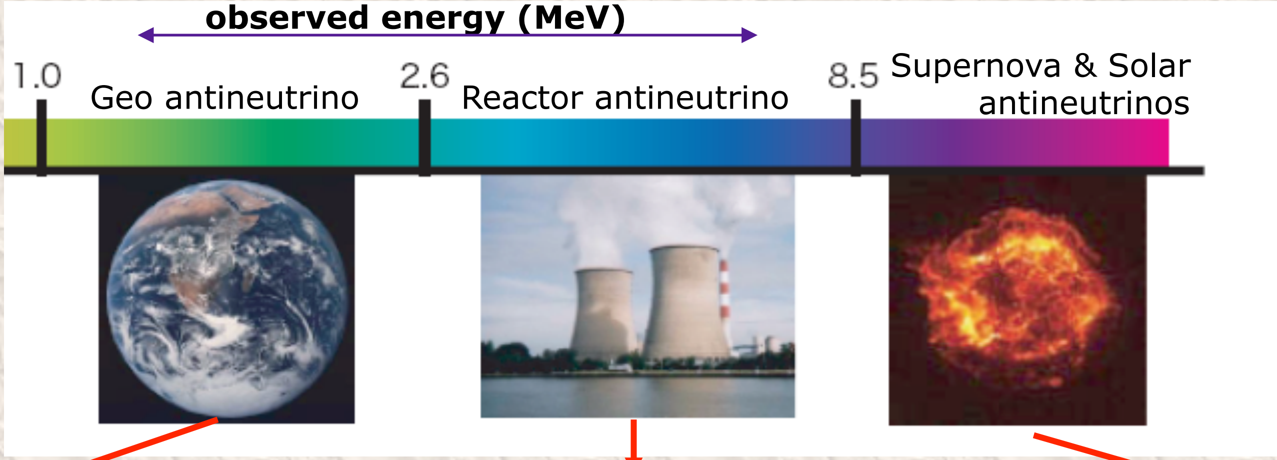
From the KamLAND to the KamLAND-Zen, or from looking for antineutrinos to looking for no neutrinos.

Yuri Efremenko

University of Tennessee
Feb 5, 2014

KamLAND-Kamioka Large Anti Neutrino Detector

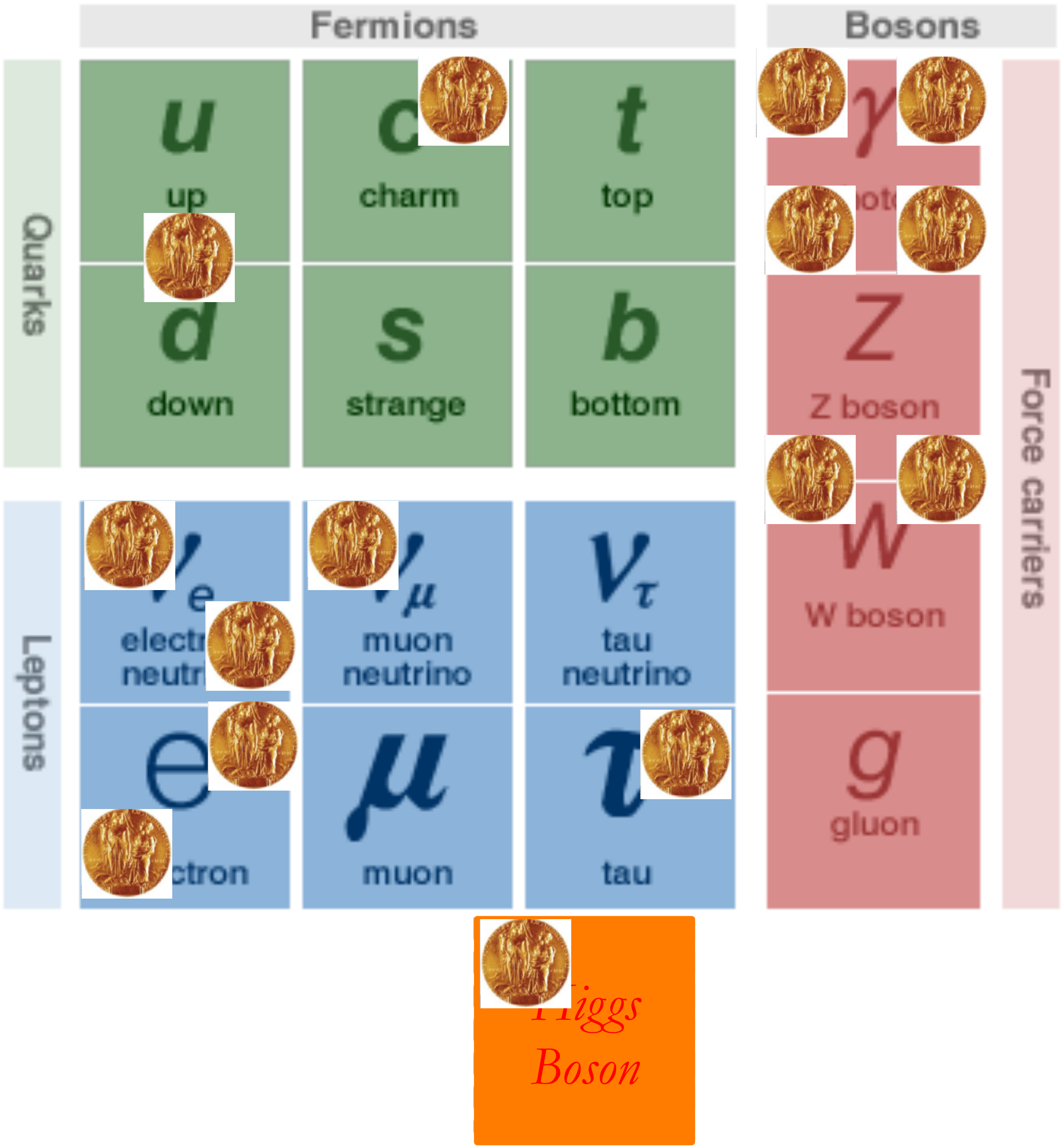


Nature Geoscience 4 (647-651), 2011
PRL 100, 221803 (2008)
Nature 436(499-503), 2005

Phys.Rev.D83:05200, 2011
Phys.Rev.Lett.100:221803,2008
Phys.Rev.Lett.94:081801,2005
Phys.Rev.Lett.90:021802,2003

Astrophys.J. 745:193 2012
Phys.Rev.Lett.92:071301,2004

THE STANDARD MODEL Recognition



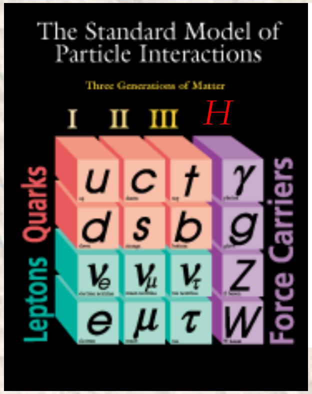
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ ot	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electr neutr	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e ctron	μ muon	τ tau	g gluon	

iggs
Boson

What do we know about neutrinos?

F. A. Scott, *Phys. Rev.* 48, 391 (1935)

I. They do exist



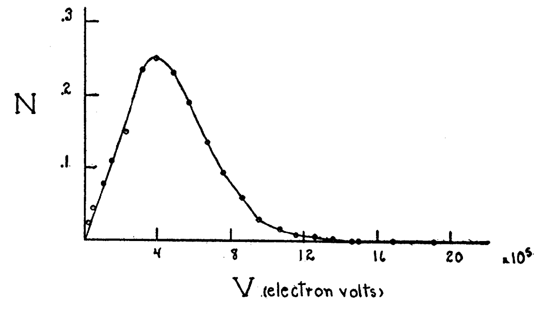
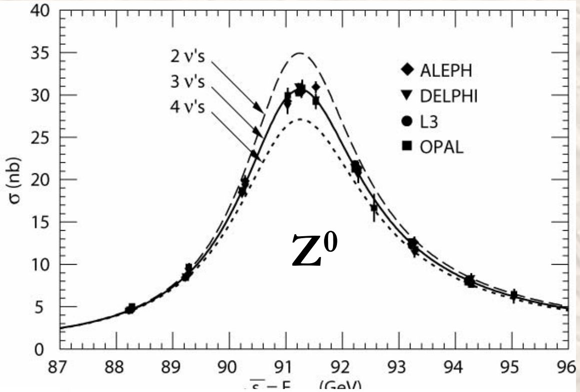
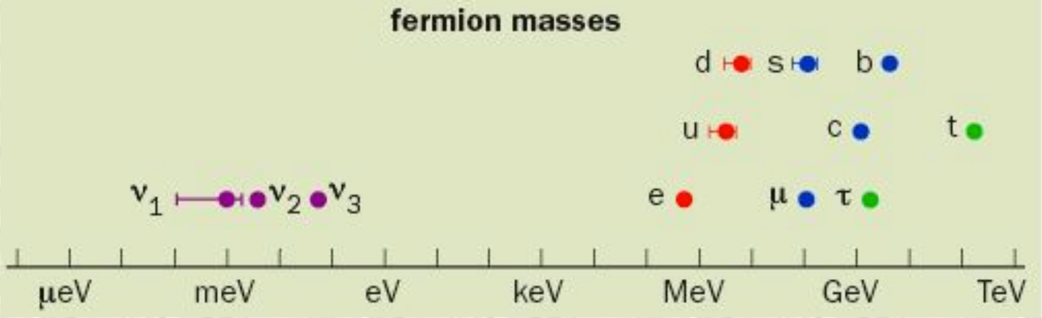


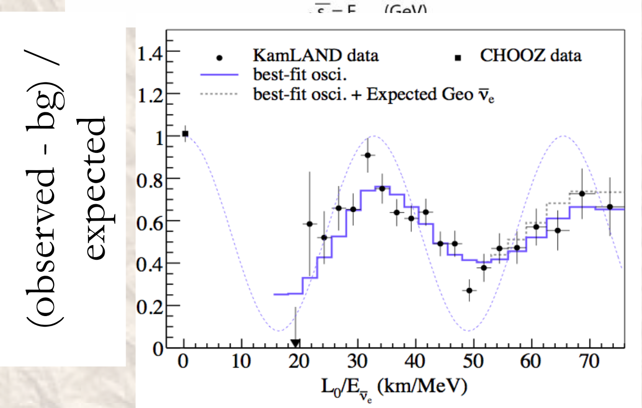
FIG. 5. Energy distribution curve of the beta-rays.

II. There are three light neutrino species $N_\nu=2.984\pm0.008$



III. Neutrinos do oscillate and therefore they are massive





Neutrino Oscillations

The idea of neutrino oscillations existed long before Davis experiment: Pontecorvo (1958), Maki, Nakagawa, and Sakata (1962), and Pontecorvo and Gribov (1969)

If m_ν is non-zero, then mixing between different neutrino flavors is possible

$$|\nu_j\rangle = \sum_j U_{jl} |\nu_l\rangle$$

What is produced and detected is weak eigenstate $|\nu_j\rangle$

U_{jl} is a 3 x 3 unitary matrix (like the CKM matrix for quarks)

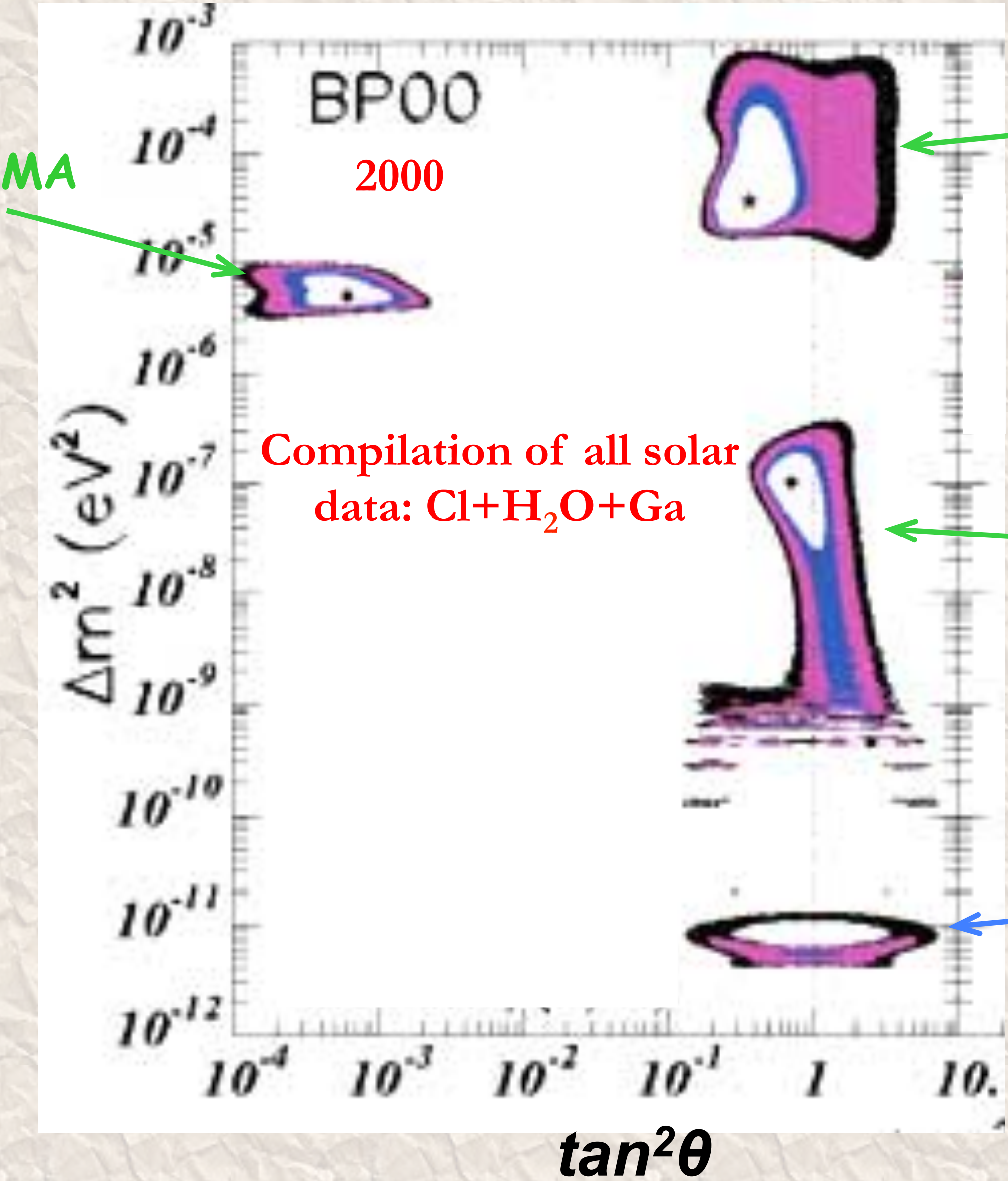
What propagates is the mass eigenstate $|\nu_l\rangle$

$$U_{jl} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Simplified expression for two flavor oscillations in a vacuum:

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

KamLAND was Build to Study Solar Neutrino Deficit with Reactors (1998)



2000

Compilation of all solar data: $Cl+H_2O+Ga$

SMA

LMA

LOW

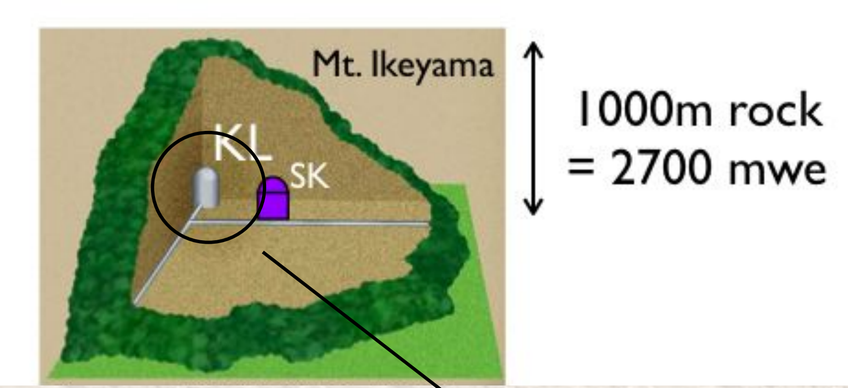
Vacuum

It was a gamble because KamLAND has sensitivity to LMA only

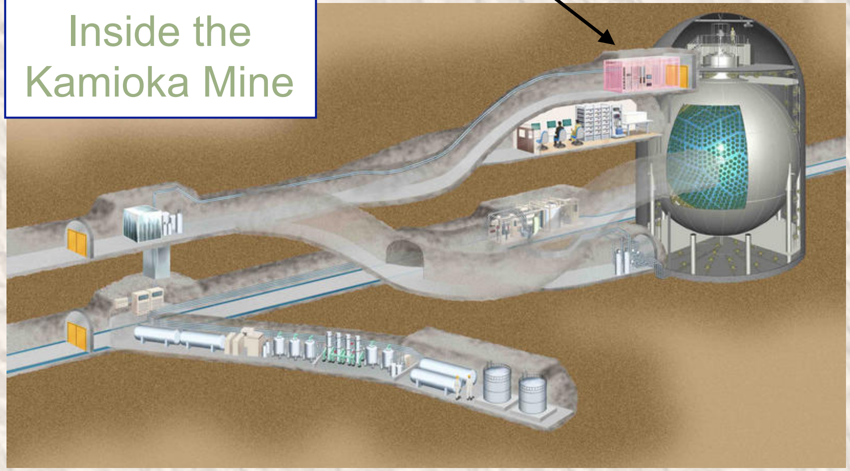
KamLAND -Kamioka Liquid-scintillator Anti-Neutrino Detector

Surrounded by 55 Japanese Reactor Units

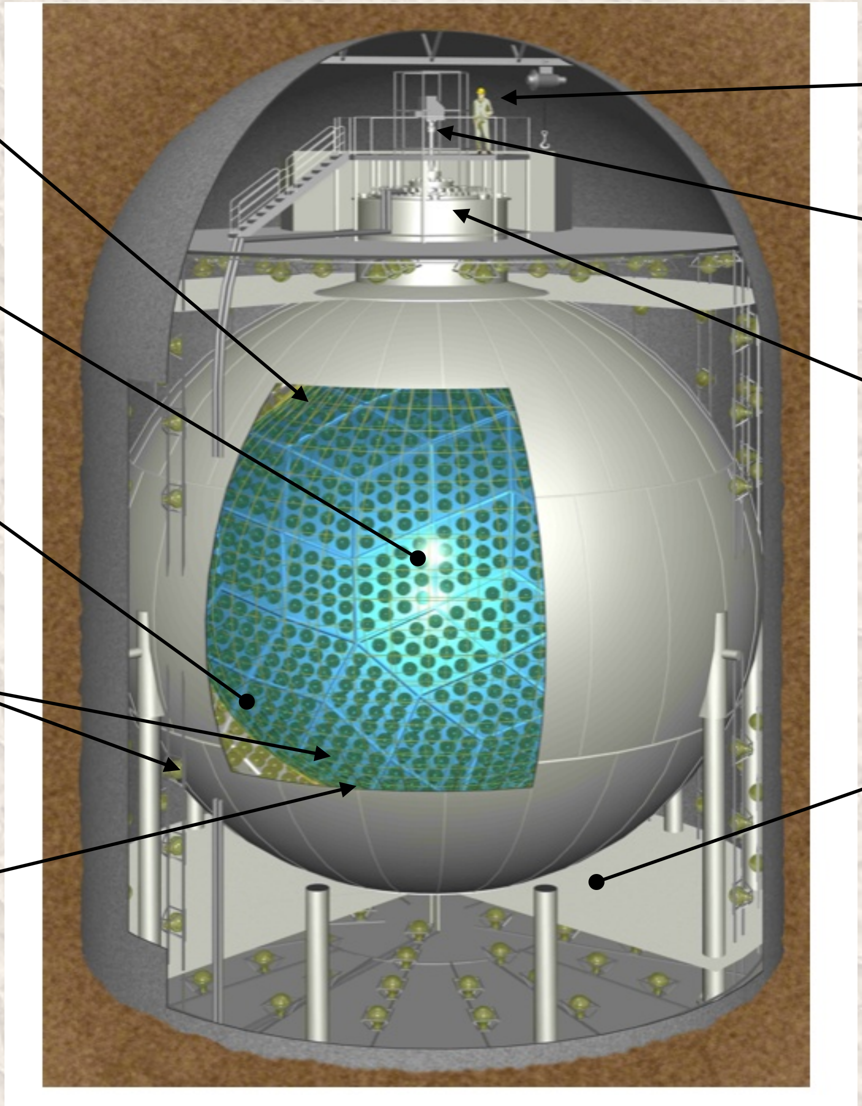
Detecting reactor $\bar{\nu}_e$ 1km beneath Mt. Ikeyama



Inside the Kamioka Mine



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

Glove box

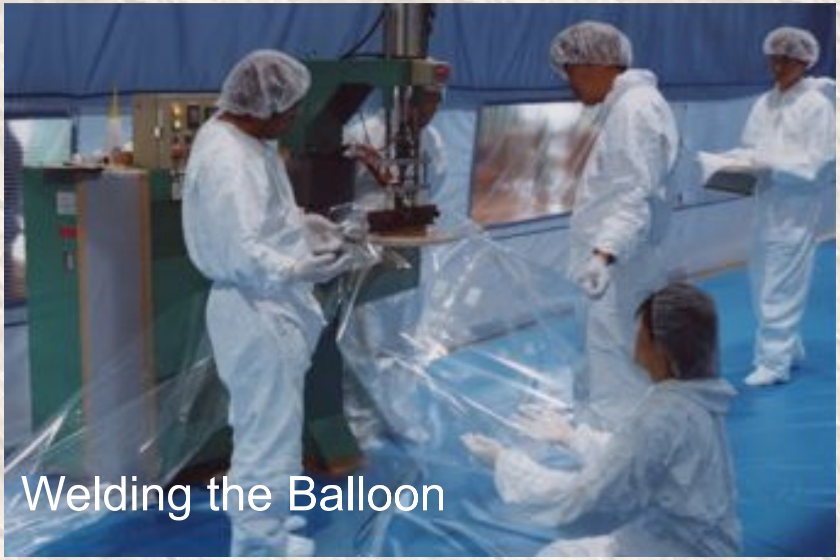
Chimney
(access point)

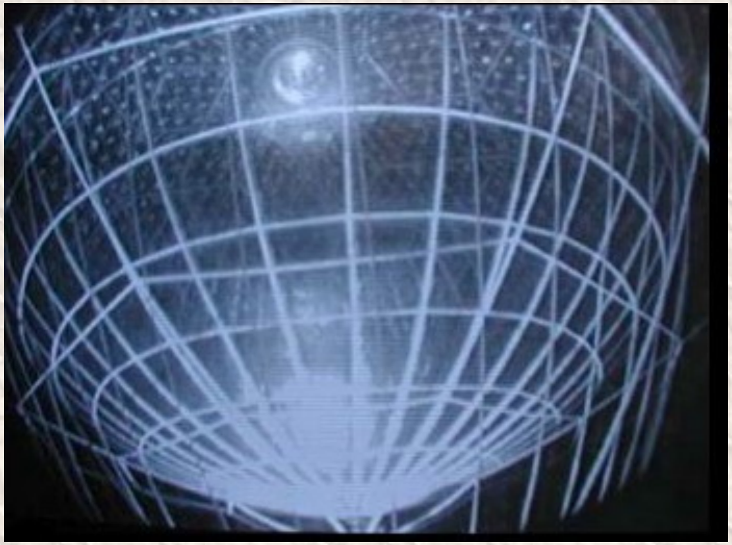
Outer Detector
(3.2 kton Water
Cherenkov)

The Target Volume

Liquid Scintillator:

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


Welding the Balloon

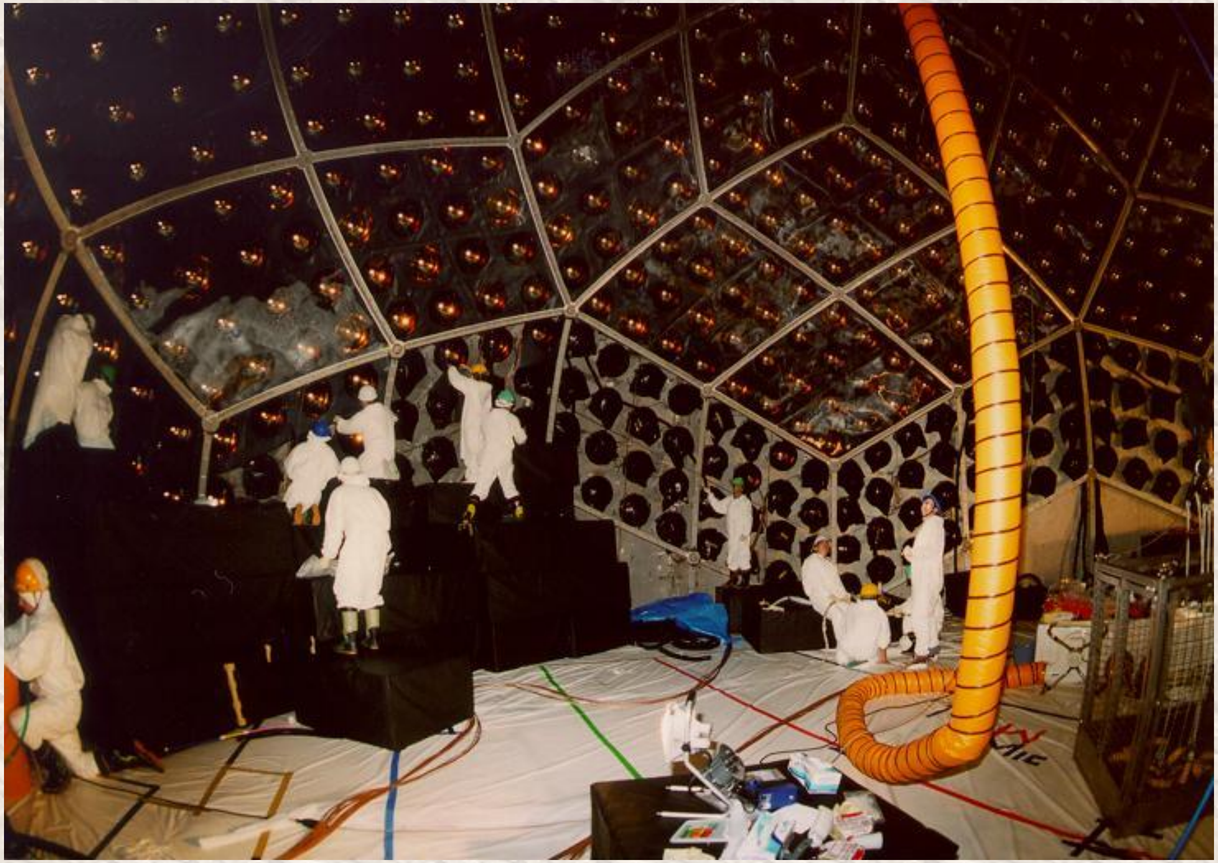


Balloon:

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

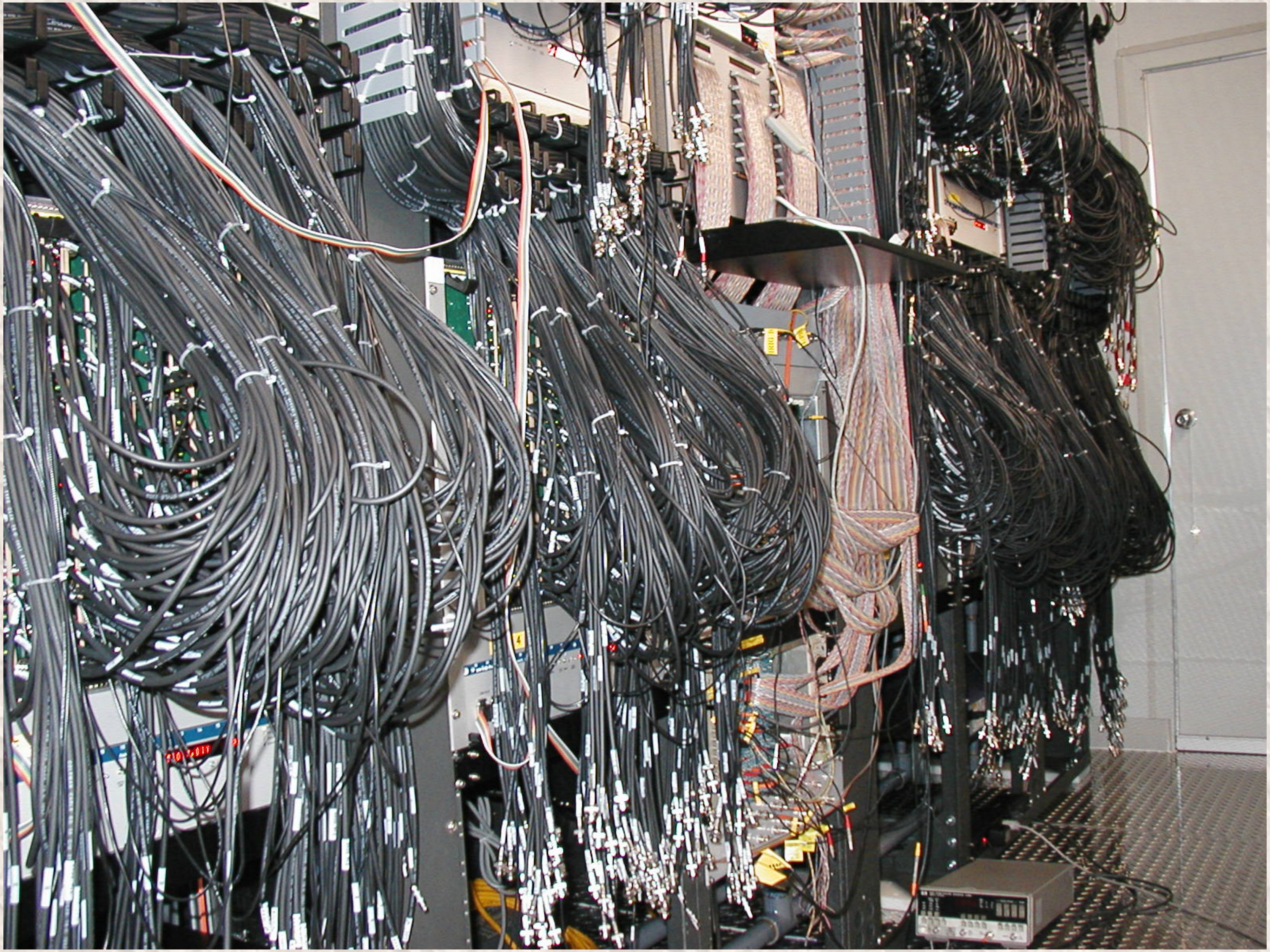
KamLAND Photomultipliers

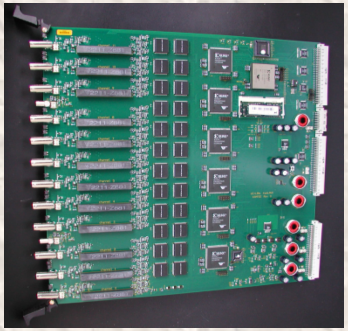
PMT and acrylic panel installation (2000)



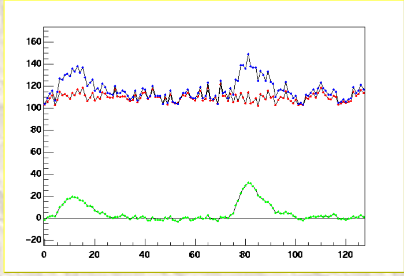
- 1325 17” tubes
- 554 20” tubes (since Feb. ‘03)
- ~300 hits for 1 MeV energy deposit
- Transit time spread < 3 ns on 17” tubes
- acrylic panels protect against radioactive backgrounds

Cables and Electronics





12 ch. per board,
400 MHz sampling
Generates trigger
Connected to GPS
(Custom build at
LBNL)



In 2010 second set of electronics was commissioned. Both working in parallel now.

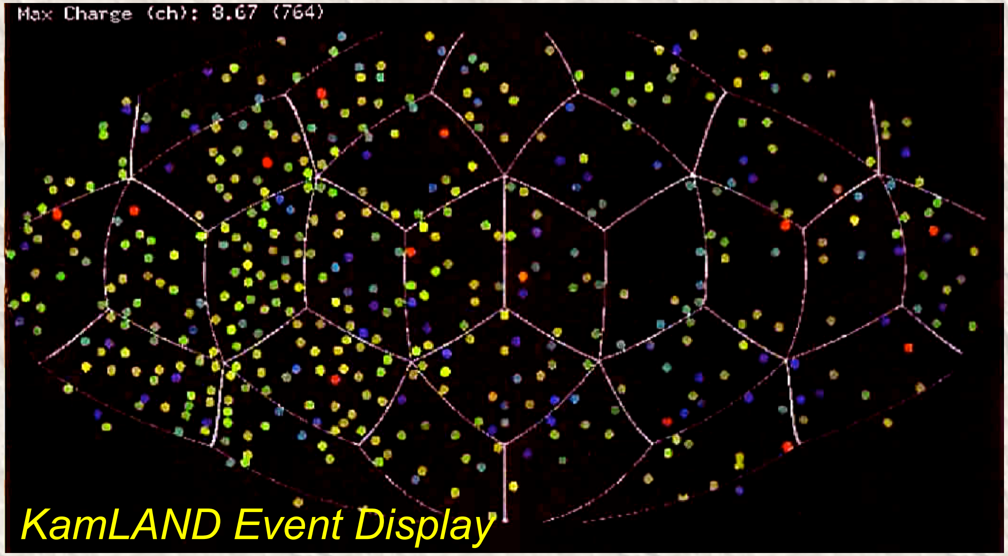
Event Reconstruction

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



KamLAND Event Display

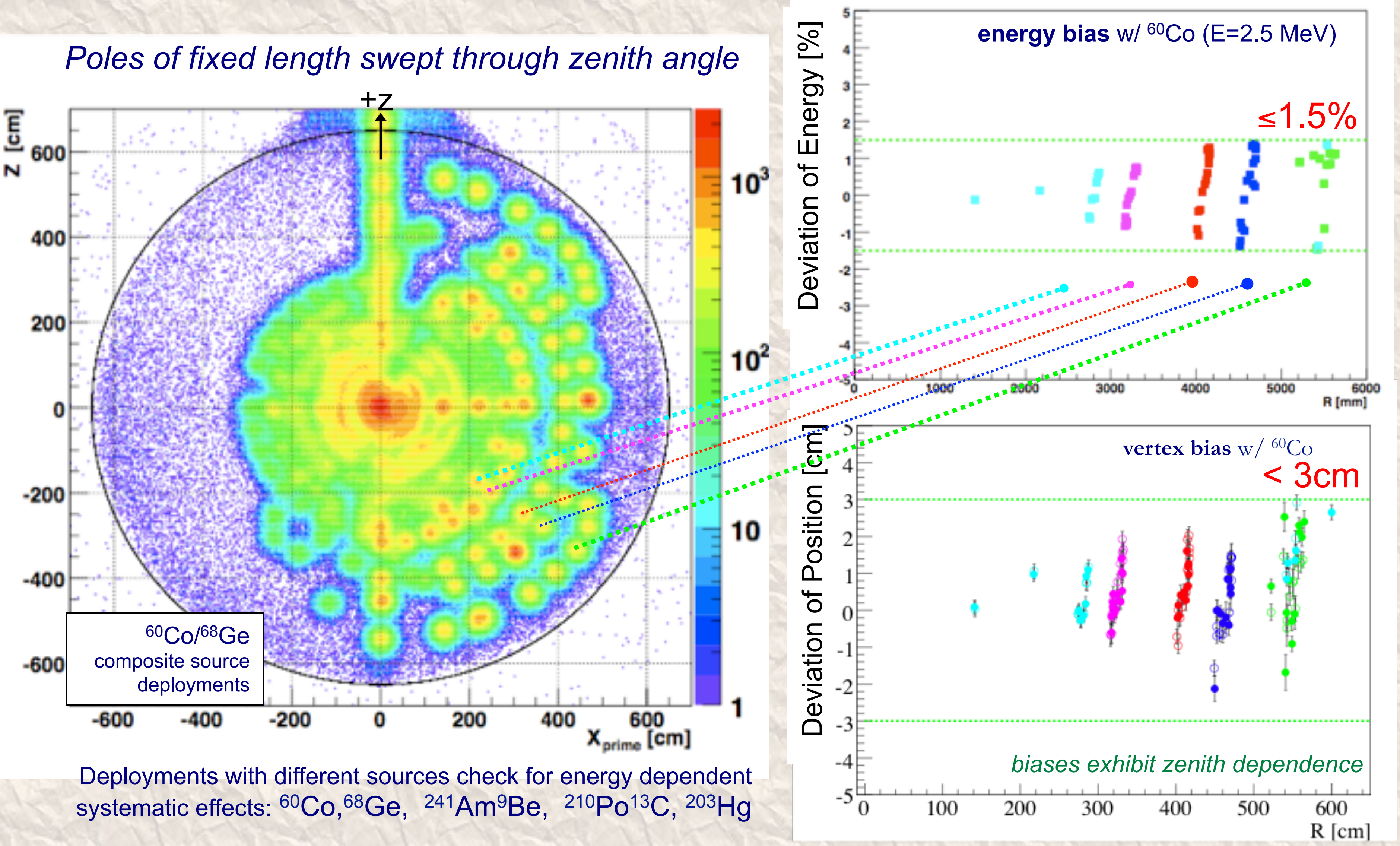
Vertex Reconstruction

- Determined by Very Precise Timing of Hits (~few ns resolution)

$$\frac{\sigma_X}{X} = \frac{12cm}{\sqrt{E(MeV)}}$$

Example of Calibration

Poles of fixed length swept through zenith angle



^{60}Co/^{68}Ge composite source deployments

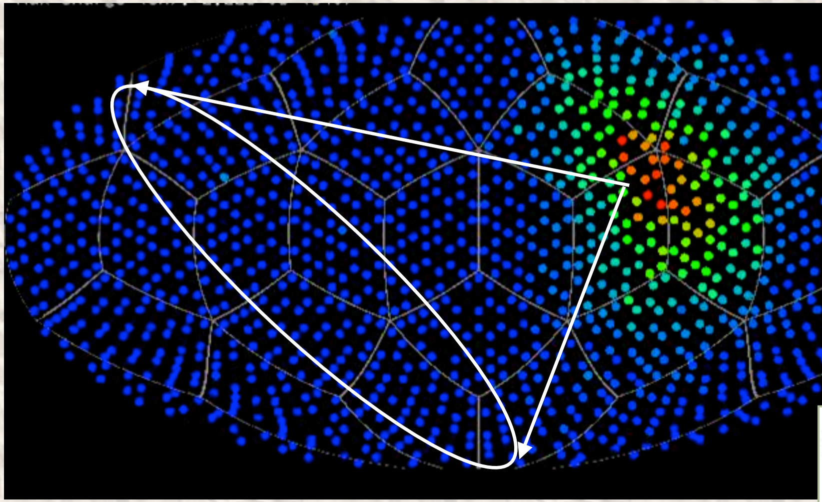
≤1.5%

< 3cm

biases exhibit zenith dependence

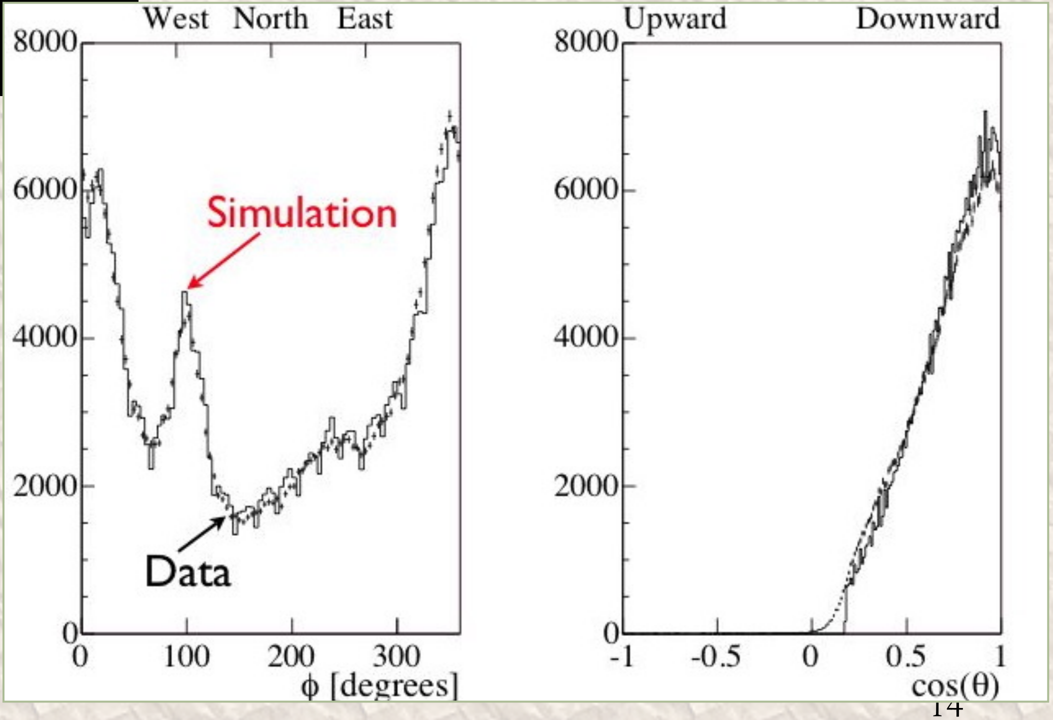
Deployments with different sources check for energy dependent systematic effects: ^{60}Co, ^{68}Ge, ^{241}Am^{9}Be, ^{210}Po^{13}C, ^{203}Hg

