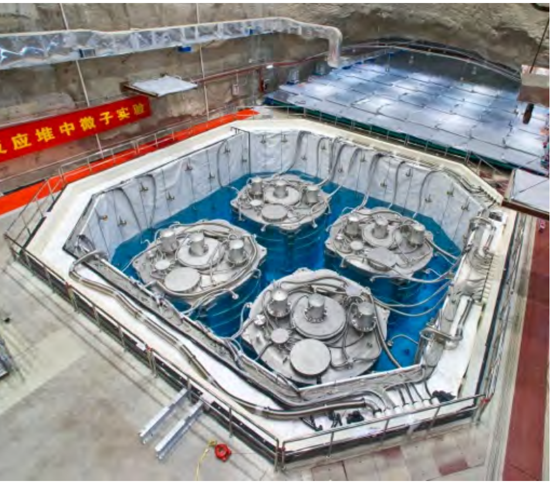
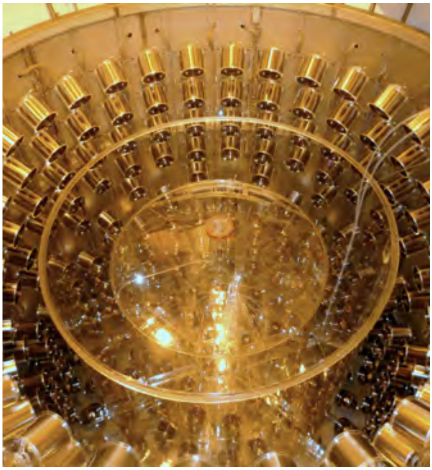
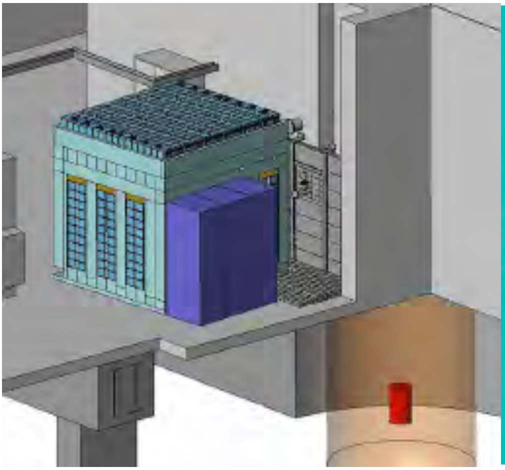
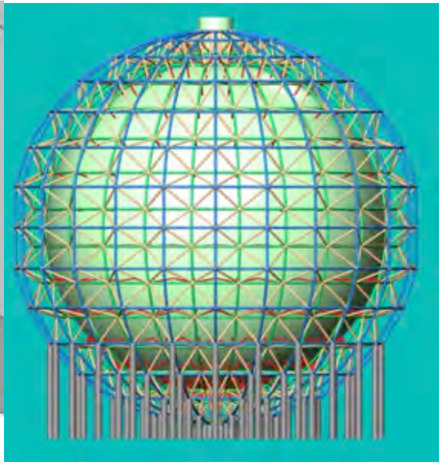
Reactor Neutrino Experiments



Karsten M. Heeger
Yale University

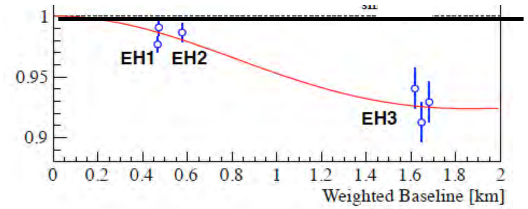
ACP, January 14, 2015

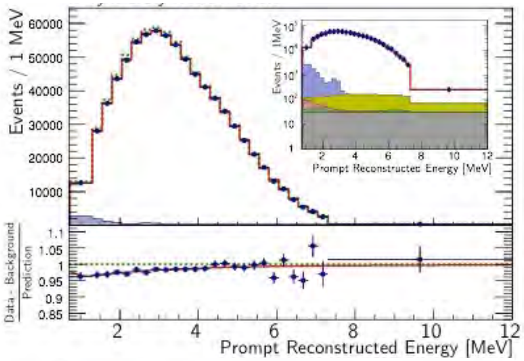
Reactor Antineutrinos

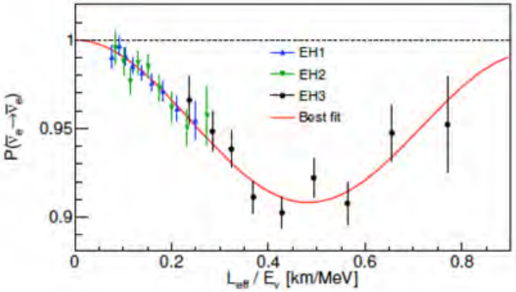
A Tool for Discovery

2012 - Measurement of θ_{13} with Reactor Neutrinos

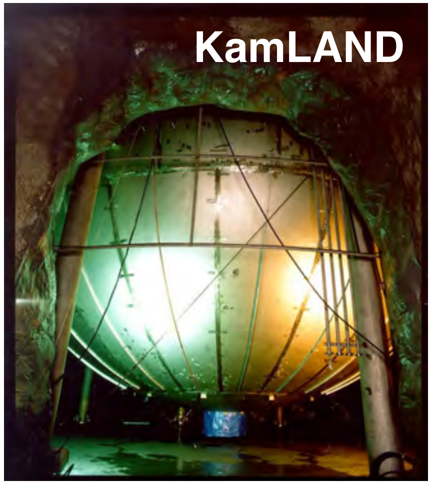
Daya Bay,
Double Chooz
RENO







2003 - First observation of reactor antineutrino disappearance

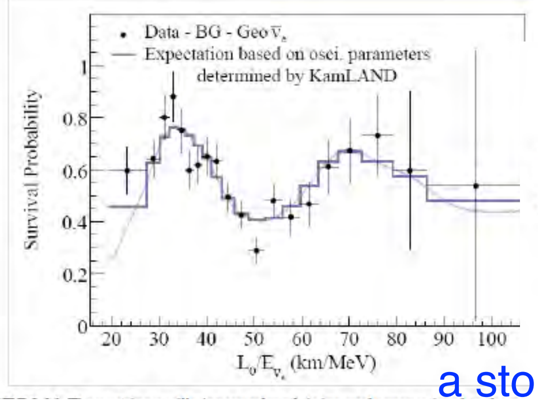


KamLAND

1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos

Savannah River

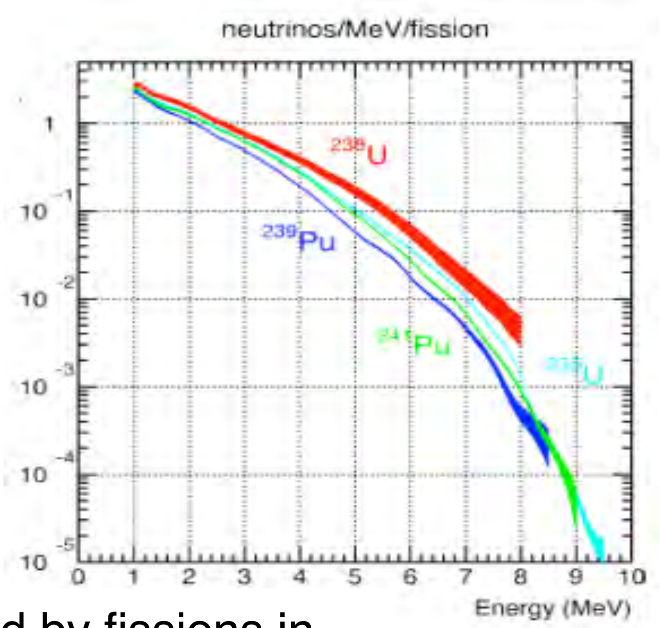


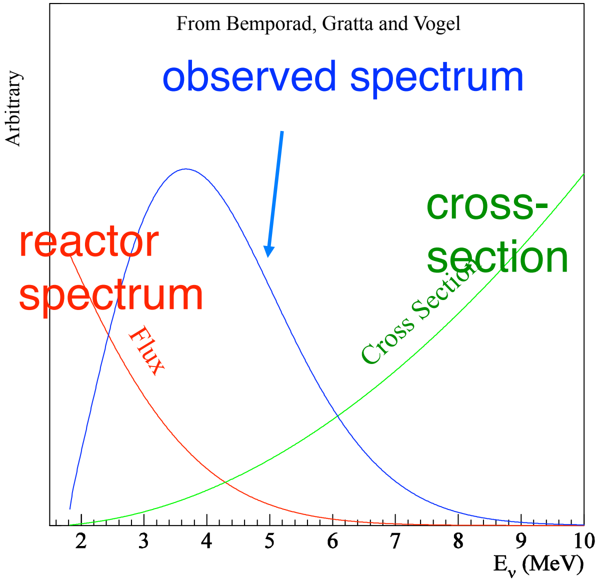
a story of varying baselines...

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





observed spectrum

reactor spectrum

cross-section

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

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

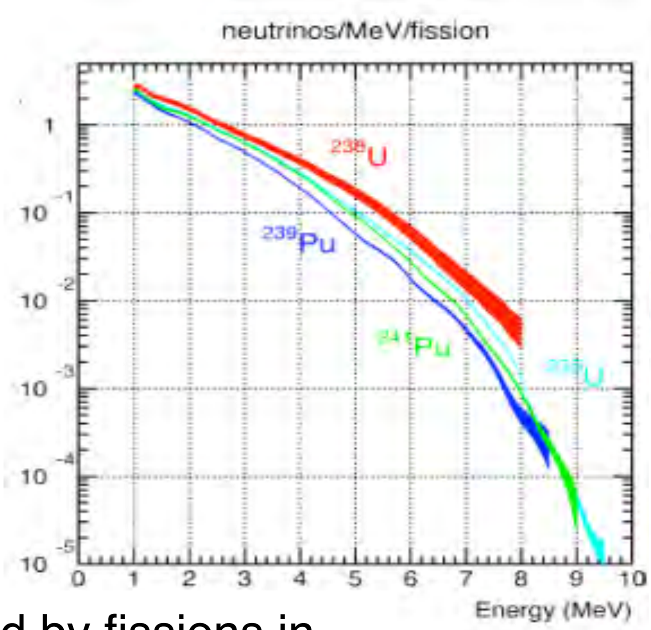
mean energy of $\bar{\nu}_e$: 3.6 MeV

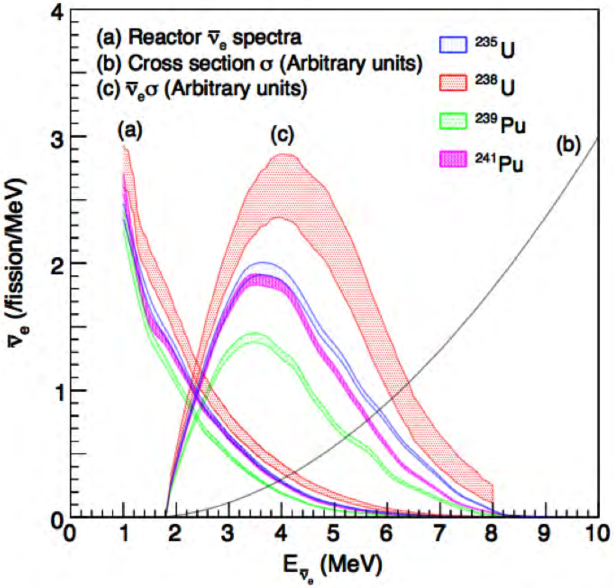
only disappearance
experiments possible

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 ν_e are produced by fissions in
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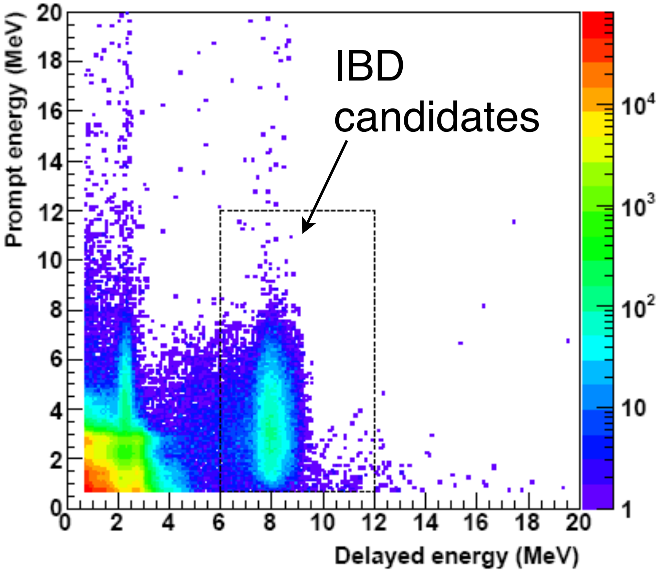
mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance
experiments possible

Antineutrino Candidates (Inverse Beta Decay)

Prompt + Delayed Coincidence

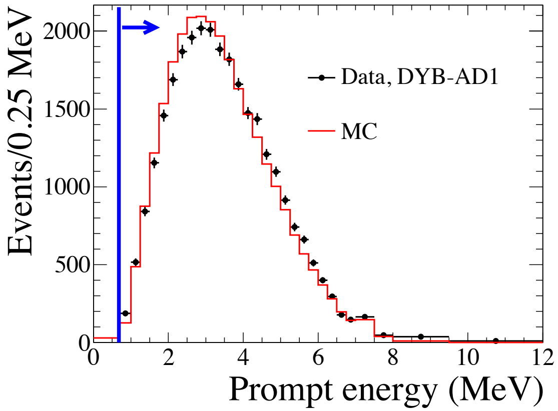


$$\overline{\nu}_e + p \rightarrow e^+ + n$$

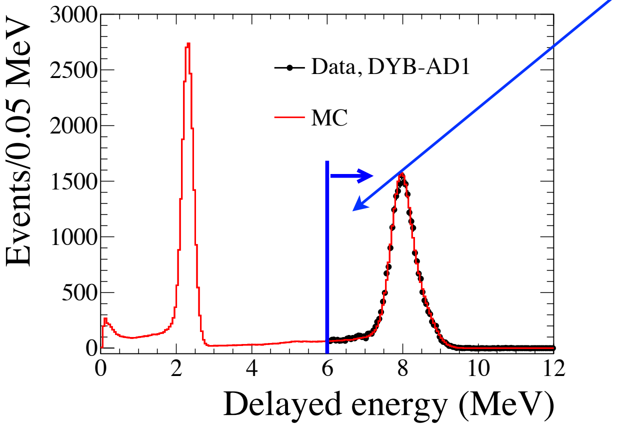
prompt event:
positron deposits energy and annihilates (~ns)

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

Prompt Energy Signal

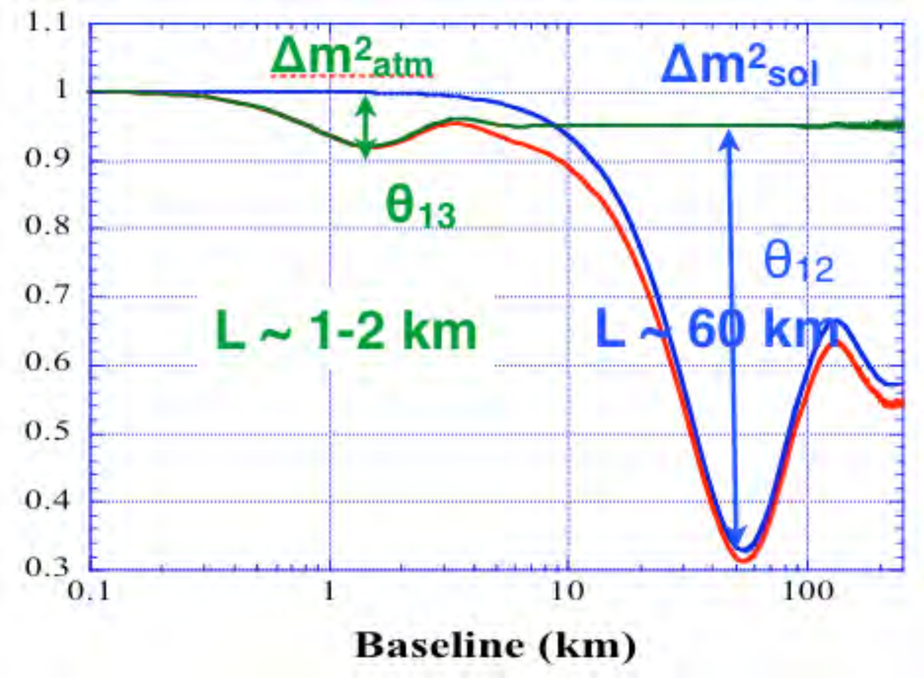


Delayed Energy Signal



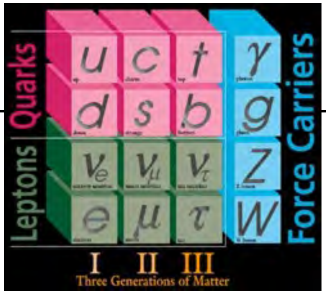
Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

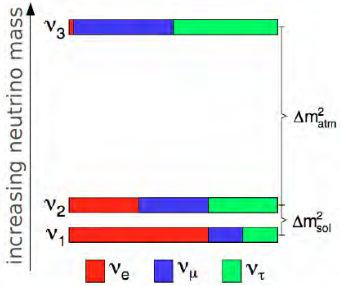
Oscillation Measurements



Neutrino Mixing

Mixing Angles





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

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$\sin^2\theta_{23}$

$0.50^{+0.07}_{-0.06}$

maximal?

