Reactor Neutrino Oscillation Experiments

- Recent Results and Future Prospects -

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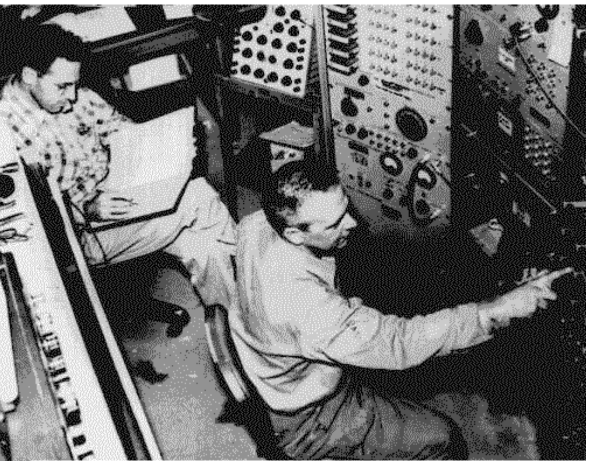
University of Wisconsin

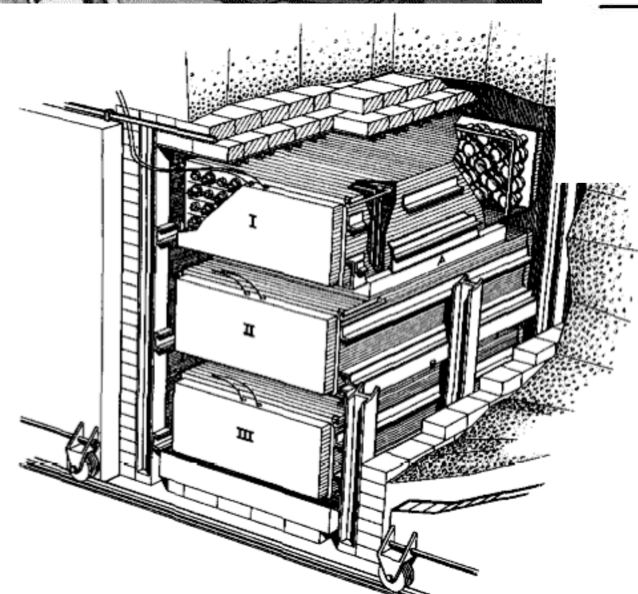
(on behalf of the KamLAND and Daya Bay collaborations)

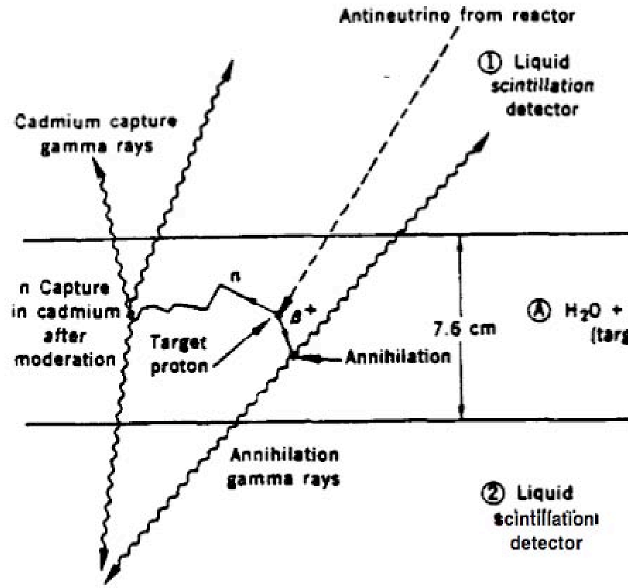
TAUP2007, Sendai, Japan

Early History

1956 - "Observation of the Free Antineutrino" by Reines and Cowan



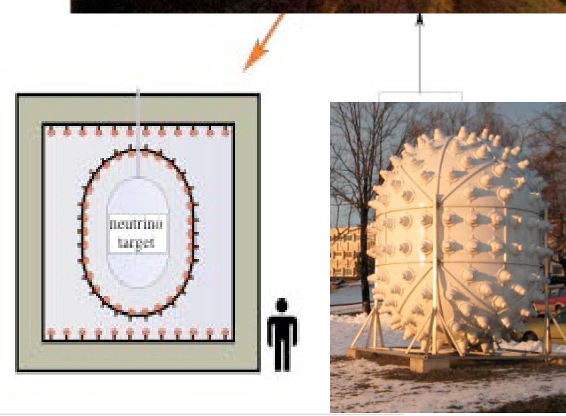




inverse beta decay

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

1990's - Oscillation Searches at Chooz + Palo Verde: $\bar{\nu}_e \rightarrow \nu_x$



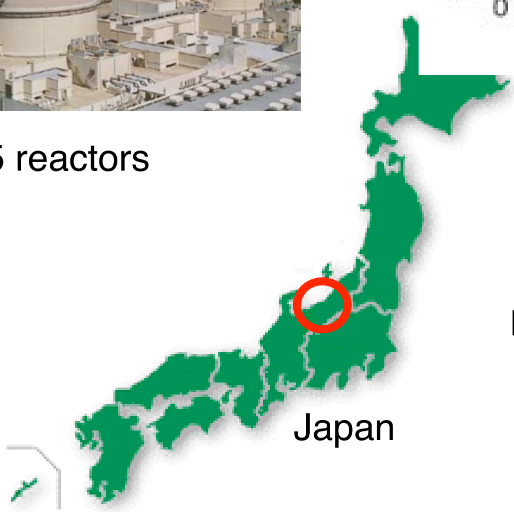
Chooz, Ardennes, France

reactor $\bar{\nu}_e$ flux measurement with 1 detector

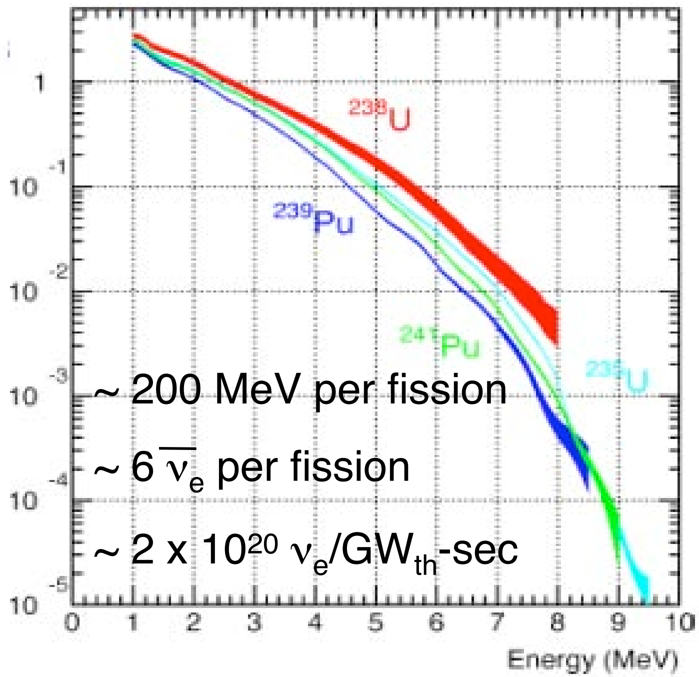
Measurement of Reactor Antineutrinos in KamLAND

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

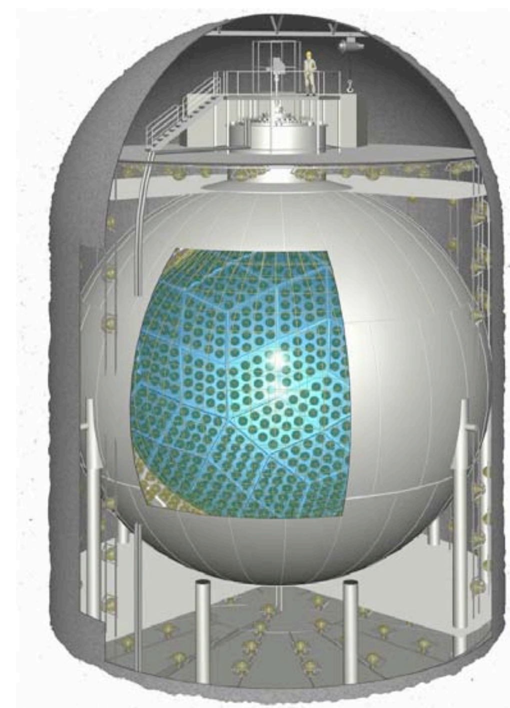
^{235}U:^{238}U:^{239}Pu:^{241}Pu =
0.570: 0.078:0.0295:0.057

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

Antineutrino Detection in KamLAND

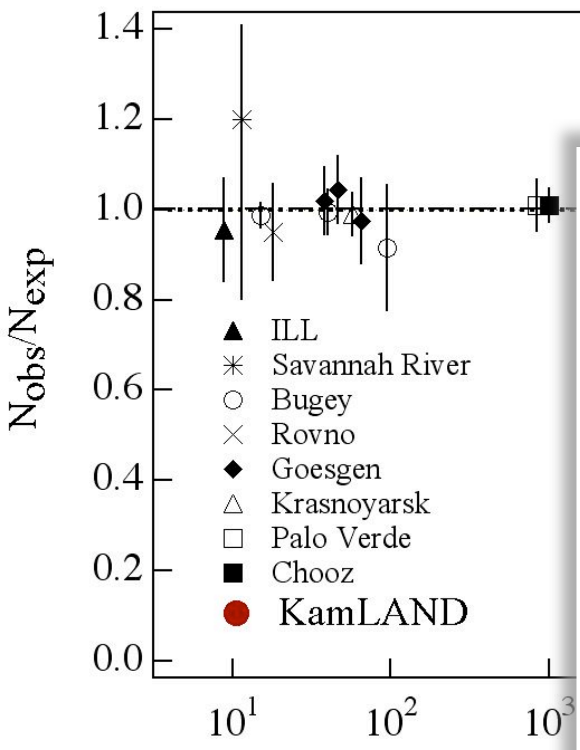
$\overline{\nu}_e + p \rightarrow e^+ + n$

through inverse β-decay



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

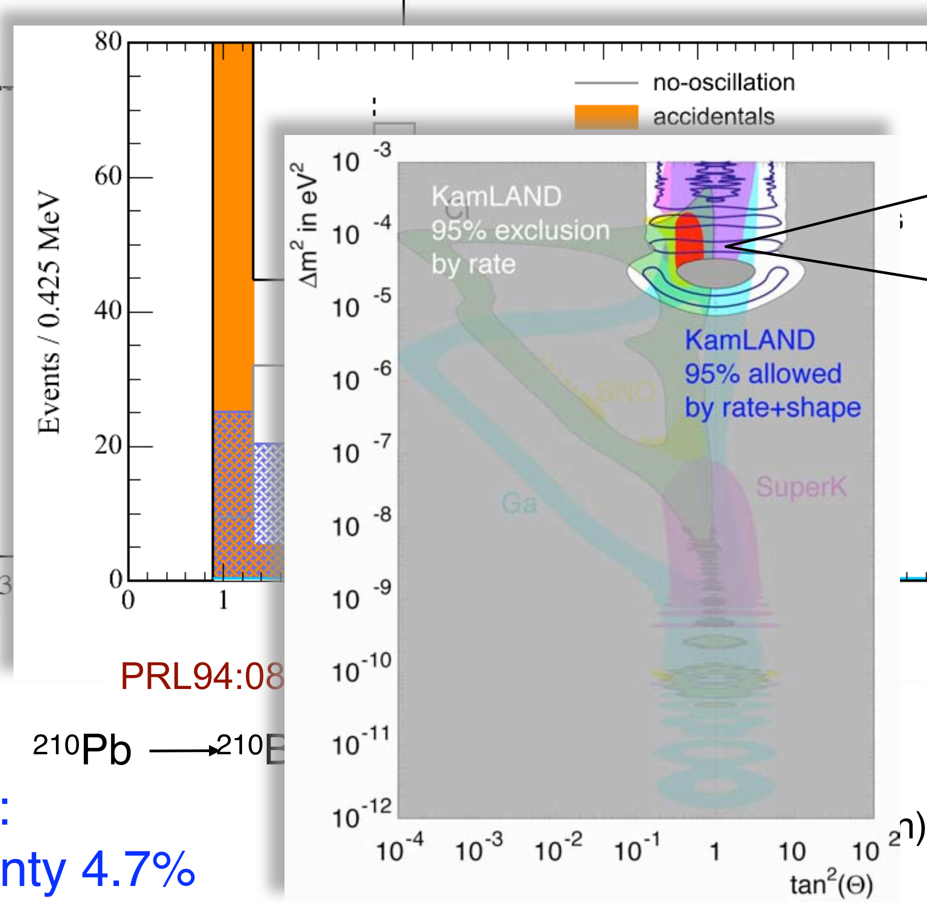
Reactor Neutrino Physics 1956-2004

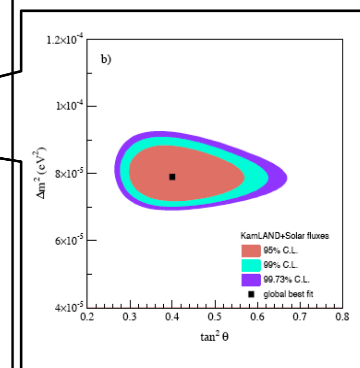


PRL 90:021802 (2003)

