Reactor Neutrinos:
Recent Results and Future Prospects

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IPA, May 6, 2015

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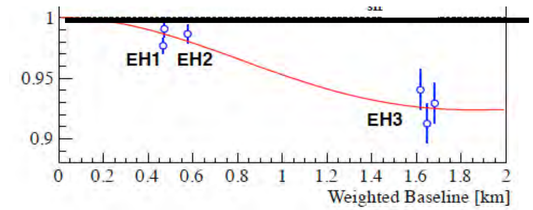
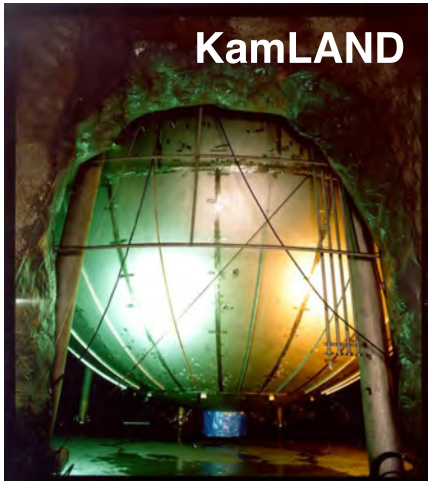
Reactor Antineutrinos

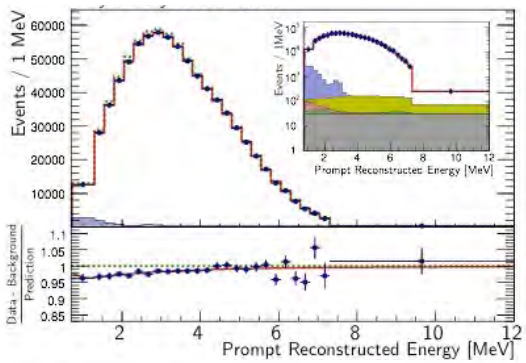
A Tool for Discovery

2012 - Measurement of θ_{13} with Reactor Neutrinos



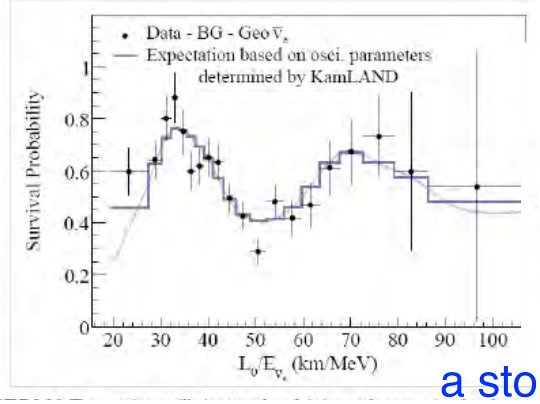
2003 - First observation of reactor antineutrino disappearance

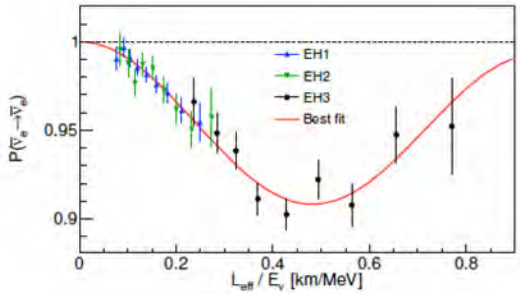




1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos





a story of varying baselines...

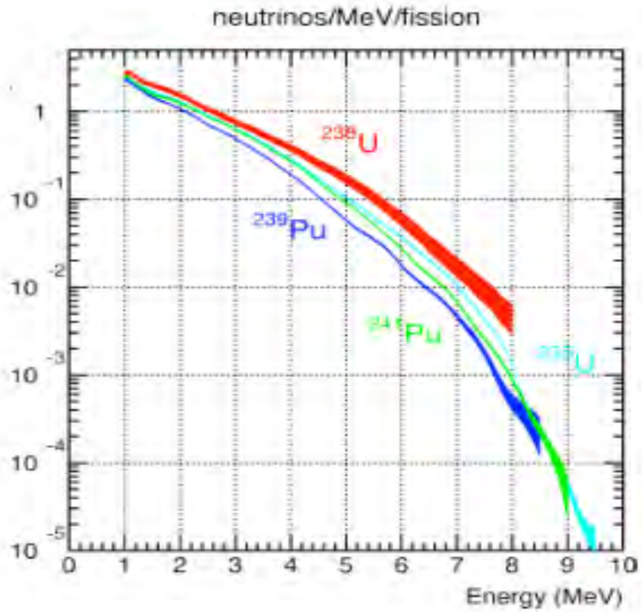
Reactor Antineutrino Flux and Spectrum

Source

$\bar{\nu}_e$ from β-decays, pure $\bar{\nu}_e$ source

of n-rich fission products

on average ~6 beta decays until stable



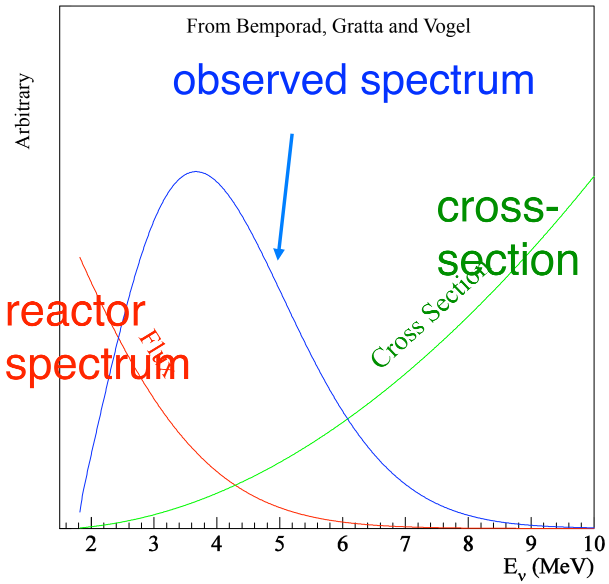
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

$$\frac{d^2N(E,t)}{dEdt} \equiv \sum_i \frac{W_{th}(t)}{\sum_j f_j(t)e_j} f_i(t)S_i(E)c_i^{ne}(E,t) + S_{SNF}(E,t) \quad (1)$$

Detection

inverse beta decay

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

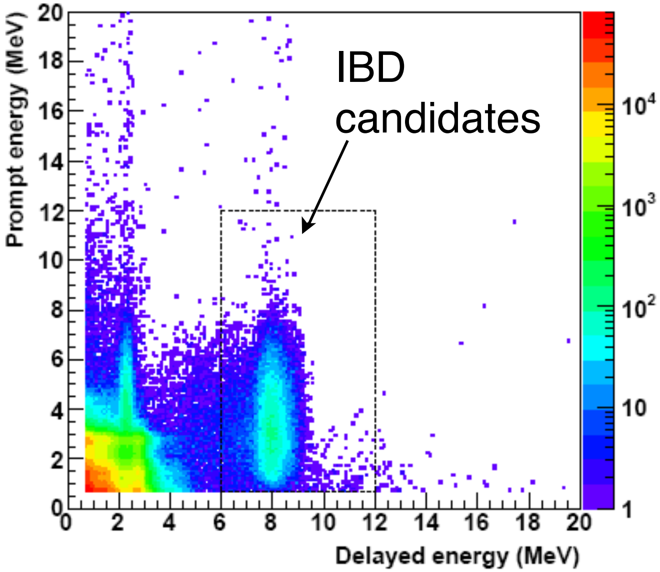


mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance experiments possible

Antineutrino Candidates (Inverse Beta Decay)

Prompt + Delayed Coincidence

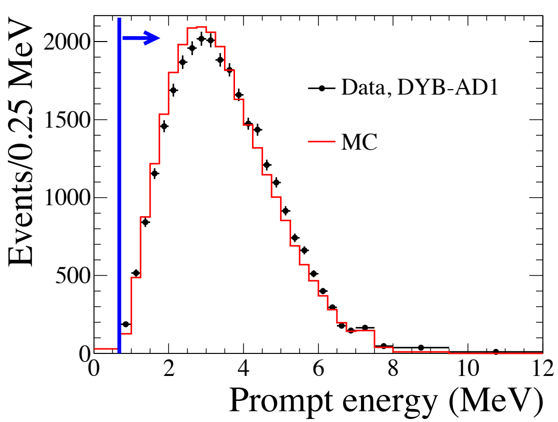


$\overline{\nu}_e + p \rightarrow e^+ + n$

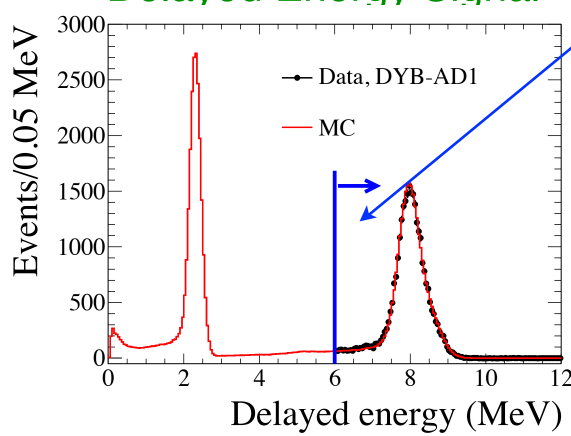
prompt event:
positron deposits energy and annihilates (~ns)

delayed event:
neutron thermalizes and captures on **Gd**

Prompt Energy Signal

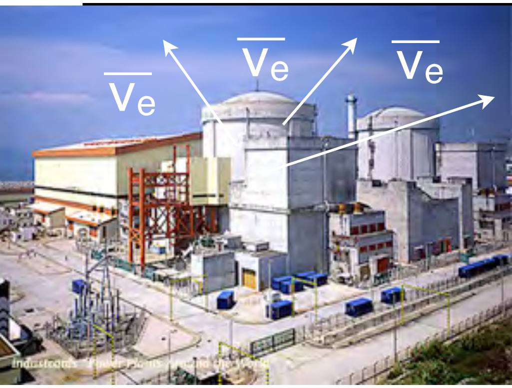


Delayed Energy Signal

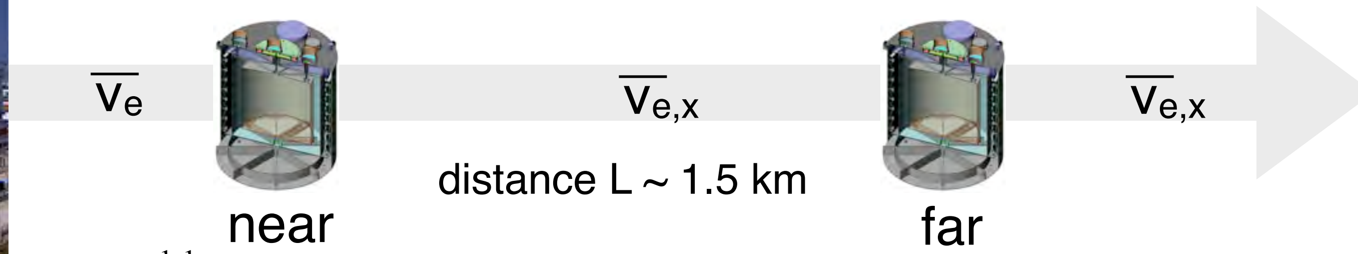


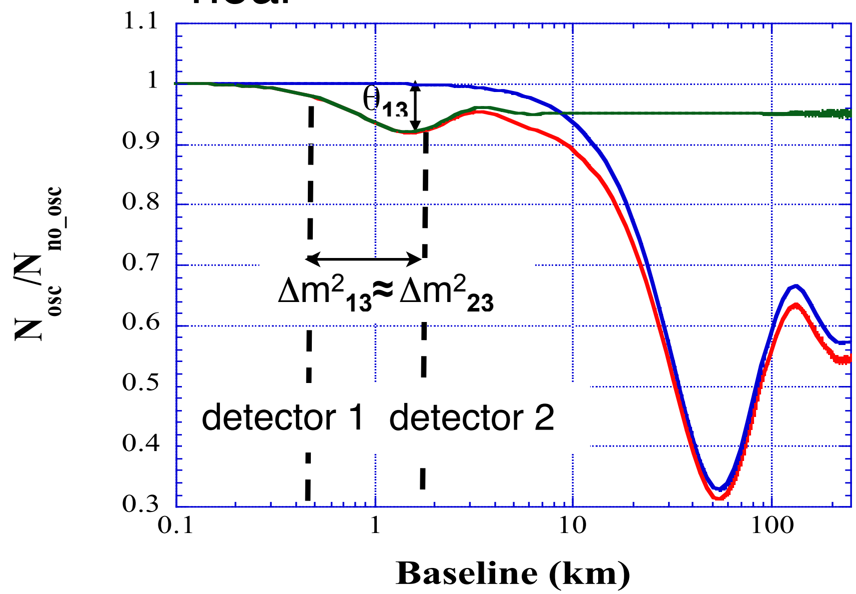
Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

Principle of Relative Measurement of $\bar{\nu}_e$ Flux



Relative measurement between near and far detectors





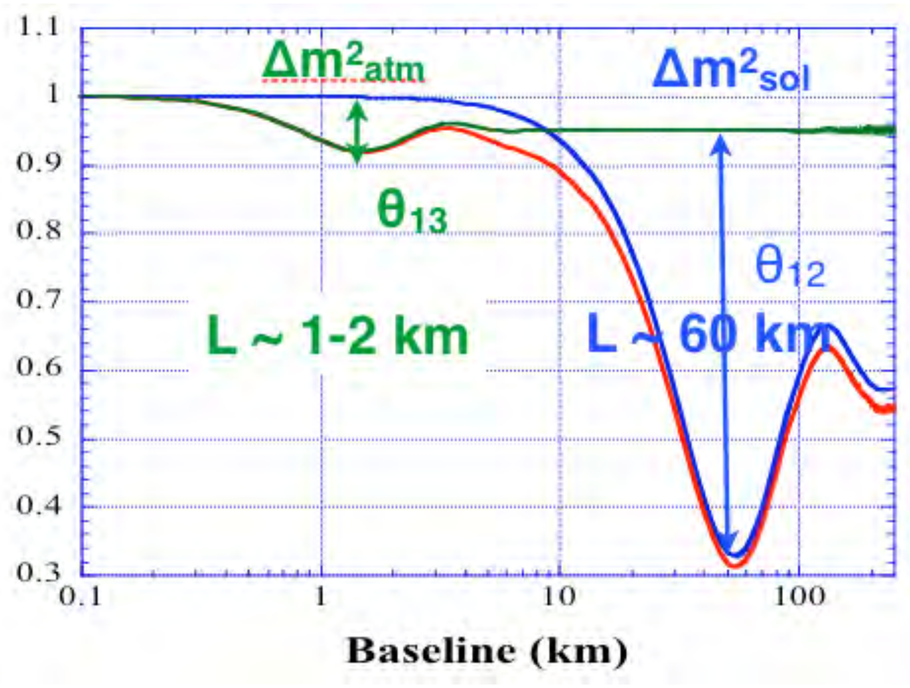
Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