Muon Tracking



Source of cosmogenic backgrounds

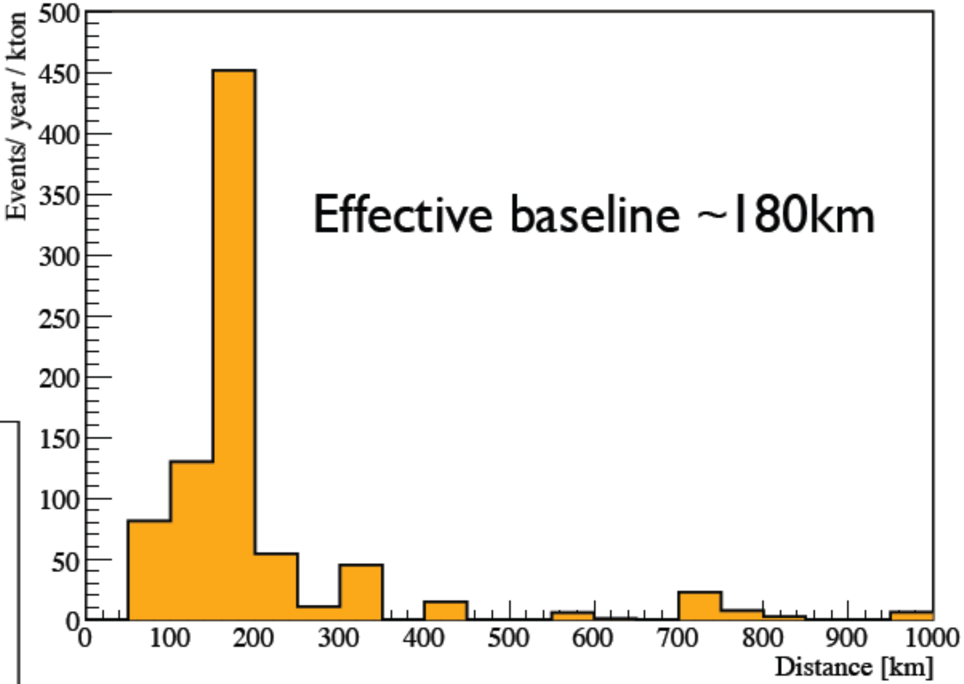
Rate of Muons hitting
KamLAND OD: ~1 Hz
KamLAND ID: 0.3 Hz

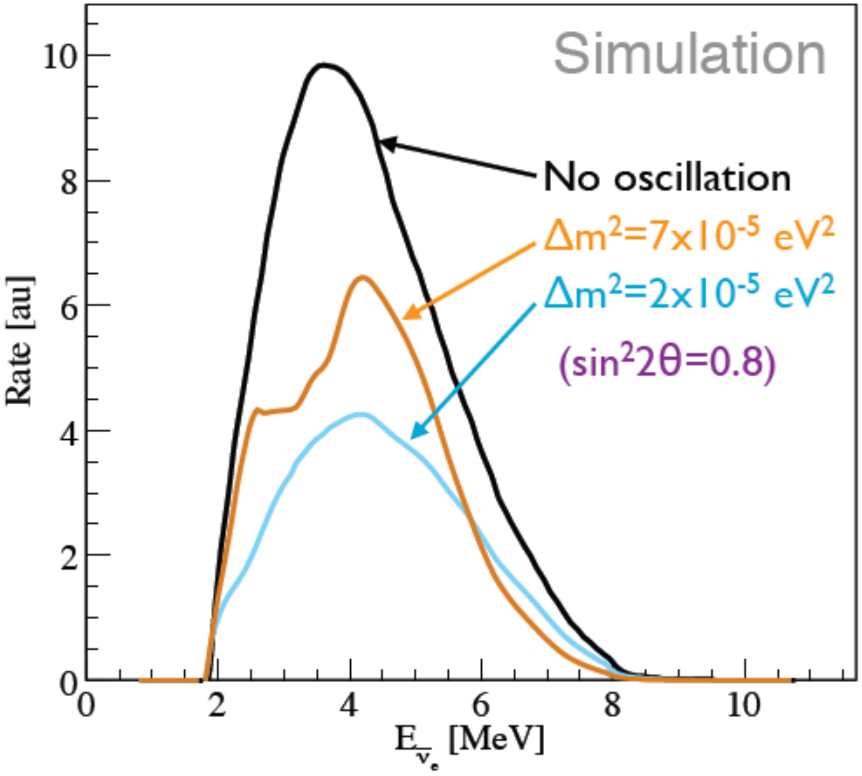


Good agreement with
simulation of muons passing
through compicated mountain
topography

Expected Signal from Nuclear Reactors

70 GW (7% of world total) is generated at 130-220 km distance from Kamioka





m rock

00 mwe

7° 18′43.495″

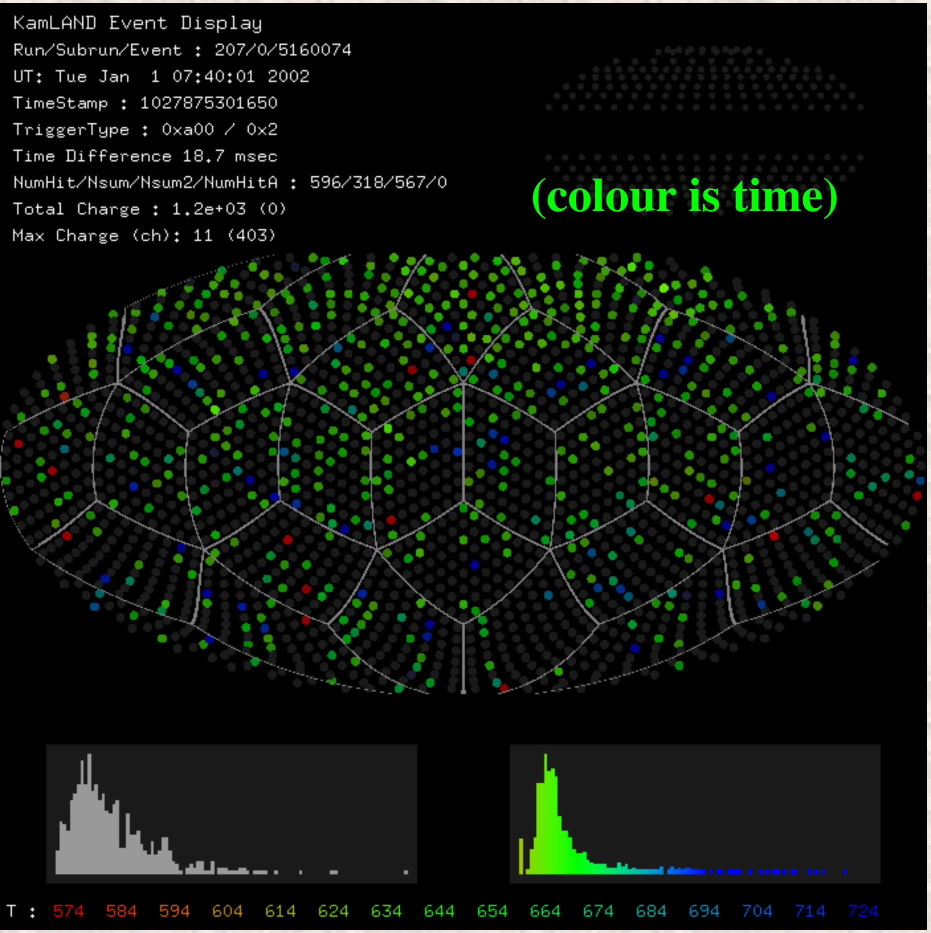
6° 25′35.562″

358 m

Reactor neutrino flux:
~6×10^6 cm^{-2}s^{-1}

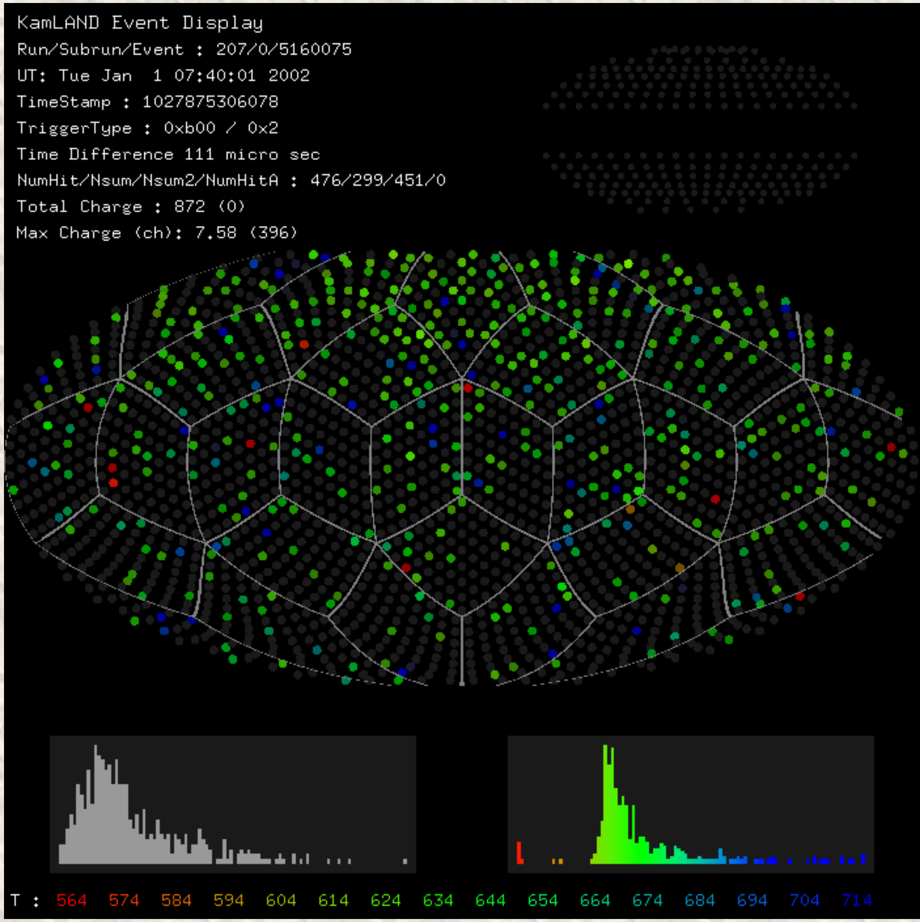
$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \;\; \sin^2 \frac{1.27\Delta m^2 L}{E}$$

Antineutrino event



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160074
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875301650
TriggerType : 0xa00 / 0x2
Time Difference 18.7 msec
NumHit/Nsum/Nsum2/NumHitA : 596/318/567/0
Total Charge : 1.2e+03 (0)
Max Charge (ch): 11 (403)
```

(colour is time)



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160075
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875306078
TriggerType : 0xb00 / 0x2
Time Difference 111 micro sec
NumHit/Nsum/Nsum2/NumHitA : 476/299/451/0
Total Charge : 872 (0)
Max Charge (ch): 7.58 (396)
```

Prompt Signal
$E = 3.20$ MeV

$\Delta t = 111\ \mu s$
$\Delta R = 34$ cm

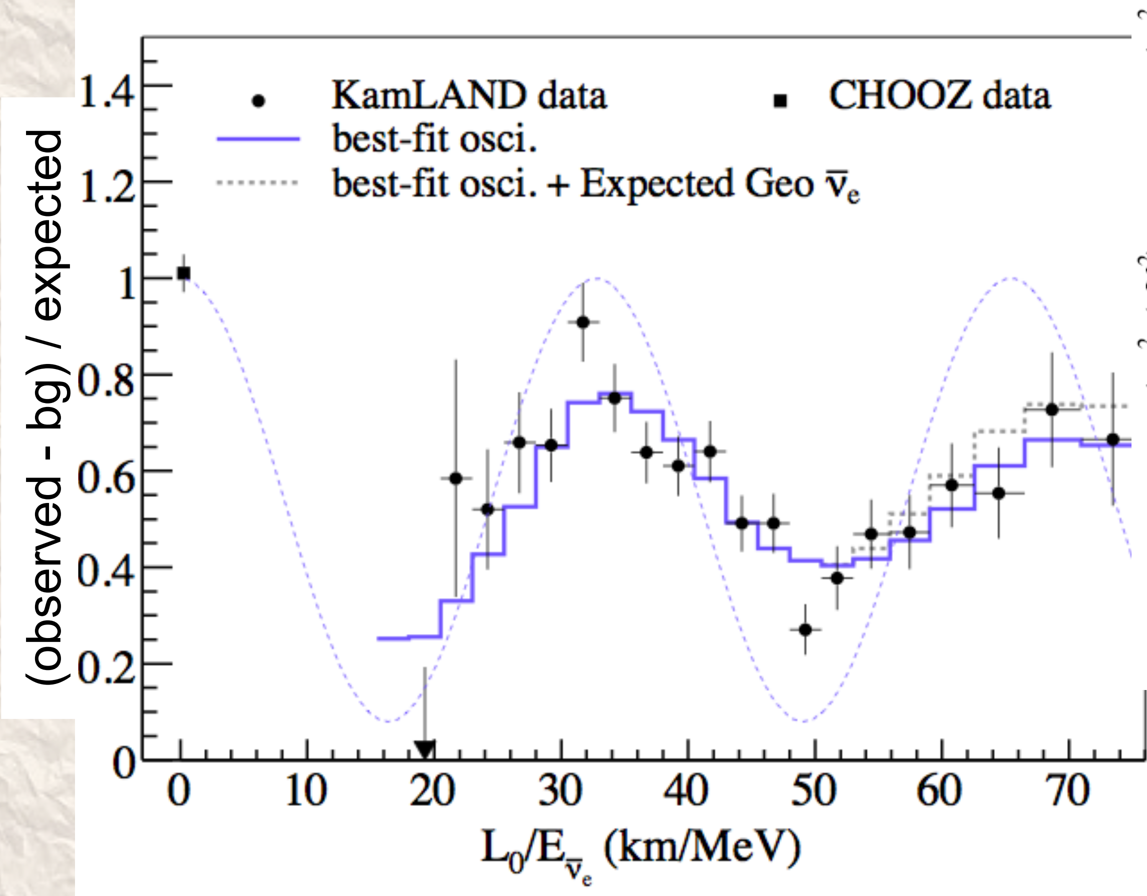
Delayed Signal
$E = 2.22$ MeV

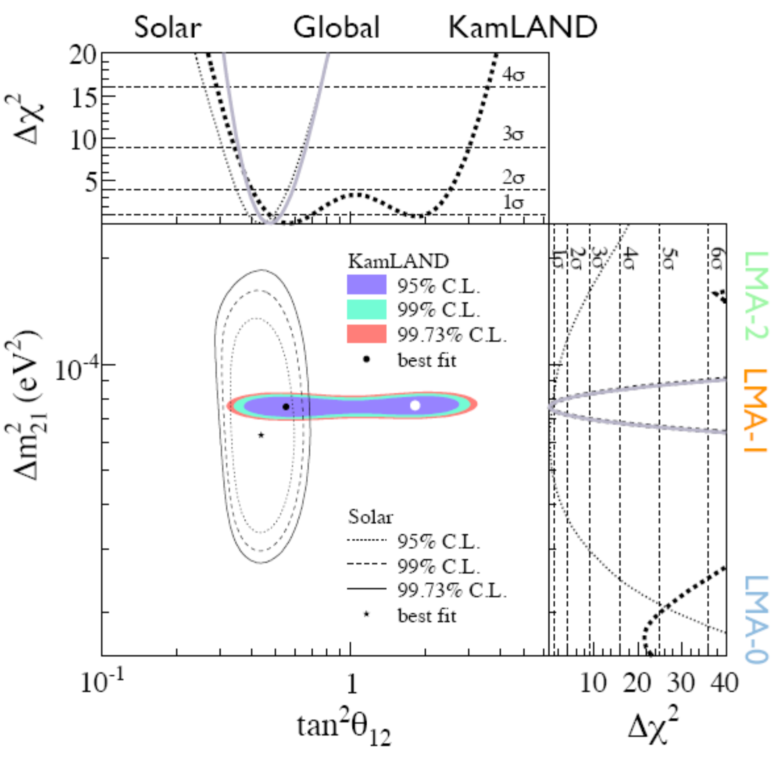
$\bar{\nu}_e + p \rightarrow e^+ + n$

$n + p \rightarrow d + \gamma(2.2\ \text{MeV})$

Oscillation Results

Data from March 2002 till November 2009





L = 180km flux-weighted average reactor distance

Combined Best-Fit Parameters:

$$\Delta m_{21}^2 = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \text{eV}^2$$

$$\tan_{12}^2\theta = 0.452^{+0.035}_{-0.033}$$

$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.27\Delta m^2 L}{E}$$

Geo Neutrinos

28 July 2005 | www.nature.com/nature | £10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

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Vital CO_2 flux from Amazon vegetation

BREAST CANCER
Gene signature for metastasis

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Everything has a fingerprint

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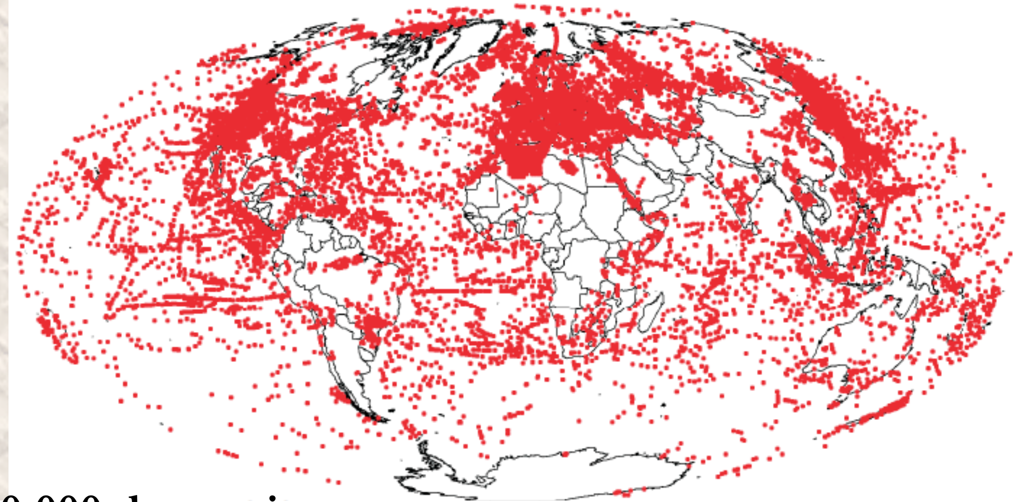
nature outlook INDIA

EARTHLY POWERS

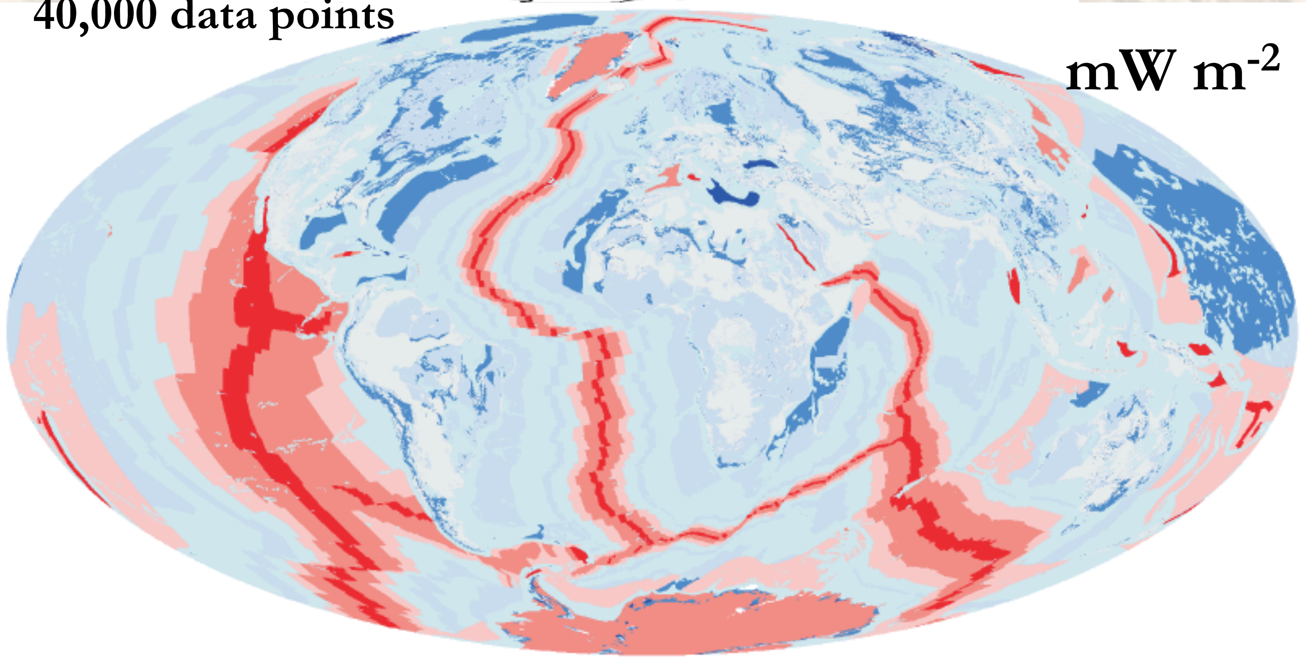
Geoneutrinos reveal Earth's inner secrets

Earth's Total Surface Heat Flow



40,000 data points

Conductive heat flow measured from bore-hole temperature gradient and conductivity



Surface heat flow

46±3 TW (1)

47±2 TW (2)

(1) **Jaupart et al (2008)** *Treatise of Geophys.*

(2) **Davies and Davies (2010)** *Solid Earth*

Anti-neutrinos from the Earth

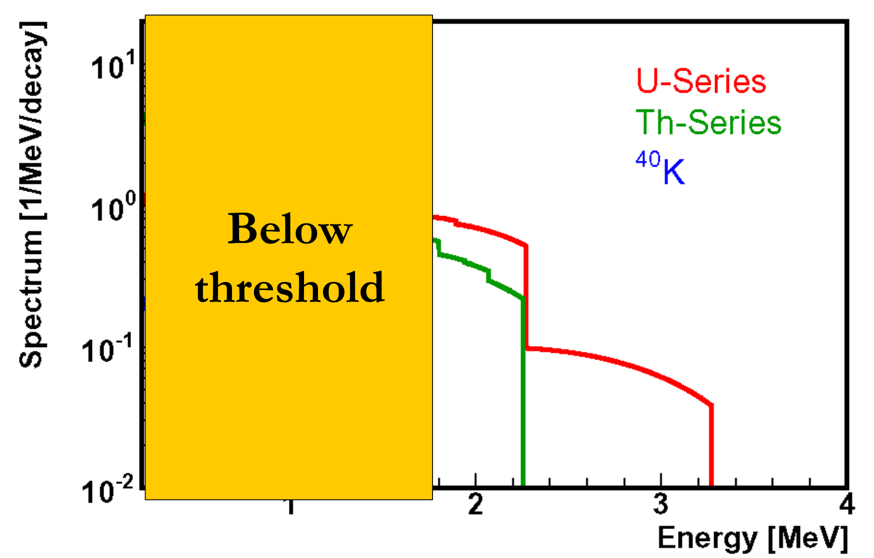
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 52$ [MeV]

$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 47$ [MeV]

$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 43$ [MeV]

$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31$ [MeV] (89.3%)

$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.505$ [MeV] (10.7%)

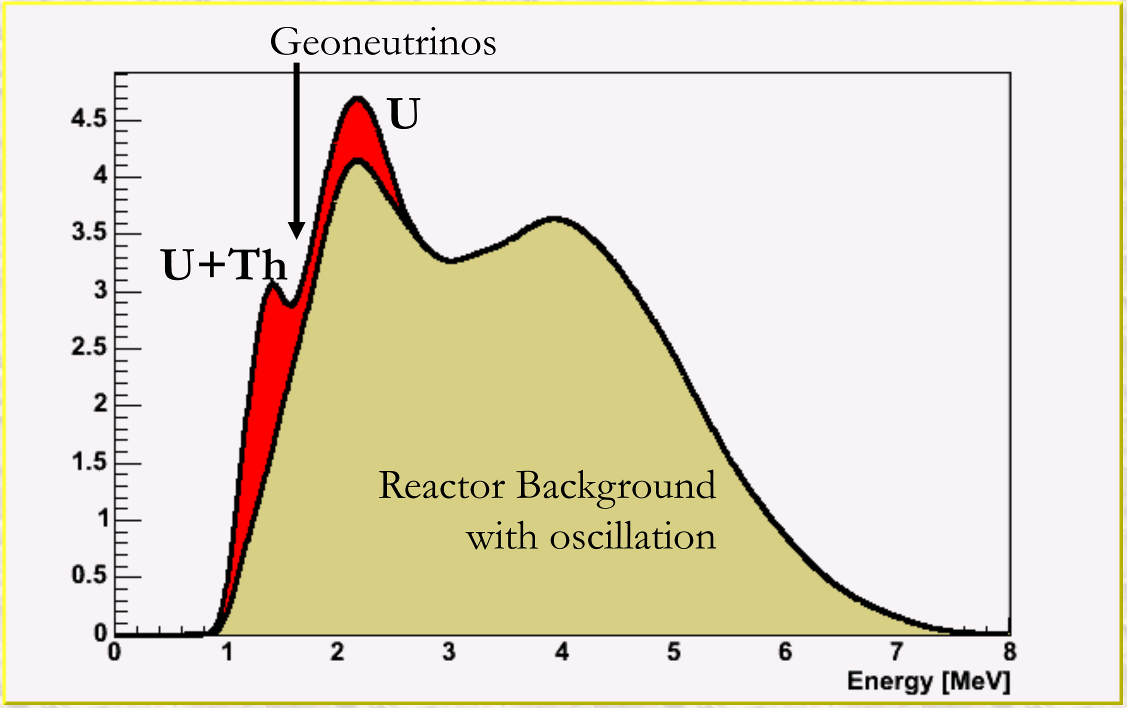


Isotope	Abundance, relative	T ½, By.	Heat* production, TW
^{232}Th	1	14.1	8.5
^{238}U	0.25	4.5	7.7
^{235}U	0.0018	0.7	0.33
^{40}K	2.8	1.3	3.2
Total radiogenic			~20 (50% of total)

*Based on the Bulk silicate Earth model

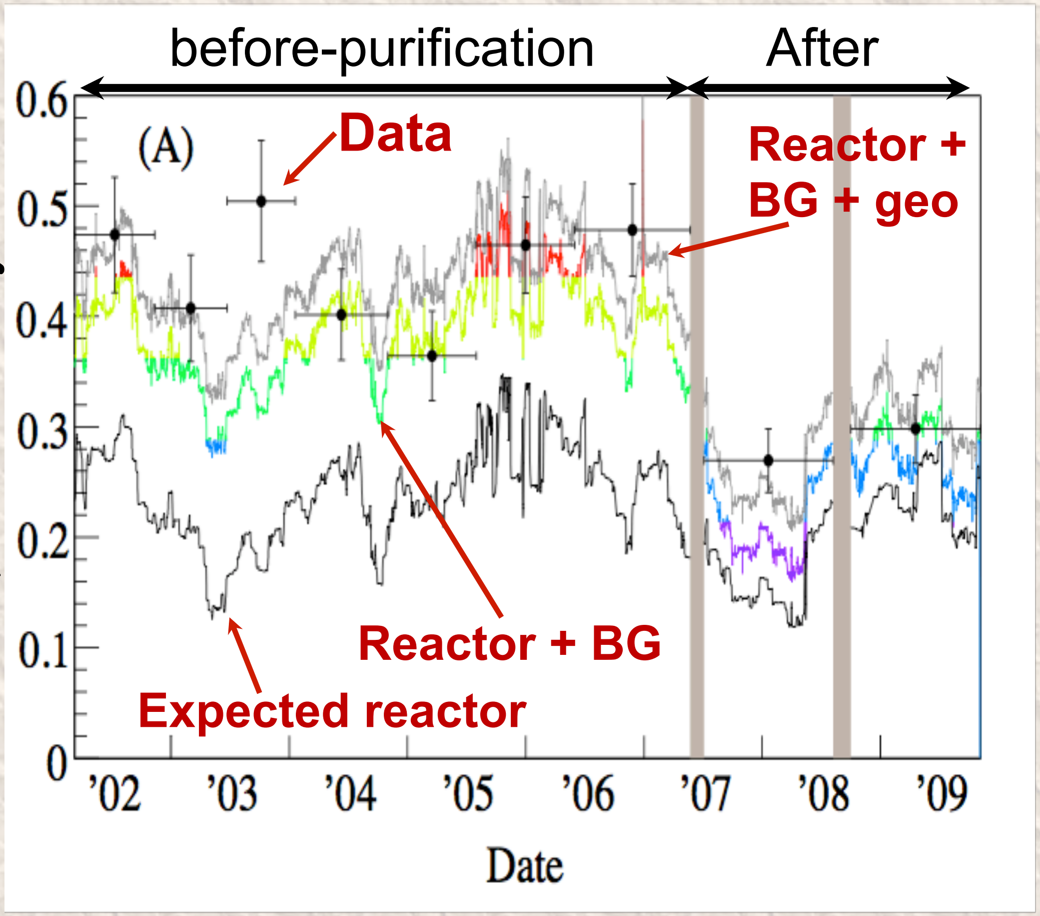
Anti-neutrinos at the KamLAND

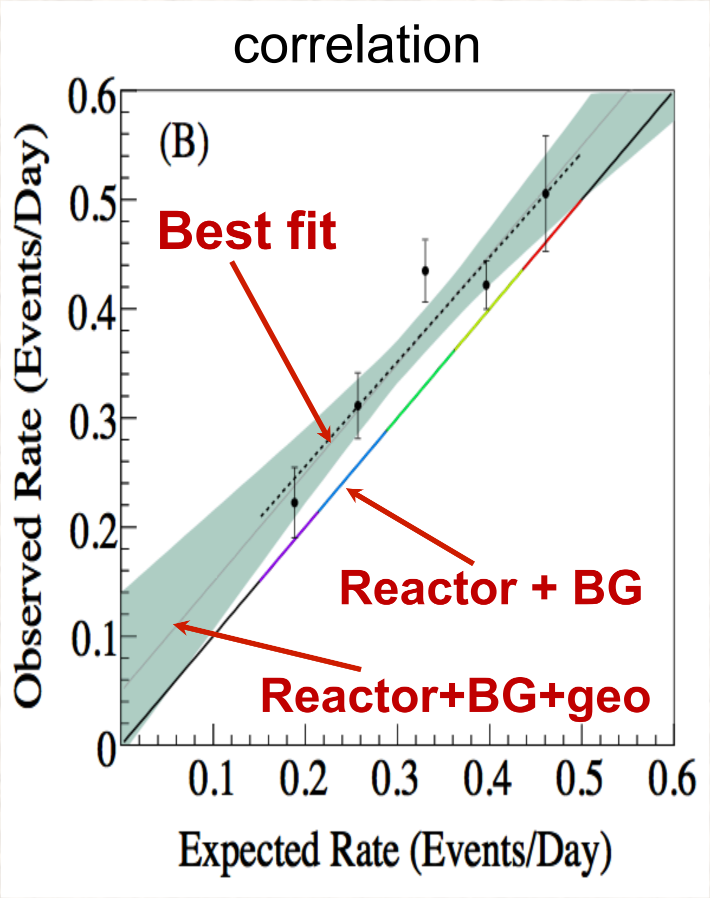
International Nuclear Safety Center at ANL, Oct 2002



KamLAND was designed to measure reactor anti-neutrinos and they are the most significant background for geo-neutrinos.

Event rate time variation: 0.9 MeV - 2.6 MeV

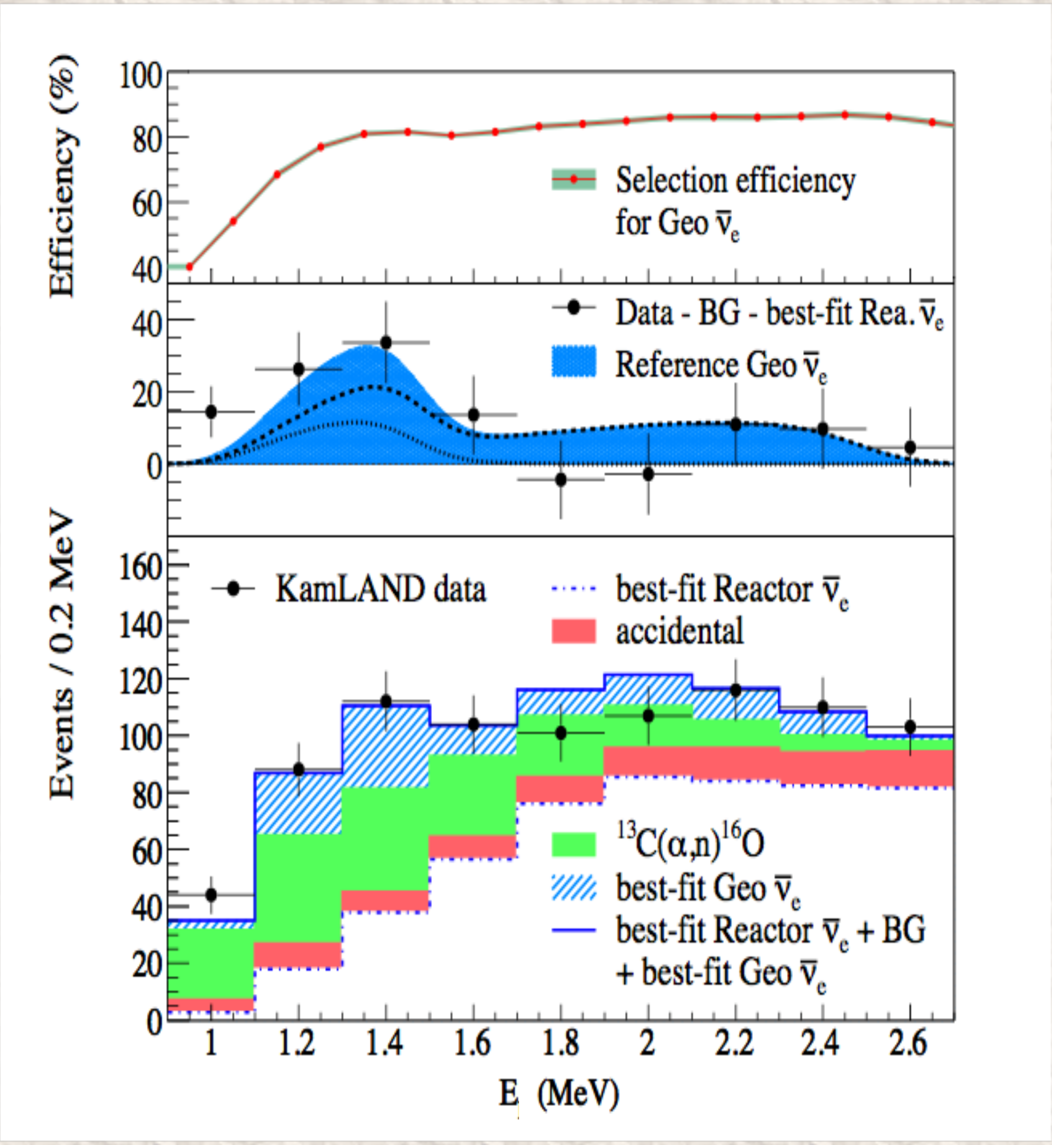




We see constant excess above the estimated reactor neutrino + non-neutrino background at 0.9 < E < 2.6 MeV region

2011, Geo Science

4126 ton-yr data-set (2135 days)



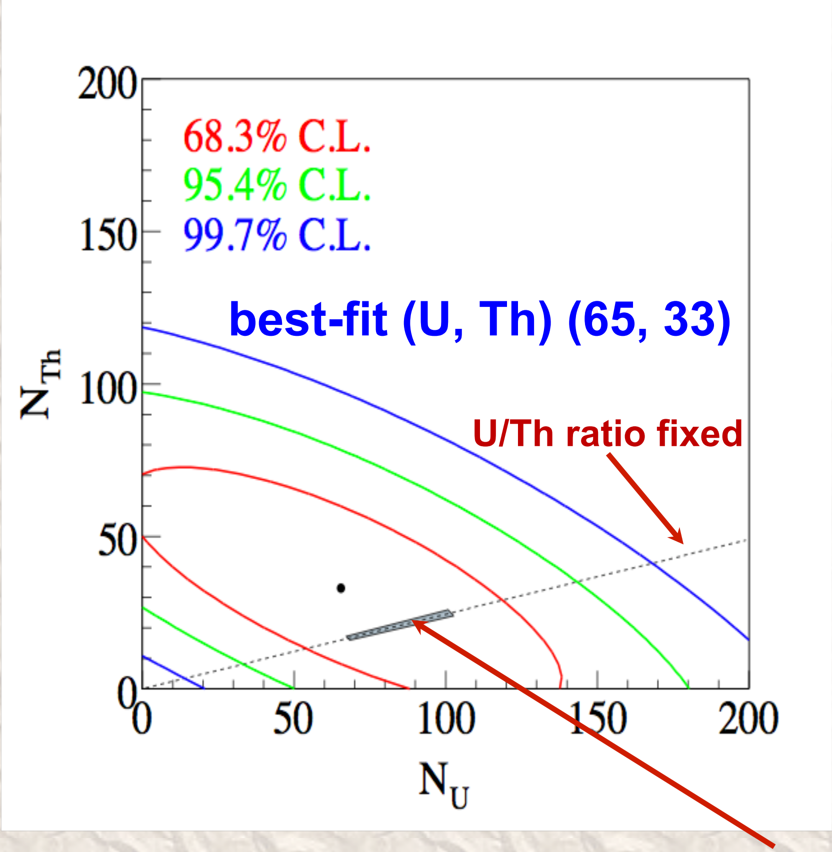
Rate analysis
($0.9 < E < 2.6$ MeV)

841 candidates

^{9}Li	2.0 ± 0.1
Accidental	77.4 ± 0.1
Fast neutron	< 2.8
(α, n)	165.3 ± 18.2
Reactor ν	484.7 ± 26.5
BG total	729.4 ± 32.3

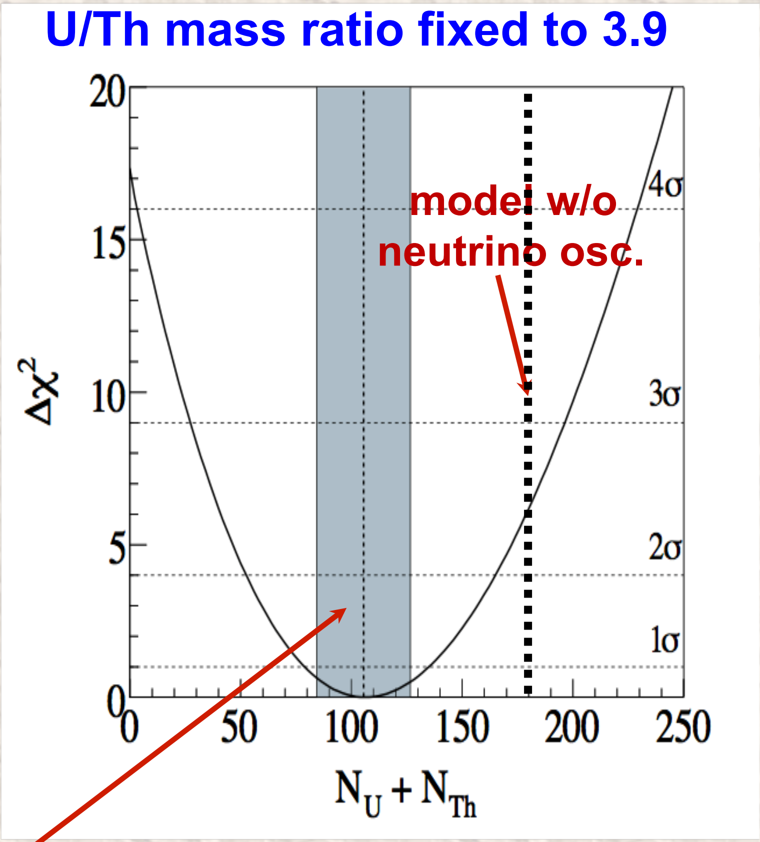
excess 111^{+45}_{-43} events

Fixing U/Th ratio



best-fit (U, Th) (65, 33)

U/Th ratio fixed



U/Th mass ratio fixed to 3.9

model w/o neutrino osc.

