Exploring the Standard Model and Beyond with Neutrino Oscillations

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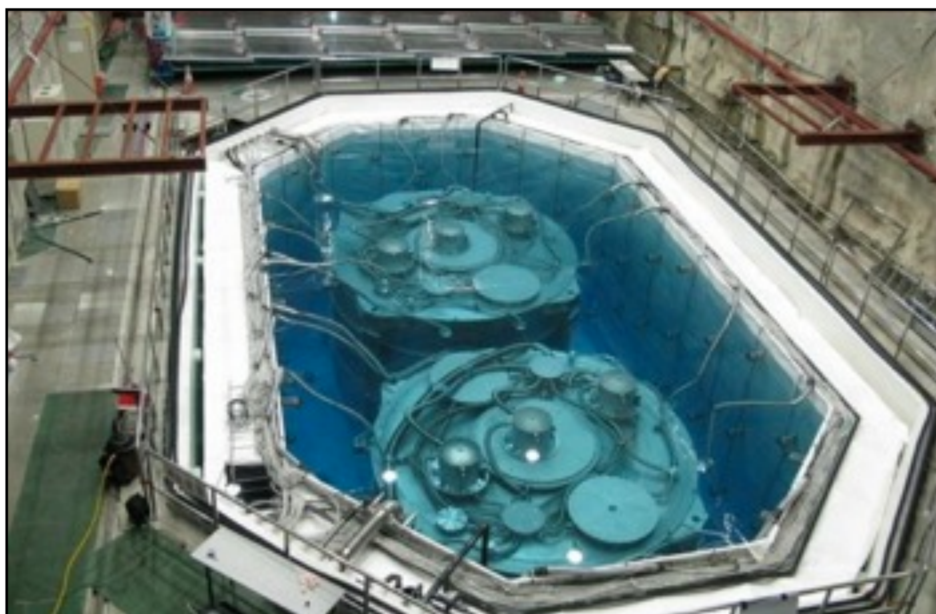
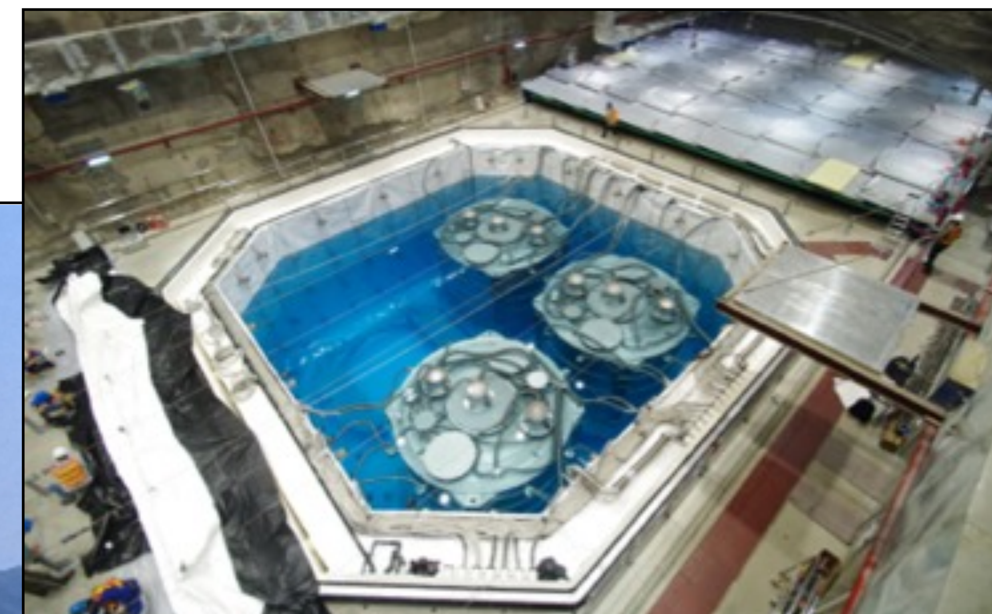
University of Cincinnati

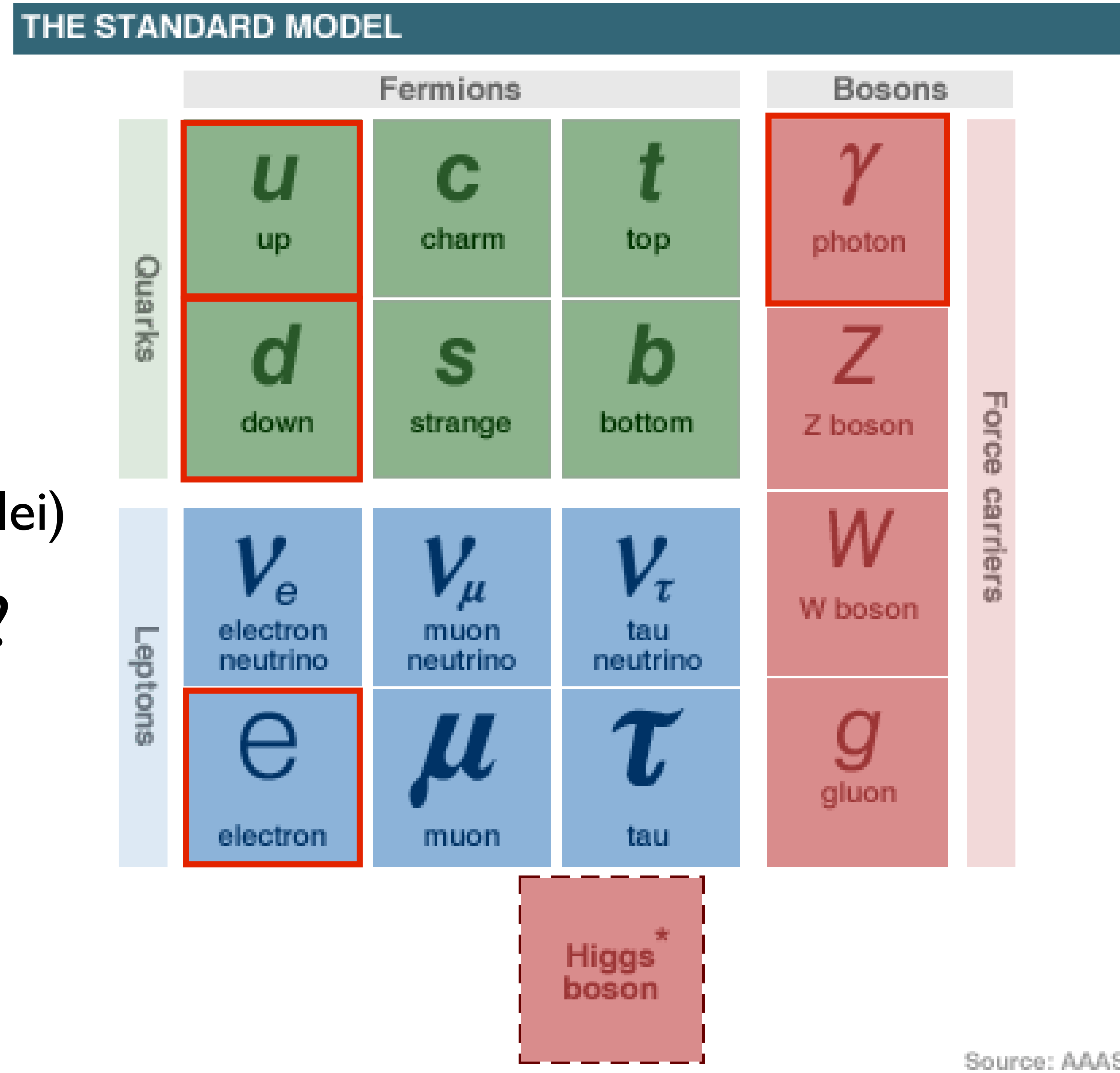
4/18/2013

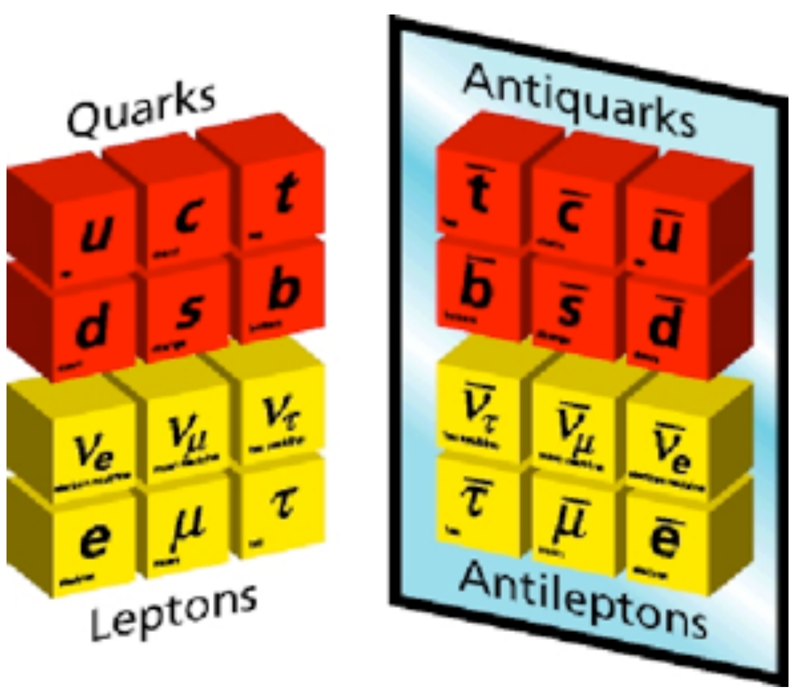




The Standard Model

- Describes all particles and how they interact
- Some are familiar:
    - Photons
    - Electrons
    - Up and down quarks (a.k.a nuclei)
- What are their properties?
- Don’t forget antiparticles!





A Little History Lesson: Periodic Table

Periodic Table of the Elements

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

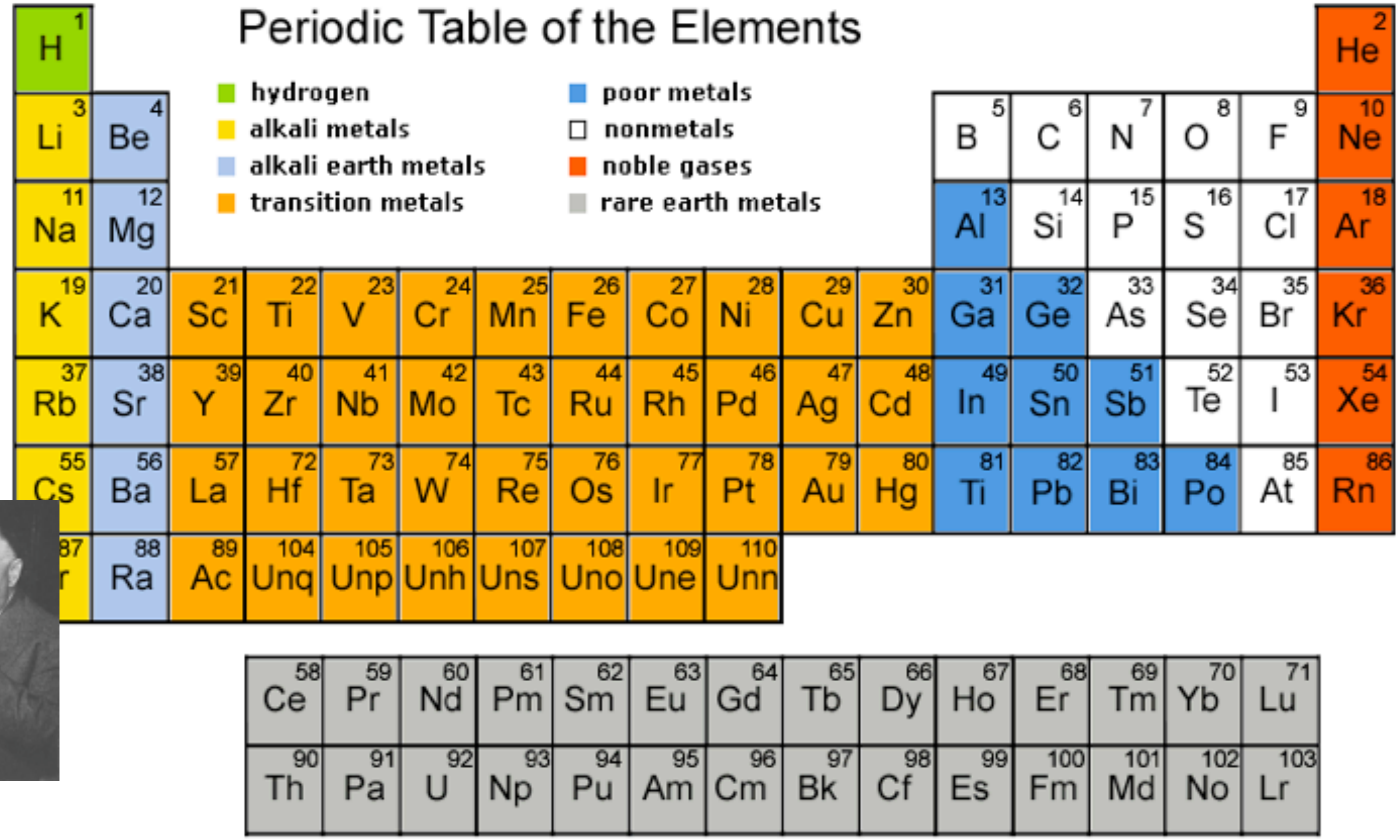
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

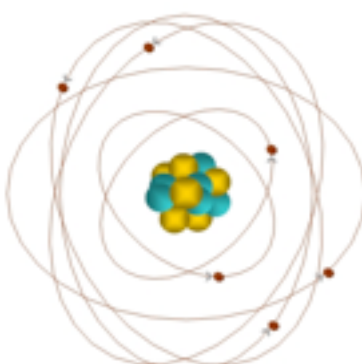
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

- Assembled: 1869

From Los Alamos Science **25**

A Little History Lesson: Periodic Table





- Assembled: 1869
- Understood: 1900s-1930s

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37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 r	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

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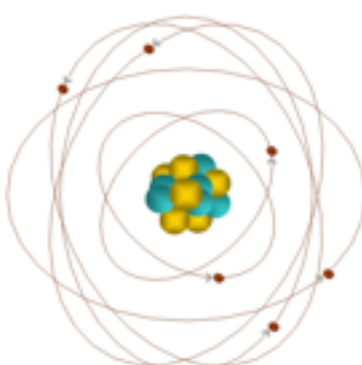
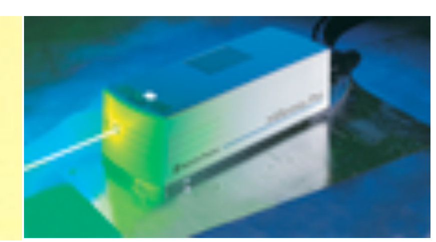
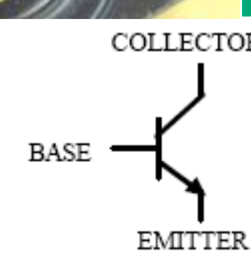
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



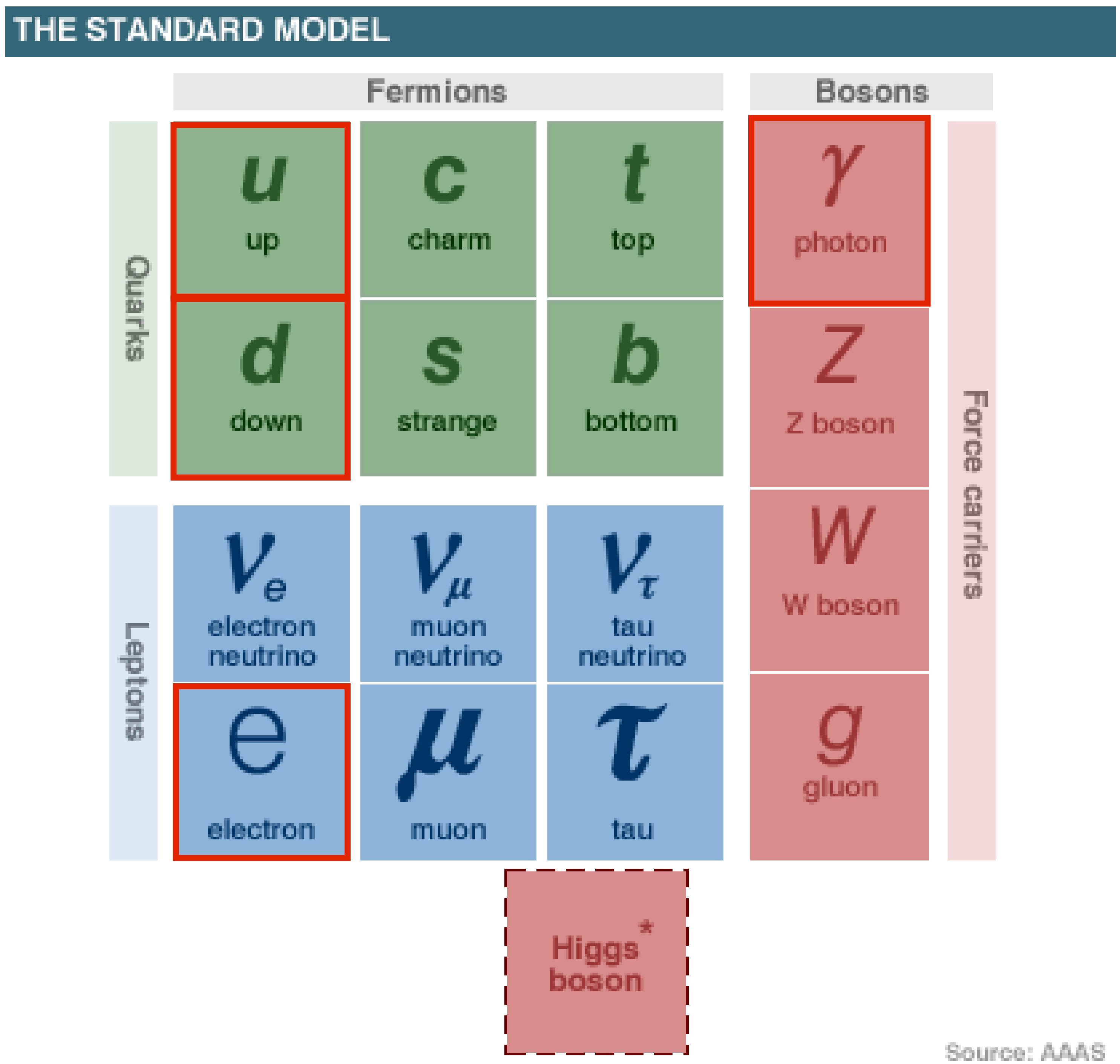
- Assembled: 1869
- Understood: 1900s-1930s
- Technology: 1950s and beyond
- Nearly a century of development and discovery!





The Standard Model

- Fundamental particles: elements that make up the elements!
- We're about 50 years into the discovery process.

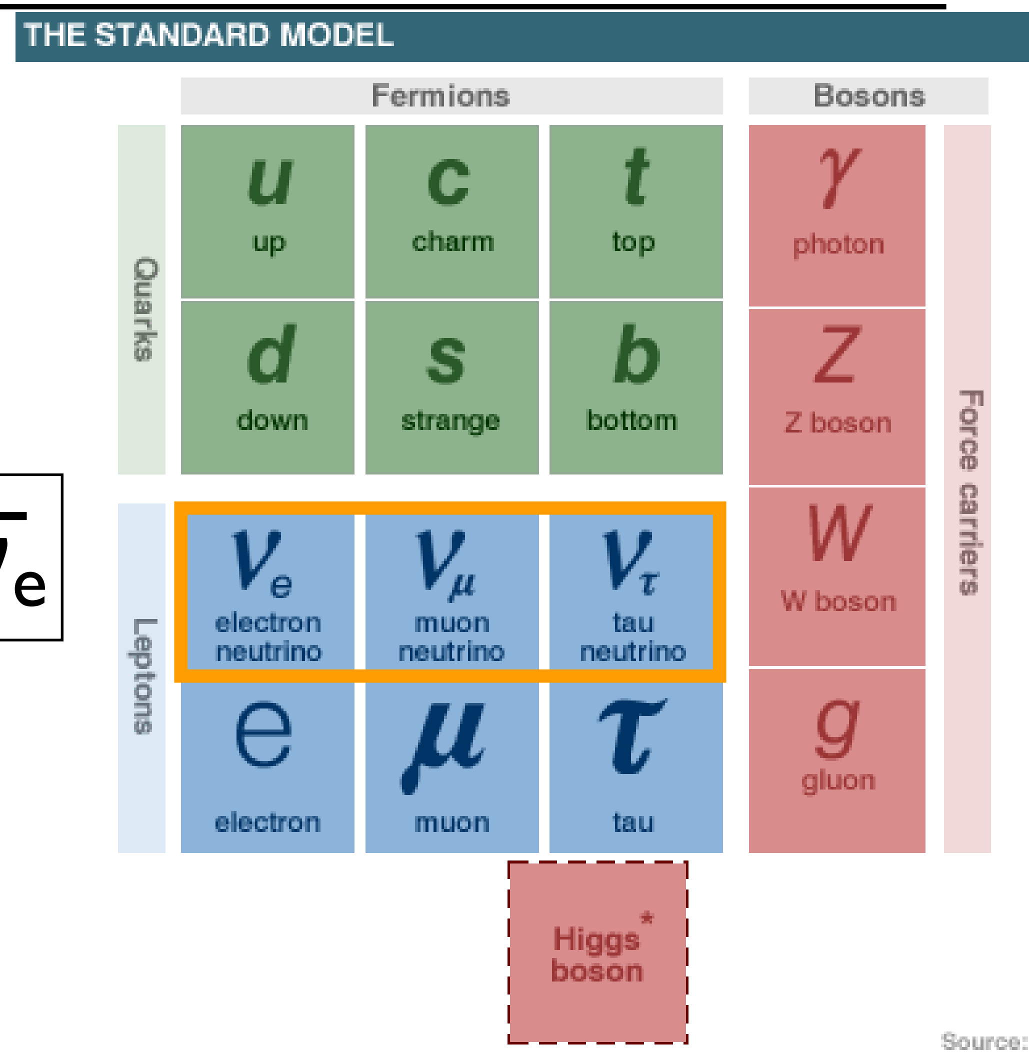


Neutrinos!

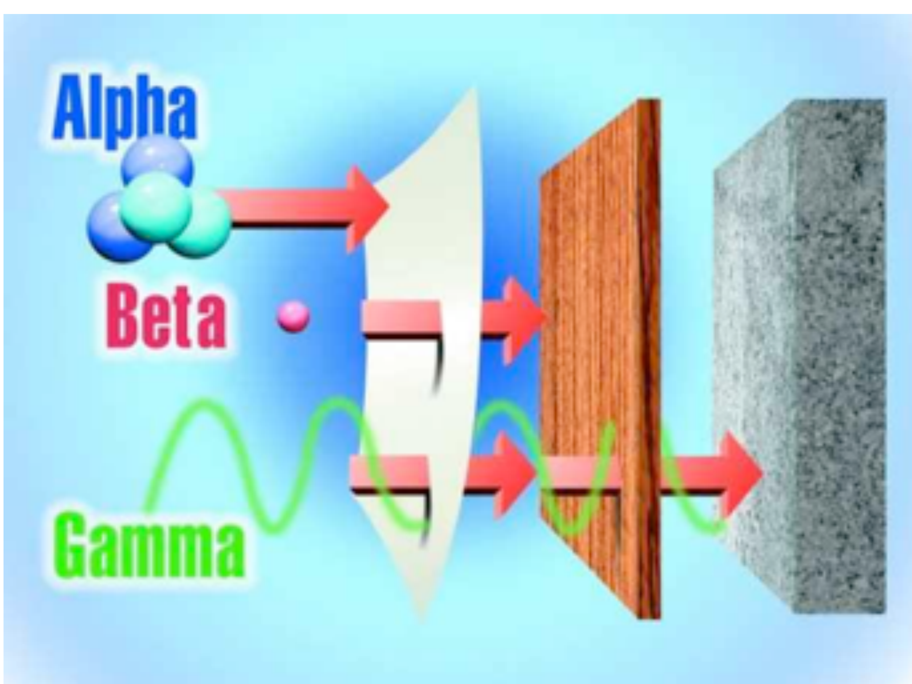
- Chargeless, spin 1/2
- Made anywhere radioactive decays, nuclear interactions are taking place
  - Sun
  - Nuclear reactors
  - The big bang
  - Supernovae

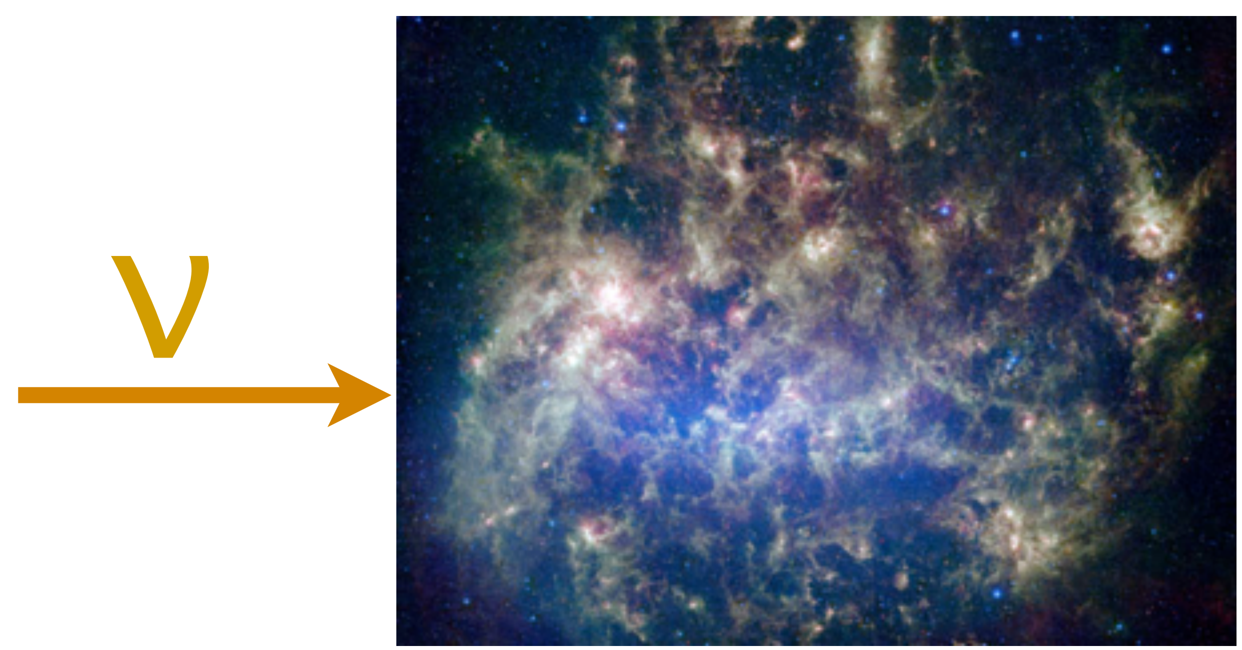
$$^{14}C \rightarrow {}^{14}N + e^- + \overline{\nu}_e$$

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



- Weakly interacting: harmless!





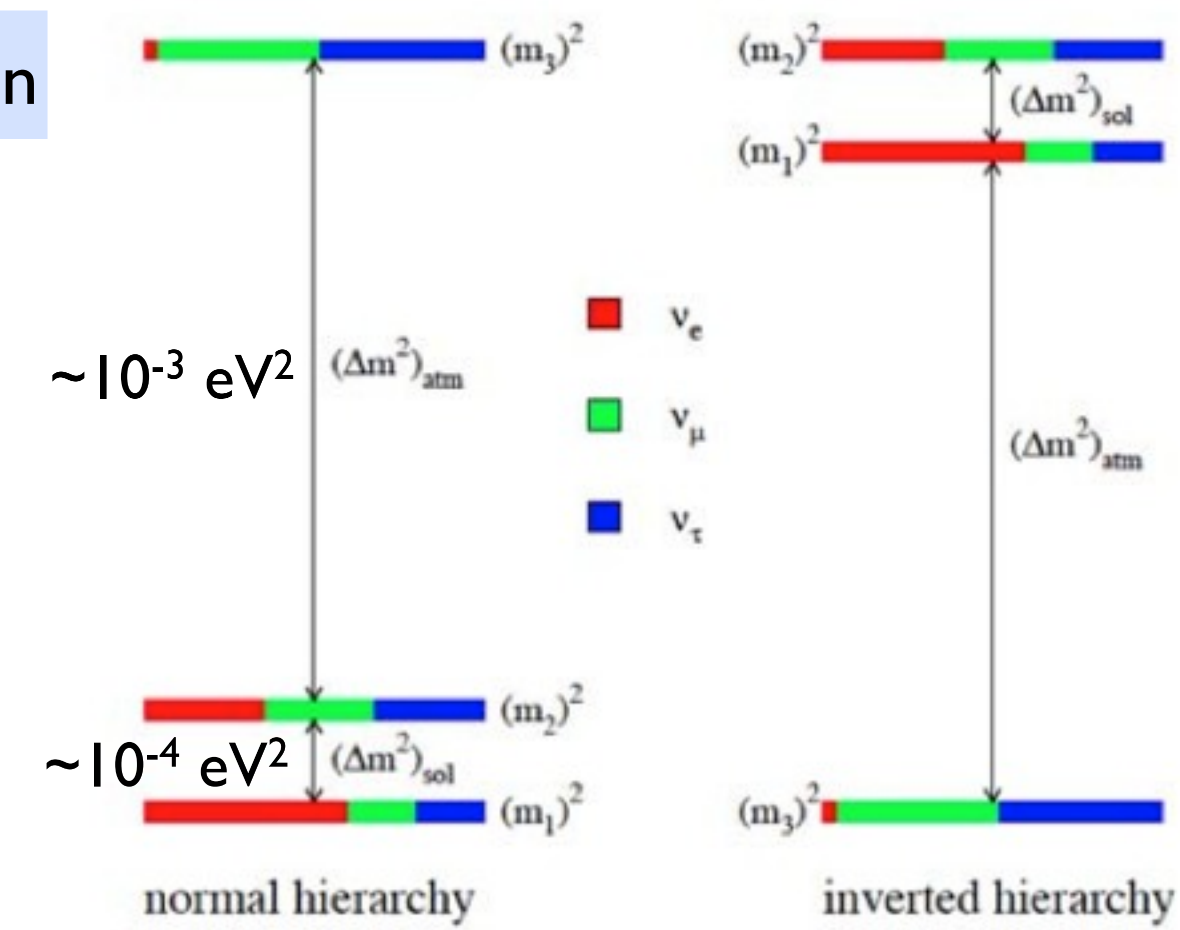
Neutrino Oscillations

- Neutrinos are not massless:
  - Flavor and mass eigenstates are different:

$c_{ij} = \cos(\theta_{ij})$;
$s_{ij} = \sin(\theta_{ij})$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}e^{i\alpha_1/2}\nu_1\\ e^{i\alpha_2/2}\nu_2\\ \nu_3\end{pmatrix}$$

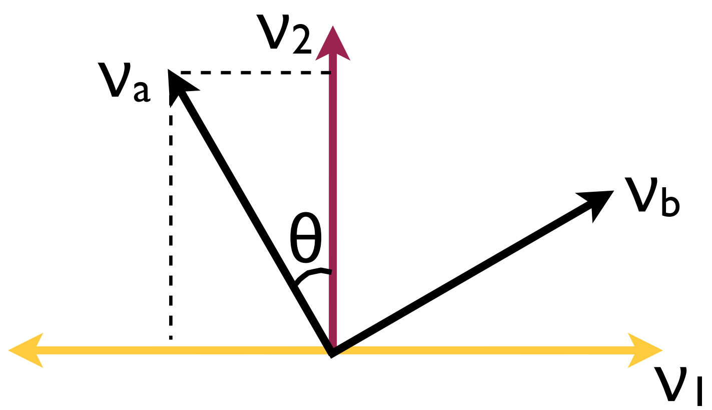
- Leads to neutrino flavor transformation
- Parameters governing oscillation:
  - Neutrino mass differences
  - Mixing angles
  - CP-violating phase, δ



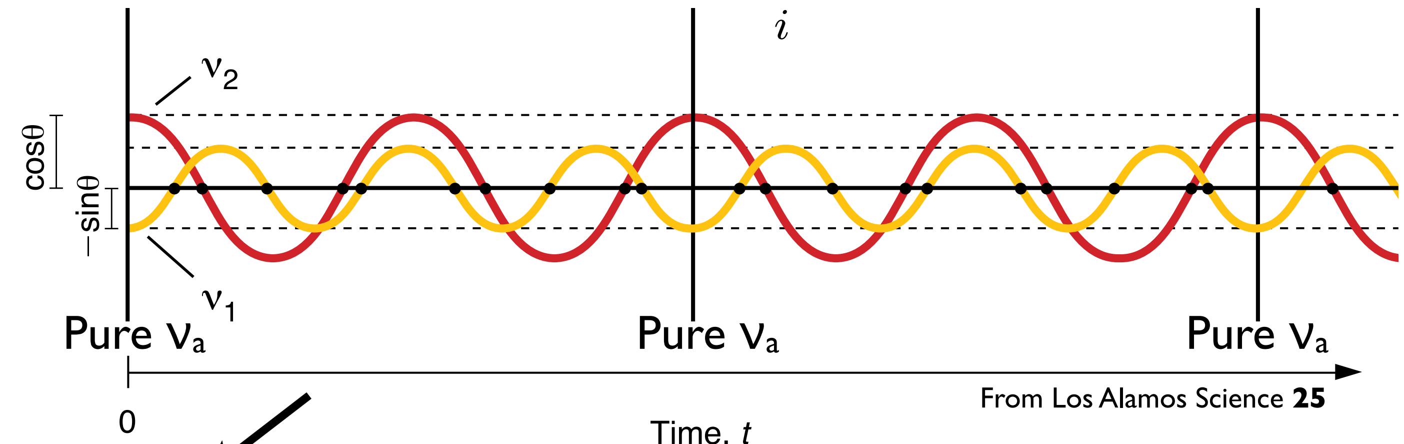
Neutrino Oscillations

Two neutrino case:

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



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

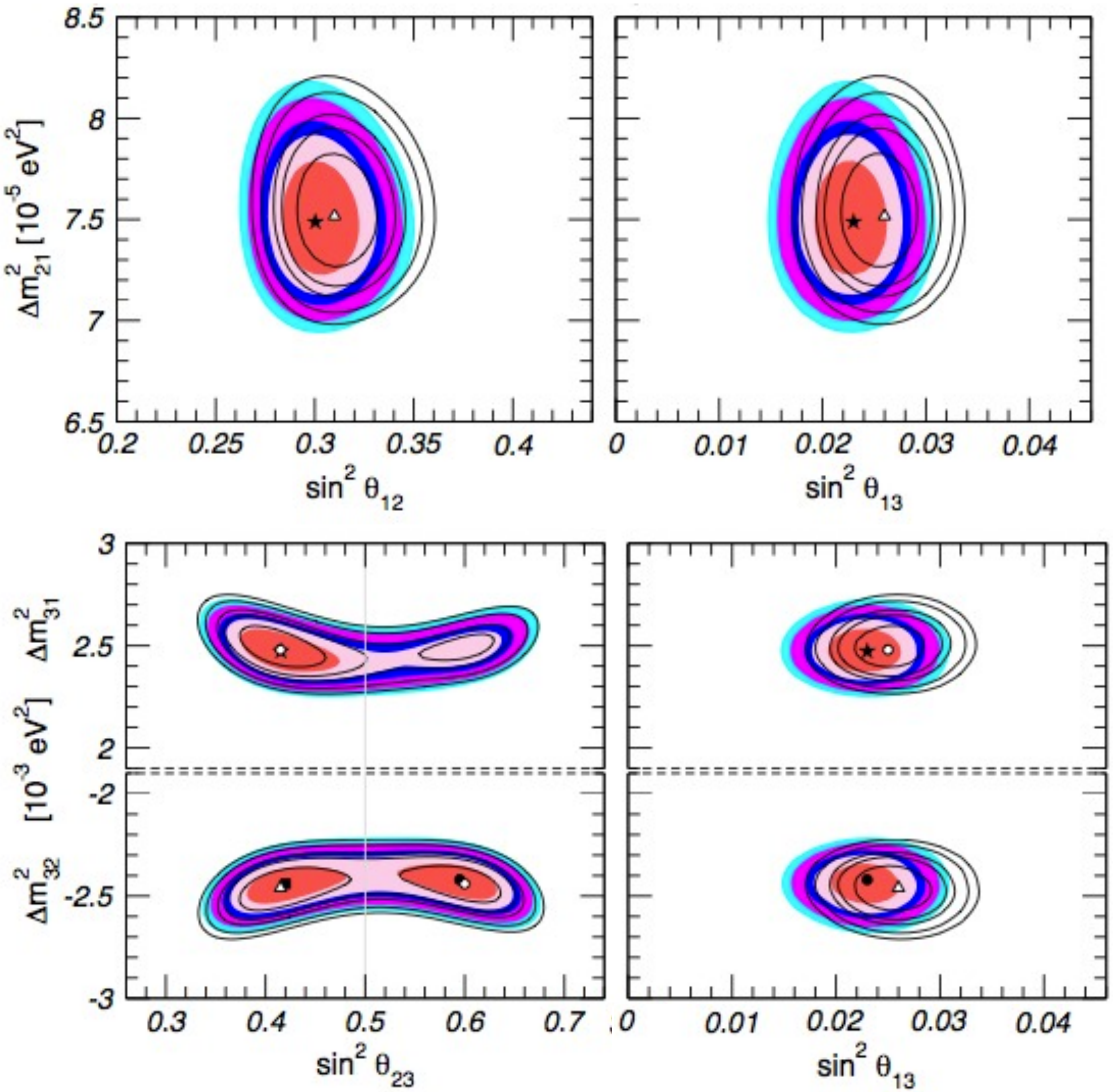


$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu (GeV)} \right]$$

- Important quantities:
  - θ: Oscillation amplitude
  - Δm^2: Oscillation frequency
  - L/E: Experimental parameter
  - Oscillation maximum when $L(km) = \frac{1.24 E_\nu (GeV)}{\Delta m^2 (eV^2)}$

An Exciting Time for Oscillations

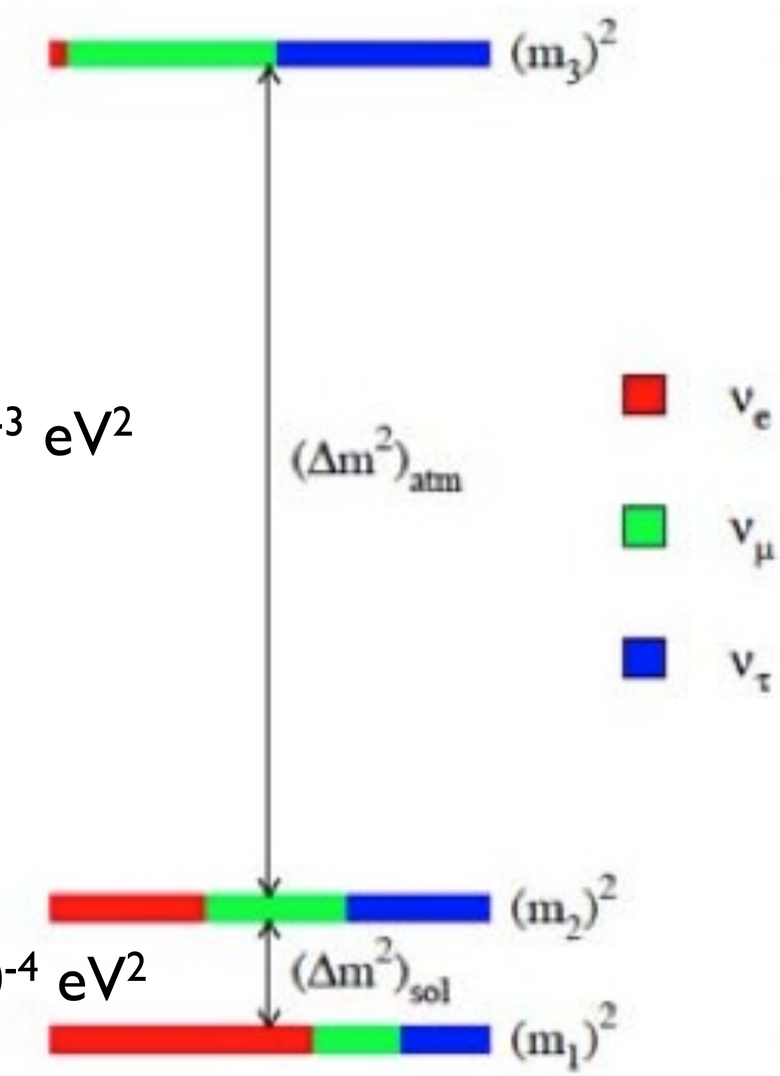
- Most oscillation parameters measured in last decade



- $\theta_{23}, \theta_{12}, \Delta m_{21}, |\Delta m_{32}|$ measured in 2000s
- 2012: The year of θ_{13}
- Remaining unknowns: $\delta_{cp}, |\Delta m_{32}|$

~10^{-3} eV^2

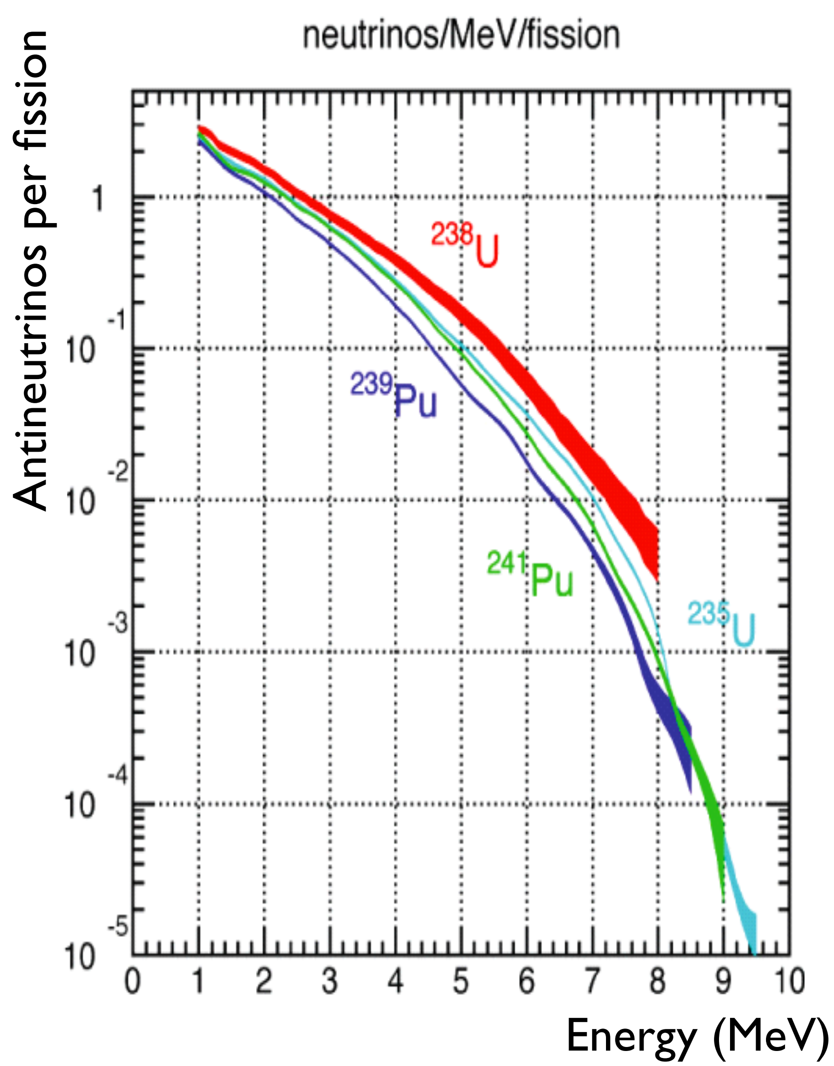
~10^{-4} eV^2

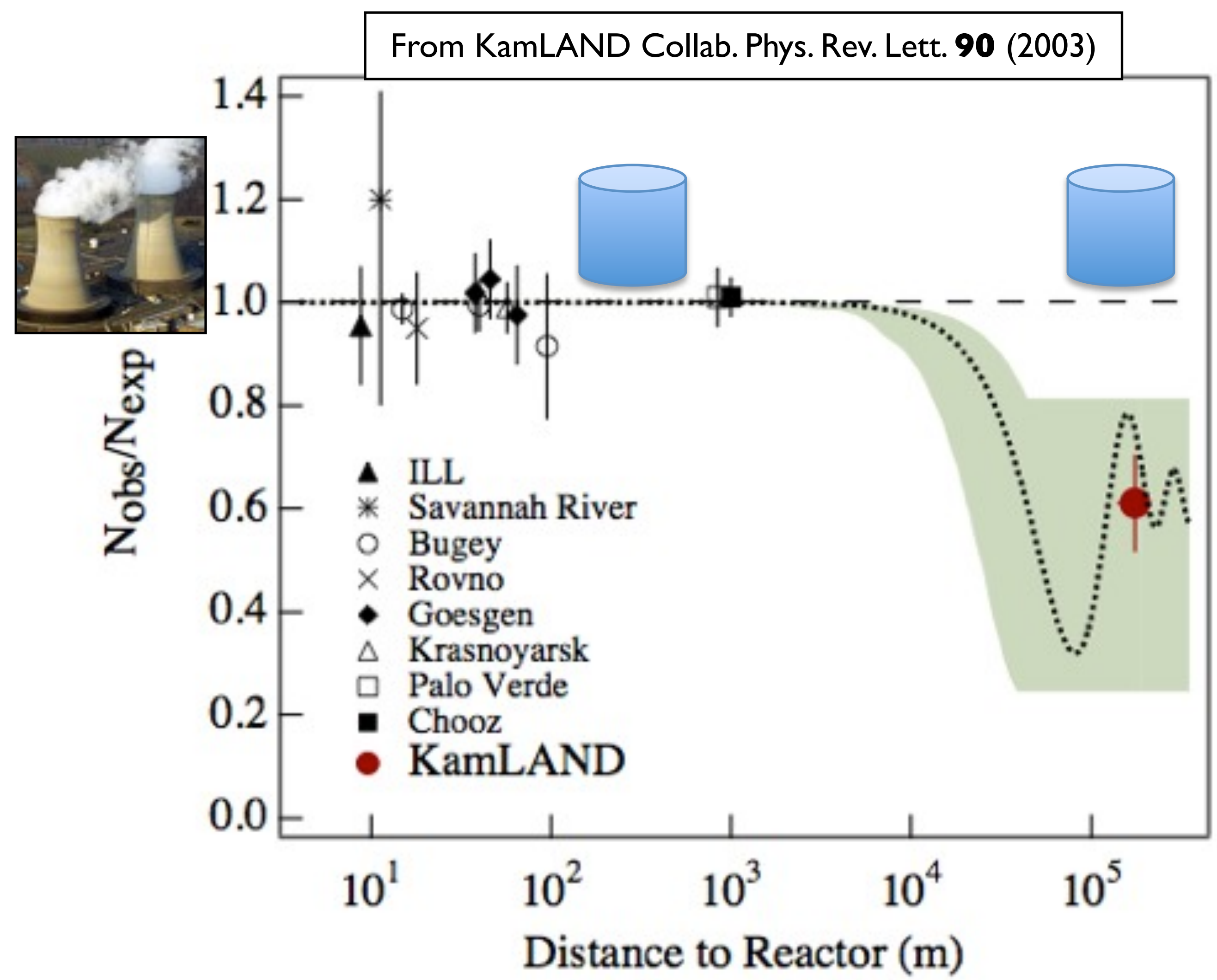


Reactor Oscillation Experiments

- Reactors: a pure, strong, isotropic source of MeV energy $\bar{\nu}_e$
- Measure this source with detectors at one or two distances
  - Clean measurement, only 2 parameters present

$$P_{ee} \approx 1 - \sin^2 2\theta \; \sin^2\left[1.27\Delta m^2 (eV^2) \frac{L(km)}{E_\nu (GeV)}\right]$$

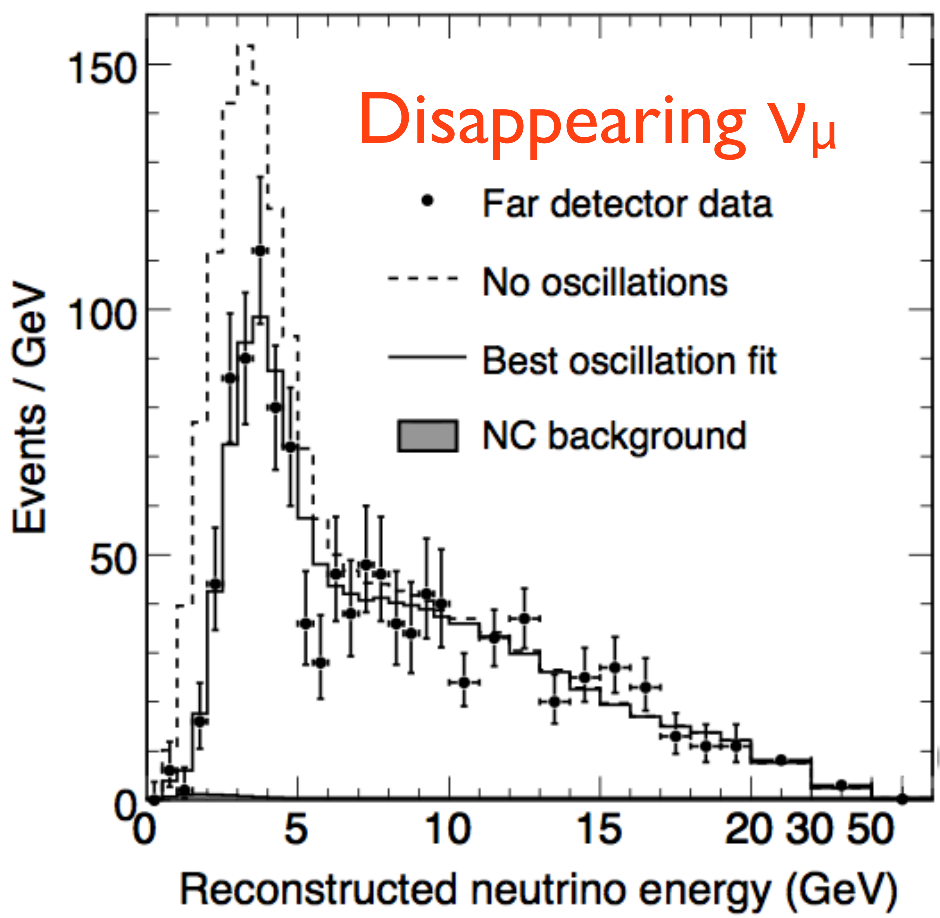


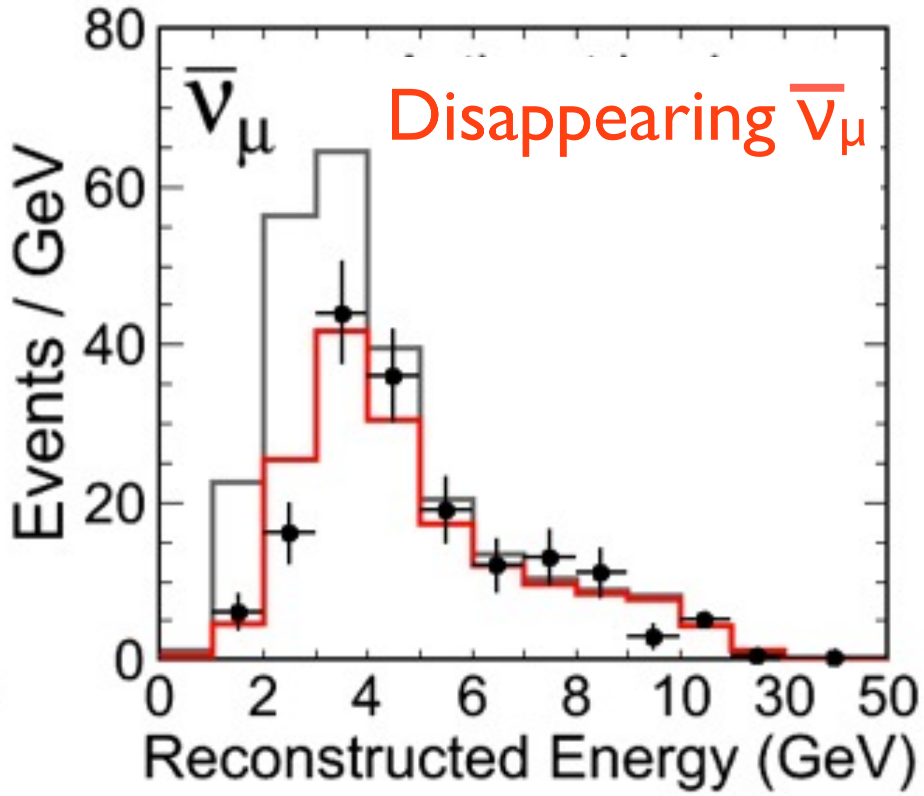


Accelerator Oscillation Experiments

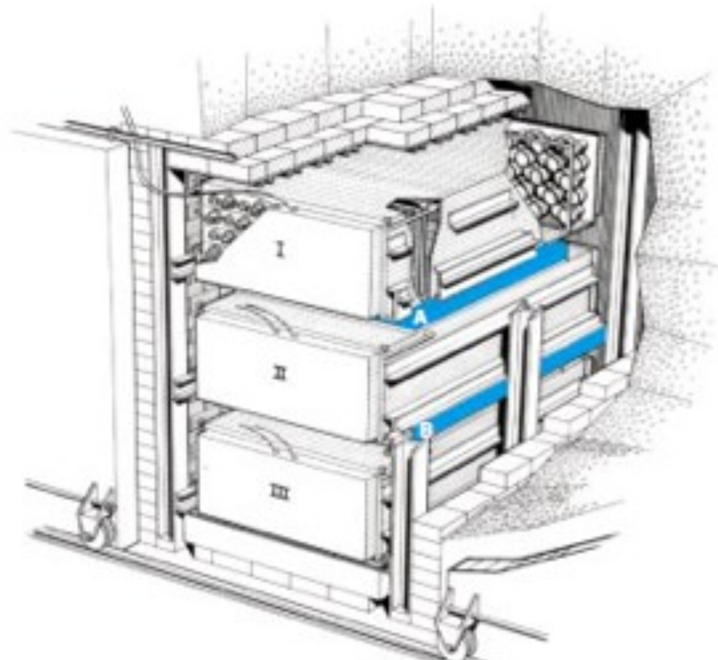
- Accelerators: an unpure beam of either GeV energy $\nu_\mu, \overline{\nu}_\mu$
  - Created by decaying pions created in a proton beam dump
  - Measure this source at near and far distances to look for oscillation
  - Lots of parameters here being measured at the same time...

