Detection of reactor and solar neutrinos in KamLAND

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- Future Plan
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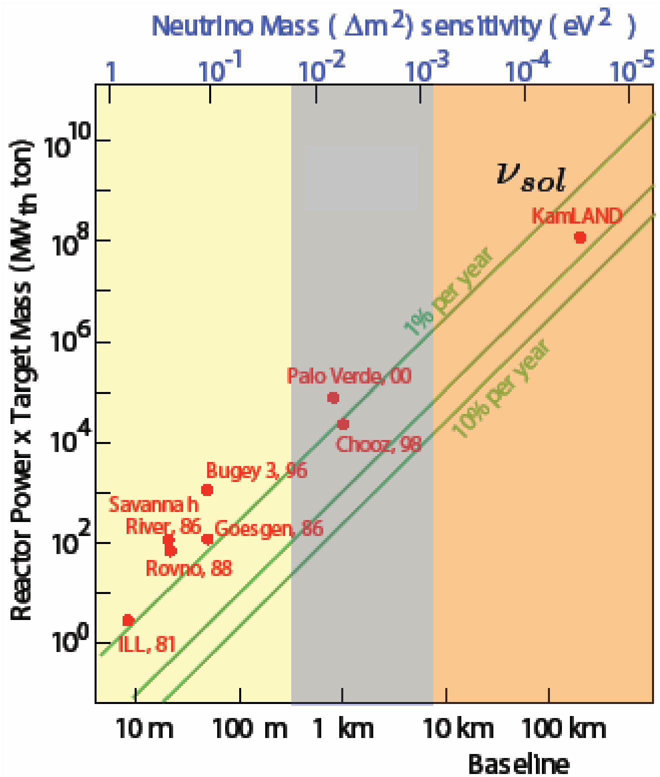
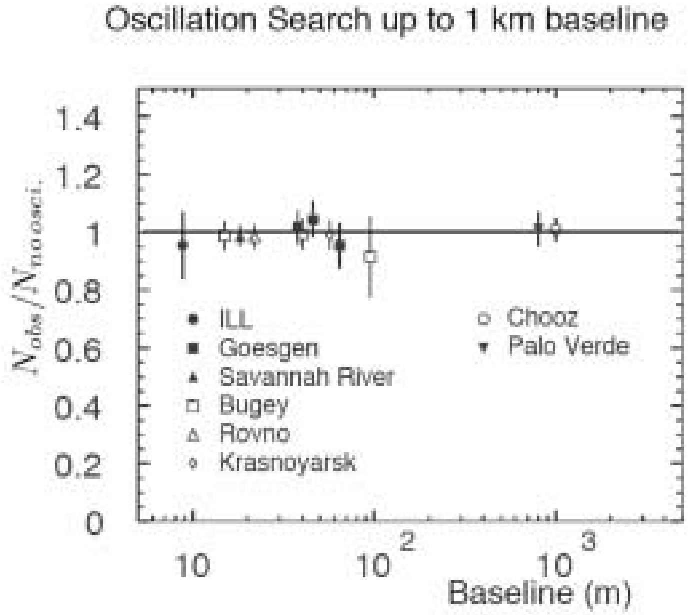
Reactor neutrino observation

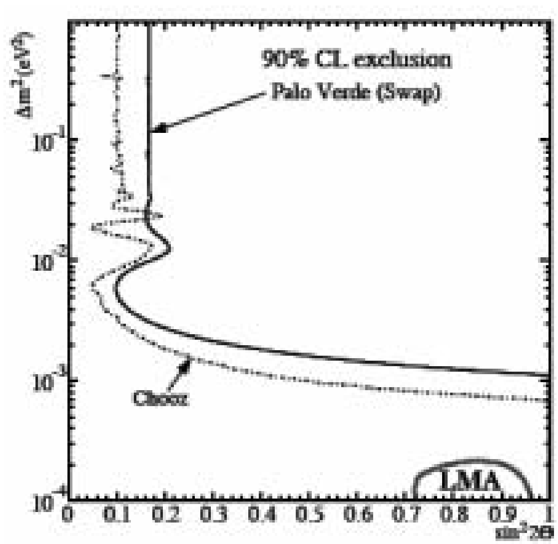
	The first neutrino observation	At present
	1956	2001
	Reines and Cowan	KamLAND
Reactor power	700 MW	70 GW (effective)
Proton target	200 liters water	1000 ton LS
Signal detection	1400 liters LS	1000 ton LS
	55 PMTs	1879 PMTs
Depth	12m	1000m
Baseline	11m	~180km

By many important improvements
on knowledge of reactor neutrino
and detection technique

Past experiments



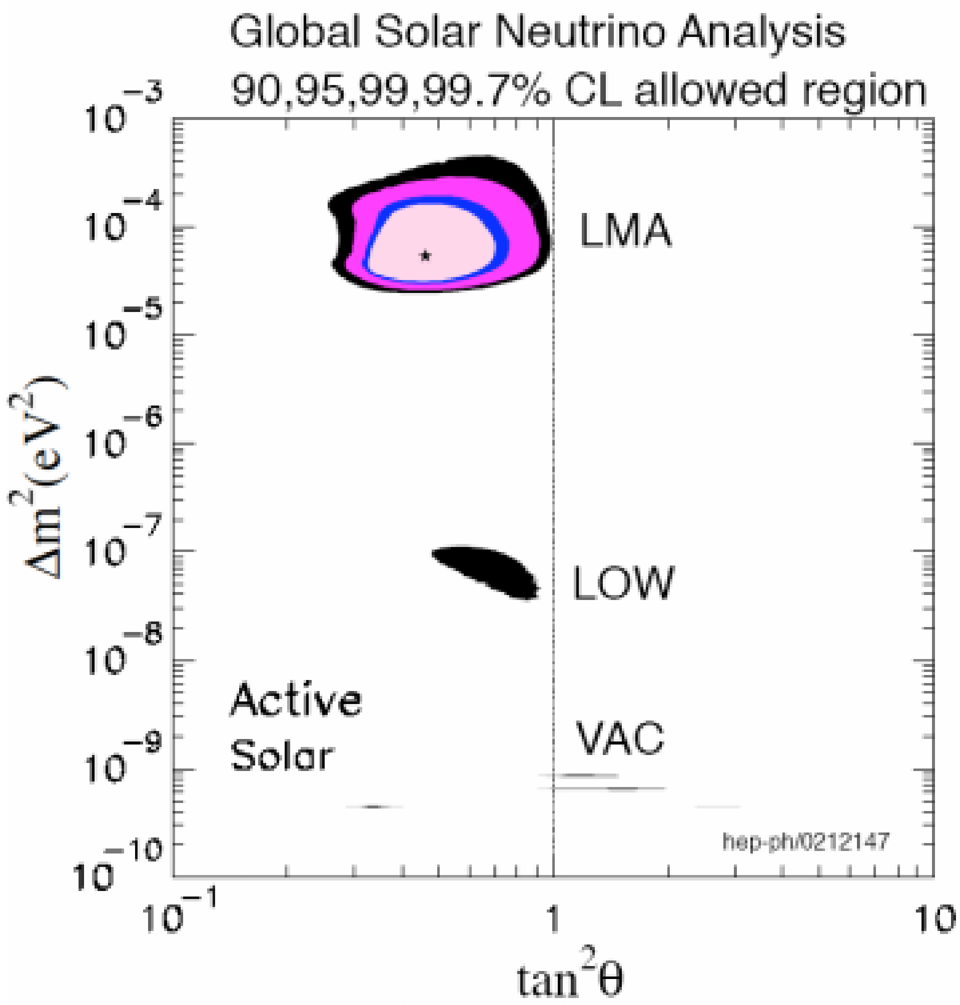




$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2(1.27 \times \frac{\Delta m^2(eV^2)L(m)}{E(MeV)})$$

$$E_{reactor} \sim 5MeV$$

Status before KamLAND

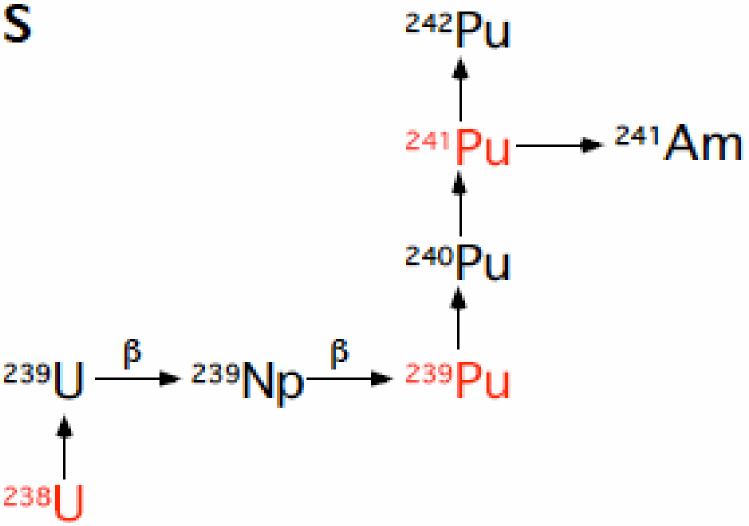


We need

more than 100km baseline
powerful reactor
big detector
deep underground site

to explore the LMA solution

Reactor Neutrinos



- Only 4 fissile nuclei (U235,U238,Pu239,Pu241) are important. The others contribute only 0.1% level.

- Fission fragments repeat beta-decay and emit anti-electron-neutrinos (electron-neutrino contamination is ~10ppm level above 1.8 MeV).

- Fission rate is strongly correlated with thermal power output (measurable at much better than 2% accuracy).

$$^{235}U : 201.7\pm0.6,\ ^{238}U : 205.0\pm0.9,\ ^{239}Pu : 210.0\pm0.9,\ ^{241}Pu : 212.4\pm1.0MeV$$

M.F.James, J.Nucl.Energy 23(1969)517

- One fission causes ~6 neutrino emission in average. Thus, neutrino intensity is $\sim 2\times10^{20}\,\bar{\nu}_e/GW_{th}/sec$.

- Fission spectra reach equilibrium within a day above ~2 MeV. Except only a few cases such as;

$$^{106}Ru \xrightarrow{T_{1/2}=372days} Rh \xrightarrow[E_{max}=3.541MeV]{} Pd$$

$$^{144}Ce \xrightarrow{T_{1/2}=285days} Pr \xrightarrow[E_{max}=2.996MeV]{} Nd$$

V.I.Kopeikin et al., Physics of Atomic Nuclei, 64-5(2001)849

Neutrino Spectra

U235, Pu239, Pu241

Beta spectra were measured with a spectrometer irradiating thermal neutrons at ILL.

Fitting with 30 hypothetical beta branches and convert each branches to neutrino spectrum.

K.Schreckenbach et al., Phys.Lett.B160(1985)325
A.A.Hahn et al., Phys.Lett.B218(1989)365

