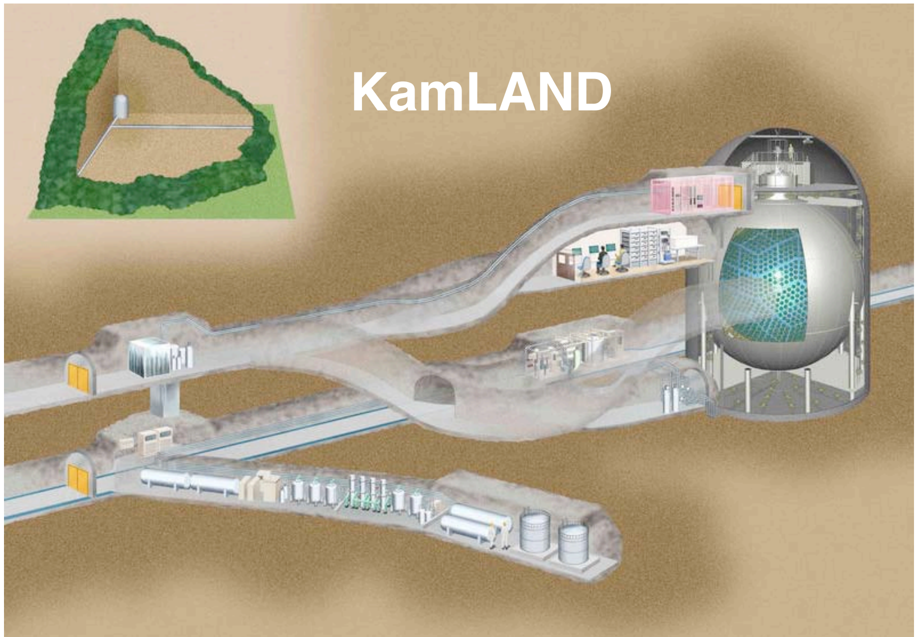
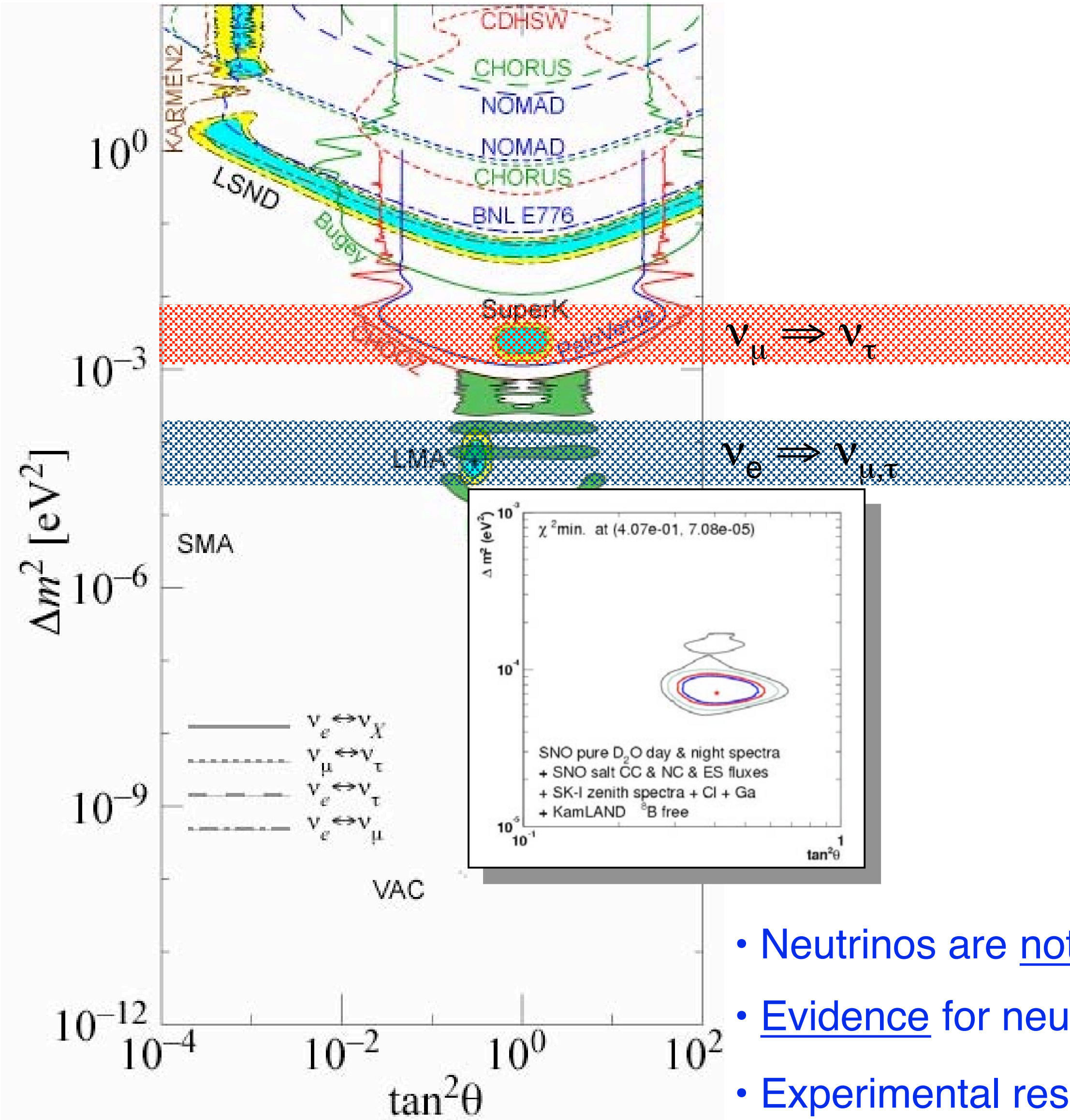


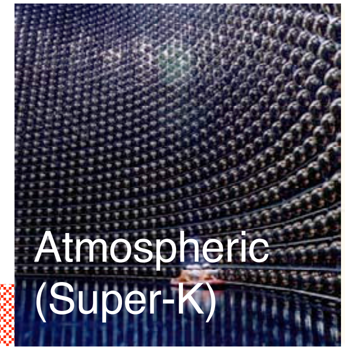
Reactor Neutrino Oscillation Experiments: Results and Prospects for the Future

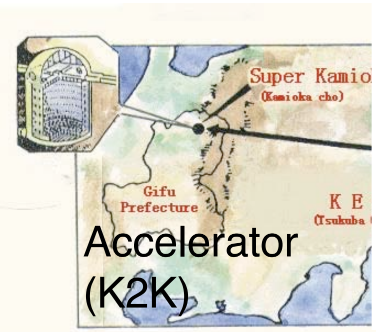
Karsten M. Heeger

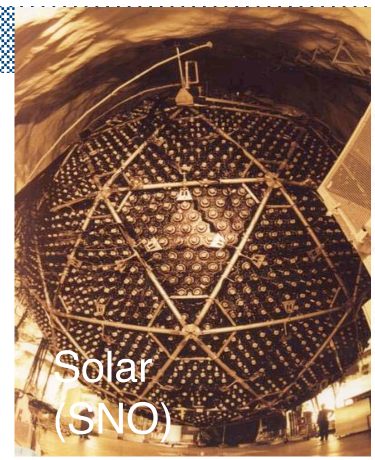
Lawrence Berkeley National Laboratory

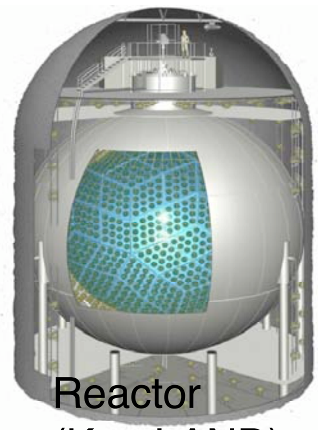
Recent Results in Neutrino Physics











- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$
- Experimental results show that *neutrinos oscillate*

Oscillation Parameters and Reactor Experiments

Reactor and Beamstop Neutrinos →

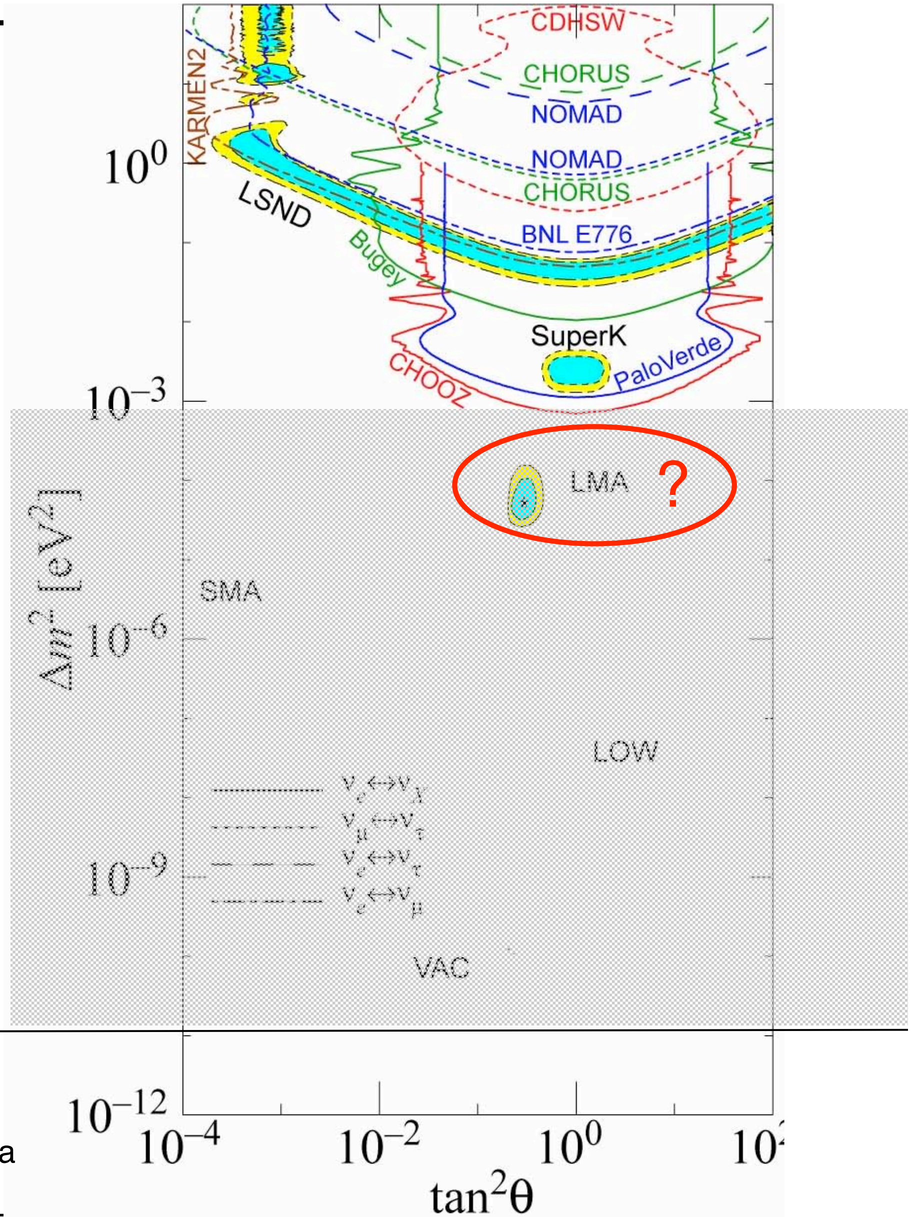
$\nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e$

Atmospheric and Reactor Neutrinos →

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

Solar and Reactor Neutrinos →

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



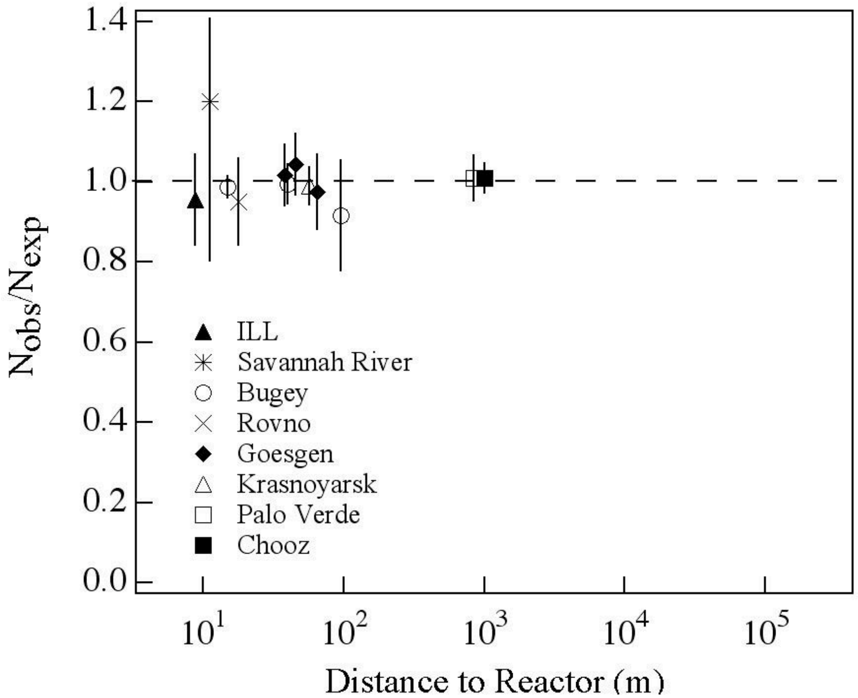
Large mixing favored

***LMA** solution can be tested with reactor neutrinos*

Status: Summer 2002

Murayama

Search for Neutrino Oscillations with Reactor Neutrinos



50 Years of Reactor Neutrino Physics

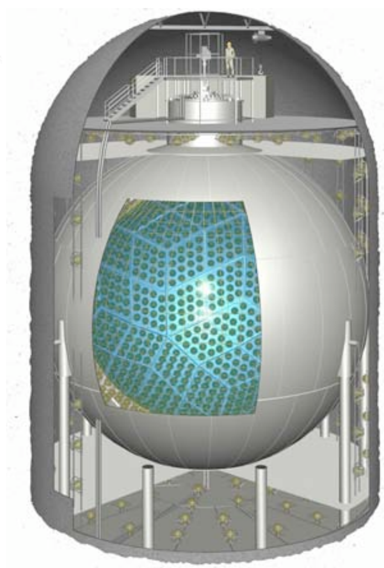
1953 First reactor neutrino experiment

1956 *"Detection of Free Antineutrino",*
F. Reines and C.L. Cowan

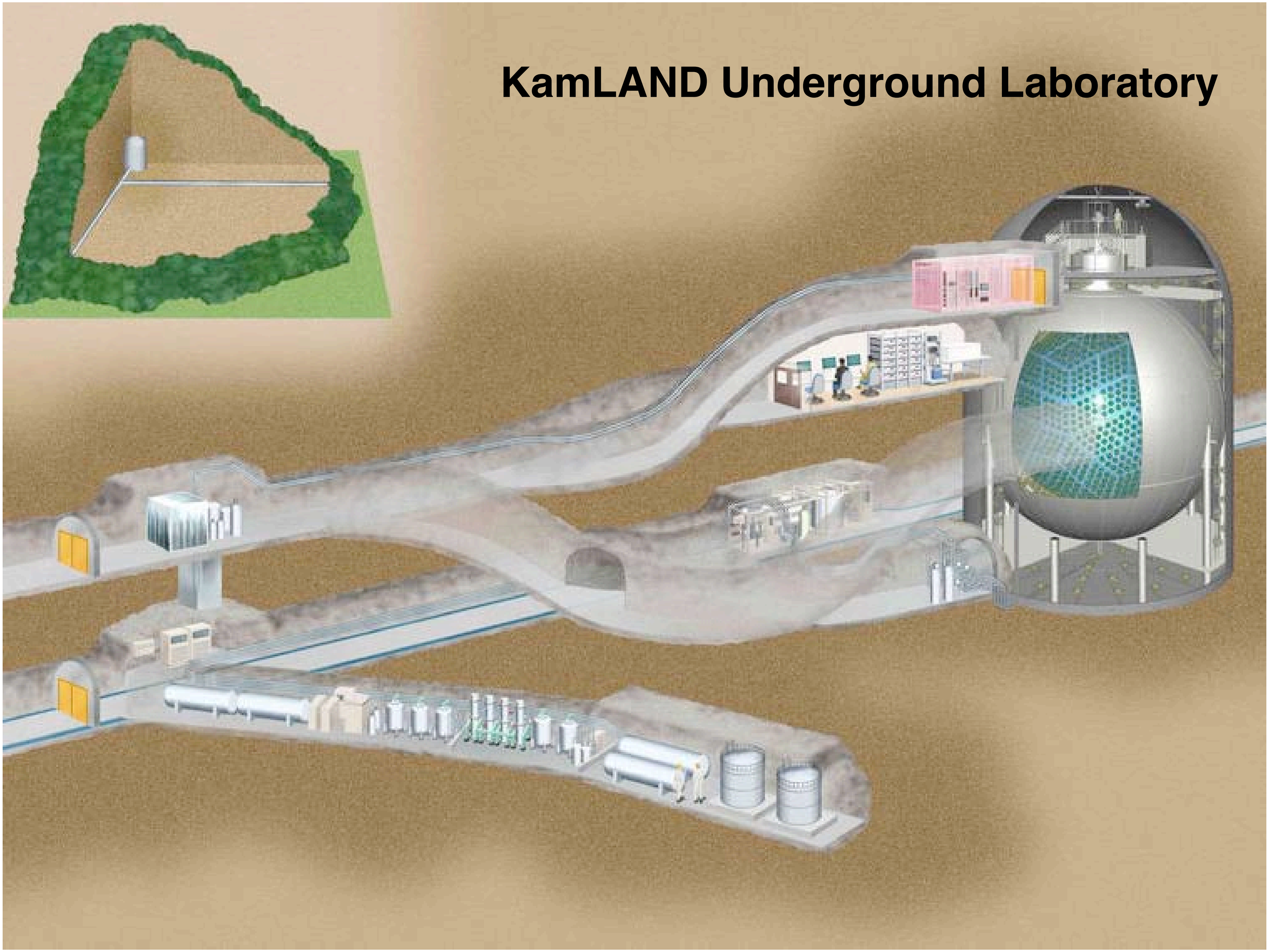
→ Nobel Prize in 1995

No signature of neutrino oscillations until 2002!