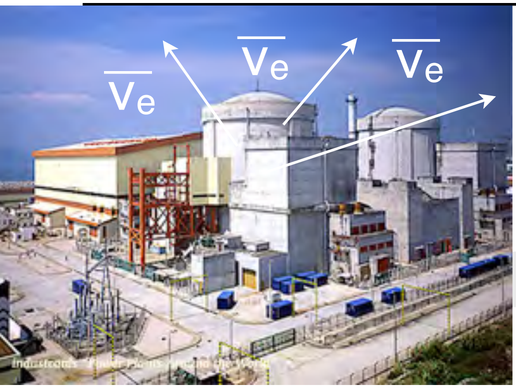
$\sin^2\theta_{13}$

$\sin^2\theta_{12}$

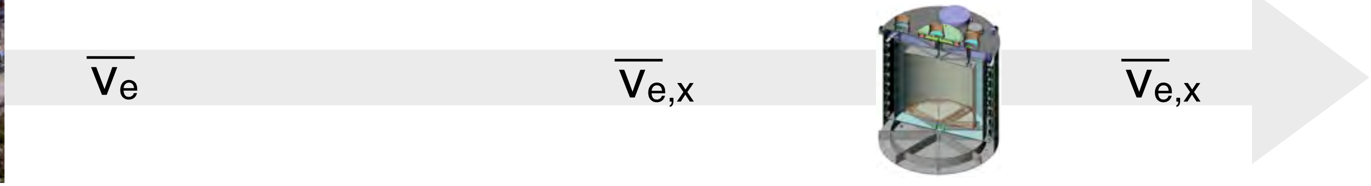
$0.318^{+0.019}_{-0.016}$

large, but not maximal!

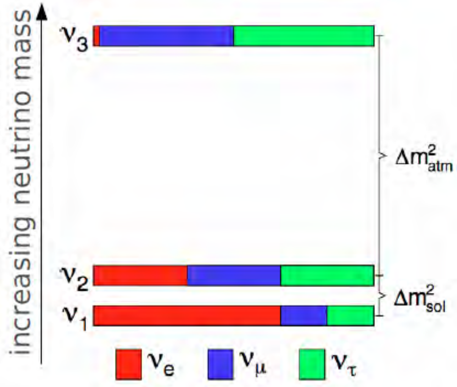
Reactor Neutrino Oscillations



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



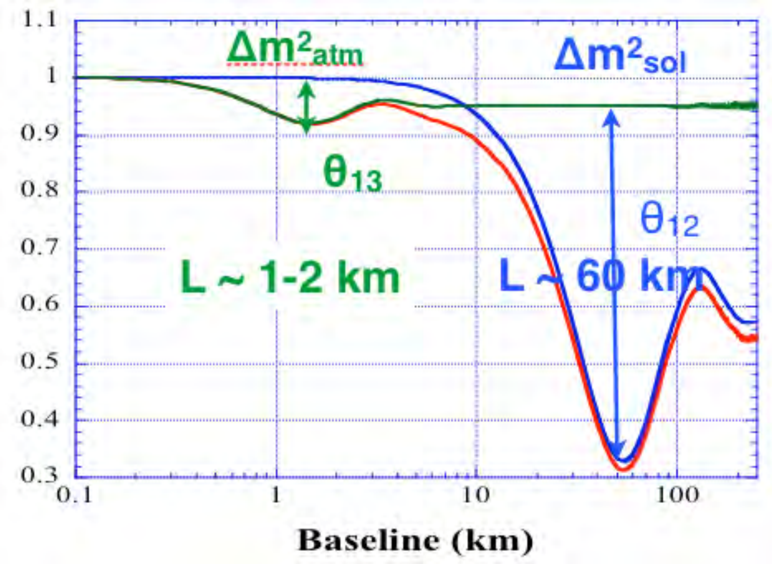
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



Δm^2_{23} = ~2.4 x 10^{-3} eV^2

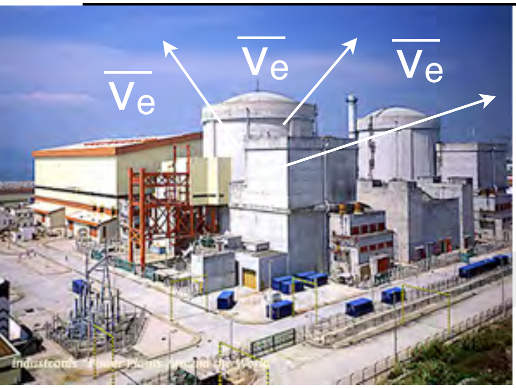
Δm^2_{12} = ~7.6 x 10^{-5} eV^2

amplitude of oscillation θ



oscillation frequency L/E →Δm^2

Reactor Neutrino Oscillations



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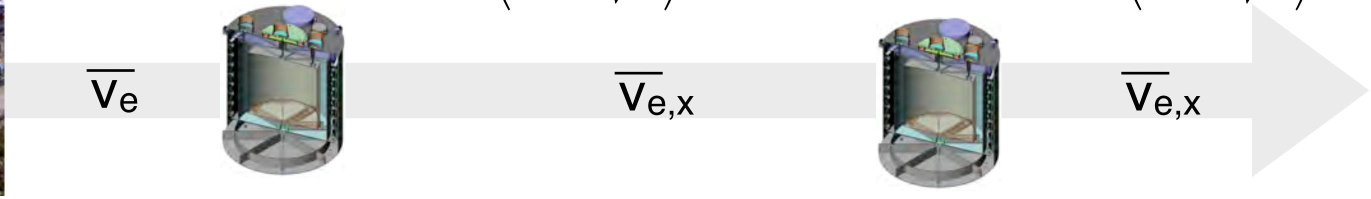
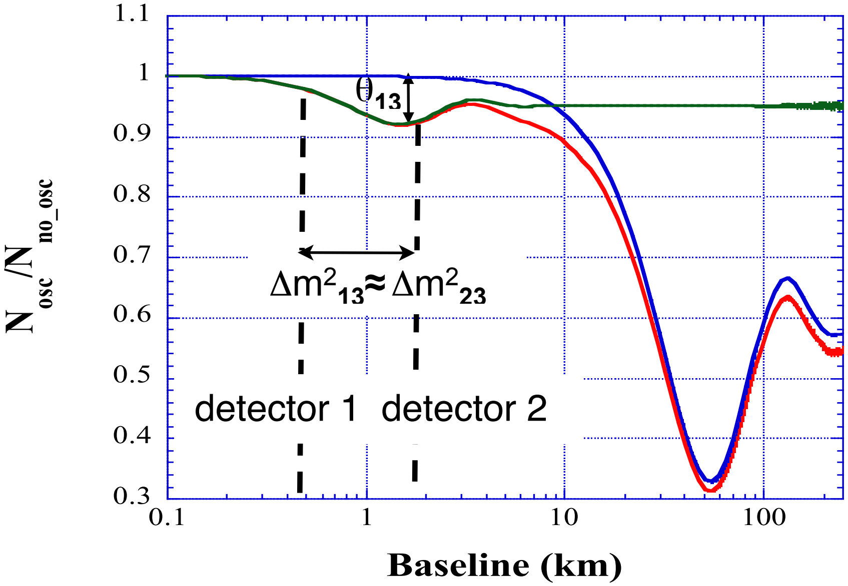


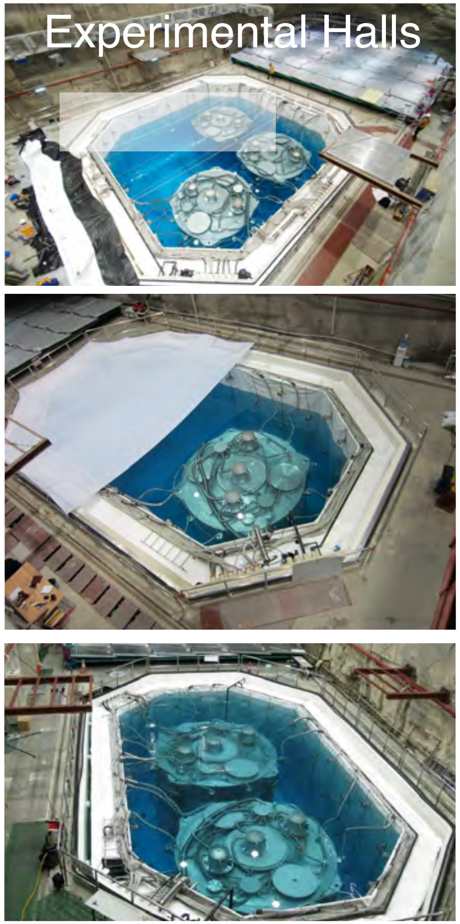
Absolute Reactor Flux
Largest uncertainty in previous measurements

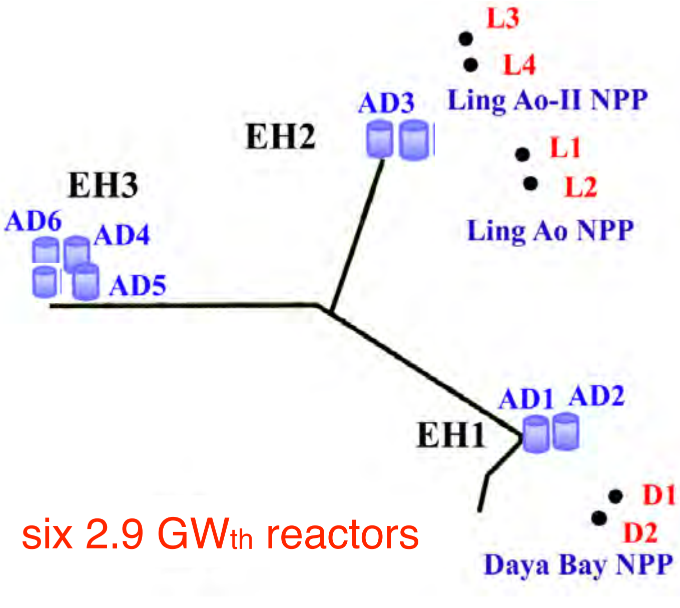
Relative Measurement
Removes absolute uncertainties!



relative measurement (largely) cancels reactor systematics

Daya Bay Reactor Experiment



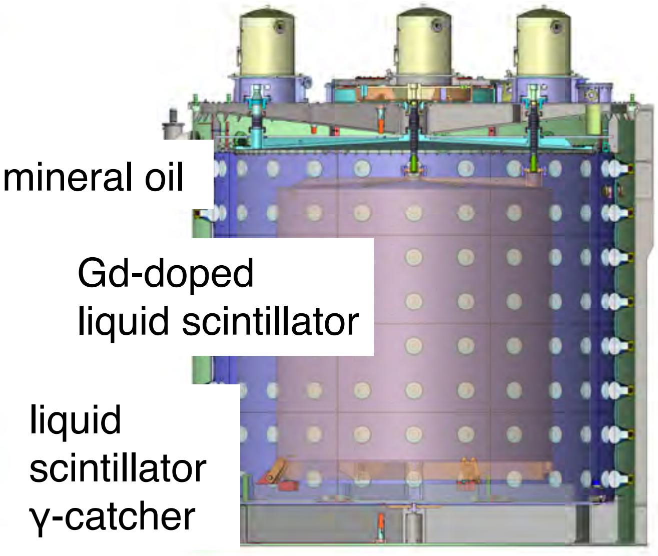


six 2.9 GW$_{th}$ reactors

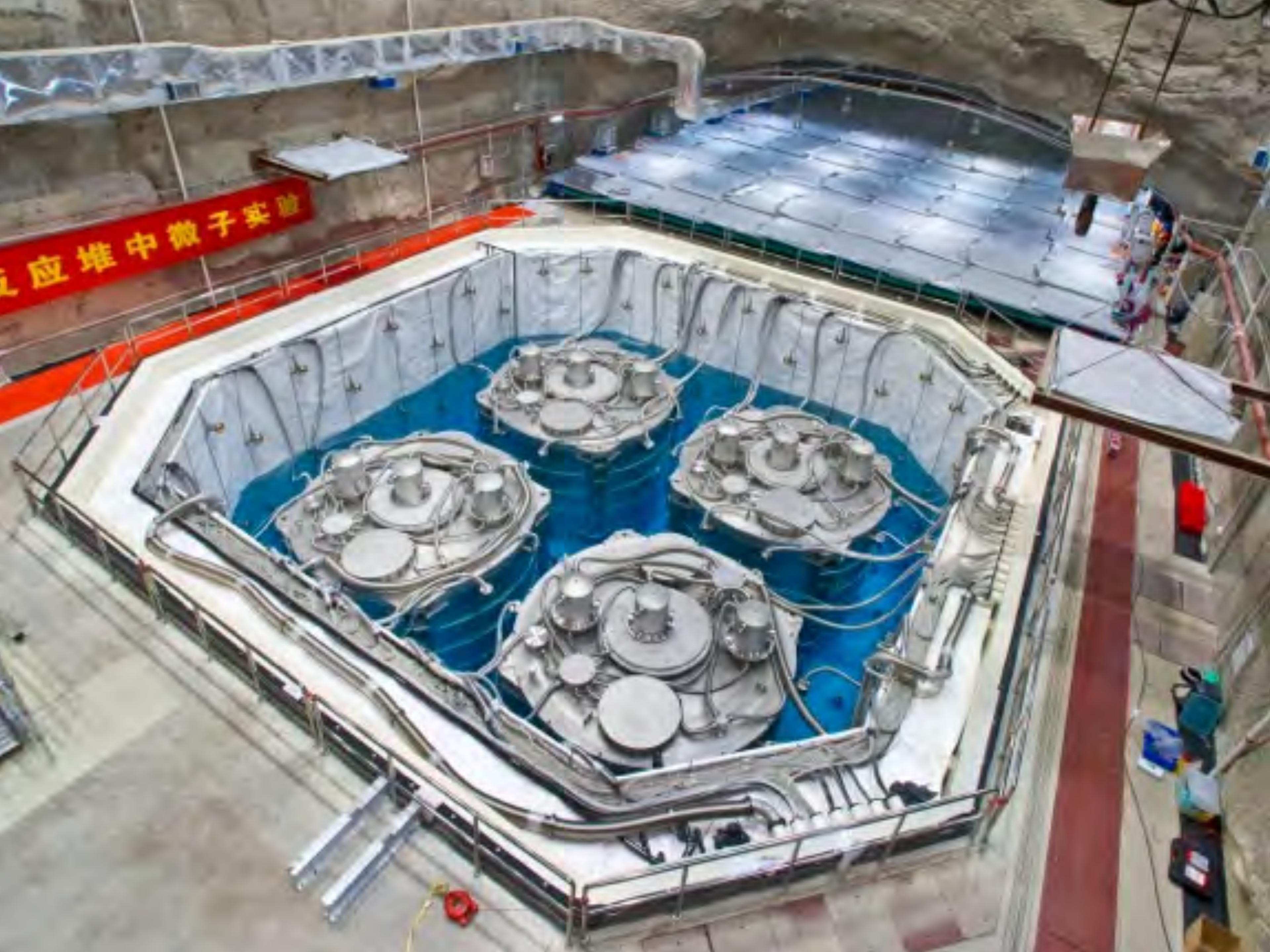
6 detectors, Dec 2011- Jul 2012
217 days

