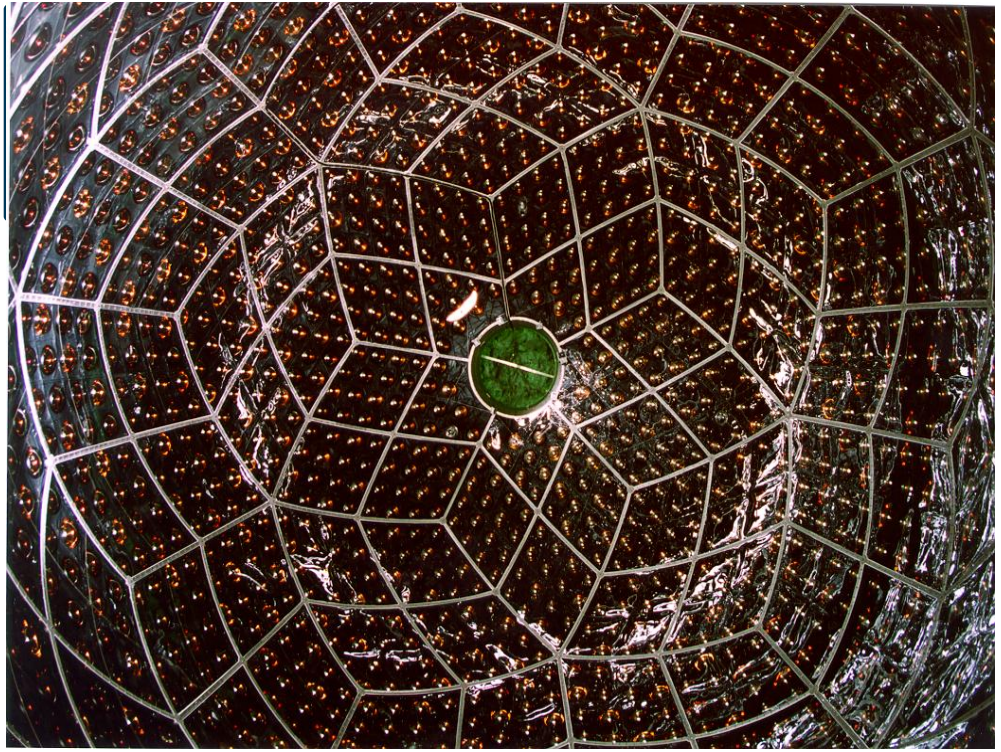
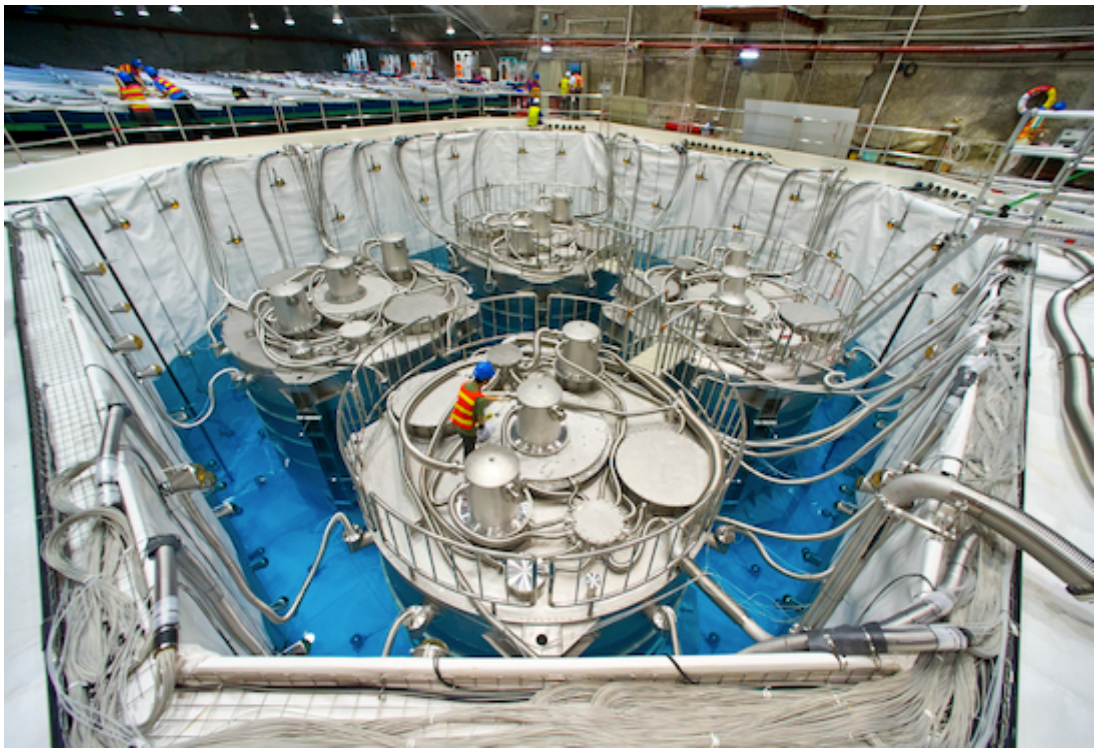




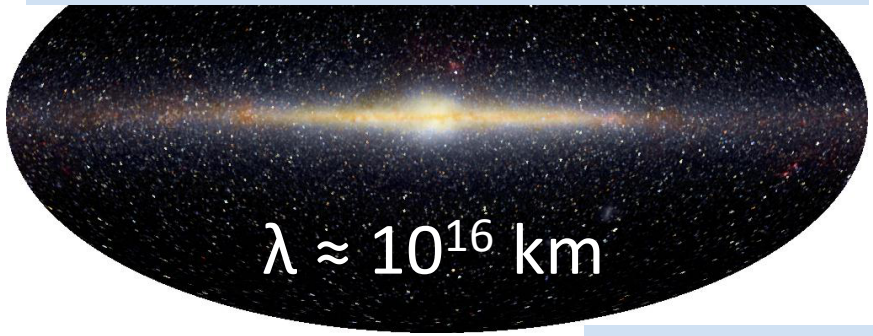
Past and Future Lessons from Neutrino Physics

Dan Dwyer (LBNL)

Feb. 11, 2014

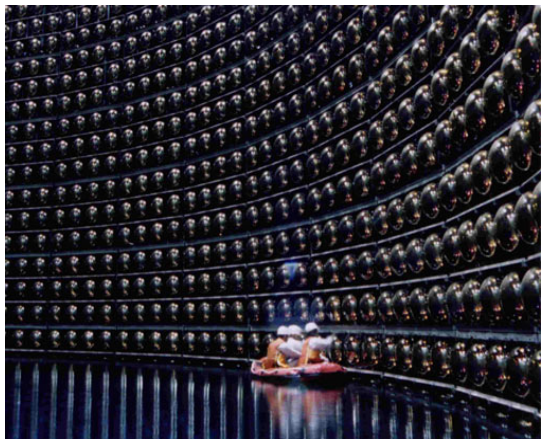
Why Study Neutrinos?

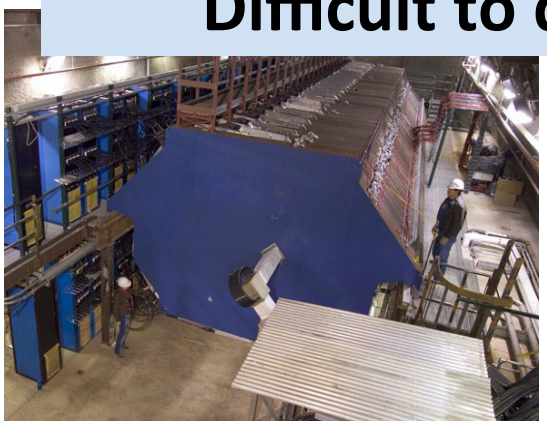
Almost non-interacting

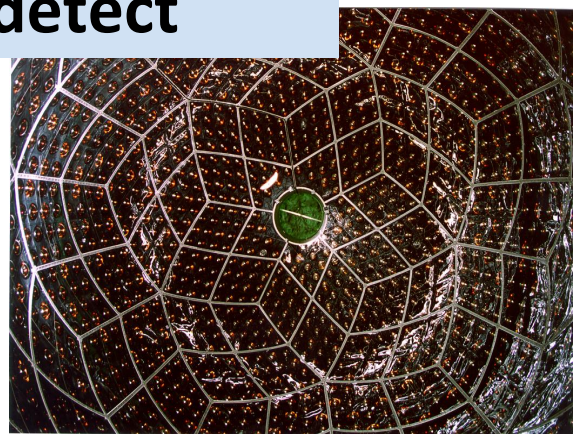


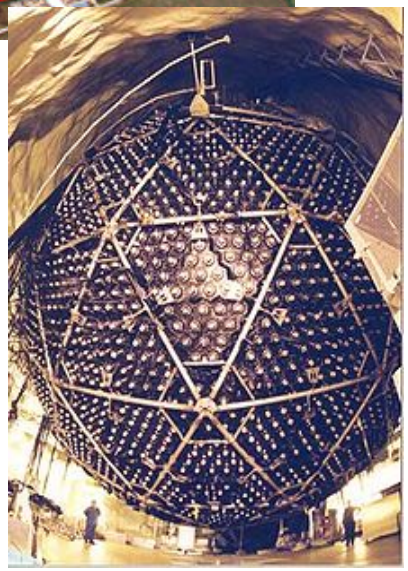
Difficult to manage

Difficult to detect









Despite Adversity,

Significant progress in neutrino physics over the past decade.

Substantial change to Standard Model:

Lepton flavor is not conserved. *Neutrinos have mass.*

Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

Principle: Interaction (flavor) eigenstates ≠ Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Physical Parameters:

We want to know θ's and Δm²'s

θ:

3 angles between mass/flavor eigenstates set **oscillation amplitude**

$\theta_{12}, \theta_{23}, \theta_{13}$

Δm²:

Differences in 3 neutrino masses determine **oscillation frequency** (distance)

$\Delta m^2_{21} = m^2_2 - m^2_1$

$\Delta m^2_{31} = m^2_3 - m^2_1$

δ_{CP}: Off-diagonal phase

($\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$)

Oscillation Measurements

Oscillation changes neutrino flavor

Oscillation Frequency:

Neutrino oscillates according to it's proper time $\tau \approx L/E_\nu$

$$\Delta_{ji} \simeq 1.267 \frac{L[\mathrm{m}]\Delta m^2_{ji}[\mathrm{eV}^2]}{E[\mathrm{MeV}]}$$

Example:

Probability to still detect as same flavor at distance L

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

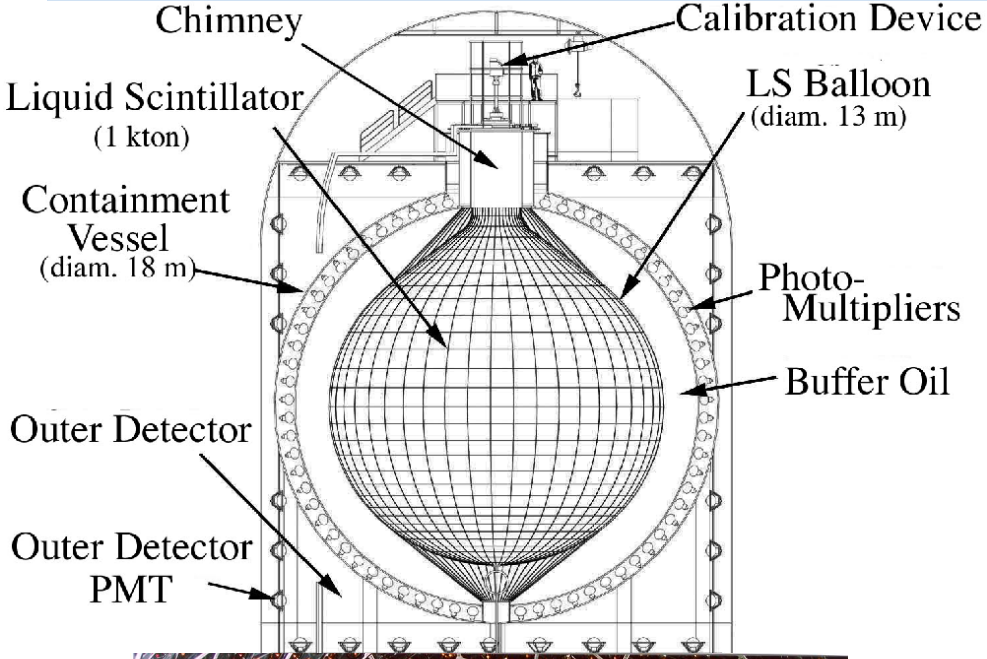
Farm-to-Table Physics

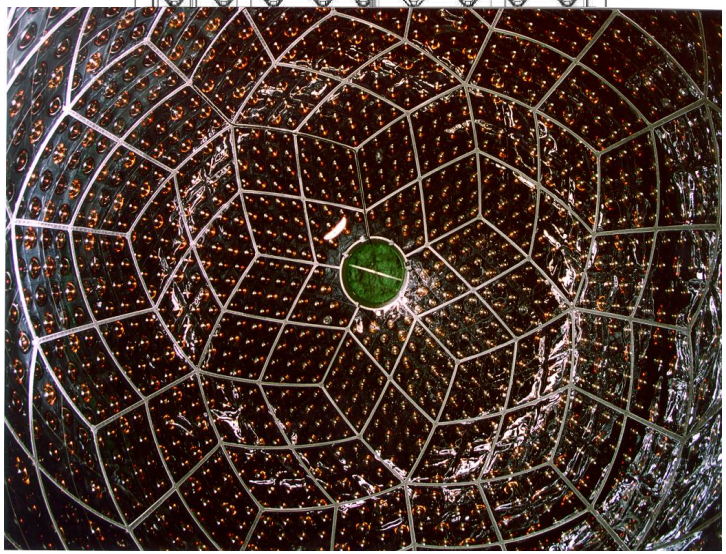
?

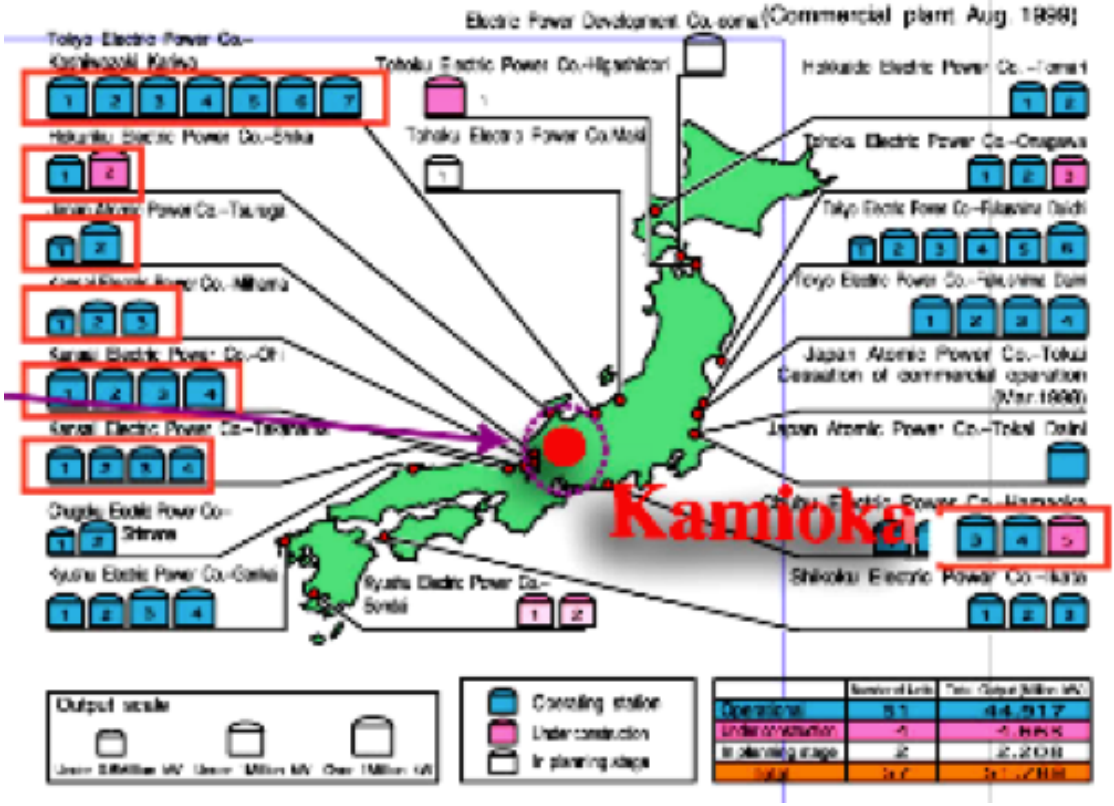
Good experiments require knowledge from the ground up.

The KamLAND Experiment

Liquid scintillator target (1 kton) measures reactor $\overline{\nu}_e$ flux







Measured roughly 1 $\overline{\nu}_e$ per day.

Understanding of backgrounds and energy calibration essential.

Lesson

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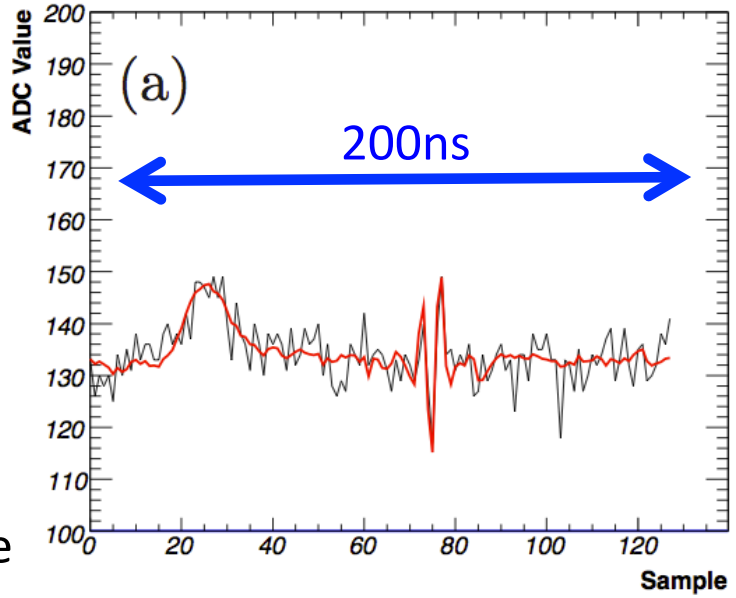
Signal Processing

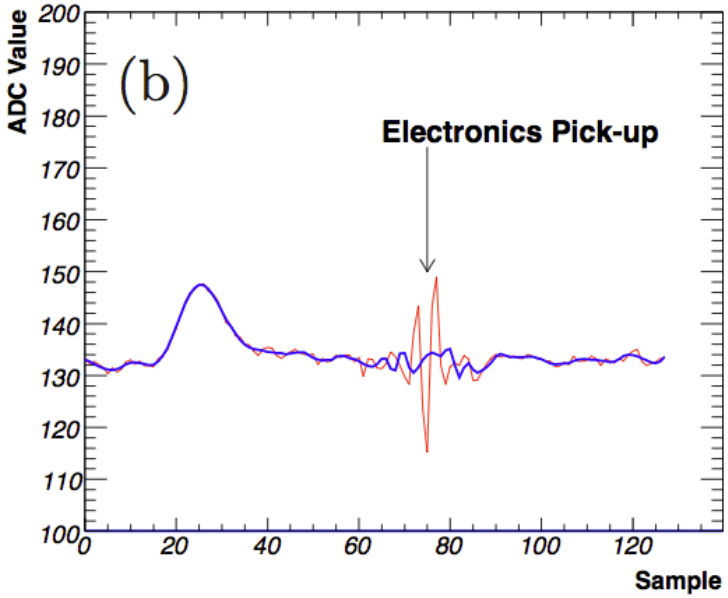
ATWD:

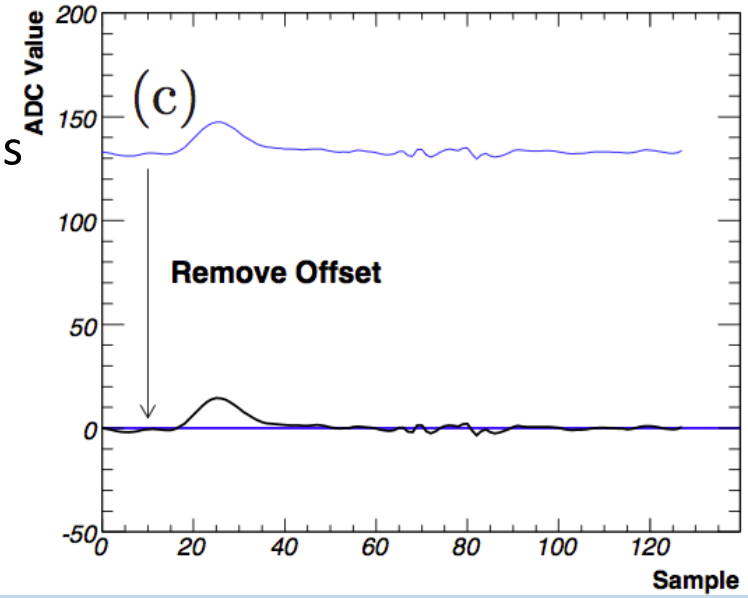
Analog Transient Waveform Digitizer

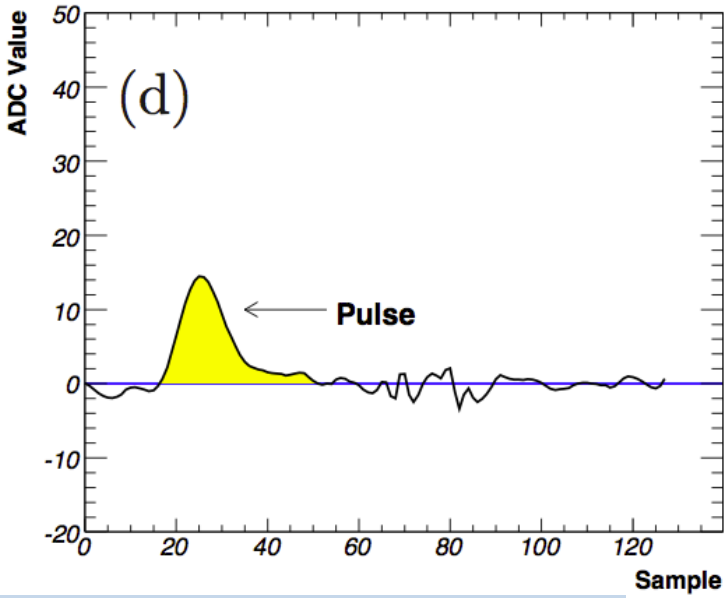
Provide charge-time of photomultiplier signal.

Developed methods to optimally use signal waveforms.