Results from solar experiments suggest study of reactor neutrinos with a baseline of ~ 180 km

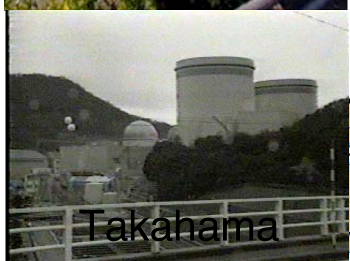


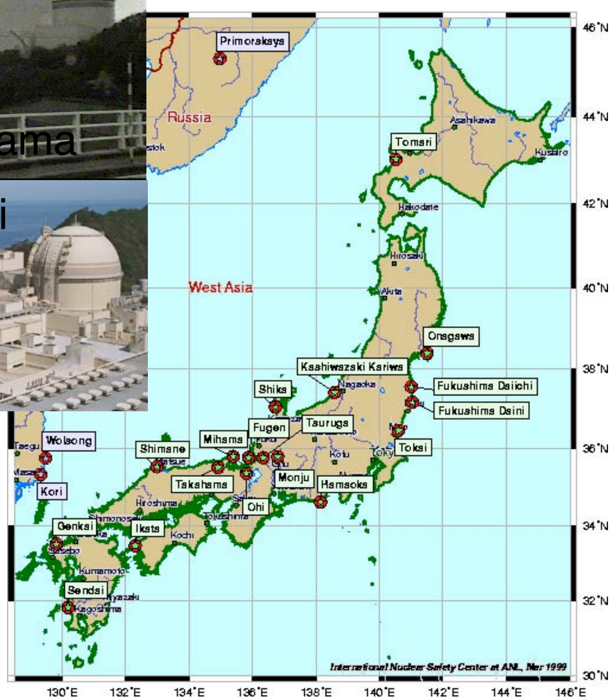
KamLAND Underground Laboratory



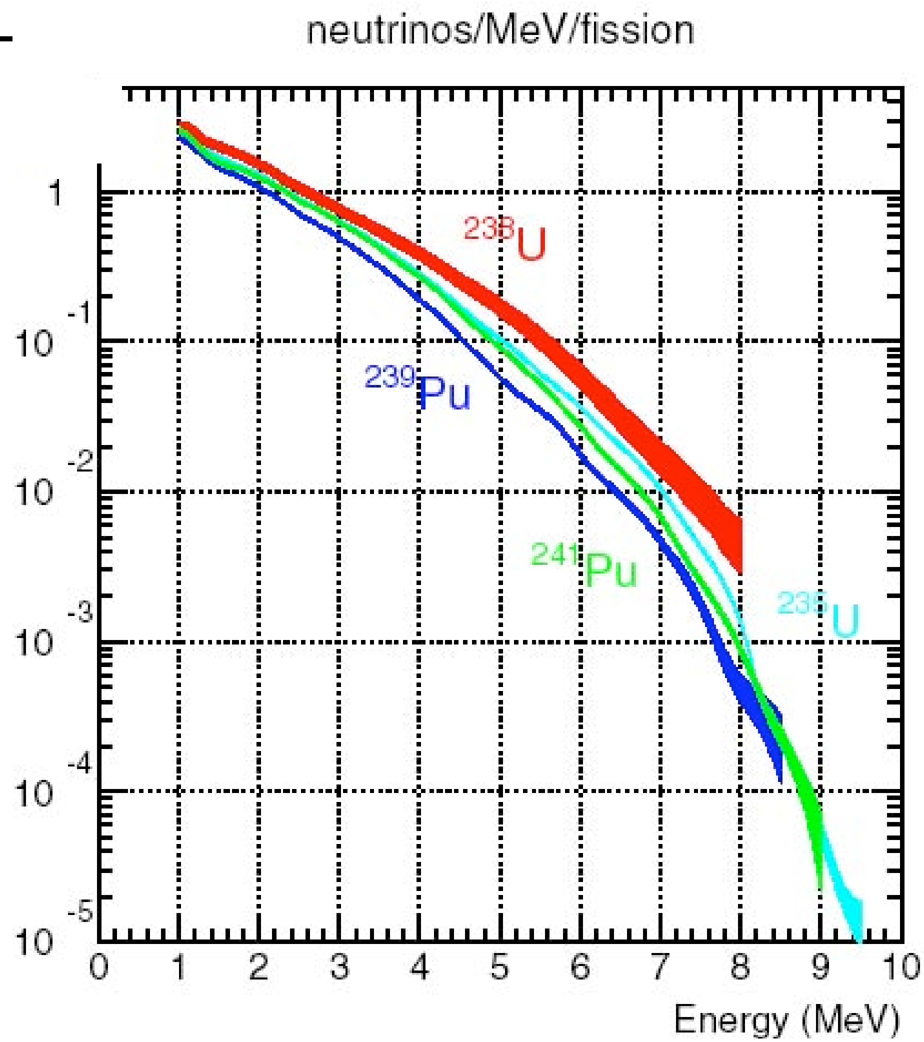
Reactor Antineutrinos

From Japanese Reactors





Spectrum from Principal Reactor Isotopes



~ 200 MeV per fission

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

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

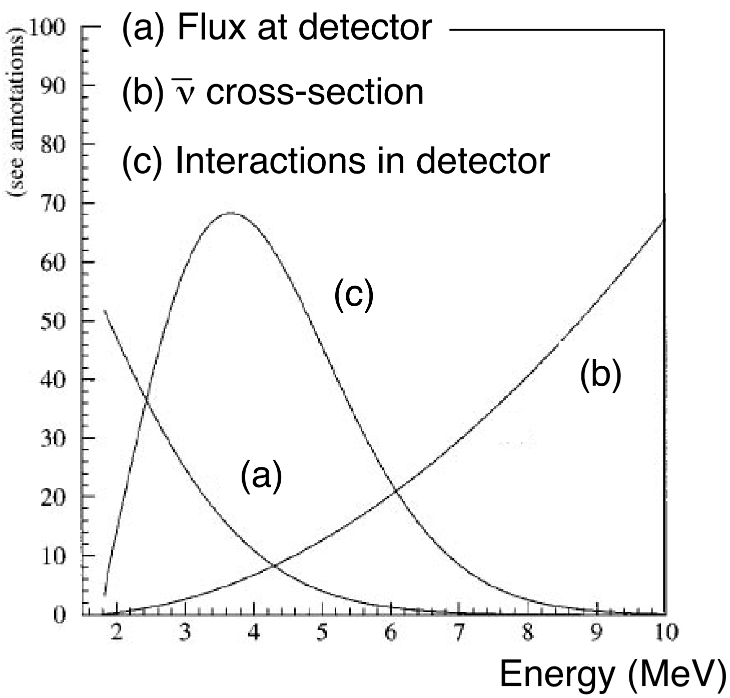
KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

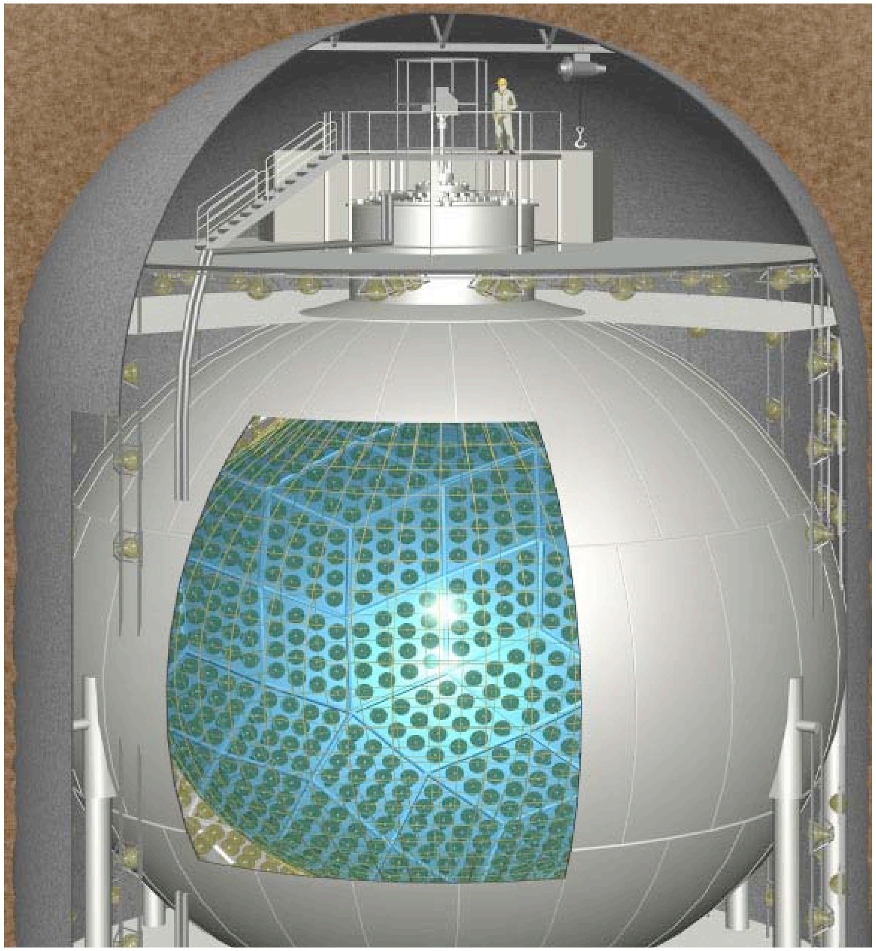
Uses reactor neutrinos to study $\overline{\nu}$ oscillation with a baseline of L ~ 140-210 km

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

Prompt e^+ annihilation

Delayed n capture, ~ 190 μs capture time

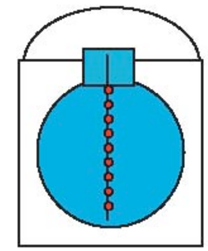


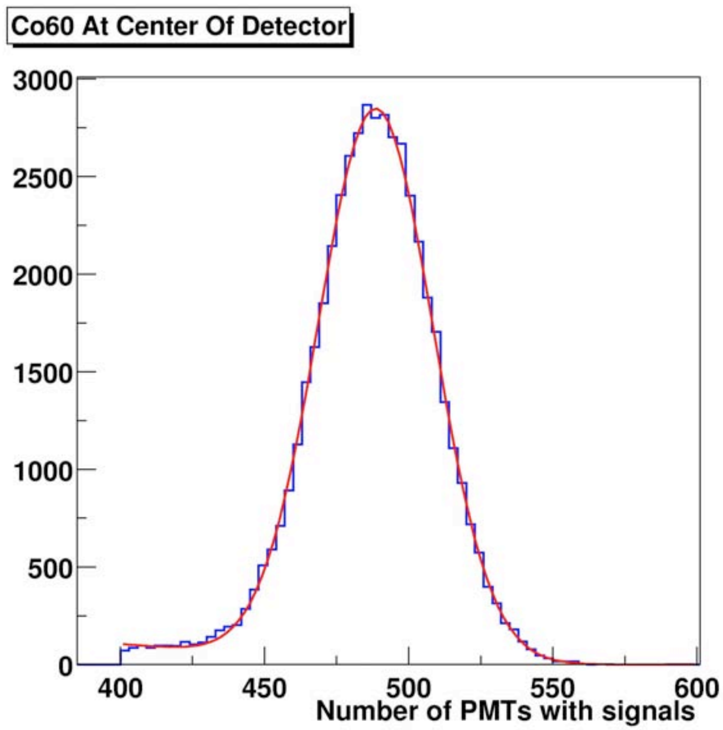


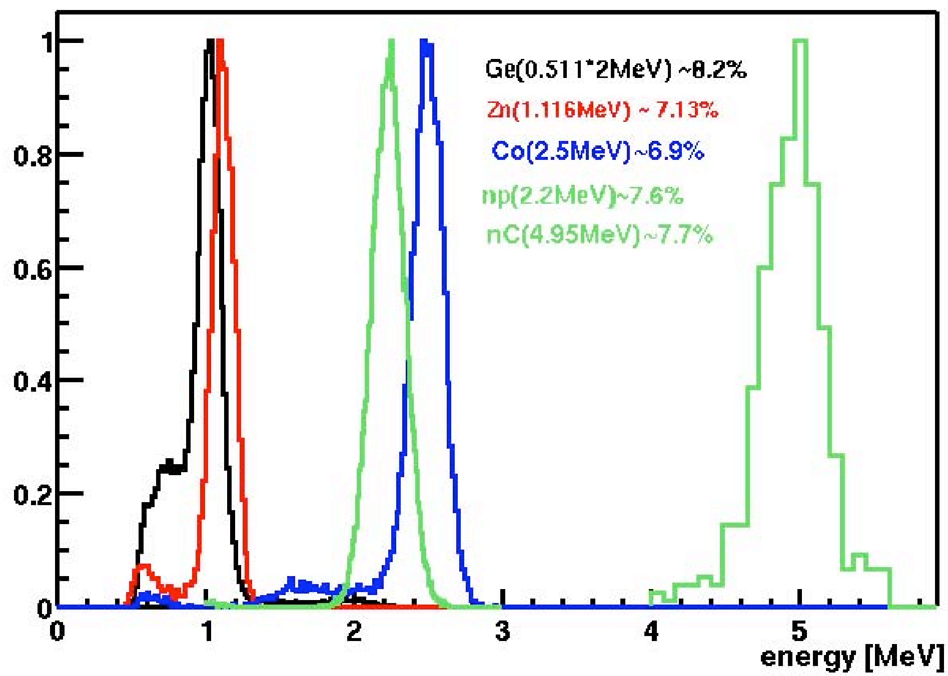
KamLAND studies the disappearance of $\overline{\nu}_e$ and measures

- interaction rate
- energy spectrum

Detector Energy Scale and Response







^{60}Co: 1.173+1.333 MeV

ΔE_{syst} = 1.91% at 2.6 MeV → 2.13 % for $\overline{\nu}_e$

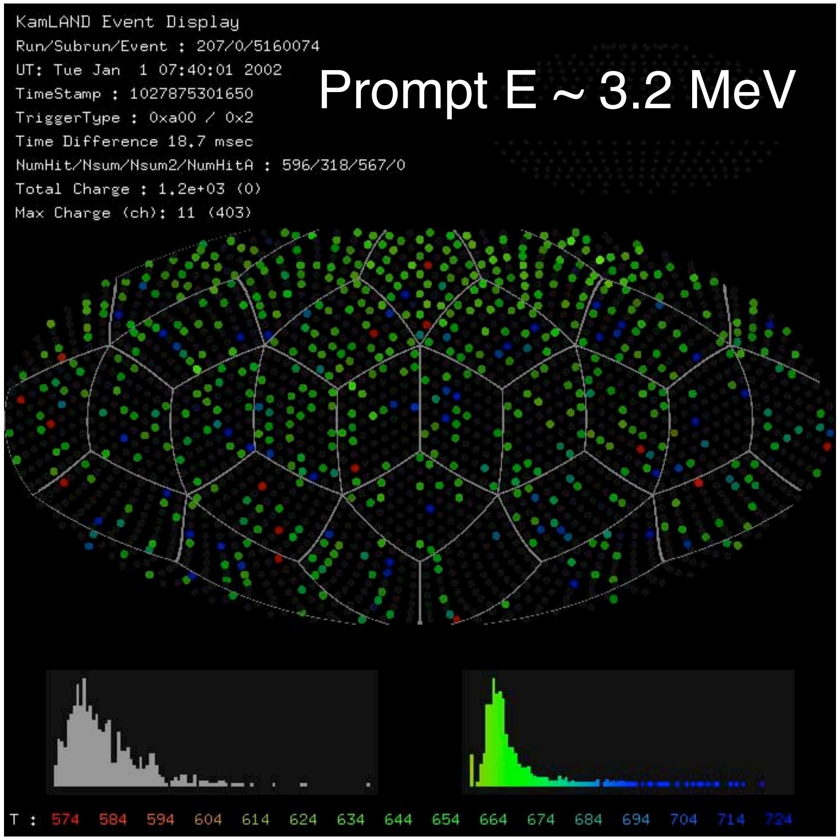
$\Delta E/E \sim 7.5\% / \sqrt{E}$

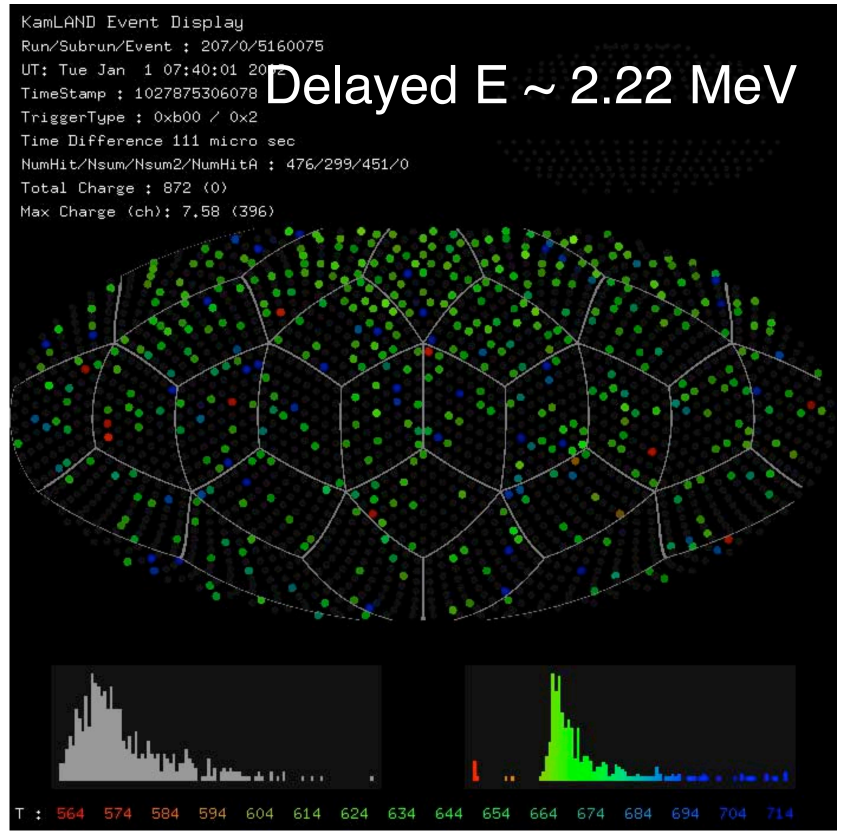
Light yield ~ 300p.e./MeV

Energy varies by < 0.5% within 10 m.

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

Candidate Neutrino Event



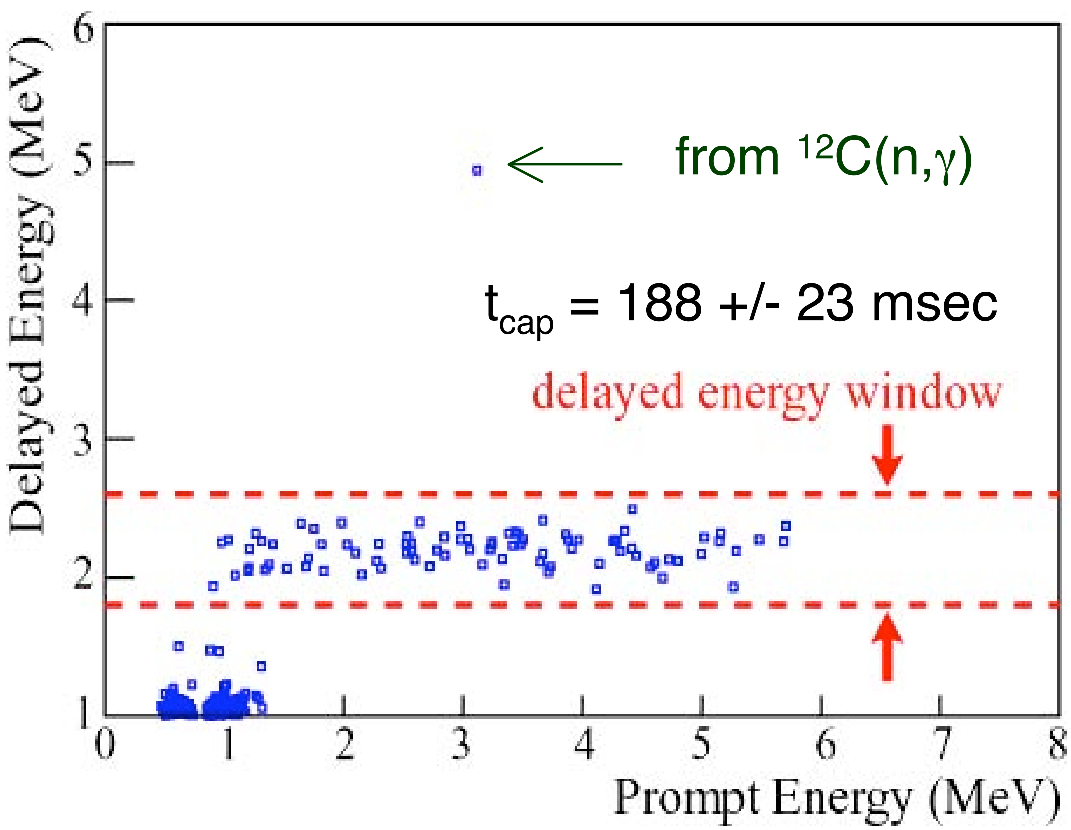


Δt~110 msec

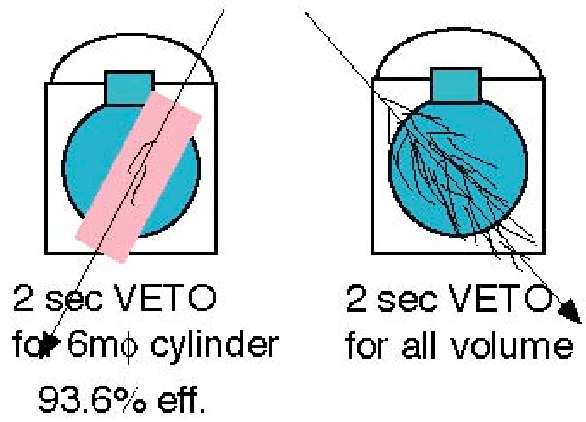
ΔR~0.35 m

Event Selection

Delayed Energy Window



Muon veto



Vertex and Time Correlation

$R < 5$ m

$0.5 < |dT| < 660$ msec

$|dR| < 1.6\ m$

$|dZ| > 1.2\ m$

Reactor Anti-Neutrino Observation at KamLAND

Observed	**54 events** 162 ton•yr, $E_{prompt} > 2.6$ MeV	*Excludes physics background from geo-ν*
Expected	**86.8 ± 5.6 events**	
Background	1 ± 1 events	
accidental	*0.0086 ± 0.0005*	*Measured: Δt_{pd}=0.02-20 s.*
$^{9}Li/^{8}He$	*0.94 ± 0.85*	*Confirmed by τ within 3%.*
fast neutron	*< 0.5*	*From observed n signal and known neutron production in rock.*

Note: error from background << total systematic error

KamLAND - Systematic Uncertainties

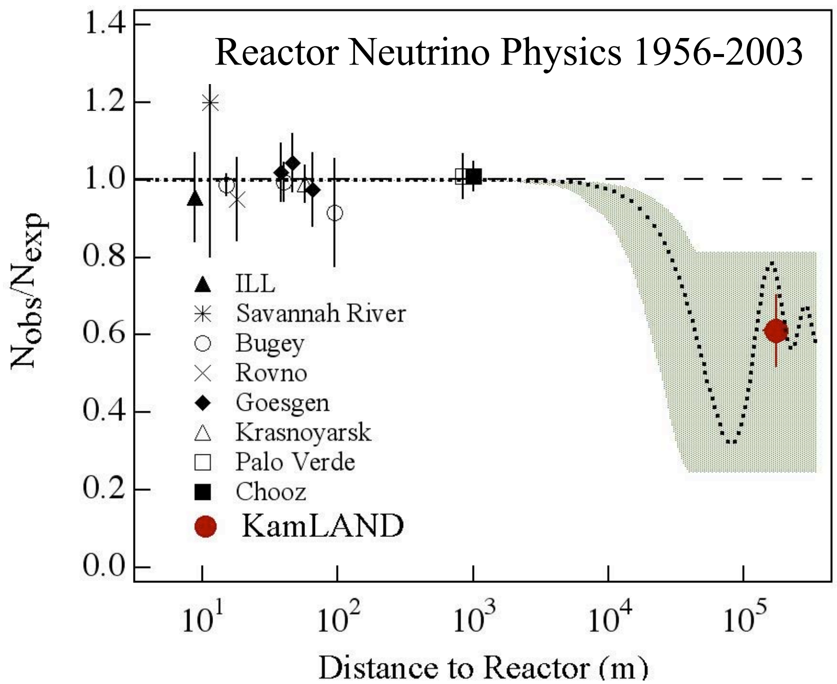
E > 2.6 MeV

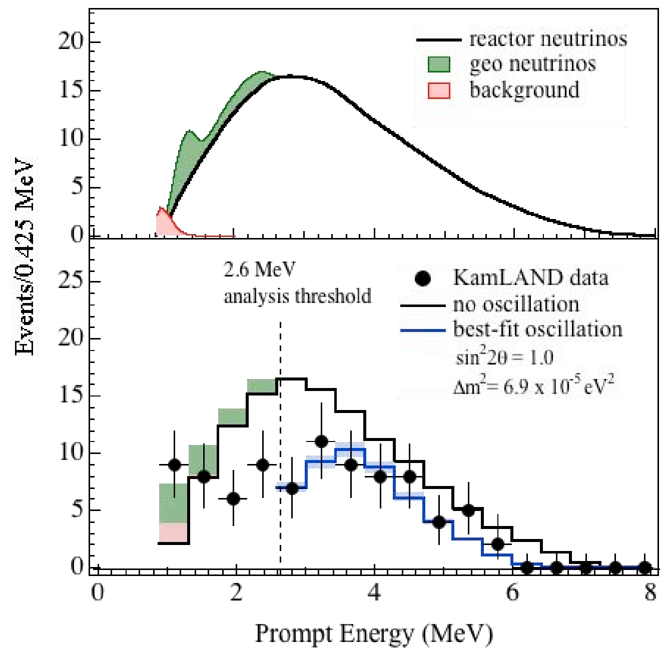
	%		
Total liquid scintillator mass	2.1	FV	• volume calibration
Fiducial mass ratio	4.1		
Energy threshold	2.1		• energy calibration or analysis w/out threshold
Tagging efficiency	2.1		• detection efficiency
Live time	0.07		
Reactor power	2.0	*given by reactor company, difficult to improve on*	
Fuel composition	1.0		
$\bar{\nu}_e$ spectra	2.5	*theoretical, model-dependent*	
cross section	0.2		
Total uncertainty	6.4 %		

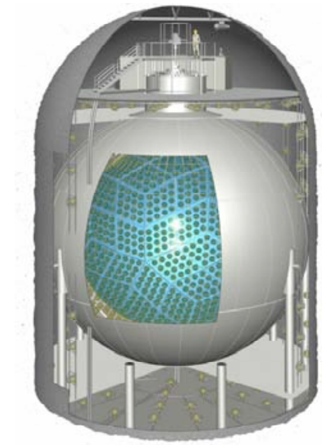
KamLAND Results in 2002/2003

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

PRL 90:021802, 2003







• KamLAND provides evidence for neutrino oscillations together with solar experiments.