now running with 8 detectors

Antineutrino Detector

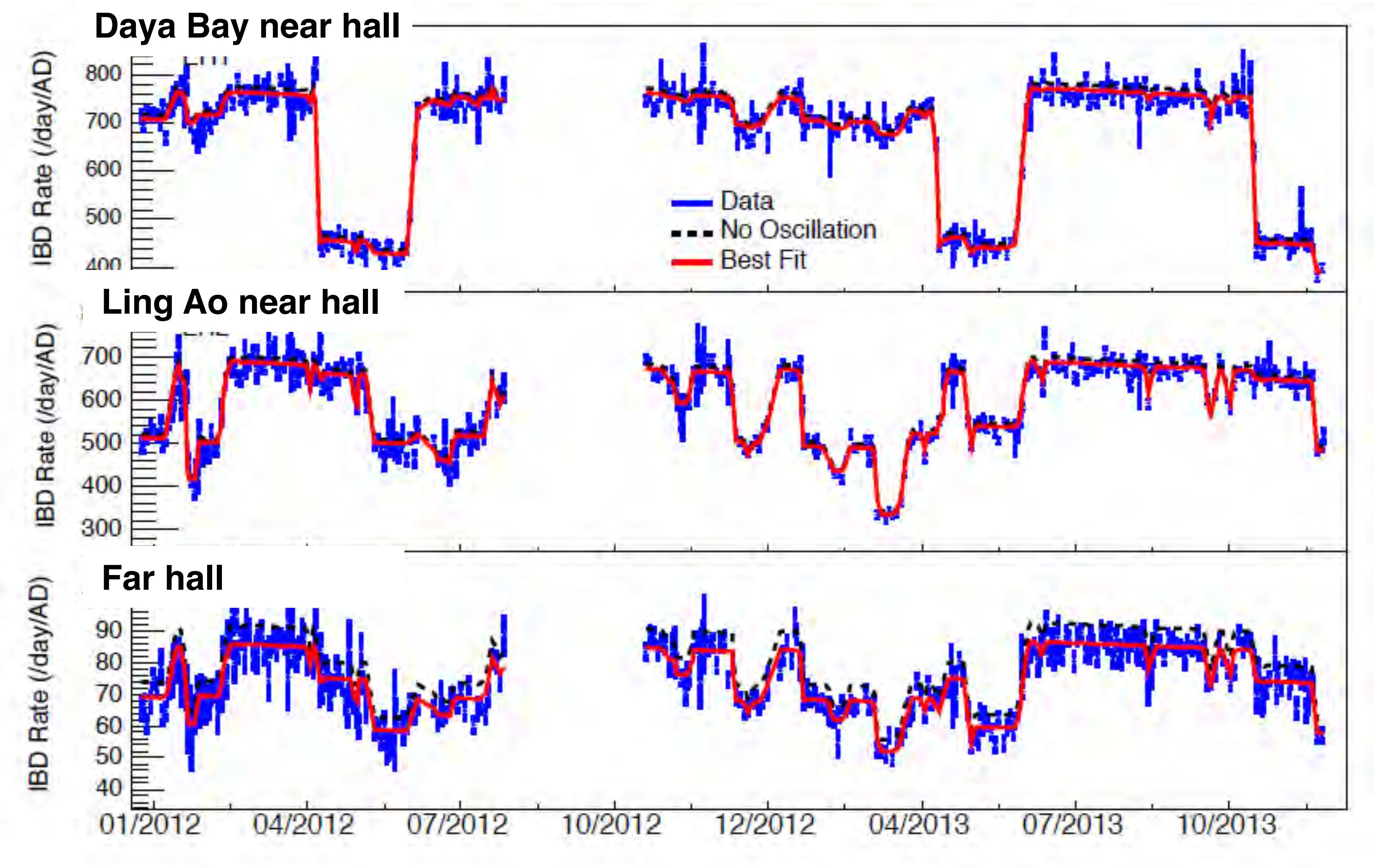


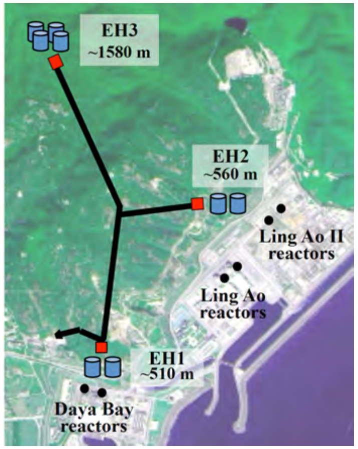
target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: (7.5 / √E + 0.9)%


应堆中微子实验

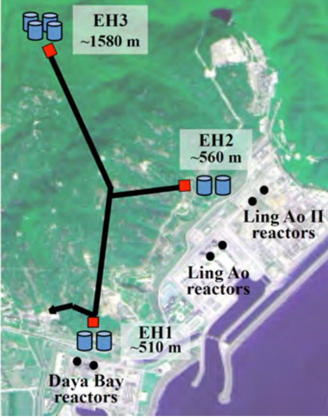
Daya Bay Antineutrino Rate vs Time

Over 1 Million Antineutrino Interactions Detected

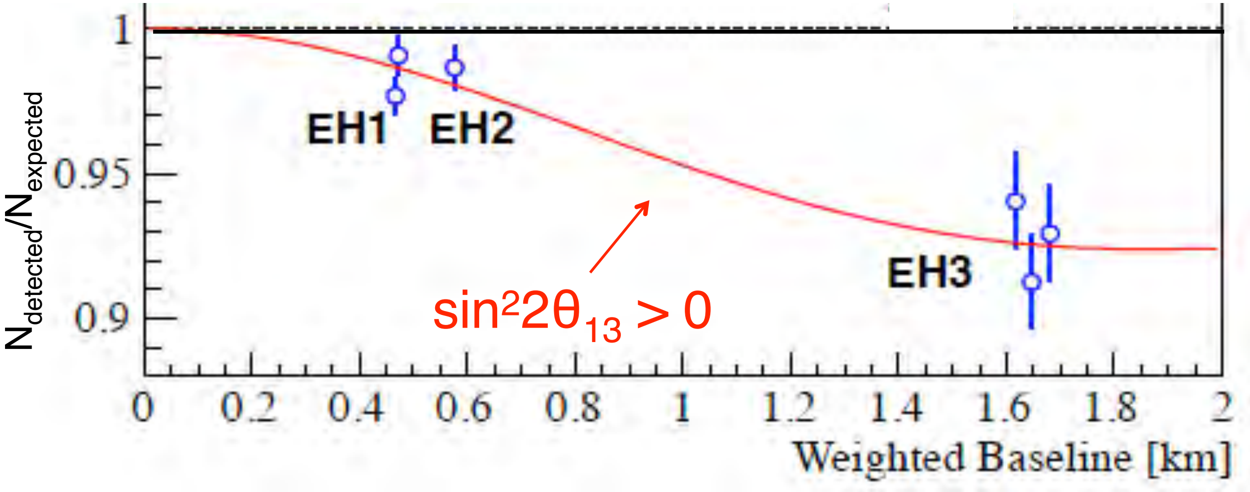


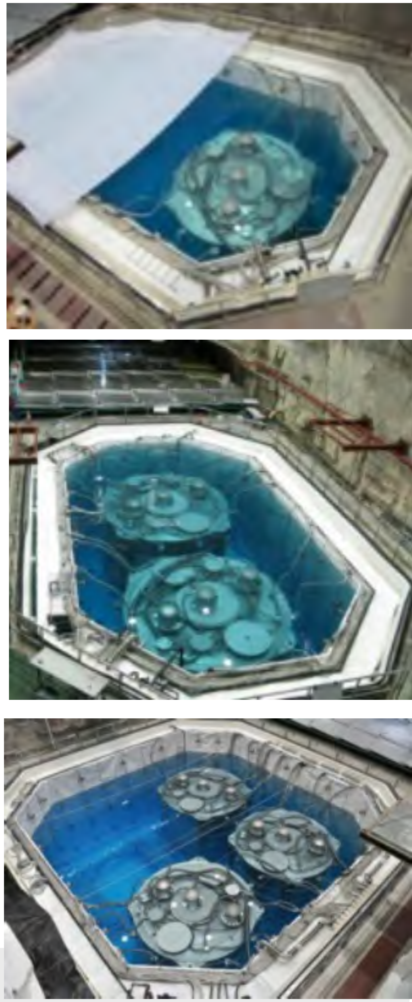


Observation of $\overline{\nu}_e$ Disappearance



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





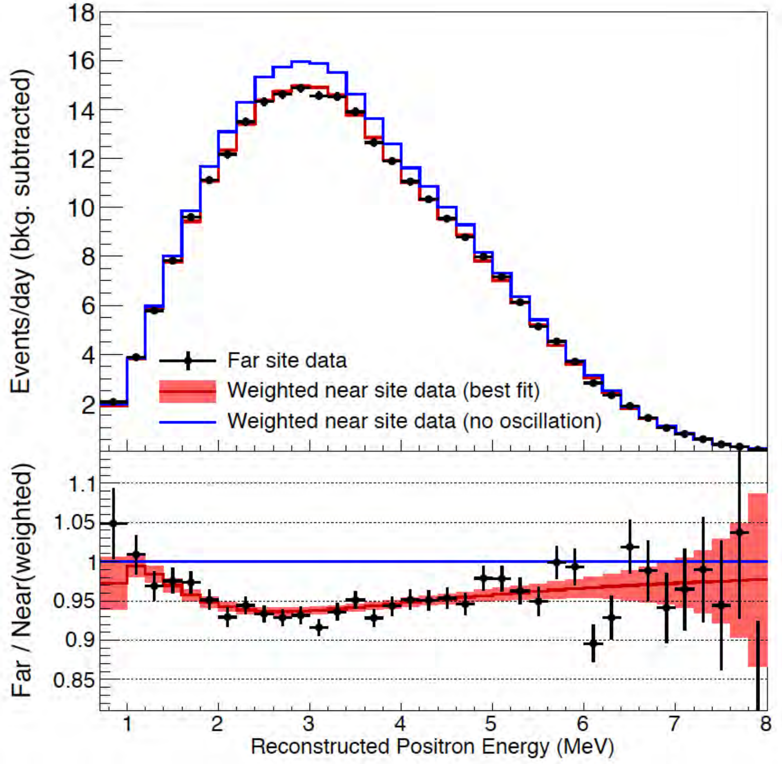
Obtained the most precise value of θ_{13}:

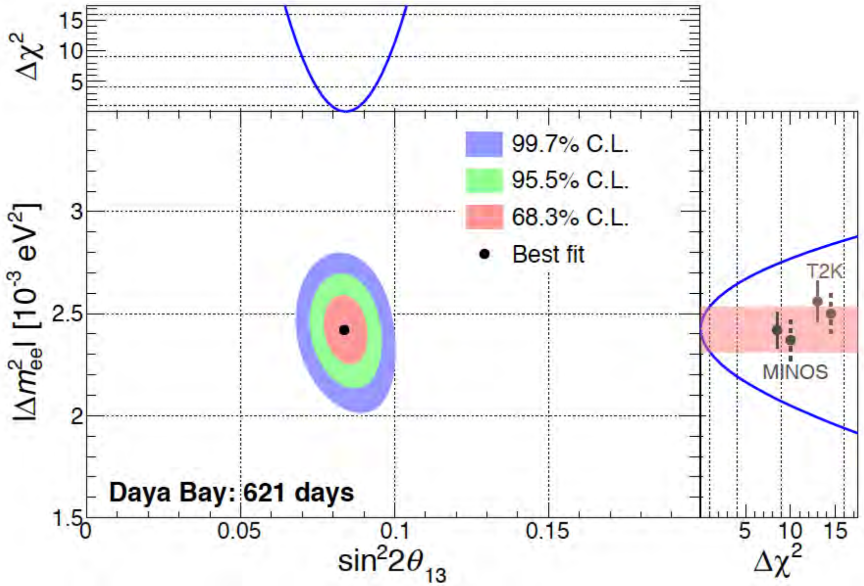
$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ [CPC **37**, 011001]

One of Science's breakthroughs of year 2012

Daya Bay Neutrino Oscillation

621 days of data, n+Gd





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

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

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

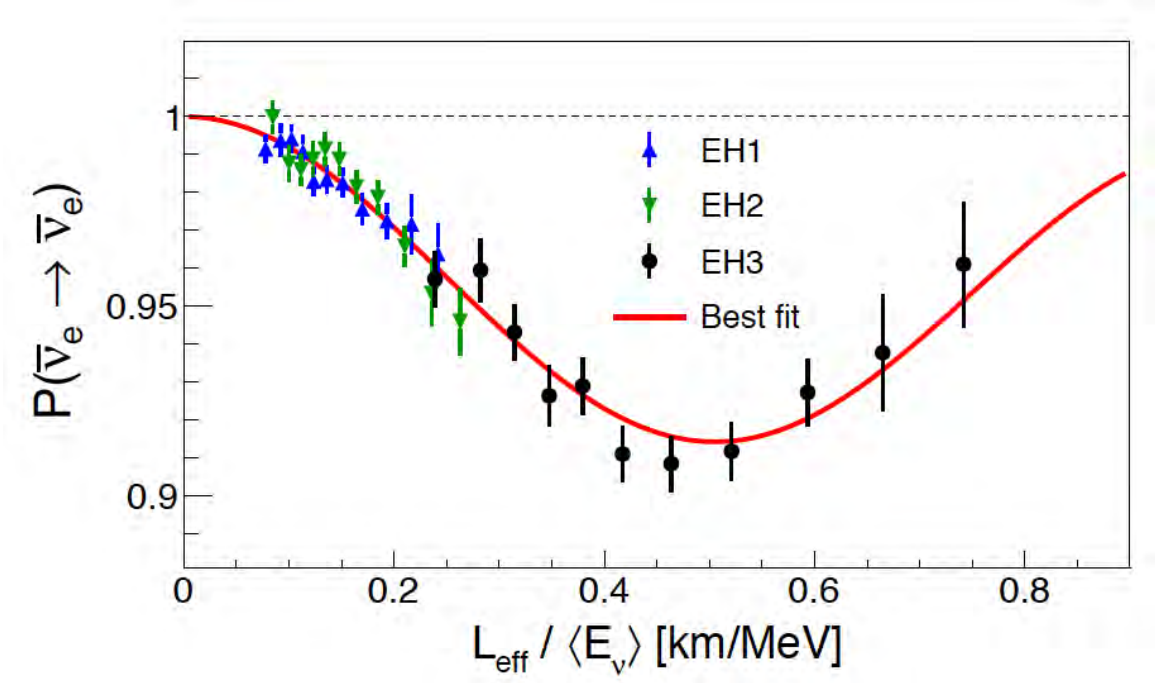
most precise measurement of $\sin^2 2\theta_{13}$ (6%), and Δm^2_{ee} in the electron neutrino disappearance channel (4%)

