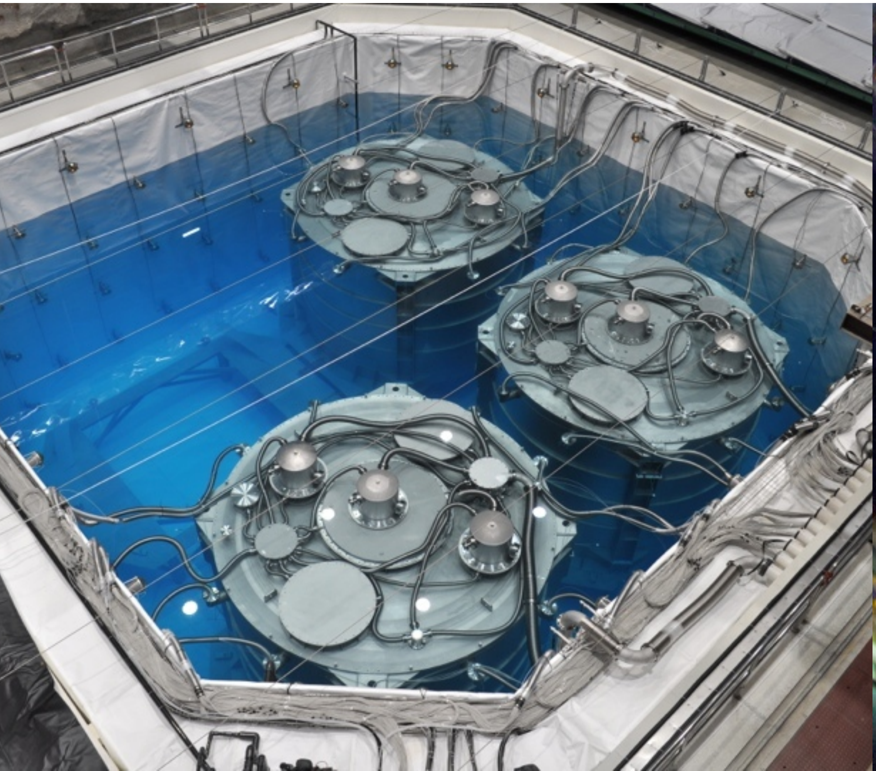
Reactor Neutrino Experiments: Recent Results and Future Prospects

Karsten M. Heeger, University of Wisconsin



NDM2012, June 13, 2012

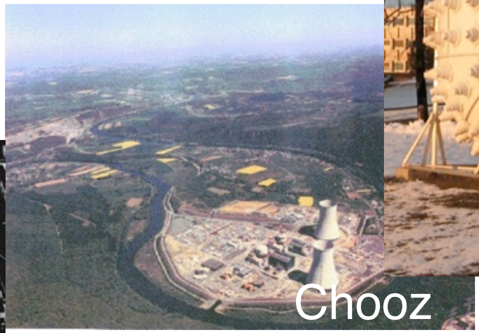
2011/2012 - The year of θ_{13} and reactor neutrinos

2008 - Precision measurement of Δm_{12}^2. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

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



1956 - First observation of (anti)neutrinos

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

55 years of liquid scintillator detectors
a story of varying baselines...

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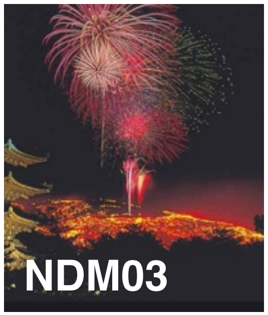

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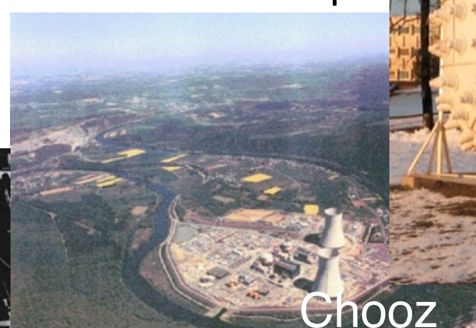

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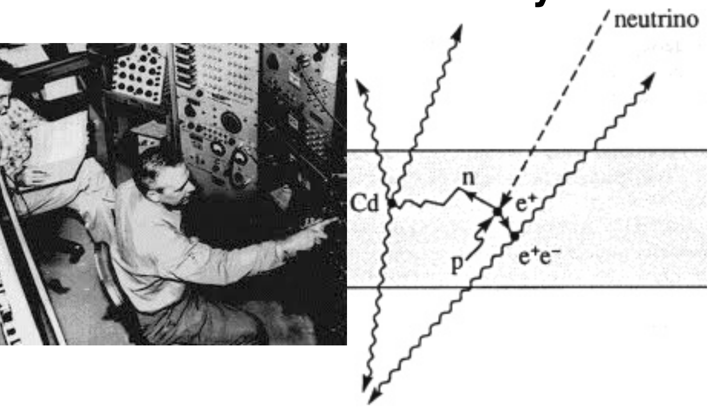
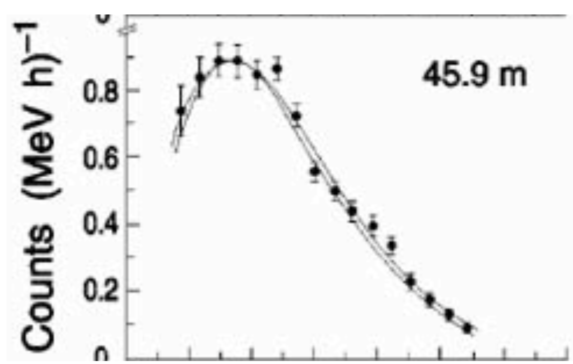
Physics with Reactor $\overline{\nu}_e$

Discoveries and Precision Measurements of Neutrino Properties

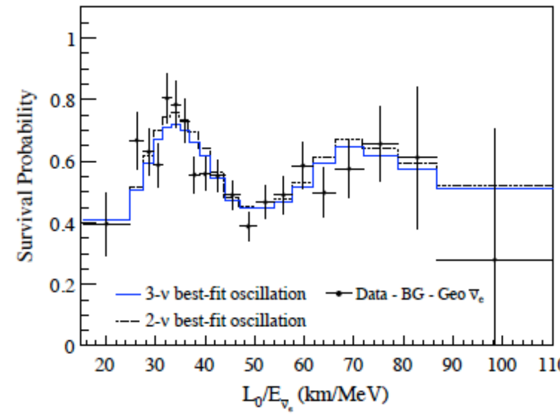
Antineutrino Discovery



Reactor $\overline{\nu}_e$ Spectra

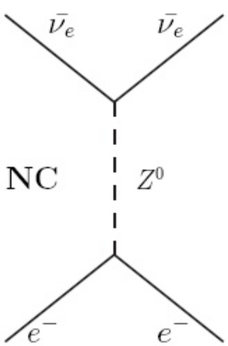


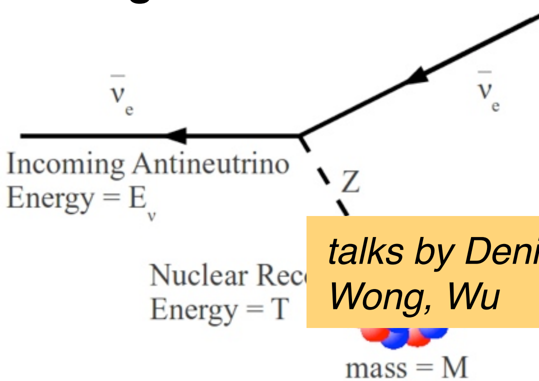
$\overline{\nu}_e$ Oscillations



Searches for New Physics

neutrino magnetic moment and **coherent scattering** searches

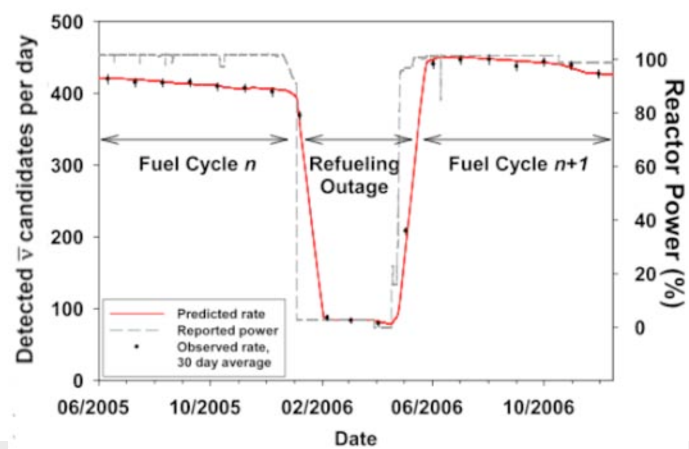




talks by Deniz, Wong, Wu

Reactor Monitoring and Application

fuel burnup and isotopic composition

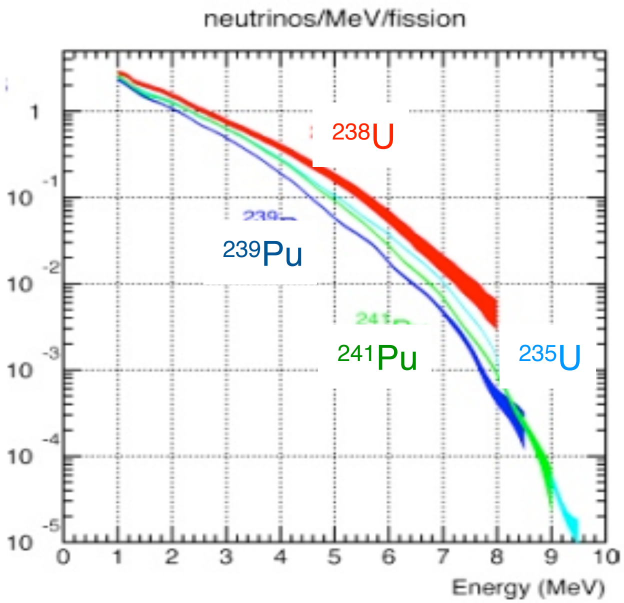


Reactor Antineutrinos

Source

$\bar{\nu}_e$ from β-decays

of n-rich fission products



$^{235}U:^{238}U:^{239}Pu:^{241}Pu$ =

0.570: 0.078: 0.0295: 0.057

~ 200 MeV per fission

~ 6 ν_e per fission

~ 2 x 10^{20} $\bar{\nu}_e/GW_{th}$-sec

pure $\bar{\nu}_e$ source

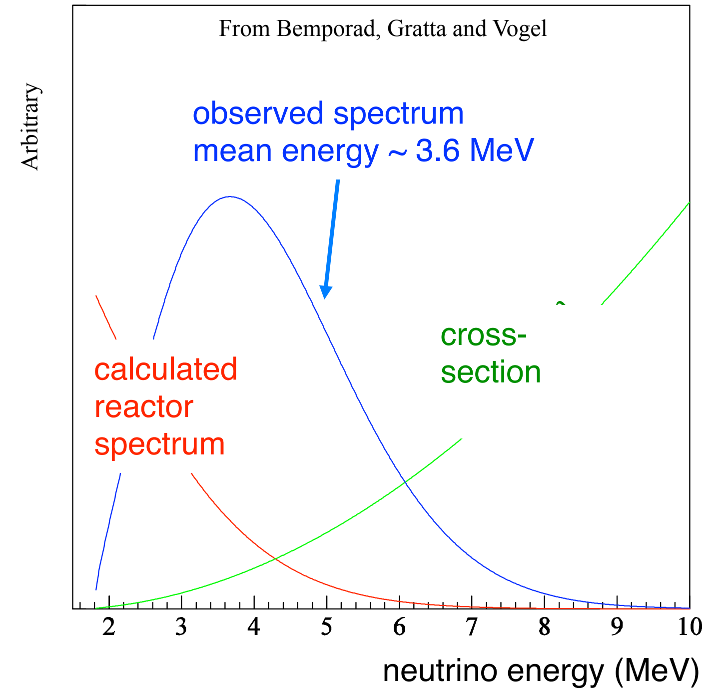
Detection

inverse β-decay

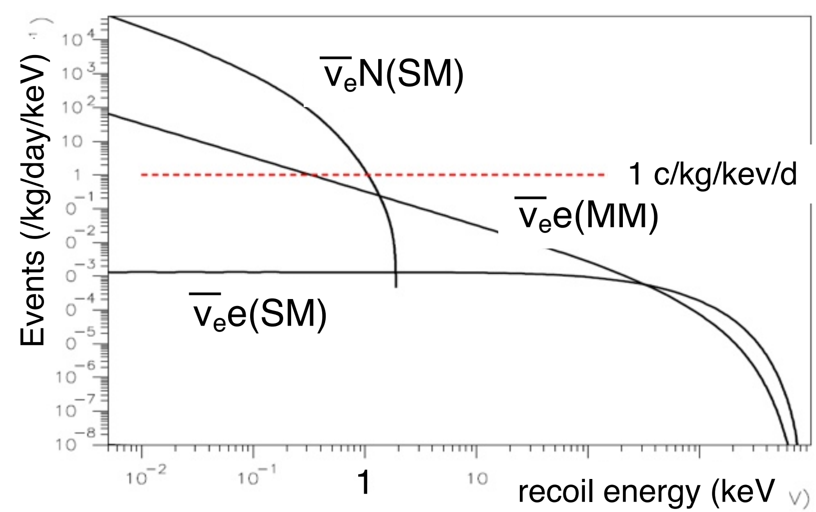
$\bar{\nu}_e + p \rightarrow e^+ + n$

observable **rate** and energy **spectrum**

only disappearance experiments possible



$\bar{\nu}_e$ scattering



Oscillation Experiments with Reactors

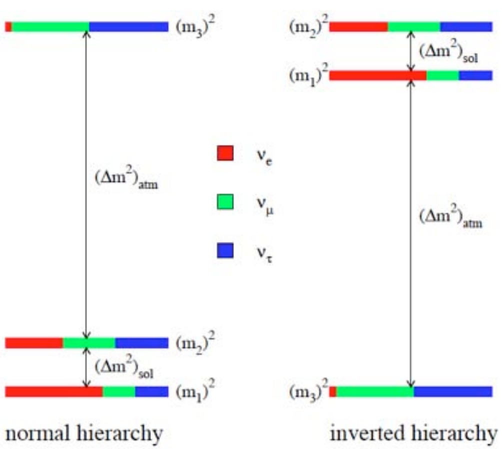
Measure (non)-1/r² behavior of $\overline{\nu}_e$ interaction rate

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

L/E → Δm^2

amplitude of oscillation → θ

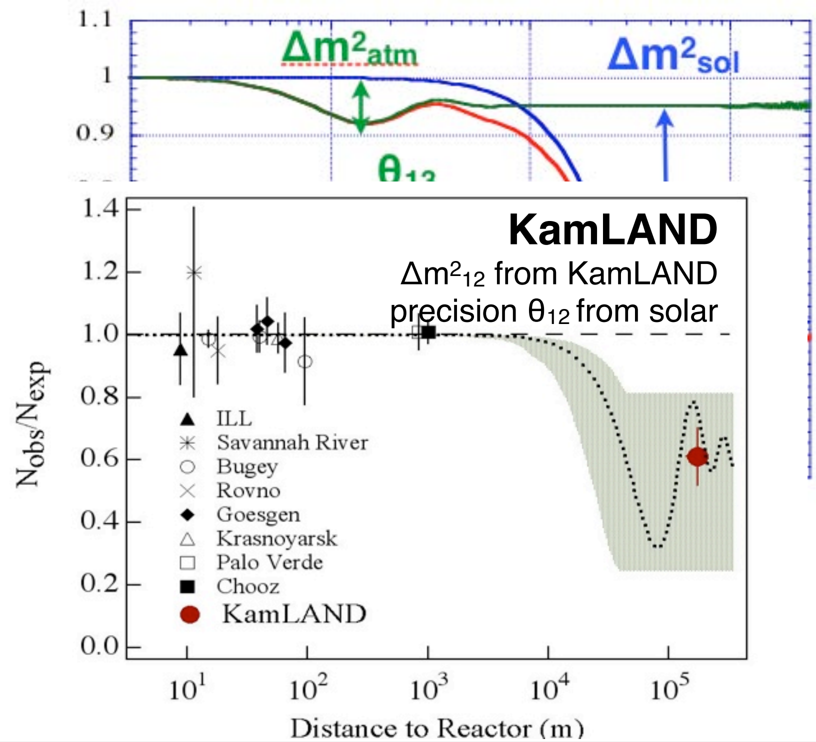
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



$\Delta m^2_{12} \sim 7.6 \times 10^{-5}$ eV²

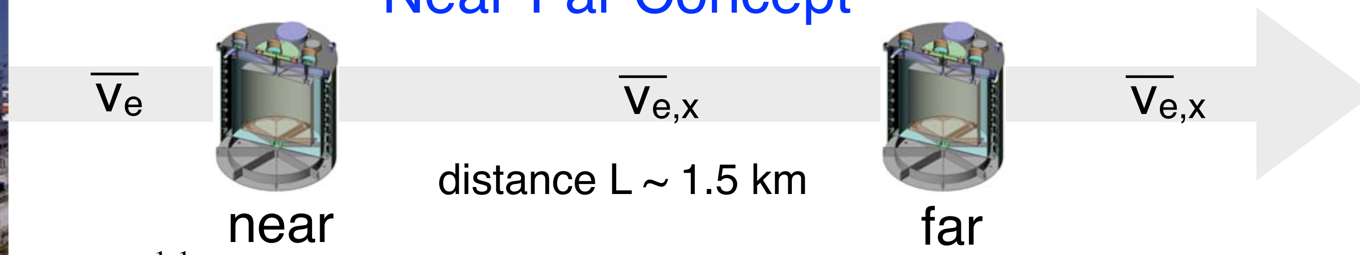
$\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV²