Search for $\overline{\nu}_e$ from Sun

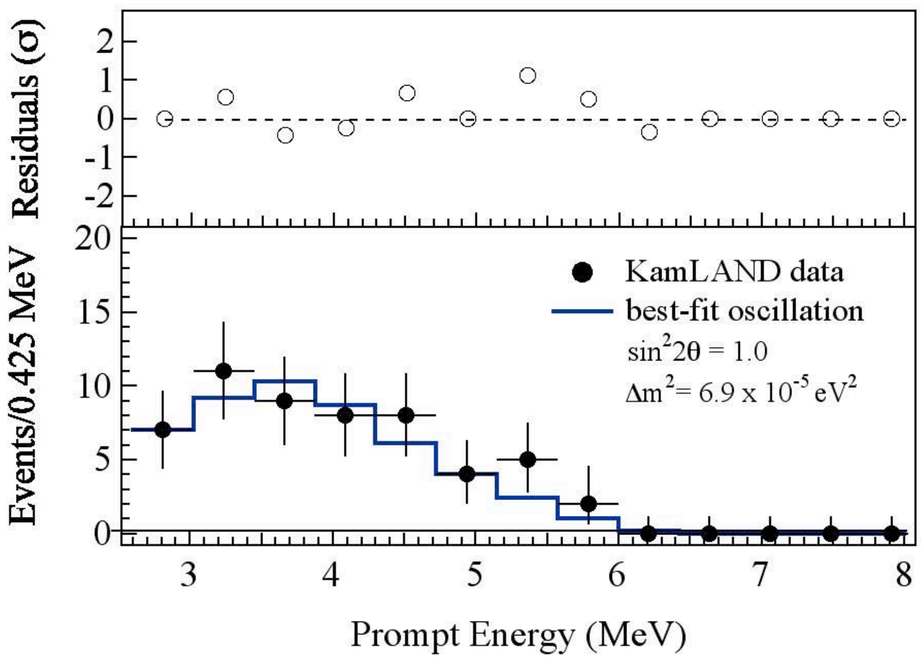
PRL 92:071301, 2004

$\Phi_{\overline{\nu}e}$ = 3.7 x 10^2 cm^{-2} s^{-1}

Improvement by factor x30

Is the KamLAND Neutrino Spectrum Distorted?

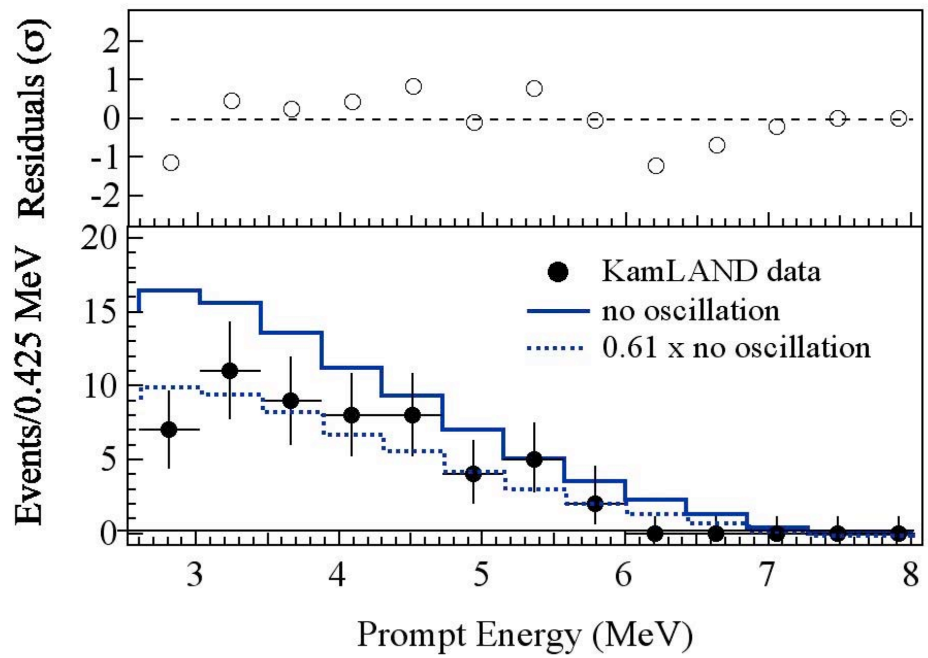
2-ν oscillation: best-fit



$\chi^2_{/\,8\ \mathrm{d.o.f}} = 0.31$

Data and best oscillation fit consistent at 93% C.L.

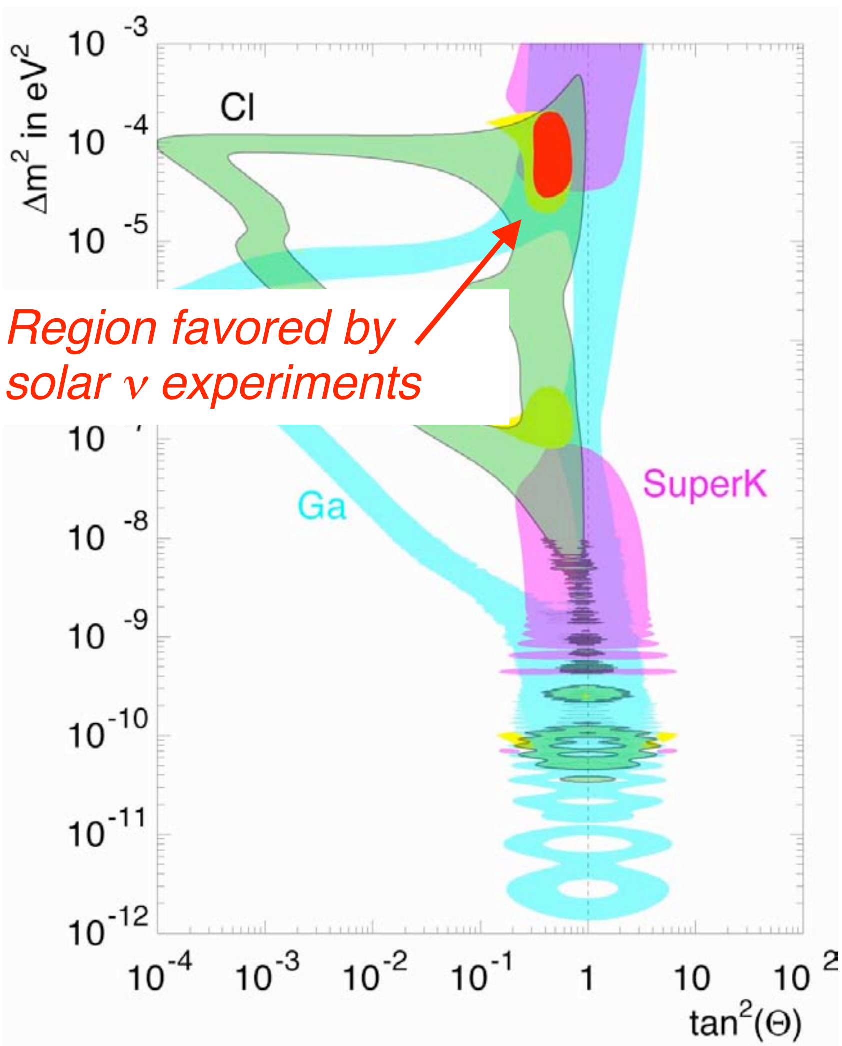
No oscillation, flux suppression



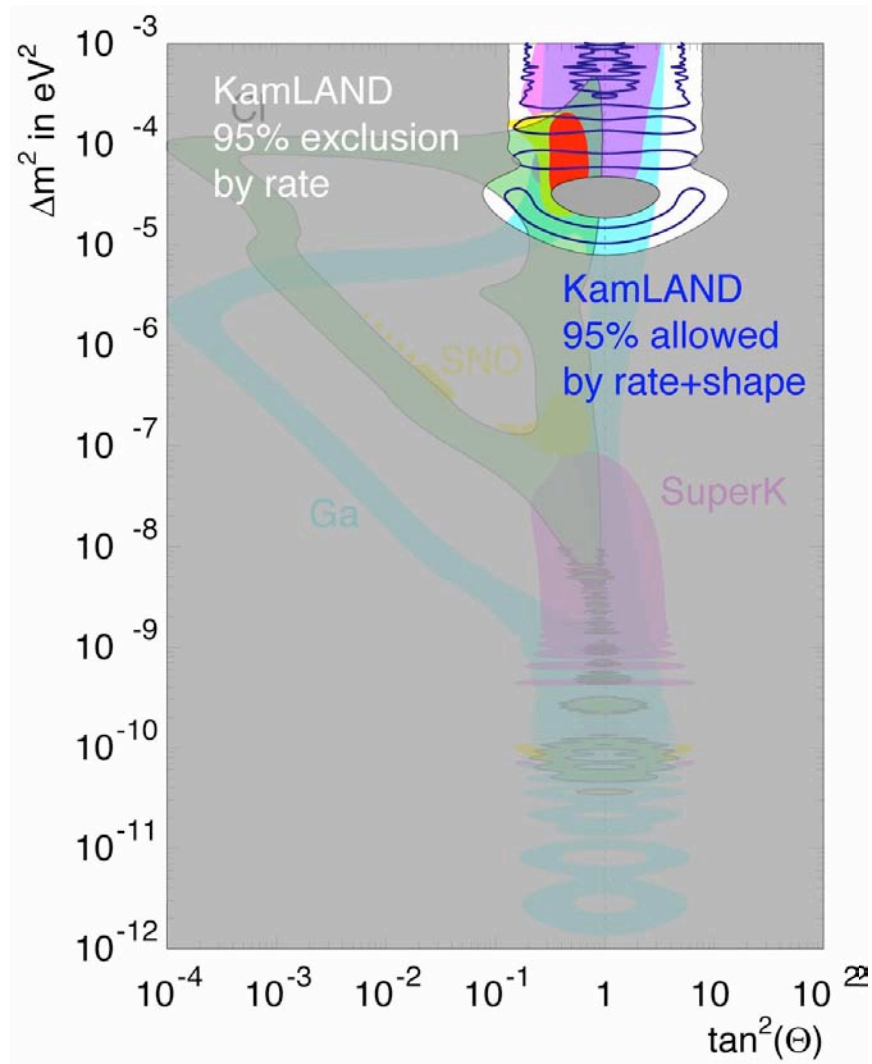
Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo

Oscillation Parameters *Before* and *After* KamLAND

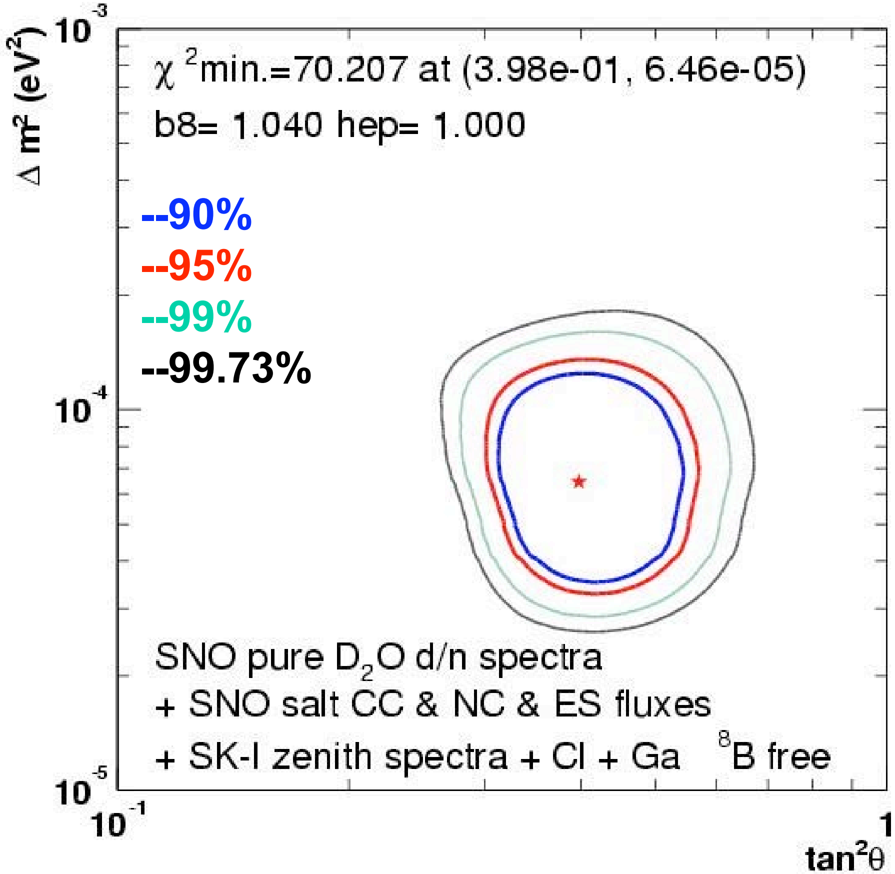
Before KamLAND



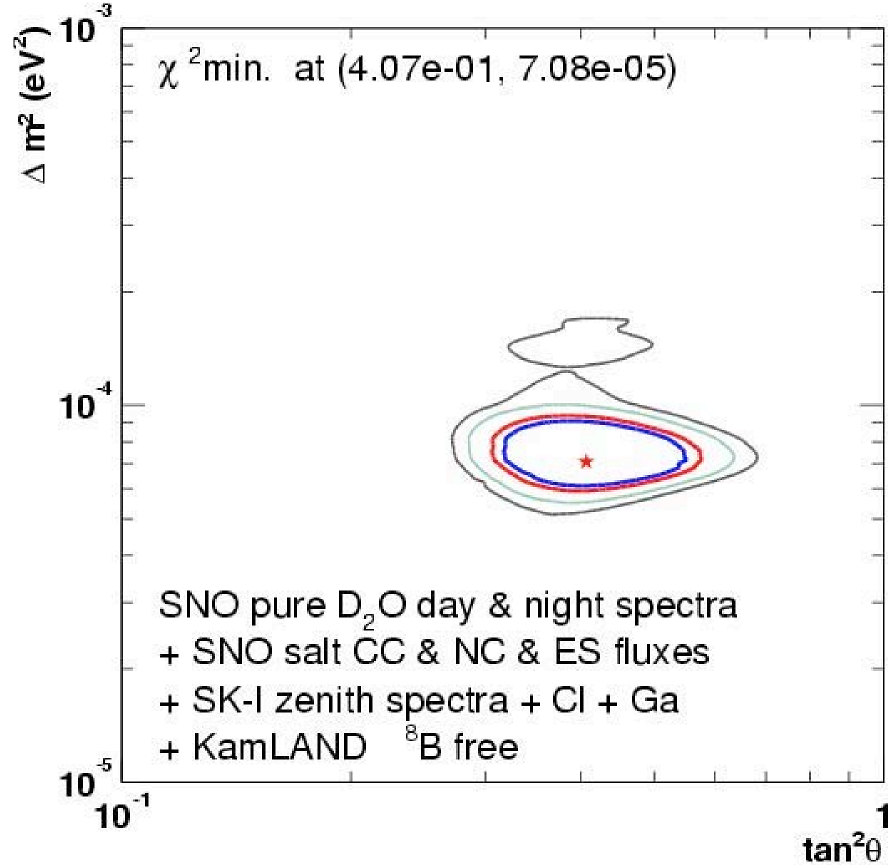
After KamLAND



Determination of Oscillation Parameters Δm_{12}^2, θ_{12}



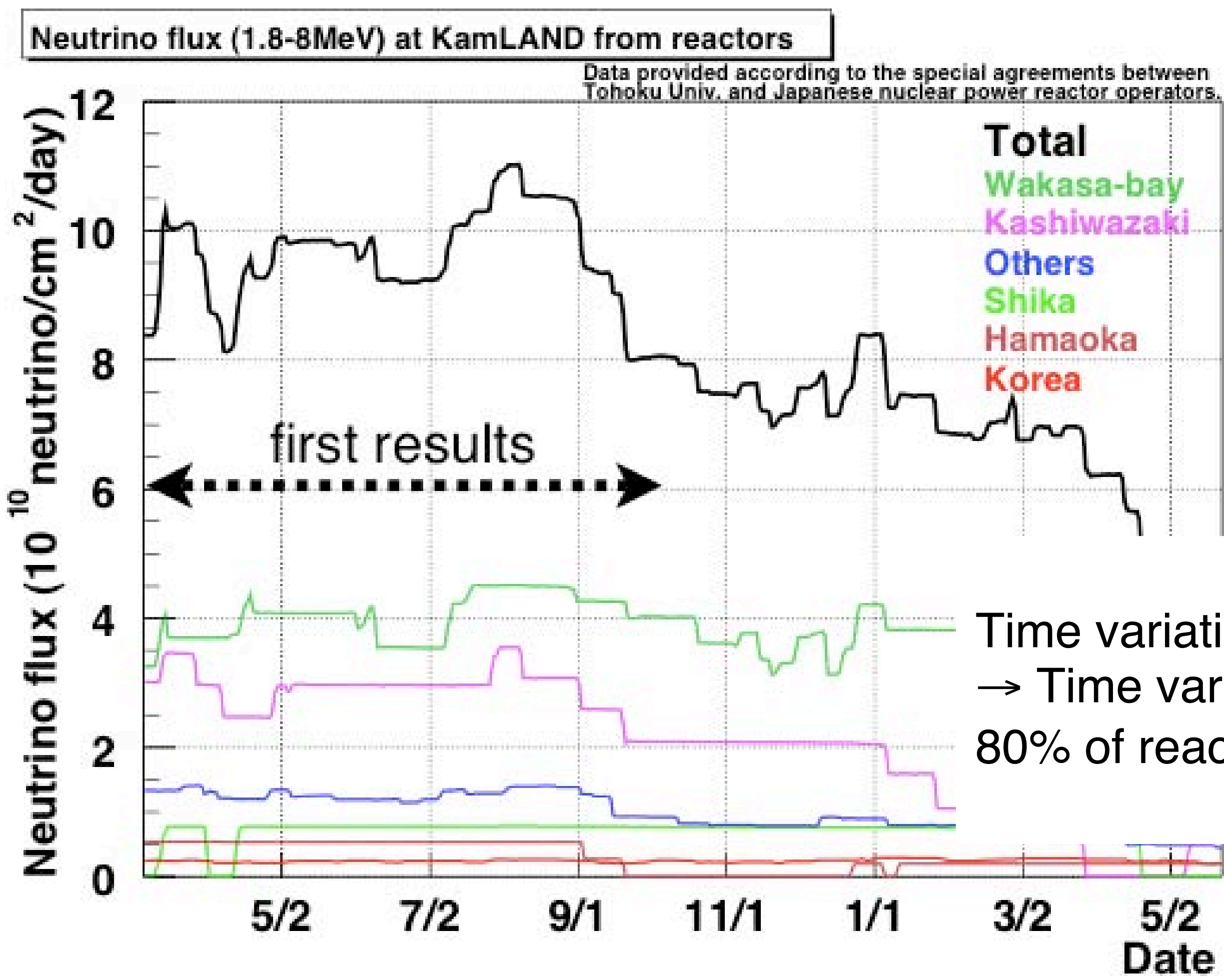
Ref: SNO solar global fit



LMA I only at > 99% CL

What's next for KamLAND?