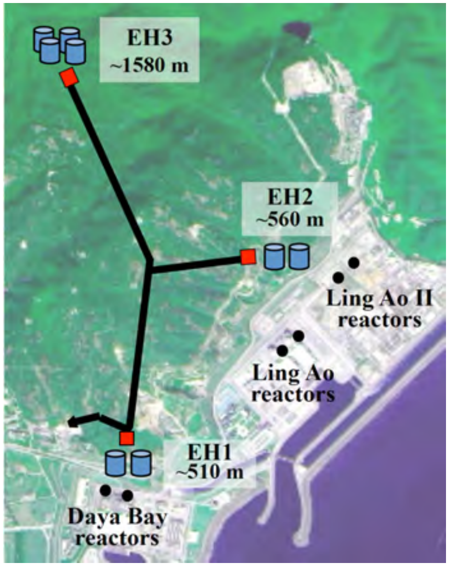
Phys.Rev.Lett. 115 (2015) 11, 111802

Daya Bay Neutrino Oscillation

Neutrino oscillation is energy and baseline dependent

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

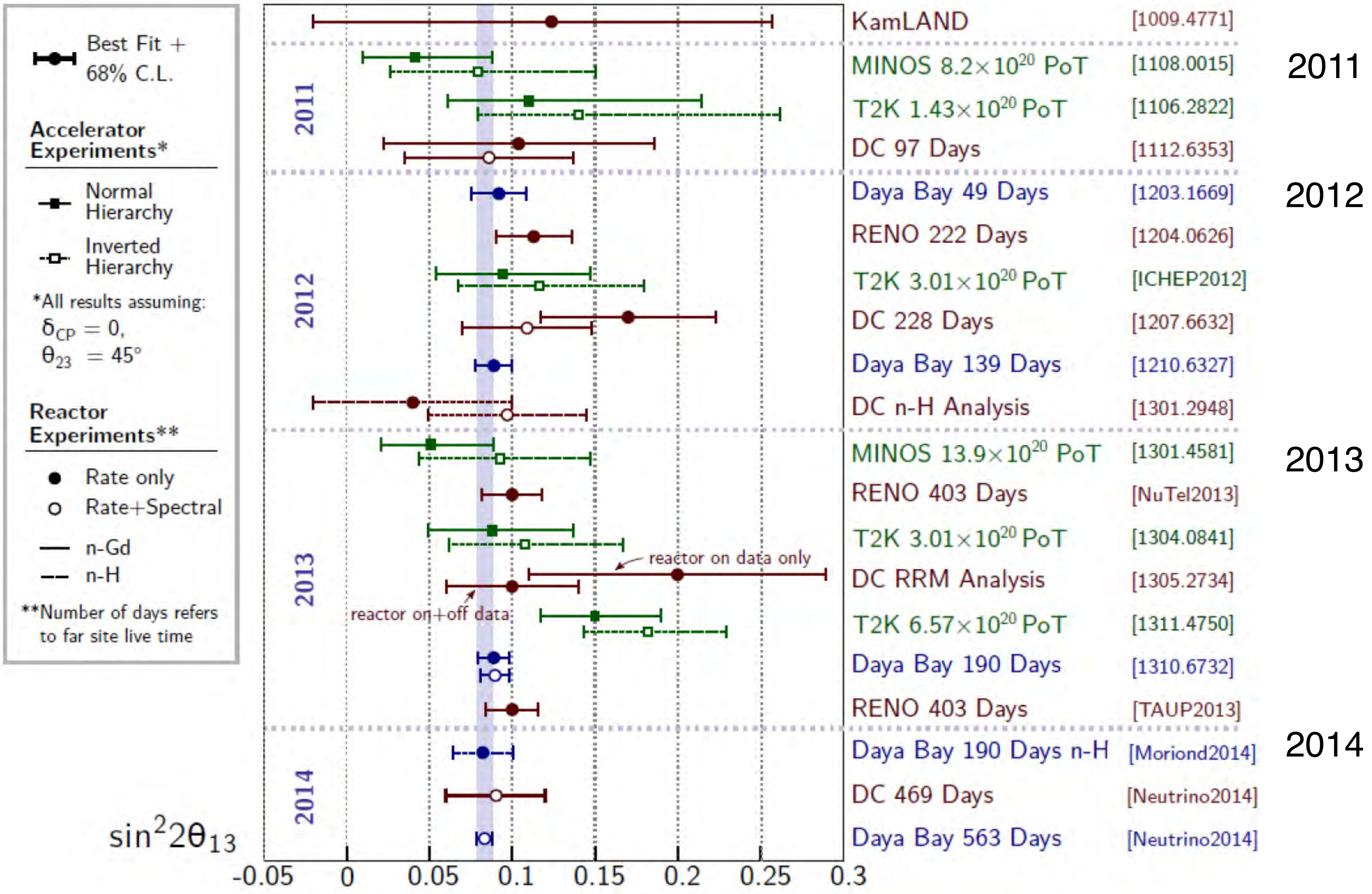




Daya Bay demonstrates L/E oscillation

Phys.Rev.Lett. 115 (2015) 11, 111802

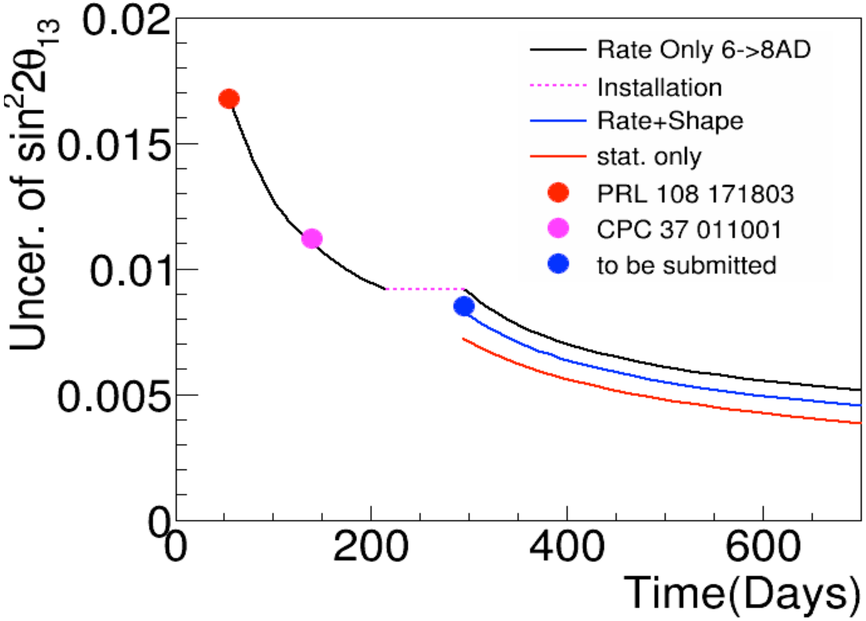
Daya Bay Precision Measurement of θ_{13}



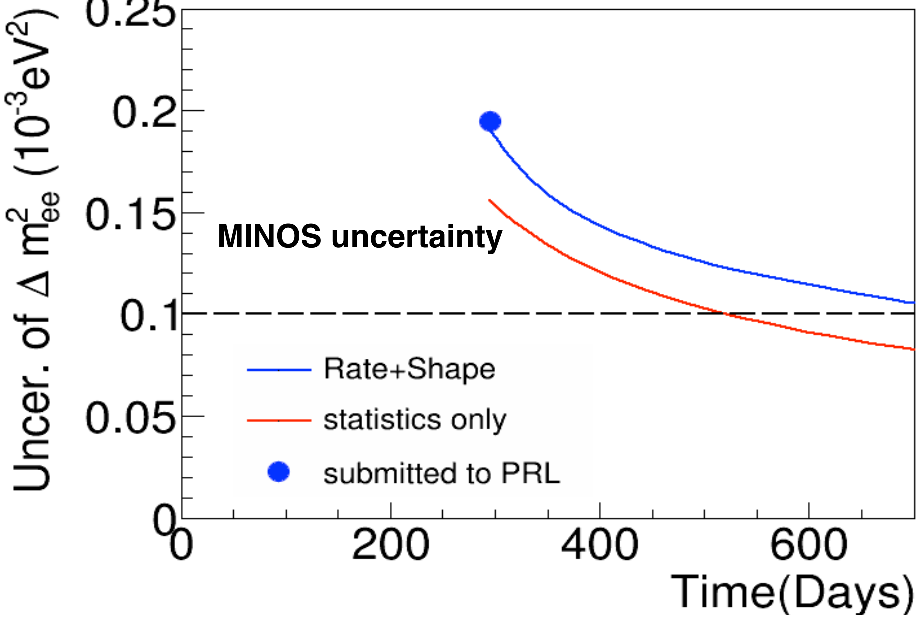
Daya Bay Sensitivity Projections

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.

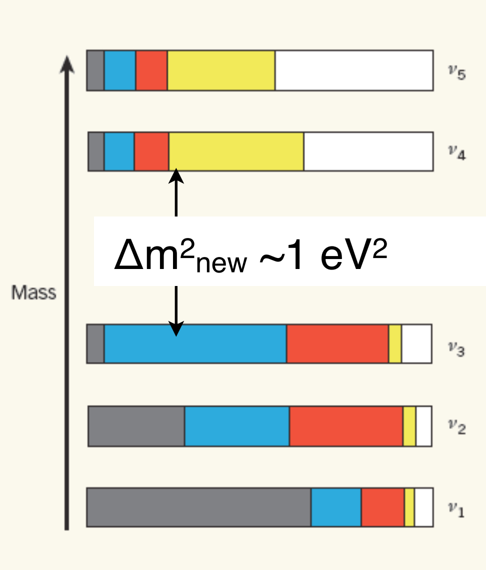
Major systematics:

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.

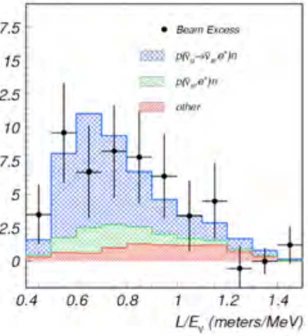
ν Anomalies
Beyond 3 Neutrinos?



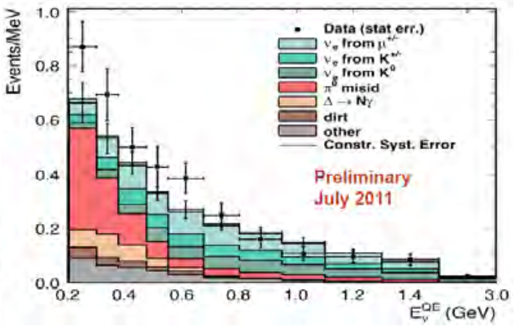
$\Delta m^2_{new} \sim 1\ eV^2$

Neutrino Anomalies - More than 3 ν?

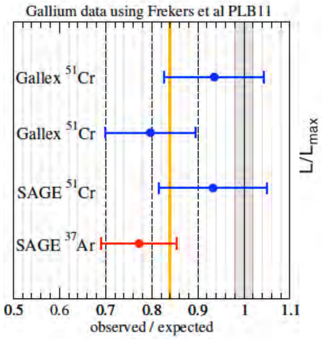
LSND



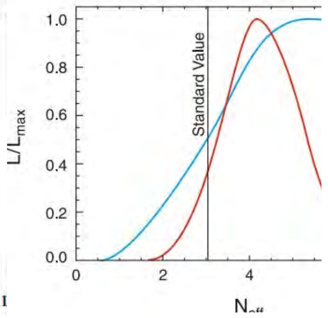
MiniBoone



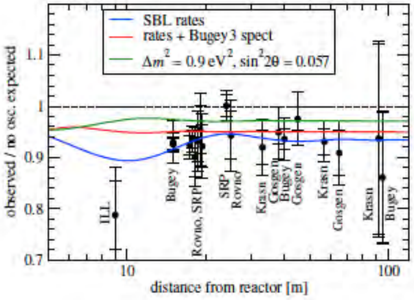
Ga Source



Cosmology (WMAP)



Reactor

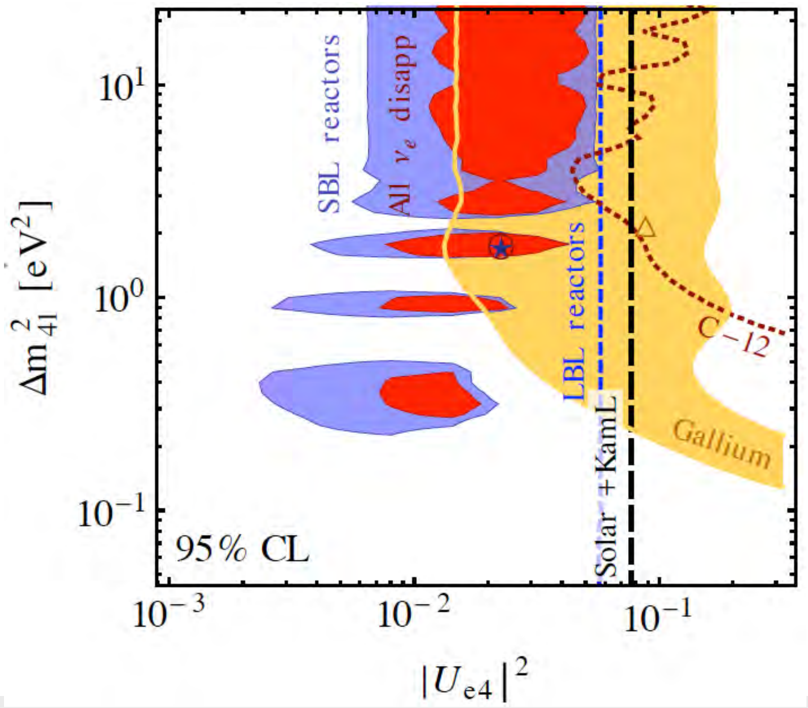


Anomalies in 3-ν global oscillation data

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

new oscillation signal requires:

$\Delta m^2 \sim O(1 eV^2)$ and $\sin^2 2\theta > 10^{-3}$
"sterile" neutrino states

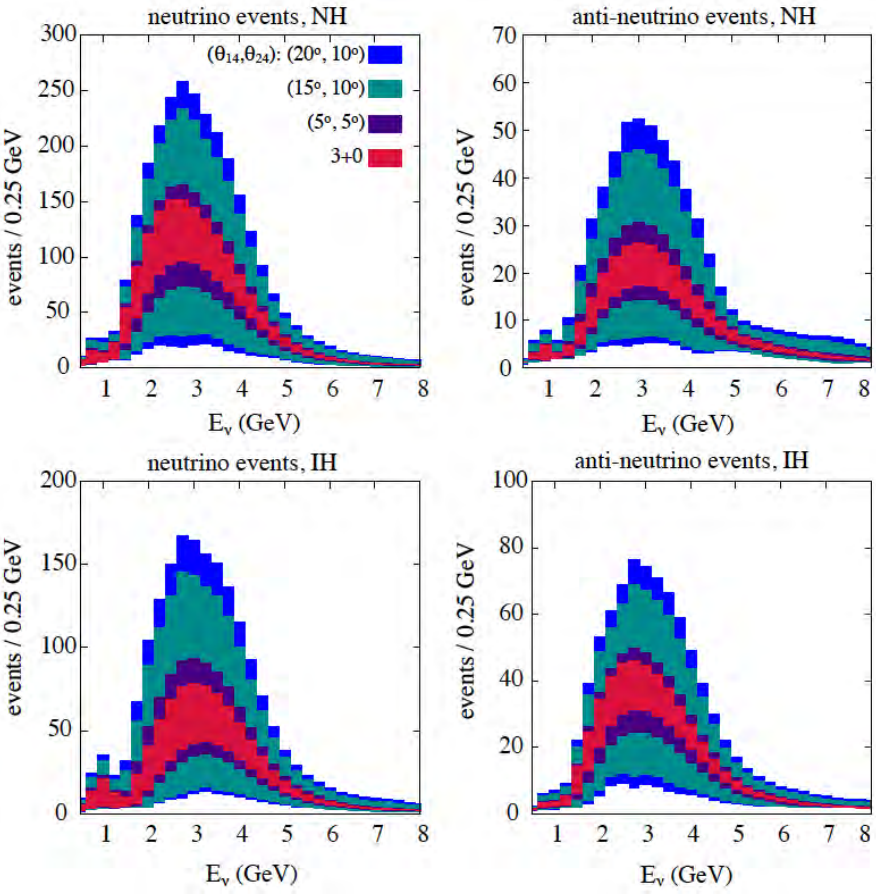


Implications for Future Neutrino Program

Discovery of eV-scale sterile neutrinos would be a paradigm change for particle physics.

