Reactor and Solar Neutrino Experiments

Recent Highlights and Future Opportunities

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Reactor Neutrinos

2012
Year of θ_{13} with Reactor Neutrinos

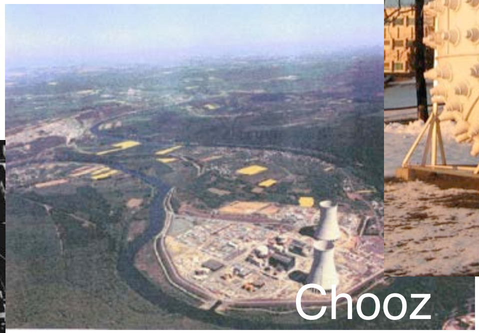
2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

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

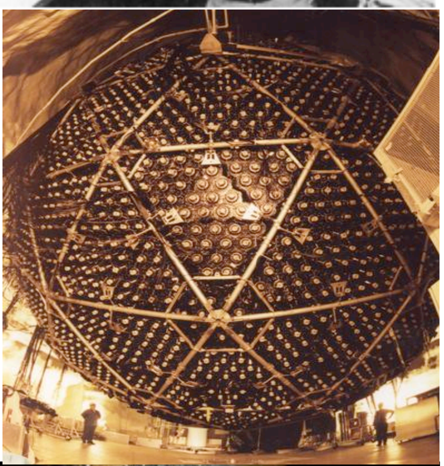
1956 - First observation of (anti)neutrinos

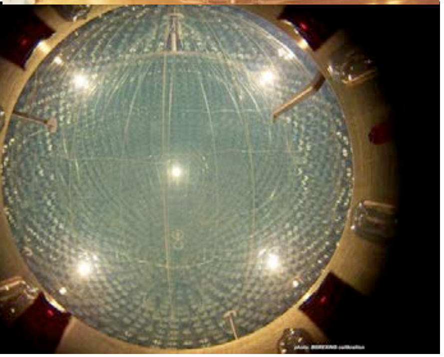


Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

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

Solar, Reactor, and Atmospheric Neutrinos Discoveries





1968 Ray Davis detects 1/3 of expected solar neutrinos.
(Nobel prize in 2002)

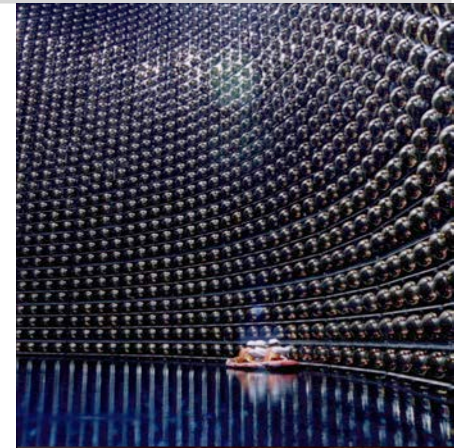
1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

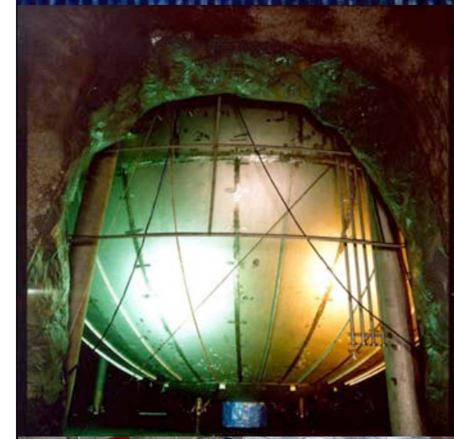
2001/2002 SNO finds evidence for solar ν_e flavor change.

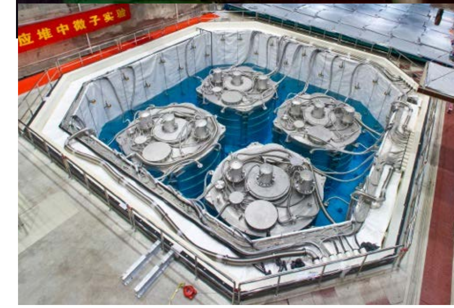
2003 KamLAND discovers disappearance of reactor $\bar{\nu}_e$

2007 Borexino detection of ^{7}Be solar neutrinos

2012 Daya Bay, RENO, Double Chooz measure θ_{13}



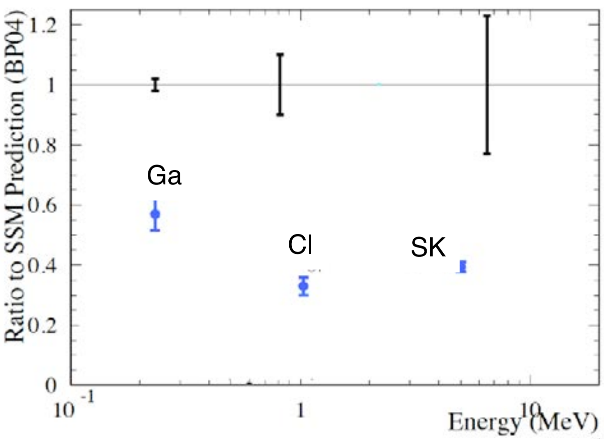




Era of Precision Neutrino Physics

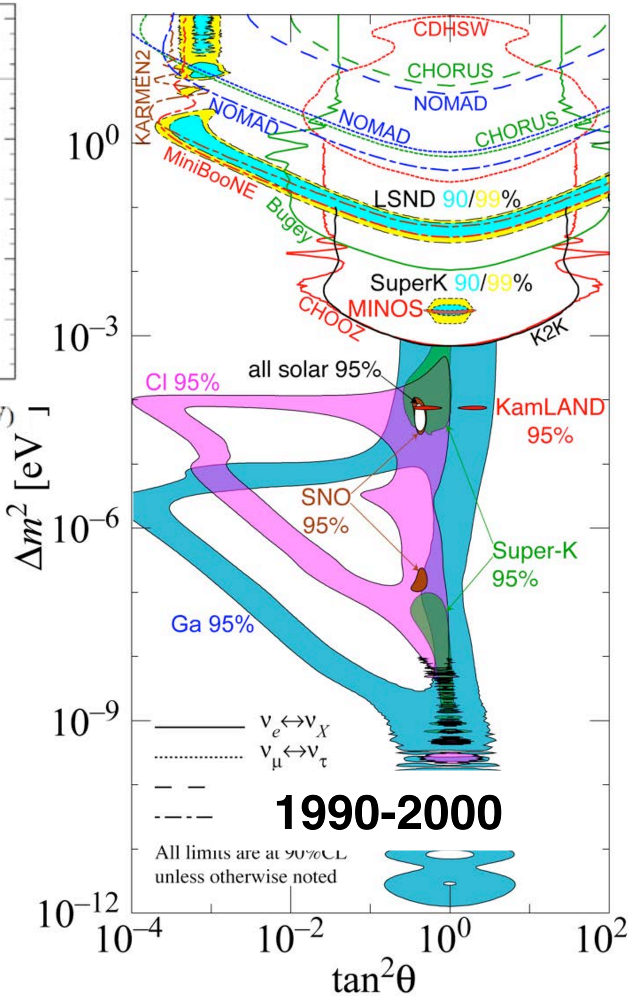
solar neutrino problem | **oscillation searches** | **precision measurements**

solar neutrino problem



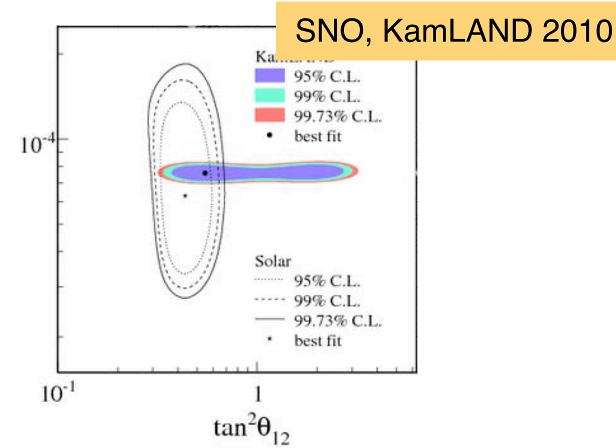
1960-1990

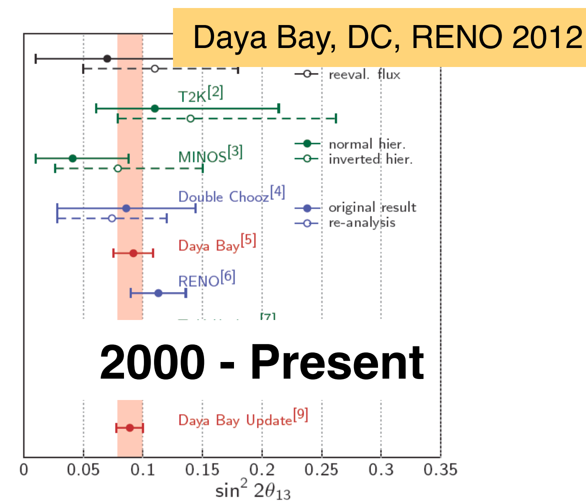
oscillation searches



1990-2000

precision measurements

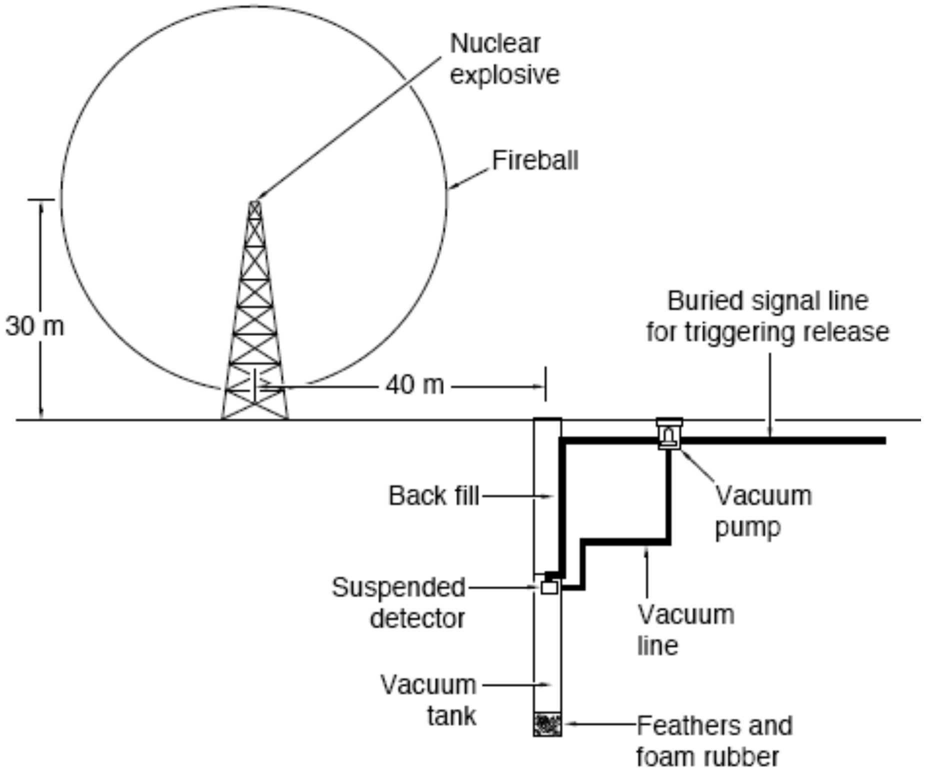




2000 - Present

Neutrino mass and mixing first physics beyond the SM → precision studies

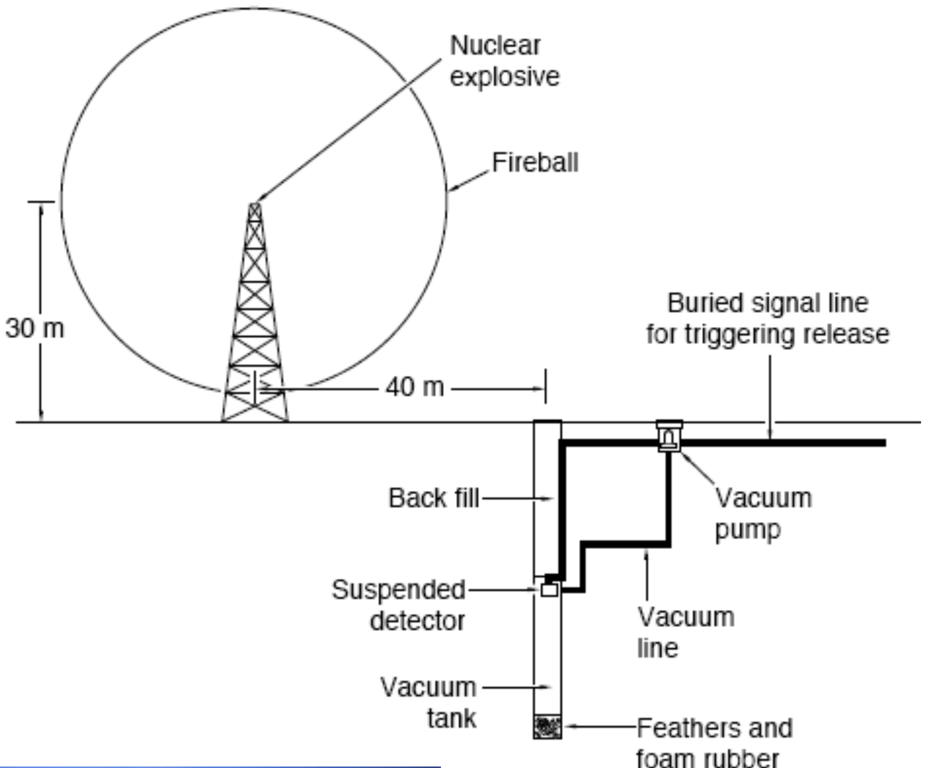
Towards First Detection of Neutrino




Clyde Cowan Jr.


Frederick Reines

Towards First Detection of Neutrino




Clyde Cowan Jr.


Frederick Reines

Reactors are intense and pure sources of $\overline{\nu}_e$

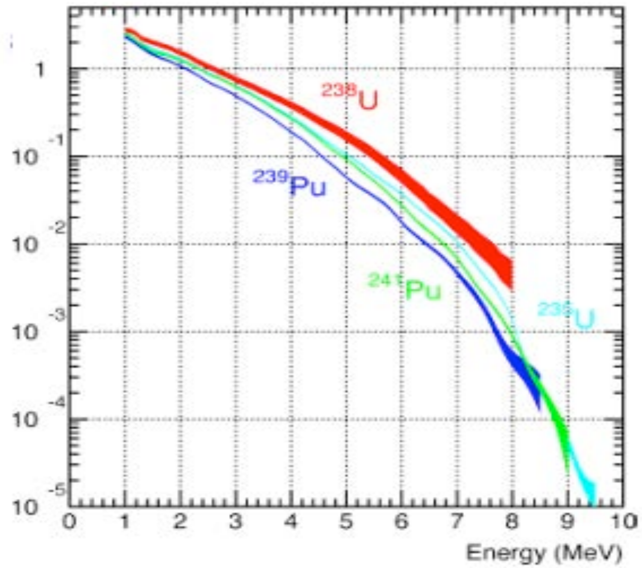
B. Pontecorvo Natl.Res.Council Canada Rep. (1946) 205
Helv.Phys.Acta.Suppl. 3 (1950) 97

Reactor Antineutrinos

Source

$\bar{\nu}_e$ from β-decays

of n-rich fission products



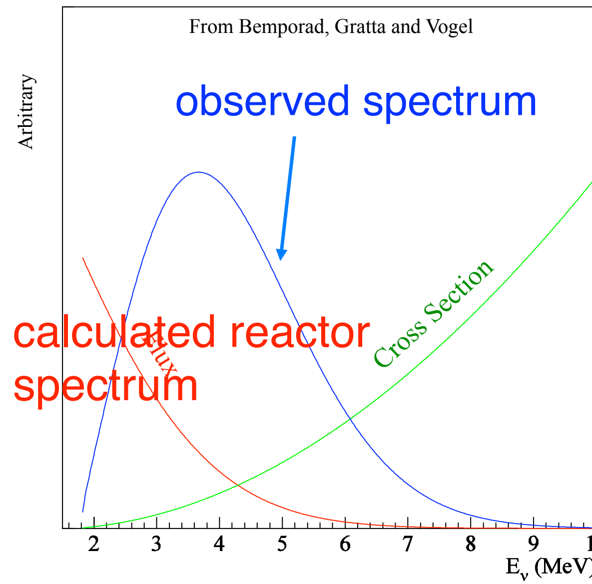
pure $\bar{\nu}_e$ source

> 99.9% of ν_e are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Detection

inverse beta decay

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



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

only disappearance experiments possible

The Savannah River Detector

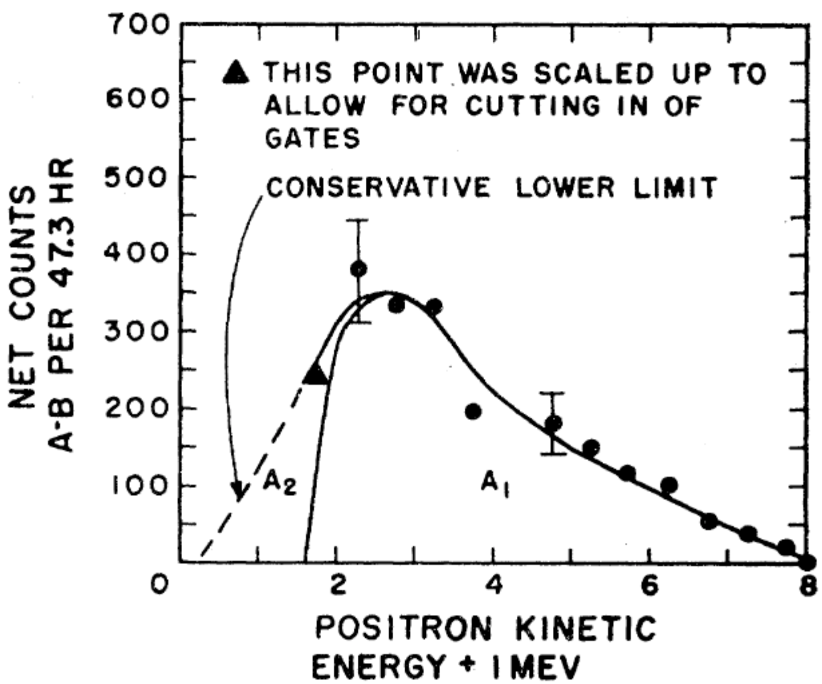
First Observation of Antineutrinos (1959)

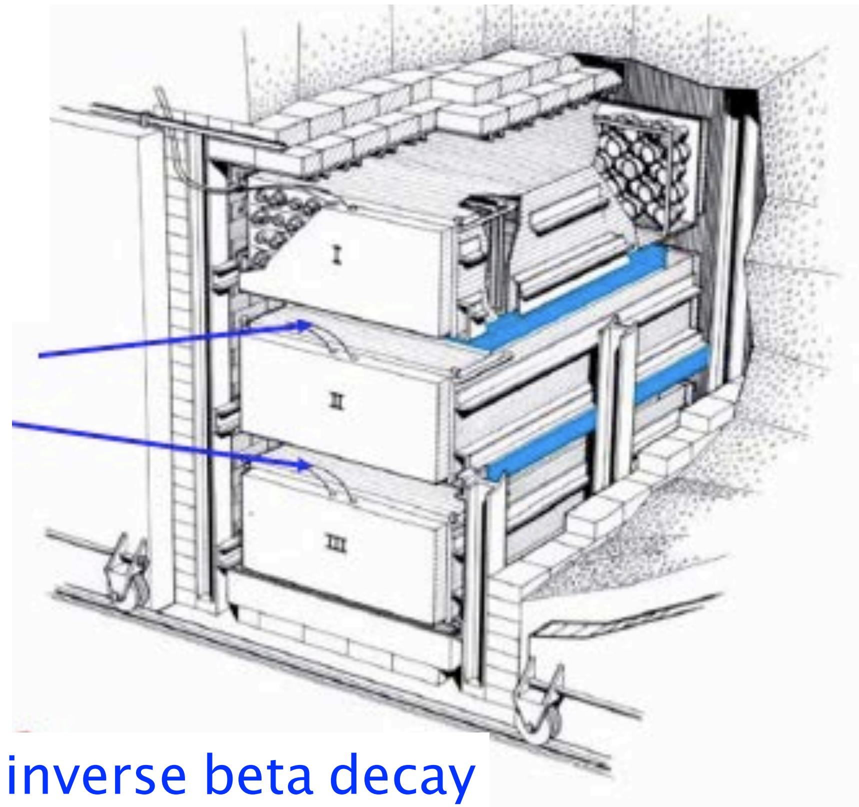
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs


Clyde Cowan Jr.


Frederick Reines

first reactor $\overline{\nu}_e$ spectrum





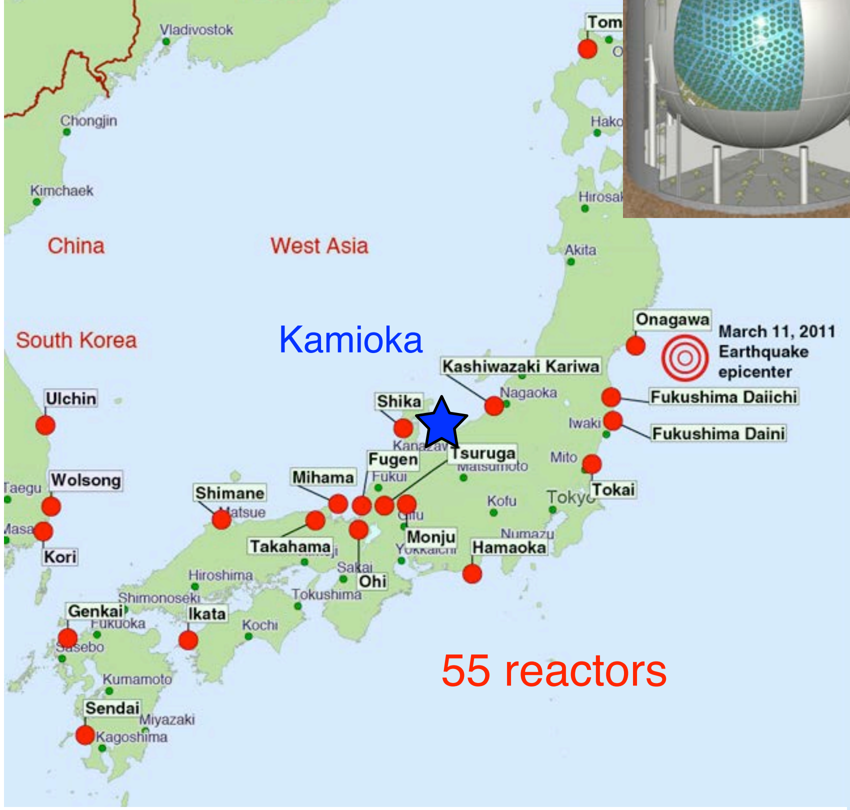
inverse beta decay

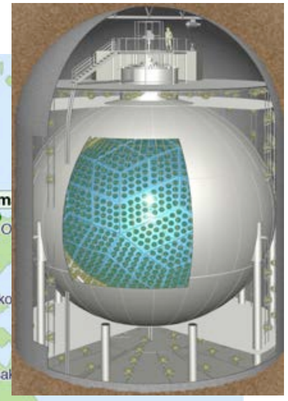
$\overline{\nu}_e + p \rightarrow e^+ + n$

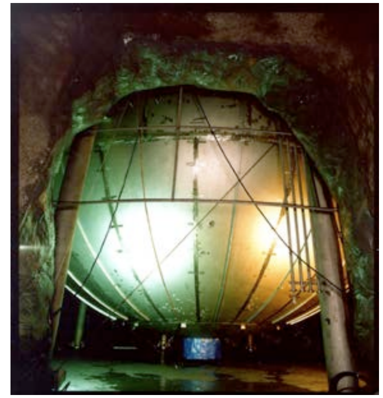
Reines, Cowan, Phys Rev 113, (1959)273

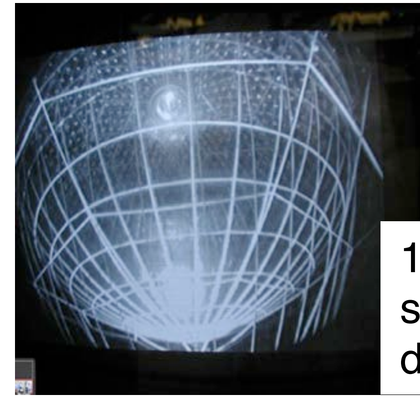
Observation of Reactor $\bar{\nu}_e$ Disappearance

KamLAND 2003

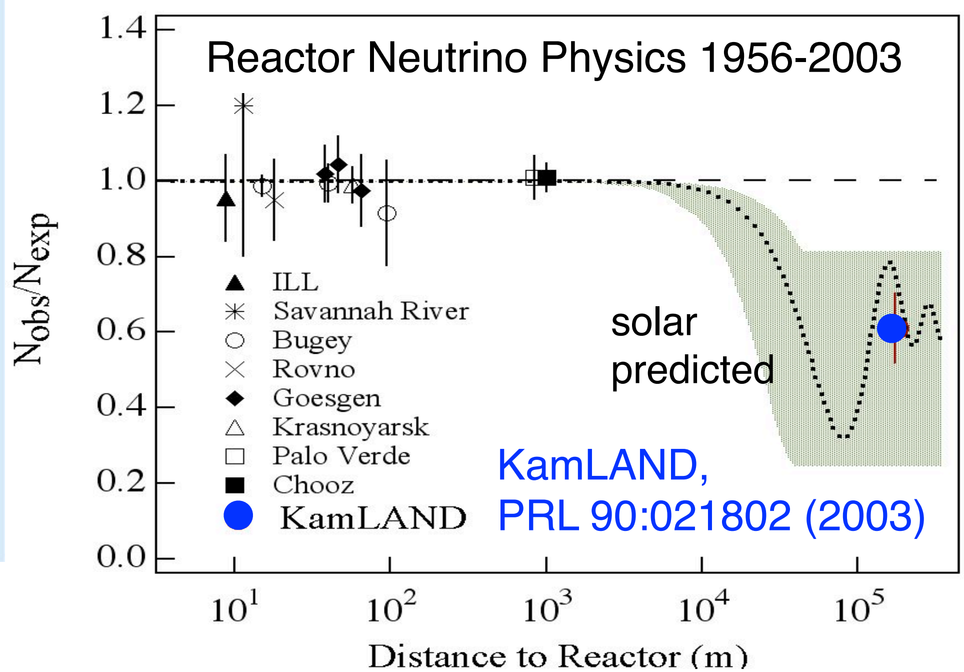






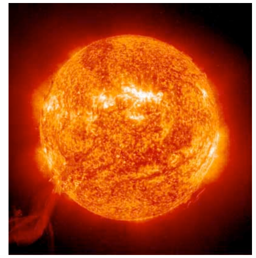


1kt liquid scintillator detector



mean, flux-weighted reactor distance ~ 180km

Neutrino Astrophysics



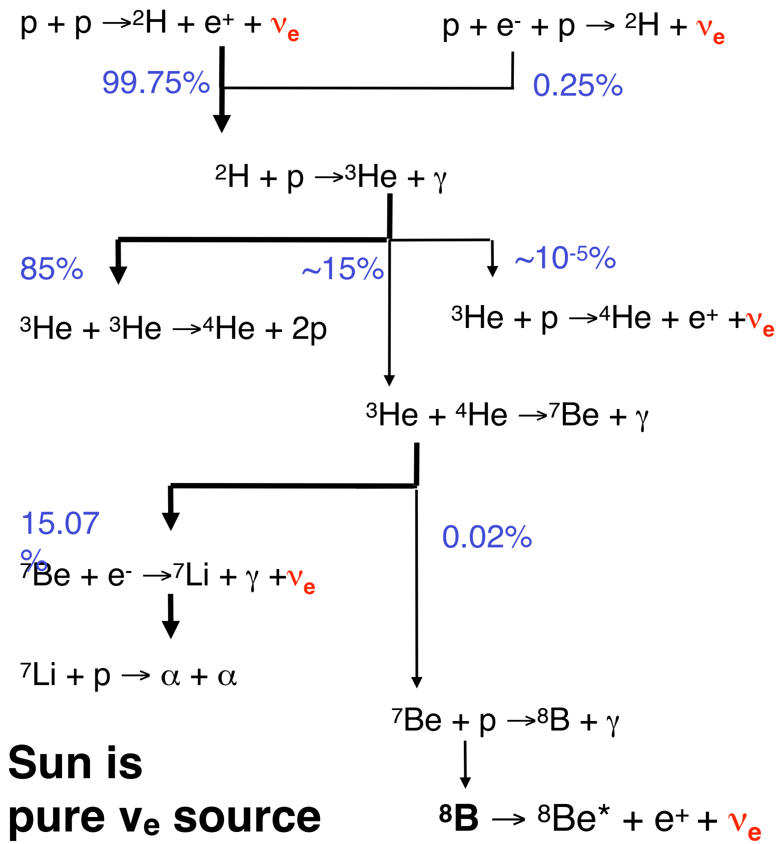
1938 Bethe & Critchfield

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

1947 Pontecorvo, 1949 Alvarez
propose neutrino detection through
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^{-}$

1960's Ray Davis builds chlorine detector.
John Bahcall, generates first solar model calculations and ν flux predictions.

