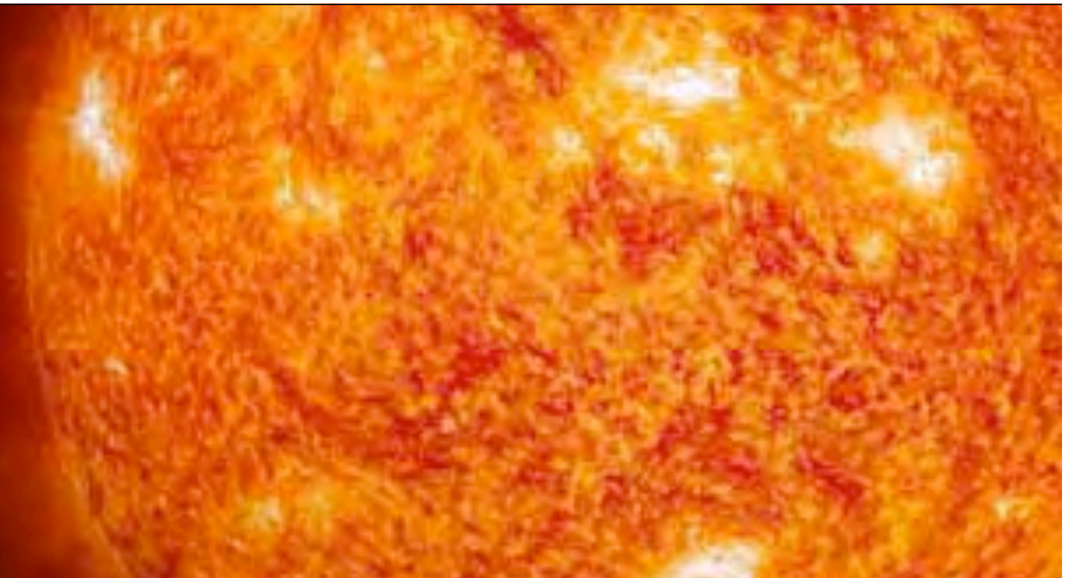
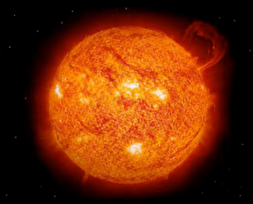


KamLAND

Rencontres de Moriond
March 13, 2009

Lindley Winslow
Lawrence Berkeley National Lab
Massachusetts Institute of Technology



Outline

- Motivation.
- Some Details of the Experiment.
- Recent Results (Phys.Rev.Lett100:221803,2008).
- Low Background Phase - the Future.

Precision Measurement of Neutrino Oscillation Parameters with KamLAND

S. Abe,[1] T. Ebihara,[1] S. Enomoto,[1] K. Furuno,[1] Y. Gando,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] Y. Kibe,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Konno,[1] A. Kozlov,[1] Y. Minekawa,[1] T. Mitsui,[1] K. Nakajima,[1,*] K. Nakajima,[1] K. Nakamura,[1] M. Nakamura,[1] K. Owada,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] Y. Takemoto,[1] K. Tamae,[1] A. Terashima,[1] H. Watanabe,[1] E. Yonezawa,[1] S. Yoshida,[1] J. Busenitz,[2] T. Classen,[2] C. Grant,[2] G. Keefer,[2] D.S. Leonard,[2] D. McKee,[2] A. Piepke,[2] M.P. Decowski,[3] J.A. Detwiler,[3] S.J. Freedman,[3] B.K. Fujikawa,[3] F. Gray,[3,†] E. Guardincerri,[3] L. Hsu,[3,‡] R. Kadel,[3] C. Lendvai,[3] K.-B. Luk,[3] H. Murayama,[3] T. O'Donnell,[3] H.M. Steiner,[3] L.A. Winslow,[3] D.A. Dwyer,[4] C. Jillings,[4,§] C. Mauger,[4] R.D. McKeown,[4] P. Vogel,[4] C. Zhang,[4] B.E. Berger,[5] C.E. Lane,[6] J. Maricic,[6] T. Miletic,[6] M. Batygov,[7] J.G. Learned,[7] S. Matsuno,[7] S. Pakvasa,[7] J. Foster,[8] G.A. Horton-Smith,[8] A. Tang,[8] S. Dazeley,[9,¶] K.E. Downum,[10] G. Gratta,[10] K. Tolich,[10] W. Bugg,[11] Y. Efremenko,[11] Y. Kamyshkov,[11] O. Perevozchikov,[11] H.J. Karwowski,[12] D.M. Markoff,[12] W. Tornow,[12] K.M. Heeger,[13] F. Piquemal,[14] and J.-S. Ricol[14]

(The KamLAND Collaboration)

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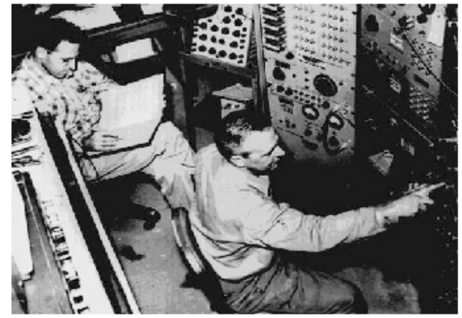
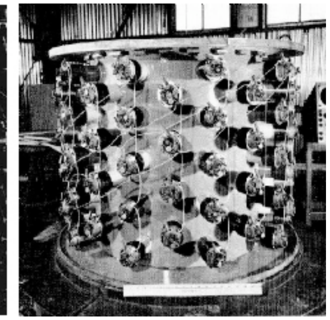
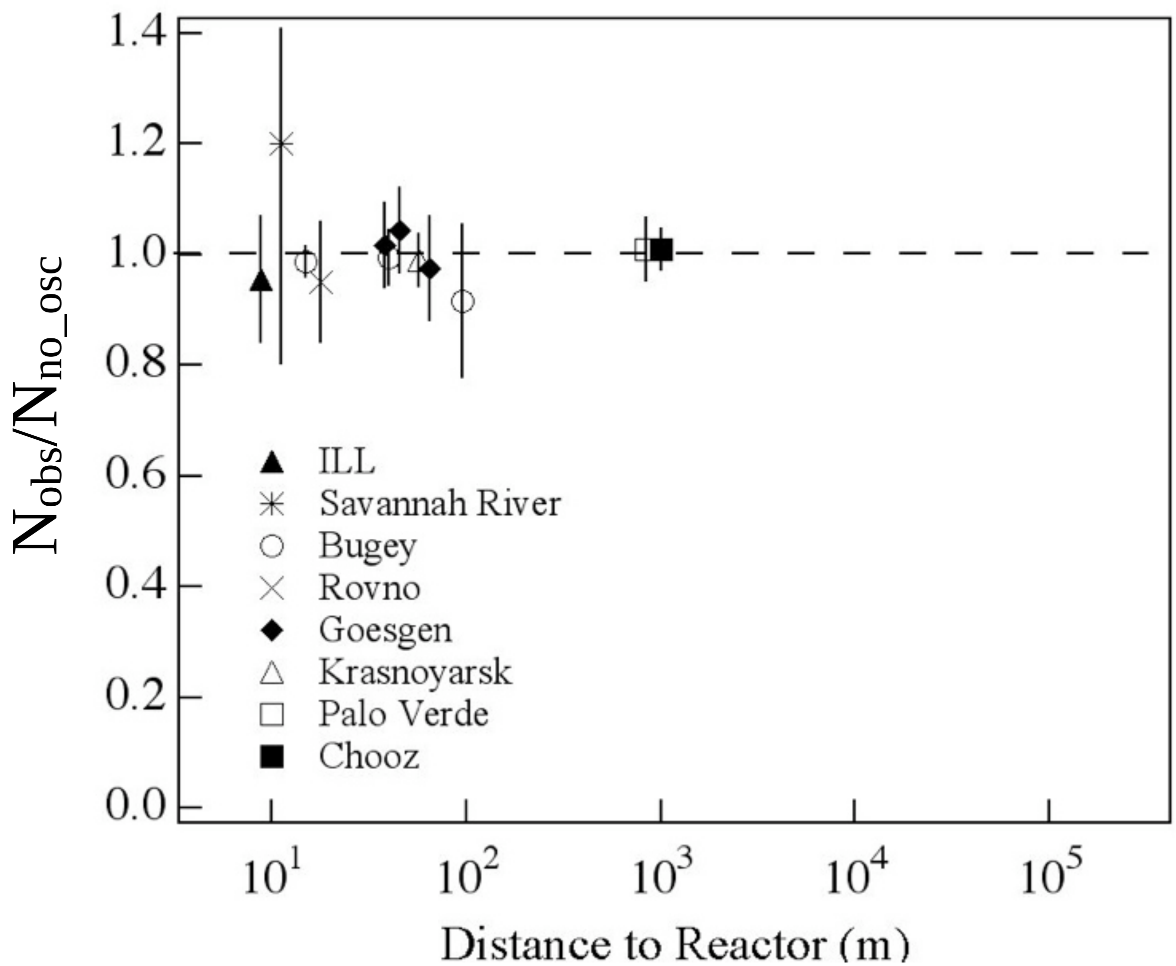
Reactor Anti-neutrino Problem!



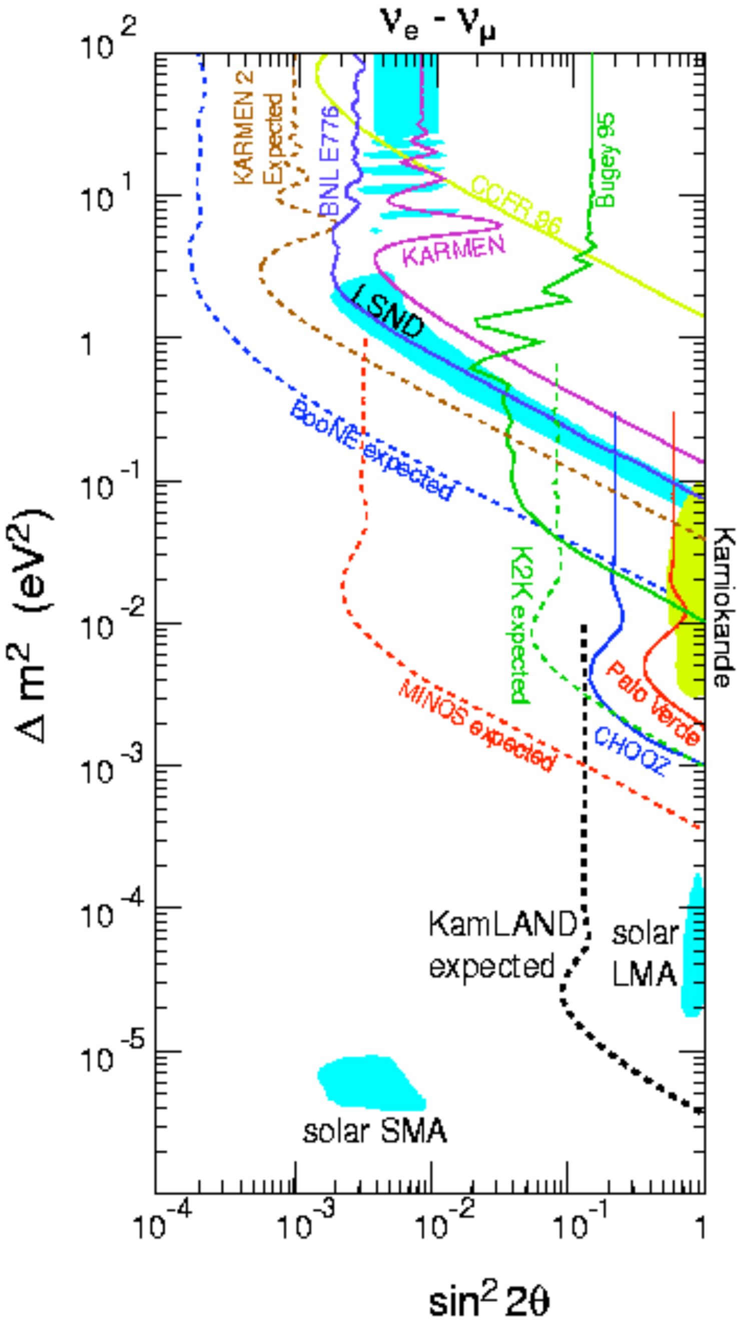


- Reactor experiments had not found a deficit of anti-neutrinos like that seen in the solar experiments.

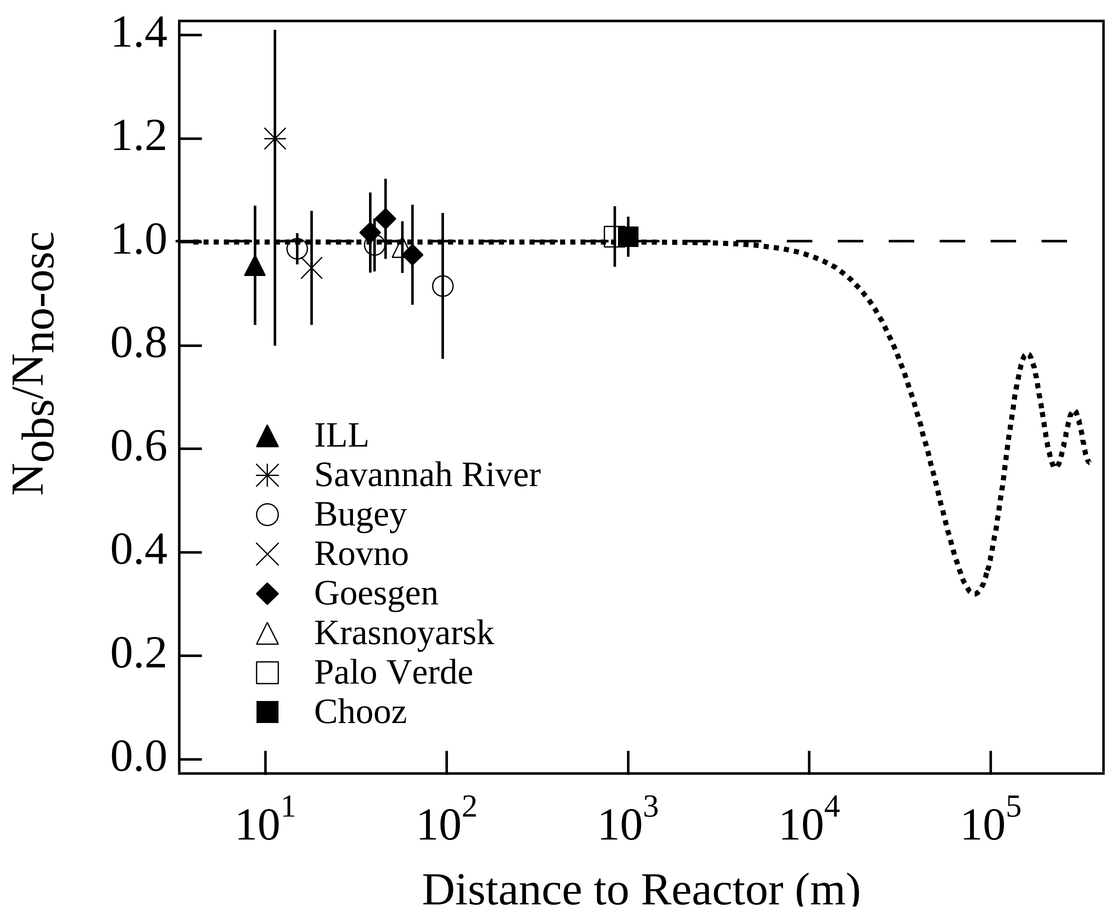


Planning For KamLAND

- If large mixing angle solution is right then an experiment will need to be more than 100 km from the source.

