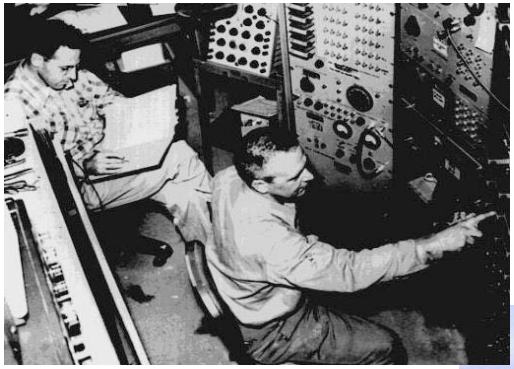
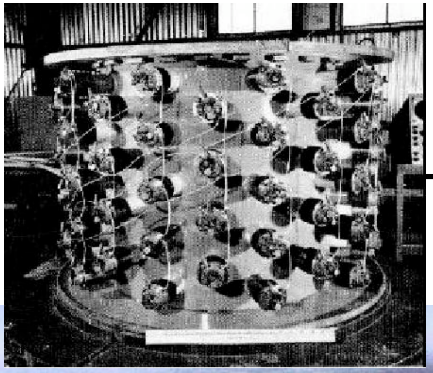
Precision Neutrino Physics with Reactors & Beyond

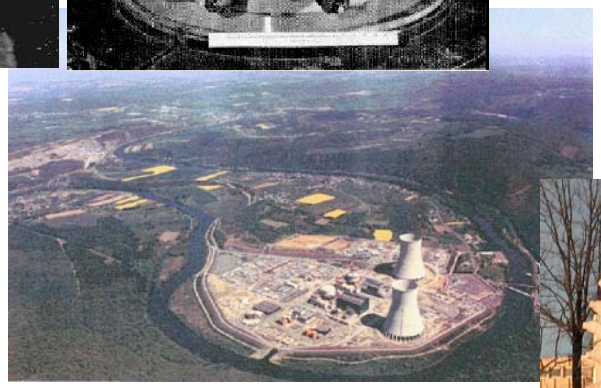
Karsten Heeger, LBNL

Neutrino Physics at Reactors





1956
First observation of neutrinos



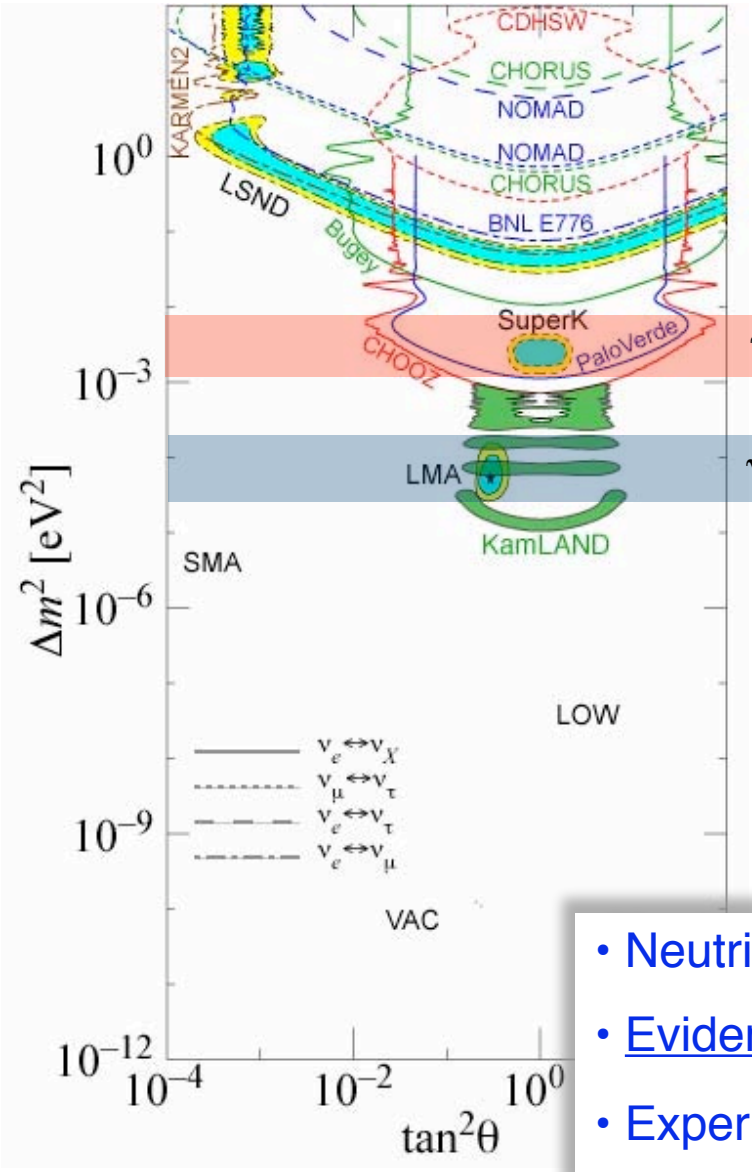
1980s & 1990s
Reactor neutrino experiments in U.S. and Europe

1995
Nobel Prize to Fred Reines

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

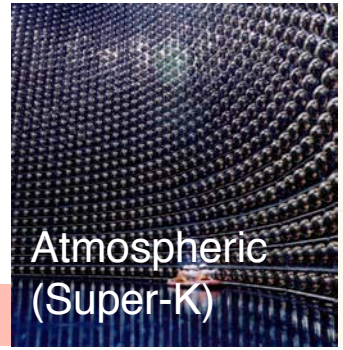
2002
Discovery of reactor antineutrino oscillations at KamLAND

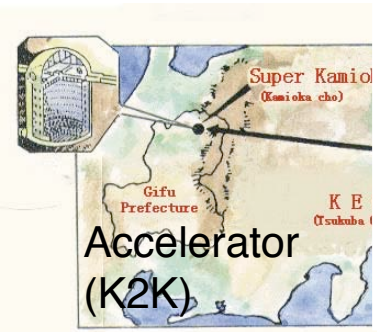
1998-Present: Discovery Era in Neutrino Physics



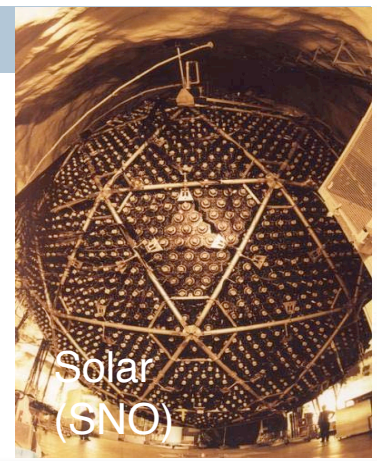
$\nu_\mu \Rightarrow \nu_\tau$

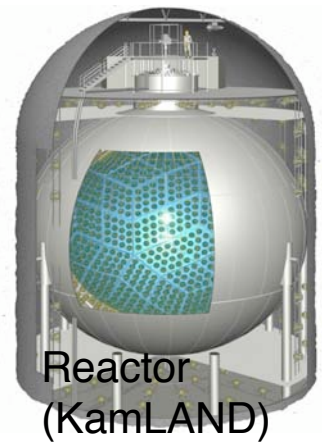
$\nu_e \Rightarrow \nu_{\mu,\tau}$





Accelerator
(K2K)

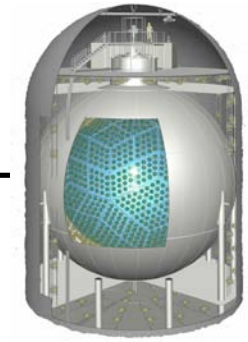




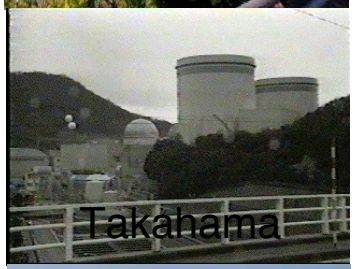
- Neutrinos are <u>not massless</u>
- <u>Evidence</u> for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that *<u>neutrinos oscillate</u>*

7 years of discoveries have revolutionized the field.

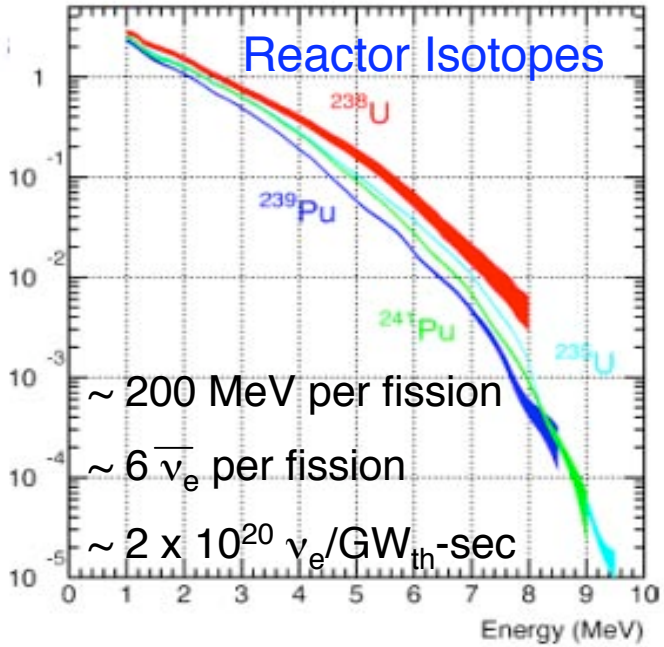
KamLAND: Designed to Measure Reactor $\overline{\nu}_e$