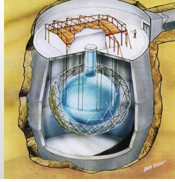
Light Element Fusion Reactions

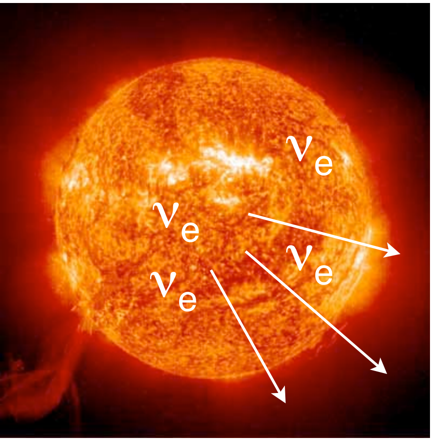


Sun is pure ν_e source

"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars…" (Bahcall, 1964)

Solar Neutrino Problem and SNO



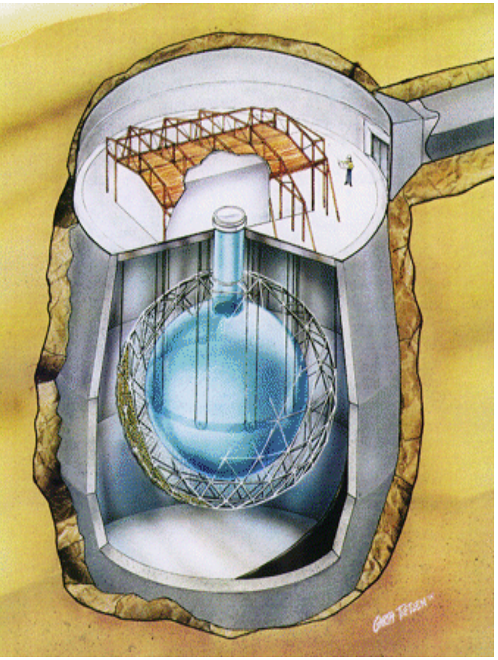


Solar Neutrino Problem (before 2001)

Too few ν_e observed from the Sun.

Even with all solar neutrino fluxes as free parameters, cannot reproduce the data. $P_{MSM} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)



Resolution of the Solar Neutrino Problem (2001) with the Sudbury Neutrino Observatory (SNO)

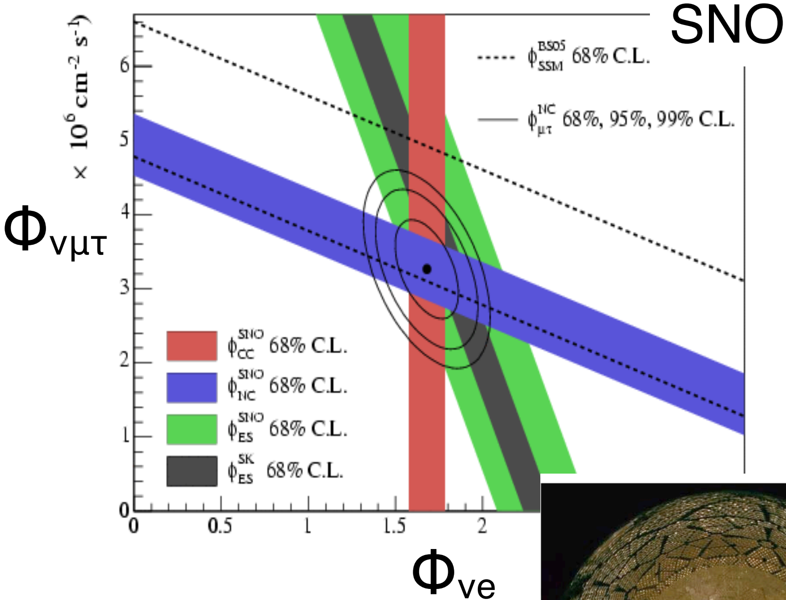
Neutral-Current	$\nu_e + \nu_\mu + \nu_\tau$
Charged-Current	ν_e
Elastic Scattering	$\nu_e + 0.15\,(\nu_\mu + \nu_\tau)$

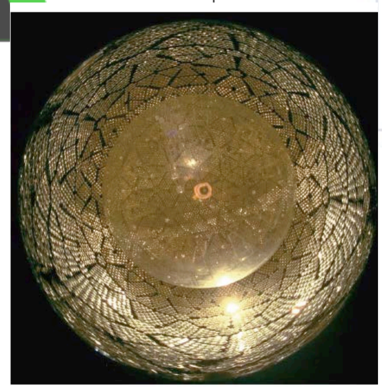
model-independent test of flavor change

Direct Evidence for Neutrino Oscillations

Solar ν_e

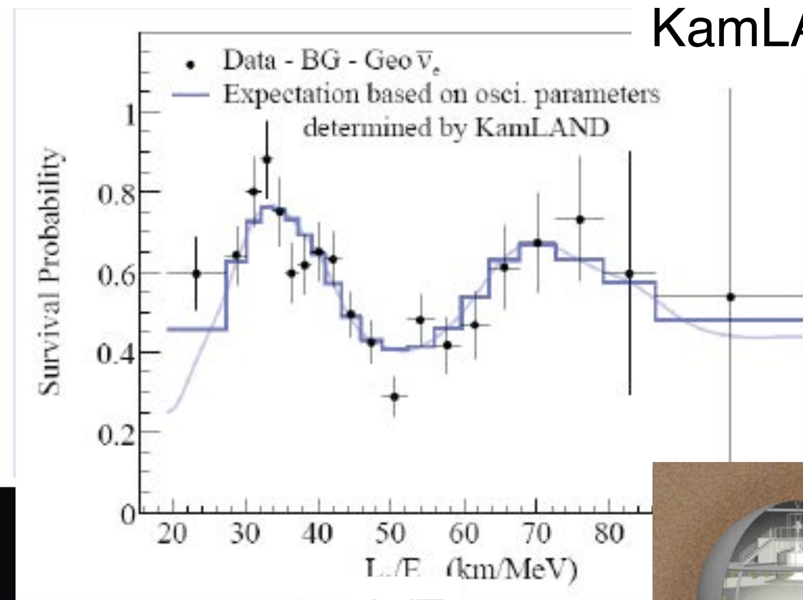
SNO

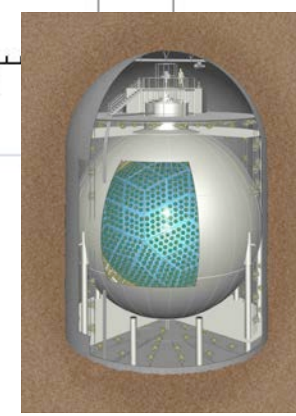




Reactor $\overline{\nu}_e$

KamLAND





BOARD ON PHYSICS AND ASTRONOMY NP2010 Committee *Nuclear Physics: Exploring the Heart of Matter*

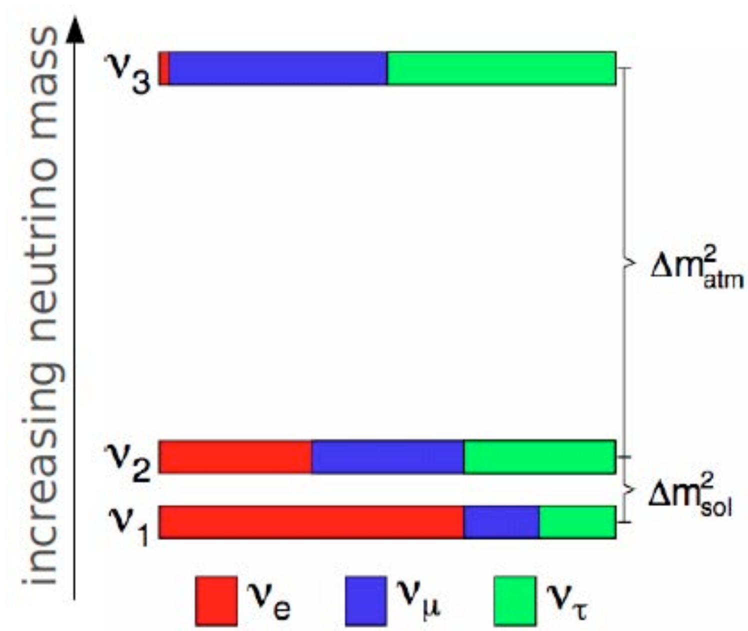
Neutrino Oscillation

Neutrino Oscillation Imply Neutrino Mass

mass eigenstates ≠ flavor eigenstates

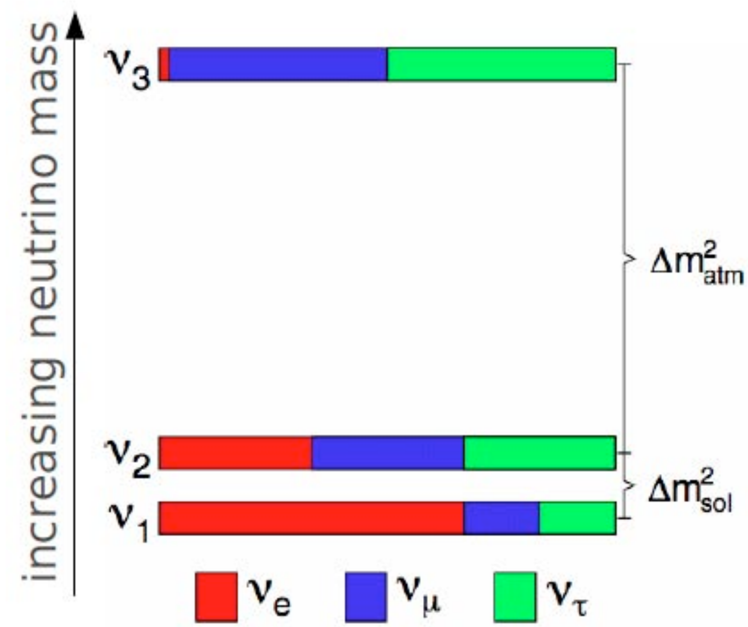
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

flavor composition of neutrinos changes as they propagate



Neutrino Oscillation

Neutrino Oscillation Imply Neutrino Mass



mass eigenstates ≠ flavor eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

flavor composition of neutrinos changes as they propagate

2-neutrino case

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

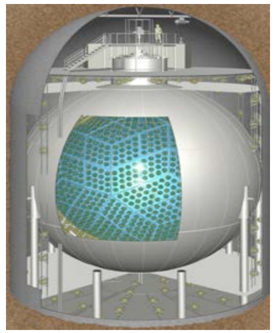
energy and baseline dependent

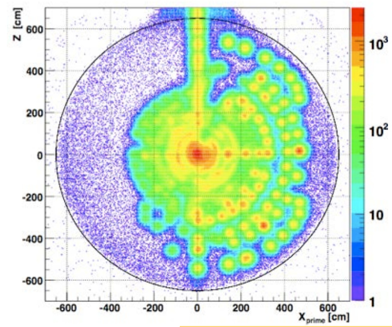
osc frequency depends on Δm^2

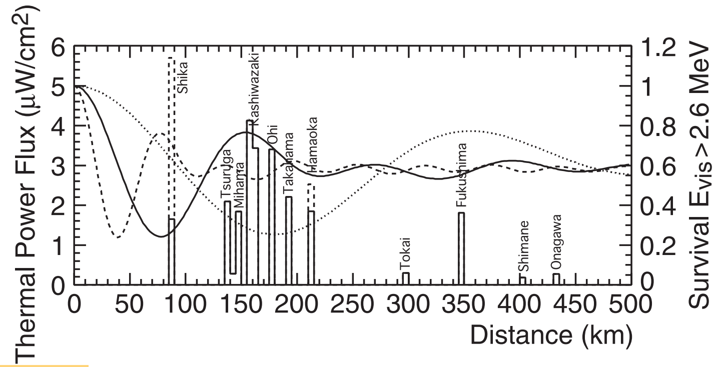
amplitude depends on θ

Recent Highlights with Reactor Antineutrinos

KamLAND 2007-2010

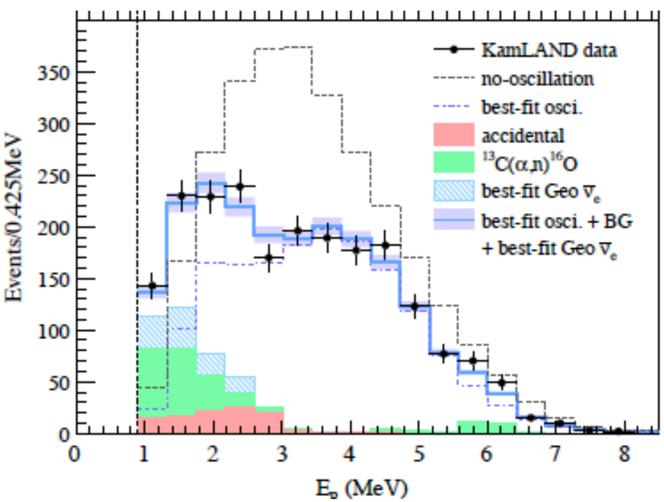


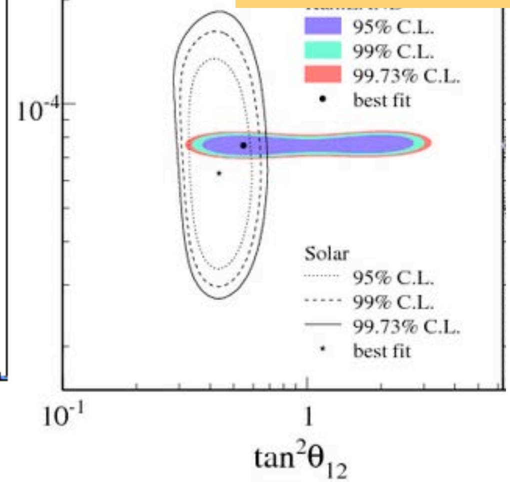


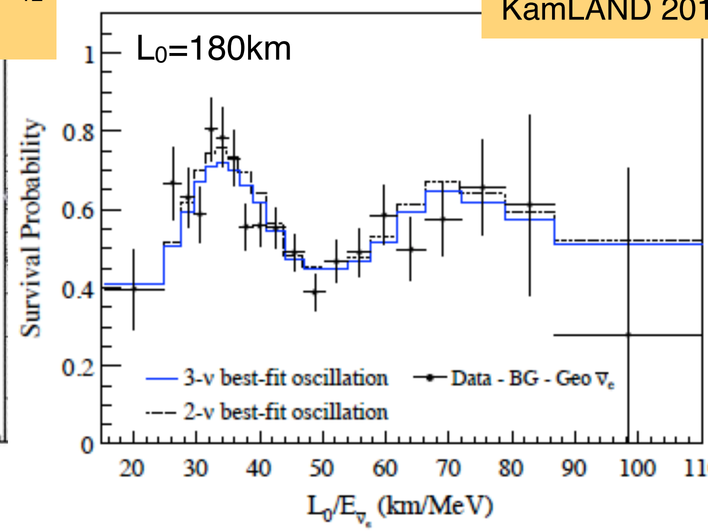


KamLAND → Δm^2_{12}
SNO → θ_{12}

KamLAND 2010







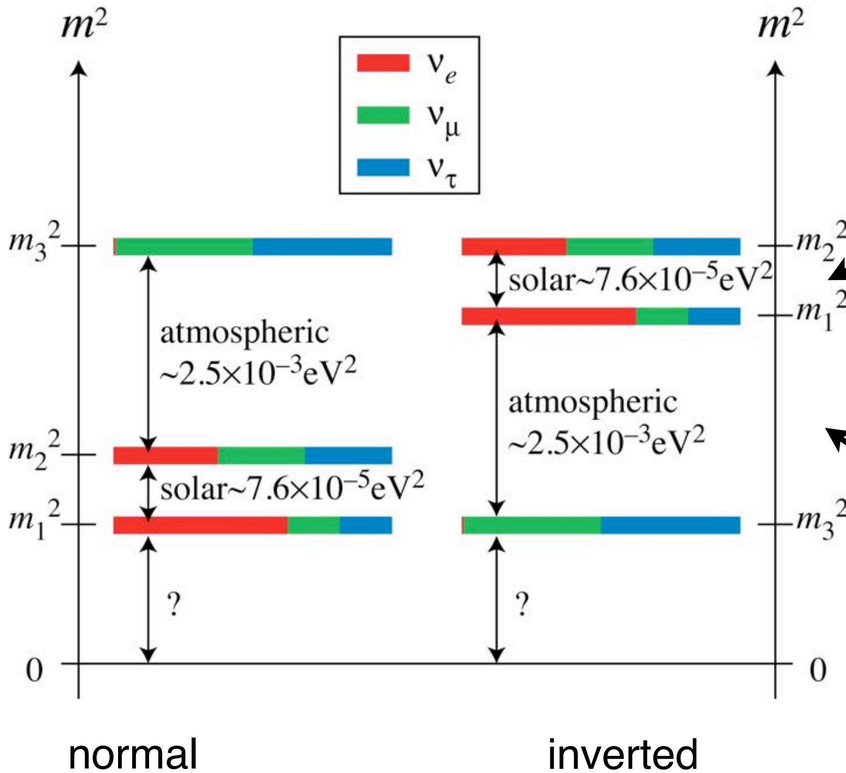
Evidence for spectral distortion

KamLAND has measured Δm_{12}^2 to ~2.8%

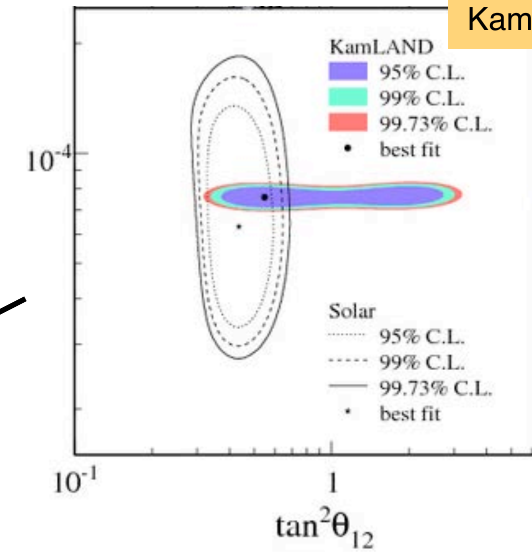
Direct evidence for oscillation

Measurement of Fundamental Parameters

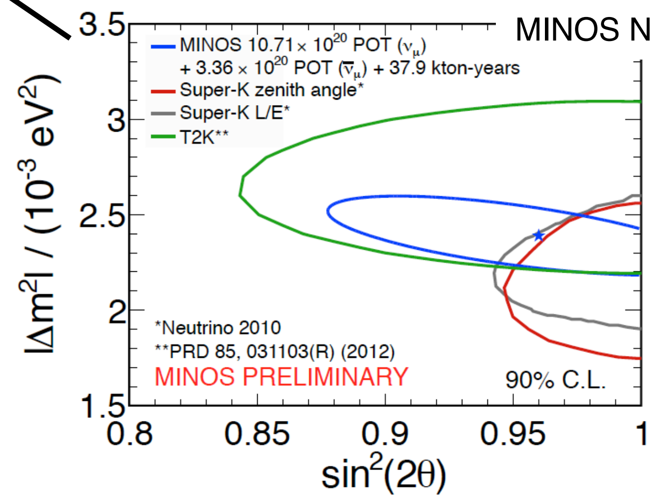
Mass Splittings



KamLAND 2010



MINOS Nu2012



Measurement of Fundamental Parameters

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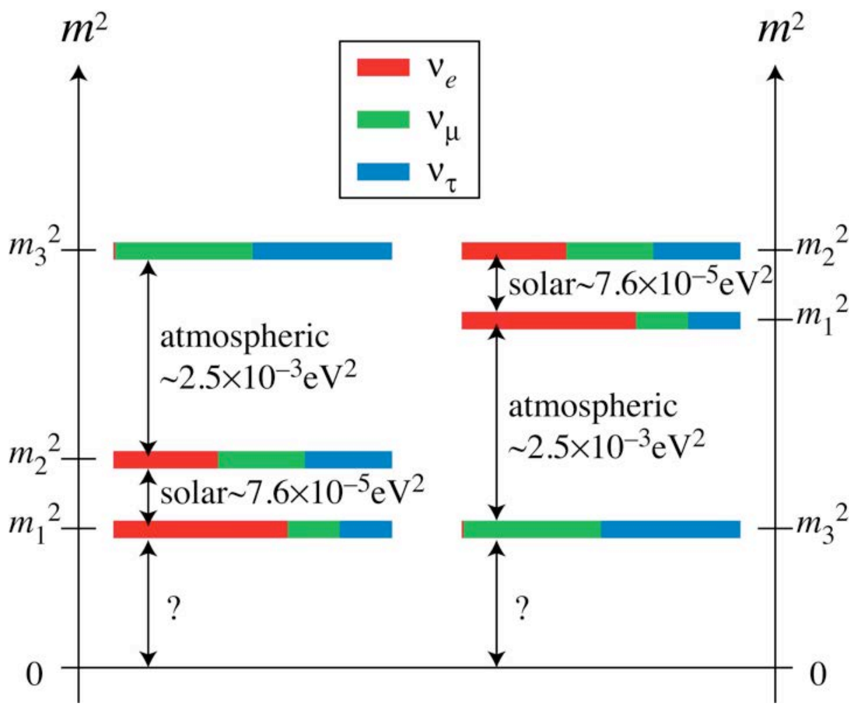


normal inverted

$$\Delta m^2_{21} = 7.5 \pm 0.19 \left({}^{+0.59}_{-0.50}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31}(\mathrm{N}) = 2.45^{+0.067}_{-0.071} \left({}^{+0.22}_{-0.20}\right) \times 10^{-3}\ \mathrm{eV}^2$$

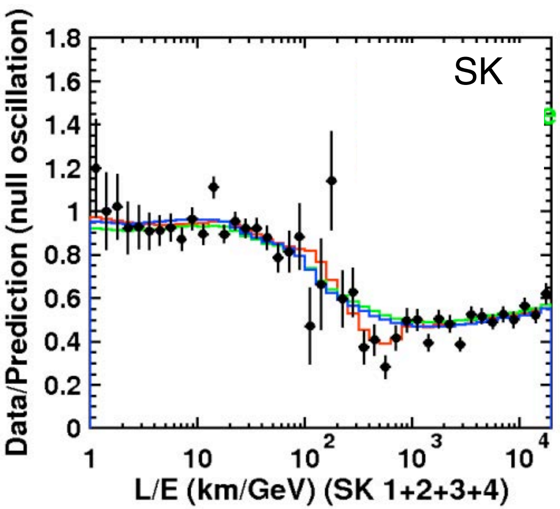
$$|\Delta m^2_{32}|(\mathrm{I}) = 2.43 \pm 0.068 \left({}^{+0.22}_{-0.20}\right) \times 10^{-3}\ \mathrm{eV}^2$$