KamLAND 2002

KamLAND 2004





largest systematic error:
fiducial volume uncertainty 4.7%

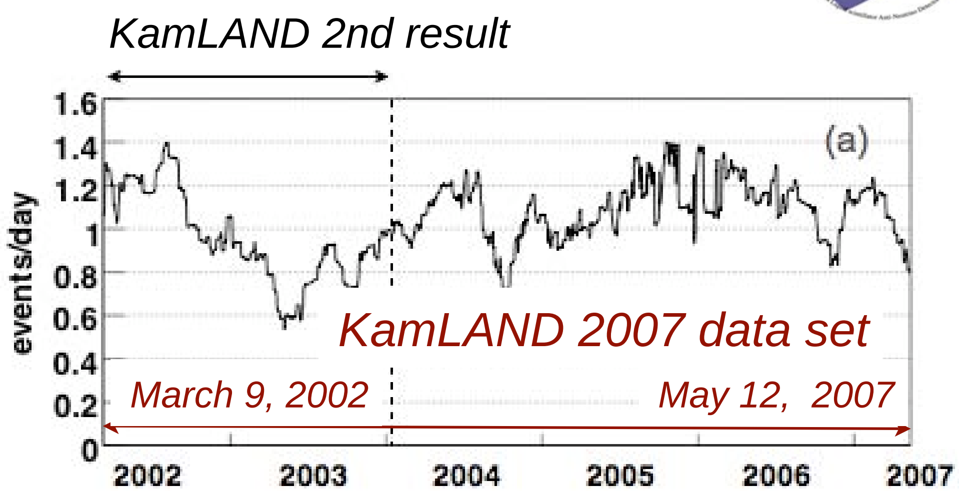
Precision Neutrino Oscillation Parameters with KamLAND

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

  → see I. Shimizu's talk
- reduced systematic in target protons (fiducial volume)

  → see following slides

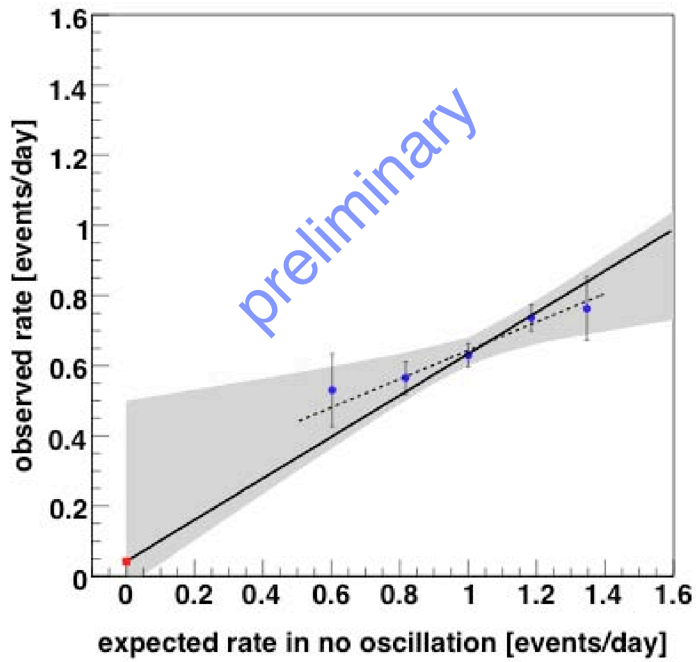


In KamLAND 2007 analysis:

fiducial volume: $R_p, R_d < 6.0m$

livetime 1491 days

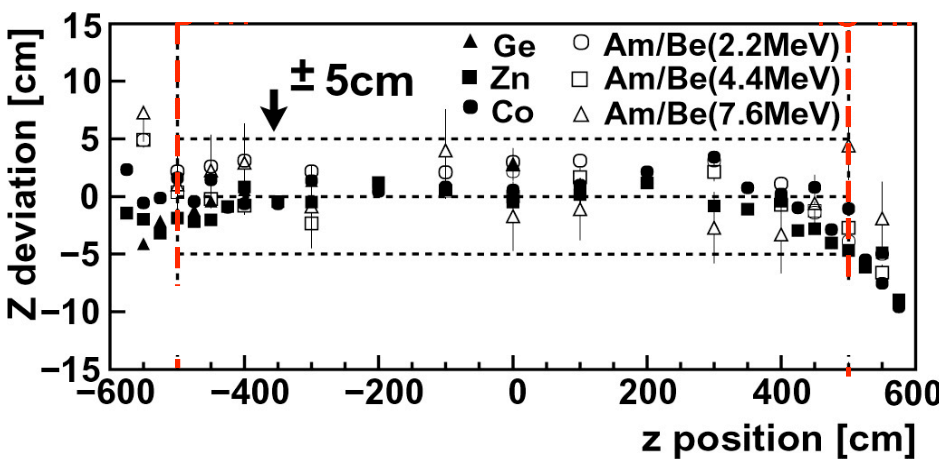
exposure: 2.44×10^{32} proton-year

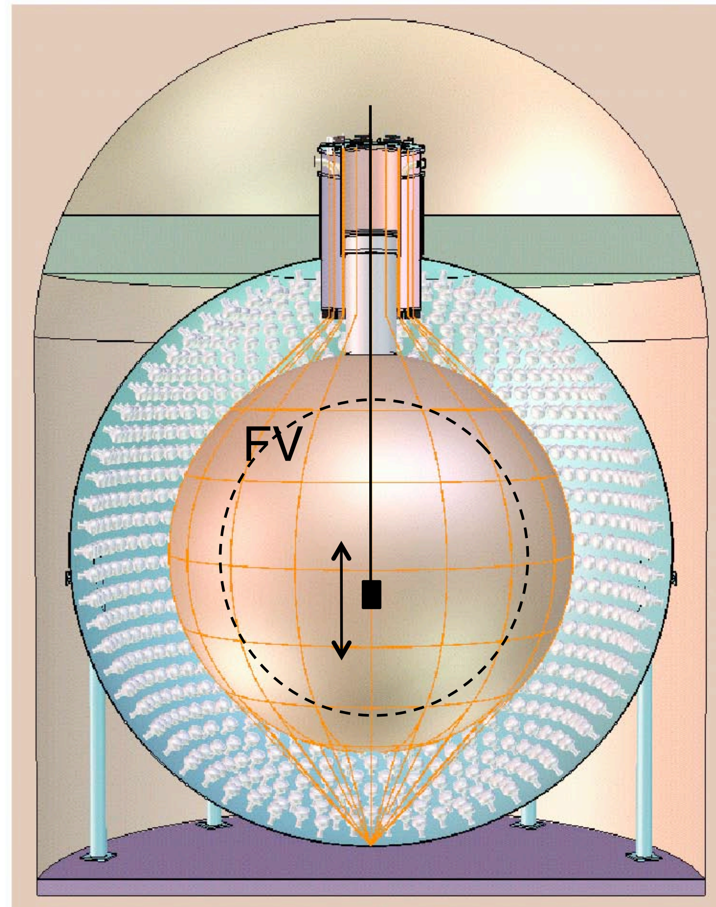


KamLAND "Z-axis Calibration"

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		



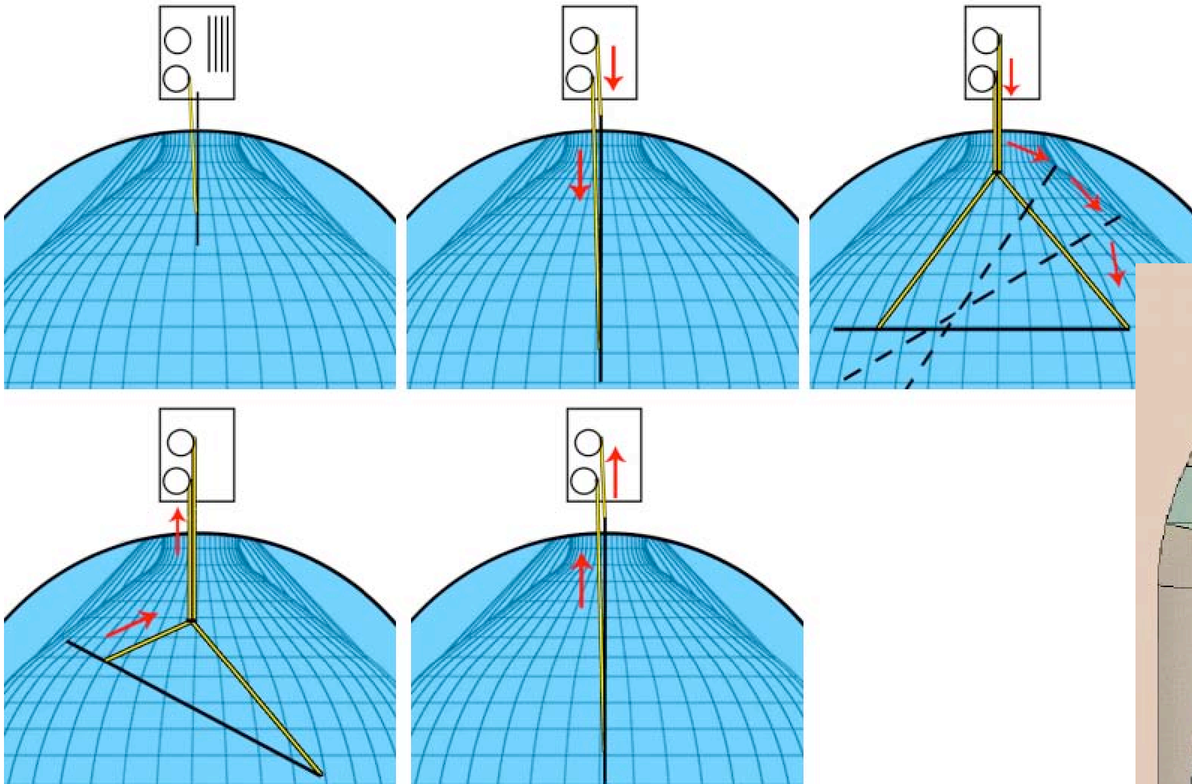


new: also used a $^{210}Po^{13}C$ source to study the $^{13}C(\alpha,n)^{16}O$ reaction and to calibrate MC code

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

KamLAND 4π "Full-Volume" Calibration

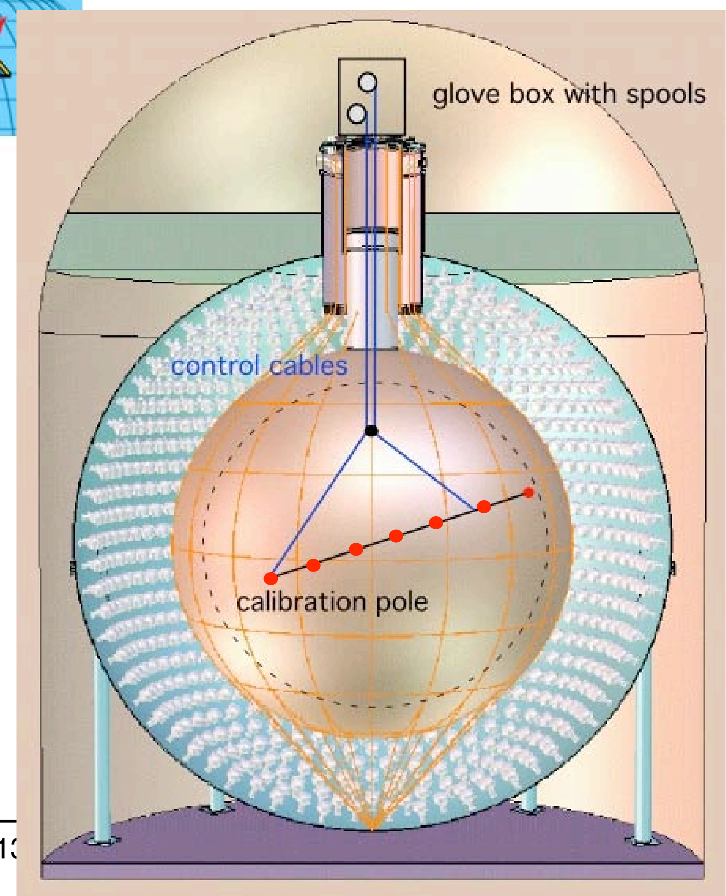
Calibration throughout entire detector volume