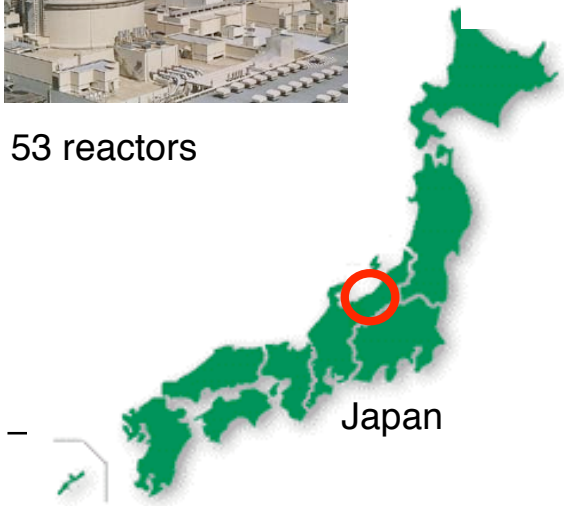


Japanese Reactors



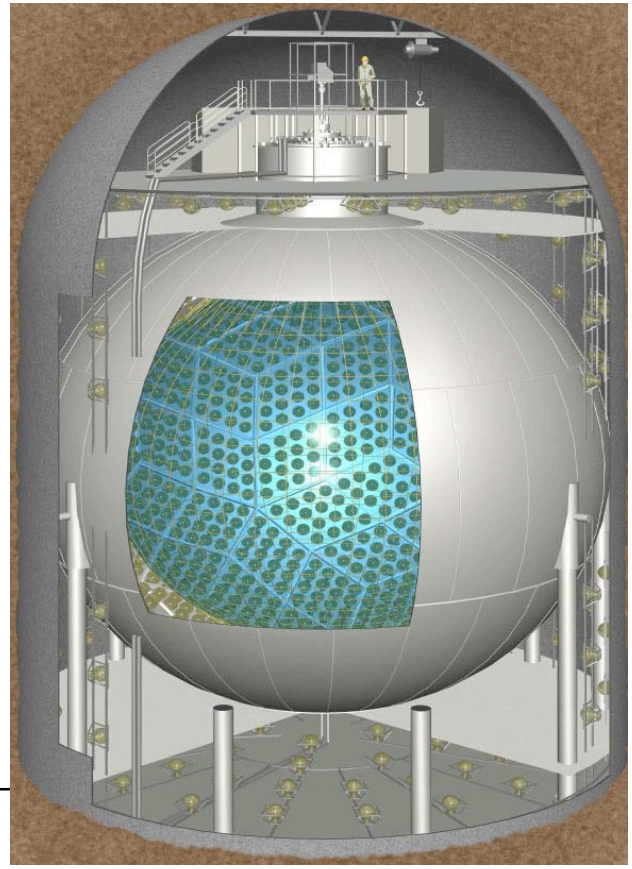
53 reactors



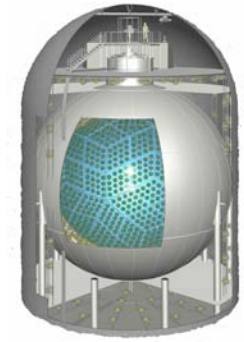


Anti-Neutrino Detection
through inverse β-decay

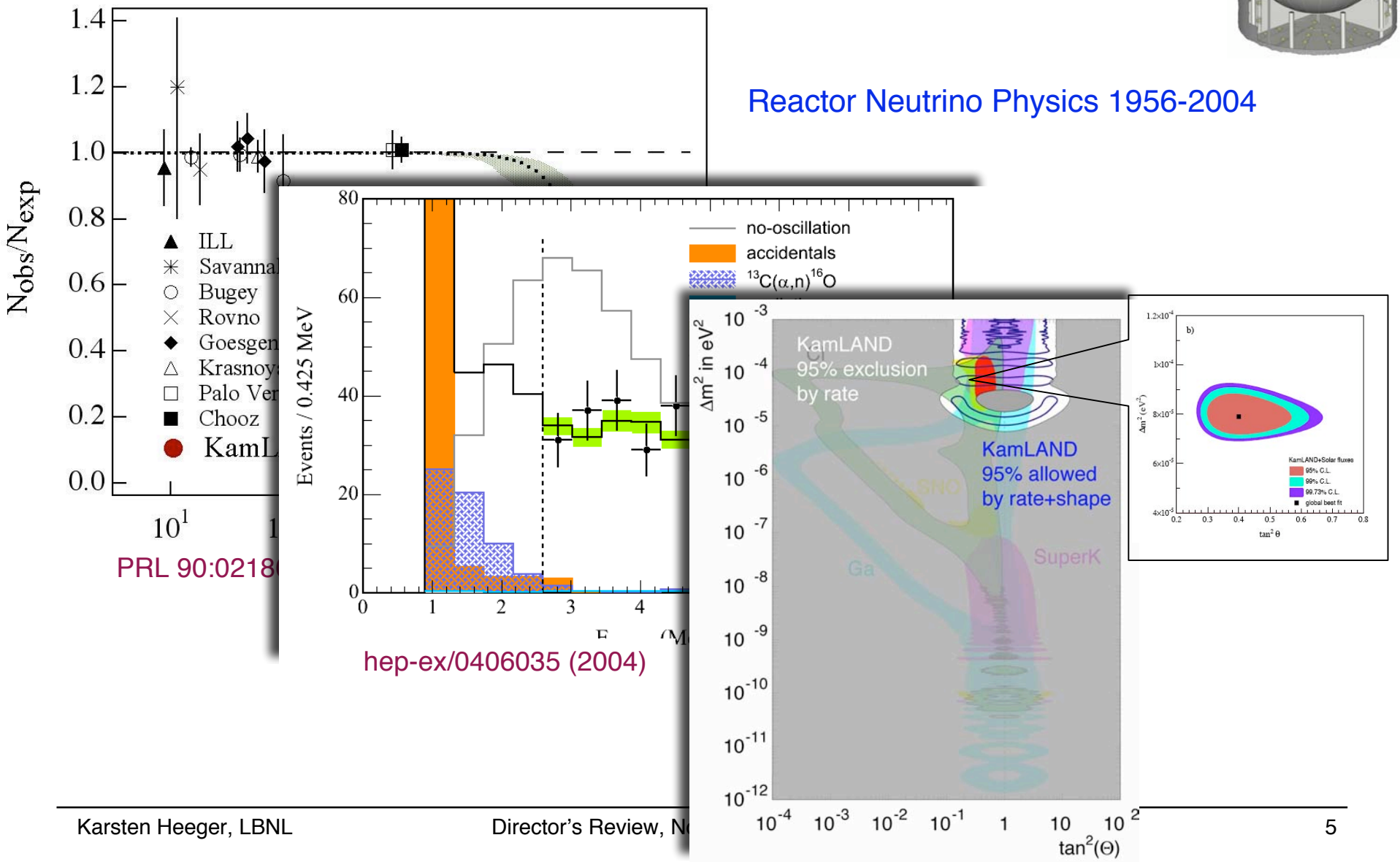
$\overline{\nu}_e + p \rightarrow e^+ + n$



KamLAND in 2003/2004: Direct Evidence for Reactor $\overline{\nu}_e$ Oscillation



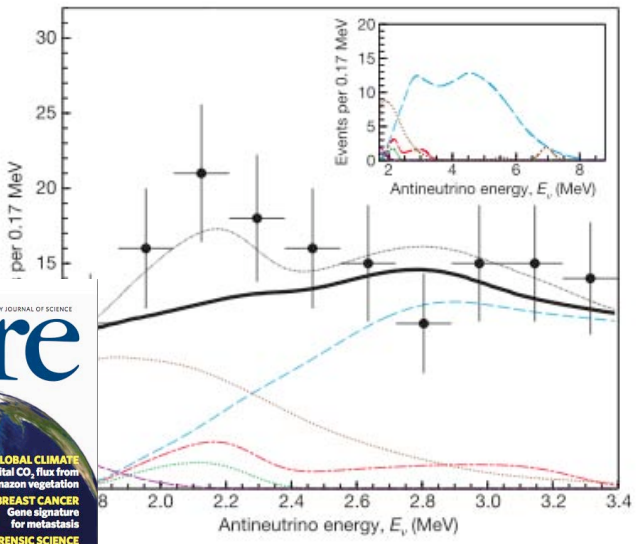
Reactor Neutrino Physics 1956-2004



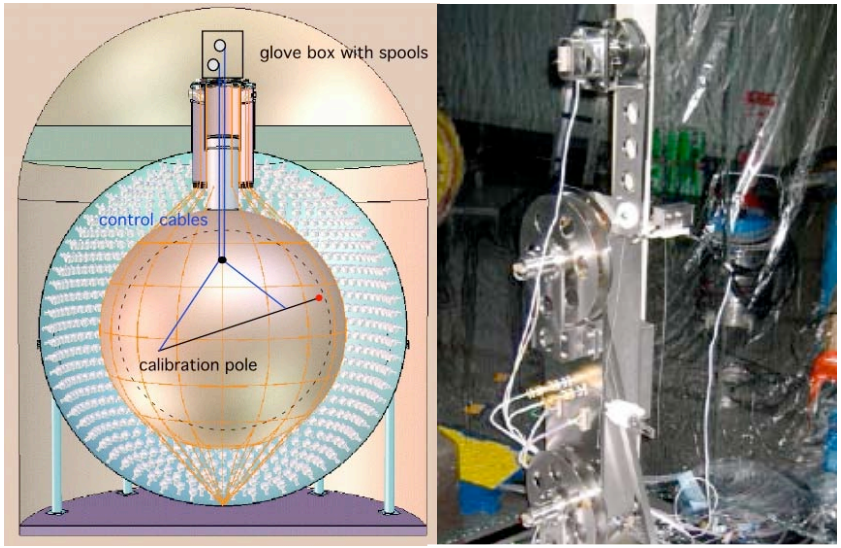
KamLAND in 2005

Discoveries

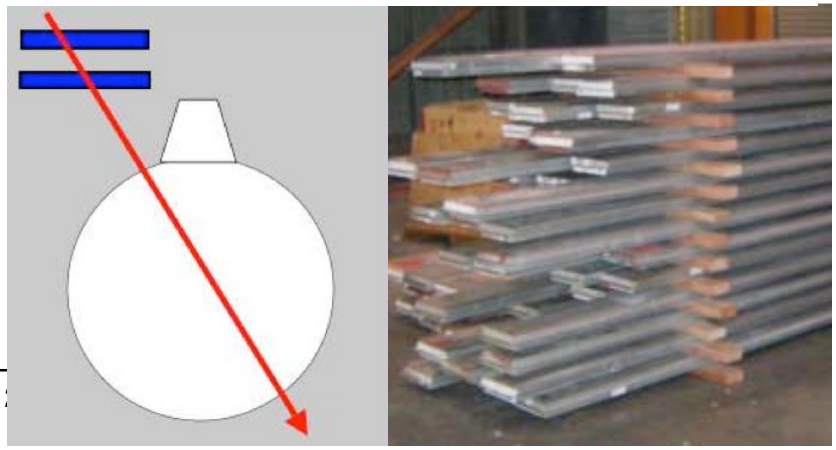
2003 Observation of $\overline{\nu}_e$ disappearance
2004 Evidence for $\overline{\nu}_e$ oscillation
2005 First Observation of Geoneutrinos



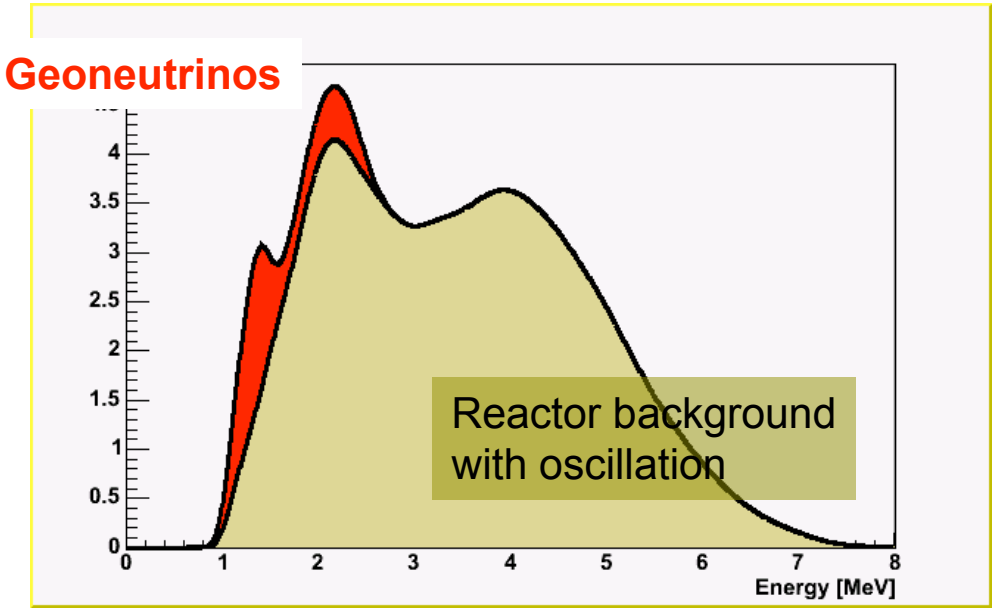
Completed Construction & Testing of 4π Calibration System

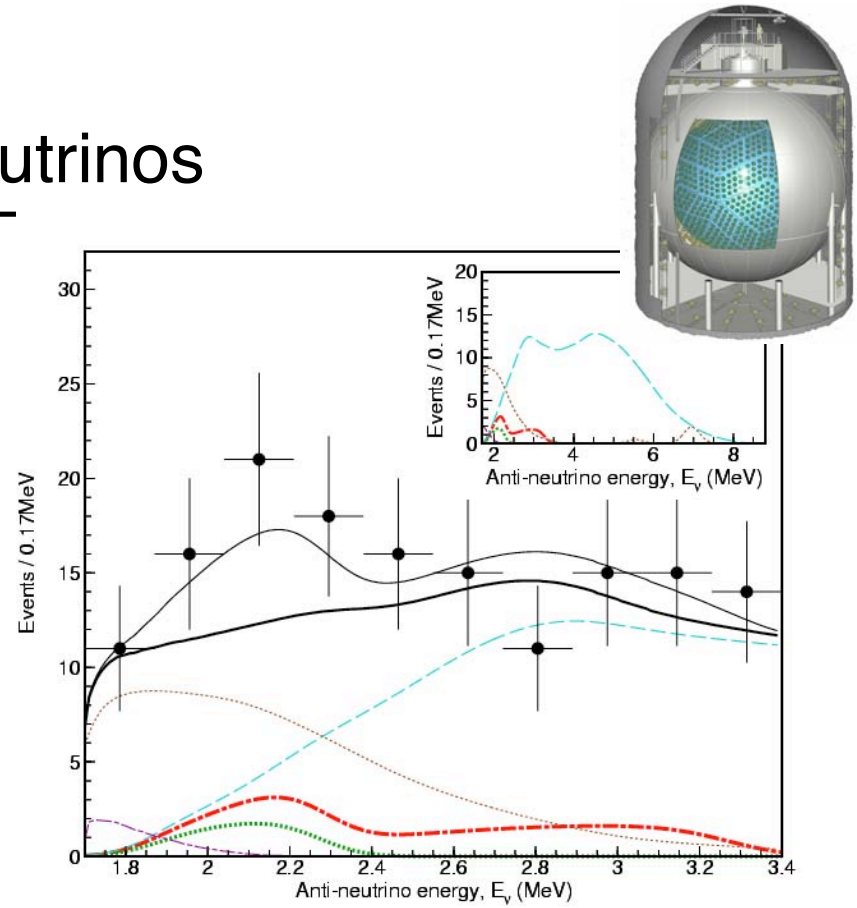


Muon Tracker Construction



KamLAND in 2005: First Observation of Geo-Antineutrinos





Nature 436, 499-503 (28 July 2005)

First experimental investigation of geoneutrinos.