Continued Running



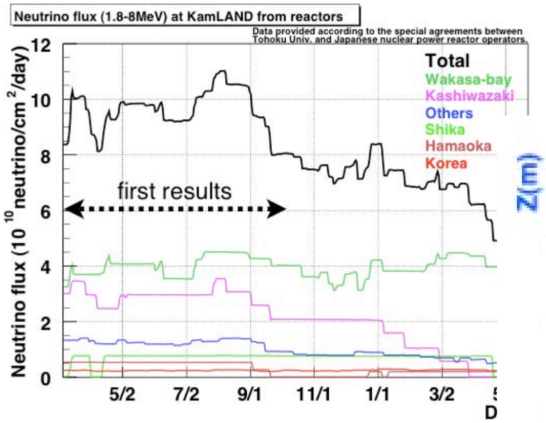
Time variation of reactor flux

→ Time variation of baseline

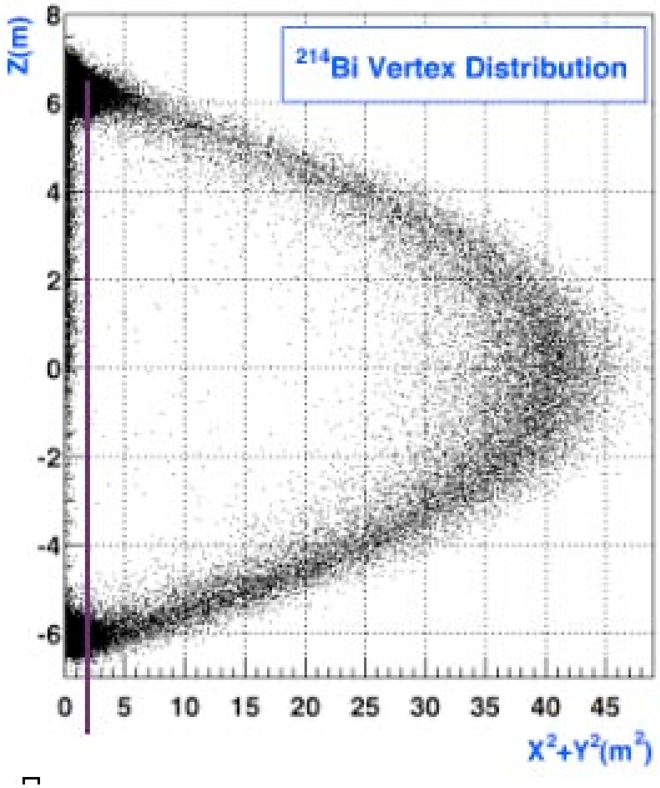
80% of reactors within 140-210 km

What's next for KamLAND?

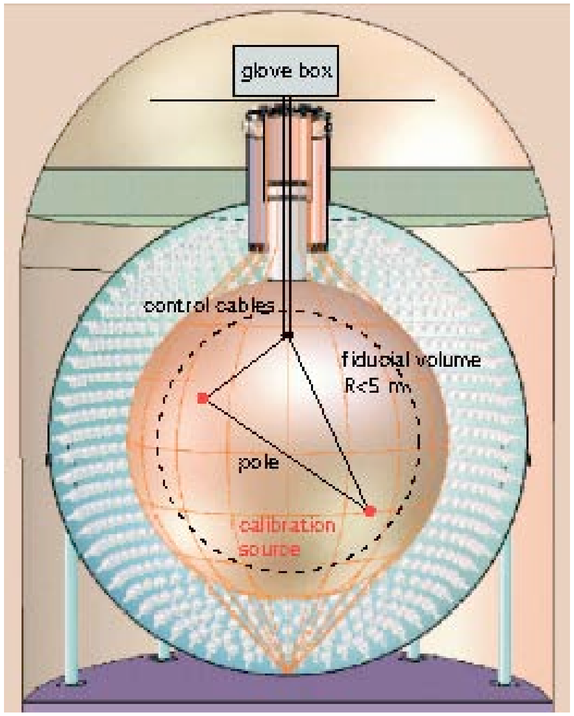
Continued Running



Enlarge Fiducial Volume

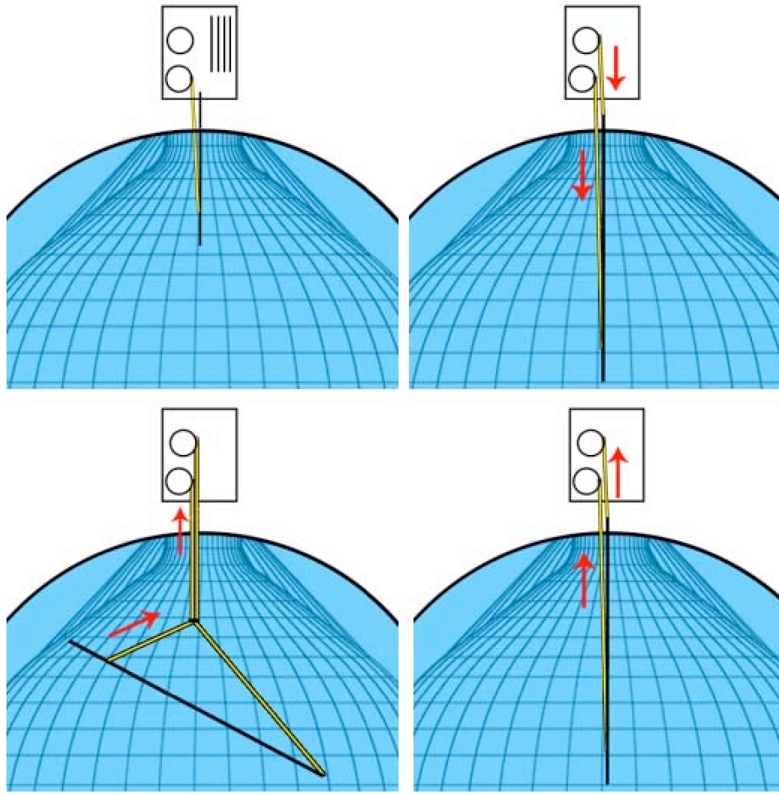


Improve Calibration



KamLAND Off-Axis Calibration

Calibration throughout entire detector volume

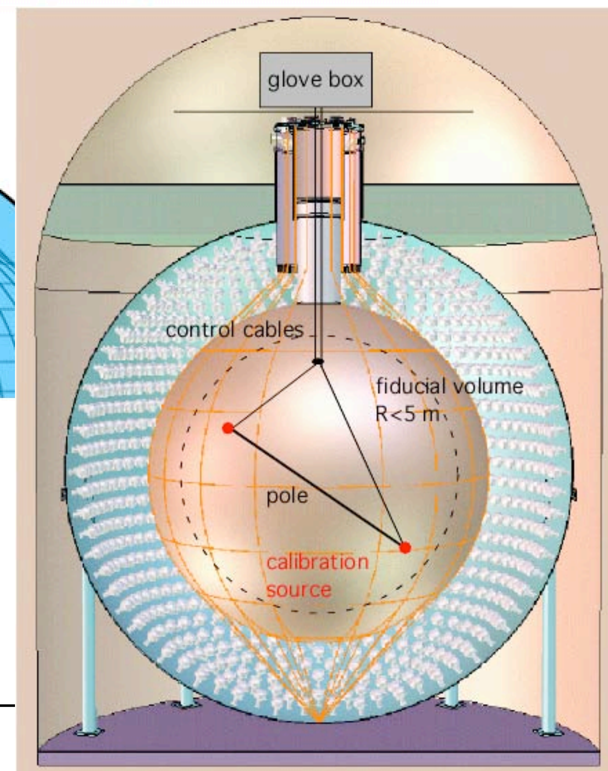


Fiducial volume:
R < 5 m

$\Delta R_{FV} = 5$ cm
$\rightarrow \Delta V = 3\%$

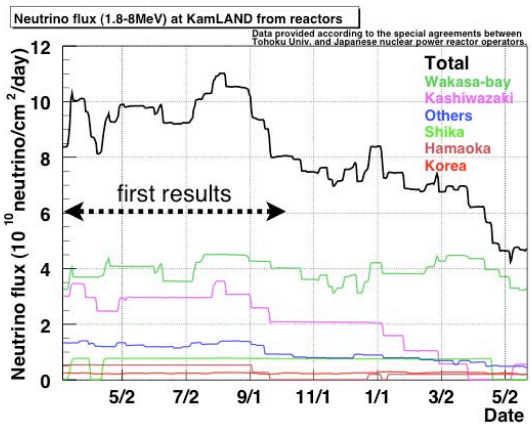
Position Dependence of Detector Response

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

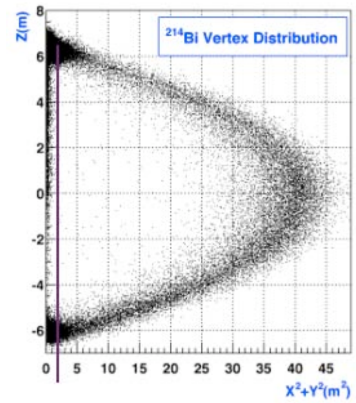


What's next for KamLAND?

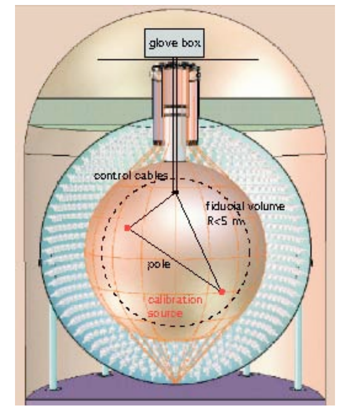
Continued Running



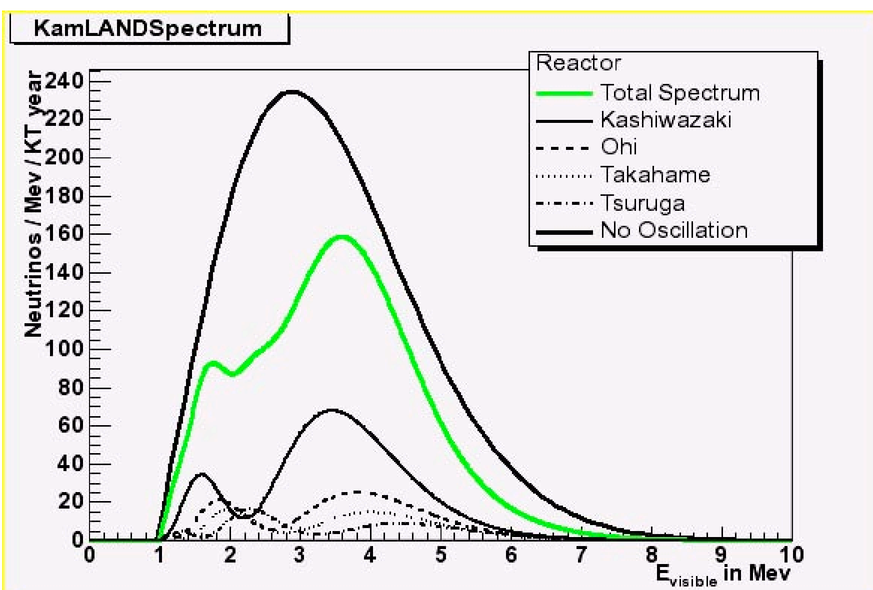
Enlarge Fiducial Volume



Improve Calibration

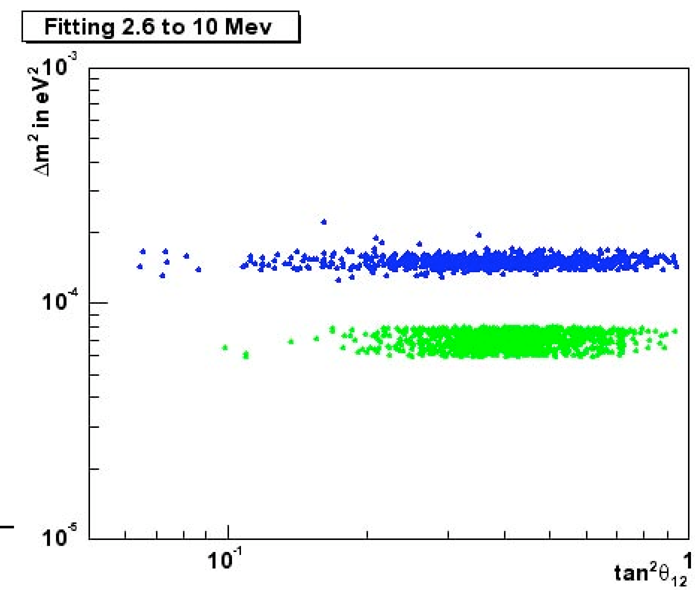


Search for Spectral Distortions



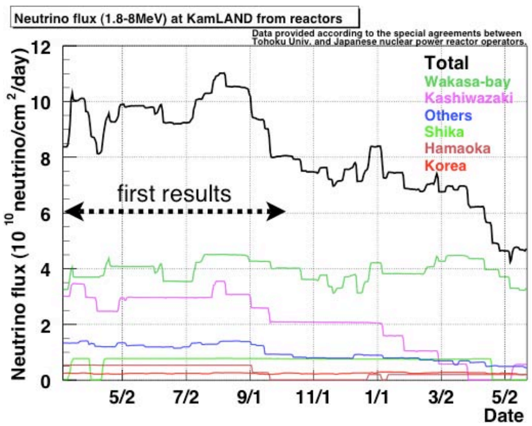
, 2004

Improve Δm^2 and θ_{12}

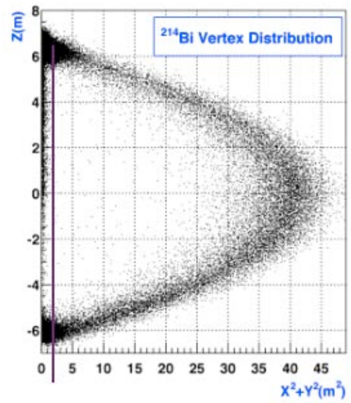


What's next for KamLAND?

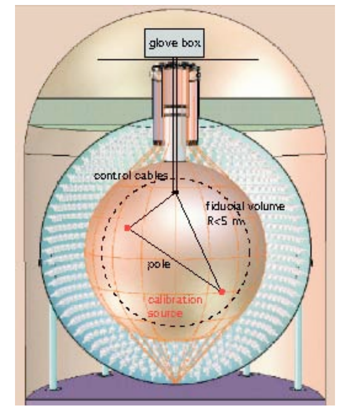
Continued Running



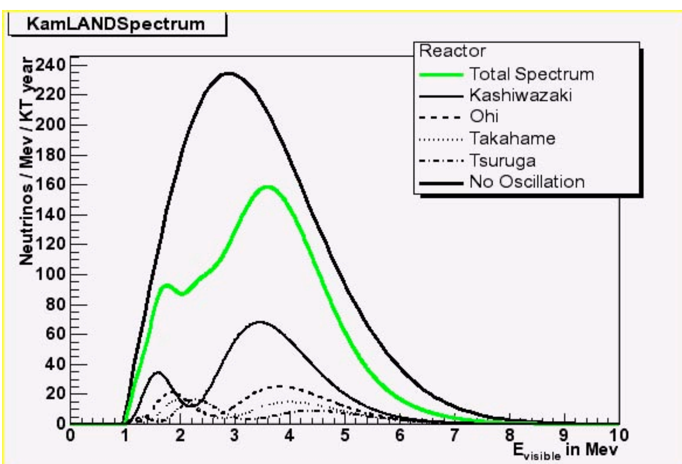
Enlarge Fiducial Volume



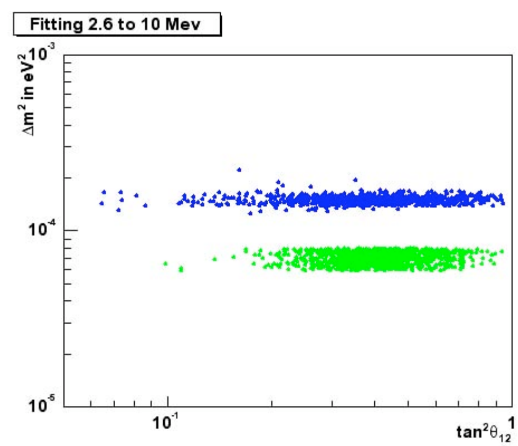
Improve Calibration



Search for Spectral Distortions



Improve Δm^2 and θ_{12}

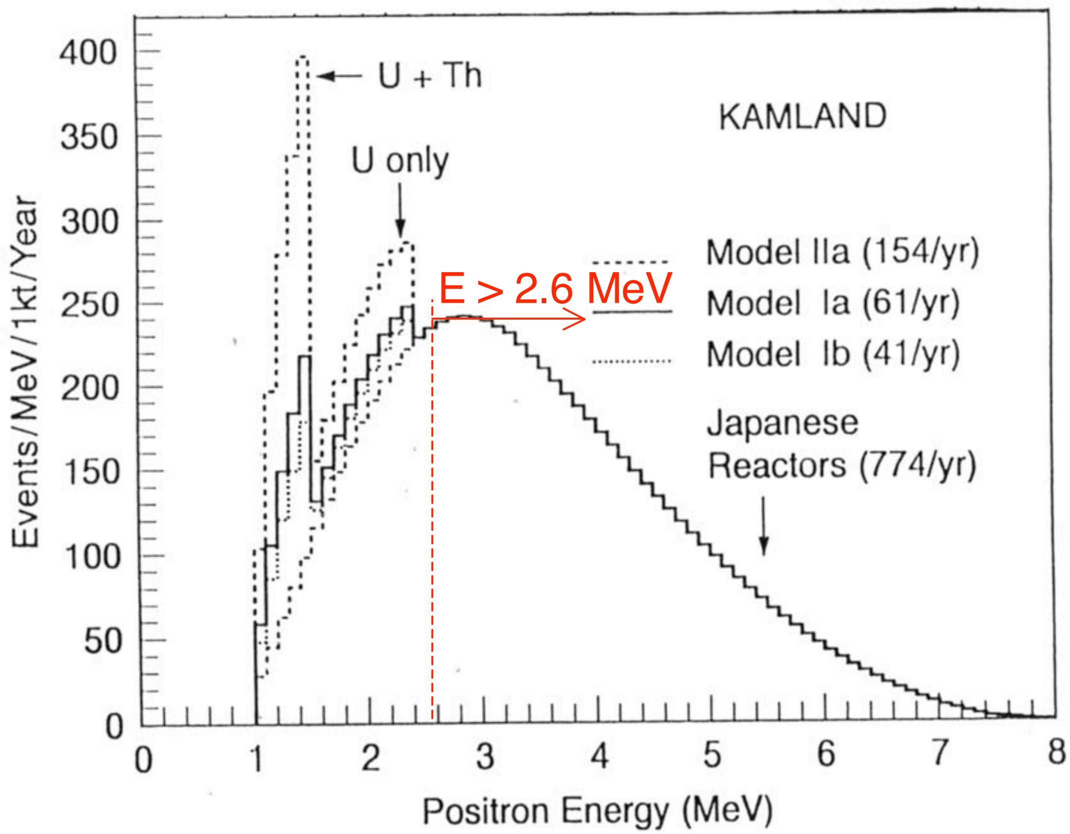


Search for geo-, supernova, and relic-supernova anti-neutrinos.
Nucleon decay studies.