BSE model prediction
EPSL 258, 147 (2007)

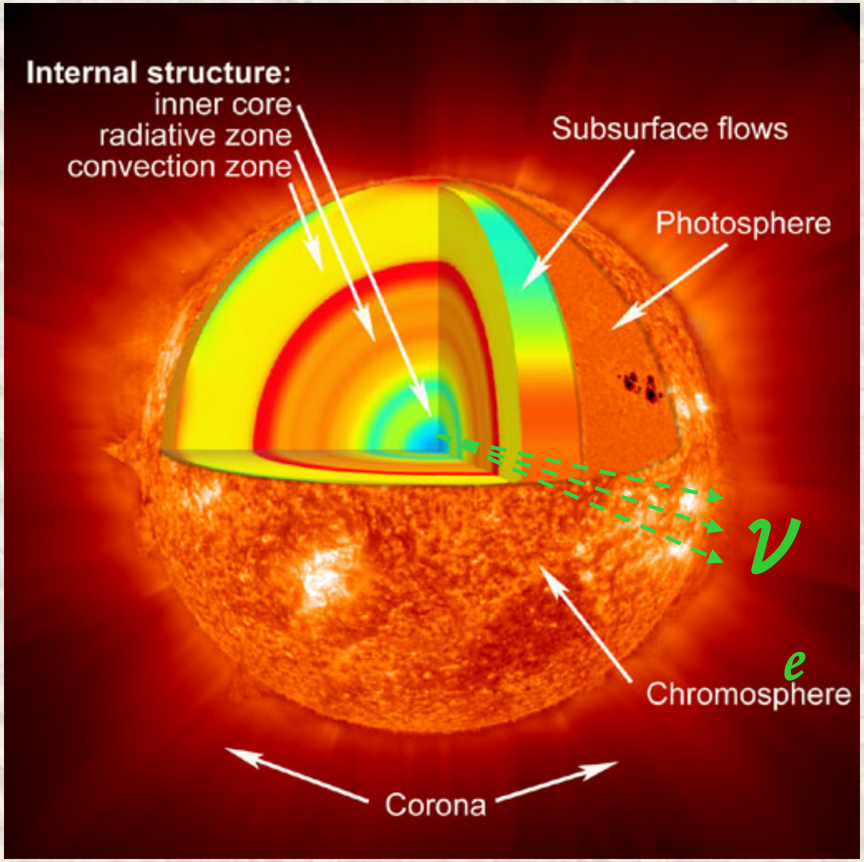
Nature 436, 28 (2005)
PRL 100, 221803 (2008)
Nature Geoscience 4, 647 (2011)

$$N_{geo} = 106^{+29}_{-28} \text{ events}$$

$$F_{geo} = 4.3^{+1.2}_{-1.1} \times 10^6 \text{ /cm}^2\text{/sec}$$

This is a conformation that radiogenic is responsible to up to ~50% of the total heat emitted by the Earth

Solar Antineutrinos



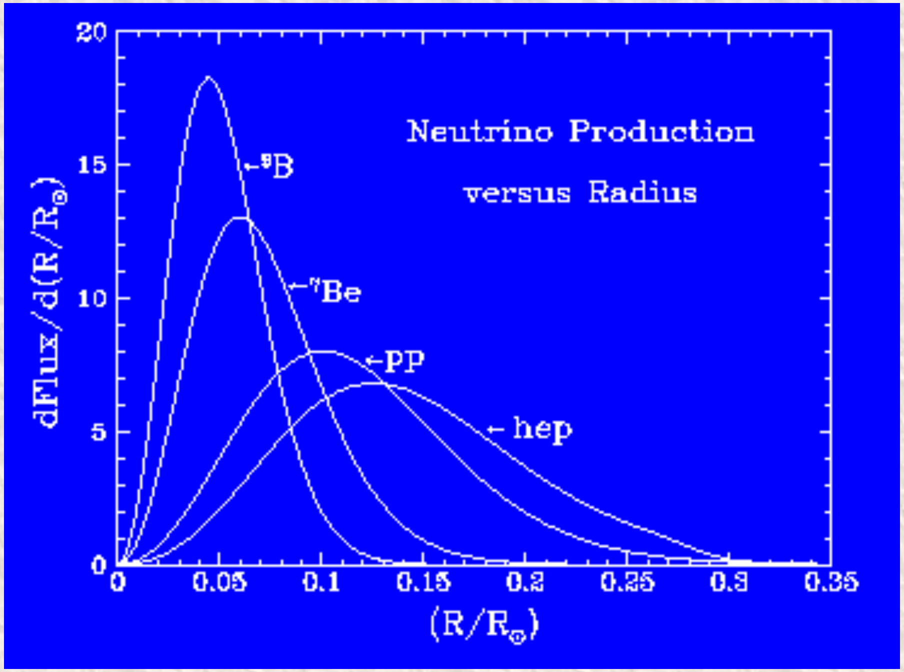
Solar Layers

L.B. Okun, M.B. Voloshin, M.I. Vysotsky 1986. 26 pp. ITEP-86-82. Sov.Phys. JETP 64 (1986) 446-452

$$\nu_{eL} \xrightarrow{\text{SFP}} \overline{\nu}_{\mu R} \xrightarrow{\text{osc.}} \overline{\nu}_{eR}$$

$B_T \sim 10^7$G

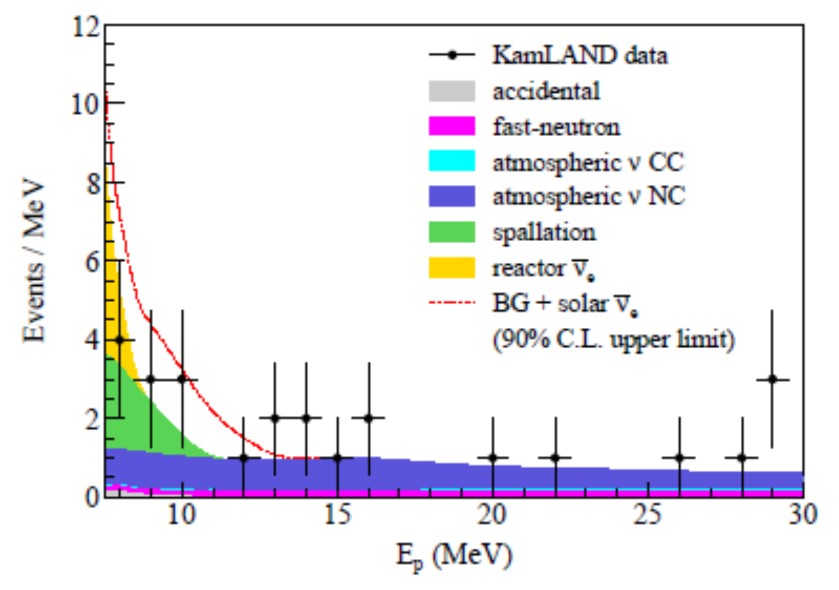
Vacuum oscillations



$$P(\nu_{eL} \rightarrow \overline{\nu}_{eR}) = 1.8\times10^{-10}\left[\frac{\mu_\nu}{10^{-12}\mu_B}\times\frac{B_T(0.05R_s)}{10\text{kG}}\right]^2 \sin^2 2\theta_{12}$$

E. Akhmedov and J Pulido, Phys. Lett B 553, 7 (2003)

Llimit on Solar Antineutrinos (4.5 kty)



Upper limits on solar electron antineutrino flux for 8.8-30 MeV:

$$\Phi_{\bar{\nu}_e} < 93.4\, cm^{-2} s^{-1} \; for$$

Neutrino conversion probability: **$P<5.3\times10^{-5}$**

product of neutrino magnetic moment and magnetic field in the core of the Sun:

$$\frac{\mu}{10^{-12}\mu_B}\frac{B_T(0.05R_S)}{10kG} < 5.9\times10^{2}$$

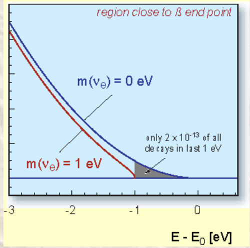
$\mu_\nu = 3.2 \cdot 10^{-19}(m_\nu/eV)\, \mu_B$ S.M.
$\mu_\nu < 3.0 \cdot 10^{-12} \mu_B$ Red Giants.
$\mu_\nu < 3.2 \cdot 10^{-11} \mu_B$ GEMMA

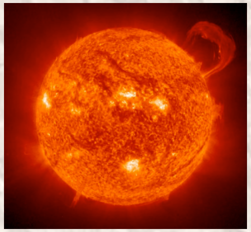
Astrophys.J. 745:193 2012
Phys.Rev.Lett.92:071301,2004

Transition to the KamLAND-Zen

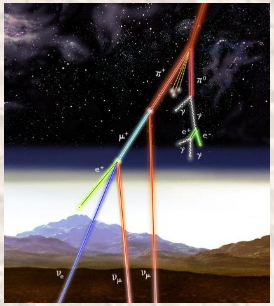
During initial stage of KamLAND proposal we thought about option to modify KamLAND with the goal to search for the neutrino less double beta decay.

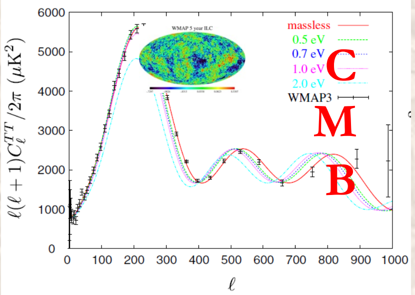
Discovery of $0\nu2\beta$ process will give answer on neutrino nature (Majorana) and give a tool to measure neutrino mass





Neutrino mass

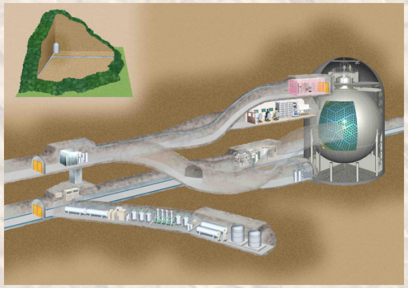


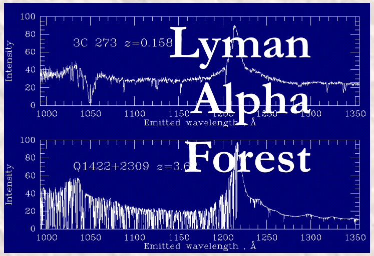


C
M
B

$$0.05\ \mathrm{eV} < \Sigma m_{\nu} < \sim 0.5\ \mathrm{eV}$$

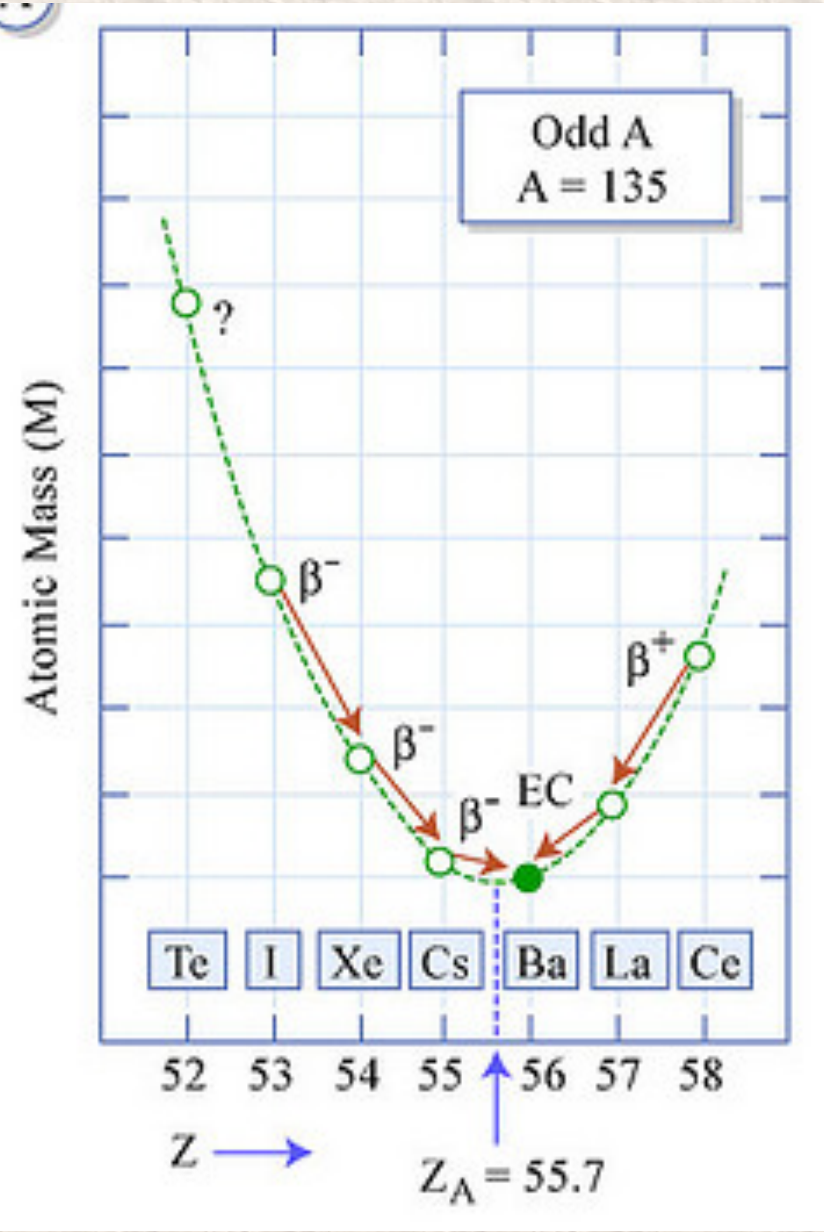
(oscillations) *(others)*



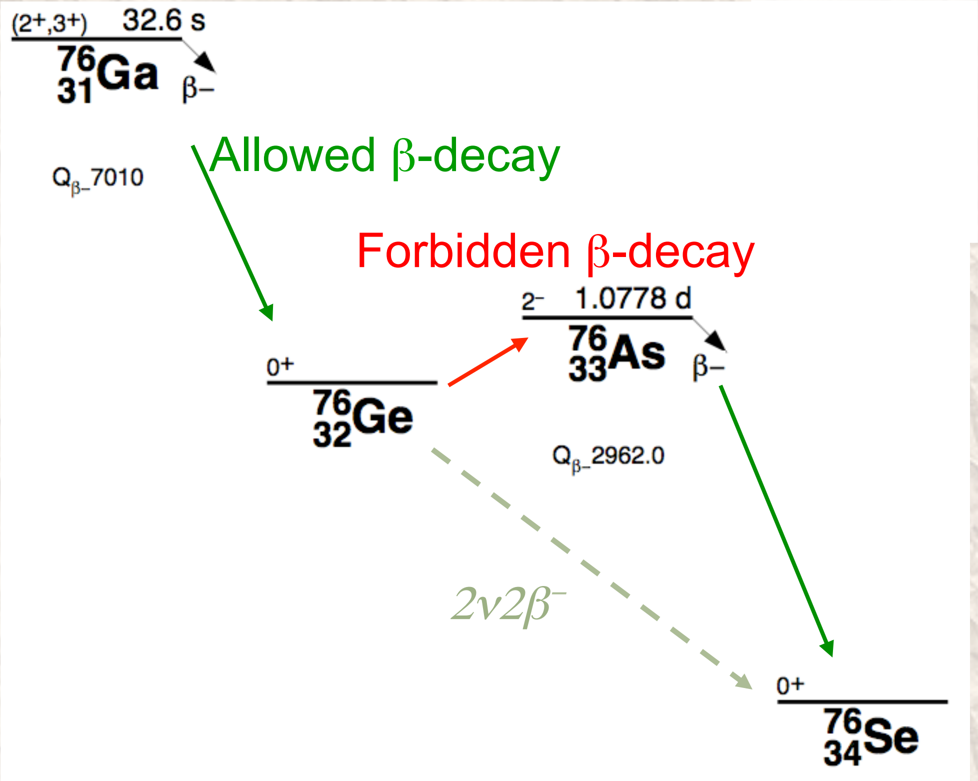


Lyman
Alpha
Forest

Mass Parabola



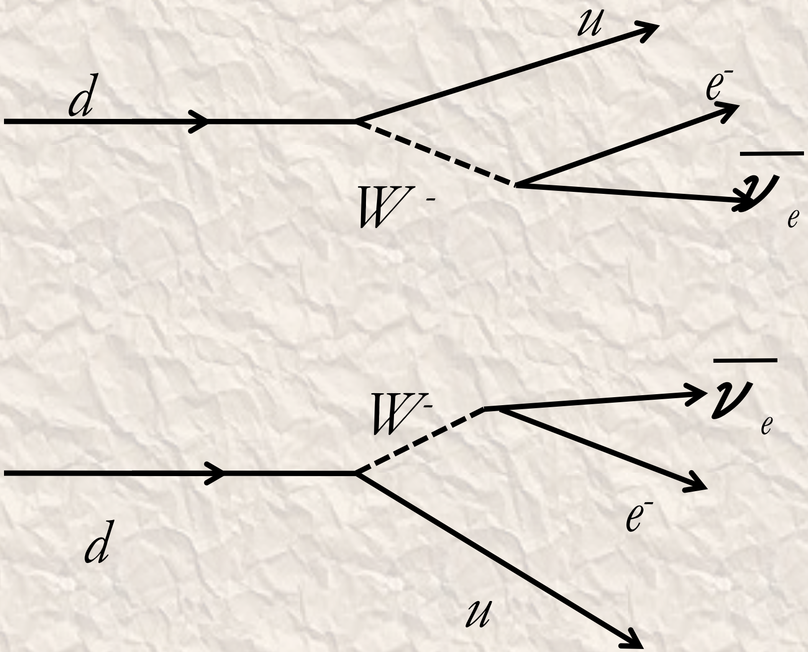
However for some isotopes

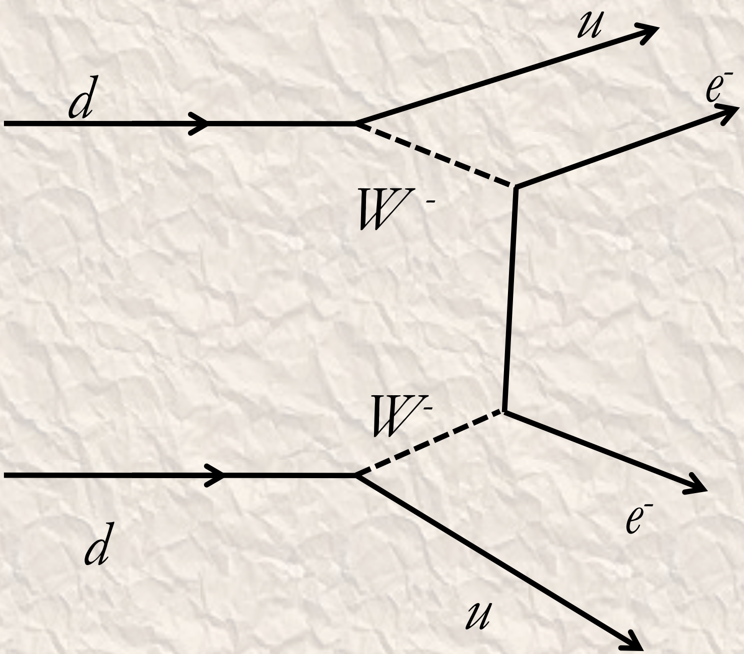


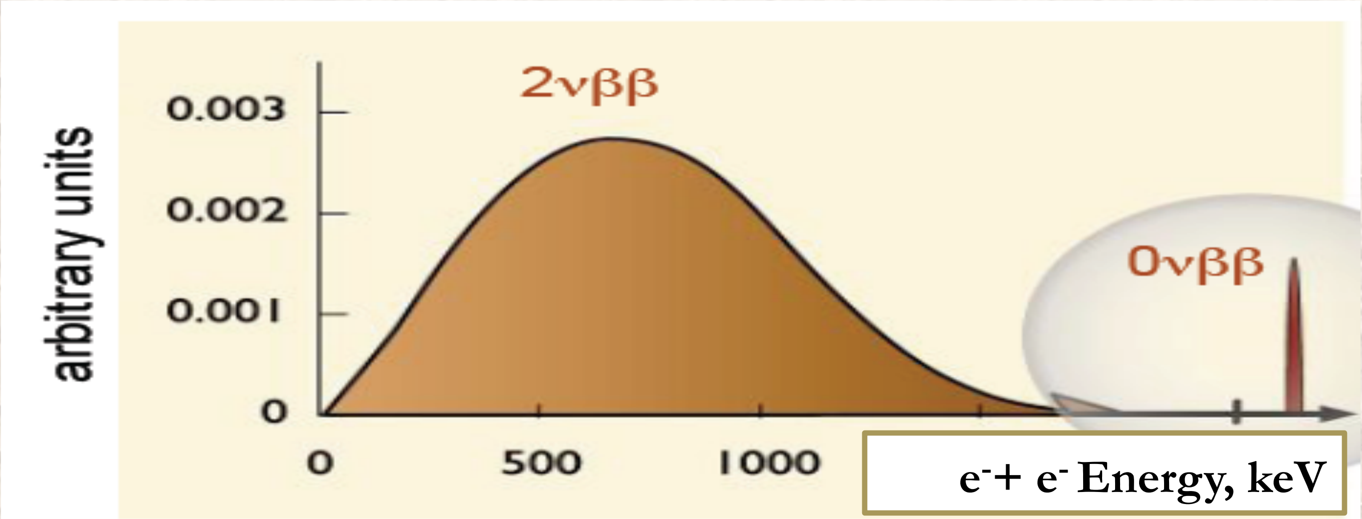
$2\upsilon 2\beta$: decay second order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\bar{\nu}_e$$

Two neutrinos or zero neutrinos?

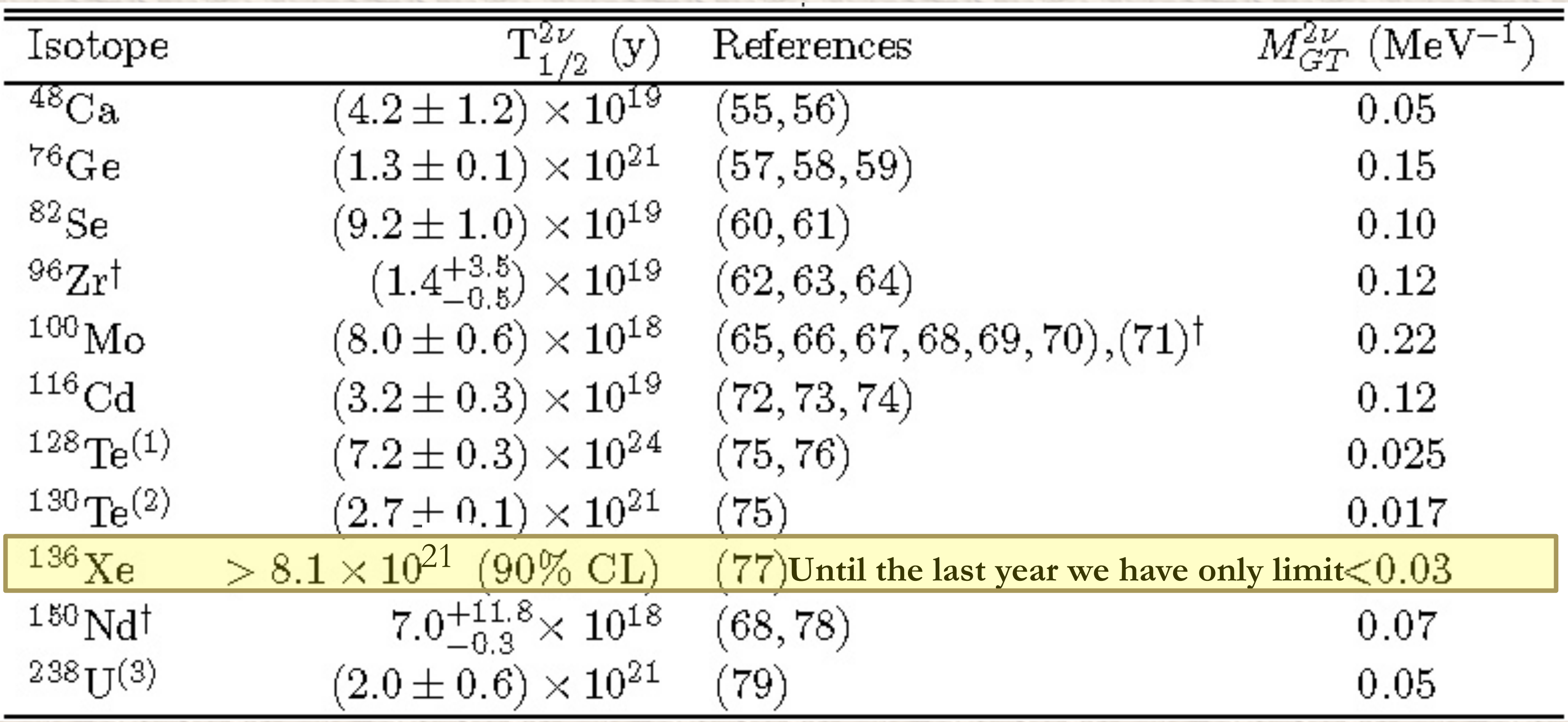






Some Candidates

ββ2ν-mode:



Isotope	$T_{1/2}^{2\nu}$ (y)	References	$M_{GT}^{2\nu}$ (MeV^{-1})
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$	(55, 56)	0.05
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$	(57, 58, 59)	0.15
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$	(60, 61)	0.10
^{96}Zr†	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$	(62, 63, 64)	0.12
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$	(65, 66, 67, 68, 69, 70), (71)†	0.22
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$	(72, 73, 74)	0.12
^{128}Te$^{(1)}$	$(7.2 \pm 0.3) \times 10^{24}$	(75, 76)	0.025
^{130}Te$^{(2)}$	$(2.7 \pm 0.1) \times 10^{21}$	(75)	0.017
^{136}Xe	$> 8.1 \times 10^{21}$ (90% CL)	(77) **Until the last year we have only limit**	< 0.03
^{150}Nd†	$7.0^{+11.8}_{-0.3} \times 10^{18}$	(68, 78)	0.07
^{238}U$^{(3)}$	$(2.0 \pm 0.6) \times 10^{21}$	(79)	0.05

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G_{2\nu}(Q_{\beta\beta}, Z) \, | M_{GT}^{2\nu} |^2$$

Neutrino Less Double beta decay

ββ0ν-mode:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta},Z)\,|M^{0\nu}|^2 < m_\nu >^2$$

$$\langle m_\nu \rangle = \left|\sum_{i=1}^{3} U_{ei}^2 \cdot m_i\right| \approx \left|(0.87)^2 \cdot m_1 + (0.5)^2 \cdot \sqrt{m_1^2 + \Delta m_{21}^2} \cdot e^{2i\beta} + s_{13}^2 \cdot m_3 \cdot e^{-2i(\gamma-\delta)}\right|$$

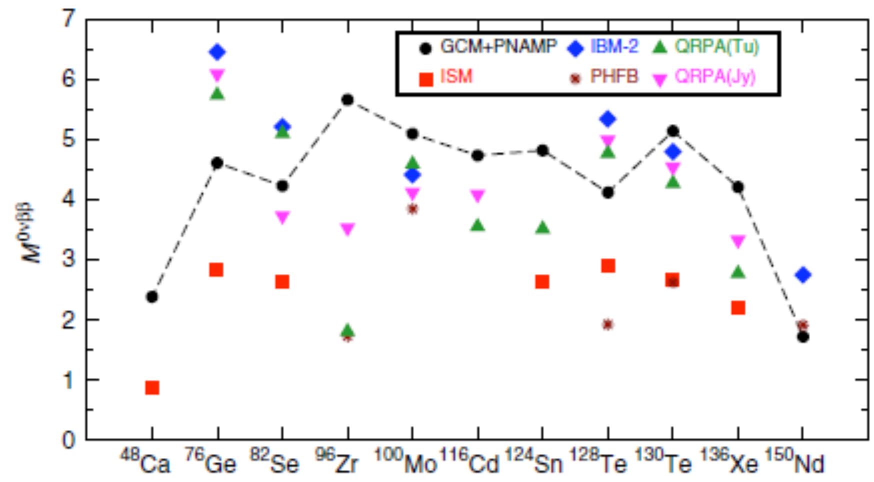


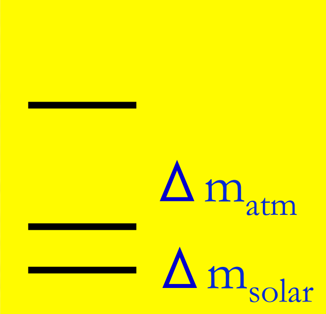
FIG. 3 (color online). Nuclear matrix elements calculated for different methods (ISM [5,22], QRPA(Jy) [8], QRPA(Tu) [7], IBM-2 [12], PHFB [10]) with UCOM short-range correlations. QRPA values are calculated with $g_A = 1.25$ and IBM-2 and PHFB results are multiplied by 1.18 to account for the difference between Jastrow and UCOM [29].

Nuclear Physics Require Multiple Isotope Program !!!

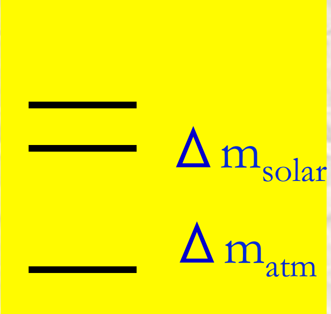
Region of Interest

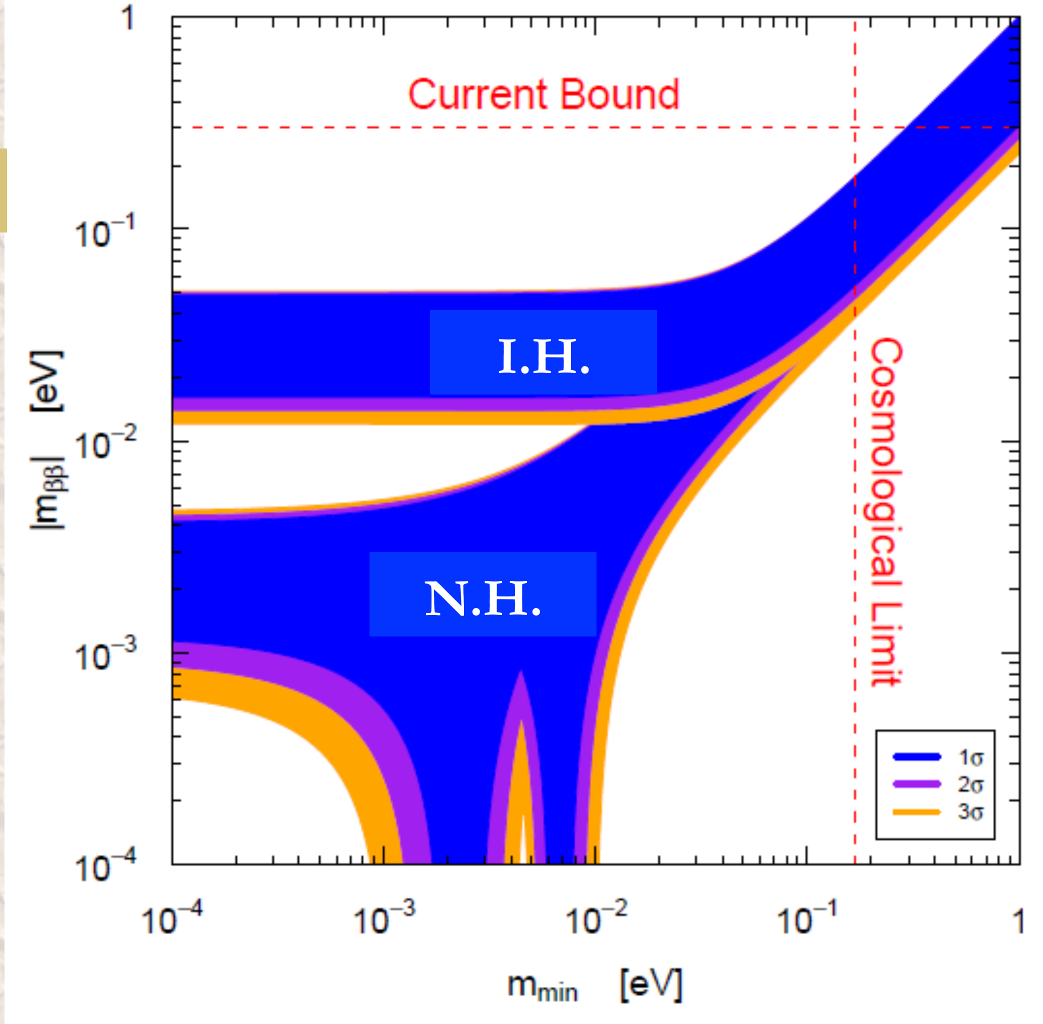
$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right| \approx \left| (0.87)^2 \cdot m_1 + (0.5)^2 \cdot \sqrt{m_1^2 + \Delta m_{21}^2} \cdot e^{2i\beta} + s_{13}^2 \cdot m_3 \cdot e^{-2i(\gamma-\delta)} \right|$$

Hierarchical

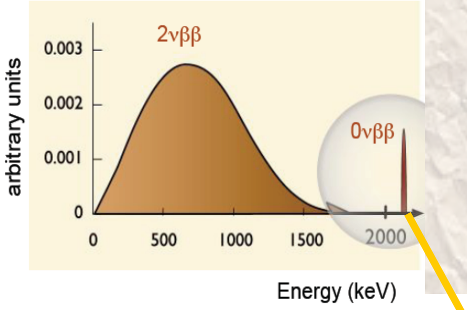


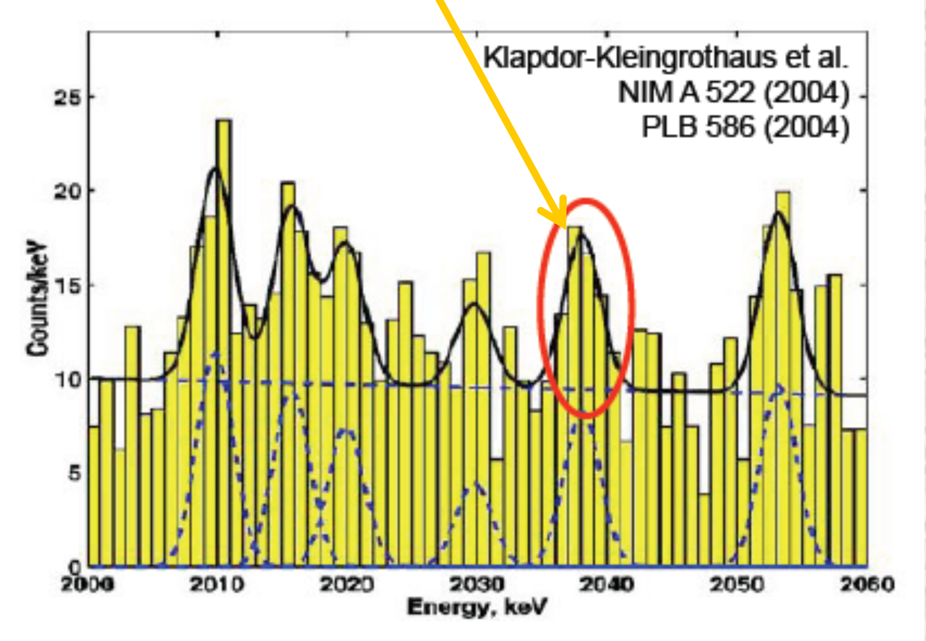
Inverse hierarchical

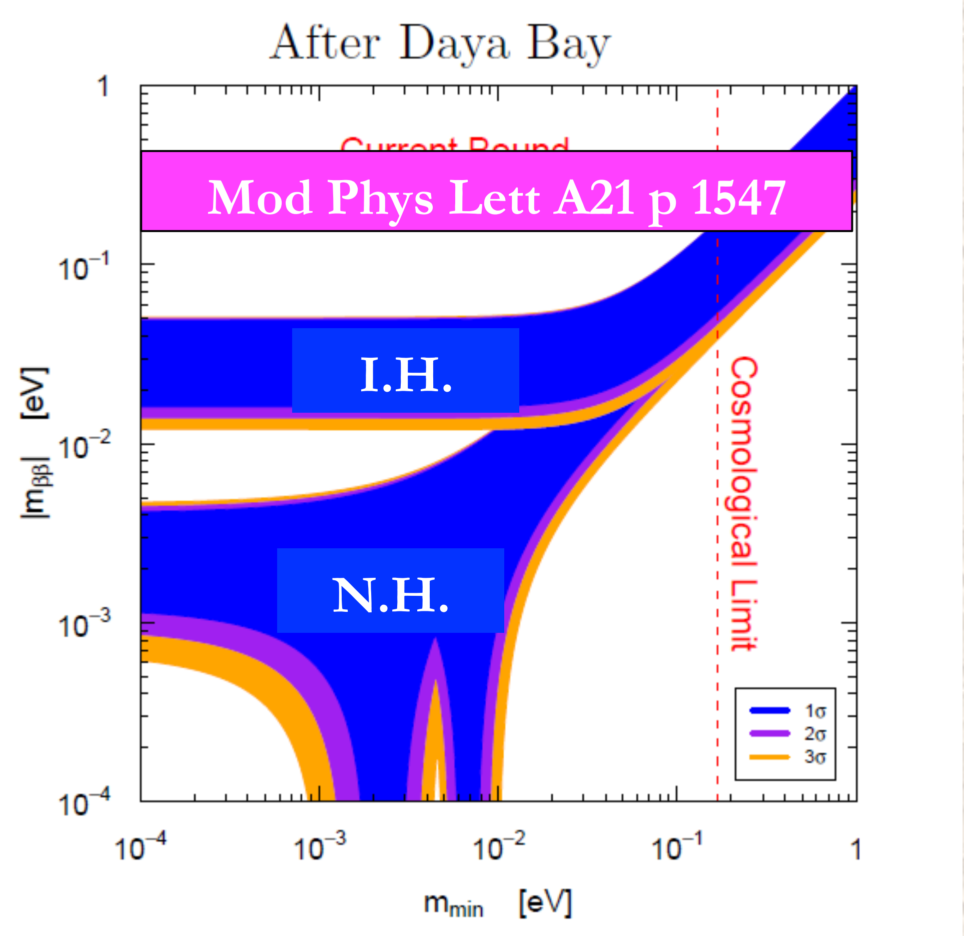




Claim of Discovery by a fraction of H-M collaboration (KKDC analysis)





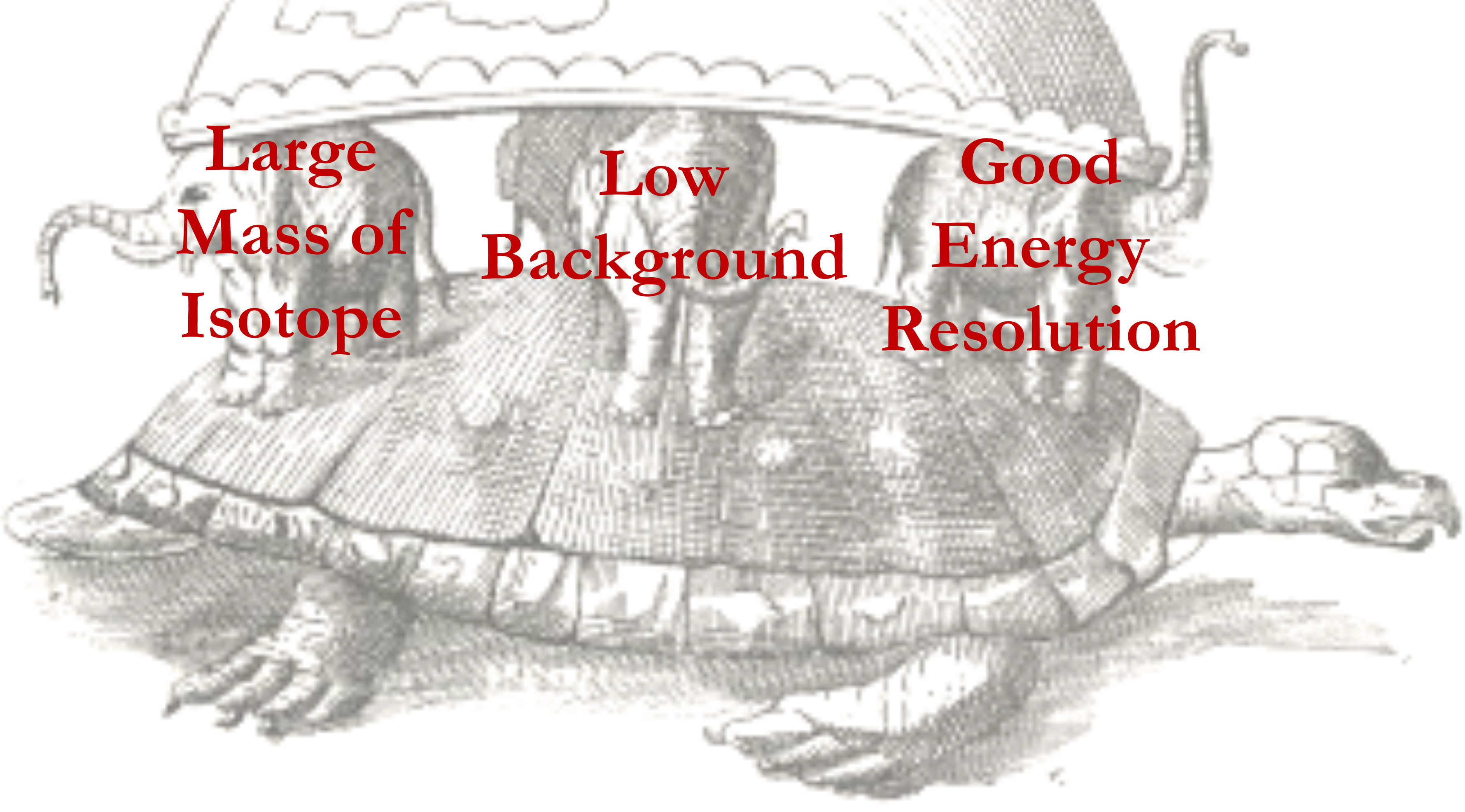


10 years of efforts
~10 kg of detectors build with isotopicaly enriched Ge detectors
Located at a ultrapure environment

Claim of 4 sigma effect. Corresponds to 170-450 meV effective neutrino mass

Background level ~ 400 events/t/y/R.O.I.