Observed 4.5 to 54.2 geoneutrinos with 90% C.L.

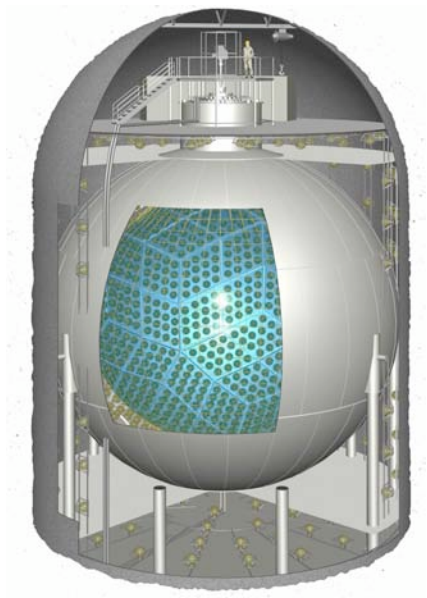
99% upper limit on geoneutrino rate corresponds to radiogenic power from and Th decays of less than 60TW.

Measurement is consistent with the current geological models.

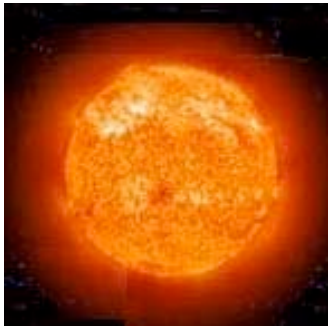
KamLAND Neutrino Program

Reactor Anti-Neutrinos

PRL 90:021802 (2003)
hep-ex/0406035 (2004)

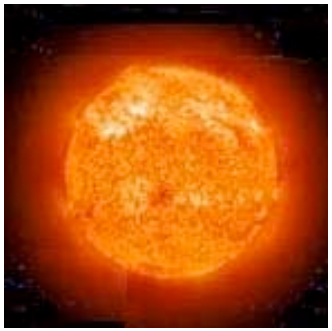


Solar ^{7}Be Neutrinos



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

Anti-Neutrinos from the Sun



Phys.Rev.Lett.92:071301,2004

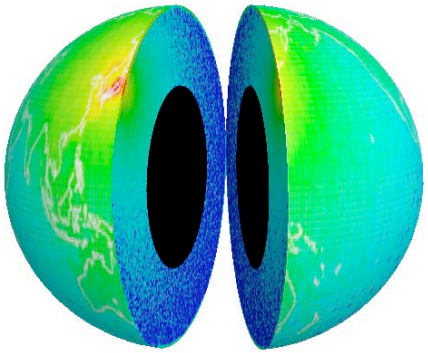
$\Phi_{\nu e} = < 3.7 \times 10^2\ cm^{-2}\ s^{-1}$

improvement by factor x30

Ongoing Physics Studies

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

Terrestrial Antineutrinos



Nature 436, 499-503 (28 July 2005)

KamLAND Collaboration

California Institute of Technology	**Kansas State University**	**University of Alabama**	**Tohoku University**
Drexel University	**LBNL/UC Berkeley**	**University of Hawaii**	**TUNL**
IHEP, Beijing	**Louisiana State University**	**University of New Mexico**	
KEK	**Stanford University**	**University of Tennessee**	

Berkeley KamLAND Group

LBNL Physics | LBNL Nuclear Science | UC Berkeley

LBNL Physics Division
Kam-Biu Luk * (Faculty Senior Scientist)
Hitoshi Murayama (Faculty Senior Scientist)
Herbert Steiner (Faculty Senior Scientist)
Richard Kadel * (Senior Staff Scientist)

Karsten Heeger * (Chamberlain Fellow/Staff)
Christian Lendvai * (Postdoc)

UCB Physics

Mark Reddick (undergraduate)
Albert Rai (undegraduate student)

also involved in θ_{13} effort

LBNL Nuclear Science
Stuart Freedman * (PI)
Brian Fujkawa * (Staff Scientist)

Fred Bieser (Engineer)

Bruce Berger * (Postdoc)
Lauren Hsu * (Postdoc)

Dan Dwyer (UCB Graduate Student)
Tommy O'Donnel (UCB Graduate Student)
Lindley Winslow (UCB Graduate Student)
Dipanjan Ray (UCB Student)

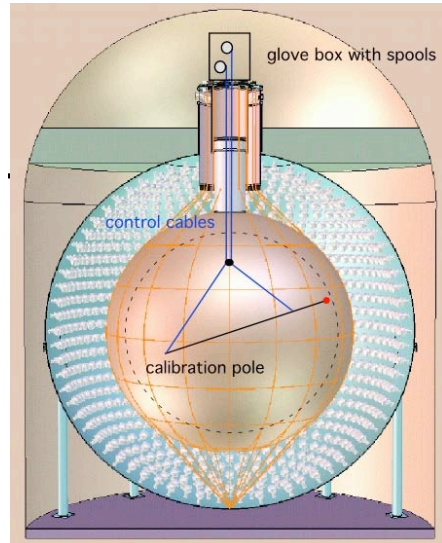
UCB Physics
Andrew Franck (Engineer)

Patrick Decowski * (Postdoc)
Fred Gray * (Postdoc)

LBNL Physics Division Contributions to KamLAND

4π Calibrations

- Co-leaders of calibration group.
- Developed 4π calibration system, last major hardware upgrade during reactor phase.

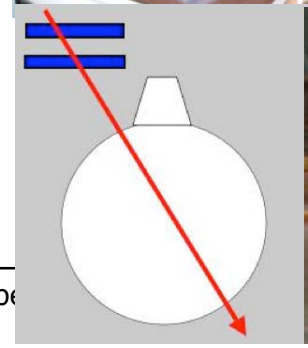


Ultra-Low-background Counting

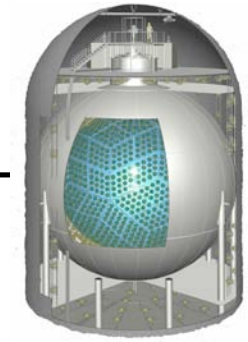
- Responsible for low-background counting facility and radiopurity measurements.
- Screening of calibration systems.

Muon Tracker

- Designed muon tracking system. Under construction.



KamLAND - Systematic Uncertainties



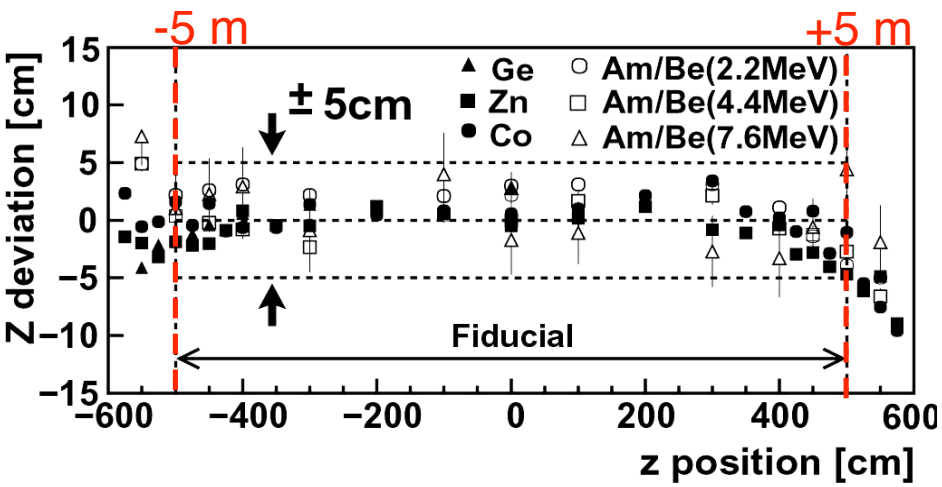
E > 2.6 MeV

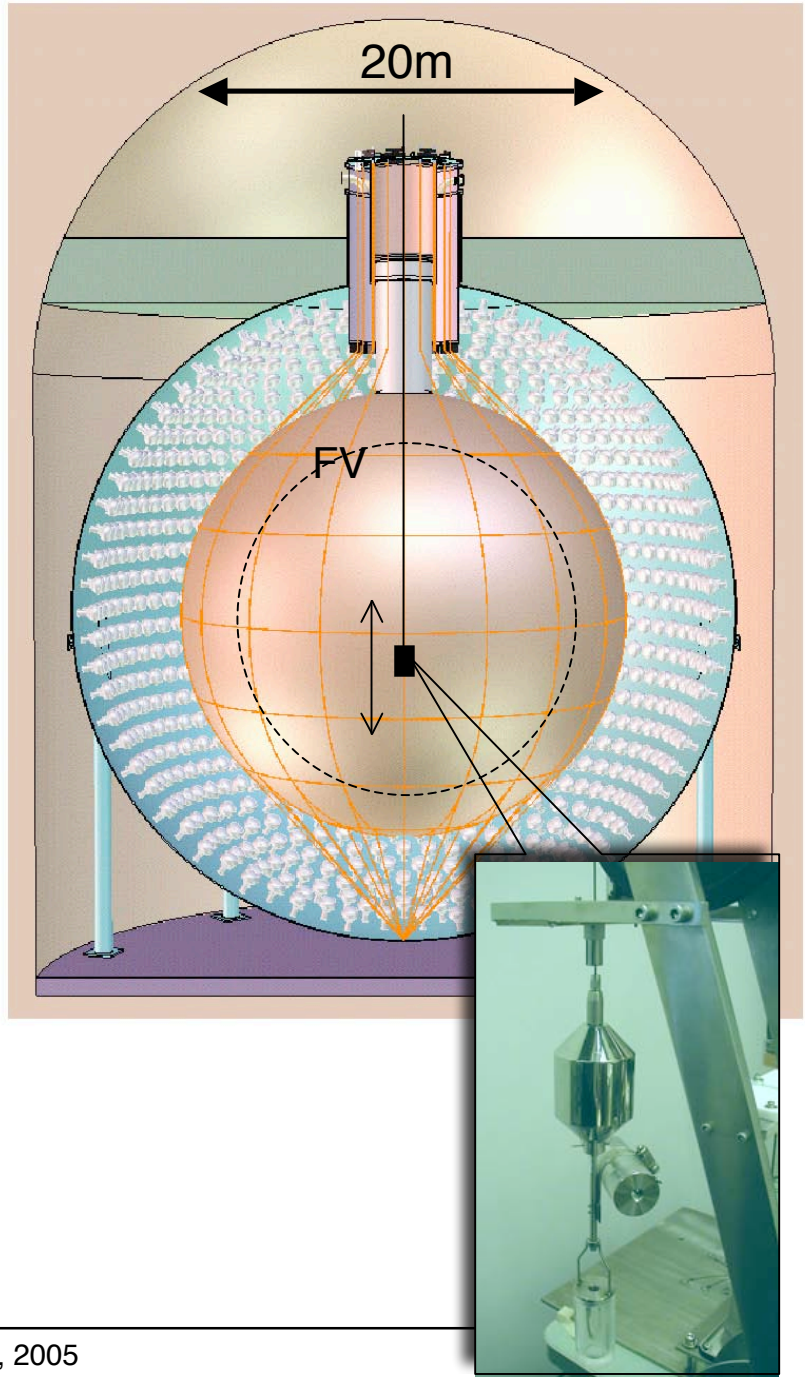
	%	
Fiducial volume	4.1	volume calibration
Energy threshold	2.3	energy calibration or analysis w/out threshold
Cut efficiency	1.6	
Live time	0.06	
Reactor power	2.1	*given by reactor company, difficult to improve on*
Fuel composition	1.0	
$\bar{\nu}_e$ spectra	2.5	
cross section	0.2	*theoretical, model-dependent*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