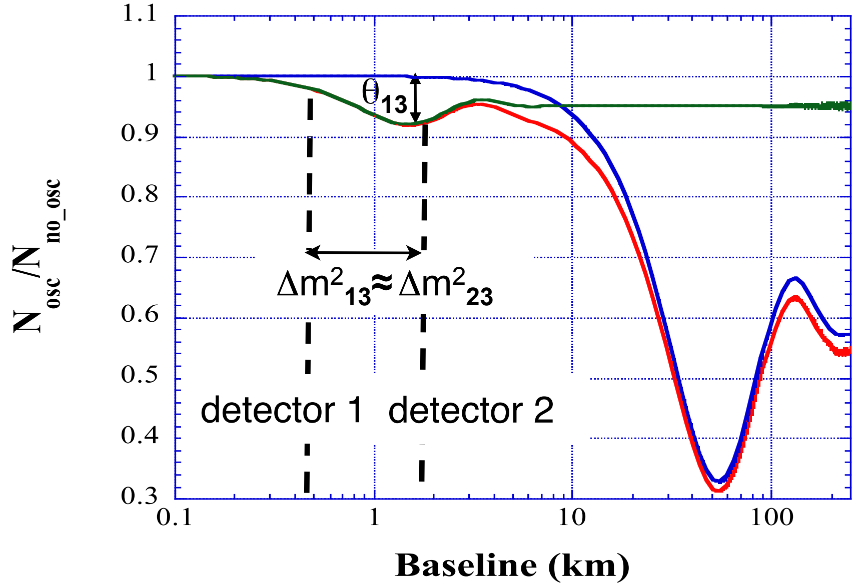
$\Delta m^2_{23} \approx \Delta m^2_{13}$



Measuring θ_{13} with Reactor Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

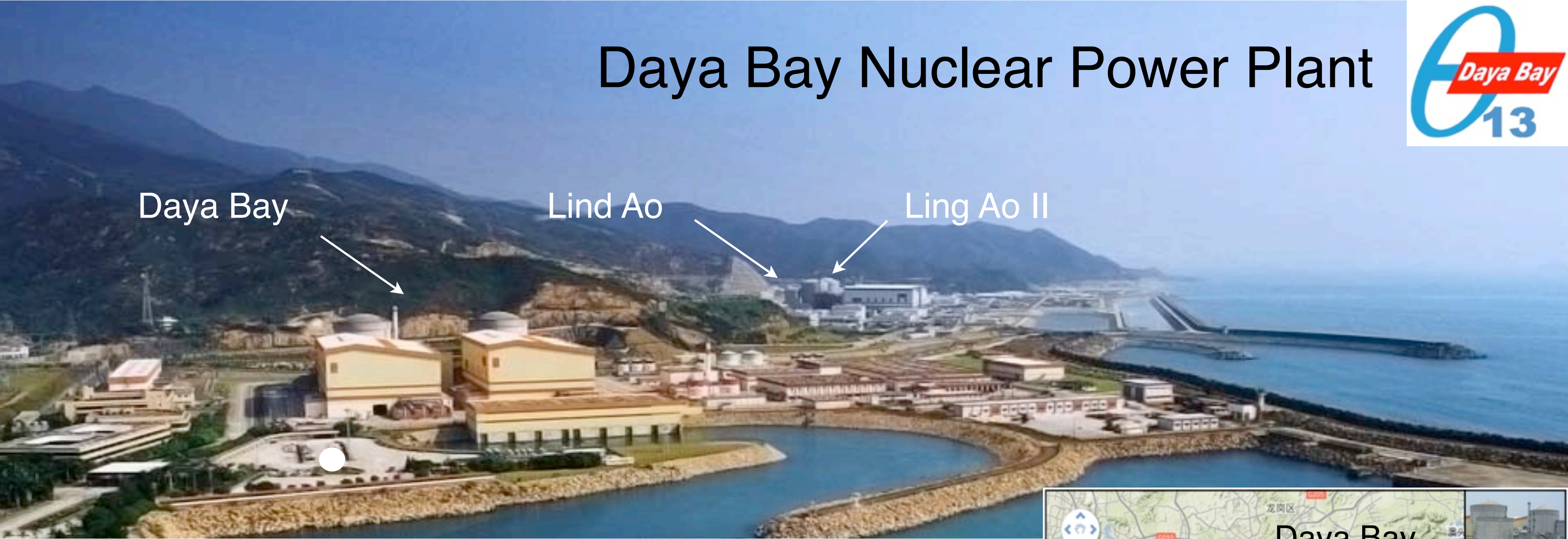
Relative Measurement
Removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

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

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

Daya Bay Nuclear Power Plant

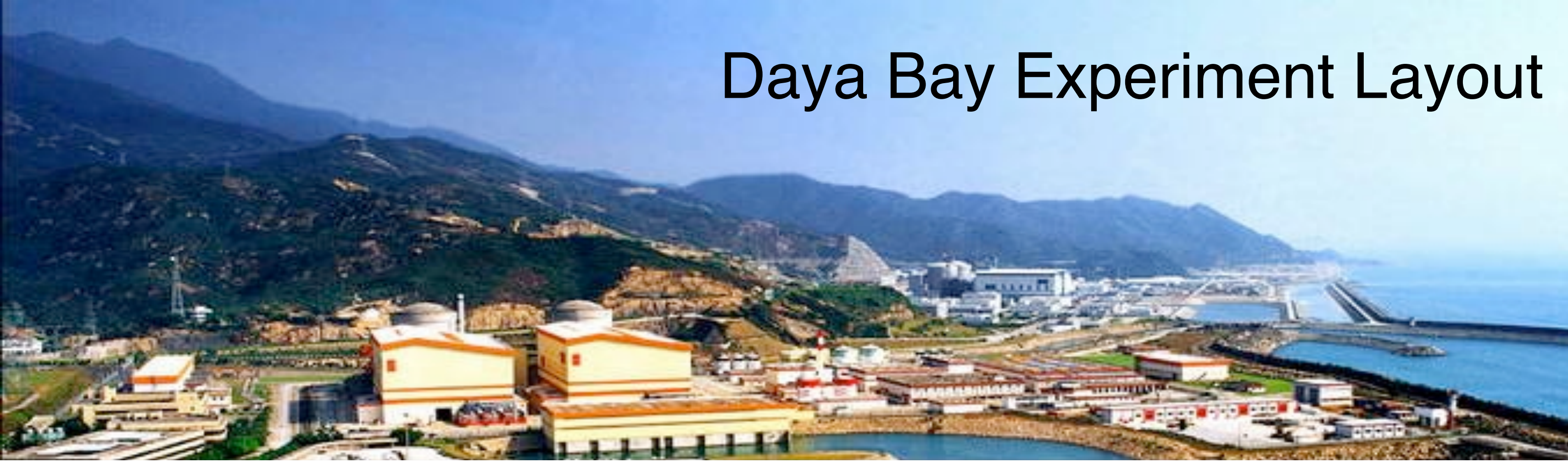


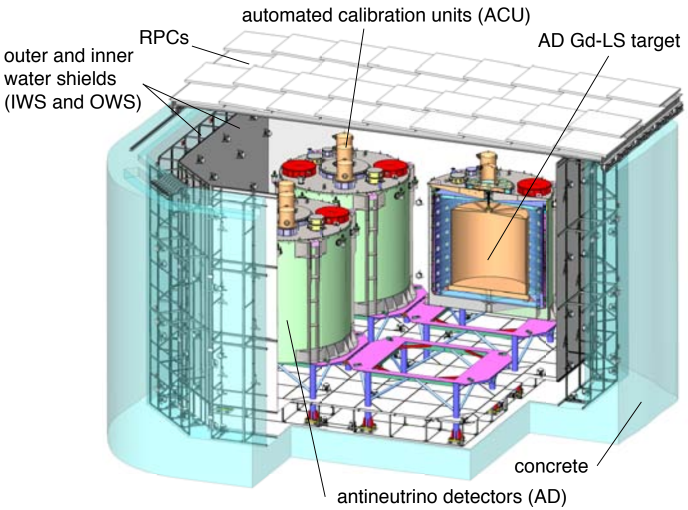
A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW_{th} (6 x 2.95 GW_{th})
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

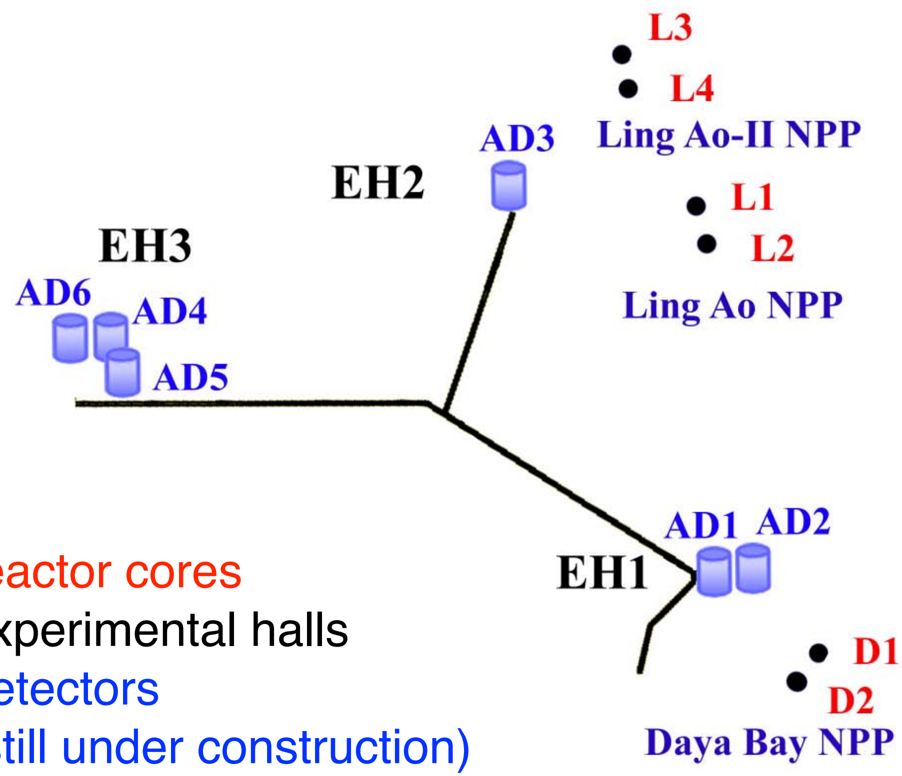
Reactors produce ~2×10^{20} antineutrinos/sec/GW

Daya Bay Experiment Layout





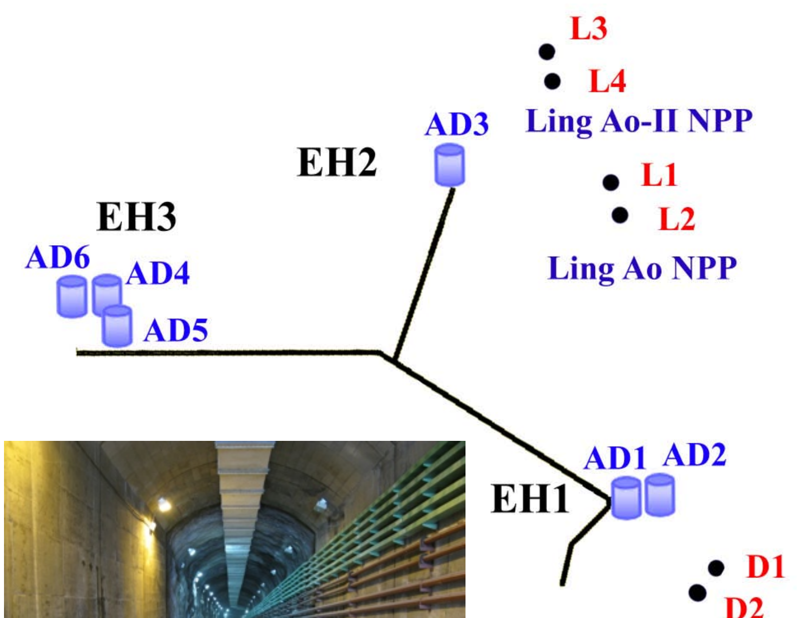
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

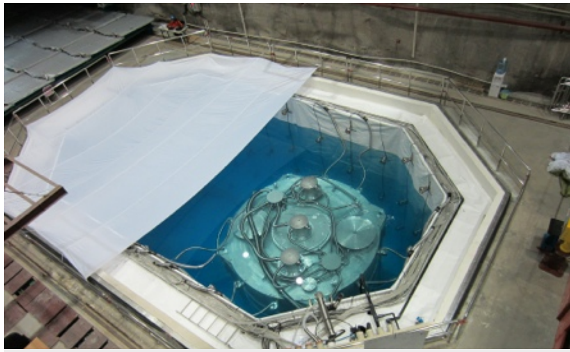


6 reactor cores
3 experimental halls
6 detectors
(2 still under construction)

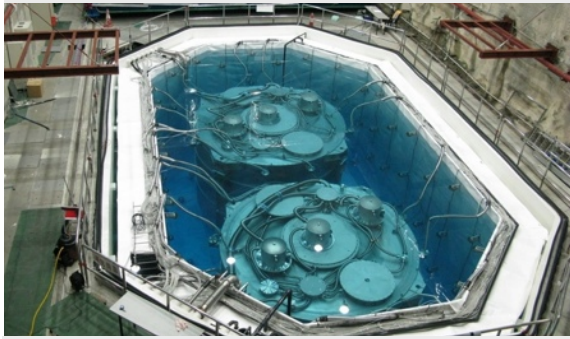
Daya Bay Experiment Layout

Hall 3: began 3 AD operation on Dec. 24, 2011





Hall 2: began 1 AD operation on Nov. 5, 2011

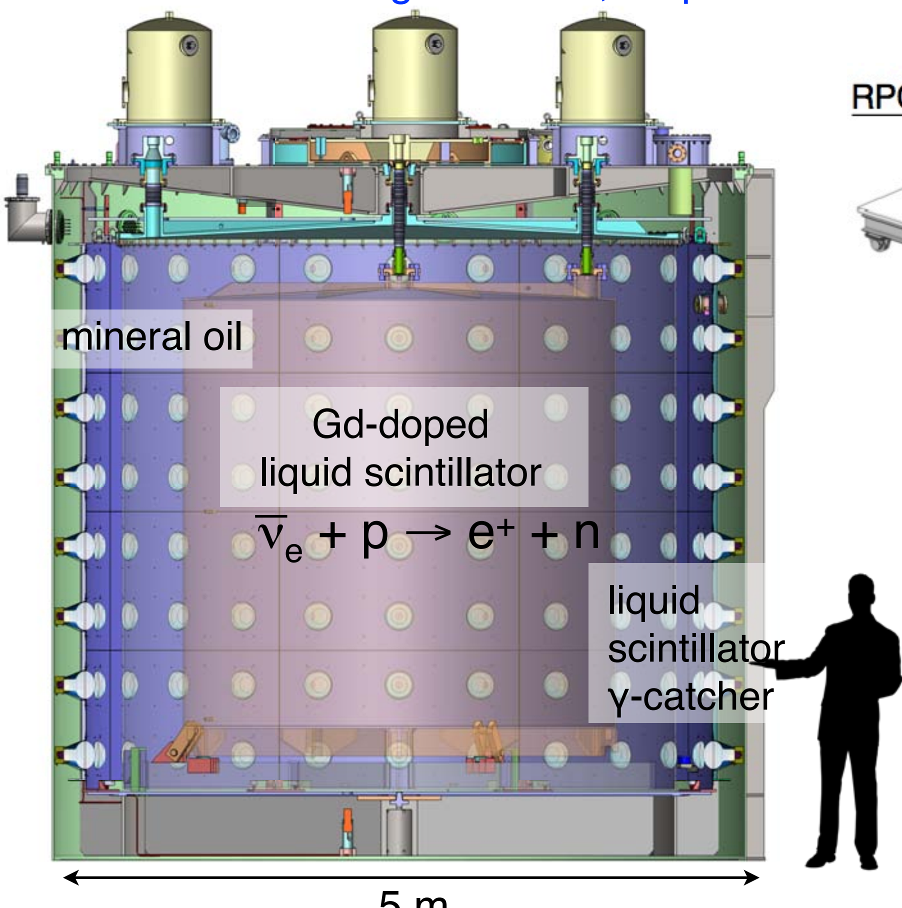


Hall 1: began 2 AD operation on Sep. 23, 2011

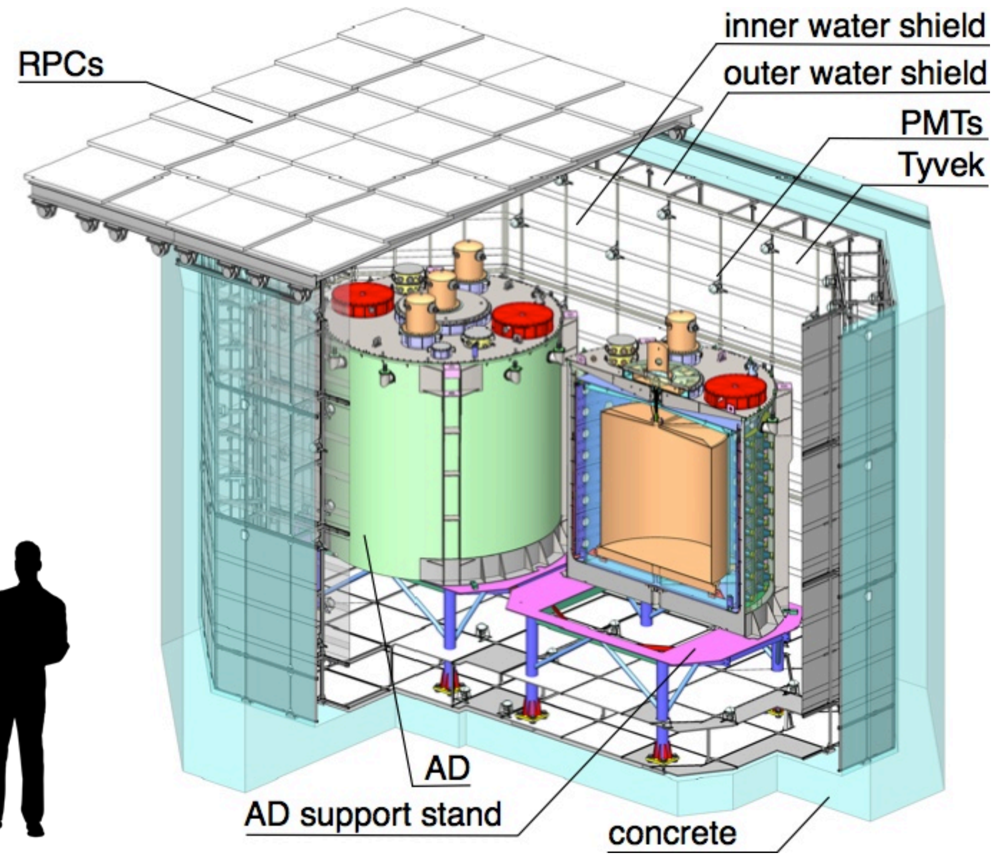
Daya Bay Detectors

6 “functionally identical” detectors
Gd-LS defines target volume, no position cut