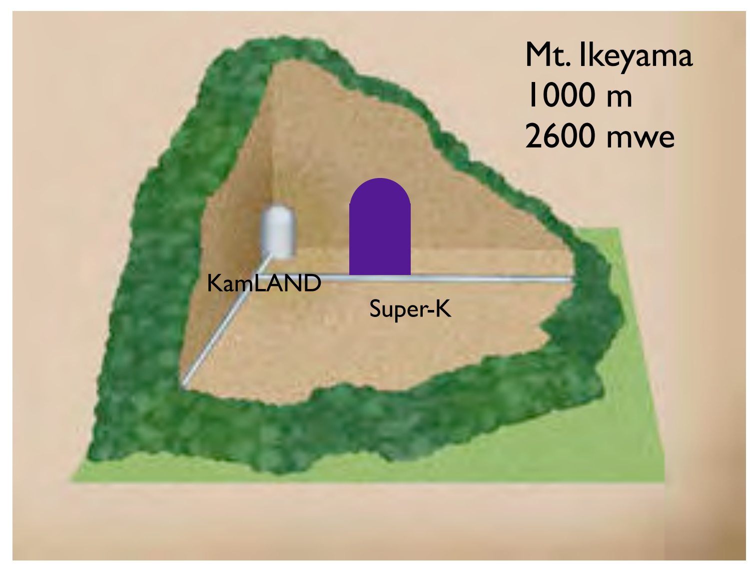


From KamLAND proposal.



Planning For KamLAND

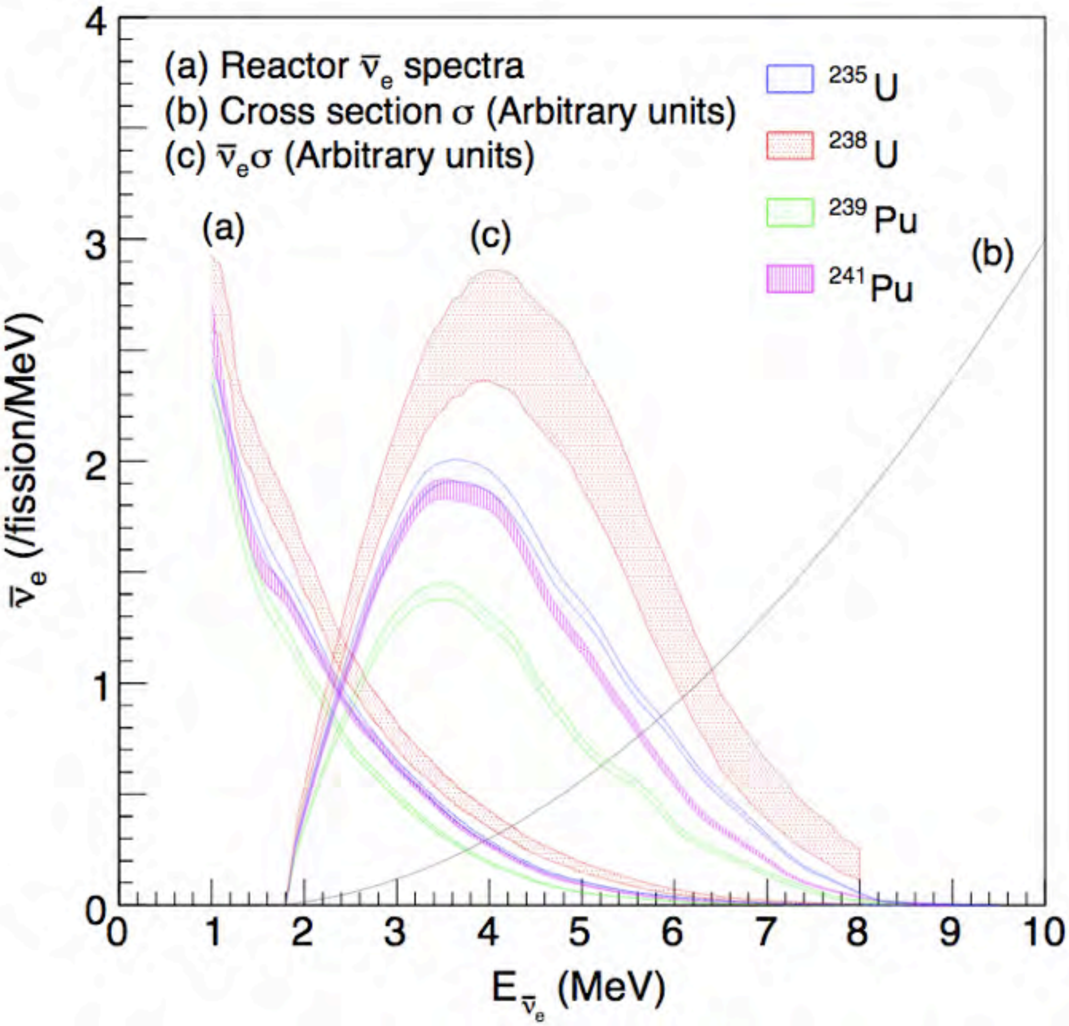
- The Kamioka mine in Japan is a logical place to house such a experiment.
- Japan is the third largest producer of nuclear power.
- Most reactors right on the coast.



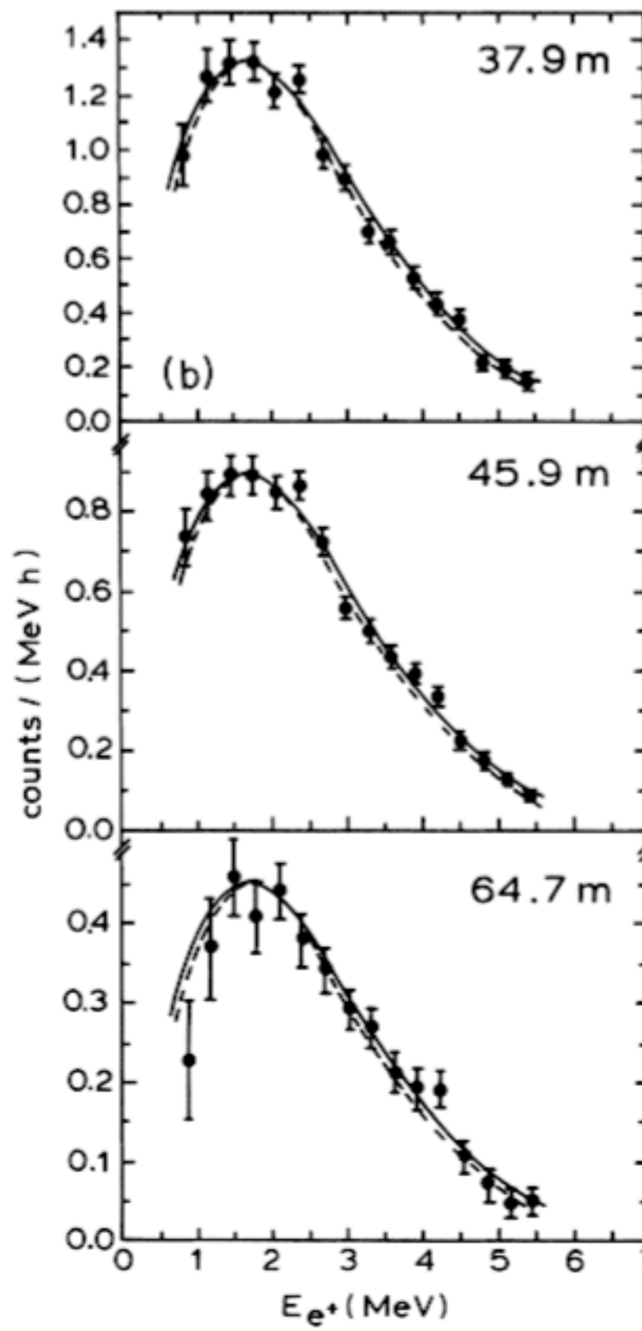
Calculating the Reactor Spectrum:

- Power companies provide number of fissions per isotope per day per reactor.

Nakajima NIMA 569, 837-844 (2006)

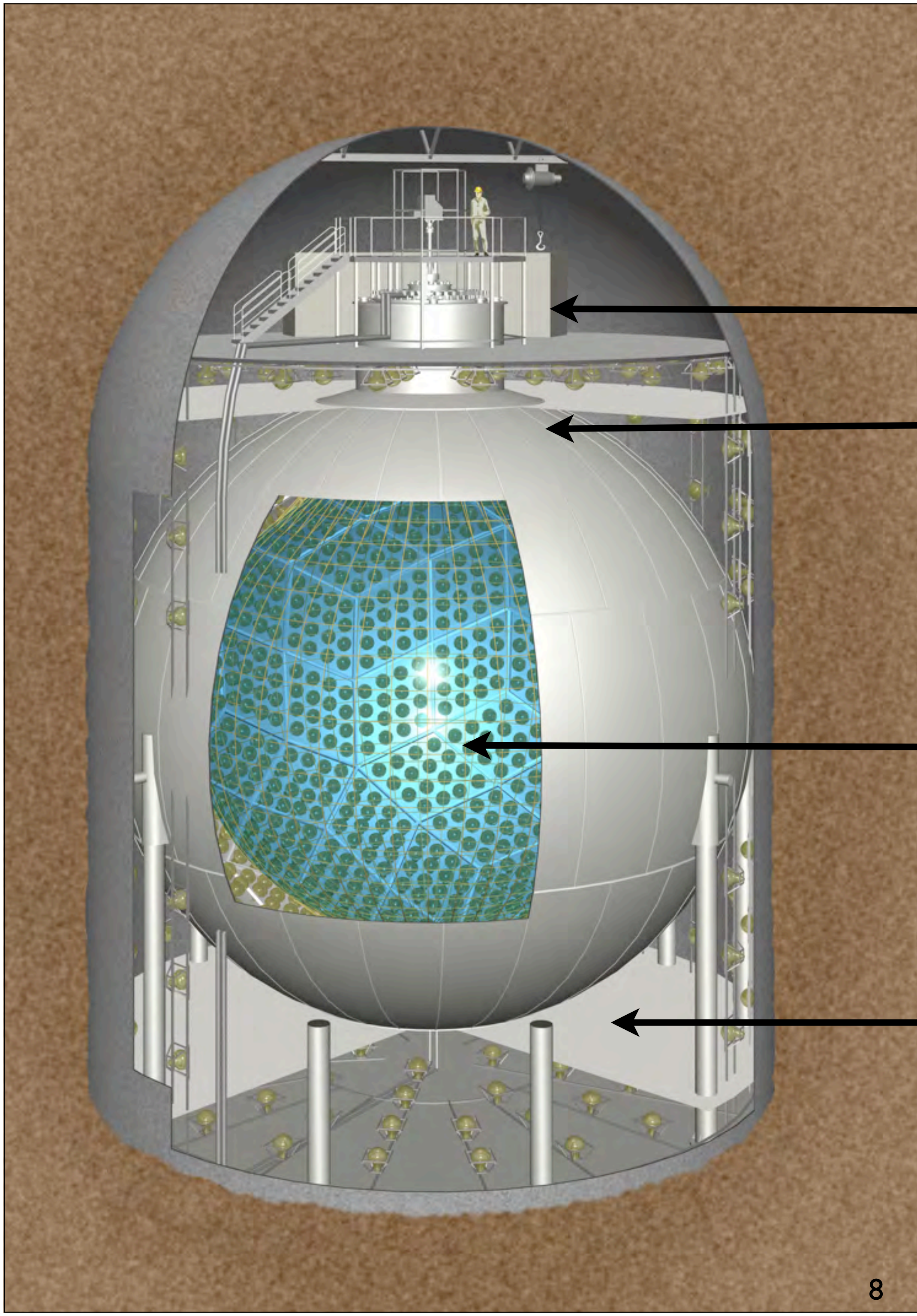


Gösgen Measured Reactor Spectrum



Phys. Rev. D 34, 2621-2636 (1986)

KamLAND: The Detector



A Kilo-Tonne Liquid Scintillator!

Electronics Hut

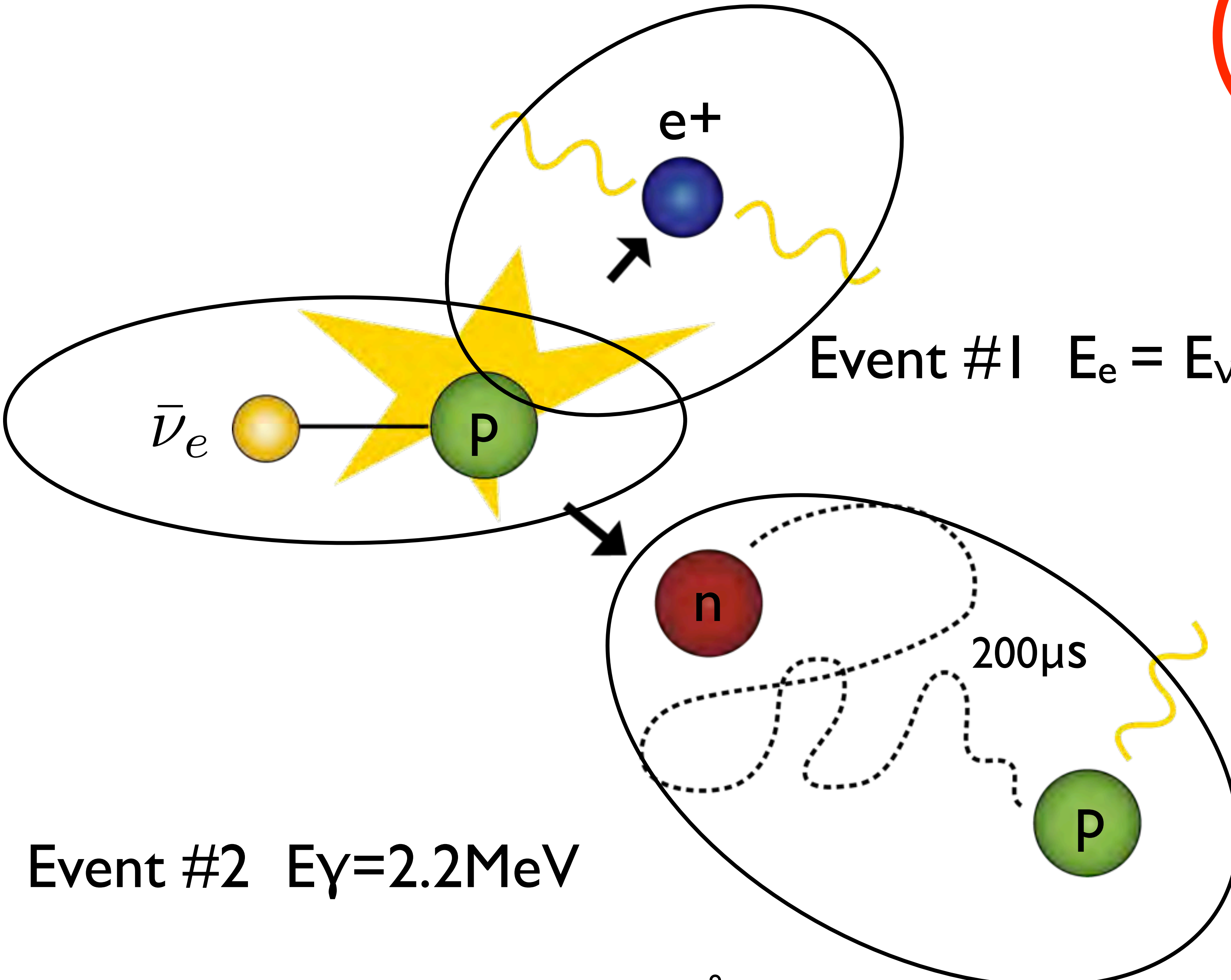
Stainless Steel Sphere
- 8.5m radius
- 1325 17'' PMTs
- 554 20'' PMTs

Nylon Balloon
- 6.5m radius
- Separates BO and LS.