$2\beta 0\nu$ Experiment

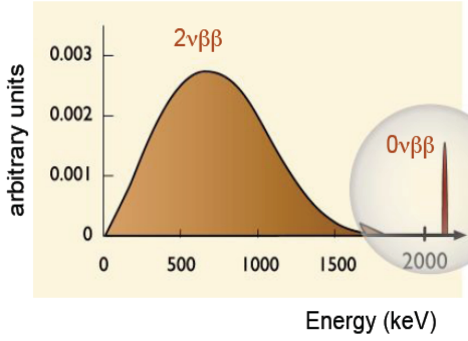


Large Mass of Isotope

Low Background

Good Energy Resolution

Représentation de la Terre d'après les Hindous.

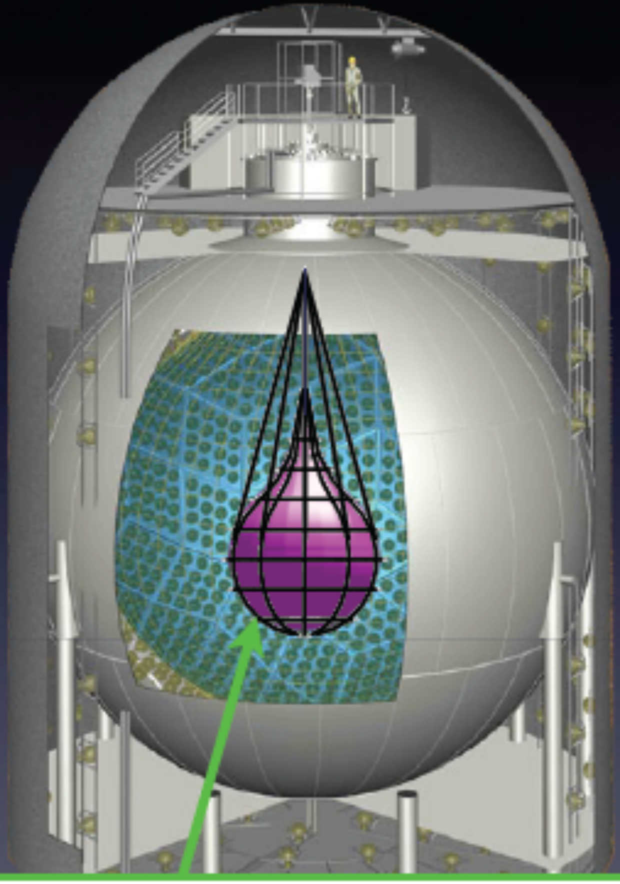


Some Present and future experiments

Experiment	Isotope	Mass, kg	Aim, $T_{1/2}$, y	Sensitivity $\langle m_\nu \rangle$, meV	Status
CUORE	**^{130}Te**	200	$1\cdot 10^{26}$	**50-130**	Funded
GERDA	**^{76}Ge**	I. 17 II. 40 III.1000	$2\cdot 10^{25}$ $2\cdot 10^{26}$ $6\cdot 10^{27}$	 **60-200** **10-40**	Funded Funded R&D
MAJORANA	**^{76}Ge**	I. 20-30 II. 1000	10^{26} $6\cdot 10^{27}$	**90-300** **10-40**	Funded R&D
EXO	**^{136}Xe**	200 1000	$(4\text{-}5)\cdot 10^{25}$ 10^{27}	**80-240** **20-50**	Funded R&D
SuperNEMO	**^{82}Se**	100-200	$(1\text{-}2)\cdot 10^{26}$	**40-110**	R&D
KamLAND-Zen	**^{136}Xe**	330 1000	$\sim 2\cdot 10^{26}$ $\sim 6\cdot 10^{26}$	**40-110** **23-58**	Funded R&D
SNO+	**^{150}Nd**	50 500	$\sim 6\cdot 10^{24}$ $\sim 3\cdot 10^{25}$	**120-410** **55-180**	Funded R&D

KamLAND-Zen

Focus is on the large mass, low background, and existing detector



^{136}Xe 400 kg loaded LS in mini-balloon, R=1.7m

^{136}Xe 400 kg:

- 2.7 wt% dissolved into LS
- easy handling/ enrichment (90%)
- longer 2ν beta decay life time
- $T^{2\nu}$ >10^{22} years (cf: ~$10^{19\text{-}20}$)

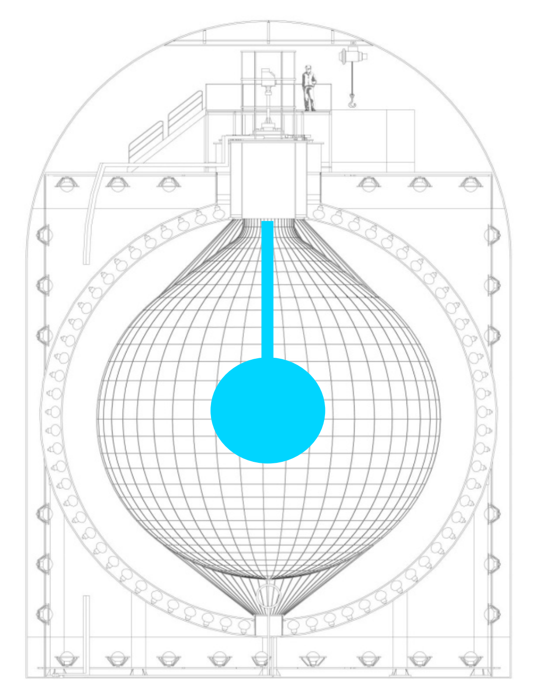
KamLAND exists:

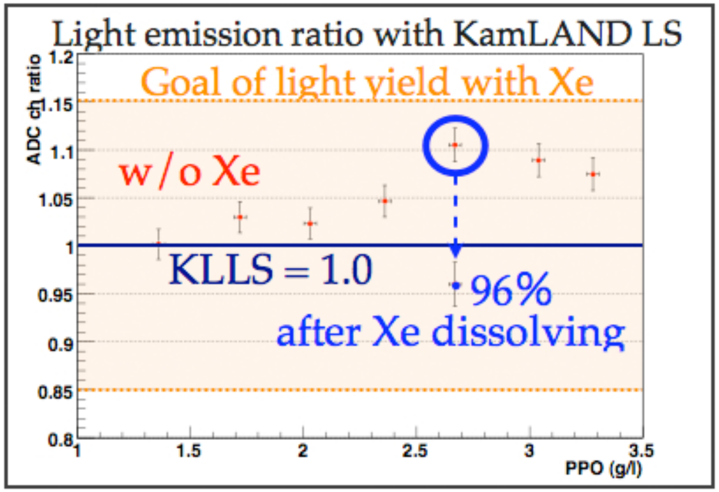
- ultra pure environment (U/Th~10^{-17} g/g)
- LS techniques
- Balloon experience
- LS Density control techniques
- Reactor/Geo neutrino

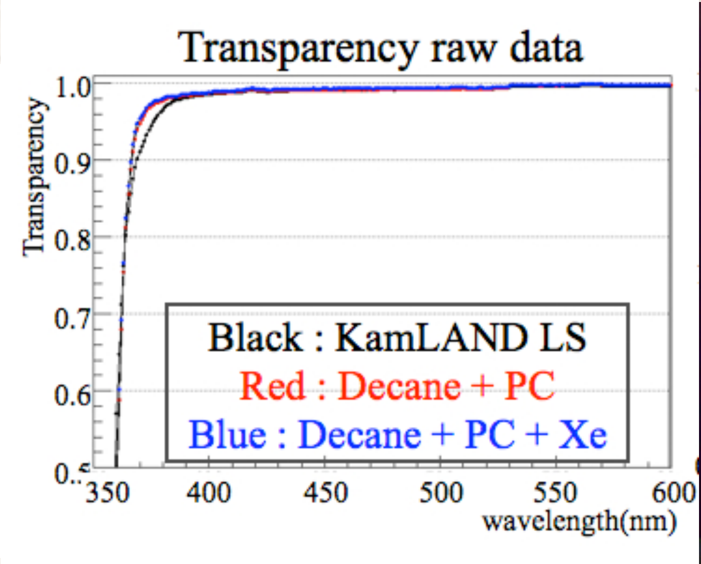
Scintillator

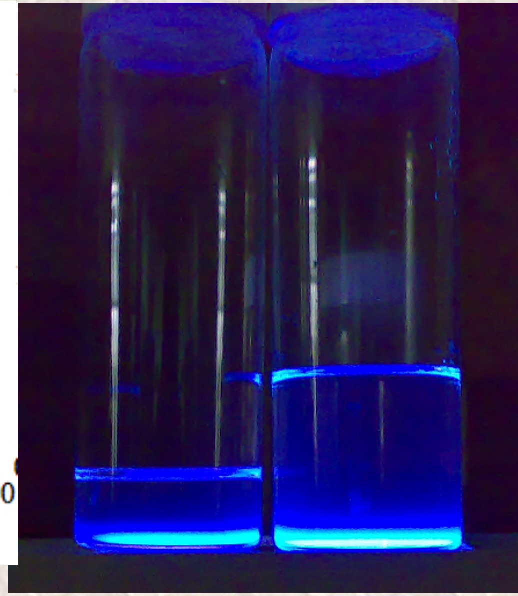
Mini Balloon is very thin so Xe loaded scintillator should have the same density as the KamLAND scintillator

Xe loaded LS		KamLAND LS
PC 17.7%		PC 20%
Decane 82.3%	=	Dodecane 80%
PPO(~2.7g/l)		PPO(1.36g/l)
Xe 3.0wt%		

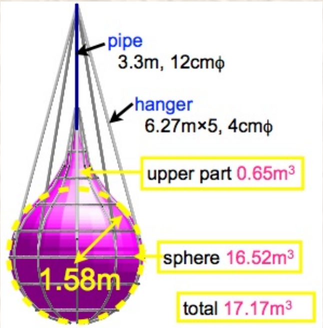




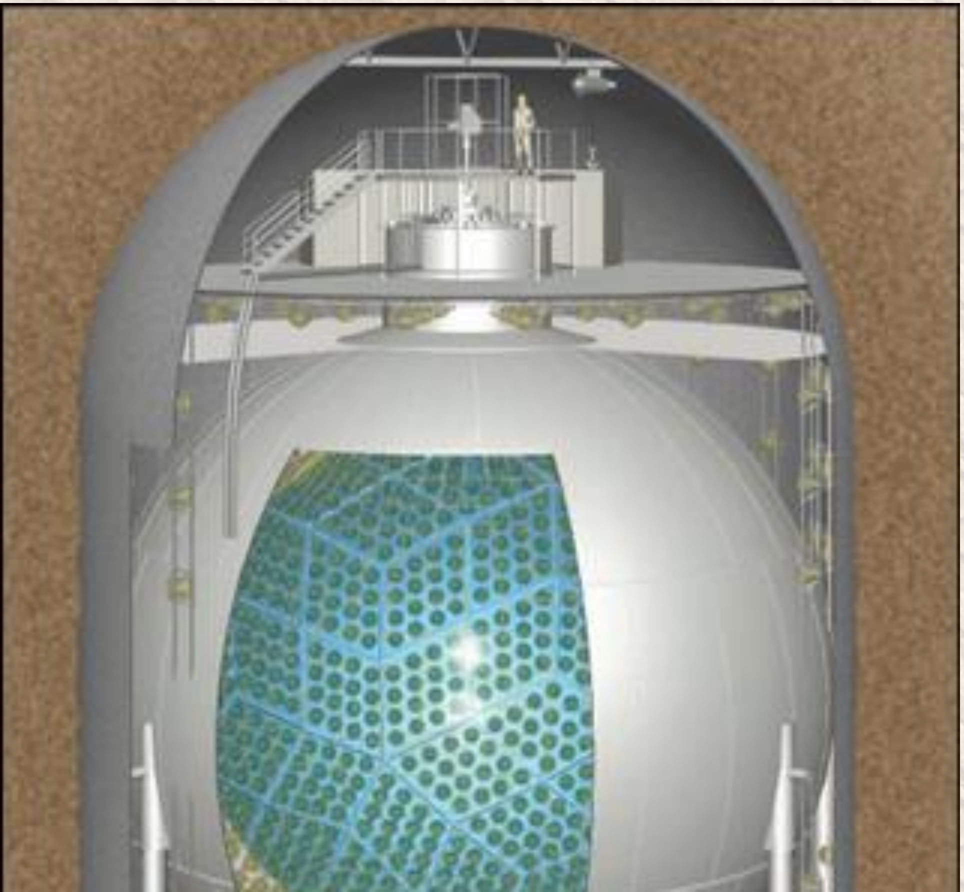




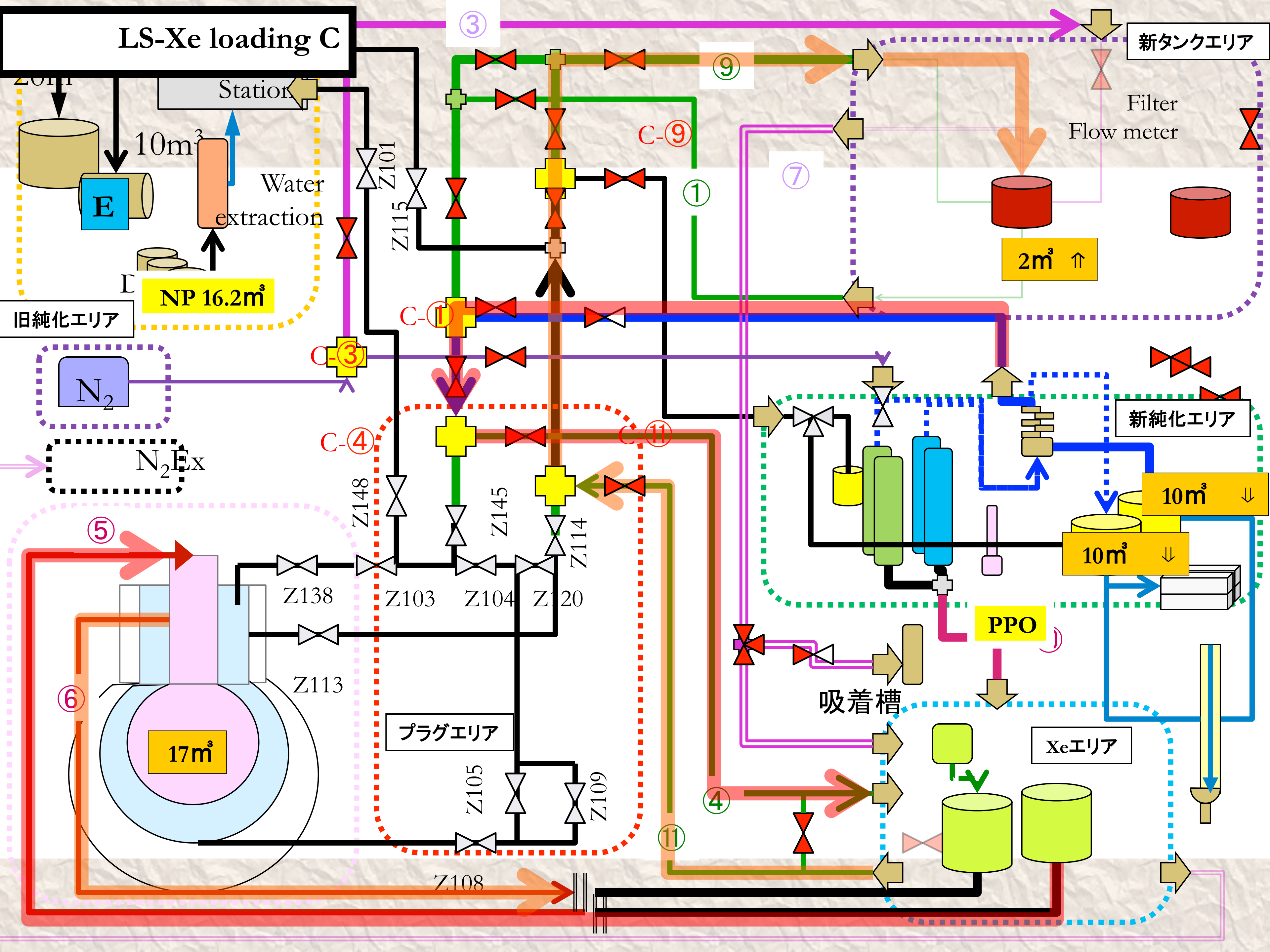
KamLAND Deck Modific ions



Need s y Mini
balloon etector



LS-Xe loading C



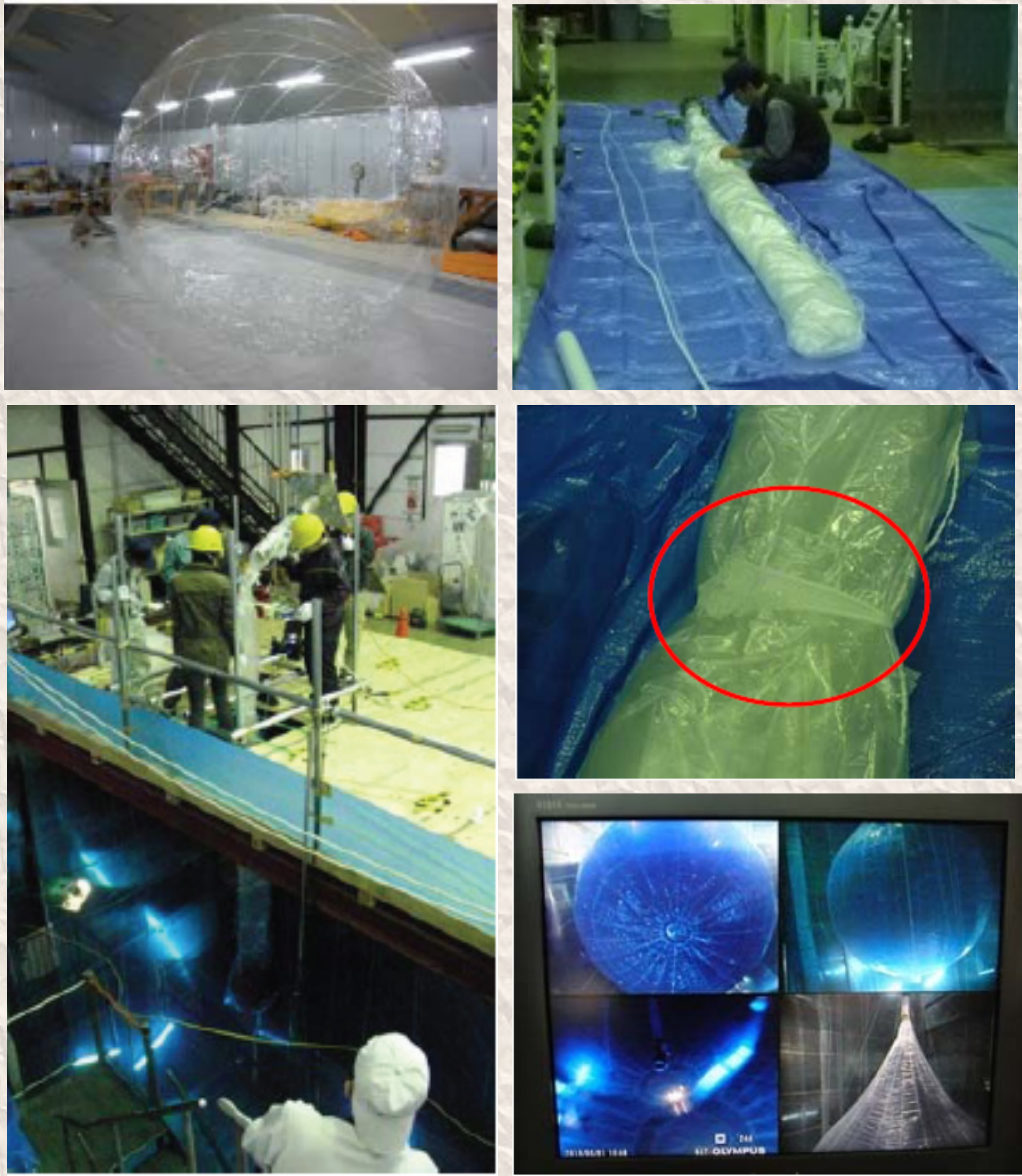
Scintillator Handling Infrastructure

Mini Balloon. *Thickness - 25 μm*

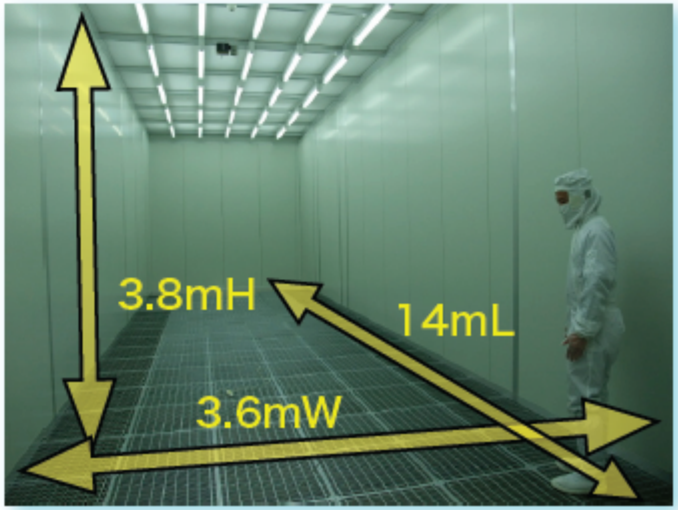
Assembly/Deployment

- Weld Balloon together, test it for a leaks.
- Fold it and wrap inside protective layer (Cocoon)
- Move to the detector site.
- Remove transportation protective layer in a clean environment
- Lower its bottom while it is folded via chimney.
- Filled it with small amount (~100 l.) of scintillator with density higher than that of KamLAND scintillator.
- Deploy it all the way, remove protective layer and straps.
- Expand it using regular liquid scintillator
- Replace regular scintillator with Xe loaded scintillator

Test deployment of Mini Balloon Prototype



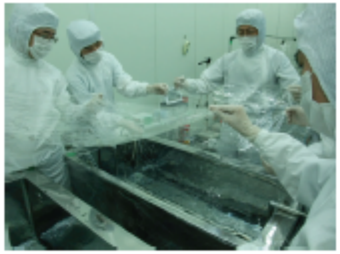
Mini-balloon fabrication in super clean room (2011.May~July)



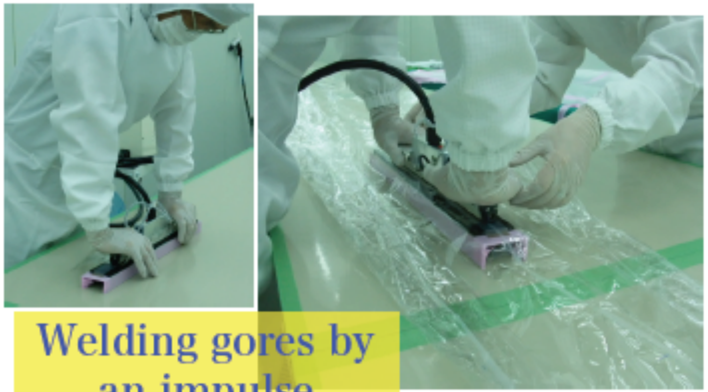
A super-clean room in the Nishizawa center, Tohoku Univ.

Class 1 (=1 particle(>0.1μm) /feet^3)

Film rinsing with ultra-pure water using an ultrasonic machine



Carefully checking films.



Welding gores by an impulse welding machine

Helium leak check

Repairing works

July 2011

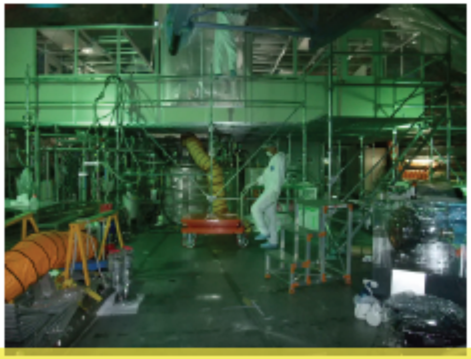

Putting the nylon belts



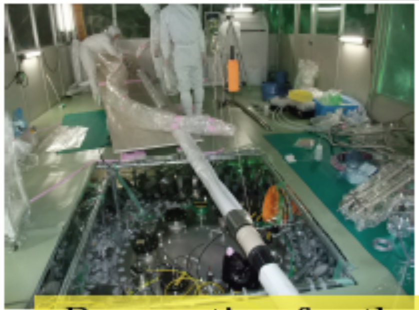
Packing

Shipping to Kamioka

Kamioka in the mine


A clean tent at the KamLAND dome area


Mini-balloon into the tent


Preparation for the deployment


Monitoring camera

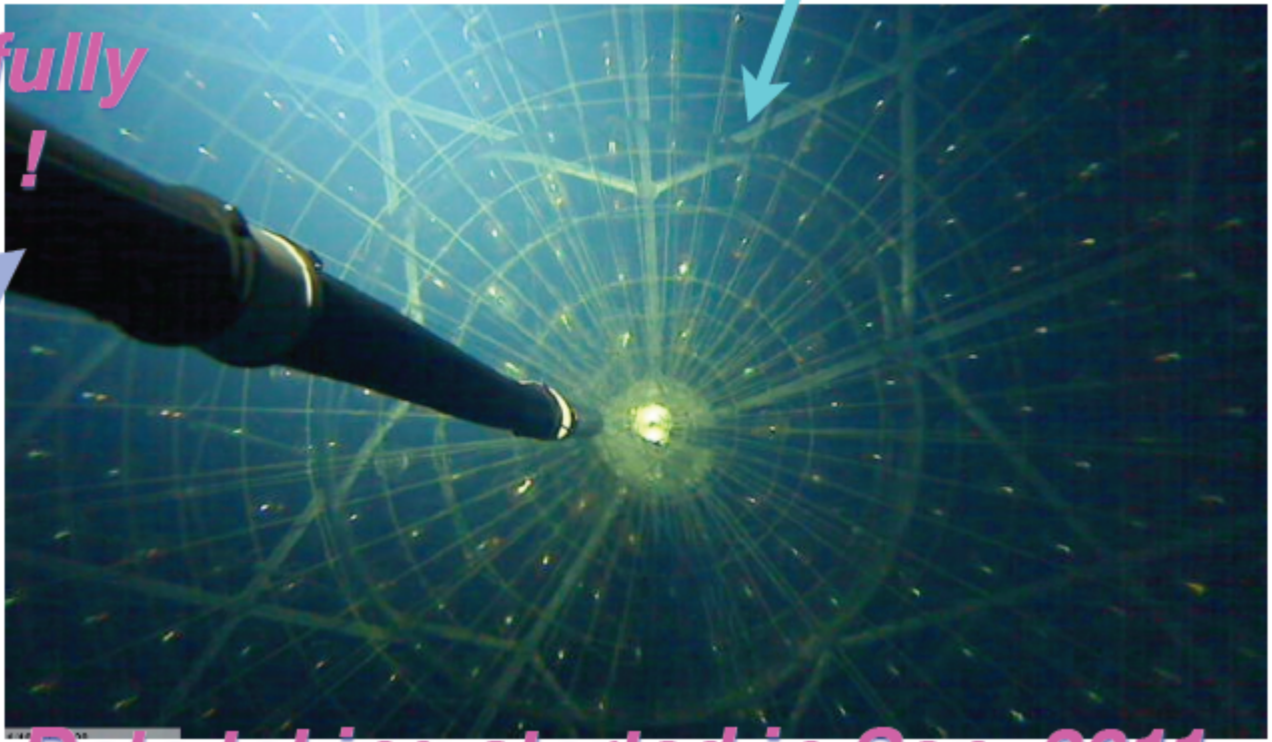

Camera installation


Connecting the corrugated tube

Install the mini-balloon into KamLAND (Aug.2011)

View by a monitor camera
from the detector top.
The mini-balloon edge can be
seen by the deformed shape of
the beam in the tank.

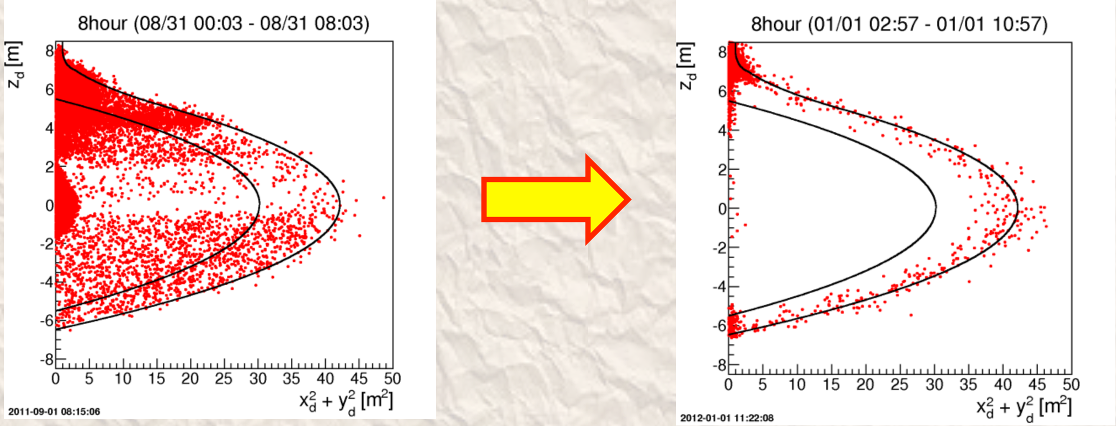
Succesfully done !

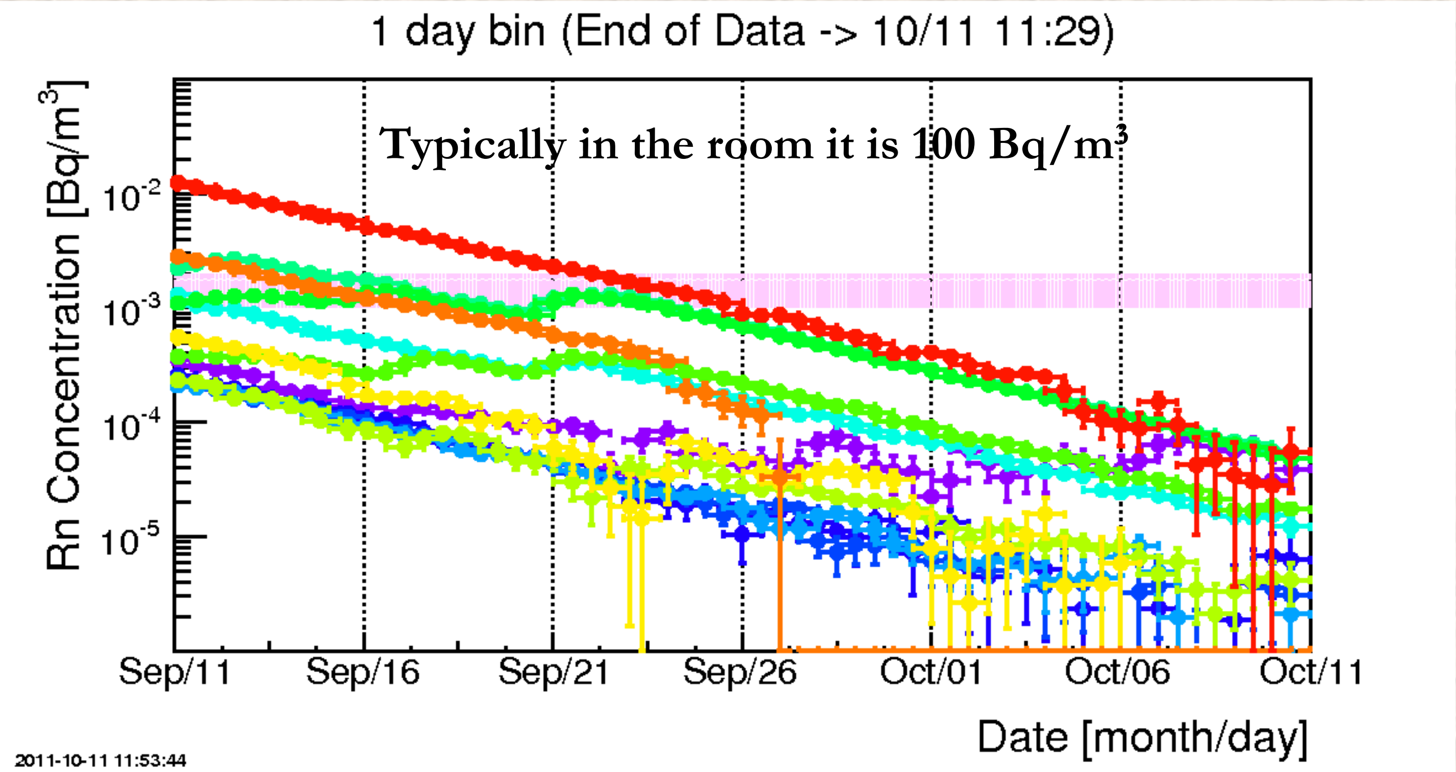


Connection
pipe

Data taking started in Sep. 2011

We have to wait for Radon to decay

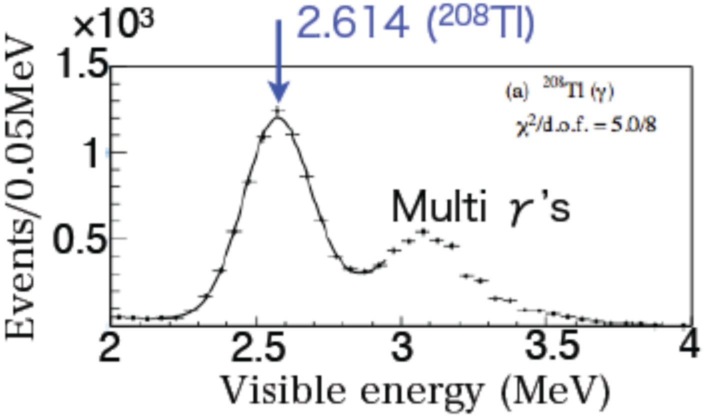




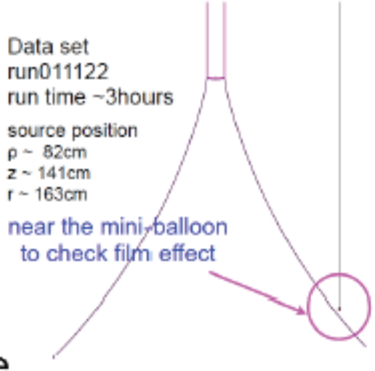
Typically in the room it is 100 Bq/m^3

Energy calibration

ThO_2W γ-ray source (2.614MeV ^{208}Tl), ^{214}Bi($\beta+\gamma$'s) from ^{222}Rn (initial stage), 2.225MeV γ's from spallation neutron captures on protons are utilized.

