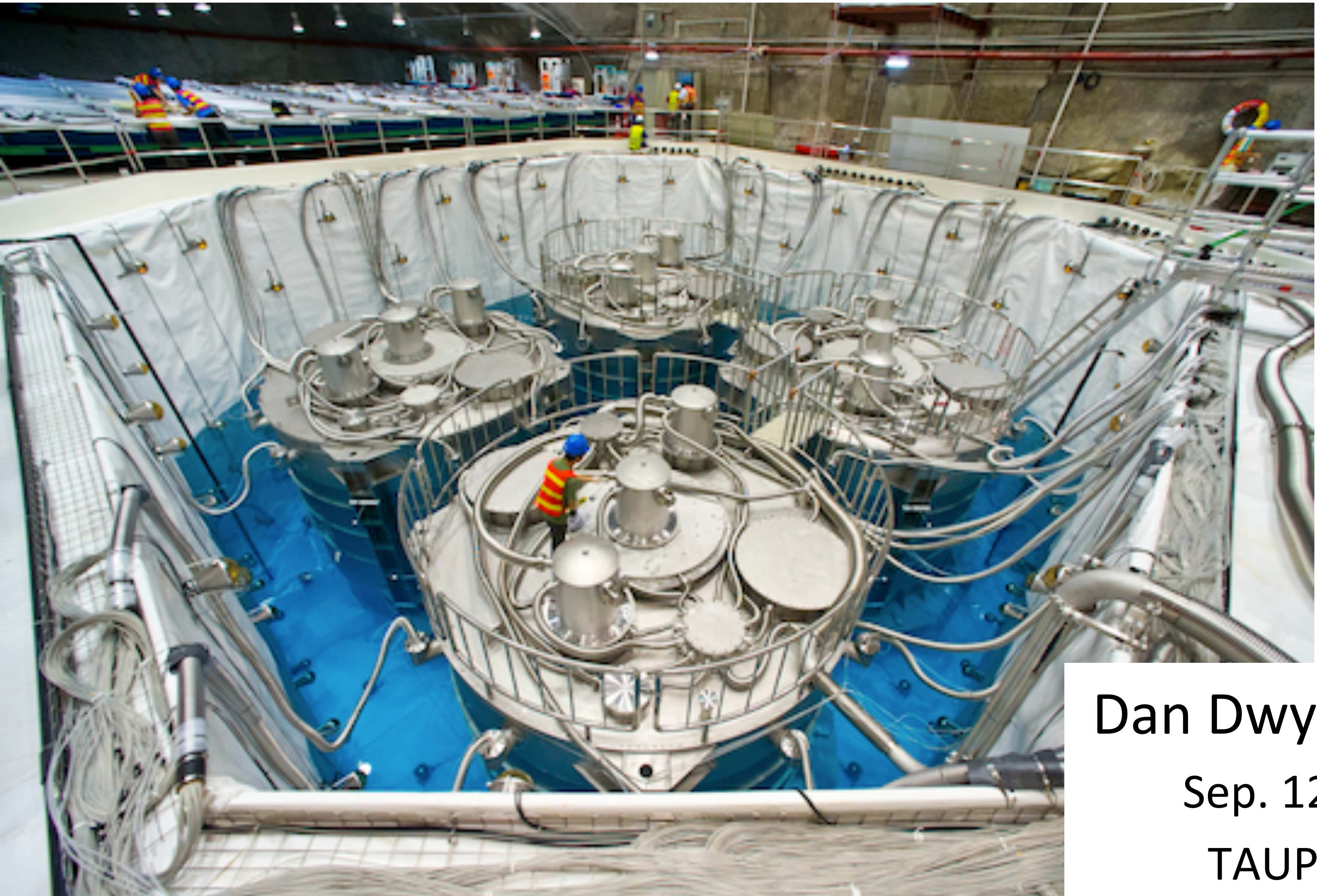
The Neutrino Mixing Angle θ_{13}: Reactor and Accelerator Experiments



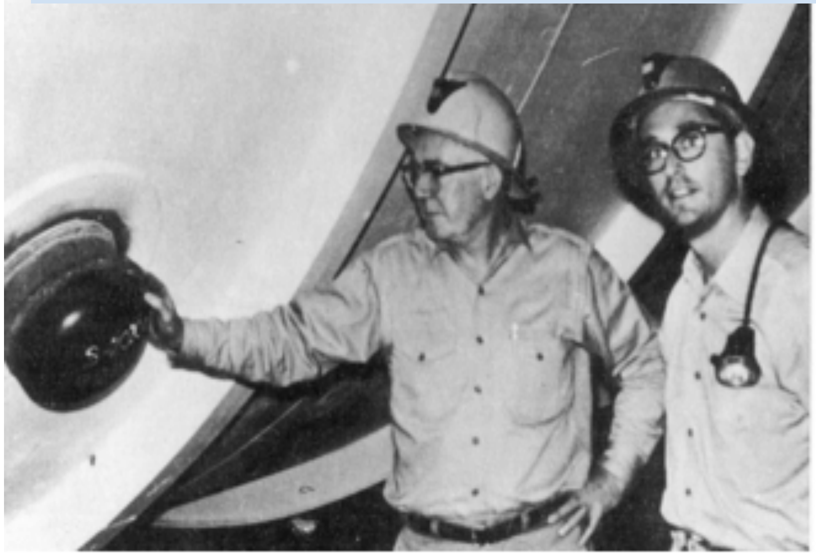
Dan Dwyer (LBNL)

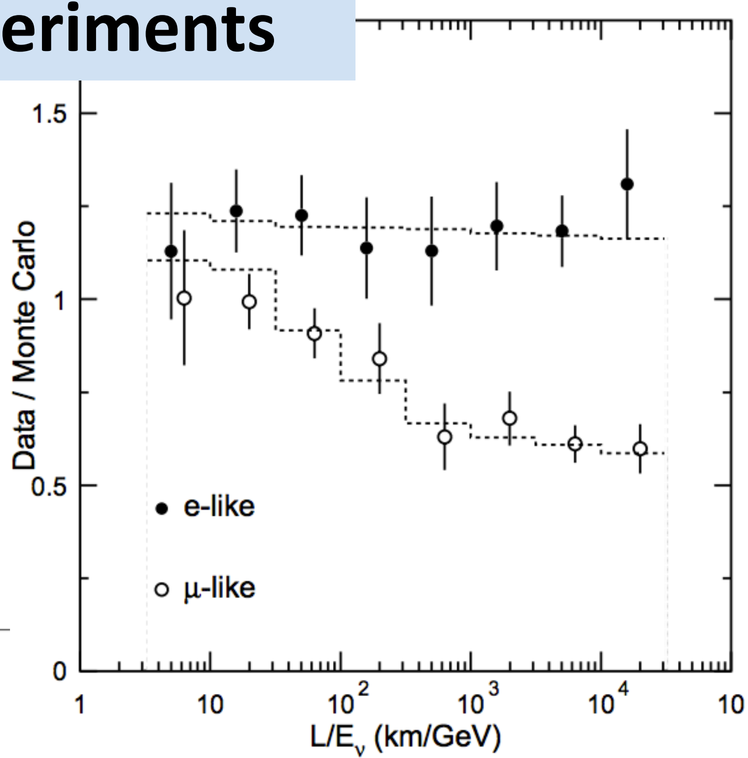
Sep. 12, 2013

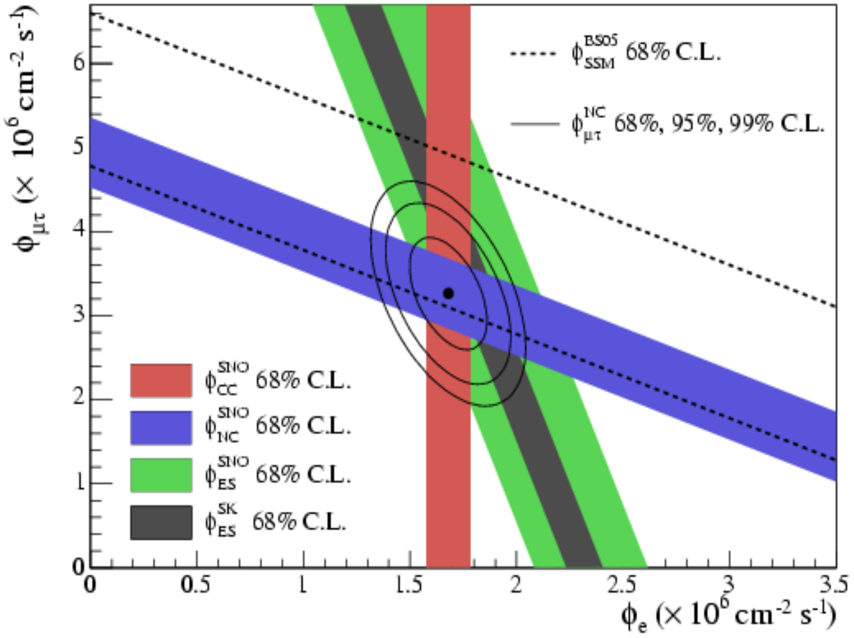
TAUP 2013

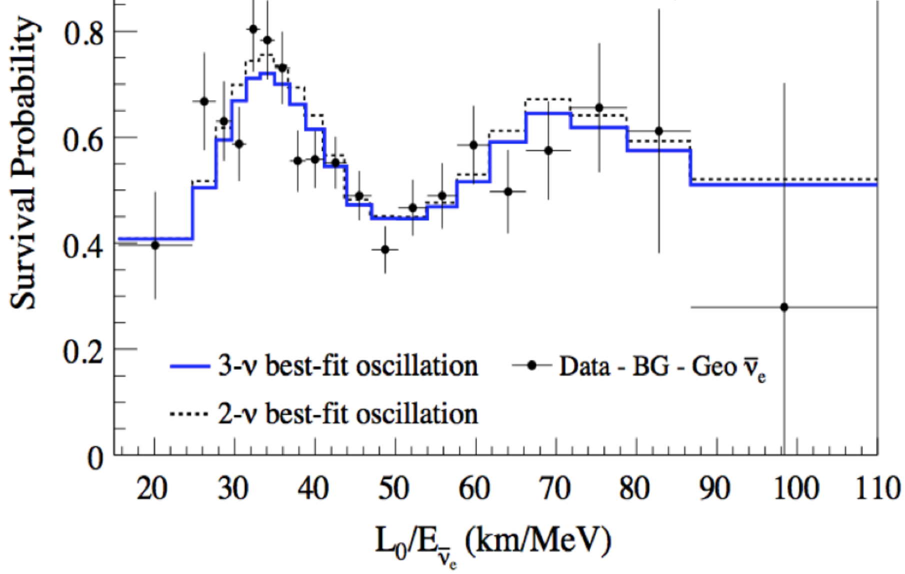
A Brief History of Oscillations

Summarized in four key experiments

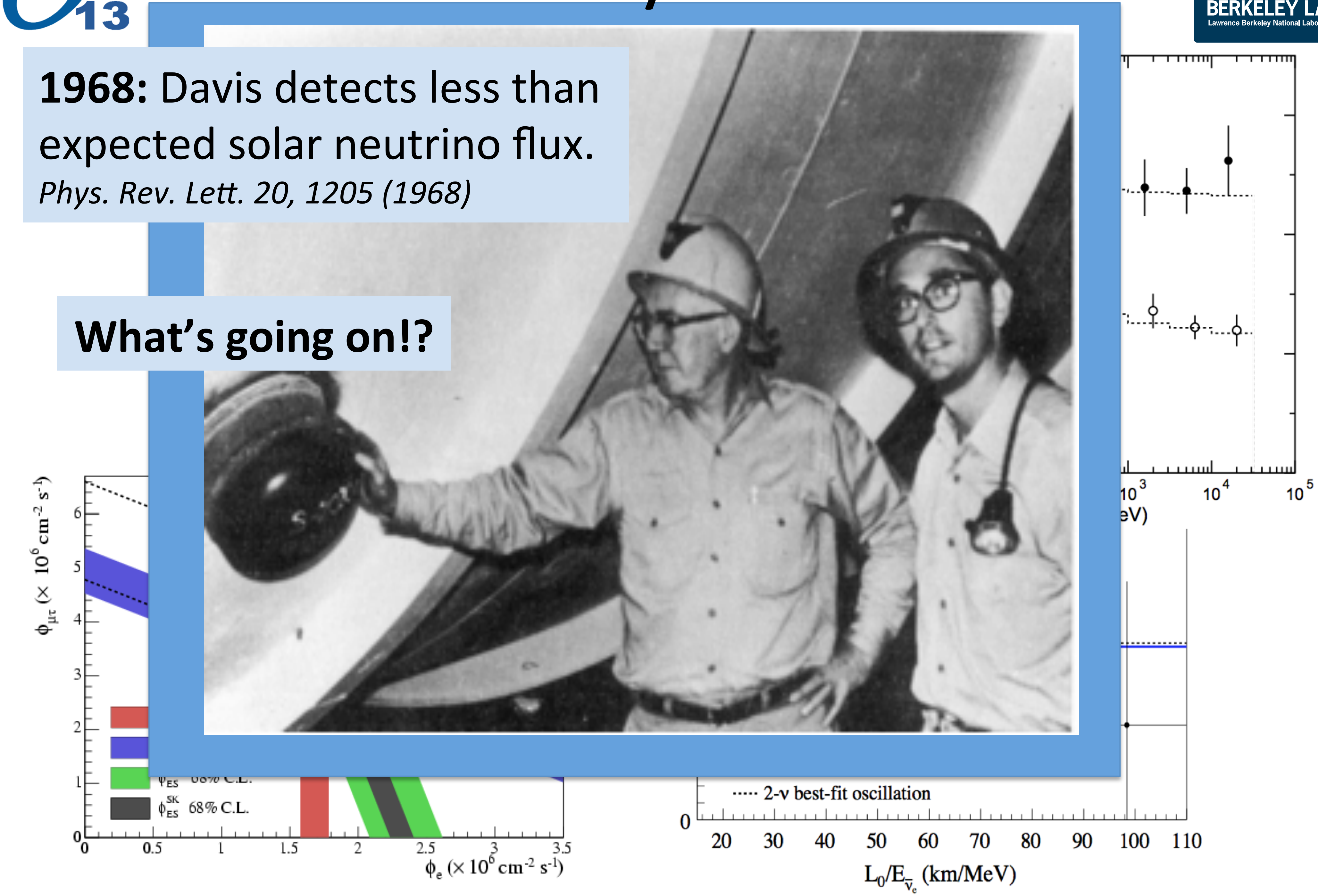








A Brief History of Oscillations



1968: Davis detects less than expected solar neutrino flux.

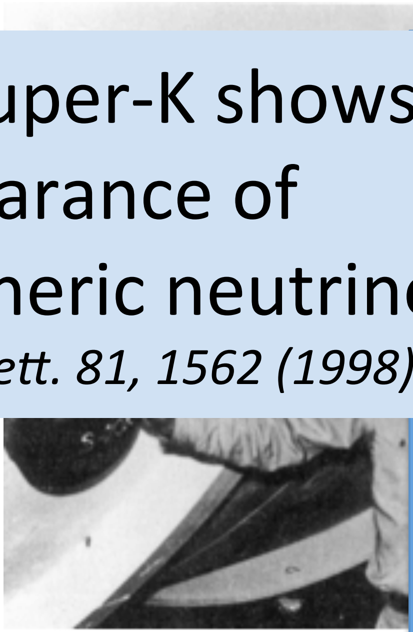
Phys. Rev. Lett. 20, 1205 (1968)

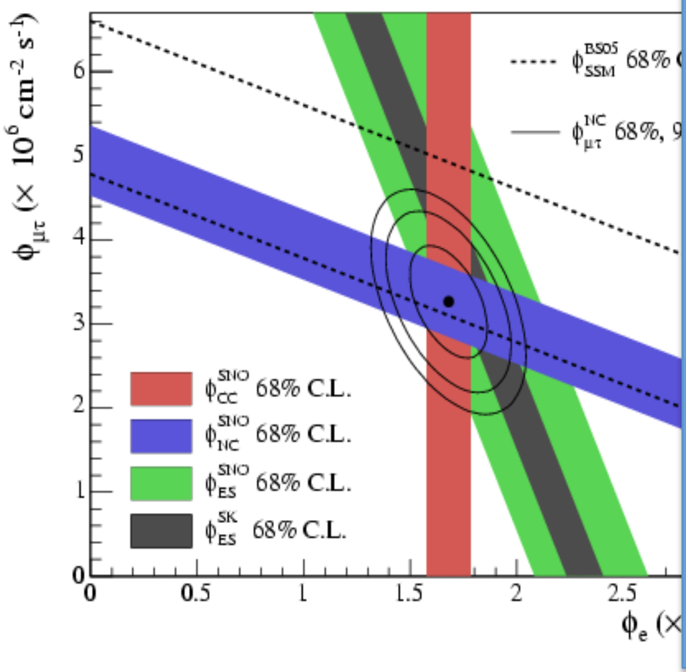
What's going on!?

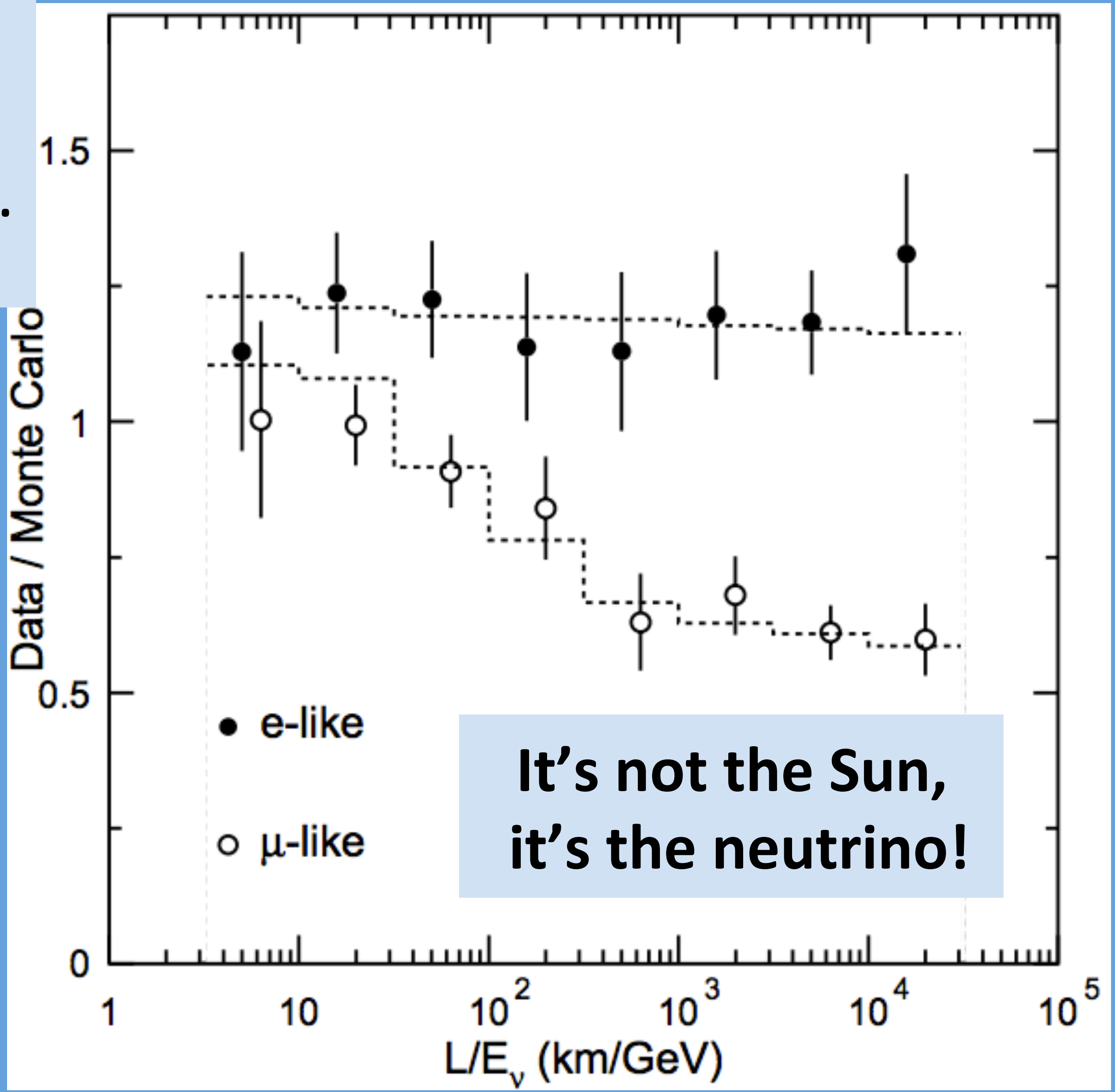
A Brief History of Oscillations

1998: Super-K shows disappearance of atmospheric neutrinos.