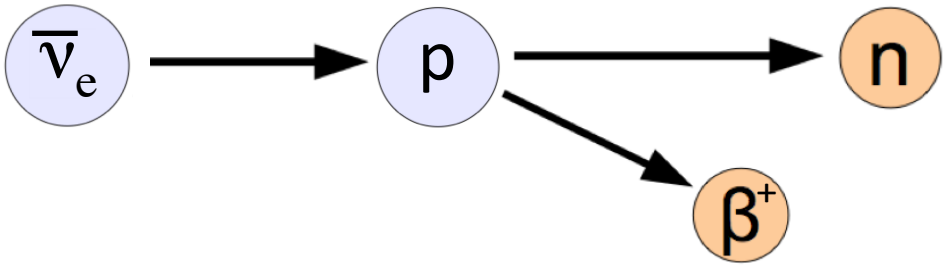
Necessary for understanding $\overline{\nu}_e$ energy and position

Cosmogenic Background

Antineutrino Signal:

Prompt: inverse β-decay positron

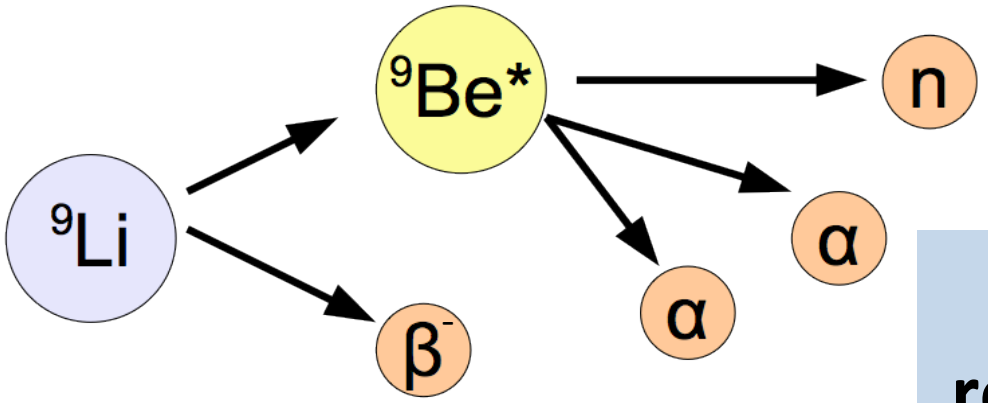
Delayed: neutron capture

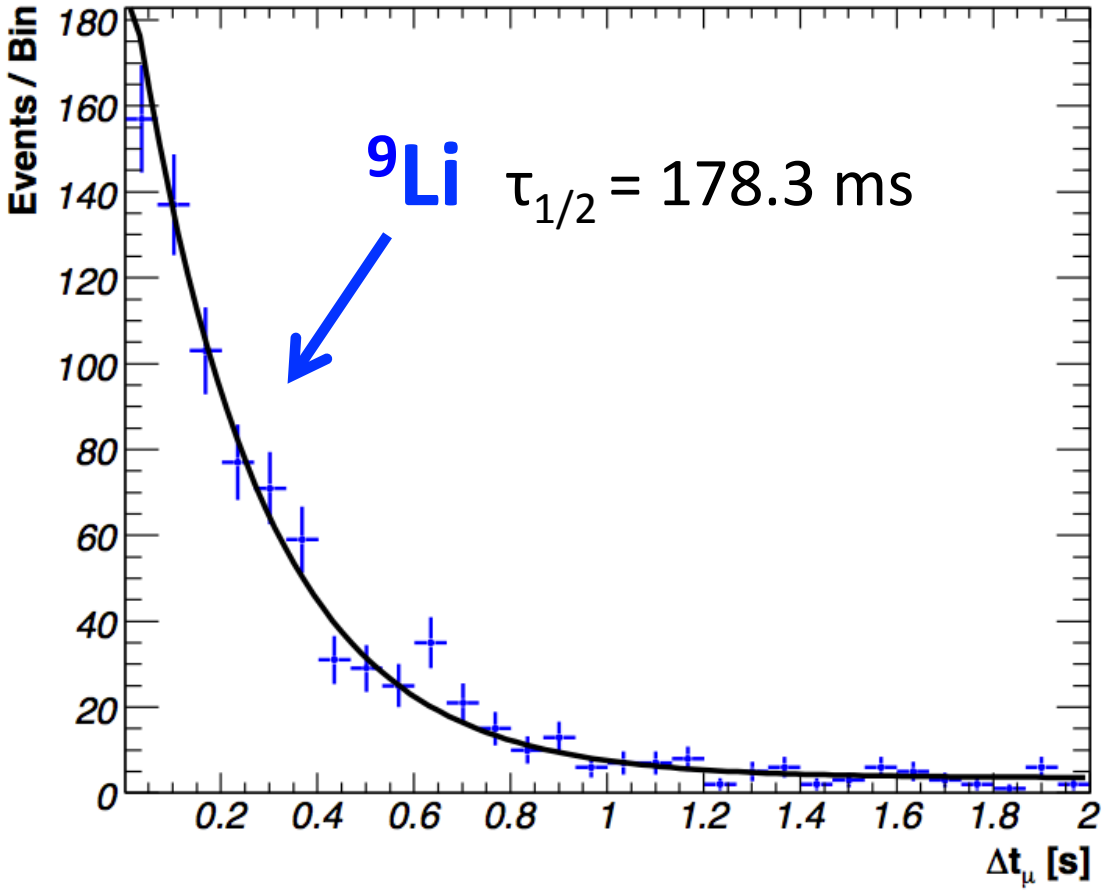


Cosmogenic Background:

Prompt: β-decay electron

Delayed: neutron capture

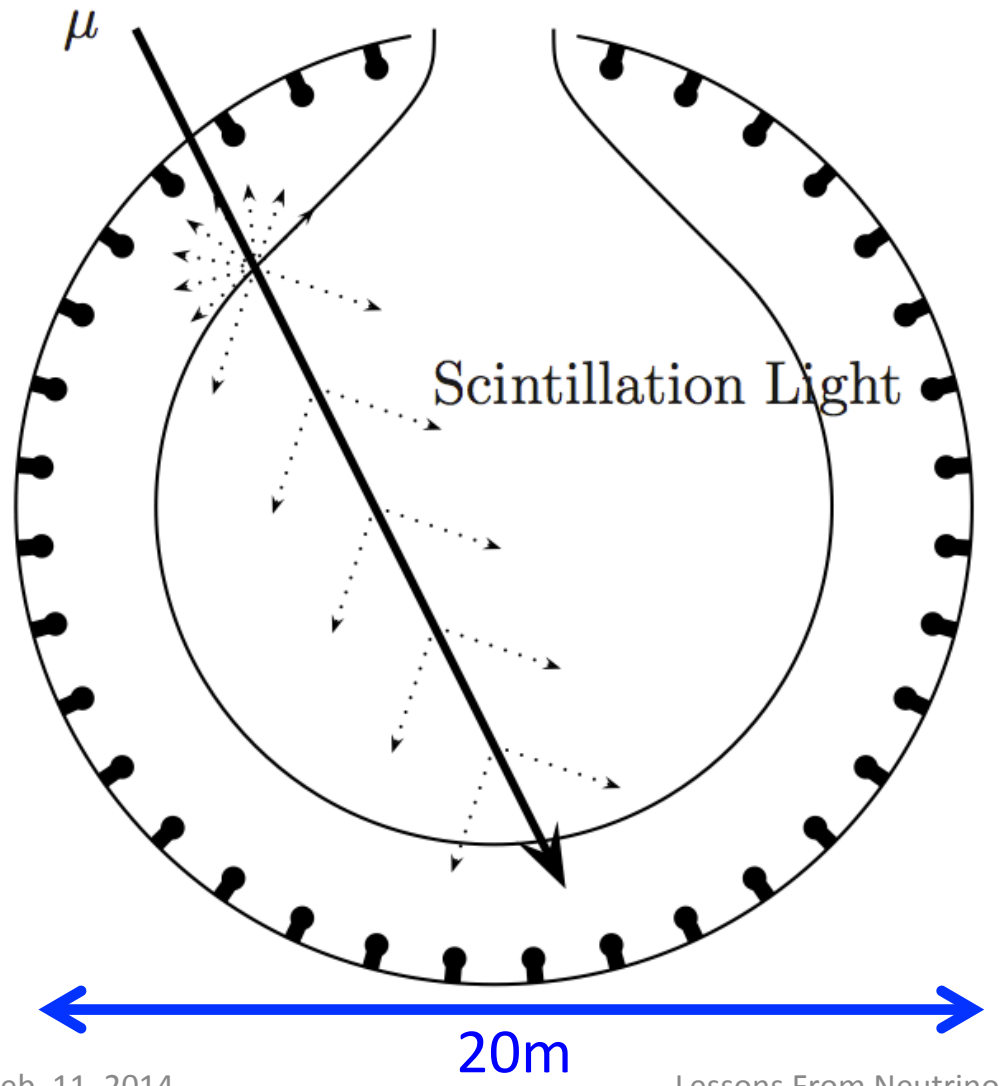


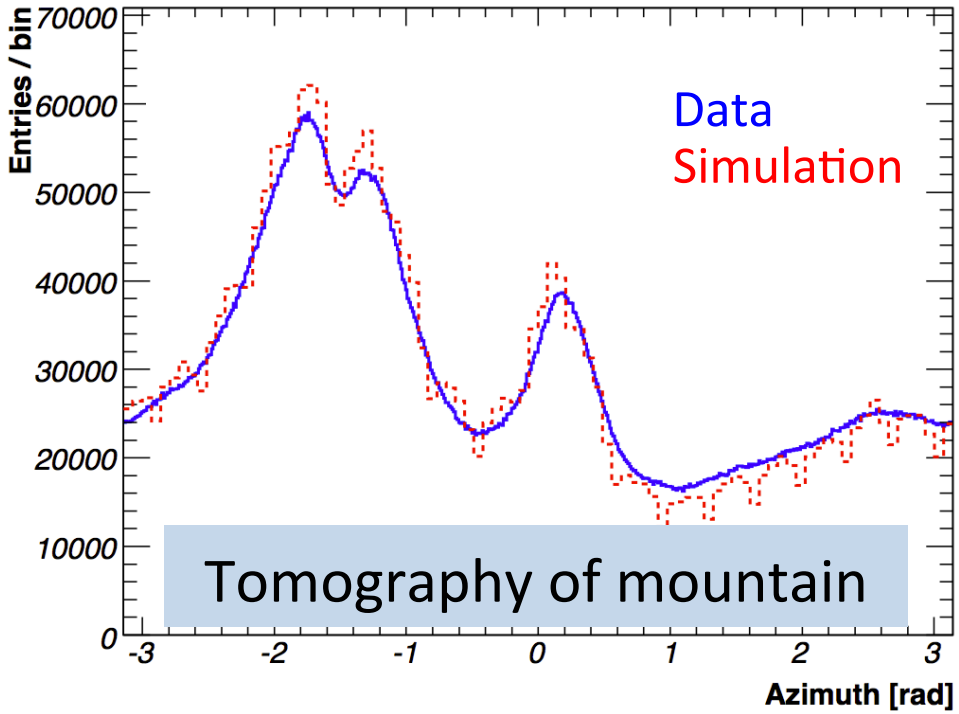


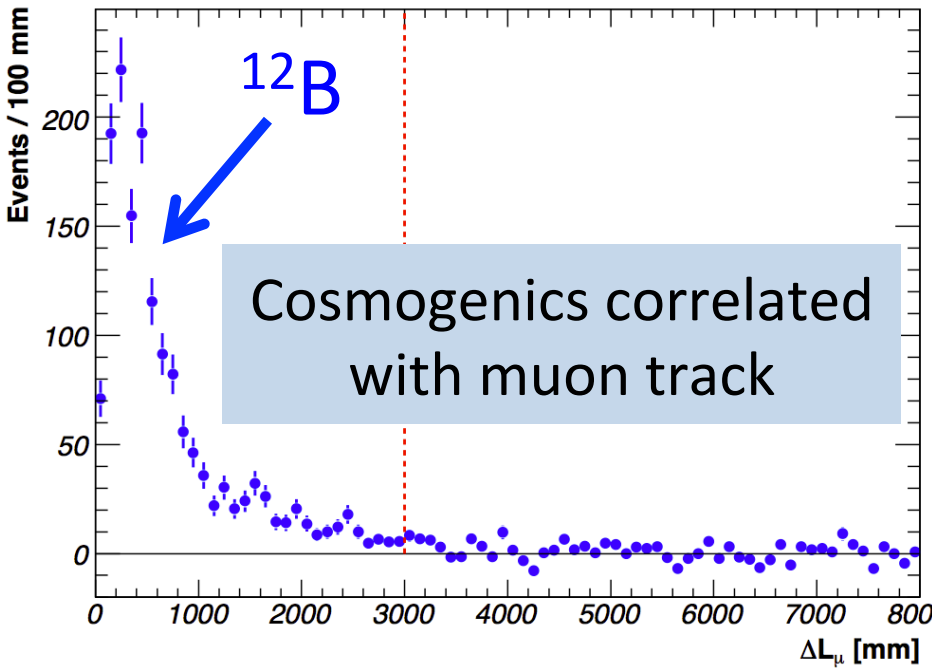
Identified subset of muons responsible for most background

Muon Reconstruction

Developed method to determine muon track, in environment of light saturation.

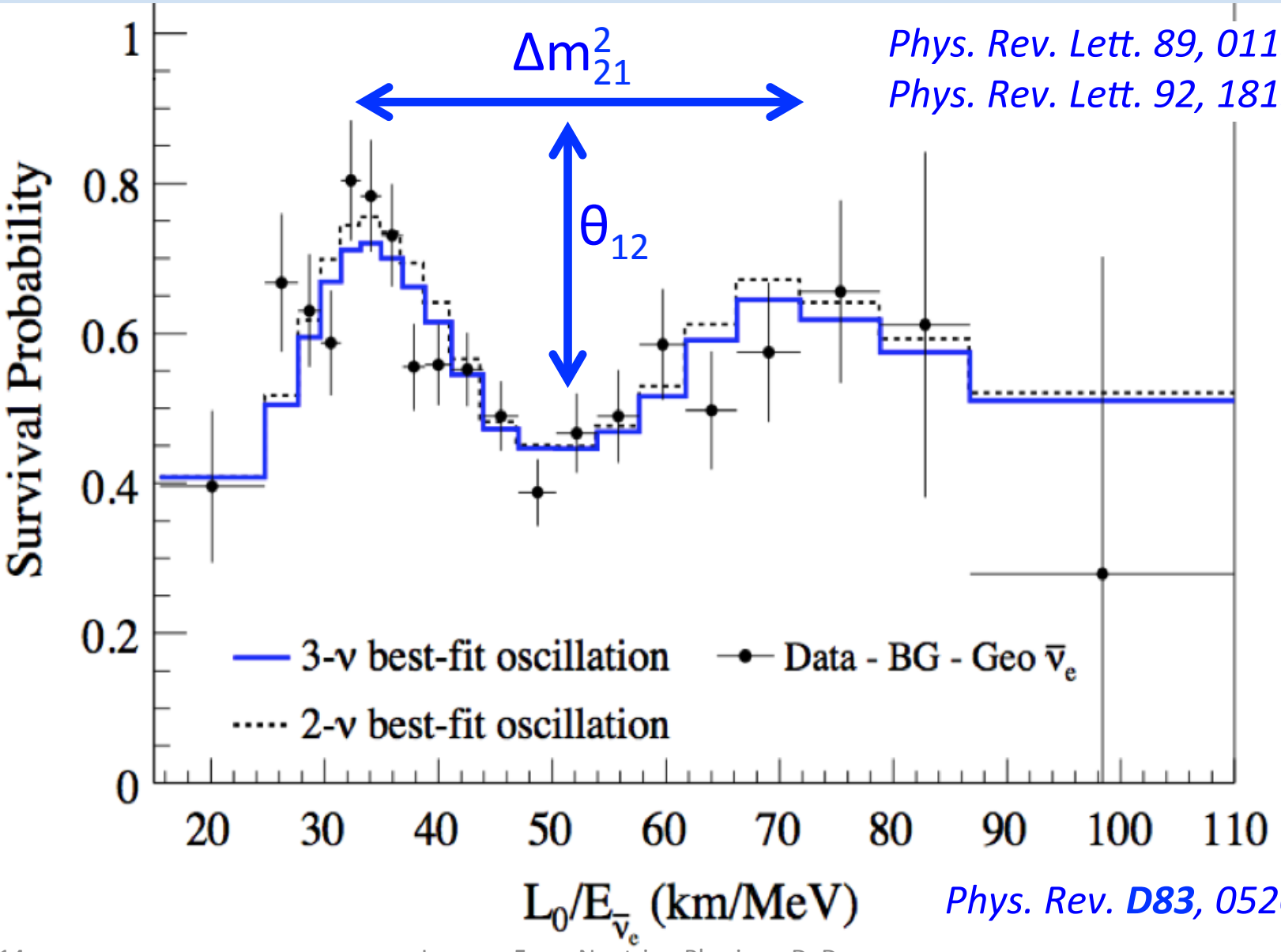






Oscillation at KamLAND

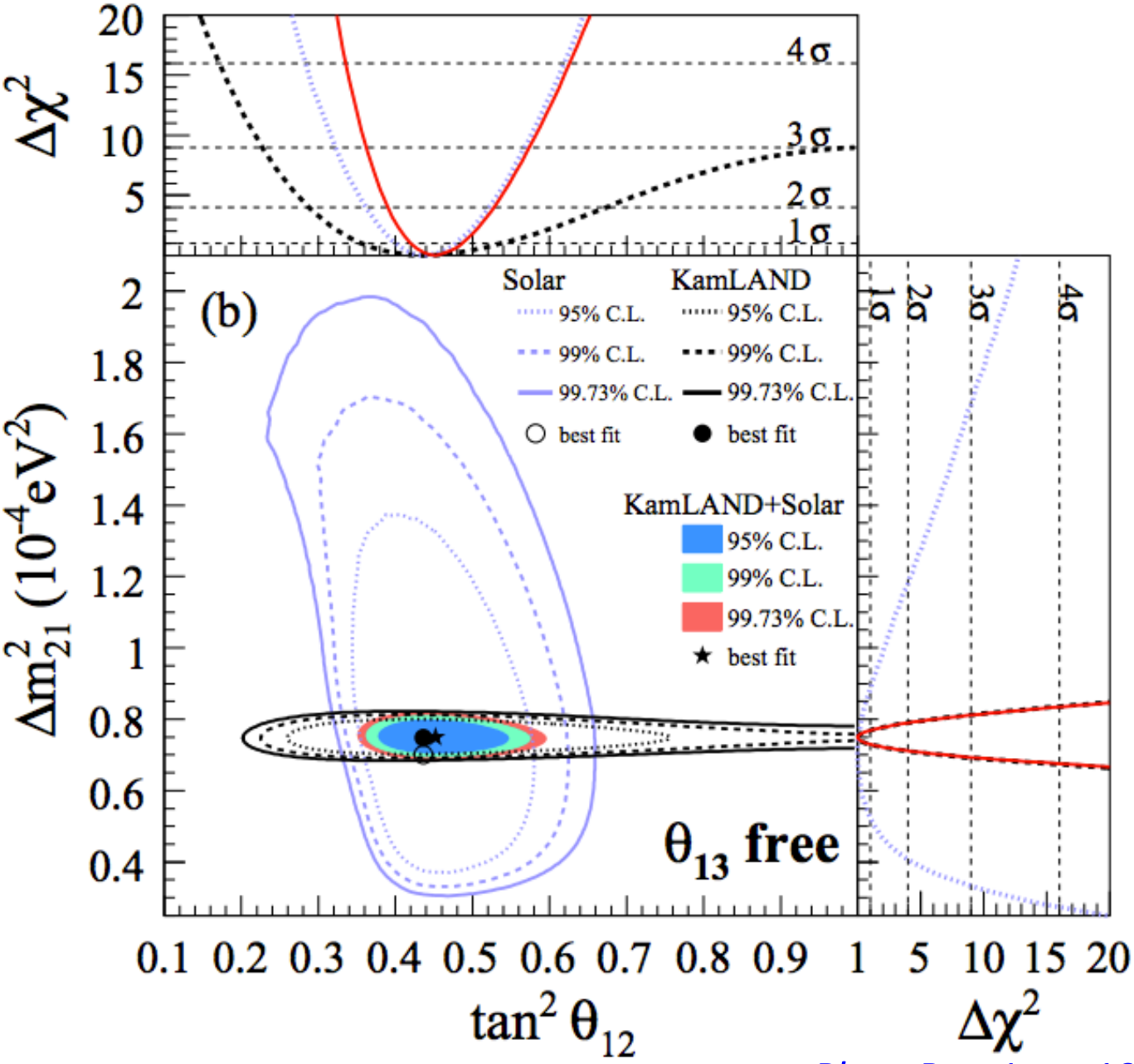
2002: KamLAND shows distinct signature of ν oscillation.



Phys. Rev. Lett. 89, 011301 (2002)
Phys. Rev. Lett. 92, 181301 (2004)

*Phys. Rev. **D83**, 052002 (2011)*

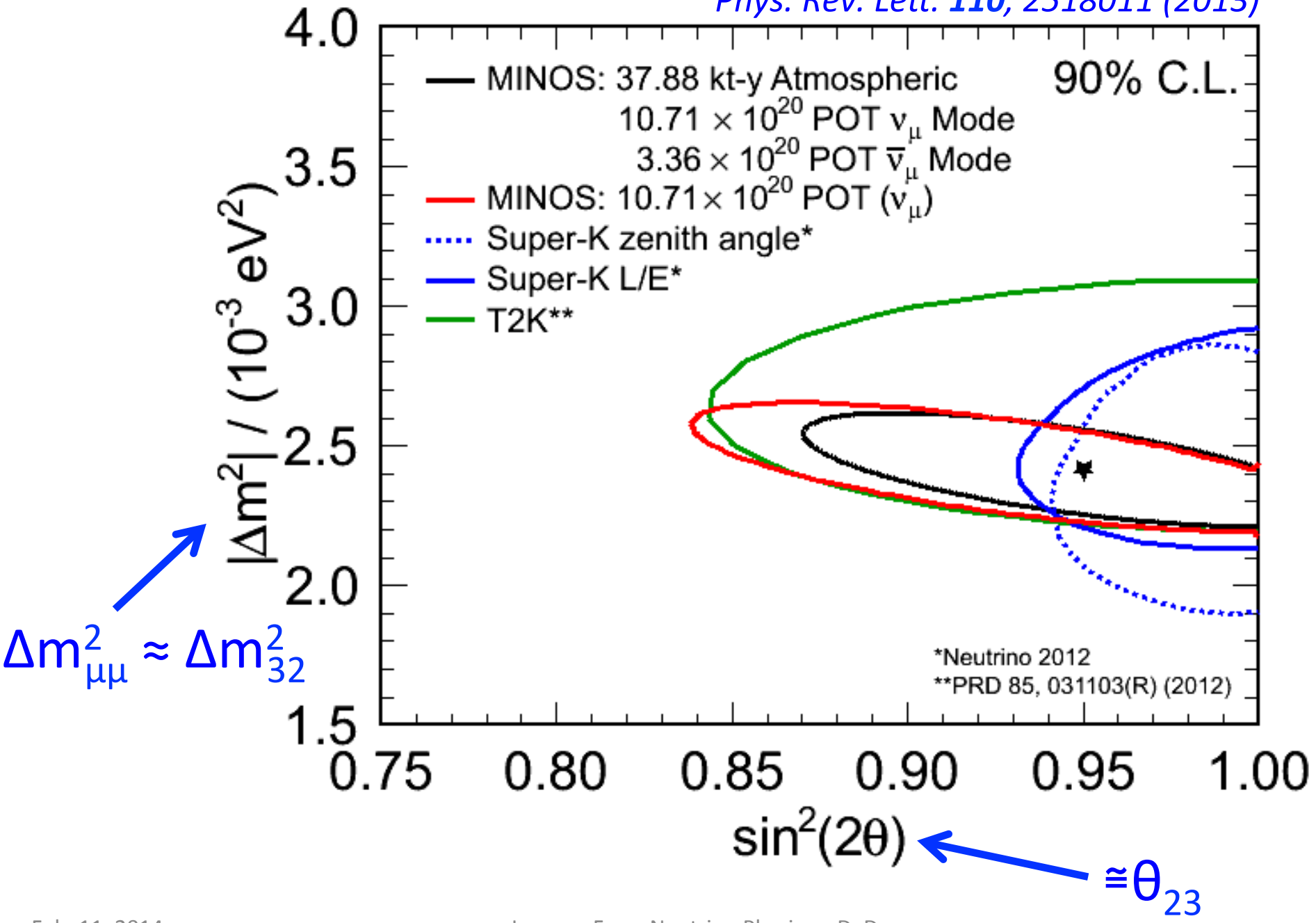
KamLAND and Solar Results



Phys. Rev. Lett. 100, 221803 (2008)
*Phys. Rev. **D83**, 052002 (2011)*

Accelerator and Atmospheric ν_μ

*Phys. Rev. Lett. **110**, 2518011 (2013)*

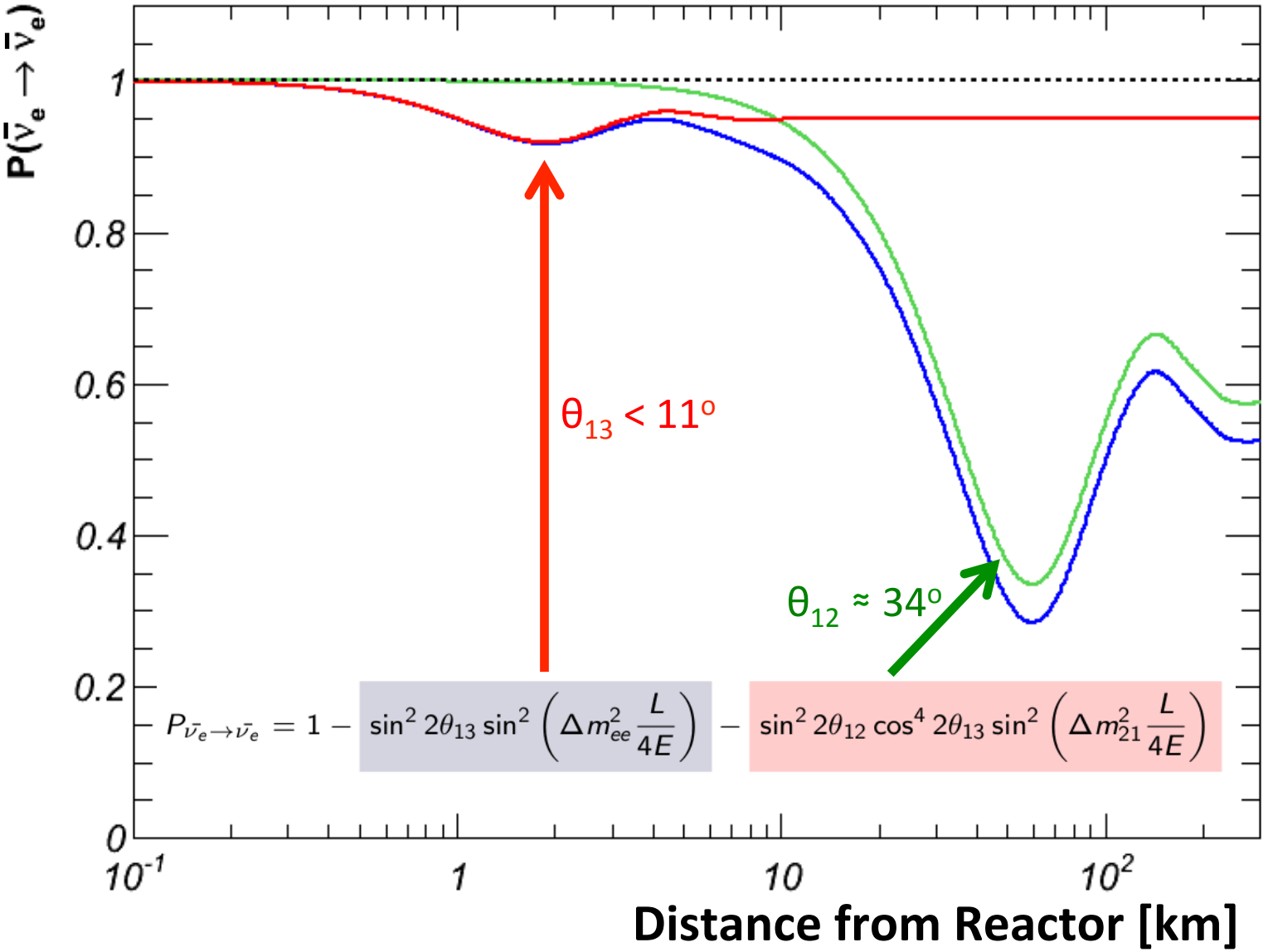


$\Delta m^2_{\mu\mu} \approx \Delta m^2_{32}$

$\cong \theta_{23}$

θ_{13}: The Remaining Angle

Reactor $\bar{\nu}_e$ experiments sensitive to θ_{13} oscillation at ~1.6 km



2000:

CHOOZ, Palo Verde experiments at 1 km limited $\theta_{13} < 11^o$

~2006:

Double CHOOZ, RENO, Daya Bay experiments plan new measurements

Measuring θ_{13}

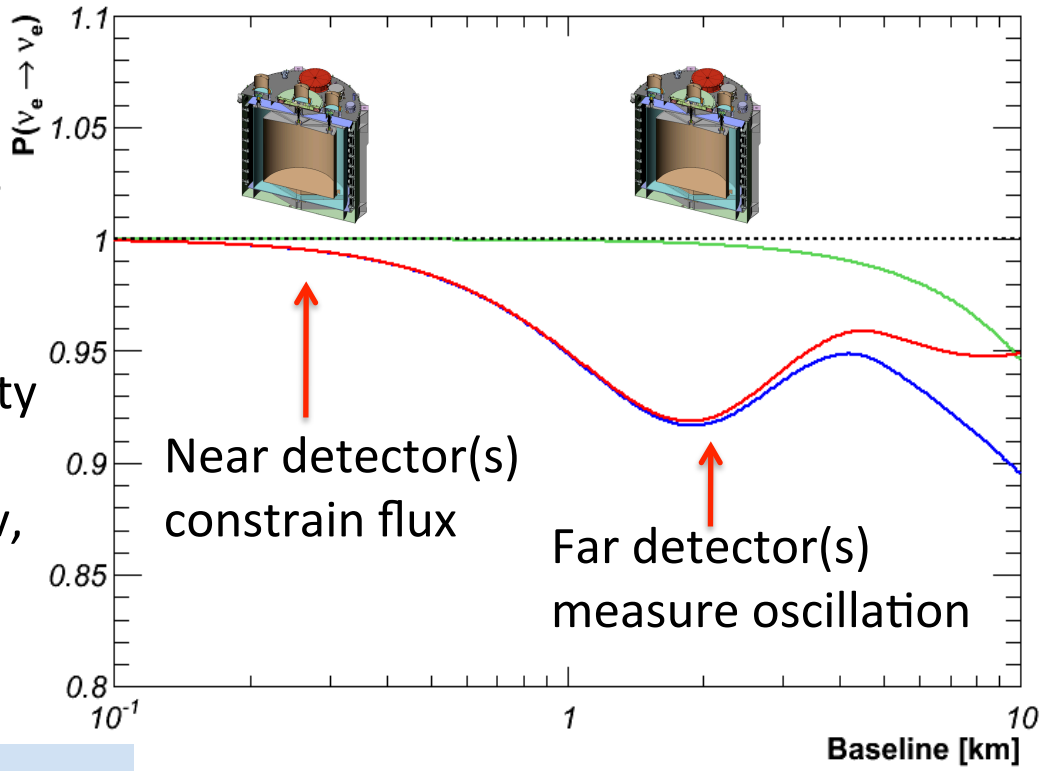
Absolute Reactor Flux:

Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors remove absolute uncertainty

First proposed by L. A. Mikaelyan and V.V. Sinev, *Phys. Atom. Nucl.* ***63****, 1002 (2000)*



Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

Detector Target Mass

Detector efficiency

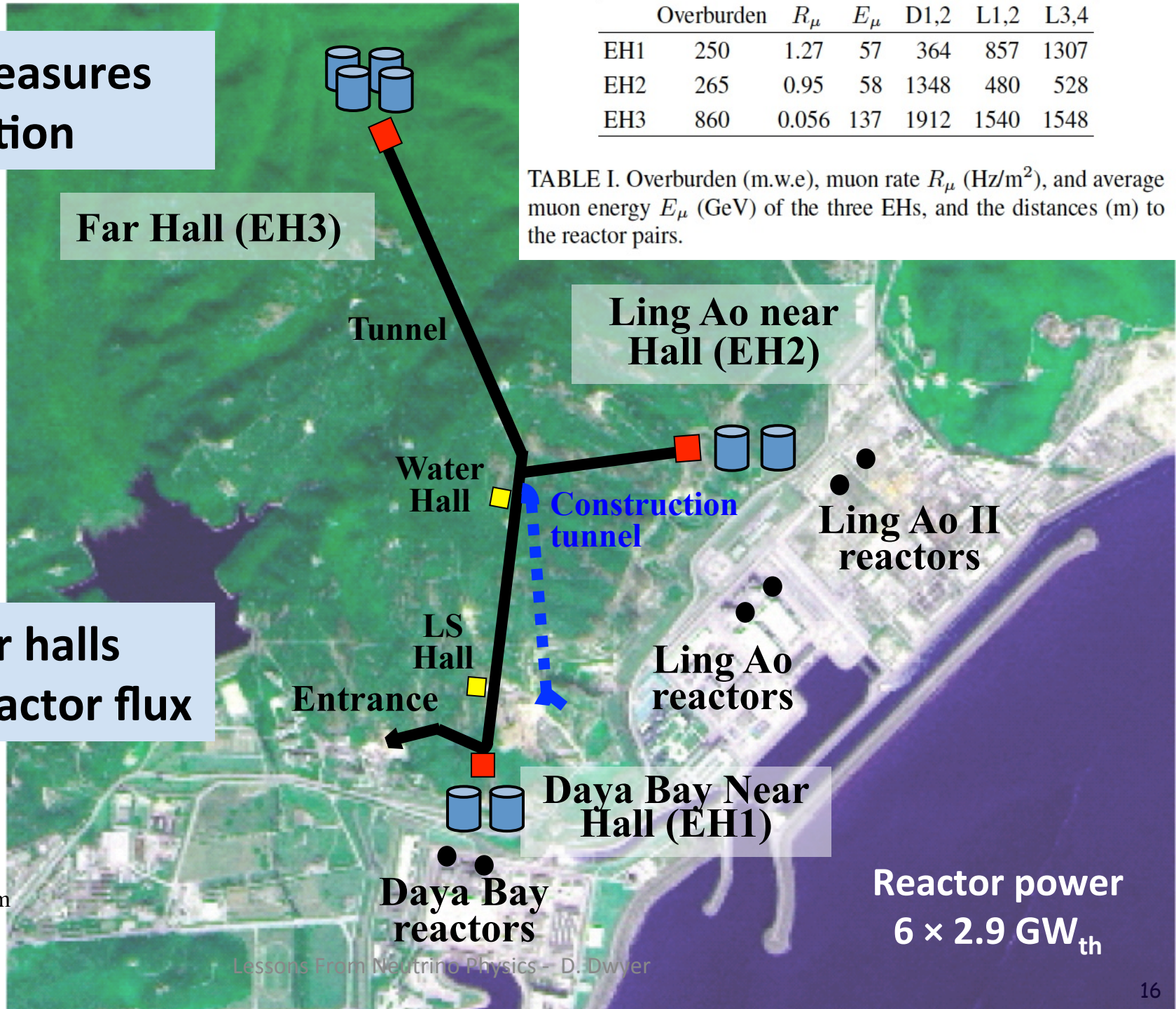
Experiment Layout

Far hall measures oscillation

Two near halls constrain reactor flux

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

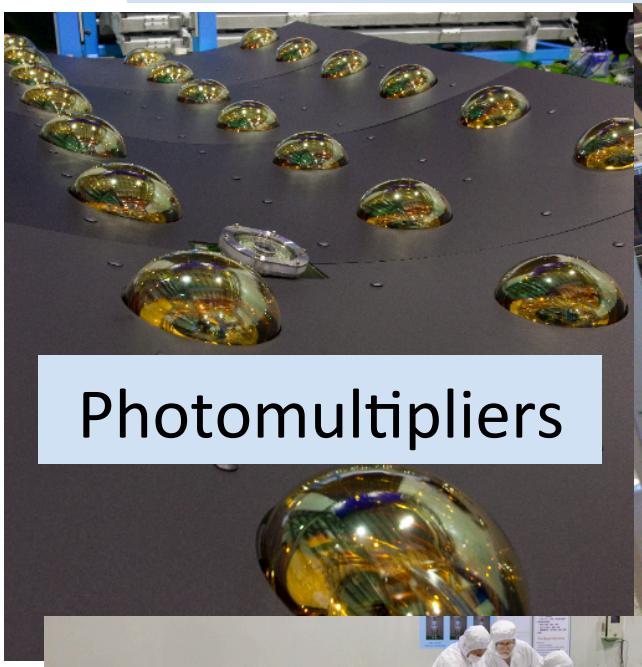


Lesson

Don't Complain!

Commissioning

Punishment: Responsible for experiment integration

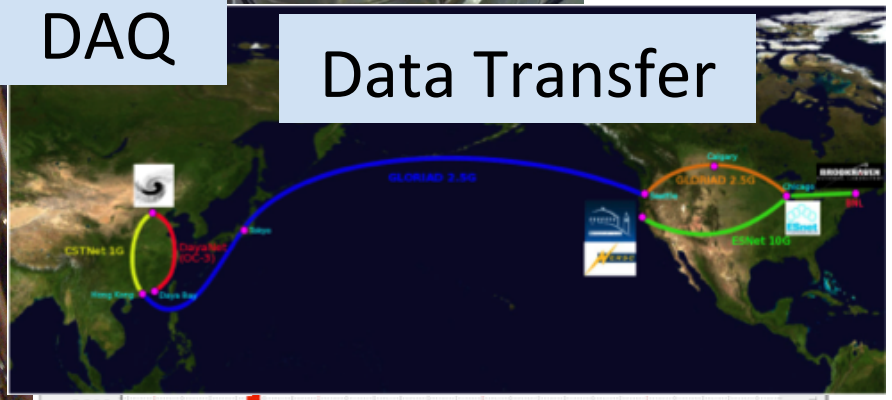


Photomultipliers

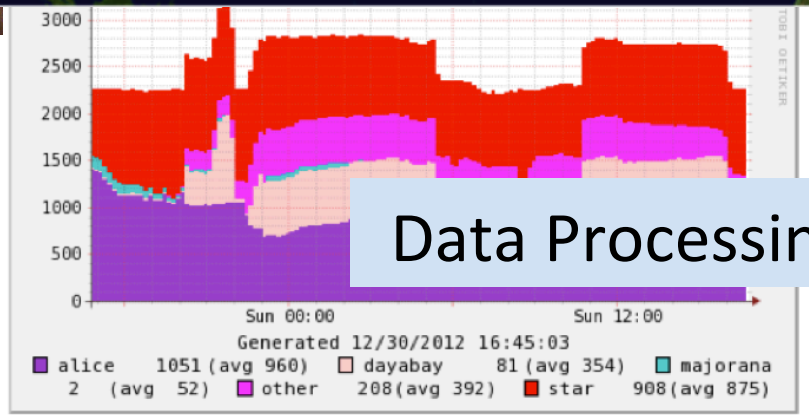
Electronics

Automated Calibration

DAQ



Data Transfer



Data Processing

Detector Interfaces and Monitoring

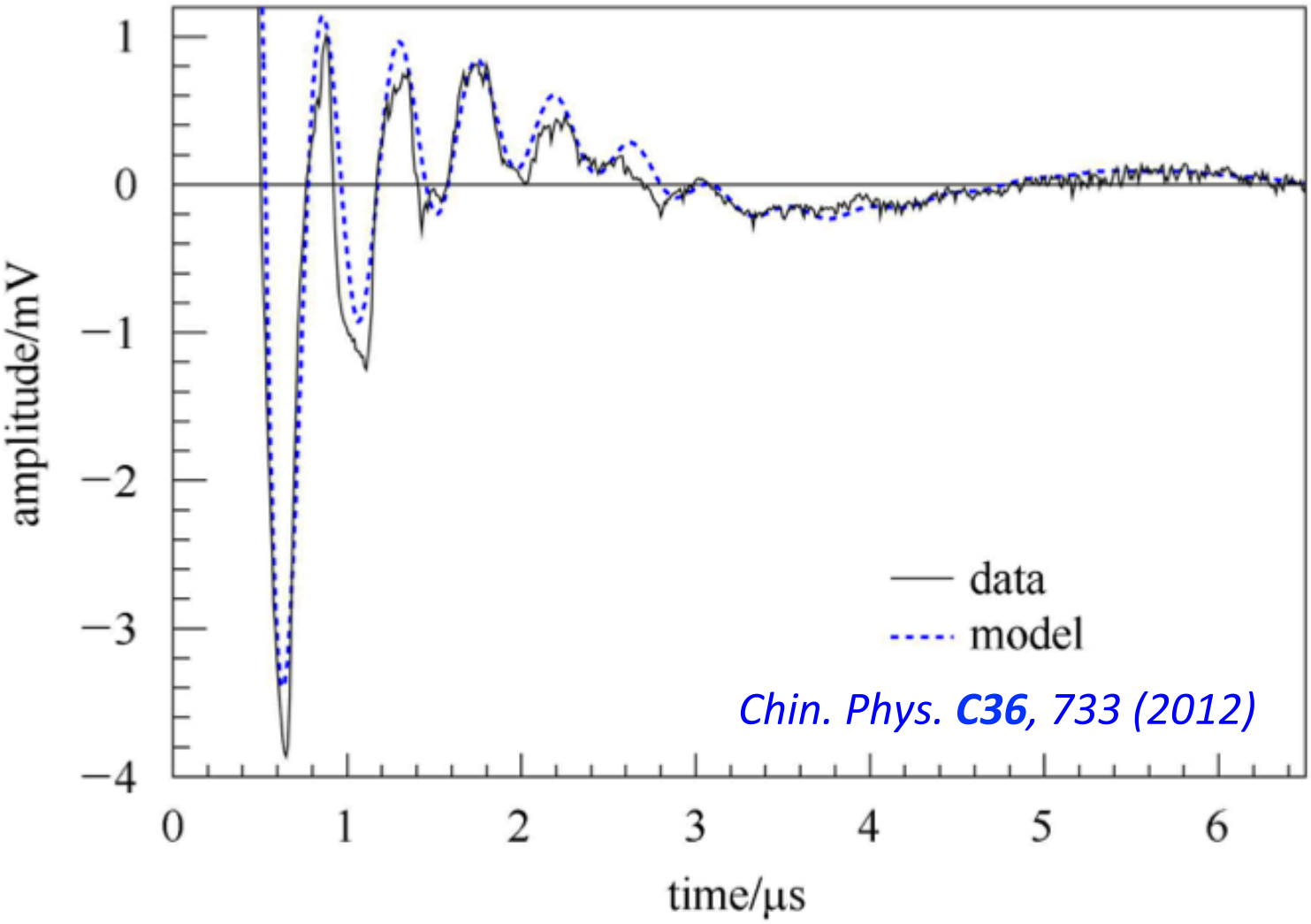
PMT Ringing

PMT/Electronics recovery essential for $\bar{\nu}_e$ measurement

Significant fluctuation following PMT pulse.

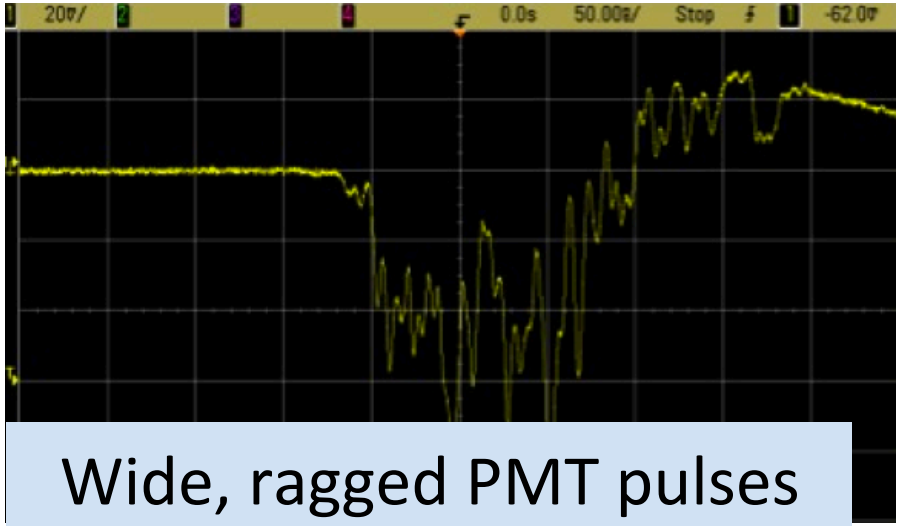
Issue mitigated via improvements in electronics.

Developed empirical model to simulate PMT and electronics.