Calibration volume: R < 5.5 m

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

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

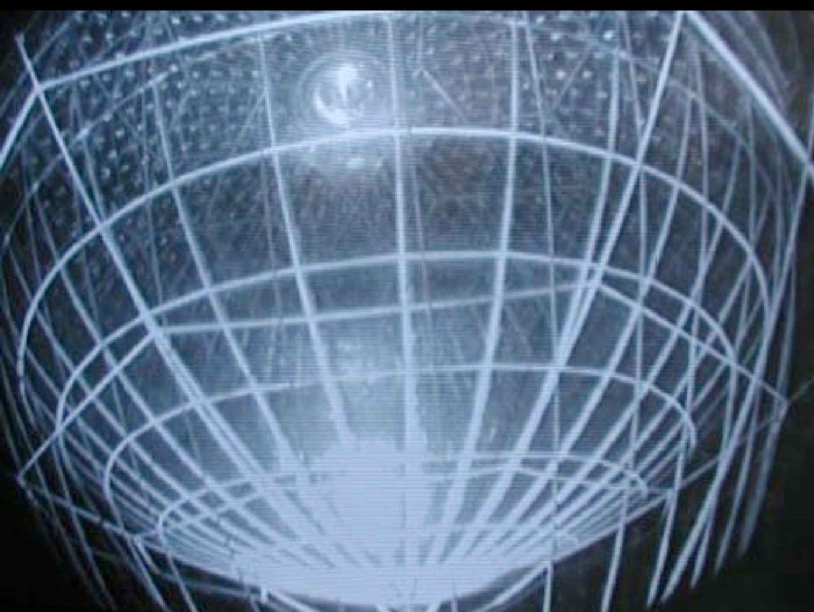


Can study position dependence of detector response:

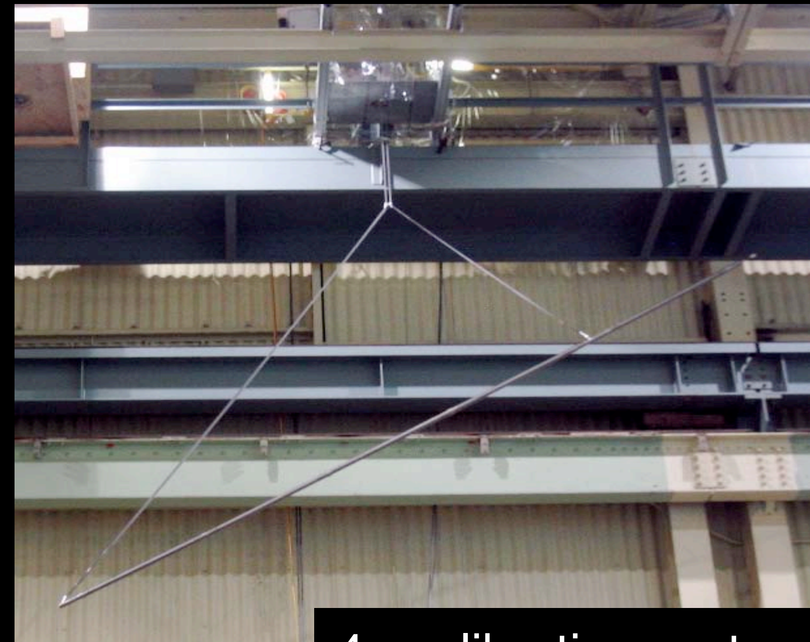
Event energy	$E(r,\theta,\phi)$
Vertex reconstruction	$R_{fit}(r,\theta,\phi)$

4π Full-Volume Calibration

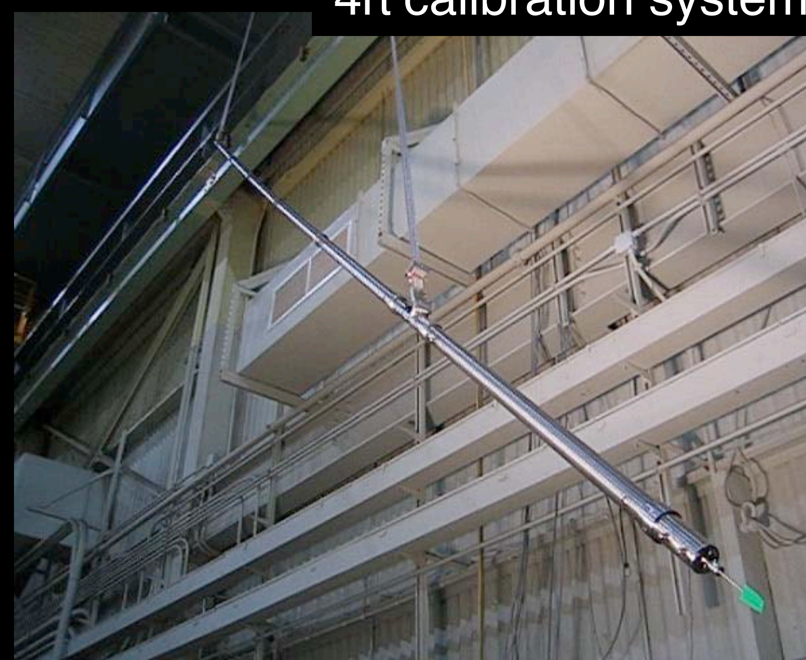
calibration deck



inside view of KamLAND detector

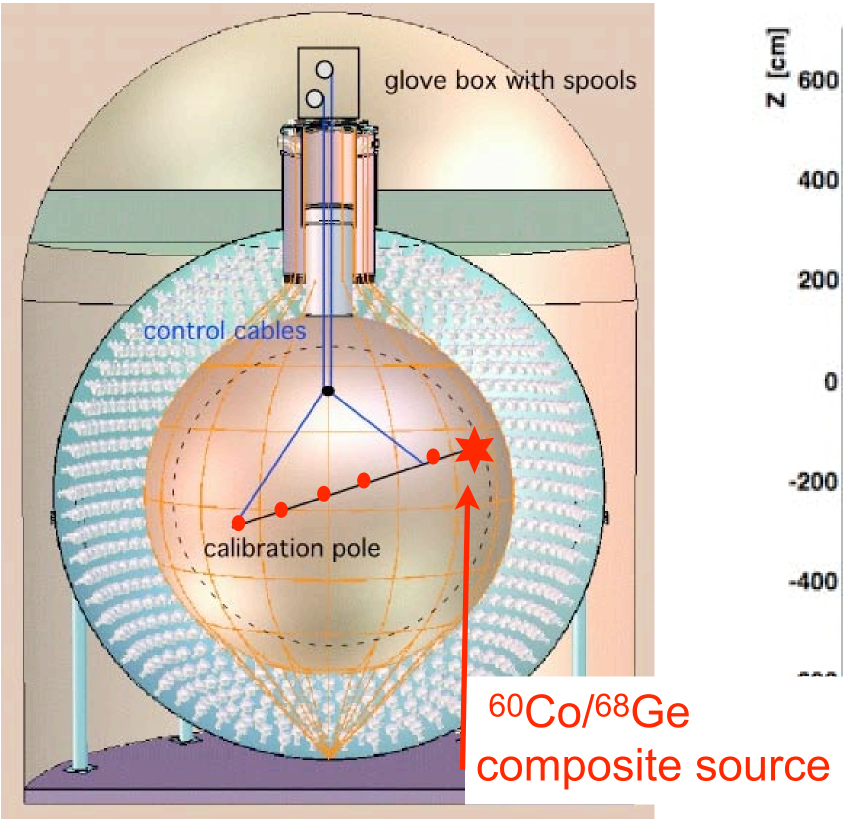


4π calibration system

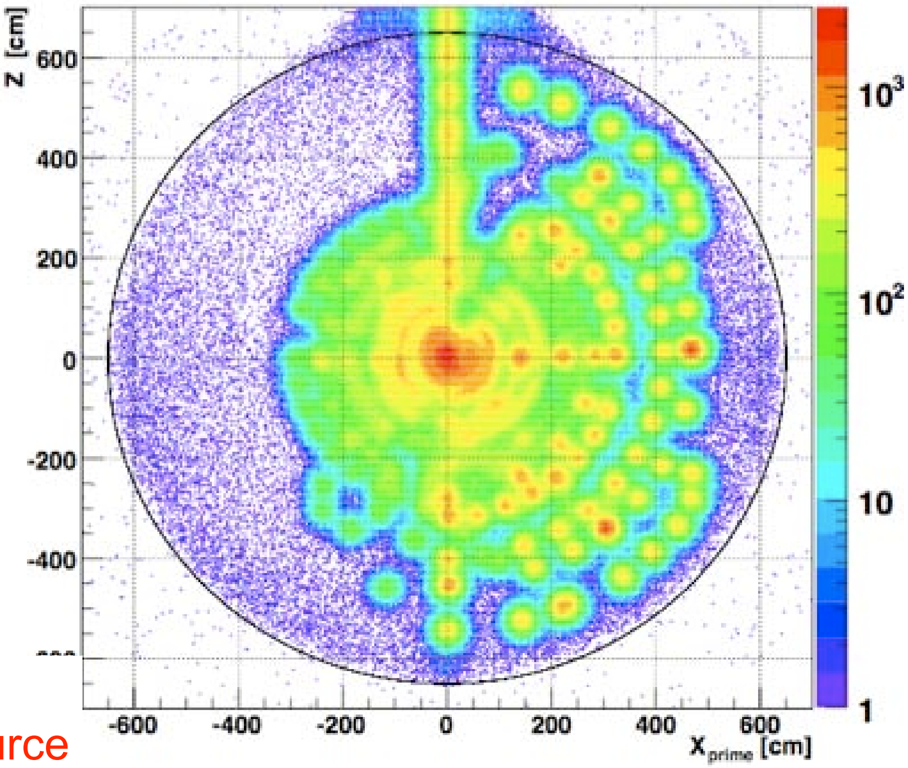


4π Full-Volume Calibration of KamLAND

Artist's conception of 4π system



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



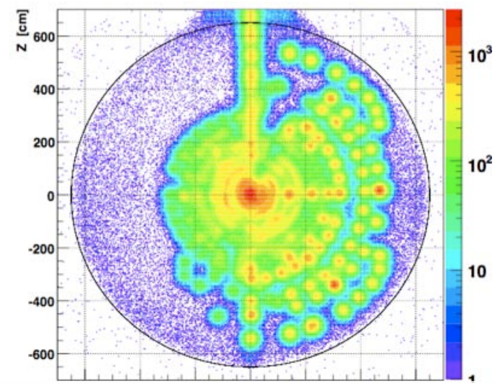
X_{prime} axis is defined by azimuth angle of the source.

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

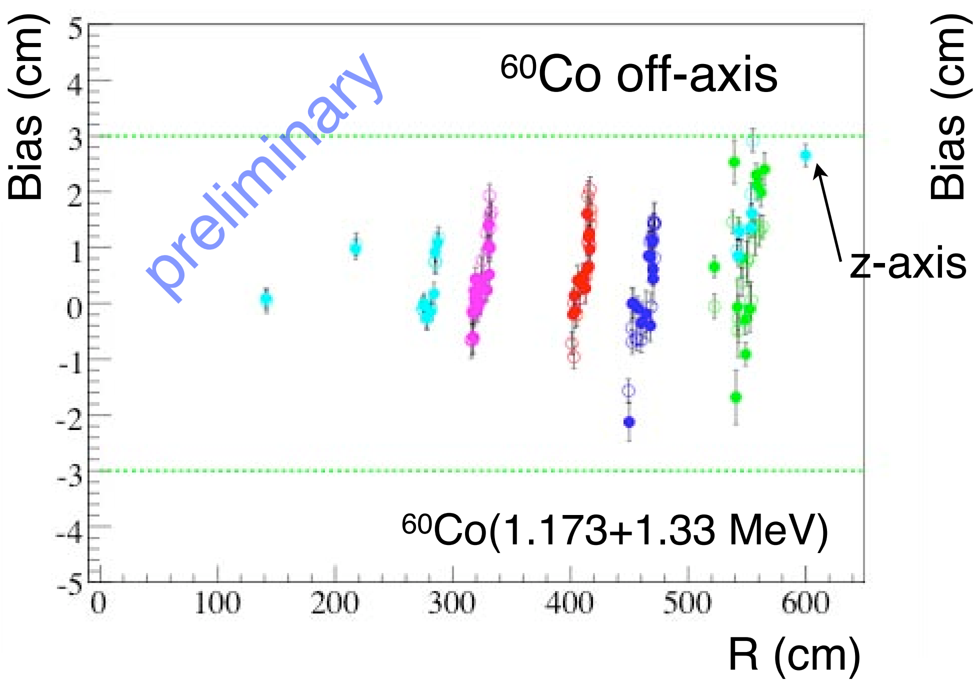
Radial Dependence of Vertex Reconstruction Biases