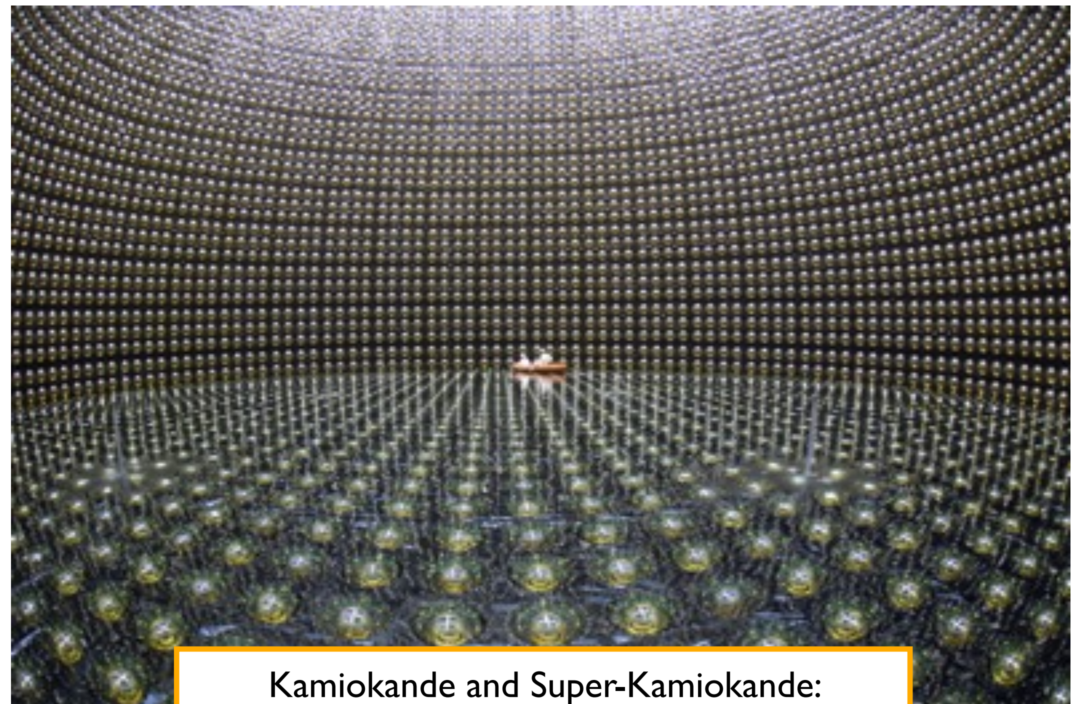
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+ 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} + \ldots$$

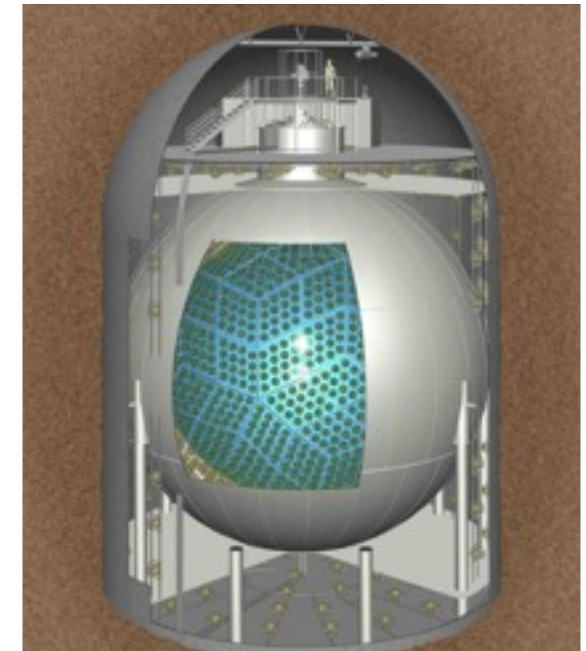




50+ Years of Neutrino Experiments







The Savannah River Detector:
First Unambiguous Neutrino Discovery!

Kamiokande and Super-Kamiokande:
atmospheric neutrino oscillations and more!

KamLAND: First Reactor
Neutrino Oscillations!

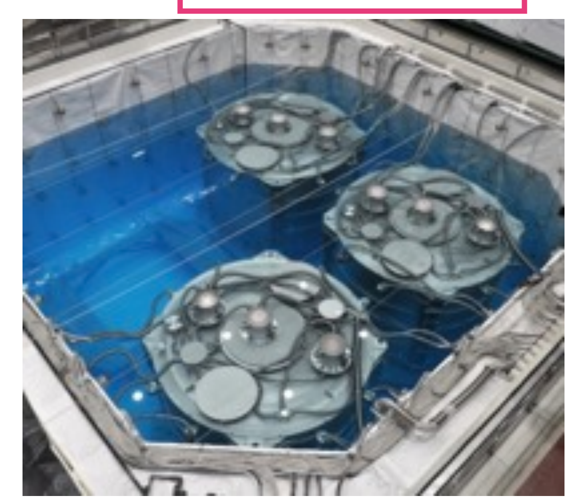
1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s

Davis's Homestake Experiment
Inception of Solar Neutrino Problem

Short-baseline reactor experiments, like
CHOOZ, search for oscillation signatures

SNO: Solves solar neutrino problem,
evidence of solar oscillations

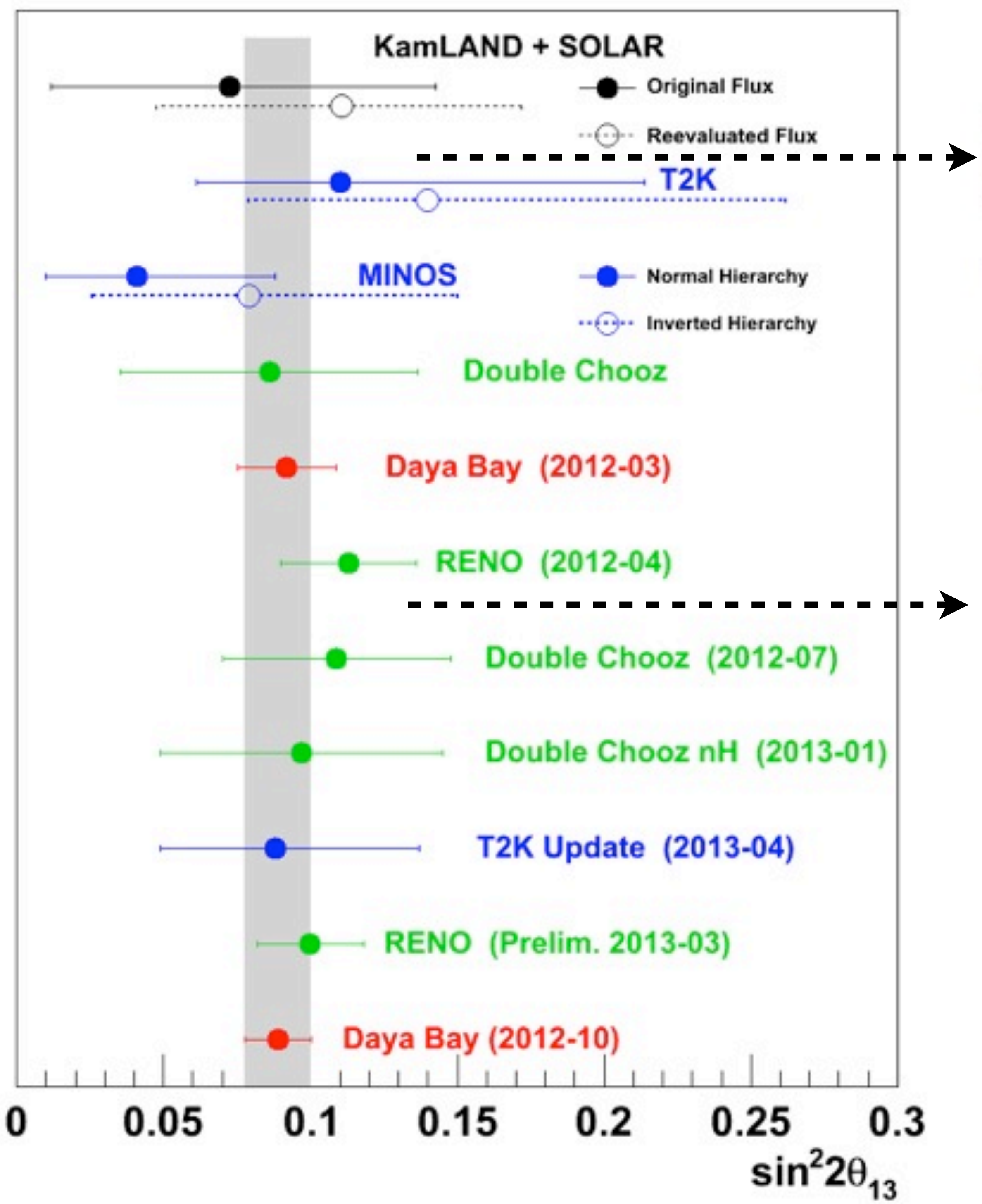
Precision Era:
Daya Bay, RENO,
Double Chooz,
MINOS, T2K...

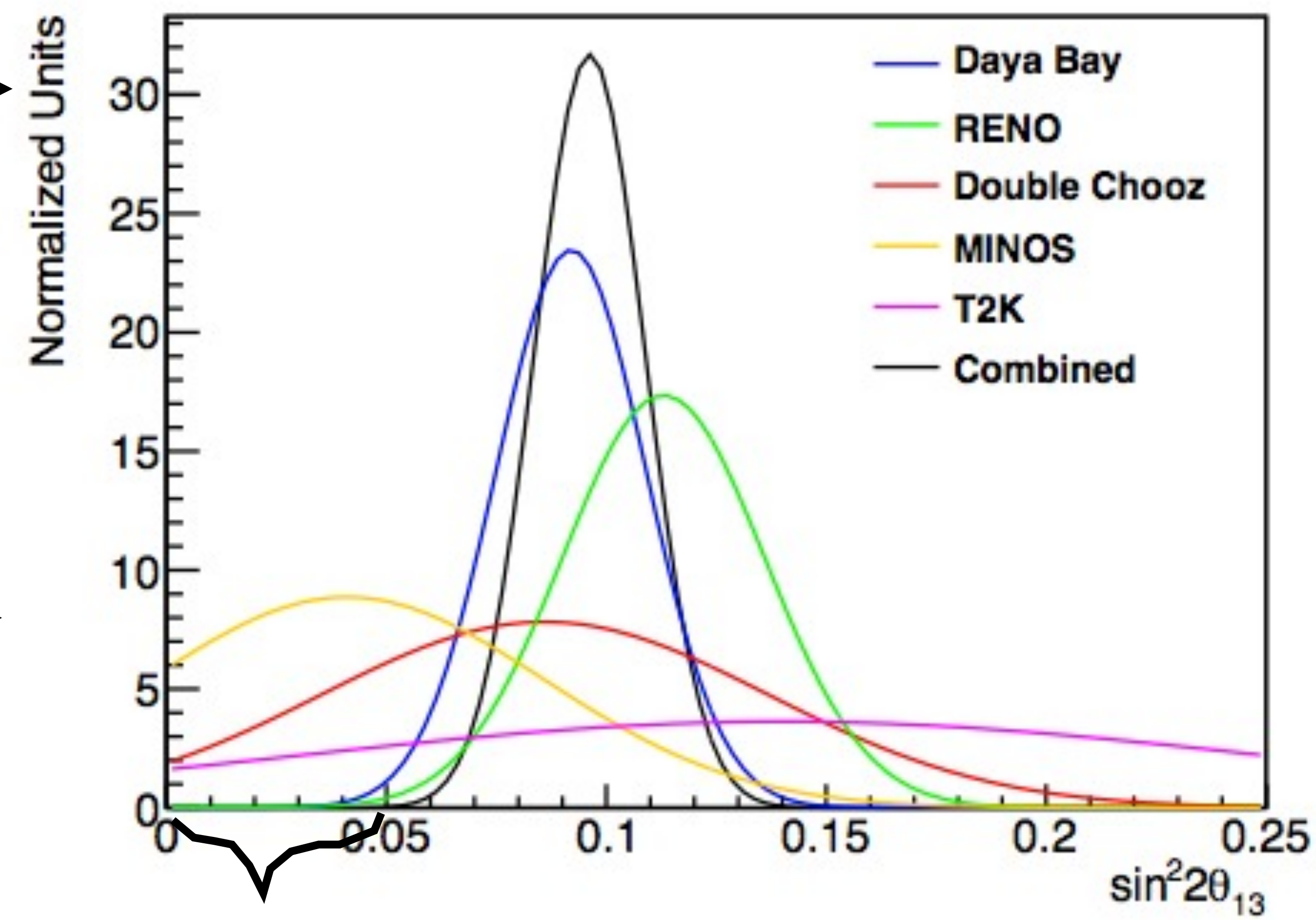


Measuring θ_{13} at Daya Bay

θ_{13} Discovery

Daya Bay provided the first definitive measurement of θ_{13} and demonstrated for first time 5σ exclusion of $\theta_{13}=0$



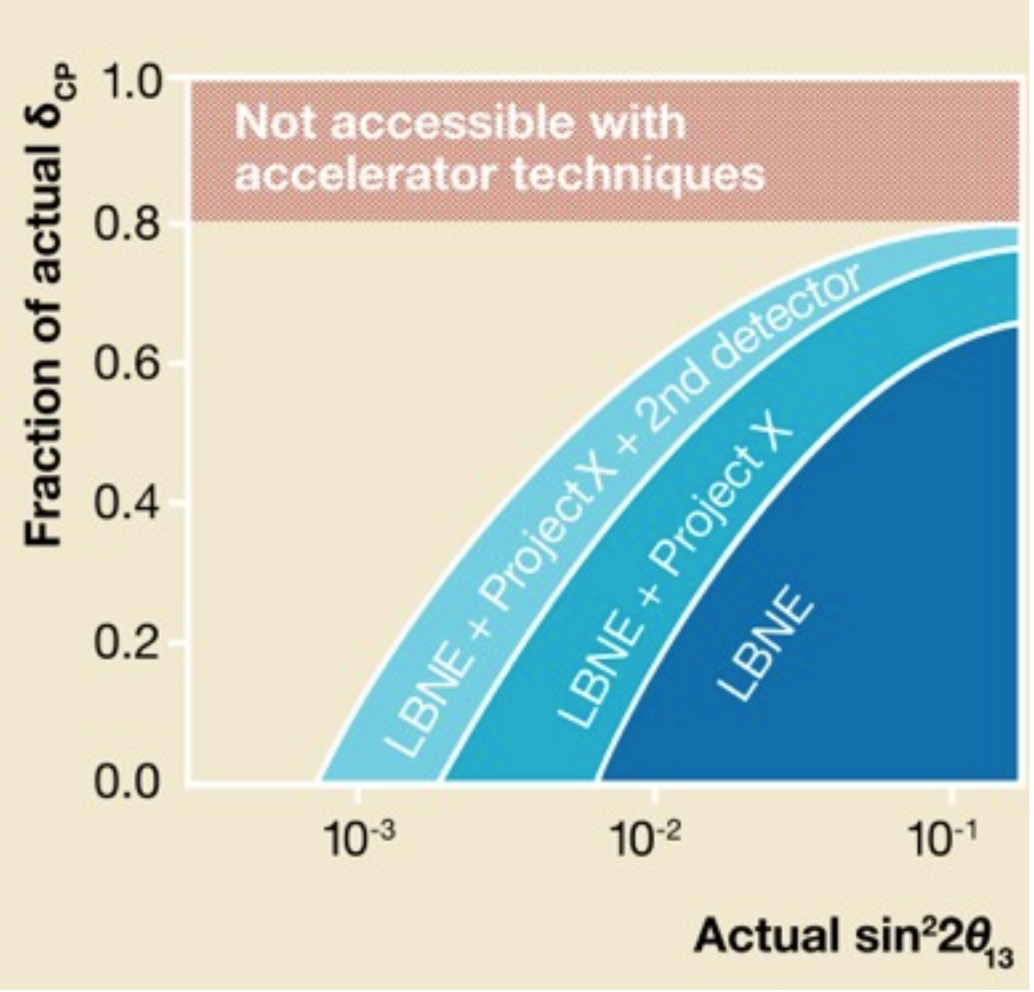


Extremely high combined significance: >7σ: Machado, *et al.*, arXiv: 1111.3330

Why θ_{13}?

- It was the last unknown mixing angle
- Helps in measuring δ_{cp}
  - Complex phase behaves differently for neutrino, antineutrino oscillation
- If difference is large, neutrinos could play a big role in matter-antimatter asymmetry in the universe
- A large, well-measured θ_{13} makes these future measurements easier

$$\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}$$



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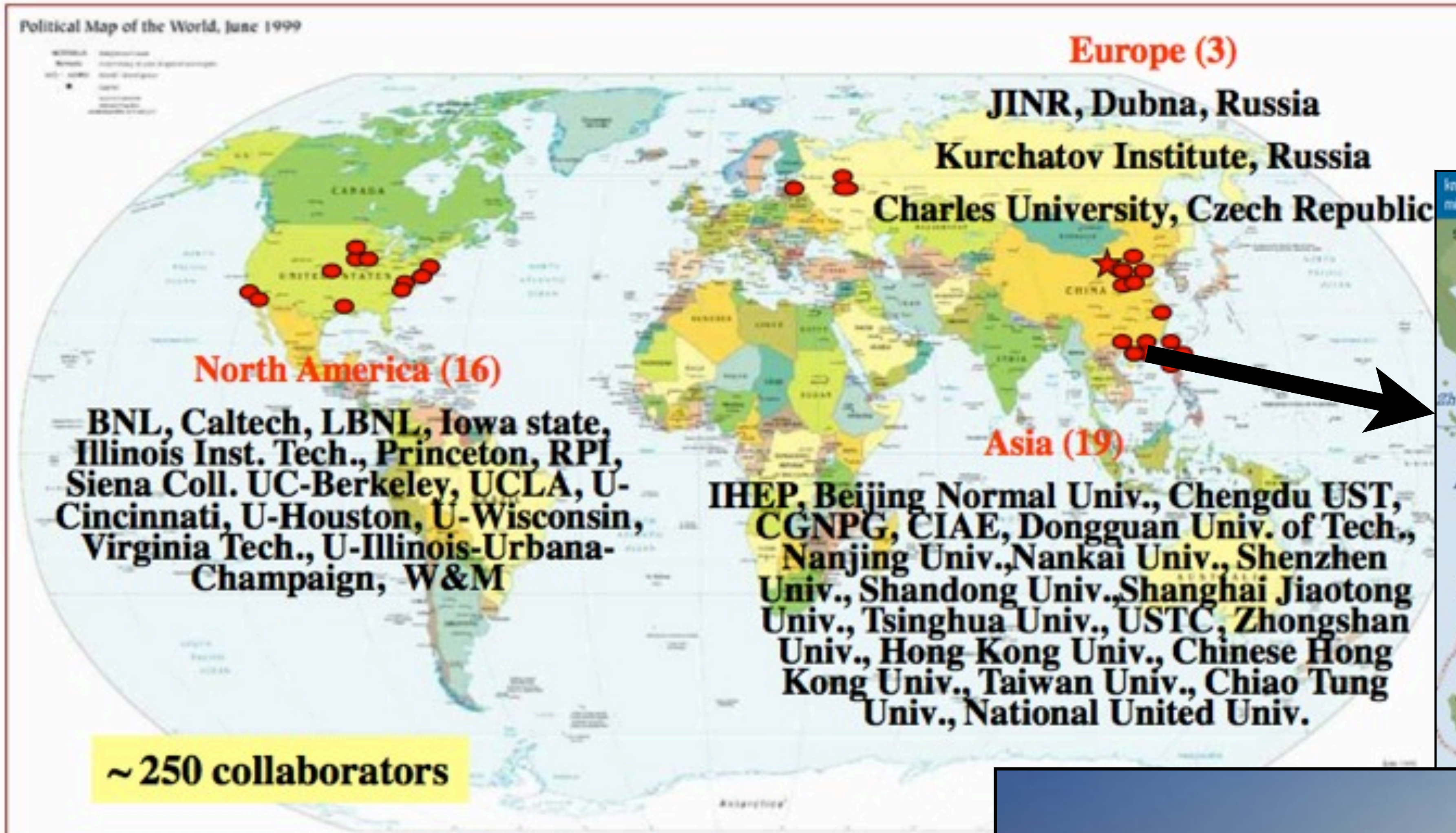
The Daya Bay Reactor $\bar{\nu}_e$ Experiment



Guangdong Daya Bay Nuclear Power Station, Shenzhen, China

Daya Bay Collaboration, courtesy of Roy Kaltschmidt

Daya Bay: A Relative Measurement

- Near-far sites allow relative measurement:

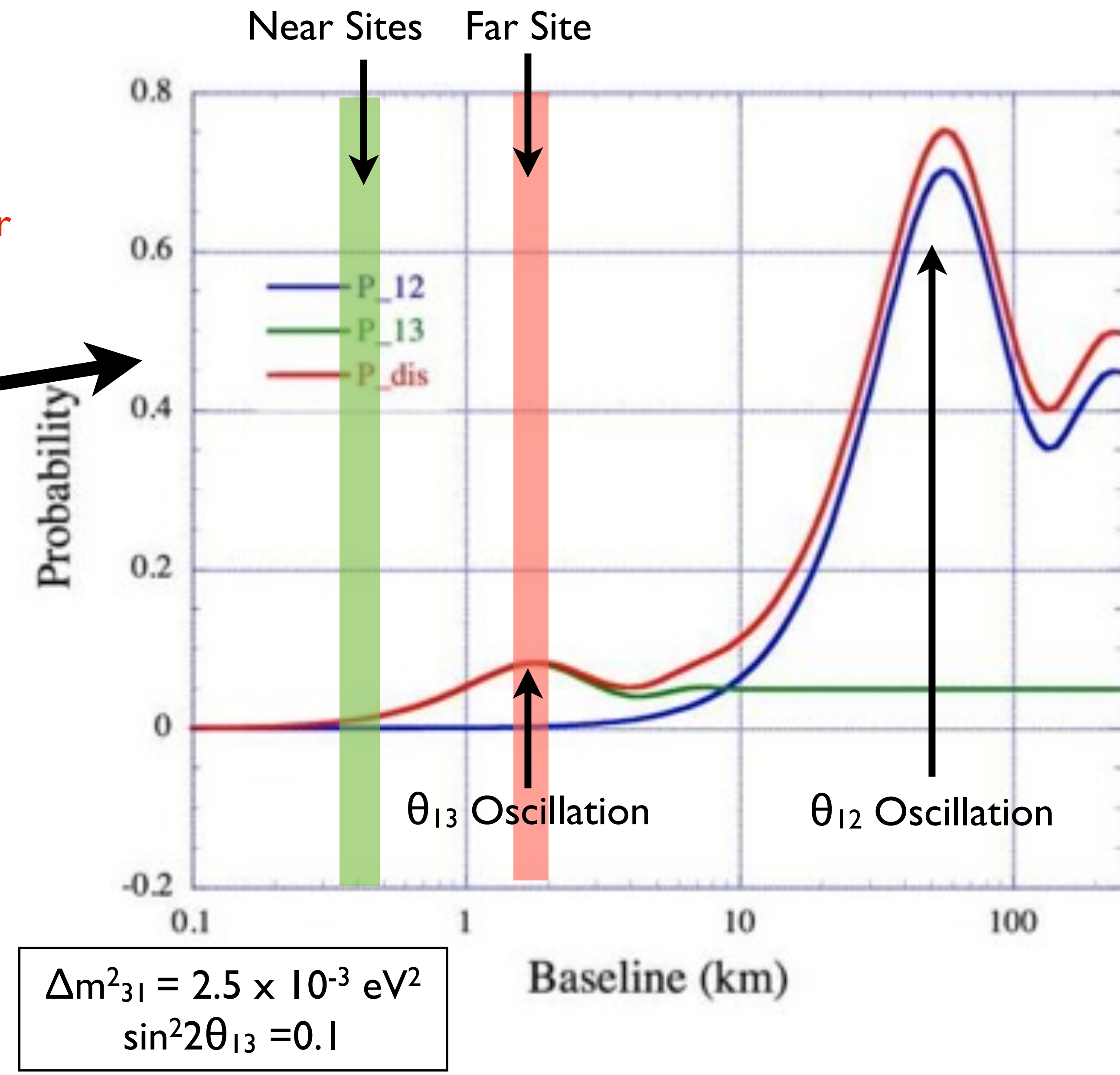
\# Protons

Interaction cross-section

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

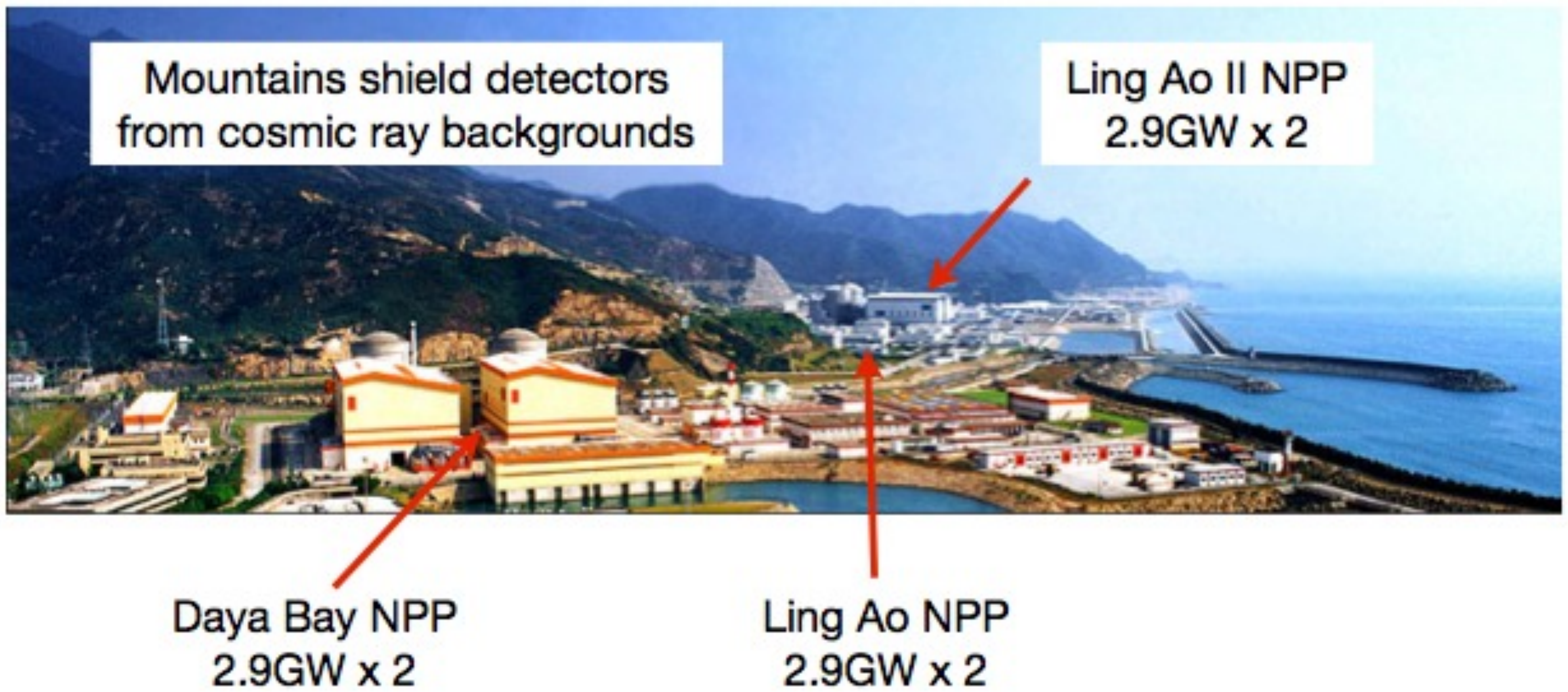
Baseline · Efficiency · Reactor spectrum, power

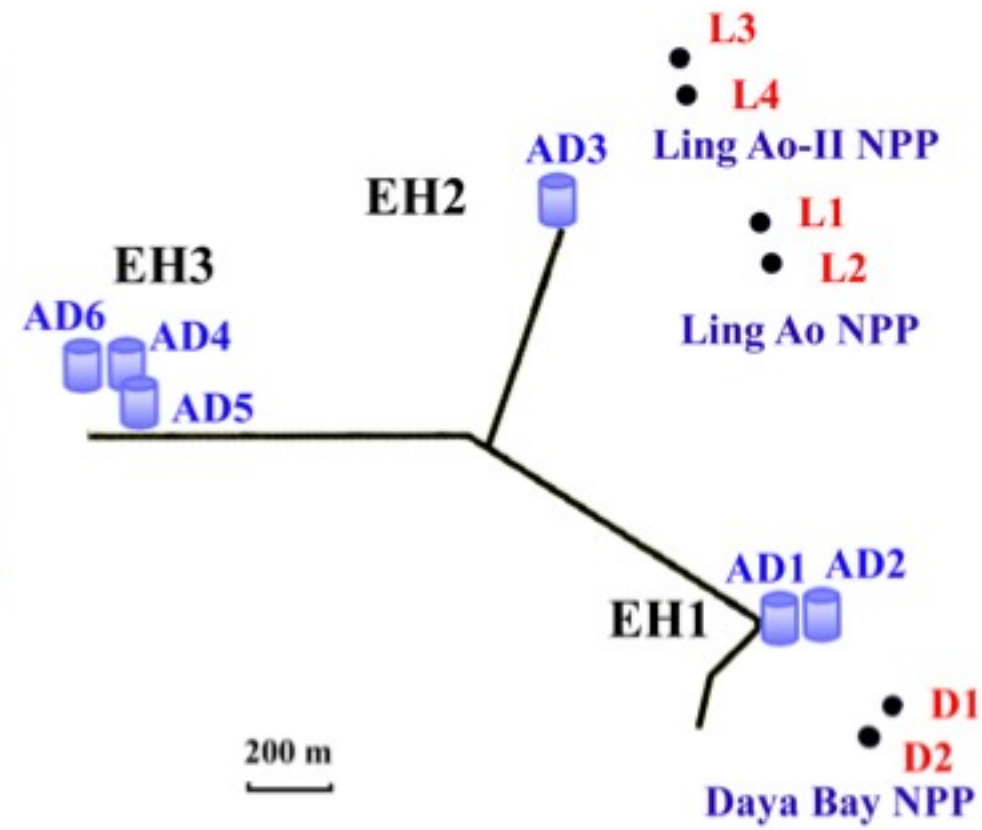
$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right) \left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2 \left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right) \left[\frac{P_\mathrm{sur}(E, L_\mathrm{f})}{P_\mathrm{sur}(E, L_\mathrm{n})}\right]$$



- Correlated uncertainties cancel:
  - Interaction cross-section
  - Reactor shape, thermal power
  - Largest detector systematics
  - Detector cancellation is maximized if all detectors are functionally identical
- Baseline optimized for a θ_{13} measurement

Daya Bay: An Ideal Location



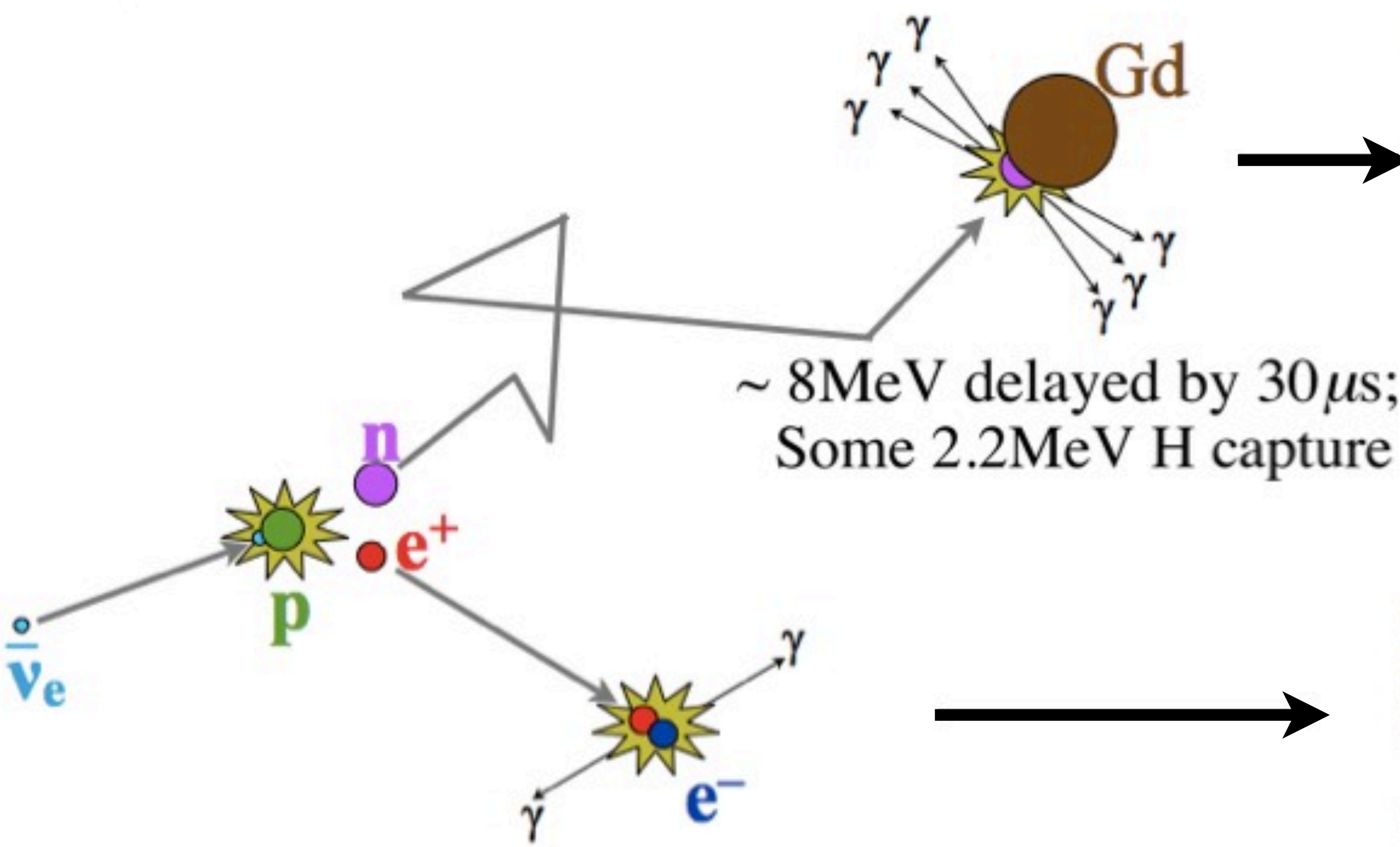


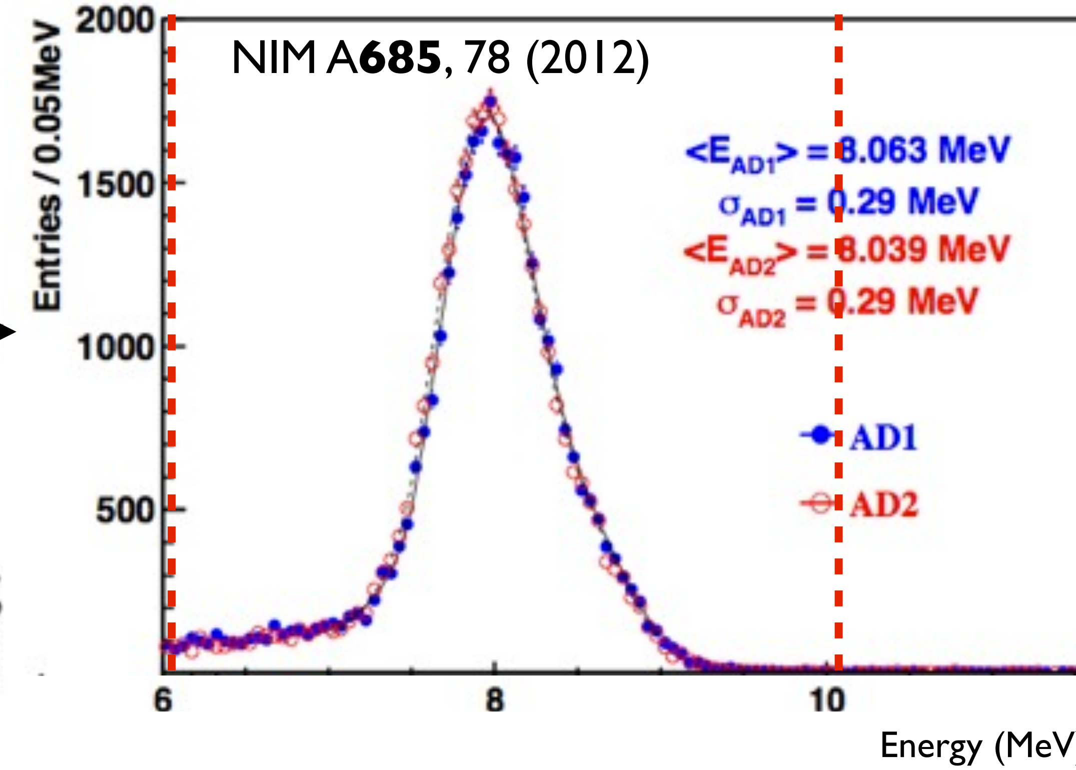
- Three reactor sites with 2 cores, 17.5 GW_{th} total
  - Top 5 most powerful nuclear power complexes
- 6 detectors at three experimental halls (EHs)
  - Extensive overburden and muon veto system
  - Two near sites to sample flux from each reactor group
  - 3 detectors (60 T) at far site to increase statistics
  - Multiple detectors in EH1 to cross-check detector performance of functionally identical detectors