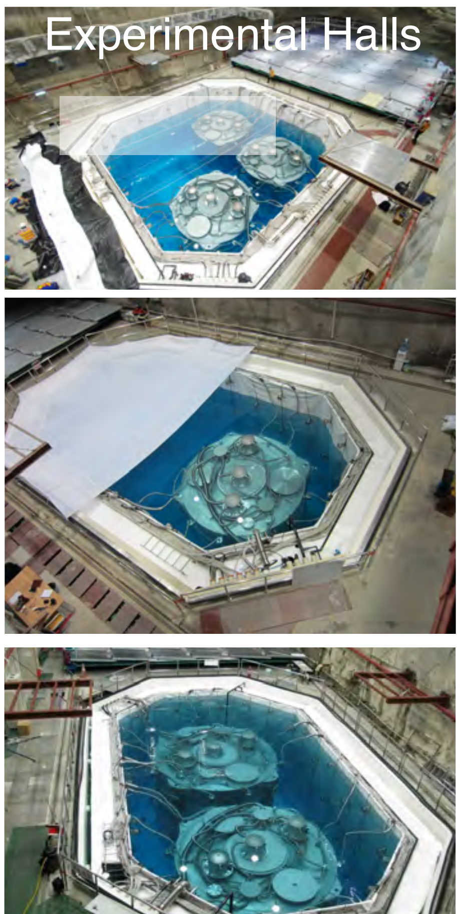
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

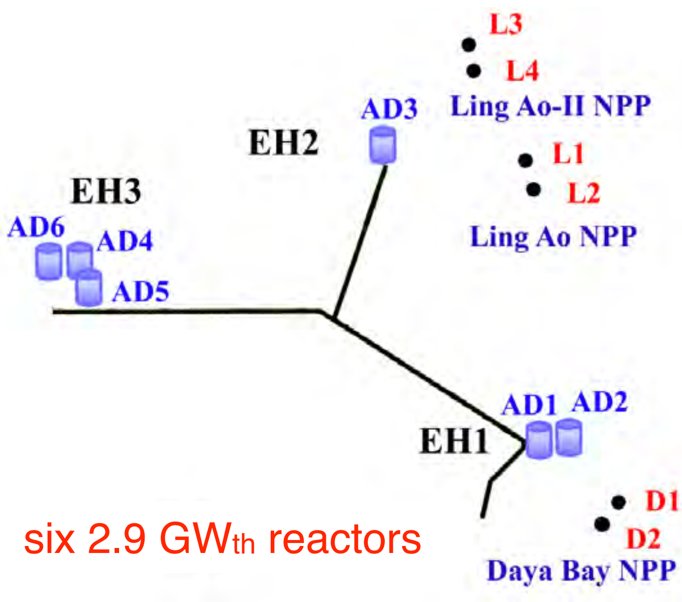
far/near $\bar{\nu}_e$ ratio — target mass — distances — efficiency — oscillation deficit

Oscillation Measurements



Daya Bay Reactor Experiment



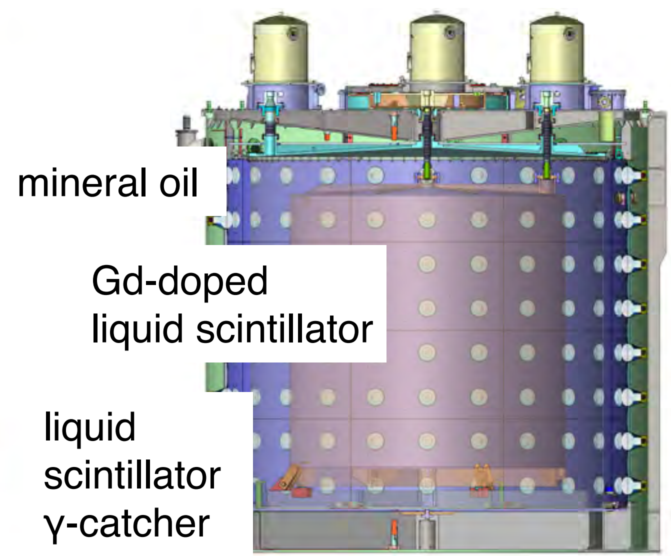


six 2.9 GW_{th} reactors

6 detectors, Dec 2011- Jul 2012
217 days

now running with 8 detectors

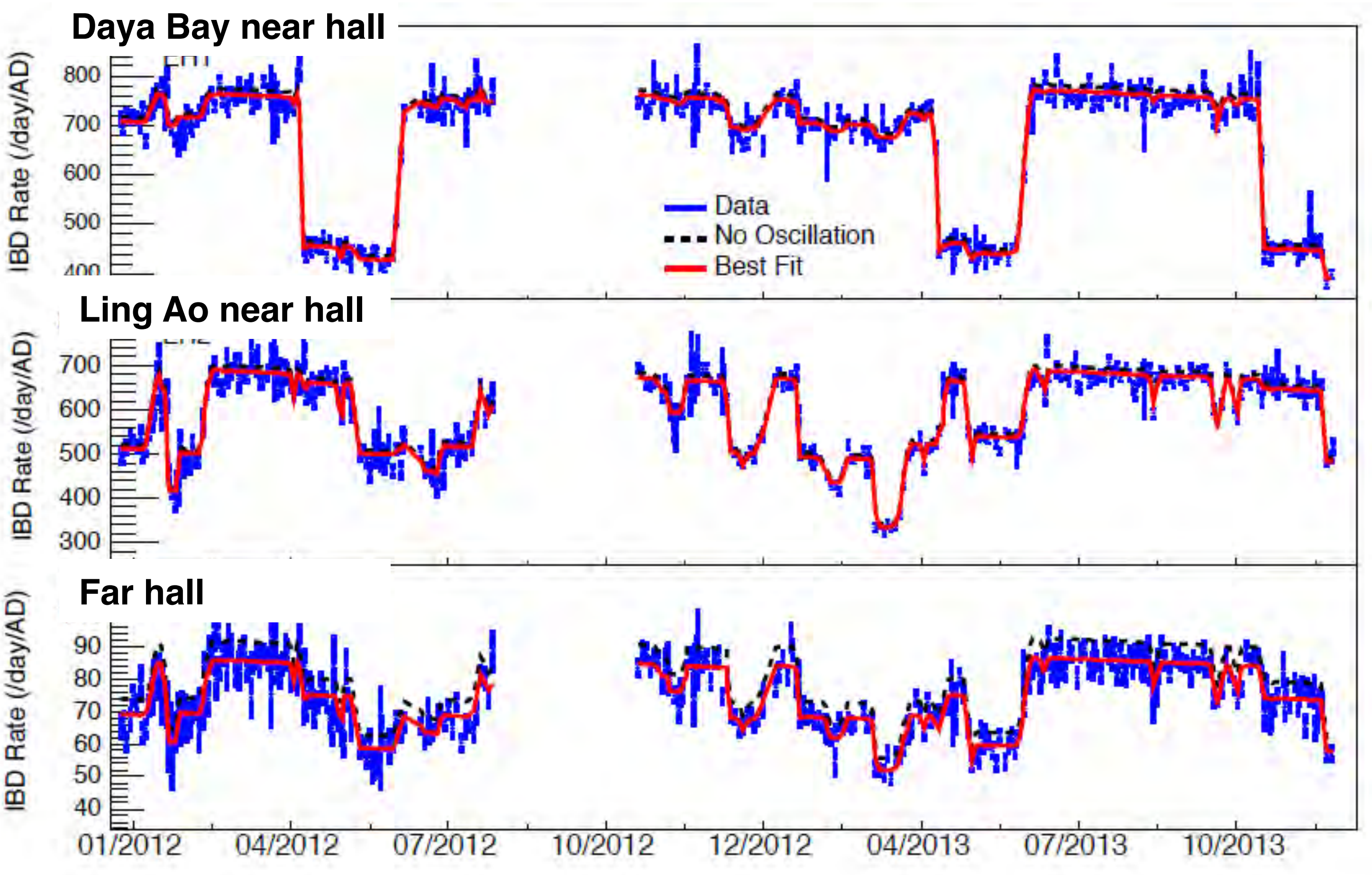
Antineutrino Detector

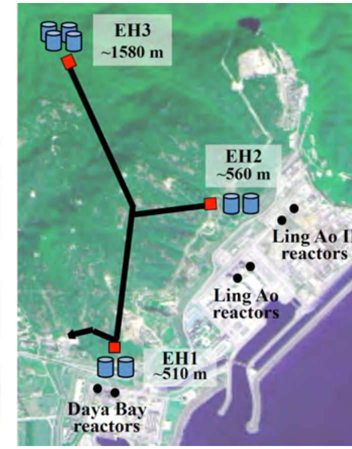


target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

Antineutrino Rate vs Time

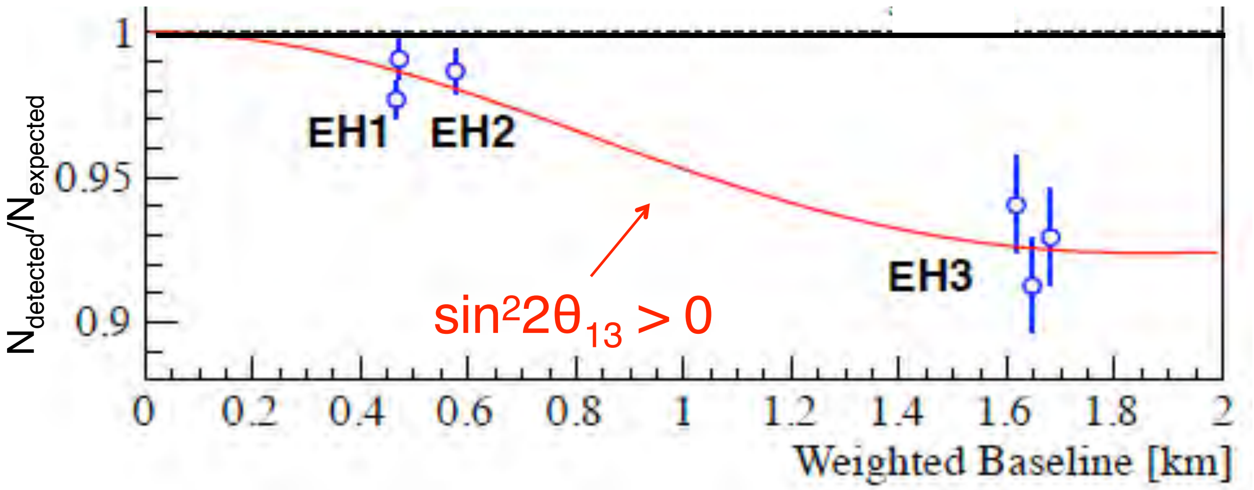
Over 1 Million Antineutrino Interactions Detected





Observation of $\overline{\nu}_e$ Disappearance

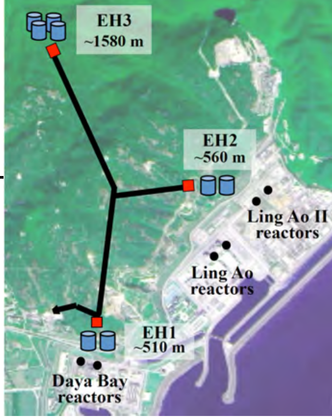
Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\overline{\nu}_e$ at short baseline. [PRL **108**, 171803]

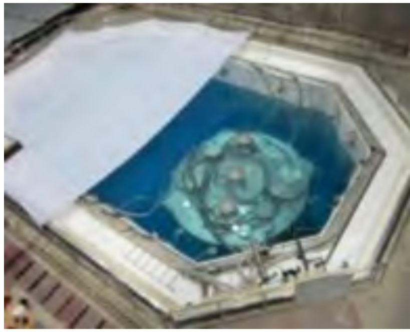


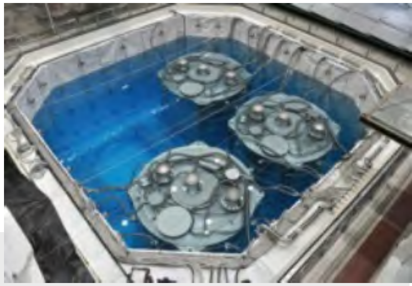
Obtained the most precise value of θ_{13}:

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

One of Science's breakthroughs of year 2012



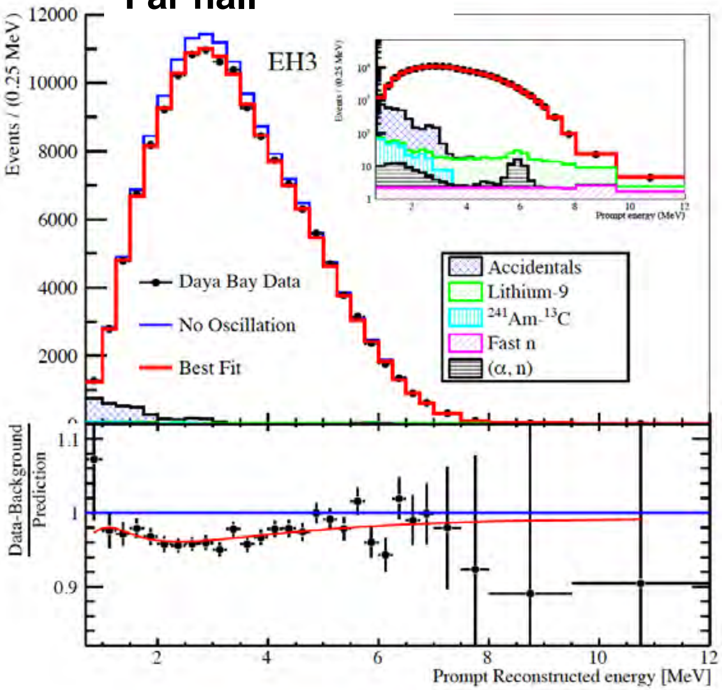




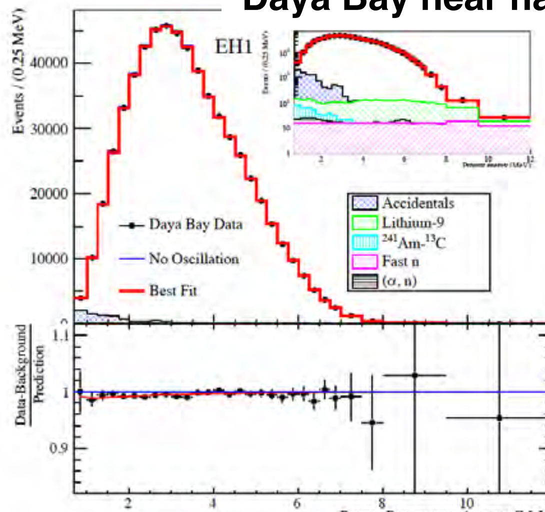
Energy Spectra

Prompt positron spectra measured in near, far detector halls

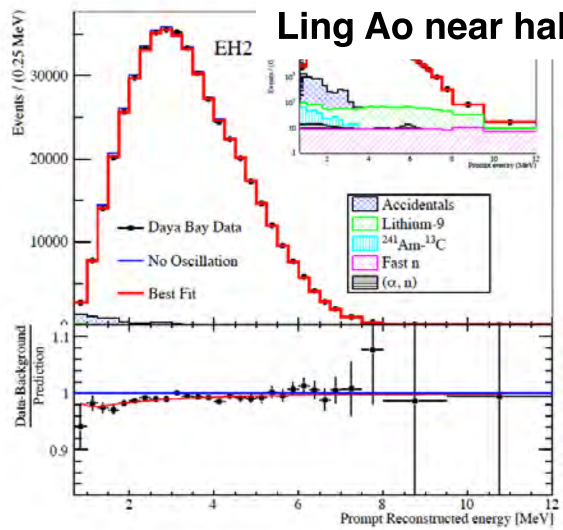
Far hall

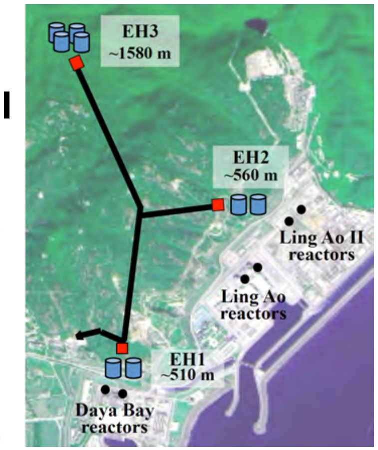


Daya Bay near hall



Ling Ao near hall



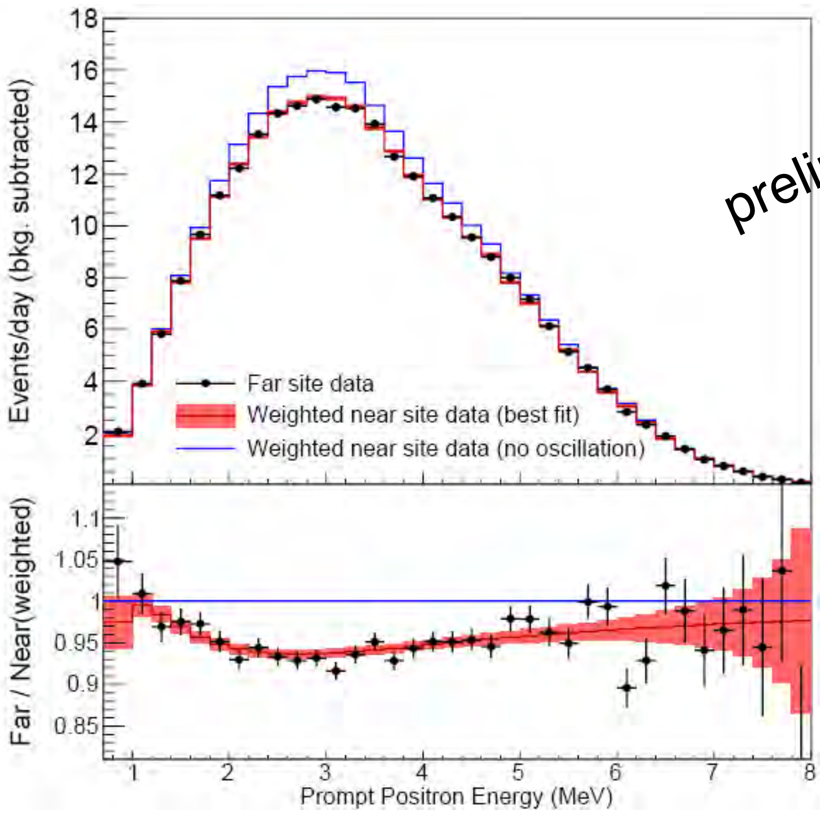


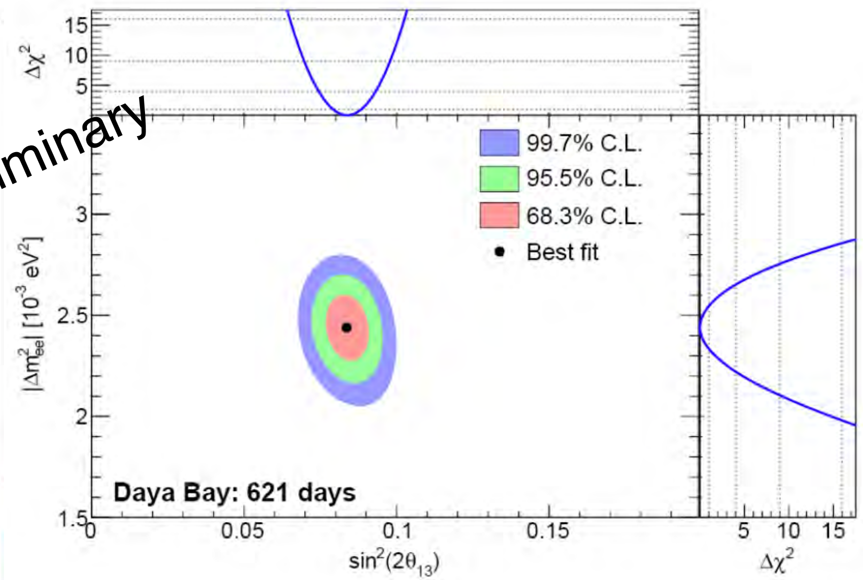
~300,000 inverse beta decay (IBD) events in near detectors

~42,000 IBD in far detector, spectral distortions consistent with neutrino oscillations

Daya Bay Oscillation Results

621 days of data, n+Gd





- far site expected spectra based on near-site observed spectra
- current analysis is designed to be (almost) independent of any reactor flux models

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

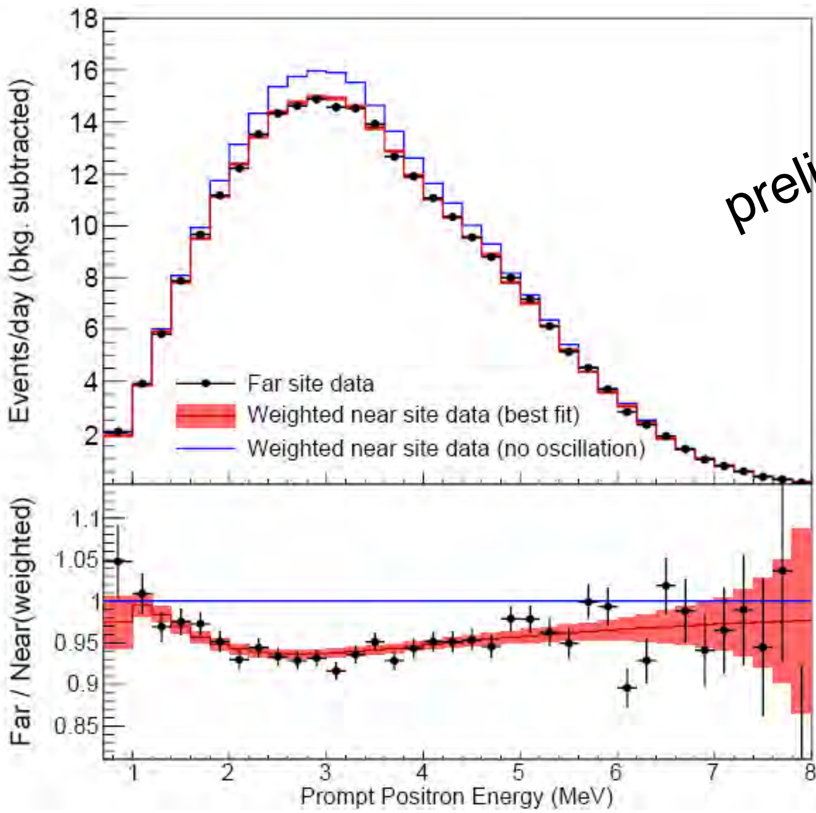
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} \mathrm{eV}^2$$

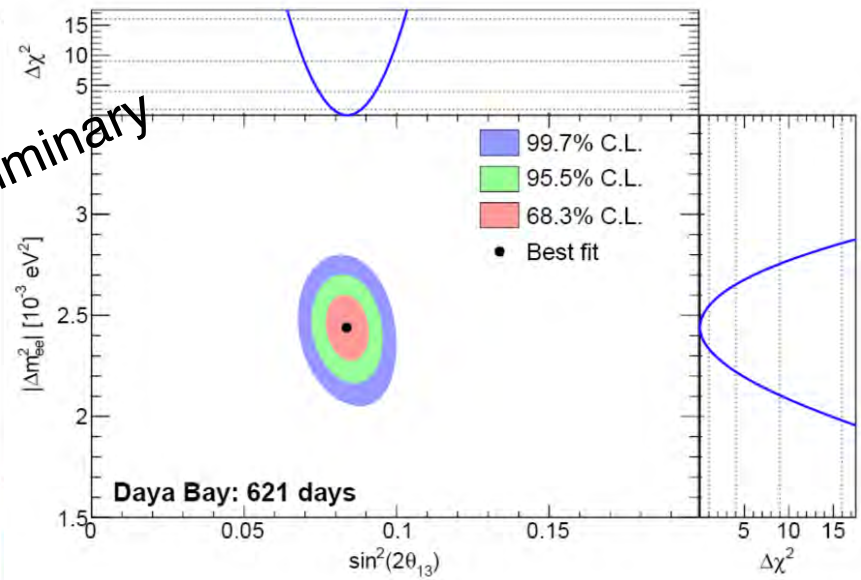
$$\chi^2/NDF = 134.7/146$$

consistent results from nH analysis

Daya Bay Oscillation Results

621 days of data, n+Gd





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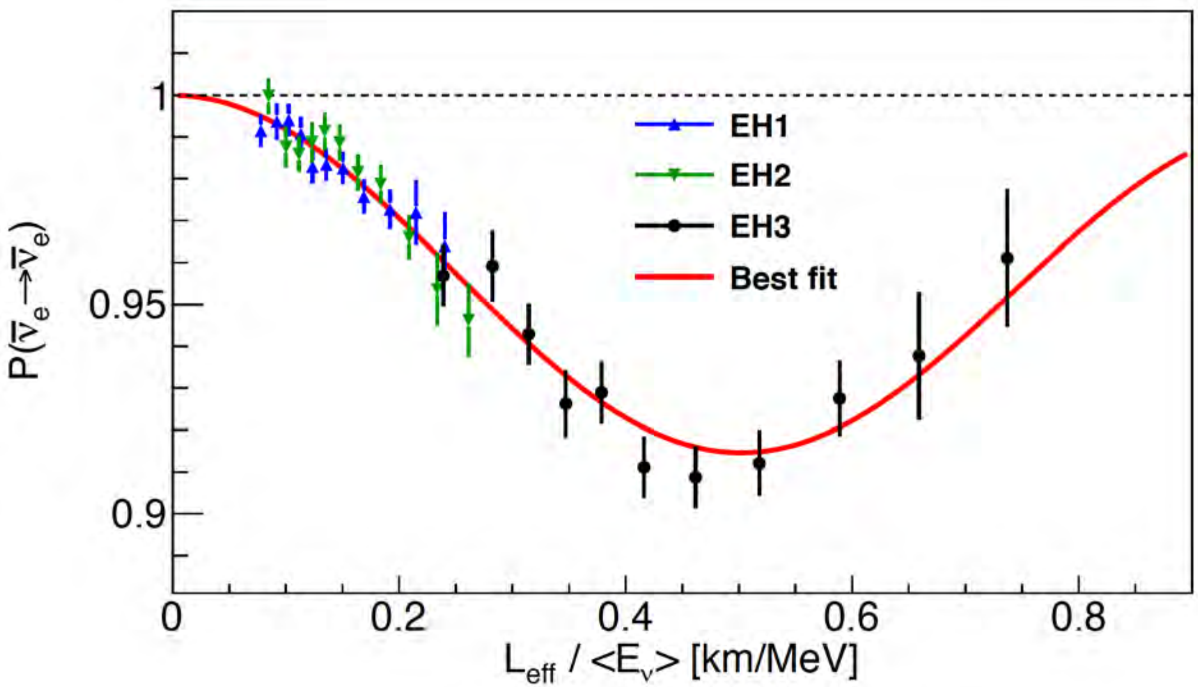
$$\chi^2/NDF = 134.7/146$$

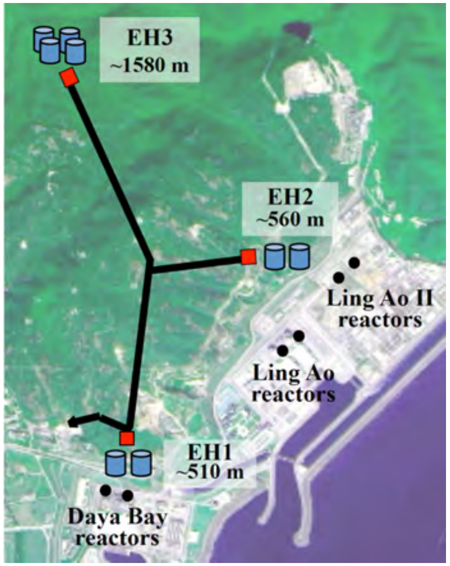
most precise measurement of $\sin^2 2\theta_{13}$ (6%), and Δm^2_{ee} in the electron neutrino disappearance channel (4%)