U238

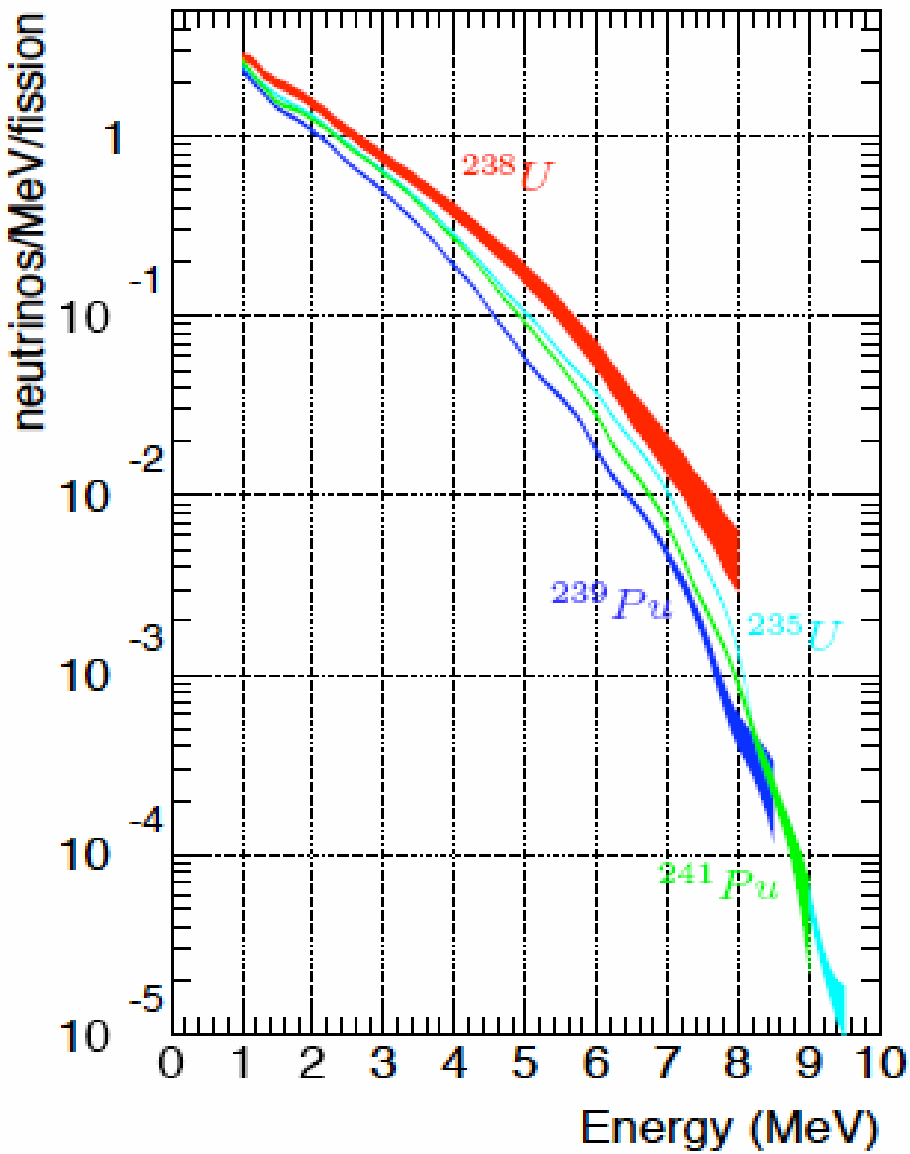
No fission with thermal neutrons

Theoretical calculation tracing 744 unstable fission products

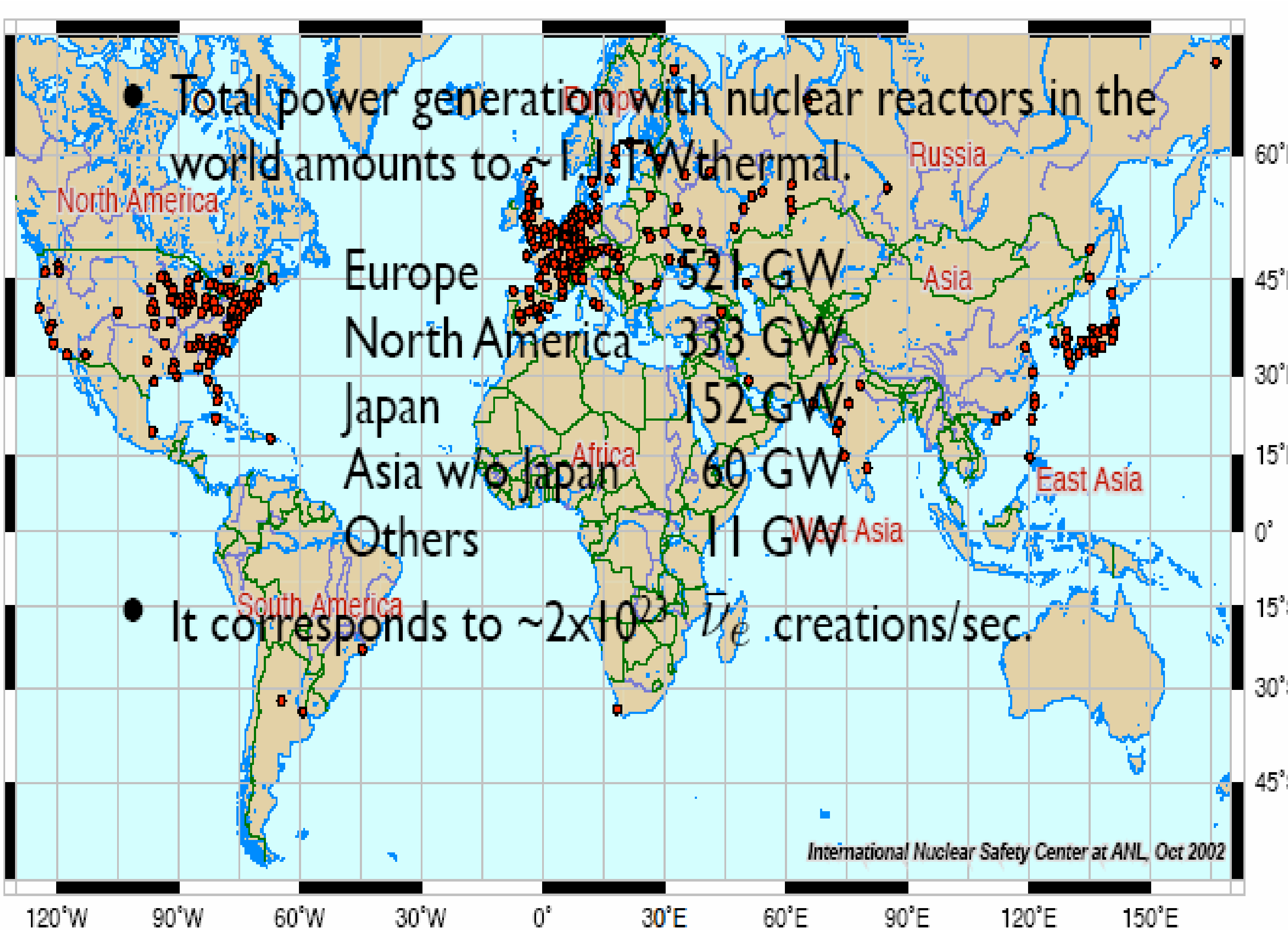
Error is larger, but small contribution ~8%

P.Vogel et al., Phys. Rev. C24(1981)1543

Knowing time evolution of fuel composition, error from spectra calculation is ~2.3%.



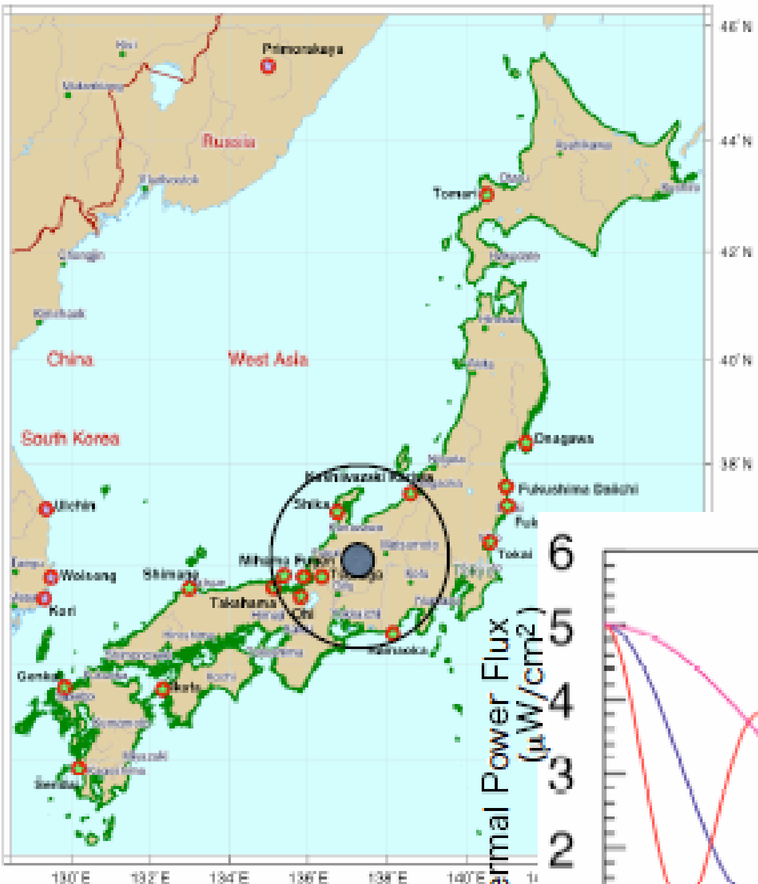
Reactors in the world



- Total power generation with nuclear reactors in the world amounts to ~1.1TWthermal.

Europe	521 GW
North America	333 GW
Japan	152 GW
Asia w/o Japan	60 GW
Others	11 GW

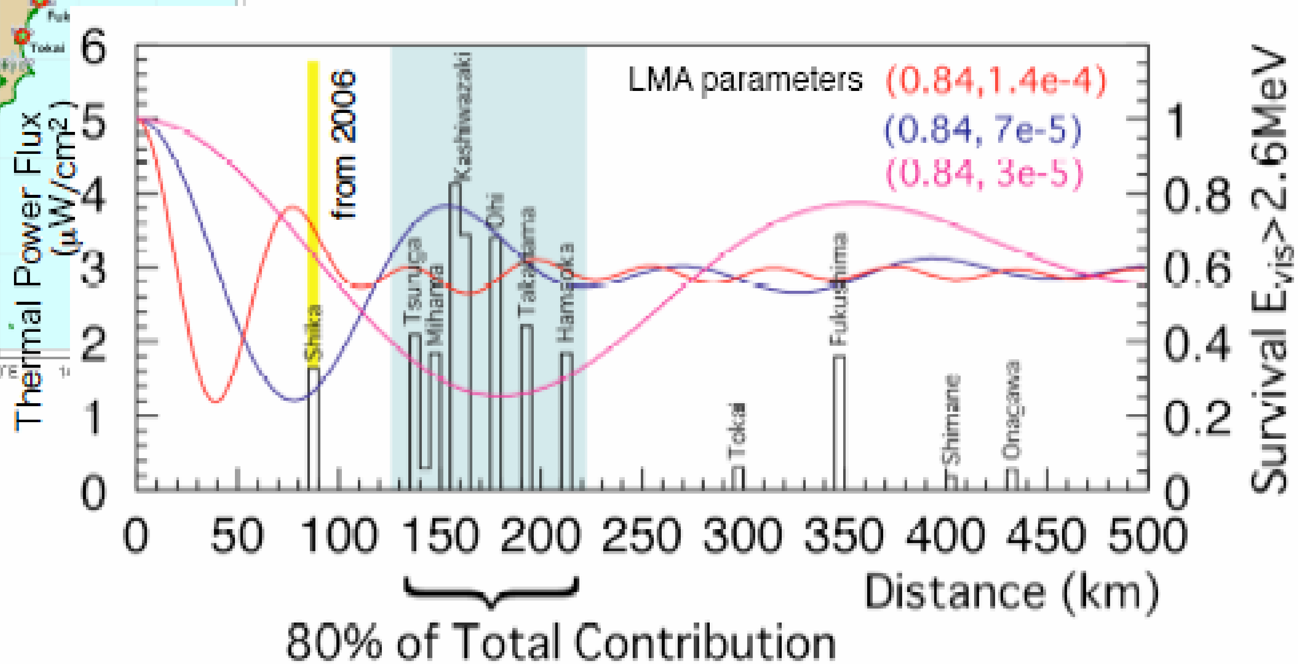
- It corresponds to ~2x10^{23} $\bar{\nu}_e$ creations/sec.



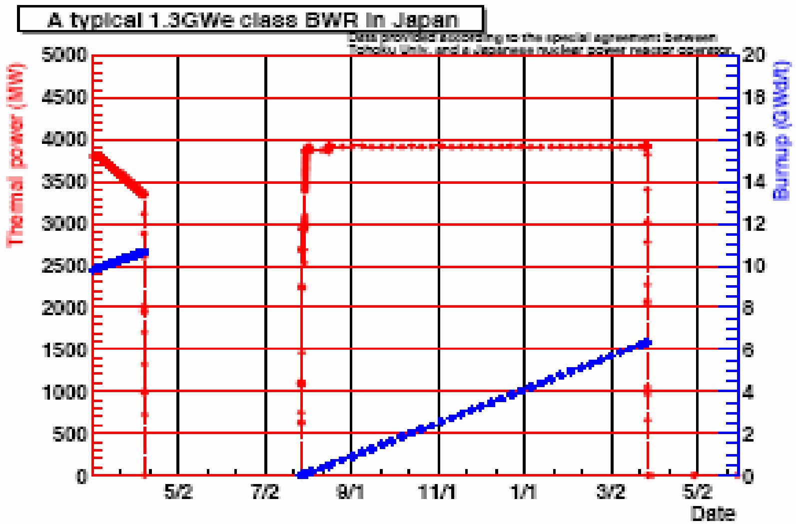
70 GW (7% of world total) is generated at 130-240 km distance from Kamioka.

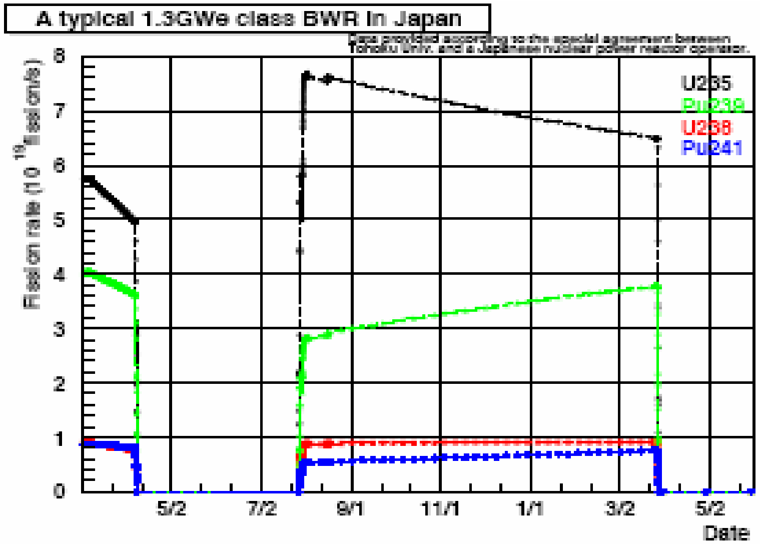
Reactor neutrino flux, $\sim 5 \times 10^6/cm^2/sec$ requires O(kiloton) underground detector.

There is a former Kamiokande cavity at 1000 m (2700 mwe) underground.