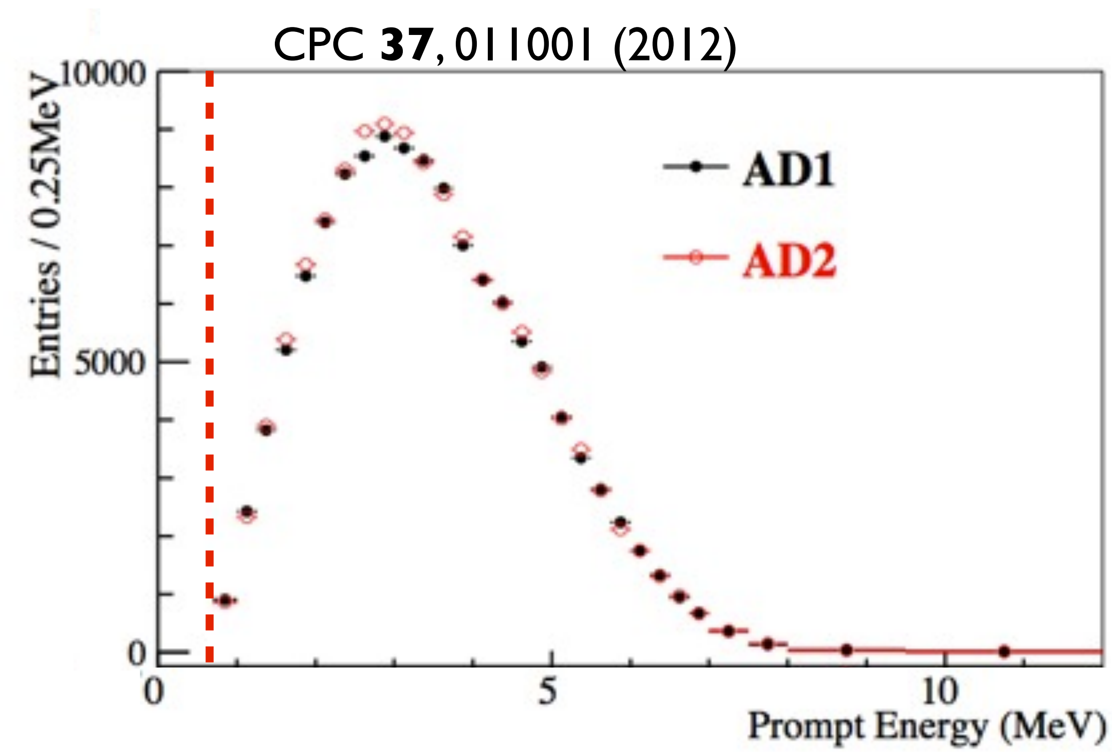
Detection Method: Inverse Beta Decay

- 0.1% Gd-doped liquid scintillator (GdLS) as an inverse-beta target

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



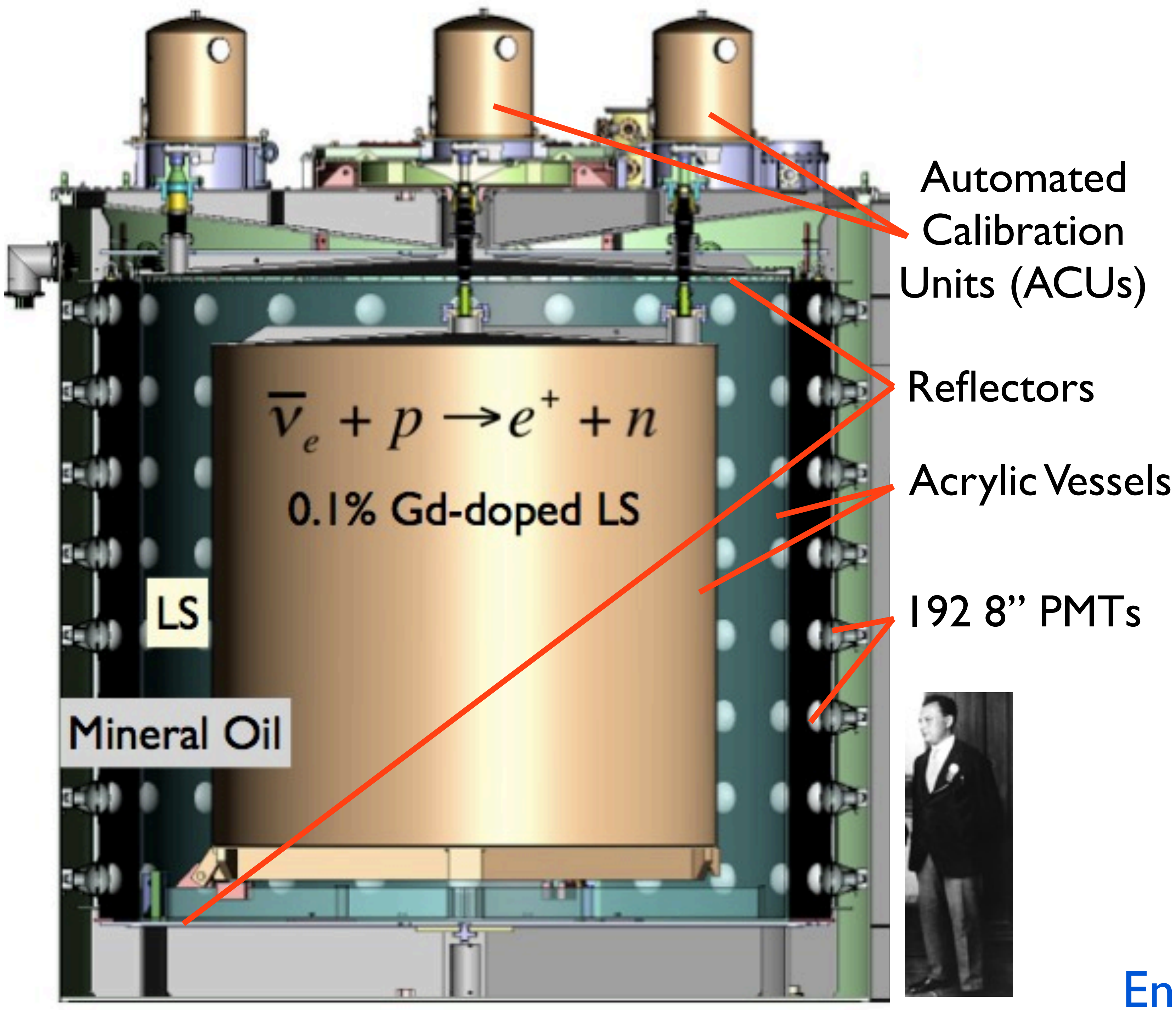


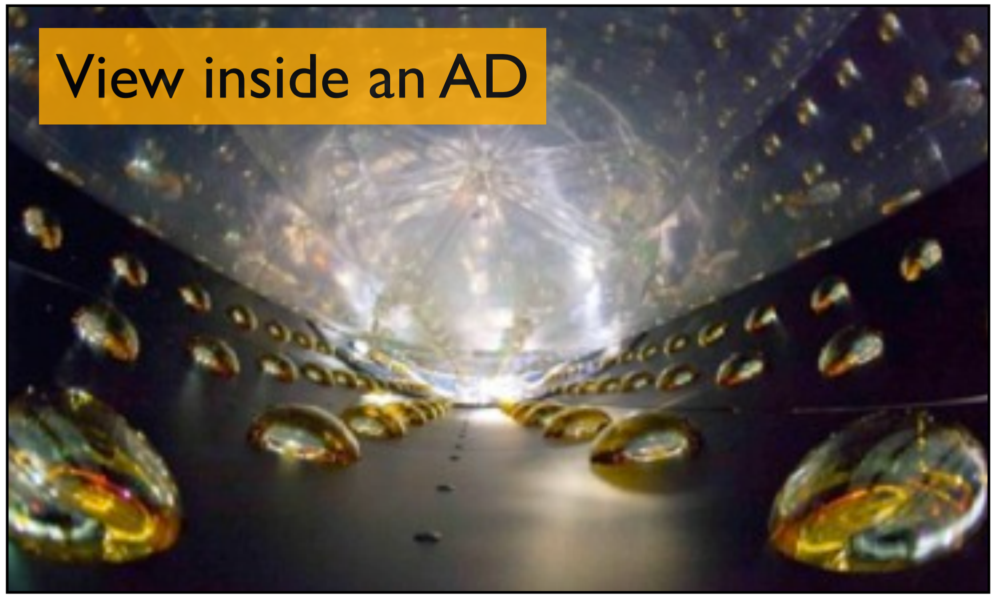


$$E_{e^+} = E_{\bar{\nu}_e} - 1.29\text{MeV}$$

The Daya Bay Antineutrino Detectors

8 deployed 'identical' 3-zone detectors

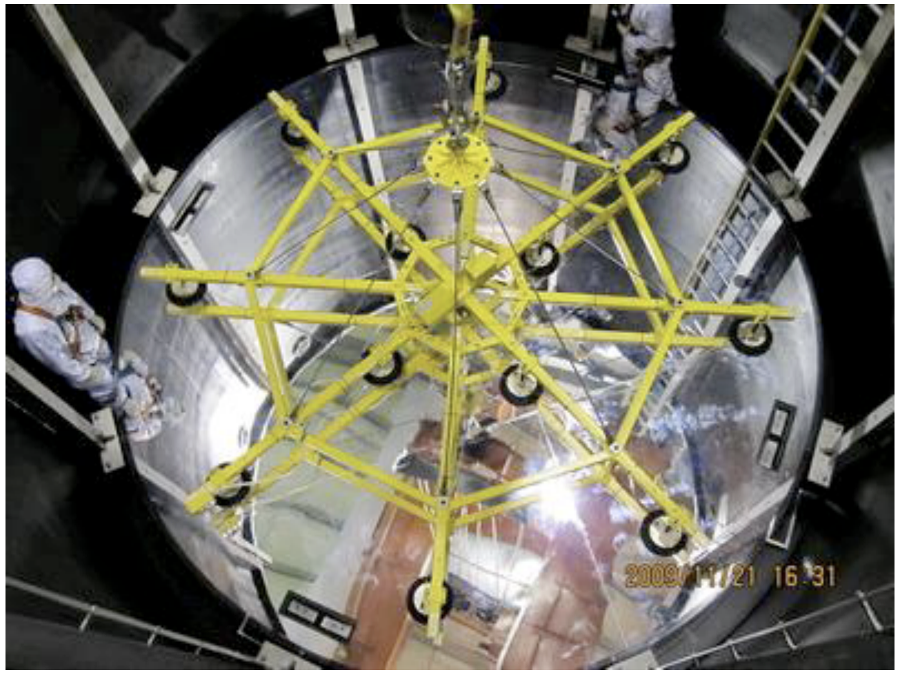




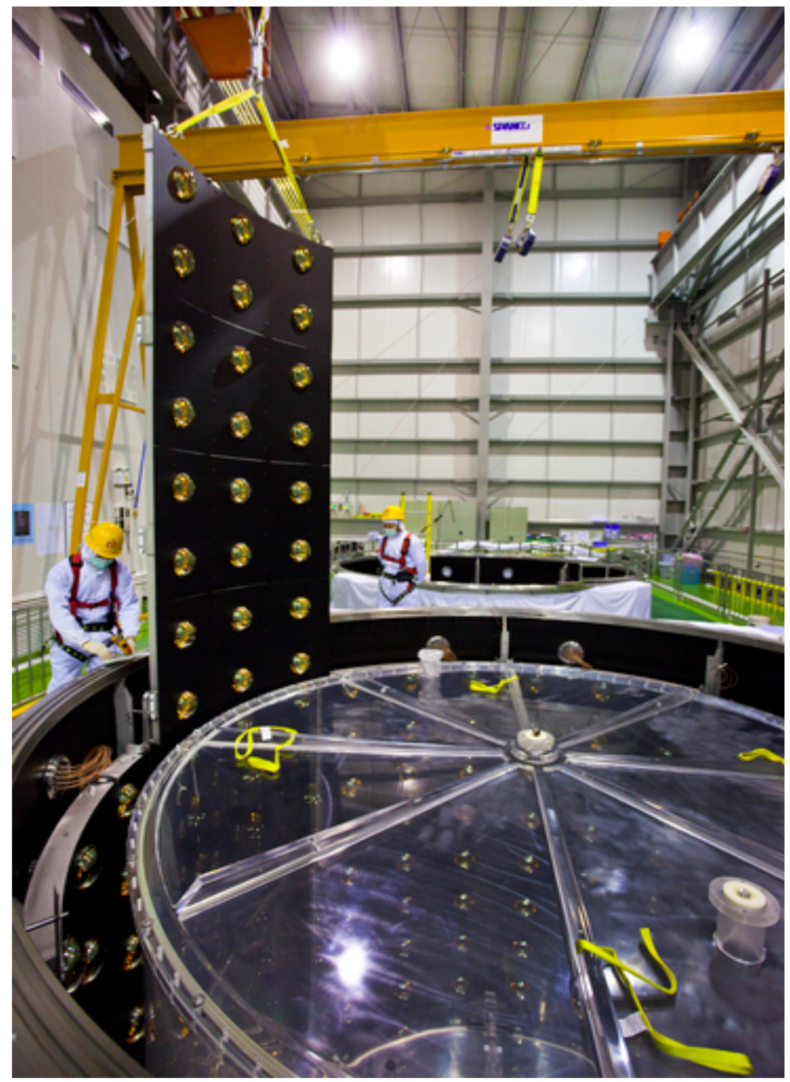
Target Mass: 20 tons
Energy Resolution: ~8%\√E
Light Yield: ~165 photoelectrons/MeV

Pictures of Construction

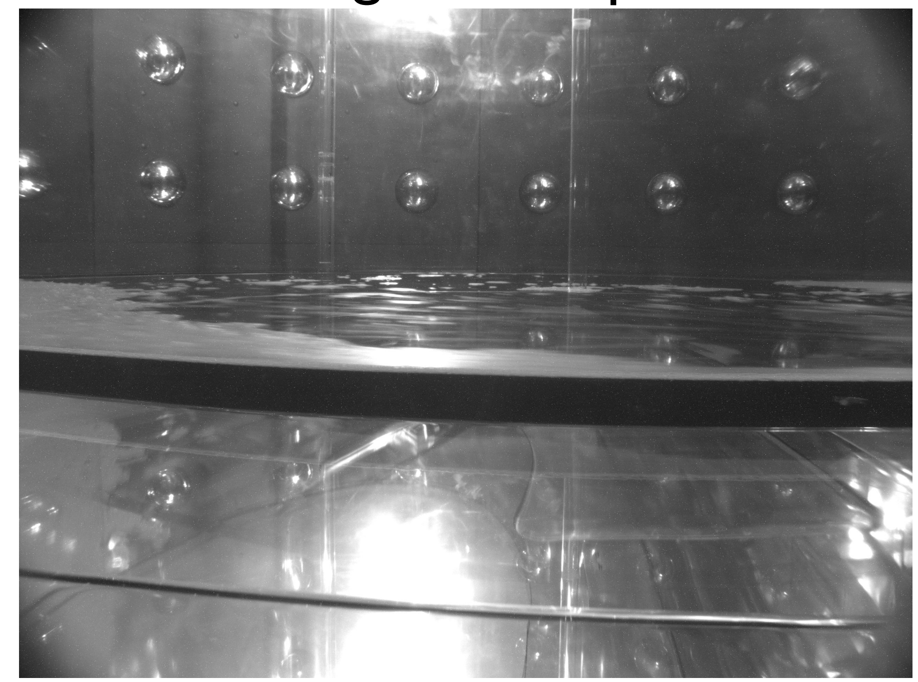
Installing Bottom Reflector



Installing PMT Ladders



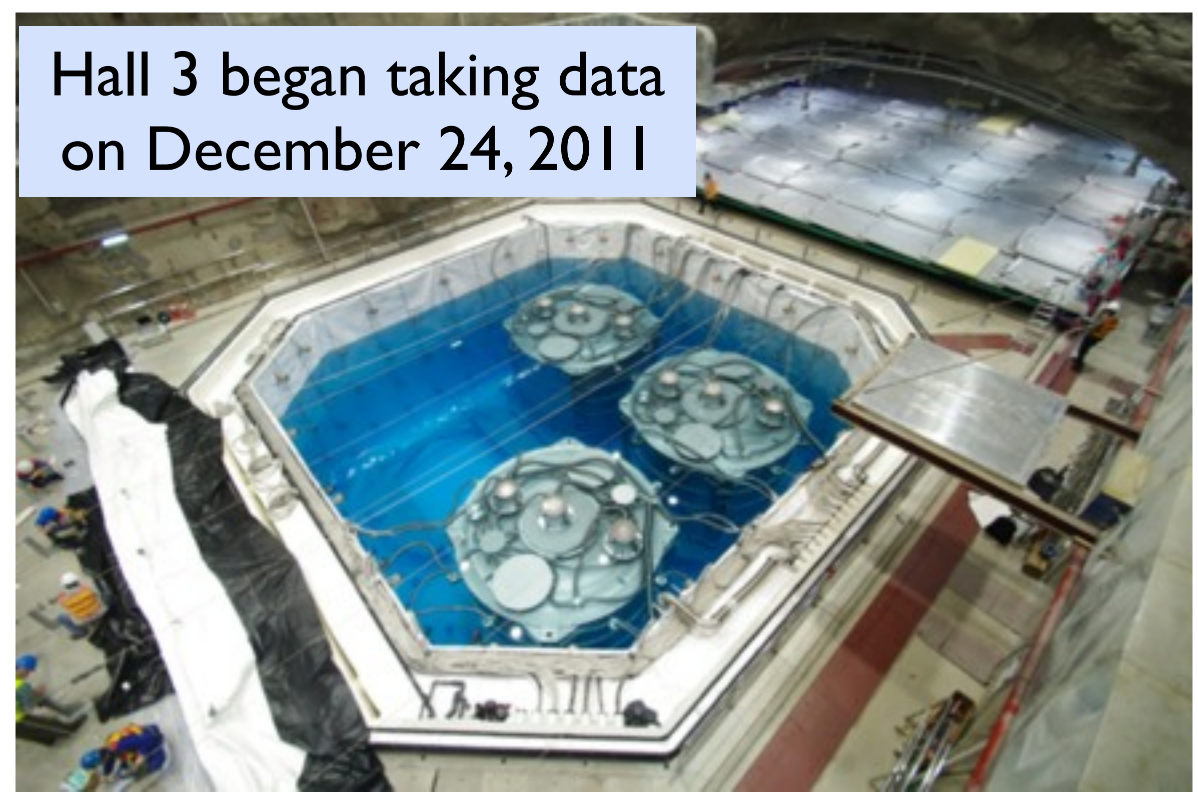
Filling With Liquid



Installing Outer Acrylic Vessel

Installing Filled Detector in Pool

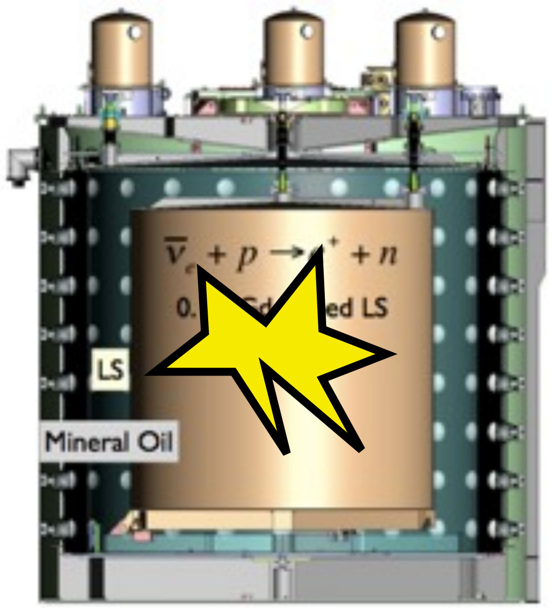
Daya Bay Experimental Halls



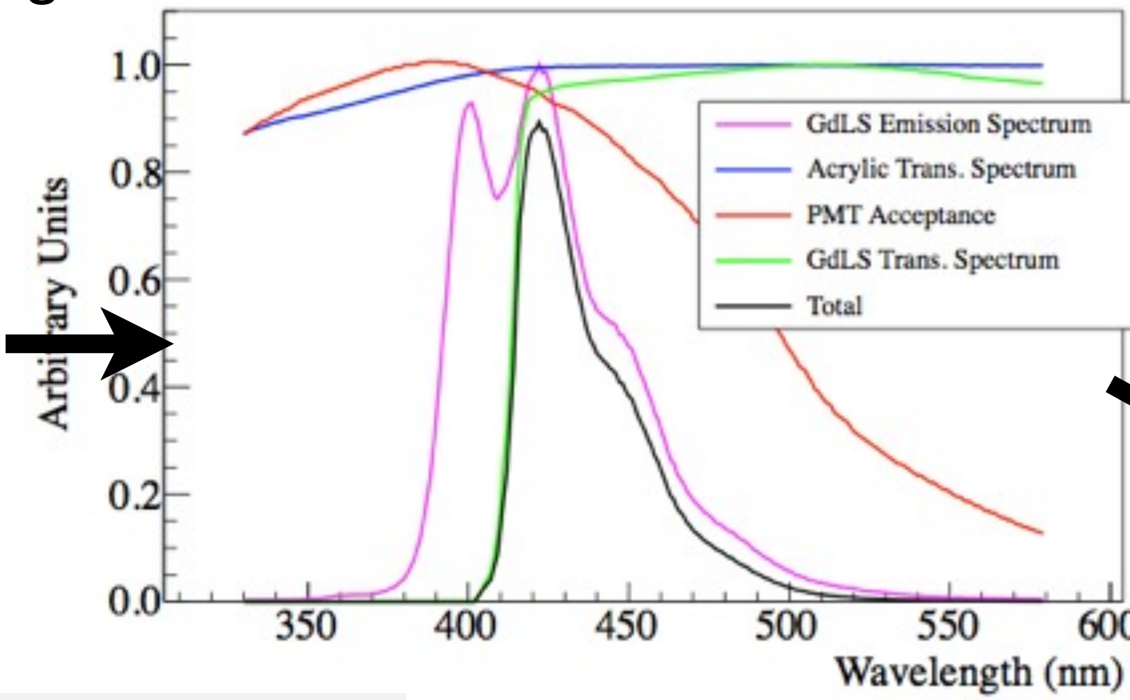
- Two more ADs installed in Summer 2012
- All published results use 6-AD dataset

Signal Extraction

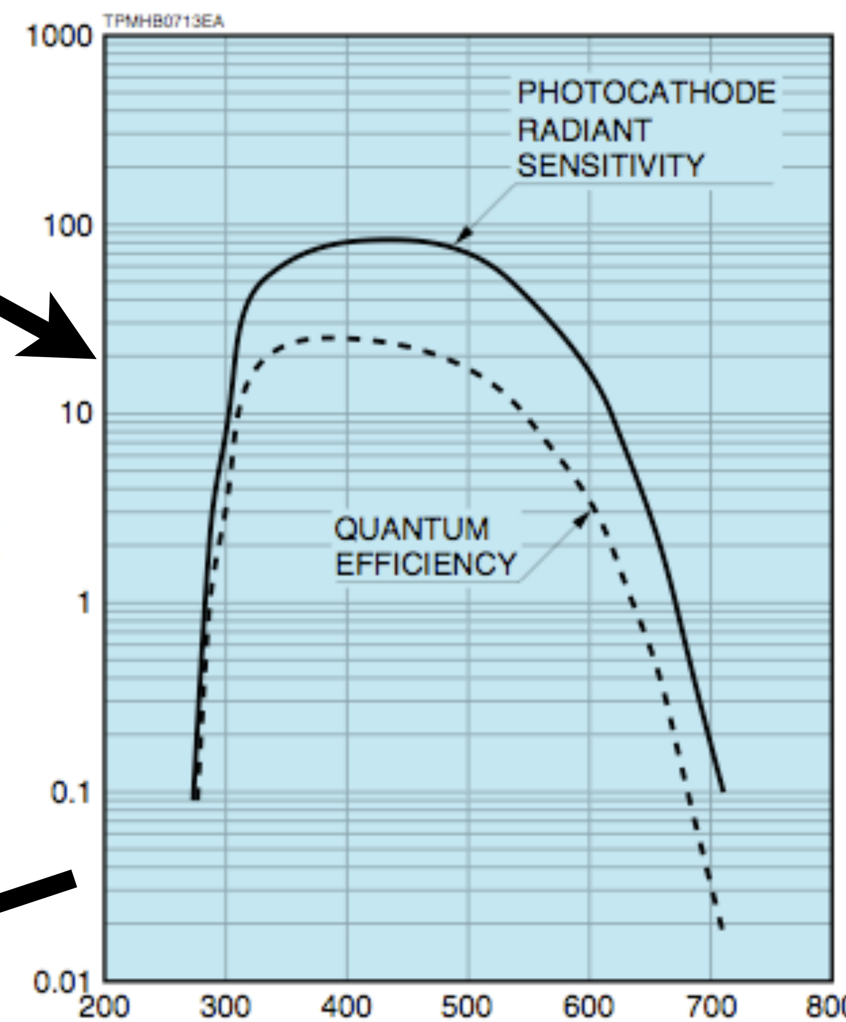
Interaction's positrons, neutron captures create light

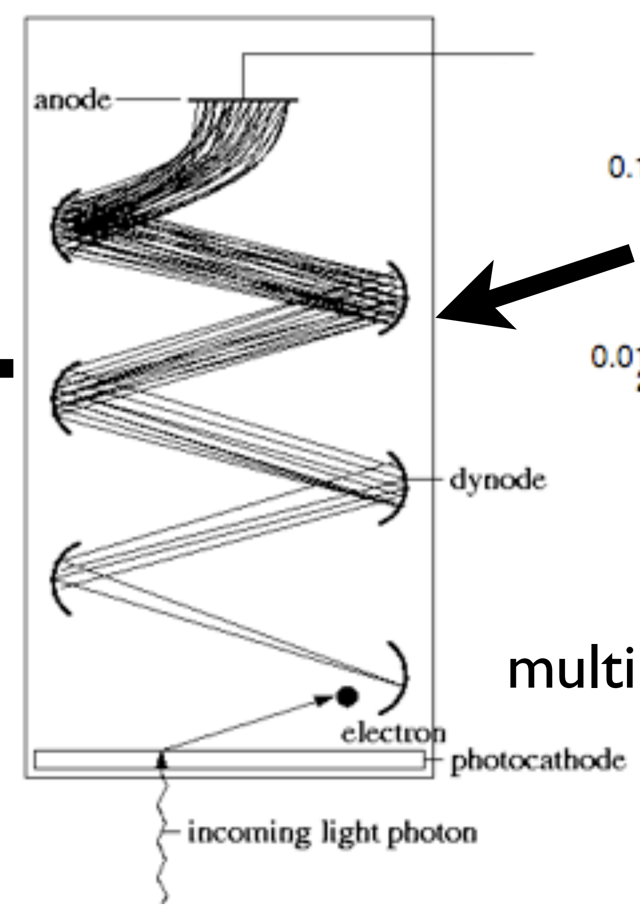


Light travels/absorbs in liquid

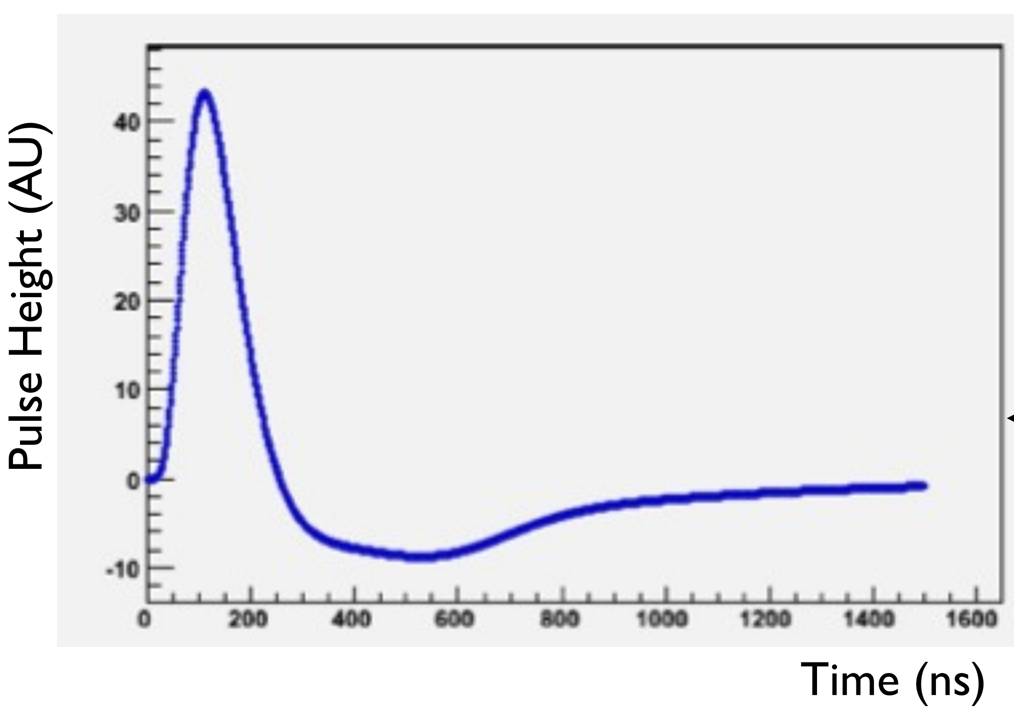


Photons make photoelectrons on PMT photocathode





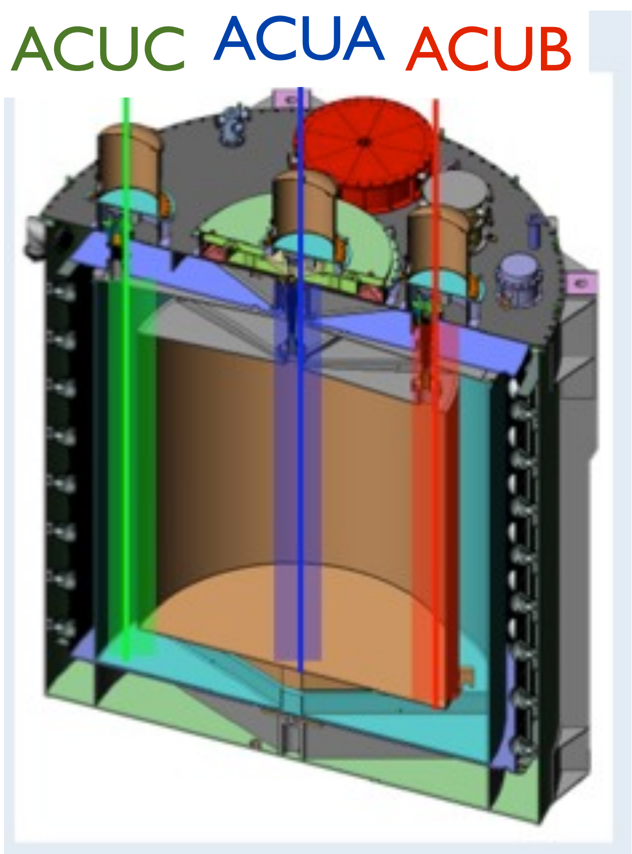
Electron signal is multiplied in PMT dynodes



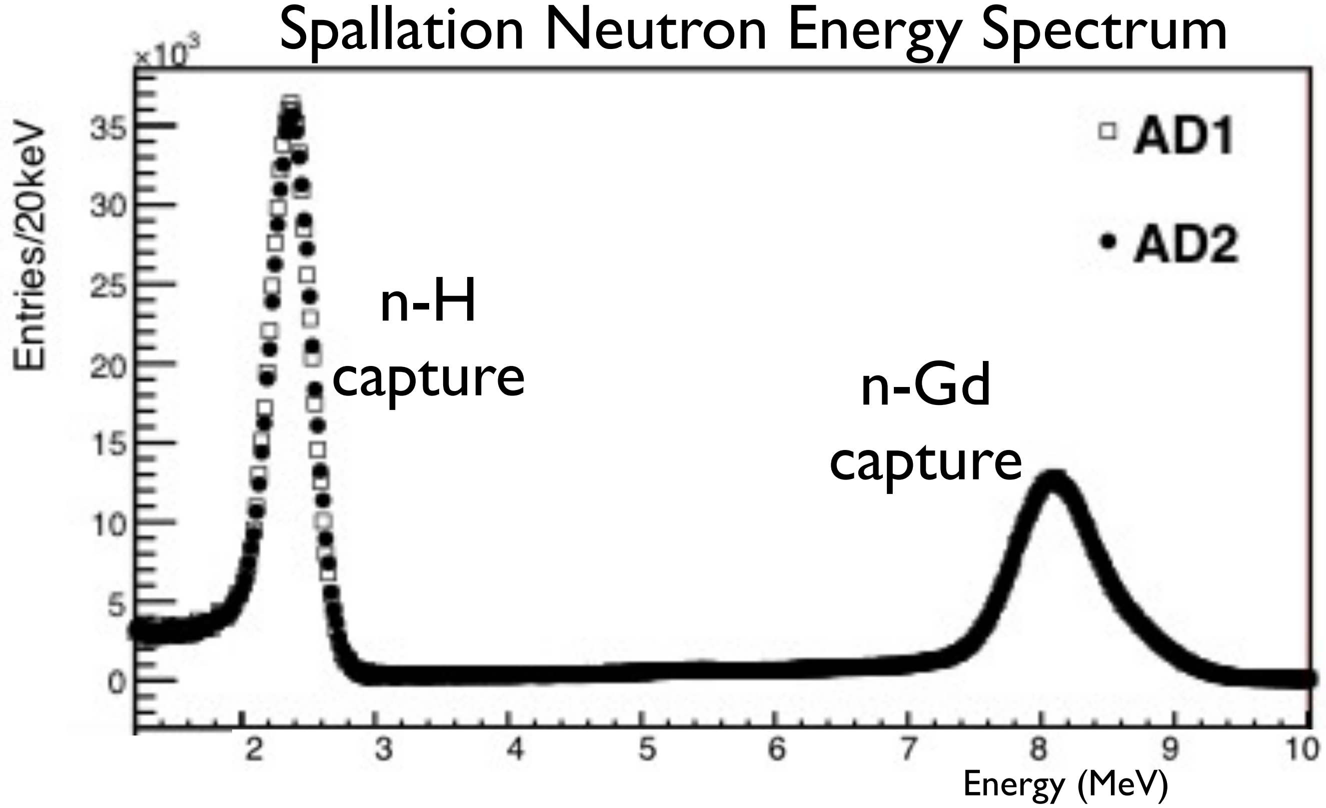
PMT signal is amplified, shaped, digitized to give total charge. If sum in all channels is high enough, trigger readout of data

Detector Calibration

- Weekly calibration unit (ACU) runs:
  - Gamma (Co-60, Ge-68) and neutron (AmC) sources
  - Low-intensity LED light source
- Muon-produced spallation neutrons
  - Uniformly distributed in AD, like IBD delayed signal
  - Neutron capture energy peaks, like IBD delayed signal
  - Will calibrate delayed energy cut with low uncertainty

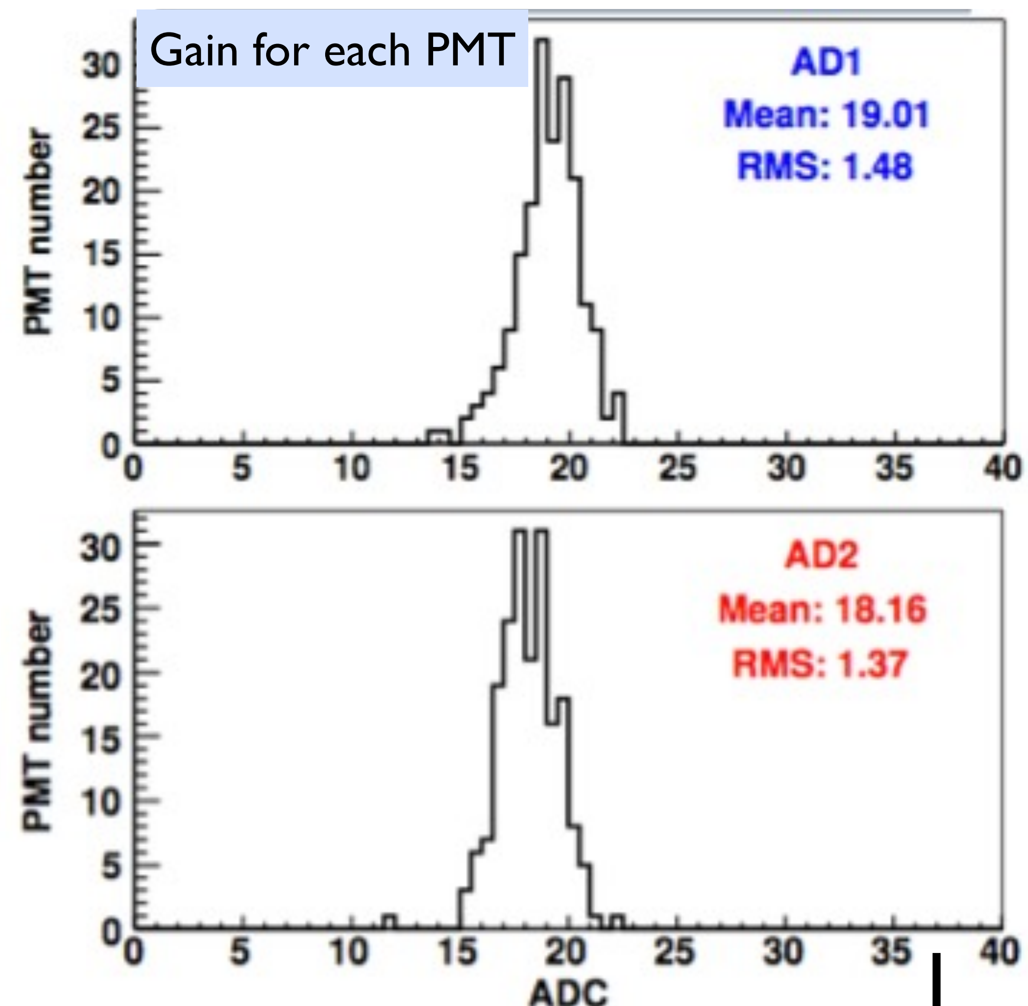


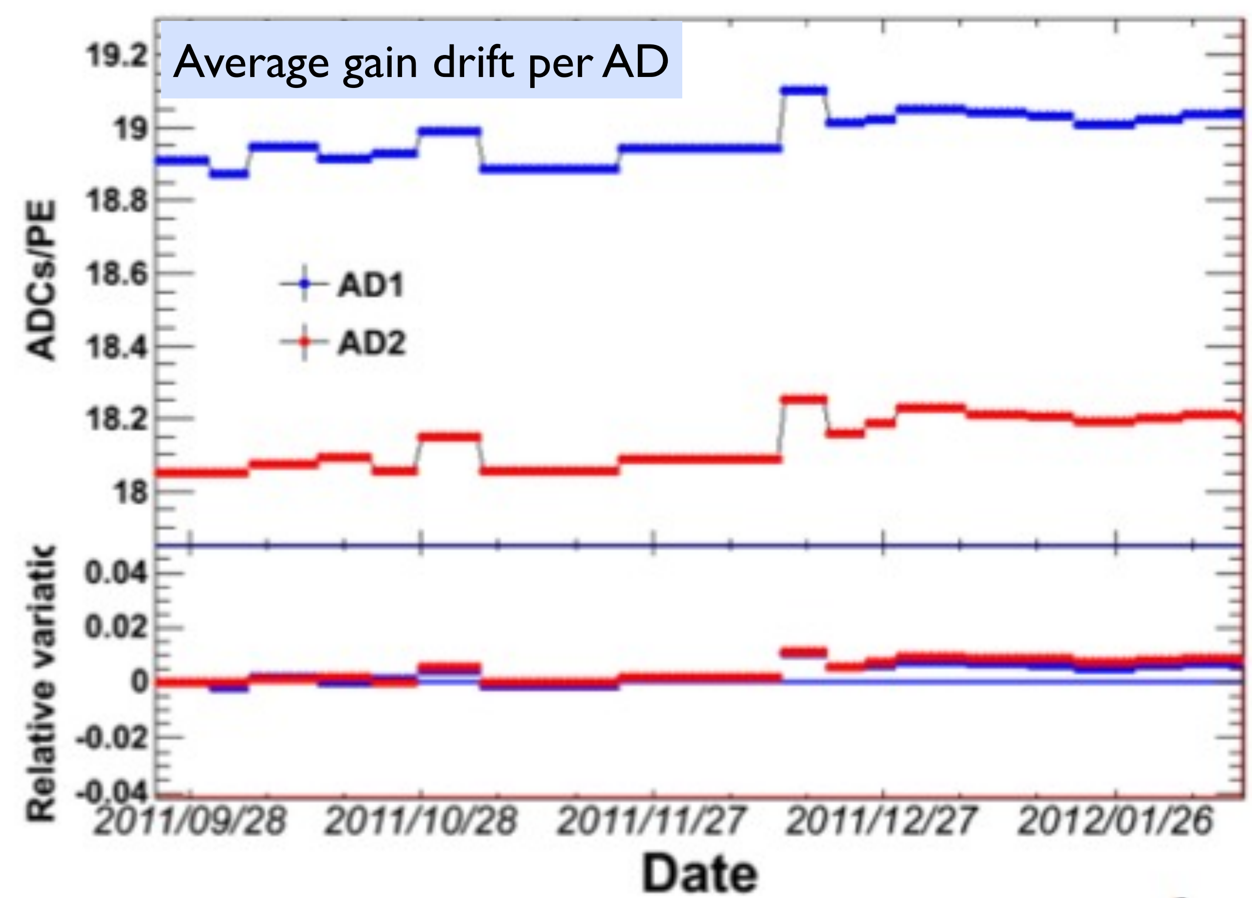
Spallation Neutron Energy Spectrum

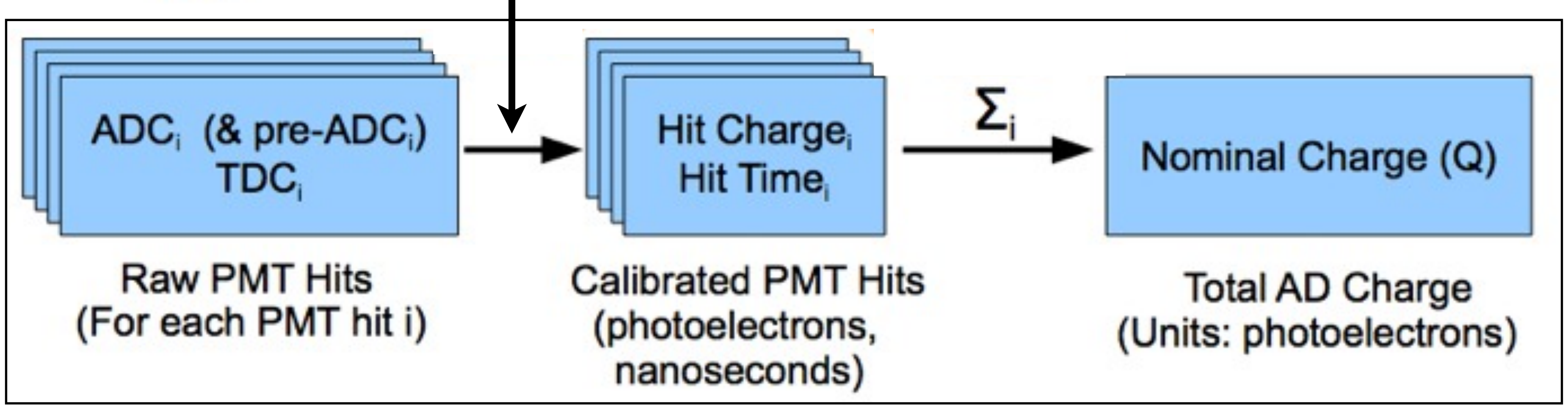


Calibration: PMTs and Electronics

- PMT calibration: removes time drift from PMTs and electronics
  - Calibrate voltage per photoelecton (gain): fitting PMT's single-photoelectron peak



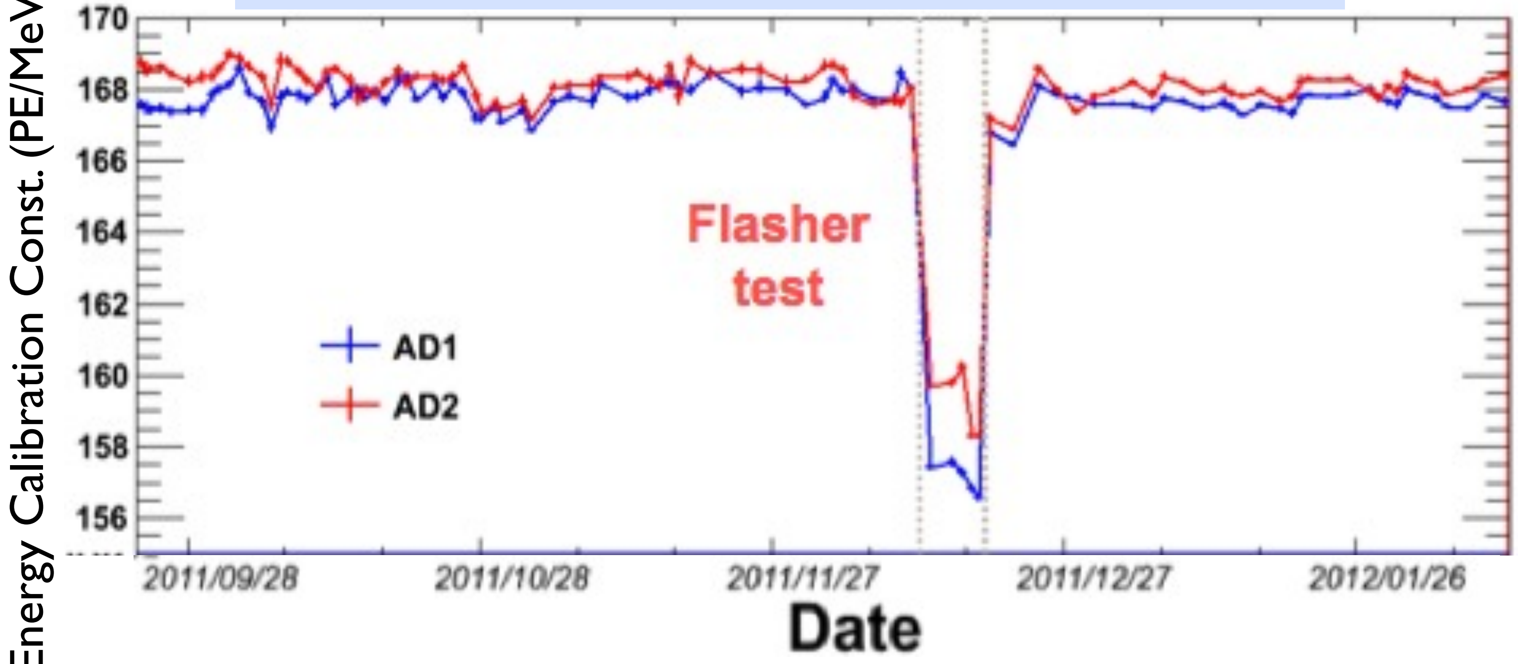




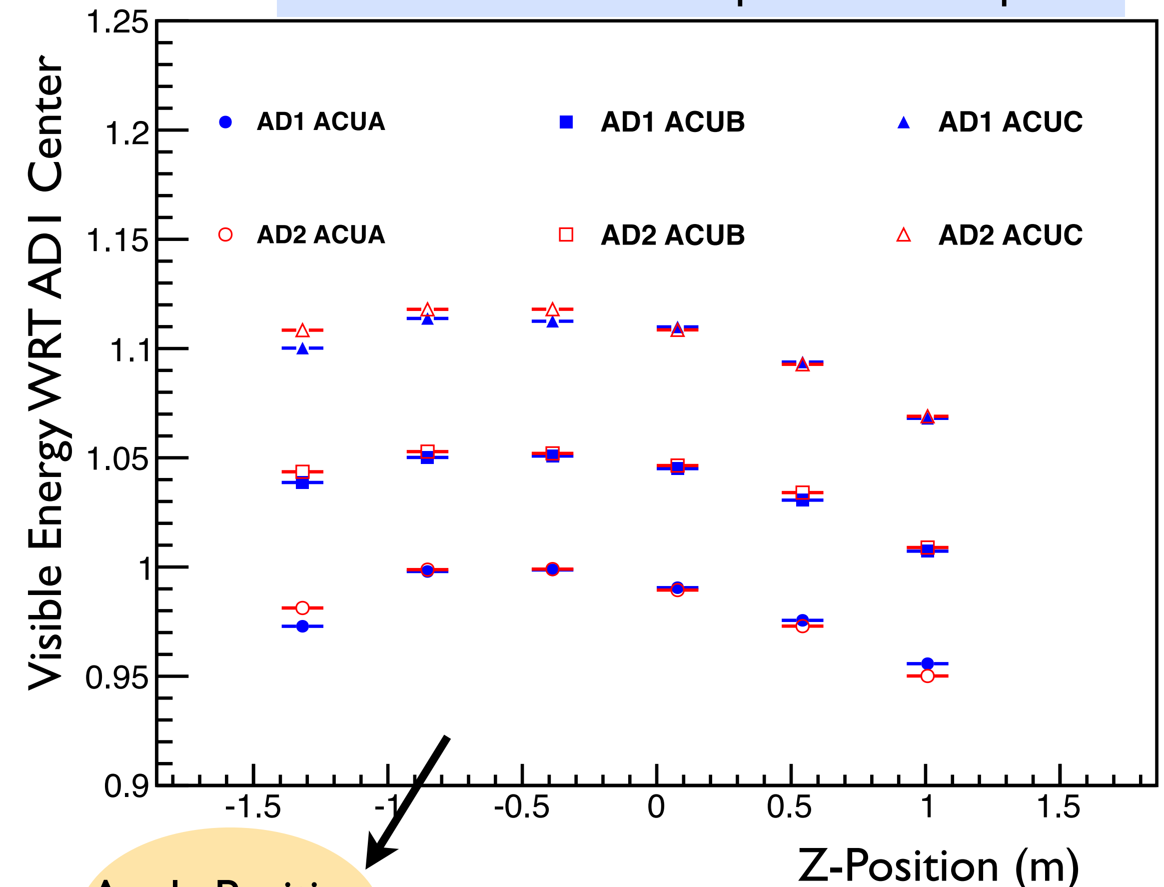
Energy Scale Calibration

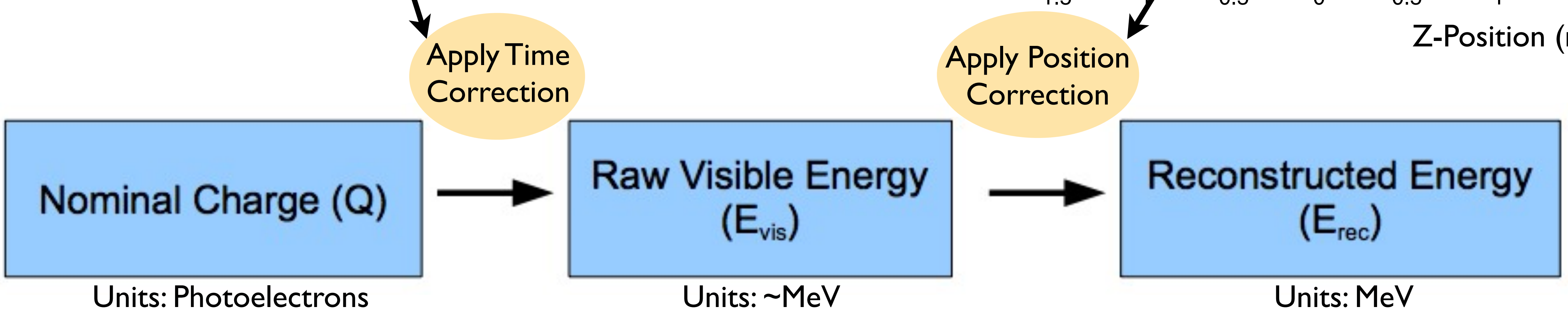
- Provides consistent measure of energy based on the 8MeV spallation n-Gd peak
- Removes position, time variations in light collection
- Allows for constant monitoring of energy scale during physics runs

energy constant time drift from spallation n-Gd peak



Position-variation of spallation n-H peak





Anti-Neutrino (IBD) Selection

- Use time coincidence between IBD prompt and delayed signals to select neutrino candidates

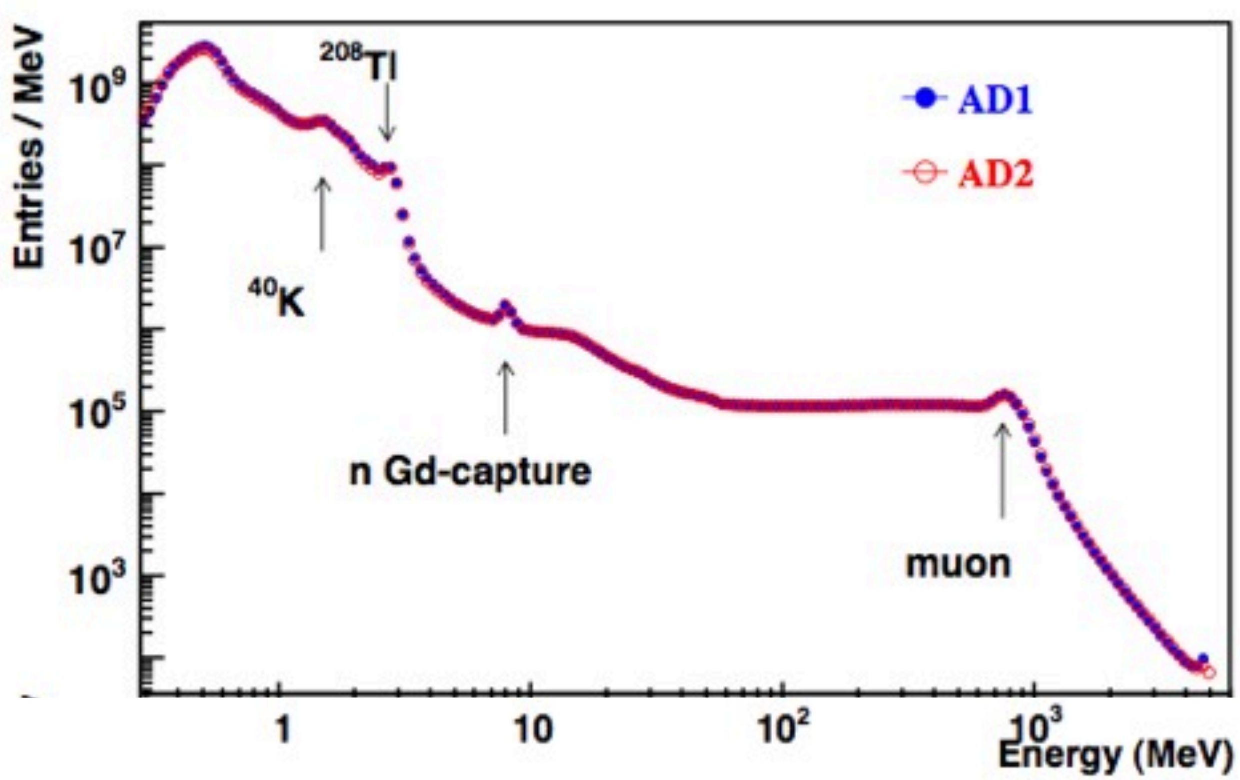
- Selection Cuts:
  - Reject Flashers
  - Prompt Energy: $0.7<E_p<12$ MeV
  - Delayed Energy: $6<E_p<12$ MeV
  - Capture time: $1 < \Delta t < 200$ μs
  - Muon Veto
    - Pool Muon: Reject 0.6 ms
    - AD Muon (>20MeV): Reject 1ms
    - Shower Muon (>2.5 GeV): Reject 1s
  - Multiplicity
    - No other signal >0.7 MeV within 200 μs of IBD signals
  - Spill-in/out Correction

- Remaining Backgrounds:
  - Uncorrelated Accidentals: two uncorrelated events 'accidentally' passing selection cuts
  - Correlated:
    - Muon Spallation: $^{8}He/^{9}Li$
    - Muon Spallation: Fast Neutrons
    - Correlated signals from $^{241}Am^{12}C$ source
    - Rn decay chains - negligible

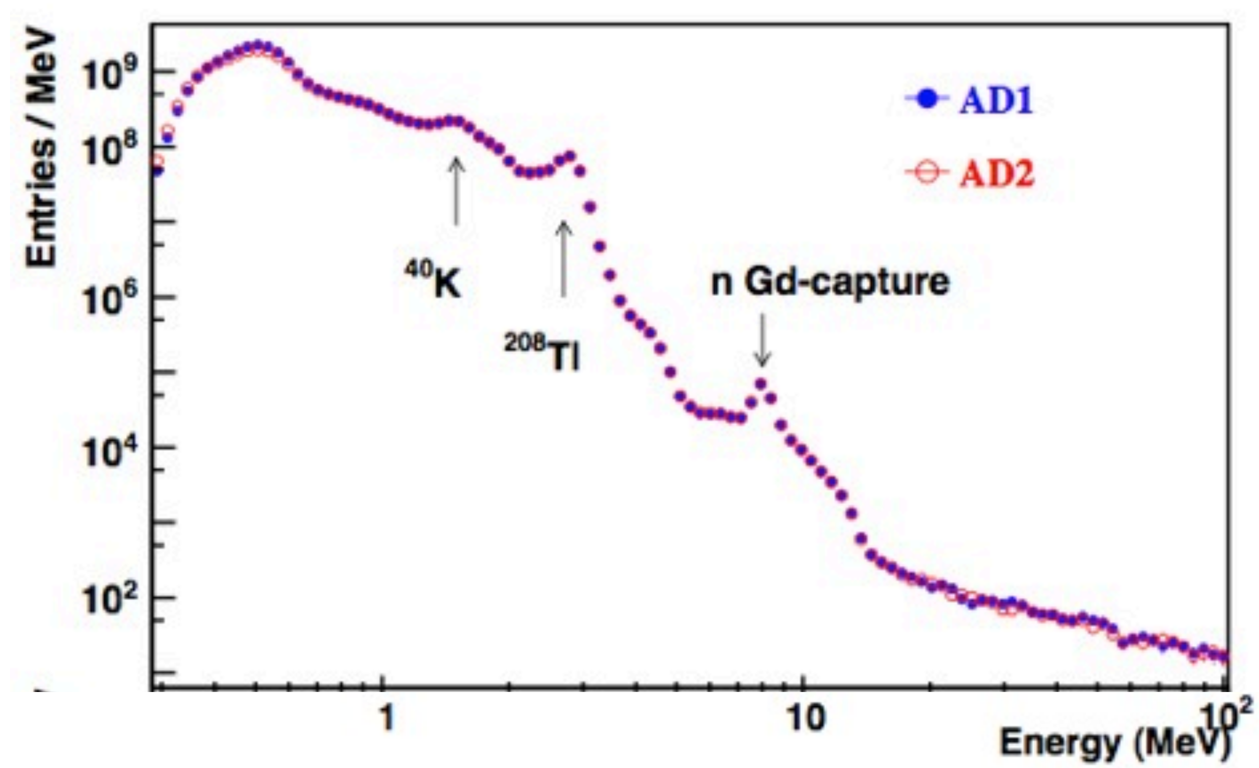
Anti-Neutrino (IBD) Analysis

- After calibration, we start an analysis with the following spectra:

All triggers, after preselection: >80 Hz

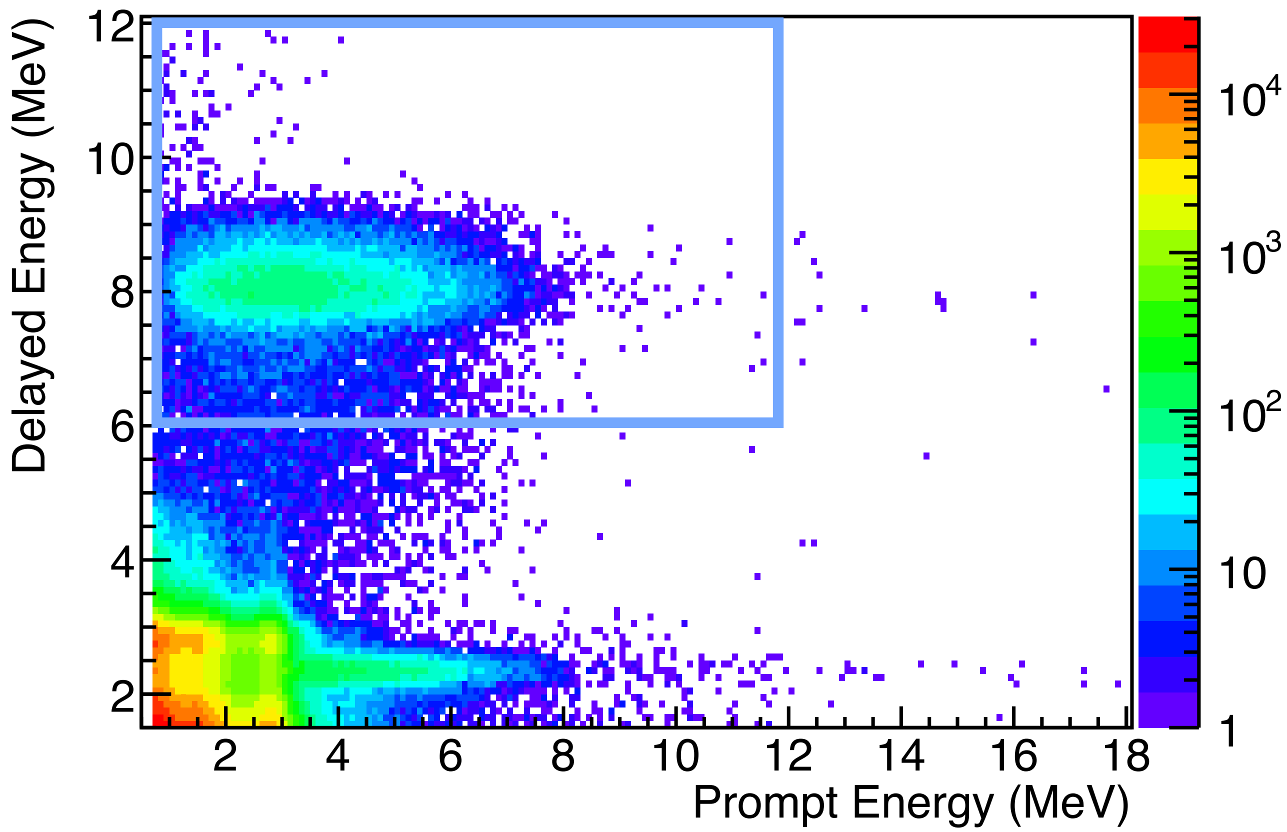


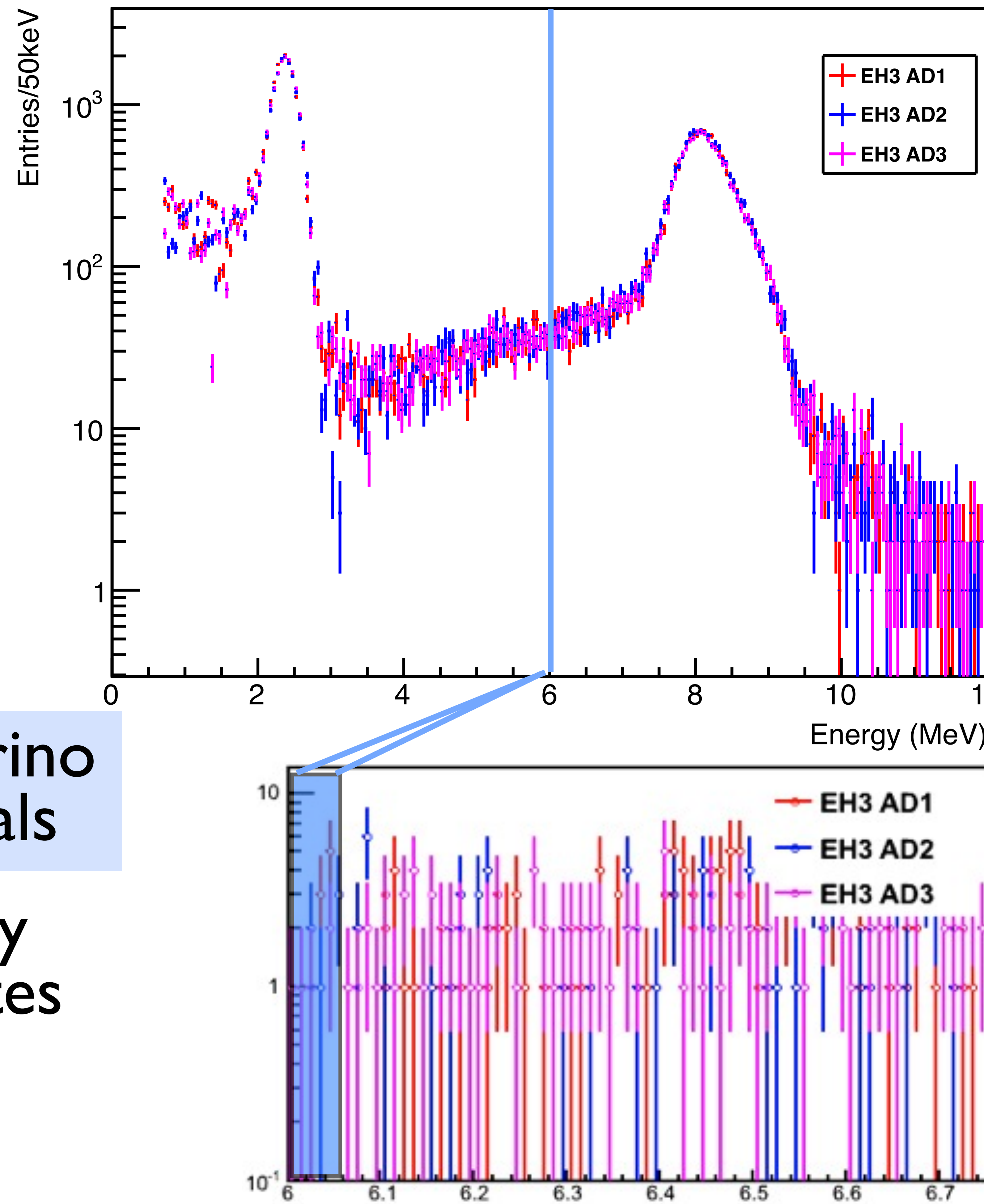
After muon veto: ~65 Hz (5.6 M daily triggers!)



Our task: pull IBD candidates out of this!
(~800/day at Near, ~80/day at Far!)

Major Factor: Energy Cuts





- Clear separation of antineutrino events from most other signals
- Relative efficiency uncertainty between detectors contributes largest systematic: 0.12%
    - A byproduct of 0.5% relative energy scale uncertainty

Summary of Inverse Beta Analysis

> 200k antineutrino interactions!

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763		126.2646	
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
$^{8}He/^{9}Li$ (/day)	2.9±1.5		2.0±1.1		0.22±0.12	
Am-C corr. (/day)	0.2±0.2					
$^{13}C(\alpha, n)^{16}O$ (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Consistent rates for side-by-side detectors

Uncertainties

- Dominated by statistical uncertainty at the far site: 1%

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	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%

F.P. An *et al.*, PRL 108 171803 (2012)

Can see the benefit of a relative measurement here

Background

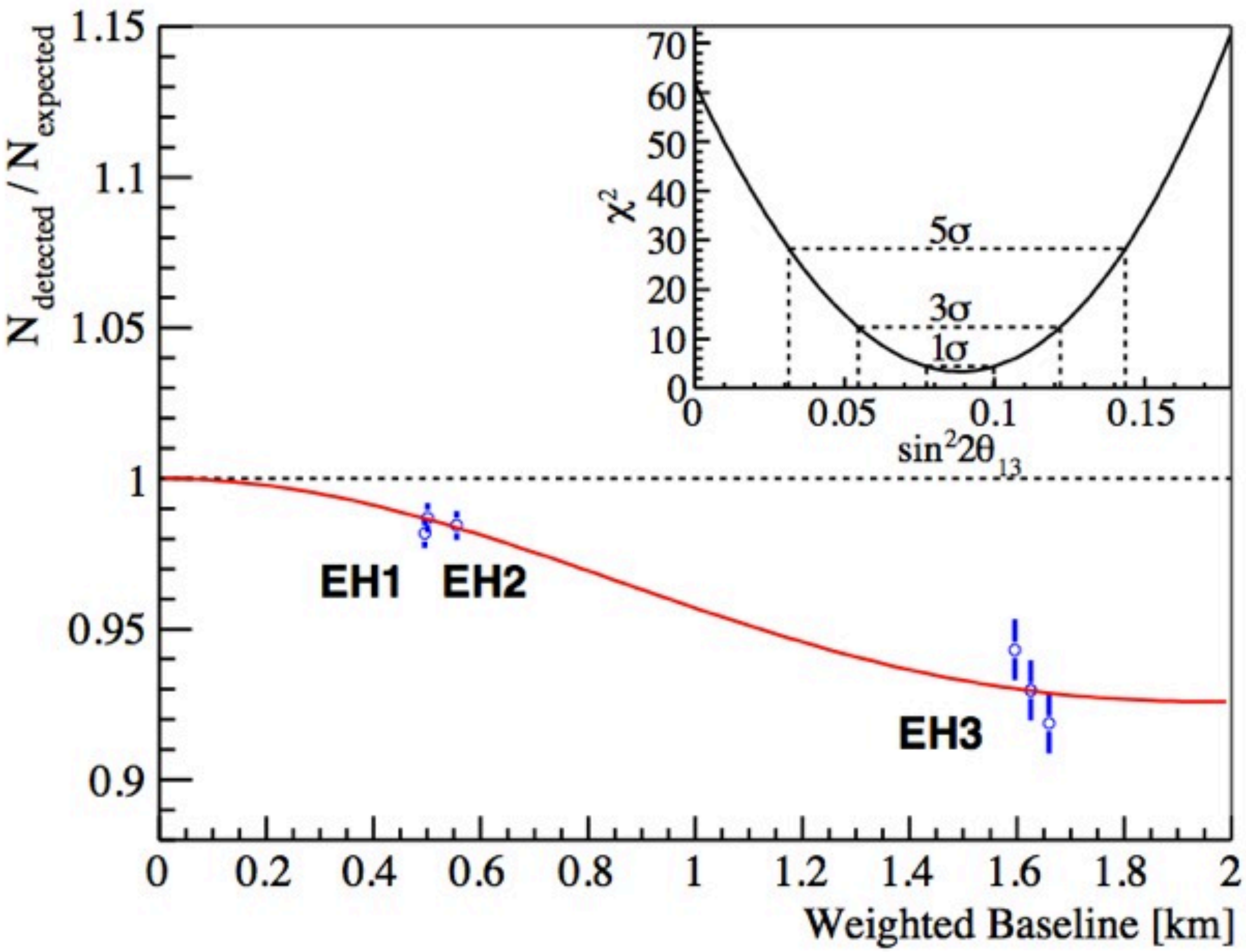
	Uncertainty (%)
Accidentals	0.1
^{8}He/^{9}Li	0.2
Fast Neutron	0.1
^{241}Am^{12}C Source	0.3
^{13}C(α,n)^{16}O	0.04

Note: Many backgrounds are correlated between detectors, and will contribute less than this to near-far systematics budget

- Reactor uncertainty contribution, near-far measurement: < 0.1%
- Baseline uncertainties: 0.02%

Rate Analysis

Estimate θ_{13} using measured rates in each detector.



Use standard chisquare fit method, utilizing nuisance parameters to account for systematic uncs.

Overall normalization is a free parameter, not utilized in fit

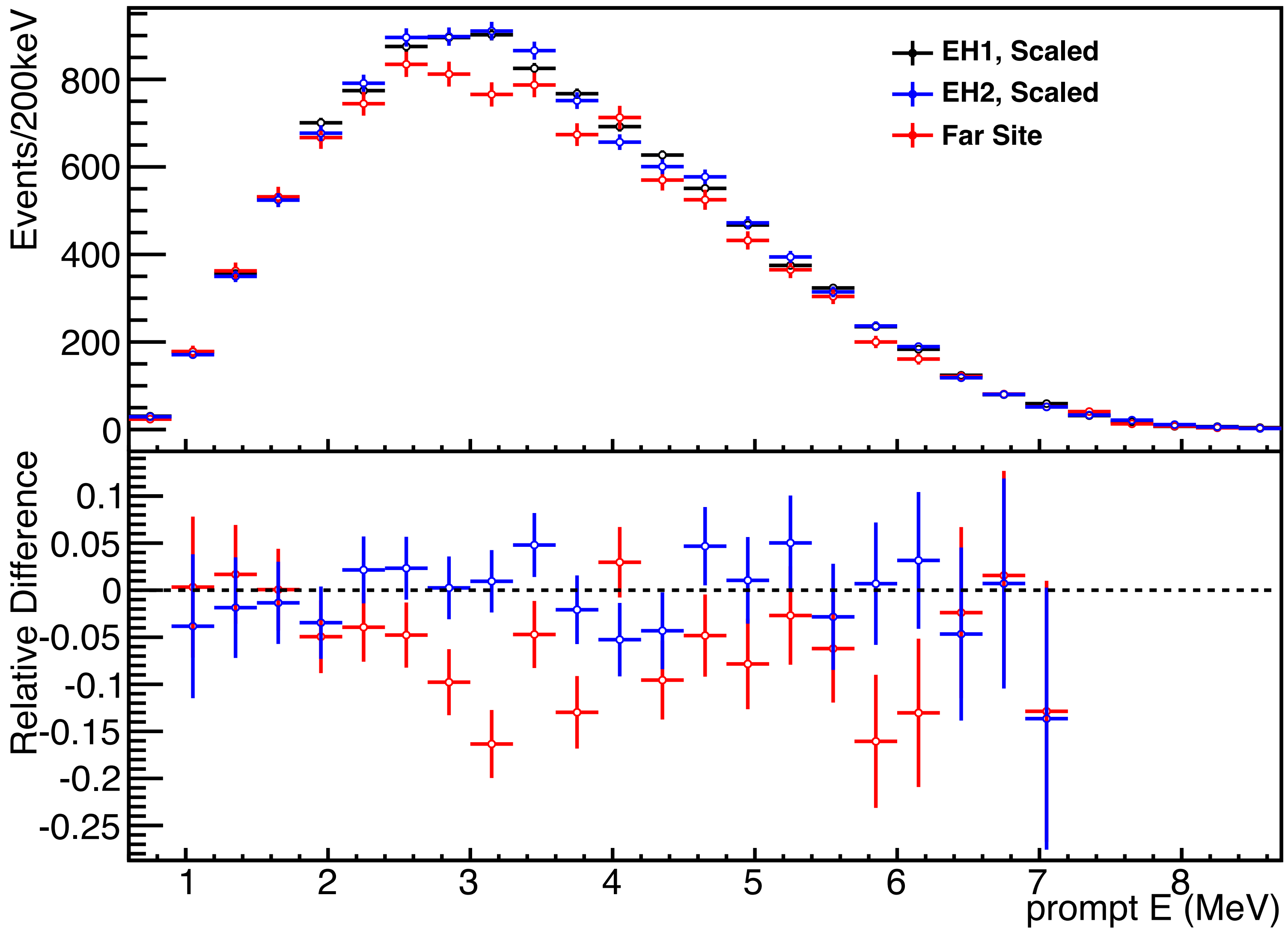
$\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$

The most precise measurement of $\sin^2 2\theta_{13}$ to date

CPC **37**, 011001 (2013), arXiv:1210.6327

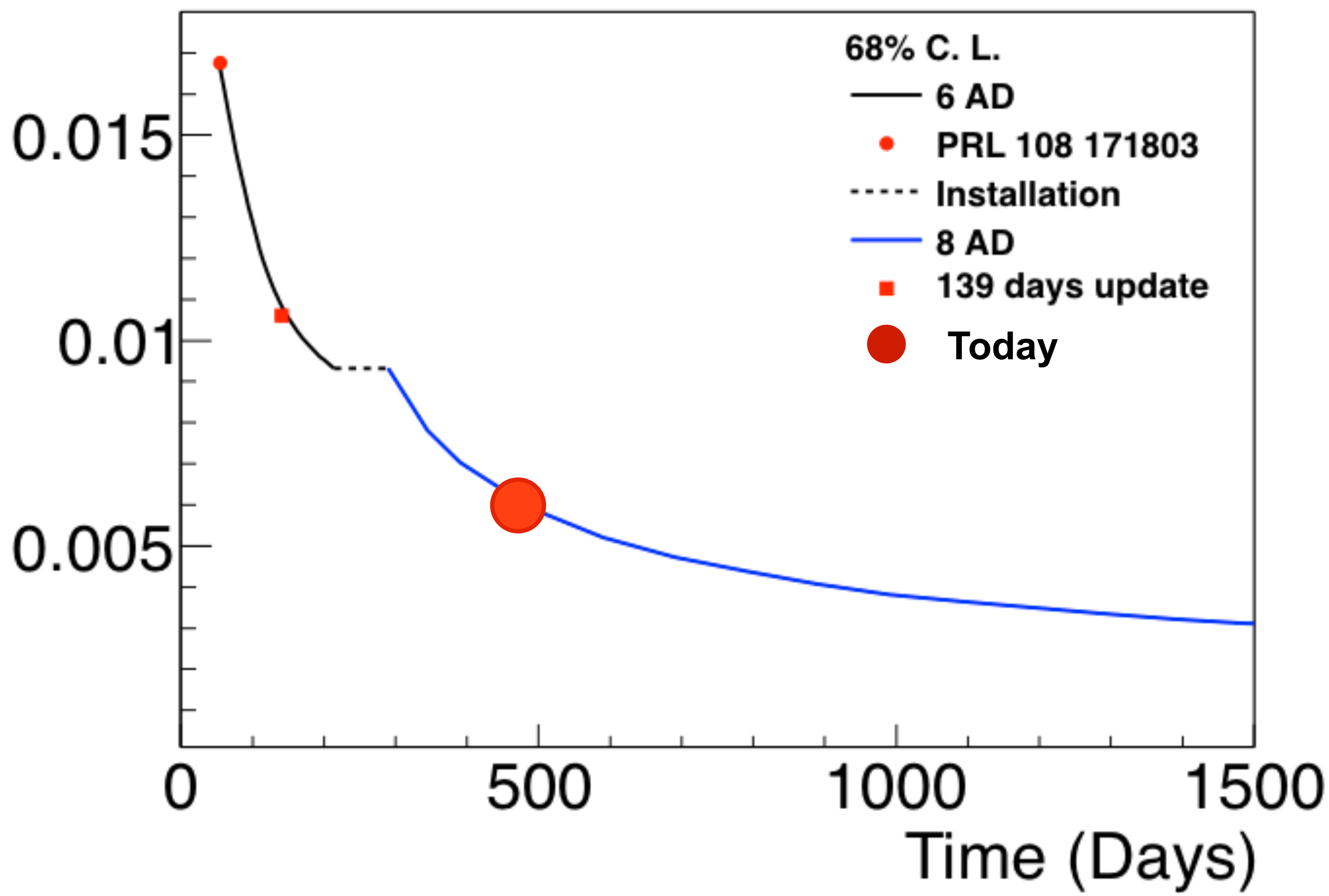
Spectral Measurement

- Clear hints of a spectral distortion in far hall
- Working on shape-based oscillation analysis; coming soon!
- Will provide further confidence in θ_{13} measurement
  - Also will provide $|\Delta m_{31}|$ measurement close to current best precision limits



Future Improvements

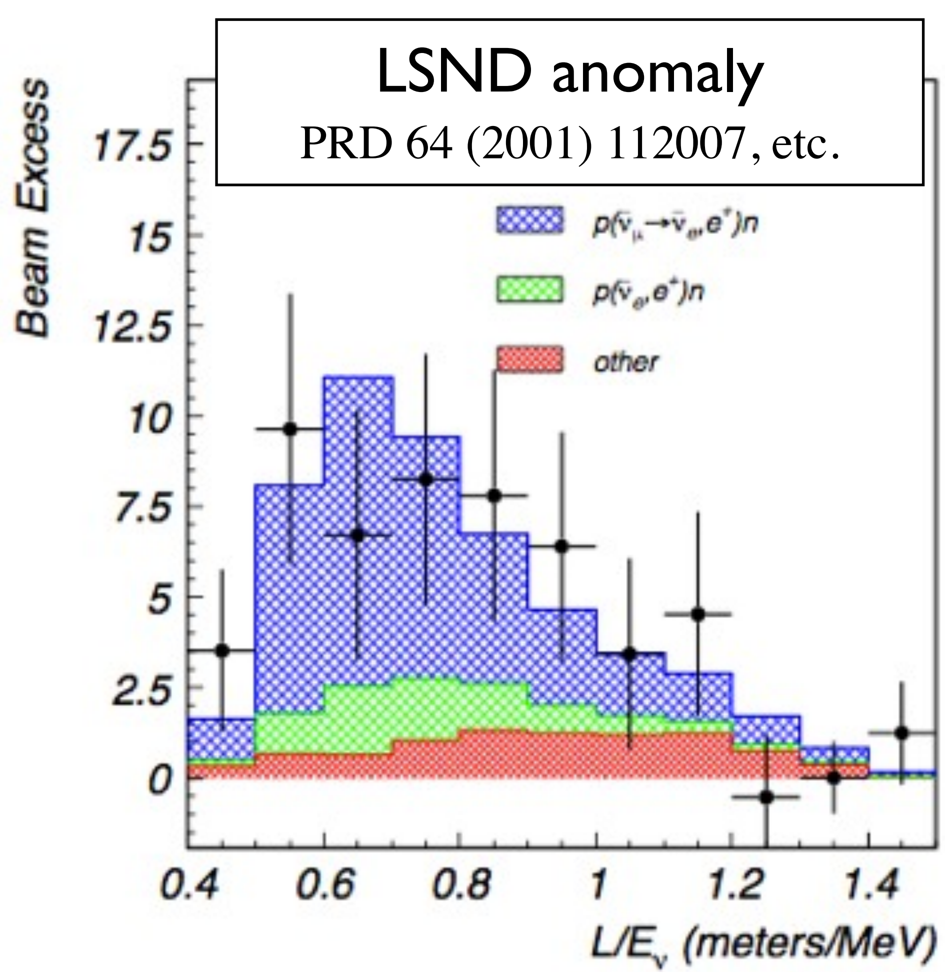
- Experiment is currently statistics-limited, so precision will improve greatly in following years
  - Extra precision helps future experiments' abilities to see CP-violation
- Absolute reactor spectrum shape and flux measurement will also be done; useful to nuclear physicists

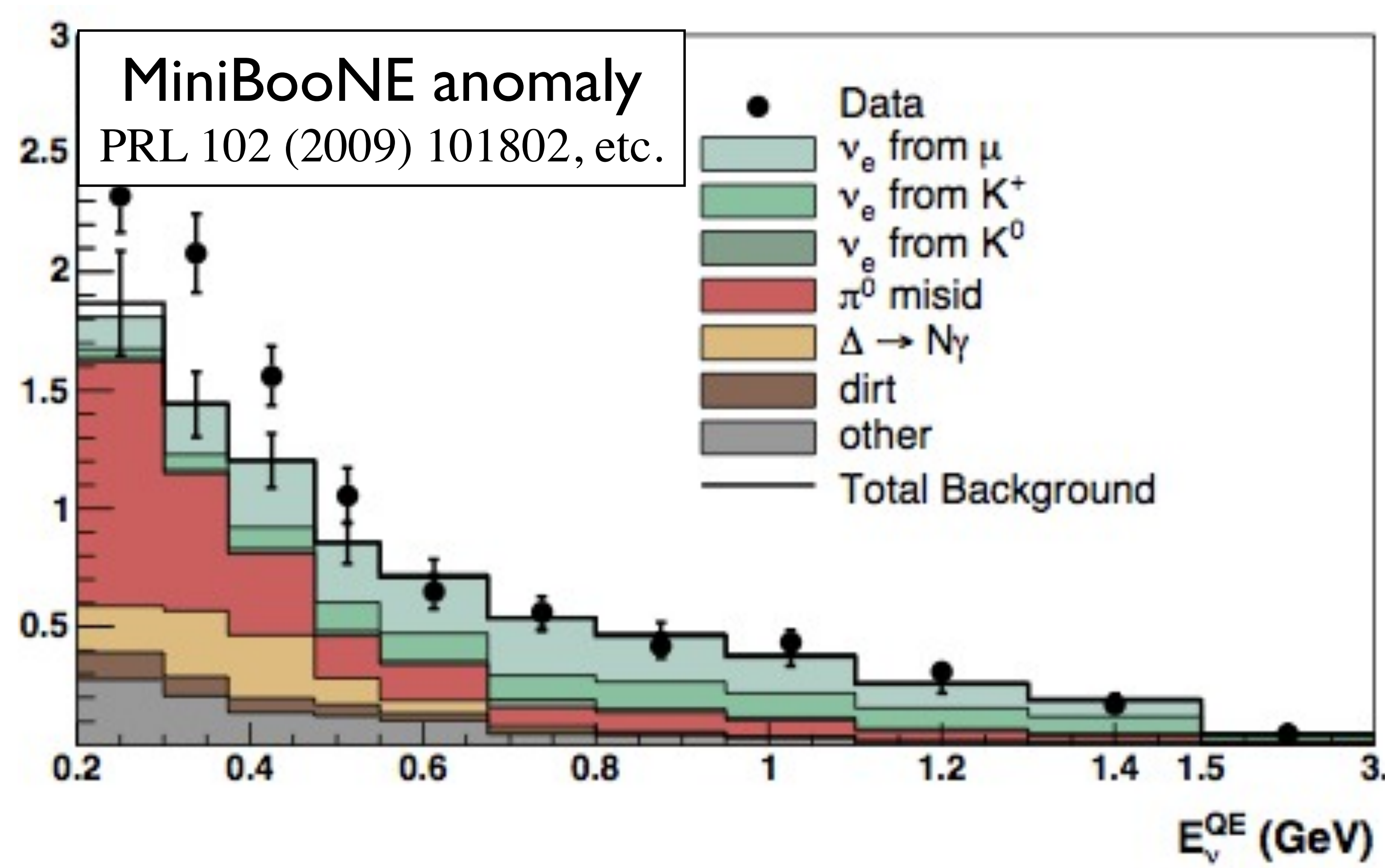


More Neutrinos?

Some Unanswered Questions

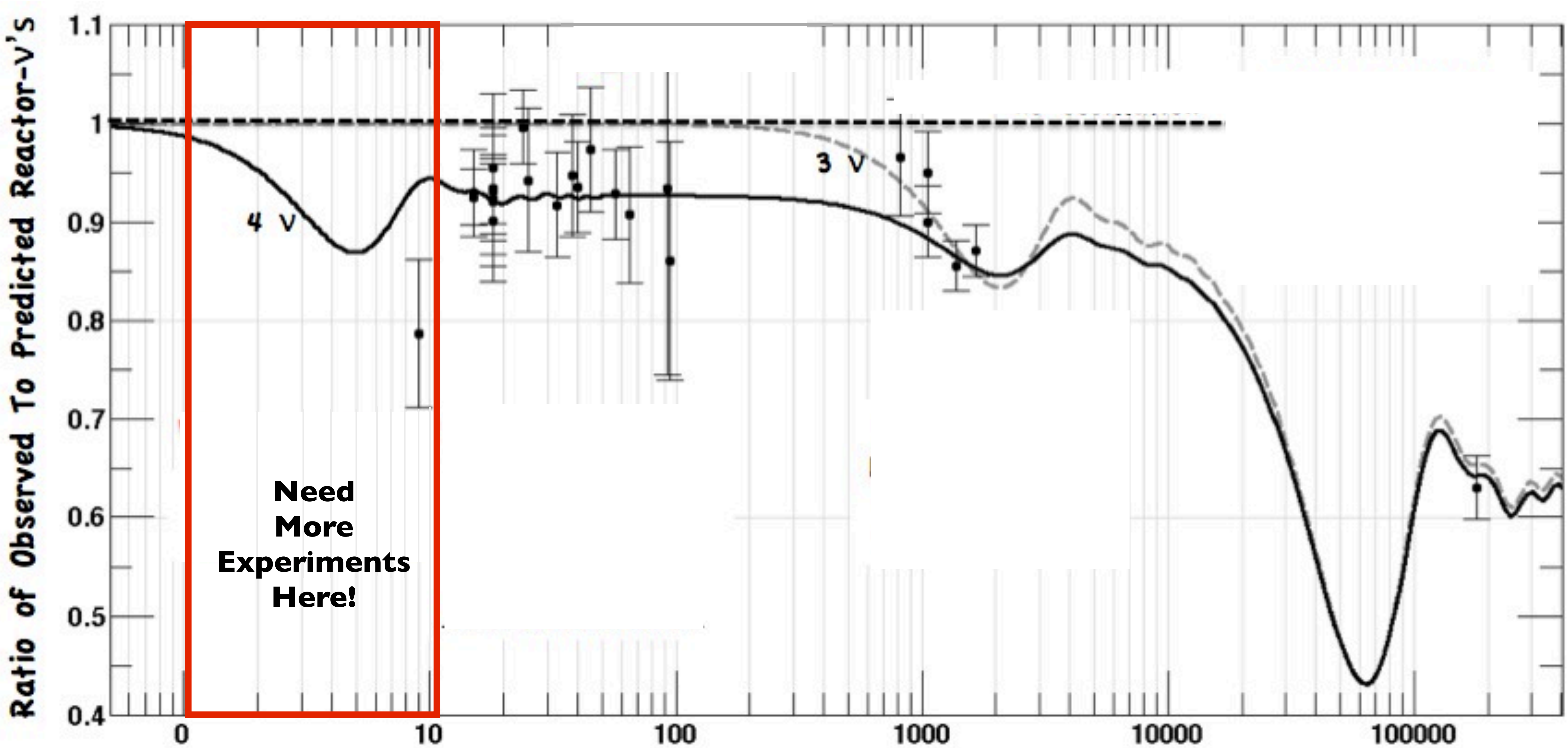
- LSND: Pure $\bar{\nu}_\mu$ source, but detect $\bar{\nu}_e$ in detector even though L/E is not right for oscillation...
  - MiniBooNE: Same, but also with ν_μ to ν_e!
  - Mass-splittings around 1eV^2 suggested
- Collider experiments: can't just be another normal neutrino
- Would have to be sterile: can't interact with other SM particles





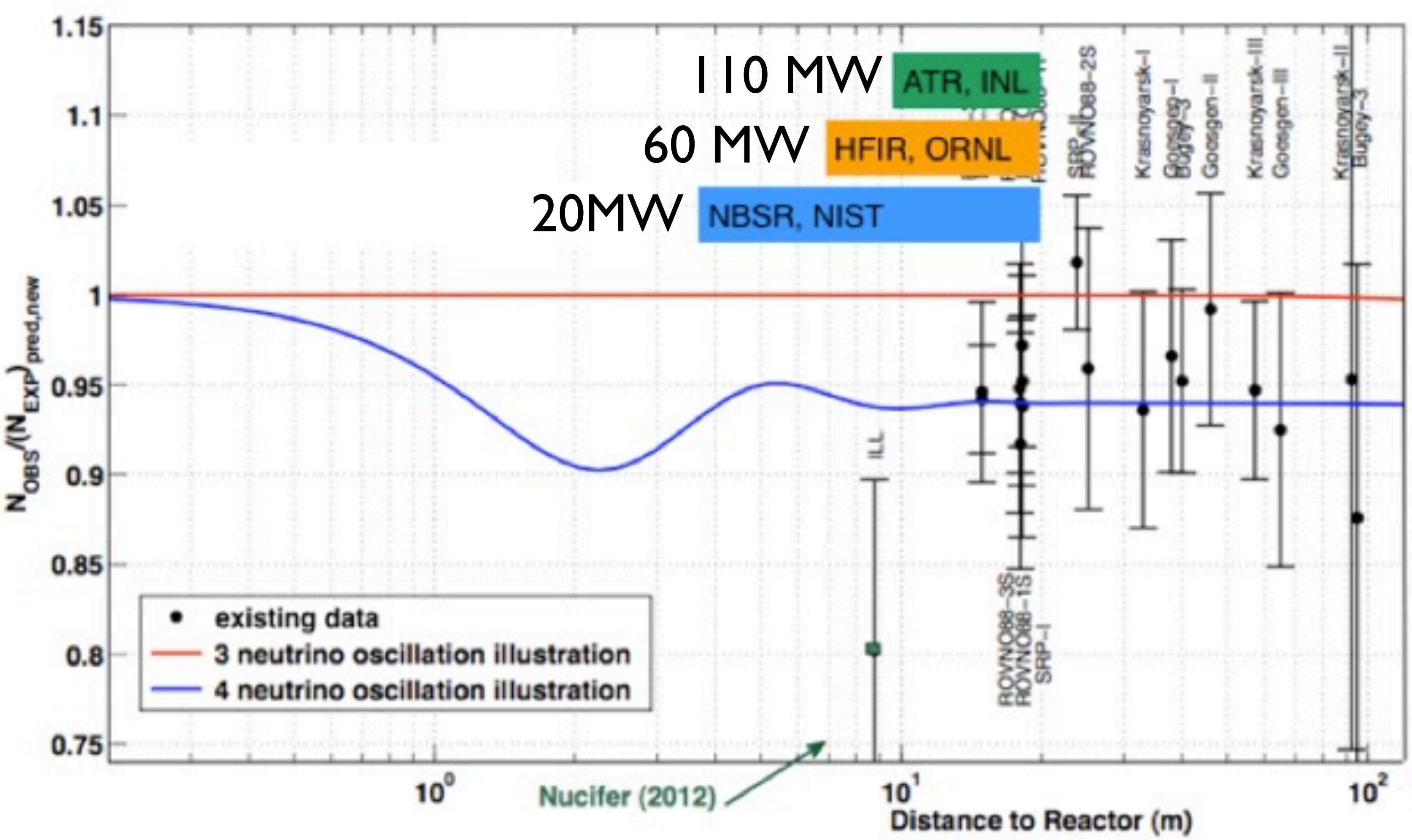
Critical Mass: The Reactor Anomaly

- Also a deficit between expected and detected reactor fluxes!
  - Could happen if an additional eV-scale neutrino existed



US Reactors: Sites

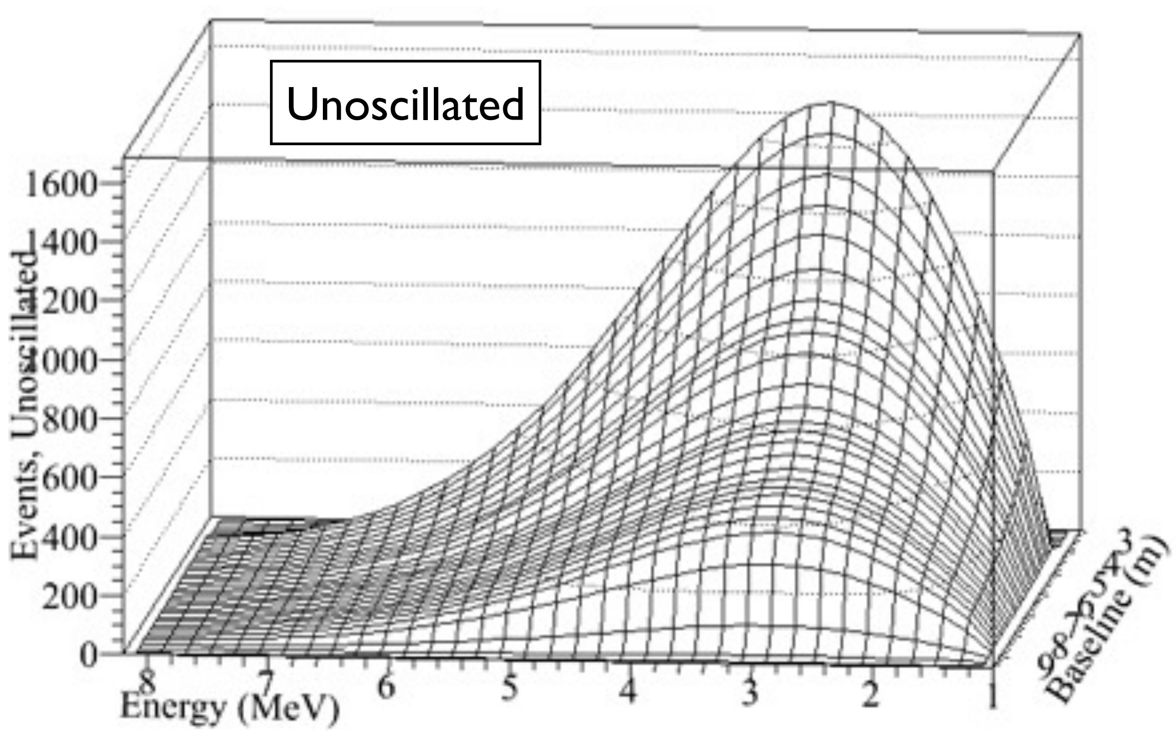
- Good candidate reactor sites in US
- Needs:
  - Small core size: research reactors
  - High power for more statistics
  - Close proximity to core

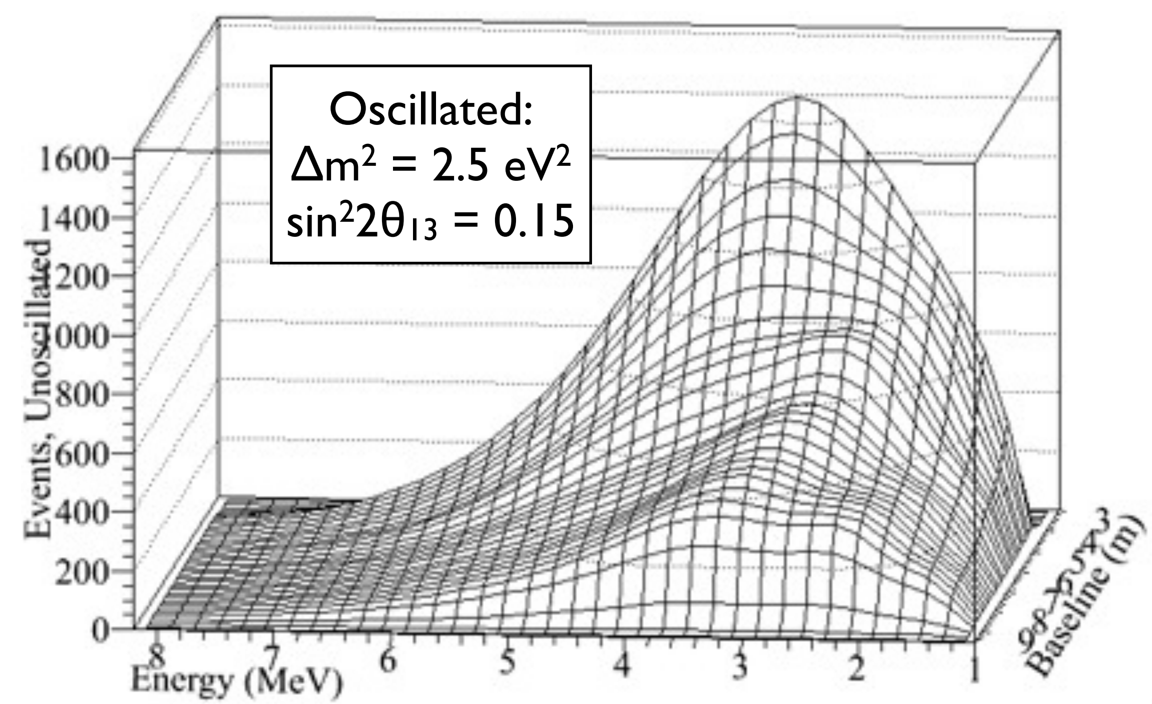


NBSR at NIST

Very Short Baseline Osc Signal

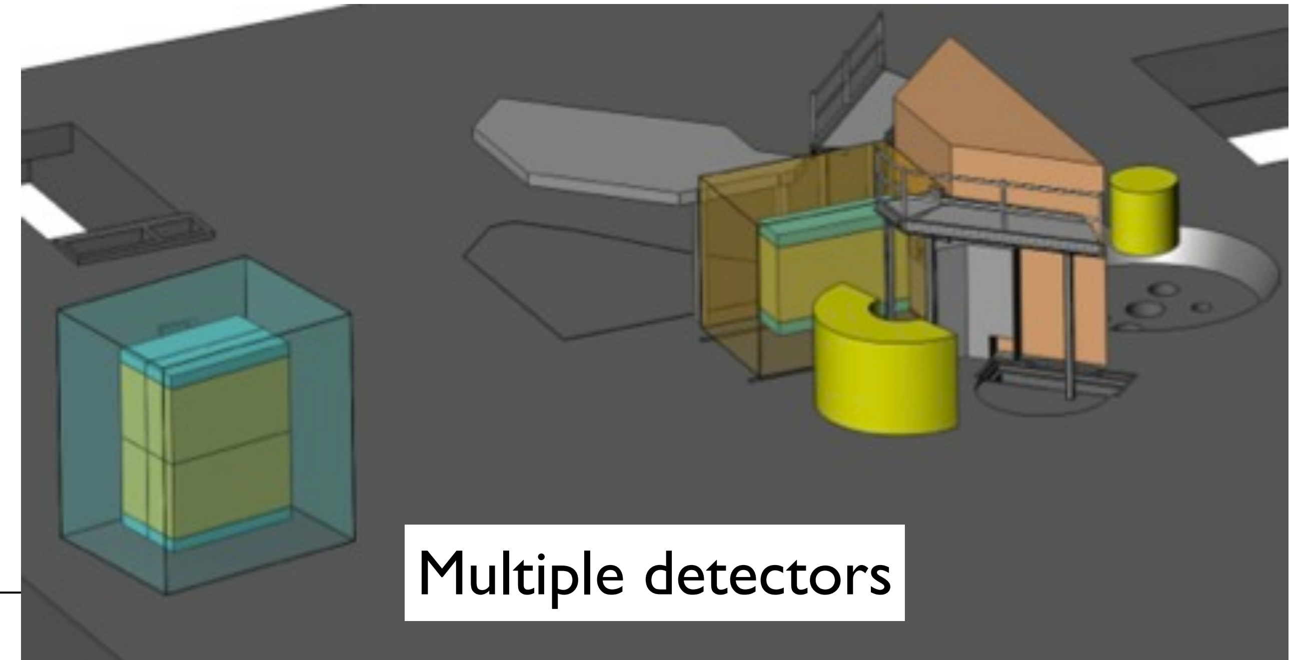
- Small Daya Bay-like scintillator detector
  - Multiple-m^3 sized with long baseline spread
  - 30% detection efficiency, 10% energy resolution
  - Optically segmented target for position resolution, background reduction
- Look for reactor oscillation distortions with position, energy

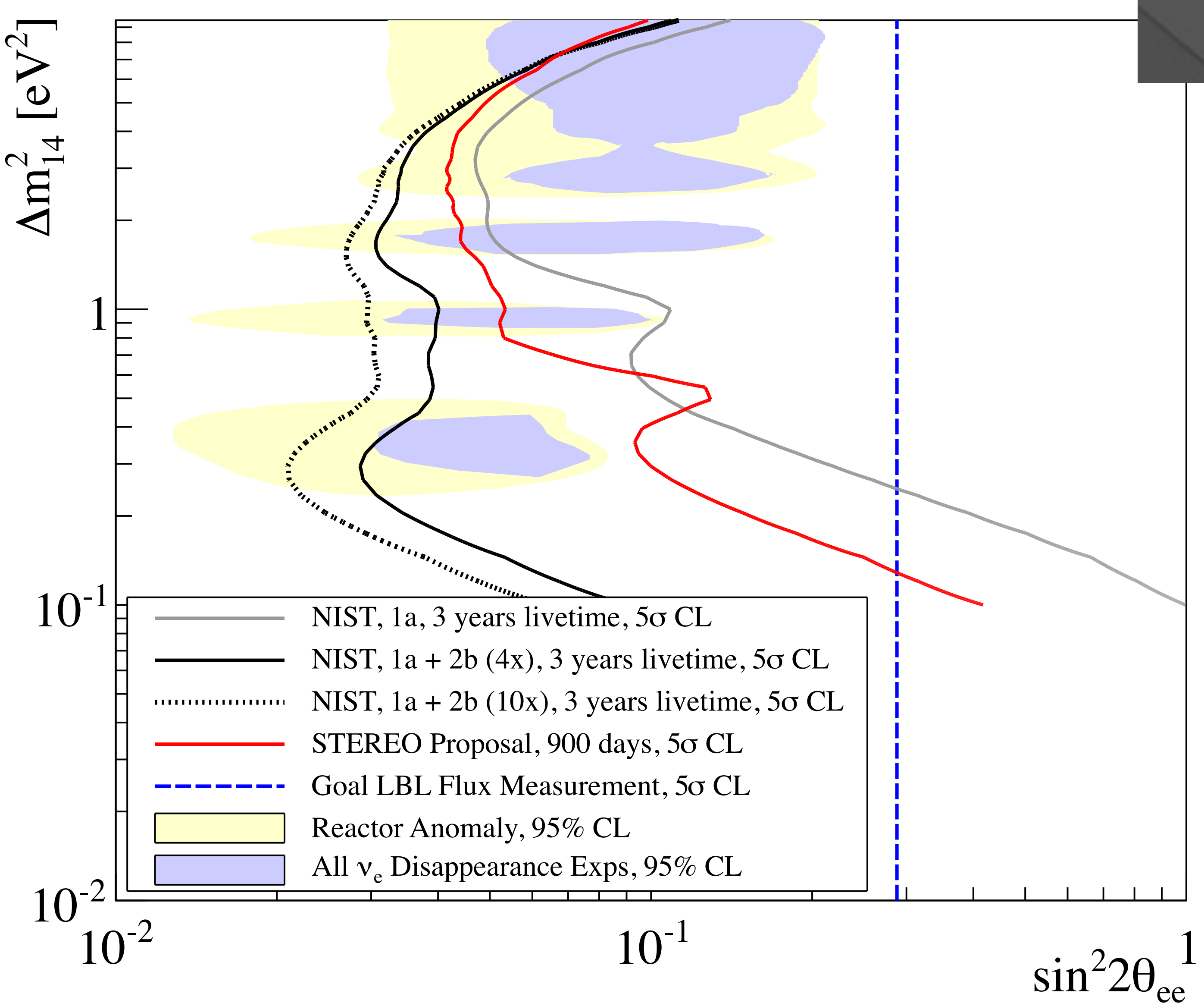




US Reactors: Sensitivity

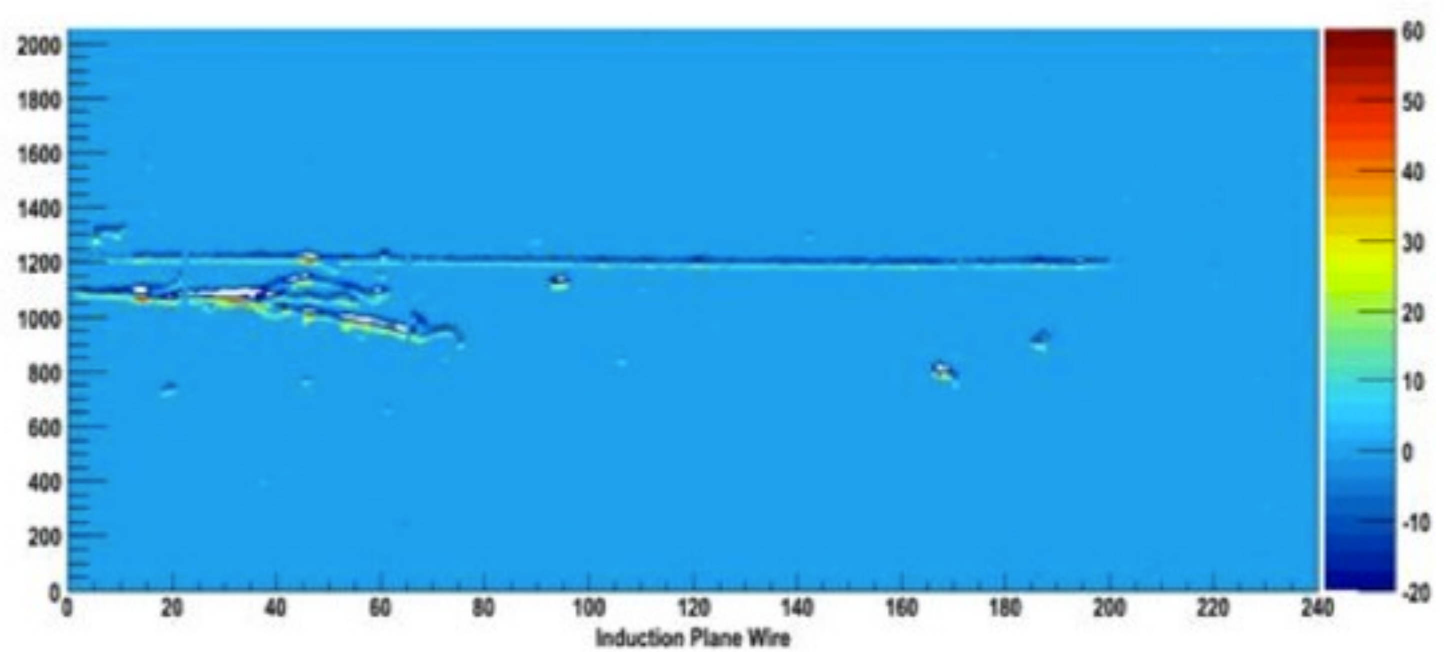
- Looking at a 2-detector deployment at NIST
- Can rule out most suggested sterile neutrino space

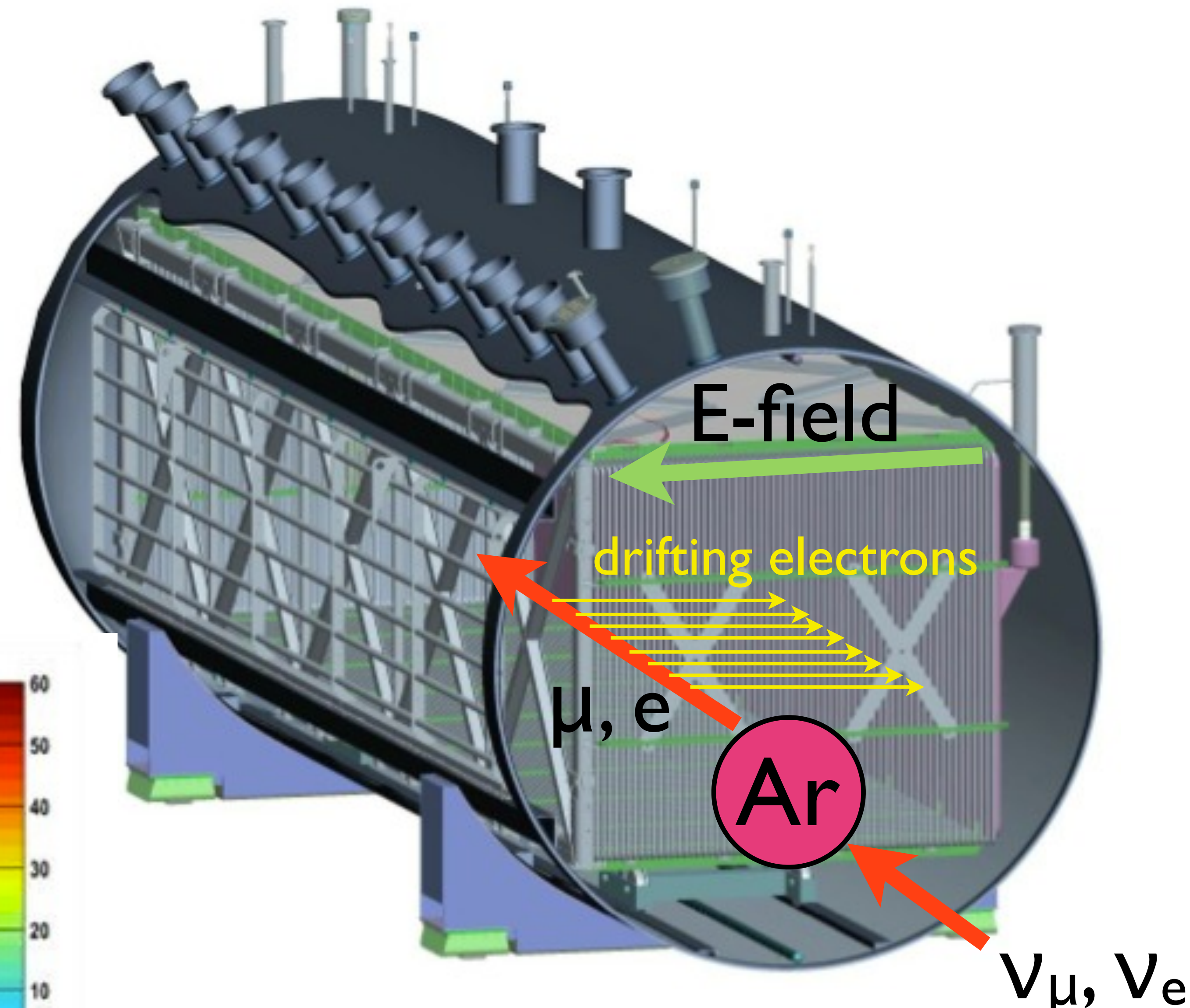




MicroBooNE

- Another way to address anomaly: repeat MiniBooNE with a better detector -- liquid argon TPC
  - Shoot neutrino beam through 83 m^3 active volume liquid argon
  - Drifted ionization electrons give a track on side sense wires
  - Additional scintillation light
  - Beautiful particle tracks, excellent, position, energy resolution
  - Maybe signal was background, mis-identified?





Summary

- Huge advances have been made in neutrino physics, even in the past year!
- The Daya Bay experiment has measured θ_{13} with incredible precision, and will improve its measurement in next few years

$$\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$$

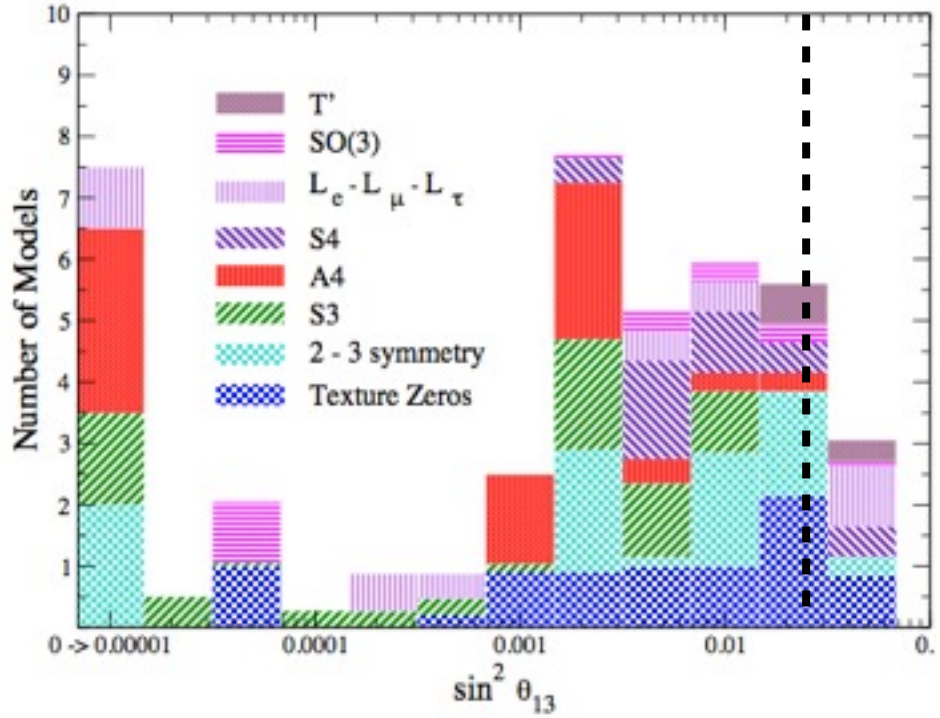
- Hints at new neutrino types can be decisively investigated with very-short-baseline reactor experiments
- Stay tuned!

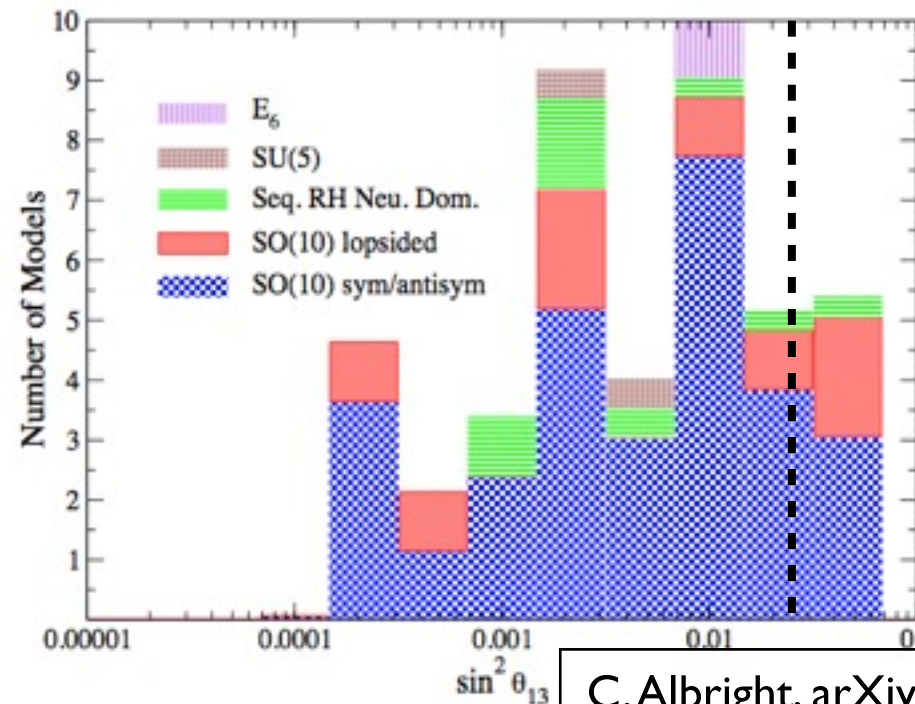
Backup

Impacts of Large θ$_{13}$

- Theoretical possibilities are greatly reduced: simple tri-bimaximal mixing is out.

Flavor Symmetries

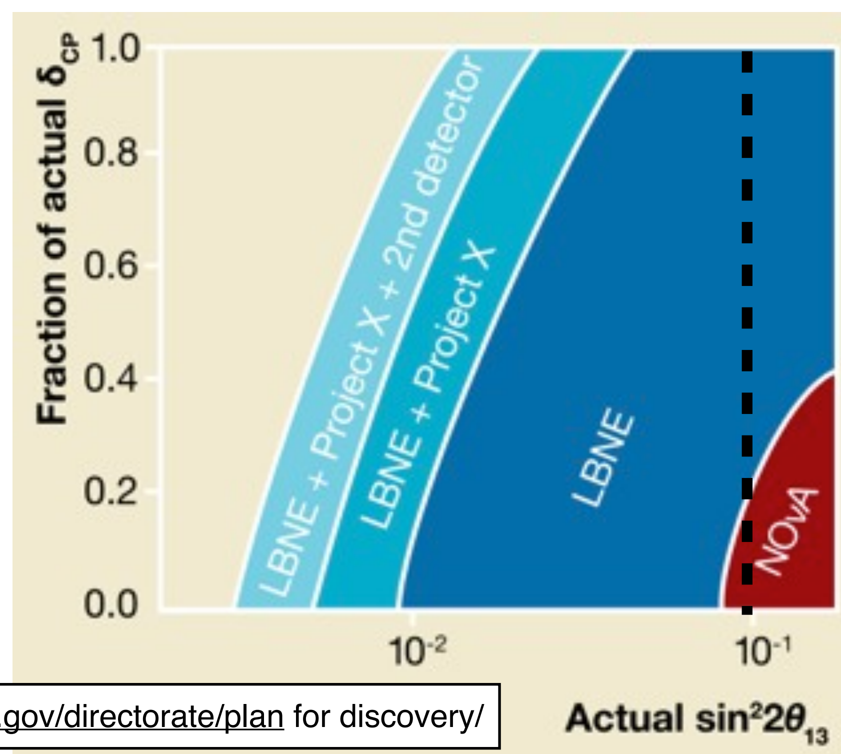


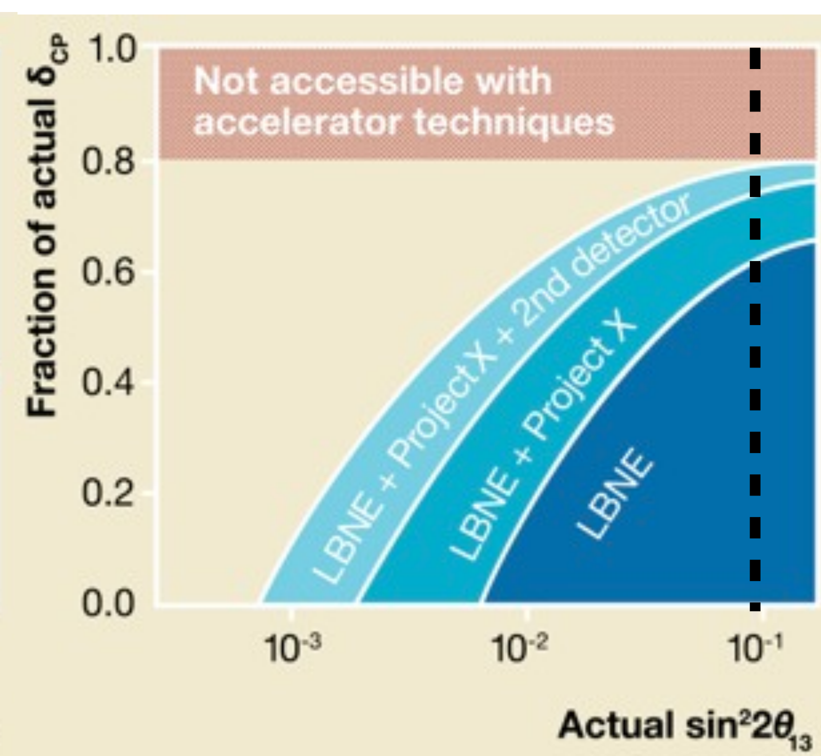


GUTs

C. Albright, arXiv:0911.2437v1 (2009)

- Prospects for mass hierarchy and δ$_{cp}$ greatly improved at future neutrino exps.





http://www.fnal.gov/directorate/plan for discovery/

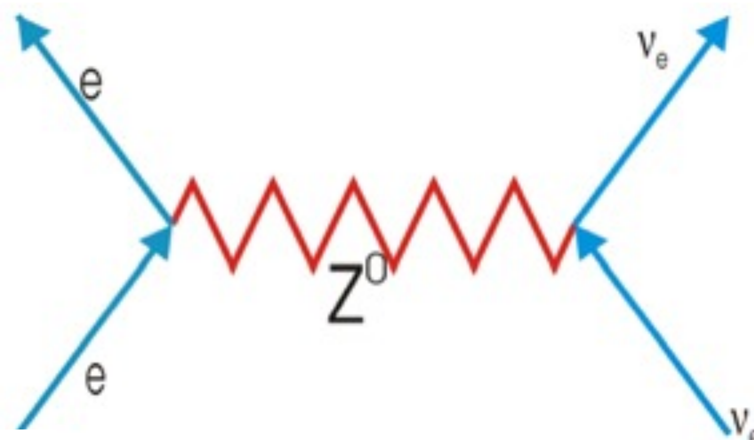
SM Neutrino Interactions

- Leptons with no charge, so no strong, EM interactions
- Interact via left-handed weak force:

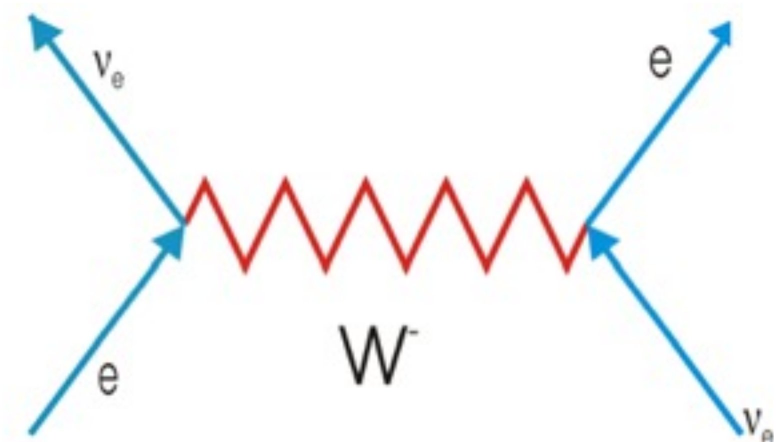
$$J_\mu^{W,CC} = \sum_i (\overline{\psi}\gamma_\mu(1-\gamma_5)\psi)$$

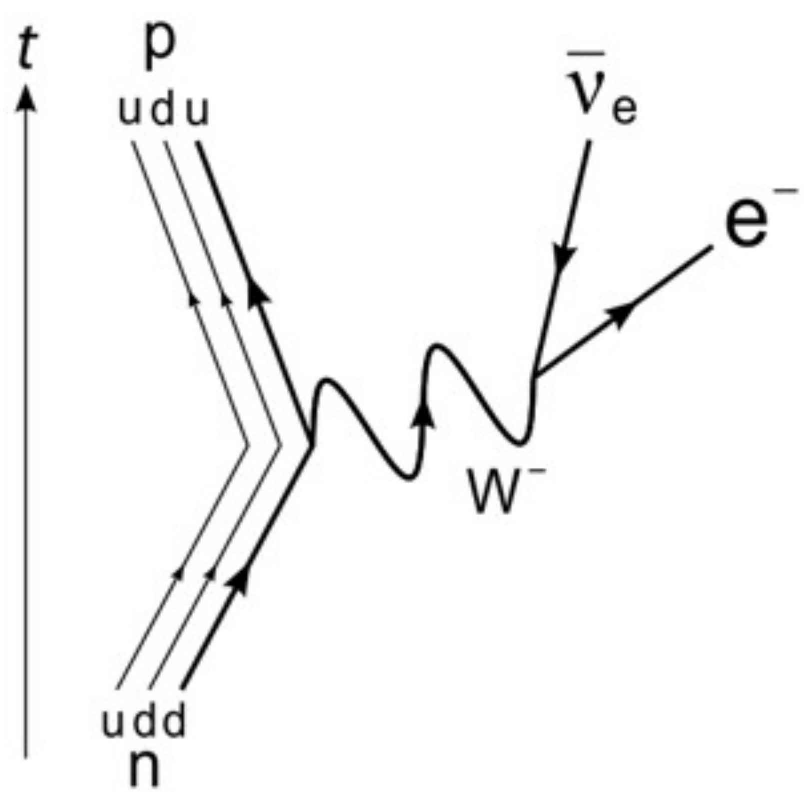
$$J_\mu^{W,NC} = \sum_i (\overline{\psi}\gamma_\mu(g_{v_i} - g_{A_i}\gamma_5)\psi)$$

Neutral Current



Charged Current Current





- We particularly care about inverse beta decay:

See-Saw Mechanism

- Start with a nu mass Legrangian:

$$-\mathscr{L}^D_{m_\nu} = m_D \overline{\nu^0_R} \nu^0_L + h.c.$$ Dirac Terms

$$-\mathscr{L}^M_{m_\nu} = \frac{m_R}{2} \overline{(\nu^0_R)^c} \nu^0_R + h.c.$$ Majorana Terms

- Write in matrix formulation:

$$-\mathscr{L}_{m_\nu} = -\frac{1}{2} \begin{pmatrix} \overline{(\nu^0_L)^C} & \overline{\nu^0_R} \end{pmatrix} M_\nu \begin{pmatrix} \nu^0_L \\ (\nu^0_R)^C \end{pmatrix} + h.c.$$

$$M_\nu = \begin{pmatrix} m_L & m_D^T \\ m_D & m_R \end{pmatrix}$$

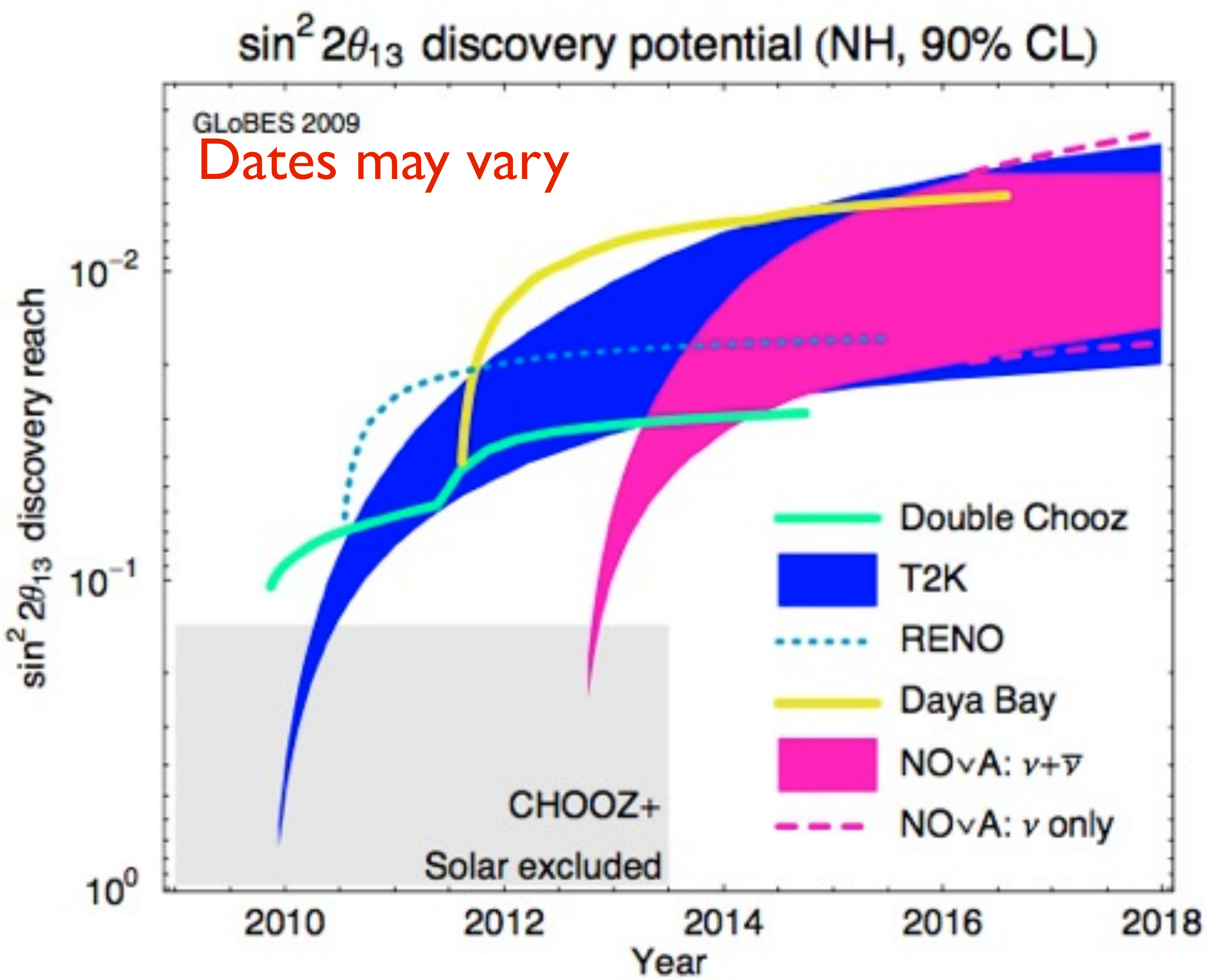
- Diagonalize mass matrix to get mass eigenstates:

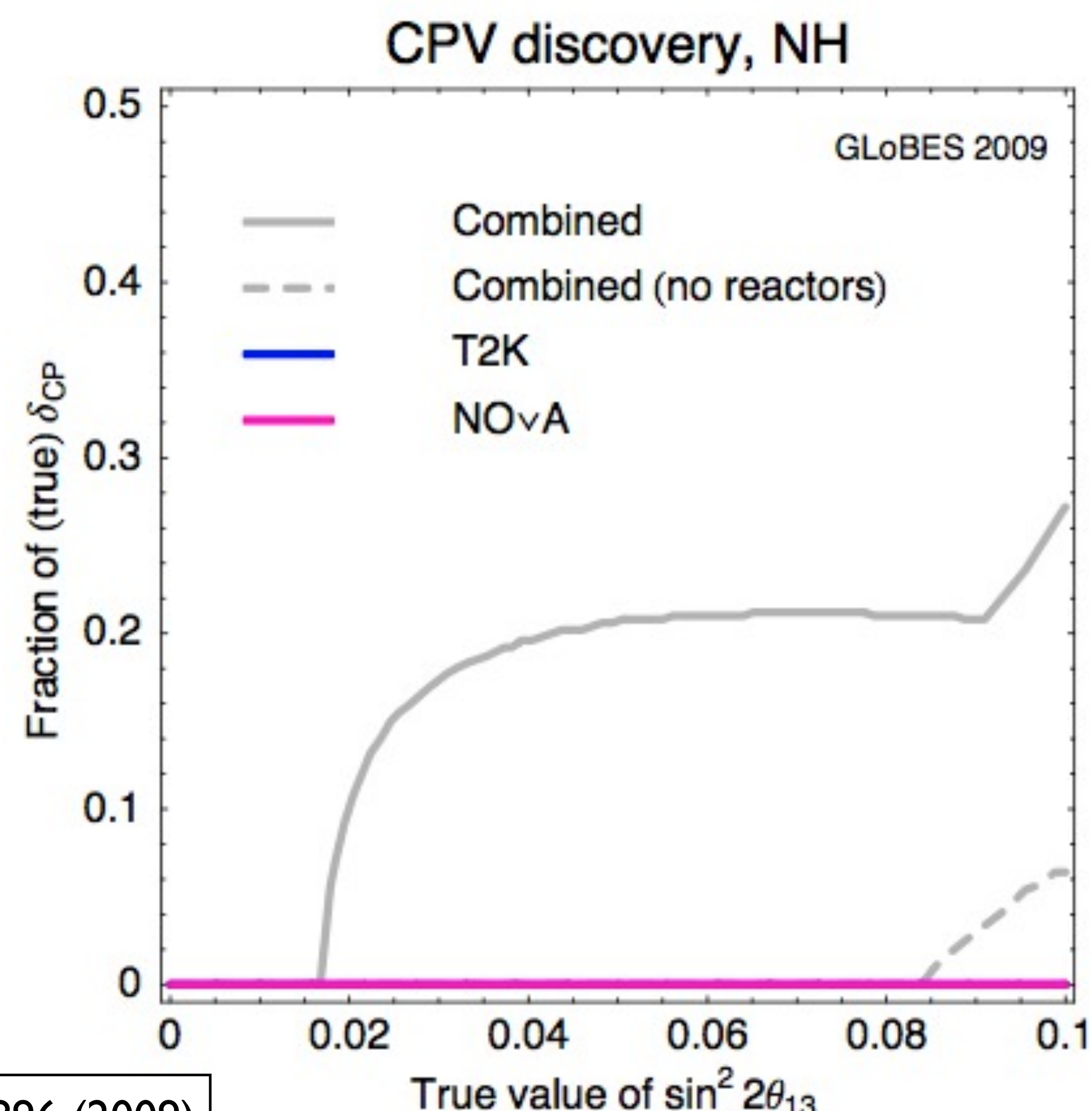
$$-\mathscr{L}_{m_\nu} = \frac{1}{2} \begin{pmatrix} \overline{\nu} & \overline{N} \end{pmatrix} \begin{pmatrix} m_D^2/m_R & 0 \\ 0 & m_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

- If m_D is the quark mass scale, and m_R is some heavy mass scale, we get sets of light (~eV) and heavy (~10^{15}) neutrinos
- Neutrinos must be Majorana particles!

The Reactor θ_{13} Gateway

- Sensitive, 'clean' measurements of θ_{13} can be done at reactors
  - Independent of CP-violation, mass hierarchy
- With reactor θ_{13} precisely measured, accelerators can probe δ_{cp}, mass hierarchy





Huber et. al, arXiv:0907.1896 (2009)

Accelerator Oscillation

$$L(km) = \frac{1.24 E_\nu(GeV)}{\Delta m^2(eV^2)}$$

Same Δm^2 as Daya Bay

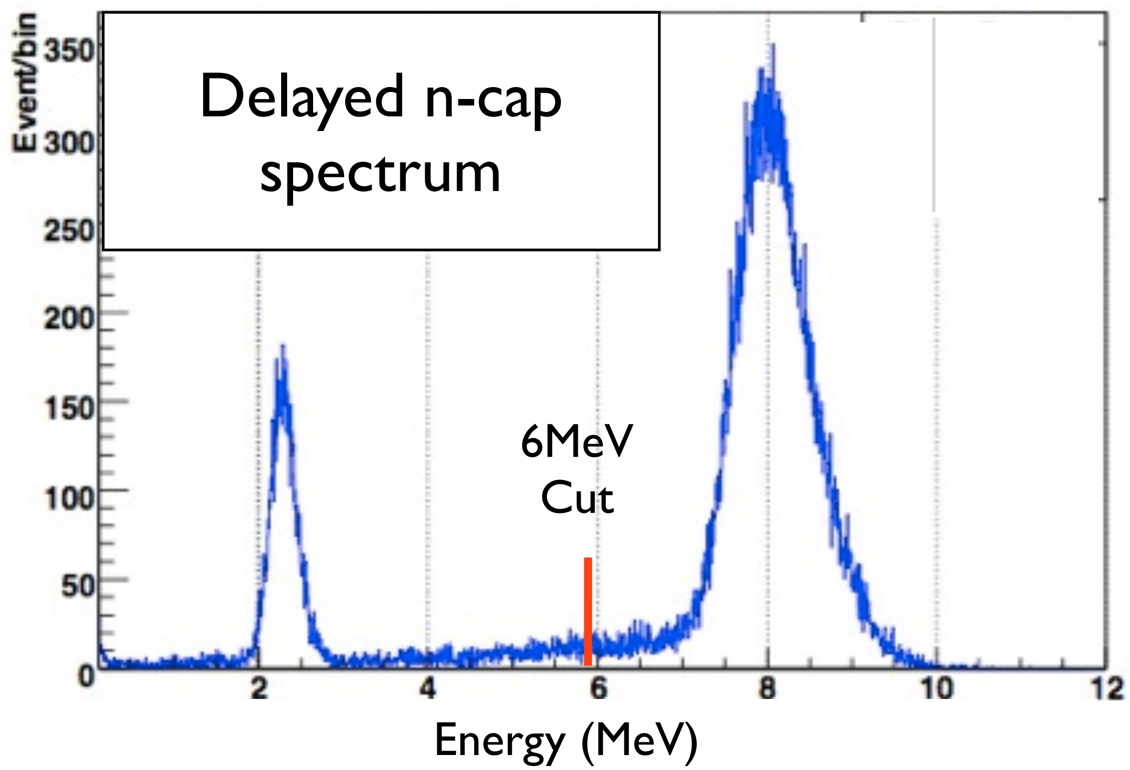
Higher Energy: ~GeV

So higher baselines: 1000 km

$$\begin{aligned}
P(\overline{\nu}_\mu \to \overline{\nu}_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\
&+ 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} \\
&- 8c_{13}^2 s_{13}^2 s_{23}^2 c_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\
&+ 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta]\sin^2\Delta_{21} \\
&- 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left(\cos\Delta_{32} - \frac{\sin\Delta_{13}}{\Delta_{13}}\right).
\end{aligned}$$

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

- Relative detector systematics: the expected dominant experimental uncertainty



$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

A product of relative energy scale differences

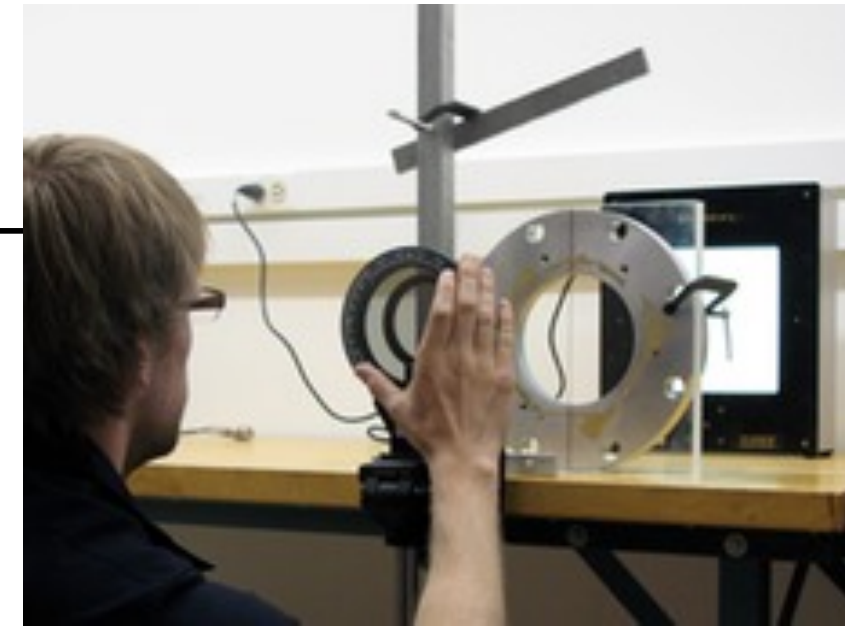
Design Estimate: 0.3%

For Comparison, Chooz: 1.5%

- To achieve or surpass this systematic:
  - Must precisely understand relative energy scale differences between detectors
  - Minimize differences by making detectors as physically identical as possible

Acrylic Vessels (AVs)

A Ready-to-install OAV!



Designed AV Stress Testing System in Lab

On-site characterization measurements

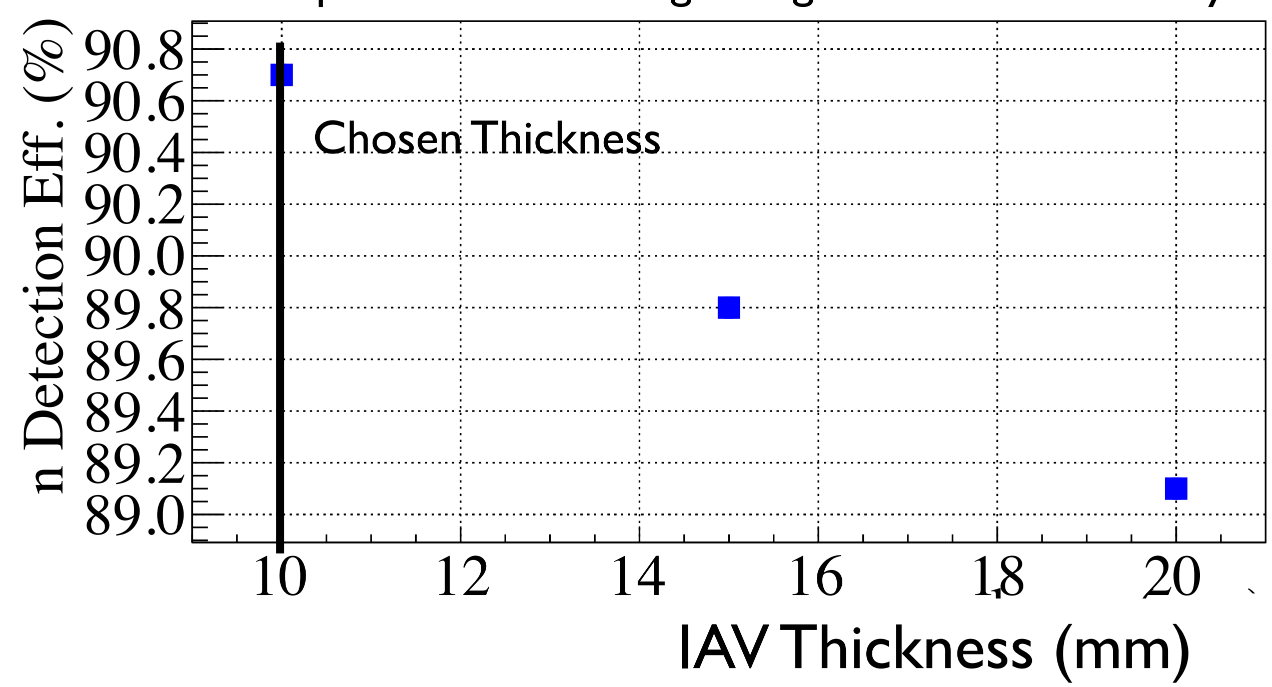
AV Cleaning at Daya Bay

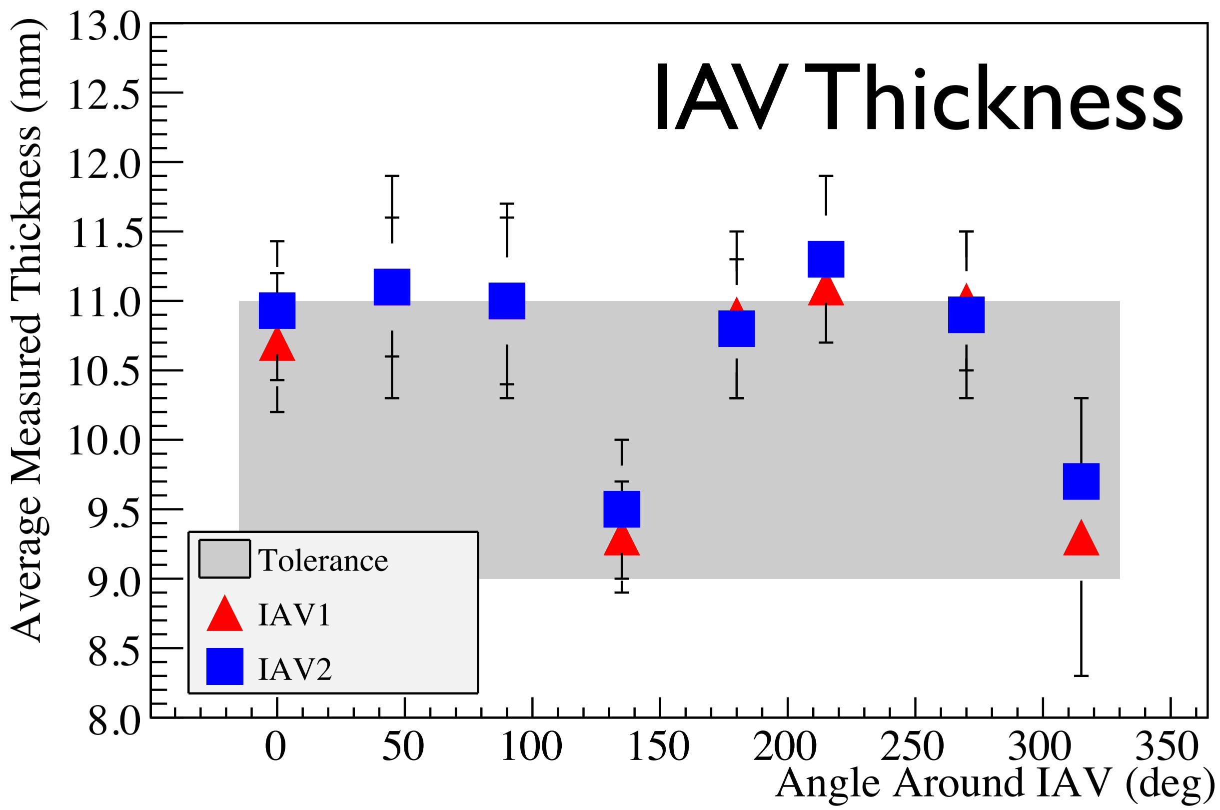
- Played a major role in AV design, construction, assembly and characterization
- Much laboratory and on-site hardware work

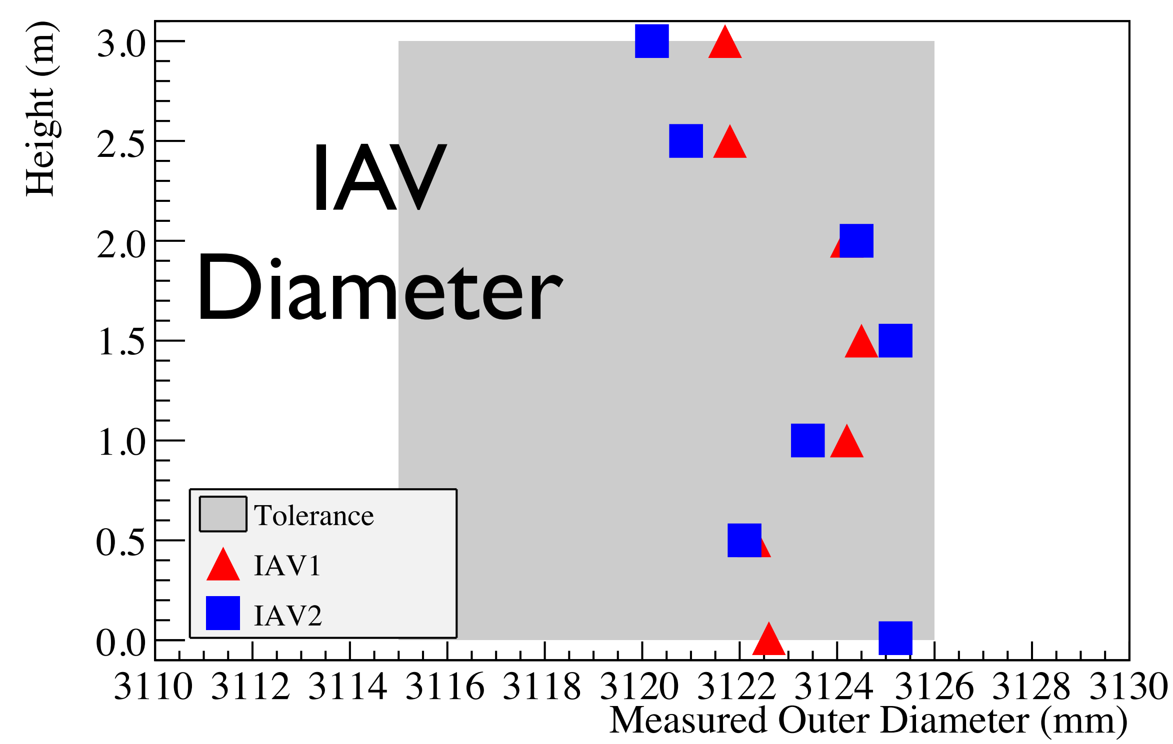
AV Geometric Design/Characterization

- Design led by engineering and physics requirements:
  - Wide cylindrical AVs give largest target volume while allowing easier transport
  - Thin vessel walls give highest detection efficiency
    18mm for OAV, 10mm for IAV
  - Conical tops ensure a completely filled target
- Great care taken to produce, characterize similar geometries
- H.R. Band, *et. al.*, accepted to JINST

An Example: thin IAV walls give high detection efficiency



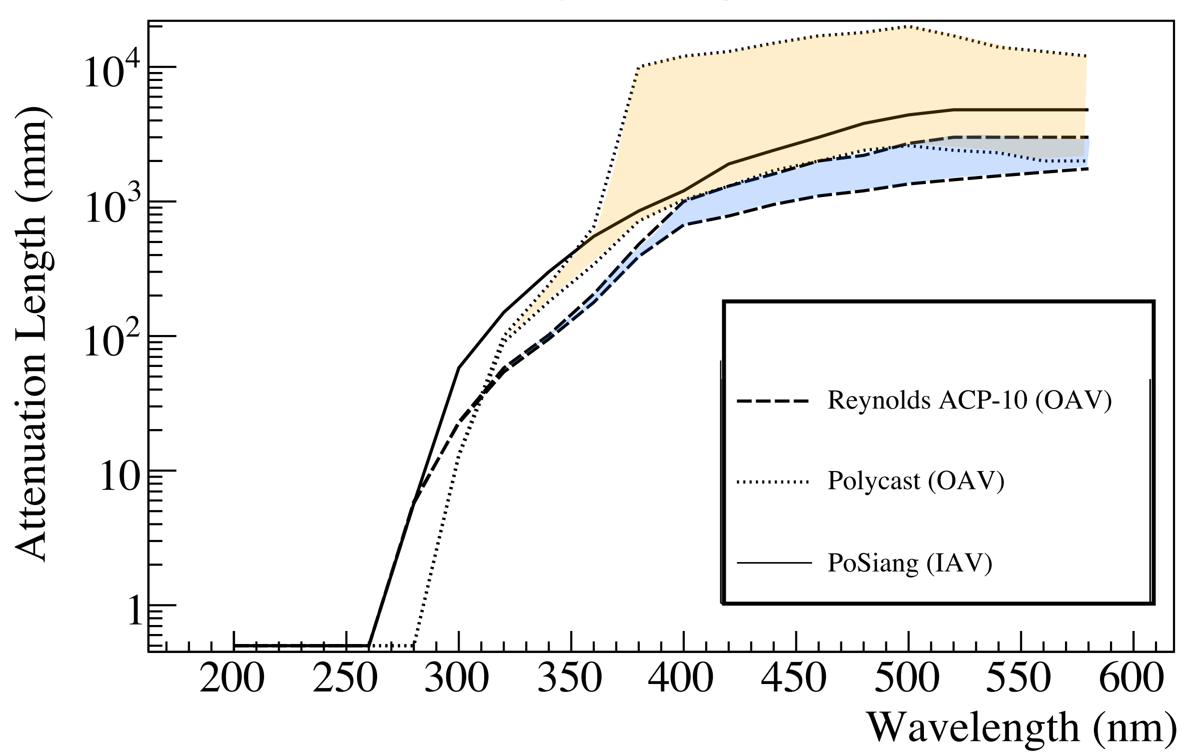




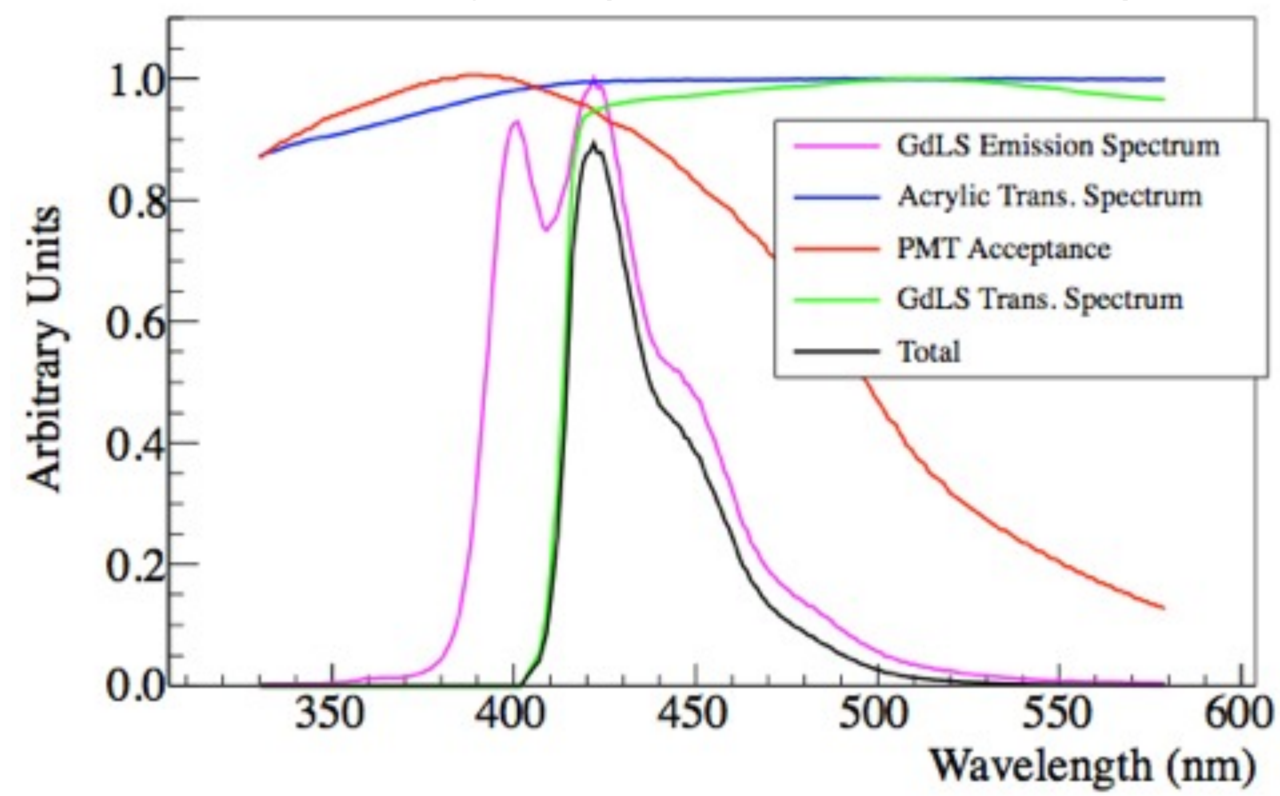
AV Optical Design/Characterization

- Acrylic optical properties required to match light output of scintillator
- Great care taken to produce, characterize similar AV optical properties
  - H.R. Band, *et. al.*, accepted to JINST: excellent agreement between ADs
  - Littlejohn, *et. al.*, JINST 4:T09001,2009: Degradation from UV exposure is minimal and identical for all AVs

Measured range of acrylic attenuation

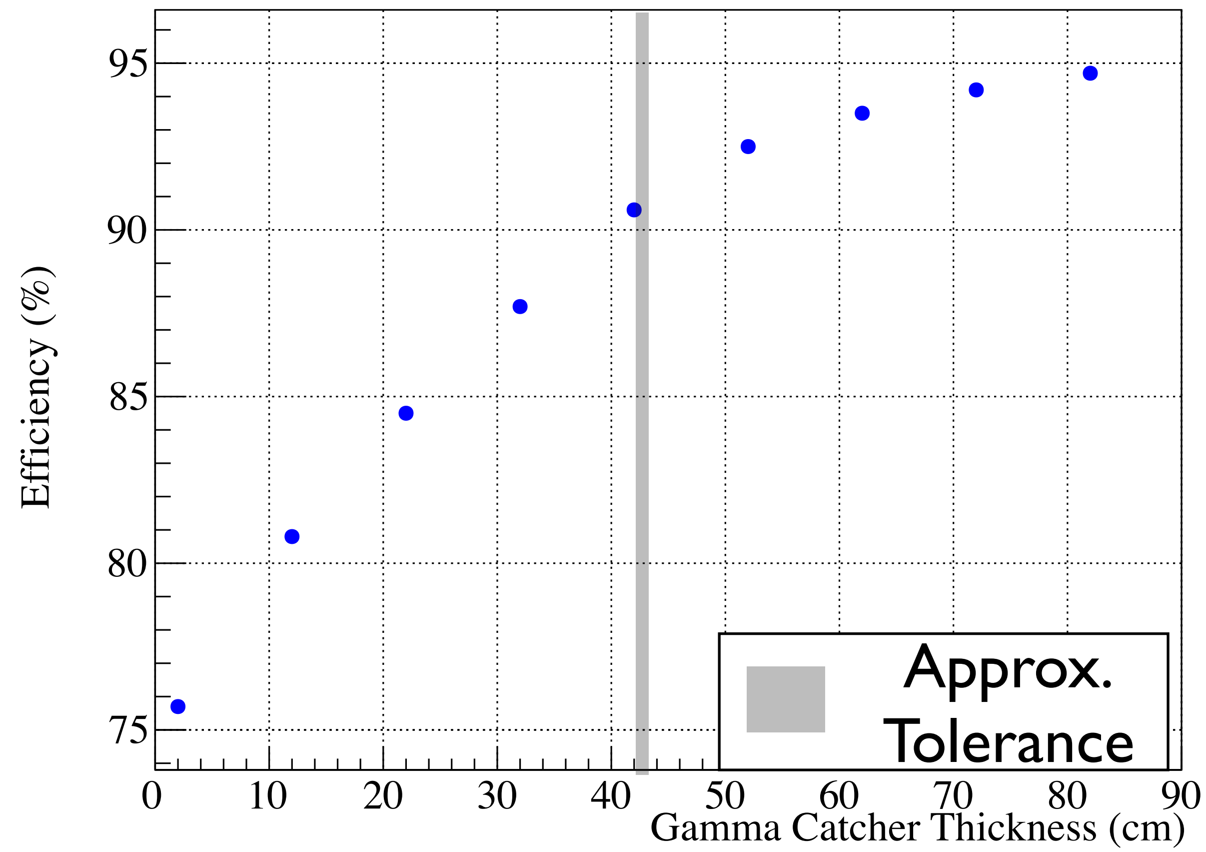


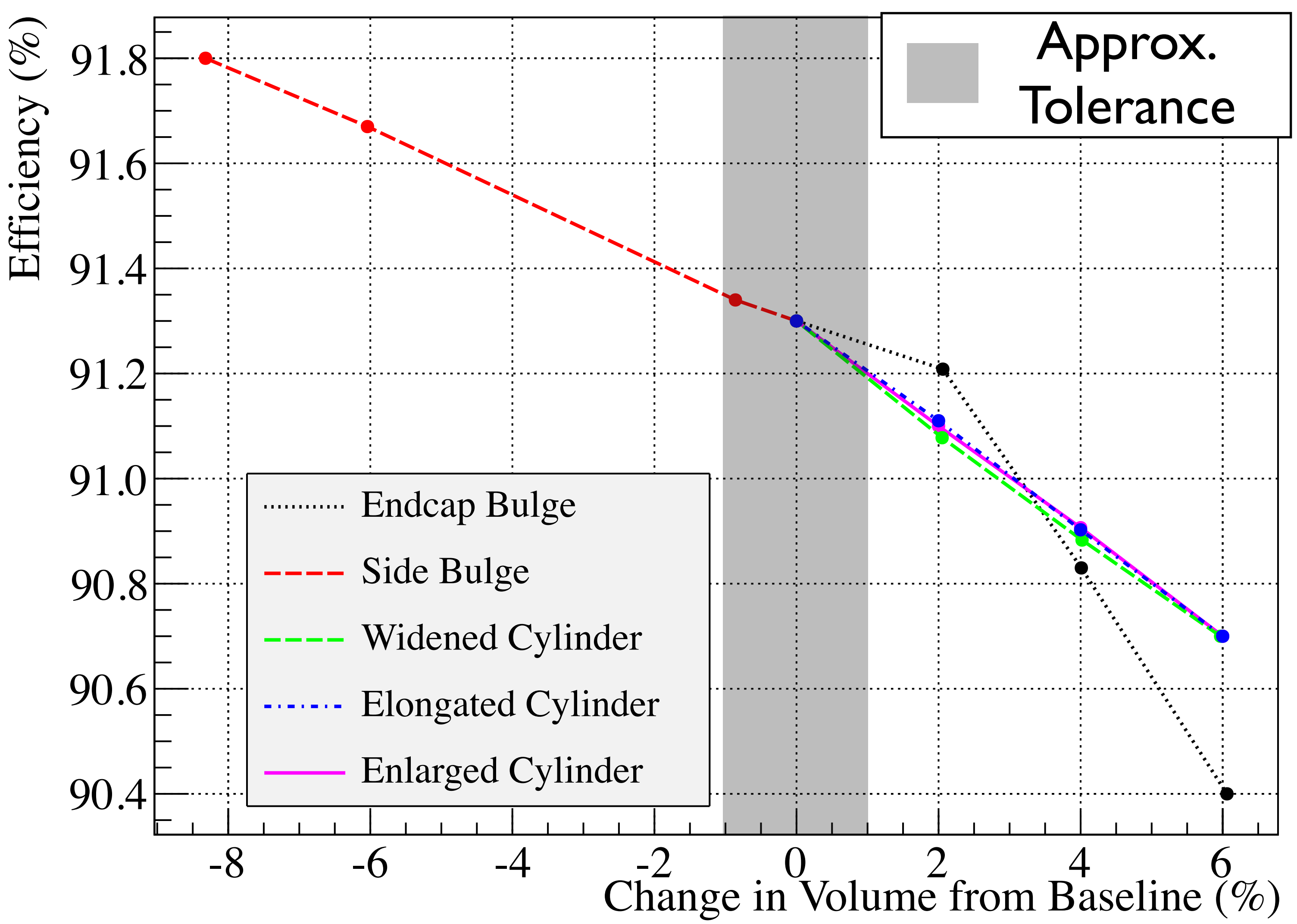
Scintillator light output matches PMTs and acrylic!

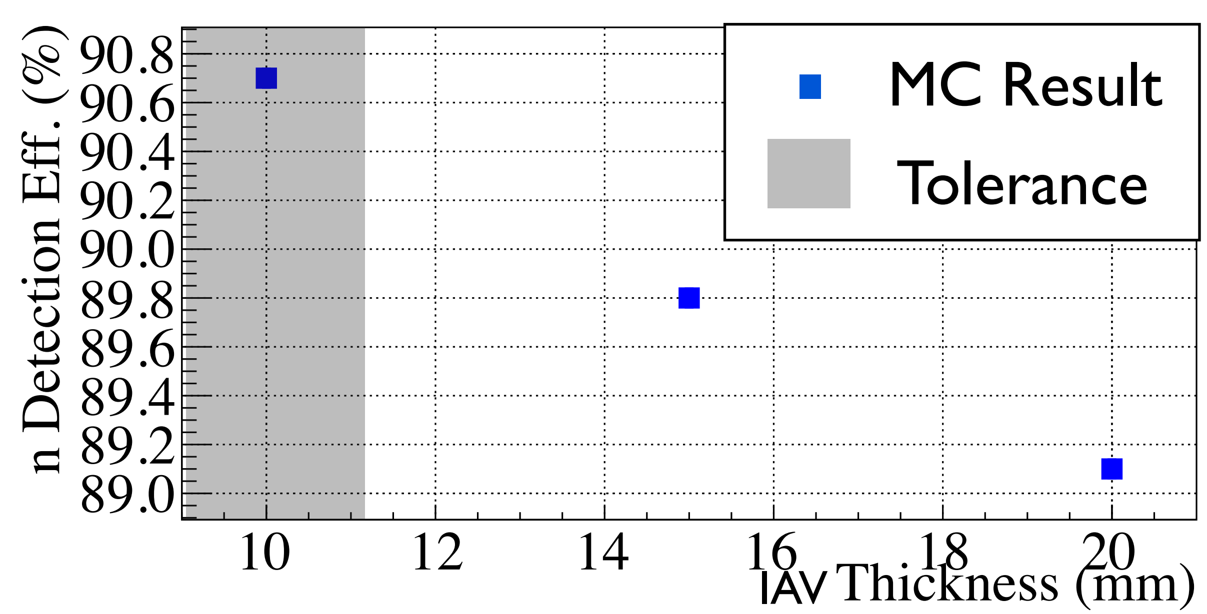


Detector Design and Characterization

- I did simulations verifying that produced AD should be 'functionally identical:'
  - ADs will have identical neutron detection efficiency to <0.1%
    - Small compared to expected 0.3%
  - Light yield differences between ADs will be less than 1%
  - Resolution between ADs will vary negligibly

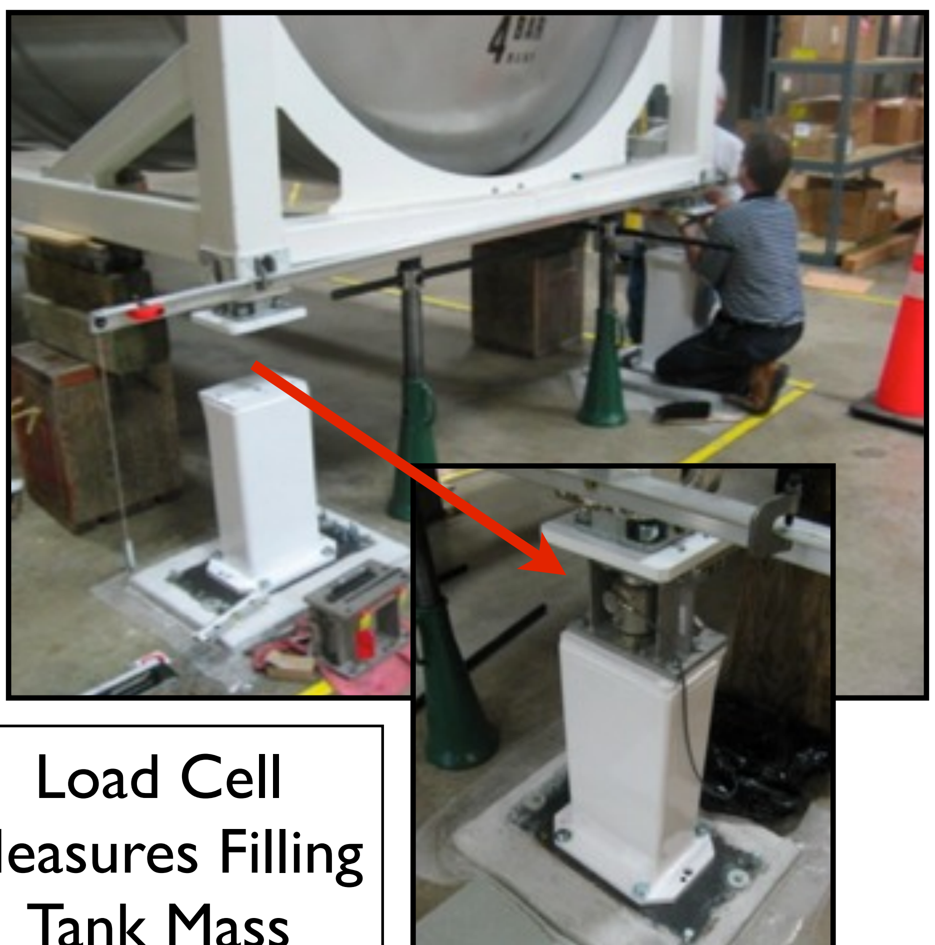




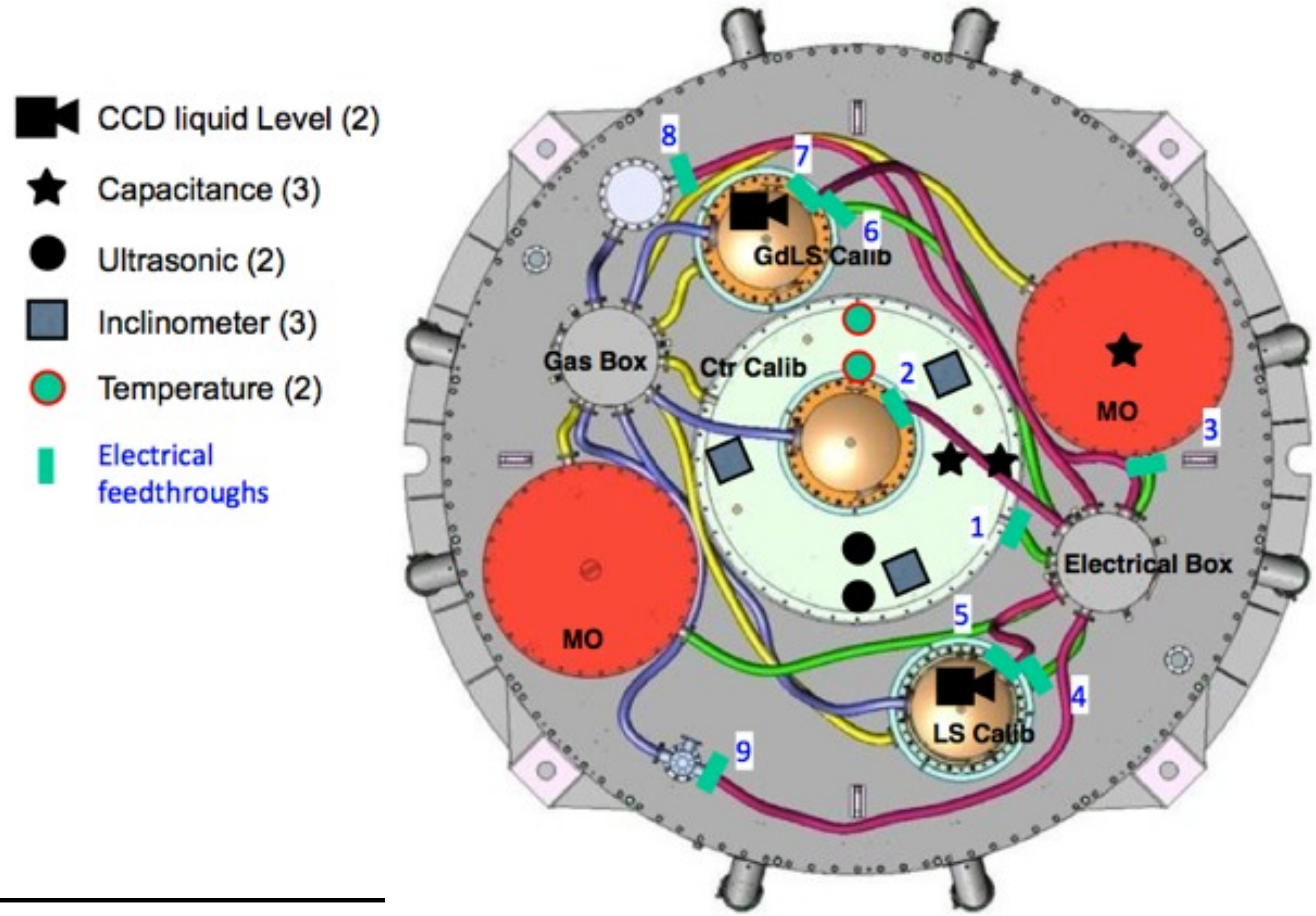


Target Mass

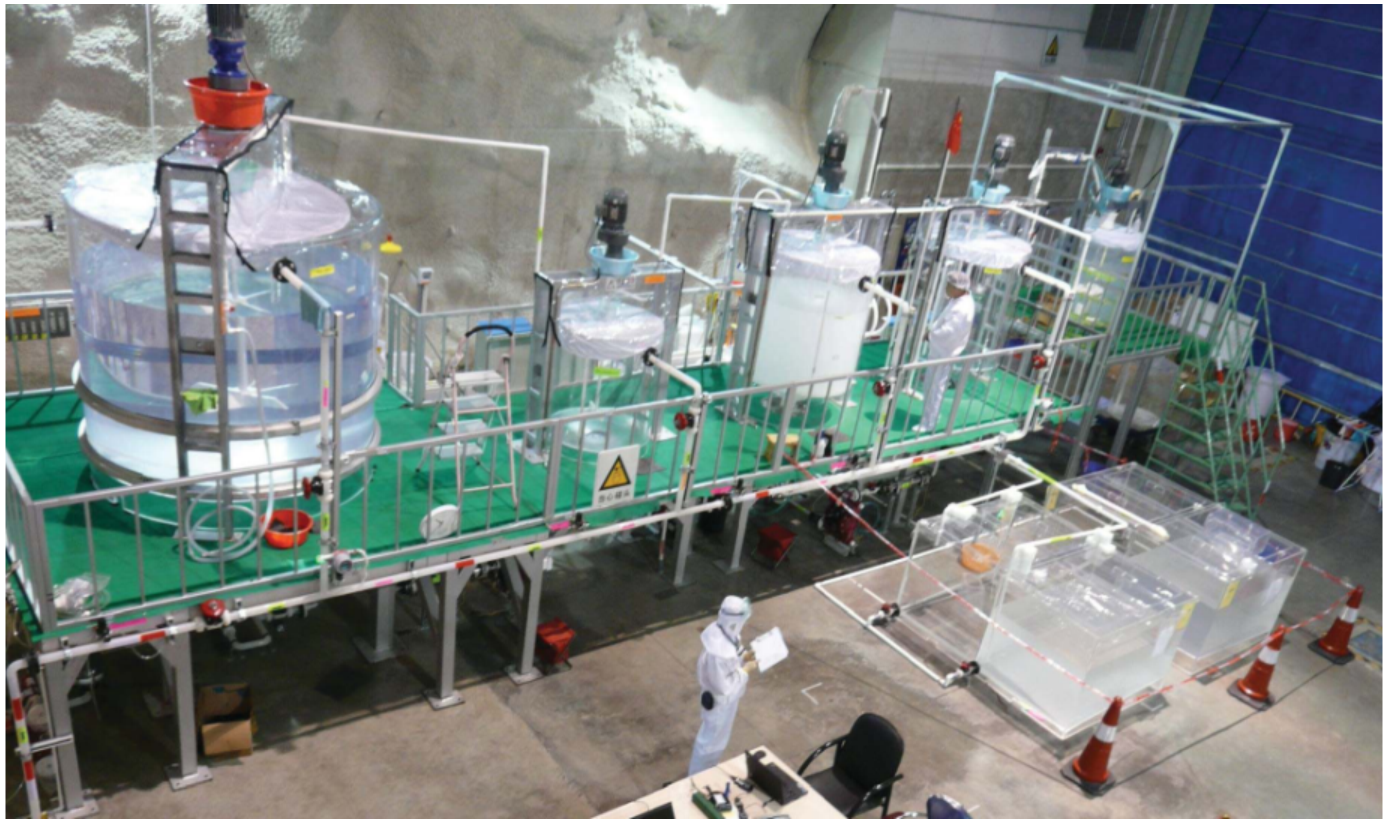
- Target mass measured to <0.02% for each AD
- Level sensors in overflow tanks measure changes in target mass
- Target mass is currently blinded
  - Near site masses will be unblinded for AD1/AD2 comparison



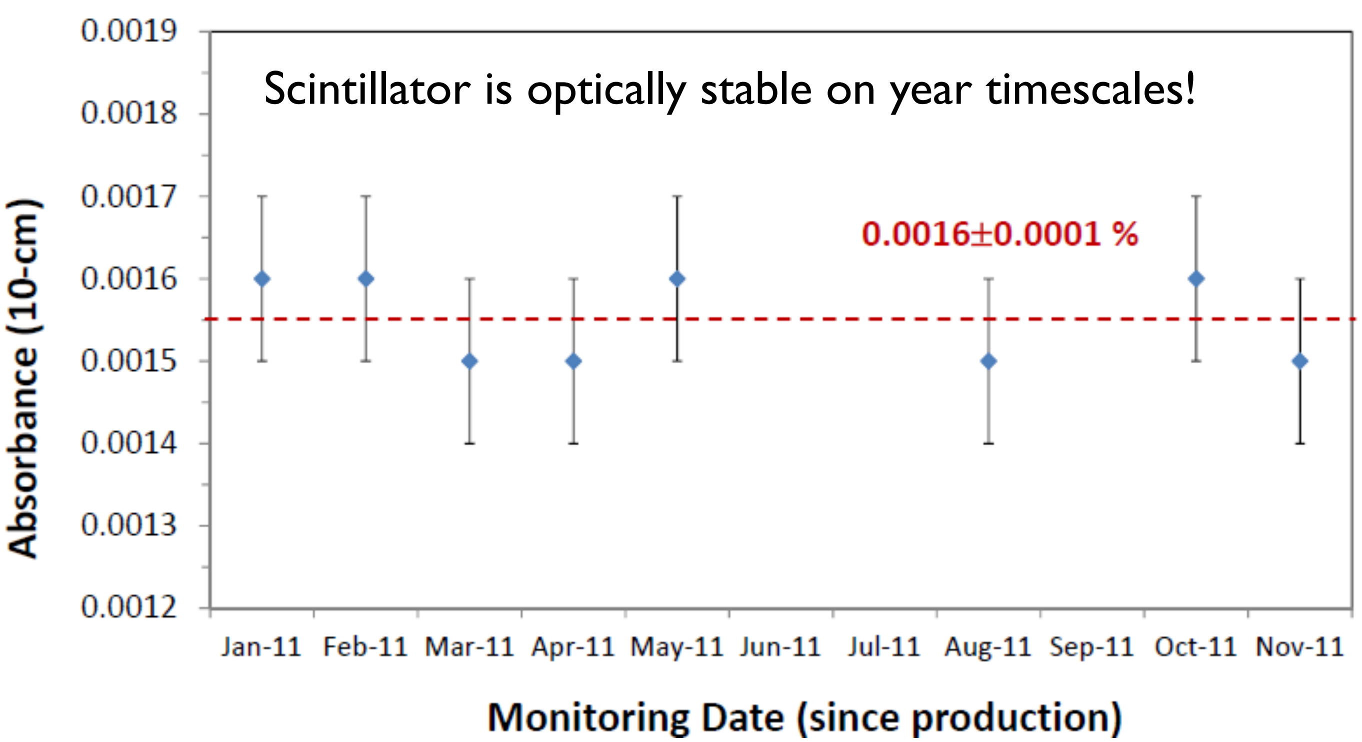
Load Cell Measures Filling Tank Mass

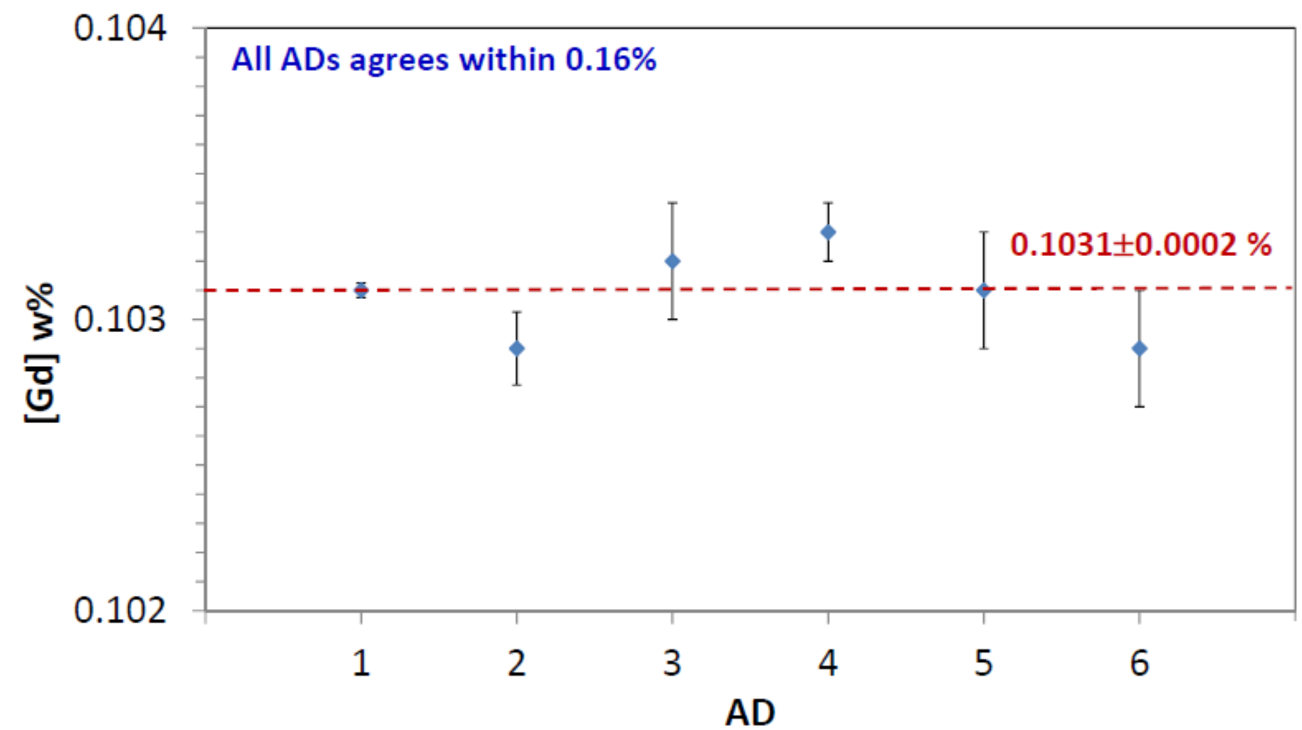


Detector Liquids

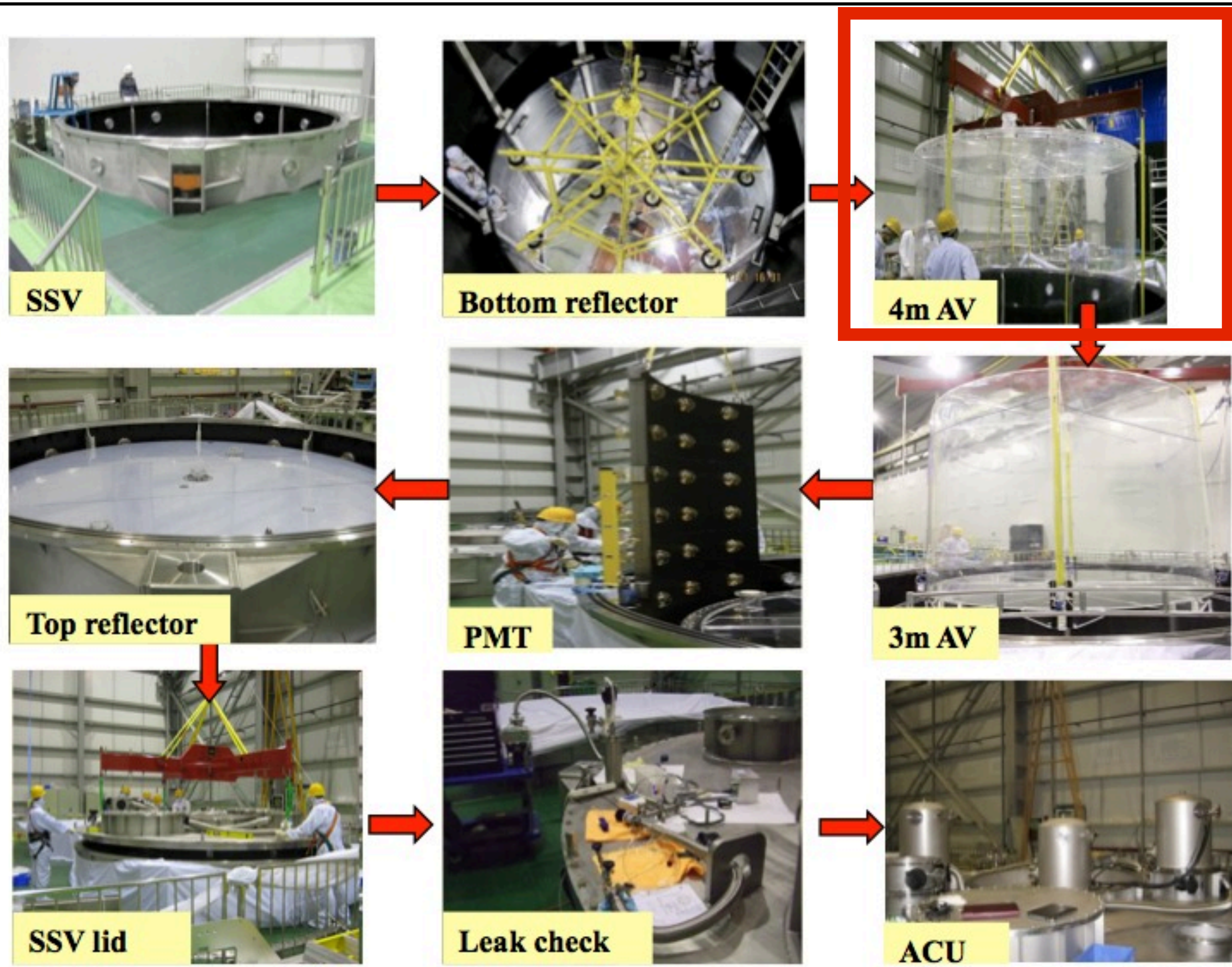


- Scintillator is completely produced and stable:
    - Gd (0.1%) + linear alkyl benzene + Fluors
    - 185 tons produced in 4-ton batches
    - 3 years R&D, 1 year prototype monitoring





Detector Construction



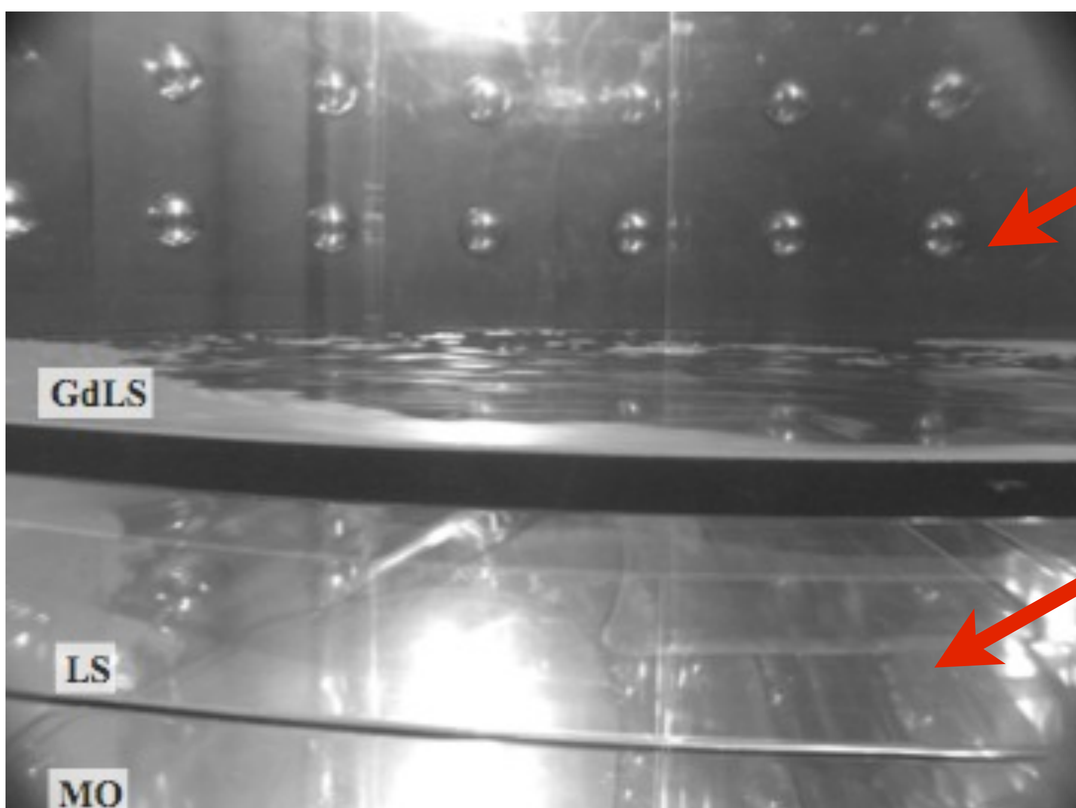
Filling and Mass Measurement

- GdLS mass measured with load cells to 0.03%, flowmeters to 0.1%

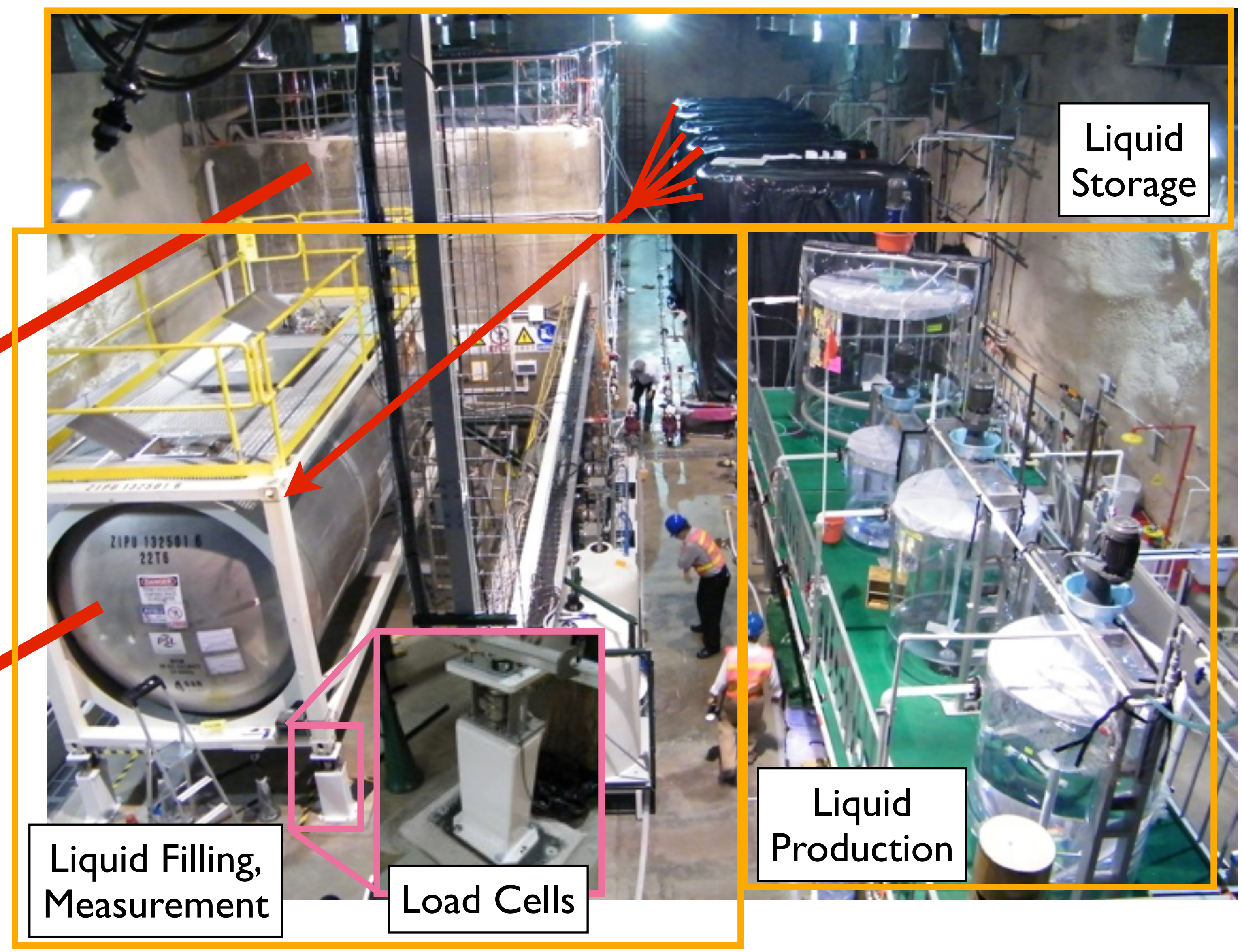
$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

- Detectors filled equally from common batches of liquid to ensure identical ADs

View with monitoring camera inside AD during filling



Provided by M. McFarlane



Identicalness: Liquid Properties

- Many controls on properties of MO, LS, GdLS between ADs:

Possible source of Non-Identicalness	Method of Control
Batch-to-batch production variations	Storage tanks mix and hold 8 batches
Tank-to-tank variations	Fill each AD evenly from all 5 storage tanks
Storage tank vertical stratification	Recirculate storage tanks
Time-dependent optical properties	No evidence for this, but fill detectors in pairs anyway
Cross-Check:	Take samples before and after filling for property testing