Daya Bay Neutrino Oscillation

Neutrino oscillation is energy and baseline dependent

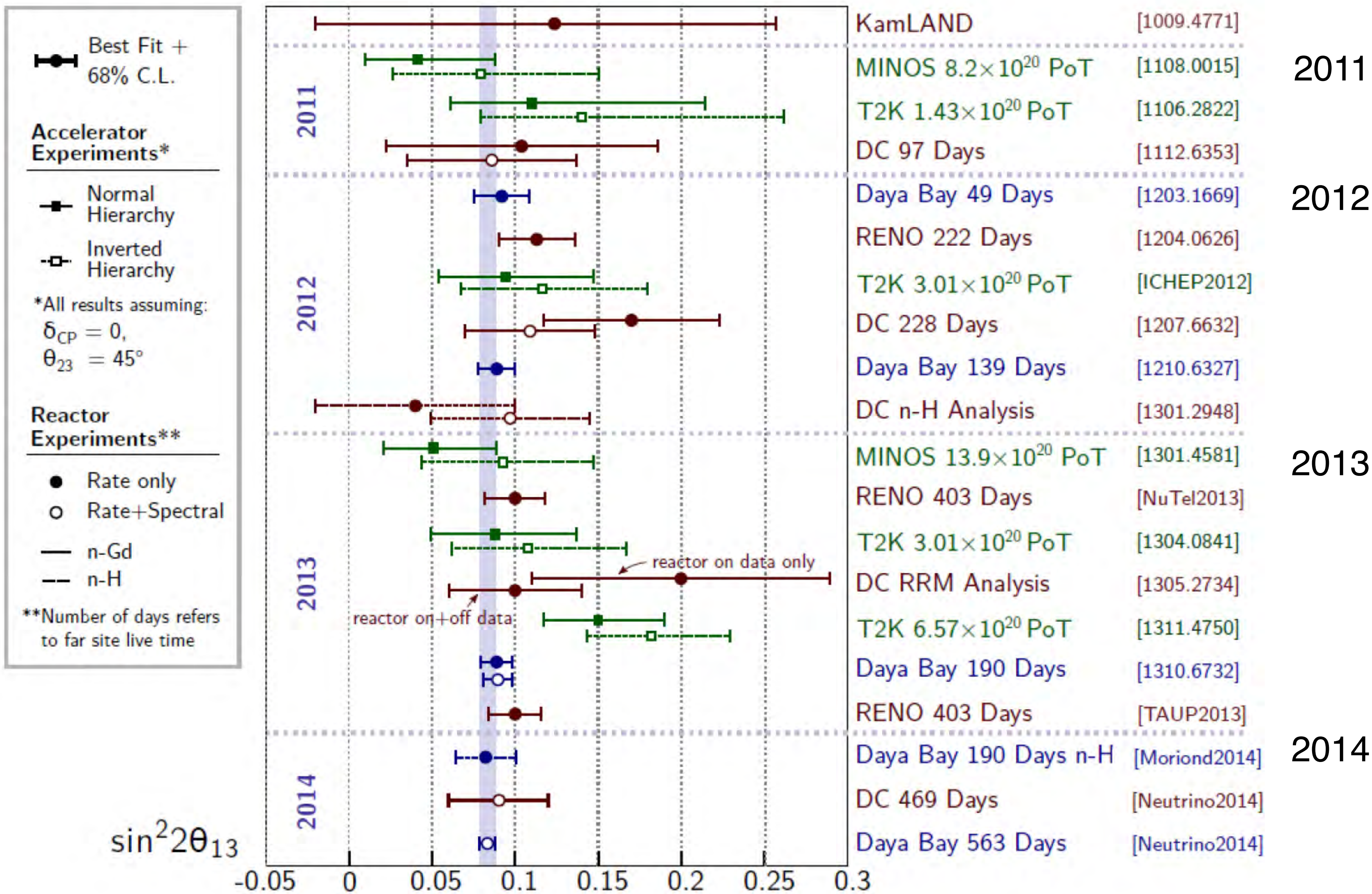
$$P_{i\to j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$





Daya Bay demonstrates L/E oscillation

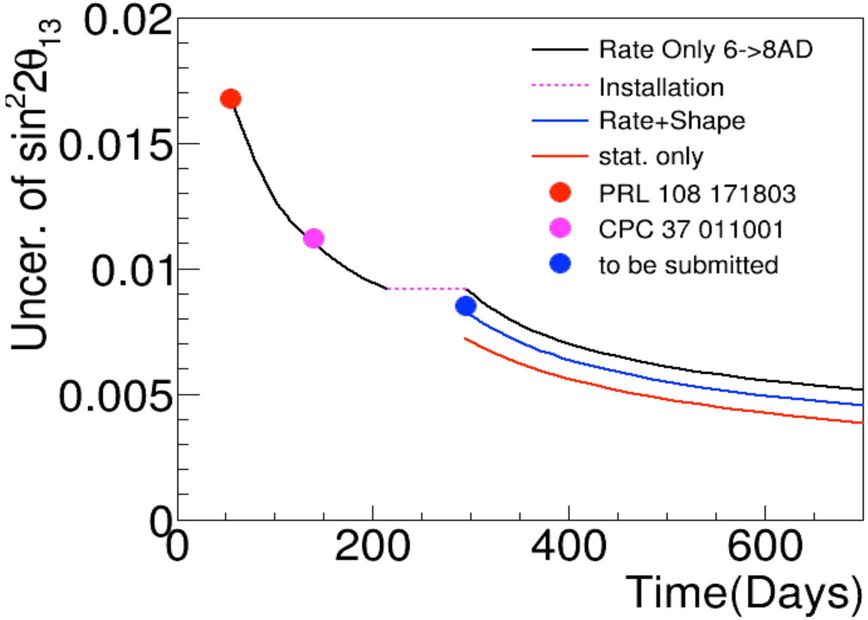
A Precision Measurement of θ13



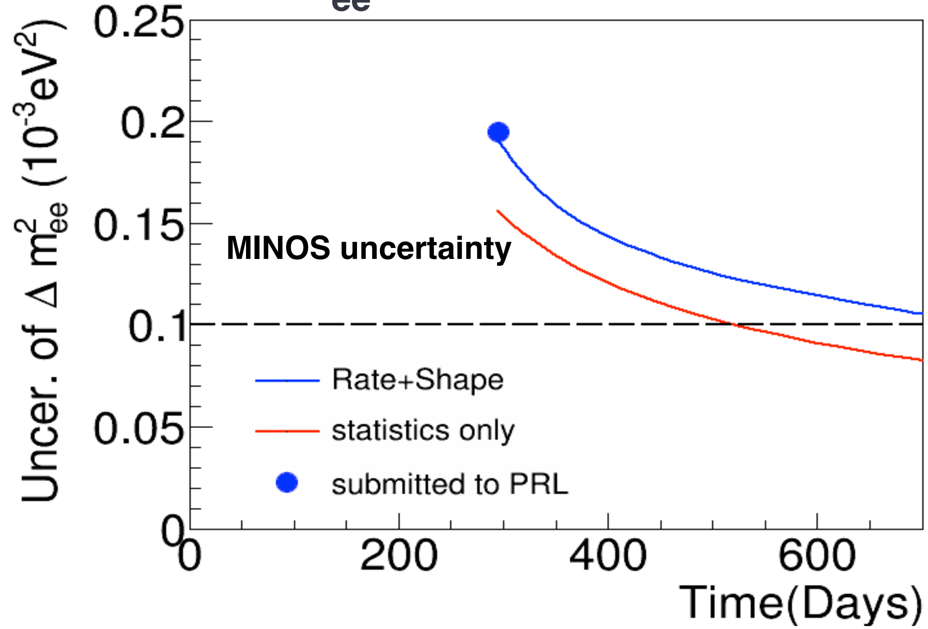
Daya Bay Sensitivity Projections

Precision Measurements in $\sin^2 2\theta_{13}$ and Δm^2_{ee}

$\sin^2 2\theta_{13}$



Δm^2_{ee}



Daya Bay remains statistically limited through 2015. Will also improve systematics.

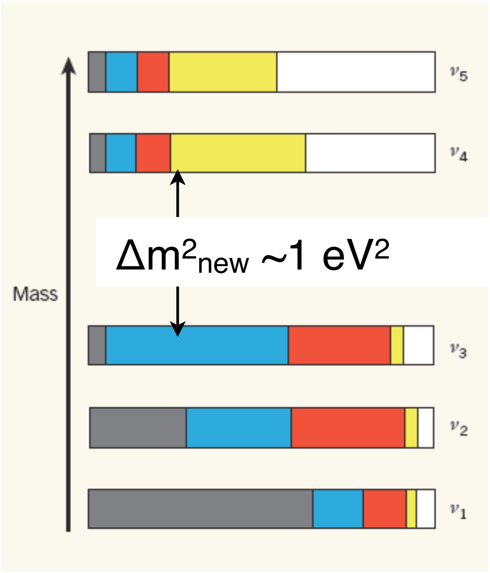
Major systematics:

θ_{13}: Relative + absolute energy, and relative efficiencies

$|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds

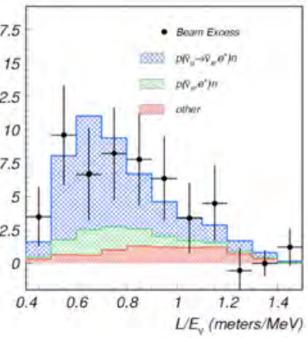
Aim to improve precision of $\sin^2 2\theta_{13}$ and Δm^2_{ee} to 3% by 2017.

Beyond 3 Neutrinos?

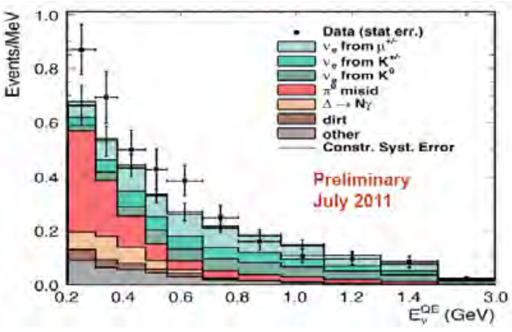


Neutrino Anomalies - More than 3 ν?

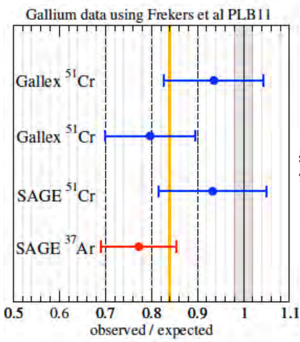
LSND



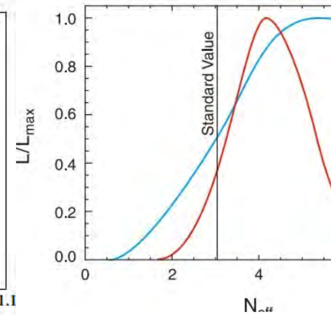
MiniBoone



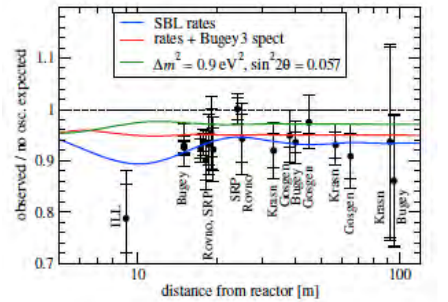
Ga Source



Cosmology (WMAP)



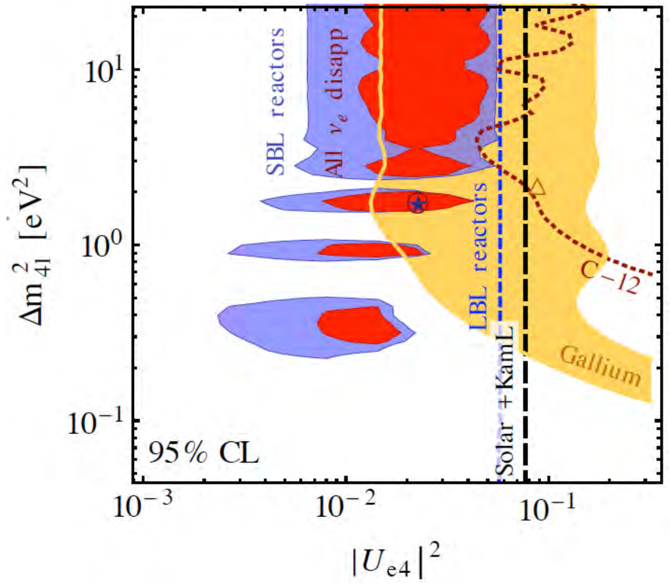
Reactor



Anomalies in 3-ν global oscillation data

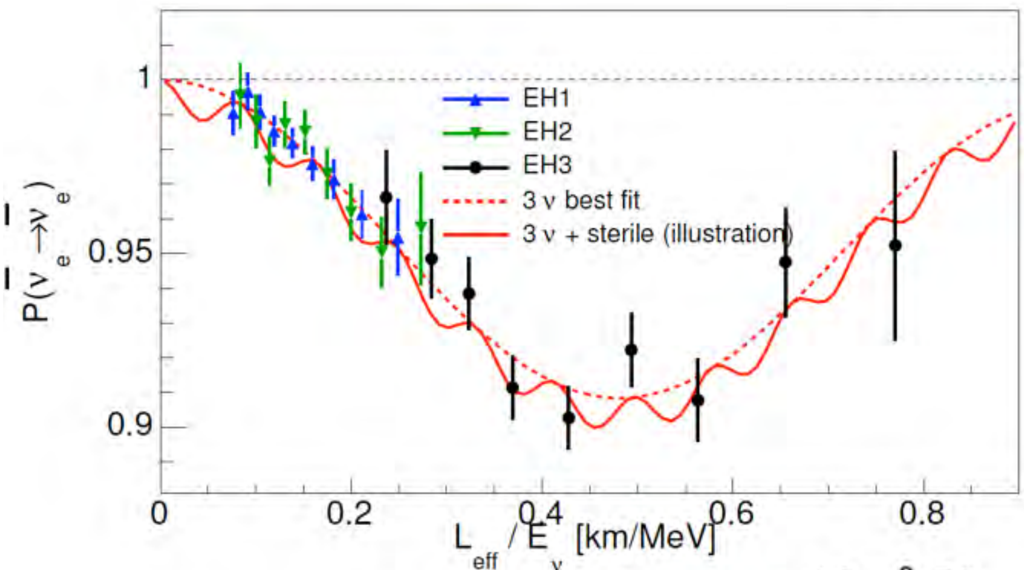
LSND ($\overline{\nu}_e$ appearance)
MiniBoone (ν_e appearance)
Ga anomaly
N_{eff} in cosmology
Reactor anomaly and spectral feature ($\overline{\nu}_e$ disappearance)

new oscillation signal requires:
$\Delta m^2 \sim O(1eV^2)$ and $\sin^2 2\theta > 10^{-3}$