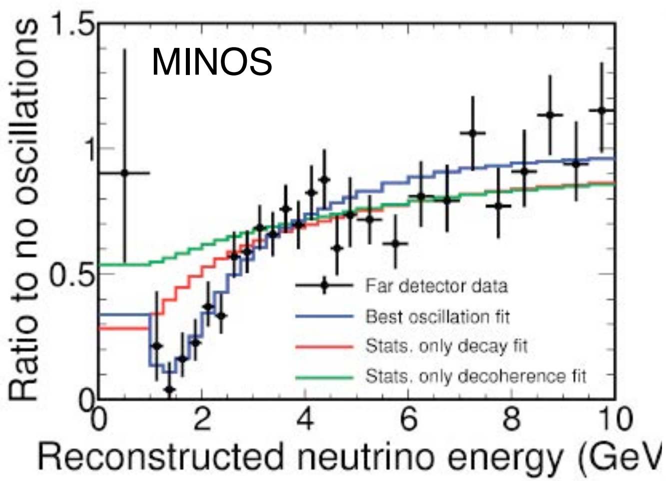
KamLAND has measured Δm_{12}^2 to ~2.8%

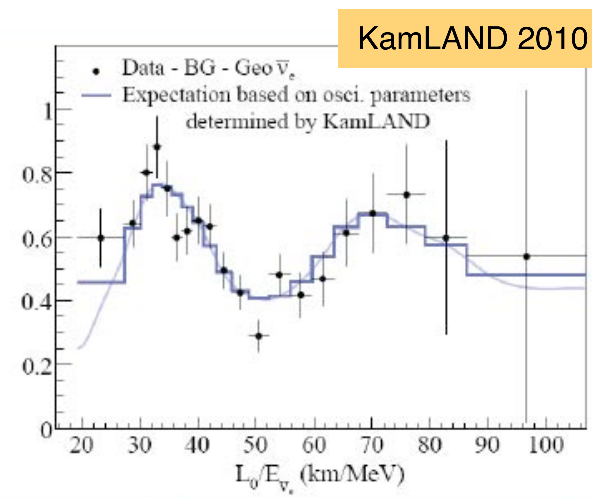
Neutrino Oscillation Measurements

Recent Observations

- atmospheric ν_μ and $\bar{\nu}_\mu$ disappear most likely to ν_τ (SK, MINOS)
- accelerator ν_μ and $\bar{\nu}_\mu$ disappear at L~250, 700 km (K2K, T2K, MINOS)
- some accelerator ν_μ appear as ν_μ at L~250, 700 km (T2K, MINOS)
- solar ν_e convert to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at L~200 km (KamLAND)
- reactor $\bar{\nu}_e$ disappear at L~1 km (DC, Daya Bay RENO)





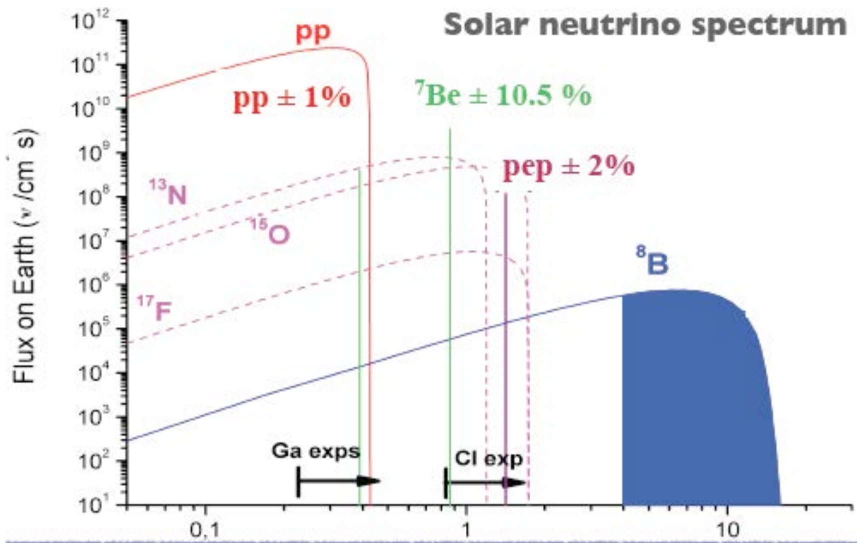


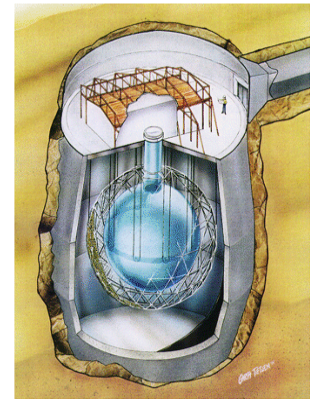
Experiments have demonstrated vacuum oscillation L/E pattern

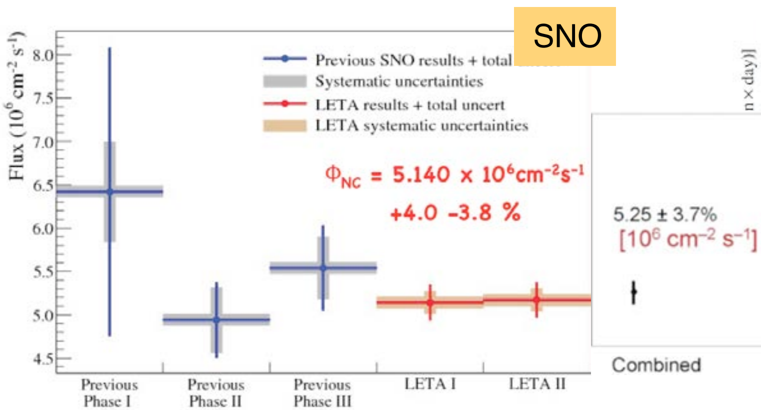
$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

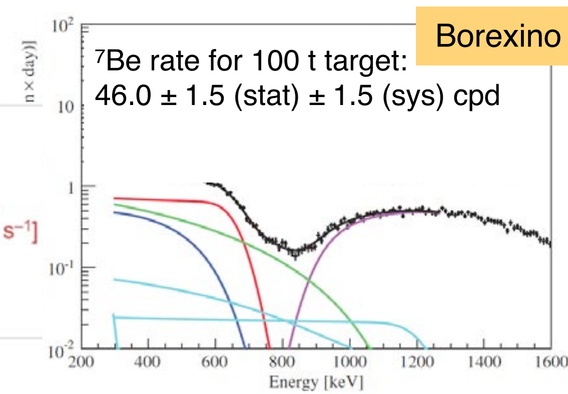
Recent Highlights with Solar Neutrinos

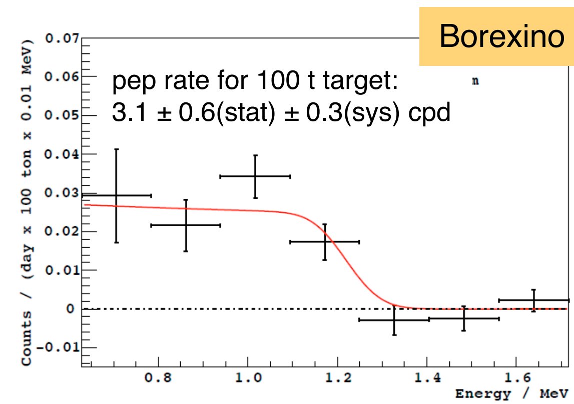
Solar Neutrino Measurements











^{8}B flux measured (SNO LETA + combined)

3.5MeV thresholds achieved in SNO & SK
first direct extraction of ν_e survival probability

Measurement of ^{7}Be flux

SNO complete → SNO+

Detection of pep neutrinos

Limit on CNO rate < 7.1 cpd/ 100 t

Borexino continues

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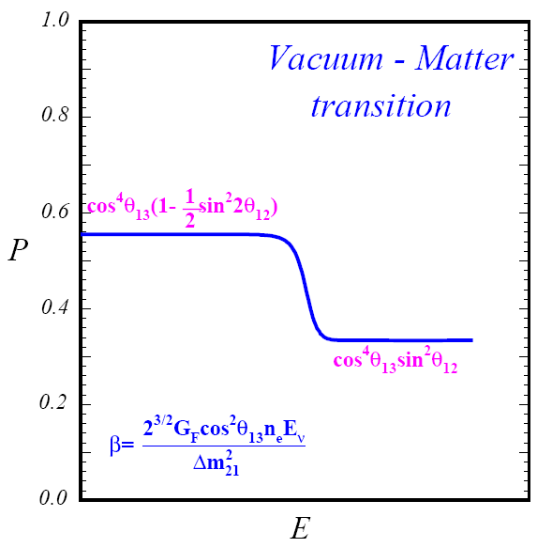
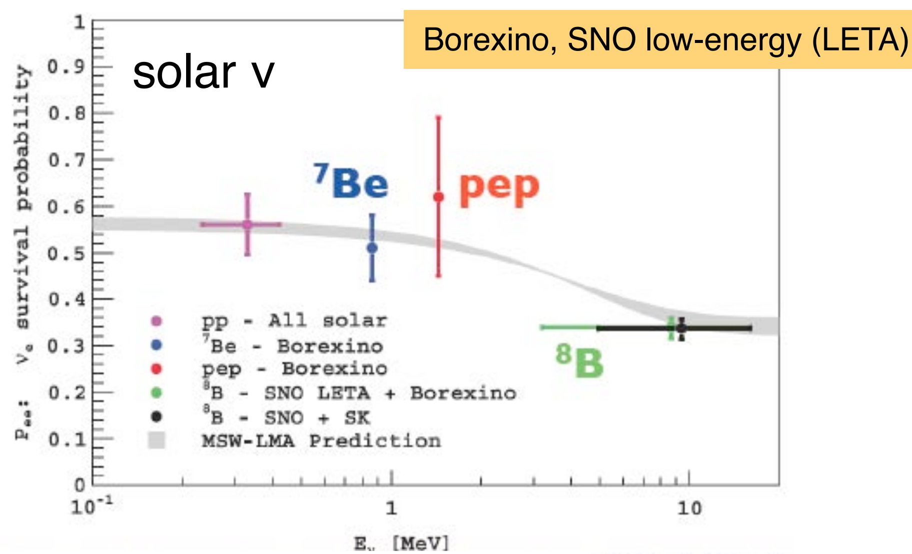
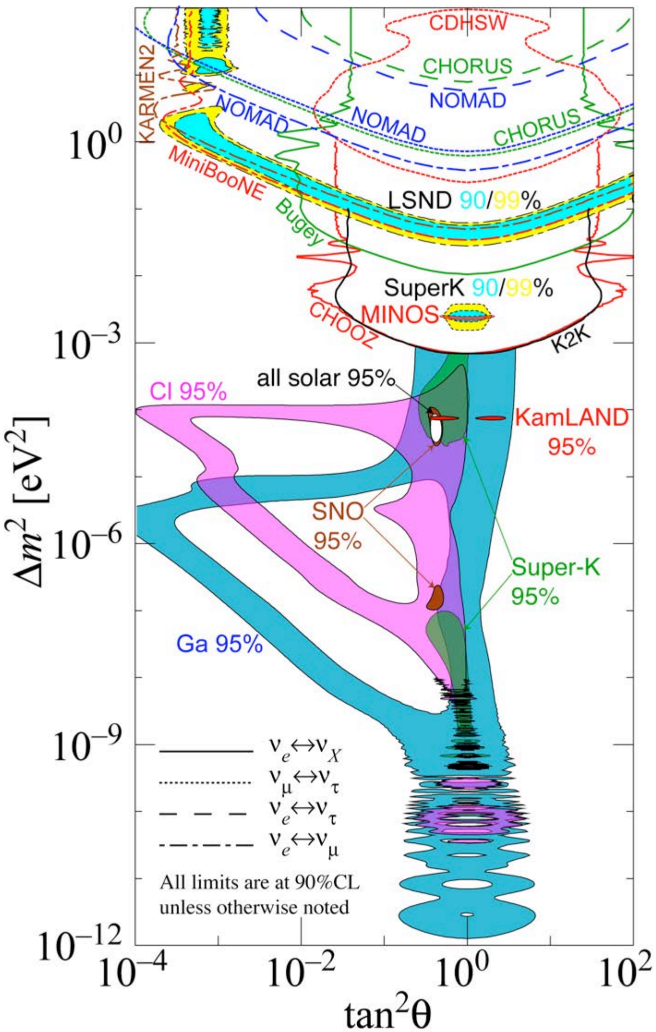




Vacuum to matter transition (MSW conversion) in Sun has been observed

Completing the 3-ν Oscillation Picture

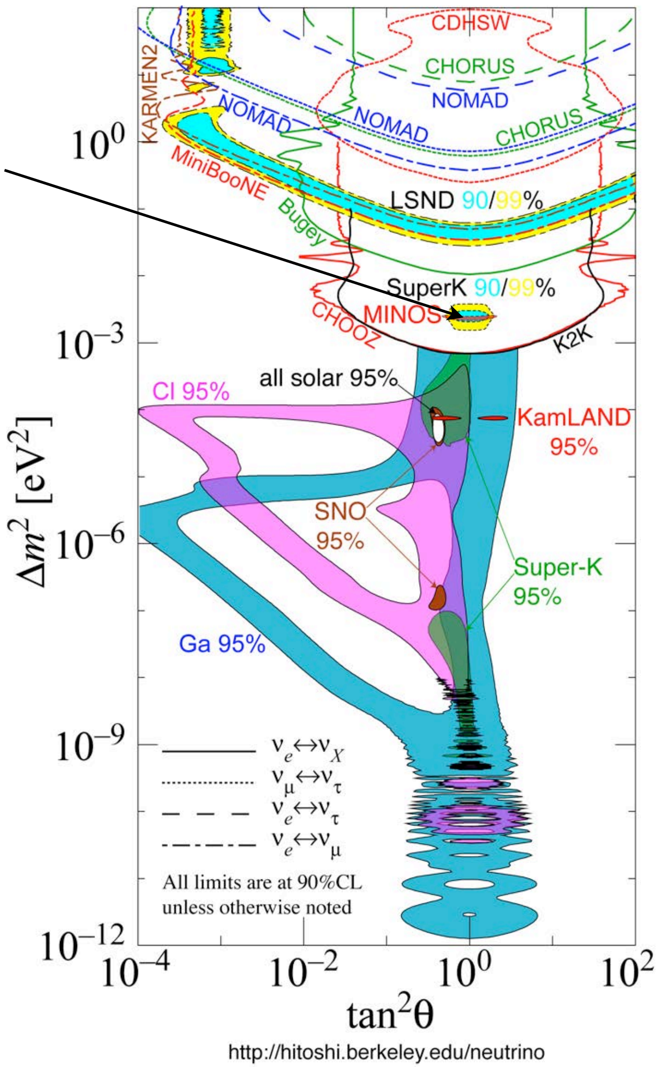


http://hitoshi.berkeley.edu/neutrino

Completing the 3-ν Oscillation Picture

atmospheric/beam neutrinos

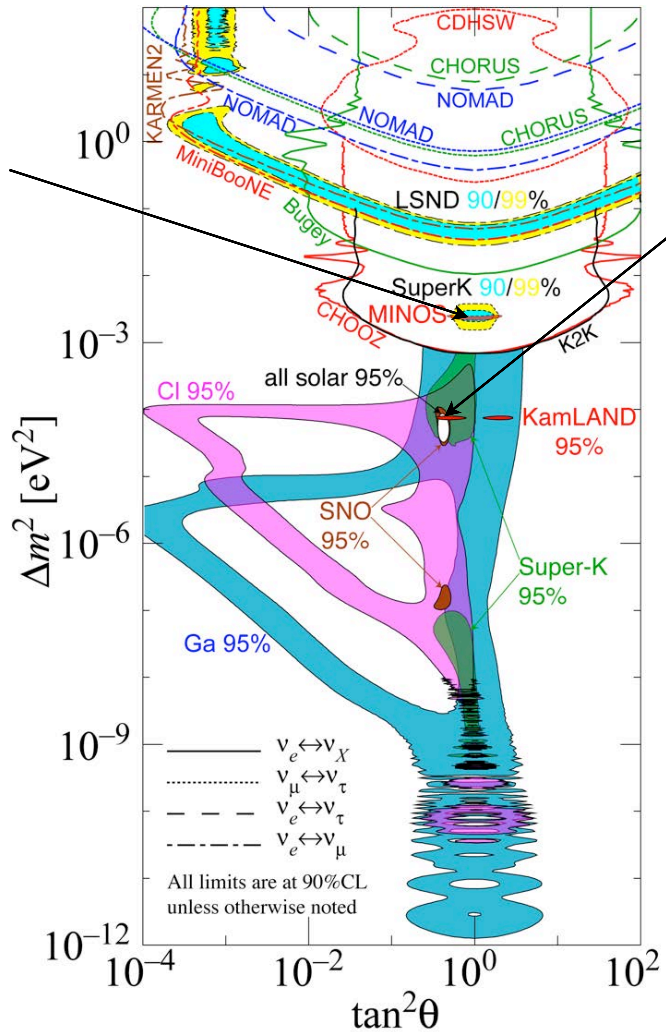
θ_{23}, Δm^2_{23}



Completing the 3-ν Oscillation Picture

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}



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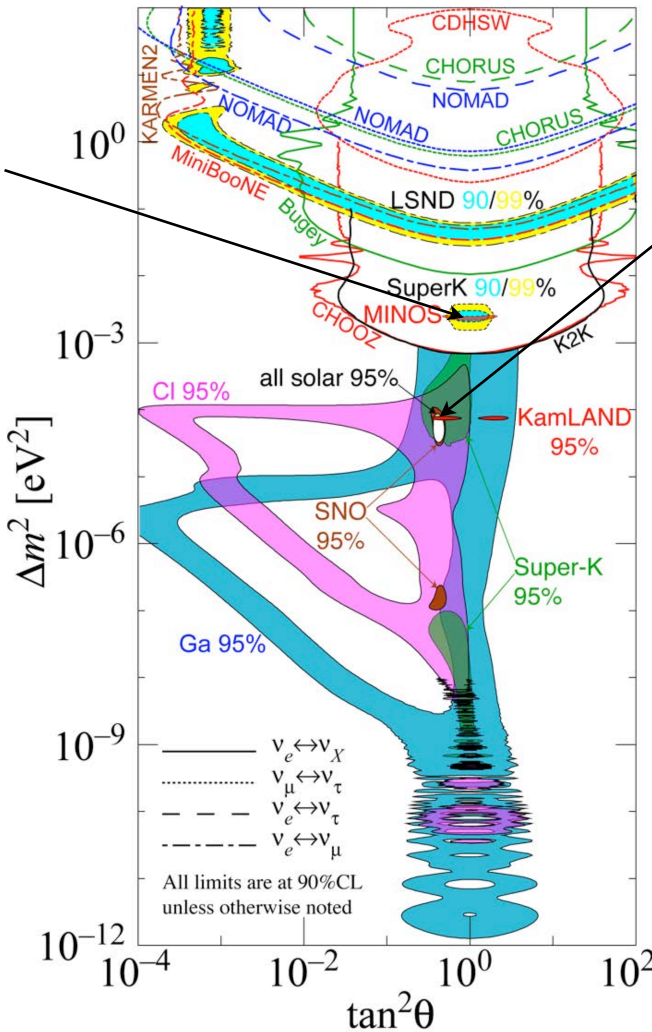
solar/reactor neutrinos

θ_{12}, Δm^2_{12}

Completing the 3-ν Oscillation Picture

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}



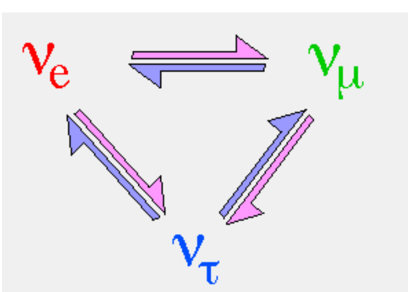
http://hitoshi.berkeley.edu/neutrino

solar/reactor neutrinos

θ_{12}, Δm^2_{12}

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

3-flavor picture needed



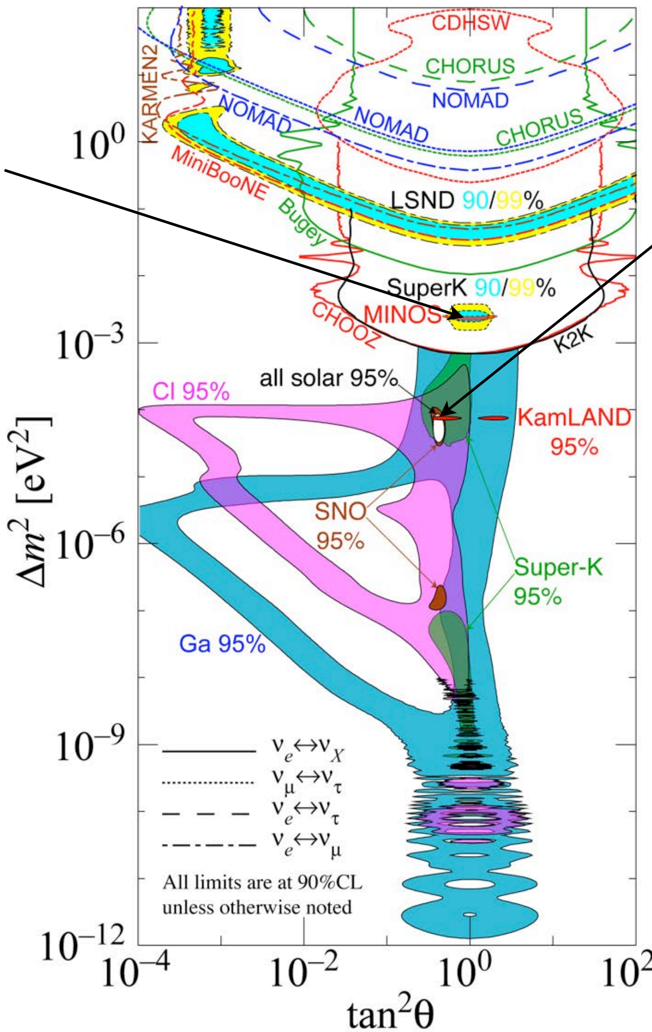
Completing the 3-ν Oscillation Picture

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

θ_{12}, Δm^2_{12}



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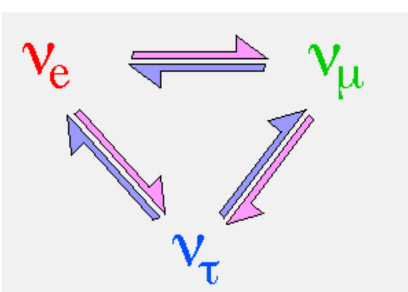
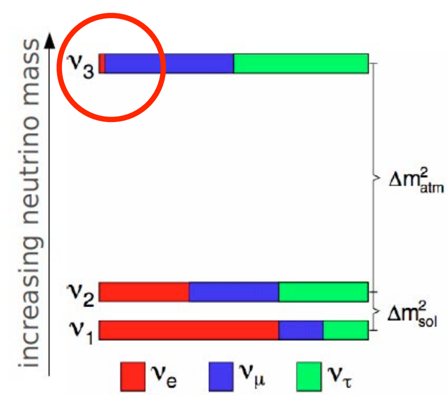
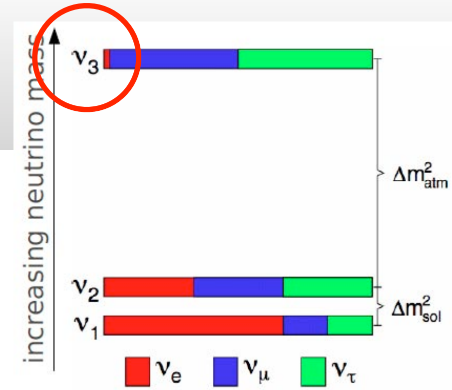




Neutrino Oscillation - Before 2011



Mixing Angles

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

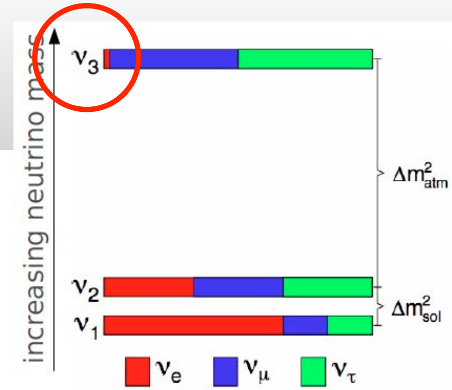
U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2 + i\beta} \end{pmatrix}$$

atmospheric, K2K	reactor and accelerator	SNO, solar SK, KamLAND	$0\nu\beta\beta$
$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	
$0.50^{+0.07}_{-0.06}$		$0.318^{+0.019}_{-0.016}$	
maximal?	small? zero?	large, but not maximal!	

