Search for new physics using underground detectors

IPMU

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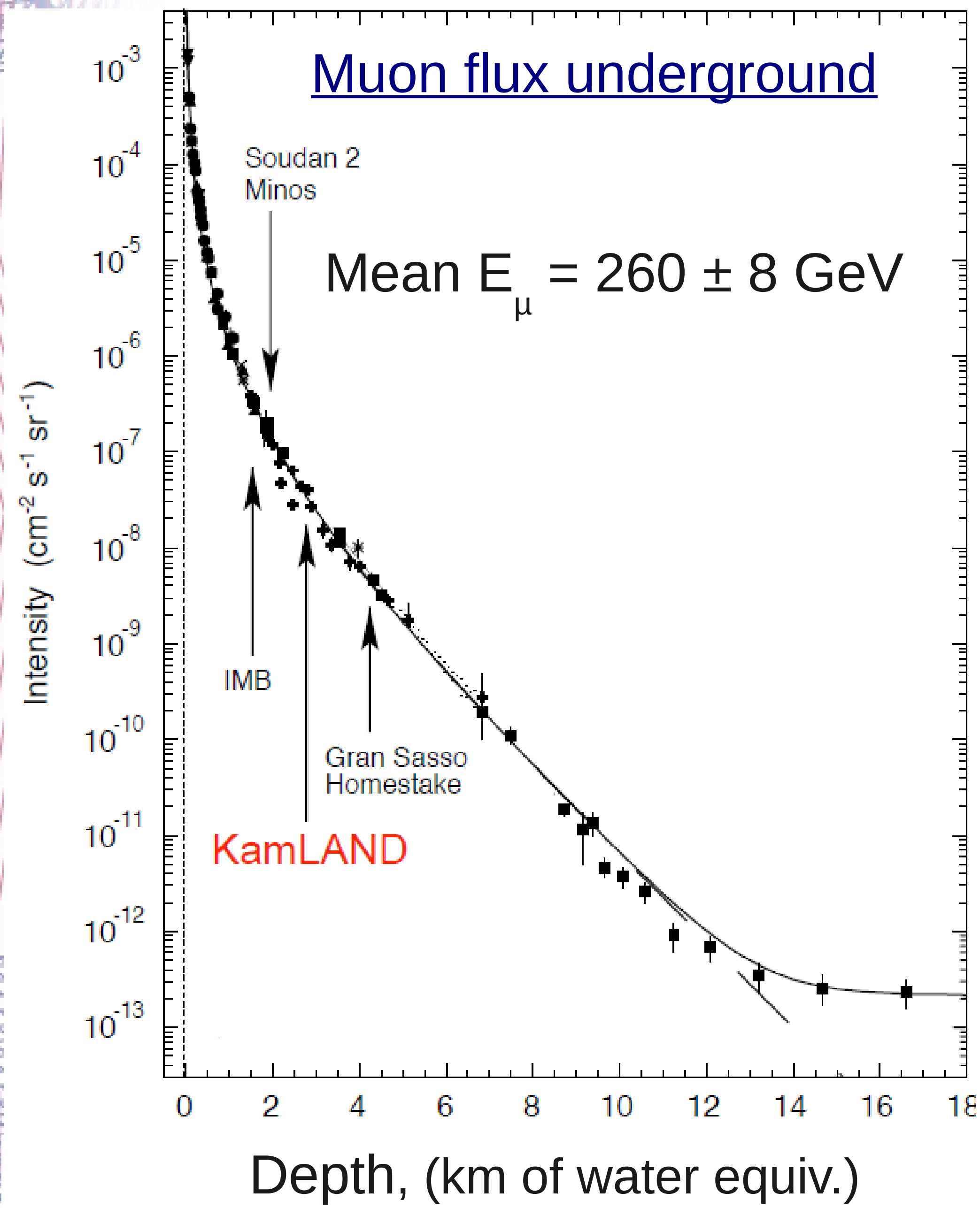
Our main goal – search for (very) rare events

- A classic example of the rare event search is nucleon decay search. It was not found yet but created many useful by-products such as discovery of neutrino oscillation.
- Another example: search for nature of neutrino particles (Dirac vs Majorana) using neutrino-less double beta decay (half life longer than 10^{25}year). So far no events were found.
- Do we seach only for illusive and potentially even non-existing events? No. We detect also some existing particles.
- In good times of old nuclear Japan every day we detected one reactor anti-neutino. Now that all gone.
- At the same time every month we find 2 anti-neutrino events from the Earth as a compensation.

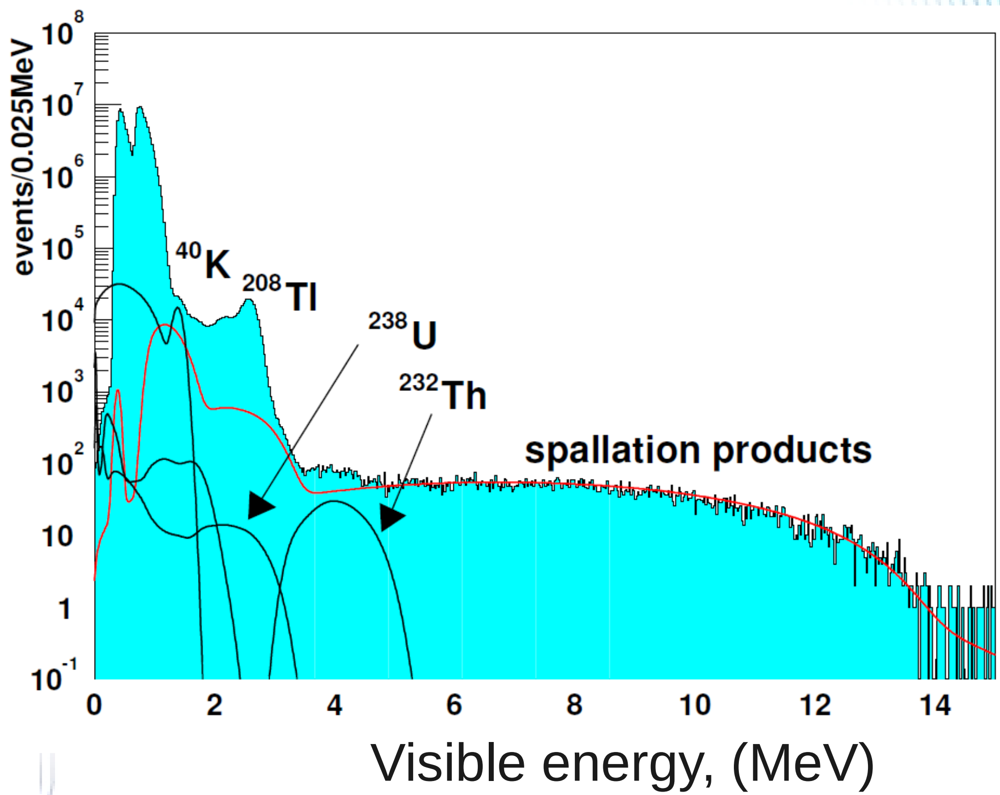
Outline

- Underground detectors (mainly using KamLAND located at Kamioka mine as an example): background composition, design features, material purity requirements
- Neutrino physics and astrophysics (0.1-50MeV)
- Double-beta decay search (few MeV)
- Direct Dark Matter detection (~10keV)

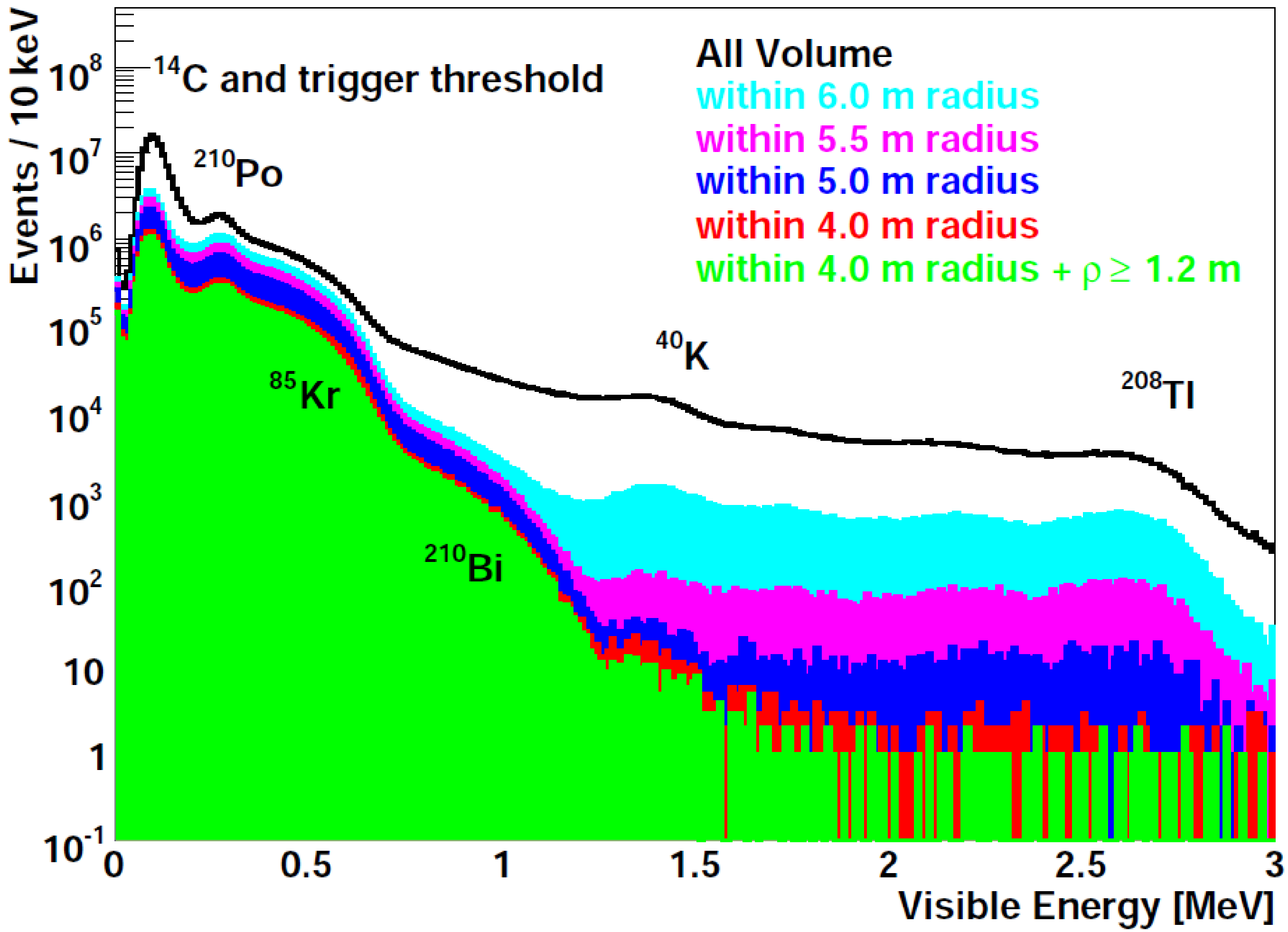
Cosmic-ray muon background



1000 m of rock reduces the muon event rate to 0.34Hz in the KamLAND detector. High energy muon events cause dead time, and create non-stable products in **^{12}C + μ** → neutrons, ^{11}C, ^{10}C, ^{9}C, ^{12}B, ^{9}Li, ^{8}B, ^{11}Be, ^{8}Li , ...



Background from natural and artificial radioactivity



Rock material at Kamioka mine

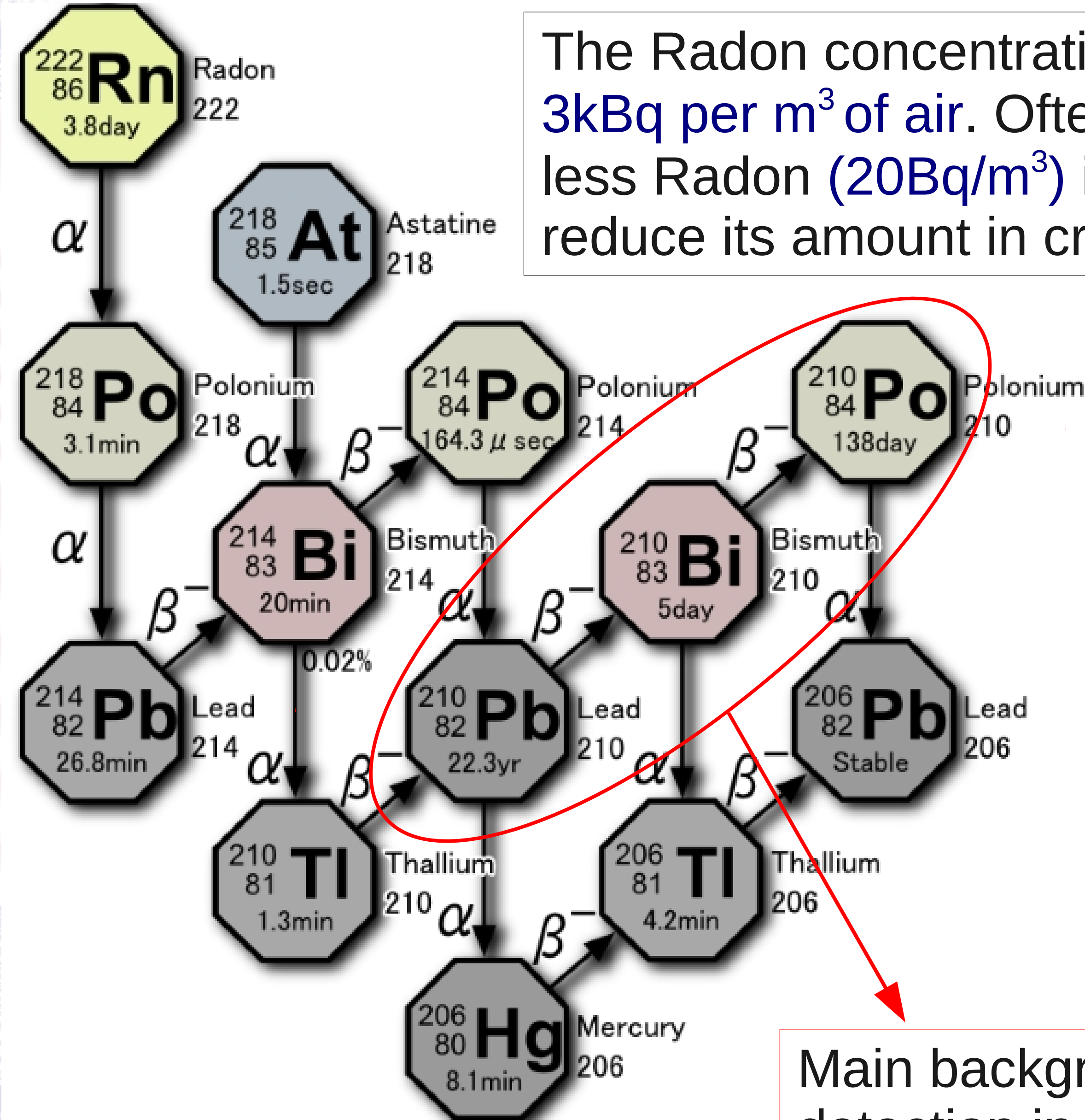
U: ~1.0 ppm

Th: ~3.2 ppm

K: ~ 1.6 %

^{238}U, ^{232}Th and daughter products, ^{40}K in a rock, water and detector materials; ^{222}Rn gas and its daughters (^{214}Pb, ^{214}Po, ^{214}Bi, ^{210}Pb, ^{210}Po, ^{210}Bi), ^{85}Kr are background sources in a few MeV energy region. ^{14}C is a low energy β-emitter of cosmogenic origin present in organic materials, such as scintillator.