Dual tagging systems: 2.5 meter water shield and RPCs



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

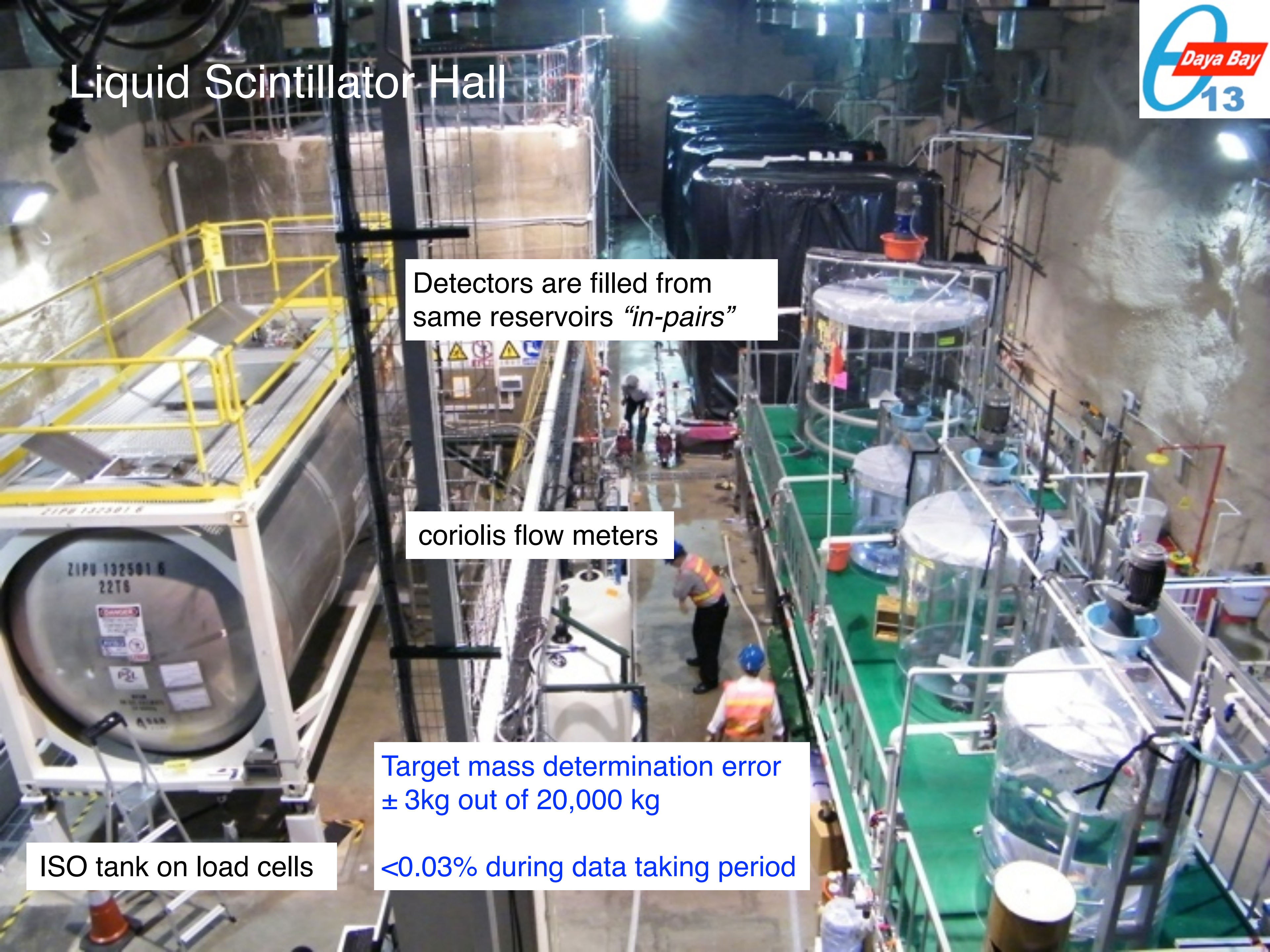


Two-zone ultrapure water Cherenkov detector

multiple detectors allow comparison and cross-checks

Liquid Scintillator Hall

Liquid Scintillator Hall



Detectors are filled from same reservoirs *“in-pairs”*

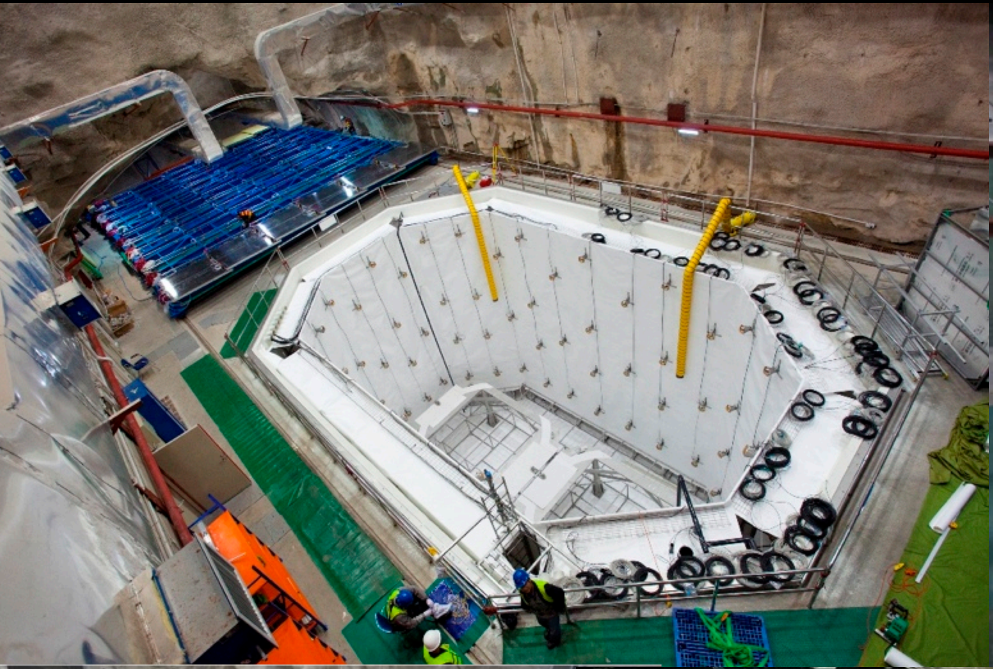
coriolis flow meters

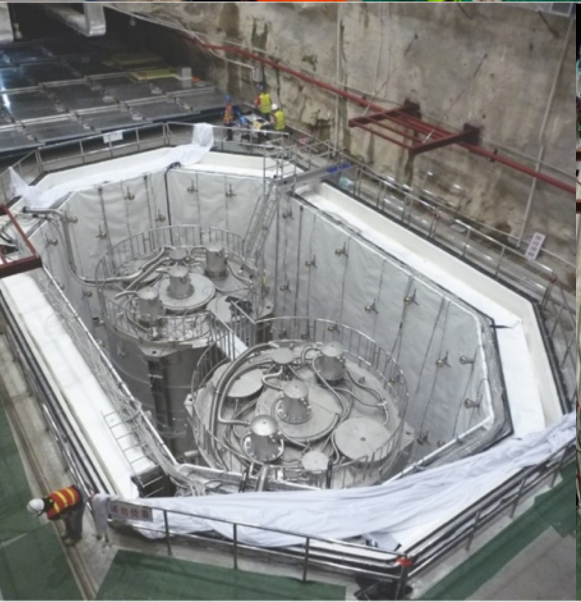
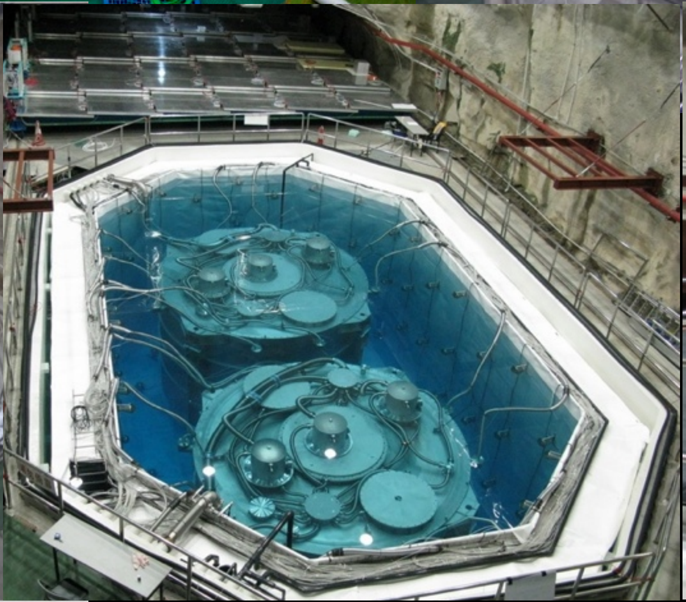
Target mass determination error ± 3kg out of 20,000 kg

<0.03% during data taking period

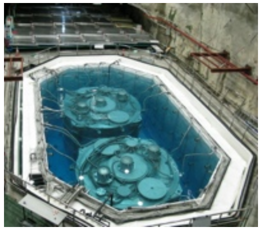
ISO tank on load cells

Antineutrino Detector Installation - Near Hall



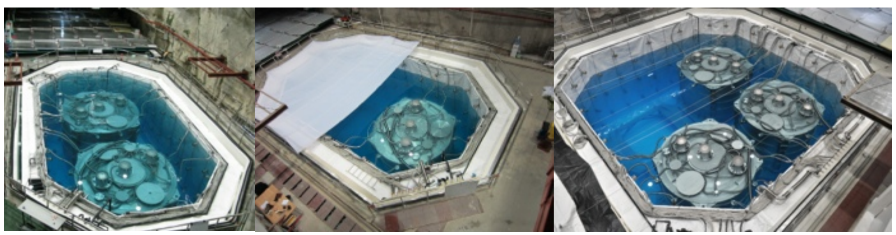

Data Periods



Daya Bay Collab.
arXiv:1202:6181 (2012)
accepted in NIMA

Two Detector Side-by-Side Comparison

- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics 2x better than TDR
- **Detector-related relative uncertainty: 0.2%**



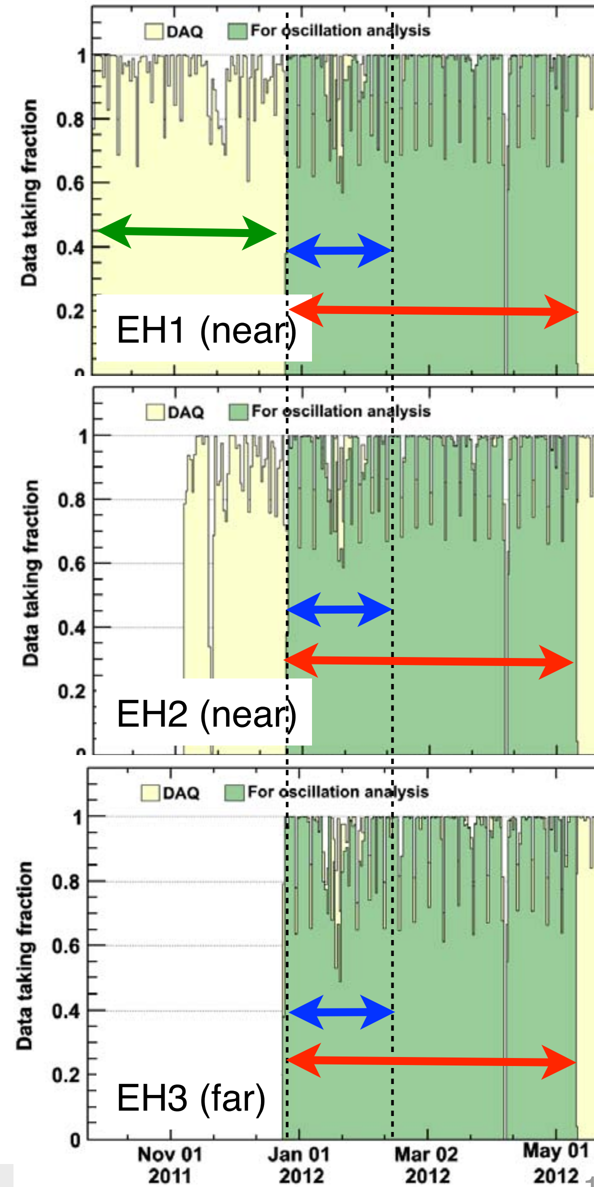
First Oscillation Analysis

Daya Bay Collab.
Phys.Rev.Lett. 108 (2012) 171803

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
- Antineutrino data: ~89%
- **observed 6% deficit in detected $\overline{\nu}_e$ at far site**

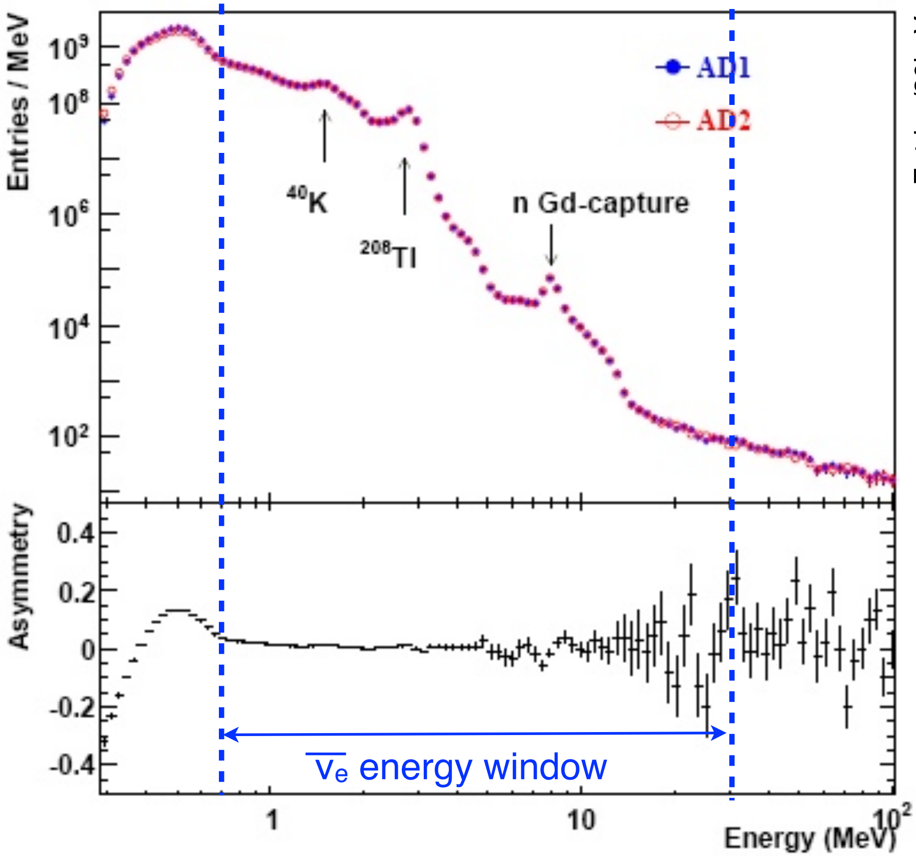
June 2012 Oscillation Analysis

- Dec. 24, 2011 – May 11, 2012
- 2.5x previous data set



Detector Side-by-Side Comparison

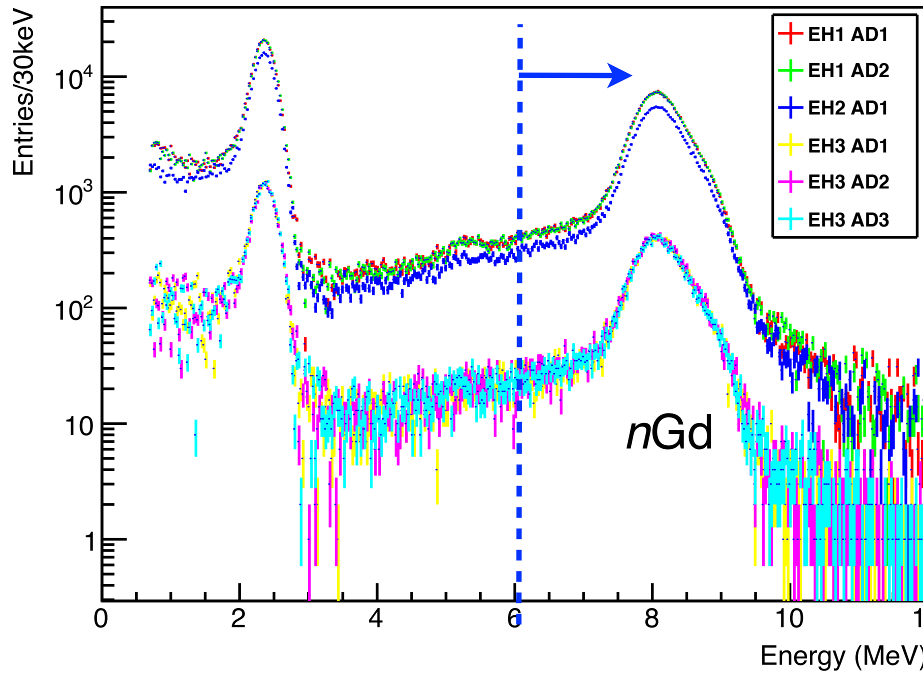
Singles Spectrum of AD1,2 in EH1



asymmetry $A = 2 \times \frac{AD1 - AD2}{AD1 + AD2}$

→ AD's have functionally identical detector response

Spallation Neutron Capture



response of all detectors to neutrons constrains largest systematic uncertainty

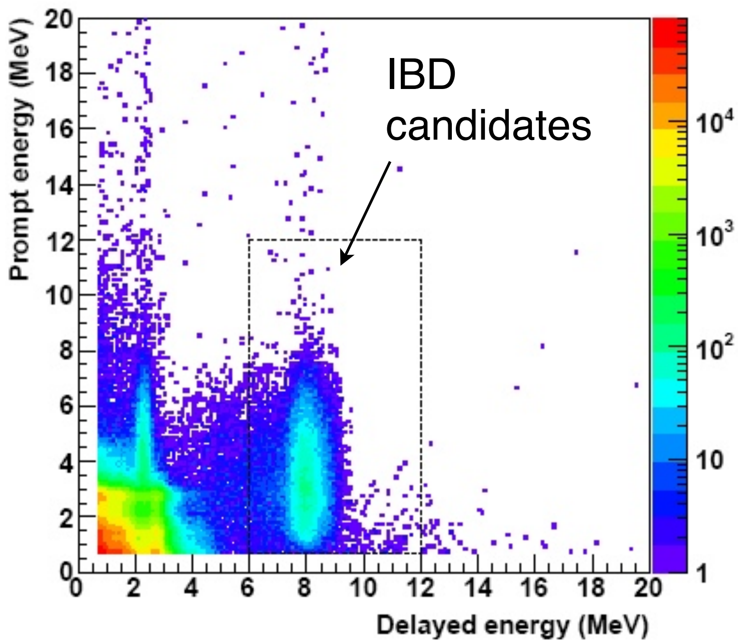
→ multiple detectors allow comparison and cross-checks

