Results and Prospects of Neutrino Oscillation Experiments at Reactors

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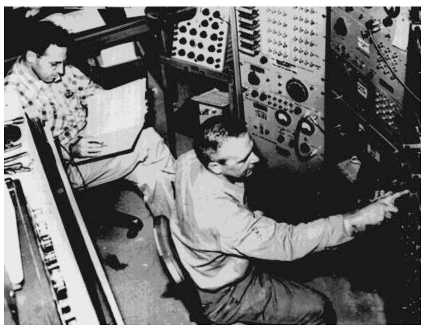
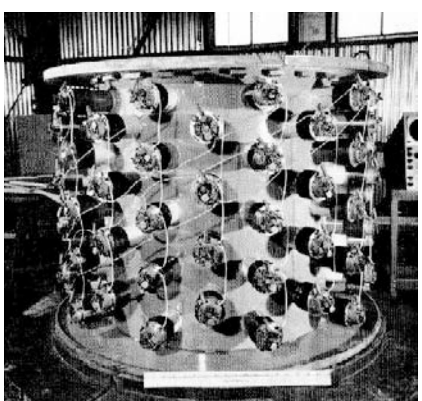
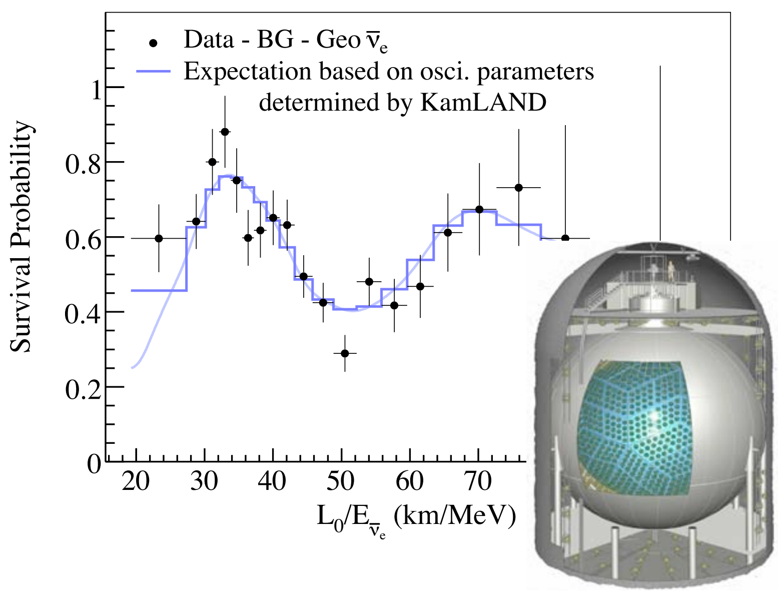
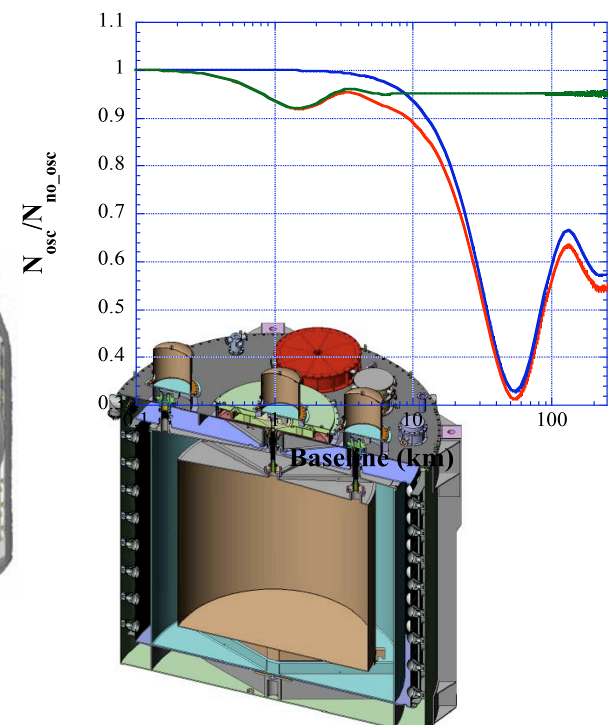








La Thuile, March 3, 2009

Neutrino Physics at Reactors

Next - Discovery and precision measurement of θ_{13}

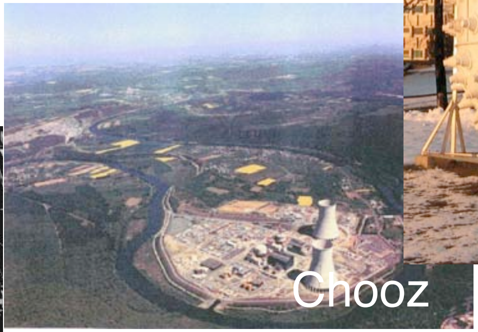
2008 - Precision measurement of Δm_{12}^2

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

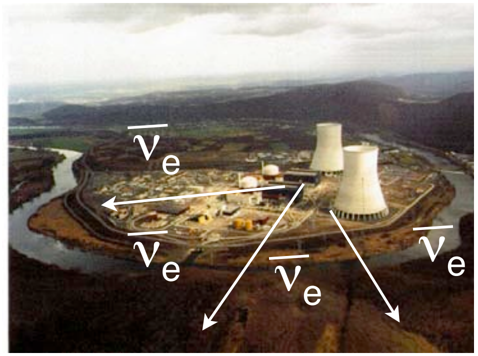
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

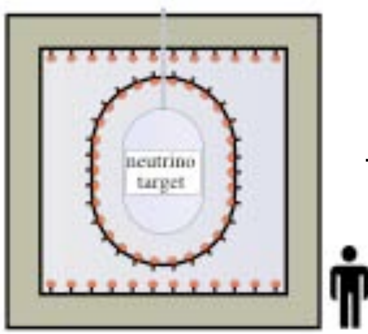
Past Oscillation Searches with Reactor Antineutrinos

Best Limit from Chooz

thermal power 8.5 GW

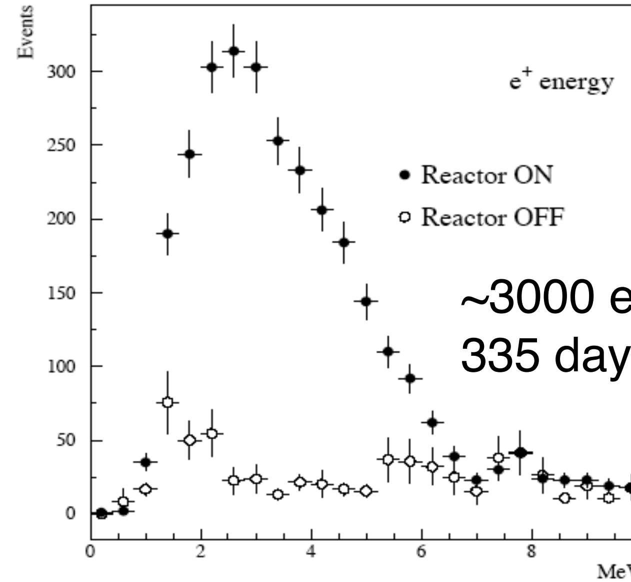
1 km baseline



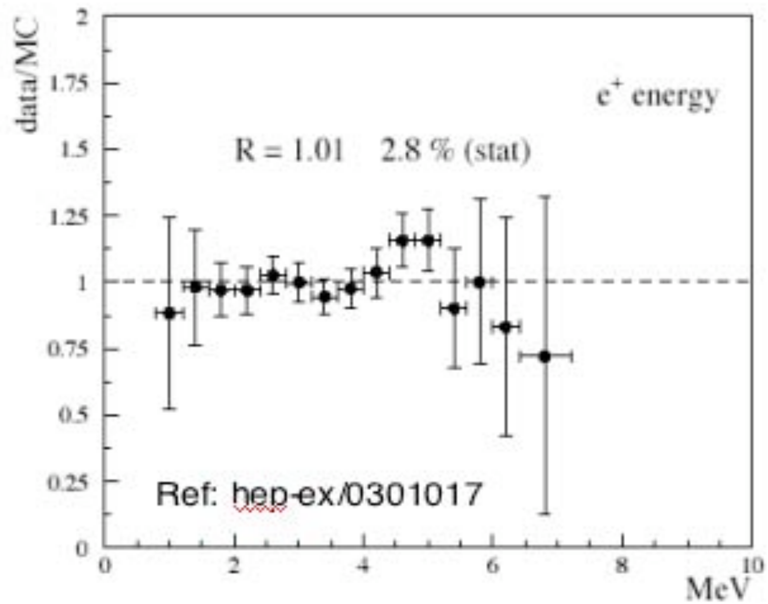


5 ton target

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



~3000 events
335 days



No evidence for oscillation

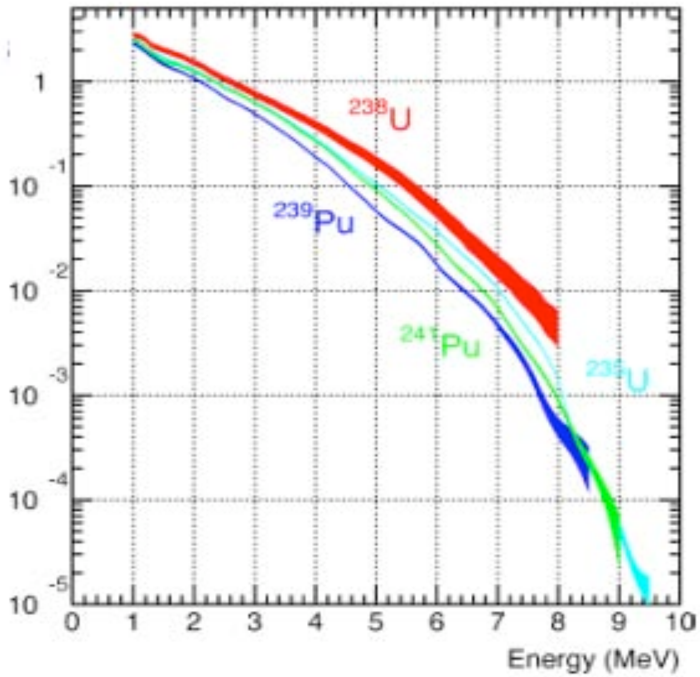
Absolute measurement with 1 detector

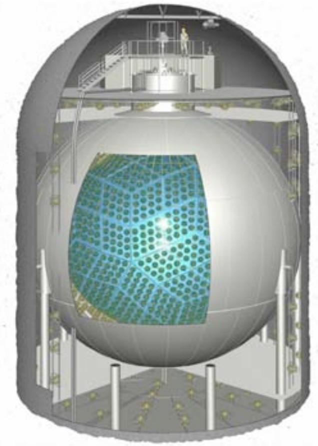
Measuring Reactor Antineutrinos in Japan