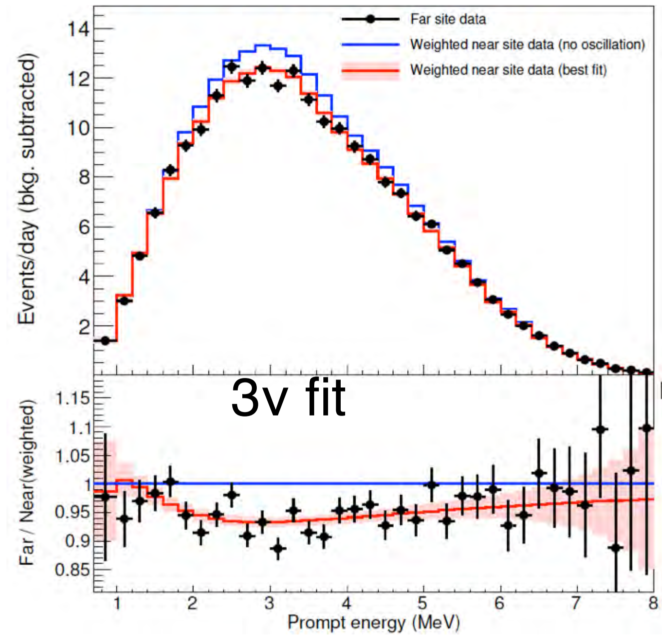
Understanding reactor flux and spectrum anomalies requires reactor measurements

Search for Sterile Neutrinos at Daya Bay



$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

look for additional spectral distortions and rate deficit



expand to 3+1ν fit

sterile neutrinos would appear as additional spectral distortion and overall rate deficit

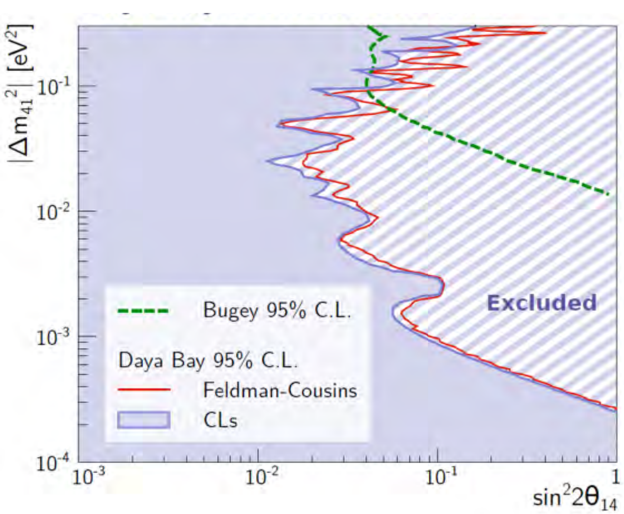
relative rate+shape comparison
- independent of reactor model, loss of sensitivity at high Δm^2

Probe largely unexplored region at $\Delta m^2_{41} < 0.1$ eV^2

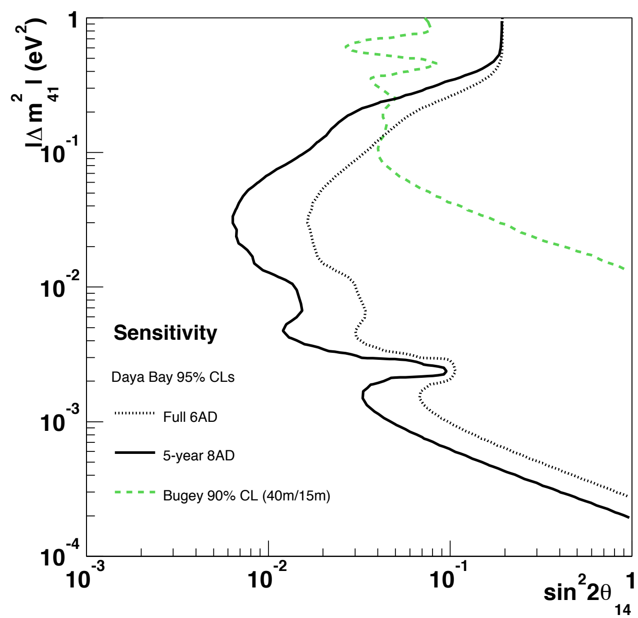
Daya Bay Sterile ν Results

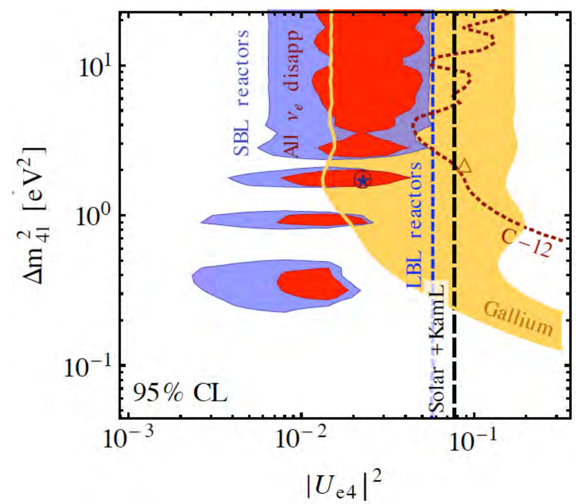
Daya Bay sets new limits in region of $\Delta m^2_{41} < 0.1$ eV^2
Daya Bay consistent with standard 3-flavor neutrino model

Recent Results
6 detectors



Future Sensitivity
8 detectors



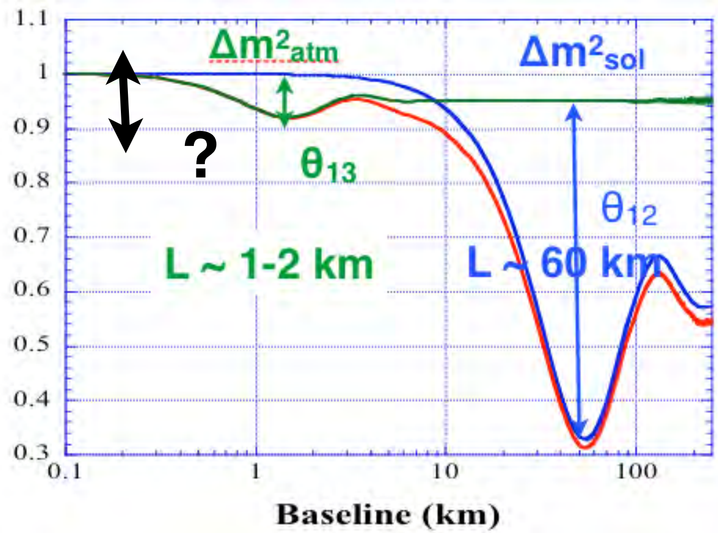


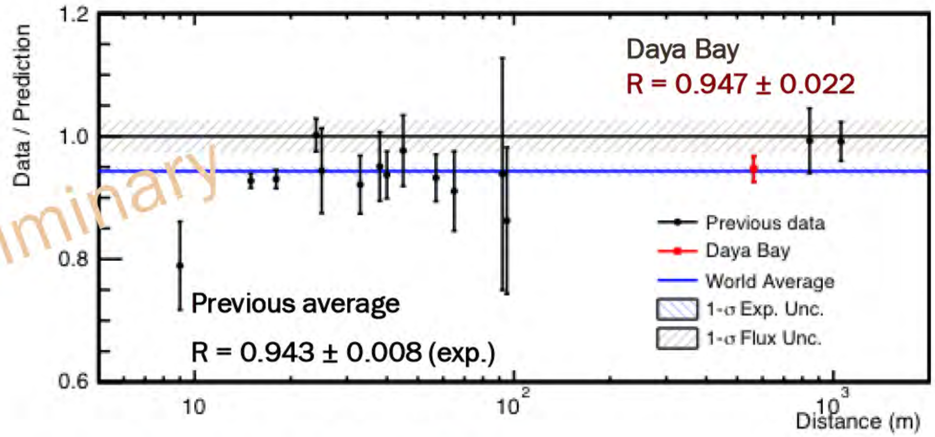
best fit regions

Current results are limited by statistics. Expect improvement with the full 5-year data set.

Measurement of Absolute Reactor $\bar{\nu}$ Flux

Do we understand the total number of $\bar{\nu}$ from a reactor?





Effective baseline of Daya Bay: L_{eff} = 573m

- Flux weighted detector-reactor distances of 3 ADs in near sites only.

Effective fission fractions α_k of Daya Bay ^{235}U: ^{238}U: ^{239}Pu: ^{241}Pu = 0.586: 0.076: 0.288: 0.050

- Mean fission fractions from 3 ADs in near sites only.

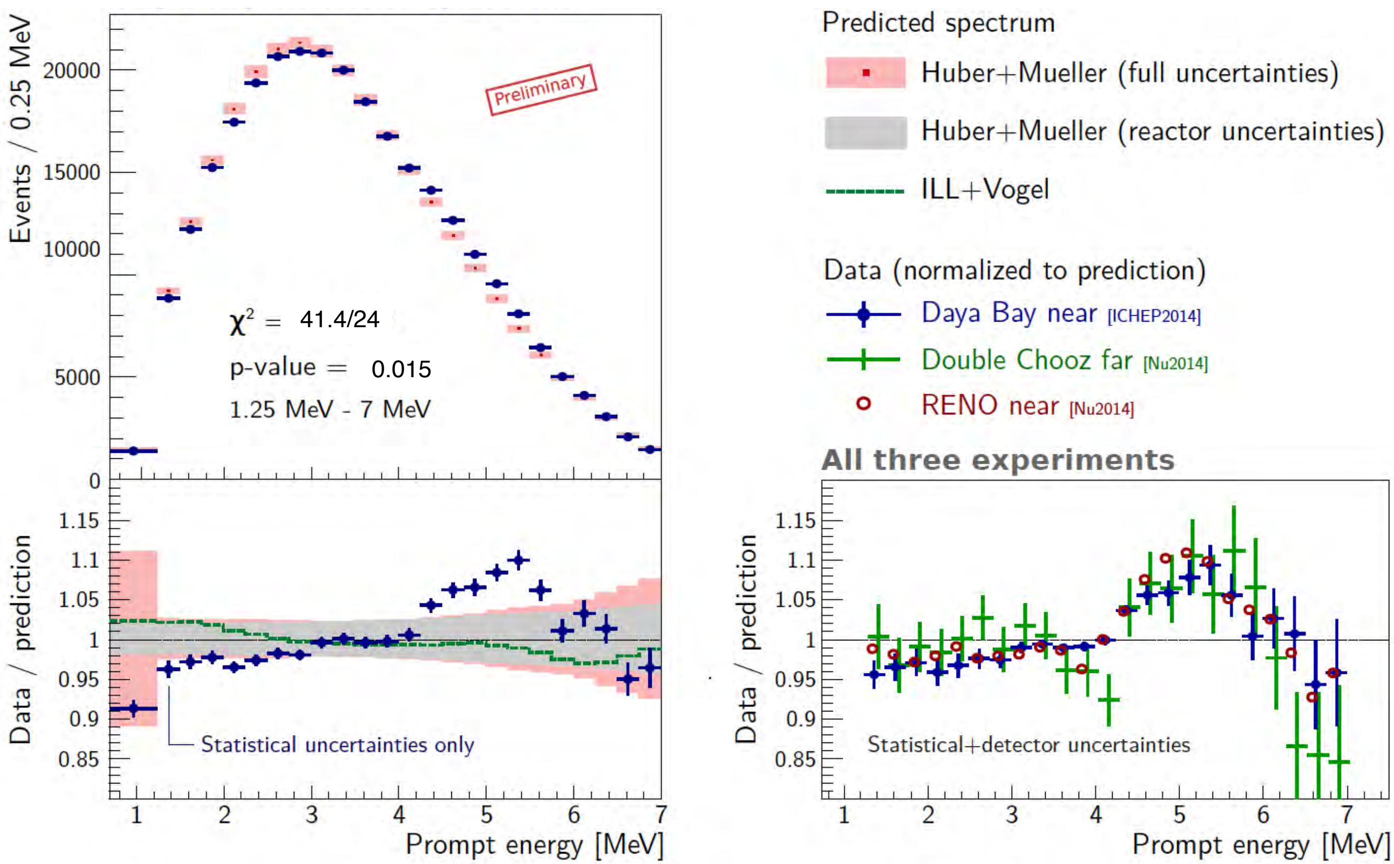
Results based on 3 near site Antineutrino Detectors (ADs)

Daya Bay reactor flux measurement consistent with previous results.