Antineutrino Candidates (Inverse Beta Decay)

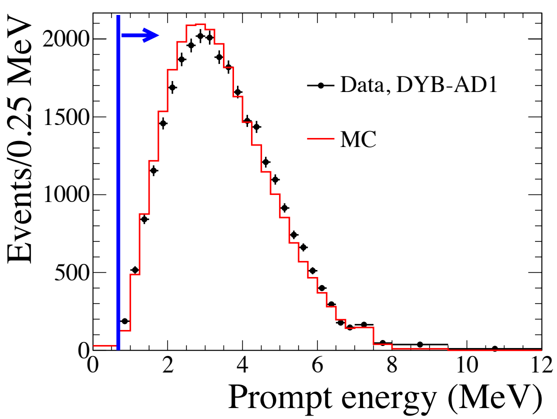
Prompt + Delayed Selection

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

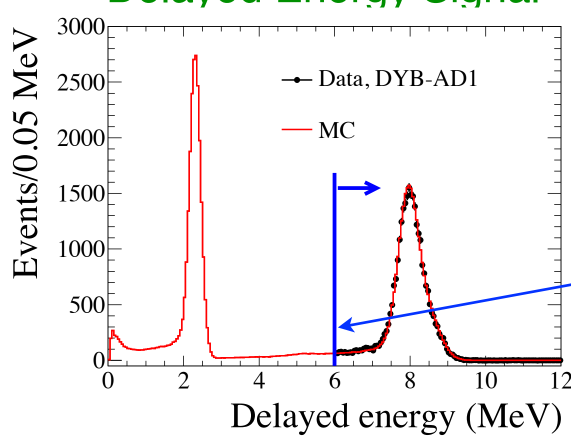
- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.



Prompt Energy Signal



Delayed Energy Signal



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

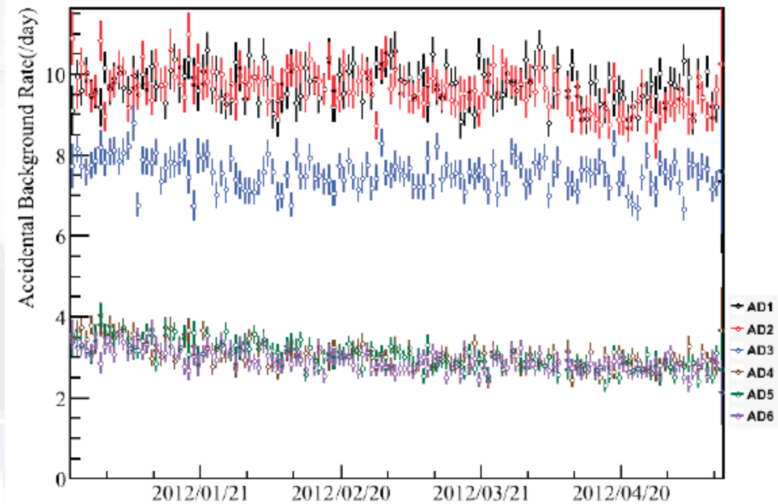
Background Summary

Total backgrounds: 5%(2%) in far(near) halls.

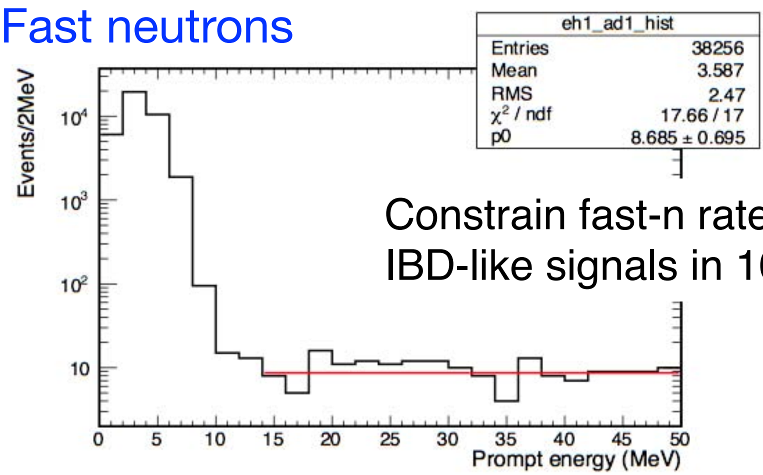
	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
fast neutrons	0.12	0.05	0.07	0.03
$^{8}He/^{9}Li$	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
$^{13}C(\alpha, n)^{16}O$	0.01	0.006	0.05	0.03

Backgrounds uncertainties are 0.3%(0.2%) in far(near) halls.

Accidentals

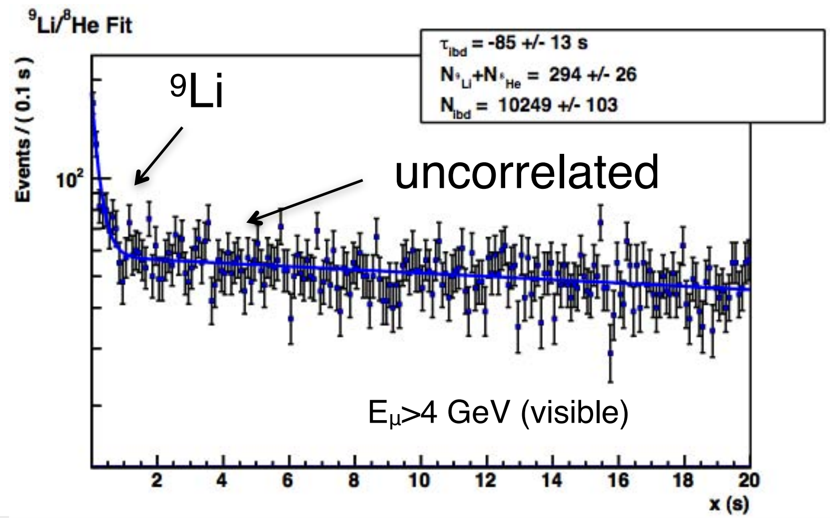


Fast neutrons



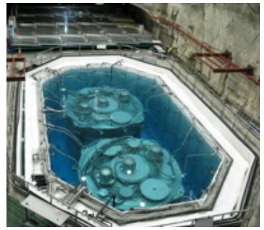
Constrain fast-n rate using IBD-like signals in 10-50 MeV

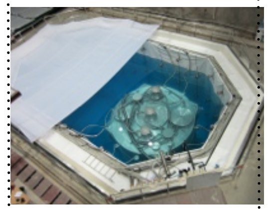
Correlated β-n decay

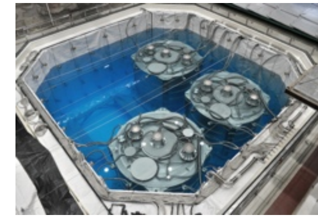


Daya Bay Data Set Summary

~200k near
~30k far detector
antineutrino interactions





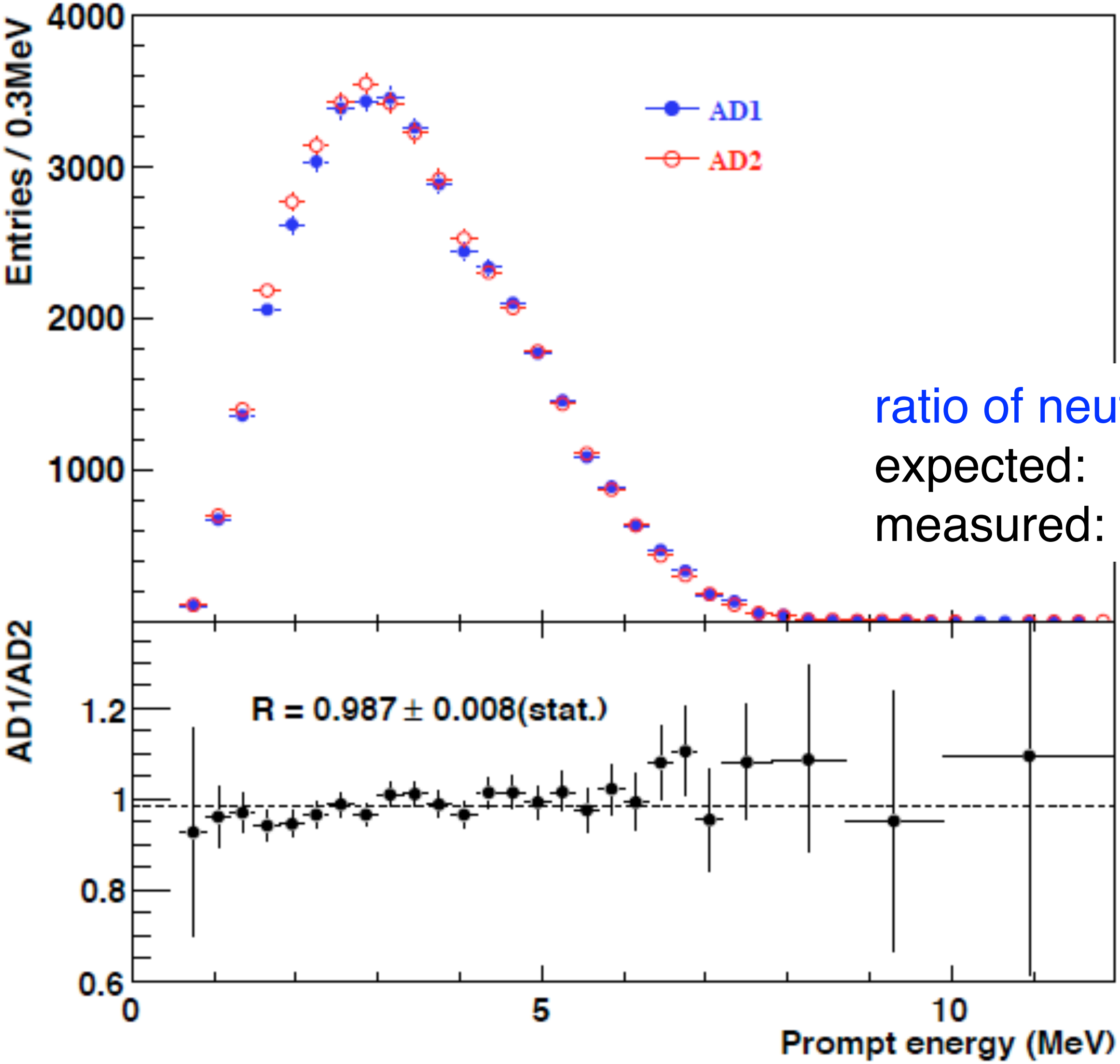


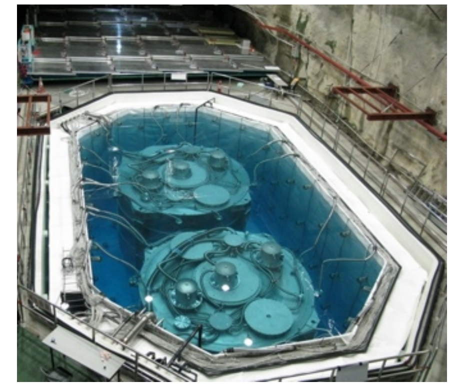
	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	**69121**	**69714**	**66473**	**9788**	**9669**	**3452**
DAQ live time (day)	127.5470		127.3763		126.2646	
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{8}He/^{9}Li (/day)	2.9±1.5		2.0±1.1		0.22±0.12	
Am-C corr. (/day)			0.2±0.2			
^{13}C(α, n)^{16}O (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.00**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

rates /day/AD

consistent rates for side-by-side detectors
uncertainty dominated by statistics

Side-by-Side Comparison in Near Hall





ratio of neutrino events in AD1 and AD2

expected: **0.981**

measured: **0.987± 0.008 (stat) ± 0.003**

ratio is not 1 because of baseline difference

Daya Bay Collab. arXiv: 1202:6181 (2012)

Reactor Flux Expectation

Antineutrino flux is estimated for each reactor core

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:

- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

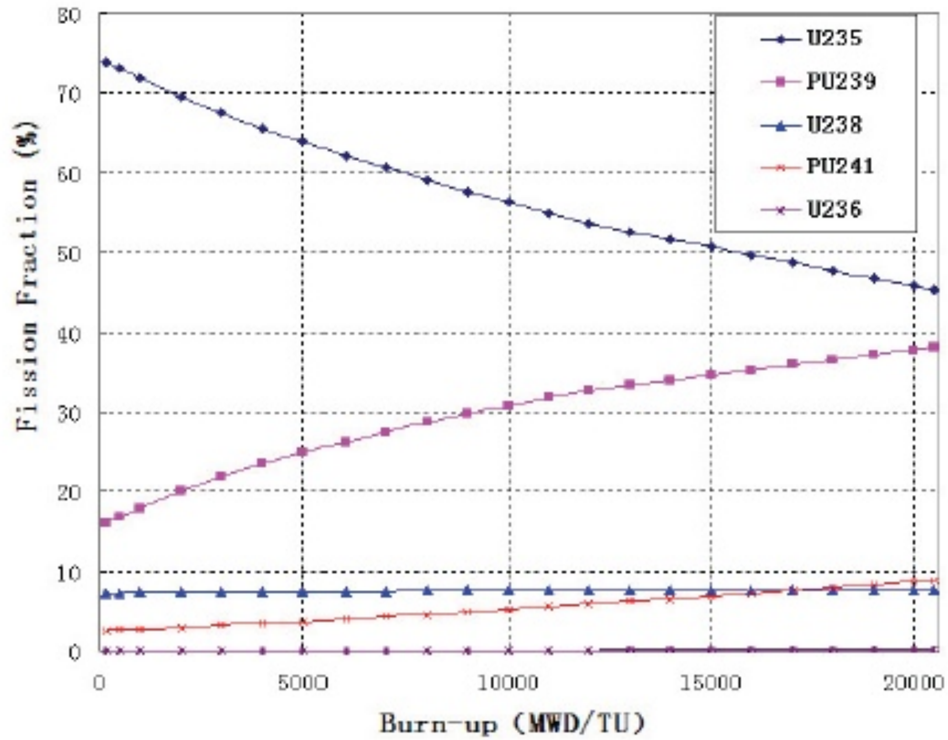
Energy released per fission: e_i

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

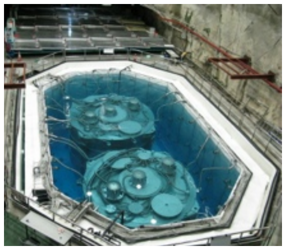
Isotope fission rates vs. reactor burnup

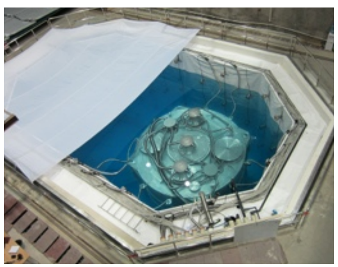


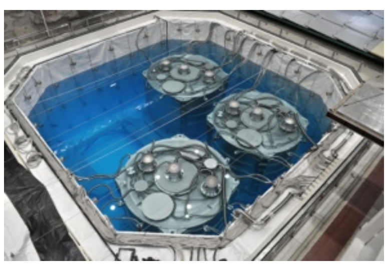
Flux model has negligible impact on far vs. near oscillation measurement

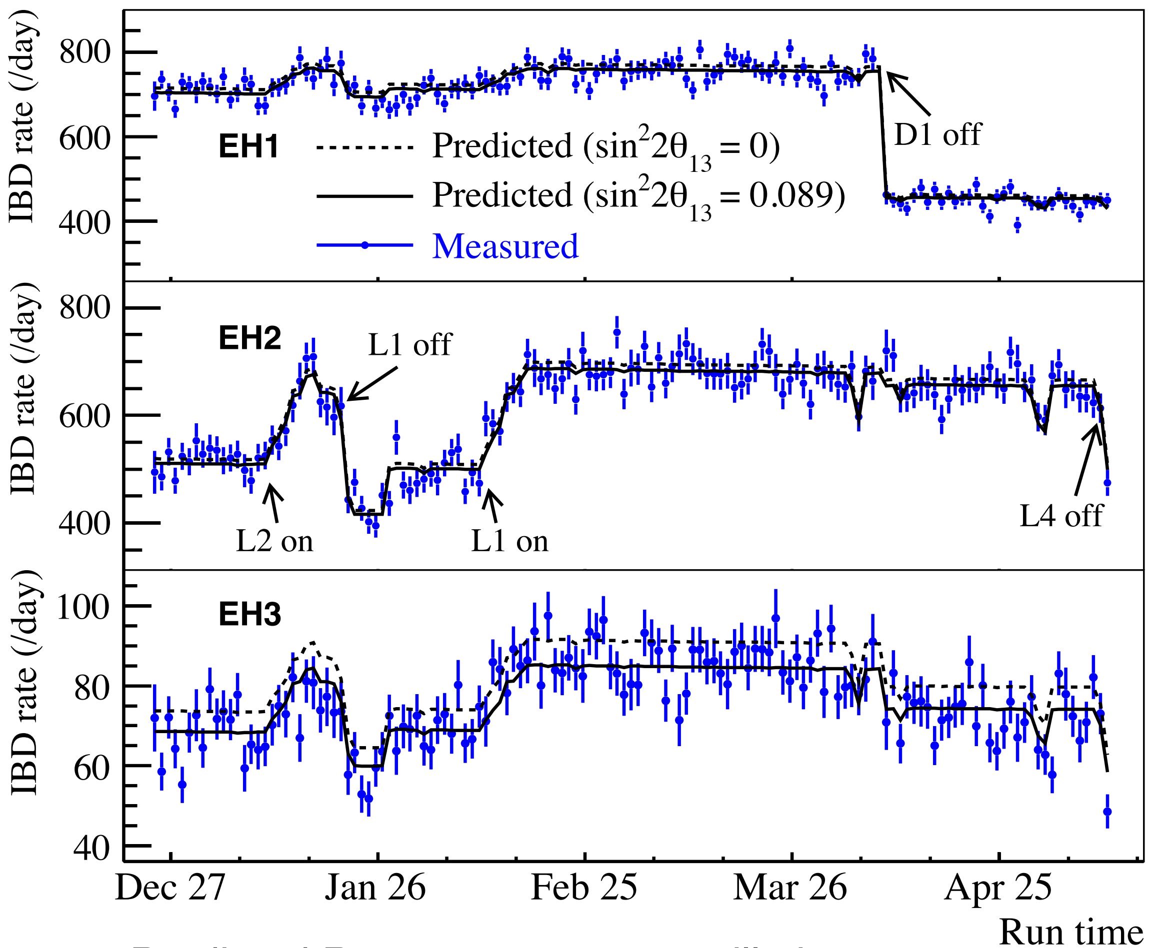
Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations









Predicted Rate assumes no oscillation.
Normalization is determined by fit to near detector data.