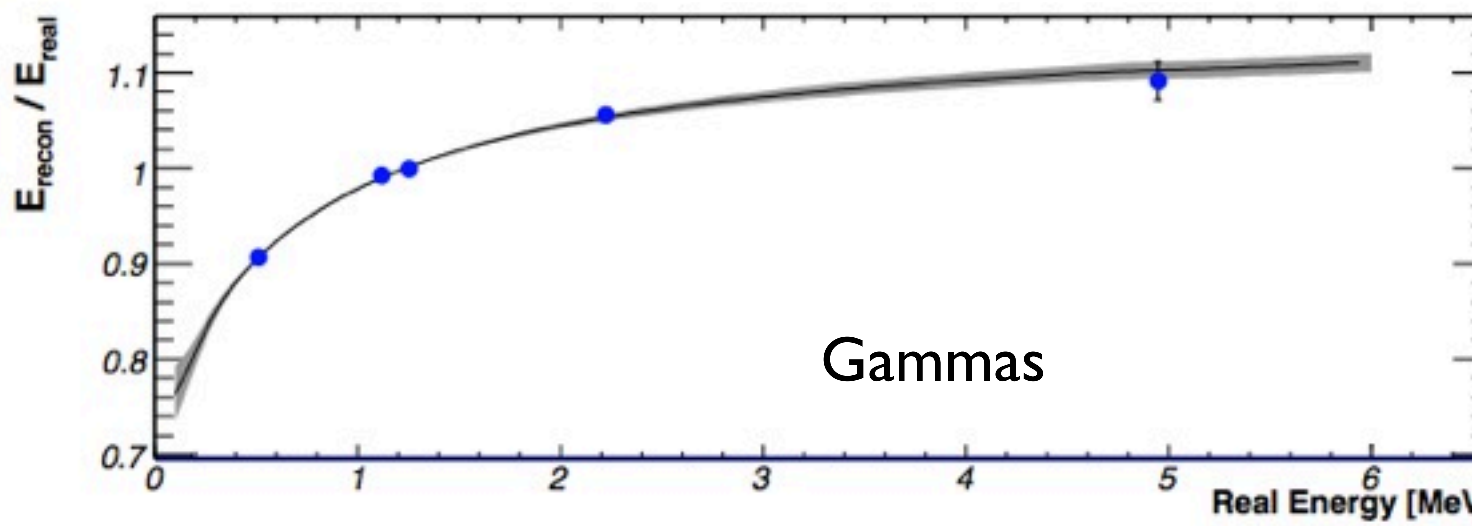
- This should ensure identical properties between ADs:
  - H/C ratio
  - H/Gd ratio
  - Optical properties

Scintillator Non-Linearity

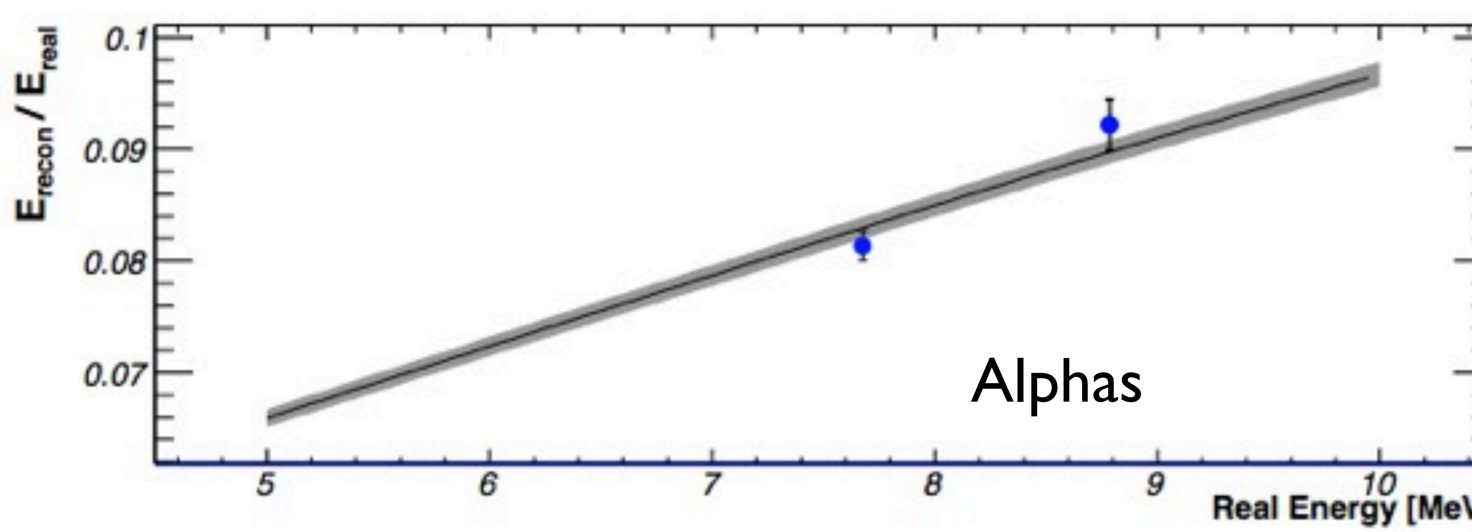
Non-linear relationship between total energy and scintillation light:

$$E_q = \int_0^E \frac{1}{1 + k_b \frac{dE}{dx}} dE.$$

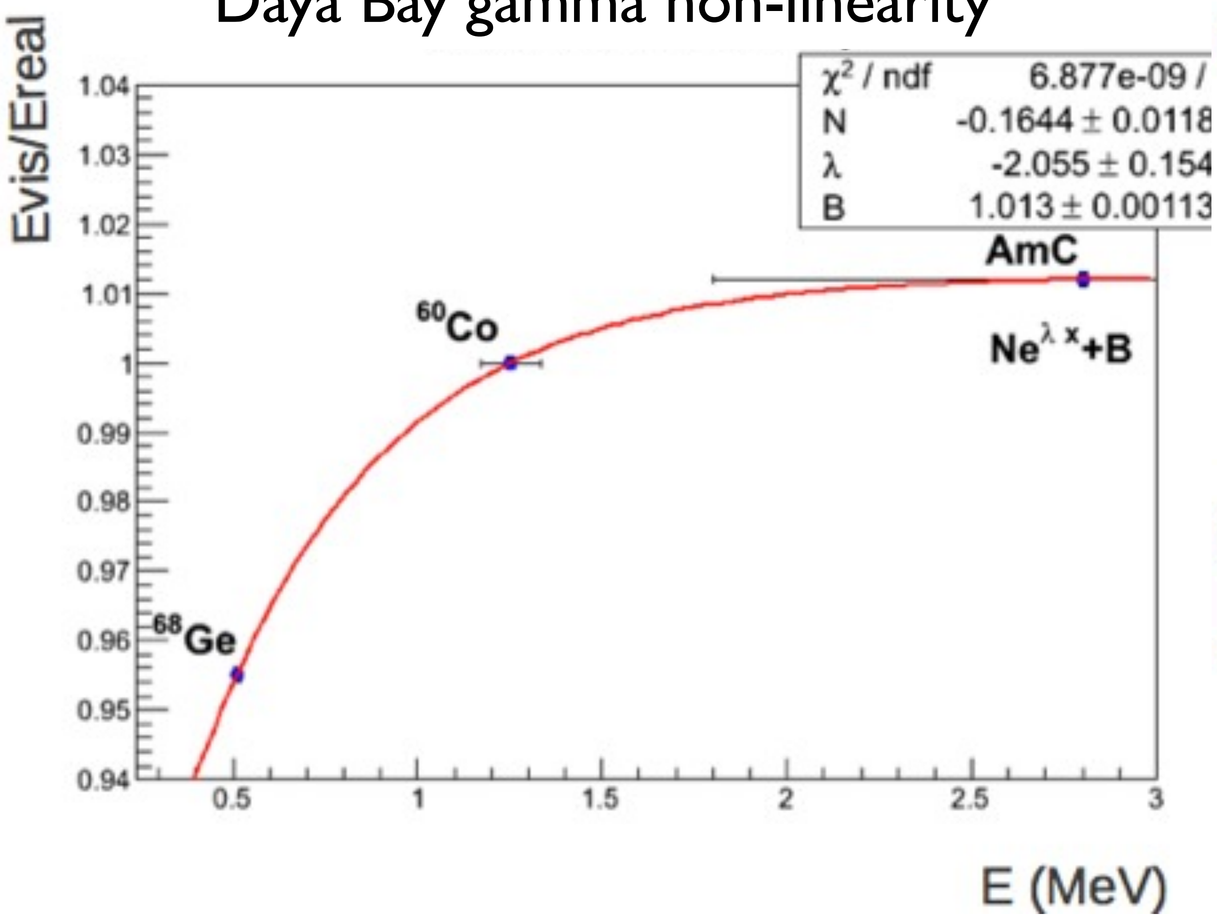
KamLAND non-linearity



D. Dwyer, Ph.D. Thesis

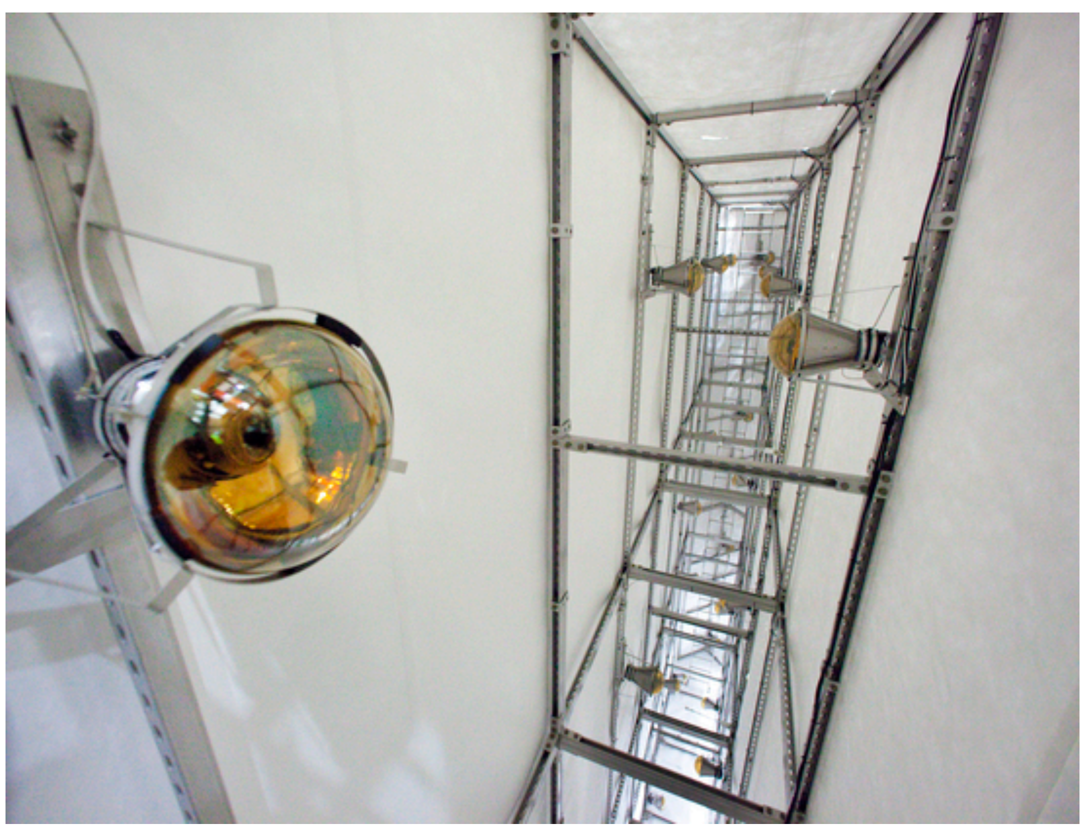


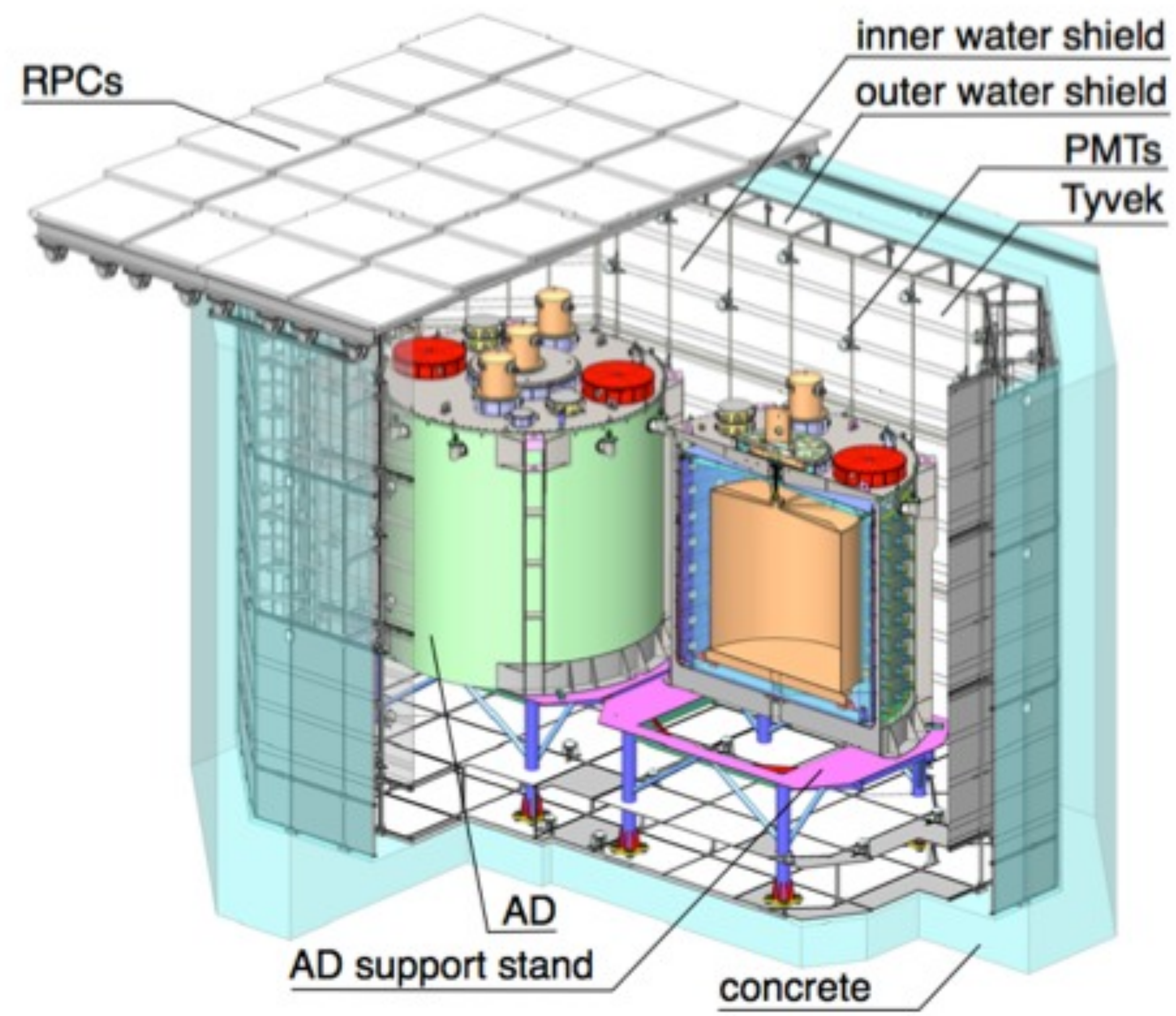
Daya Bay gamma non-linearity



Daya Bay Muon Veto System

- A three-part muon detector:
  - Optically separated inner and outer water pool
    - Passive gamma and neutron shielding
    - Active muon ID for rejecting cosmogenic backgrounds: 288 (near) and 384 (far) PMTs
  - RPC: Resistive plate chambers
    - Independent muon tagging





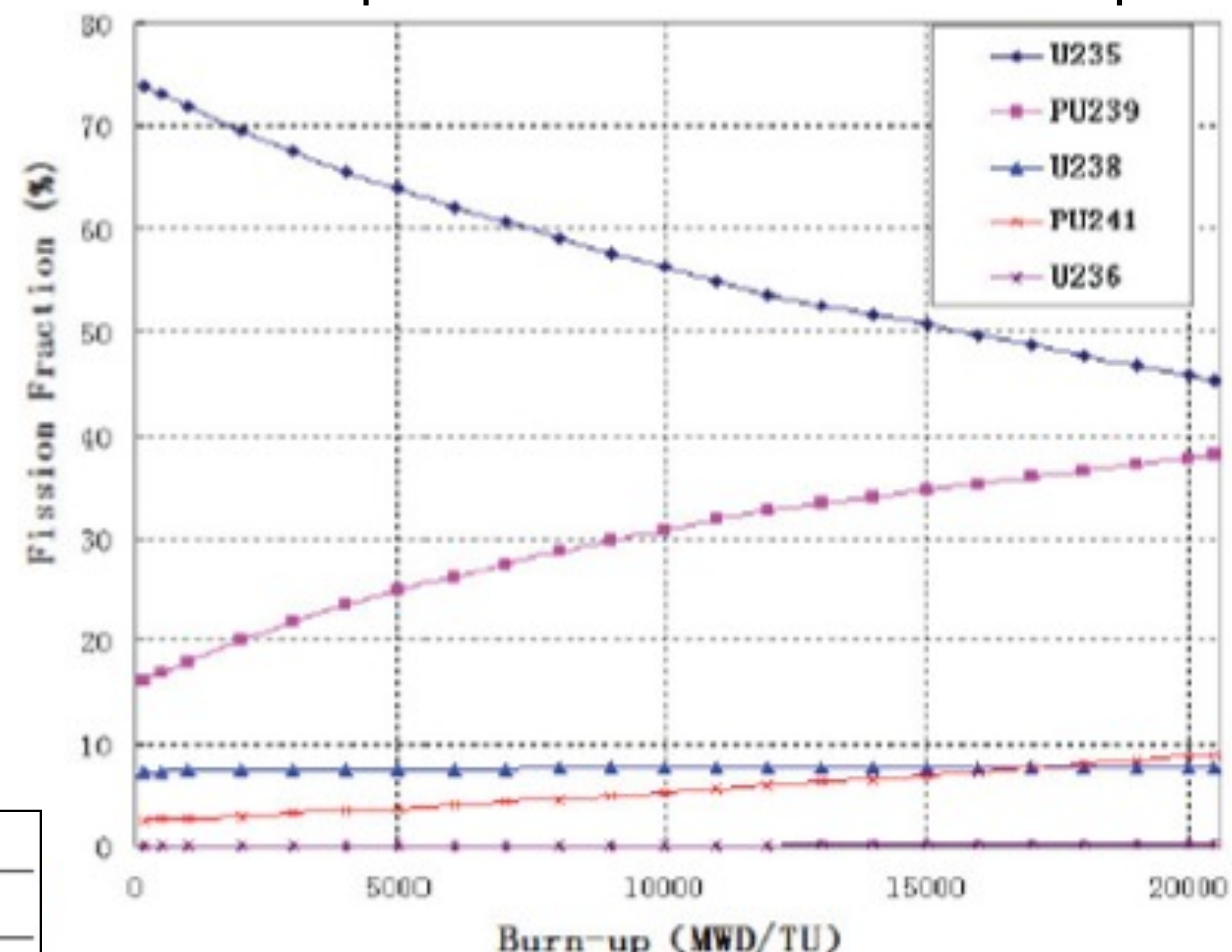
Reactor Antineutrino Flux Predictions

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



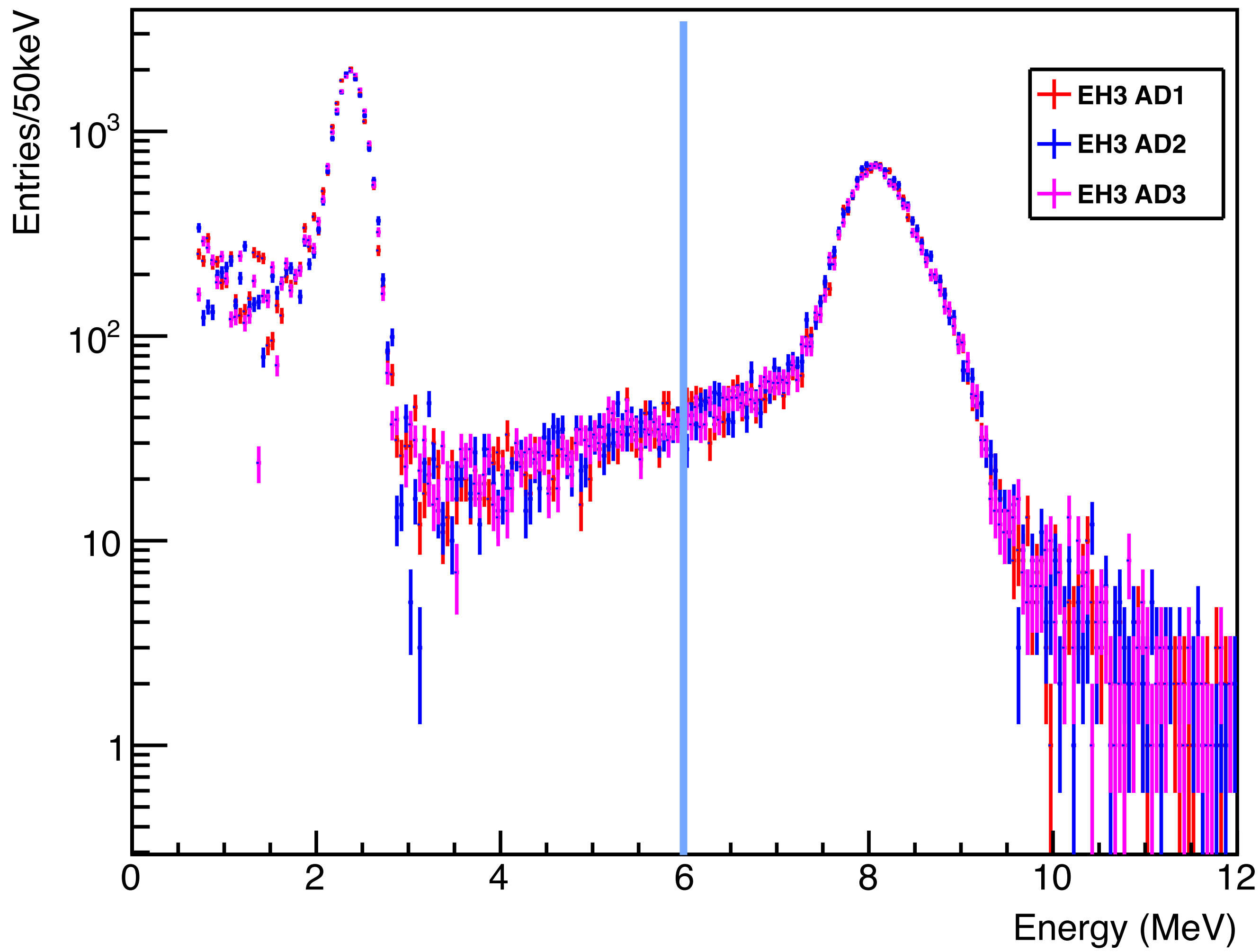
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

TABLE III. Summary of systematic uncertainties.

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

Relative Energy Scale Calibration

- Consistent energy scale = Consistent energy cut efficiency
  - Don't need to know absolute energy scale, efficiencies
  - Just need to know that cut energy is the same between all detectors
  - So what we should look for is relative differences in AD energy scales
    - Note: will eventually need full absolute energy scale calibration for shape analysis



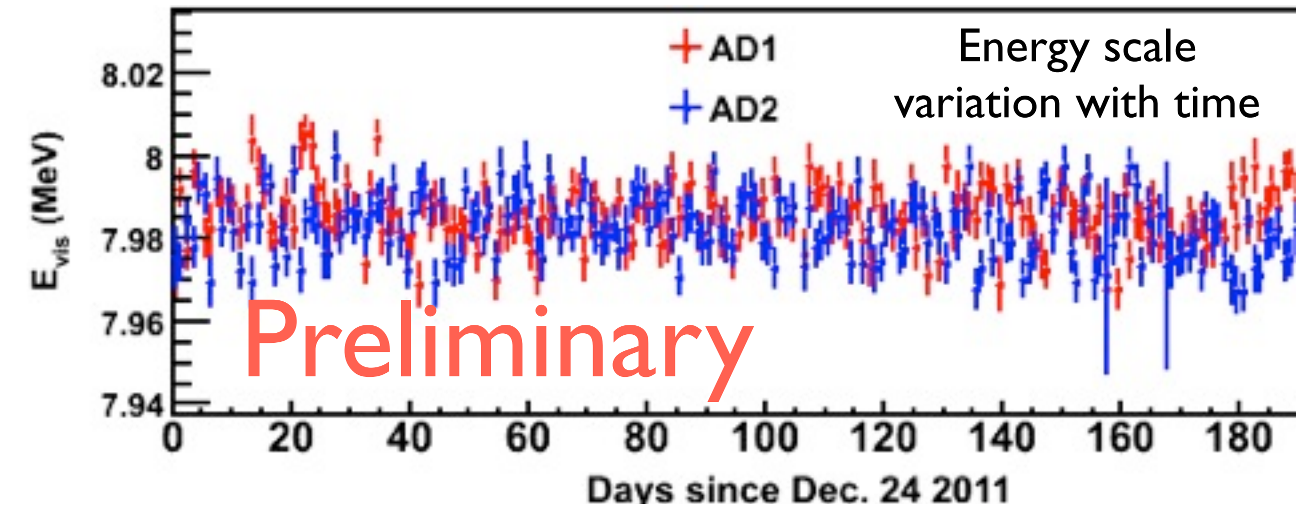
- Compare energy peaks between ADs to look for differences:
  - Different time-dependences
  - Different position-dependence
  - Different energy- and particle type-dependences

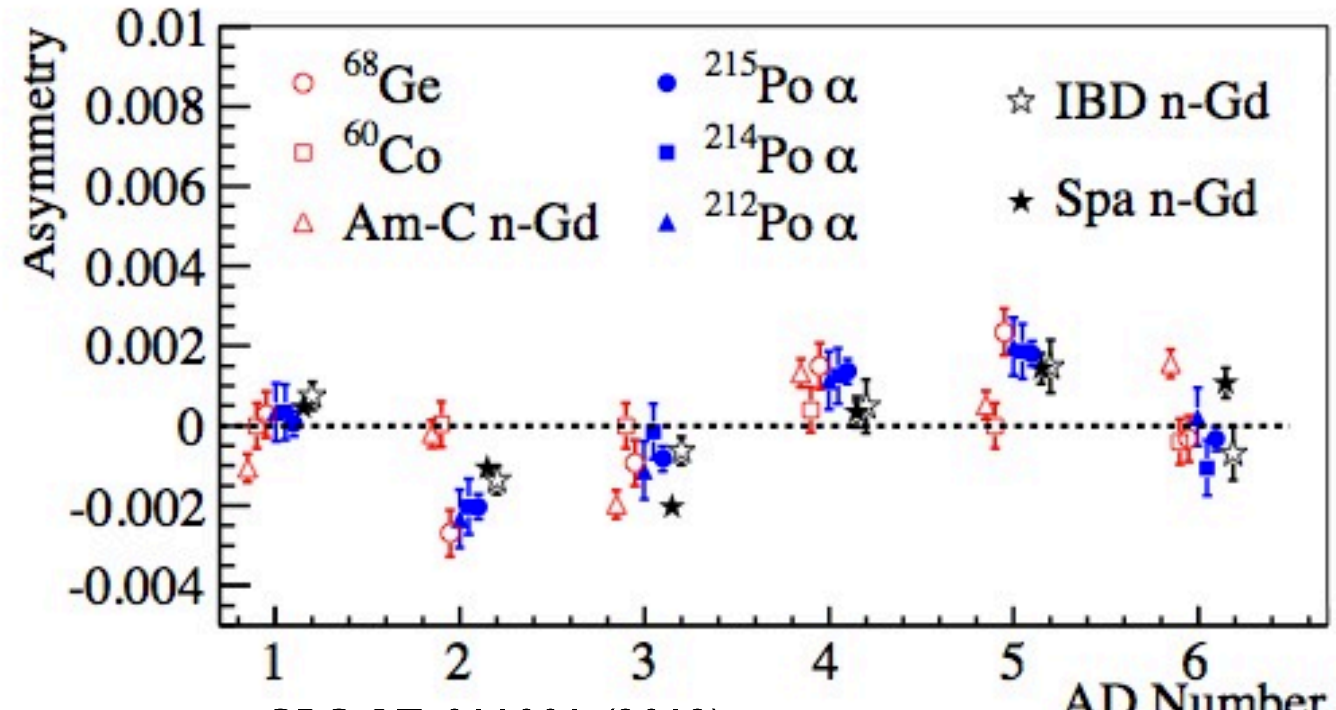
Relative Energy Scale Calibration

- Relative time variation very small (<0.1%)

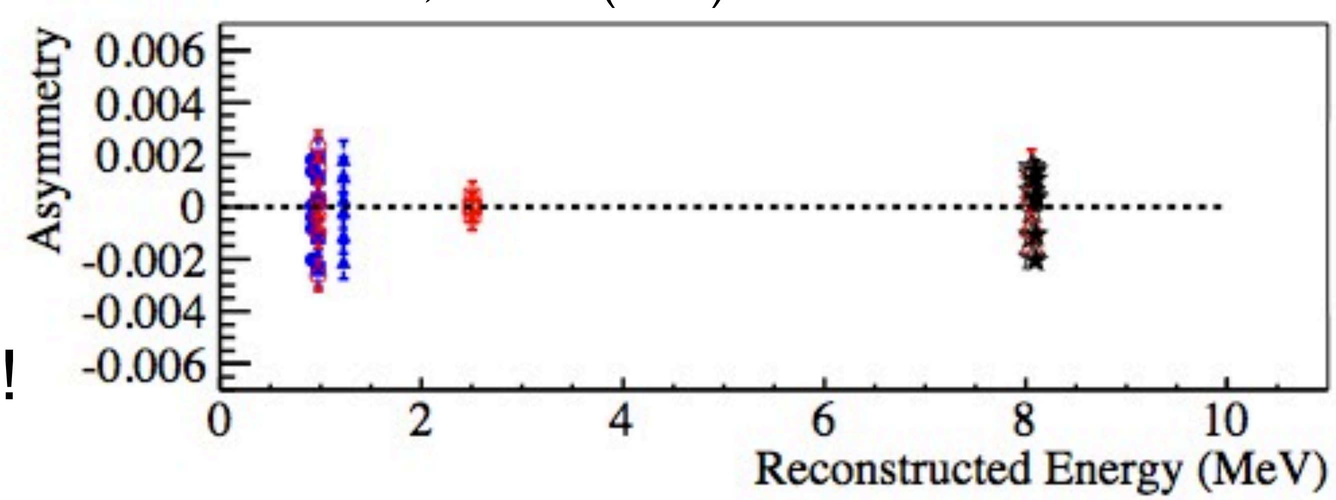
- Examine per-AD deviation from mean e-scale
  - No clear dependence on AD, energy, or position distribution

- Conservatively estimate relative energy scale uncertainty as 0.5%
  - Leads to 0.12% delayed energy cut efficiency
  - Previously expected to be largest relative detector systematic at 0.3%!!



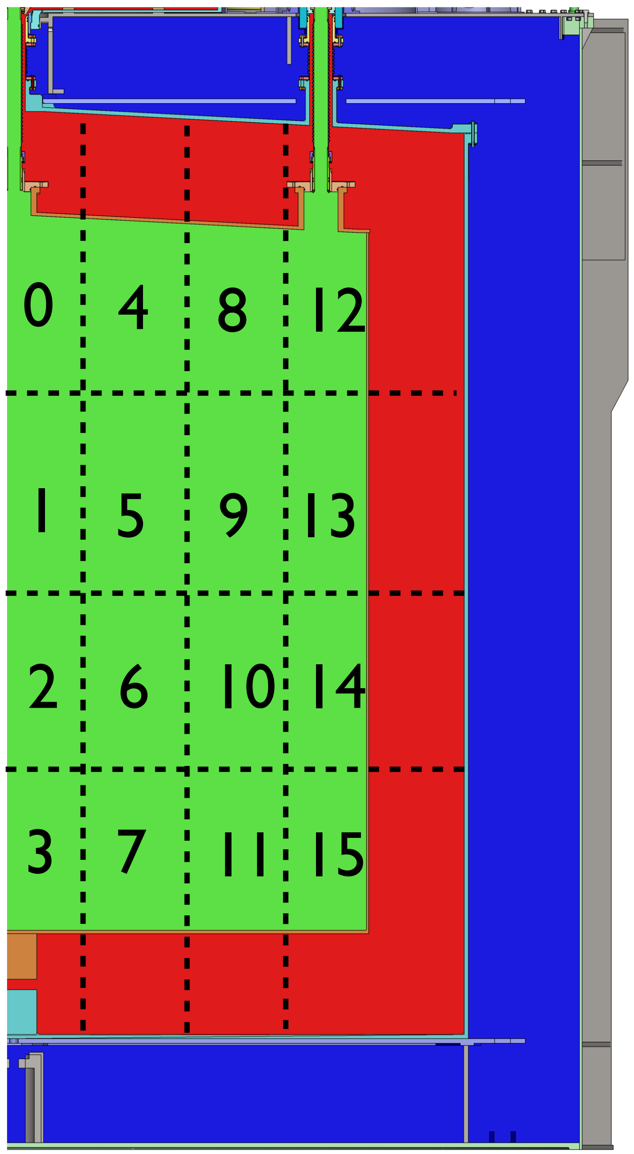


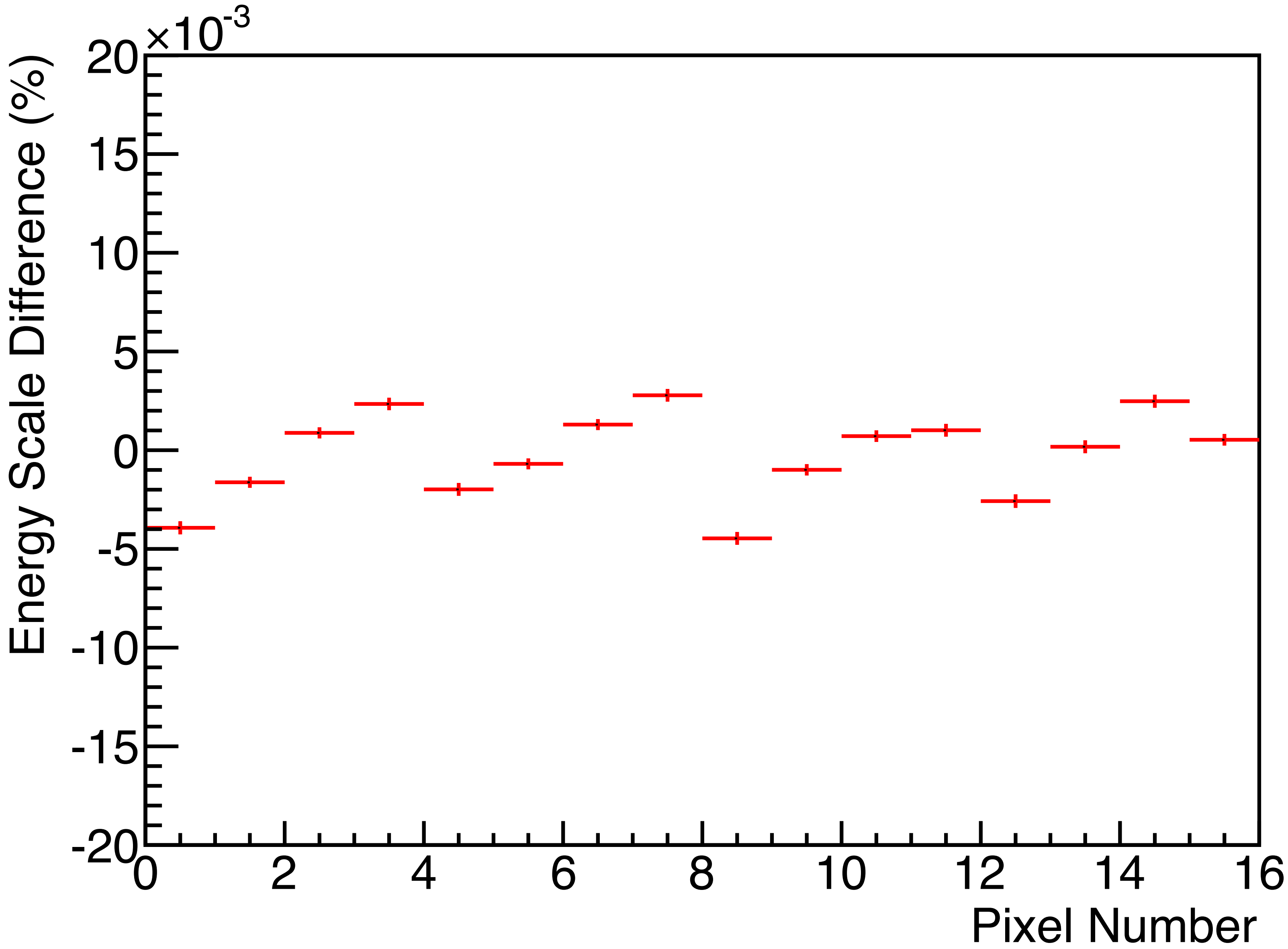
CPC **37**, 011001 (2012)



Relative Energy Scale Calibration

- Position-dependence differences:
  - Look at AD1/AD2 difference in n-Gd energy peak versus location
  - Can sample entire target volume, rather than only ACU z-axes!

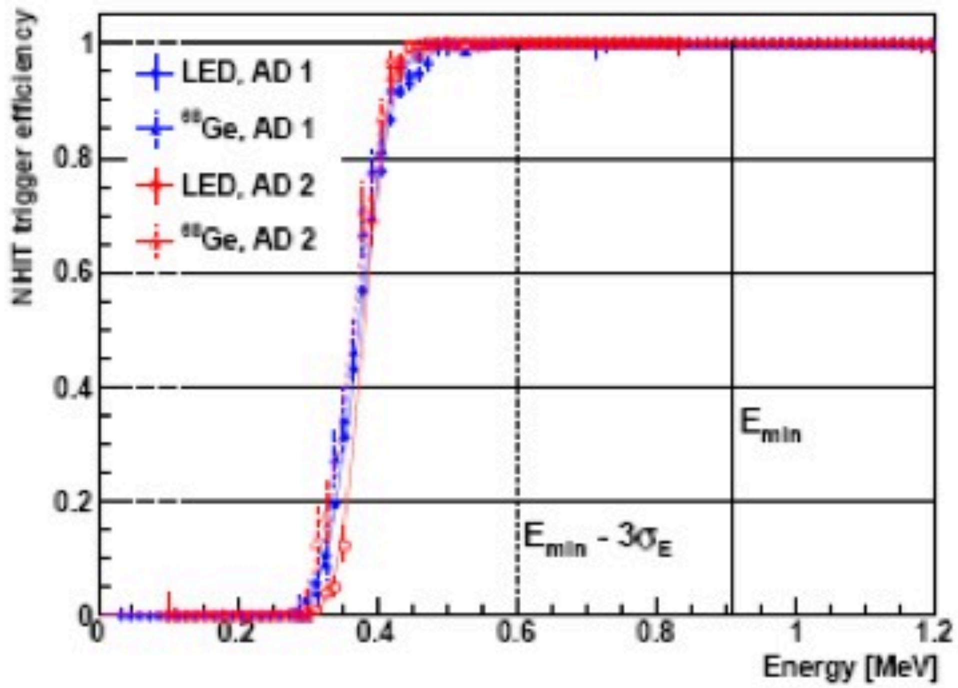


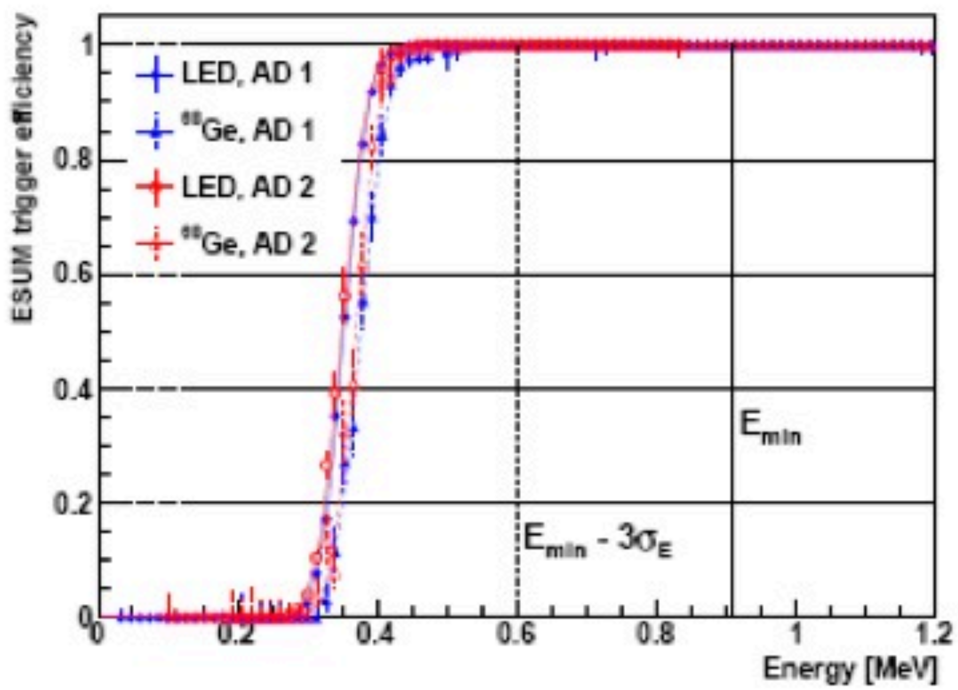


- All regions of target have identical energy scale with an RMS of 0.25%

Pre-selection: Trigger

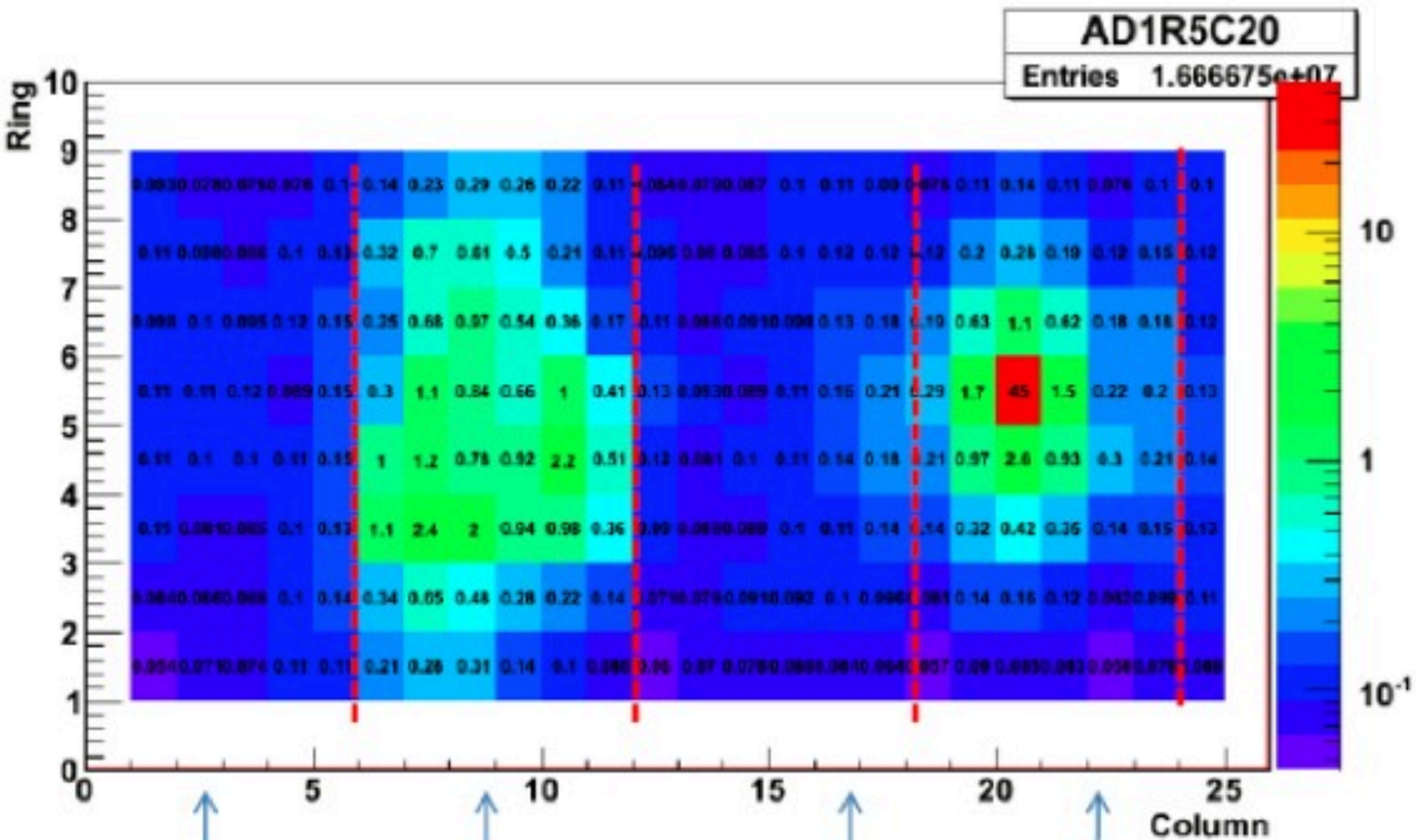
- Trigger thresholds:
  - Discriminator: 1/4 PE
  - AD:
    - NHit trigger: >45 PMTs
    - ESum trigger: >0.4 MeV
  - Inner Water Veto: >6 PMTs
  - Outer Water Veto: >7PMTs
- Trigger Efficiency:
  - Absolute efficiency cross-checked between 2 independent AD triggers
  - No measurable inefficiency >0.7 MeV



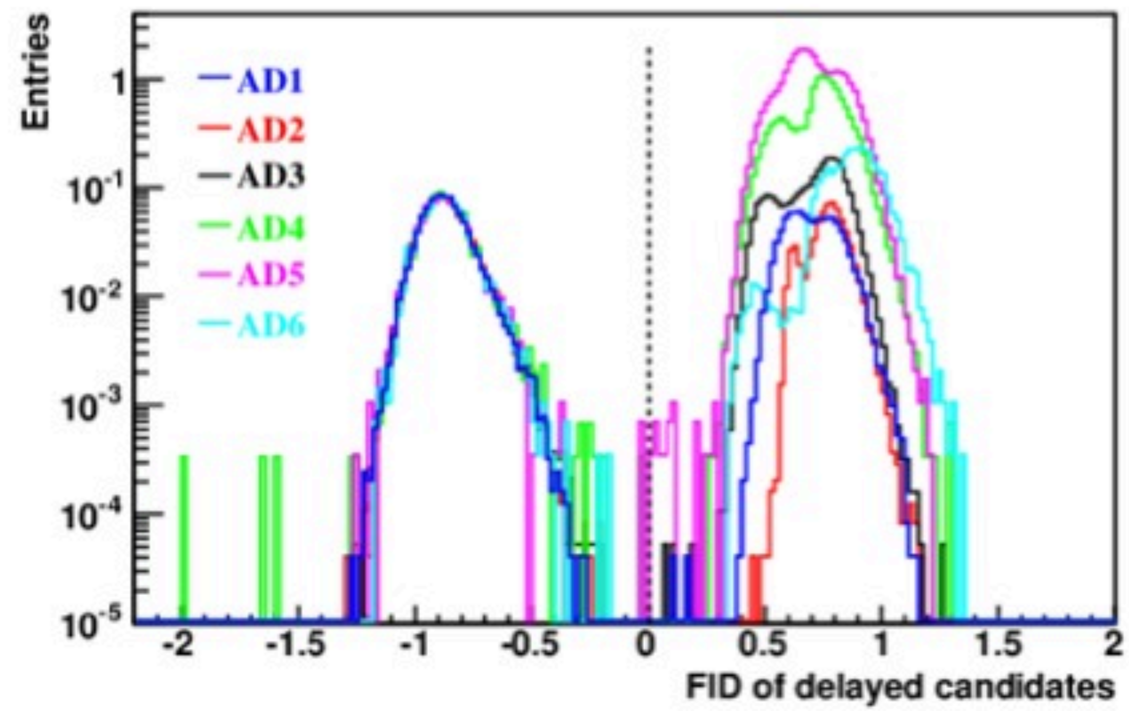


Pre-selection: Flasher Removal

Flashing PMTs:
- Instrumental background from ~5% of PMTS
- 'Shines' light to opposite side of detector
- Easily discriminated from normal signals



Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1, where the hottest PMT locates

