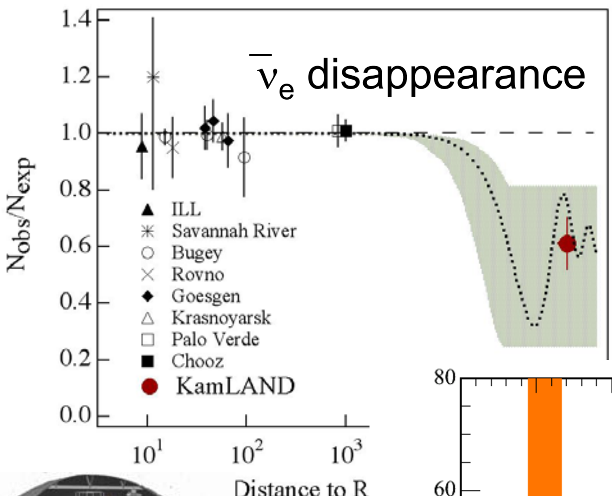
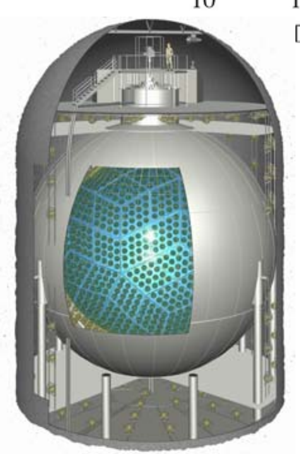
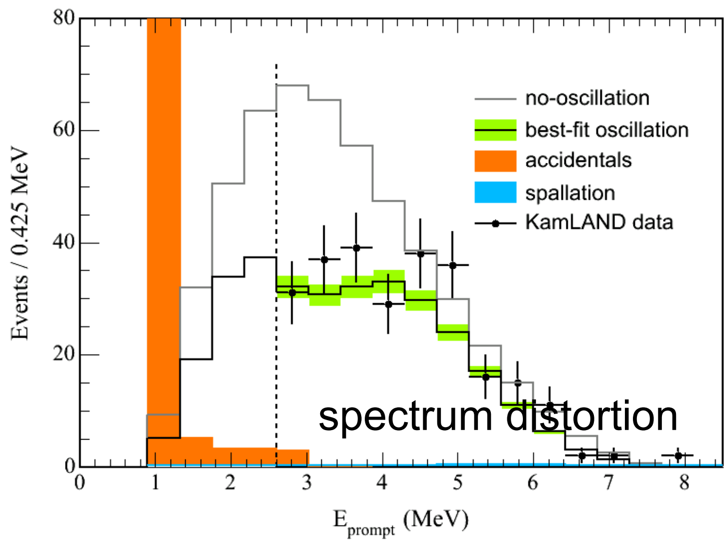
Neutrino Oscillation Physics with Reactors

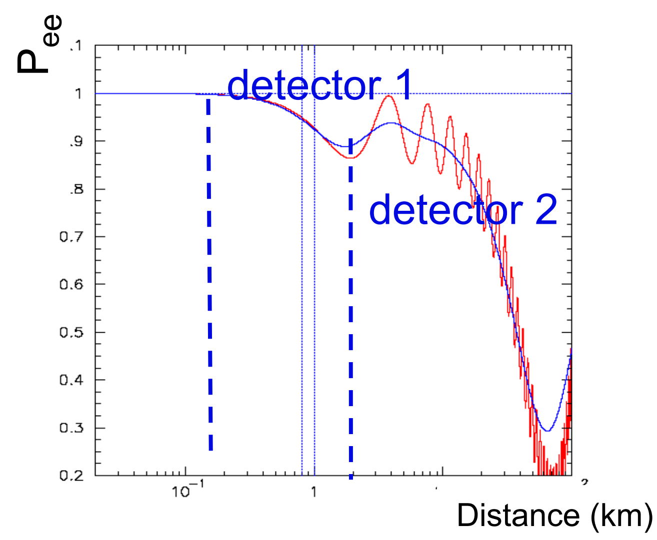
KamLAND and Measuring θ_{13} with Reactors

Karsten Heeger, LBNL

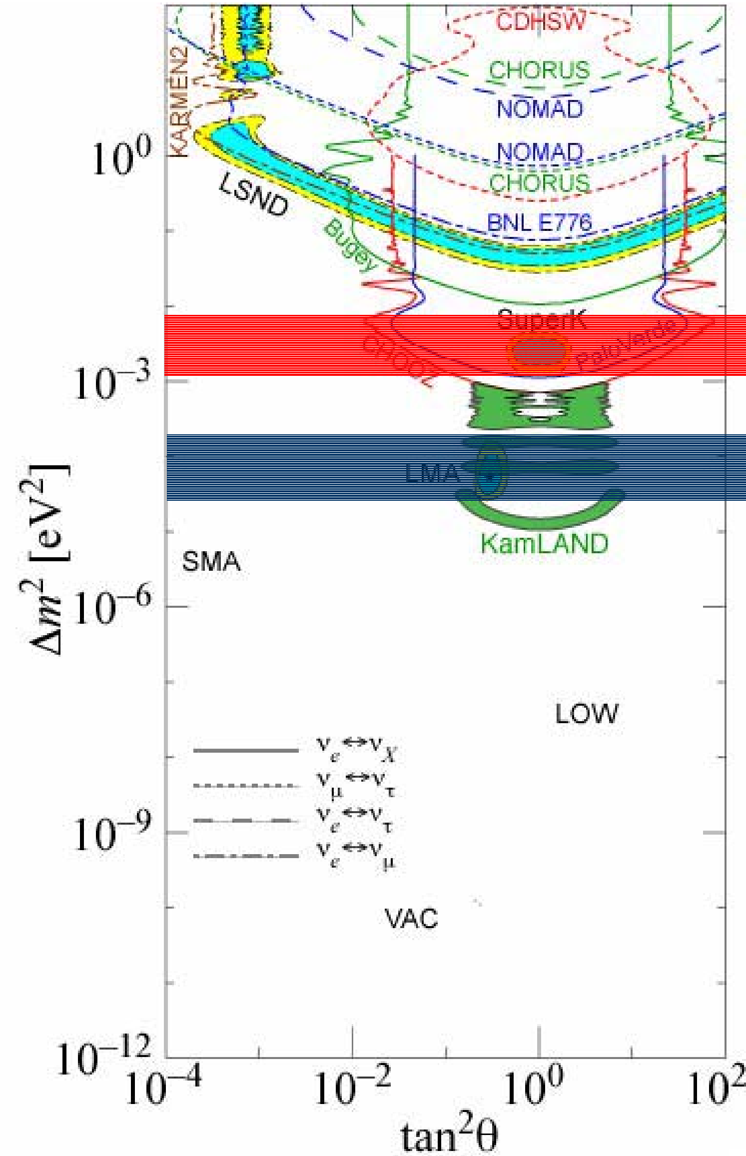


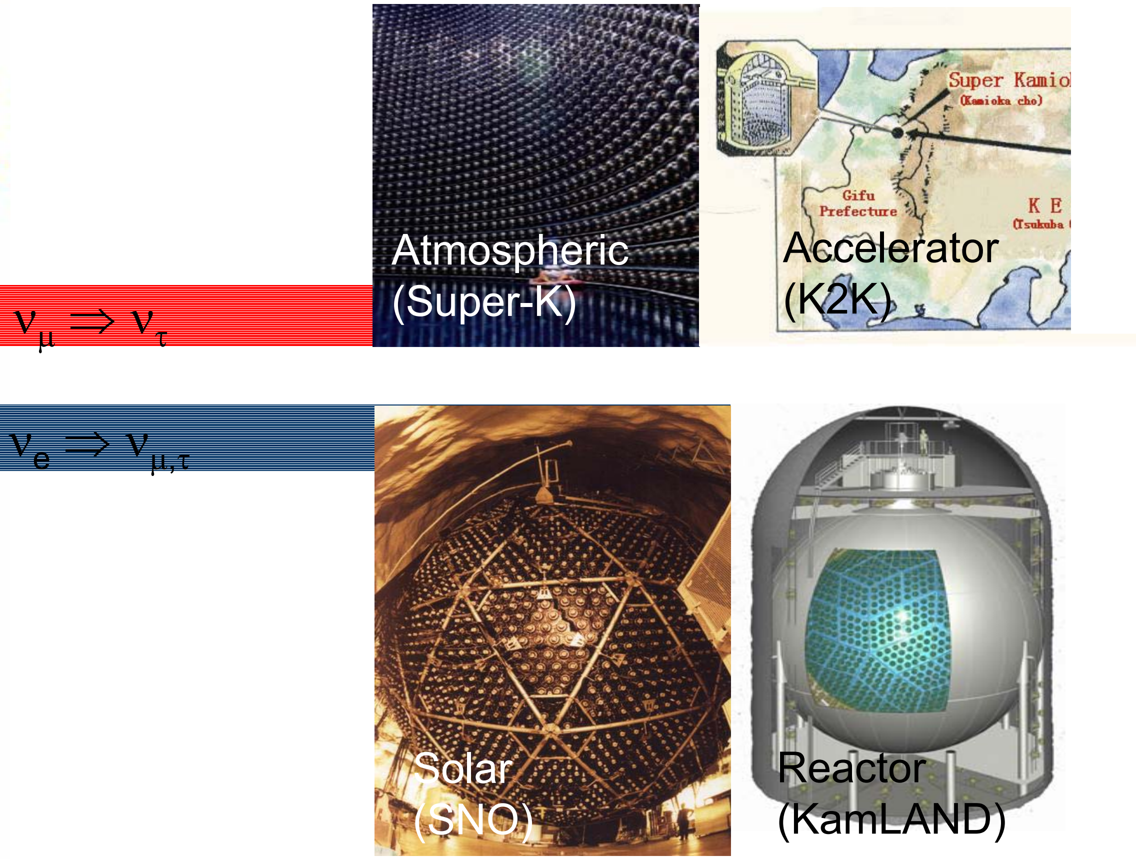






Discovery Era in Neutrino Physics



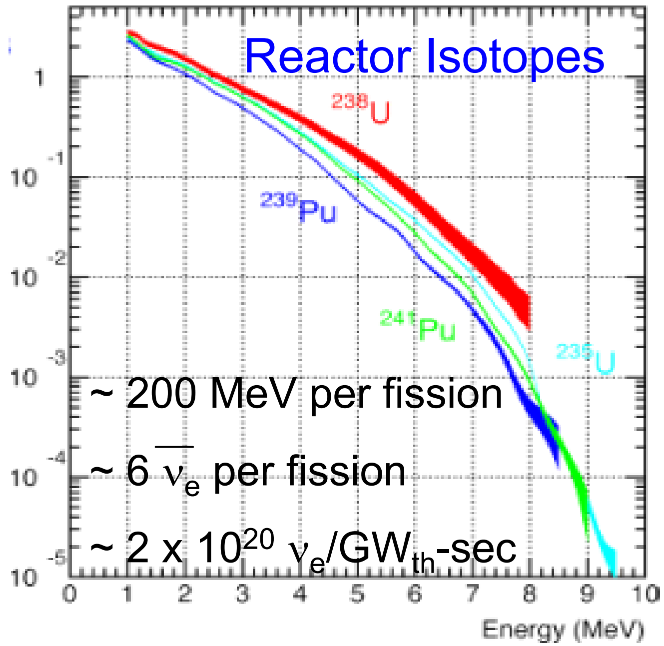


- Neutrinos are <u>not massless</u>
- <u>Evidence</u> for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that <u>*neutrinos oscillate*</u>

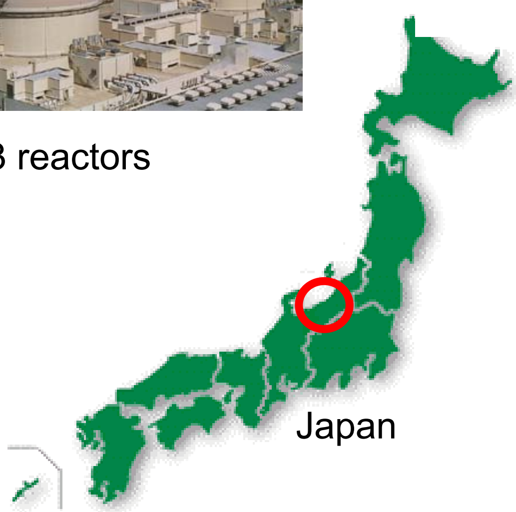
Except for LSND, Δm_{ij}^2 measured *and* confirmed.