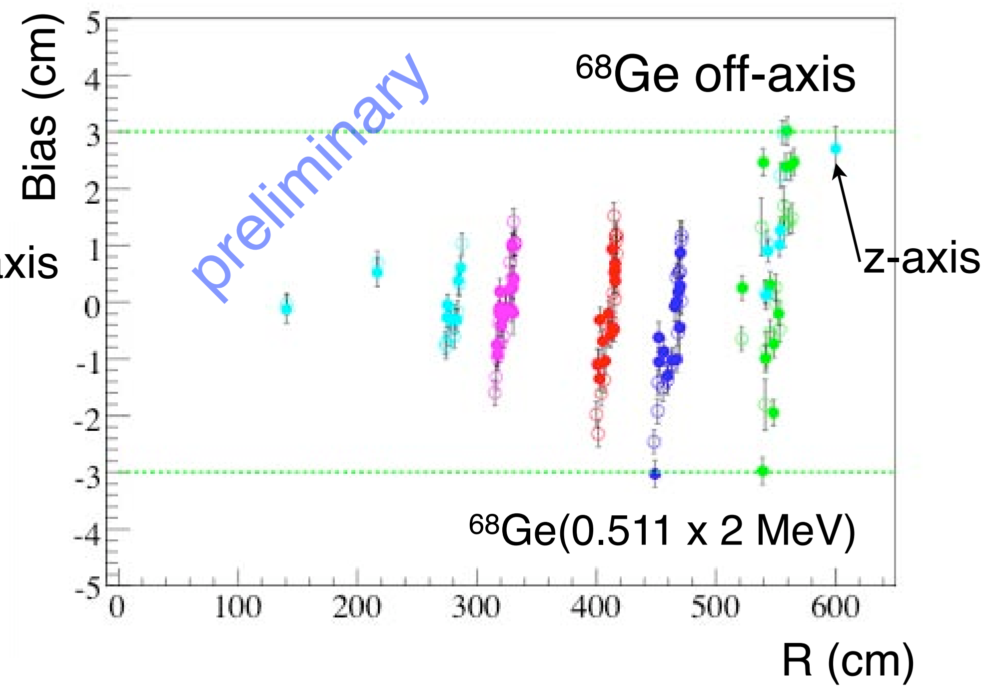
source location radii R ~ 2.8, 3.3, 4.1, 4.6, 5.5m

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



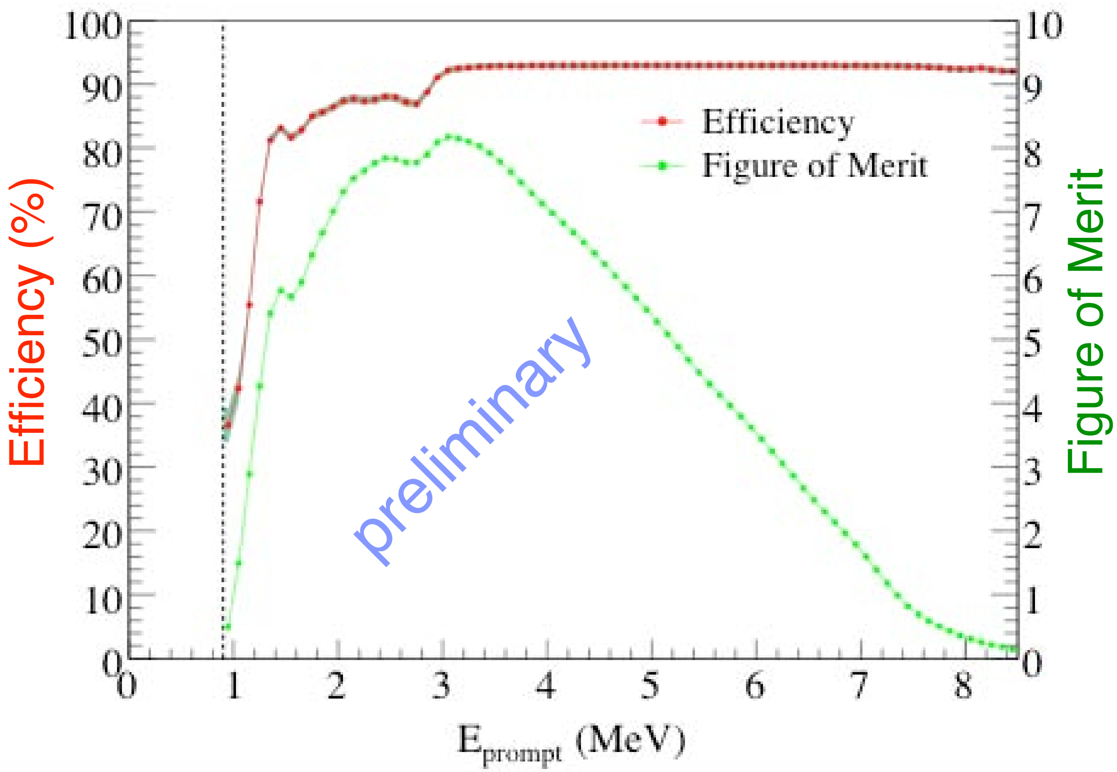
spallation products are used to extend fiducial volume from 5.5 to 6m





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

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

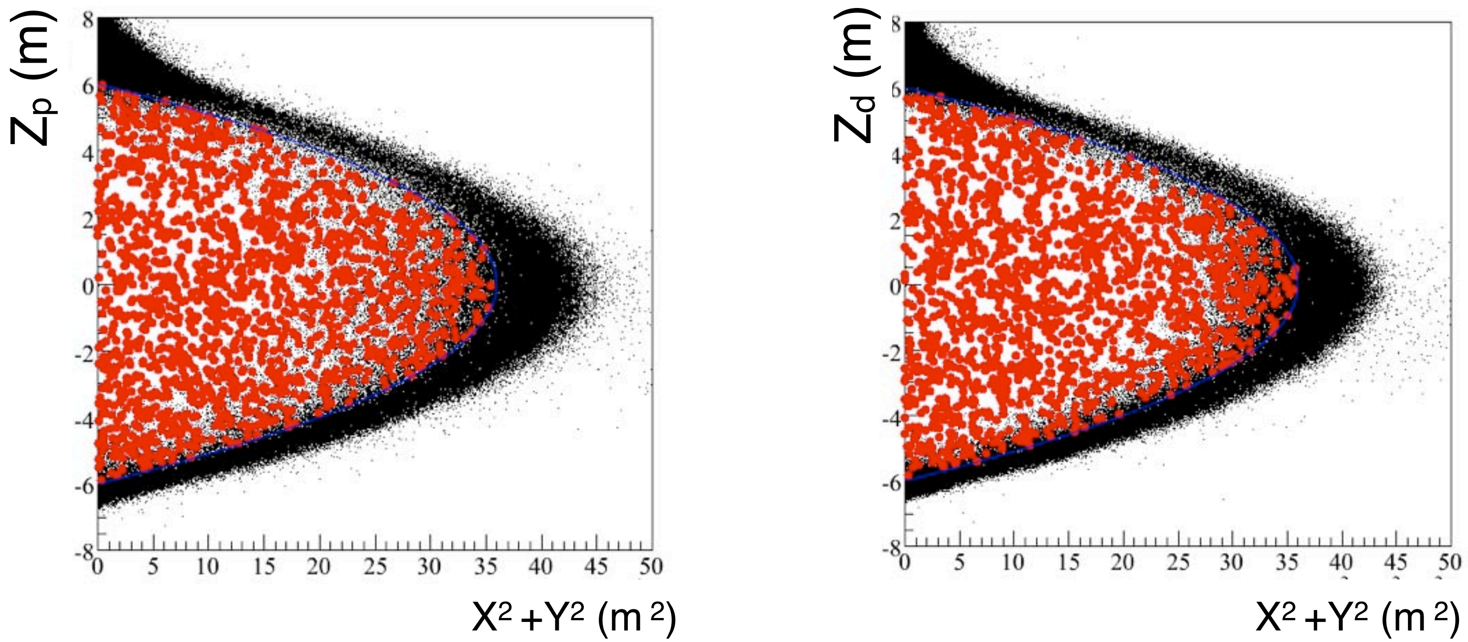
4. maximize figure of merit

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

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

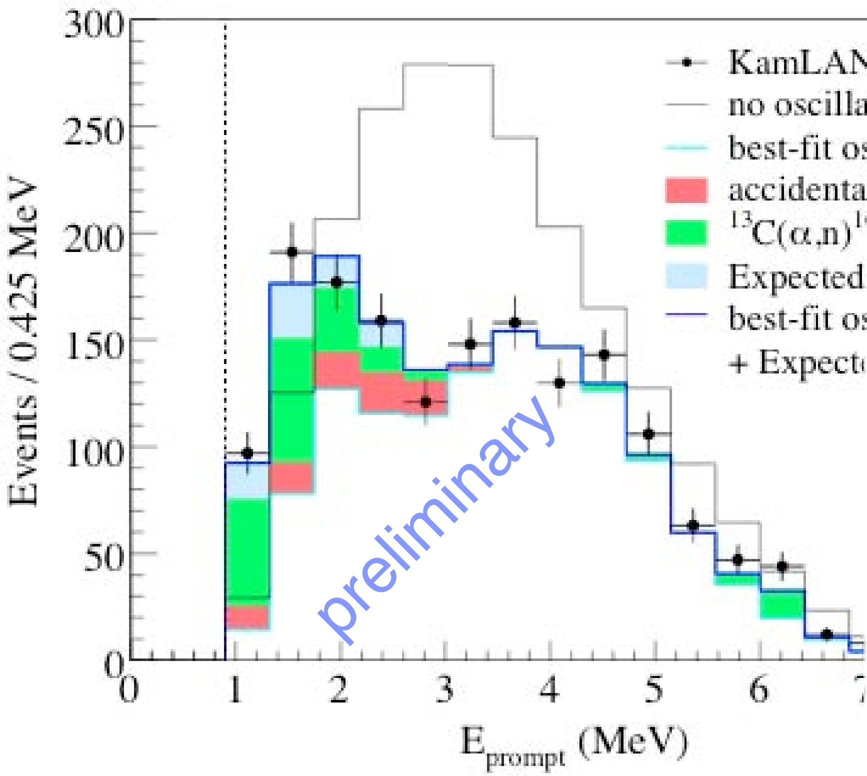


red = events with fiducial volume and likelihood ratio cut

→ likelihood selection will be discussed in Shimizu's talk

KamLAND 2007 Data

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



number of events

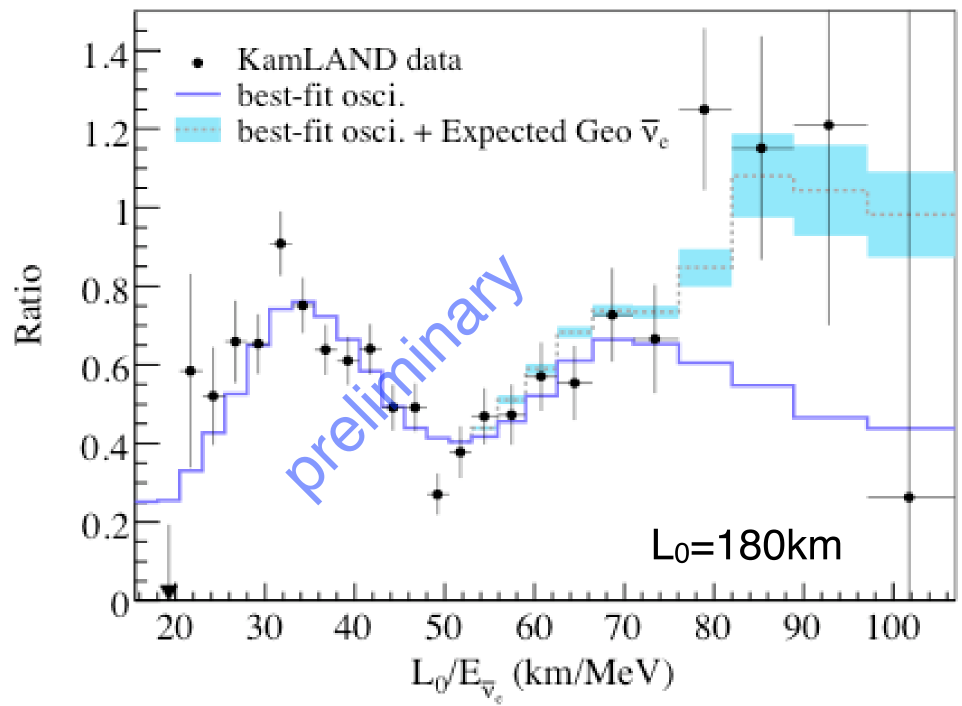
expected (no-oscillation): 2178

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.)