KamLAND z-axis Calibration

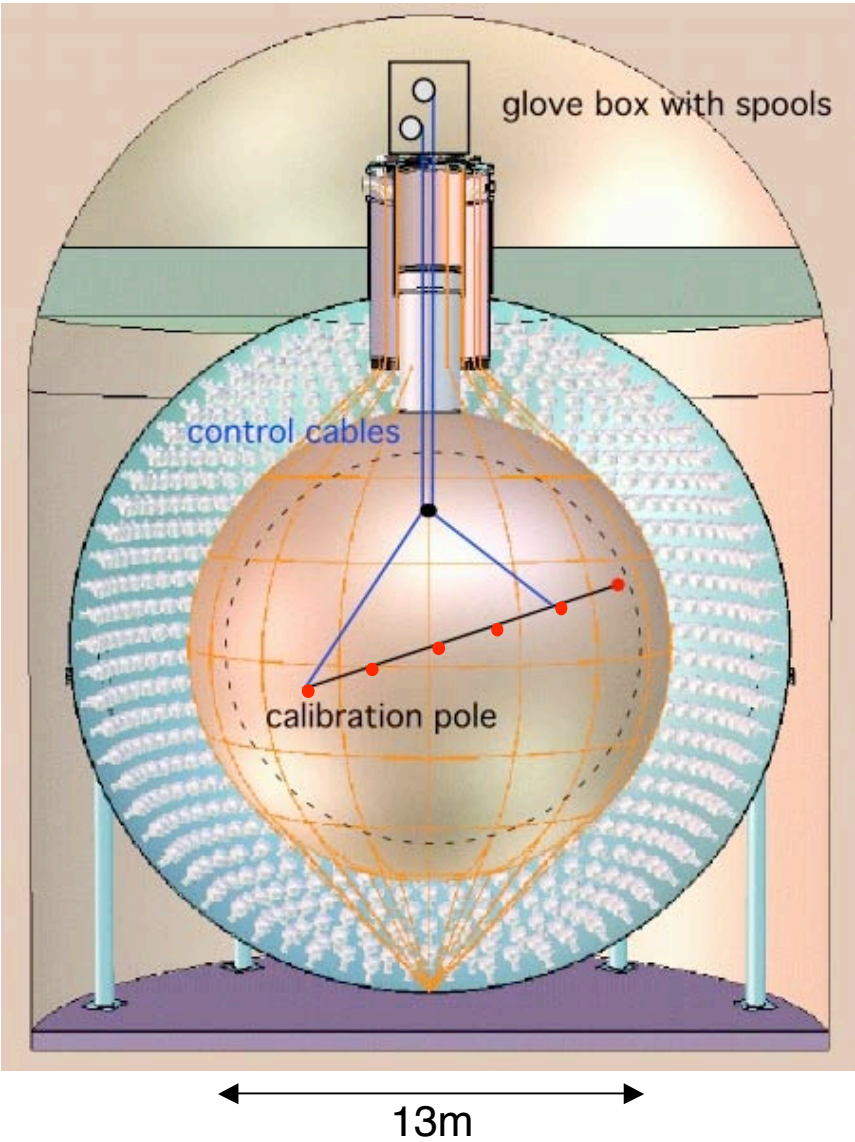
Routine Calibration Sources

^{68}Ge	e^+	2 x 0.511 MeV
^{65}Zn	γ	1.116 MeV
^{60}Co	γ	2.506 MeV
AmBe	γ, n	2.22, 4.44, and 7.65 MeV
Laser and LEDs		





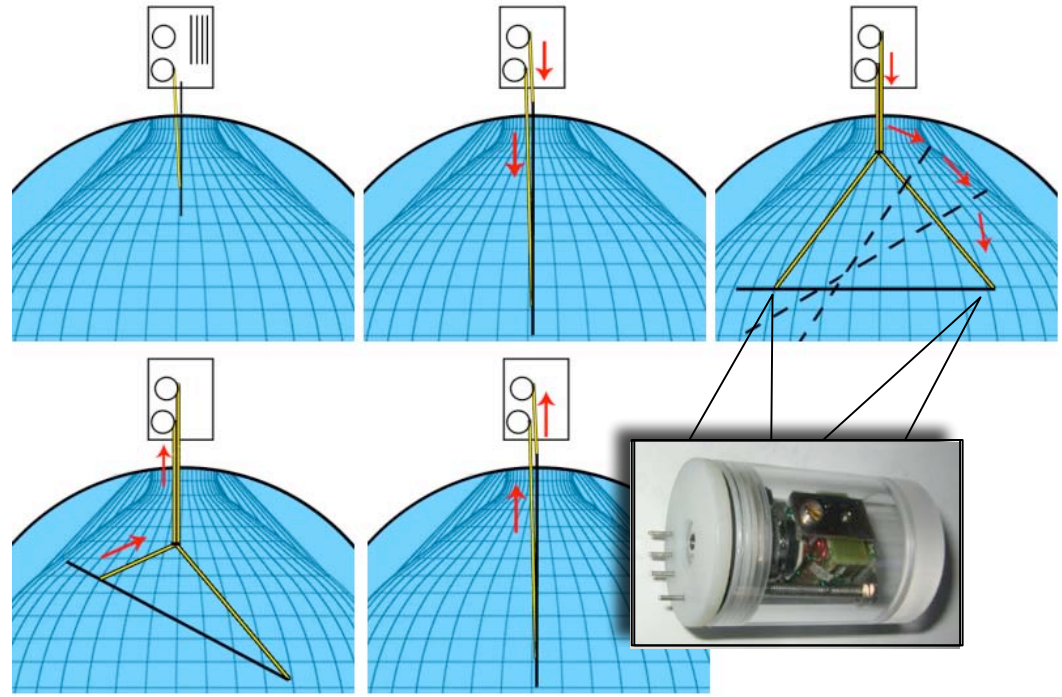
KamLAND 4π Calibration



Understanding the Detector Response

Event energy $E(r,\theta,\phi)$

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



Source Positioning Requirements

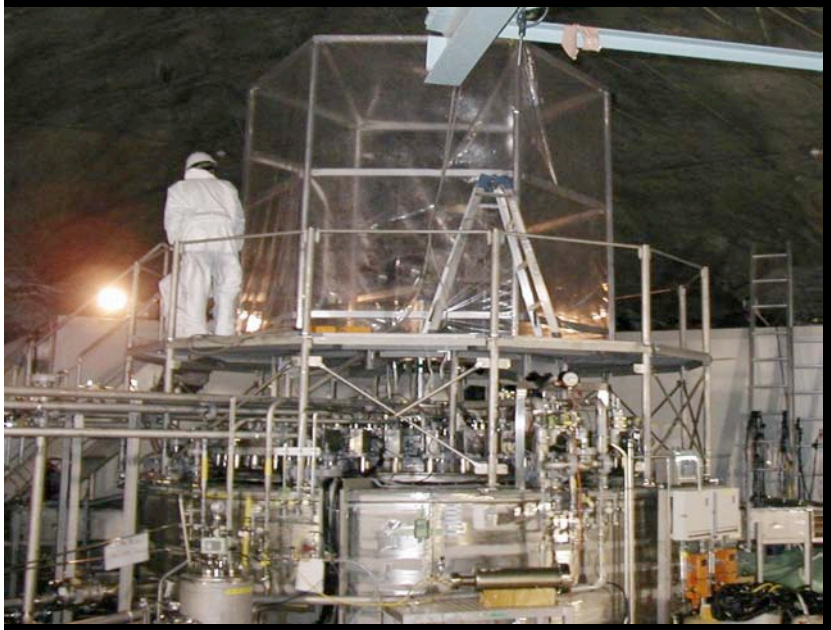
Fiducial volume: $R < 5.5$ m

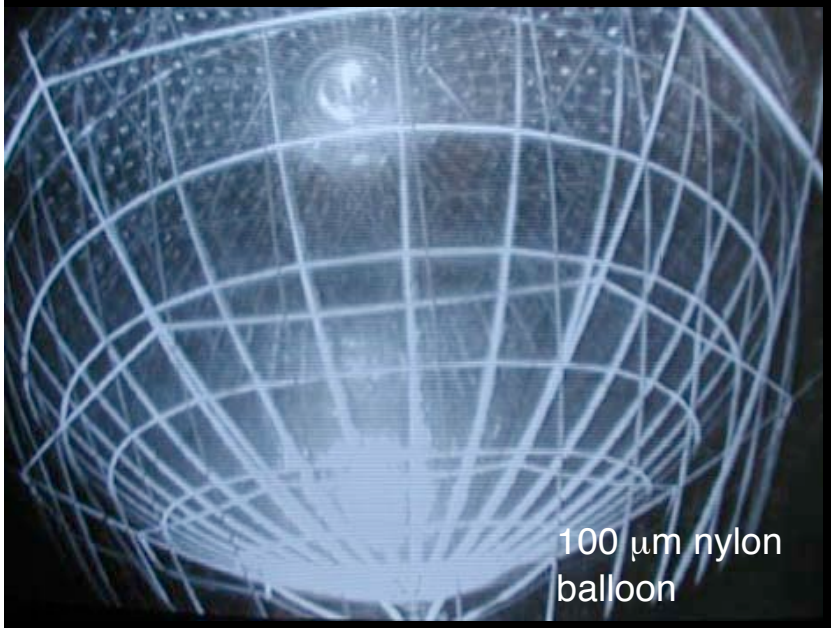
$\Delta R_{FV} = 5$ cm $\rightarrow \Delta V = 2.7\%$

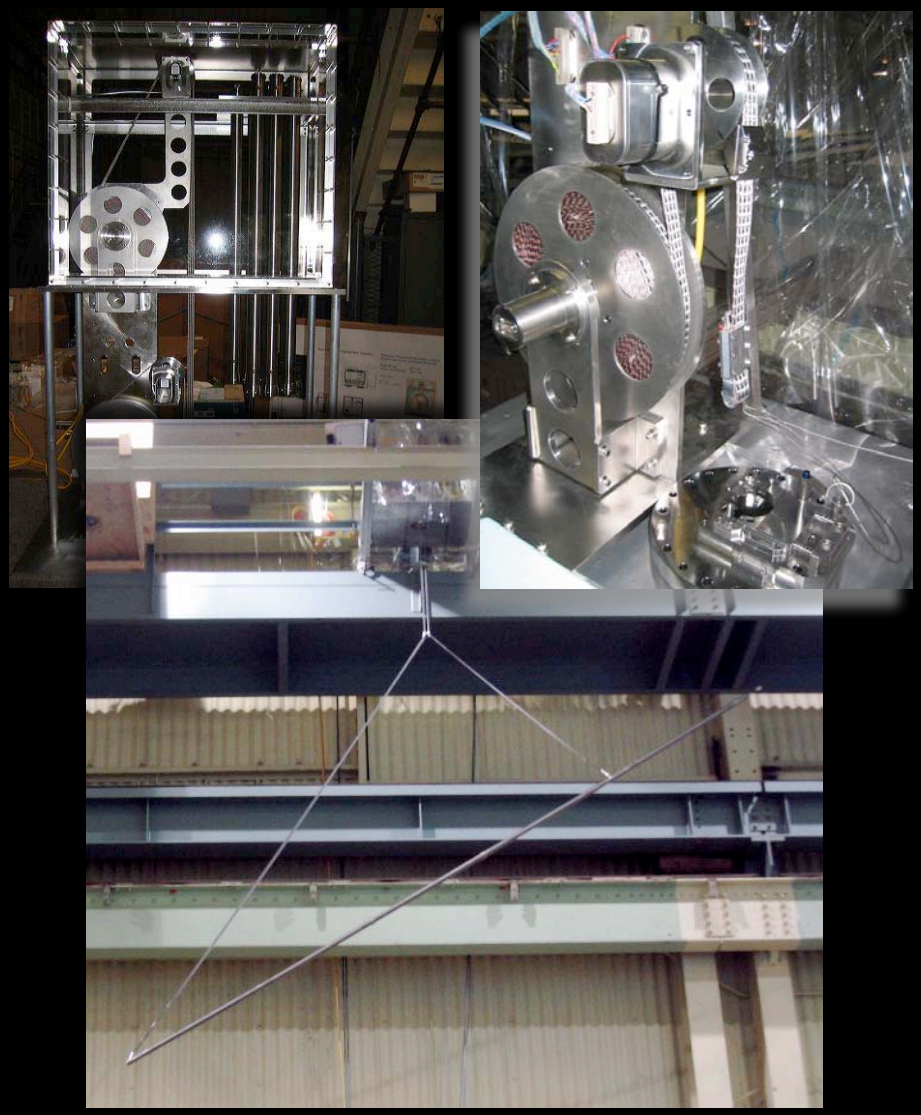
$\Delta R_{FV} = 2$ cm $\rightarrow \Delta V = 1.1\%$