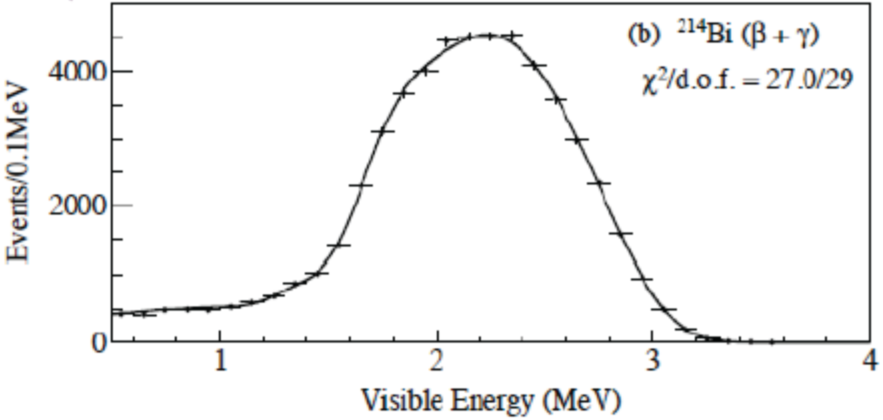


ThO2W source



Data set
run011122
run time ~3hours
source position
ρ ~ 82cm
z ~ 141cm
r ~ 163cm
near the mini-balloon
to check film effect

Energy resolution
$$= (6.6\pm0.3)\%/\sqrt{E[\mathrm{MeV}]}$$



Energy scale parameter are tuned to reproduce the observed ^{214}Bi spectrum.

Vertex reconstruction

Bias study process

refractive index distribution

measurement
with Abbe's
refractometer
(**eye check**)

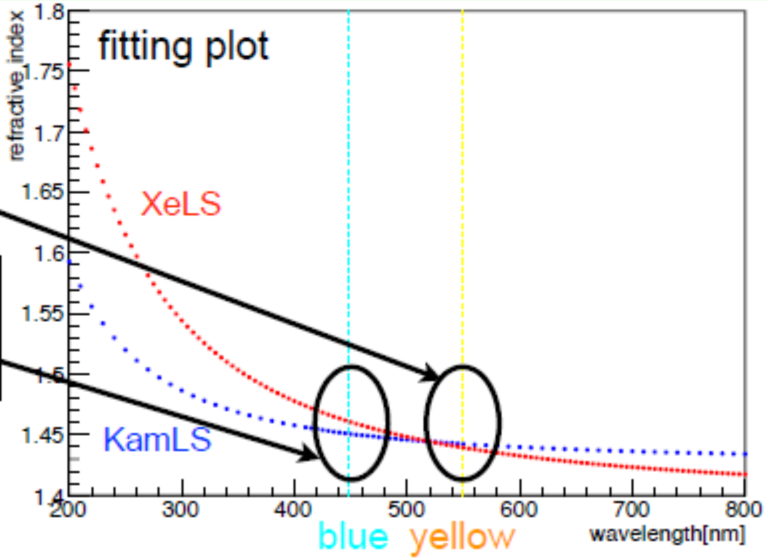
yellow

$n_{KamLS} > n_{XeLS}$
~ 0.5%

blue

$n_{KamLS} < n_{XeLS}$
~ 1.0%

KamLS : measured in 2001 old
XeLS : measured in 2010



set to MC

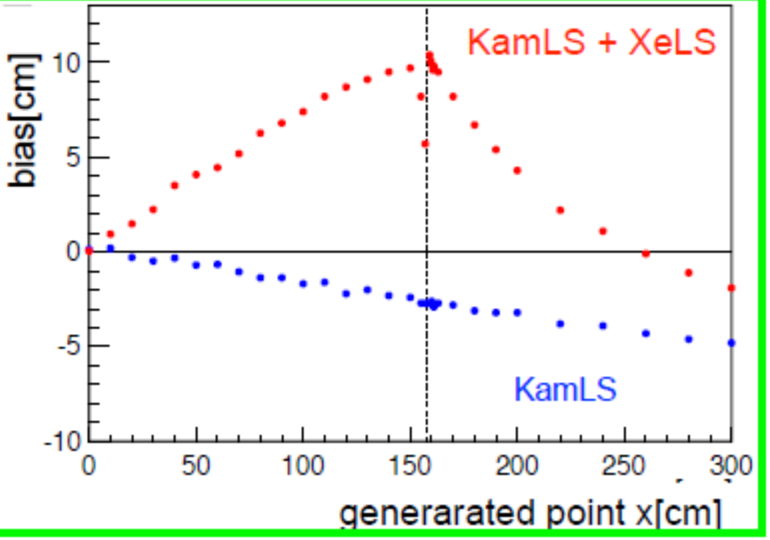
generate e^-(1.5MeV) along x axis in MC

big bias near the IB ~ 10cm

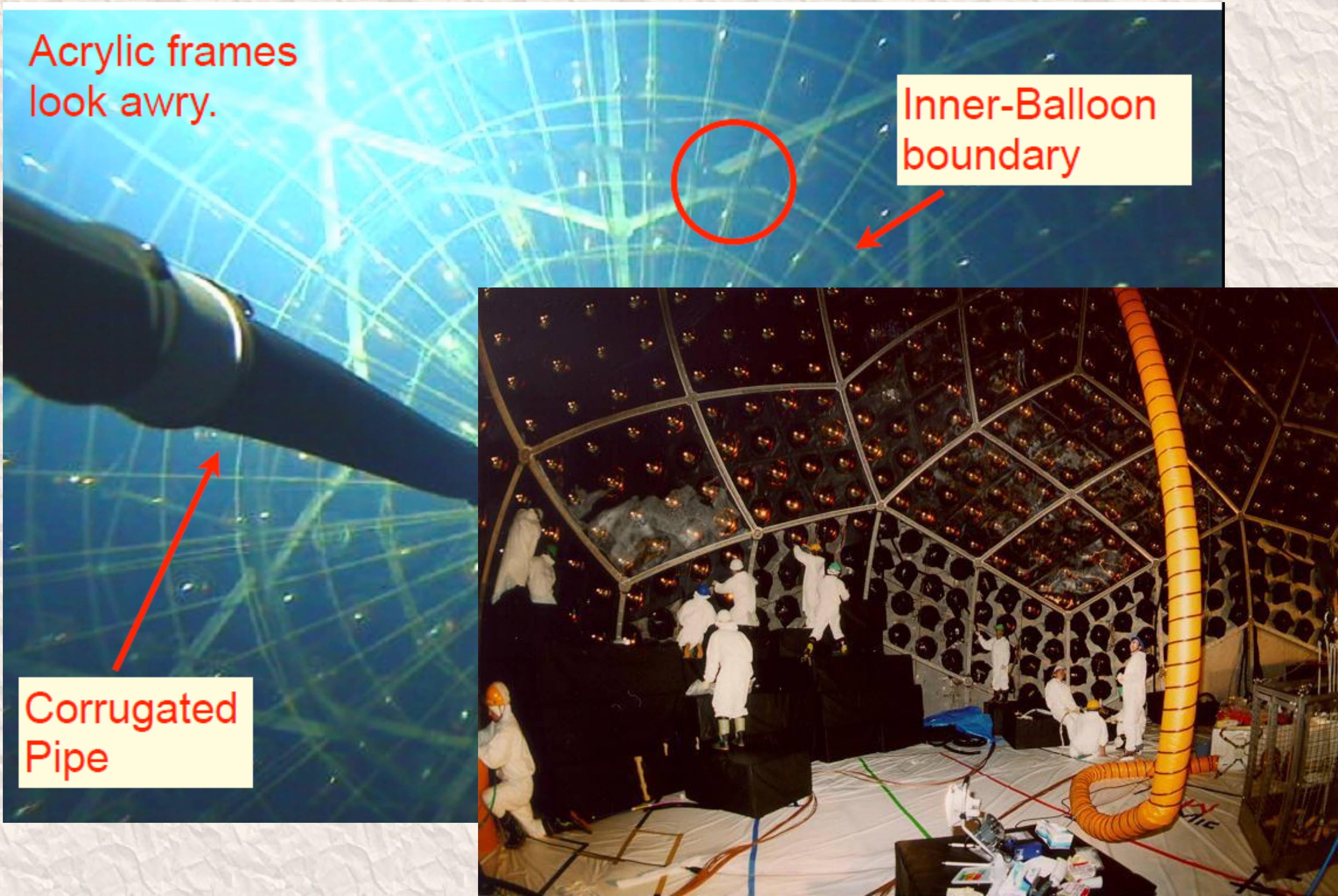
- the bias is true?
- measurement is wrong?

→ **tune refractive index with ray trace**

How?



How to recalibrate refractive index?



Acrylic frames look awry.

Inner-Balloon boundary

Corrugated Pipe

How to tune n_{XeLS}, n_{KamLS}

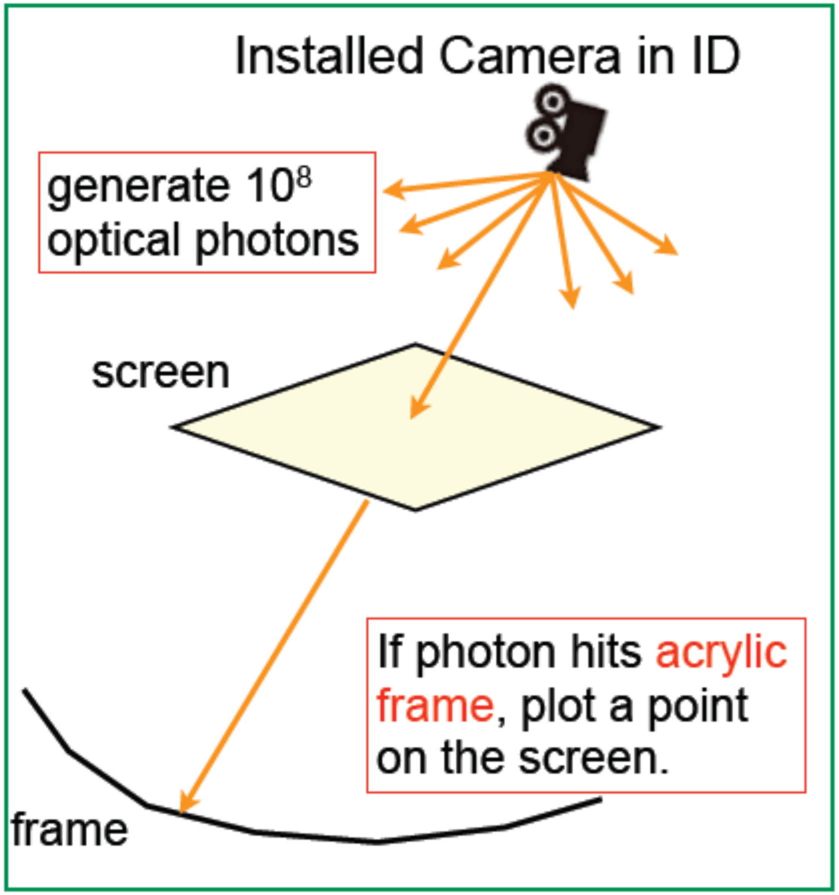
Check...

1. **$n_{KamLS} > n_{XeLS}$ ~ 0.5%** yellow

2. **$n_{KamLS} < n_{XeLS}$ ~ 1.0%** blue

each situations reproduces the picture?

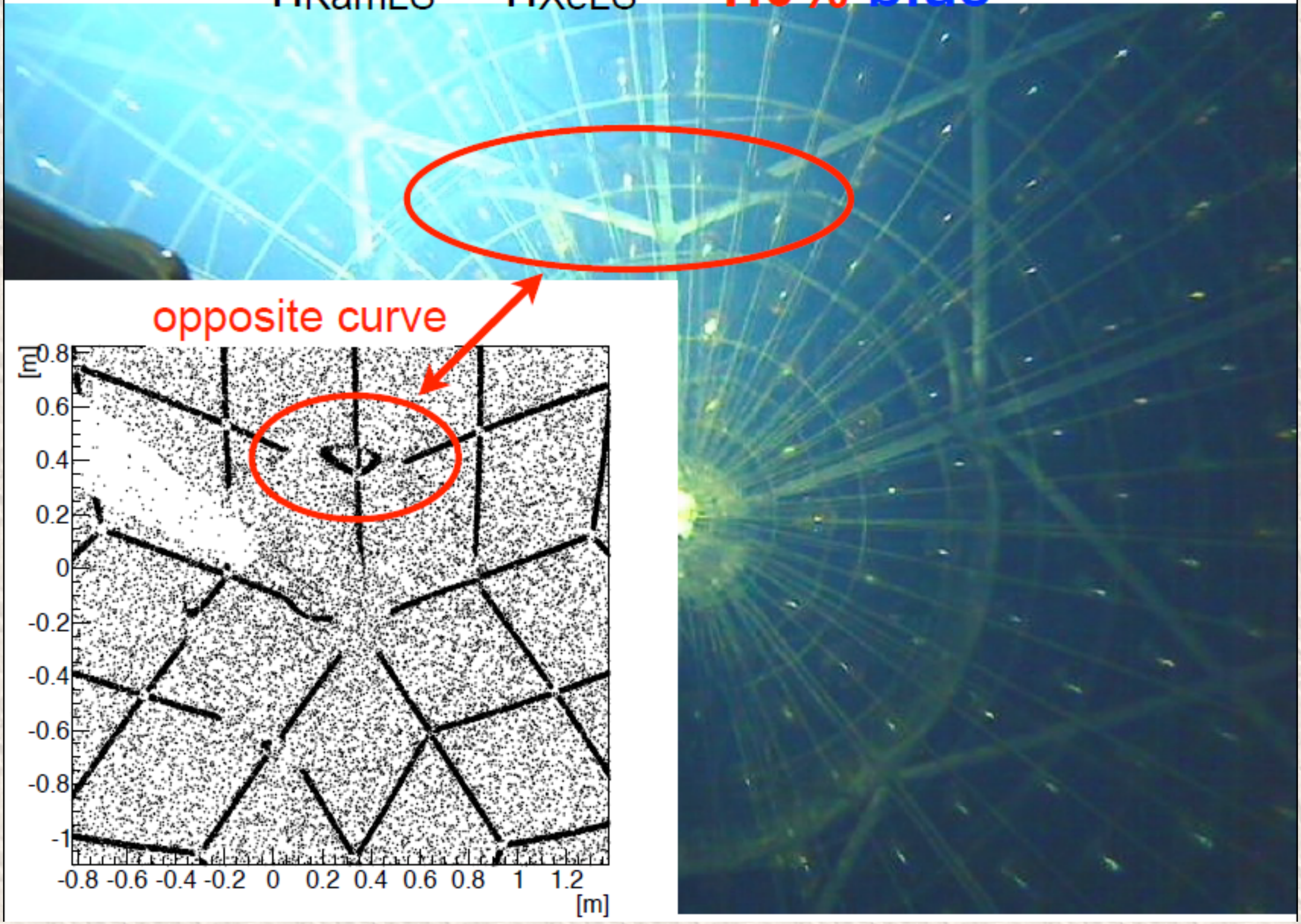
Simulation



generate 10^8 optical photons

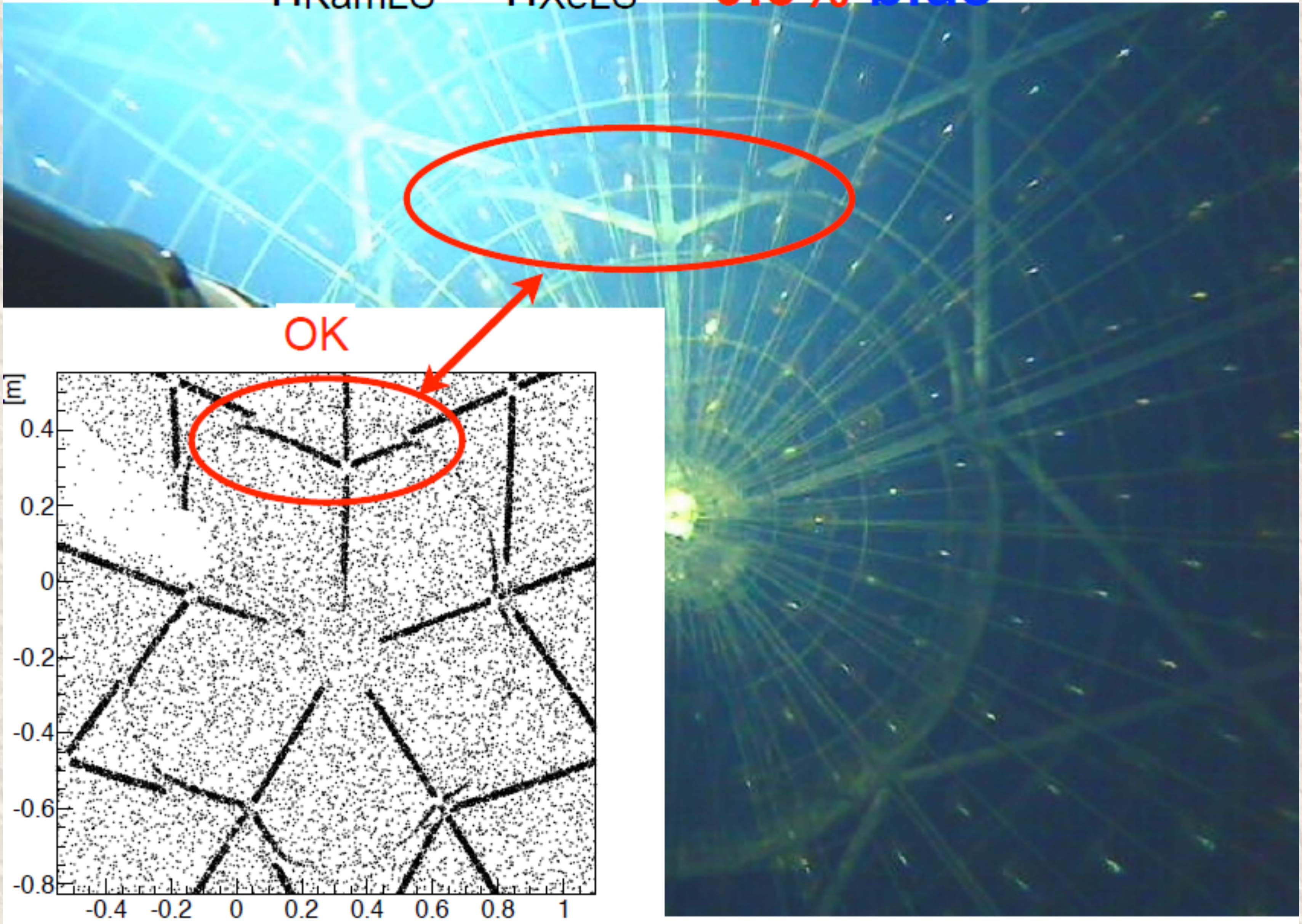
If photon hits acrylic frame, plot a point on the screen.

$n_{KamLS} < n_{XeLS}$ ~ 1.0% blue



opposite curve

$n_{KamLS} > n_{XeLS}$ ~ 0.5% blue

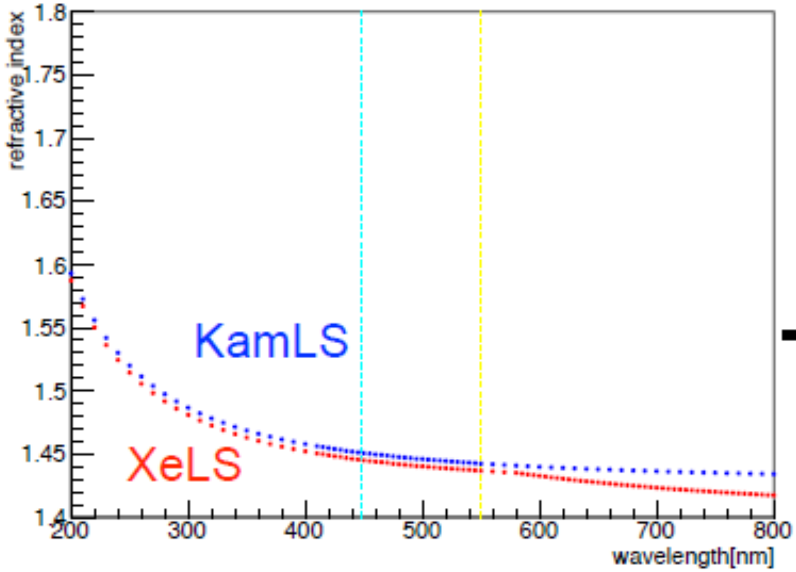


Result

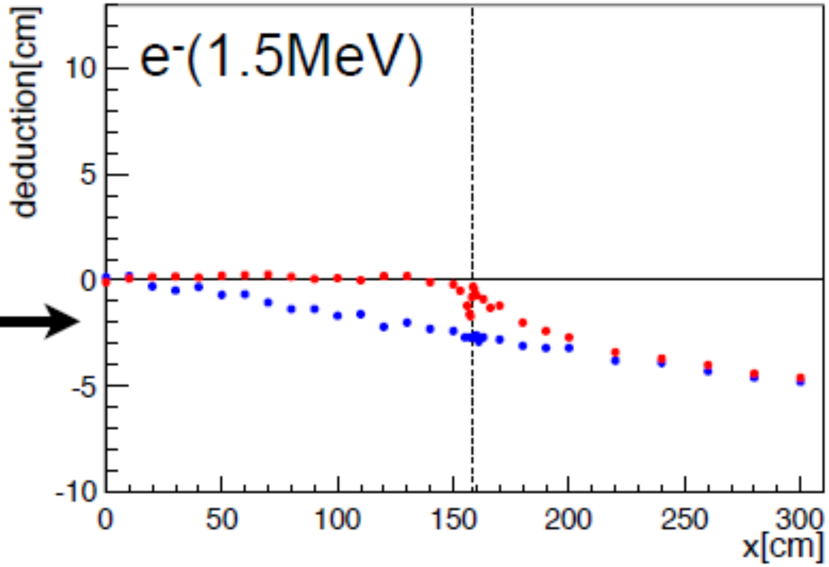
1. $n_{KamLS} > n_{XeLS}$ ~ **0.5%** yellow **OK**

2. ~~$n_{KamLS} < n_{XeLS}$ ~ **1.0%**~~ blue → $n_{KamLS} > n_{XeLS}$ ~ **0.5%** blue **OK**

modified simulation settings

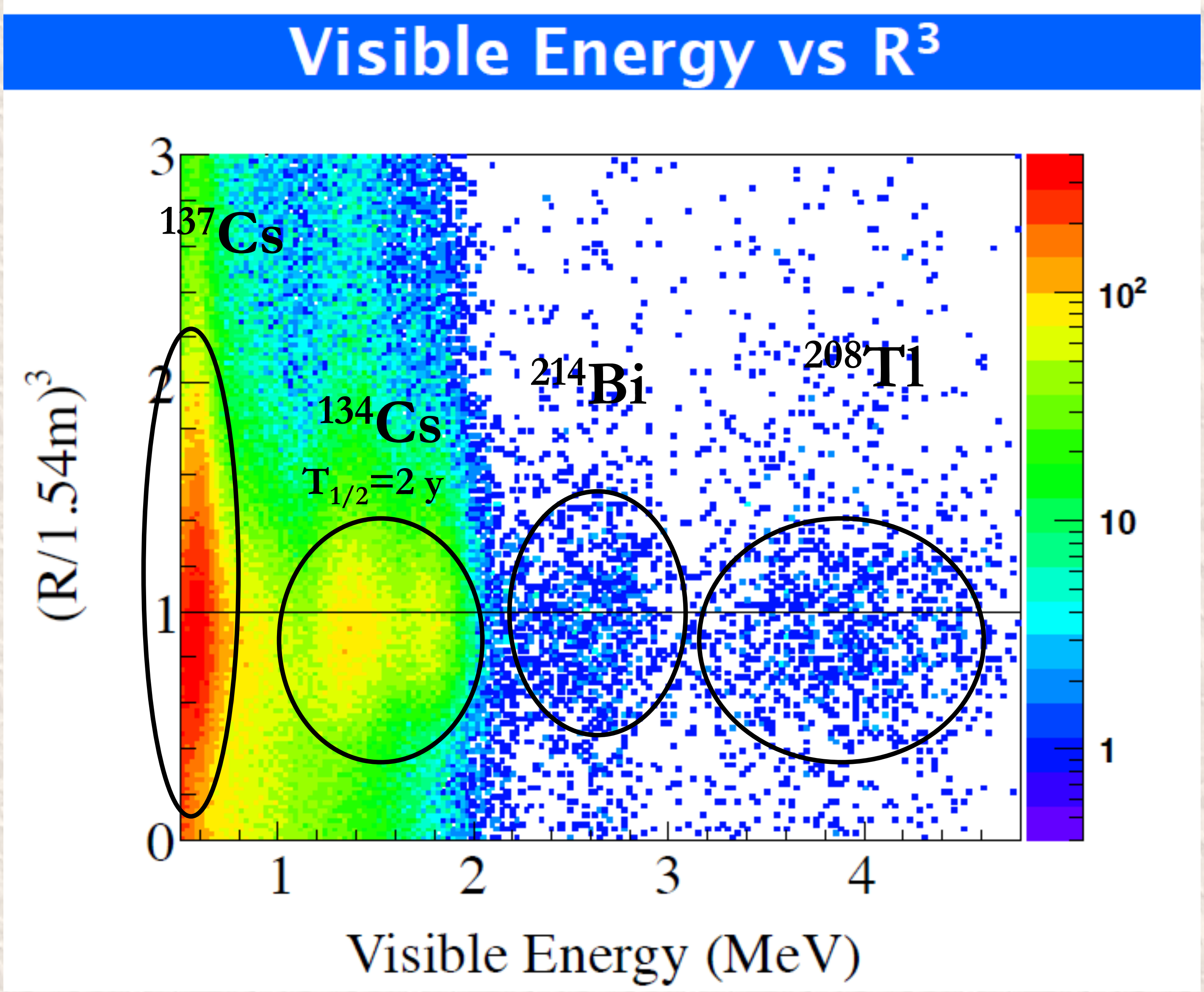


→



The bias become small.

After calibration of energy and vertex reconstruction we can look into Physics



Unfortunate Timing

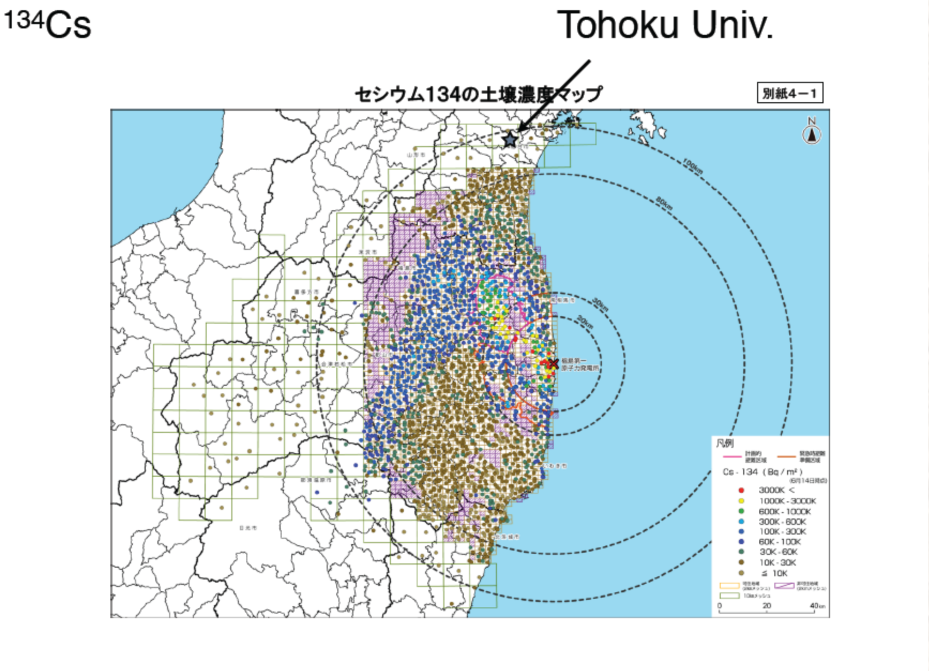
April 2011 – all materials were ready and stored at Sendai clean room to build mini balloon

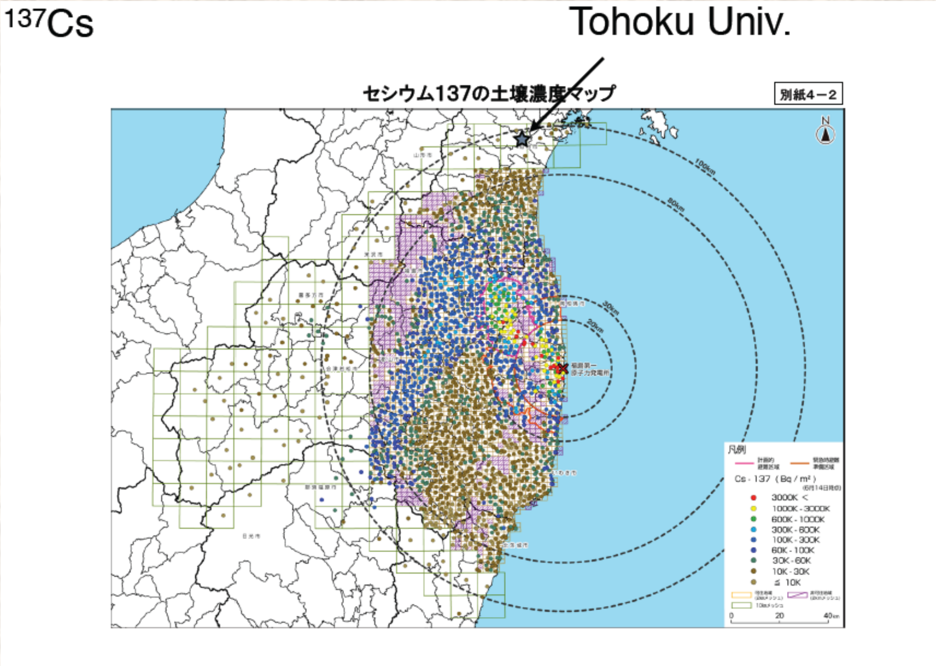
May- July 2011 Balloon was build

August 2011 balloon was transported to Kamioka and deployed in the KamLAND

March 11, 2011

Cesium from Fukushima



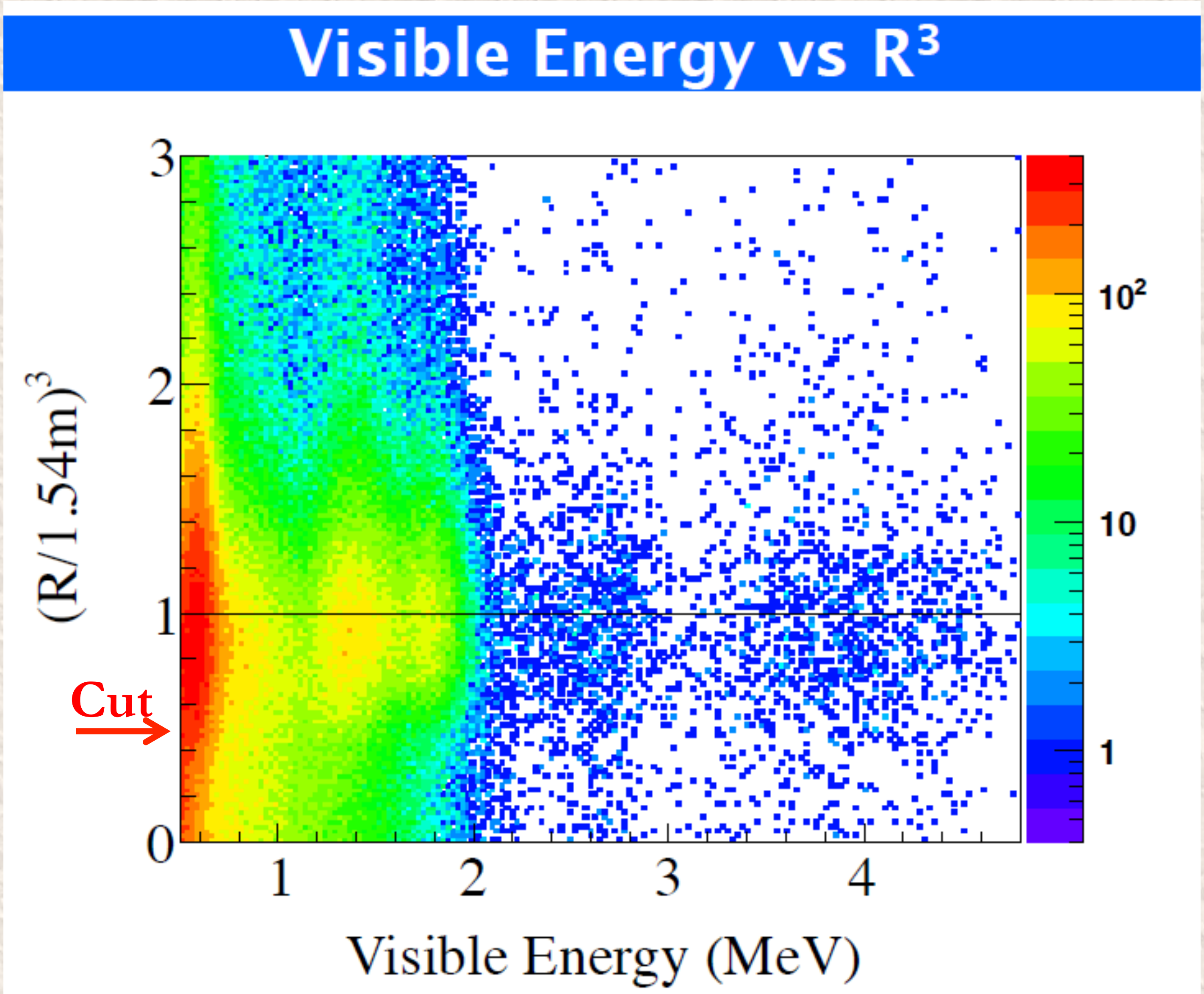


^{134}Cs $t_{1/2}$=2.07 y **^{137}Cs $t_{1/2}$=30.06 y**

Ratio of two Cs isotopes in soil samples at Sendai is the same as on the mini-balloon!

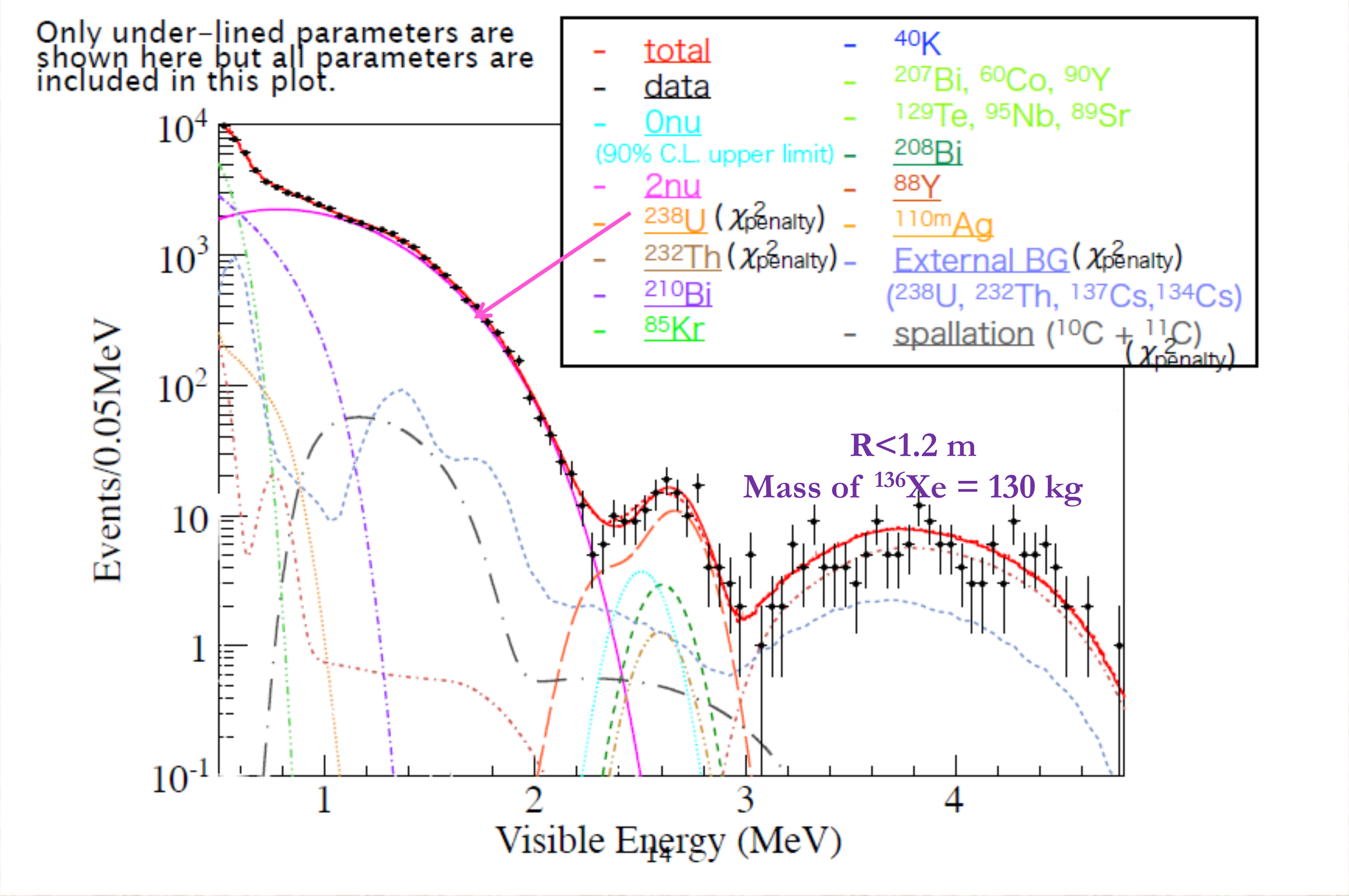
However all contamination on the balloon we can cut away by sacrificing fiducial mass

Radial Cut



Cs contamination helps us to define mini balloon position!!!