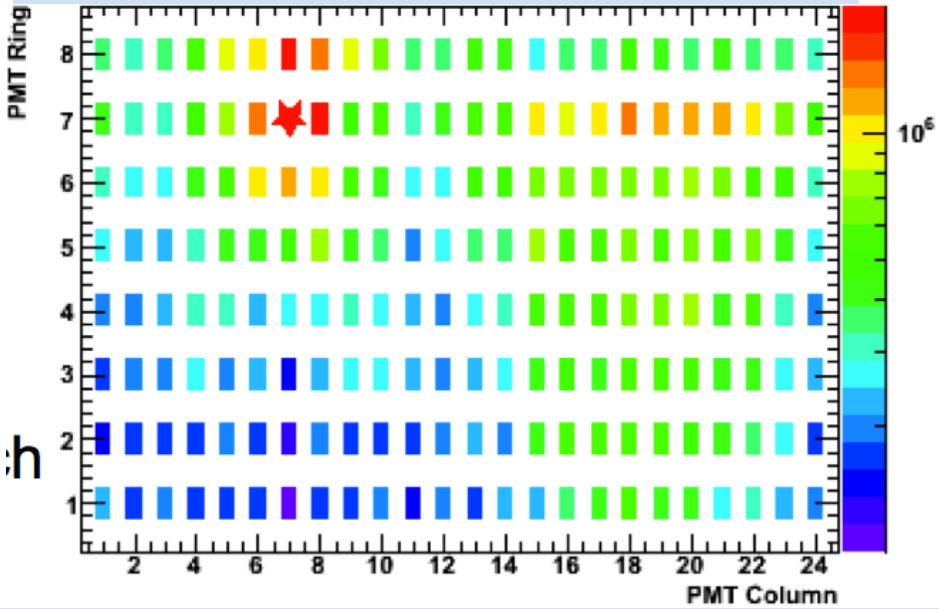


PMT Light Emission

Unexpected noise due to PMT light emission

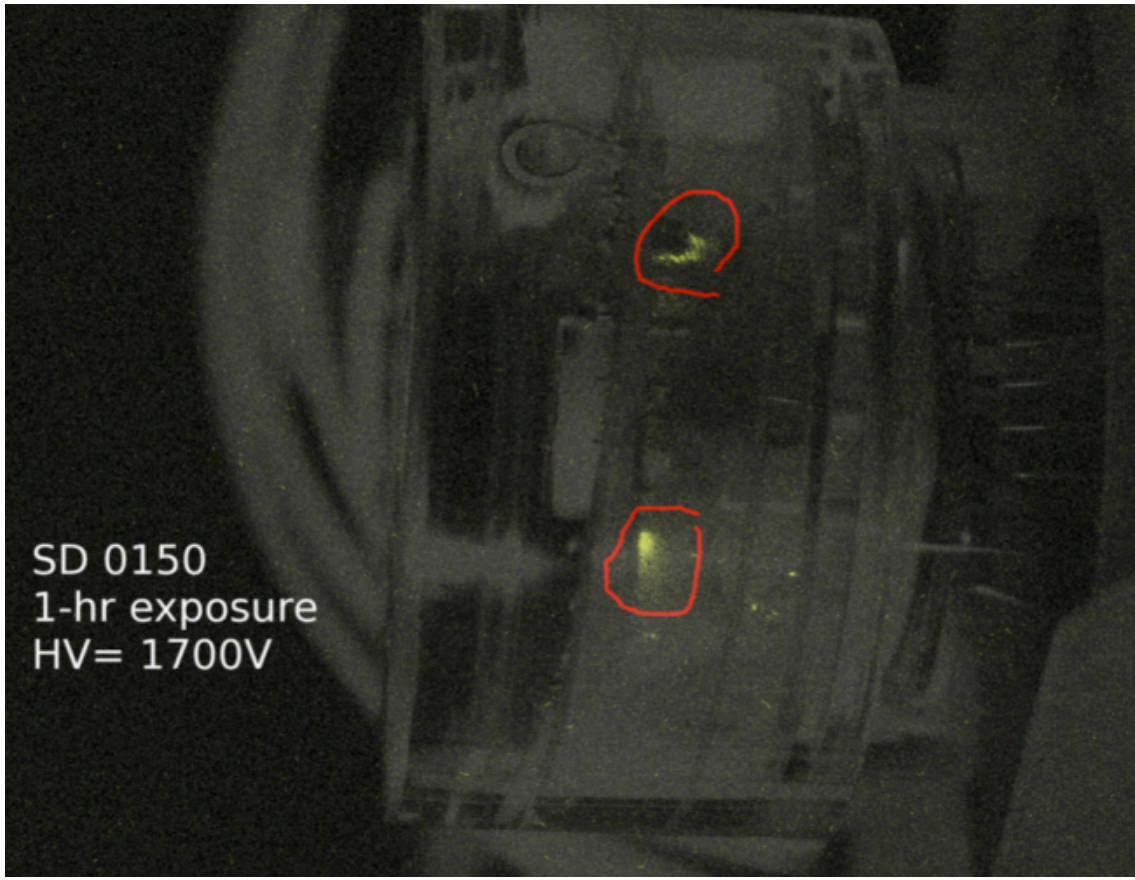


Wide, ragged PMT pulses



Unique hit pattern in detector

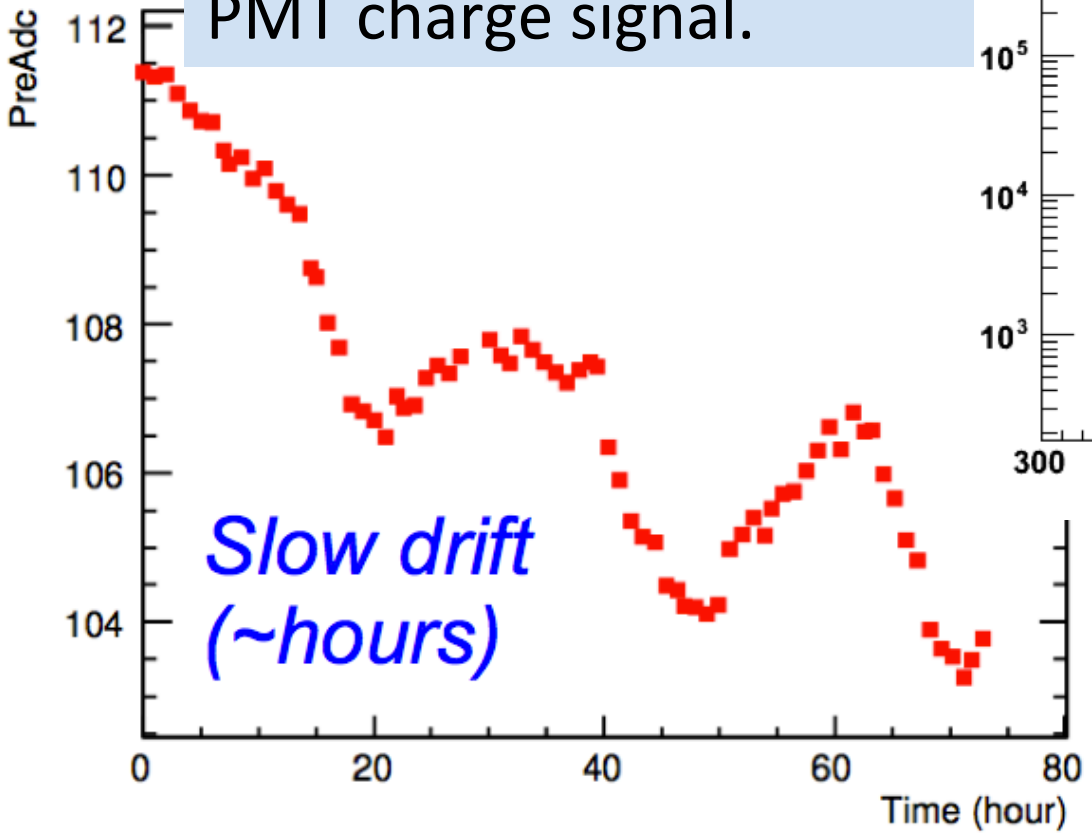
Light emission localized to PMT base



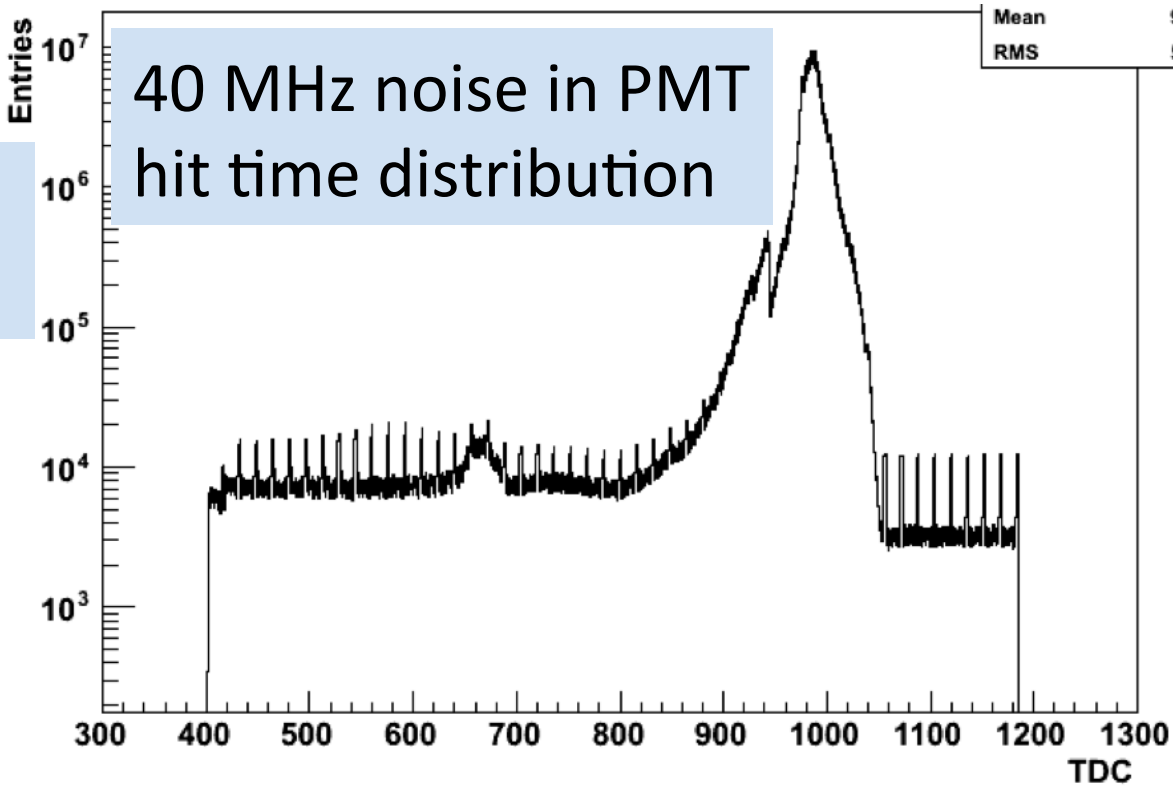
Electronics and Triggering

Identified unexpected features of electronics and triggering

Unexpectly large drift in PMT charge signal.



40 MHz noise in PMT hit time distribution

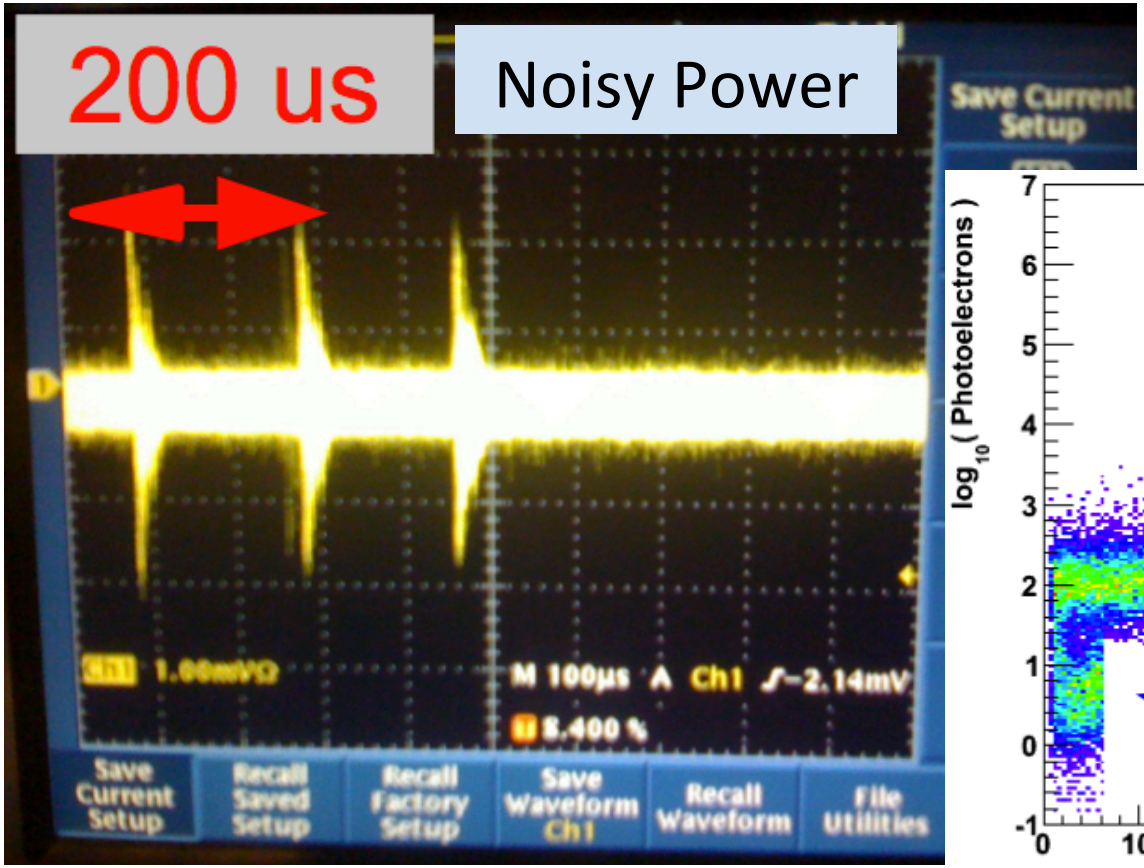


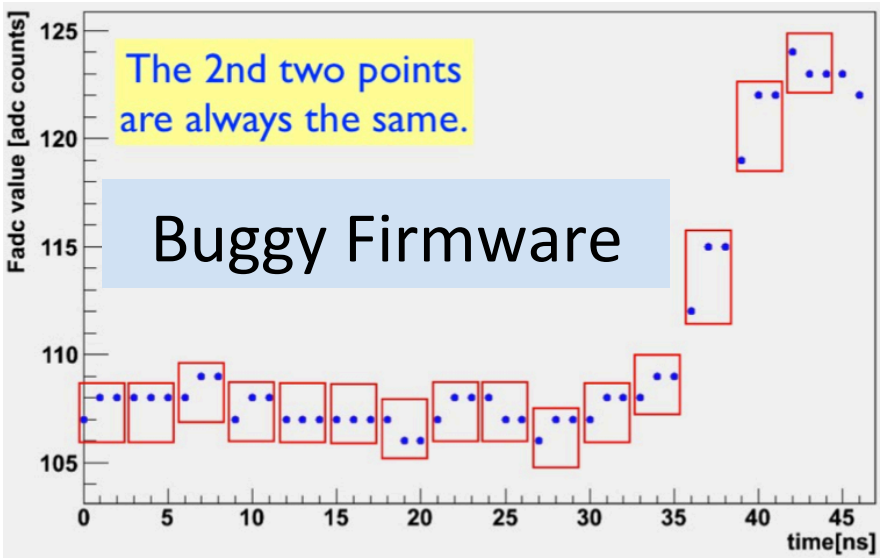
Early commissioning results led to improvements in electronics design.

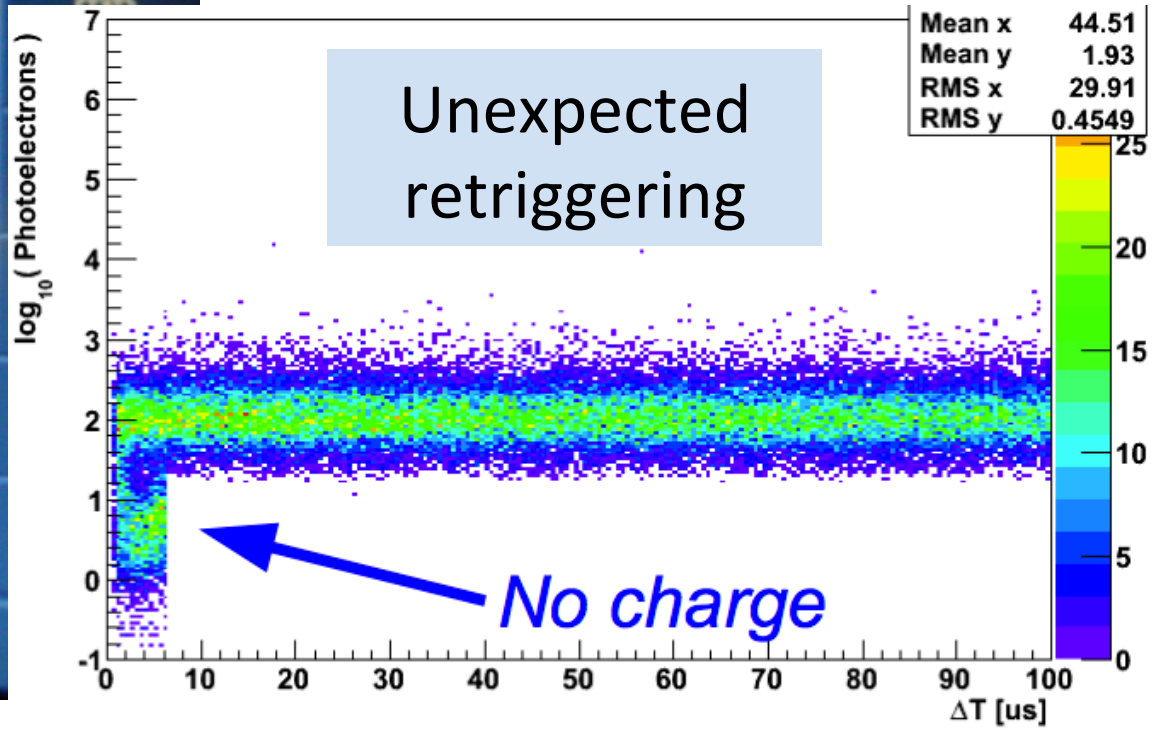
Electronics and Triggering

Many other issues found and fixed

- Unexpected gaps in data
- Event times in 1970
- Same PMT signal present in two events
- Electronics time offset jumps







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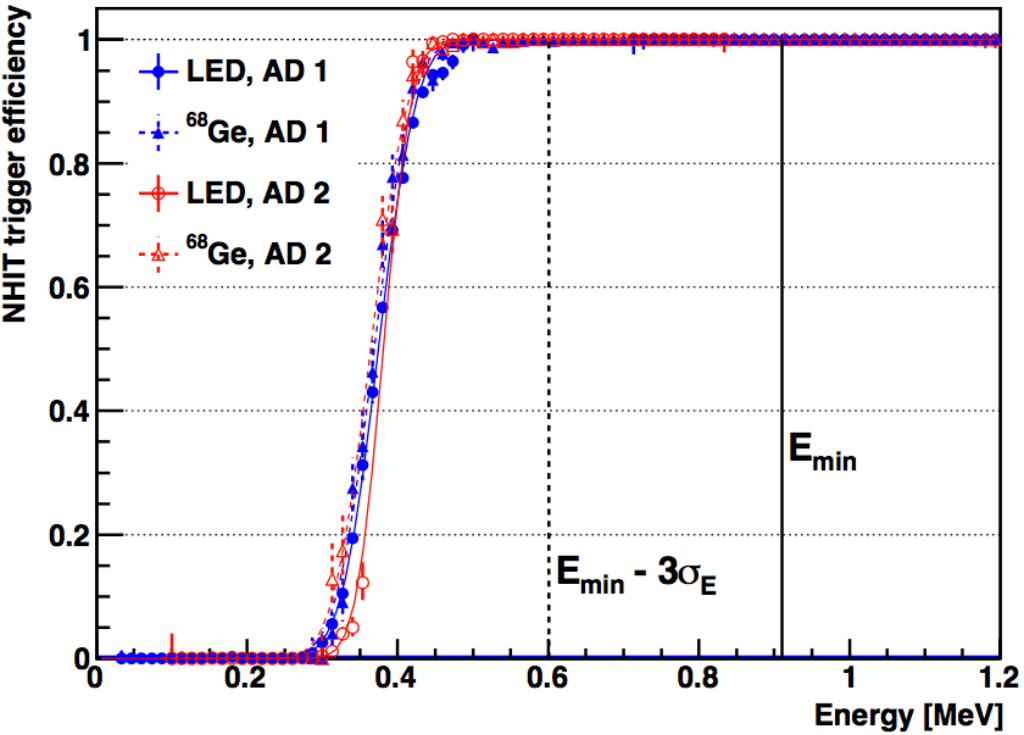
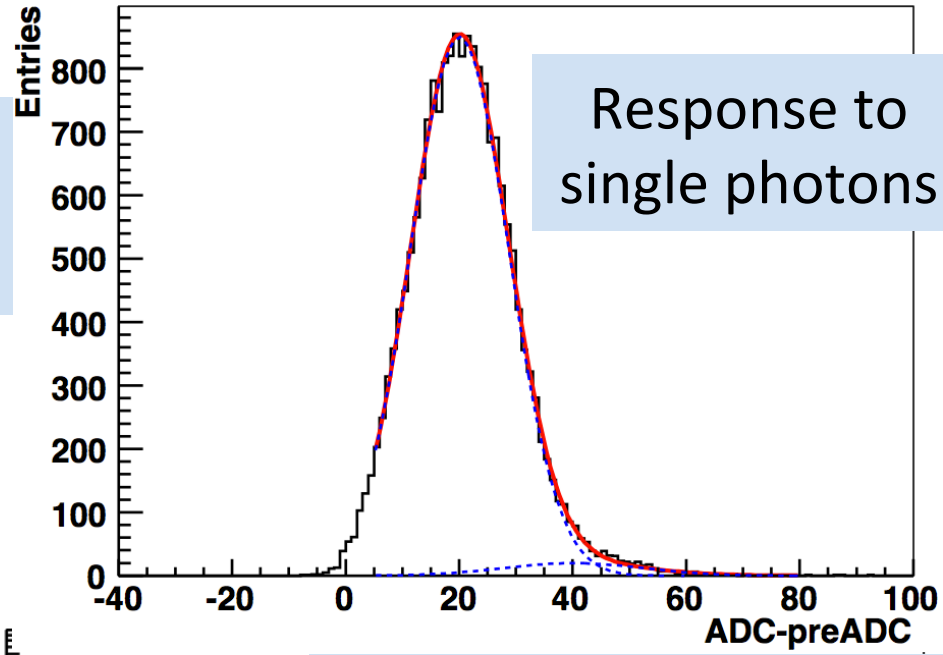
Good Outcome

Extensive commissioning effort resulted in successful detectors

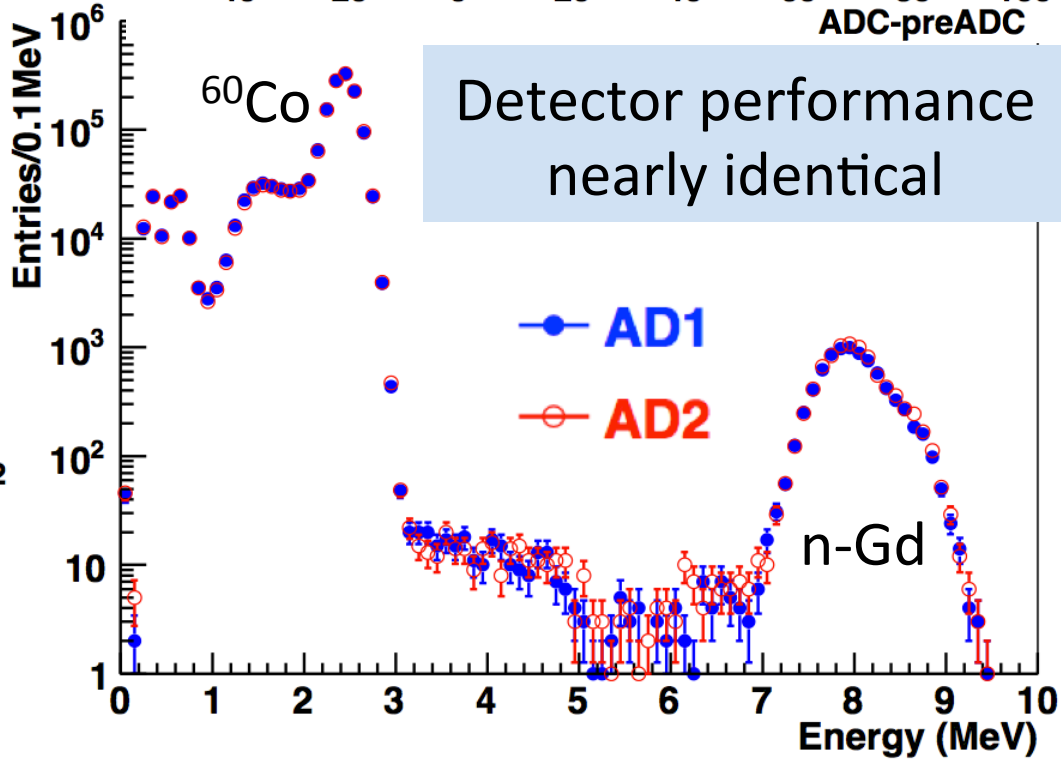
Nucl. Instr. Meth ***A685****, 78 (2012)*



Trigger efficiency sufficient for antineutrino detection



Response to single photons



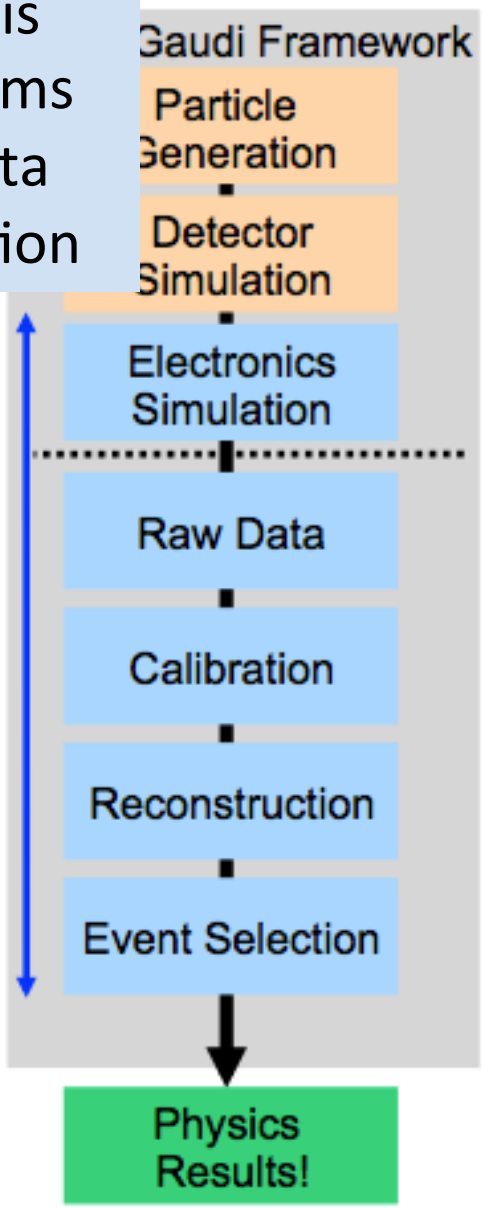
Detector performance nearly identical

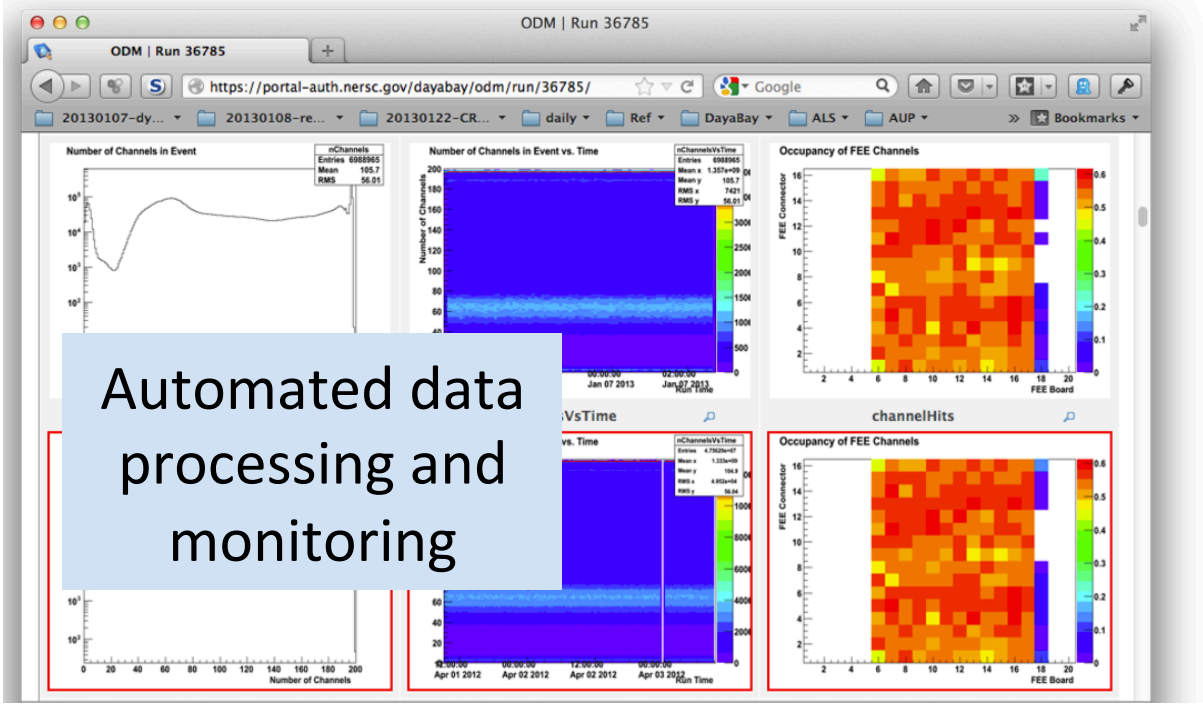
Lesson

Be Prepared!

Developed tools needed for commissioning and analysis

Analysis algorithms and data description





Automated data processing and monitoring

Analysis Examples (or A Treatise on Cat-skinning)

What is the best / simplest / fastest way for me to examine event data and generate my histograms?

