The Elusive Neutrinos – neutrino oscillation, mixing and mass hierarchy

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What is Neutrino?
什麼是微中子？

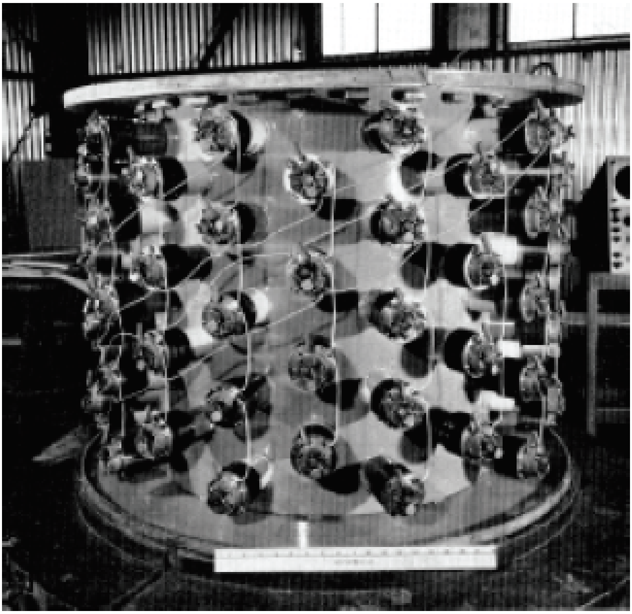
It's nothing, almost nothing. As would say F.Reines, it is "... the most tiny quantity of reality ever imagined by a human being". Despite that (or because of that!), this particle never ceased to question physicists and to give headaches to the one who wants to detect it.

Discovery of neutrino

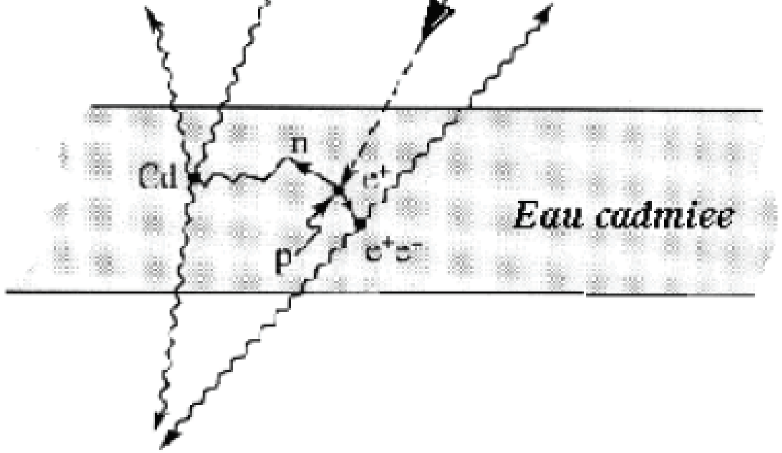
Reines & Cowen

1956

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



Detector of the 1953 experiment



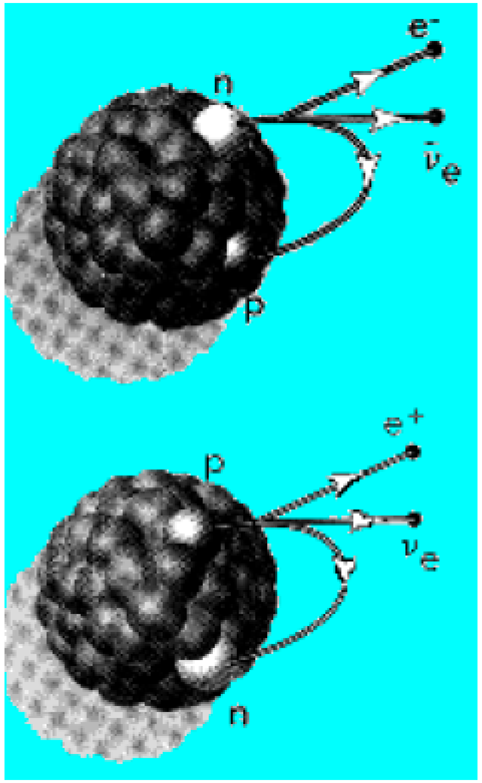
Scheme of the 1956 experiment

At Solvay conference in Bruxelles, in October 1933, Pauli says, speaking about his particles:

"... their mass can not be very much more than the electron mass. In order to distinguish them from heavy neutrons, mister Fermi has proposed to name them "neutrinos". It is possible that the proper mass of neutrinos be zero... It seems to me plausible that neutrinos have a spin 1/2... We know nothing about the interaction of neutrinos with the other particles of matter and with photons: the hypothesis that they have a magnetic moment seems to me not funded at all."

Spin 1/2, nearly massless, neutral particle!

from neutron decay



Physicists continue their quest !

1956

It took until 1956 before neutrinos were detected
They are difficult to detect

"All you have to do is imagine something that does practically nothing. You can use your son-in-law as a prototype"
-Richard Feynman illustrating the difficulty in detecting neutrinos

-Also, like your son-in-law, they change form when you are not looking

Double coincidence method reduces background

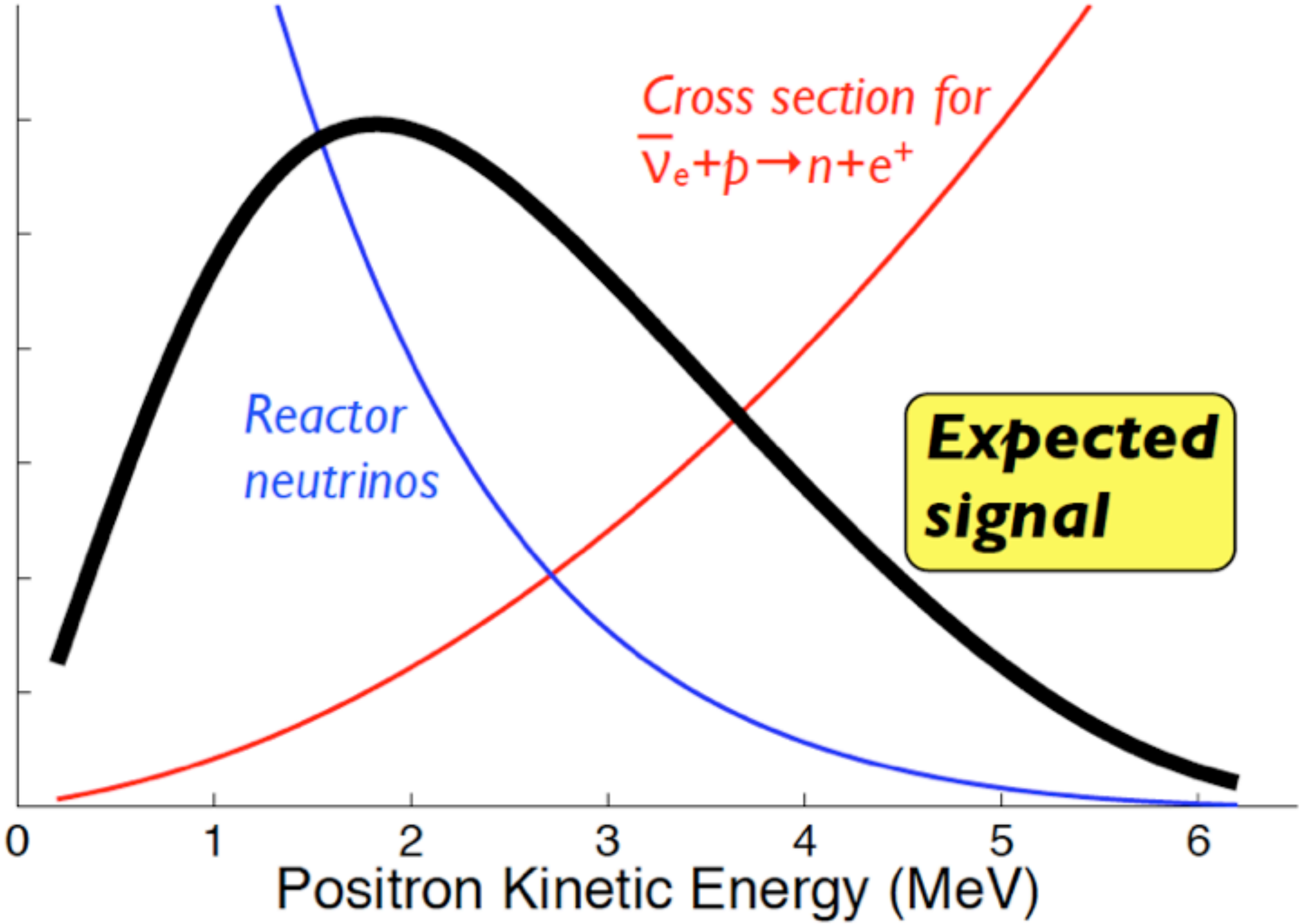
$\overline{\nu}_e + p \rightarrow e^+ + n$

Prompt signal in scintillator

Delayed 8 MeV total gammas on cadmium capture

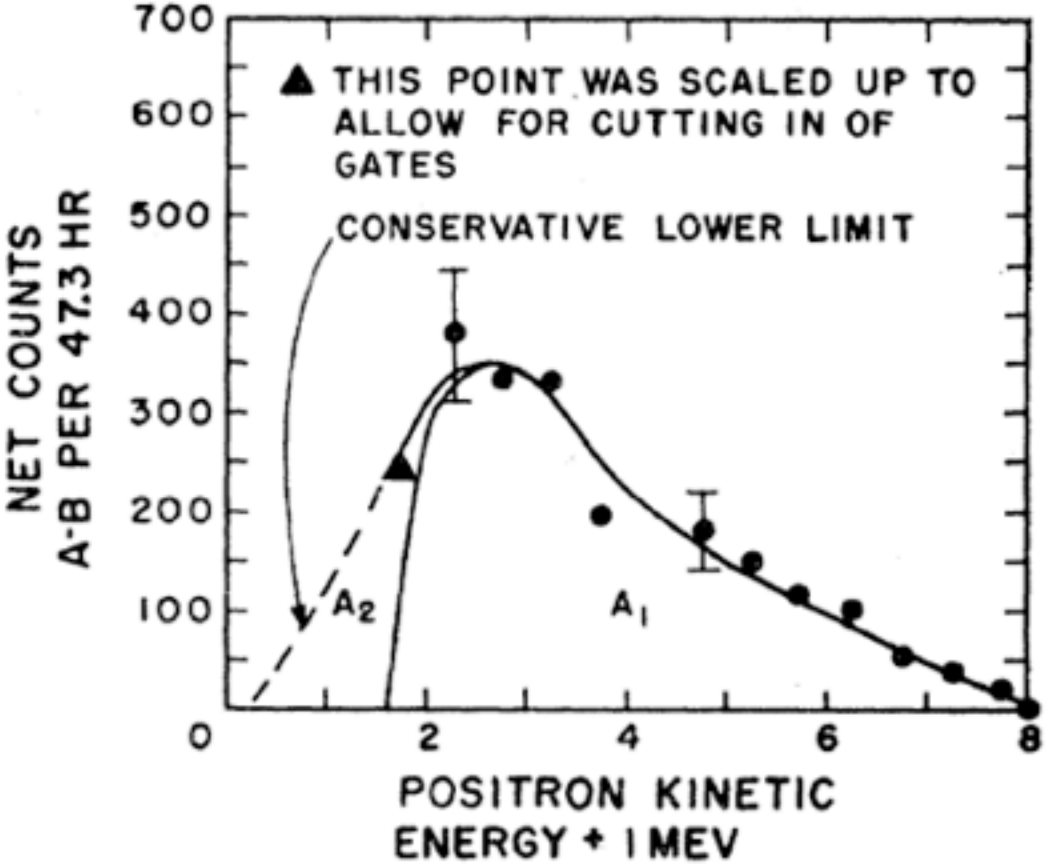
Short baseline (a few meters) + huge neutrino flux (>10 trillion $cm^{-2}s^{-1}$) enables small detector

Calculating the Neutrino Signal

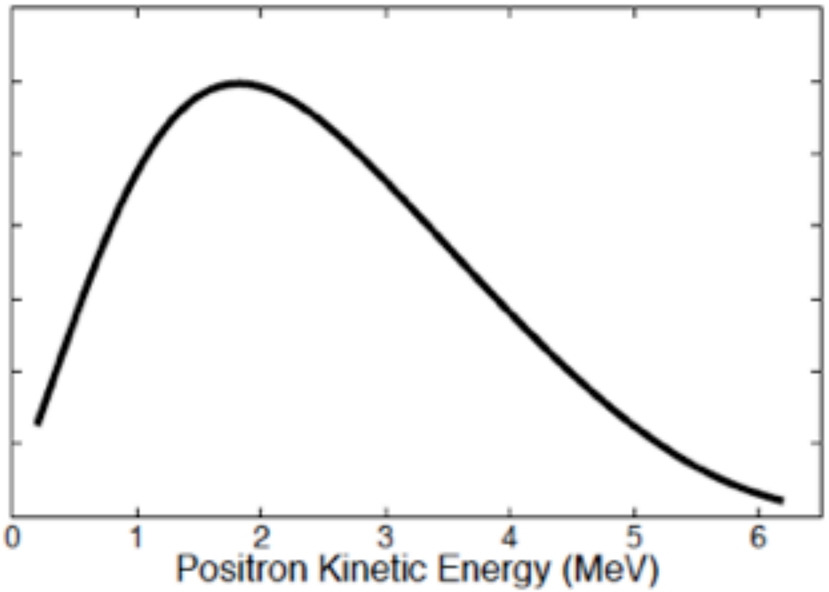


Measuring the Neutrino Signal

Reines and Cowan, Phys.Rev. 113(1959)273



Predicted Signal



Fred Reines
1995 Nobel Prize in Physics

Neutrinos?

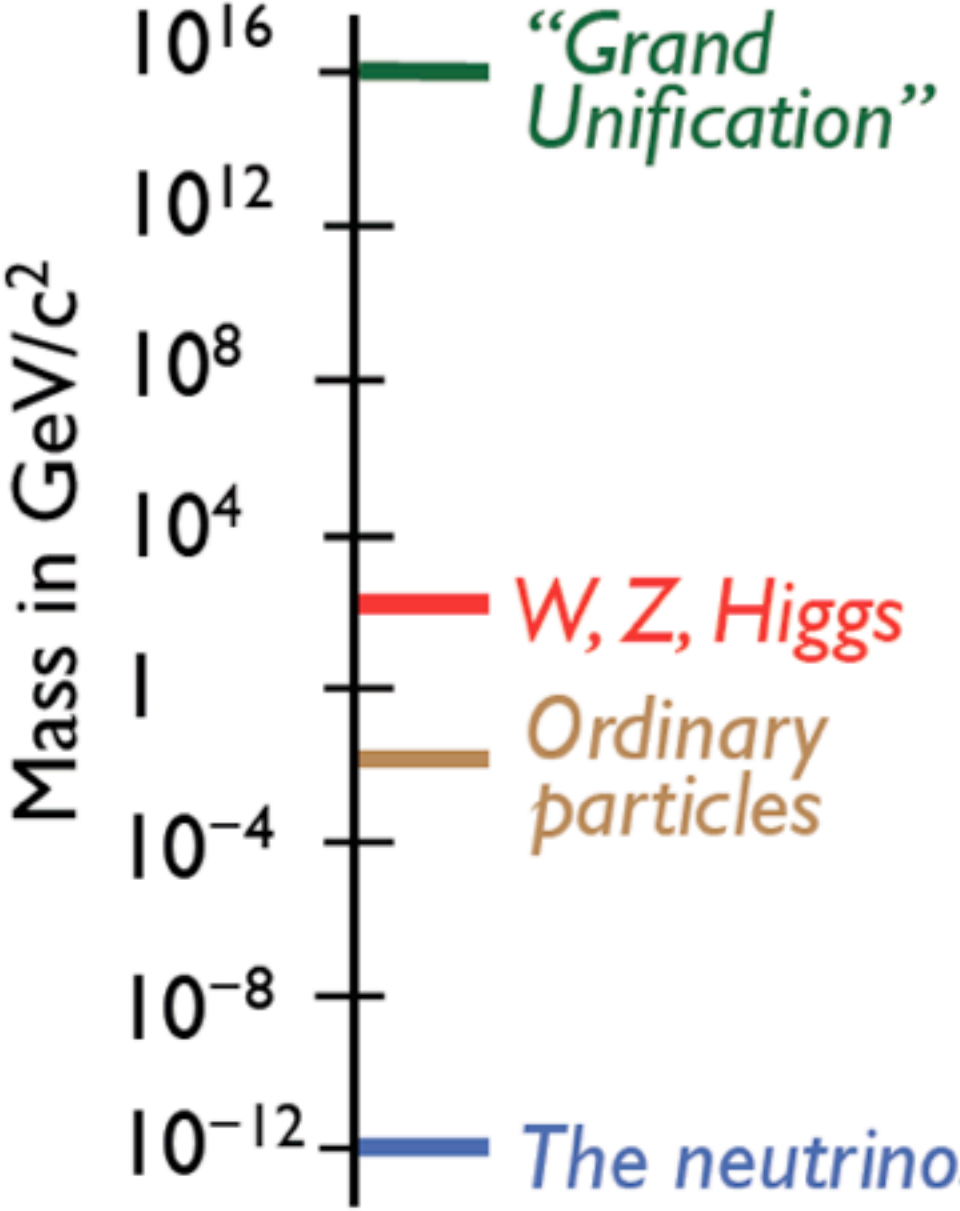
Neutrinos are weird!

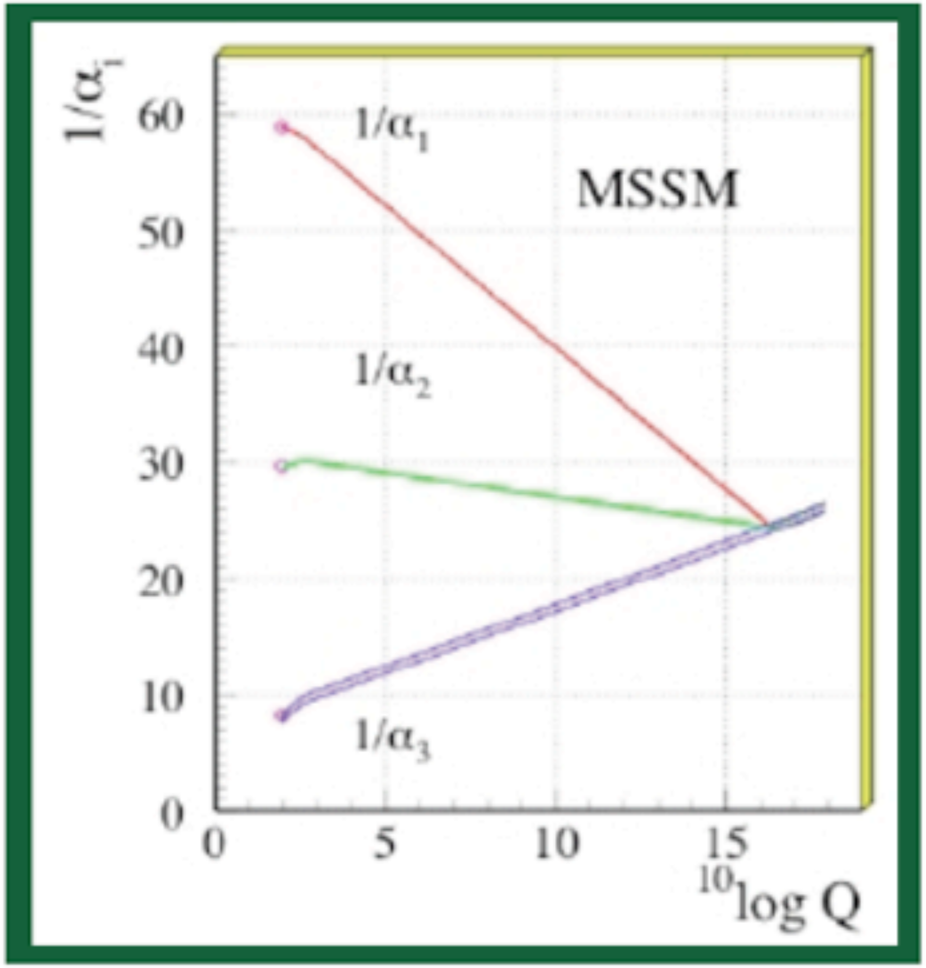
- Neutral, spin-1/2 “fundamental” particles
- Only appear in the “weak interaction”
- Very tiny mass, but not massless (< 2.2 eV)

Neutrinos might hold a key to the Universe

- One of those things that is just too cool to be an accident...

Masses of "Elementary" Particles





The neutrinos! Why such huge gaps??

The "SeeSaw" Mechanism

A "Grand" View of Neutrino States

$$\begin{bmatrix} 0 & -m \\ -m & M \end{bmatrix}$$

New "eigenvalues" are M and m^2/M

Take $M \approx 10^{16}$ GeV and $m \approx 10^2$ GeV

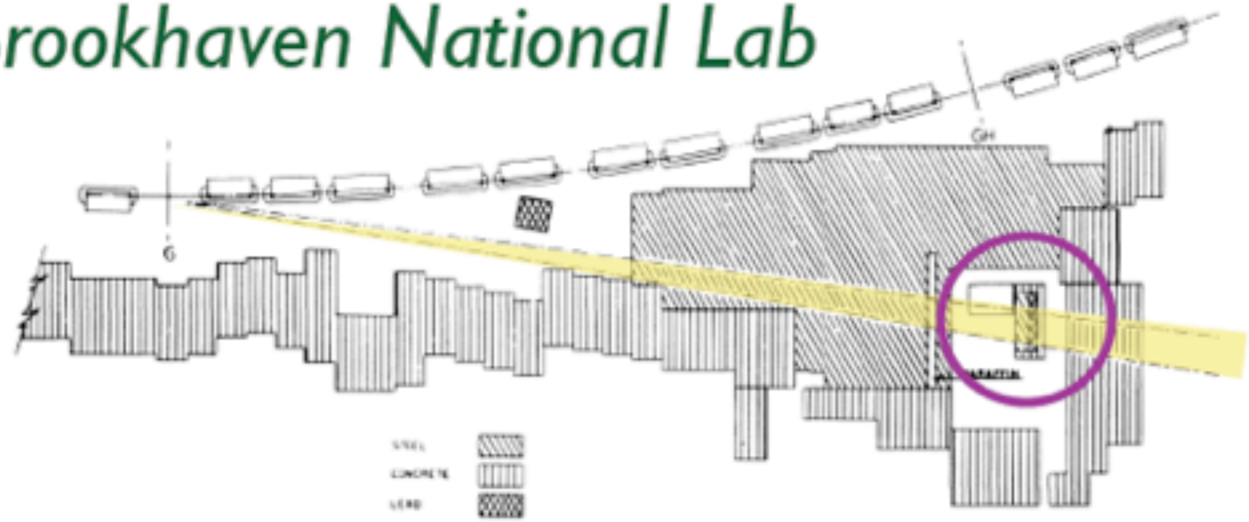
Then $m^2/M \approx 10^{-12}$ GeV $= 10^{-3}$ eV (!)

=Neutrino mass!?

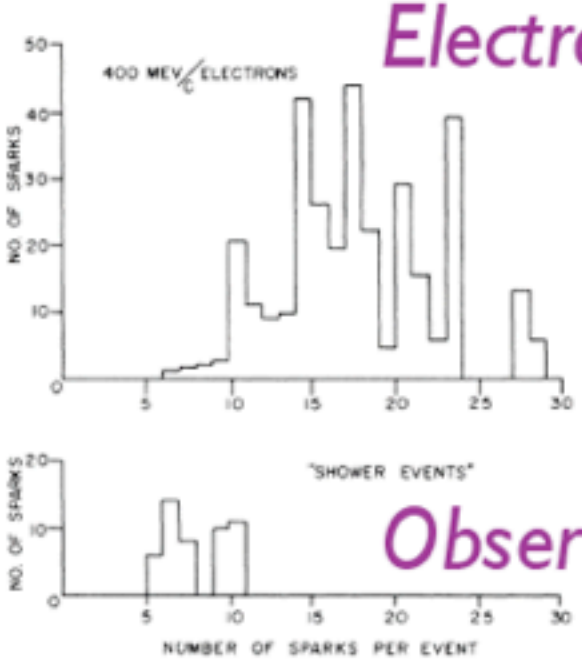
Neutrinos and Accelerators

"Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos"

Accelerator at Brookhaven National Lab



Phys.Rev.Lett. 9(1962)36

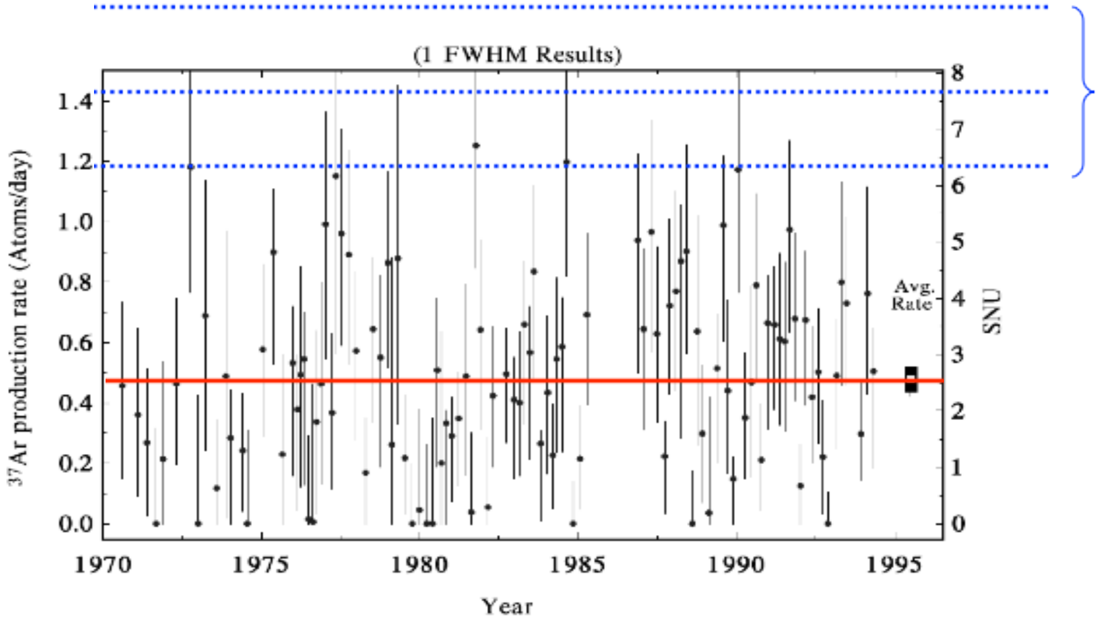


Electrons

Observed

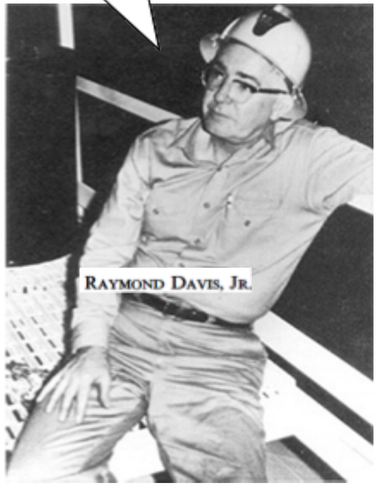
Lederman, Schwartz, Steinberger
1988 Nobel Prize in Physics

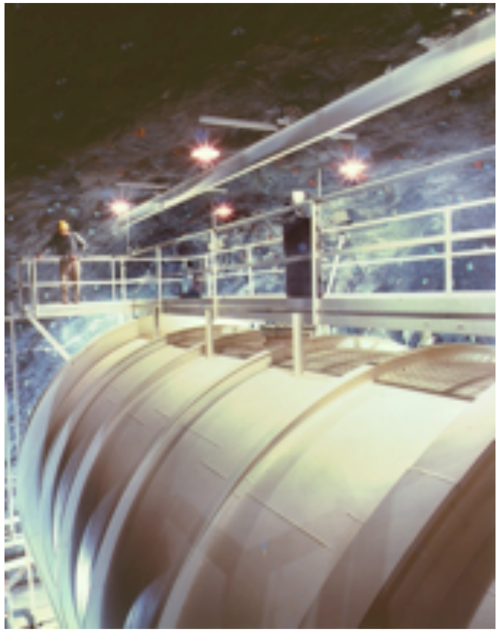
The Missing Solar Neutrinos



Expected rate of ν_e from the sun

Some of the ν_e from the sun are missing.