Reactor $\bar{\nu}$ Spectrum

New Feature in 4-6 MeV Region of Spectrum

Spectral feature seen by Daya Bay, Double Chooz, and Reno



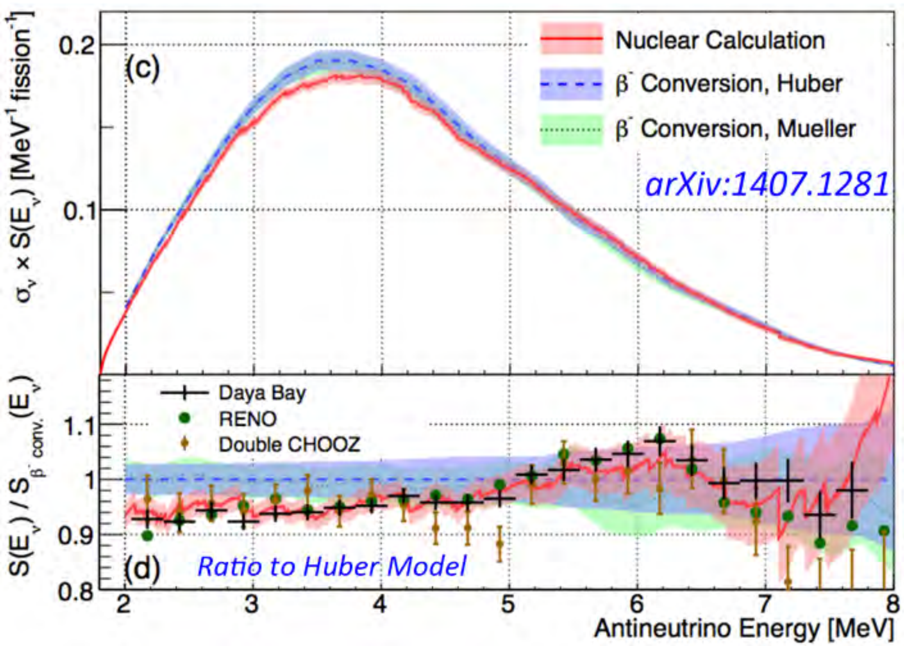
Excess events around 5 MeV reactor power correlated & time independent, match IBD events

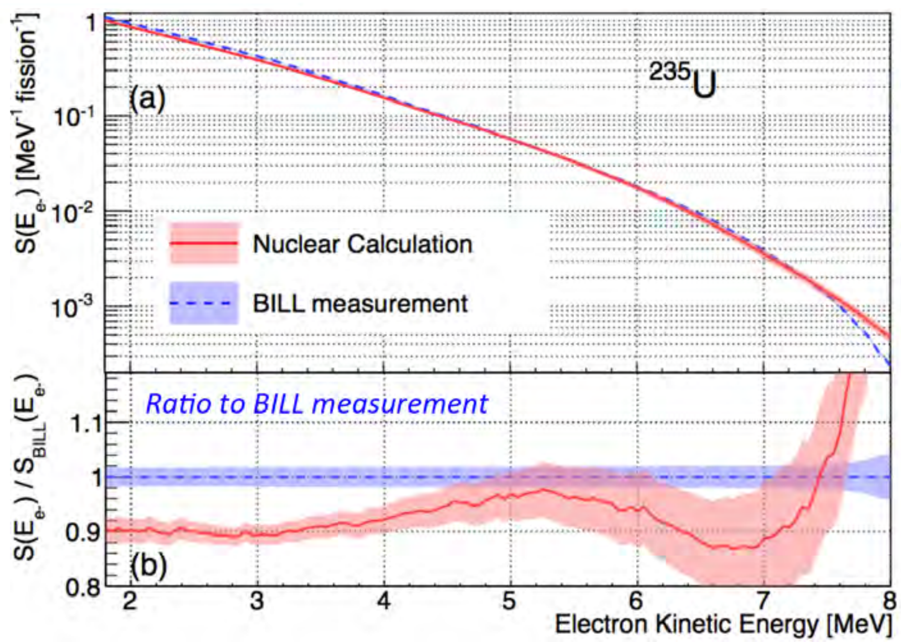
Discrepancy ~2σ over entire energy range, ~4σ locally

Predicting the Reactor Spectrum

Ab initio approach using nuclear databases of beta branches

Conversion approach of measured beta spectrum





Direct calculation appears to agree with preliminary measurements from recent reactor experiments

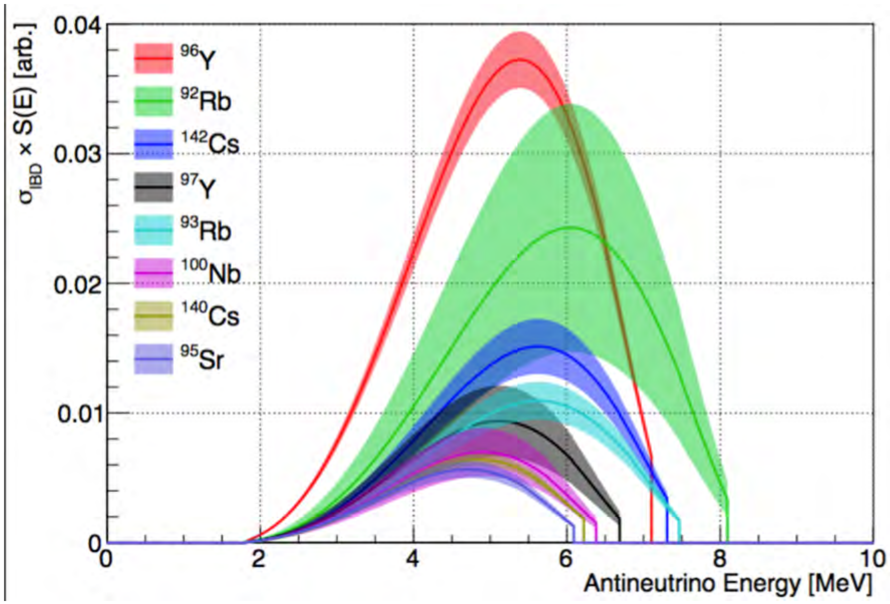
Direct calculation of ^{235}U β^- spectrum disagrees with BILL measurement

Experimental data needed to understand spectrum and constrain reactor models

From Dwyer, Langford arXiv:1407.1281

Predicting the Reactor Spectrum

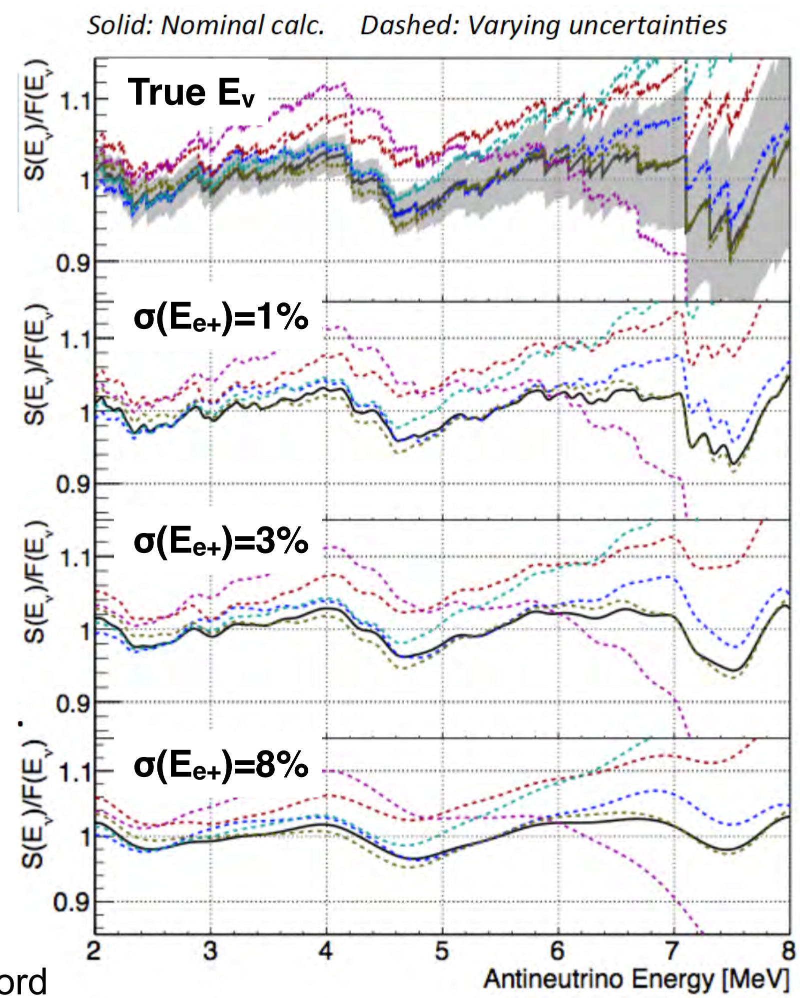
Eight Beta Branches dominate 5-7 MeV shape



High-energy $\bar{\nu}$ create edge. Identifies significant decay branch.

Need to improve energy resolution of current detectors (6-8%) to see details.

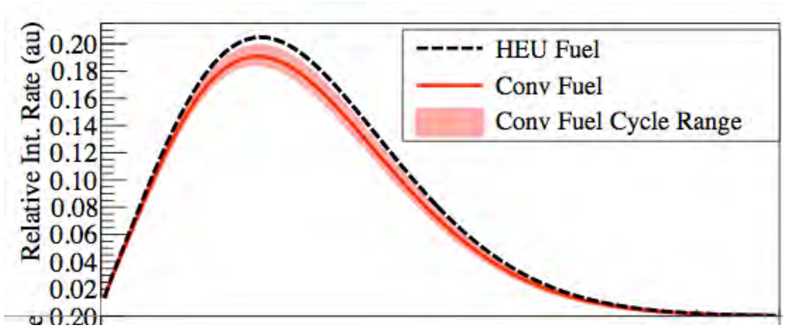
Calculations predict discontinuities in spectrum



From Dwyer, Langford

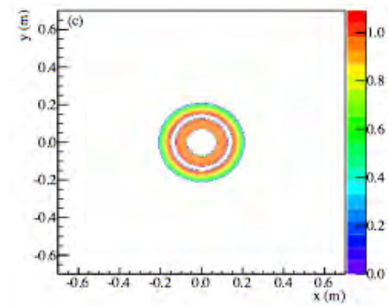
Reactor Experiments at Short Baselines

Measurement of Reactor Spectrum



HEU core provides static spectrum of mainly U-235.

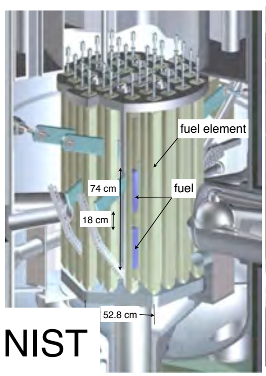
Short Distance (<10 m) From Point Source



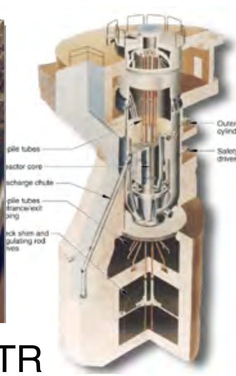
Compact core (< 1m) avoids oscillation washout

Precision study of the reactor spectra at short baselines

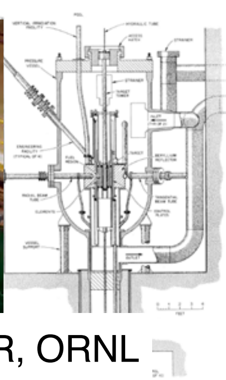
US operates high-powered research reactors



NBSR, NIST



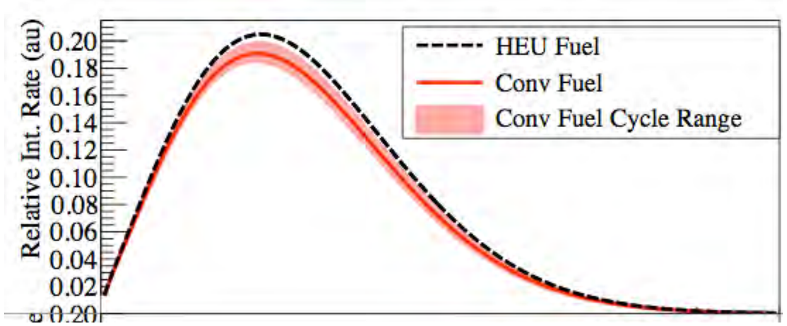
ATR



HFIR, ORNL

Reactor Experiments at Short Baselines

Measurement of Reactor Spectrum



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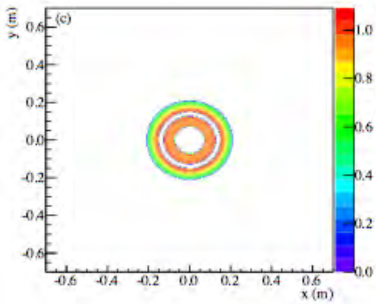
Short Distance (<10 m) From Point Source

commercial core



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Precision study of the reactor spectra at short baselines

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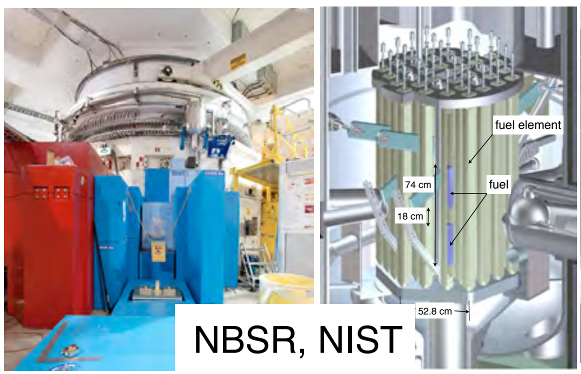
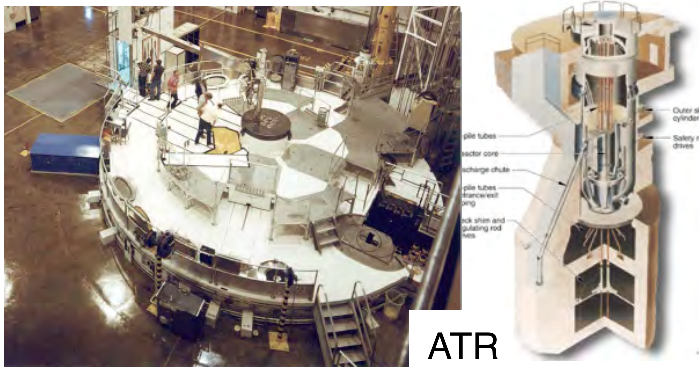
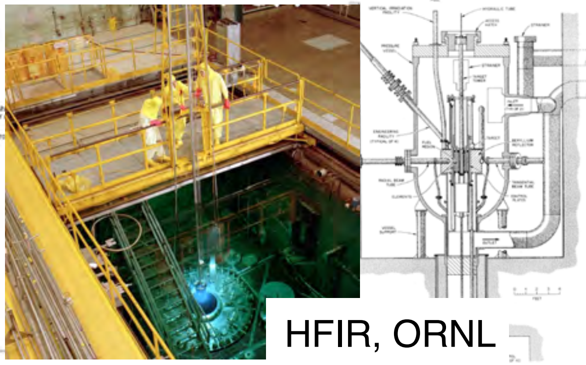