If this is your question, then please read this section. As discussed in the preceding sections, you can directly use ROOT to inspect NuWa event data files. Within ROOT, there are a few different methods to process event data. Alternatively, you can use the full power NuWa to process data. To demonstrate these different methods, a set of example scripts will be discussed in this section. Each example script generates the exact same histogram of number of hit PMTs versus reconstructed energy in the AD, but uses how to "chain" trees from multiple files, and how to "friend" data tree be found in the dybgaudi:Tutorial/Quickstart software package.

- `dybTreeDraw.C:` ROOT script using `TTree::Draw()`
- `dybTreeGetLeaf.C:` ROOT script using `TTree::GetLeaf()`
- `dybTreeSetBranch.C:` ROOT script using `TTree::SetBranchAddress()`
- `dybNuWaHist.py:` NuWa algorithm using the complete data classes

Analysis Manual and Tutorials

First Look

Sent out first Near vs. Far $\bar{\nu}_e$ on Christmas morning

Daya Bay:

Anti-neutrinos detected at all three sites.

(see circled events)

First 10 hours of data.

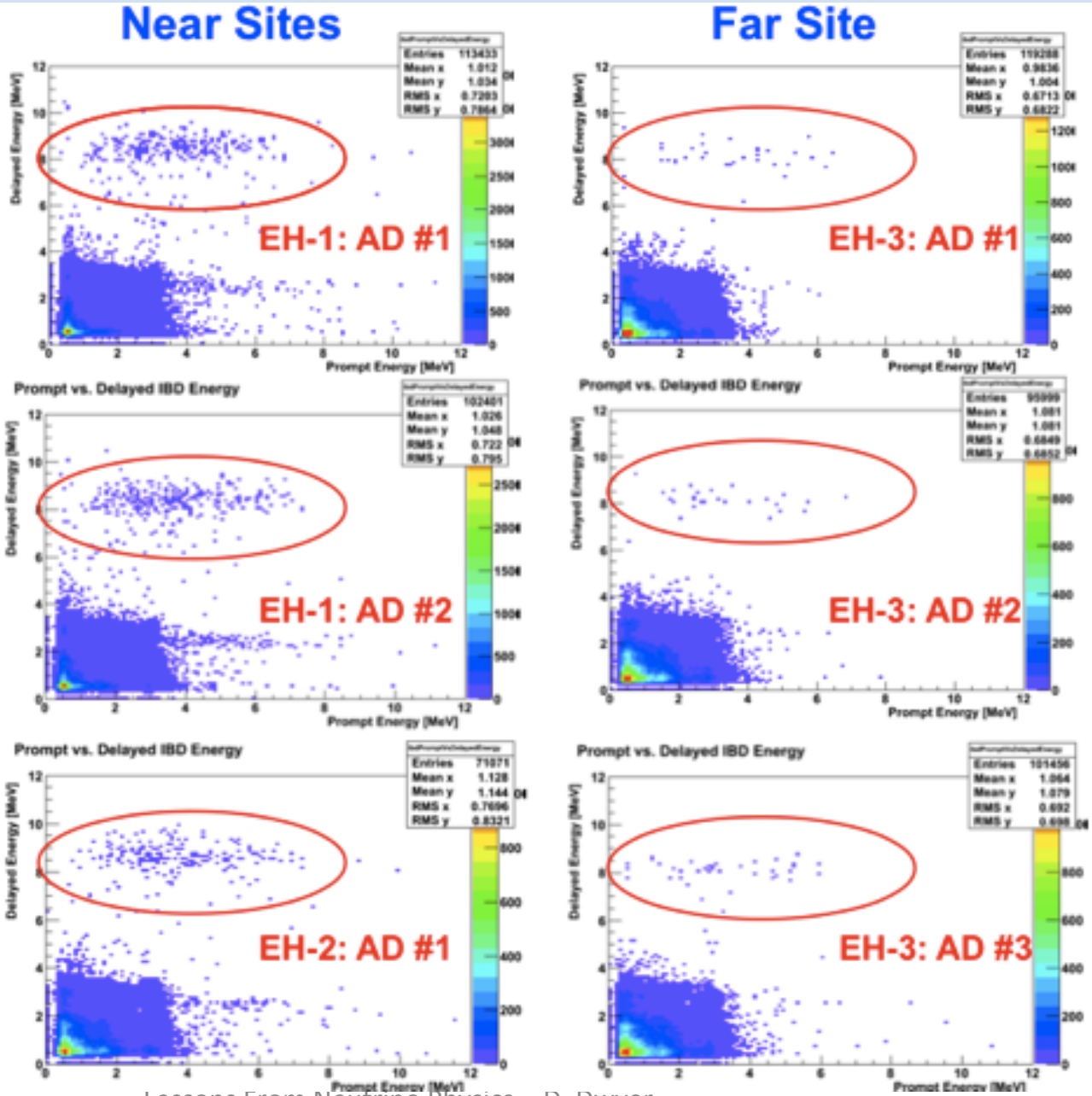
Merry Christmas!

Run Numbers:

EH-1: 21221

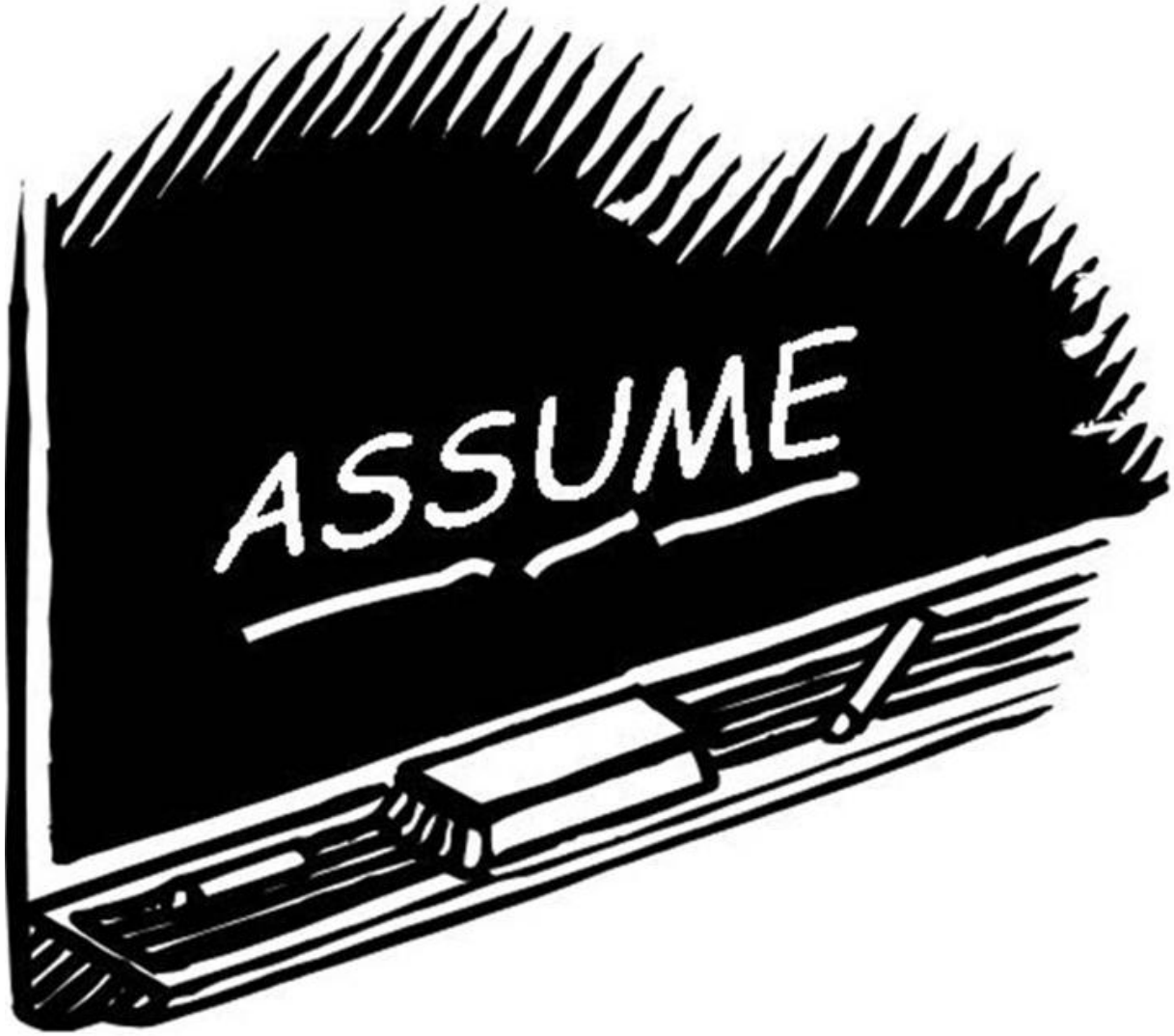
EH-2: 21222

EH-3: 21223



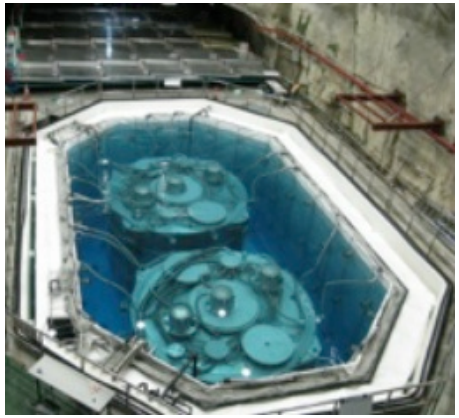
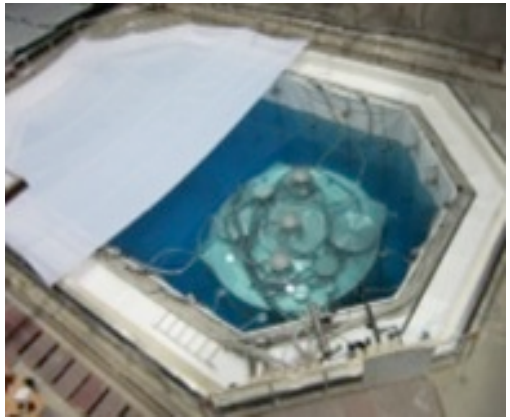
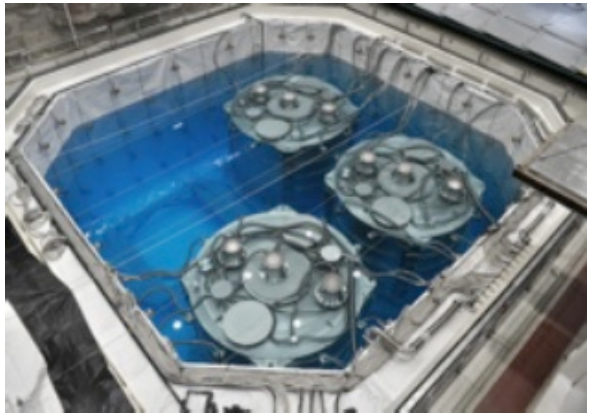
Lesson

When you assume…



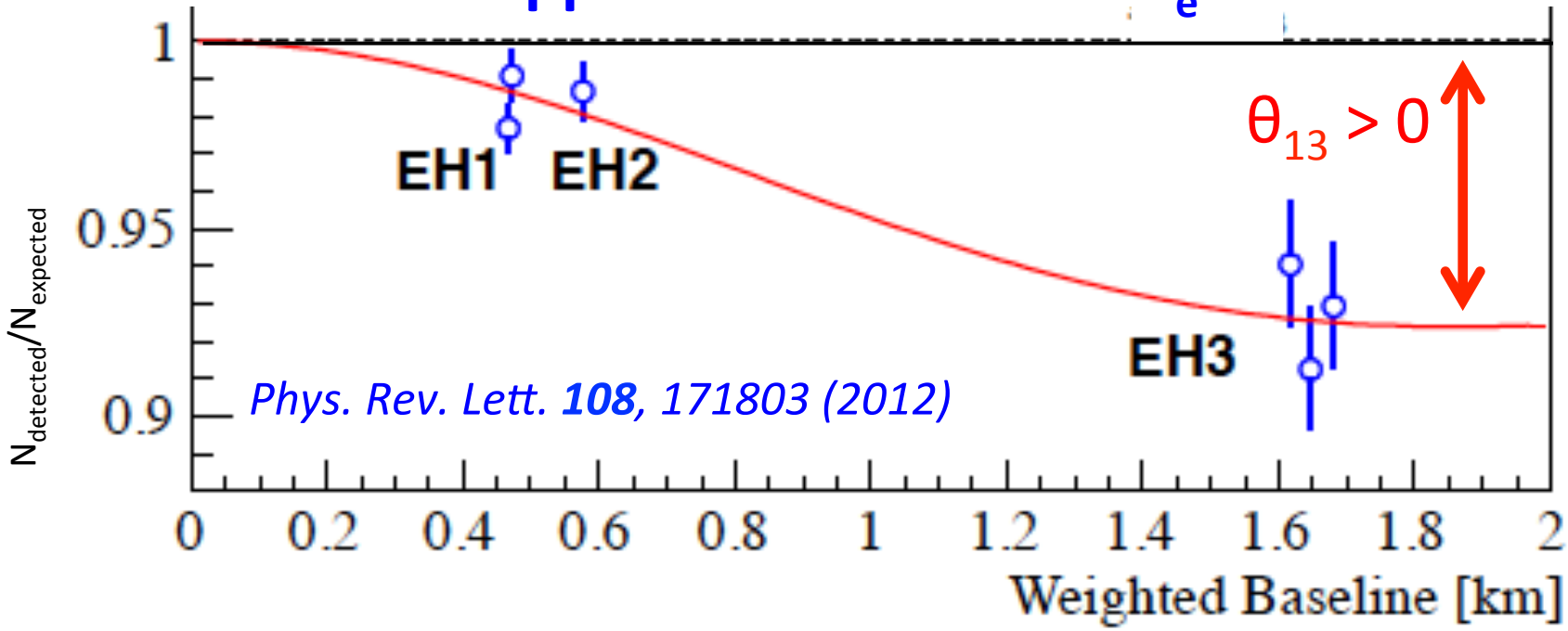
Bigger than Expected

Discovery of $\bar{\nu}_e$ disappearance

March 2012: Using 55 days of data with 6 detectors,

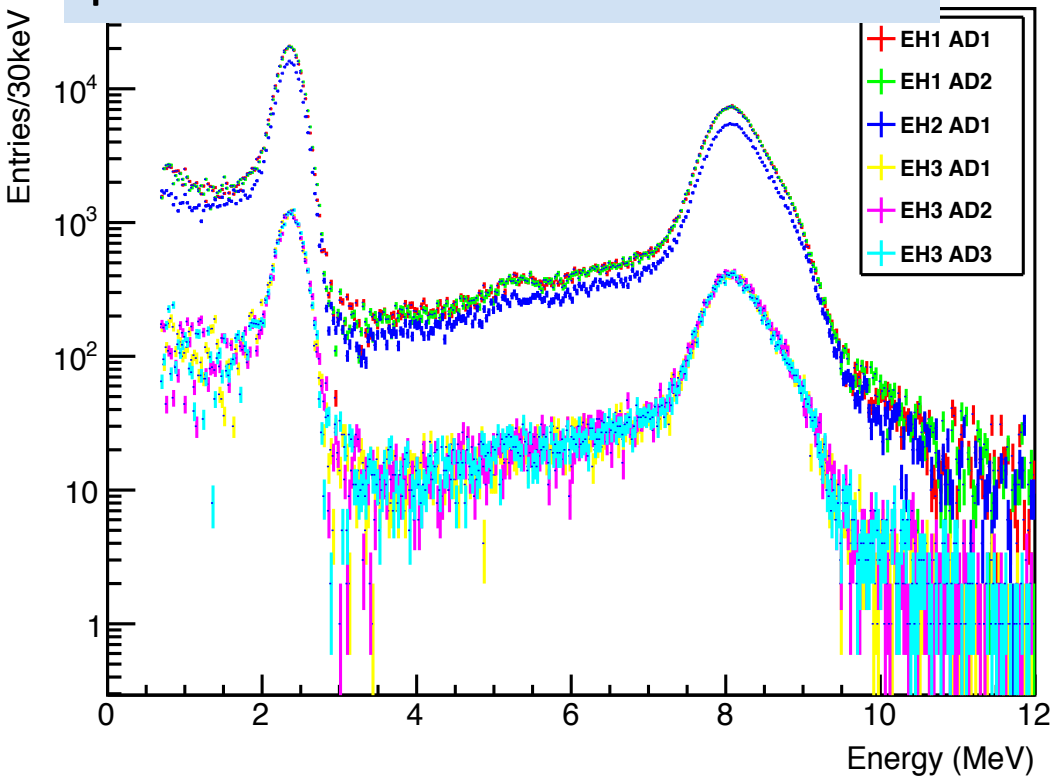
Discovered disappearance of reactor $\bar{\nu}_e$ at ~1.6 km.



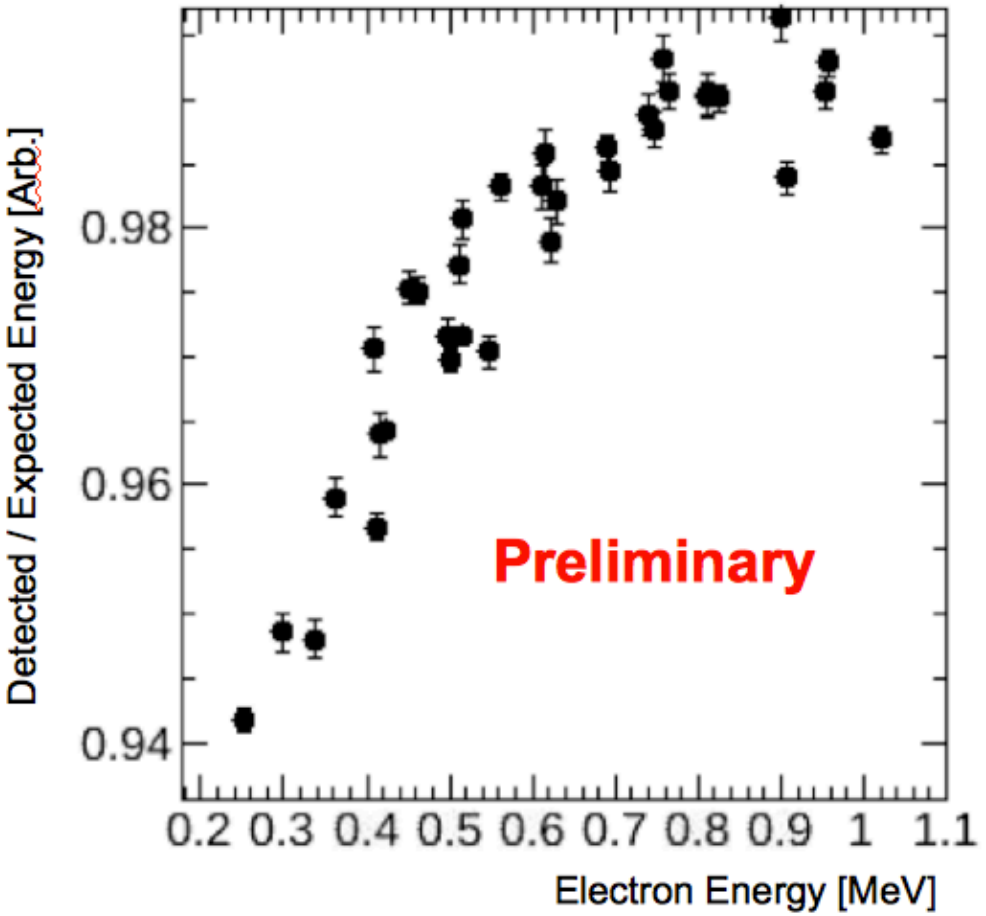
New Approaches

Explore new methods to improve calibration and analysis

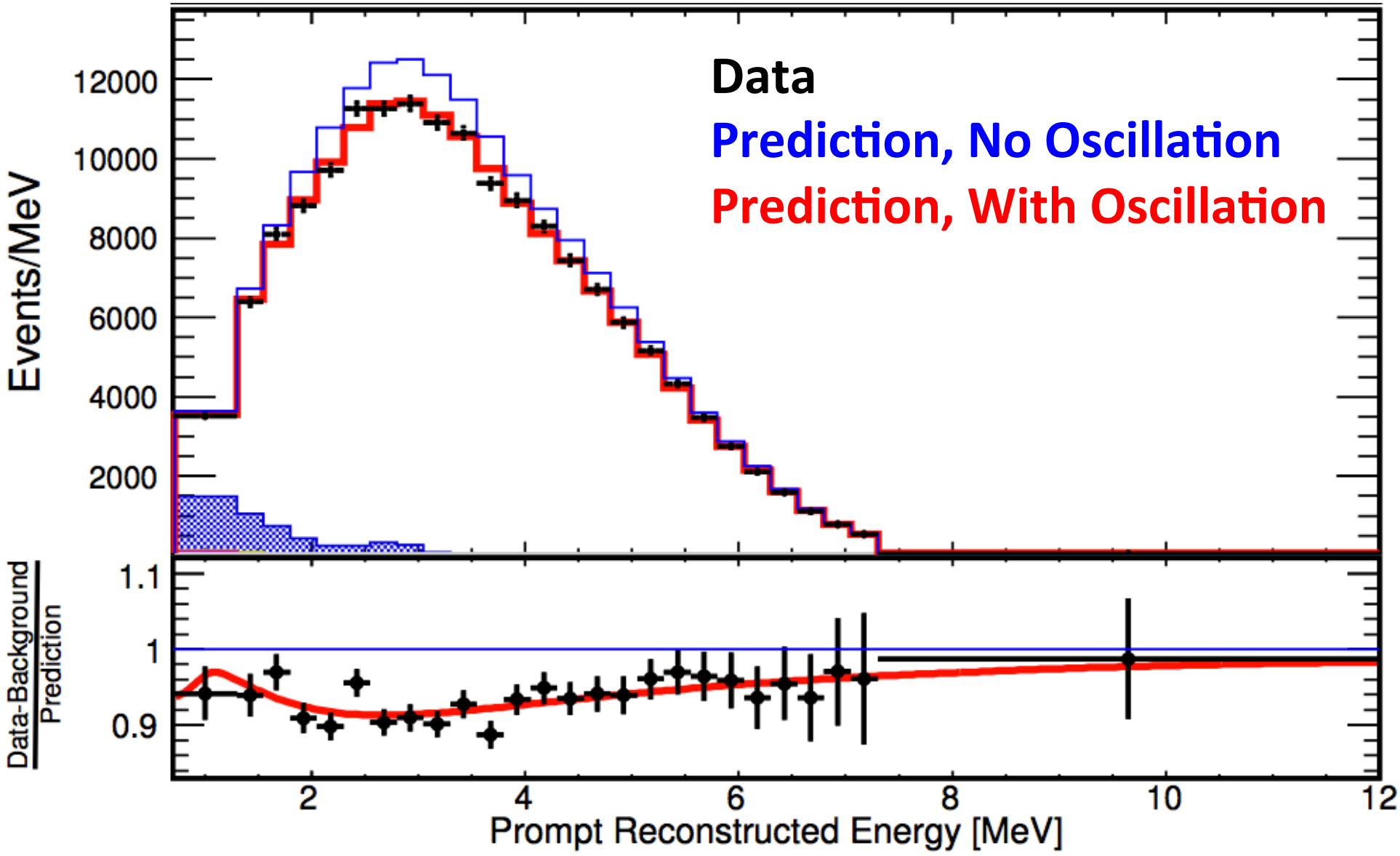
Use cosmogenic neutrons for precise detector calibration.



Measure energy nonlinearity in-situ and ex-situ.