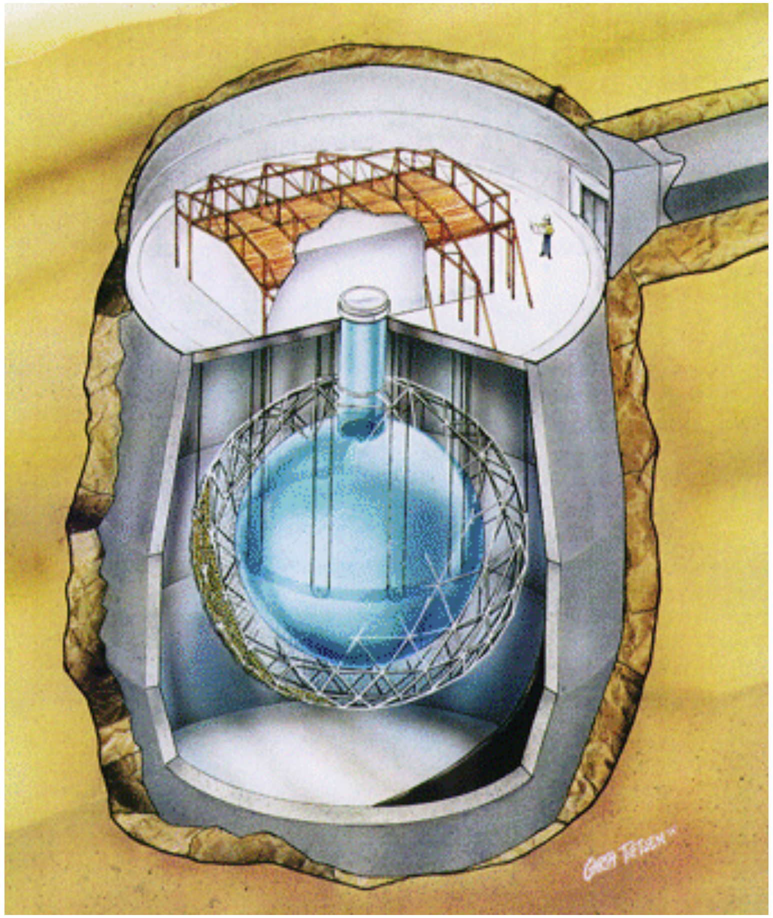


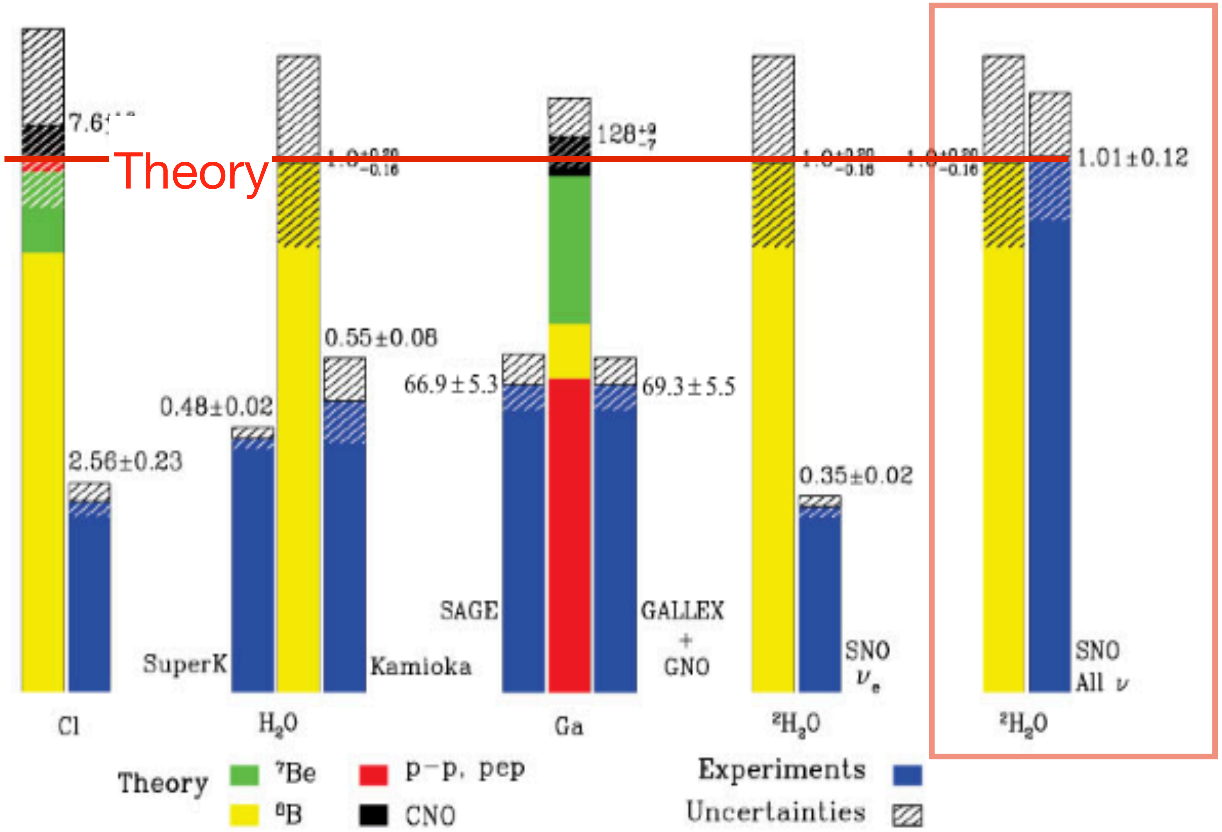


The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

Are Due to Neutrino Oscillation

SNO





ν_e missing

but $\nu_e + \nu_\mu + \nu_\tau$ agree

Neutrino Oscillation?

In 1957 Pontecorvo proposes a process called neutrino oscillation

- Initially the process $\nu_L \leftrightarrow \overline{\nu_L}$, later after the ν_μ was discovered he proposes $\nu_e \leftrightarrow \nu_\mu$

Assume there are two forms of neutrino, and they oscillate from one to the other. Relativistic quantum mechanics predicts that the probability of observing a particular type goes like this:

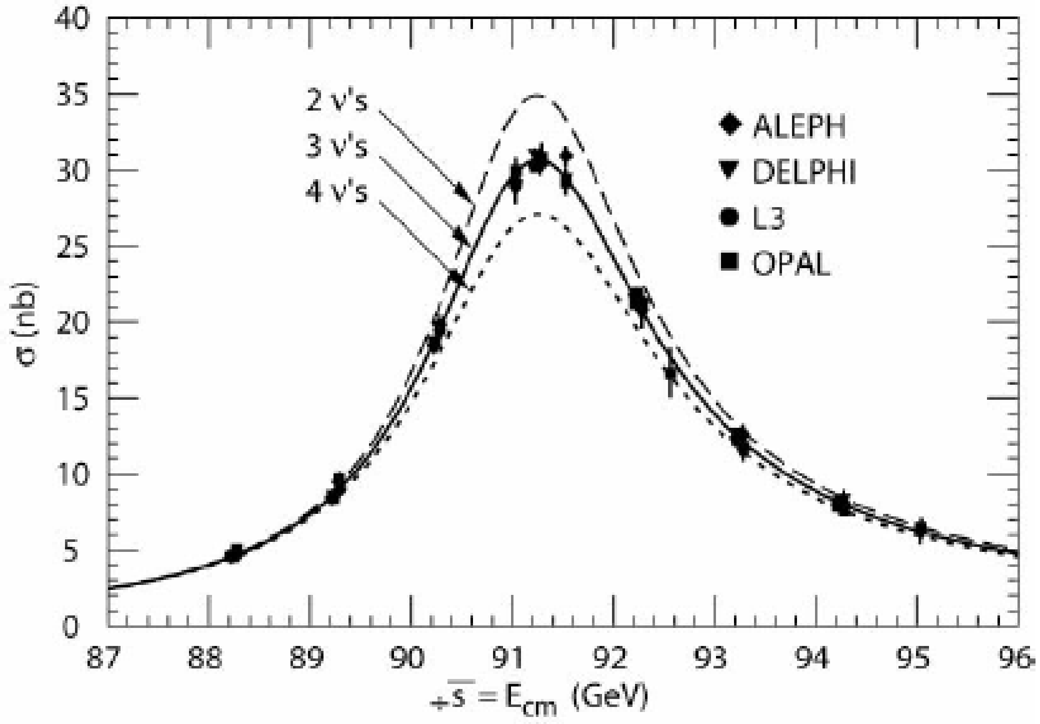
$$P(\nu_x \rightarrow \nu_x) = 1 - \sin^2(2\theta_{xy}) \sin^2(1.27\ \Delta m^2_{12} L/E)$$

here L is distance in meters, E energy in MeV, $\Delta m_{12}^2 = |m_1^2 - m_2^2|$ in eV^2

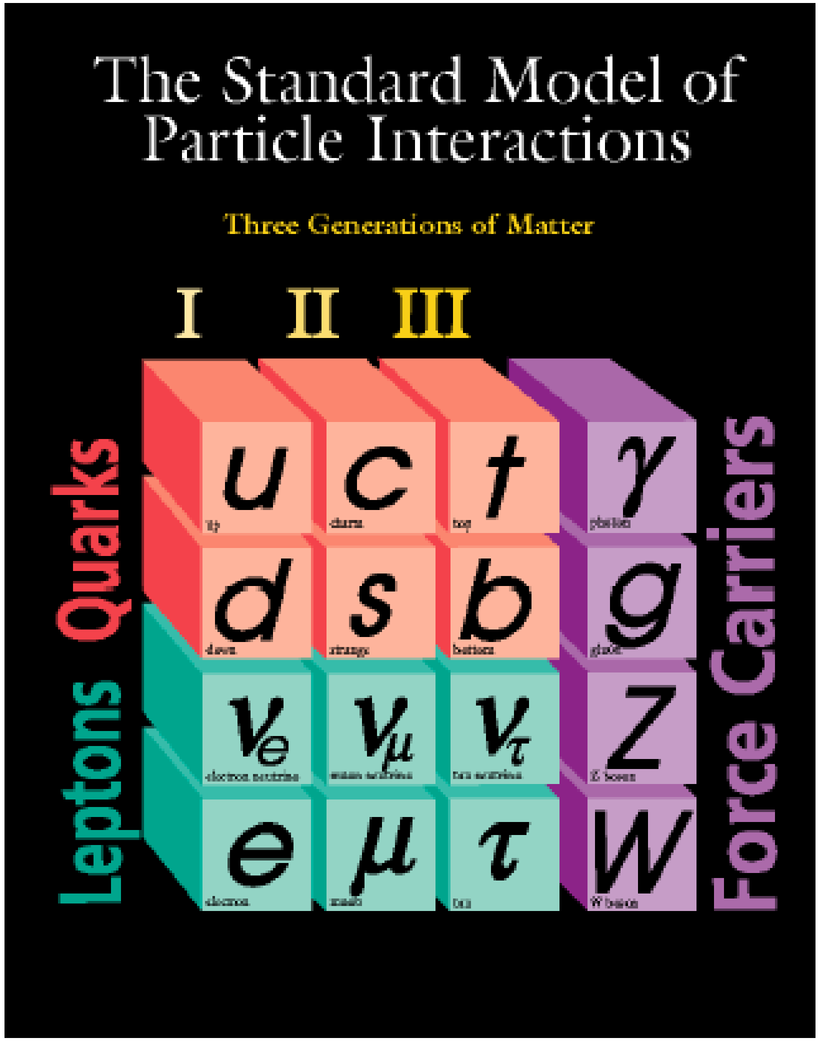
Notice that if Δm_{12}^2 is large, the frequency of oscillation is large

Also invented a way to detect neutrinos (from the sun) and anti-neutrinos (from reactors)

The Elusive Neutrino

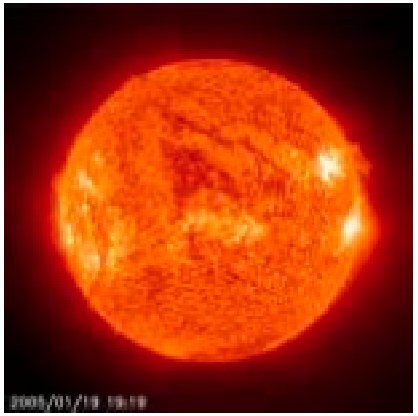


The past two decades have seen the neutrino family take its place in the Standard Model

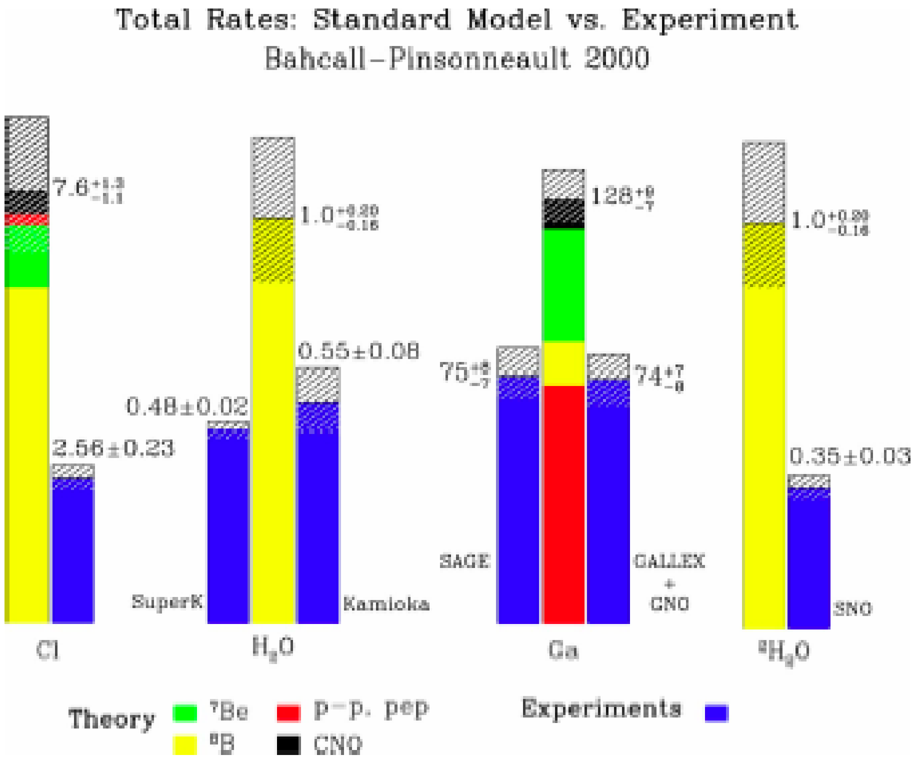


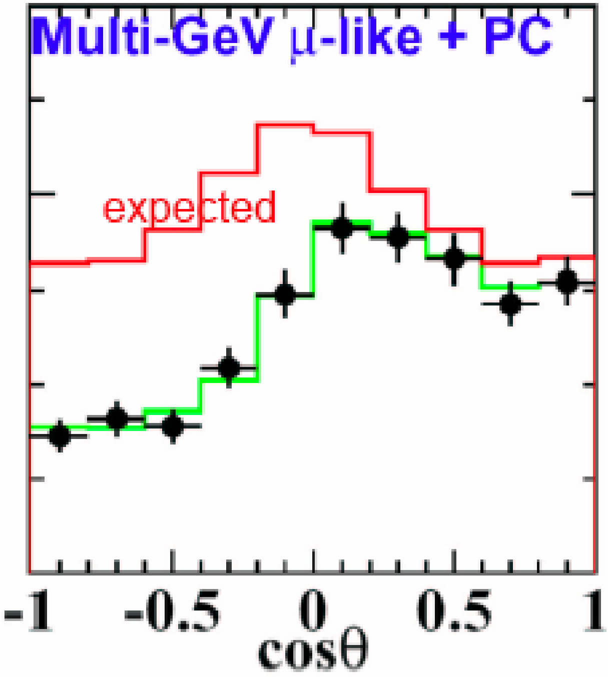
+ Higgs boson

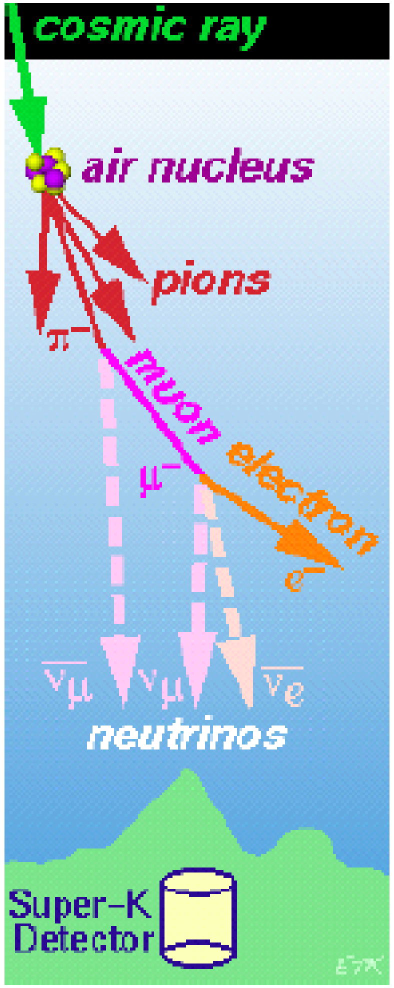
The Elusive Neutrino



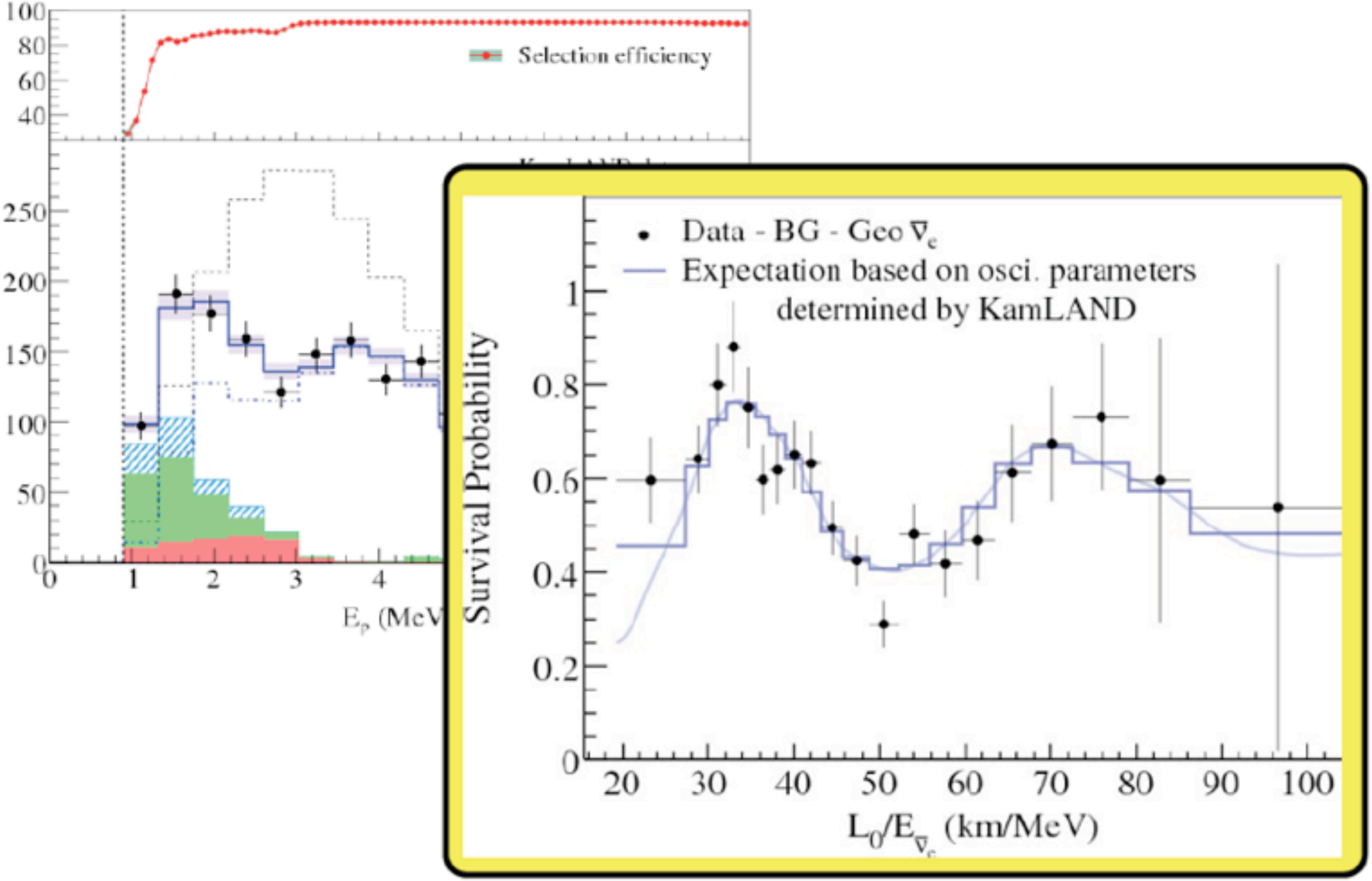
Solar and Atmospheric Neutrinos
Missing in Action

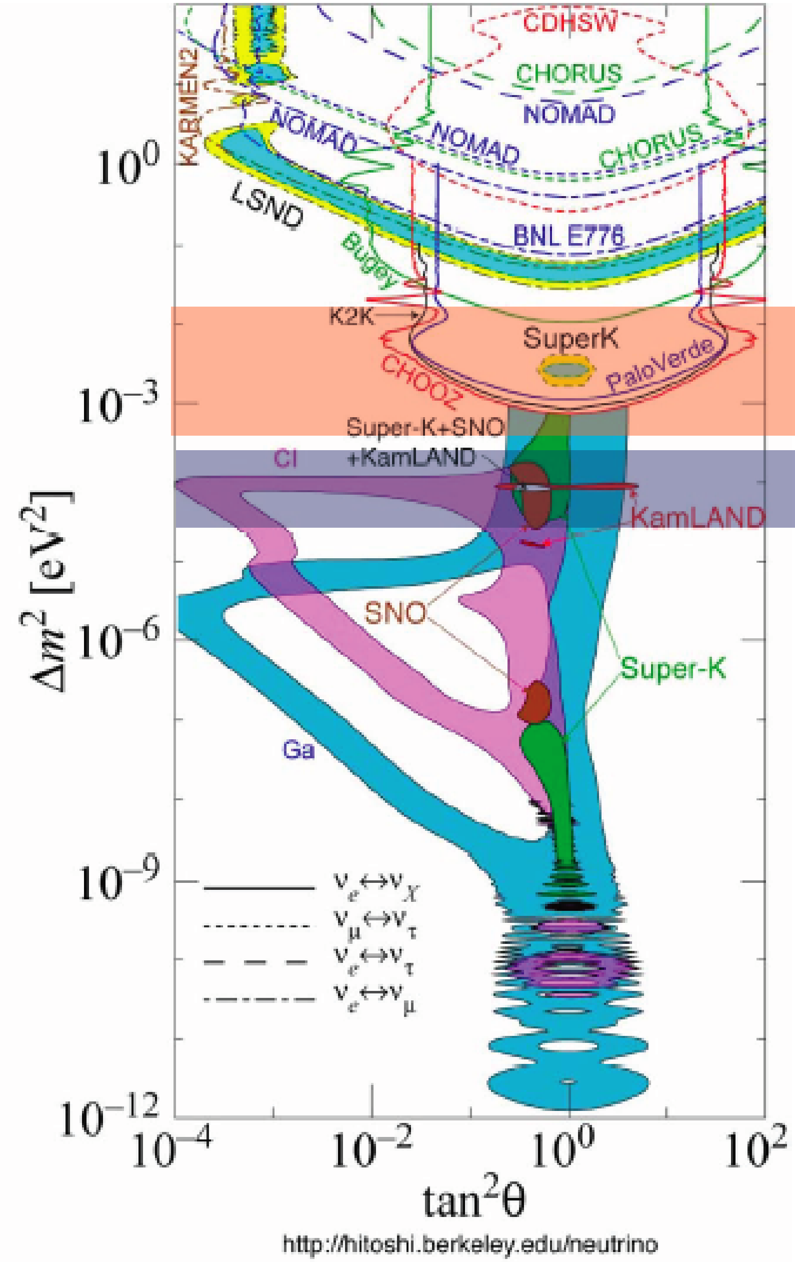






It Really Is Neutrino Oscillations!



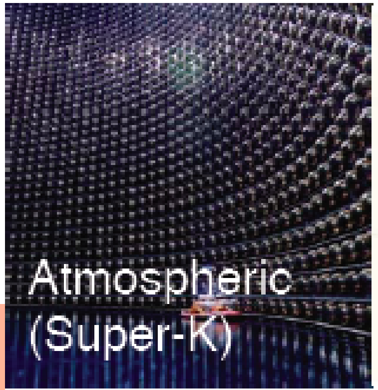


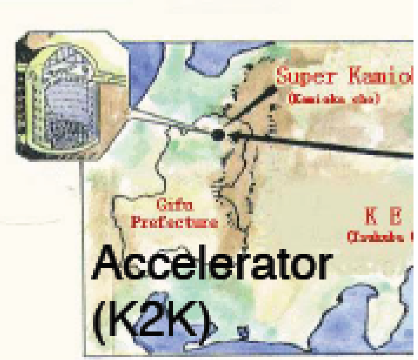
http://hitoshi.berkeley.edu/neutrino

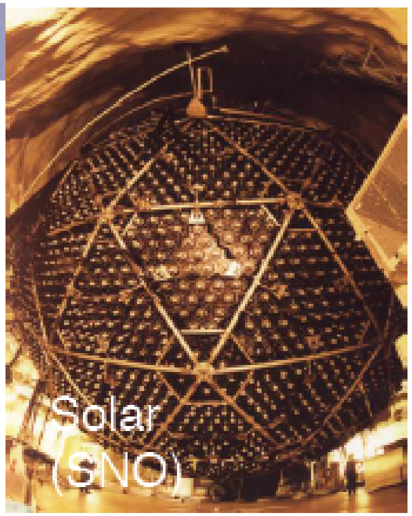
$\nu_\mu \Rightarrow \nu_\tau$

$\nu_e \Rightarrow \nu_{\mu,\tau}$

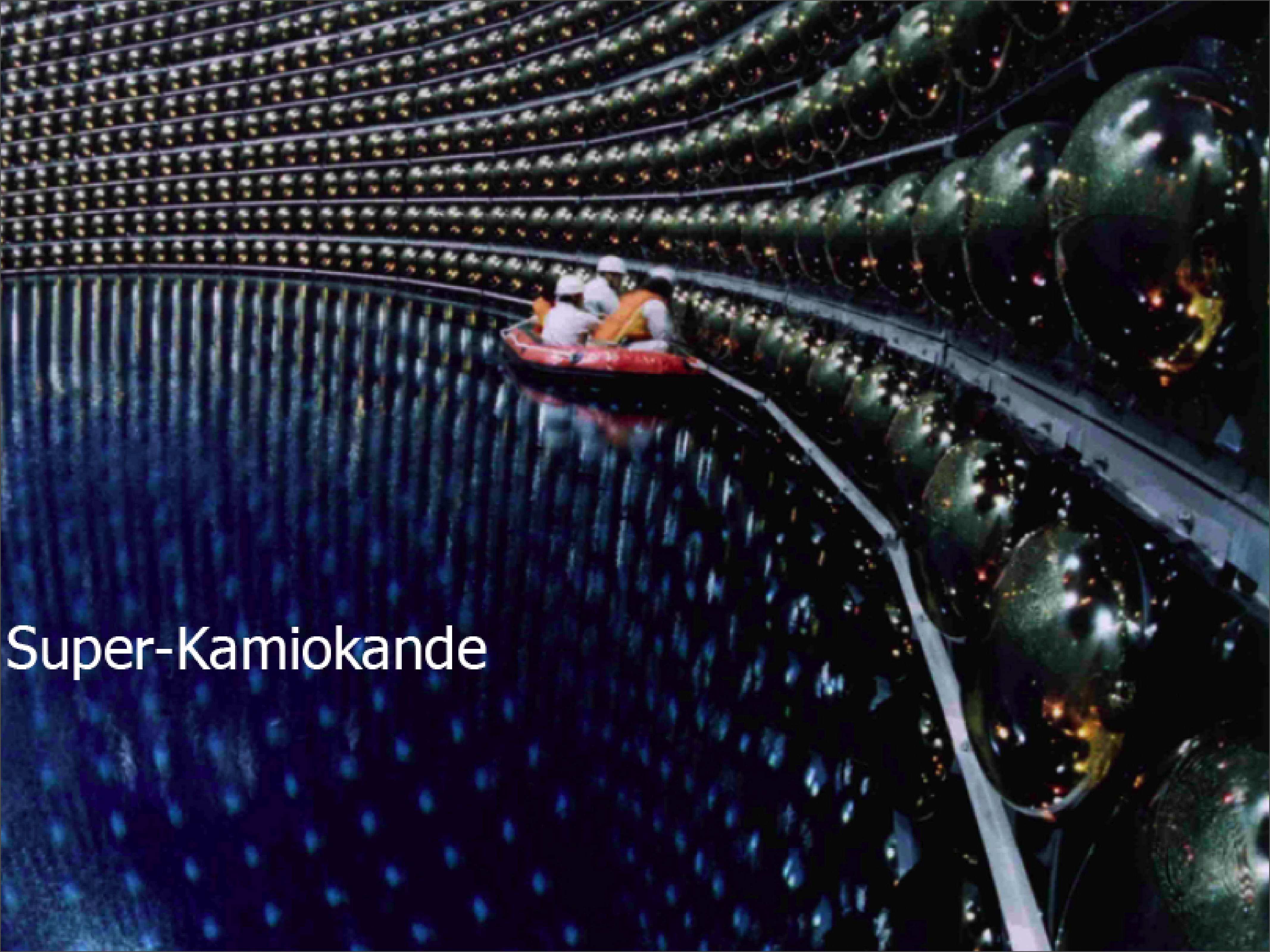
Δm_{ij}^2 measured *and* confirmed.





