Reactor Neutrino Experiments - Lecture II

- Precision Oscillation Physics With Reactor Antineutrinos -

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http://neutrino.physics.wisc.edu

Outline

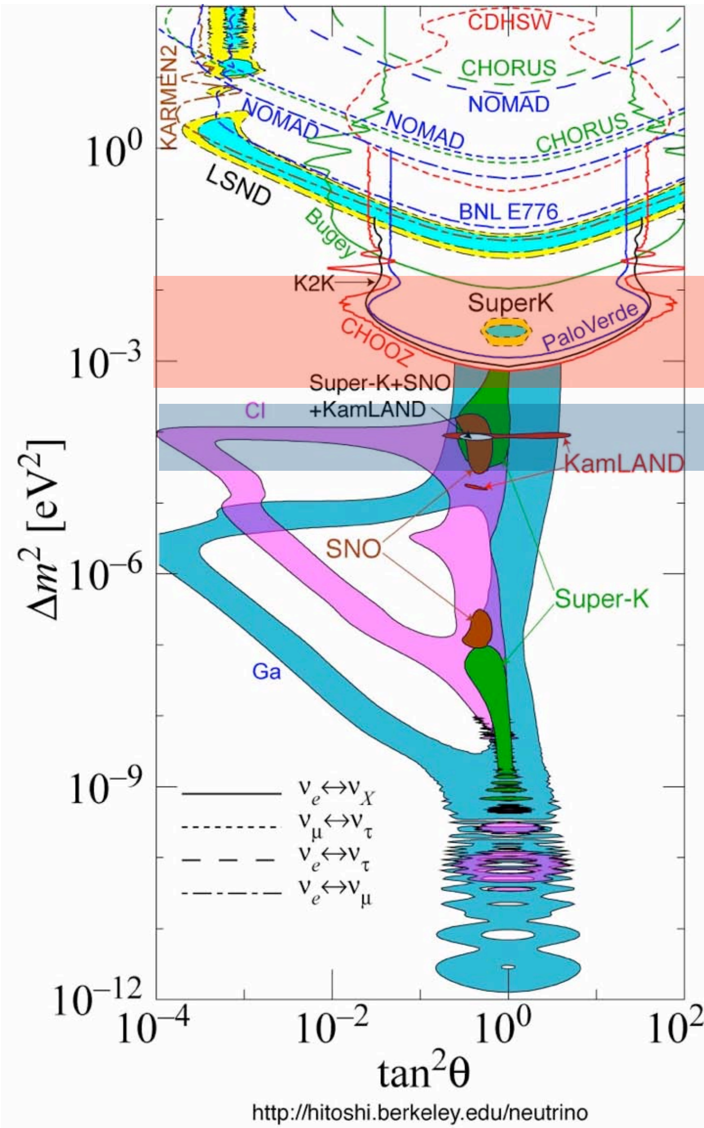
Lecture I - The First 50 Years: From The Discovery of the Antineutrino to the First Observation of Antineutrino Disappearance

- The Reactor as an Antineutrino Source
- Detection of Antineutrinos
- Discovery of the Free Antineutrino
- Search for Neutrino Oscillation with Reactor Antineutrinos
- Observation of Reactor Antineutrino Disappearance at KamLAND
- Other Reactor Neutrino Experiments

Lecture II - Precision Oscillation Physics with Reactor Antineutrinos

- Precision Measurement of Δm^2_{12} at KamLAND
- Evidence for Oscillation of Reactor Antineutrinos at KamLAND
- Search for the Unknown Neutrino Mixing angle θ_{13}
- Future Opportunities: Precision Measurement of θ_{12}
- Applied Neutrino Physics: Reactor Monitoring with Antineutrinos

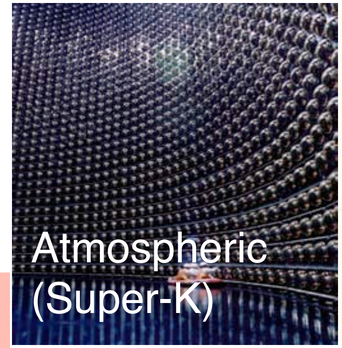
Discovery Era in Neutrino Physics: 1998 - Present

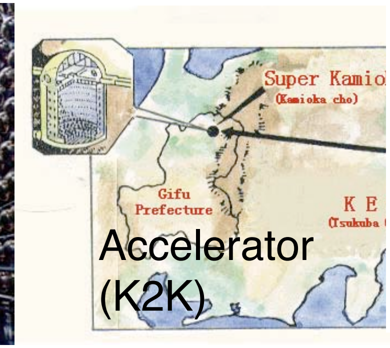


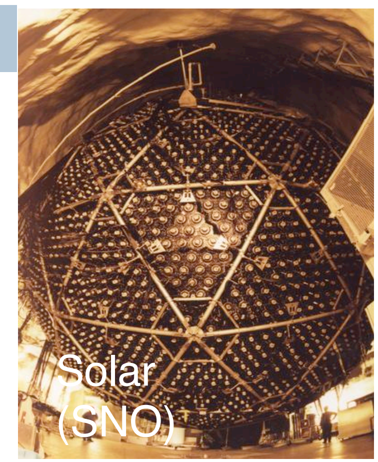
$\nu_\mu \Rightarrow \nu_\tau$

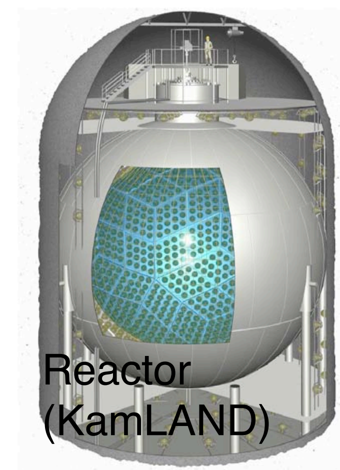
$\nu_e \Rightarrow \nu_{\mu,\tau}$

Δm_{ij}^2 measured *and* confirmed.



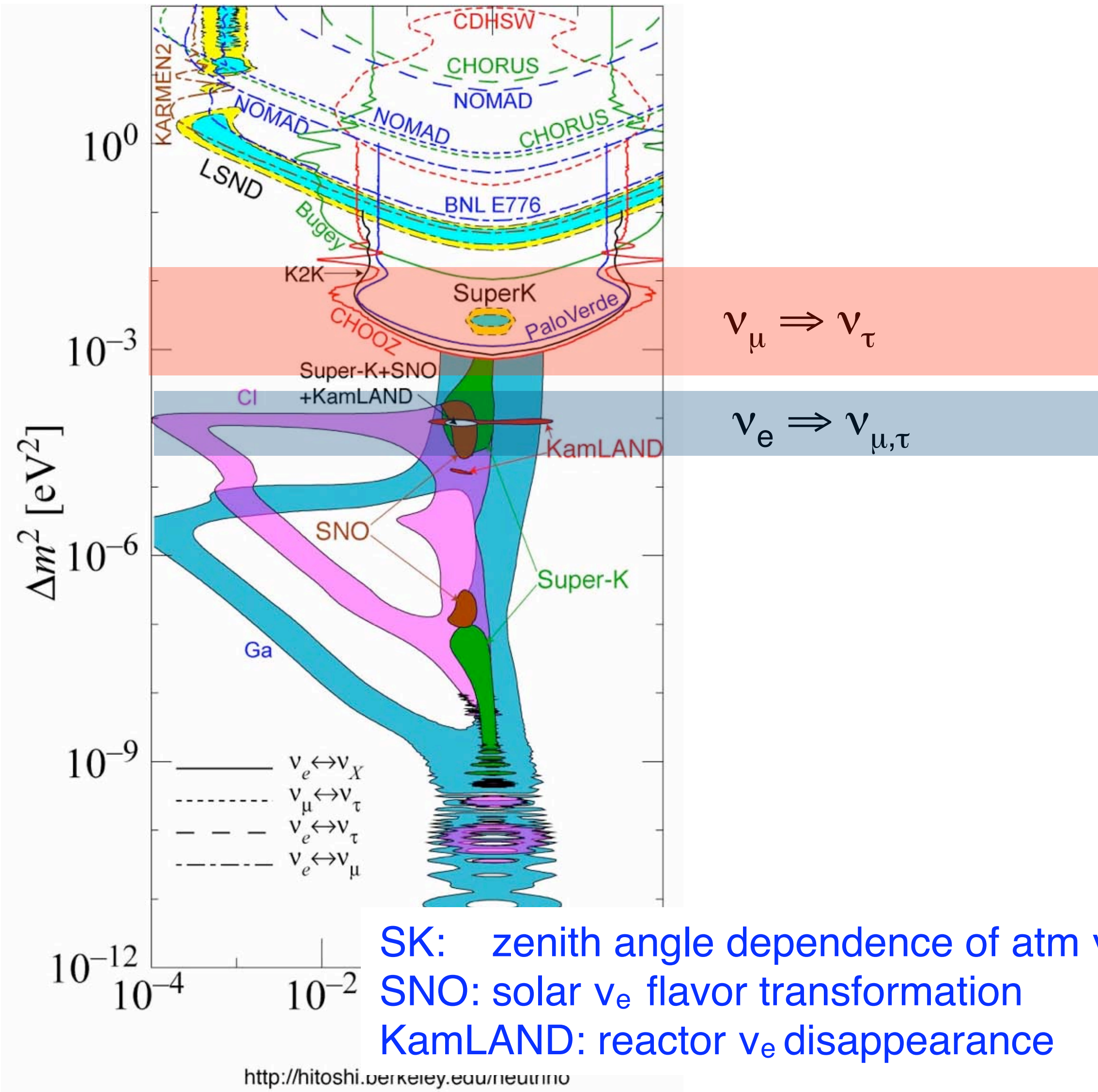


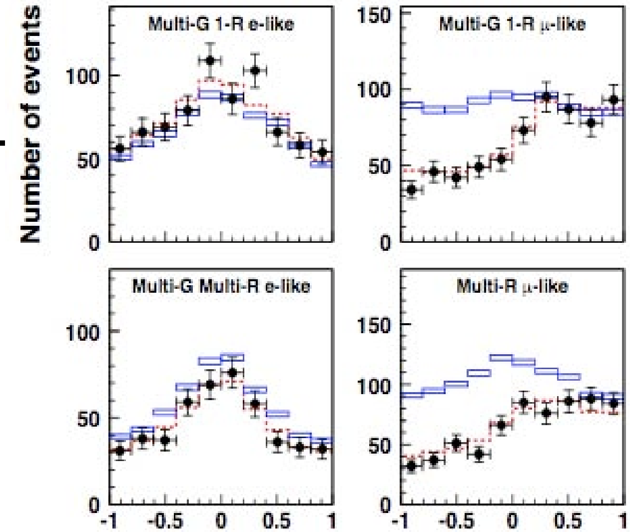


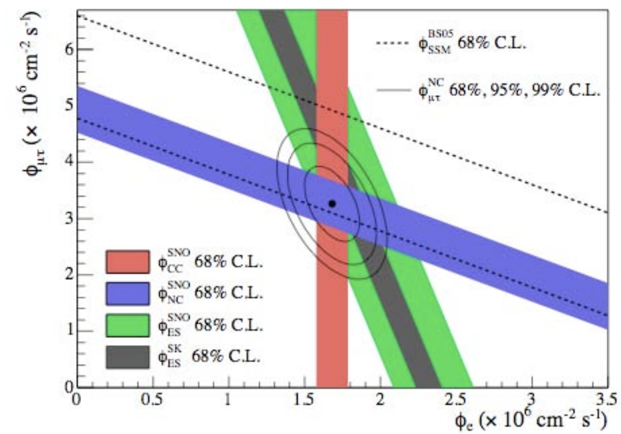


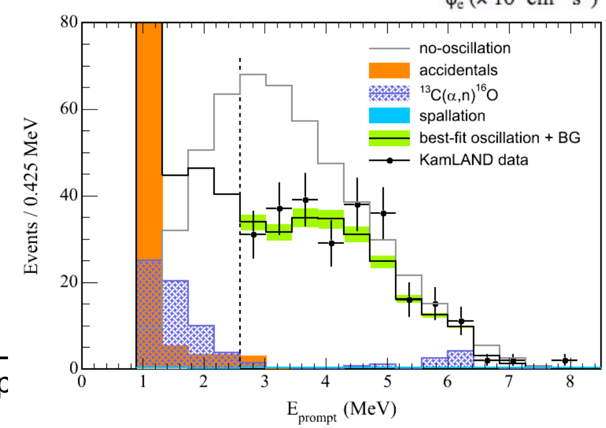
SK: zenith angle dependence of atm ν_μ
SNO: solar ν_e flavor transformation
KamLAND: reactor $\overline{\nu}_e$ disappearance

Discovery Era in Neutrino Physics







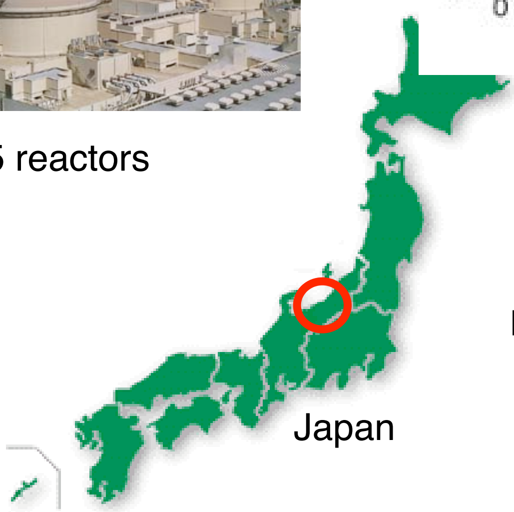


SK: zenith angle dependence of atm ν_μ
SNO: solar ν_e flavor transformation
KamLAND: reactor ν_e disappearance

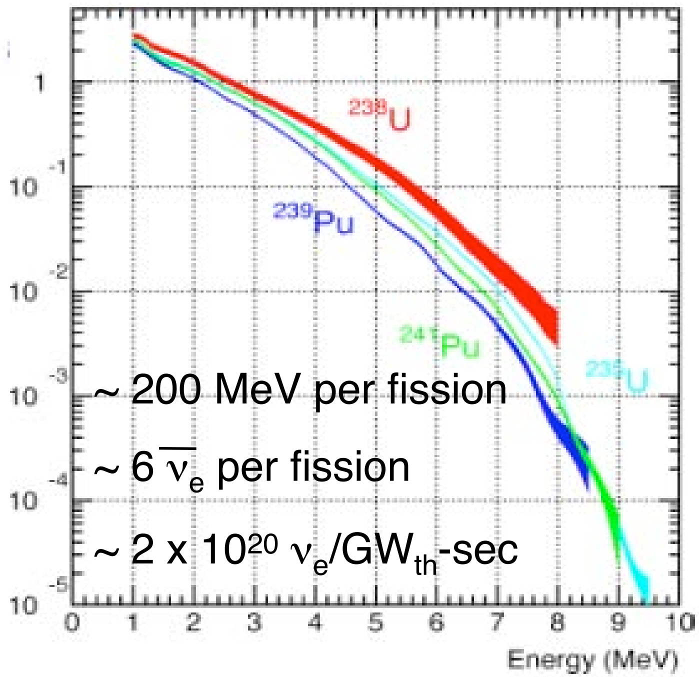
Measurement of Reactor Antineutrinos in KamLAND

Japanese Reactors

55 reactors



Reactor Isotopes



~ 200 MeV per fission

~ 6 $\overline{\nu}_e$ per fission

~ 2 x 10^{20} ν_e/GW_{th}-sec

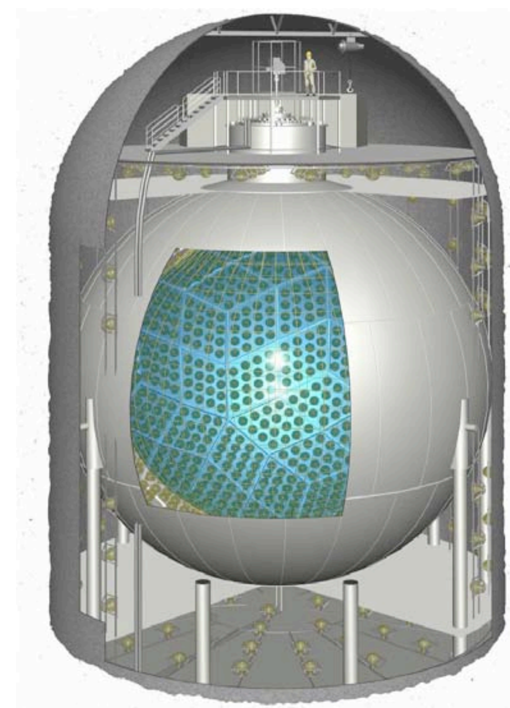
$^{235}U:^{238}U:^{239}Pu:^{241}Pu$ =
0.570: 0.078:0.0295:0.057

reactor $\bar{\nu}$ flux ~ 6 x $10^6/cm^2/sec$

Antineutrino Detection in KamLAND

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

through inverse β-decay

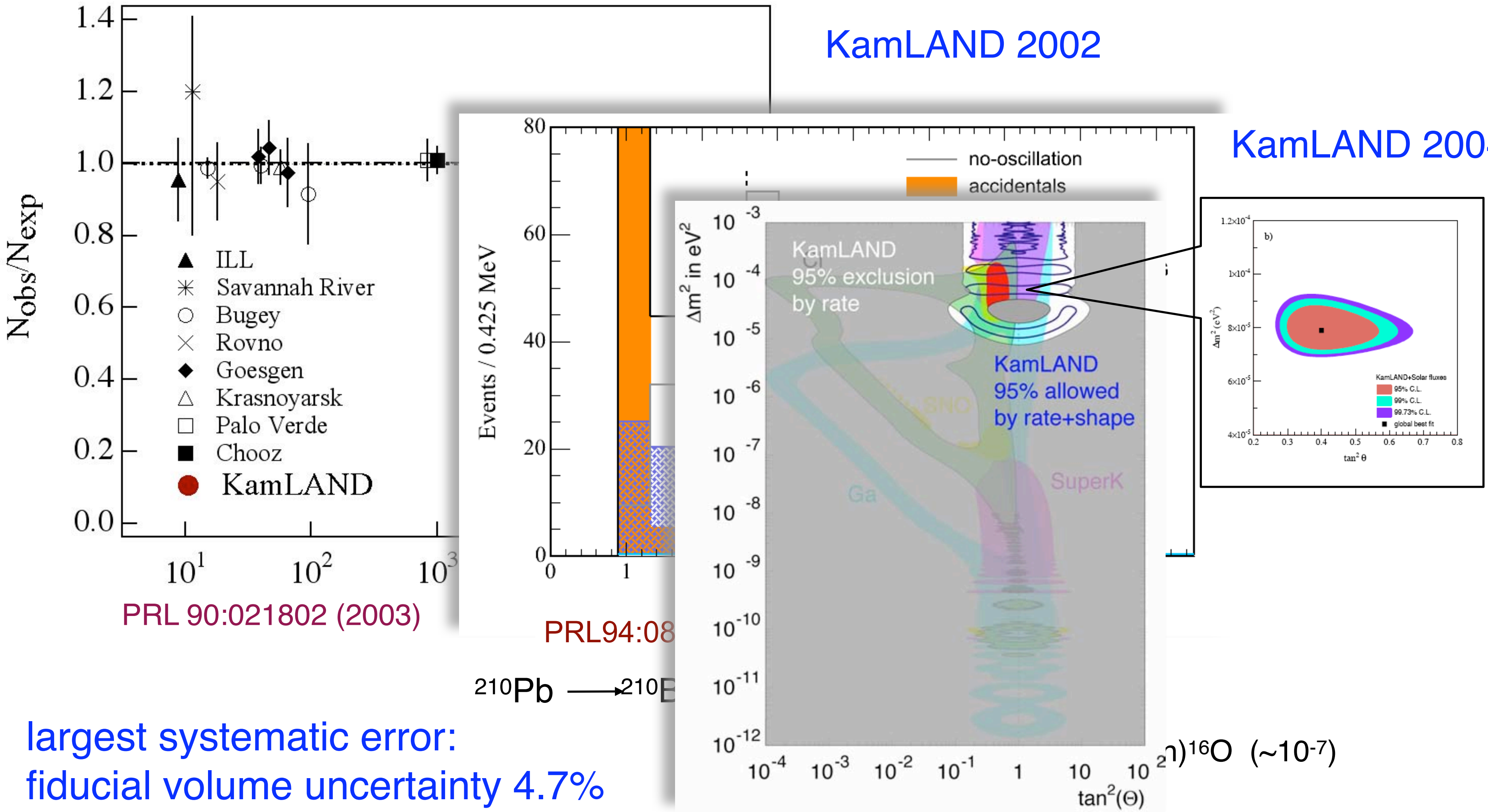


Reactor $\overline{\nu}_e$ disappearance at KamLAND

Reactor Neutrino Physics 1956-2004

KamLAND 2002

KamLAND 2004



PRL 90:021802 (2003)

PRL94:08

^{210}Pb → ^{210}B

n)^{16}O (~10^{-7})

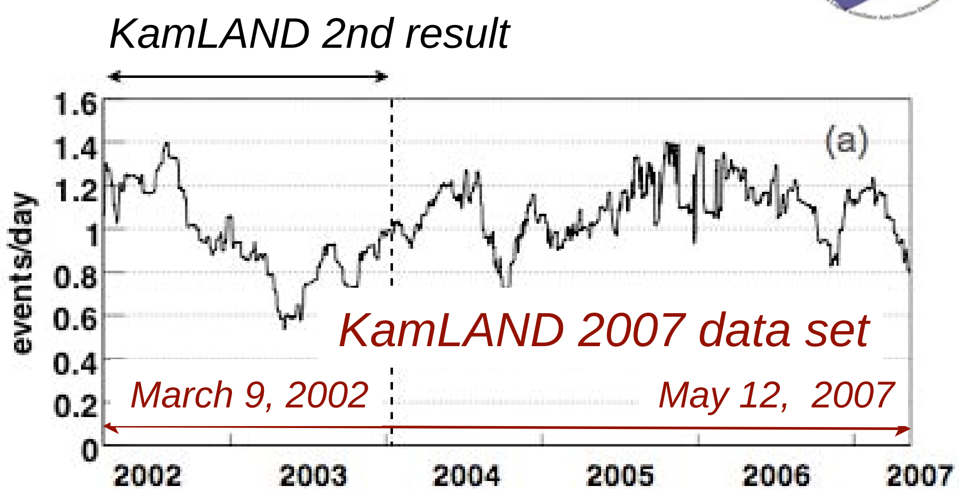
largest systematic error:
fiducial volume uncertainty 4.7%

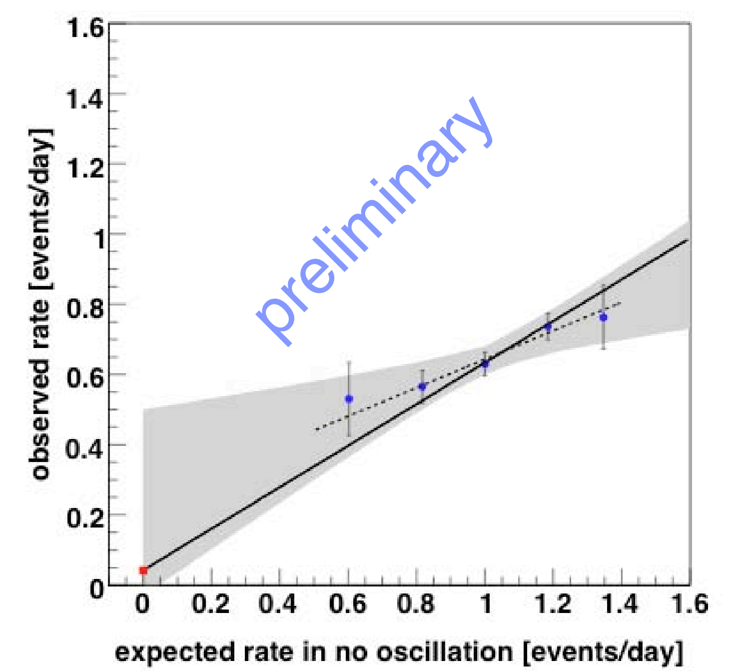
Precision Neutrino Oscillation Parameters with KamLAND

Updates to 2007 KamLAND analysis:

- increased livetime
- lowered analysis threshold
- modified analysis to enlargen the fiducial volume
- reduced uncertainty in $^{13}C(\alpha,n)^{16}O$ backgrounds

- reduced systematic in target protons (fiducial volume)





In KamLAND 2007 analysis:

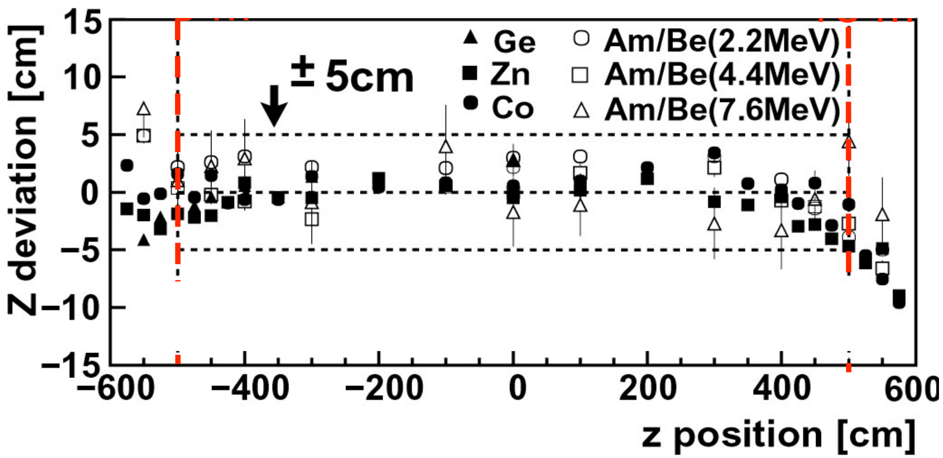
fiducial volume: R_p, R_d < 6.0m
livetime 1491 days
exposure: 2.44×10^{32} proton-year

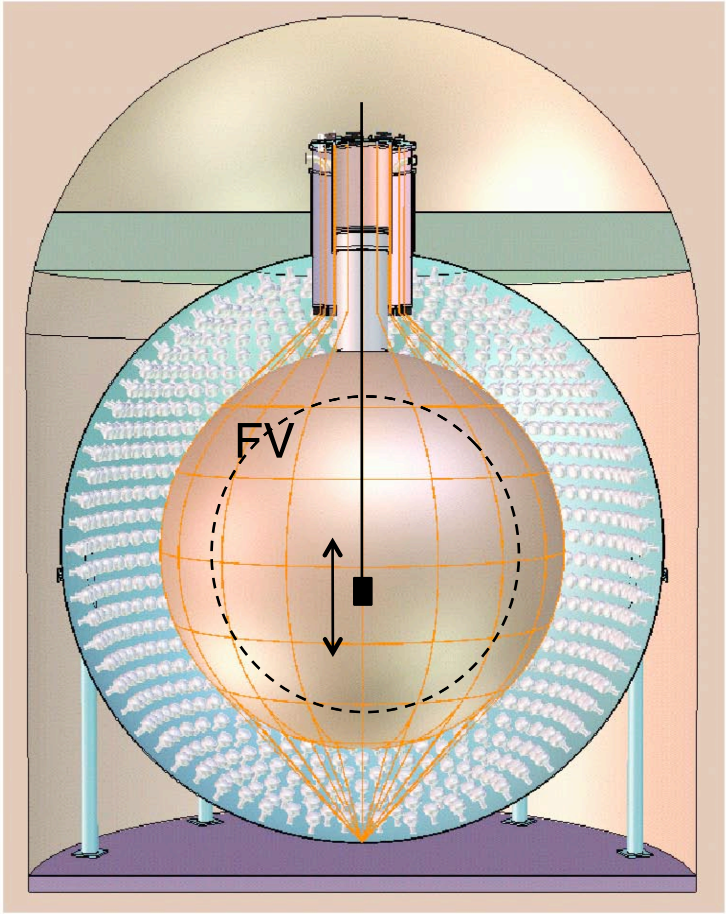
KamLAND "Z-axis Calibration"

Routine Calibration Sources

^{68}Ge	e^+	2 x 0.511 MeV
^{65}Zn	γ	1.116 MeV
^{60}Co	γ	2.506 MeV
^{241}Am^{9}Be		γ, n 2.22, 4.44, and 7.65 MeV
^{203}Hg		
^{137}Cs		

Laser and LEDs



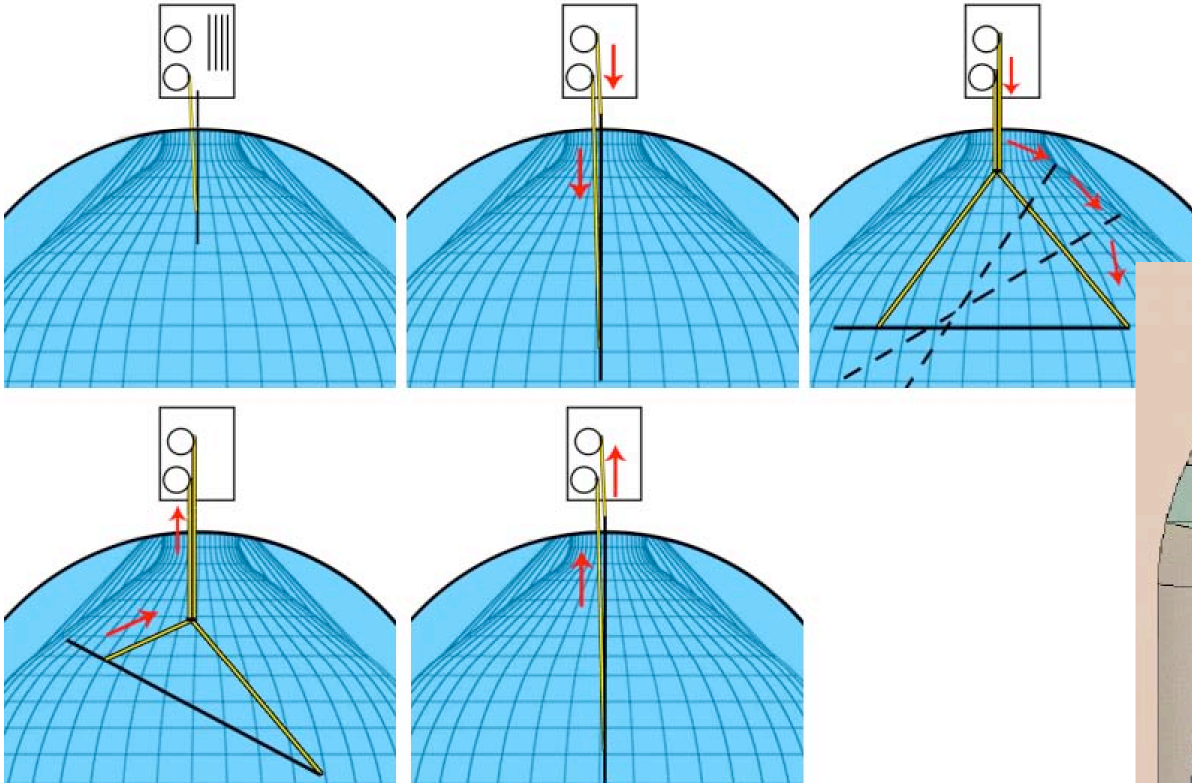


new: also used a ^{210}Po^{13}C source to study the ^{13}C(α,n)^{16}O reaction and to calibrate MC code

energy resolution $\sigma = 6.5\% /\sqrt{E}$
vertex reconstruction resolution $\sim 12\text{cm}/\sqrt{E}$