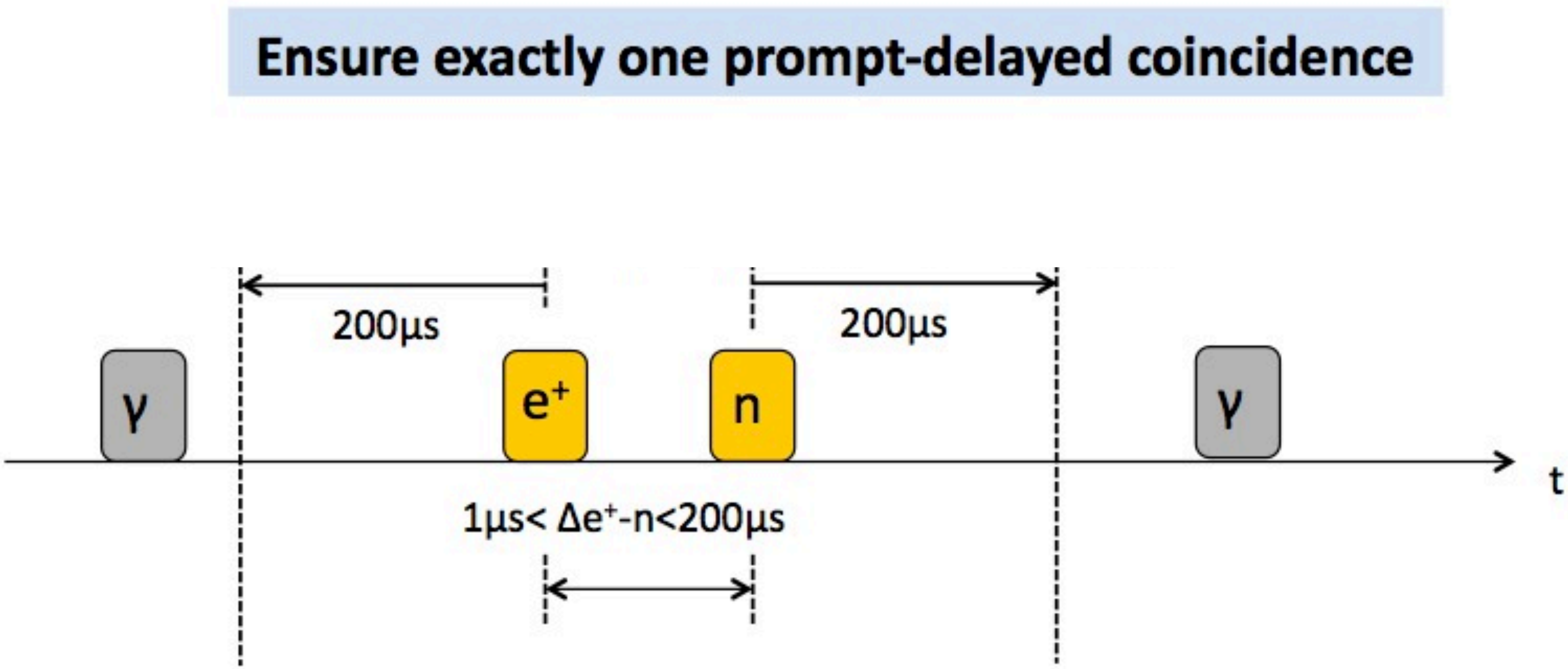


$$\log\left(\left(\frac{Quadrant}{1.}\right)^2 + \left(\frac{MaxQ}{0.45}\right)^2\right) < 0$$

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

Inefficiency to antineutrinos signal: 0.024% ± 0.006%(stat)
Contamination: < 0.01%

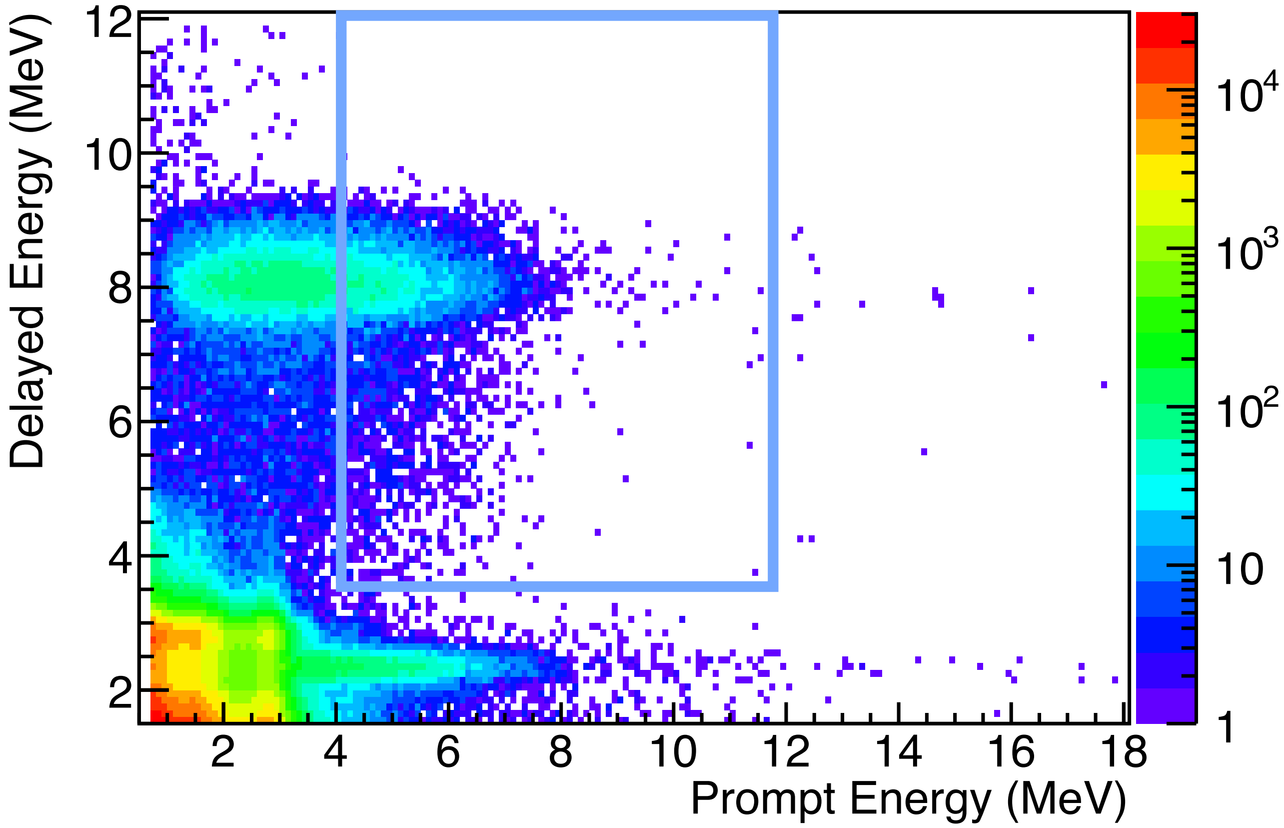
Efficiency: Multiplicity

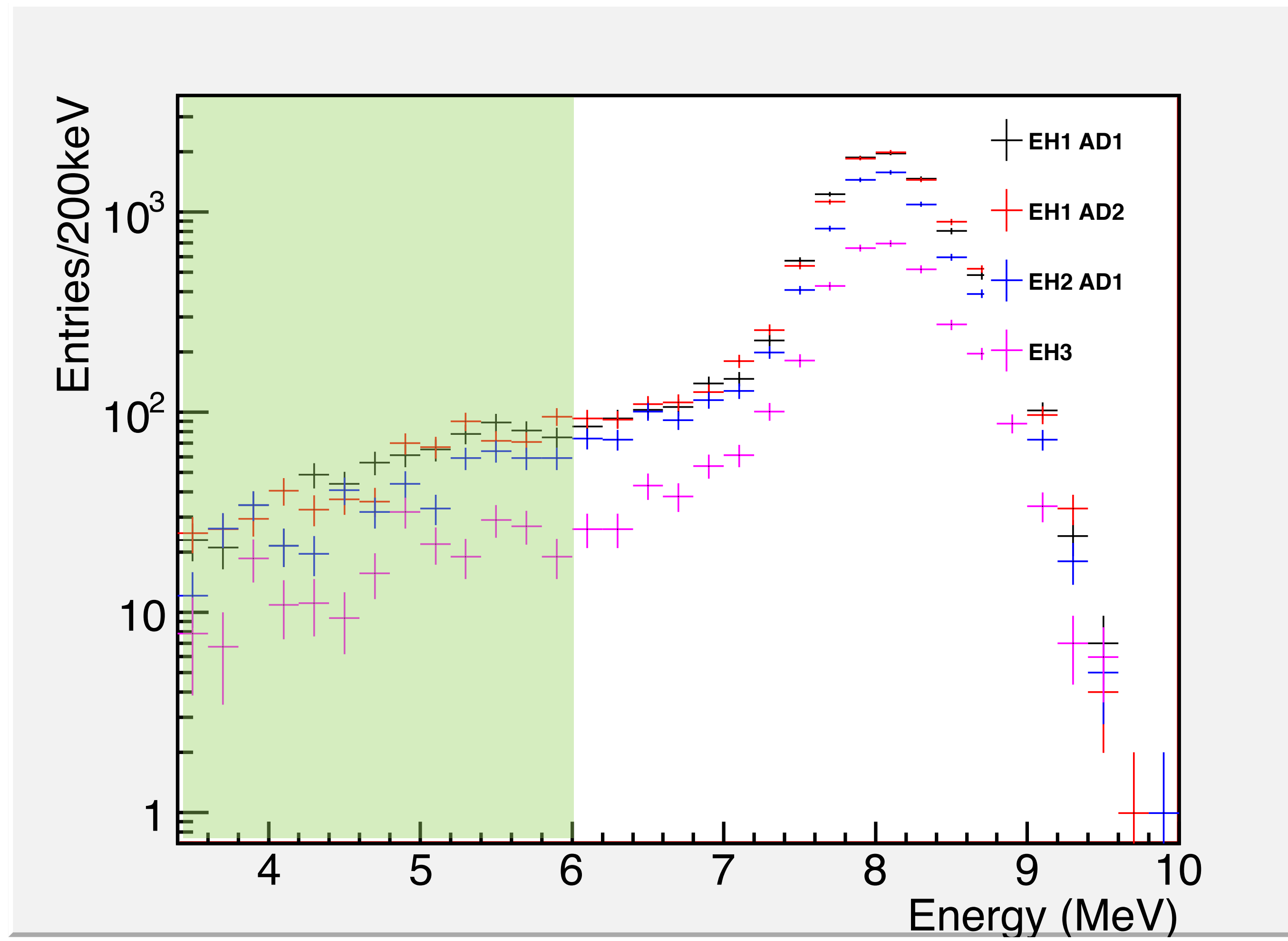


- If we have an extra trigger near IBD, which triggers are which?
- Reject all IBD with extra triggers above 0.7 MeV within 200 μs of a coincidence
- Introduces 2.5% inefficiency, negligible uncertainty since singles are well-measured

Neutron Efficiency: Identical Tail Shape

- This estimate assumes identical tail shapes for each AD; need to test this assumption:

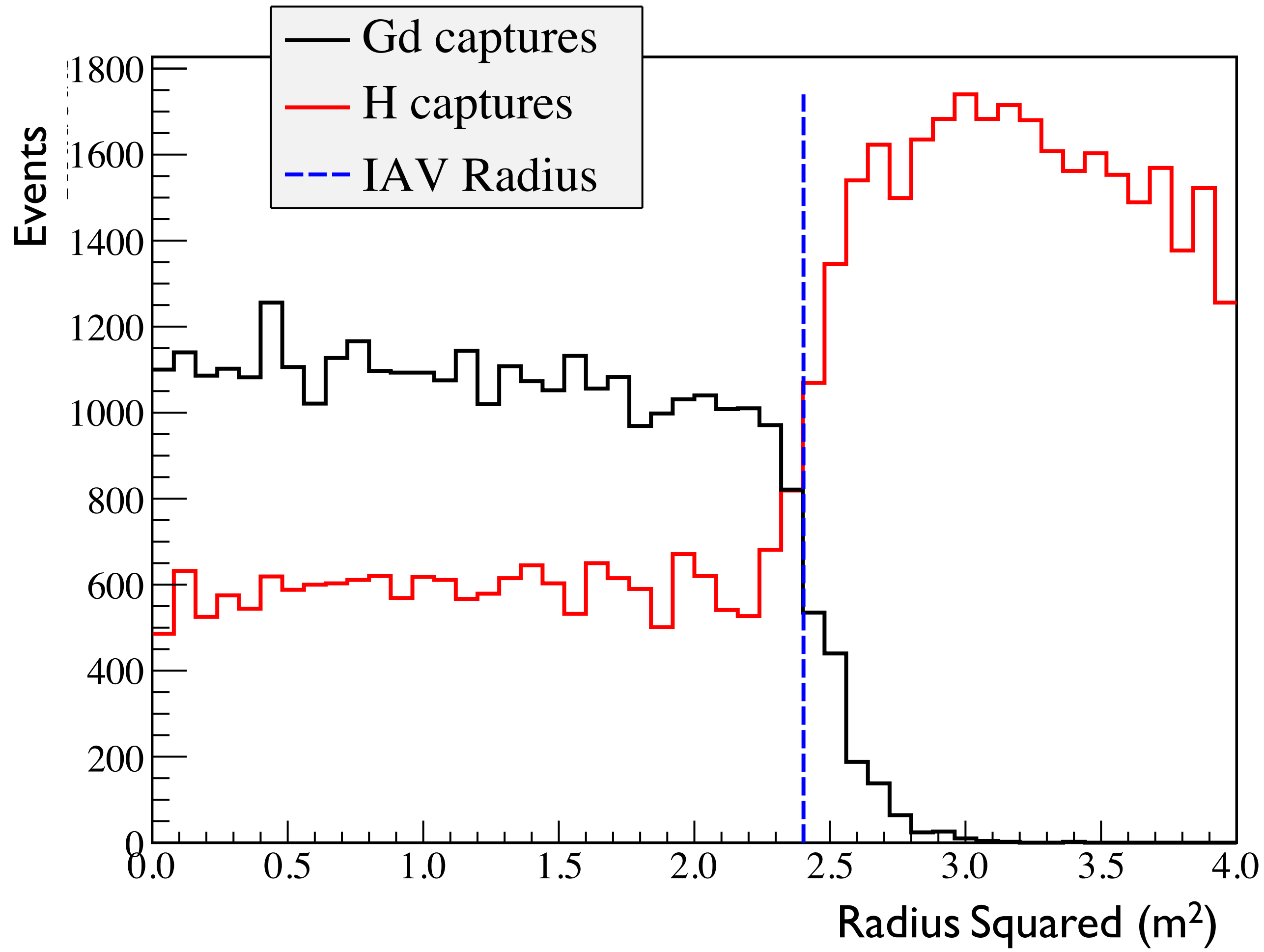




- Select a high-purity IBD sample by requiring E_{prompt} > 4MeV
- Compare IBD neutron tail size to rest of distribution
- Results consistent with identical tail shapes between detectors
- Demonstrates why having identical detectors is so important: our relative efficiency uncertainty estimates aren't valid otherwise!

Spill-In/Out

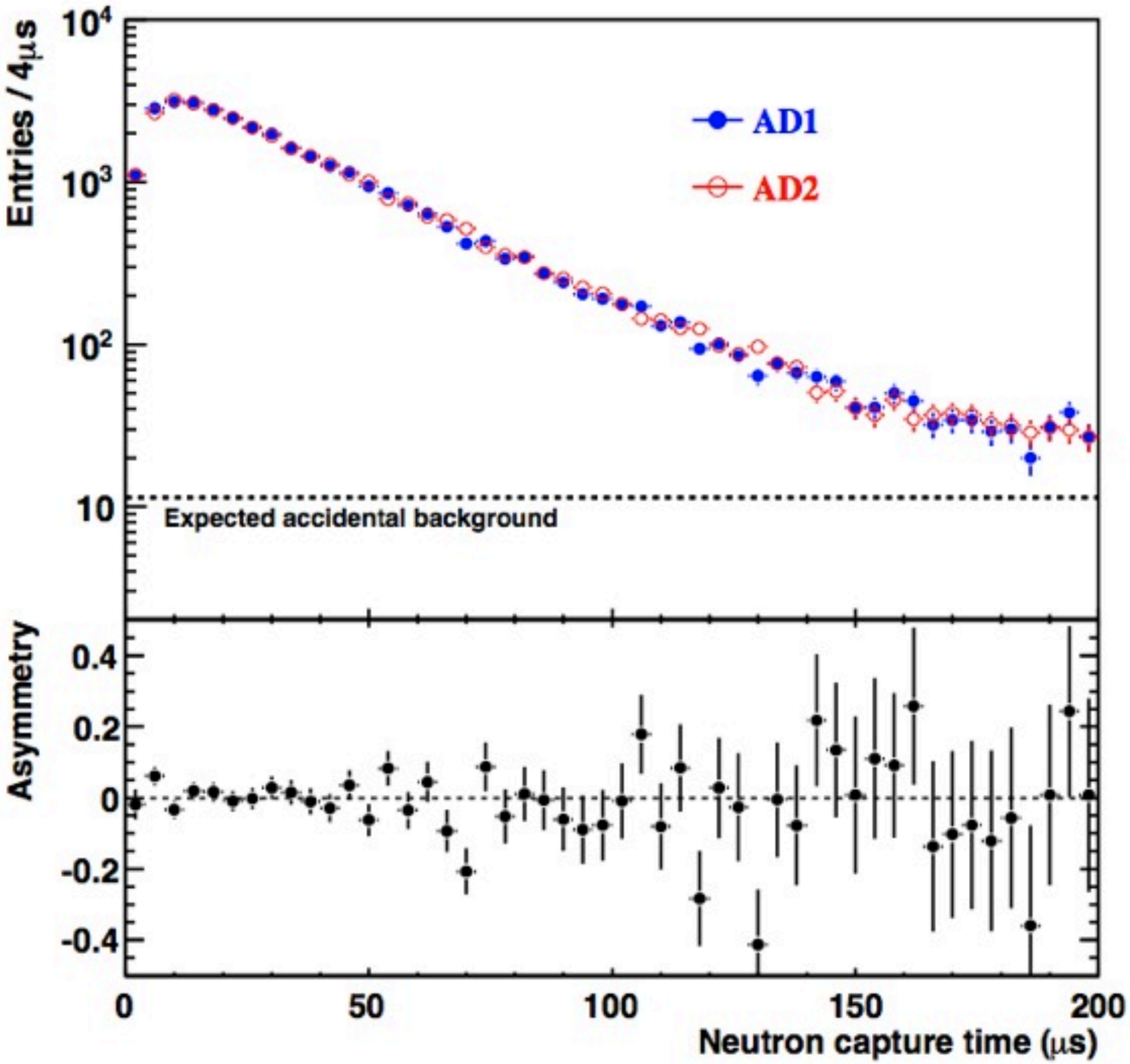
- We know target mass, total IBD interactions, are the same to 0.03% for all ADs
- Are IBD contributions from other regions the same for all ADs?



- Physical detector differences can cause differing number of SI-SO events:
  - From characterization, only relevant physical differences are in IAV dimensions and thickness (~1mm)
- Simulated these variations:
  - 1mm IAV thickness variation changes spill-in IBD 0.02%
  - cm-level changes in IAV height, diameter change spill in much less than 0.01%.

Capture Time Cut Efficiency

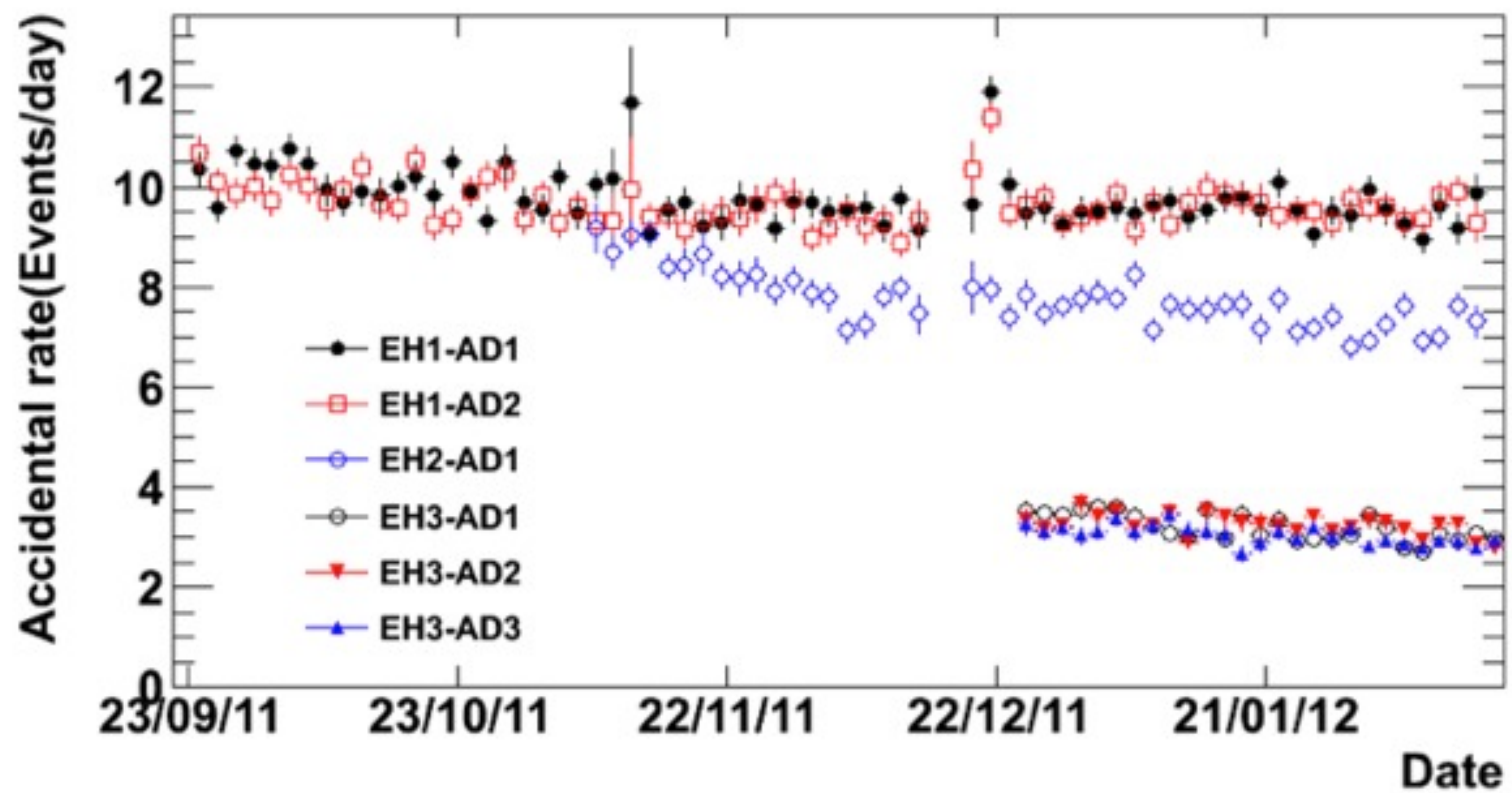
Consistent IBD capture time measured in all detectors



- Contributors:
  - Relative timing uncertainty: estimated to be 10 ns
  - Difference in tail shape: arises from difference in spill-in effect, which we know is very small.
- Leads to very small relative time cut uncertainty: 0.01%

Backgrounds: Accidentals

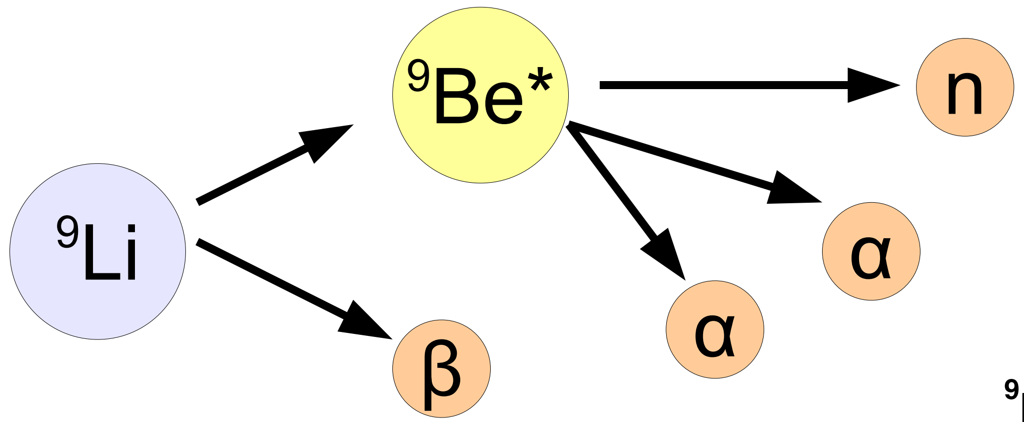
- Two uncorrelated singles can accidentally mimic an IBD event
- A well-understood background, since singles can be counted with high statistics
- Can estimate B/S with less than 0.1% uncertainty



	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
B/S	1.37%	1.38%	1.44%	4.58%	4.77%	4.43%

Backgrounds: $^{8}He/^{9}Li$

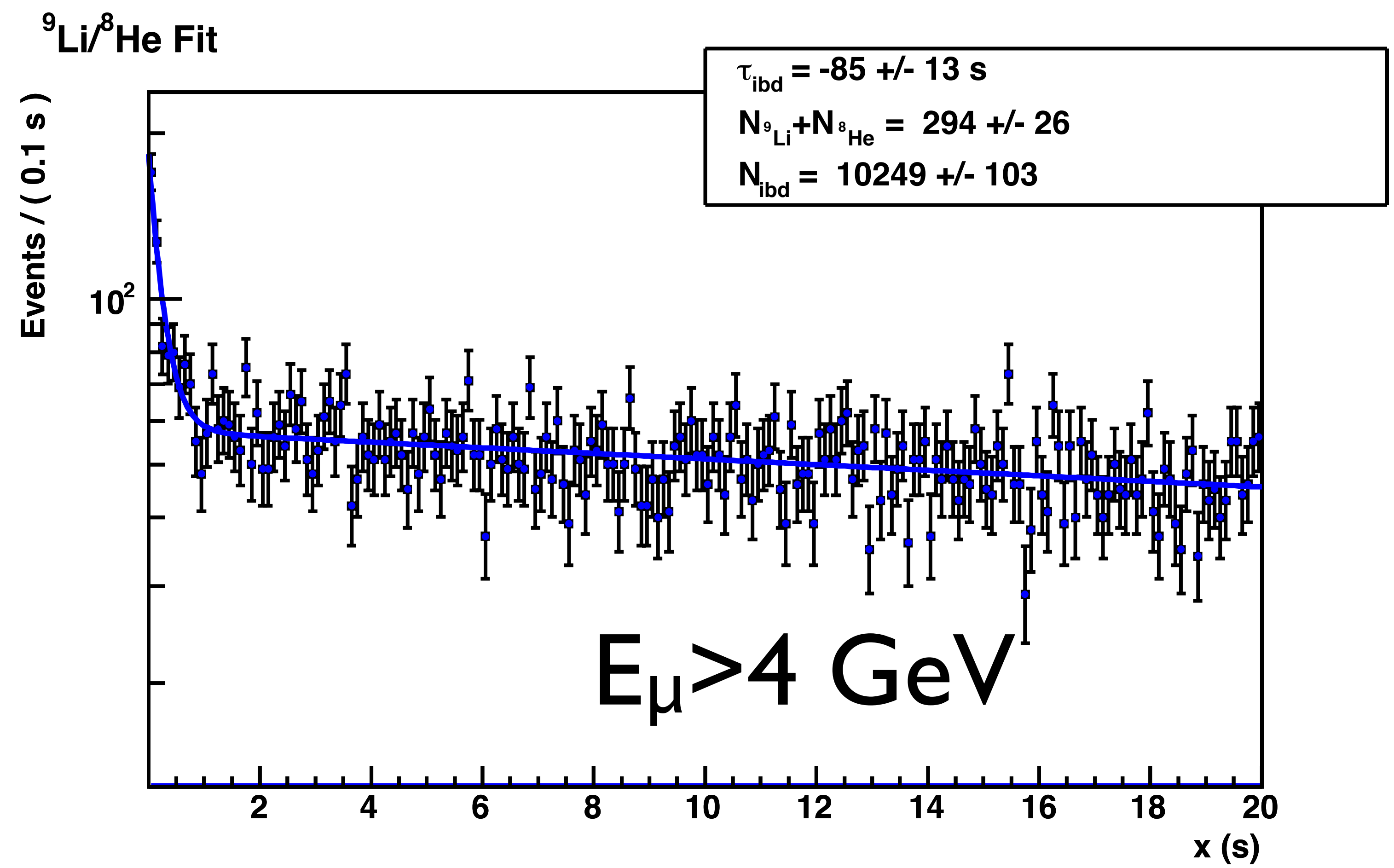
β-n decay:
- Prompt: β-decay
- Delayed: neutron capture



^{9}Li: $\tau_{1/2} = 178$ ms, Q = 13. 6 MeV

^{8}He: $\tau_{1/2} = 119$ ms, Q = 10.6 MeV

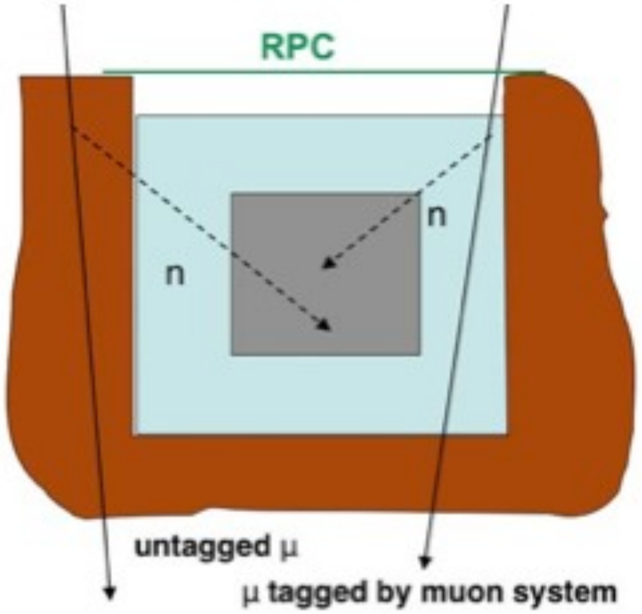
- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signals

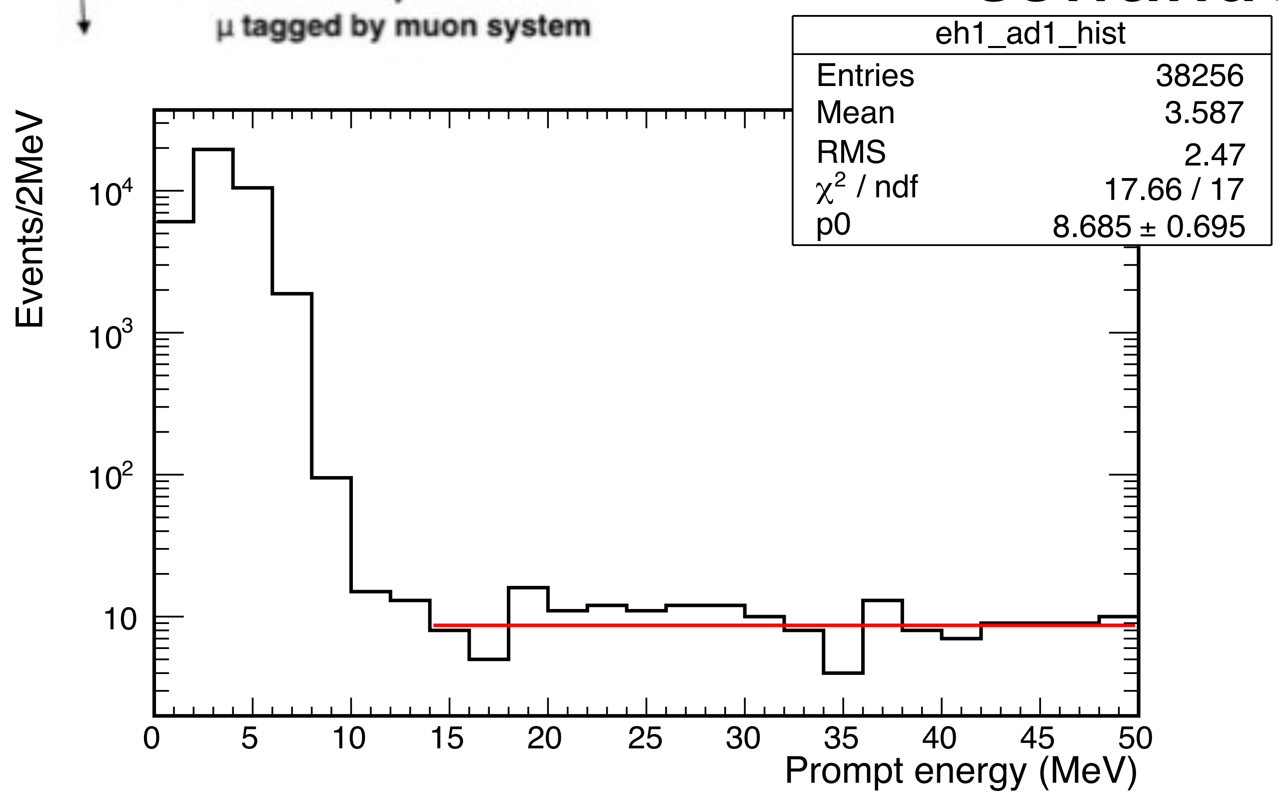


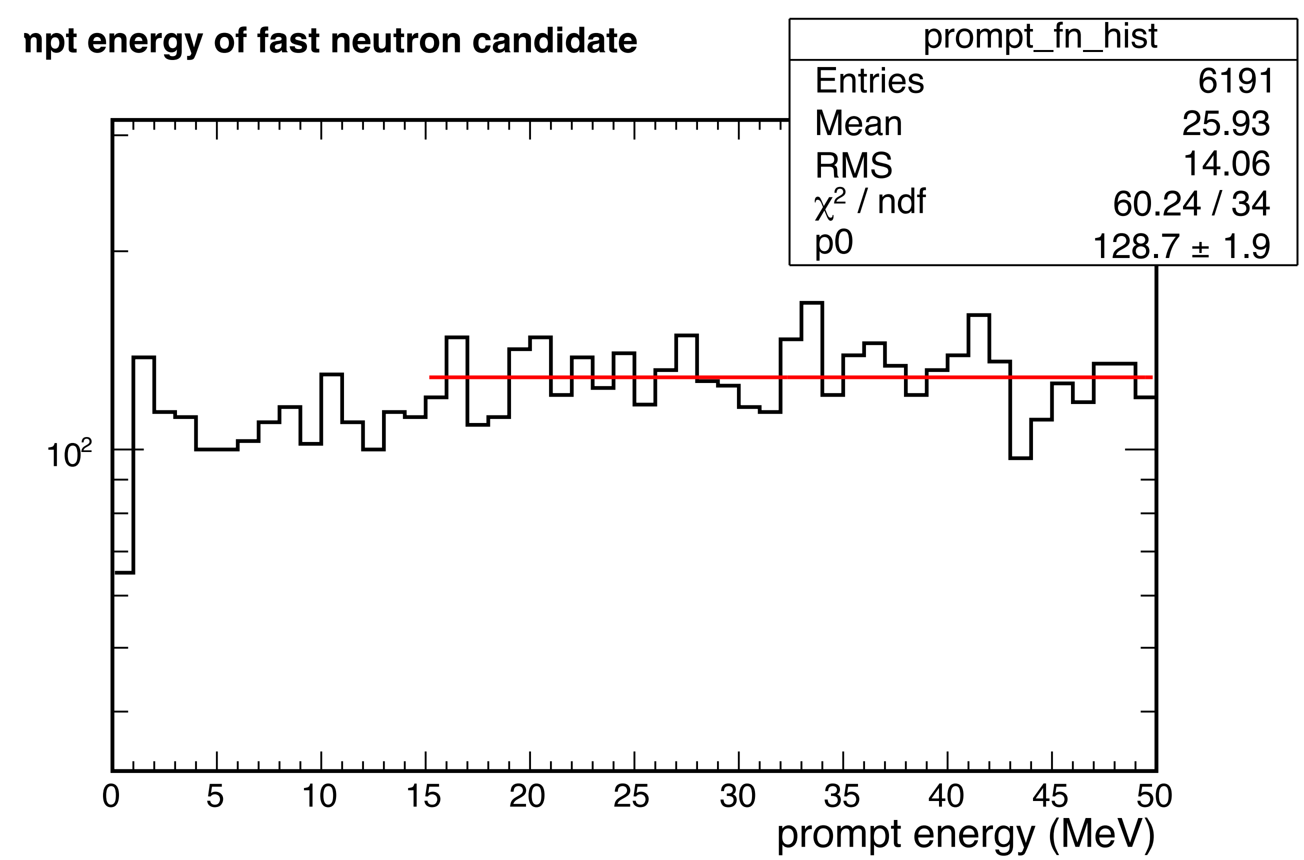
- Muon veto cuts control B/S to 0.4% ± 0.2%

Backgrounds: Fast Neutron

- Hard-to-shield cosmogenic products
- Produce proton recoils (prompt) and n-Gd capture (delayed)
- Muon-tagged fast neutrons: continuous prompt spectrum







- Statistical subtraction of continuous spectrum controls B/S to 0.1% ± 0.1%

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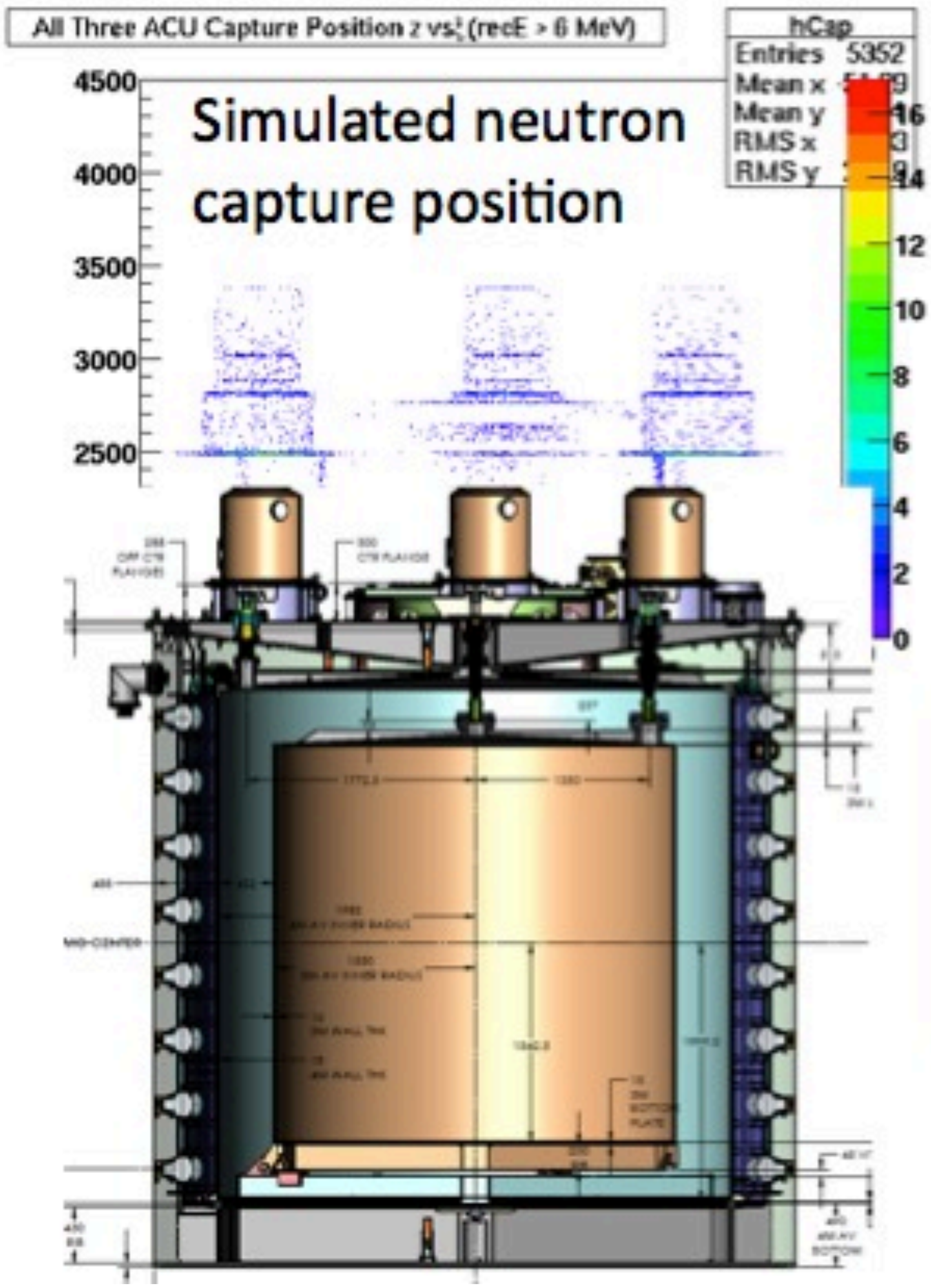
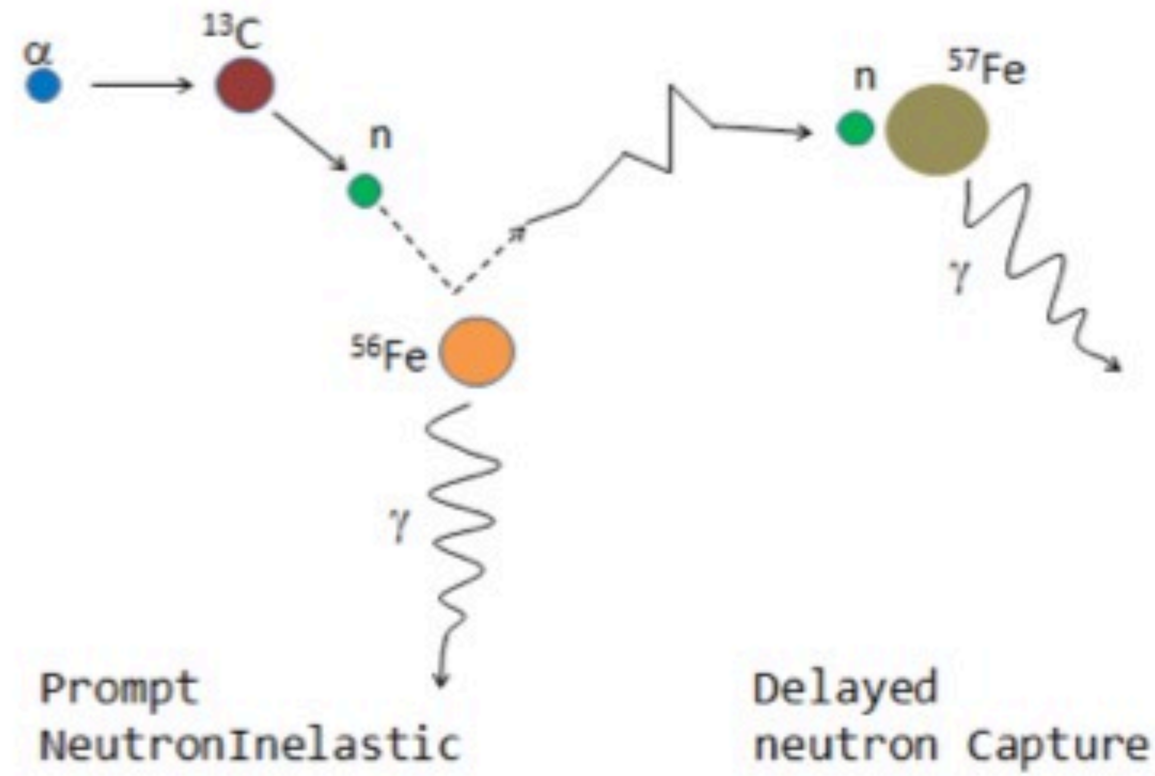
Backgrounds: $^{241}Am^{12}C$ Source

Weak (0.5Hz) neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.



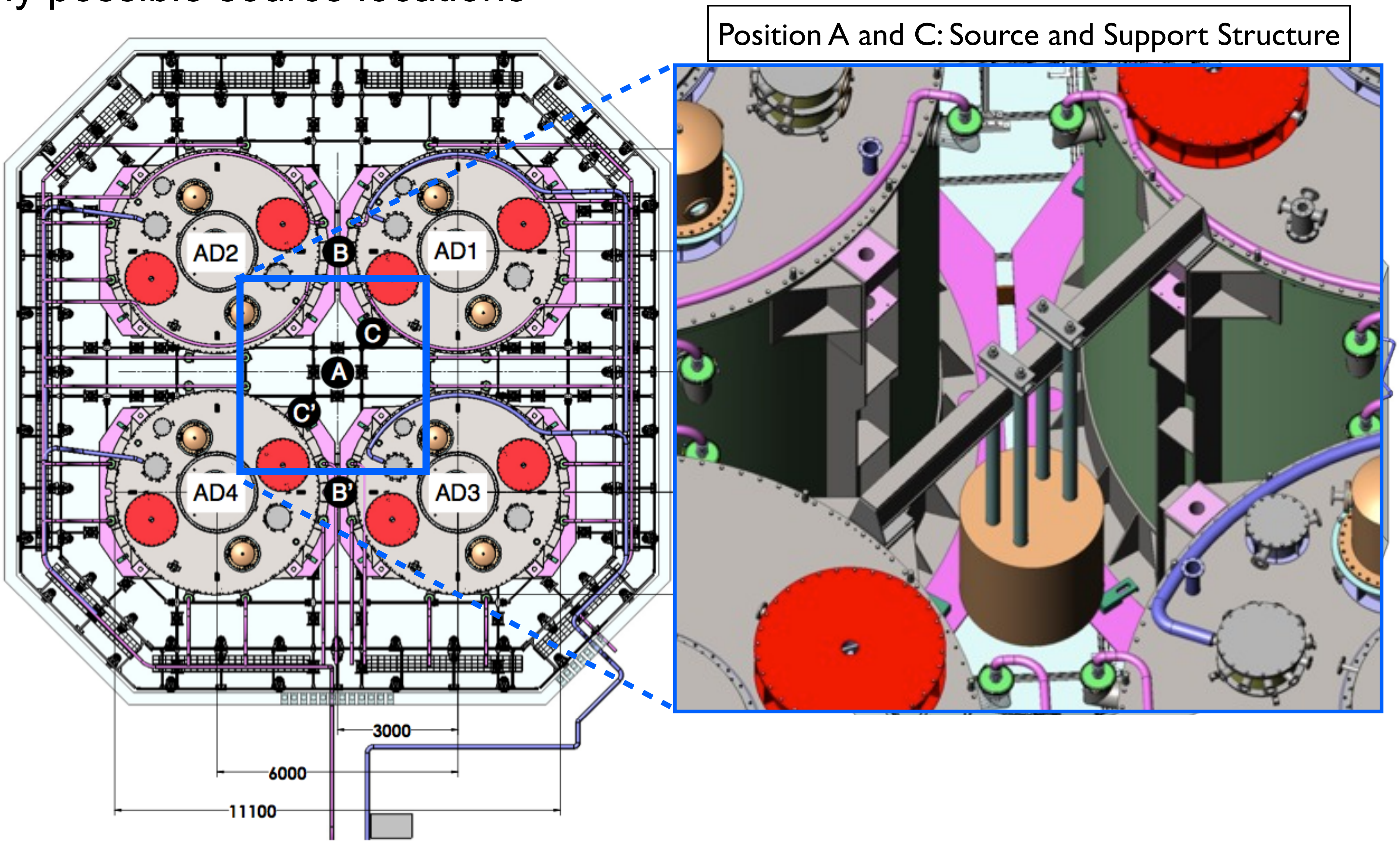


Constrain far site B/S to 0.3 ± 0.3%:

- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation

More Neutrinos?

- D. Dwyer, K. Heeger, B. Littlejohn, P. Vogel; arXiv:1109.6036
- 18 PBq ^{144}Ce source at the Daya Bay far site
  - Look for very short baseline oscillation from large Δm_{new}^2
  - 35 cm thick Tungsten source shield, water pool reduce gamma backgrounds
  - Many possible source locations



After θ_{13}: A Sterile Neutrino Search

- With 1 year of running, 30k-40k IBD detections
- Backgrounds:
  ~0.5 m thick shielding, water pool, shield gammas
  Reactor neutrino flux well-known to <1% from near halls
- Detector systematics:
  - Well-understood from Daya Bay θ_{13} measurement
- Sensitivity:
  - Shape+rate analysis can rule out large majority of reactor anomaly, 3+1 global fits to 95% CL with one year of data.