Uncertainty Summary

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

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

For near/far oscillation, only uncorrelated uncertainties are used.

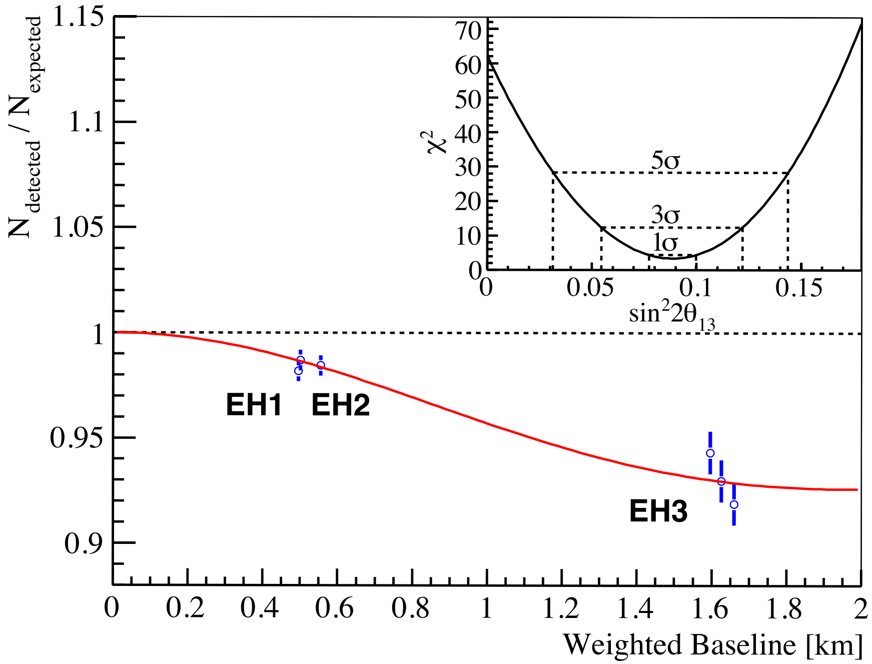
Largest systematics are smaller than far site statistics (~1%)

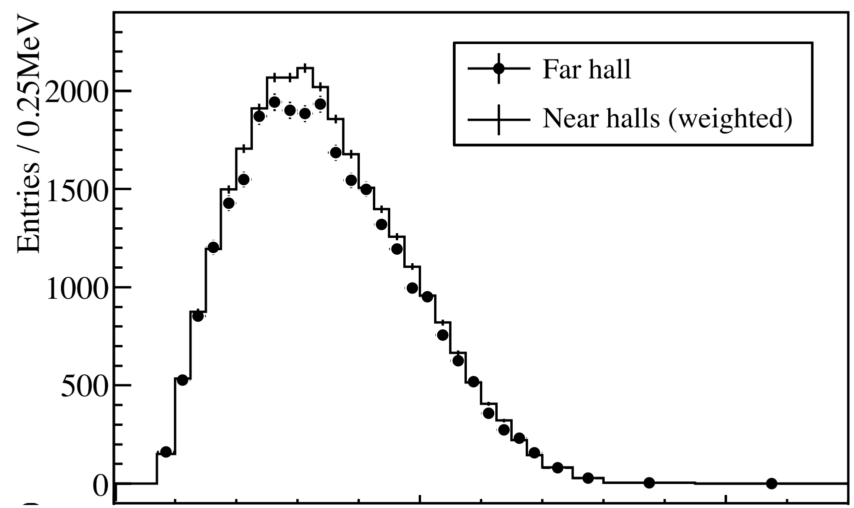
uncorrelated detector uncertainty

Influence of uncorrelated reactor systematics is reduced to by far vs near measurement.

uncorrelated reactor uncertainty

Rate Deficit & Near/Far Ratio





$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

Far vs. near relative measurement.
Absolute rate is not constrained.

$\sin^2 2\theta_{13}$ =
0.089 ± 0.010 (stat) ± 0.005 (syst)

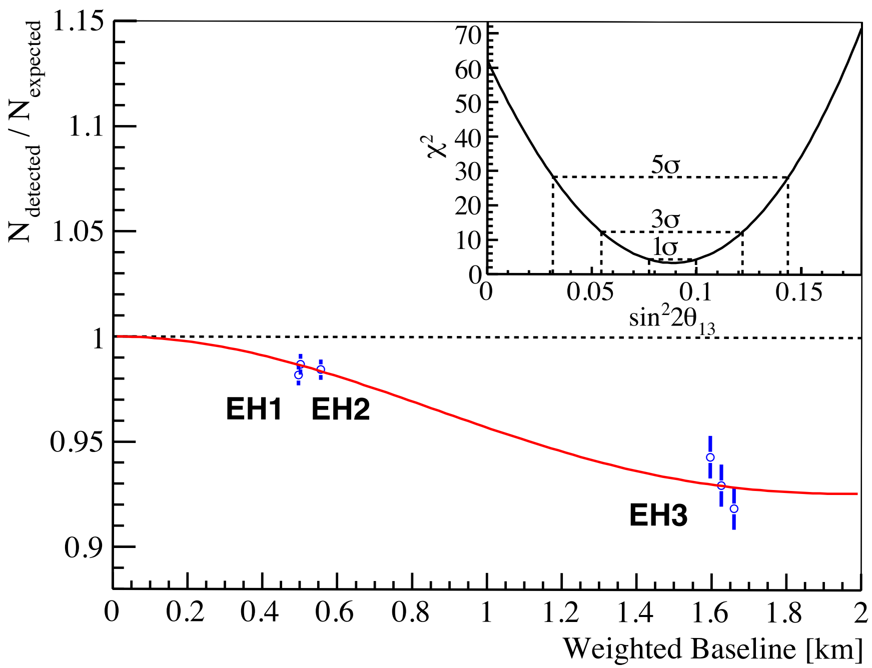
Most precise measurement of $\sin^2 2\theta_{13}$ to date.

M_n are the measured rates in each detector. Weights α_i, β_i are determined from baselines and reactor fluxes.

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

Clear observation of far site deficit.

Rate Deficit & Near/Far Ratio



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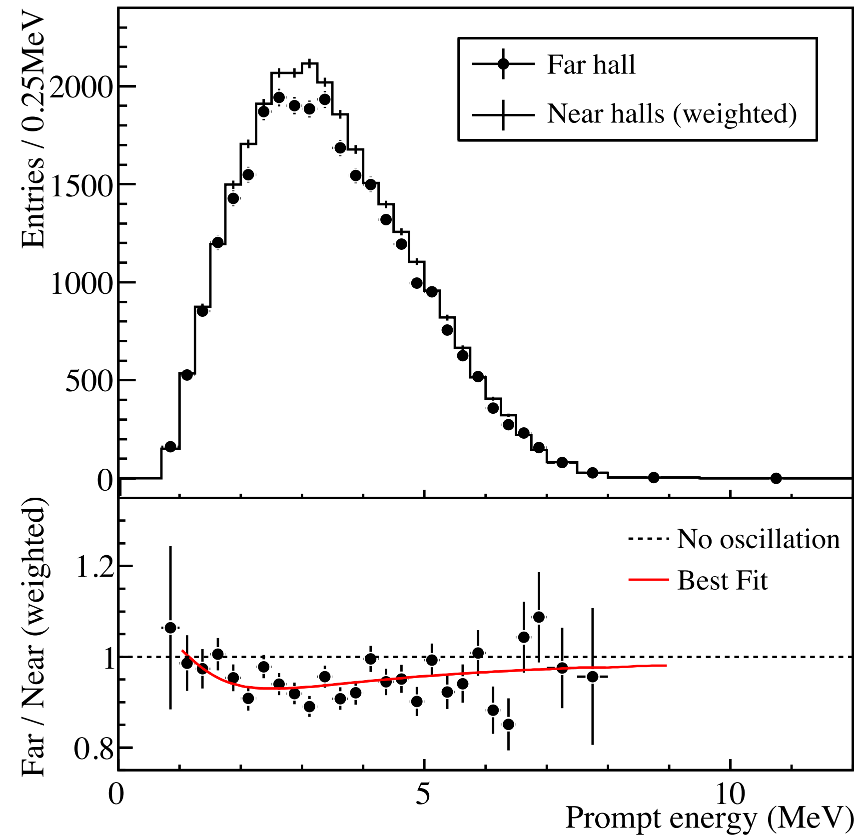
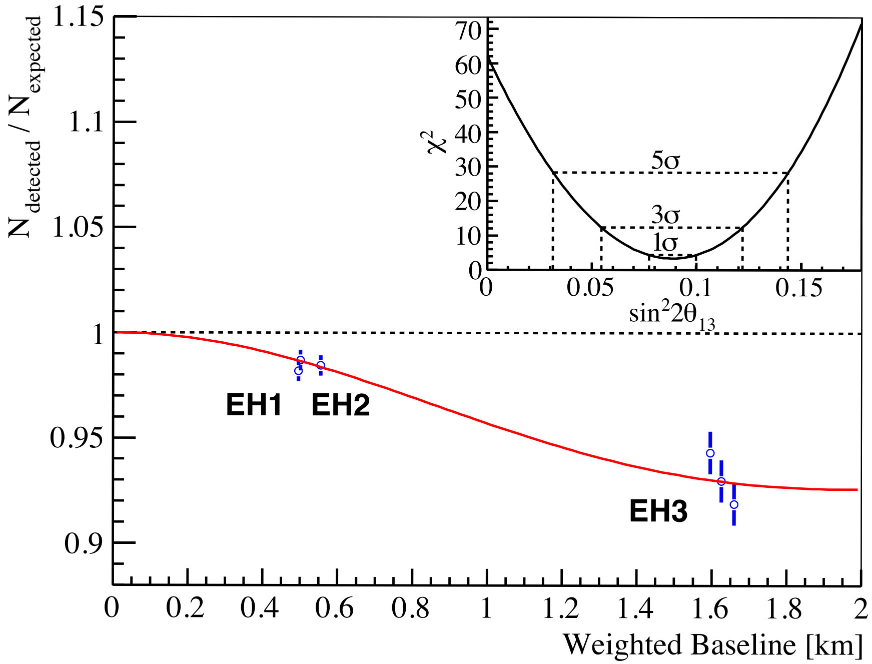
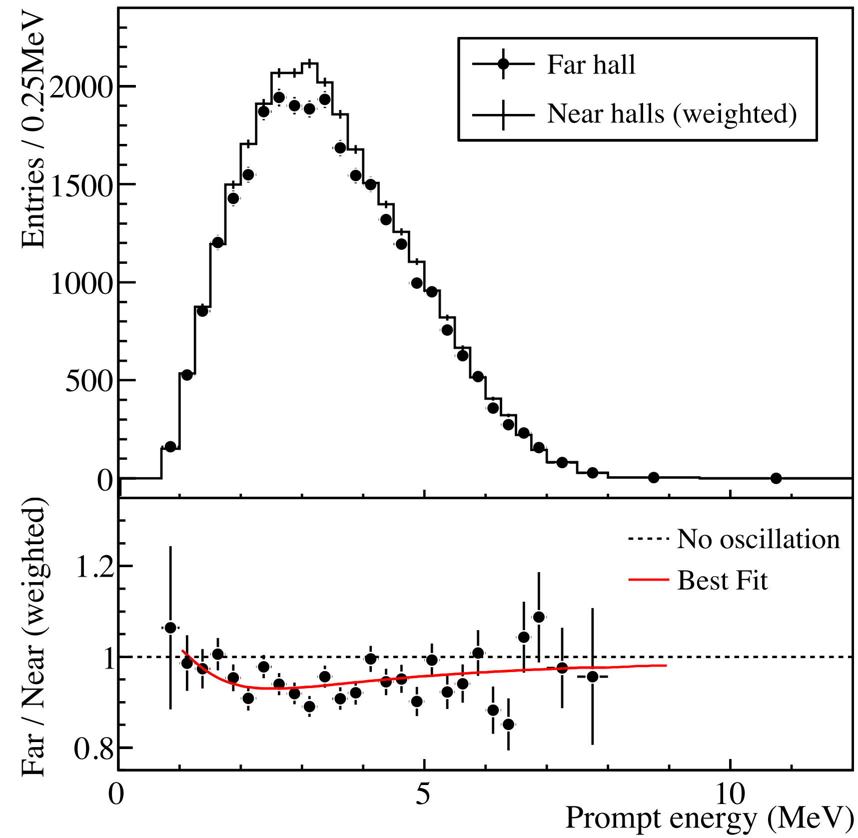


Spectral distortion consistent with expected oscillation from rate analysis*
(* Caveat: Spectral systematics not yet fully studied)

Rate Deficit & Near/Far Ratio





Far vs. near relative measurement.
Absolute rate is not constrained.

$\sin^2 2\theta_{13}$ =
0.089 ± 0.010 (stat) ± 0.005 (syst)

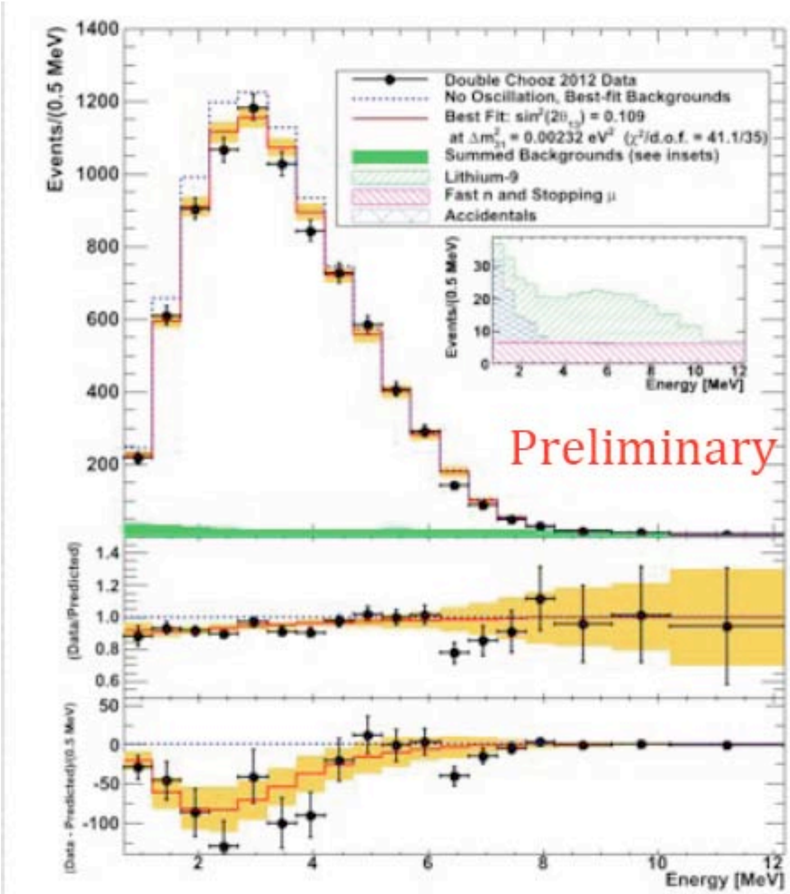
Most precise measurement of $\sin^2 2\theta_{13}$ to date.

Next
- shape analysis for oscillation (θ_{13}, Δm^2_{13})
- spectral shape vs reactor prediction
- absolute flux normalization

stay tuned!