Japanese Reactors

55 reactors

Reactor Antineutrinos





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

~ 200 MeV per fission

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

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

reactor $\bar{\nu}$ flux at KamLAND

~ 6 x $10^6/cm^2/sec$

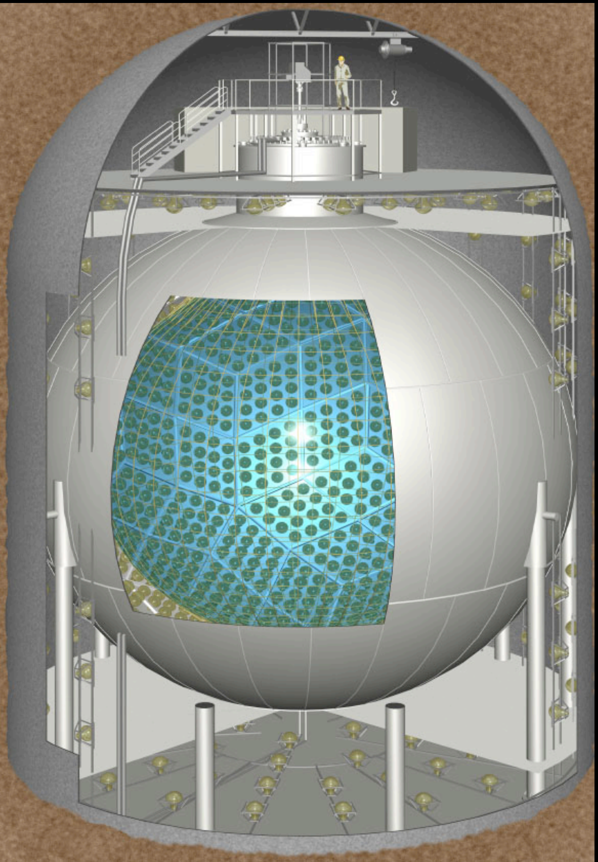
KamLAND Antineutrino Detector

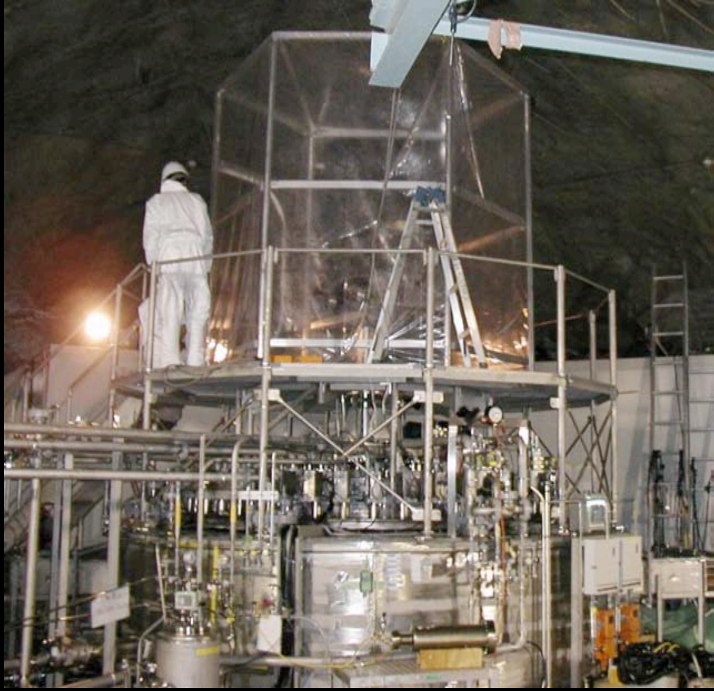
$\bar{\nu}_e + p \rightarrow e^+ + n$

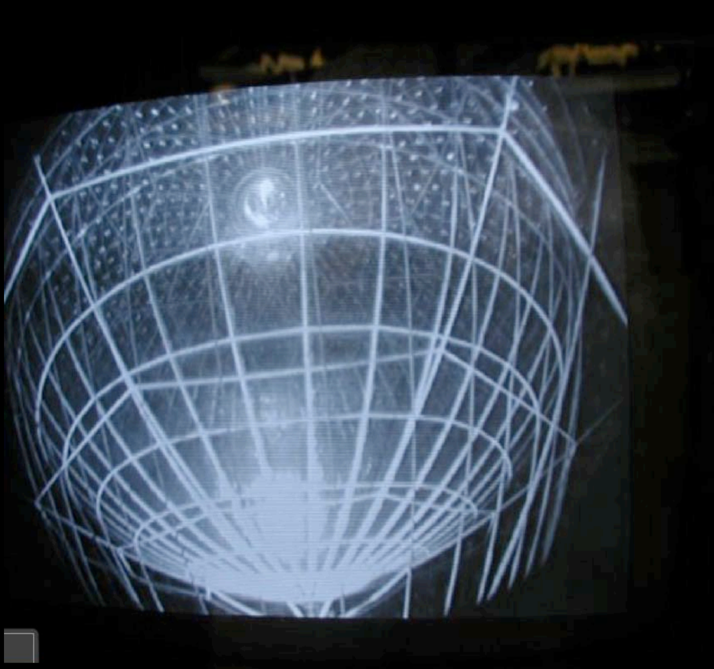
$$E_{\overline{\nu}_e} \simeq E_p + \overline{E}_n + 0.8\,\mathrm{MeV},$$

through inverse β-decay

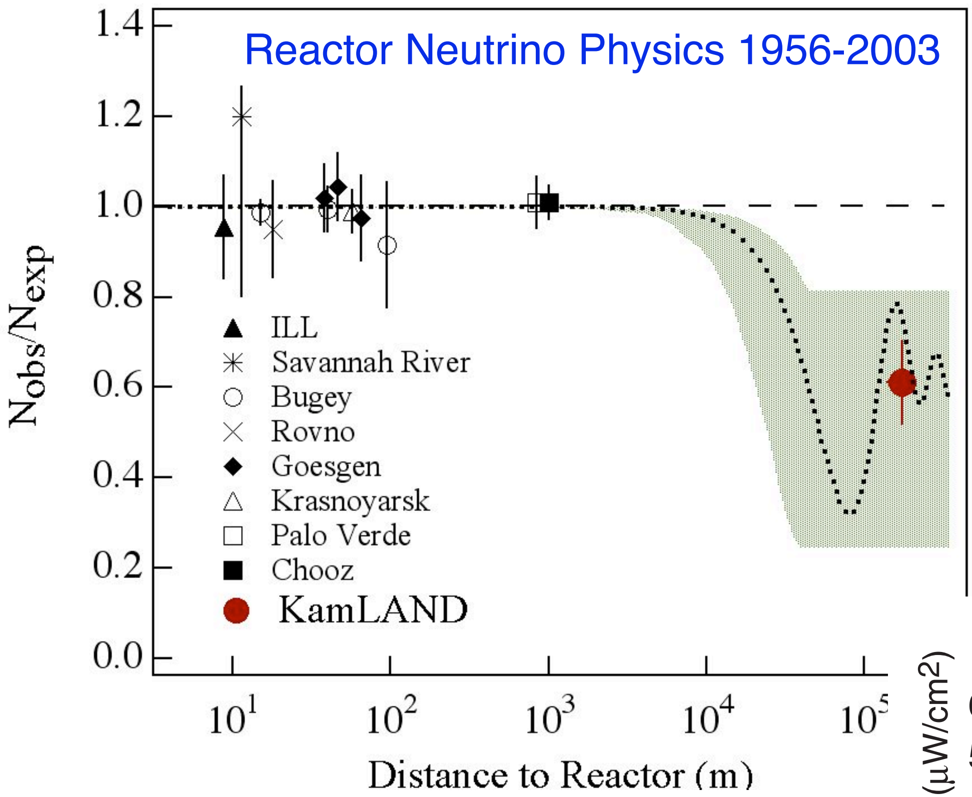
liquid scintillator target:
- proton rich > 10^{31} protons
- good light yield







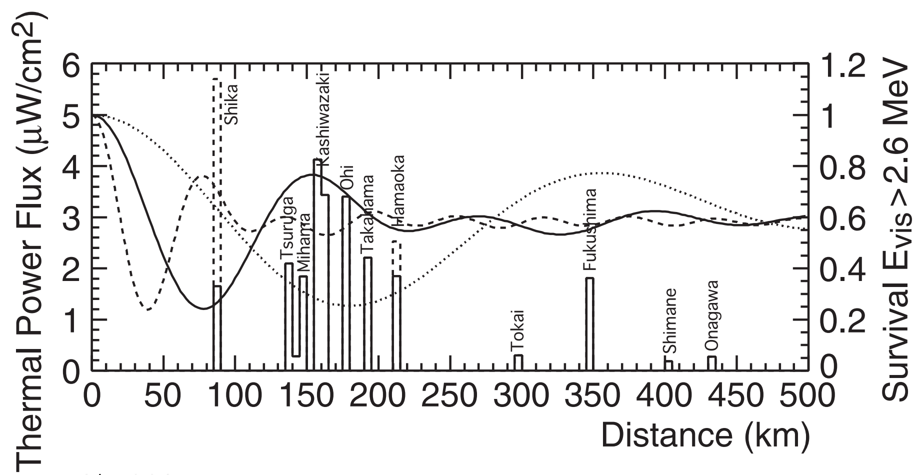
KamLAND 2003: First Direct Evidence for Reactor $\overline{\nu}_e$ Disappearance



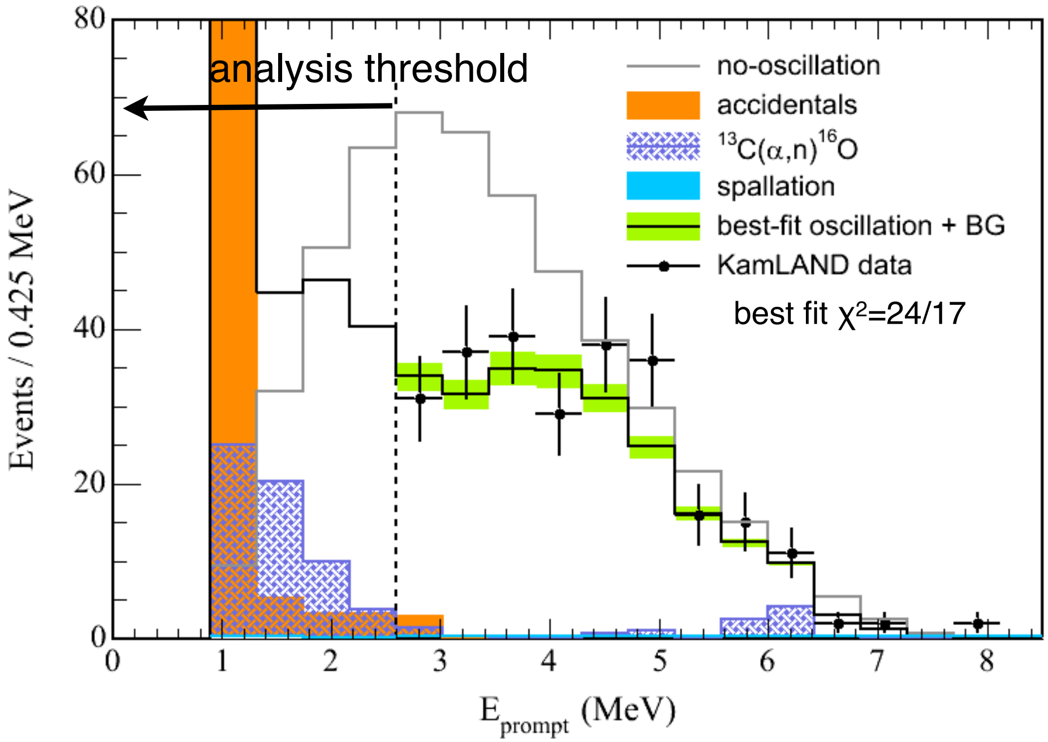
PRL 90:021802 (2003)

Observed $\overline{\nu}_e$	54 events
No-Oscillation	86.8 ± 5.6 events
Background	1 ± 1 events
Livetime:	162.1 ton-yr

mean, flux-weighted reactor distance ~ 180km



KamLAND 2005: Evidence of Spectral Distortion in Energy Spectrum



Phys.Rev.Lett.94:081801,2005

Observed $\overline{\nu}_e$	258 events
No-Oscillation	365.2 ± 23.7 (syst.)
Background	17.8 ± 7.3 events
Livetime:	766.3 ton-yr

fiducial volume syst.: 4.7%

total systematics = 6.5%

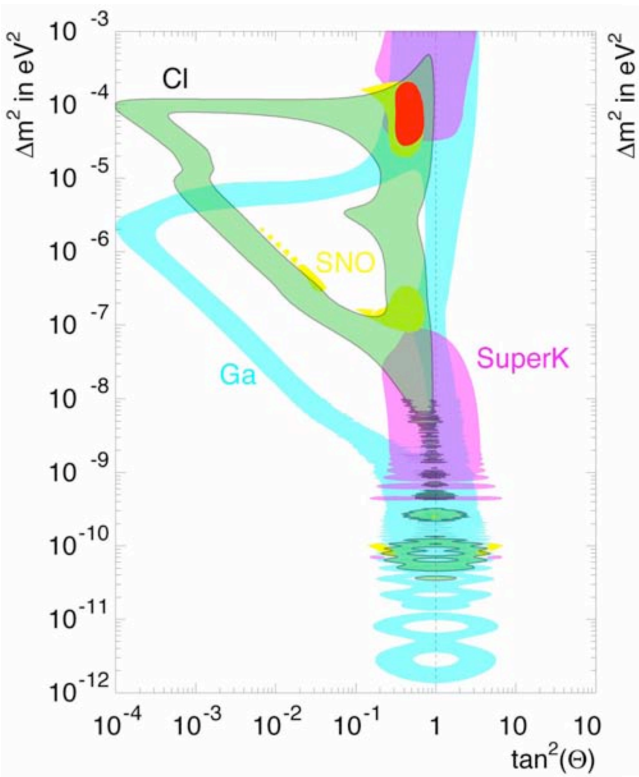
Spectral Distortions: A unique signature of neutrino oscillation!