→ Redundant instrumentation

KamLAND 4π Calibration System

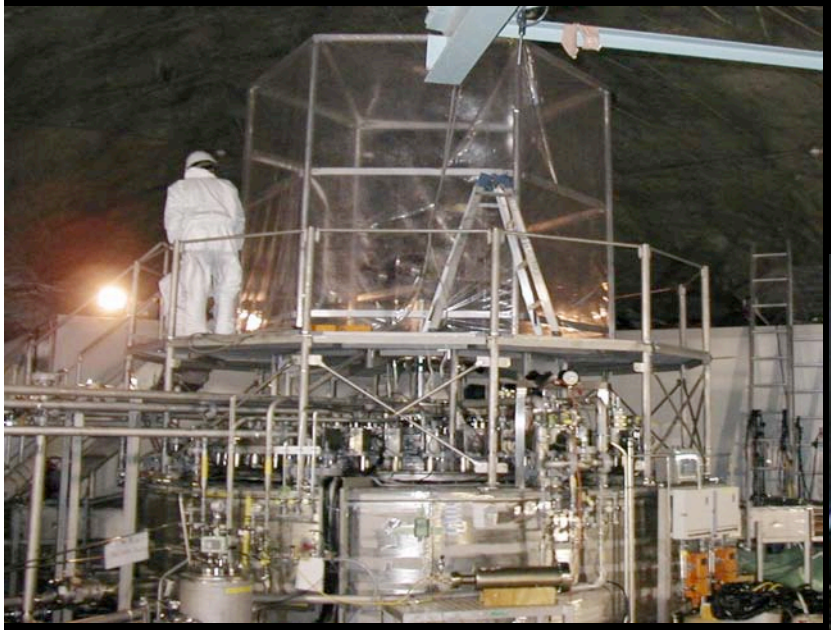


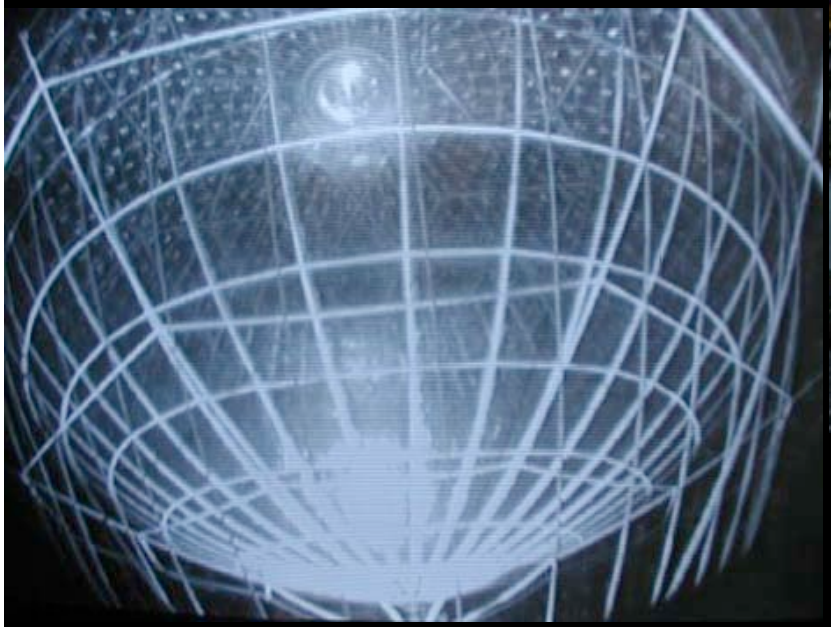




Construction and testing complete.
Installation in late 2005.

Positioning Calibration Sources with the 4π System



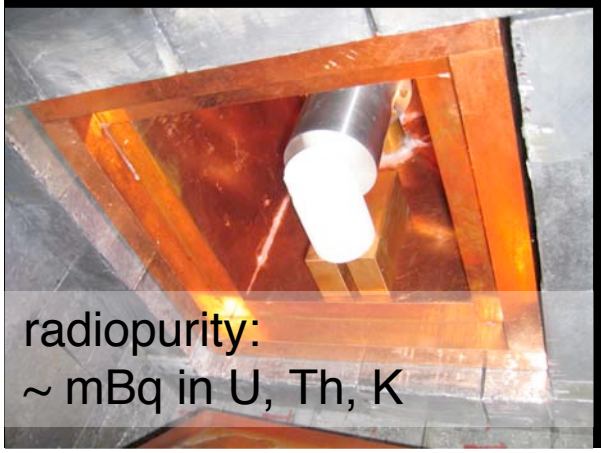


4π Cleaning and Assembly at LBNL

Extensive use of LBNL cleaning shop and clean room facilities.