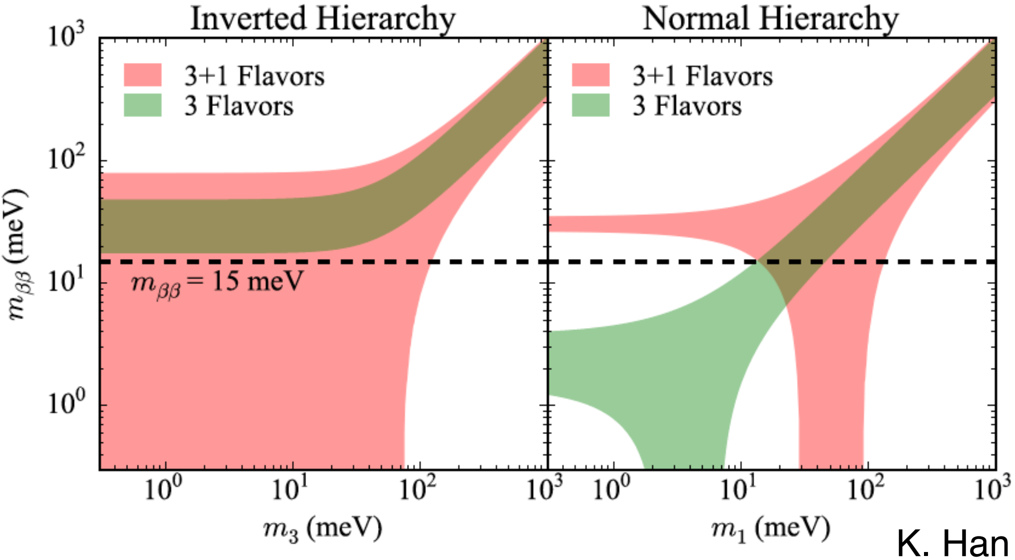
- Expected neutrino spectrum and sensitivity to CP violation for long-baseline neutrino program
- Effective neutrino mass measured by $0\nu\beta\beta$

DUNE



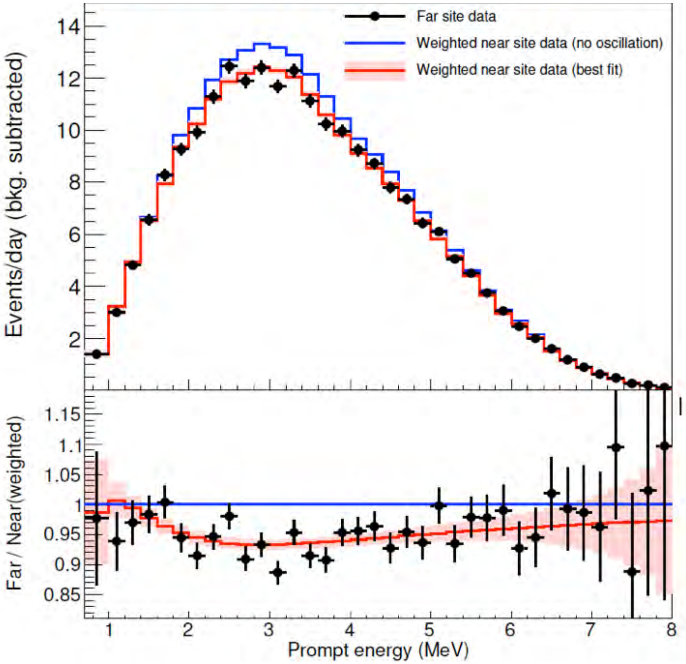
Gandhi, Kayser, Masud, Prakash arXiv: 1508.06275

Neutrinoless Double Beta Decay

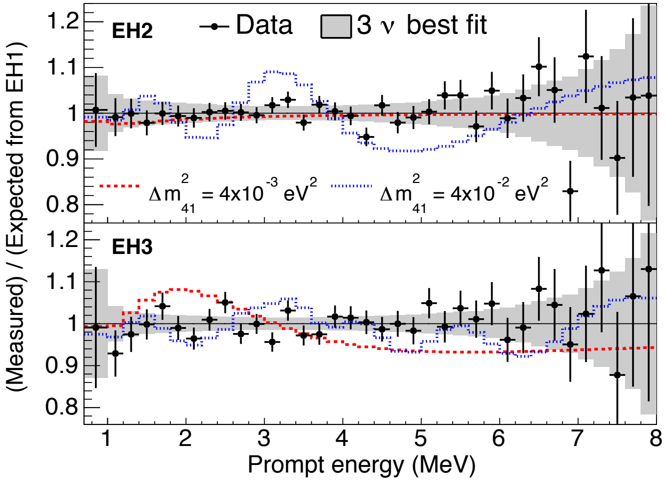


K. Han

Search for Sterile Neutrinos at Daya Bay



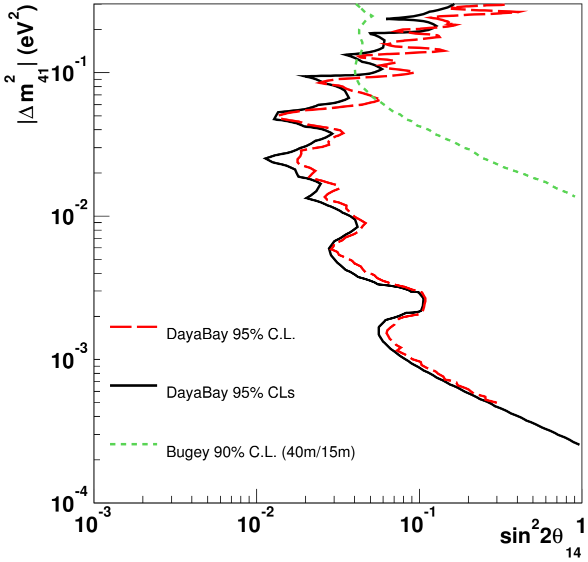
Phys. Rev. Lett. 113, 141802 (2014)



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$

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

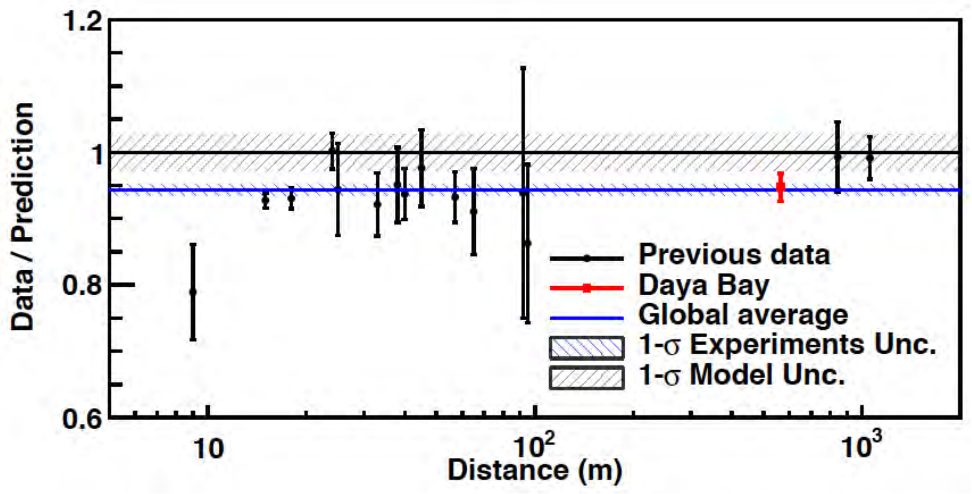
Daya Bay probes largely unexplored region at $\Delta m^2_{41} < 0.1\ \mathrm{eV}^2$



Reactor Flux and Spectrum “Anomalies”

Flux Deficit

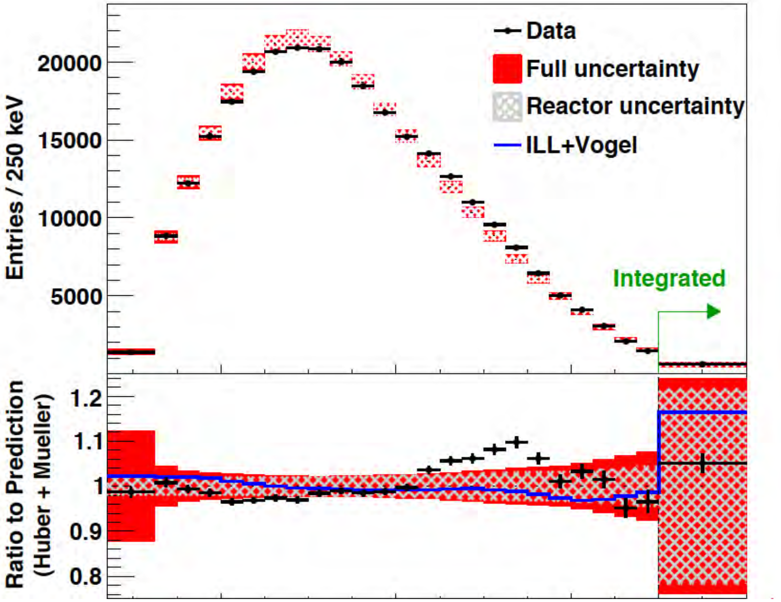
Consistent with previous experiments



Extra neutrino oscillations or artifact of flux predictions?

Understanding reactor flux and spectrum anomalies requires reactor measurements

Spectral Deviation



New feature in 4-6 MeV region of spectrum.

arXiv:1508.04233, accepted by PRL
Daya Bay collaboration

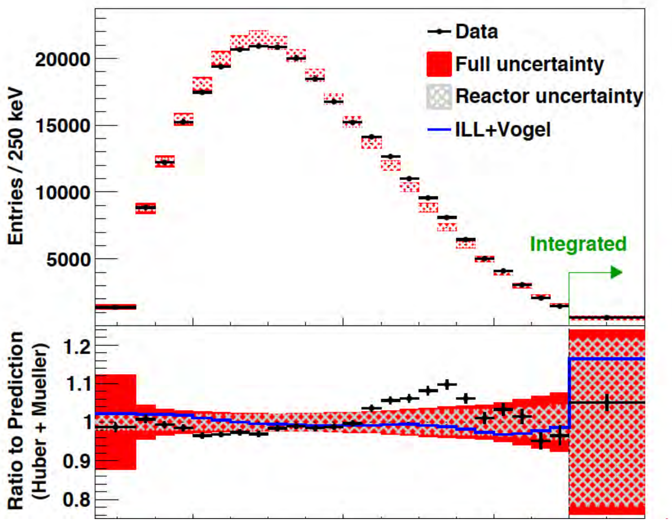
Reactor Spectrum Anomaly

Spectral deviation

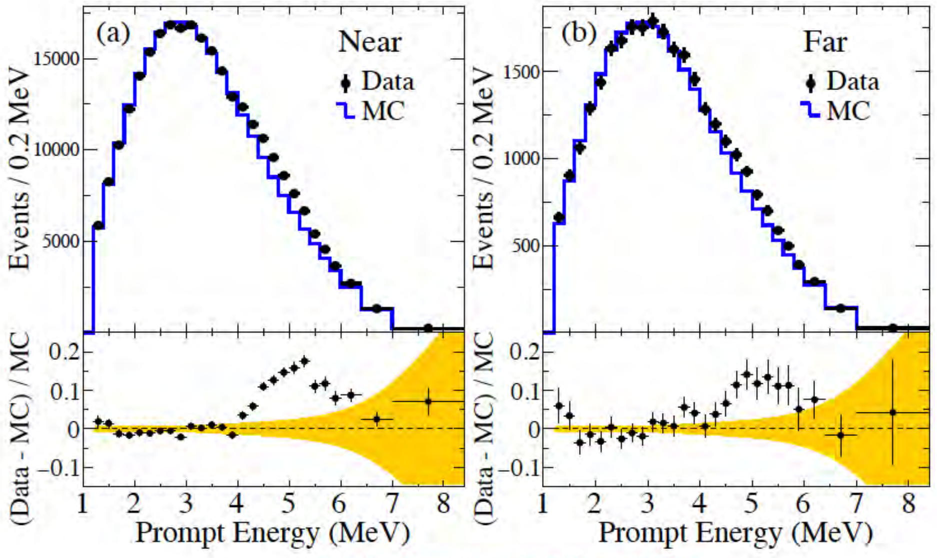
- 10% excess in 4-6 MeV region when compared to model calculations