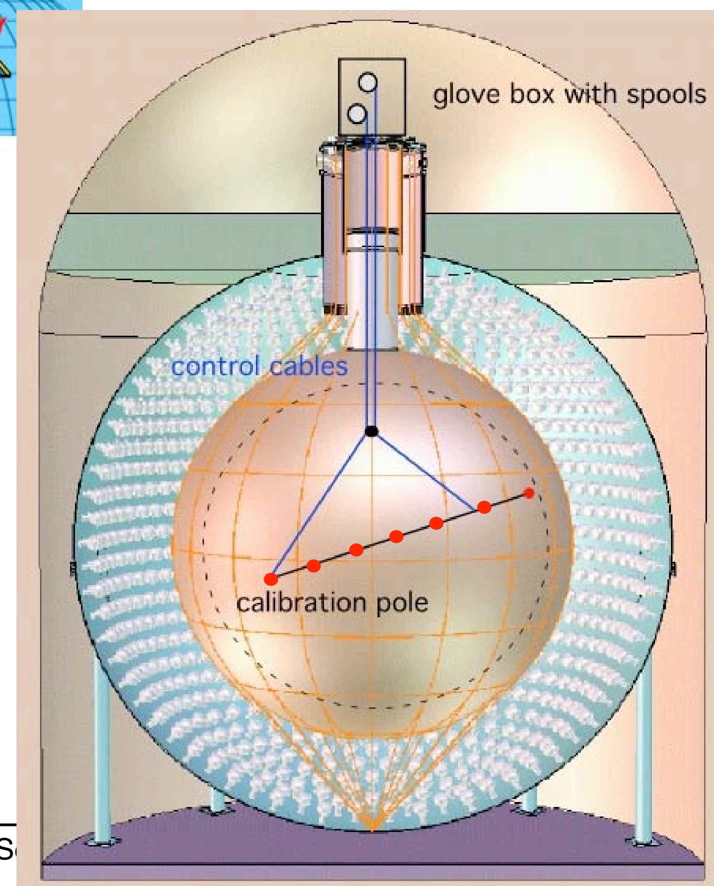
KamLAND 4π “Full-Volume” Calibration

Calibration throughout entire detector volume



Calibration volume: R < 5.5 m

$\Delta R_{FV} = 5$ cm $\rightarrow \Delta V = 2.7\%$
$\Delta R_{FV} = 2$ cm $\rightarrow \Delta V = 1.1\%$

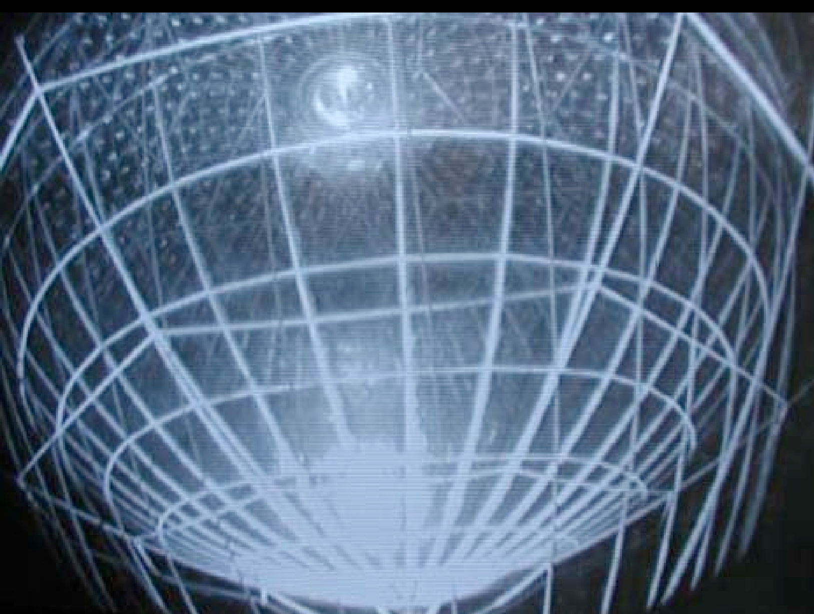


Can study position dependence of detector response:

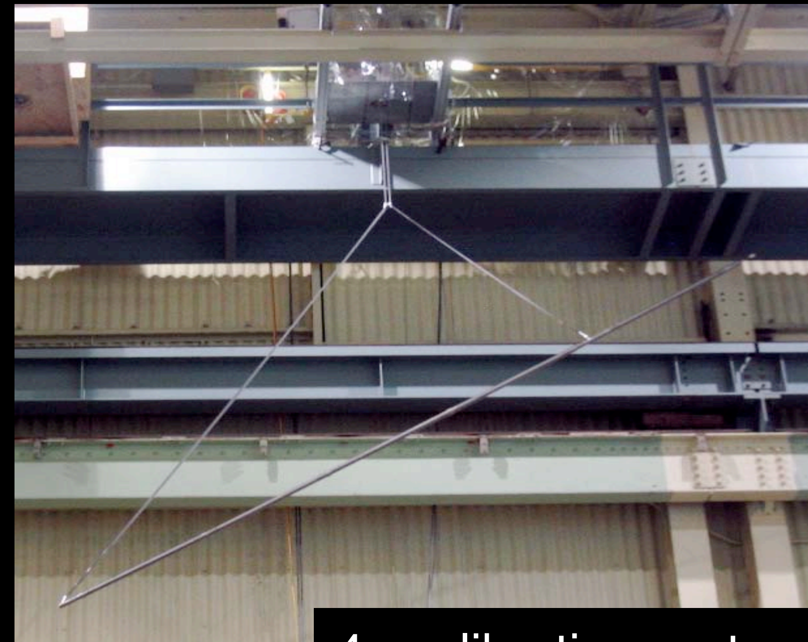
Event energy	$E(r,\theta,\phi)$
Vertex reconstruction	$R_{fit}(r,\theta,\phi)$

4π Full-Volume Calibration

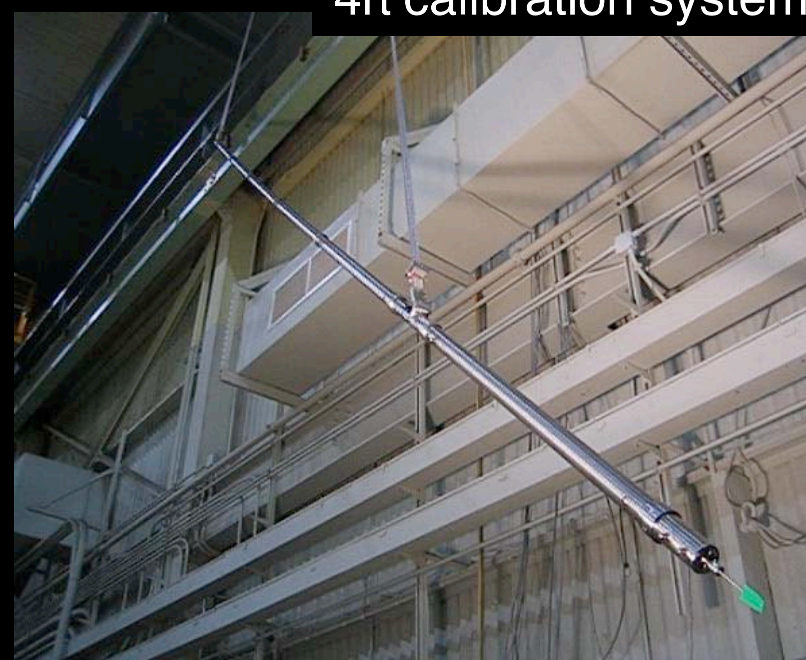
calibration deck

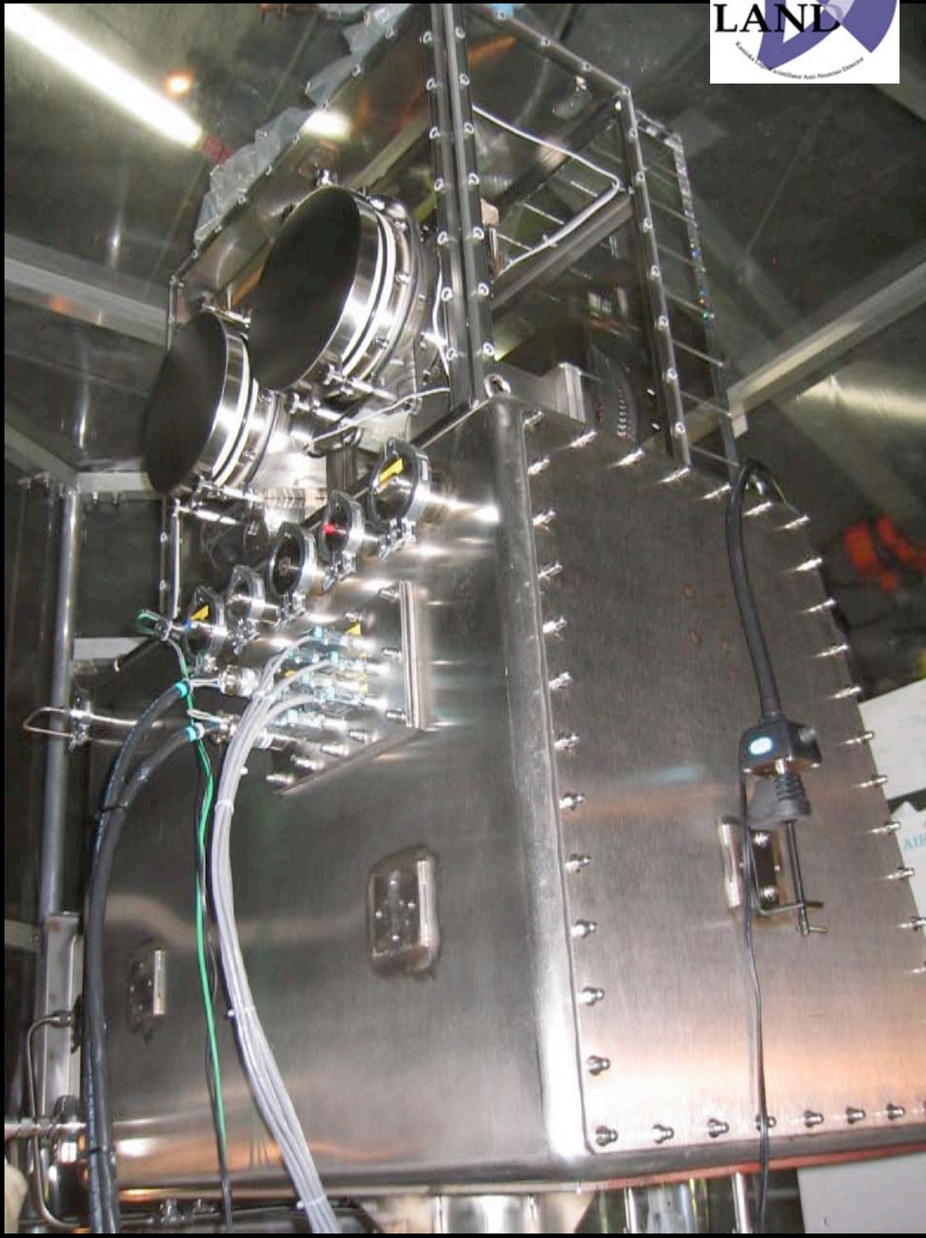


inside view of KamLAND detector

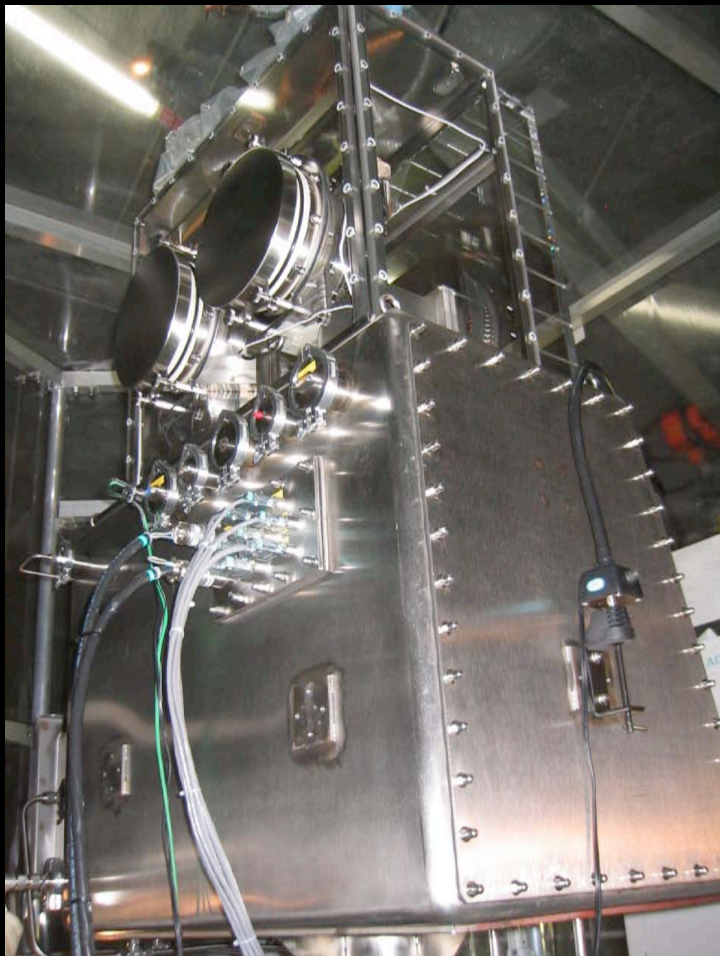


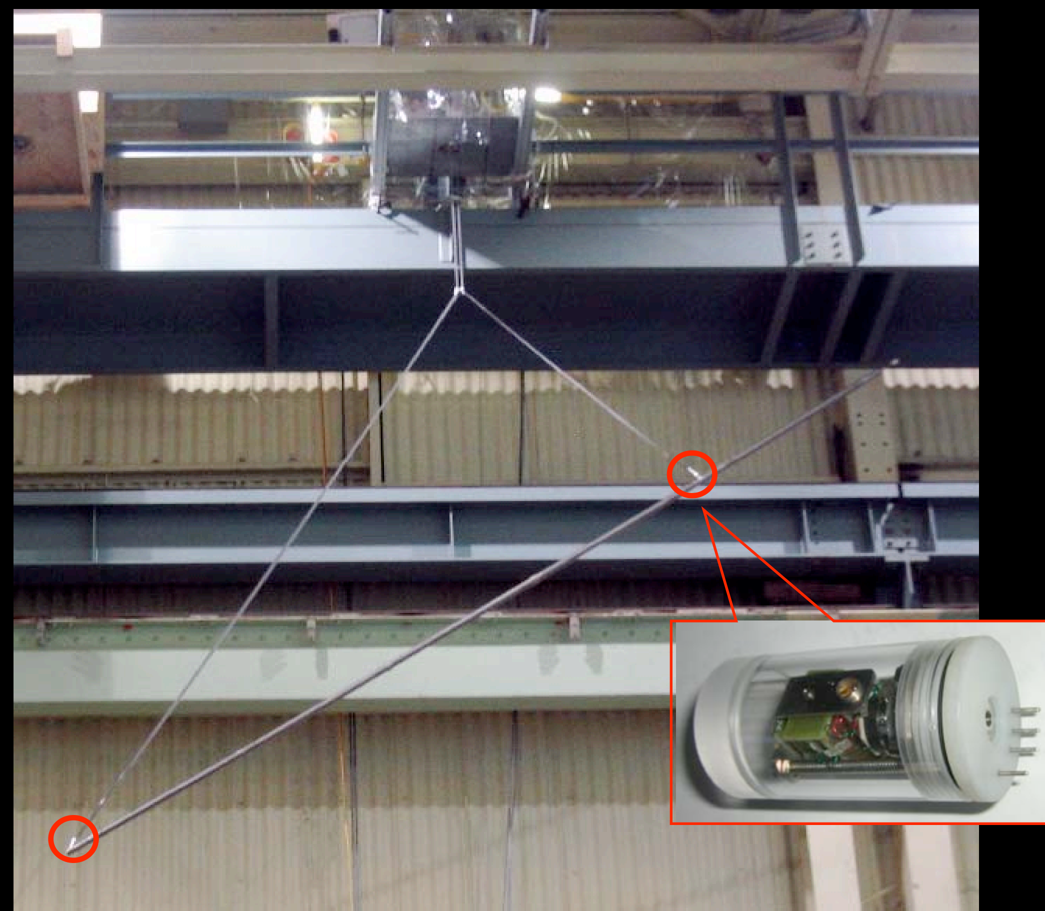
4π calibration system





KamLAND Calibration Upgrade

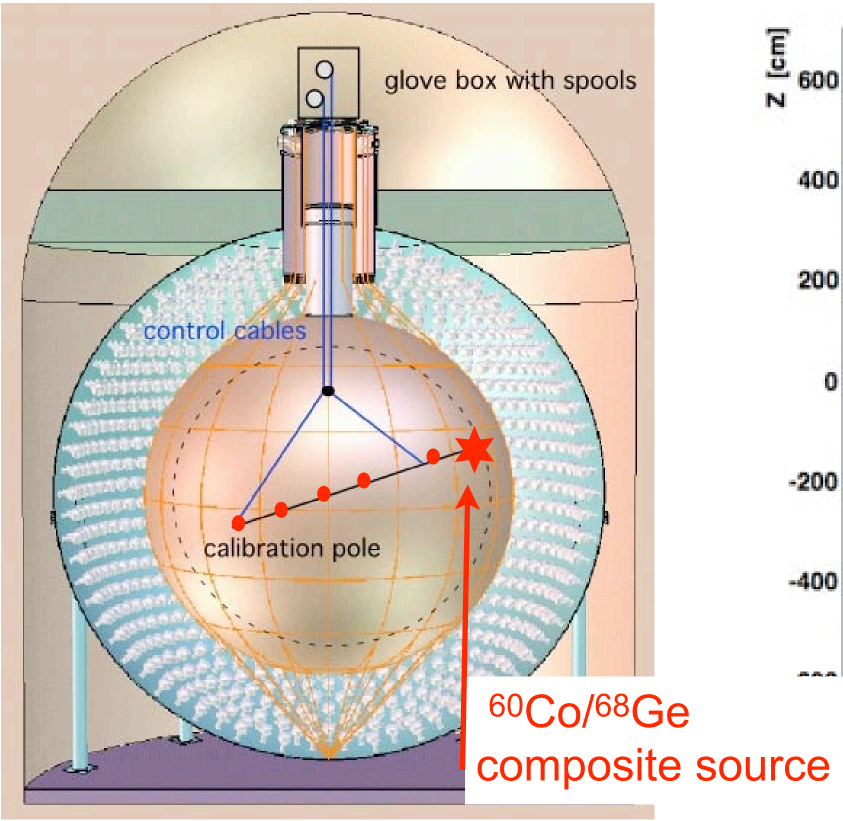




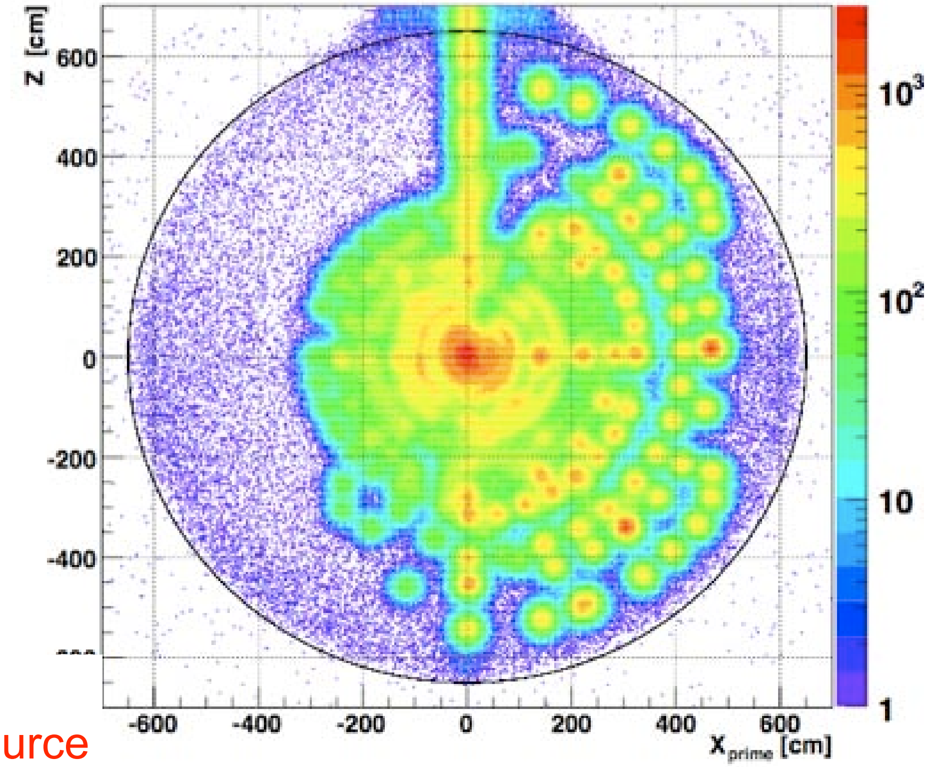
Installation completed in
December 2005

4π Full-Volume Calibration of KamLAND

Artist's conception of 4π system



Vertex distribution of $^{60}Co/^{68}Ge$ composite source in 4π calibration runs.



X_{prime} axis is defined by azimuth angle of the source.

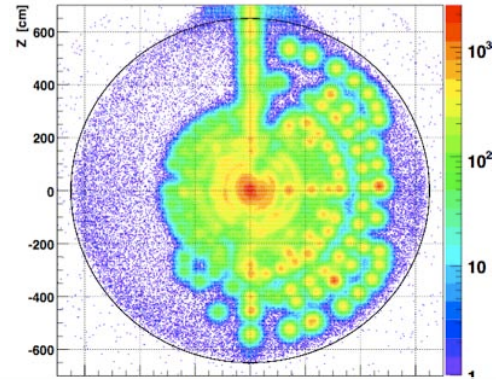
Source positions are used determined to check the radial dependence of vertex and energy biases.

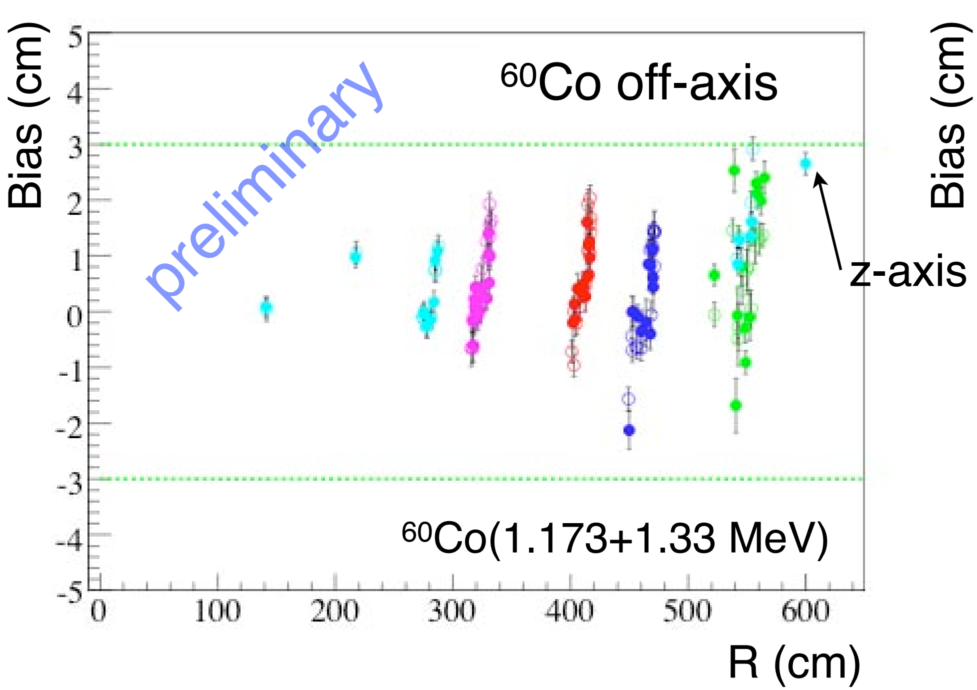
Radial Dependence of Vertex Reconstruction Biases

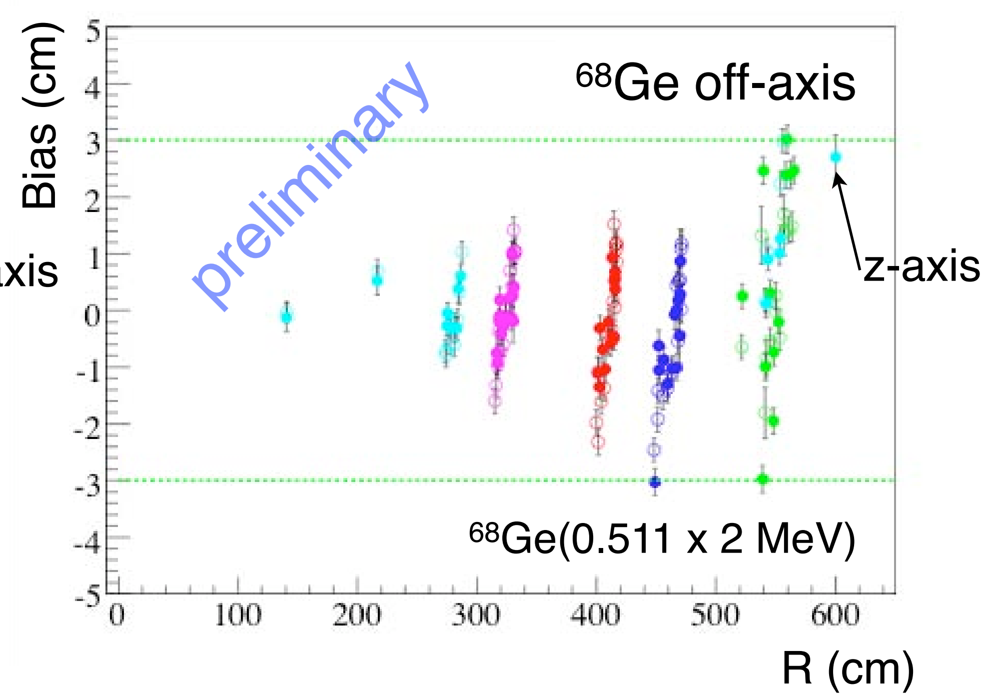
source location radii R ~ 2.8, 3.3, 4.1, 4.6, 5.5m

→ for the range shown below all biases are within 3cm

spallation products are used to extend fiducial volume from 5.5 to 6m

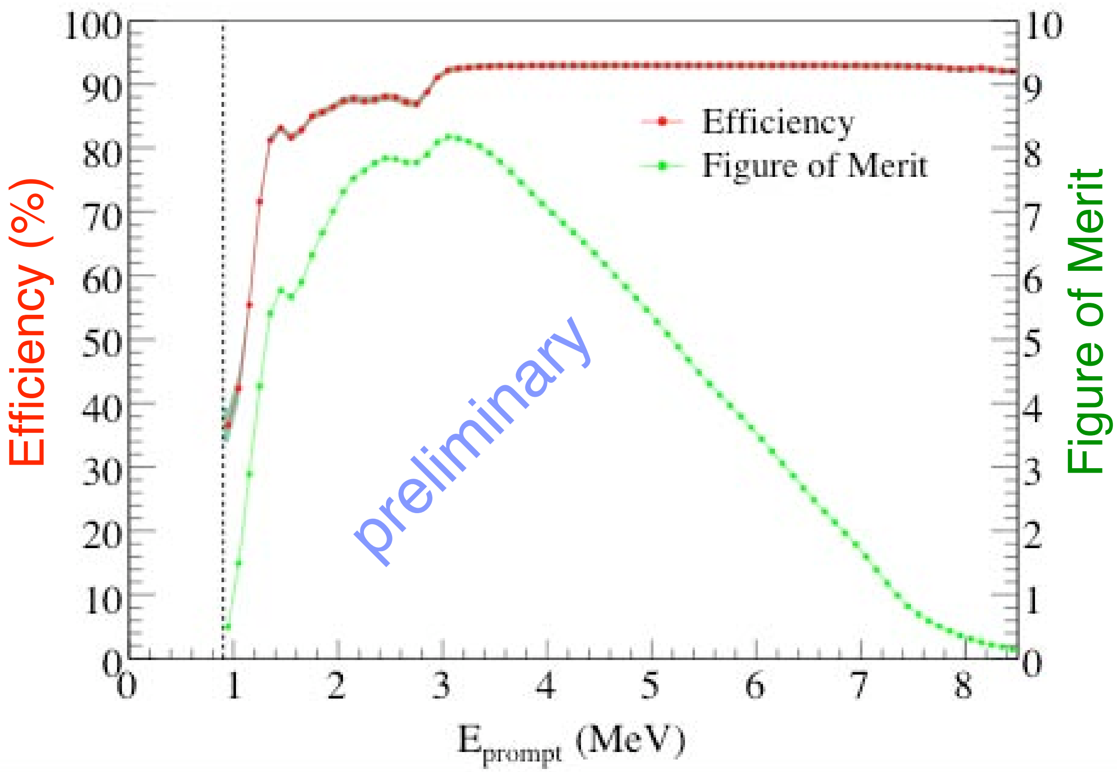






KamLAND Event Selection and Figure-of-Merit

1. construct PDF for accidental coincidence events $f_{acc}(E_{\rm d}, \Delta R, \Delta T, R_{\rm p}, R_{\rm d})$
   - pair coincidence events in a delayed-coincidence window between 10ms and 20s



2. construct PDF of $\overline{\nu}_e$ signal using GEANT4

$$f_{\overline{\nu}_e}(E_{\rm d}, \Delta R, \Delta T, R_{\rm p}, R_{\rm d})$$

3. introduce discriminator

$$L(E_{\rm p}) = \frac{f_{\overline{\nu}_e}}{f_{\overline{\nu}_e} + f_{acc}}$$

4. maximize figure of merit

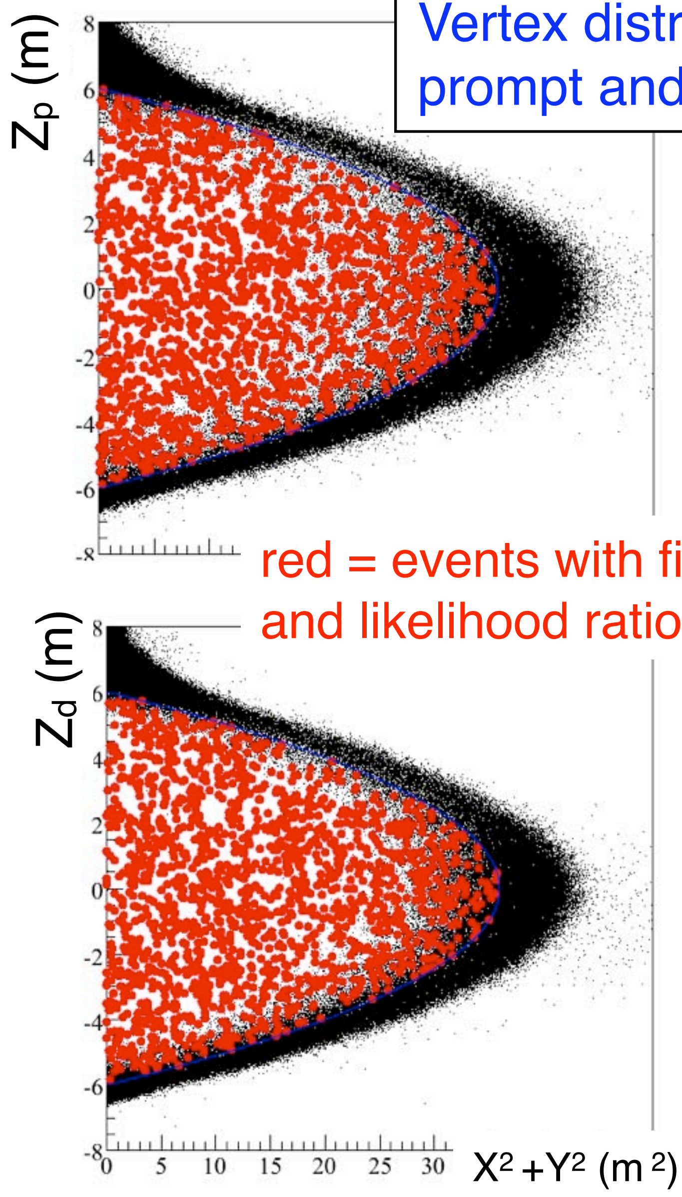
$$\frac{S}{\sqrt{S+B_{acc}}}$$

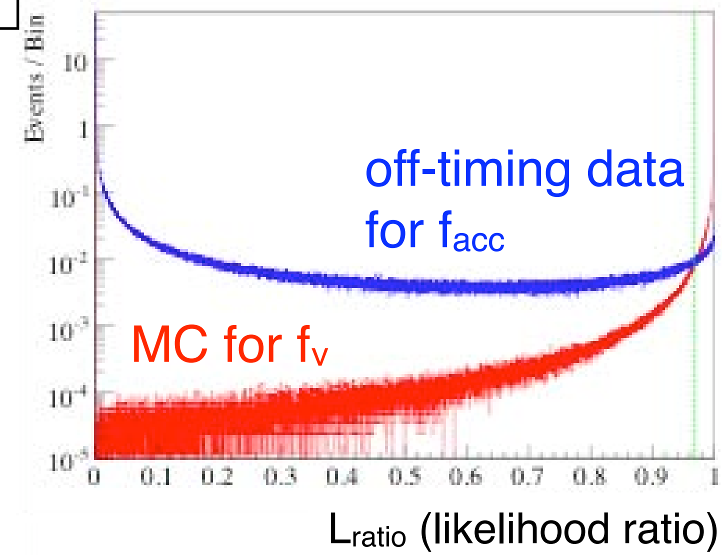
shaded region indicates the 1 sigma error band caused by the uncertainties in the likelihood selection

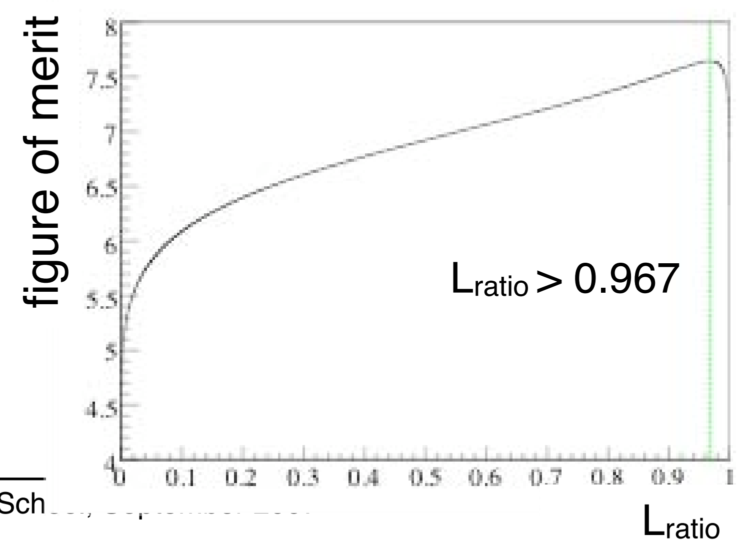
KamLAND 2007 Data Set

Vertex distribution of prompt and delayed events

red = events with fiducial volume and likelihood ratio cut

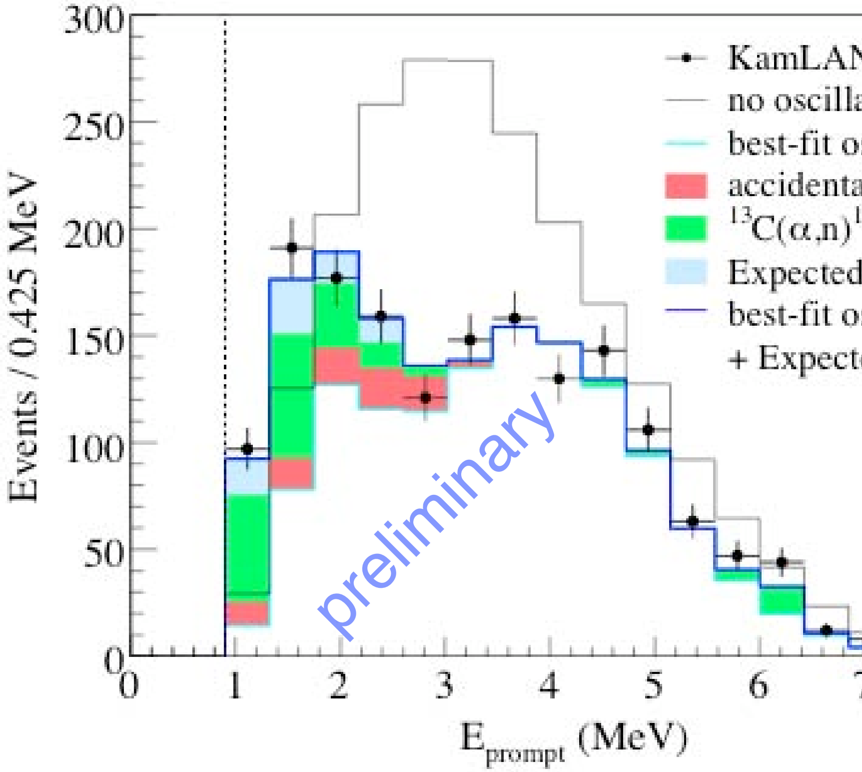






KamLAND 2007 Data

Prompt event energy spectrum for $\bar{\nu}_e$



number of events

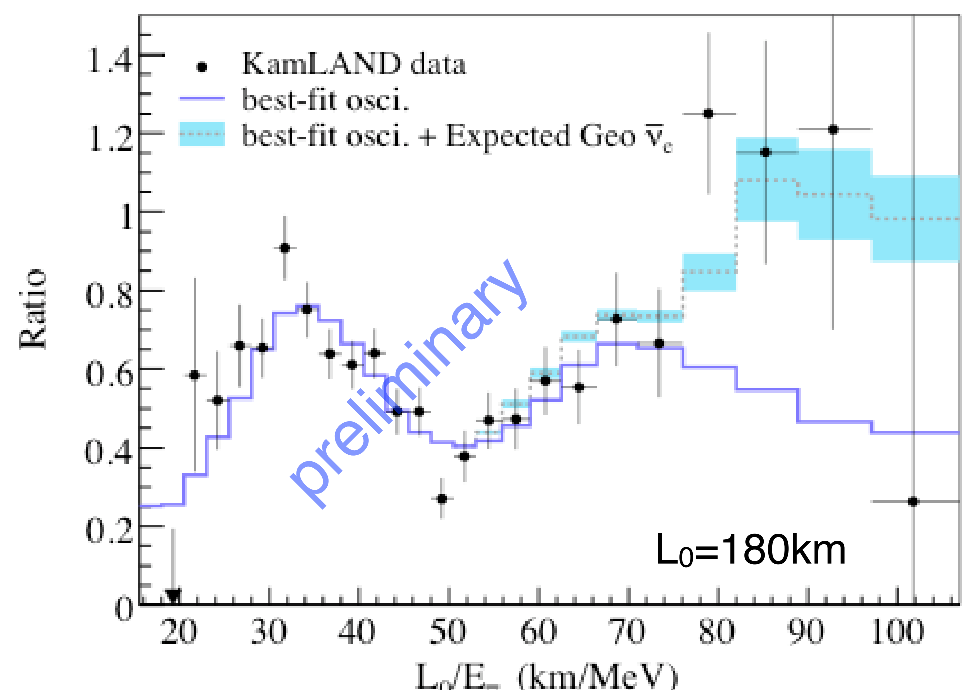
expected (no-oscillation): 2178

observed: 1609

bkgd: 276

significance of disappearance

(with 2.6 MeV threshold): 8.5σ



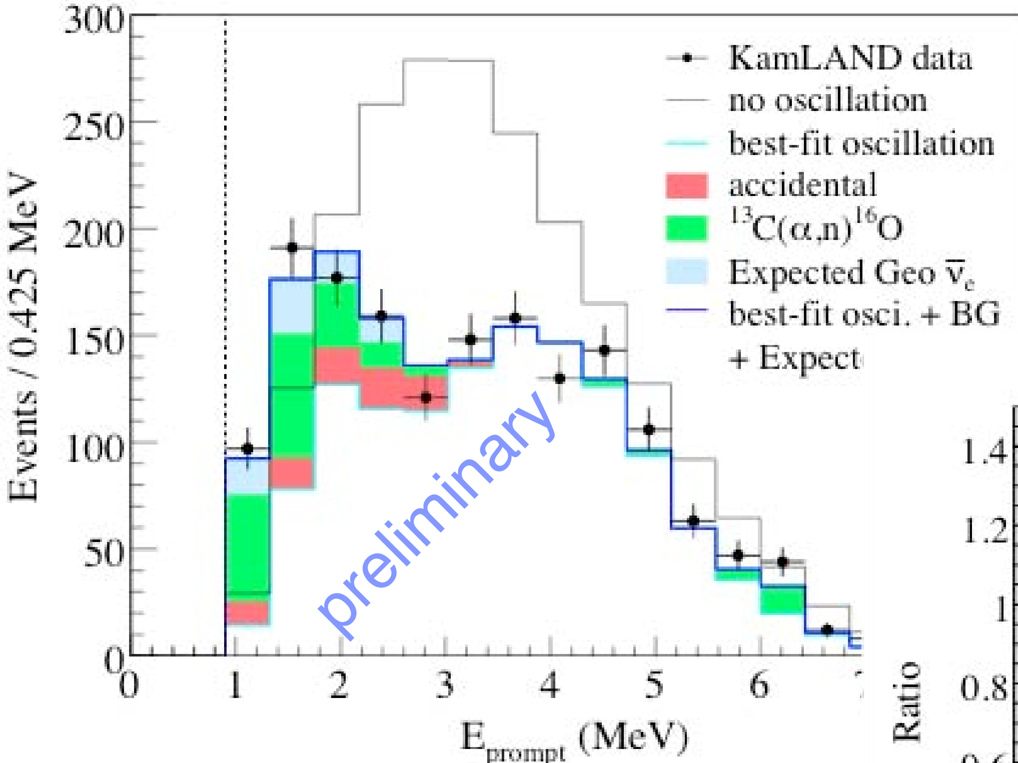
no-osc χ^2/ndf=63.9/17

significance of distortion: 5.2σ

best-fit χ^2/ndf=20.96/16 (18% C.L.)

KamLAND 2007 Data

Prompt event energy spectrum for $\overline{\nu}_e$



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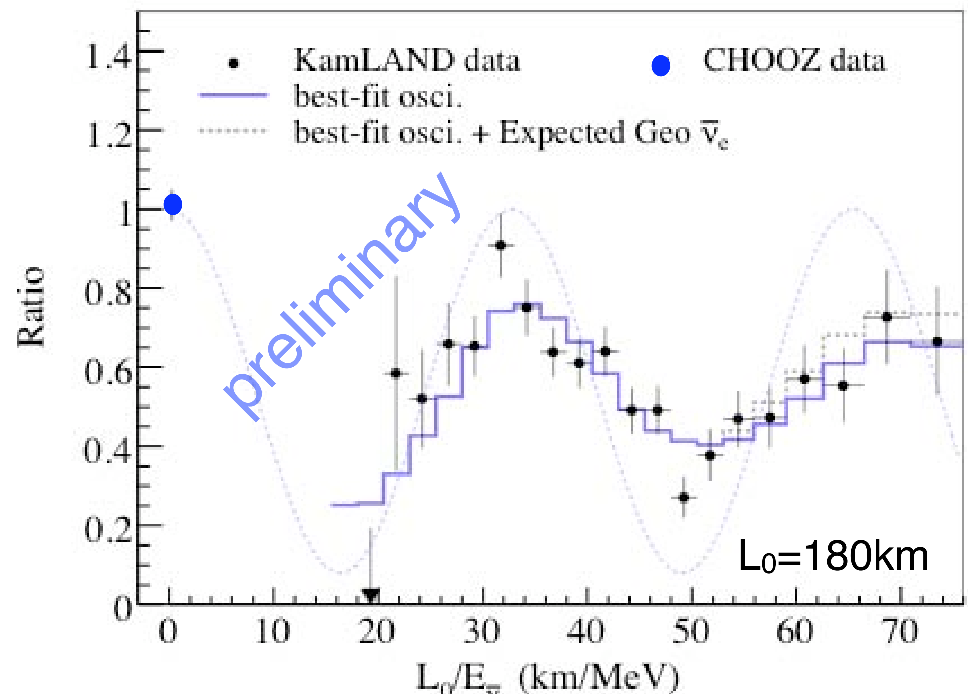

no-osc χ^2/ndf=63.9/17

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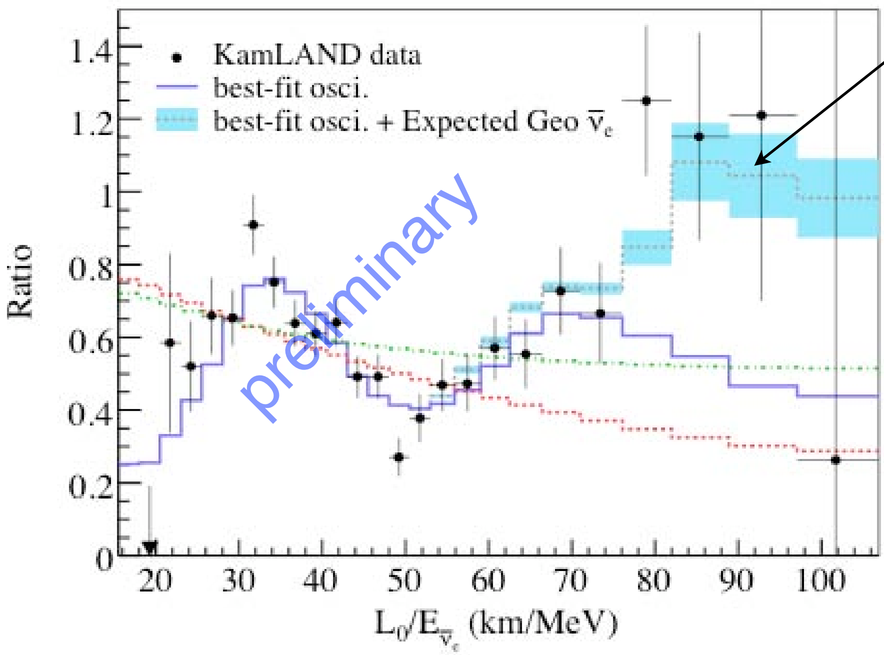
best-fit χ^2/ndf=20.96/16 (18% C.L.)

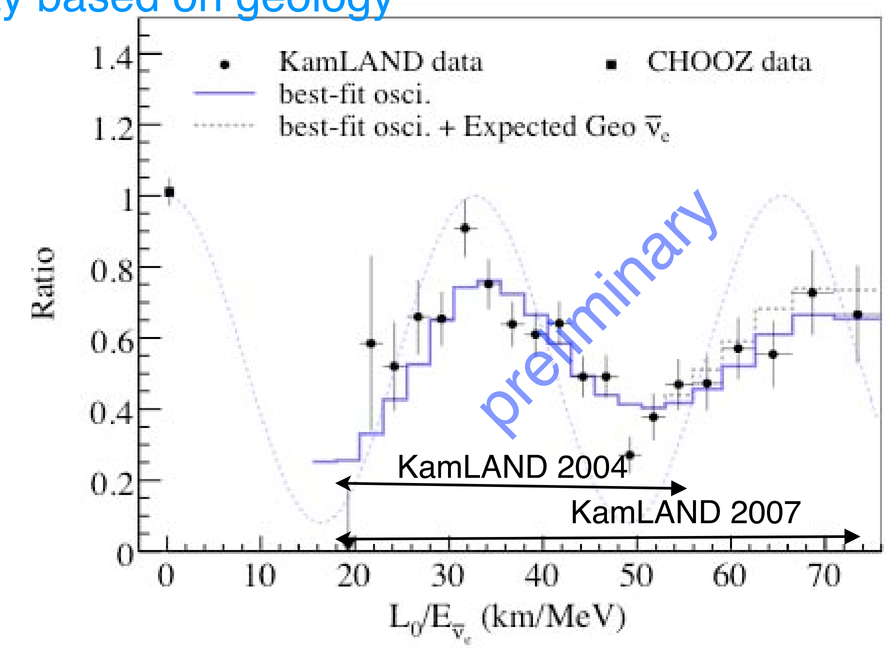
KamLAND 2007 Data

Ratio of the observed anti-neutrino spectrum to the expectation for no-oscillation as a function of L_0/E.

$$\text{Ratio} = \frac{\text{(Observed-Bkg)}}{\text{No-Oscillation Expectation}} \text{ without geo-neutrinos}$$

20% geo-neutrino flux uncertainty based on geology



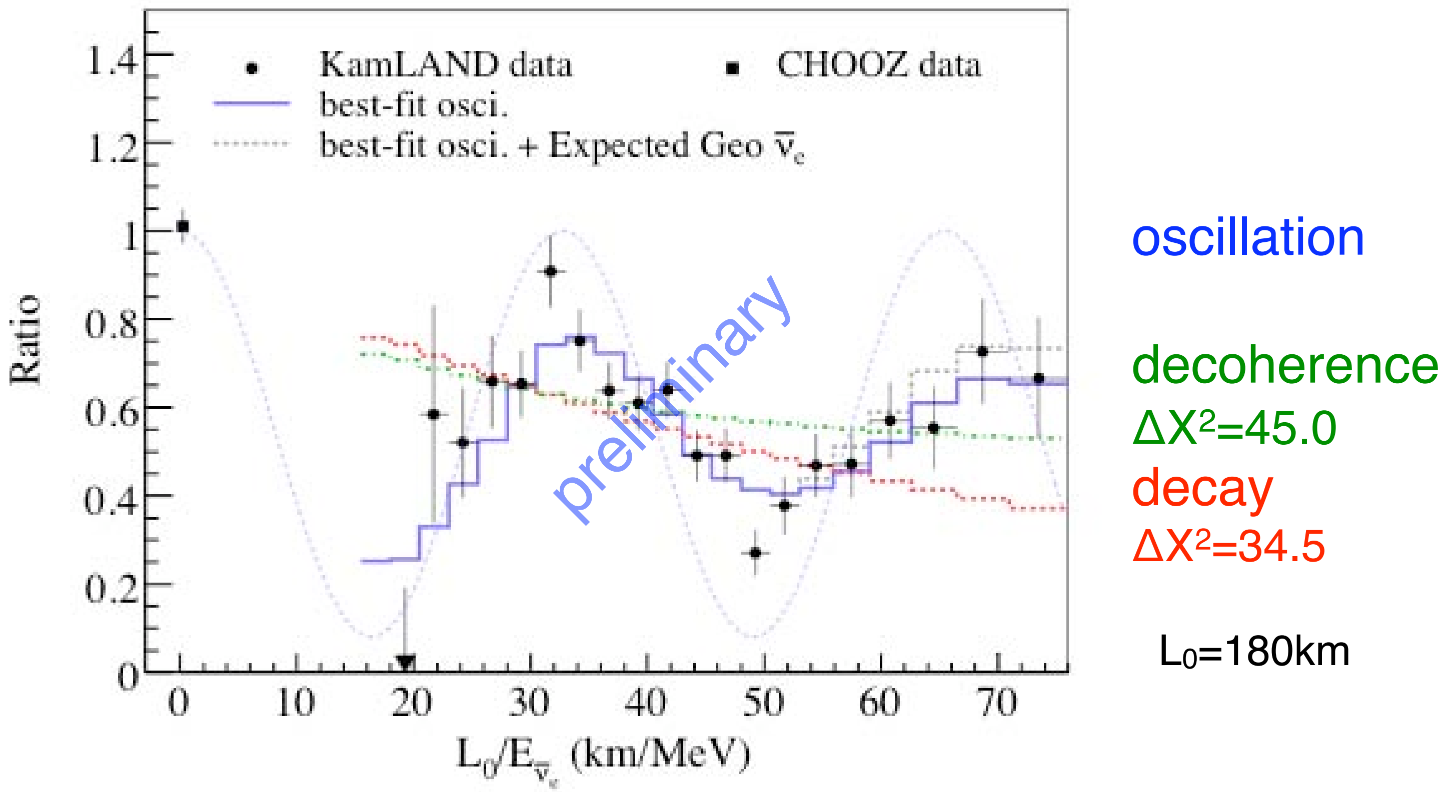


L/E plot shows oscillatory behavior

KamLAND 2007 Data

Alternative Hypotheses

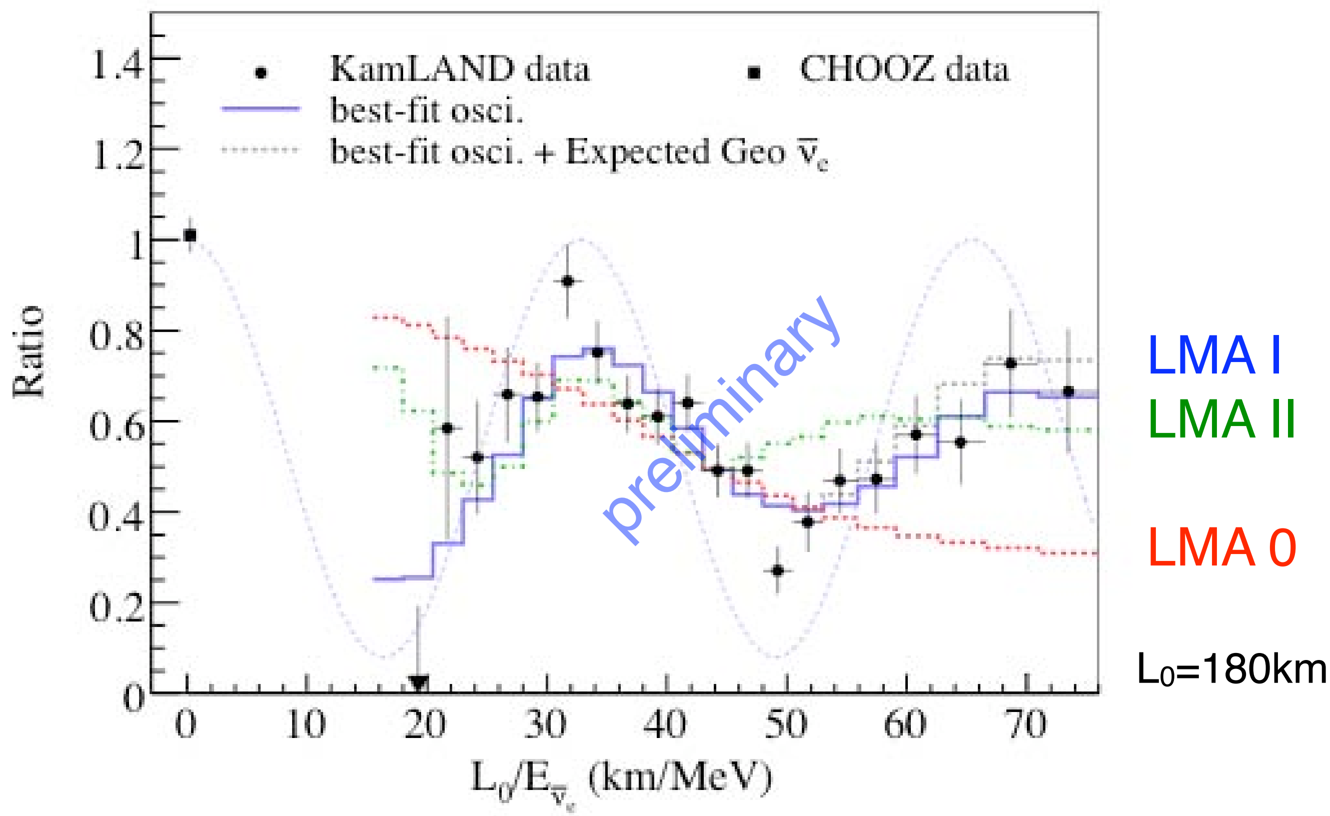
The solid, dash and dot-dash curves show the expectation for the best-fit oscillation, best-fit decay, and best-fit decoherence.



best fit = neutrino oscillation

KamLAND 2007 Data

Alternative Oscillation Wavelength



The solid, dash and dot-dash curves show the expectation for the best-fit LMA I, LMA 0, and LMA II.

LMA 0 and LMA II are disvafored at > 4σ

Systematic Uncertainties and Backgrounds

Systematic Uncertainties

Principal change from 2004 → 2007:
fiducial volume 4.7% → 1.8%

- energy threshold, cut eff.
  → energy scale, L-selection

Detector related		Reactor related	
Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
Energy scale	1.5	Reactor power	2.1
L-selection eff.	0.6	Fuel composition	<1.0
OD veto	0.2	Long-lived nuclei	0.3
Cross section	0.2	Time lag	0.01
Livetime	0.03		
Sum of syst. uncert.:	2.4		3.4

preliminary

total systematics: 4.1%

Background	Contribution
Accidentals	80.5 ± 0.1
^{9}Li/^{8}He	13.6 ± 1.0
Fast neutron & Atmosperic ν	<9.0
^{13}C(α,n)^{16}O G.S.	157.2 ± 17.3
^{13}C(α,n)^{16}O ^{12}C(n,nγ)^{12}C (4.4 MeV γ)	6.1 ± 0.7
^{13}C(α,n)^{16}O 1st exc. state (6.05 MeV e^+e^-)	15.2 ± 3.5
^{13}C(α,n)^{16}O 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total excluding geo-neutrinos	276.1 ± 23.5

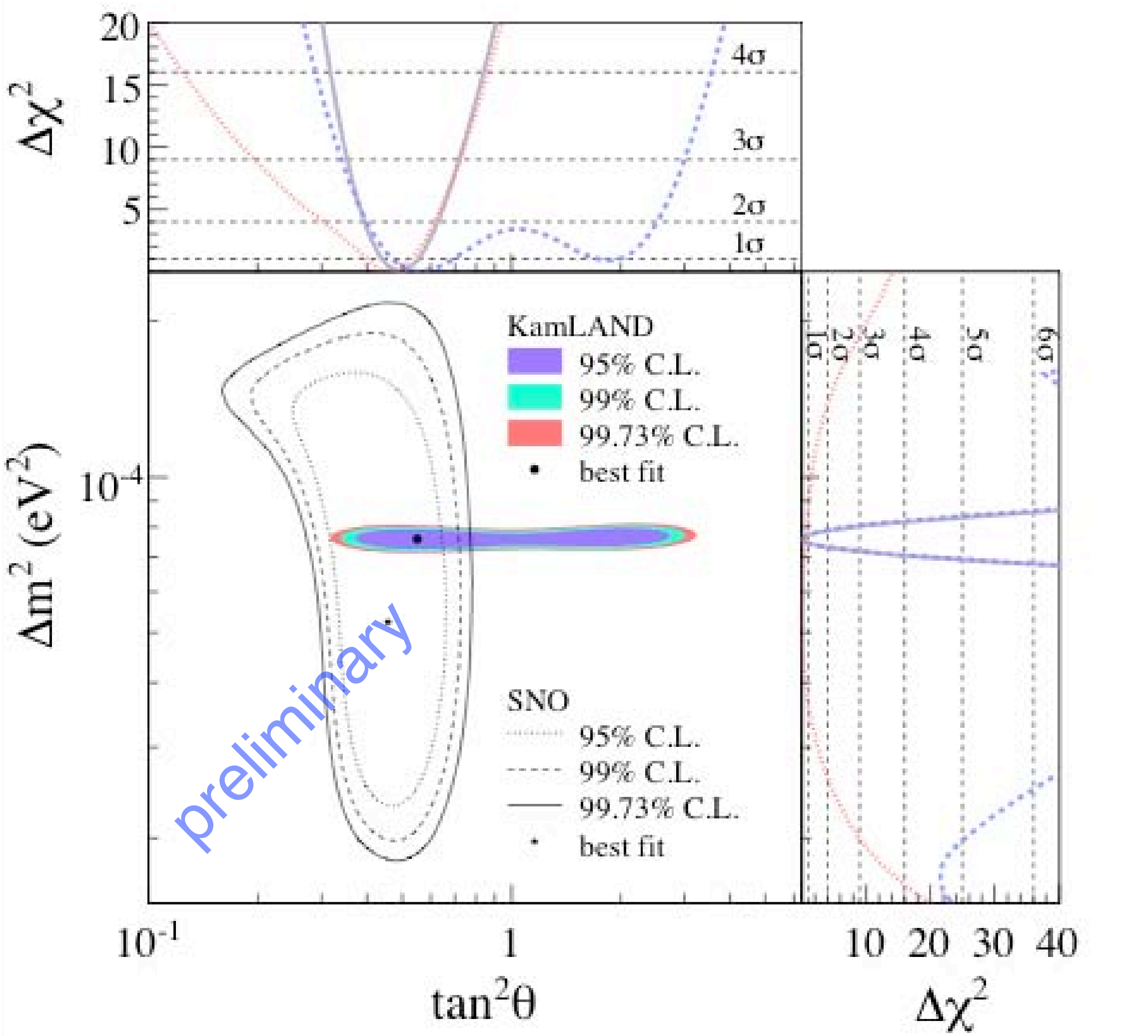
preliminary

estimated backgrounds in the data set

(number of events)

KamLAND Oscillation Parameters

Rate-Shape-Time Analysis



KamLAND only

$\tan^2\Theta = 0.56\ ^{+0.14}_{-0.09}$

$\Delta m^2 = 7.58\ ^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$

KamLAND+SNO

$\tan^2\Theta = 0.49\ ^{+0.14}_{-0.09}$

$\Delta m^2 = 7.59\ ^{+0.20}_{-0.21} \times 10^{-5}\ eV^2$

Ref: SNO contour from http://www.sno.phy.queensu.ca/

KamLAND Collaboration

RCNS, Tohoku University

University of Alabama

UC Berkeley/LBNL

California Institute of Technology

Colorado State University

Drexel University

University of Hawaii

Kansas State University

Louisiana State University

Stanford University

University of Tennessee

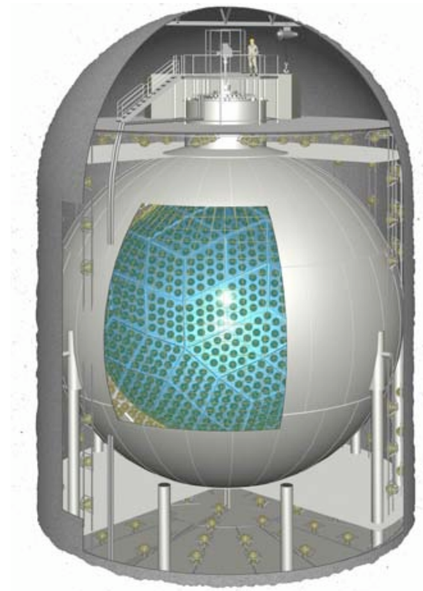
UNC/NCSU/TUNL

IN2P3-CNRS and University of Bordeaux

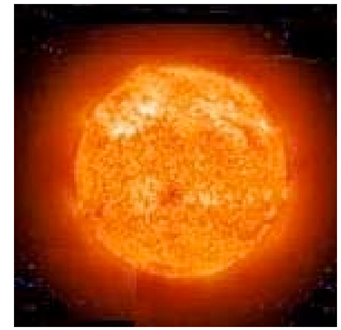
University of Wisconsin

KamLAND (Anti-)Neutrino Program

Reactor Antineutrinos

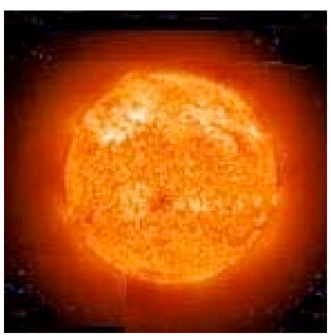


Solar ^{7}Be Neutrinos



$\nu_e + e^- \rightarrow \nu_e + e^-$

Anti-Neutrinos from the Sun

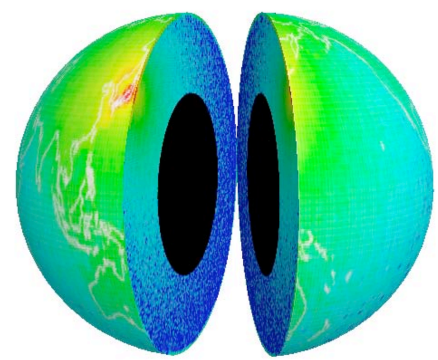


PRL 92:071301 (2004)

Other Physics Studies

- Oscillation analysis of $\bar{\nu}_e$ spectrum
- Nucleon decay studies
- Supernova watch
- Muon spallation

Terrestrial Antineutrinos

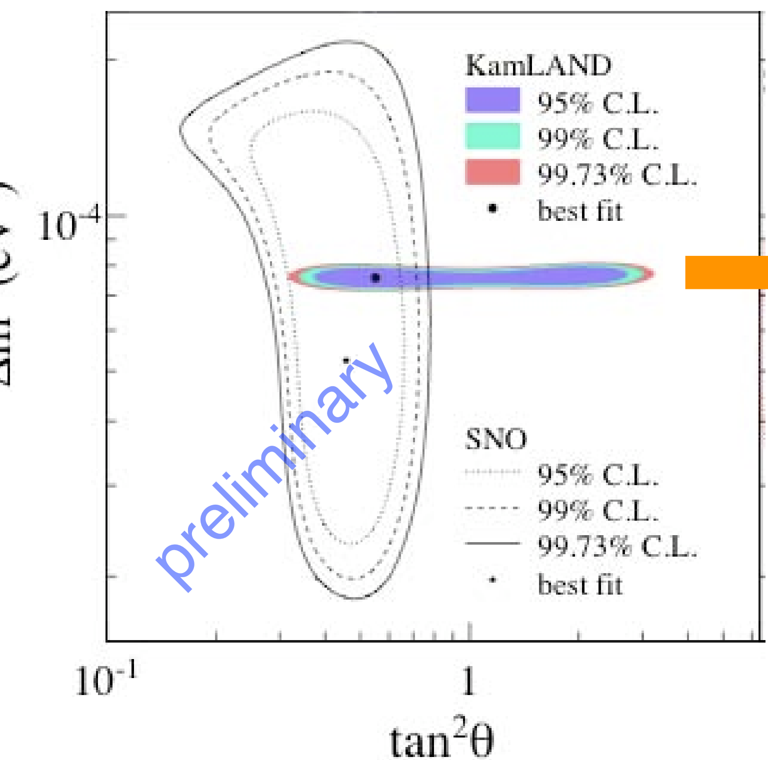


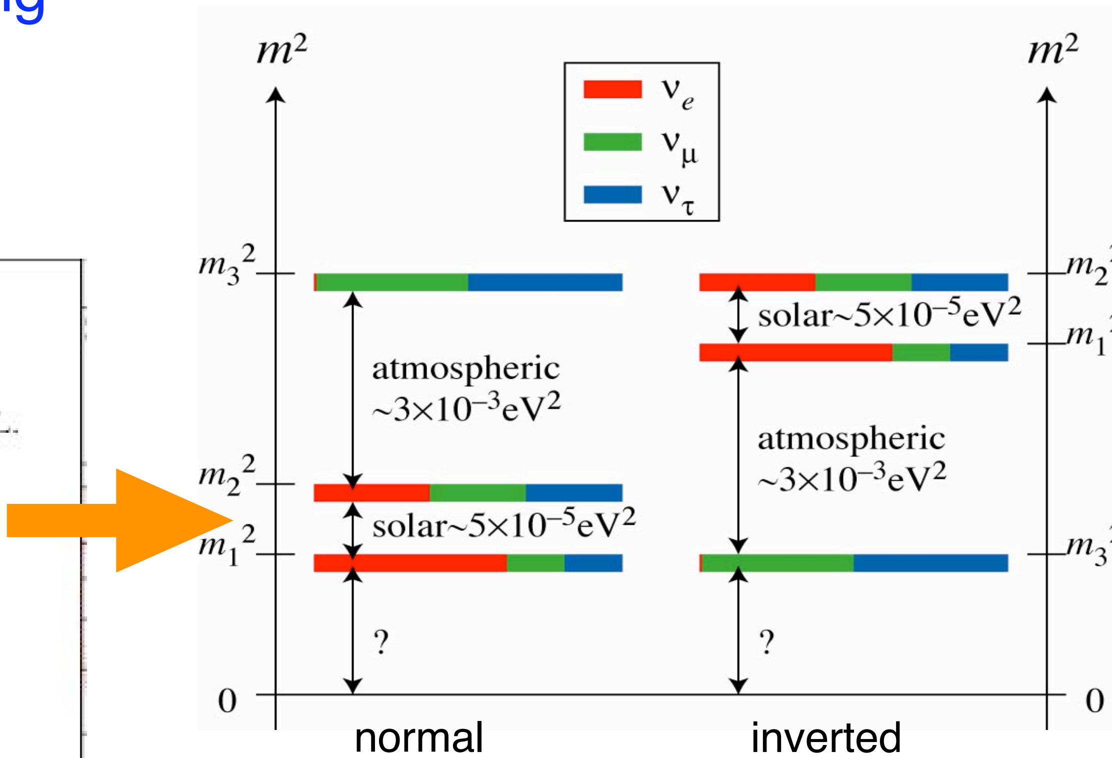
Nature 436, 499-503 (28 July 2005)

Precision Measurement of Oscillation Parameters

Neutrino Mass Splitting

KamLAND 2007



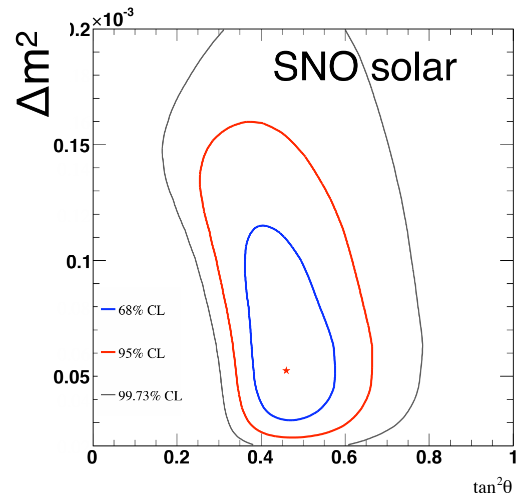


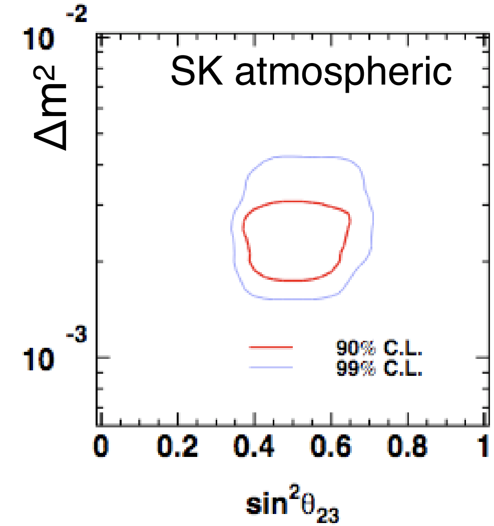
- KamLAND provides best measurement of Δm^2_{12} to 2.8% precision

- KamLAND improves the definition of $\tan^2\theta$ when combined with the SNO data (assumption of CPT invariance)

Precision Measurement of Oscillation Parameters

Neutrino 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

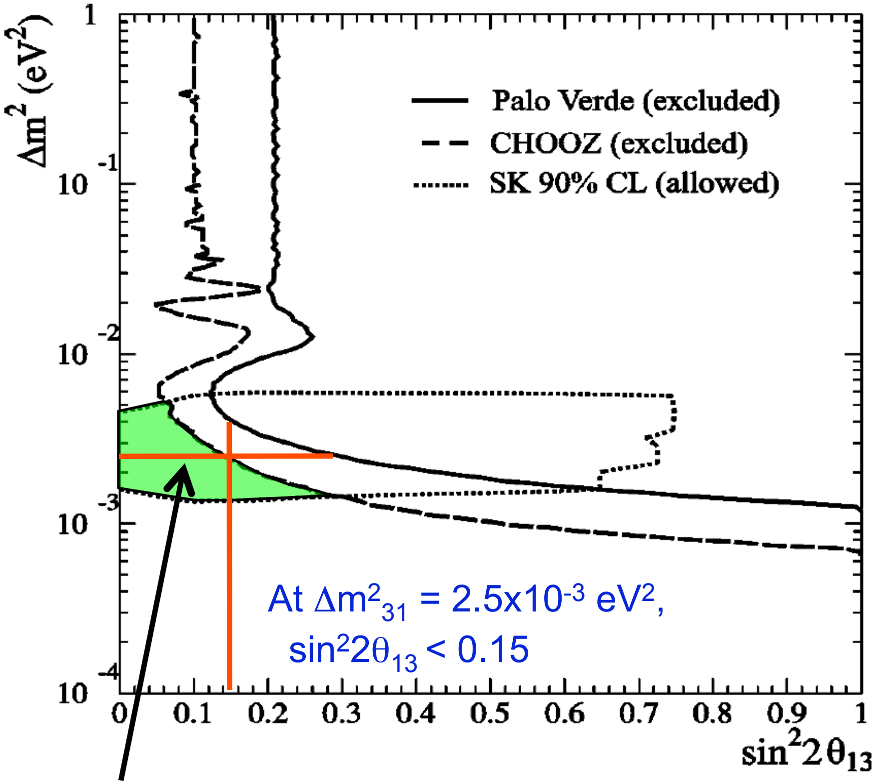
Maki, Nakagawa, Sakata, Pontecorvo

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

atmospheric, K2K	reactor and accelerator	SNO, solar SK, KamLAND	$0\nu\beta\beta$
$\theta_{23} = \sim 45°$	$\theta_{13} = ?$	$\theta_{12} \sim 32°$	

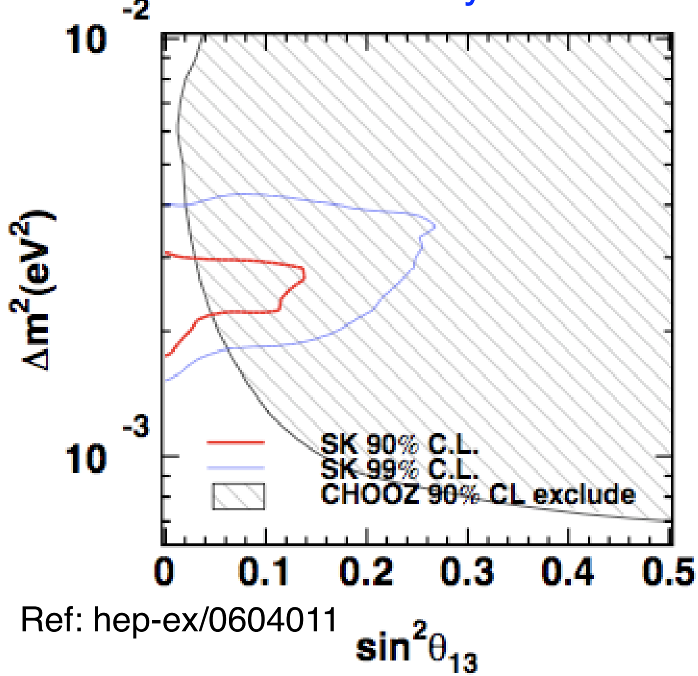
Current Knowledge of θ_{13}

Direct search at Chooz and Palo Verde



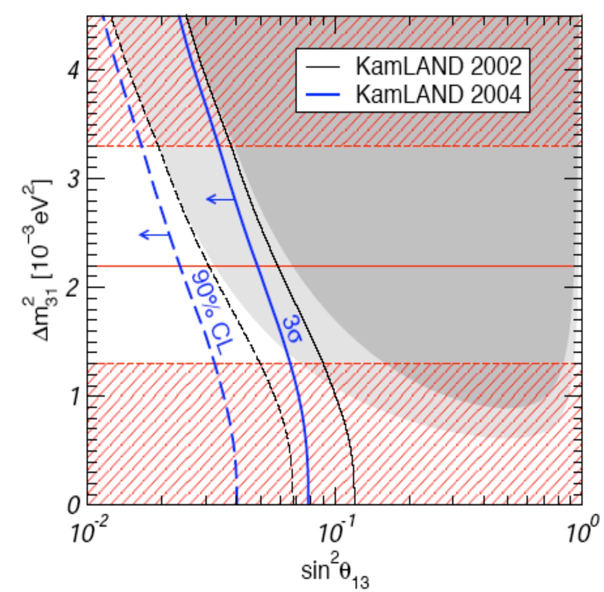
allowed region

SK 3-flavor oscillation analysis



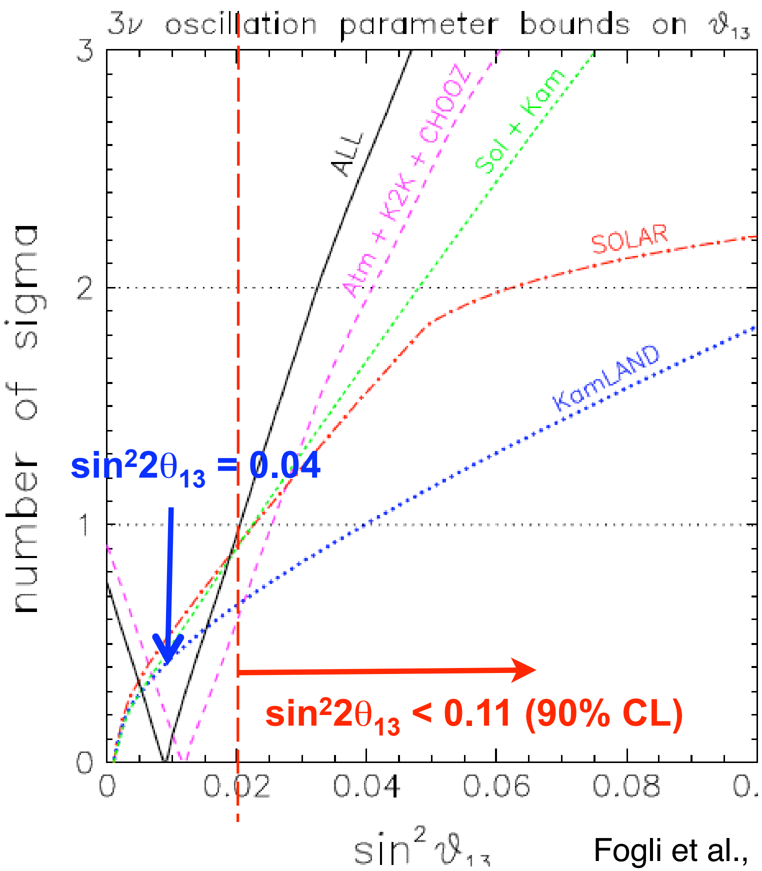
Ref: hep-ex/0604011

Global analysis of solar+other data



Experiment & Theory

Global Fit



Fogli et al., hep-ph/0506083

$$\begin{aligned} \sin^2\theta_{13} &= 0.9^{+2.3}_{-0.9} \times 10^{-2} \,, \\ \delta m^2 &= 7.92\,(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2 \,, \\ \sin^2\theta_{12} &= 0.314\,(1^{+0.18}_{-0.15}) \,, \\ \Delta m^2 &= 2.4\,(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2 \,, \\ \sin^2\theta_{23} &= 0.44\,(1^{+0.41}_{-0.22}) \,. \end{aligned}$$

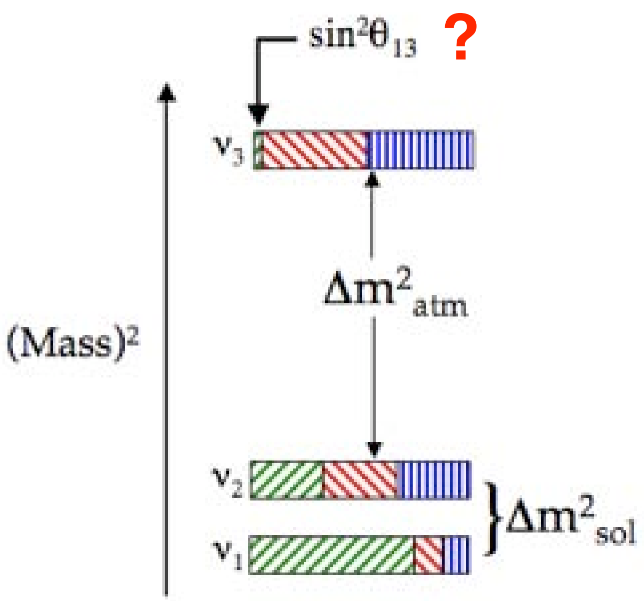
Theory

Model(s)	Refs.	$\sin^2 2\theta_{13}$
Minimal SO(10)	[22]	0.13
Orbifold SO(10)	[23]	0.04
SO(10) + Flavor symmetry	[24]	$1.2 \cdot 10^{-6}$
	[25]	$7.8 \cdot 10^{-4}$
	[26–28]	0.01 .. 0.04
	[29–31]	0.09 .. 0.18
SO(10) + Texture	[32]	$4 \cdot 10^{-4}$ .. 0.01
	[33]	0.04
$SU(2)_L \times SU(2)_R \times SU(4)_c$	[34]	0.09
Flavor symmetries	[35–37]	0
	[38–40]	$\lesssim 0.004$
	[41–43]	10^{-4} .. 0.02
	[40, 44–47]	0.04 .. 0.15
Textures	[48]	$4 \cdot 10^{-4}$ .. 0.01
	[49–52]	0.03 .. 0.15
3 × 2 see-saw	[53]	0.04
	[54] (n.h.)	0.02
	(i.h.)	$> 1.6 \cdot 10^{-4}$
Anarchy	[55]	> 0.04
Renormalization group enhancement	[56]	0.03 .. 0.04
M-Theory model	[57]	10^{-4}

we don't know θ_{13} ...

Ref: FNAL proton driver report, hep-ex/0509019

θ_{13} and Particle Physics



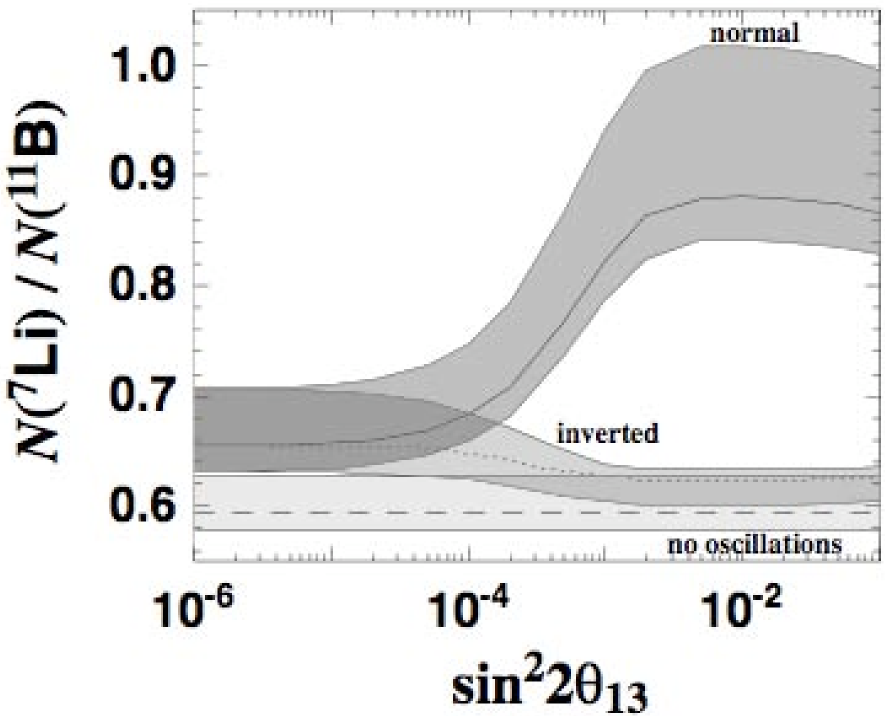
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

Is there μ–τ symmetry in neutrino mixing?

Can we search for leptonic ~~CP~~?

θ_{13} and Nuclear Astrophysics

neutrino oscillation effects on supernova light-element synthesis



astr-ph/0606042

understanding the origin of matter (vs antimatter)

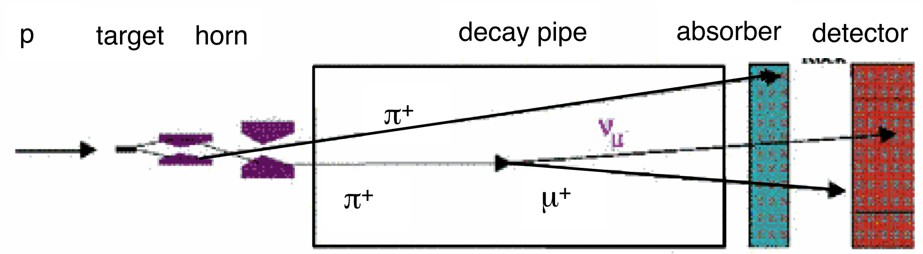
Leptogenesis

Fukugita, Yanagida, 1986

- Out-of-equilibrium L-violating decays of heavy Majorana neutrinos leading to L asymmetry but leaving B unchanged. B_L-L_L is conserved.

Measuring θ_{13}

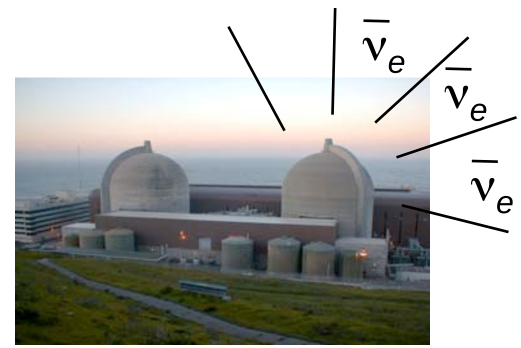
Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13},δ_{CP}
- baseline *O(100 -1000 km)*, matter effects present

Method 2: Reactor Neutrino Oscillation Experiment



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

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km)*, no matter effects

θ_{13} from Reactor and Accelerator Experiments

reactor ($\bar{\nu}_e$ disappearance)

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

- Clean measurement of θ_{13}
- No matter effects

mass hierarchy

CP violation

matter

accelerator (ν_e appearance)

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31} [\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta] \sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta] \sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

Resolving the θ_{23} Parameter Ambiguity

Super-K, T2K ν_μ disappearance $\theta_{23} = 45 \pm 9°$

NOvA, T2K ν_e appearance experiments measure $P[\nu_\mu \rightarrow \nu_e]$

$P(\nu_\mu \rightarrow \nu_e) =$

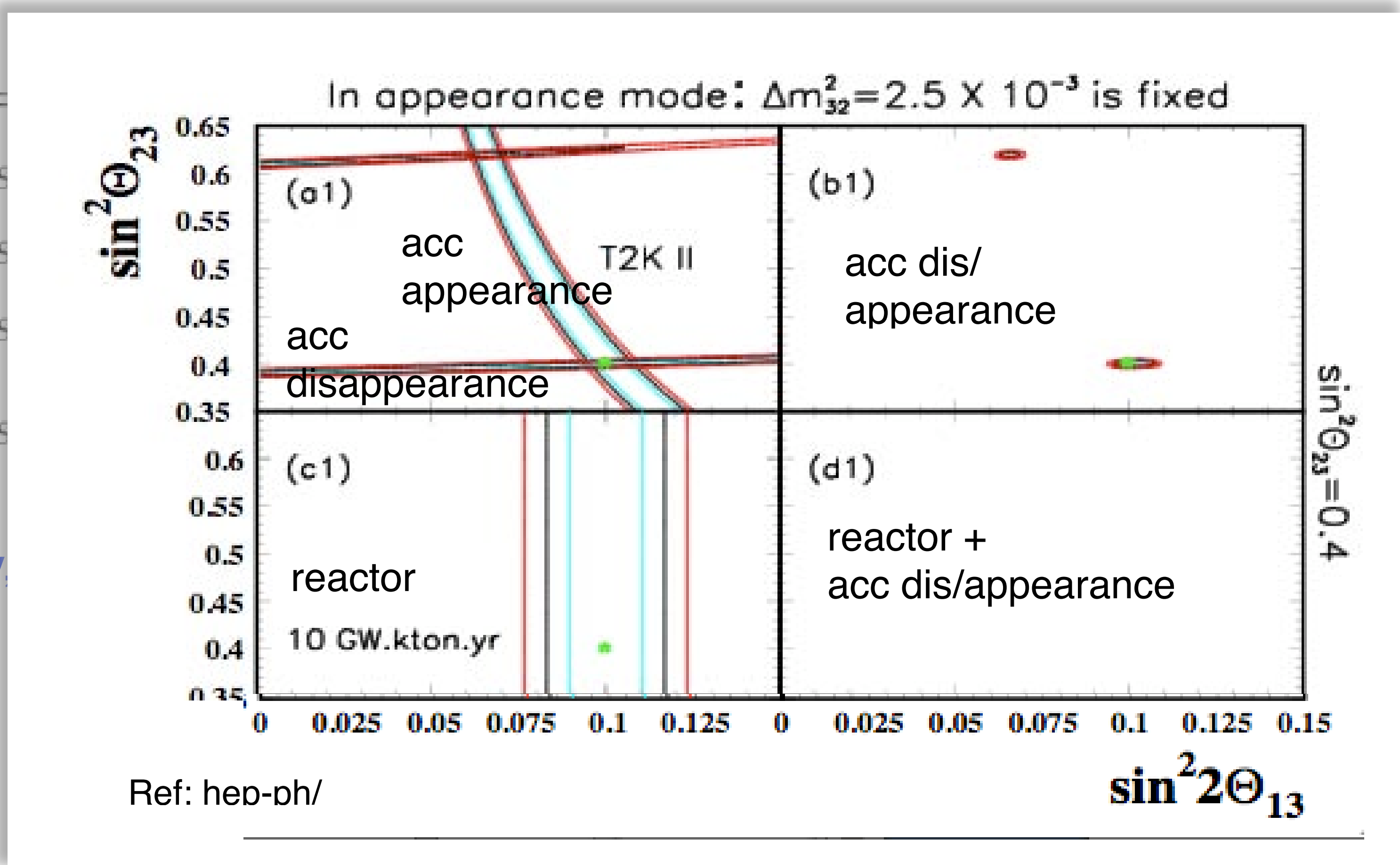
$+ 8c_{13}^2 s$

$- 8c_{13}^2 s$

$+ 4c_{13}^2 s$

$- 8c_{13}^2 s$

Approximately,



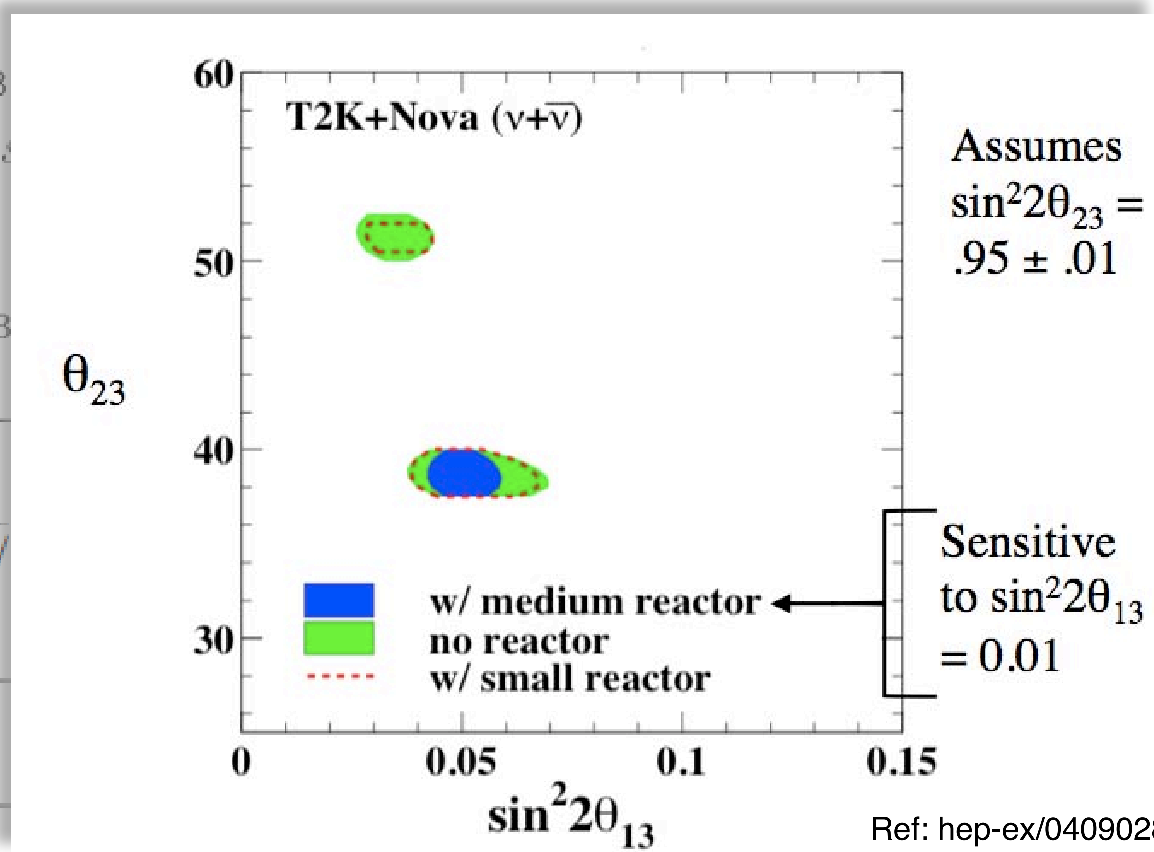
Ref: hep-ph/

Resolving the θ_{23} Parameter Ambiguity

Super-K, T2K ν_μ disappearance $\theta_{23} = 45 \pm 9°$

NOvA, T2K ν_e appearance experiments measure $P[\nu_\mu \rightarrow \nu_e]$

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 \ldots$$
$$+ 8c_{13}^2 s_{13} s_{23} c_{23} \ldots$$
$$- 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \ldots$$
$$+ 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 \ldots$$
$$- 8c_{13}^2 s_{13}^2 s_{23}^2 (1 \ldots$$



Approximately, $\Delta m_{21}^2 / \ldots$

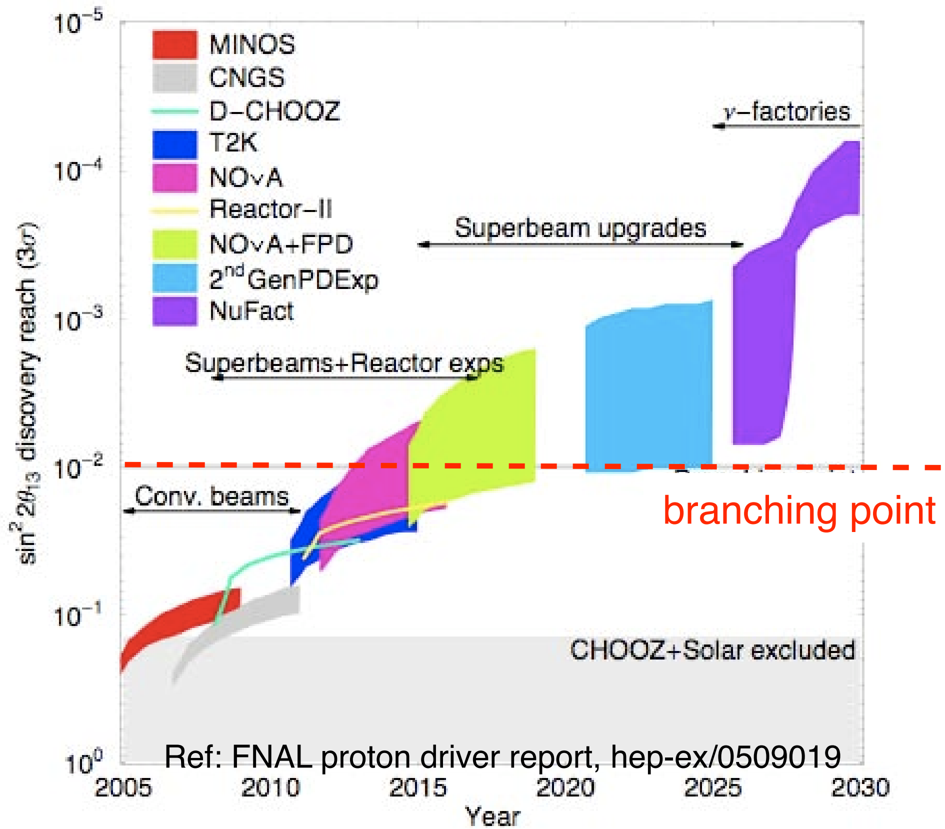
$P(\nu_\mu \ldots$

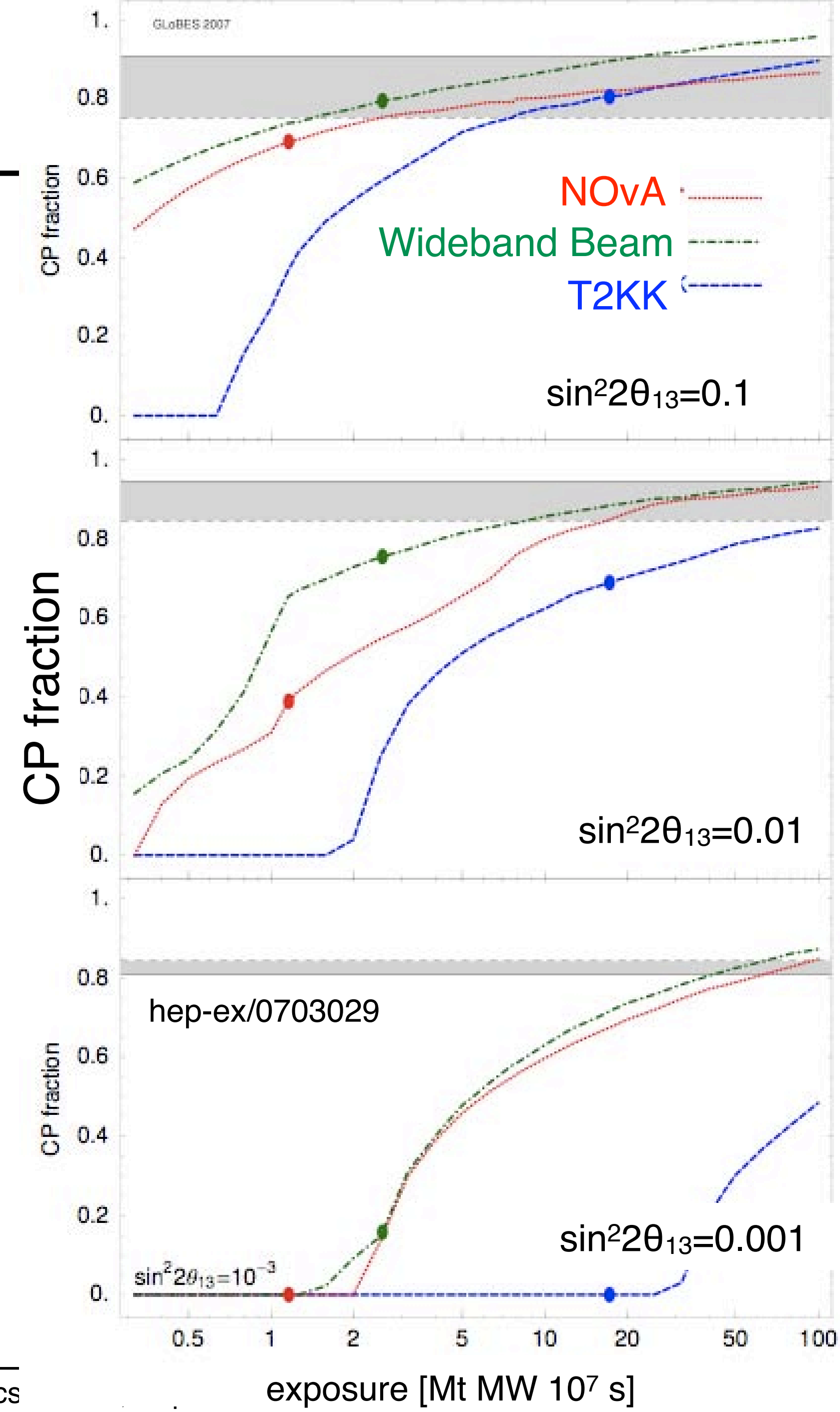
$P(\nu_\mu \ldots$

Ref: hep-ex/0409028

Branch Point: $\sin^2 2\theta_{13} < 0.01$

for techniques to measure CP violation ...





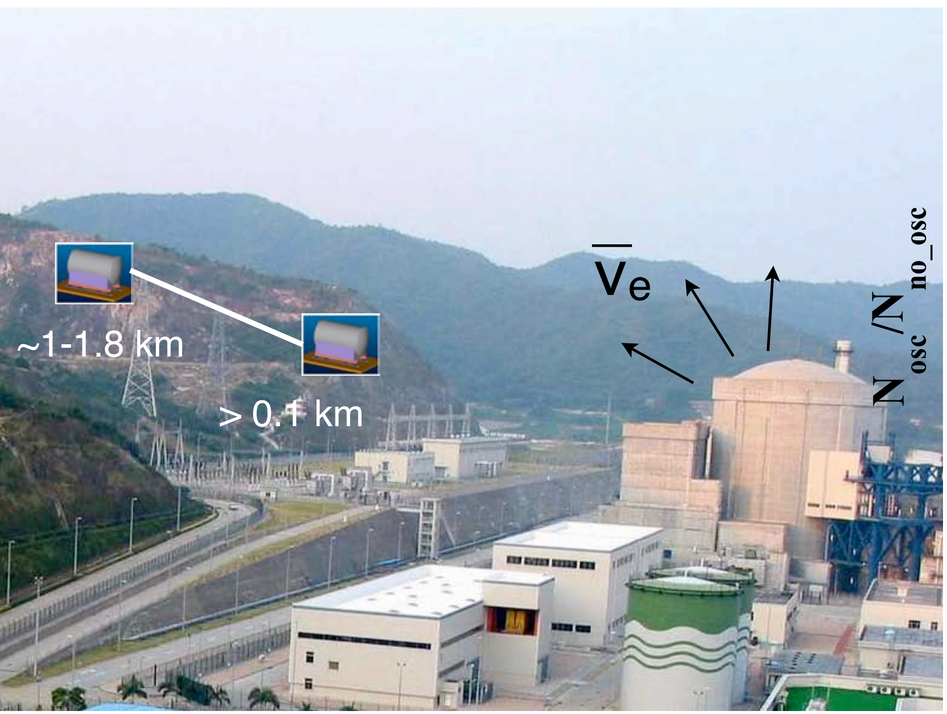
High-Precision Measurement of θ_{13} with Reactor Antineutrinos

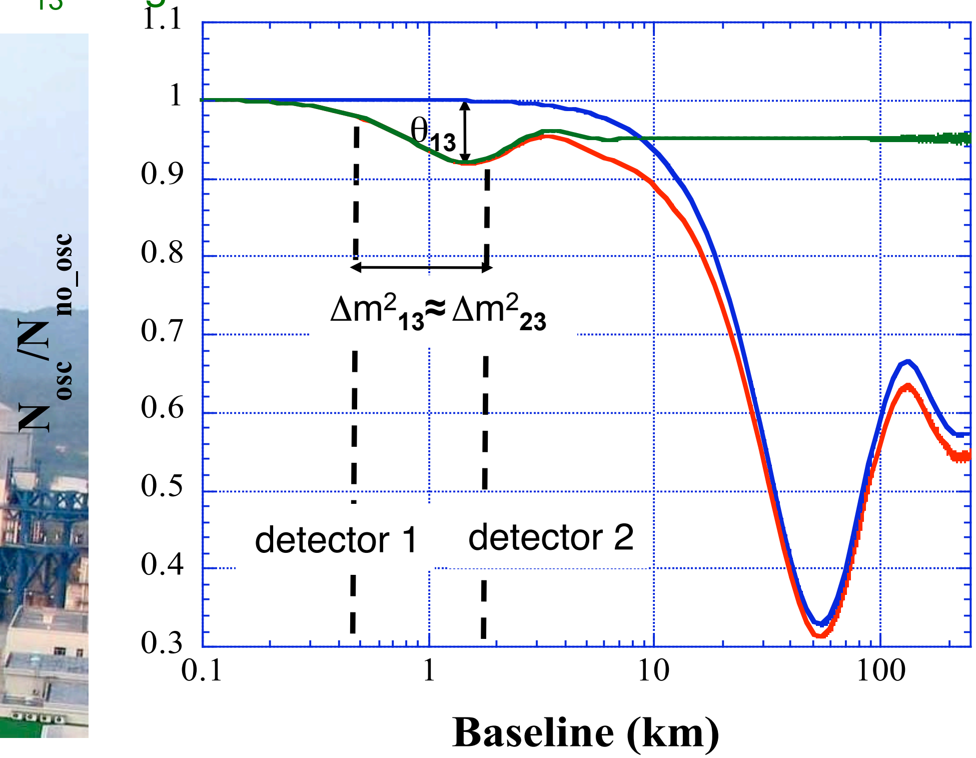
Search for θ_{13} in new oscillation experiment with multiple detectors

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

Small-amplitude oscillation due to θ_{13} integrated over E

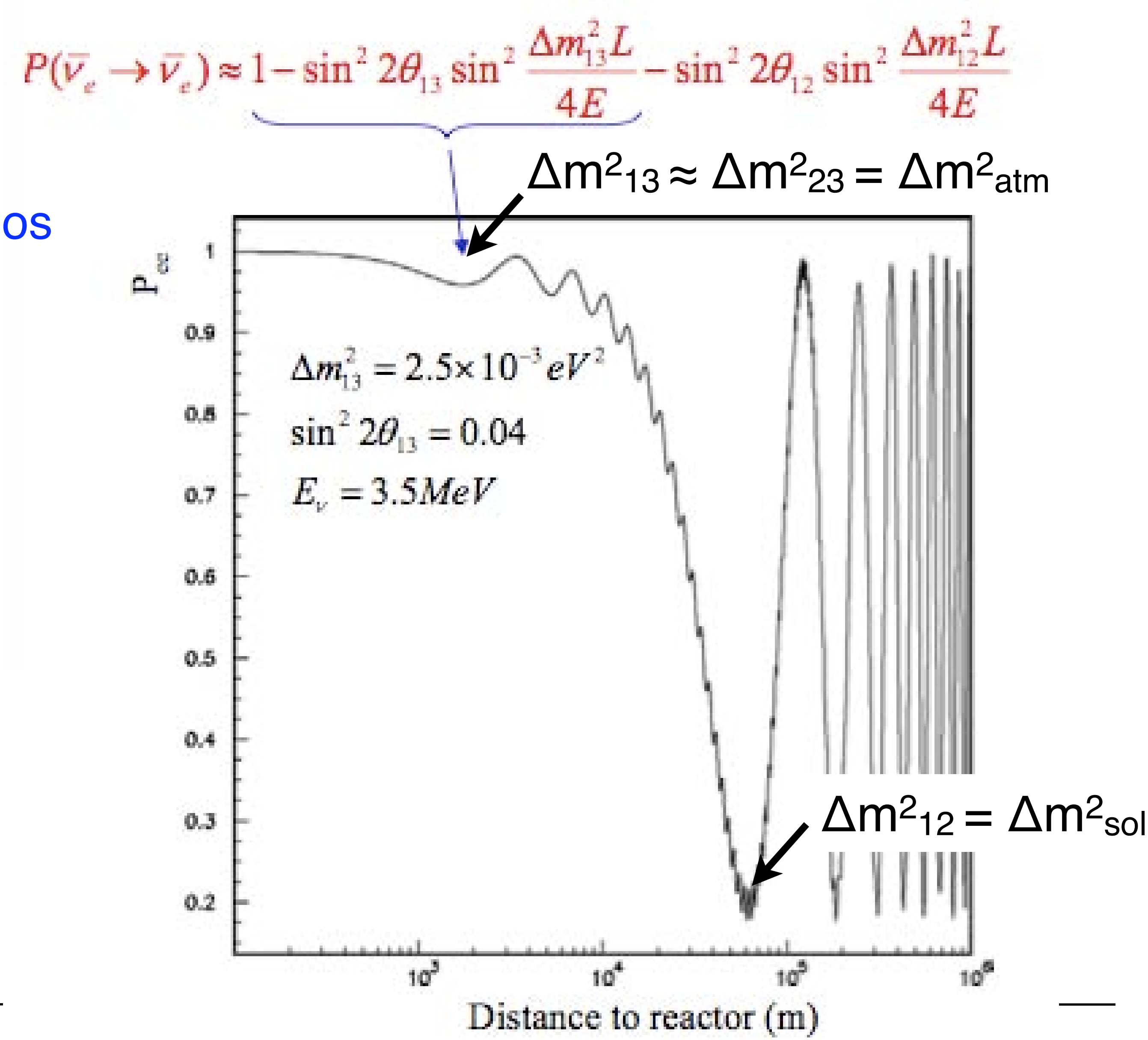
Large-amplitude oscillation due to θ_{12}





Two Oscillation Wavelengths: Δm^2_{atm} and Δm^2_{sol}

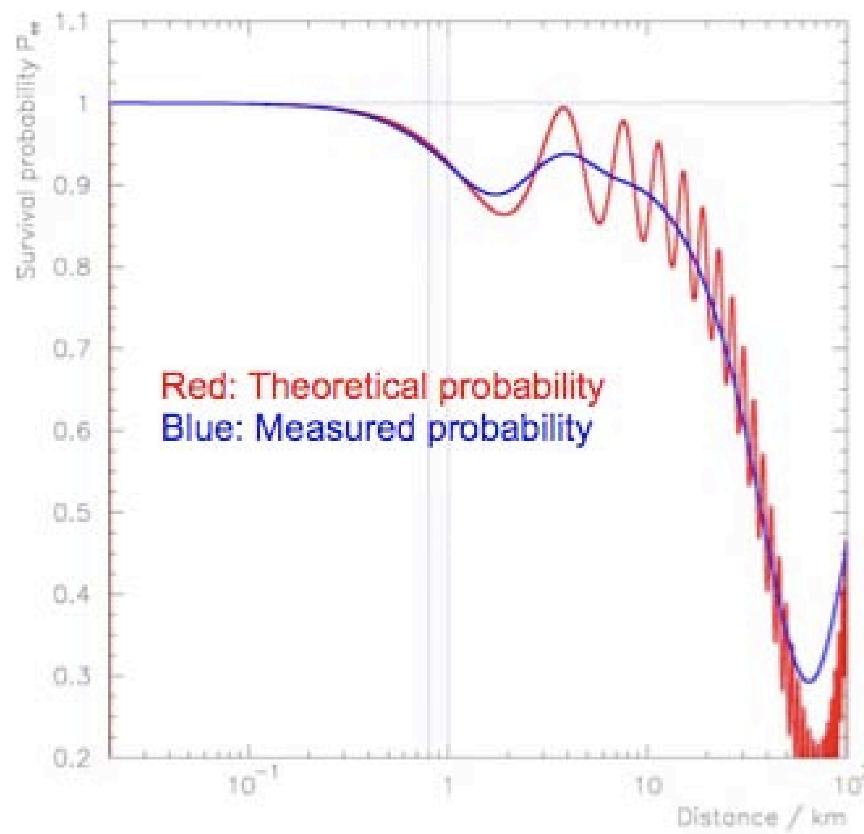
reactor antineutrinos oscillate with two wavelengths



Experimental Resolution

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

- Oscillation probability is dependent on neutrino energy and distance from source-detector
- Oscillatory behavior is "washed" out by:
  - Finite energy resolution
    - Effectively integrate over the ~7-10 % uncertainty in the measured energy
  - Spread in distances from reactor
    - Reactor core size
    - Varying distances from multiple reactors



Detecting Reactor $\bar{\nu}_e$

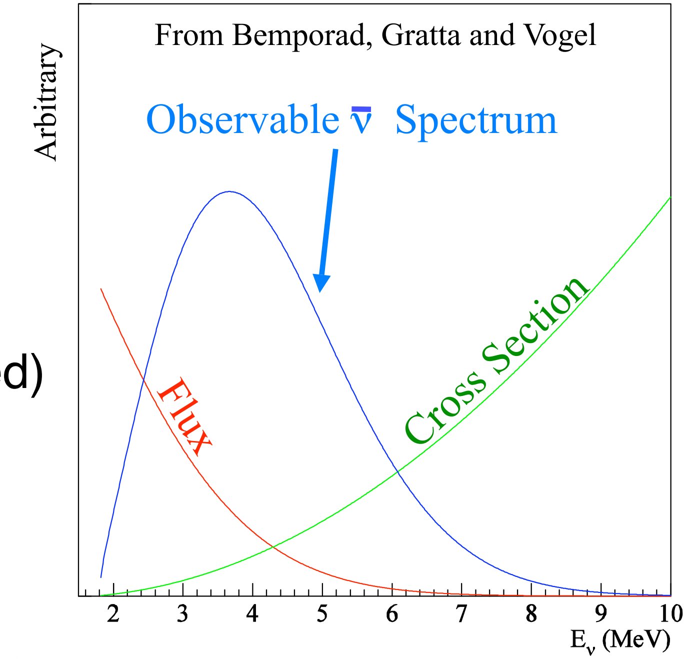
$\bar{\nu}_e + p \rightarrow e^+ + n$

0.3 b $\quad \rightarrow + p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b $\quad \rightarrow + Gd \rightarrow Gd^*$

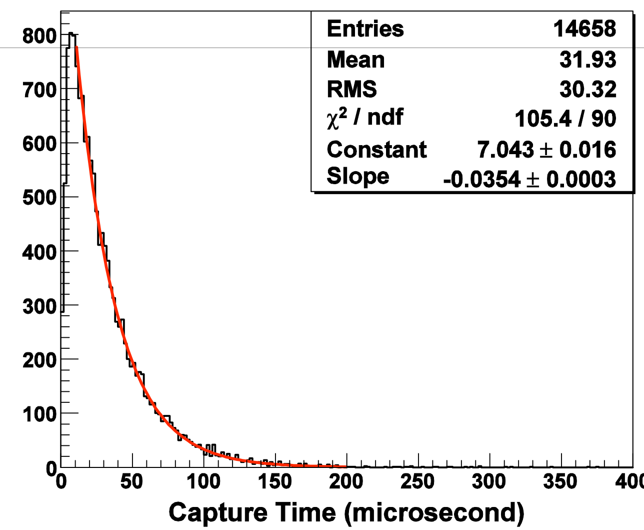
$\rightarrow Gd + \gamma$'s (8 MeV) (delayed)

coincidence signal allows background suppression



0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time (τ~28 μs)
- Good light yield



^{155}Gd $\quad \Sigma\gamma$=7.93 MeV

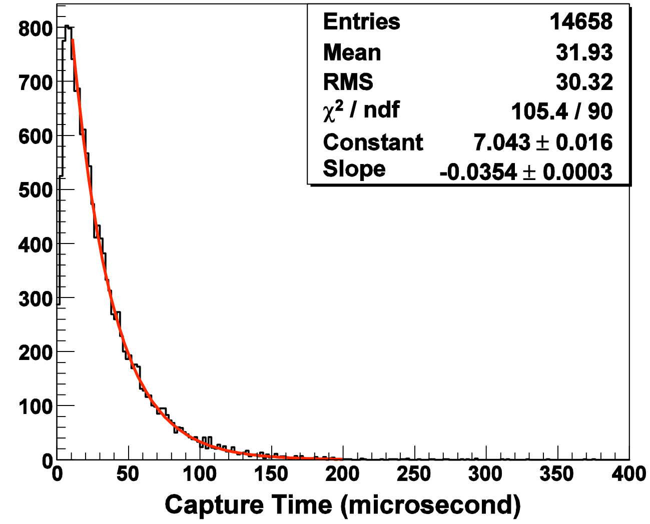
^{157}Gd $\quad \Sigma\gamma$=8.53 MeV

other Gd isotopes with high abundance have very small neutron capture cross sections

Detector Target

0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time (τ~28 μs)
- Good light yield



	fraction by weight
C	0.8535
H	0.1288
N	0.0003
O	0.0164
Gd	0.0010

Isotopic Abundance

Gd(152)	*0.200*
Gd(154)	*2.18*
Gd(155)	*14.80*
Gd(156)	*20.47*
Gd(157)	*15.65*
Gd(158)	*24.84*
Gd(160)	*21.86*

^{155}Gd Σγ=7.93 MeV

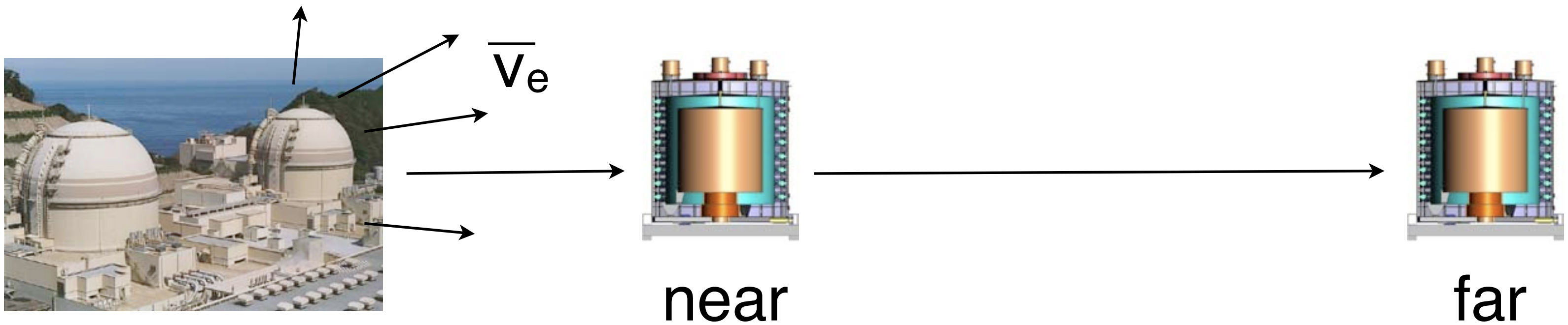
^{157}Gd Σγ=8.53 MeV

other Gd isotopes with high abundance have very small neutron capture cross sections

Gd capture	86.7%
H capture	13.2%
C capture	0.08%

Principle of Relative Measurement

Measure ratio of interaction rates in detector (+shape)



$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

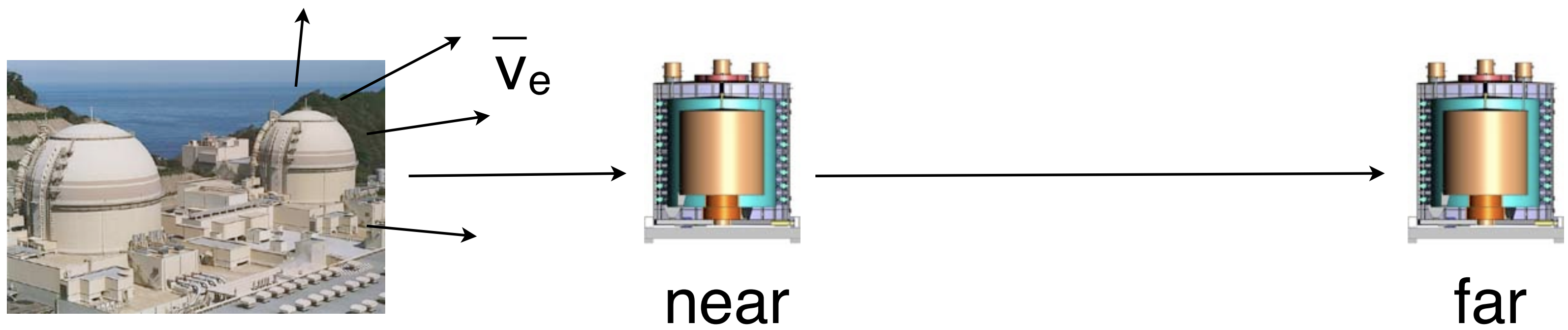
Measured Ratio of Rates

Detector Mass Ratio, H/C

Detector Efficiency Ratio

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

Concept of Reactor θ_{13} Experiments



Strategy/Method

1. relative measurement between detectors at different distances
2. cancel source (reactor) systematics
3. need "identical detectors" at near and far site

Concept of "Identical Detectors"

identical target + identical detector response

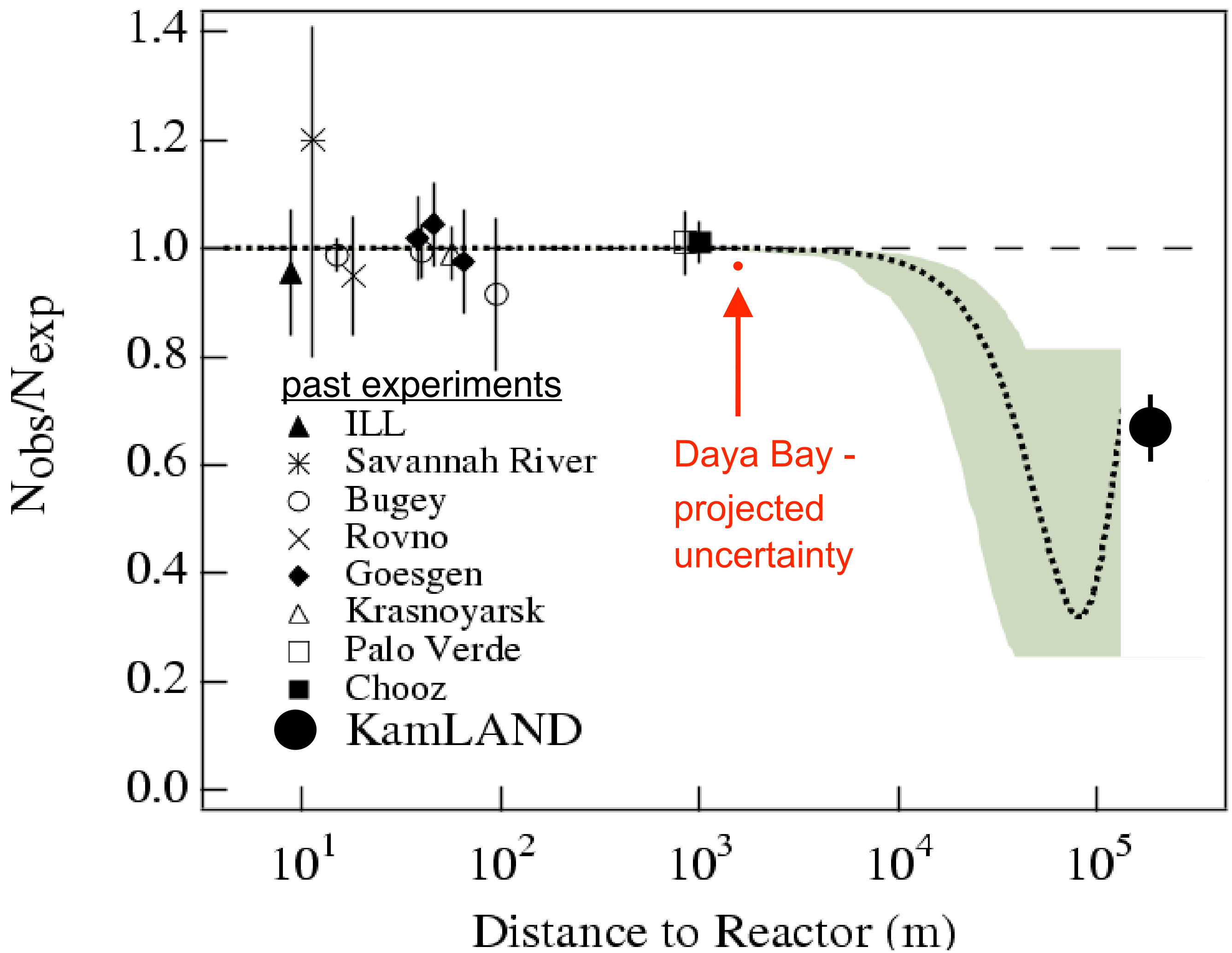
→ relative target mass (measure to < 0.1%)

→ relative target composition between pairs of detectors (e.g. fill pairs of detectors from common reservoir)

→ calibrate relative antineutrino detection efficiency of detector pair to < 0.25%

Ratio of Measured to Expected $\overline{\nu}_e$ Flux

Expected precision in Daya Bay to reach $\sin^2 2\theta_{13} < 0.01$



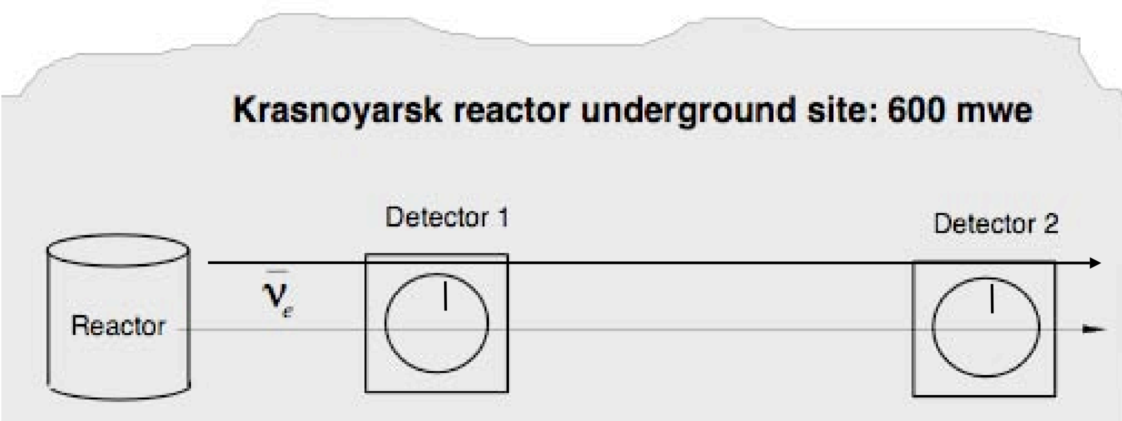
past experiments = 1 detector

next generation > 2 detectors

Ref: KamLAND, Daya Bay, McKeown

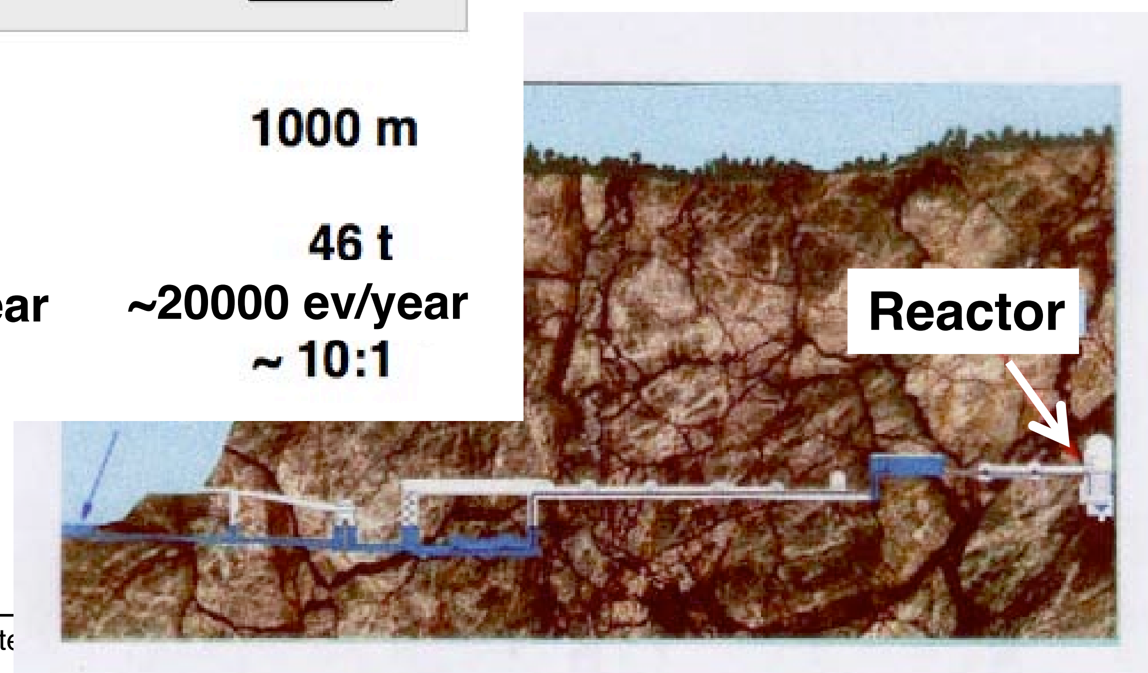
Reactor θ_{13} Experiment at Krasnoyarsk, Russia

Original Idea: First proposed at Neutrino2000



	115 m	**1000 m**
Target:	**46 t**	**46 t**
Rate:	**~1.5 x 10^6 ev/year**	**~20000 ev/year**
S:B	**>>1**	**~ 10:1**

Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure



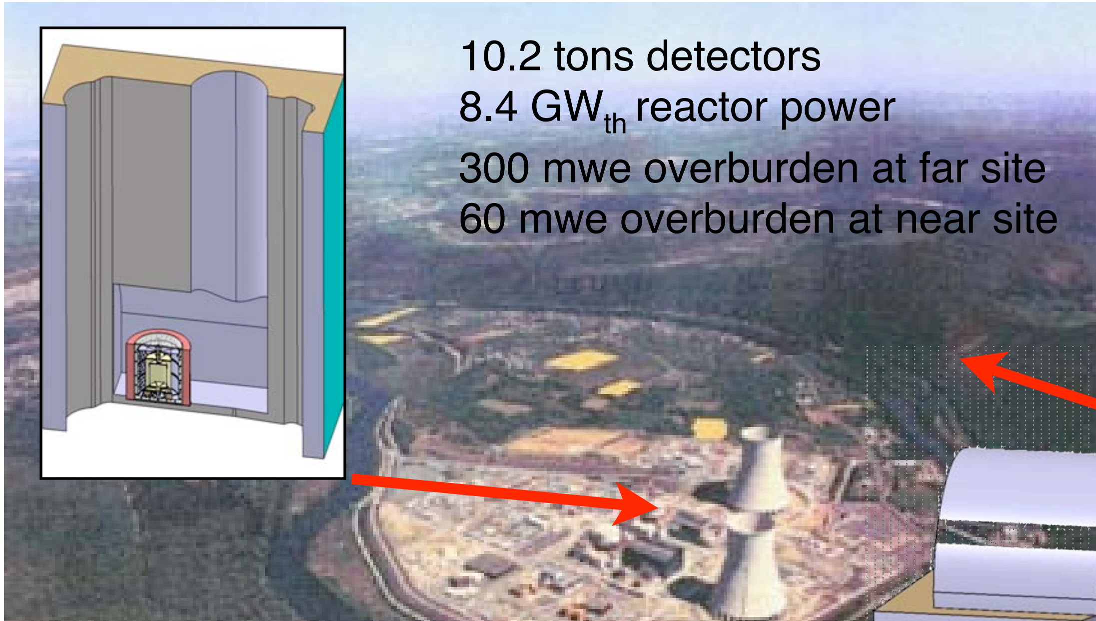
Ref: Marteyamov et al, hep-ex/0211070

World of Proposed Reactor θ_{13} Neutrino Experiments

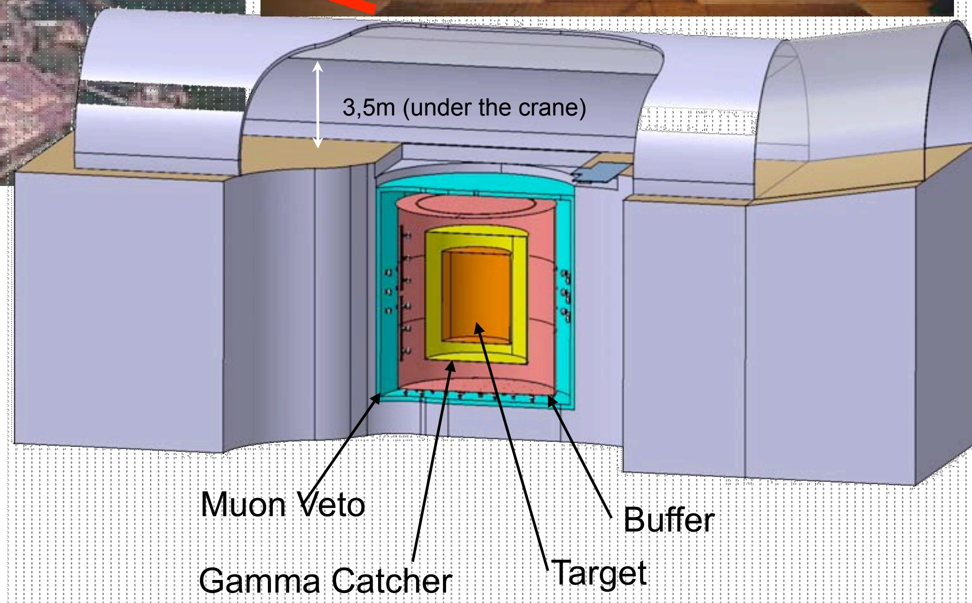
Double Chooz, Daya Bay, and Reno have strong international collaborations.
→Ready to start construction.