~97% from Japan
~2.5% from Korea

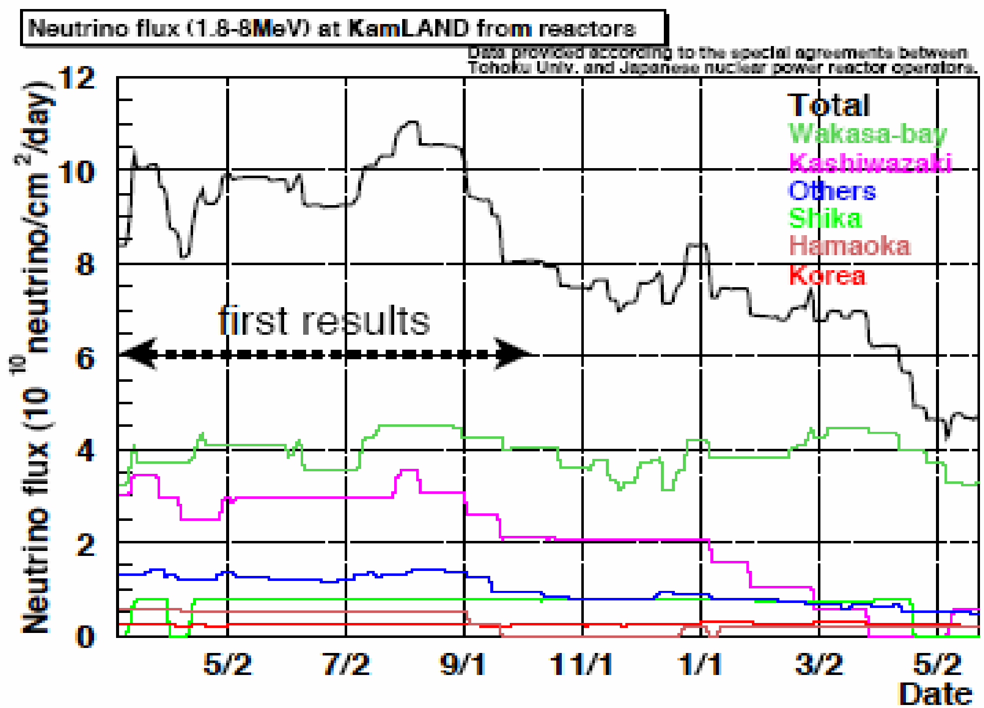


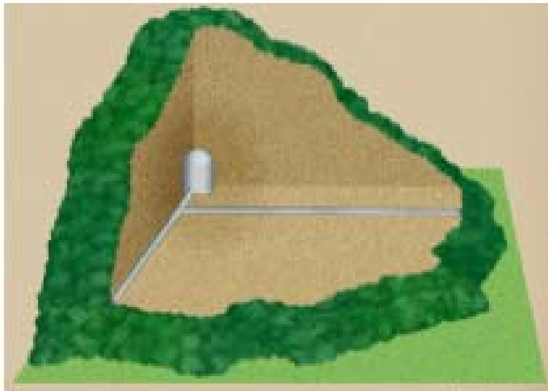


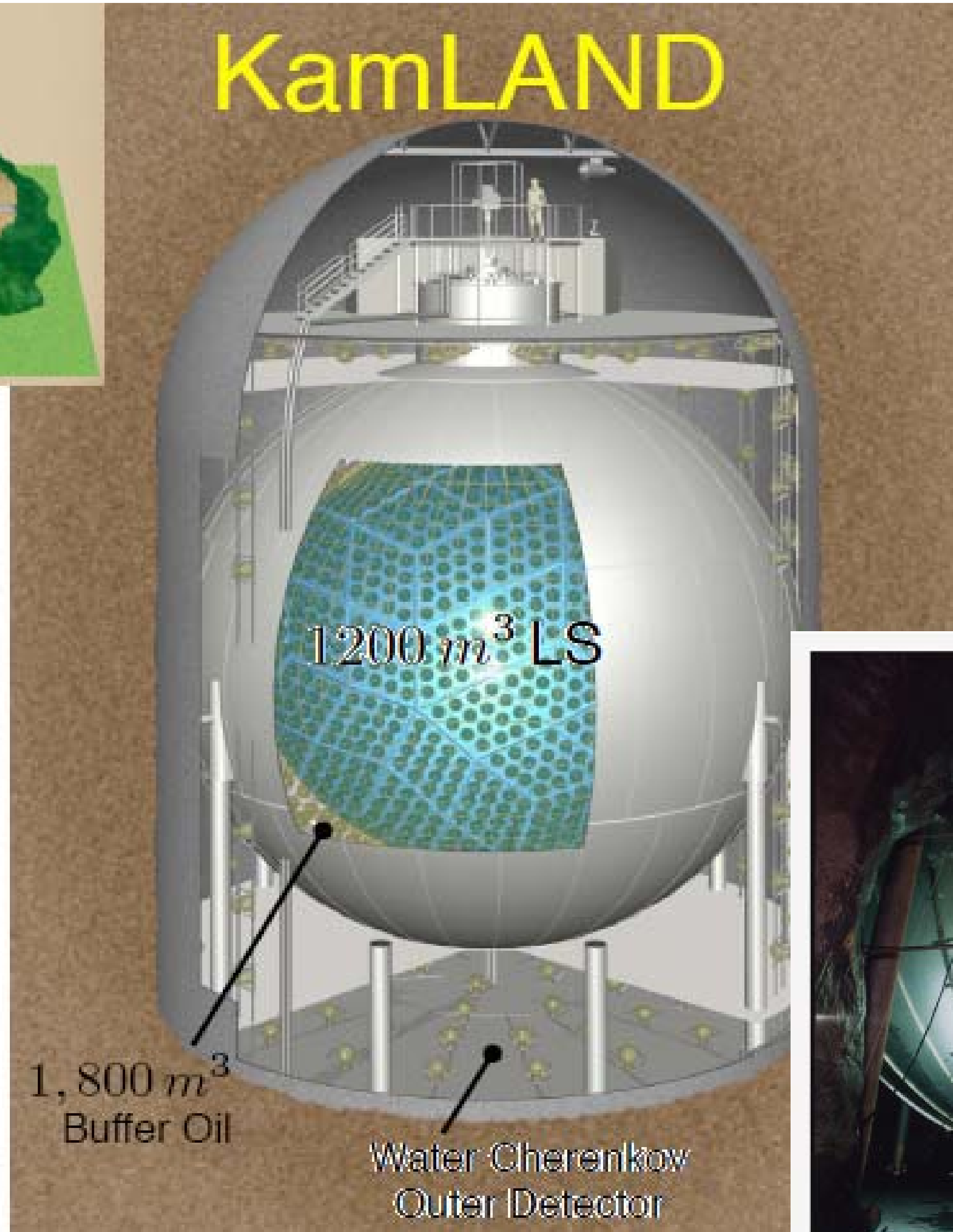
Available information

History of thermal power,
new fuel volume ratio,
fuel enrichment,
burn up
from 52 Japanese reactors

History of electric power
from 18 Korean reactors





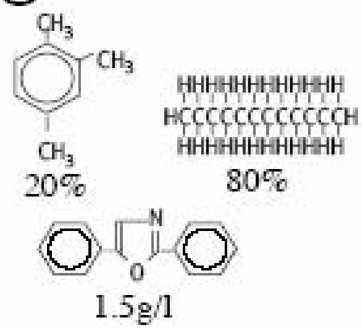


BO

50% dodecane
50% isoparaffin

$$\frac{\rho_{LS}}{\rho_{BO}} = 1.0004$$

LS



$$\rho = 0.78g/cm^3$$

$$8,000photons/MeV$$

$$\lambda \sim 10\,m$$

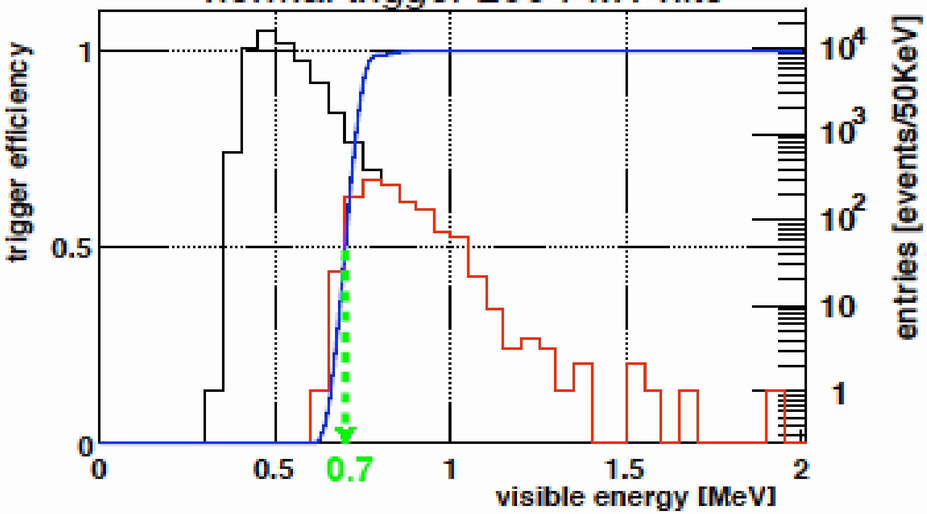
34% photo-coverage
with
1325 17" and 554 20"
photo-tubes

KamLAND Collaboration

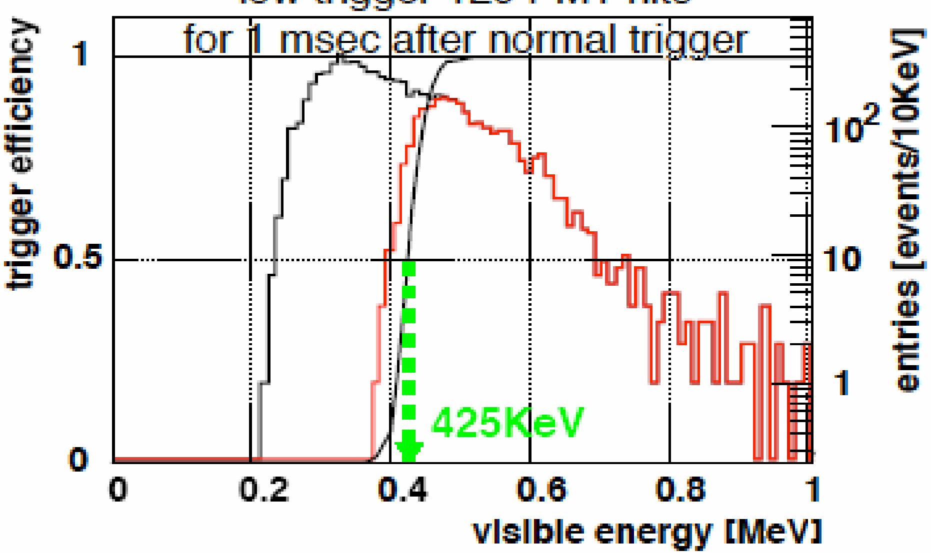
- Tohoku University: K.Eguch, S.Enomoto, K.Furuno, J.Goldman, H.Hanada, H.Ikeda, K.Ikeda, K.Inoue, K.Ishihara, W.Itoh, T.Iwamoto, T.Kawaguchi, T.Kawashima, H.Kinoshita, Y.Kishimoto, M.Koga, Y.Koseki, T.Maeda, T.Mitsui, M.Motoki, K.Nakajima, M.Nakajima, T.Nakajima, H.Ogawa, T.Sakabe, I.Shimizu, J.Shirai, F.Suekane, A.Suzuki, K.Tada, O.Tajima, T.Takayama, K.Tamae,H.Watanabe
- University of Alabama: J.Busenitz, Z.Djurcic, K.McKinny, D-M.Mei, A.Piepke, E.Yakushev
- LBNL Berkeley: B.E.Berger, Y.D.Chan, M.P.Decowski, D.A.Dwyer, S.J.Freedman, Y.Fu, B.Fujikawa, K.M.Heeger, K.T.Lesko, K-B.Luk, H.Murayama, D.R.Nygren, C.E.Okada, A.W.Poon, H.M.Steiner, L.A.Winslow
- California Institute of Technology: G.A.Horton-Smith, R.D.McKeown, J.Ritter, B.Tipton, P.Vogel
- Drexel University: C.E.Lane, T.Miletic
- University of Hawai Manoa: P.W.Gorham, G.Guilian, J.G.Leanned, J.Maricic, S.Matsuno, S.Pakvasa
- Louisiana State University: S.Dazeley, S.Hatakeyama, M.Murakami, R.C.Svoboda
- University of New Mexico: B.D.Dieterle, M.DiMauro
- Stanford University: J.Detwieler, G.Gratta, K.Ishii, N.Tolich, Y.Uchida
- University of Tennessee: M.Batygov, W.Bugg, H.Cohn, Y.Efremenko, Y.Kamyshkov, A.Kozlov, Y.Nakamura
- TUNL/ NCSU: L.De Braeckeleer, C.R.Gould, H.J.Karwowski, D.M.Markoff, J.A.Messimore, K.Nakamura, R.M.Rohm, W.Tornow, A.R.Young
- IHEP Beijing: Y-F.Wang

Event Trigger

normal trigger 200 PMT hits



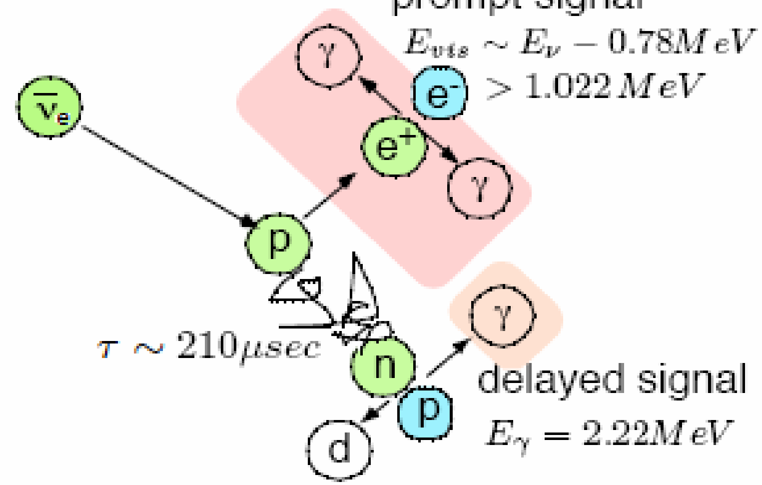
low trigger 120 PMT hits



Neutrino signal

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

$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806MeV$$



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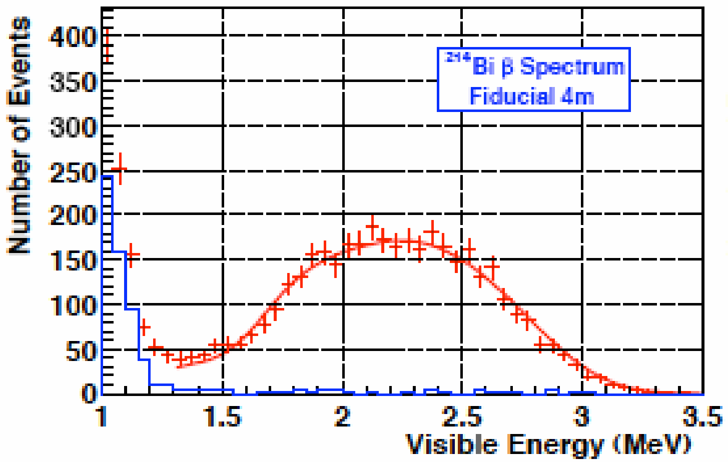
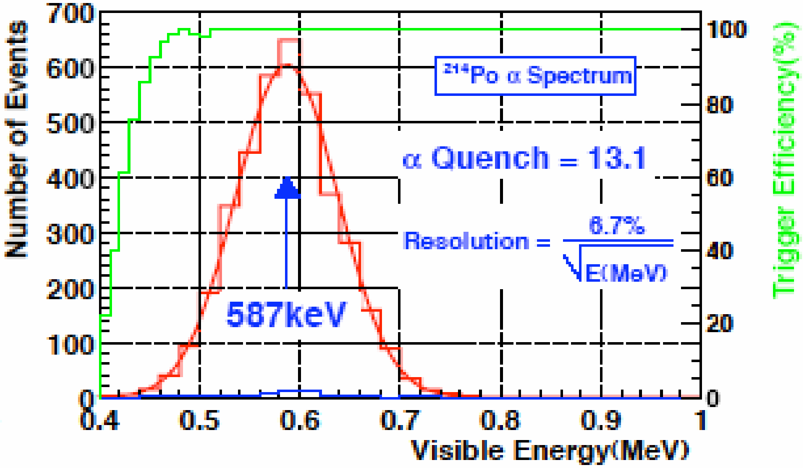
low trigger for impurity measurement

$$^{214}Bi \xrightarrow[\tau=237\mu s]{\beta,\gamma} {}^{214}Po \xrightarrow[7.687MeV]{\alpha} {}^{210}Pb$$