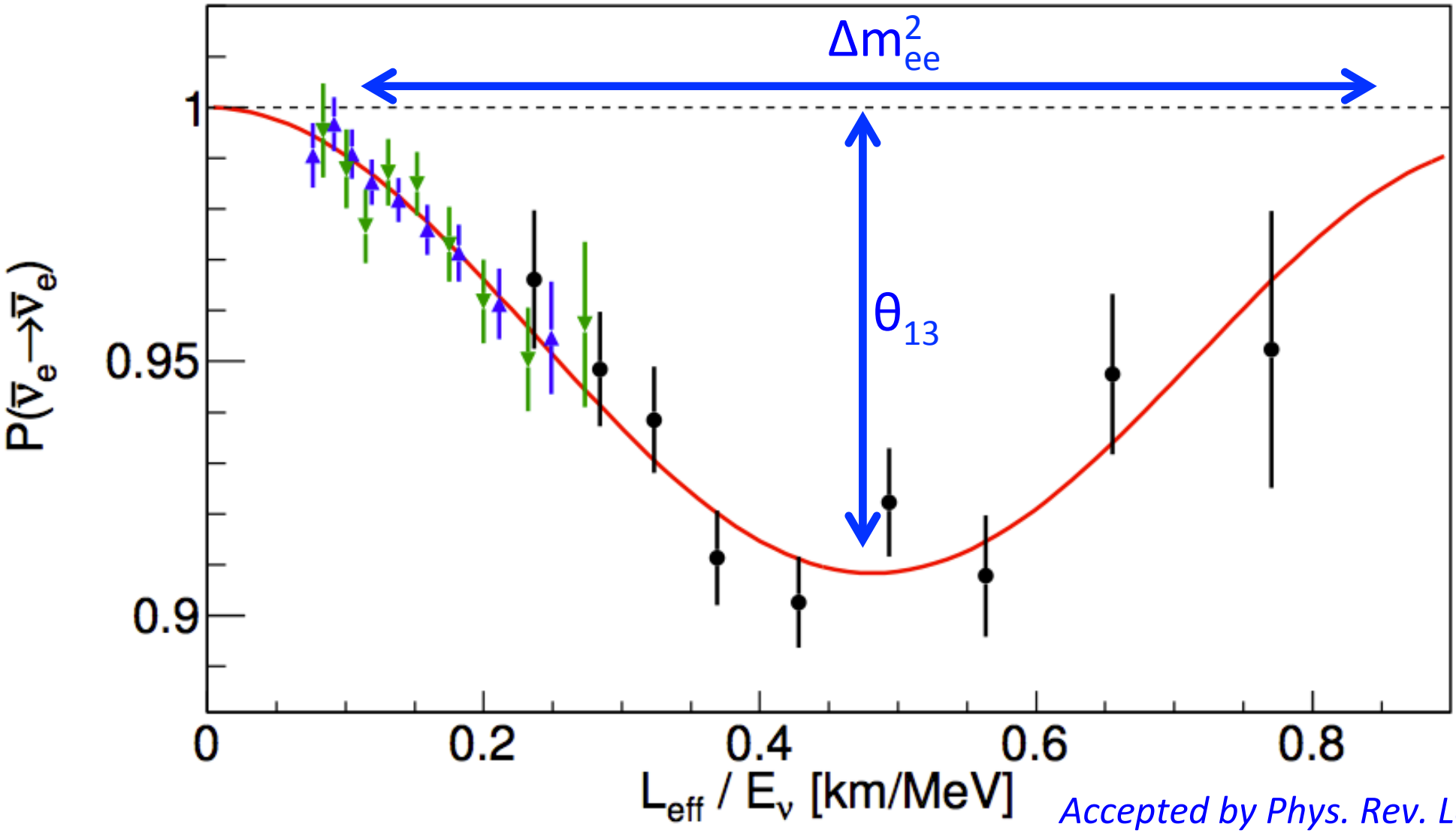
Spectral Distortion



Spectral distortion consistent with oscillation model

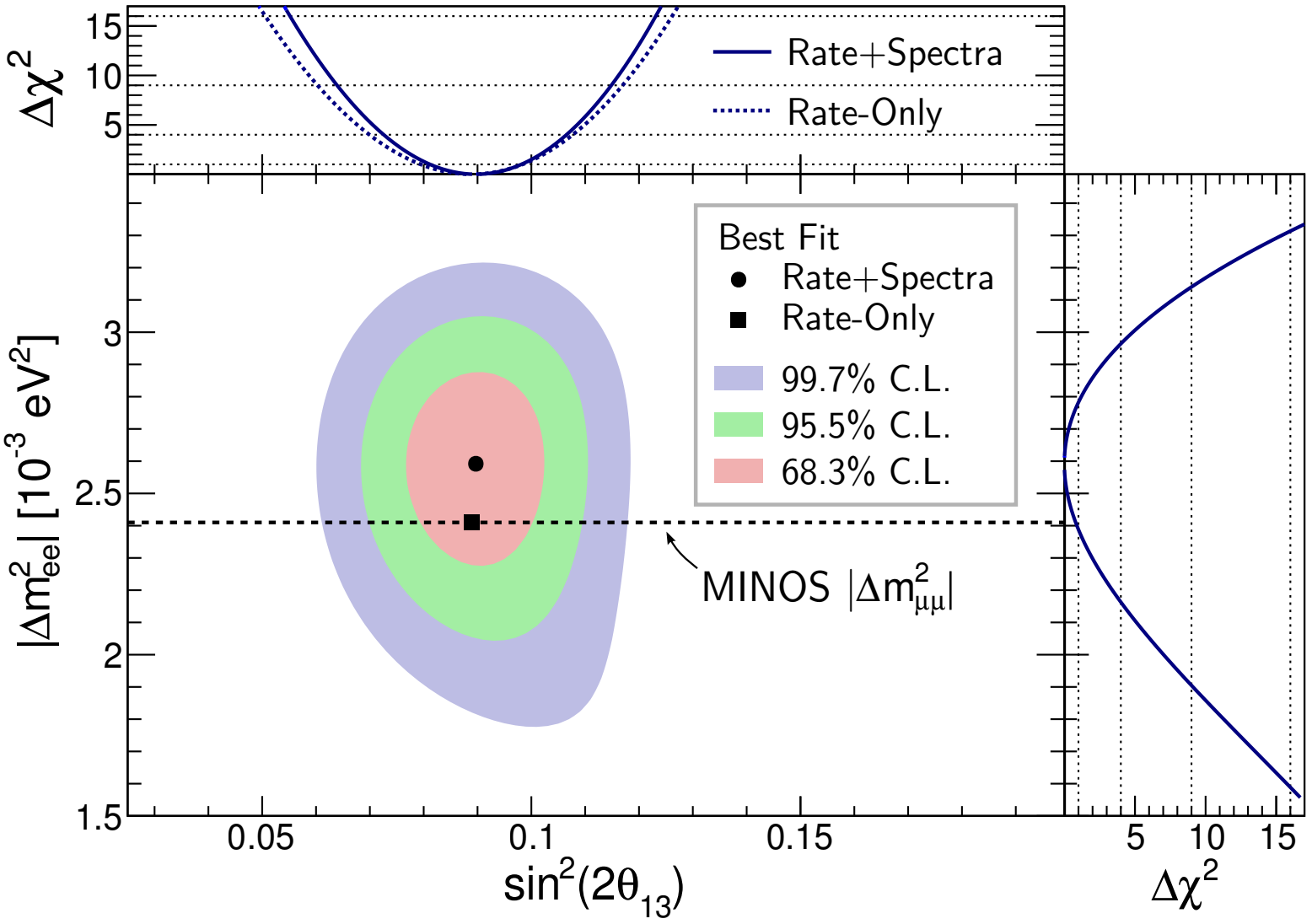
Antineutrino Oscillation

Recast spectral distortion as $\bar{\nu}_e$ proper time (L/E)



Accepted by Phys. Rev. Lett.

Rate+Spectra Oscillation Results



$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$ $\quad |\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\ eV^2$

Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

All Mixed Up

Neutrino mass and flavor eigenstates strongly mixed!

Measured Mixings:

$\theta_{12} \approx 34^o$, $\theta_{23} \approx 40^o$, $\theta_{13} \approx 9^o$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ -0.50 & 0.58 & 0.64 \\ 0.26 & -0.60 & 0.75 \end{pmatrix}$$

assuming $\delta_{CP} = 0$

Future Lessons from Neutrino Physics

Extra Flavor

Are there more than 3 neutrino states?

Existing anomalies may motivate sterile neutrinos:

Reactor:

Measured 5% deficit relative to reactor models.

Gallium:

Deficit in radioactive source experiments.

LSND:

Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

MiniBooNE:

Excess of low energy ν_e, $\bar{\nu}_e$.

Many Proposed Experiments

Table 7: Proposed sterile neutrino searches.

Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
CeLAND [259]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
Daya Bay Source [260]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
SOX [261]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
BEST [64]	^{51}Cr	ν_e	disapp.	Russia	small
PROSPECT [262]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
STEREO	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	N/A[4]
DANSS [263]	Reactor	$\bar{\nu}_e$	disapp.	Russia	N/A[4]
OscSNS [205]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, U.S.	medium
LAr1 [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
LAr1-ND [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
MiniBooNE+ [203]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
MiniBooNE II [265]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
ICARUS/NESSiE [266]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	N/A[4]
IsoDAR [111]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
nuSTORM [192]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

[1] Rough recost categories: small: <$5M, medium: $5M-$50M, large: $50M-$300M.
[2] U.S. scope only.
[3] Multiple sites are under consideration [267].
[4] No U.S. participation proposed.

arXiv:1310.4340

Reactor Anomaly

Daya Bay will constrain some sterile models

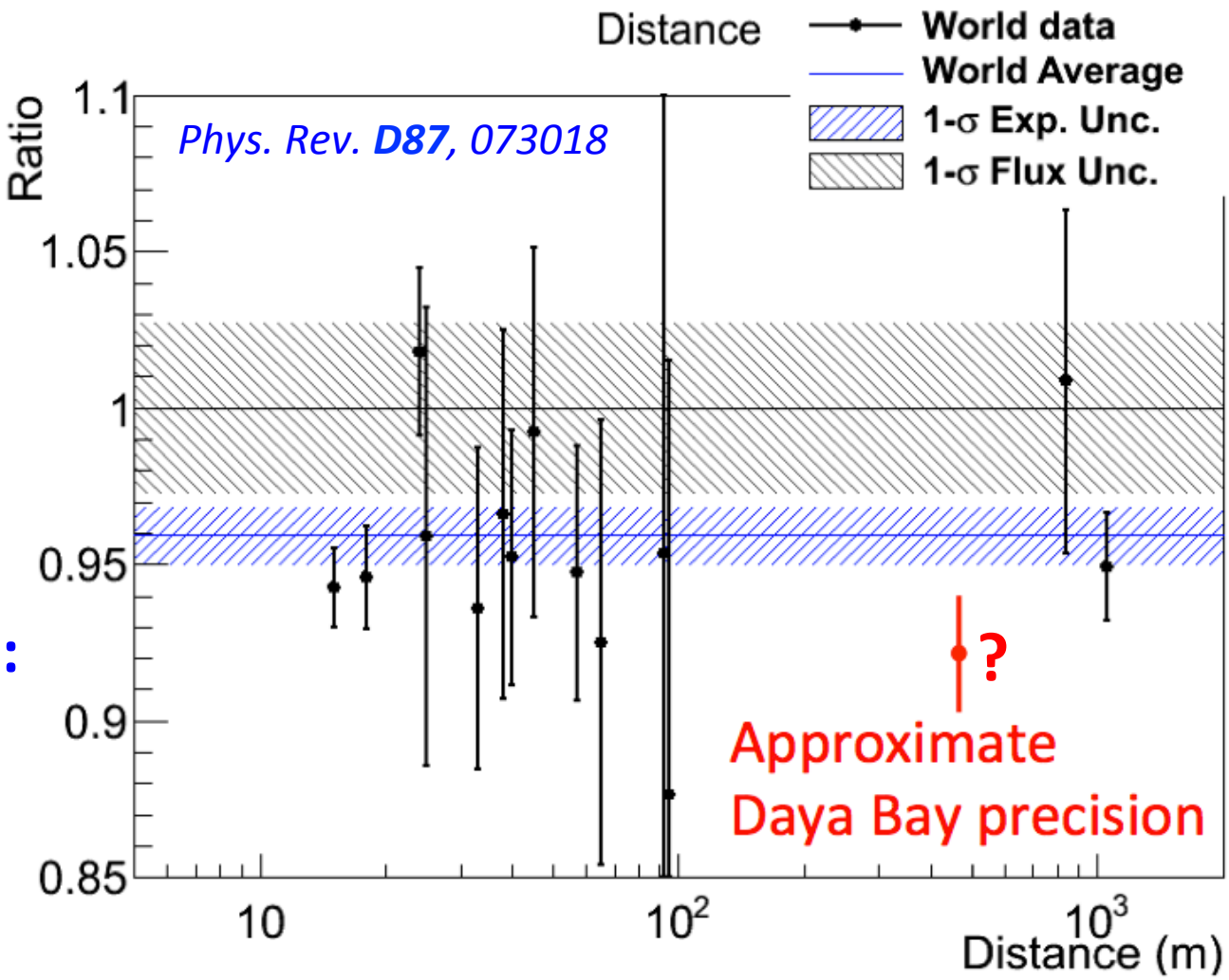
Daya Bay:

Will provide precise total reactor flux at ~400 m.

Comparison of near and far spectra will limit sterile mixing at percent level.

PROSPECT, STEREO, DANSS:

Dedicated new experiments to test at ~10 m distance.



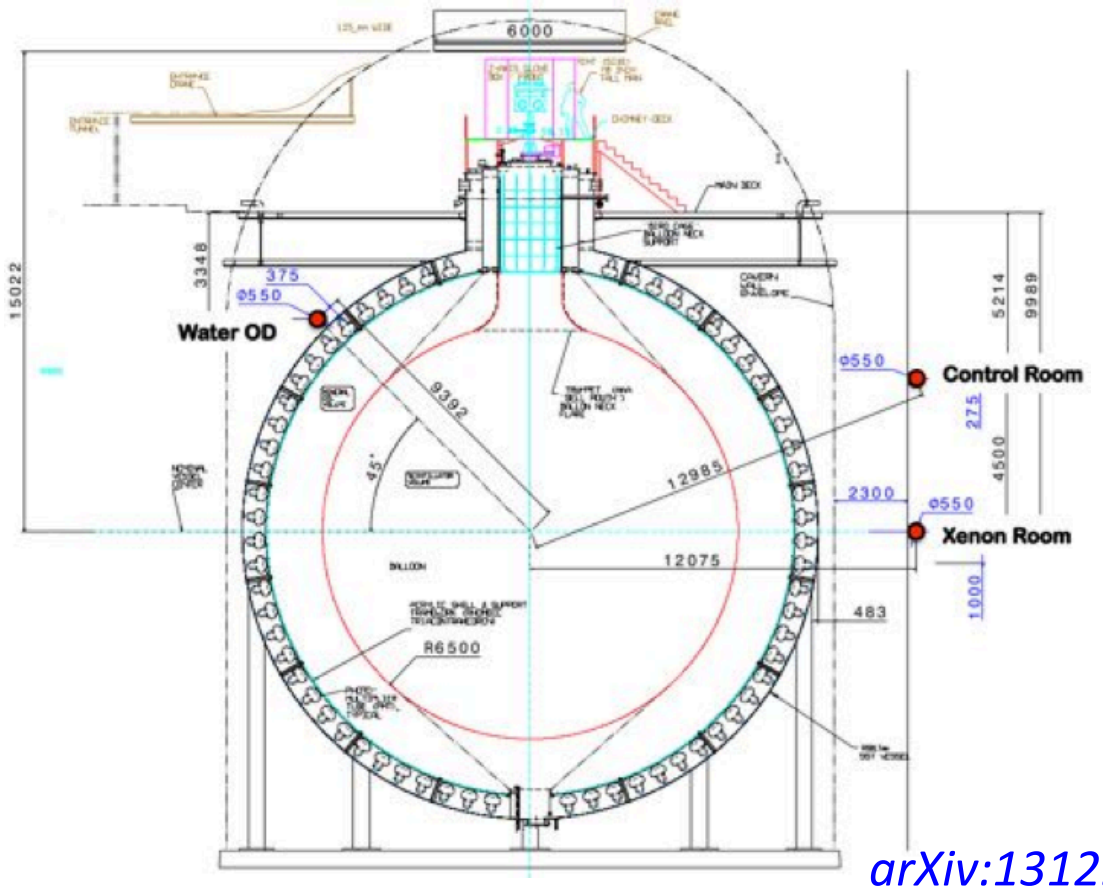
Antineutrino Source

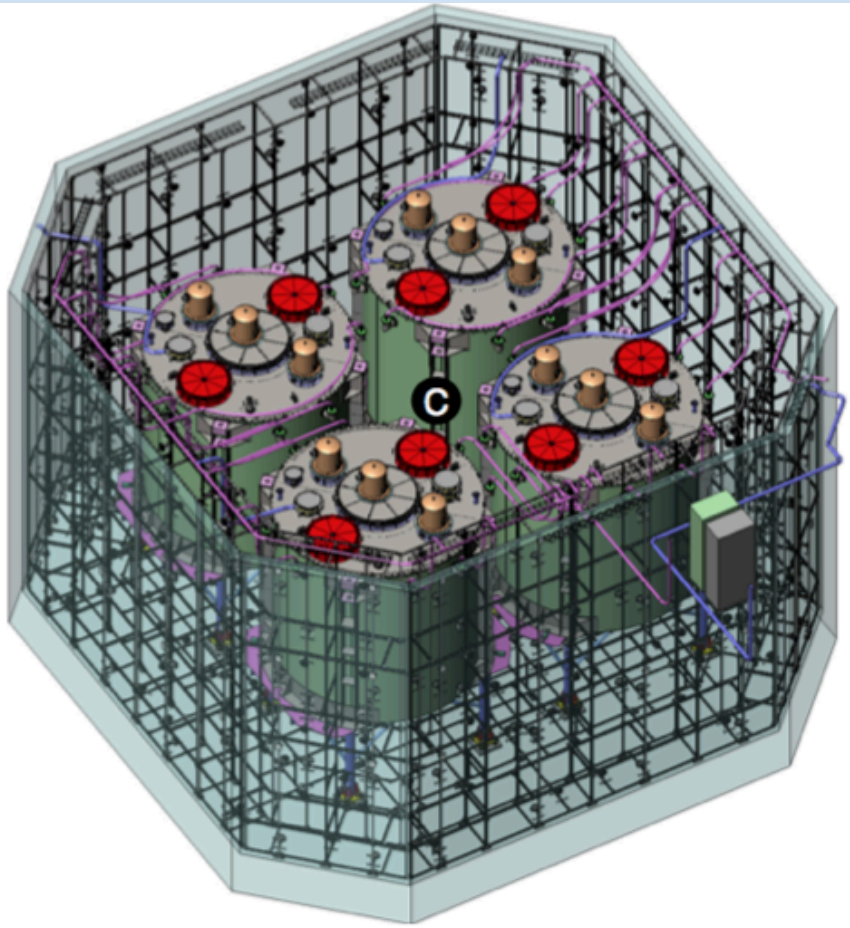
A compact $\bar{\nu}_e$ source is ideal for testing reactor anomaly

Intense ^{144}Ce radioactive source

Phys. Rev. Lett. 107, 201801 (2011)

Probe 1 eV^2 mass splittings (~1 m distance)





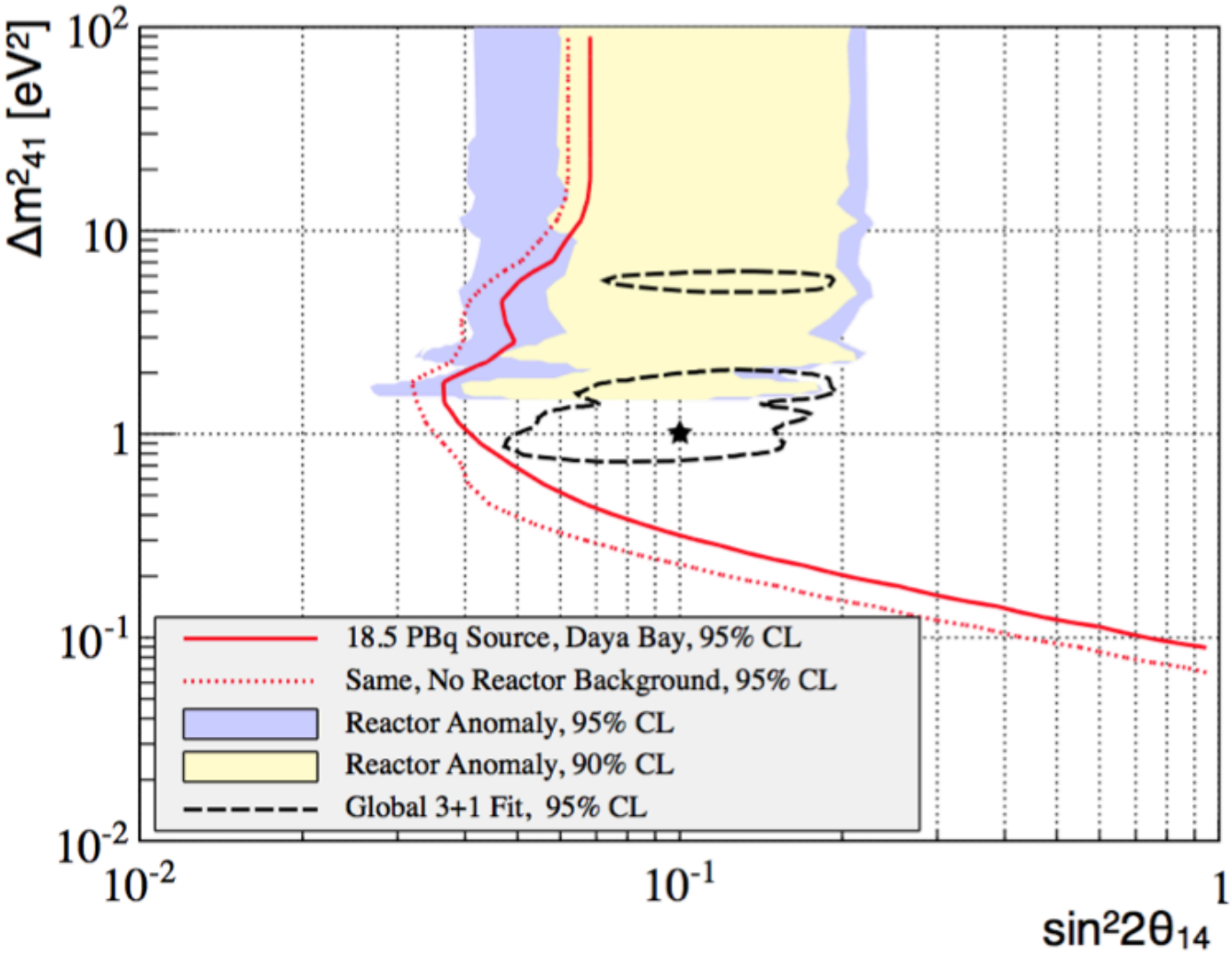
Explored measurement using Daya Bay facility

*Phys. Rev. **D87**, 093002 (2013)*

arXiv:1312.0896

Experiment Reach

Known detectors allow reliable exclusion of sterile models



Advantages:

- Well-understood detectors
- Clear signal
- Low-background

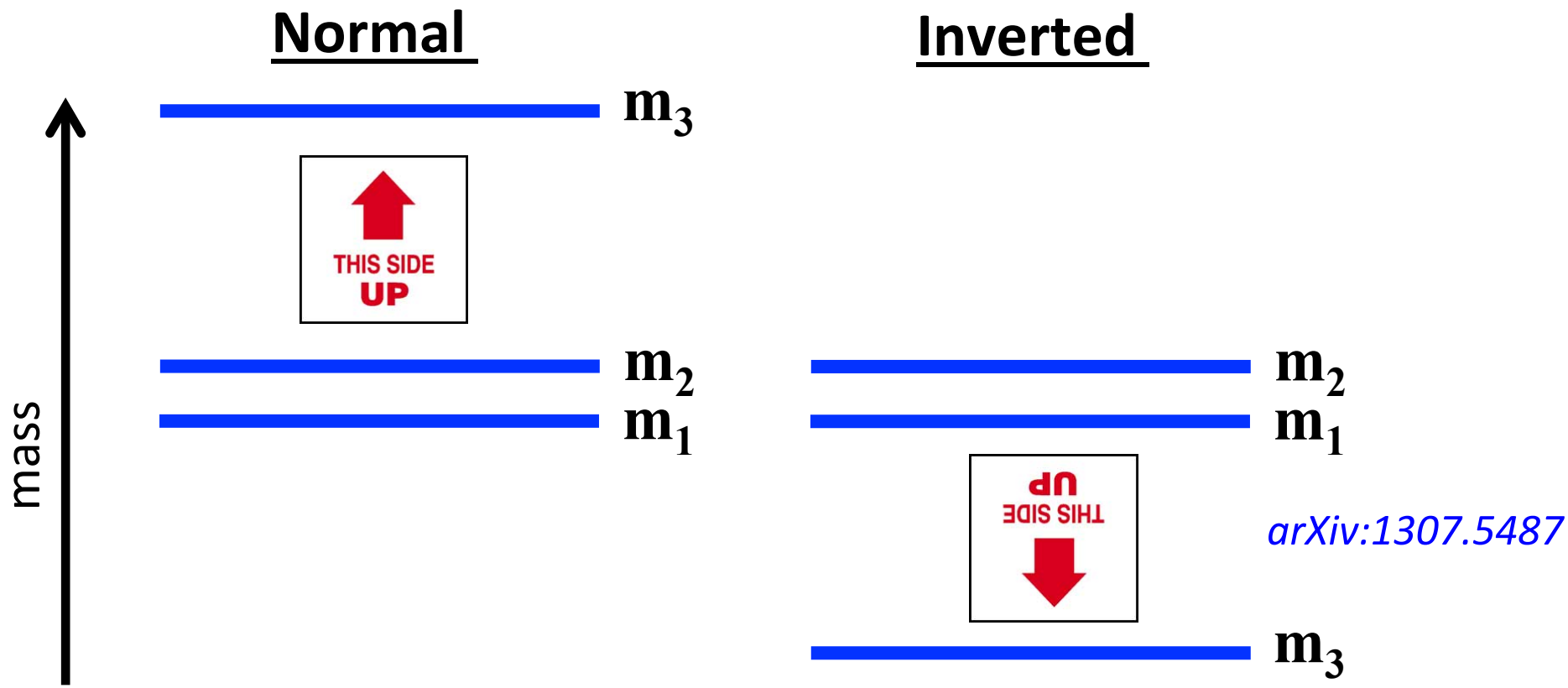
Concerns:

- Backgrounds from ^{144}Ce source
- Source manufacture
- Source transport

Neutrino Mass Hierarchy

What is the ordering of the three ν mass eigenstates?