^{222}Rn is one of the most serious backgrounds



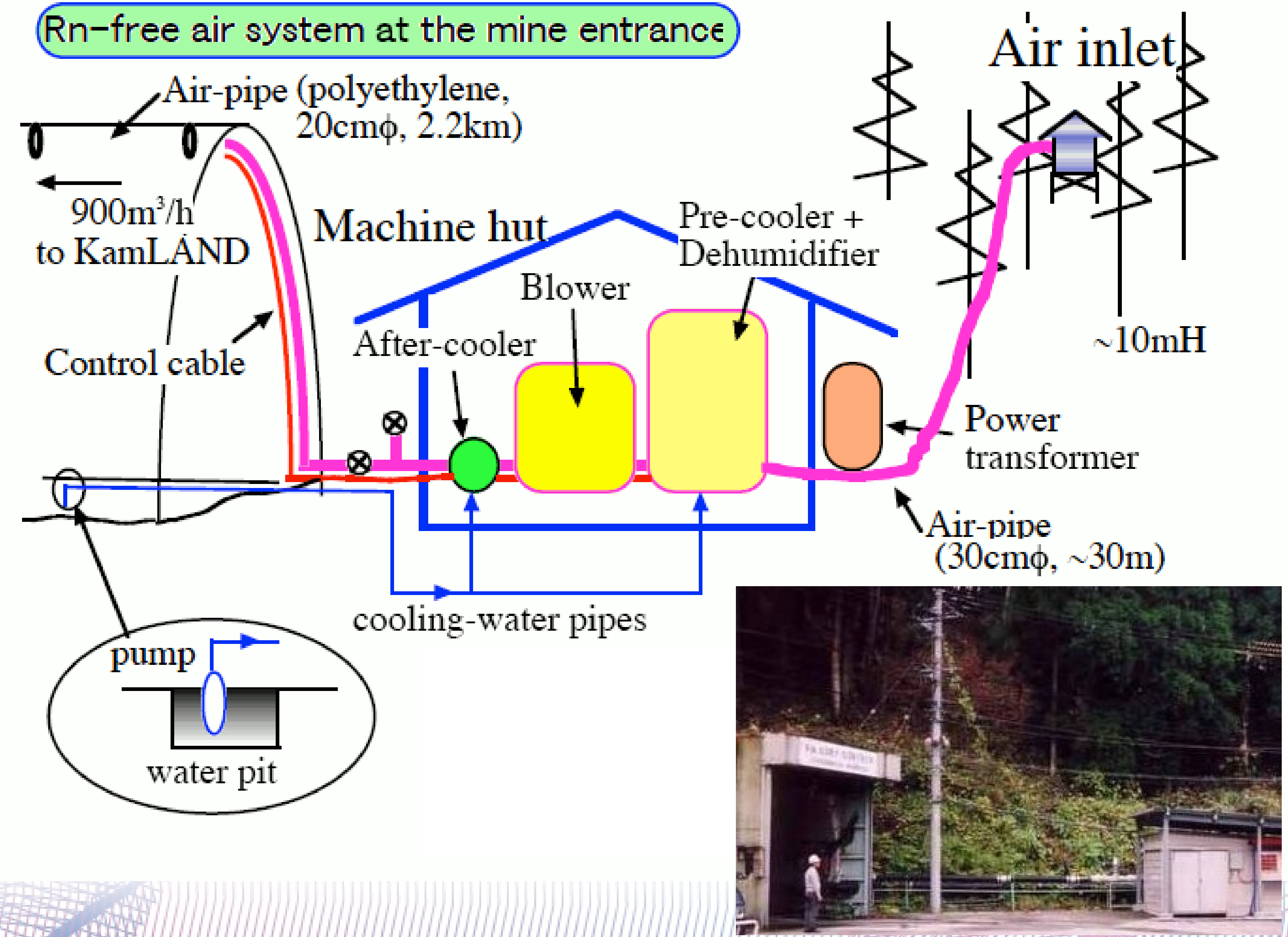
The Radon concentration underground could be 3kBq per m^3 of air. Often outside air that contains less Radon (20Bq/m^3) is used (SK, KamLAND) to reduce its amount in critical underground locations.

Radon amount is also reduced by using:

- Radon shields
- Cold Radon traps
- Pure Nitrogen purge

Main background for solar ν detection in KamLAND and Borexino

KamLAND Radon-less air system

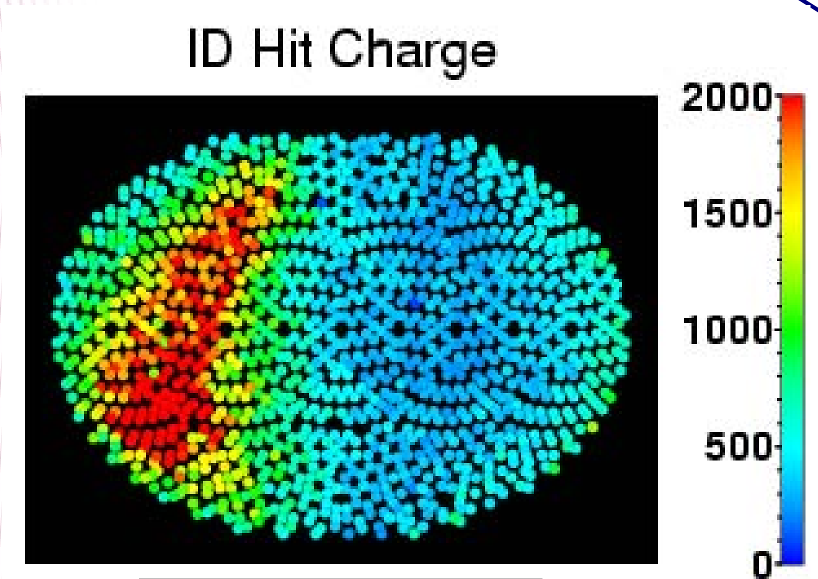


Construction and operation of a low background detector

- All detector materials require radiopurity screening (e.g. by using underground high-purity Ge detectors, ICP-MS)
- Cosmogenic radio isotopes with a long half-life created at a sea level need to be avoided or removed. Careful surface cleaning procedures have to be implemented for all solid materials.
- Usage of clean rooms, strict handing procedures and control is needed to prevent solid dust accumulation
- Material contacts with Radon should be minimized, sometimes by using a constant flow of a pure Nitrogen gas (in KamLAND 8L/min)
- Usage of purification systems is often required
- A multi-layer detector design, self-shielding against external γ-rays and fast neutrons from rock are commonly used
- If possible, use events specific signatures to distinguish those from background (various timing information, particle type identification)

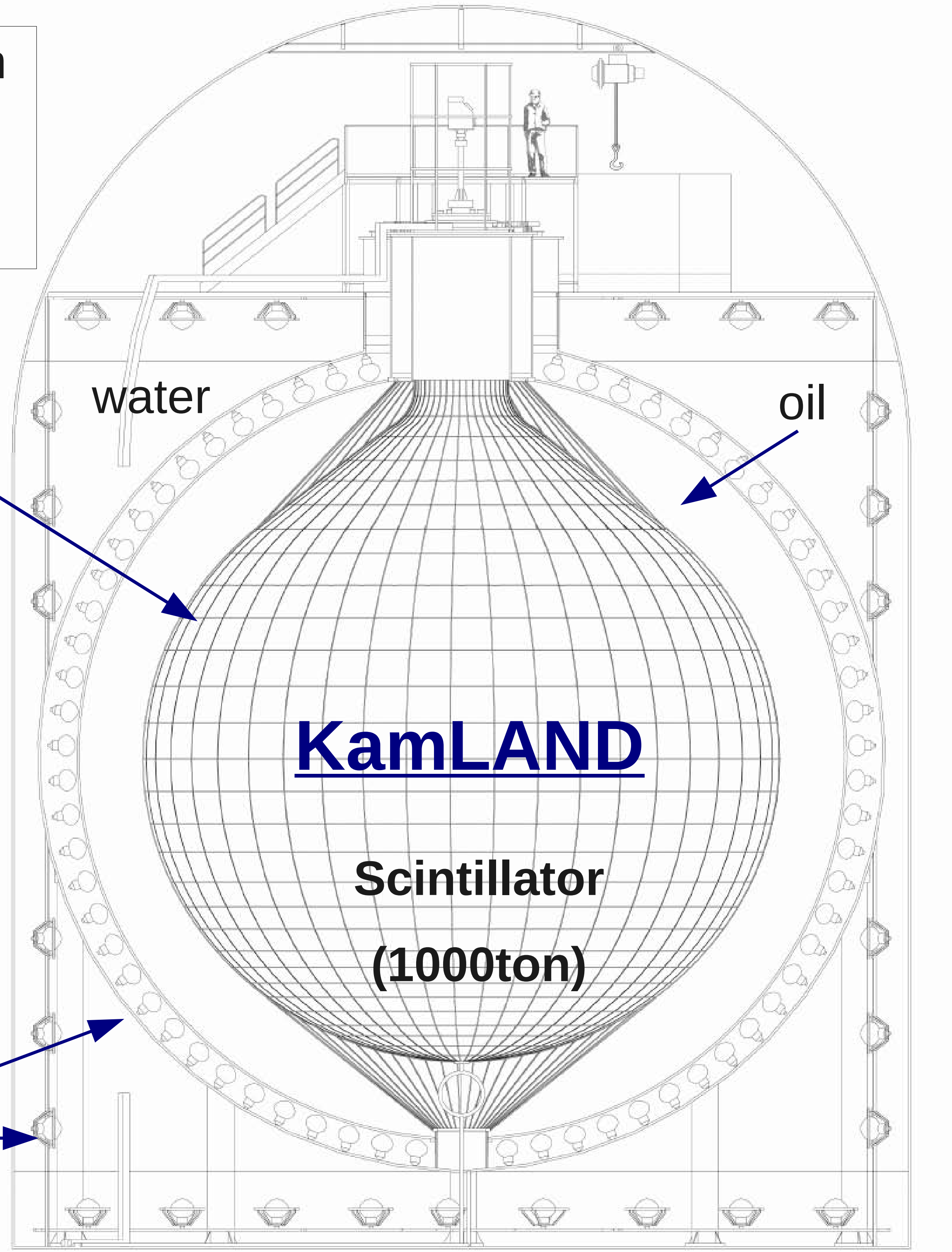
Charged particles interaction with matter results in: scintillation and Cherenkov light emission

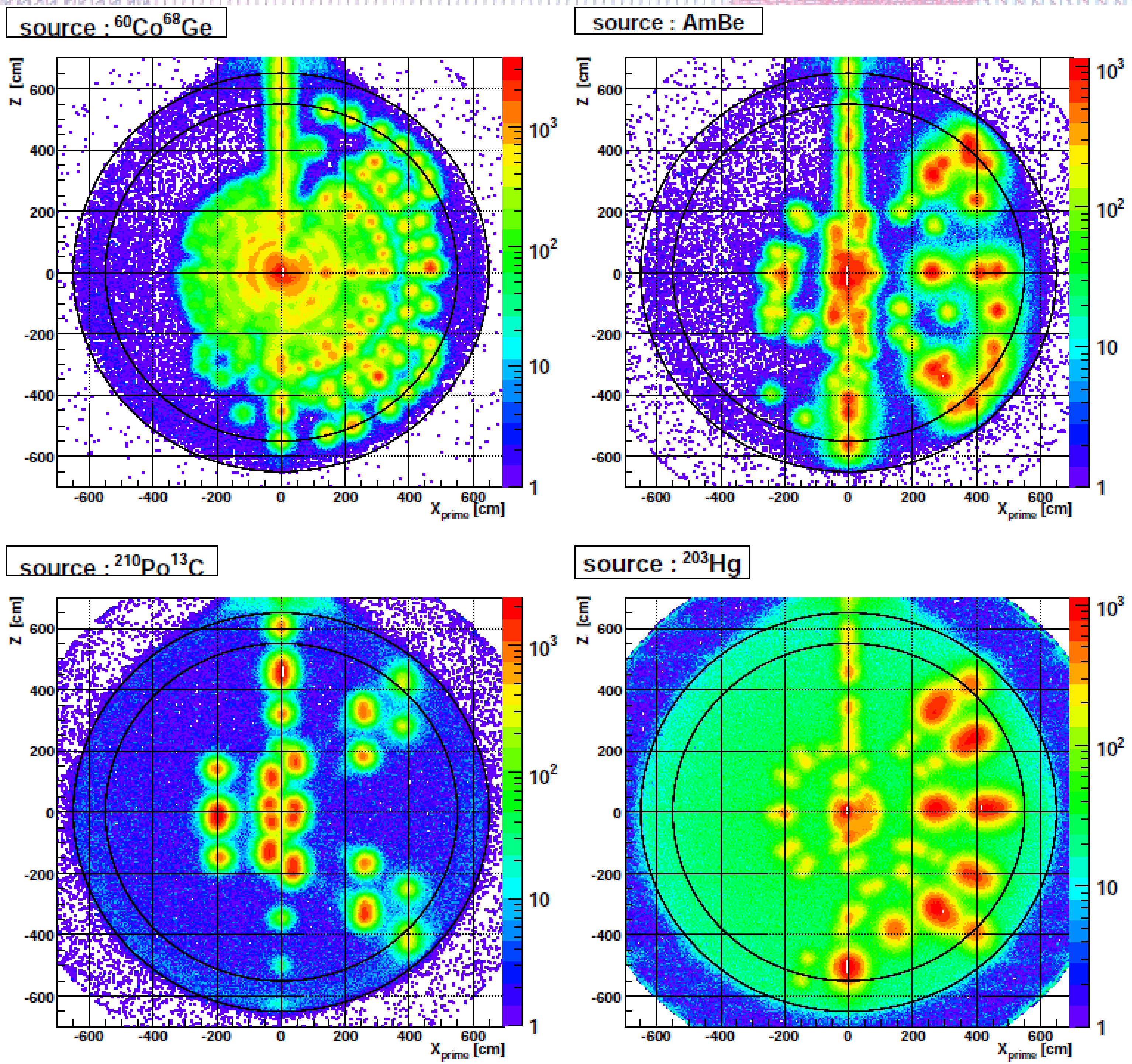
13m-diameter 135μm-thick plastic balloon



Muon track in KamLAND

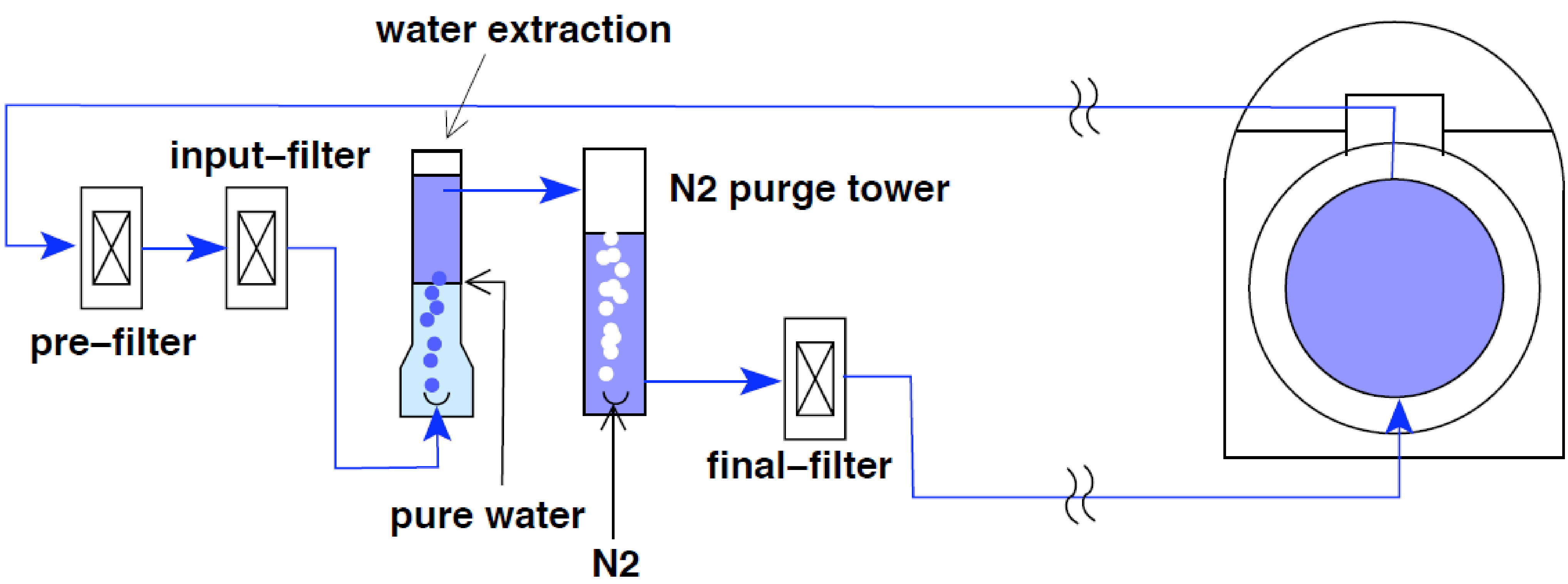
Photo-detectors: (50cm PMTs)





