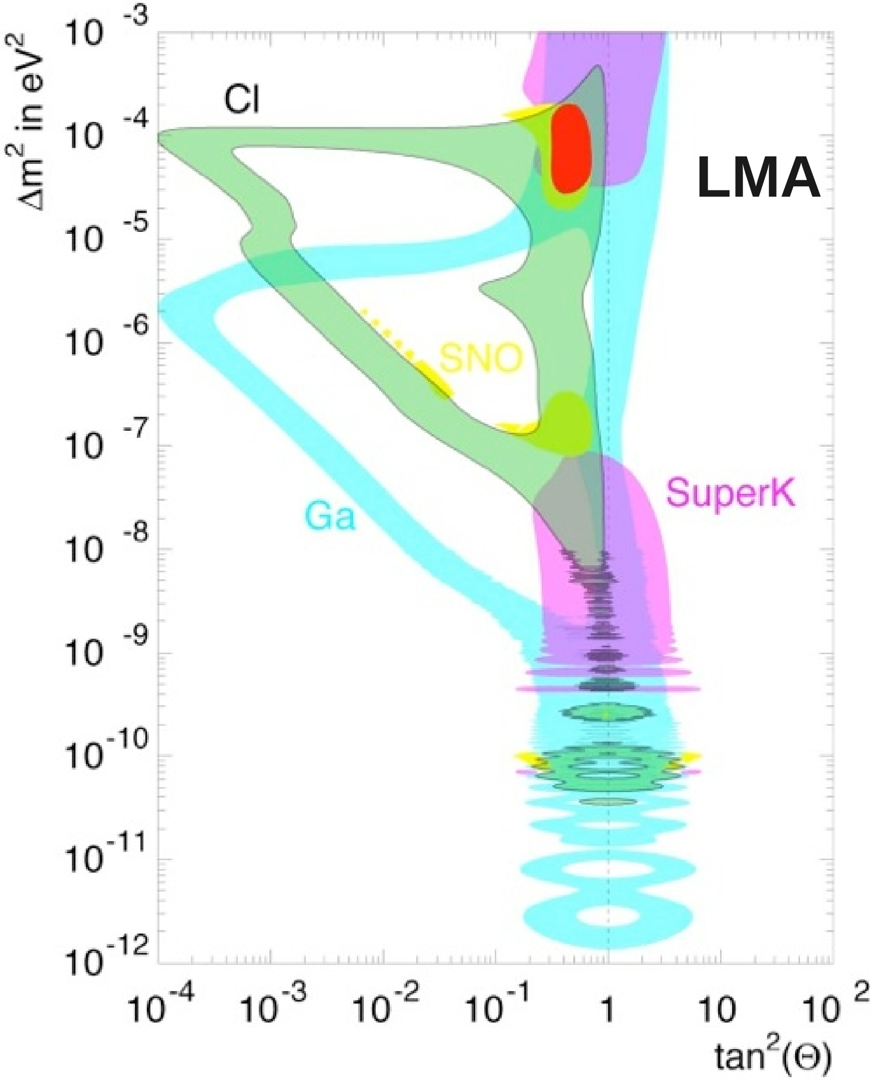
Status of the KamLAND physics program

Kavli IPMU

Alexandre Kozlov

Valday, January 27, 2014

Main idea behind the KamLAND



- A **100-200km** baseline was needed to test the **LMA** solution to the Solar neutrino problem.
- In 1994, the first long baseline reactor anti-neutrino experiment was proposed by A. Suzuki.
- A high reactor anti-neutrino flux allowed to measure the reactor anti-neutrino spectrum distortion and, therefore, determine $\mathbf{\Delta m^2}$ with a high accuracy.

$$P(E_\nu, L) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2[eV^2]\,L[m]}{E_\nu[MeV]}\right)$$

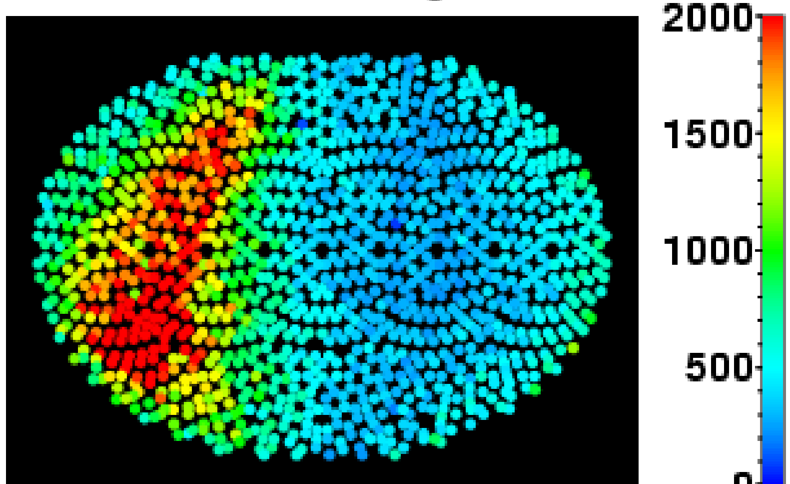
Research topics studied at KamLAND

- Neutrino oscillations
- Geo-neutrino
- Nucleon decay
- Solar neutrino
- Double-beta decay
- SN and pre-SN neutrinos
- Dark matter

Charged particles interaction with matter results in scintillation and Cherenkov light emission

Ø 13m 135μm-thick plastic balloon

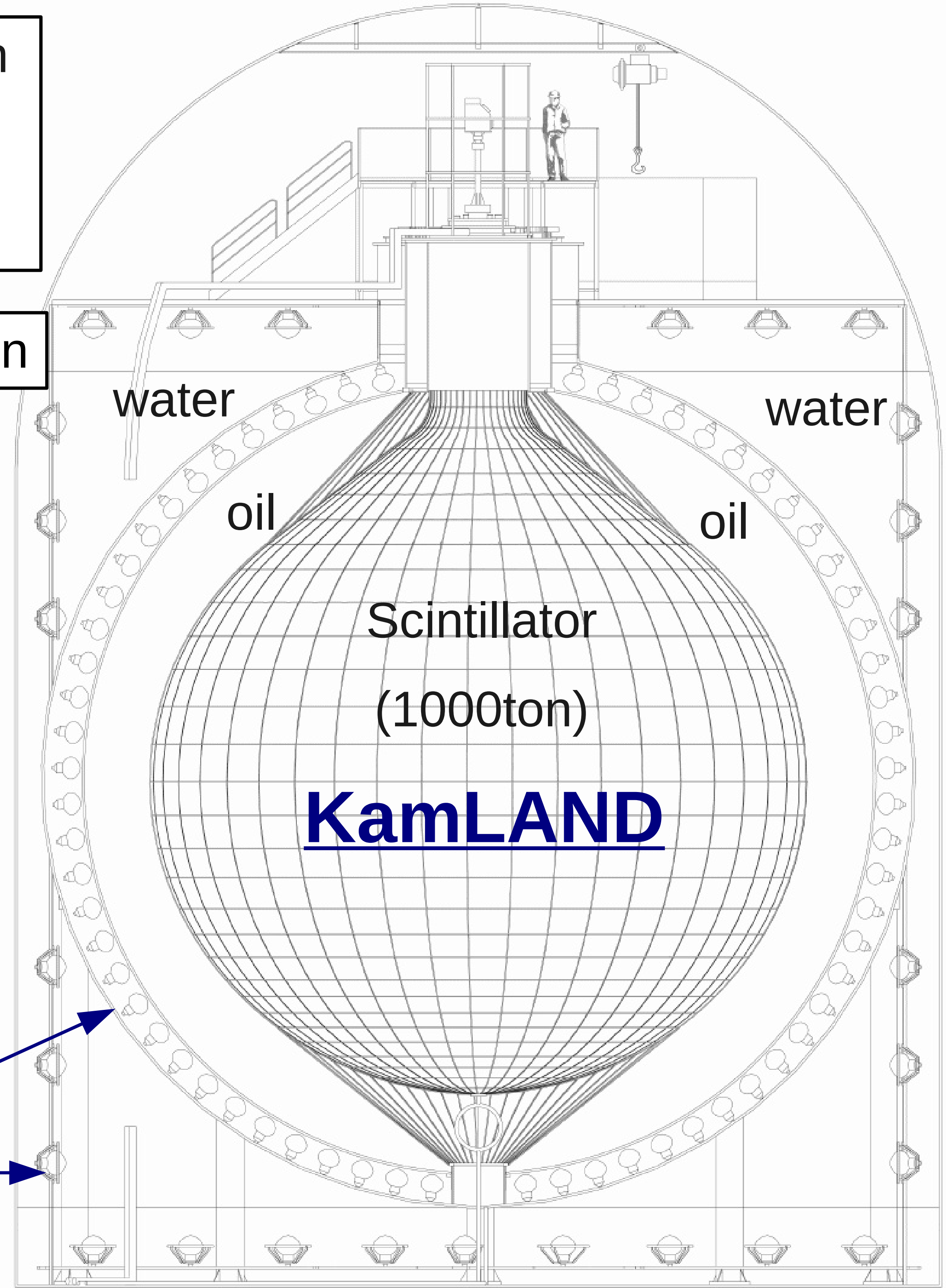
PMT Charge, p.e.



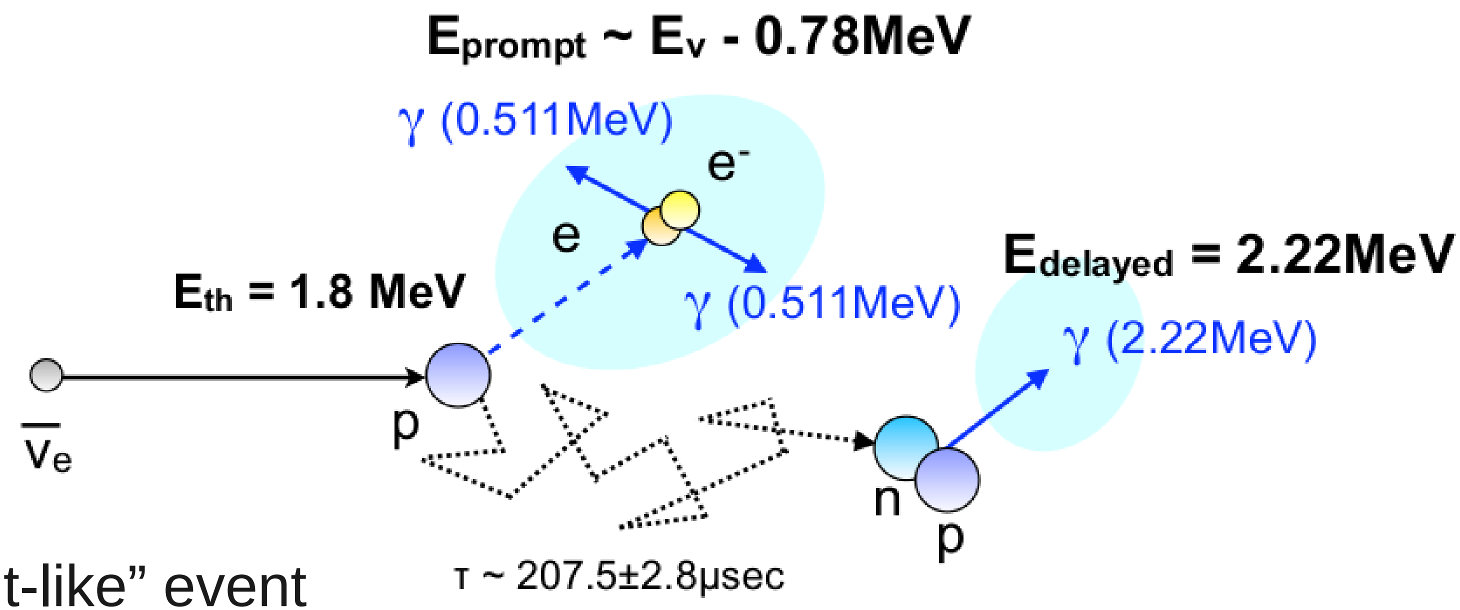
Muon track in KamLAND

Photo-detectors:

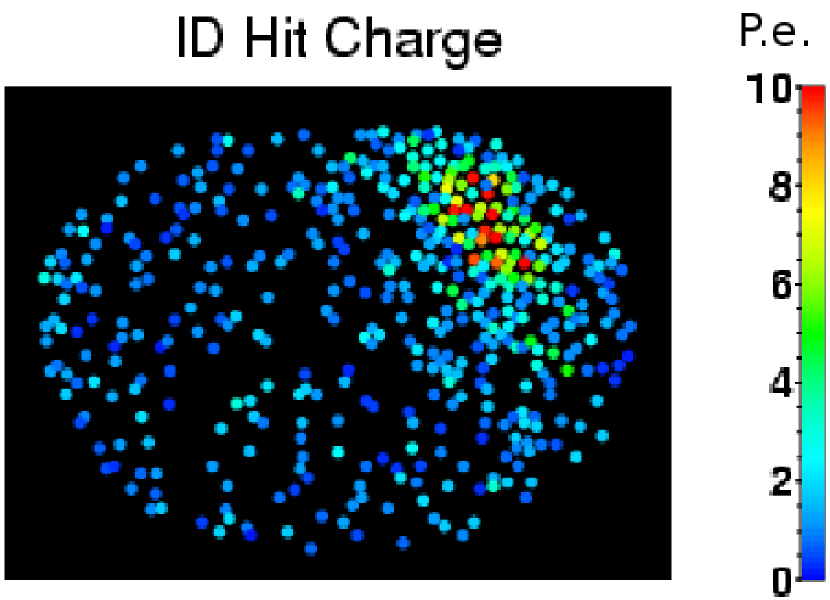
(Ø 50cm PMTs)



The anti-neutrino detection at KamLAND



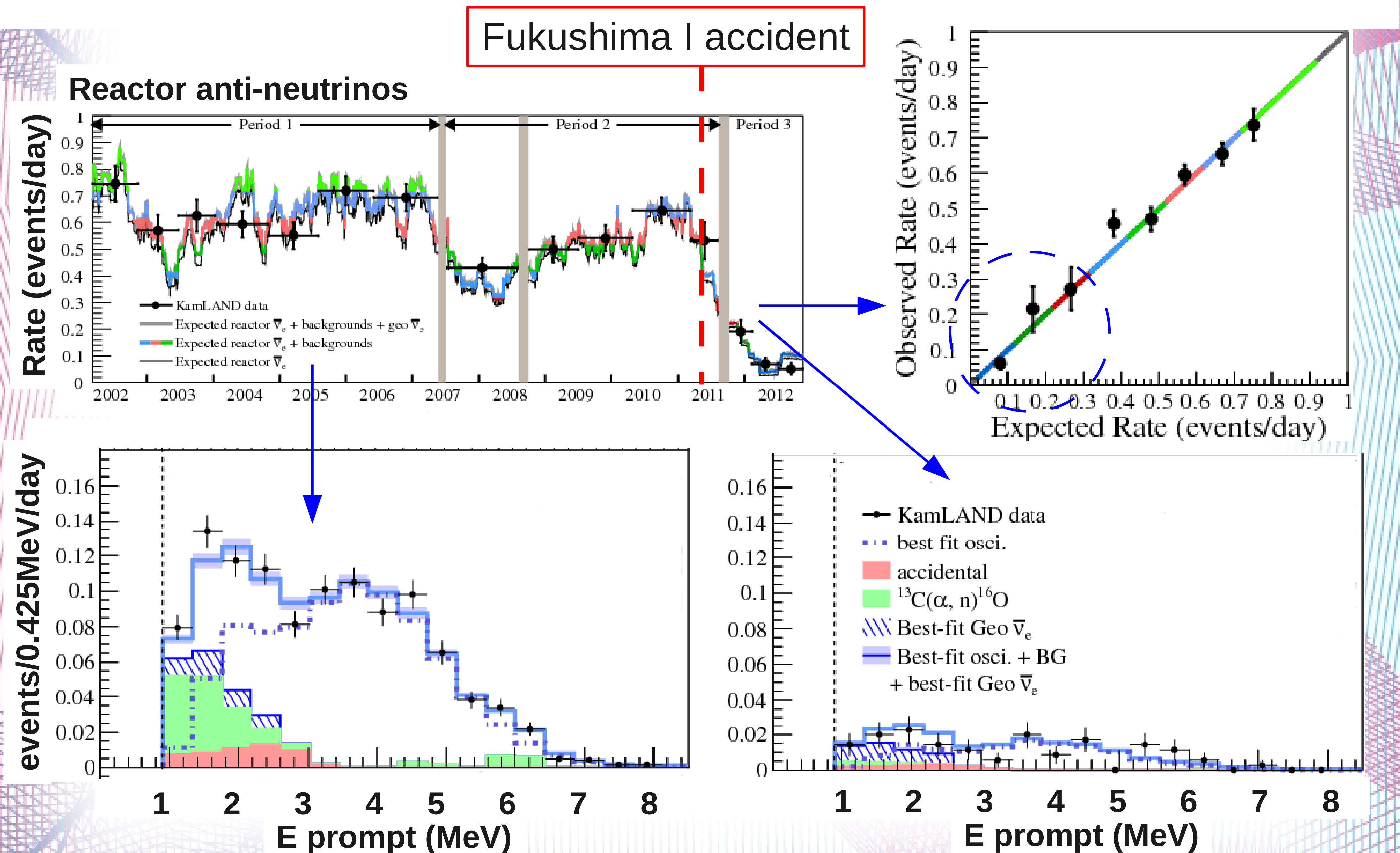
A "point-like" event



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

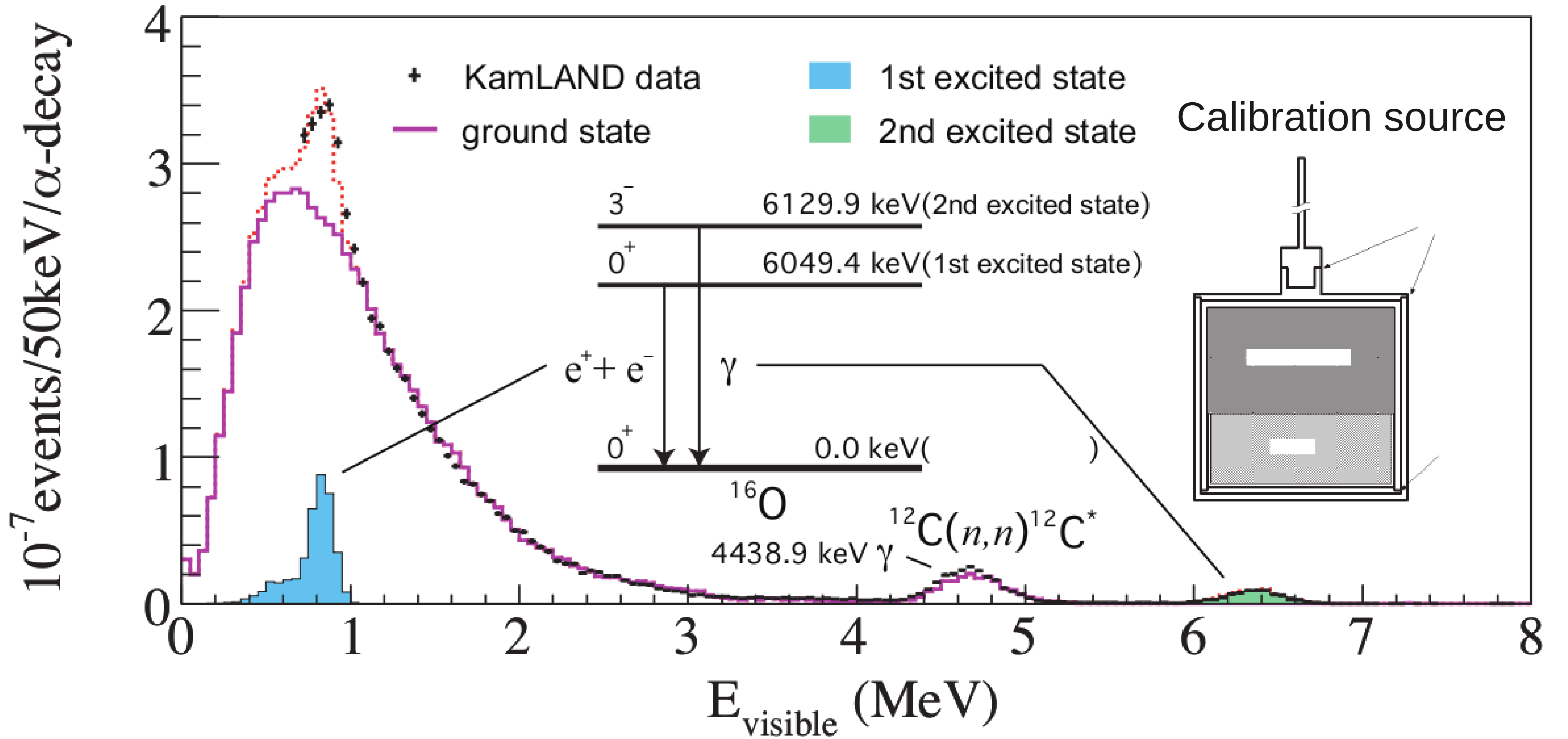
Time-and-space correlated prompt and delayed "point-like" event pairs can be easily separated from the accidental background.

The anti-neutrino flux variations at KamLAND



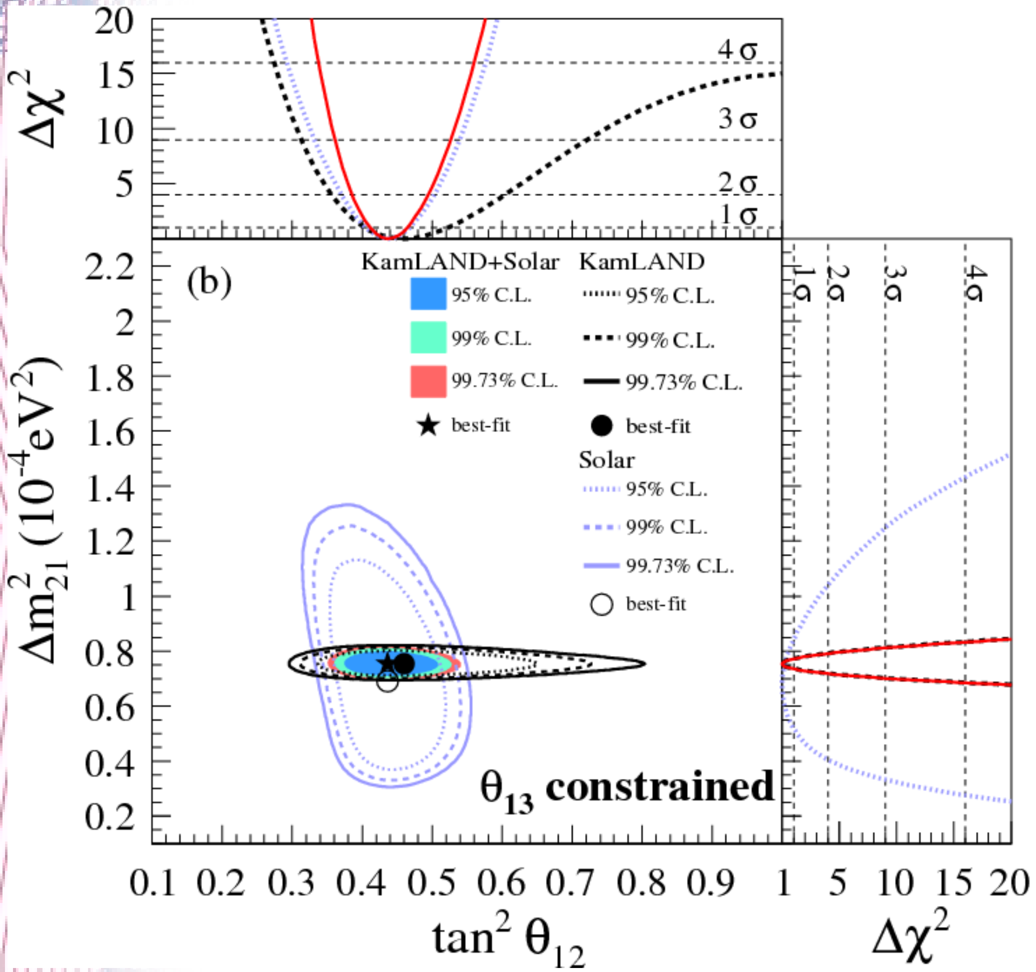
a unique opportunity to constrain backgrounds for oscillation analysis

The (α,n) correlated background



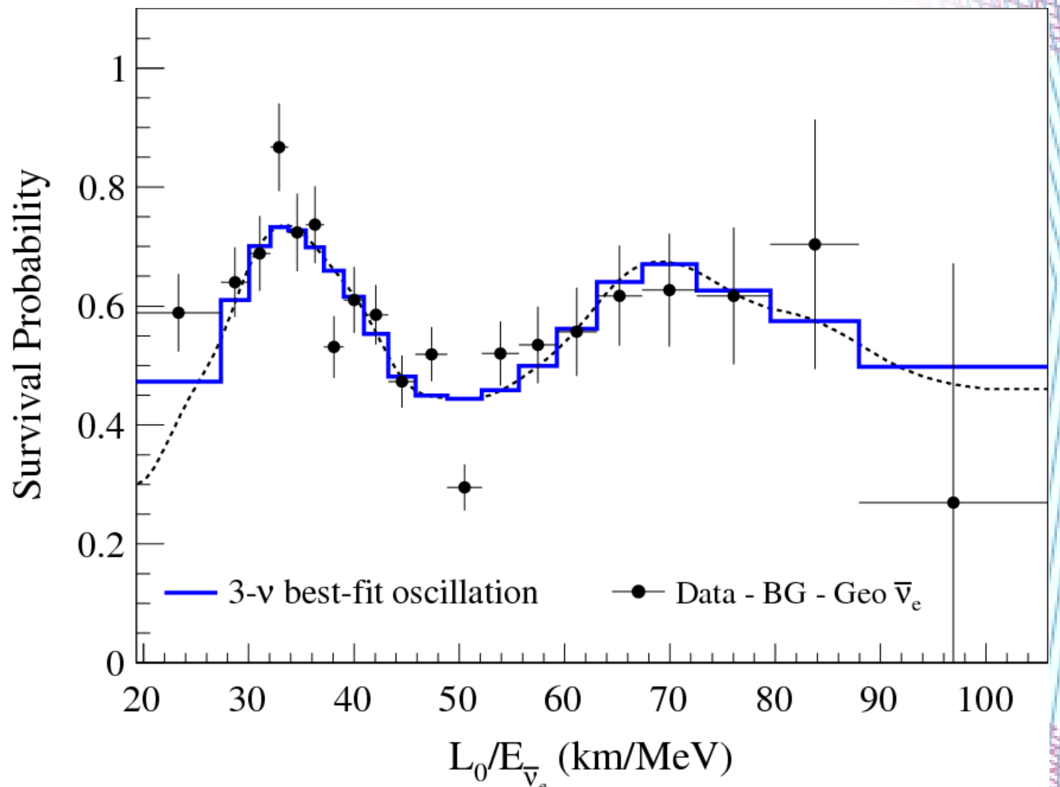
- Fast neutrons can be produced in the ${}^{13}C(\alpha,n)X$ reaction. In KamLAND main source of α-particles was decay of the ${}^{222}Rn$ daughter: **${}^{210}Po$**
- During 2007-2008 distillation campaign the ${}^{210}Po$ decay rate was reduced by a **factor of 20**

High precision neutrino oscillation data



L/E plot

(observed - B.G.) / (no osci. expected)



$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$

$\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\ eV^2$

$\sin^2\theta_{13} = 0.023 \pm 0.002$

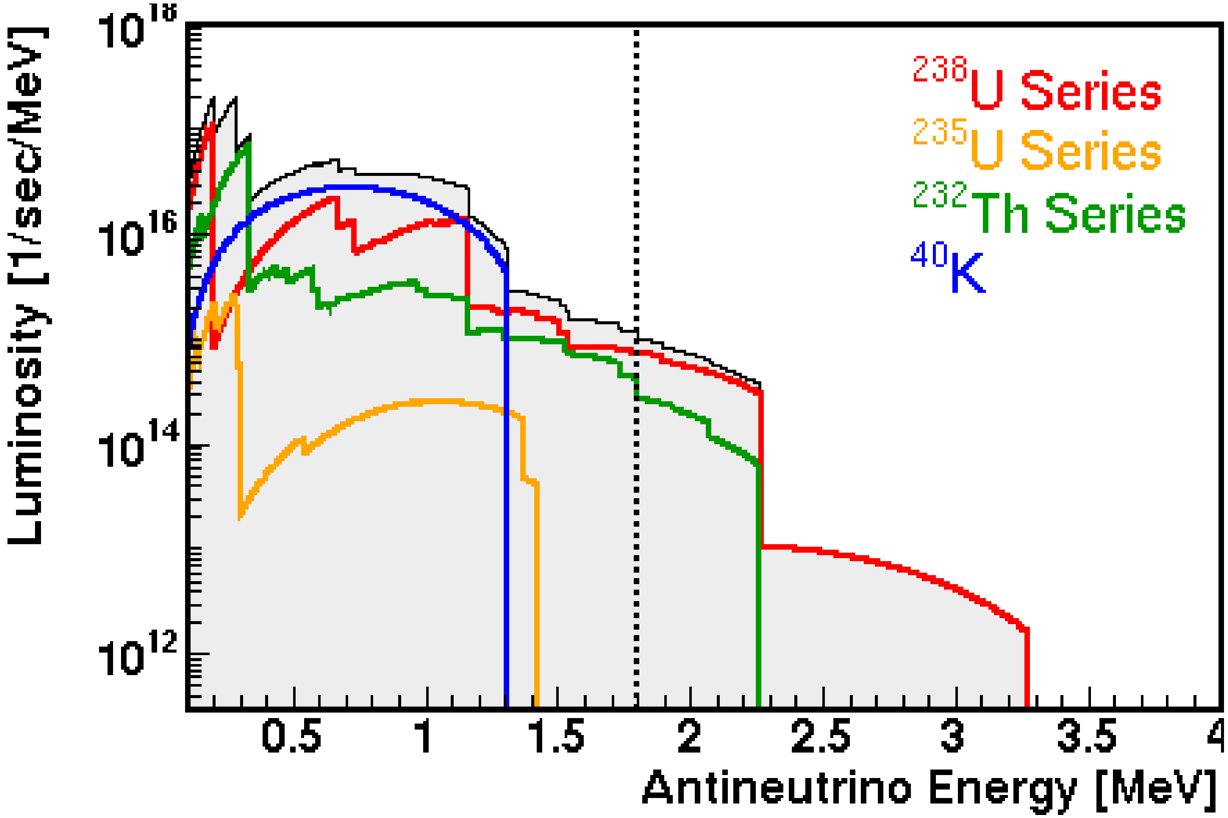
2.3% error

KamLAND data covers 2 cycle of oscillation

strong evidence for neutrino oscillation

PRD 88, 033001 (2013)

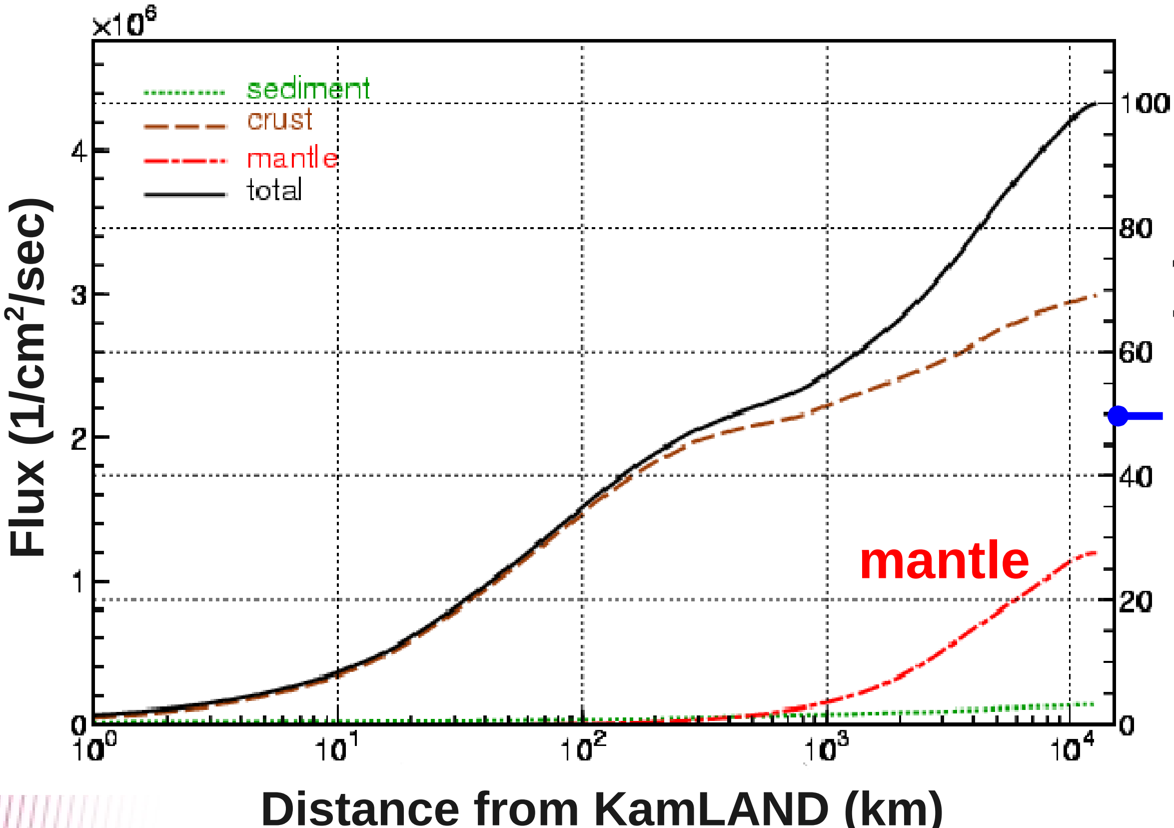
Anti-neutrinos from the Earth crust and mantle

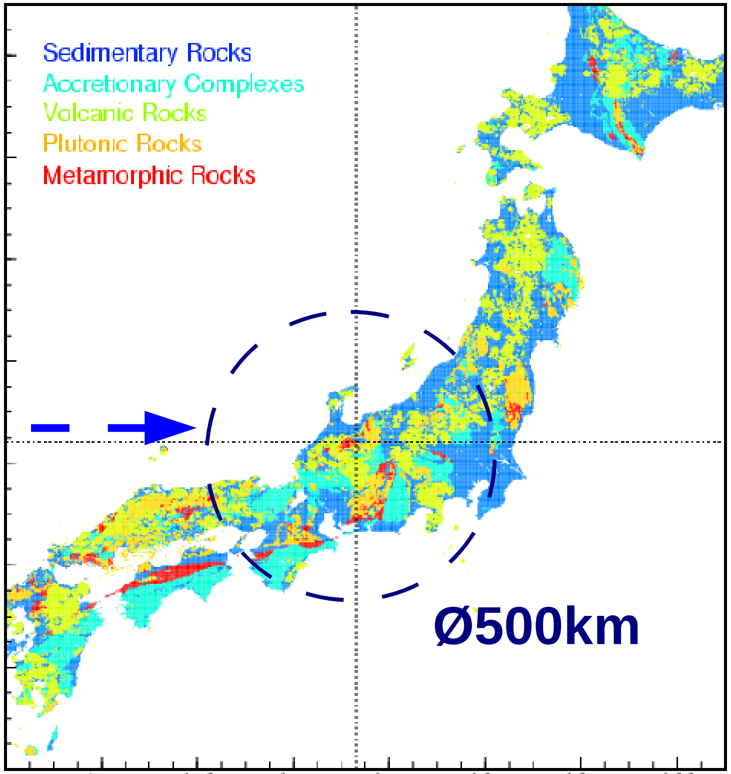


^{238}U ($T_{1/2}$= 4.47×10^{9}y) → ^{206}Pb + 8^{4}He + 6e^{-} + **6**$\bar{\nu}_e$+ 51.7MeV (100%)

^{232}Th ($T_{1/2}$= 14×10^{9}y) → ^{208}Pb + 6^{4}He + 4e^{-} + **4**$\bar{\nu}_e$+ 42.7MeV (100%)

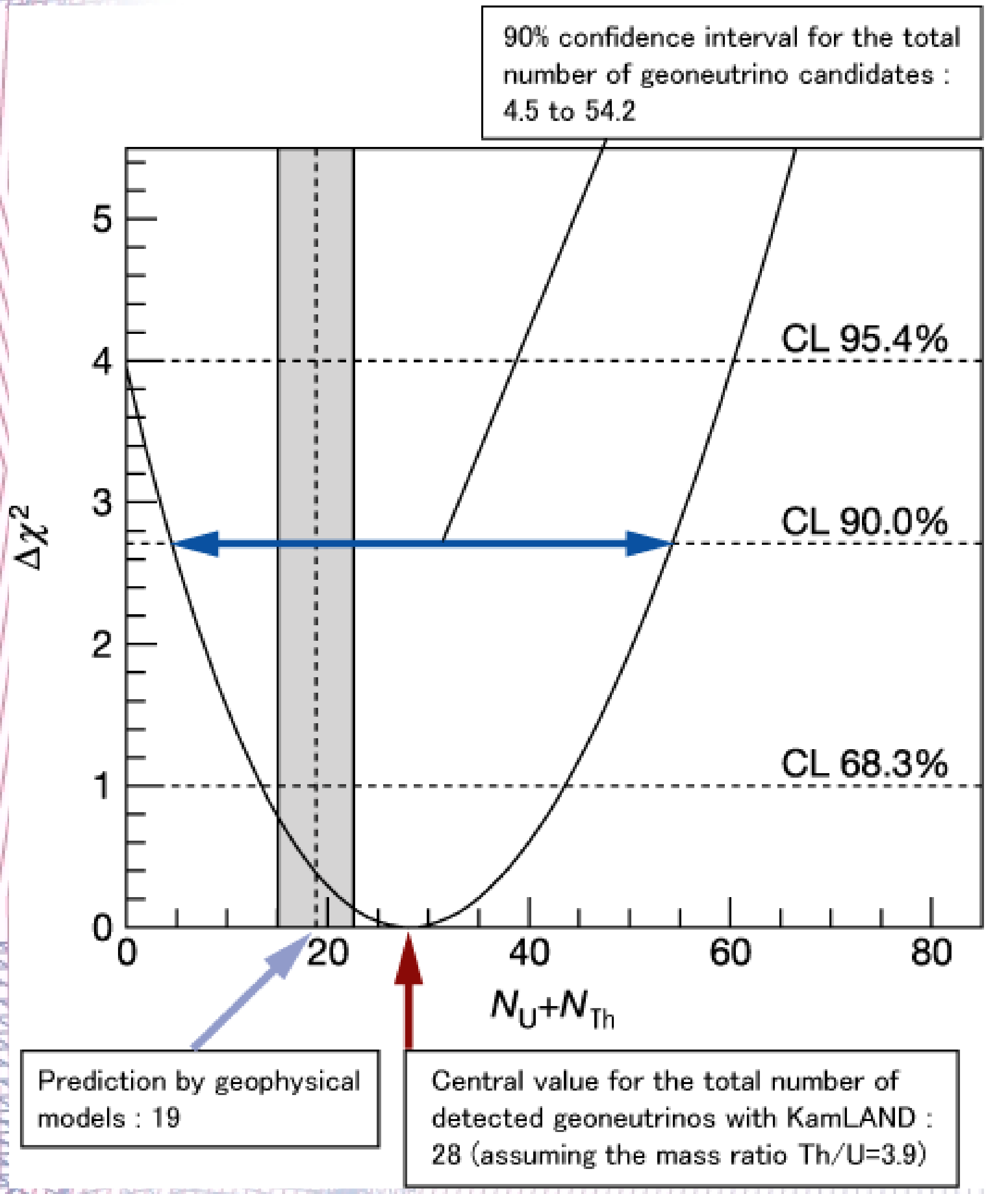
The geo-neutrino flux at the KamLAND location



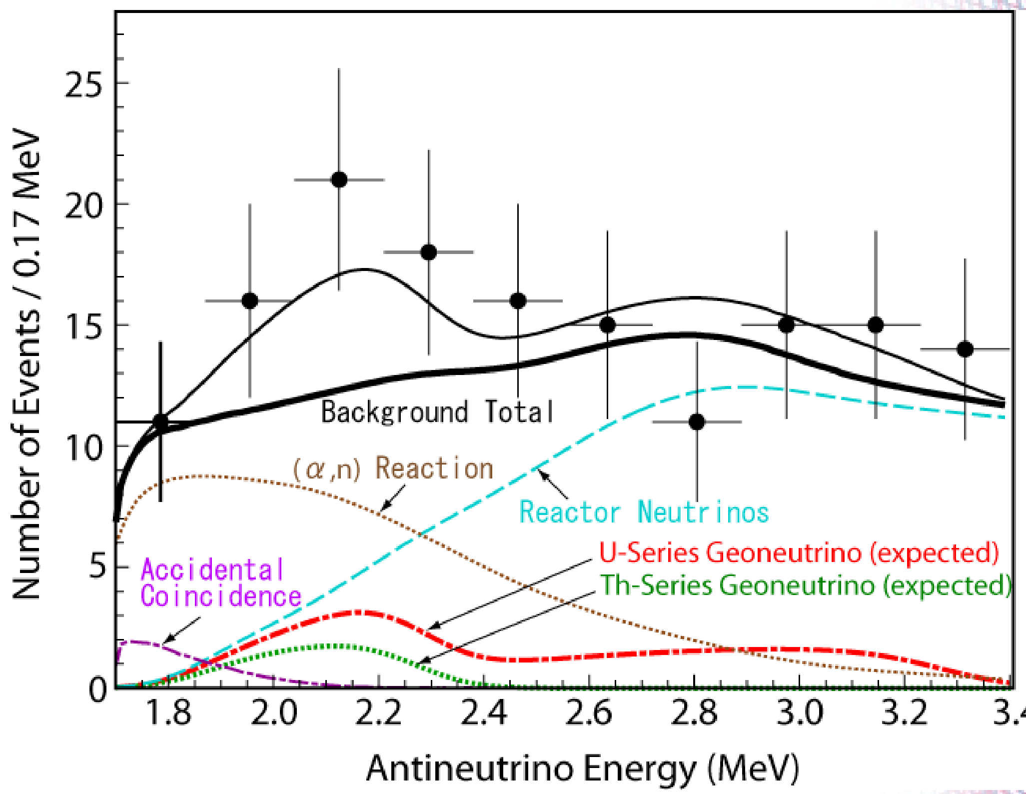


Geo-neutrinos carry information about the absolute amount and distribution of the **U/Th/K** in the crust, mantle and core. This information may help to understand mechanisms of Earth formation, and its dynamics.

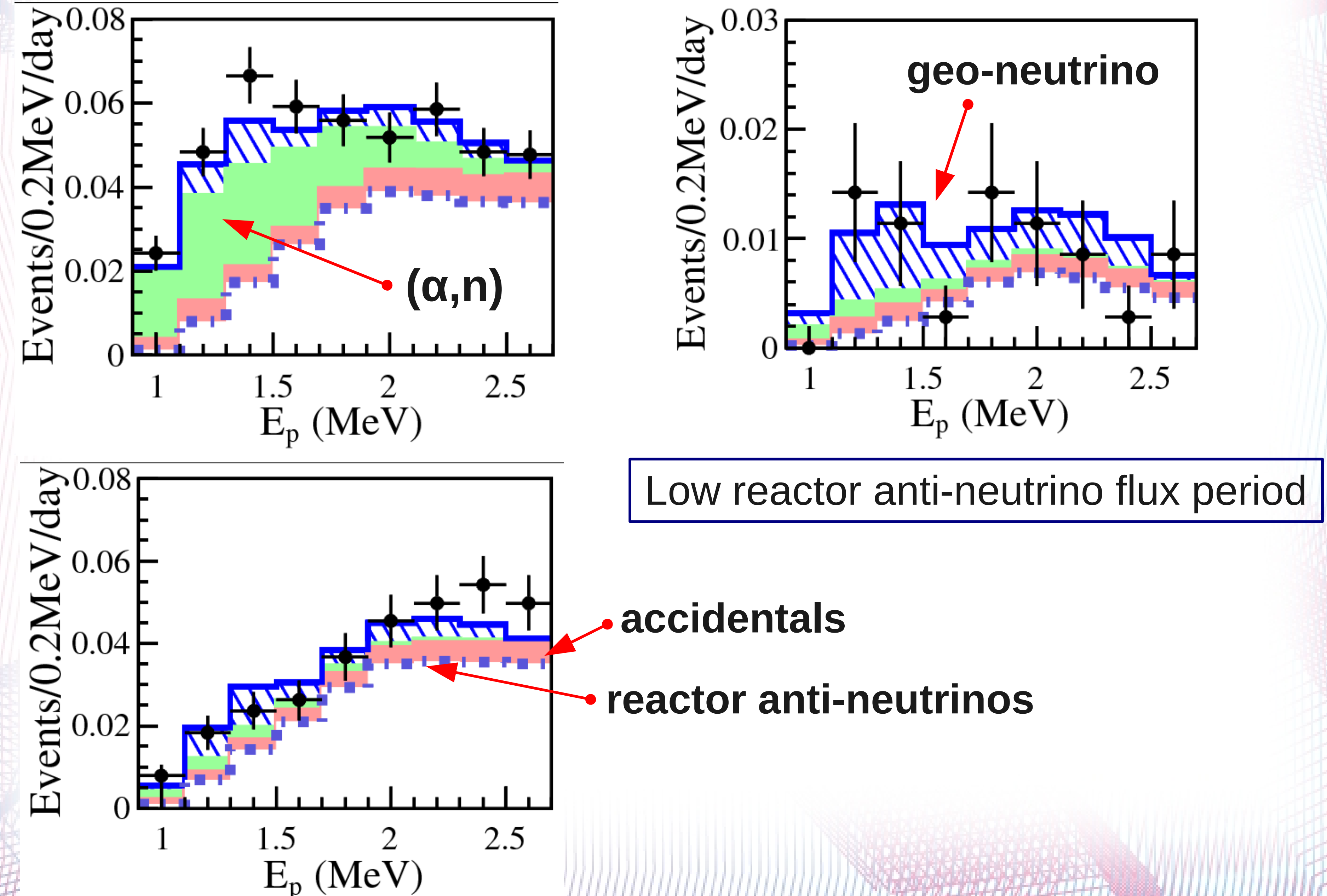
The first geo-neutrino result



Nature 436:499-503, 2005

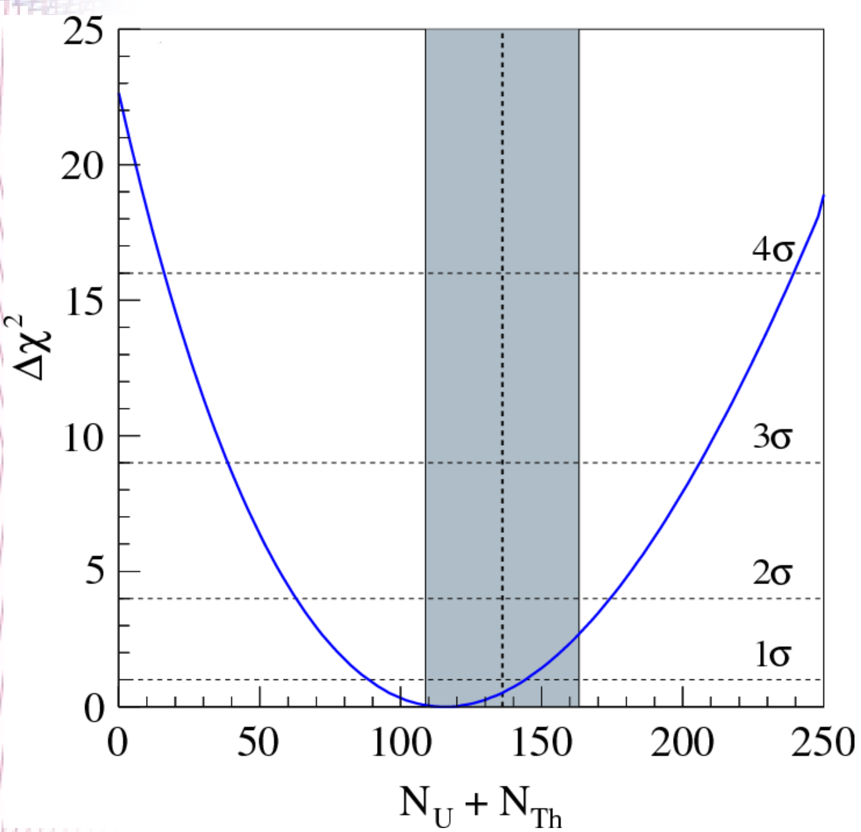


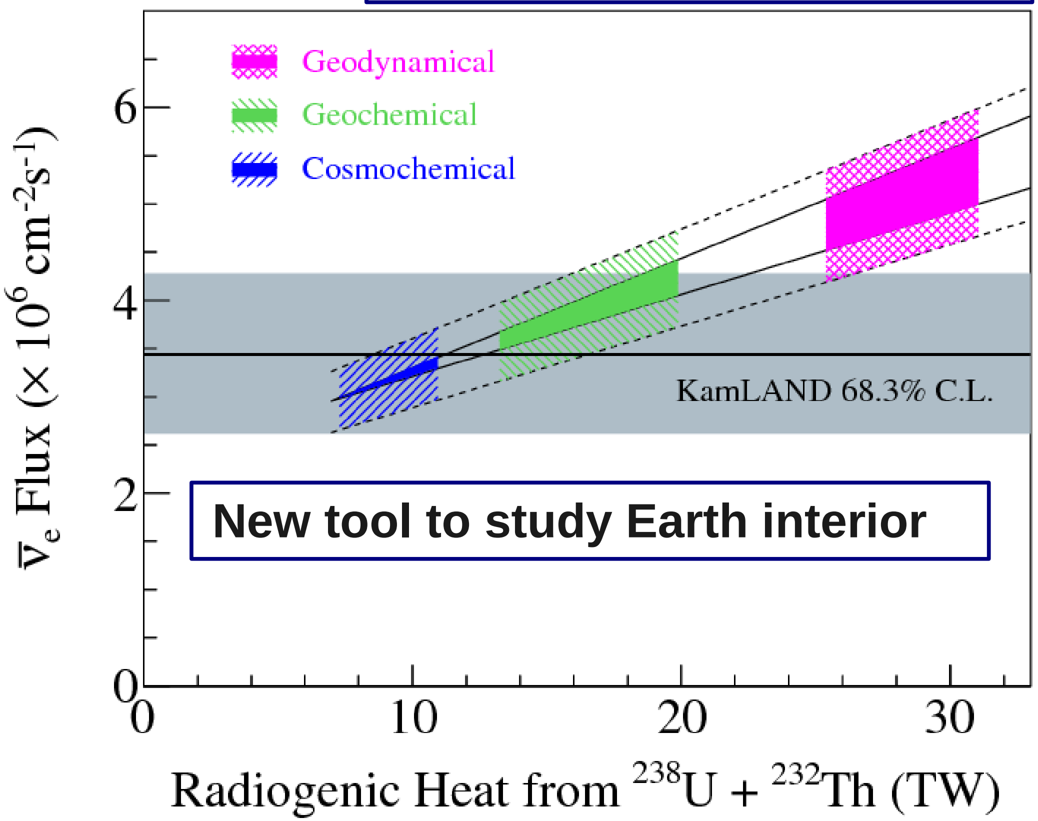
Background for geo-neutrino detection



The latest geo-neutrino result

PRD 88, 033001 (2013)



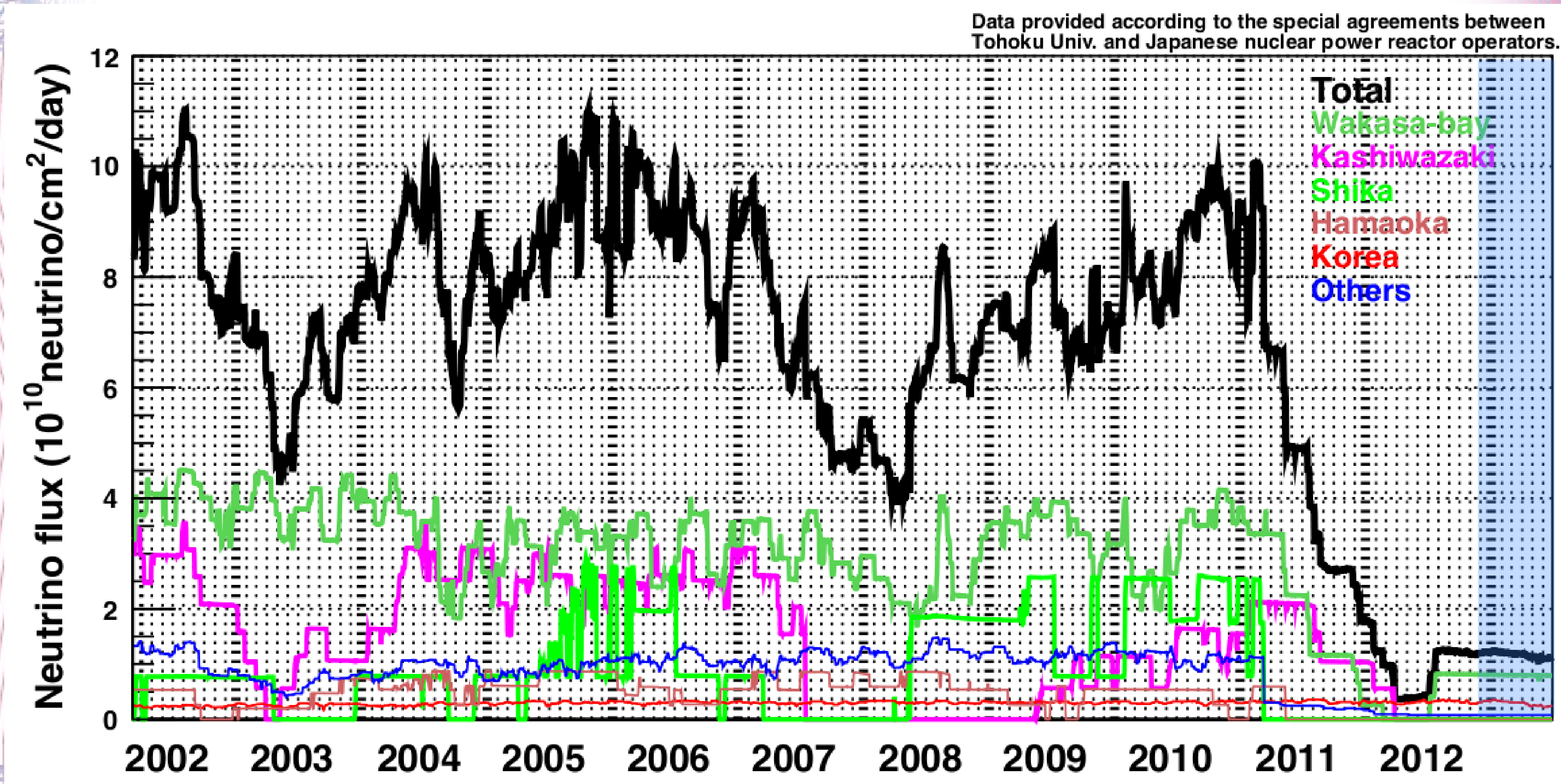


New tool to study Earth interior

The anti-neutrino event rate from **Uranium/Thorium β-decay**: **1 event/month**

The KamLAND result for the **radiogenic heat**: **$14.2^{+7.9}_{-5.1}$ TW** while heat flow from the Earth's surface is **47±2 TW**

Future prospects for geo-neutrino detection



- Since September 2013 all Japanese reactors were shutdowned.
- Few reactors may be restated later this year but situation should remain favorable during the year 2014.

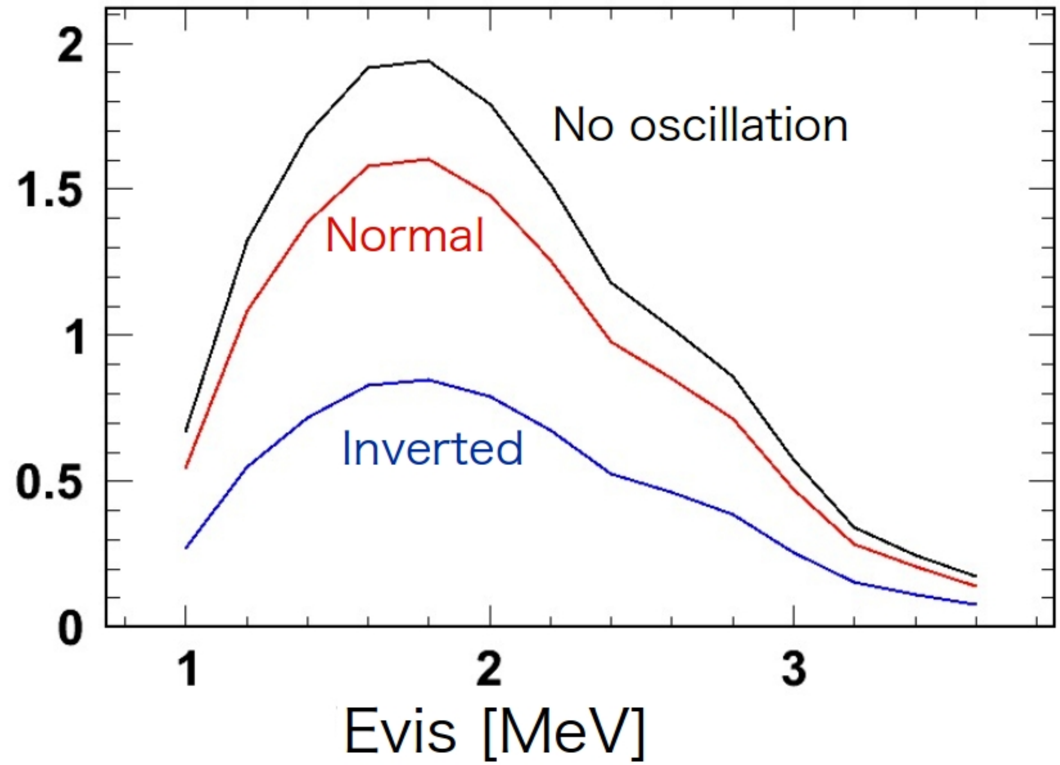
Pre-SN anti-neutrino detection (from Si core)

Red supergiants

- Antares (170pc)
- Betelgeuse (200pc)

Wolf-Rayer star

- Gamma Velorum (340pc)



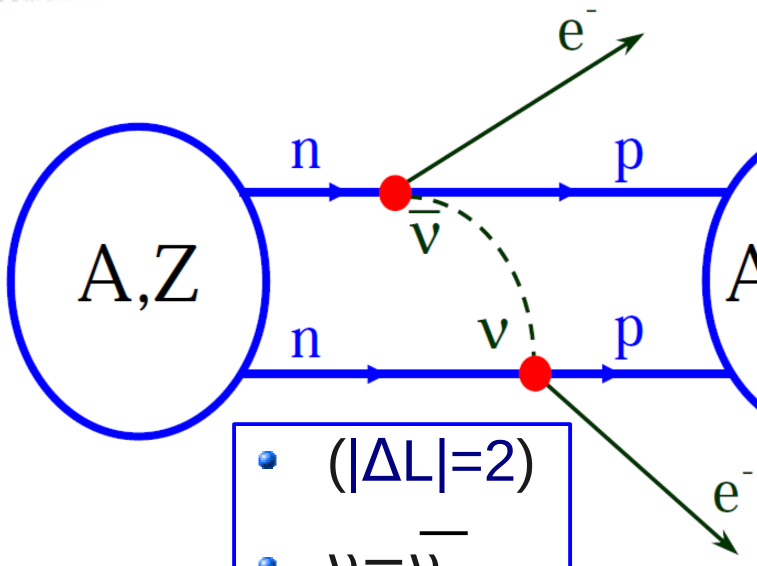
Betelgeuse type at 200pc

Number of events

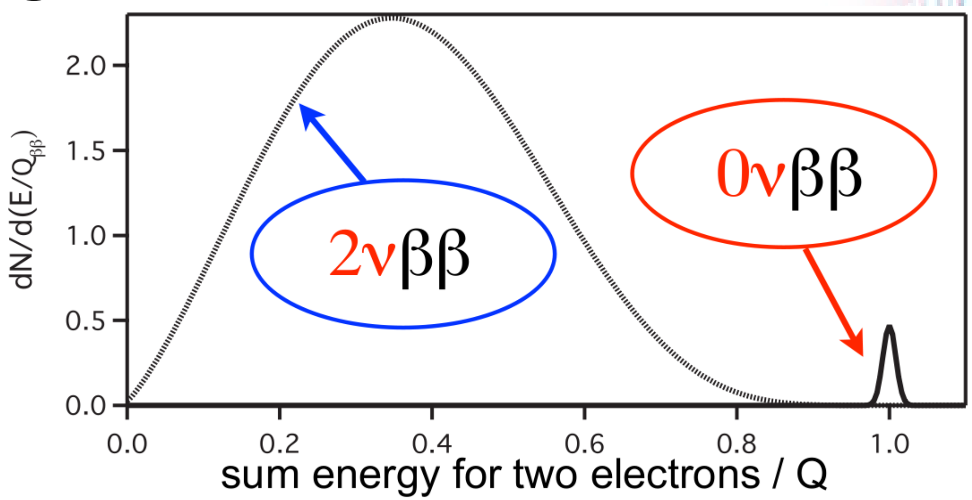
48-24h	24-3h	3-0h	Time
1.6	6.1	9.2	Normal
0.7	2.9	4.4	Inverted

Alarm system is being developed

The 0νββ test of seesaw mechanism by Yanagida



- (|ΔL|=2)
- ν=ν̄



Basic process: dd → uue⁻e⁻.

Decay rate ~ (neutrino mass)^2

Test of the **Leptogenesis** as explanation
(Fukugita & Yanagida)
for **baryon asymmetry of the Universe**

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^{\;2}$$

$G^{0\nu}(Q_{\beta\beta}, Z) - ph.\ space\ factor$

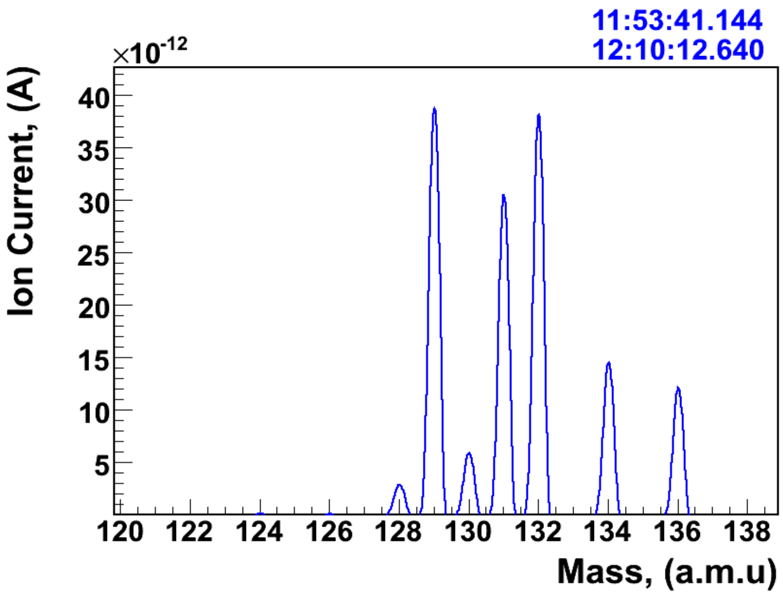
$|M^{0\nu}| - NME$

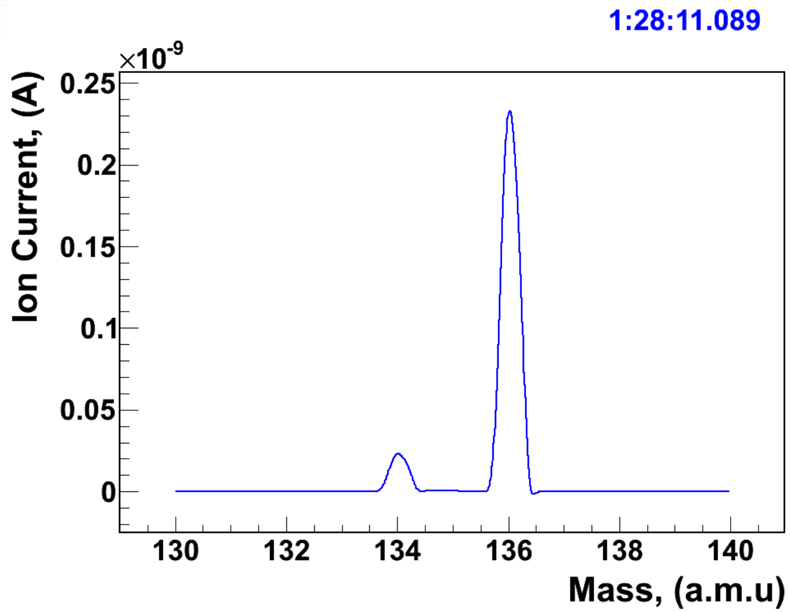
$m_{\beta\beta} = |\sum_i U_{ei}^2 \cdot m_{\nu i}| - eff.\ mass\ of\ \nu$

The $0\nu\beta\beta$ isotope selection for KamLAND

- A highest possible S/N value taking into account known background composition (dominated by ^{10}C, ^{208}Tl, ^{11}Be, ^{214}Bi), the candidate isotope decay energy $Q_{\beta\beta}$, and existence of muon spallation background
- A slowest $2\nu\beta\beta$ decay rate to minimize background due to a relatively low energy resolution of KamLAND
- Availability of isotope, possibility of a mass production within a short time period, a high enrichment level, and lowest cost per kg
- Best radiopurity (U, Th, K), and existence of purification methods
- Possibility to produce a stable liquid scintillator with a high light yield, and a high light transparency

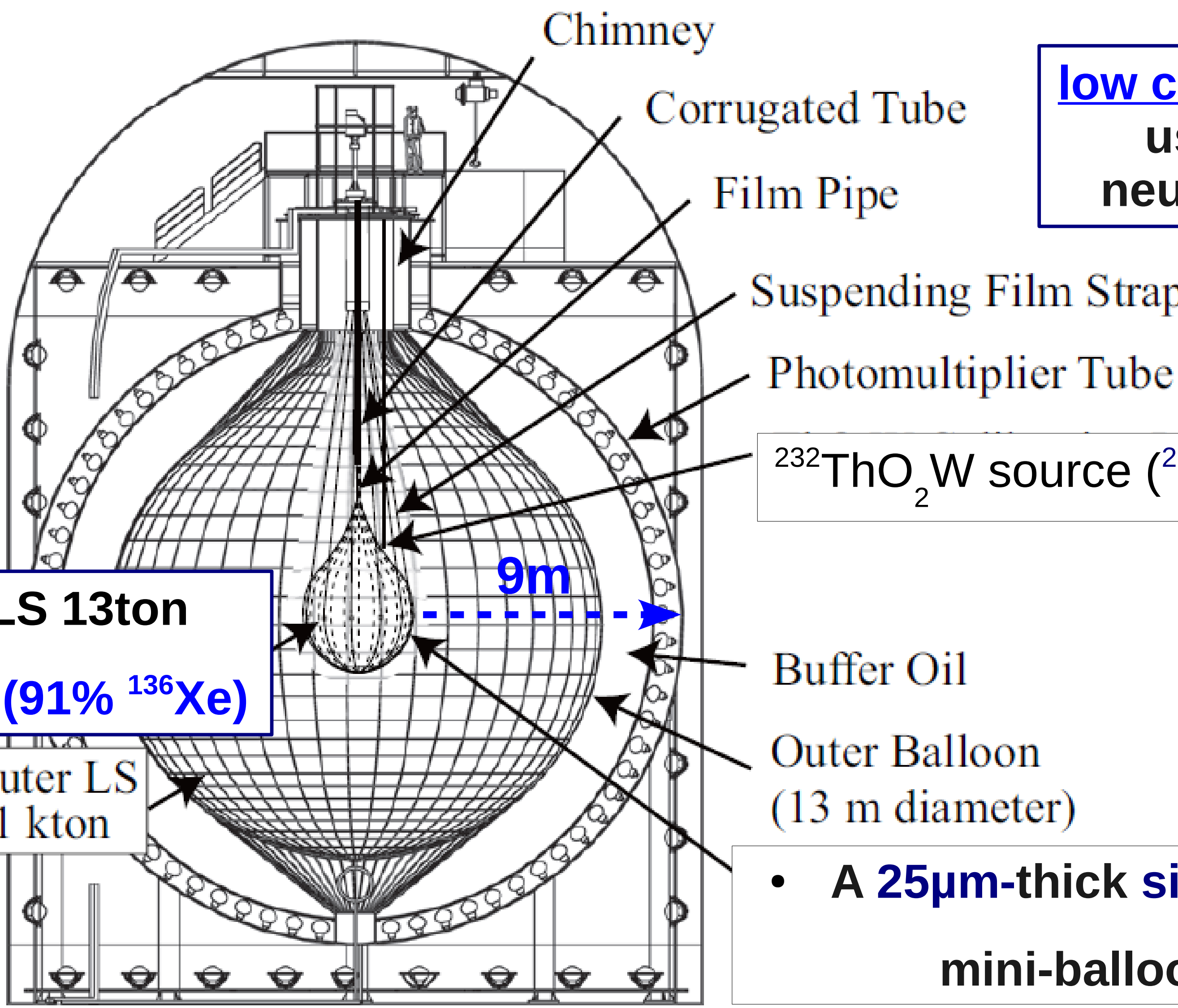
Xenon-136 was selected as best candidate





- available facilities for production at a ton scale in Russia
- low cost compared to other enriched isotopes
- high enrichment level (91%)
- radioactive impurities removed during enrichment process; additional purification is possible using well established techniques
- soluble in LS (>3wt%)
- slowest $2\nu2\beta$ background rate: $T_{1/2}(2\nu\beta\beta) > 10^{22}$ years (prior to EXO)
- no substantial light yield, and no transparency reduction in Xe loaded LS

The KamLAND-Zen experiment



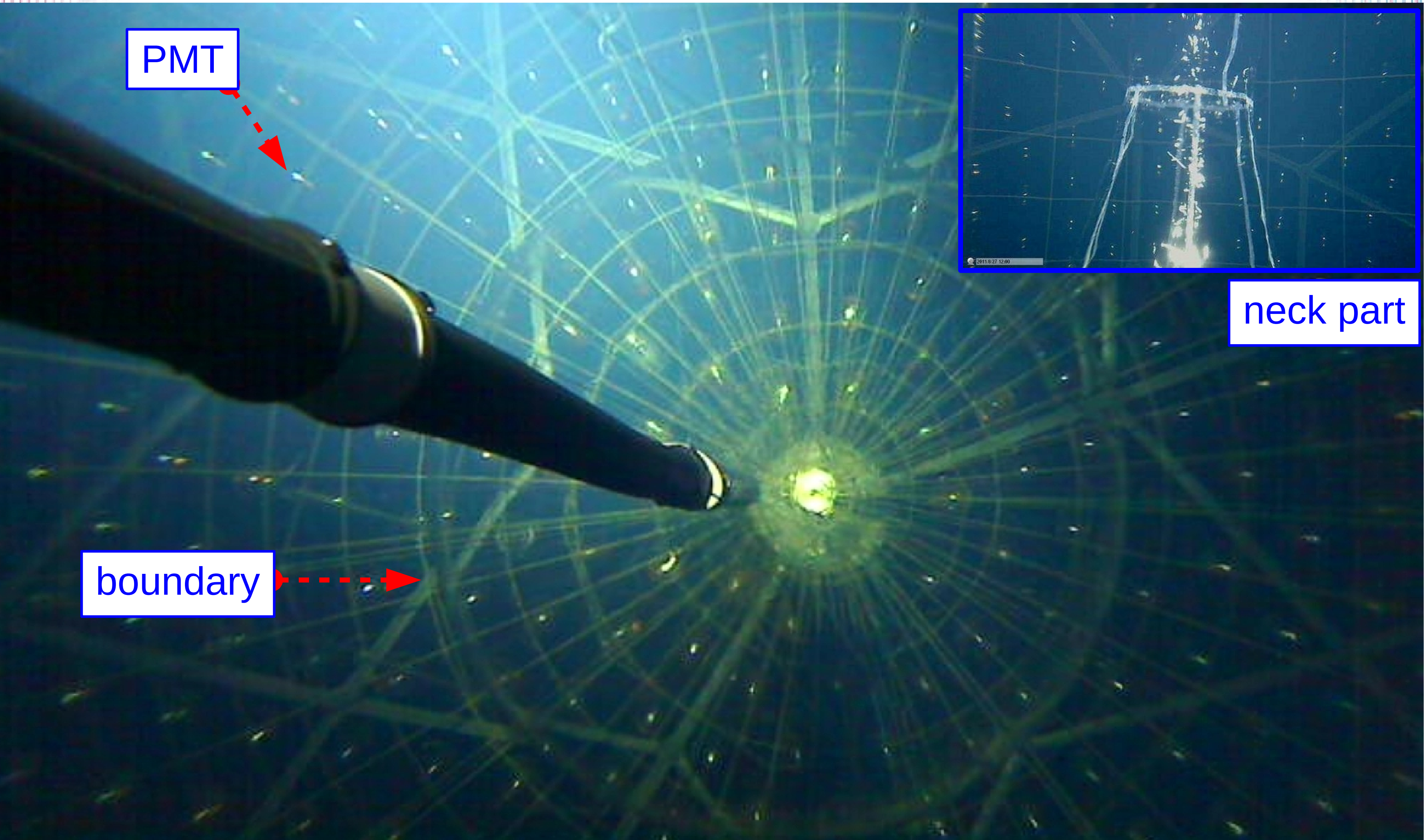
low cost & quick start
using existing neutrino detector!

- 9m thick shielding against γ-rays and neutrons produced in rock
- Possibility to scale up the 0νββ experiment by replacing the mini-balloon

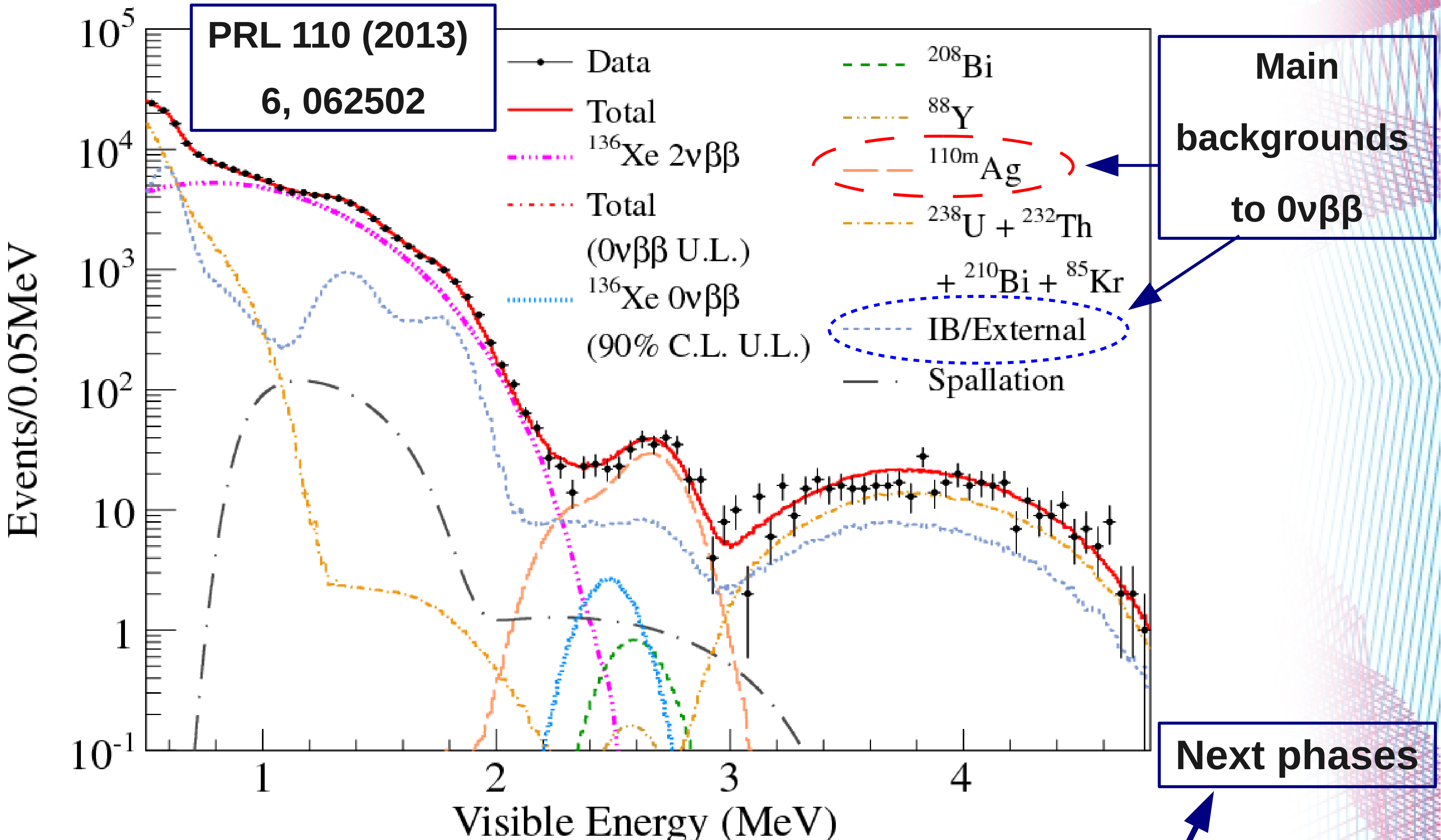
Clean room used to operate KamLAND-Zen

The mini-balloon inside KamLAND

refractive index differs by ~ 0.5% inside and outside of mini-balloon

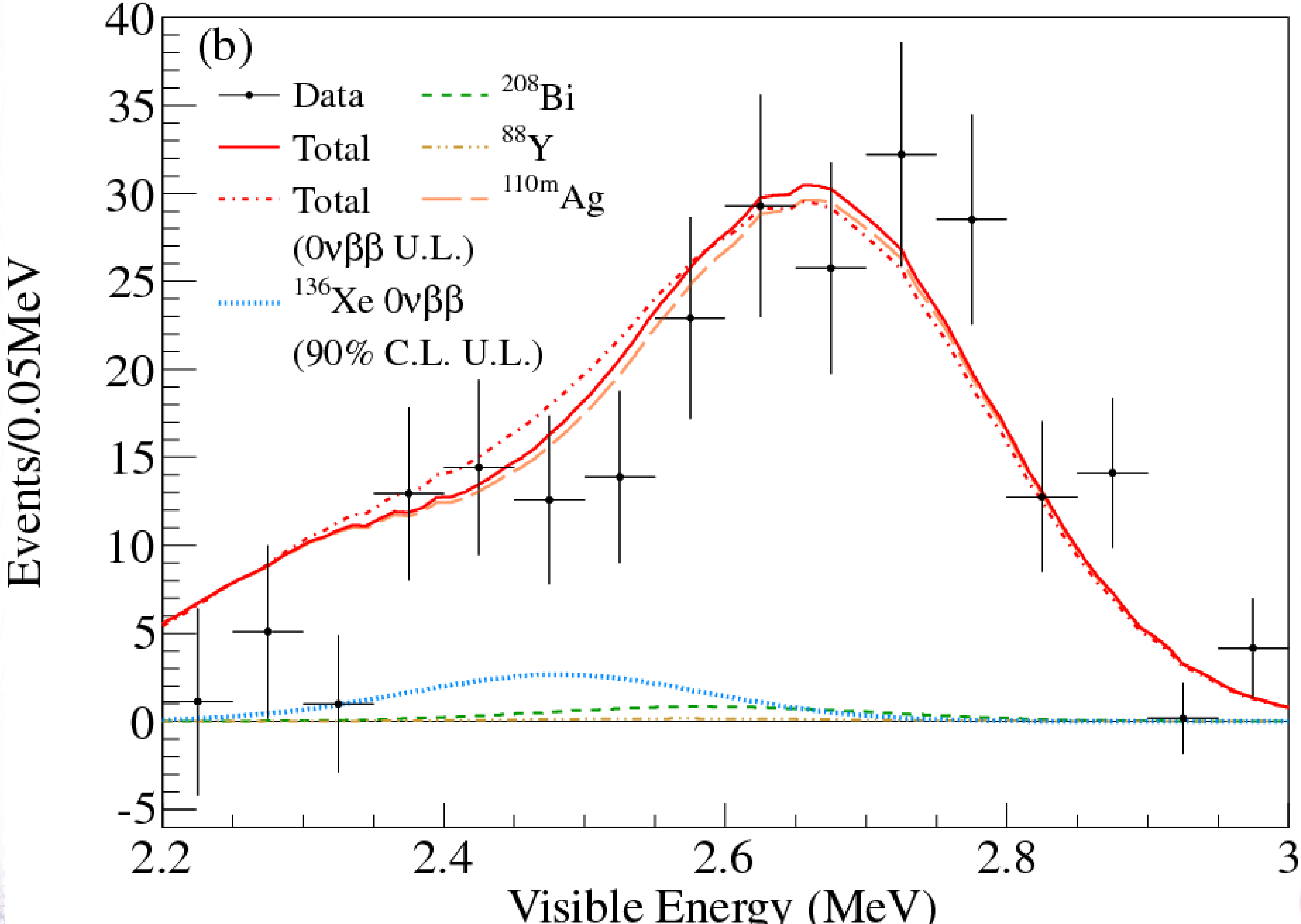


Result from the 1st phase of KamLAND-Zen



- Remove ^{110m}**Ag** from the Xenon loaded scintillator
- Reduce amount of ^{214}**Bi** (Uranium) in the mini-balloon material

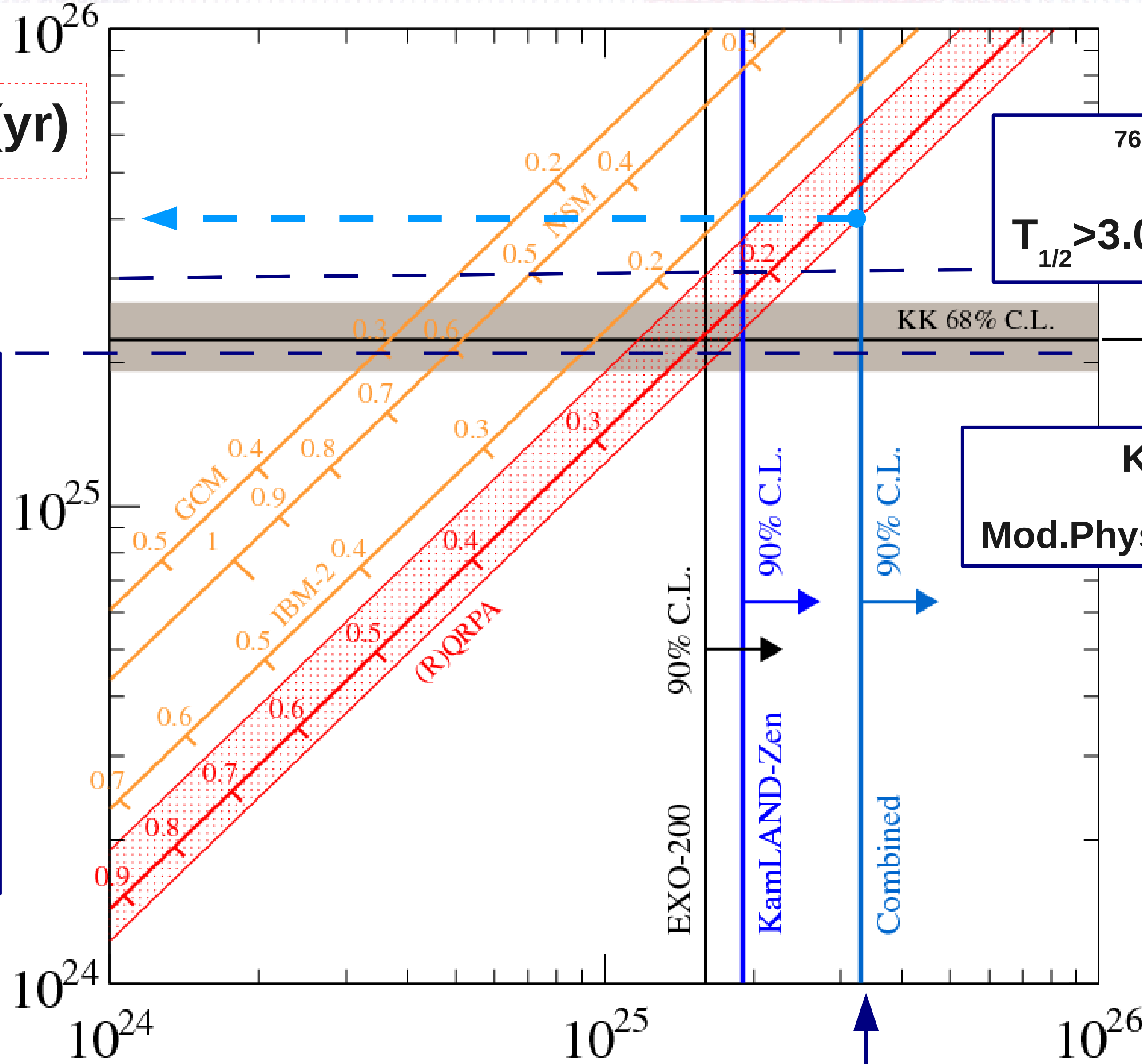
The ^{110m}Ag background



PRL 110 (2013) 6, 062502

$T_{1/2} > 1.9 \times 10^{25}$ y at 90% CL (^{136}Xe world best limit)

$T_{1/2}$ ^{76}Ge (yr)



^{76}Ge combined

$T_{1/2} > 3.0 \times 10^{25}$ y at 90% CL

GERDA Phase I

$T_{1/2} > 2.1 \times 10^{25}$ y at 90% CL

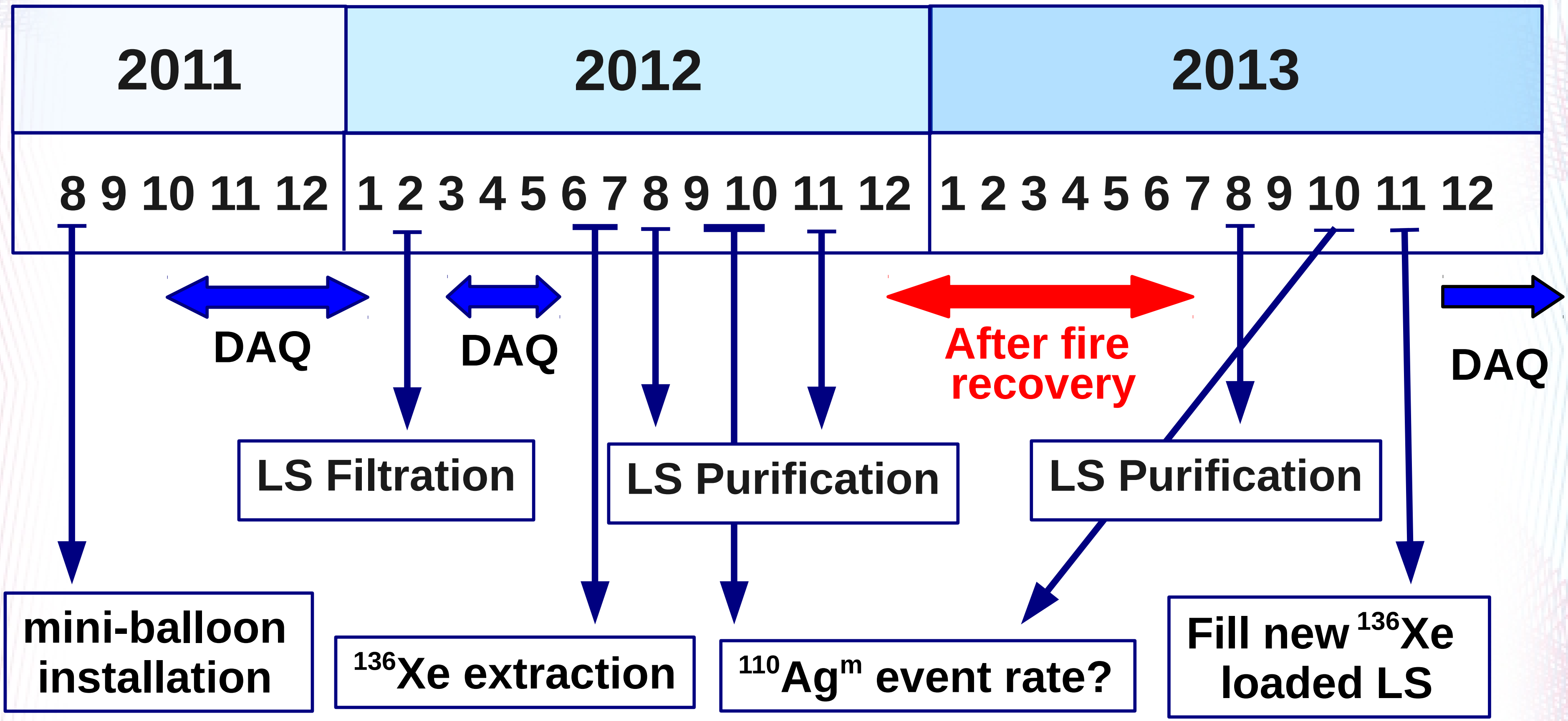
Klapdor et al.

Mod.Phys.Lett.A21(2006)1547

$T_{1/2}$ ^{136}Xe (yr)

$m_{\beta\beta}$ < 120~250 meV - excluded the KK claim at >97.5% C.L. assuming light Majorana neutrino exchange and existing nuclear models

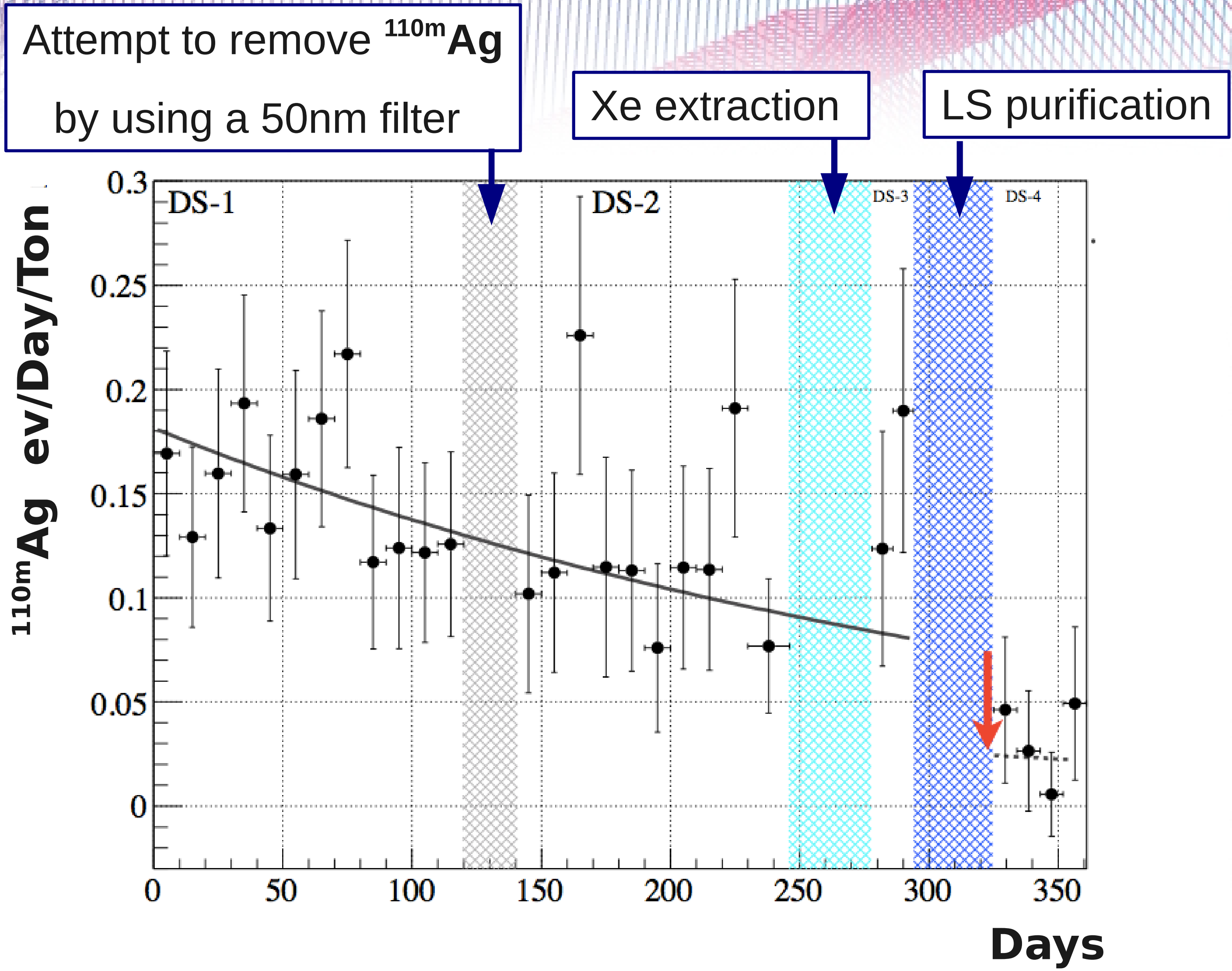
The KamLAND-Zen timetable



Second phase: **380-390kg of Xe** to achieve **80meV** sensitivity in **2014**

The mini-balloon operation

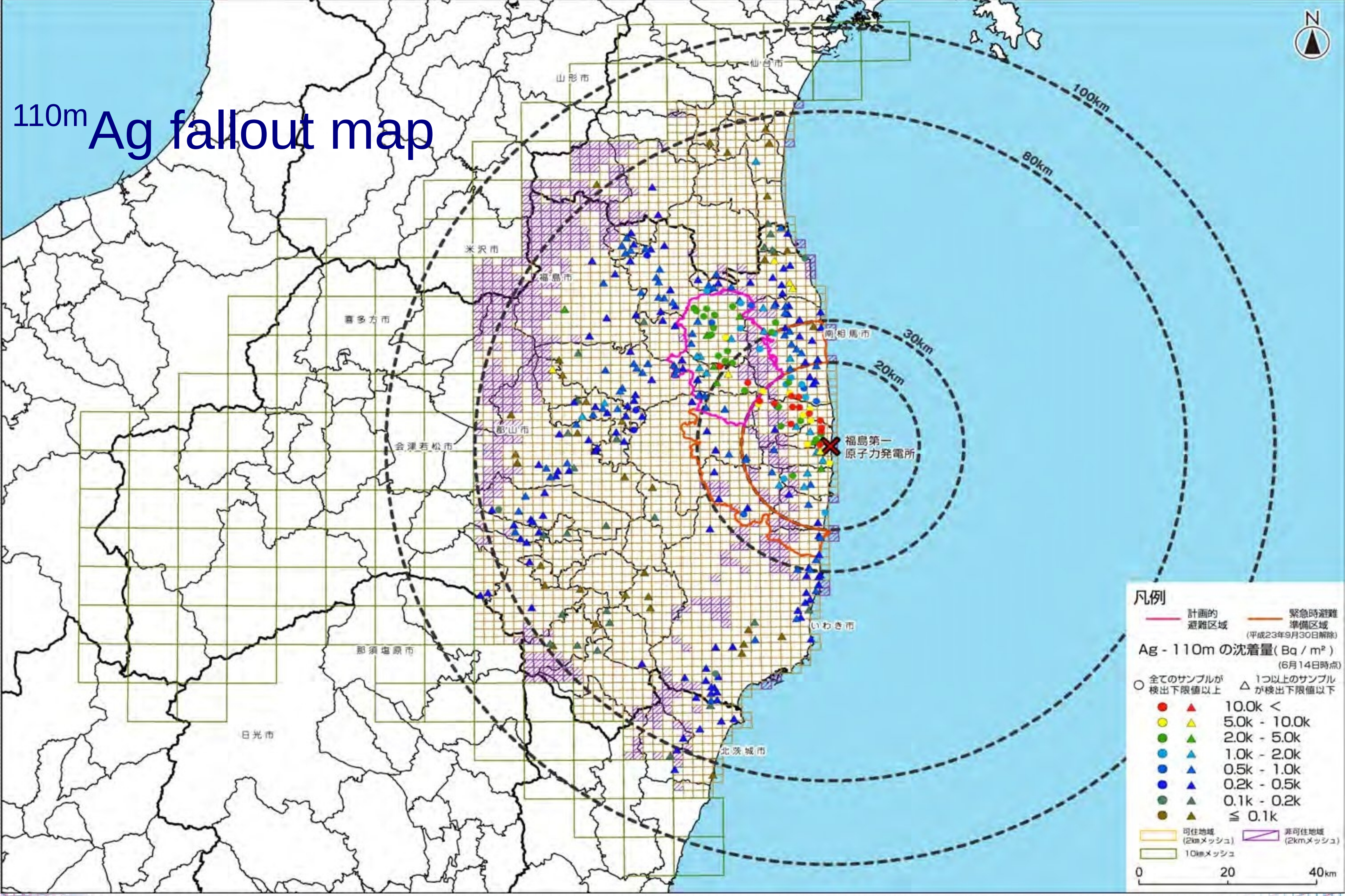
- The 25µm mini-balloon is fragile and needs to be inflated all the time to avoid cracks in the mini-ballon film.
- The mini-ballon weight should not normally exceed 10-15kg.
- Any rapid changes in the mini-balloon weight should be avoided.
- In order to fill (extract) Xe-loaded LS it is necessary to remove (supply) the same amount of a scintillator without Xenon. Precise control of incoming Xe-loaded LS and outcoming dummy scintillator density is required.
- All scintillator containing enriched Xenon needs to be stored for re-processing (Xe gas extraction).



1) ^{110m}**Ag** contamination during mini-balloon fabrication by **Fukushima-I fallout**, and

2) cosmogenic production by Xenon spallation

^{110m}Ag fallout map



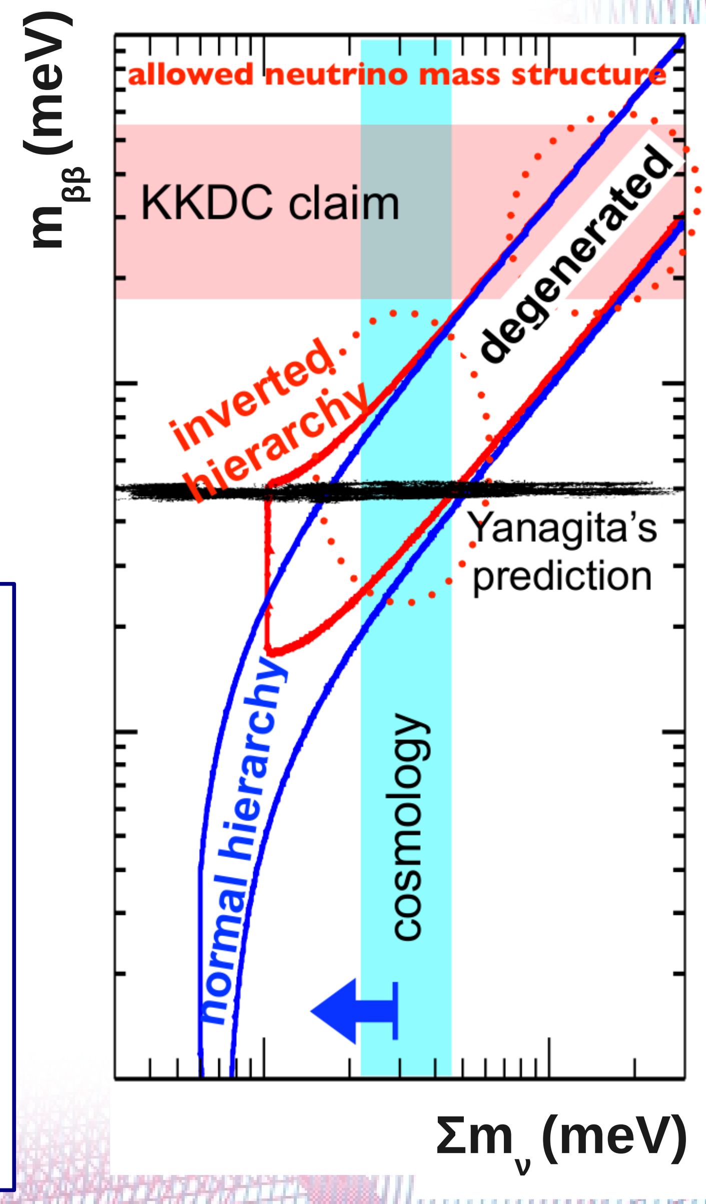
^{110m}Ag was detected in soil samples near RCNS building using Ge detector


Nov 2012


July 2013

Near future for the KamLAND-Zen

- Confirm removal of the ^{110m}**Ag background**. Loaded **scintillator +** ^{136}**Xe (380-390kg)**. Expected sensitivity is **$m_{\beta\beta}$~ 80 meV**
- Construct a new cleaner mini-balloon to reduce the ^{214}**Bi background** from the Nylon film. Load **scintillator +** ^{136}**Xe (600-800kg)**. Expected sensitivity is **$m_{\beta\beta}$~ 40-60 meV**



The seesaw with Occam's razor

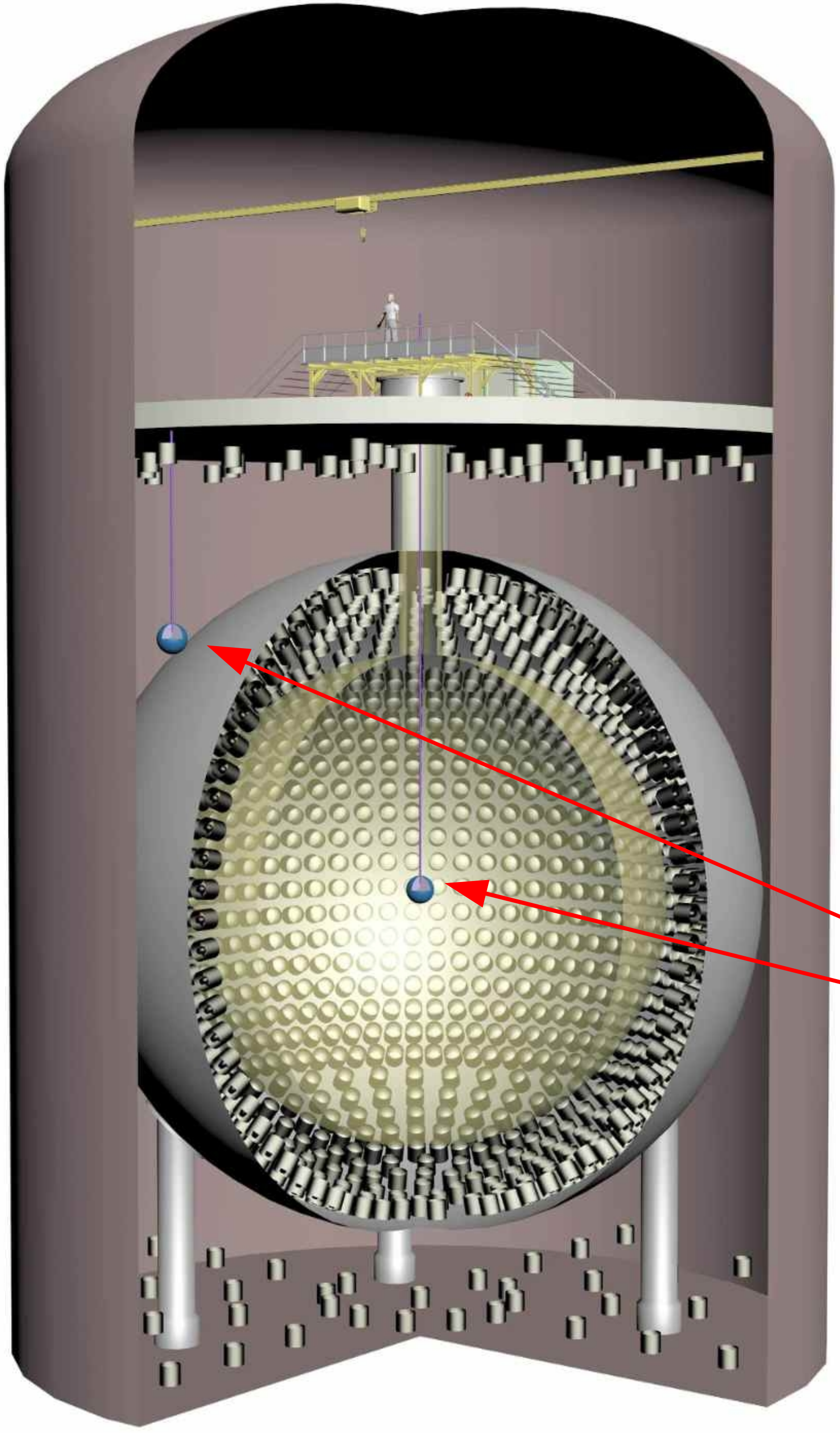
(Frampton, Glashow, Yanagida)

CP violation in neutrino oscillation ↔ baryon asymmetry of the Universe

The normal hierarchy is excluded – consistent with the **inverted hierarchy**.

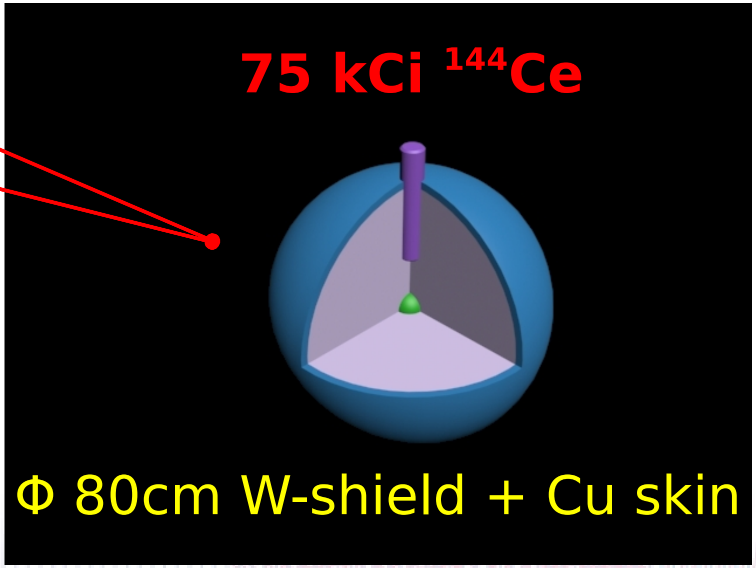
It predicts **$m_{\beta\beta}$ = (47±1) meV**

Sterile neutrino search



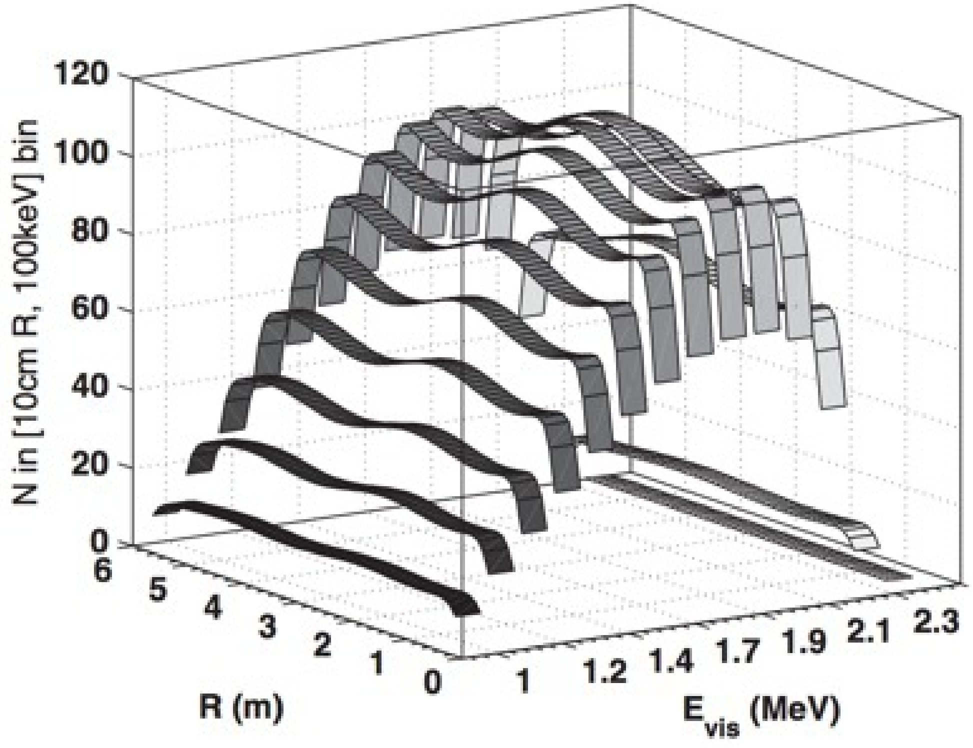
Search for the existence of oscillations into a 4^{th} neutrino.

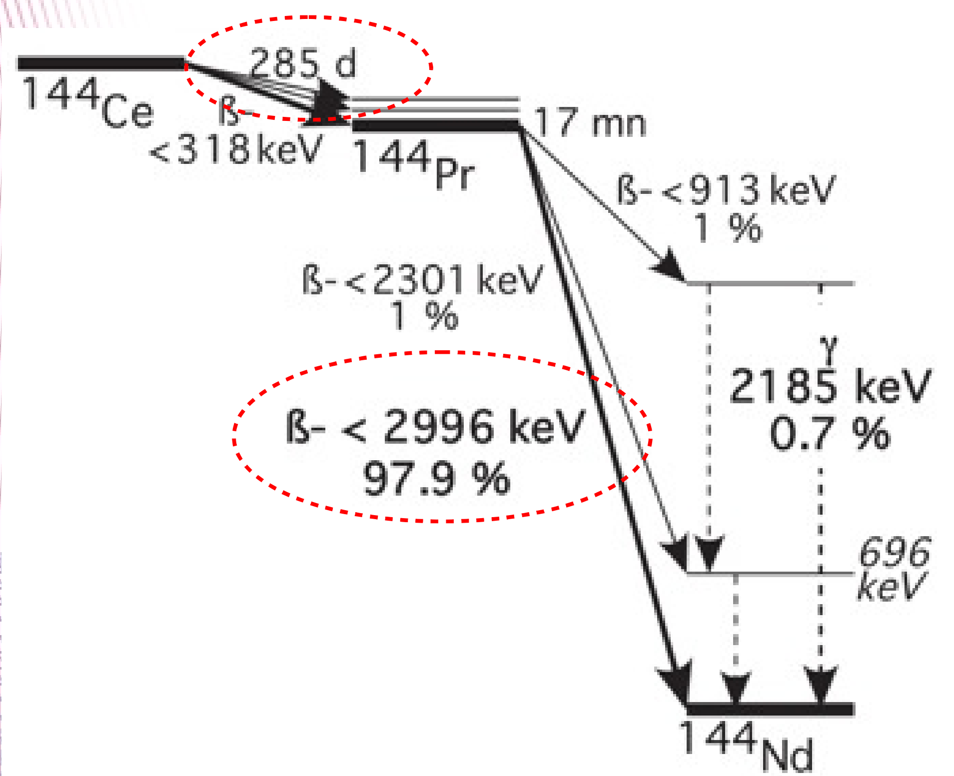
To probe Δm^2 values from 0.1 to a few eV^2 one can use anti-neutrinos with energies of typical of radioactive decays (few MeV) and a baseline of several meters.



Sterile neutrino search

search for an **oscillation pattern** as a function of **L/E$_\nu$**





75 kCi ^{144}Ce anti-neutrino source

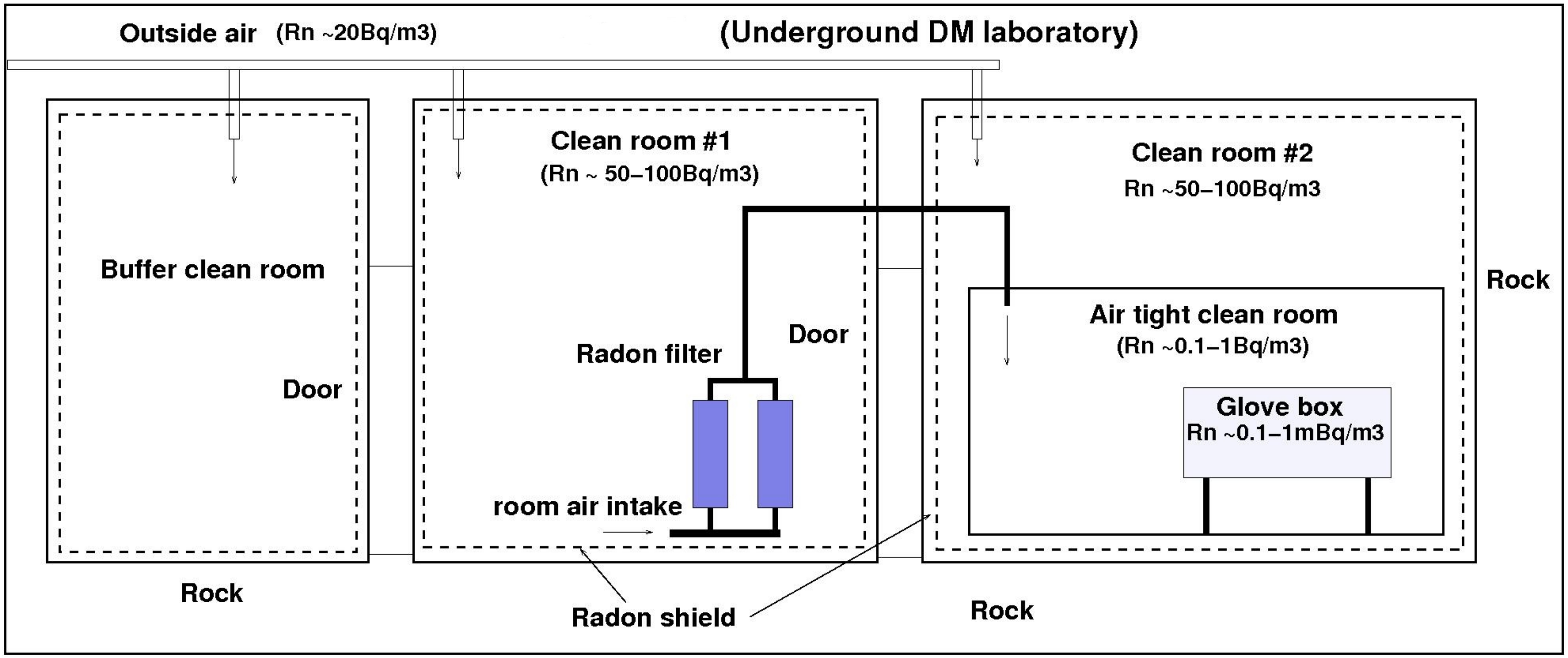
^{144}Pr β-decay Q-value: 3.0 MeV

~1 eV^2 oscillation search

L / E > 1 [m / MeV]

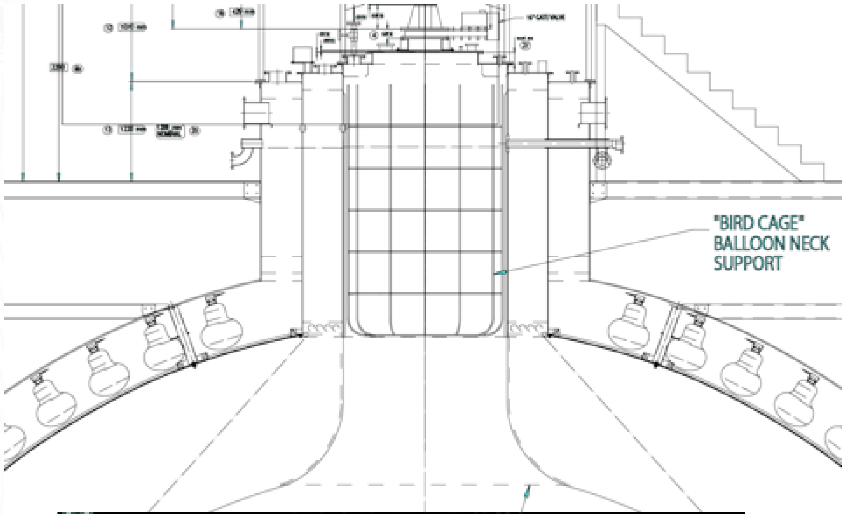
~ 40k events per year

Clean environment for a new R&D



- Construction of two clean rooms at the Kamioka mine equipped with a compact Radon filter.
- Installation of a new Canberra HPGe detector in home-made shielding assembled from an ultra-low background Pb (30cm) and OFHC Cu (stored 8-10years underground).

The KamLAND upgrade (2016)



We plan to install:

- a new high light yield LS;

- light collecting mirrors;

- new high Q.E. PMTs.

- Re-build OD muon veto;

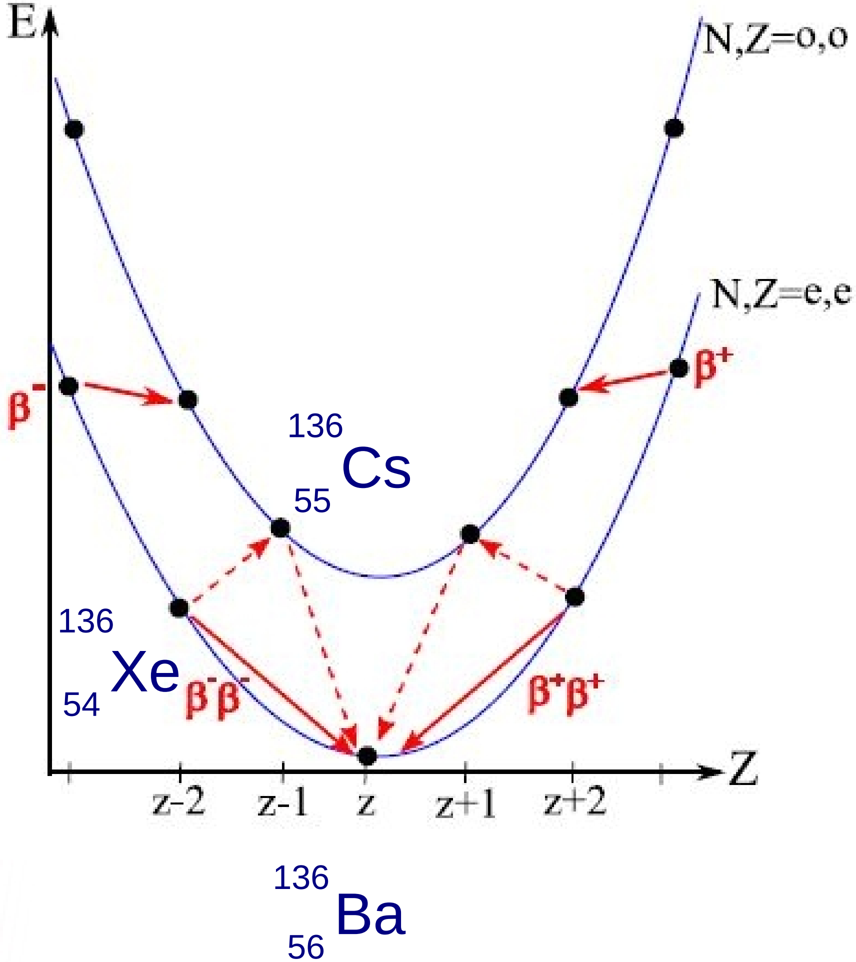
- implement design modifications ...

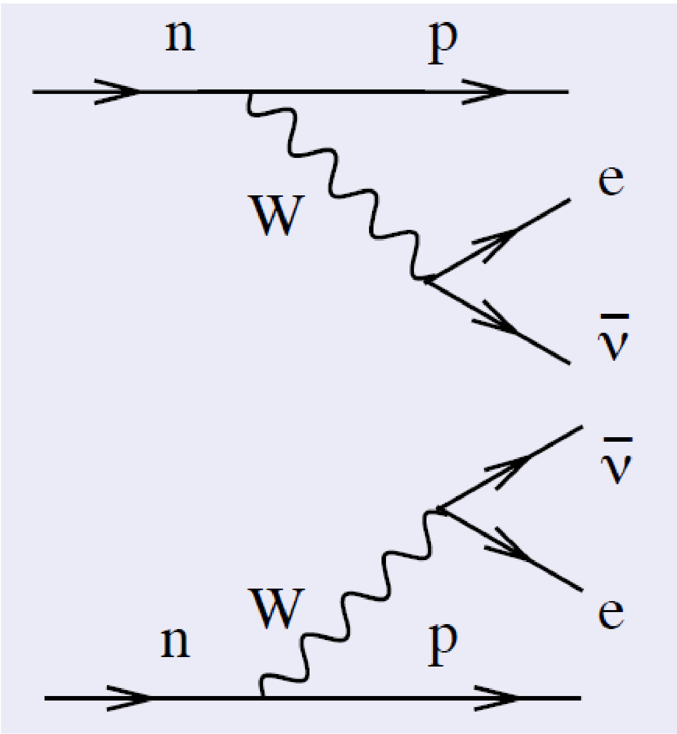
Summary

- We found a way to remove the ^{110m}Ag background to the ^{136}Xe ββ measurement. The KamLAND-Zen experiment was restarted in Dec 2013. We take physics data now.
- We have a well established plan how to upgrade the KamLAND-Zen further in the next few years.
- We continue to use unique chance to improve neutrino oscillation and geo-neutrino results during the time window with a low reactor anti-neutrino flux (all Japanese nuclear reactors were stopped in 2013).
- We pursue R&D towards Dark Matter search, sterile neutrino search using a ^{144}Ce anti-neutrino source.
- We work on future KamLAND detector upgrade.

Thank you for your patience.

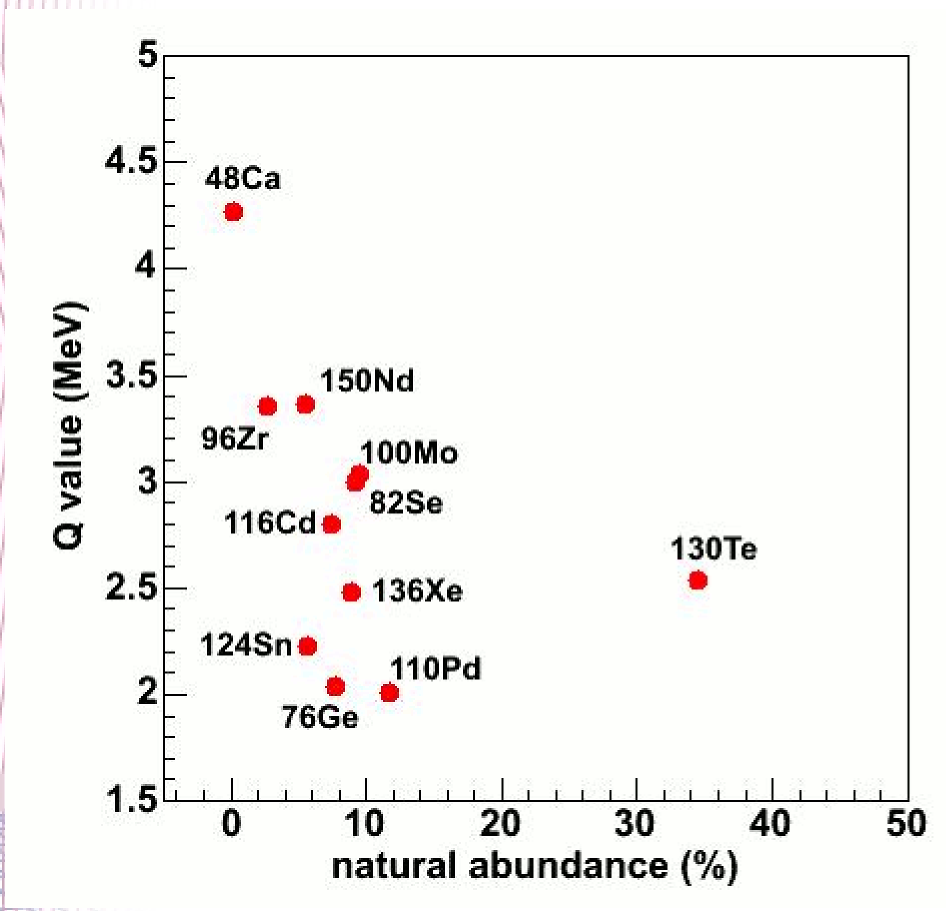
Conventional 2νββ-decay





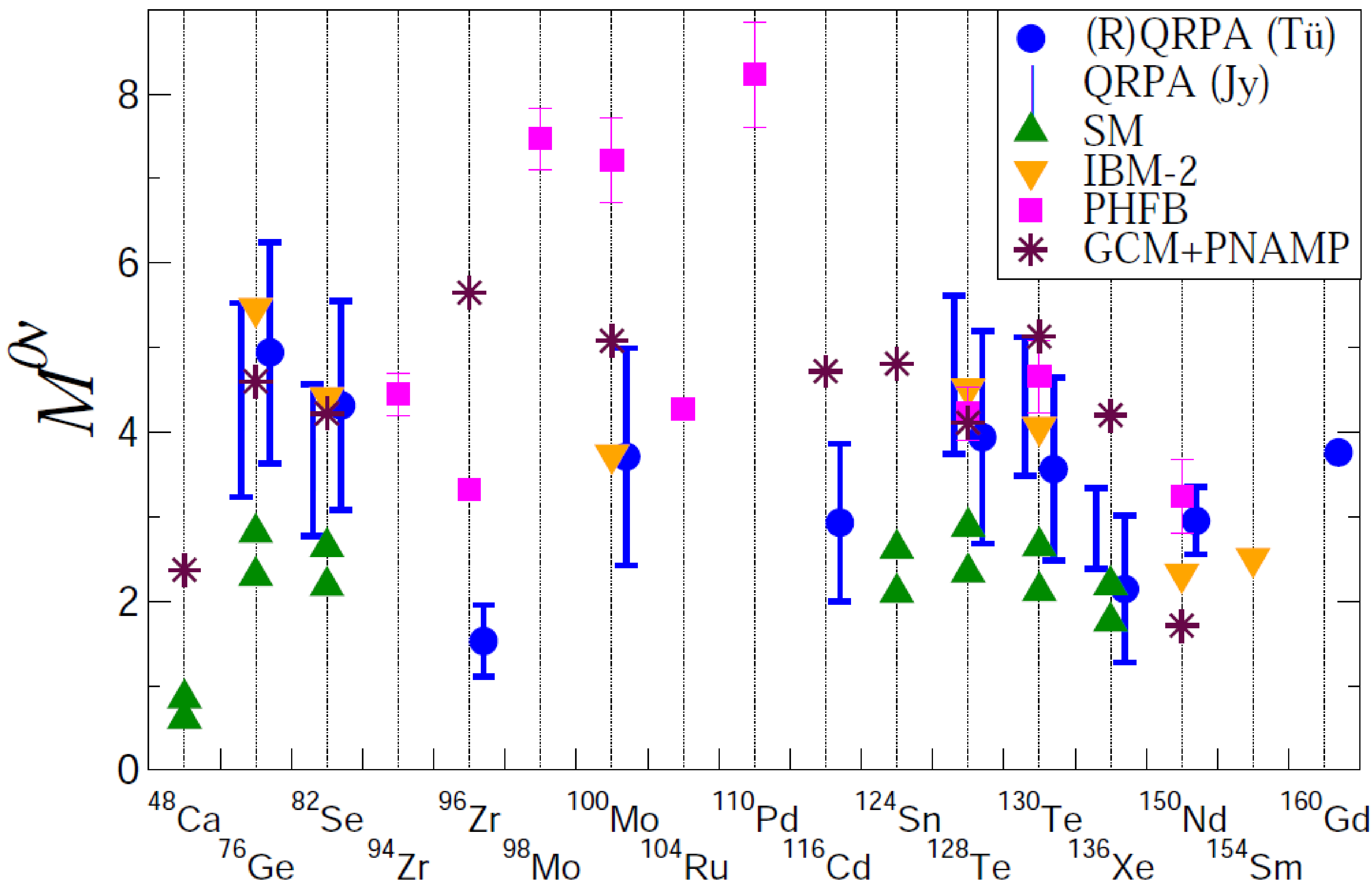
β-decays that change the nuclear charge Z by a value of ±1 are energetically impossible but a transition via two consecutive β-decays is possible. A double beta decay (2νββ) in the form of (Z,A) → (Z+2,A) + $2e^-$ + 2 ν_e was proposed first by M. Goeppert-Mayer in 1935.

Most promising double-beta decay isotopes



Isotope	Measured $T_{1/2}(2\nu)$, y
^{150}Nd	$(1.4 \pm 0.7) \cdot 10^{20}$
^{136}Xe	$(2.38 \pm 0.14) \cdot 10^{21}$
^{130}Te	$(7.0 \pm 0.9 \pm 1.1) \cdot 10^{20}$
^{128}Te	$(7.2 \pm 0.4) \cdot 10^{24}$
^{116}Cd	$(2.9 \pm 0.4) \cdot 10^{19}$
^{100}Mo	$(5.7 \pm 1.2) \cdot 10^{20}$
^{96}Zr	$(2.1 \pm 0.6) \cdot 10^{19}$
^{82}Se	$(9.6 \pm 1.0) \cdot 10^{19}$
^{76}Ge	$(1.77 \pm 0.12) \cdot 10^{21}$
^{48}Ca	$(4.3 \pm 2.2) \cdot 10^{19}$

Nuclear matrix elements calculations



Significant progress in theoretical calculations of NME was achieved recently

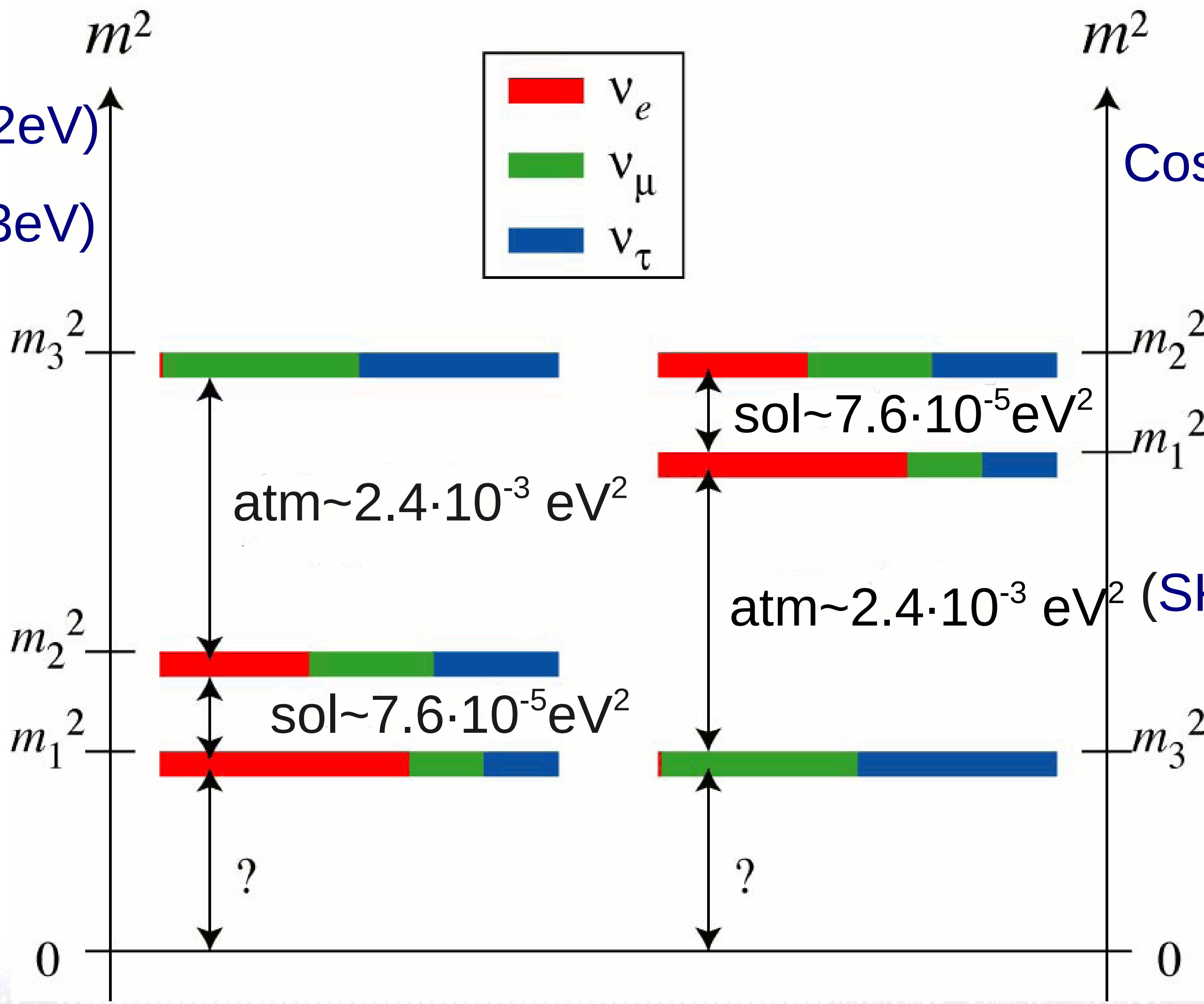
Neutrino mass pattern

SN1987A (20eV)

^{3}H decay (2eV)

0νββ (0.3eV)

Cosmology (1eV)



(KamLAND)

(SK, MINOS,T2K)

^{137}Cs fallout map