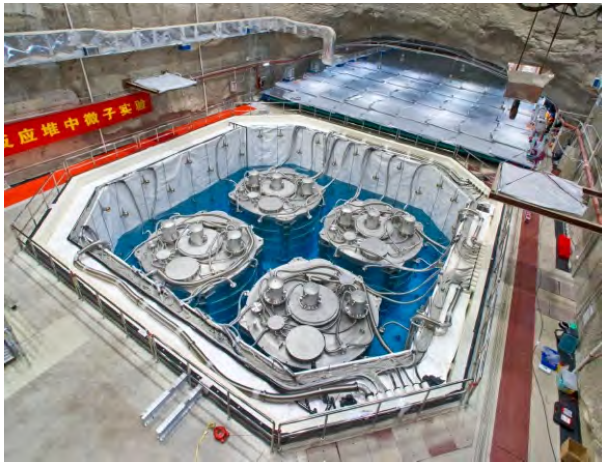
Reactor Neutrinos
Recent Results and Future Prospects

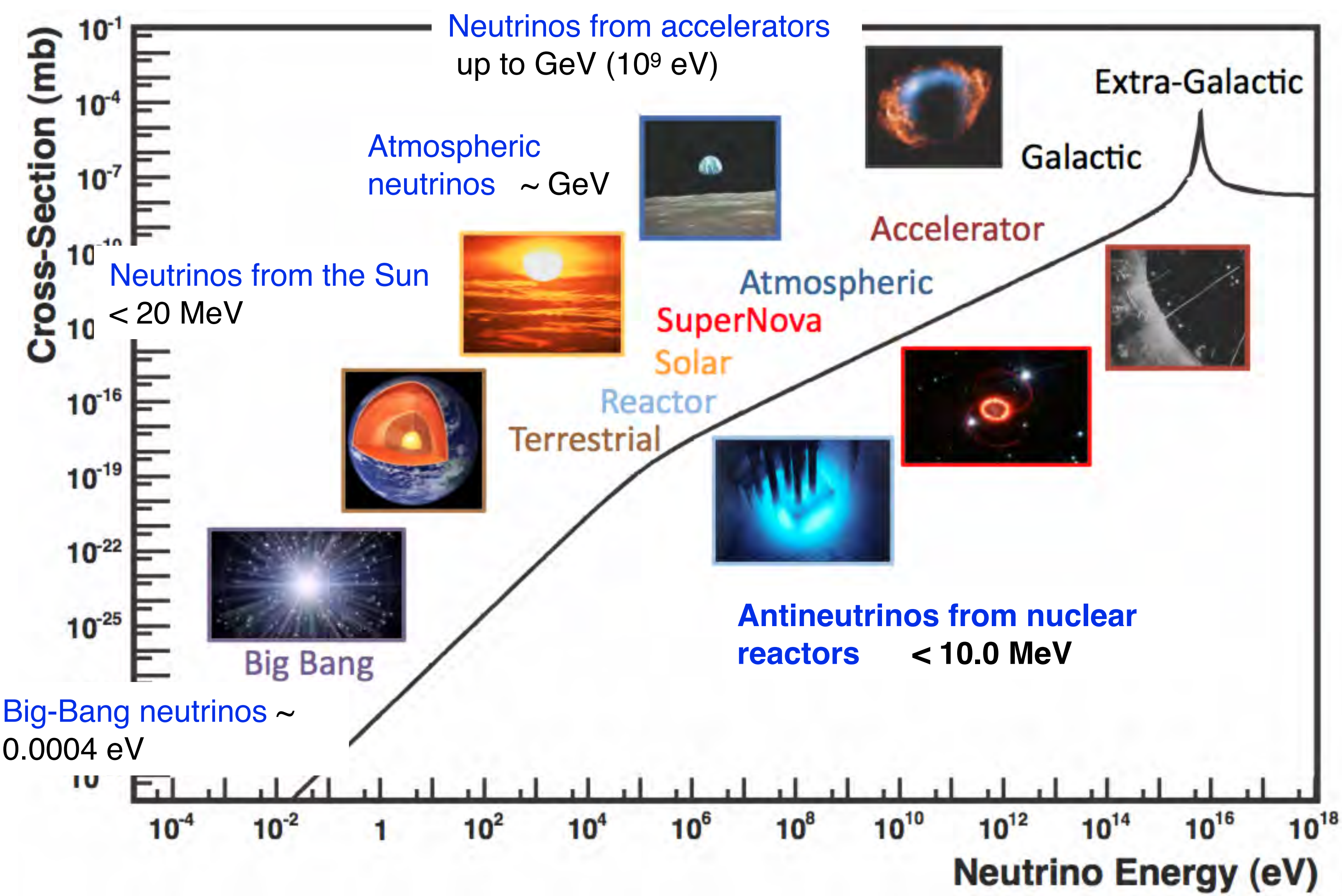
  

Karsten M. Heeger
Yale University

May 9, 2017

Yale Wright Laboratory

Neutrino Sources



Neutrinos from accelerators up to GeV (10^9 eV)

Atmospheric neutrinos ~ GeV

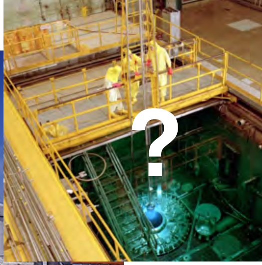
Neutrinos from the Sun < 20 MeV

Big-Bang neutrinos ~ 0.0004 eV

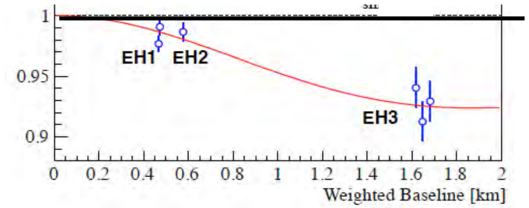
Antineutrinos from nuclear reactors **< 10.0 MeV**

Reactor Antineutrinos

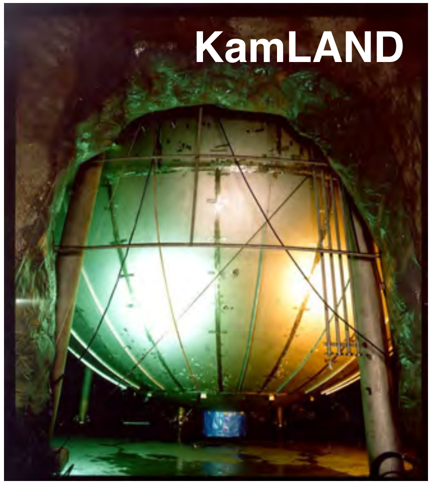
A Tool for Discovery

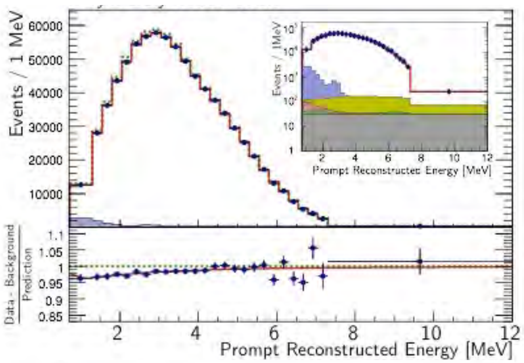


2012 - Measurement of θ_{13} with Reactor Neutrinos



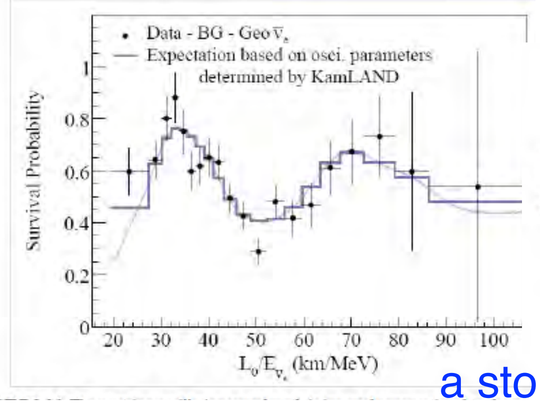
2003 - First observation of reactor antineutrino disappearance

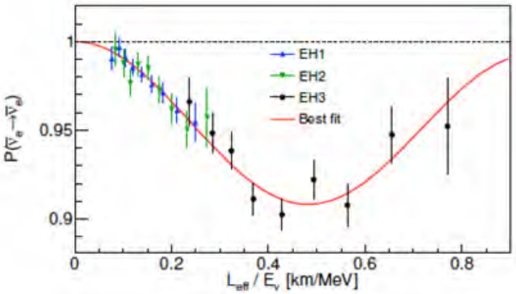




1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos



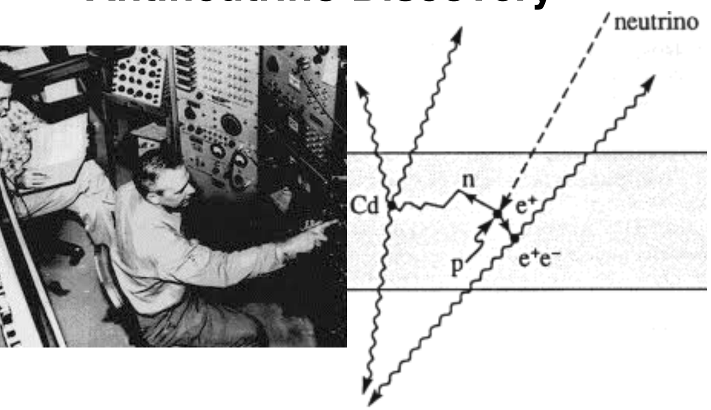


a story of varying baselines...

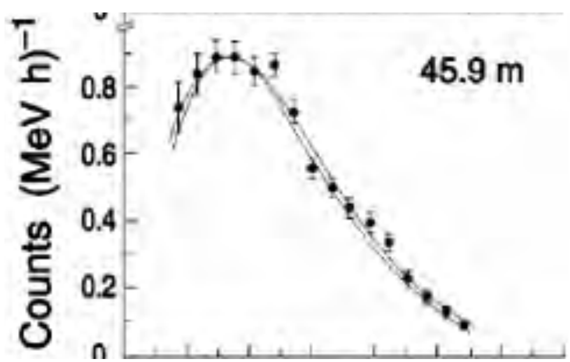
Physics with Reactor Antineutrinos

Discoveries and Precision Measurements of Neutrino Properties

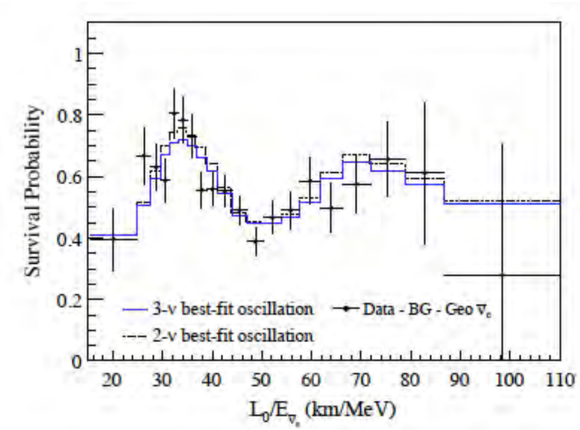
Antineutrino Discovery



Reactor $\overline{\nu}_e$ Spectra

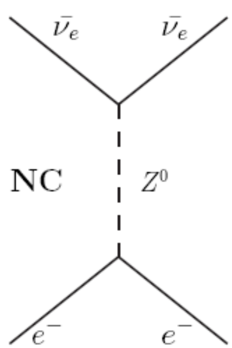


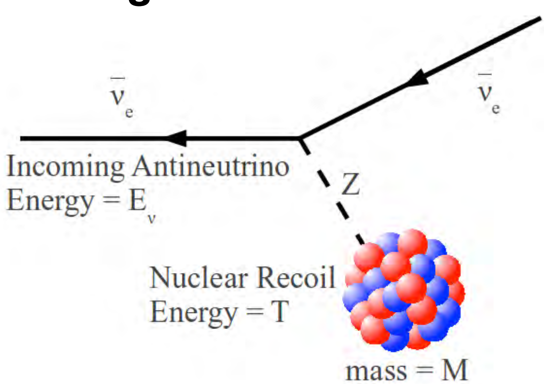
$\overline{\nu}_e$ Oscillation



Searches for New Physics

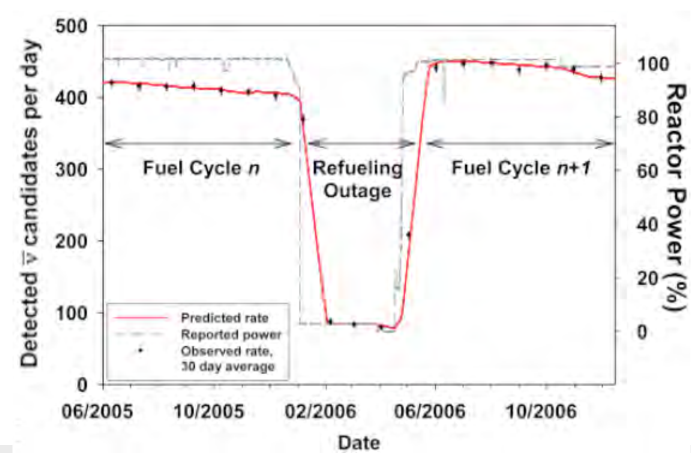
neutrino magnetic moment and **coherent scattering** searches





Reactor Monitoring and Application

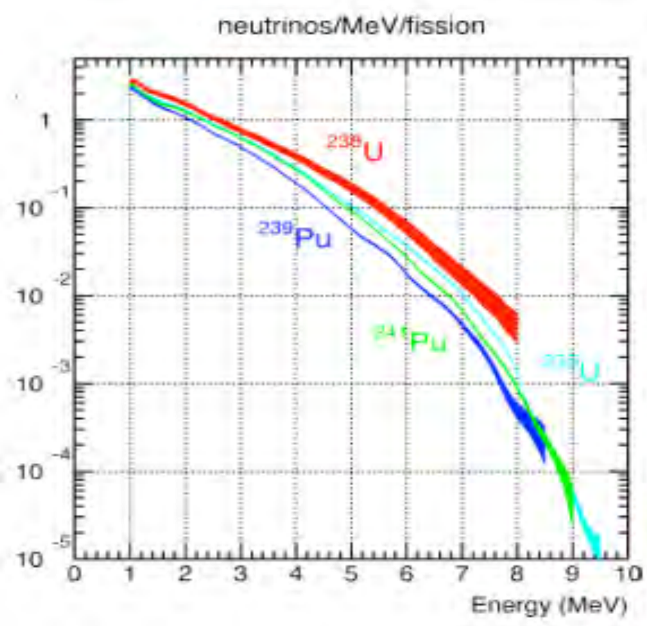
fuel burnup and isotopic composition

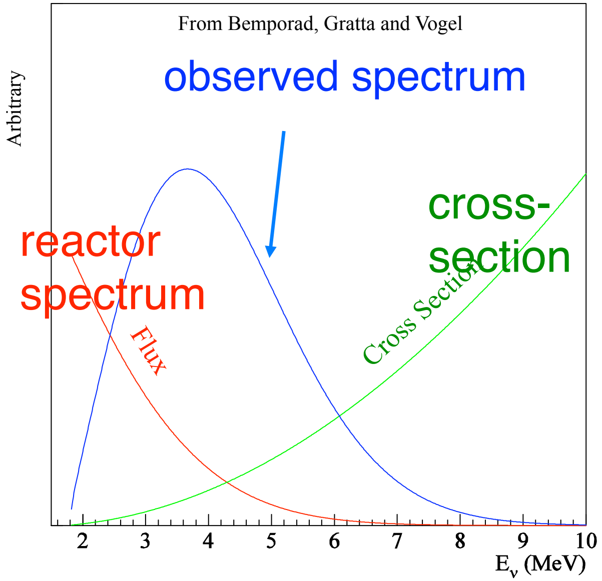


Reactor Antineutrinos

$\bar{\nu}_e$ 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

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

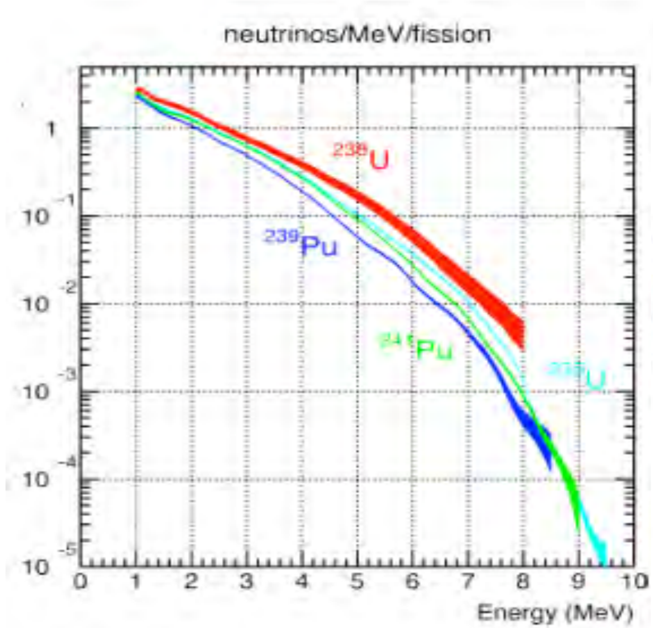
only disappearance experiments possible

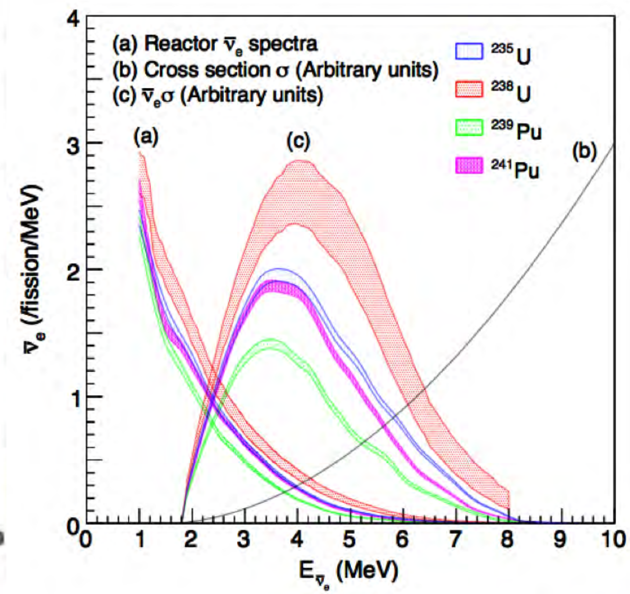
Reactor Antineutrinos

$\bar{\nu}_e$ 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

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

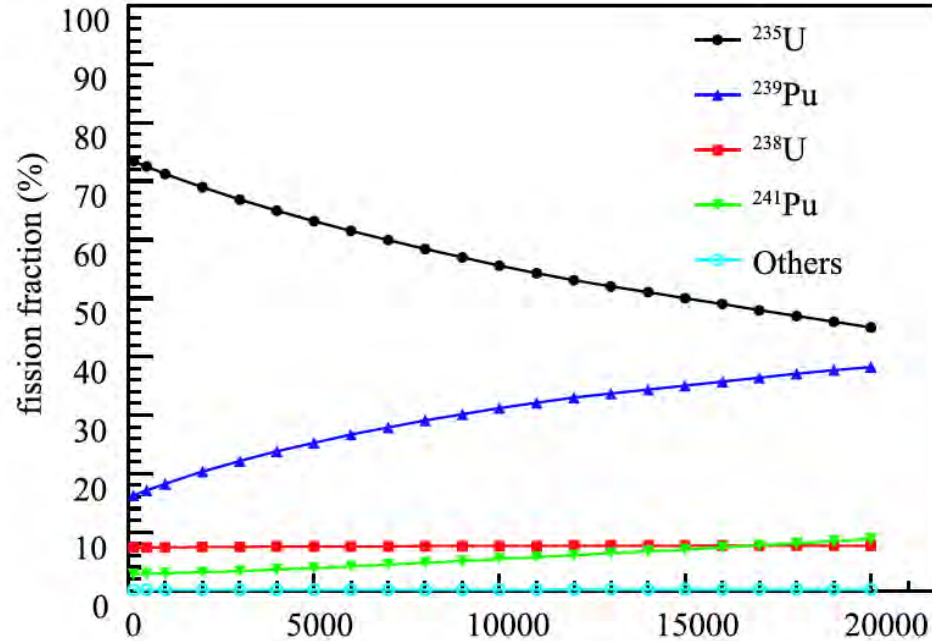
only disappearance experiments possible

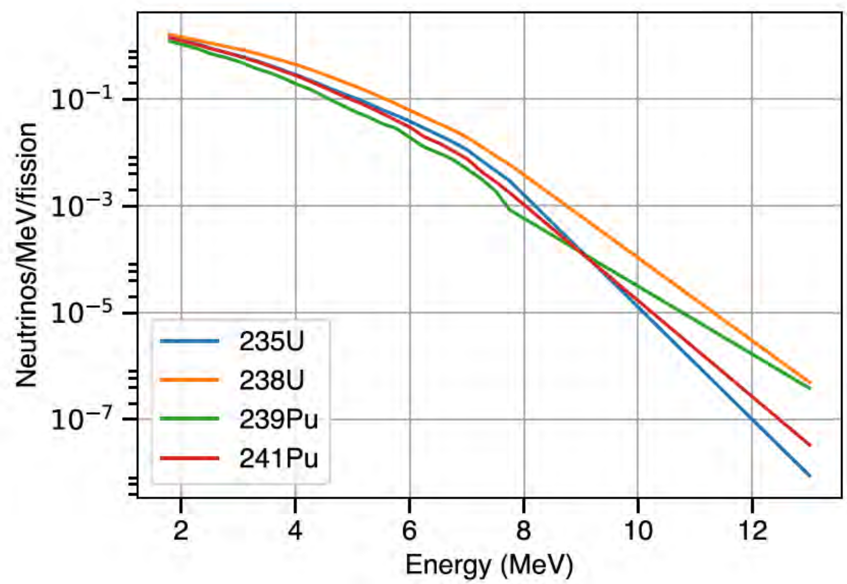
Reactor Antineutrinos

$\bar{\nu}_e$ from β-decays, pure $\bar{\nu}_e$ source
of n-rich fission products
on average ~6 beta decays until stable

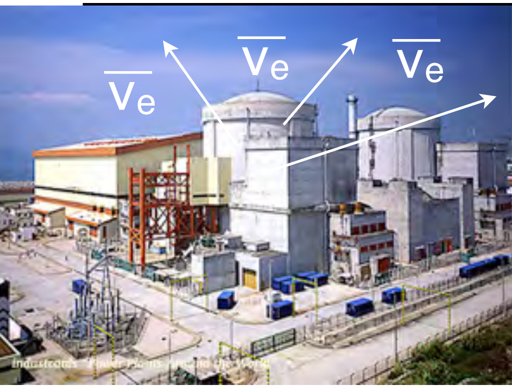
reactor flux and spectra can be determined using the fission fractions

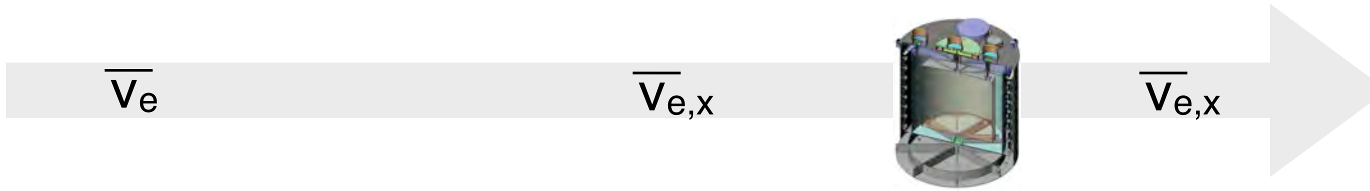
uranium isotopes have higher average energy and higher neutrino yield per fission





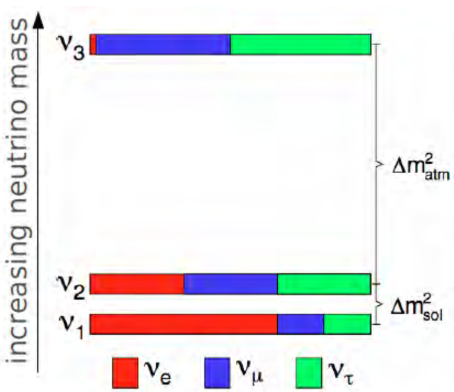
Reactor Neutrino Oscillation Experiments





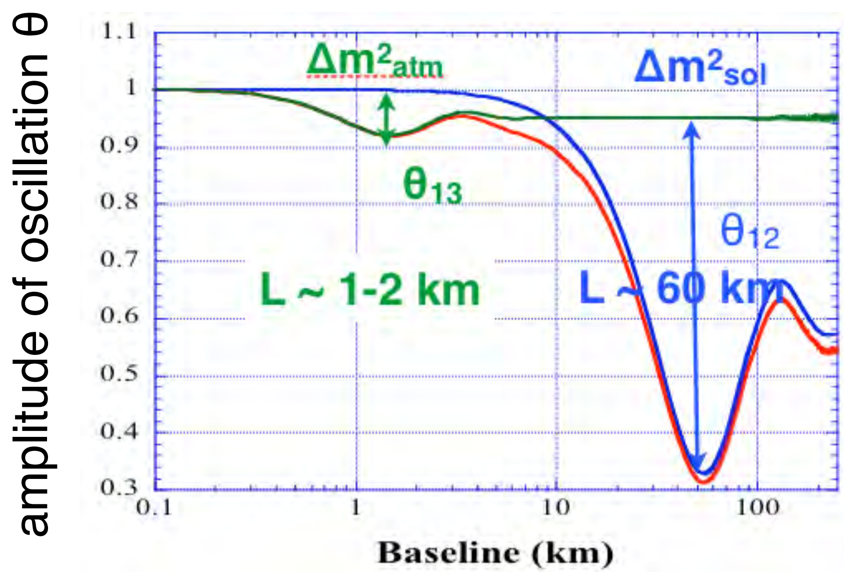
Measure (non)-$1/r^2$ behavior

for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



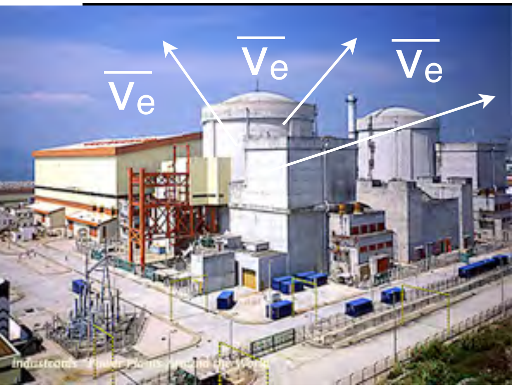
Δm^2_{23} = ~2.4×10^{-3} eV^2

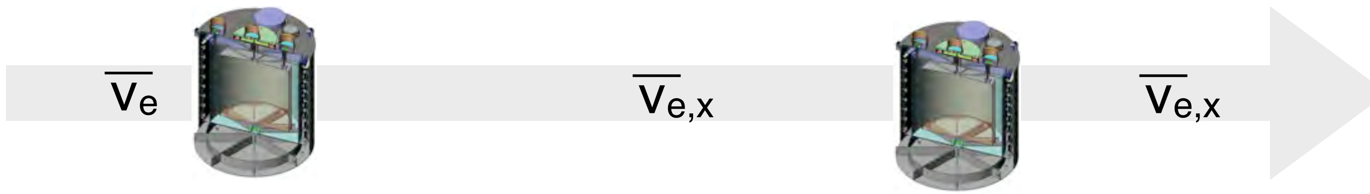
Δm^2_{12} = ~7.6×10^{-5} eV^2



oscillation frequency L/E → Δm^2

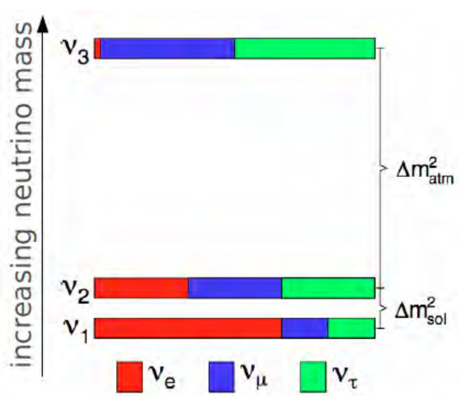
Reactor Neutrino Oscillation Experiments





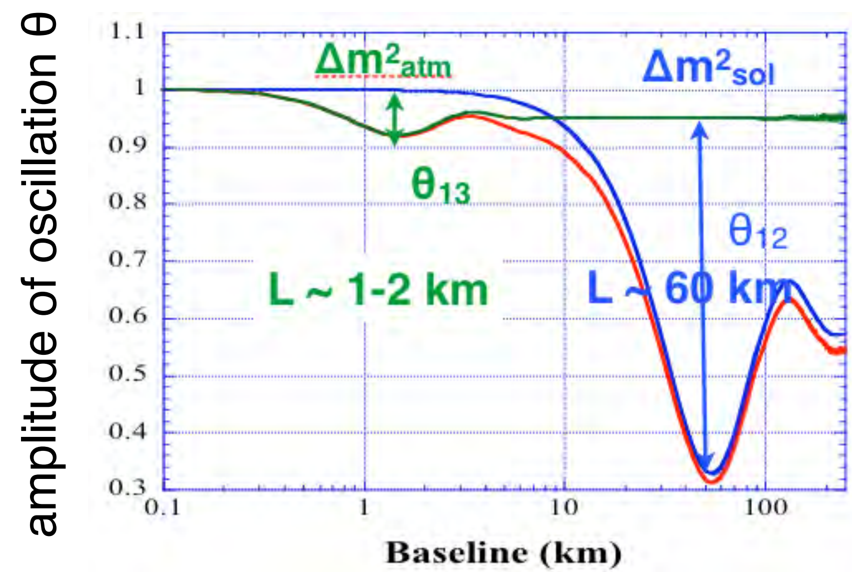
Measure (non)-1/r² behavior

for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



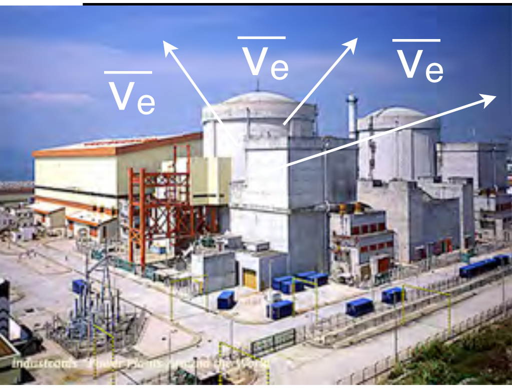
Δm^2_{23} = ~2.4 x 10^{-3} eV²

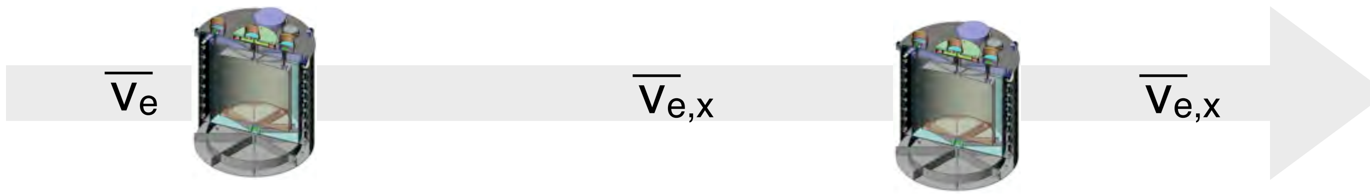
Δm^2_{12} = ~7.6 x 10^{-5} eV²



oscillation frequency L/E → Δm^2

Relative Measurement of $\bar{\nu}_e$ Flux and Spectrum

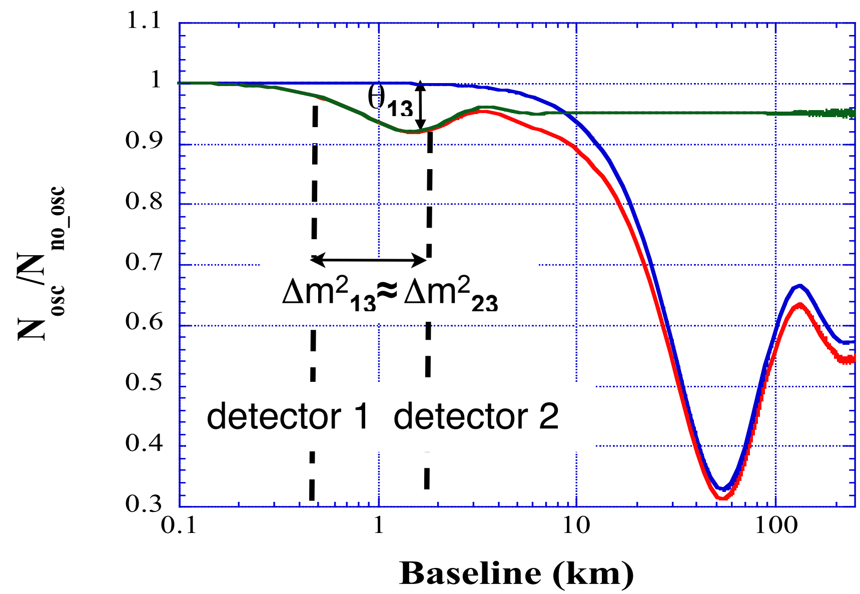




$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

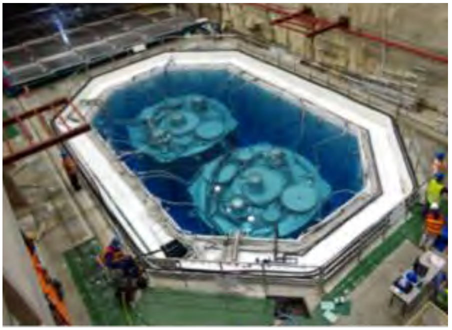
Absolute Reactor Flux
Largest uncertainty in previous measurements

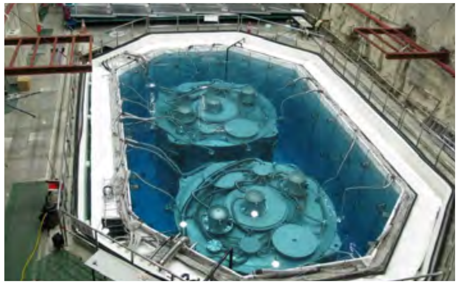
Relative Measurement
Removes absolute uncertainties!

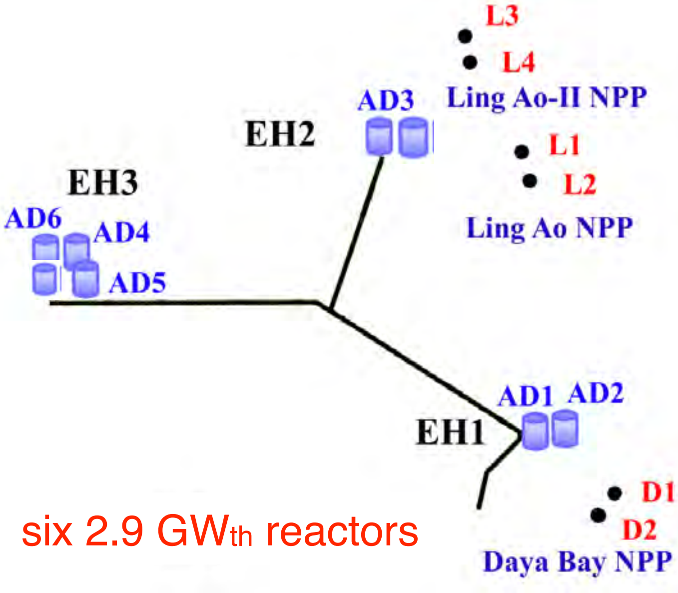


relative measurement (largely) cancels reactor systematics

Daya Bay Reactor Experiment

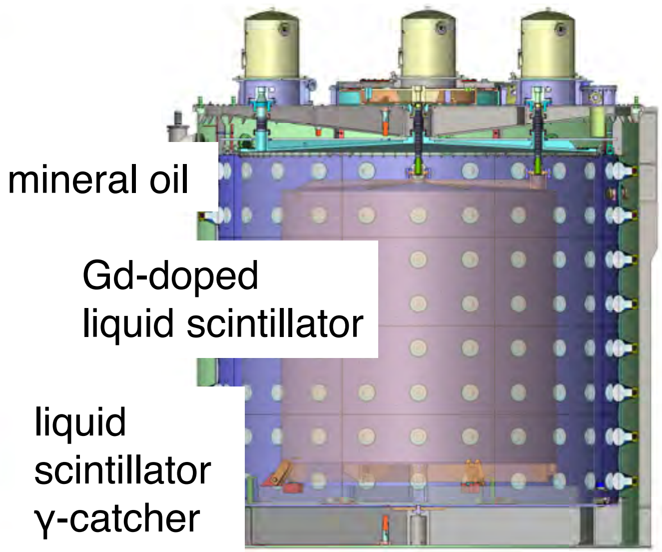






six 2.9 GW_{th} reactors

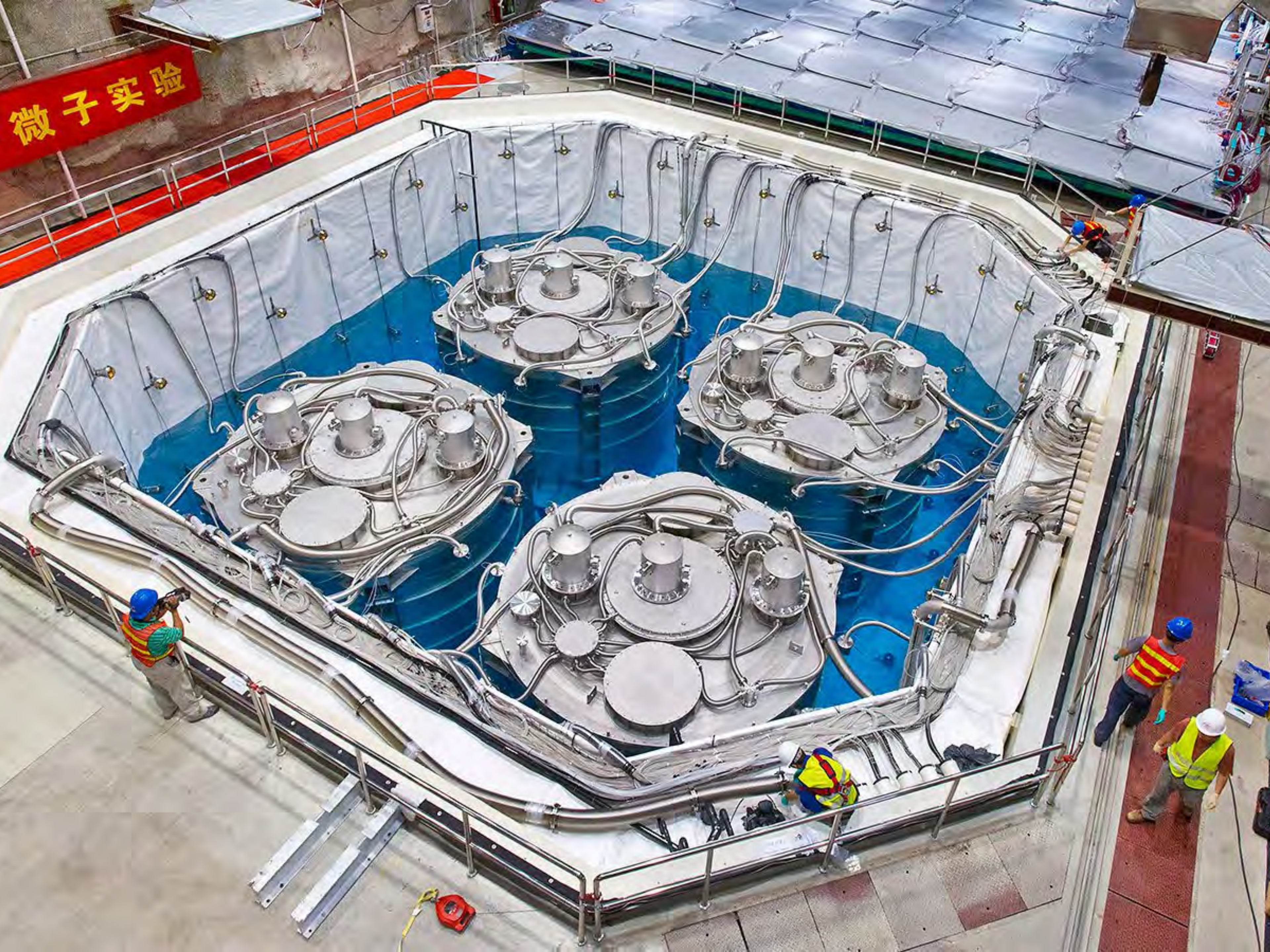
Antineutrino Detector



6 detectors, Dec 2011- Jul 2012

now running with 8 detectors

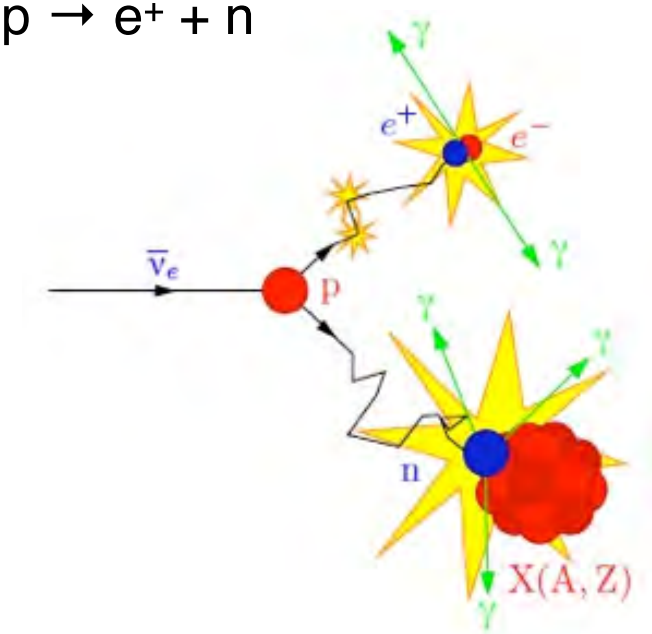
target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$


微子实验

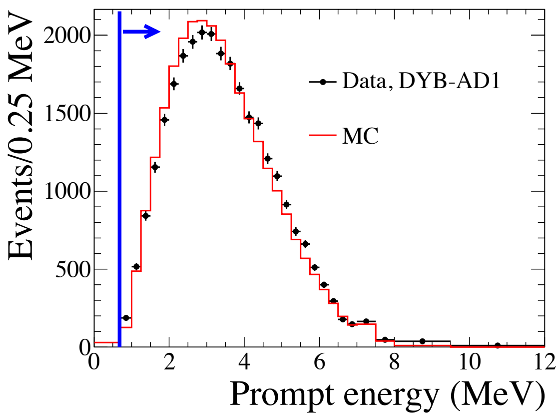
Antineutrino Candidates (Inverse Beta Decay)

Inverse Beta Decay

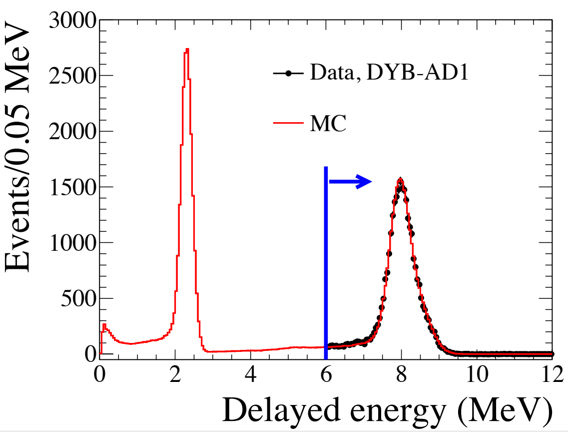
$\overline{\nu}_e + p \rightarrow e^+ + n$



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

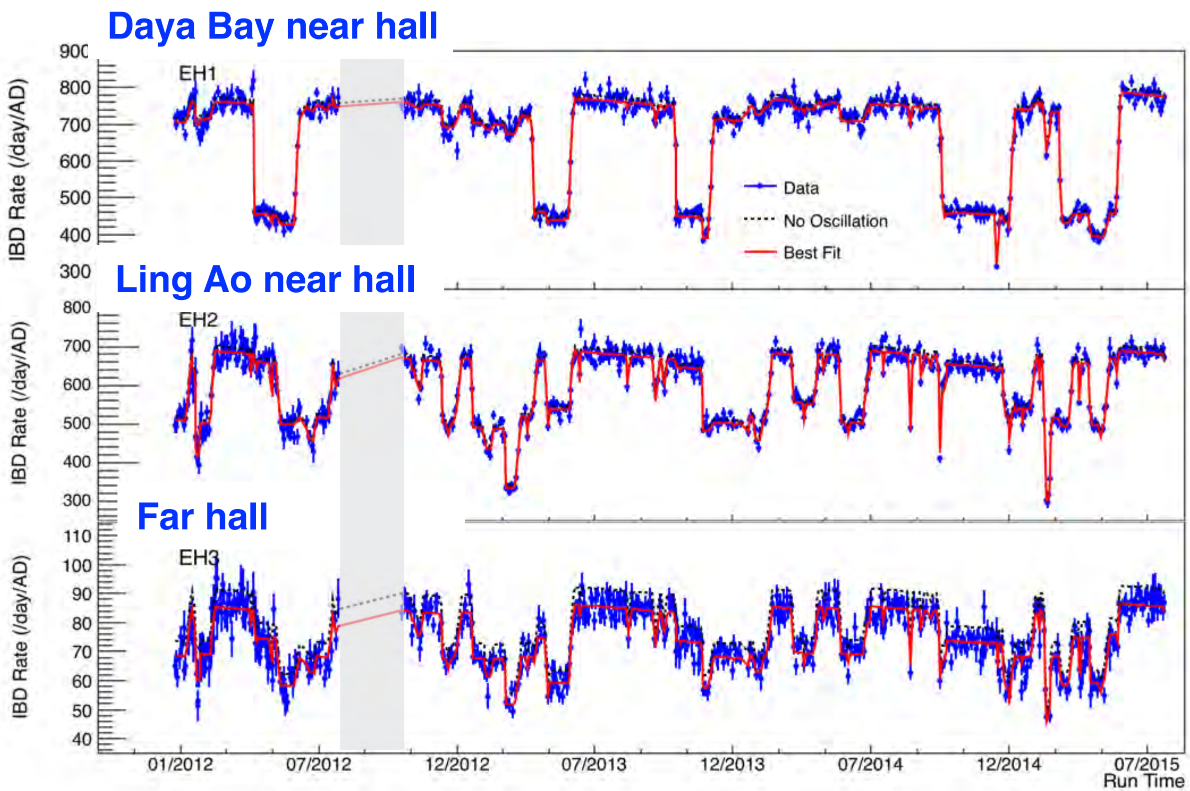


delayed event:
neutron thermalizes and captures on **Gd**

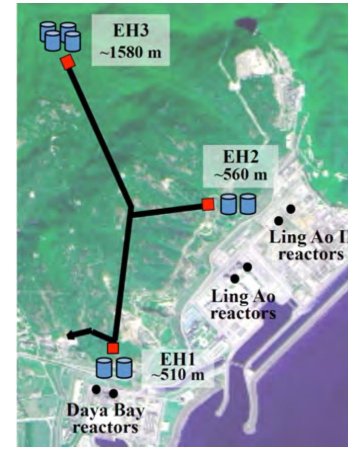


Prompt + Delayed Coincidence

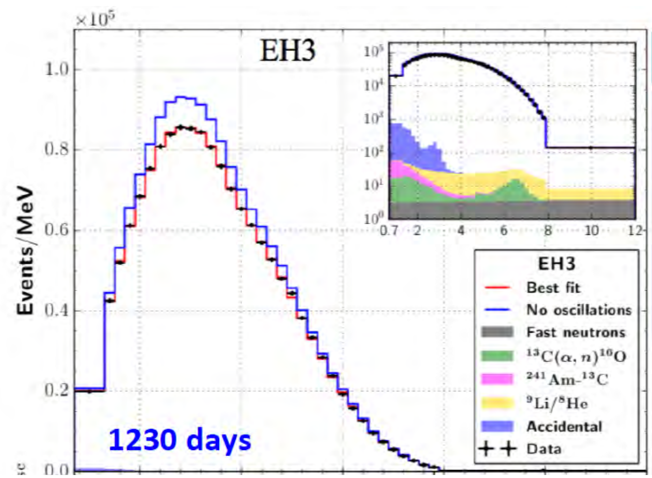
Daya Bay Antineutrino Rate & Spectrum



Rate



Spectrum

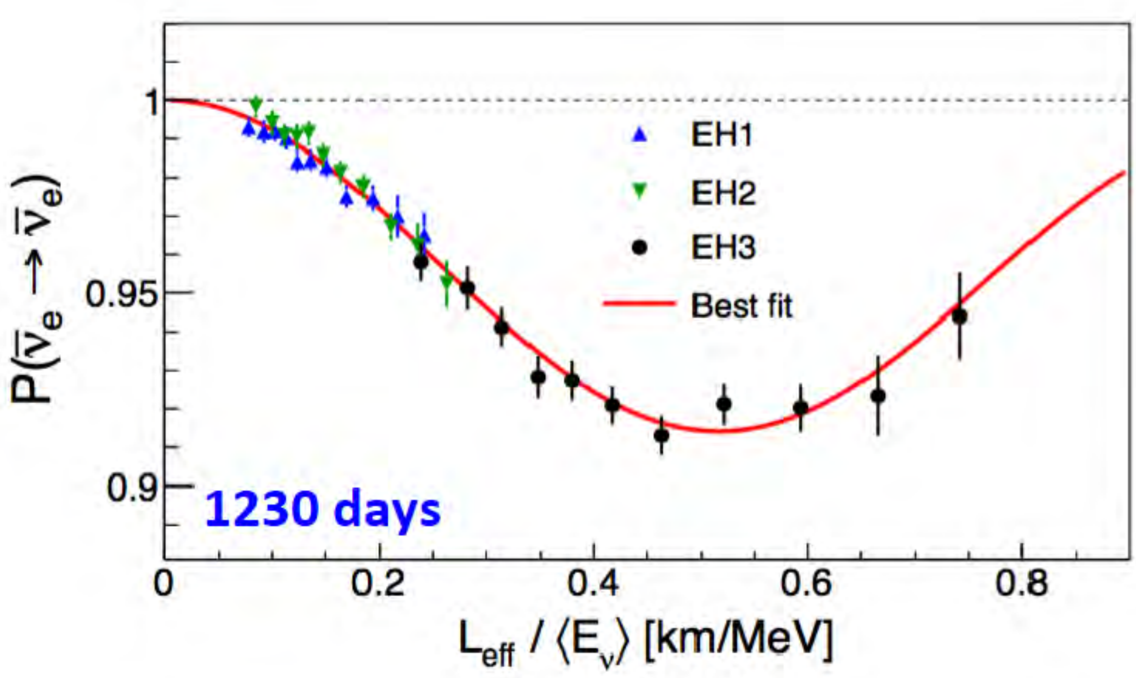


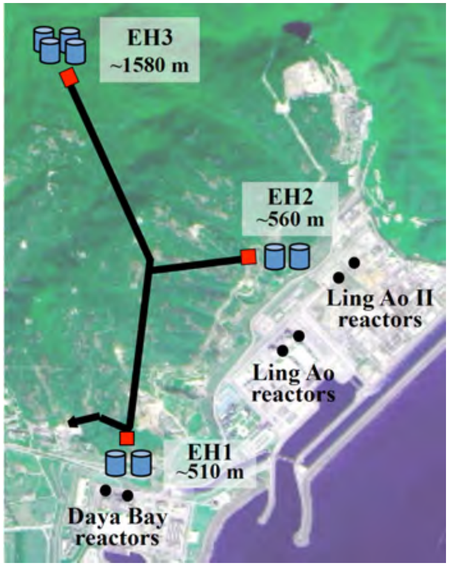
- 6 reactors, complicate cycle
- max of 2 reactors refueled at each time
- weekly average fission fractions for each core provided by the power company

Daya Bay Neutrino Oscillation

Neutrino oscillation is energy and baseline dependent

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



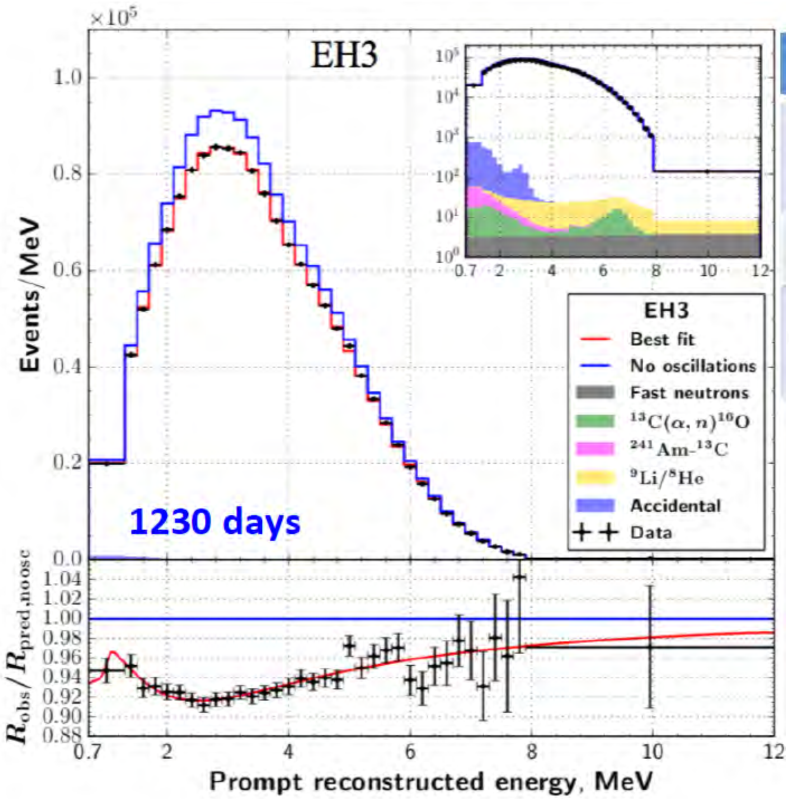


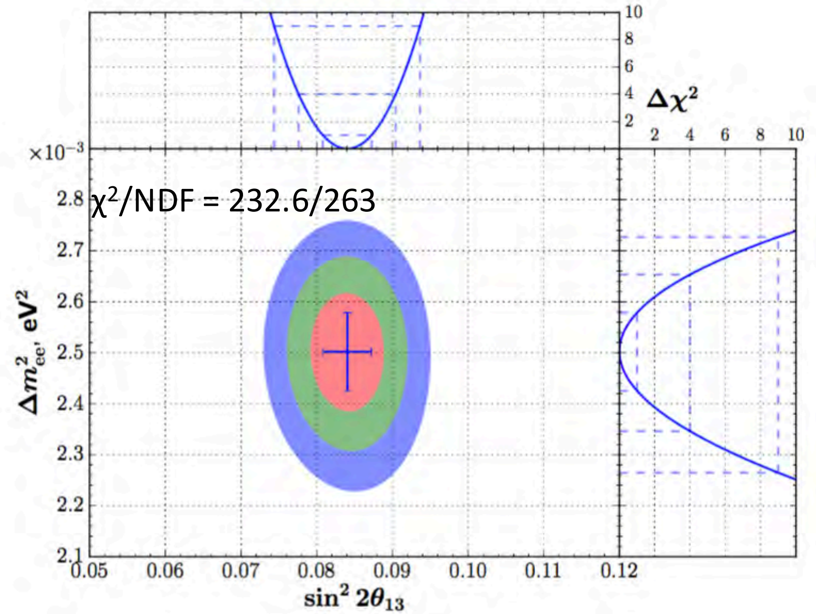
Daya Bay demonstrates L/E oscillation

Phys. Rev D 95, 072006 (2017).
Daya Bay

Daya Bay Neutrino Oscillation

nGd





$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2$$

$\sin^2 2\theta_{13}$ uncertainty: 3.9%

$|\Delta m^2_{32}|$ uncertainty: 3.4%

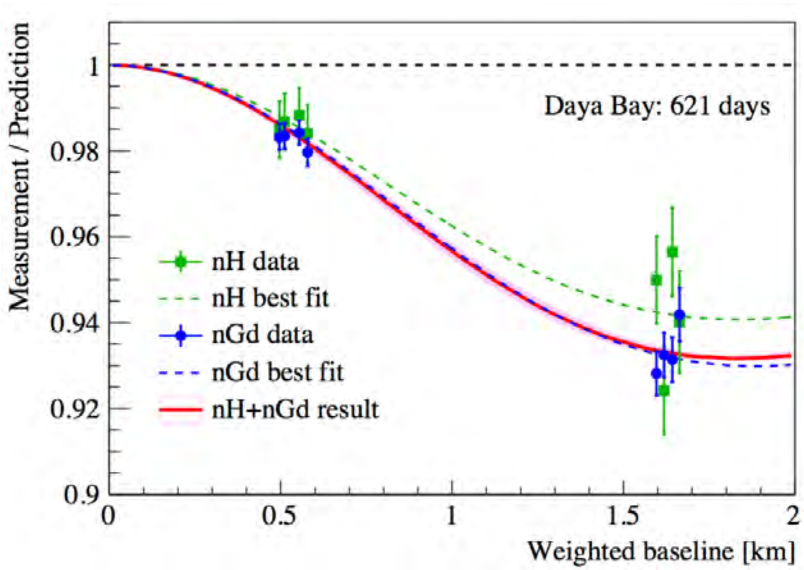
Consistent results with reactor and accelerator experiments

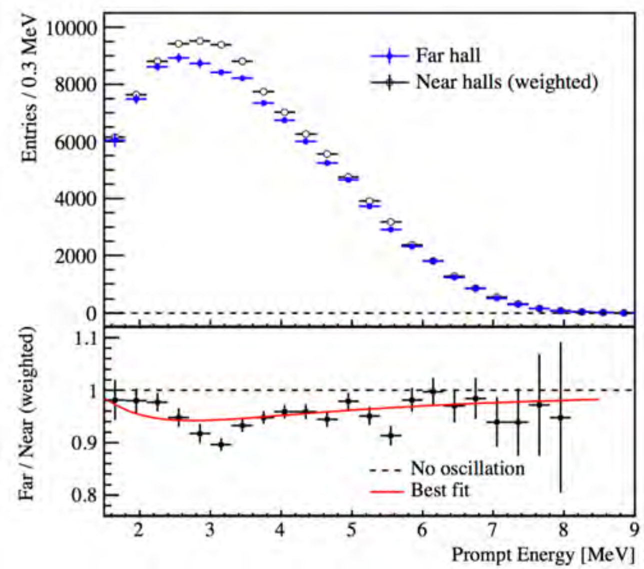
Phys. Rev D 95, 072006 (2017). Daya Bay

Daya Bay Neutrino Oscillation

nH

This analysis is statistically and (largely) systematically independent from the nGd one

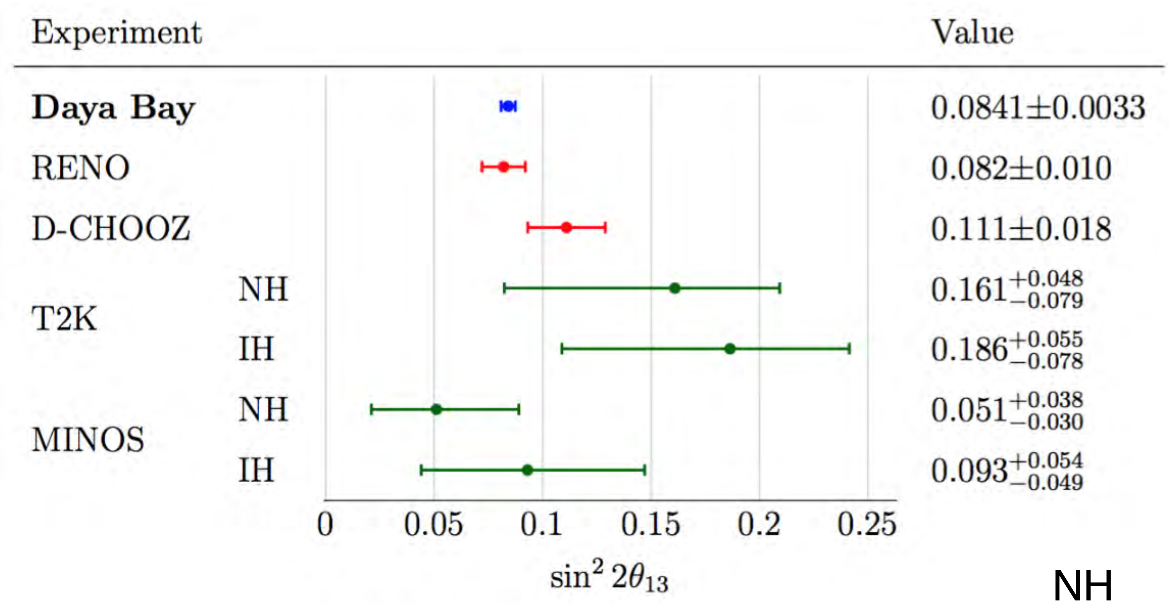




Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.11$, $\chi 2/ndf = 6.3/6$

Phys. Rev. D 93, 072011 (2016)

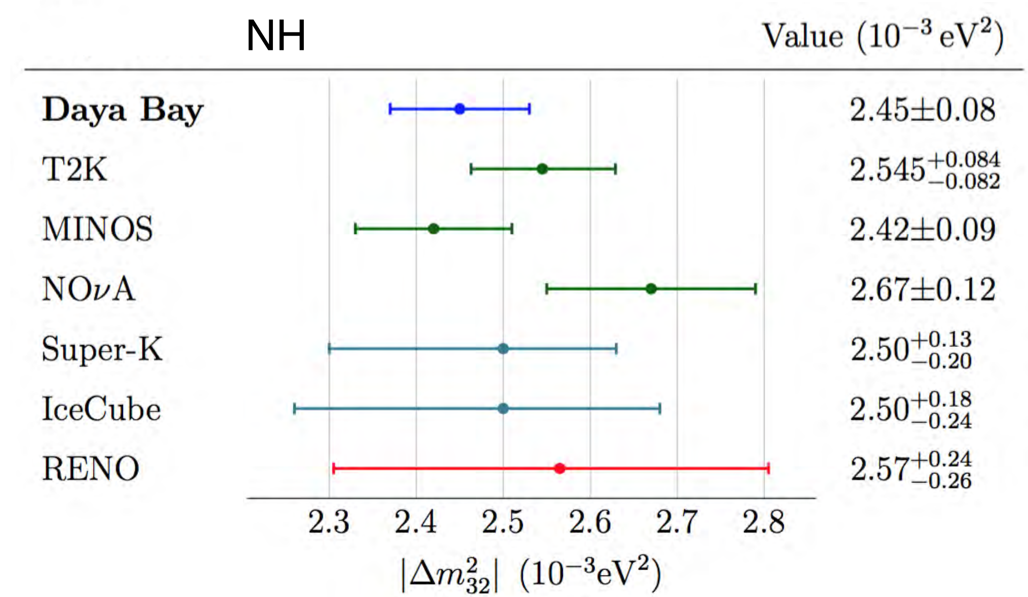
Global Comparison



$|\Delta m2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}eV^2$

NH: Δm^2_{32}= [2.45 ± 0.08] × $10^{-3}eV^2$

IH: Δm^2_{32}= [-2.55 ± 0.08] × $10^{-3}eV^2$



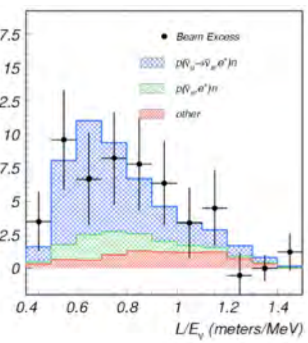
$\sin^2 2\theta_{13}$ uncertainty: 3.9%

$|\Delta m^2_{32}|$ uncertainty: 3.4%

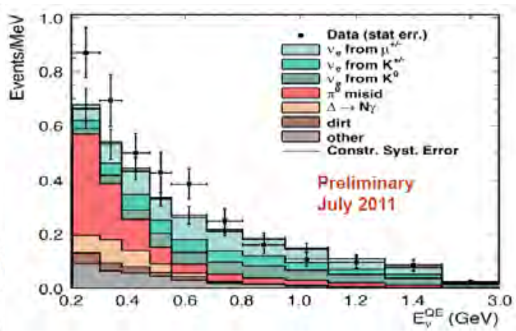
Consistent results with reactor and accelerator experiments

Neutrino Anomalies - New Physics?

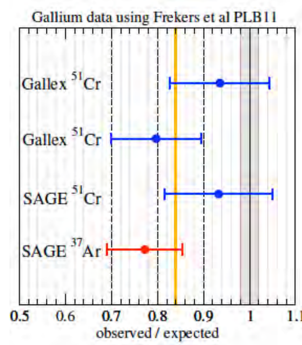
LSND



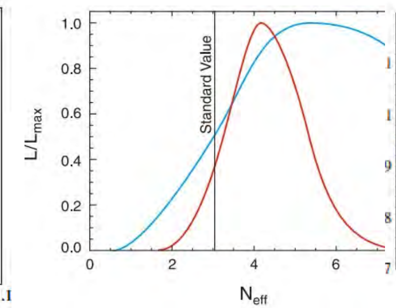
MiniBoone



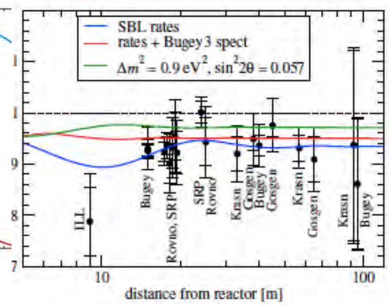
Ga Source



Cosmology (WMAP)

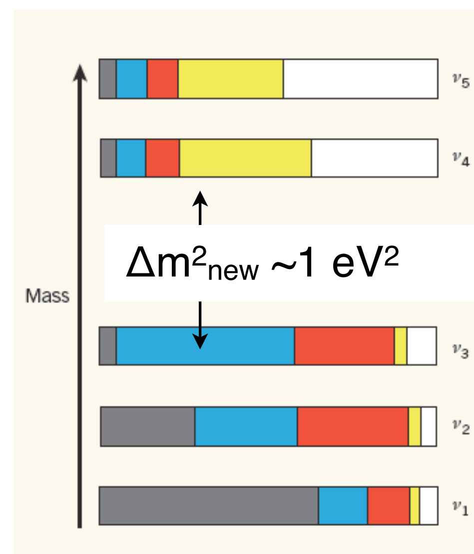


Reactor



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)



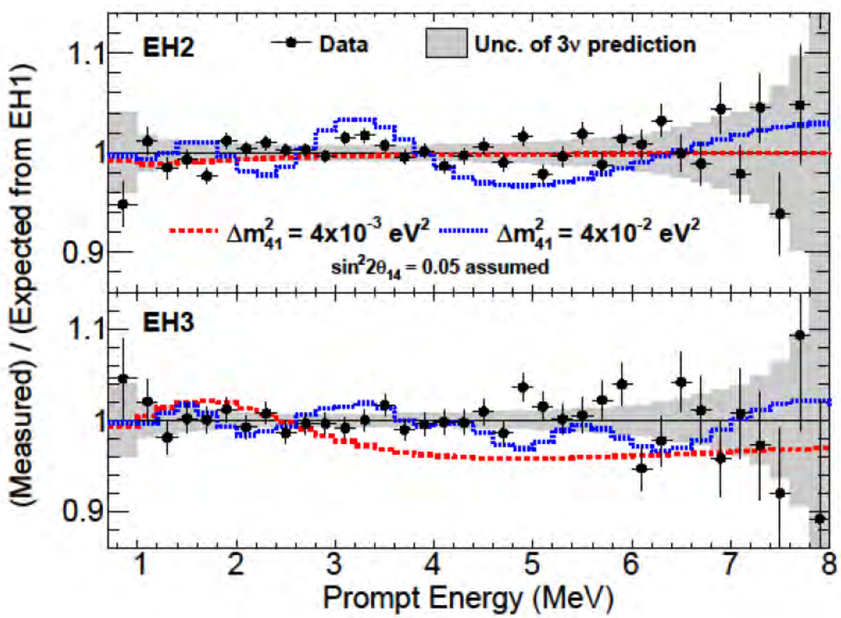
new oscillation signal requires:
$\Delta m^2 \sim O(1eV^2)$, $\sin^2 2\theta > 10^{-3}$

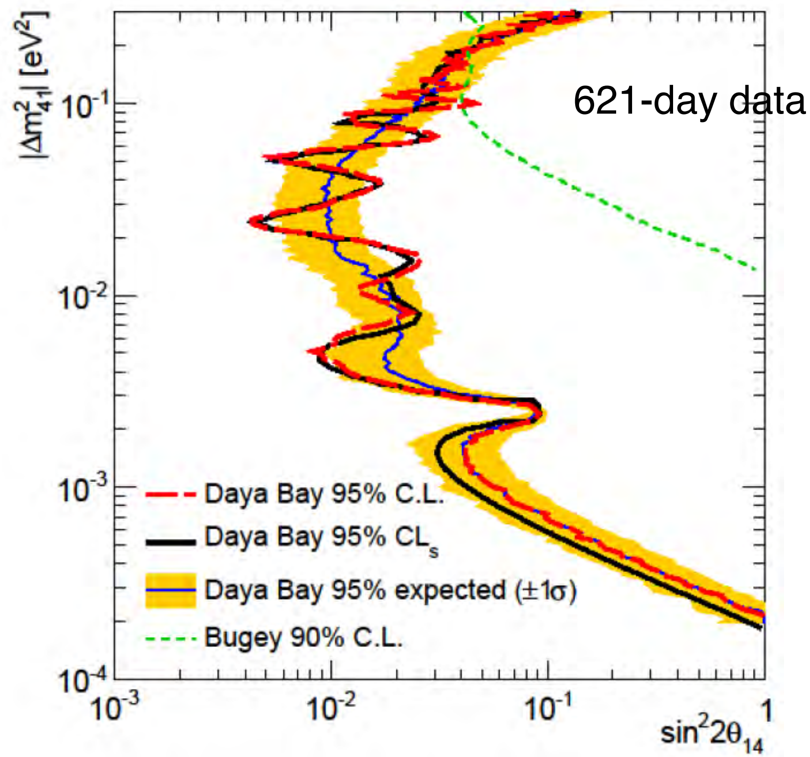
Sterile Neutrino Search: Daya Bay

Daya Bay's high-statistics dataset can be used to search if there is room for a fourth neutrino:

$$P_{ee} \approx 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

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





No hint of light sterile neutrino
Most stringent limit for $\Delta m^2_{41} < 0.1$ eV^2

Phys. Rev. Lett. 117, 151802 (2016)

Sterile Neutrino Search: Daya Bay+Minos+Bugey

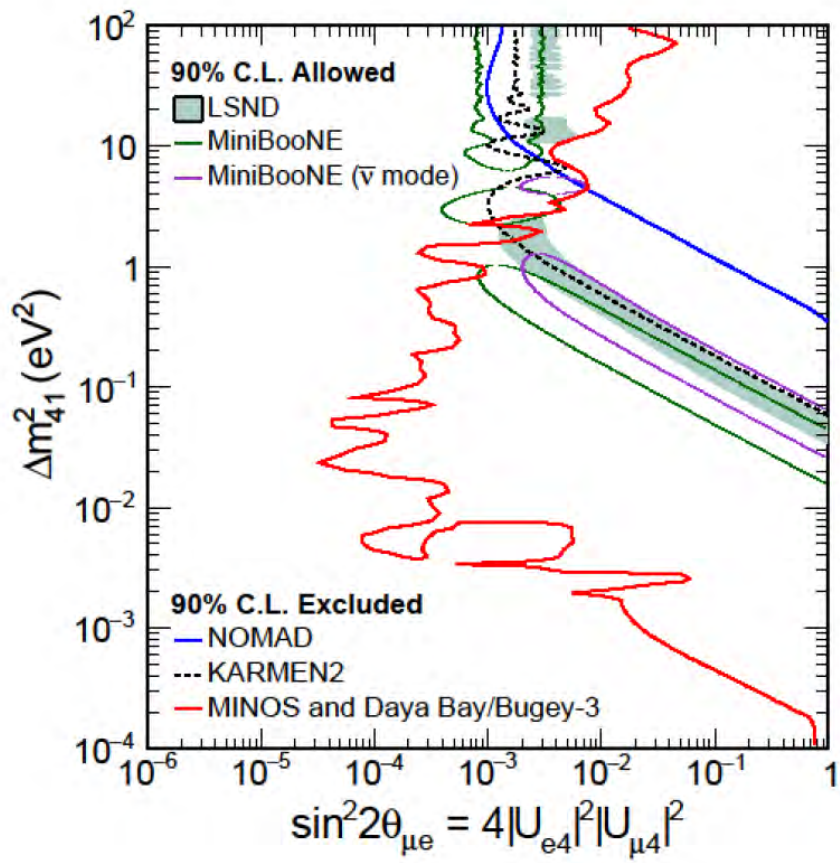
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Daya Bay is sensitive to $|U_{e4}|^2 = \sin^2\theta_{14}$.

But LSND & MiniBooNE are sensitive to $|U_{e4}|^2 |U_{\mu 4}|^2$

$$P_{\nu_\mu \to \nu_e}(L/E) \approx 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

where $4|U_{e4}|^2 |U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2\theta_{24}$
$= \sin^2 2\theta_{\mu e}$



Combined ν_e disappearance of Daya Bay and Bugey with ν_μ disappearance of MINOS

Excluded parameter space allowed by MiniBooNE & LSND for $\Delta m^2_{41} < 0.8$ eV^2

Phys. Rev. Lett. 117 (2016) no.15, 151801

Sterile Neutrino Search: Daya Bay+Minos+Bugey

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Daya Bay is sensitive to $|U_{e4}|^2 = \sin^2\theta_{14}$.

But LSND & MiniBooNE are sensitive to $|U_{e4}|^2\,|U_{\mu 4}|^2$

$$P_{\nu_\mu \to \nu_e}(L/E) \approx 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

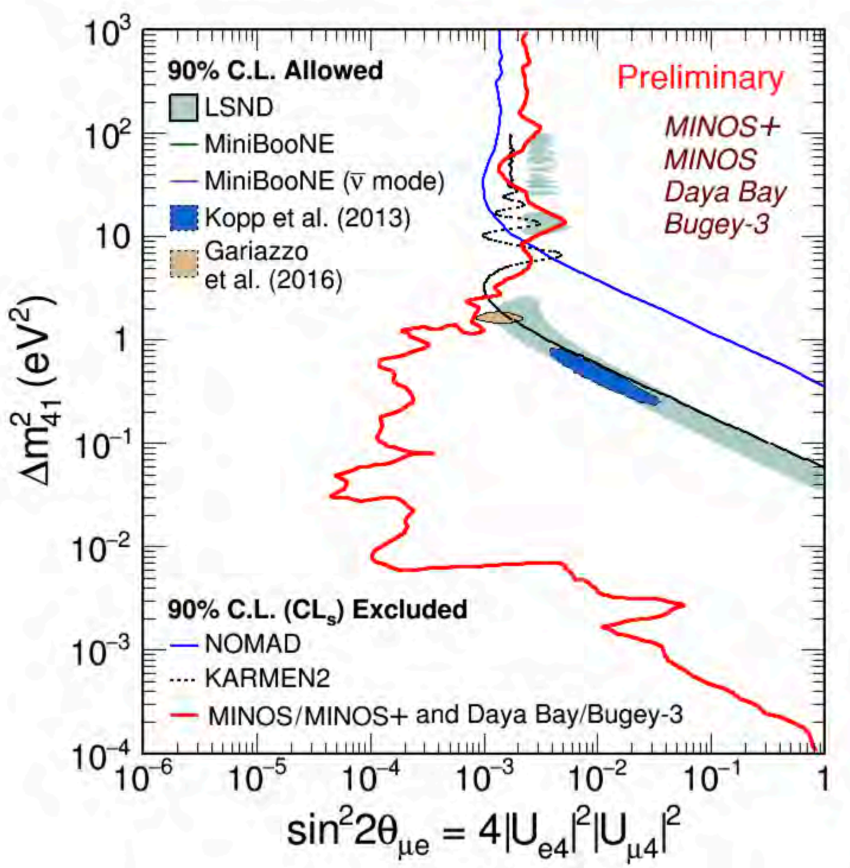
where $4|U_{e4}|^2\,|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24}$
$= \sin^2 2\theta_{\mu e}$

38

Combined ν_e disappearance of Daya Bay and Bugey with ν_μ disappearance of MINOS

Excluded parameter space allowed by MiniBooNE & LSND for $\Delta m^2_{41} < 0.8$ eV^2

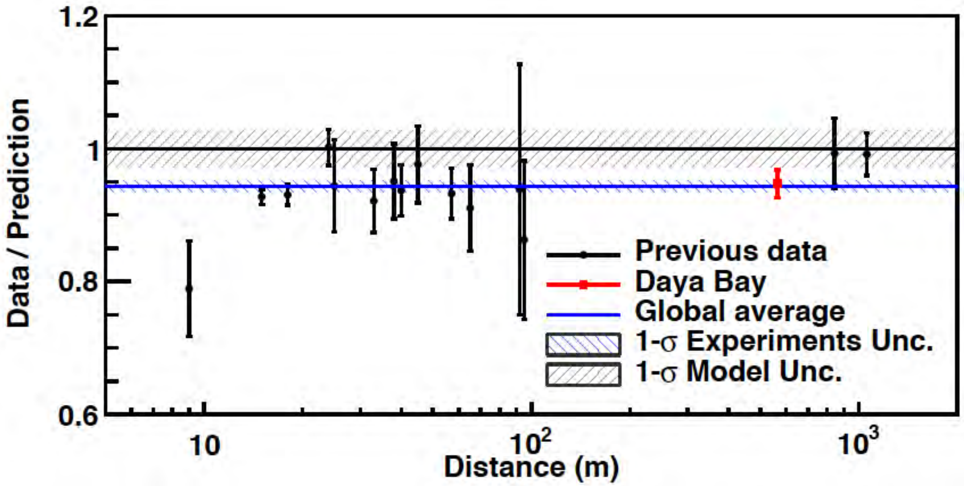
Phys. Rev. Lett. 117 (2016) no.15, 151801



Reactor Antineutrino “Anomalies”

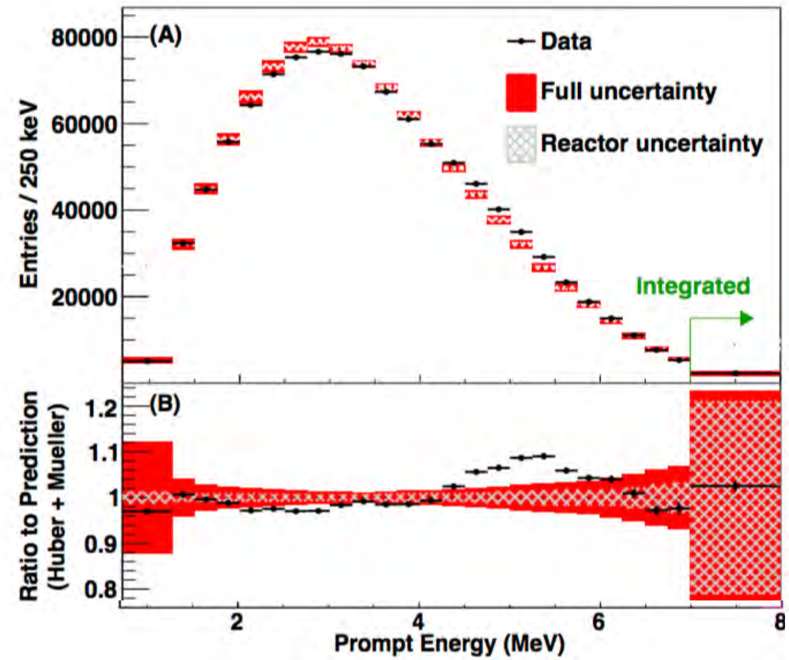
Flux Deficit

Consistent with previous experiments



Extra neutrino oscillations or artifact of flux predictions?

Spectral Deviation



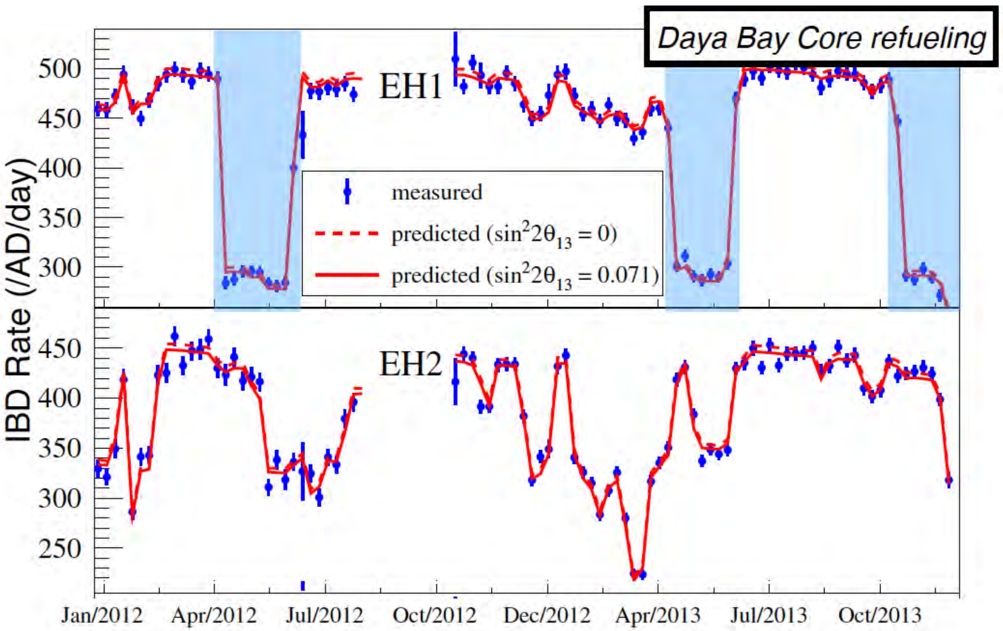
New feature in 4-6 MeV region of spectrum.

Understanding reactor flux and spectrum anomalies requires additional data

Phys. Rev D 95, 072006 (2017).
Daya Bay

Time Dependence of Fission Yield

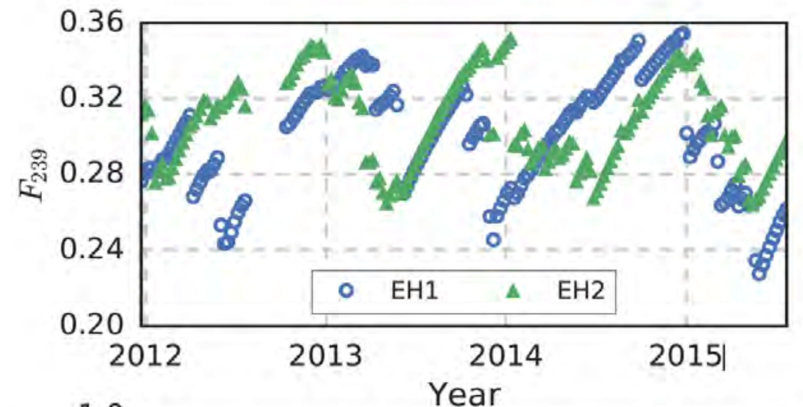
arXiv: 1704.01082, accepted by PRL
Daya Bay collaboration

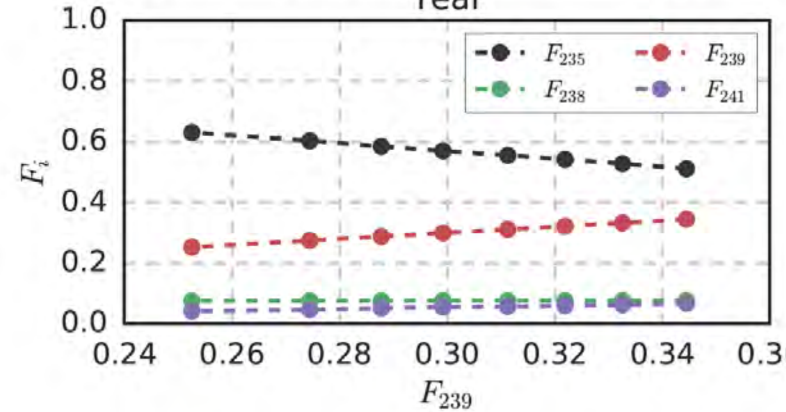


1230 days of daya, 2.2M IBD events, majority of neutrinos come from ^{235}U and ^{239}Pu fission. Weekly average fission fractions for each core provided by power company.

effective fission fractions viewed by each AD

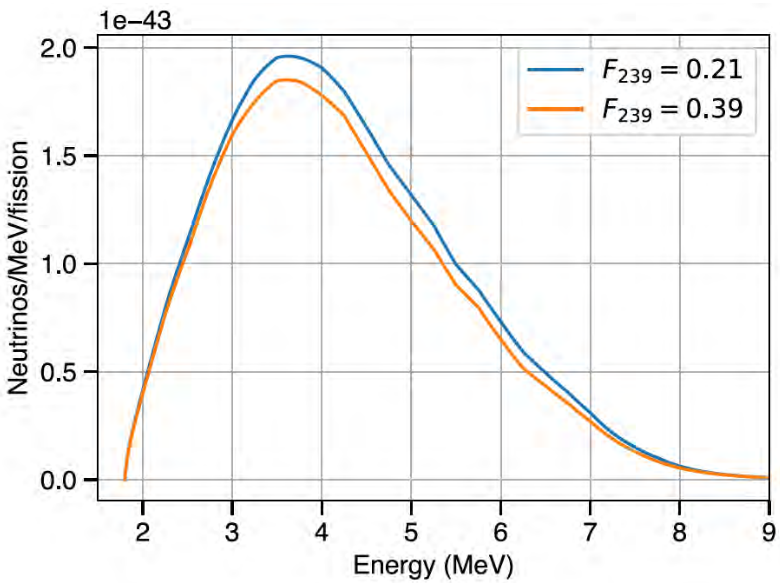
To simplify time-dependence, sort data according to the ^{239}Pu fission fraction

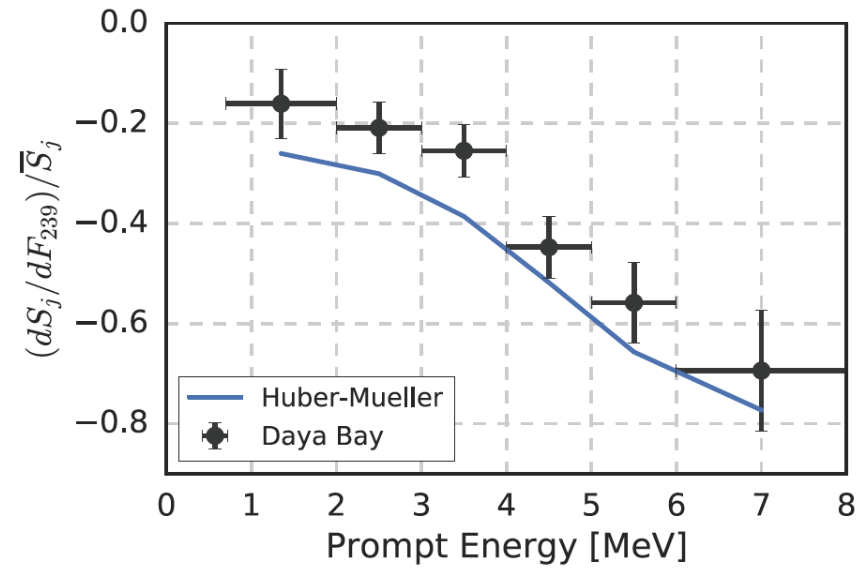




$$F_i(t) = \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r f_{i,r}(t)}{L_r^2 \overline{E}_r(t)} \Bigg/ \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r}{L_r^2 \overline{E}_r(t)}.$$

Reactor Spectrum and Fission Fractions



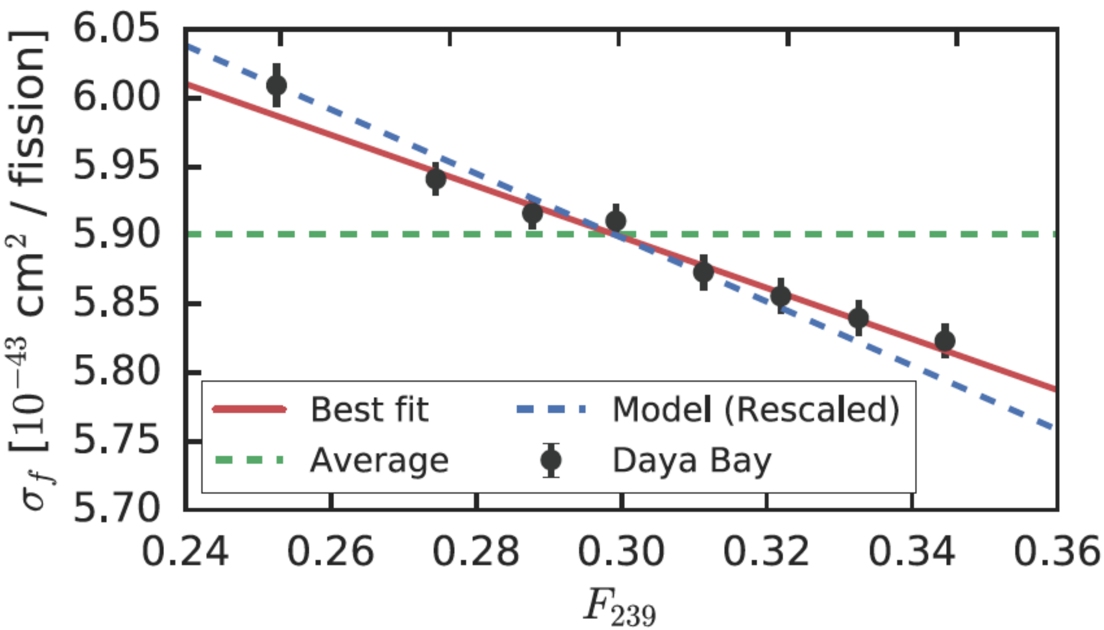


- As ^{239}Pu increases, flux should decrease and the spectrum should become “softer”
- Observe a definitive change in the measured spectrum.
- Decreases overall, larger effect at high energies

The shape of the spectral evolution is very consistent with model predictions

arXiv: 1704.01082, submitted to PRL
Daya Bay collaboration

Antineutrino Yield per Fission



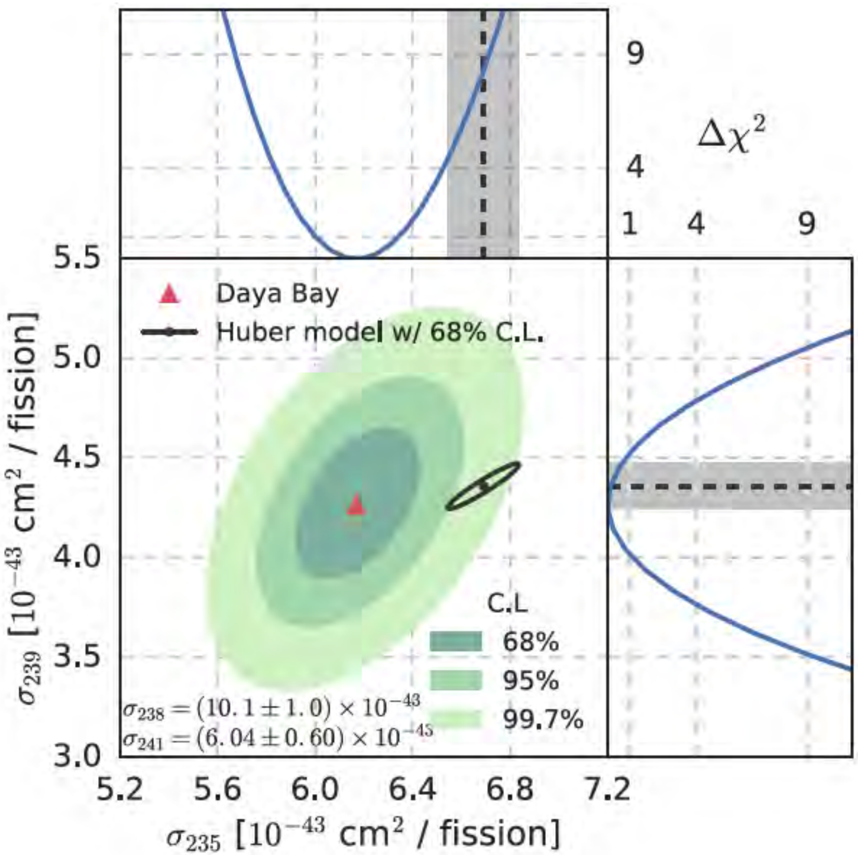
rejects at >10σ hypothesis of constant antineutrino flux as a function of ^{239}Pu

slope of σ_f vs F239 depends on the ratio of the ^{235}U and ^{239}Pu yields

measured evolution in total IBD yield disagrees with recent predictions at 3.1 σ

arXiv: 1704.01082, submitted to PRL
Daya Bay collaboration

Fission Parent Neutrino Yield



Model-independent measurement of the fission neutrino yields

Observed 7.8% discrepancy between observed and predicted ^{235}U yield.

Overall deficit in reactor flux does not result from equal fraction deficits from primary isotopes ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu

A sterile neutrino deficit would be independent of fuel composition.
A measurement of an ^{235}U (HEU) reactor is needed!

arXiv: 1704.01082, submitted to PRL
Daya Bay collaboration

Reactor Antineutrinos

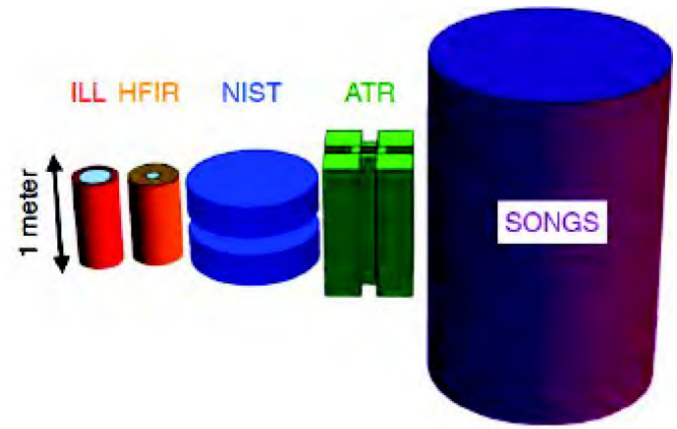
High-powered research reactors

highly-enriched (HEU):
mainly U-235, ~10-100 MW_{th},

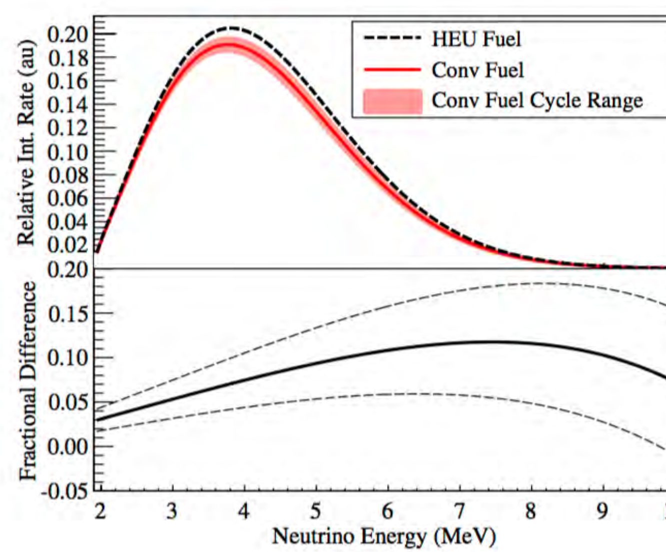
Commercial power reactors

low-enriched (LEU):
many fission isotopes, ~GW_{th}

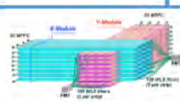
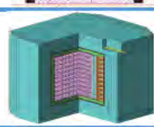
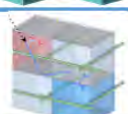
"Point Source" vs Extended Core



HEU core provides static spectrum of ^{235}U



Short-Baseline Reactor Experiments Worldwide

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

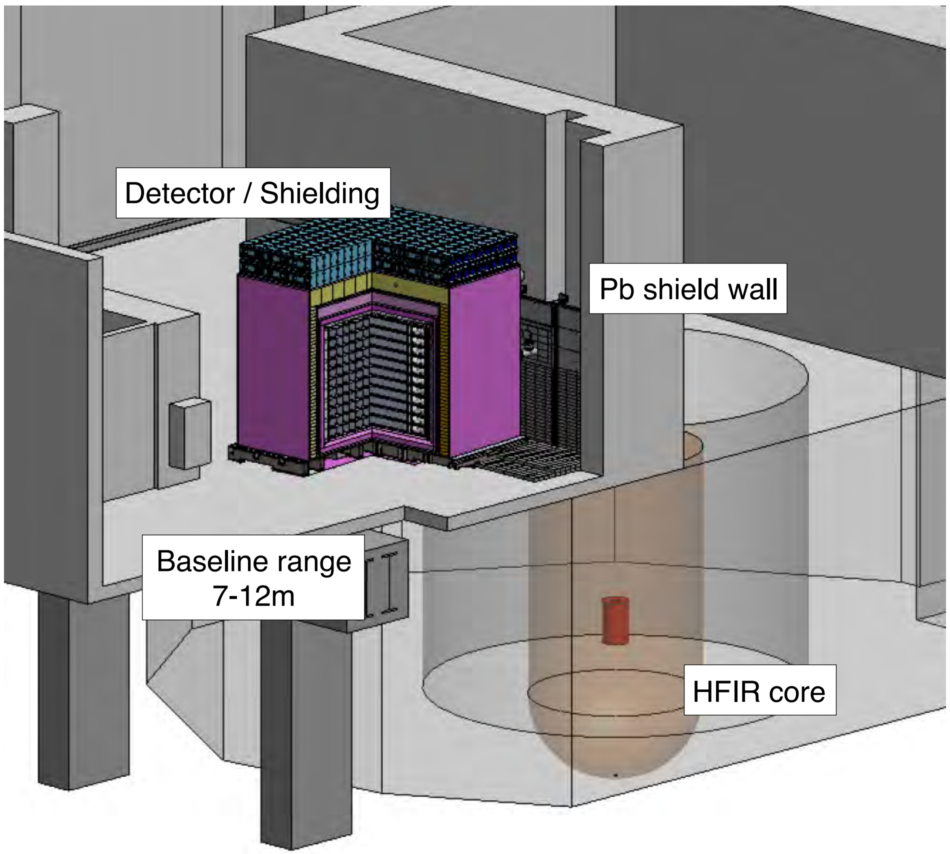
From N. Bowden

Precision Reactor Oscillation and Spectrum Experiment

Physics Objectives

1. Search for short-baseline ν oscillation at distances <10m
2. Precision measurement of ^{235}U reactor $\bar{\nu}_e$ spectrum

prospect.yale.edu



Experimental Approach

reactor model-independent search for neutrino oscillations

measurement of ^{235}U spectrum with high energy resolution $<4.5\%/\sqrt{E}$ (σ/E)

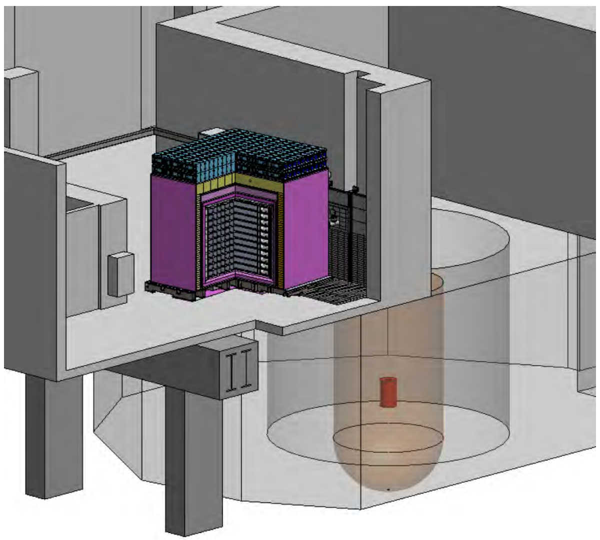
background rejection capabilities at near-surface through fiducialization

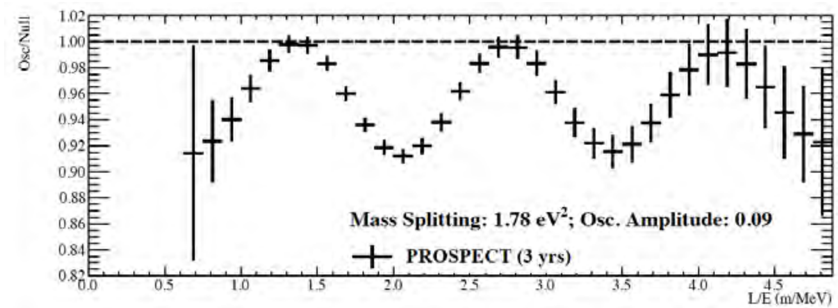
see P. Surukuchi, Tues afternoon

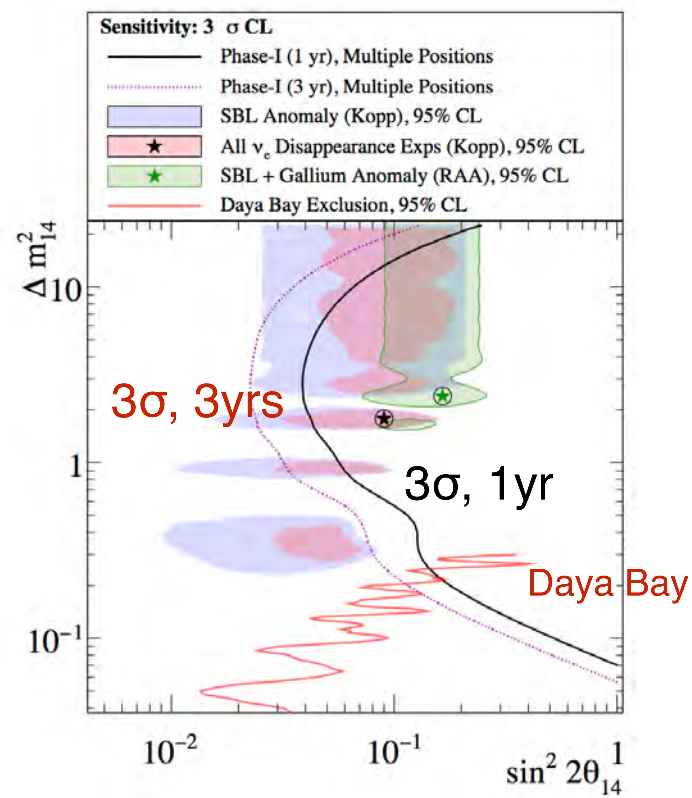
PROSPECT Physics

A Precision Oscillation Experiment

Direct model-independent test of oscillation of eV-scale neutrinos







Objectives

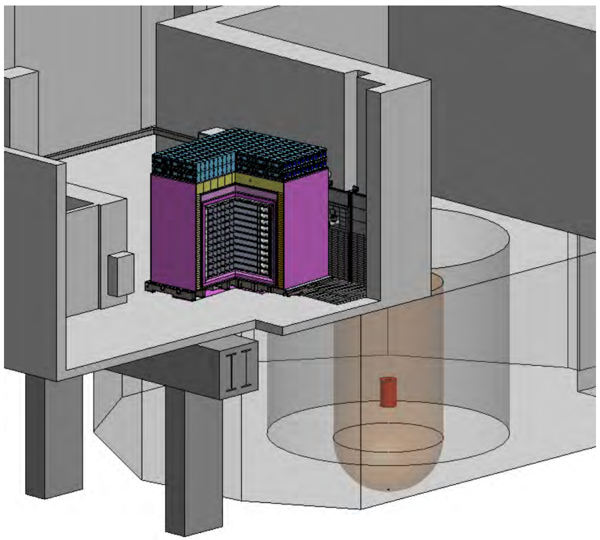
4σ test of best fit after 1 year

>3σ test of favored region after 3 years

PROSPECT Physics

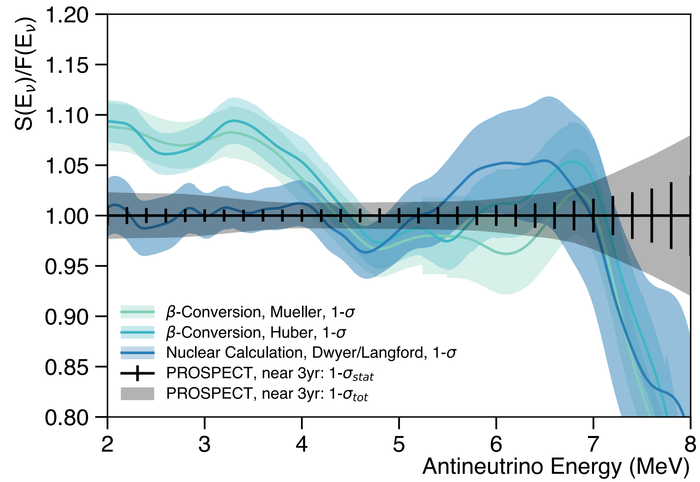
A Precision Spectrum Experiment

A precision measurement of spectrum to address "bump"

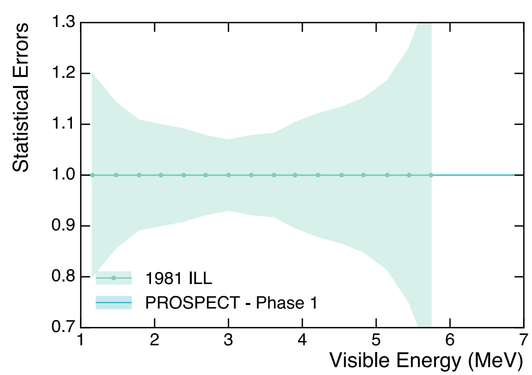


Objectives
Measurement of ^{235}U spectrum
Compare different reactor models
Compare different reactor cores

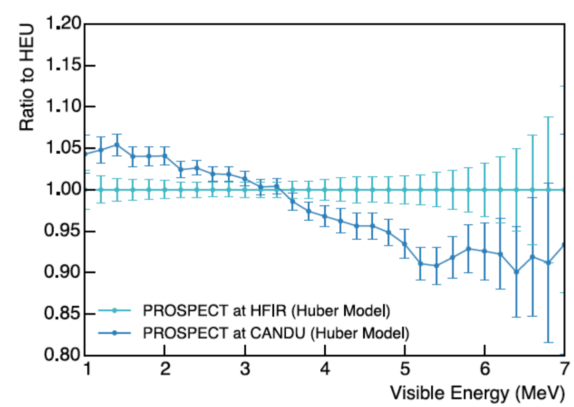
Testing models of the $^{235}U\ \overline{\nu}_e$ energy spectrum



Improvement on ILL

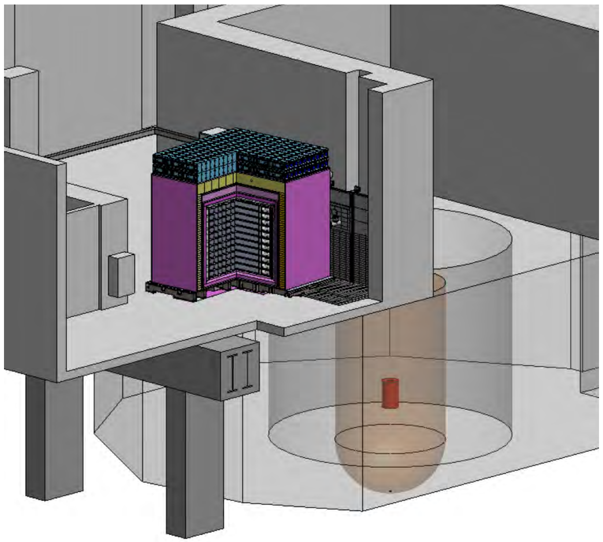


Different reactor cores

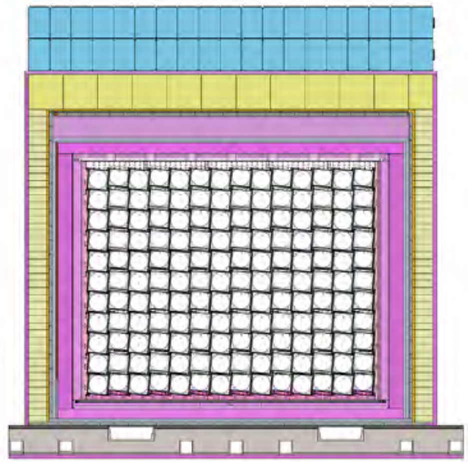


Precision Reactor and Oscillation Experiment

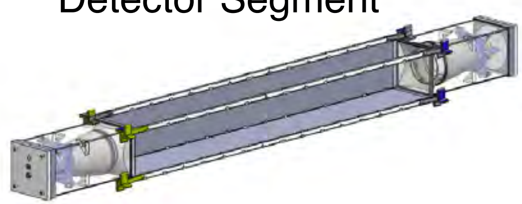
Segmented, ^{6}Li loaded Detector



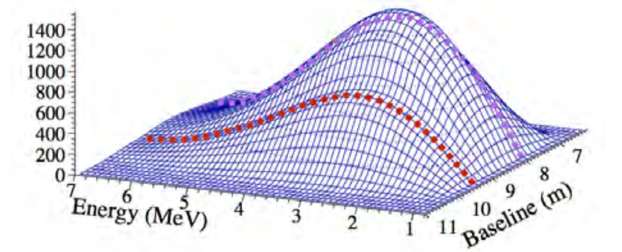
Active Inner Detector
+Shielding



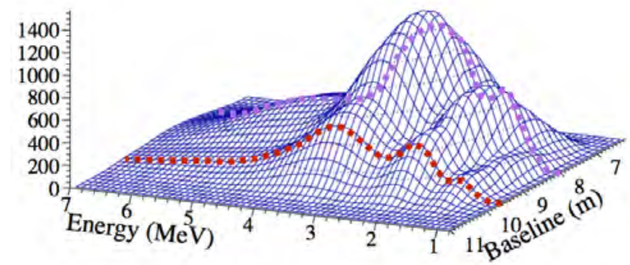
Detector Segment



unoscillated spectrum



oscillated spectrum



Detector Design

- ^{6}Li liquid scintillator
- minimum dead material
- double-ended PMT readout,
- light guides, 5” PMTs
- ~5%/√E resolutions

Segmented Detector

relative measurement of L/E within detector

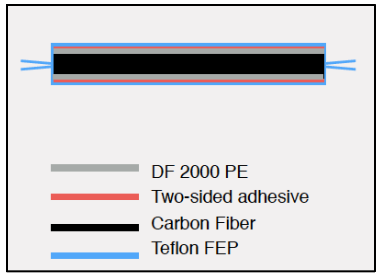
Relative Spectrum Measurement

search for relative shape distortions independent of reactor models/ predictions

Development of Detector Components

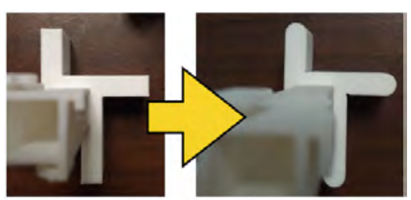
Low-Mass Optical Separators

High reflectivity, high rigidity, low mass reflector system developed



- Array formed using 3D printed "pinwheel" spacers
- Chemical compatibility of all materials validated

Component design refined for final production

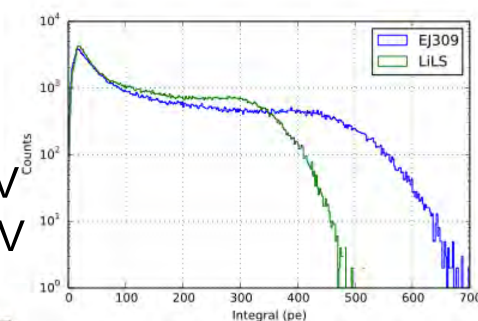


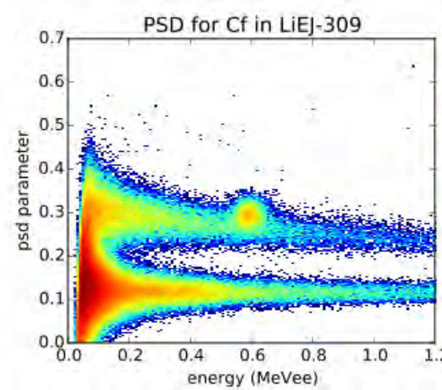
^{6}Li-Loaded Liquid Scintillator

- Developed non-toxic, non-flammable formulations based on EJ-309, LAB, Ultima Gold
- EJ-309 selected as baseline

Light Yield

- EJ-309 base: 11500 ph/MeV
- LiLS: 8200 ph/MeV



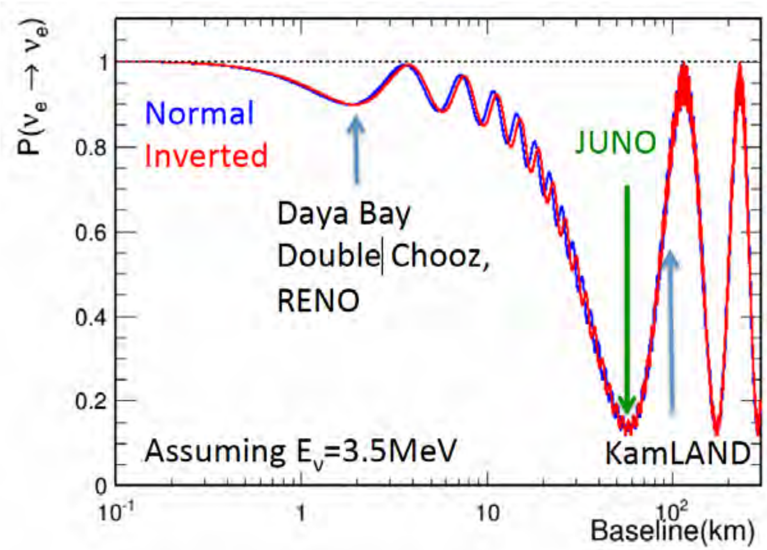


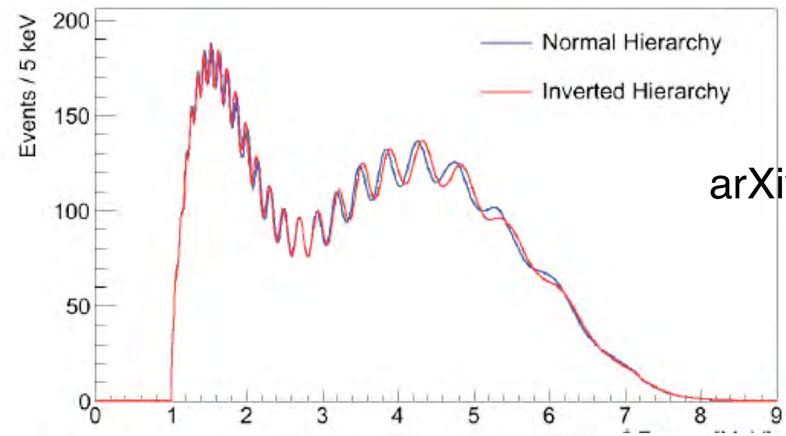
Excellent PSD performance for neutron capture & heavy recoils

Full-scale production for PROSPECT underway

Prototyping and Detector Assembly

Mass Hierarchy and Reactor Neutrinos

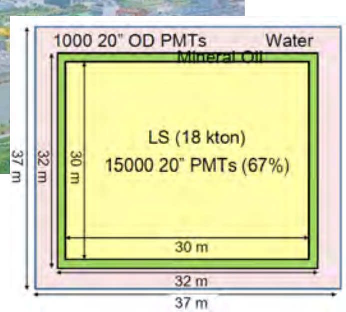


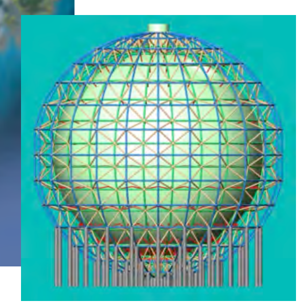


arXiv:1307.5487

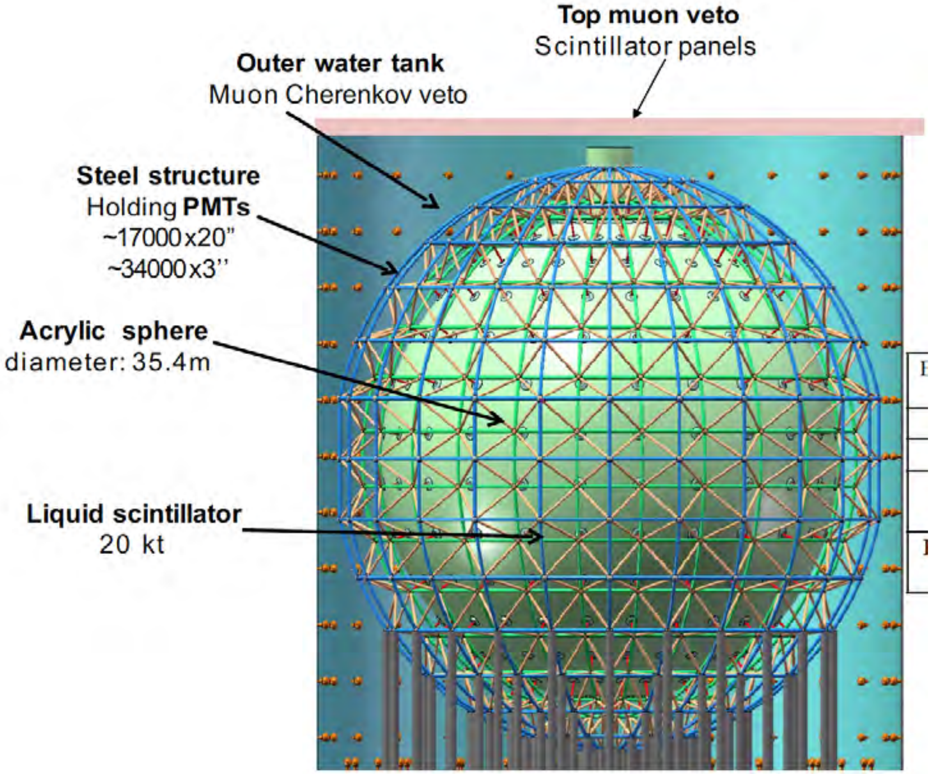
determine mass hierarchy from precision measurements of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$





JUNO

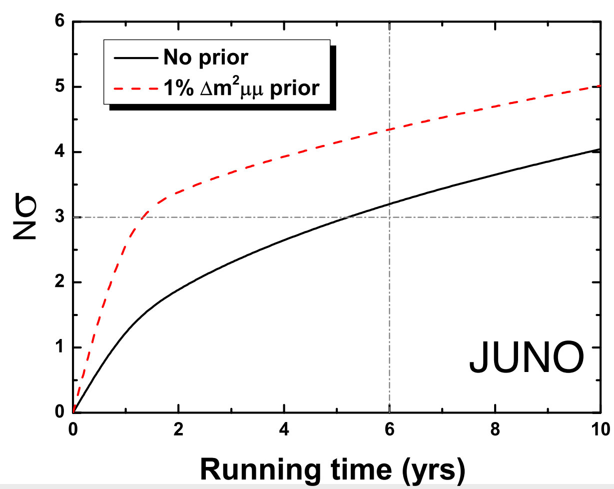


Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1kton	**20 kton**
Coverage	~ 12%	~ 34%	~ 34%	~ 80%
Energy resolution	$7.5\%/\sqrt{E}$	$\sim 5\%/\sqrt{E}$	$\sim 6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	~ 160 p.e./MeV	~ 500 p.e./MeV	~ 250 p.e./MeV	**~ 1200 p.e./MeV**

Precision 3-ν Oscillation Physics

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	10% (~4% in 3 yrs)	15%

Mass Hierarchy Sensitivity



Summary & Outlook

Reactor neutrinos are a tool for discoveries.

- Reactors are flavor pure source of $\bar{\nu}_e$.
- 60 years after Reines and Cowan reactor $\bar{\nu}_e$ hold promise to reveal new physics

Precision oscillation physics

- firmly established neutrino oscillations over km-long baselines
- most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$, 1230 days of data
- stringent limit for neutrino mixing to light sterile neutrino for $|\Delta m^2_{41}| < 0.2$ eV^2

Flux and spectrum

- has measured time dependence of flux and spectrum
- flux evolution disagrees with models, discrepancy in ^{235}U neutrino yield

New data are required to address the reactor rate and spectrum anomalies.

Short Baseline Experiments aim to resolve current reactor anomalies

- probe favored region for eV-scale sterile neutrinos at $>3\sigma$ within 3 years
- measure the ^{235}U $\bar{\nu}_e$ spectrum, complementary to LEU measurements
- proceeding with construction of detector, data taking to start in 2017

Medium Baseline Experiments aim to measure the mass hierarchy

Stay tuned!