Water Cerenkov Veto
- 225 20'' PMTs

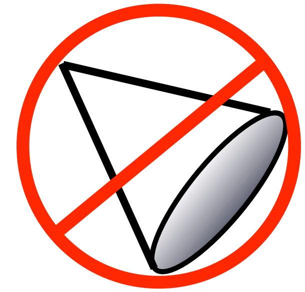
KamLAND LS is 80% mineral oil, 20% psuedo-cumene, and 1.36 g/L PPO.

Anti-Neutrino Detection - Inverse Beta Decay



Event #1 $E_e = E_\nu$ - 0.8MeV

Event #2 Eγ=2.2MeV



The Earth

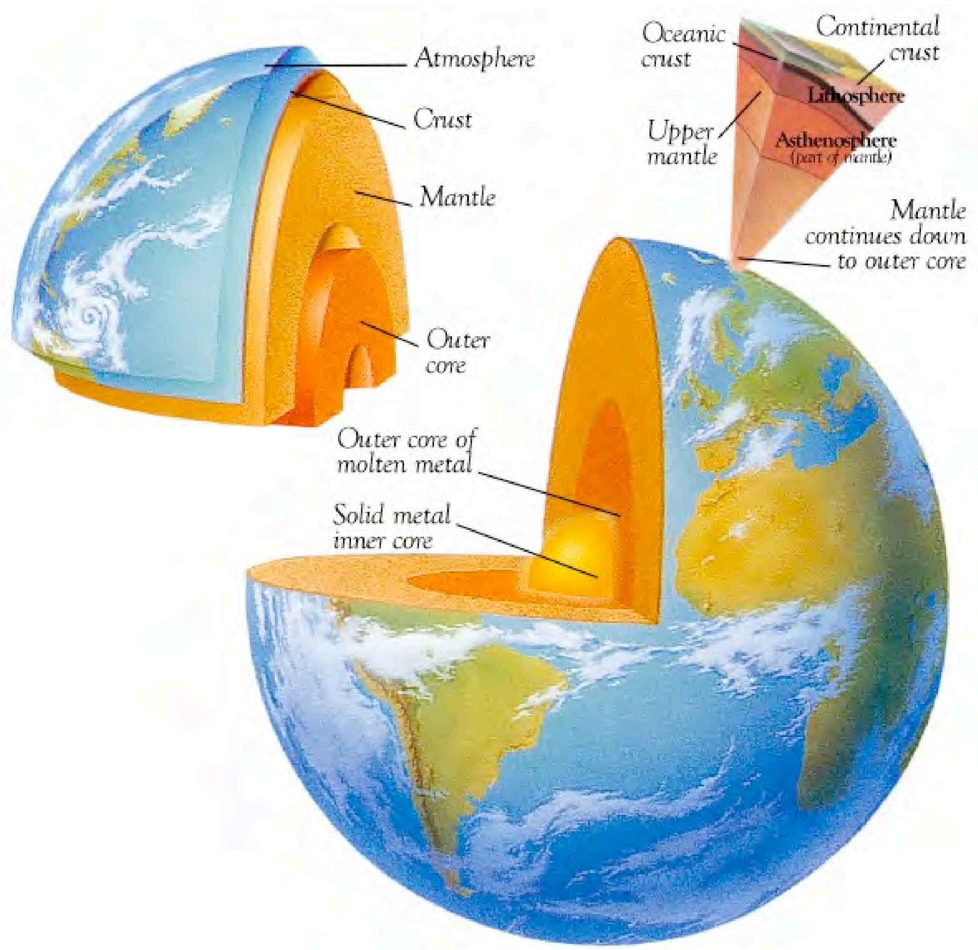
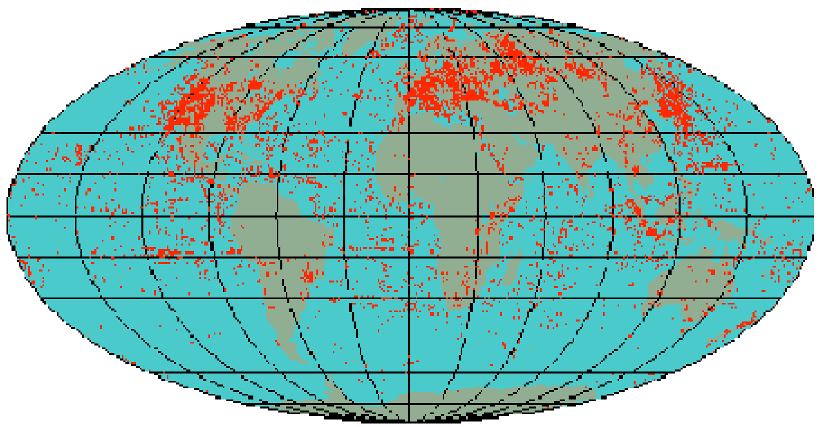
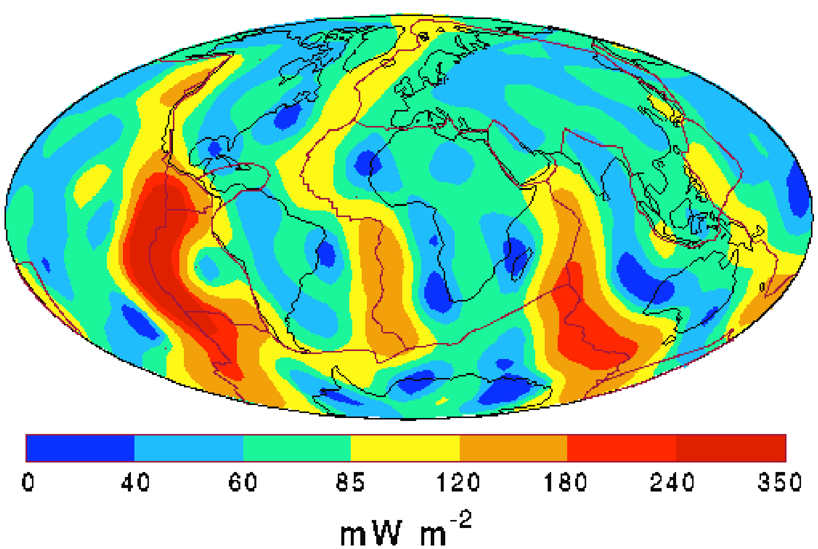


Image By: Colin Rose and Dorlen Kindersley

Geophysics - Total Heat Flow





- Conductive heat flow measured from bore-holes temperature and conductivity gradient.

- Total Heat Flow

  44.2±1.0TW

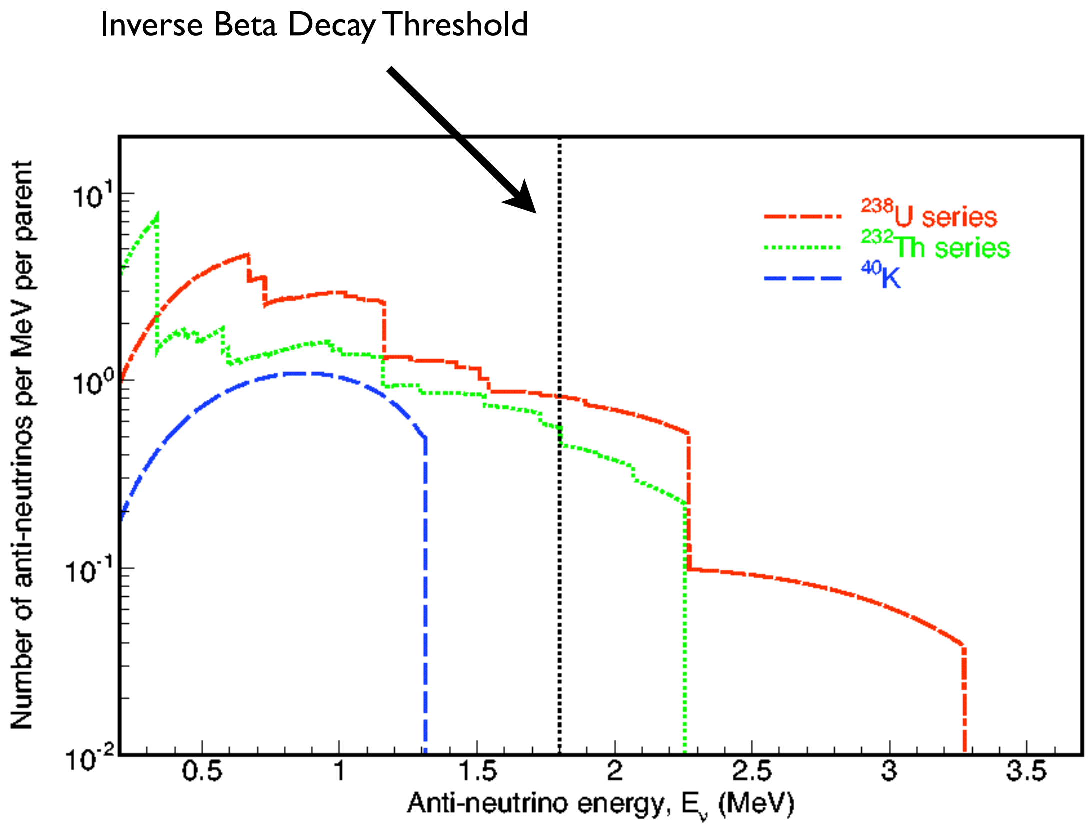
  or

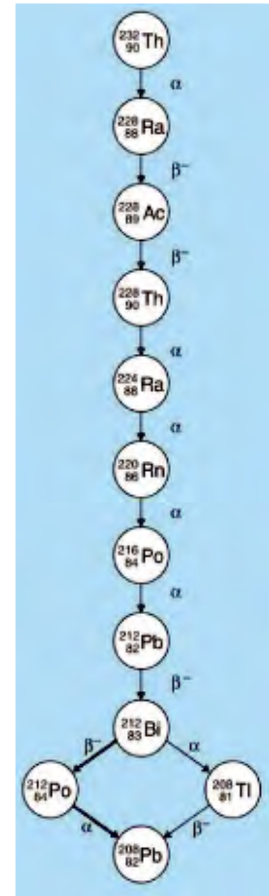
  31±1TW *

* Most recent analysis of same data.

arXiv:hep-ph/0508049v2
Nature 436:499-503,2005

Total Heat Flow - Radioactive Decay





- Heat is produced by the decay of ^{238}U (8TW), ^{232}Th (8TW) and ^{40}K (3TW).
- U and Th are lithofiles so they should be drawn to the crust.
- The U/Th Ratio is well constrained by measurements of chondritic meteorites.

Find the Anti-Neutrinos:

- Fiducial Volume Cut.

  R < 5.5 m

- Time Between Prompt and Delayed:

  0.5μs < ΔT < 1000μs

- Spatial Separation:

  ΔR < 2m

- Energy Cuts:

  2.6 MeV < E_{prompt} < 8.5 MeV

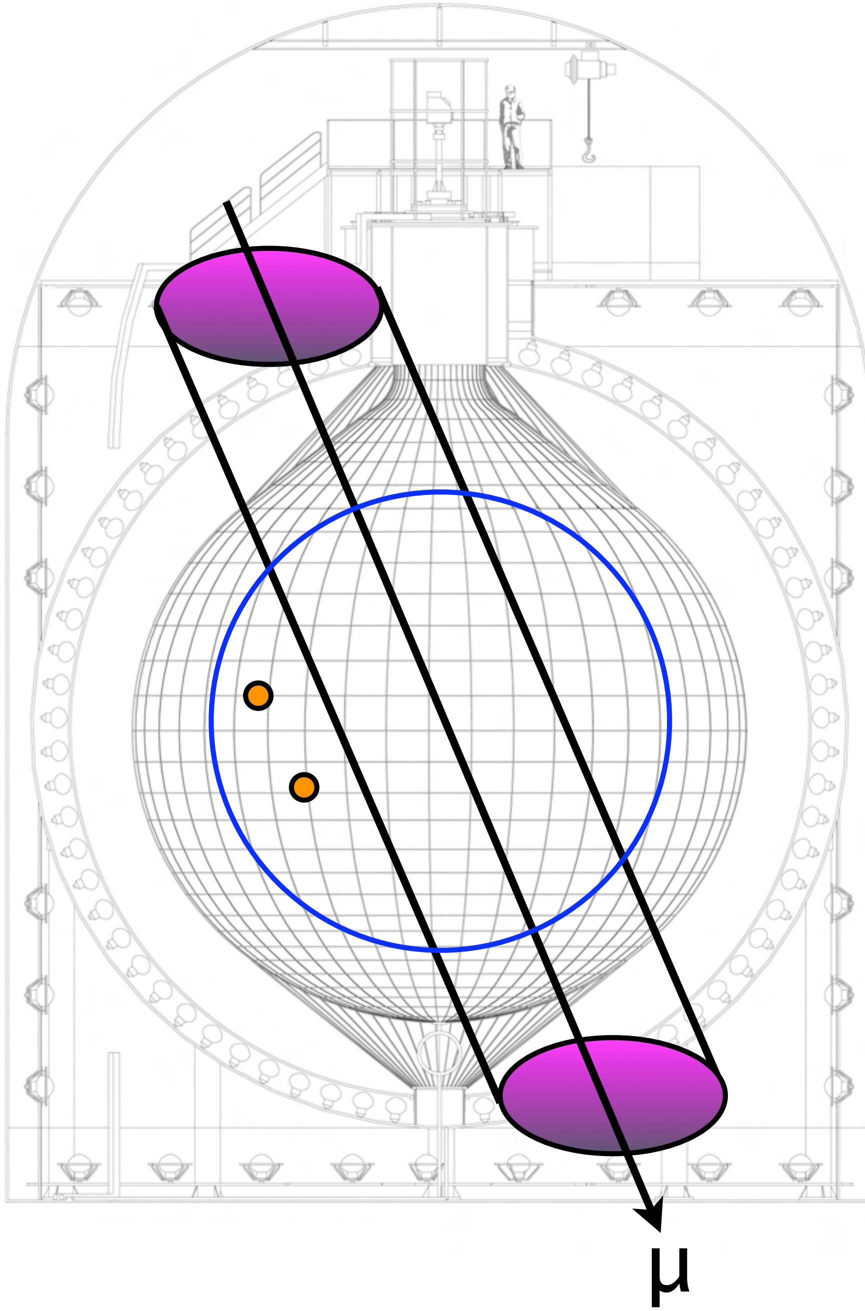
  1.8 MeV < $E_{delayed}$ < 2.6 MeV

- Spallation Cuts
  - ➡ Any muon:

    2ms veto.
  - ➡ Well tracked muon:

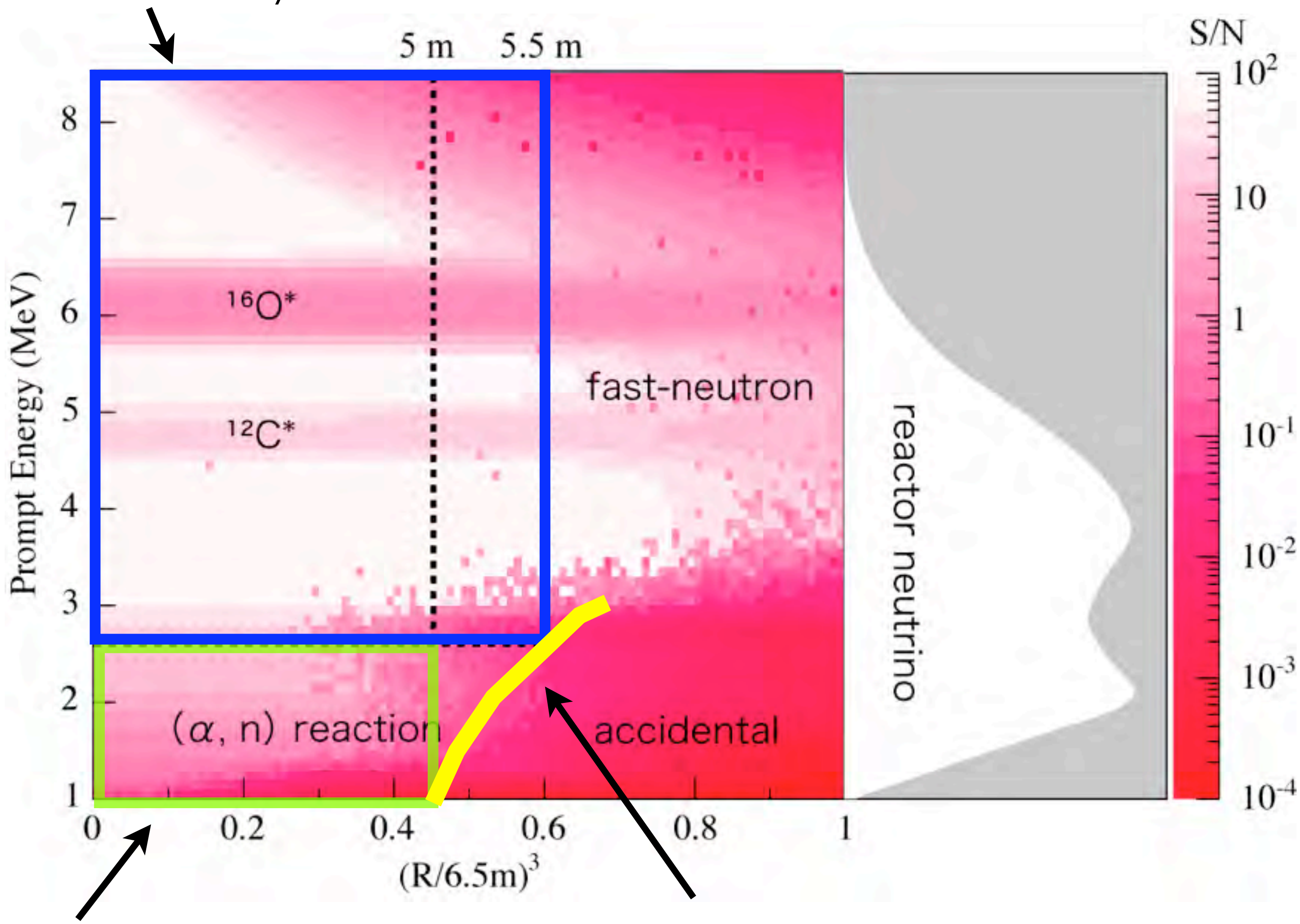
    veto 2s over 3m cylinder.
  - ➡ High Energy or poorly tracked muon,

    2s whole detector veto.



A New Analysis Method

Previous Reactor Analysis



Previous Geo-neutrino Analysis

Cut you would like to apply.

Construct the L-Selector Cut:

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

$f_{\bar{\nu}}$

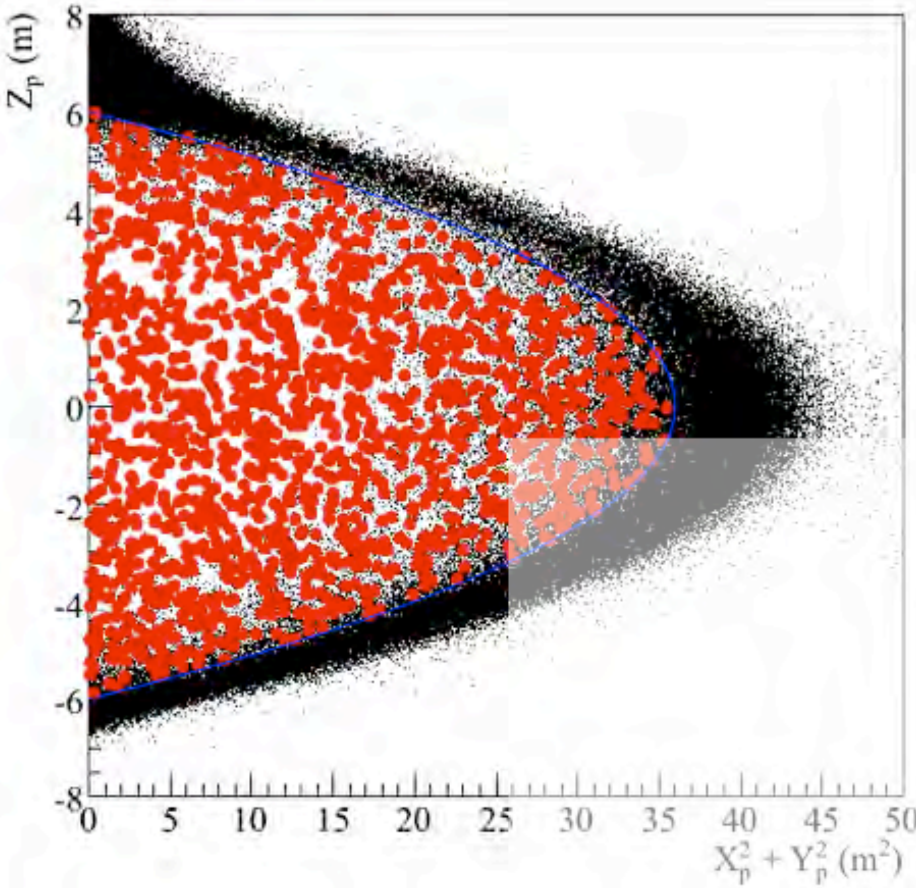
- PDF for anti-neutrino event.
- Created from Monte Carlo.
- Function of E_d, dR, dT, R_p, R_d.

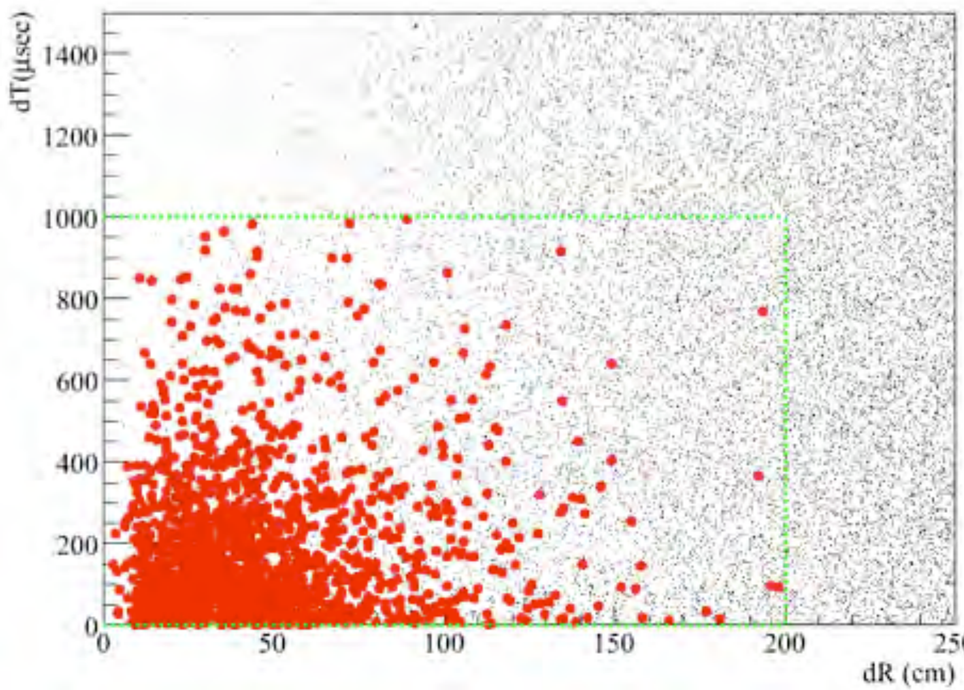
$f_{accidental}$

- PDF for accidental event.
- Created from data.
- Function of E_d, dR, dT, R_p, R_d.

The Candidates:

- The advantage of the L-Selector is very visible in the dR vs. dT plot.
- The need to continue using a 6m fiducial volume cut is due to the high event rate on the balloon.



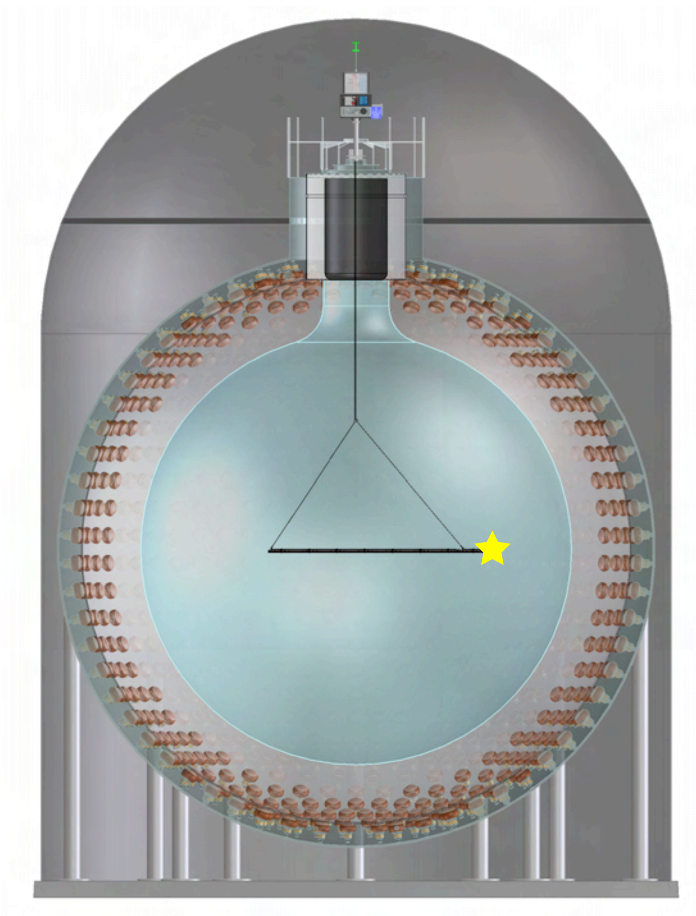


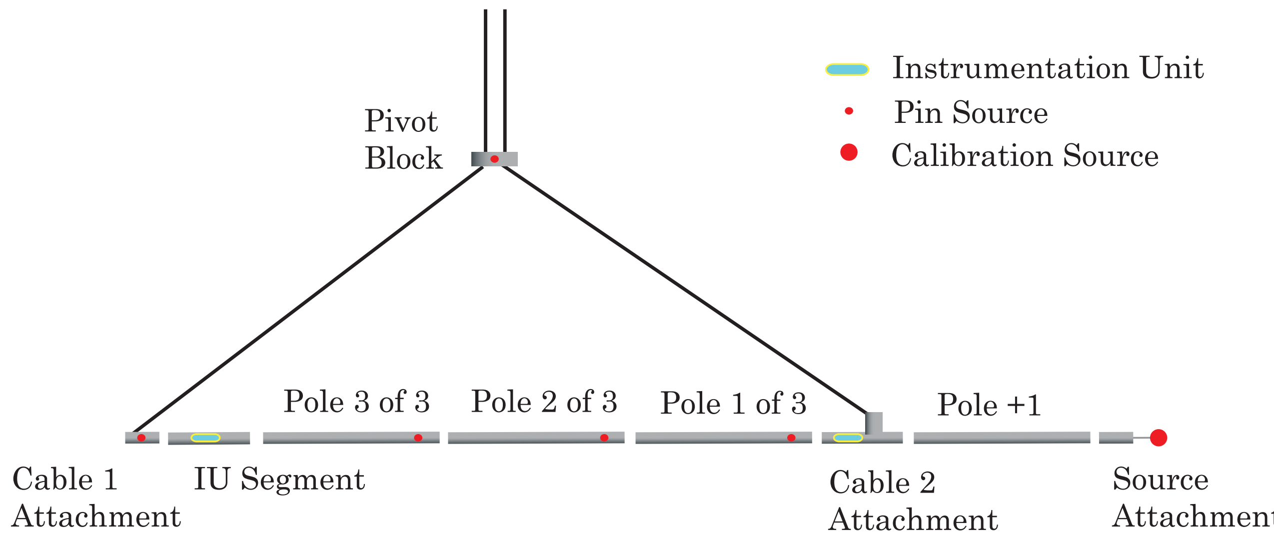
Improving these Results:

- Reduce fiducial volume systematic with full volume calibration system.

TABLE I: Estimated systematic uncertainties (%).