NBSR, NIST



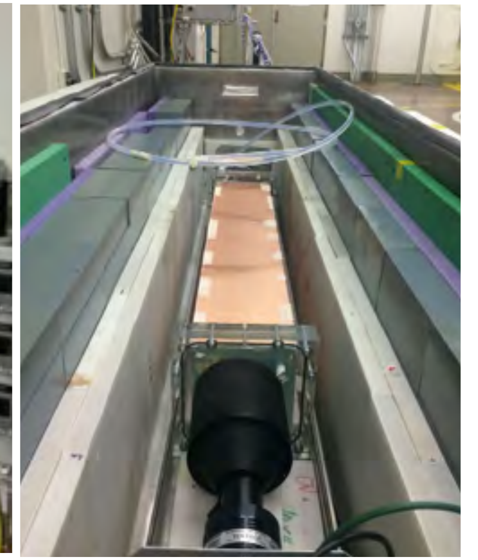
ATR

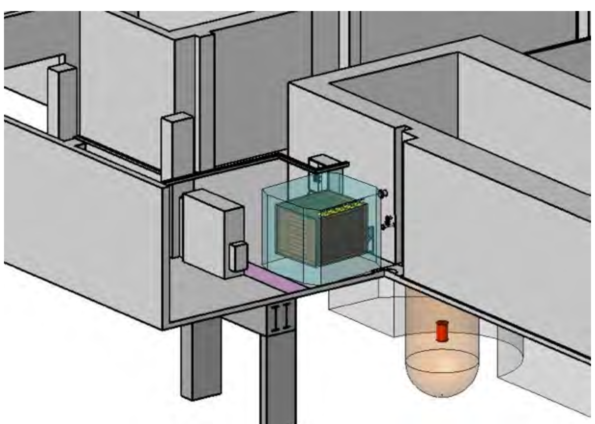


HFIR, ORNL

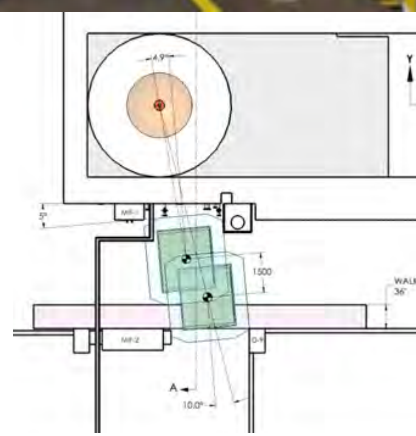
PROSPECT

A Precision Oscillation and Spectrum Experiment

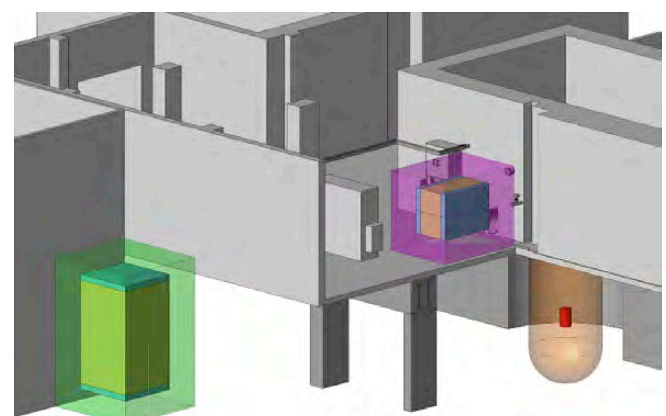




phase 1



phase 1+



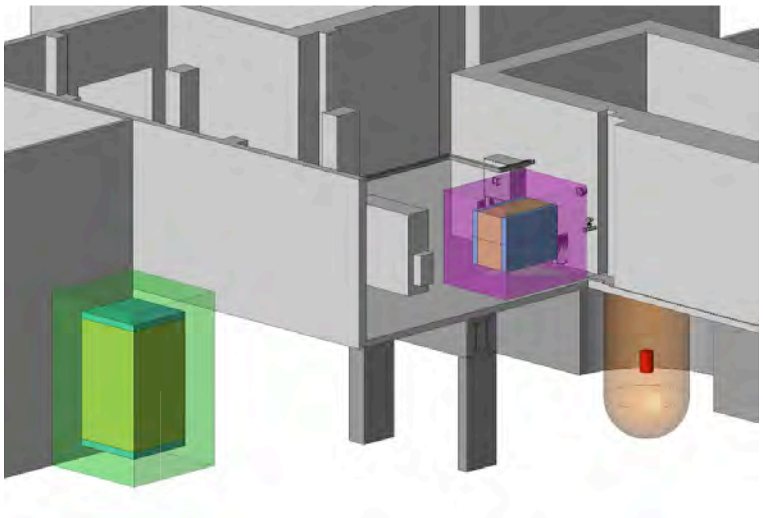
phase 2

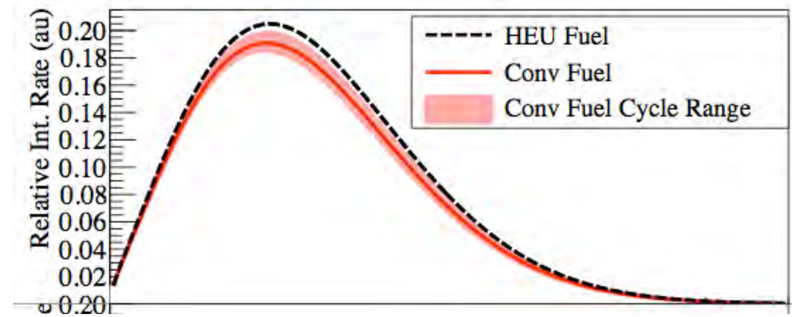
http://prospect.yale.edu
arXiv: 1309.7647

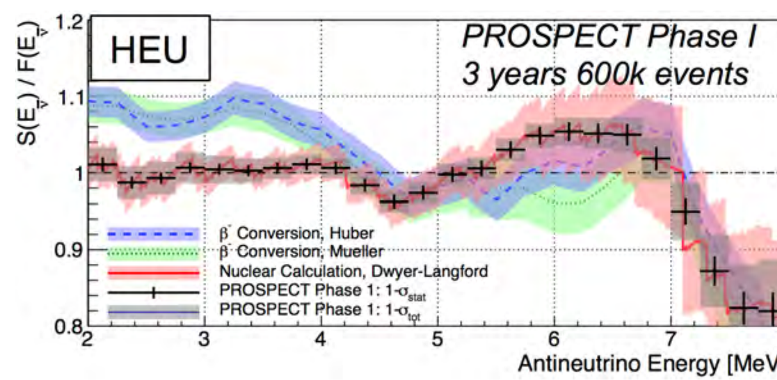
PROSPECT Physics

A Precision Oscillation and Spectrum Experiment

2 Detectors







Primary Physics Objectives

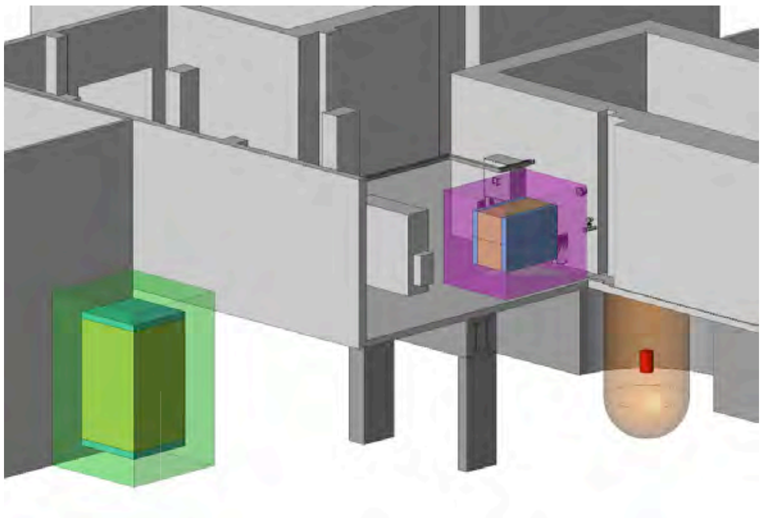
1. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards

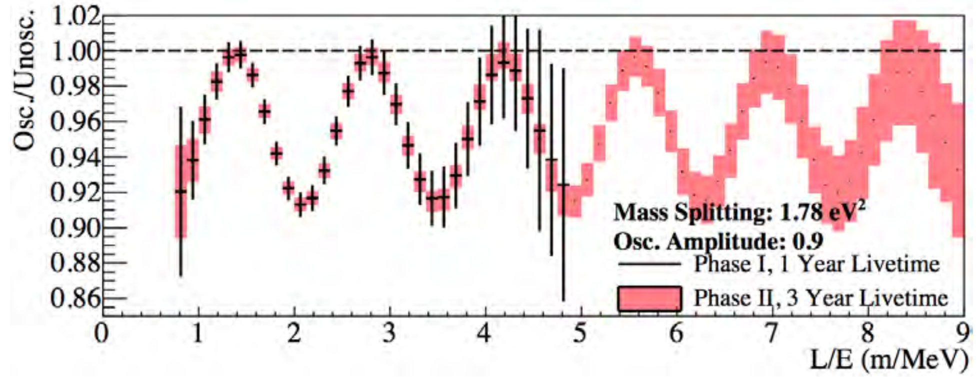
2. Search fort short-baseline oscillation within near detector and between near and far detector

PROSPECT Physics

A Precision Oscillation and Spectrum Experiment

2 Detectors





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1. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards

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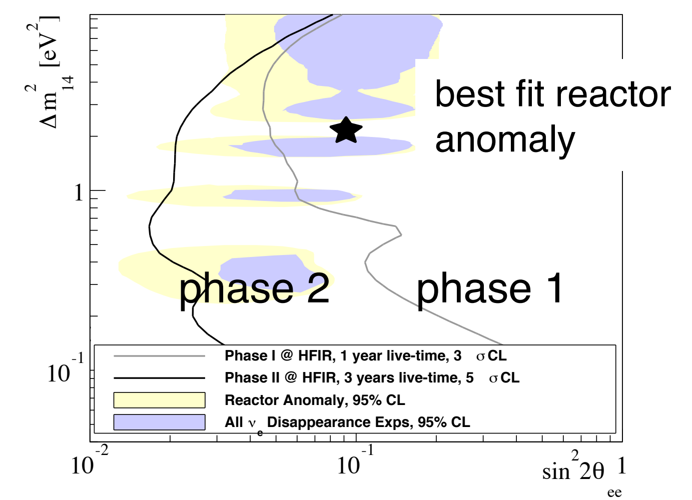
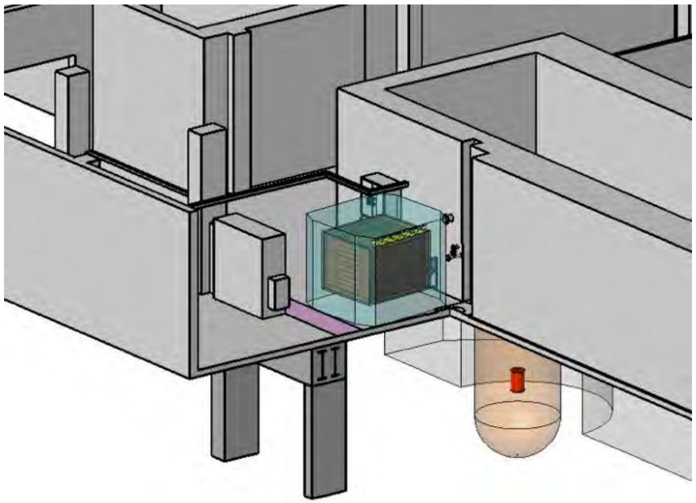
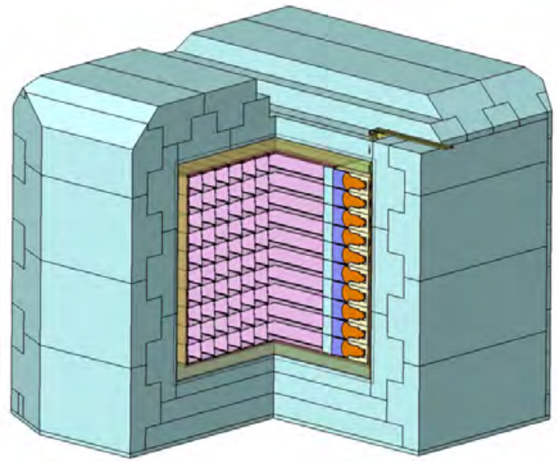


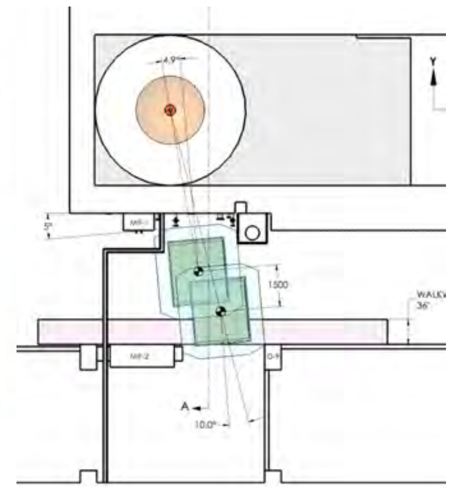
PROSPECT Concept

A Phased Approach

Near Detector - Phase I







Requirements
- detector close to reactor core
- measurement of spectrum as a function of distance
- high efficiency, uniform detector response

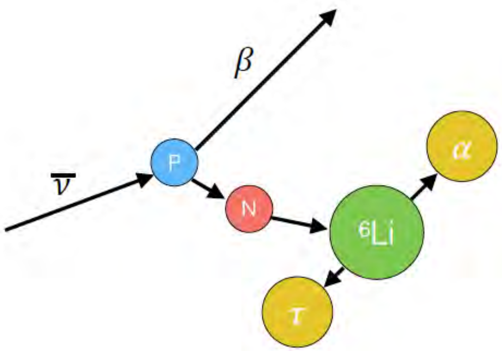
Systematic check by moving near detector by ~1/2 detector length