Neutrino Oscillation - Before 2011



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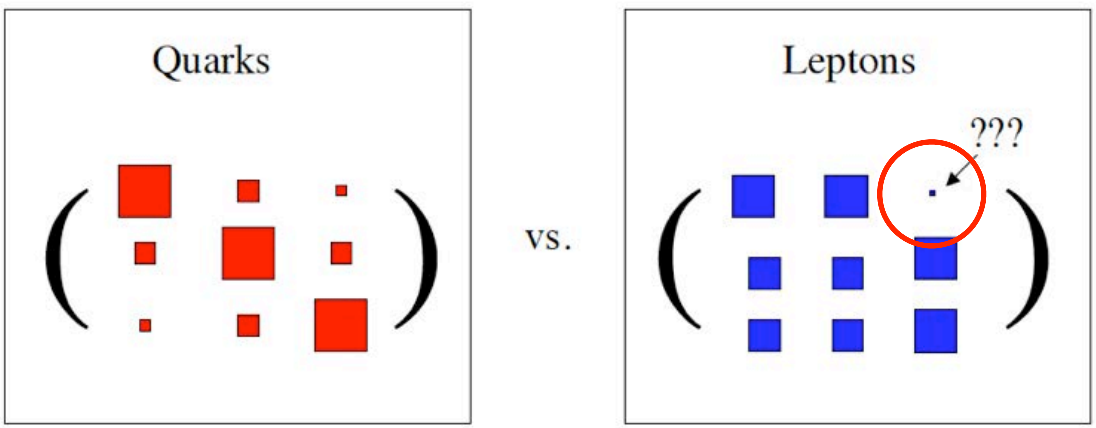
atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$



Indications for θ_{13} in 2011

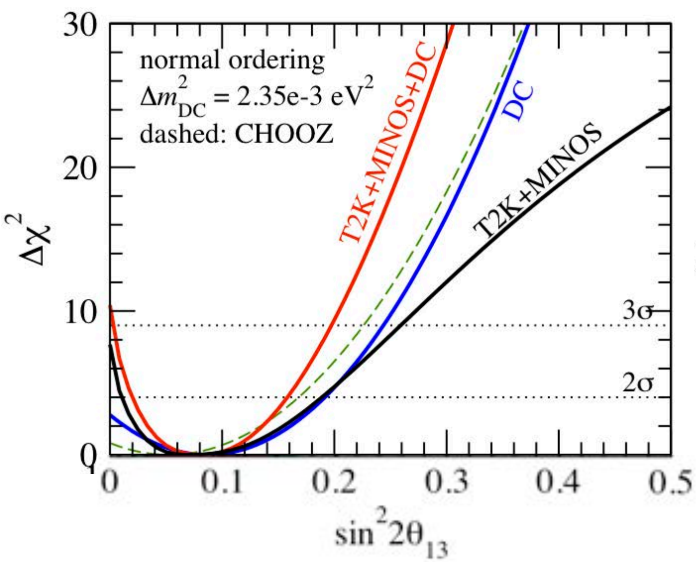
T2K $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$

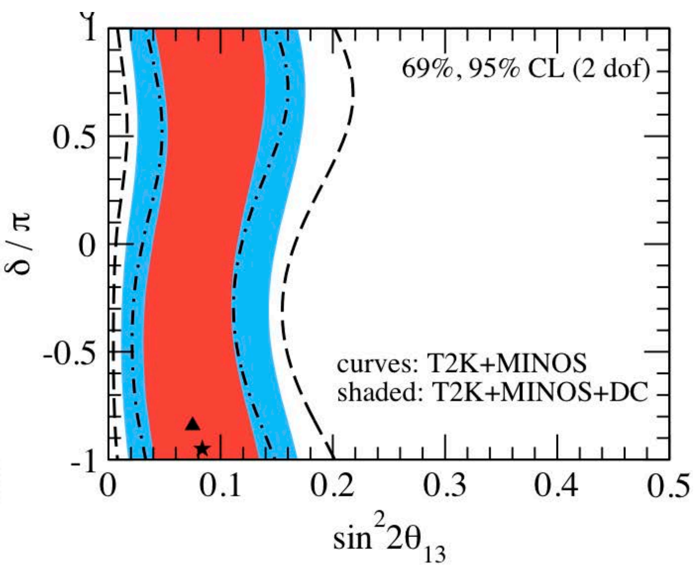
θ_{13}=0 disfavored @ 2.5σ

MINOS $2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$

θ_{13}=0 disfavored @ 89% C.L.

Double Chooz $\sin^2(2\theta_{13})$=0.085 ± 0.029(stat) ± 0.042(syst)

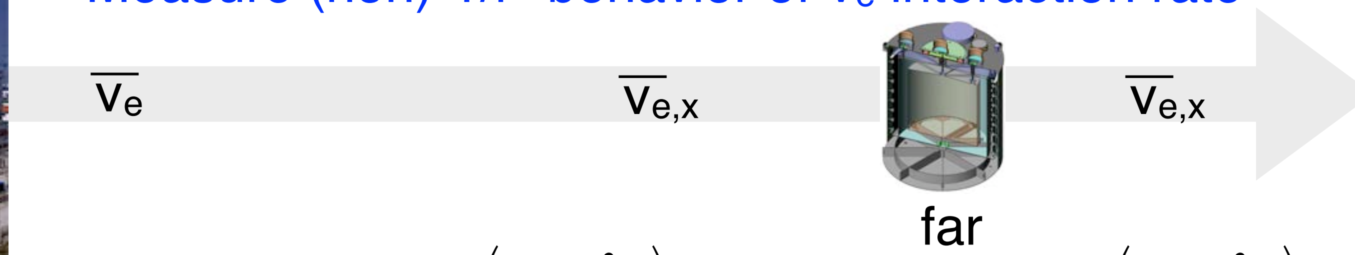




A definitive precision experiment needed

Reactor Neutrino Oscillation Experiments

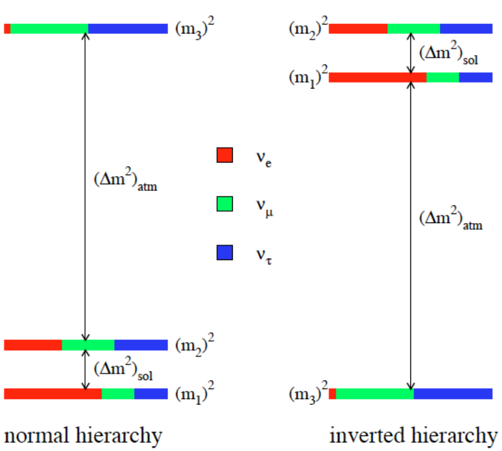
Measure (non)-1/r² behavior of $\bar{\nu}_e$ interaction rate



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

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

L/E → Δm^2 amplitude of oscillation → θ



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

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

Reactor Neutrino Oscillation Experiments

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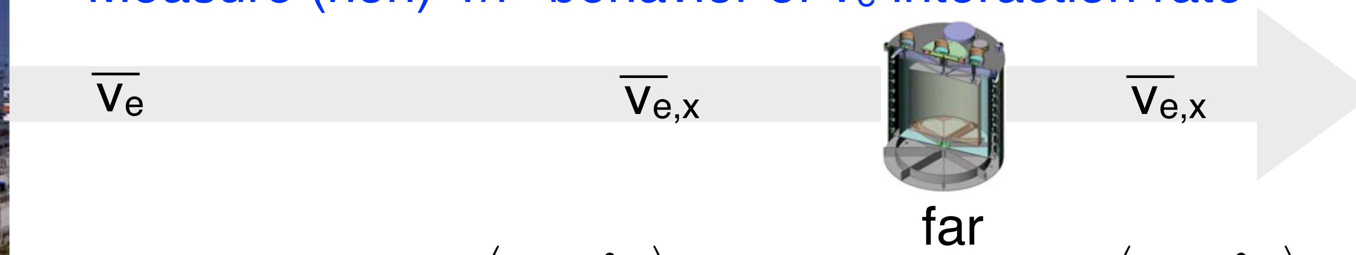

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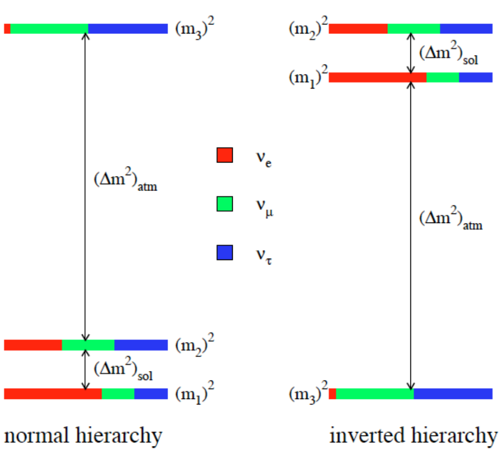

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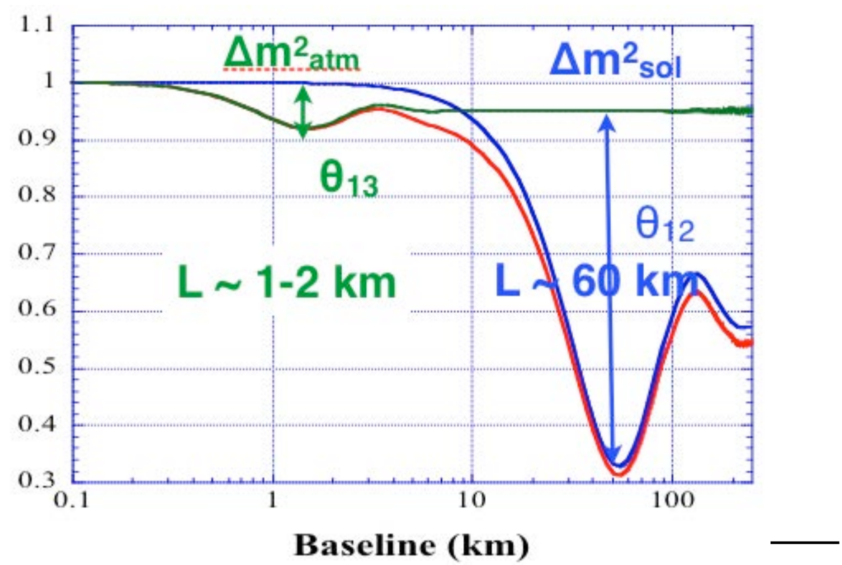
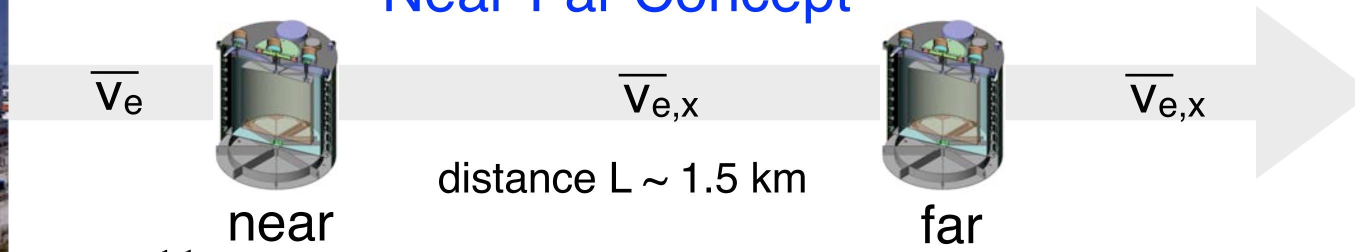
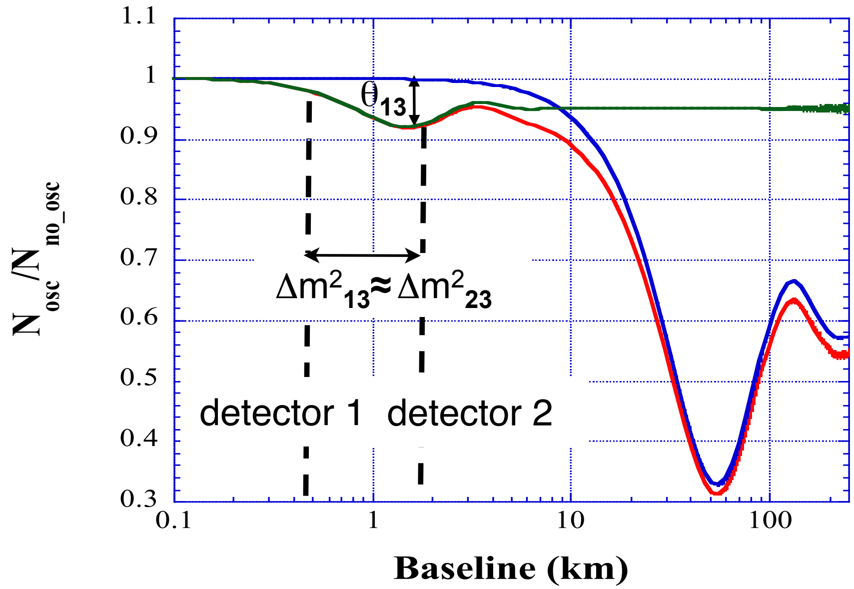


Measuring θ_{13} with Reactor Experiments

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

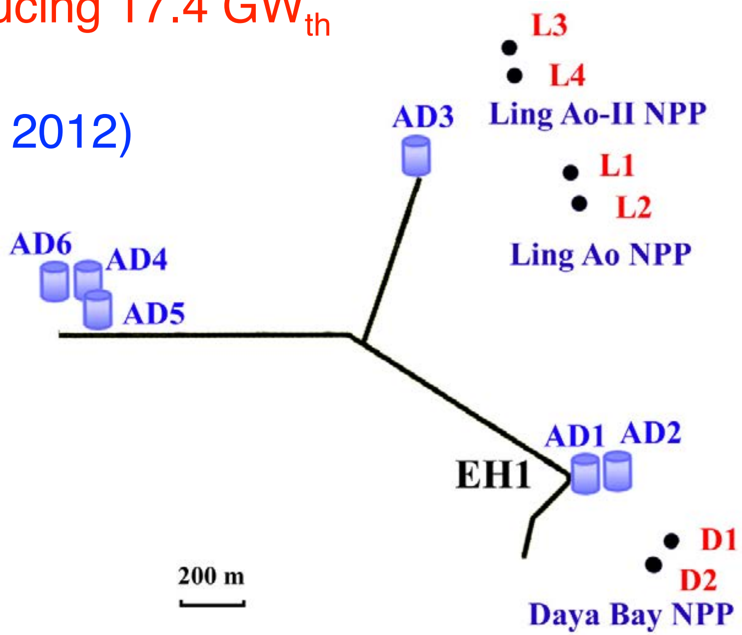
Daya Bay Nuclear Power Plant

6 reactor cores producing 17.4 GW_{th}

3 experimental halls

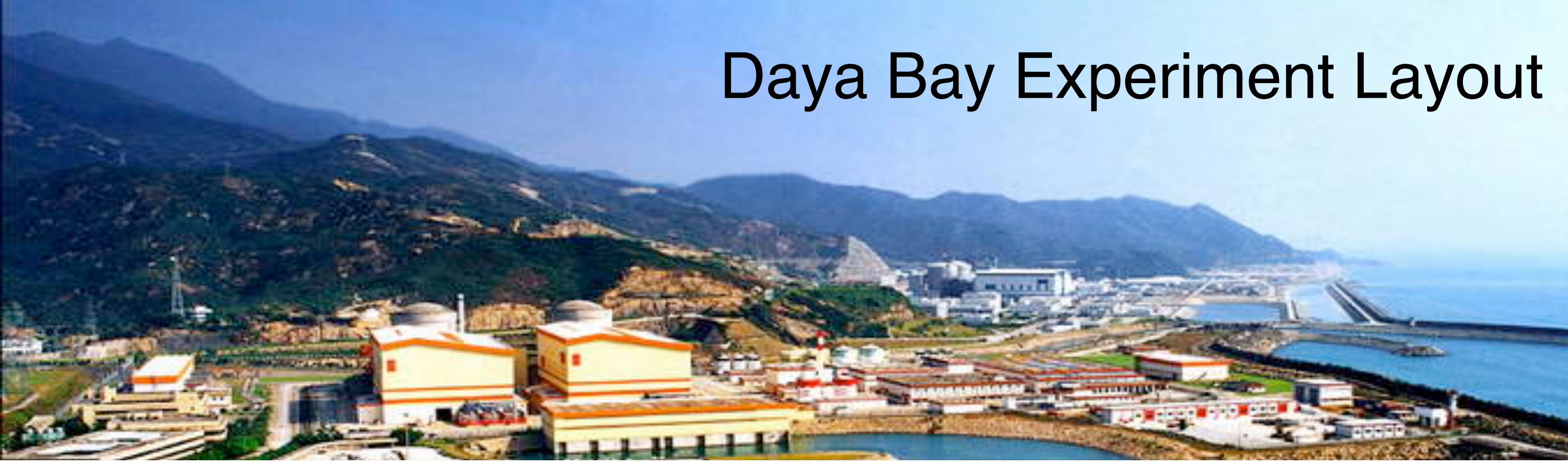
6 detectors (summer 2012)

now 8 detectors

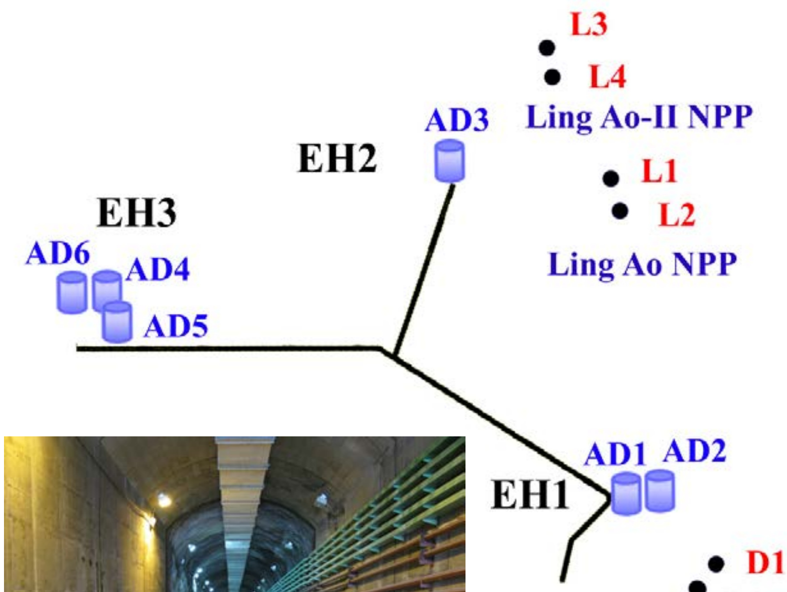


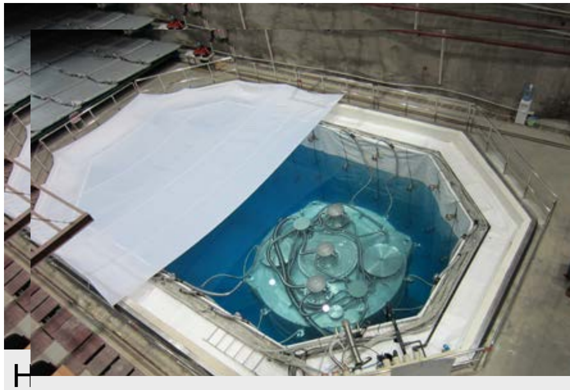
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Daya Bay Experiment Layout

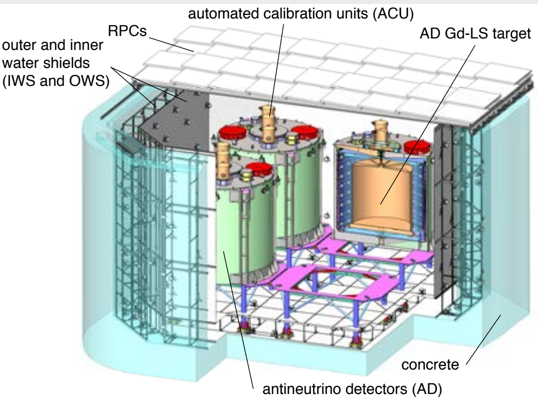


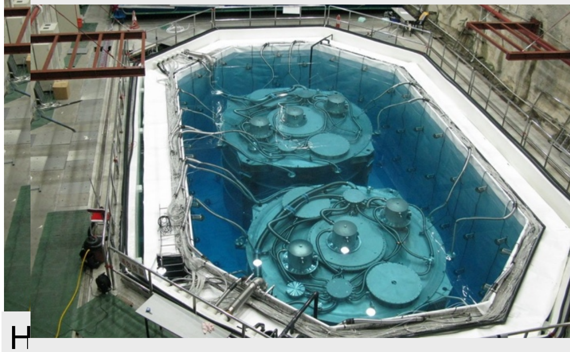
Hall 3: began 3 AD operation on Dec. 24, 2011





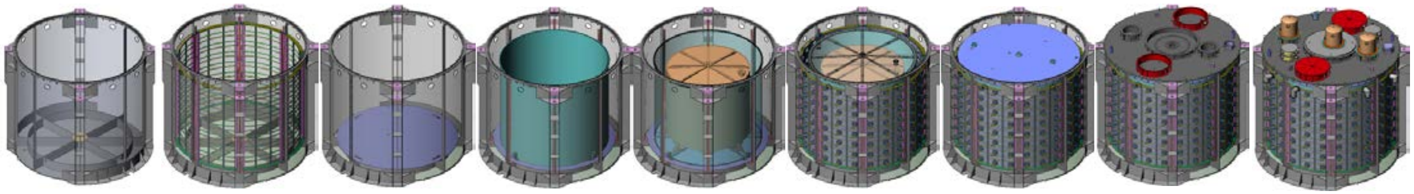
Hall 2: began 1 AD operation on Nov. 5, 2011