Impurity Measurement

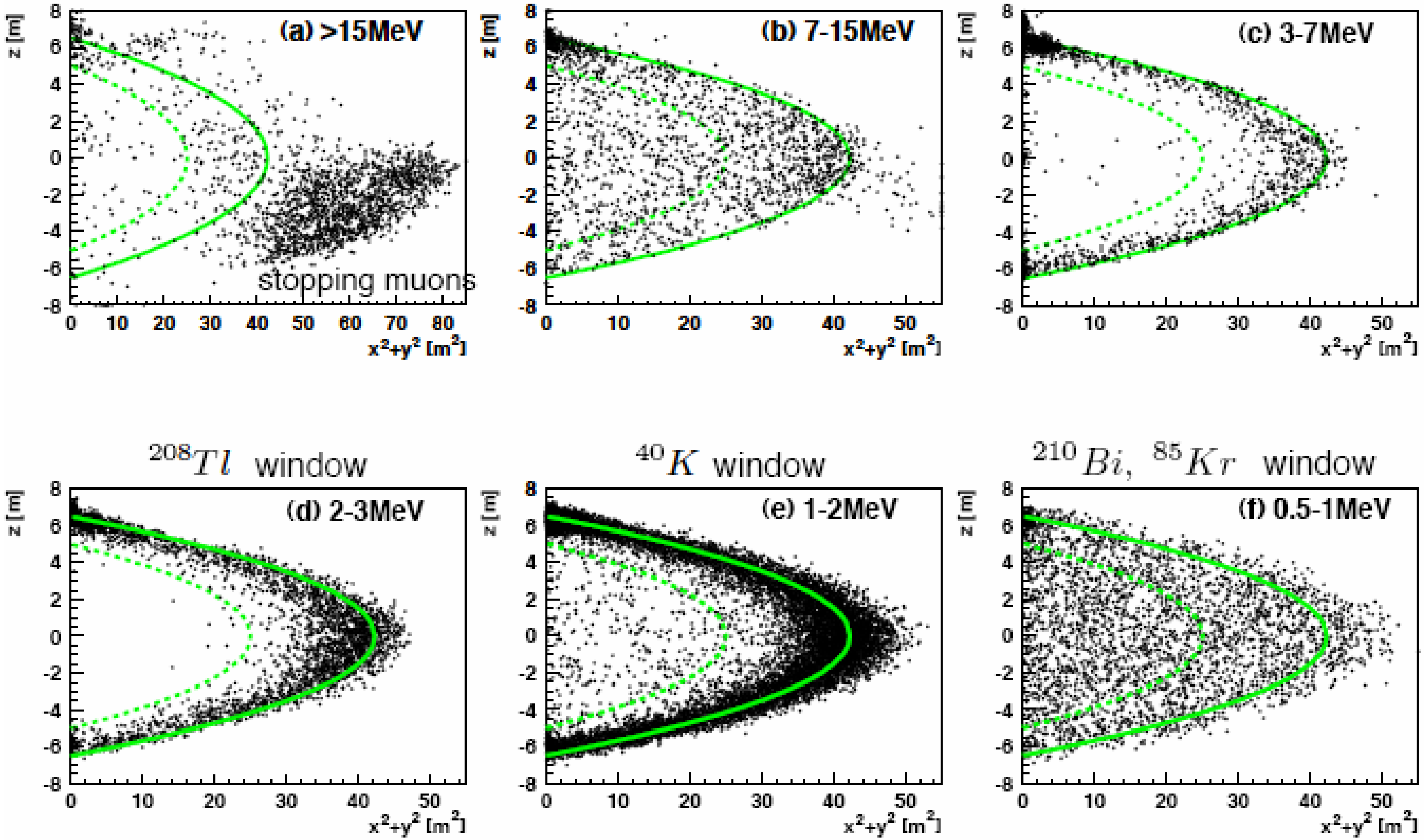




Impurities in the LS			Requirements Reactor	Solar
^{222}Rn	$0.03\mu Bq/m^3$	$^{214}Bi \rightarrow ^{214}Po(\tau = 237\mu sec)$		
^{238}U	$(3.5 \pm 0.5) \times 10^{-18} g/g$	assume equilibrium	$10^{-13} g/g$	$10^{-16} g/g$
^{232}Th	$(5.2 \pm 0.8) \times 10^{-17} g/g$	$^{212}Bi \rightarrow ^{212}Po(\tau = 0.431\mu sec)$	$10^{-13} g/g$	$10^{-16} g/g$
^{40}K	$< 2 \times 10^{-16} g/g$	single rate	$10^{-14} g/g$	$10^{-18} g/g$
^{85}Kr	$\sim 1\, Bq/m^3$	single rate/delayed coincidence		$1\, \mu Bq/m^3$
^{210}Pb	$\sim 100\, mBq/m^3$	single rate		$1\, \mu Bq/m^3$

Impurities on the Balloon		
$^{222}Rn \quad 4.0 \times 10^{-4}\, Bq$	$^{238}U \quad 3.1 \times 10^{-8}\, g$ ~0.9g mine dust	$^{232}Th \quad 9.7 \times 10^{-4}\, Bq$ ~0.1g mine dust

Vertex Distribution



Background

(in 162 ton-yr sample)

Accidental Coincidence

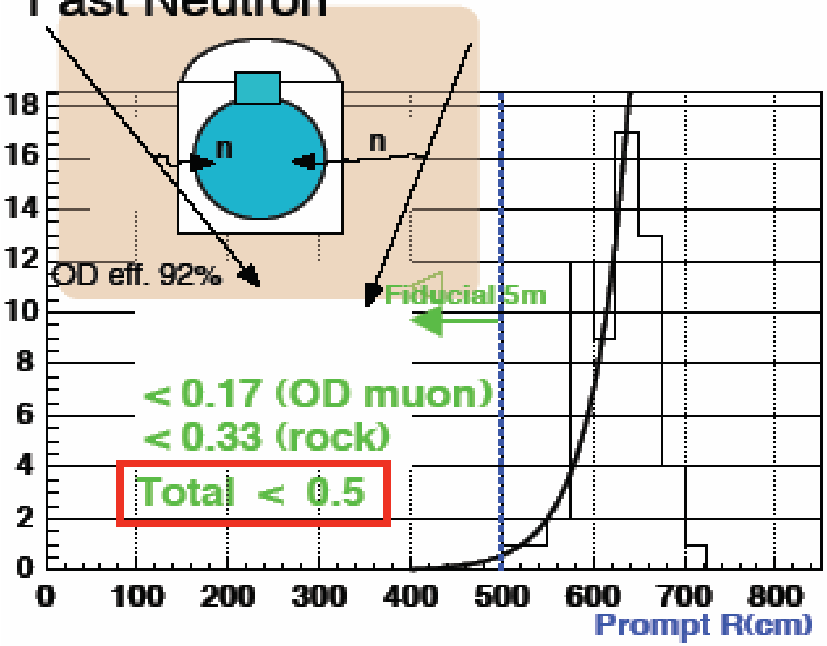
(2.6 MeV threshold)

0.0086 ± 0.0005

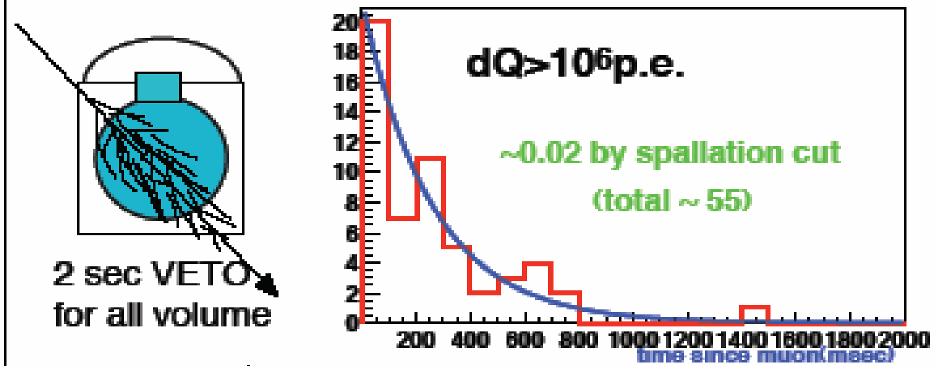
(0.9 MeV threshold)

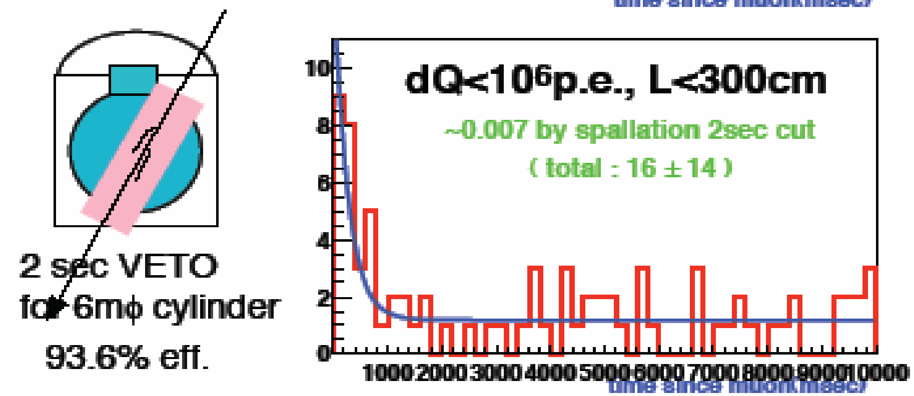
$1.81 \pm 0.08 \quad {}^{210}Bi + {}^{208}Tl$

Fast Neutron

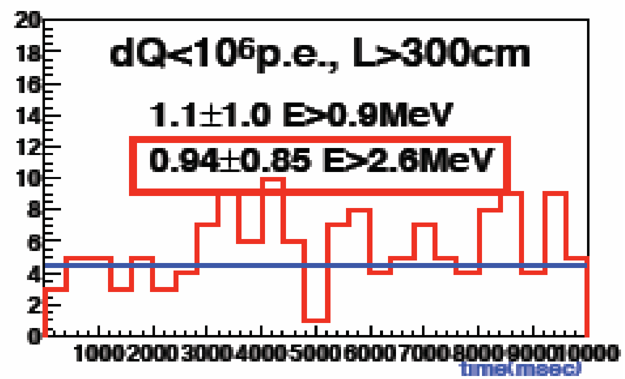


Spallation Products (^{9}Li β+n decay)





Remaining BG

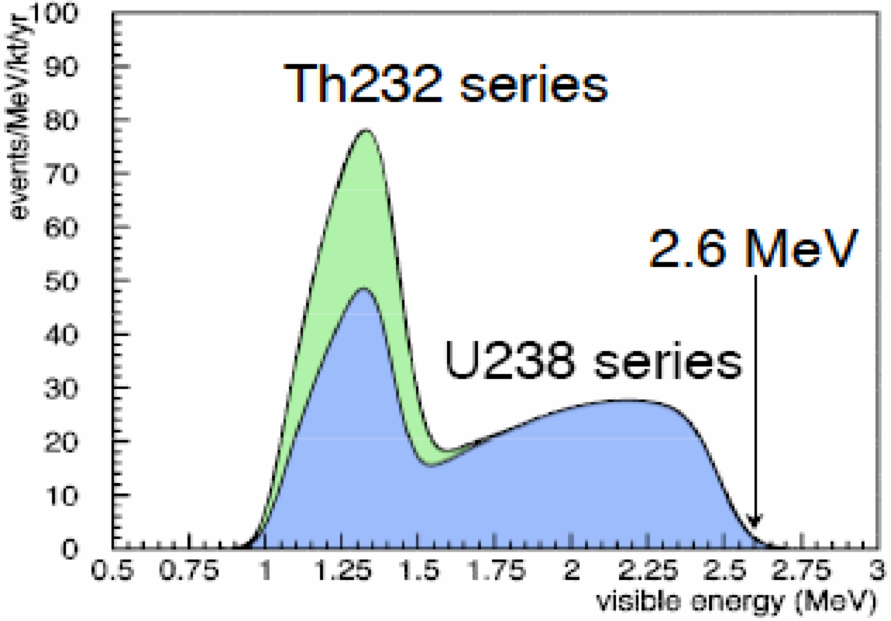


Background

(in 162 ton-yr sample)

	0.9 MeV	2.6 MeV
Total B.G.	2.9 ± 1.1	1 ± 1

Another important B.G.