Geo-Neutrino Signal

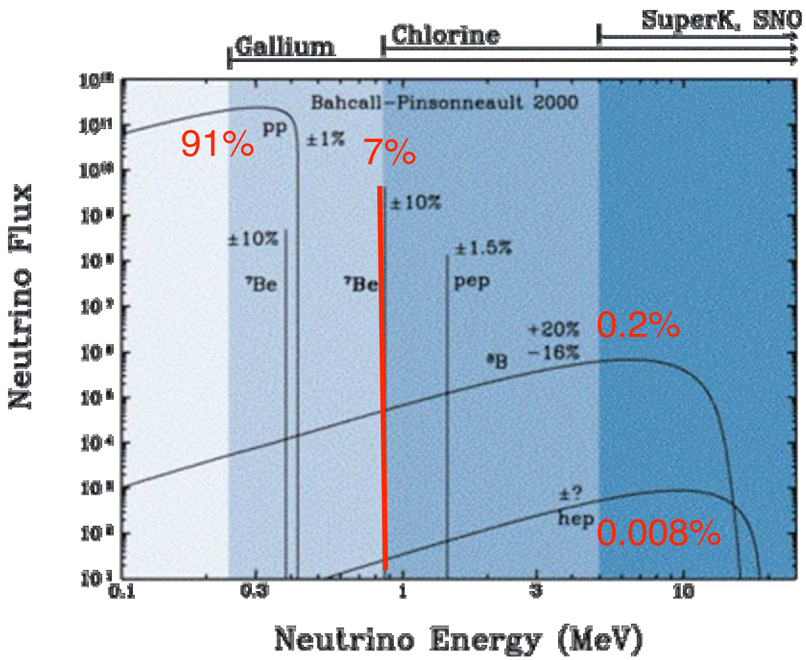
U/Th decays in the Earth produce radiogenic heat (40-60% of 40TW)

$E_{\nu(geo)} < 2.49$ MeV

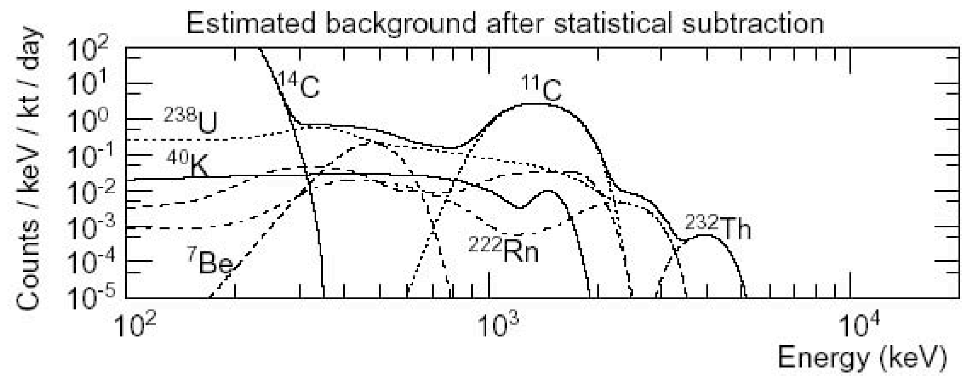


Raghavan et al. PRL 80 (1998)

A Background Challenge: ^{7}Be Solar Neutrinos at KamLAND



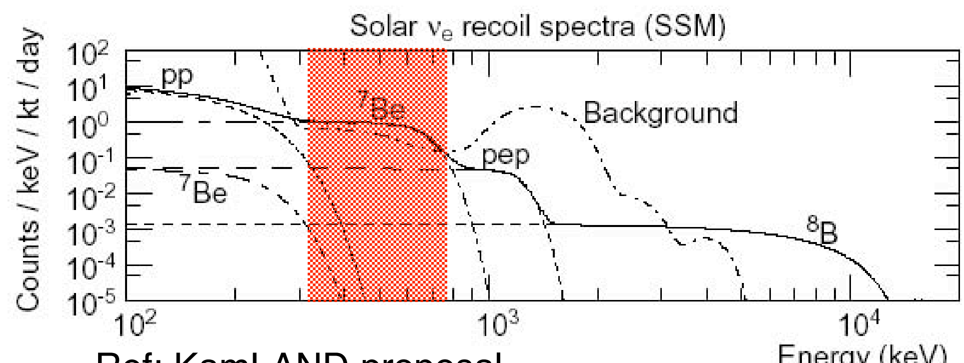
Direct detection of solar ^{7}Be neutrinos through elastic scattering
→ Singles signal



- ^{7}Be ν_e measurement can improve solar models.

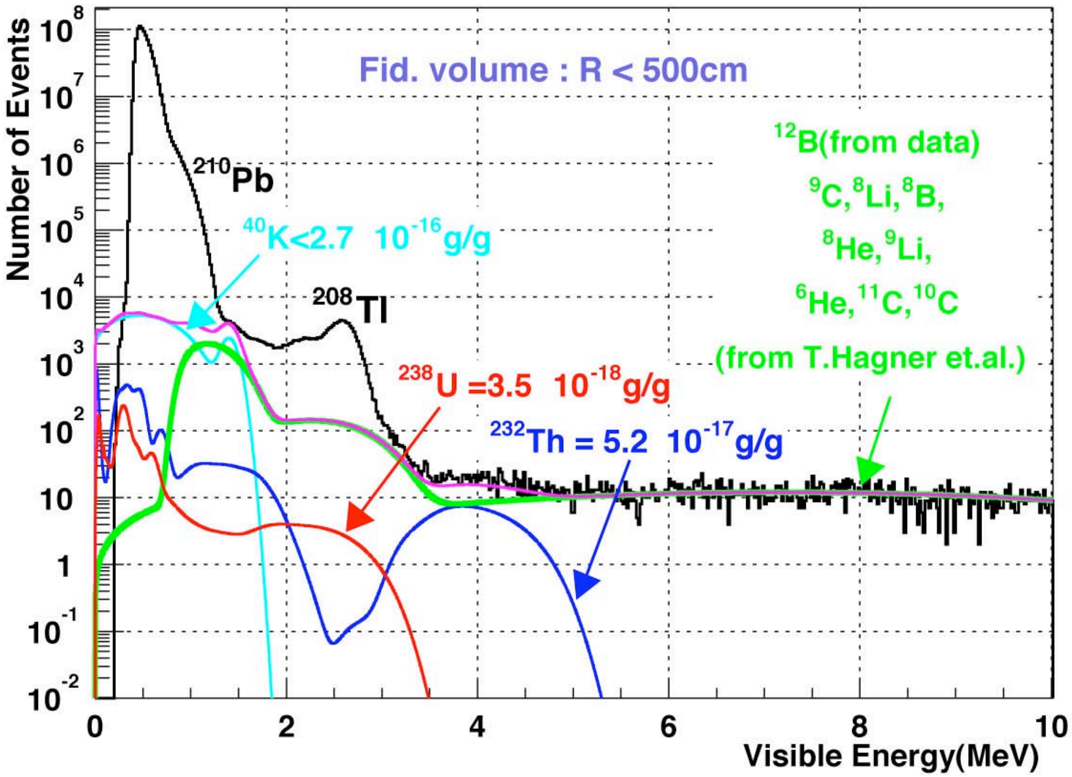
- Unlikely to improve on θ_{12}.

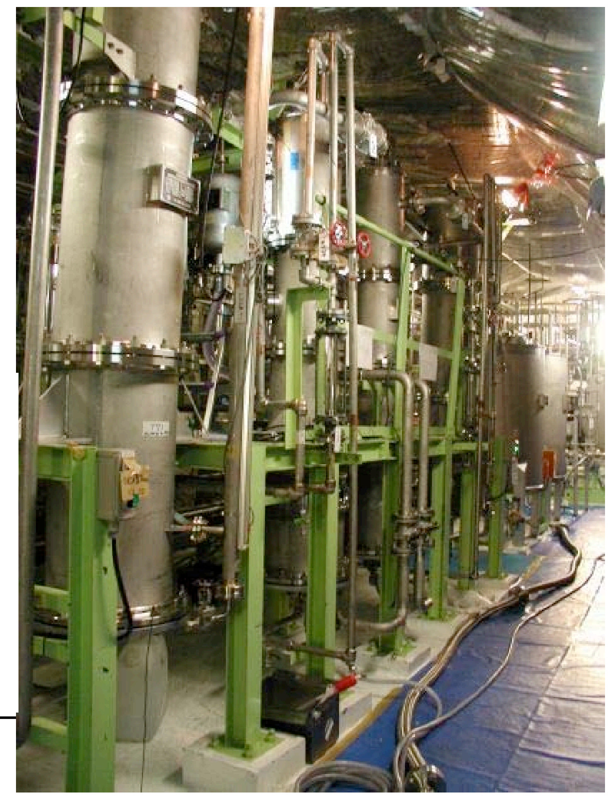
- Checks oscillation prediction of ^{7}Be ν_e flux.



Ref: KamLAND proposal

A Background Challenge: ^{7}Be Solar Neutrinos at KamLAND





- Backgrounds in the ^{7}Be signal region currently about 10^6 times too high

- Working on purification methods to remove
  - ^{85}Kr (from nitrogen used in purification)
  - ^{210}Pb, ^{210}Pb (from decay of radon that got into the system)

U_{MNSP}, θ_{13}, and $\not{CP}$

U_{MNSP} Neutrino Mixing Matrix

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

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

?

atmospheric, K2K	reactor and accelerator	SNO, solar SK, KamLAND	$0\nu\beta\beta$
$\theta_{23} = \sim 45°$	$\tan^2\theta_{13} < 0.03$ at 90% CL	$\theta_{12} \sim 32°$	
maximal	*small … at best*	*large*	

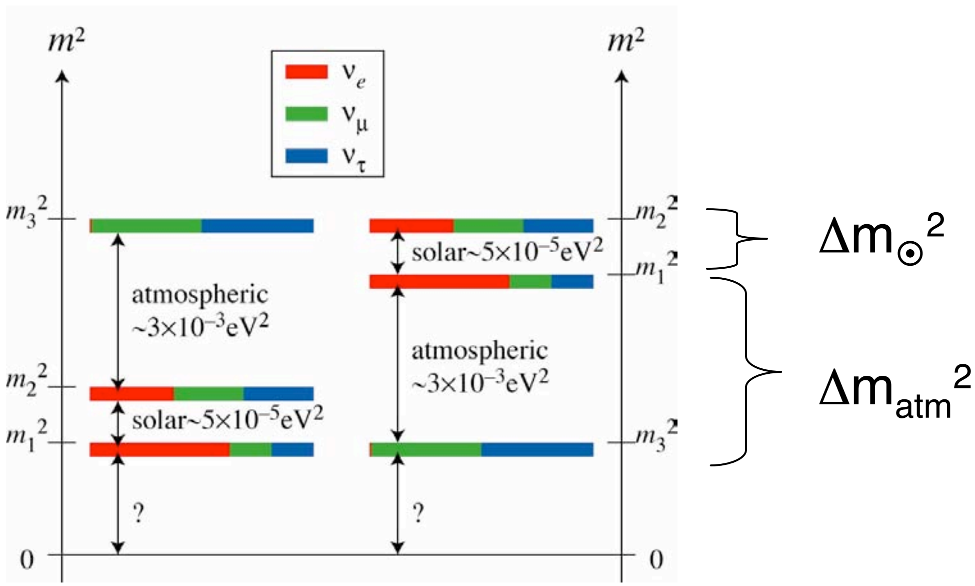
No good 'ad hoc' model to predict θ_{13}.
If $\theta_{13} < 10^{-3}\,\theta_{12}$, perhaps a symmetry?

θ_{13} yet to be measured
determines accessibility to CP phase

Outstanding Questions

I) What is size of $\sin^2(2\theta_{13})$?

II) What Is the mass hierarchy? Sign of Δm_{13}^2



III) Is there CP violation? Measure δ.

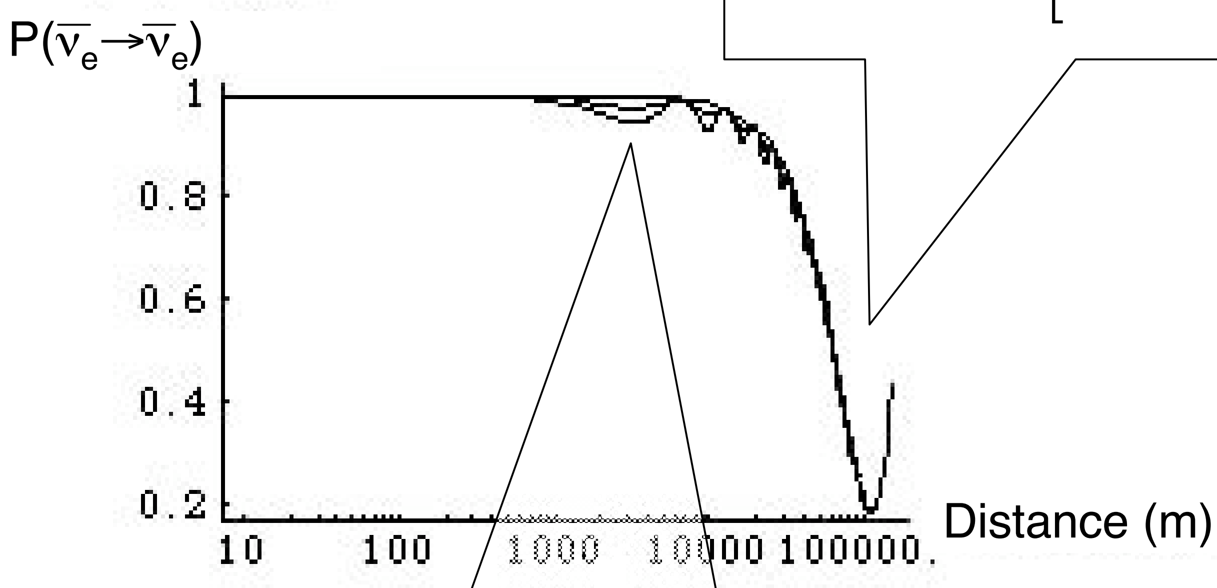
Amount of CP violation is given by $J_{lepton} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1}\underbrace{\sin(2\theta_{12})}_{\sim 0.9}\underbrace{\sin(2\theta_{23})}_{\sim 1}\sin(2\theta_{13})\sin(\delta_{CP})$

Search for Subdominant Oscillation Effects

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

Dominant θ_{12} Oscillation

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



Subdominant θ_{13} Oscillation

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

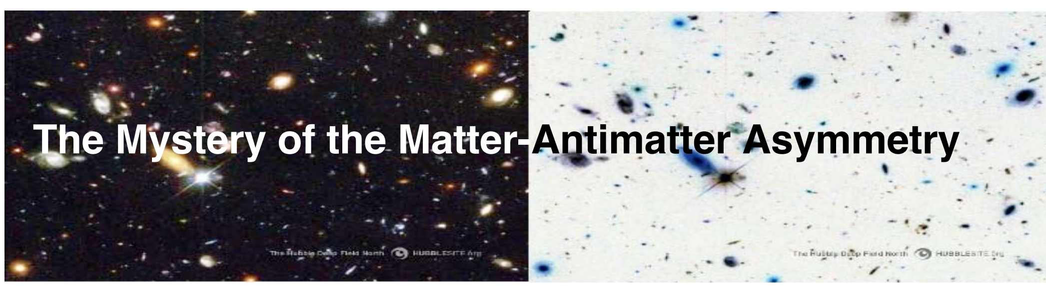
Oscillation Measurements Probe Fundamental Physics

Physics at high mass scales, physics of flavor, and unification:

- Why are the mixing angles *large, maximal, and small*?
- Is there CP violation, T violation, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?

$$U_{MNSP} = \begin{pmatrix} big & big & small? \\ big & big & big \\ big & big & big \end{pmatrix} \quad \overset{?}{\Longleftrightarrow} \quad V_{CKM} = \begin{pmatrix} big & small & tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

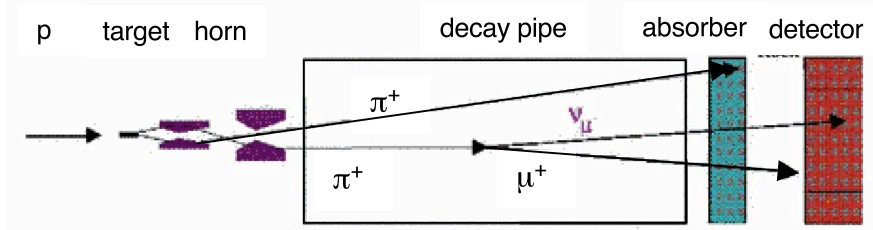
- Leptogenesis and the role of neutrinos in the early Universe



θ_{13}

Measuring θ_{13}

Method 1: Accelerator Experiments

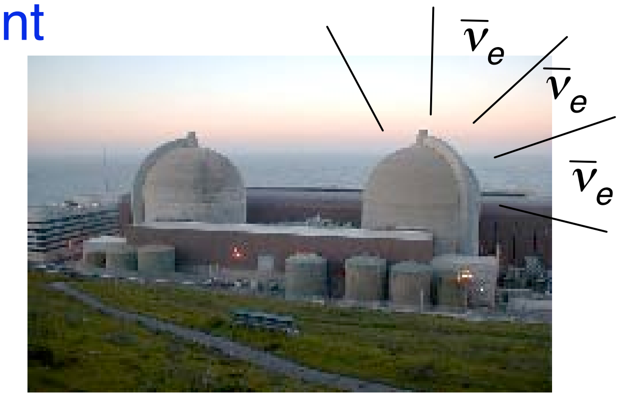


$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^{\ 2} L}{4E_\nu} + \ldots$$

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

Method 2: Reactor Neutrino Oscillation Experiment

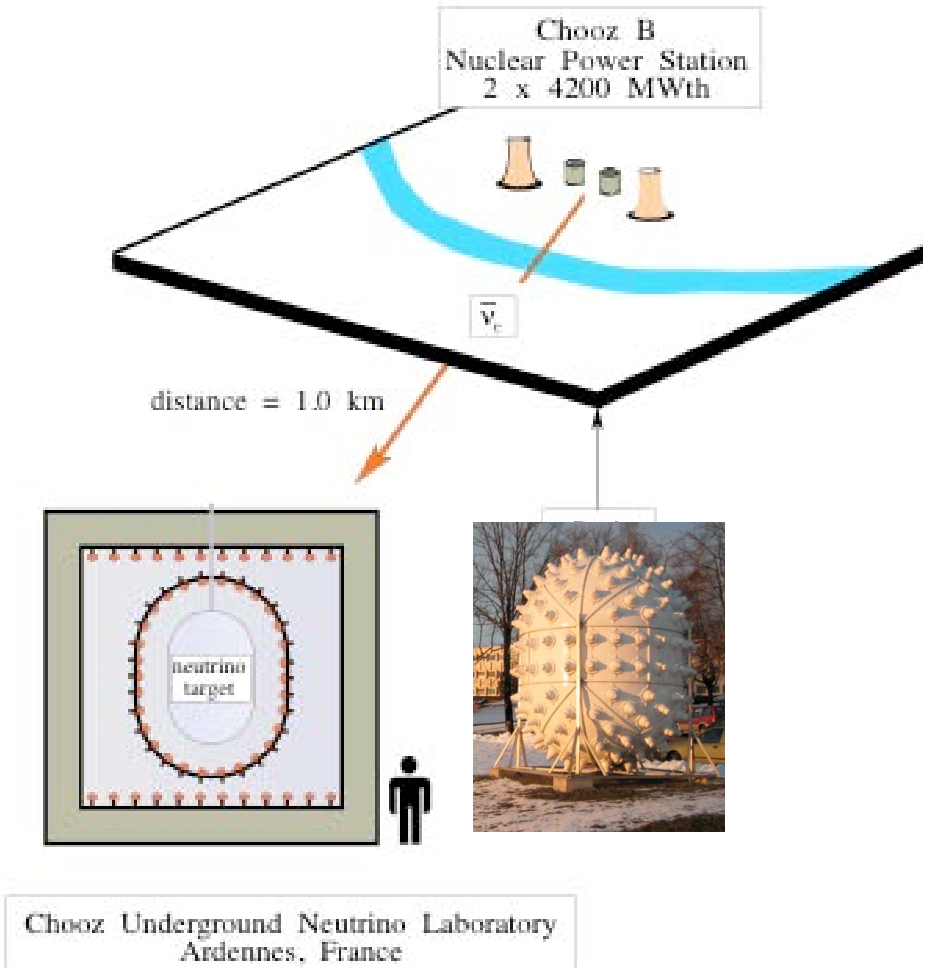
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^{\ 2} L}{4E_\nu} + \left(\frac{\Delta m_{21}^{\ 2} L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{13}$$

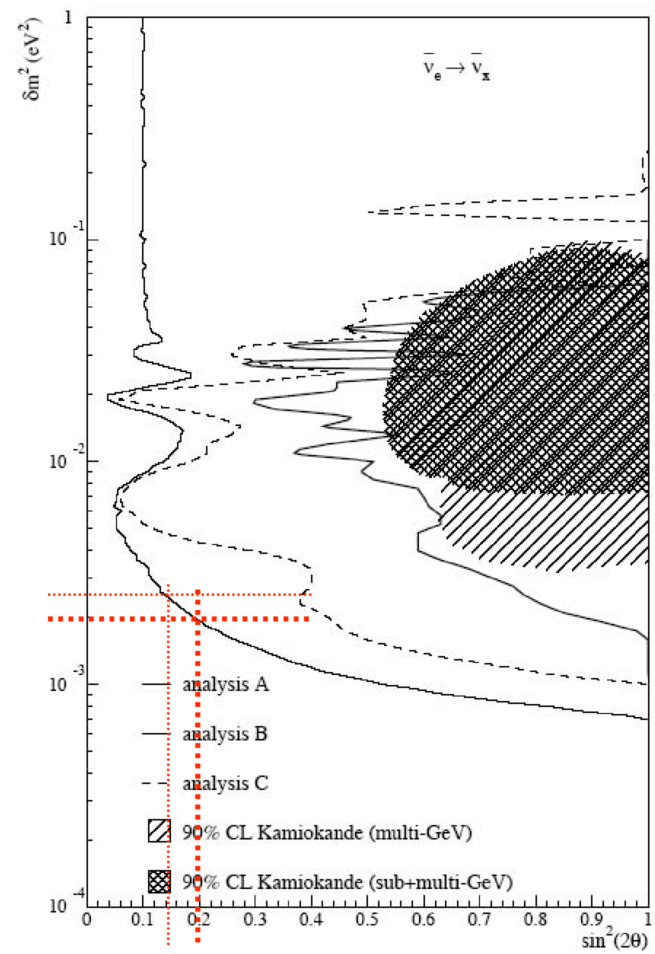


- disappearance experiment $\overline{\nu}_e \rightarrow \overline{\nu}_x$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