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
$^{13}C(\alpha,n)^{16}O$ G.S.	157.2 ± 17.3
$^{13}C(\alpha,n)^{16}O$ $^{12}C(n,n\gamma)^{12}C$ (4.4 MeV γ)	6.1 ± 0.7
$^{13}C(\alpha,n)^{16}O$ 1st exc. state (6.05 MeV e^+e^-)	15.2 ± 3.5
$^{13}C(\alpha,n)^{16}O$ 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total excluding geo-neutrinos	276.1 ± 23.5

preliminary

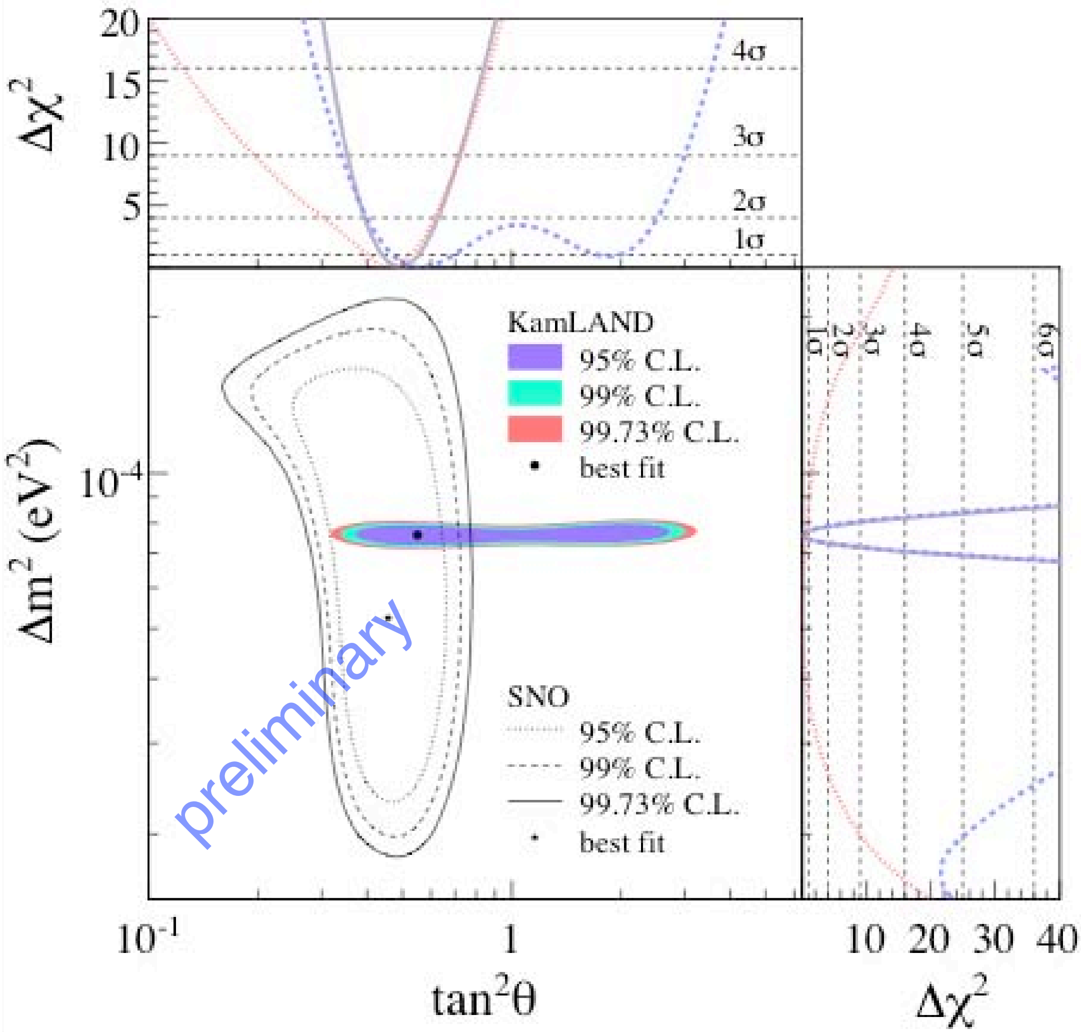
estimated backgrounds in the data set

(number of events)

→ geo-neutrinos will be discussed in Shimizu's talk

KamLAND Oscillation Parameters

Rate-Shape-Time Analysis



KamLAND only

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

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

KamLAND+SNO

$\tan^2\Theta = 0.49\ ^{+0.07}_{-0.05}$

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

For more details on reactor analysis see:
- talk by I.Shimizu, Fri, afternoon
- poster by K. Ichimura
- poster by Y. Minekawa

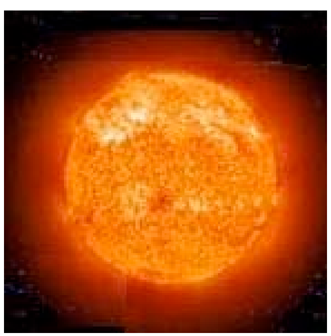
Ref: SNO contour from
http://www.sno.phy.queensu.ca/

KamLAND (Anti-)Neutrino Program

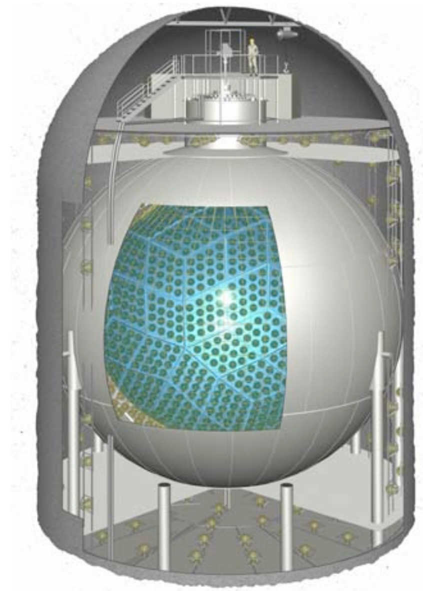
Reactor Antineutrinos

→ *Fri, Room A: I. Shimizu*
→ *posters: K. Ichimura*
→ *posters: Y. Minekawa*

Anti-Neutrinos from the Sun



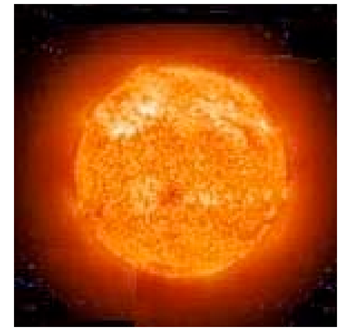
PRL 92:071301 (2004)



Other Physics Studies

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

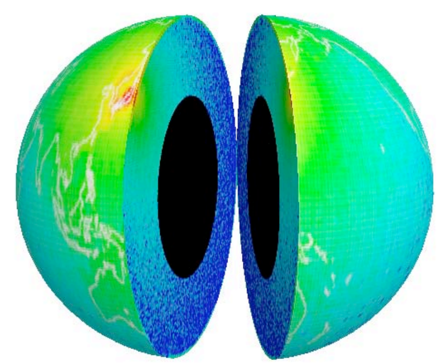
Solar ^{7}Be Neutrinos



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

→ *Wed, Room B: Y. Kishimoto*

Terrestrial Antineutrinos



Nature 436, 499-503 (28 July 2005)

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

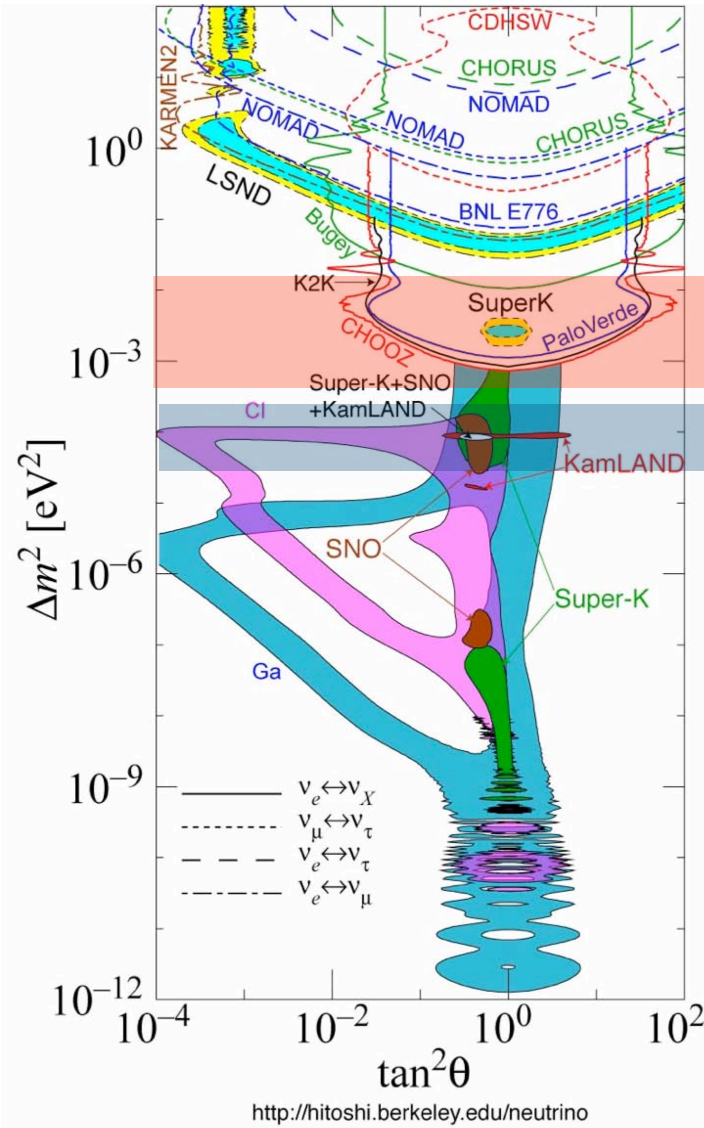
University of Tennessee

UNC/NCSU/TUNL

IN2P3-CNRS and University of Bordeaux

University of Wisconsin

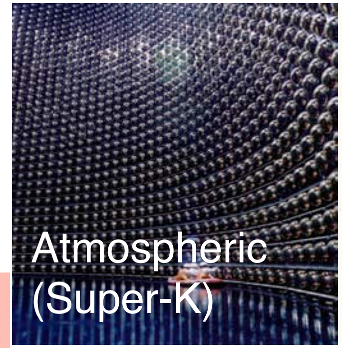
Discovery Era in Neutrino Physics: 1998 - Present

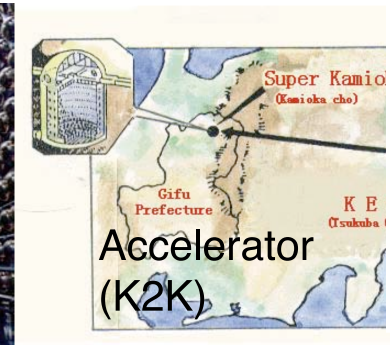


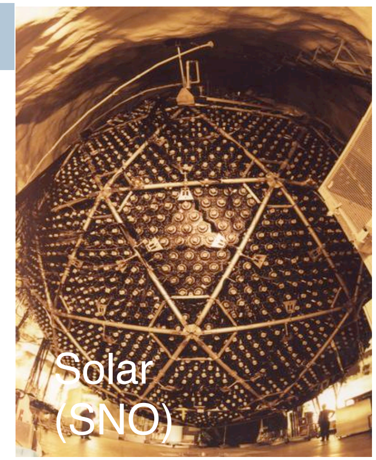
$\nu_\mu \Rightarrow \nu_\tau$

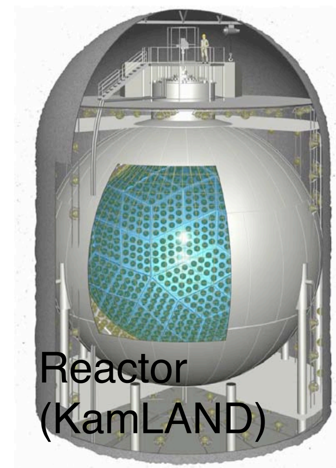
$\nu_e \Rightarrow \nu_{\mu,\tau}$

Δm_{ij}^2 measured *and* confirmed.









SK: zenith angle dependence of atm ν_μ

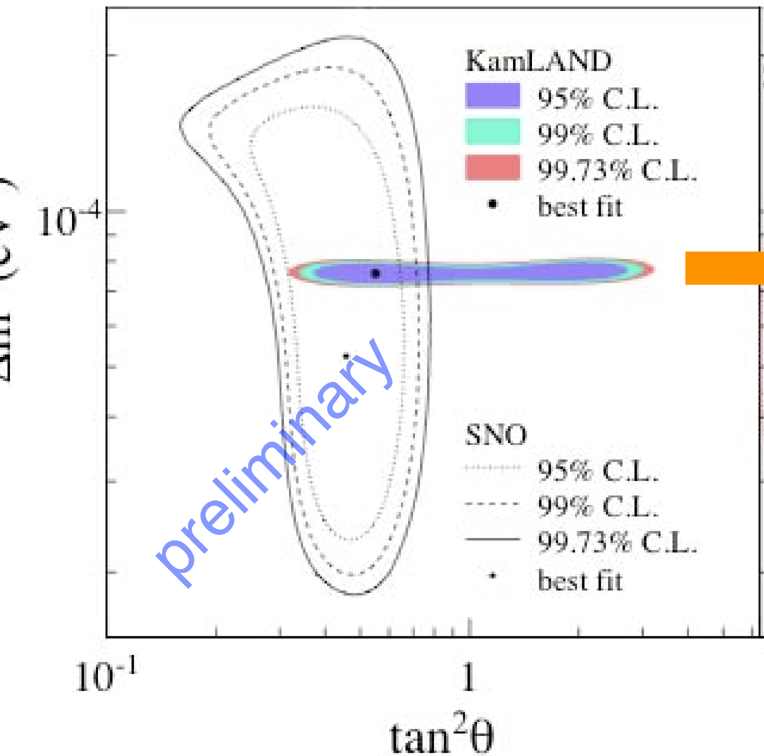
SNO: solar ν_e flavor transformation

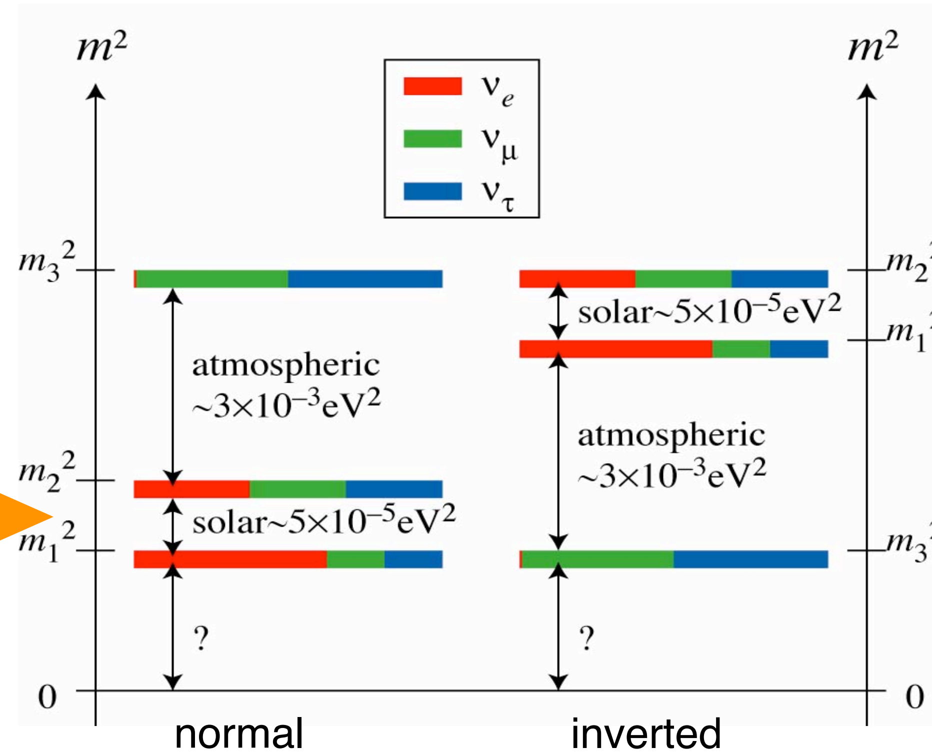
KamLAND: reactor $\overline{\nu}_e$ disappearance