A guess (16 TW)

~9 events (0.9 MeV)

~0.04 events (2.6 MeV)

$\bar{\nu}_e$ from the earth has never been observed, before.
If observed, it opens a new field of “Neutrino Geo-physics.”

Event Selection

(1) fiducial cut $R < 5\,m$ 3.46×10^{31} free protons

(2) timing correlation $0.5 < dT < 660\,\mu sec,\ \tau = 212\,\mu sec$

(3) vertex correlation $|r_{prompt} - r_{delayed}| < 1.6\,m$

(4) delayed energy $1.8 < E < 2.6\,MeV$

(5) thermometer cut $\sqrt{x^2 + y^2} > 1.2\,m$

detection efficiency 78.3%

(6) spallation cut

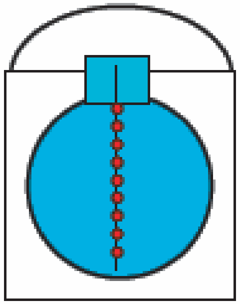
all vol. $(dQ > 10^6\,p.e.)$ or $L < 3\,m$ $(dQ < 10^6\,p.e.)$ VETO for $2\,sec$

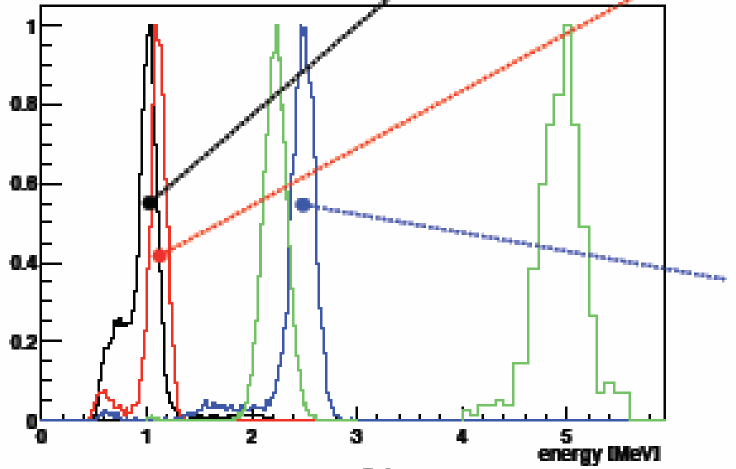
dead time 11.4 %

(7) energy threshold $E_{vis} > 2.6\,MeV$

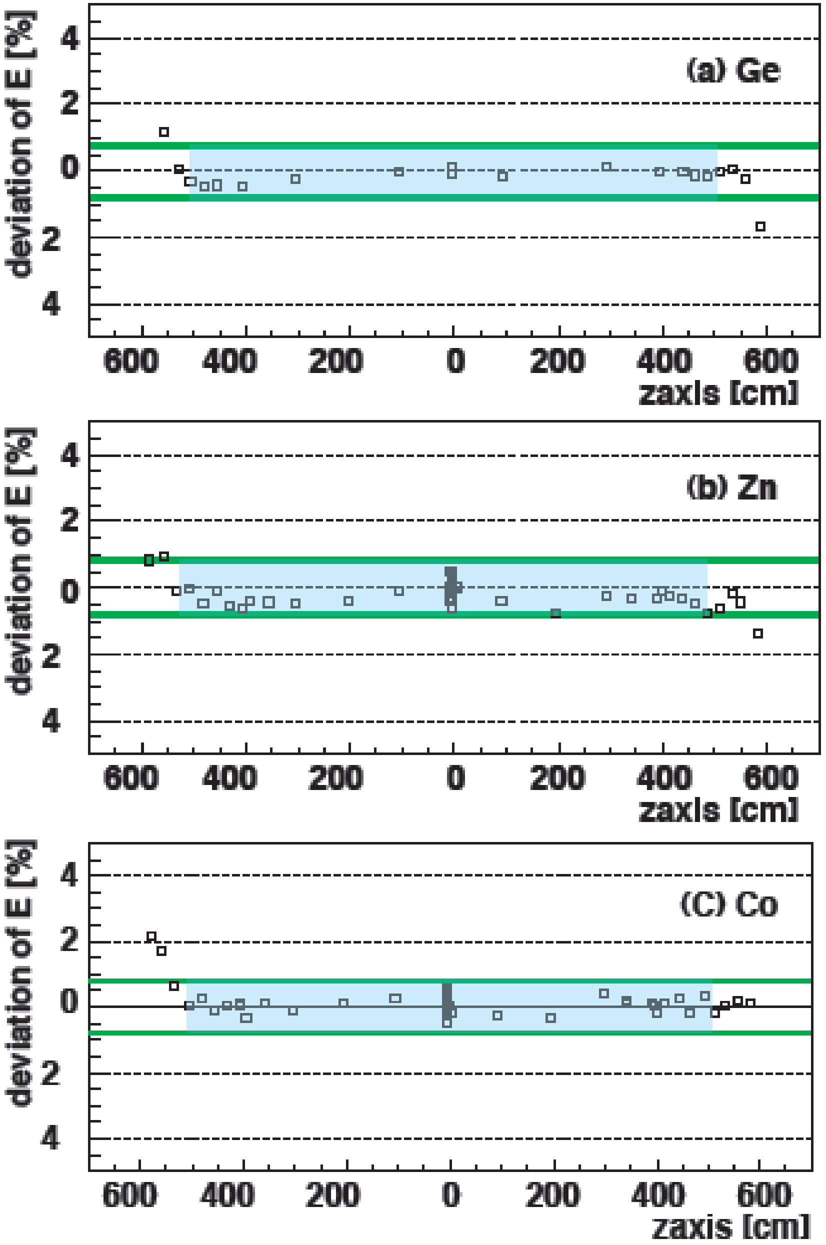
Endpoint energy of geo-$\bar{\nu}_e$ event is 2.5 MeV.

Energy Calibration with Radioactive Sources

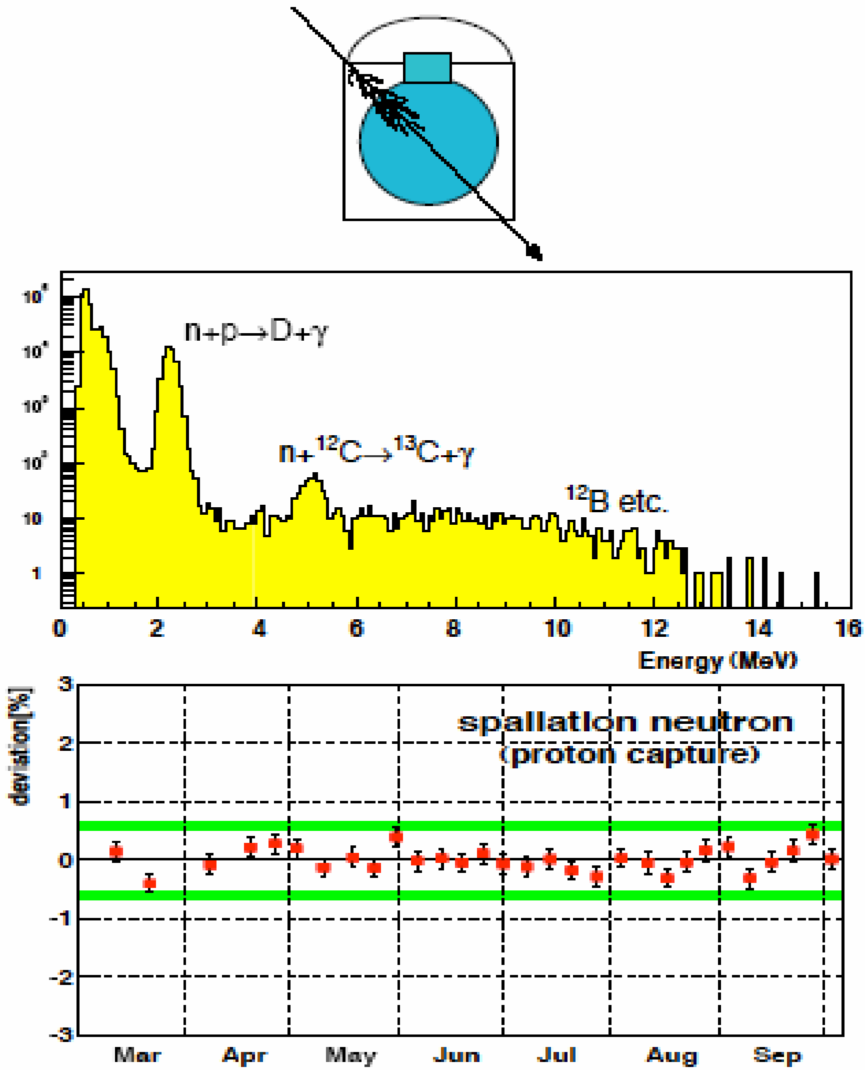




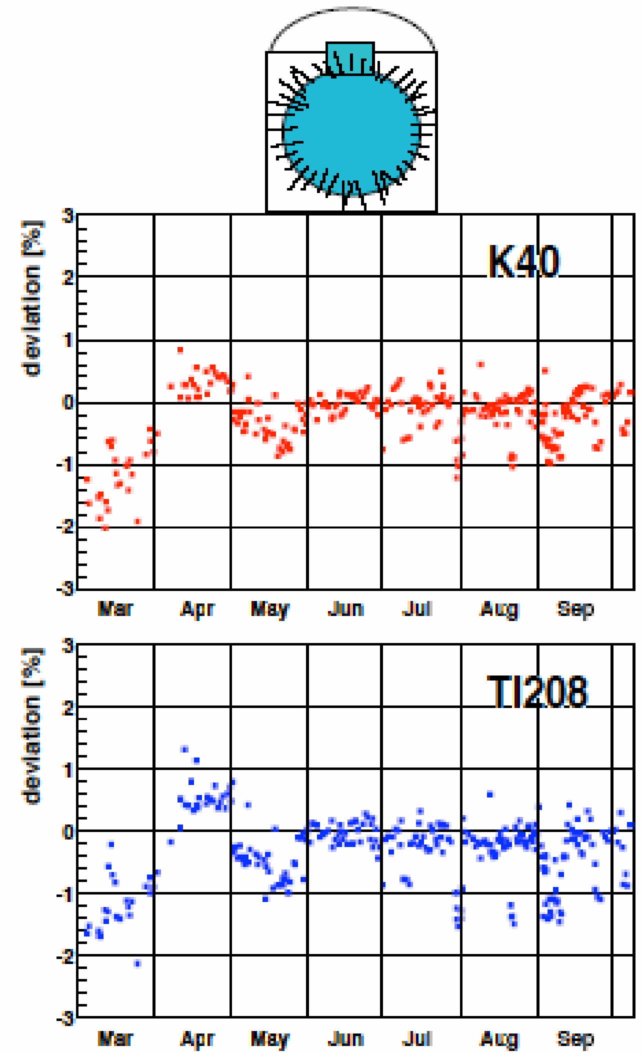
$$\frac{\sigma}{E} \sim \frac{7.5\%}{\sqrt{E}}$$



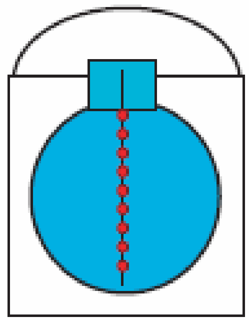
Energy Calibration with Muon Spallation

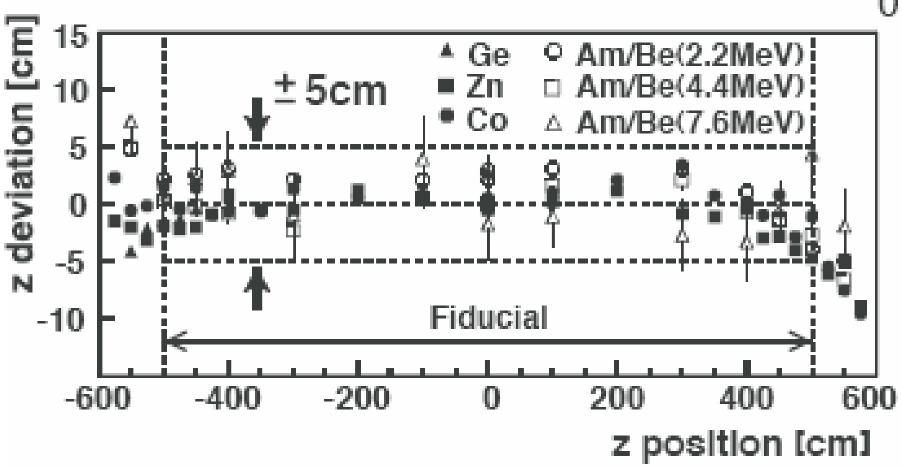


with gammas from material



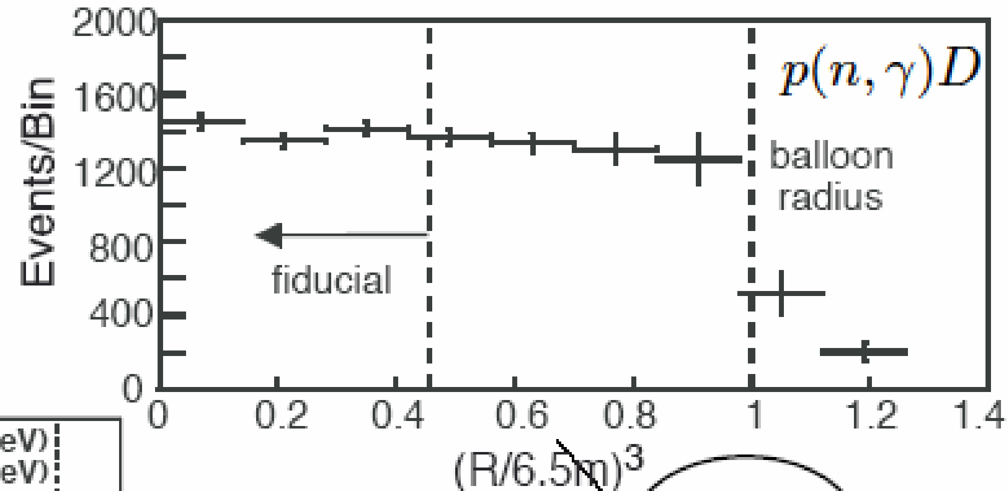
Fiducial Volume Calibration
with Radioactive Sources