Concept
2.5 ton active volume of liquid scintillator
~150 optical segments, thin wall separation
double-ended readout

http://prospect.yale.edu
arXiv: 1309.7647

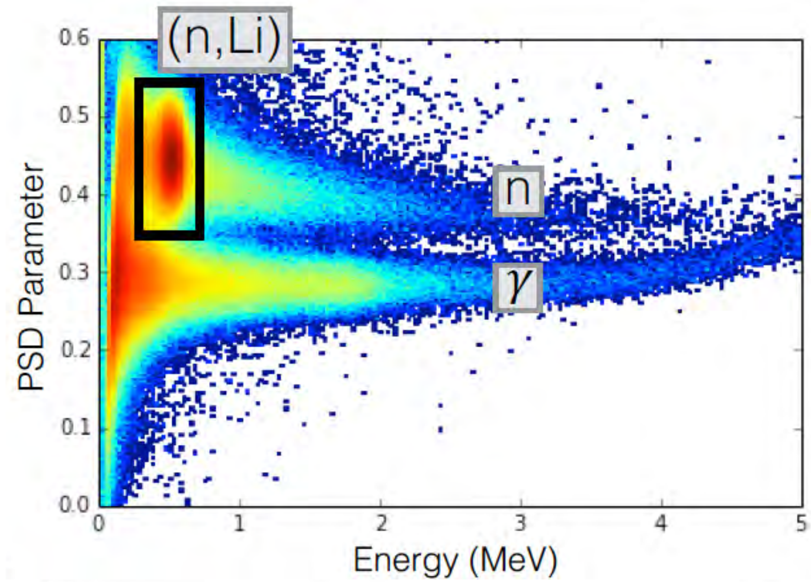
PROSPECT Event Detection

Event Identification



Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

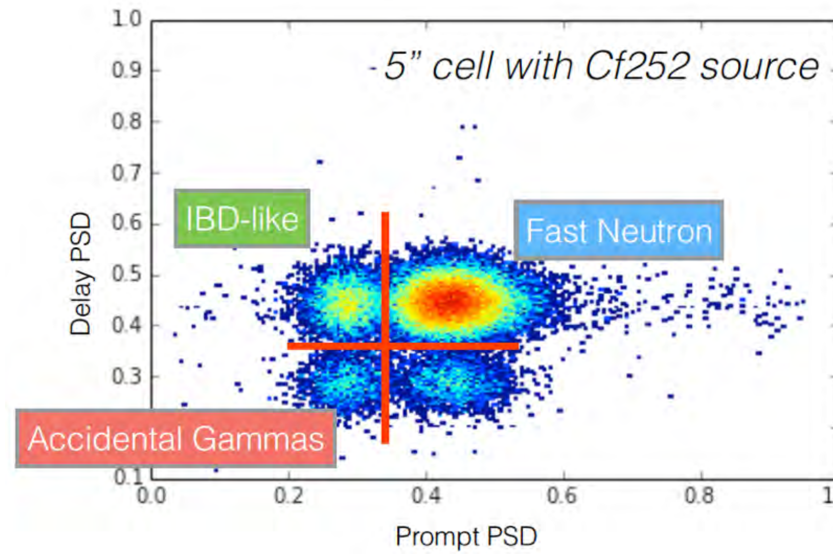
Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li



inverse beta decay
γ-like prompt, n-like delay

fast neutron
n-like prompt, n-like delay

accidental gamma
γ-like prompt, γ-like delay



Phased PROSPECT Detectors

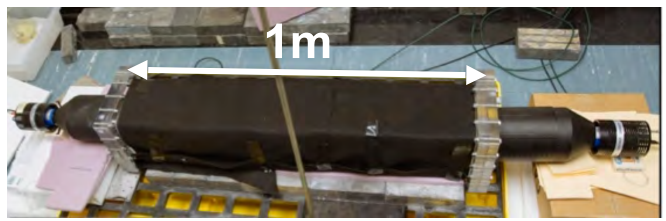
PROSPECT 0.1
Aug. 2014

5cm
0.1 liter
LS cell

PROSPECT 2
Dec. ‘14/Jan. ‘15

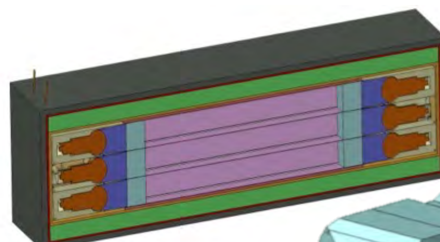
12.5cm
2 liter
LS cell

PROSPECT 20
Early 2015



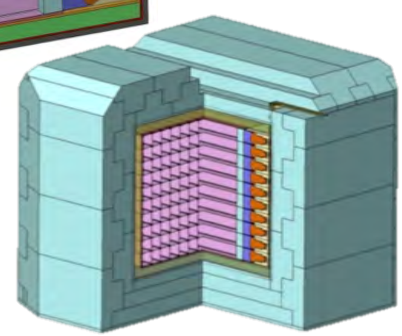
1m
20 liter
LS cell

PROSPECT N×20
Summer 2015*



N×20 liter
LS segments

PROSPECT 2ton
Summer 2016*

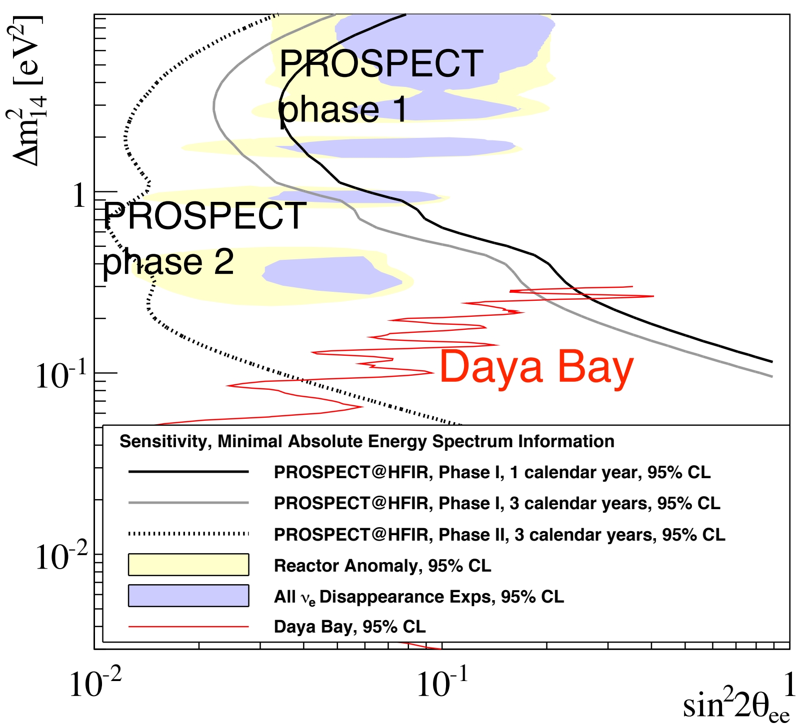


*** Technically driven schedule**

Worldwide Short-Baseline Reactor Experiments

Short-baseline reactor experiments
Variety of approaches worldwide to address experimental challenges (background rejection)

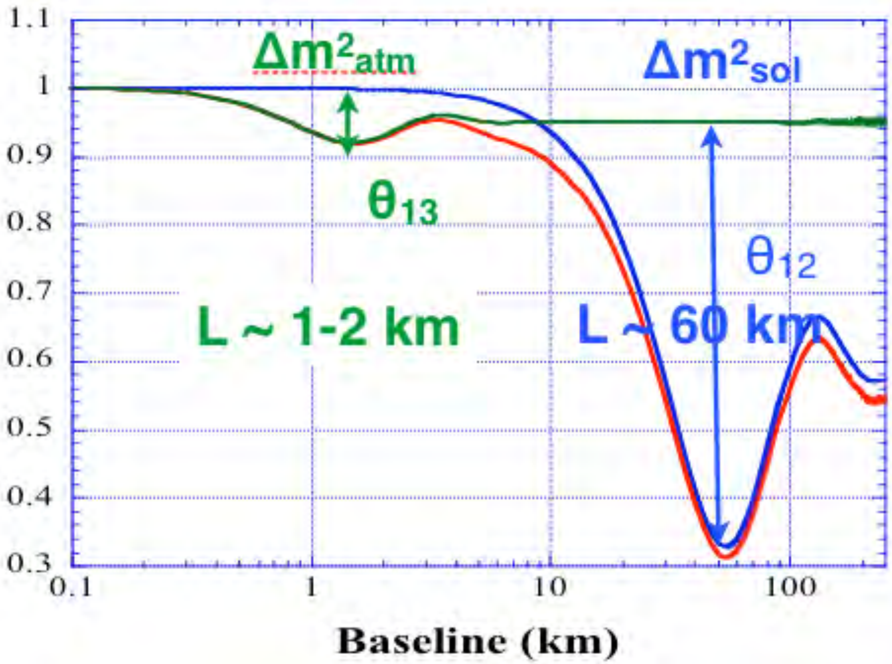
Project	Gd	6Li	10B	Segm.	Move Det.	2 Det.
Nucifer (FRA)	■			0		
Poseiden (RU)	■			1		
Stereo (FRA)	■			1	●	
Neutrino 4 (RU)	■			1	●	
Hanaro (KO)	■	■		2	●	●
DANSS (RU)	■			2	●	
PROSPECT (USA)		■		2	●	●
SoLid (UK)		■		3		
NuLat (USA)			■	3	●	



Physics Reach to 3+1 Oscillations
Short and intermediate reactor experiments (e.g. Daya Bay and PROSPECT) probe relevant parameter space

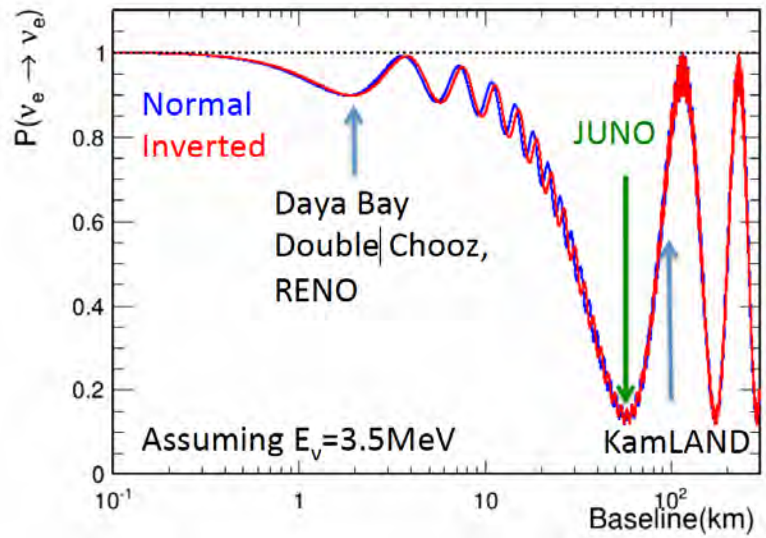
Mass Hierarchy and Reactor Neutrinos

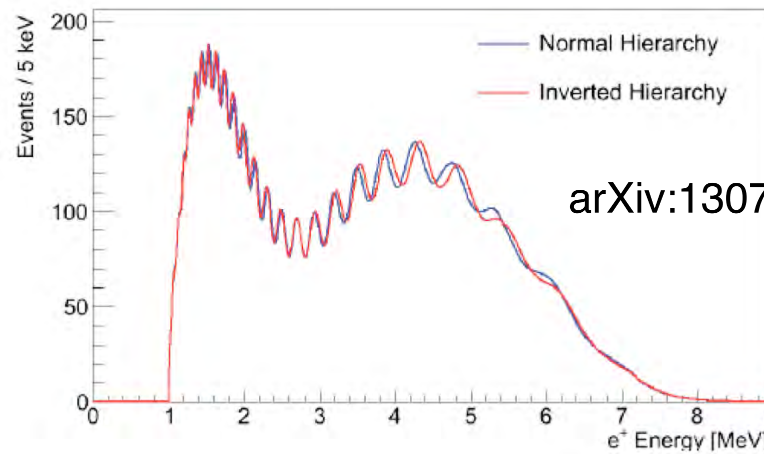
Precision Measurement at ~ 58km



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

$$-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$





arXiv:1307.5487

Δm^2_{21} is only 3% of $|\Delta m^2_{32}|$

mass hierarchy is contained in the spectrum independent of the unknown CP phase

Summary & Outlook

Reactor neutrinos are a tool for discovery.
Reactors are flavor pure sources of $\overline{\nu}_e$

Current reactor experiments **(L~1-2km)** provide precision data on θ_{13}, and **reactor antineutrino flux and spectra**. Daya Bay flux measurement is consistent with previous short-baseline measurements (~5% deficit). Positron spectrum appears inconsistent with current predictions in 4-6 MeV region.

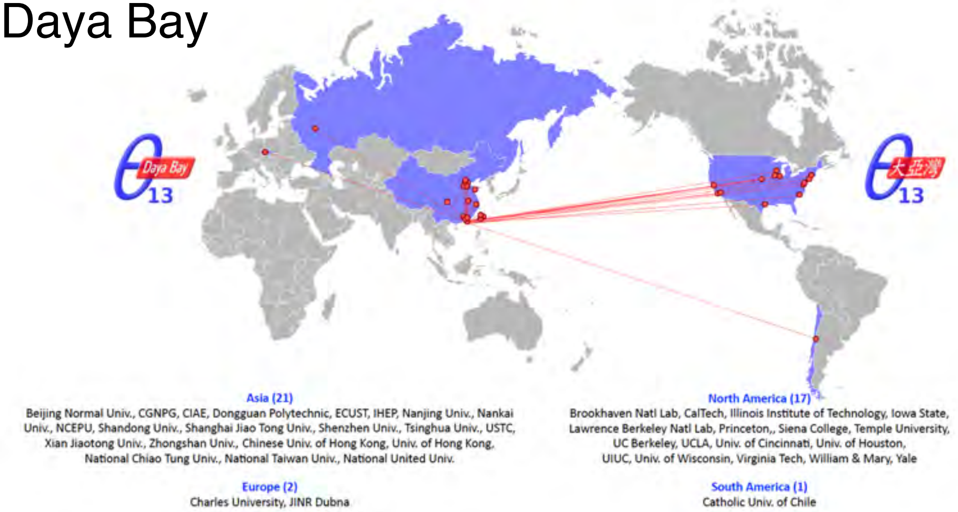
Short-baseline **(L~10m)** experiments (e.g. PROSPECT) offer opportunities for **precision studies of reactor spectrum** and a definitive search for **short-baseline oscillation** and **sterile neutrinos**.

Medium-baseline experiments **(L~60km)** (e.g JUNO, RENO-50) are technically demanding but may offer <1% **precision oscillation physics and a window to the mass hierarchy.**

Acknowledgements

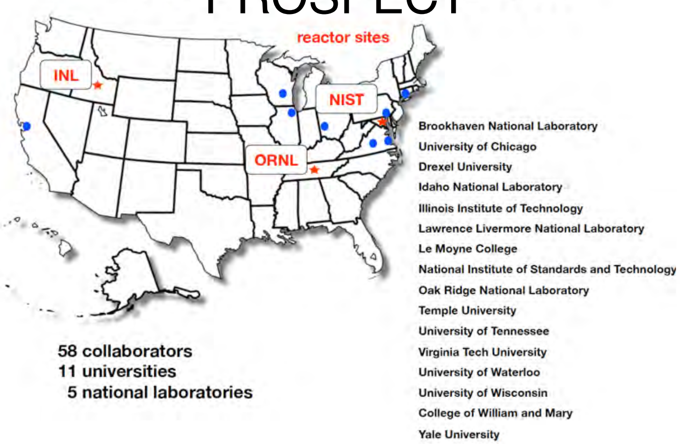
Thanks to Daya Bay, JUNO, and PROSPECT collaborators for materials

Daya Bay



JUNO Collaboration

PROSPECT



Similar results from Double Chooz and RENO collaborations.

Many new experimental ideas. Apologies for not being able to cover all experiments.