Other Reactor Experiments

Double Chooz

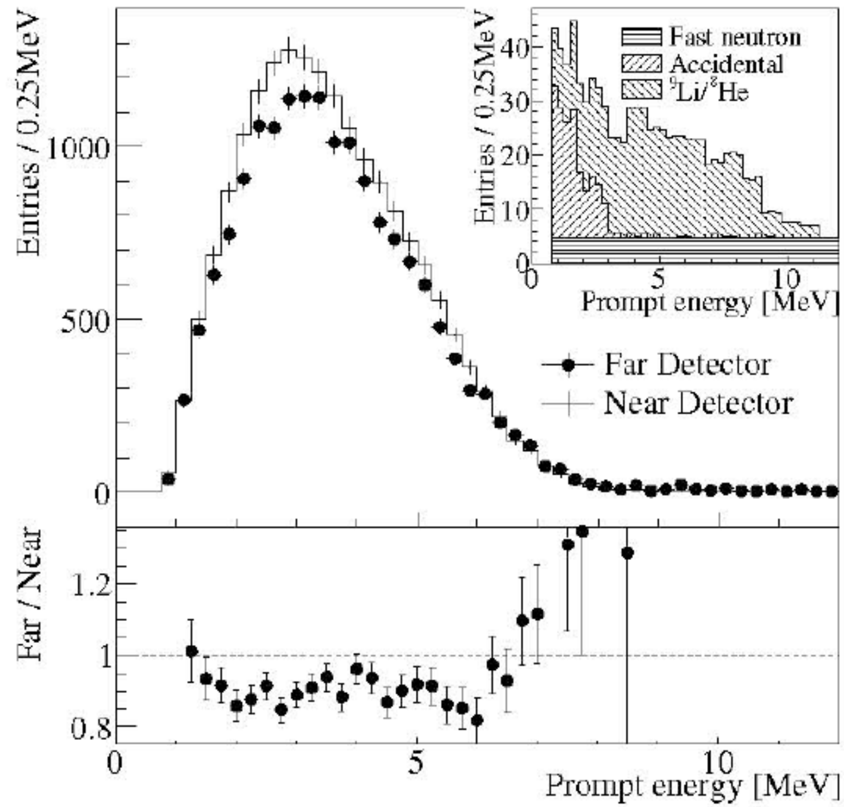


Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

Ref: Ishitsuka, Neutrino2012

RENO



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

PRL, 108 (2012) 191802

Global θ_{13} Measurements

2011/2012 -The year of θ_{13}

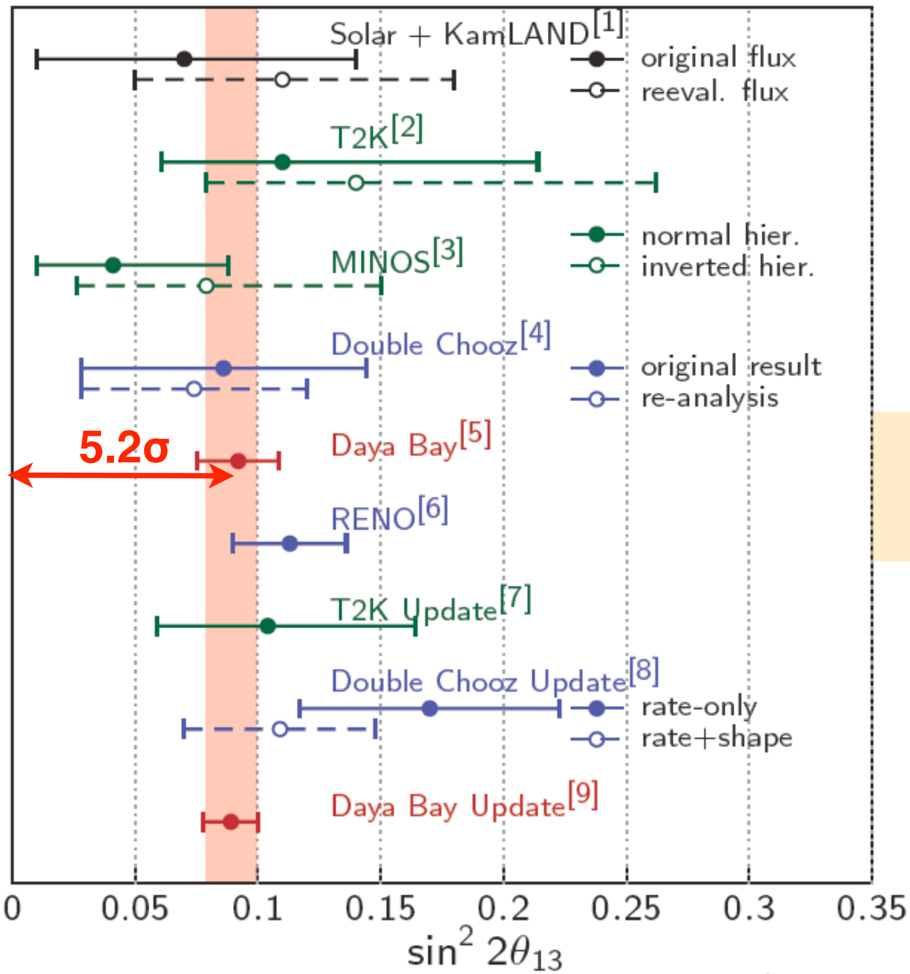


Fig adapted from S.Jetter

2011 - Early indications of

2012 Mar - Daya Bay observes non-zero θ_{13}
2012 Apr - Reno confirms

2012 Jun - Updates at Neutrino2012

Global θ_{13} Measurements

2011/2012 -The year of θ_{13}

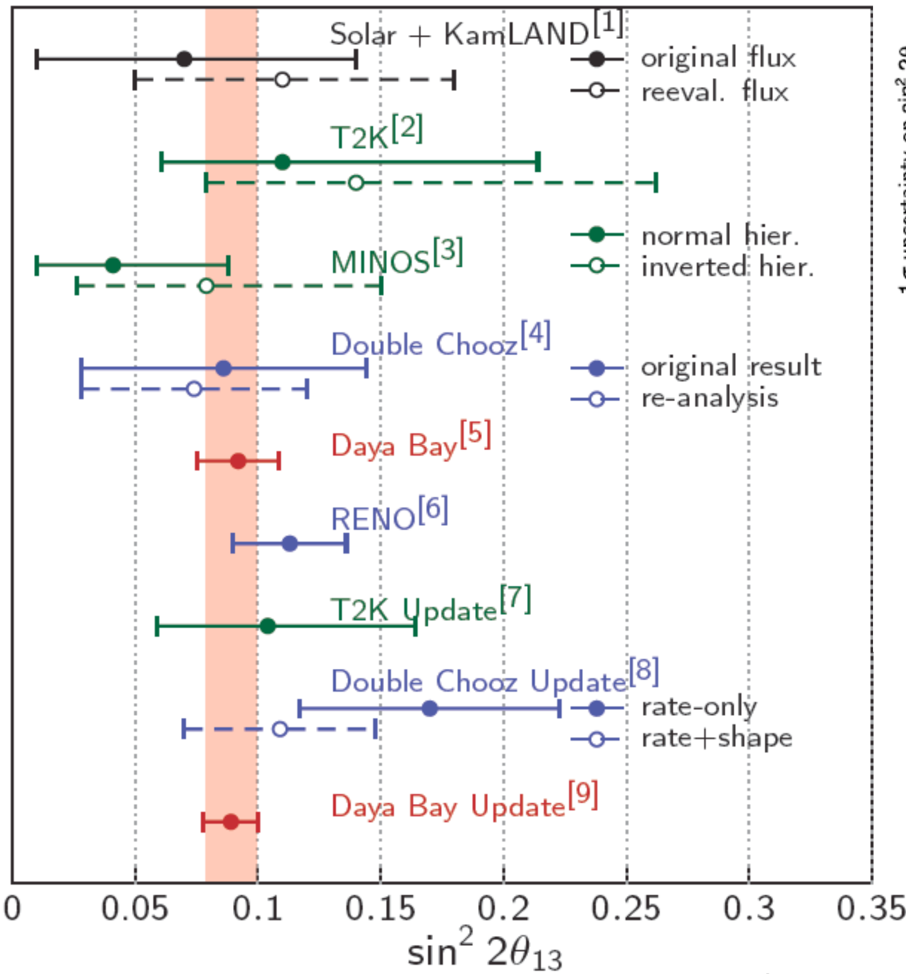
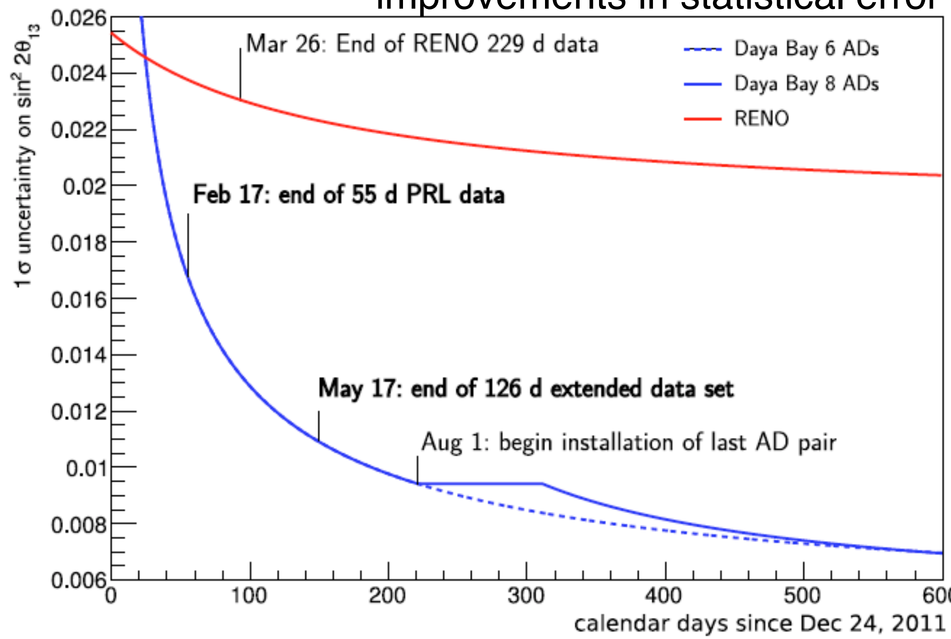


Fig adapted from S.Jetter

Daya Bay Future

improvements in statistical error



Will continue to provide most precise measurement of $\sin^2 2\theta_{13}$ in the world.

Statistical and systematic uncertainties become equal in 560 days.

Will deploy 2 more detectors in 2012 and perform additional calibrations

Global θ_{13} Measurements

Future Outlook

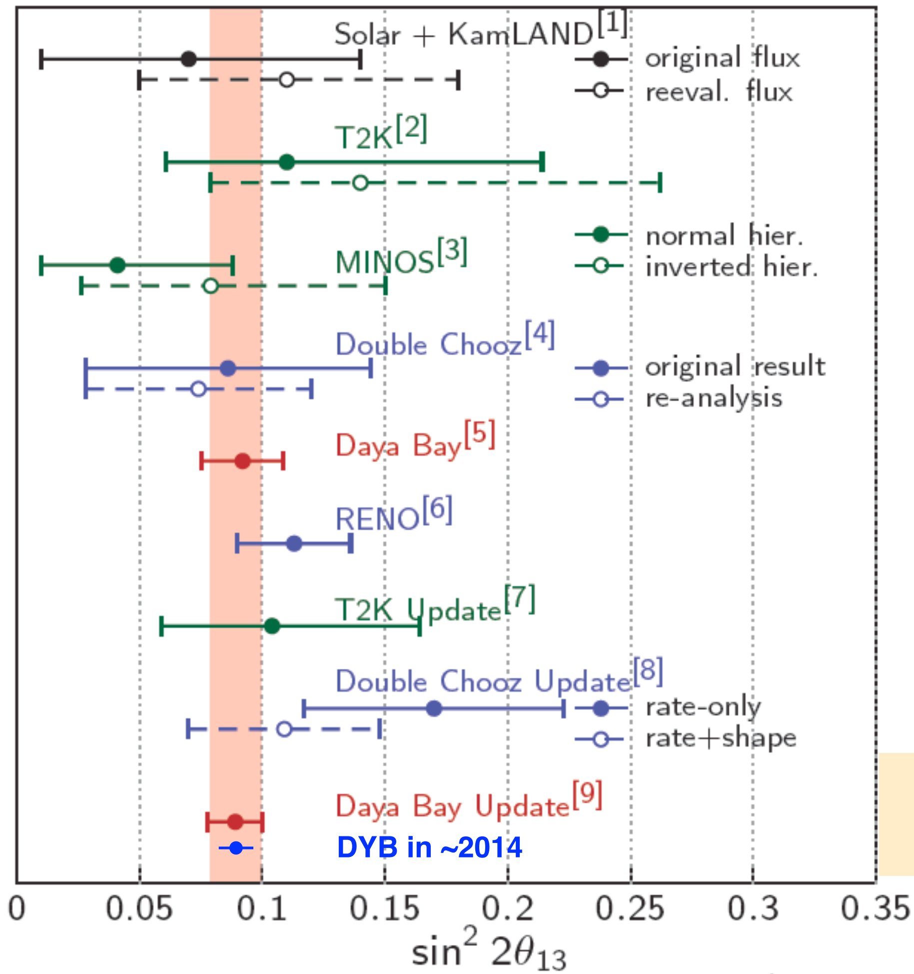
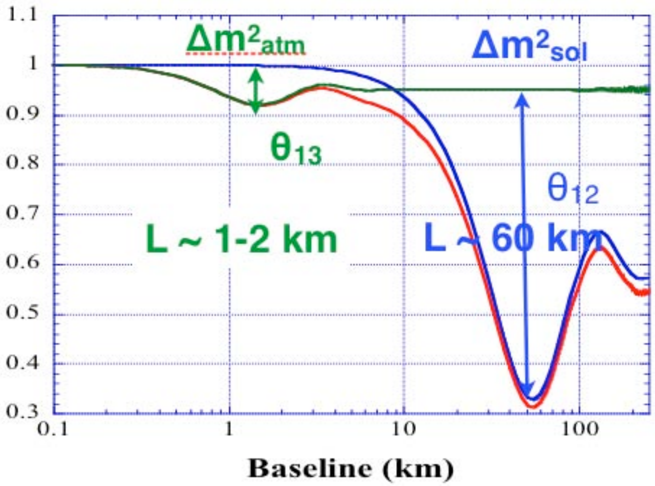


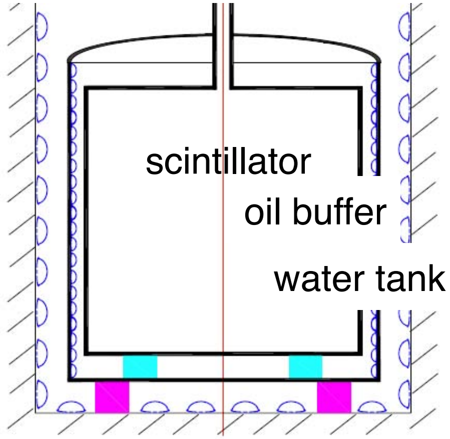
Fig adapted from S.Jetter

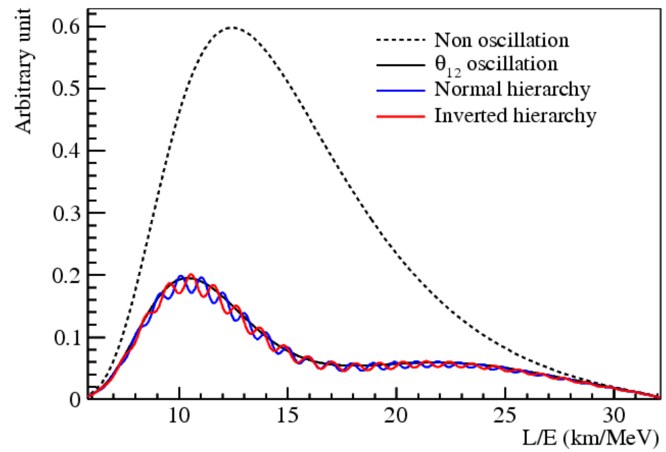
With ~3 years of Daya Bay running, reduce uncertainty from ~13% to ~4-5%.

θ_{12} and Mass Hierarchy

Measure spectrum at 1st oscillation maximum of θ_{12} oscillation







$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

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

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

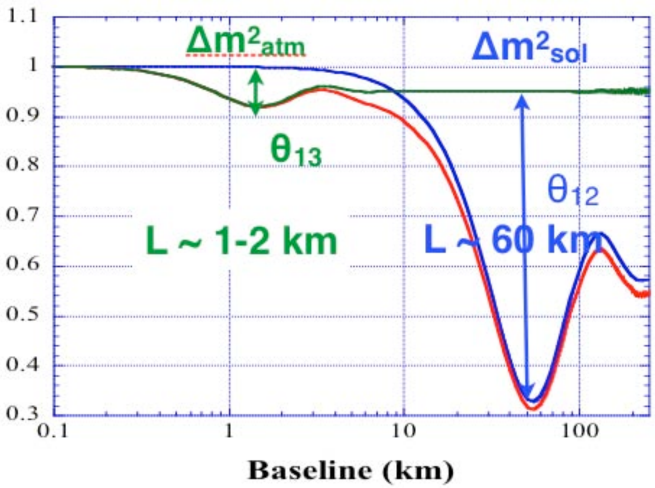
Δm^2_{21} is only 3% of $|\Delta m^2_{32}|$

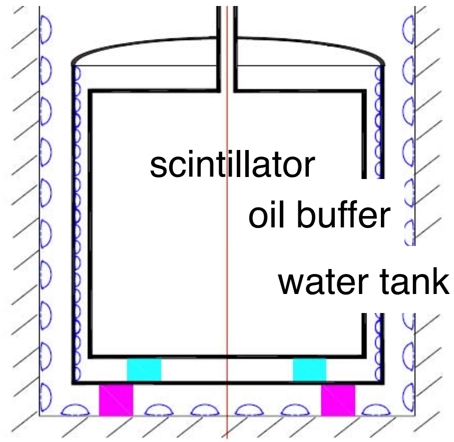
S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

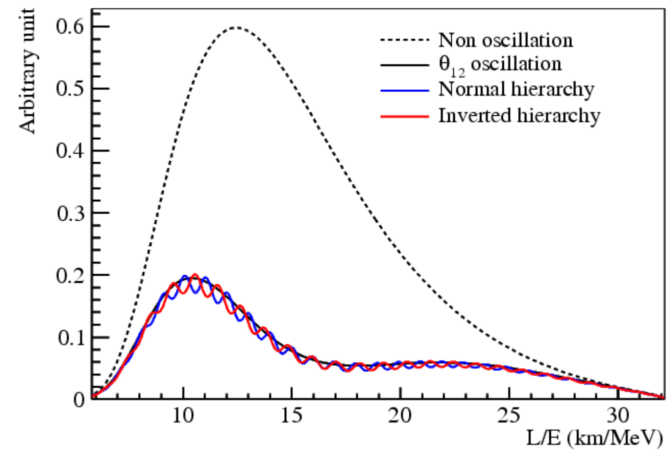
L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