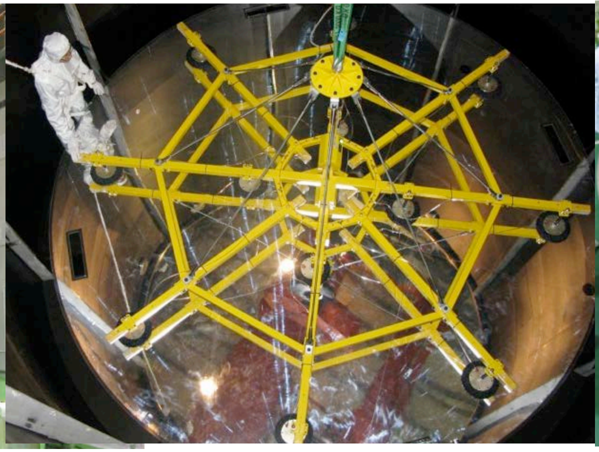


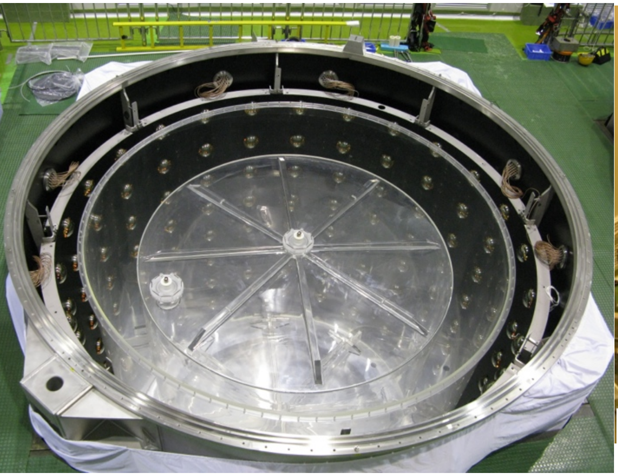


Hall 1: began 2 AD operation on Sep. 23, 2011

Antineutrino Detector Assembly

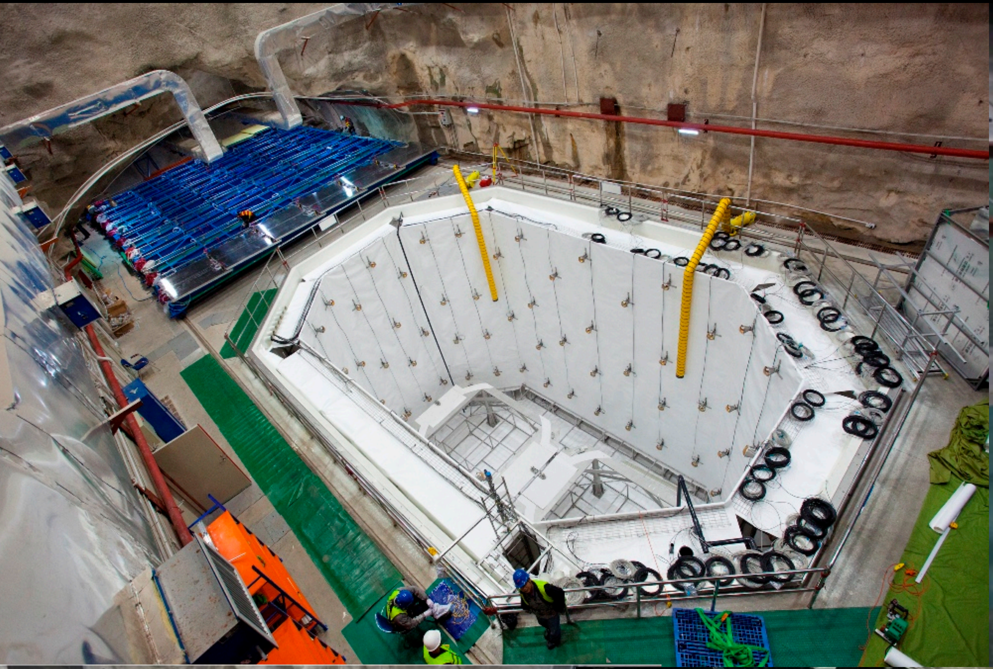


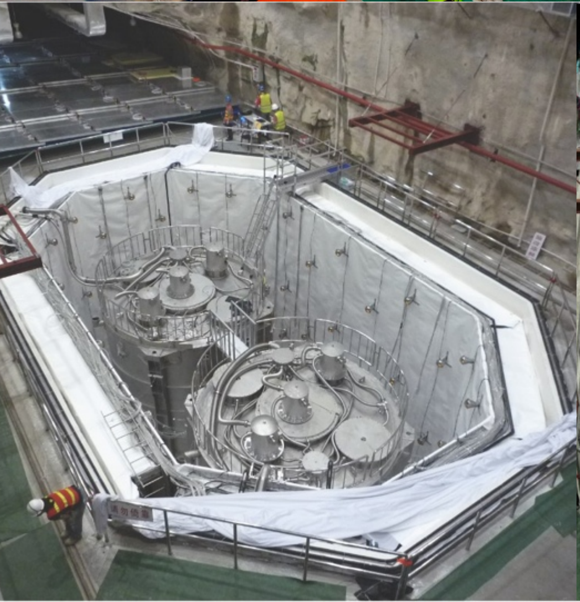


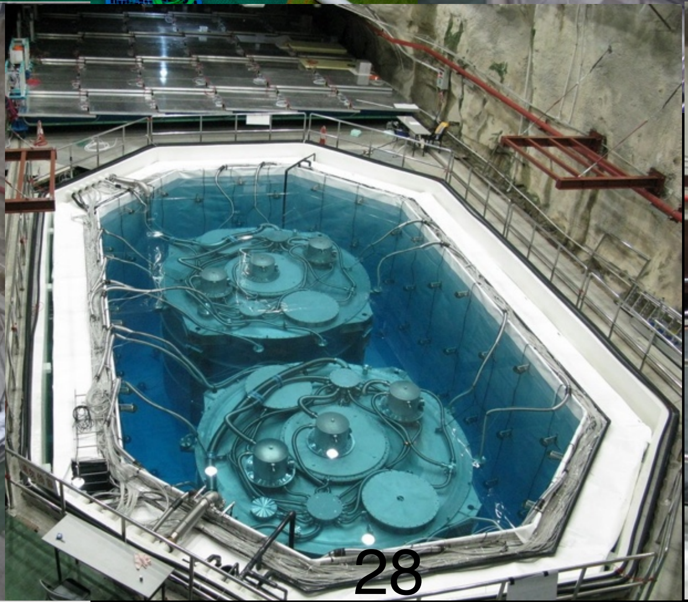


detector assembly in pairs

Antineutrino Detector Installation - Near Hall

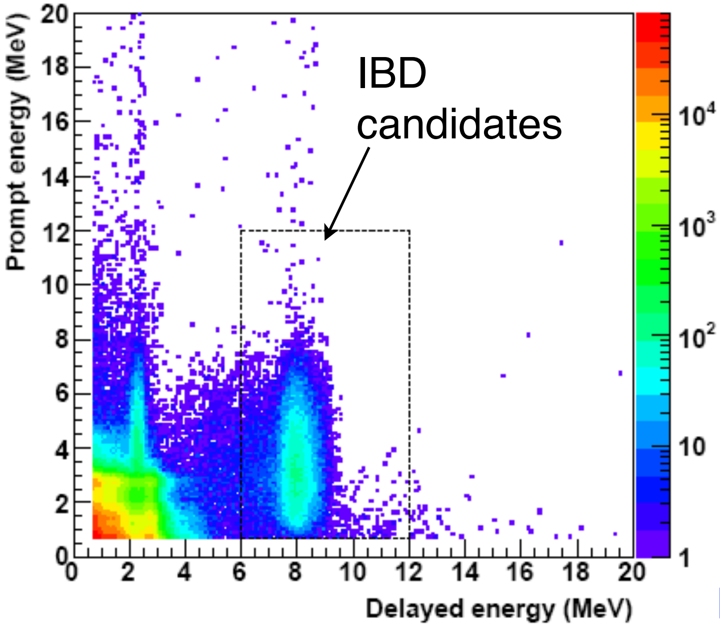






Daya Bay Antineutrino Candidates

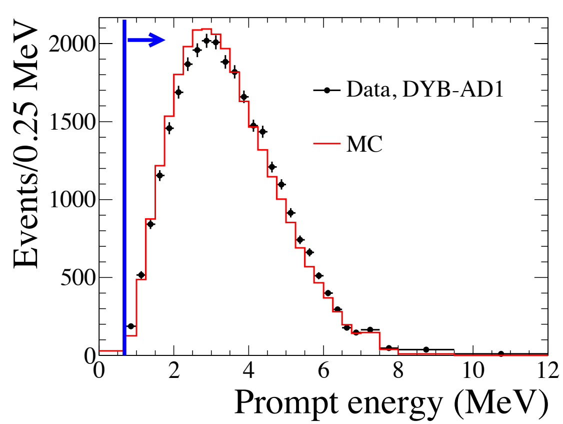
Inverse Beta-Decay Selection $\overline{\nu}_e + p \rightarrow e^+ + n$



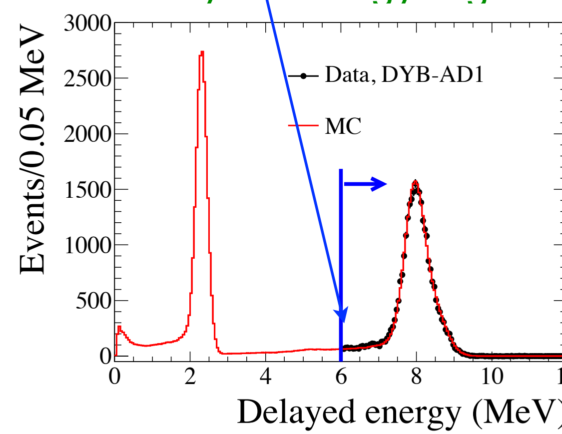
Prompt vs Delayed

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

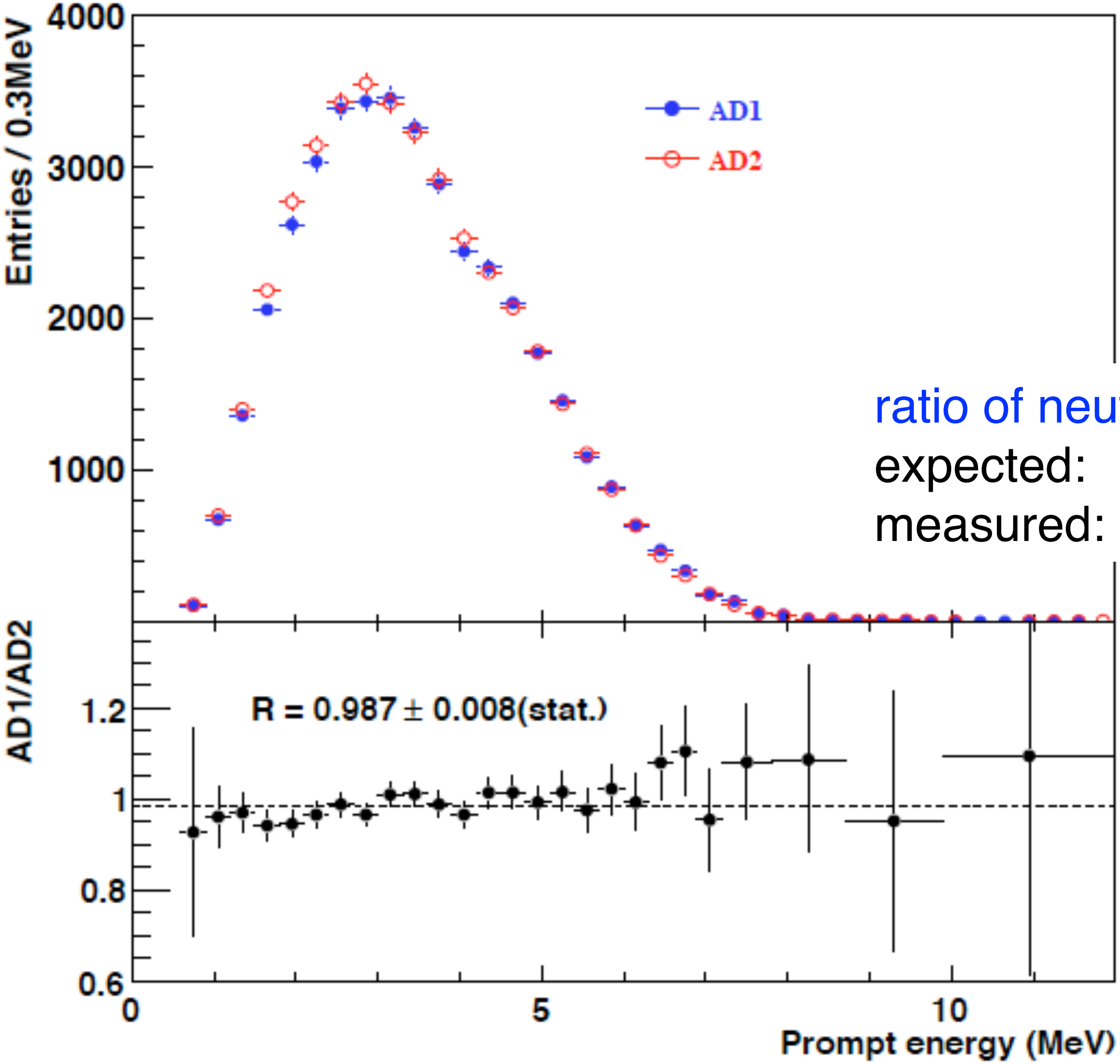
Prompt Energy Signal

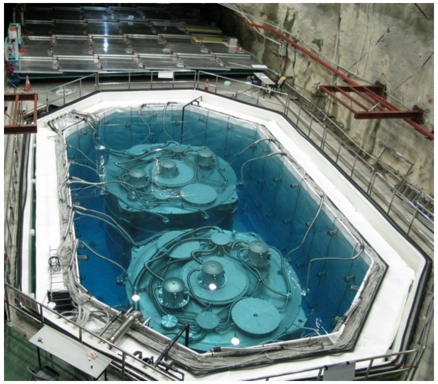


Delayed Energy Signal



Side-by-Side Comparison in Near Hall





ratio of neutrino events in AD1 and AD2

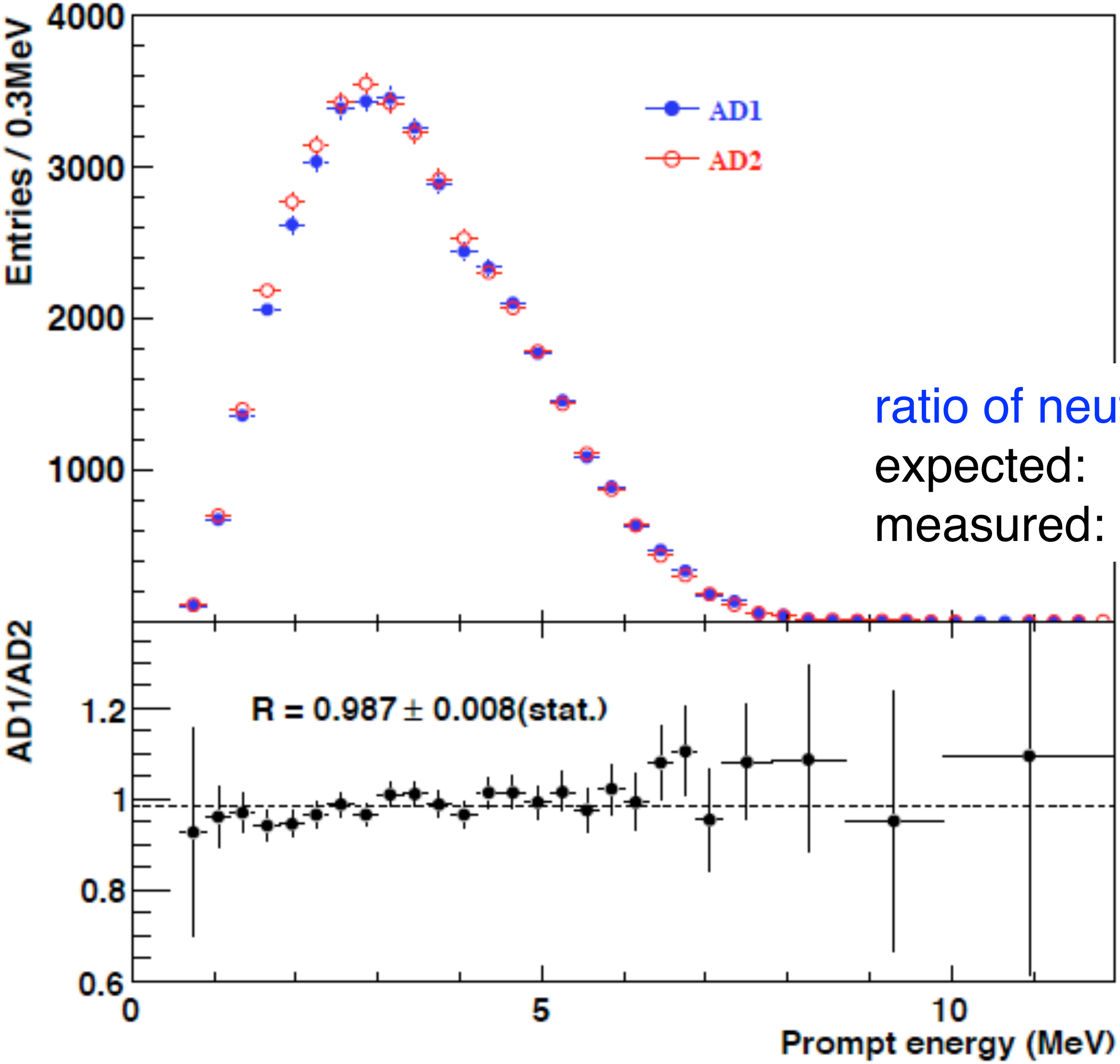
expected: **0.981**

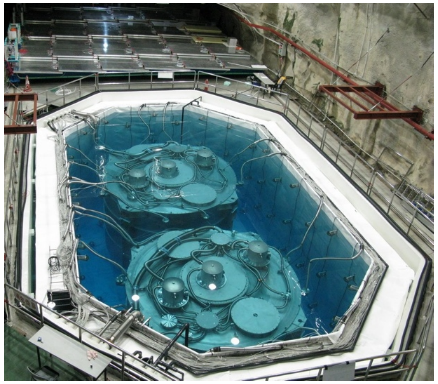
measured: **0.987± 0.008 (stat) ± 0.003**

ratio is not 1 because of baseline difference

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

Side-by-Side Comparison in Near Hall





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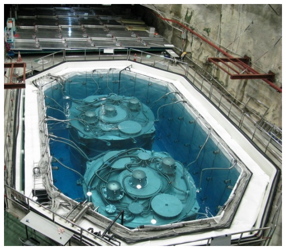
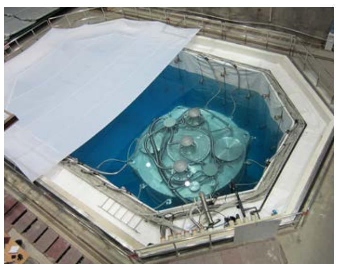
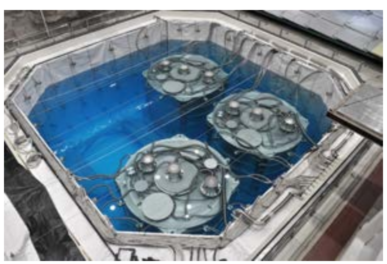
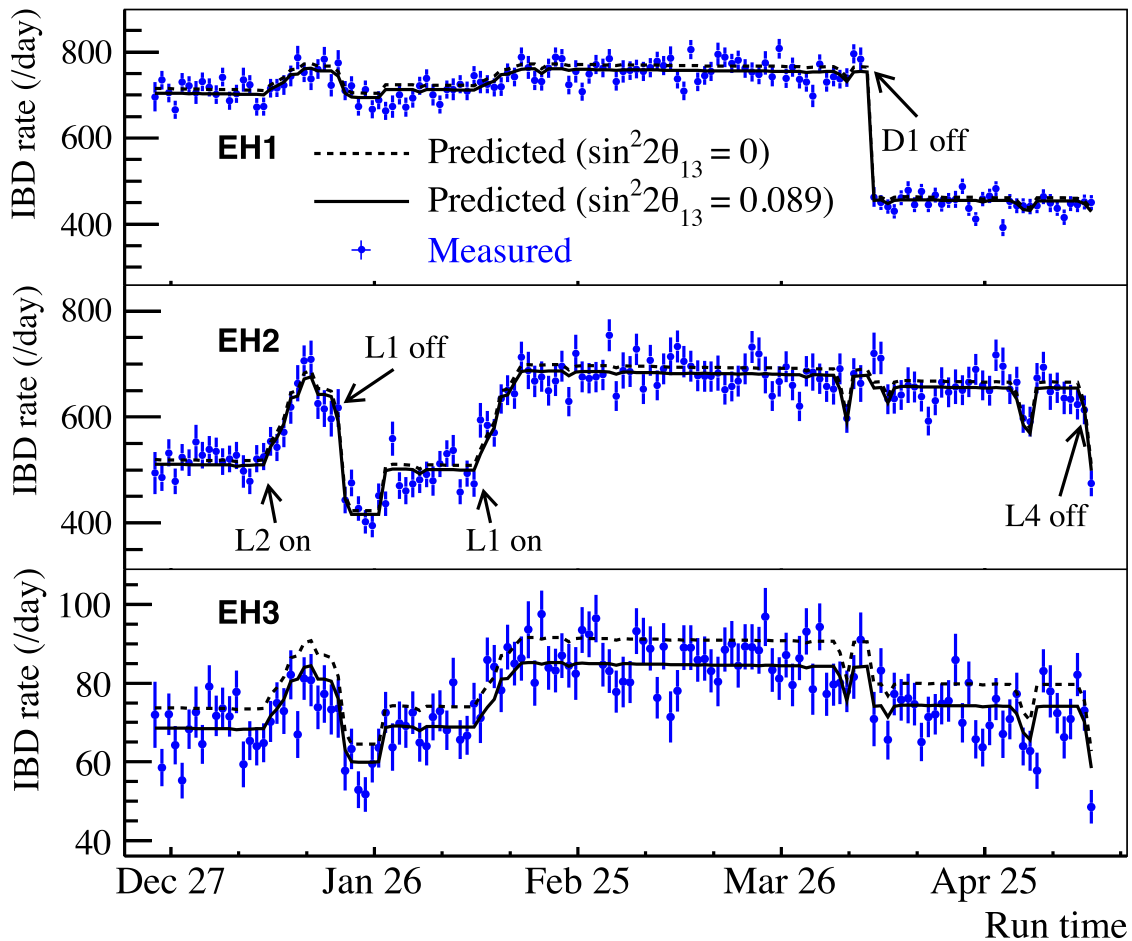
Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations



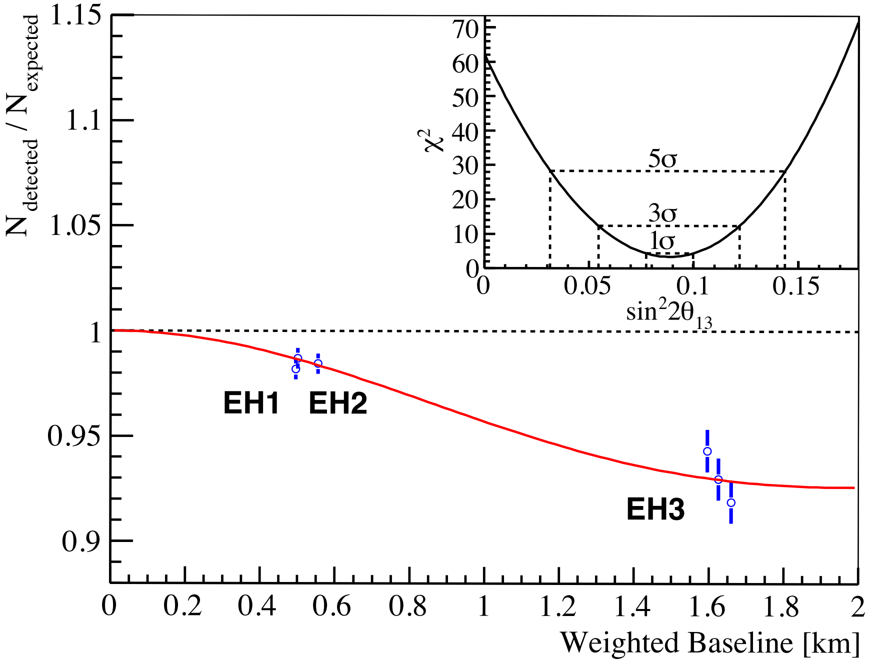






Predicted Rate assumes no oscillation.
Normalization is determined by fit to near detector data.

Daya Bay



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

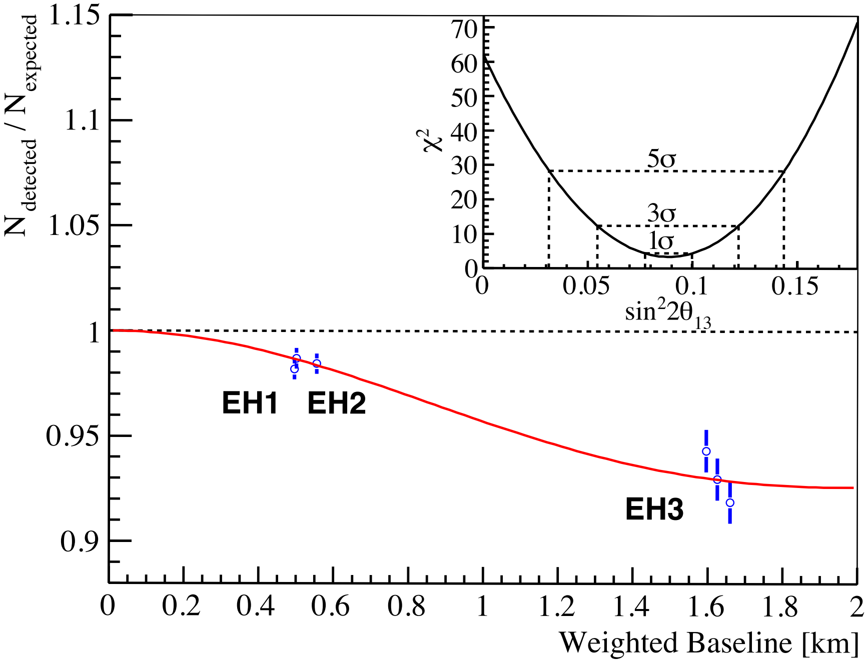
$\sin^2 2\theta_{13}$ =

0.089 ± 0.010 (stat) ± 0.005 (syst)

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

θ_{13} Results

Daya Bay



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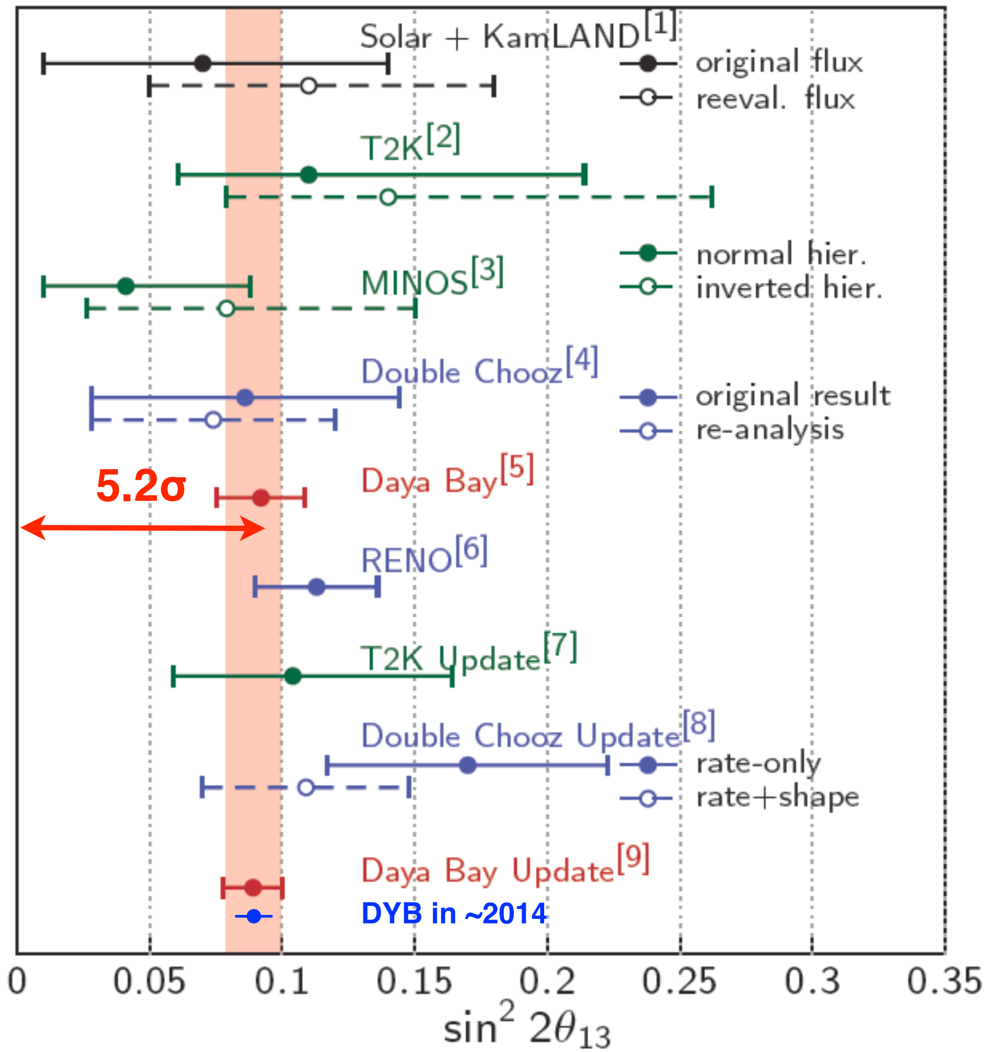
Global θ_{13} Measurements



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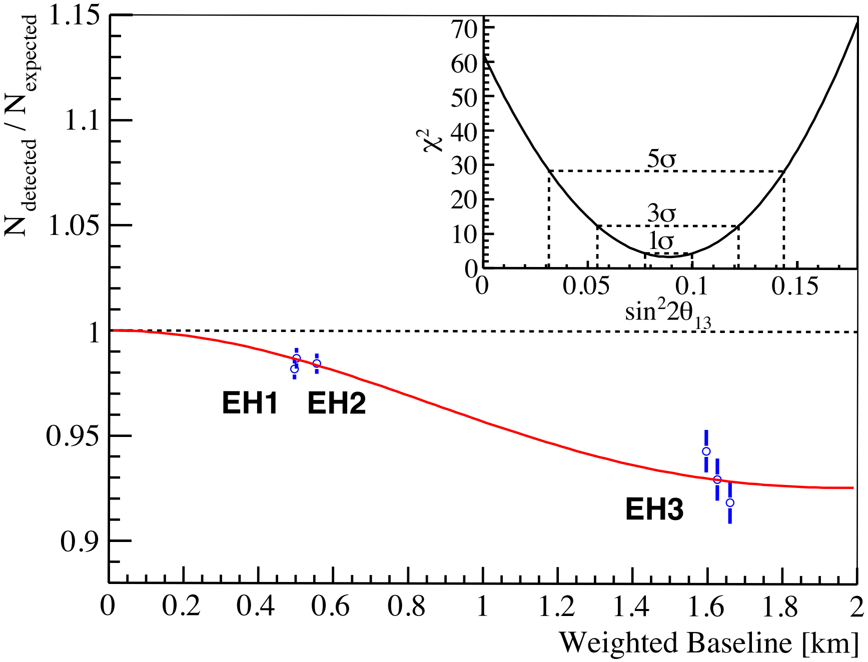
Daya Bay



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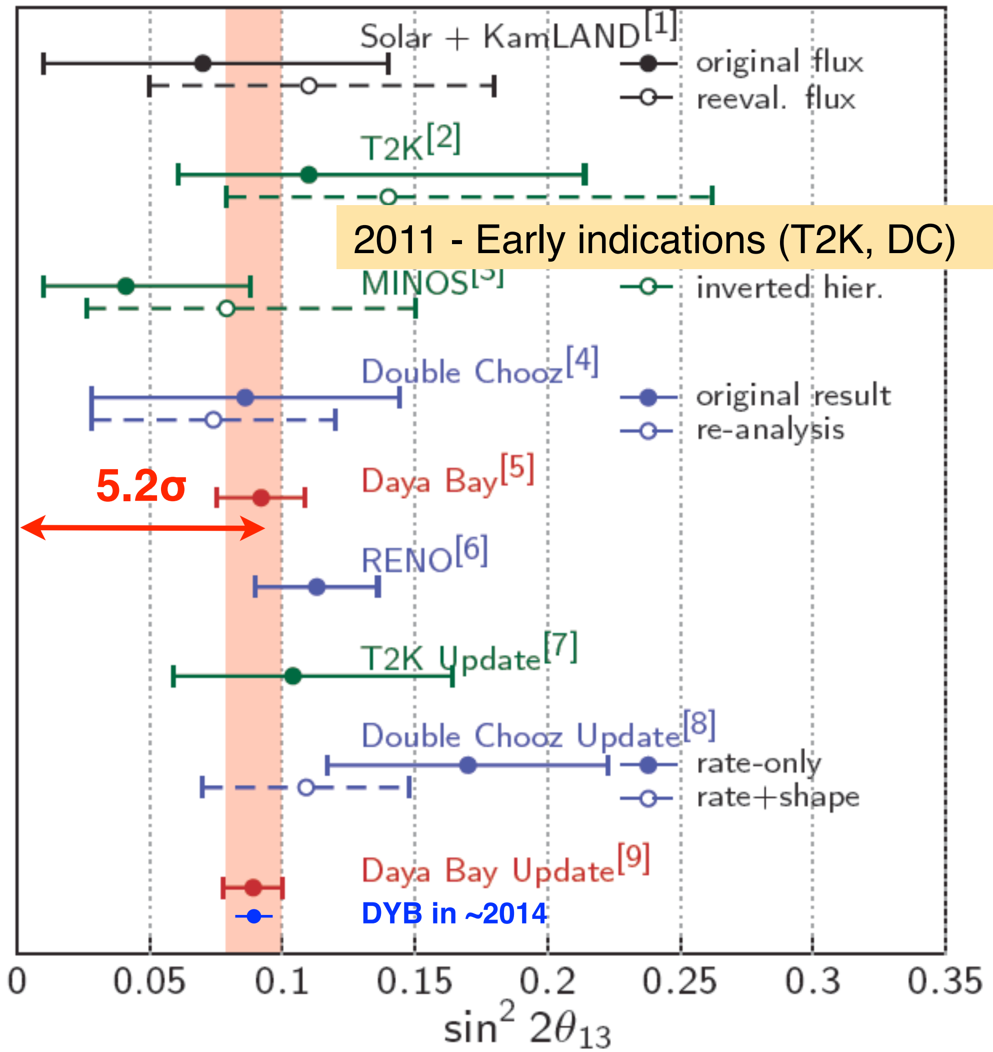

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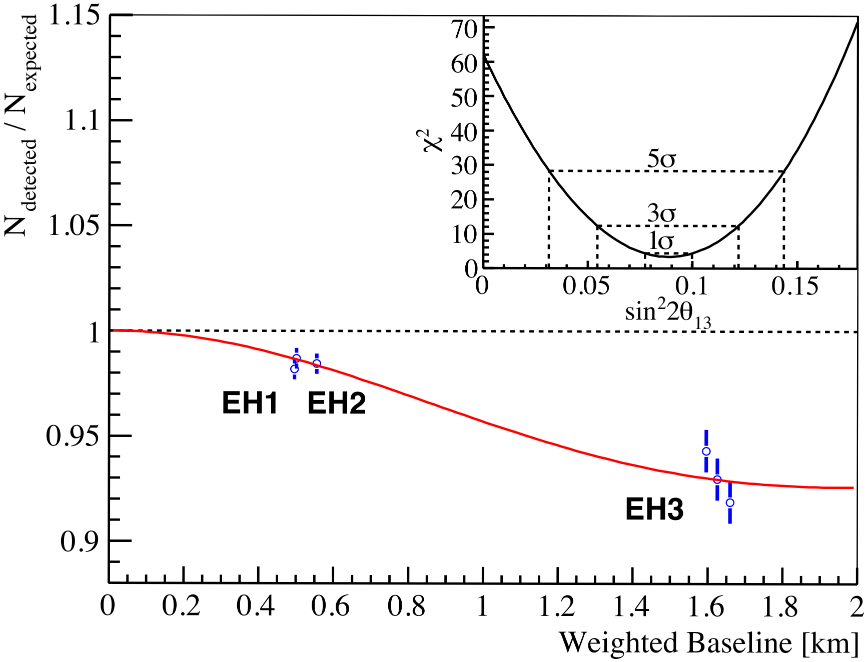

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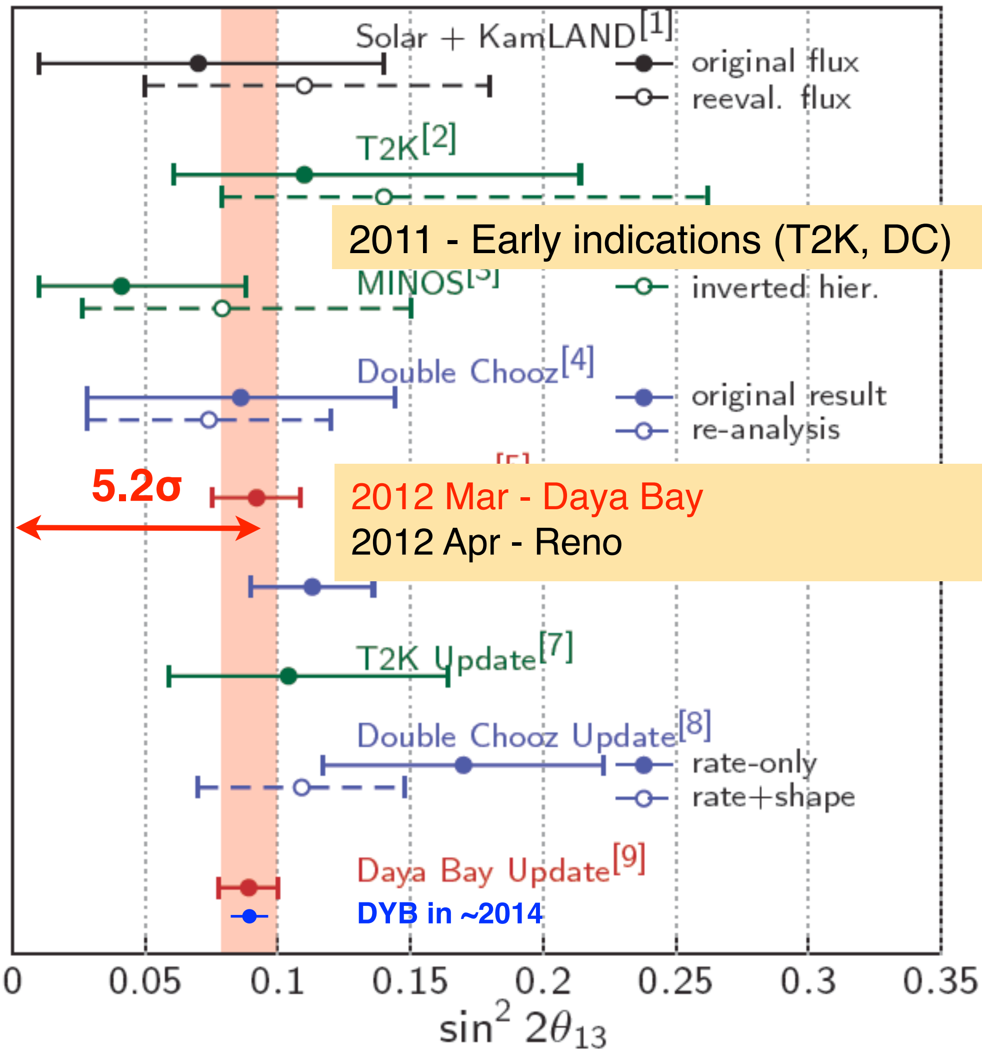

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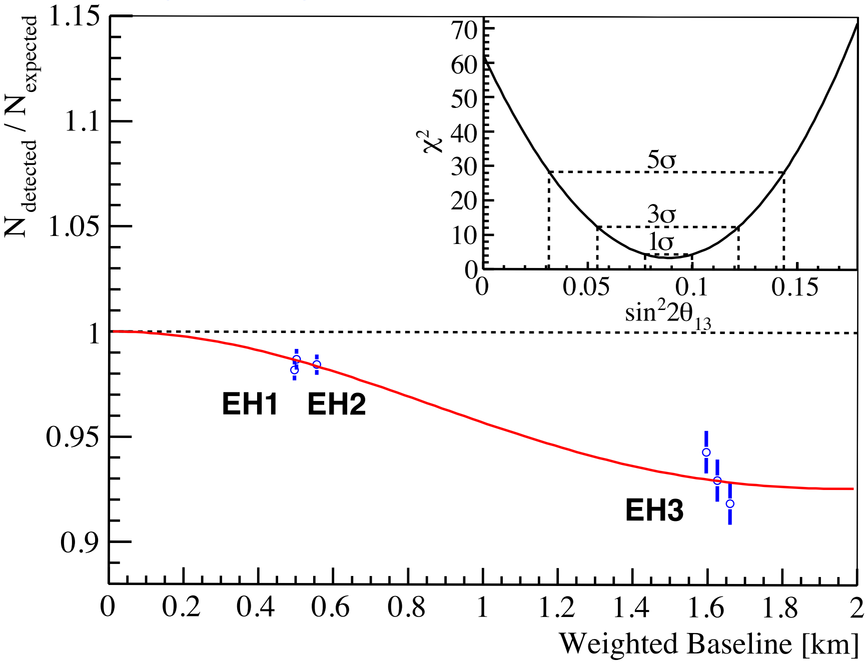

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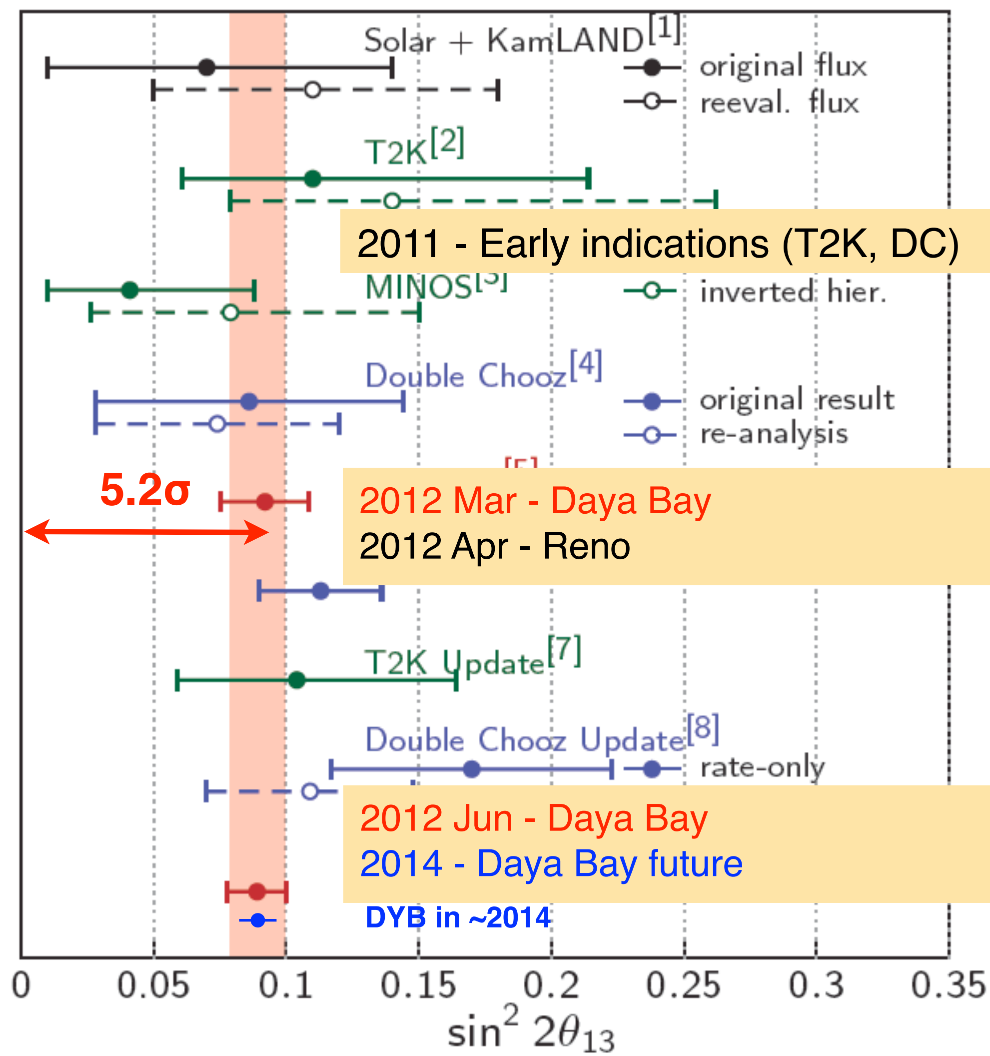
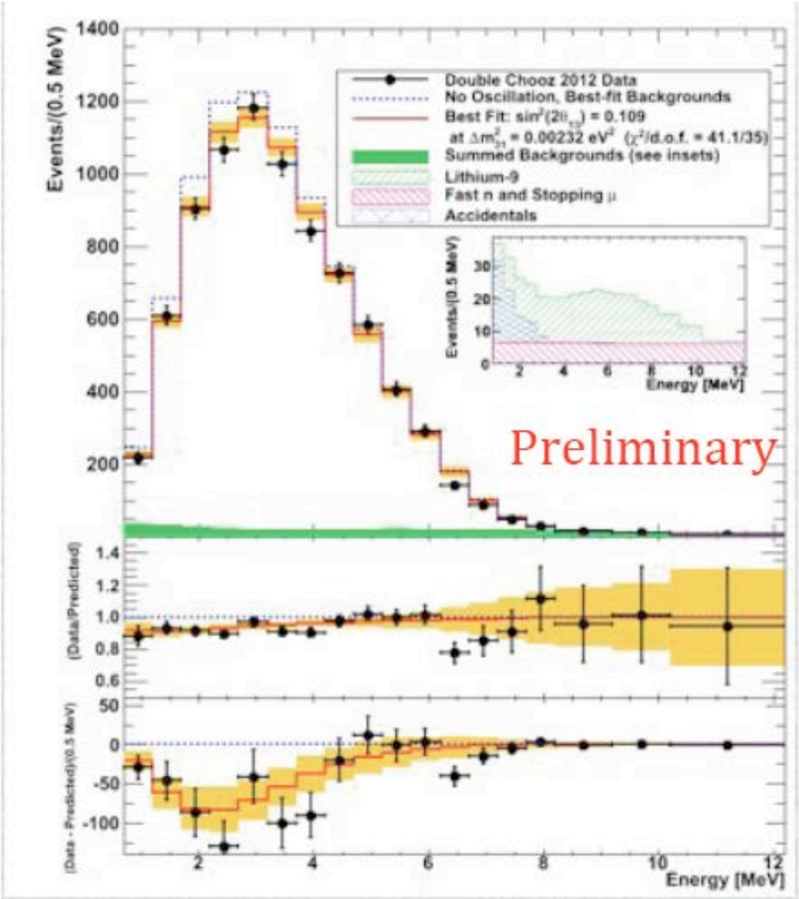


Other Reactor θ_{13} Experiments

Double Chooz

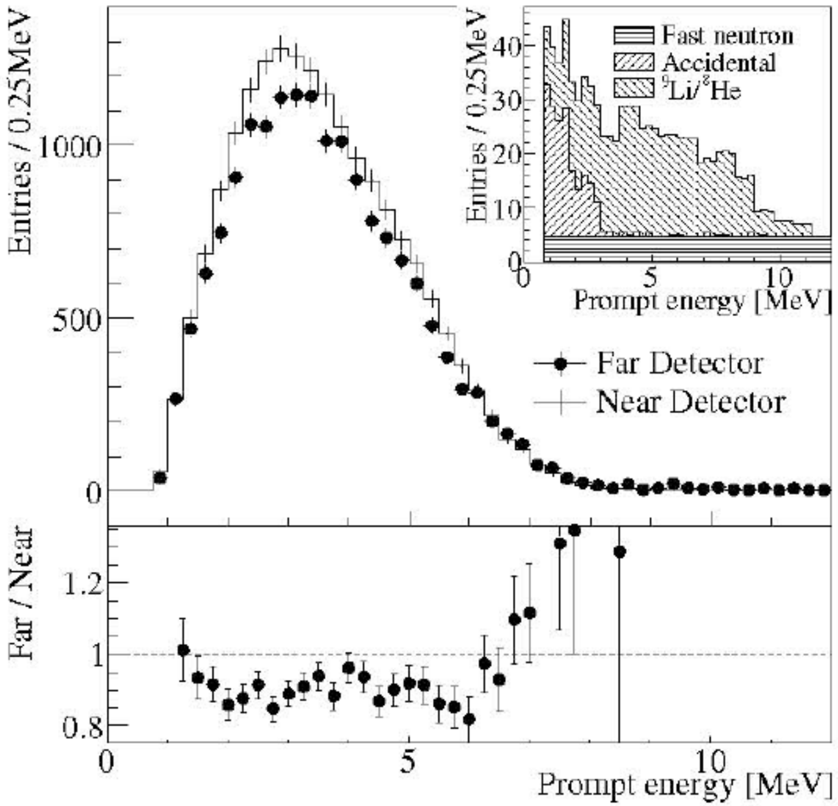


Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$

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

Ref: Ishitsuka, Neutrino2012

RENO

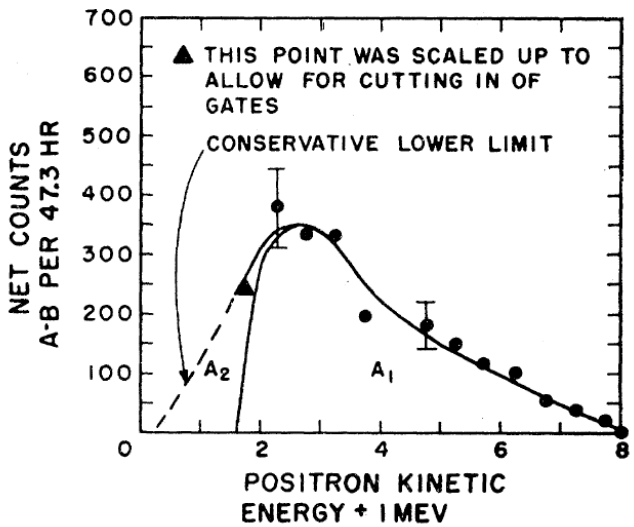


$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

PRL, 108 (2012) 191802

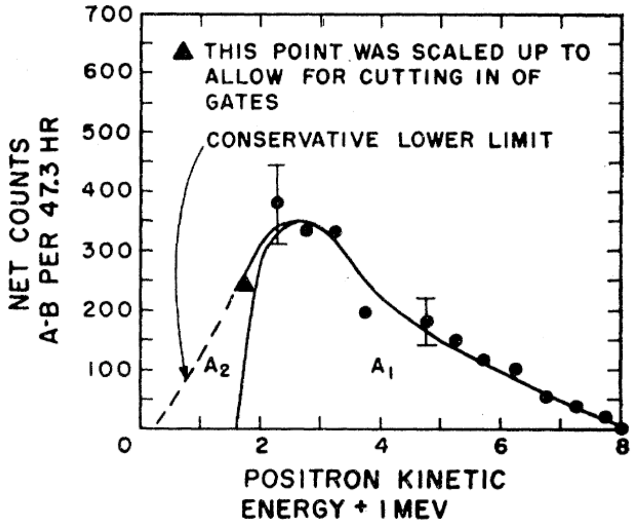
Towards a Precision Reactor Spectrum

Reines 1959

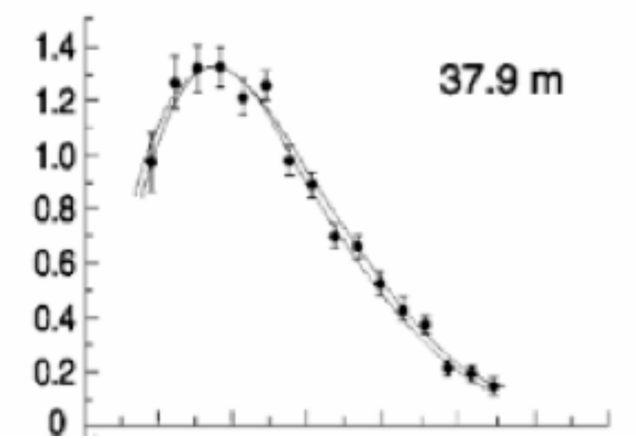


Towards a Precision Reactor Spectrum

Reines 1959

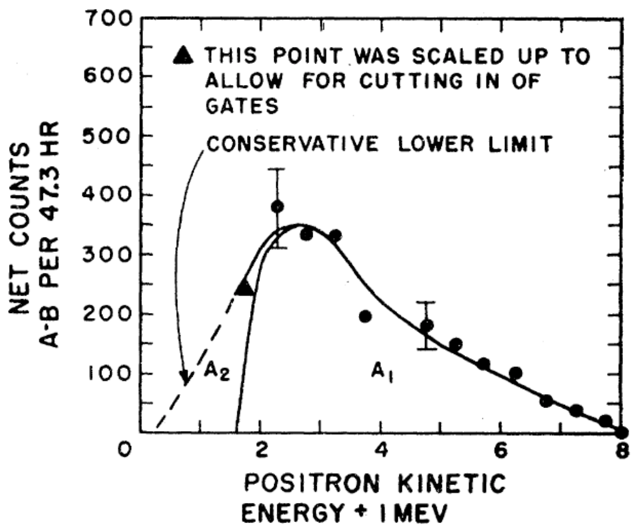


Goesgen 1986

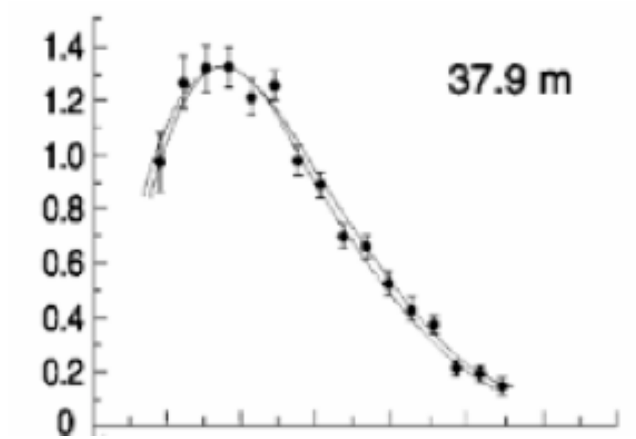


Towards a Precision Reactor Spectrum

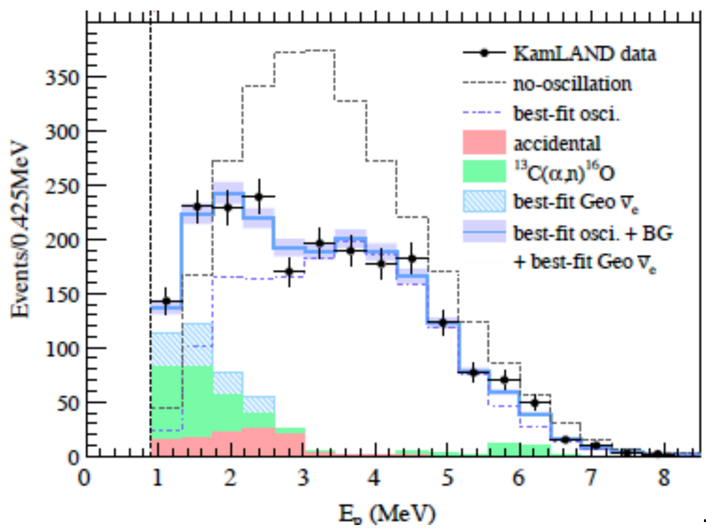
Reines 1959



Goesgen 1986

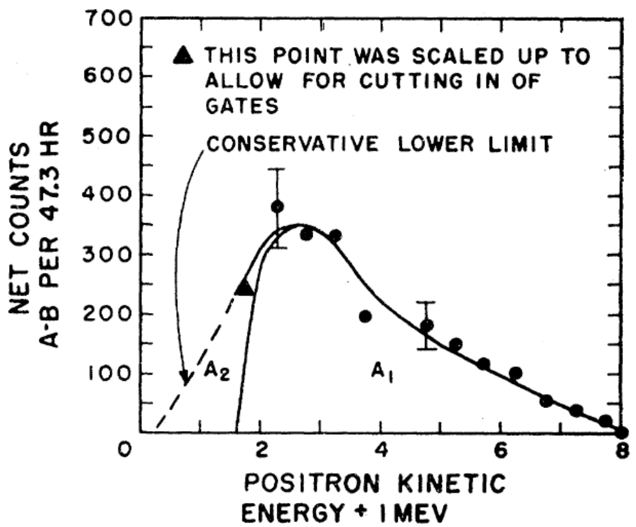


KamLAND 2010

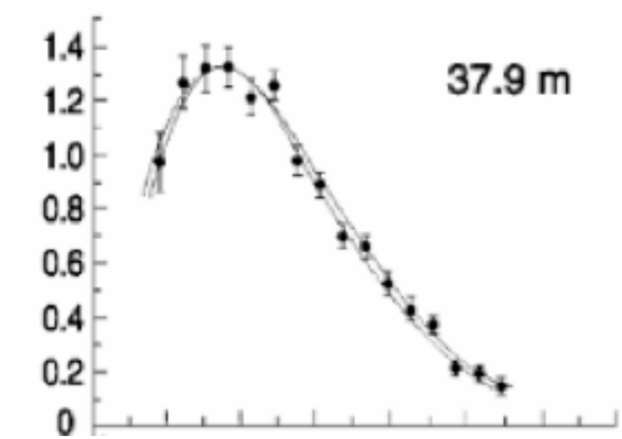


Towards a Precision Reactor Spectrum

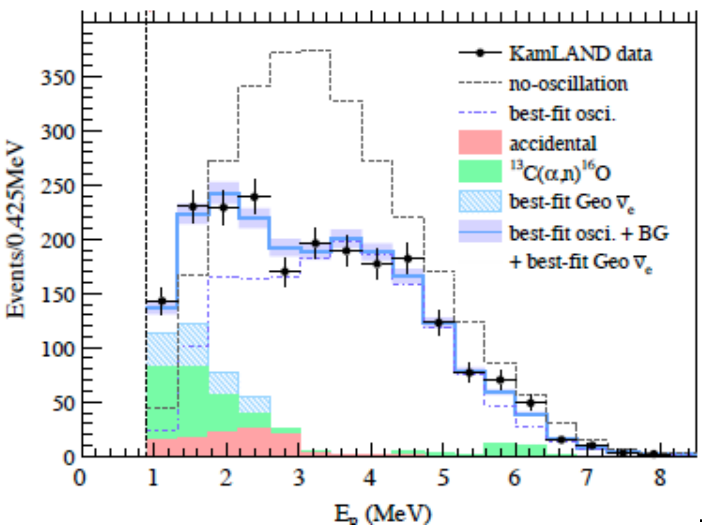
Reines 1959



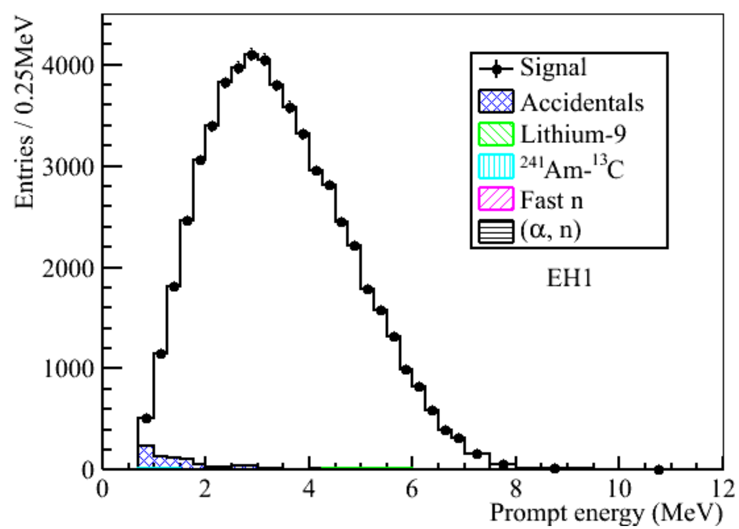
Goesgen 1986



KamLAND 2010

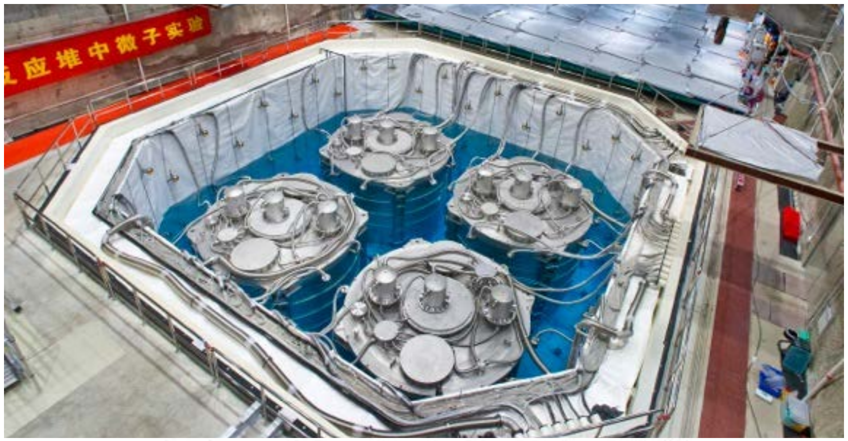


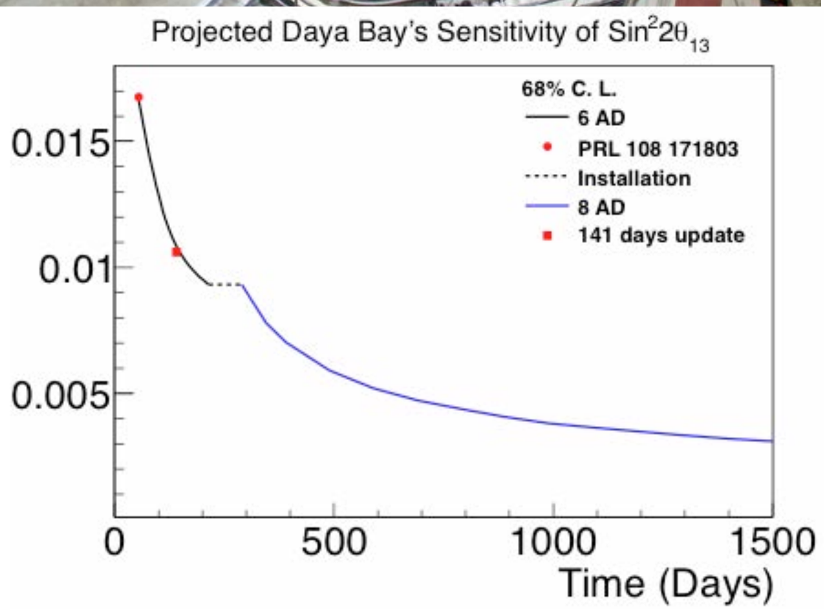
Daya Bay (> 200,000 events at near site)



θ_{13} - What's Next for Daya Bay?

Installed and commissioned remaining detectors in October 2012.





Manual calibration program in summer 2012

Physics Goals

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

Measurement of **Δm^2_{ee}**

Reactor flux and **spectra measurements**

Neutrino Oscillation

Mixing Angles & Mass Splittings

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

$\theta_{23} = 40.4^\circ{}^{+0.8^\circ}_{-1.8^\circ}$ — maximal?

$\theta_{13} = 8.7^\circ \pm 0.45^\circ$ — not so small

$\theta_{12} = 32.4^\circ \pm 0.8^\circ$ — large, but not maximal!

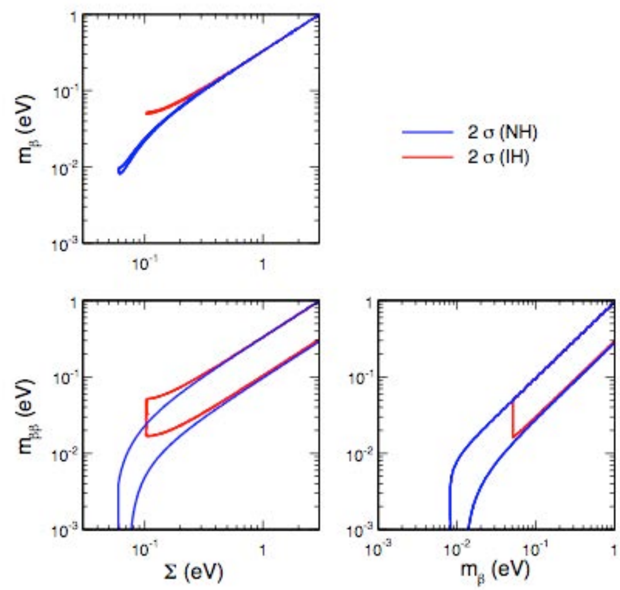
All three neutrino mixing angles are now known!

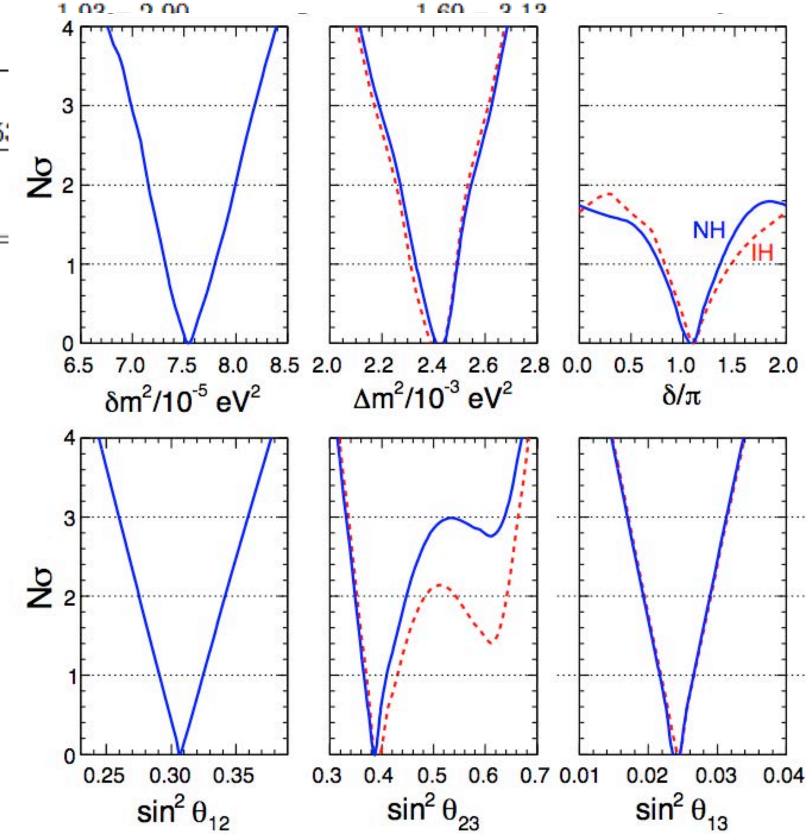
Neutrino Oscillation - 2012

3-ν Global Analyses

Ref: Fogli et al 1205.5254 and Nu2012

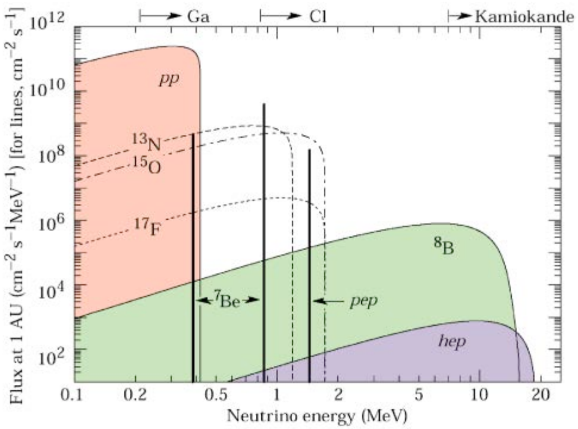
Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67		
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10		
$\sin^2\theta_{23}/10^{-1}$ (IH)			3.5[illegible]	
δ/π (NH)				
δ/π (IH)				

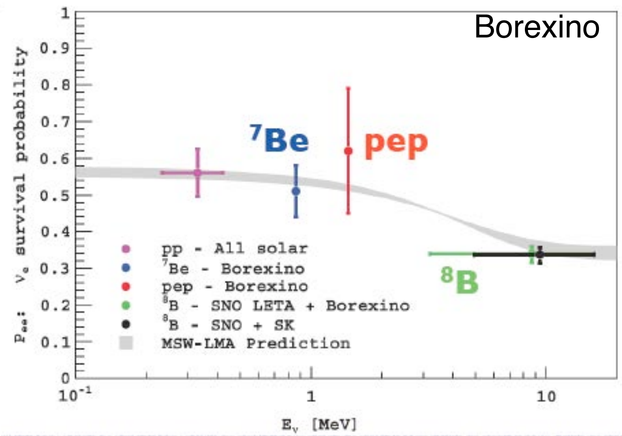


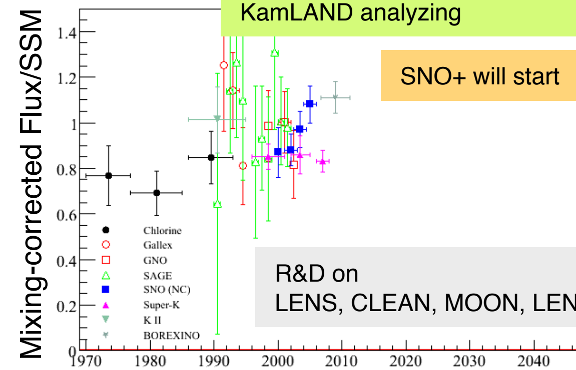


complete suite of measurements can over-constrain the 3-ν framework

Future Solar Neutrino Measurements





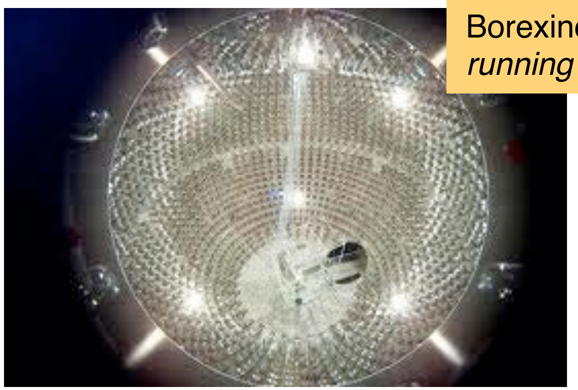


Borexino, Super-K continue
KamLAND analyzing

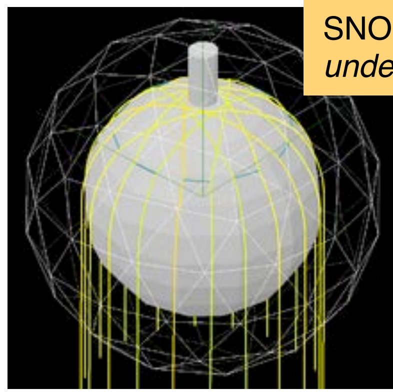
SNO+ will start

R&D on
LENS, CLEAN, MOON, LENA

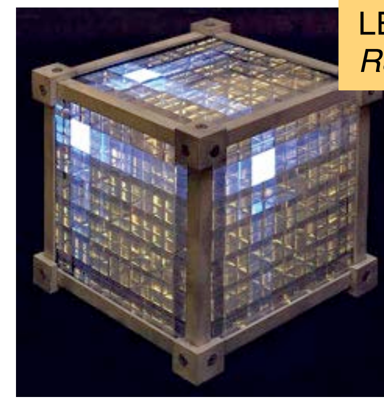
Fig: Klein, Intensity Frontier 2011



Borexino
running



SNO+
under construction

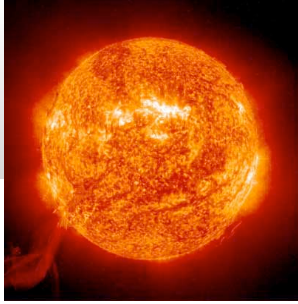


LENS
R&D

Science Goals

1. improved measurement of pep, ^{7}Be, ^{8}B, → test MSW, probe vacuum-matter transition
2. exclusive measurement of CNO → probe solar metallicity
3. exclusive measurement of pp flux → test luminosity constraint

Future Solar Neutrino Measurements



Sun is a "reactor" we understand

Goal is a 1% measurement of the total ν luminosity. Comparison with electromagnetic luminosity will test for sterile neutrinos etc.

Only two fluxes are significant, *pp* and ^{7}Be. Others are precise enough (CNO?). ^{7}Be is already at ~0.8% accuracy.

A neutral-current measurement at low energies seems out of reach for the foreseeable future.

Therefore we must use CC and/or ES measurements and oscillation parameters to deduce the total active flux.

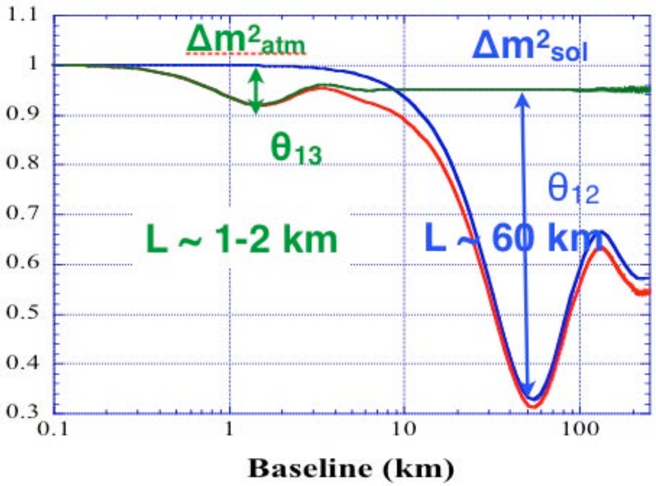
For a 1% measurement:
- precisely known cross-sections
- precisely known oscillation parameters (we have 5%)
- high statistics
- low systematics

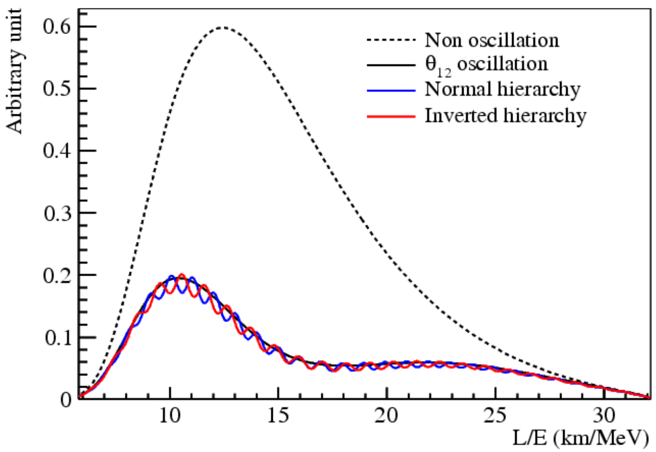
Ref: Robertson Aspen 2013

~1% measurement of solar ν luminosity appears achievable. Need good *pp* or *pep* measurement by ES.

Future Reactor $\overline{\nu}_e$ Experiments

Measuring Mass Hierarchy





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

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

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

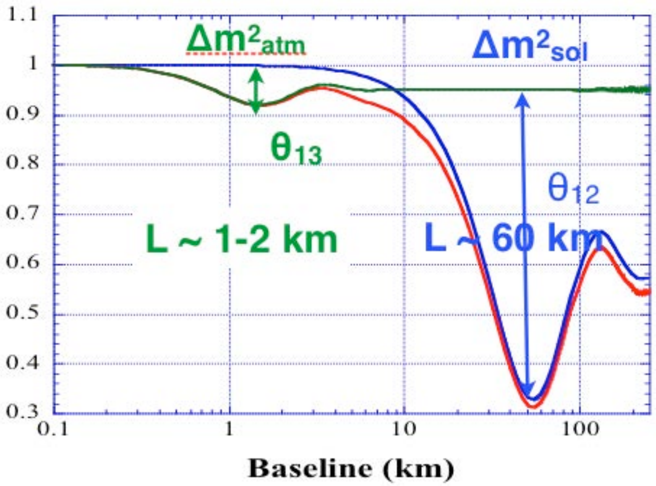
Δm^2_{21} is only 3% of $|\Delta m^2_{32}|$

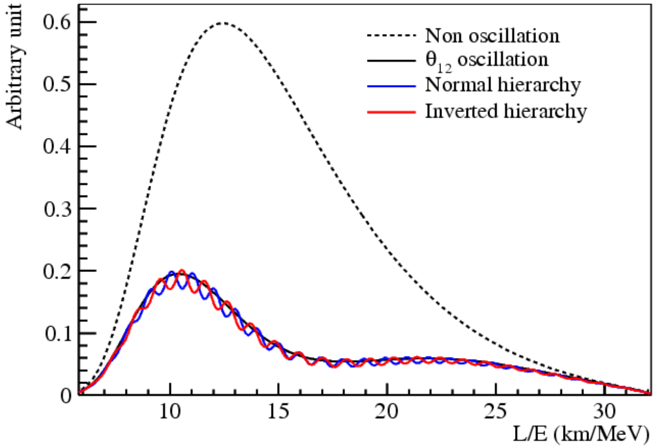
S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

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

Future Reactor $\overline{\nu}_e$ Experiments

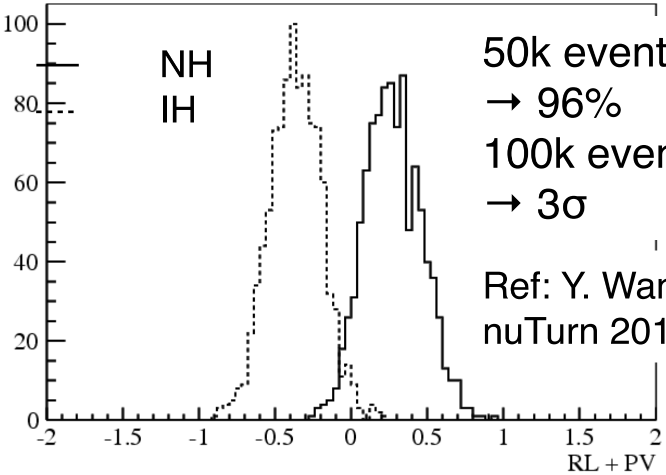
Example: Daya Bay II





Site Investigation

Mass Hierarchy Sensitivity



50k events = 20 kton, 3 years → 96%

100k events → 3σ

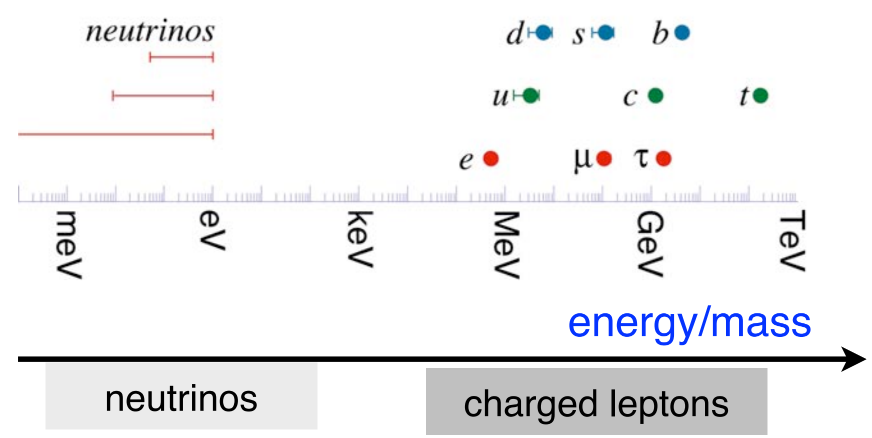
Ref: Y. Wang, J. Cao, et al nuTurn 2012

Sub-1% precision 3-ν oscillation physics in Δm^2_{12}, Δm^2_{23}, and $\sin^2\theta_{12}$ possible

Neutrinos - Open Questions

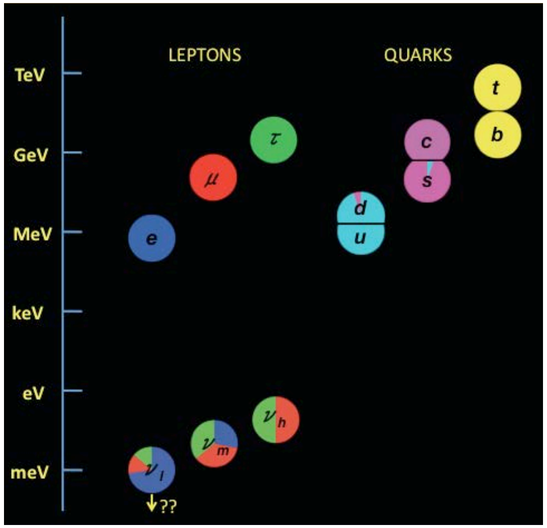
The Origin of Mass

- Why are neutrinos so light?
- Do neutrinos have Majorana mass?
- What is the absolute mass scale?
- Normal or inverted mass ordering?
- Are there more than 3ν?



The Flavor Puzzle

- Why is lepton mixing so different from quarks?
- CP violation?
- θ_{23} octant?