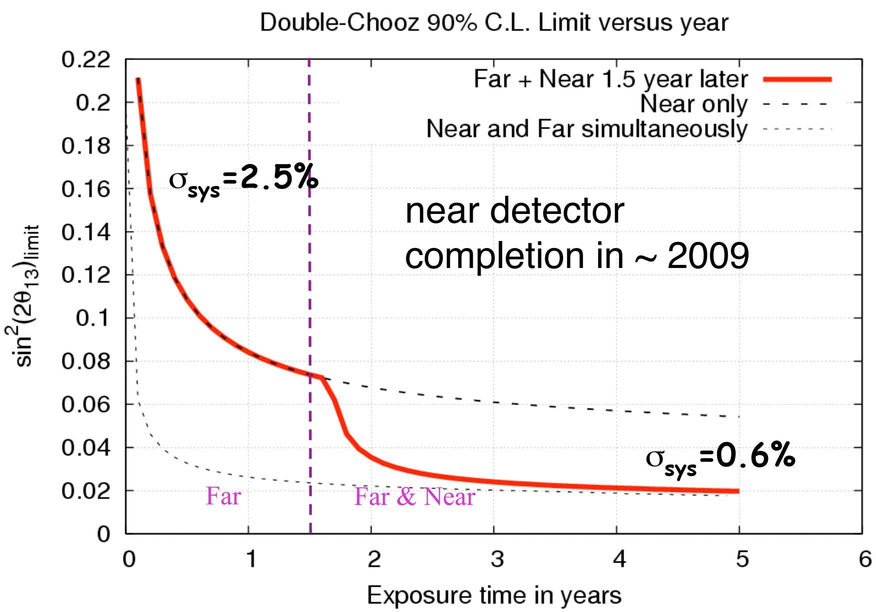
Proposed and R&D.

Double Chooz



10.2 tons detectors
8.4 GW_{th} reactor power
300 mwe overburden at far site
60 mwe overburden at near site



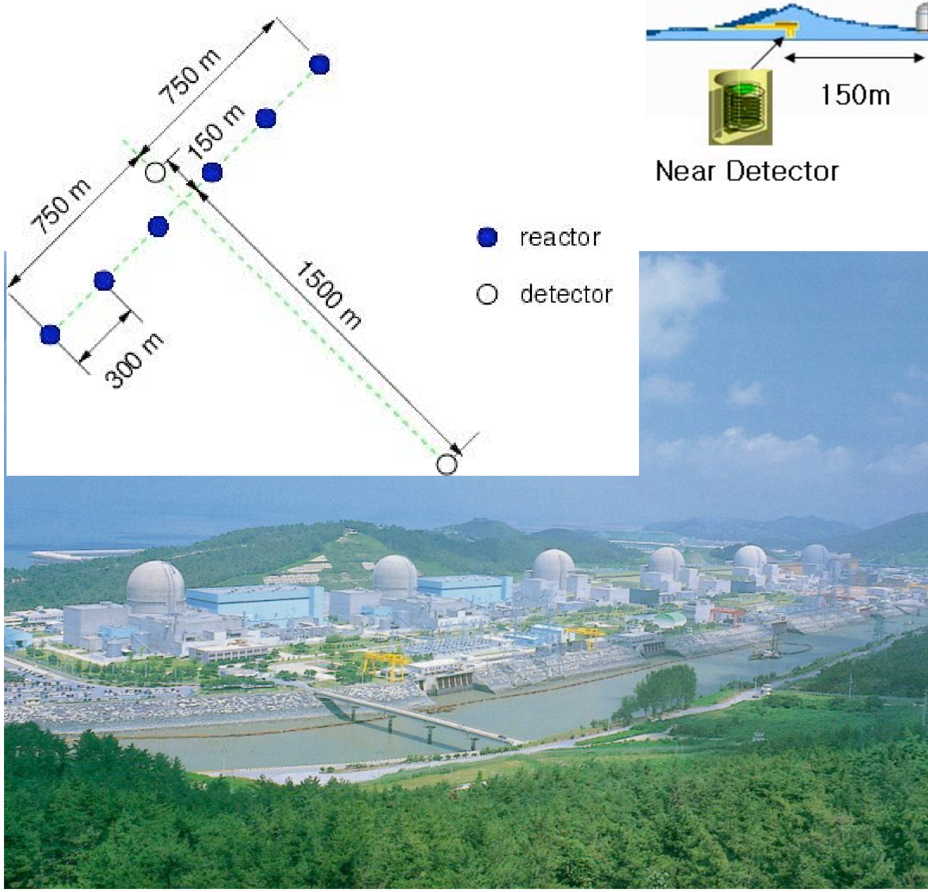


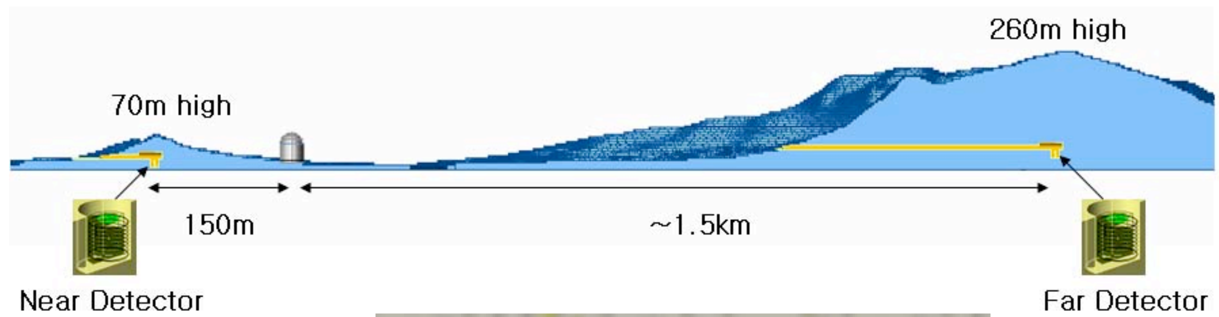
near detector completion in ~ 2009

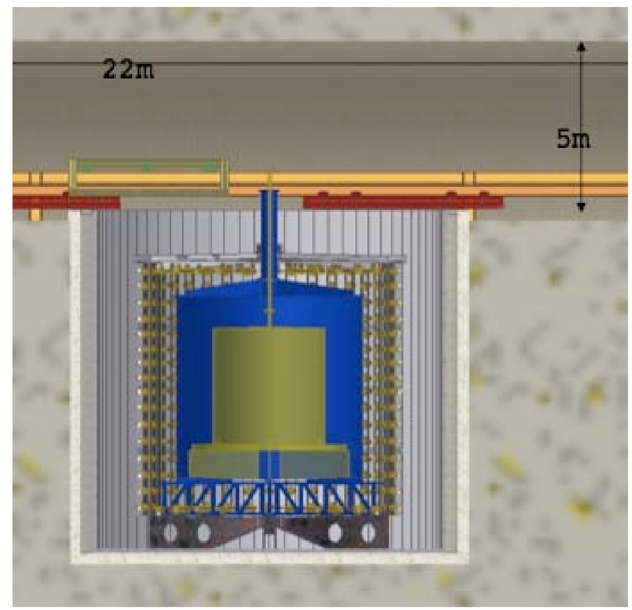
$\sin^2 2\theta_{13} < 0.03$ @ 90.C.L. in 3 years

Reactor Experiment for Neutrino Oscillations (RENO) at YongGwang, Korea

http://neutrino.snu.ac.kr/RENO/





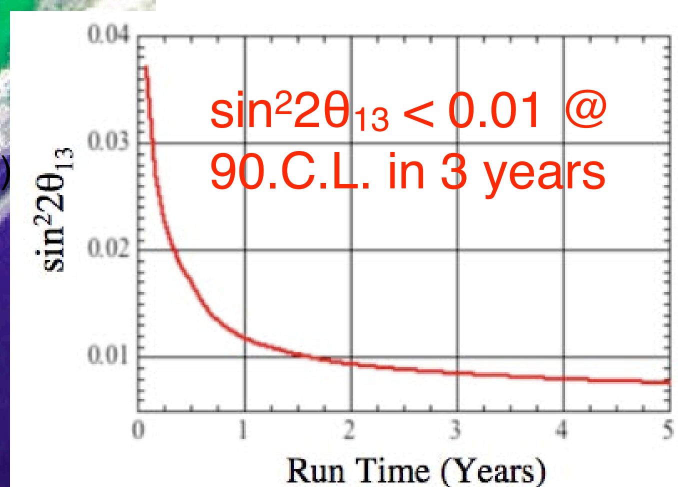


$\sin^2 2\theta_{13} < 0.02$ @ 90.C.L. in 3 years

Daya Bay, China

http://dayawane.ihep.ac.cn/

Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613



Daya Bay, China

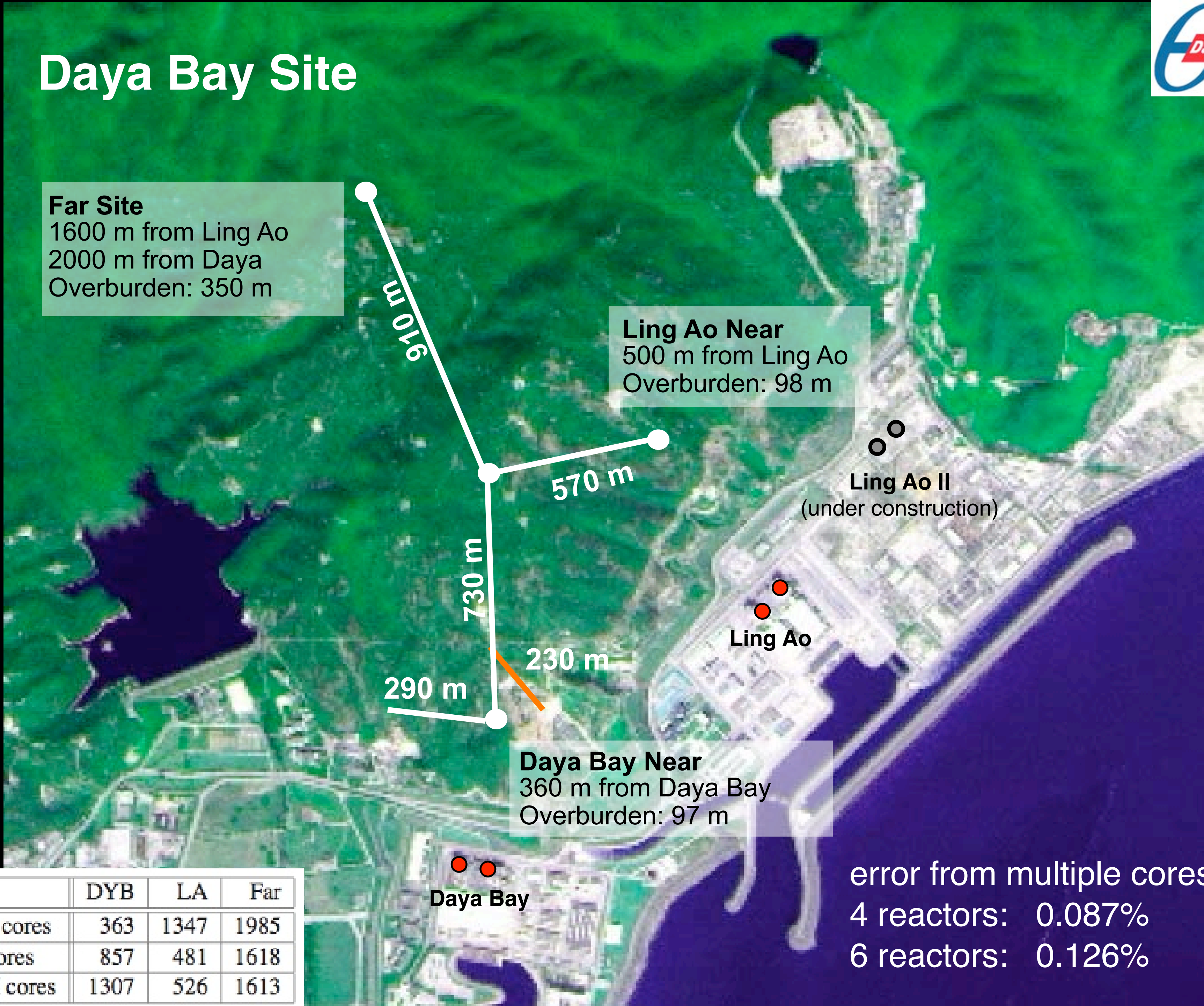
Powerful ν_e Source:
Multiple reactor cores.
(at present 4 units with 11.6 GW_{th},
in 2011 6 units with 17.4 GW_{th})

Shielding from Cosmic Rays:
Up to 1000 mwe overburden nearby.

Adjacent to mountain.

http://dayawane.ihep.ac.cn/

Daya Bay Site



Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

error from multiple cores

4 reactors: 0.087%

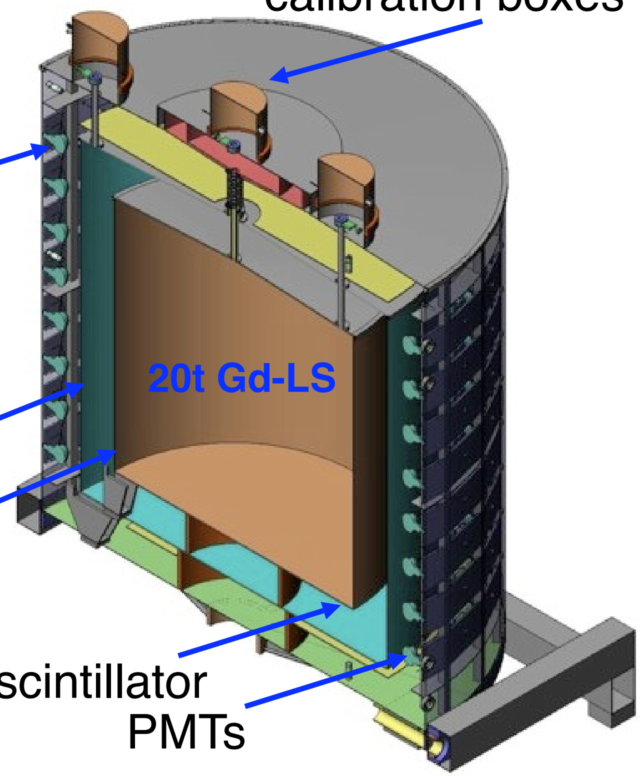
6 reactors: 0.126%

Baseline Design of Detector and Halls

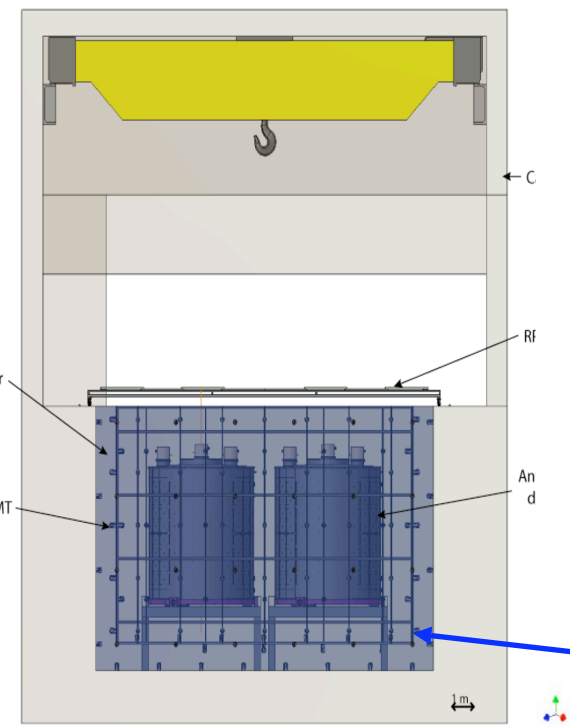
multiple 3-zone antineutrino detectors

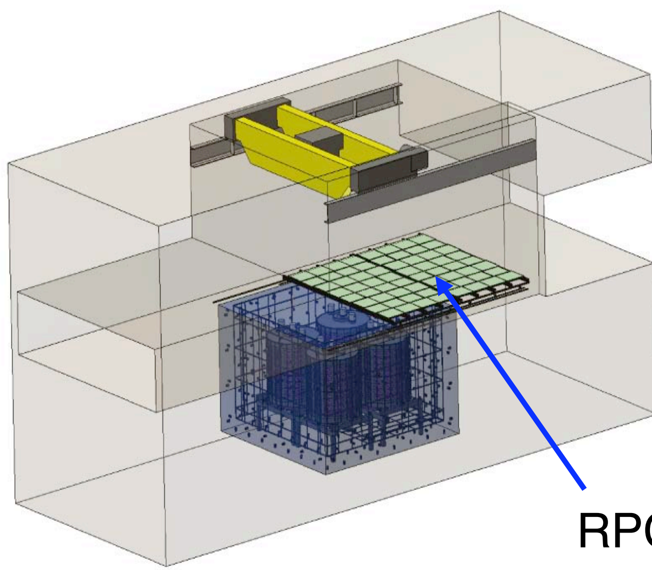
muon detectors

- water pool and Cherenkov counter
- RPC on top for tracking muons



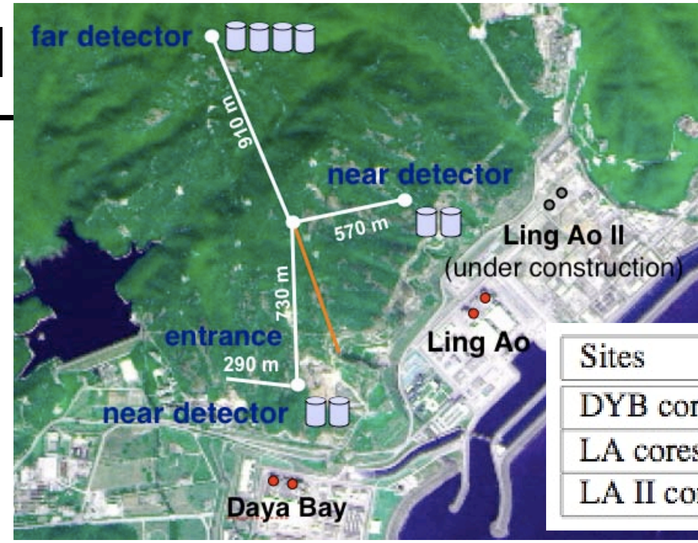
8 antineutrino detectors





3 experimental halls and muon systems

Event Rates and Signal



Antineutrino Interaction Rates

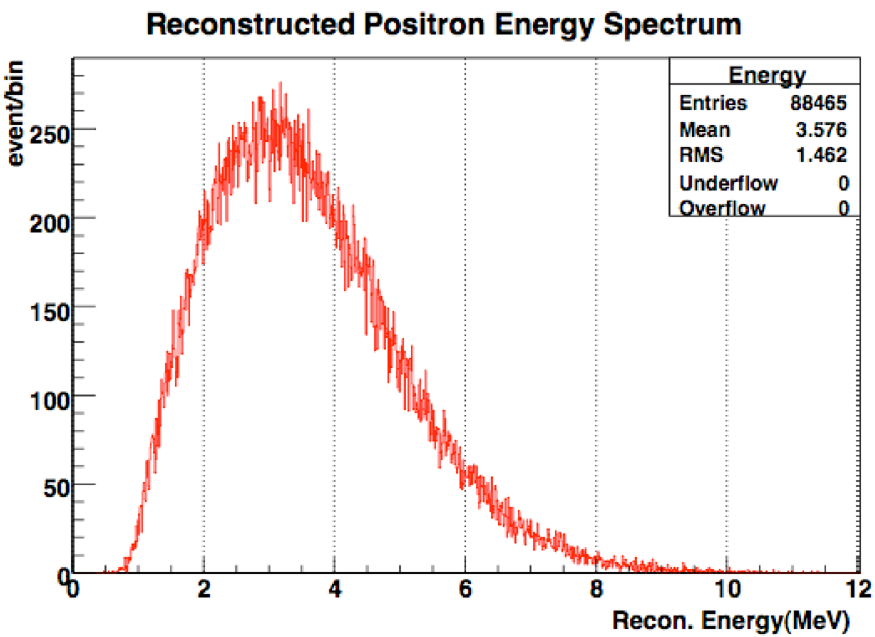
(events/day per 20 ton module)

Daya Bay near site	960
Ling Ao near site	~760
Far site	90

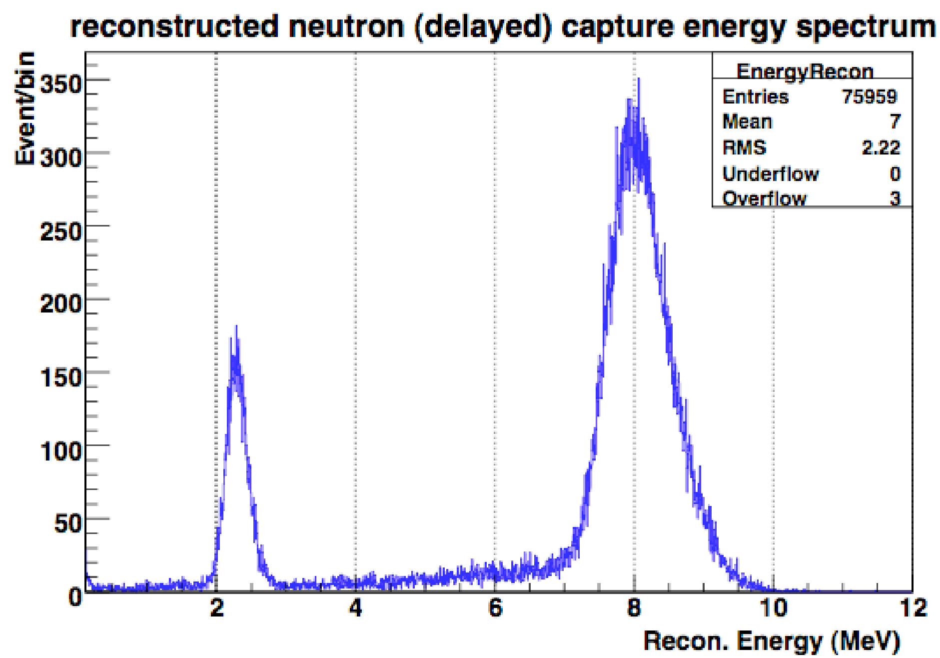
Distances to Sites (m)

Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Prompt Energy Signal



Delayed Energy Signal



Statistics comparable to single detector in far hall

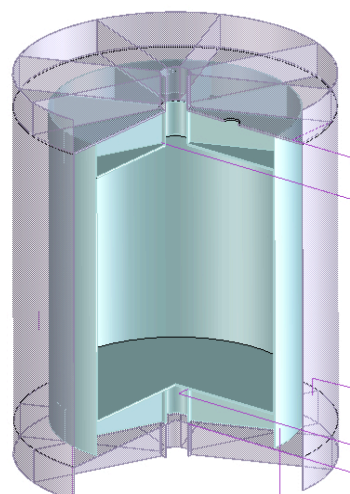
Design, R&D, and Prototyping for Daya Bay

Design of civil infrastructure

groundbreaking on October 13, 2007

Joint R&D program in US and China on Gd-LS Production

Acrylic Vessel Prototyping



Detector Prototypes at IHEP and in Hong Kong

Upcoming Reactor θ_{13} Neutrino Experiments

	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)	Exposure in 3 yrs (ton-GW-y)
Angra *proposed / R&D*	Brazil	4.1	300/1500	250/2000	500	~ 6150
Daya Bay *construction start in '07*	China	11.6 17.4 after 2010	360(500)/1750	260/910	80	**~ 4180**
Double-CHOOZ *under construction*	France	8.7	150/1067	80/300	8	**~ 210**
RENO *ready to start construction*	Korea	17.3	150/1500	230/675	15.4	**~ 800**

** experiments are underway*

Systematic Errors from the Detector

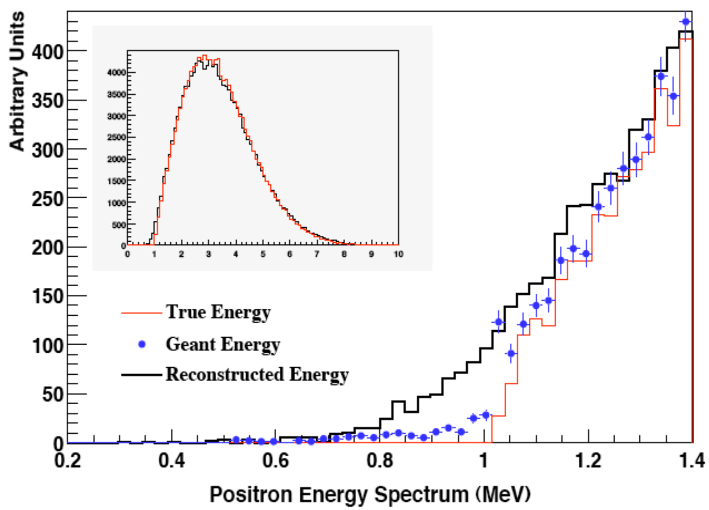
Number of Protons

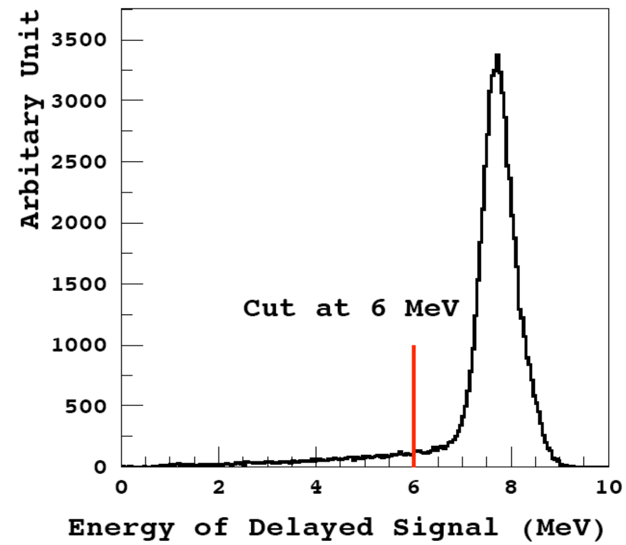
- reproducability: volume flow < 0.02%, mass flow < 0.1%
- combustion analysis, NMR or neutron beam to determine H/C ratio

Position & Time Cuts

- no position cuts: volume defined by neutron capture on Gd.
- time cuts: time window 1-200μs, precision <10ns, uncertainty < 0.03%

Energy Cuts





Low-energy threshold: Routine calibration using positron annihilation source (^{68}Ge)

Calibrate the 6 MeV cut → relative uncertainty in neutron efficiency <0.2%.

Gd/H Ratio

1% mass uncertainty causes 0.12% change in n-capture efficiency

Goal of Future Precision Reactor Neutrino Experiments

Detector-Related Uncertainties

Daya Bay as an example: most ambitious in reducing error between detectors

Absolute measurement **Relative measurement**

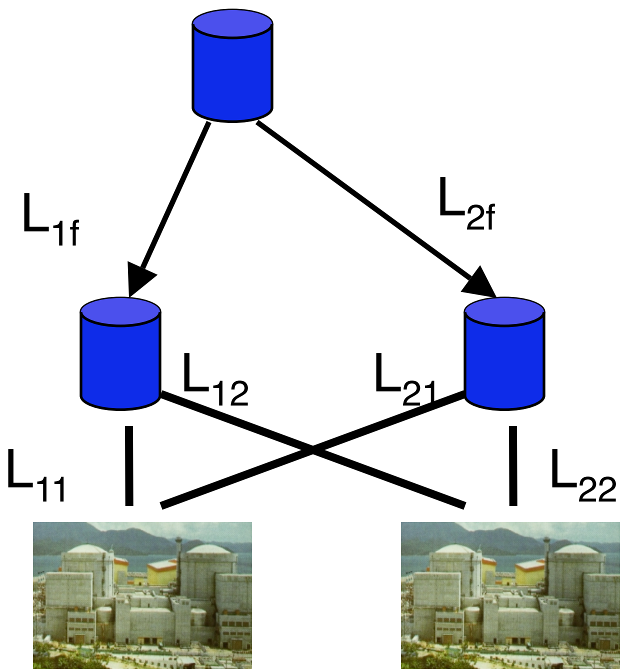
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	<0.01	<0.01	<0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

Ref: Daya Bay TDR

O(0.2%) precision for relative measurement between detectors at near and far sites

Reactor Related Systematic Uncertainty

For multi cores, **reweight oversampled** cores to maximize near/far cancellation of the reactor power fluctuation.



$$\alpha = \frac{\frac{1}{L_{22}^2 L_{1f}^2} - \frac{1}{L_{21}^2 L_{2f}^2}}{\frac{1}{L_{11}^2 L_{2f}^2} - \frac{1}{L_{12}^2 L_{1f}^2}}$$

$$\frac{\text{Near}}{\text{Far}} = \alpha \frac{\text{Near1}}{\text{Far}} + \frac{\text{Near2}}{\text{Far}}$$

Assuming 30 cm precision in core position

Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Background Sources

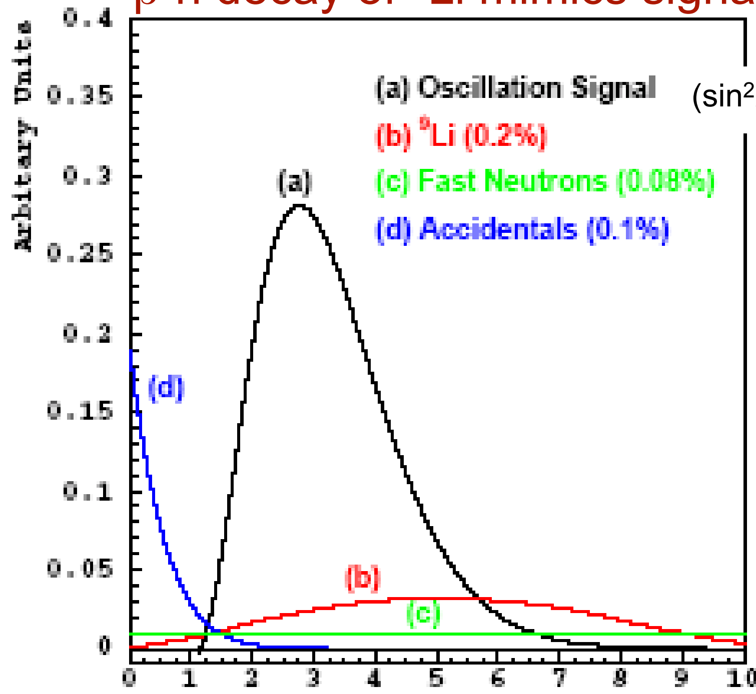
1. Natural Radioactivity: PMT glass, steel, rock, radon in the air, etc

2. Slow and fast neutrons produced in rock & shield by cosmic muons

3. Muon-induced cosmogenic isotopes: $^{8}He/^{9}Li$ which can β-n decay

- Cross section measured at CERN (Hagner et. al.)
- Can be measured in-situ, even for near detectors with muon rate ~ 10 Hz:

β-n decay of ^{9}Li mimics signal



($\sin^2 2\theta_{13}$=0.01)

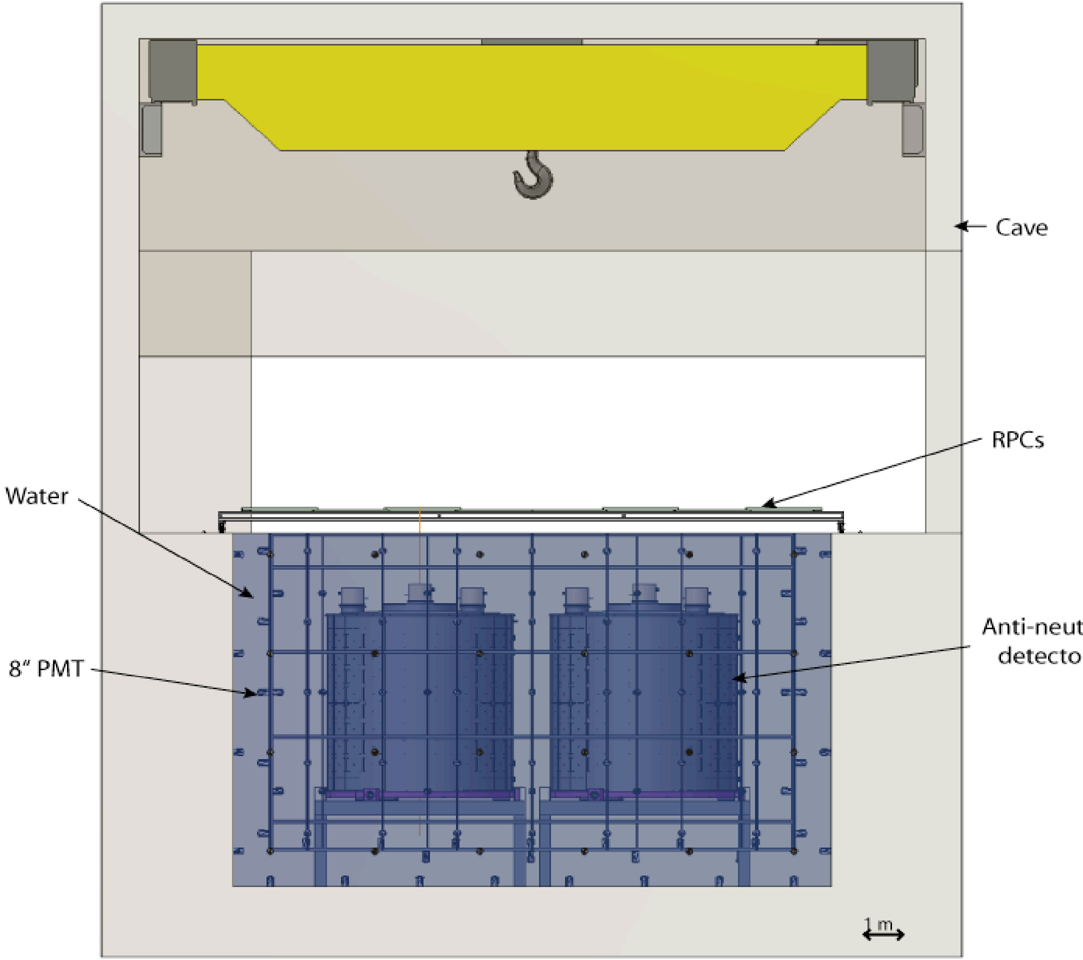
Visible e^+ energy (MeV)

Background Reduction with Muon Veto

Muon System: Water Pool with PMTs + RPC

- Muon Veto
  - spallation neutrons
  - 99.5% efficient

- Water shield (2.5m)
  - rock neutrons
  - radioactivity



Backgrounds After Muon Veto

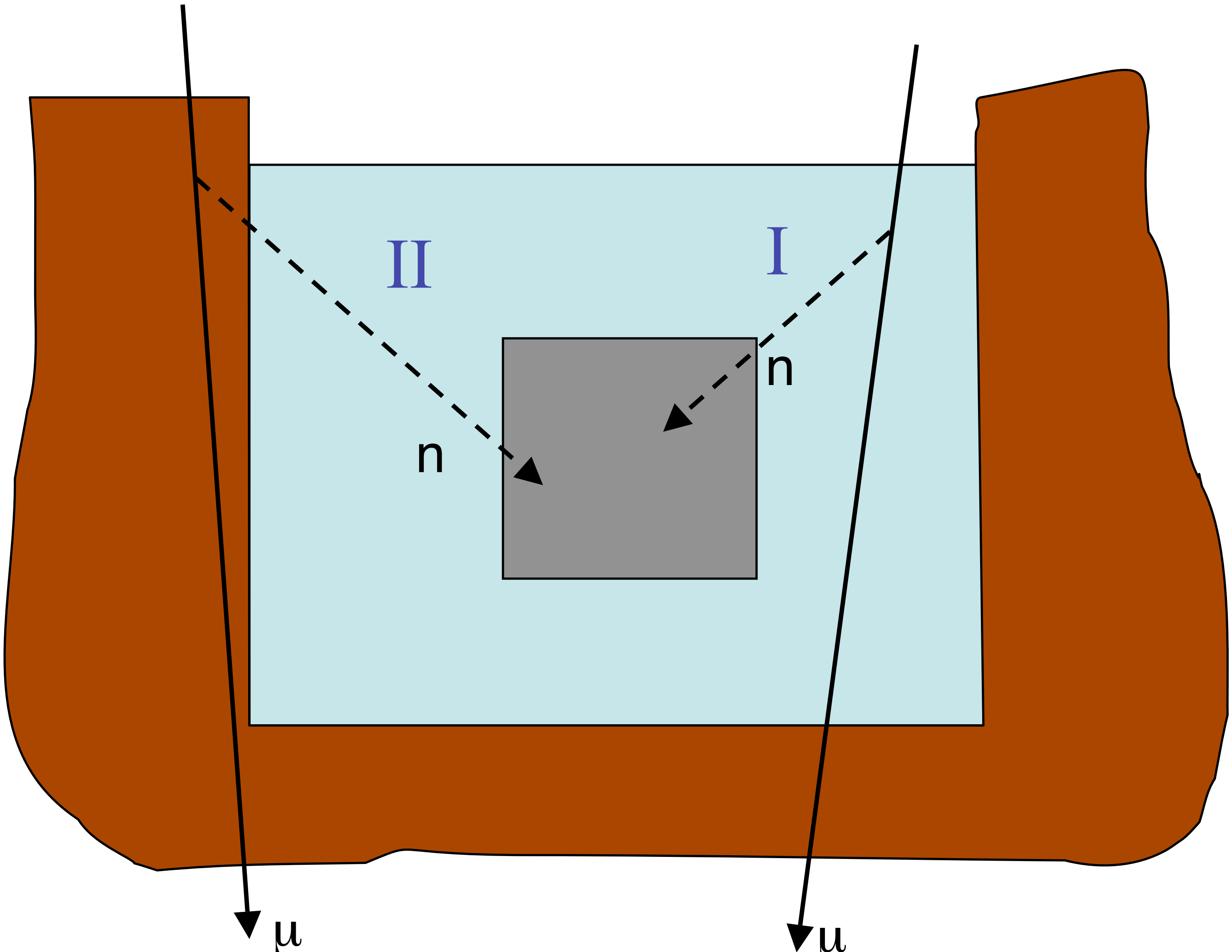
Assuming 99.5% muon veto, even with delayed coincidence event signature, the following backgrounds remain:

- Fast neutrons (prompt recoil, delayed capture)
- $^{9}Li/^{8}He$ ($T_{1/2}$= 178 msec, β decay w/neutron emission, delayed capture)
- Accidental coincidences

(Other smaller contributions can be neglected)

⇒ All three remaining backgrounds are small (<1%) and can be measured and/or constrained using data.

Fast Neutrons from Muons



$^{9}Li/^{8}He$

$^{9}Li \rightarrow e^{-} + \overline{\nu}_e + {}^{9}Be^{*} \rightarrow {}^{8}Be + n$

Q=13 MeV

$T_{1/2}$= 178 msec

(Long $T_{1/2}$ & poor spatial correlation with μ track make rejection problematic.)

Rates computed from CERN measurements (Hagner et al.,)

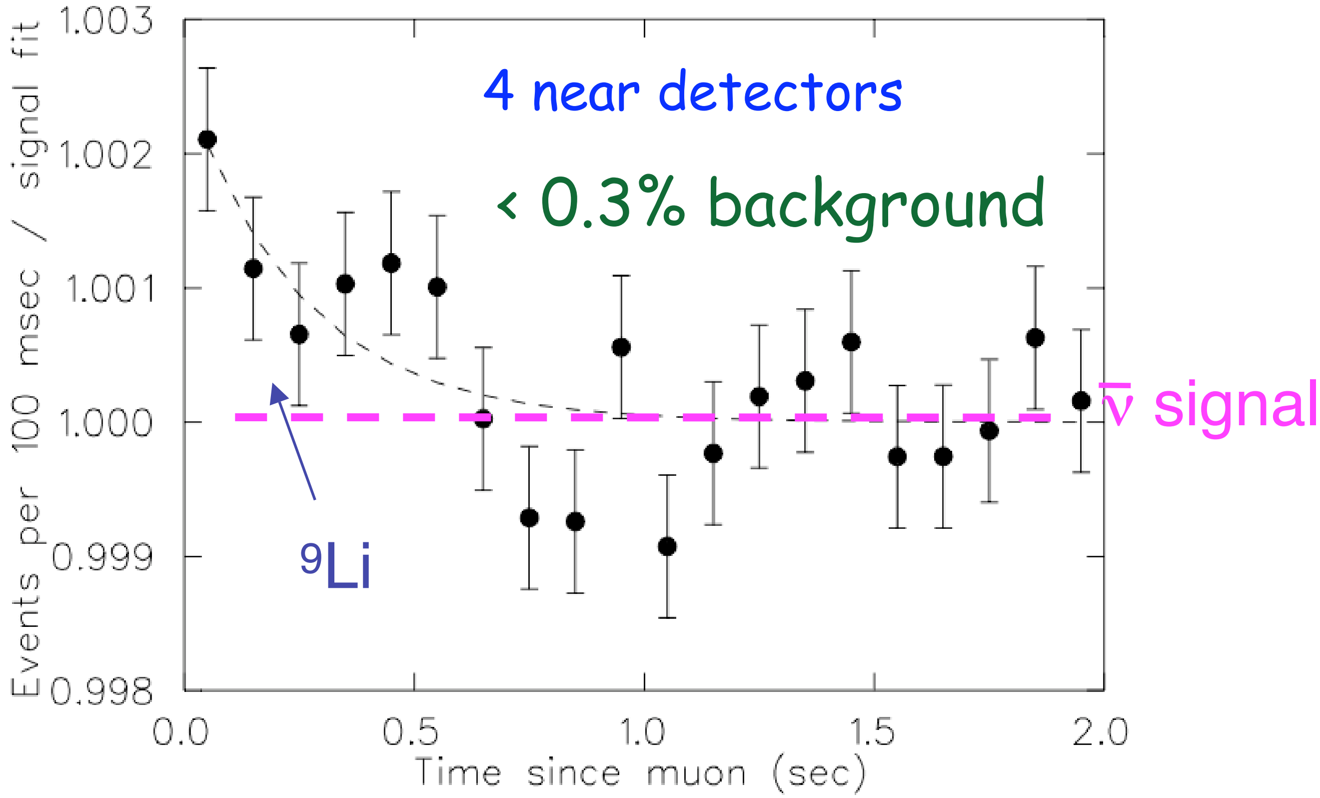
	DYB site	LA site	Far site
$(^{8}He+^{9}Li)$/day/module	3.7	2.5	0.26

Note: B/S ~ 0.3% for all sites

⇒ Strategy: measure rate and statistically subtract from event sample. Issue: dead time from long veto on showering muons?

Measuring $^{9}Li/^{8}He$

Measure time since muon for candidate events



Projected results: $\sigma(B/S)$ = 0.3% (near), 0.1%(far)

Accidental Background

Prompt: γ from radioactivity (~50Hz/module)

Delayed: 1.) untagged single neutron capture
2.) Cosmogenic beta emitters (6-10 MeV, mostly ^{10}B)
3.) U/Th → O, Si (α,n γ[6–10 MeV])

	DB	LA	Far
neutrons	18/day	12/day	1.5/day
betas	210/day	141/day	14.6/day
(α,nγ)	<10/day	<10/day	<10/day
coinc rate	2.3/day	1.3/day	0.26/day
B/S	~2×10^{-3}	~2×10^{-3}	~3×10^{-3}

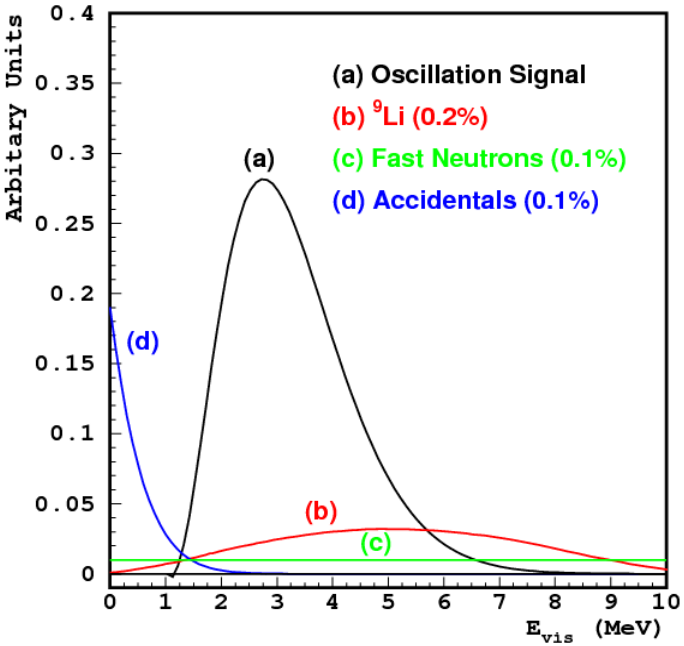
(use neutron capture time window τ~200μsec)

⇒ Tiny, and subtractable.

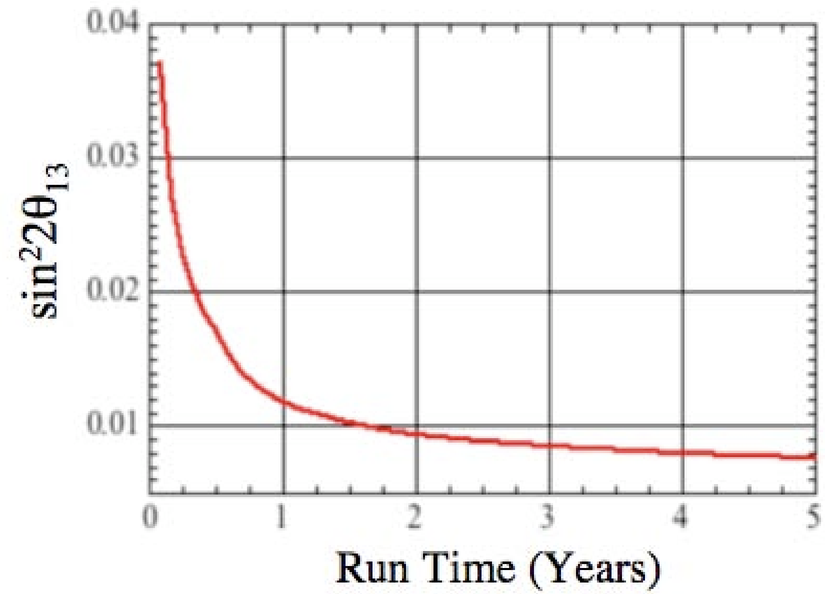
Daya Bay Background Summary

	Daya Bay site	Ling Ao site	Far site
Accidental/signal	<0.2%	<0.2%	<0.1%
Fast n / signal	0.1%	0.1%	0.1%
^{9}Li-^{8}He / signal	0.3%	0.2%	0.2%

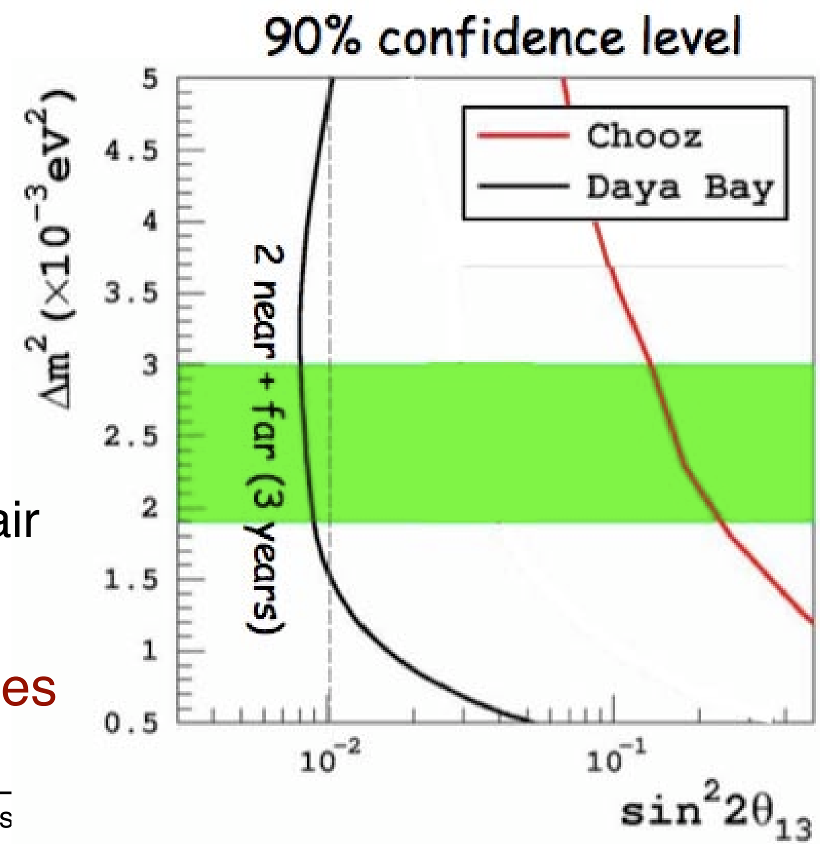
- B/S ~ same for near and far sites
- constrained by measurements to required precision
- input to sensitivity calculations (assume 100% uncertainty)



Daya Bay Sensitivity & Milestones

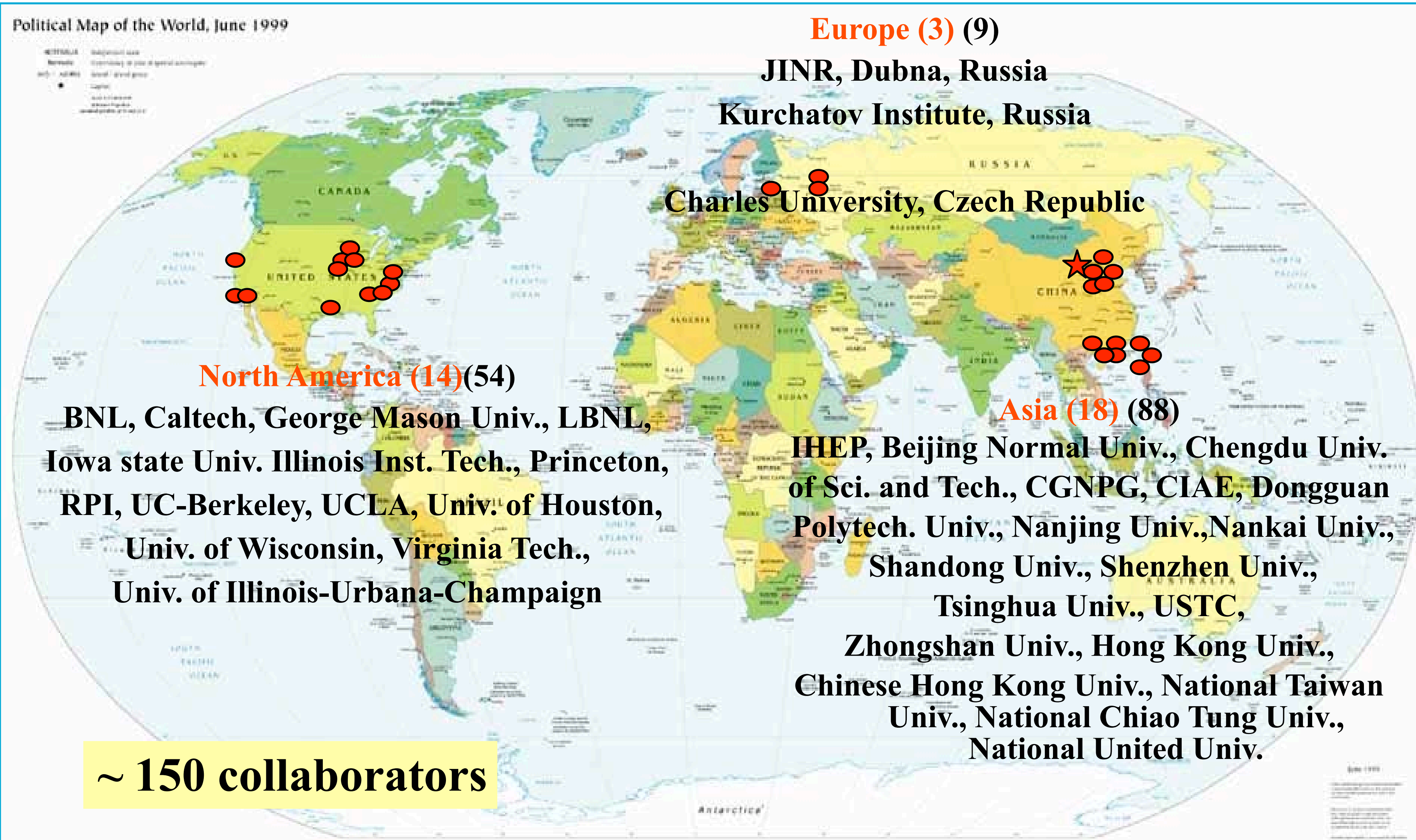


- Reactor-related systematics: 0.09% (4 cores)
  0.13% (6 cores)
- Relative detector systematics: 0.38% (baseline)
- Backgrounds will be measured: < 0.2%



- Apr 2007 completed DOE CD-1 review
- Oct 2007 start civil construction
- Oct 2008 delivery of Gd-LS to Daya Bay
- Aug-Dec 2008 assembly of first detector pair
- Aug 2009 start data taking at near site
- mid 2010 start data taking at near+far sites

Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(54)

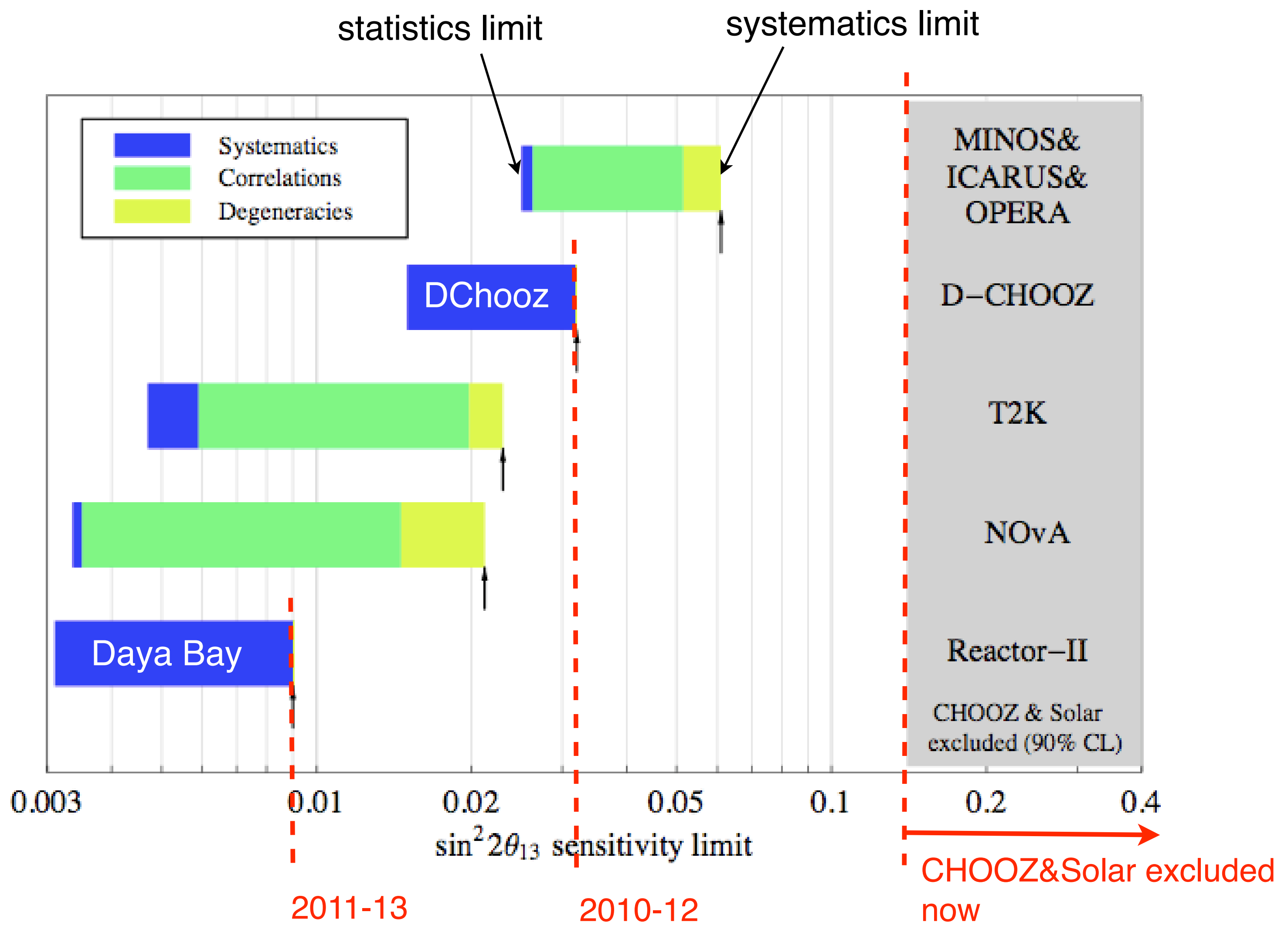
BNL, Caltech, George Mason Univ., LBNL, Iowa state Univ. Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (18) (88)

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

~ 150 collaborators

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

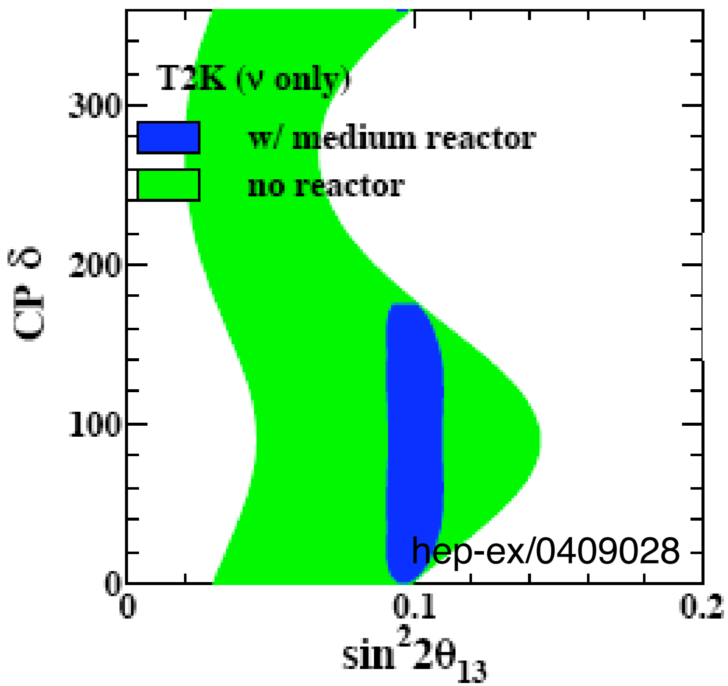


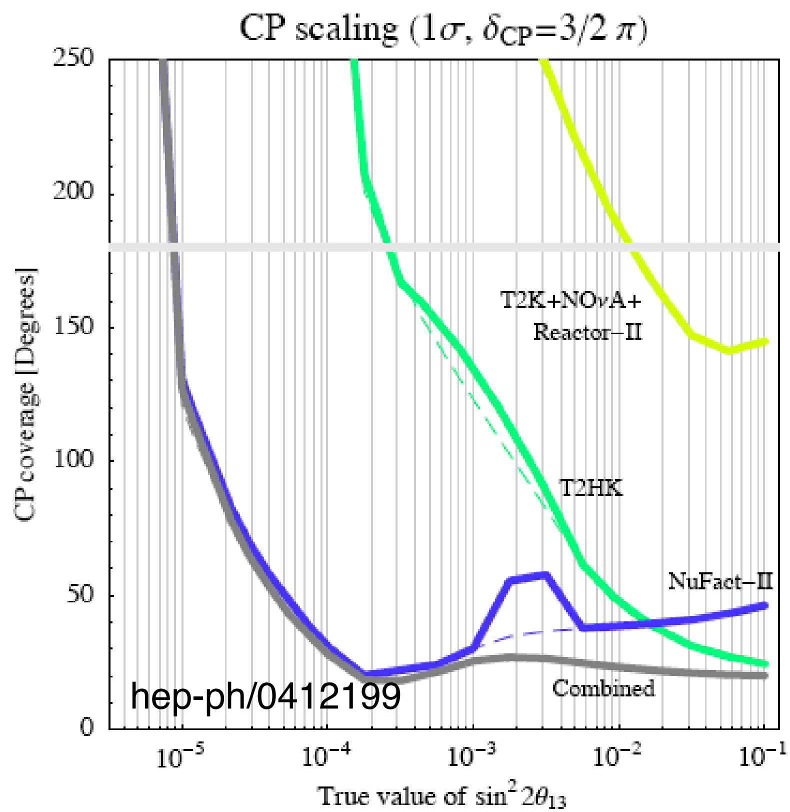
Ref: FNAL proton driver report, hep-ex/0509019

Towards Measuring CP Violation in Neutrinos

Next-generation experiments will not measure CP violation but some values of δ_{CP} could be excluded.

Allowed 90% CL region for $\sin^2 2\theta_{13}=0.1$, $\delta=90$





Why measure **$\sin^2 2\theta_{13}$ to 1%?**

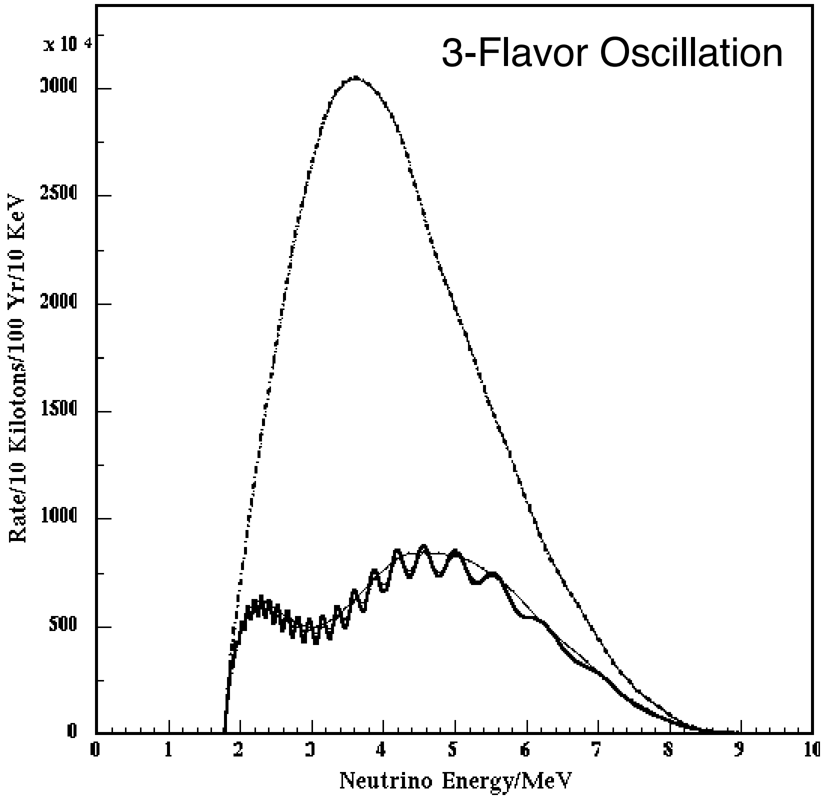
Planning future facilities:

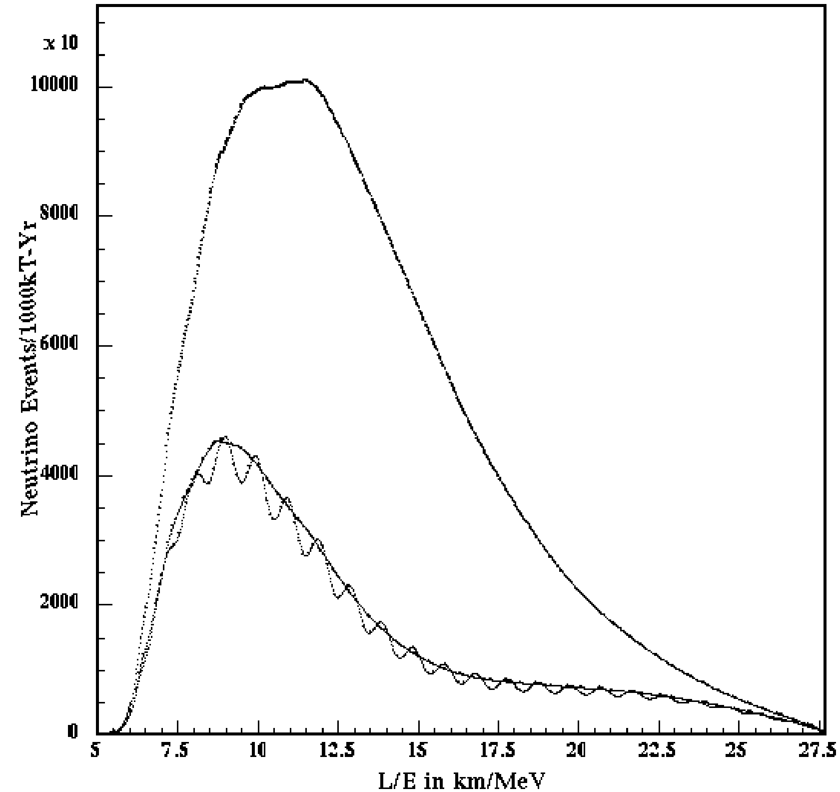
$\sin^2 2\theta_{13} \geq 10^{-2}$: reactor finds θ_{13} → superbeams

$\sin^2 2\theta_{13} < 10^{-2}$: NuFact with L~3000 km

An Alternative Method of Measuring θ_{13}

Fourier Transform Approach





- "High-frequency" amplitude in energy spectrum is θ_{13}
- In L/E plot, a purely sinusoidal component
- Invites the use of Fourier Transform for analysis

slides from J. Learned et al.

Fourier Transformed Spectrum

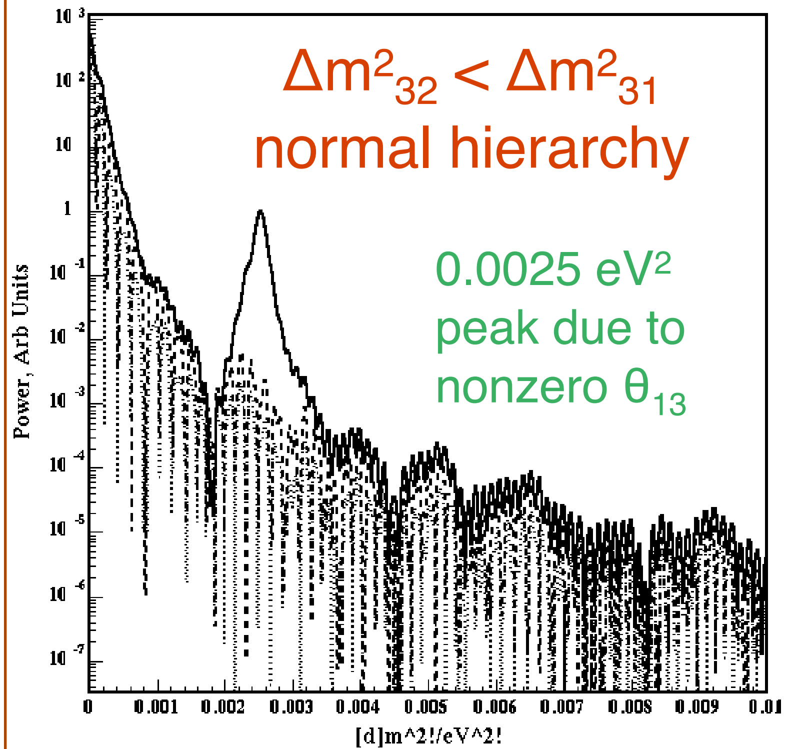
- Size of peak proportional to θ_{13}.
- The asymmetry tells about hierarchy

Preliminary

50 kt-y exposure at 50 km range

$\sin^2(2\theta_{13}) \geq 0.02$

$\Delta m^2_{31} = 0.0025$ eV^2 to 1% level

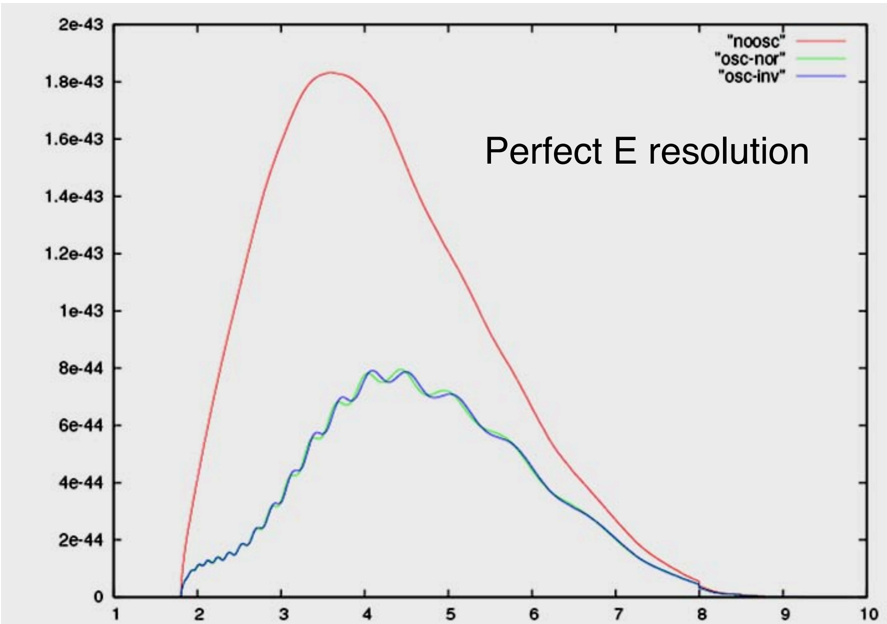


Includes energy smearing

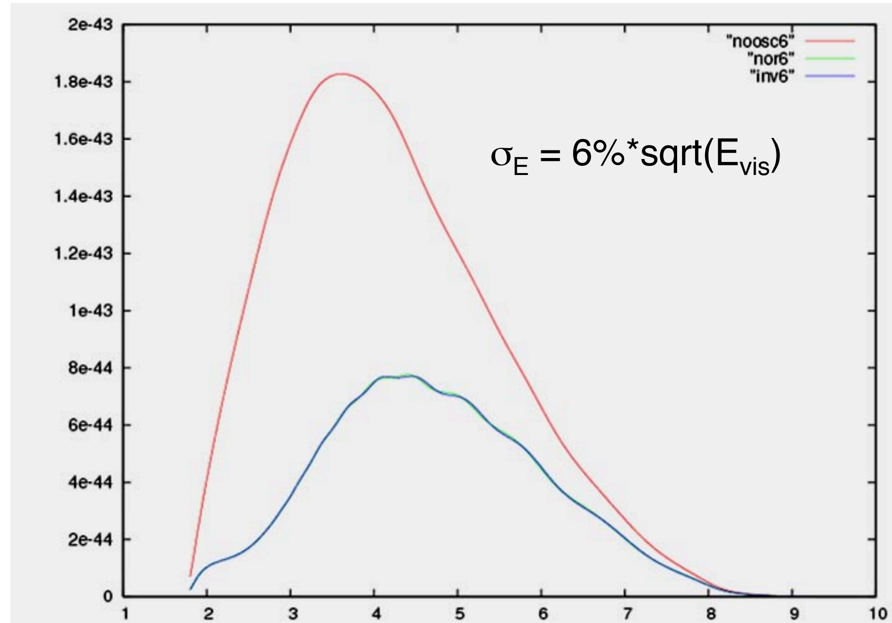
Learned, Dye,Pakvasa, Svoboda *hep-ex/0612022*

slides from J. Learned et al.

Mass Hierarchy Discrimination



Eν, MeV



Eν, MeV

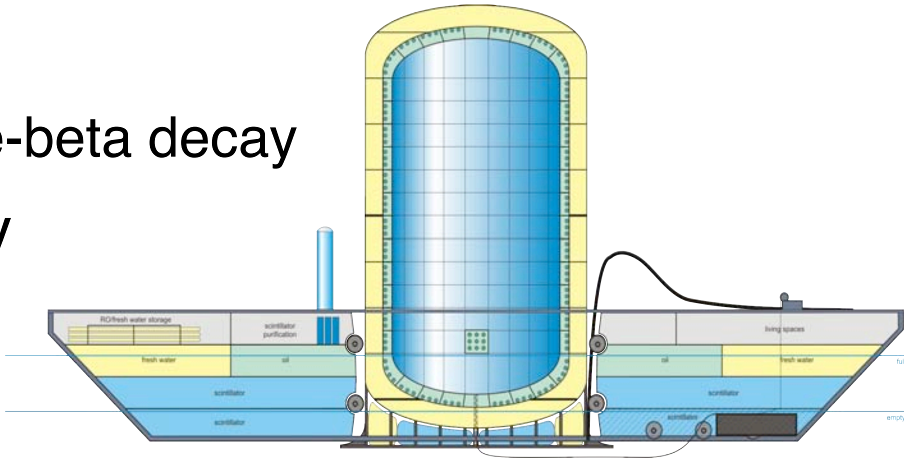
- Uses the difference in spectra
- Efficiency depends heavily on energy resolution

slides from J. Learned et al.

Hanohano Project

Detector for Geo and Reactor Antineutrinos

- 10-kt LS detector in ocean
- Primary detection method: inverse-beta decay
- Ocean-based detector, with key features:



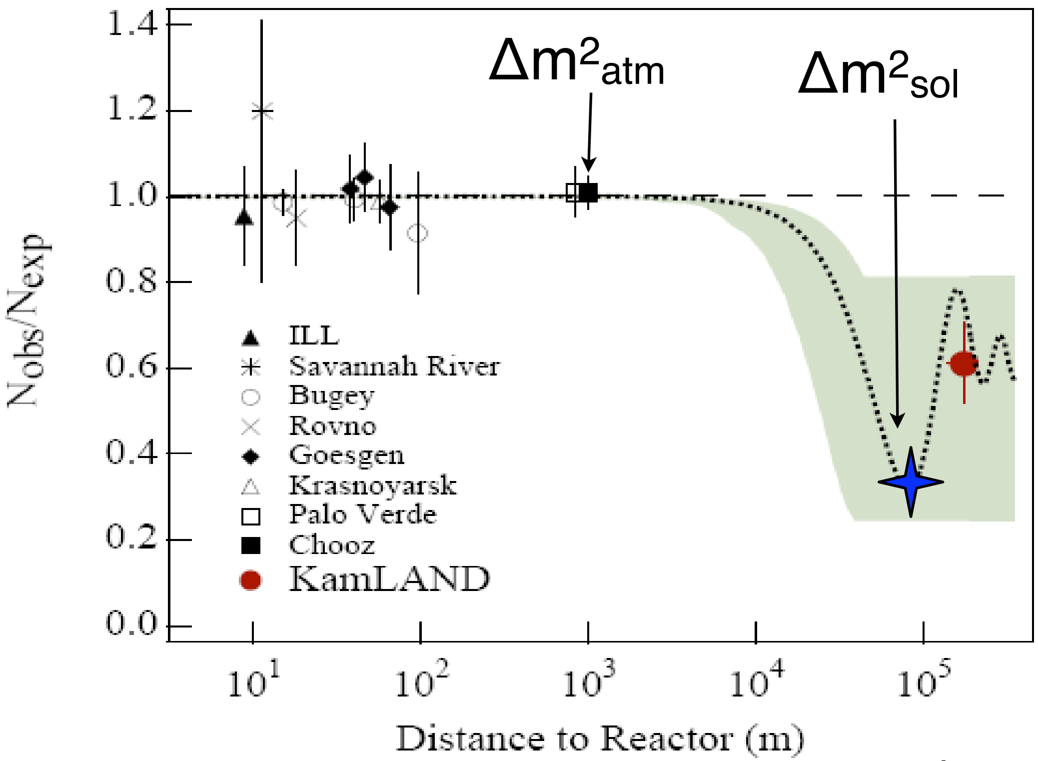
  - Adjustable baseline
  - Ability to avoid reactor background in the geo-neutrino studies
  - Unique sensitivity to mantle geo-neutrinos
  - Ability to avoid reactor background when needed
  - Additional physics measurements achievable to higher precision, due to large size

slides from J. Learned et al.

Precision Measurement of θ_{12} with Reactor Antineutrinos

A Future Opportunity?

$P(\nu_e \to \nu_e) \approx 1 - \sin^2(2\theta_{12}) \sin^2(\Delta m^2_{21} L/4E)$



60 GW·kt·y exposure at 50-70 km

- ~4% systematic error from near detector
- $\sin^2(\theta_{12})$ measured with ~2% uncertainty

Bandyopadhyay et al., Phys. Rev. D67 (2003) 113011.
Minakata et al., hep-ph/0407326
Bandyopadhyay et al., hep-ph/0410283

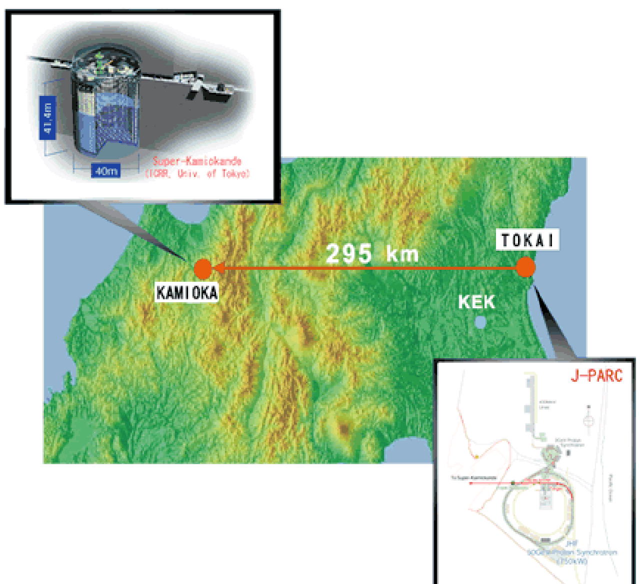
Measurement of the Oscillation Parameters: A Summary

- Mass Splitting
  - KamLAND measures Δm_{12}^2 to 2.8% precision. Best measurement of Δm_{12}^2.
- Neutrino Mixing Angles
  - KamLAND helps constrain the lower bound of the mixing angle θ_{12}. (Best measurement of θ_{12} from solar experiments.)
  - Next-generation reactor experiments will provide best sensitivity to θ_{13} in a clean, degeneracy-free measurement. (using baseline from $\Delta m^2_{13} \approx \Delta m^2_{23} = \Delta m^2_{atm}$)
  - Future long-baseline reactor antineutrino experiments may be used for a precision measurement of θ_{12} (using baseline from $\Delta m^2_{12} = \Delta m^2_{sol}$)

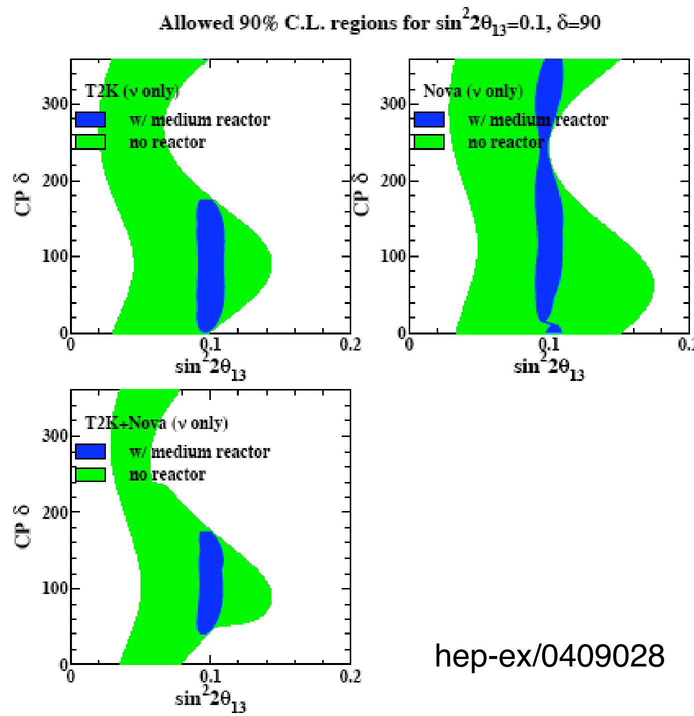
Future of Neutrino Oscillation Physics: Next 10 Years

Measurement of θ_{13} with reactor antineutrinos

Accelerator neutrino studies of $\nu_\mu \rightarrow \nu_e$

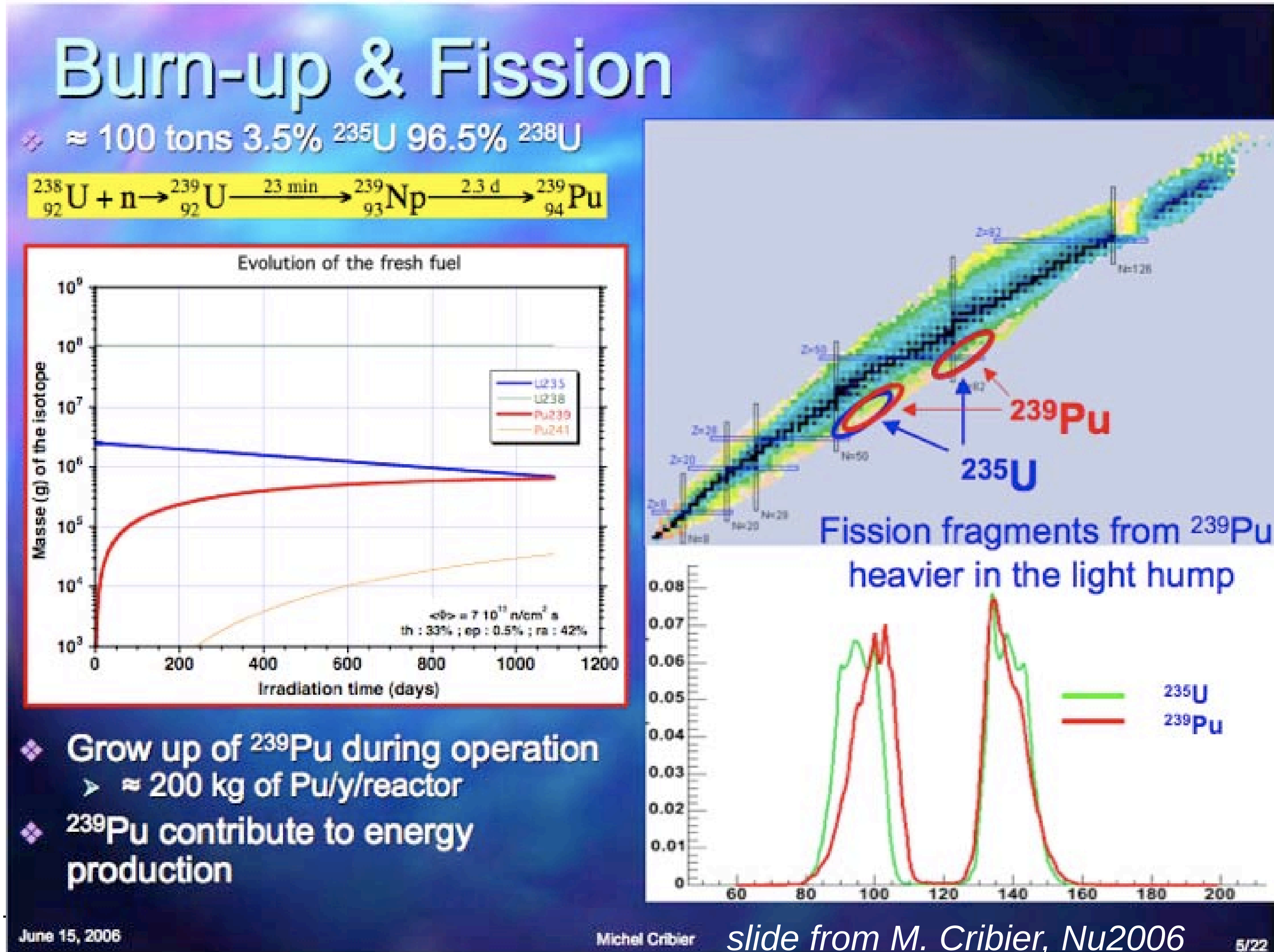


Constraining CP-violating parameters in combined analysis



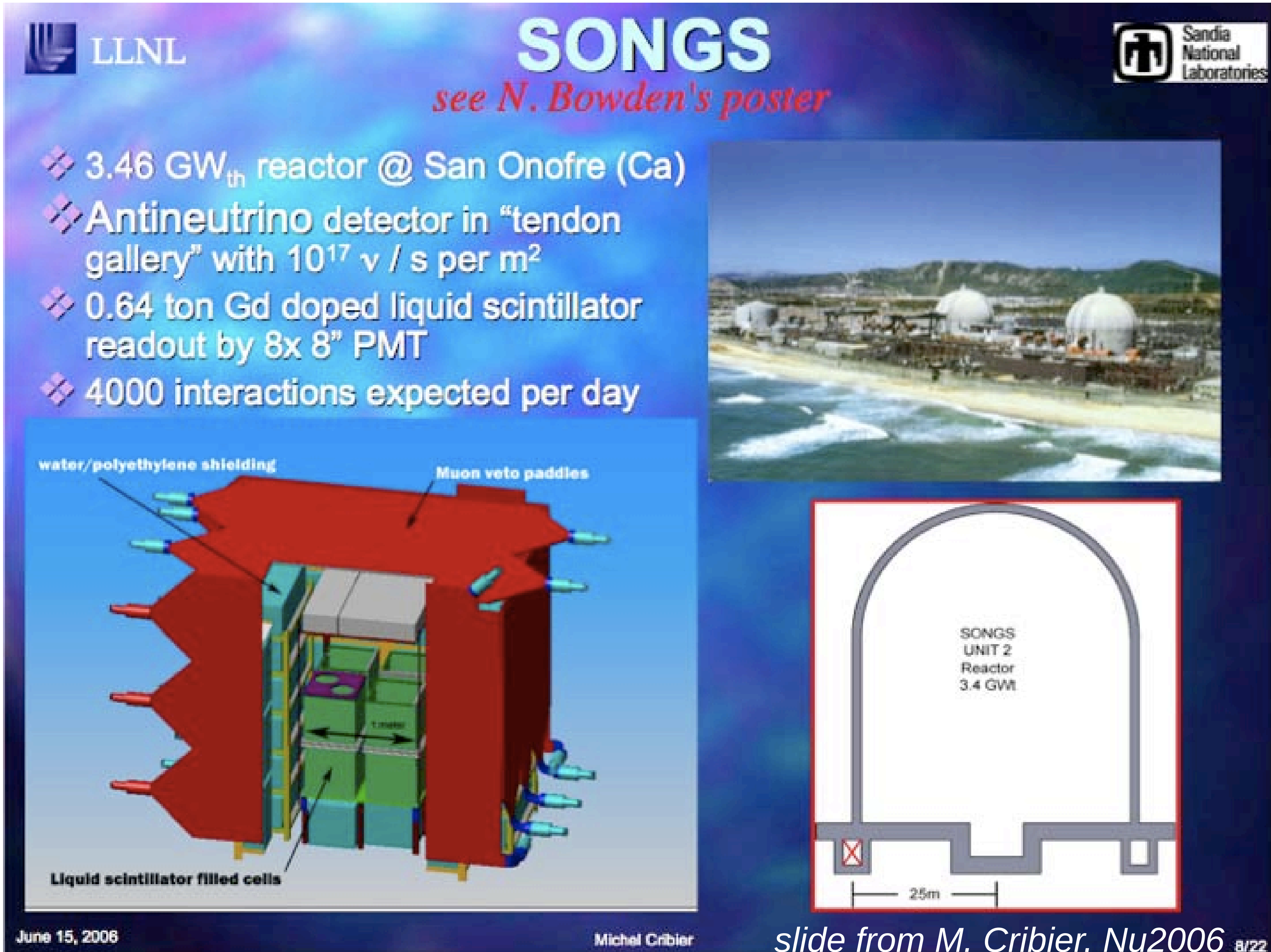
hep-ex/0409028

Applied Neutrino Physics: Reactor Monitoring



slide from M. Cribier, Nu2006

Reactor Monitoring in US



slide from M. Cribier, Nu2006

Proposal for Reactor Monitoring in Brazil

slide from M. Cribier, Nu2006

Neutrino Physics at Reactors: Past, Present, Future

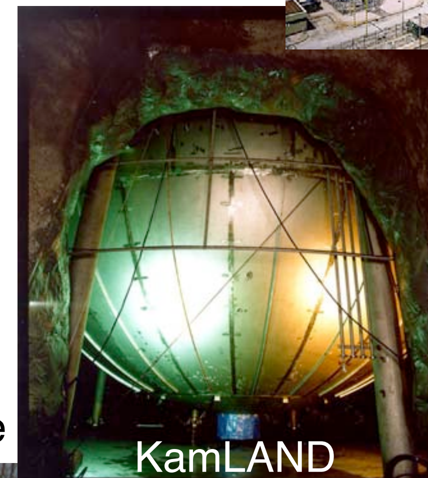
Next - Precision measurement of θ_{13}

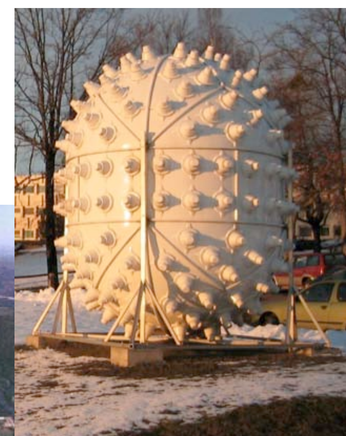
2007 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2004 - Evidence for spectral distortion

2003 - First observation of reactor antineutrino disappearance

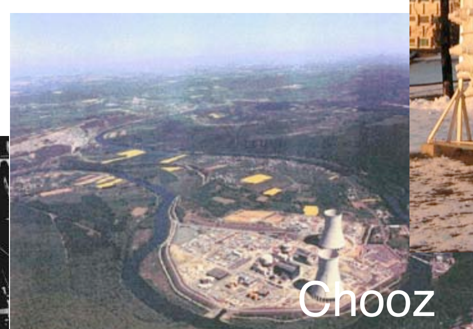
1995 - Nobel Prize to Fred Reines at UC Irvine



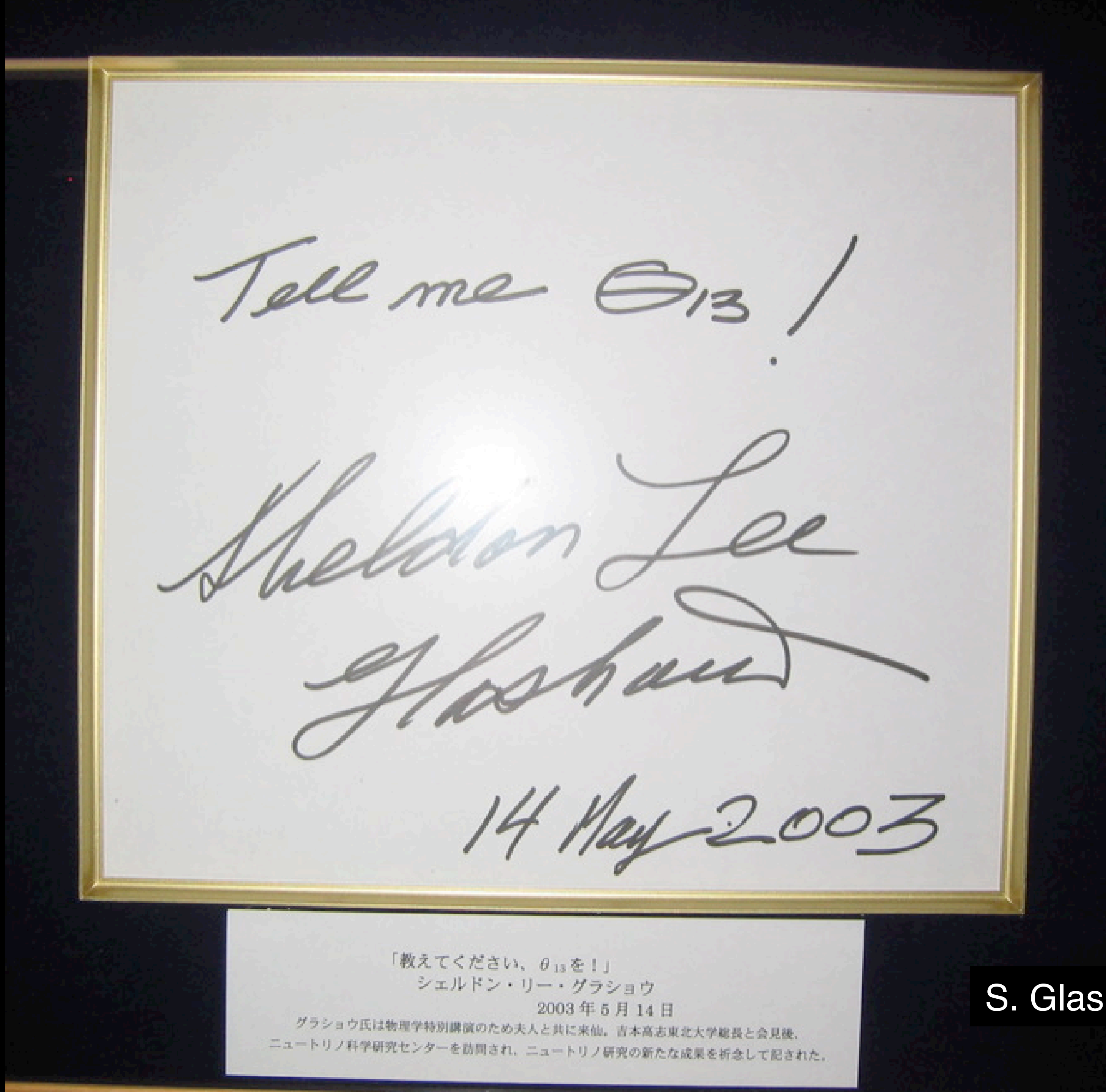


1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos



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


Tell me θ13 !
Sheldon Lee Glashow
14 May 2003
「教えてください、θ13を！」
シェルドン・リー・グラショウ
2003年5月14日
グラショウ氏は物理学特別講演のため夫人と共に来仙。吉本高志東北大学総長と会見後、
ニュートリノ科学研究センターを訪問され、ニュートリノ研究の新たな成果を祈念して記された。

S. Glashow