Phys. Rev. Lett. 81, 1562 (1998)

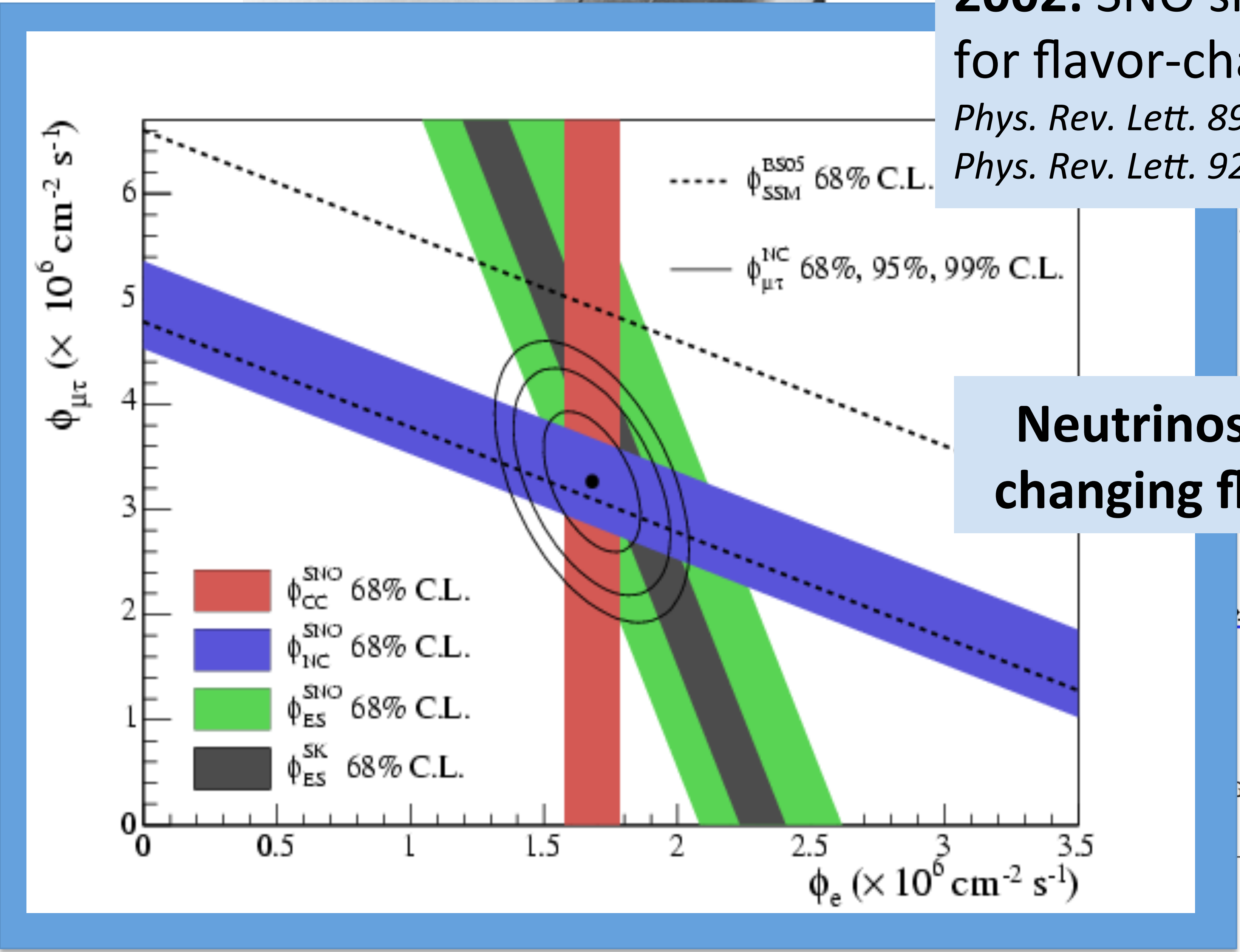


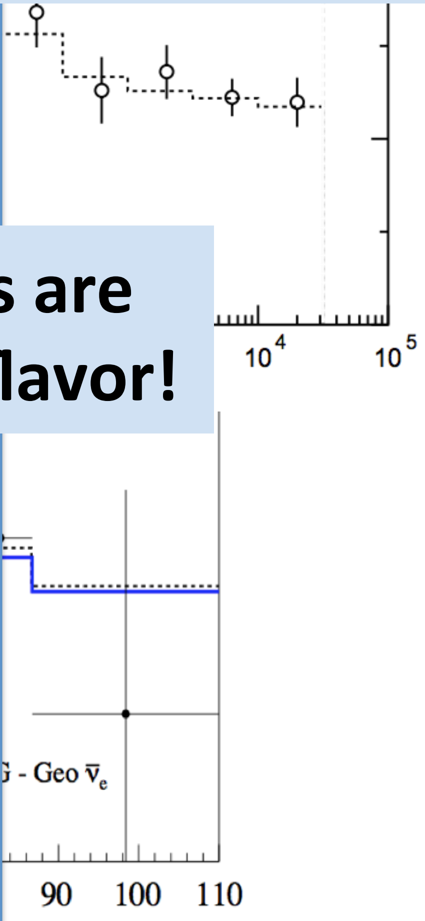




It's not the Sun, it's the neutrino!

A Brief History of Oscillations





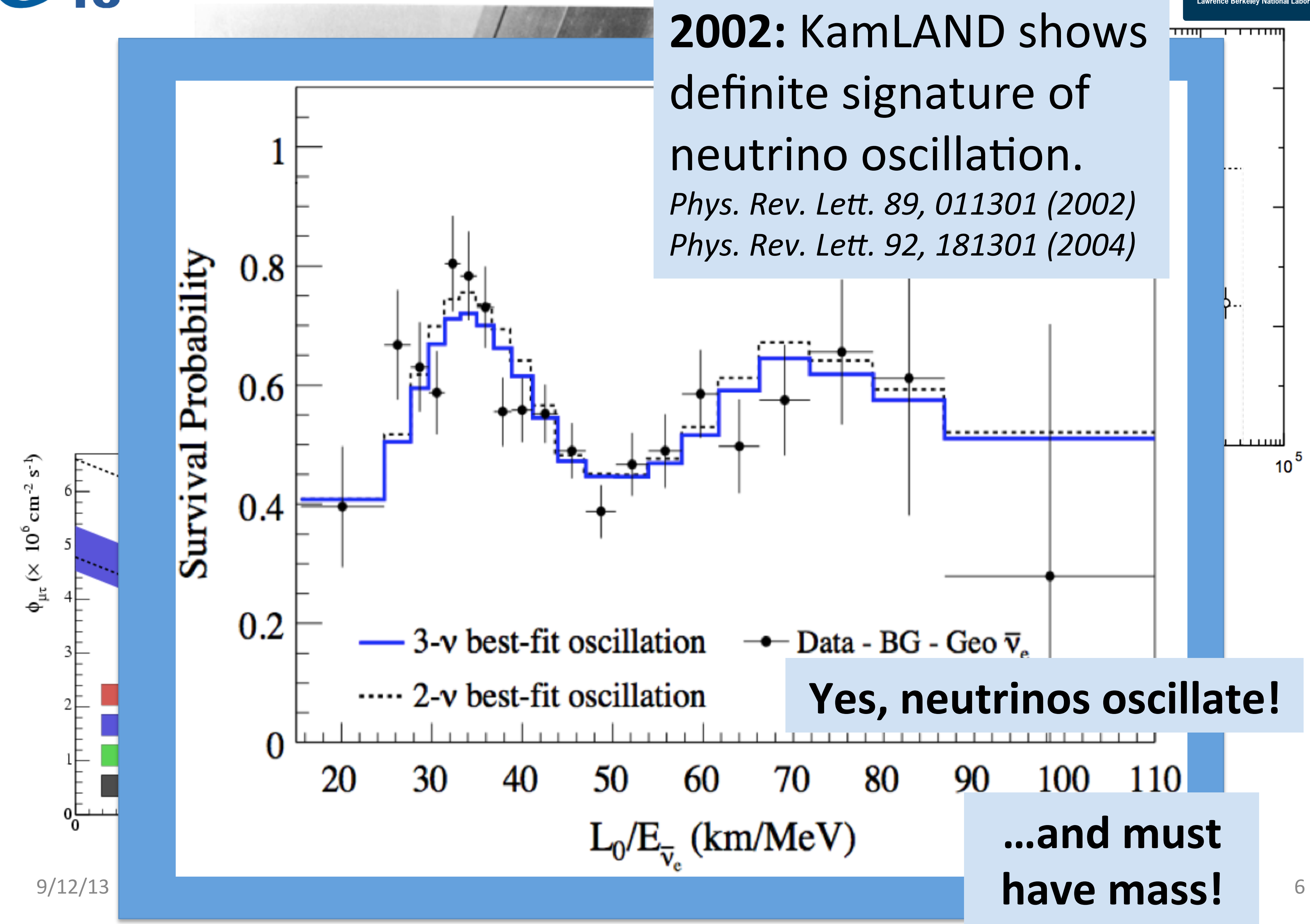
2002: SNO shows evidence for flavor-change!

Phys. Rev. Lett. 89, 011301 (2002)

Phys. Rev. Lett. 92, 181301 (2004)

Neutrinos are changing flavor!

A Brief History of Oscillations



2002: KamLAND shows definite signature of neutrino oscillation.

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

Yes, neutrinos oscillate!

…and must have mass!

A Decade of Progress

The neutrino mixing matrix only recently measured.

$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$\theta_{23} \approx 45^\circ$

Atmospheric ν

Accelerator ν

$\theta_{13} \approx 9^\circ$

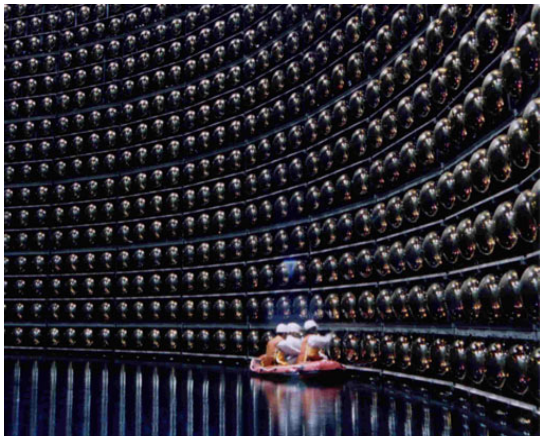
Short-Baseline Reactor ν

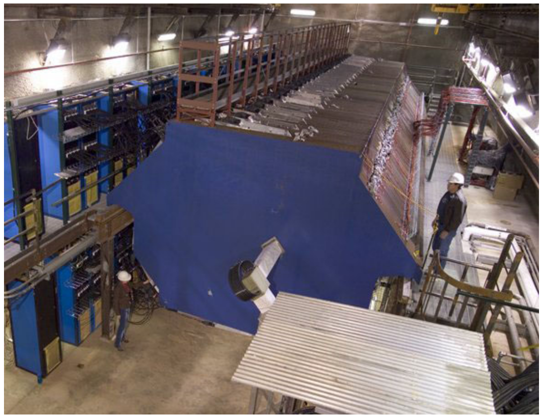
Accelerator ν

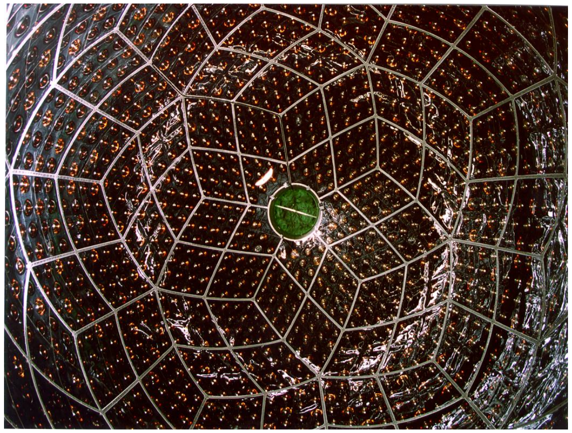
$\theta_{12} \approx 35^\circ$

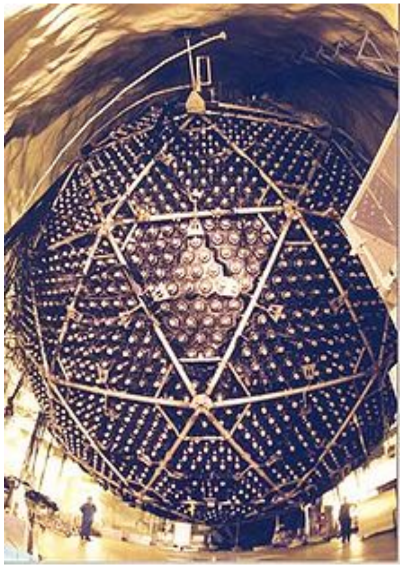
Solar ν

Long-Baseline Reactor ν



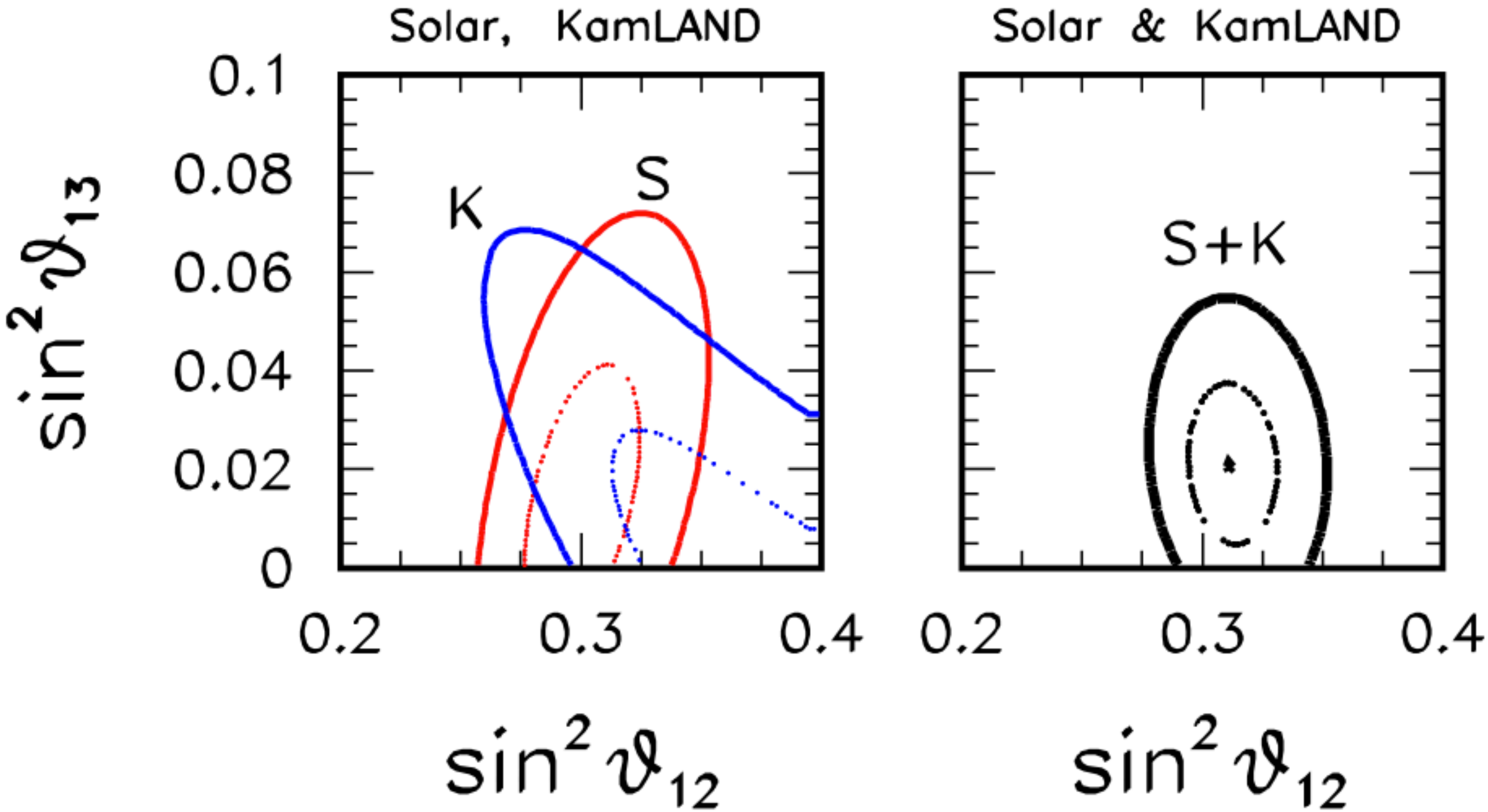






Solar and KamLAND

Existing oscillation data slightly preferred non-zero θ_{13}



G. Fogli et al., Phys. Rev. Lett. 101, 141801 (2008)

*G. Fogli et al., Phys. Rev. **D**84, 053007 (2011)*

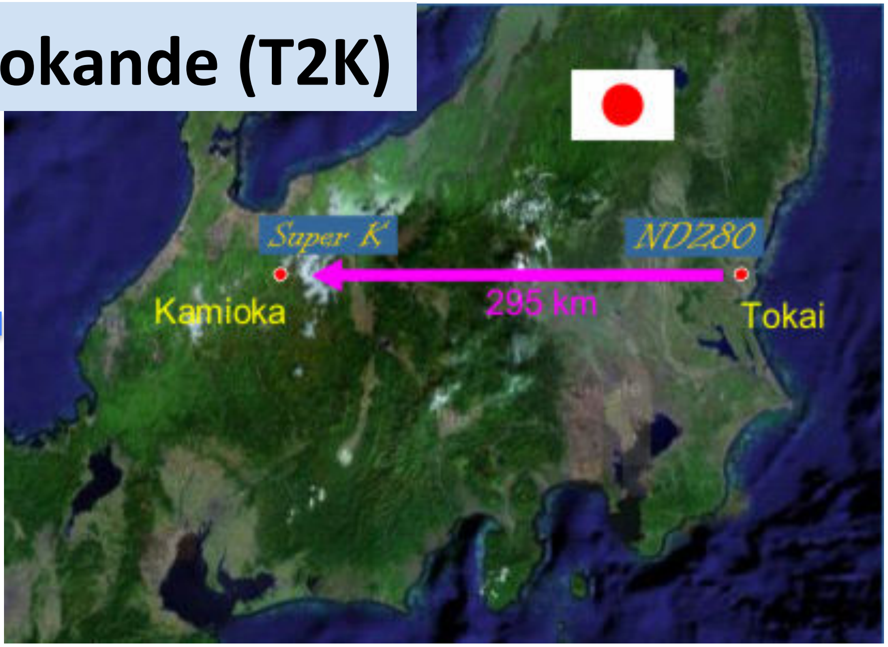
*KamLAND, Phys. Rev. **D**83, 052002 (2011)*

Accelerator Measurements

Look for appearance of ν_e in ν_μ beam.