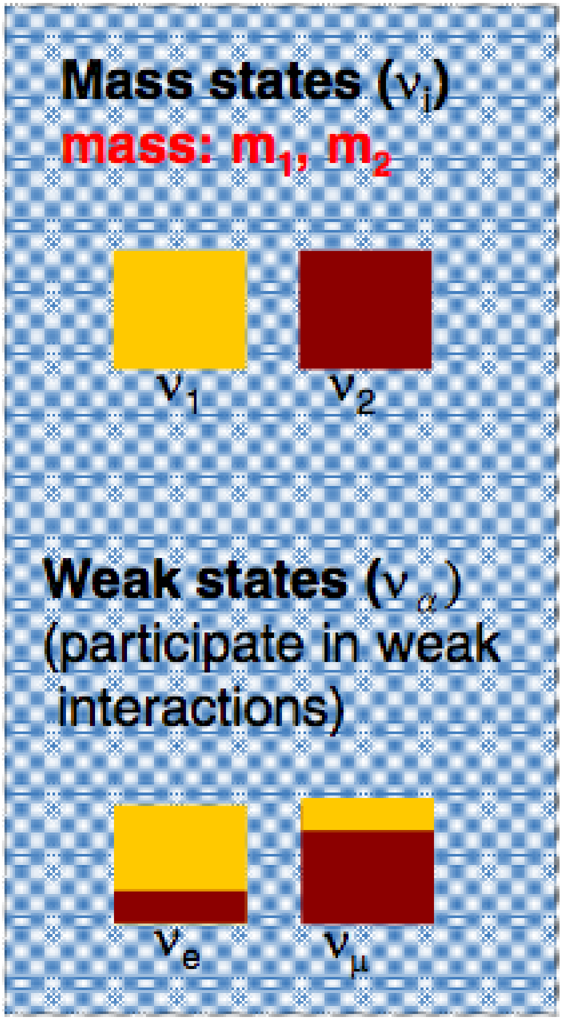


- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that *neutrinos oscillate*



Super-Kamiokande

2-Flavor Neutrino Oscillation in Vacuum



Mass states (ν_i)

mass: m_1, m_2

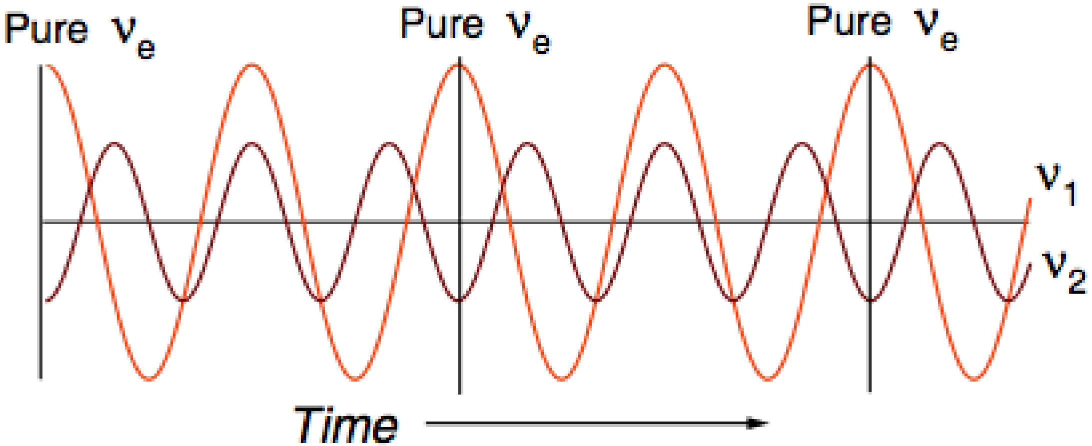
Weak states (ν_α)
(participate in weak interactions)

Principle:

Mass eigenstates $\neq$

Interaction (weak) eigenstates

$$\begin{pmatrix} |\nu_e(t)\rangle \\ |\nu_\mu(t)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1(t)\rangle \\ |\nu_2(t)\rangle \end{pmatrix}$$



$$\nu_\alpha = U\nu_i$$

2-Flavor Neutrino Oscillation in Vacuum

- One can then calculate the appearance probability:

θ : oscillation amplitude

$$P_{e\mu} = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 [\mathrm{eV}^2] \frac{L[m]}{E[\mathrm{MeV}]} \right)$$

$\boxed{\Delta m^2 = m_1^2 - m_2^2}$

Δm^2: oscillation frequency

Experimenter's choice

- The survival probability is

$$P_{ee} = |\langle \nu_e | \nu_e(t) \rangle|^2 = 1 - P_{e\mu}$$

- In the generalized case, *U* is a 3x3 unitary matrix.

$$|\nu_e\rangle = \sum U^*_{ei} \, |\nu_i\rangle$$

Significance of θ_{13}

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & \boxed{U_{e3}} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \; ?$$

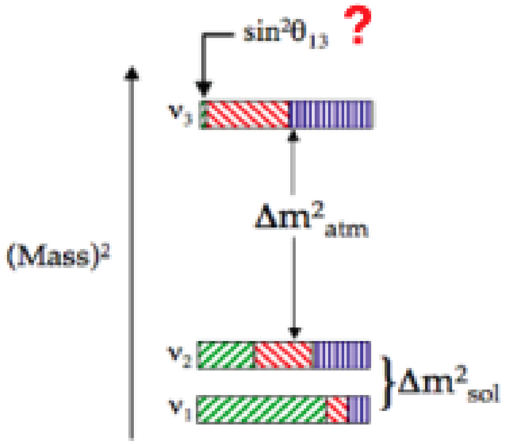
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \boxed{e^{-i\delta_{CP}} \sin\theta_{13}} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

atmospheric, accelerator	reactor, accelerator	SNO, solar SK, KamLAND	0νββ
θ_{23} = ~ 45°	θ_{13} = ?	θ_{12} ~ 32°	
$\Delta m^2_{32} \approx 2.4 \times 10^{-3}$ eV^2		$\Delta m^2_{21} \approx 7.9 \times 10^{-5}$ eV^2	

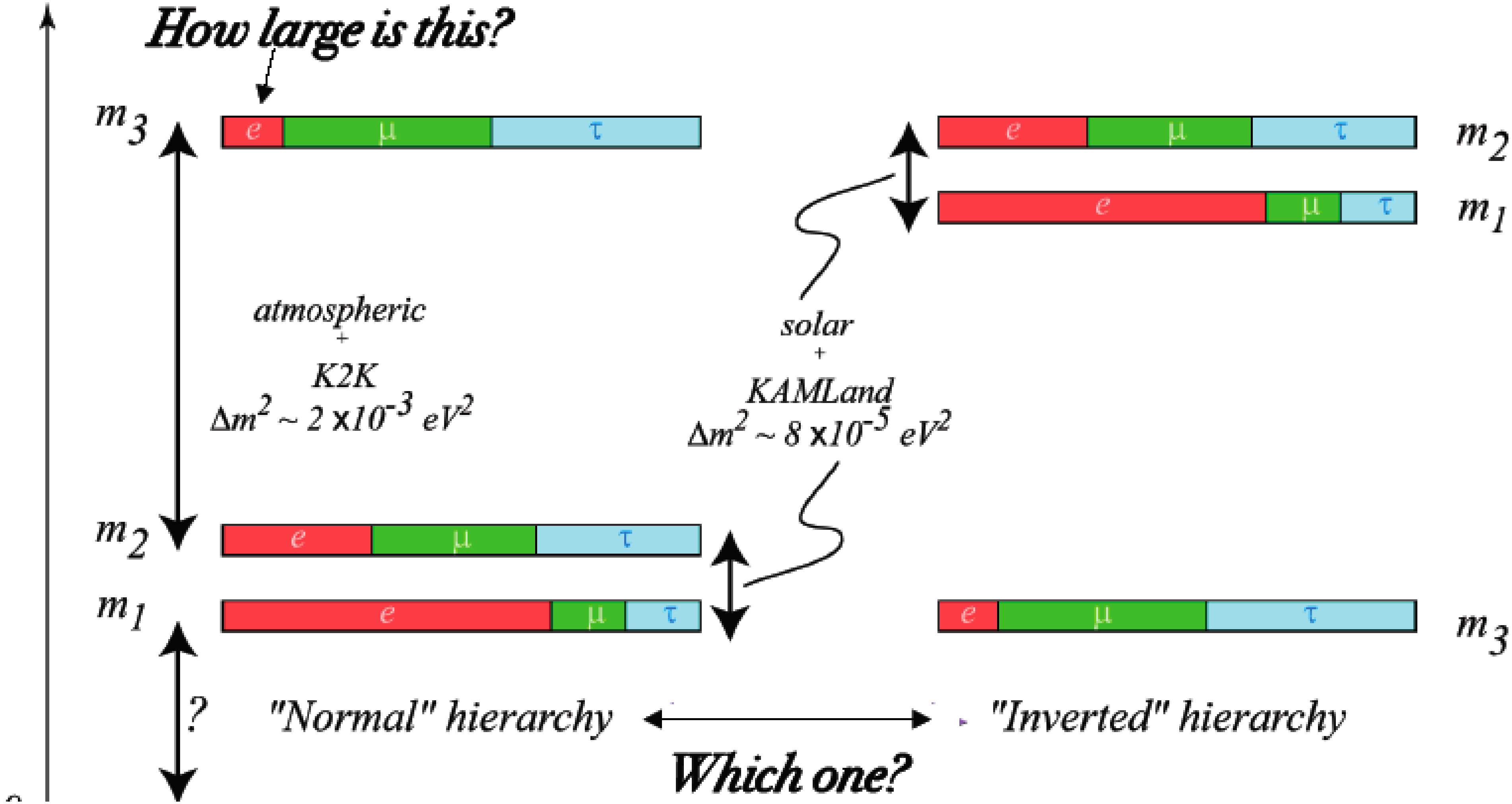
$\Delta m^2_{31} \approx 2.5 \times 10^{-3}$ eV^2

- What is ν_e fraction of ν_3?
- U_{e3} is the gateway to *CP* violation in neutrino sector:

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta$$

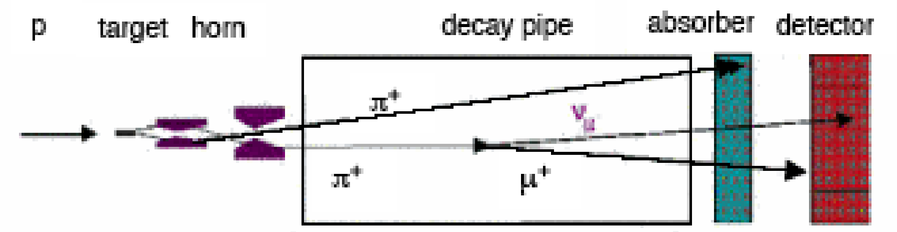


Mass mixing parameters



Some Methods For Determining θ_{13}

Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) + \ldots$$

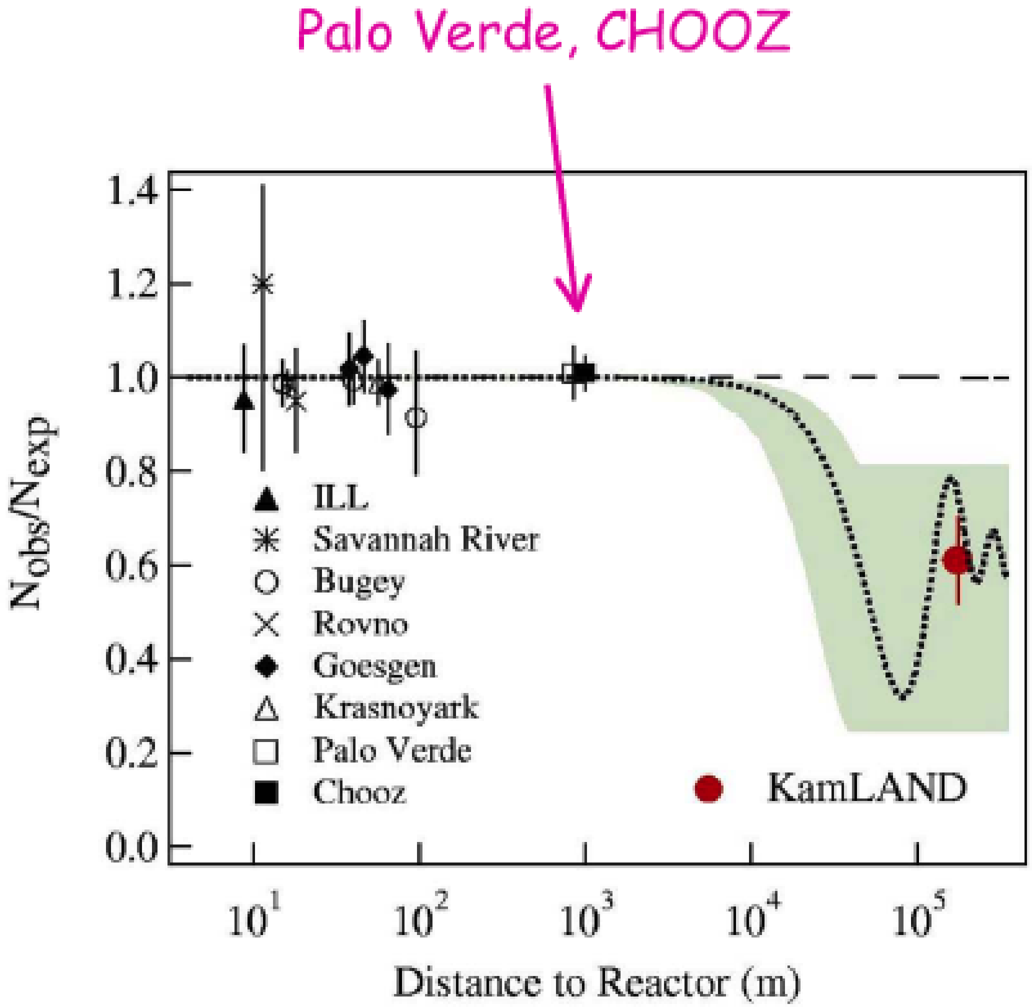
- $\nu_\mu \rightarrow \nu_e$ appearance experiment
- need other mixing parameters to extract θ_{13}
- baseline *O(100-1000 km)*, matter effects present
- expensive

Method 2: Reactor Experiments

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

- $\bar{\nu}_e \rightarrow X$ disappearance experiment
- baseline *O(1 km)*, no matter effect, no ambiguity
- relatively cheap

Limitations of Past and Current Reactor Neutrino Experiments



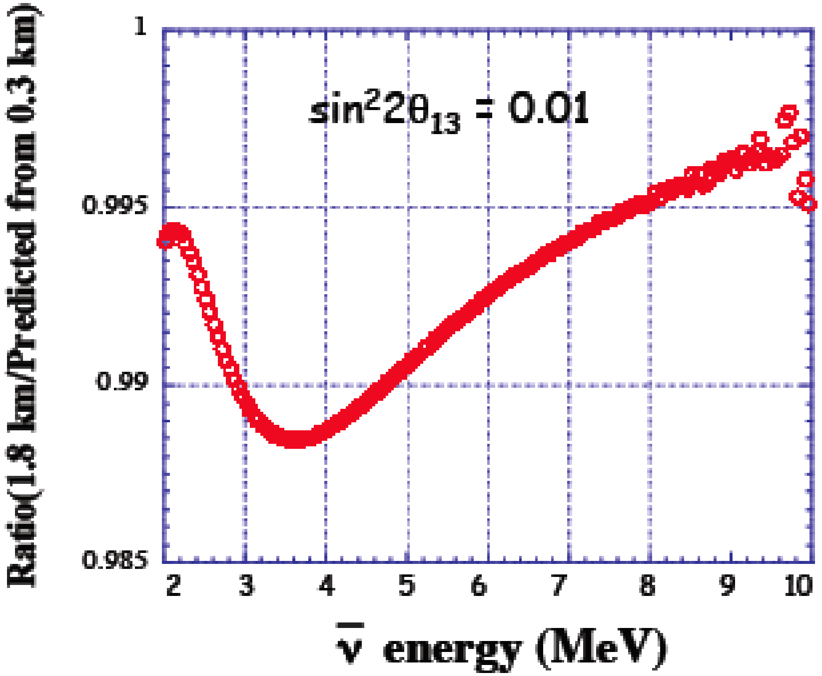
Typical precision is 3-6% due to

- limited statistics
- reactor-related systematic errors:
  - energy spectrum of $\bar{\nu}_e$ (~2%)
  - time variation of fuel composition (~1%)
- detector-related systematic error (1-2%)
- background-related error (1-2%)

Daya Bay: Goal And Approach

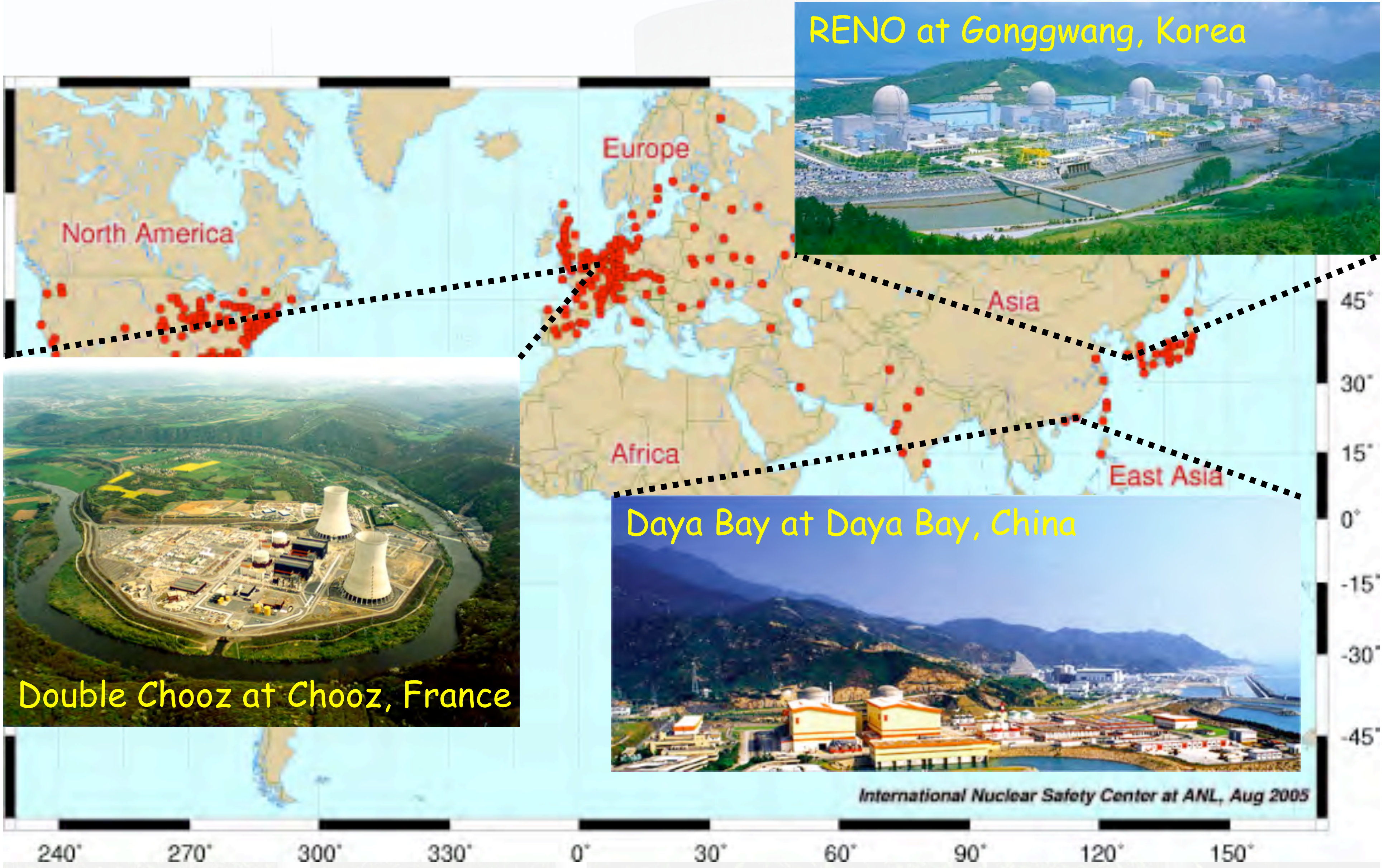
- Determine $\sin^2 2\theta_{13}$ with a sensitivity of ≤0.01

  by measuring deficit in $\bar{\nu}_e$ rate and spectral distortion.



- Recommendation of the APS Neutrino Study Group:
  - *An expeditiously deployed multidetector reactor experiment with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.*

Reactor-based θ_{13} Experiments



RENO at Gonggwang, Korea

Double Chooz at Chooz, France

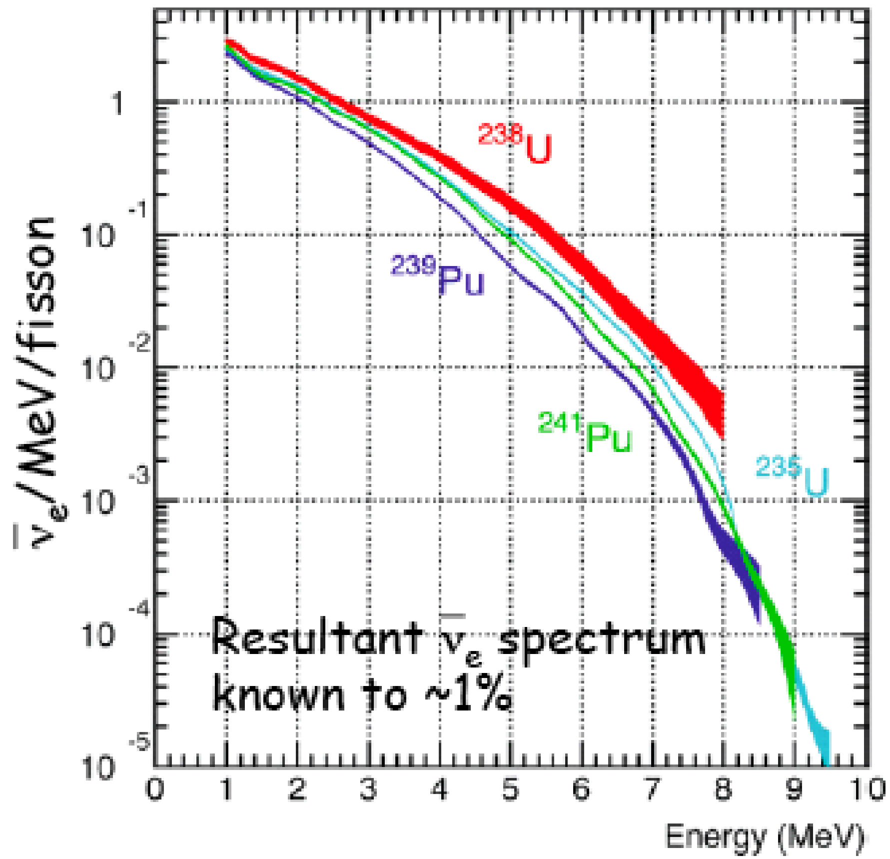
Daya Bay at Daya Bay, China

International Nuclear Safety Center at ANL, Aug 2005

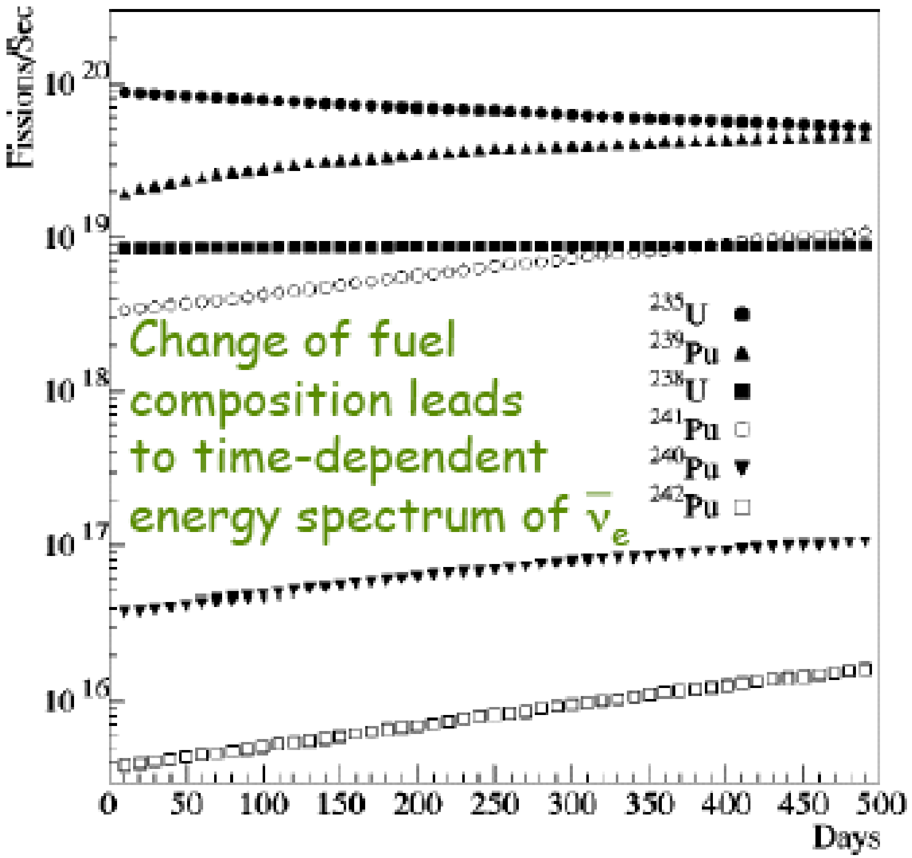
Reactor $\bar{\nu}_e$

- Fission processes in nuclear reactors produce huge number of low-energy $\bar{\nu}_e$:

3 GW_{th} generates 6×10^{20} $\bar{\nu}_e$ per sec



Resultant $\bar{\nu}_e$ spectrum known to ~1%

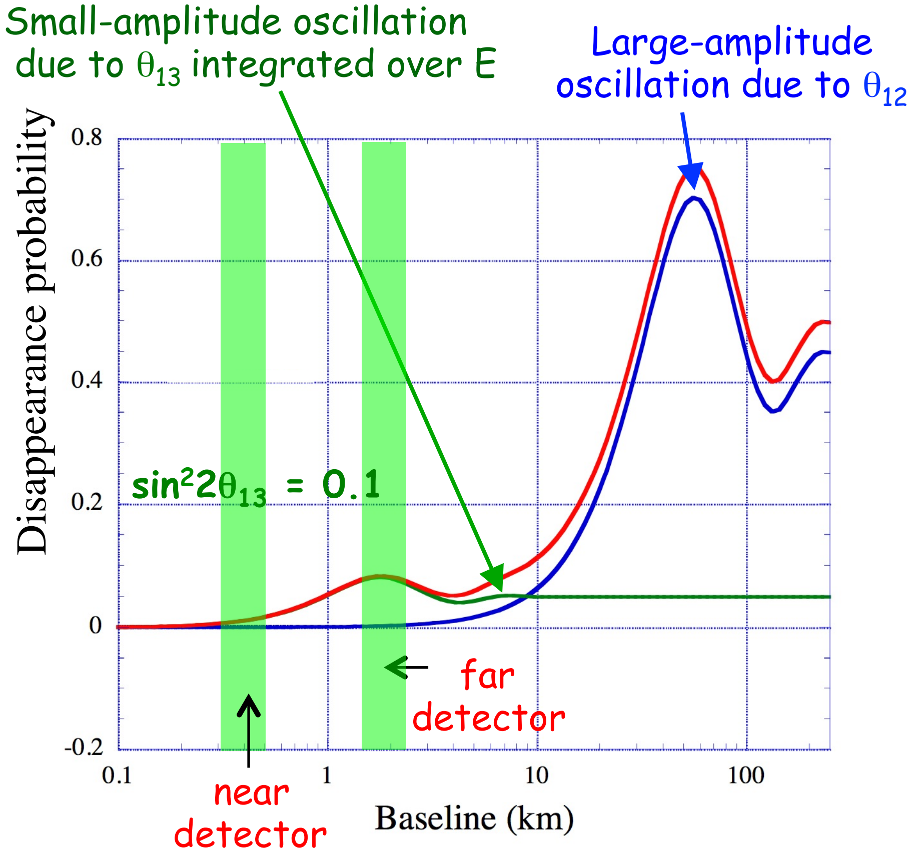


Change of fuel composition leads to time-dependent energy spectrum of $\bar{\nu}_e$

Determining θ_{13} With Reactor $\bar{\nu}_e$

- Look for disappearance of electron antineutrinos from reactors:

$$P(\bar{\nu}_e \to x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



- Perform a relative measurement:

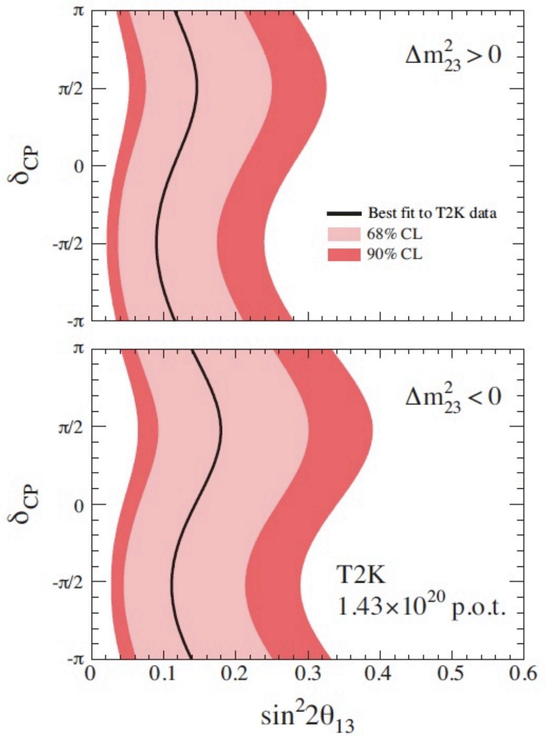
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{1-P_{Far}}{1-P_{Near}}\right)$$

$\bar{\nu}_e$ rate	$1/r^2$	number of protons	detection efficiency	yield $\sin^2 2\theta_{13}$

All correlated errors cancelled.