Current Knowledge of θ_{13} from Reactors

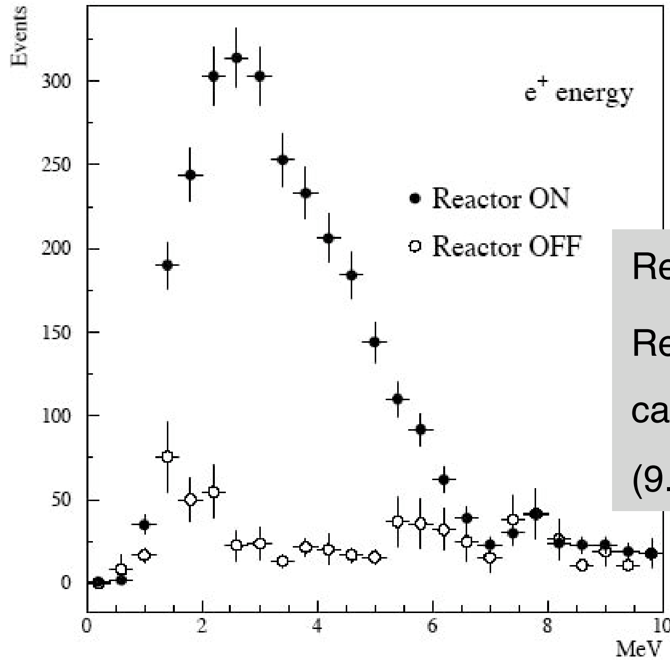
Reactor anti-neutrino measurement at 1 km at Chooz + Palo Verde: $\overline{\nu}_e \rightarrow \overline{\nu}_x$

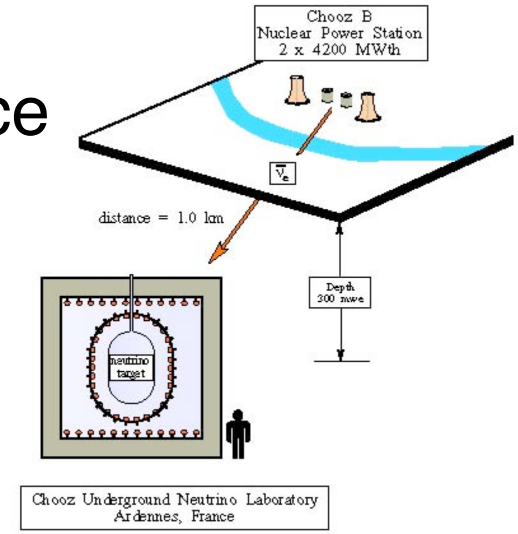




M. Appollonio, hep-ex/0301017

Chooz, France





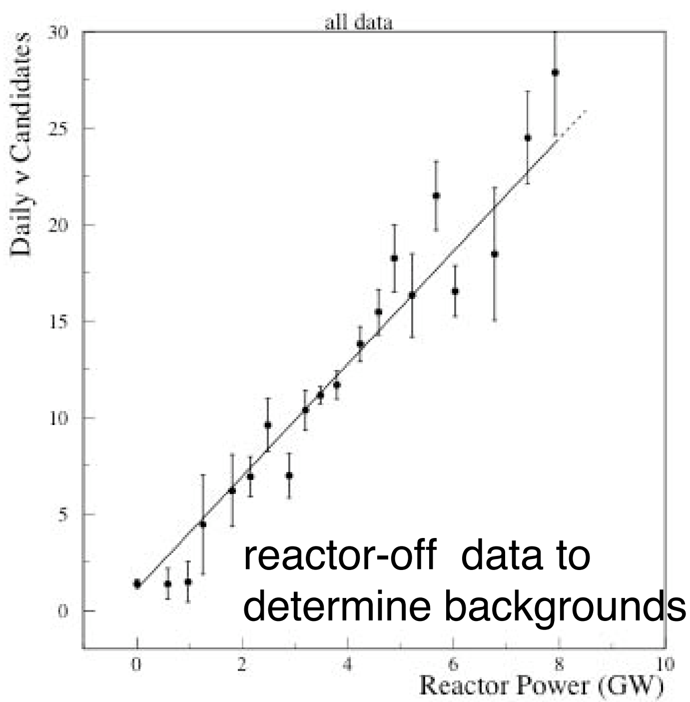
Reactor on: 2991

Reactor off: 287

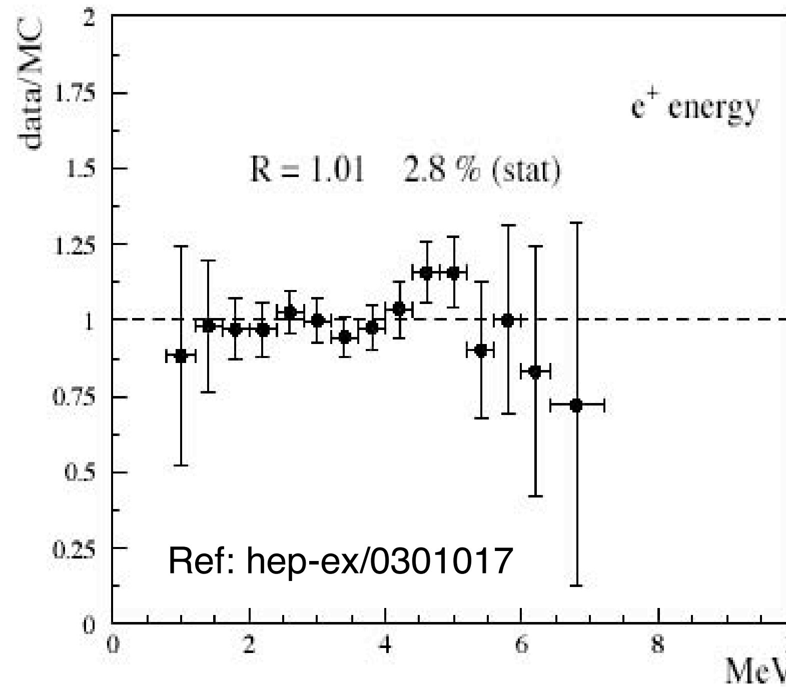
candidate $\overline{\nu}_e$ events.

(9.5% backgrounds!)

Chooz was unique! Determined backgrounds during reactor-off period

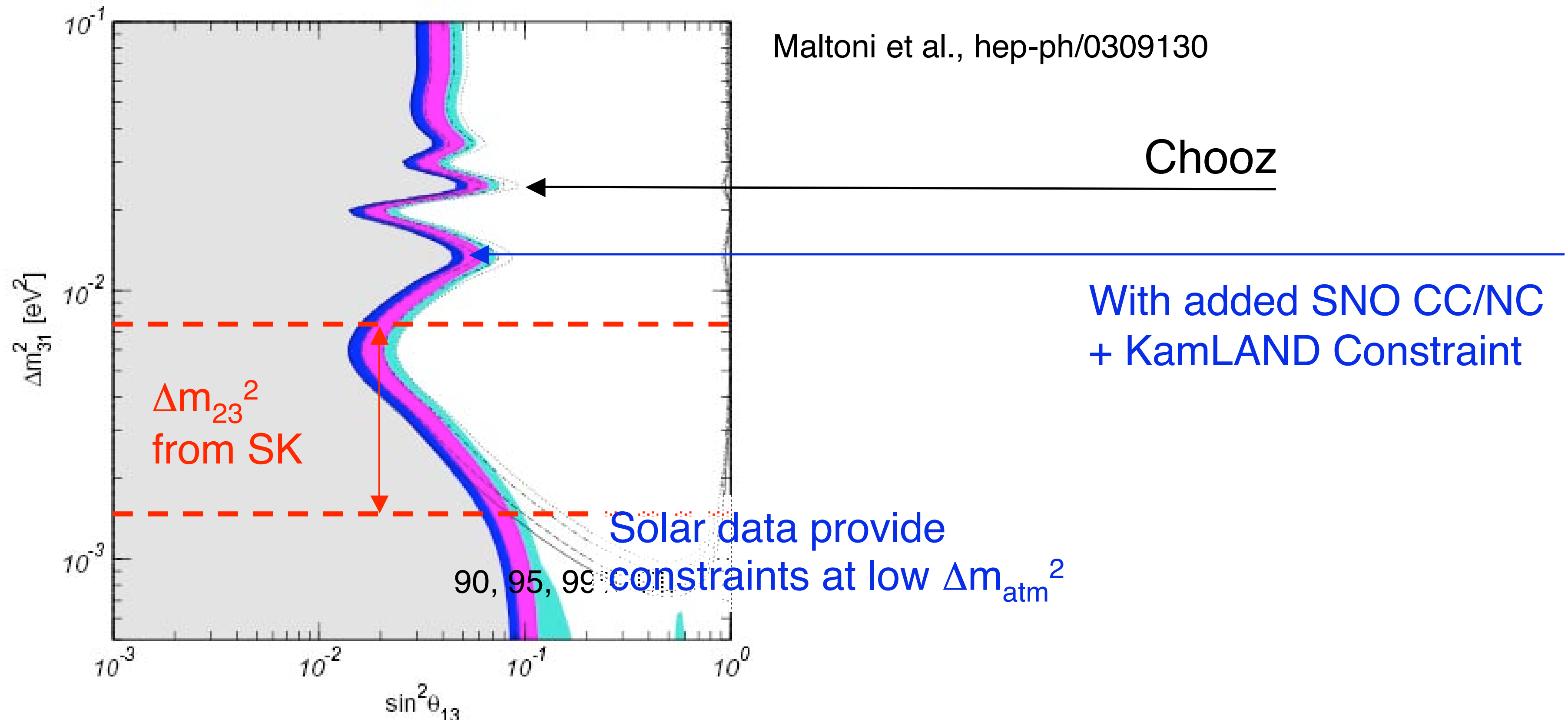


reactor-off data to determine backgrounds



Ref: hep-ex/0301017

Global Constraints on θ_{13}



parameter	best fit	2σ	3σ	5σ
Δm^2_{21} [10^{-5}eV^2]	6.9	6.0–8.4	5.4–9.5	2.1–28
Δm^2_{31} [10^{-3}eV^2]	2.6	1.8–3.3	1.4–3.7	0.77–4.8
$\sin^2\theta_{12}$	0.30	0.25–0.36	0.23–0.39	0.17–0.48
$\sin^2\theta_{23}$	0.52	0.36–0.67	0.31–0.72	0.22–0.81
$\sin^2\theta_{13}$	0.006	≤ 0.035	≤ 0.054	≤ 0.11

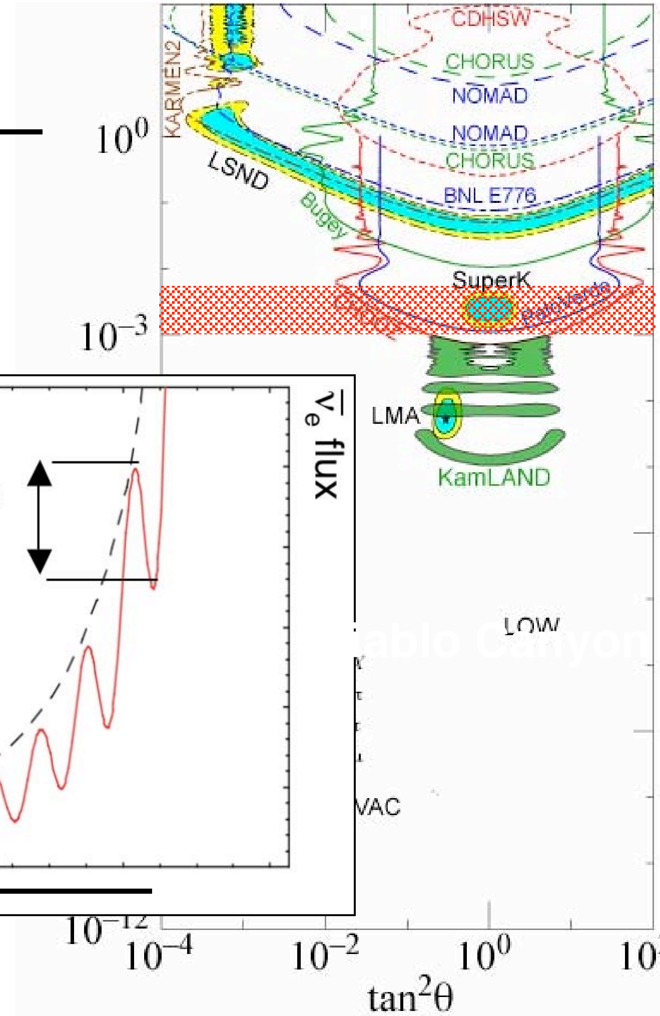
$\sin^2(2\theta_{13}) = 0.02$ (global best fit)

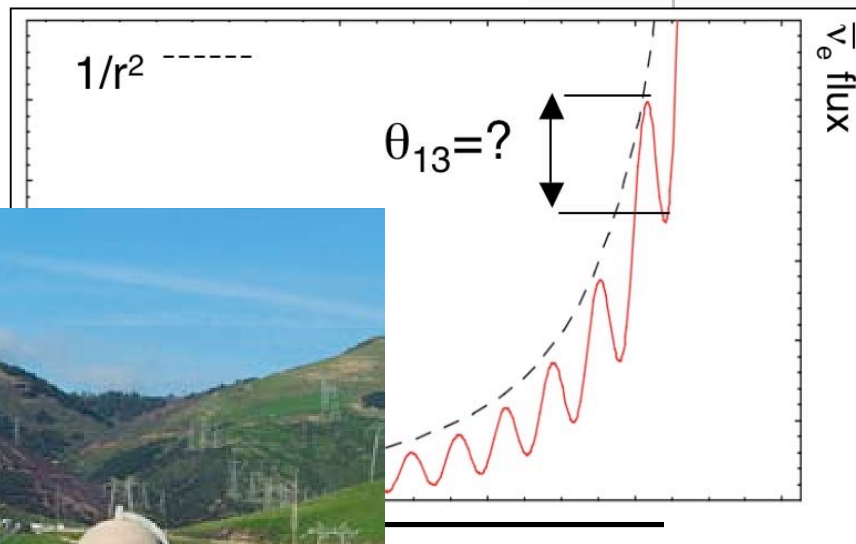
Measuring θ_{13} with Reactor Neutrinos

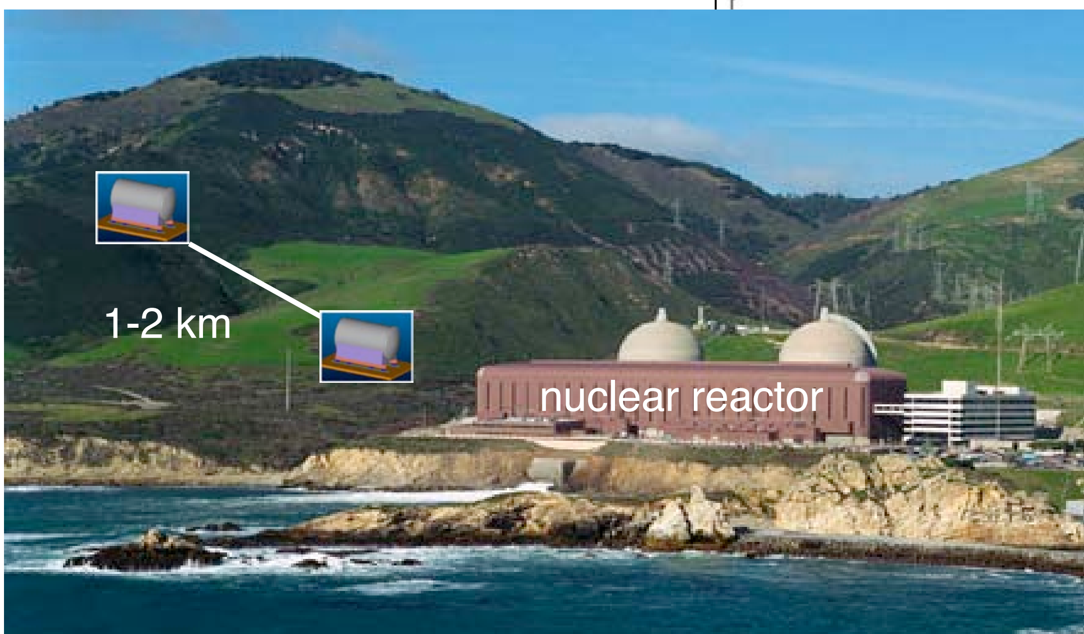
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right) \cos^4\theta_{13} \sin^2 2\theta_{12}$$

$$- \sin^2 2\theta_{sterile} \sin^2 \frac{\Delta m_{sterile}{}^2 L}{4E_\nu}$$

atmospheric frequency dominant,
sterile contribution possible







- underground scintillator $\bar{\nu}$ detectors, 50-100 t
- study relative rate difference and spectral distortions
- projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01\text{-}0.02$

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

coincidence signal
prompt e^+ annihilation
delayed n capture (in μs)

Site Criteria for a θ_{13} Reactor Experiment

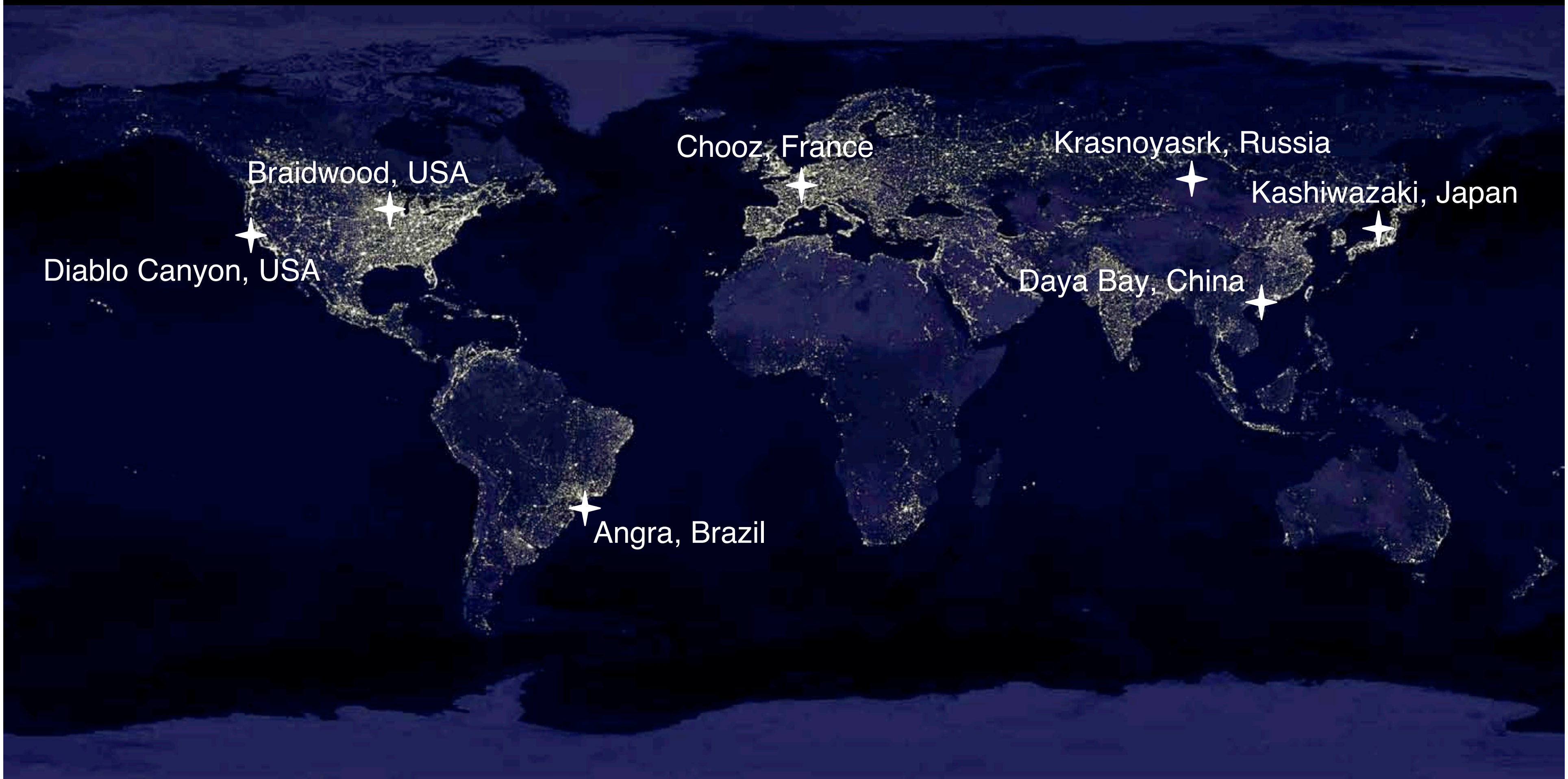
Site Criteria

- powerful reactor
- overburden (> 300 mwe)
- underground tunnels or detector halls

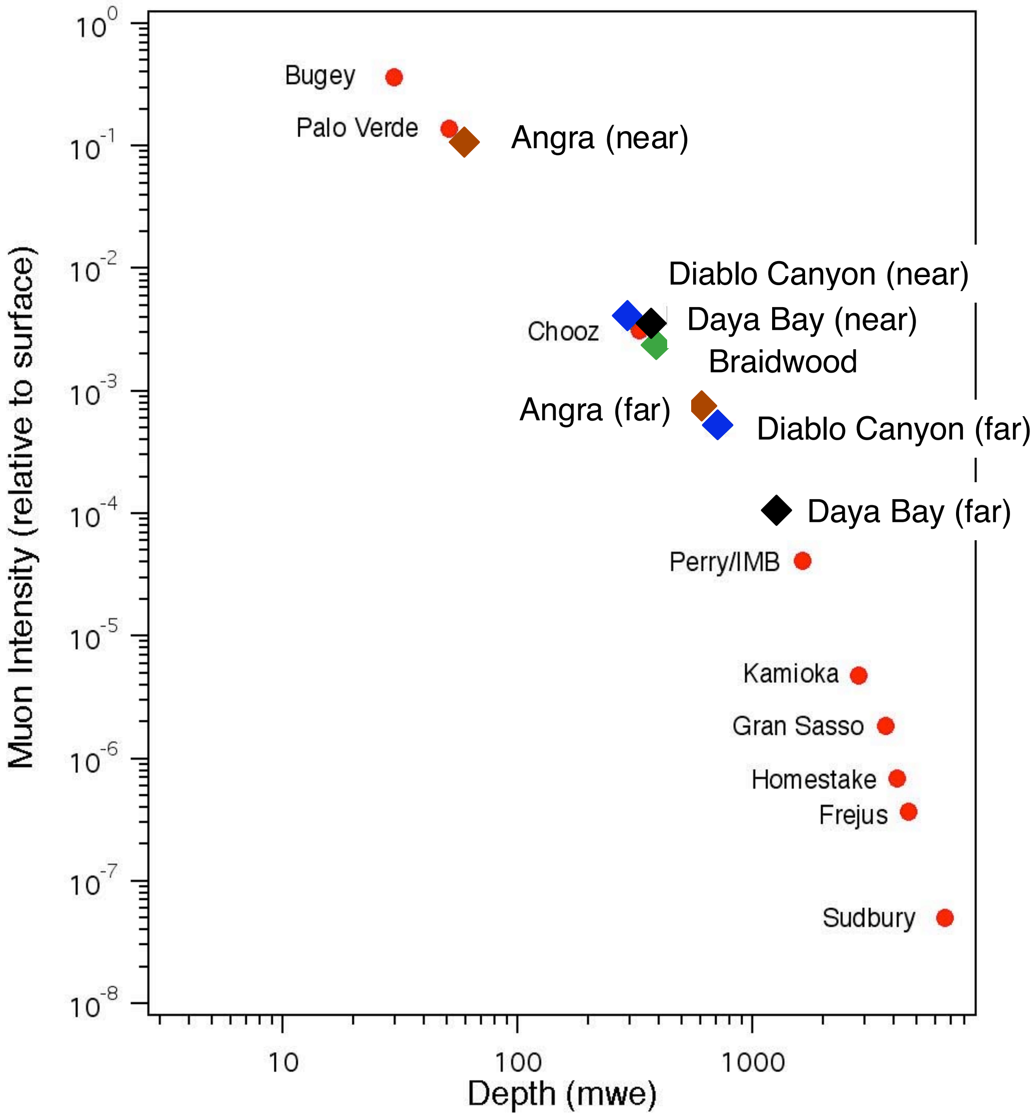
→ Variable/flexible baseline for *optimization to* Δm^2_{atm} and *to demonstrate subdominant* oscillation effect.

→ Optimization of experiment specific to site. Site selection critical

World of Proposed Reactor Neutrino Experiments

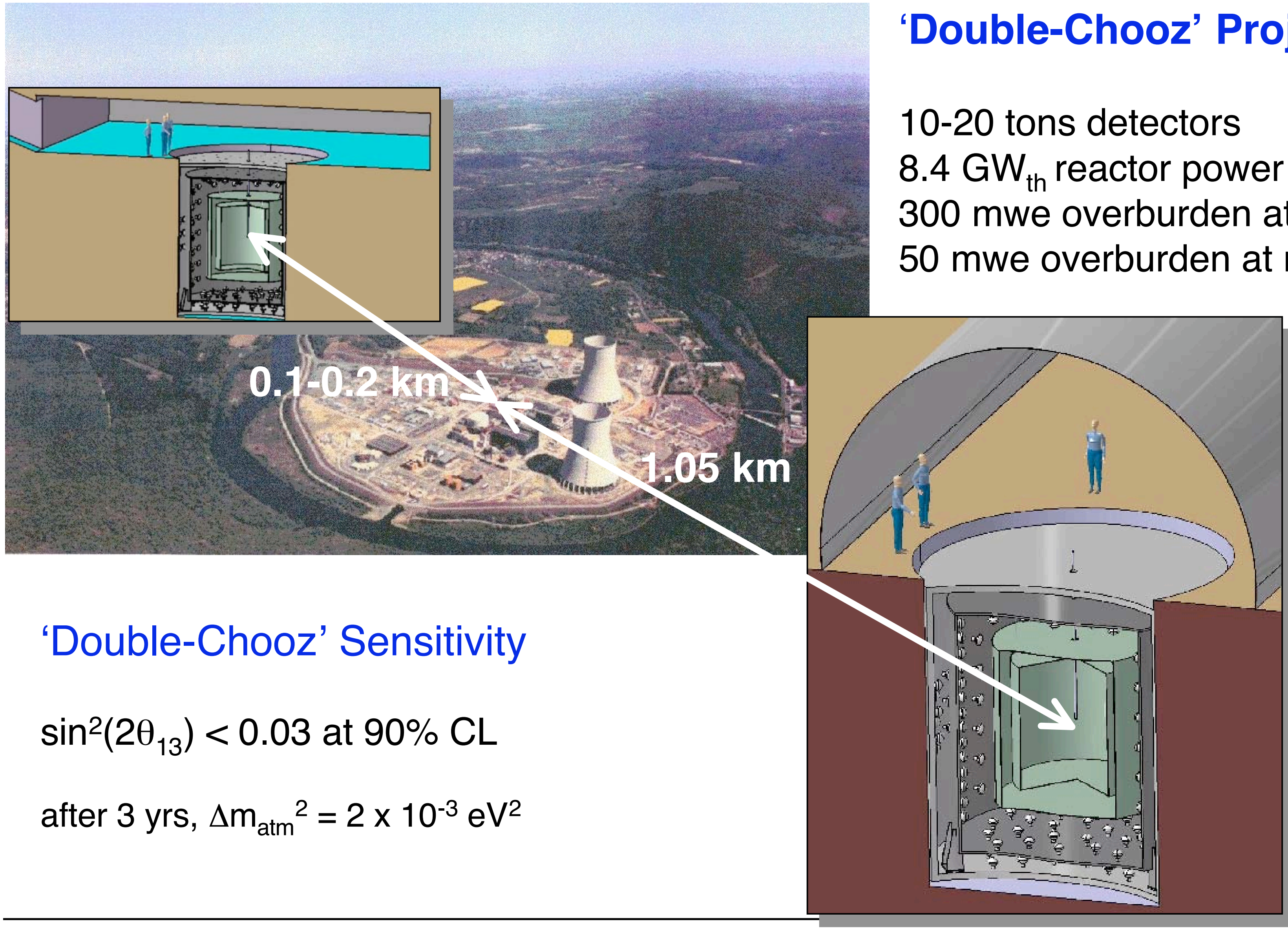


Overburden and Muon Flux



Site	*Near/Far (mwe)*
Angra dos Reis	50 / 600
Braidwood	300 / 300
Chooz	50 / 300
Daya Bay	200 / 800
Diablo Canyon	150 / 700
KASKA	150 / 400

Chooz, France



‘Double-Chooz’ Project

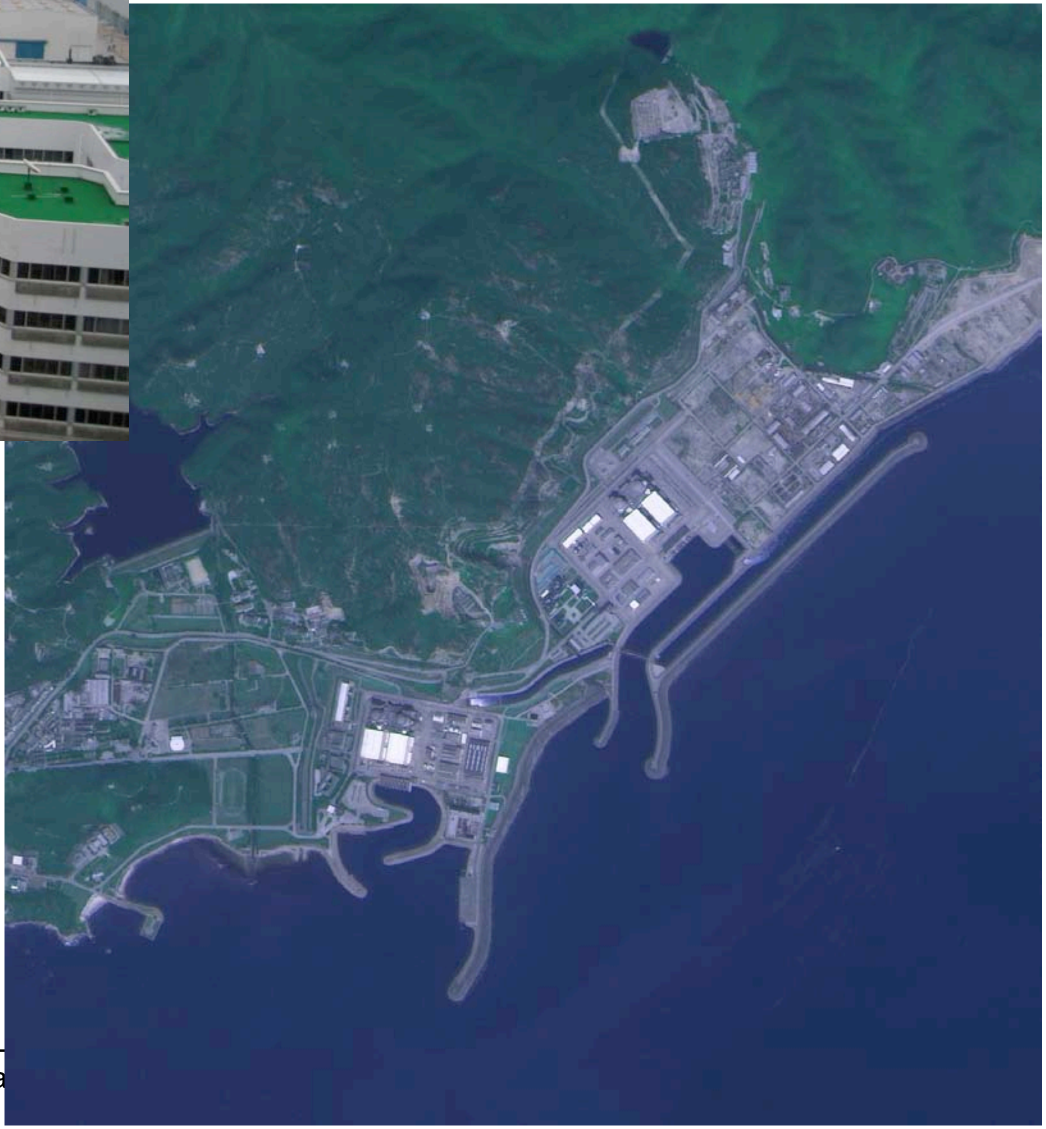
10-20 tons detectors
8.4 GW_{th} reactor power
300 mwe overburden at far site
50 mwe overburden at near site

‘Double-Chooz’ Sensitivity

$\sin^2(2\theta_{13}) < 0.03$ at 90% CL

after 3 yrs, $\Delta m_{atm}^2 = 2 \times 10^{-3}\ eV^2$

Daya Bay, China



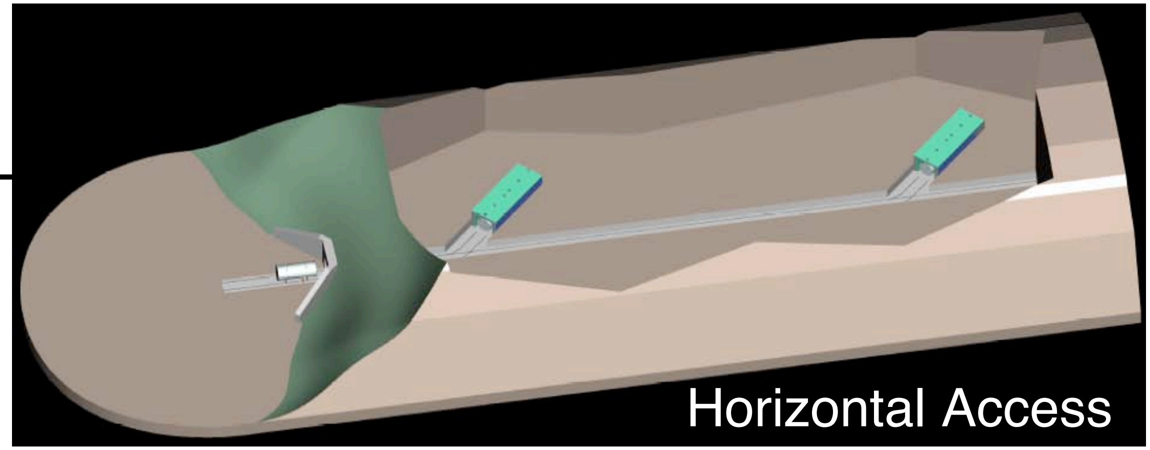
Power

11.6 GW_{th} (17.4 GW_{th} by 2010)

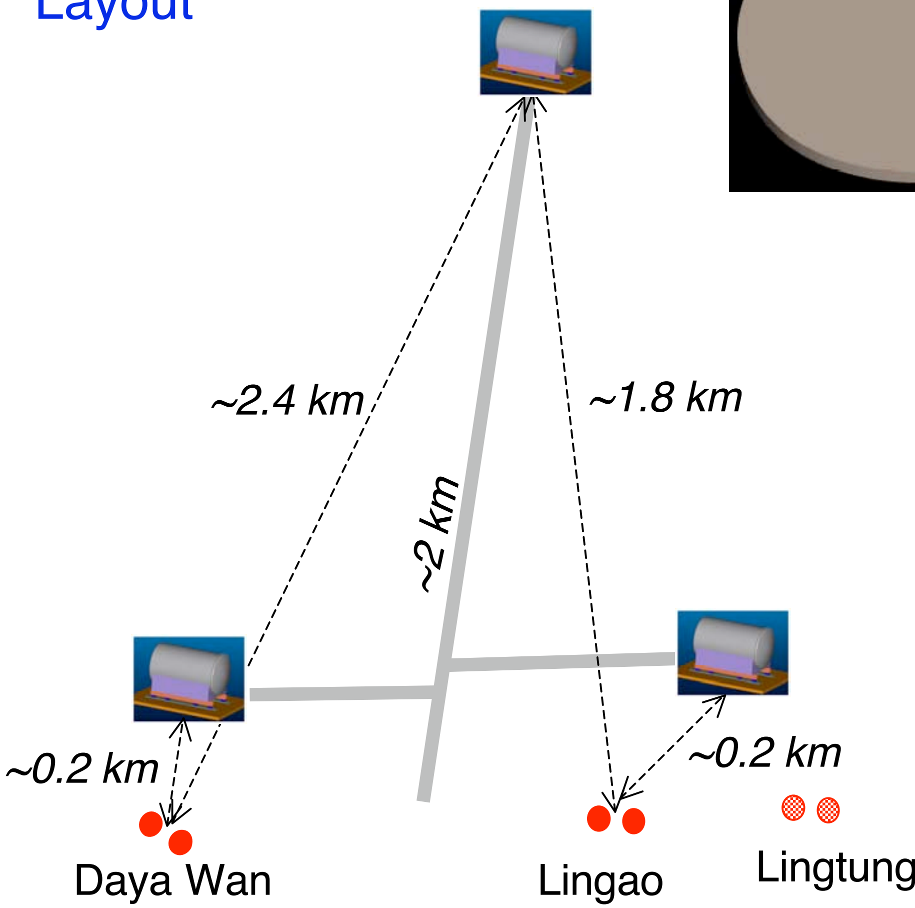
Overburden

Near 200-300 mwe
Far >700 mwe

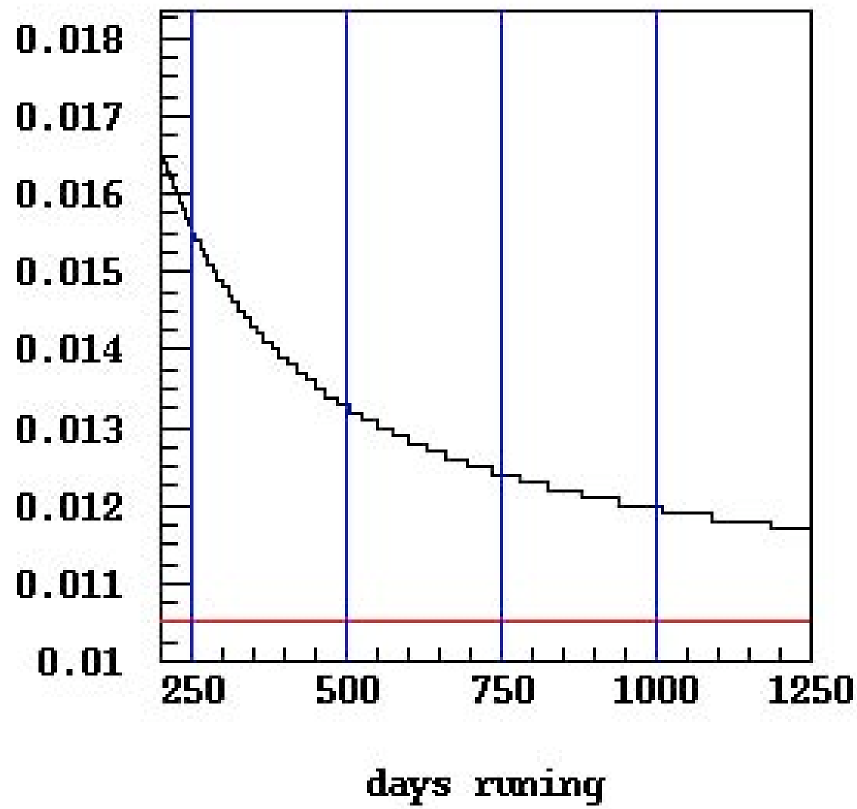
Daya Bay, China



Layout



Sensitivity



assume
- detector uncorrelated error is 0.5%
- reactor uncorrelated error 2%

Future Constraints on θ_{13}

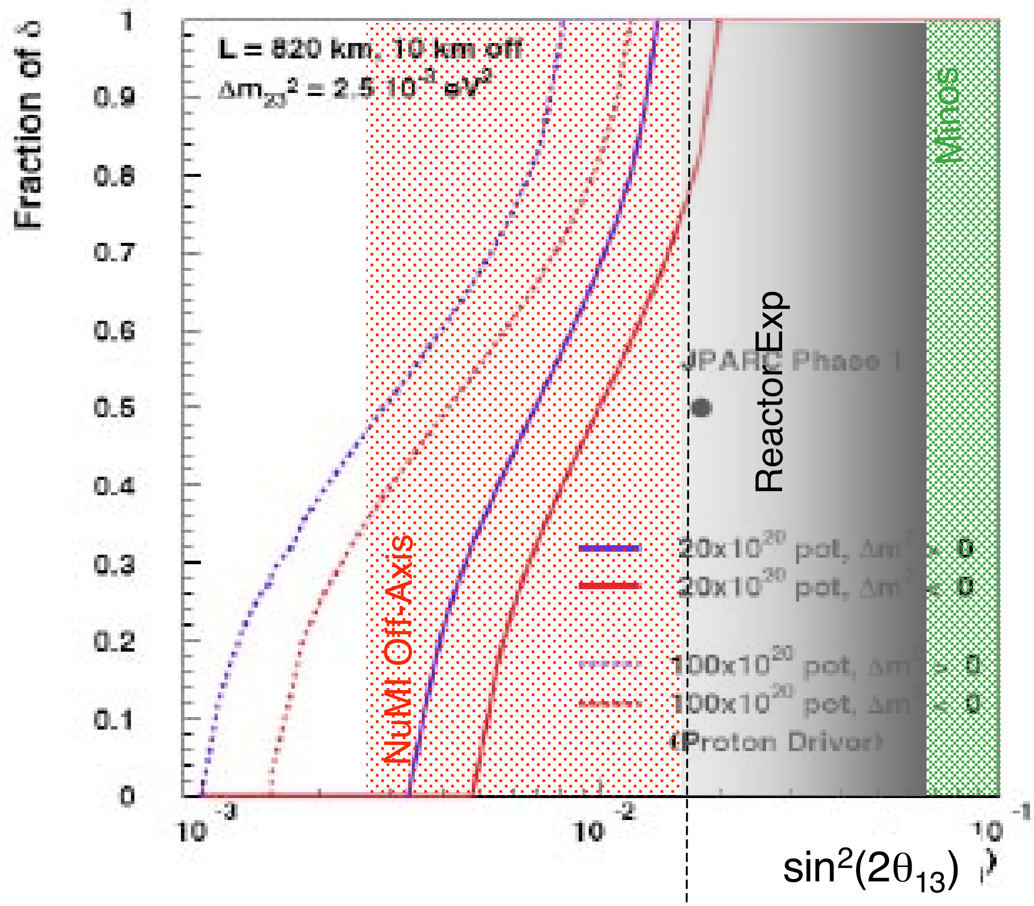
Experiment	***$sin^2(2\theta_{13})$***	***θ_{13}***	***When?***
CHOOZ	< 0.11	< 10	
NUMI Off- Axis (5 yr)	< 0.006-0.015	< 2.2	2012
JPARC-nu (5 yr)	< 0.006-0.015	< 2.2	2012
MINOS	< 0.07	< 7.1	2008
ICARUS (5 yr)	< 0.04	< 5.8	2011
OPERA (5 yr	< 0.06	< 7.1	2011
Angra dos Reis (Brazil)	< 0.02-0.03	< 5	?
Braidwood (US)	< 0.02-0.03	< 5	[2009]
Chooz-II (France)	< 0.03	< 5	[2009]
Daya Bay (China)	< 0.012	< 3	[2009]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]
Krasnoyarsk (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]

Upper limits correspond to 90% C.L.

Reactor & Long Baseline Experiments

Measuring $\sin^2(2\theta_{13})$

3 σ Sensitivity to $\sin^2(2\theta_{13})$



reactor 90% CL= 0.01 and $\delta(\sin^2(2\theta_{13})) = 0.006$

Chooz
90% CL — $\sin^2(2\theta_{13}) \leq 0.14$

Minos
3-σ sensitivity — $\sin^2(2\theta_{13}) = 0.07$

θ_{13} Reactor Exp
90% CL — $\sin^2(2\theta_{13}) < 0.01\text{-}0.02$

NuMI Off-Axis
3-σ sens. — $\sin^2(2\theta_{13}) < 0.007$

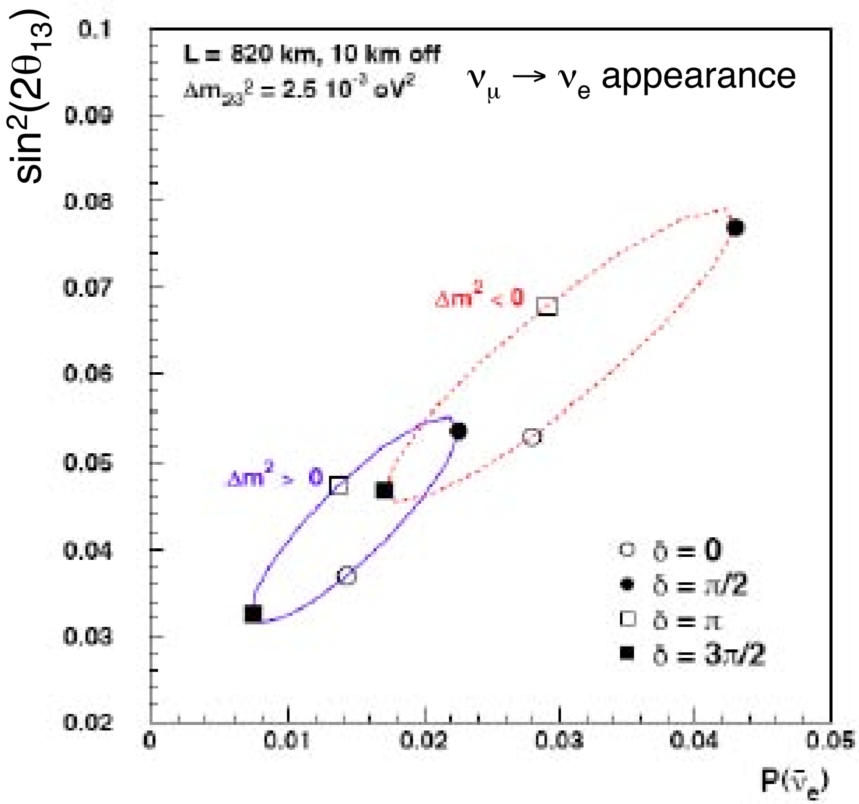
at $\Delta m_{atm}^2 = 2.5 \times 10^{-3}\ eV^2$

Ref: NuMI Off-Axis Collaboration, Progress Report 12/2003

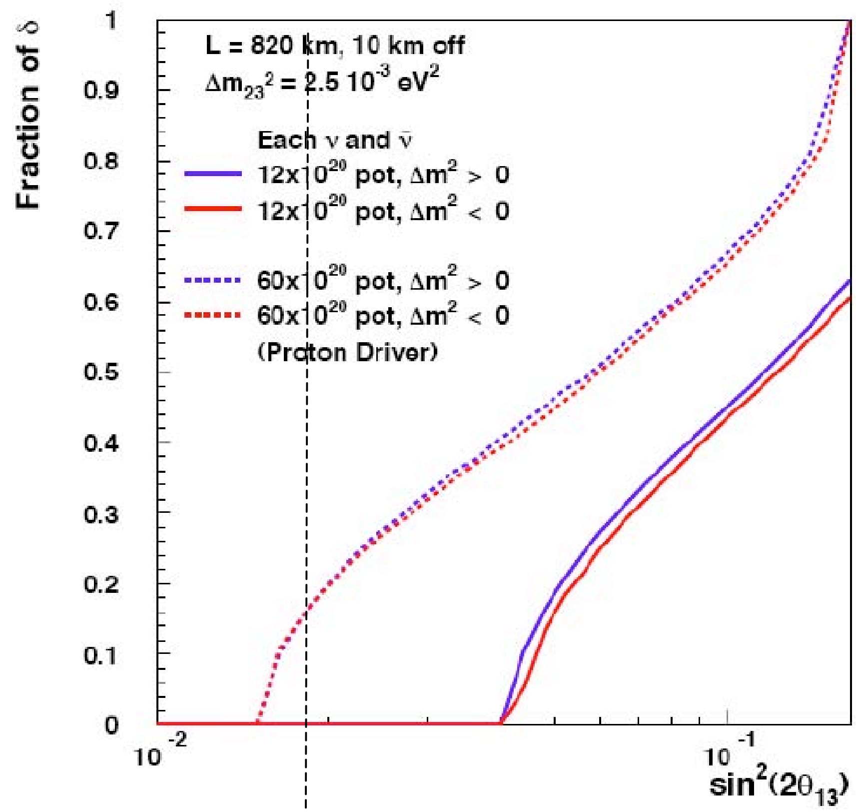
Reactor & Long Baseline Experiments

Determining Mass Hierarchy

$\sin^2(2\theta_{13})$ vs $P(\bar{\nu}_e)$ for $P(\bar{\nu}_e)=0.02$



2 σ Resolution of the Mass Hierarchy



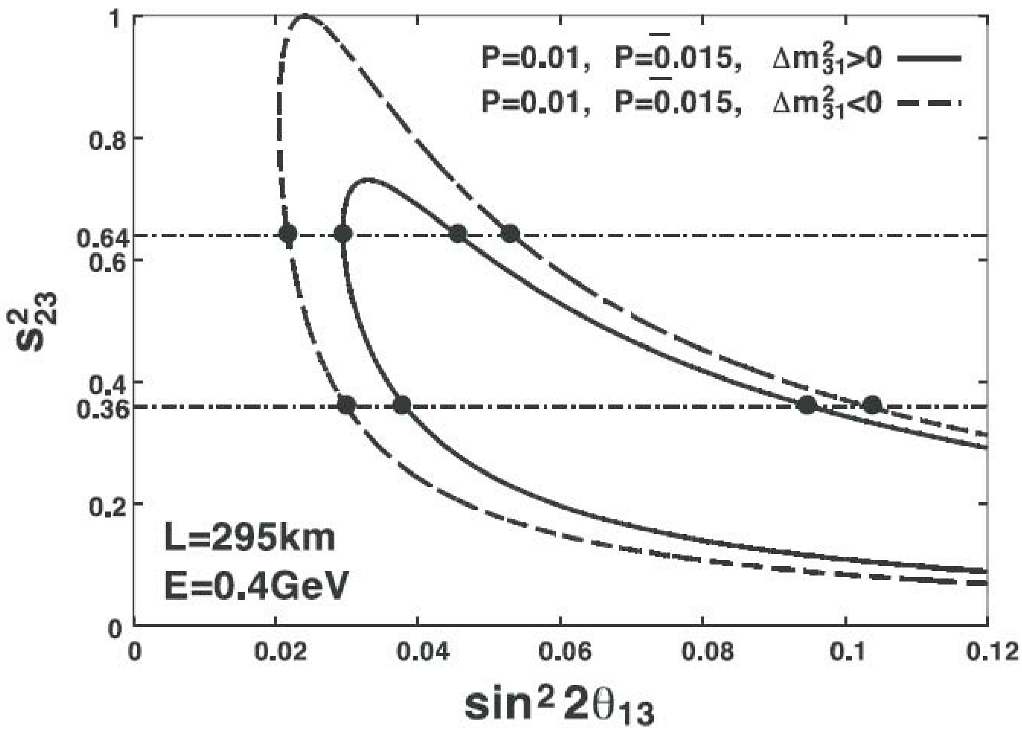
reactor 90% CL= 0.01
and $\delta(\sin^2(2\theta_{13})) = 0.006$

Ref: NuMI Off-Axis Collaboration, Progress Report 12/2003

Reactor & Long Baseline Experiments

Parameter Degeneracy

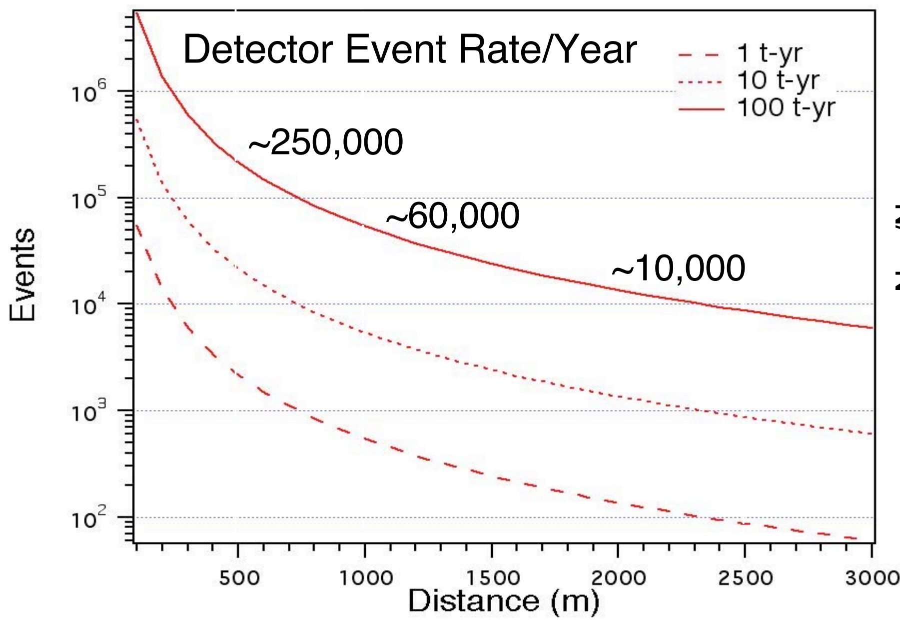
Reactor experiments help resolve the parameter degeneracy. Help with $\sin^2 2\theta_{23}$ ambiguity, especially if $\sin^2 2\theta_{23} \neq 1$

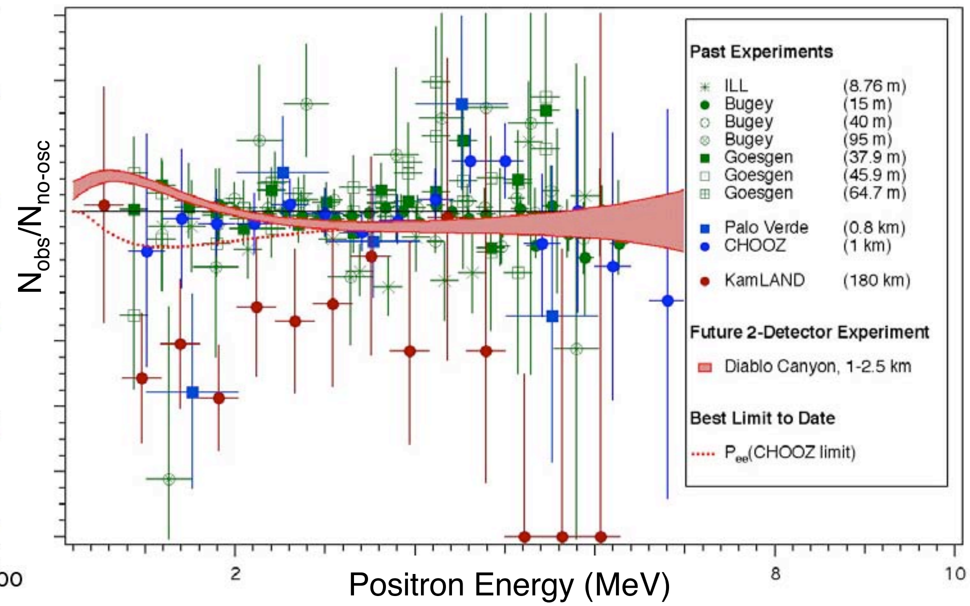


Ref: hep-ph/0211111

Sensitivity of $\sin^2 2\theta_{13} \sim 0.01$ has discovery potential and is interesting for future accelerator experiments and neutrino models.

Statistics and Systematics



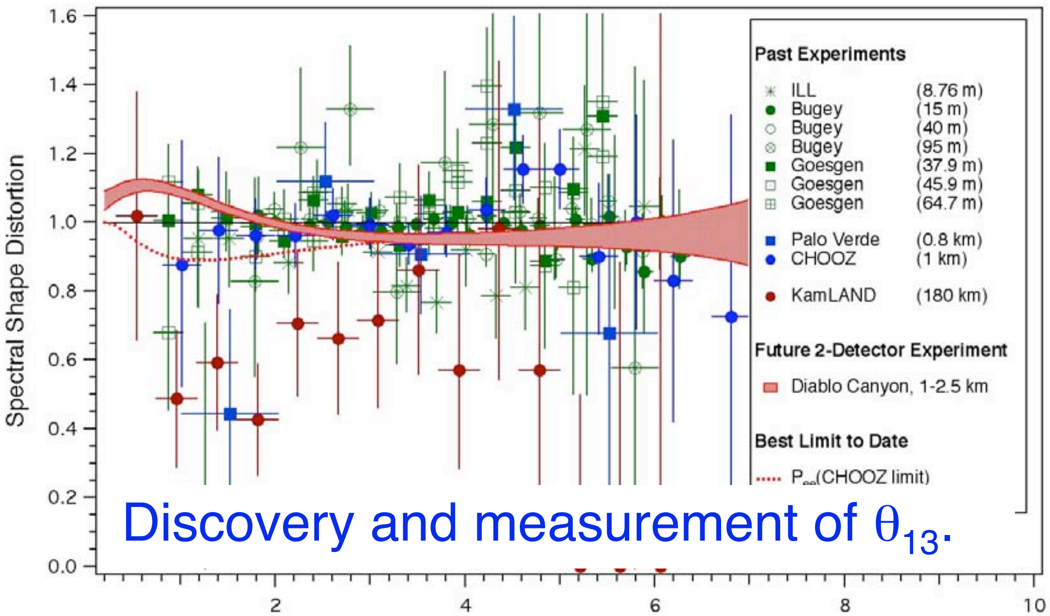


Statistical error: $\sigma_{stat} \sim 0.5\%$ for $\mathcal{L}$ = 300t-yr

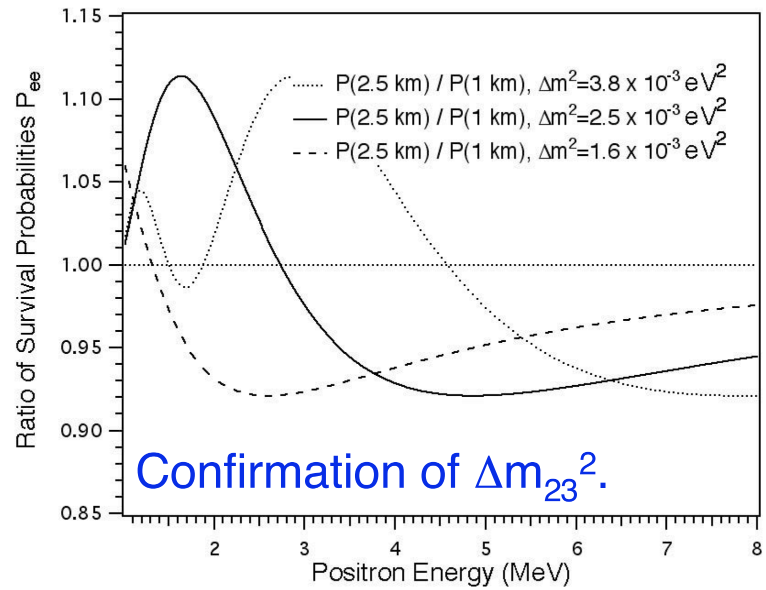
Reactor Flux	• near/far ratio, choice of detector location	$\sigma_{flux} < 0.2\%$
Detector Efficiency	• near and far detector of same design • calibrate *relative* detector efficiency	$\sigma_{rel\ eff} \leq 1\%$
Target Volume &	• no fiducial volume cut	$\sigma_{target} \sim 0.3\%$
Backgrounds	• external active and passive shielding	$\sigma_{acc} < 0.5\%$ $\sigma_{n\ bkgd} < 1\%$

Total Systematics $\sigma_{syst} \sim 1\text{-}1.5\%$

Goals of a Reactor Neutrino Oscillation Experiment

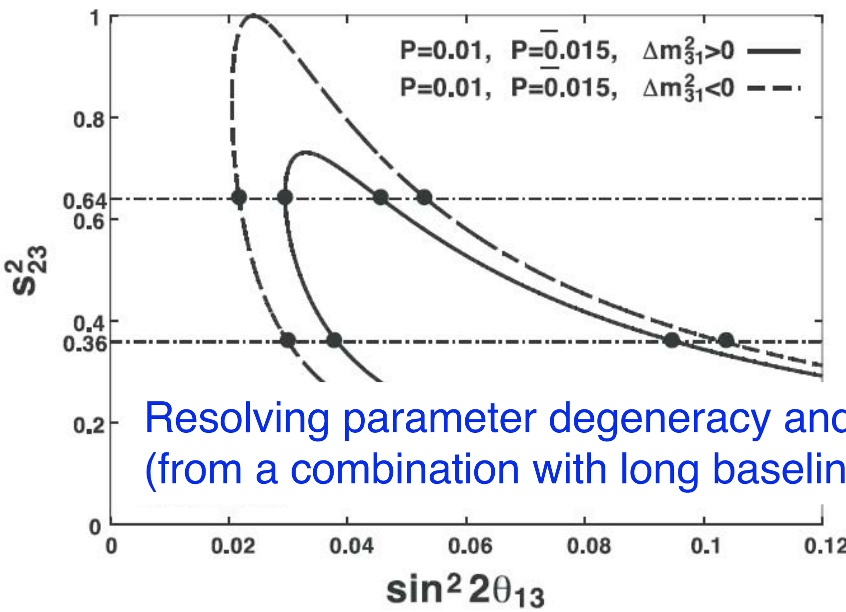


Discovery and measurement of θ_{13}.

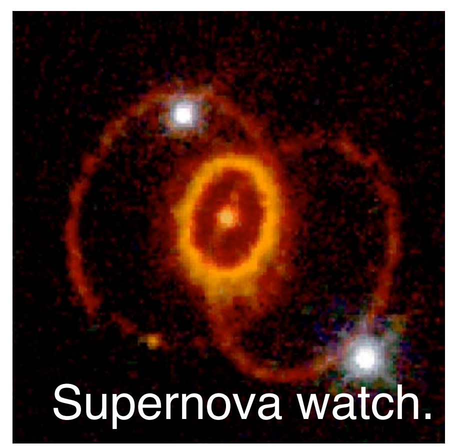


Confirmation of Δm_{23}^2.

Search for the effect of sterile ν.



Resolving parameter degeneracy and limits on ~~CP~~
(from a combination with long baseline exp.)



Supernova watch.

Neutrino Physics at Reactors

1956
First observation of neutrinos

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

1995
Nobel Prize to Fred Reines at UC Irvine

2002
Discovery of massive neutrinos and oscillations

2004 and beyond
Understanding the role of neutrinos in the universe

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

KamLAND Collaboration

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K.Nakajima, H.Ogawa, K.Oki, K.Owada, I.Shimizu, J.Shirai, F.Suekane, A.Suzuki, K.Tada, O.Tajima, K.Tamae, H.Watana
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