Neutrinos - Open Questions

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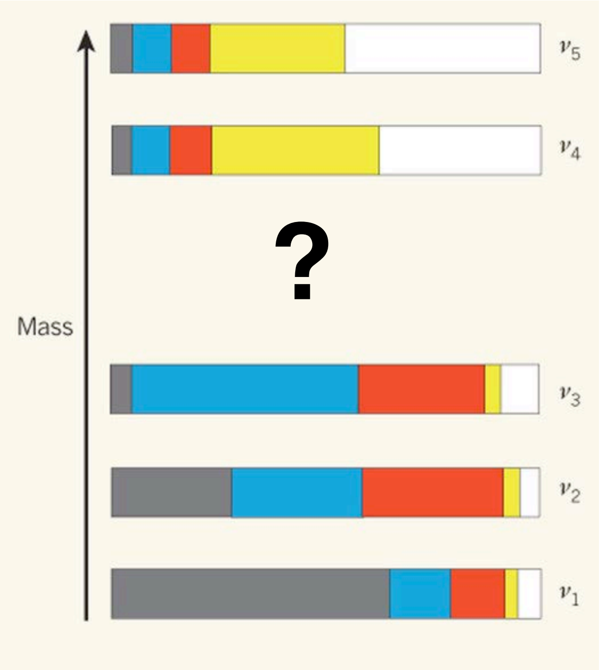

The Flavor Puzzle

- Why is lepton mixing so different from quarks?
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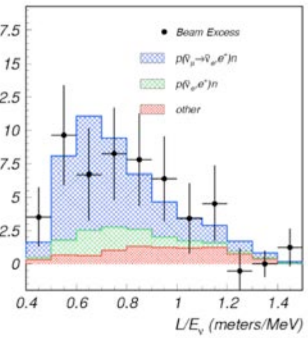
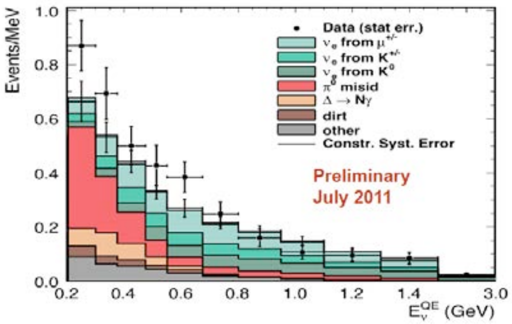
- θ_{23} octant?

Neutrino Anomalies - Beyond 3ν?

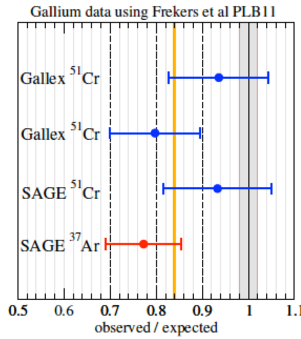
LSND



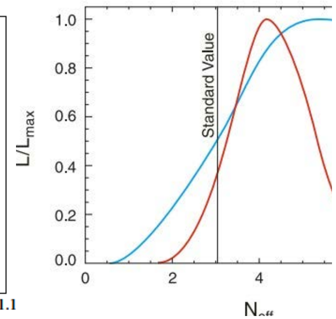
MiniBoone



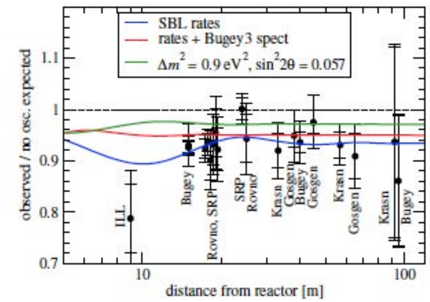
Ga Source



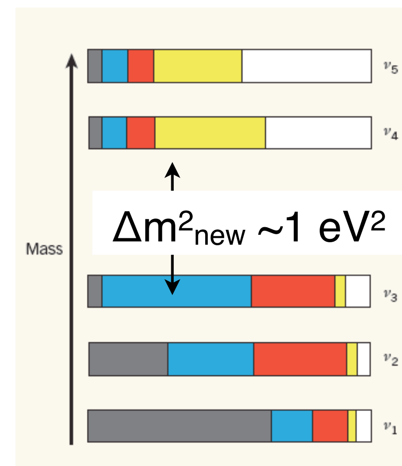
Cosmology (WMAP)



Reactor



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



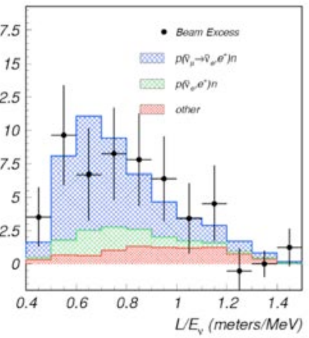
Anomalies in 3-ν interpretation of global oscillation data

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

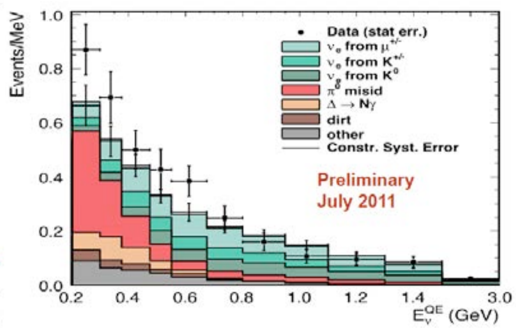
systematics or experimental effect? ➔ need to test each effect

Neutrino Anomalies - Beyond 3ν?

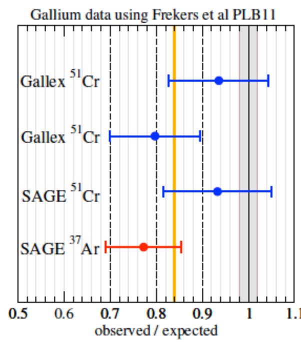
LSND



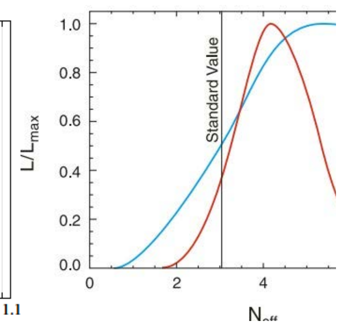
MiniBoone



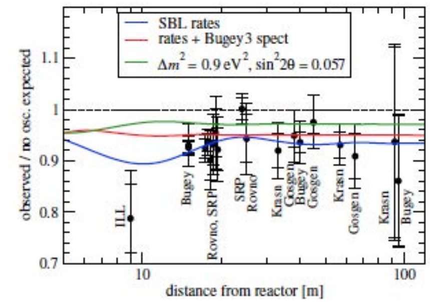
Ga Source



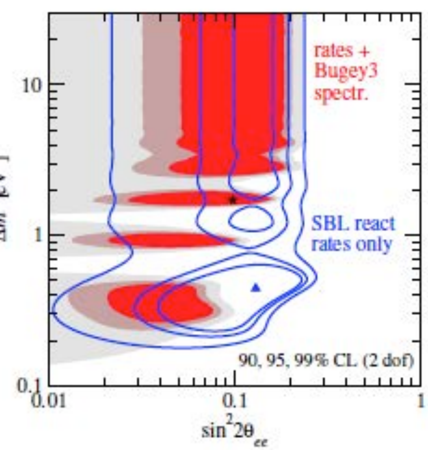
Cosmology (WMAP)

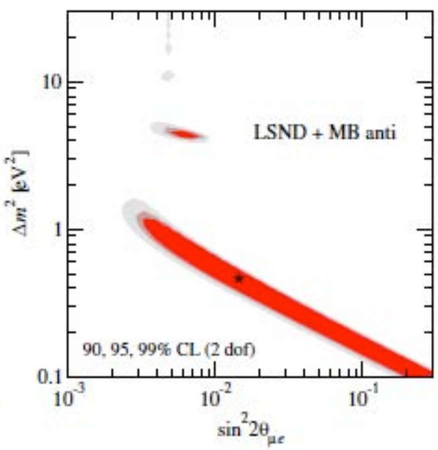


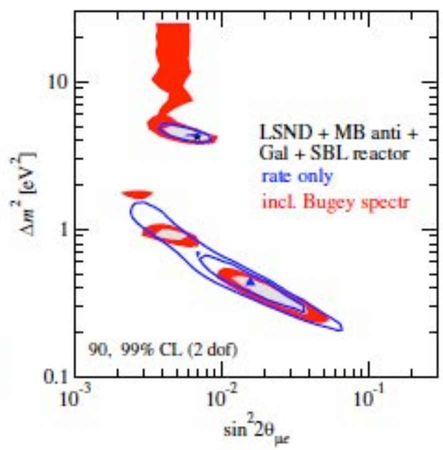
Reactors



Are $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ consistent?







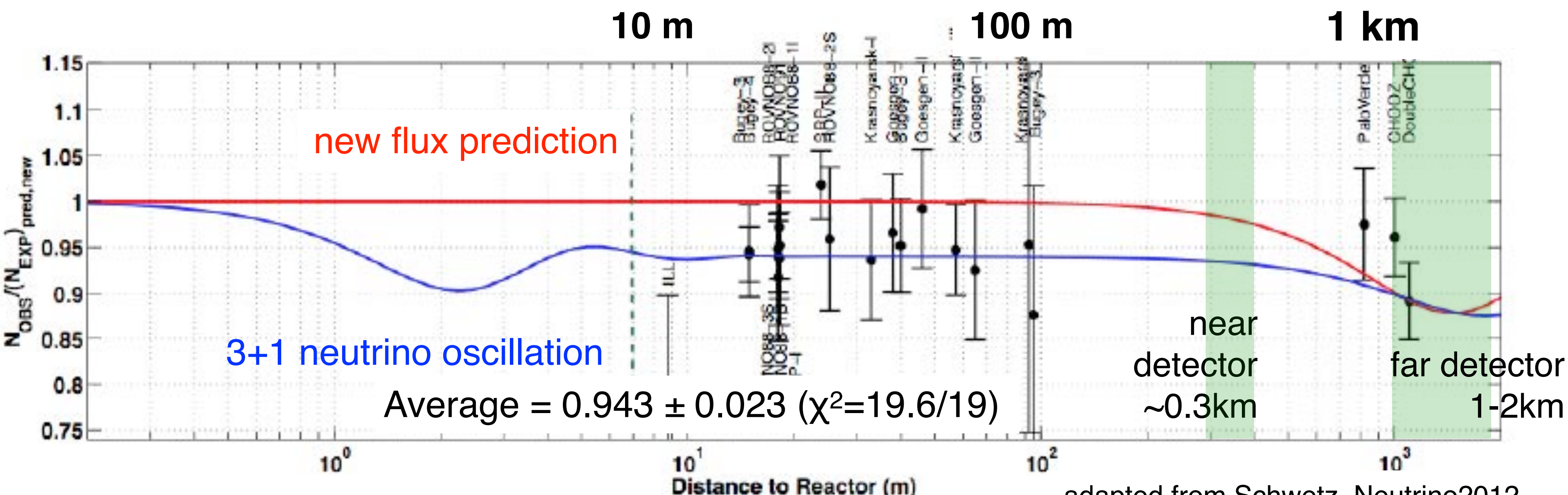
$\nu_e \rightarrow \nu_e$ disappearance $\sin^2 2\theta_{ee}$

$\nu_\mu \rightarrow \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$

$\nu_\mu \rightarrow \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

strong tension if all three are combined, tension also in 3+2 fit

Reactor Anomaly and θ_{13} Experiments



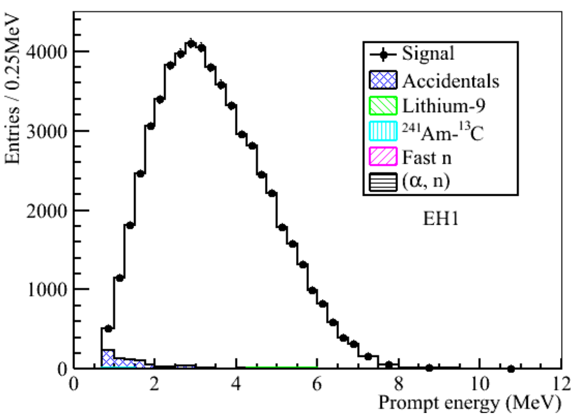
adapted from Schwetz, Neutrino2012

Do we understand the flux normalization?

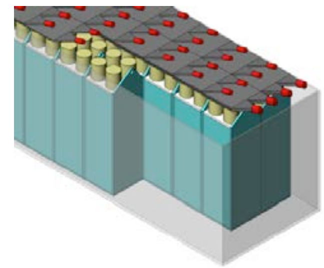
	Double Chooz	RENO	Daya Bay
detector syst	2.1%	1.5% (correlated)	1.9% (correlated)
reactor syst	1.8%	2.0% (correlated)	3.0% (correlated)

reactor θ_{13} experiments not optimized to resolve 'anomaly'

Do we understand the reactor $\overline{\nu}_e$ spectrum?

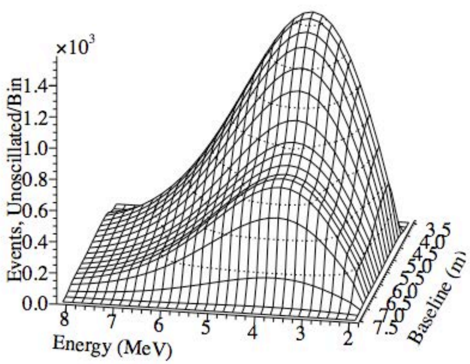


Sterile Neutrinos would require $\Delta m^2 \sim O(1eV^2)$

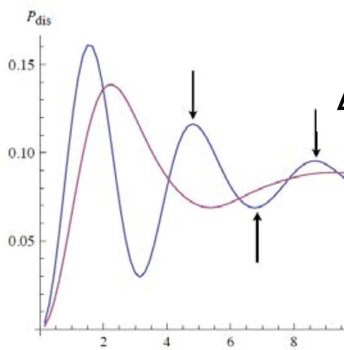


segmented, extended detector

Reactor Antineutrinos

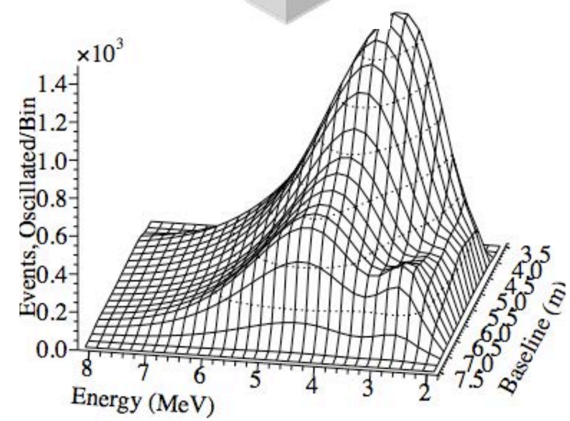


$\overline{\nu}_e$ Oscillation

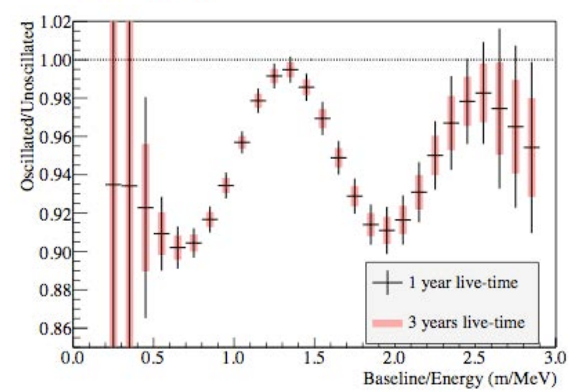


$\Delta m^2 \sim 2$ eV²

distance, R



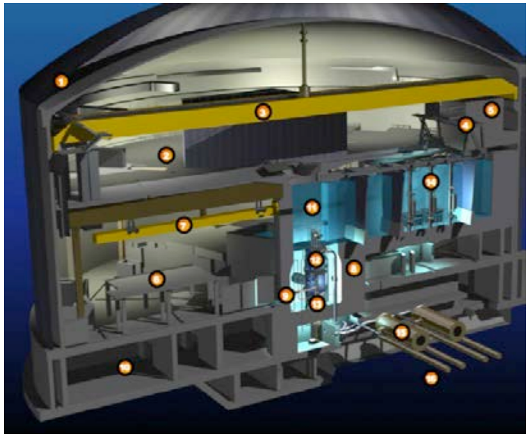
~O(10)m

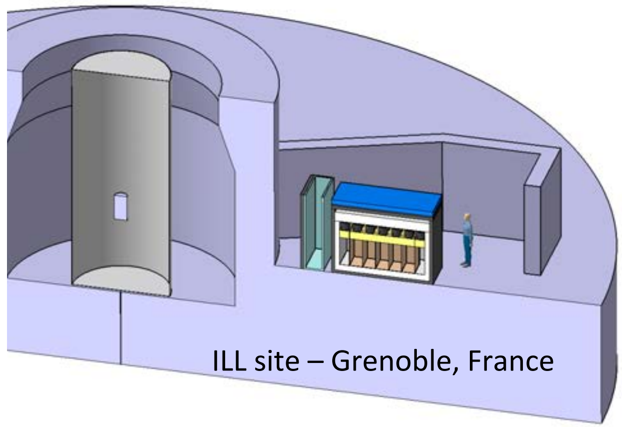


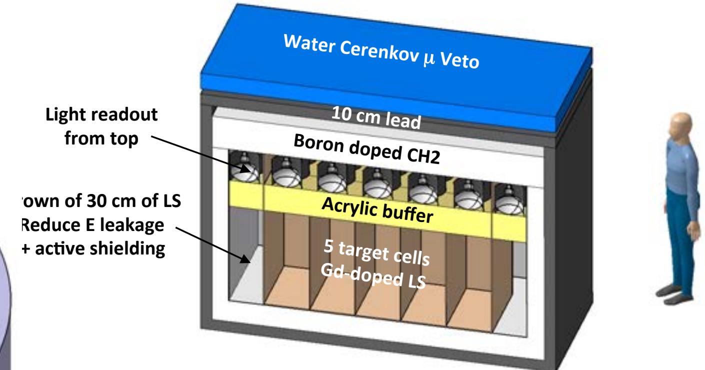
Energy and baseline dependent Effect

New Short-Baseline Reactor Experiments

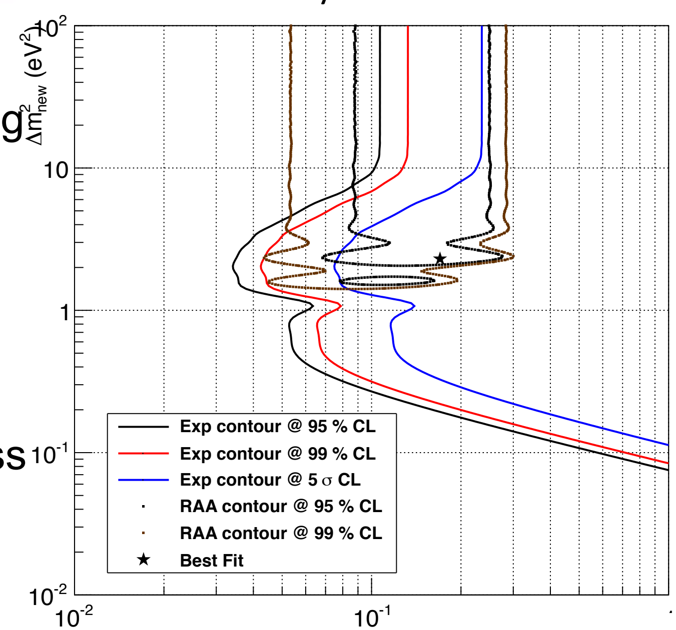
STEREO at ILL







Shape analysis +
3.5 % uncertainty on normalization



Reactor Site

50 MW compact core
(φ=40cm, h=80 cm)

Short baseline
[7-9] m

Pure ^{235}U spectrum

Background Rejection

Large passive and active shielding
15 m.w.e. overburden

Pulse Shape Discrimination

Segmented detector

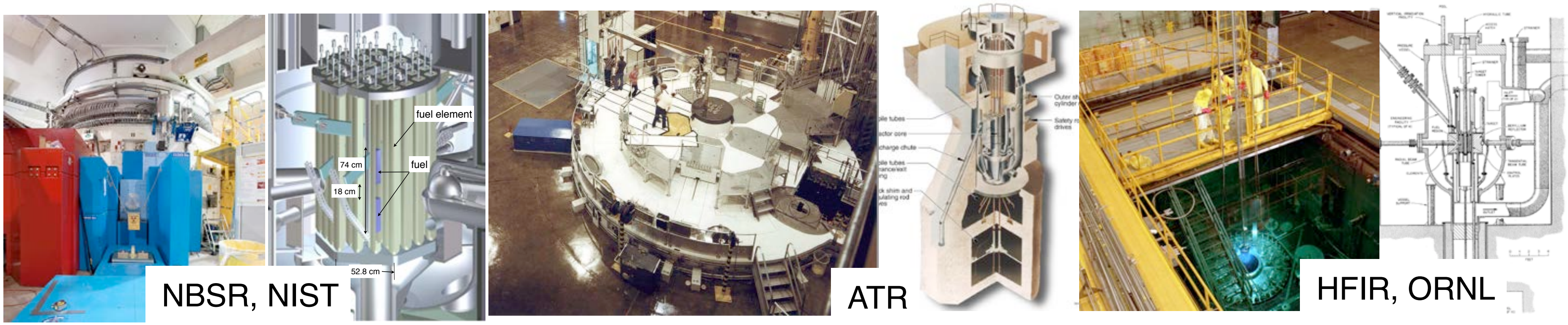
On-site measurements in progress

Aim for first data in 2015
Funding decision in 2013

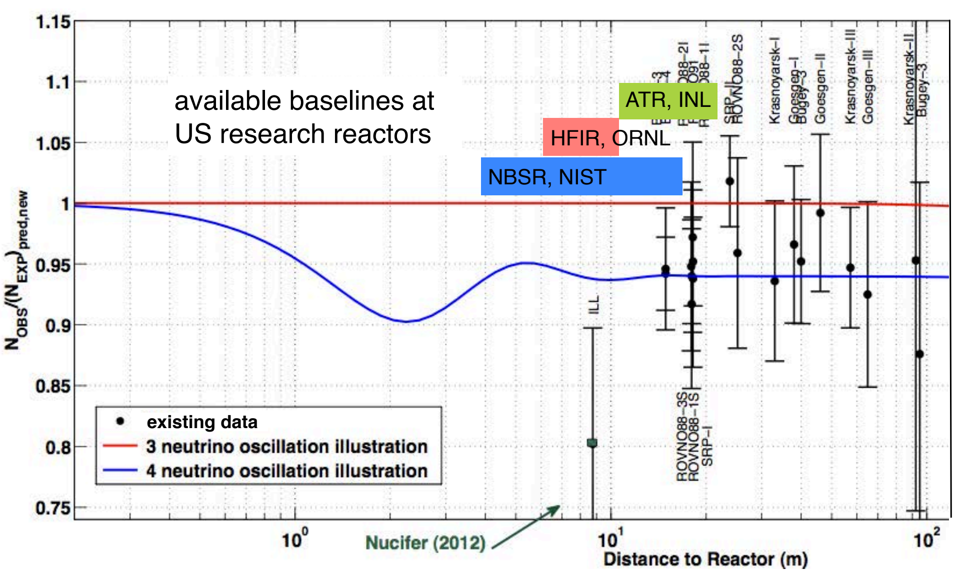
Ref: Lhuillier

New Short-Baseline Reactor Experiments

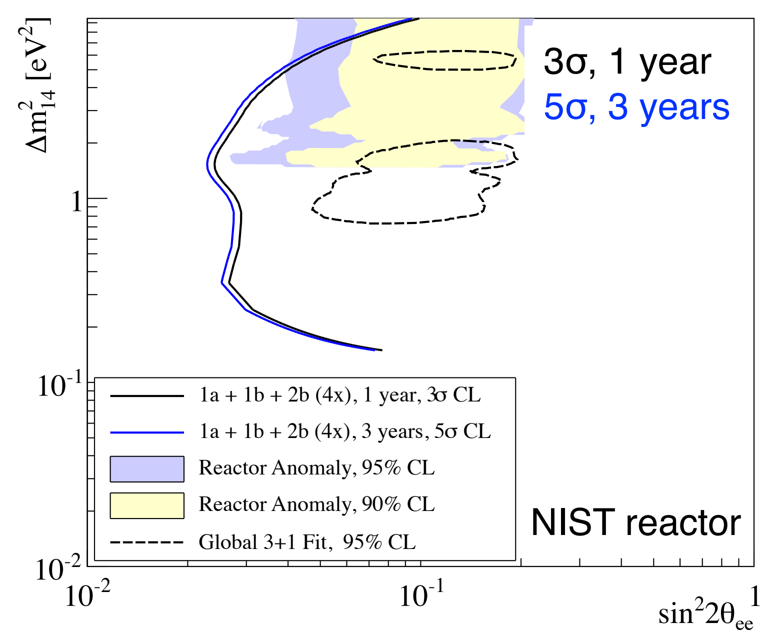
High-Power US Research Reactors



Shortest Accessible Baselines

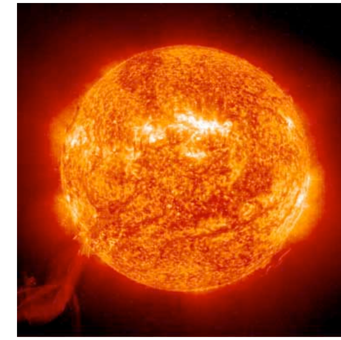


Discovery Potential



Summary

The Sun and reactors are **flavor pure sources** of ν_e and $\overline{\nu}_e$ respectively.



Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$, and **reactor antineutrino spectra**. 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.

The **Sun is the ultimate "reactor"**; a **1% measurement of the solar ν luminosity may be achievable in the future** testing solar and particle physics.