Knowledge of θ_{13} before 2012

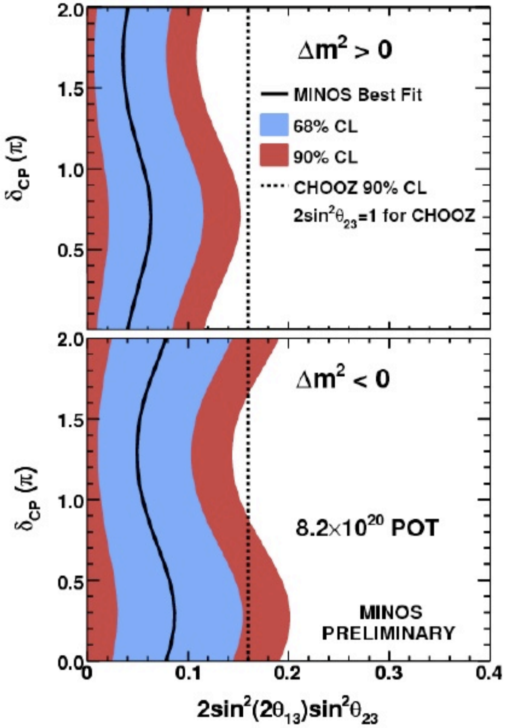
T2K



PRL**107**,041801 (2011)

2.5 σ over bkg

MINOS



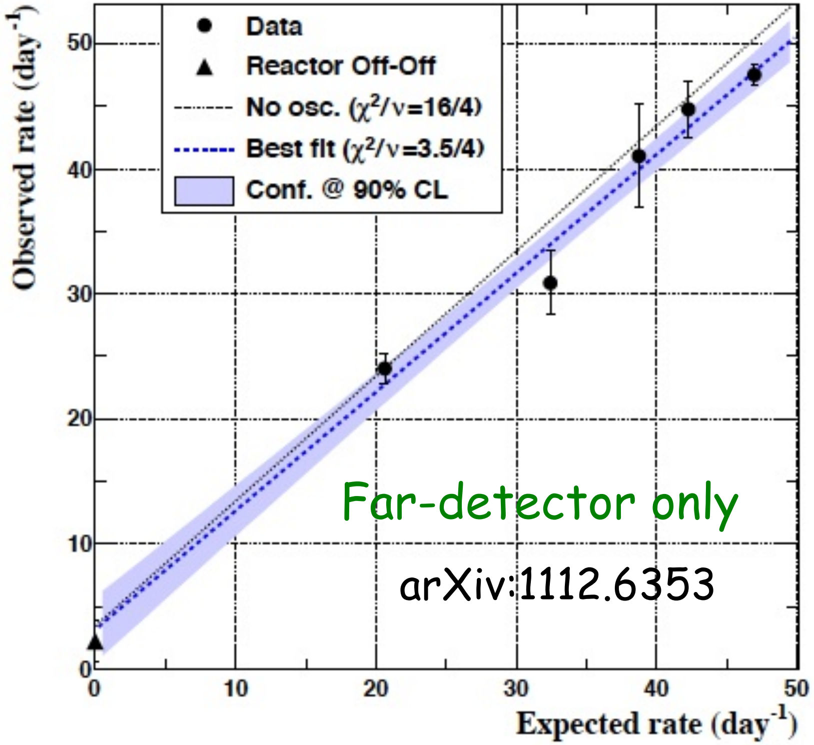
PRL**107**, 181802 (2011)

1.7 σ over bkg

Some hints of a non-zero θ_{13}

1.7 σ

Double Chooz



Far-detector only

arXiv:1112.6353

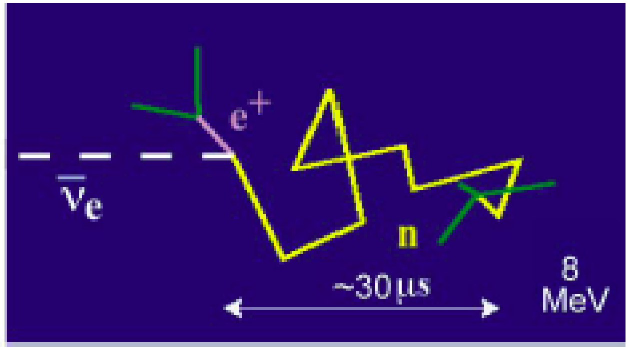
$$\frac{N_{obs}}{N_{pre}} = 0.944 \pm 0.016 \pm 0.040$$

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041 \pm 0.030$$

Detecting Low-energy $\bar{\nu}_e$

- The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator:

$$\bar{\nu}_e + p \to e^+ + n \quad \text{(prompt)}$$



0.3b → $+ p \to D + \gamma(2.2\ \text{MeV})$ (delayed)

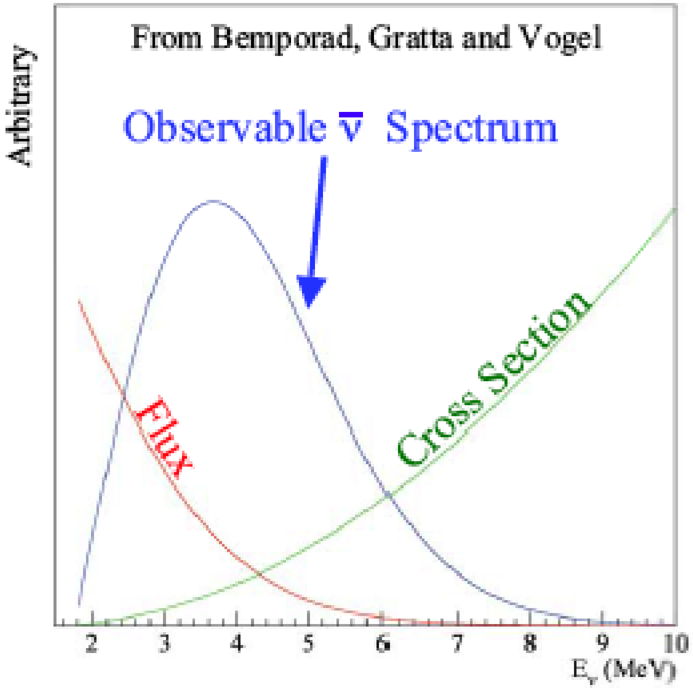
50,000b → $+ Gd \to Gd^*$

→ $Gd + \gamma\text{'s}(8\ \text{MeV})$ (delayed)

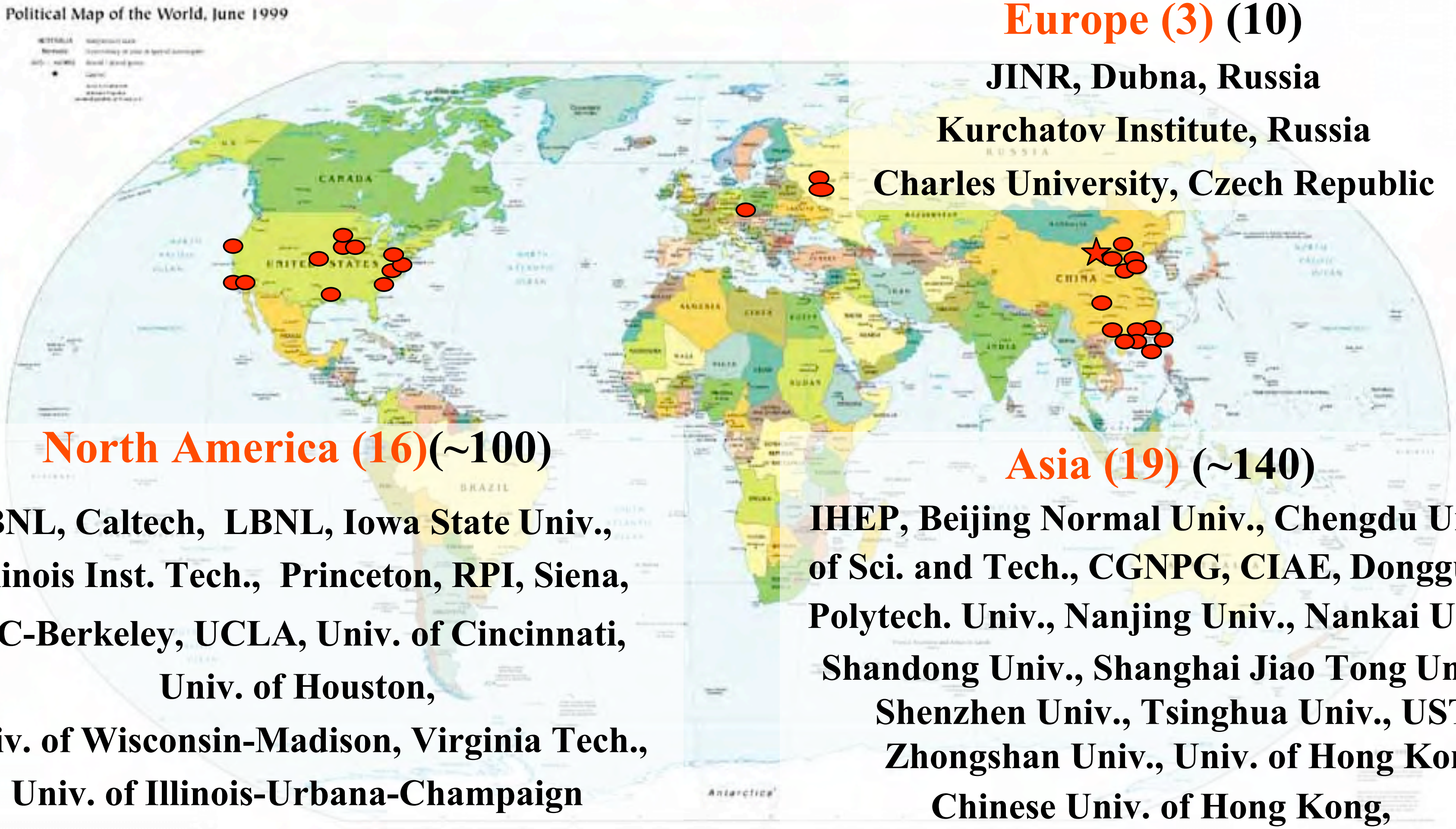
- Time- and energy-tagged signal is a good tool to suppress background events.

- Energy of $\bar{\nu}_e$ is given by:

$$E_{\bar{\nu}} \approx T_{e+} + \underbrace{T_n}_{\text{10-40 keV}} + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$


From Bemporad, Gratta and Vogel

The Daya Bay Collaboration



Europe (3) (10)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (16)(~100)

BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (19) (~140)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

~ 250 collaborators

台大, 交大 and 聯合
from Taiwan

Daya Bay Collaboration Meeting in CUHK

Daya Bay Nuclear Power Complex

- ~55 km from Hong Kong central
- All 6 reactors are in commercial operation
- one of top 5 most powerful nuclear power plants in the world

$6 \times 2.95\ GW_{th} = 17.7\ GW_{th}$

Where To Place The Detectors ?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

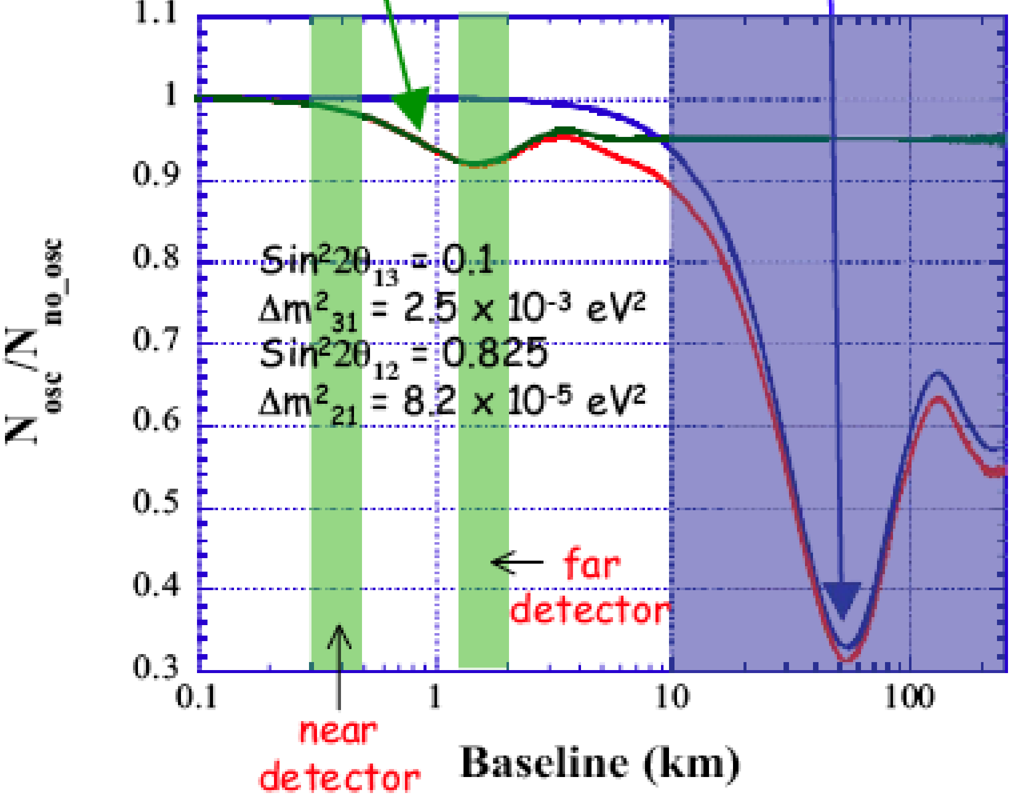
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

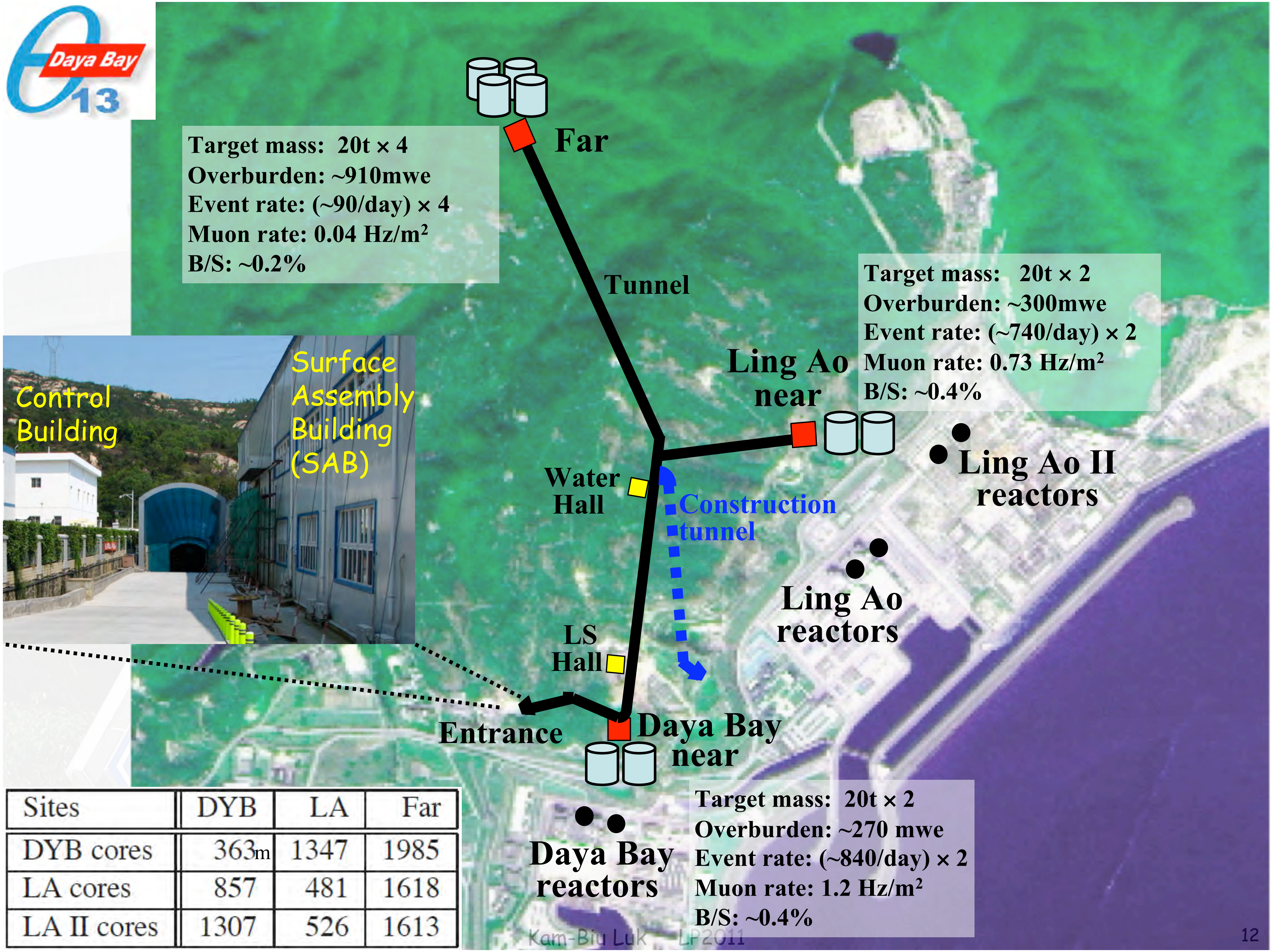
- Place near detector(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic

- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}

Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}





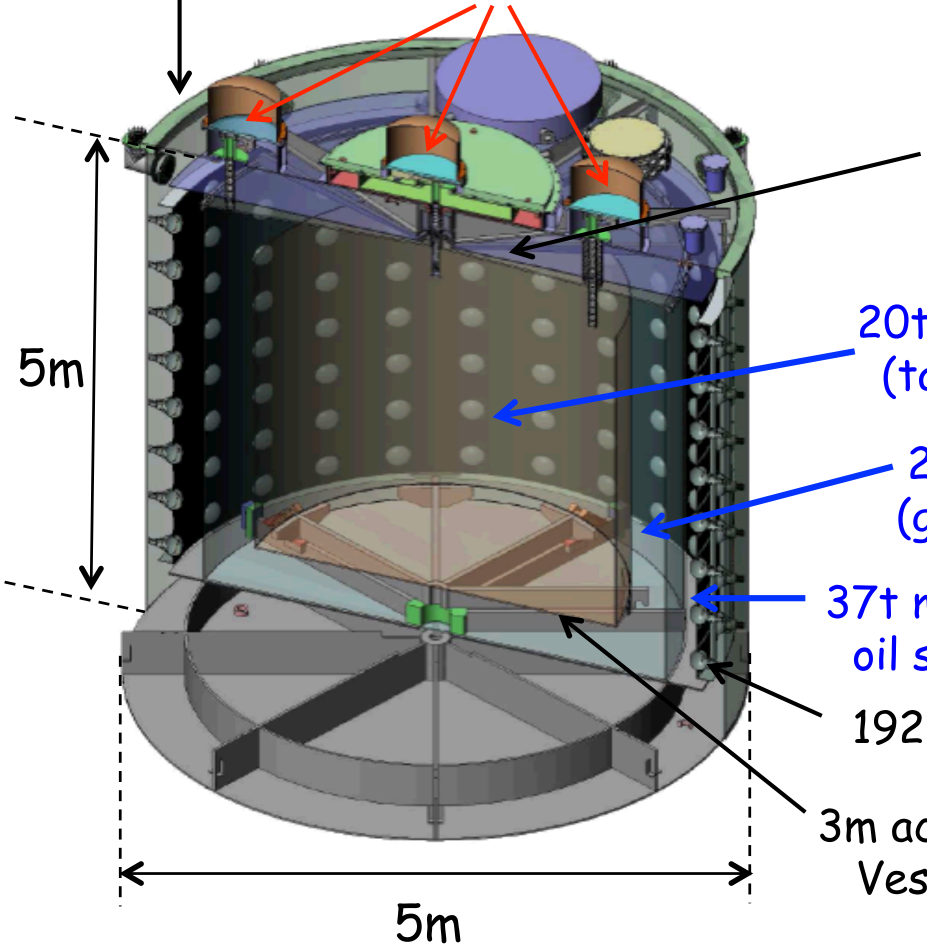
Target mass: 20t × 4
Overburden: ~910mwe
Event rate: (~90/day) × 4
Muon rate: 0.04 Hz/m²
B/S: ~0.2%

Target mass: 20t × 2
Overburden: ~300mwe
Event rate: (~740/day) × 2
Muon rate: 0.73 Hz/m²
B/S: ~0.4%

Target mass: 20t × 2
Overburden: ~270 mwe
Event rate: (~840/day) × 2
Muon rate: 1.2 Hz/m²
B/S: ~0.4%

Sites	DYB	LA	Far
DYB cores	363m	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Daya Bay Detector Design



Stainless steel
Tank

Calibration units
(LED, ^{68}Ge,
AmC-Co)

4m acrylic tank sandwiched
between top and bottom reflectors

20t Gd-LS
(target)

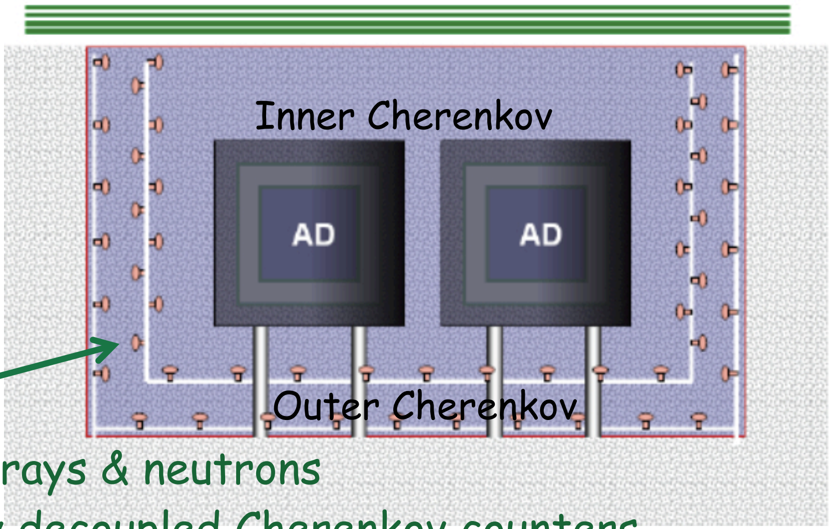
20t liquid scint.
(gamma catcher)

37t mineral
oil shield

192 PMTs

3m acrylic
Vessel

Four layers of RPC's
to tag muons



2.5m water:
- attenuates gamma rays & neutrons
- forms two optically decoupled Cherenkov counters

Detecting Reactor $\bar{\nu}_e$

- Use the inverse β-decay reaction in Gd-doped liquid scintillator:

$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

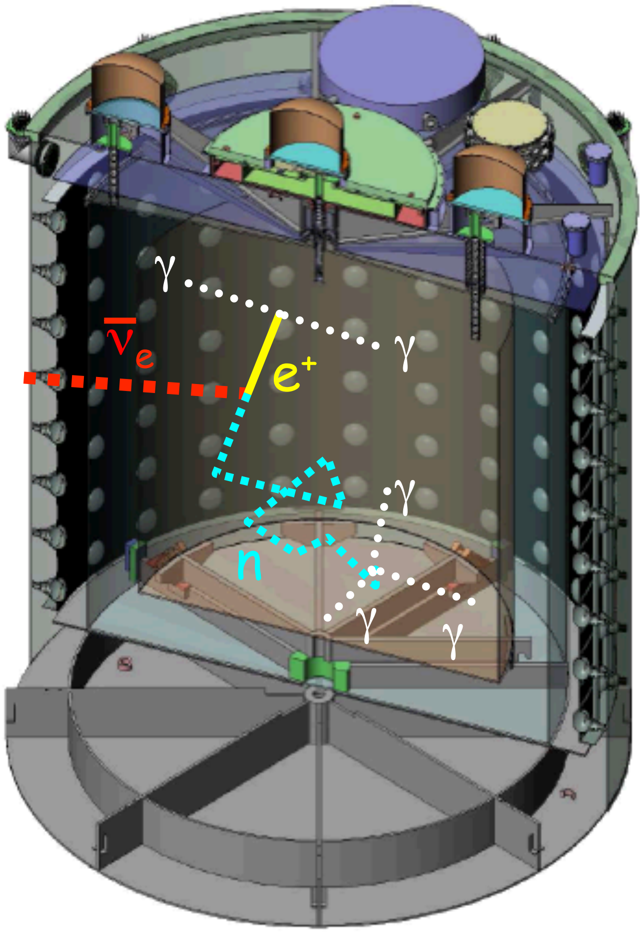
~180μs

$\hookrightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed signal)

$\hookrightarrow + Gd \rightarrow Gd^*$

~30μs for 0.1% Gd

$\hookrightarrow Gd + \gamma\text{'s}(8\ \text{MeV})$ (delayed signal)



- Energy of $\bar{\nu}_e$ is given by:

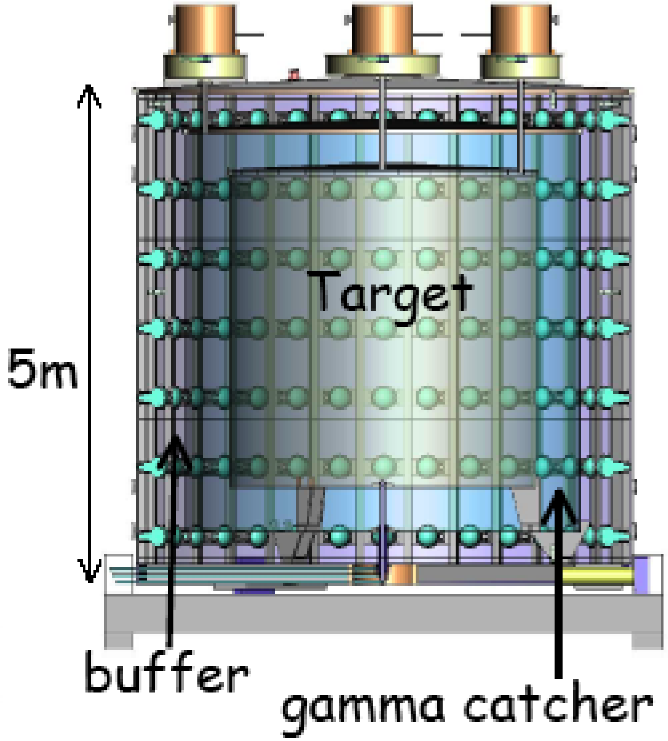
$$E_\nu \approx T_{e+} + \underset{10\text{-}40\ \text{keV}}{T_n} + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

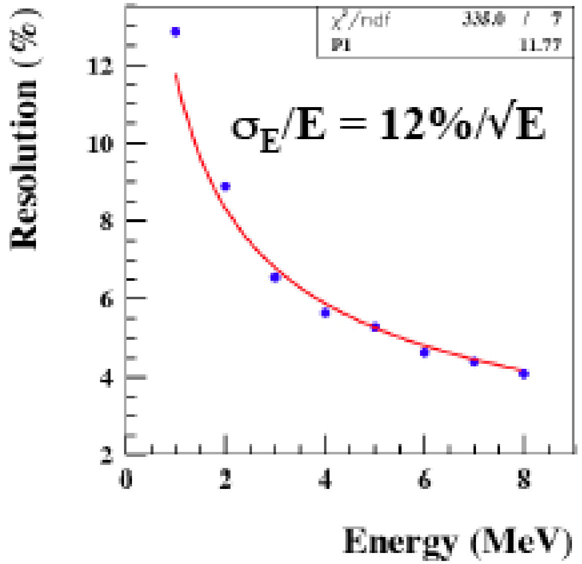
- Time- and energy-tagged signal is a good tool to suppress background events.

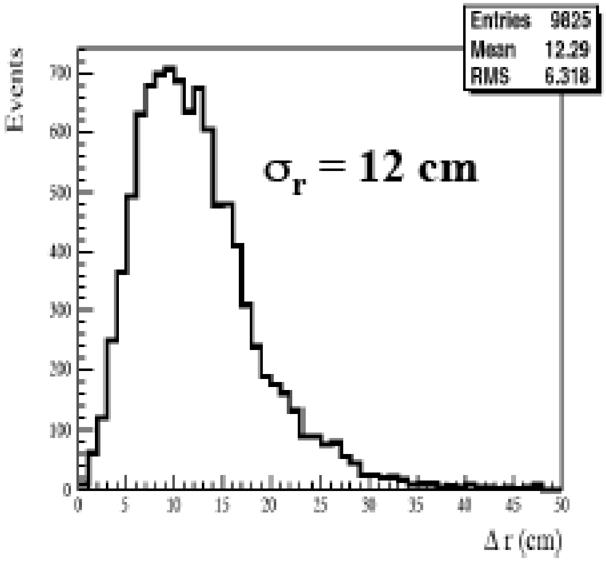
Antineutrino Detectors

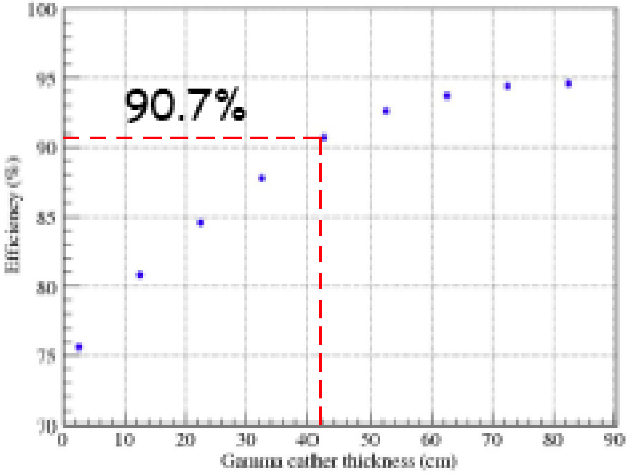
- Three-zone cylindrical detector design
  - Target: 20 T (0.1% Gd-LS), radius = 1.55 m
  - Gamma catcher: 20 T (LS), thickness = 0.42 m
  - Buffer : 40 T (mineral oil) , thickness = 0.48 m
- Low-background 8" PMT: 192
- Reflectors at top and bottom
- Photocathode coverage:

  5.6 % → 12% (with reflectors)



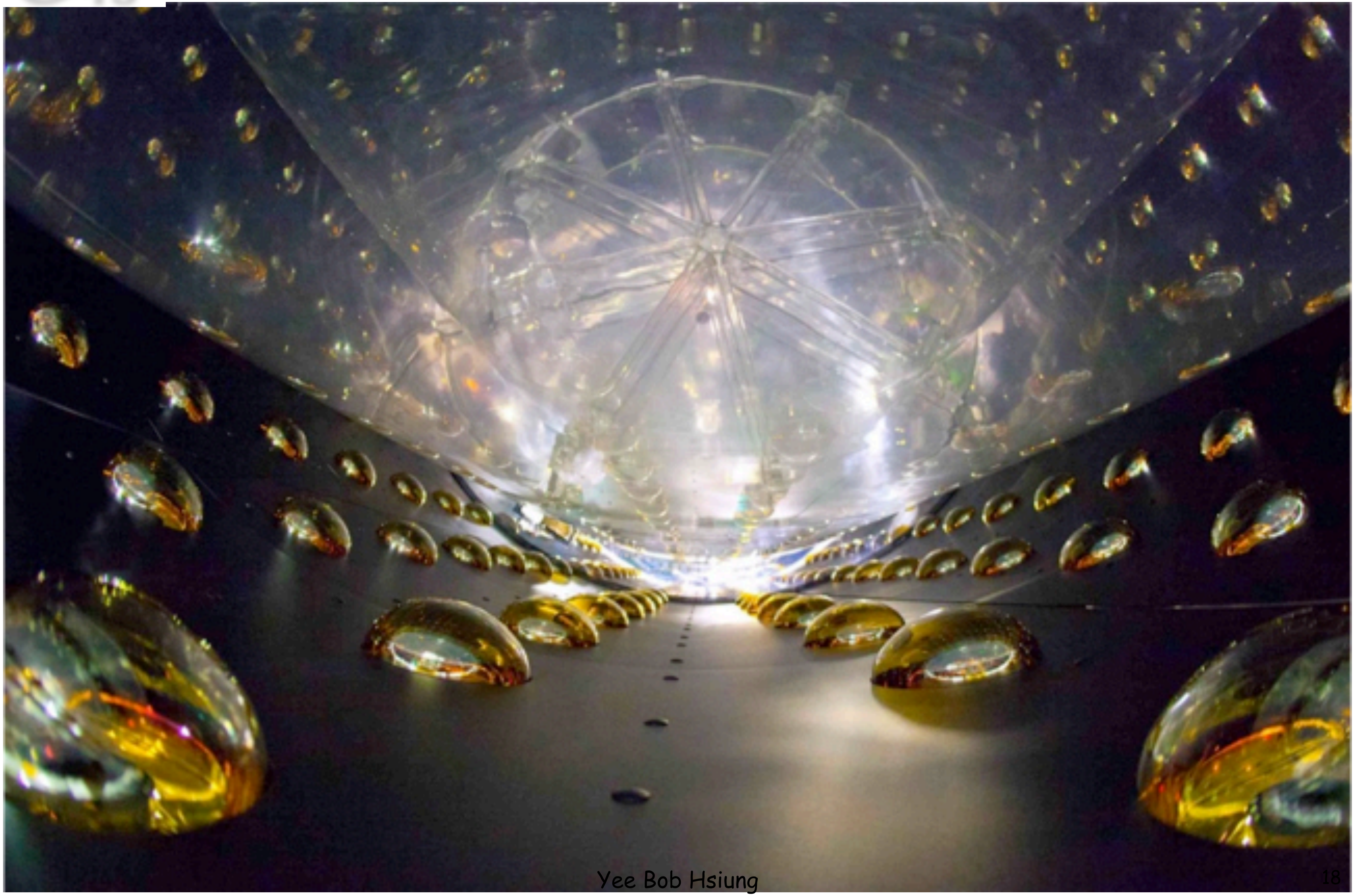






- Eight 'identical' detector modules

Interior of Antineutrino Detector

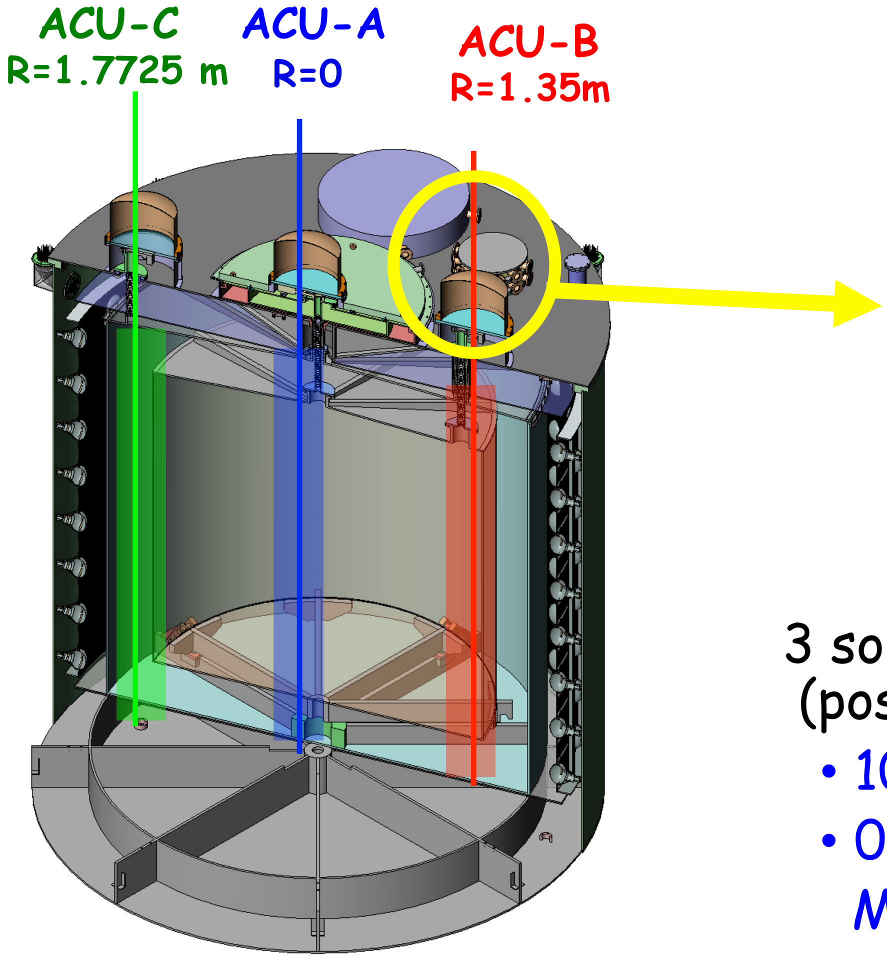


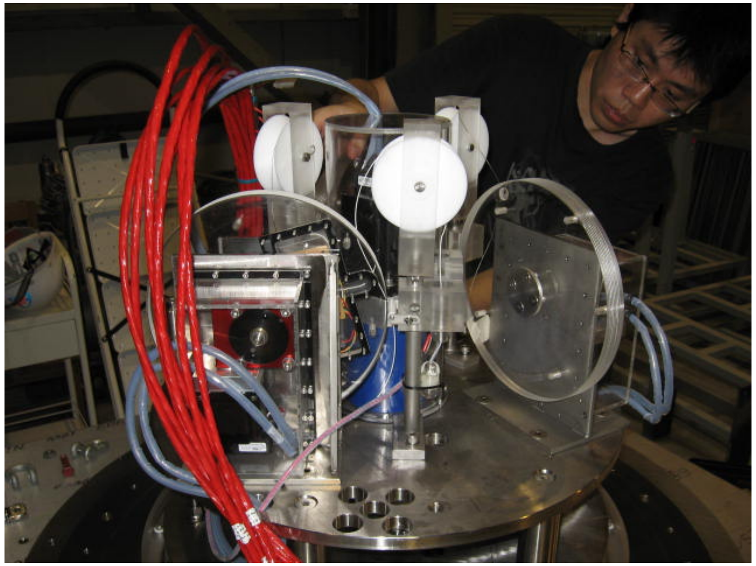
3m IAVs produced in Taiwan

- All 3m inner acrylic vessels are produced in Taiwan
- 10mm thick wall, 15mm top /bottom covers
- Completely sealed with two penetration ports for Gd-LS filling and calibations.
- UV transparent down to 300nm wavelength

Calibration System of Antineutrino Detectors

3 Automatic calibration 'robots' (ACUs) on each detector





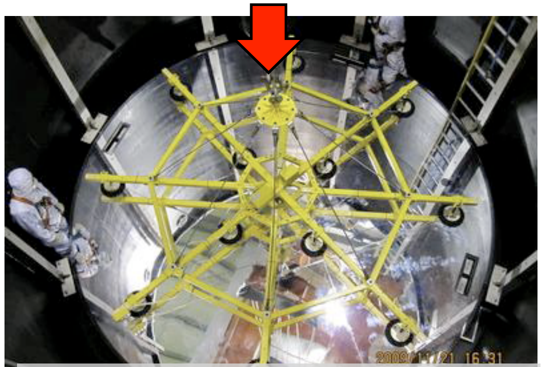
Three axes: center, edge of target, middle of gamma catcher

3 sources for each z axis on a turntable (position accuracy < 5 mm):

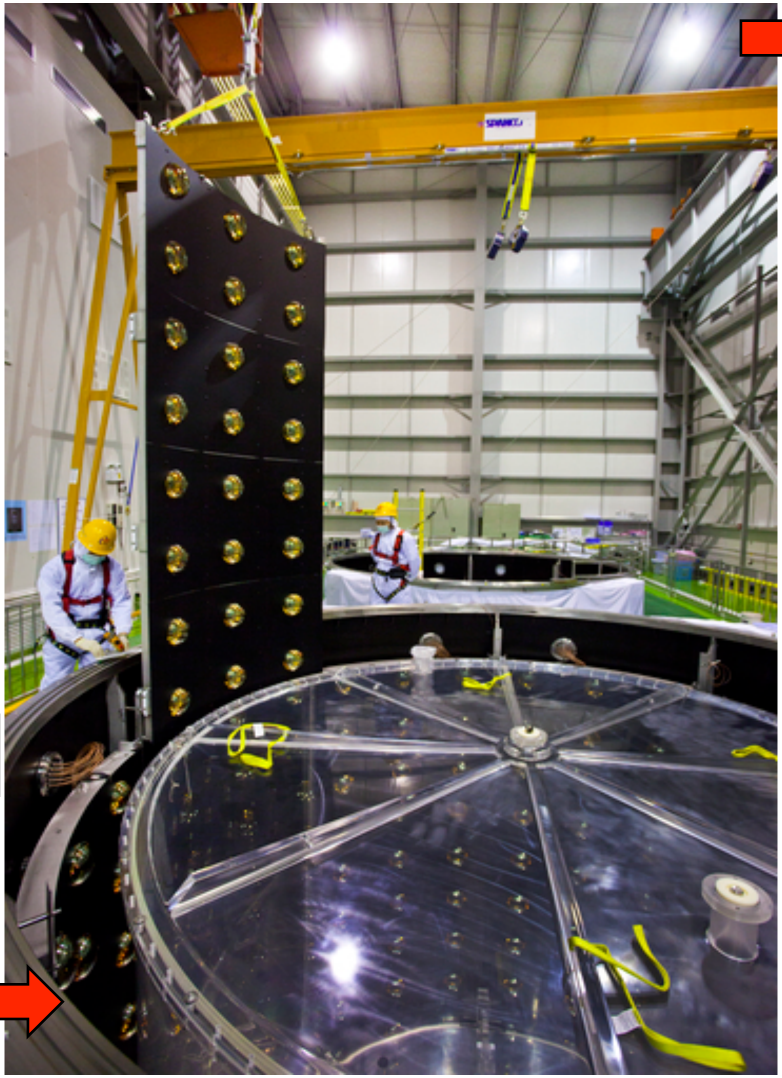
- 10 Hz ^{68}Ge (2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for PMT gain and timing

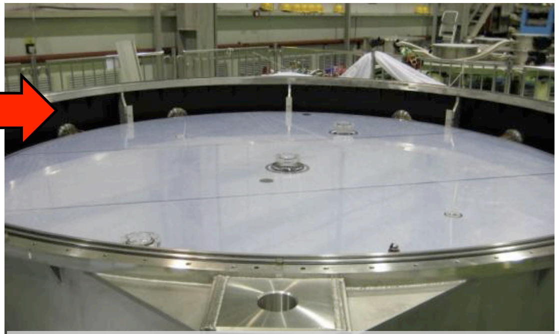
Assemble Antineutrino Detectors

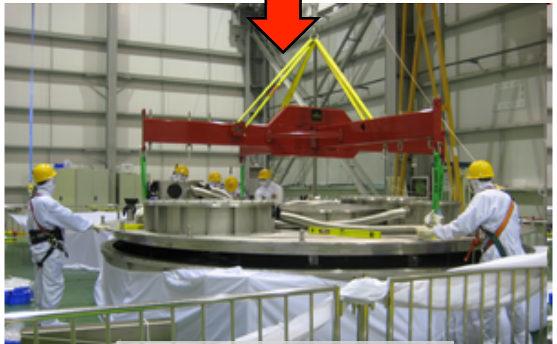

Stainless Steel Vessel (SSV) in assembly pit

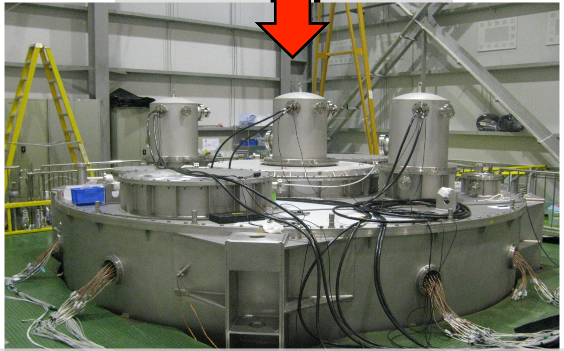

Install lower reflector


Install Acrylic Vessels


Install PMT ladders

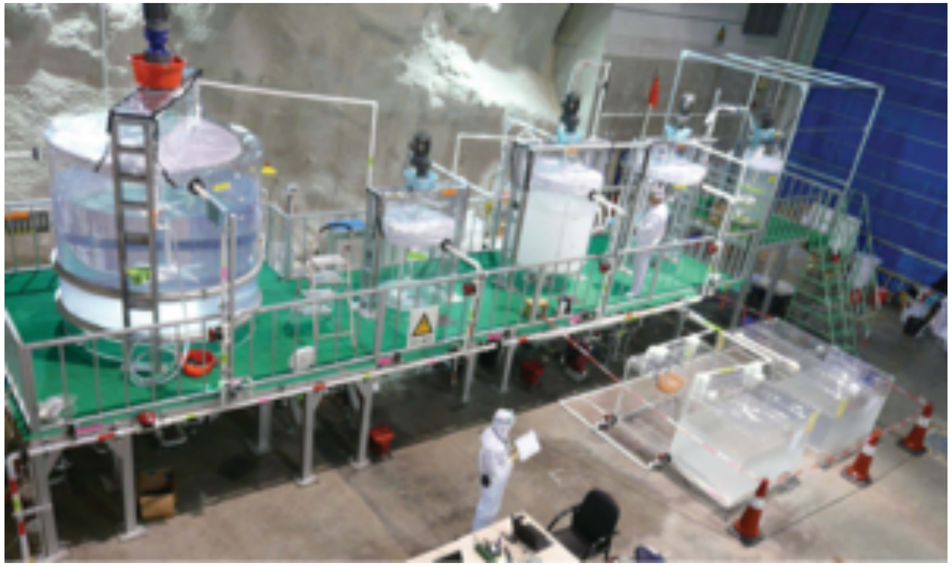

Install top reflector

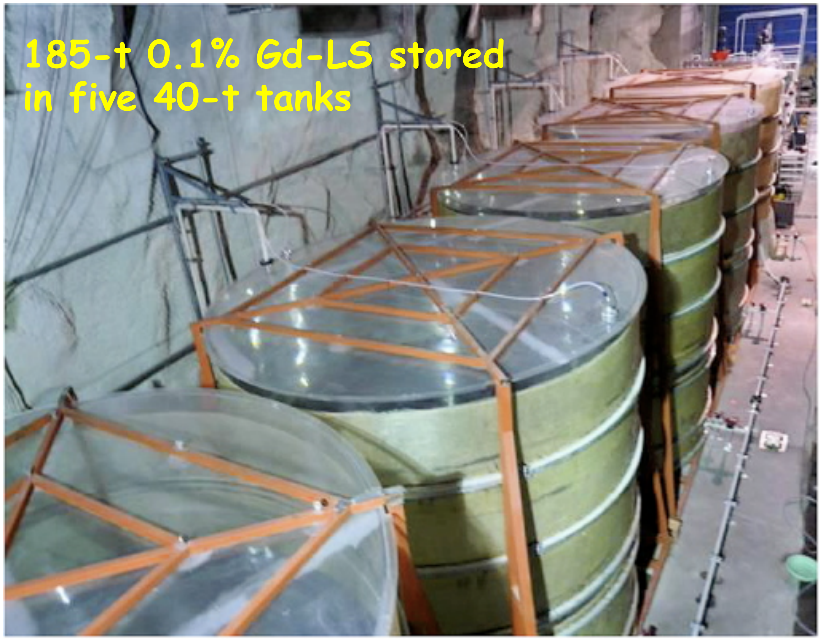

Close SSV


Install calibration units

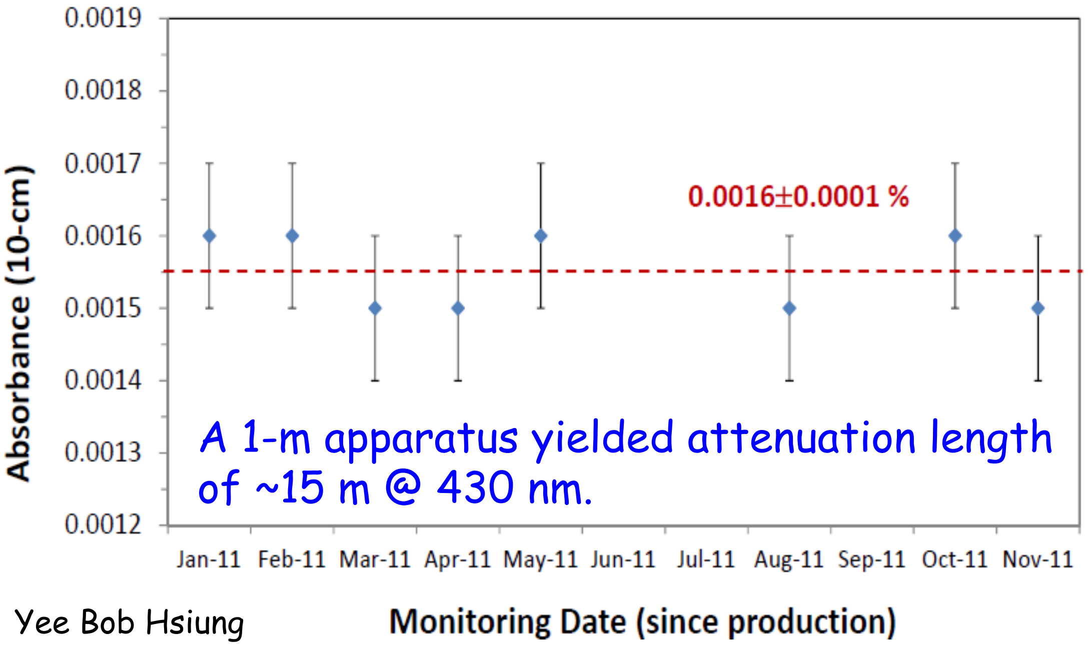
Liquid Scintillators

- Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L) + LAB
- Number of proton: (7.169±0034) × 10^{25} p per kg
- 185-ton Gd-LS + 196-ton LS production



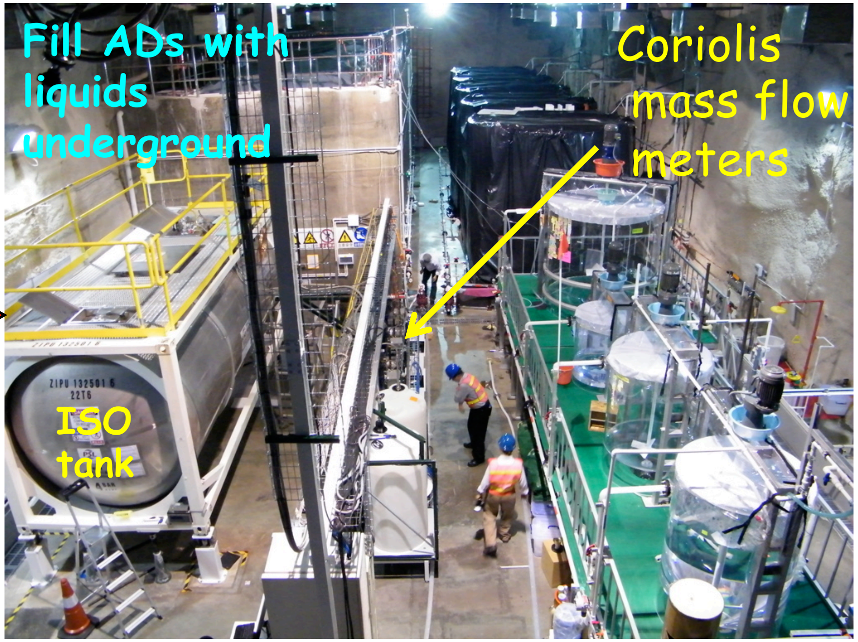


185-t 0.1% Gd-LS stored in five 40-t tanks

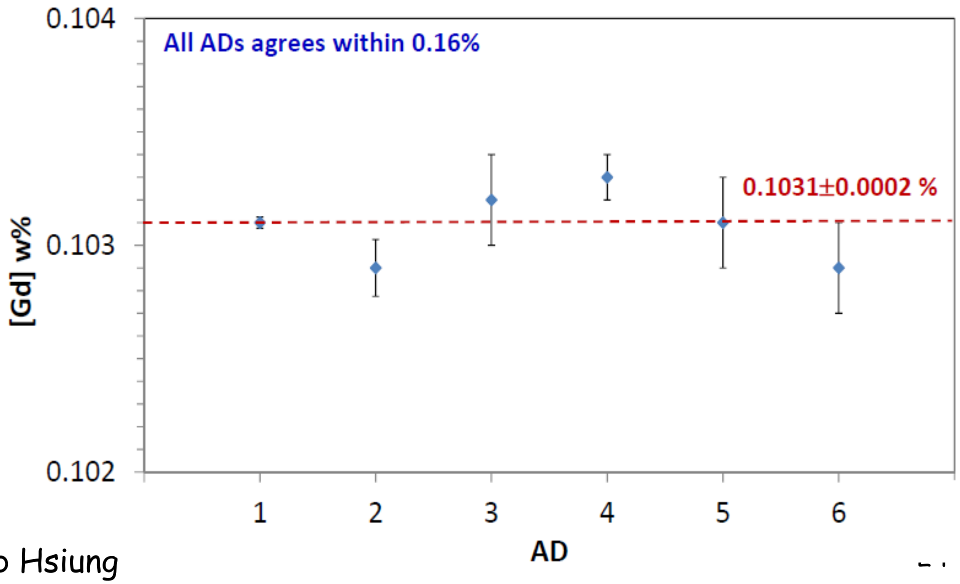


A 1-m apparatus yielded attenuation length of ~15 m @ 430 nm.

Fill Antineutrino Detectors (ADs)

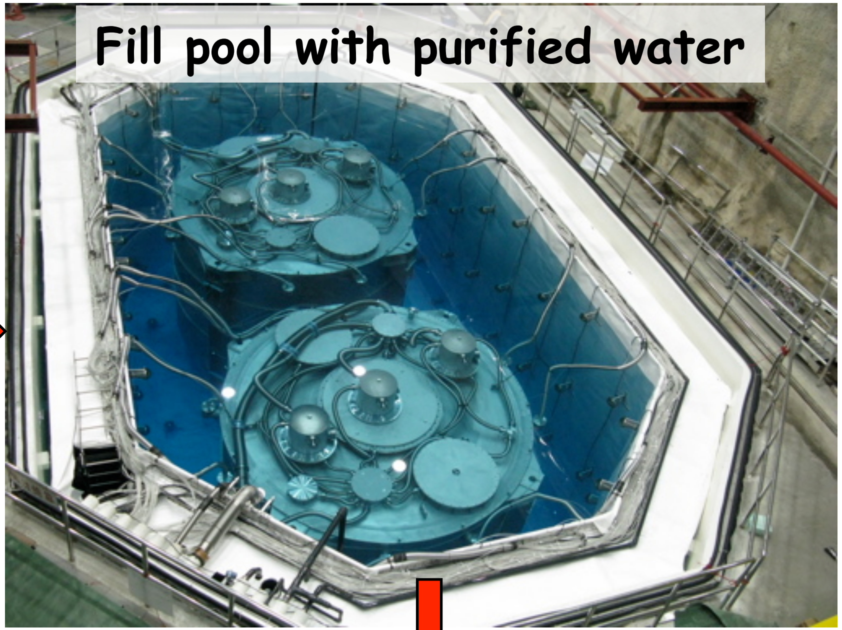


- Target mass is measured with:
  - (1) 4 load cells supporting the 20-t ISO tank
  - (2) Coriolis mass flow meters
  - Absolute uncertainty: 0.02%
  - Relative uncertainty: 0.02%
- Temperature is maintained constant
- Filling is monitored with in-situ sensors



Daya Bay Near Hall (EH1)


Install filled AD in pool

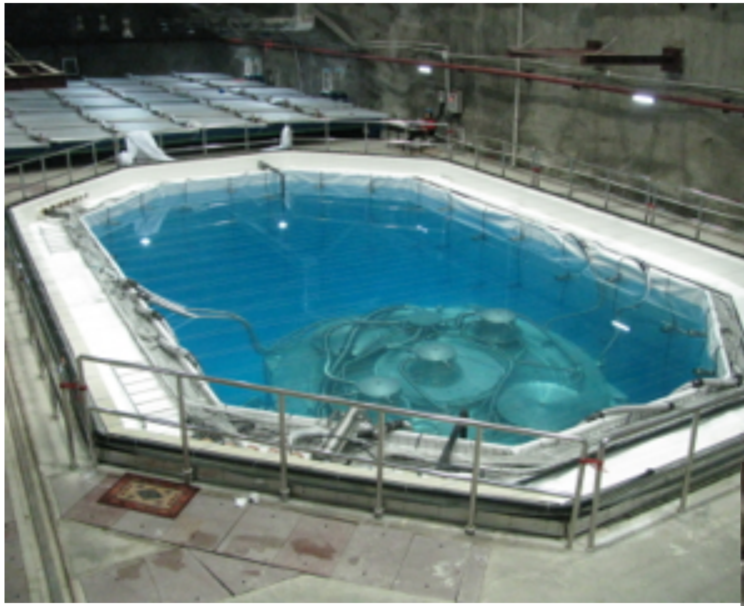

Fill pool with purified water


Place cover over pool

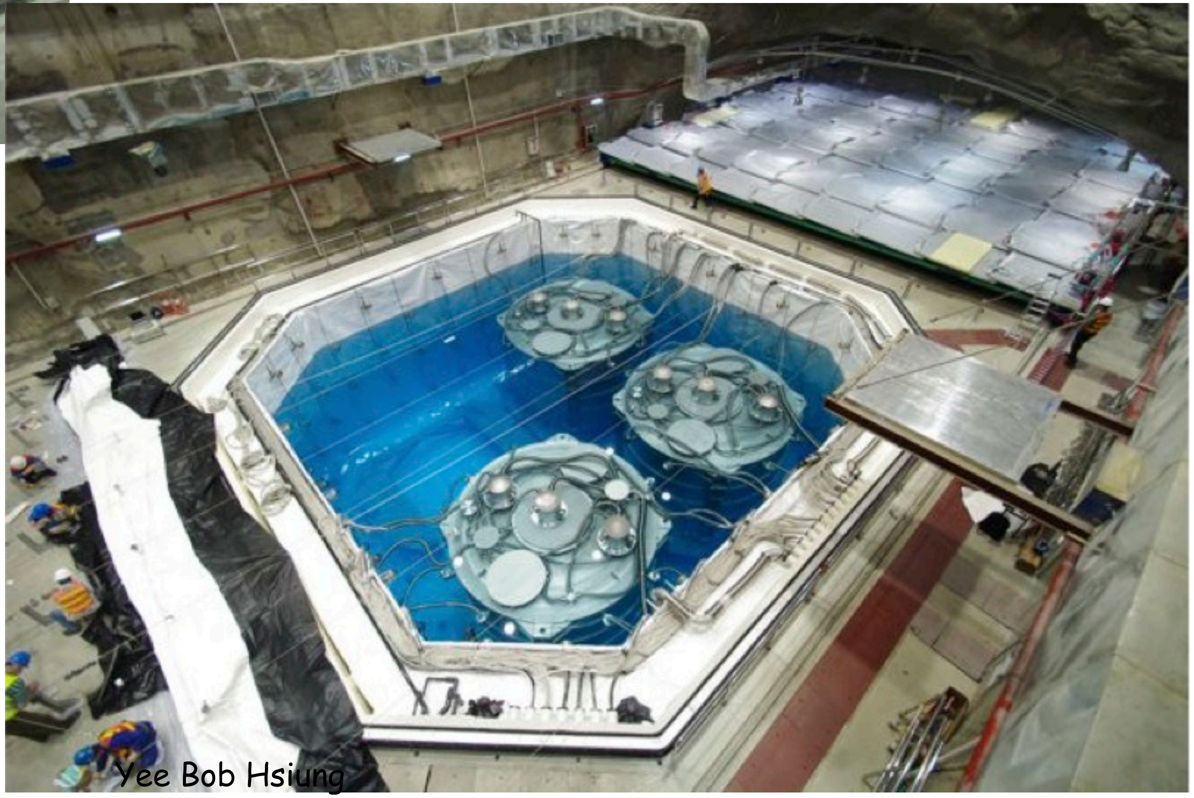

Data taking started on 15 Aug 2011

Roll RPC over cover

Getting Ling Ao Near and Far Halls Ready



EH 2 (Ling Ao Near Hall):
Began operation on
5 Nov 2011



Yee Bob Hsiung

EH 3 (Far Hall):
Started data-taking on
24 Dec 2011

Triggers & Their Performance

Discriminator threshold:

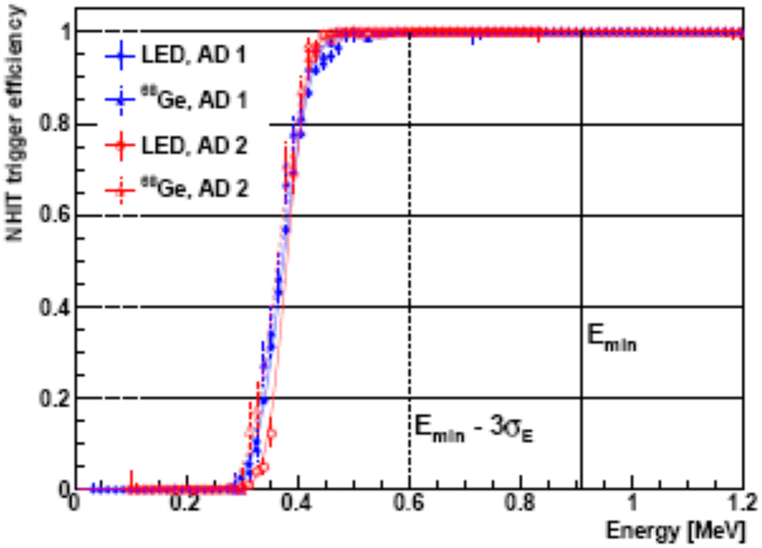
- ~0.25 p.e. for PMT signal

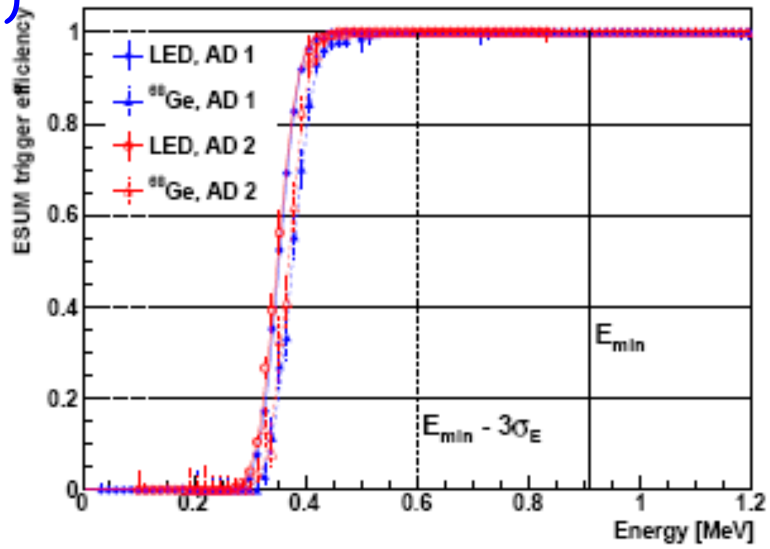
Triggers:

- AD: ≥ 45 PMTs (digital trigger)
  ≥ 0.4 MeV (analog trigger)
- Inner Water Cherenkov: ≥ 6 PMTs
- Outer Water Cherenkov: ≥ 7 PMTs (near)
  ≥ 8 PMTs (far)
- RPC: 3/4 layers in each module

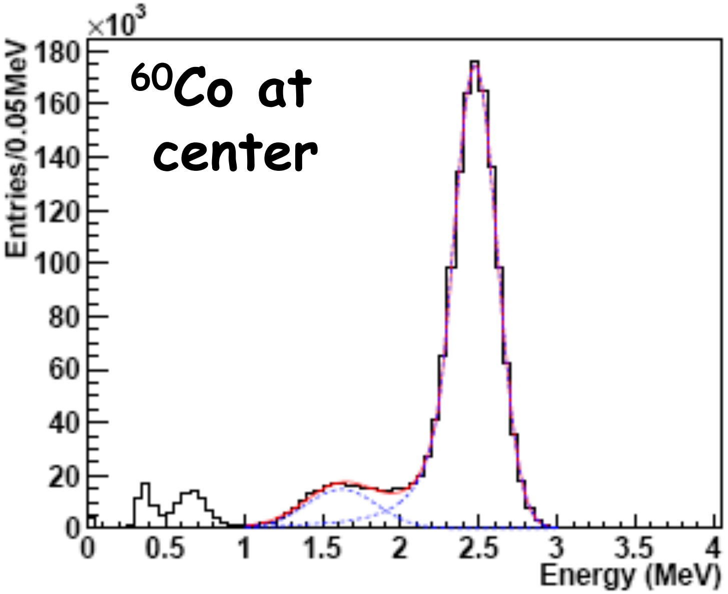
Trigger rate:

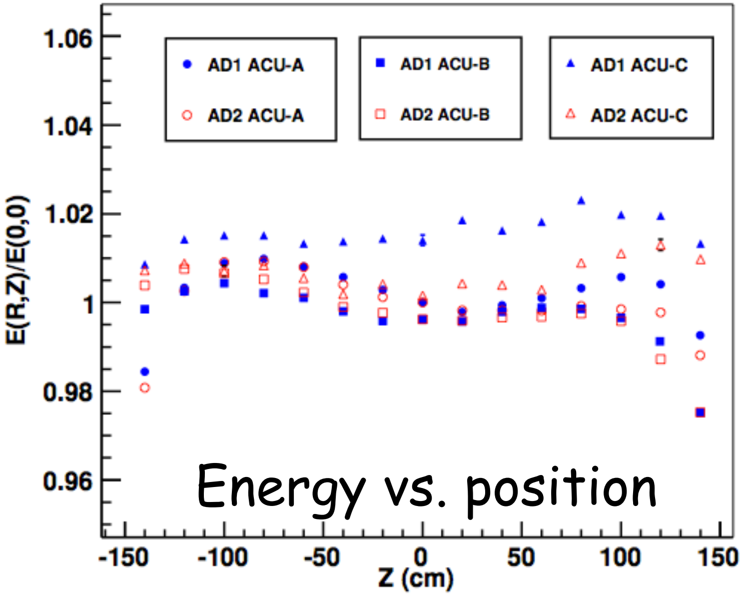
- AD: < 280 Hz
- Inner Water Cherenkov: < 160 Hz
- Outer Water Cherenkov: < 200 Hz

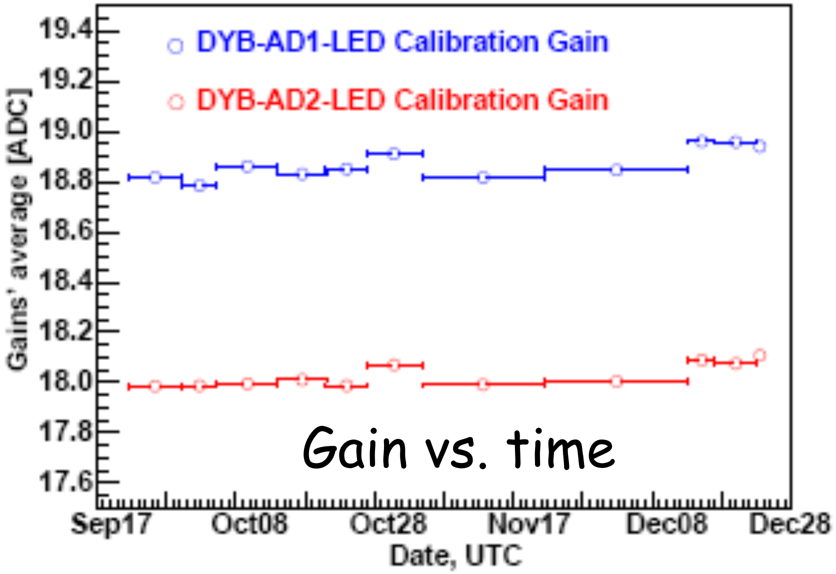


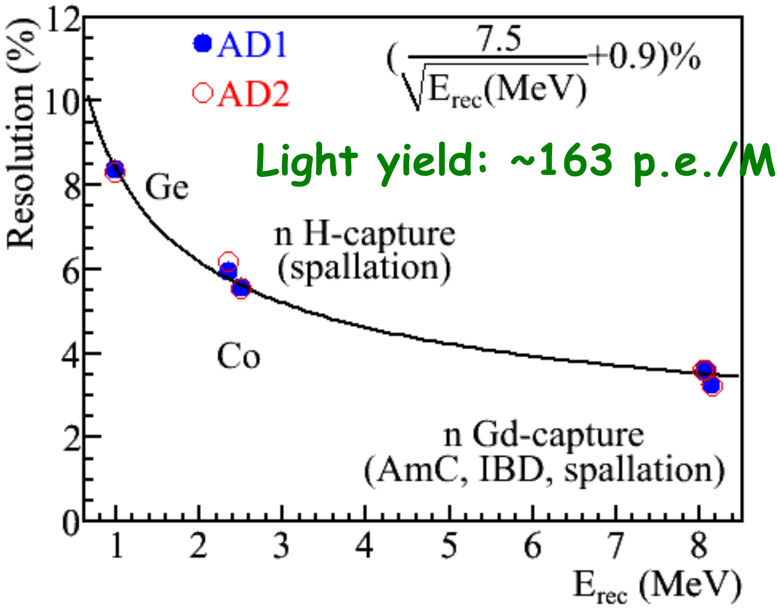


Energy Calibration


^{60}Co at center


Energy vs. position


Gain vs. time


Light yield: ~163 p.e./MeV

Selecting Antineutrino (IBD) Candidates

Use Prompt + Delayed correlated signal to select antineutrino candidates.

Selection:

-Prompt: 0.7 MeV < E_p < 12 MeV

-Delayed: 6.0 MeV < E_d < 12 MeV

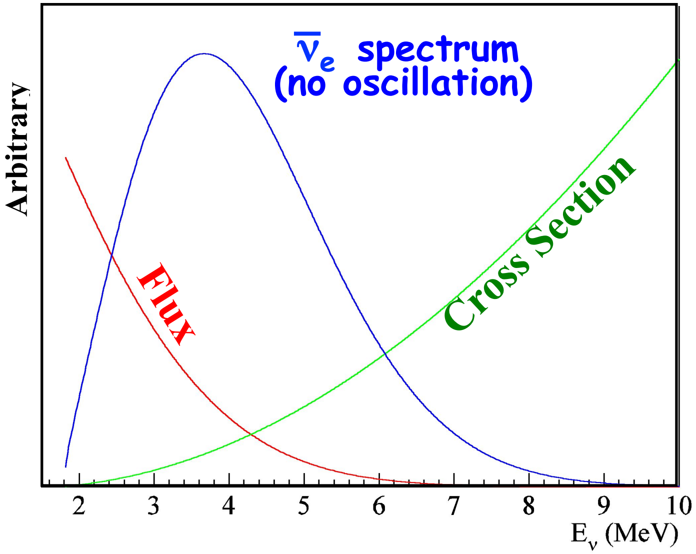
-Capture time: 1 μs < Δt < 200 μs

-Reject Flashers

- Muon Veto:
    - Pool Muon: Reject 0.6ms
    - AD Muon (>20 MeV): Reject 1ms
    - AD Shower Muon (>2.5GeV): Reject 1s

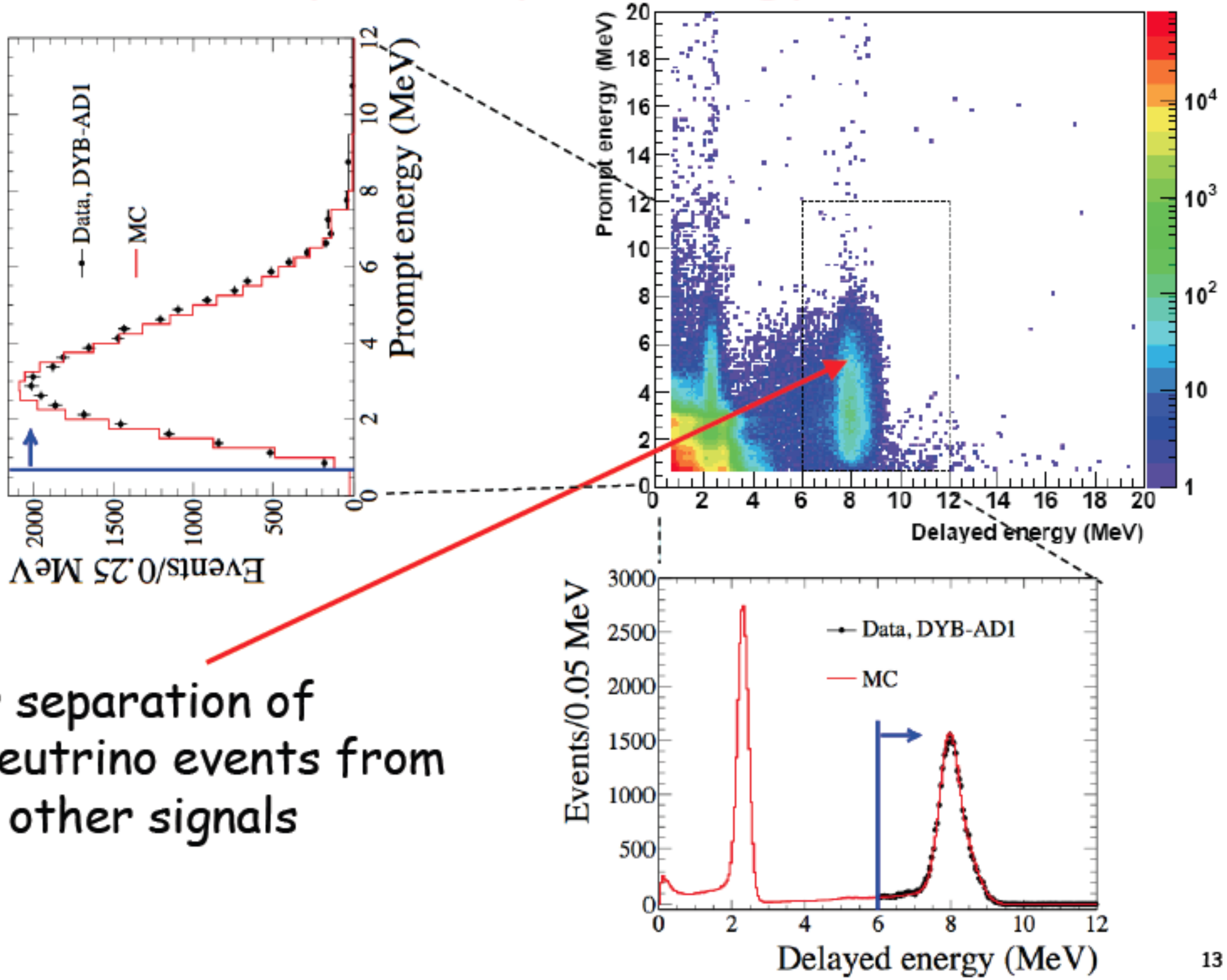
- Multiplicity:

  No other signal > 0.7 MeV
  in -200 μs to 200 μs of IBD.



From Bemporad, Gratta and Vogel

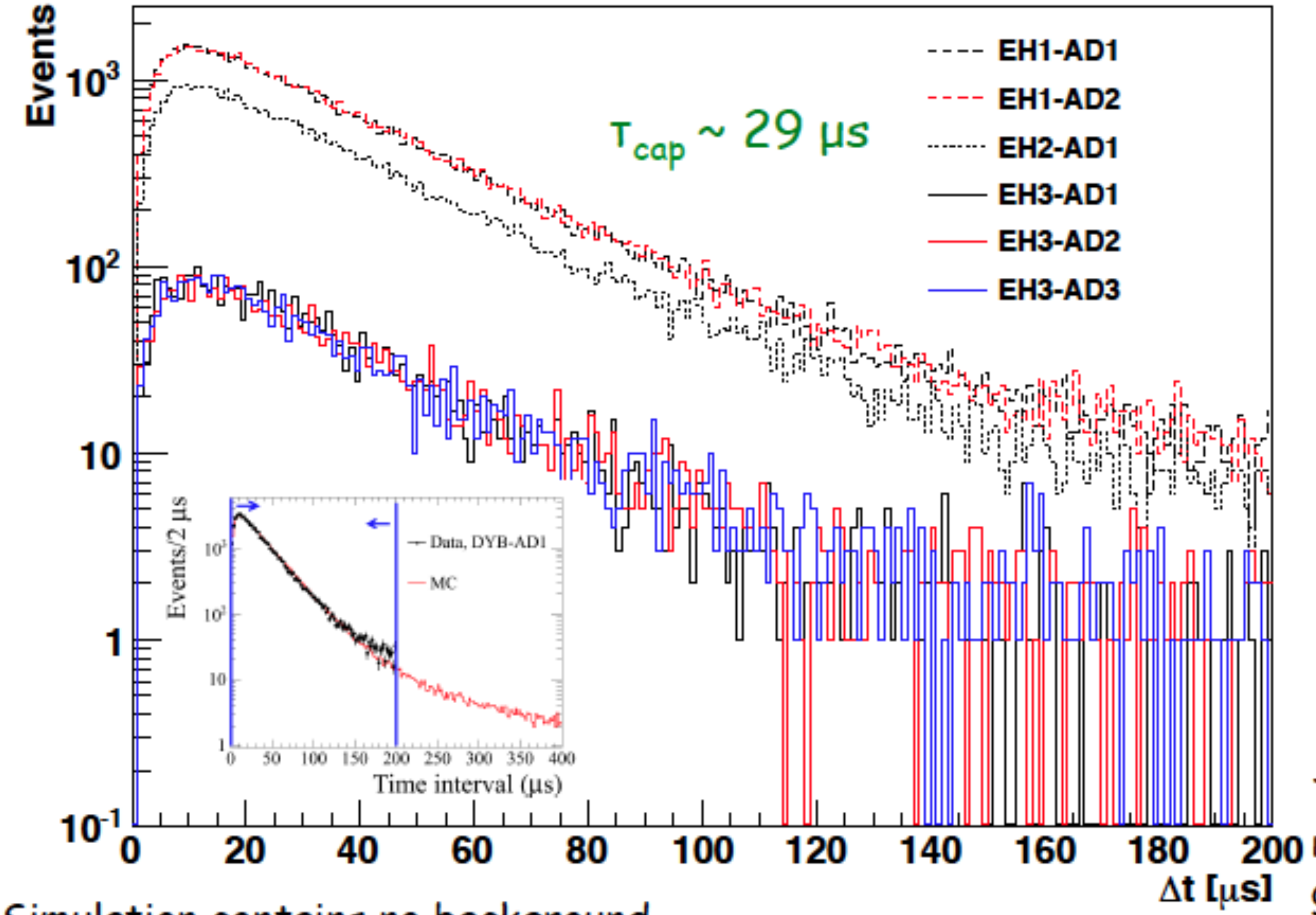
Prompt/Delayed Energy



Clear separation of antineutrino events from most other signals

Neutron Capture Time

Consistent capture time measured in all detectors



Time between neutron generation and capture on Gd

Simulation contains no background
(deviates from data at >150 μs)

Measured capture times imply relative H/Gd capture efficiency: <0.1% between detectors.

Analyzed Data Sets

Two detector comparison [1202.6181]

- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis [1203:1669]

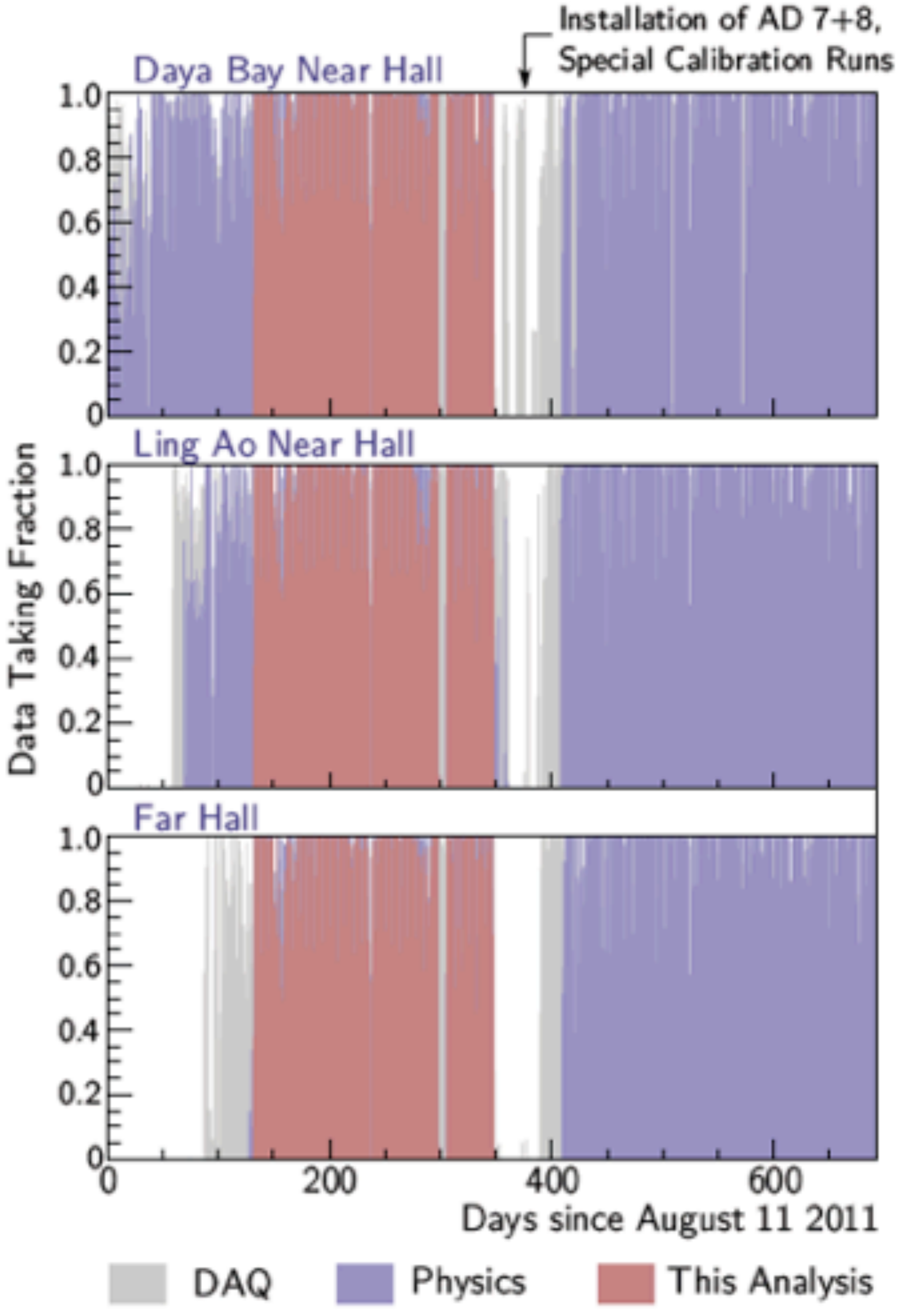
- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803

Improved oscillation analysis [1210.6327]

- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

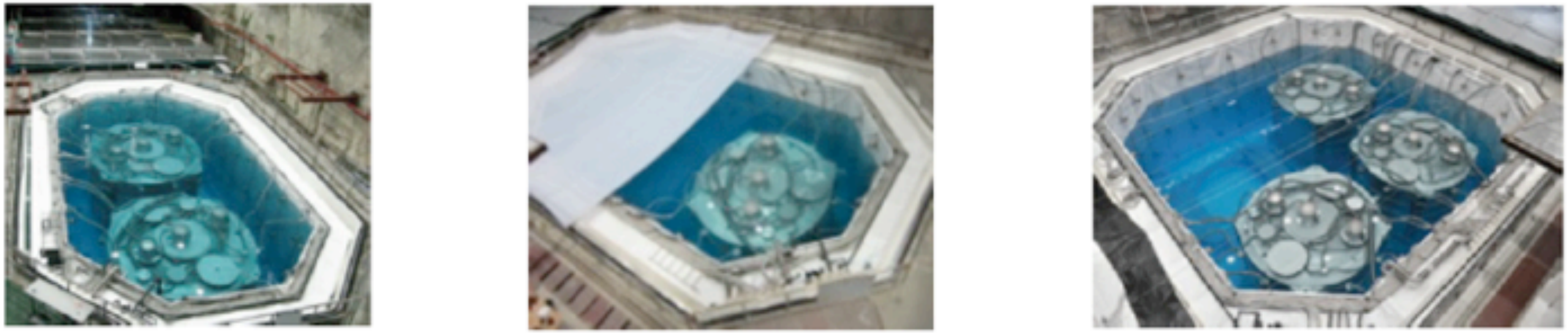
Spectral Analysis

- 217 days complete 6 AD period
- 55% more statistics than CPC result

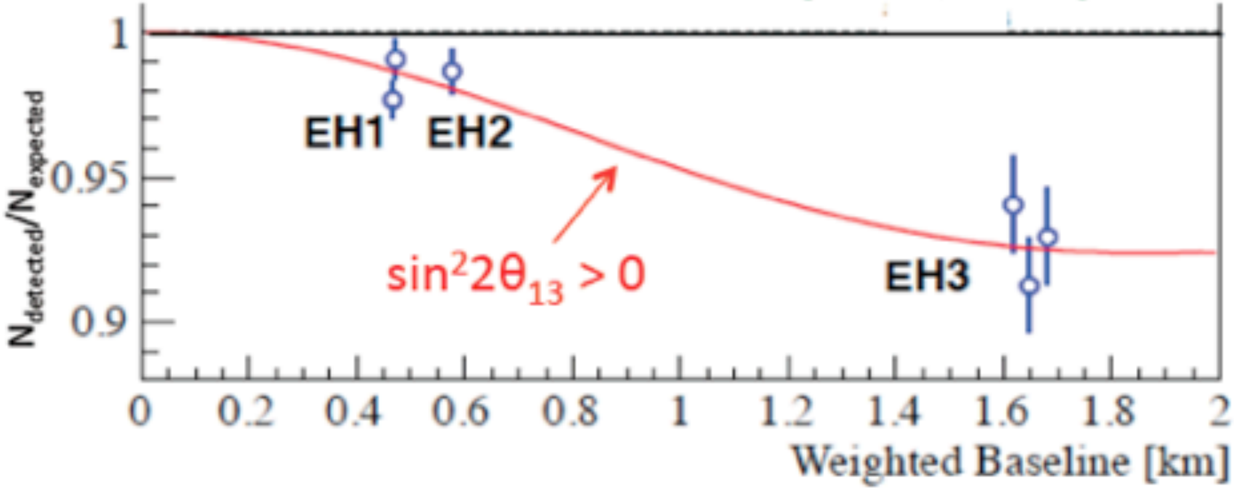


PRL 112, 061801 (2014)

Initial Results



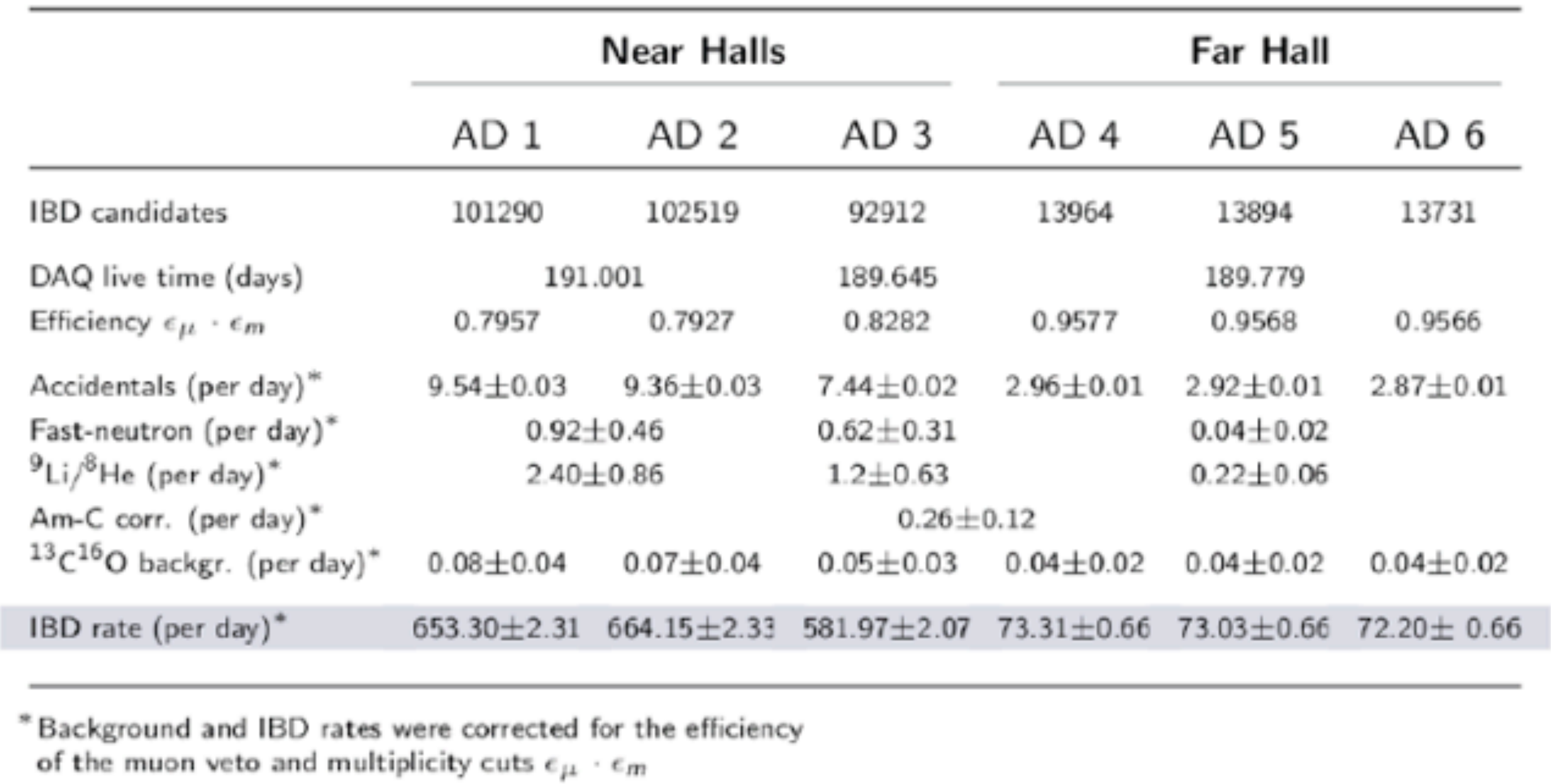
Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\overline{\nu}_e$ at short baseline in March 2012. [PRL **108**, 171803]



Obtained the most precise value of θ_{13} in Jun. 2012:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$$ [CPC **37**, 011001]

Signal and Background Summary



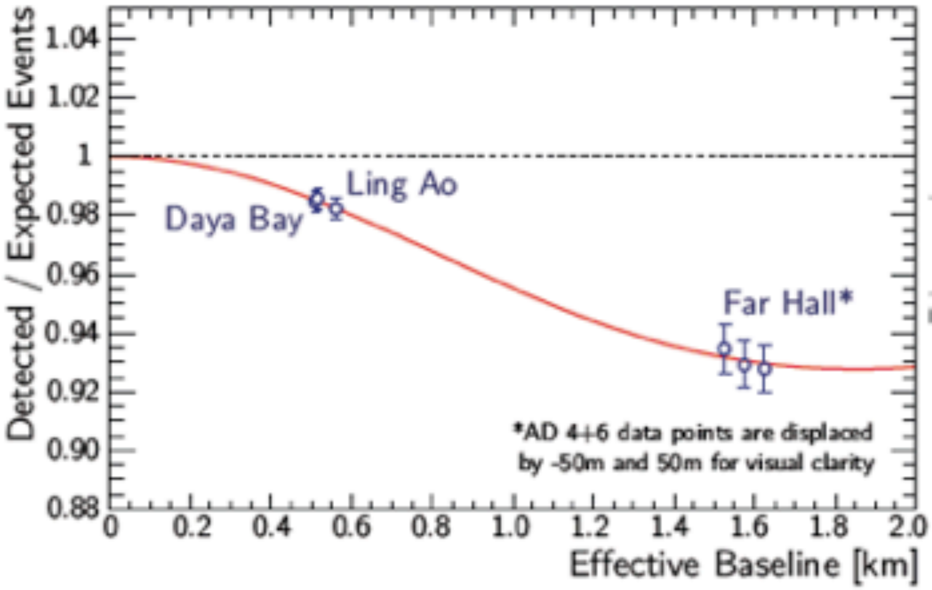
	Near Halls			Far Hall		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (days)	191.001		189.645	189.779		
Efficiency $\epsilon_\mu \cdot \epsilon_m$	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (per day)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast-neutron (per day)*	0.92±0.46		0.62±0.31	0.04±0.02		
^{9}Li/^{8}He (per day)*	2.40±0.86		1.2±0.63	0.22±0.06		
Am-C corr. (per day)*	0.26±0.12					
^{13}C^{16}O backgr. (per 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
IBD rate (per day)*	653.30±2.31	664.15±2.33	581.97±2.07	73.31±0.66	73.03±0.66	72.20± 0.66

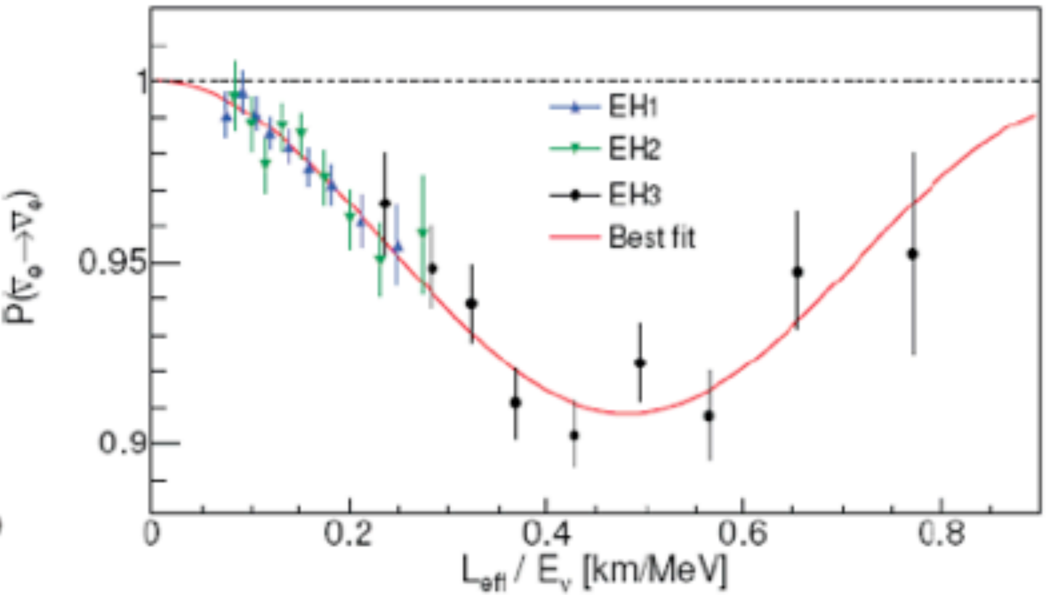
* Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $\epsilon_\mu \cdot \epsilon_m$

Collected more than 300k antineutrino interactions

- Consistent rates for side-by-side detectors
- Uncertainties still dominated by statistics

Rate-Only Oscillation Results

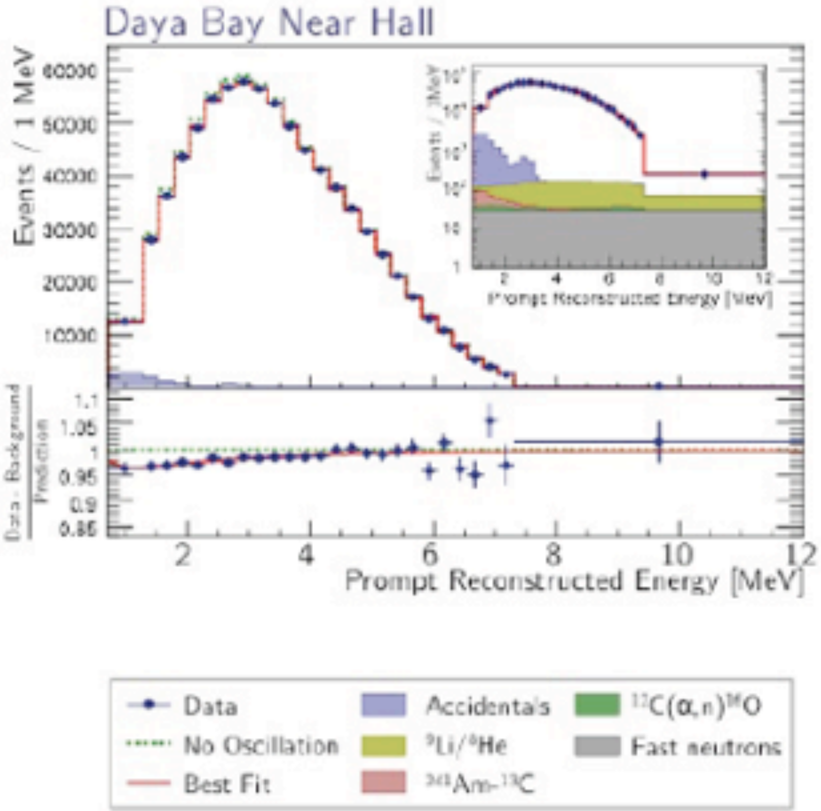


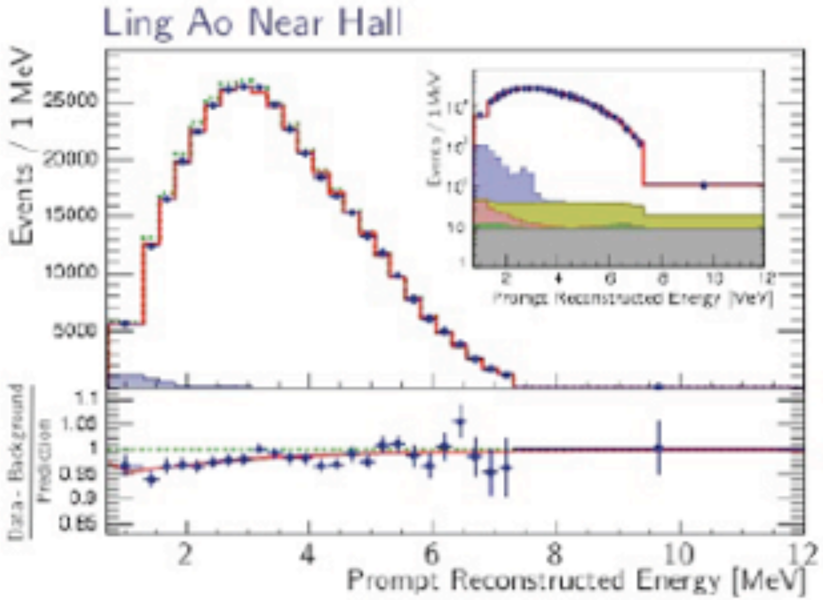


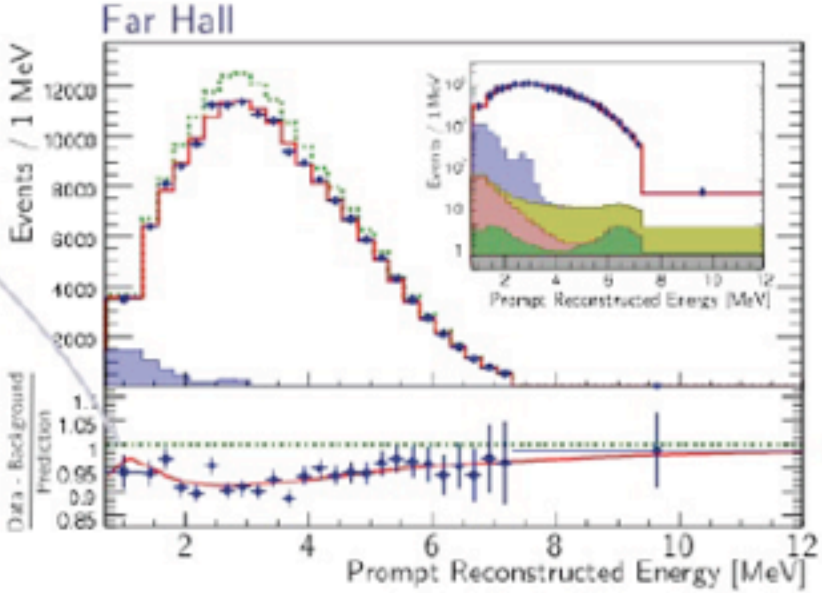
$$\sin^2 2\theta_{13} = 0.089 \pm 0.009$$

- Uncertainty reduced by statistics of complete 6 AD data period
- Standard approach: $\chi^2/N_{DoF} = 0.48/4$
- $|\Delta m^2_{ee}|$ constrained by MINOS result for $|\Delta m^2_{\mu\mu}|$
- Far vs. near relative measurement: absolute rate not constrained
- Consistent results from independent analyses, different reactor flux models

Prompt IBD Spectra





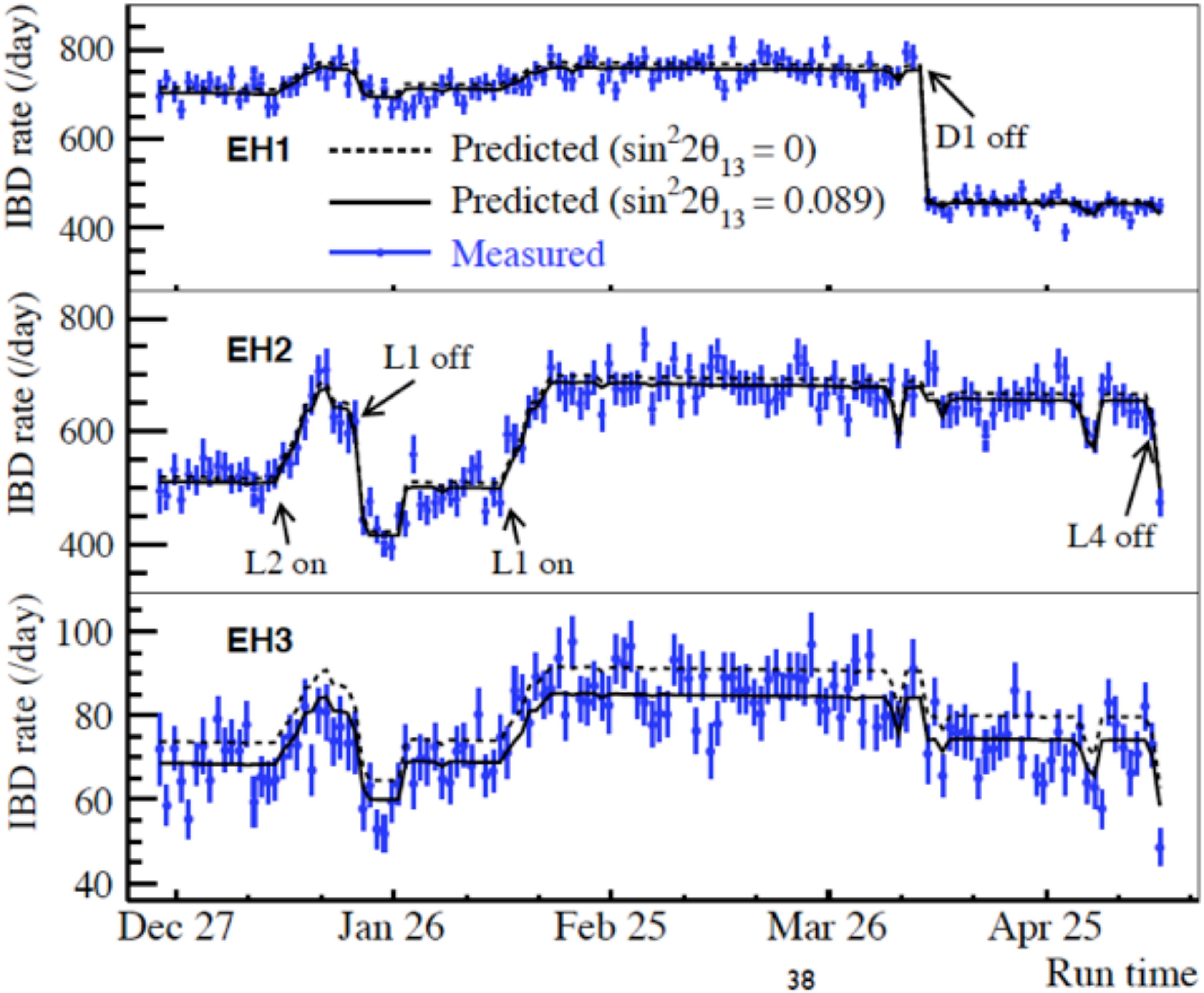


Shape distortion from energy losses in acrylic

Spectral distortion consistent with oscillation

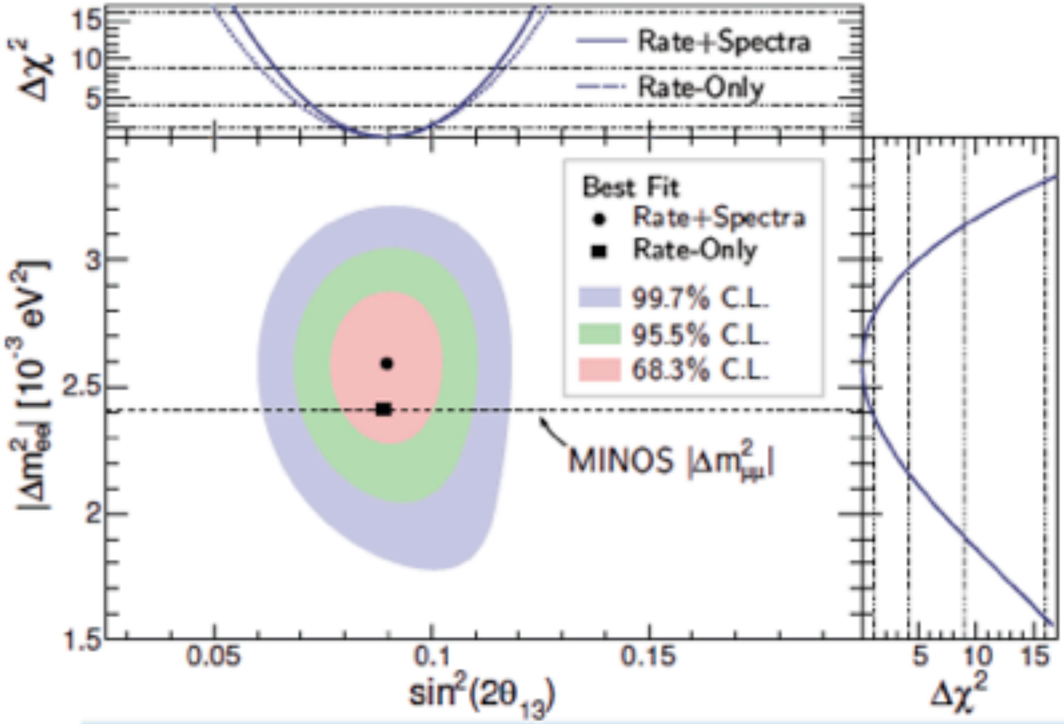
- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

Now Compare "Near" and "Far"



There is a deficit in EH3, the farthest hall!

Rate+Spectra Oscillation Results



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

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

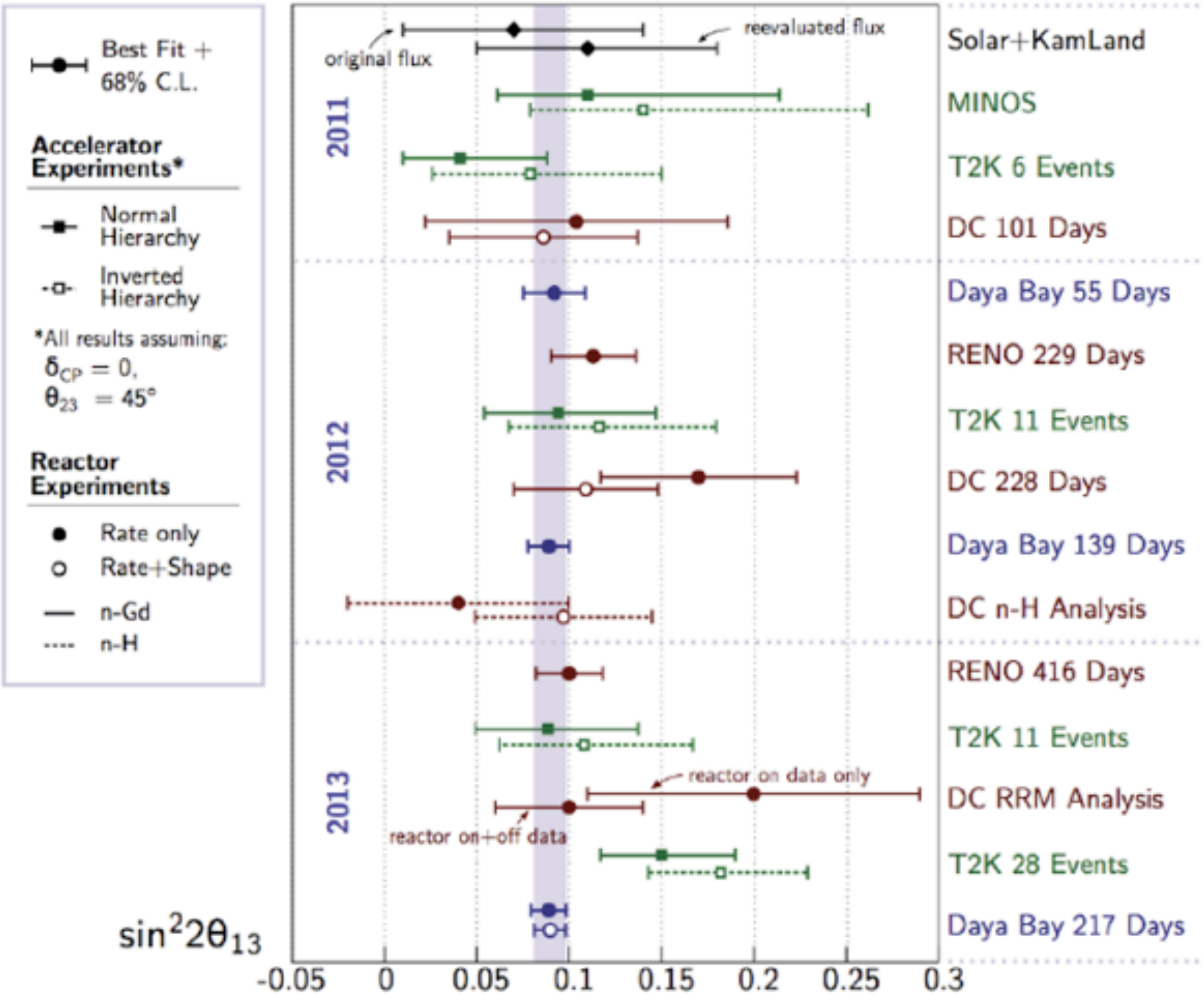
$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$

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

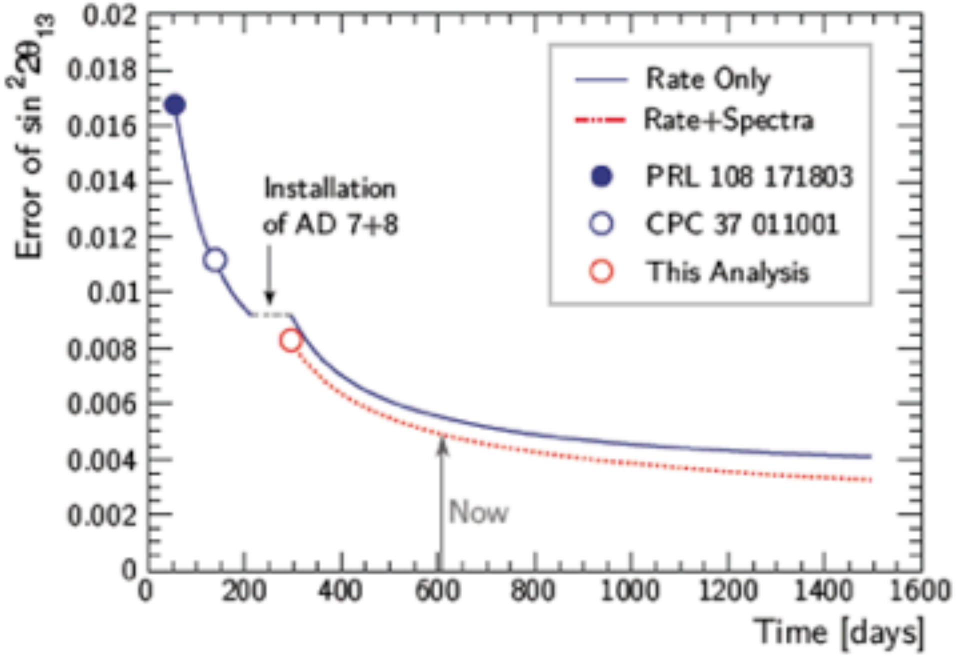
	Normal MH Δm^2_{32} $[10^{-3}\mathrm{eV}^2]$	Inverted MH Δm^2_{32} $[10^{-3}\mathrm{eV}^2]$
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

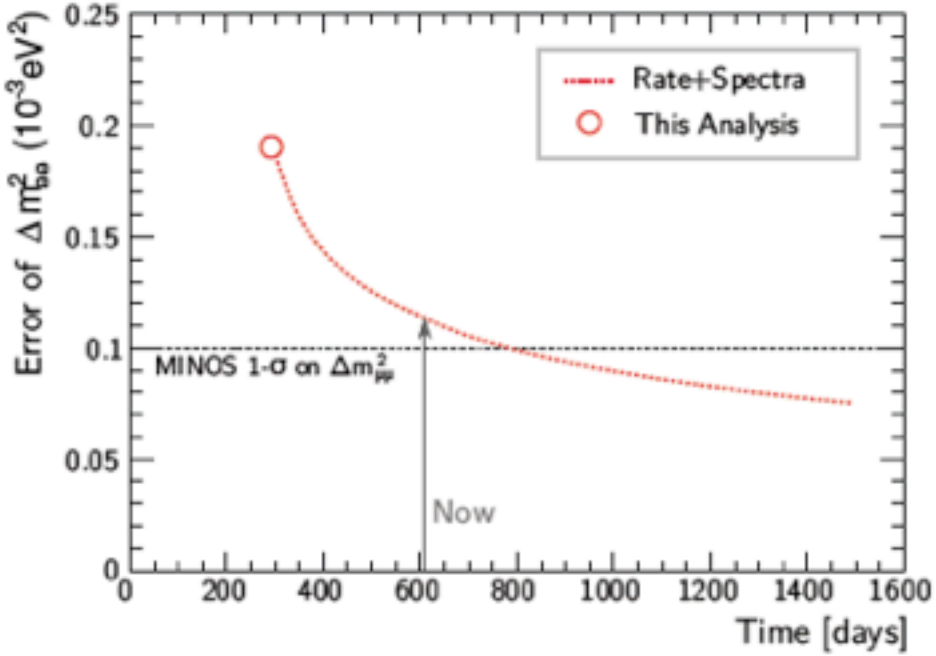
A. Radovic, DPF2013

Global Comparison of θ_{13} Measurements



Sensitivity Projection





Sensitivity still dominated by statistics

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - θ_{13}: Reactor model, relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
- Precision of mass splitting measurement closing in on results from μ flavor sector