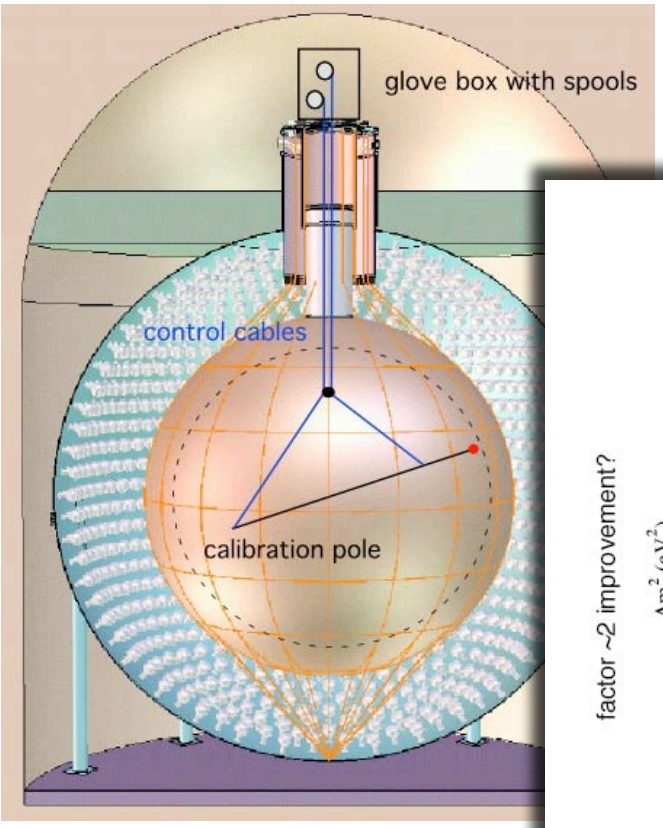
On-Site Preparations

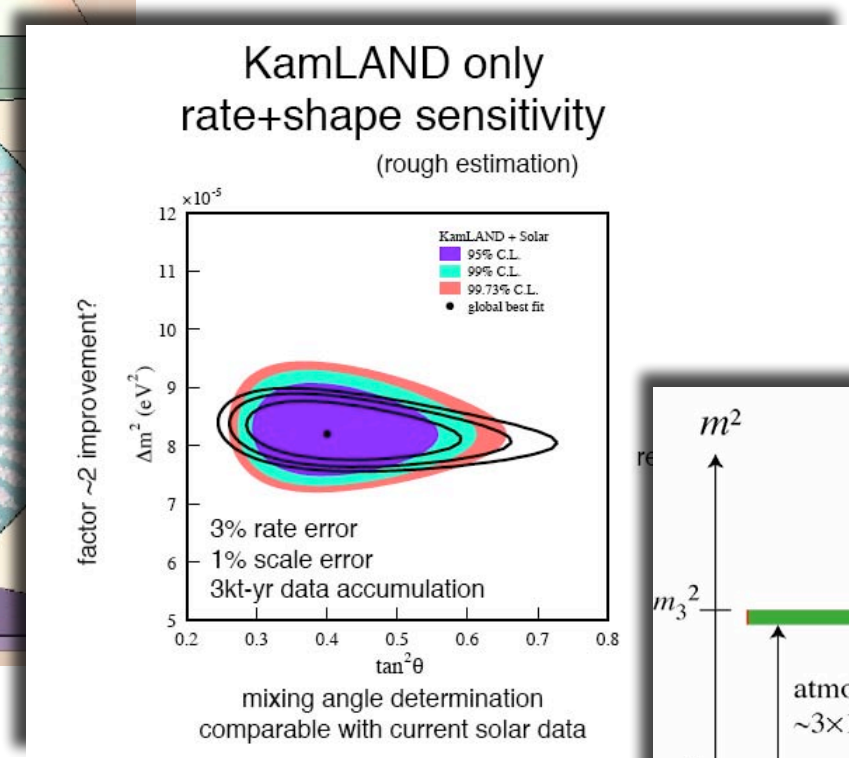
September 2005 - Present

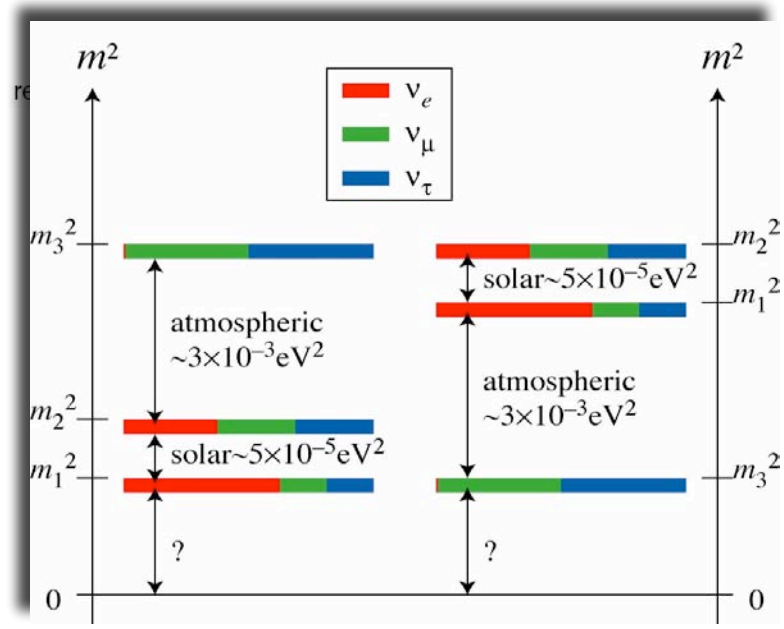


radiopurity:
~ mBq in U, Th, K

Precision Measurement of Oscillation Parameters

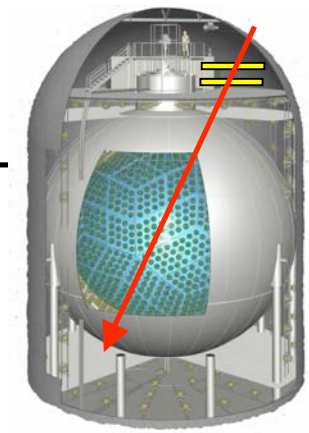




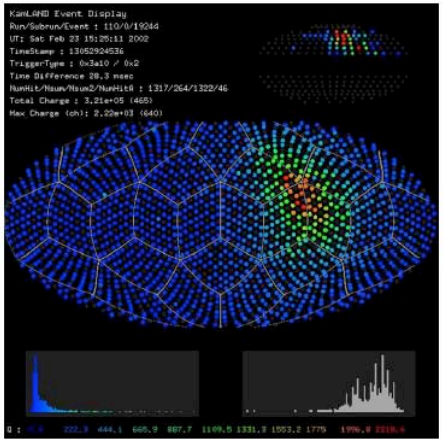


Reduce dominant systematics 6.5→3-4%
Improve sensitivity to Δm^2_{12} and θ_{12}

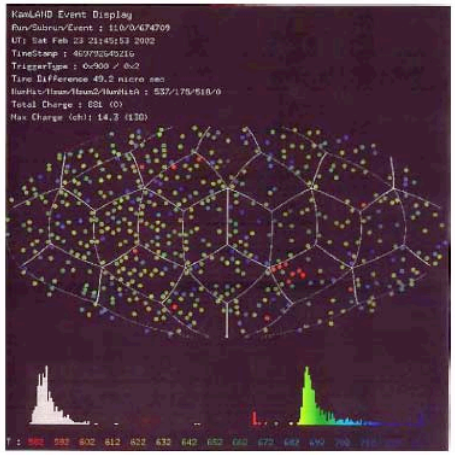
Muon Studies in KamLAND



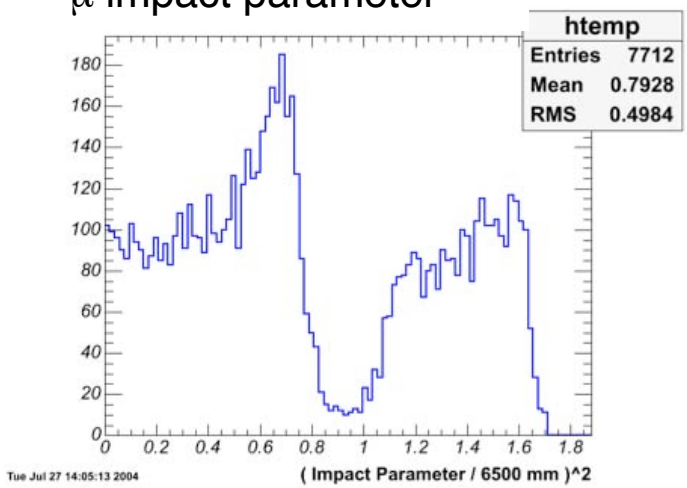
Muon Event - 1V



Neutron Event - 1mV



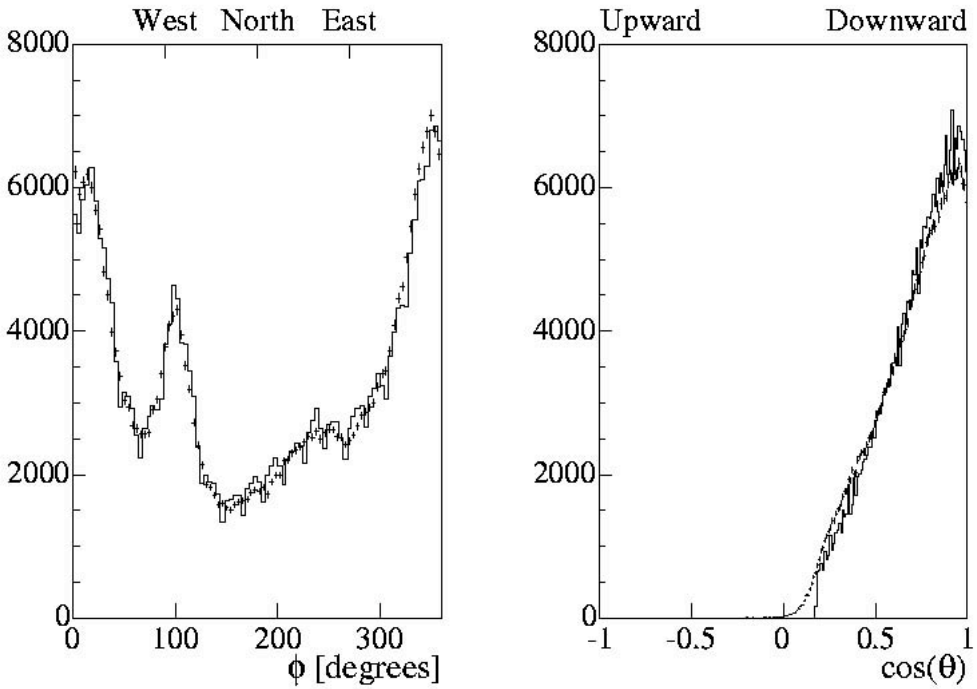
μ impact parameter

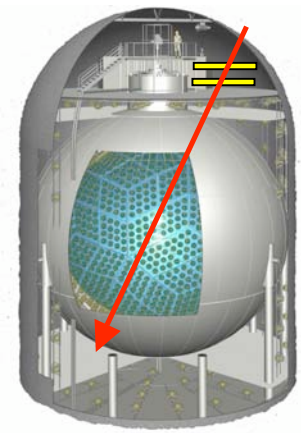


Open Questions

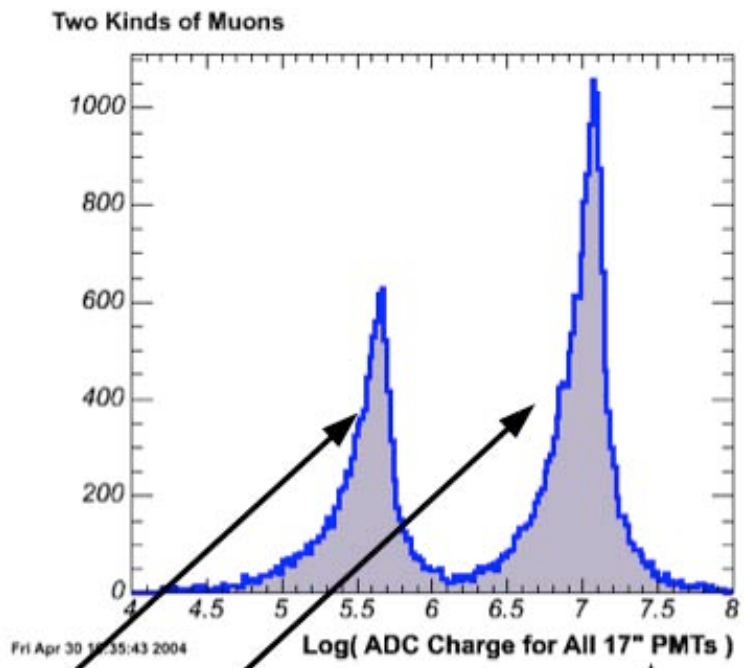
- How well are we reconstructing muons?
- Do we ever miss muons?
- What is the nature of showering muons?
- What does a muon that clips the ID reconstruct as?
- Can we verify the ID and OD muon efficiencies?
- Study muon related spallation backgrounds.

Muons at KamLAND





μ rate= 0.33 Hz
E~ 100 GeV



~ 320 muons per day in tracker
~130 in coincidence with inner detector
7.5-10 cm positioning accuracy

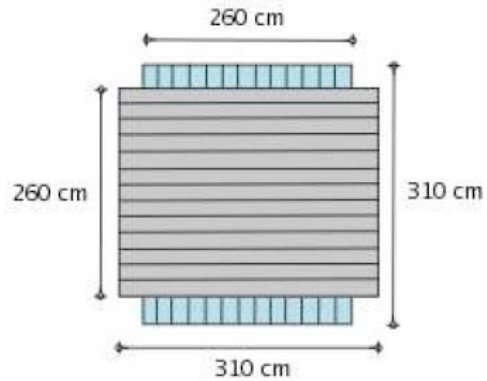
For physics analyses with E>2.6 MeV largest background from spallation products (→ showering μ)

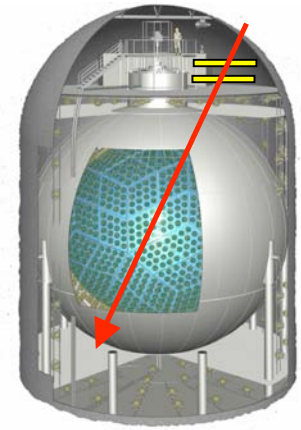
oil muons

liquid scintillator muons

"showering" muons

KamLAND Muon Tracker Construction





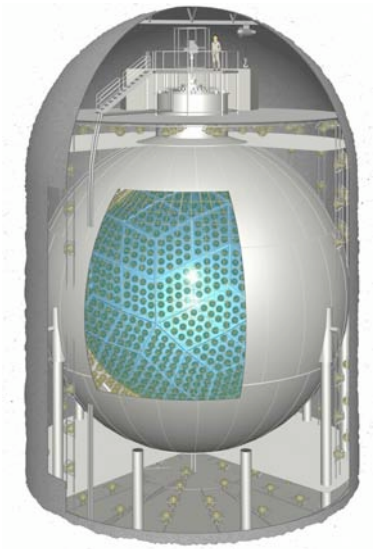
Student-Driven Project

Lindley Winslow, (lead) graduate student
Tommy O'Donnell, graduate student
Albert Lai, undergraduate
Mark Reddick, undergraduate

Activities

Construction of frame
Electronics assembly and testing
System integration
Installation on-site

Beyond KamLAND …



Understanding Neutrino Oscillation and Properties

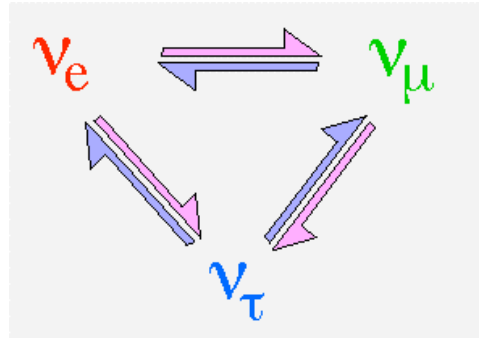
mixing parameters
mass + hierarchy
~~CP~~

Understanding Neutrinos in the Universe

mass
leptogenesis

Neutrino Mixing

U_{MNSP} Matrix



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

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

?

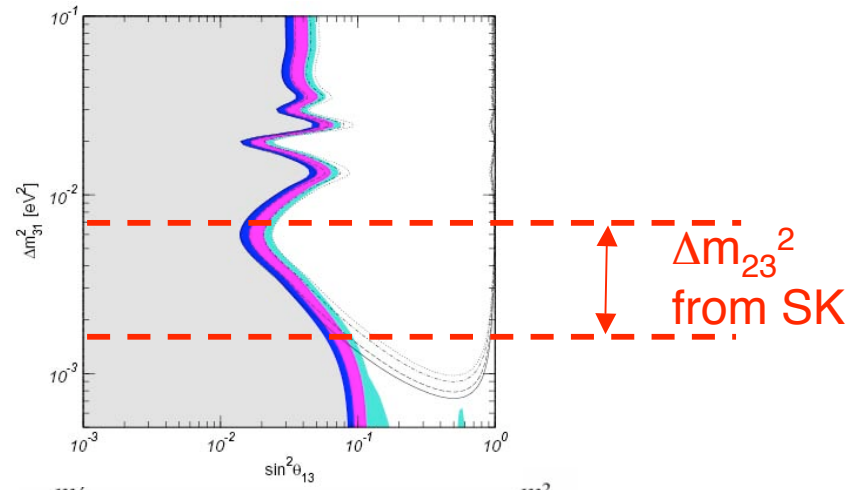
$\theta_{23} = \sim 45°$ $\qquad$ $\theta_{13} = ?$ $\qquad$ $\theta_{12} \sim 32°$

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

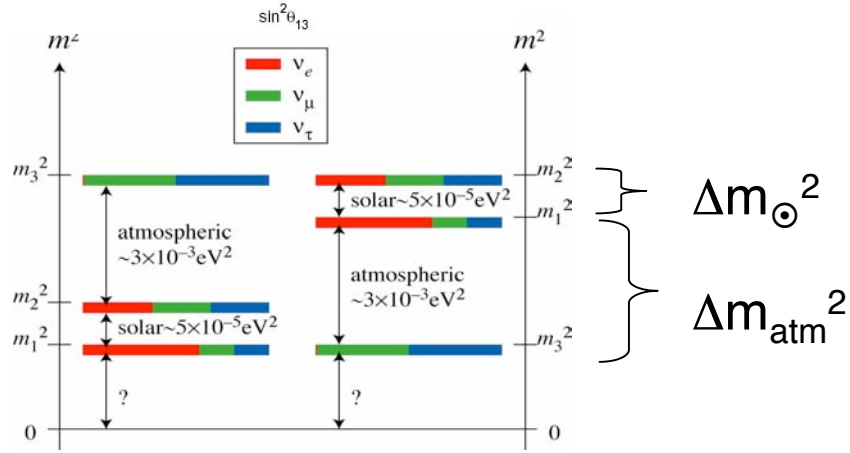
θ_{13} yet to be measured
determines accessibility to CP phase