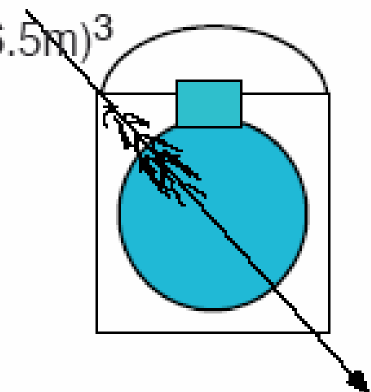




$$\sigma_{x,y,z} \sim \frac{30\,cm}{\sqrt{E}}$$

with Spallation Events





$$\frac{\Delta V}{V} = \pm 4.1\% \quad p(n,\gamma)D$$

$$\pm 3.5\% \quad {}^{12}B$$

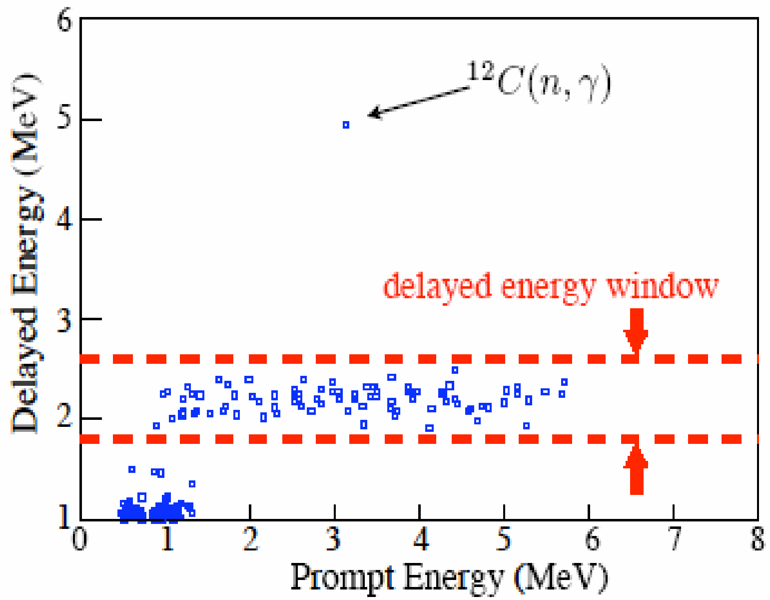
Statistical error dominates

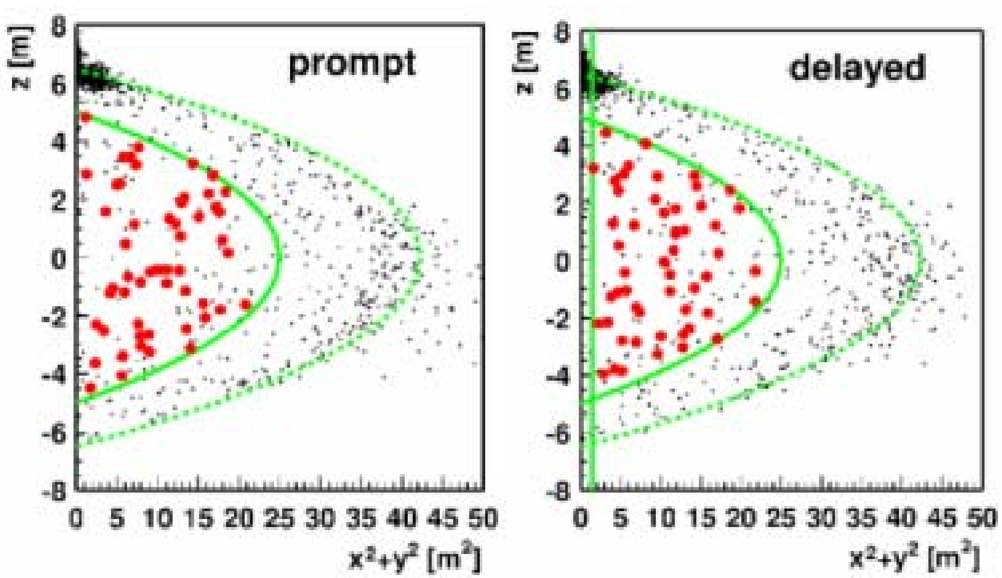
So far Achieved Systematic Errors

	0.9MeV	2.6MeV		
Thermal Power	2.0	2.0	Reactor related 3.4%	Japanese reactors contribute ~97% of neutrino flux.
Korean Reactors	0.25	0.25	Reactor related 3.4%	Only electric power is known but contribution is ~2.5%.
Other Reactors	0.35	0.35	Reactor related 3.4%	Contribution is only 0.7%.
Burn-up effect	1.0	1.0	Reactor related 3.4%	fraction of U235/U238/Pu239/Pu241
Long-life Nuclei	0.5	0.002	Reactor related 3.4%	contribution of Ru106 and Ce144
Time-lag of beta decay	0.3	0.3	Reactor related 3.4%	<1 day time lag for an equilibrium
Neutrino Spectra	2.3	2.5	Reactor related 3.4%	PLB160(1985)325, PLB218(1989)365, PRC24(1981)1543
Cross section	0.2	0.2		PRD60(1999)053003, PRC67(2003)035502
Total LS mass	2.1	2.1	Detector 5.5%	$1171 \pm 25\ m^3$
Fiducial Volume Ratio	4.1	4.1	Detector 5.5%	vertex distribution of spallation neutron
Energy Threshold	-	2.1	Detector 5.5%	position 1.4%, time 0.6%, quench 1.02%, dark 0.4% ->1.91%
Efficiency of Cuts	2.1	2.1	Detector 5.5%	capture time, space correlation, energy window
Live Time	0.07	0.07	Detector 5.5%	
Total	6.0%	6.4%		

Analysis Data set

4 Mar. ~ 6 Oct. 2002
145.1 live days
162 ton-year exposure



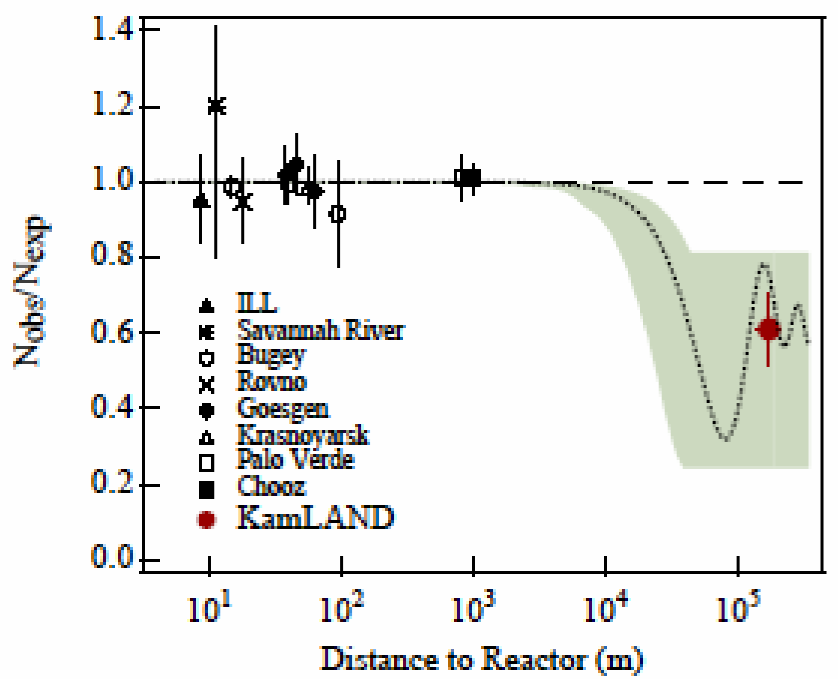


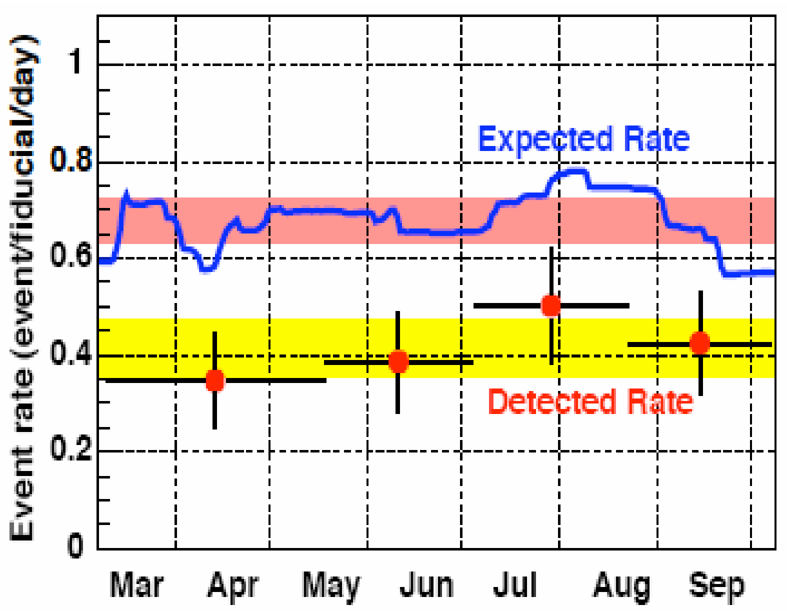
KamLAND collaboration
Phys.Rev.Lett.90(2003)021802

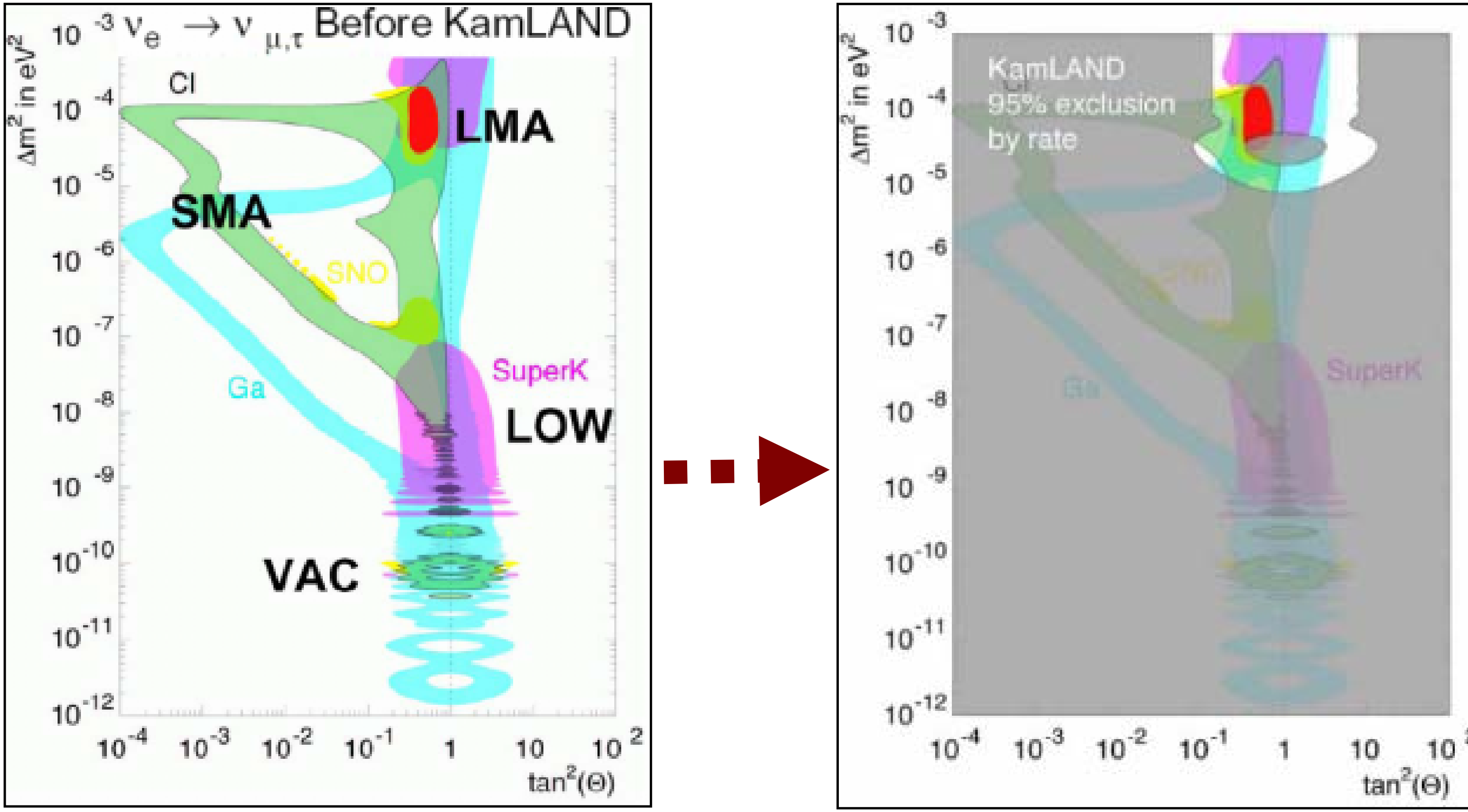
Rate Analysis Result

Analysis threshold	2.6MeV	0.9MeV
Expected signal	86.8±5.6	124.8±7.5
BG	1±1	2.9±1.1 (+9 geo neutrino)
Observed	54	86

neutrino disappearance 99.95C.L.
R=0.611±0.085(stat)±0.041(syst)

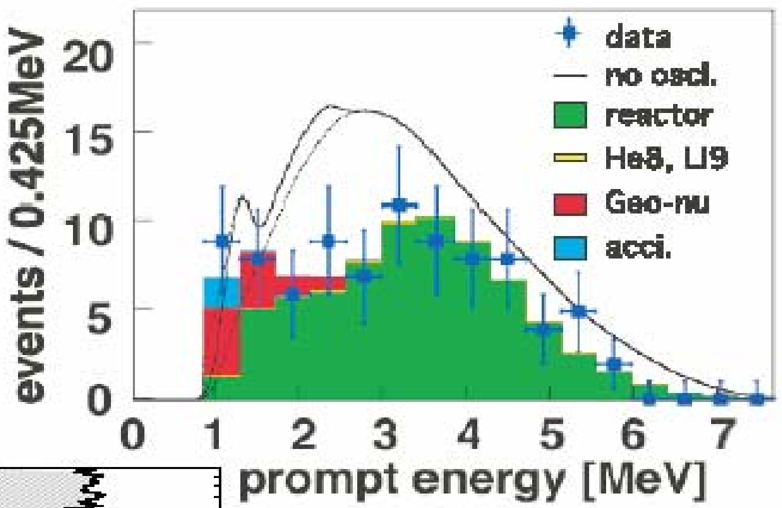


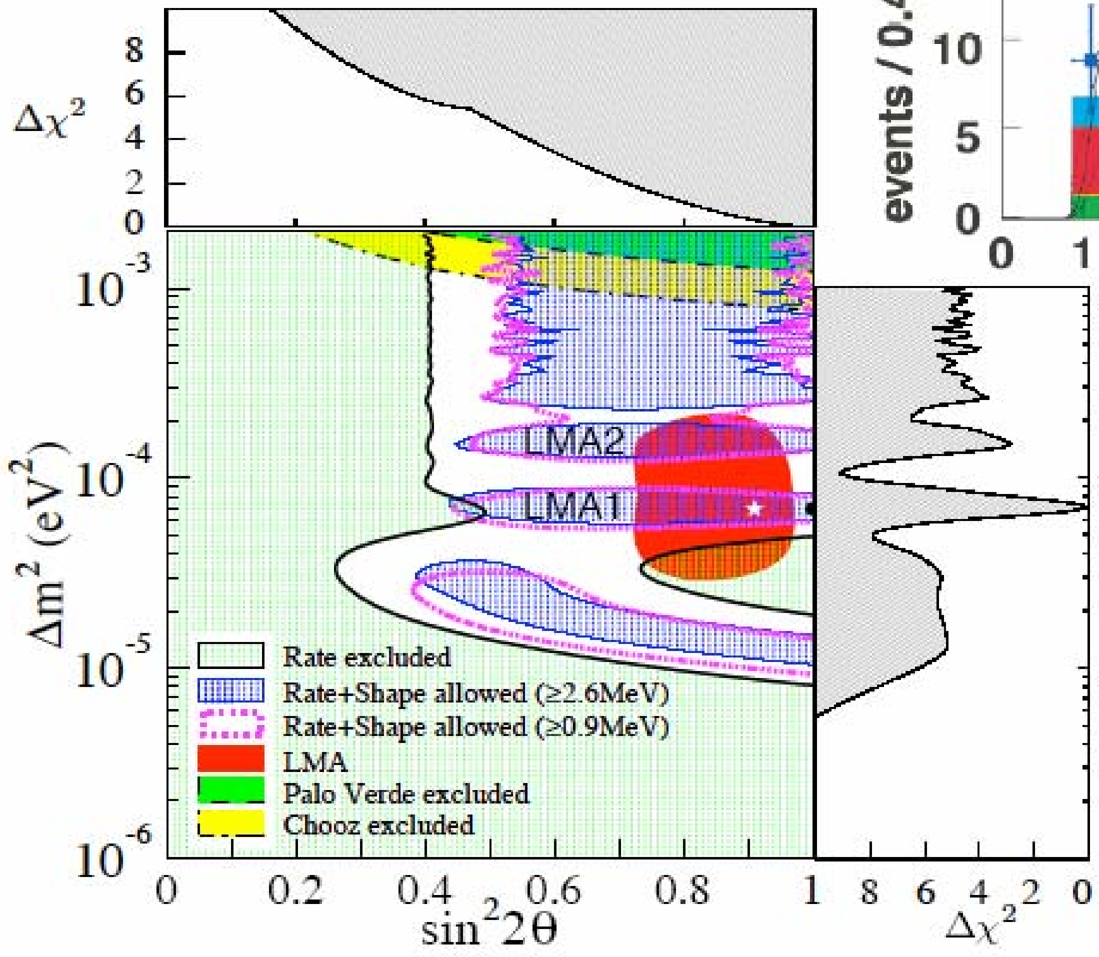




LMA is only candidate!

Rate + Shape Analysis





Best Fit E > 2.6 MeV

$$\sin^2 2\theta = 1.0$$

$$\Delta m^2 = 6.9 \times 10^{-5} eV^2$$

Best Fit E > 0.9 MeV

$$\sin^2 2\theta = 0.91$$

$$\Delta m^2 = 6.9 \times 10^{-5} eV^2$$

$$\bar{\nu}_{geo}(^{238}U) = 4$$

$$\bar{\nu}_{geo}(^{232}Th) = 5$$

hint of geo-nu,
but consistent with 0 at 95% CL

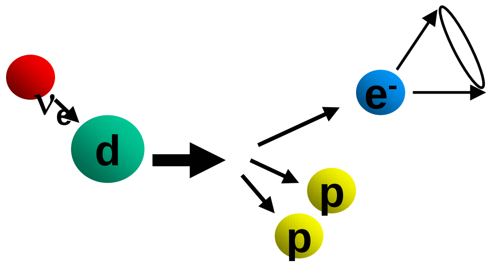
Recent SNO result

Recent SNO result

Charged Current (CC):

$\nu_e + d \Rightarrow p + p + e^-$

Electron neutrinos only`

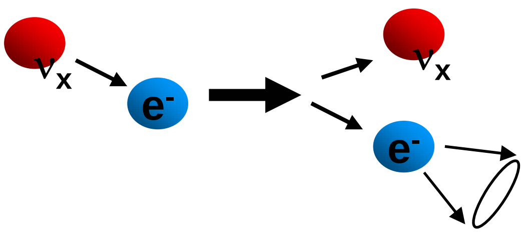


Elastic Scattering (ES):

$\nu_x + e^- \Rightarrow \nu_x + e^-$

Direction strongly correlated to neutrino direction

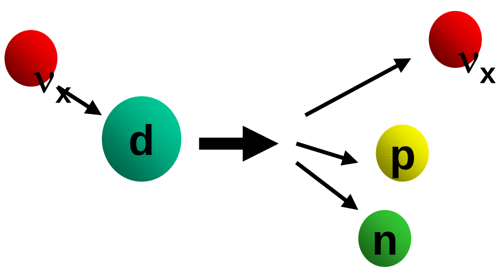
$0.154\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



Neutral Current (NC):

$\nu_x + d \Rightarrow p + n + \nu_x$

Same for all neutrino flavors



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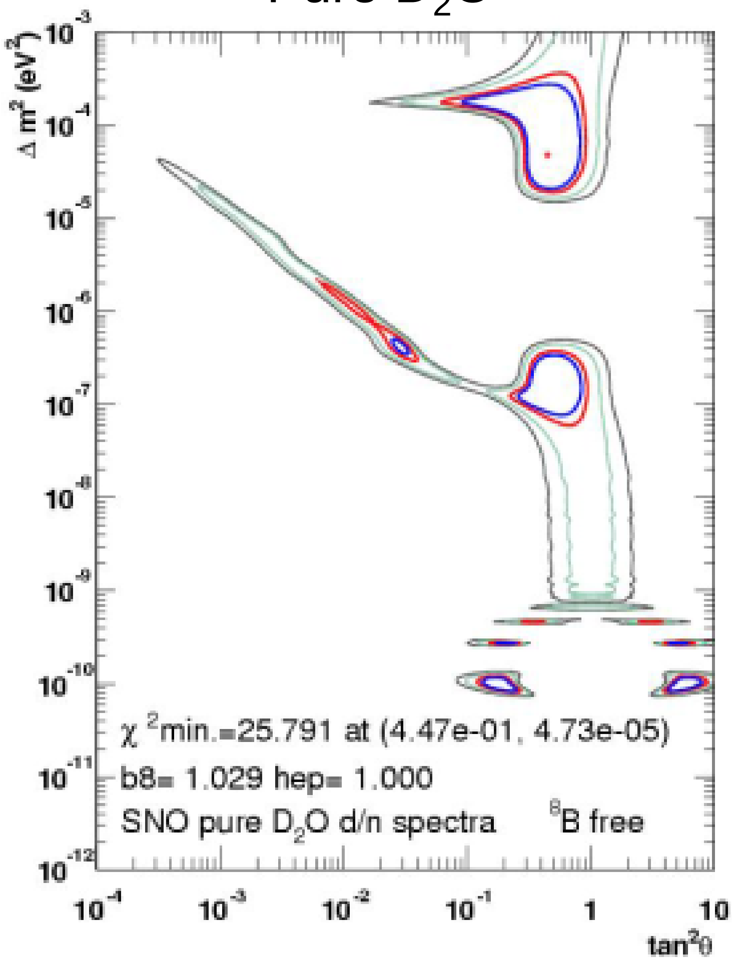
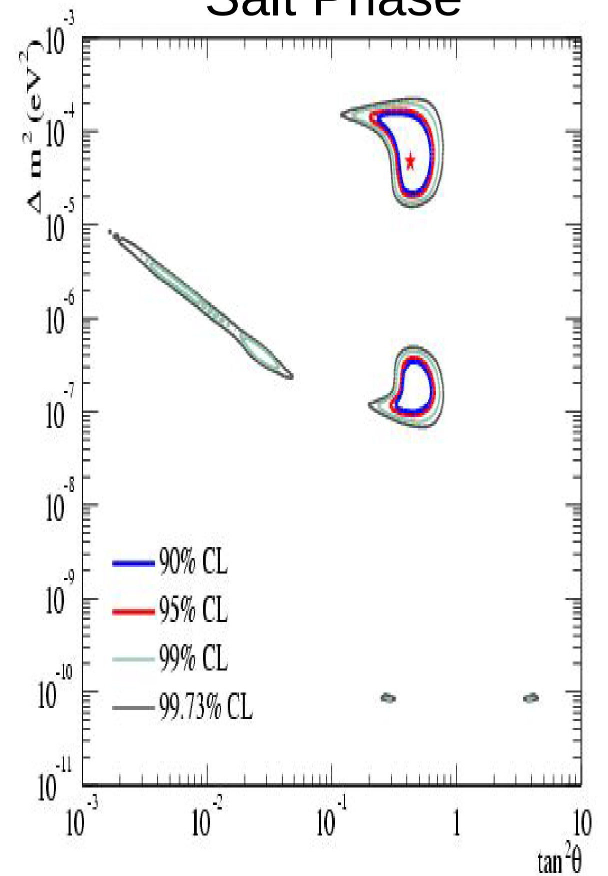
Oscillation Parameters - SNO Only

Pure D_2O

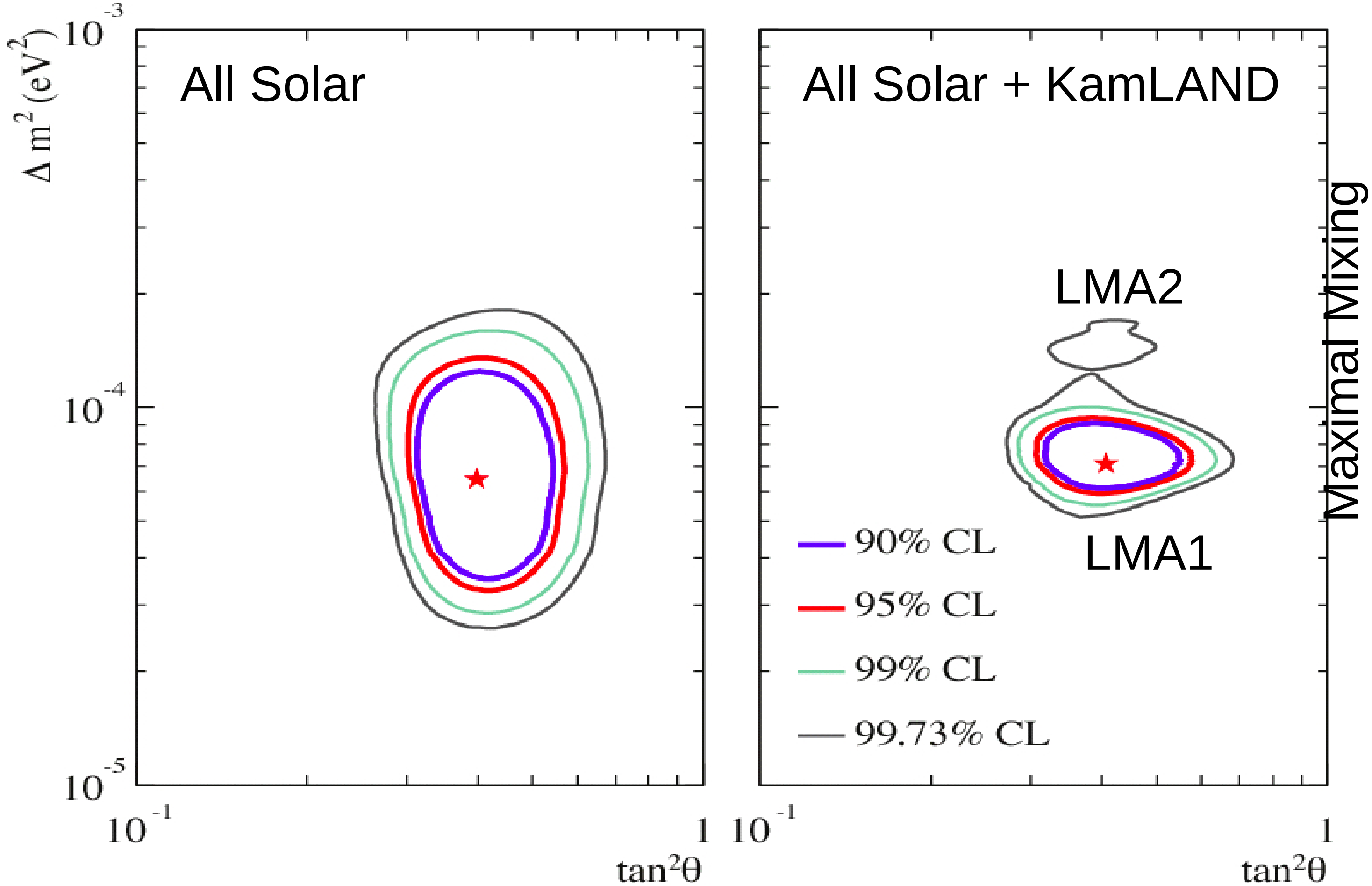


Salt Phase



SNO collaboration nucl-ex 0309004

Global Oscillation Parameters after Salt



SNO collaboration nucl-ex 0309004

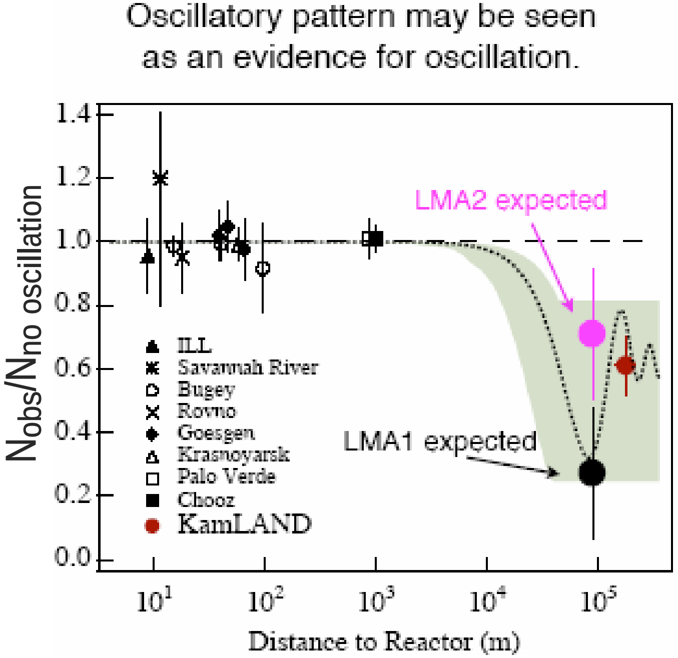
SNO salt phase 1st result summary

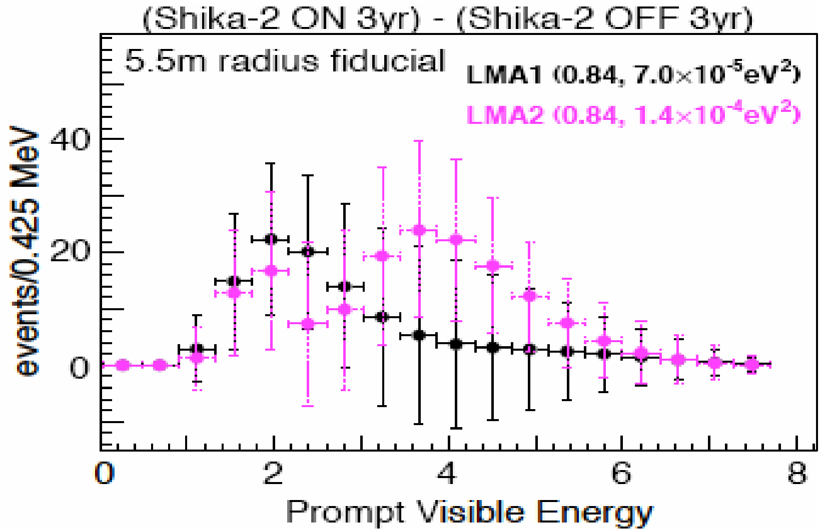
- Neutrinos change flavor
  - CC/NC= 0.306±0.026 ±0.024, >7σ from 1
- NC Flux results are in agreement with SSM predictions (but experimental error bars are now smaller than model uncertainties)
- Neutrino Oscillation Parameters:
  - No LMA2 (KamLAND should see shape distortion in LMA1)
  - Excludes maximal mixing at 5.4 σ
- MSW matter effects are now required, >5 σ
  - Fogli et al., hep_ph/0309100

KamLAND future plan

- Analysis data update: maybe soon
- 4 **π** Calibration system operation (~2004)
- Shika2 reactor will work at 88km ~2006
- ^{7}Be solar neutrino observation phase ~2007

Shika2 will start n 2006 at 88km distance

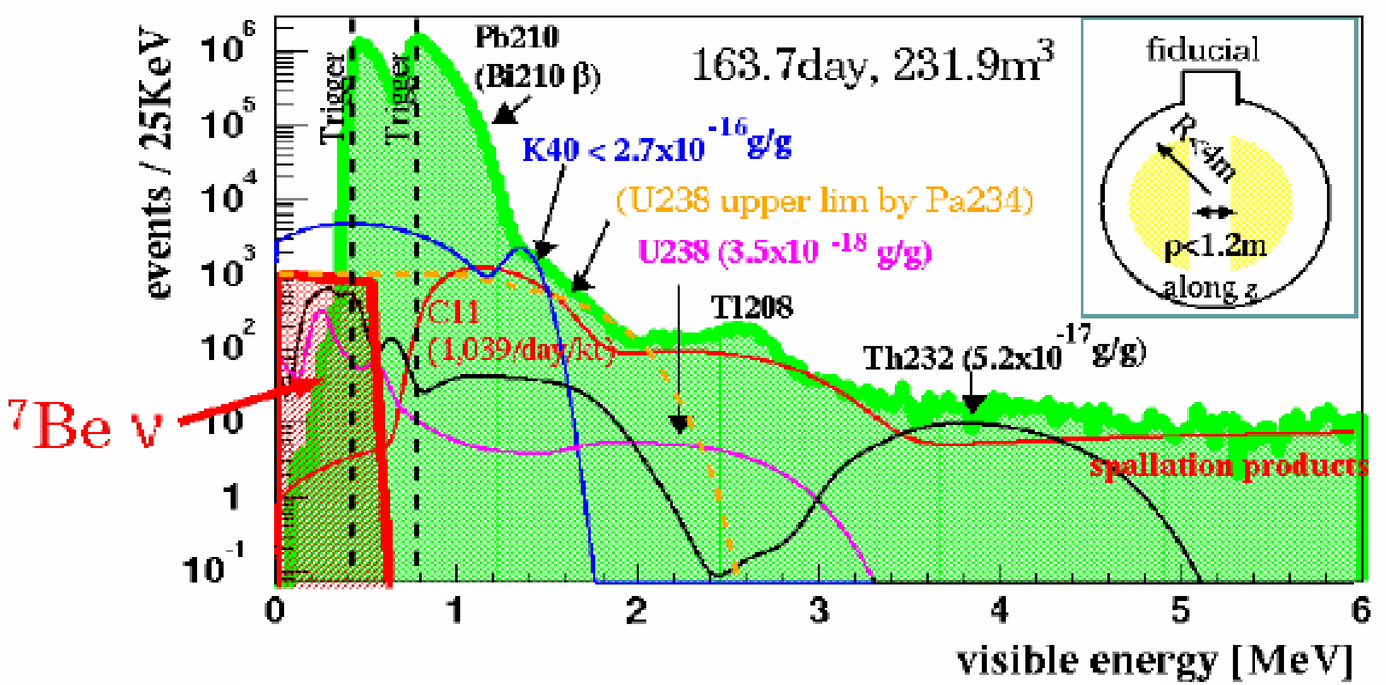




$$R_{LMA2} = \frac{121 \pm 36}{173}$$

$$R_{LMA1} = \frac{45 \pm 37}{173}$$

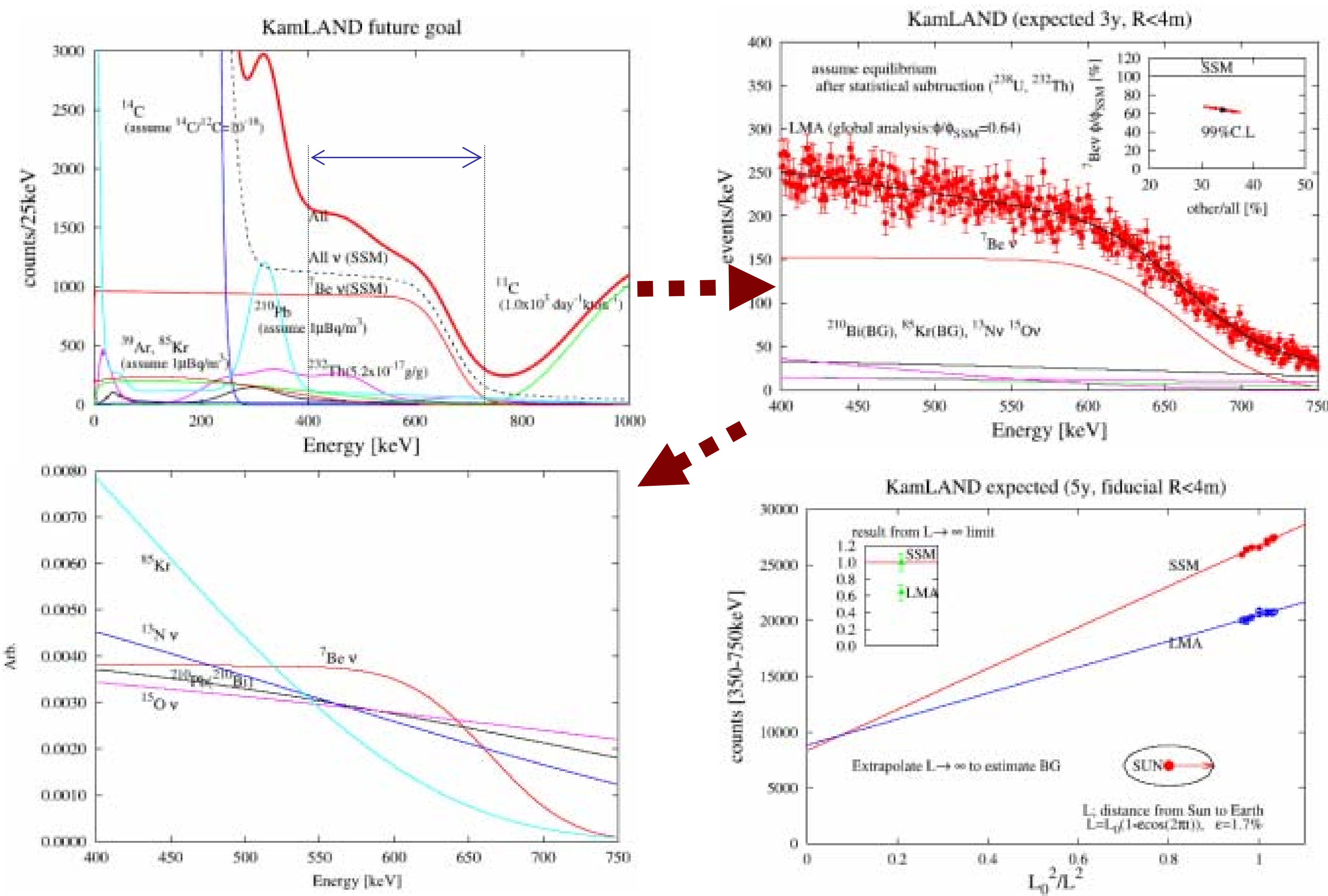
toward 7Be solar neutrino detection



We need the purification again!

Background	now	goal
^{238}U(by Bi-Po)	3.5×10^{-18}g/g	**OK!!**
^{238}U(by ^{234}Pa)	$\mathbf{O}(10^{-15}$g/g)(Max.)	10^{-18}g/g
^{232}Th (by Bi-Po)	5.2×10^{-17}g/g	**OK!!**
^{40}K	2.7×10^{-16}g/g(max.)	$< 10^{-18}$g/g
^{210}Pb	$\sim 10^{-20}$g/g	5×10^{-25}g/g $\sim 1\mu$Bq/m^3
^{85}Kr, ^{39}Ar	^{85}Kr =0.7Bq/m^3	1μBq/m^3
^{222}Rn (after purification)	^{238}U $= 3.5 \times 10^{-18}$g/g $= 3.3 \times 10^{-8}$Bq/m^3	**OK!!** (1μBq/m^3)
^{222}Rn (during purification)		1mBq/m^3 ^{210}Pb $= 0.5\mu$Bq/m^3 after decay

We are developing new purification and gas protection technique now!


KamLAND future goal
counts/25keV
Energy [keV]
All
All ν (SSM)
7Be ν(SSM)
14C
11C
210Pb
39Ar, 85Kr
232Th(5.2x10-17g/g)
KamLAND (expected 3y, R<4m)
assume equilibrium
after statistical subtraction (238U, 232Th)
LMA (global analysis:φ/φSSM=0.64)
events/keV
SSM
99%C.L.
other/all [%]
210Bi(BG), 85Kr(BG), 13Nν 15Oν
Arb.
85Kr
13N ν
7Be ν
15O ν
KamLAND expected (5y, fiducial R<4m)
result from L→∞ limit
SSM
LMA
counts [350-750keV]
Extrapolate L→∞ to estimate BG
SUN
L; distance from Sun to Earth
L=L0(1-εcos(2πt)), ε=1.7%

Summary

KamLAND has observed an evidence for reactor neutrino disappearance at ~180km distance with 99.95% C.L.

$$R = 0.611 \pm 0.085 \pm 0.041$$

Assuming CPT invariance, only the LMA solution is compatible with the deficit.

KamLAND is running on stable condition. KamLAND will give high sensitivity data to survey the LMA region.

We started R&D for detection of ^{7}Be solar neutrinos on KamLAND