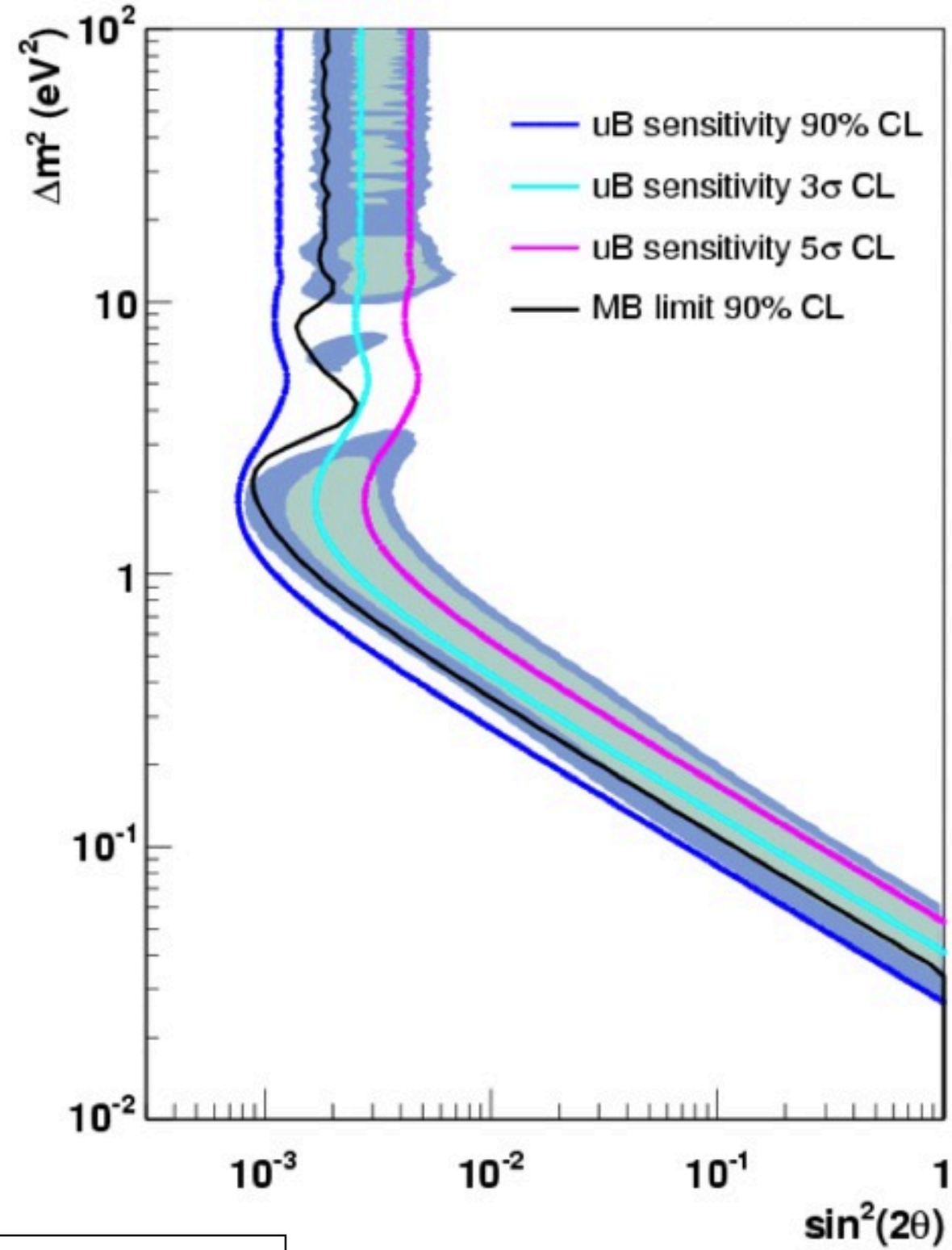
TPC Feedthrough:
Calibration, Amplification

TPC Readout Crate:
Digitization

DAQ Server:
Packing data;
Sending to storage

MicroBooNE Oscillation Physics Potential



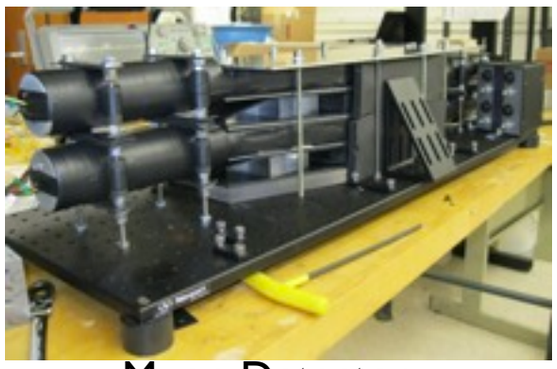


- MicroBooNE event topology and e/γ info will reduce backgrounds regardless of the source of MiniBooNE excess
- If ν_e-like, sensitivity to oscillations significantly improved

MicroBooNE TDR (2012)