Simple, rescaled reactor spectrum is excluded at 99.6% CL(χ^2=37.3/18)

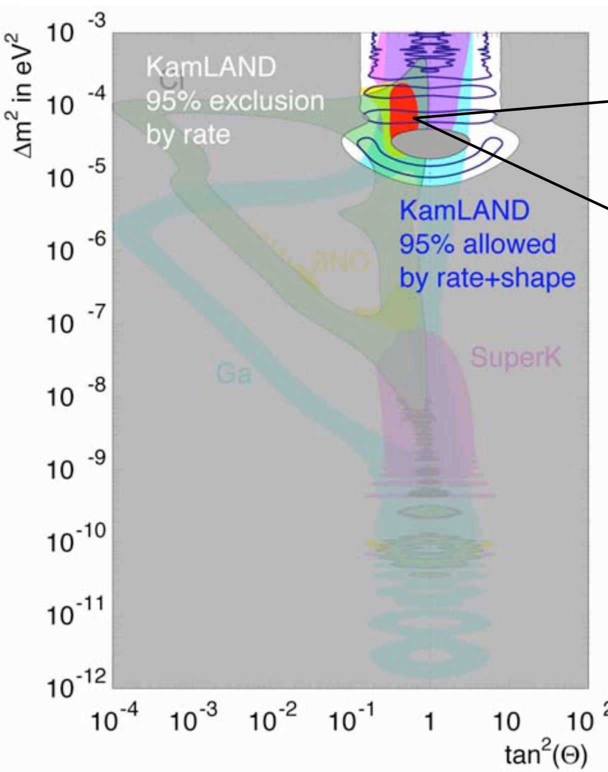
Next Step: Reduce systematic error with improved calibrations.

Measuring θ_{12} and Δm_{12}^2 with Solar ν and KamLAND

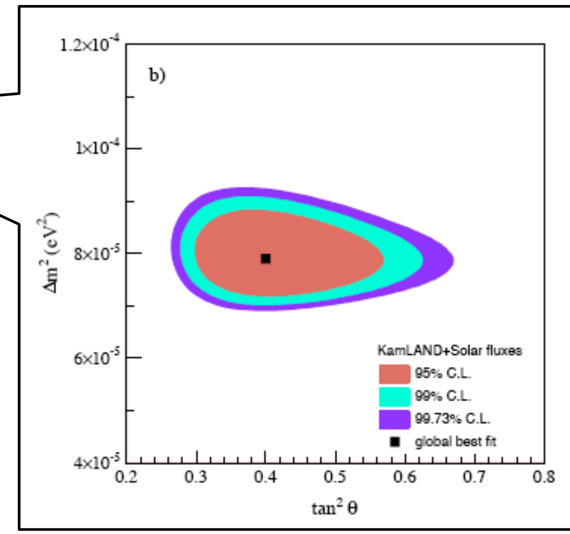
Solar Neutrinos



Solar Neutrinos
+ KamLAND 2003
($\bar{\nu}_e$ rate)



Solar Neutrinos
+ KamLAND 2005
($\bar{\nu}_e$ rate+spectrum)



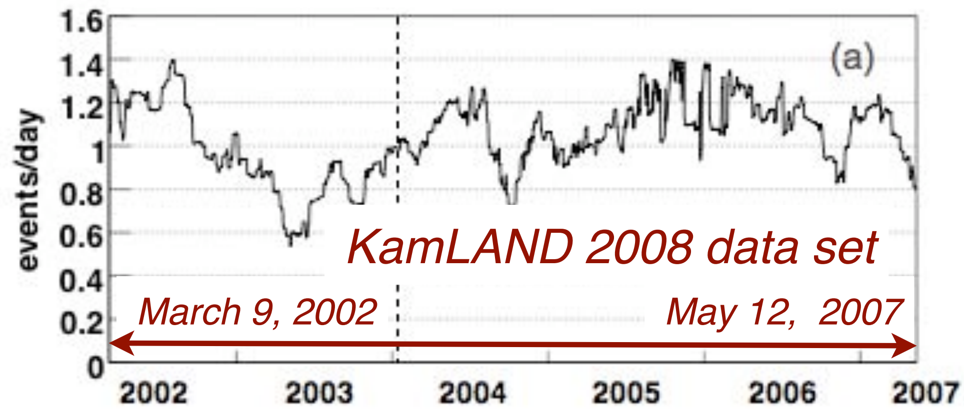
Agreement between oscillation parameters for $\bar{\nu}$ and ν

Beginning of precision neutrino physics

KamLAND 2008:
Precision Measurement of Neutrino Oscillation Parameters

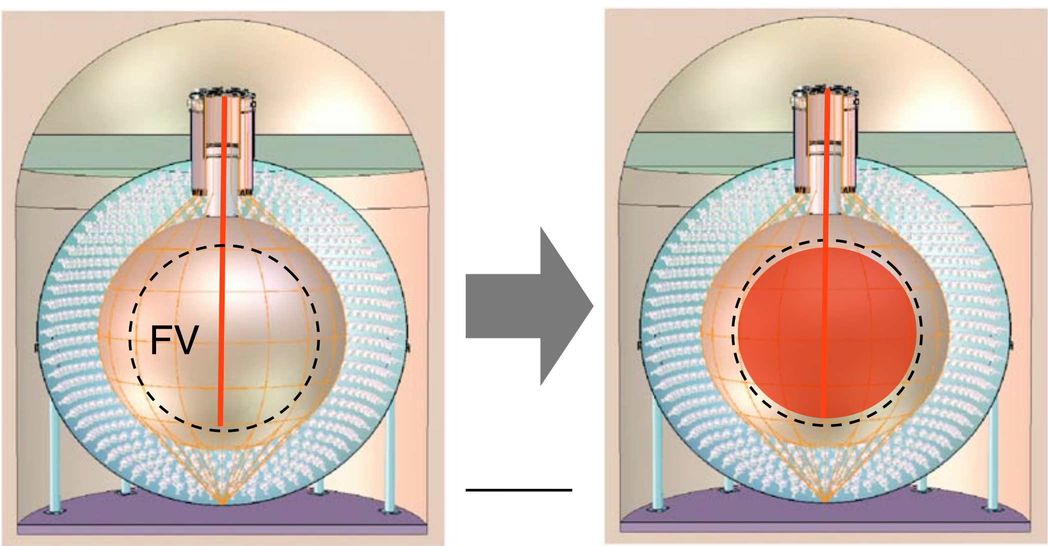
Phys.Rev.Lett.100:221803,2008

increased livetime



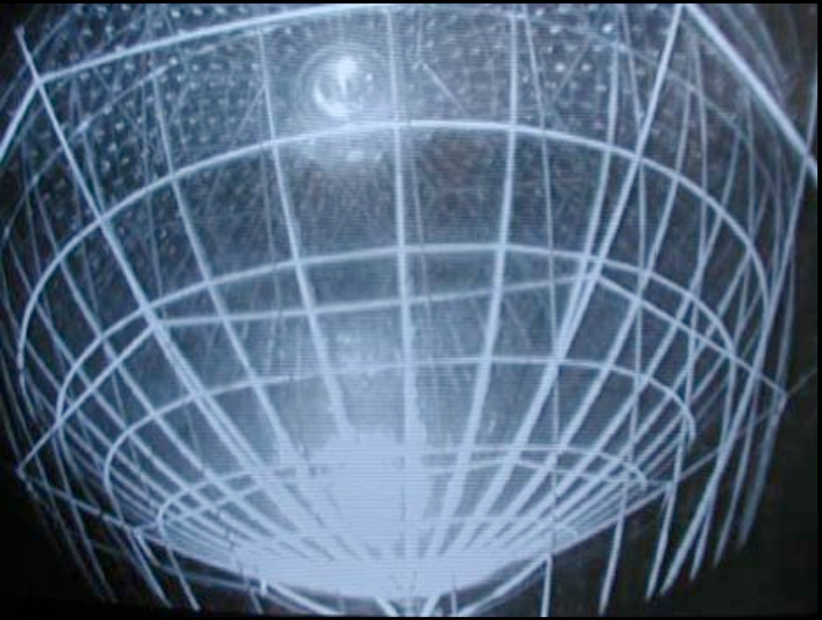
- increased livetime: 1491 days
- lowered analysis threshold
- modified analysis to enlargen the fiducial volume
R_{prompt}, $R_{delayed} < 6.0$m
- reduced uncertainty in $^{13}C(\alpha,n)^{16}O$ backgrounds
- reduced systematics in target protons by calibrating fiducial volume

improved calibration



KamLAND Full-Volume Calibration

calibration deck

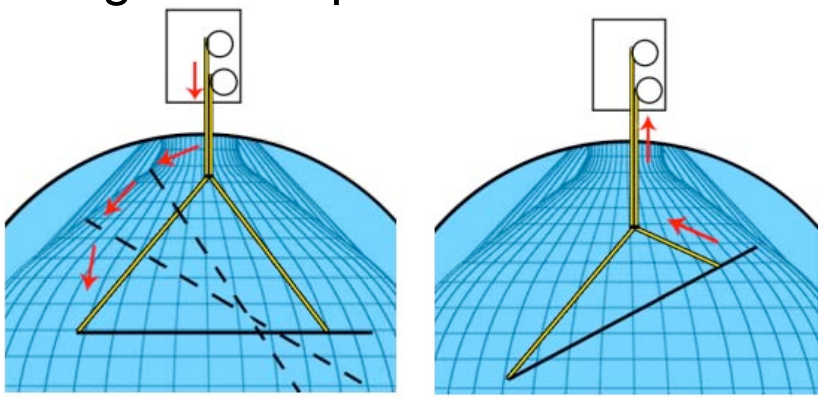


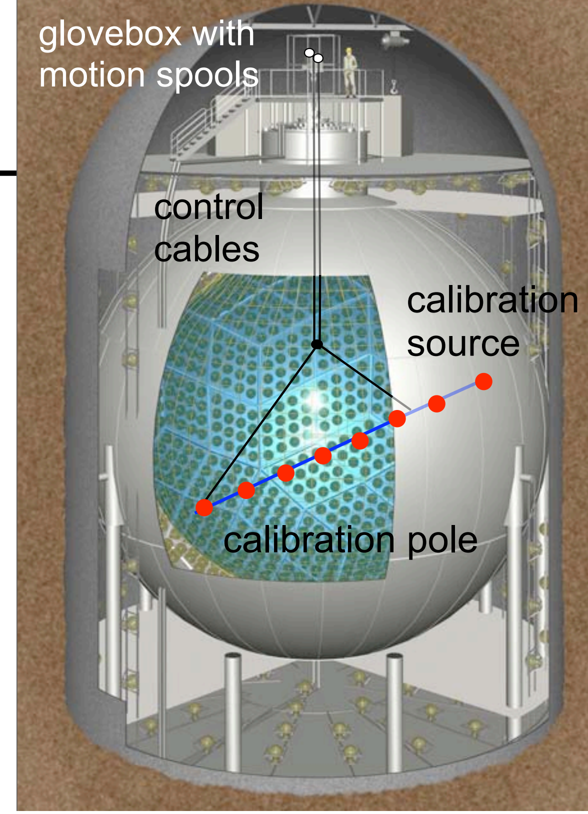
inside view of KamLAND detector

4π calibration system

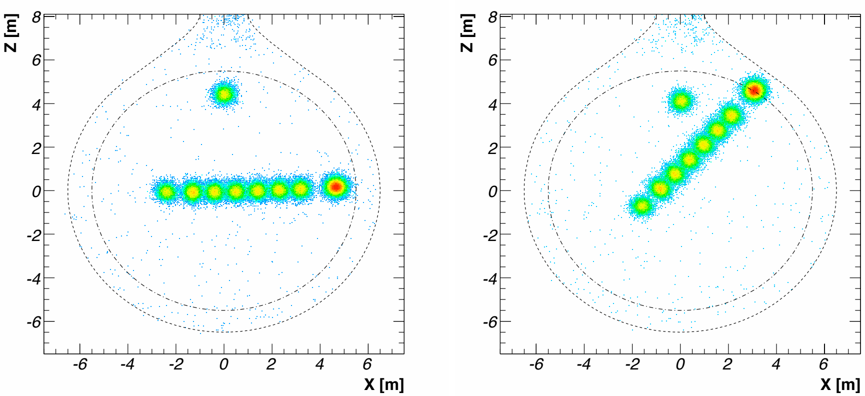
Full-Volume Calibration

Design Concept





Calibration Data

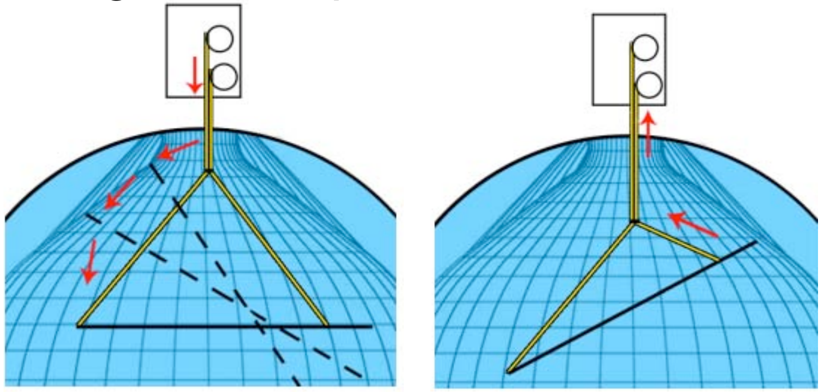


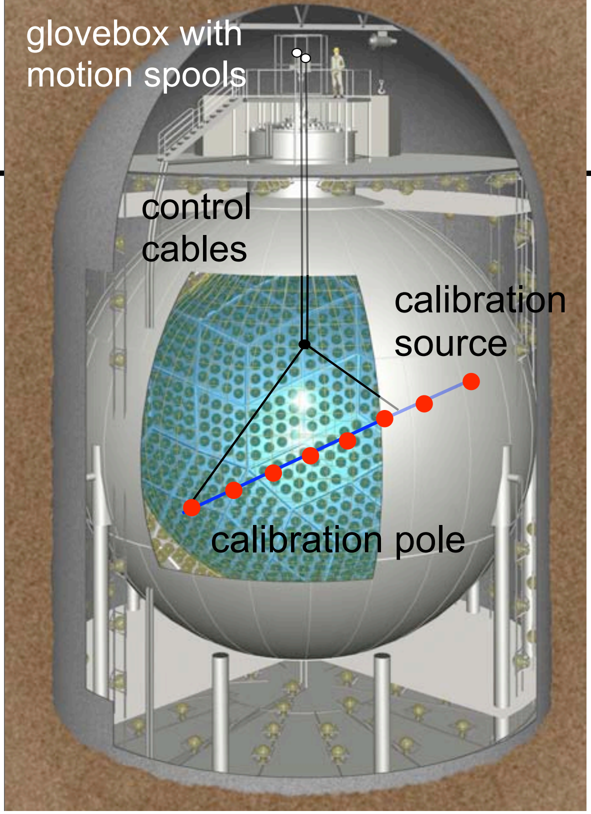
^{60}Co sources along pole

$^{60}Co/^{68}Ge$ source at end

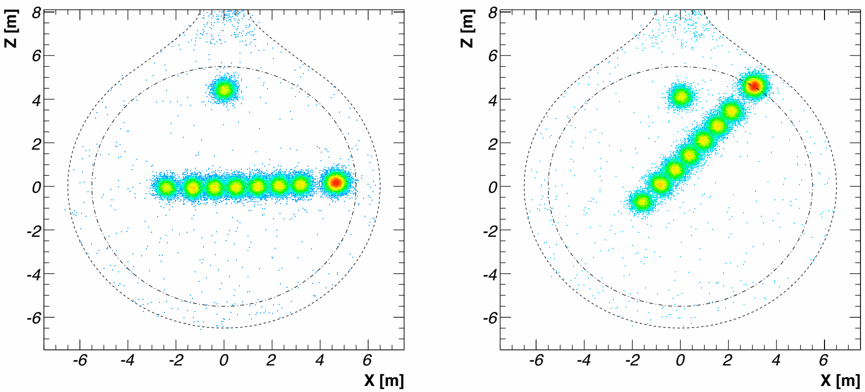
Full-Volume Calibration

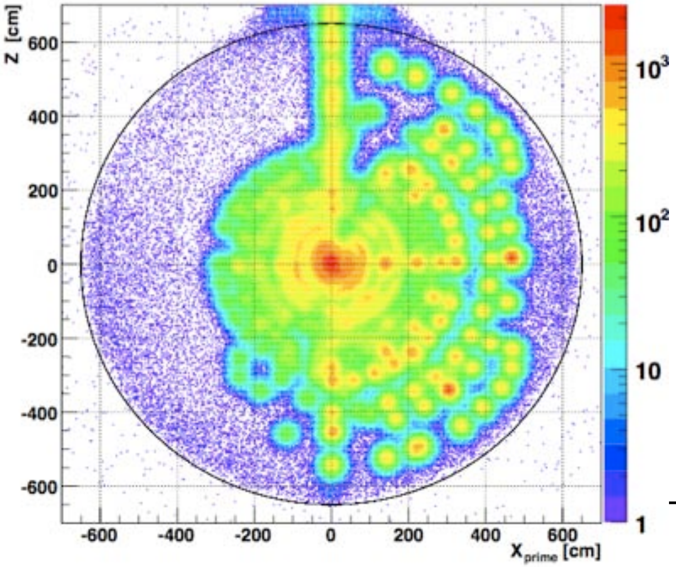
Design Concept





Calibration Data

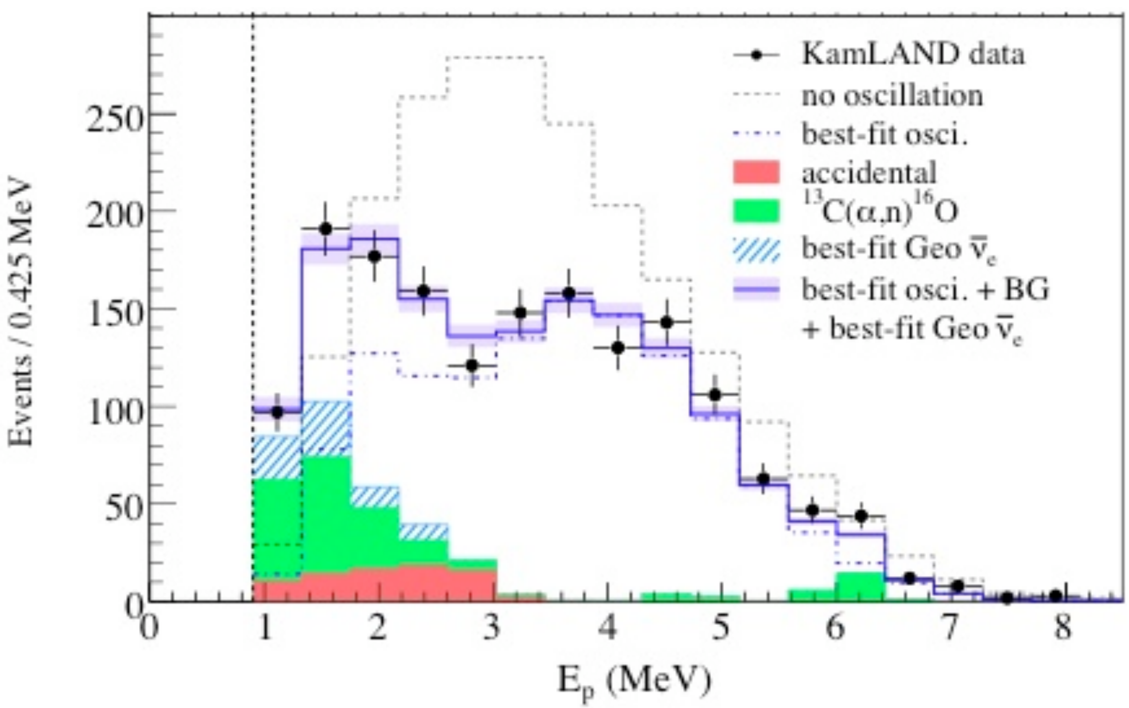




Reconstructed vertex distribution of $^{60}Co/^{68}Ge$ composite source in 4π calibration runs.

KamLAND 2008: Precision Measurement of Oscillation

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



number of events

expected: 2179 ± 89 (syst)
observed: 1609
bkgd: 276 ± 23.5

significance of disappearance
(with 2.6 MeV threshold): 8.5σ
no-osc χ^2/ndf=63.9/17

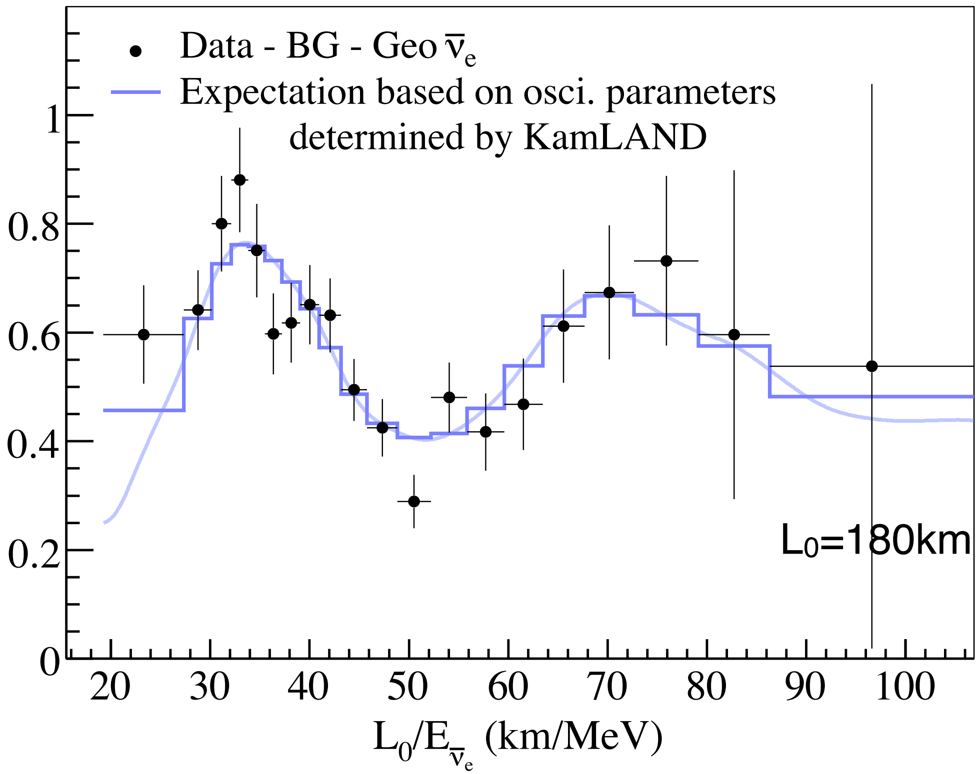
significance of distortion: > 5σ
best-fit χ^2/ndf=21/16 (18% C.L.)

systematic uncertainties:
fiducial volume reduced from
4.7% → 1.8%

total systematics: 4.1%

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\overline{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

L/E Dependence



Phys.Rev.Lett.100:221803,2008

oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$

decay $P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$

decoherence $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$

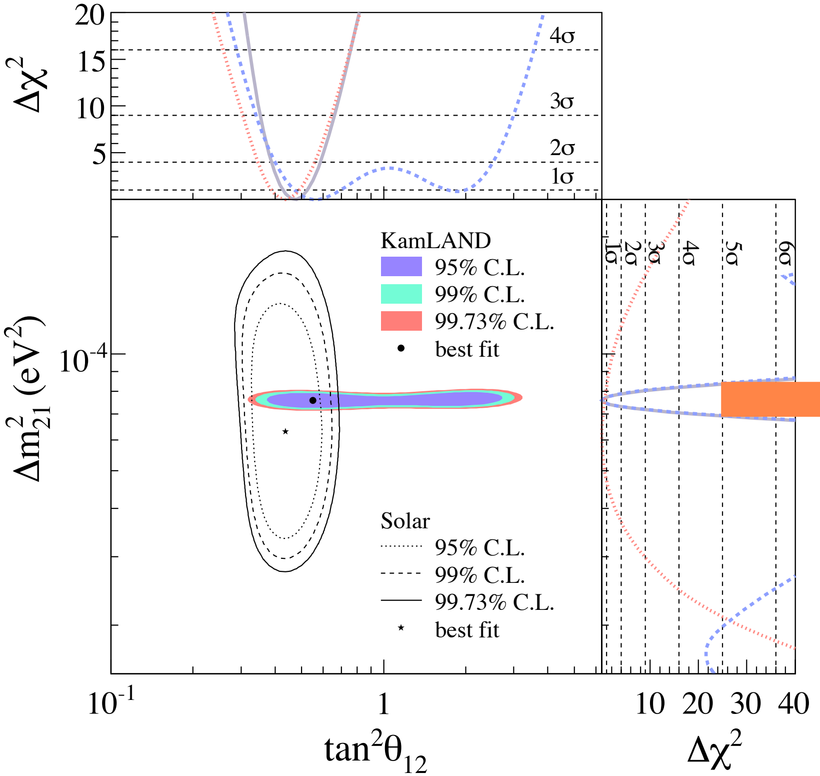
L/E figure demonstrates $\bar{\nu}$ oscillation.

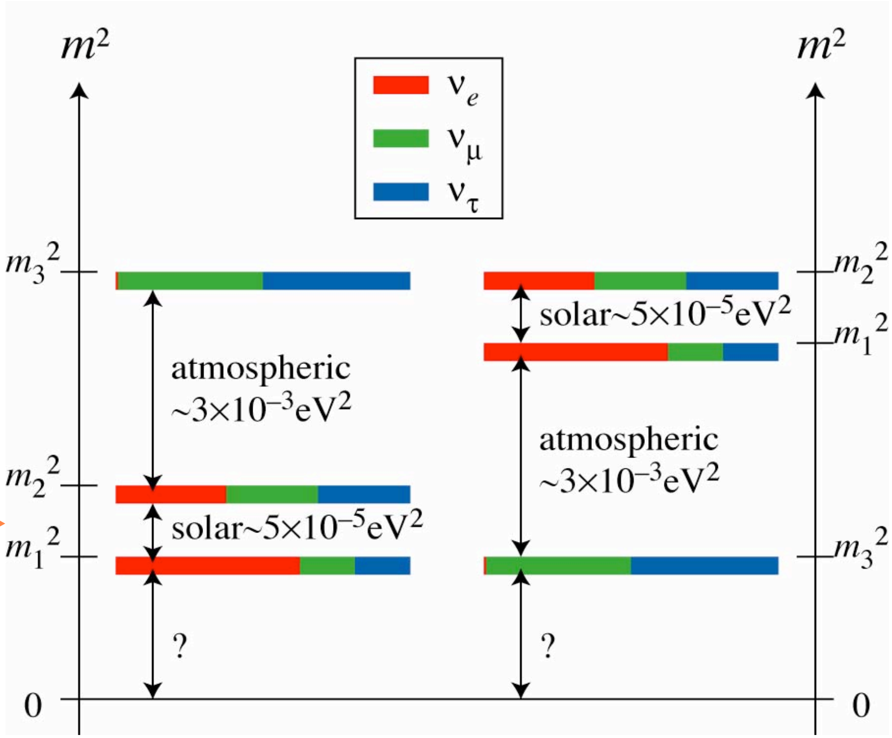
2002-2008 SNO observes neutrino flavor change, finds evidence for neutrino mass

2003-2008 KamLAND demonstrates $\bar{\nu}$ oscillation, precision measurement of Δm^2

KamLAND 2008: Oscillation Parameters

Rate-Shape-Time Analysis





KamLAND makes precise determination of Δm_{12}^2 (~2.8%)

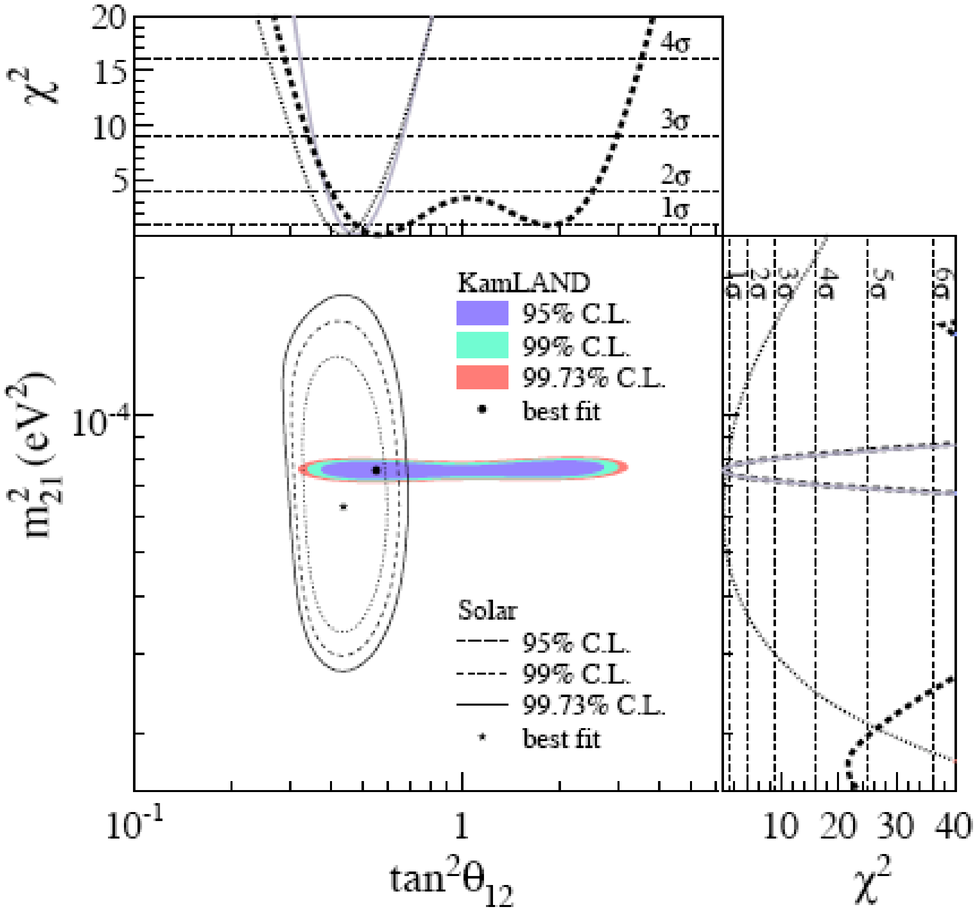
KamLAND+solar

(combined under assumption of CPT invariance)

$\Delta m^2 = 7.59^{+0.06}_{-0.05} \times 10^{-5}\ \mathrm{eV}^2$

$\tan^2\Theta = 0.47^{+0.21}_{-0.21}$

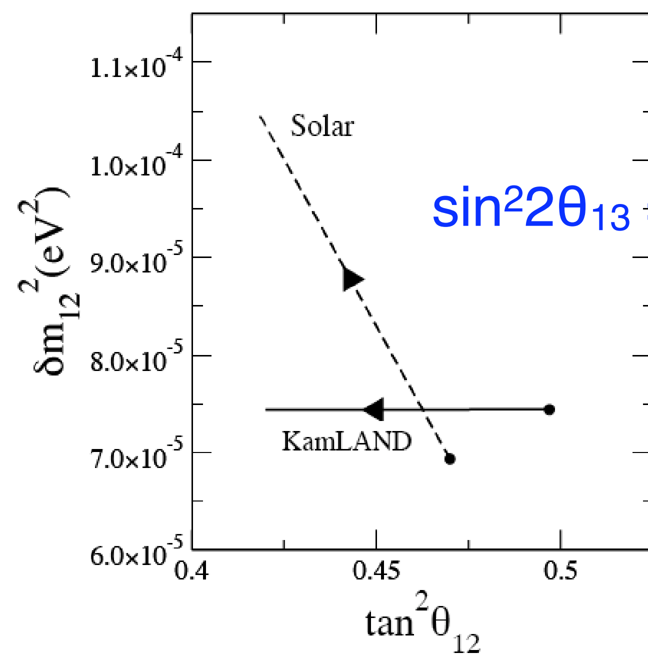
KamLAND and Solar Neutrino Fits



KamLAND and solar best fit values are not quite the same.

solar ν versus reactor $\overline{\nu}$

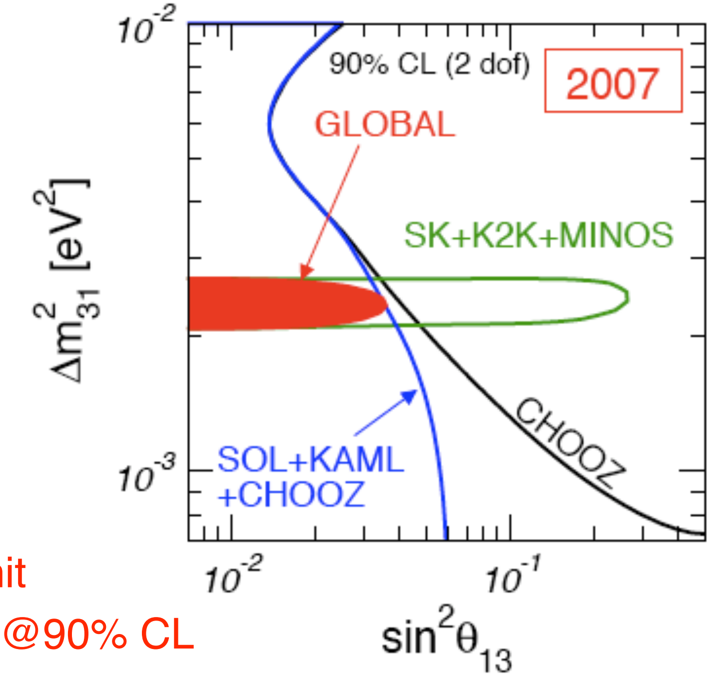
CPT-violation? Other new physics?



$\sin^2 2\theta_{13} \neq 0$?

Balantekin & Yilmaz, J. Phys. G **35**, 075007 (2008) (arXiv:0804.3345 [hep-ph]).

Understanding the Mixing Angles



Neutrino Mixing Matrix

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

current best limit

$\sin^2 2\theta_{13} < 0.11$ @90% CL

arXive:0710.5027

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

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

$\theta_{23} = \sim 45°$

maximal?

$\theta_{13} = ?$

$\theta_{12} \sim 32°$

large, but not maximal!

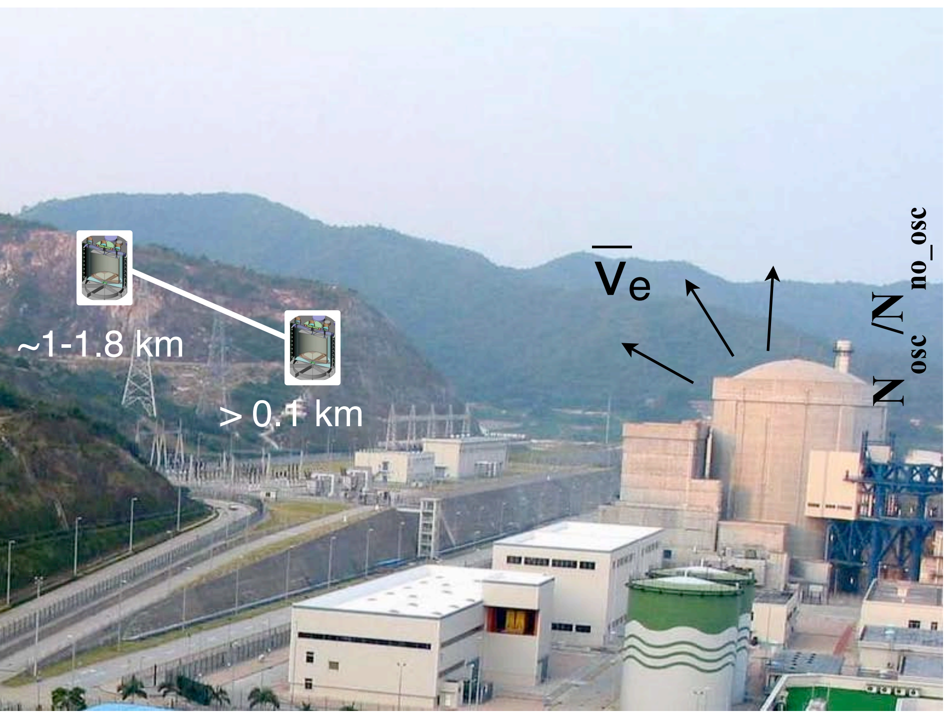
Precision Measurement of θ_{13} with Reactor Antineutrinos

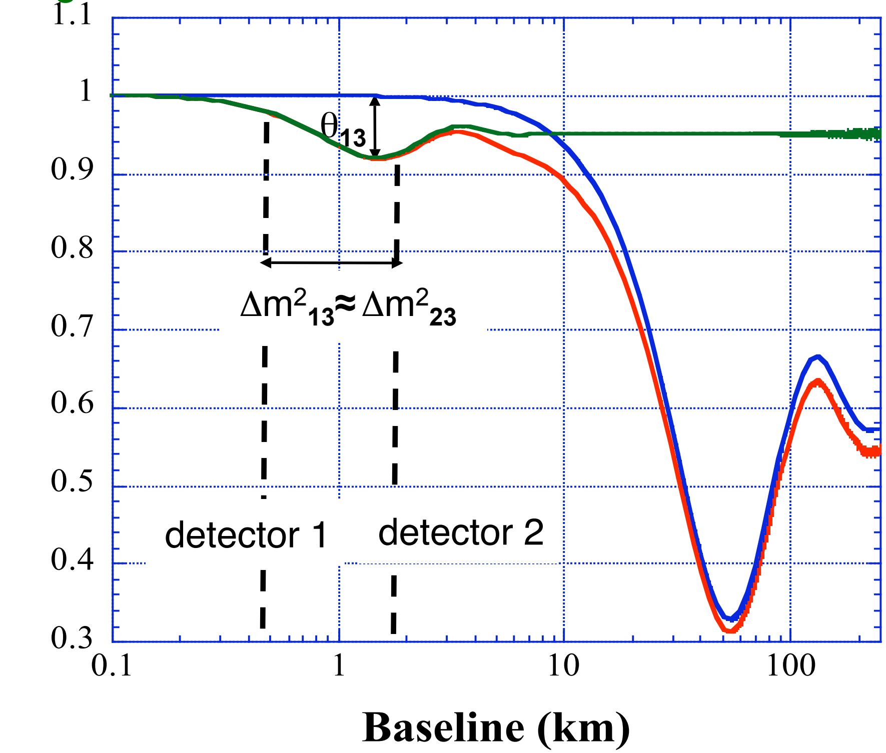
Search for θ_{13} in new oscillation experiment with multiple detectors

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

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

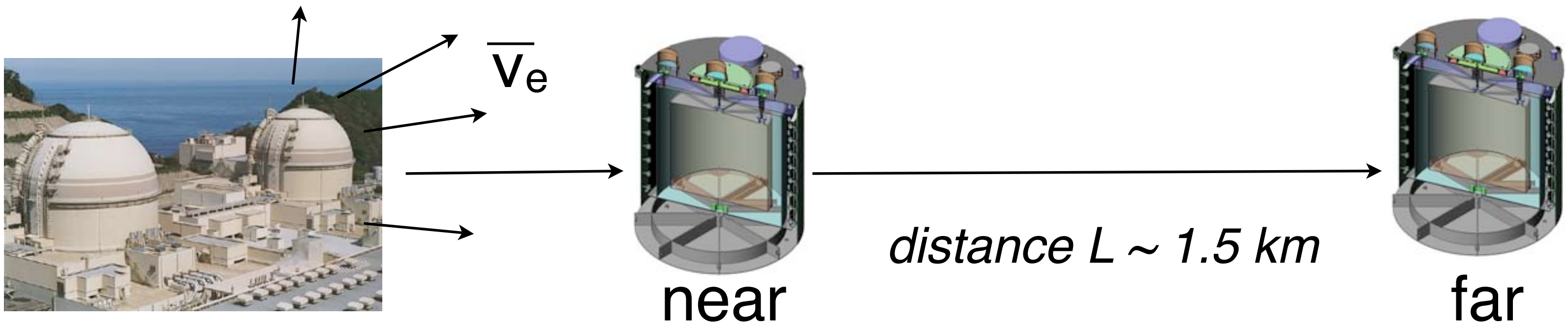
Large-amplitude oscillation due to θ_{12}





Concept of Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



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

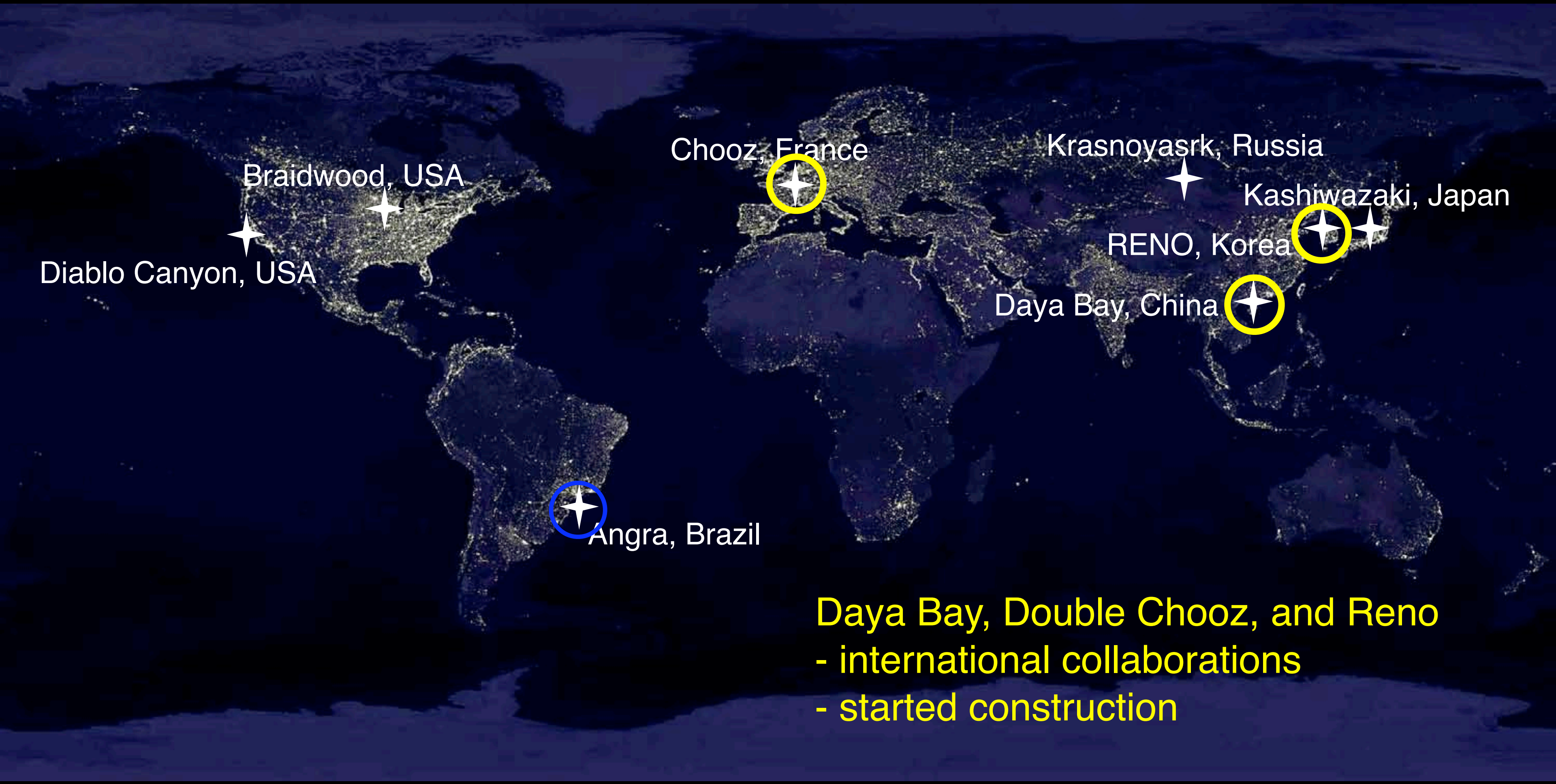
Measured Ratio of Rates

Detector Mass Ratio, H/C

Detector Efficiency Ratio

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

World of Proposed Reactor θ_{13} Neutrino Experiments



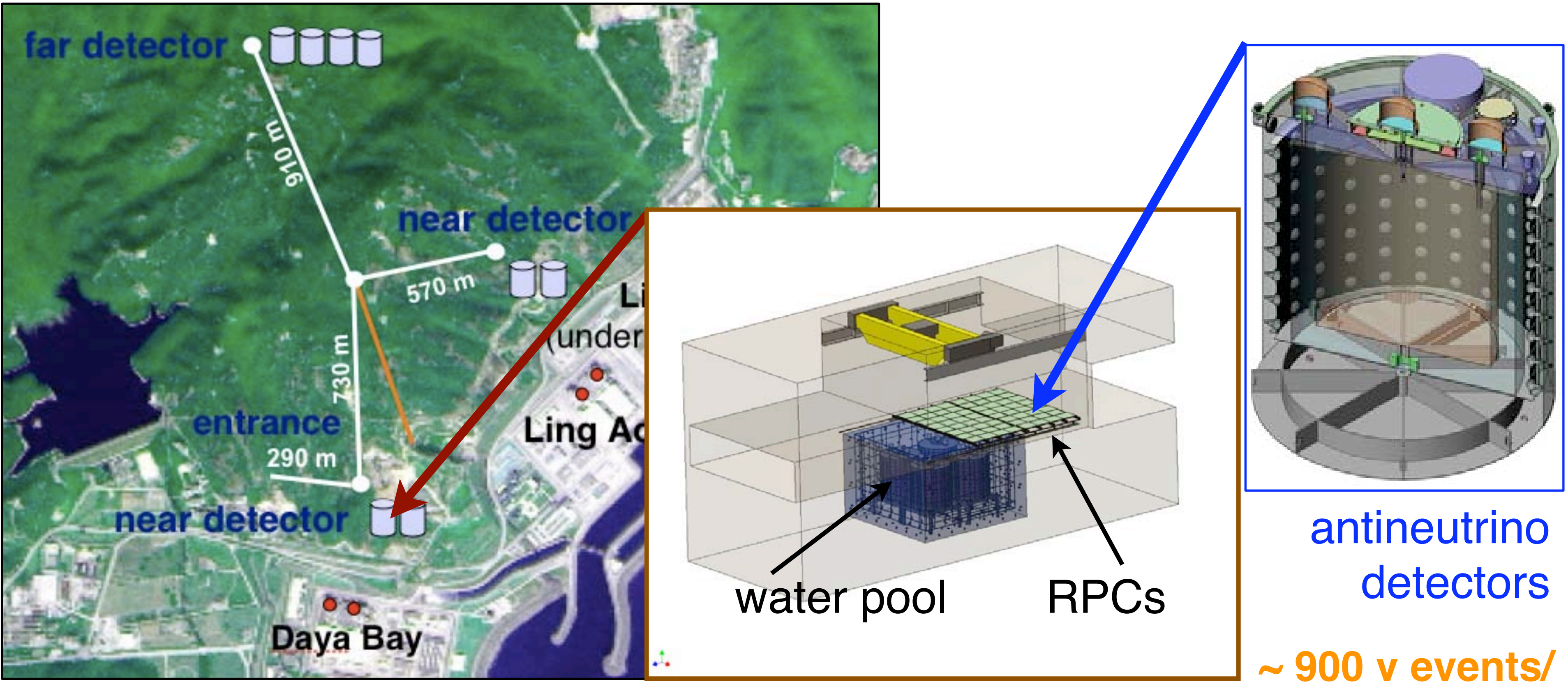
Daya Bay, Double Chooz, and Reno
- international collaborations
- started construction

Angra
- R&D
- nuclear proliferation studies

Daya Bay
- most precise experiment
- only experiment to reach $\sin^2 2\theta_{13} < 0.01$

Daya Bay, China

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

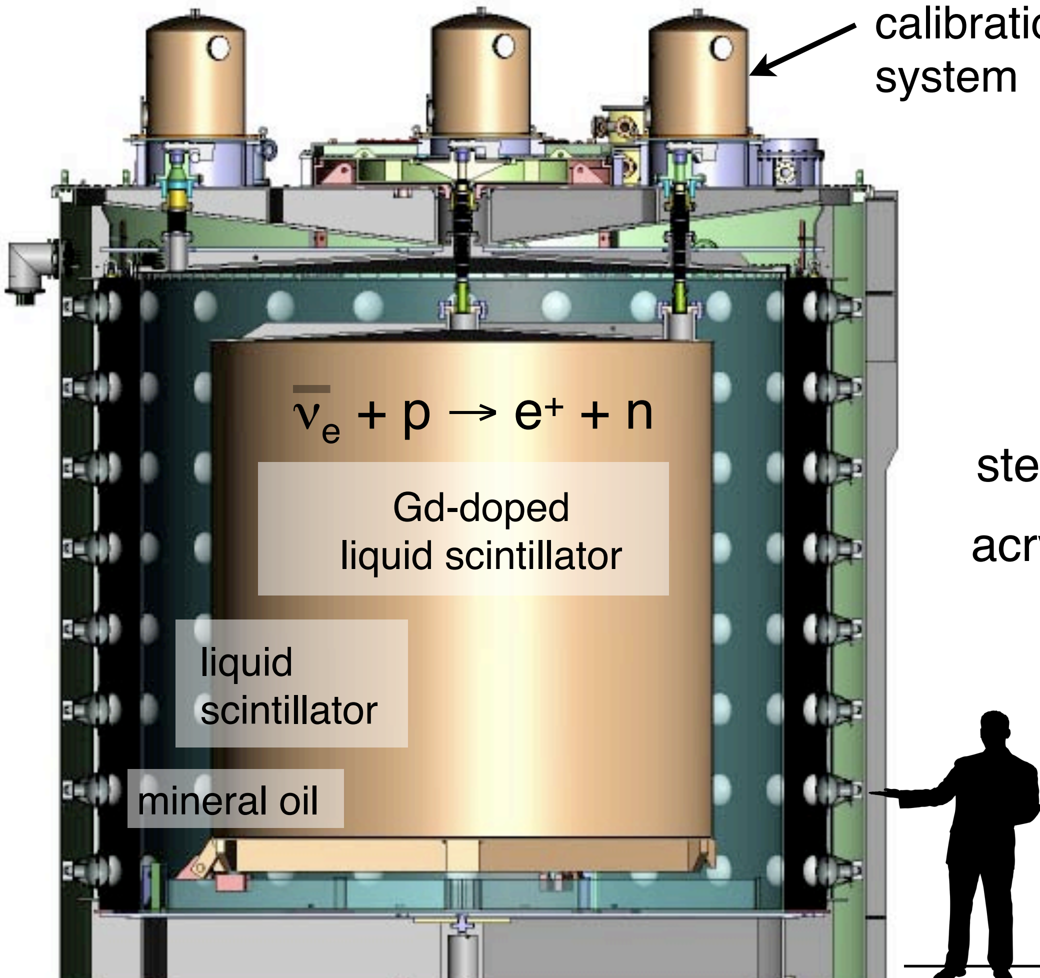


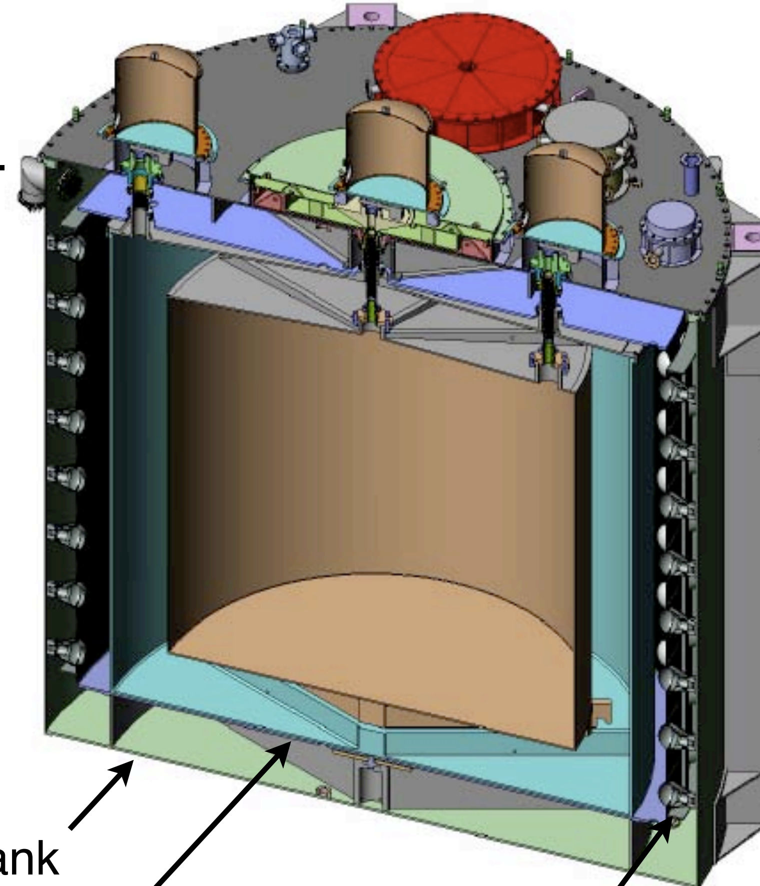
antineutrino detectors

~ 900 ν events/ detector/day

Daya Bay Antineutrino Detectors

- 8 “identical”, 3-zone detectors
- no position reconstruction, no fiducial cut

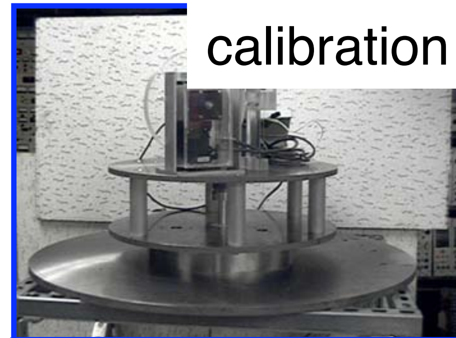


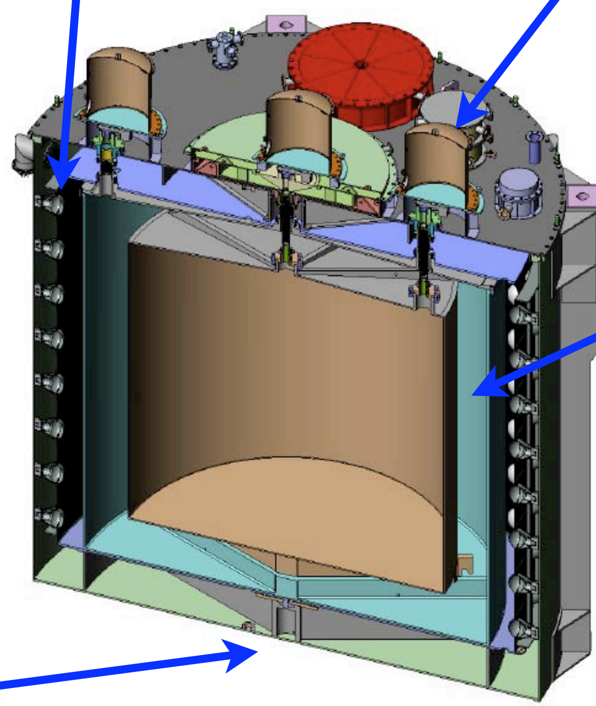


target mass:	20t per detector
detector mass:	~ 110t
photosensors:	192 PMTs
energy resolution:	12%/√E

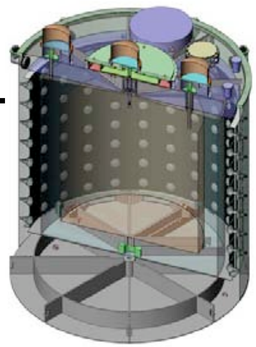
Daya Bay Antineutrino Detector Construction

photomultipliers





Antineutrino Event Rates and Signal



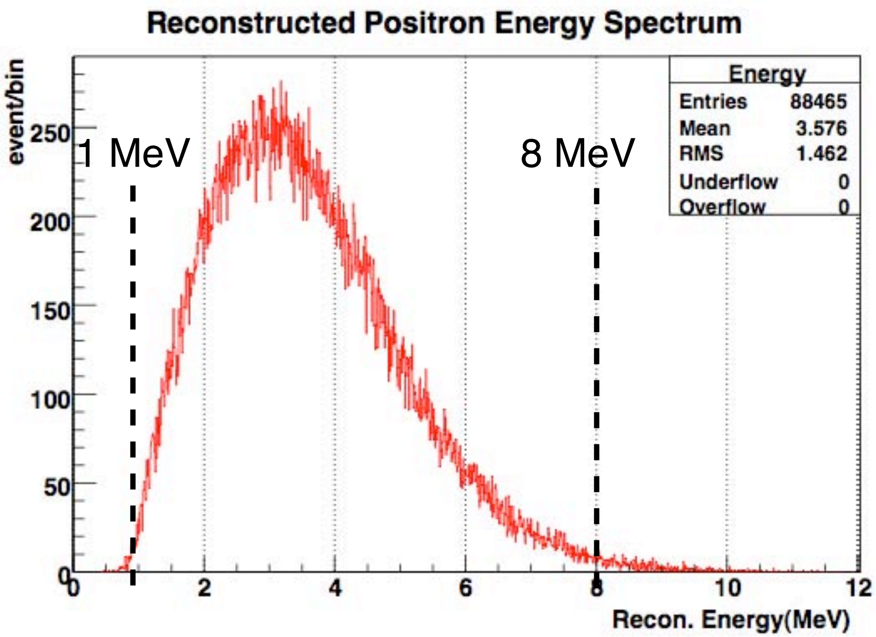
Daya Bay near site	840	events/day
Ling Ao near site	760	per 20 ton module
Far site	90	

$\nu_e + p \rightarrow e^+ + n$

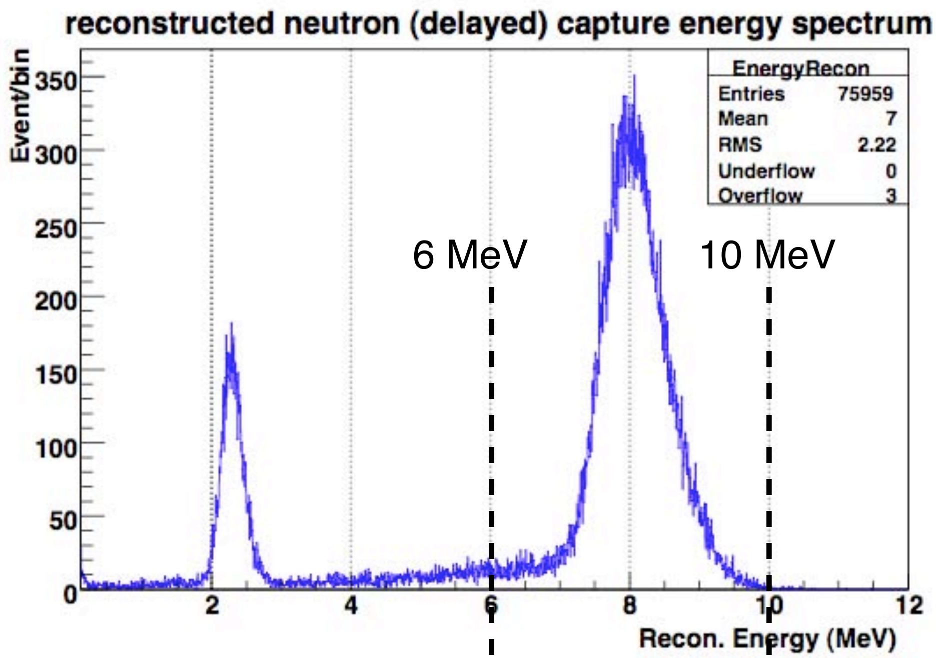
0.3 b → $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b → $+ Gd \rightarrow Gd^* \rightarrow Gd + \gamma$'s (8 MeV) (delayed)

Prompt Energy Signal



Delayed Energy Signal



Systematic Uncertainties

Detector-Related Uncertainties

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(0.2-0.3%) precision for relative measurement between detectors at near and far sites

Construction Progress and Schedule

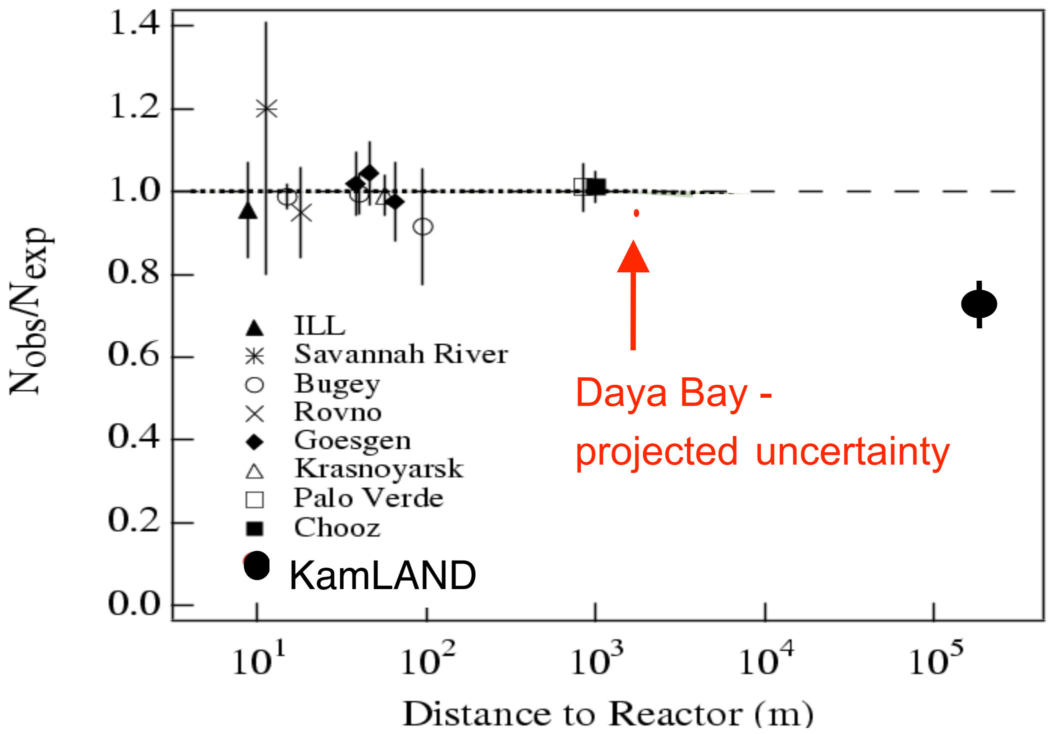
March 2009:
Assembly building occupancy

Summer 2009: Near Hall occupancy

Summer 2010: Near Hall ready for data

Summer 2011: Far Hall ready for data

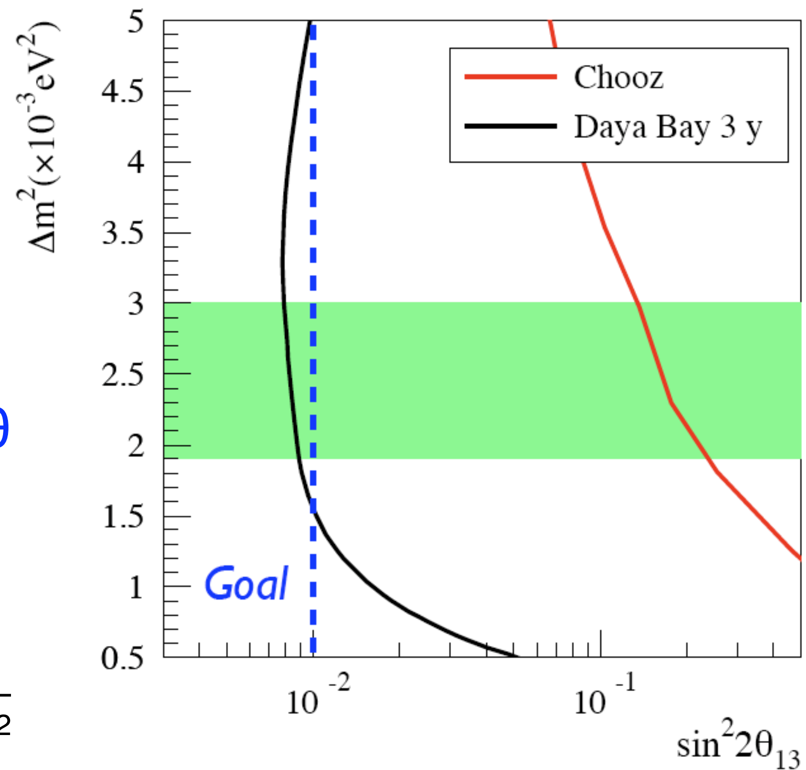
Expected Precision and Sensitivity of Daya Bay



Expected Precision to $\overline{\nu}_e$ Flux

past reactor experiments
= 1 detector

next generation of experiments
> 2 detectors



Daya Bay Sensitivity to $\sin^2 2\theta$

$\sin^2 2\theta_{13}$ < 0.01 @ 90% CL
in 3 years of data taking

Search for θ_{13}: A Possible Scenario

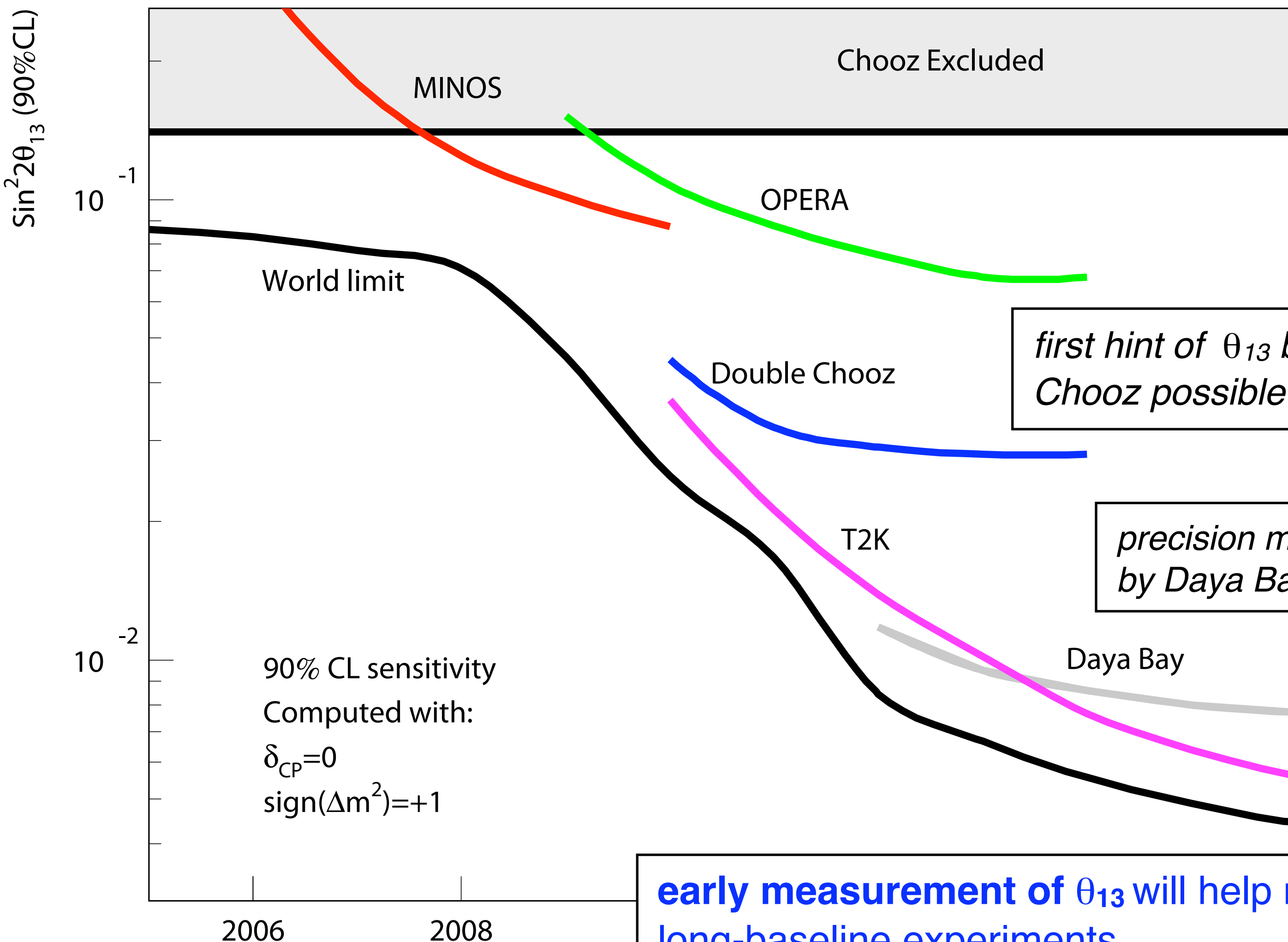


Fig: M. Mezzetto

first hint of θ_{13} by Double Chooz possible if θ_{13} large

precision measurement at 1% level by Daya Bay

early measurement of θ_{13} will help make decision on future long-baseline experiments

precision measurement of θ_{13} for unambiguous discovery and combined analysis with T2K and NOvA

Summary and Conclusions

Non-accelerator experiments were key in discovering neutrino mass and oscillations in the past decade (1998-2008).

Reactor experiments have made and will make significant contributions:

- KamLAND discovered reactor $\bar{\nu}_e$ oscillation and has made precise measurement of Δm^2_{12}

- Daya Bay reactor experiment will be able to provide the most accurate measurement of $\sin^2 2\theta_{13}$ in the next few years.

- Day Bay is funded, civil and detector construction are progressing. Data taking at near site will begin in 2010.

- Reactor θ_{13} experiments will help determine the future of neutrino oscillation physics (long-baseline, $\cancel{CP}$) and provide input to analysis of accelerator experiments.

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

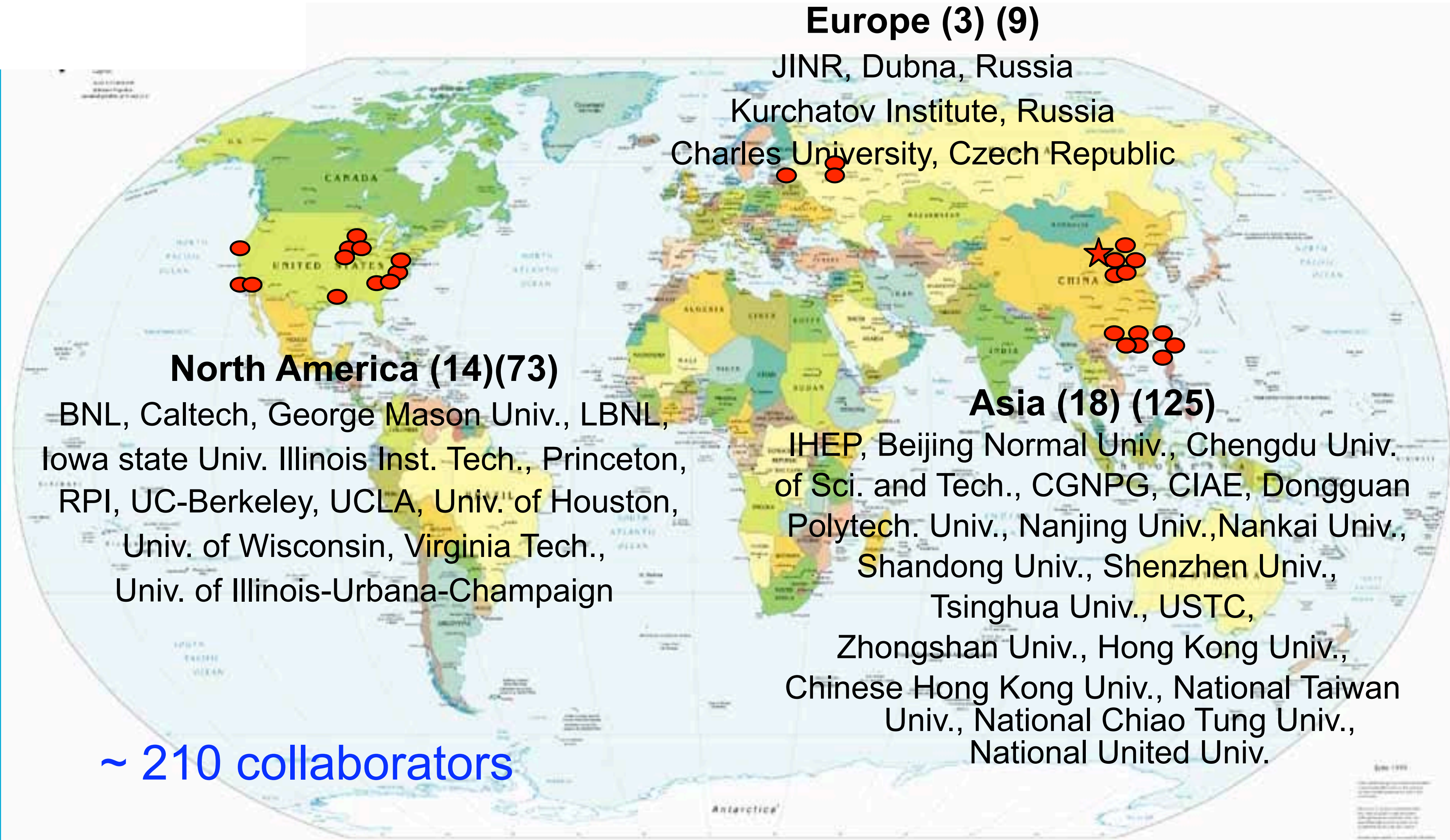
University of Tennessee

UNC/NCSU/TUNL

IN2P3-CNRS and University of Bordeaux

University of Wisconsin

Daya Bay Collaboration



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Charles University, Czech Republic

North America (14)(73)

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~ 210 collaborators