Precision Measurement of Oscillation Parameters

Neutrino Mass Splitting

KamLAND 2007



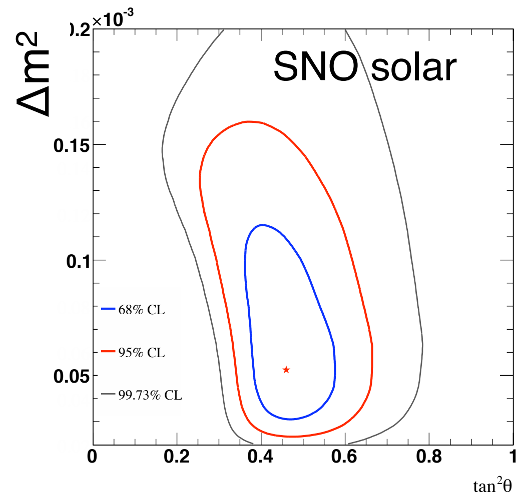


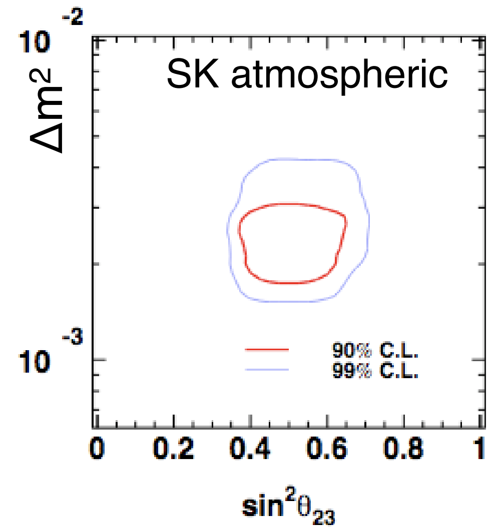
- KamLAND provides best measurement of Δm_{12}^2 to 2.8% precision

- 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 | 0νββ

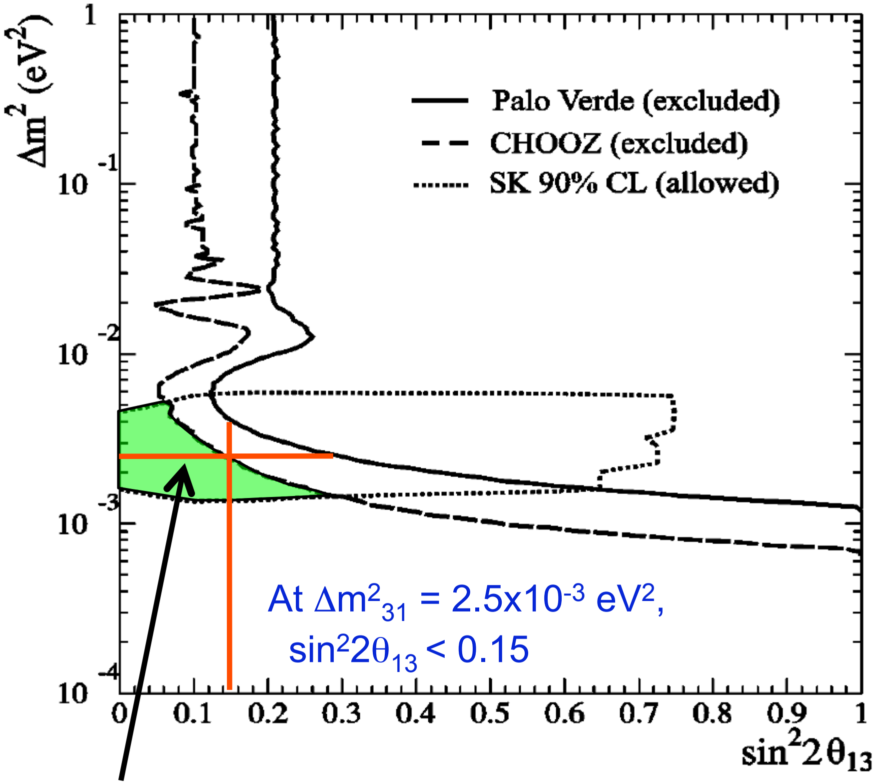
$\theta_{23} = \sim 45°$

$\theta_{13} = ?$

$\theta_{12} \sim 32°$

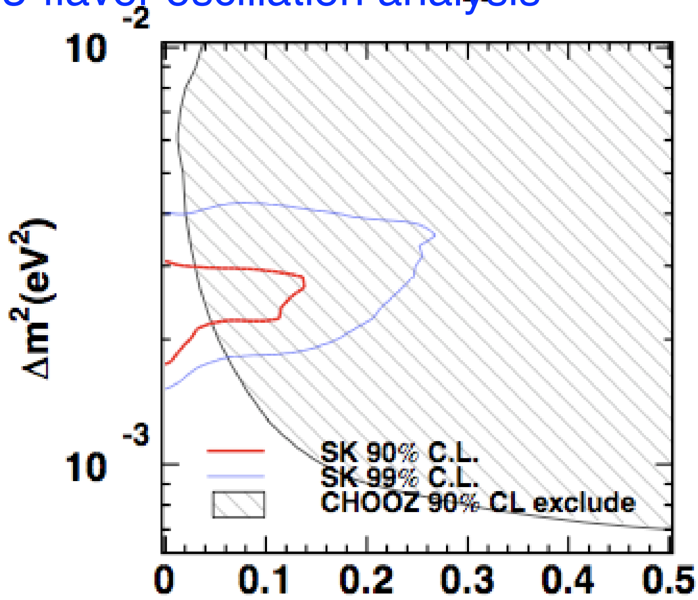
Current Knowledge of θ_{13}

Direct search at Chooz and Palo Verde



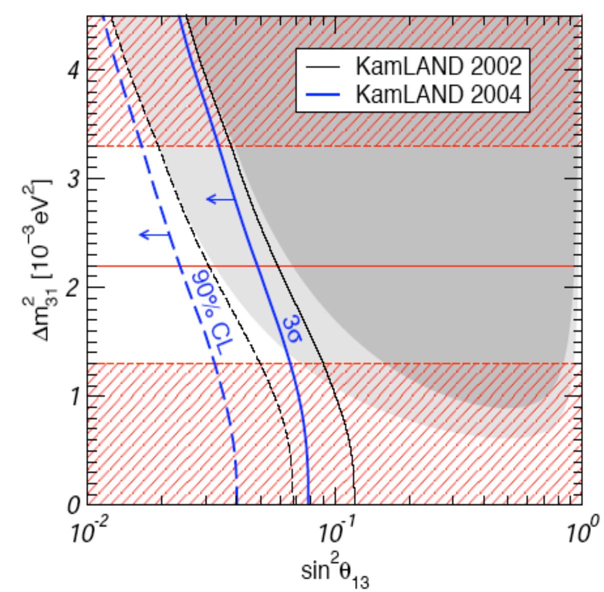
allowed region

SK 3-flavor oscillation analysis

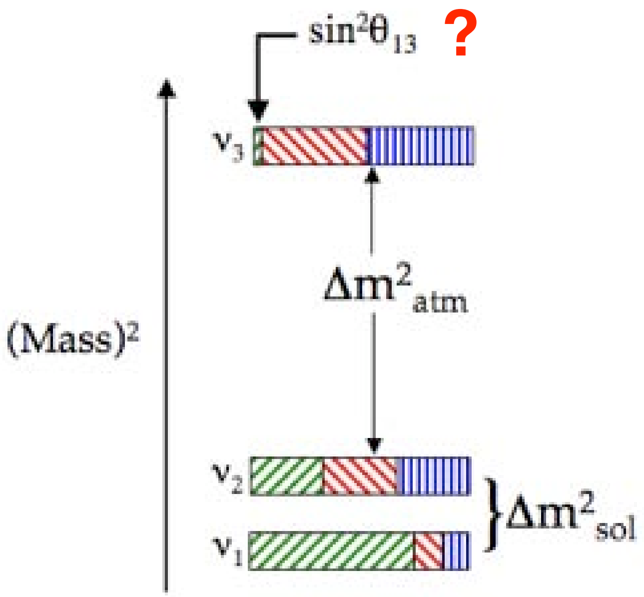


Ref: hep-ex/0604011

Global analysis of solar+other data



θ_{13} and Particle Physics



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

Is there μ–τ symmetry in neutrino mixing?

Can we search for leptonic ~~CP~~?

θ_{13} 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)

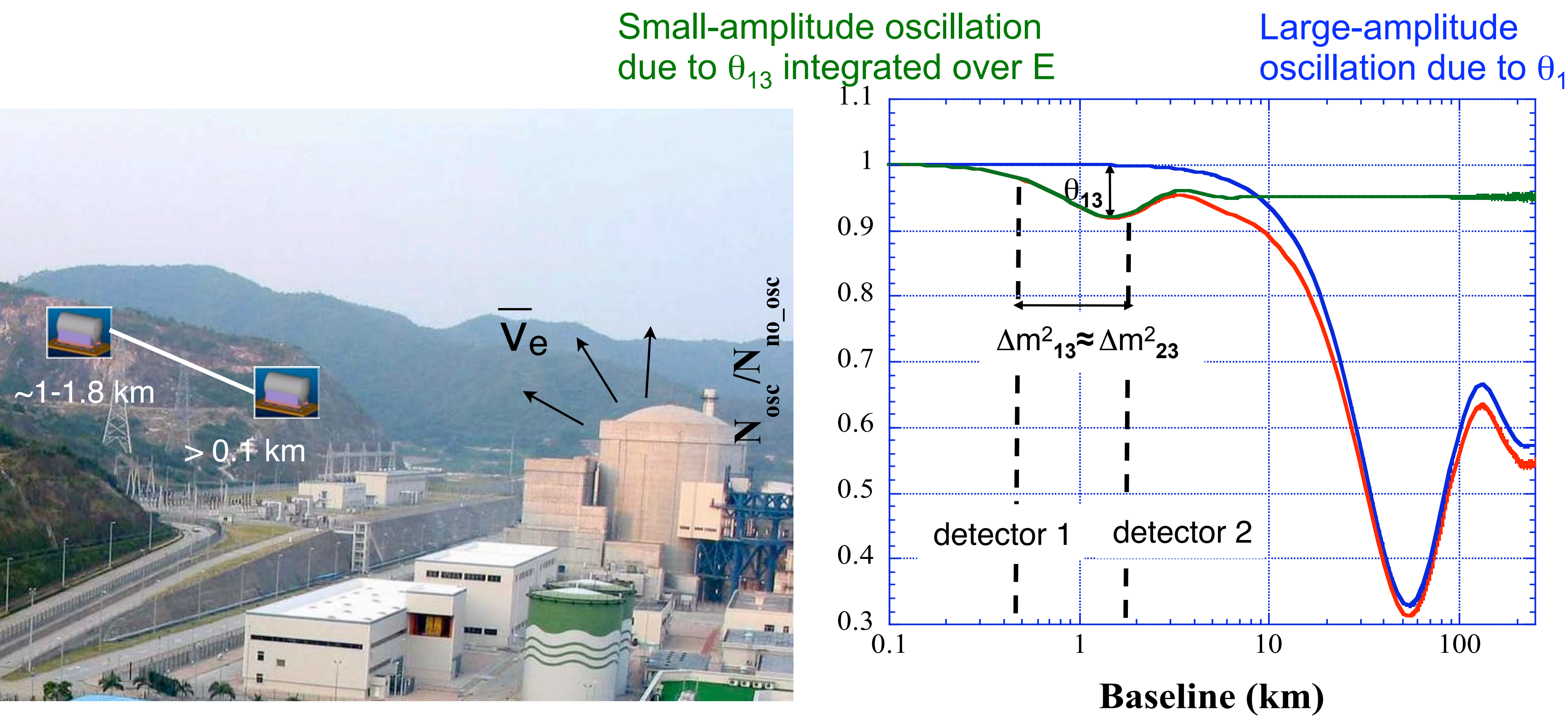
$$\begin{aligned}P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}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