PROSPECT R&D: Background Measurements

- Backgrounds are a key challenge for the experiment
  - No overburden, large amount of reactor-related high-energy gammas
- Reactor on/off surveys complete at all sites; analyzing data
  - Have specialized detectors for muon, neutron, and gammas surveys

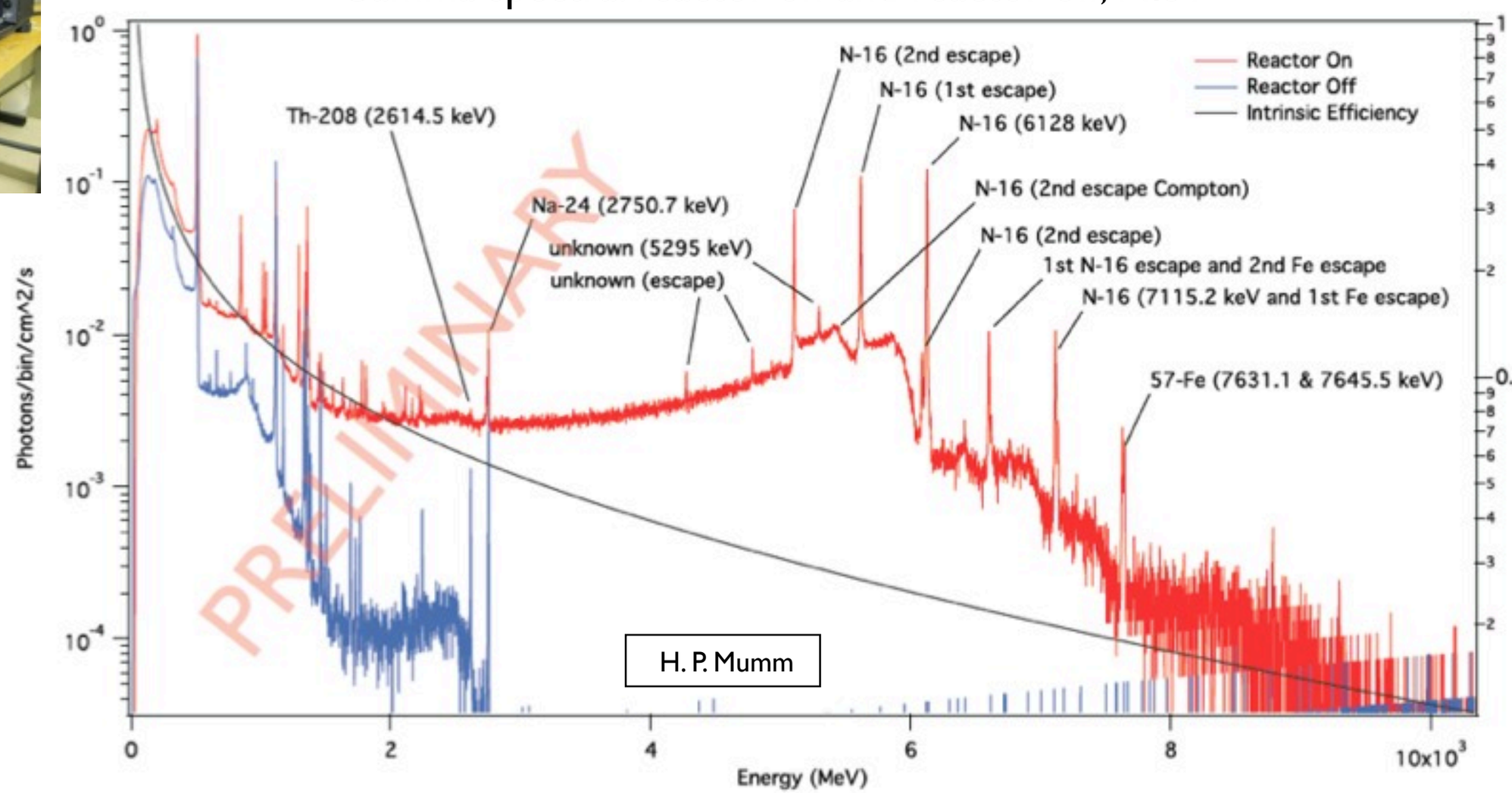


Muon Detector

Gamma Spectrometer

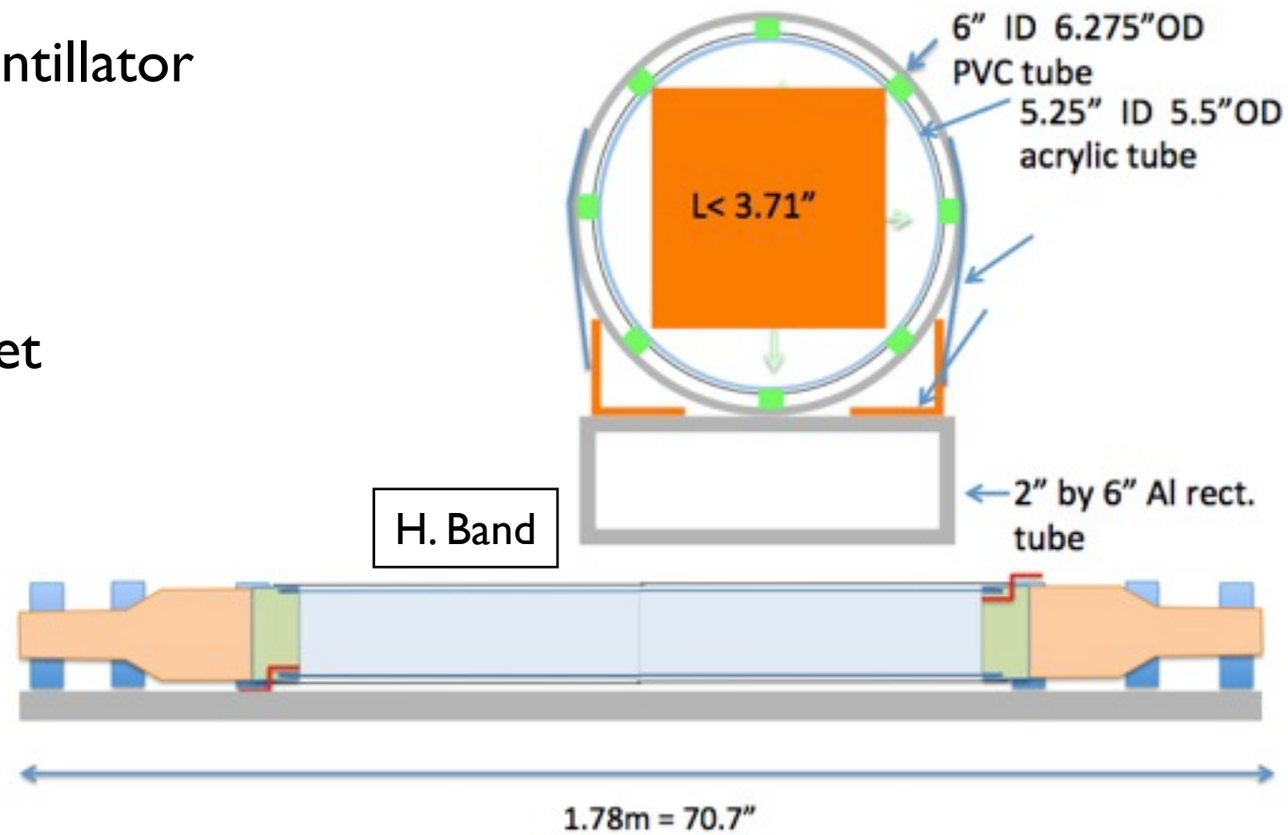
Neutron Detector: FANS-I

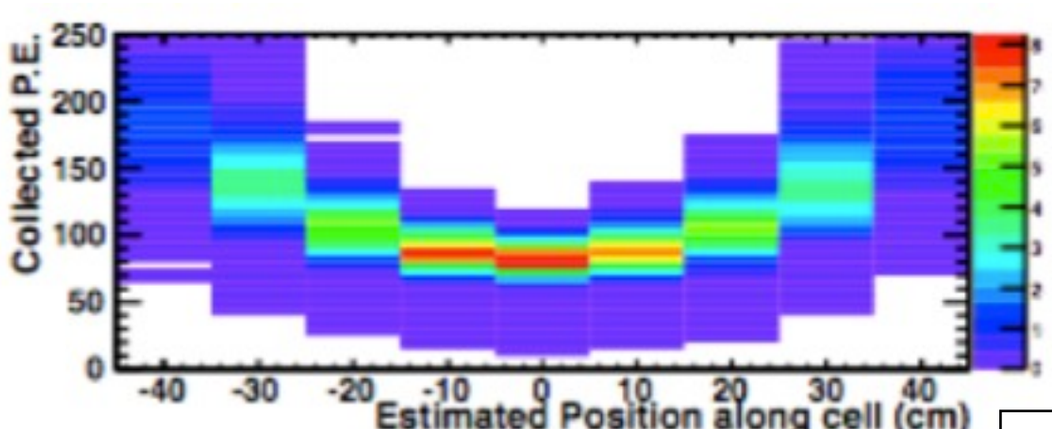
Gamma spectra: reactor-on and reactor-off, NIST

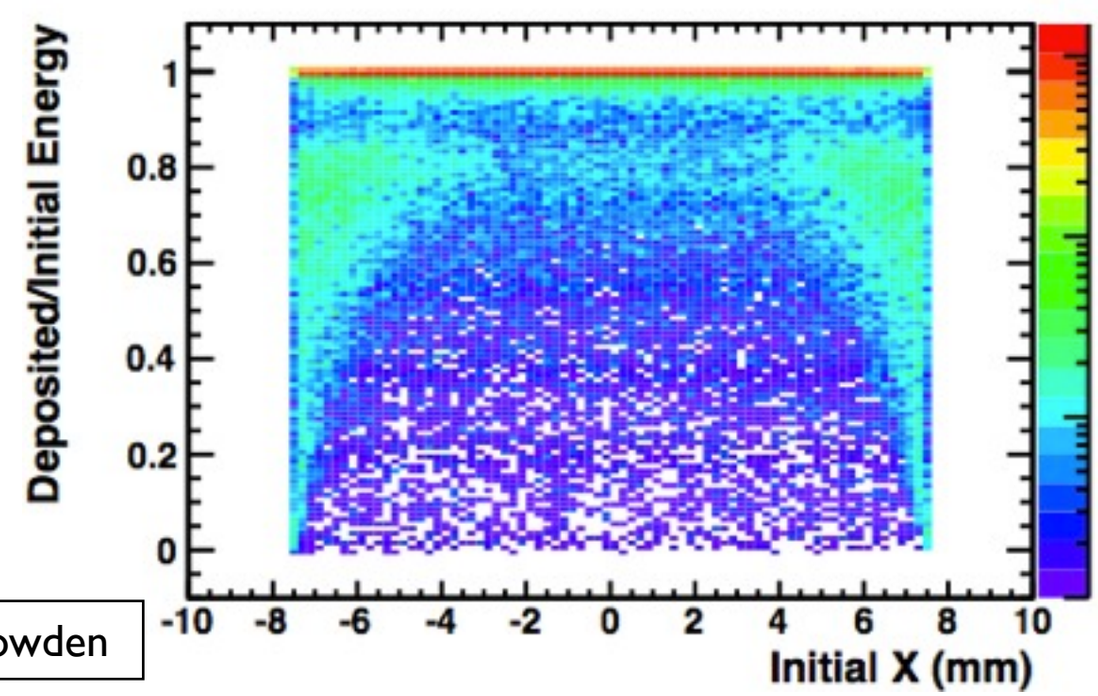


PROSPECT R&D: Detector Design

- Investigating segment design options in test cells (Yale)
  - Gd-loaded versus Li-Loaded liquid scintillator
  - Pulse-shape-discriminating liquids
  - Cell and wall dimensions and shapes
  - Use of 'positron-catcher' around target
- Investigating calibration options (Cincinnati)
  - Radioactive doping of scintillator
  - External calibration sources
  - Calibration with intrinsic backgrounds
- Concurrent MC efforts



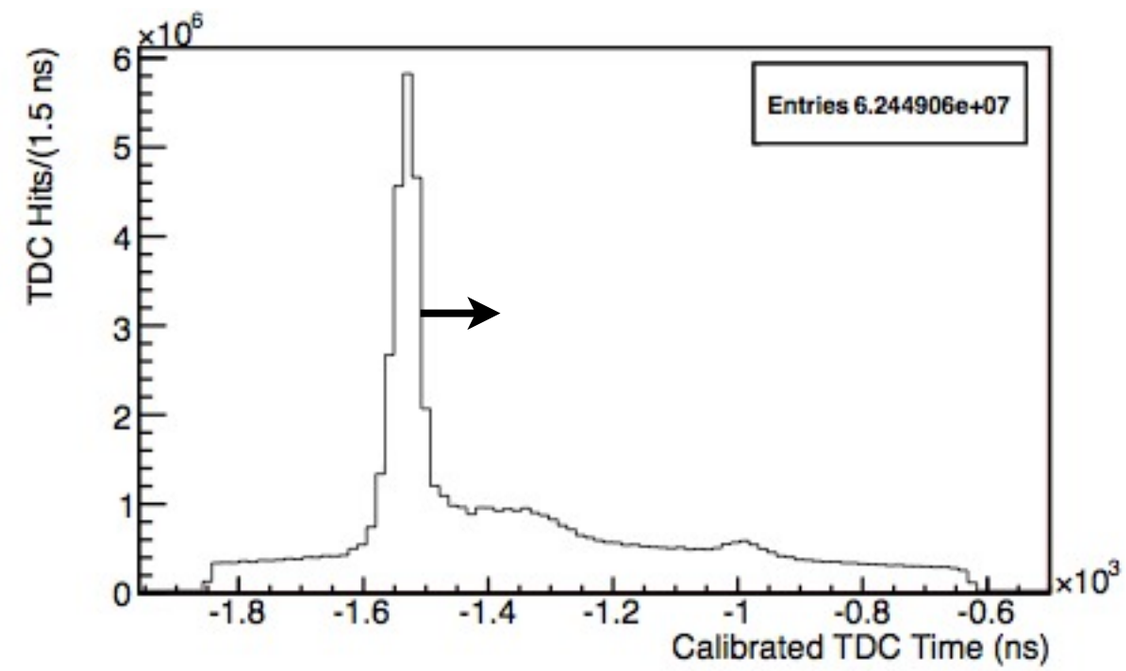


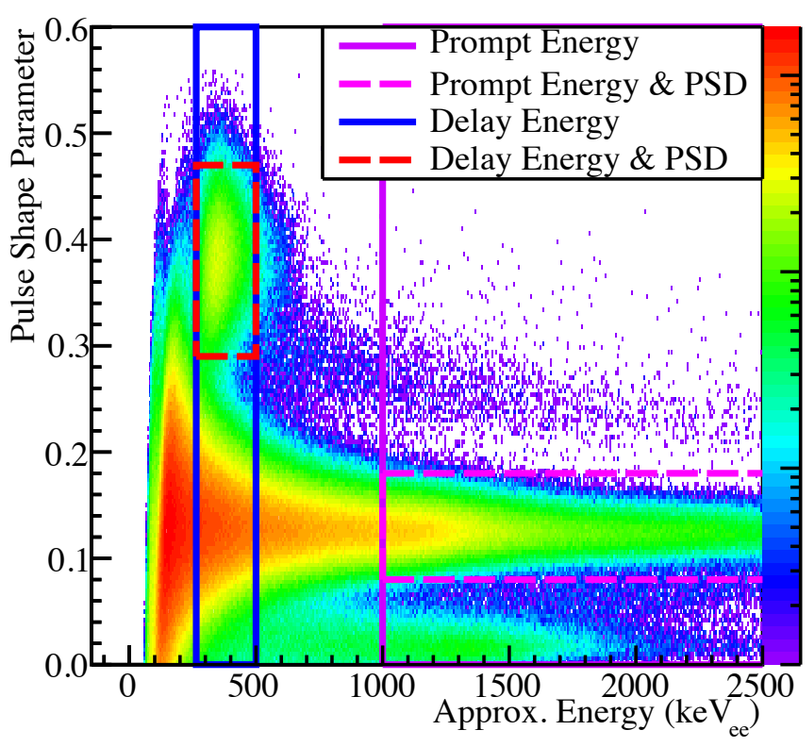


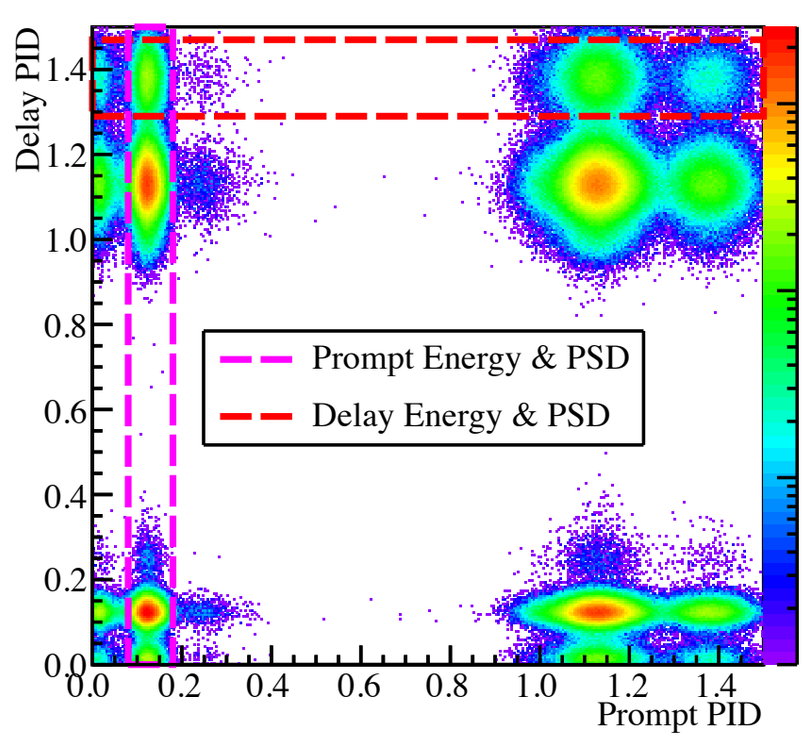
N. Bowden

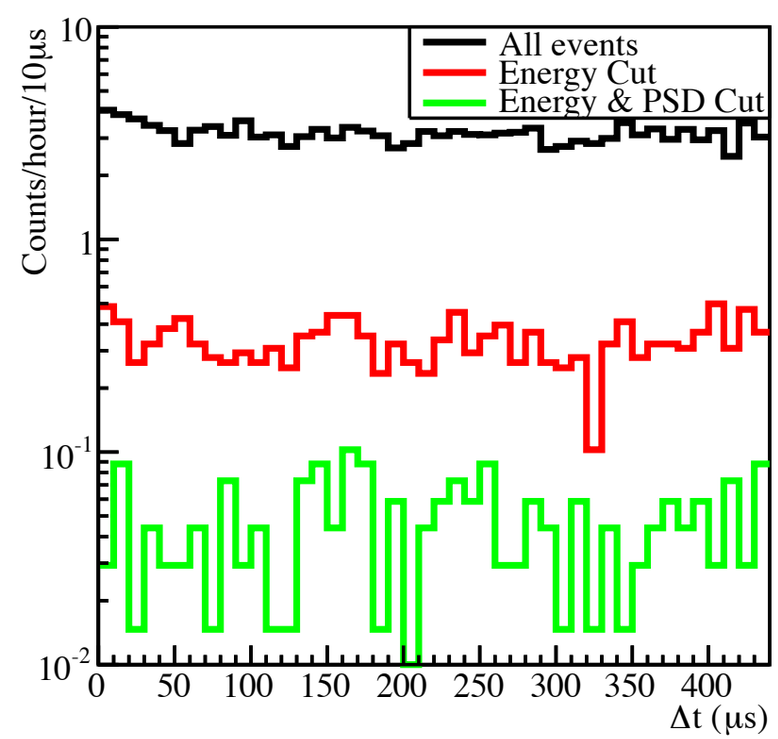
PROSPECT Background Reduction Methods

- Planning to use pulse-shape discrimination to specifically ID events with coincident positron/neutron
  - Proton energy deposition gives light production that is broader in time
  - Can remove coincidences from fast neutrons, multiple n-captures, or multiple radioactivity triggers







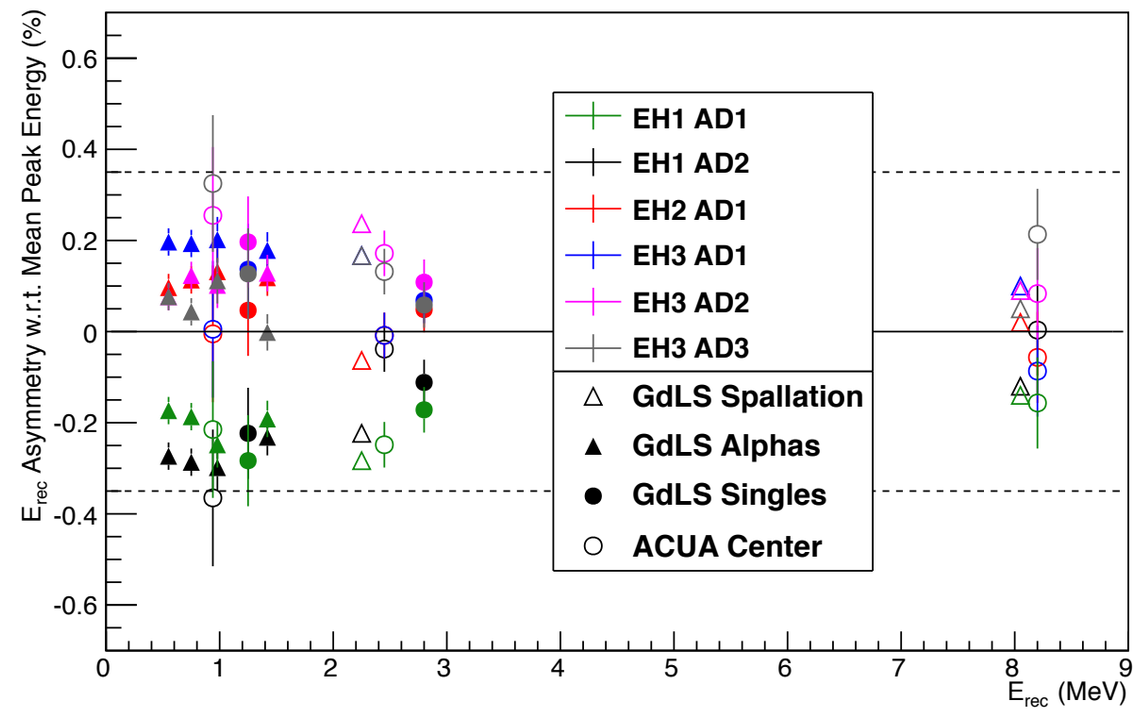


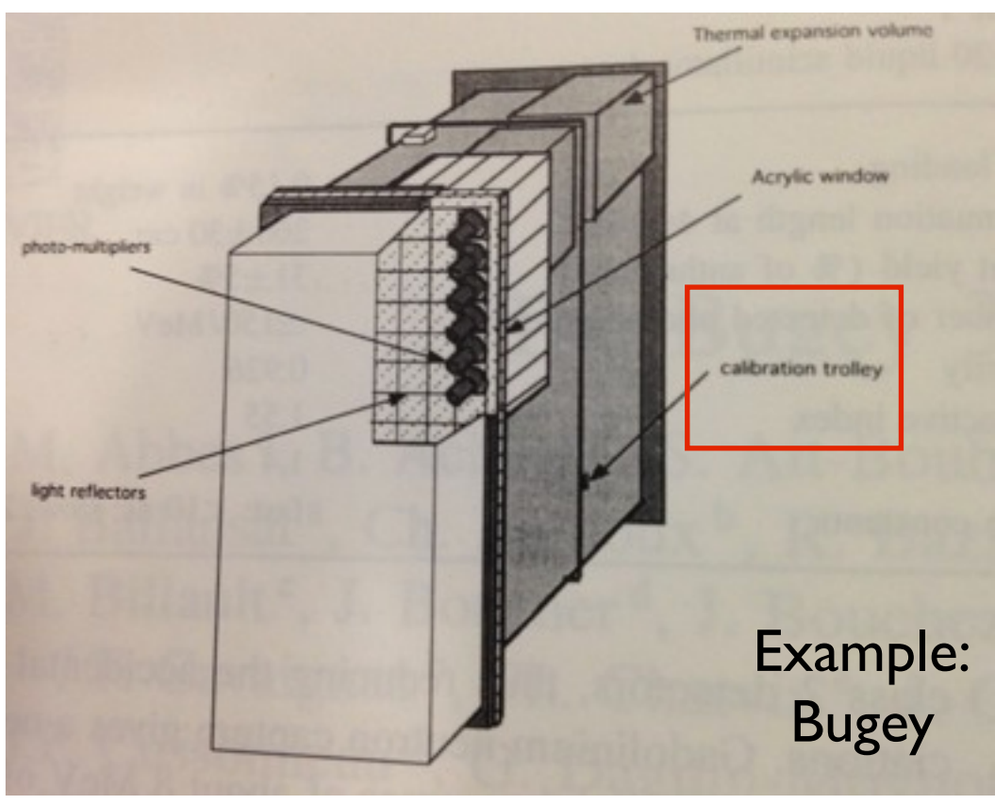
PROSPECT Background Reduction Methods

- Planning to use Li-loaded or Gd-loaded scintillator
- Gd:
  - Gives high-energy delayed signal, which can help remove radioactive bkgs
  - Many high-energy gammas from nGd escape detector; low efficiency
  - Scintillation in many segments
- Li:
  - Low-energy signal, would need to be combined with PSD
  - Very spatially confined (microns) nLi energy deposition; high efficiency
  - Scintillation in only one segment
- Event topologies in segments may allow further background rejection

PROSPECT Calibration Options

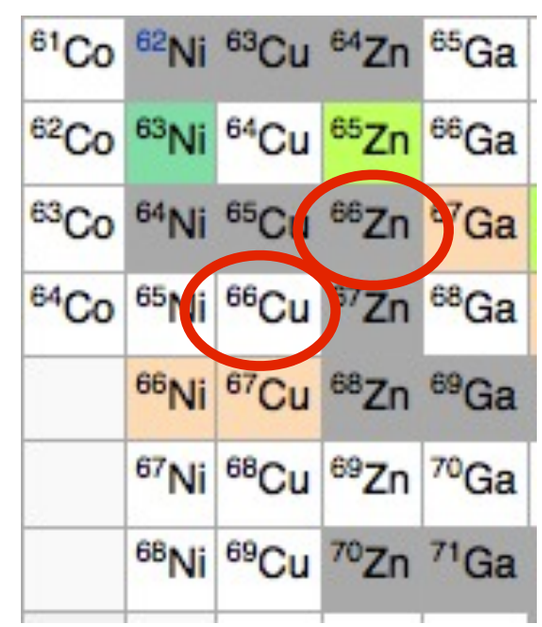
- Can calibrate energy with backgrounds, like Daya Bay
  - Won't tell how much e^+ energy is leaking out of small detector
  - Not great for absolute calibration
- Additional options:
  - External calibration sources
  - Dope segments with short-lived radioisotopes

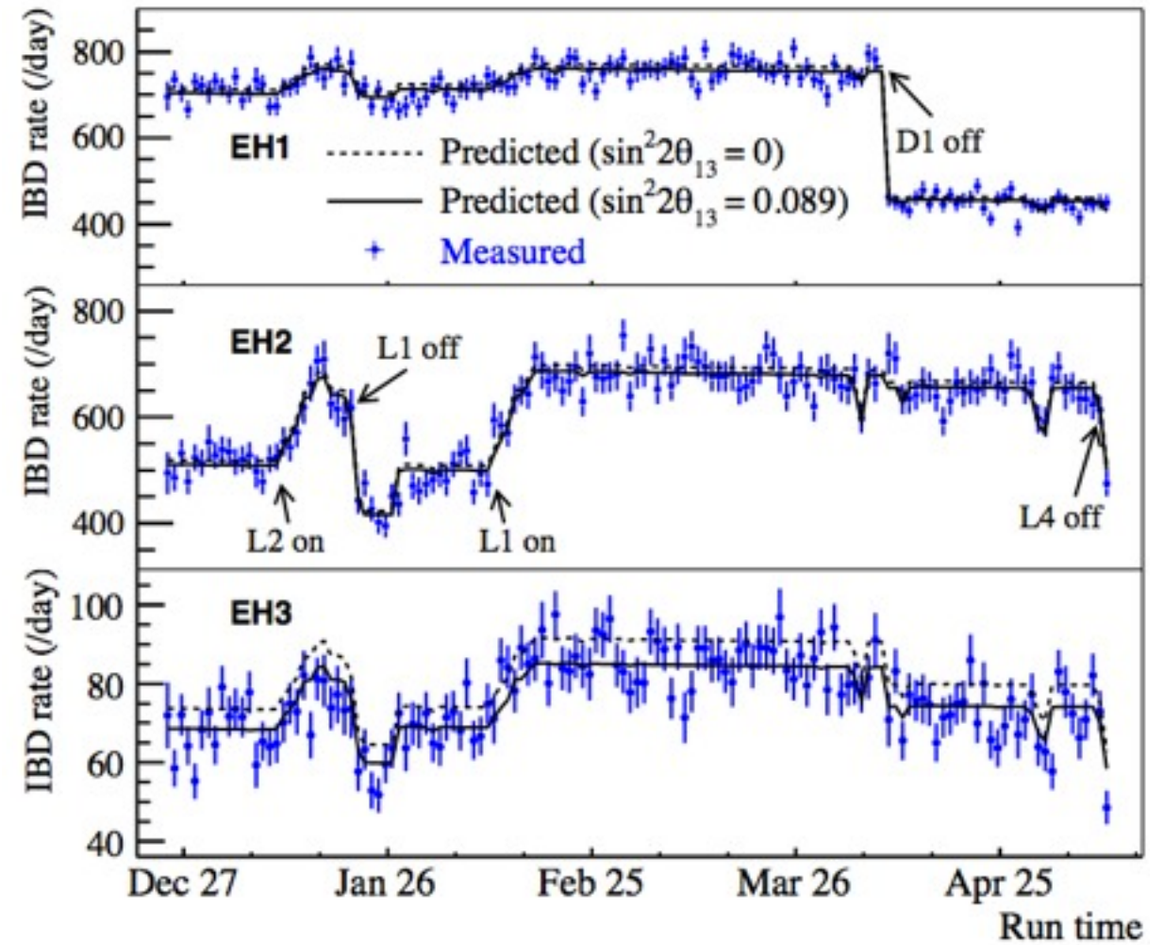
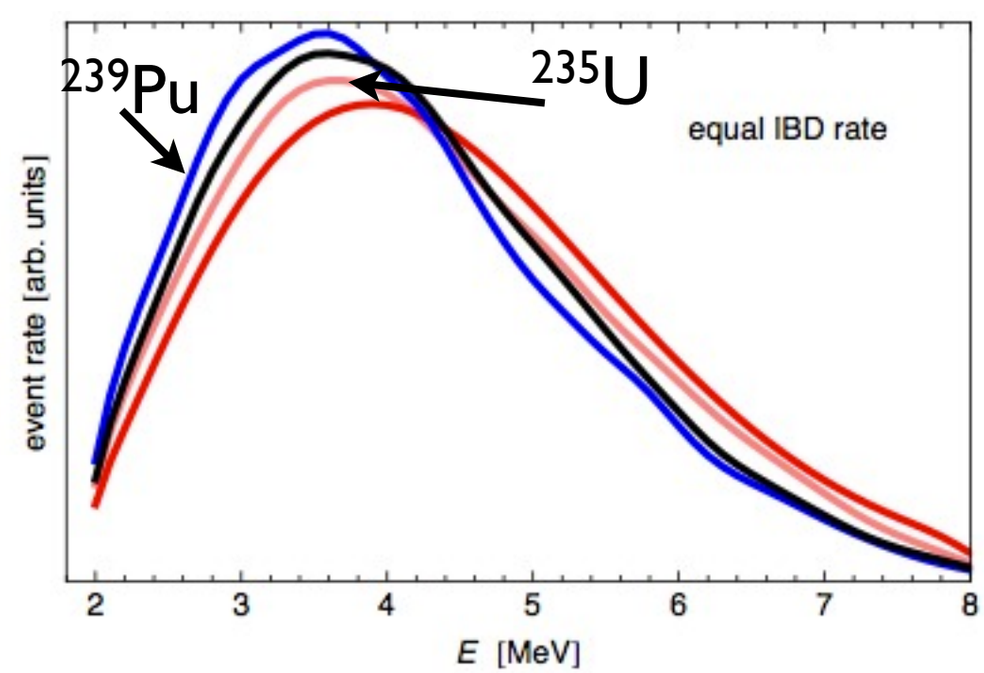




Example: Bugey

- Cu-66: Short Half-Life
- Q-value in general range of reactor neutrino energies
- 99+% of visible energy is carried off by e- in decay
- Can be produced via neutron activation at reactor



Nuclear Non-Proliferation

- IAEA Safeguards: nuclear plants **must** declare shutdown periods and fission fractions
- Neutrinos can be used to monitor the operational state of nuclear reactors
  - Done at Daya Bay
- Can also measure spectrum to determine fission fractions
  - Yet to be demonstrated
- Can these measurements be done in a cheap, compact detector on-surface?
  - Yet to be demonstrated
- Neutrino detectors could provide independent verification, prevent diversion or production of of fissile material