θ_{12} and Mass Hierarchy

Measure spectrum at 1st oscillation maximum of θ_{12} oscillation



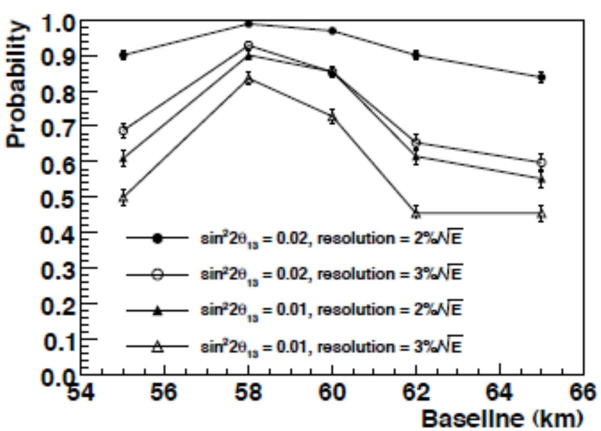


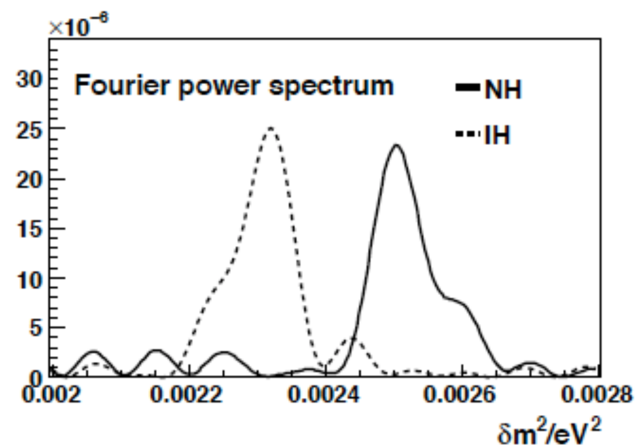


optimize baseline for detector, L=58km

extremely good E resolution of $3\%/\sqrt{E}$

e.g. 20kton, 15,000 20" PMTs





S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

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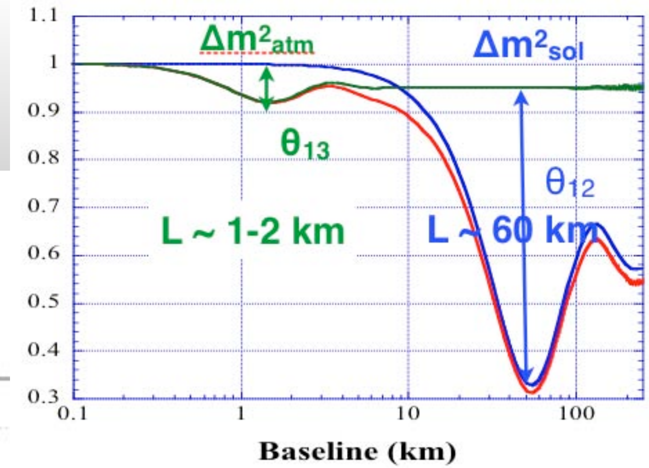
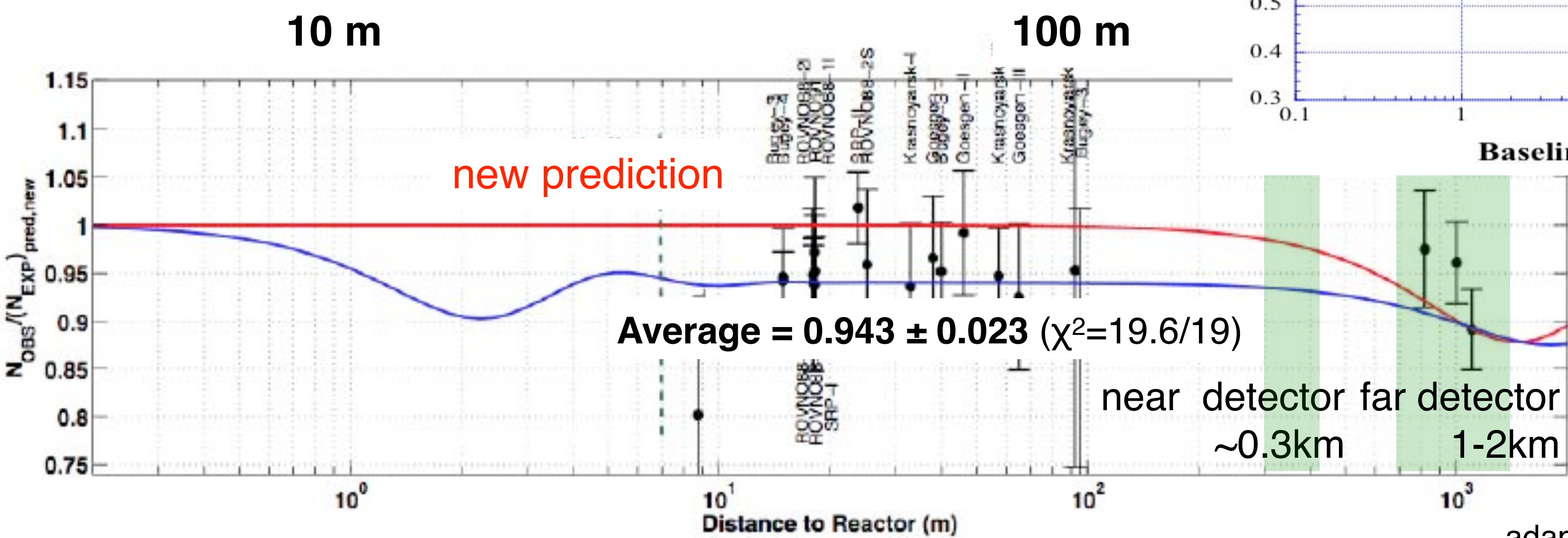
PRD78:111103, 2008
PRD79:073007, 2009

Beyond 3-ν Mixing with Reactor ν





adapted from Schwetz
Neutrino2012

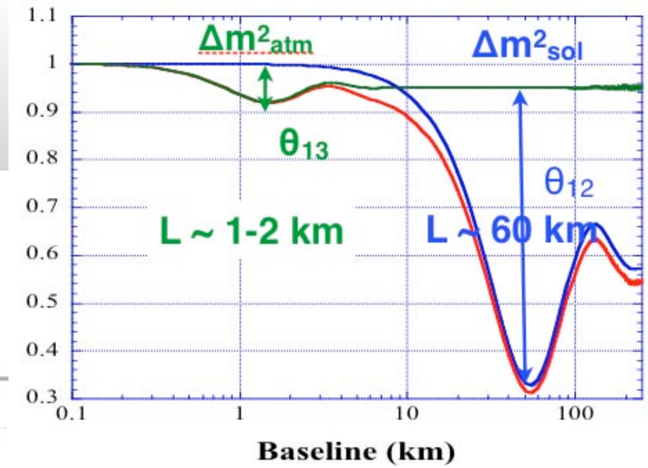
2011 $\overline{\nu}_e$ flux predictions
- new reactor antineutrino spectra
- re-analysis of 19 short-baseline reactor results
- neutron lifetime correction, off-equilibrium effects

net 3% upward
shift in energy
averaged fluxes

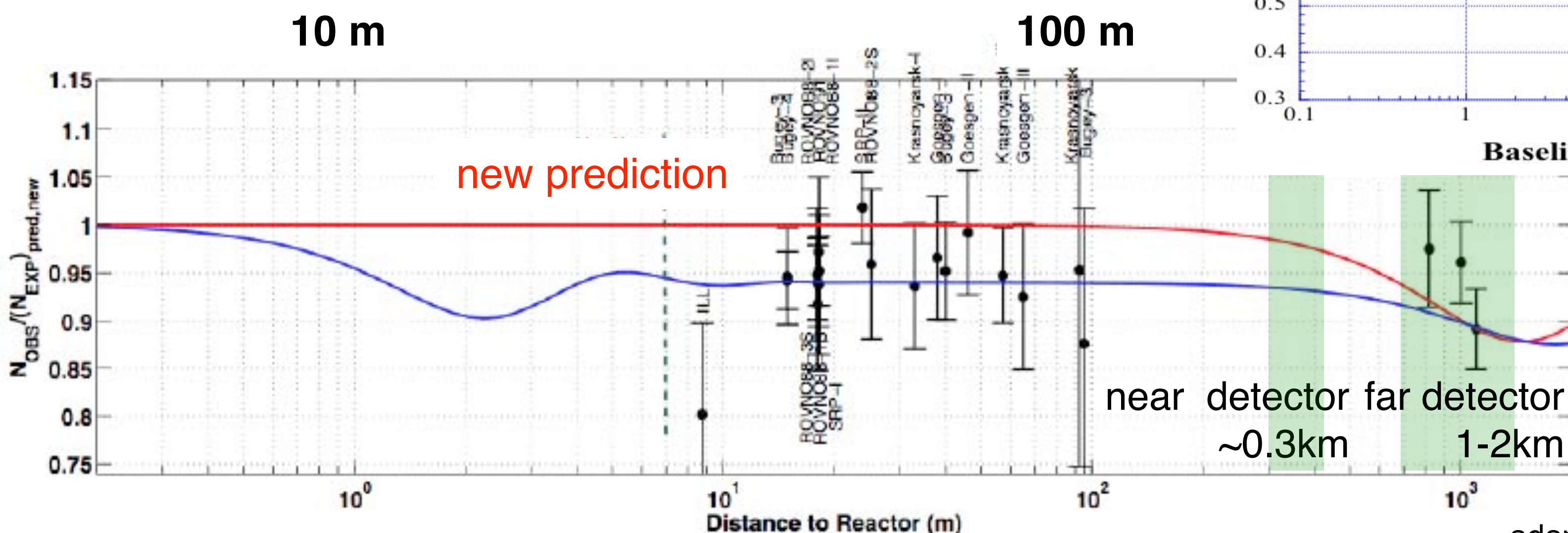
deficit from flux normalization problem or from additional oscillation at L~O(1-10m)?

nuclear physics or new physics?

Beyond 3-ν Mixing with Reactor ν



What can reactor θ_{13} experiments contribute?



adapted from Schwetz Neutrino2012

Absolute flux measurement

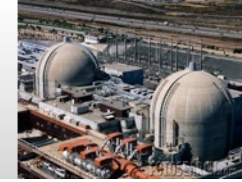
	Double Chooz	RENO	Daya Bay
detector systematic	2.1%	1.5% (correlated)	1.9% (correlated)
reactor systematic	1.8%	2.0% (correlated)	3.0% (correlated)

- difficult to make definitive statement
- work on improving correlated uncertainties

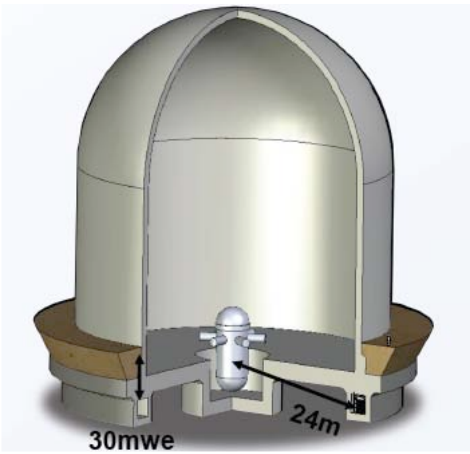
Precision Spectral Measurement

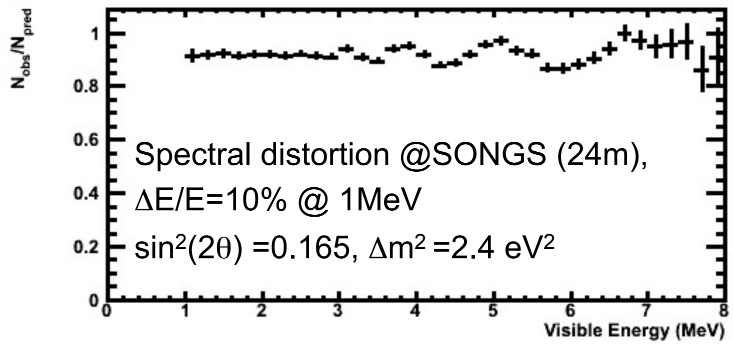
→ important to verify that we understand how to predict reactor $\bar{\nu}_e$ spectrum, reactor θ_{13} experiments not optimized to resolve 'anomaly'

Reactor Monitoring Experiments for Sterile ν Searches

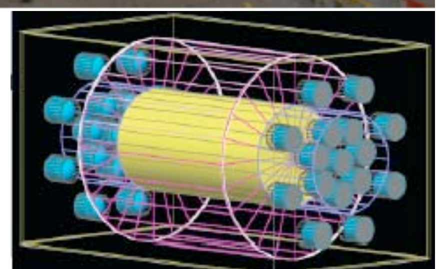


SCRAAM: Southern California Reactor Antineutrino Anomaly Monitor

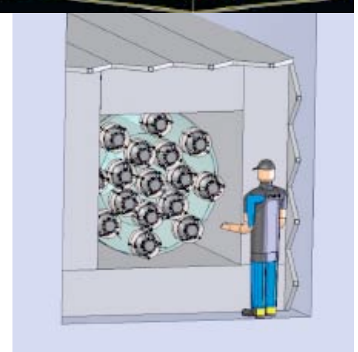


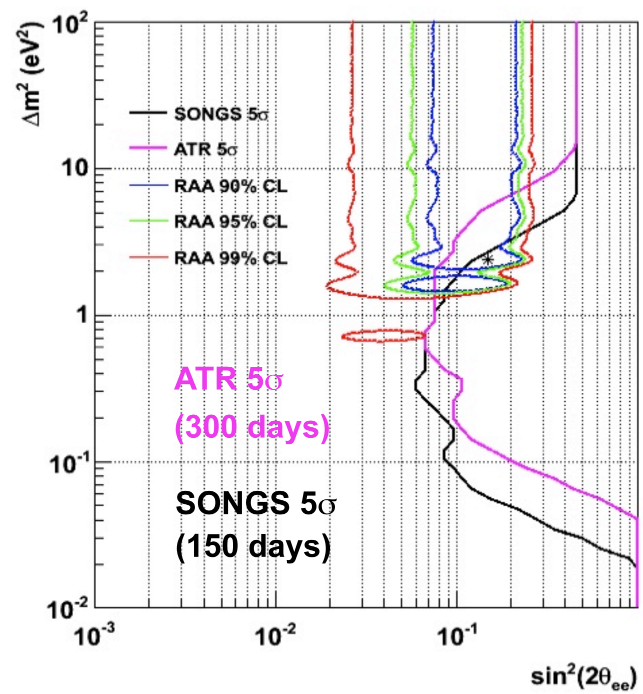


core ∅: ~3m,
fixed baseline: 24m



Adapt existing compact detector design/technology, limited by backgrounds





Limitations: Existing designs require overburden for background reduction – limits range of deployment sites, especially very close (<10m) to compact cores

Ref: Bowden, poster 153-3

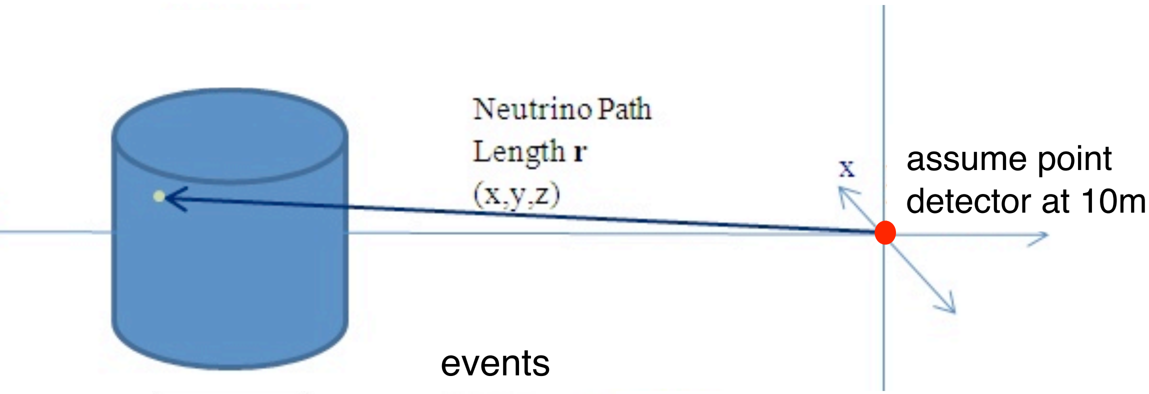
Short Baseline ν Oscillation Searches

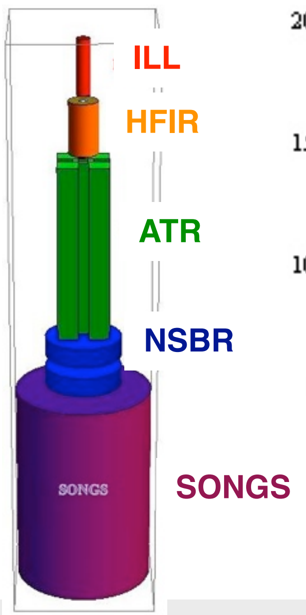
Some Experimental Issues

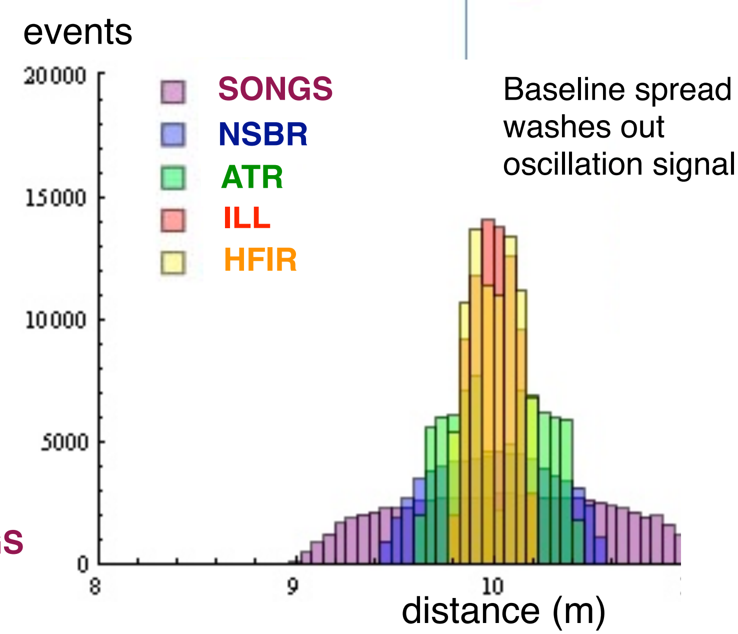
Reactor Core Size
small core preferred

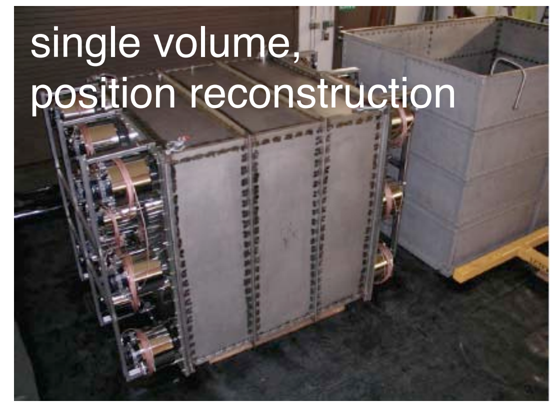
Baseline Spread
at detector from core

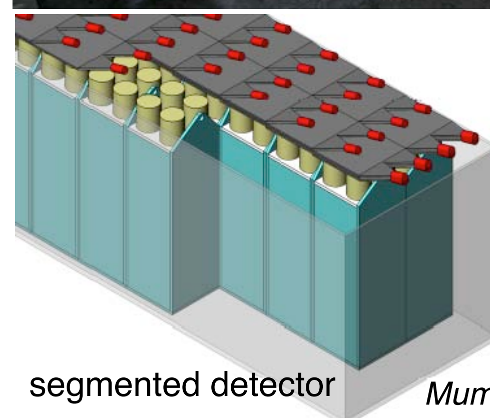
Detector Technology Choice
localize events,
PSD(?) for background rejection,
good E resolution for spectrum