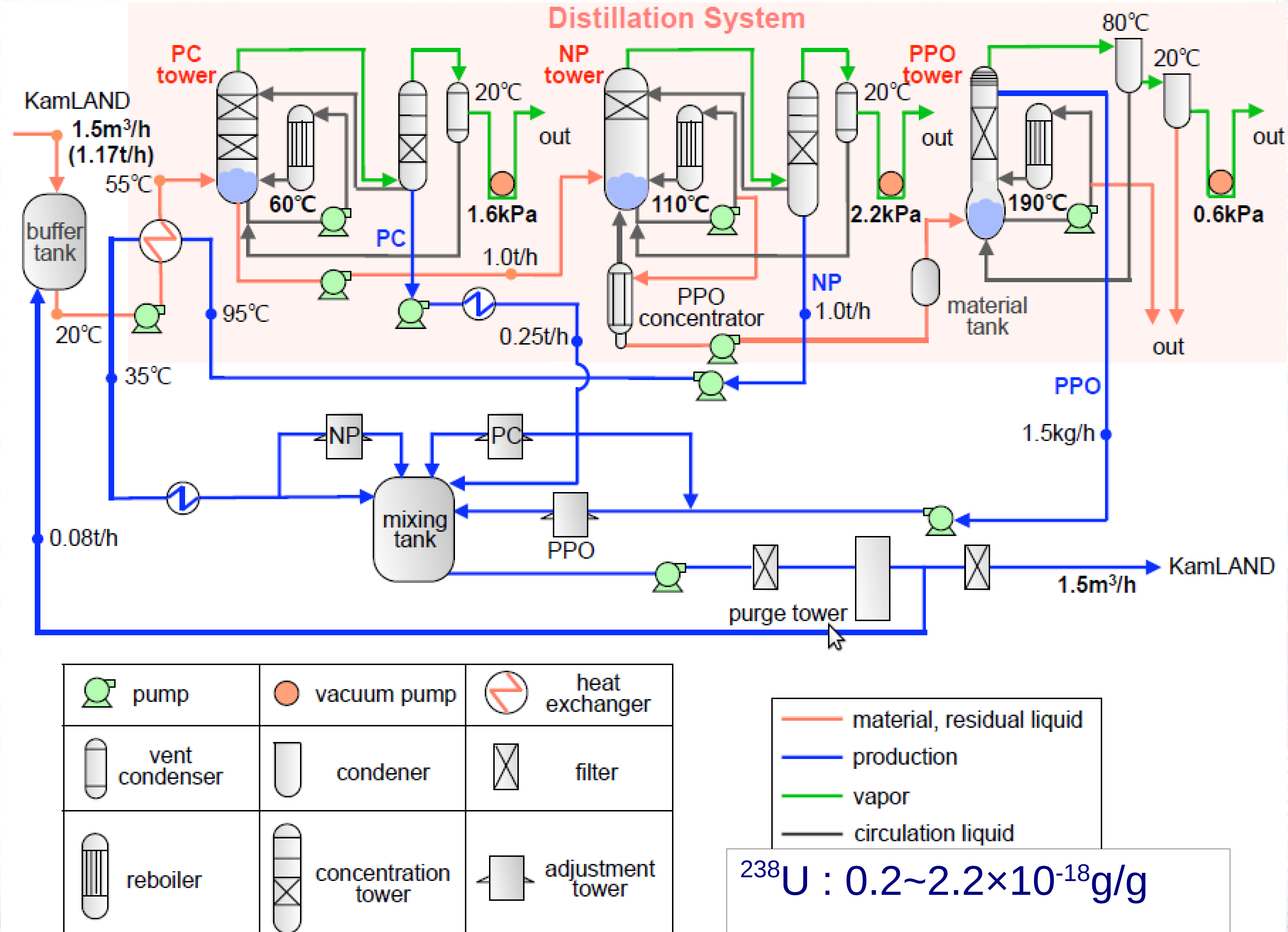
source : $^{60}Co^{68}Ge$
source : AmBe
source : $^{210}Po^{13}C$
source : ^{203}Hg
Z [cm]
X_{prime} [cm]
600
400
200
0
-200
-400
-600
1
10
10^2
10^3

First KamLAND purification system



Liquid scintillator achieved purity: ^{238}U ~$3.5\cdot10^{-18}$g/g; ^{232}Th ~$5.2\cdot10^{-17}$g/g while purifty of ordinary materials ~ 1ppm. Unfortunately, ^{222}Rn and ^{85}Kr contamination occured during the detector filling process

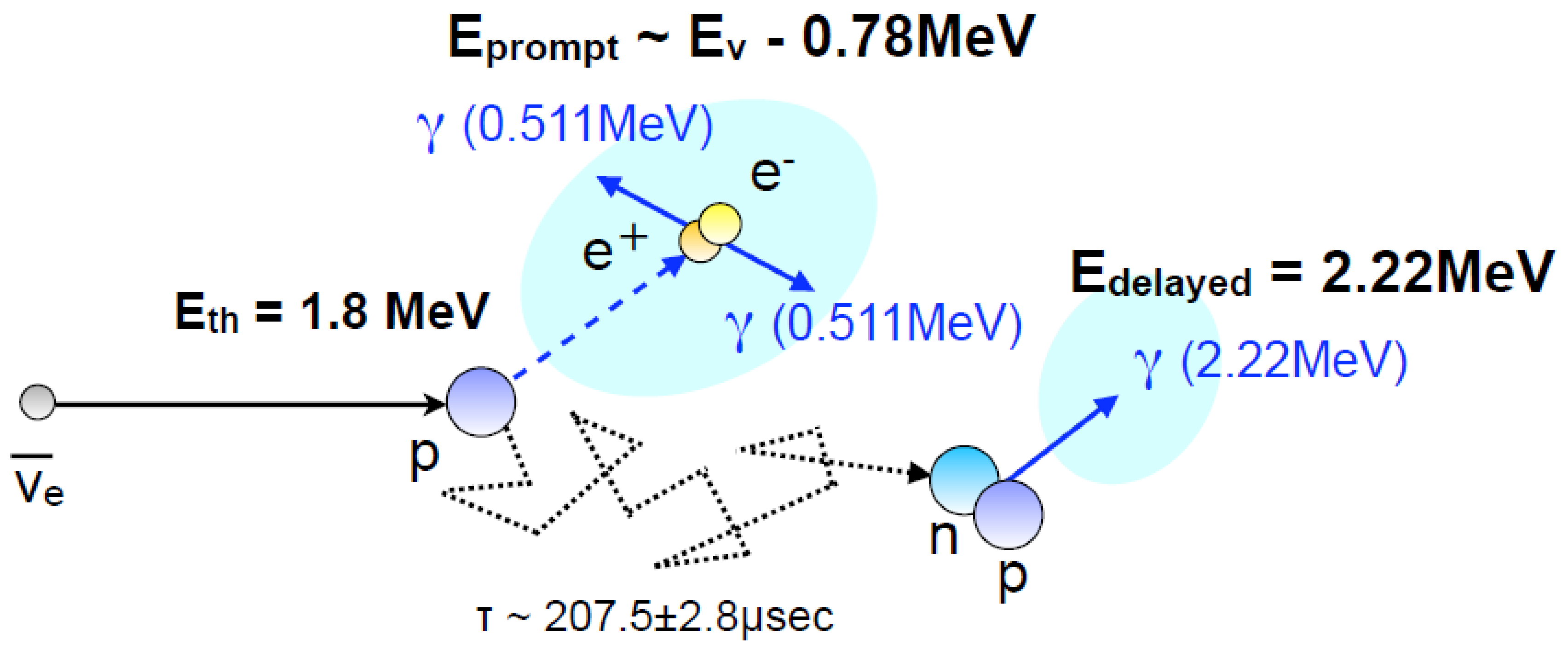
The KamLAND distillation system



^{238}U : $0.2\sim2.2\times10^{-18}$ g/g

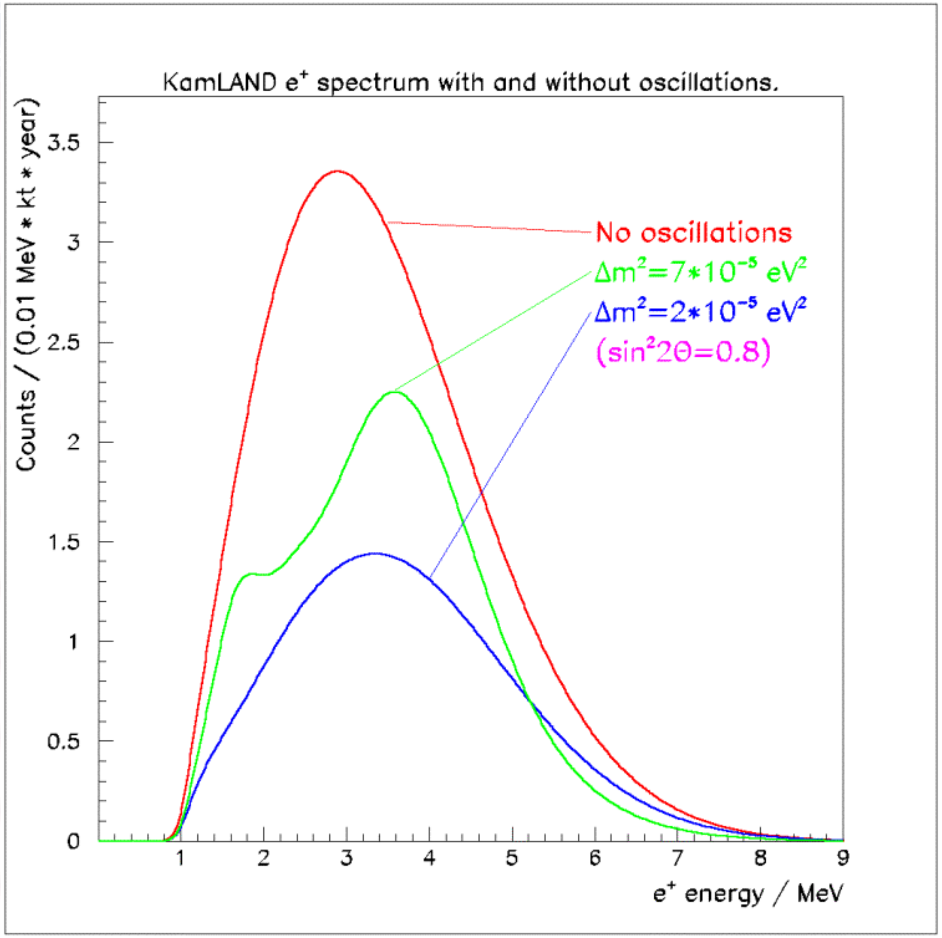
^{232}Th : $1.9\sim4.8\times10^{-17}$ g/g

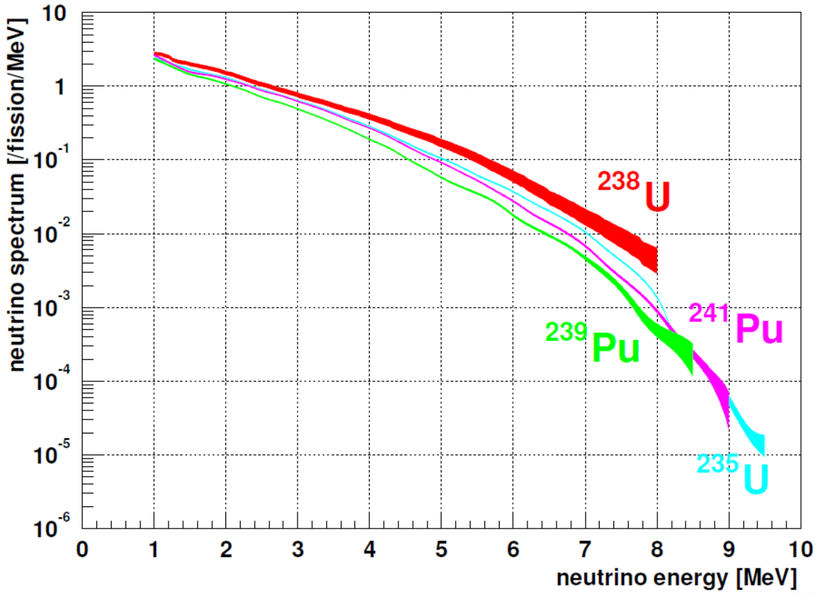
The anti-neutrino detection using organic liquid scintillators

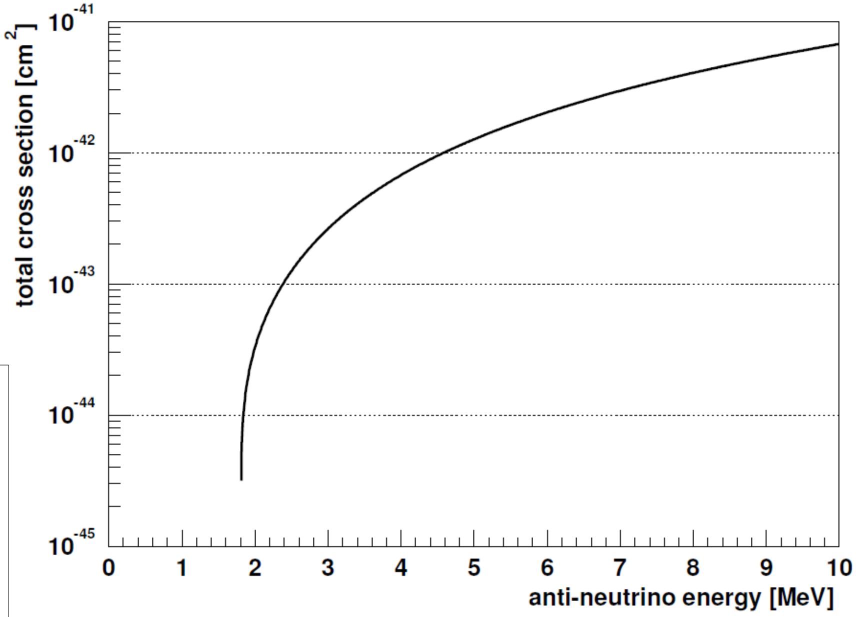


Time-and-position correlation between prompt and delayed events allows clean observation of the reactor anti-neutrinos in KamLAND, Borexino and in the future SNO+ detectors

Reactor anti-neutrino energy spectrum



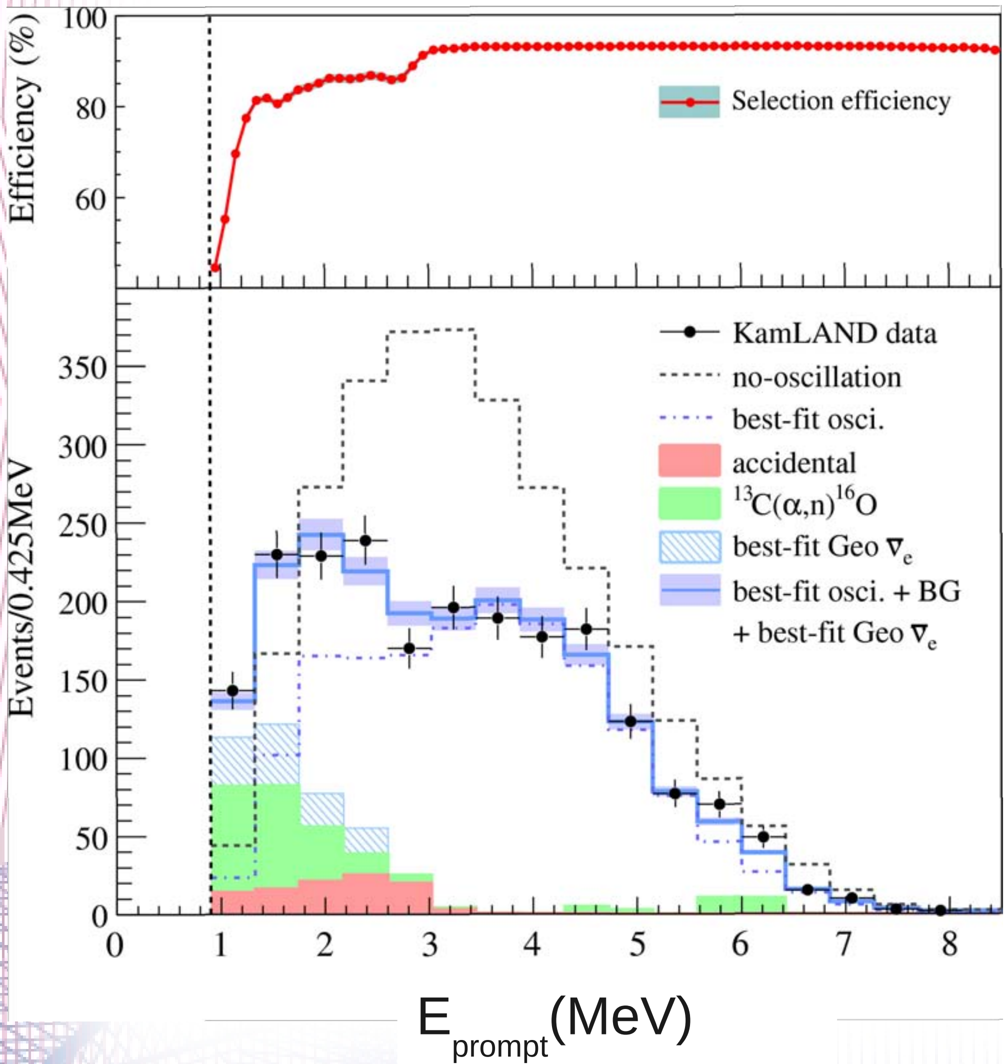


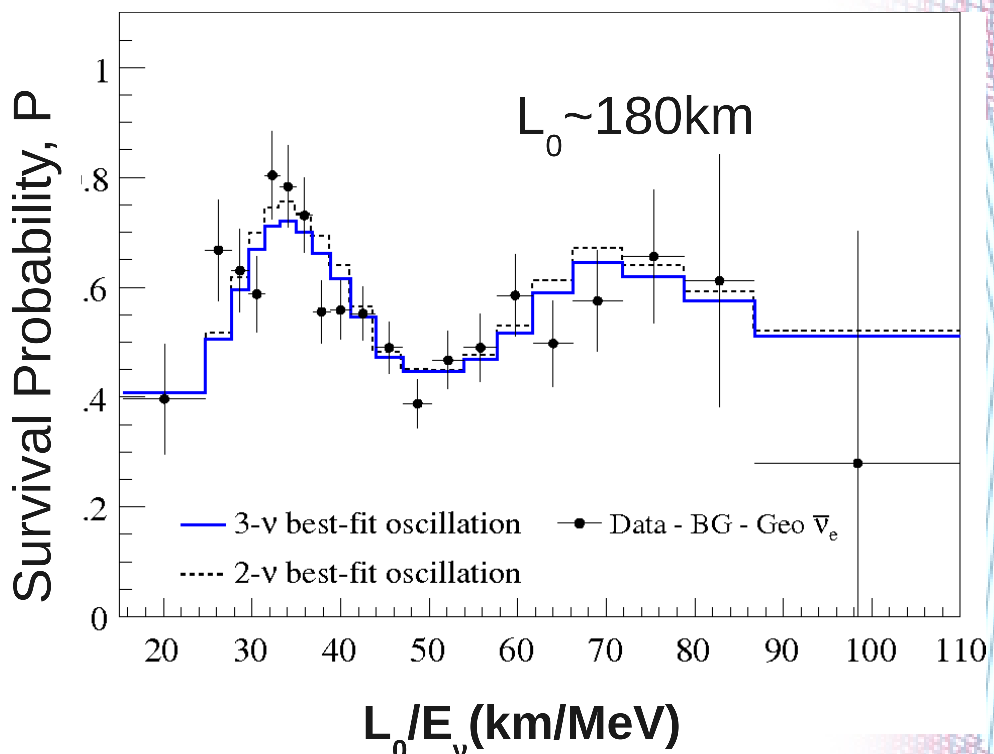


Using known reactor power, nuclear fuel composition and distance to reactors we obtain positron spectrum at KamLAND

The reactor anti-ν result PRD 83, 052002 (2011)

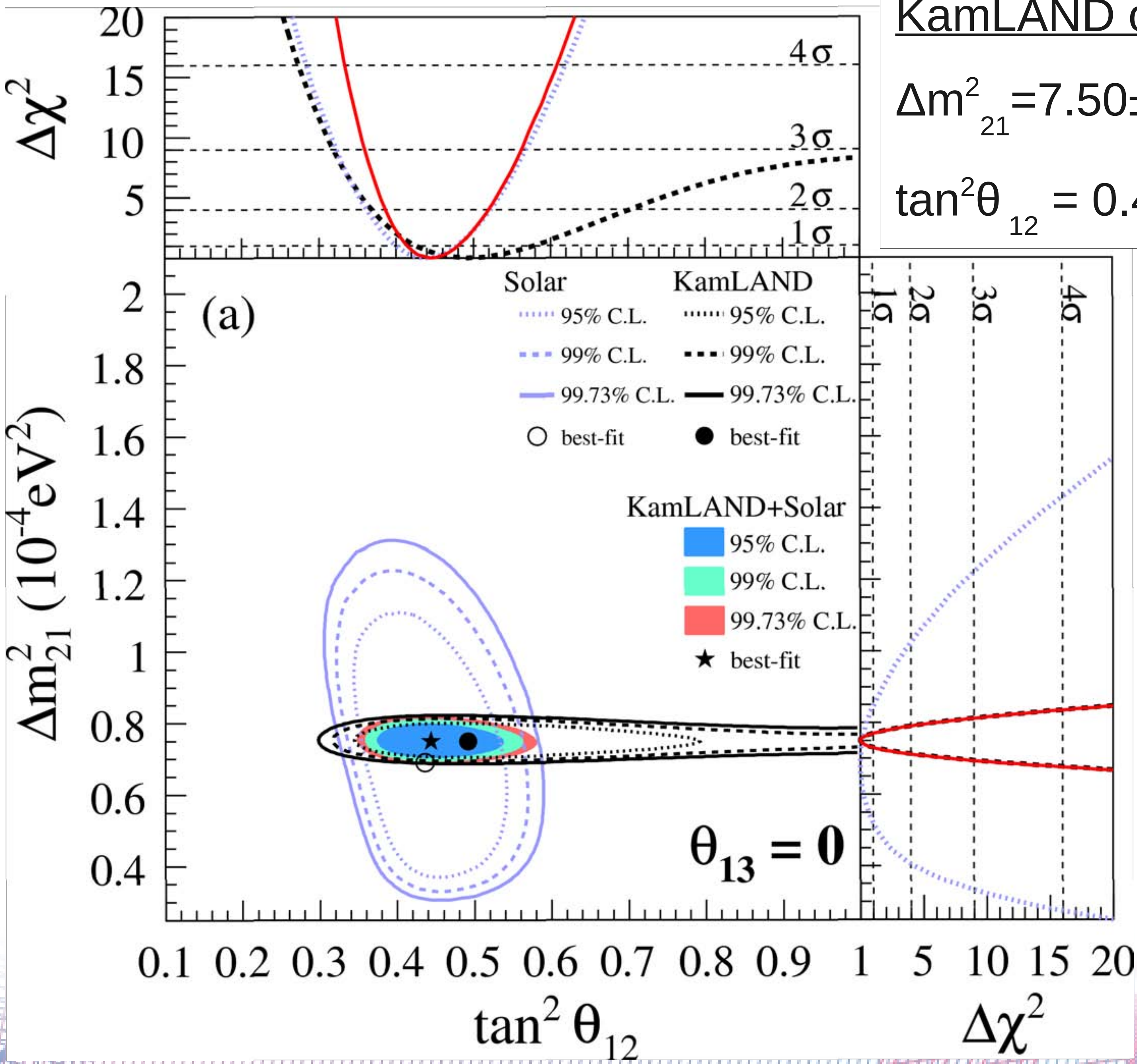
P = (number of observed - B.G.) / (expected no oscill.)





$$P^{2\nu} = 1 - \sin^2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

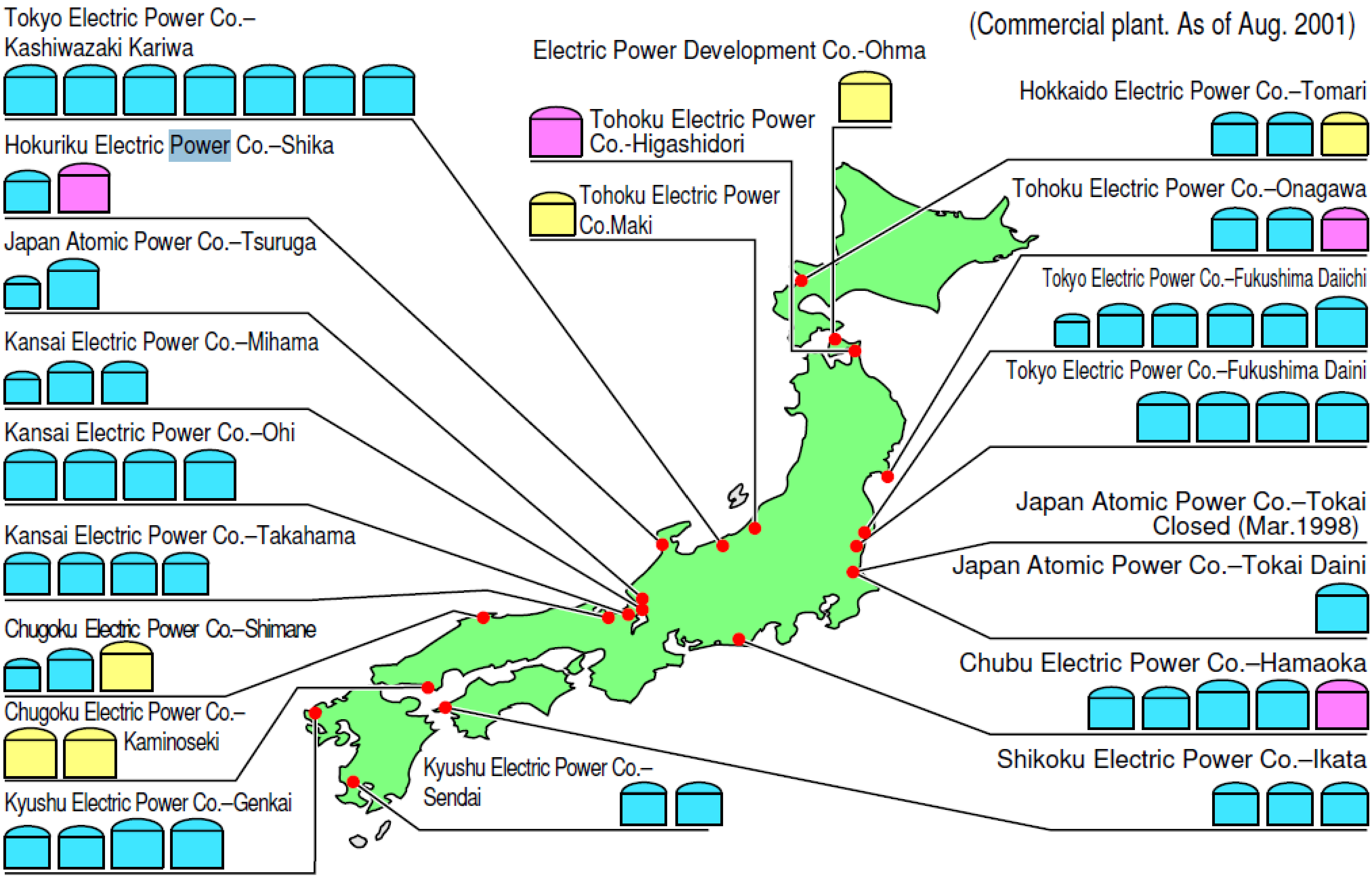
The reactor anti-ν result PRD 83, 052002 (2011)



KamLAND only

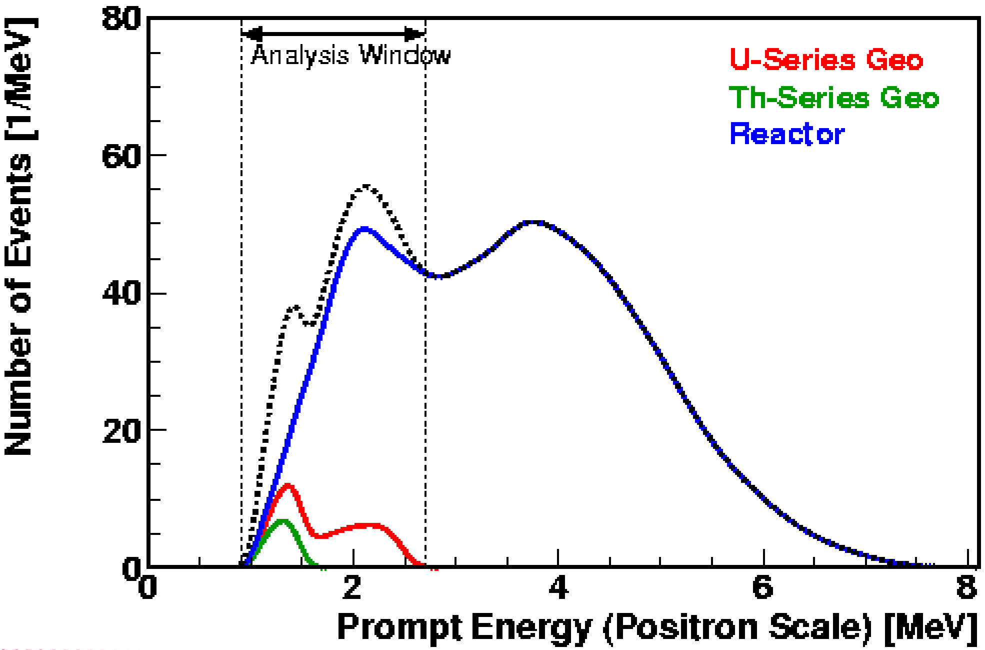
Δm^2_{21}=7.50±0.2·10^{-5} eV^2

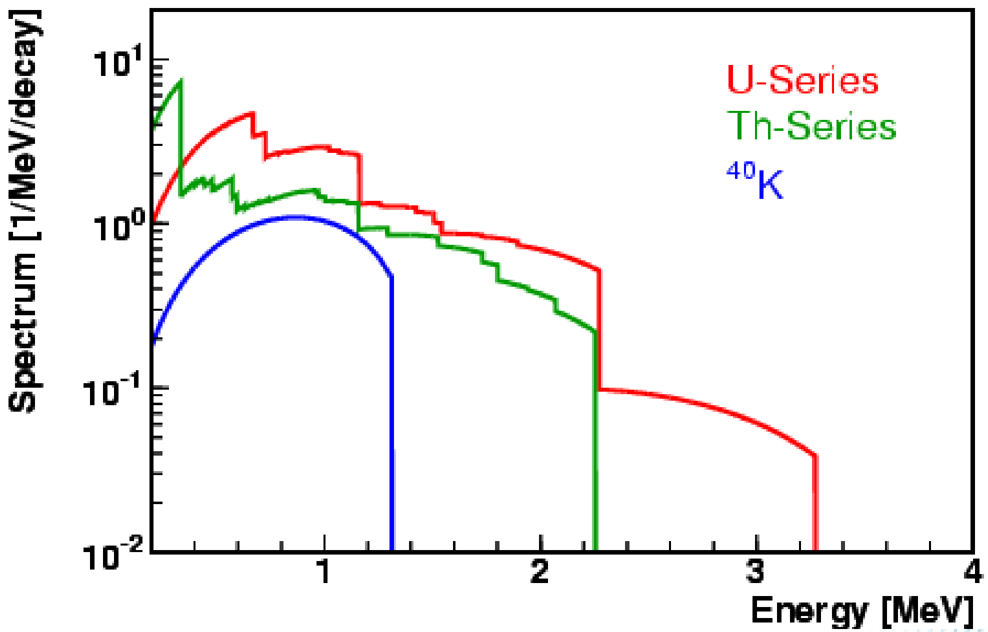
$\tan^2\theta_{12} = 0.492^{+0.086}_{-0.067}$



In May last nuclear reactor which remained operational will be shutdowned. We have unique opportunity to measure geo-neutrinos and verify background (e.g. existence of geo-reactor).

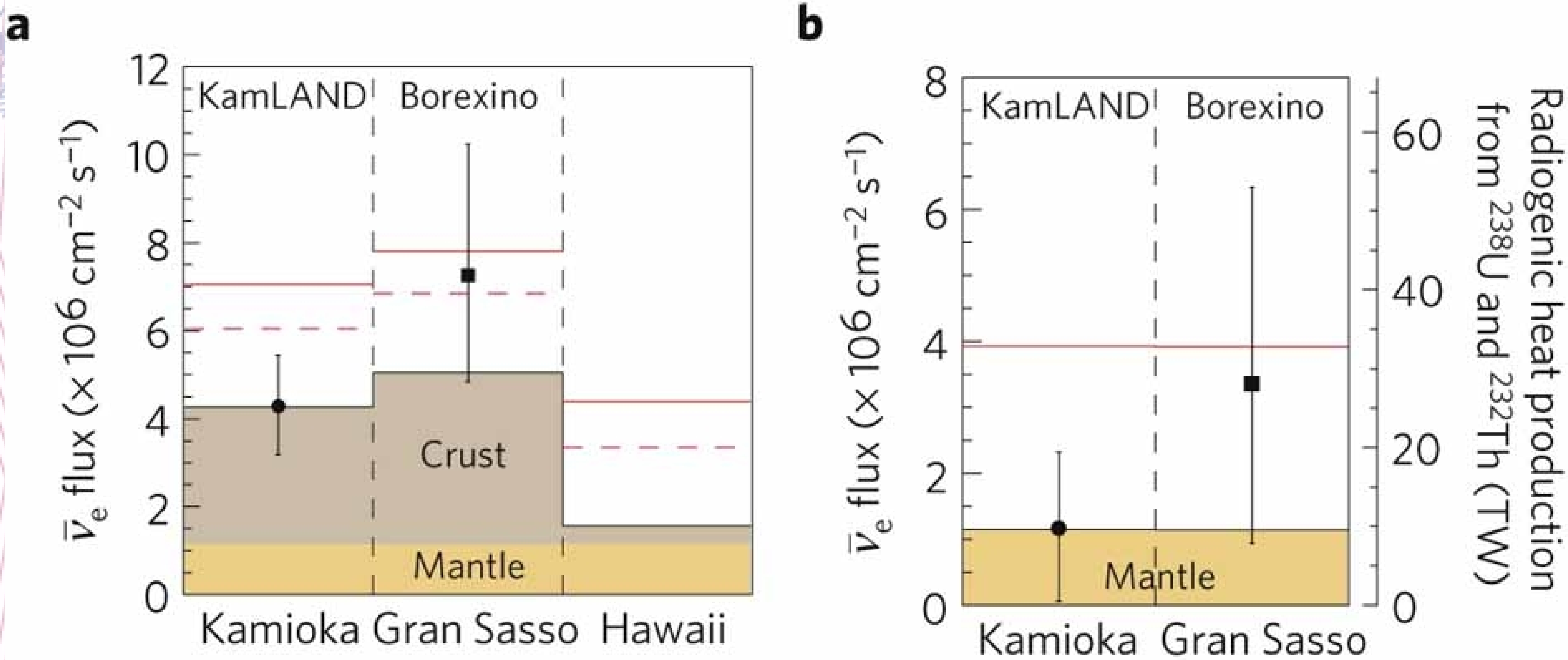
Radioactive decays in Earth crust and mantle





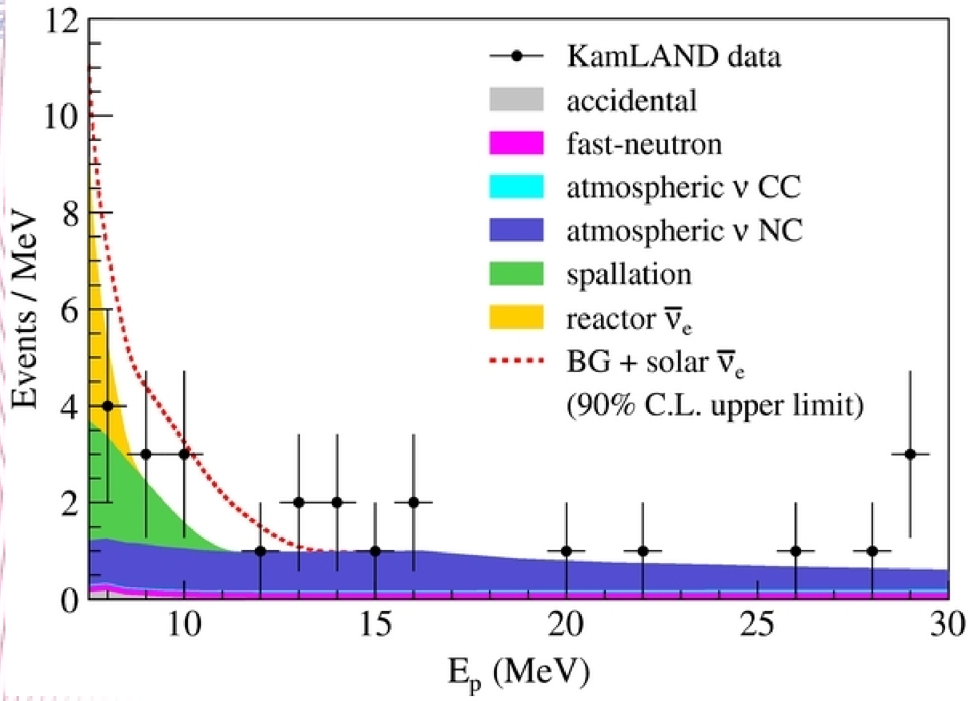
- Low energy anti-neutrinos produced in decay of U, Th
- At the KamLAND location detection of geo-neutrinos was always difficult due to a high flux of reactor anti-neutrinos
- After reactors shut-down our background situation became similar to the Borexino detector while we have 5 times larger fuducial volume
- The geo-neutrino measurement became high priority for KamLAND

The latest geo-ν result (Nature Geoscience 2011)



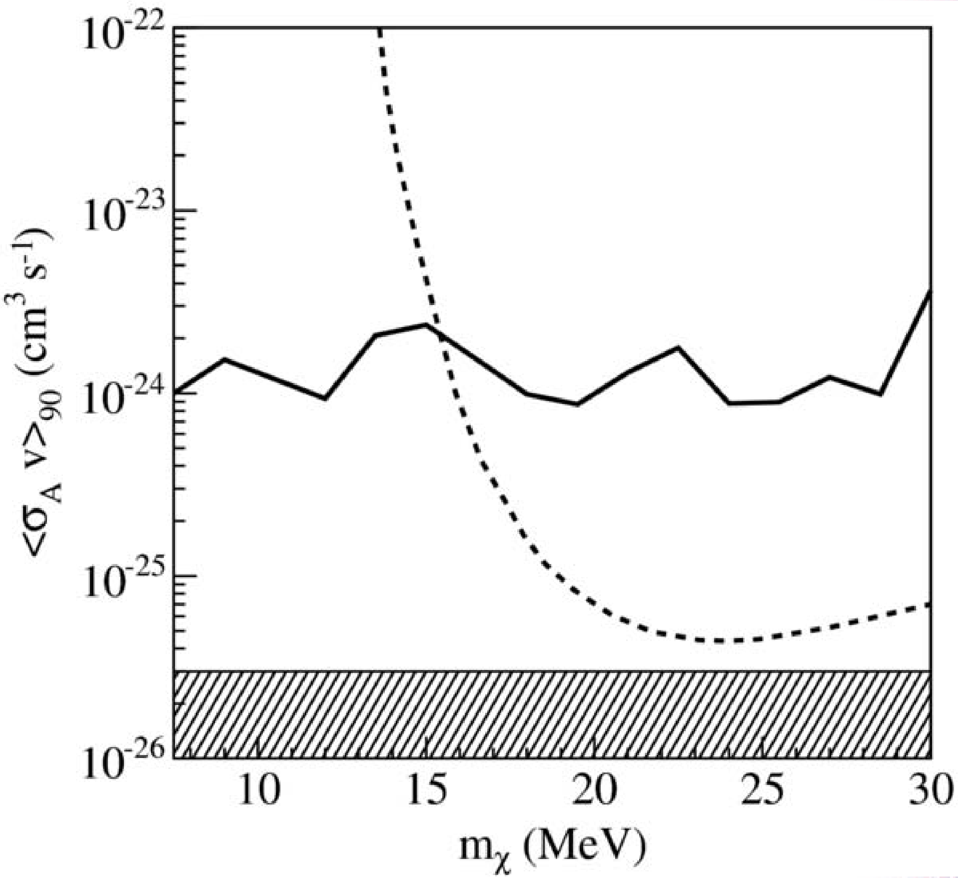
(a) geo-ν flux at Kamioka and Gran Sasso, and expected fluxes at these sites and Hawaii. The solid and dashed red lines show the fluxes for a fully radiogenic model assuming the homogeneous and sunken-layer hypotheses. (b) geo-ν flux after subtracting the estimated crustal contribution. The right axis shows radiogenic heat production assuming a homogeneous mantle. The solid red line indicates the fully radiogenic model where the contributions from the crust (7TW) and the other isotopes (4.3 TW) are subtracted from the total heat flow (44.2TW). The KamLAND data indicates presence of Earth's primordial heat supply.

The Dark Matter annihilation cross section



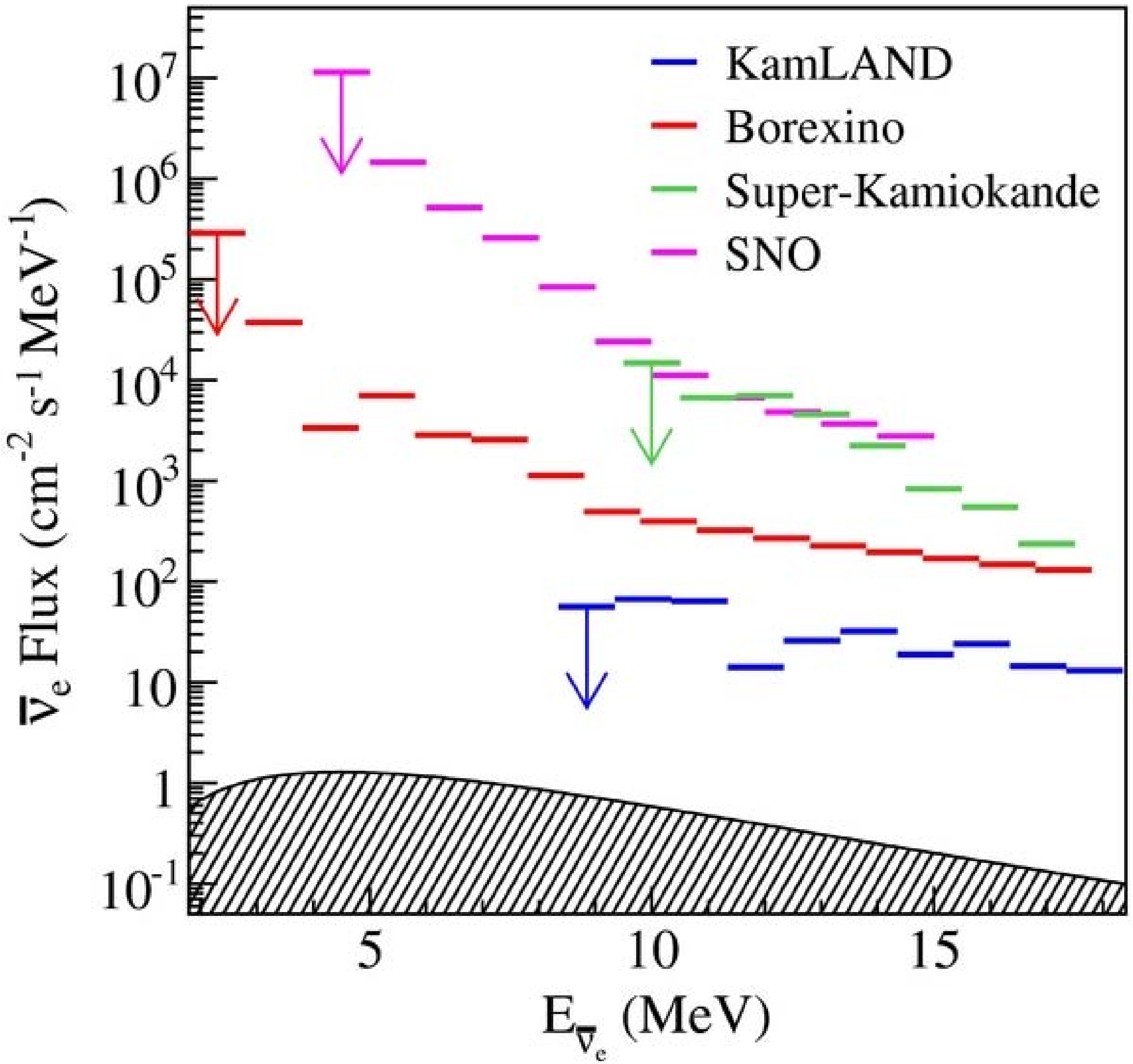
The Astroph. J. 745 (2012) 193

4.5 kton-year



The upper limit for the monochromatic flux at each energy can be translated to a limit for the dark matter annihilation cross section (Palomares-Ruiz & Pascoli 2008). Upper limits at 90% CL on the dark matter annihilation cross section from KamLAND (solid line) and Super-Kamiokande (dashed line).

Model-independent upper limit (90% CL)

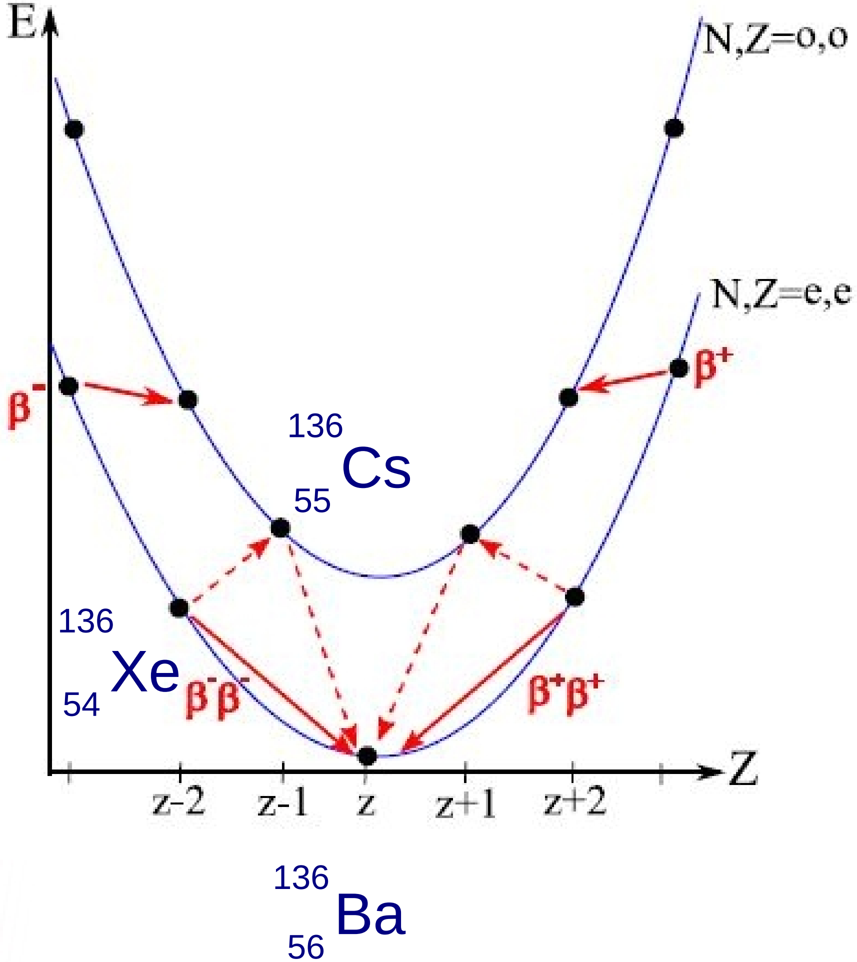


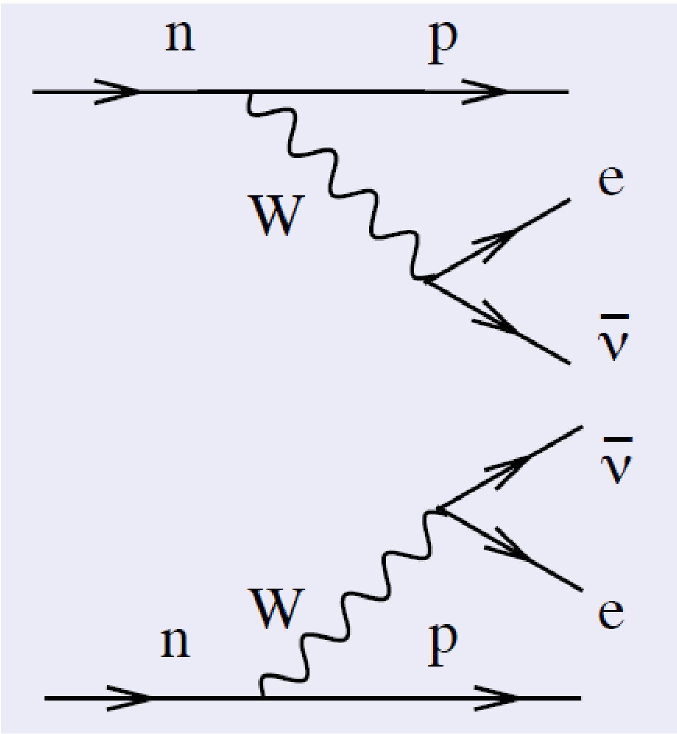
The Astroph. J. 745 (2012) 193

4.5 kton-year

The shaded curve shows the diffuse supernova flux for the reference model prediction (Ando & Sato 2004). Above the shown energy range, the Super-Kamiokande data give more stringent upper limit.

Conventional $2\nu\beta\beta$-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 ($2\nu\beta\beta$) in the form of $(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\,\nu_e$ was proposed first by M. Goeppert-Mayer in 1935.

History of the double-beta decay

Already in 1935 Maria Goeppert-Mayer (future creator of shell model of atomic nuclei) concluded that the two neutrino mode of double-beta decay would have $T_{1/2} > 10^{17}$ years:

“Double Beta-Disintegration”

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

First experimental seach for 2νββ of ^{124}Sn

E. L. Fireman, Phys. Rev. 74, 1238 (1948)

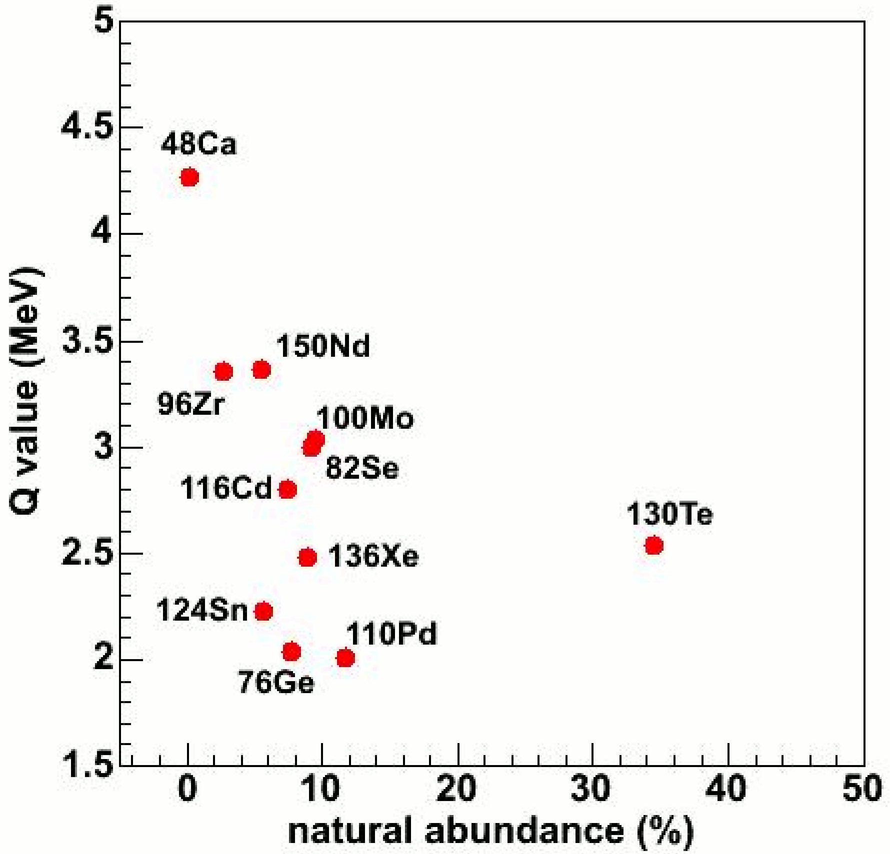
The possibility of 0νββ-decay was discussed in 1937-1939:

E. Majorana, Nuovo Cimento 14 (1937) 171

Furry W.H. Phys. Rev. 54 (1938), 56-67

Furry W.H. Phys. Rev. 56 (1939) 1184-1193

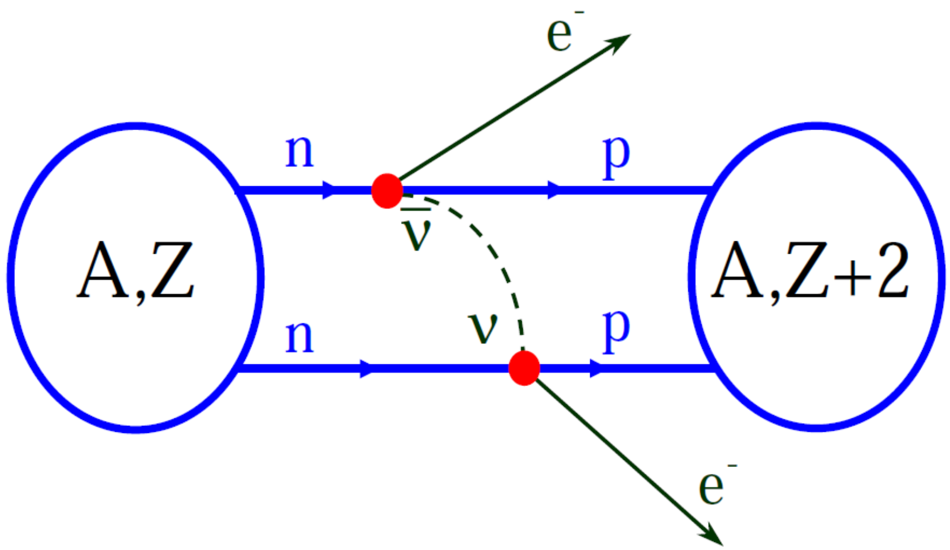
Most promising double-beta decay isotopes

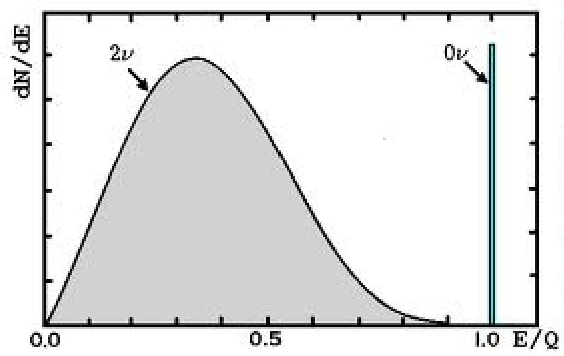


It is a very slow process. Still we observe ~1000 of $2\nu\beta\beta$ events per day in KamLAND-Zen

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 0νββ-decay





In calorimeter-type detector

Basic process: dd → uue⁻e⁻ . Decay rate ~ (neutrino mass)^2

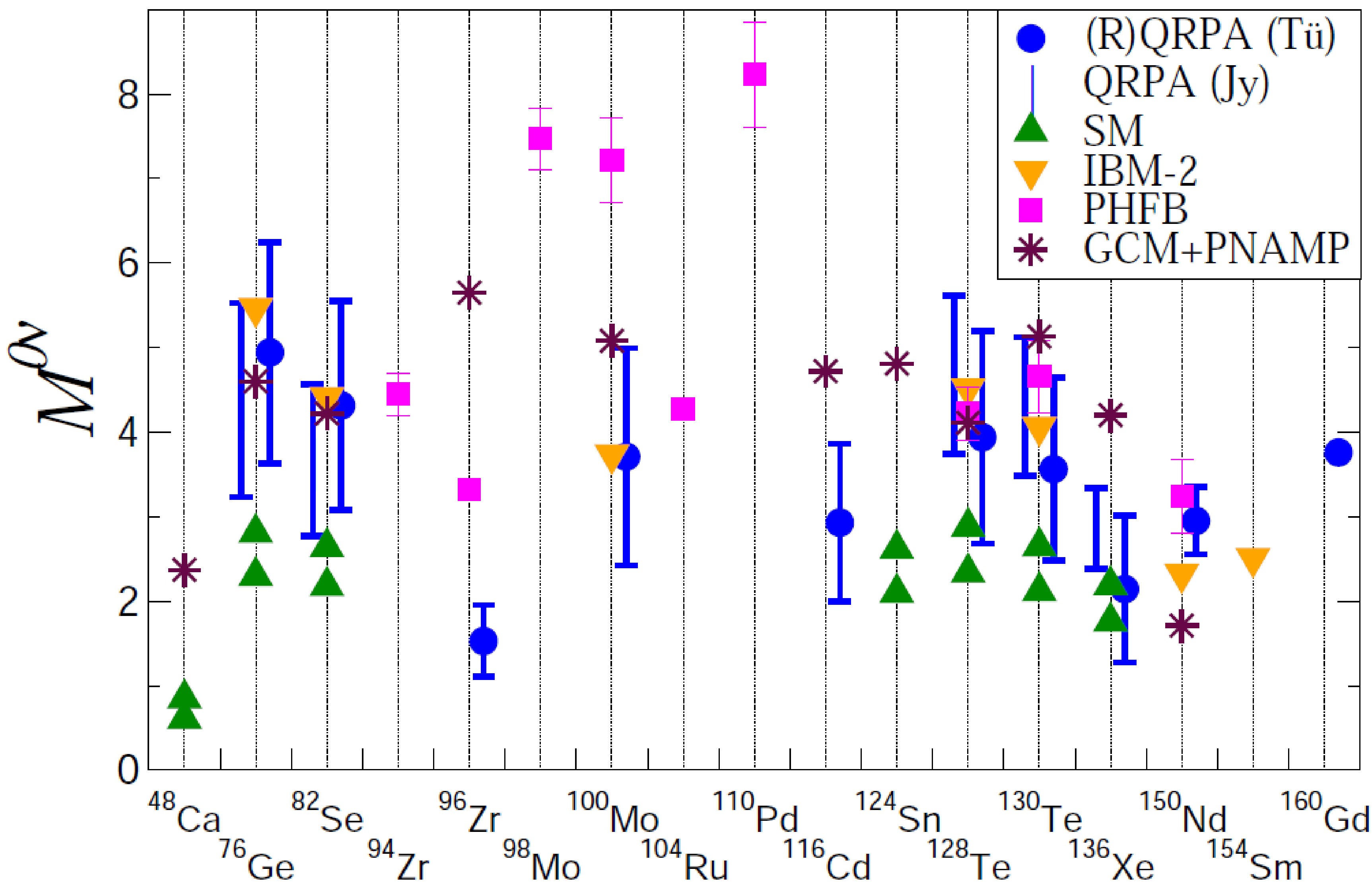
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\cdot|M^{0\nu}|^2\cdot m_{\beta\beta}{}^2$$

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

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

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 \cdot m_{\nu i}\right|$$

Nuclear matrix elements calculations

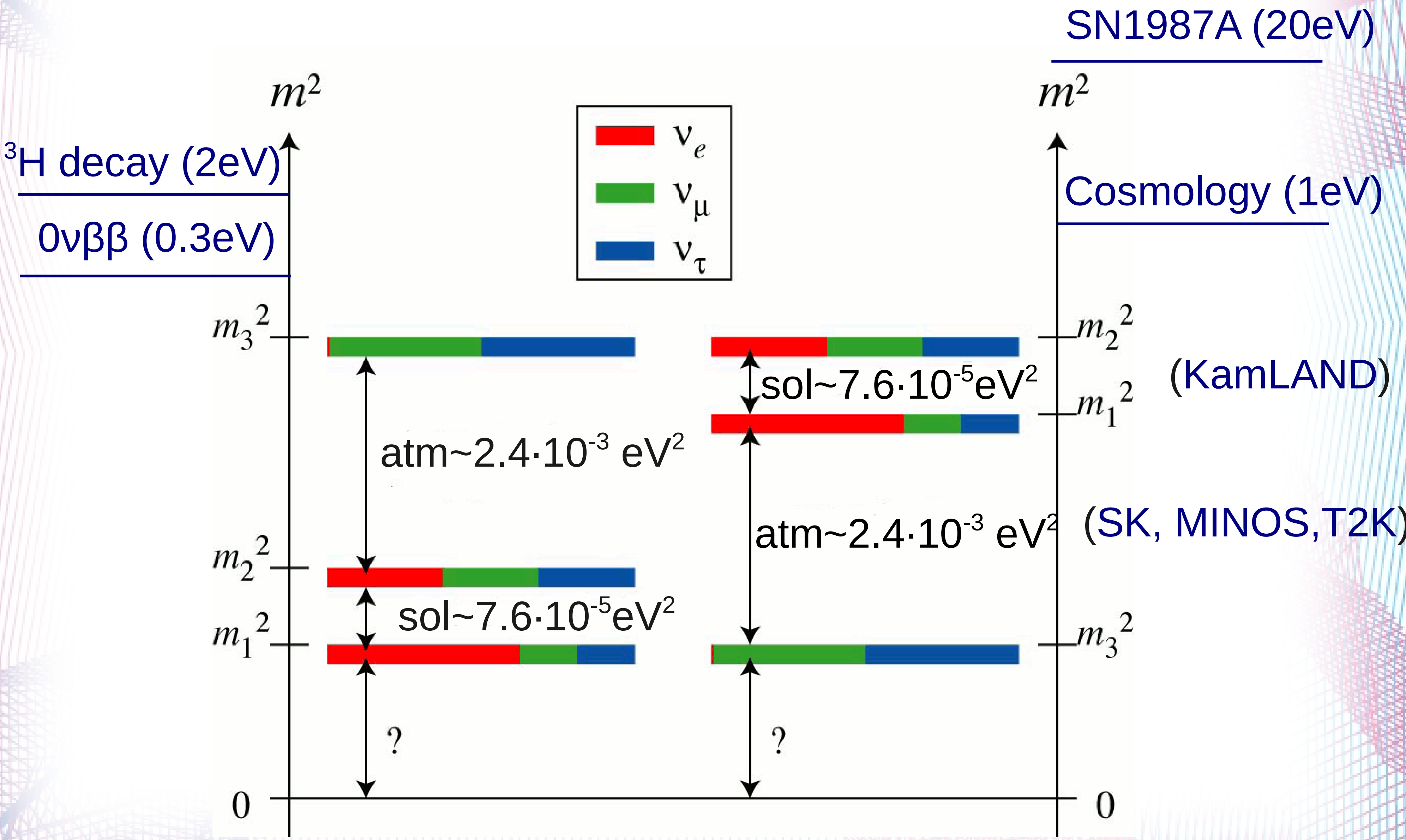


Significant progress in theoretical calculations of NME was achieved recently

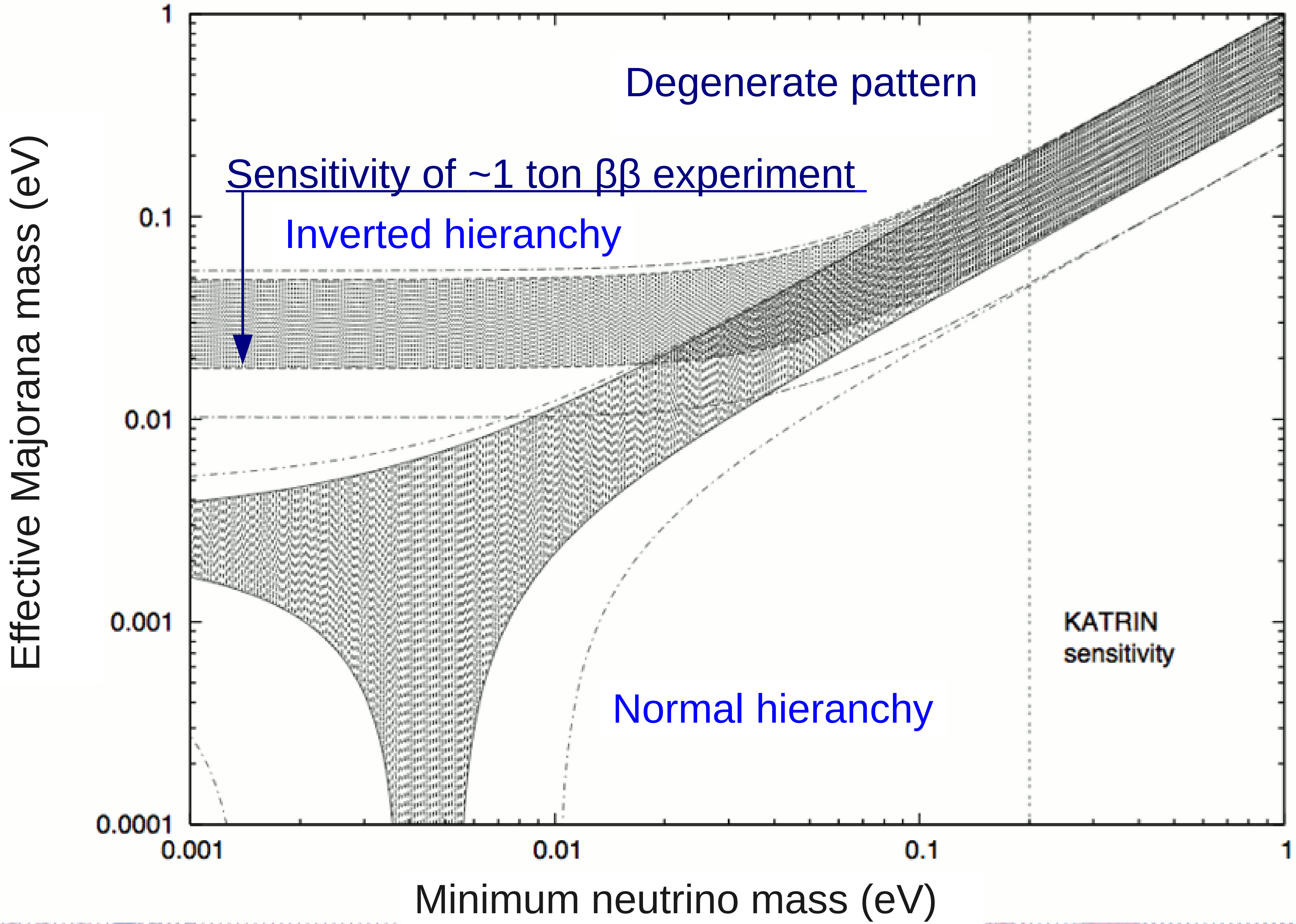
Observation of the 0νββ decay means

- Physics bejond the Standard Model
- Lepton number L is violated ($|\Delta L|=2$)
- Neutrinos are their own antiparticles
- Neutrino mass has different origin than the charged leptons and quarks masses
- Absolute scale of the neutrino mass can be determined

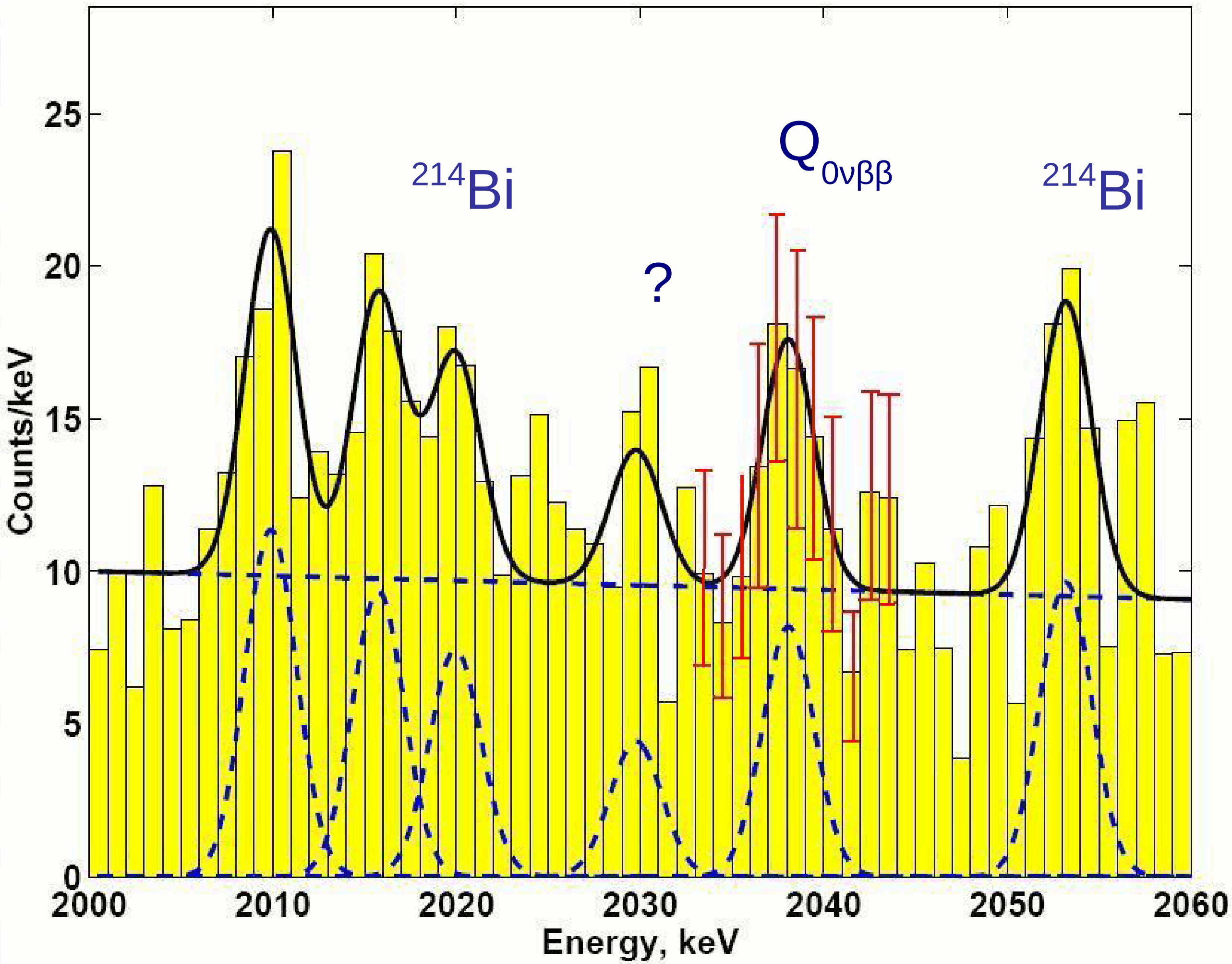
Neutrino mass pattern



Effective neutrino mass for each hierarchy



The KKDC discovery claim for $0\nu\beta\beta$ in ^{76}Ge



$T_{1/2} = 2.23\,^{+0.44}_{-0.31} \cdot 10^{24}$yr

$\langle m_{\nu\beta\beta} \rangle = 0.32 \pm 0.03$ eV

Fit model: 6 gaussians + linear background. Fitted excess at $Q_{0\nu\beta\beta}$ (^{76}Ge) was 28.75 ± 6.86 events, claimed significance 4.2 σ

H.V.Klapdor-Kleingrothaus, I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547

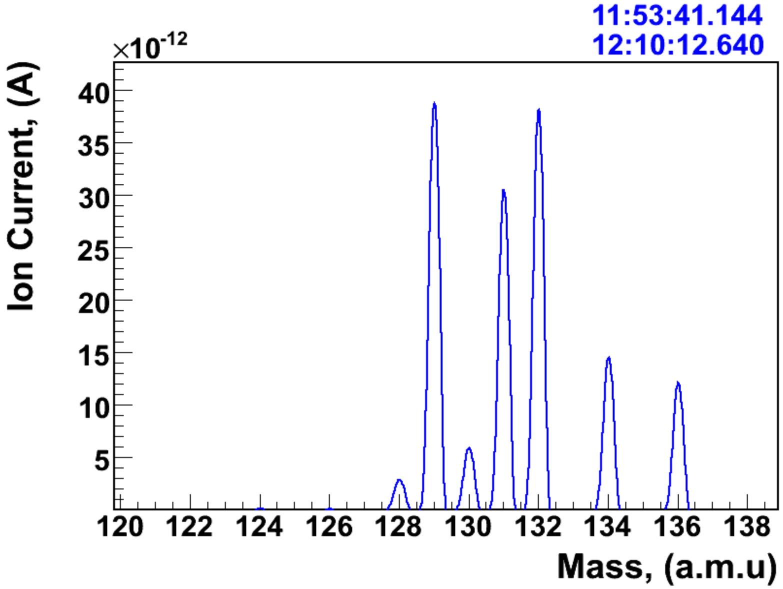
KamLAND-Zen collaboration members

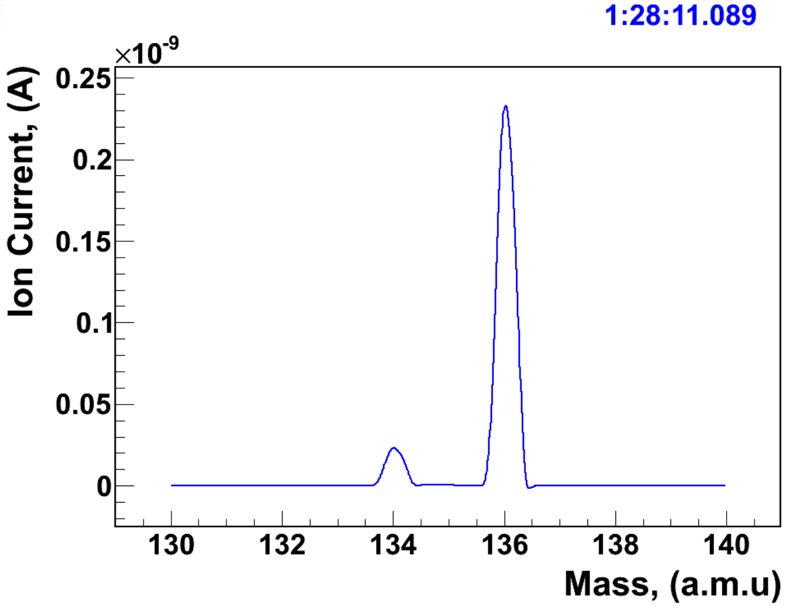
KamLAND-Zen and IPMU were born together. IPMU involvement is limited to one researcher. Hope for a stronger IPMU participation...

Main criteria for 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

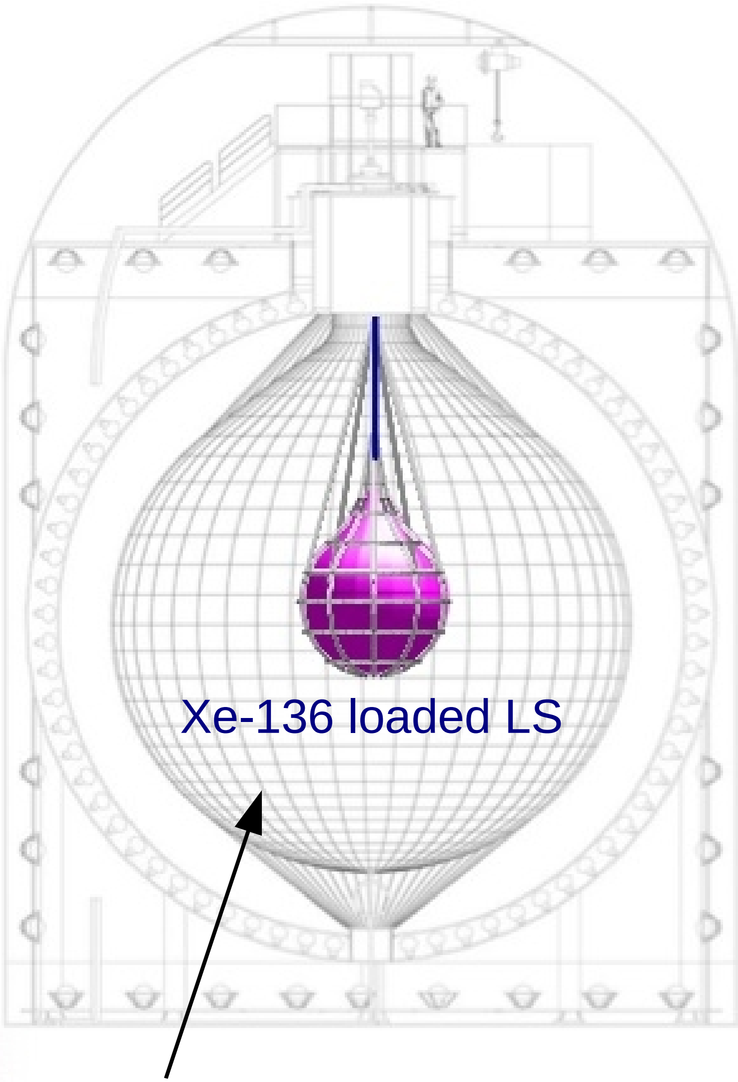
Xenon-136 was selected as best candidate





- 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 2ν2β background rate: $T_{1/2}(2\nu\beta\beta) > 10^{22}$ years (prior EXO result)
- no substantial light yield, and no transparency reduction in Xe loaded LS

The KamLAND-Zen 0νββ experiment



Old KamLAND scintillator (LS):

Dodecane 80%, Pseudocumene 20%

PPO 1.5g/L

New liquid scintillator :

Xenon 91% enriched in Xe-136 (3wt%)

Decane 80.2%, Pseudocumene 19.8%

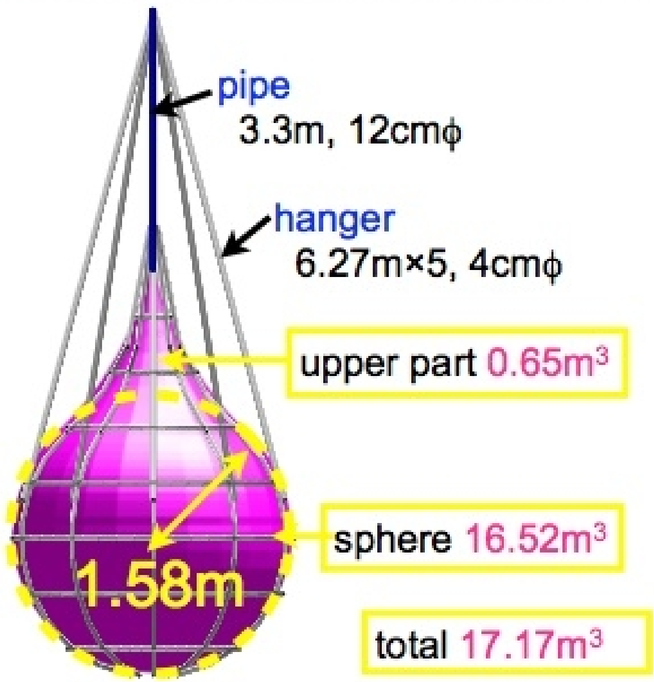
PPO 2.7g/L

Resolution: Energy 6.6%/√E (MeV)