Summary

The Daya Bay Experiment has reported the first direct measurement of the oscillation short-distance electron antineutrino oscillation frequency:

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

The measurement has also produced the most precise estimate of the mixing angle:

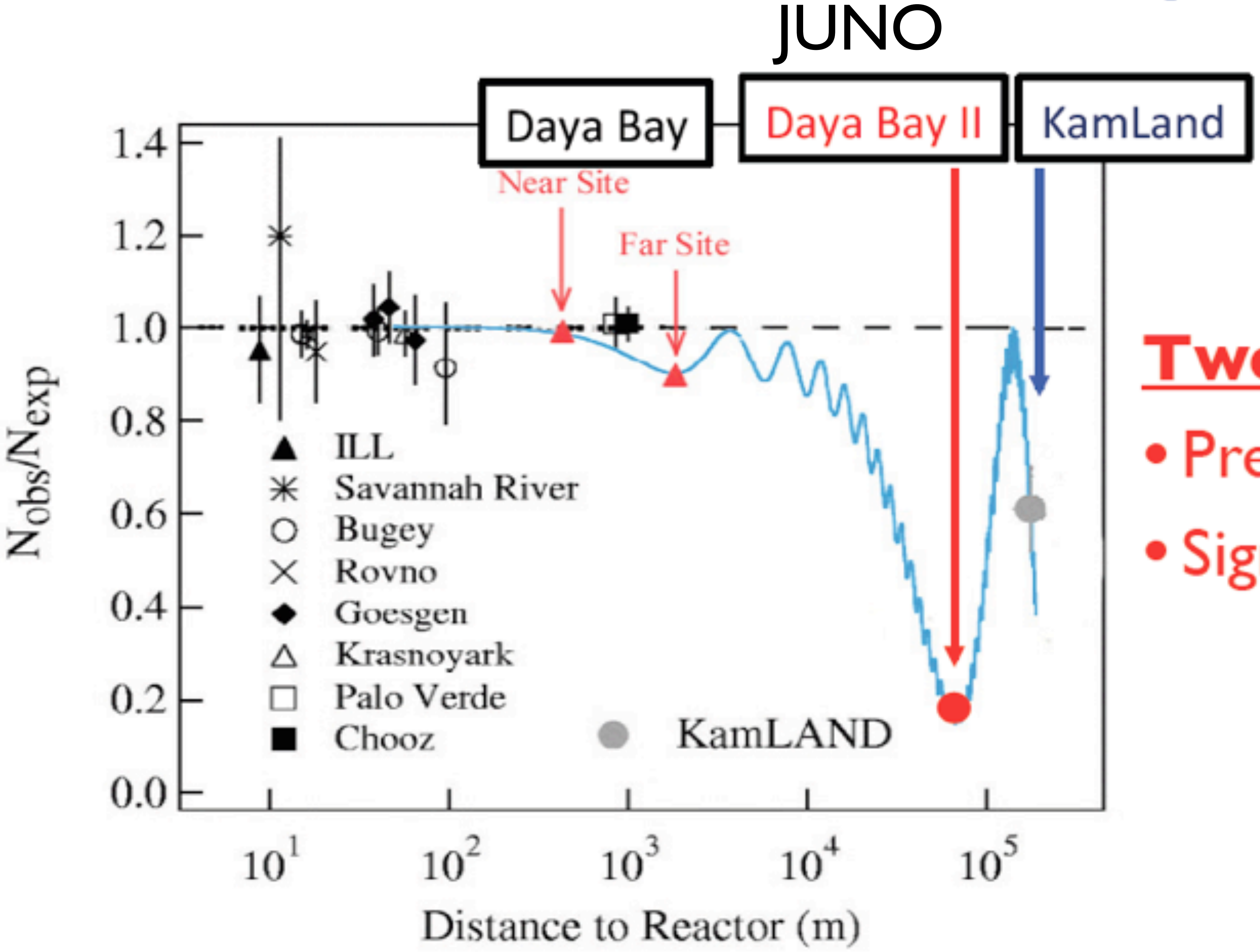
$$\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}$$

Expect more from Daya Bay:

- Measurement of the absolute reactor flux, addressing the potential reactor anomaly
- Constraints on non-standard neutrino models
- Significantly increased precision (all 8 detectors, >2 years of operation)
- Flux model comparison
- Generic neutrino spectrum

The Next Generation: Daya Bay II

JUNO



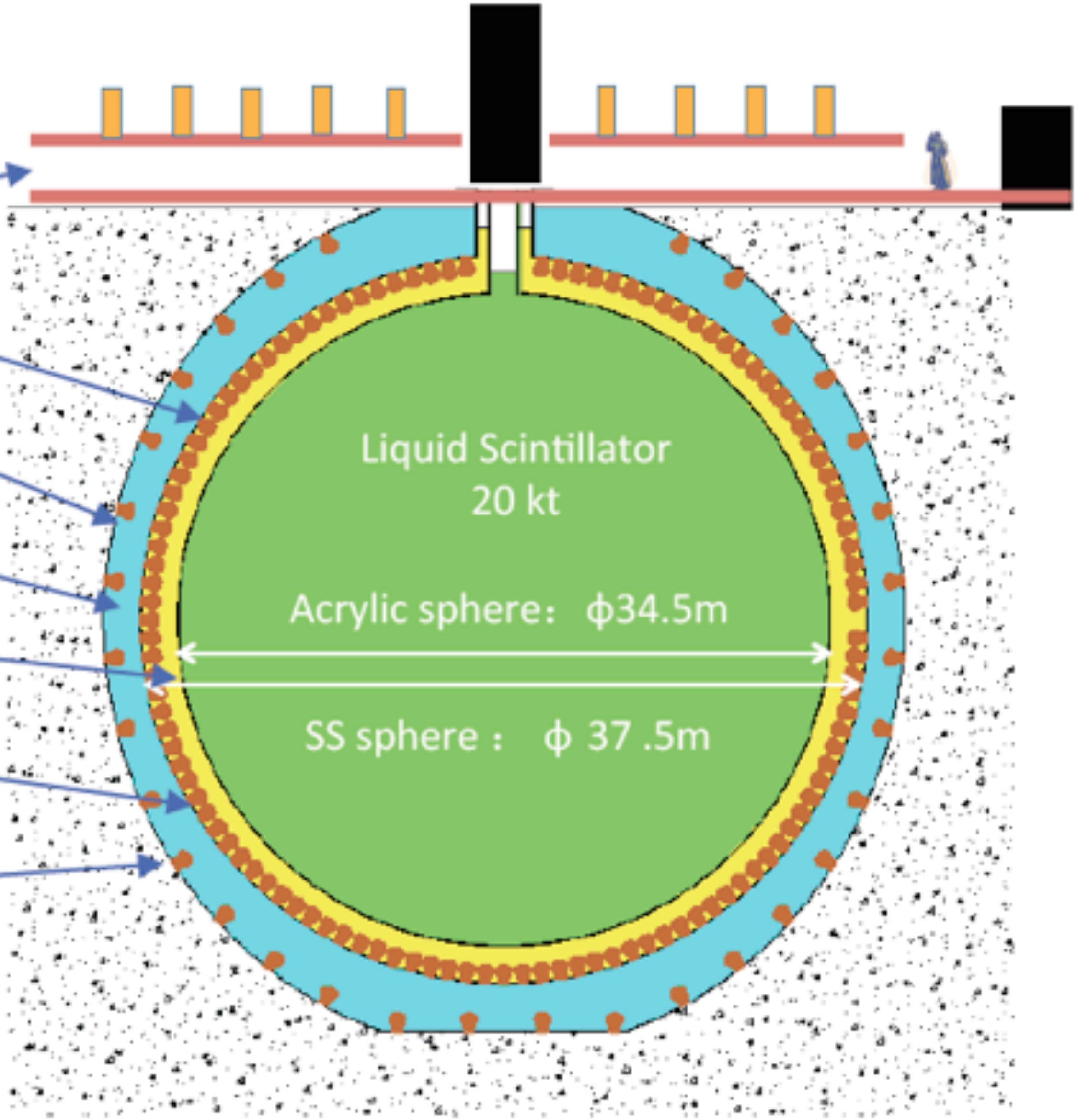
Two Goals:

- Precision θ_{12}
- Sign of Δm^2

Possible Sites

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operating	Planned	Planned	Under Cons	Under Cons
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Possible Detector Concept



Muon Tracking

Stainless Steel Tank

Water Seal

Water Buffer (10kT)

Mineral Oil Buffer (10kT)

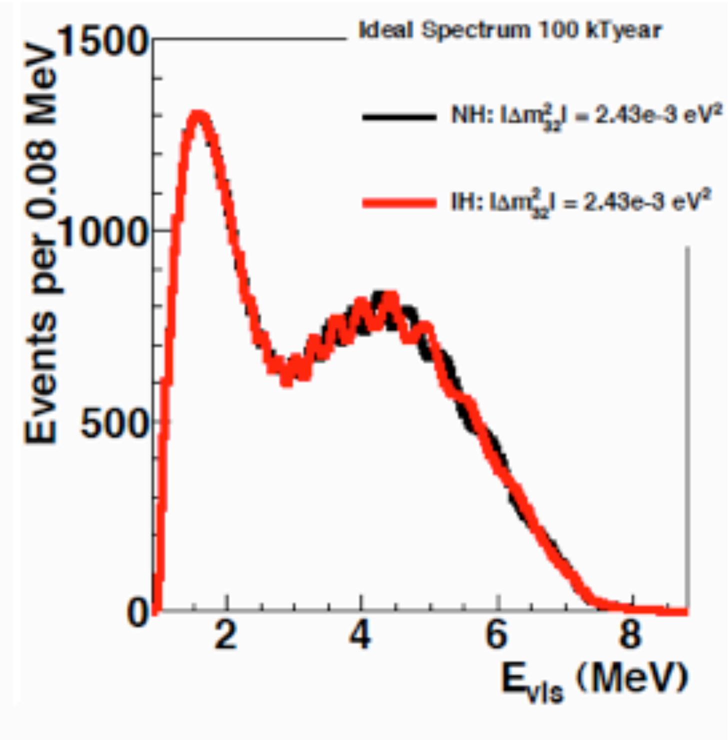
15,000 20" PMTs

20"Veto PMTs

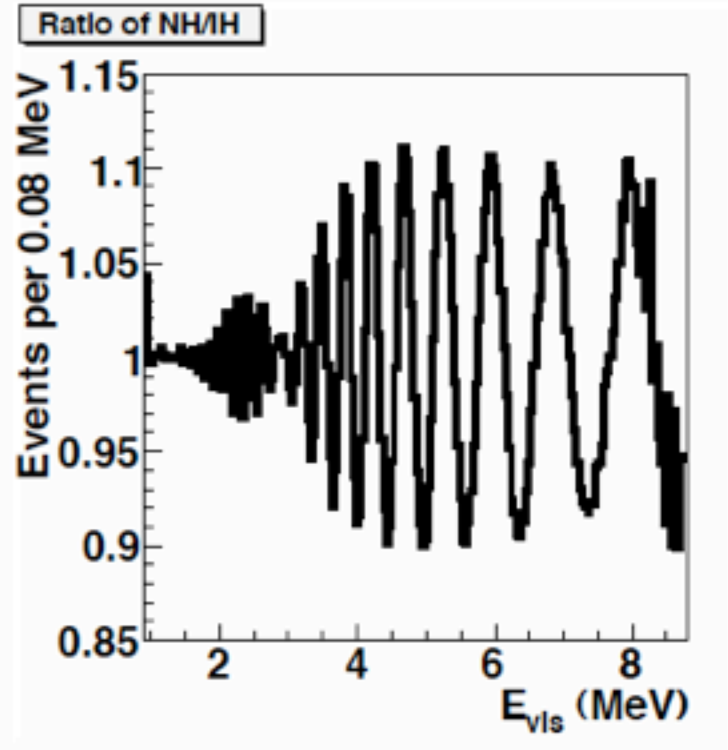
All Details Yet to be Worked Out

Expected Signal

arXiv:1208.1551v1

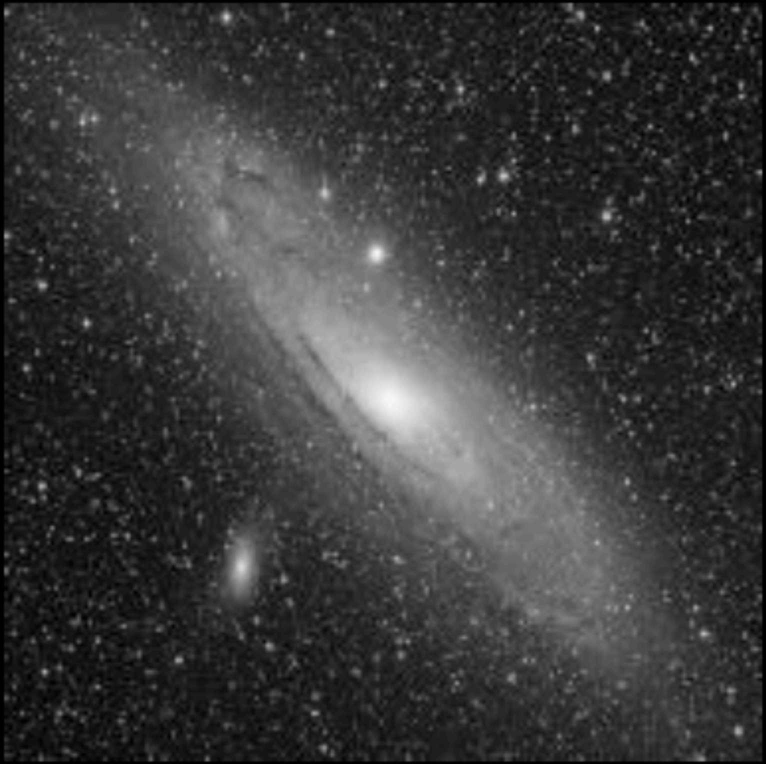


Spectrum distorted due to oscillations 1↔2 (ala KamLAND)



Discerning "Normal" from "Inverted" mass hierarchy will require good energy resolution.

- If CP violation is found in the neutrino sector:

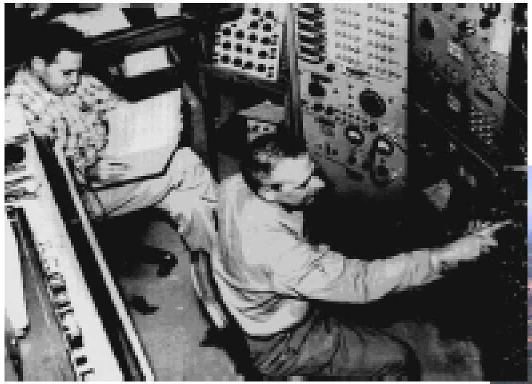


Where have all the anti-galaxies gone?

- How can we exist?

Thank You

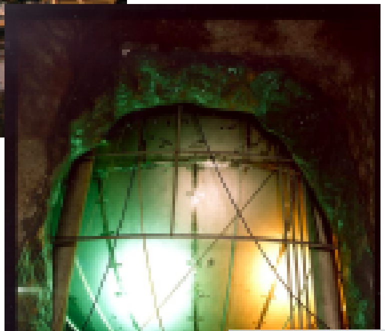
Neutrino Physics at Reactors



1956
First observation
of neutrinos

1980s & 1990s
Reactor neutrino flux
measurements in U.S. and Europe

1995
Nobel Prize to Fred Reines
at UC Irvine



2002
Discovery of reactor
antineutrino oscillation

2006 and beyond
Precision measurement of θ_{13}
Exploring feasibility of CP violation studies

Past Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Reactors in Japan

The Daya Bay Strategy

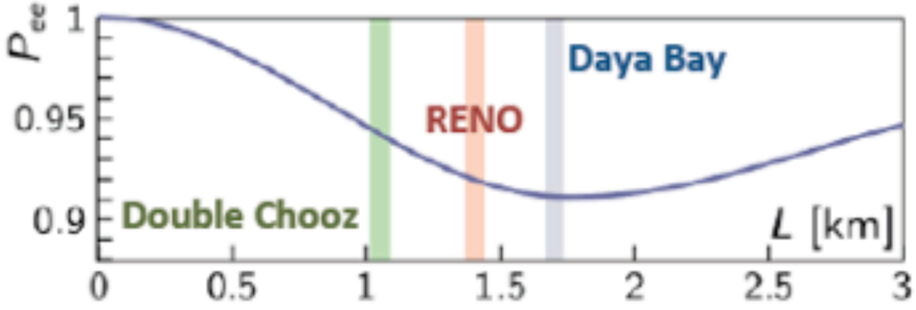
Relative measurement with 8 functionally identical detectors

- Absolute reactor flux single largest uncertainty in previous measurements

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

Baseline Optimization

- Detector locations optimized to known parameter space of $|\Delta m^2_{ee}|$
- Far site maximizes term dependent on $\sin^2 2\theta_{13}$



Go strong, big and deep!

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

Large Signal

Low Background

A Comment on the Mass Splitting

Short-baseline reactor experiments insensitive to mass hierarchy

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

One effective oscillation frequency Δm^2_{ee} is measured:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \quad \Delta m^2_{ee} \frac{L}{4E} - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \quad \Delta m^2_{21} \frac{L}{4E}$$

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

Result easily related to actual mass splitting

Normal hierarchy (+), inverted hierarchy (−):

$$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 5.21 \times 10^{-3} \mathrm{eV}^2$$

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

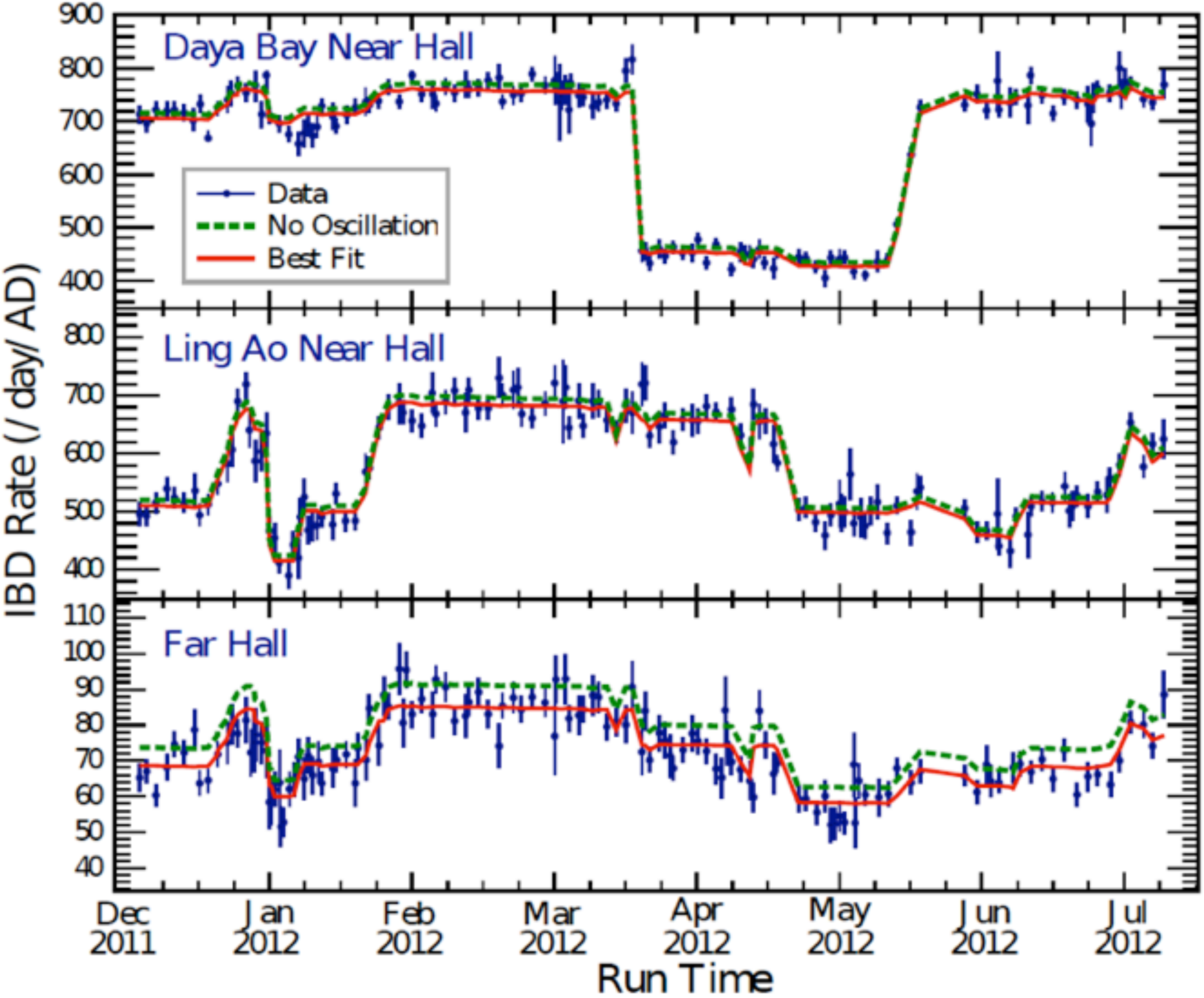
	Detector		
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Only uncorrelated uncertainties relevant to near/far oscillation analysis

Largest systematics smaller than far site statistics (~ 1%)

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Impact of uncorrelated reactor systematics reduced by relative measurement


Daya Bay Near Hall
Ling Ao Near Hall
Far Hall
Data
No Oscillation
Best Fit
IBD Rate (/ day/ AD)
900
800
700
600
500
400
110
100
90
80
70
60
50
40
Dec 2011
Jan 2012
Feb 2012
Mar 2012
Apr 2012
May 2012
Jun 2012
Jul 2012
Run Time

The near future: *CP*

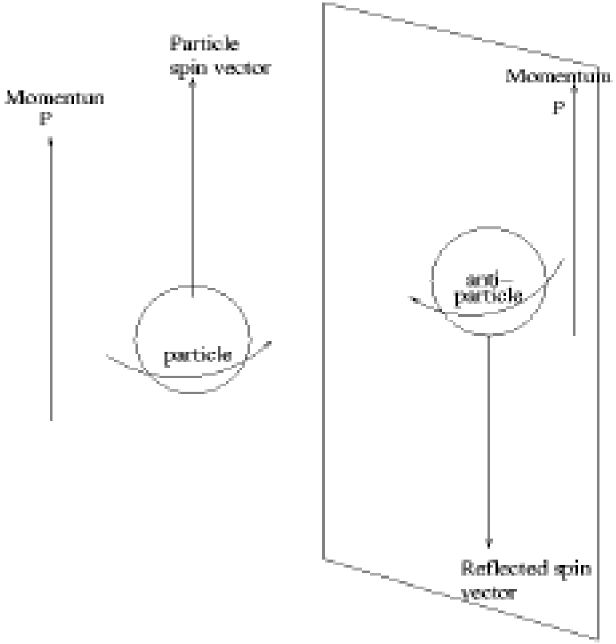
- One of the central motivations of neutrino oscillation physics

- Take a particle interaction say $(K^0_L \rightarrow \pi^- + e^+ + \nu_e)$

- Now change all the particles to anti-particles, and reflect the interaction in space (using a mirror) *Get* $(K^0_L \rightarrow \pi^+ + e^- + \bar{\nu}_e)$

- Now, is this new interaction just as probable as the first? If so *CP* conserved, if not *CP* is not conserved. In the above, decays that include the e^+ are slightly more likely

Parity + Charge Conjugation Operator
(i.e. mirror + particle --> anti-particle)



How do I measure neutrino CP violation?

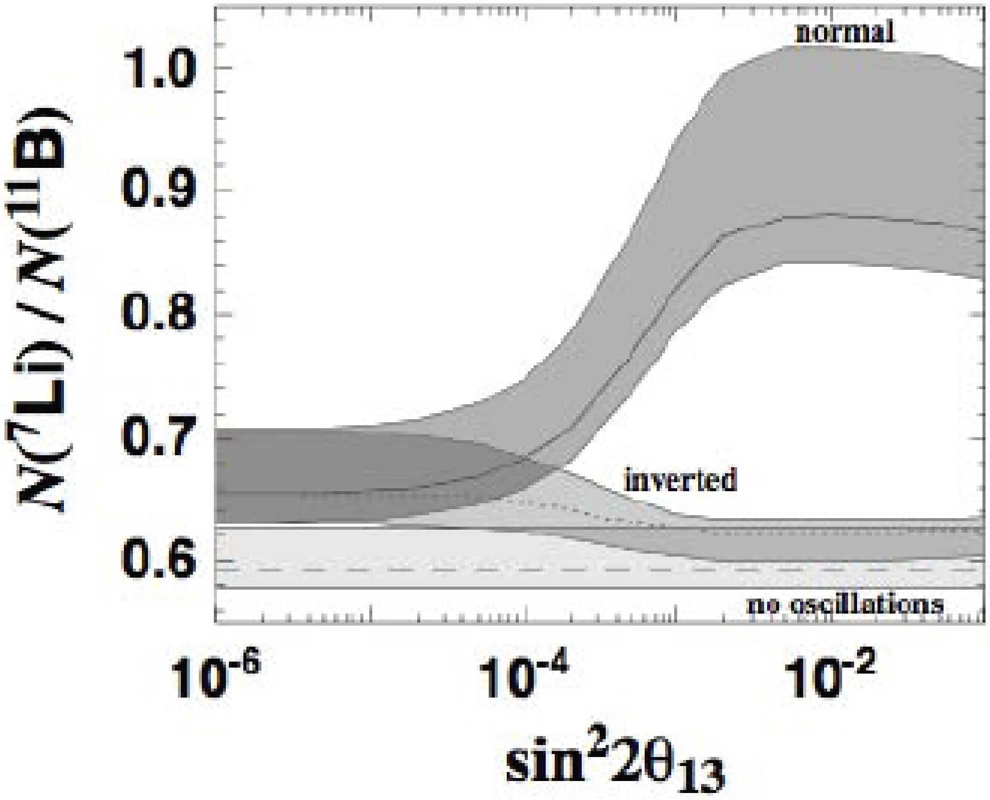
- Remember that there are not two types of neutrino, but three. So the oscillation picture gets (a lot) more complicated
- The probability equation is now:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad \simeq \quad & sin^2 2\theta_{13} sin^2 2\theta_{23} sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right) \\
\mp \quad & \alpha sin(2\theta_{13}) sin\delta sin(2\theta_{12}) sin(2\theta_{23}) \left(\frac{1.27\Delta m^2_{31}L}{E}\right) sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right) \\
- \quad & \alpha sin(2\theta_{13}) cos\delta sin(2\theta_{12}) sin(2\theta_{23}) \left(\frac{1.27\Delta m^2_{31}L}{E}\right) cos\left(\frac{1.27\Delta m^2_{31}L}{E}\right) sin\left(\frac{1.27\Delta m^2_{31}L}{E}\right) \\
+ \quad & \alpha^2 cos^2\theta_{23} sin^2 2\theta_{12}\left(\frac{1.27\Delta m^2_{31}L}{E}\right)^2
\end{aligned}
$$

- where the ∓ refers to neutrinos(-) or antineutrinos(+), and $\alpha = \Delta m^2_{12} / \Delta m^2_{23}$ (~0.03)
- *A complicated equation that suffers from parameter correlations and degeneracies. Can't separate the CP violation phase δ and oscillation angle θ_{13}*

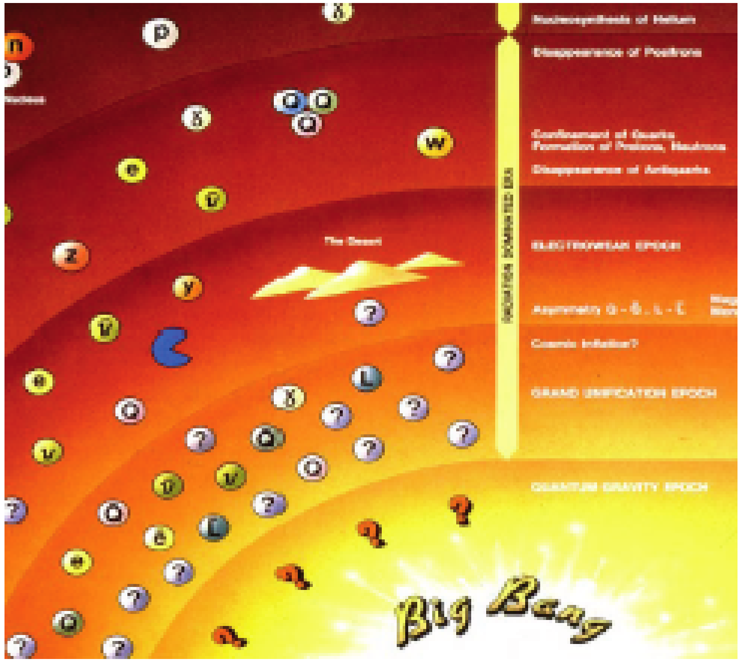
θ_{13} and Nuclear Astrophysics

neutrino oscillation effects on supernova light-element synthesis



astr-ph/0606042

understanding the origin of matter (vs antimatter)



Leptogenesis

Fukugita, Yanagida, 1986

- Out-of-equilibrium L-violating decays of heavy Majorana neutrinos leading to L asymmetry but leaving B unchanged. B_L-L_L is conserved.