Measurement of Reactor Anti-Neutrinos in KamLAND

Japanese Reactors

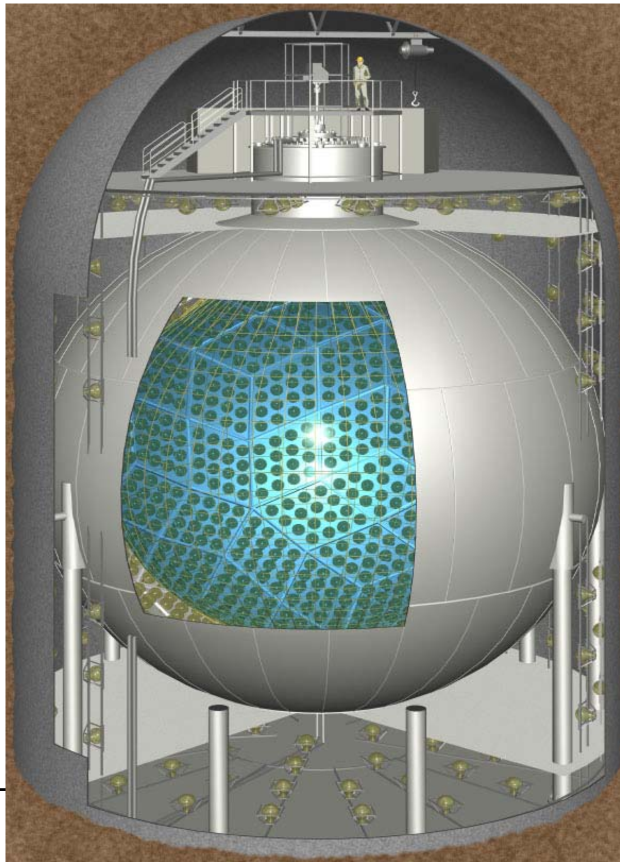


53 reactors

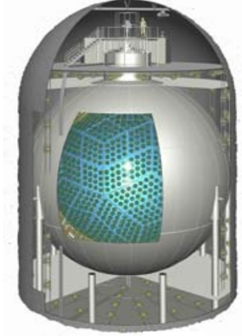


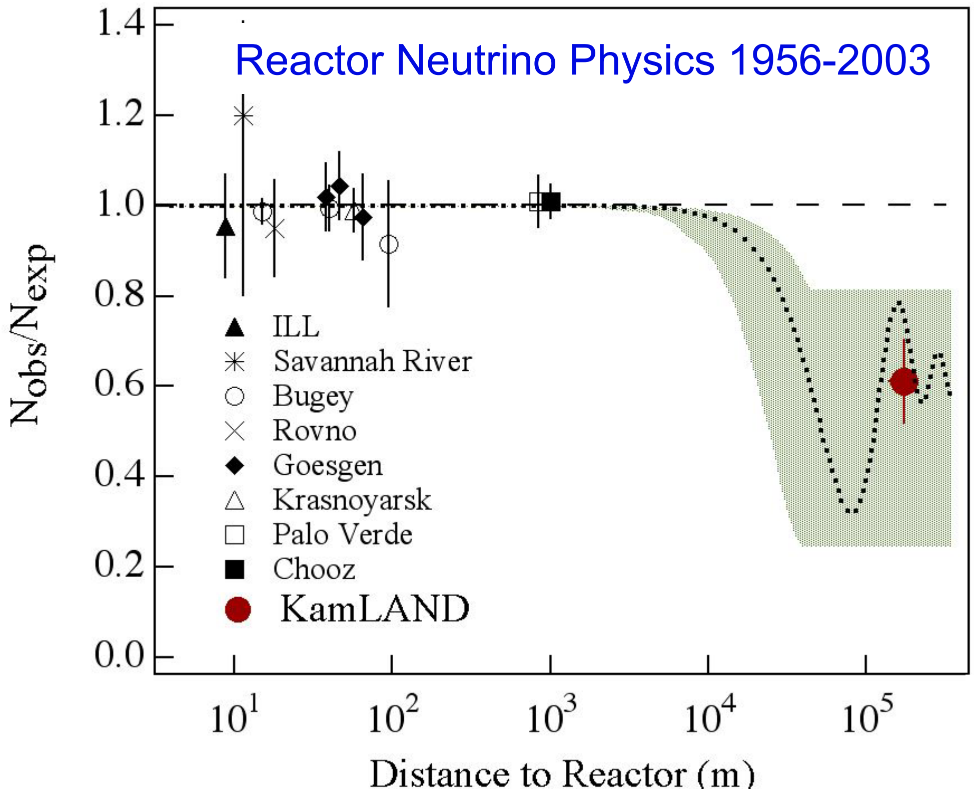
Anti-Neutrino Detection
through inverse β-decay

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



KamLAND in 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

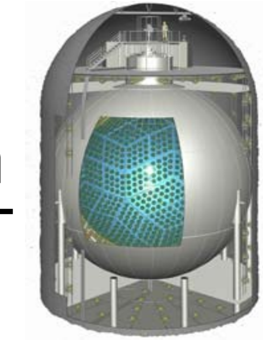
50 Years of Reactor Neutrino Physics

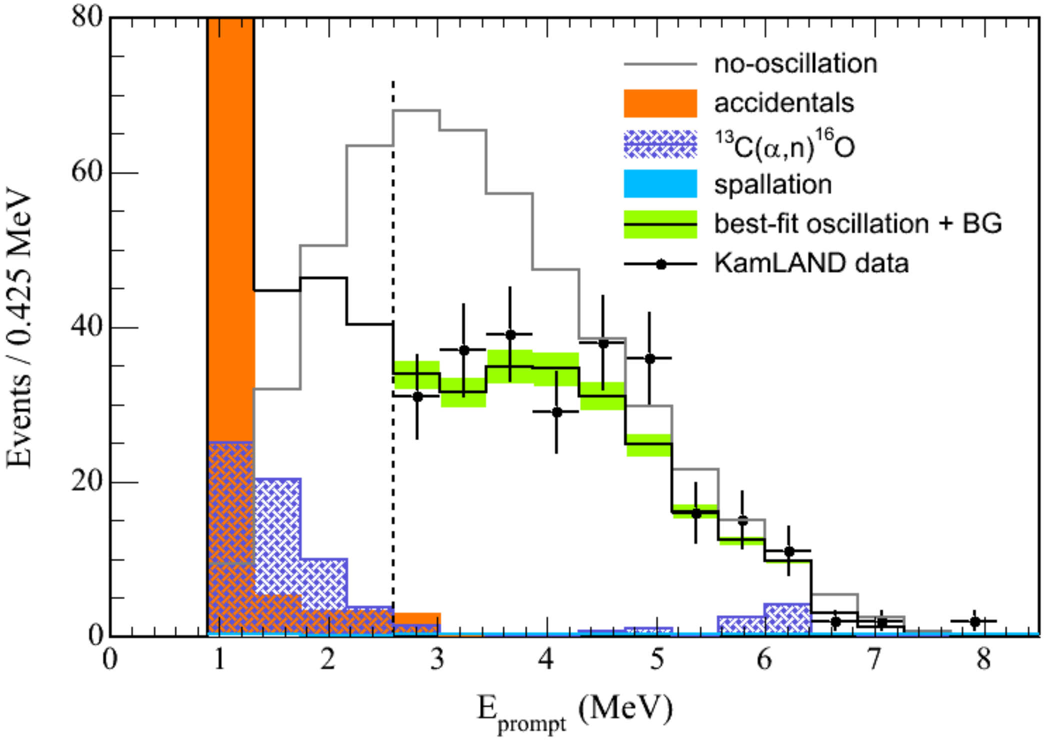
1953 First reactor neutrino experiment

1956 *"Detection of Free Antineutrino"*, Reines and Cowan → Nobel Prize in 1995

2003 KamLAND's observation of $\overline{\nu}_e$ disappearance

KamLAND in 2004:
Evidence of Spectral Distortion in Energy Spectrum





hep-ex/0406035 (2004)

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

$^{210}Pb \rightarrow {}^{210}Bi \rightarrow {}^{210}Po \xrightarrow{138d,\ \alpha} {}^{206}Pb$

$\rightarrow {}^{13}C(\alpha,n){}^{16}O$

Future

Reduce systematic error with improved calibrations.

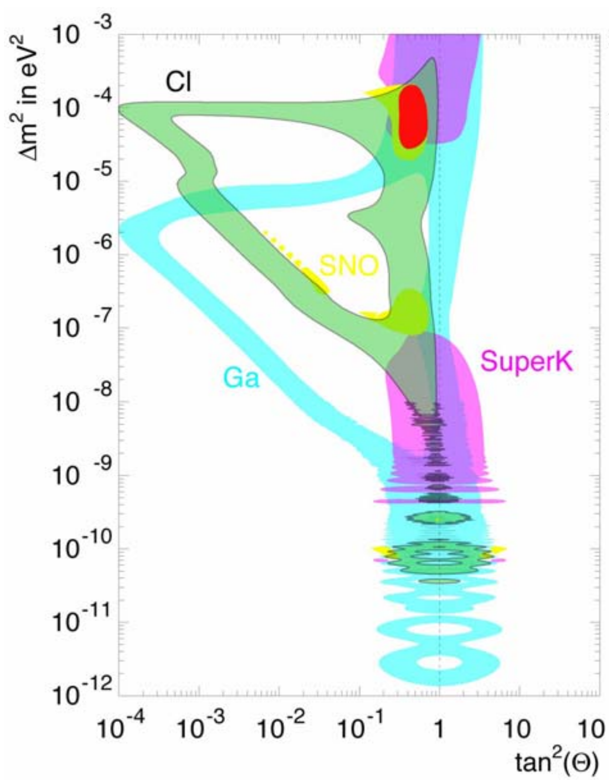
Reduce ^{210}Pb, lower analysis threshold, search for geo-neutrinos.

Spectral Distortions: A unique signature of neutrino oscillation!

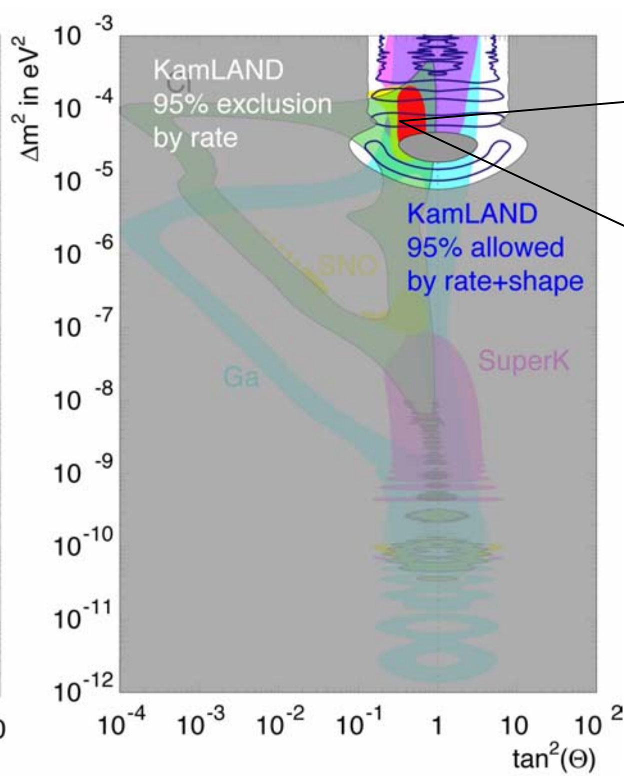
Simple, rescaled reactor spectrum is excluded at 99.6% CL(χ^2=37.3/18)

Measuring Neutrino Oscillation Parameters

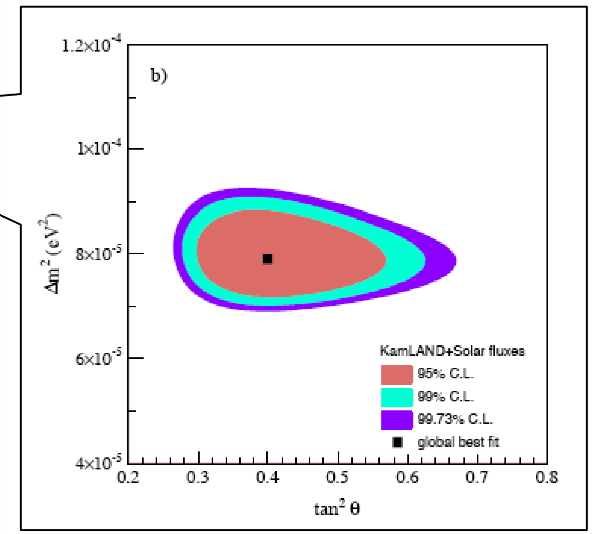
Solar Neutrinos



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



Solar Neutrinos
+ KamLAND 2004
($\bar{\nu}_e$ rate+spectrum)



Precision neutrino physics

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

Berkeley KamLAND Group

LBNL Physics | LBNL Nuclear Science | UC Berkeley

LBNL Physics Division
Kam-Biu Luk (Faculty Senior Scientist)
Hitoshi Murayama (Faculty Senior Scientist)
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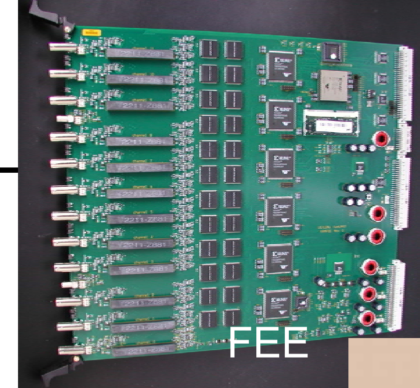
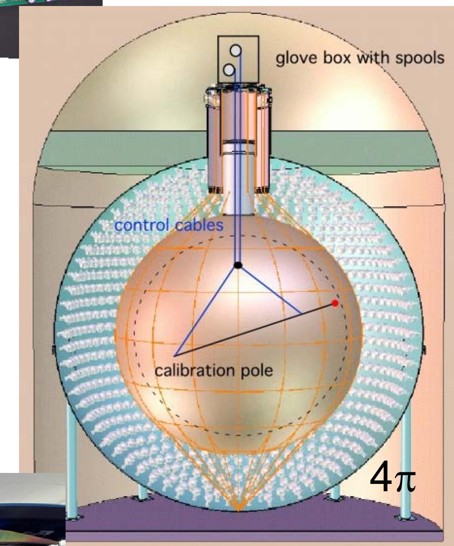
Dan Dwyer (UCB Graduate Student)
Tommy O'Donnel (UCB Graduate Student)
Lindley Winslow (UCB Graduate Student)
Dipanjan Ray (UCB Student)
Jordan Meyer (UCB Undergraduate)
Mahsa Sadrebazzaz (UCB Undergraduate)

LBNL Contributions to KamLAND



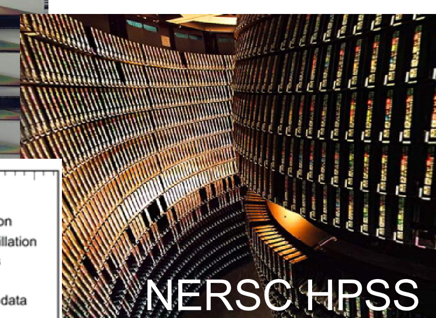
Development of Front-End Electronics

Waveforms are recorded using Analogue Transient Waveform Digitizers (ATWDs), allowing multi p.e. resolution.



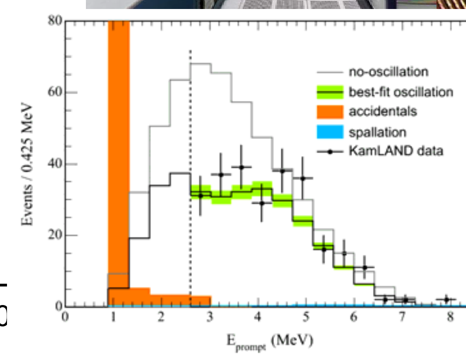
Calibrations

Co-leader of calibration group.
Developed full-volume calibration system, last major hardware upgrade during reactor phase.



KamLAND Data Analysis and Processing

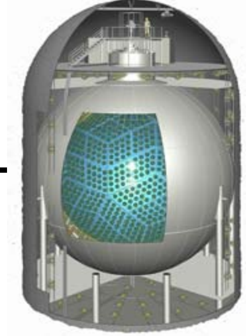
Coordinates reconstruction for the US collaboration.
Developed techniques for data compression.
PDF used for data processing and reconstruction.
KamLAND data rate: ~160 GB/day



Data Analysis

Coordinates US data processing and analysis.

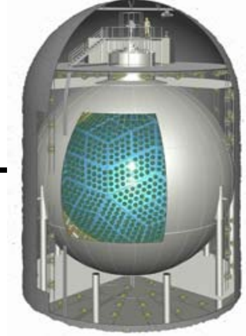
KamLAND - Systematic Uncertainties



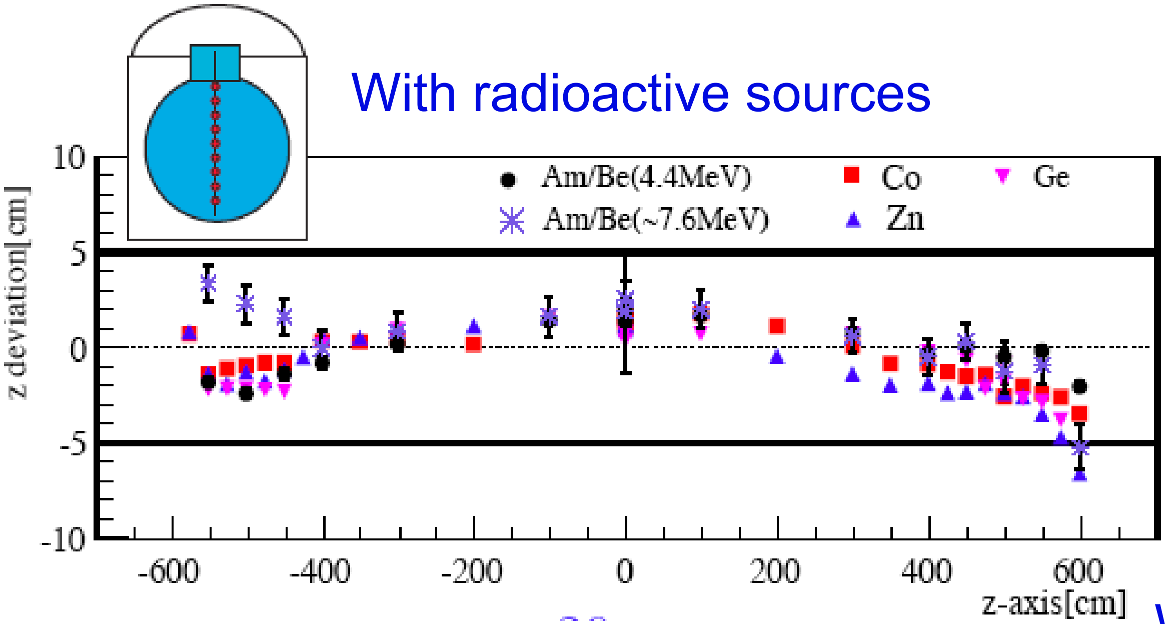
E > 2.6 MeV

	%	
Fiducial volume	4.1	volume calibration
Energy threshold	2.3	energy calibration or analysis w/out threshold
Cut efficiency	1.6	
Live time	0.06	
Reactor power	2.1	*given by reactor company, difficult to improve on*
Fuel composition	1.0	
$\overline{\nu}_e$ spectra	2.5	
cross section	0.2	*theoretical, model-dependent*
Total uncertainty	6.5 %	

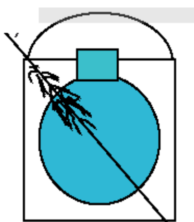
Fiducial Volume Determination

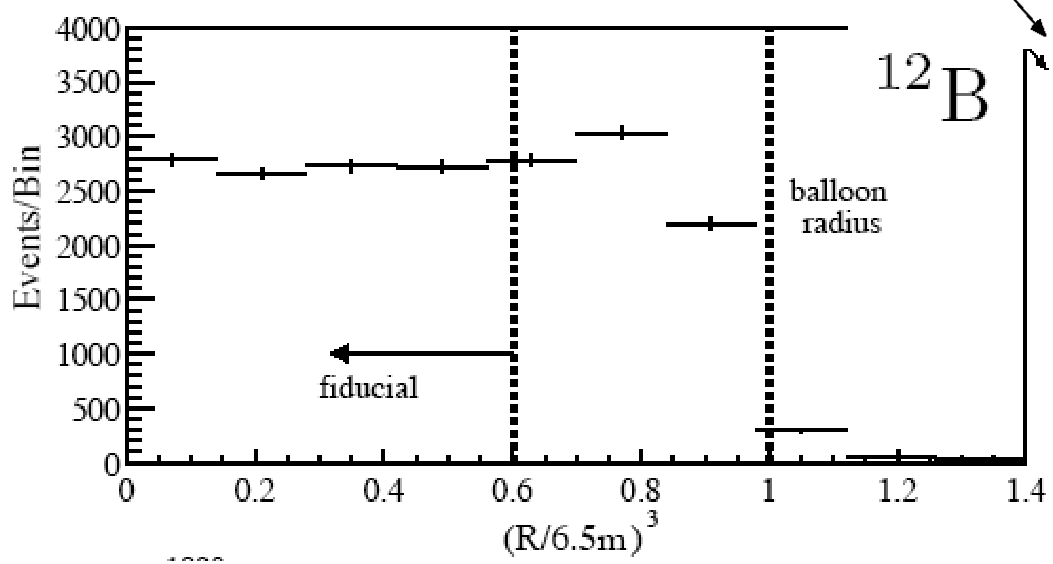


With radioactive sources



With muon spallation





Fiducial/Total Volume Ratios

Geometrical	0.595 ± 0.013
^{12}B	0.607 ± 0.006
p(n,γ)d	0.587 ± 0.013
^{9}Li relative	< 2.7%

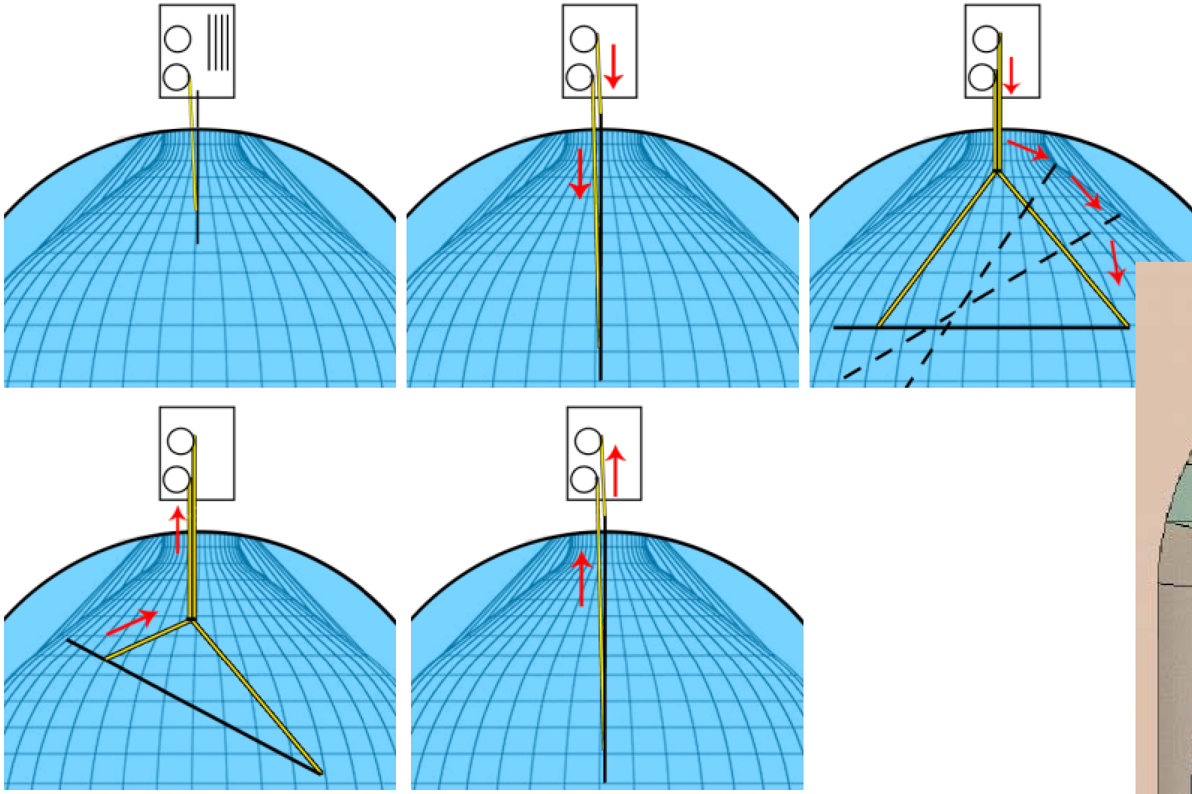
KamLAND volume error: 4.7%

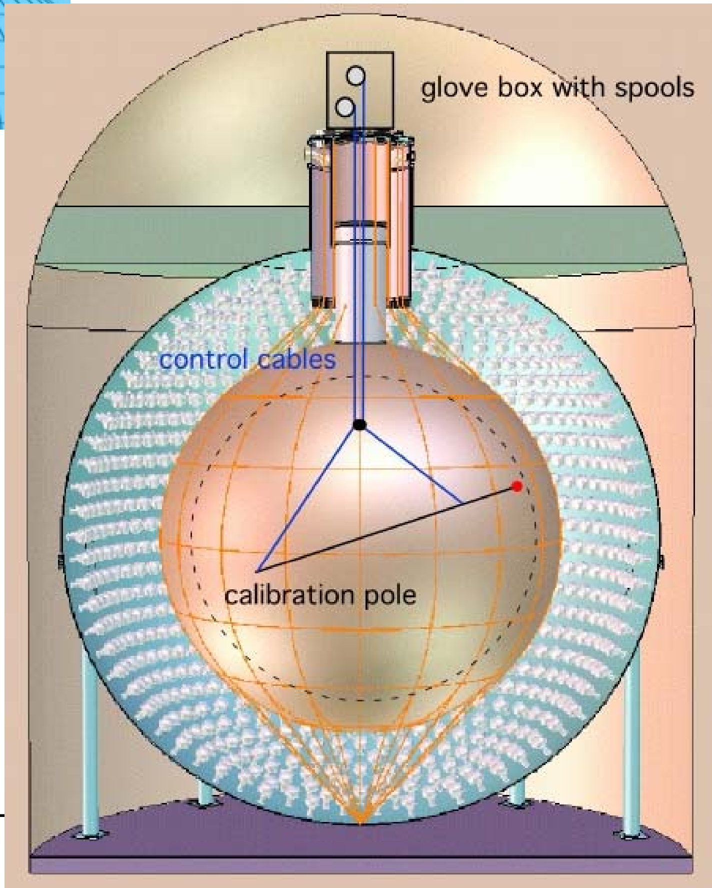
KamLAND Full-Volume Calibration

Calibration throughout entire detector volume

Fiducial volume: R < 5.5 m

ΔR_{FV} = 5 cm $\rightarrow$ ΔV= 2.7%
ΔR_{FV} = 2 cm $\rightarrow$ ΔV= 1.1%

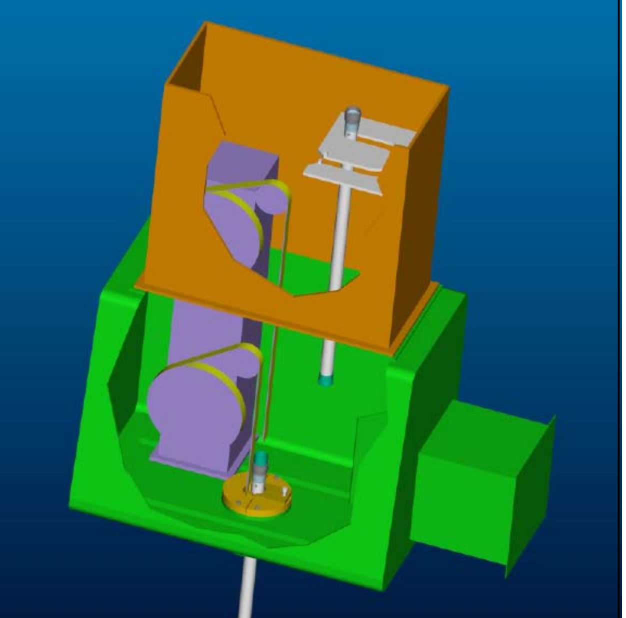




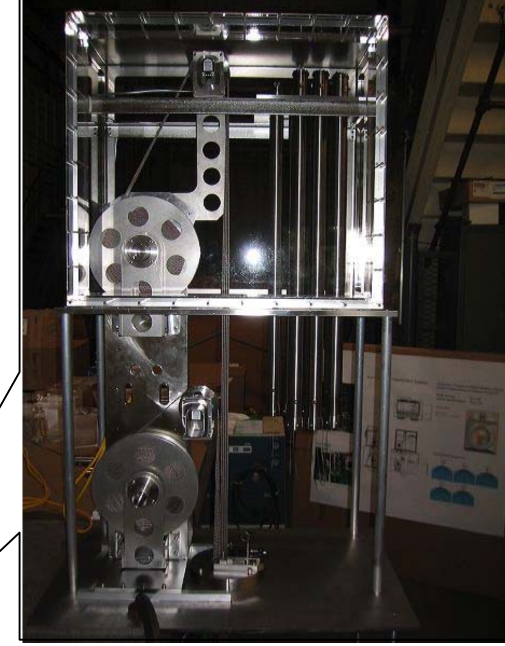
Position Dependence of Detector Response

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

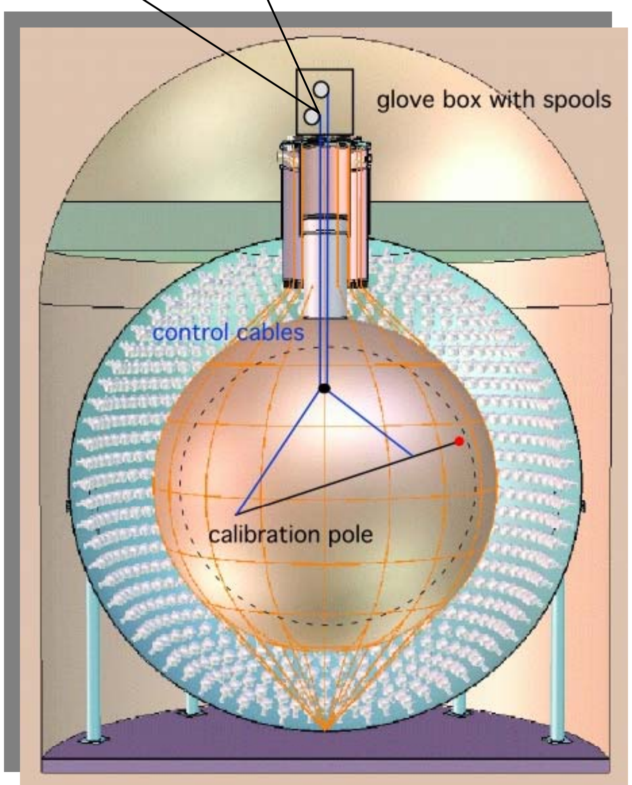
Construction of a Full-Volume Calibration System

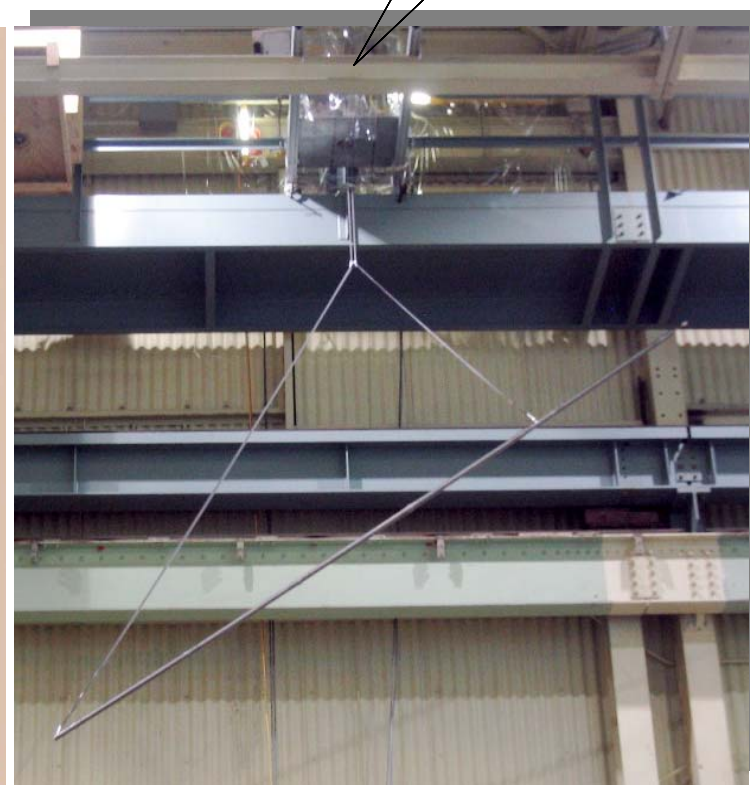


I. compatible with scintillator
II. low-background
III. precise positioning



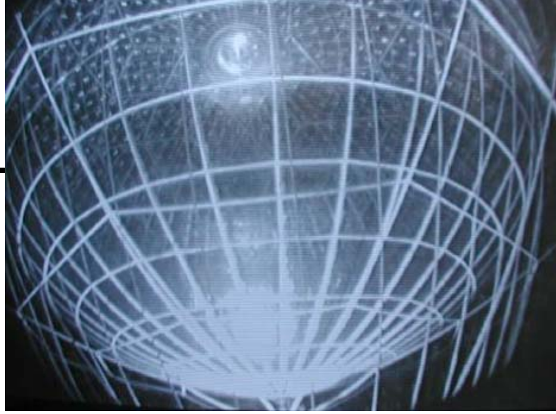
Fall 2003

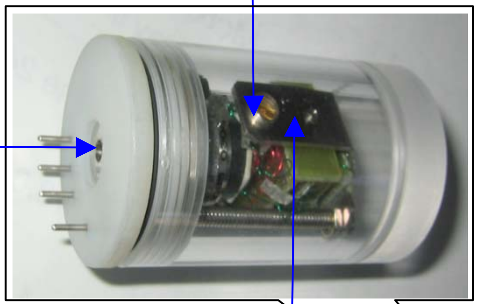


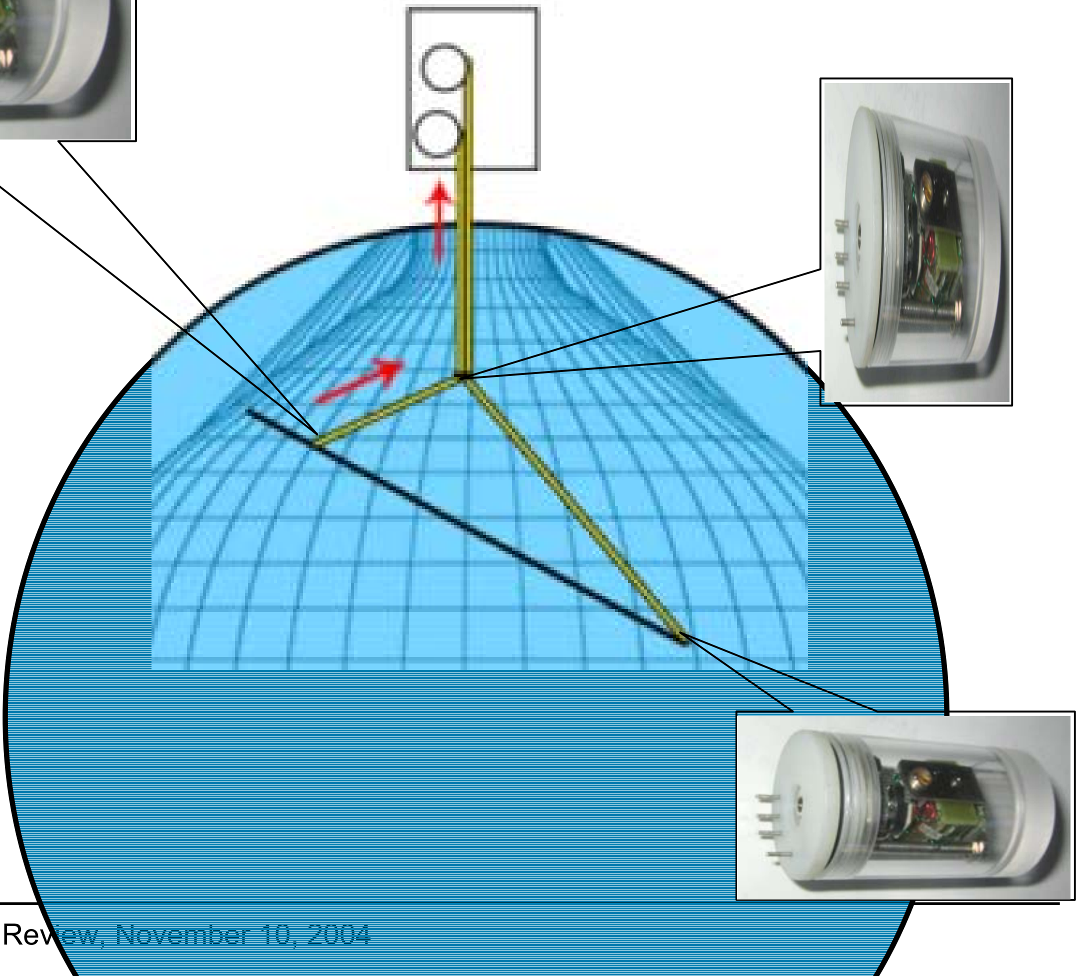


Fall 2004

Instrumentation of Calibration System







Position Information:

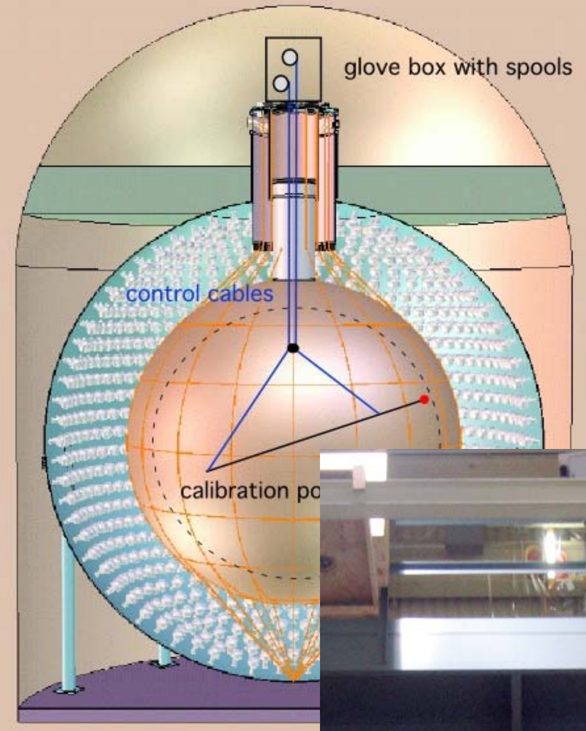
cable length < 0.5 cm

depth (3 pressure sensors) < ~1 cm

inclination of pole (accelerometers)

CCD imaging of IR LEDs

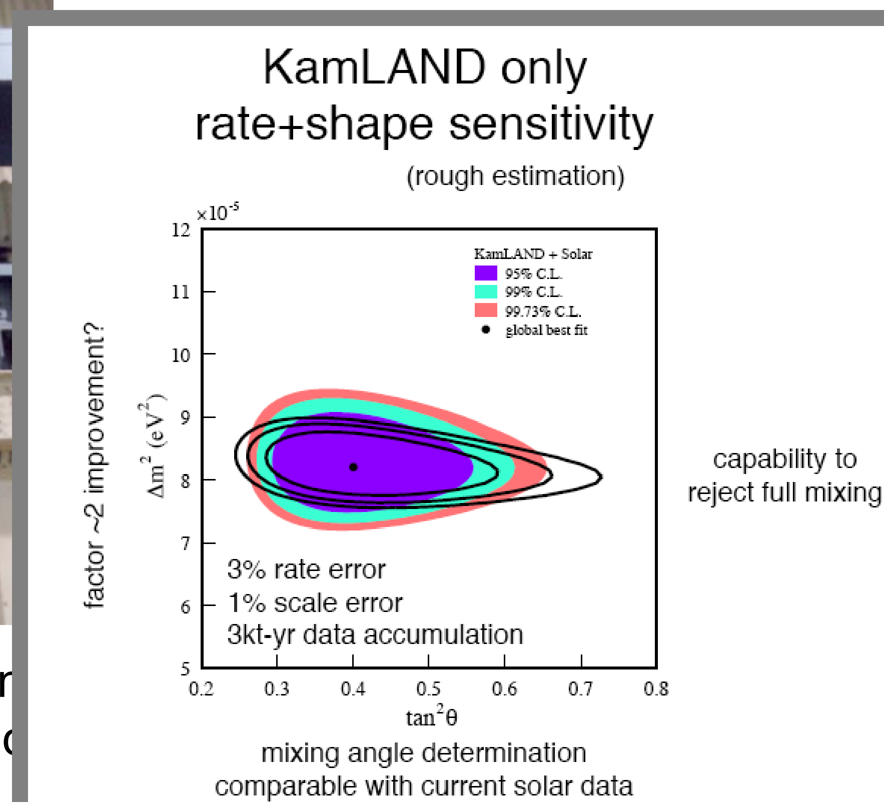
Expected positioning accuracy ~2cm



Designed and built a full-volume calibration system for KamLAND

Commissioning in early 2005

Last major detector upgrade for KamLAND



Will reduce KamLAND's systematic uncertain[...] on the fiducial volume from 4.7% to 1-2% an[...] improve its sensitivity to Δm^2_{12}.

KamLAND Neutrino Program

Reactor Anti-Neutrinos

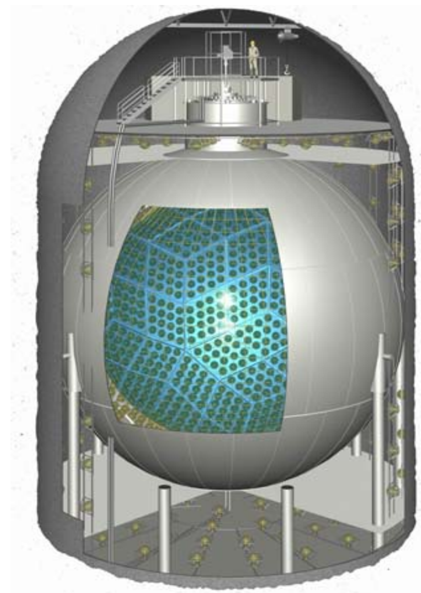
PRL 90:021802 (2003)

hep-ex/0406035 (2004)

Solar ^{7}Be Neutrinos

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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



Anti-Neutrinos from the Sun

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Phys.Rev.Lett.92:071301,2004

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

improvement by factor x30

Terrestrial Anti-Neutrinos

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

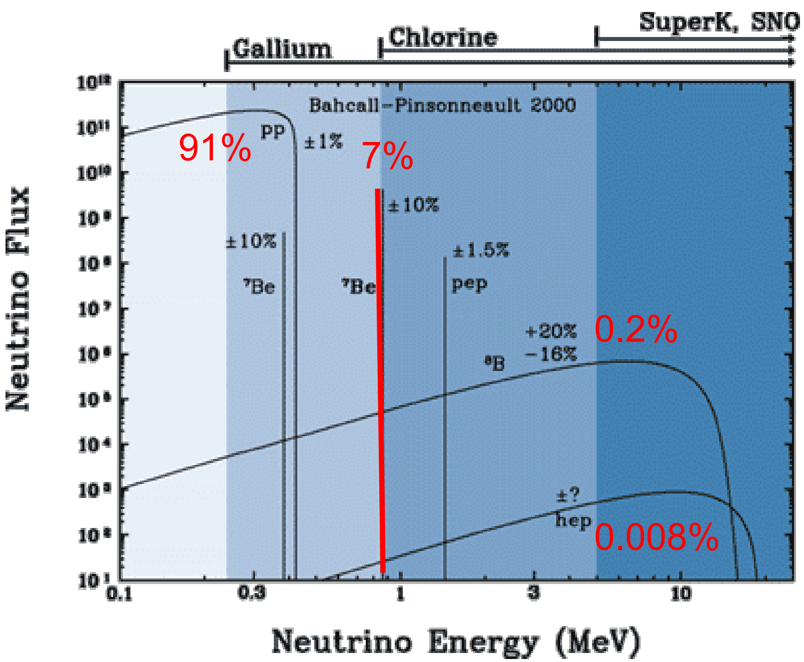
Ongoing Physics Studies

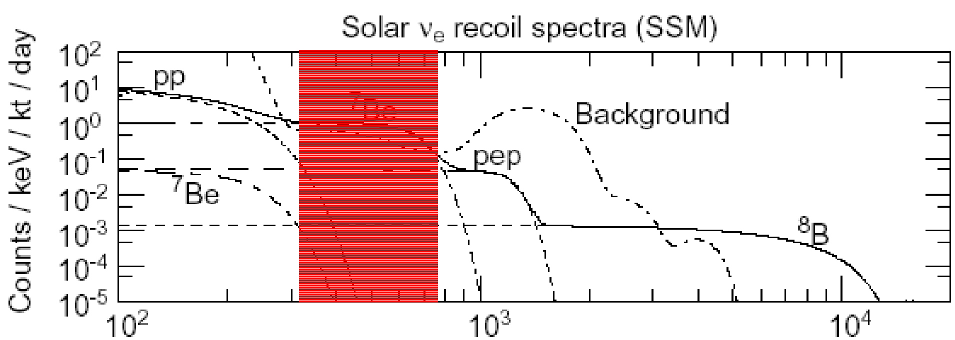
- Oscillation analysis of $\bar{\nu}_e$ spectrum
- Nucleon decay studies
- Supernova watch
- Muon spallation

^{7}Be Solar and Geo-Neutrinos: A Background Challenge

Direct detection of solar ^{7}Be neutrinos

through elastic scattering: $\nu_e + e^- \rightarrow \nu_e + e^-$

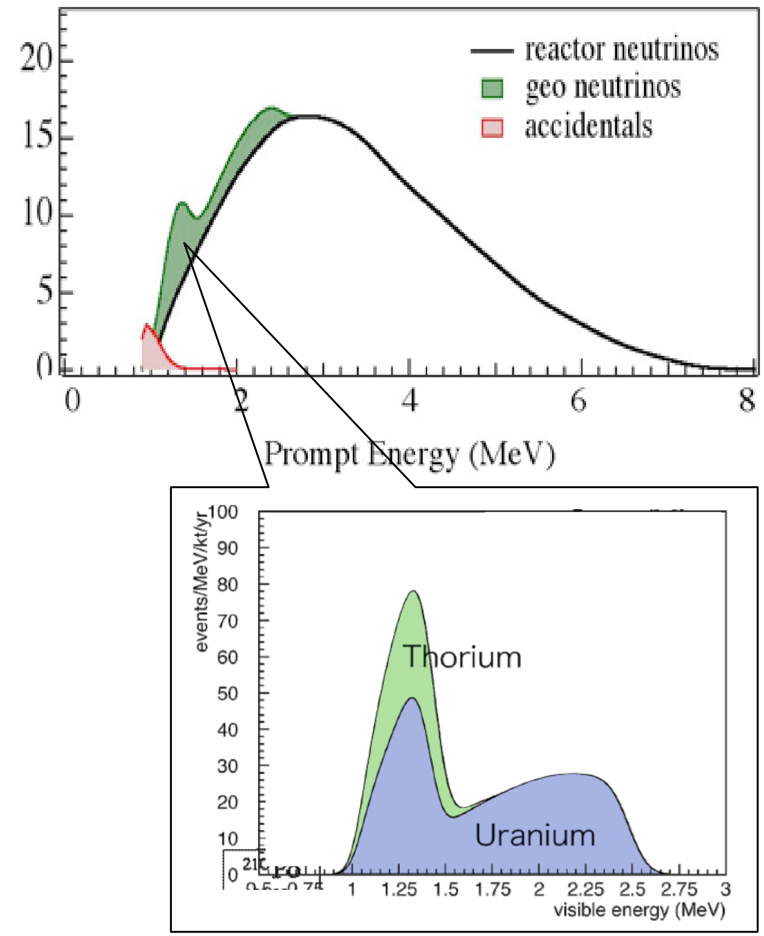




Ref: KamLAND proposal

Search for terrestrial anti-neutrinos

through inverse β-reaction: $\overline{\nu}_e + p \rightarrow e^+ + n$



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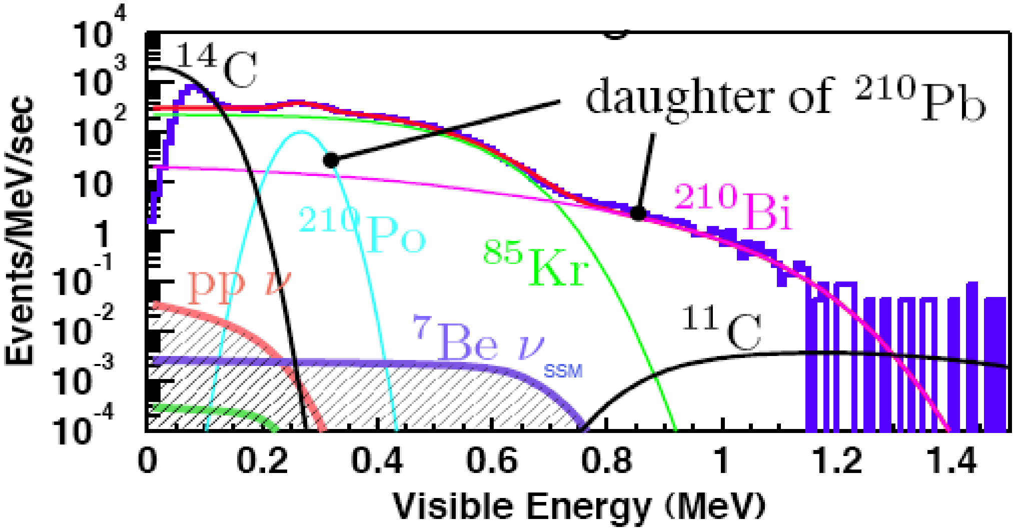
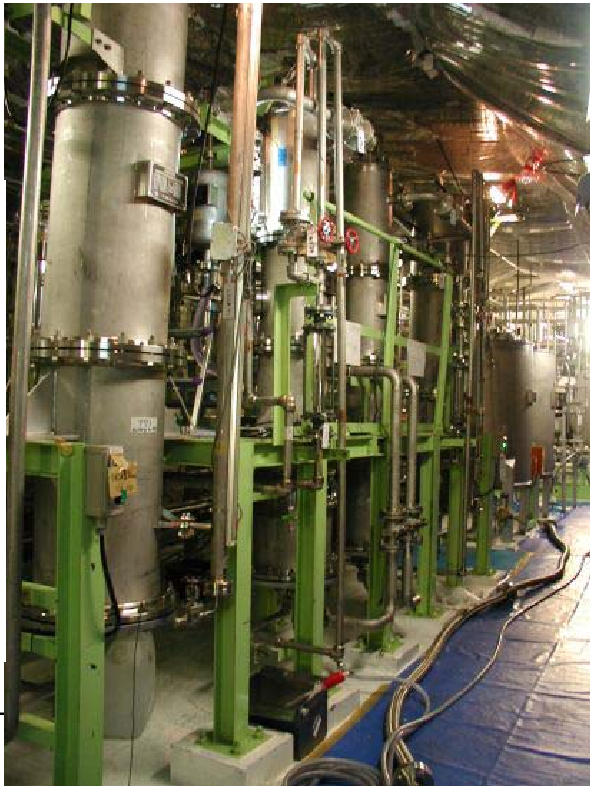
Geo-Neutrinos and ^{7}Be Solar ν: A Background Challenge





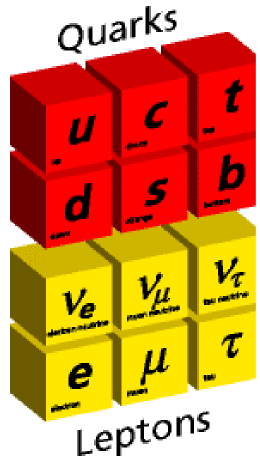
Backgrounds in the ^{7}Be signal region currently about 10^6 times too high

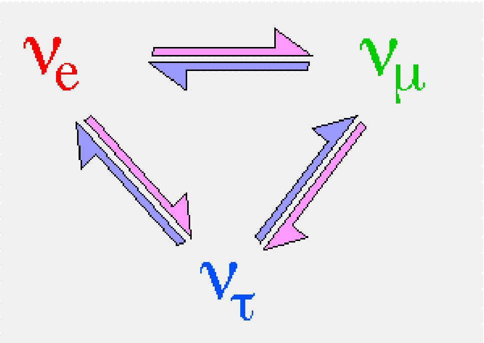
R&D on purification methods in Japan to remove

- ^{85}Kr (from nitrogen used in purification)
  ~0.7 Bq/m^3 → 1μBq/m^3
- ^{210}Pb (from decay of radon that got into the system)
  ~10^{-20} g/g → 5×10^{-25} g/g (~1μBq/m^3)

Neutrino Mixing

U_{MNSP} Matrix





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

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

?

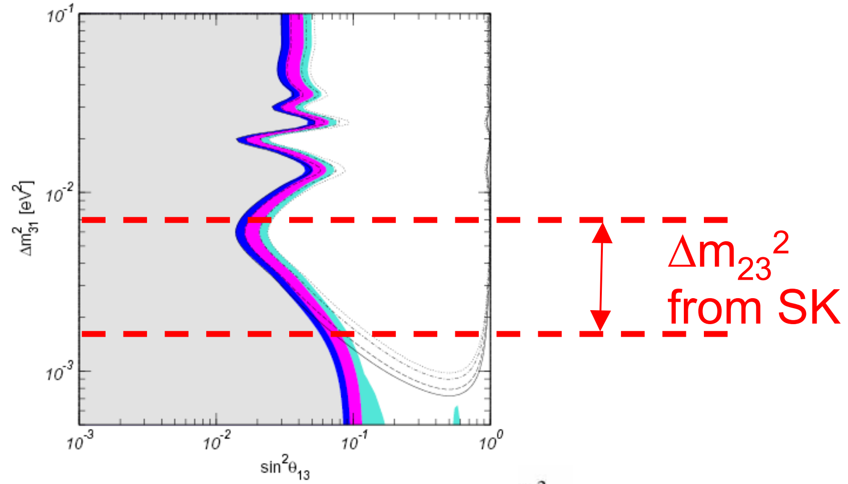
atmospheric, K2K	reactor and accelerator	SNO, solar SK, KamLAND	$0\nu\beta\beta$
θ_{23} = ~ 45°	θ_{13} = ?	θ_{12} ~ 32°	

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

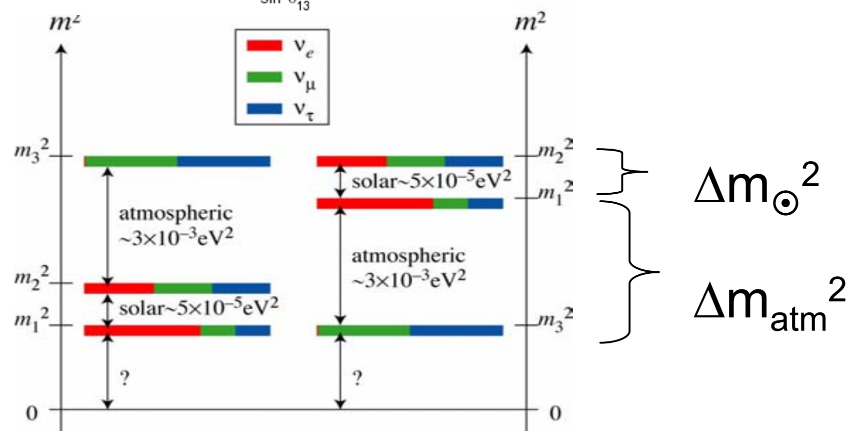
θ_{13} yet to be measured
determines accessibility to CP phase

Key Questions in Oscillation Physics

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



sign of Δm_{13}^2
mass hierarchy



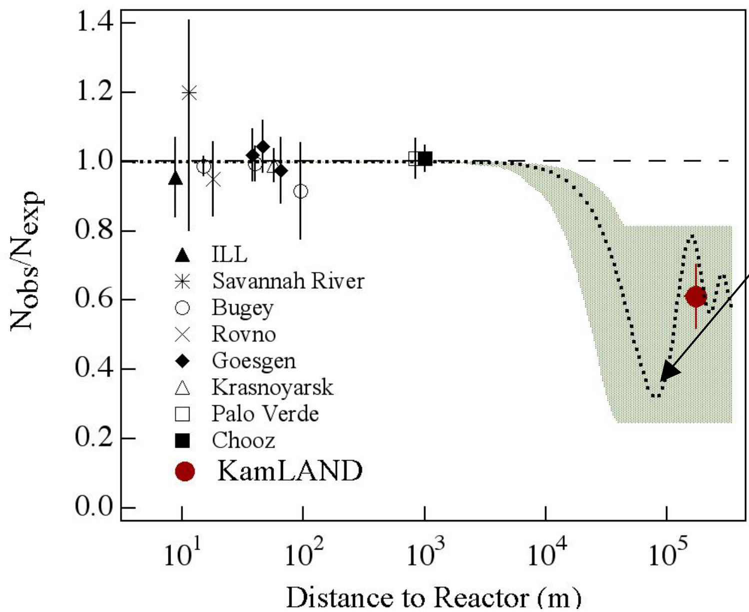
δ_{CP}

$$J_{lepton} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1}\underbrace{\sin(2\theta_{12})}_{\sim 0.9}\underbrace{\sin(2\theta_{23})}_{\sim 1}\sin(2\theta_{13})\sin(\delta_{CP})$$

Reactor Neutrino Oscillation Measurements

Past Measurements

single antineutrino detector, absolute flux measurement



Dominant θ_{12} Oscillation

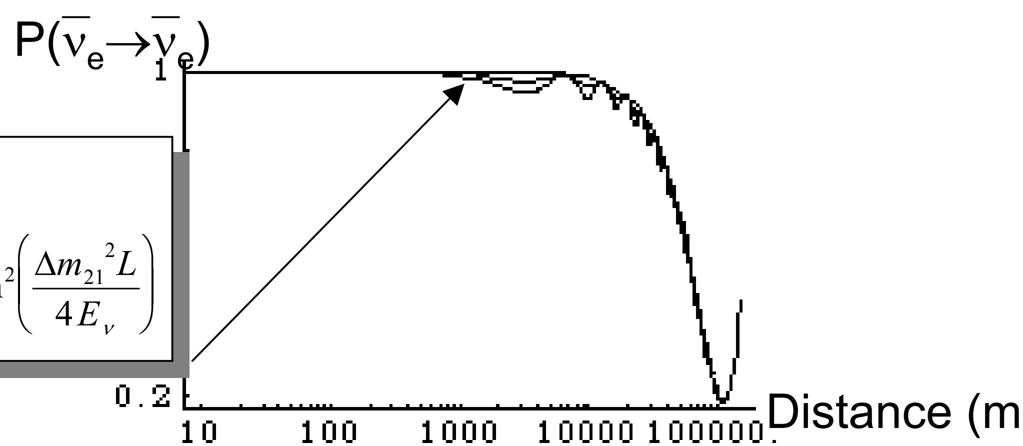
$$P_{ee} \approx 1 - \cos^4\theta_{13}\left[1 - \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{12}{}^2 L}{4E_\nu}\right)\right]$$

Future θ_{13} Reactor Neutrino Oscillation Experiment

multiple detectors, relative flux measurement

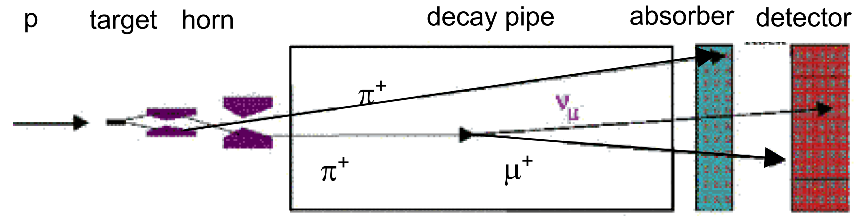
Subdominant θ_{13} Oscillation

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



Measuring θ_{13}

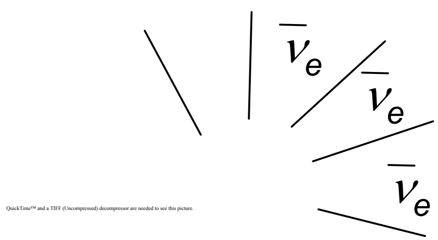
Method 1: Accelerator Experiments



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

- 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

Precision Measurement of θ_{13} with Reactor Neutrinos

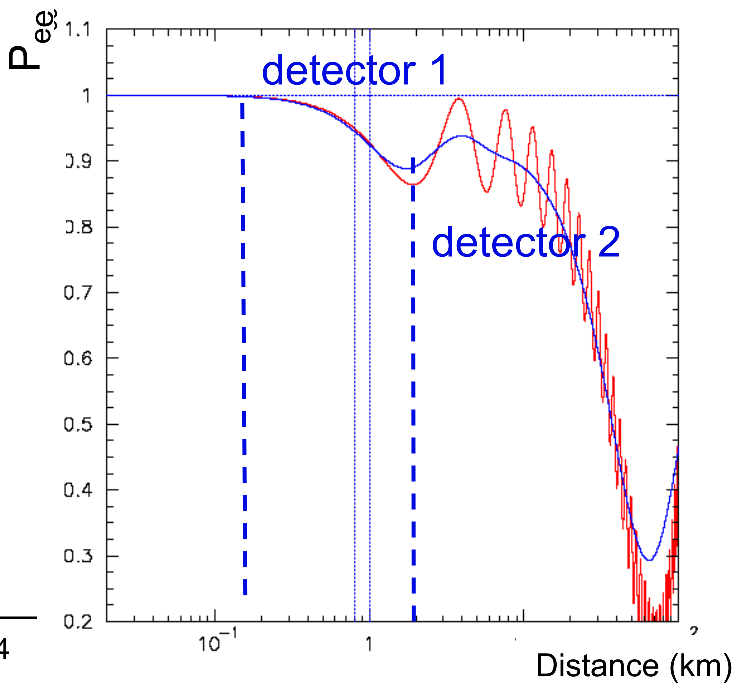
Search for U_{e3} in new oscillation experiment

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

APS Neutrino Study Recommends

- **An expeditiously deployed multi-detector reactor experiment with sensitivity to $\overline{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.**

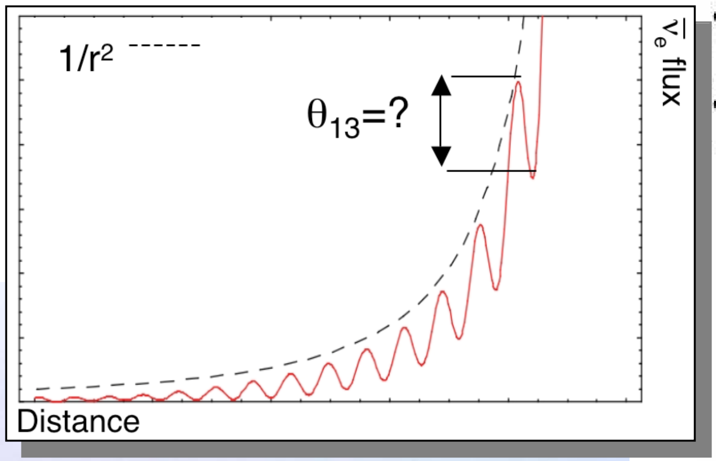


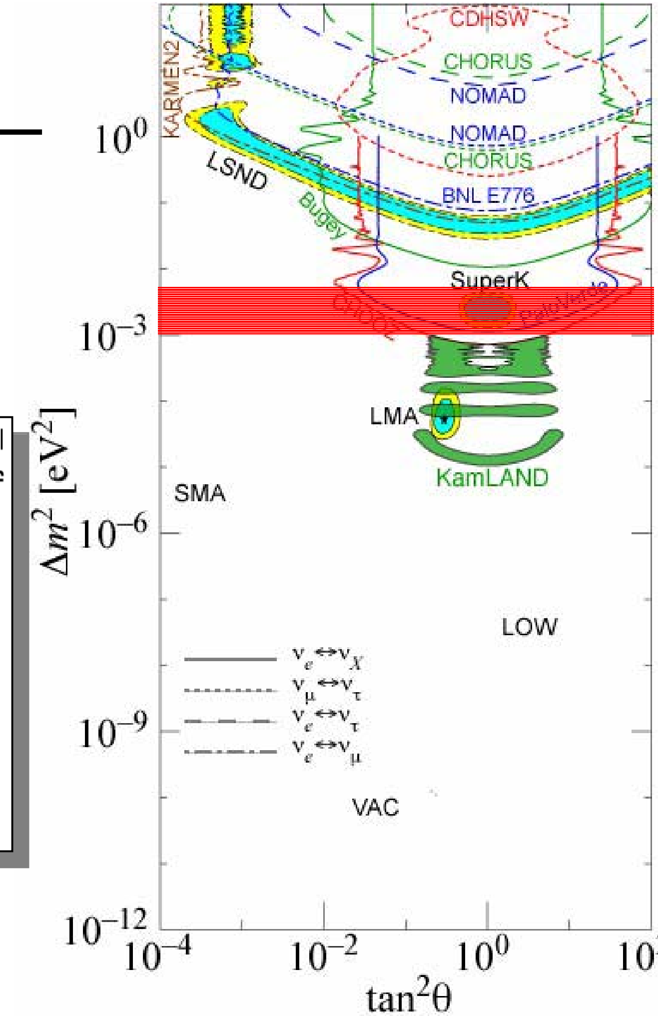
→ Daya Bay offers opportunity for timely, precision θ_{13} experiment with horizontal access

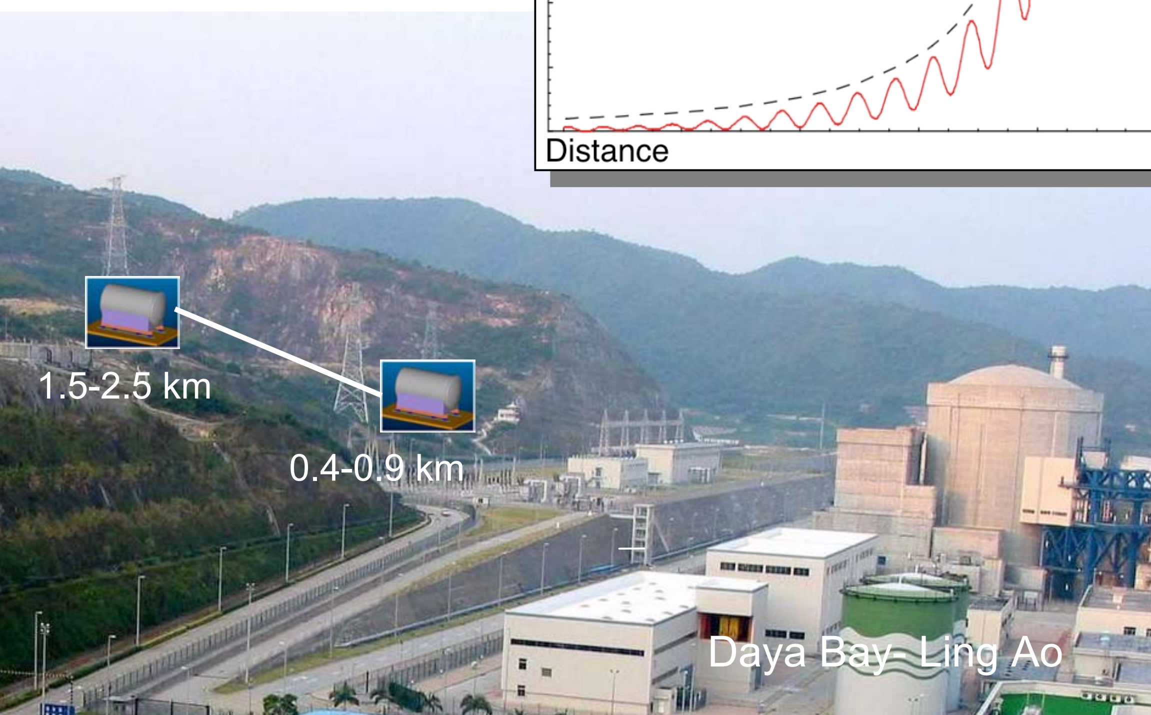
Measuring θ_{13} at Daya Bay, China

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

atmospheric frequency dominant







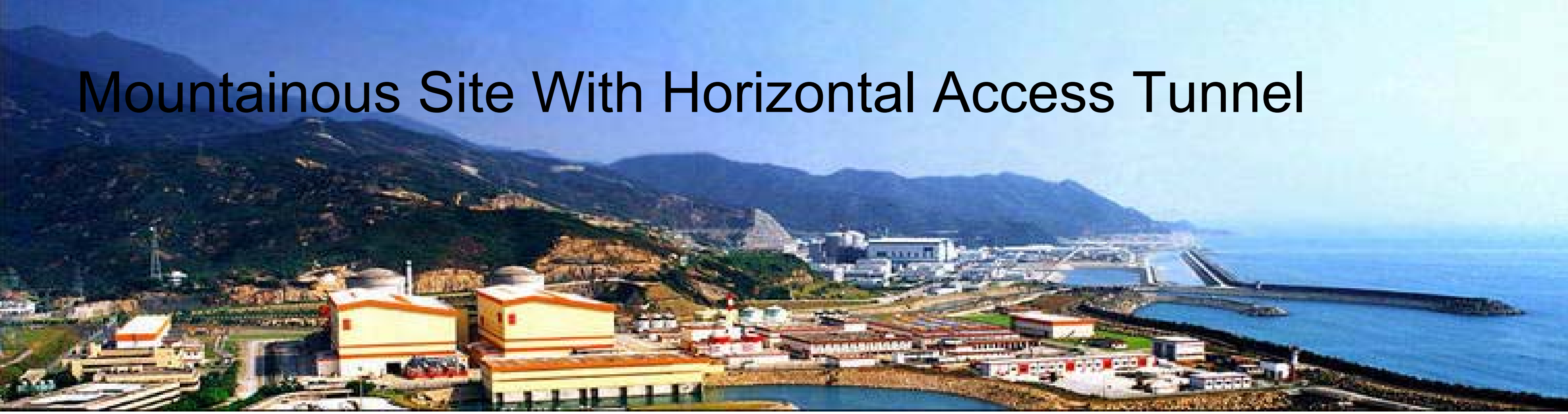
$\bar{\nu}_e + p \rightarrow e^+ + n$

coincidence signal

prompt e^+ annihilation

delayed n capture (in μs)

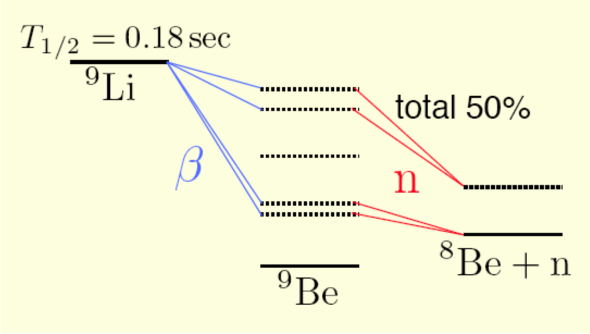
Mountainous Site With Horizontal Access Tunnel



Correlated backgrounds are related to cosmic ray muon rates

- Neutron production
- Isotope production: ^{9}Li ($t_{1/2}$=0.18s) , ^{8}He ($t_{1/2}$=0.12s)

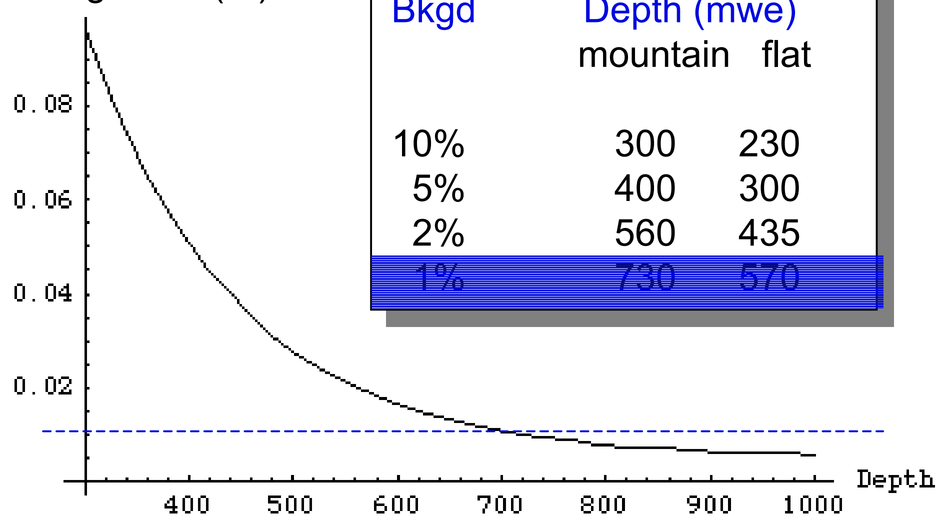
High muon rates can also introduce deadtime effects.



LBNL has championed detectors in horizontal tunnels:

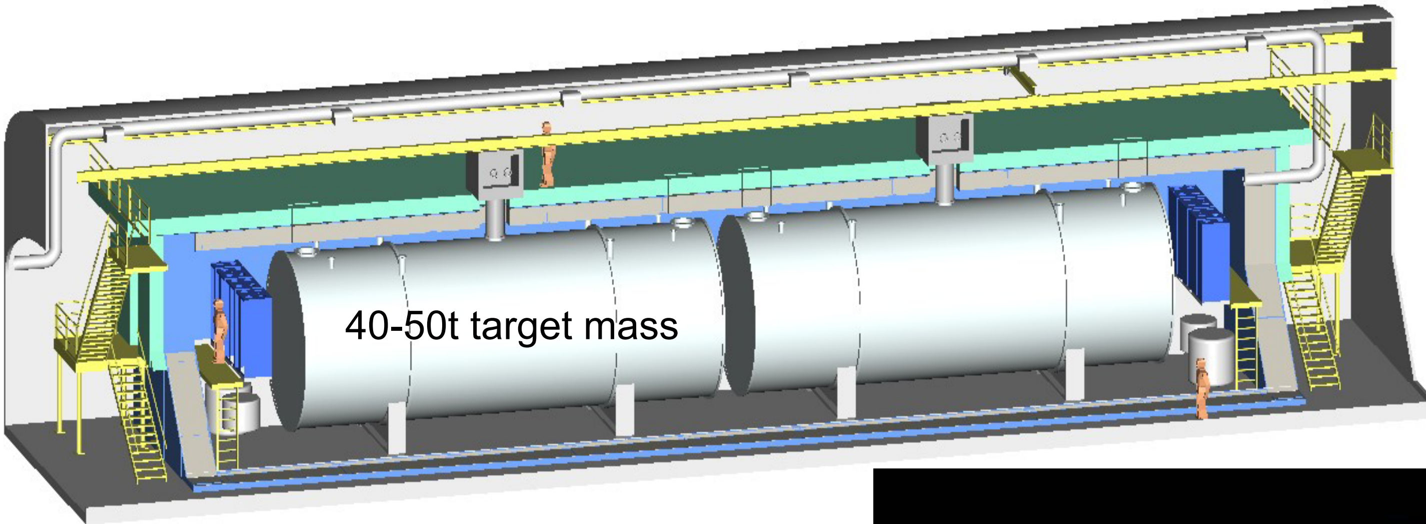
- detector positioning flexibility
- access to large overburden

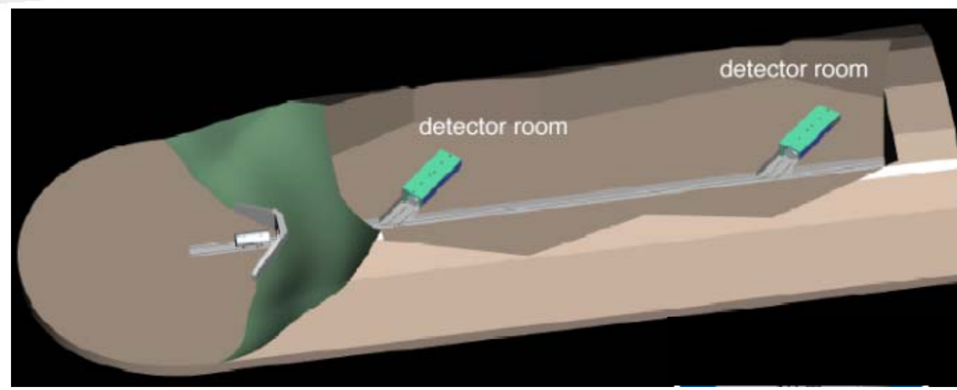
Daya Bay - Ling Ao offers up to 1000 mwe overburden.



Bkgd	Depth (mwe) mountain	flat
10%	300	230
5%	400	300
2%	560	435
1%	730	570

Design and Engineering Studies





Moveable detectors:

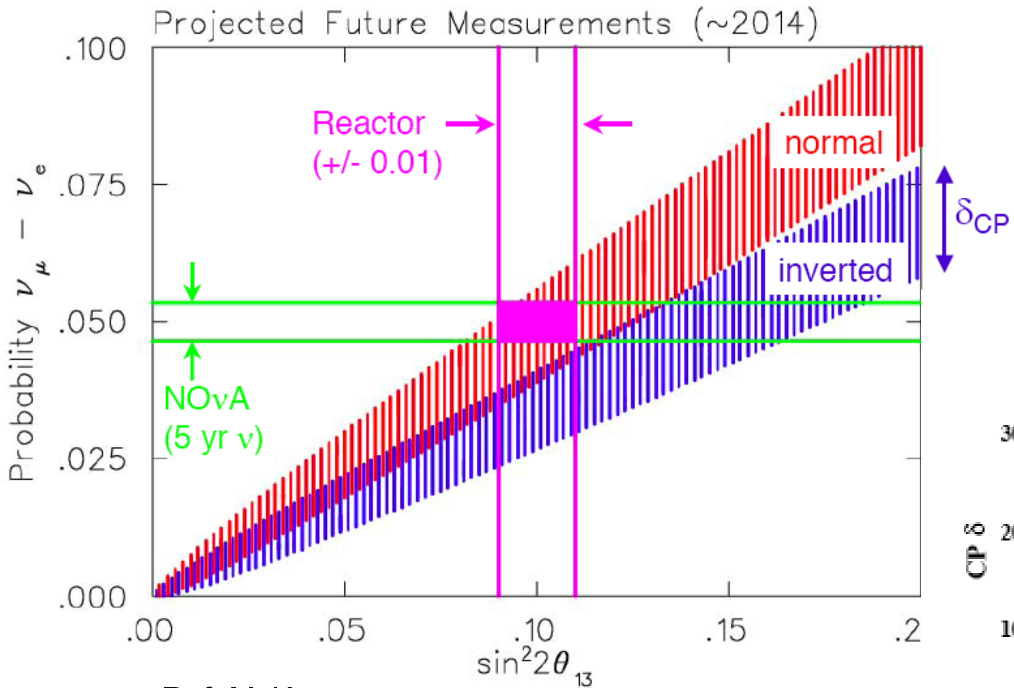
• initial calibration at common distance.

• interchange near-far detectors to measure systematics, understand backgrounds.

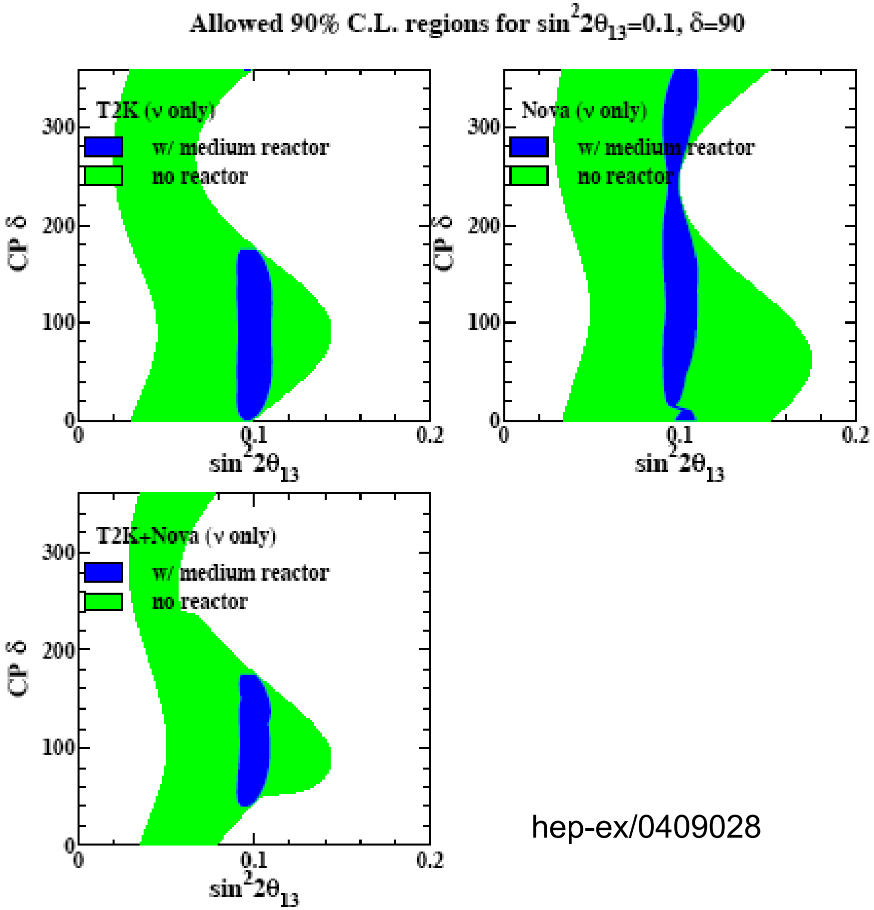
• simplify logistics.

→ design&engineering supported by LDRD
→ LBNL/UCB formed R&D collaboration with IHEP
→ UCB and Caltech submitted NSF R&D proposal
→ DOE R&D proposal in preparation

Synergy of New Reactor and Accelerator Experiments

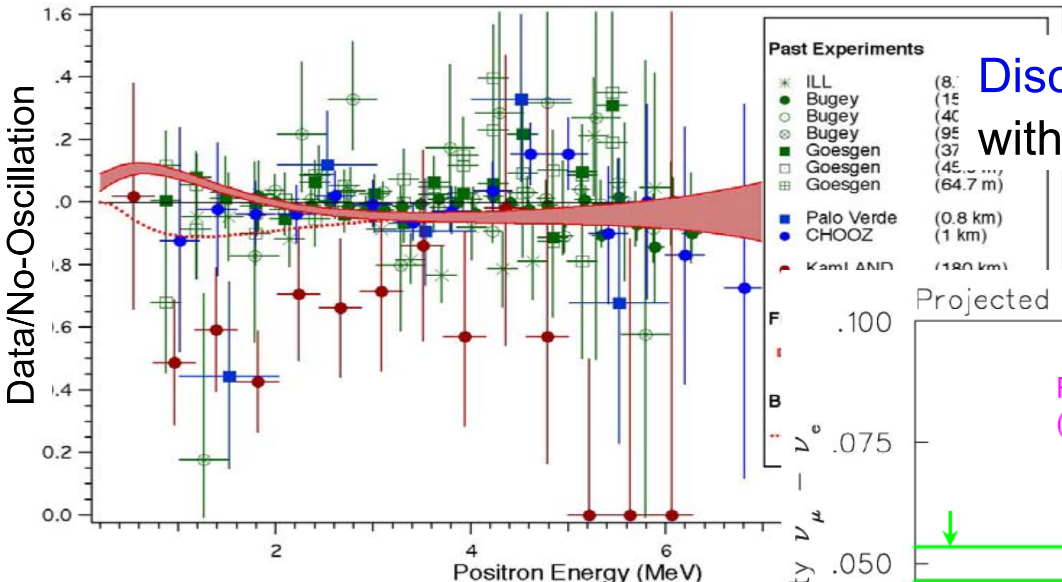


Ref: McKeown

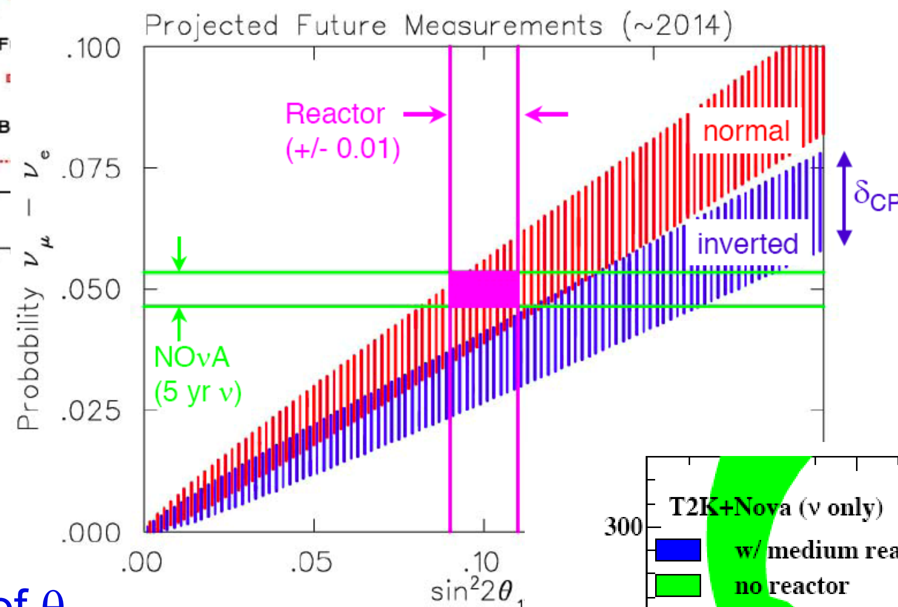


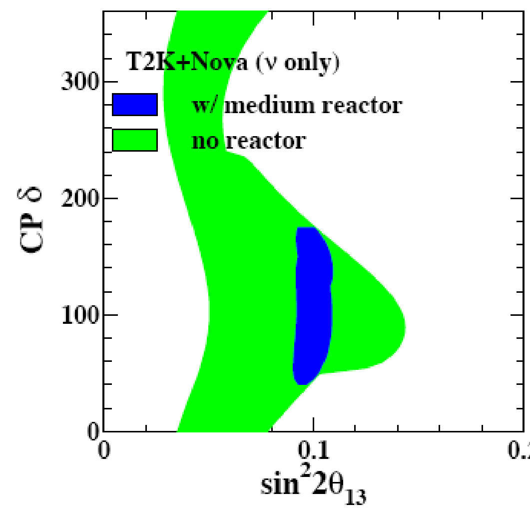
hep-ex/0409028

Scientific Goals of Reactor θ_{13} Experiment



Discovery and measurement of θ_{13} with a sensitivity of $\sin^2 2\theta_{13} \sim 0.01$





Gives most precise measurement of θ_{13}.
Will help resolve parameter degeneracies.
May help distinguish mass hierarchy.
Constrain CP.

(from a combination with long baseline experiments)

Neutrino Physics at Reactors

1956
First observation of neutrinos

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

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

1995
Nobel Prize to Fred Reines at UC Irvine

2002
Discovery of massive neutrinos and oscillations

2004 and beyond
Precision measurement of θ_{13}
Exploring feasibility of CP violation studies

KamLAND Collaboration

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