Observed in all 3 θ_{13} experiments

Daya Bay

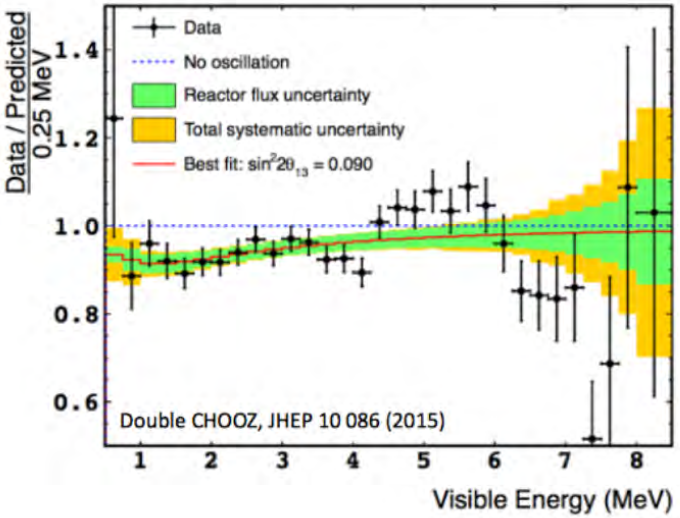


RENO



RENO: arXiv: 1511.05849

Double Chooz



Modeling the Reactor Spectrum

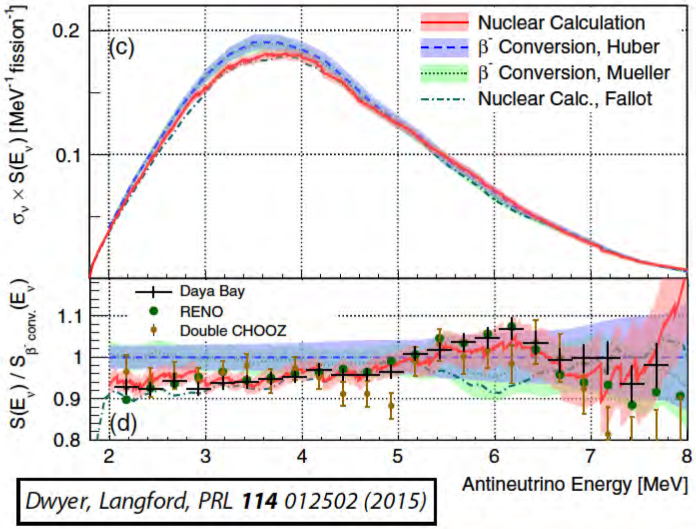
Challenges

Reactor neutrino spectrum is an admixture of thousands beta branches from fission products of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu

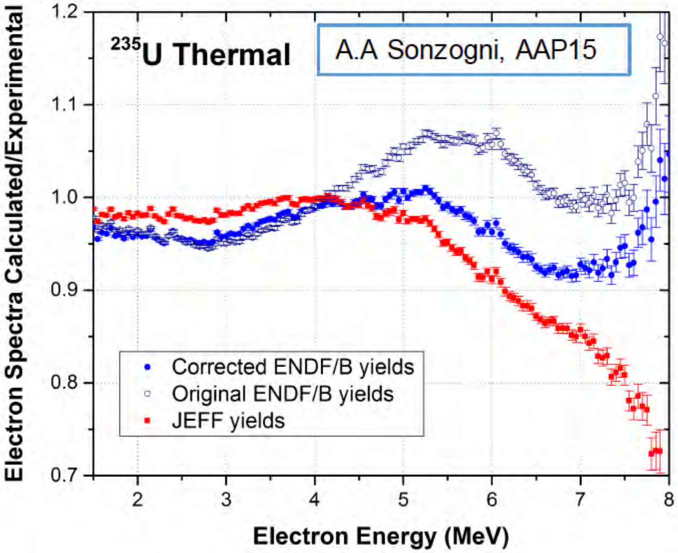
Conversion method: Cumulative neutrino spectrum from measured beta spectrum

Summation method: Combine fission yields with decay data in databases

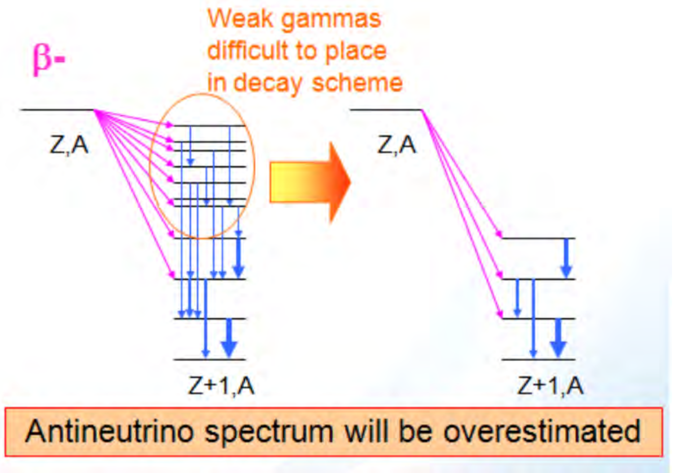
- discrepancies between databases
- decay schemes



*Dwyer, Langford, PRL **114** 012502 (2015)*



A.A Sonzogni, AAP15

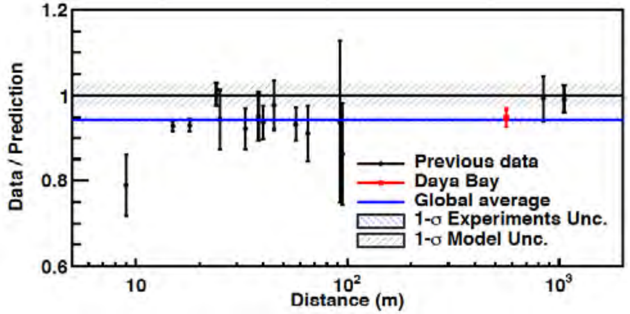


Antineutrino spectrum will be overestimated

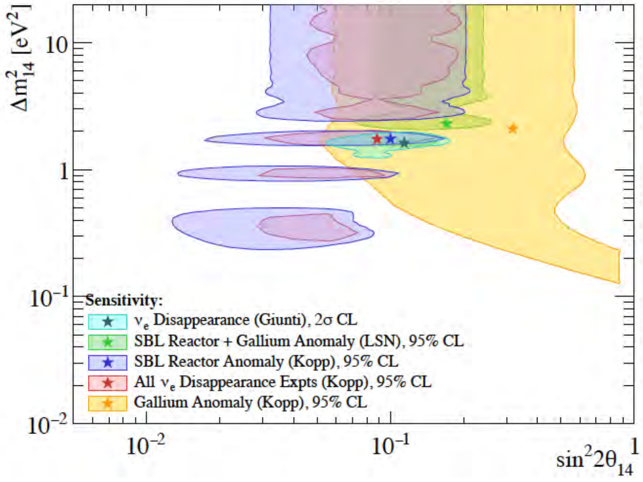
Short-Baseline Reactor Neutrino Experiments

Search for sterile neutrinos through neutrino oscillations

Test reactor anomaly

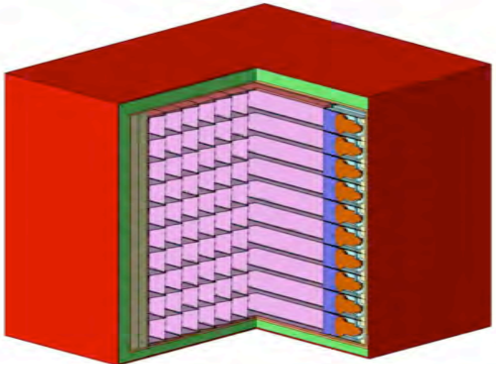


Test allowed oscillation parameter space



Measurement of the Relative Reactor Flux and Spectrum at Different Baselines

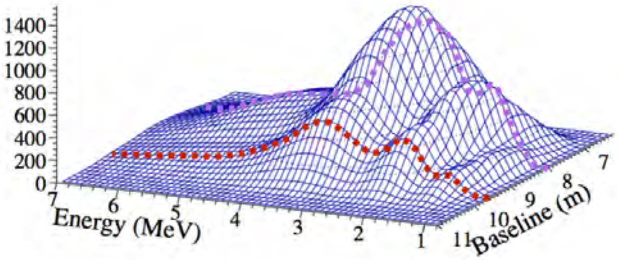
independent of reactor models/predictions



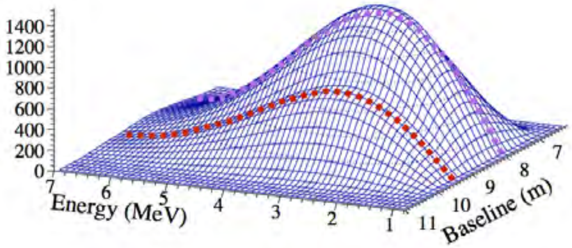
Segmented detector

Relative measurement within detector

oscillated spectrum



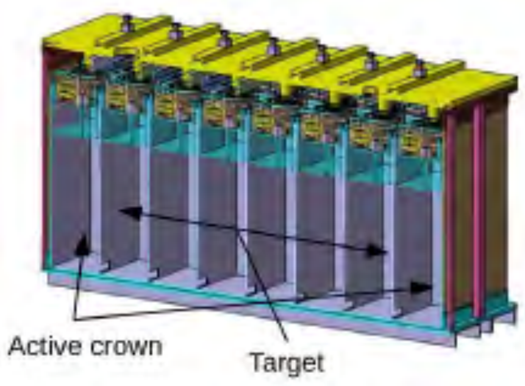
unoscillated spectrum



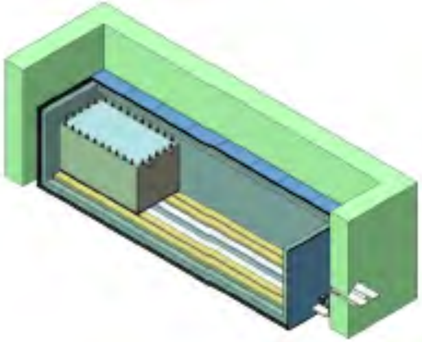
each segmented measures L/E

Short-Baseline Reactor Experiments Worldwide

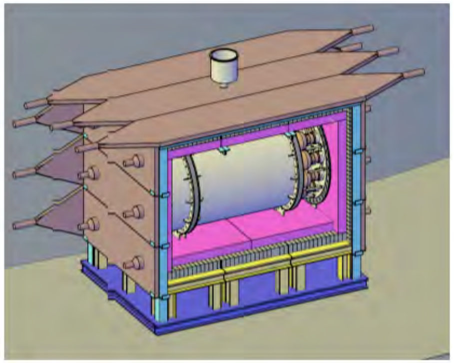
STEREO: Gd-LS detector at 10m from ILL , France



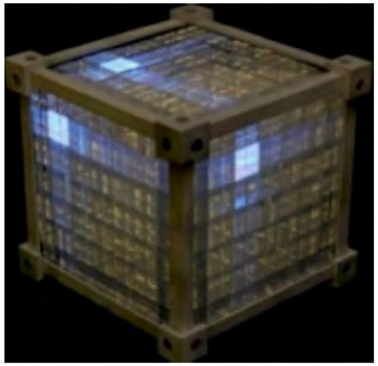
Neutrino-4: Gd-LS detector at 6-12m from SM-3, Russia



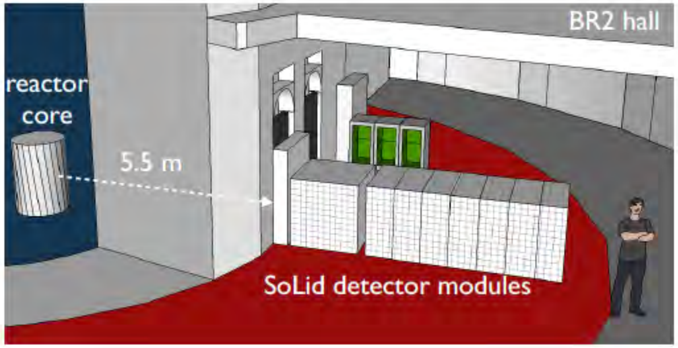
NEOS: Gd-LS detector at ~30m from Hanbit, Korea



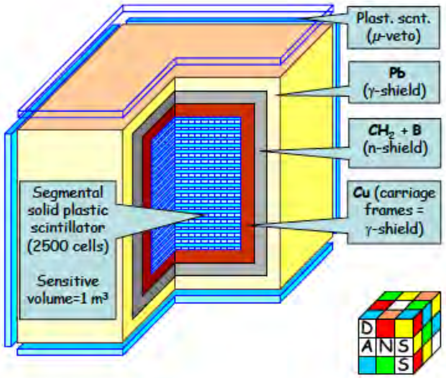
NuLAT: Boron-loaded plastic scintillator cubes



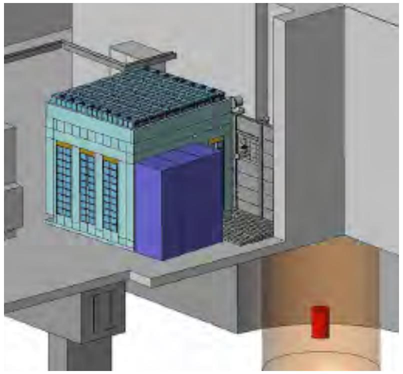
SoLid/CHANDLER: segmented composite scintillator cubes at 5.5m from BR2, Belgium



DANSS: Segmented plastic scintillator at ~10m from KNPP, Russia



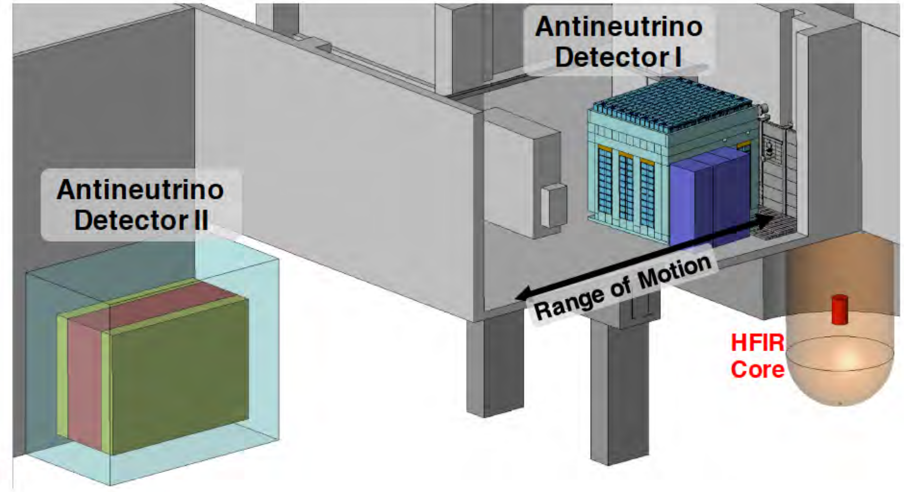
PROSPECT: Segmented 6Li liquid scintillator at 7-12m from HFIR, US



Precision Oscillation and Spectrum Experiment

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

2 detectors, movable baseline, research reactor



Phase I
one <u>movable detector</u> AD-I, ~7-12 m baseline

power: 85 MW (research)
fuel: highly enriched uranium (^{235}U)
core shape: cylindrical, compact
duty-cycle: 41%

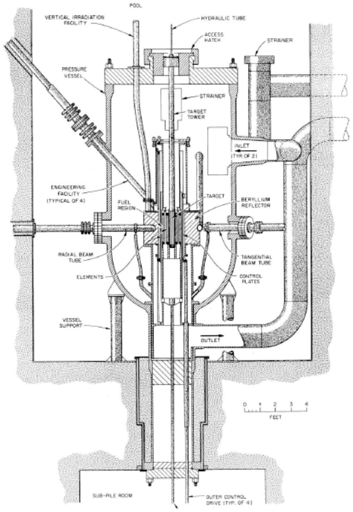
Phase II
two detectors,
<u>movable</u> AD-I, ~7-12m baseline
stationary AD-II, ~15-19m baseline

physics program, arXiv: 1512.02202
test detector studies, JINST 10 P11004 (2015)
background measurements, NIM A806 (2016) 401
whitepaper, arXiv: 1309.7647