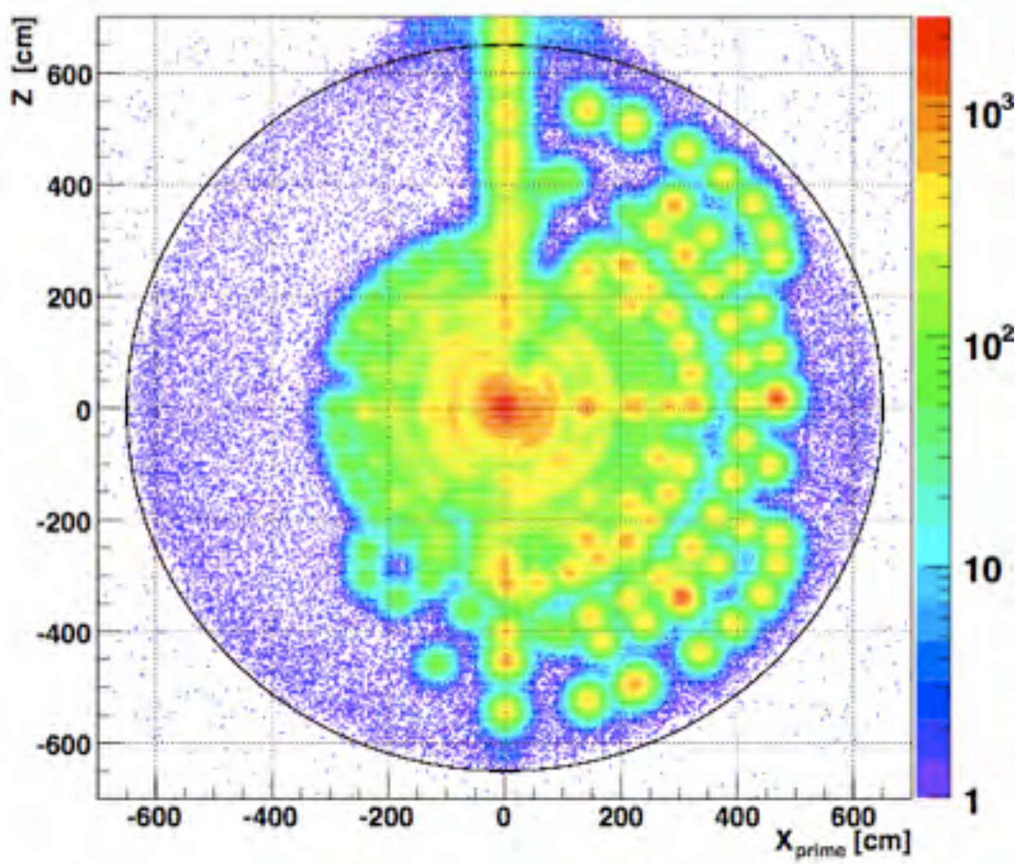
Fiducial Volume	4.7	Reactor power	2.1
Energy threshold	2.3	Fuel composition	1.0
Efficiency of cuts	1.6	$\overline{\nu}_e$ spectra [3]	2.5
Livetime	0.06	Cross section [5]	0.2
Total systematic uncertainty			6.5

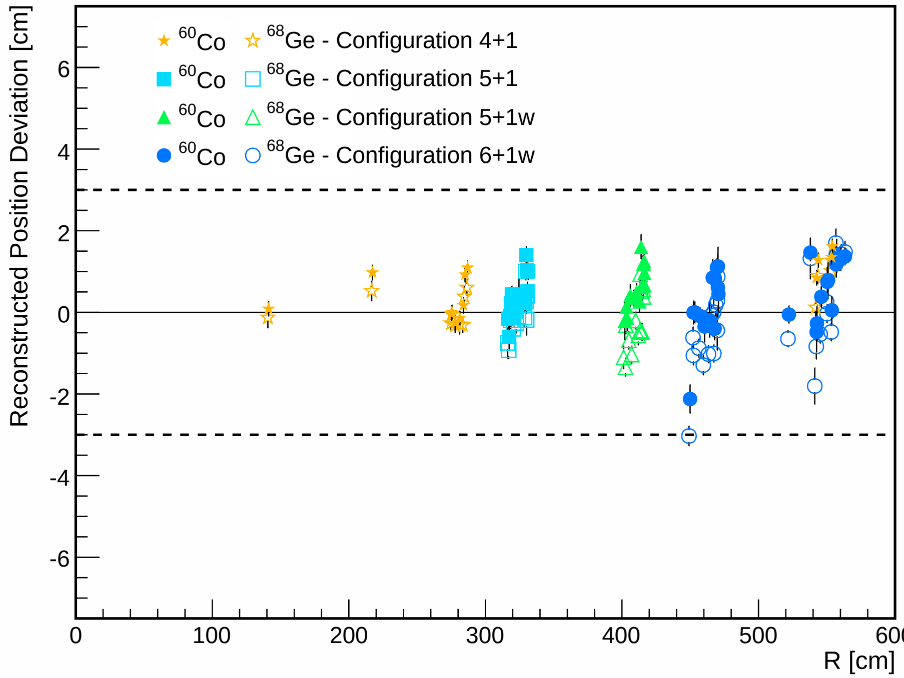




arXiv:0903.0441v1 [physics.ins-det]

After 500 hours of Calibration Data:





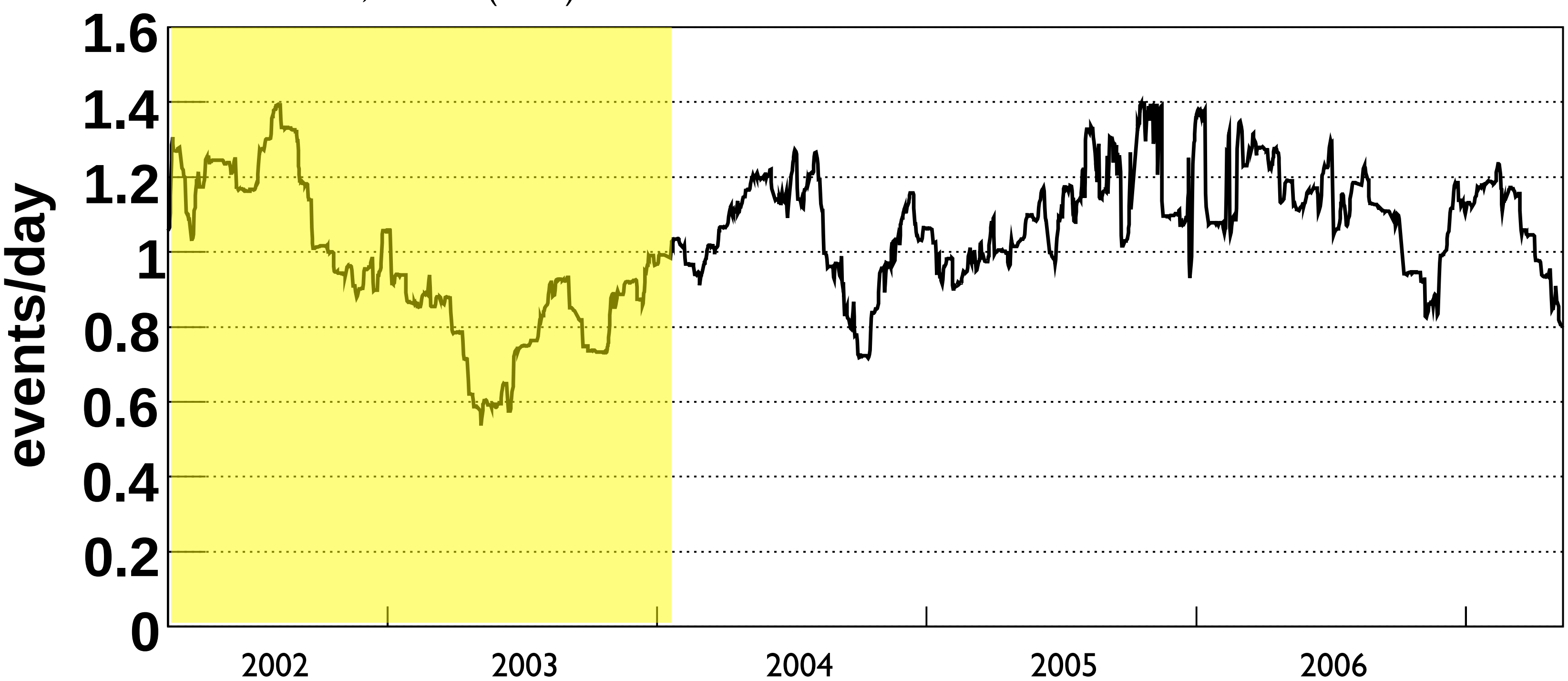
- Reconstruction bias < 3cm corresponds to a 1.8% fiducial volume uncertainty.
- Cross-check and extend with $^{12}B/^{12}N$ candidates as was done for previous result.

Better Systematic Errors and Much More Data:

TABLE I: Estimated systematic uncertainties relevant for the neutrino oscillation parameters Δm^2_{21} and θ_{12}. The total uncertainty on Δm^2_{21} is 2.0%, while the total uncertainty on the expected event rate (and mainly affecting θ_{12}) is 4.1%.

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

PRL 94, 081801 (2005)



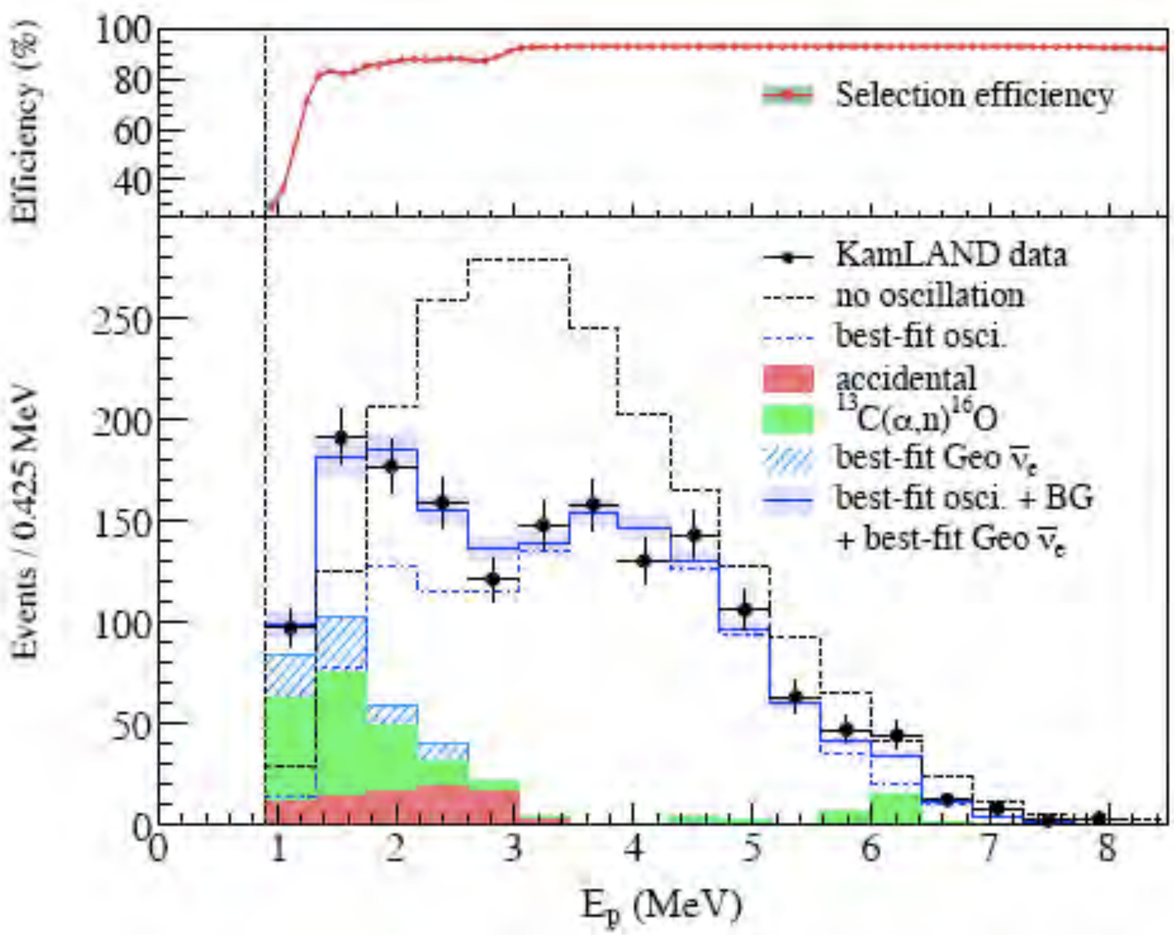
Run Time = 1491 Days

The Results:

- Unbinned fit in rate, shape and time with two flavors, earth matter effects, and the amplitude of the geo-neutrinos floating.

Expected No Osc - 2178 events
Background - 276 +/- 23.5 events
Observed - 1609 events

Disappearance Significance is greater than 8.5σ.



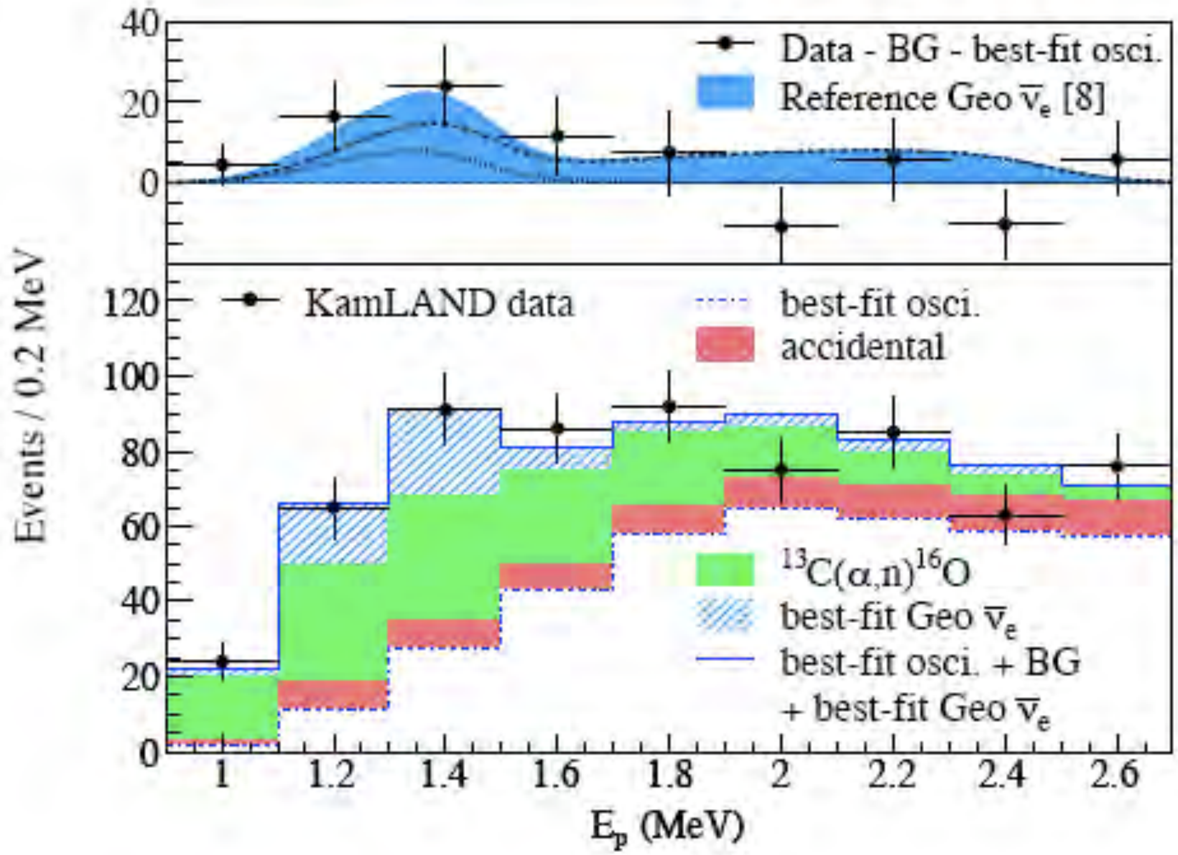
Best Fit - KamLAND Only

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

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

Spectral Distortion Significance is now greater than 5σ.