Energy Spectrum

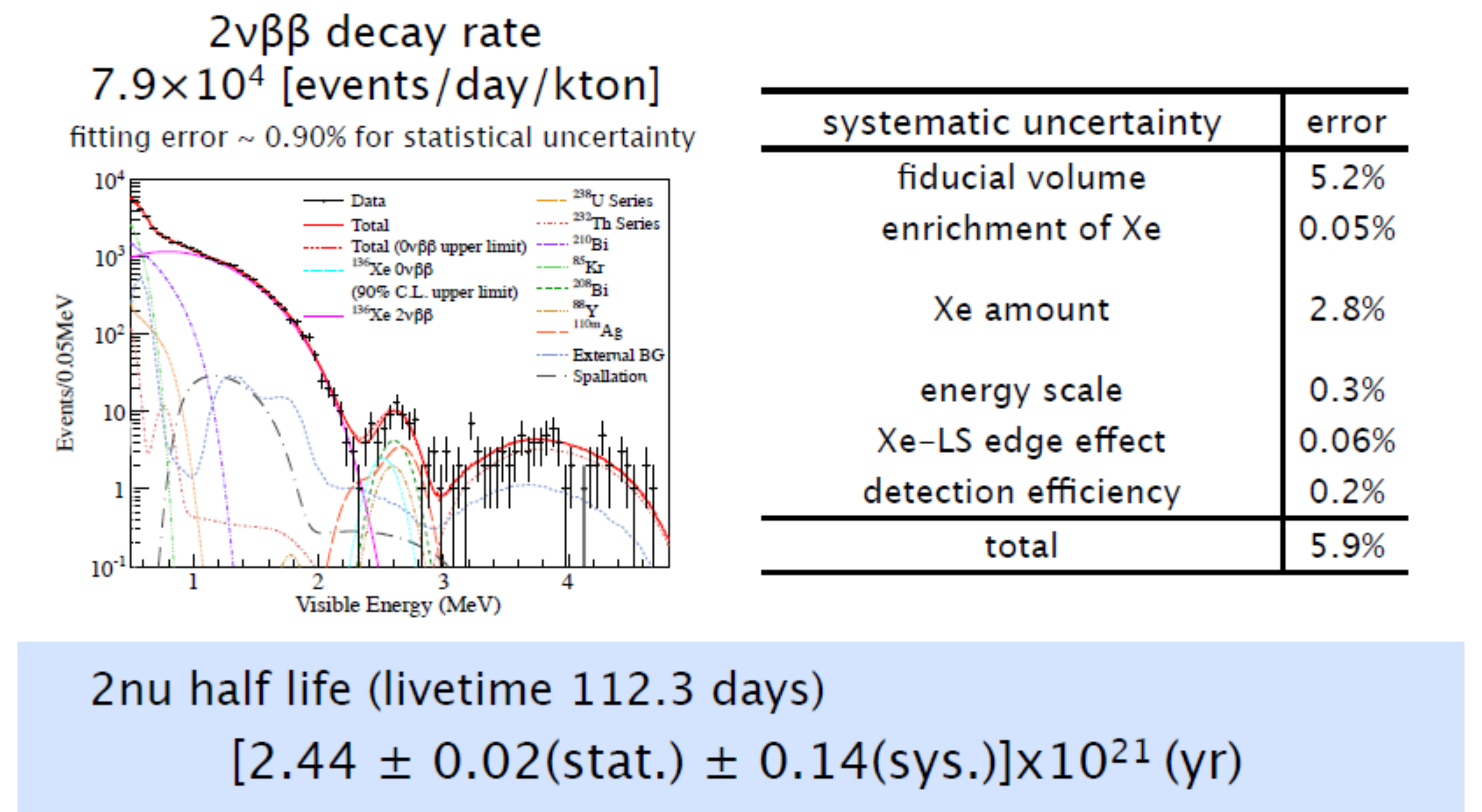

Only under-lined parameters are shown here but all parameters are included in this plot.

R<1.2 m

Mass of ^{136}Xe = 130 kg

$^{136}Xe \rightarrow {}^{136}Ba + 2\nu + 2e^-$

2ν half live time estimation



2νββ decay rate

7.9×10^4 [events/day/kton]

fitting error ~ 0.90% for statistical uncertainty

systematic uncertainty	error
fiducial volume	5.2%
enrichment of Xe	0.05%
Xe amount	2.8%
energy scale	0.3%
Xe-LS edge effect	0.06%
detection efficiency	0.2%
total	5.9%

2nu half life (livetime 112.3 days)

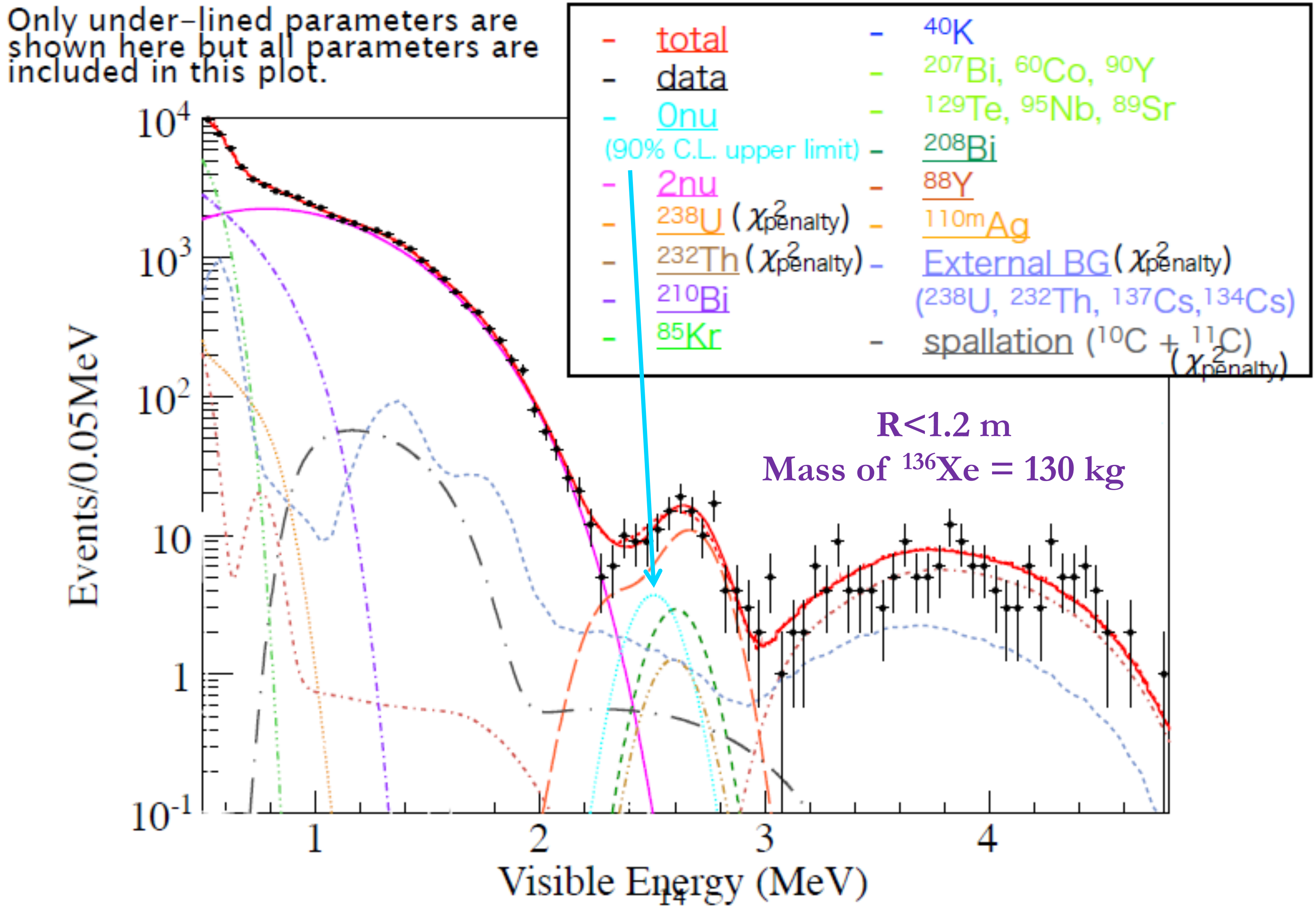
$[2.44 \pm 0.02(\text{stat.}) \pm 0.14(\text{sys.})]\times10^{21}$ (yr)

Previous result (DAMA) $t_{1/2} > 1 \cdot 10^{22}$

A few month before KamLAND, EXO published:

$t_{1/2} = (2.11 \pm 0.04(\text{stat}) \pm 0.21(\text{sys})) \cdot 10^{21}$

Energy Spectrum

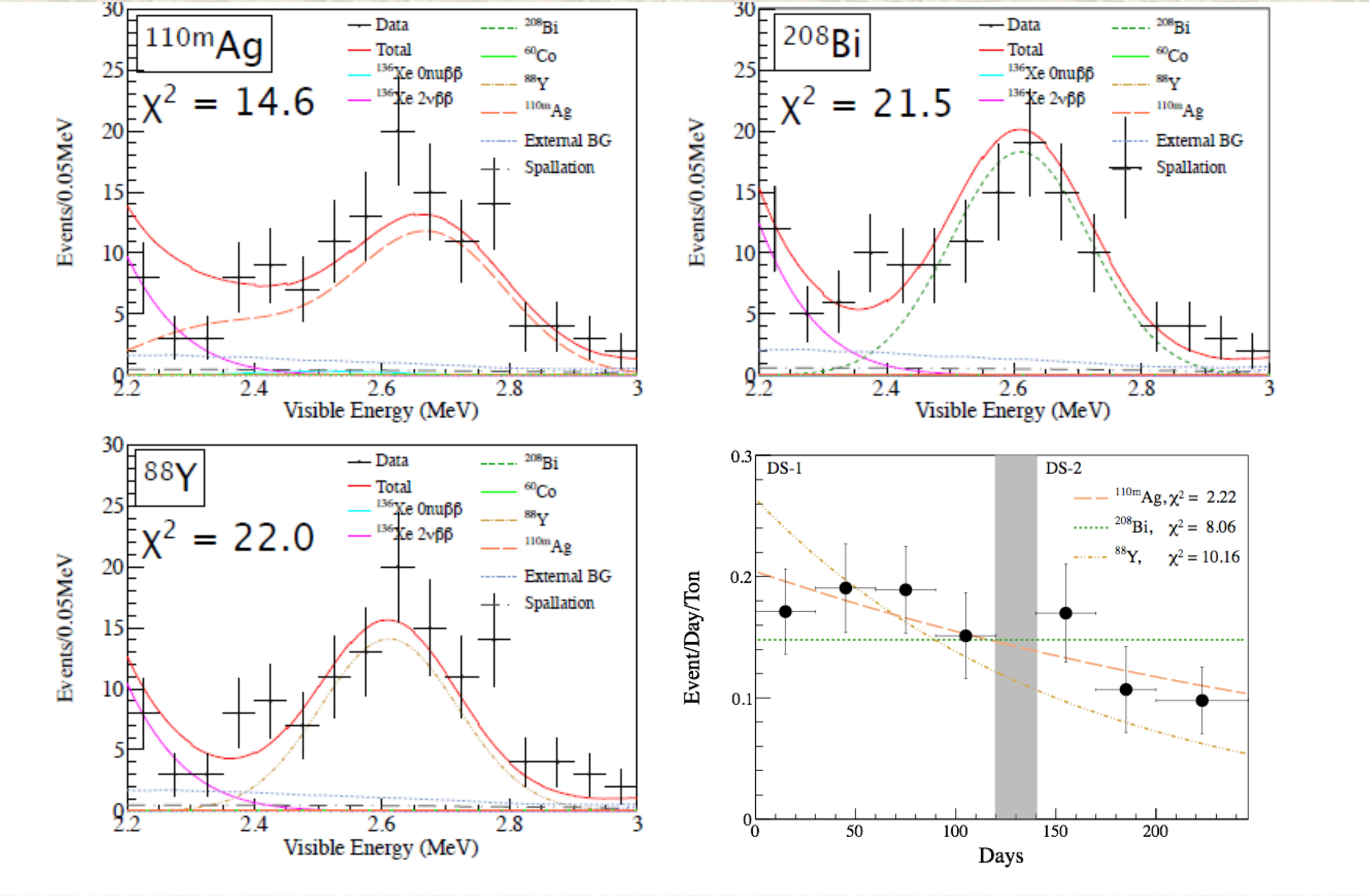


Only under-lined parameters are shown here but all parameters are included in this plot.

R<1.2 m

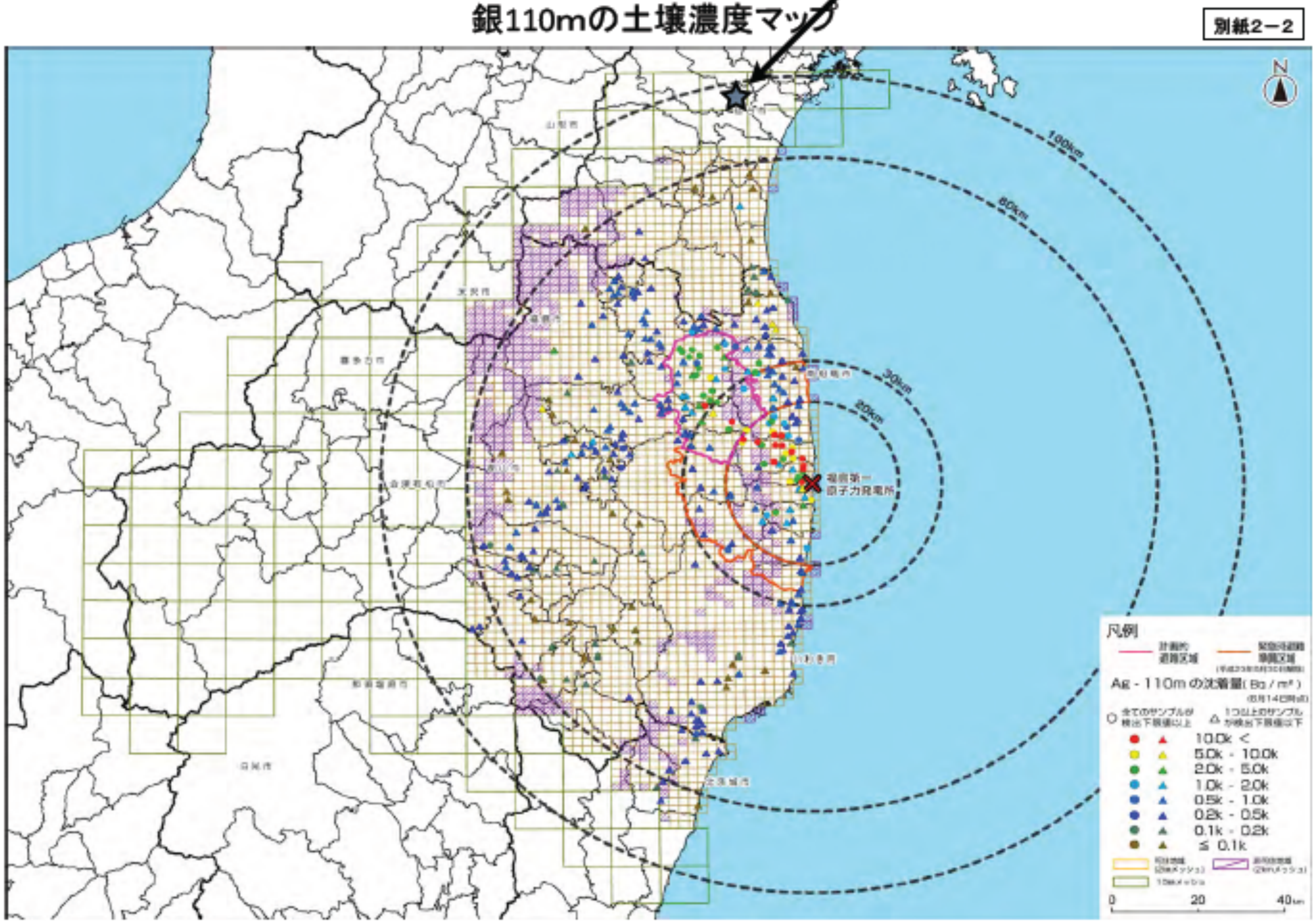
Mass of ^{136}Xe = 130 kg

Investigating background near 2.6 MeV



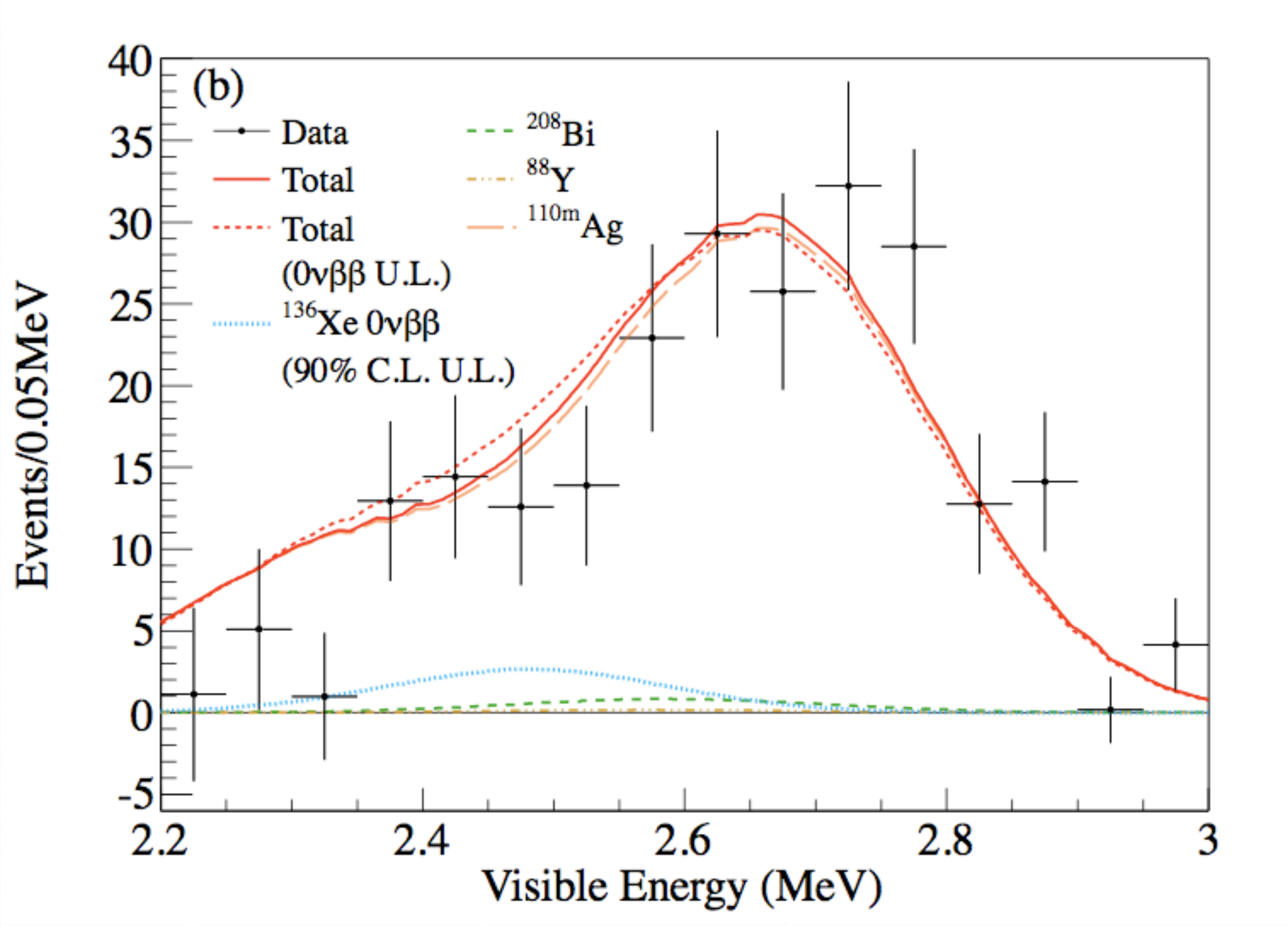
^{110m}Ag

Tohoku Univ.



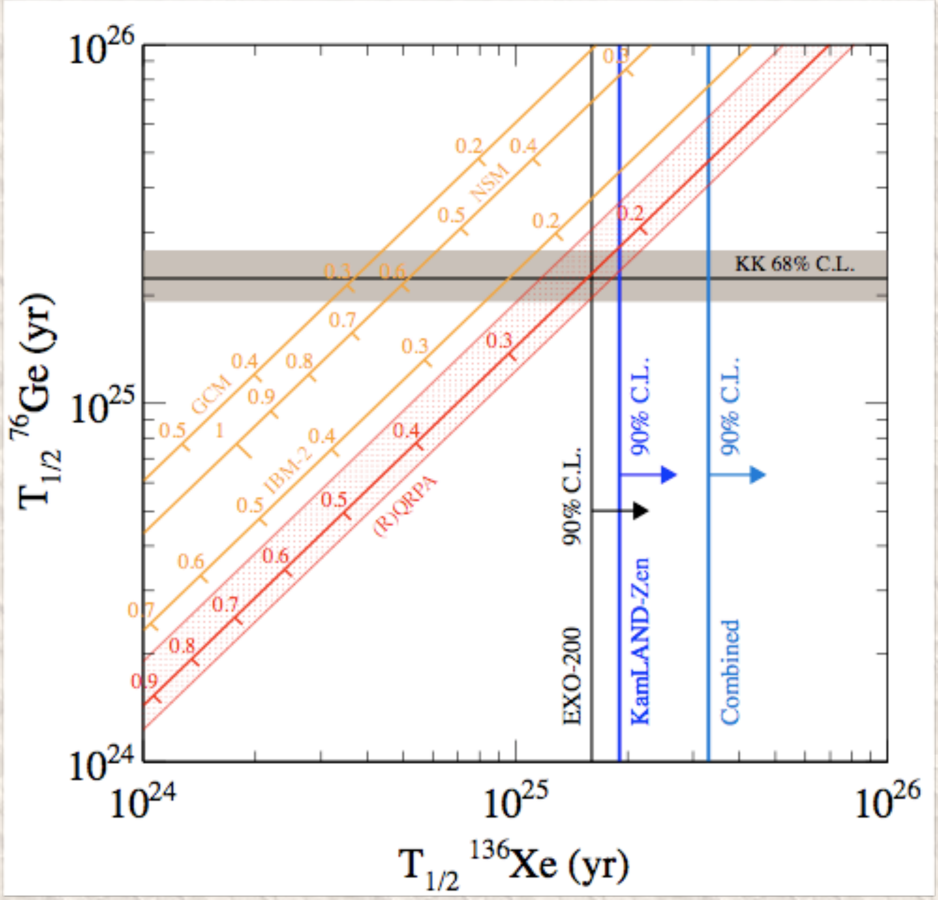
Total we got a few thousands atoms of ^{110m}Ag in the detector

Close-up of 0vBB region



$$T_{1/2}^{0\nu} > 1.9 \times 10^{25}\ \mathrm{yr} \quad (90\%\ \mathrm{C.L})$$

Combination of KL-Zen and EXO



NME is a major caveat in interpretation of half life limit

Treating spread in NME calculations as an 'error' then EXO-200 and KLZ result is inconsistent with KK claim in ^{76}Ge at 95.6% CL

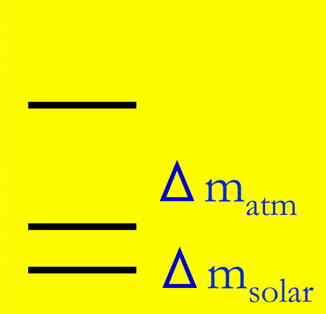
$\langle m_{\nu} \rangle$ is less than(120-250) meV

This is the Best Limit!!!

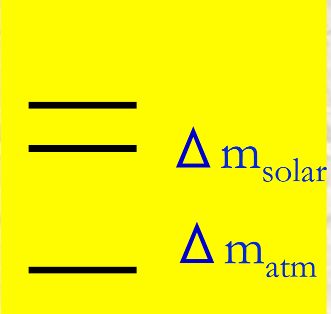
Region of Interest

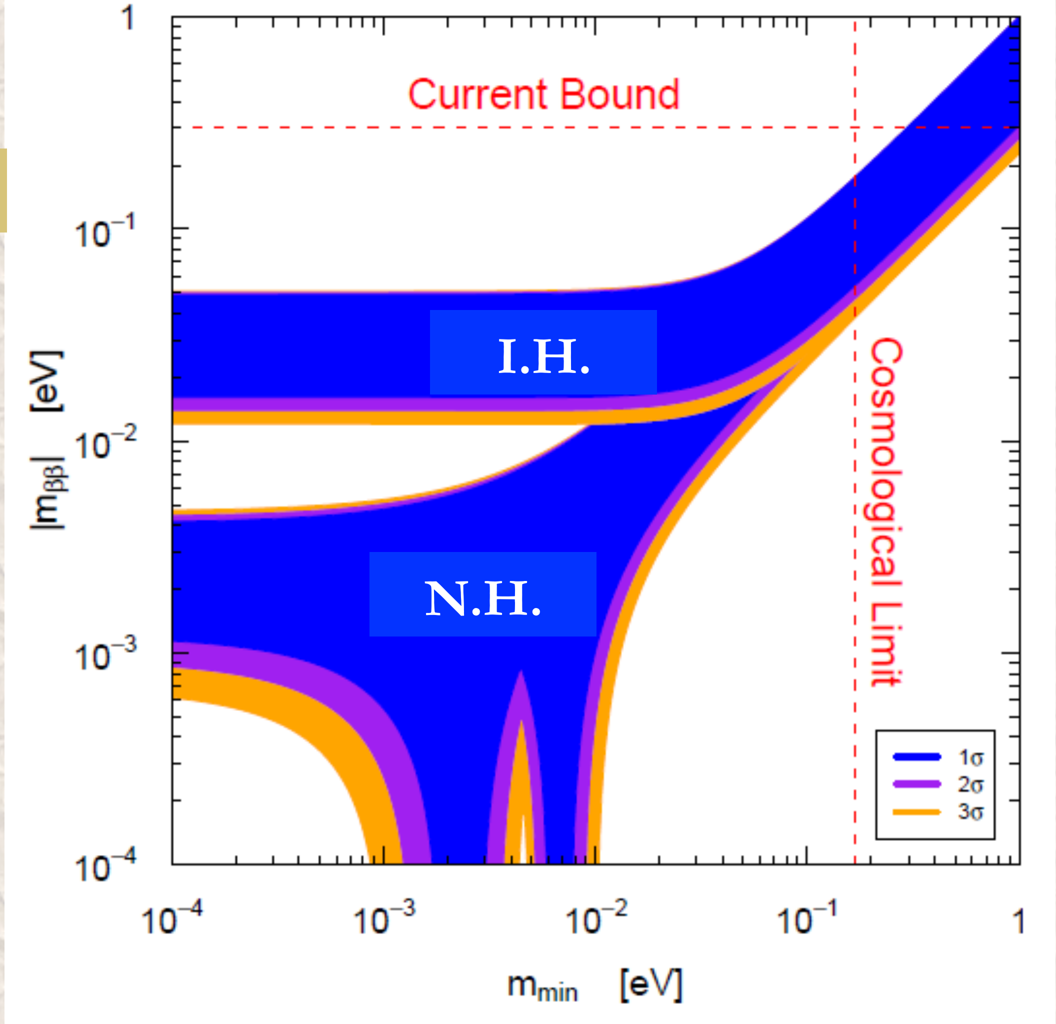
$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right| \approx \left| (0.87)^2 \cdot m_1 + (0.5)^2 \cdot \sqrt{m_1^2 + \Delta m_{21}^2} \cdot e^{2i\beta} \;\; + s_{13}^2 \cdot m_3 \cdot e^{-2i(\gamma-\delta)} \right|$$

Hierarchical

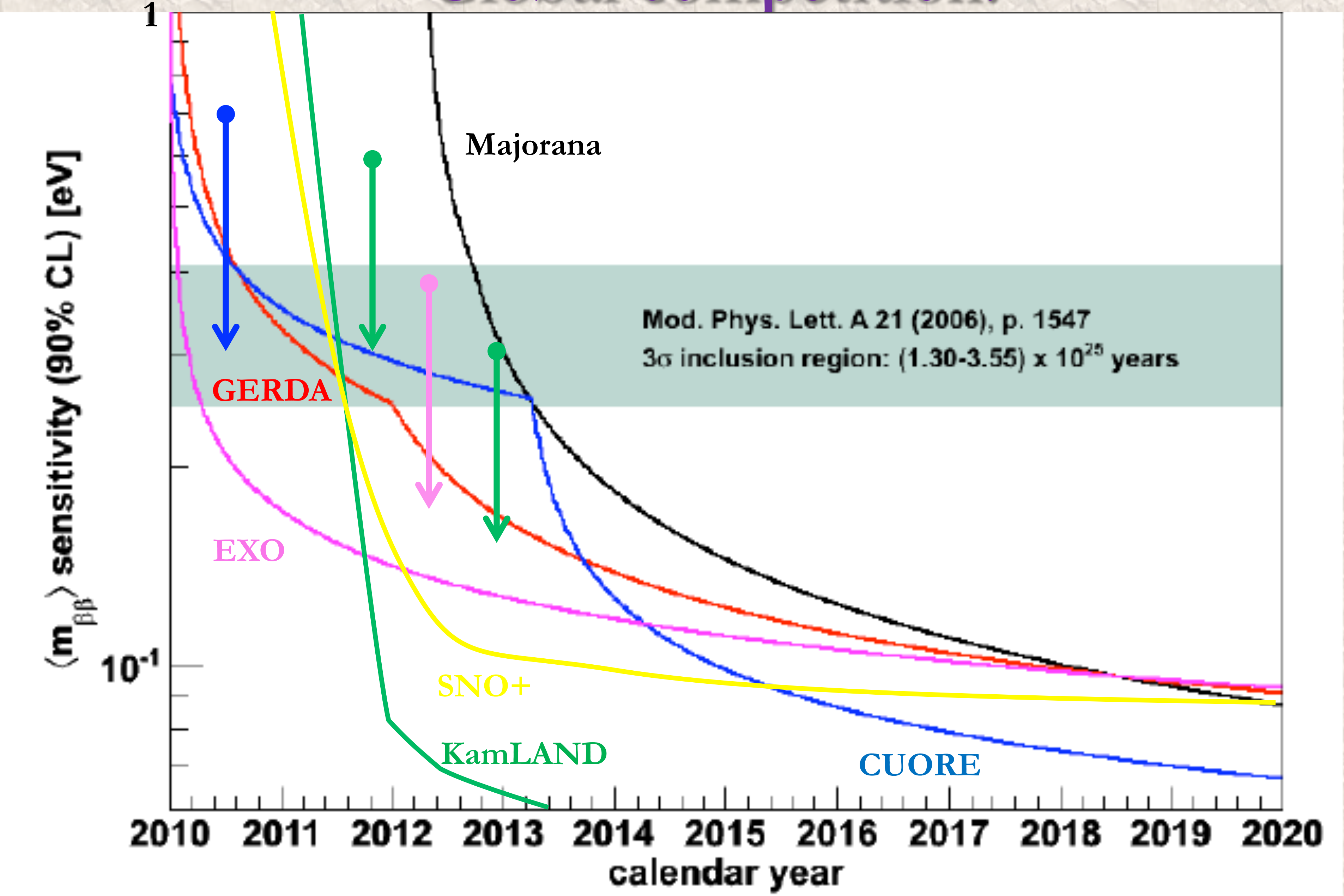


Inverse hierarchical





Global competition.

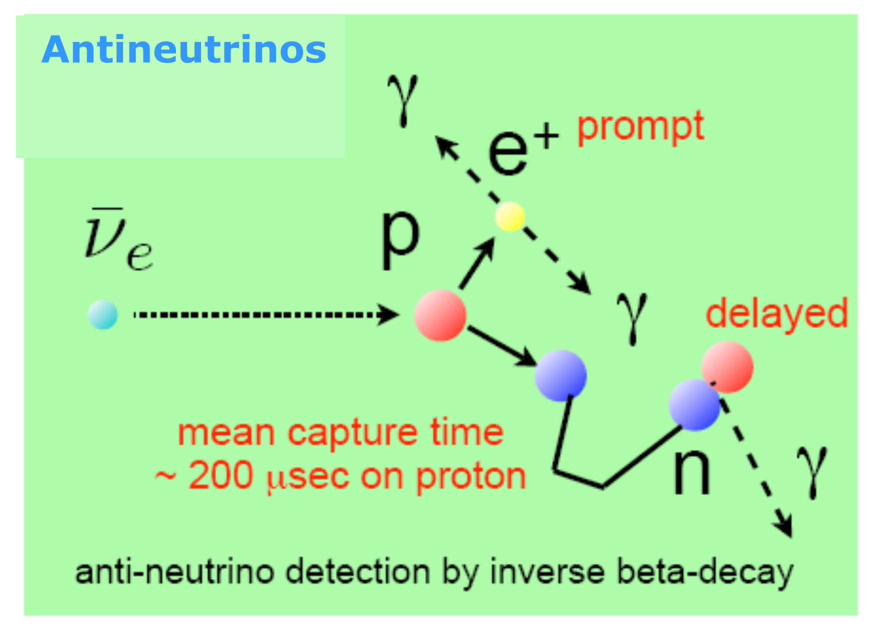


Conclusions

- KamLAND was build to test LMA of solar region of neutrino oscillations
- First clear observation of oscillation patter was discovered
- Δm_{21}^2 was measured with accuracy of 2.5%
- First detection of Geo Neutrinos (continue to accumulate statistics)
- Best limit on Conversion of Neutrinos into Antineutrinos in the Sun
- New incarnation (KamLAND-Zen) is the search for neutrino less double beta decay. Now we have best limit up to date!!! Efforts to reduce background were conducted during 2013. New runs are underway
- As always we are waiting for supernovae.

Backups

Neutrino Physics in KamLAND



anti-neutrino detection by inverse beta-decay

Observed energy (MeV)

Geo antineutrino

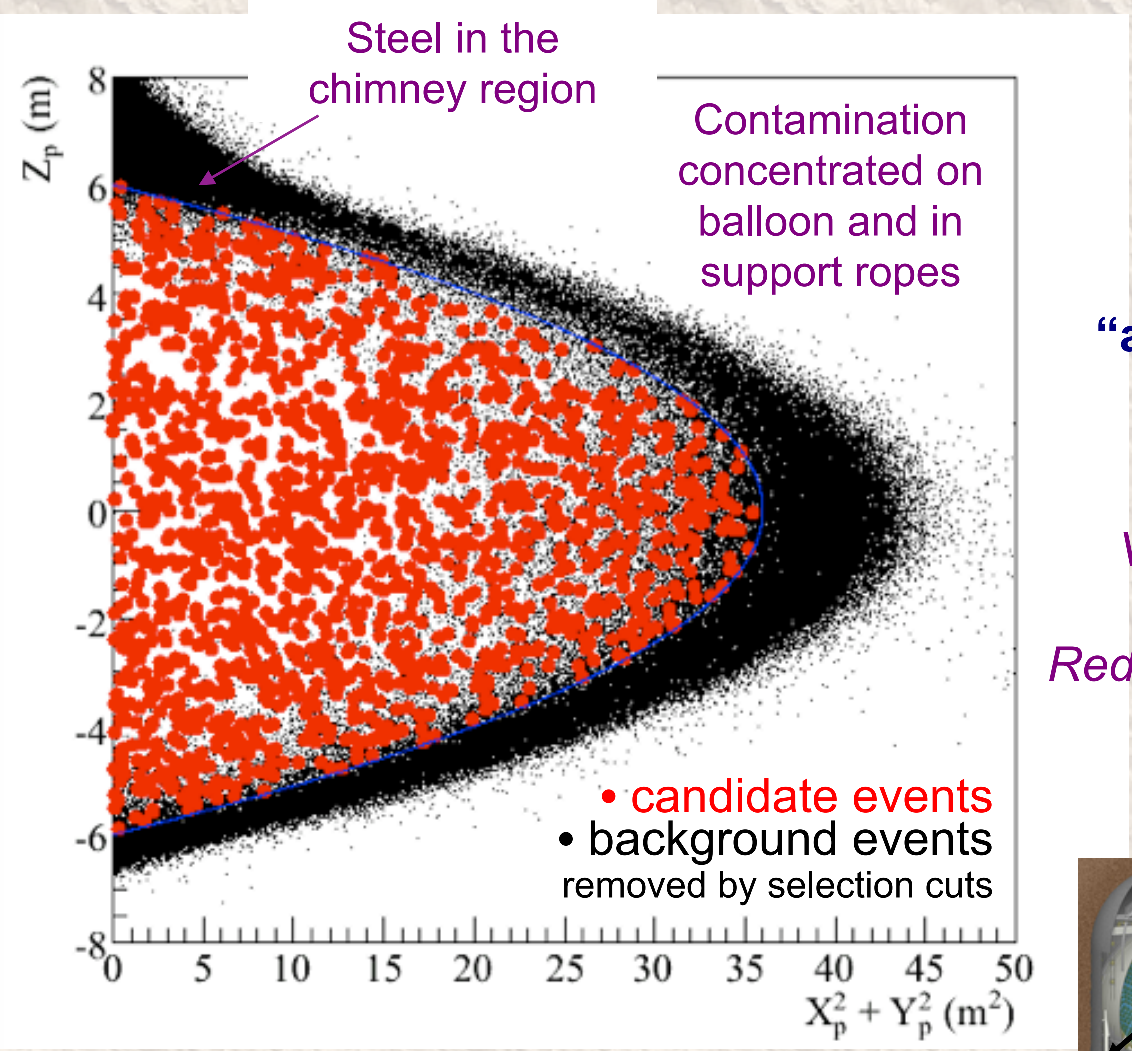
2 MeV

Reactor antineutrino

8 MeV

Solar and Supernova antineutrinos

Accidental Backgrounds



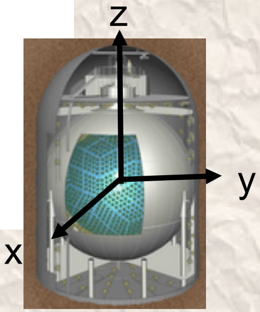
Steel in the chimney region

Contamination concentrated on balloon and in support ropes

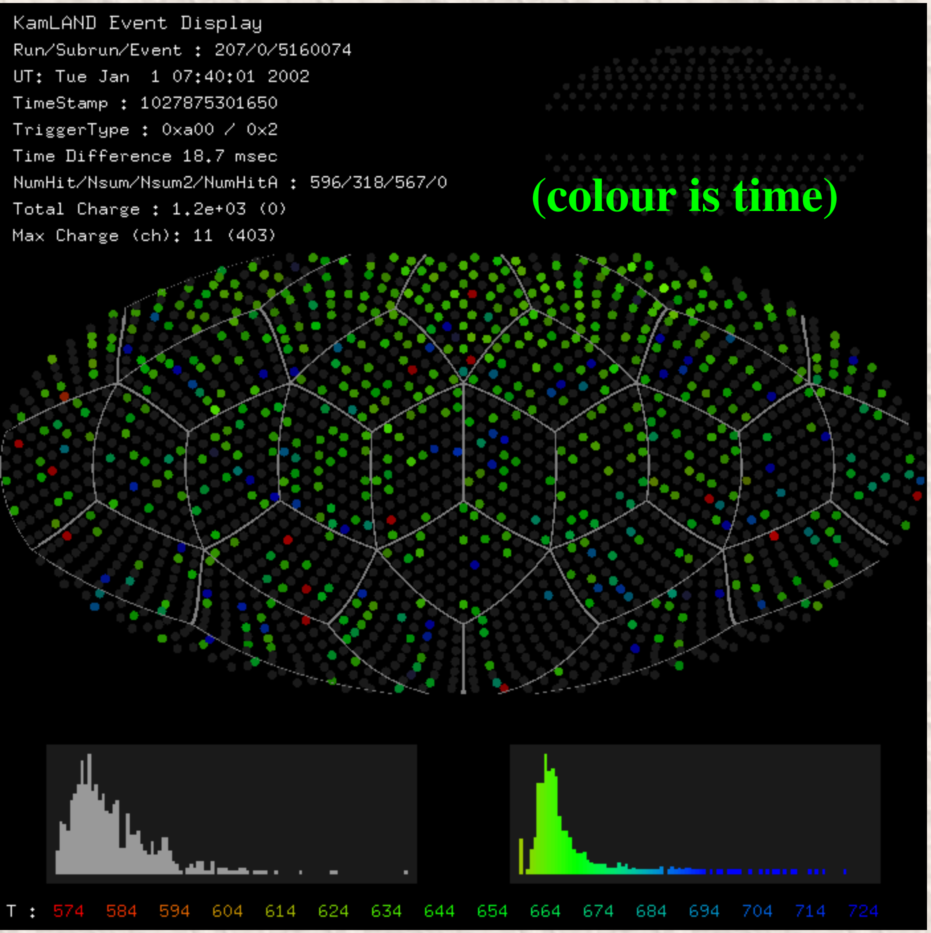
- candidate events
- background events removed by selection cuts

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.