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

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

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

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



Detecting Reactor $\bar{\nu}_e$

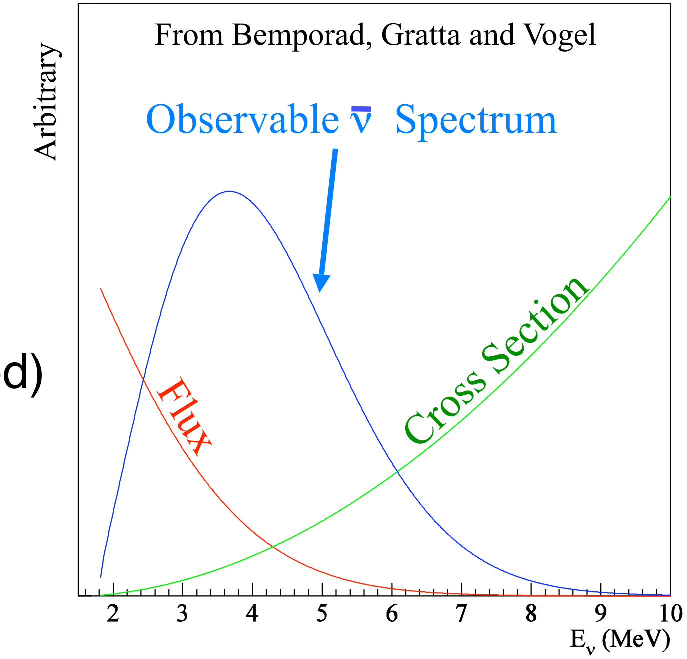
$\bar{\nu}_e + p \rightarrow e^+ + n$

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



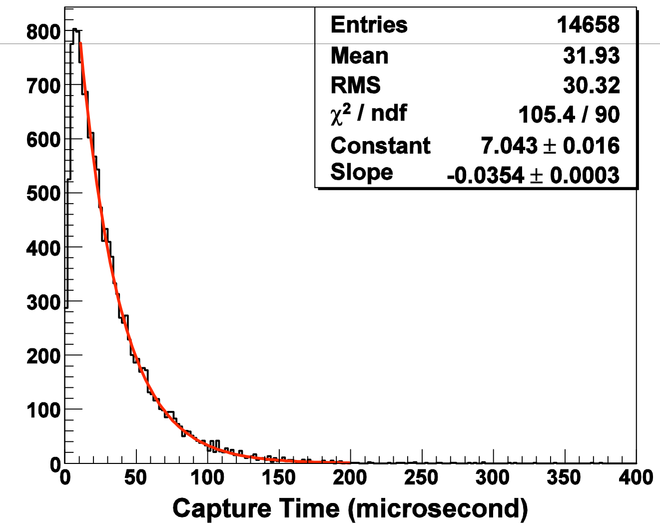
0.1% Gadolinium-Liquid Scintillator

- 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

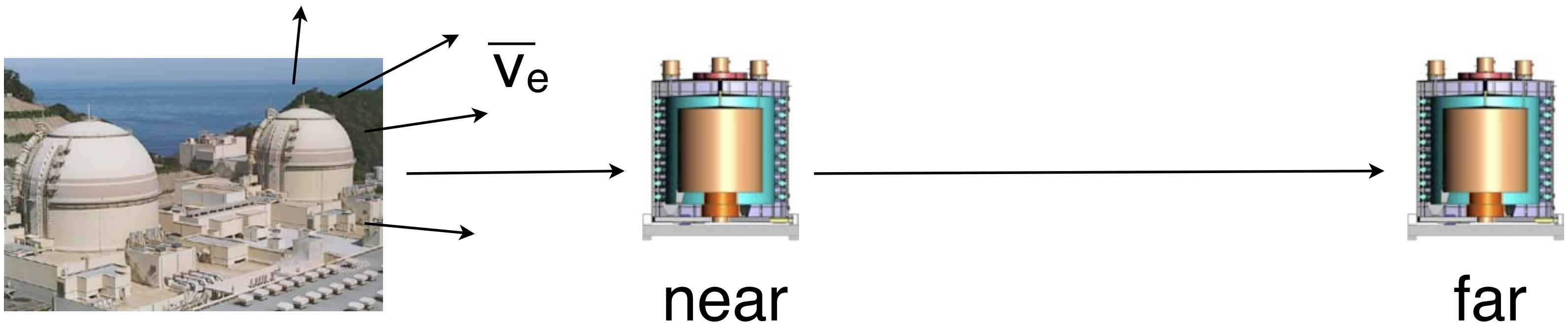
^{157}Gd $\quad \Sigma\gamma$=8.53 MeV

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



Principle of Relative Measurement

Measure ratio of interaction rates in detector (+shape)



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

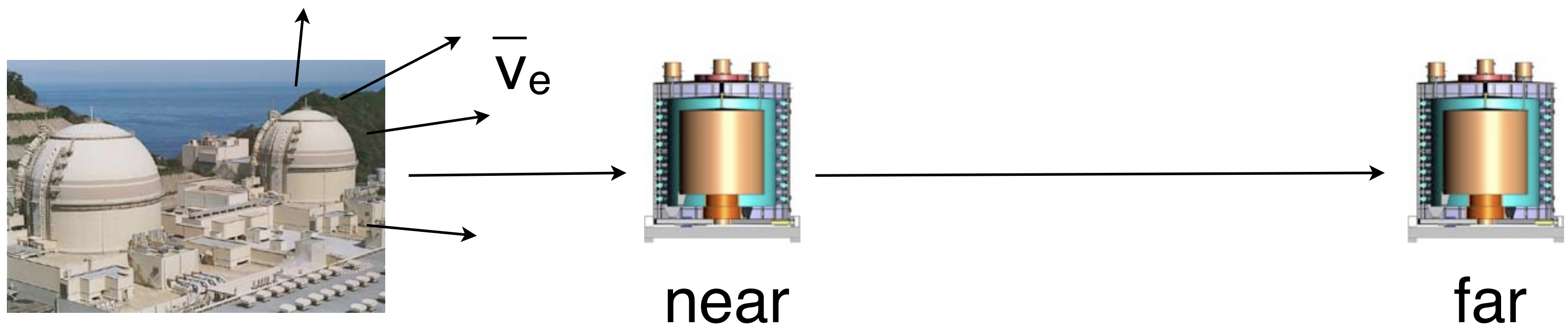
Measured Ratio of Rates

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 "<u>identical detectors</u>" at near and far site

Concept of "Identical Detectors"

identical target + identical detector response

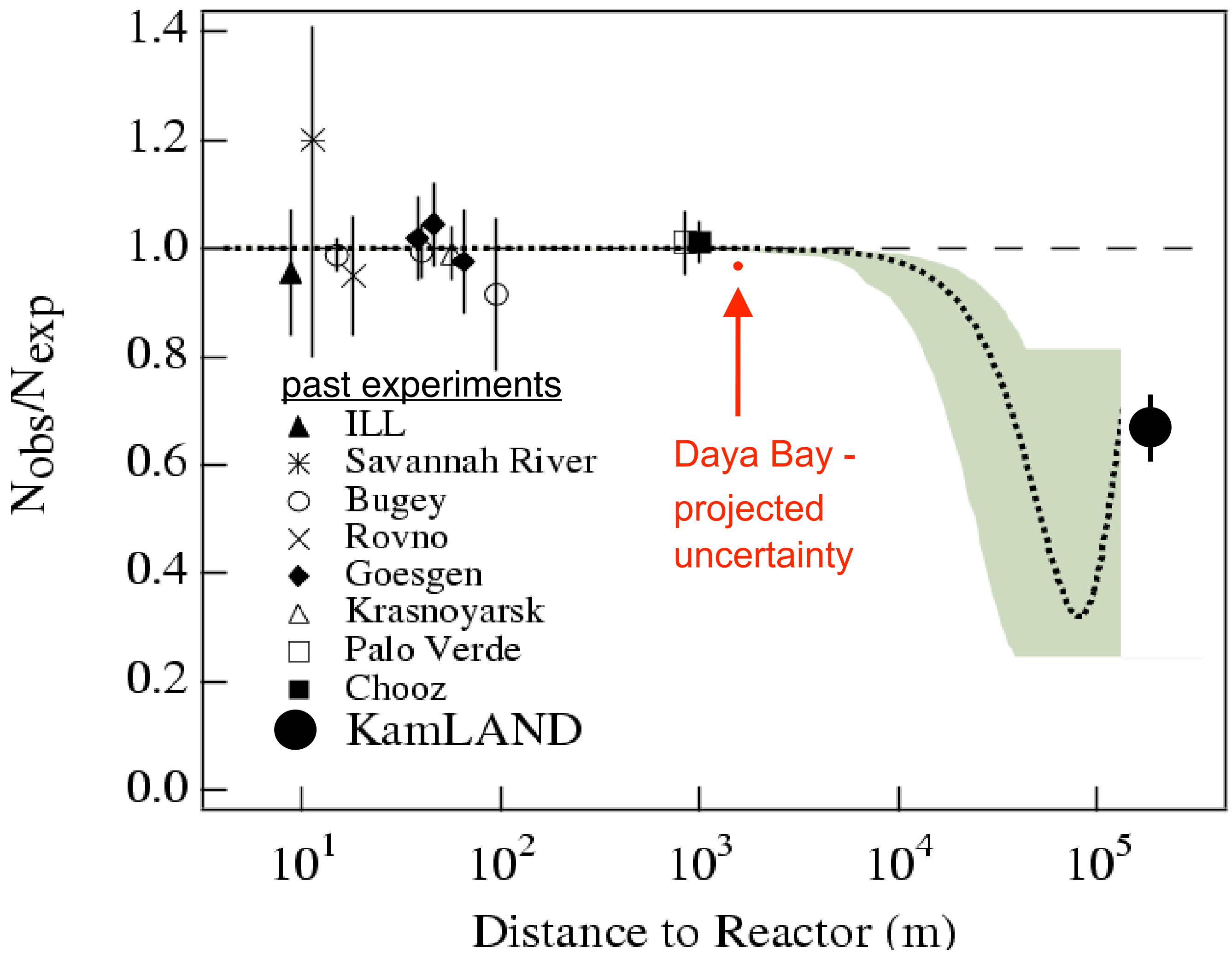
→ <u>relative</u> target mass (measure to < 0.1%)

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

→ calibrate <u>relative</u> 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

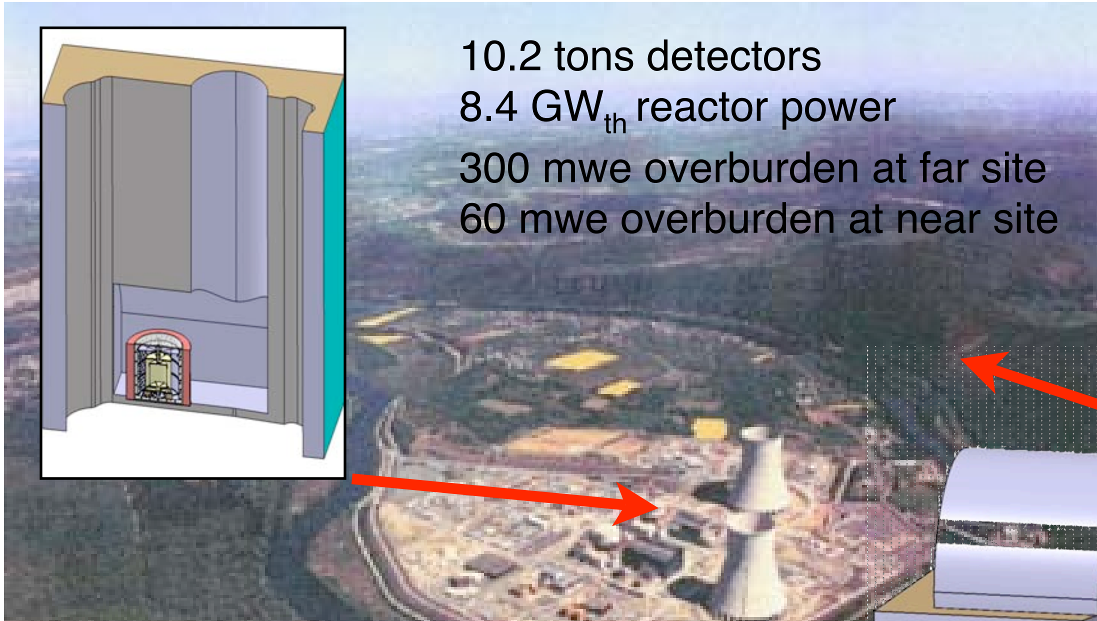
Ref: KamLAND, Daya Bay, McKeown

World of Proposed Reactor θ_{13} Neutrino Experiments

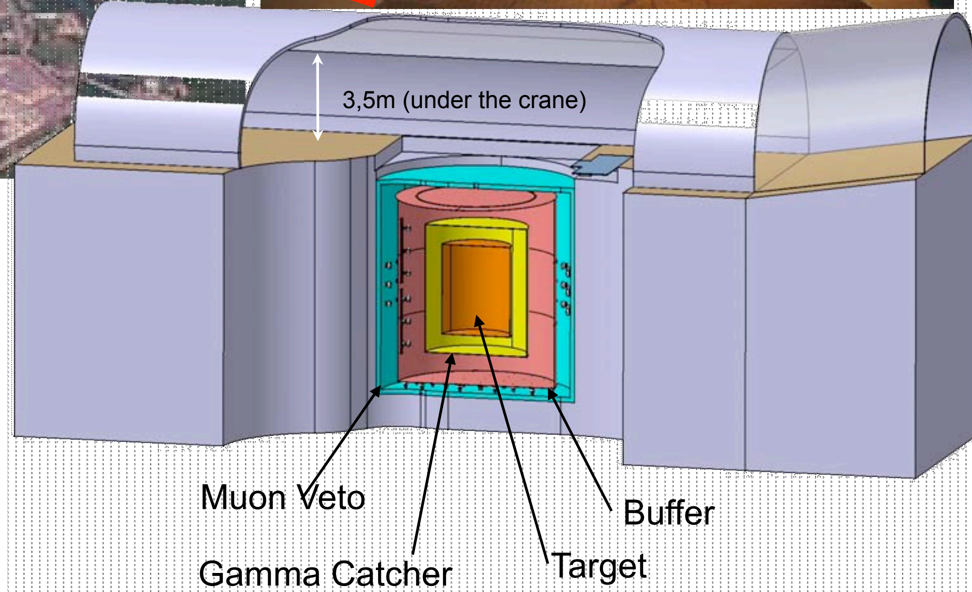
Double Chooz, Daya Bay, and Reno have strong international collaborations.
→Ready to start construction.

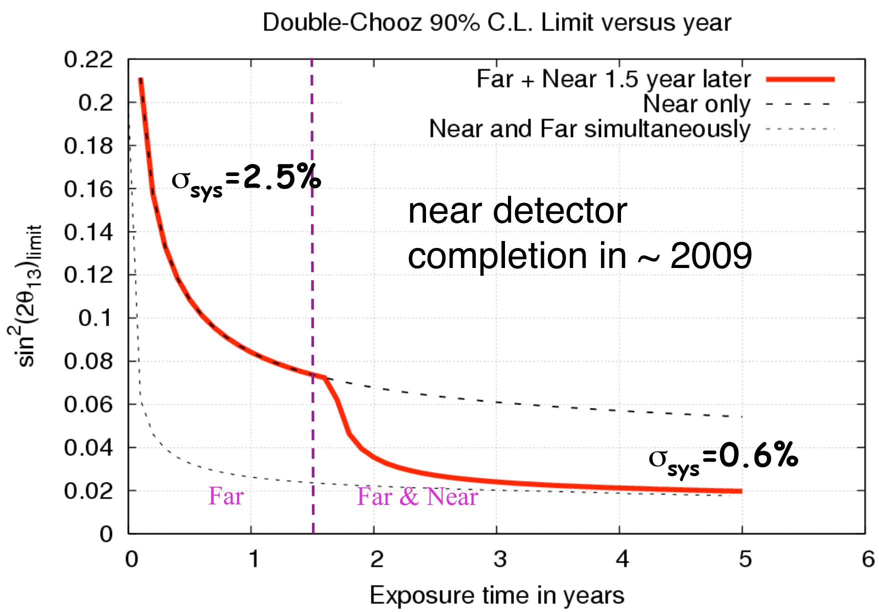
Proposed and R&D.

Double Chooz



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



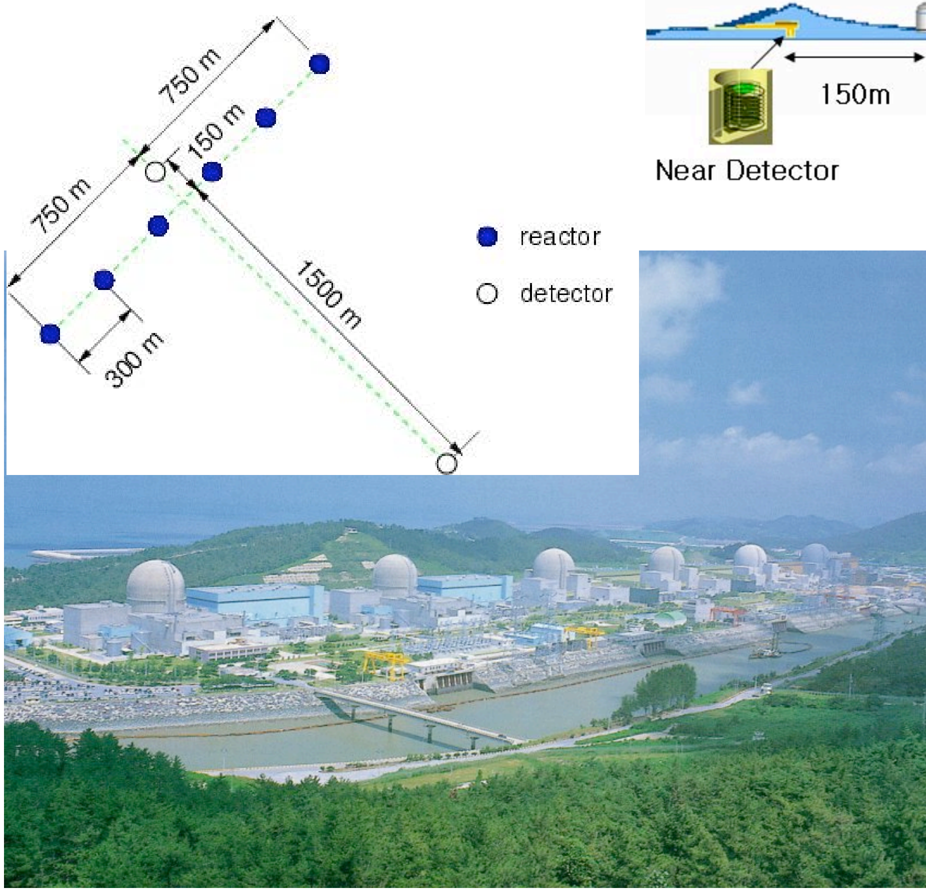


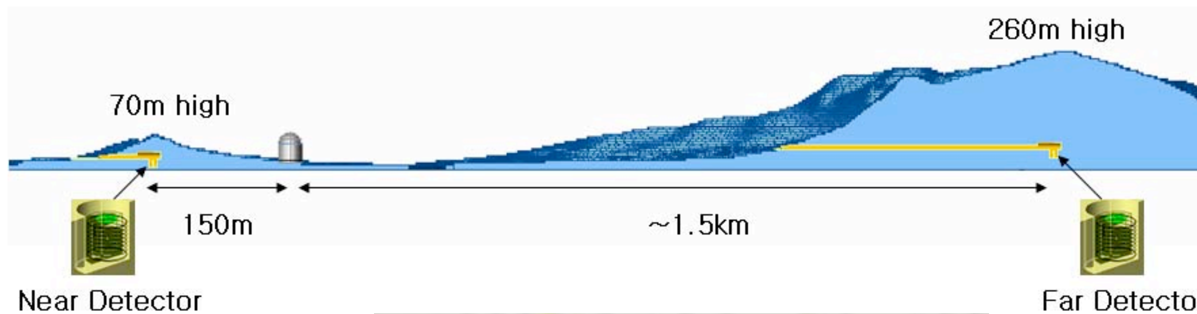
$\sin^2 2\theta_{13} < 0.03$ @ 90.C.L. in 3 years

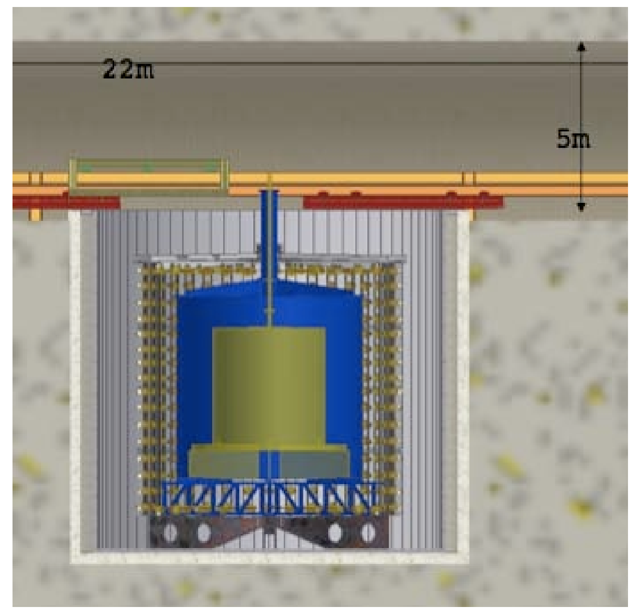
→M. Motoki, Fri afternoon

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

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







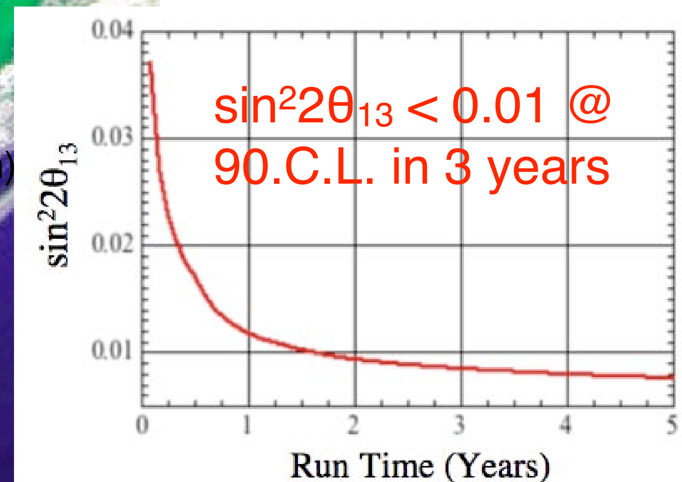
$\sin^2 2\theta_{13} < 0.02$ @ 90.C.L. in 3 years

→S.-B. Kim, Fri afternoon

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



→S. Chen, Fri afternoon

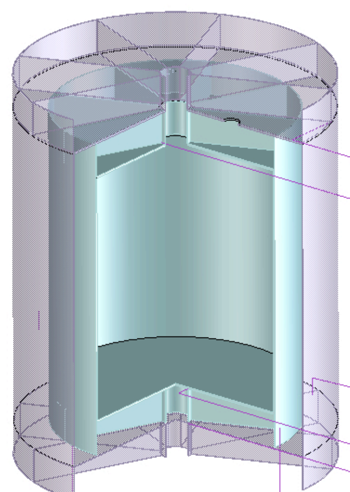
Design, R&D, and Prototyping for Daya Bay

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

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

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*

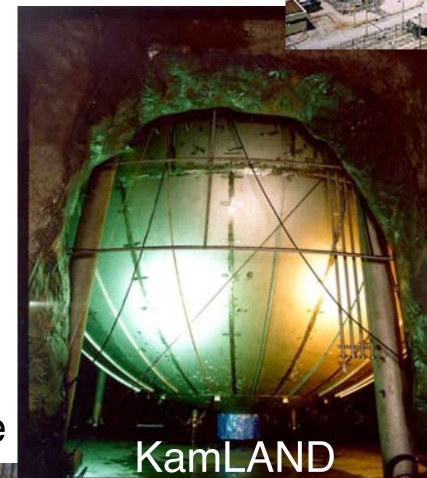
Neutrino Physics at Reactors: Past, Present, Future

Next - Precision measurement of θ_{13}

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

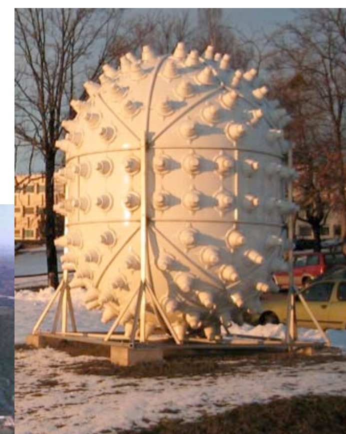
2004 - Evidence for spectral distortion

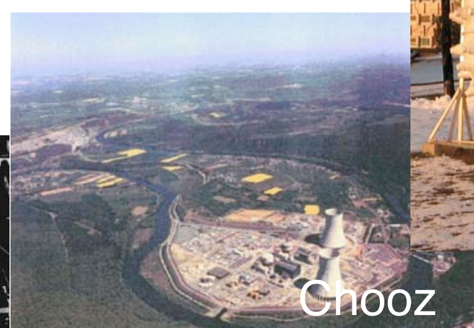
2003 - First observation of reactor antineutrino disappearance



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