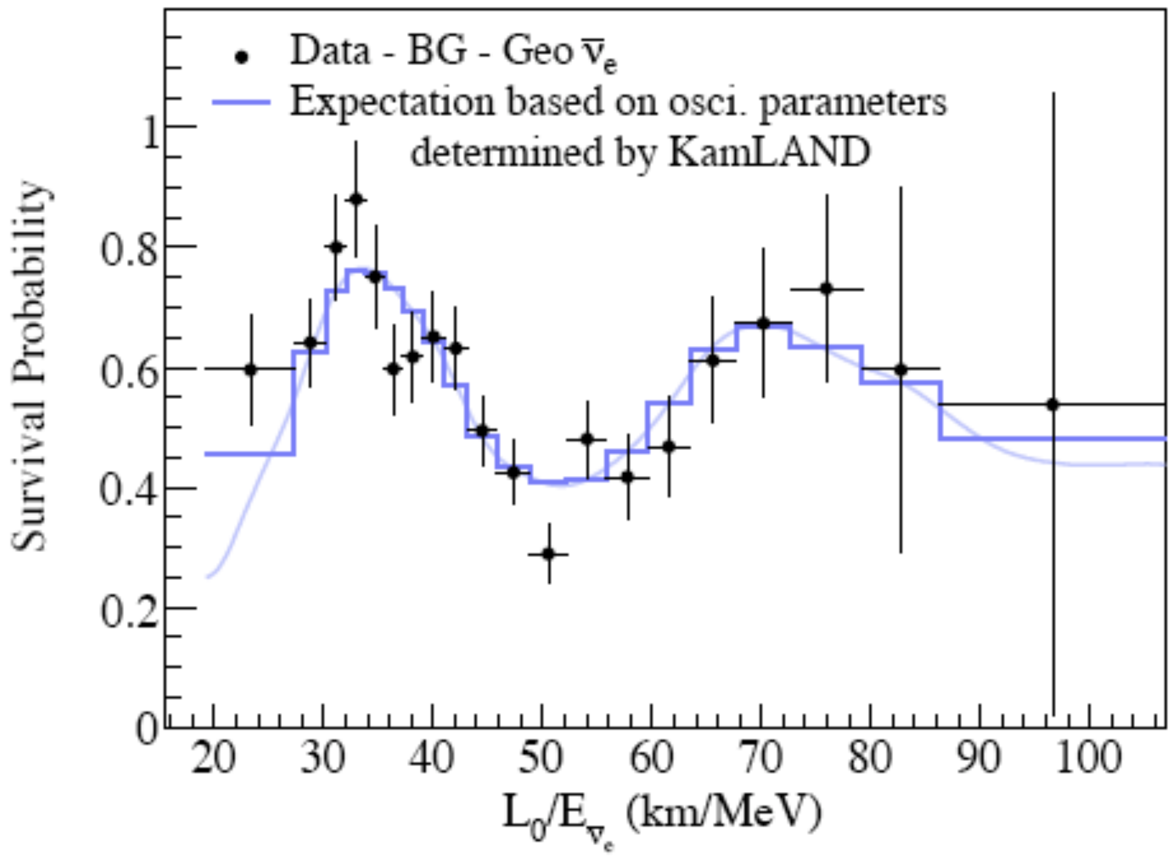
Geo-Neutrino Result:



Allow fluxes to vary:
U: 25 events
Th: 36 events
Fix Ratio U/Th to 3.9:
U+Th: 73±27 events

Flux:
$(4.4\pm1.6)\times10^6$ cm^{-2}s^{-1}
Ref. Model: 4.14×10^6 cm^{-2}s^{-1}

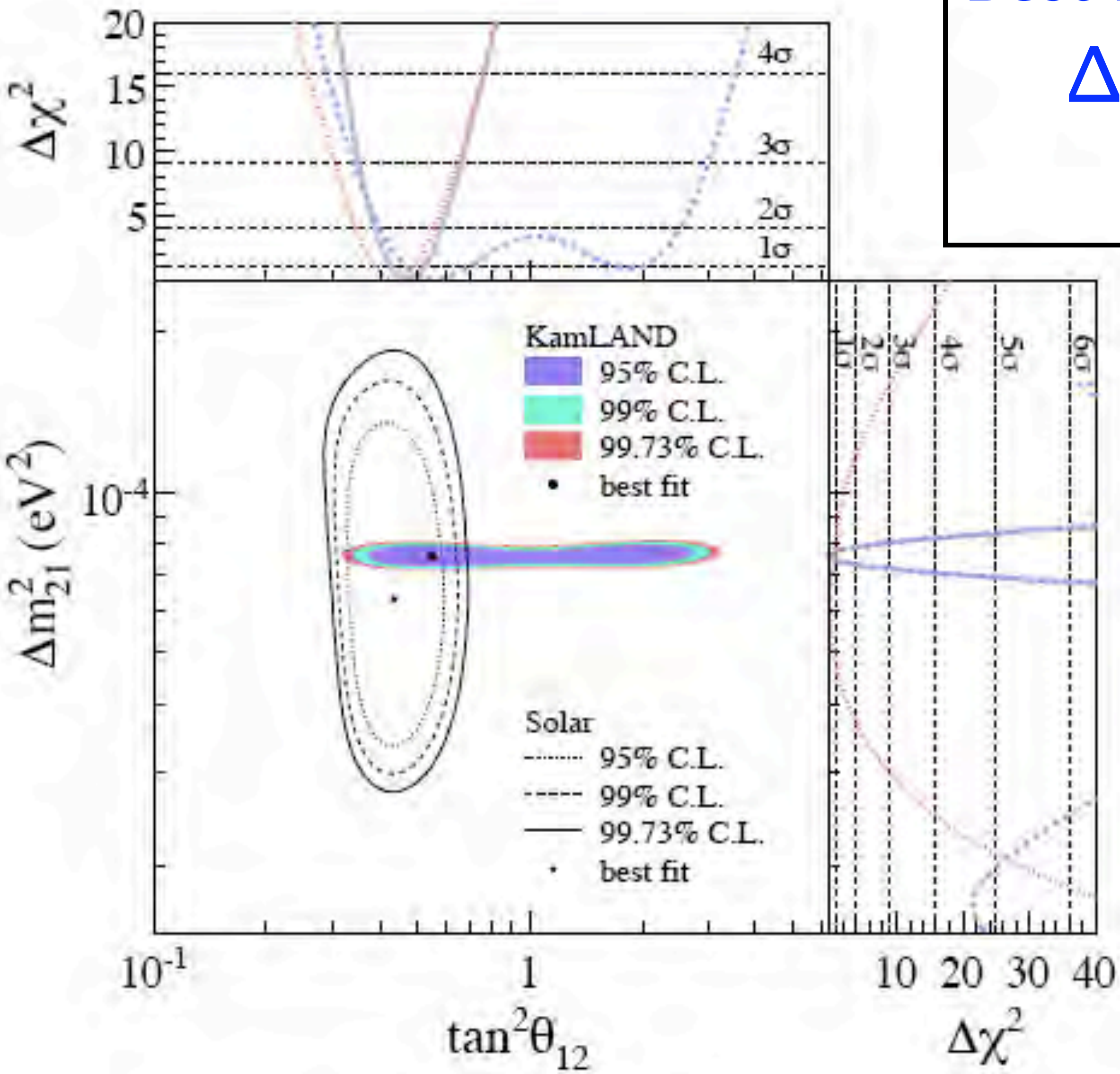
A More Intuitive way to see Oscillations:



$$P_{e,e} = 1 - sin^2 2\theta_{12} sin^2(1.27\Delta m_{12}^2 L/E)$$

L_o is the flux averaged reactor distance, 180 km.

KamLAND and Solar Contours:



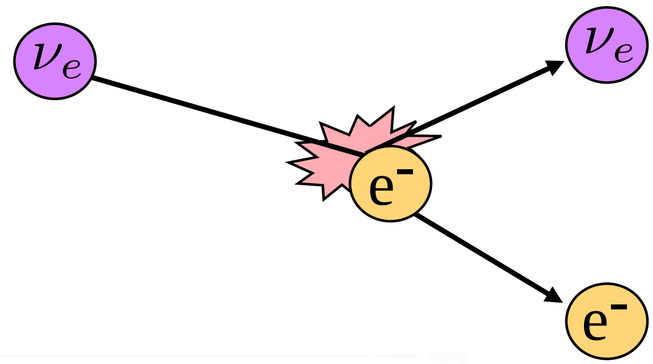
Best Fit - KamLAND + Solar

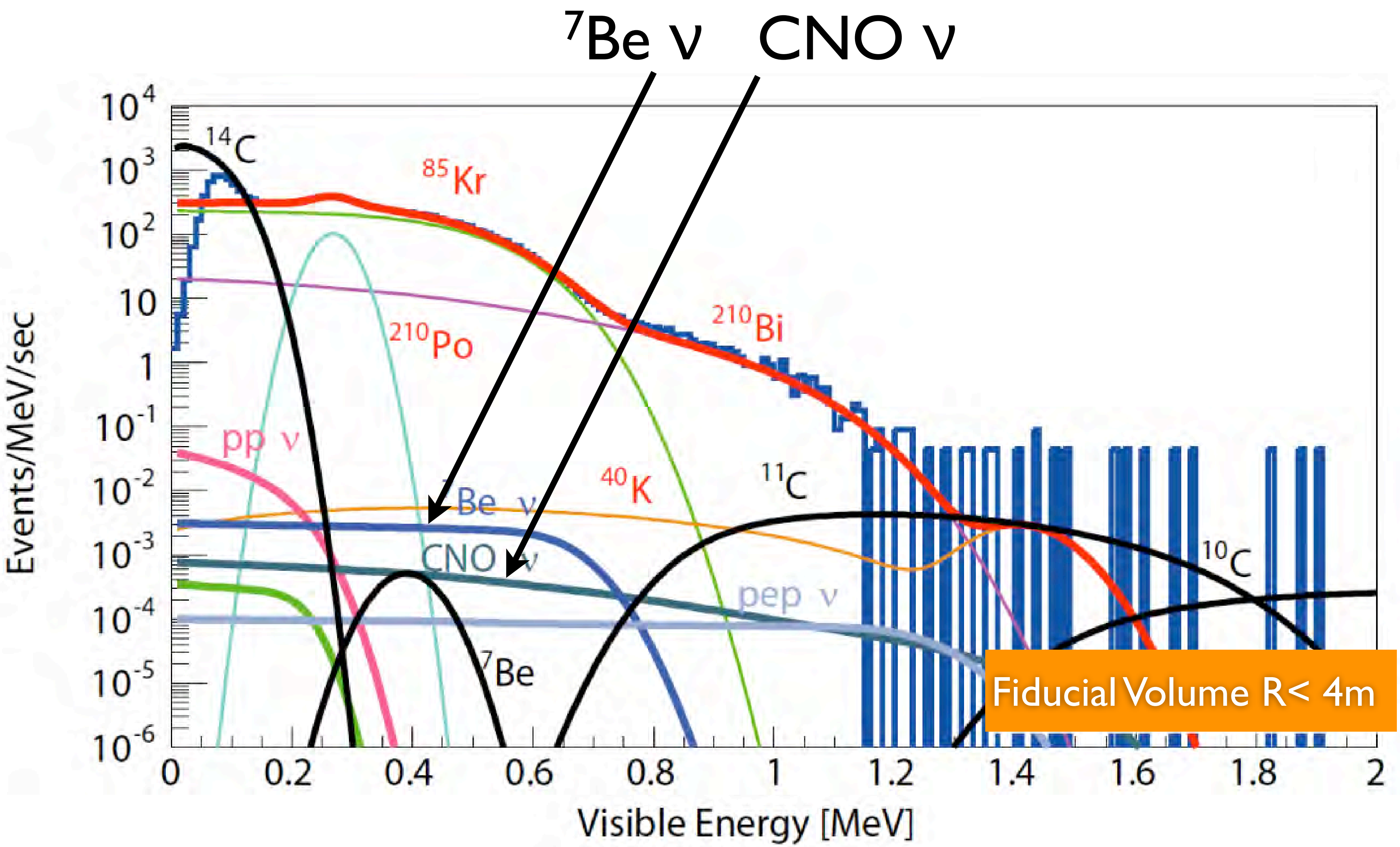
$\Delta m^2 = 7.59\,^{+0.21}_{-0.21} \times 10^{-5} eV^2$

$\tan^2\theta = 0.47\,^{+0.06}_{-0.05}$

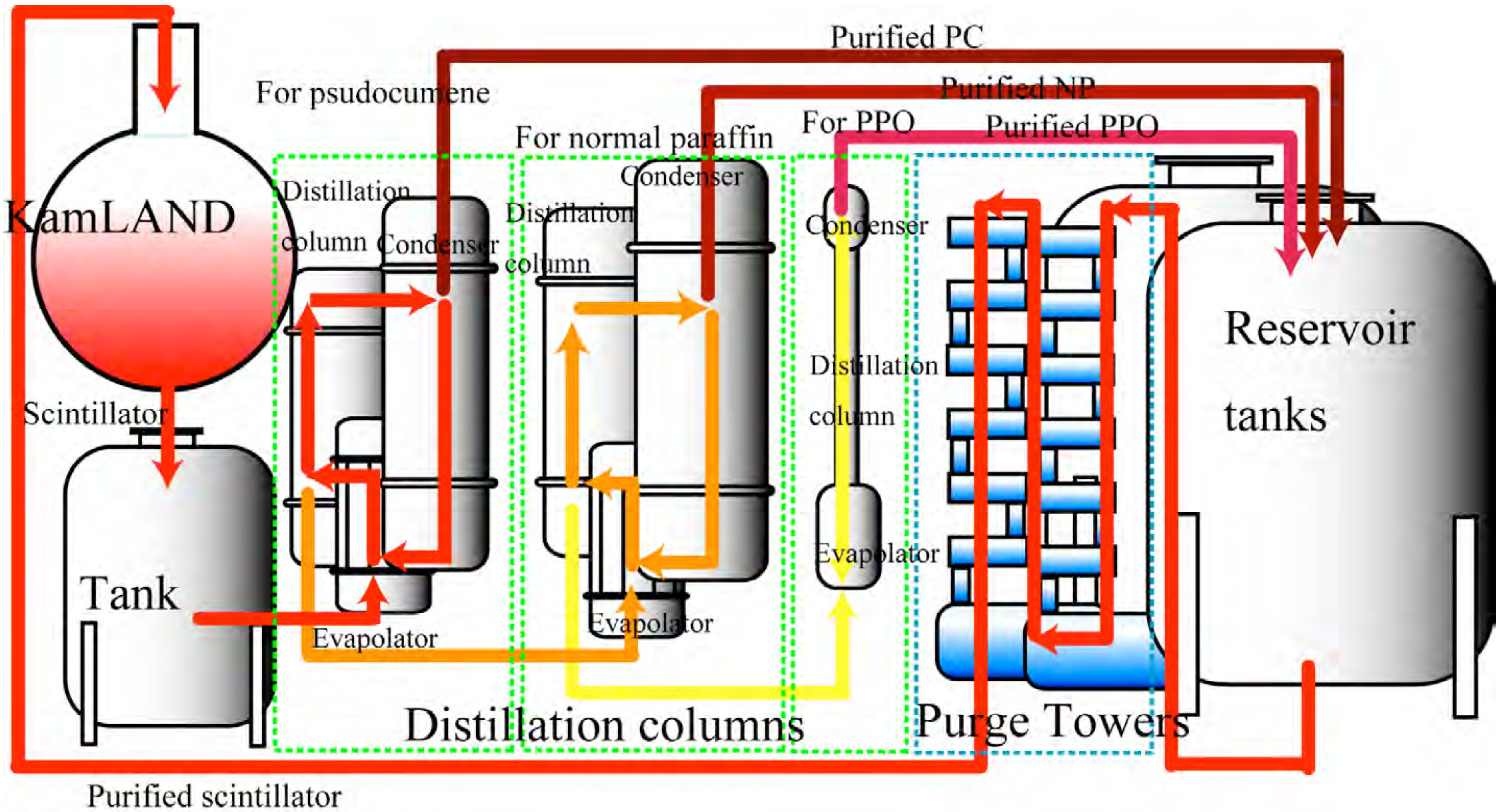
The Low Background Phase:

- Solar neutrinos and almost no background for anti-neutrino measurements.