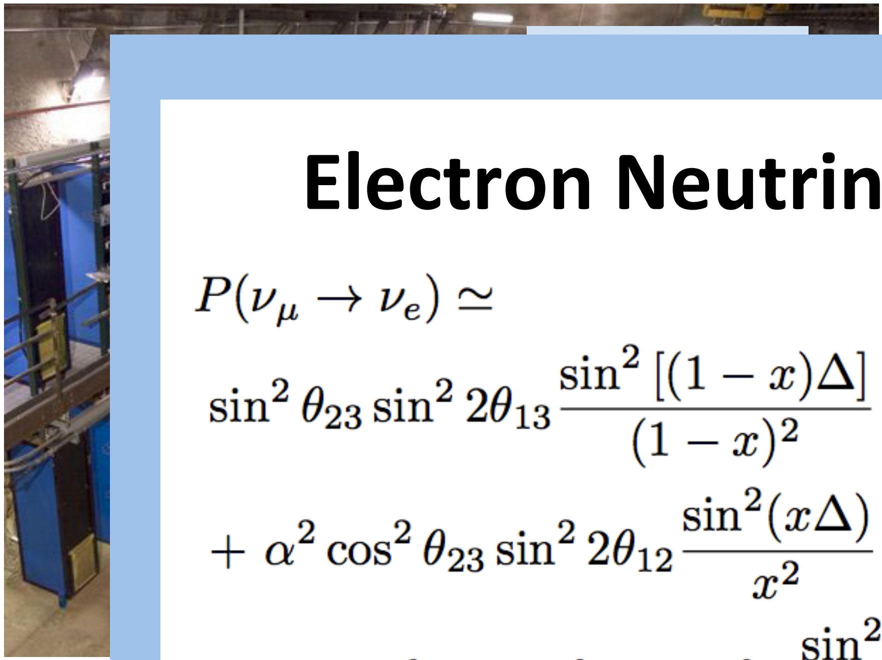
MINOS

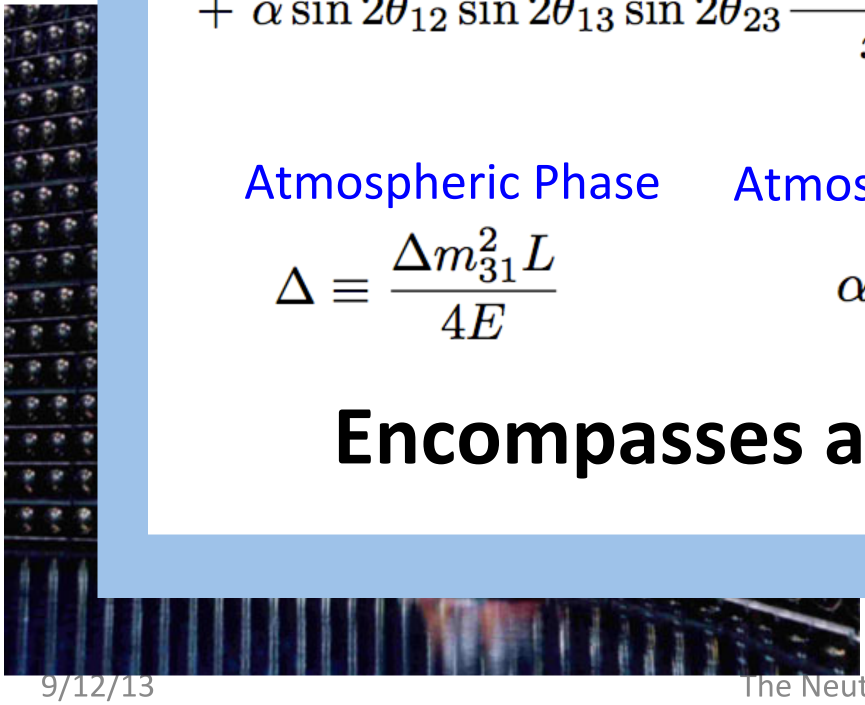
Tokai to Super-Kamiokande (T2K)



Accelerator Measurements

Look for appearance of ν in ν beam.





Electron Neutrino Appearance Probability

$$P(\nu_\mu \to \nu_e) \simeq$$

$$\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Atmospheric Oscillation

$$+\ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(x\Delta)}{x^2}$$

Solar Oscillation

Cross-term

CP-phase

$$+\ \alpha\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\frac{\sin^2(x\Delta)}{x^2}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}(\cos\Delta\cos\delta - \sin\Delta\sin\delta)$$

Atmospheric Phase

$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E}$$

Atmospheric/Solar Ratio

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

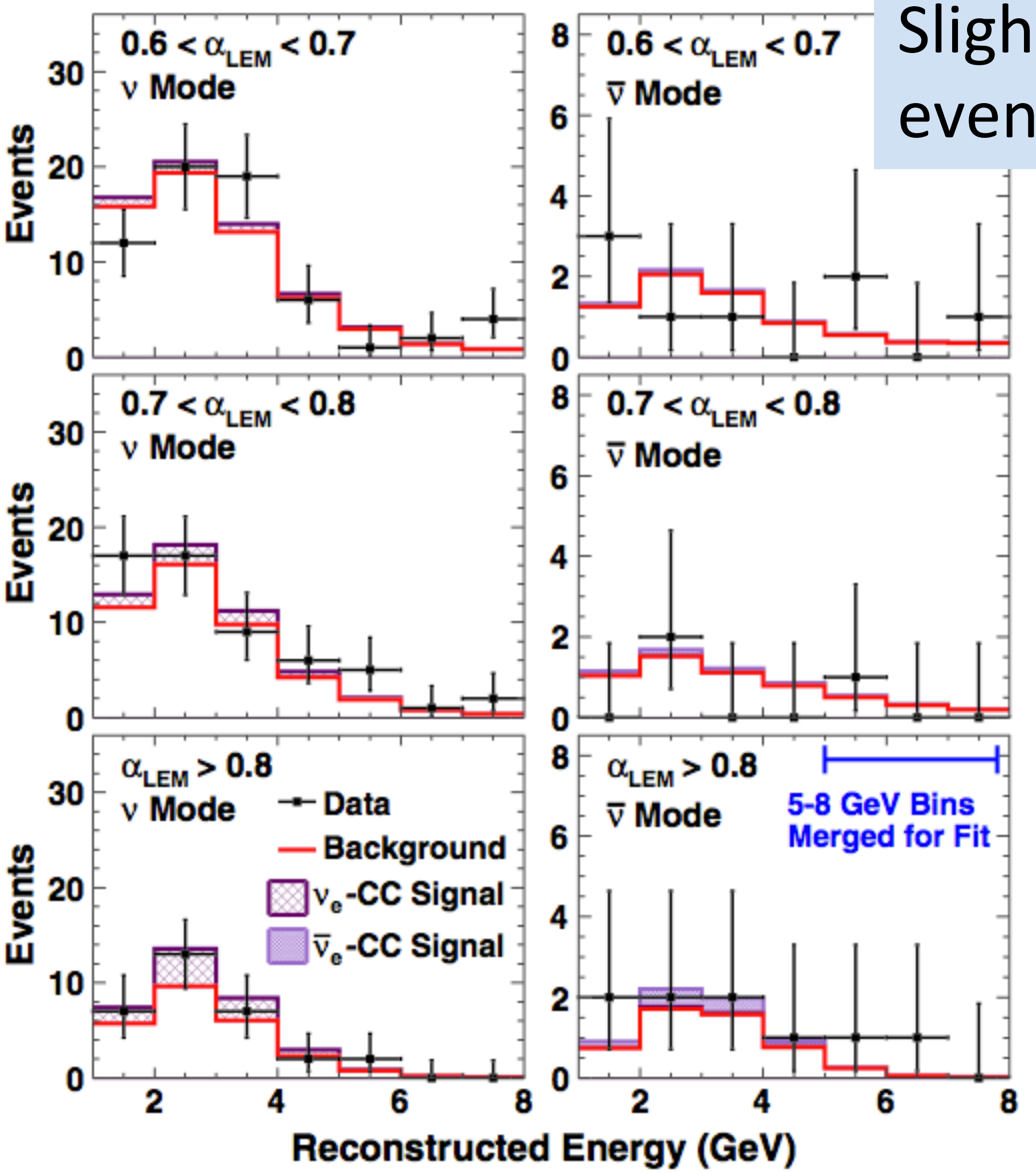
Matter Effect

$$x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

Encompasses all neutrino parameters

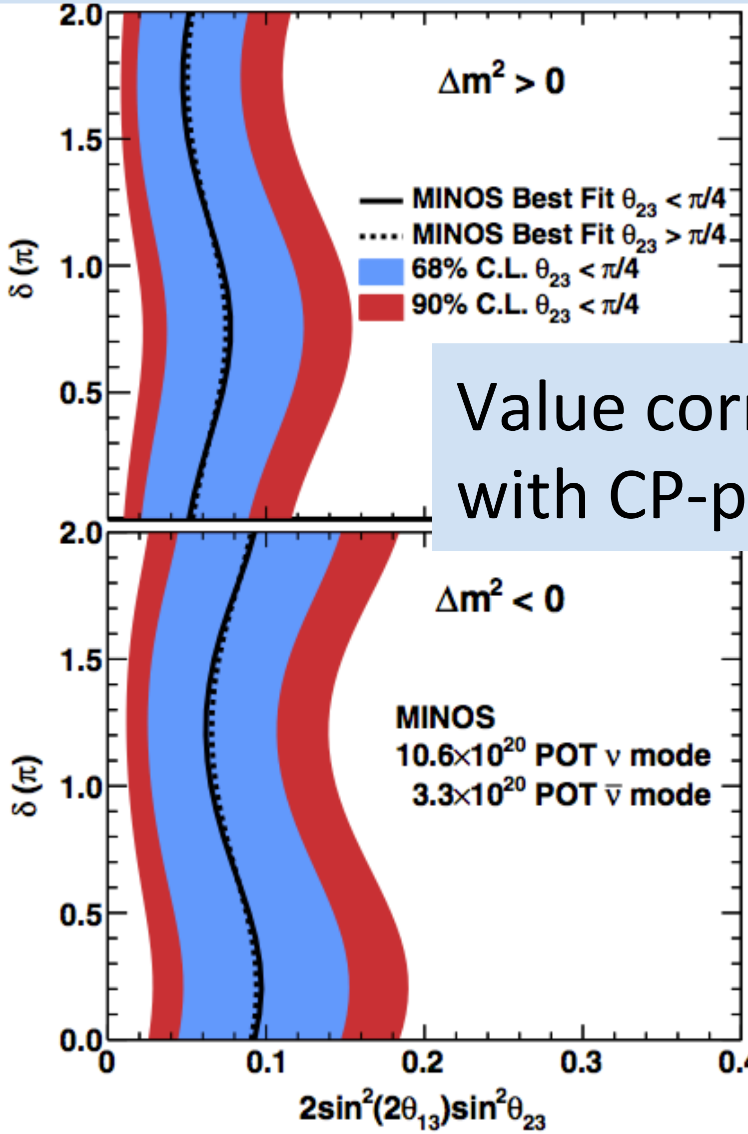
MINOS ν_e appearance

Slight excess of electron-like events suggest non-zero θ_{13}



Phys. Rev. Lett. 107 181802 (2011)

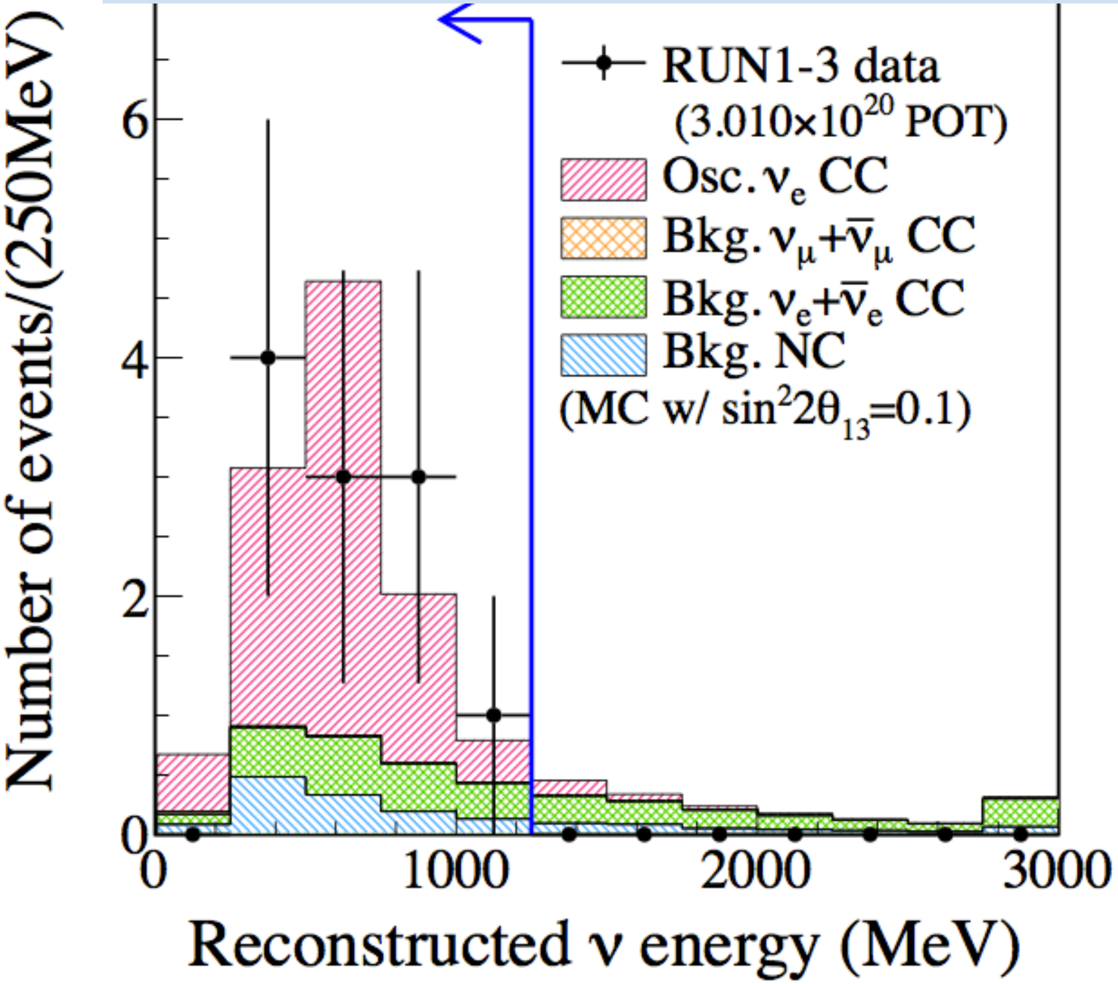
Phys. Rev. Lett. 110 171801 (2013)

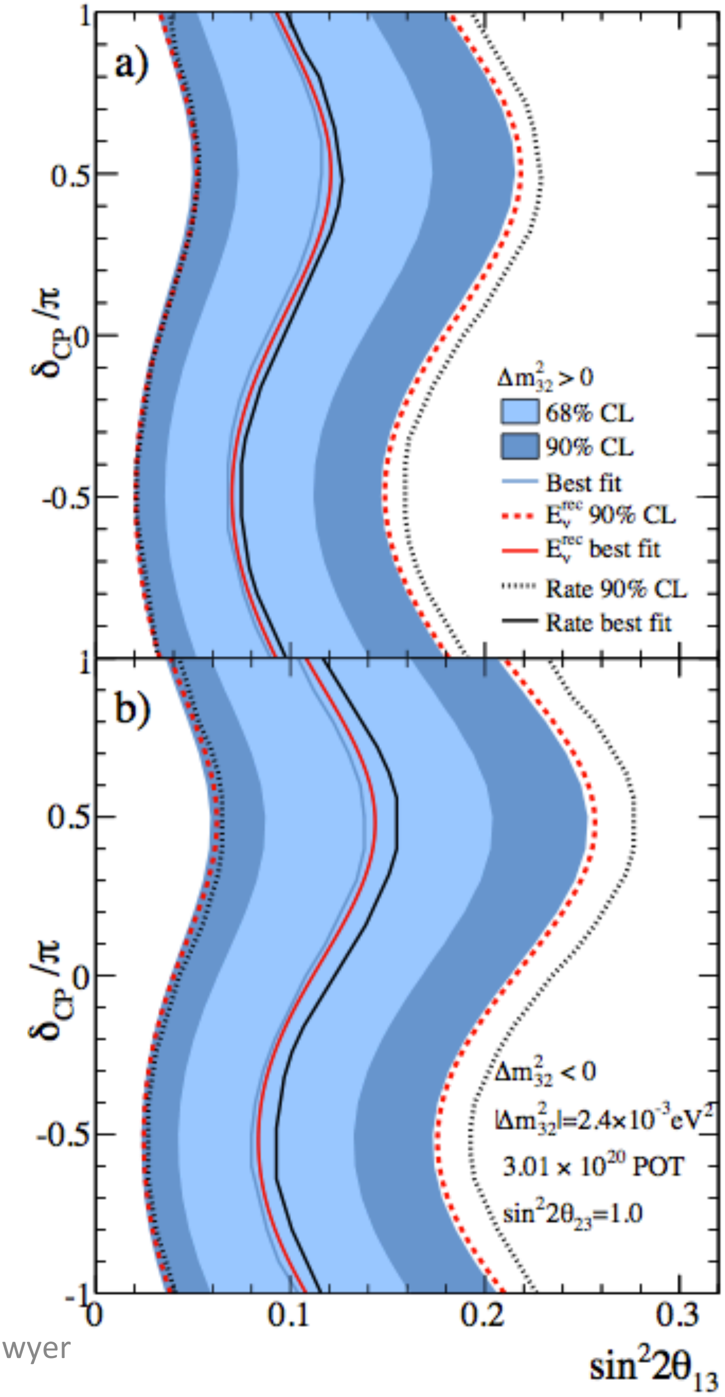


Value correlated with CP-phase δ

T2K ν_e appearance

11 electron-like events detected
(with ~3 expected background)

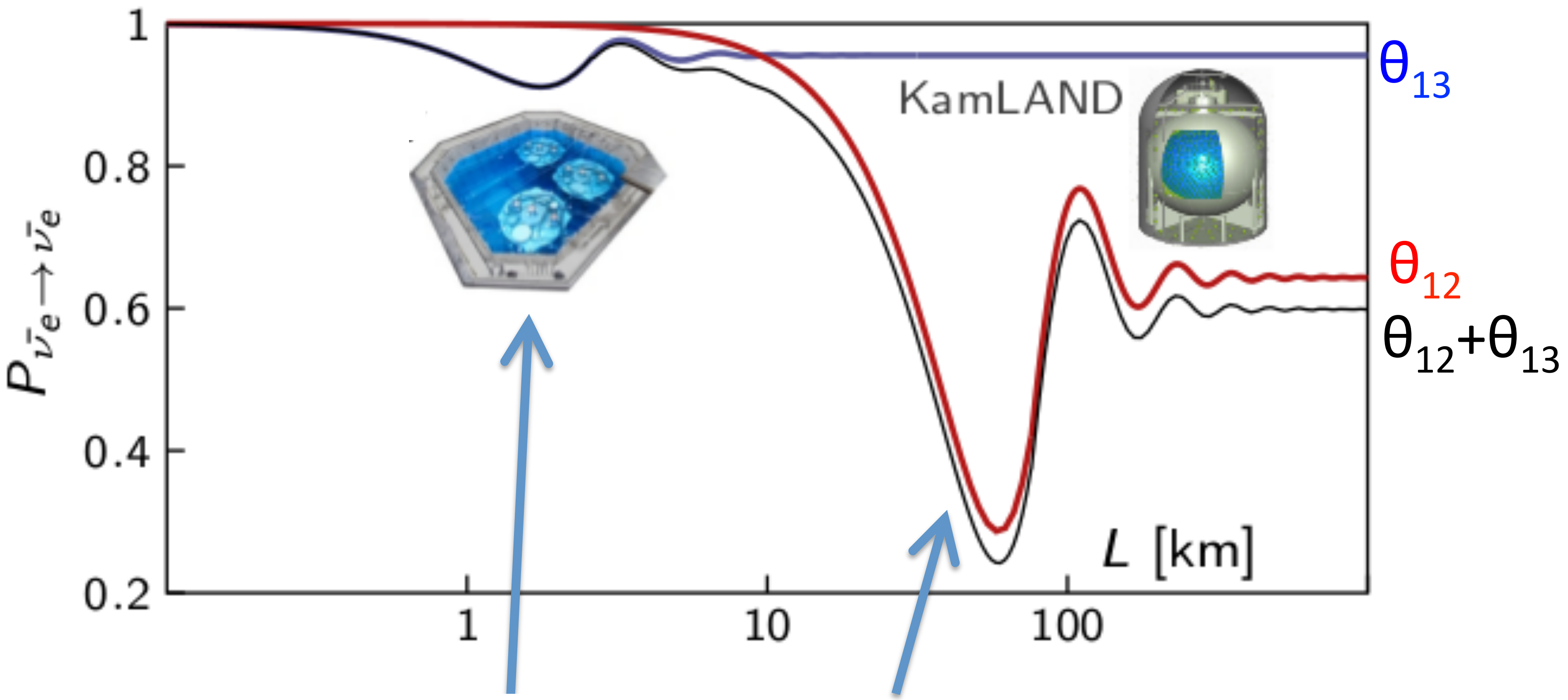




6 events: *Phys. Rev. Lett. 107, 041801 (2011)*
11 events: *Phys. Rev. **D**88, 032002 (2013)*

Reactor $\bar{\nu}_e$ measurements

Sensitive to the disappearance of electron anti-neutrinos.

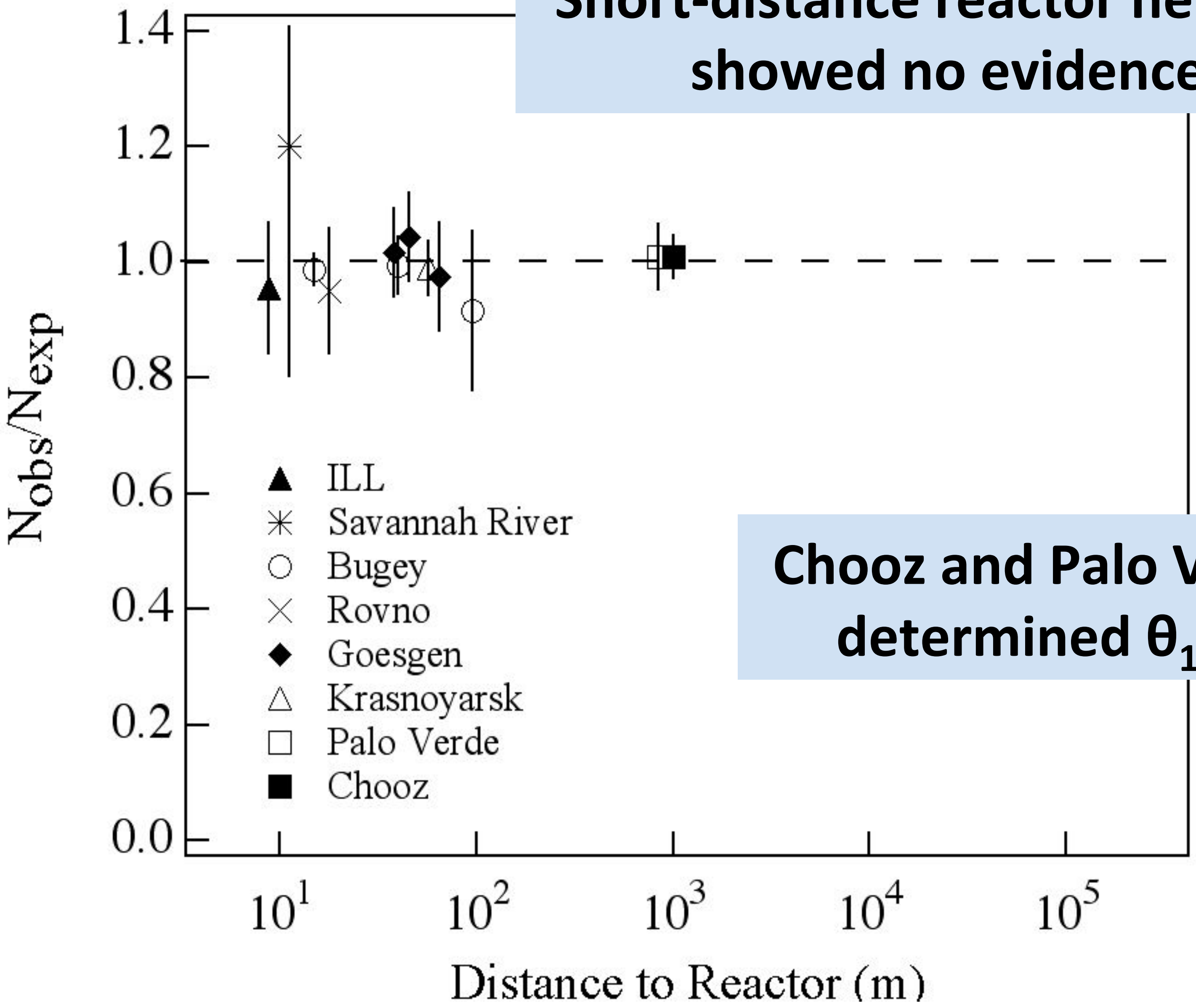


$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)$$

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

Previous Reactor Experiments

Short-distance reactor neutrino experiments showed no evidence of oscillation



Chooz and Palo Verde experiments determined $\theta_{13} < 11^\circ$ (90% CL)

A Relative Measurement

Absolute Reactor Flux:

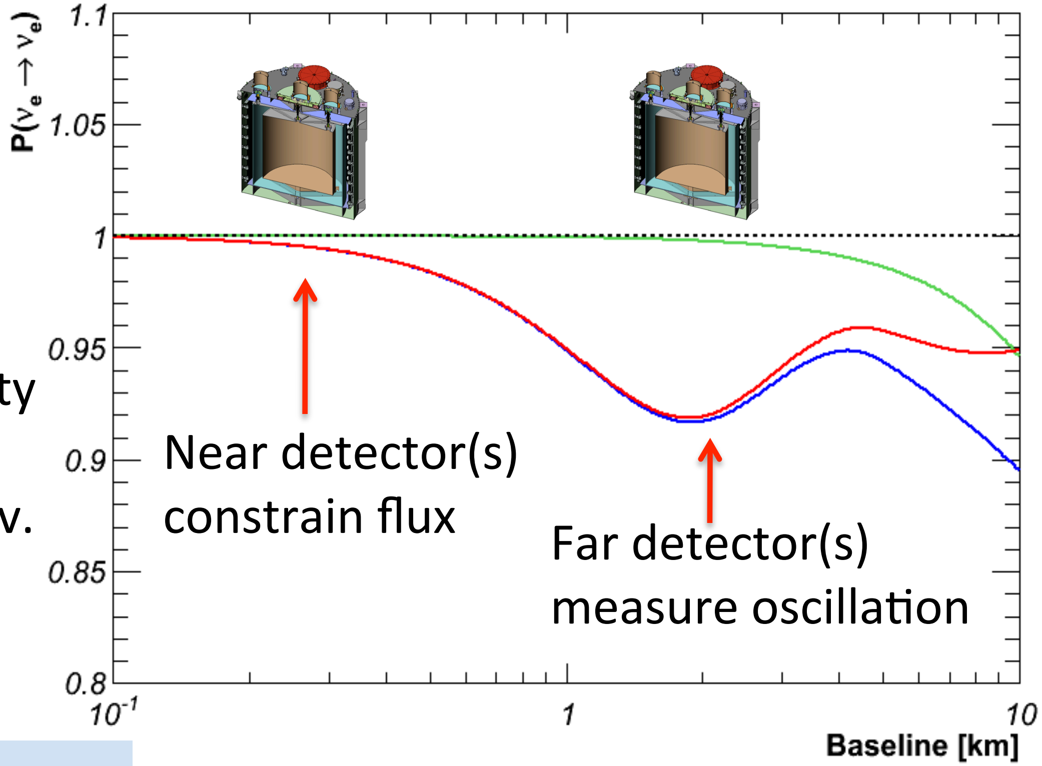
Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors remove absolute uncertainty

First proposed by L. A. Mikaelyan and V. V. Sinev.

Phys. Atomic Nucl. 63, 1002 (2000)