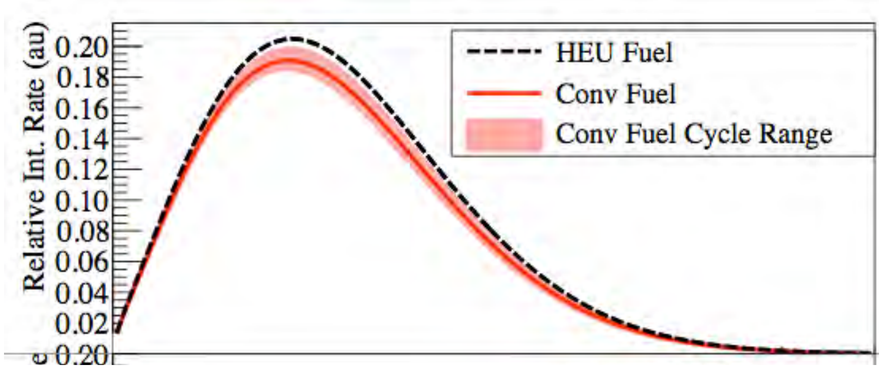
prospect.yale.edu

High Flux Isotope Reactor, Oak Ridge National Lab

US Research Reactor



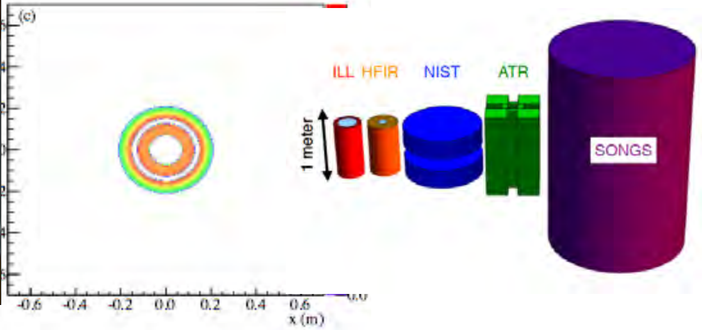
Research Reactor Spectrum



HEU core provides static spectrum of mainly ^{235}U.

power: 85 MW (research)
fuel: highly enriched uranium (^{235}U)
core shape: cylindrical
size: h=0.5m r=0.2m (compact)
duty-cycle: 41%

Compact reactor core

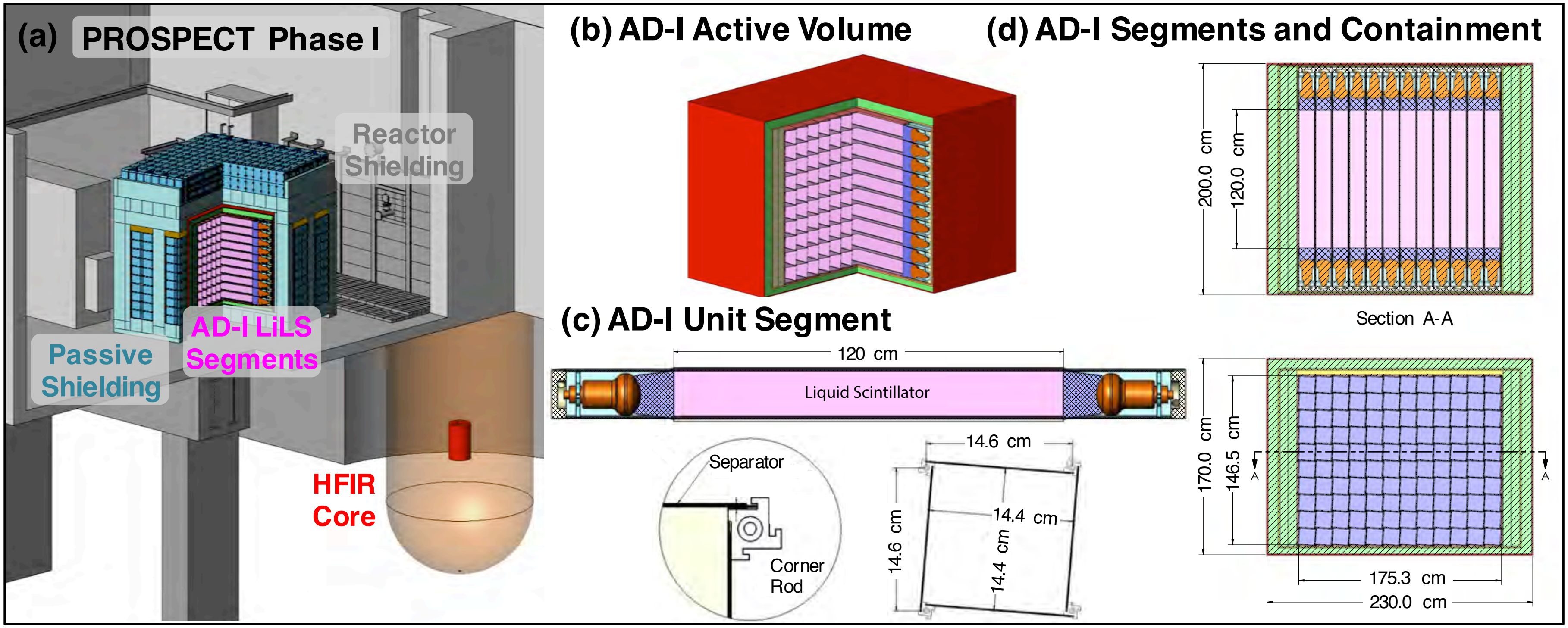


Nucl. Instrum. Meth. A806 (2016) 401–419,
arXiv:1506.03547,
PROSPECT collaboration

Compact core (< 1m) avoids oscillation washout

PROSPECT Phase I Detector System

Antineutrino Detector

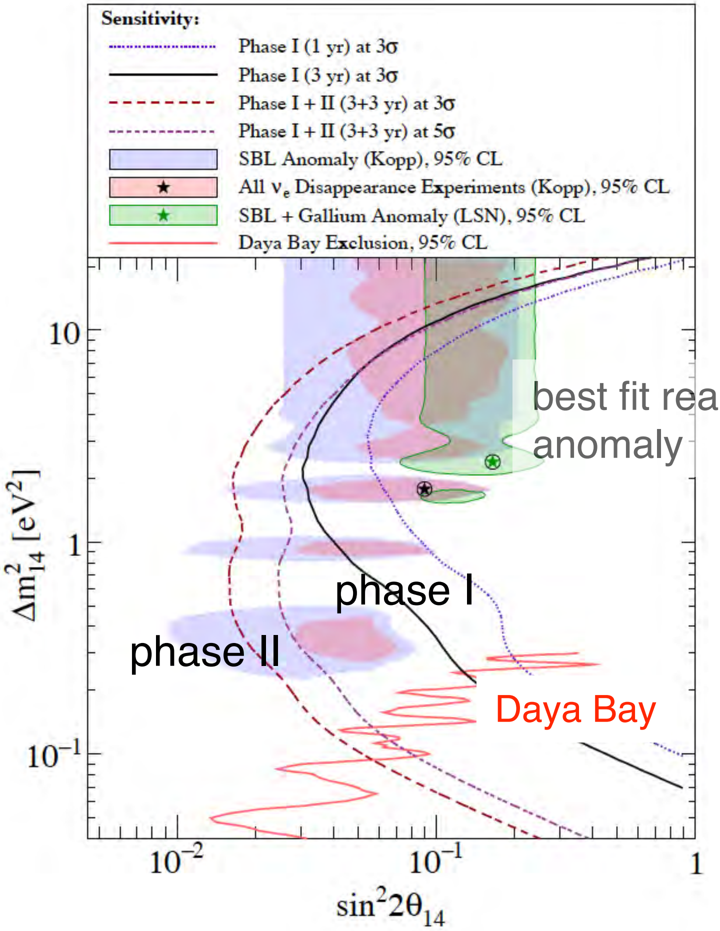


- 3000L of ^{6}Li liquid scintillator
- 120 scintillator loaded cells, ~15x15x120cm
- double ended PMT readout, light guides, <4-5%/$\sqrt{E}$ resolutions
- thin optical separators, minimal dead material
- containment vessel, filled in place

PROSPECT Physics

A Precision Oscillation Experiment

4σ test of best fit after 1 year
>3σ test of favored region after 3 years
5σ test of allowed region after 3+3 years



best fit reactor anomaly

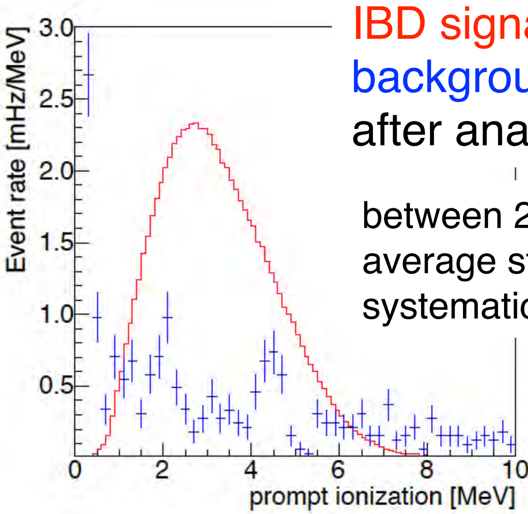
phase I

phase II

Daya Bay

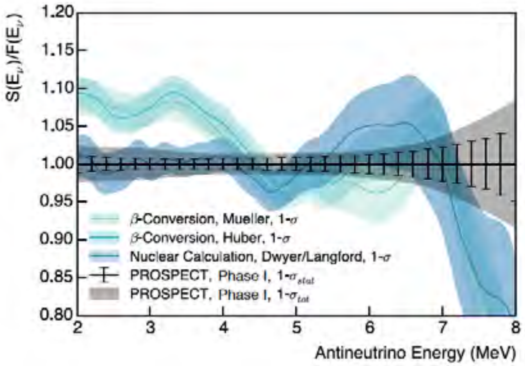
A Precision Spectrum Experiment

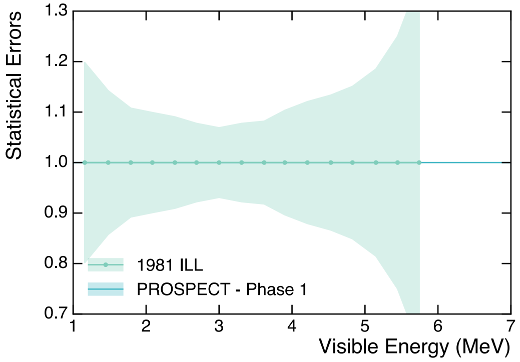
Measurement of ^{235}U spectrum
Compare different reactor models
Opportunity to compare different reactor cores



IBD signal
backgrounds
after analysis cuts

between 2-6 MeV:
average stat. precision < 1.5%,
systematics < 2%





PROSPECT Detector and Shielding Development

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 cm length
1.7 liters
^{6}LiLS

PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

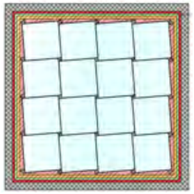
1m length
23 liters
LS, ^{6}LiLS

PROSPECT-50
Baseline design prototype
Winter 2015

1x2 segments
1.2m length
50 liters
^{6}LiLS

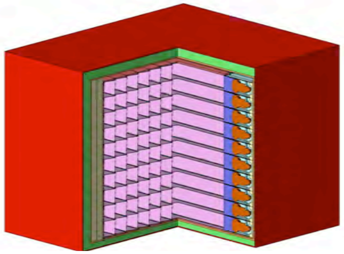
PROSPECT-400*
Fiducialization and background studies
Mid 2016

4x4 segments
1.2m length
400 liters
^{6}LiLS

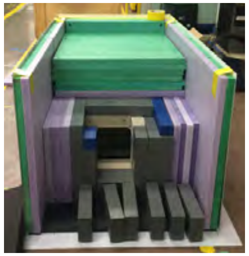


PROSPECT AD-I
Physics measurement
Late 2016

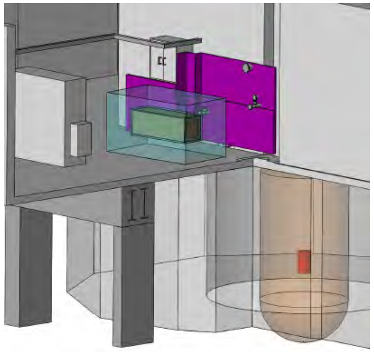
10x12 segments
1.2m length
~3 tons
^{6}LiLS



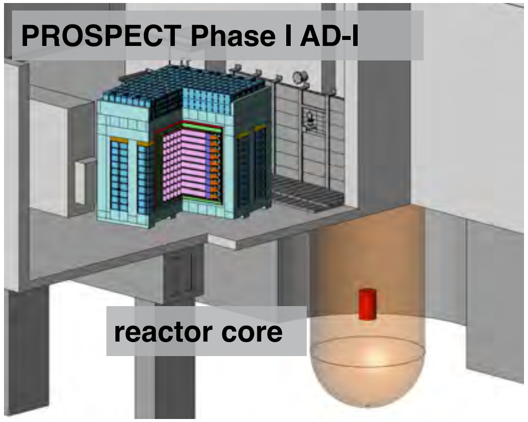
**Technically ready to proceed directly to AD-1 with available funding*



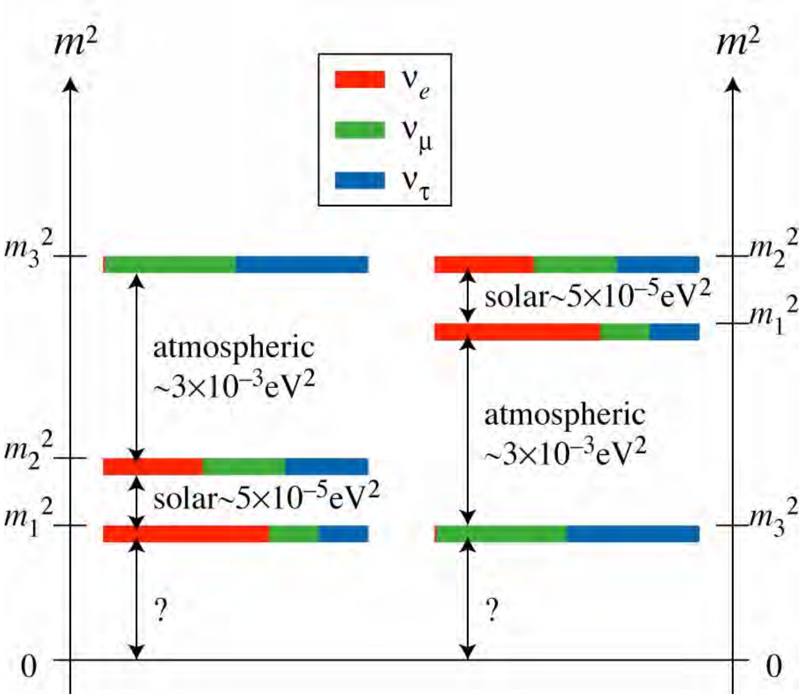
multi-layer shielding



local reactor shielding

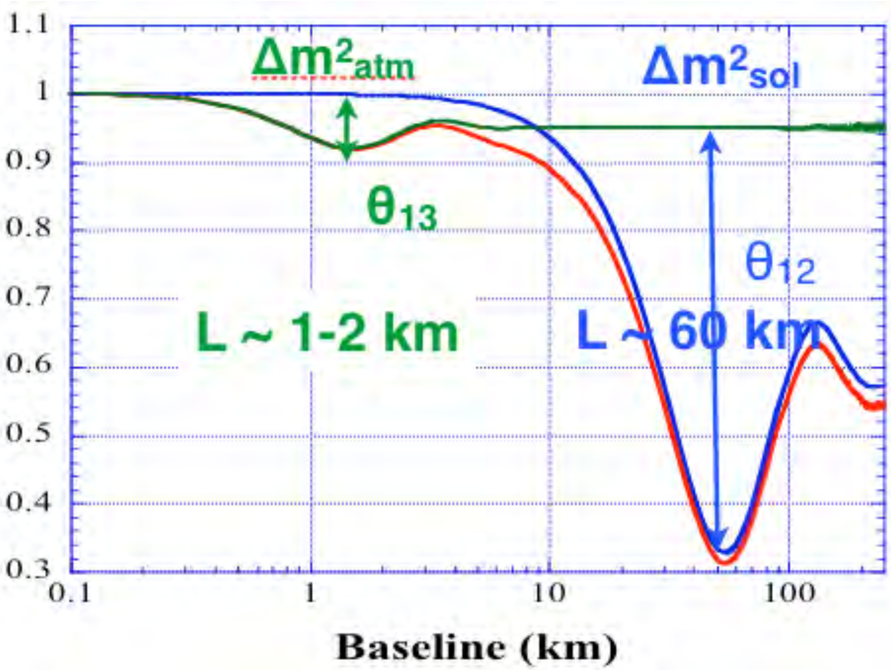


Mass Hierarchy?