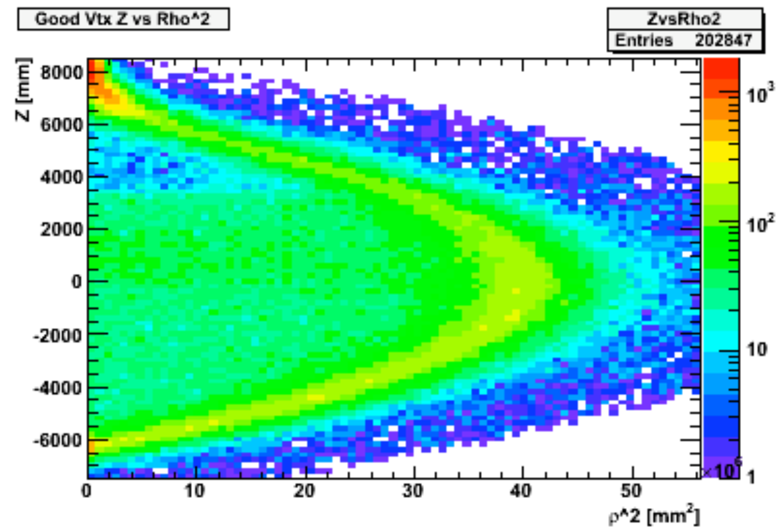
The Purification System:



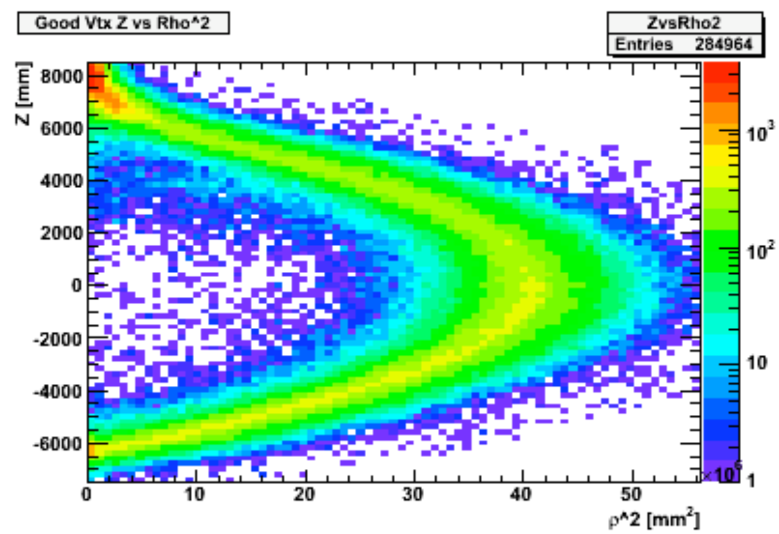
Current Status:

- First purification ran for 12 weeks starting May 2007.
- Exchanged 1.4 volumes plus an additional 173m^3.
- Pause for 6 months for blasting, (Lower background data and reactor power reduced).
- Second purification commenced in Spring of 2008.
- Second purification ended February 6, 2009.
- Exchanged 4855m^3 or 4.1 volumes.

End of First Purification - A Shifter's View.



End of Second Purification - A Shifter's View



In Summary, KamLAND Physics!

Nature 436, 490 (2005)

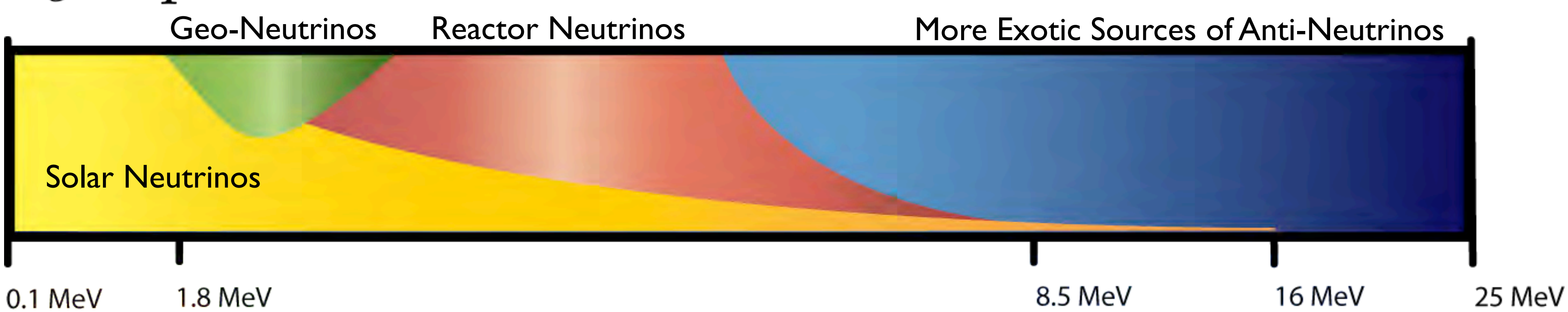
PRL 100, 221803, (2008)
PRL 94, 081801 (2005)
PRL 90, 021802 (2003)

Also:
Anti-neutrinos from the sun and other sources.
PRL 92 071301 (2004)

Neutron Disappearance
PRL 96 101802 (2006)

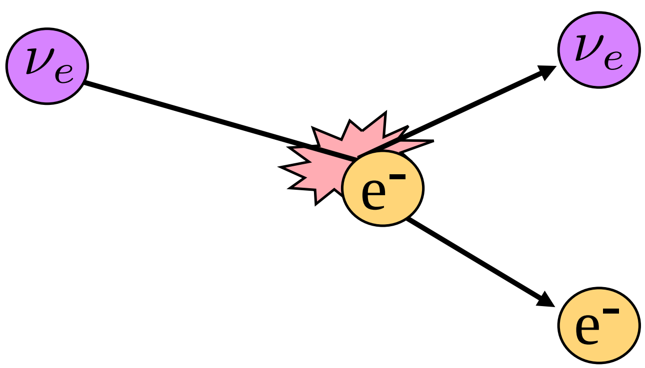
Inverse Beta Decay

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



Elastic Scattering

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



Coming Soon!

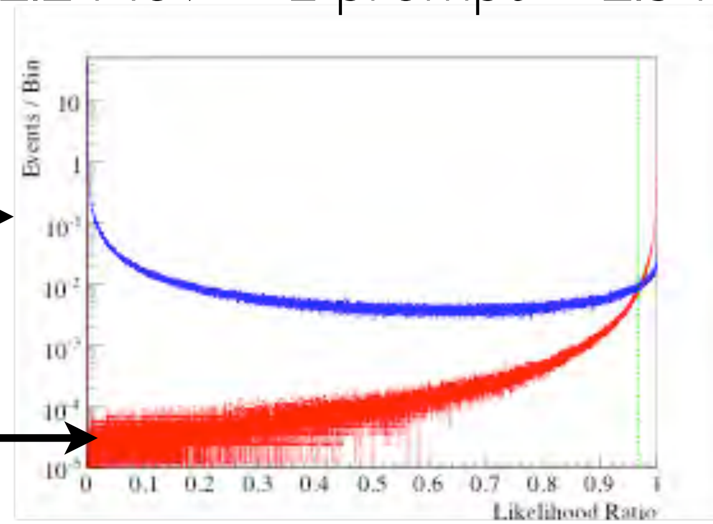
Back-up Slides Begin Now.

Construct a Figure of Merit:

Example Energy Bin:
2.2 MeV < E prompt < 2.3 MeV

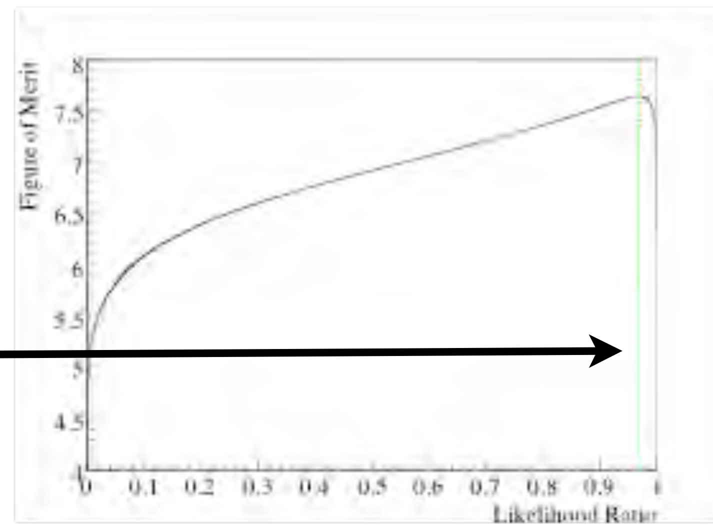
L_{ratio} for accidentals data set.

L_{ratio} for Monte-Carlo neutrino data set.



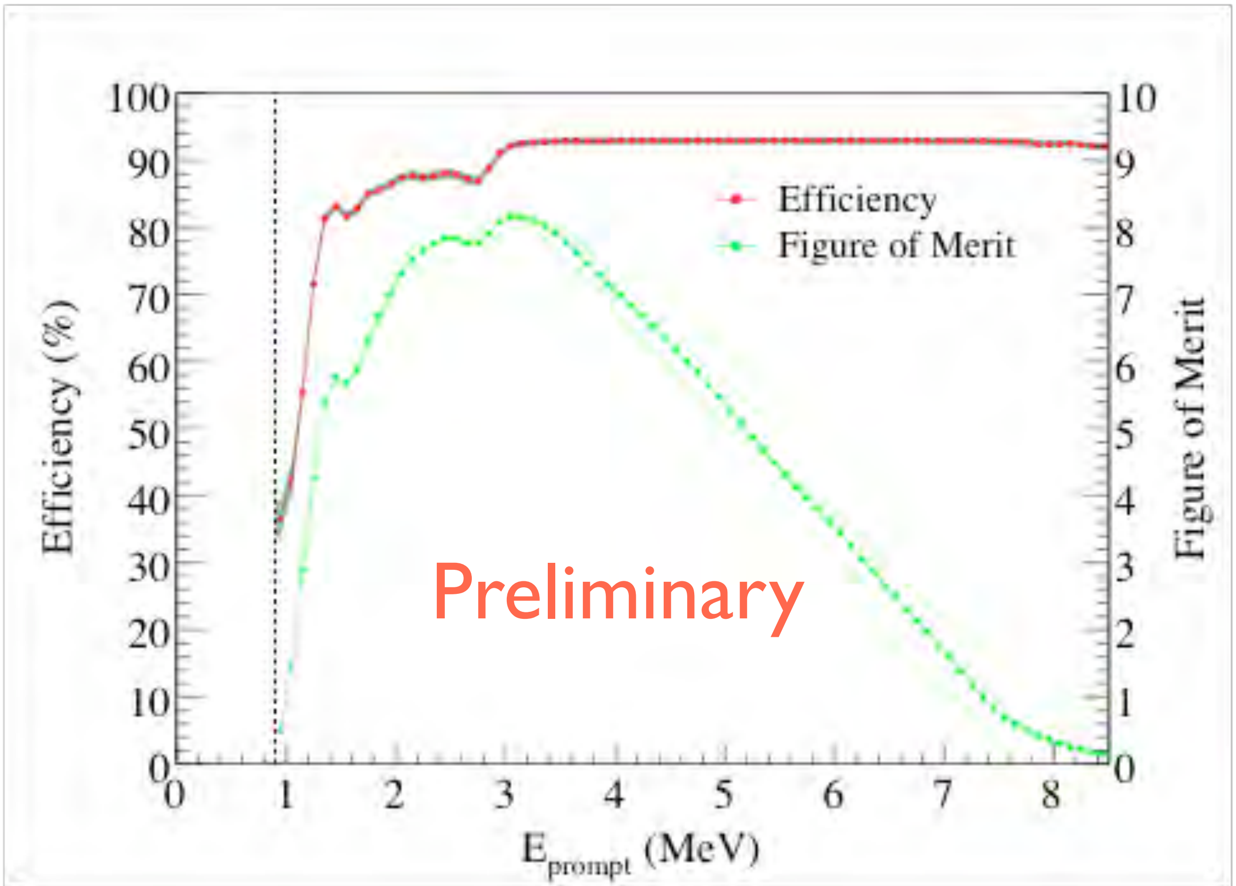
Find L_{ratio} that maximizes:

$$\frac{S}{\sqrt{(S+B)}}$$



Calculate the cut efficiency:

- The is done for all cuts using the Monte Carlo for the anti-neutrino candidates.



Now apply 6m fiducial volume, dR < 2m, and this L_{cut}.

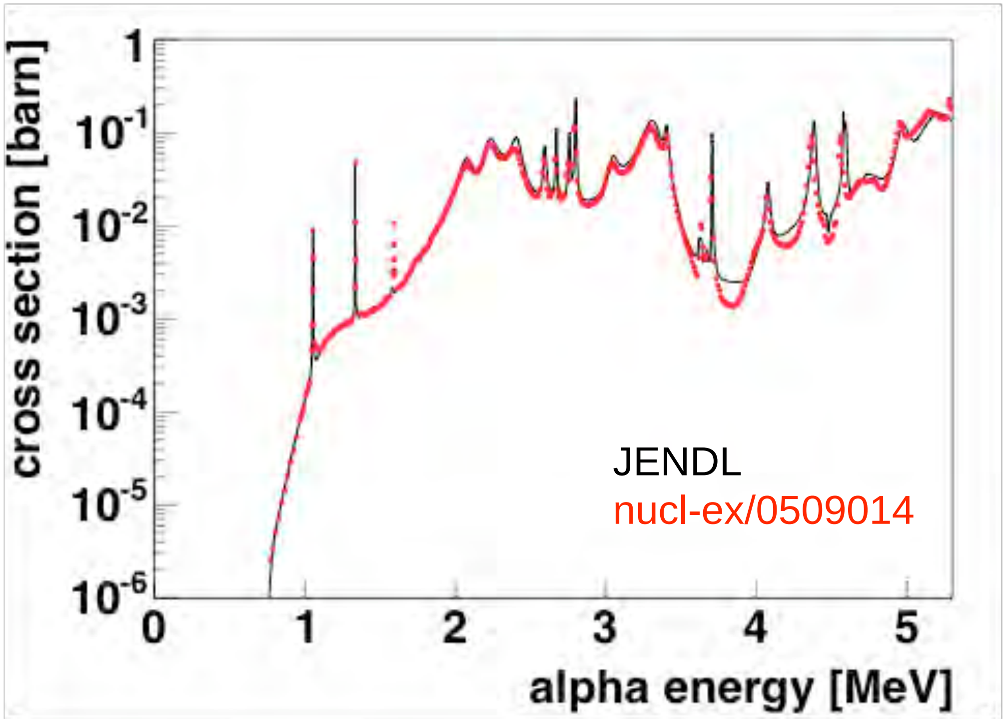
Backgrounds:

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	276.1 ± 23.5

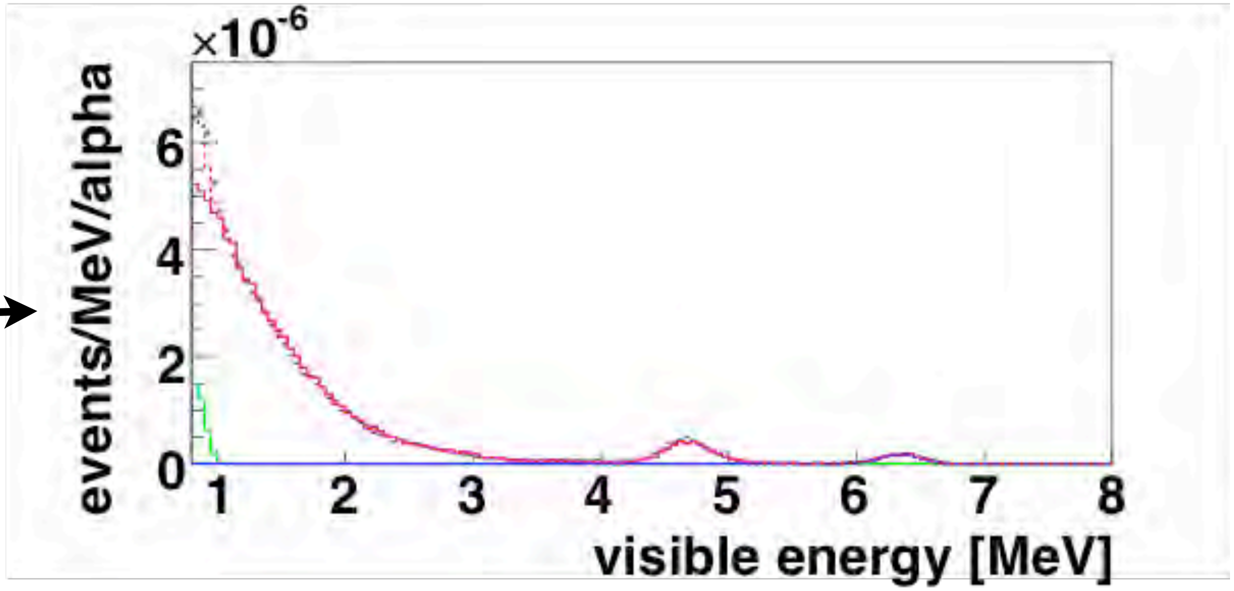
Improving these Results:

- Combination of new alpha cross section measurements and the deployment of a $^{210}Po^{13}C$ calibration source reduce the uncertainty in this background.