KamLAND	Solar ν	MINOS, Daya Bay
$\lvert\Delta m^2_{21}\rvert \approx 7.5 \times 10^{-5}$ eV^2	$\lvert\Delta m^2_{21}\rvert > 0$	$\lvert\Delta m^2_{3x}\rvert \approx 2.5 \times 10^{-3}$ eV^2



Large θ_{13} produces many experimental signs of the mass hierarchy.

Reactor $\bar{\nu}_e$ Disappearance

Three frequencies, but which is which?

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

KamLAND Oscillation (~100 km)

Daya Bay Oscillation (~km)

~0.7

~0.3

Two nearly identical oscillation frequencies

$$\Delta_{ji} \simeq 1.267\frac{L[\mathrm{m}]\Delta m^2_{ji}[\mathrm{eV}^2]}{E[\mathrm{MeV}]}$$

For both hierarchies:

$|\Delta_{32} - \Delta_{31}| = |\Delta_{21}|$ → *Frequency difference gives no hierarchy information*

But amplitudes are different:

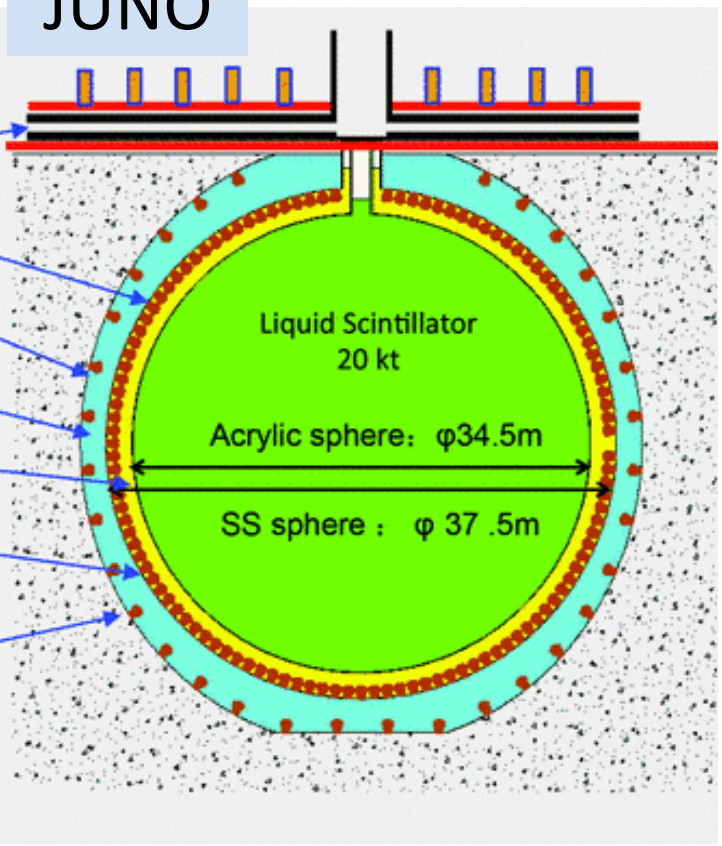
Normal Hierarchy: $|\Delta_{31}| > |\Delta_{32}|$ → *Larger amplitude at higher frequency*

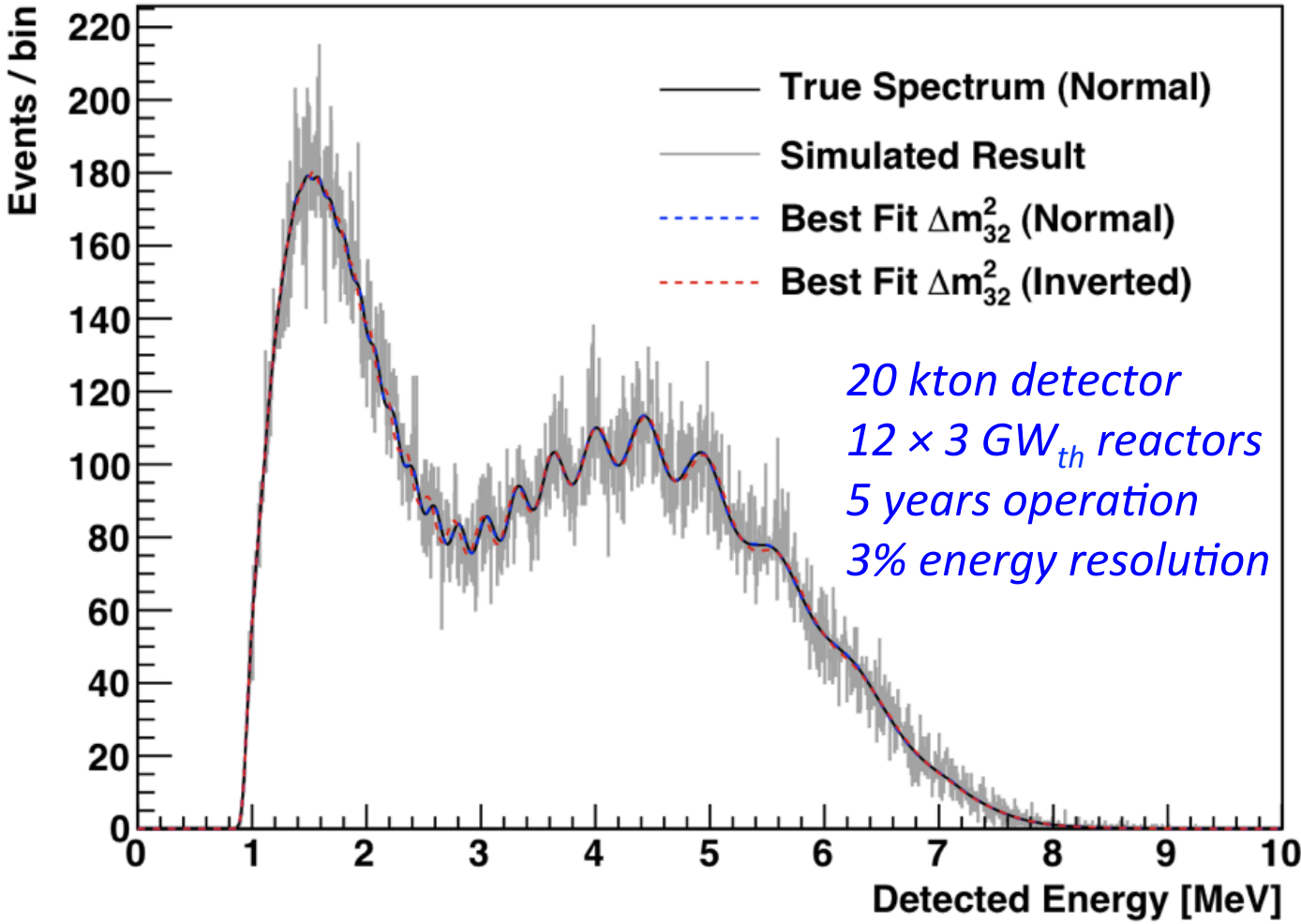
Inverted Hierarchy: $|\Delta_{31}| < |\Delta_{32}|$ → *Larger amplitude at lower frequency*

Hierarchy: Reactor $\bar{\nu}_e$

Use large scintillator detector at ~60 km from reactors

JUNO





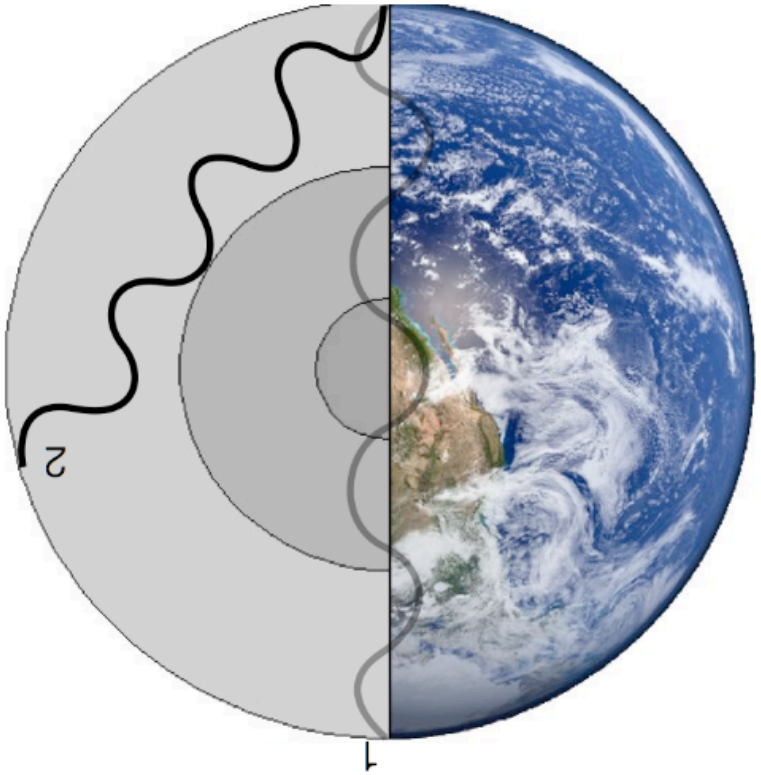
Achieving detector of sufficient resolution and calibration requires new technology.

Hierarchy: Atmospheric ν

Matter-enhanced oscillation can reveal sign of $|\Delta m^2_{3x}|$

Atmospheric neutrinos pass through earth matter to reach detector.

~Mton Detector



In Vacuum:

Oscillation probability constant for neutrinos with same proper time $\tau \approx L/E_\nu$

In Matter:

If resonance occurs, oscillation probability not constant for neutrinos with same τ.

Mass Hierarchy:

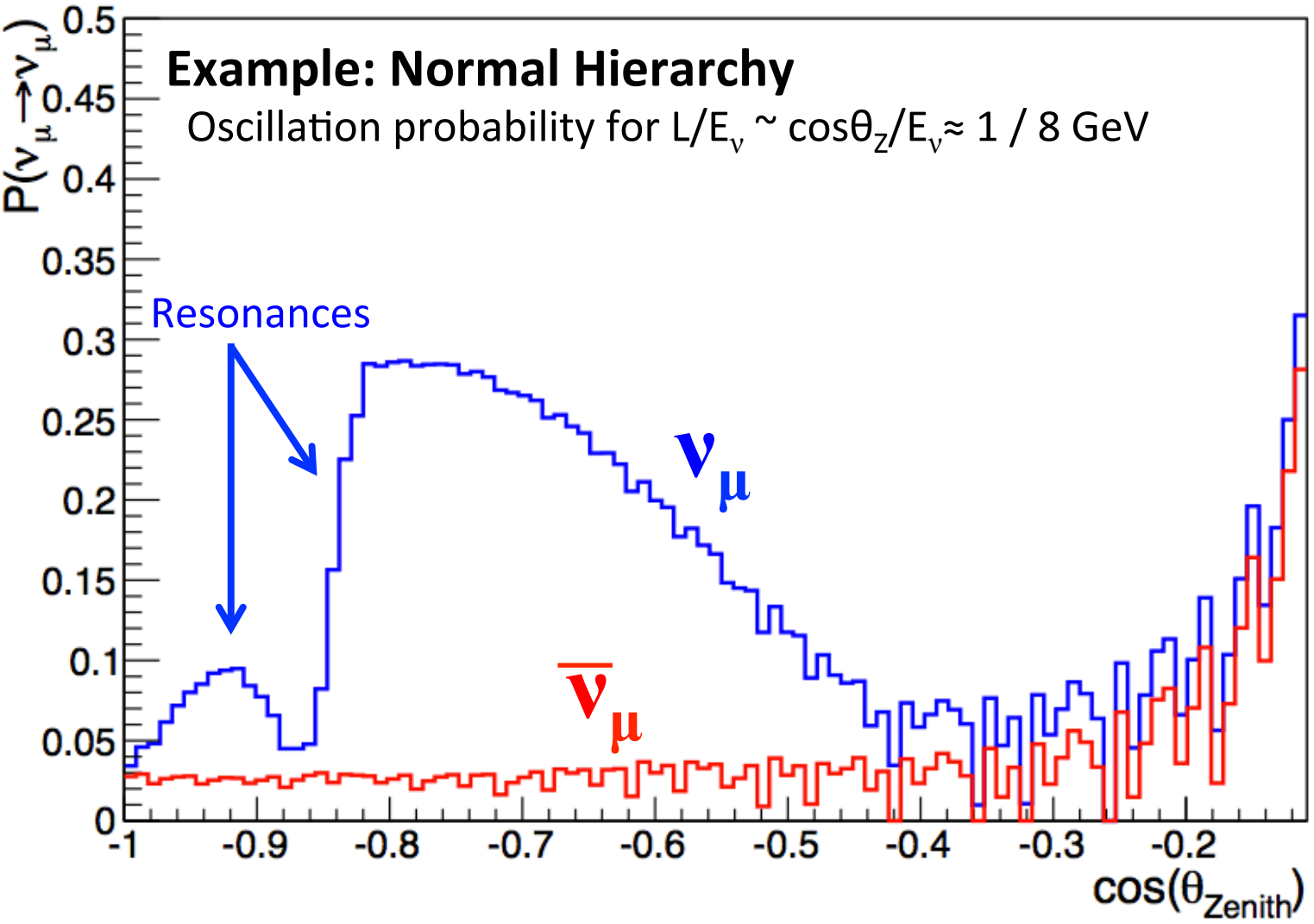
Resonance only occurs for neutrinos (Normal), or antineutrinos (Inverted).

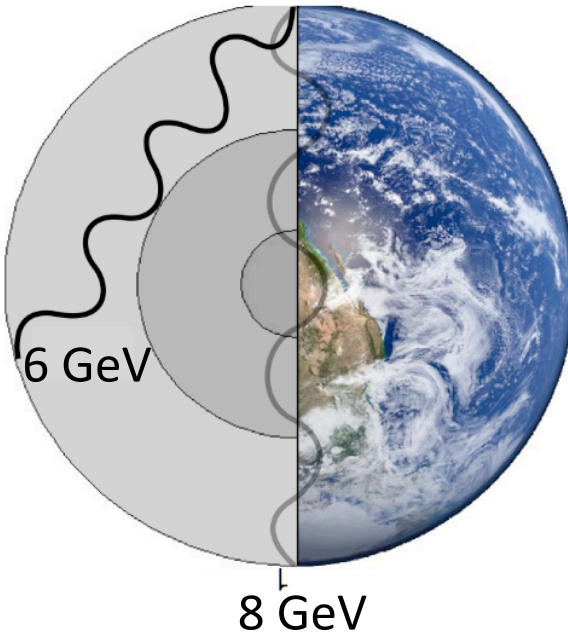
Select neutrinos with similar proper time:

$$\tau \approx L/E_\nu \approx \cos\vartheta_Z/E_\nu$$

Hierarchy: Atmospheric ν

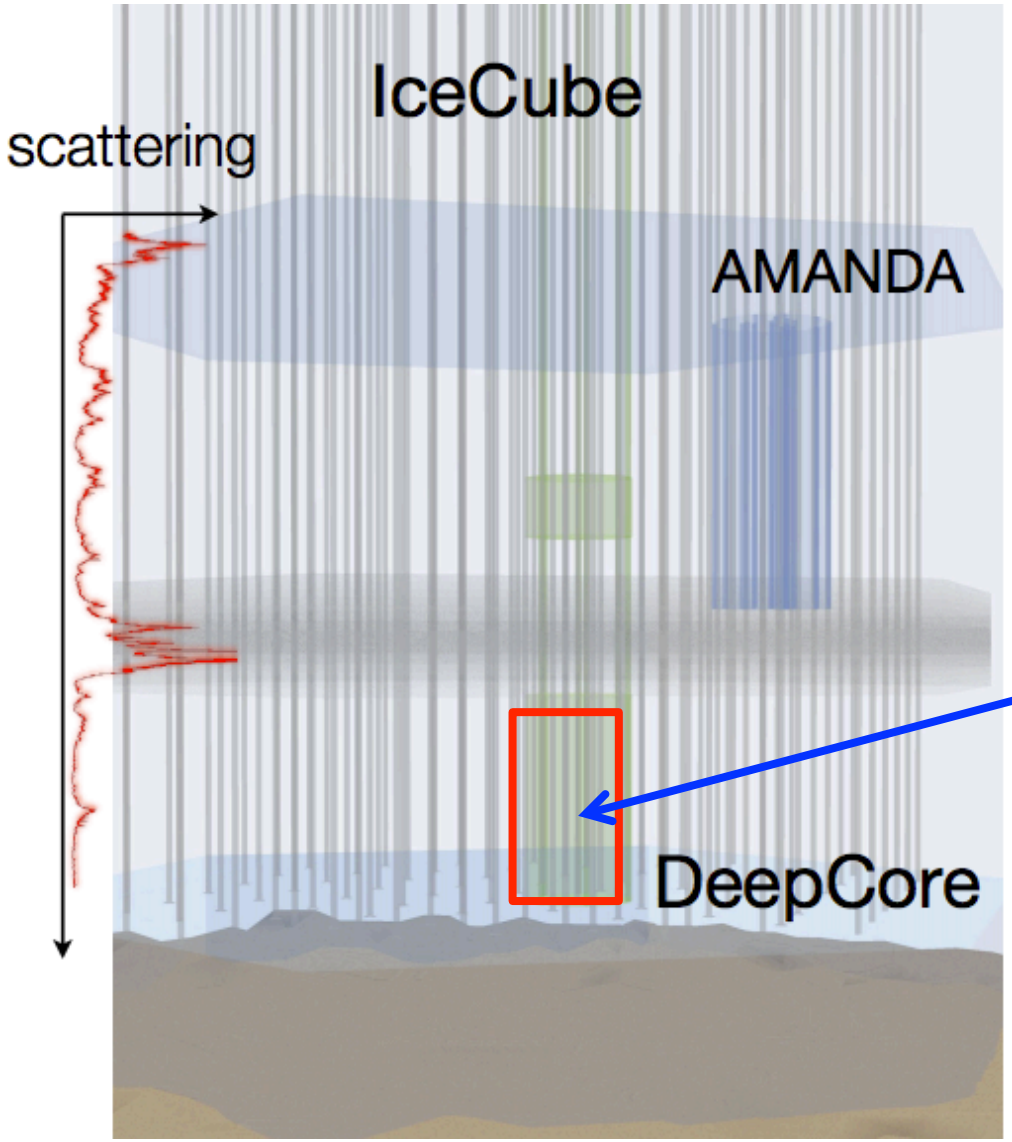
Matter-enhanced oscillation can reveal sign of $|\Delta m^2_{3x}|$