Key Questions in Oscillation Physics

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



sign of Δm_{13}^2
mass hierarchy



δ_{CP}

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

Measurement of θ_{13} with Reactor Neutrinos

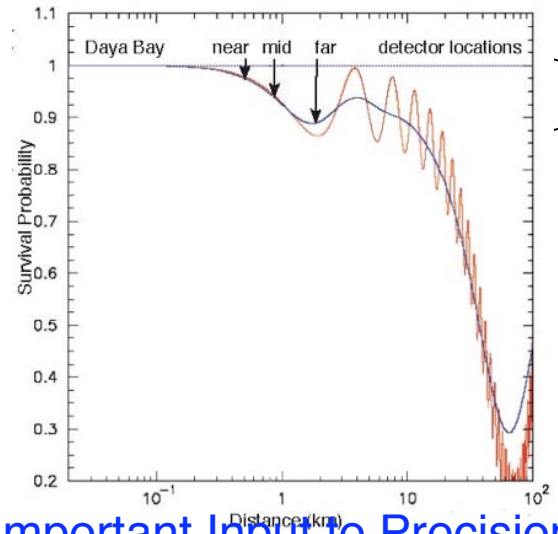
Precision Measurement of U_{e3}

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

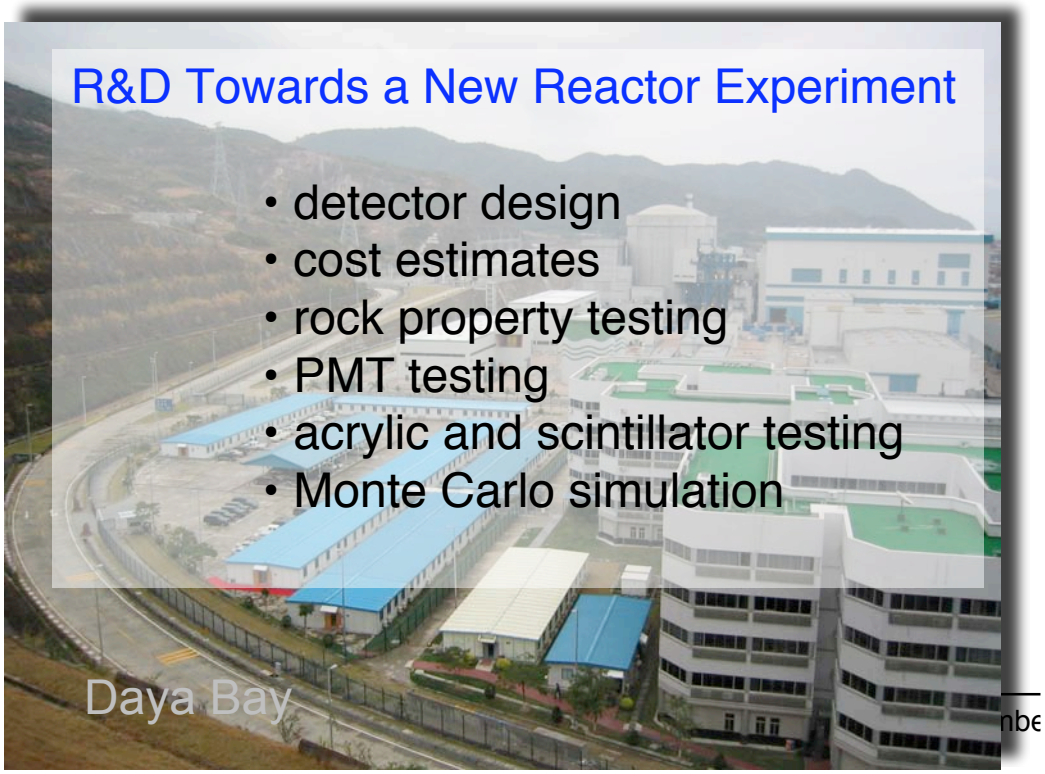
Neutrinos

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

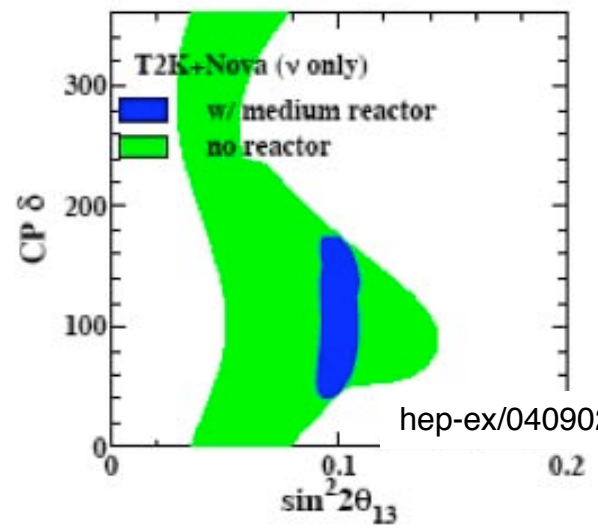
Projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01$



$\}\ \theta_{13}$



Important Input to Precision Oscillation Physics



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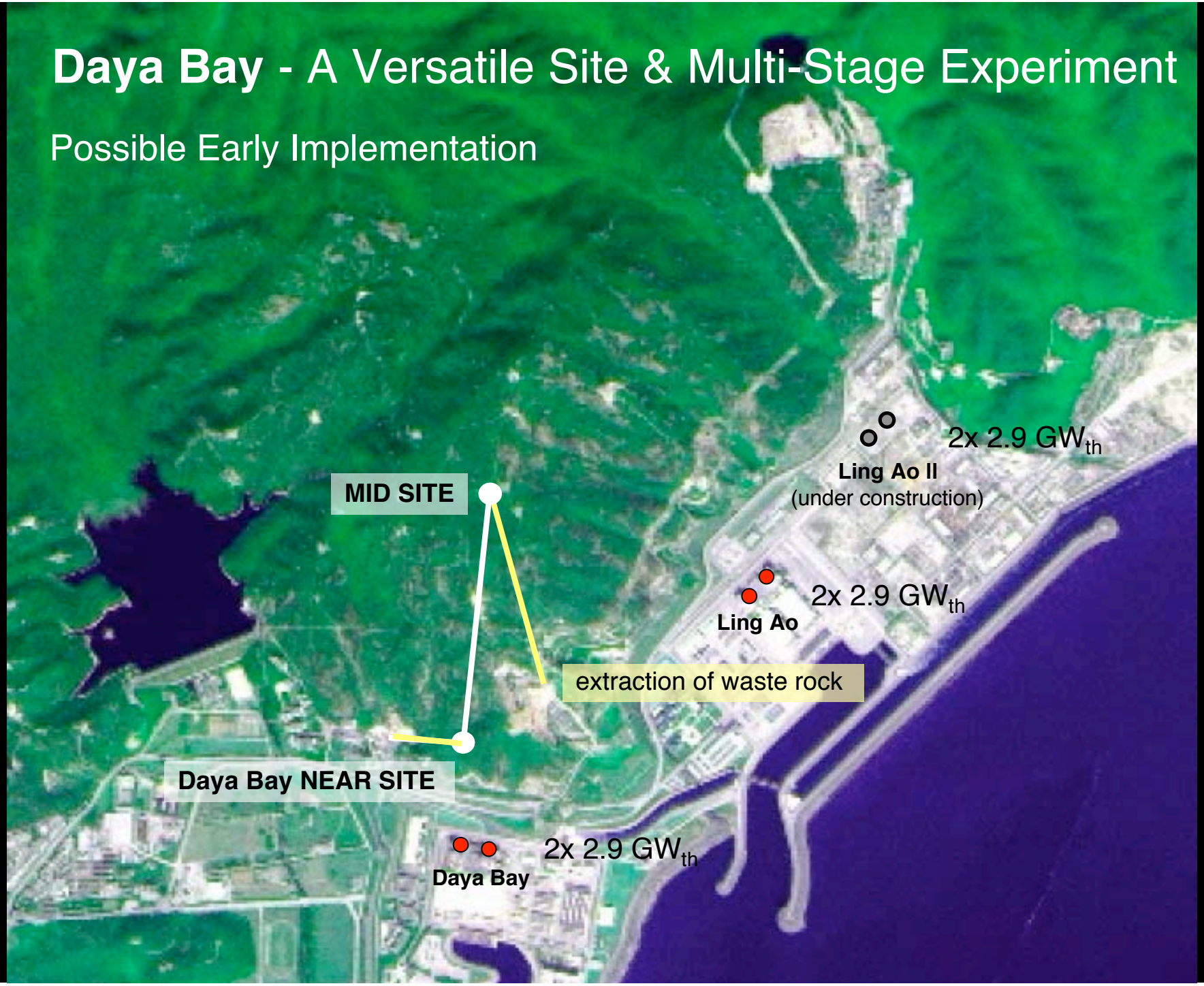
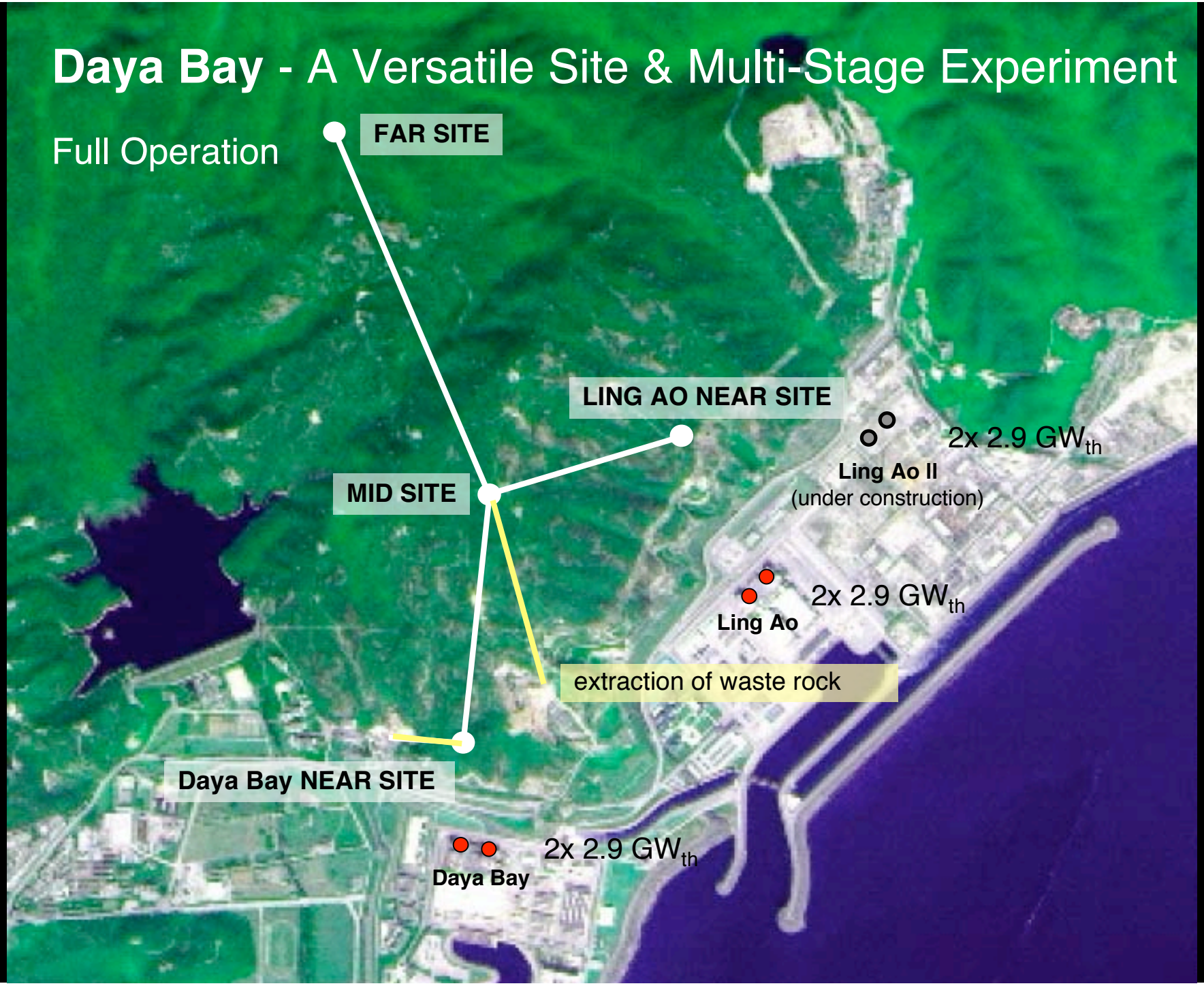
Daya Bay - A Versatile Site & Multi-Stage Experiment