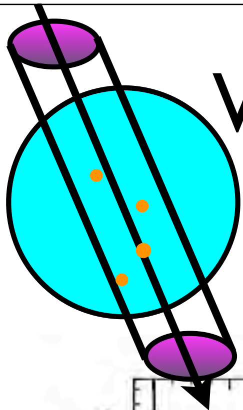
11% uncertainty in the g.s.
20% uncertainty in the excited states.



$^{210}Po^{13}C$ calibration source data compared to Monte-Carlo.



What are the Backgrounds?



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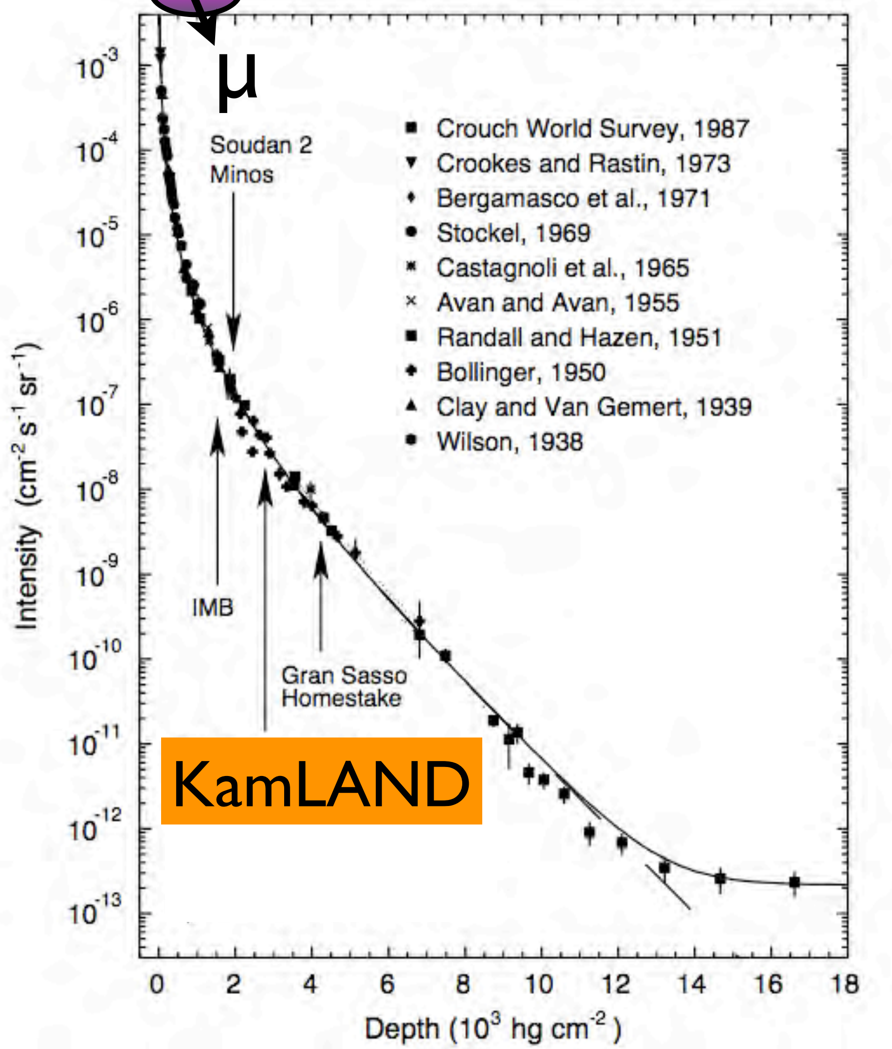
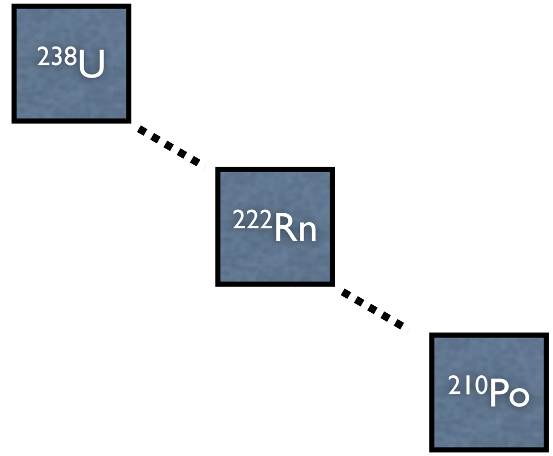


Spallation Products

Isotope	Half Life	Endpoint
n	200μs	2.2MeV
^{12}B	20ms	13.4 MeV
^{12}N	11ms	17.4 MeV
^{8}He	120ms	10.6 MeV
^{9}Li	180ms	13.6 MeV
^{16}N	7.1s	10.4 MeV
^{11}Be	13.8s	11.5 MeV
^{11}C	20.4min	0.96 MeV
^{7}Be	53days	0.86 MeV

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



What is this background?

$^{210}Po \rightarrow {}^{206}Pb + \alpha(E=5.3MeV)$

$\alpha + {}^{13}C \rightarrow n + {}^{16}O$(ground state)

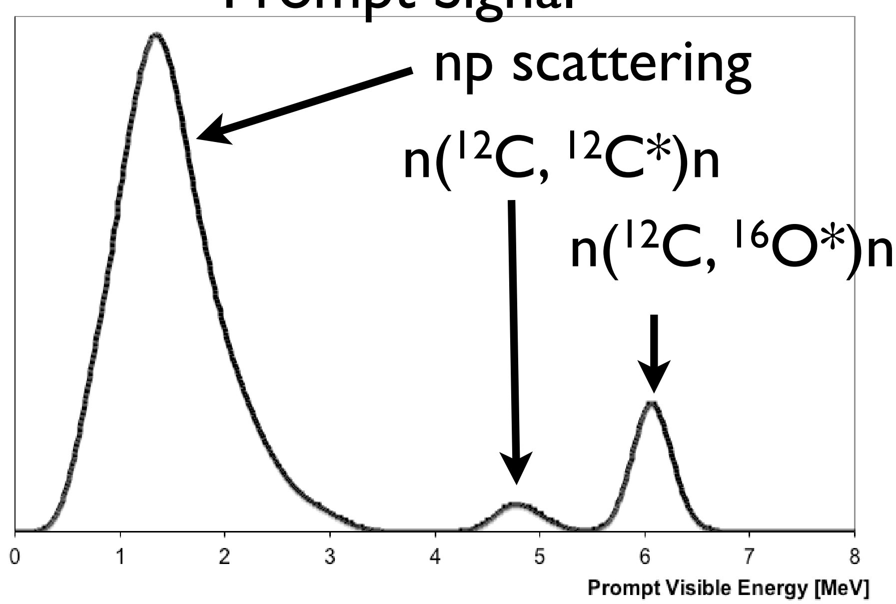
$\alpha + {}^{13}C \rightarrow n + {}^{16}O^{*}$(6.13 or 6.05 MeV)

$n + p \rightarrow n + p$

$n + {}^{12}C \rightarrow n + {}^{12}C^{*}$

$^{12}C^{*} \rightarrow {}^{12}C + \gamma(4.4MeV)$

Prompt Signal



Parameter Space:

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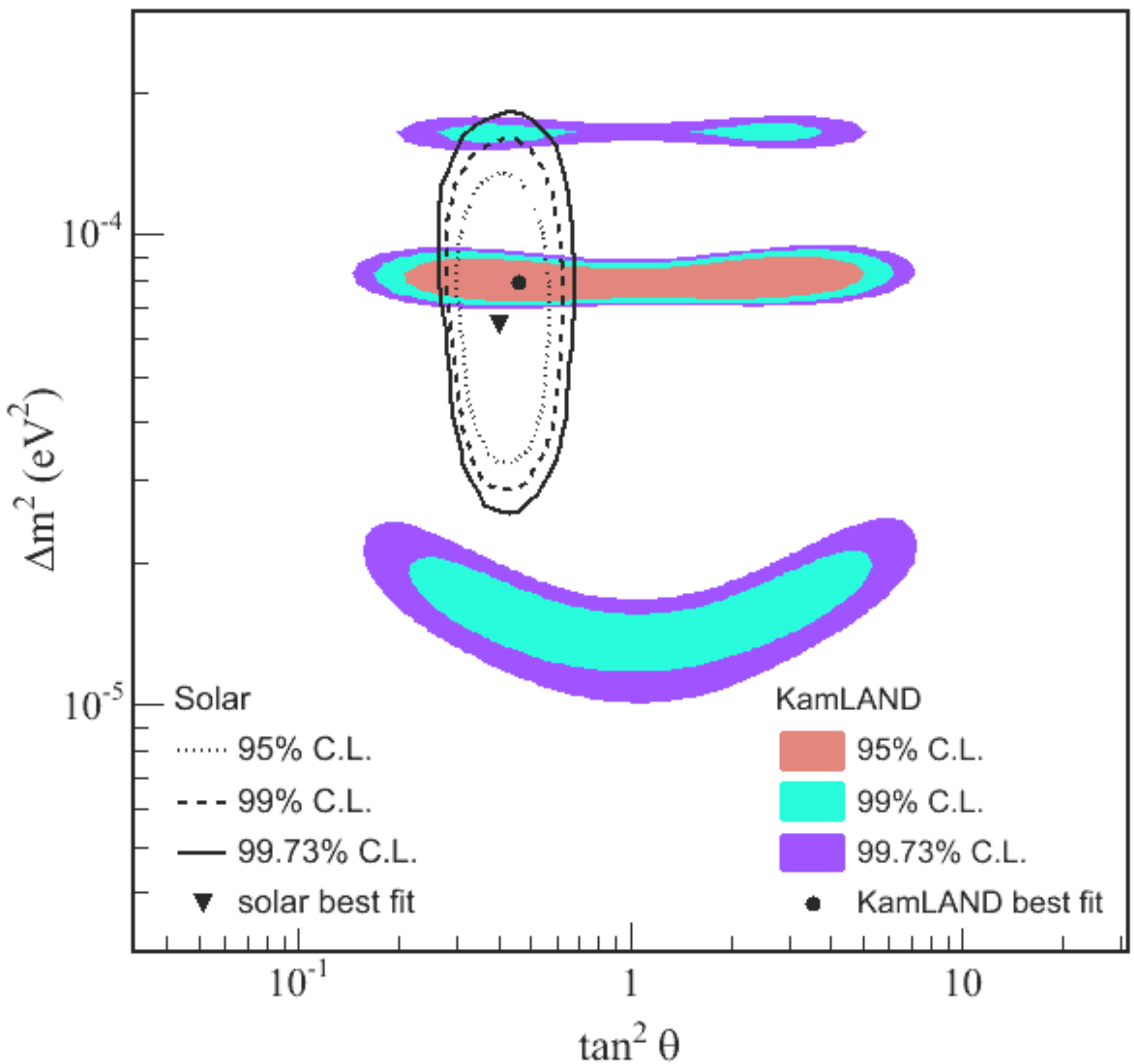
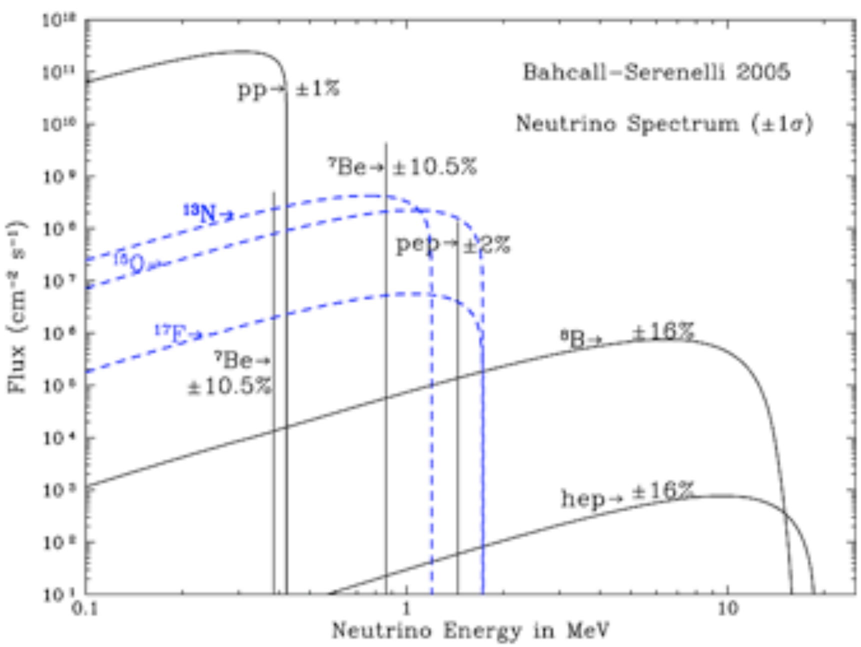
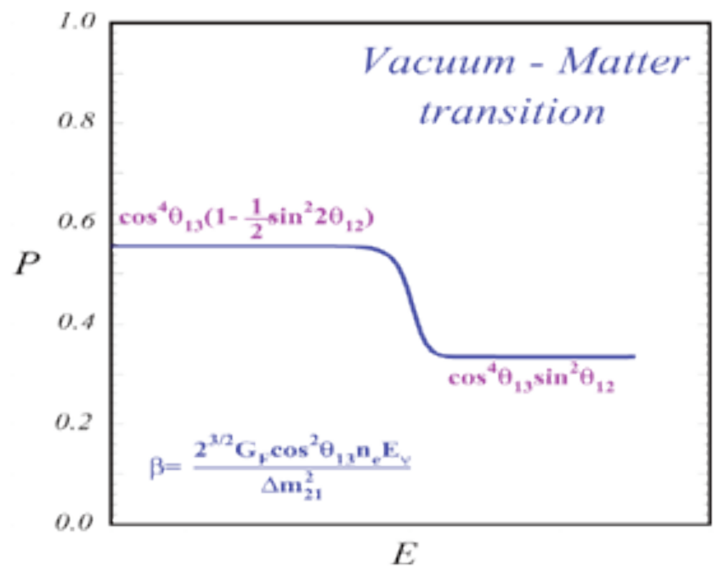


The Solar Neutrino Problem





The Solution - A Purification System:

How it works: