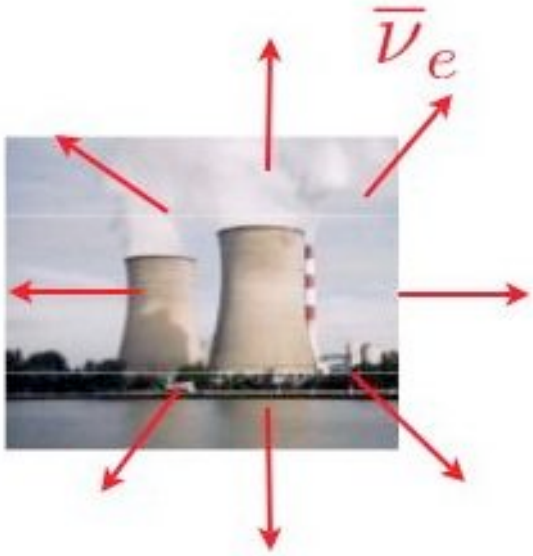
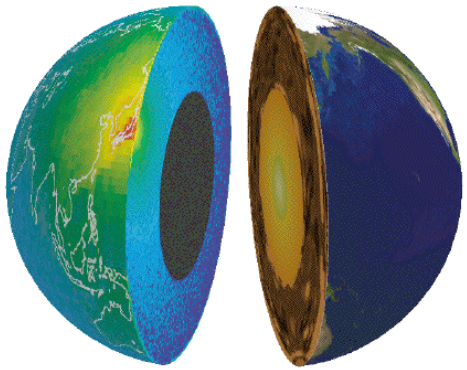
New Results From KamLAND

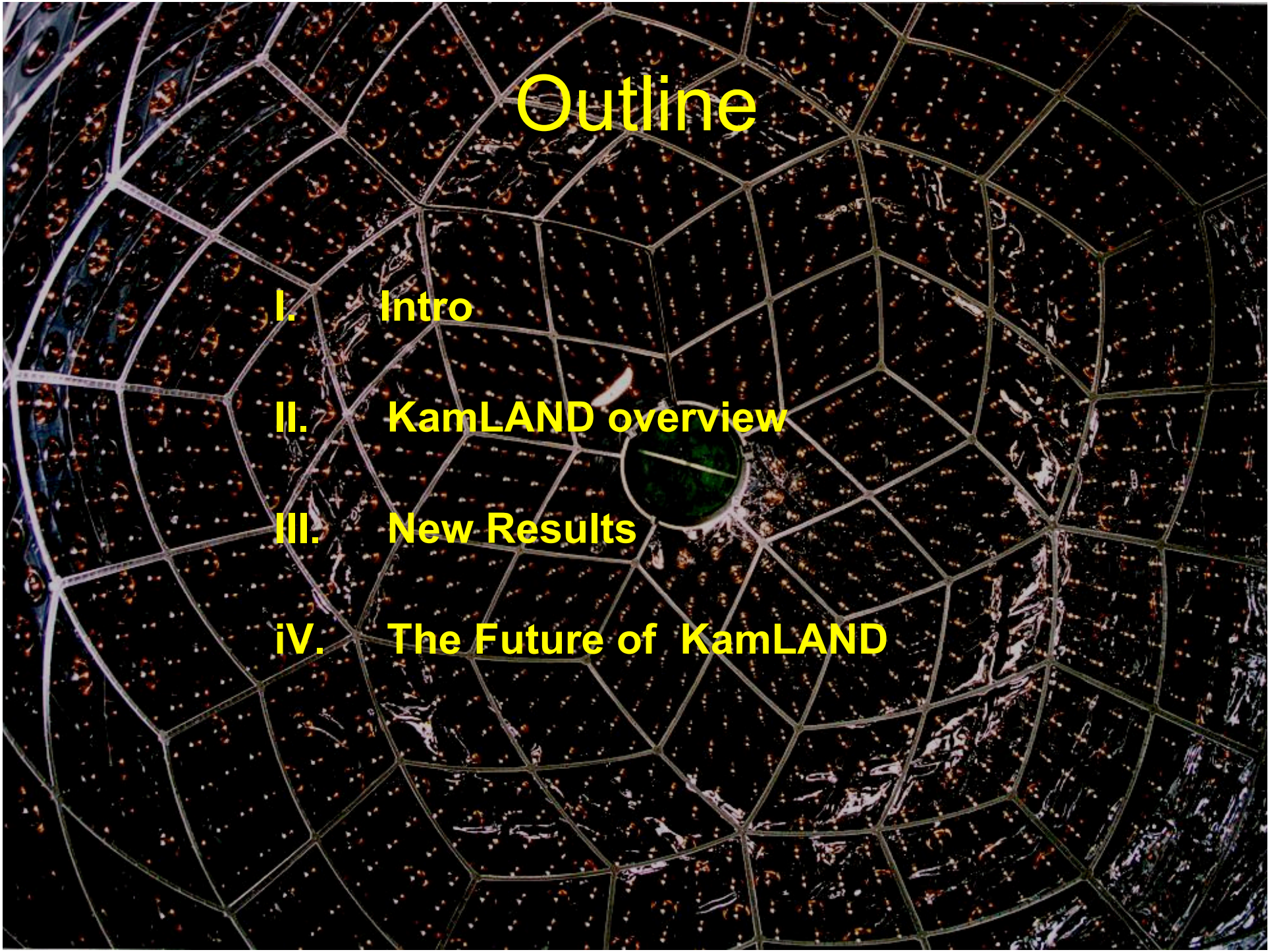


Fermilab
Wine & Cheese
Seminar

October 5, 2007



Lauren Hsu
Fermi National Accelerator Laboratory
(talk given as former member of the LBNL KamLAND group)



Outline

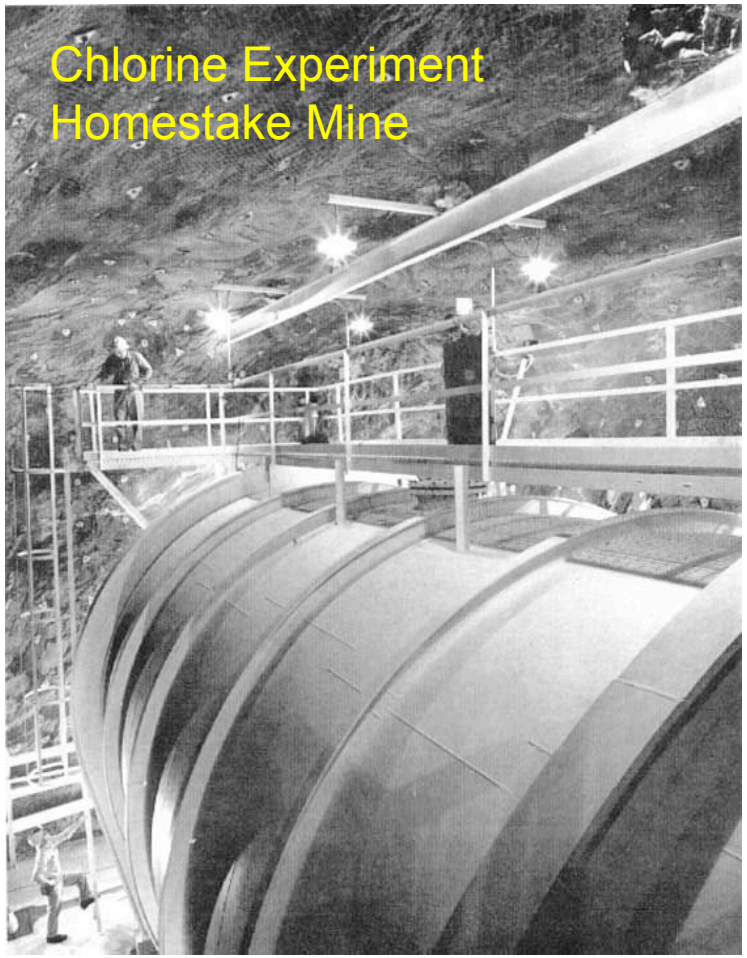
I. Intro

II. KamLAND overview

III. New Results

iV. The Future of KamLAND

The Solar Neutrino Problem



Pre-1950: p-p chain

$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$

1968: Ray Davis pioneers the radiochemical experiment, Chlorine, and observes 1/3 of predicted solar neutrino flux.

The idea of neutrino oscillations existed: Pontecorvo (1958), Maki, Nakagawa, and Sakata (1962), and Pontecorvo and Gribov (1969); but…

…difficulty of Chlorine experiment and uncertainties in solar model led to speculation that either one or both were wrong.

3 Decades of Mounting Evidence

1968 - on: Ray Davis refines his experiment and John Bahcall refines his theory, no errors found

1989: Kamiokande, real-time water Cherenkov detector, also observes deficit of solar neutrinos.

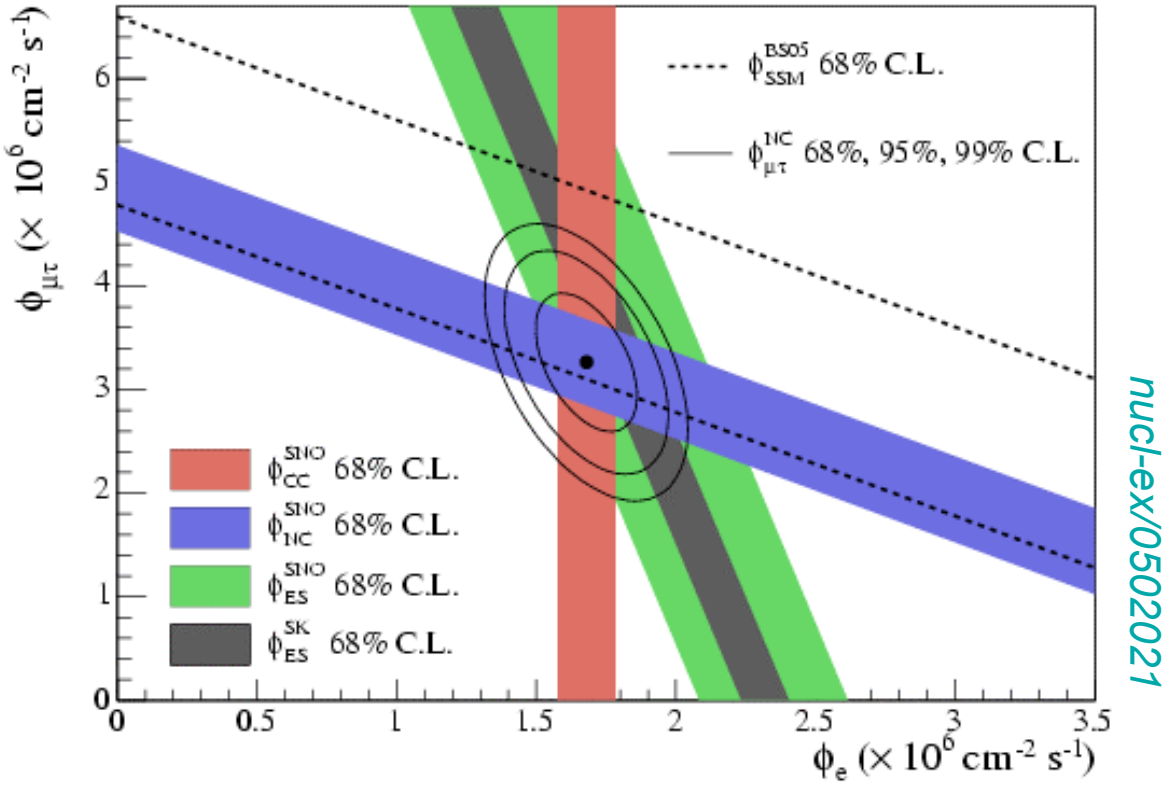
1990's: Sage and Gallex radiochemical experiments confirm deficit in solar neutrino flux

1988-1990: Kamiokande and IMB detect hints of atmospheric neutrino deficits.

1998: Super-Kamiokande announces evidence for oscillations in atmospheric neutrinos…

2001: Solution of Solar Neutrino Problem

SNO, with sensitivity to all three ν flavors demonstrates oscillation of neutrinos



nucl-ex/0502021

SNO measures total flux of ν_x to be consistent with the Standard Solar Model

Neutrino Oscillations

oscillations imply neutrinos have mass!

$$U_{MNSP} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

Solar and KamLAND — *Atmospheric* — *Future reactor or accelerator*

$$\times \begin{pmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Majorana phases

Like quarks, neutrino flavor and mass eigenstates are not the same

Simplified expression for two flavor oscillations in a vacuum:

$$P(\nu_l \rightarrow \nu_{l'}) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2(\text{eV}^2) L(\text{m}) / E_\nu(\text{MeV}))$$

Why a Reactor Neutrino Experiment?

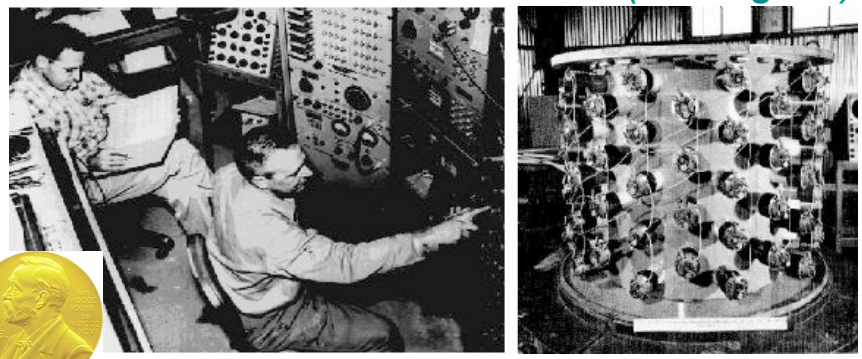
Low energy (MeV) probes small Δm^2, LMA region

$\bar{\nu}$ vs. ν oscillations

Well-understood man-made, man-controlled source

Matter effects negligible (to first order)

1955 Reines & Cowan (Poltergeist)



1995 Nobel Prize for detection of the neutrino

Basics:

- Disappearance search
- Flux and X-sections *very* well-understood → no near detector for precision measurement (few % level)
- Detection mode is via inverse beta-decay → excellent bg rejection
- Well-tested detector technology

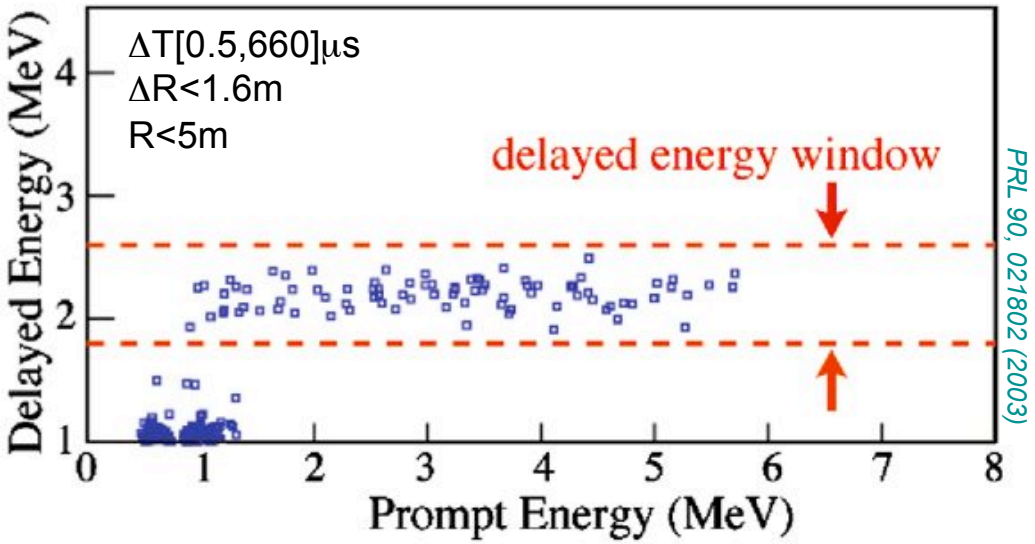
Parameter sensitivity is complimentary to solar experiments

Anti-Neutrino Signal Detection

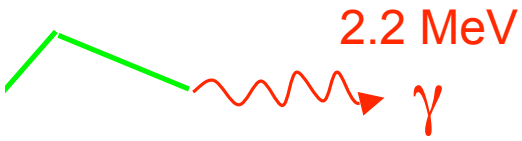
Coincident energy deposit for inverse β-decay provides powerful background rejection

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

Prompt Energy Deposit:
positron energy deposit
(K.E. + annihilation γ's)



PRL 90, 021802 (2003)



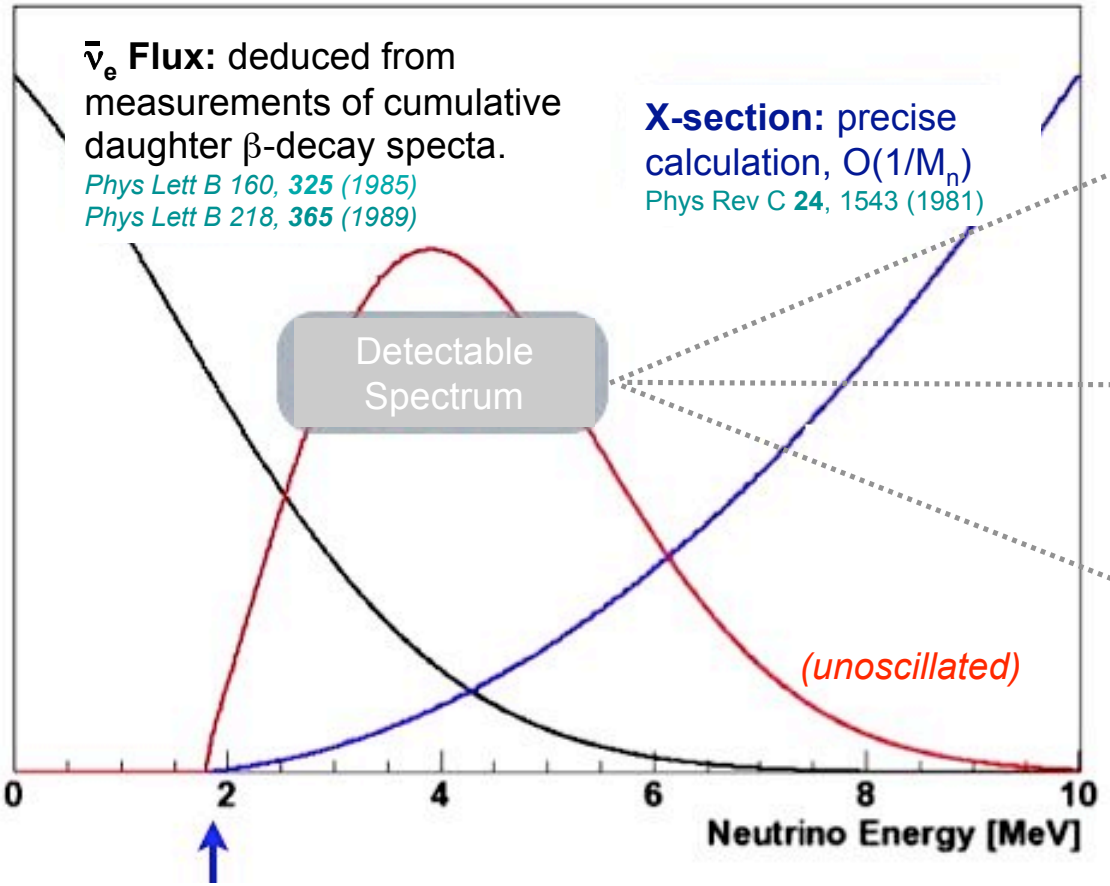
Delayed Energy Deposit:
n-capture releases 2.2 MeV γ,
~200 μs later (for KamLAND)

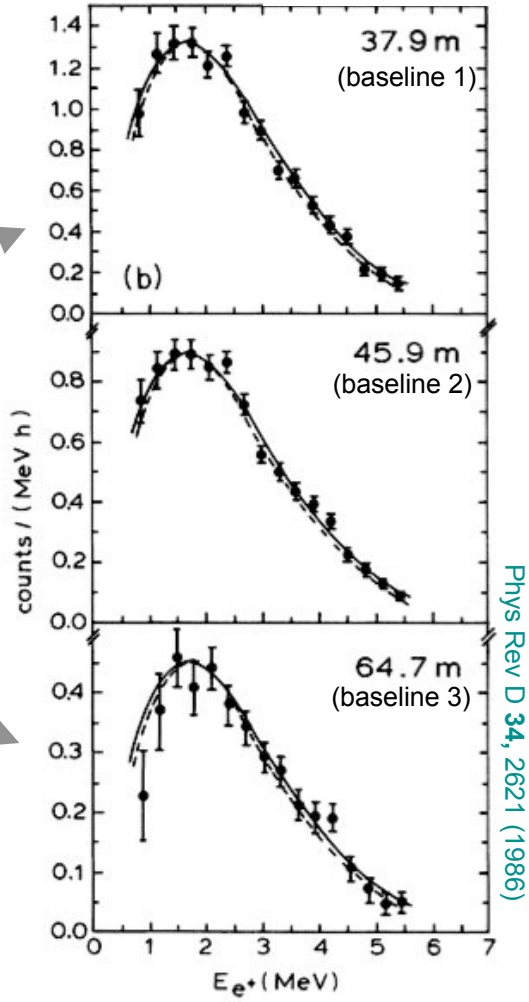
Simple kinematics gives $\bar{\nu}_e$ energy: $E_\nu = E_{prompt} + 0.8$ MeV

Anti-Neutrino Spectrum

Gösgen

Primary Fissioning Isotopes (representative ratio)
^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.61:0.13:0.20:0.06





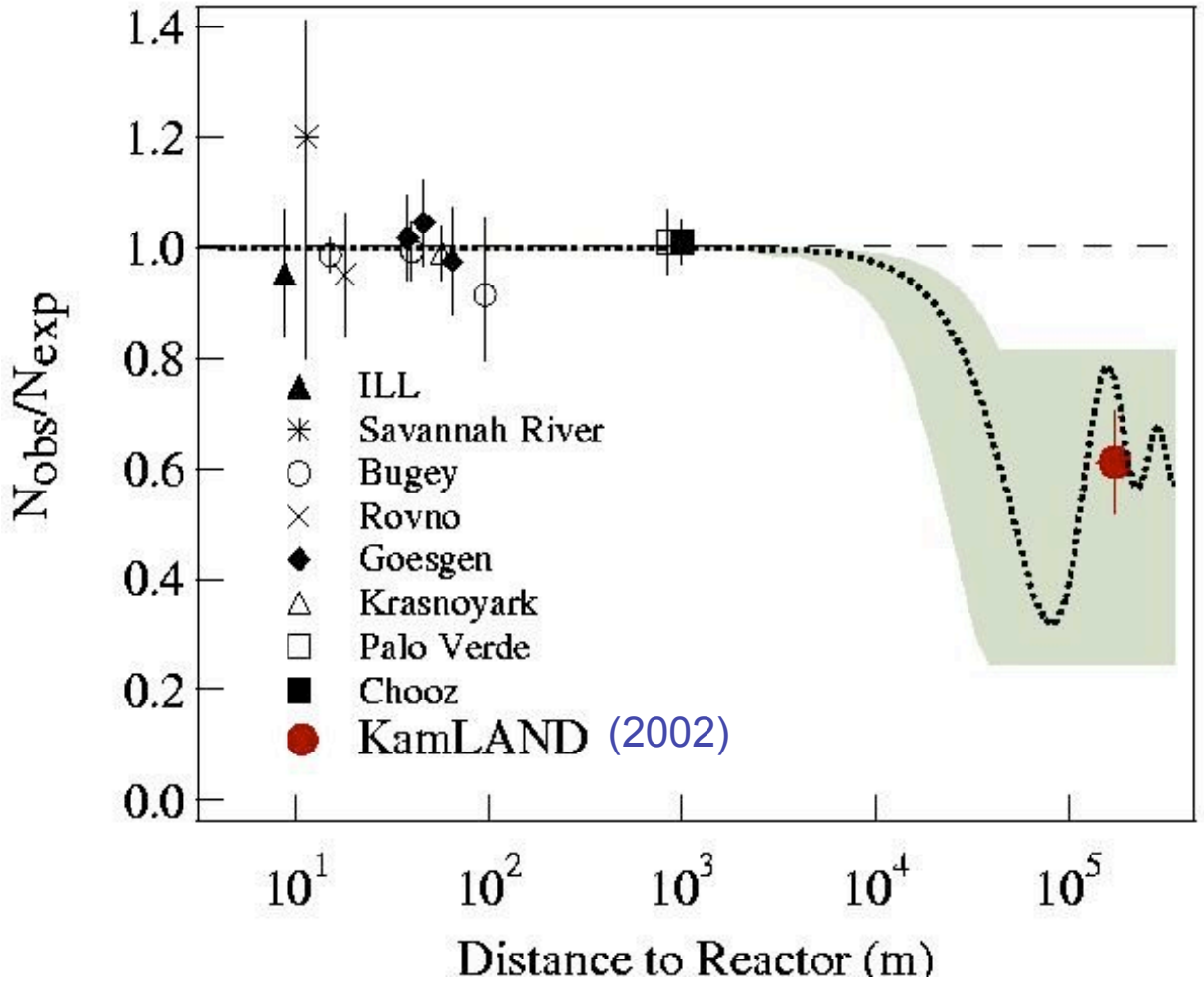
Phys Rev D **34**, 2621 (1986)

1.8 MeV inverse β-decay threshold

Predicted spectrum shown to have good agreement by earlier reactor experiments

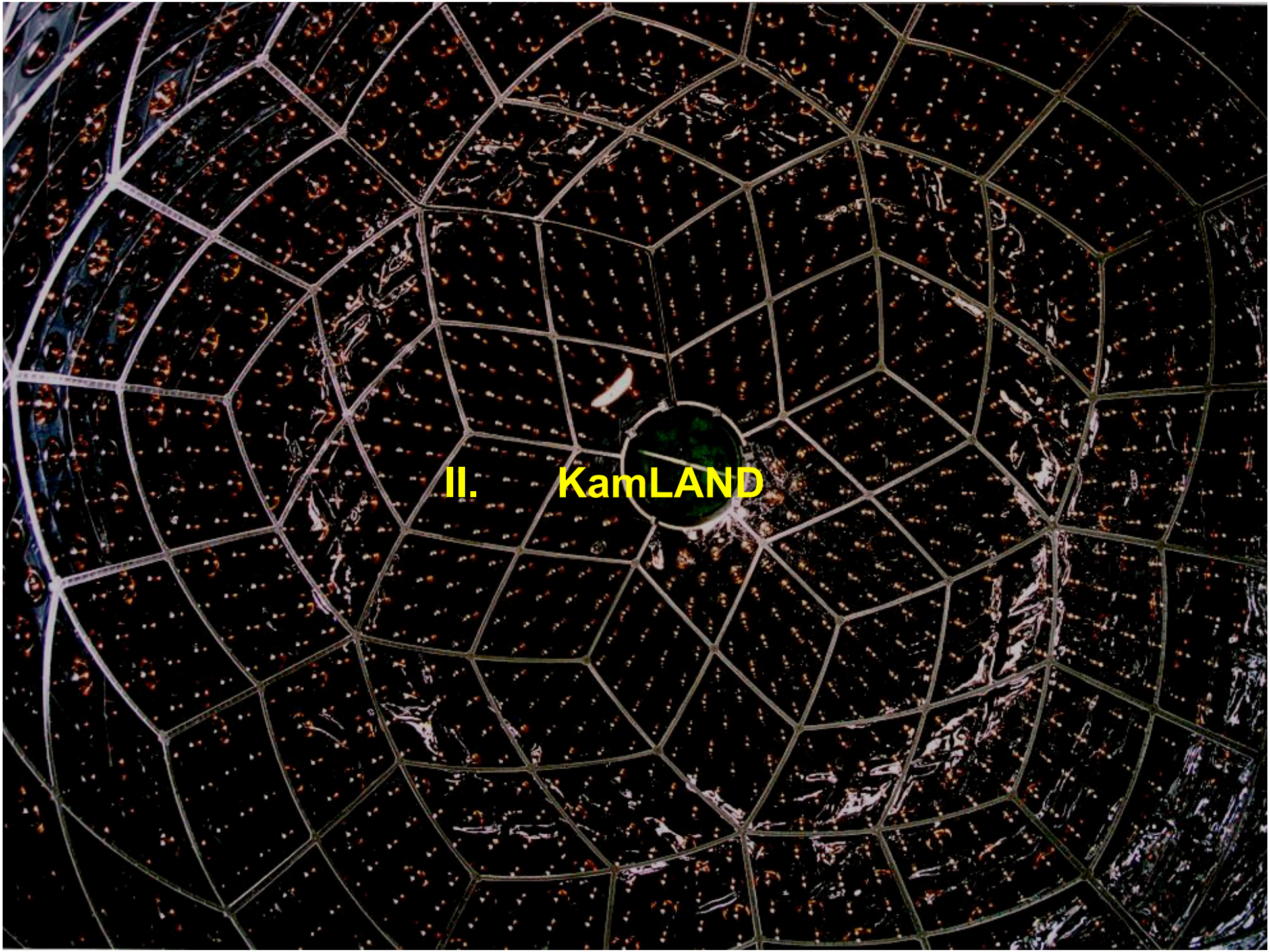
Searching for Reactor $\bar{\nu}_e$ Disappearance

Several generations of short baseline experiments ruled out higher Δm^2 region



KamLAND is the first experiment to observe disappearance of reactor $\bar{\nu}_e$

Shaded region = 95% CL LMA region based on global analysis of solar data prior to KL
*Phys Rev D **66**, 053010 (2002)*

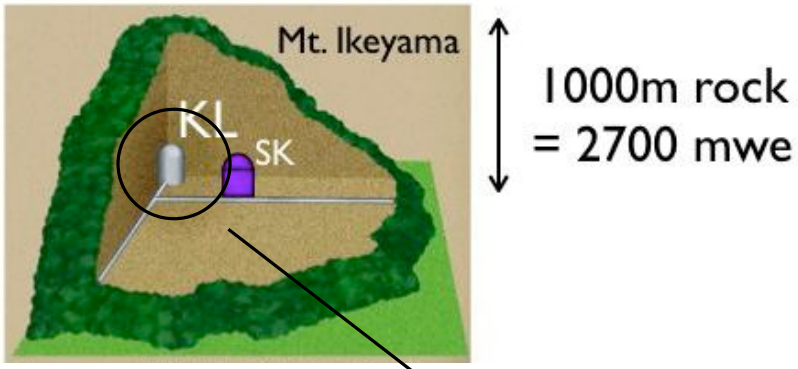

II. KamLAND

KamLAND

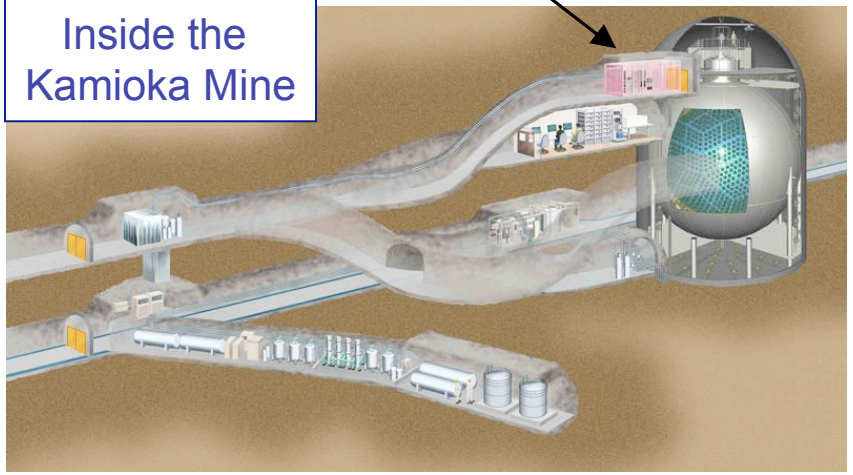
KAMioka Liquid scintillator Anti-Neutrino Detector

Surrounded by 55 Japanese Reactor Units

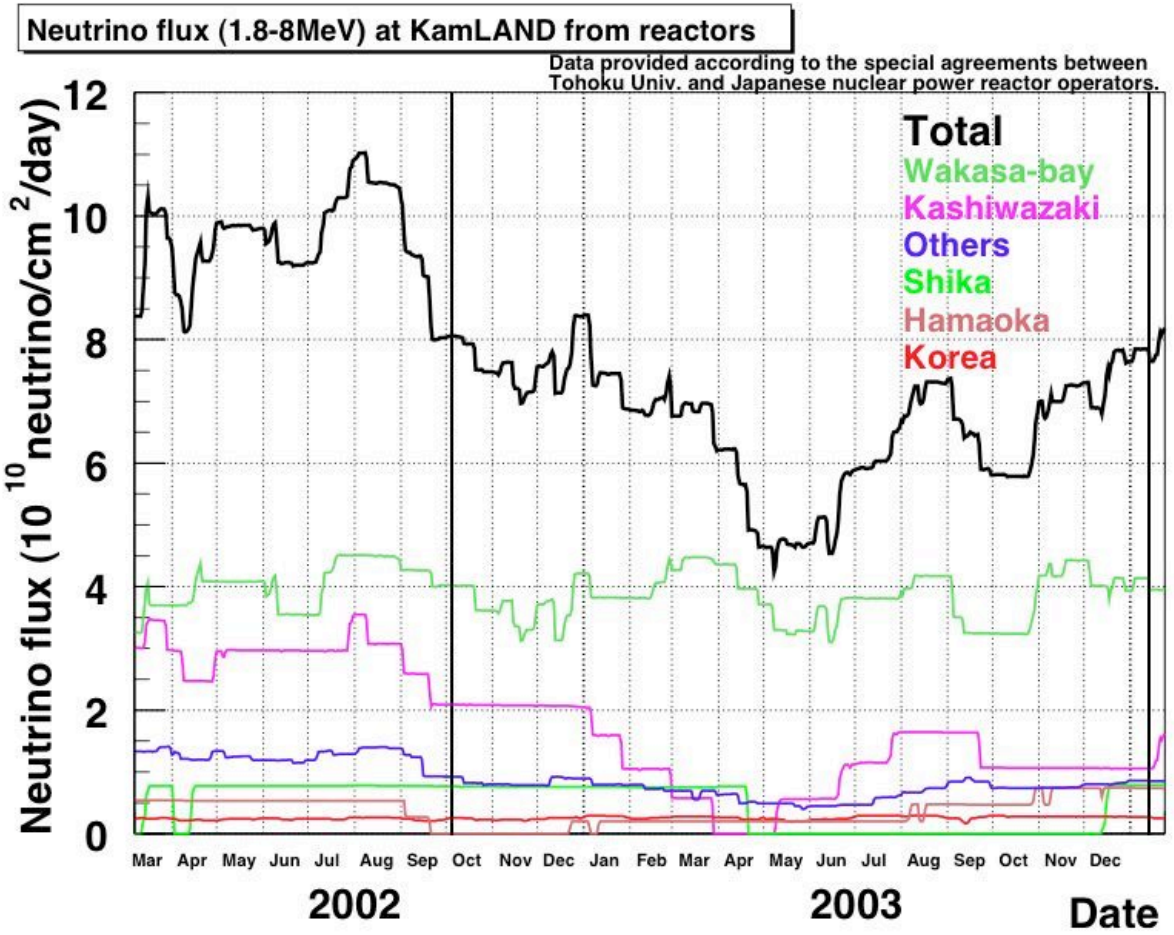
Detecting reactor $\bar{\nu}_e$ 1km beneath Mt. Ikeyama



Inside the Kamioka Mine



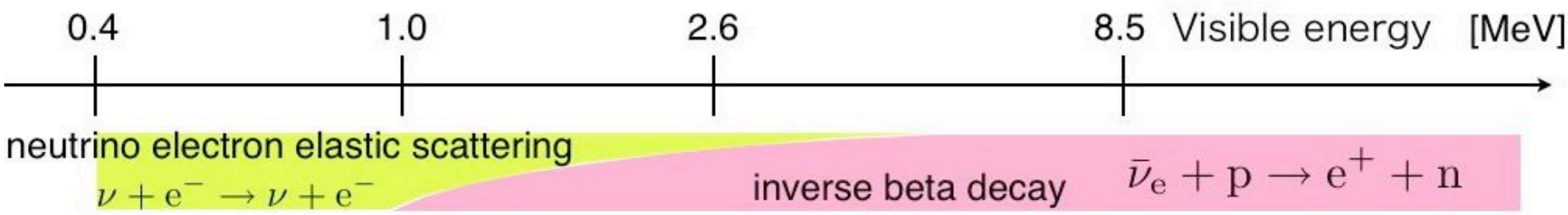
KamLAND Reactors



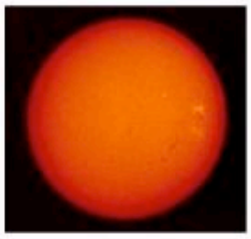
Total reactor power uncertainty is ~2% (conservative estimate)

Detailed information from Japanese reactors	95.5%
History of electric power output from Korean reactors	3.4%
Nominal power from the other reactors	1.1%

Physics Reach of KamLAND

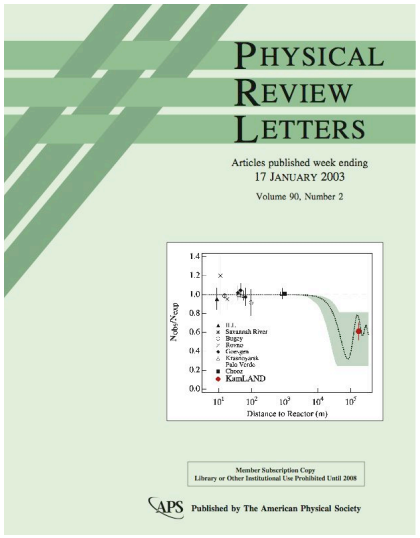


^{7}Be solar neutrino



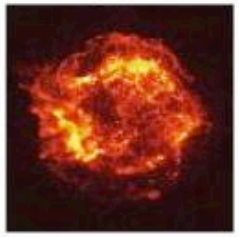
future measurement

Geological anti-neutrinos
Nature 436, 499 (2005)



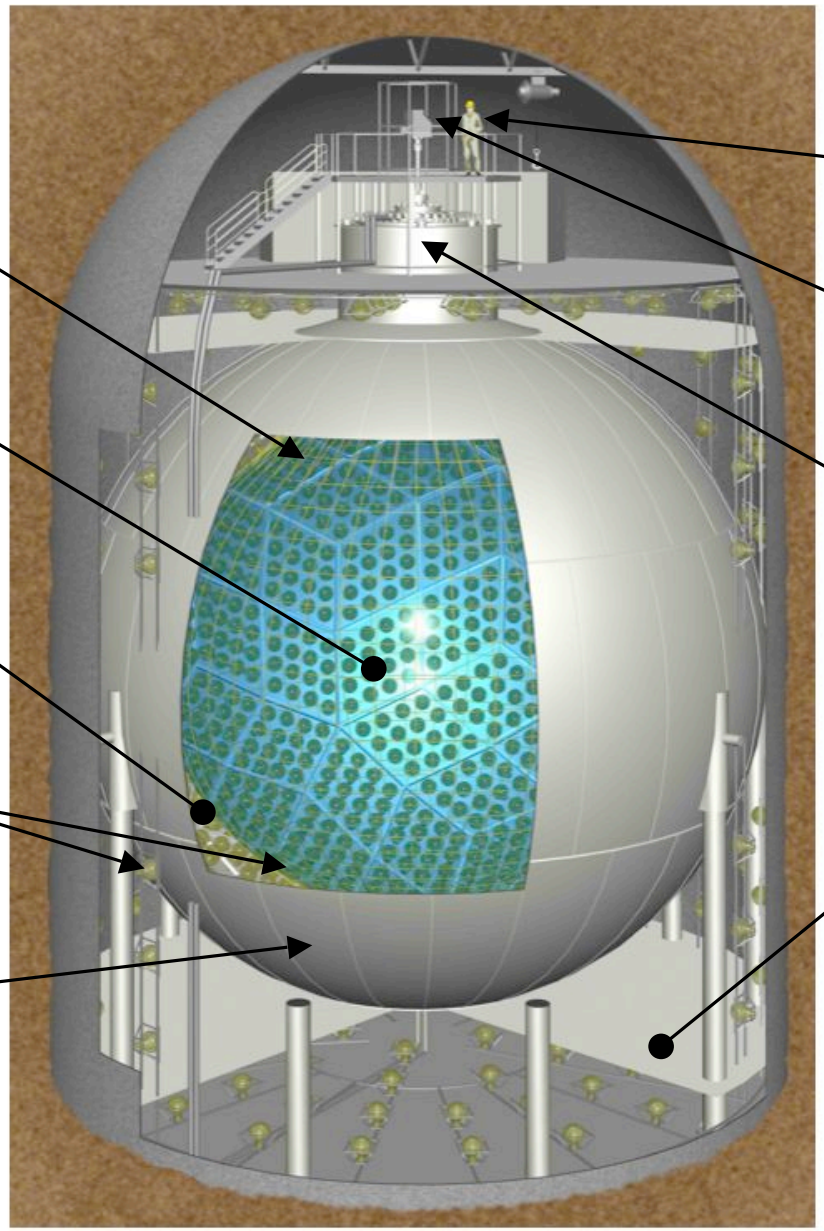
Reactor anti-neutrinos
PRL 94, 081801 (2005)
PRL 90, 021802 (2003)

supernova relic neutrino
etc.



n-Disappearance, anti-neutrino from the Sun and other sources
PRL 96, 101802 (2006)
PRL 92, 071301 (2004)

The KamLAND Detector



Balloon & support ropes

Target LS Volume (1 kton, 13m diameter)

Buffer Oil Zone

Photomultiplier Tubes (34% coverage of ID)

Stainless Steel Inner Vessel *(18m diameter)*

calibration device & operator

Glovebox

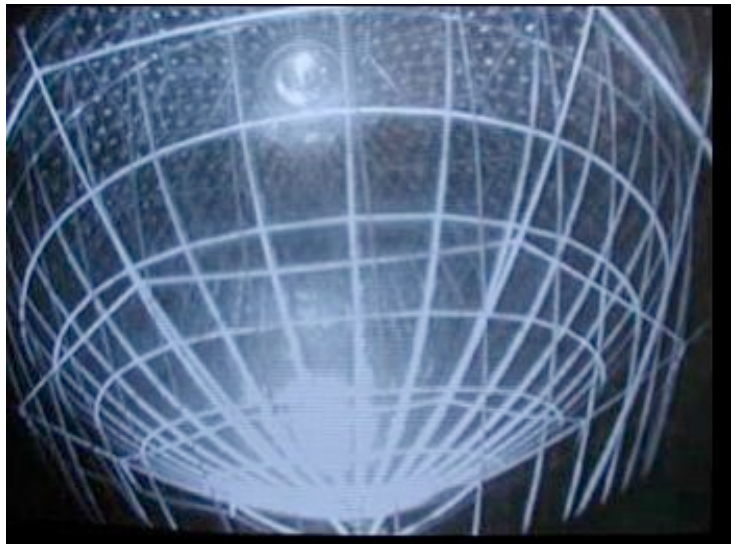
Chimney (access point)

Outer Detector (3.2 kton Water Cherenkov)

The Target Volume

Liquid Scintillator:

- proton rich: > 10^{31} protons
- 20% Pseudocume + 80% Mineral Oil + 1.36 g/l PPO
- Optimal light yield while maintaining long attenuation length (~15 m).



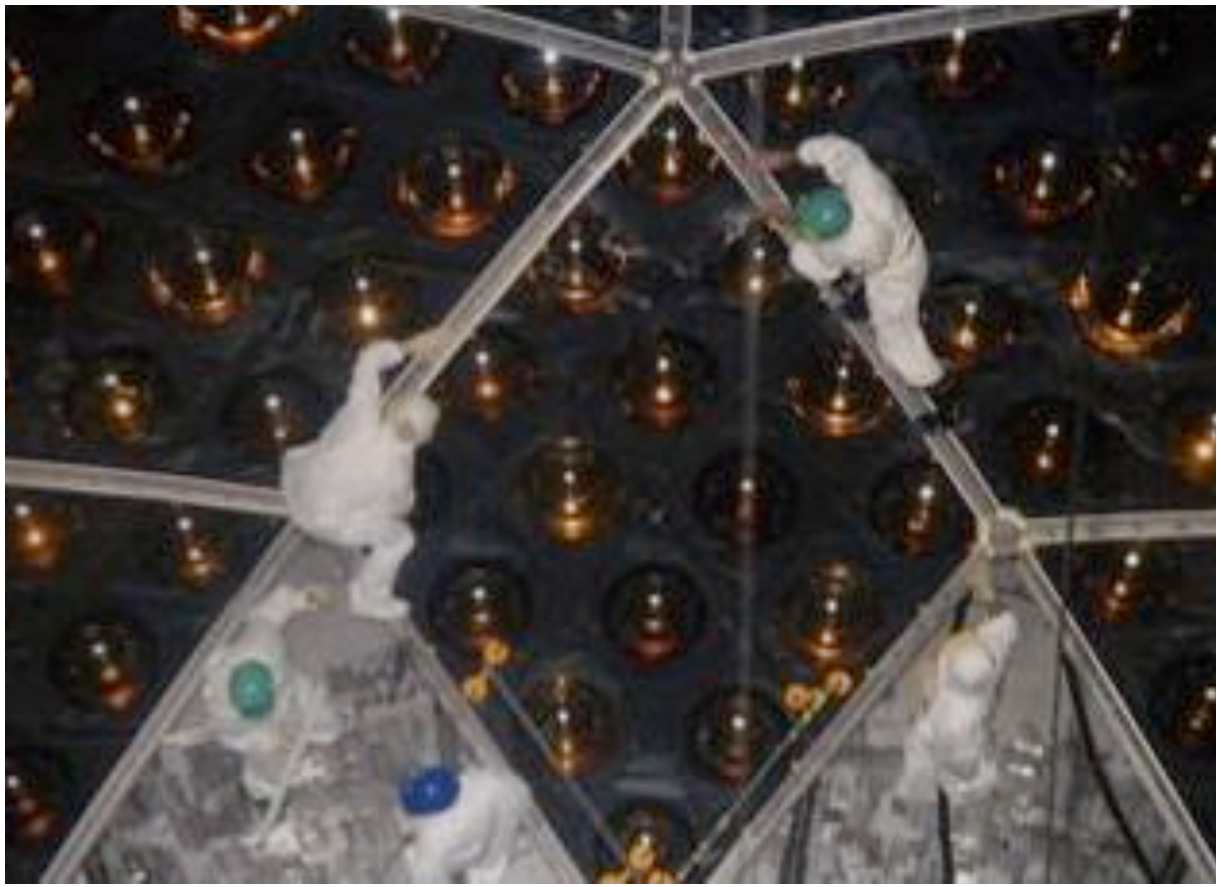
Welding the Balloon

Balloon:

- Separates target LS volume from buffer oil
- 135 μm Nylon/EVOH (ethylene vinyl alcohol copolymer)
- Supported by braided kevlar ropes and buffer oil

KamLAND Photomultipliers

PMT and acrylic panel installation (2000)



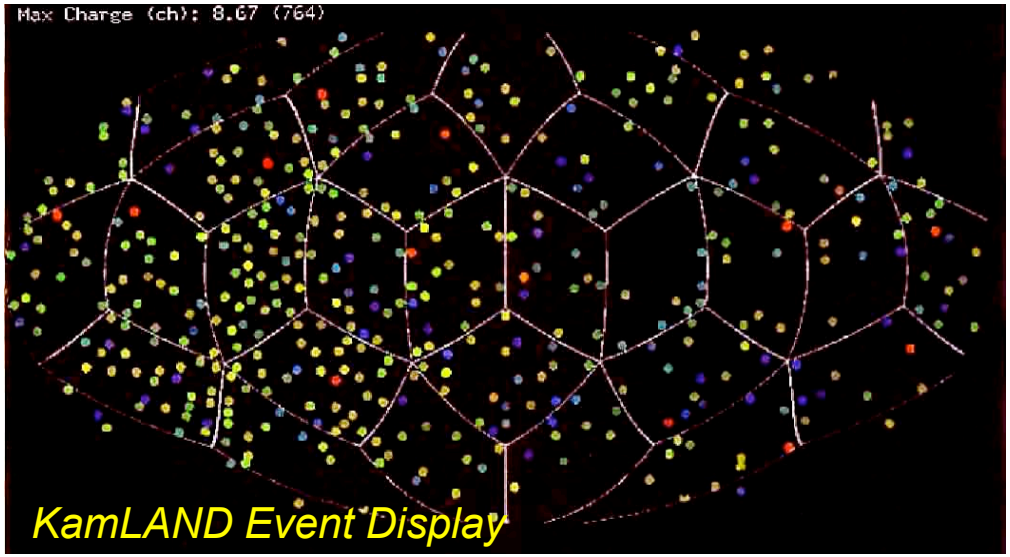
- 1325 17” tubes
- 554 20” tubes (since Feb. ‘03)
- ~200 17” hits for 1 MeV energy deposit
- Transit time spread < 3 ns on 17” tubes
- acrylic panels protect against radioactive backgrounds

Basic Data Reconstruction

How much energy deposited and where?

$$\frac{\sigma_E}{E} = \frac{6.5\%}{\sqrt{E(MeV)}}$$

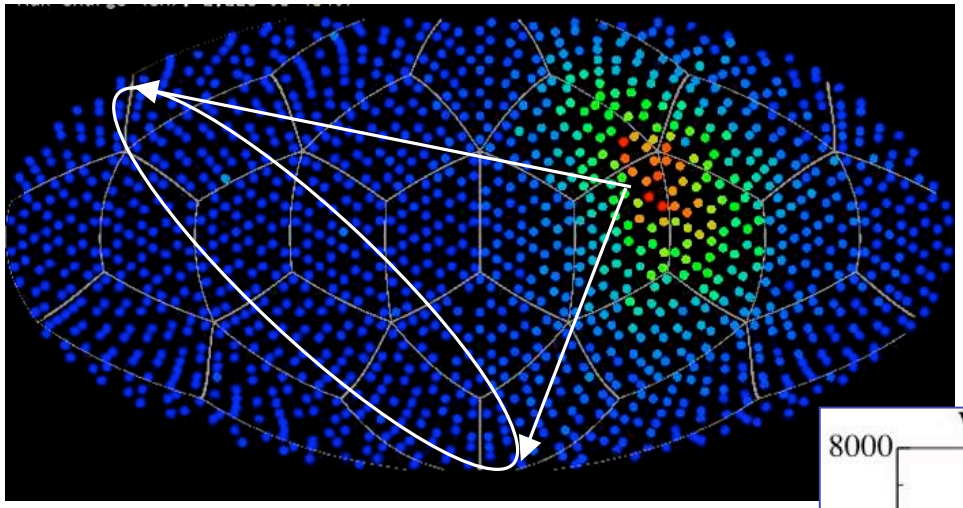
Energy Reconstruction:
- Energy ∝ Number of Hit PMT's
- Correction for Vertex Position
- Correction for Quenching and Cherenkov Radiation



Vertex Reconstruction
- Determined by Very Precise Timing of Hits (~few ns resolution)
- Inherent Detector Resolution ~12cm/√E(MeV)

no directional information on original neutrino trajectory

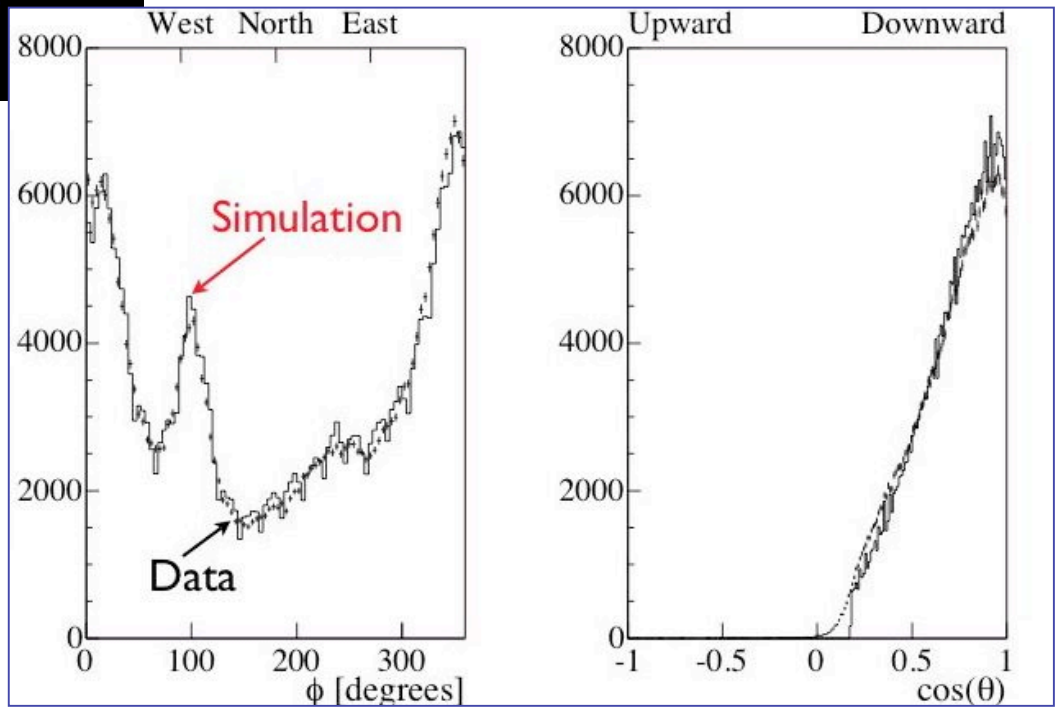
Muon Tracking



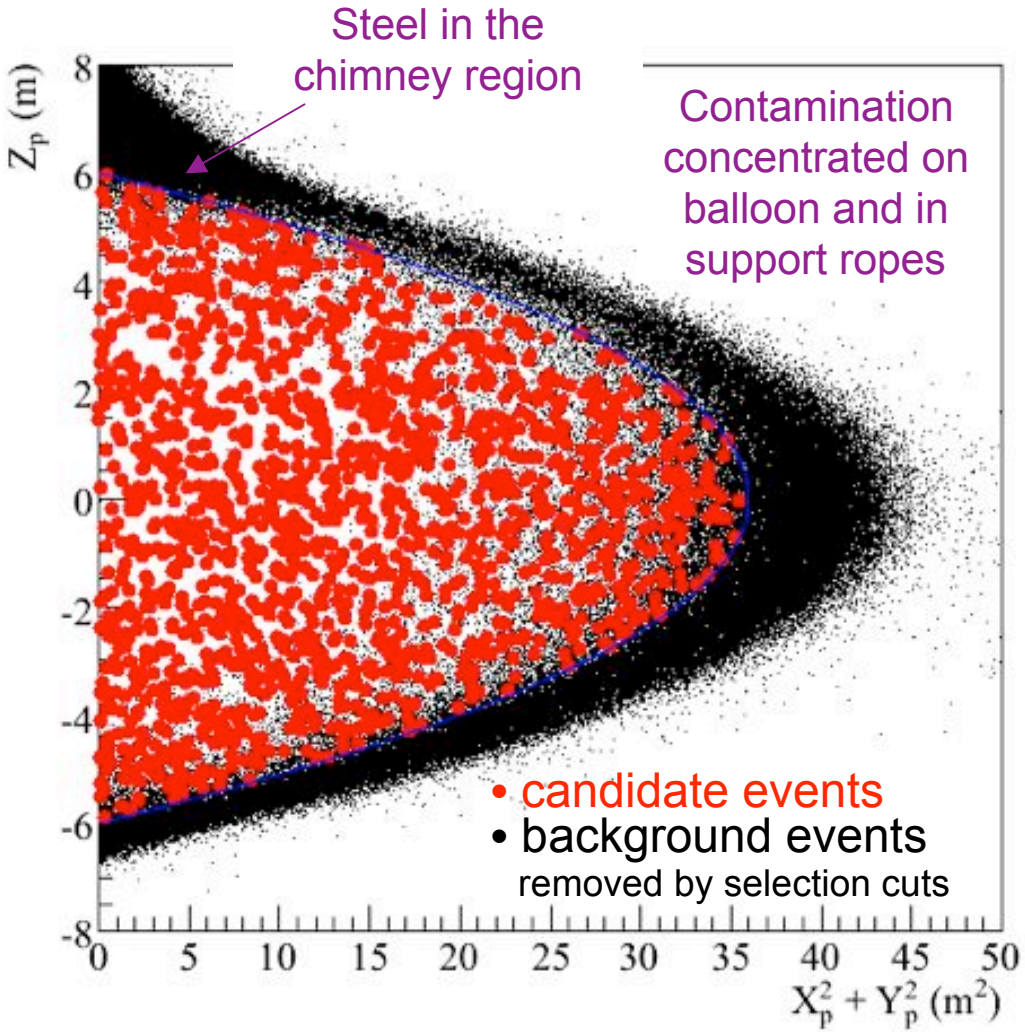
Source of cosmogenic backgrounds

Rate of Muons hitting
KamLAND OD: ~1 Hz
KamLAND ID: 0.2 Hz

- Timing of inner detector hits
- Good agreement with simulation of muons passing through detailed mountain topography

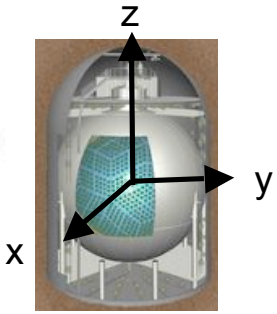


Accidental Backgrounds



High rate of single gammas from natural background radiation (U, Th, K, …) can "accidentally" mimic prompt-delayed signal

Varies greatly with energy and location within the detector. Reduced by time ($\Delta T[0.5,1000]\mu s$) and spatial ($\Delta R<2m$, $R<6m$) cuts.

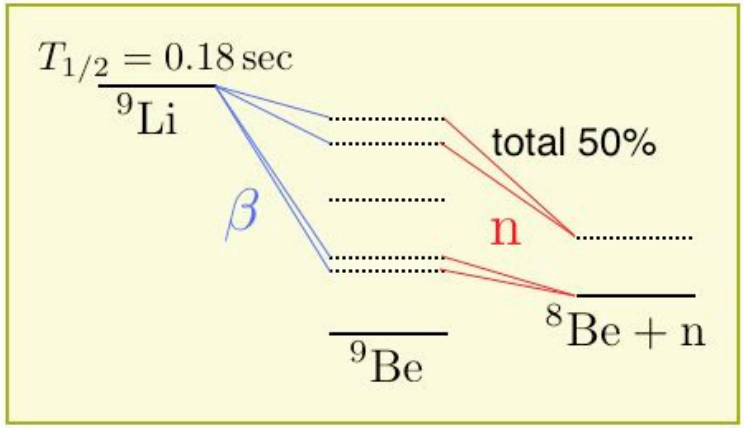


Correlated Backgrounds: Cosmogenic

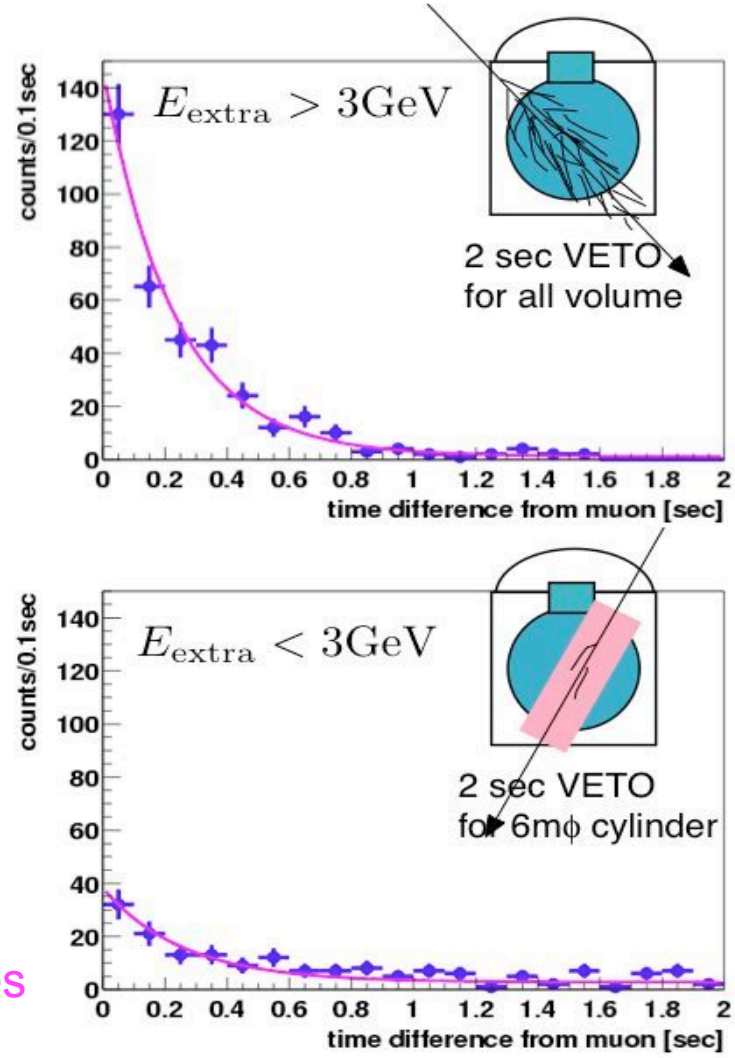
Spallation Products

Muons interact with material producing:

- fast neutrons - removed with 2ms veto after any detected muon
- delayed neutron β emitters (^{9}Li) - removed with 2 second veto around μ-track



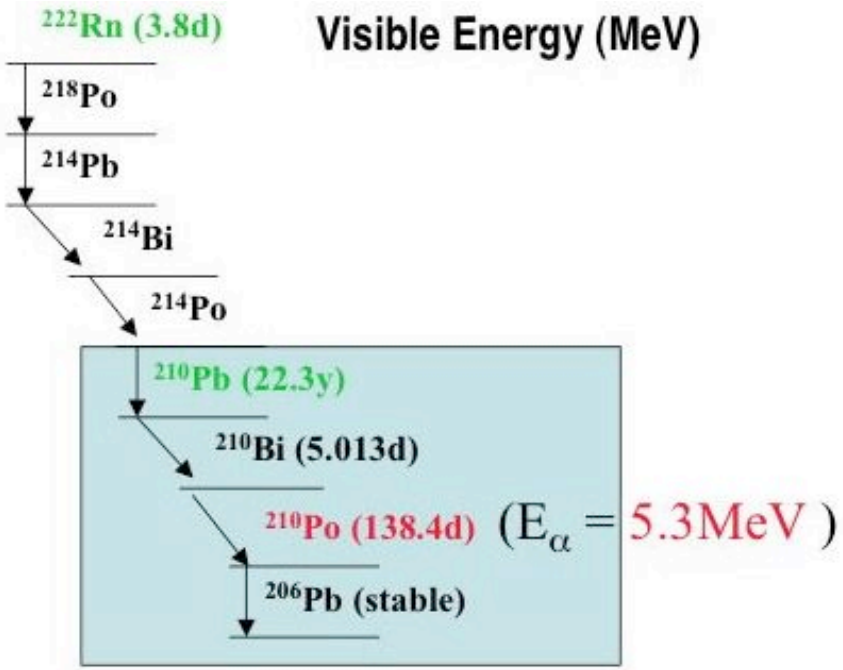
He^8 thought to be a negligible contribution



Cutting events correlated with muons removes almost all cosmogenic bg
<10% deadtime introduced by all muon cuts

Correlated Background: $^{13}C(\alpha,n)^{16}O$

Originating from Rn contamination, discovered after first publication

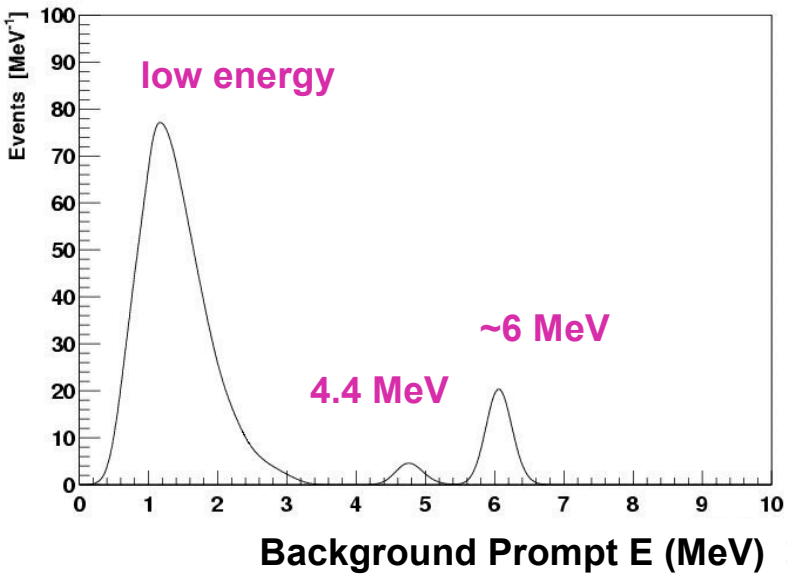


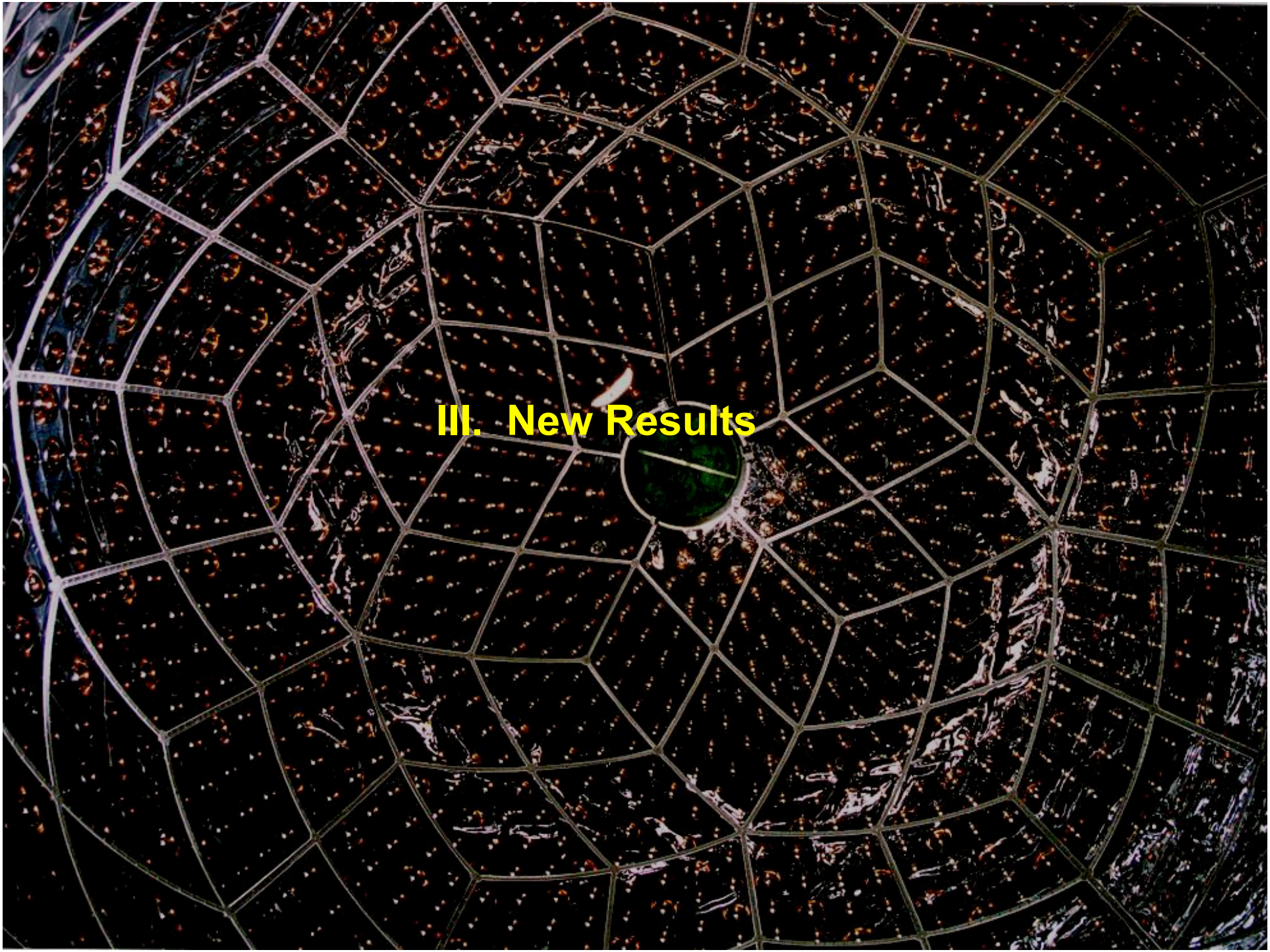
equilibrium

$^{13}C(\alpha,n)^{16}O \sim 10^{-7}$

1.1% abundance (measured)

$^{13}C(\alpha,n)^{16}O(g.s.)$	low energy
$^{13}C(\alpha,n)^{16}O(g.s.) \rightarrow ^{12}C(n,n\gamma)^{12}C$	~4.4 MeV
$^{13}C(\alpha,n)^{16}O^*(6.13)$ $^{13}C(\alpha,n)^{16}O^*(6.05)$	~6 MeV

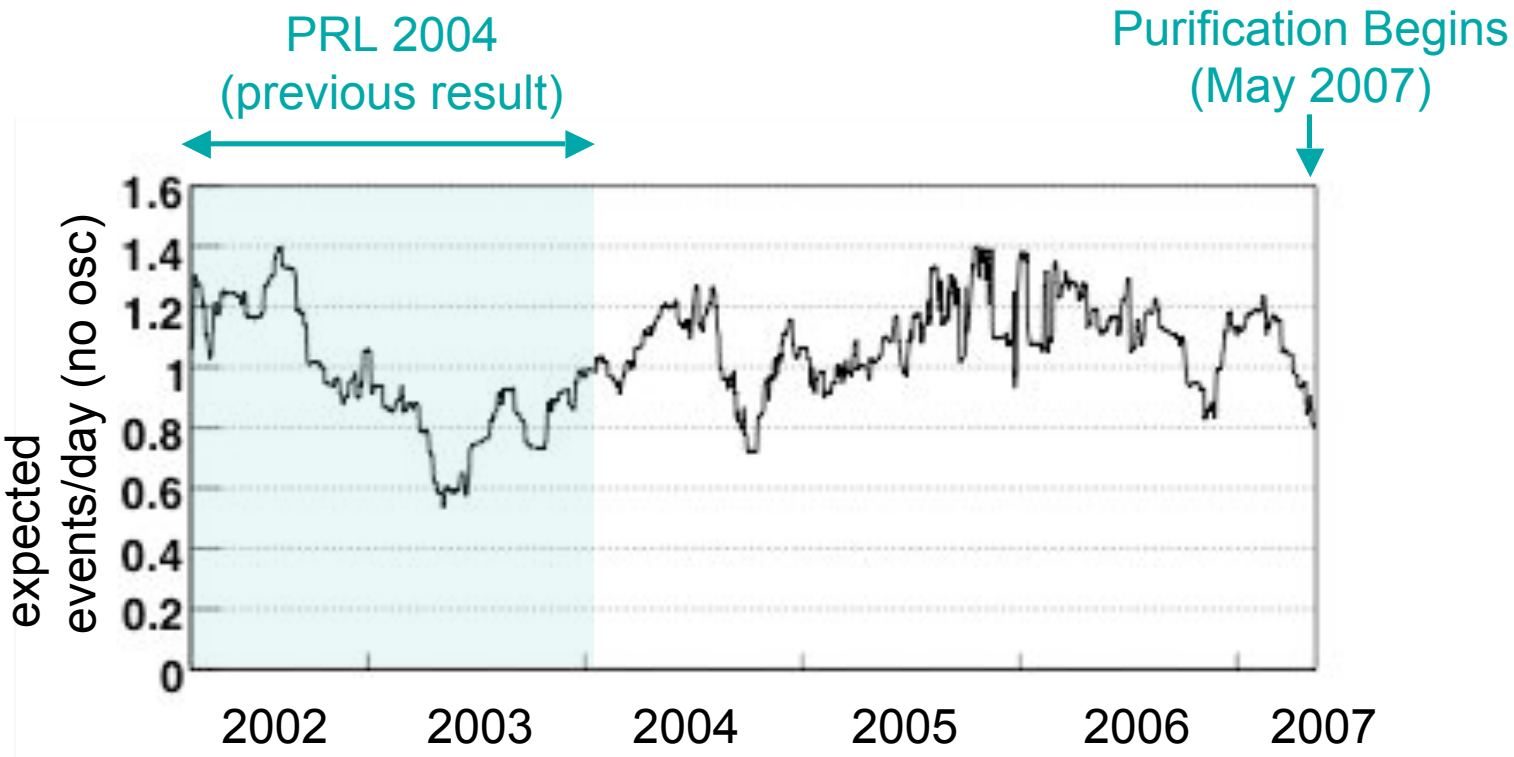



III. New Results

New Dataset

Livetime & Exposure

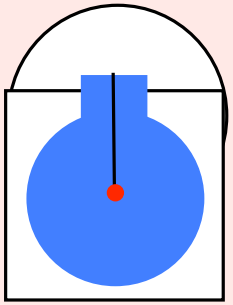
1491 days + increased fiducial volume (5.5m→6.0m)
= 2.44 x 10^{32} proton-year (2881 ton-year)
= an additional 2.8x data of previous result



Pre-existing Calibration Methods

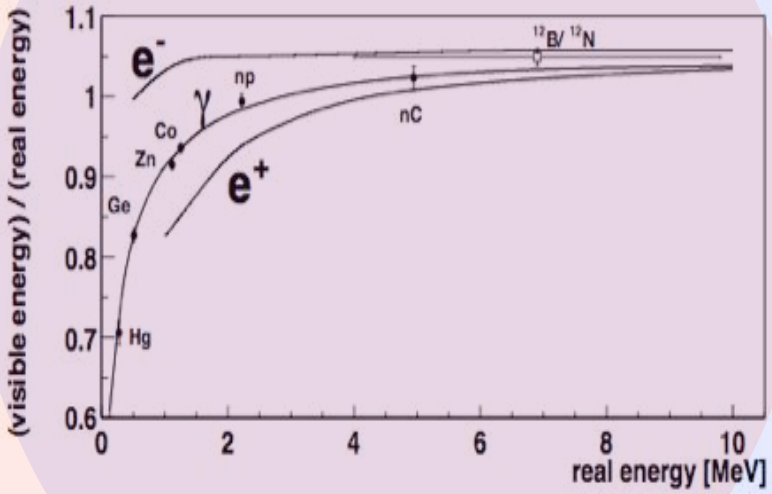
Radioactive Sources:

Manually deployed along z-axis:
^{60}Co, ^{68}Ge, ^{65}Zn, ^{203}Hg, $^{241}Am^{9}Be$, laser



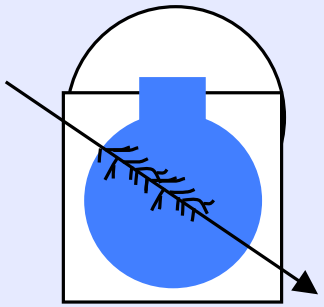
- PMT time offsets
- vertex and energy bias (along z-axis)

- PMT gain
- dark rate
- energy scale & nonlinearity



Spallation Backgrounds:

Uniform distribution throughout target volume: (n,γ), ^{12}B, ^{12}N



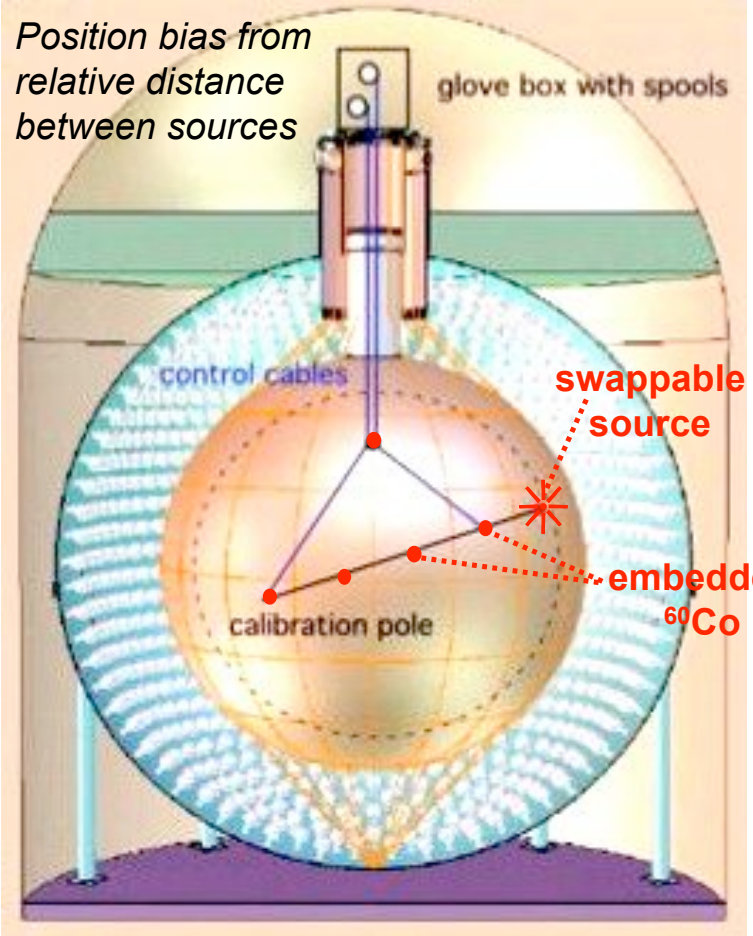
- average vertex and energy bias
- fiducial volume (w/ limited statistics)

Off-Axis Comissioning: July 2006

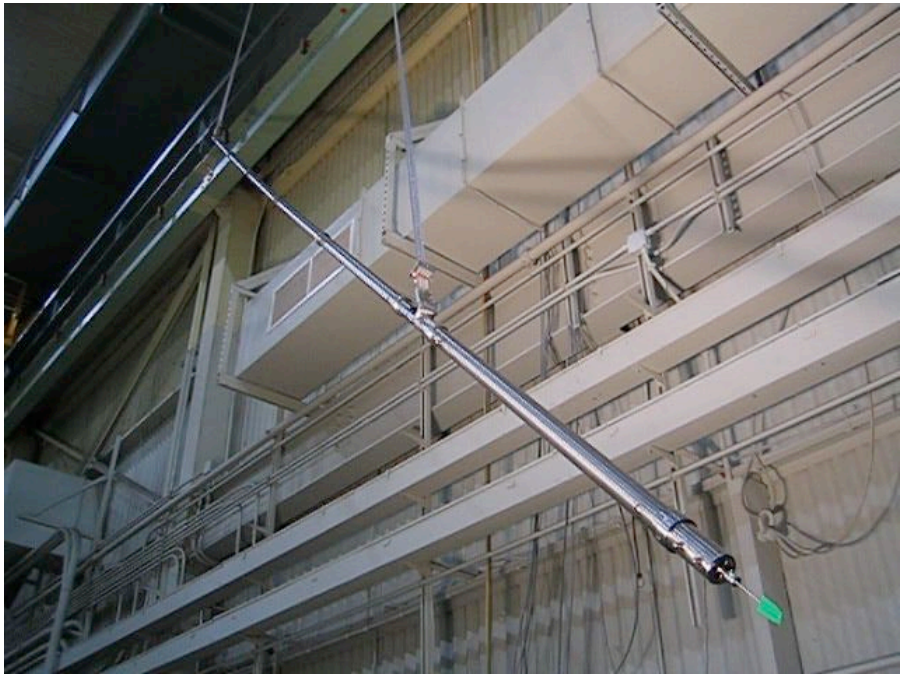
- Off-axis calibration to improve energy and vertex estimation
- Reduce fiducial volume uncertainty (dominant uncertainty on $\bar{\nu}_e$ rate)

Simple in concept, difficult in practice!

Position bias from relative distance between sources



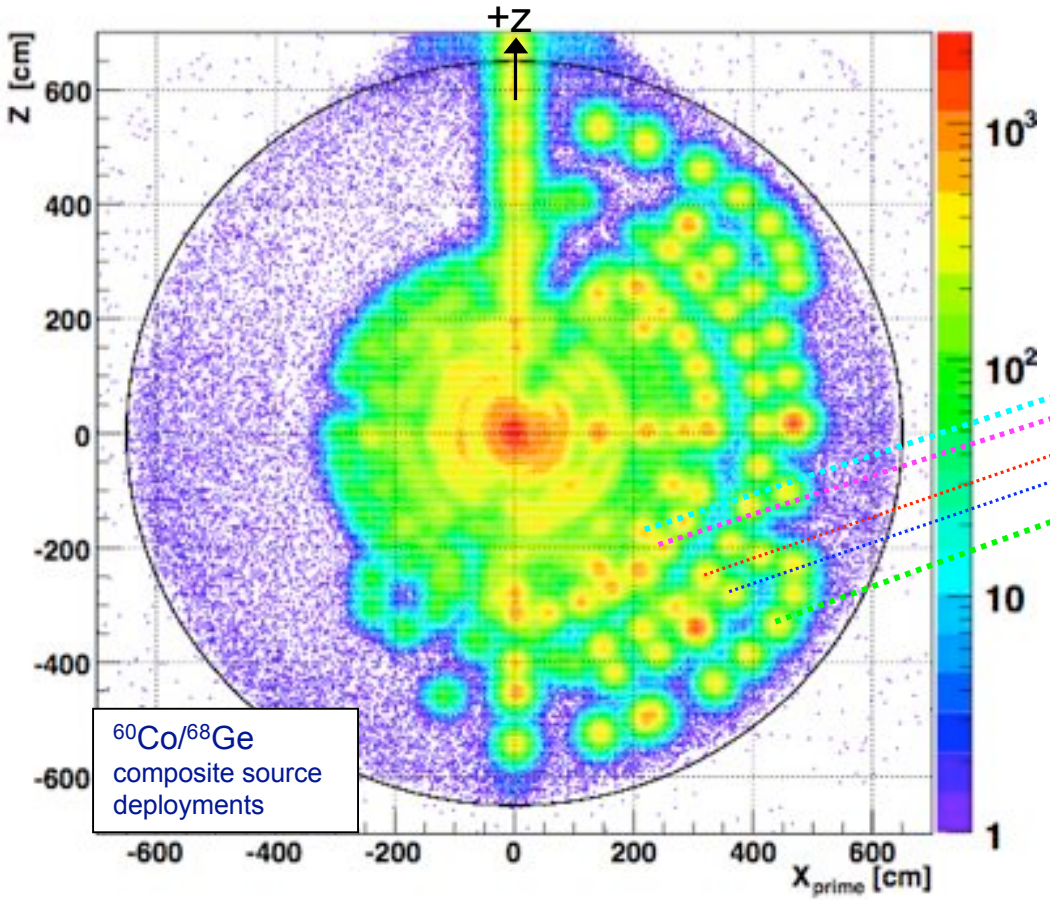
Testing 6 meter configuration at LBNL (2005)



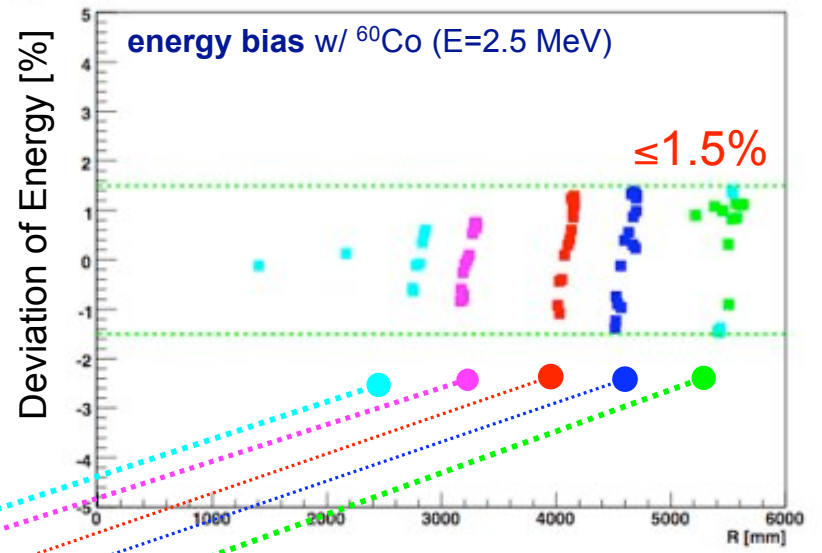
Monitor Risks to Detector: balloon safety (135 μm thick), cleanliness, LS compatibility, no pieces left behind…

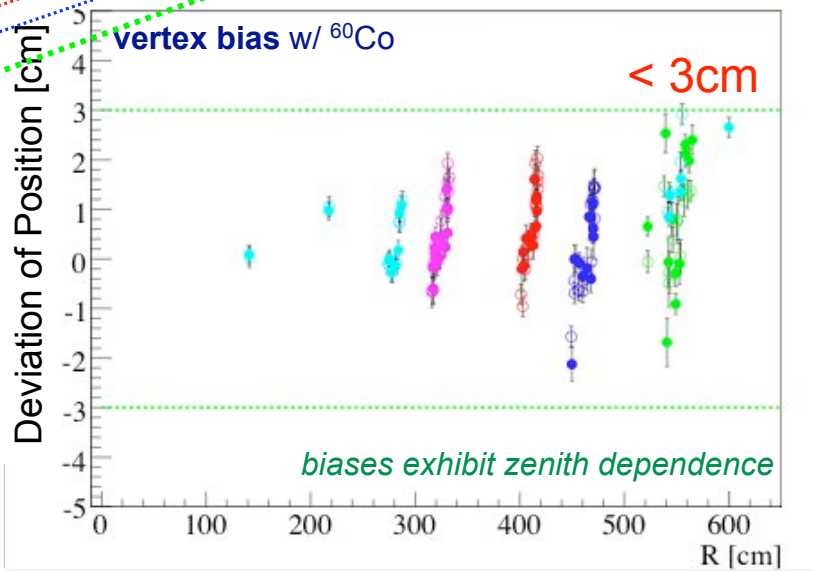
Example Off-Axis Calibration Results

Poles of fixed length swept through zenith angle

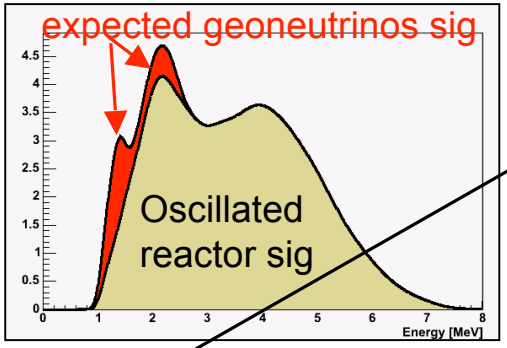


Deployments with different sources check for energy dependent systematic effects: ^{60}Co,^{68}Ge, ^{241}Am^{9}Be, ^{210}Po^{13}C, ^{203}Hg

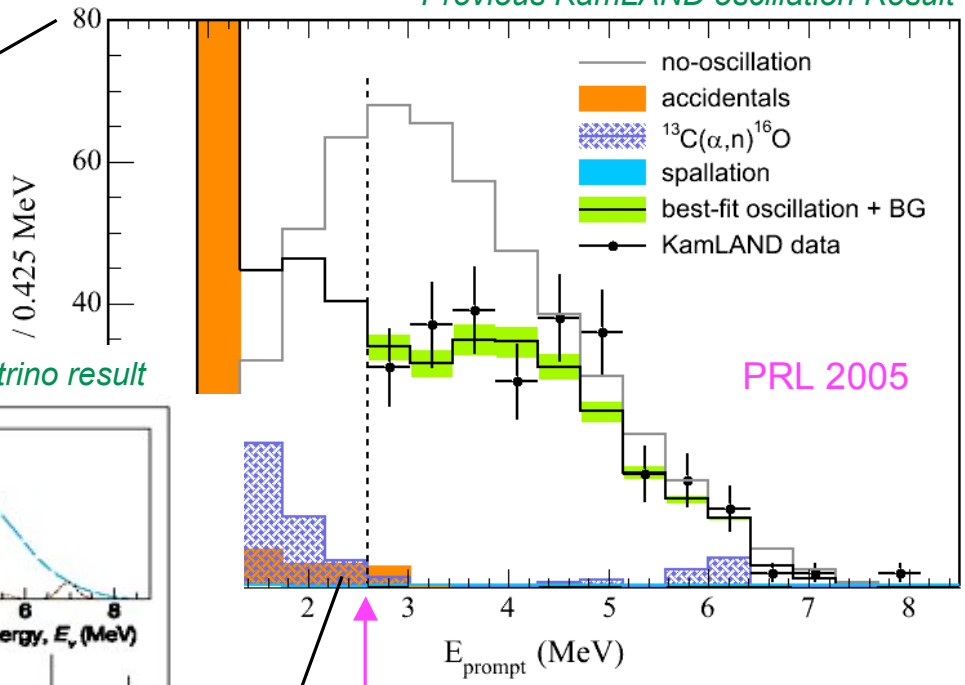




Lowering the Energy Threshold

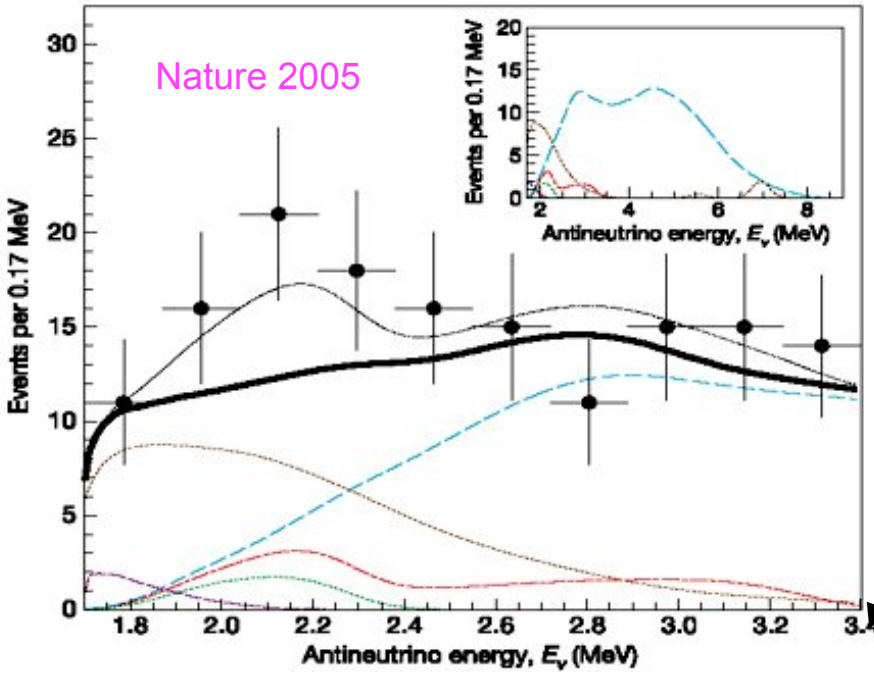


Previous KamLAND oscillation Result



PRL 2005

First geoneutrino result



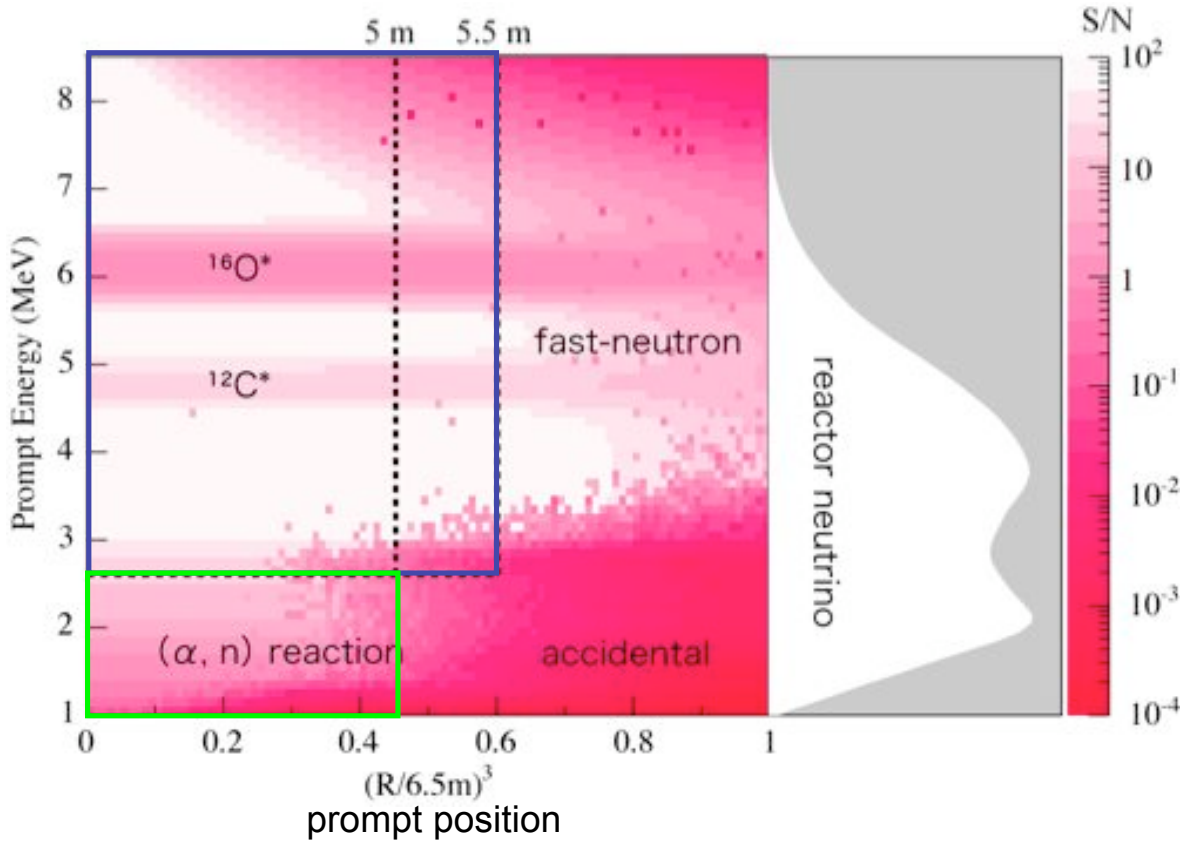
Shortly afterwards, the first geoneutrino result was published, opening up the low energy region to the oscillation analysis

New Event Selection

Previous analyses' "box-cuts" suppressed accidental background

previous oscillation result parameter space

first geoneutrino result parameter space



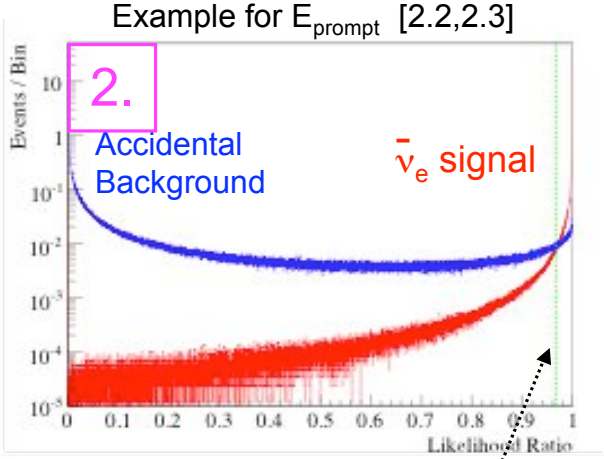
Strong Energy Dependence of Backgrounds + Lowered Energy Threshold

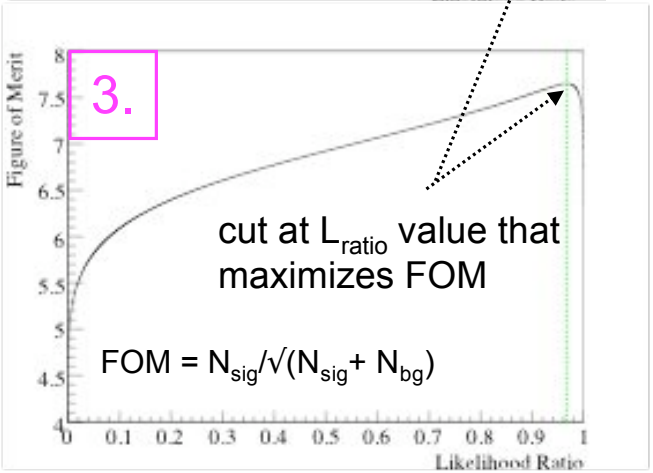
→ *requires improved event selection criteria*

Accidental Background Discriminator

Optimized for combined reactor and geoneutrino sensitivity

Example for E_{prompt} [2.2,2.3]





1.

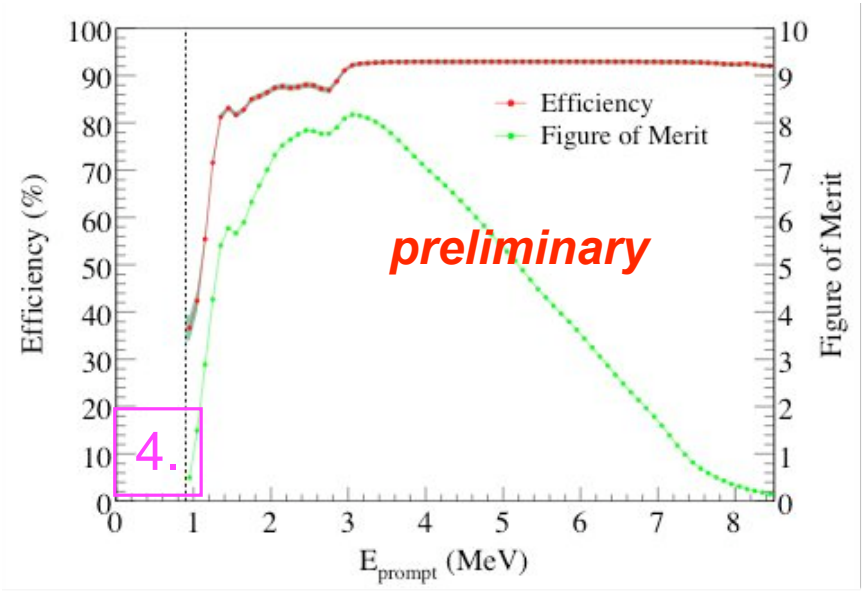
$L_{ratio}(E_{prompt}) = f_{\bar{\nu}}/(f_{\bar{\nu}} + f_{accidental})$

(L = Likelihood)

from MC simulation

from off-timing accidental data

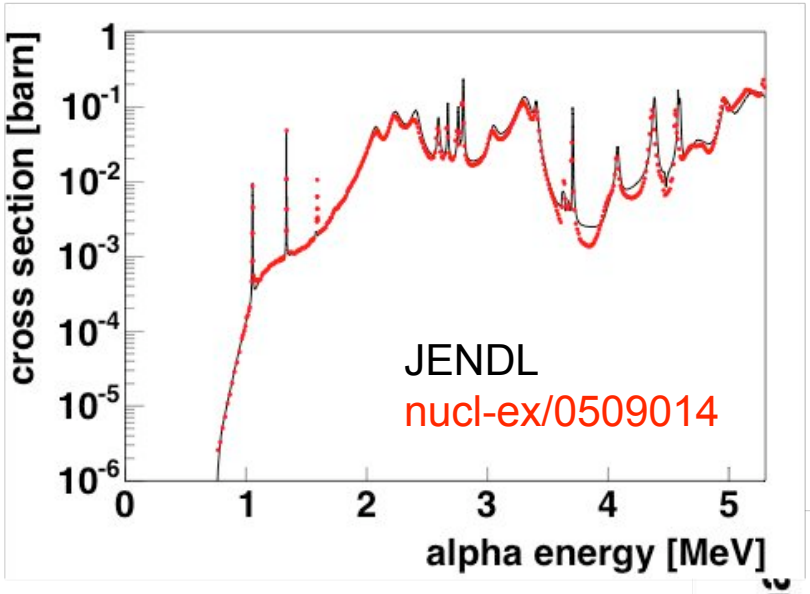
At fixed E_{prompt}: L_{ratio} depends on $E_{delayed}$, R_{prompt}, $R_{delayed}$, ΔR, ΔT



Spallation cuts are unchanged

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

New $^{210}Po^{13}C$ calibration source and new X-section measurements

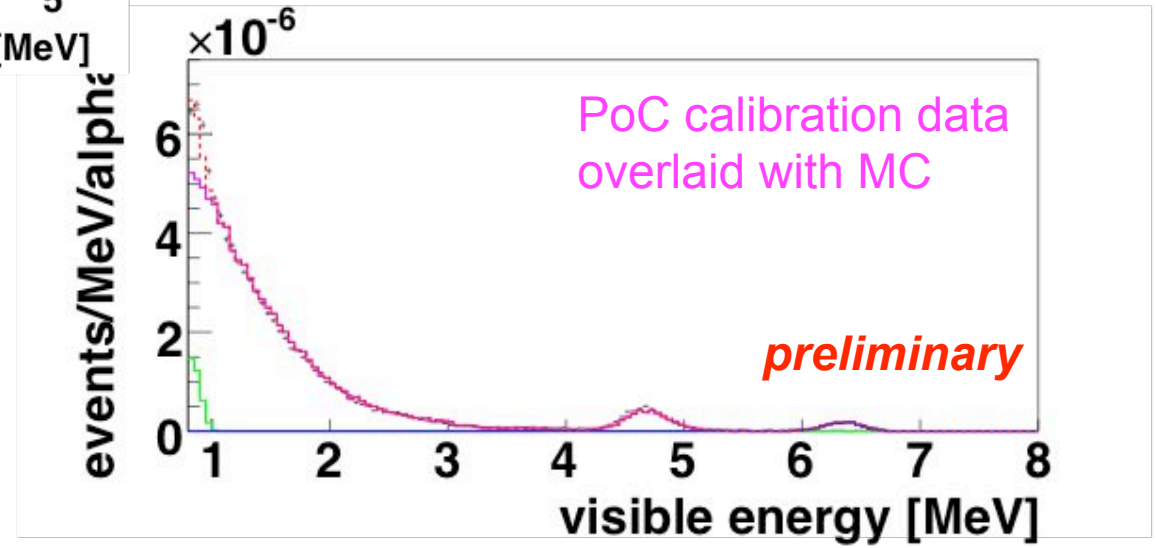


Reduced $^{13}C(\alpha,n)^{16}O$ uncertainty:

11% uncertainty in ground state
20% uncertainty in excited states

(compared to 10.3±7.1 events > 2.6 MeV in previous result)

New $^{13}C(\alpha,n)^{16}O$ X-sections + measured proton quenching input in simulation of PoC source



New Systematic Uncertainty and Background Estimates

Backgrounds

Background	Contribution
Accidentals	80.5 ± 0.1
^{9}Li/^{8}He	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
^{13}C(α,n)^{16}O G.S.	157.2 ± 17.3
^{13}C(α,n)^{16}O, ^{12}C(n,nγ)^{12}C (4.4 MeV γ)	6.1 ± 0.7
^{13}C(α,n)^{16}O 1st exc. state (6.05 MeV e^+e^-)	15.2 ± 3.5
^{13}C(α,n)^{16}O 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total excluding geo-neutrinos	276.1 ± 23.5
Geo-neutrino decays U+Th [7]	56.2+13.1

preliminary

significantly improved

reduced from 4.7%

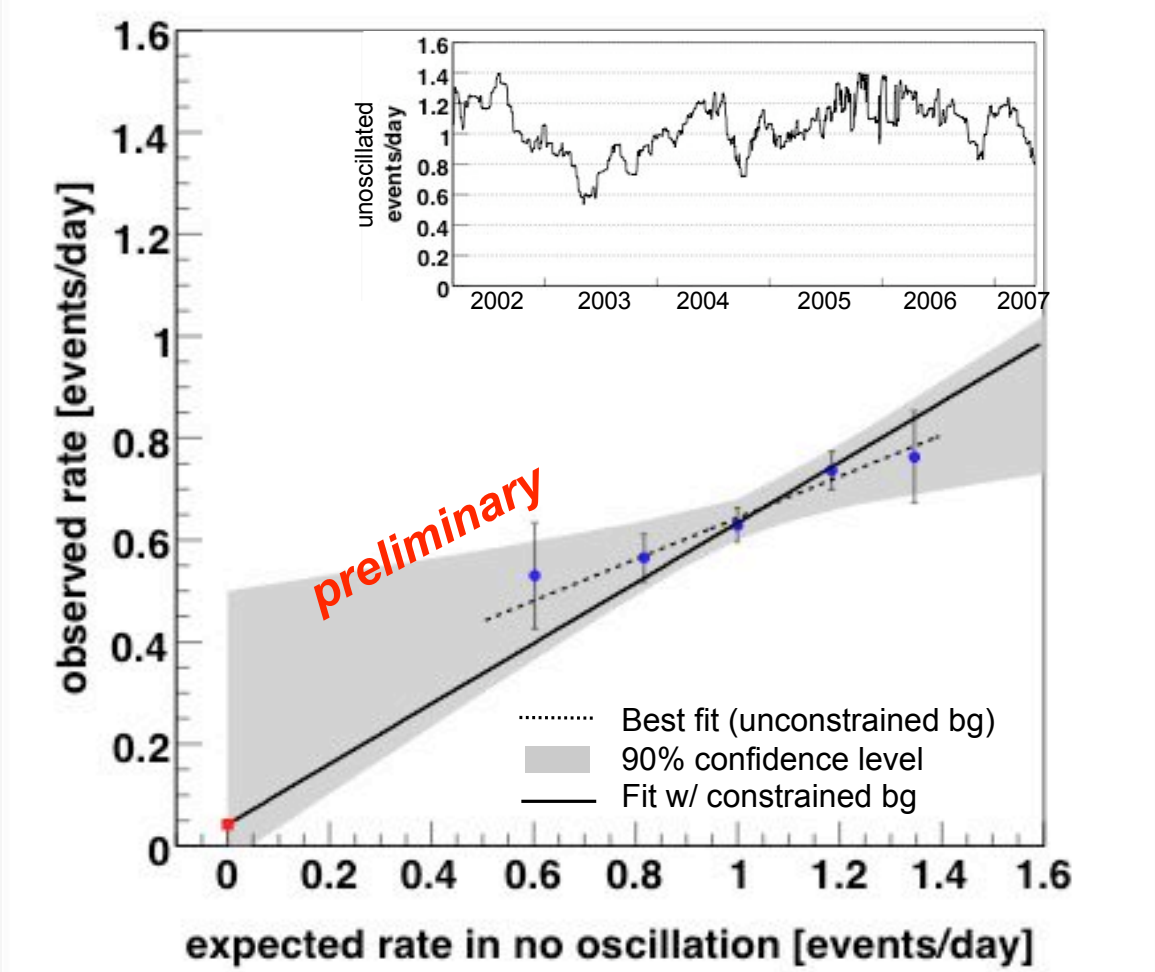
Systematic Uncertainty on Rate

Detector related		Reactor related	
Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
Energy scale	1.5	Reactor power	2.1
L-selection eff.	0.6	Fuel composition	<1.0
OD veto	0.2	Long-lived nuclei	0.3
Cross section	0.2	Time lag	0.01
Livetime	0.03		
Sum of syst. uncert.:	2.4		3.4

preliminary

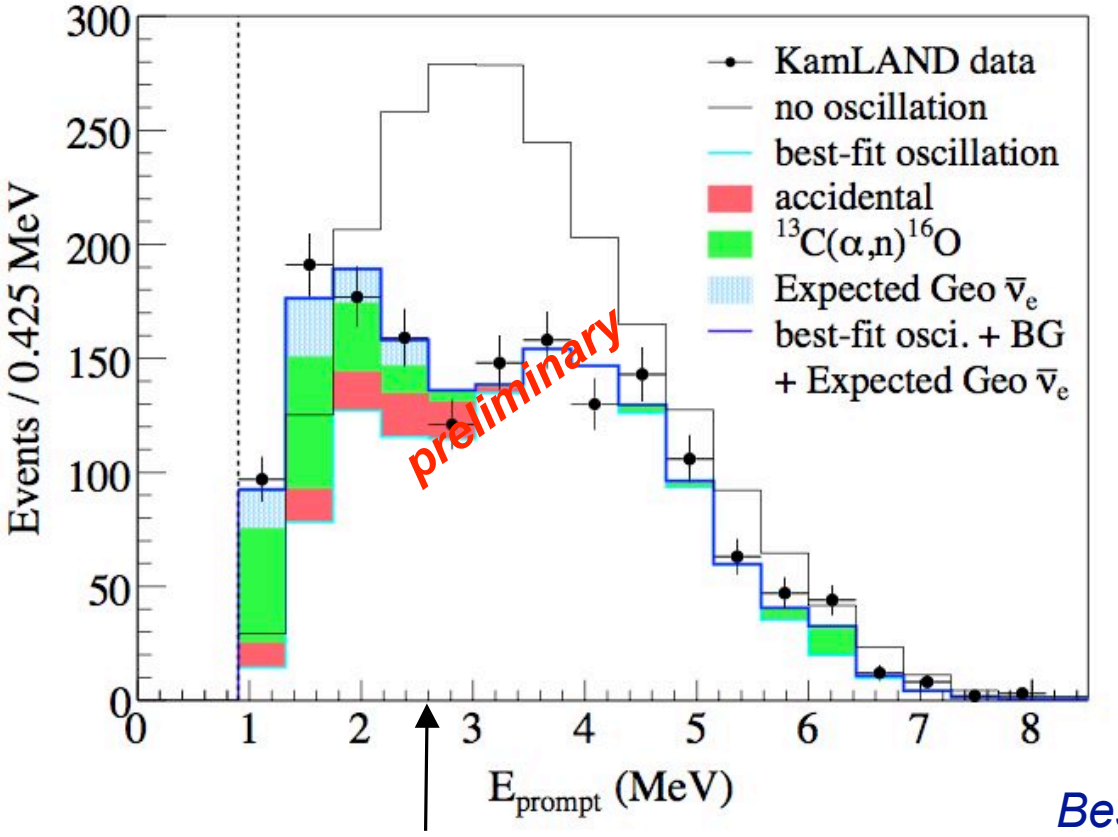
Flux Variation w/ Time

Flux variation in time adds small boost to oscillation sensitivity



KamLAND 2007 Oscillation Result

Unbinned likelihood fit (rate + shape + time)
2-flavor oscillation analysis w/ Earth-matter effects
geoneutrino U+Th amplitude is a free parameter



2178 events (+ 276.1±23.5 bg) expected for no osc.

1609 events observed
8.5σ disappearance sig.

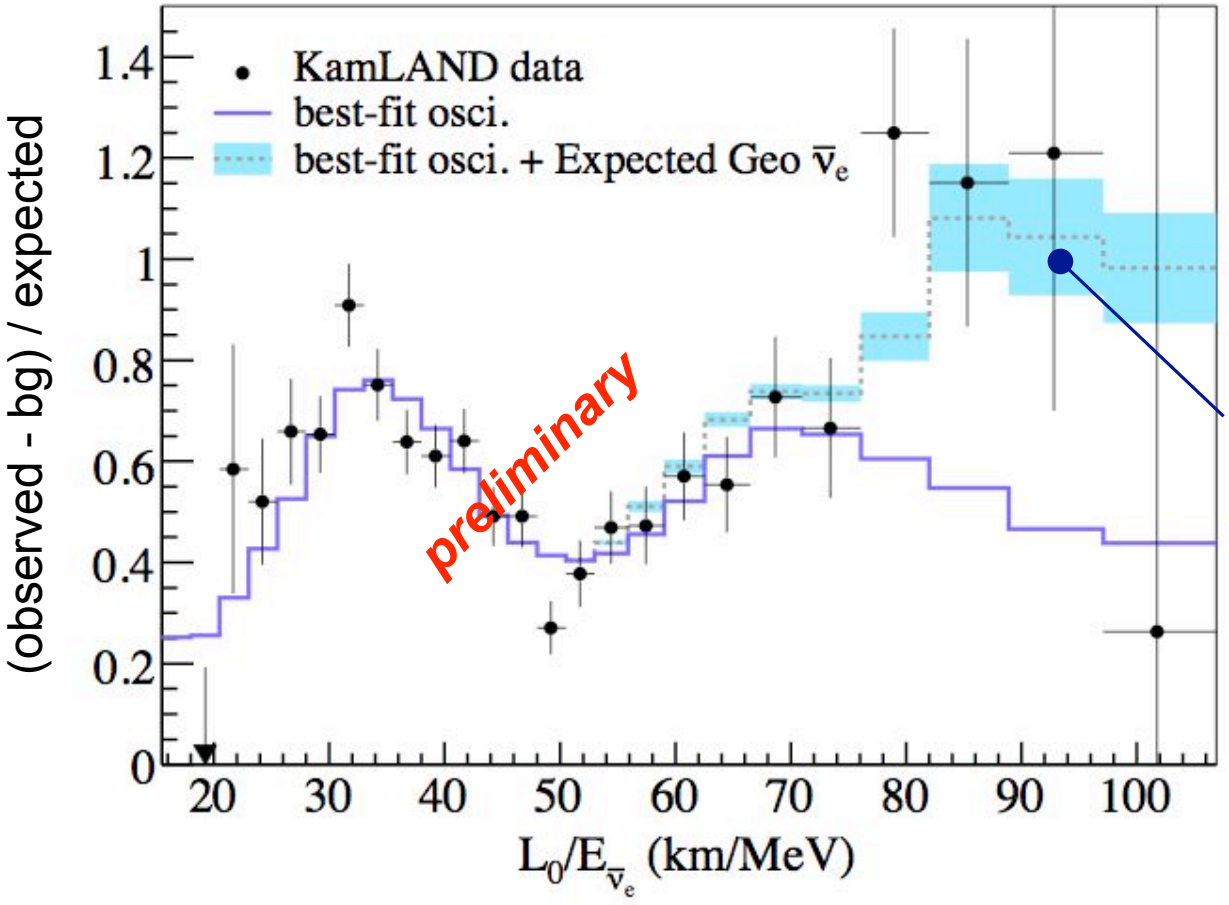
$\Delta m^2 = 7.58\,^{+0.21}_{-0.20} \times 10^{-5}$ eV^2

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

Significance of spectral distortion > 5σ

Goodness of Fit:
Best-Fit χ^2/dof = 21.0/16 (16% CL)

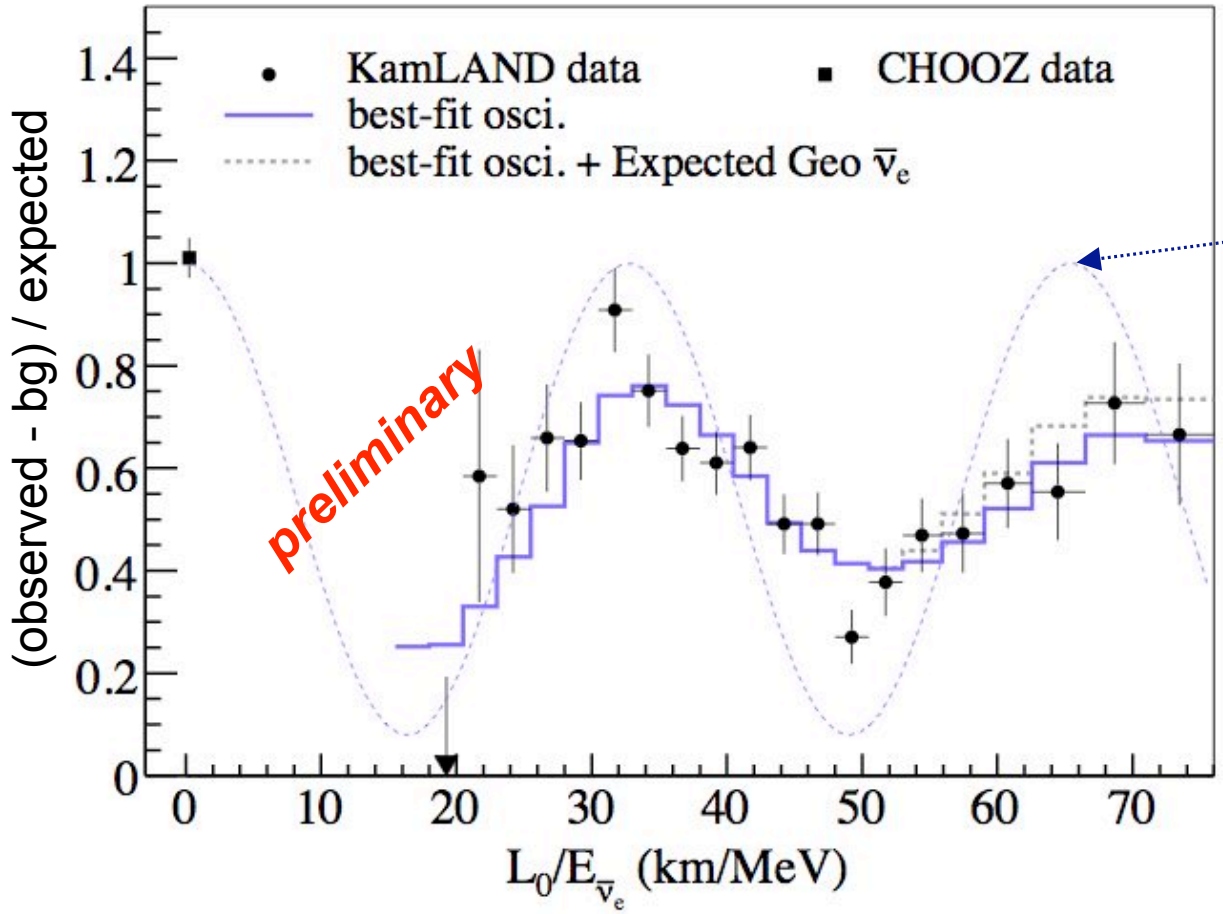
Survival Probablity + Expected Geo $\bar{\nu}_e$



Observed excess consistent with reference geoneutrino model

L_0 = 180km (flux-weighted average reactor distance)

Survival Probablity: Variation



Expected survival probablity for point source at 180km baseline

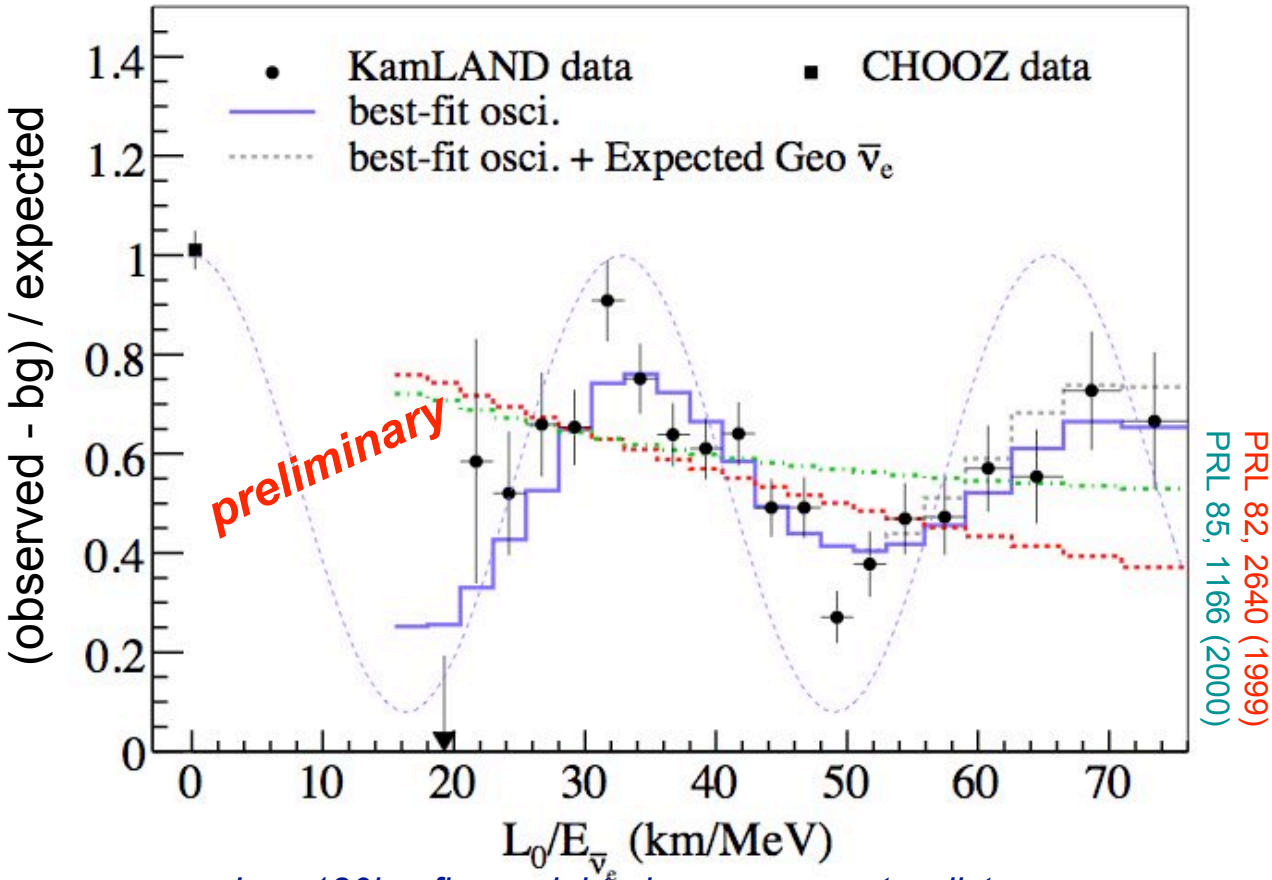
L_0 = 180km flux-weighted average reactor distance

Alternate Disappearance Hypotheses

Alternate Hypotheses Disfavored at > 3σ

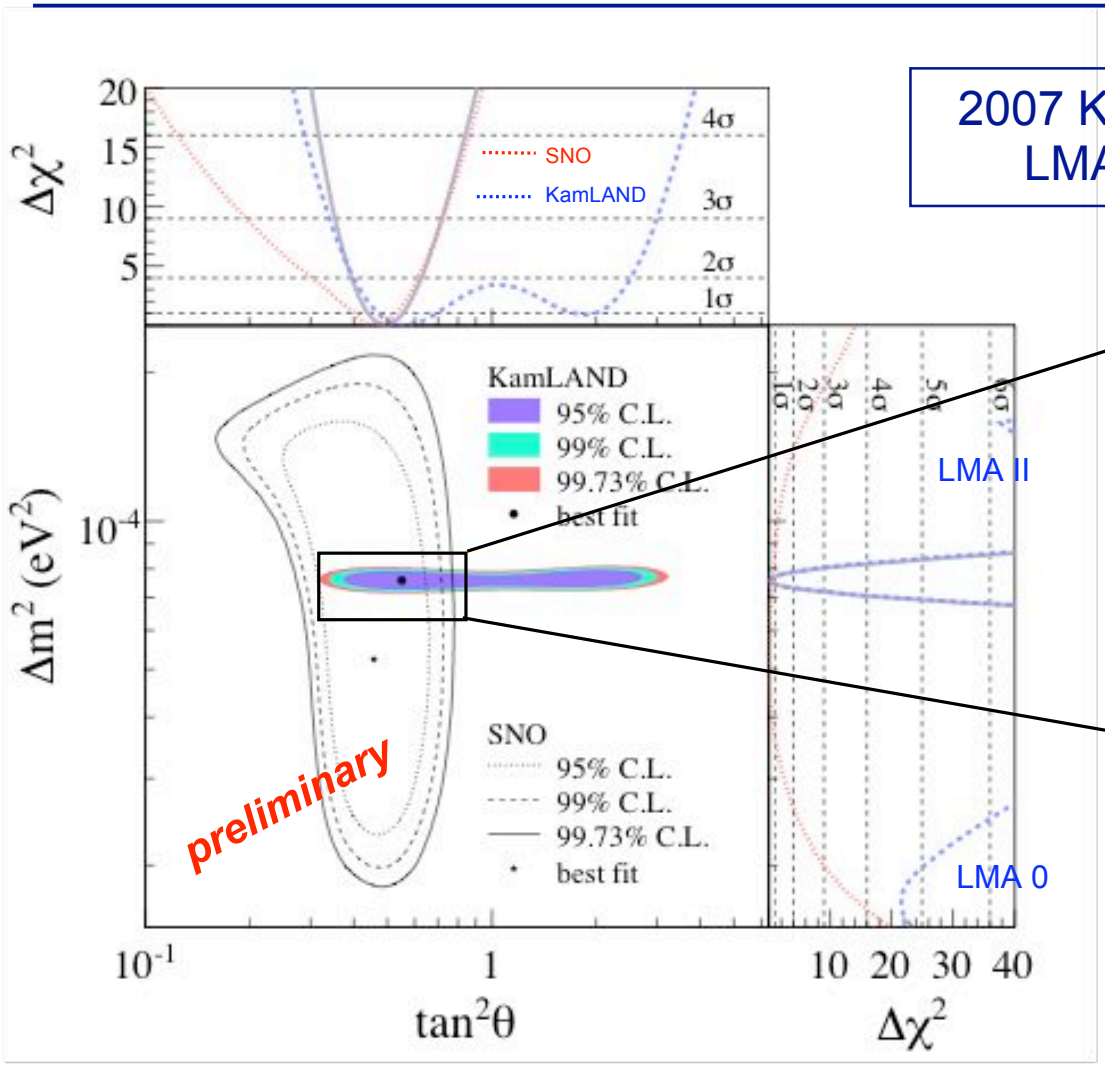
Best-Fit Decay: χ^2/dof = 46.53/16 (3.9σ)

Best-Fit Decoherence χ^2/dof = 55.18/16 (4.6σ)

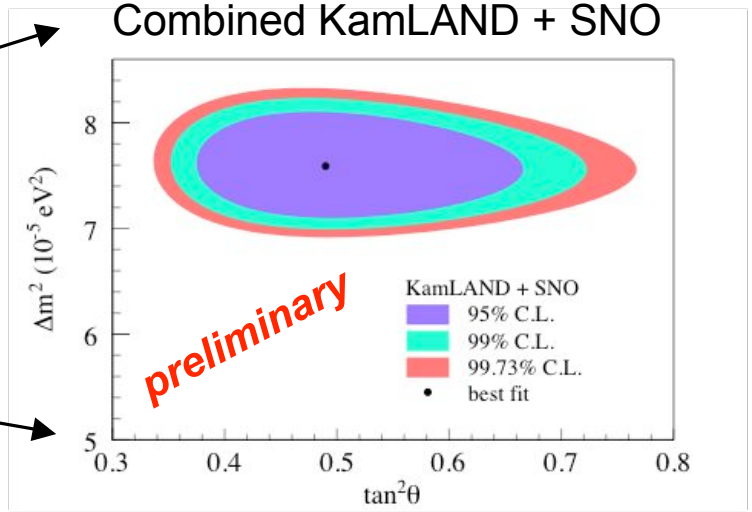


L_0 = 180km flux-weighted average reactor distance

Oscillation Parameter Space



2007 KamLAND result excludes LMA 0 and LMA II at > 4σ



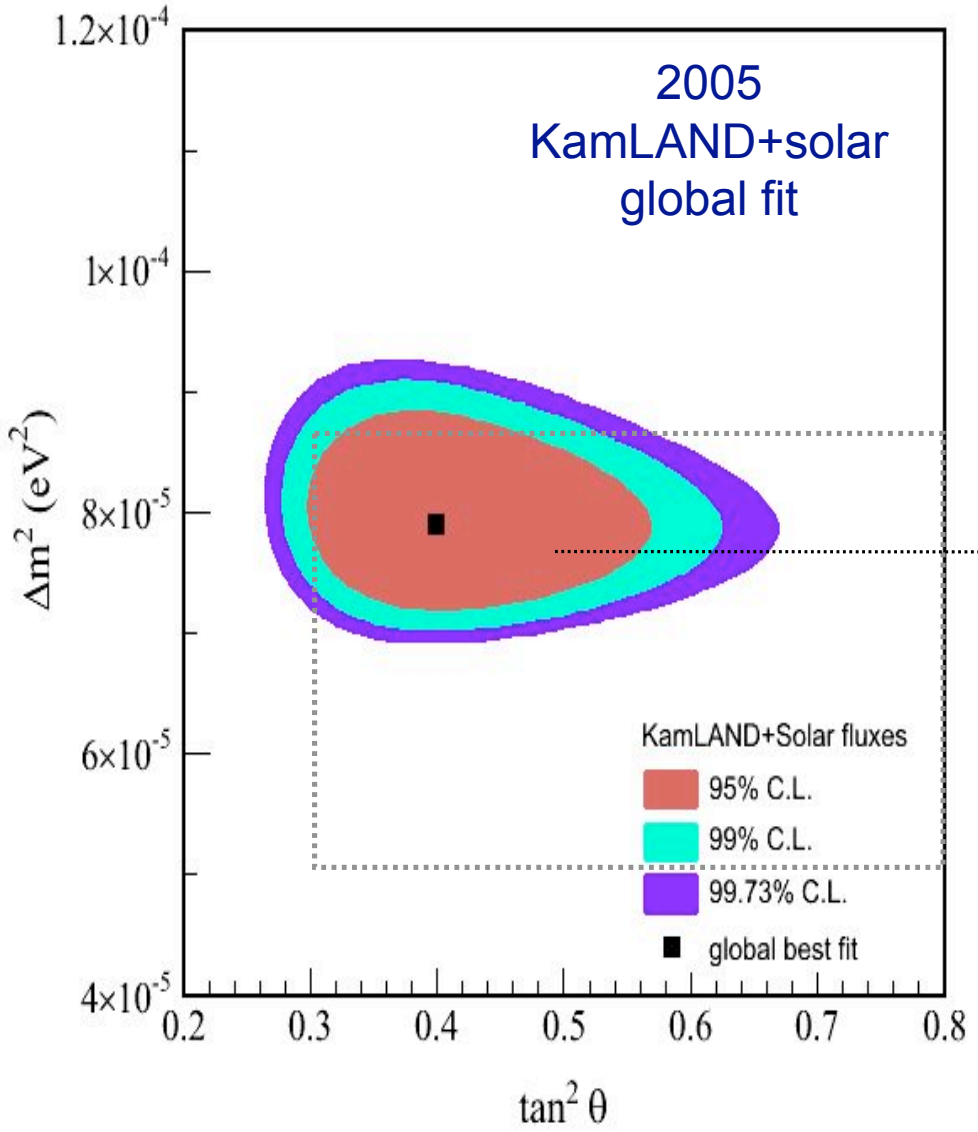
Combined Best-Fit Parameters:

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

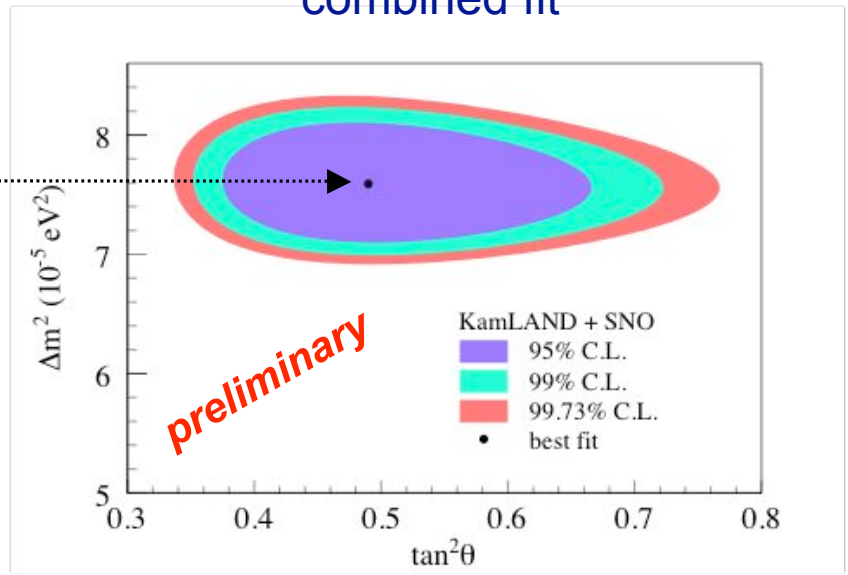
$\tan^2\theta = 0.49\ ^{+0.07}_{-0.05}$

SNO ref: Phys Rev C 72, 055502(2005)

Reduced Parameter Space



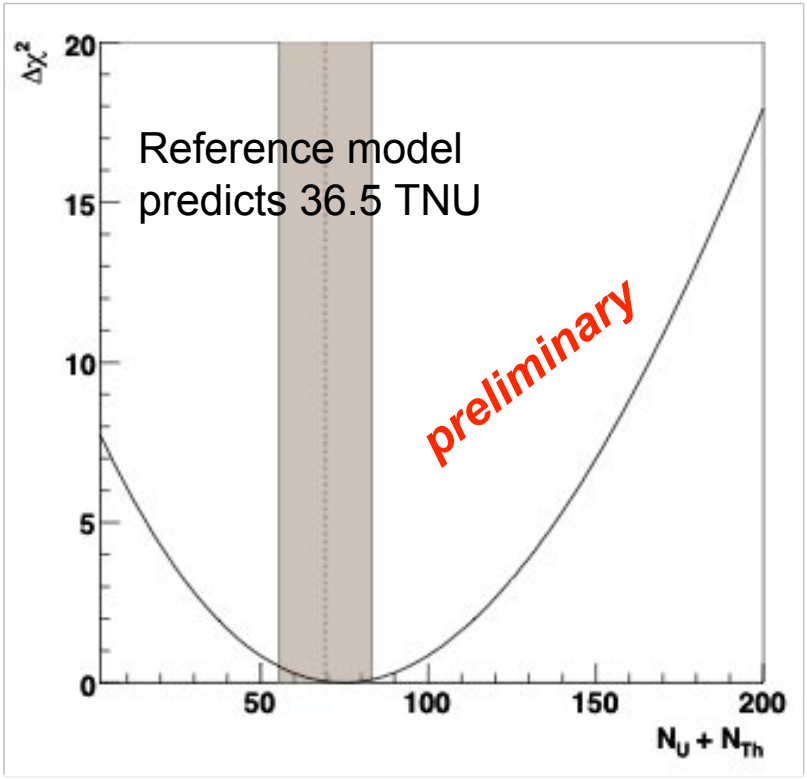
2007 KamLAND+SNO
combined fit



Geoneutrino Sensitivity

Geoneutrino fit:
Oscillation parameters constrained to best-fit KamLAND+SNO results

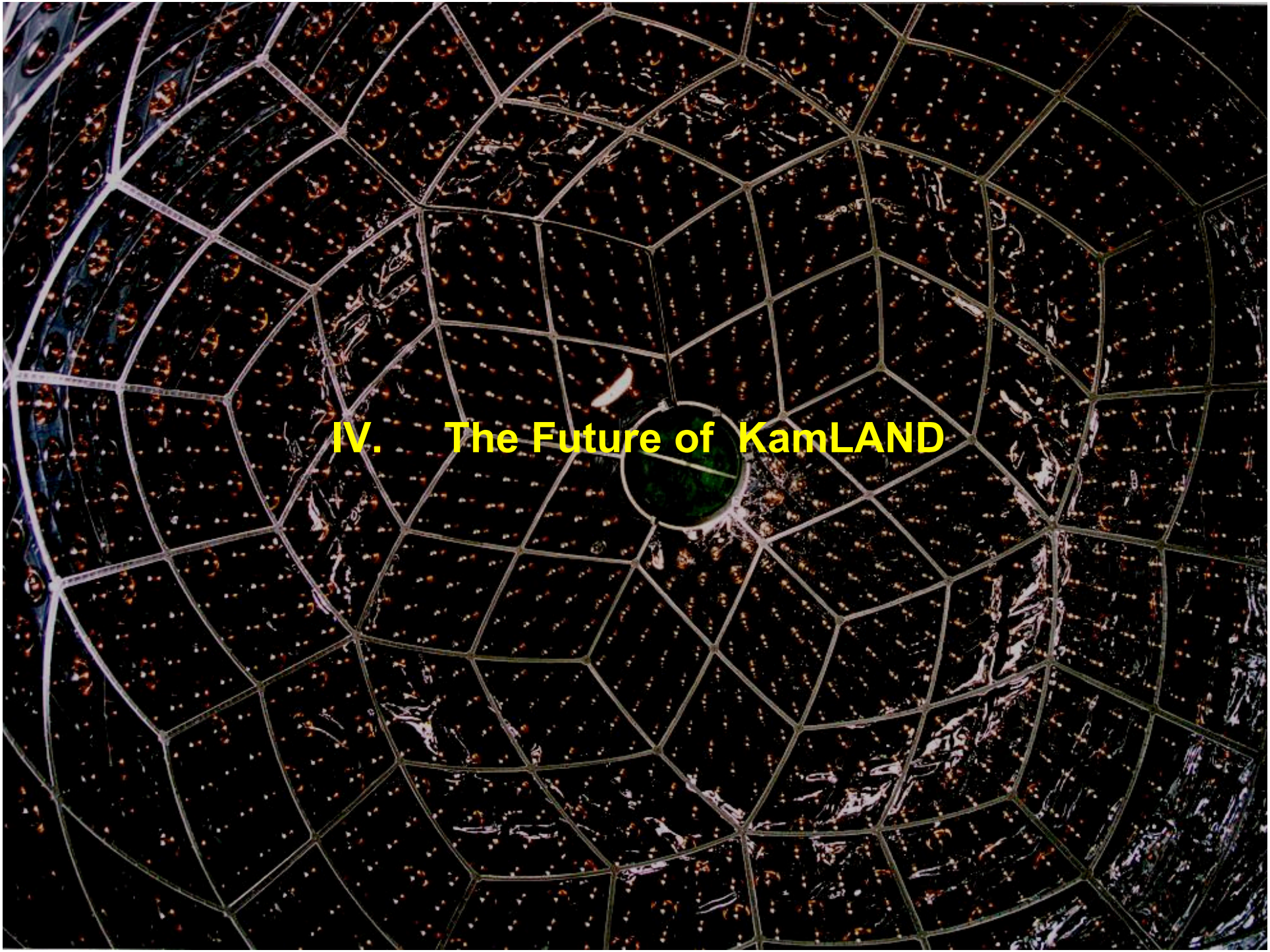
TNU =
"Terrestrial Neutrino Unit" =
events/10^{32} target protons/yr



Result:

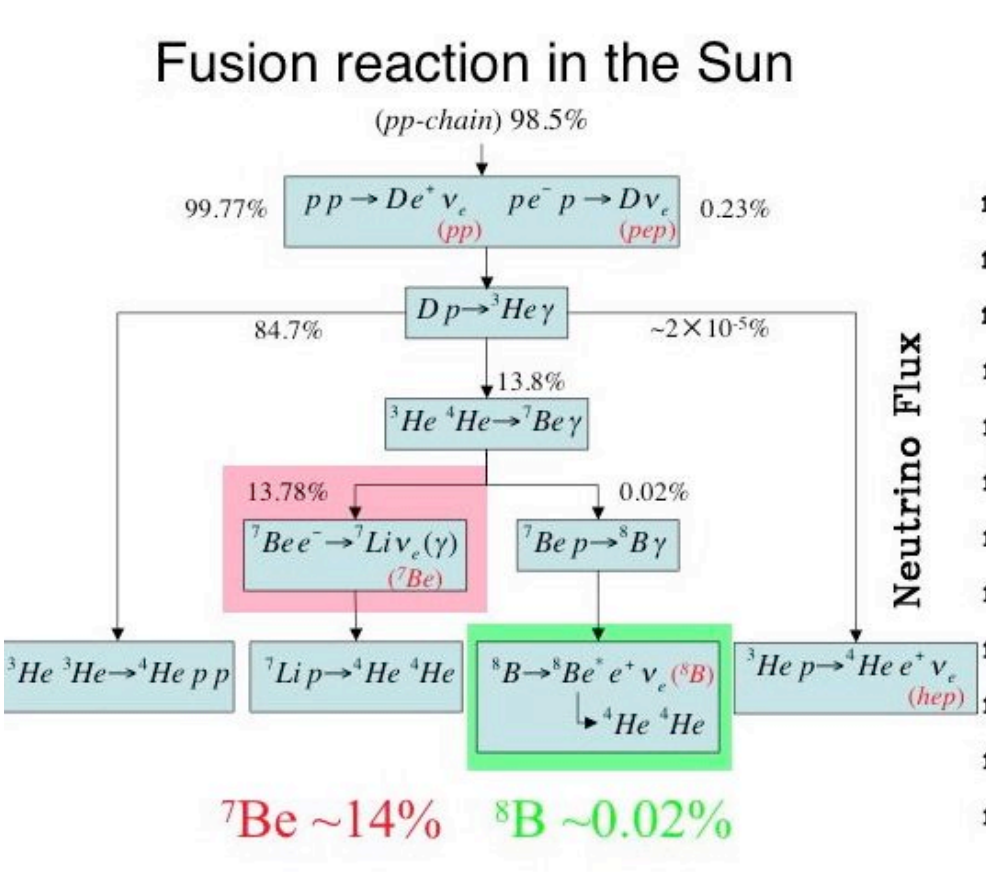
U+Th = 39.4 $^{+14.4}_{-14.3}$ TNU (constrained U:Th ratio = 3.9)

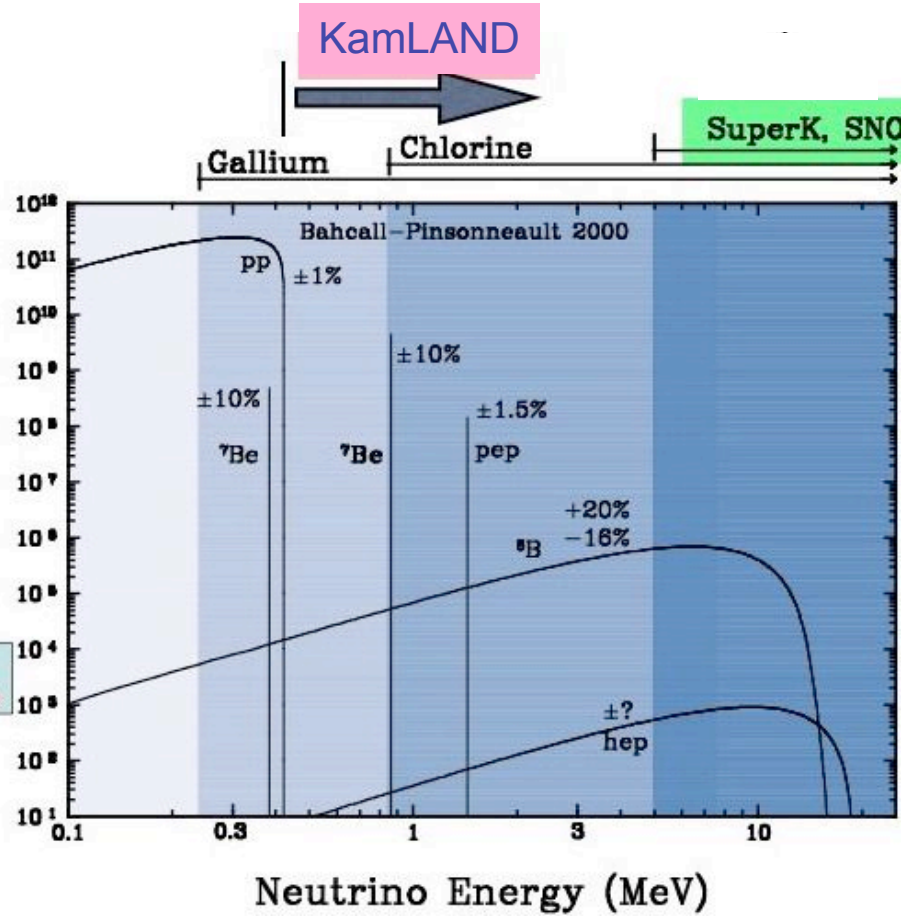
= 74.9 $^{+27.3}_{-27.2}$ events


IV. The Future of KamLAND

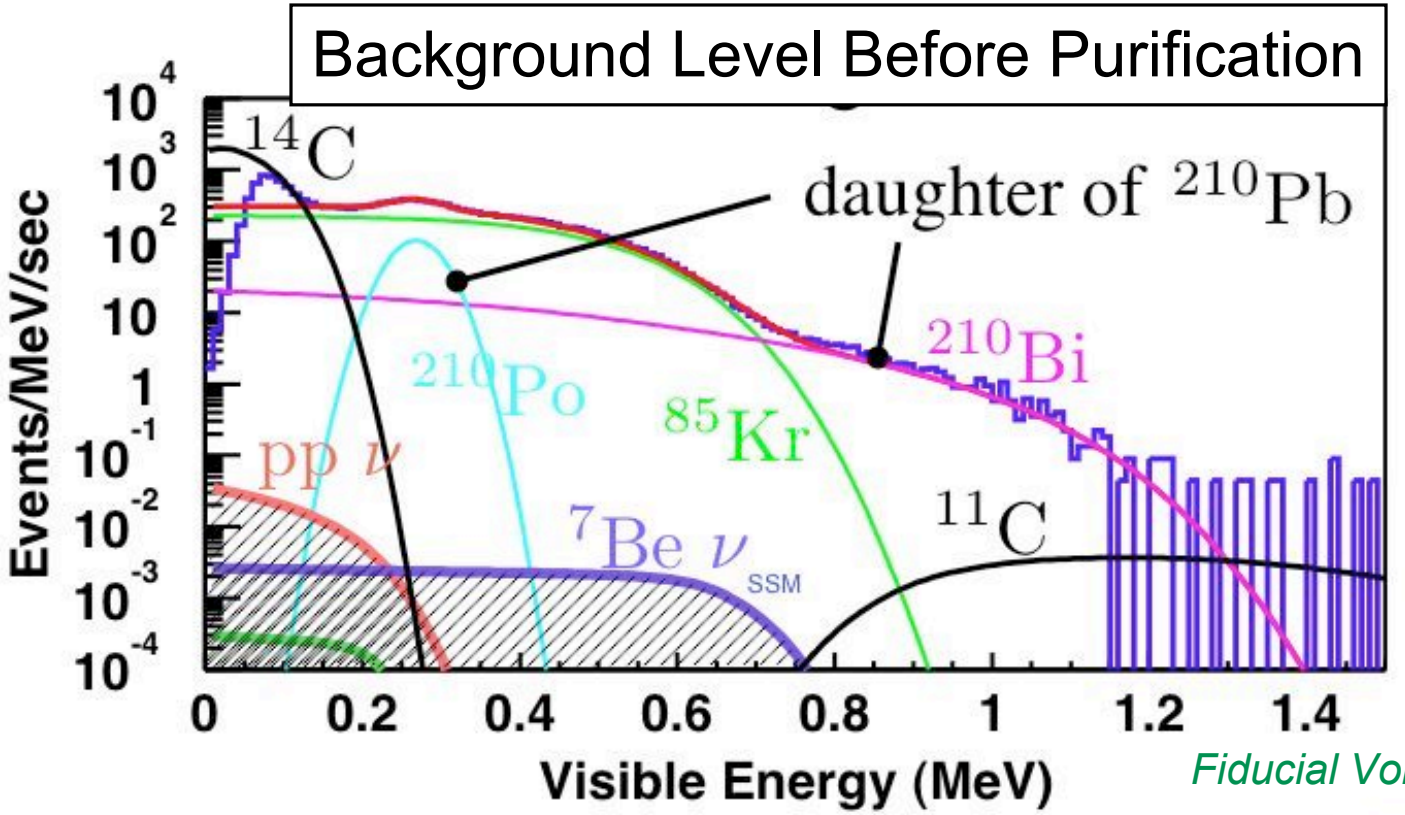
Be^7: KamLAND Low-Background Phase

- *Verification of low energy neutrino flux from Sun*
- *Observe transition from vacuum to matter-enhanced oscillations*
- *Significantly reduce bg in reactor and geoneutrino analyses*





An Ambitious Purification Project



Detect ν_e via elastic scattering
no coincidence to suppress radioactive backgrounds!

reduce ^{210}Pb by 5 orders of magnitude!
reduce ^{85}Kr by 6 orders of magnitude!

Testbench Results

Testbench R&D performed 2002-2006

distillation in ~ liter-system

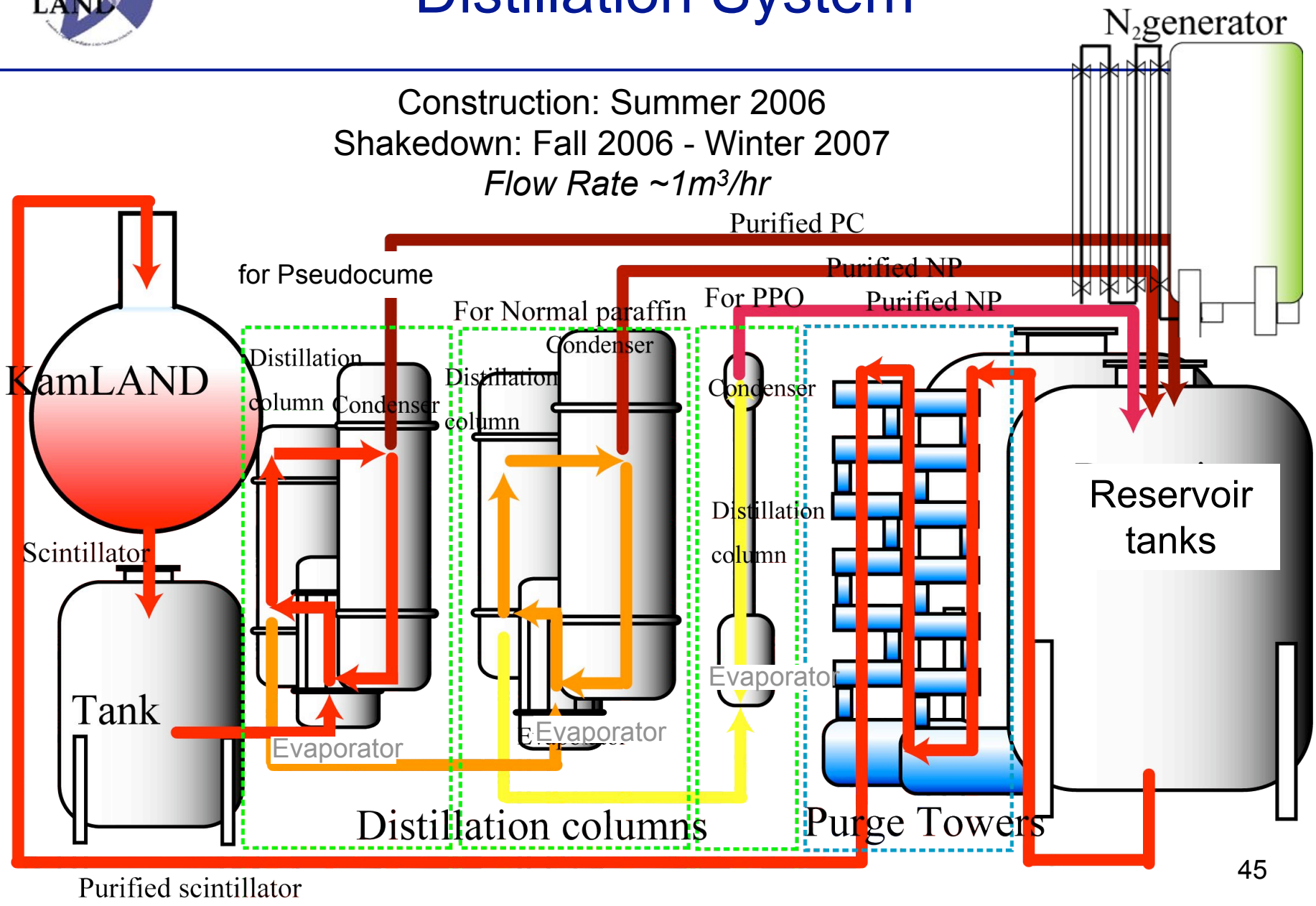
radioactive nuclei	reduction	goal
^{40}K	3.8×10^{-2} (PPO, ^{40}K)	**10^{-1} ~ 10^{-2}**
^{85}Kr	$< 1.3 \times 10^{-5}$ (Dodecane, Kr)	**10^{-5} ~ 10^{-6}**
^{210}Pb	$< 7.6 \times 10^{-5}$ (Dodecane, ^{212}Pb)	**10^{-4} ~ 10^{-5}**
^{222}Rn	6.0×10^{-4} (Dodecane, ^{222}Rn)	**~ 10^{-3}**

Reduction achieved w/ introduction of N_2

almost succeeded in the reduction goal

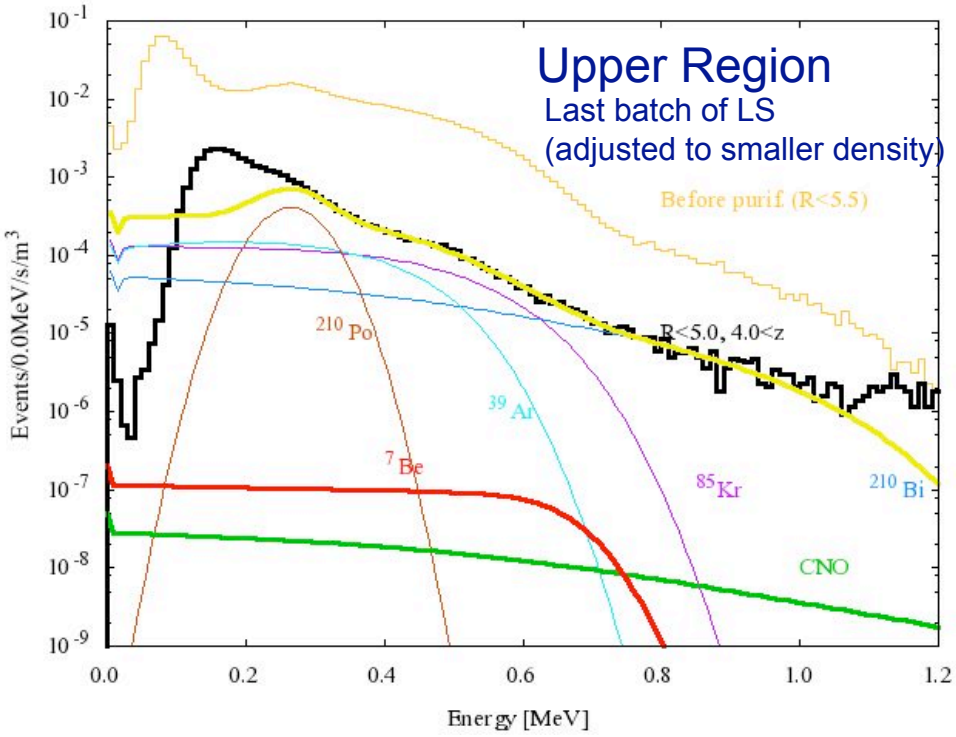
Distillation System

Construction: Summer 2006
Shakedown: Fall 2006 - Winter 2007
Flow Rate ~1m³/hr

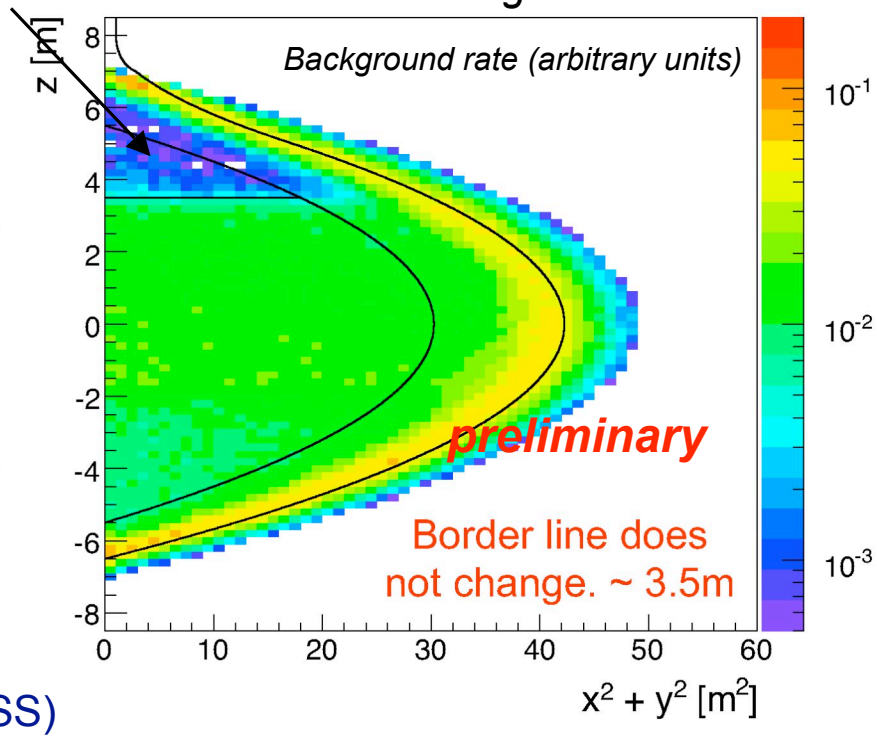


First Full-Scale Distillation

Circulation from/to detector started May 2007!



density gradient prevents mixing



- 1.4X volume exchange achieved
- Purification halted for mine blasting (for XMASS)
- Purification apparatus to be upgraded for stage II

Summary

KamLAND is the first experiment to observe disappearance of reactor anti-neutrinos (currently measured to 8.5σ significance).

New results with lowered E_{prompt} threshold exclude "no spectral distortion" case at > 5σ

New precision oscillation parameter measurement (KL only):

$\Delta m^2 = 7.58\ ^{+0.21}_{-0.20} \times 10^{-5} eV^2$ and $\tan^2\theta = 0.56\ ^{+0.14}_{-0.09}$

& improved sensitivity to geoneutrinos

Improvements with this result: enlarged dataset (2881 ton-yr), commissioning of off-axis calibration system, improved $^{13}C(\alpha,n)^{16}0$ estimation, combined reactor+geo analysis

These results conclude the first phase of KamLAND, but KamLAND is not finished yet!

Phase II of KamLAND has begun: First pass purification shows background reduction, very-low-background measurements to come.

Acknowledgements

Tohoku U.

LBNL
Stanford
CalTech
Colorado SU
Kansas SU
U. of TN
U. of AL
TUNL
Drexel
U. of NM
U. of HI
UW Madison

IHEP

CENBG

The work presented here was due to the hard work of the entire KamLAND collaboration

(and many pieces of this talk were borrowed liberally from my colleagues)