Near detector(s) constrain flux

Far detector(s) measure oscillation

Far/Near ν_e Ratio

Distances from reactor

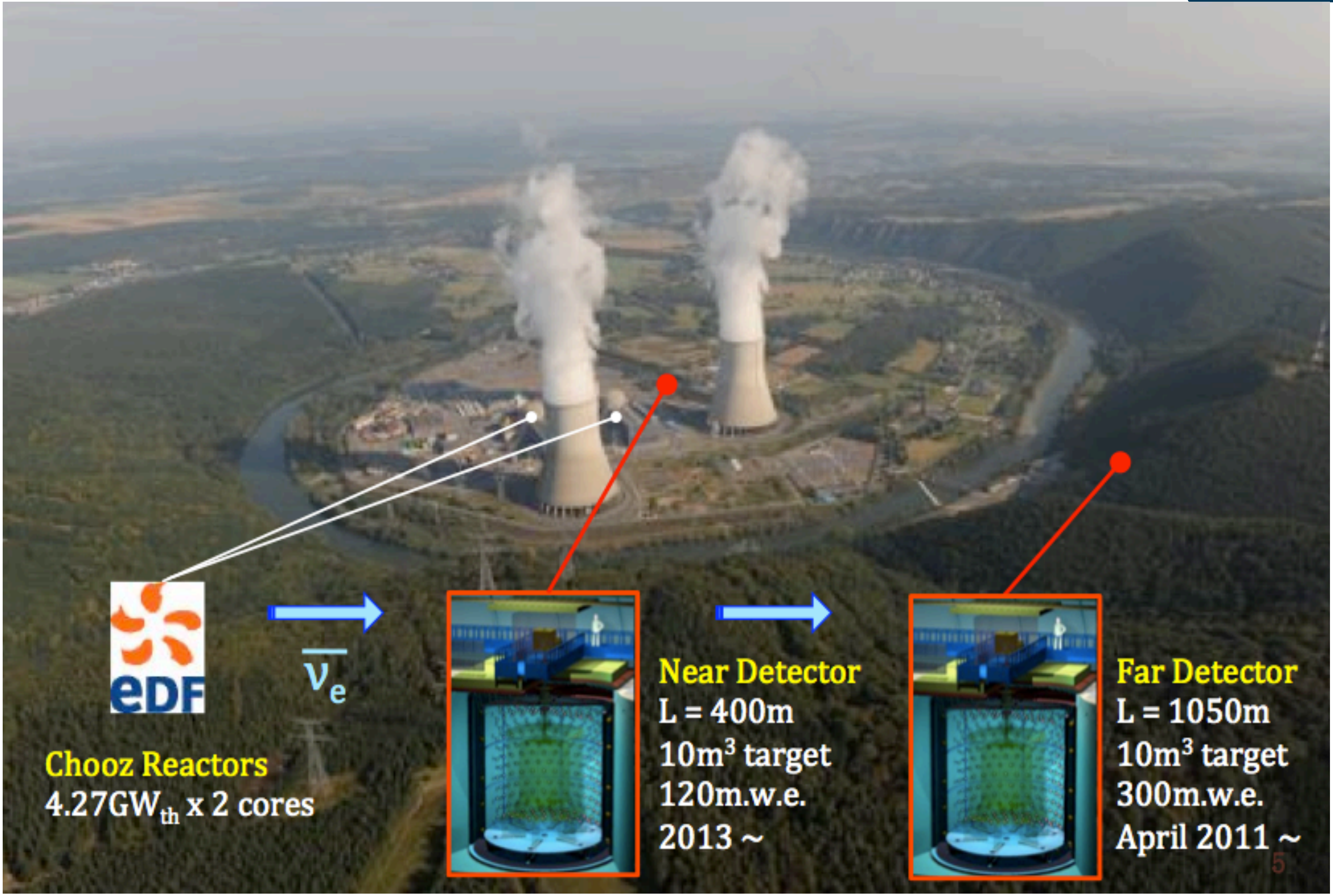
Oscillation deficit

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

Detector Target Mass

Detector efficiency

Double Chooz Experiment

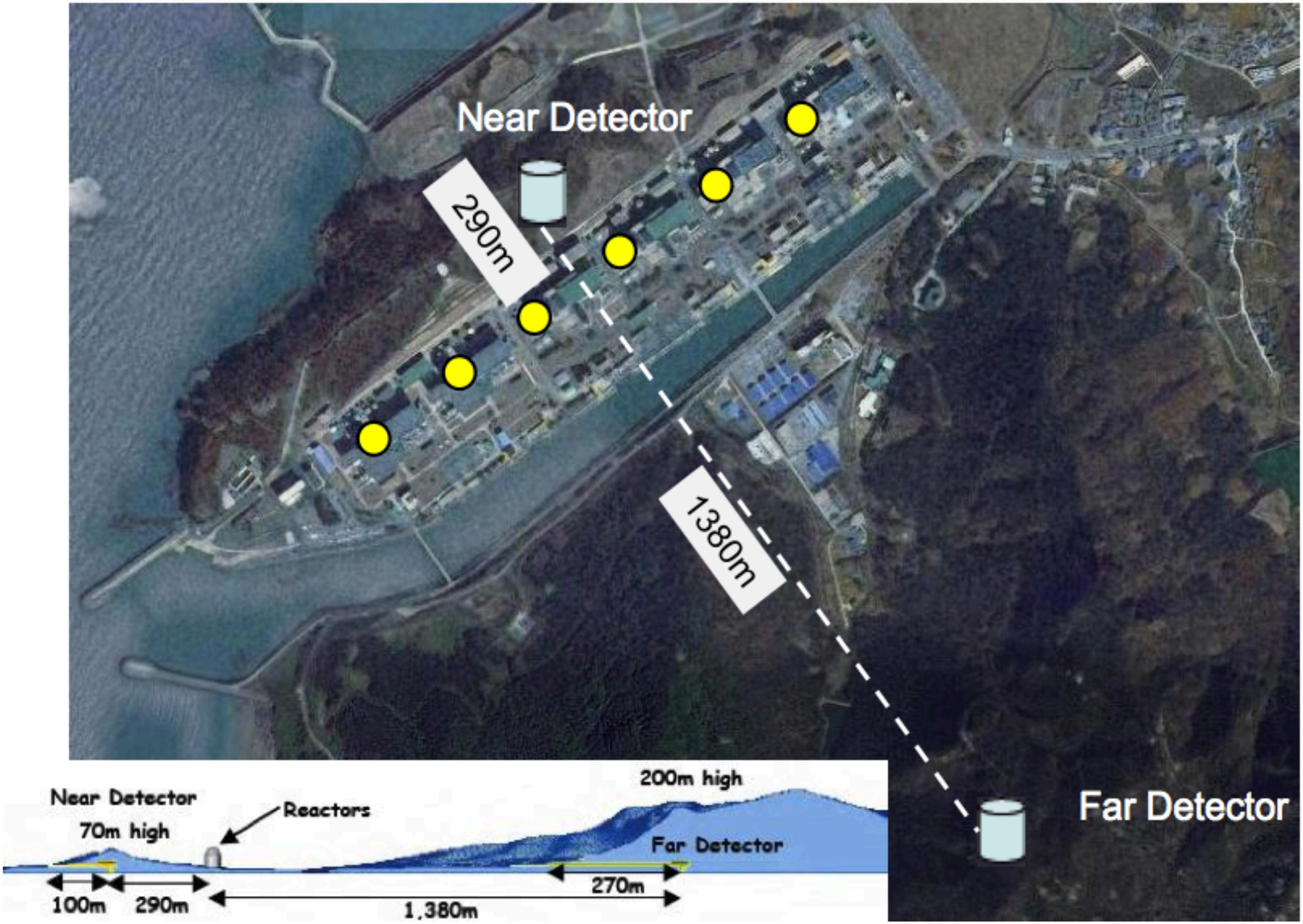


Chooz Reactors
4.27GW$_{th}$ x 2 cores

Near Detector
L = 400m
10m^3 target
120m.w.e.
2013 ~

Far Detector
L = 1050m
10m^3 target
300m.w.e.
April 2011 ~

RENO Experiment



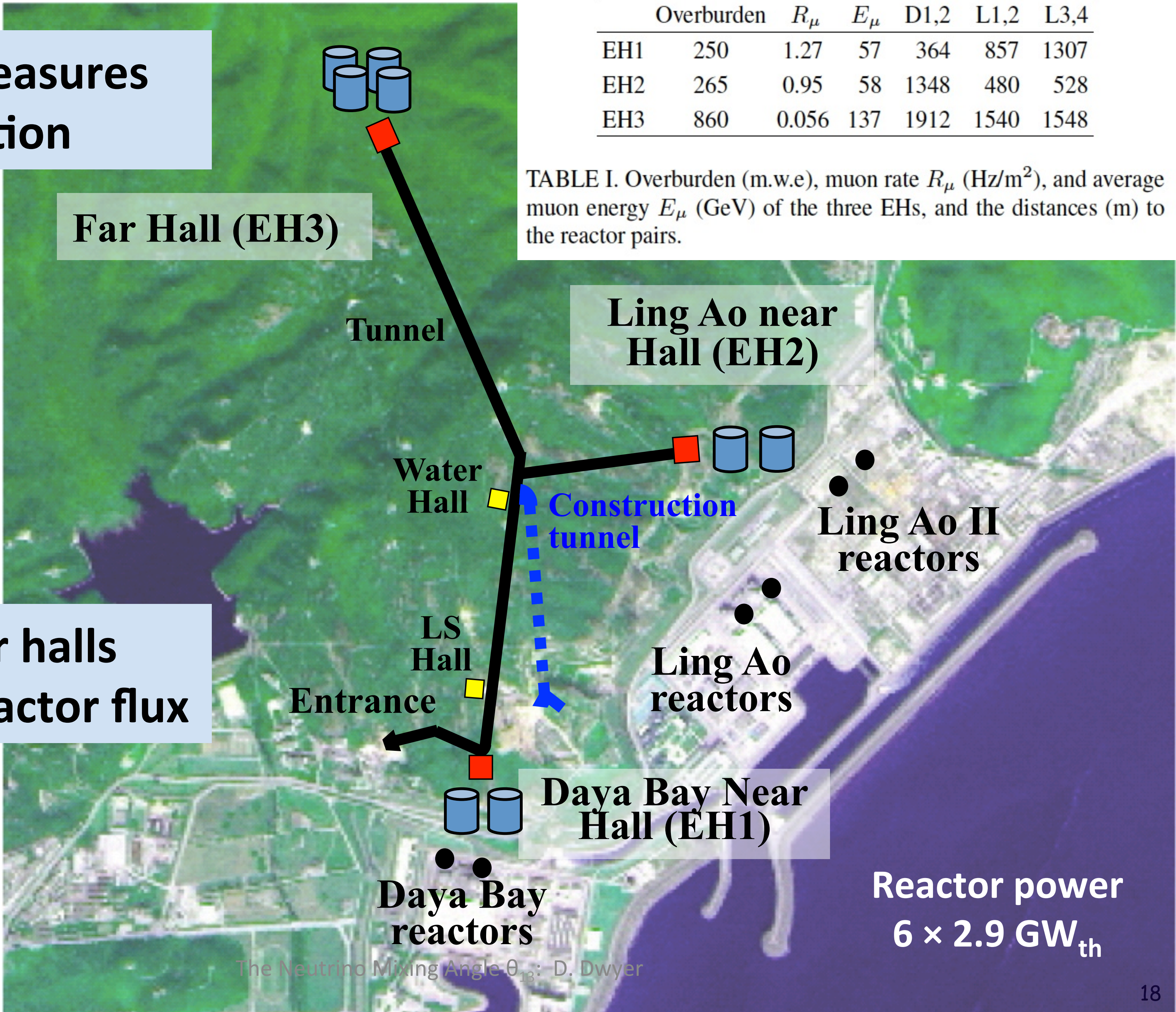
Daya Bay Experiment

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

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

Far hall measures oscillation

Two near halls constrain reactor flux

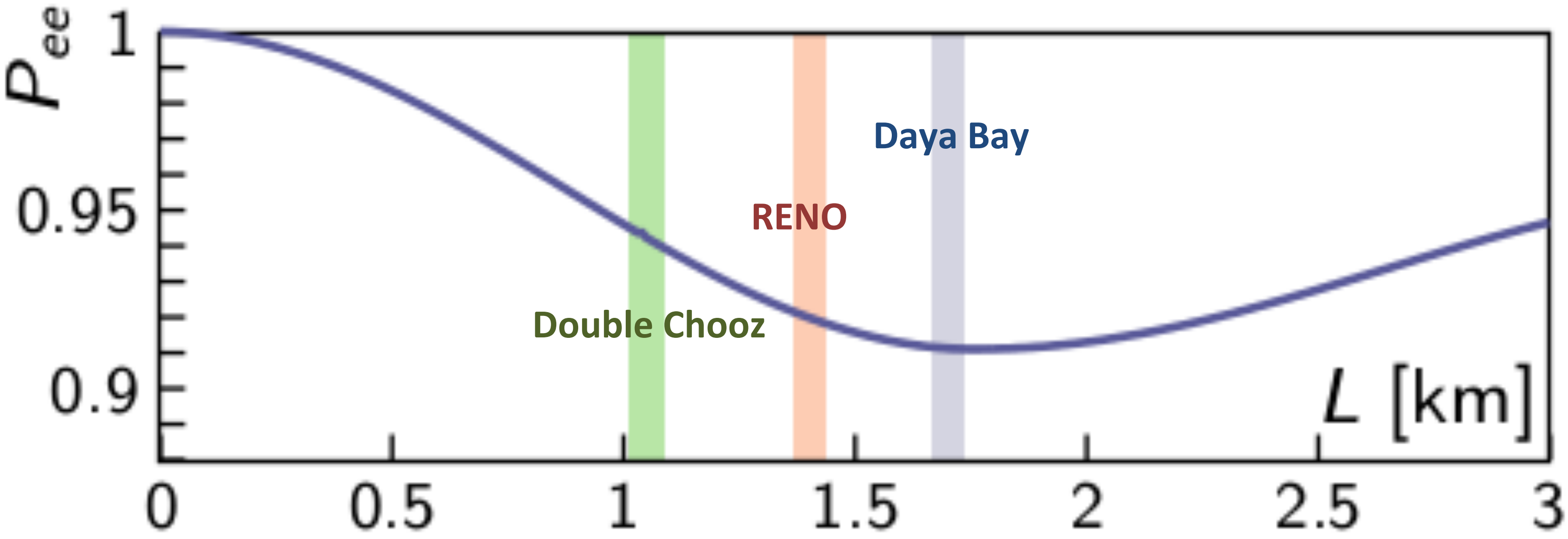


Reactor power
6 × 2.9 GW_{th}

Reactor Experiments

Baseline Optimization

Atmospheric and accelerator ν oscillation suggest oscillation greatest at ~1.8 k



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

Detection Method

Inverse β-decay (IBD):

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

$$\downarrow$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

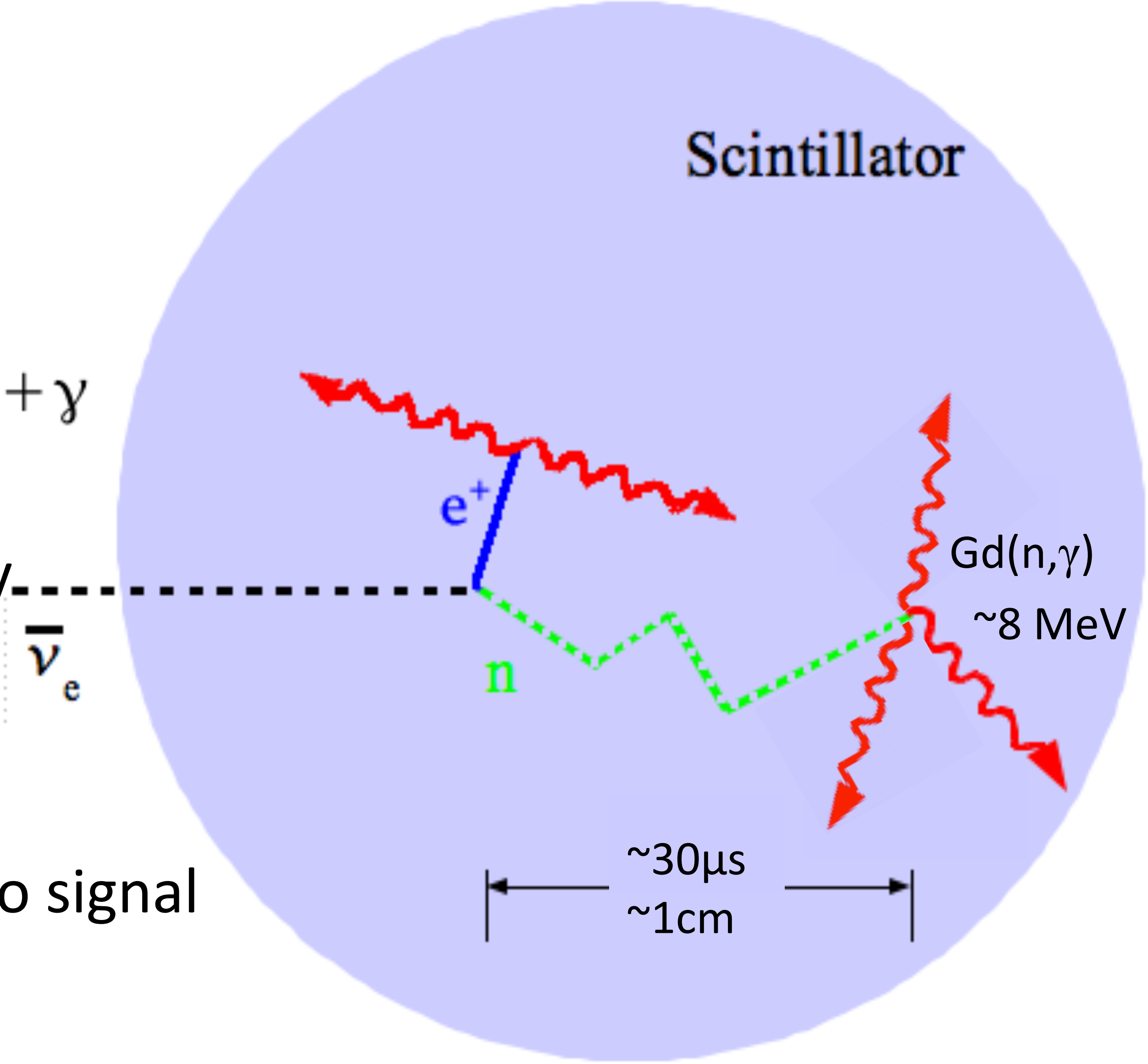
Prompt positron:

Carries antineutrino energy

$E_{e+} \approx E_{\nu} - 0.8$ MeV

Delayed neutron capture:

Efficiently tags antineutrino signal



Prompt + Delayed coincidence provides distinctive signature

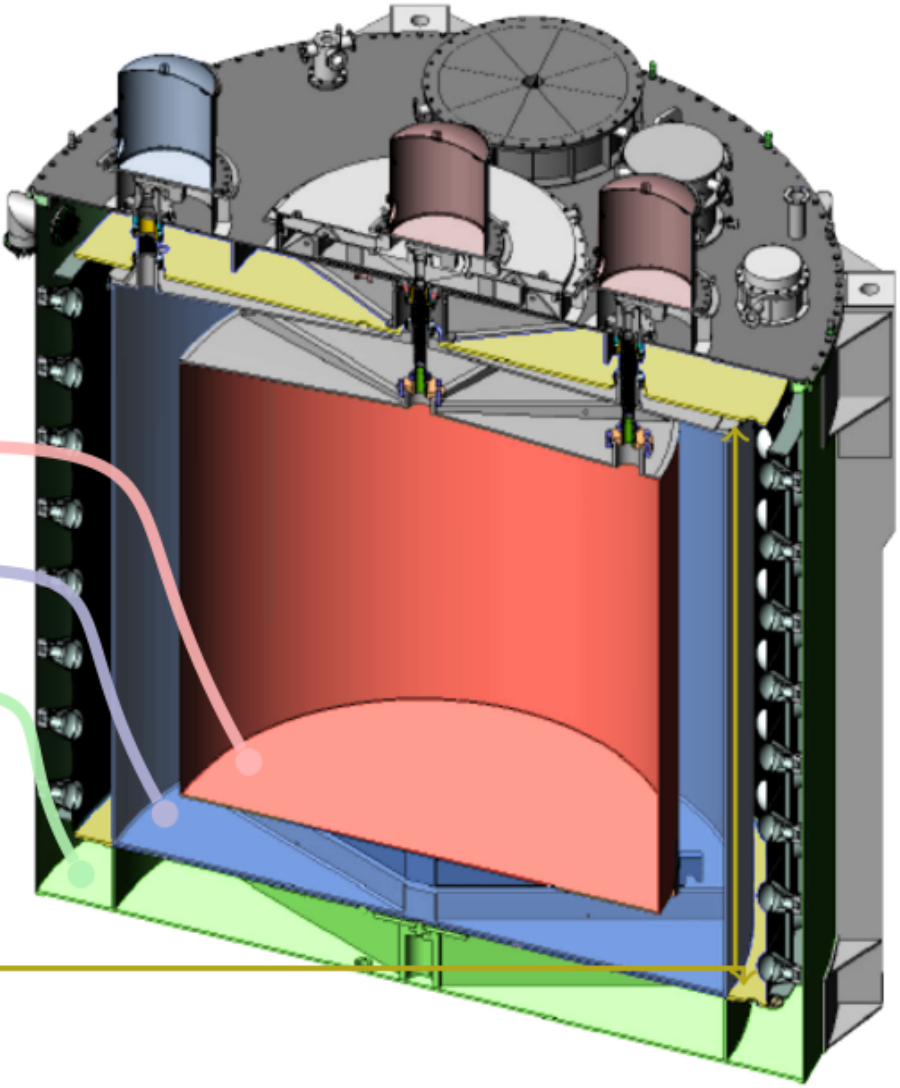
Antineutrino Detector (AD)

8 functionally identical detectors reduce systematic uncertainties

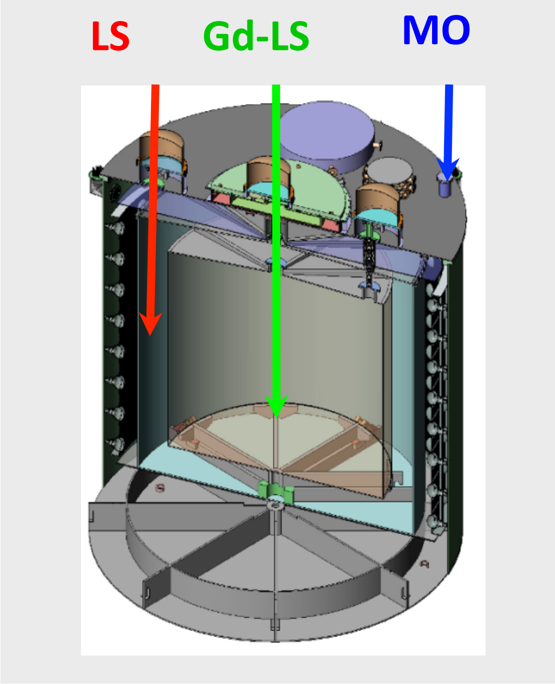
	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield and flatten detector response



Challenges: Detector Mass

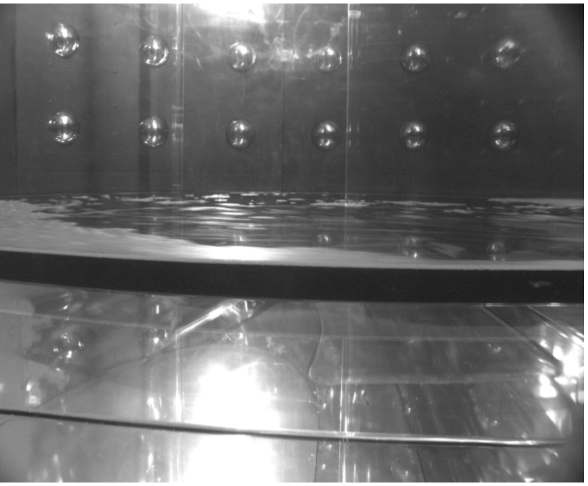



ISO tank on load cells

Detector target filled with GdLS from ISO tank.

Load cells measure 20 ton target mass to 3 kg (0.015%)

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



3 fluids filled simultaneously, with heights matched to minimize stress on acrylic vessels

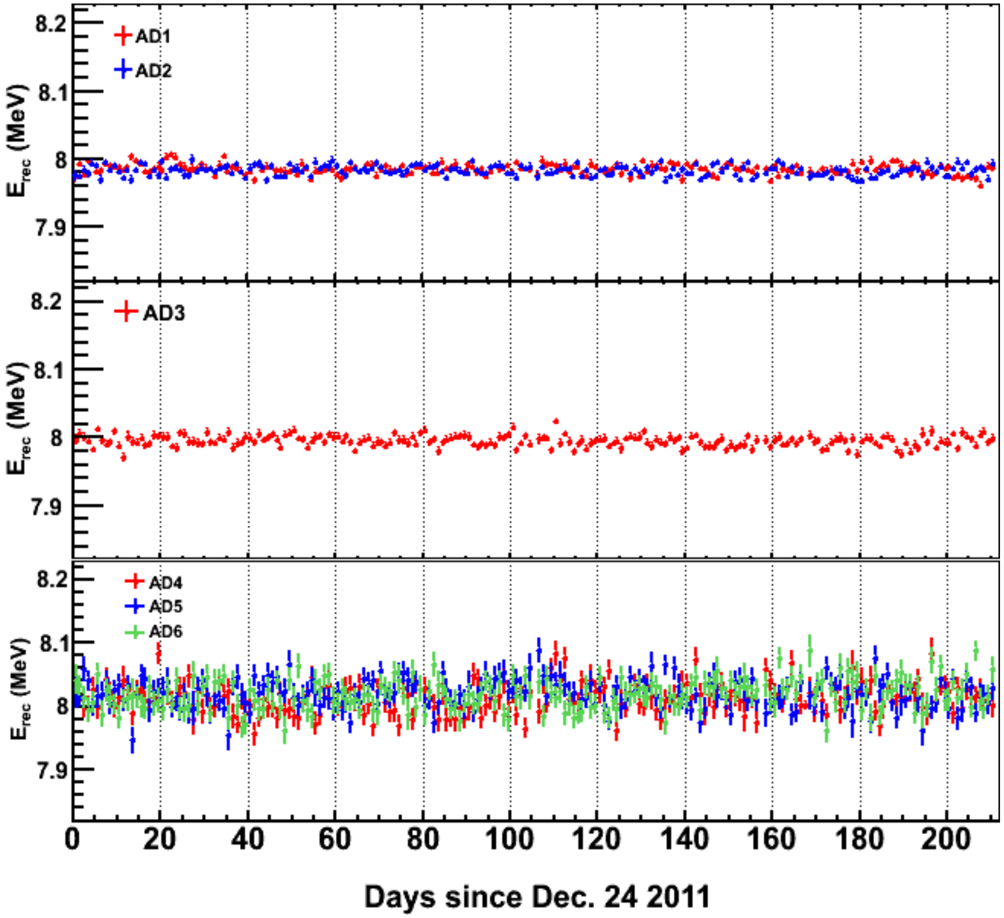
- **Gadolinium-doped Liquid Scintillator (GdLS)**
- **Liquid Scintillator (LS)**
- **Mineral Oil (MO)**

Challenges: Detector Stability

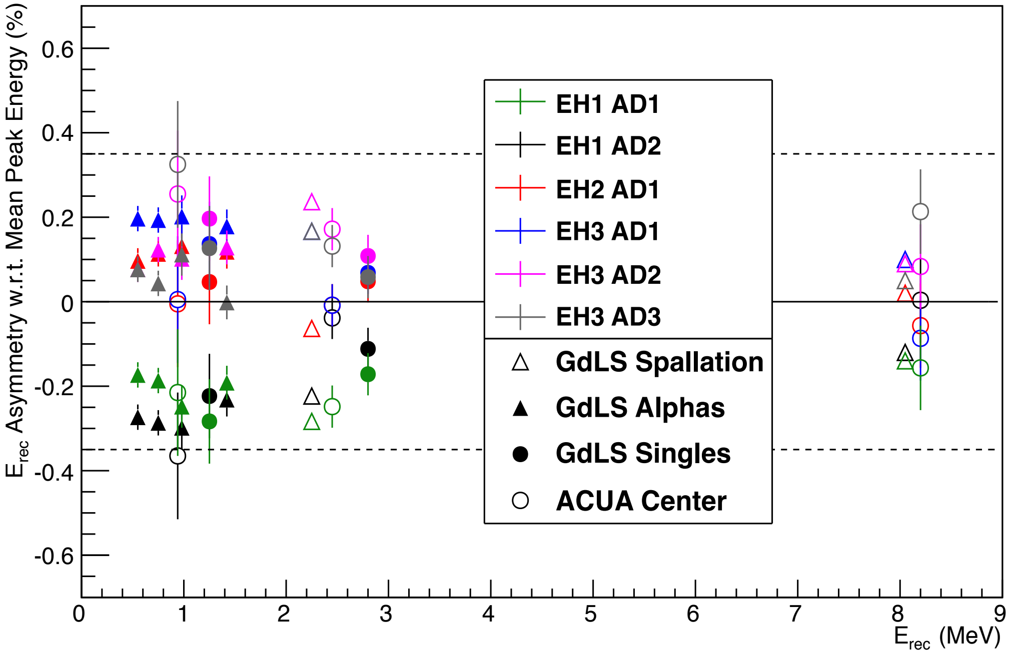
Obtain a stable and consistent Energy Response

After calibration, Daya Bay detectors are **stable to ~0.1%**, with **relative uncertainty of 0.35%**.

Spallation *n*Gd capture peak vs. time (after all calibration)



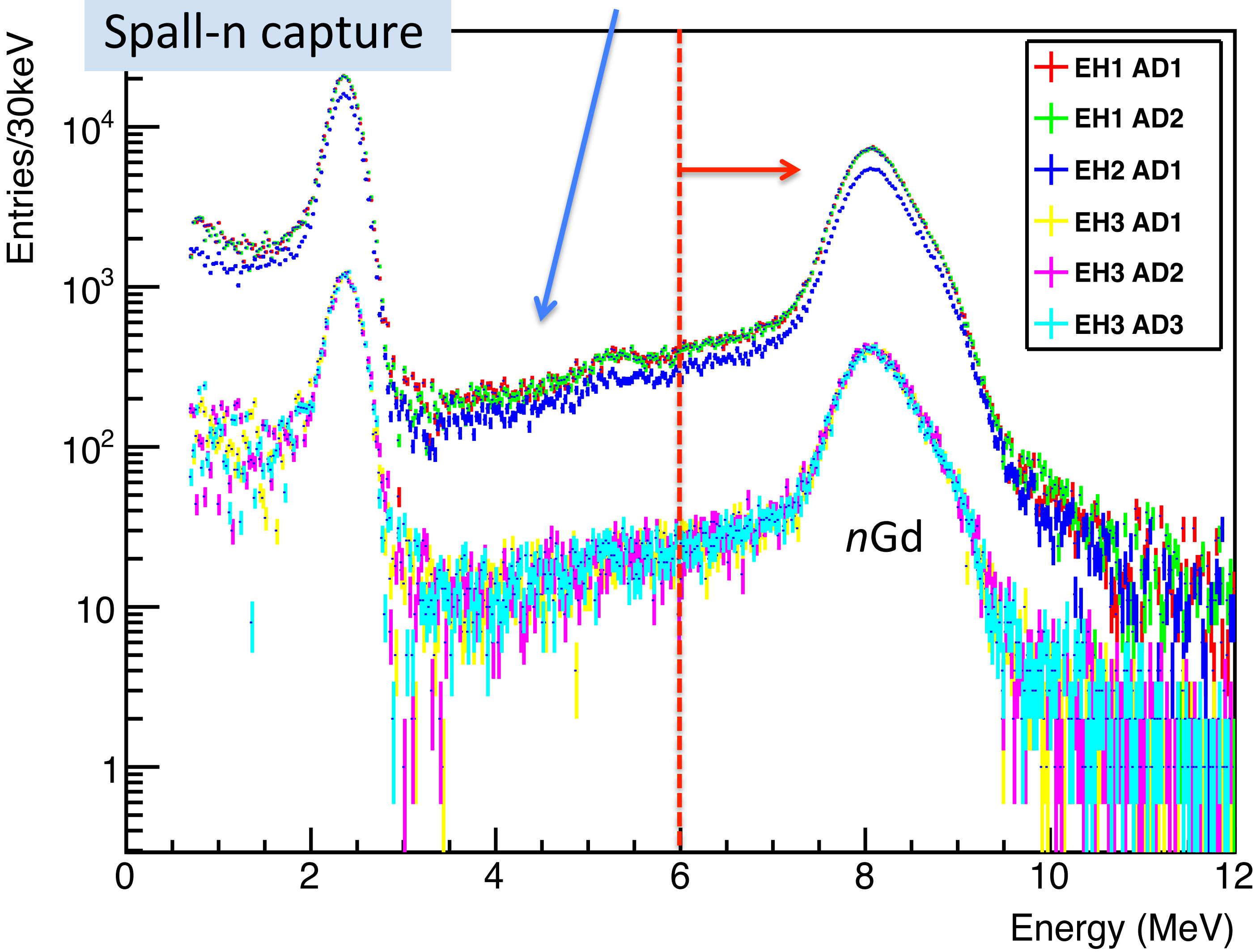
Relative energy peaks in all detectors (after calibration)



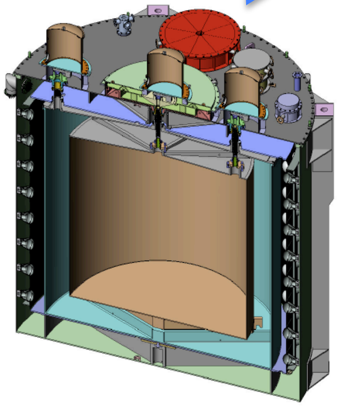
Challenges: Relative Efficiency

Largest uncertainty between Daya Bay detectors

Some *n*Gd gammas escape scintillator region, visible as tail of *n*Gd energy peak.


Spall-n capture

Motivation for 3-zone design

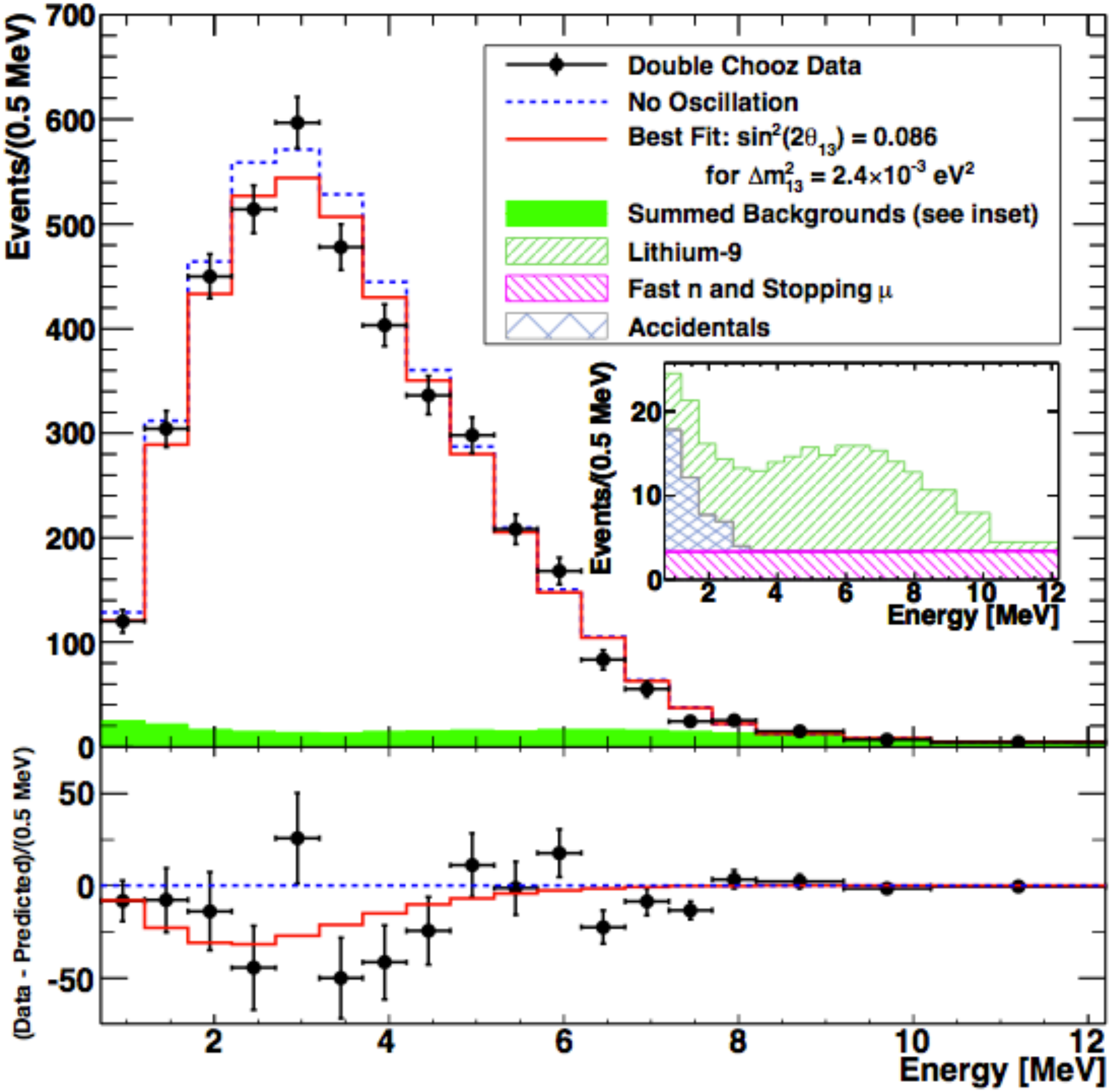


Efficiency variations estimated at 0.12%

Challenges: Underground Construction

Lawrence Berkeley Nat'l Lab
Roy Kaltschmidt, photographer

Almost-Double Chooz



Far detector only.

Use Bugey measurement (1994 to predict reactor neutrino flux.

~4000 antineutrino interactions

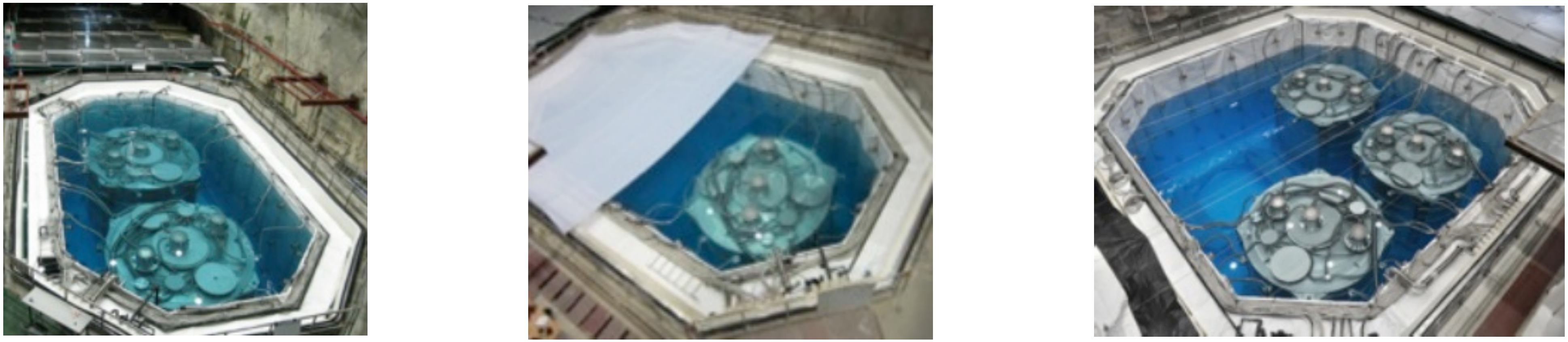
Rate and Spectral Shape also suggest non-zero θ_{13} at 1.7σ.

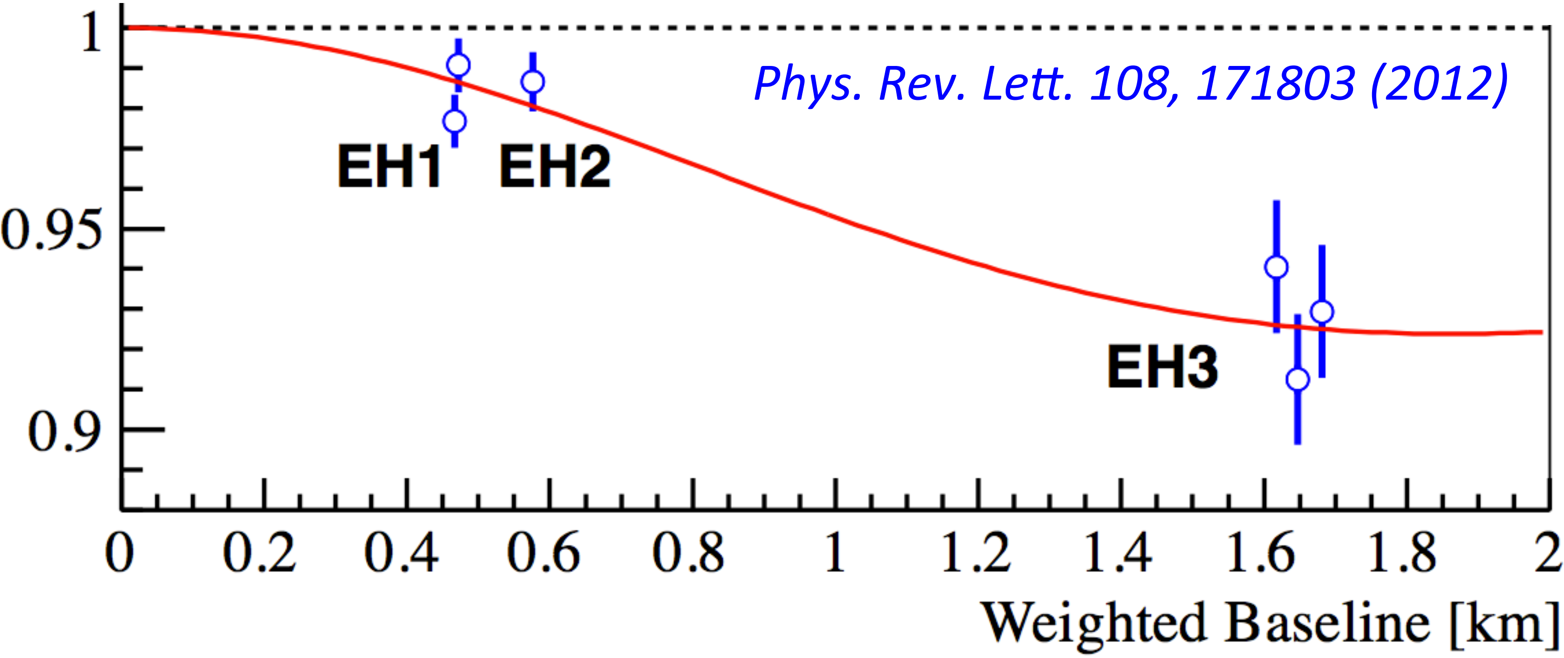
Phys. Rev. Lett. 108, 131801 (2012)

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (\text{stat})\ \pm 0.030\ (\text{syst})$$

Almost-Daya Bay

Only 6 of 8 planned detectors ready.





Phys. Rev. Lett. 108, 171803 (2012)

First definitive (>5σ) measurement of non-zero θ_{13}

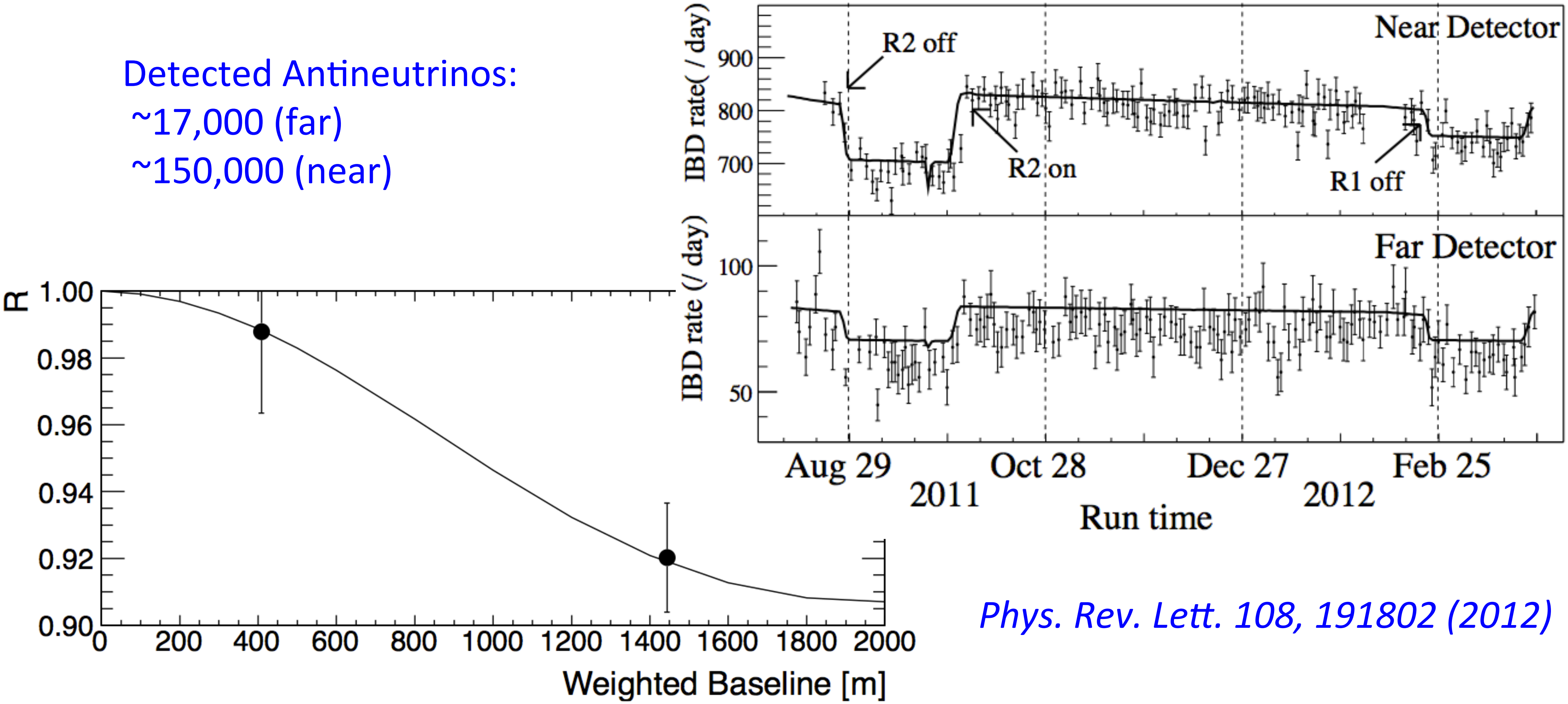
Detected Antineutrinos:
~10,000 (far)
~80,000 (near)

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

Almost-RENO

All detectors ready, but analysis was ongoing

Detected Antineutrinos:
~17,000 (far)
~150,000 (near)



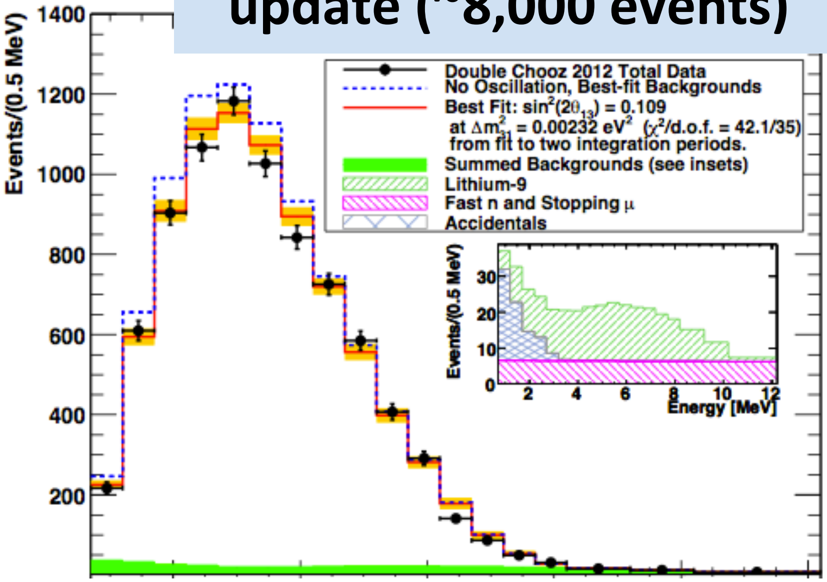
Phys. Rev. Lett. 108, 191802 (2012)

Result consistent with significantly non-zero θ_{13}.

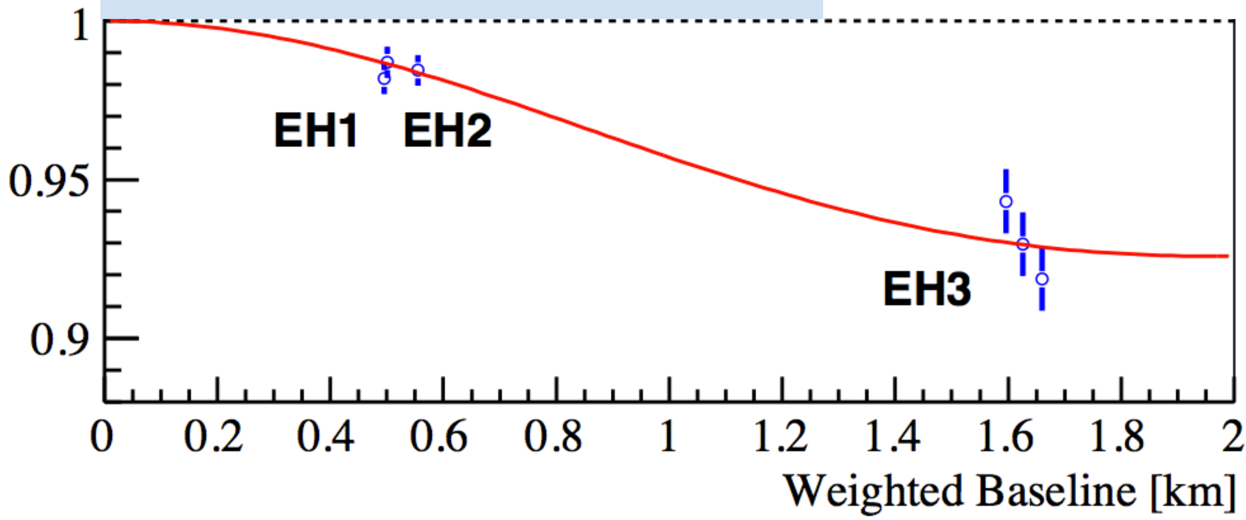
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$$

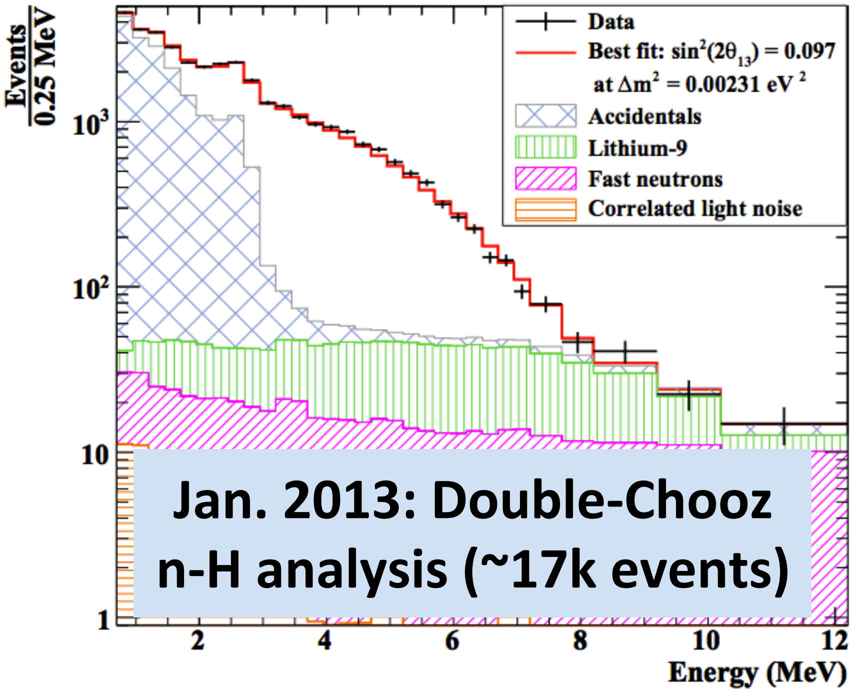
Progress

Jul. 2012: Double-Chooz update (~8,000 events)

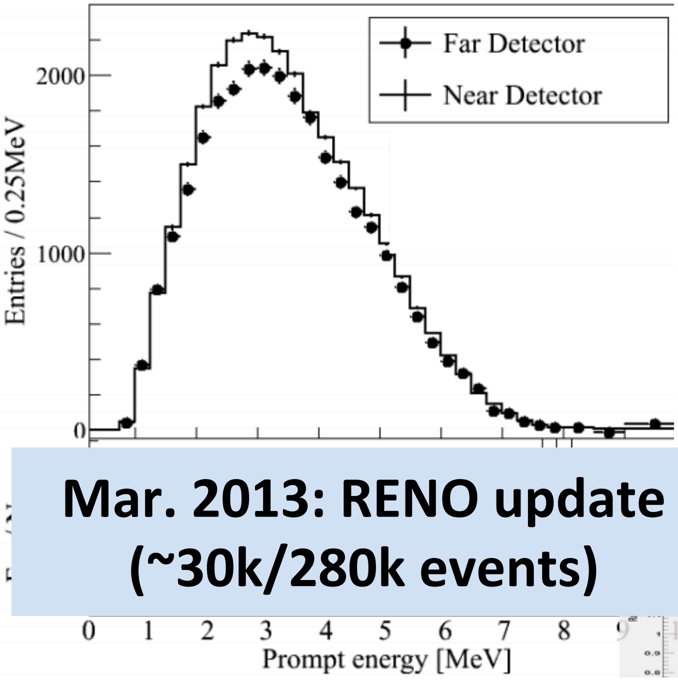


Nov. 2012: Daya Bay update (~29k/200k events)

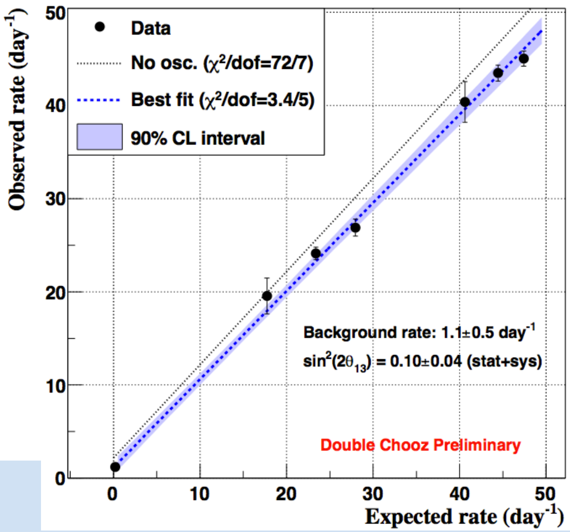




Jan. 2013: Double-Chooz n-H analysis (~17k events)



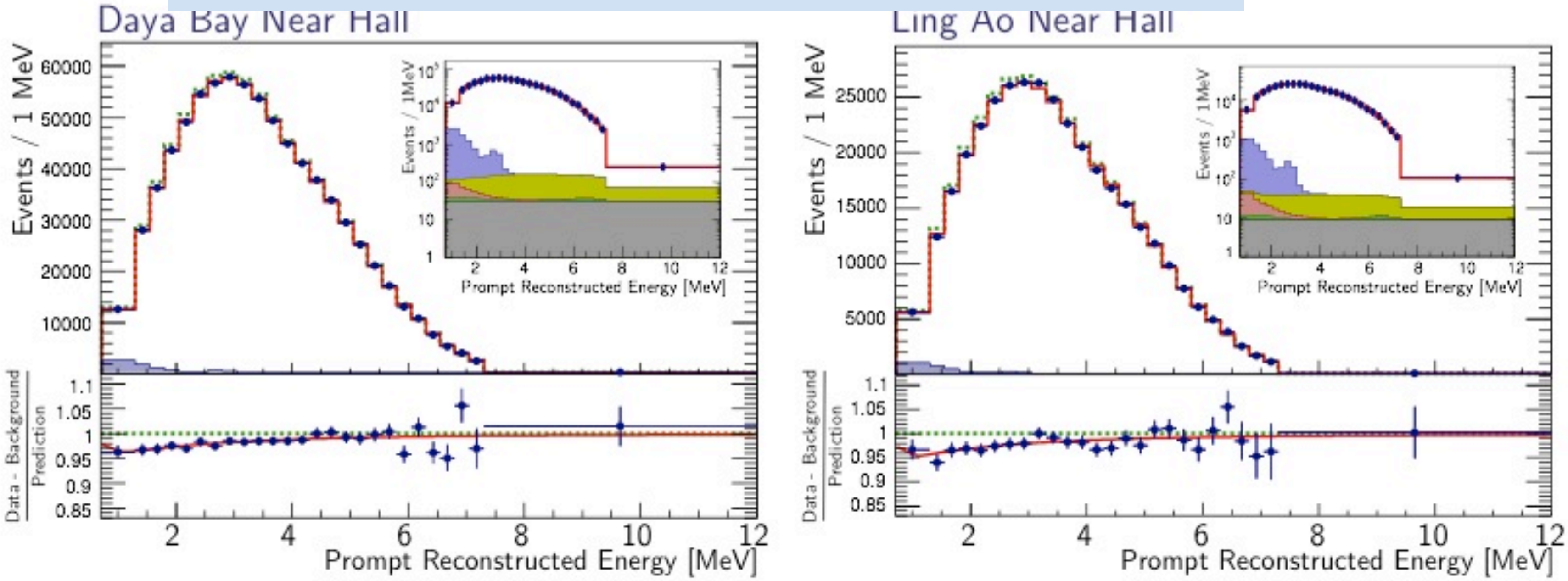
Mar. 2013: RENO update (~30k/280k events)



Aug. 2013: Double-Chooz reactor-on/off

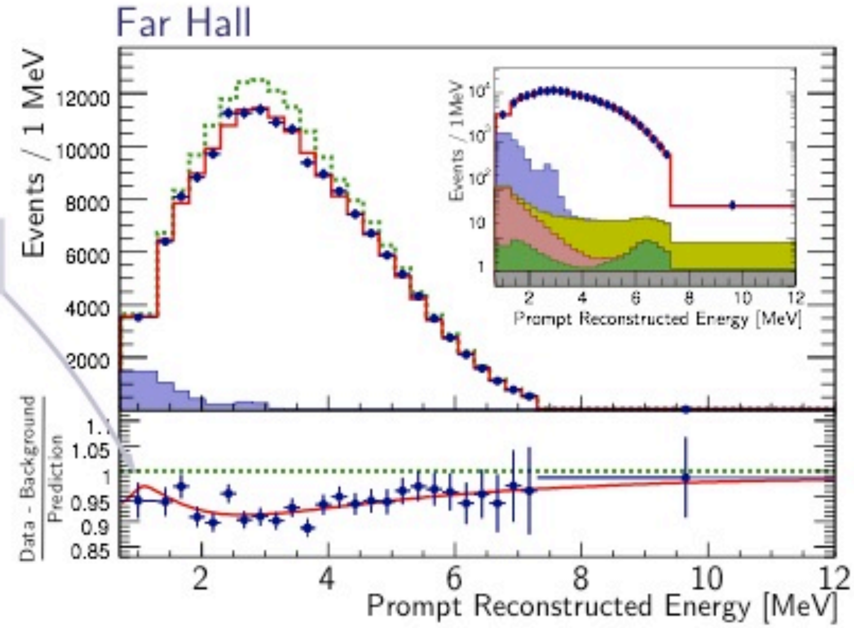
Just Released

Aug. 2013: Daya Bay Spectral Analysis



Detected Antineutrinos:
~42k (far)
~297k (near)

●— Data	🟦 Accidentals	🟩 $^{12}C(\alpha,n)^{16}O$
······ No Oscillation	🟨 $^{9}Li/^{8}He$	⬛ Fast neutrons
— Best Fit	🟥 $^{241}Am\text{-}^{13}C$	

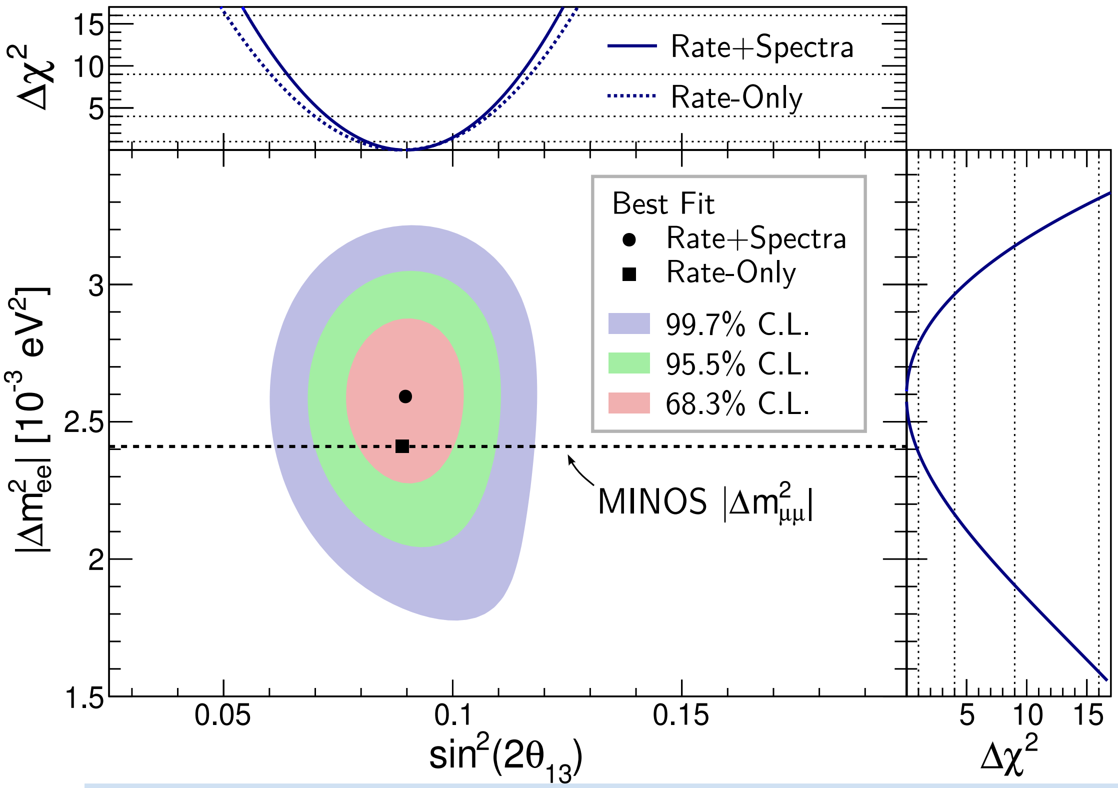


Shape distortion from energy losses in acrylic

Spectral distortion consistent with oscillation

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

Daya Bay Rate+Spectra Results



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

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

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

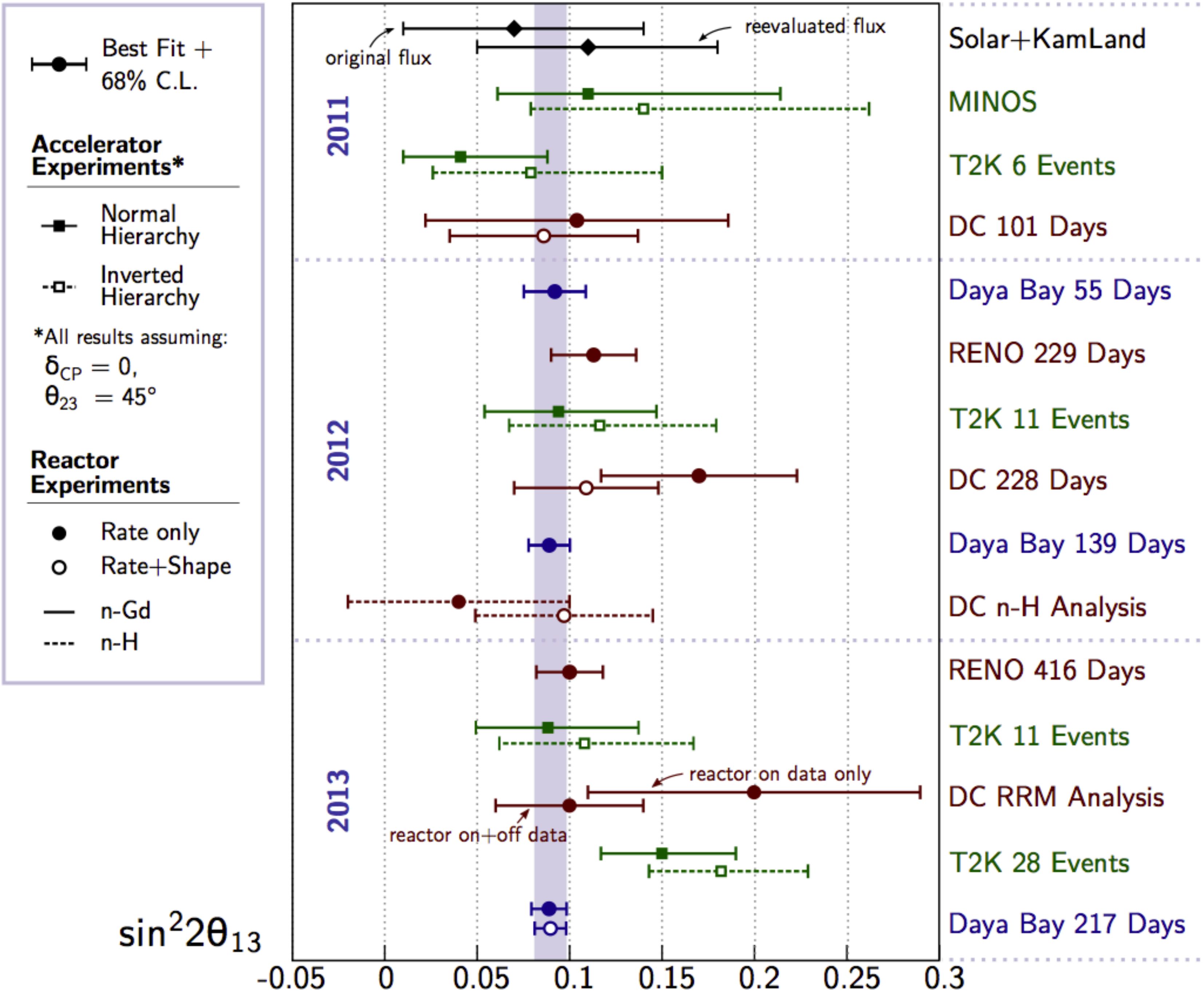
(Article in preparation)

Strong confirmation of three-flavor neutrino oscillation model

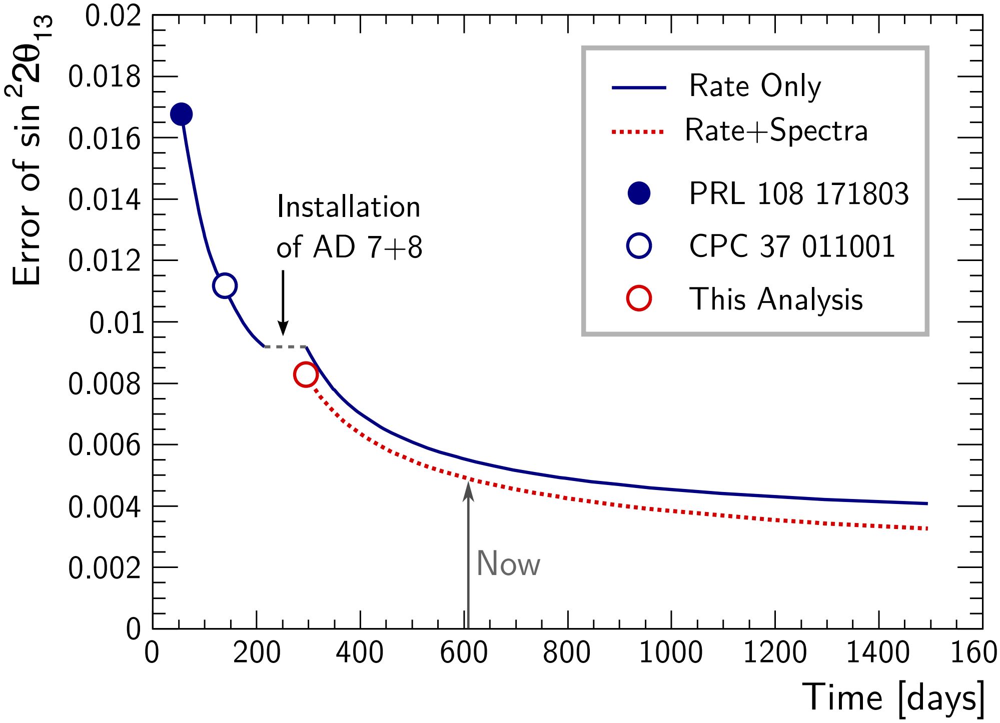
	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

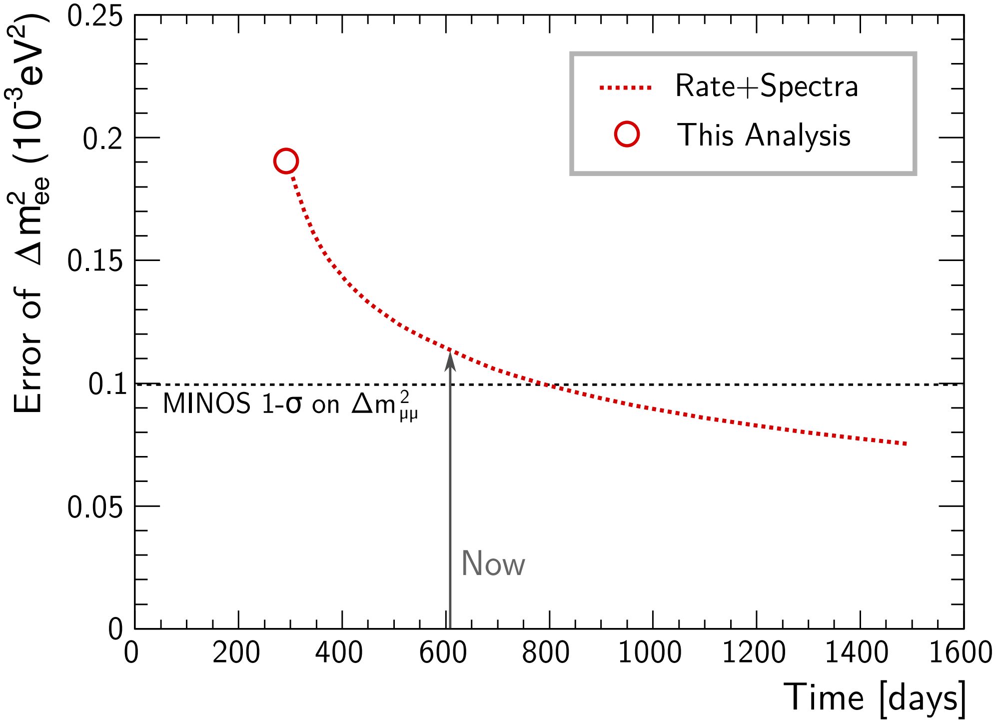
A. Radovic,
DPF2013

State of θ_{13} Measurements



Daya Bay Sensitivity

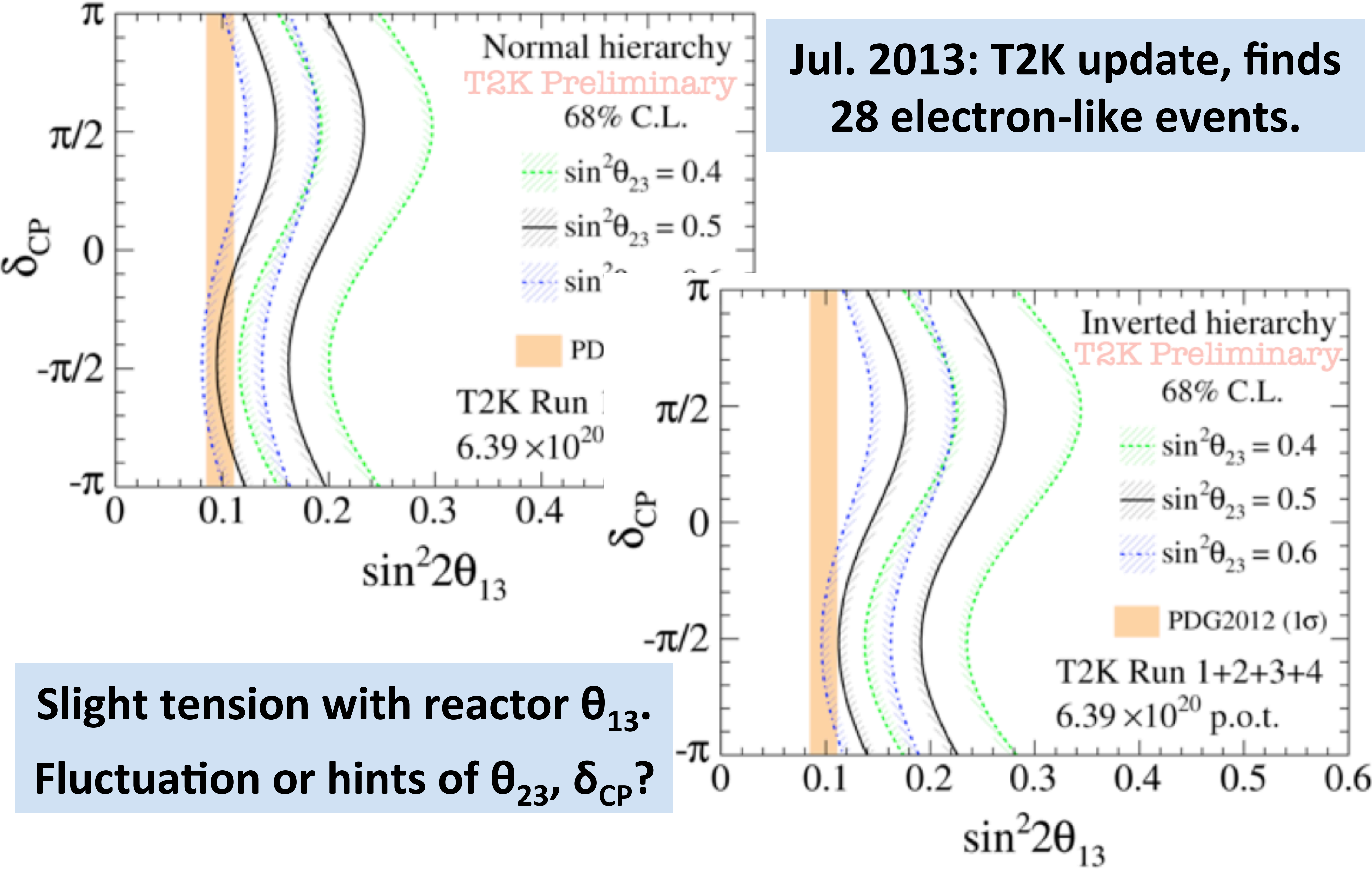




Over 1 million antineutrinos detected as of now!

Precision will soon be dominated by systematic uncertainties

Breaking Degeneracy



Jul. 2013: T2K update, finds 28 electron-like events.

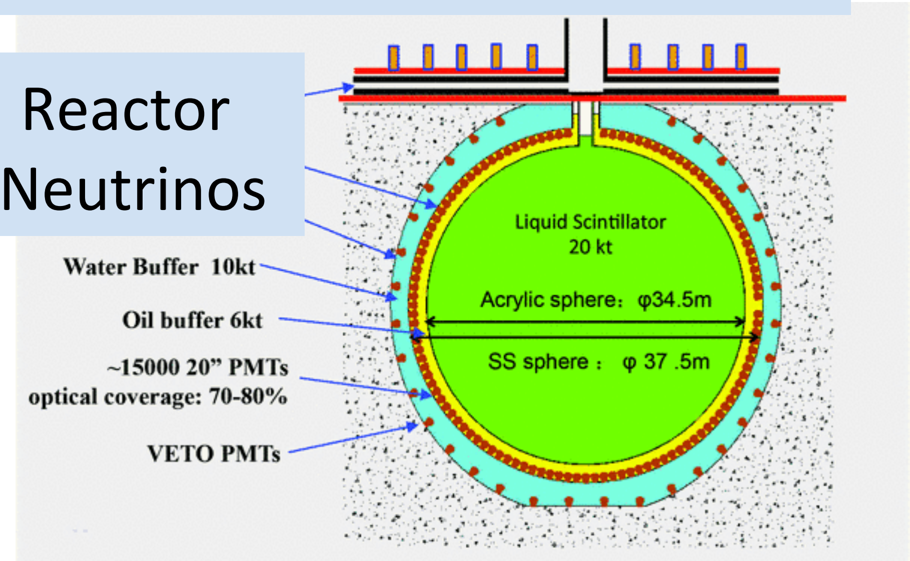
Slight tension with reactor θ_{13}.

Fluctuation or hints of θ_{23}, δ_{CP}?

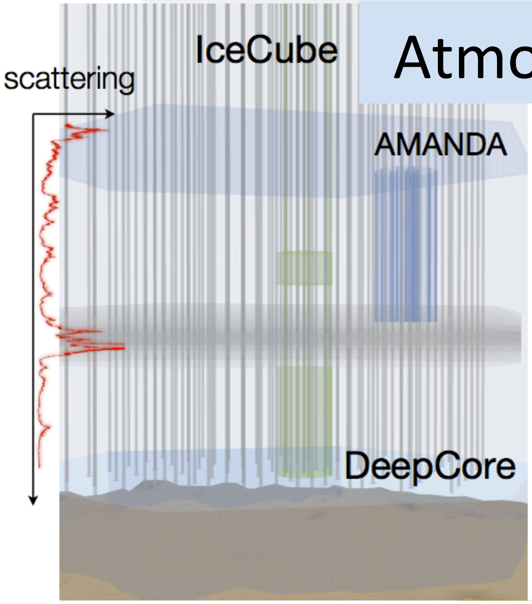
Open Doors

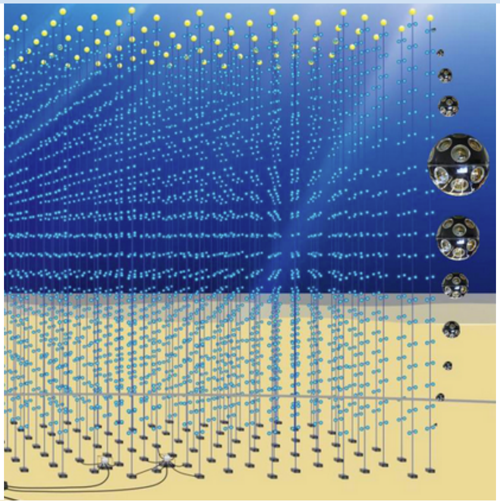
Neutrino Mass Hierarchy

Reactor Neutrinos



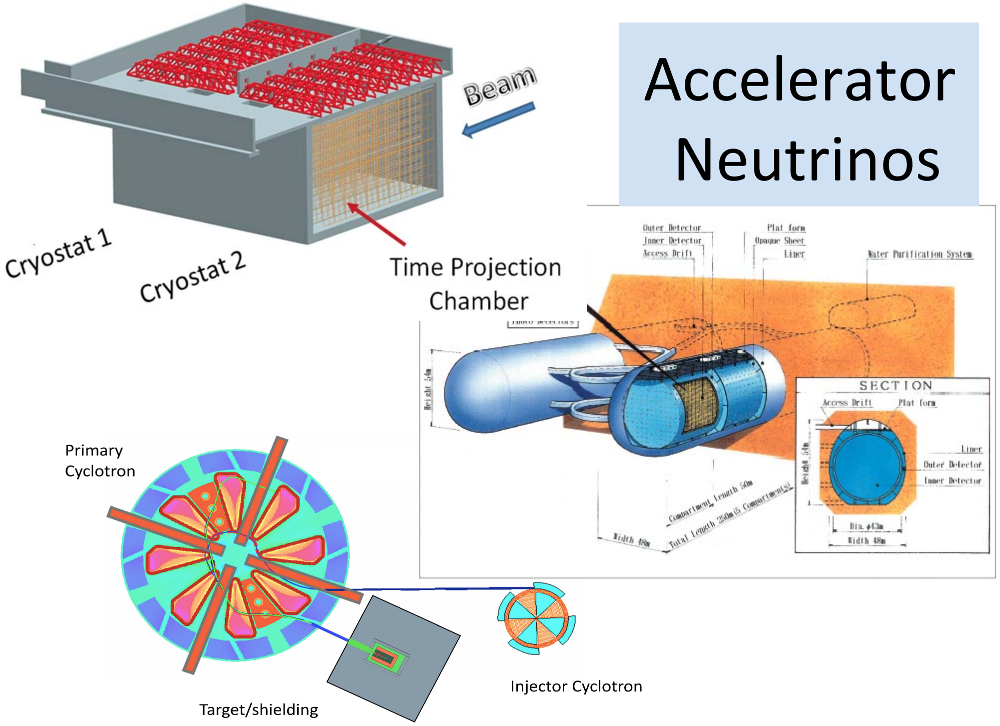
Atmospheric Neutrinos





CP-Violation for Neutrinos?

Accelerator Neutrinos



Precision Oscillation Tests

Can we explain the structure of neutrino masses and mixing?

Is the three flavor oscillation model sufficient to explain nature?