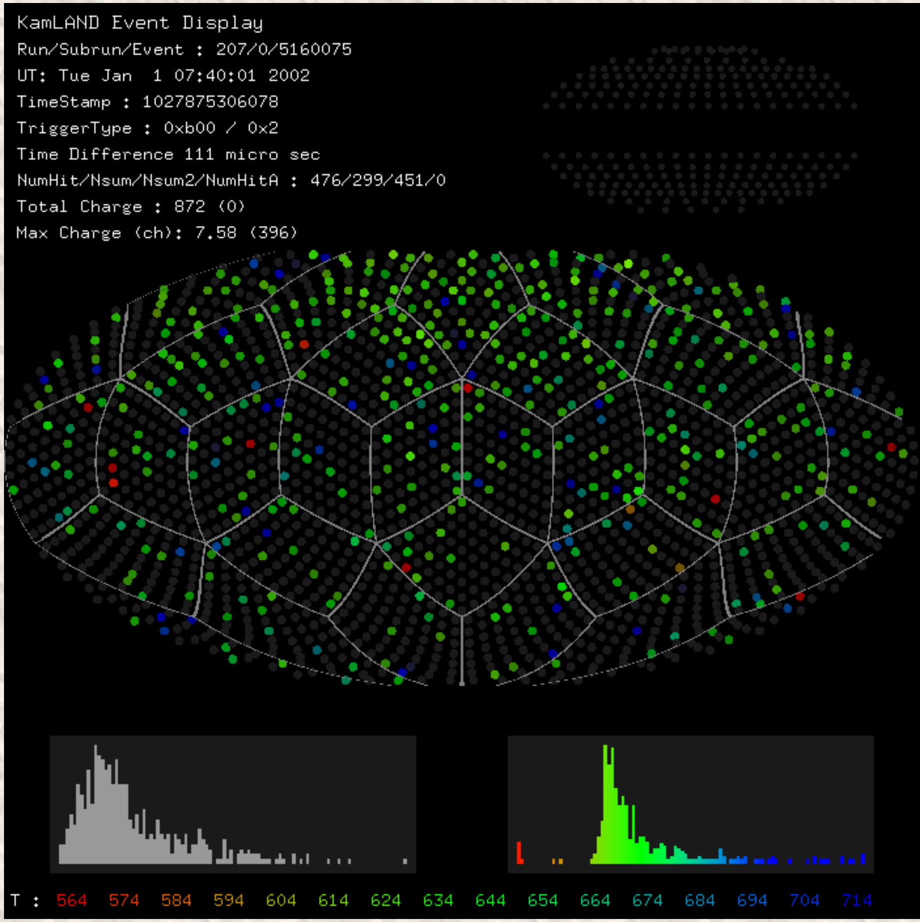


Antineutrino candidate



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160074
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875301650
TriggerType : 0xa00 / 0x2
Time Difference 18.7 msec
NumHit/Nsum/Nsum2/NumHitA : 596/318/567/0
Total Charge : 1.2e+03 (0)
Max Charge (ch): 11 (403)
```

(colour is time)



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160075
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875306078
TriggerType : 0xb00 / 0x2
Time Difference 111 micro sec
NumHit/Nsum/Nsum2/NumHitA : 476/299/451/0
Total Charge : 872 (0)
Max Charge (ch): 7.58 (396)
```

Prompt Signal
E = 3.20 MeV

Δt = 111 μs
ΔR = 34 cm

Delayed Signal
E = 2.22 MeV

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

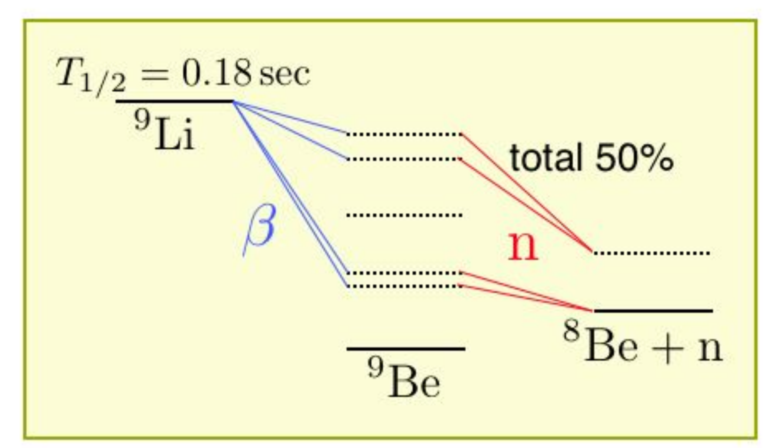
$n + p \rightarrow d + \gamma(2.2\ \text{MeV})$

Correlated Backgrounds: Cosmogenic

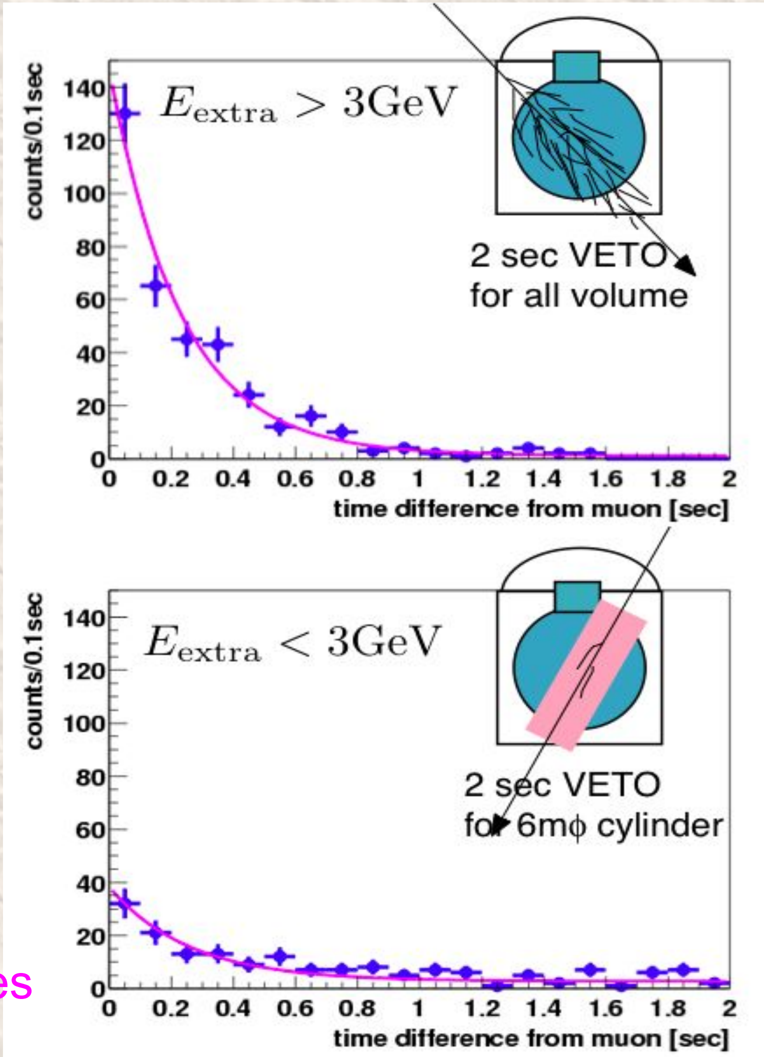
Spallation Products

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

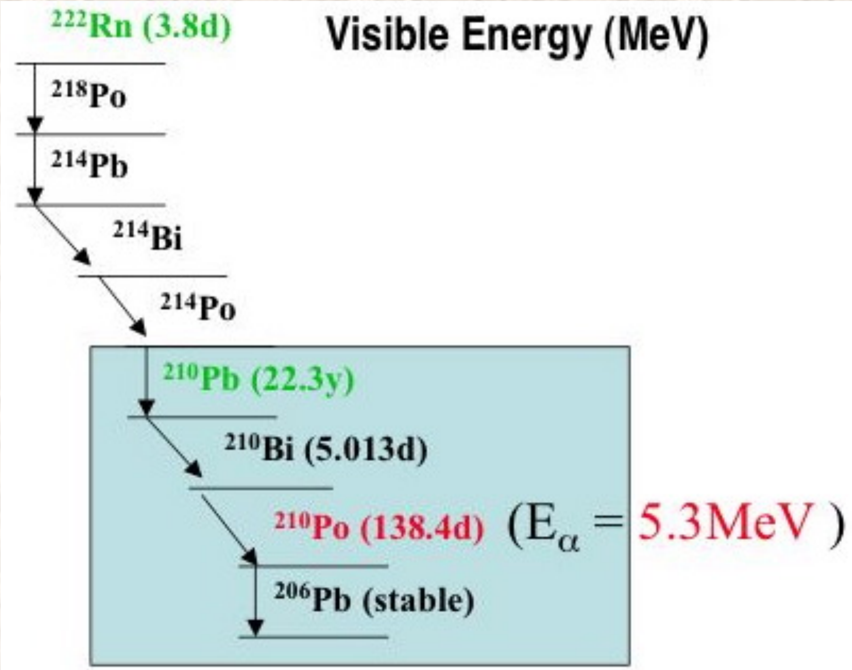


Cutting events correlated with muons removes almost all cosmogenic bg

<10% deadtime introduced by all muon cuts

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

Originating from Rn contamination, discovered after first publication



^{222}Rn (3.8d)

Visible Energy (MeV)

^{218}Po

^{214}Pb

^{214}Bi

^{214}Po

^{210}Pb (22.3y)

^{210}Bi (5.013d)

^{210}Po (138.4d) $(E_\alpha = 5.3\text{MeV})$

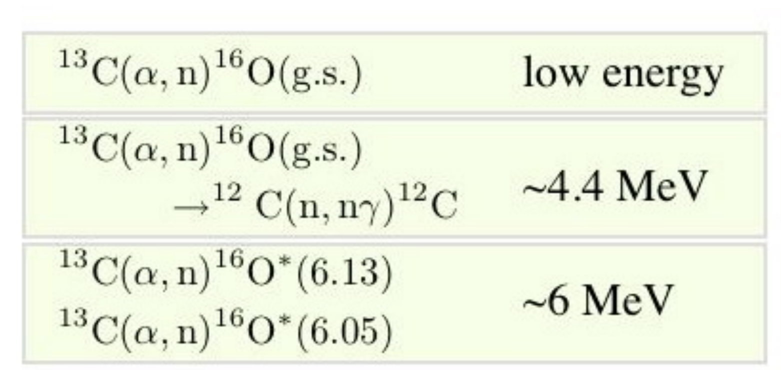
^{206}Pb (stable)

equilibrium

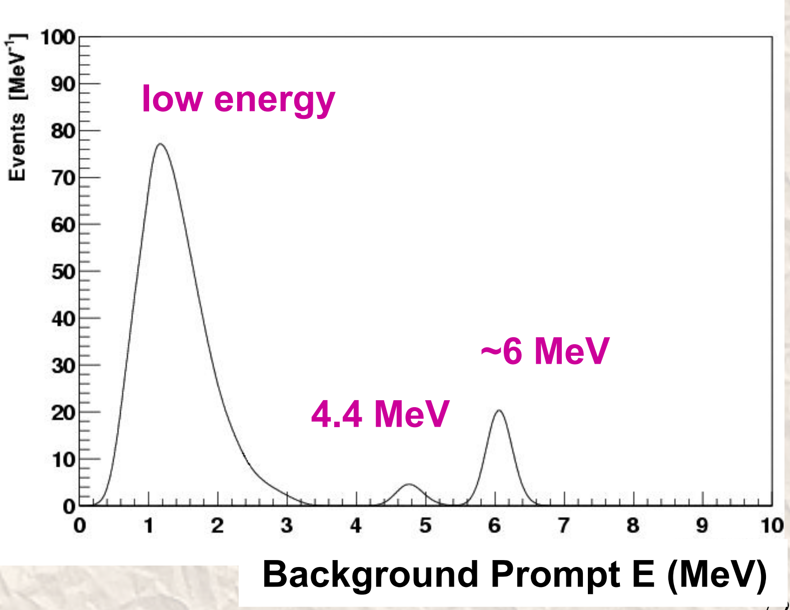
$$^{13}C(\alpha,n)^{16}O \quad \sim 10^{-7}$$

1.1% abundance (measured)

S.Harissopulos et al., Phys Rev. C72, 062801

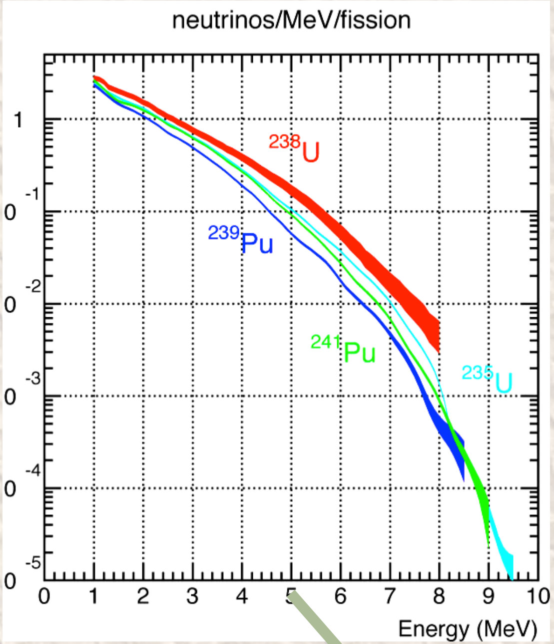


$^{13}C(\alpha,n)^{16}O$(g.s.)	low energy
$^{13}C(\alpha,n)^{16}O$(g.s.) $\rightarrow {}^{12}C(n,n\gamma)^{12}C$	~4.4 MeV
$^{13}C(\alpha,n)^{16}O^*(6.13)$ $^{13}C(\alpha,n)^{16}O^*(6.05)$	~6 MeV

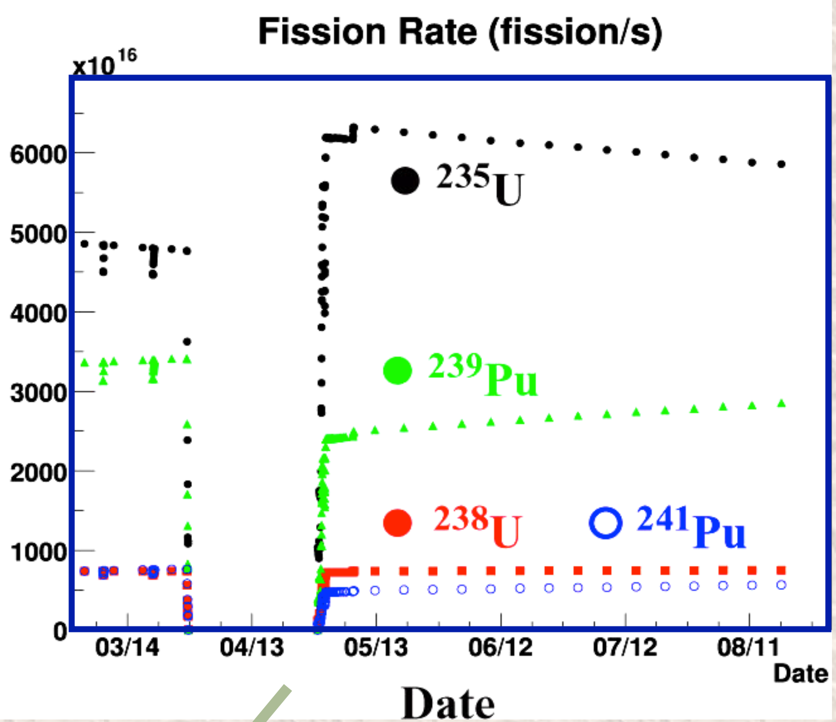


Antineutrino Production At Reactors

4 main fuel components



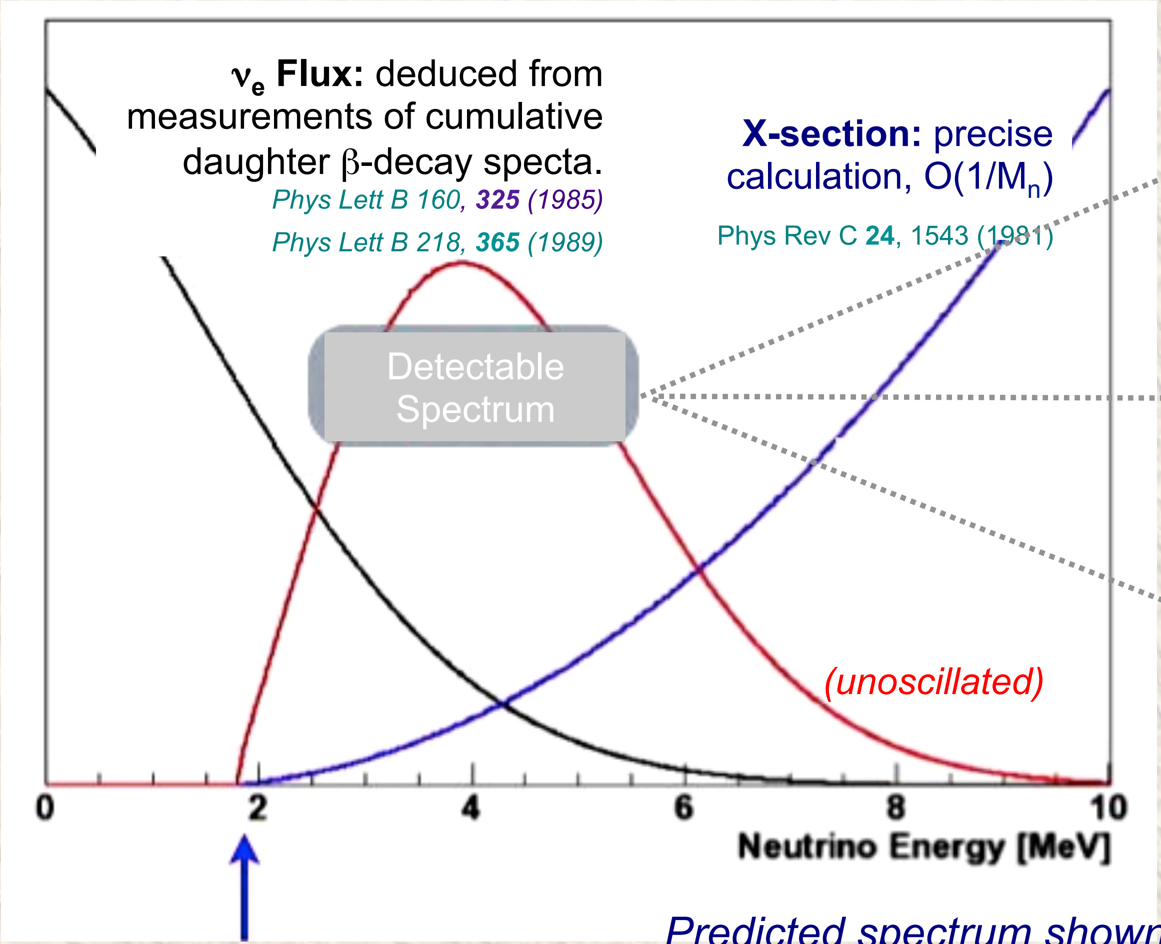
Time history of reactor reload



Calculated Neutrino Spectrum N(ν) = f(E,t)

Antineutrino Spectra

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

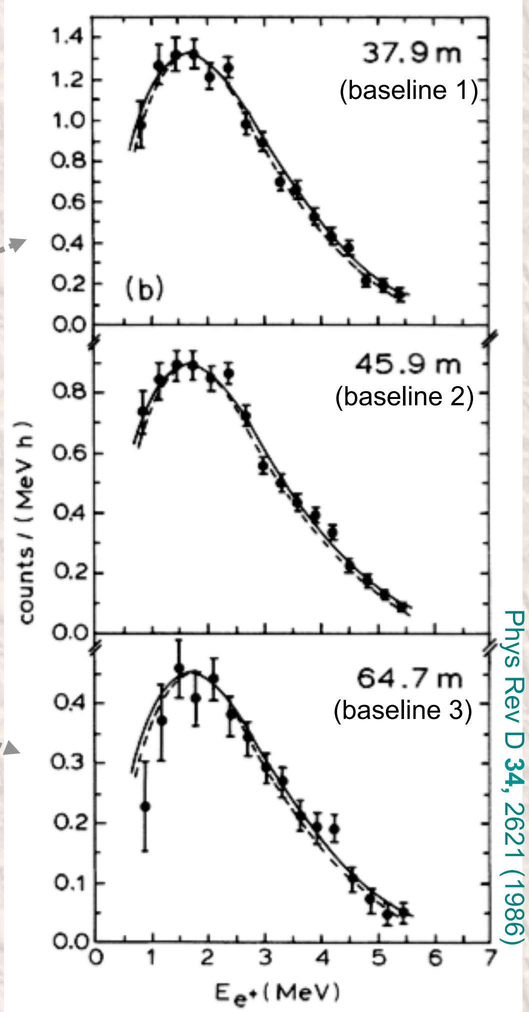


ν_e **Flux:** deduced from measurements of cumulative daughter β-decay specta.
*Phys Lett B 160, **325** (1985)*
*Phys Lett B 218, **365** (1989)*

X-section: precise calculation, $O(1/M_n)$
Phys Rev C **24**, 1543 (1981)

Detectable Spectrum

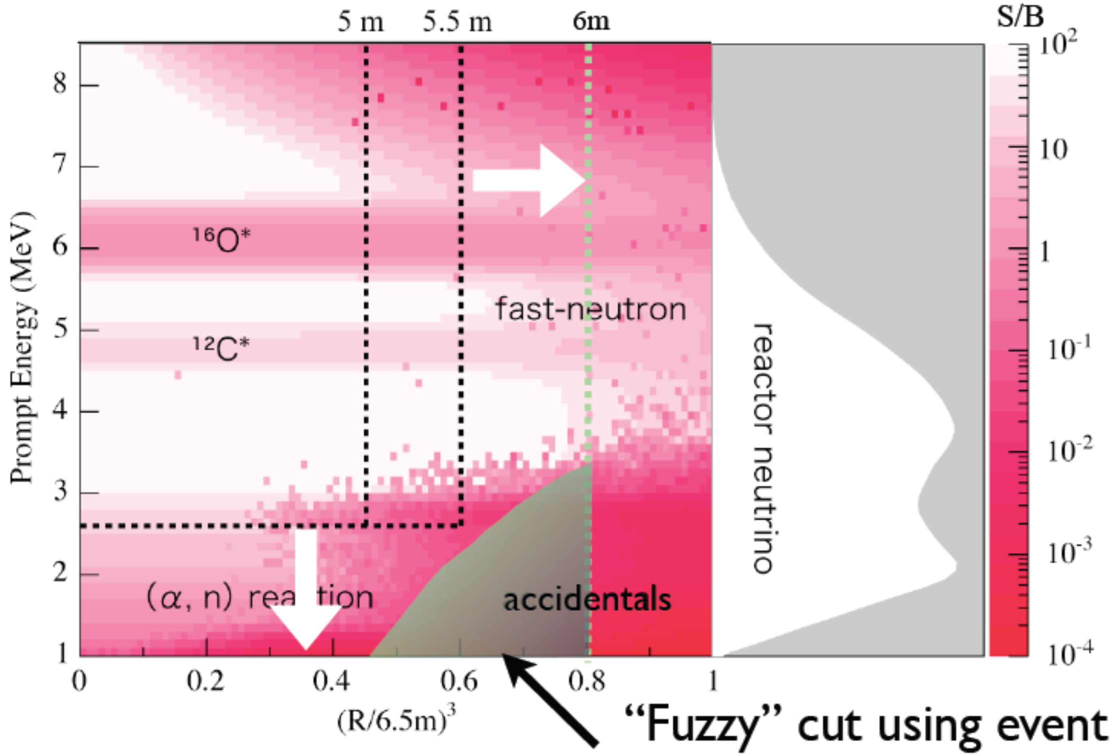
(unoscillated)



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

Predicted spectrum shown to have good agreement by earlier reactor experiments

Data Analysis



Energy threshold from 2.6MeV → 1.0MeV (Inverse Beta Decay threshold)

“Fuzzy” cut using event characteristics to distinguish signal from accidentals

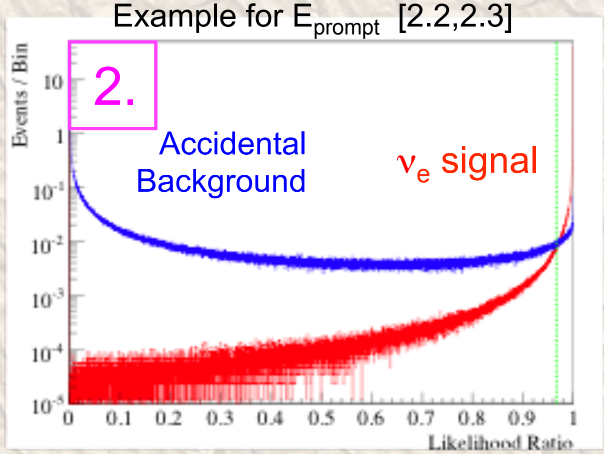
from MC simulation

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

from off-timing accidental data

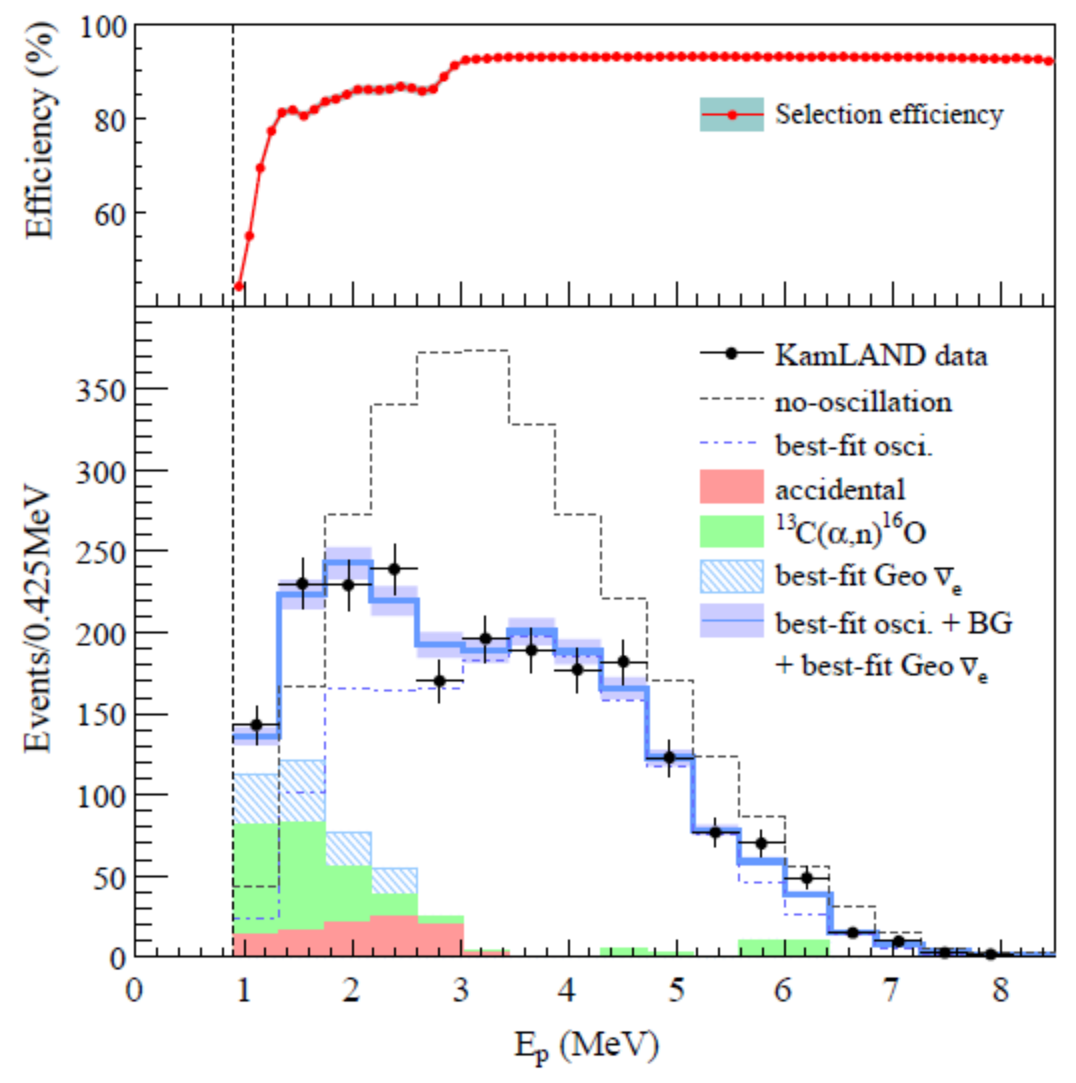
At fixed E_{prompt}: L_{ratio} depends on $E_{delayed}$, R_{prompt}, $R_{delayed}$, ΔR, ΔT

Example for E_{prompt} [2.2,2.3]



Results

Data from March 2002 till November 2009



Number of events vs R^3

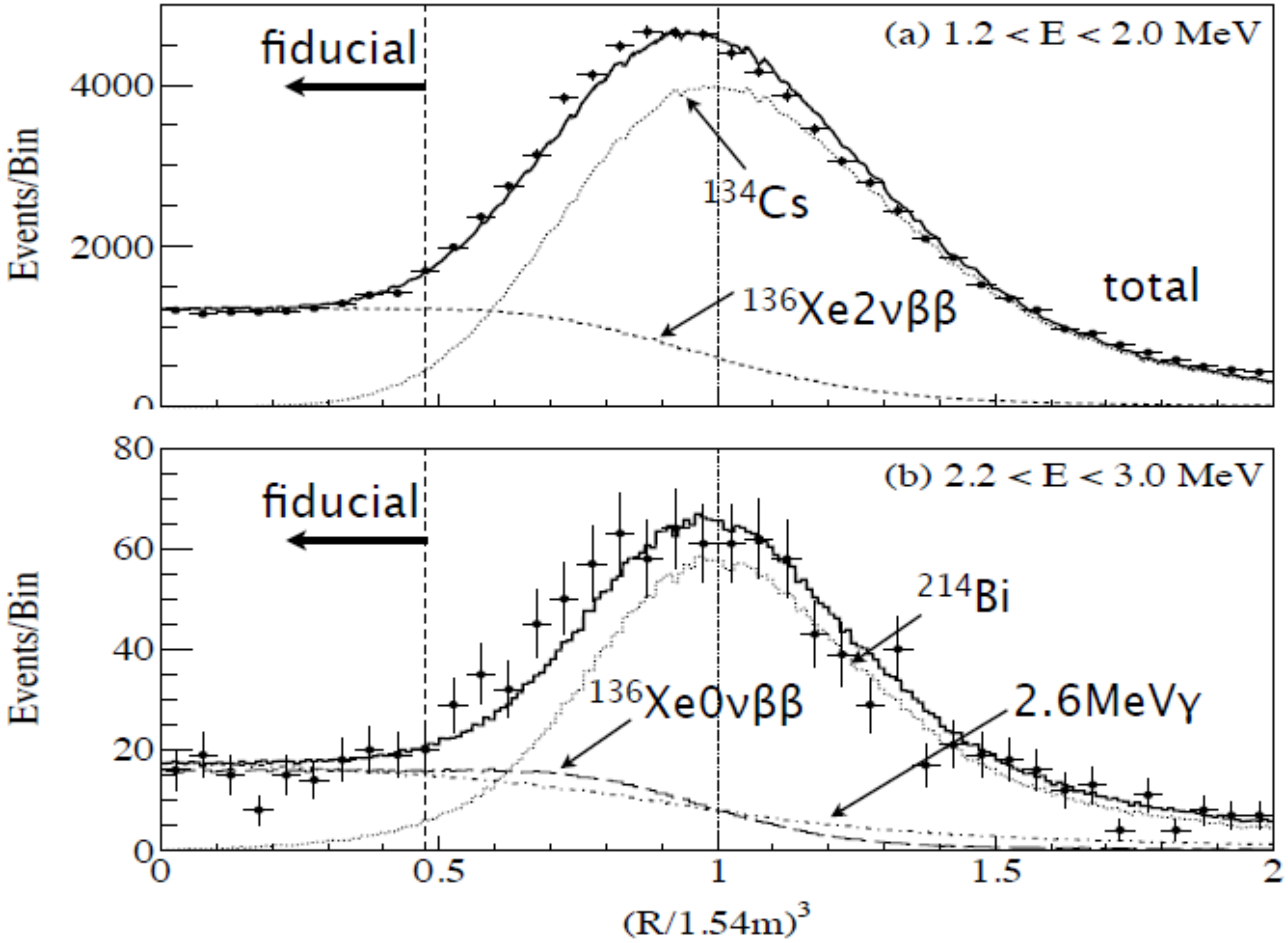
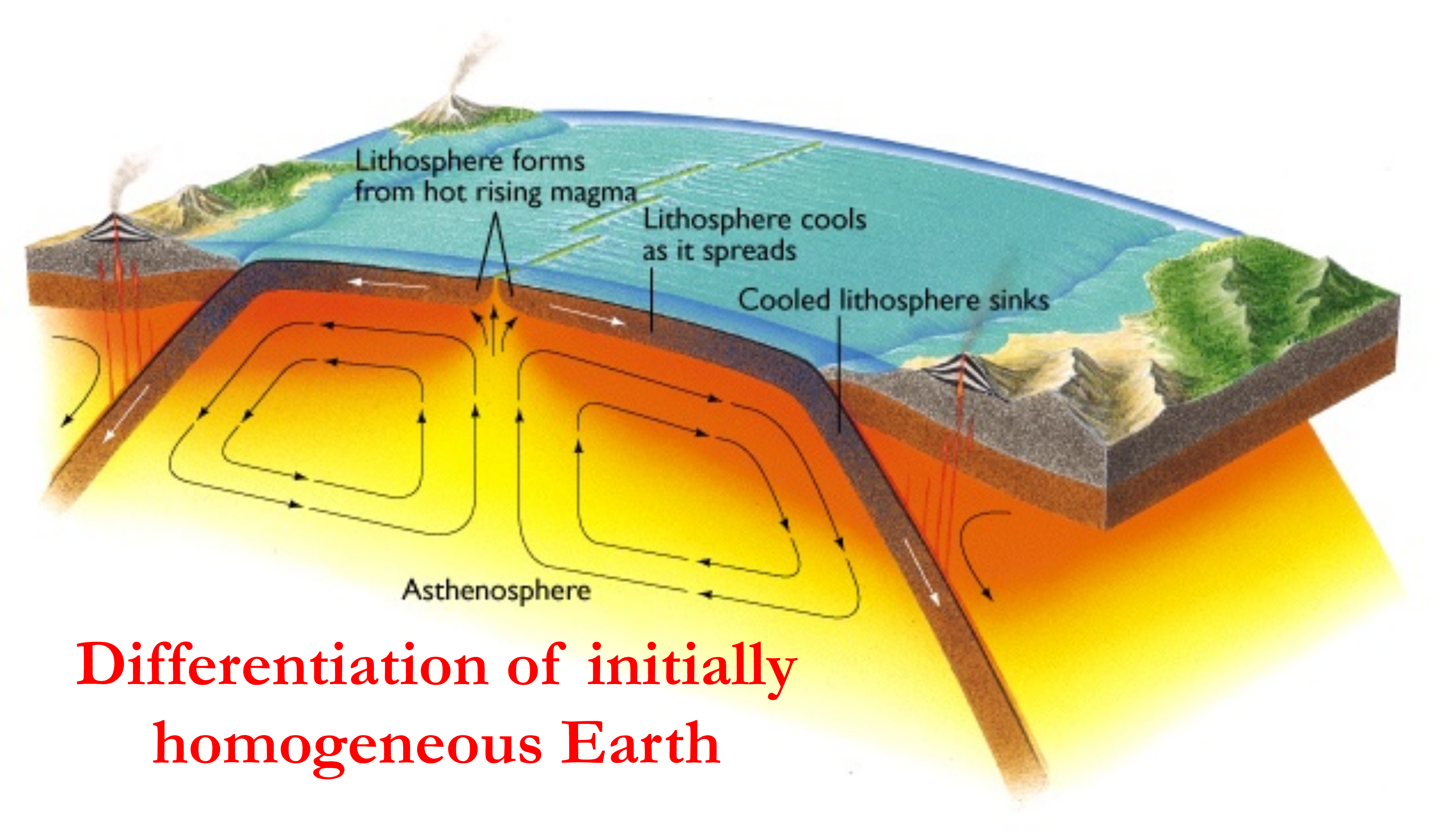


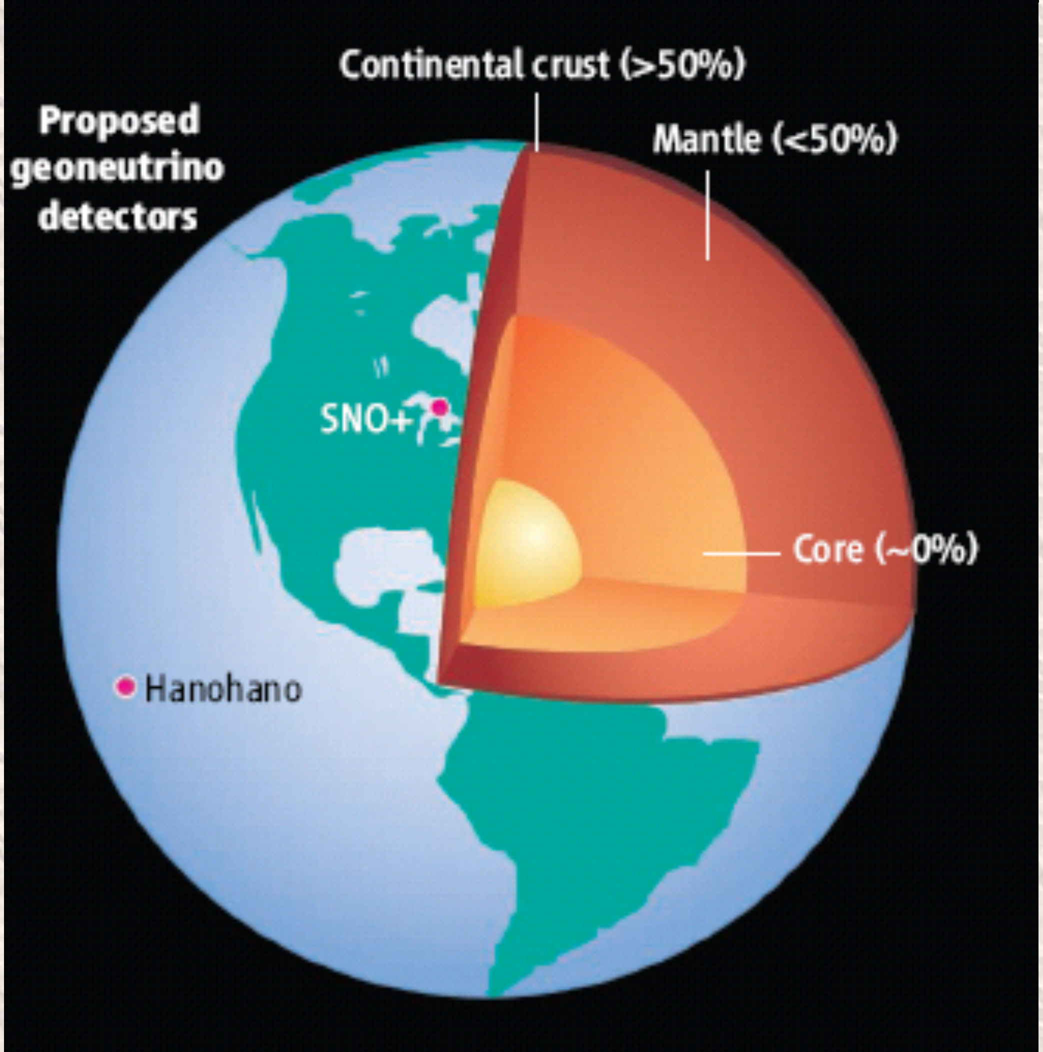
Plate Tectonics, Convection and Cooling of the Mantle



Differentiation of initially homogeneous Earth

BSE-Bulk Silicate Earth

“Differentiation”



~13 ng/g U in the Earth

Metallic sphere (core)
<<<1 ng/g U

Silicate sphere 20 ng/g U

**Javoy et al (2010) predicts 12 ng/g*

**Turcotte & Schubert (2002) 31 ng/g*

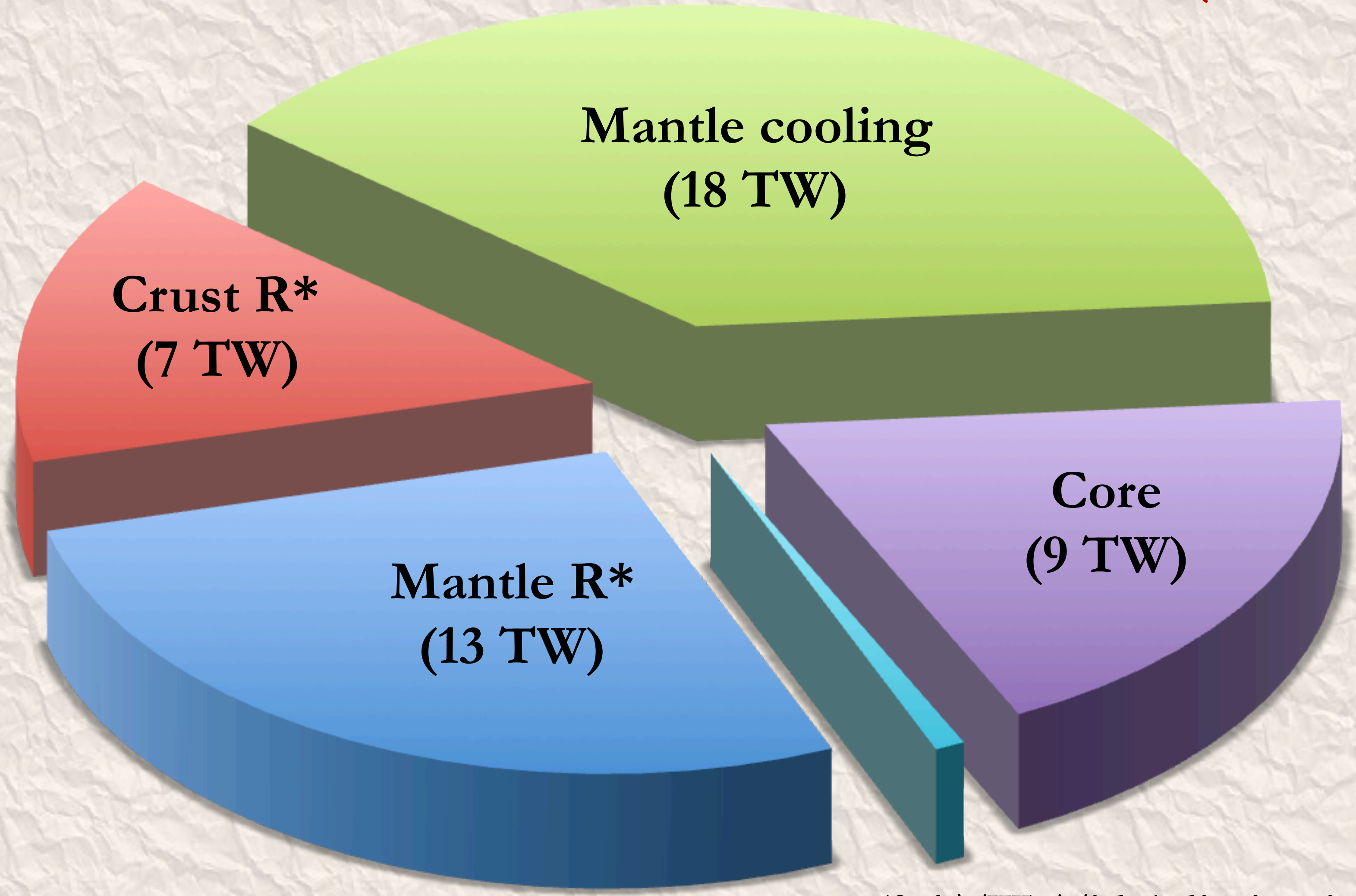
Continental Crust
1300 ng/g U

Mantle ~12 ng/g U

Chromatographic separation
Mantle melting & crust formation

One of the BSE models

Total Earth's surface heat flow 46 ± 3 (47 ± 2)



***R radiogenic heat**

(0.4 TW) Tidal dissipation
Chemical differentiation

after Jaupart et al 2008 Treatise of Geophysics

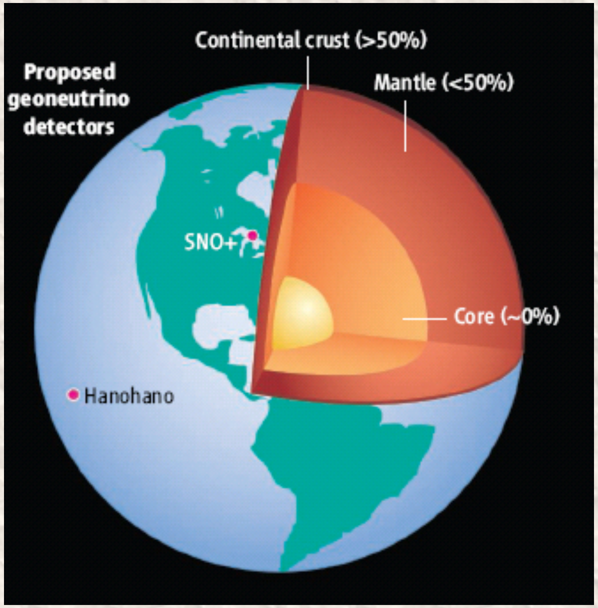
Heat Production in the Earth/Mantle

There is factor of ~3 differences in BSE models

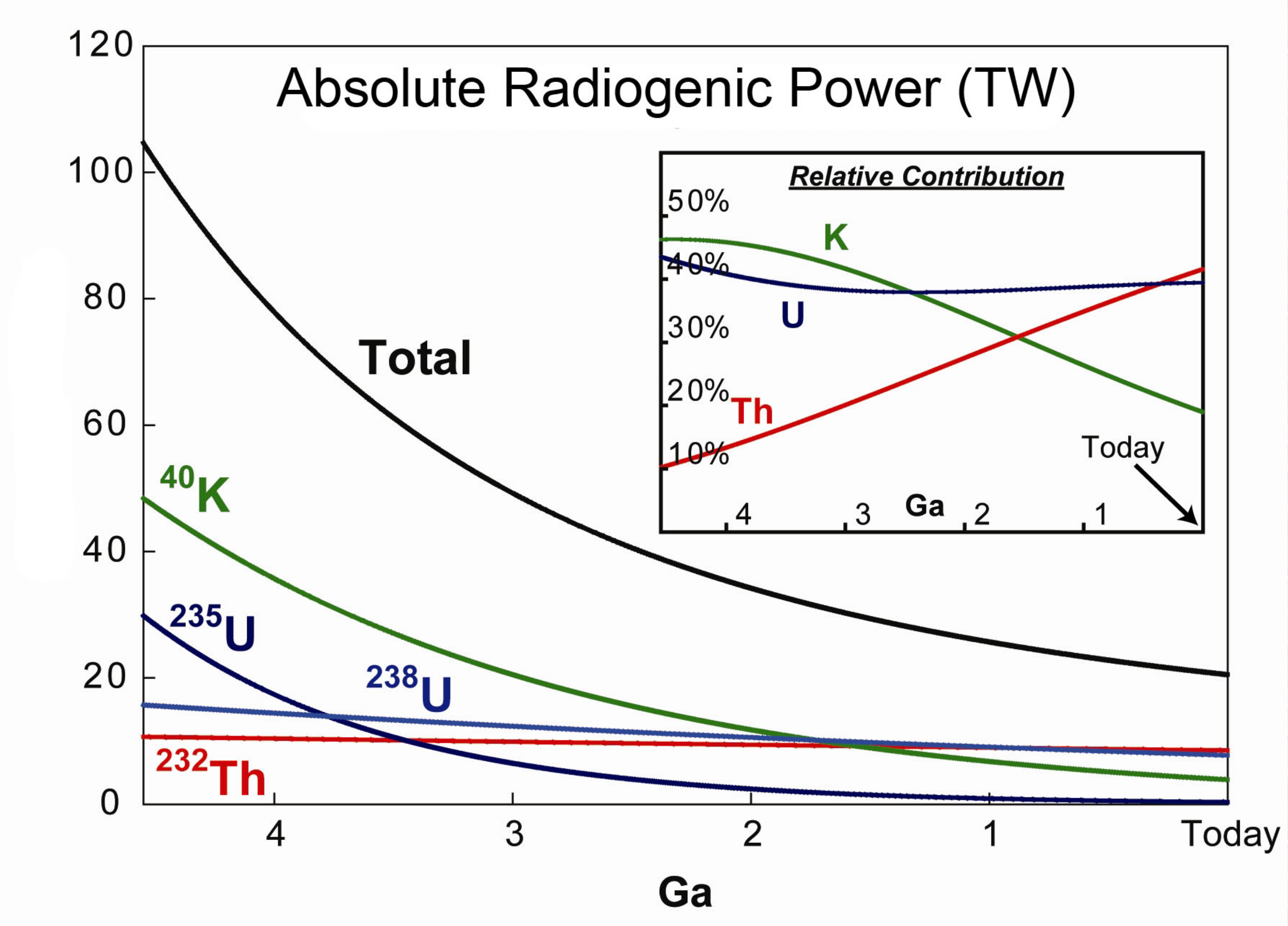
Mantle	BSE	
19	31	Turcotte & Schubert (2002)
17	28	Anderson (2007)
11	20	Palme & O'Neill (2003) Allegre et al (1995), McD & Sun ('95)
7	17	Lyubetskaya & Korenaga (2007)
3	12	Javoy et al. (2010)

TW in Mantle
(minus crust contribution
and only Th & U flux)

U content (ng/g)
(Bulk Silicate Earth)



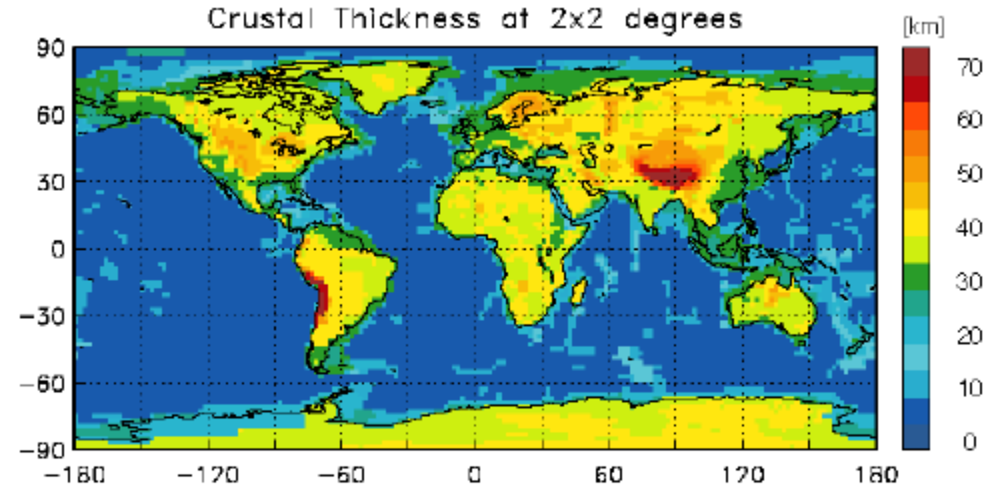
Radiogenic Heat Production History



What Geo-neutrinos can tell us:

Measure total radiogenic heat production

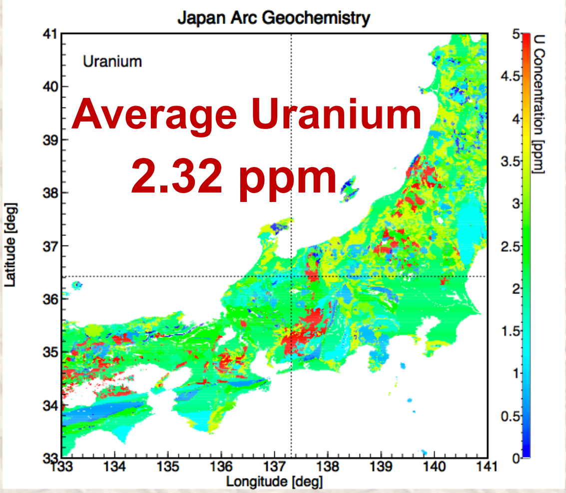
Distinguish heat generation in mantle vs. crust



Help evaluate different geo models

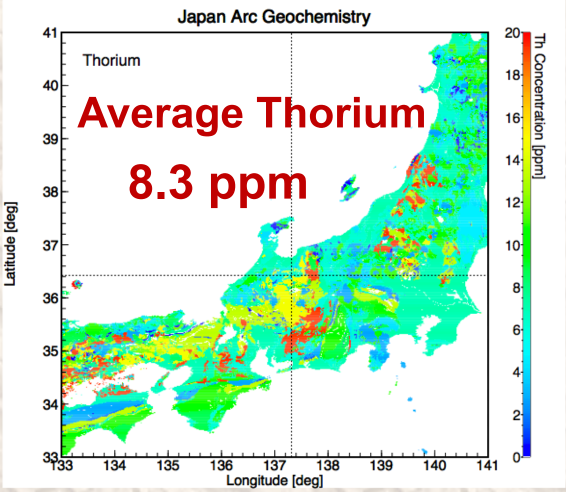
Provide input to better understand geological history of the Earth

Effects of Local Geology



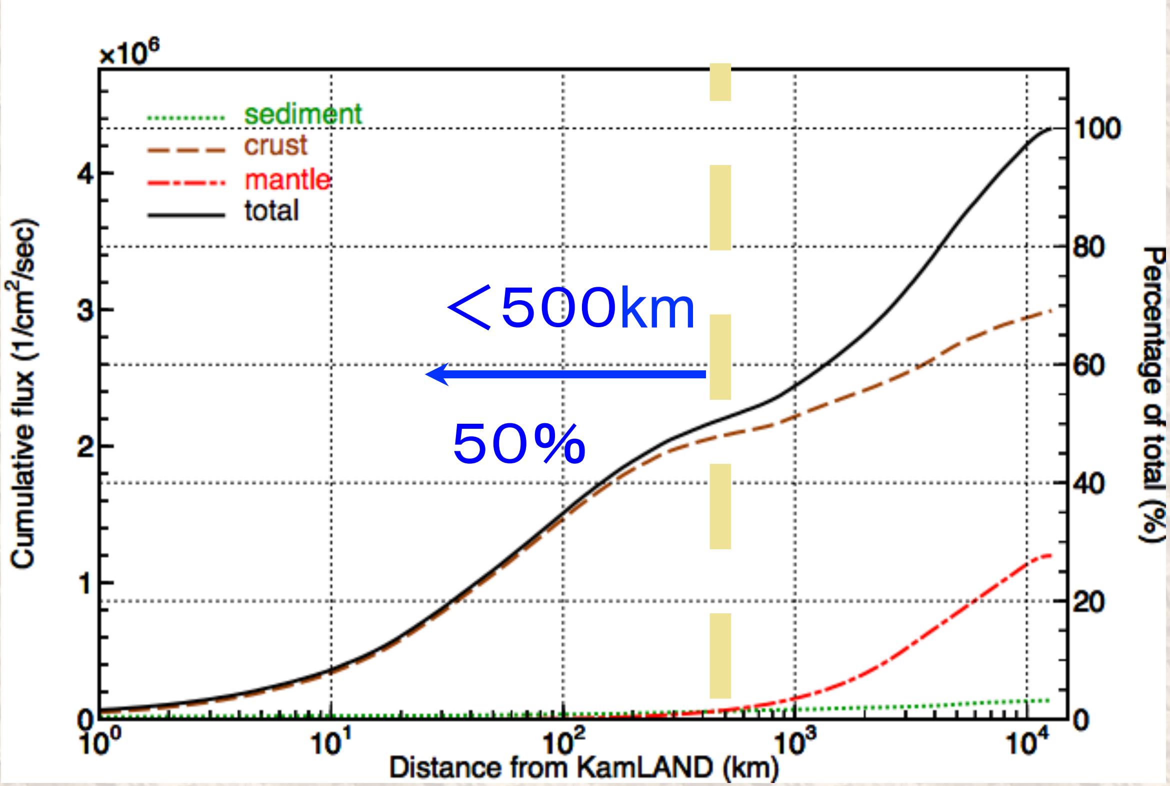
Average Uranium
2.32 ppm

17 Jun 2005 00:01:27 JST: japan-center-geochemistry.kino



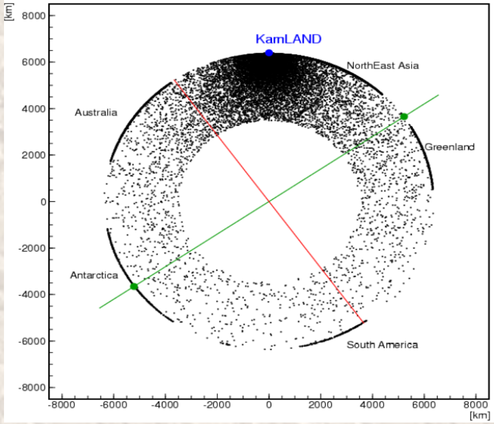
Average Thorium
8.3 ppm

17 Jun 2005 00:03:37 JST: japan-center-geochemistry.kino



<500km

50%



50% of the total flux originates from a distance > 500 km !!!

Effect of local geology
< 10% uncertainty of total flux

Post "Fukushima" Nuclear Energy in Japan

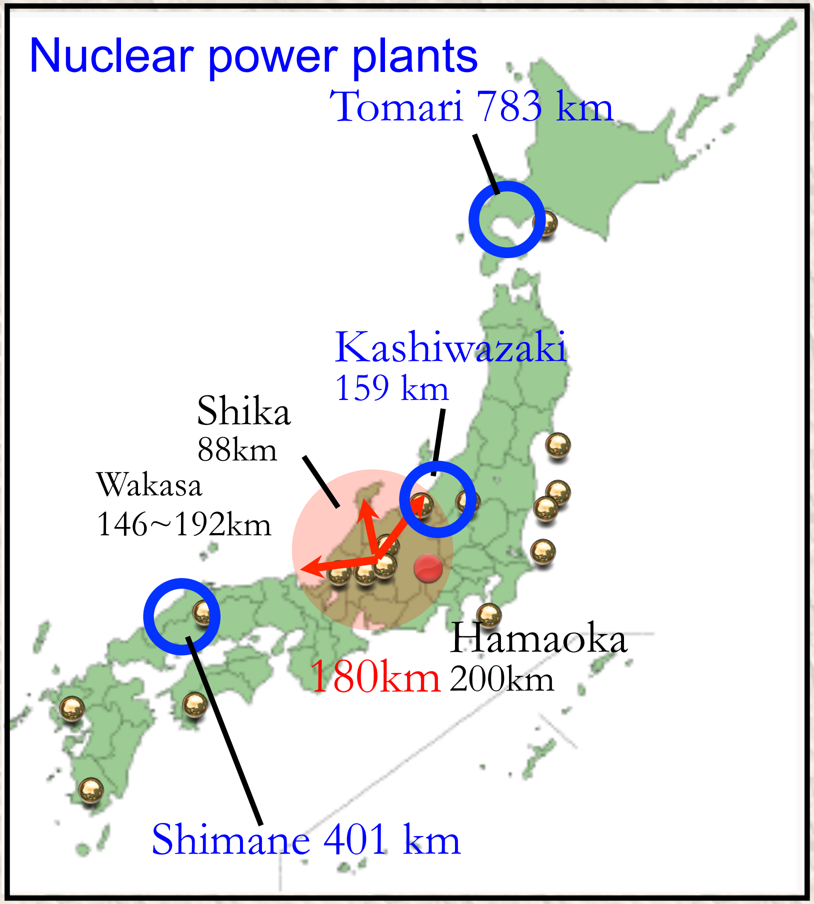
On February of 2011 about 70% on nuclear energy capacity were in operation

Every 13 month every nuclear unit should be stopped for regular maintenance

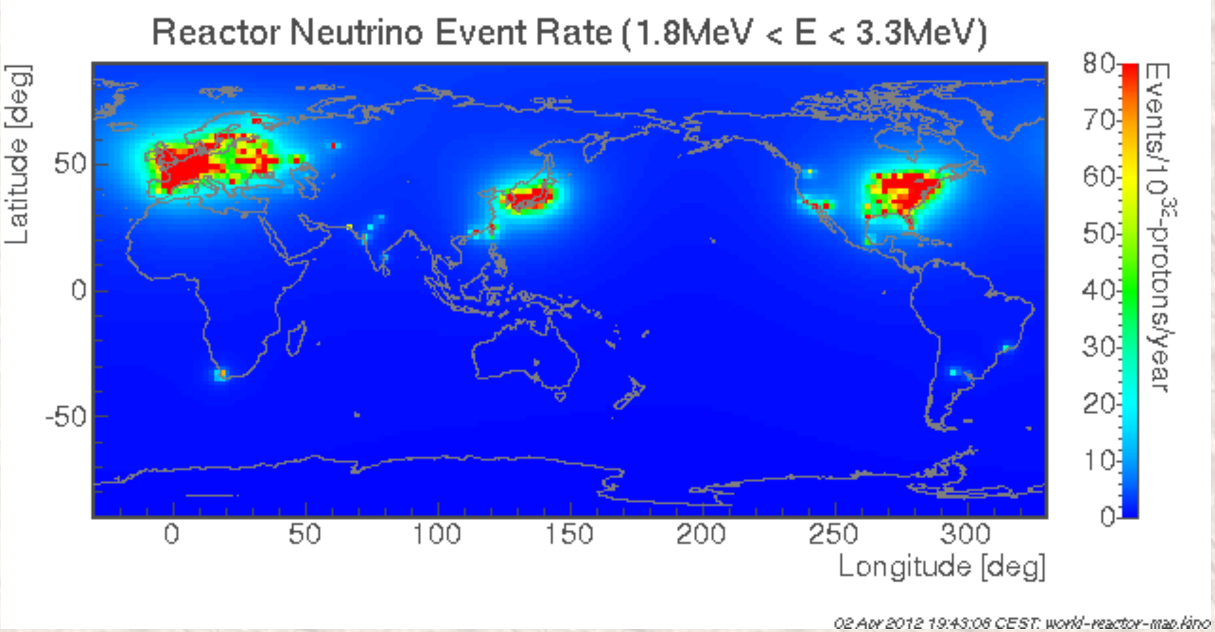
During the last year none of the units get permission to resume operation after planned shutdown.

At the end of January 2012 only 3 units were in operation at: Shimane, Kashiwazaki, Tomari

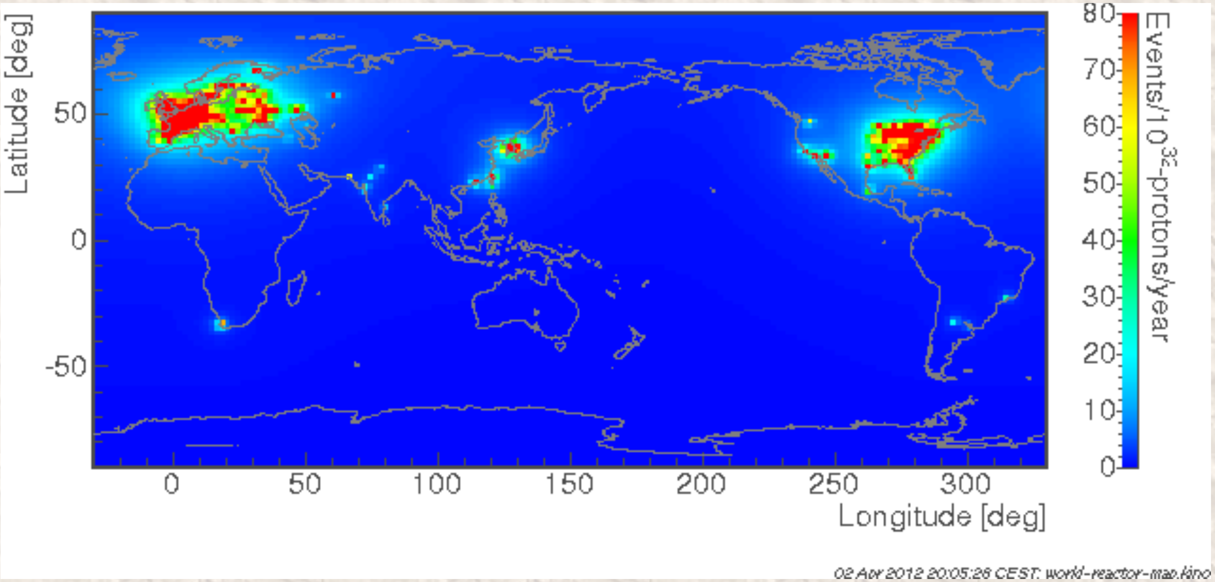
Feb 20th Shimane – off
March 26th Kashiwazaki – off
Starting from the beginning of this May there will be no nuclear power plant in Japan in operation



Changes in Reactor Anti-neutrino Flux



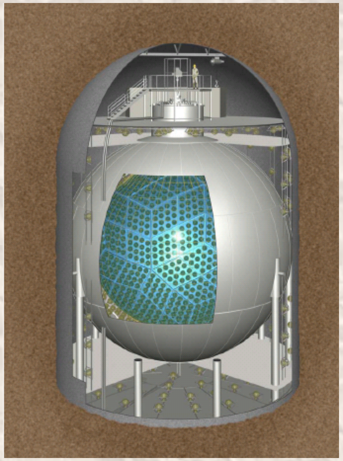
Beginning of 2011



Now

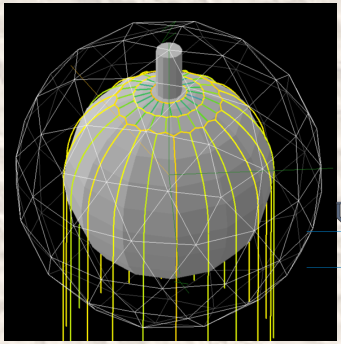
Worldwide Efforts

KamLAND, Japan 1 kt

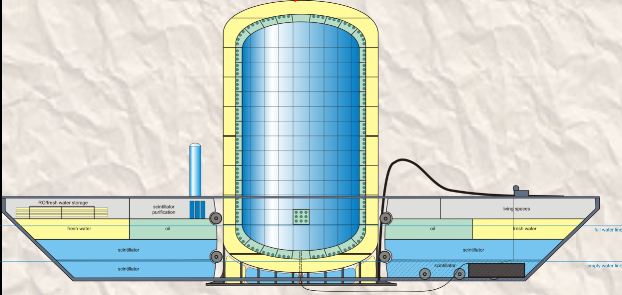


Borexino, Italy 0.3 kt

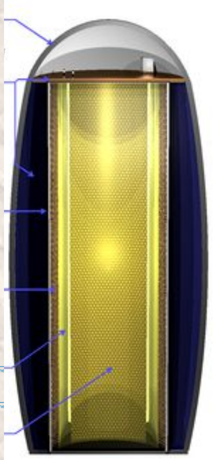
SNO+, Canada 1 kt



Hanohano, Hawaii 10kt



LENA, EU 50 kt



Location	Reactor rate <3.3 MeV TNU	Geo rate TNU*	Detector	N geo per year	Status
KAMIOKA	5.2 (now)	34.5	KamLAND	20.7	Running
FREJUS	133	43.1			
SUDBURY	44.3	50.8	SNO+	~40	About to start
GRAN SASSO	23.1	40.7	Borexino	4.2	Running
PYHASALMI	18.1	51.5	LENA	1500	Proposal
BAKSAN	9.33	50.8			
DUSEL	8.4	52.6			
HAWAII	1.1	12.5	Hanohano	75	Proposal

* Fiorentini at all, Phys Rep. 2007

Geo Reactor ?

M.Herndon and D.Hollenbach

Most of U and Th are in the core!
This hypotheses is not on the main stream of geology.

Challenges for detection

- Similar spectra as for man made reactors
- Background from nuclear power plants
- No directionality in $\nu_e + p \rightarrow n + e^+$ reaction

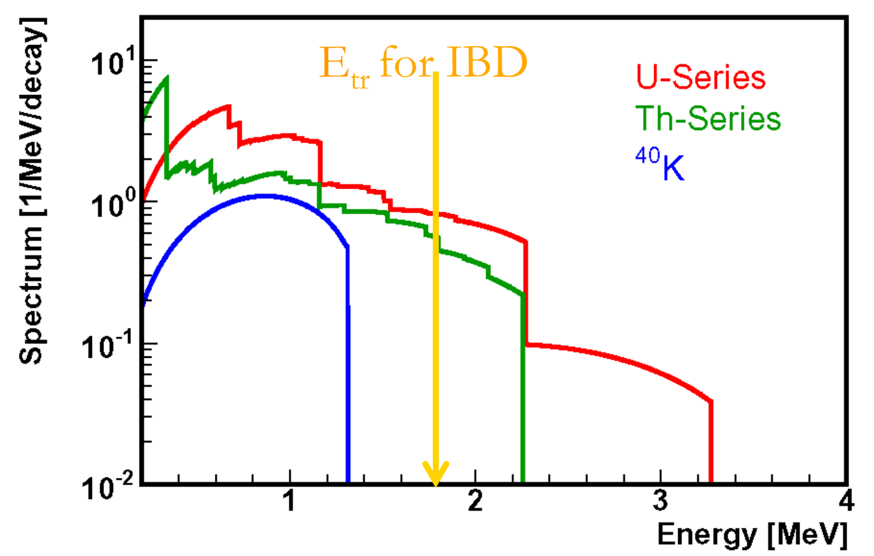
Based on the fluctuations of energy production by nuclear power plants and background subtraction upper limits are:

$P_{geo\text{-}reacto} < 3$TW (Borexino), $P_{geo\text{-}reacto} < 5.2$ TW (KamLAND)

If nuclear power plants in Japan will stay off for entire 2012, expected sensitivity for Geo-reactor at one sigma for KamLAND is ~2 TW

Perspectives for Potassium

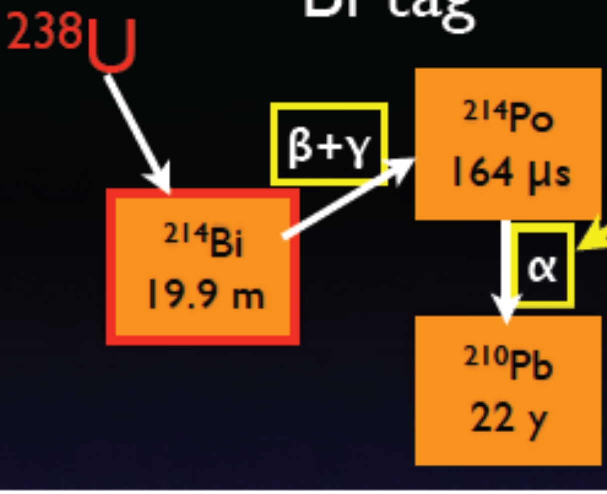
$$\boxed{\overline{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+}$$



Isotope	Abundance %	Threshold, MeV	Product	Product life time	Q keV
^{3}He	0.00014	1.04	^{3}H	12.33 y	18.6
^{14}N	99.6	1.18	^{14}C	5730 y	156
^{33}S	0.75	1.27	^{33}P	25.34 d	248
^{35}Cl	75.8	1.19	^{35}S	Stable	
^{63}Cu	69.2	1.09	^{63}Ni	100 y	67
^{106}Cd	1.25	1.22	^{106}Ag	24min	2965

mini-Balloon

^{214}Bi tag



^{238}U

^{214}Bi 19.9 m

$\beta+\gamma$

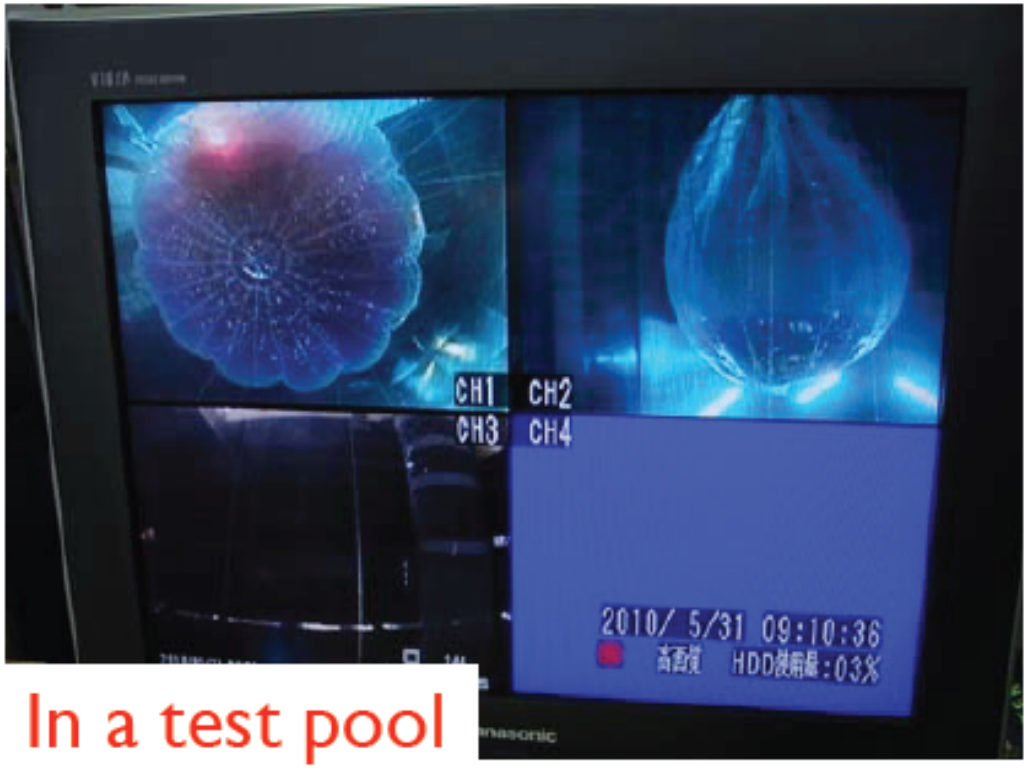
^{214}Po 164 μs

α

^{210}Pb 22 y

25 μm thick Nylon balloon

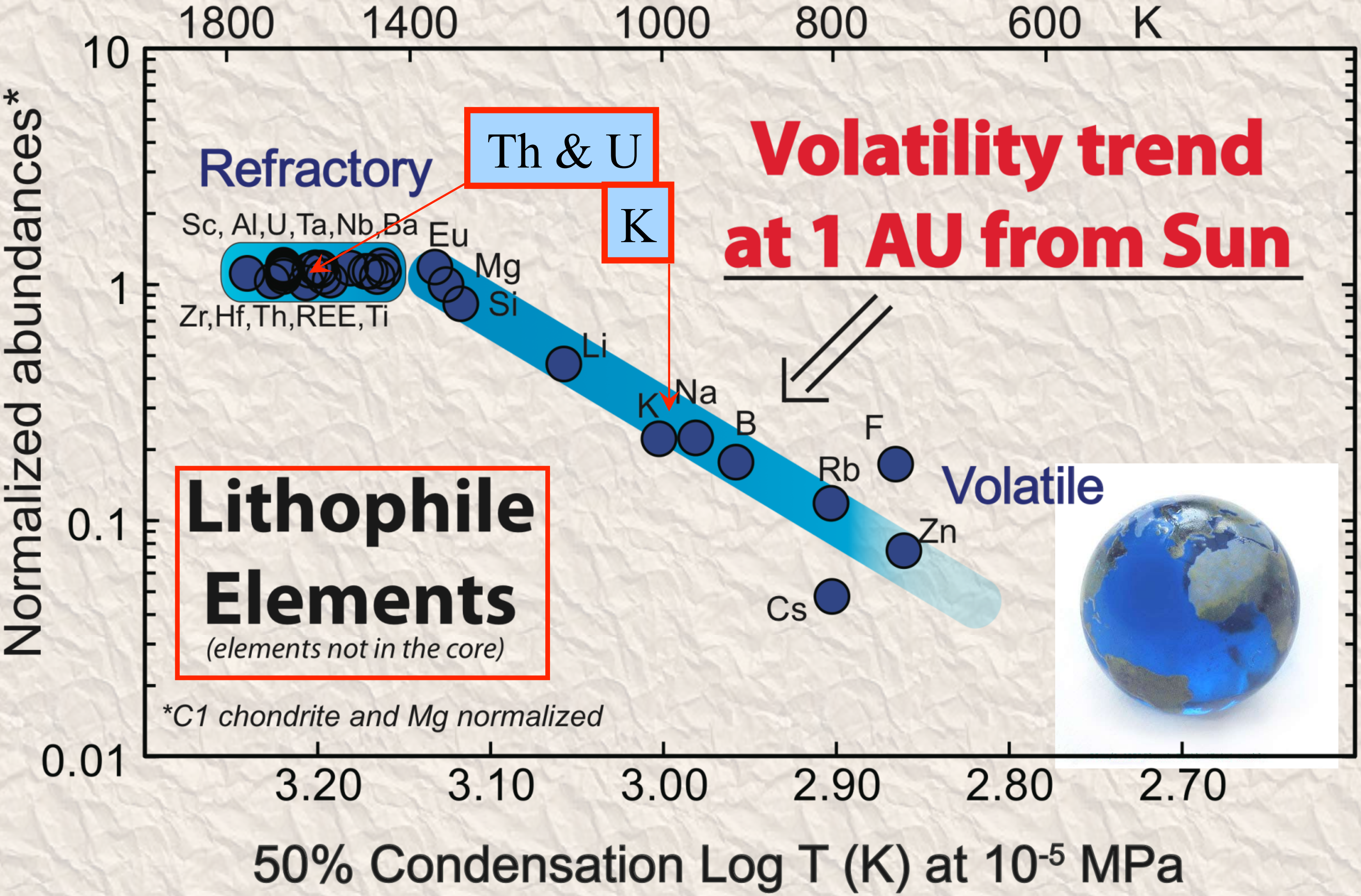
^{238}U~10^{-11}g/g (target~10^{-12}g/g)
^{232}Th~10^{-11}g/g (target~10^{-12}g/g)
^{40}K~10^{-11}g/g (target~10^{-12}g/g)



In a test pool

In a gym

Why Potassium is Interesting



Volatility trend at 1 AU from Sun

Lithophile Elements

(elements not in the core)

**C1 chondrite and Mg normalized*

from McDonough & Sun, Chem. Geol., 120, 223-253, 1995