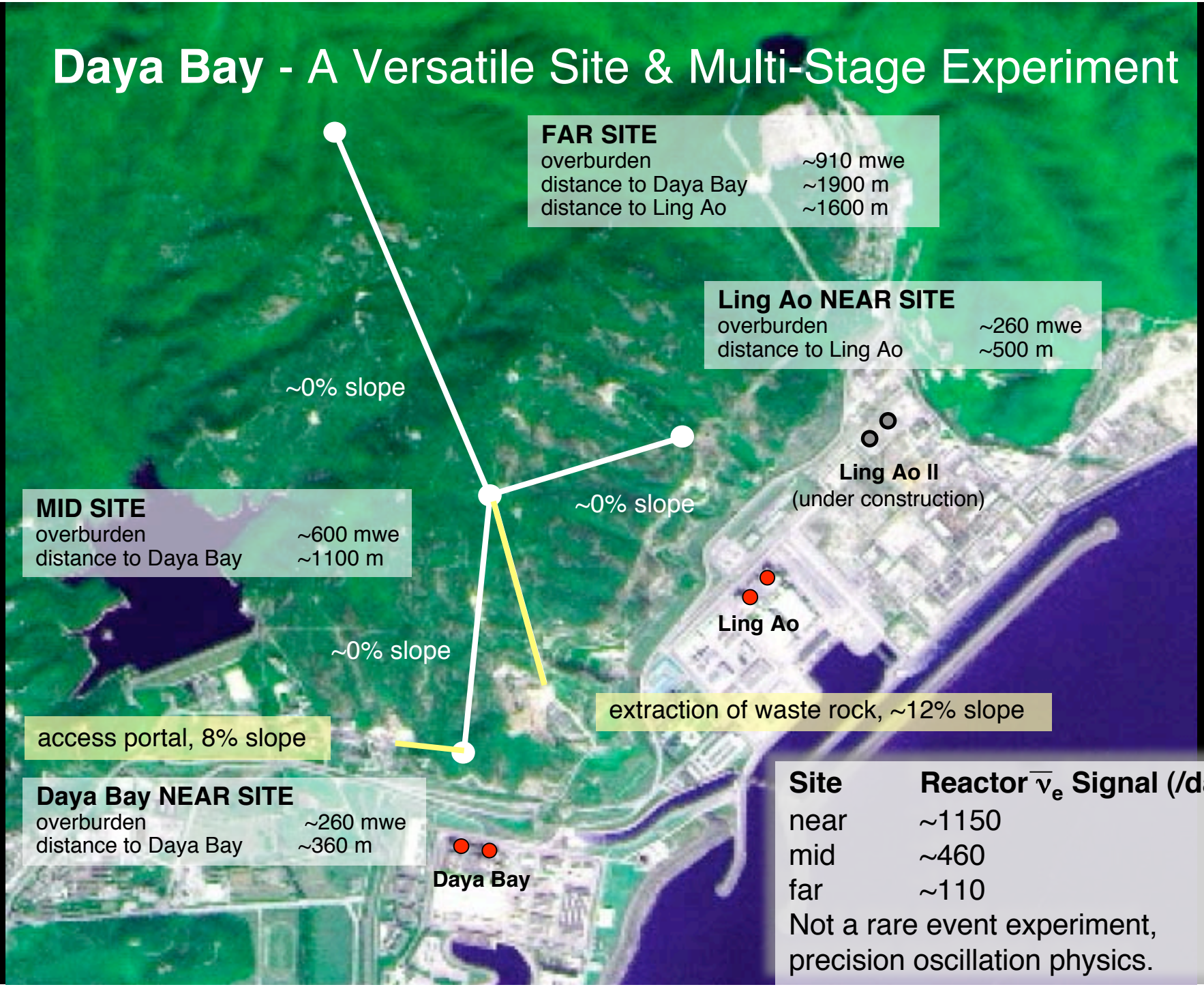
Possible Early Implementation



Daya Bay - A Versatile Site & Multi-Stage Experiment



Daya Bay - A Versatile Site & Multi-Stage Experiment



Site	Reactor $\bar{\nu}_e$ Signal (/day)
near	~1150
mid	~460
far	~110

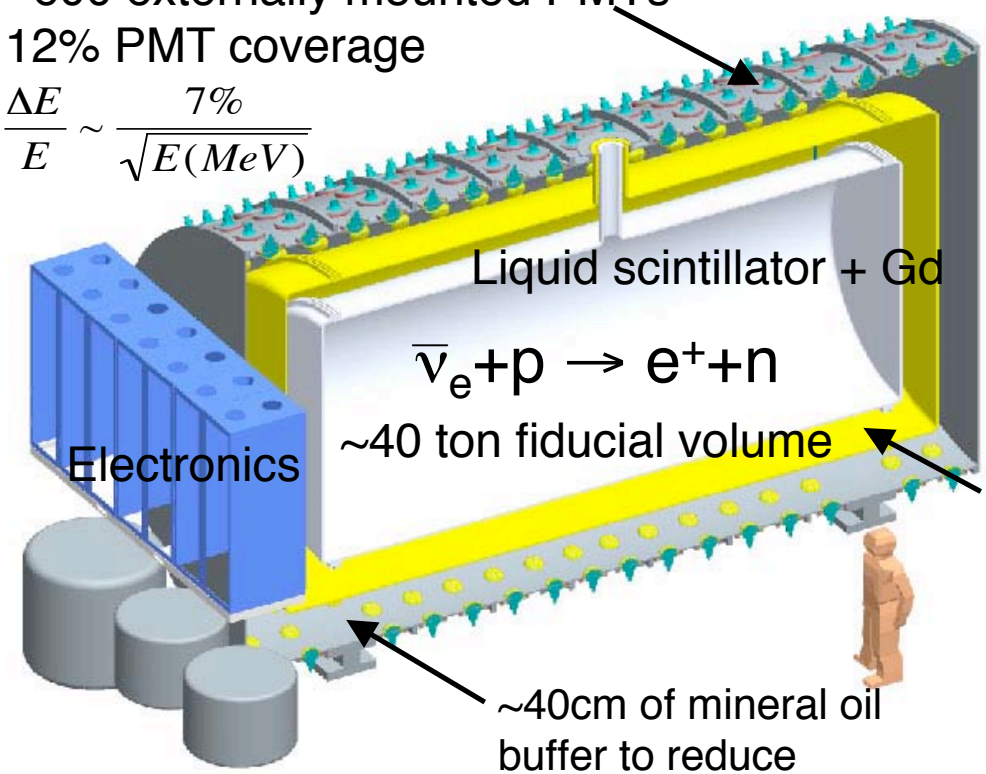
Not a rare event experiment, precision oscillation physics.

Design Studies of Detector Modules

Design & Engineering

~600 externally mounted PMTs
12% PMT coverage

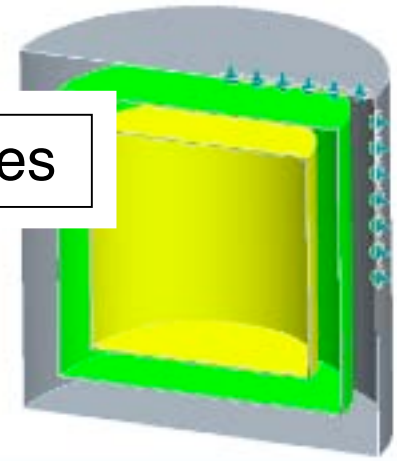
$$\frac{\Delta E}{E} \sim \frac{7\%}{\sqrt{E(MeV)}}$$



Liquid scintillator (gamma catcher)

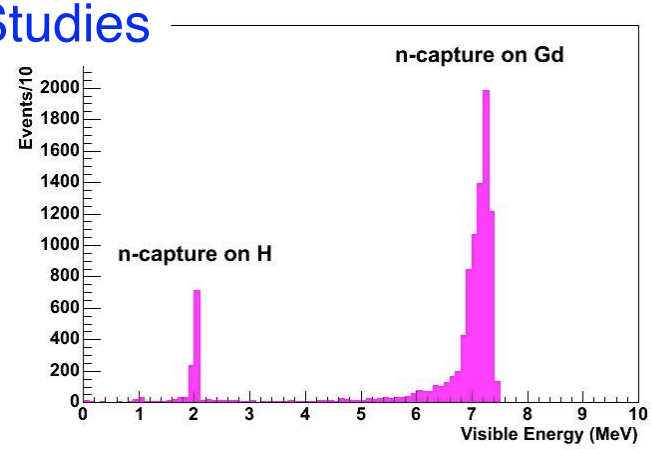
→ evaluating need for 2 or 3 zones

20-40t modules



- movable over a distance of ~2km

MC Studies



Measuring θ_{13} with Reactor Neutrinos

LDRD-Supported R&D Activities

Design&Engineering	• long term tests of acrylic and LS compatibility (soak test, tension, compression) • monochromator to test PC in vacuum • drawings and cost estimates for double acrylic vessels (incl. visit to ReynoldsPolymer in CO) • drawings and costs for SS tanks (Tarico in CA) • shielding and muon tracking design in progress
On-Site	• geophysical work (rock properties) etc. • visit to Daya Bay
R&D	• preparations for PMT selection: testing of PMT's
Equipment	• supplies scintillator panels, PMTs, etc. for muon veto for 1-ton prototype in Aberdeen tunnel in Hong Kong (K.-B. Luk, UCB)
Personnel	• hired postdoc

Awaiting report from NuSAG…

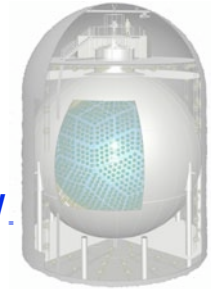
A Bright Future for Neutrino Physics

Oscillation Physics

Δm^2_{12} and θ_{12} with KamLAND

Measurement of geo-neutrinos.

Observe ^{7}Be ν, map out P_{ee} for solar ν, confirm MSW.



θ_{13} with reactor neutrinos

Resolving the mass hierarchy.

Search for CP violation in neutrinos.

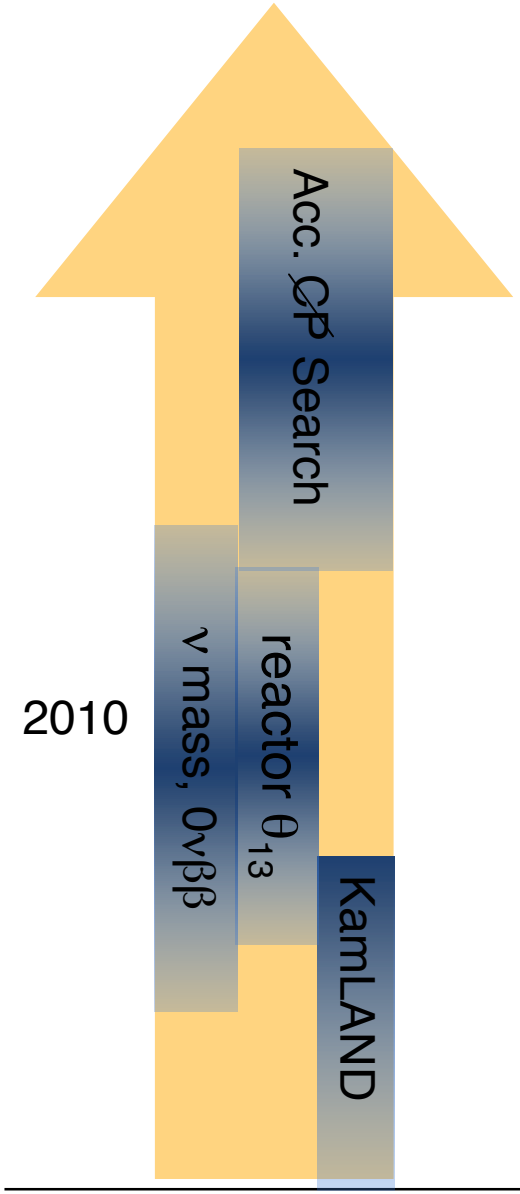
Particle Nature

Are ν's Dirac or Majorana particles?

What are the absolute masses?

Open for the Unexpected… Is U 3-dimensional? 4? 6? ∞? Are there sterile ν?

Opportunities: The Next Decade & Beyond



- Is there CP violation for neutrinos?

- Resolving the mass hierarchy.

- Probing the mass hierarchy.
- What are the absolute masses?
- Are ν's Dirac or Majorana particles?
- What is θ_{13}?

- Observe solar ^{7}Be ν, map out P_{ee} for solar ν,confirm MSW.
- Measurement of geo-neutrinos.
- Precision determination of Δm^2_{12} and θ_{12}.

we are here!

Remember: The neutrino revolution started only in 1998.