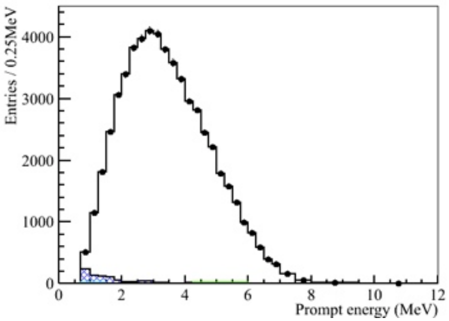






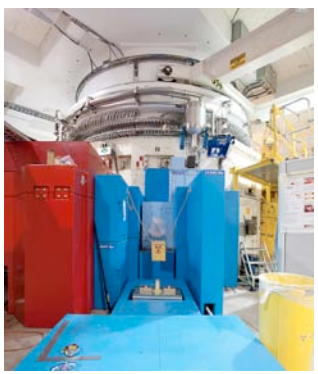
Mumm, KMH

Reactor $\overline{\nu}_e$ at Short Baselines - Scientific Opportunities



Reactor cores, fuel, and antineutrino spectra

- precision studies of r**eactor antineutrino spectra**
- studies of **fuel composition** and **burnup** cycle
- studying **HEU to LEU core conversion** at US research reactors

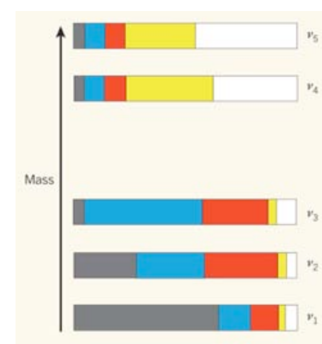


Background studies and detector development

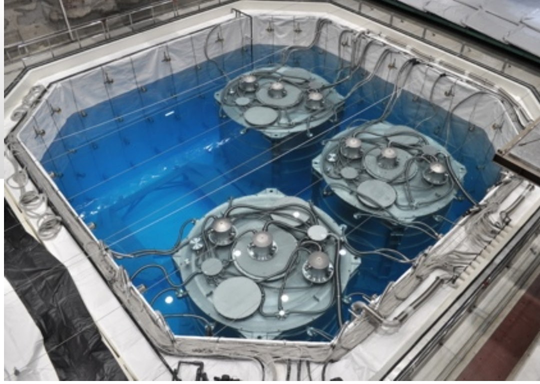
- understand **high n and γ environment** near reactors
- segmented vs monolithic detectors with position reconstruction
- **scintillators for neutron detection** (Gd and Li-doped, LAB vs water)
- test of **on-surface antineutrino detectors** with minimum overburden
- background studies during on-off cycles at research reactor

Searches for new physics

- Understanding **reactor anomal**y & test sterile ν hypothesis
    - requires unique signatures: oscillation in E and distance
- neutrino **magnetic moment** and **coherent scattering** searches



Sterile Neutrino Search at Daya Bay

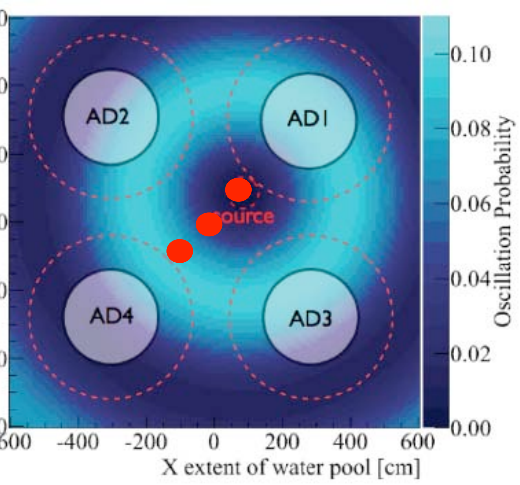


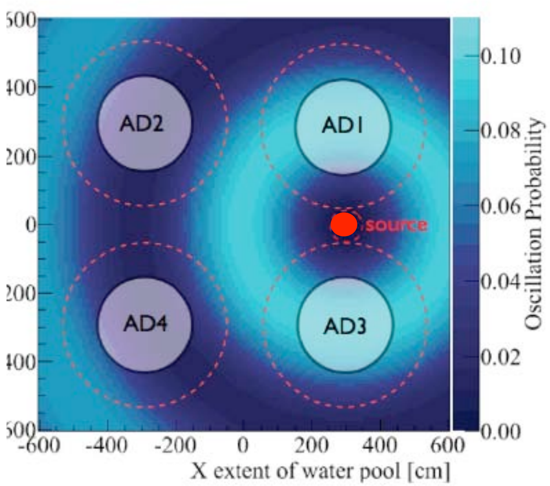
18 PBq ^{144}Ce source at the Daya Bay far site

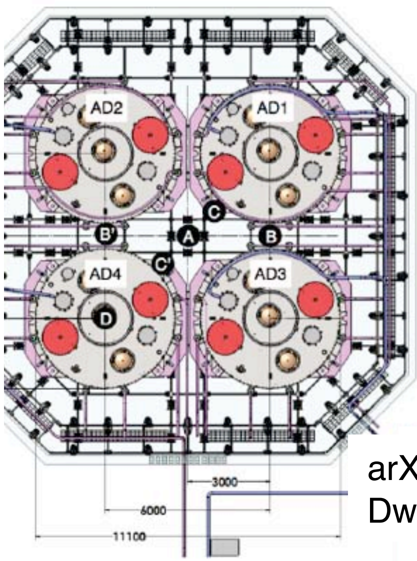
Signal

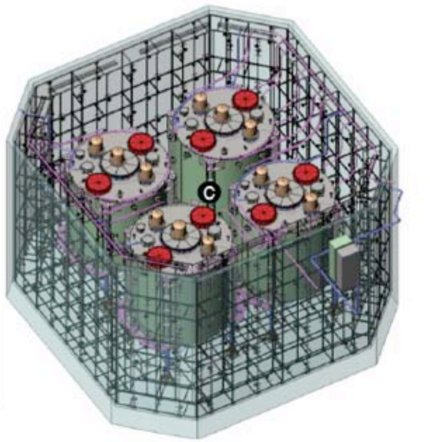
- baseline range: ~1.5 - 8 m
- ν energy range: 1.8 - 3 MeV
- 30k - 40k inverse beta-decay (IBD) events/per year

- Probing baselines from 1.5-8 m with an antineutrino source in the water pool of the Daya Bay Far Hall
- Advantageous to place source outside detectors in water pool.
- Multiple detectors allow for control of systematics.









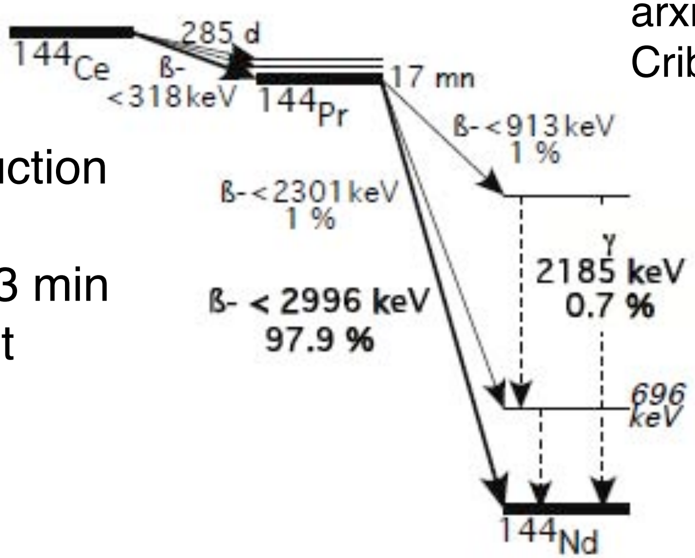
arXiv:1109.6036
Dwyer, Littlejohn, Vogel, KMH

Sterile Neutrino Search at Daya Bay

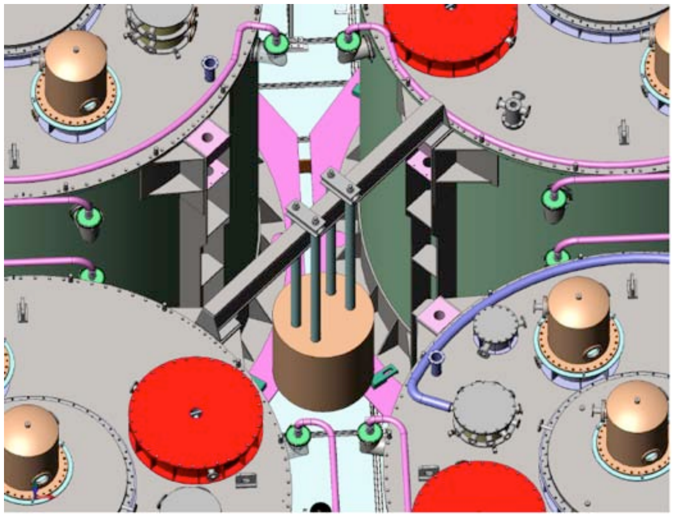
arxiv:1107.2335
Cribier et al

^{144}Ce-^{144}Pr Antineutrino Source

- Q_{β}> 1.8 MeV (IBD threshold)
- lifetime long enough to allow for production and transport
- $T_{1/2}$ (^{144}Ce)=285 days, $T_{1/2}$ (^{144}Pr)=17.3 min
- contained in fission fragments of spent nuclear fuel



Ce-144 source with W shielding



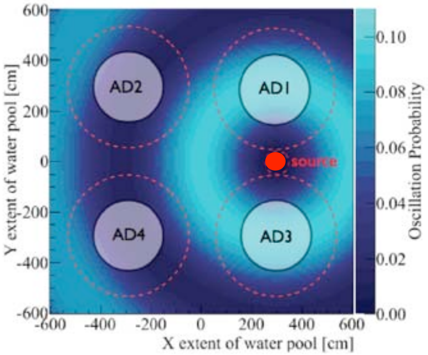
Background

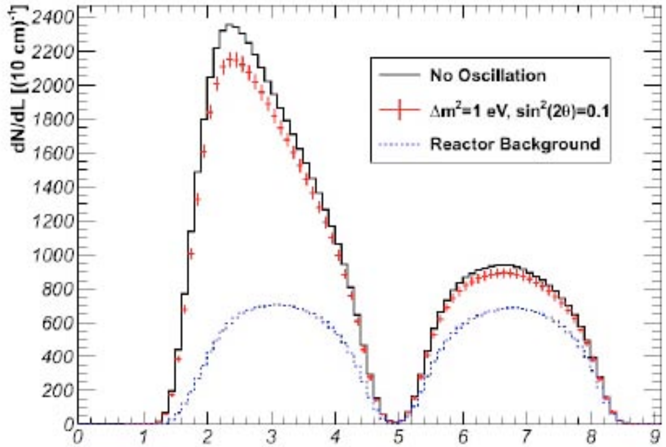
- ~0.5 m thick shielding makes source gammas negligible
- Water pool also shields, cools source outside detector
- Reactor neutrino 'background' well-known to <1% from near detectors

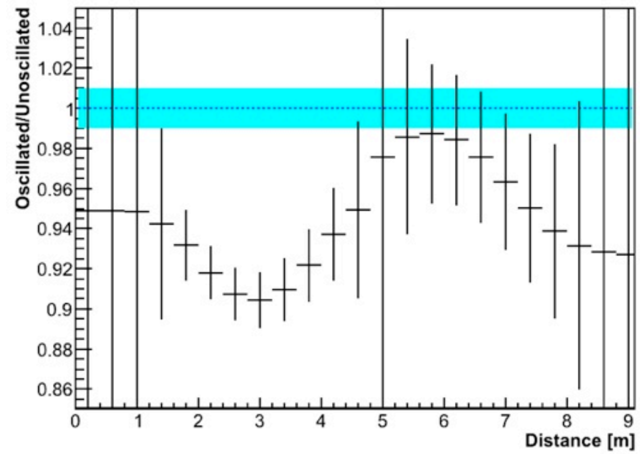
Ref: Littlejohn, KMH

Sterile Neutrino Search at Daya Bay

Signal and Event Distributions

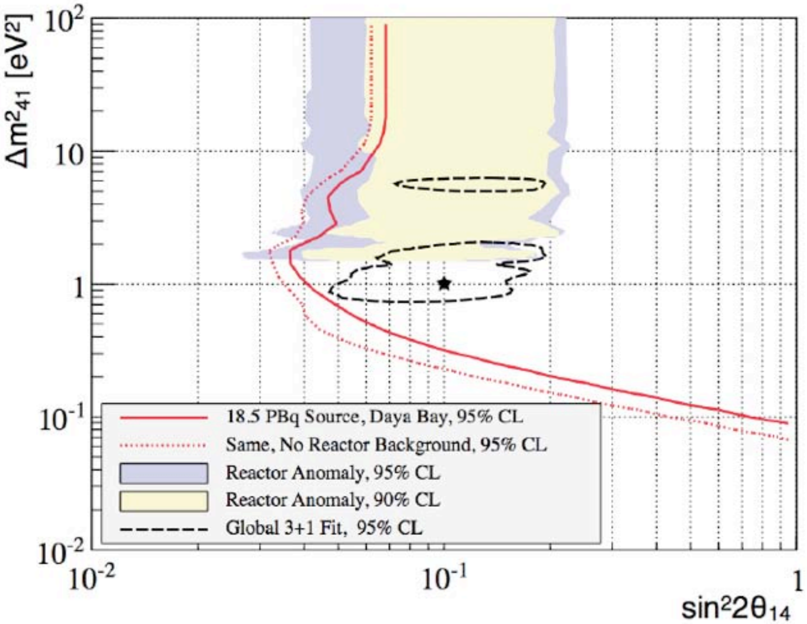






Distance (m)

arXiv:1109.6036
Dwyer, Littlejohn, Vogel, KMH



Sterile neutrino oscillations with mass > 1eV can be tested using ^{144}Ce source in the Far Hall of the Daya Bay experiment after θ_{13} measurement.

Summary

For > 50 years reactor experiments have played an important role in neutrino physics, in both discoveries and precision measurements.

Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$, and **reactor antineutrino spectra** from power reactors. Data taking for next ~3-5 years.

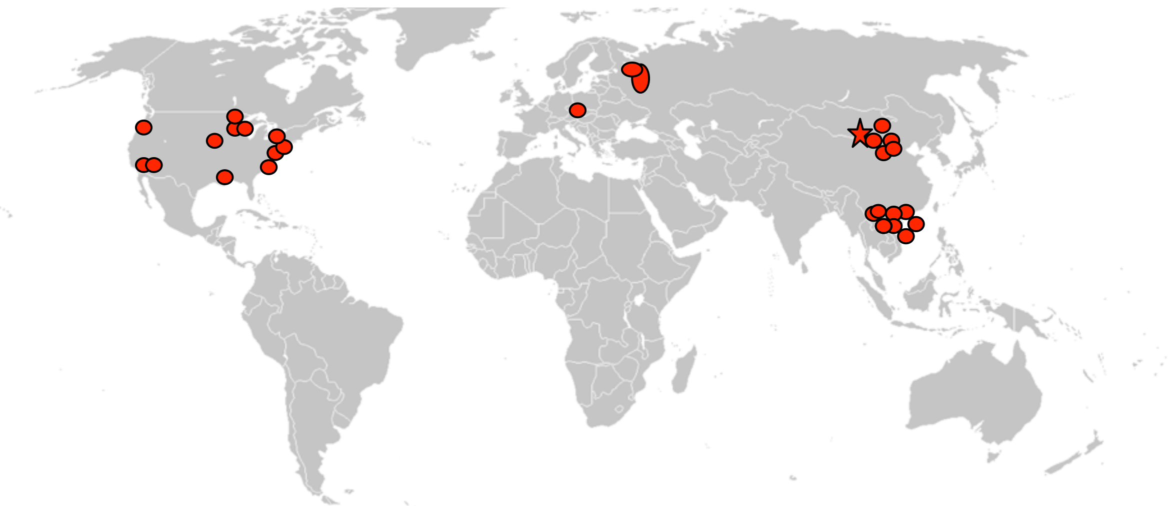
Intermediate-baseline **(L~60km**) reactor antineutrino experiments may be used for a precision measurement of $\boldsymbol{\theta_{12}}$, and determination of the **mass hierarchy**.

Very short baseline **(L~10m)** measurements offer opportunities for precision studies of the **reactor spectra**, **fuel evolution** and searches for **new physics**. On-surface **neutrino monitors** may be developed.

Reactor $\overline{\nu}_e$ enable a rich program in probing neutrino properties, detector development, and nuclear monitoring with neutrinos.

Daya Bay Collaboration

An International Effort



Asia (20)

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

North America (16)

Brookhaven Natl' Lab, Cal Tech, Cincinnati, Houston, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl' Lab, Princeton, Rensselaer Polytech, UC Berkeley, UCLA, Wisconsin, William & Mary, Virginia Tech, Illinois, Siena College

Europe (2)

Charles Univ., Dubna

~230 collaborators