Mass Hierarchy and Reactor Neutrinos

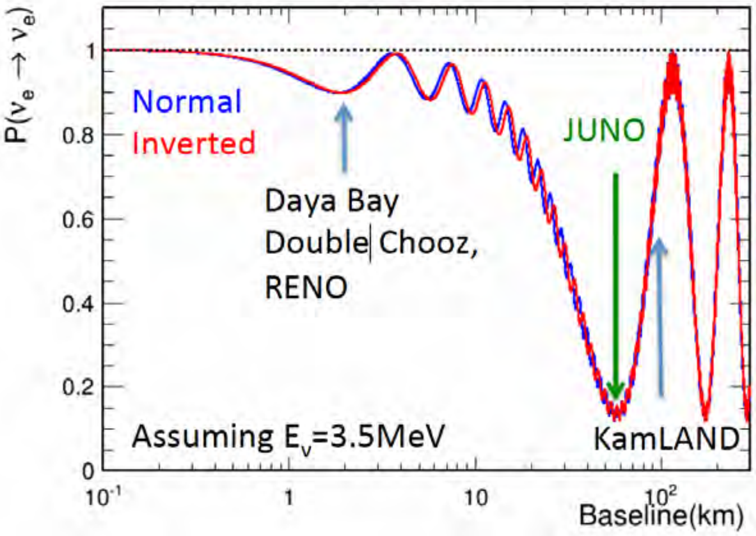
Precision Measurement at ~ 58km

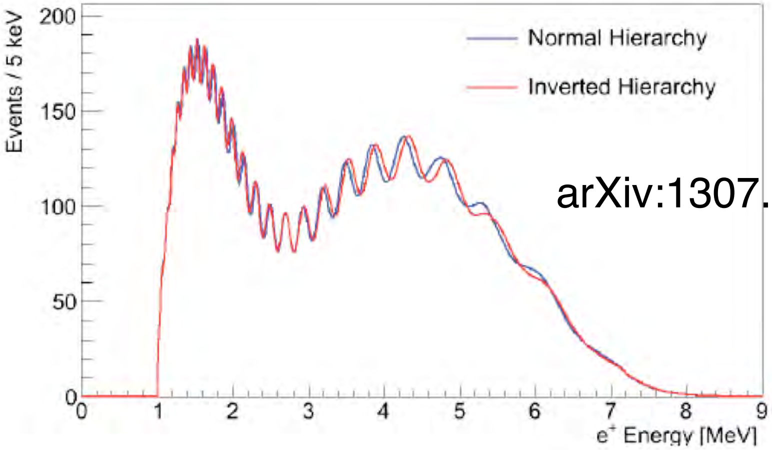


$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

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

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



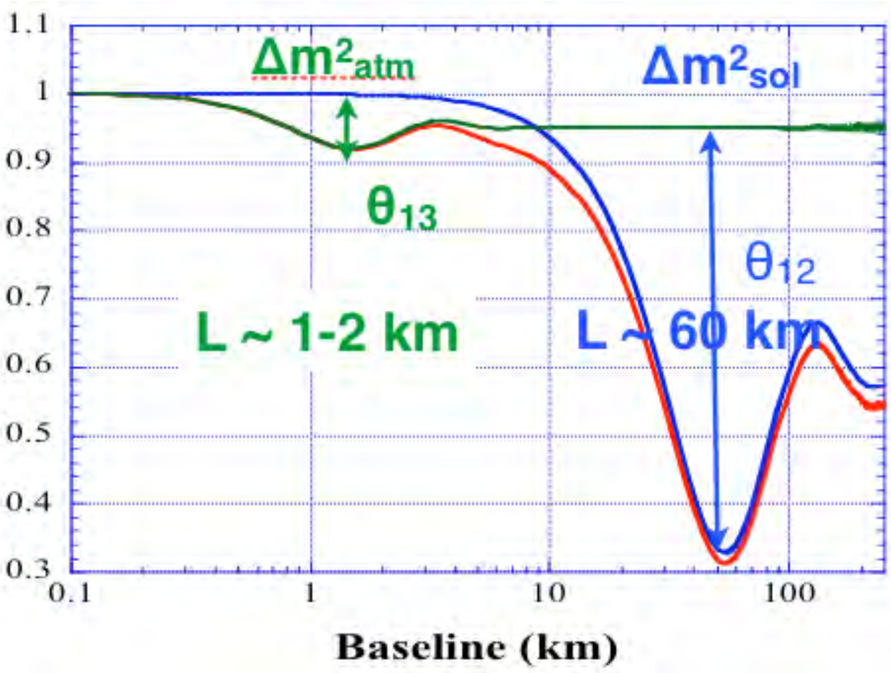


arXiv:1307.5487

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

Mass Hierarchy and Reactor Neutrinos

Precision Measurement at ~ 58km

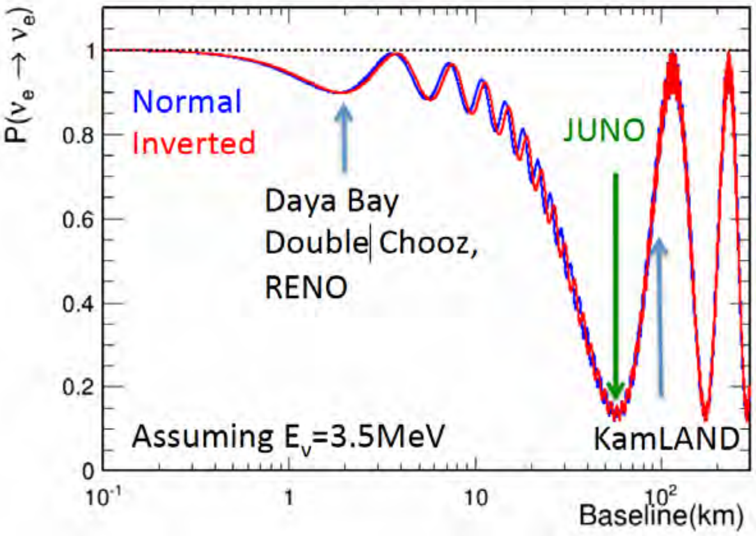


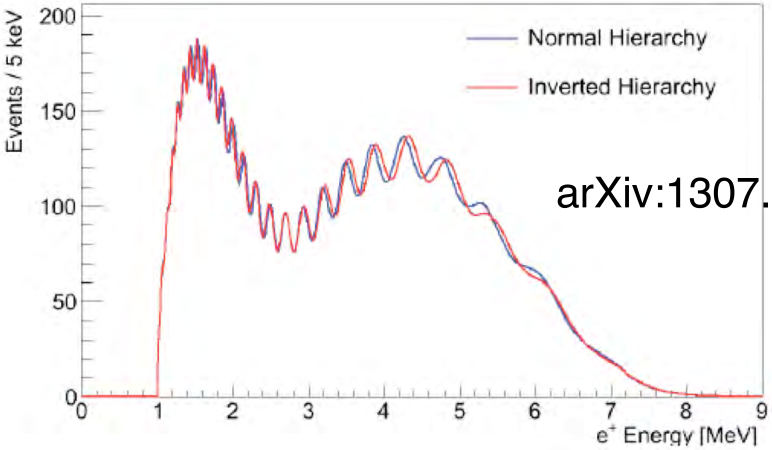
$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

$$\mathrm{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$

$$\mathrm{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

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



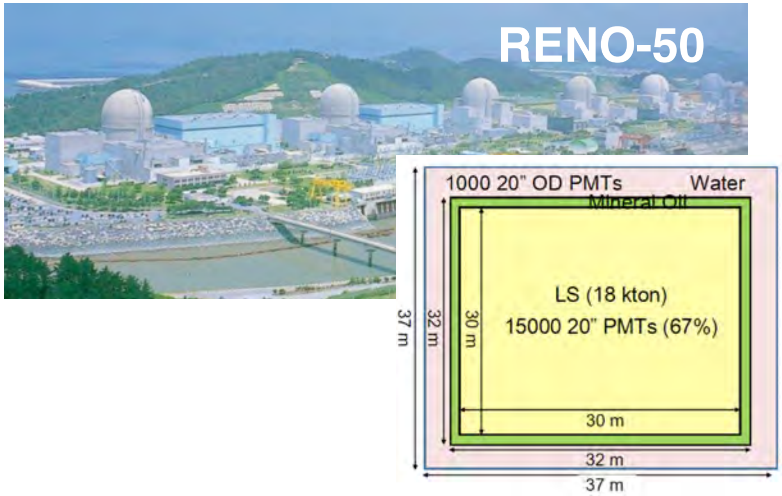


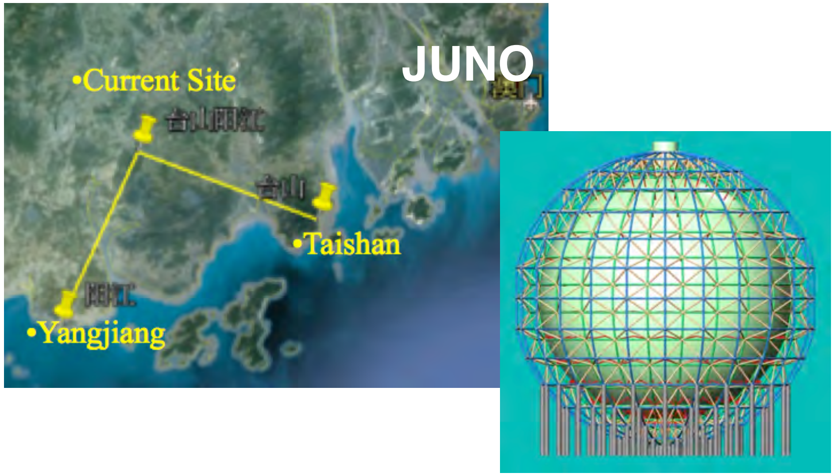
arXiv:1307.5487

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

Mass Hierarchy and Reactor Neutrinos

Proposed Projects: JUNO and RENO-50

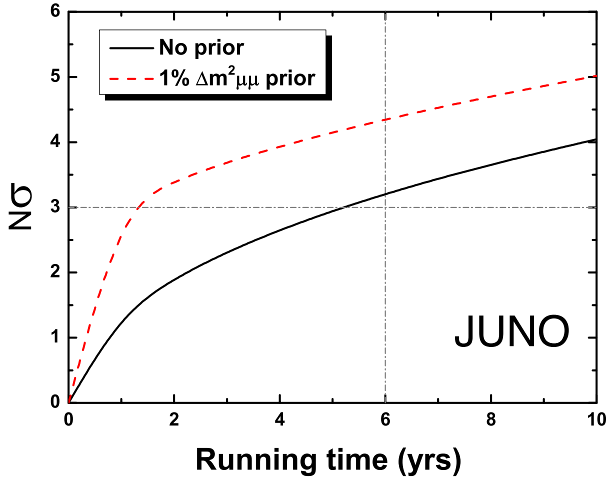




Precision 3-ν Oscillation Physics

	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%

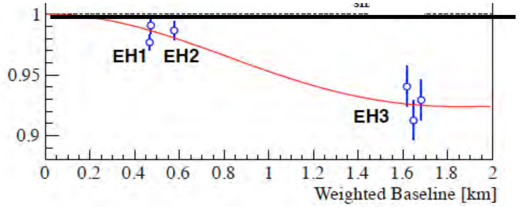
Mass Hierarchy Sensitivity

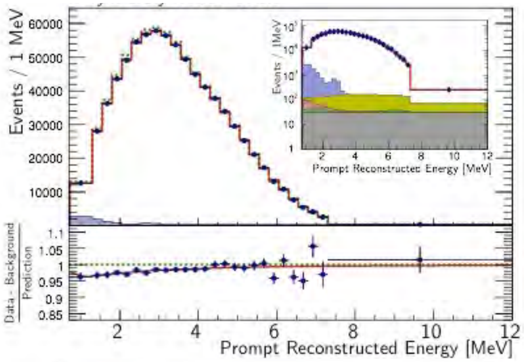


Reactor Antineutrinos in History

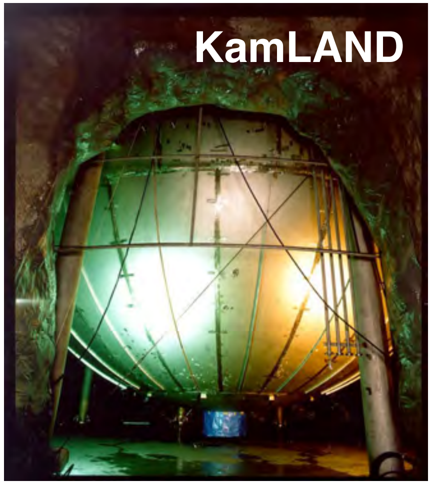
A Tool for Discovery

2012 - Measurement of θ_{13} with Reactor Neutrinos



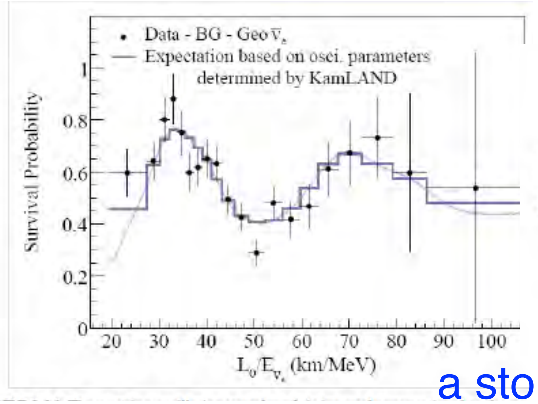


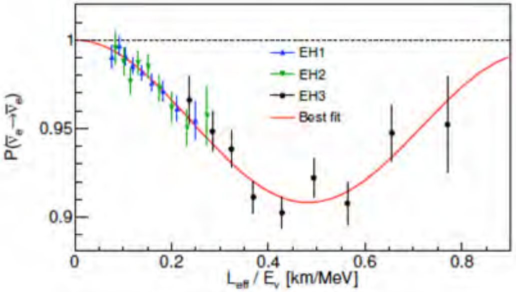
2003 - First observation of reactor antineutrino disappearance



1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos





a story of varying baselines...

Summary & Outlook

Current reactor experiments **(L~1-2km)** provide precision data on **θ_{13}**, and **reactor antineutrino flux and spectra,** and **complementary limits on sterile neutrinos.** Flux measurement is consistent with previous short-baseline measurements (~6% 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**.

Reactor experiments may inform nuclear modeling of reactors. Detectors may find applications in reactor monitoring.

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.**

After 60 years of reactor neutrino experiments, future is bright.
Active field with ongoing and planned experiments.