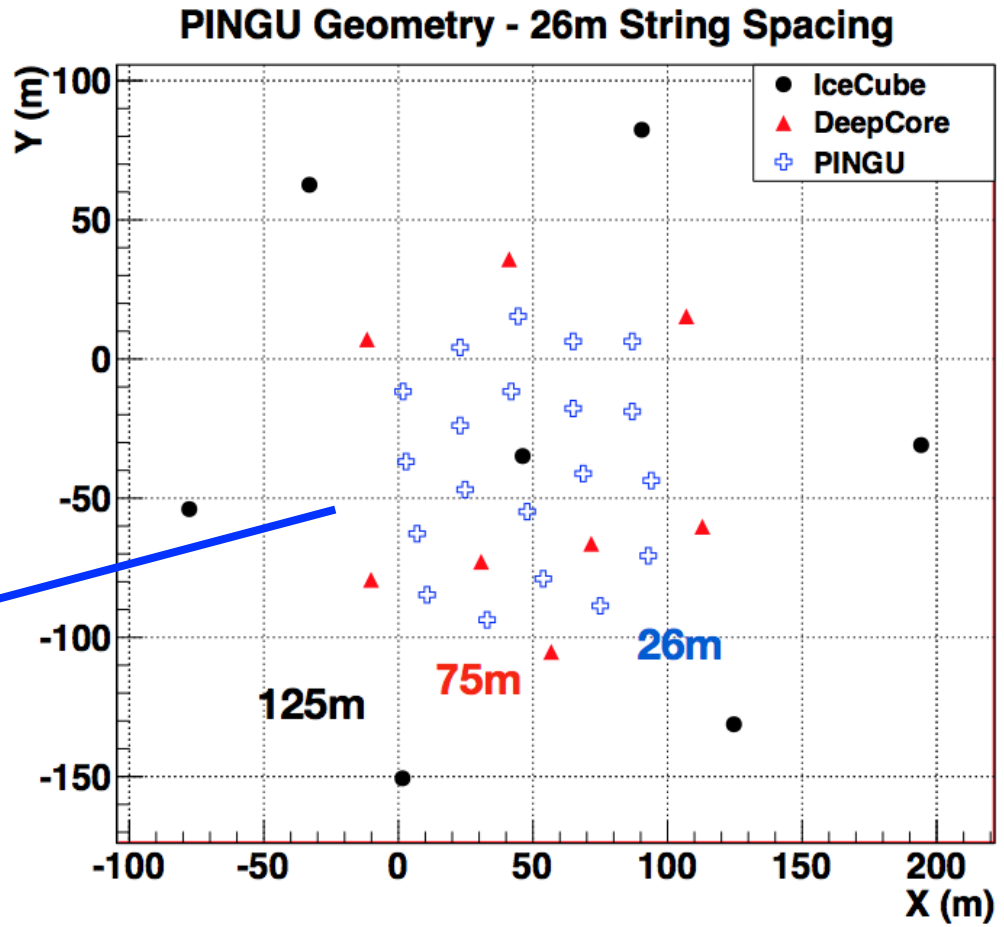


Hierarchy: Atmospheric ν

PINGU: Denser instrumentation at center of IceCube

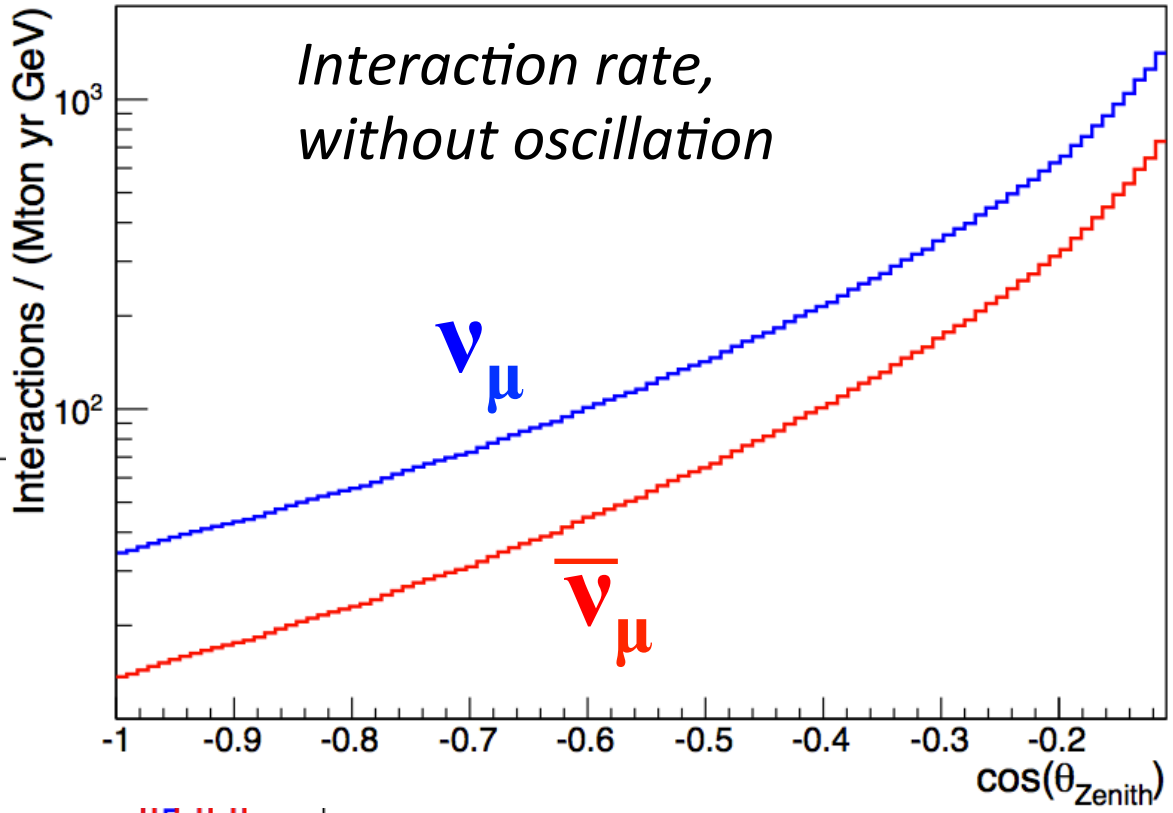


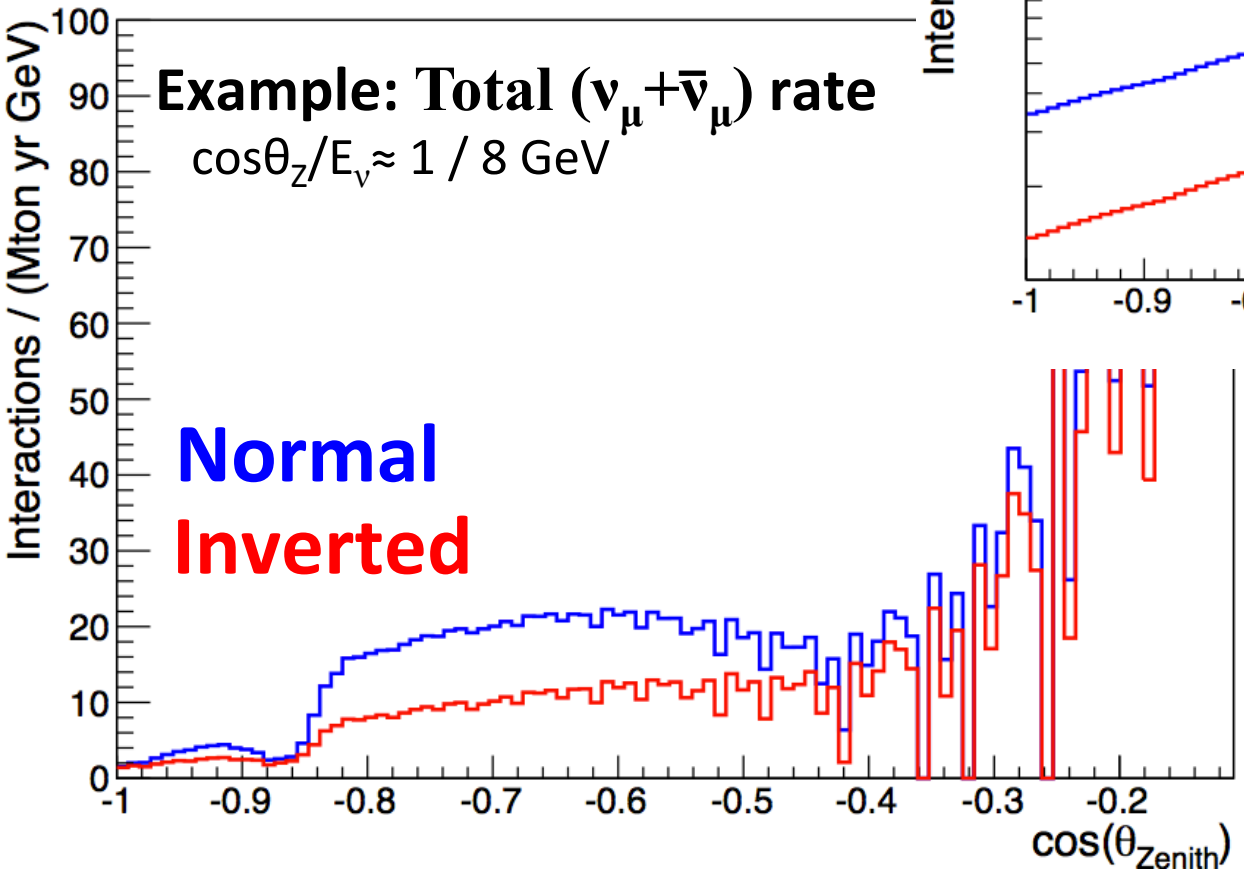
arXiv:1401.2046



Hierarchy: Atmospheric ν

Nature provides excess neutrinos vs. antineutrinos

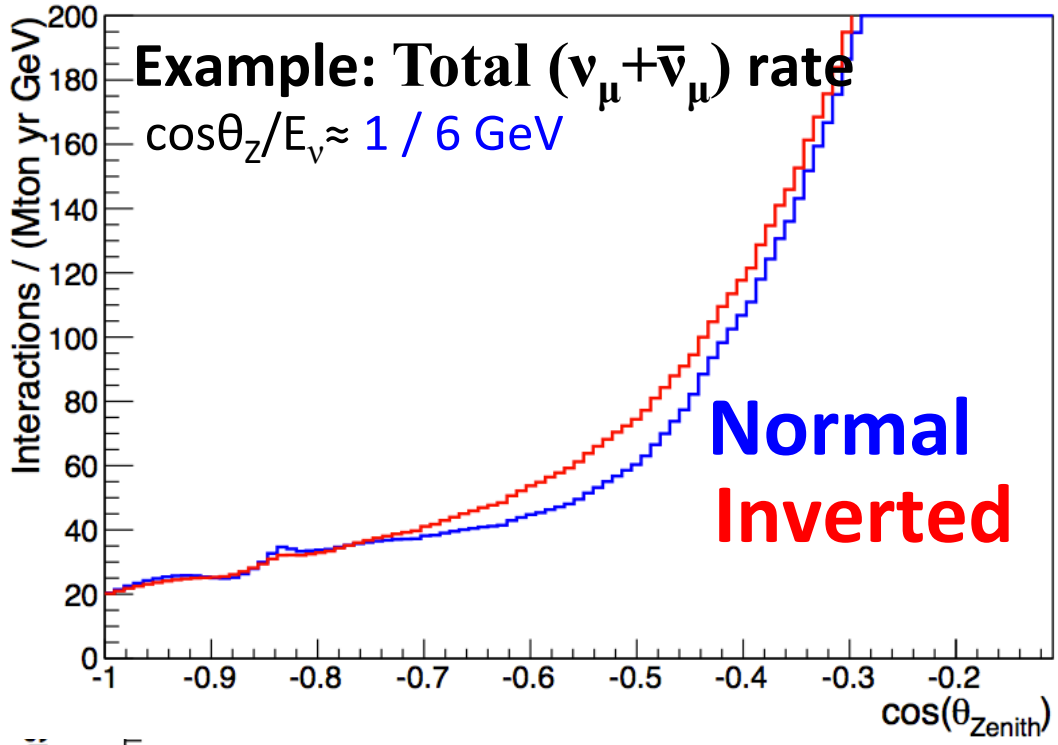


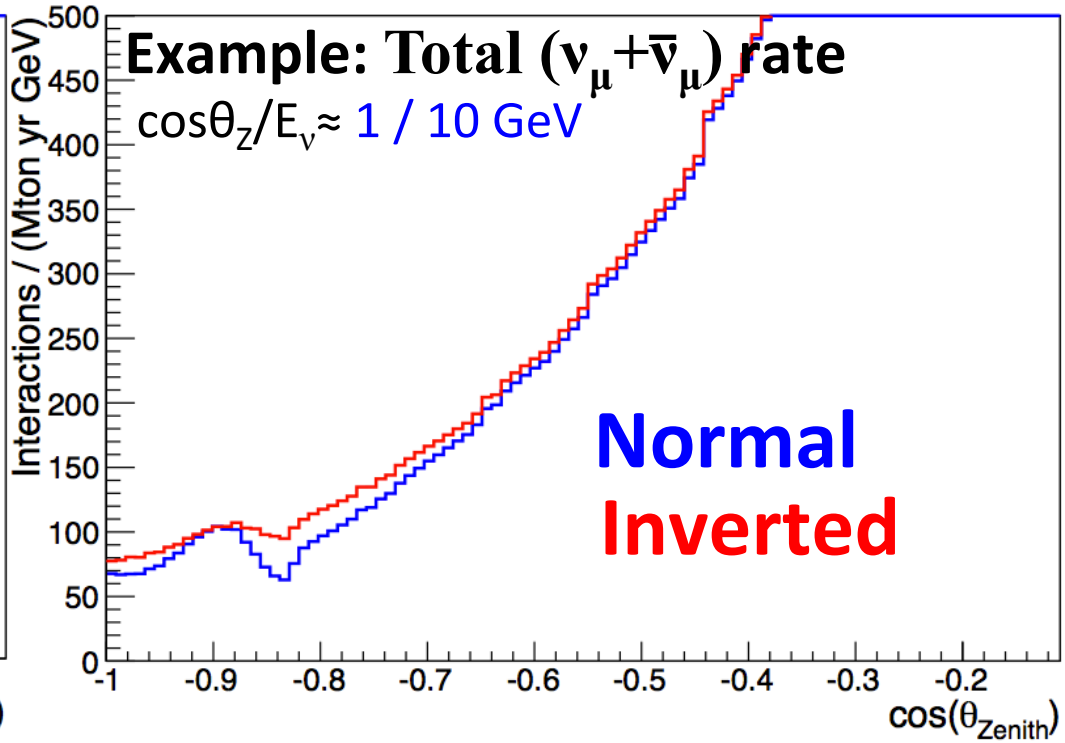


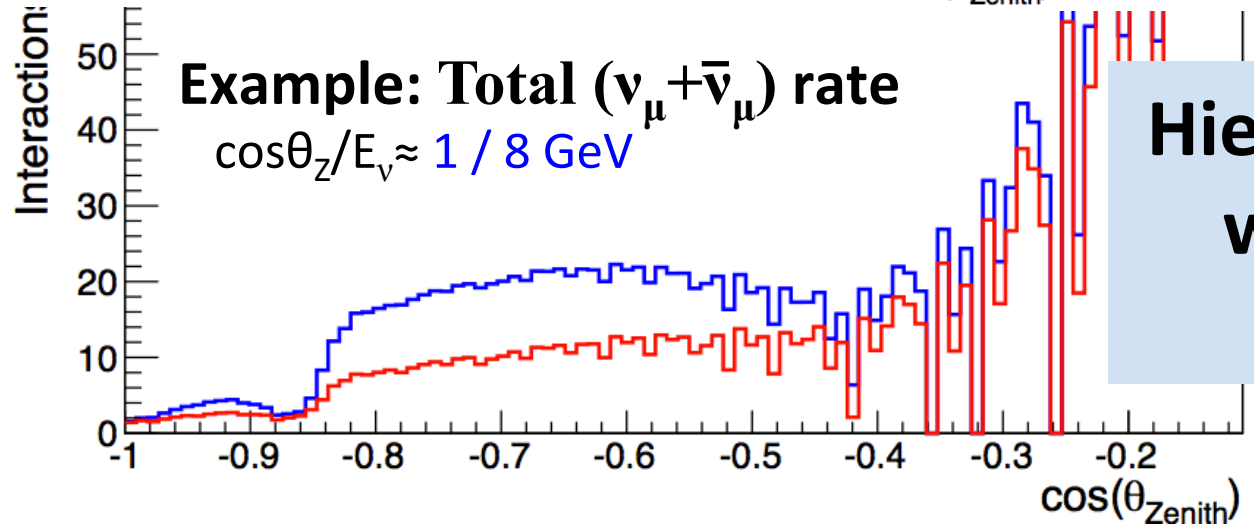
If unable to discriminate ν from $\bar{\nu}$, can still observe change in combined rate.

Detector Performance

Detector energy and angular resolution critical.



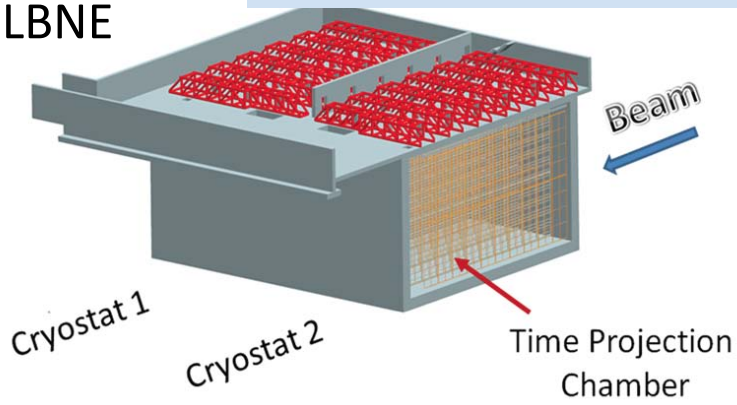


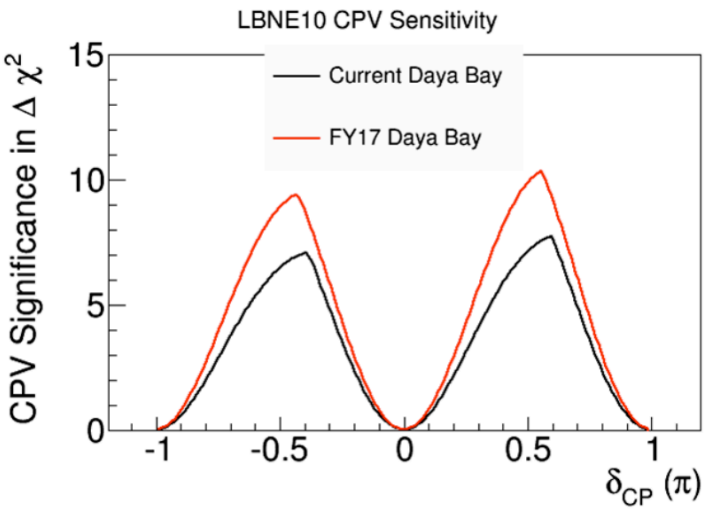


Hierarchy resonance easily washed-out if detector resolution is poor

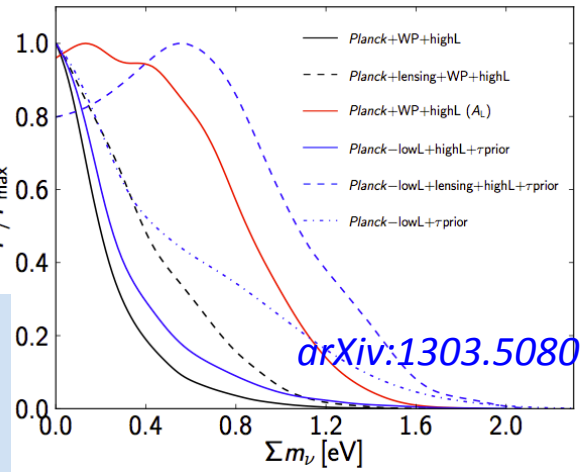
Other Big Questions

Do neutrinos violate Charge-Parity symmetry?



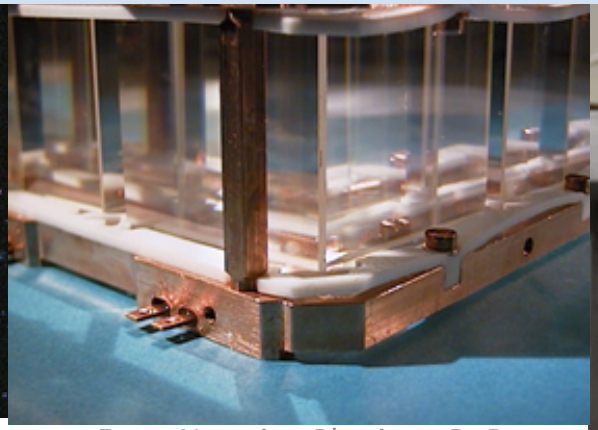


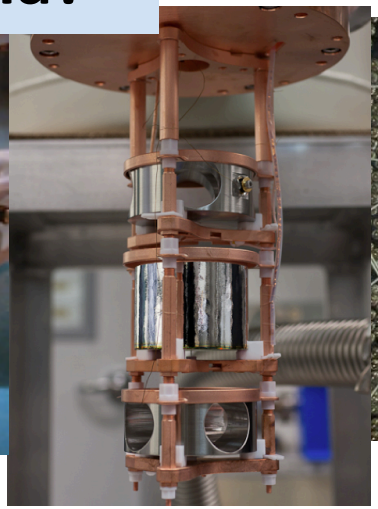
What is the absolute neutrino mass?



Can neutrinos explain matter-antimatter asymmetry?

Is the neutrino mass Dirac or Majorana?



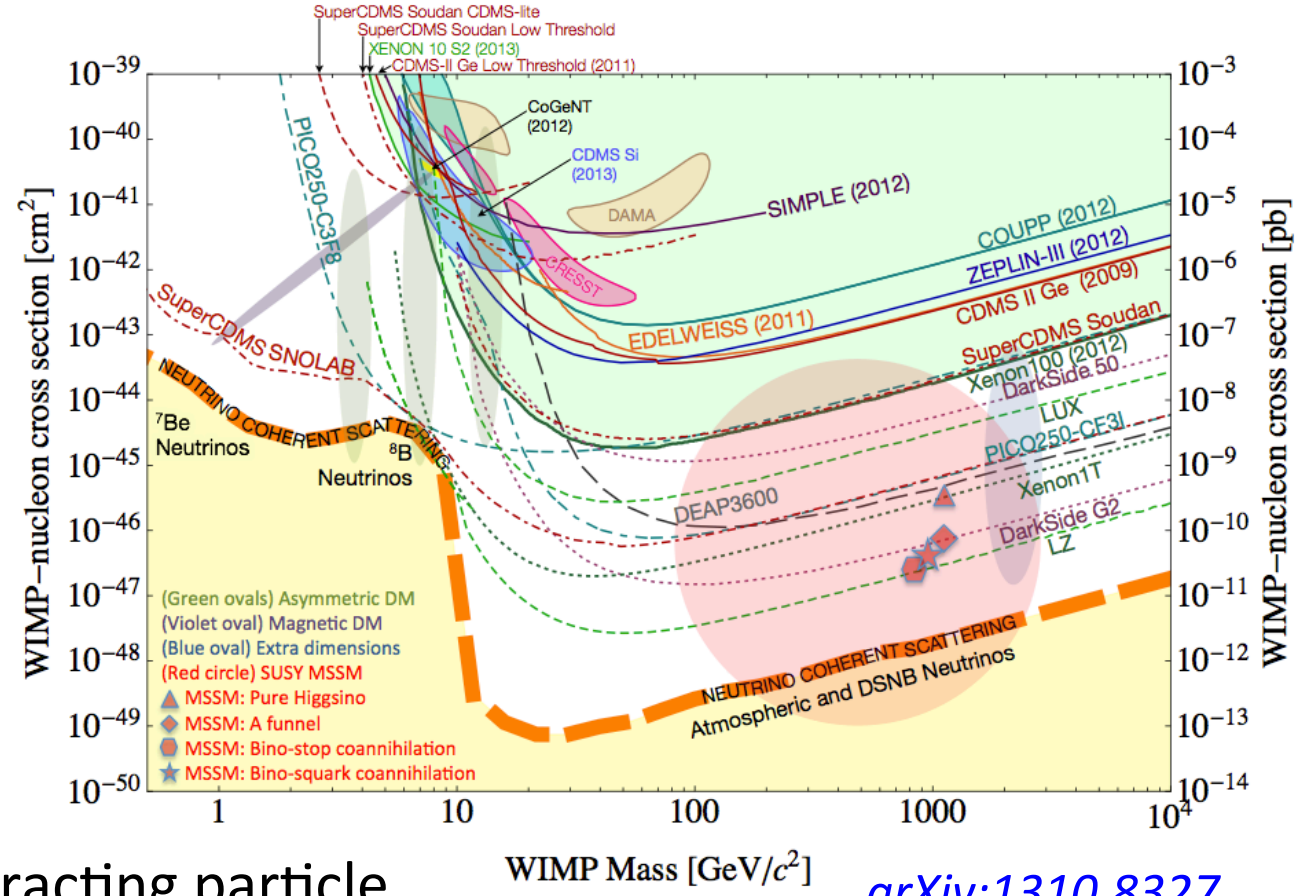


Dark Matter

Strong interplay between ν and WIMP physics

Experiment:

- Large detectors
- Low-energy physics (< MeV)
- Low-radioactivity materials
- Continuous operation



Theory:

Neutrino: Light weakly-interacting particle

WIMP: Heavy weakly-interacting particle

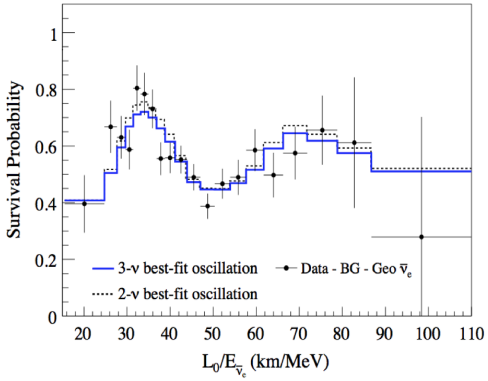
arXiv:1310.8327

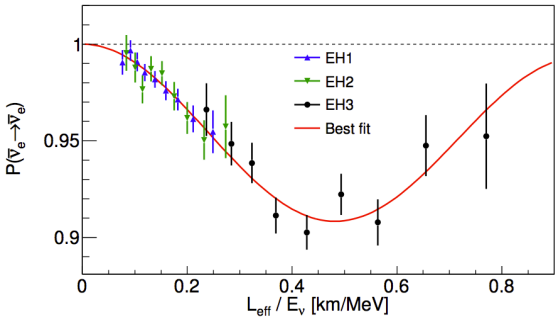
If WIMPs exist, do they have a fundamental relationship with the neutrino?

Closing

Many lessons from neutrinos so far.

Neutrinos oscillate and have mass

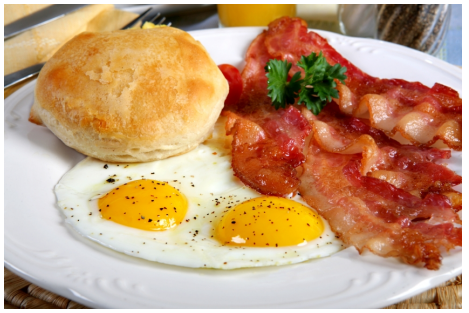




Neutrinos all mixed up

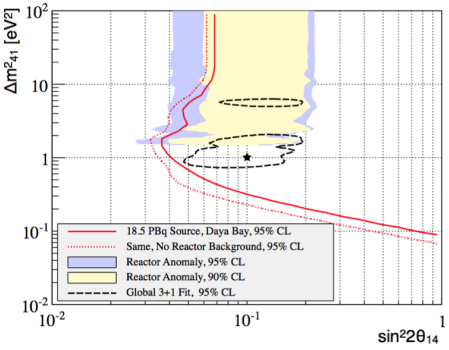
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ -0.50 & 0.58 & 0.64 \\ 0.26 & -0.60 & 0.75 \end{pmatrix}$$

Farm-to-Table Physics

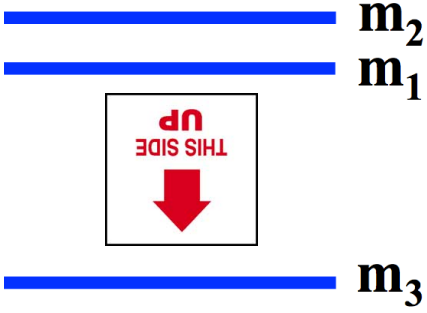


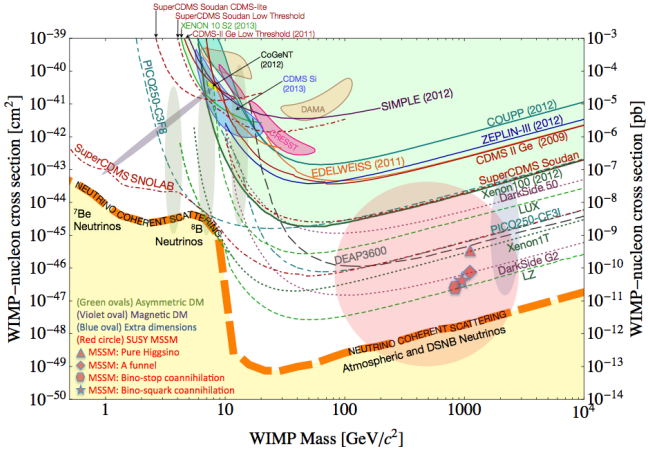
Surely more lessons to come.

Neutrino Flavors?



Neutrino Mass



Neutrinos and the Universe

Neutrinos and Dark Matter