Spatial 12.5cm/√E (MeV)

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

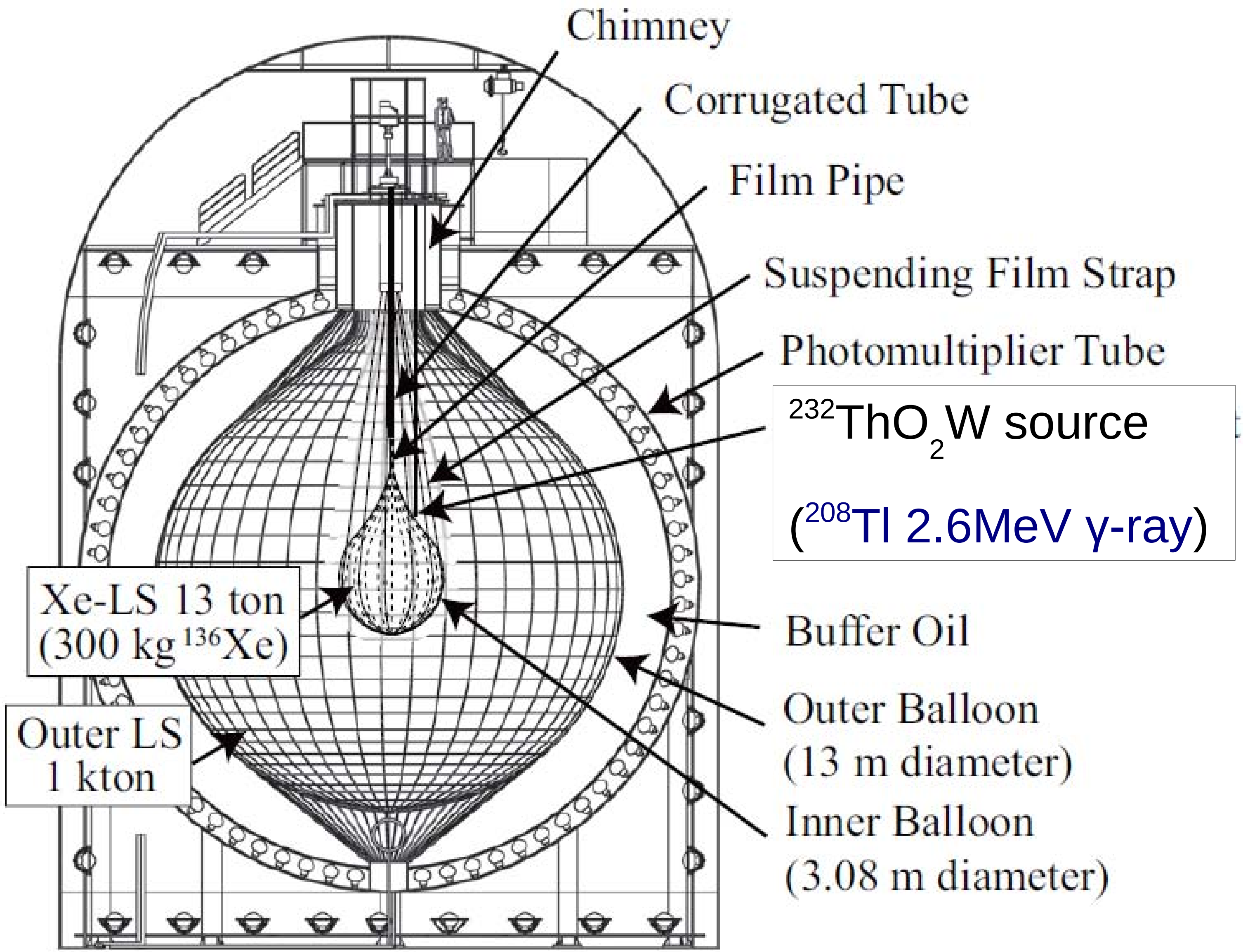
Mini-balloon construction



- A single layer Nylon film (Toyobo Co.)
- A 25µm thick, density 1.14g/cm^3
- Nylon pellets used to make film for the mini-balloon were prepared without additives containing large amounts of Uranium/Thorium
- The specially made Nylon film contains ^{238}U,^{232}Th<5·10^{-12}g/g, ^{40}K<1.2·10^{-11}g/g

- During welding of two Nylon films two additional Nylon film strips were added at the boundaries
- Welding was done using an impulse welding machines at 240-250°C in 0.5-1s pulses
- The KamLAND-Zen balloon is going to operate at less than 0.1% density difference relative to the surrounding KamLAND LS

The KamLAND-Zen calibration

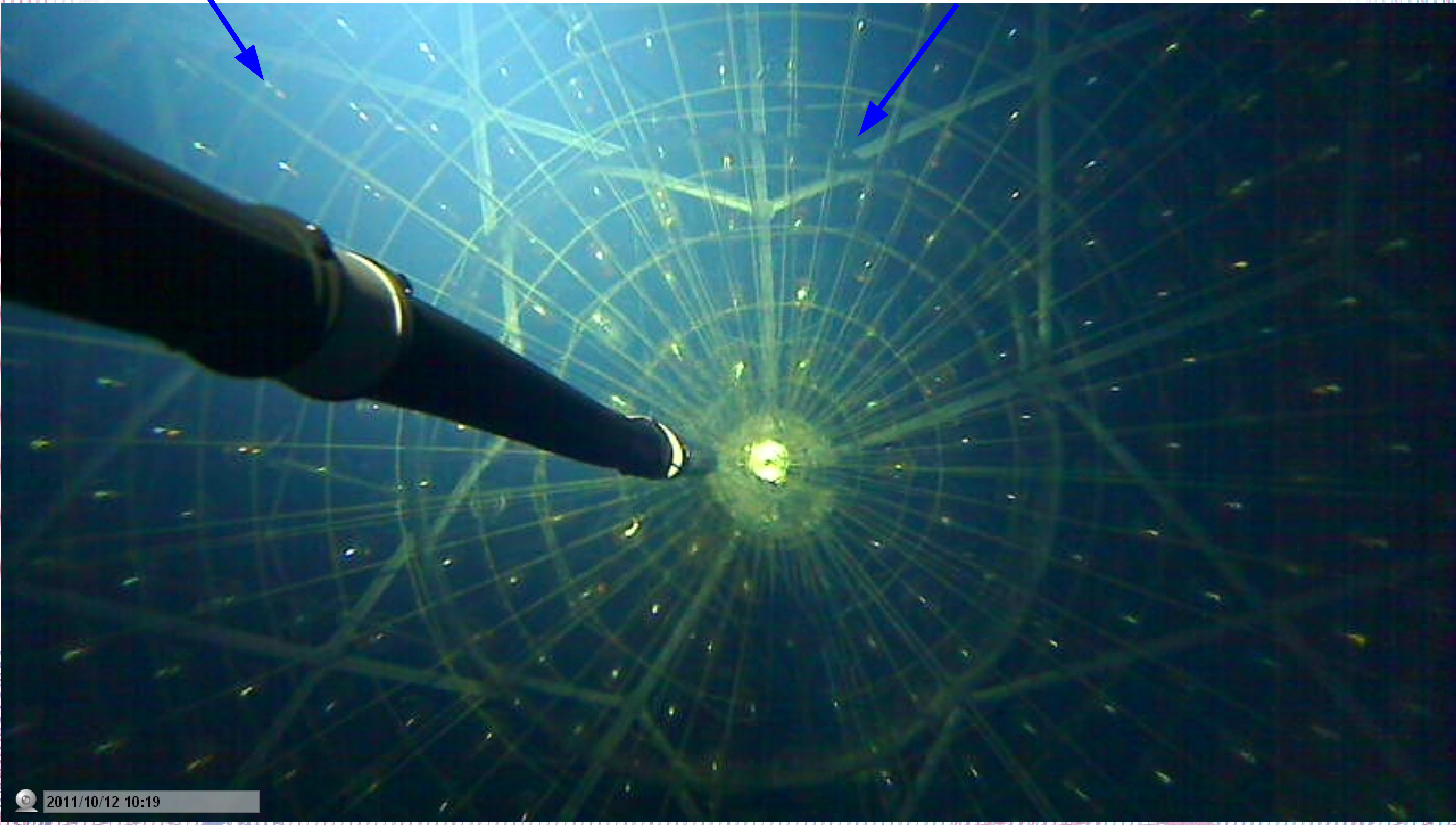


Mini-balloon inside KamLAND

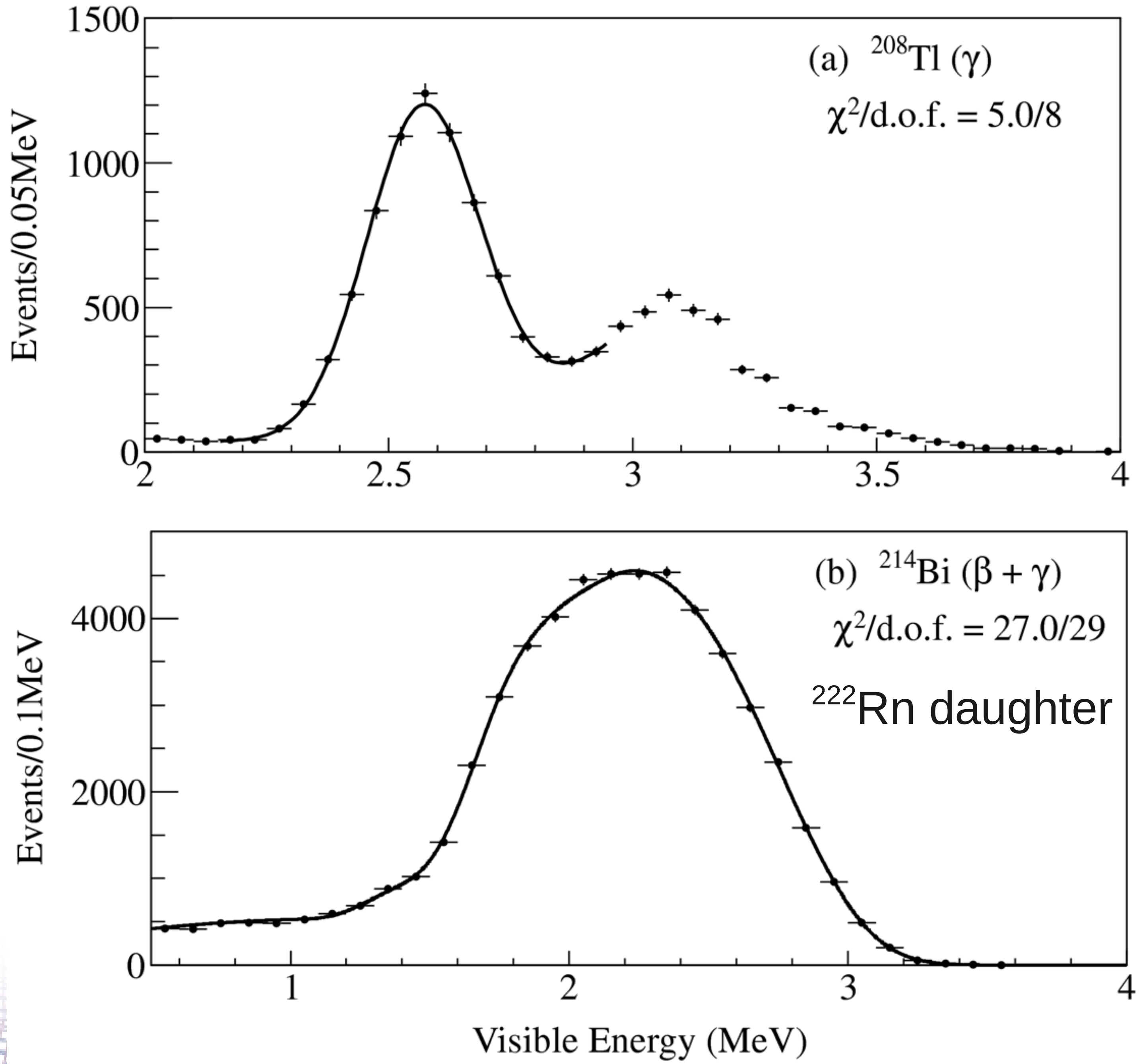
PMTs

n(LS) > n(XeLS) by ~ 0.5%

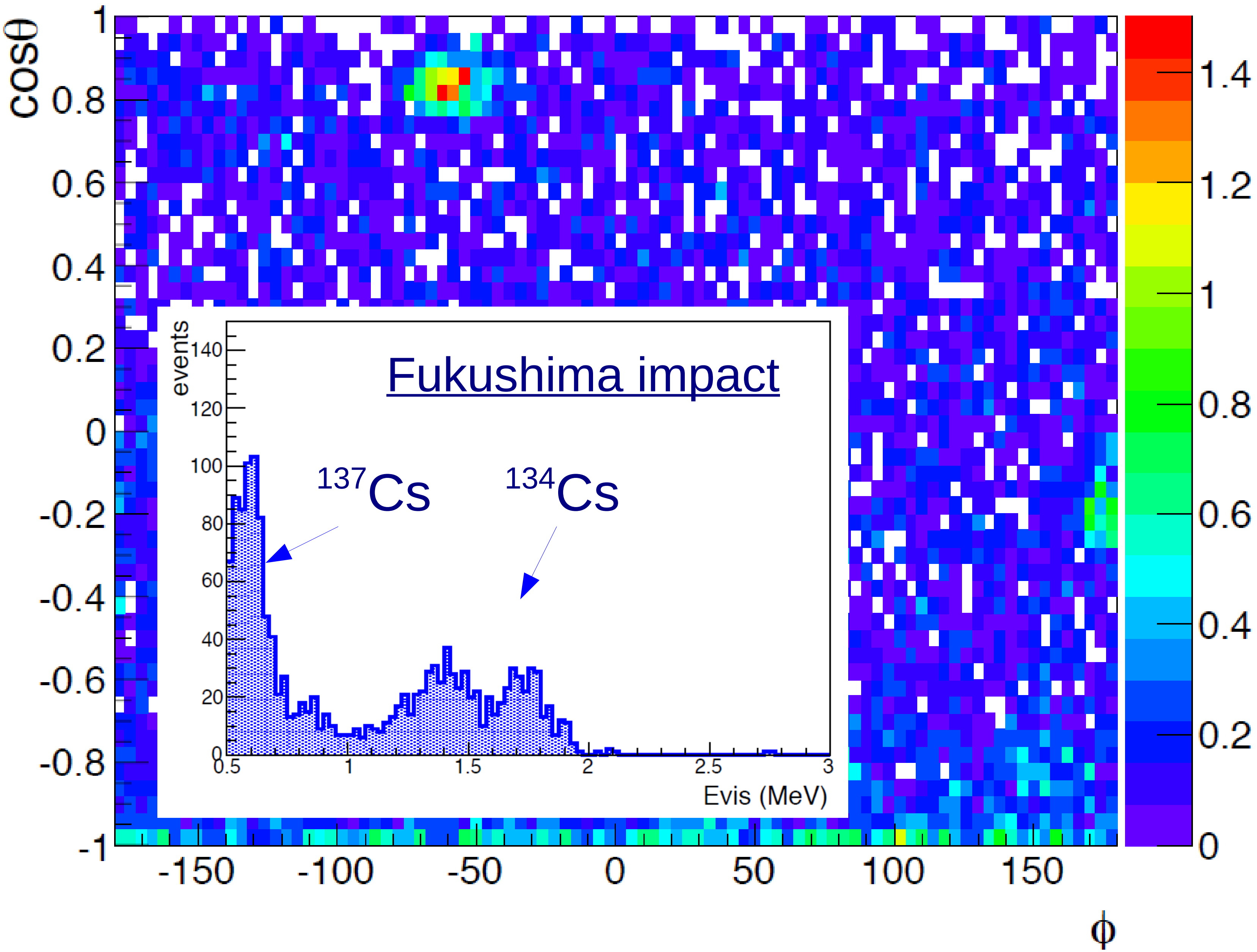
the mini-balloon boundary



The energy-scale calibration for KL-Zen

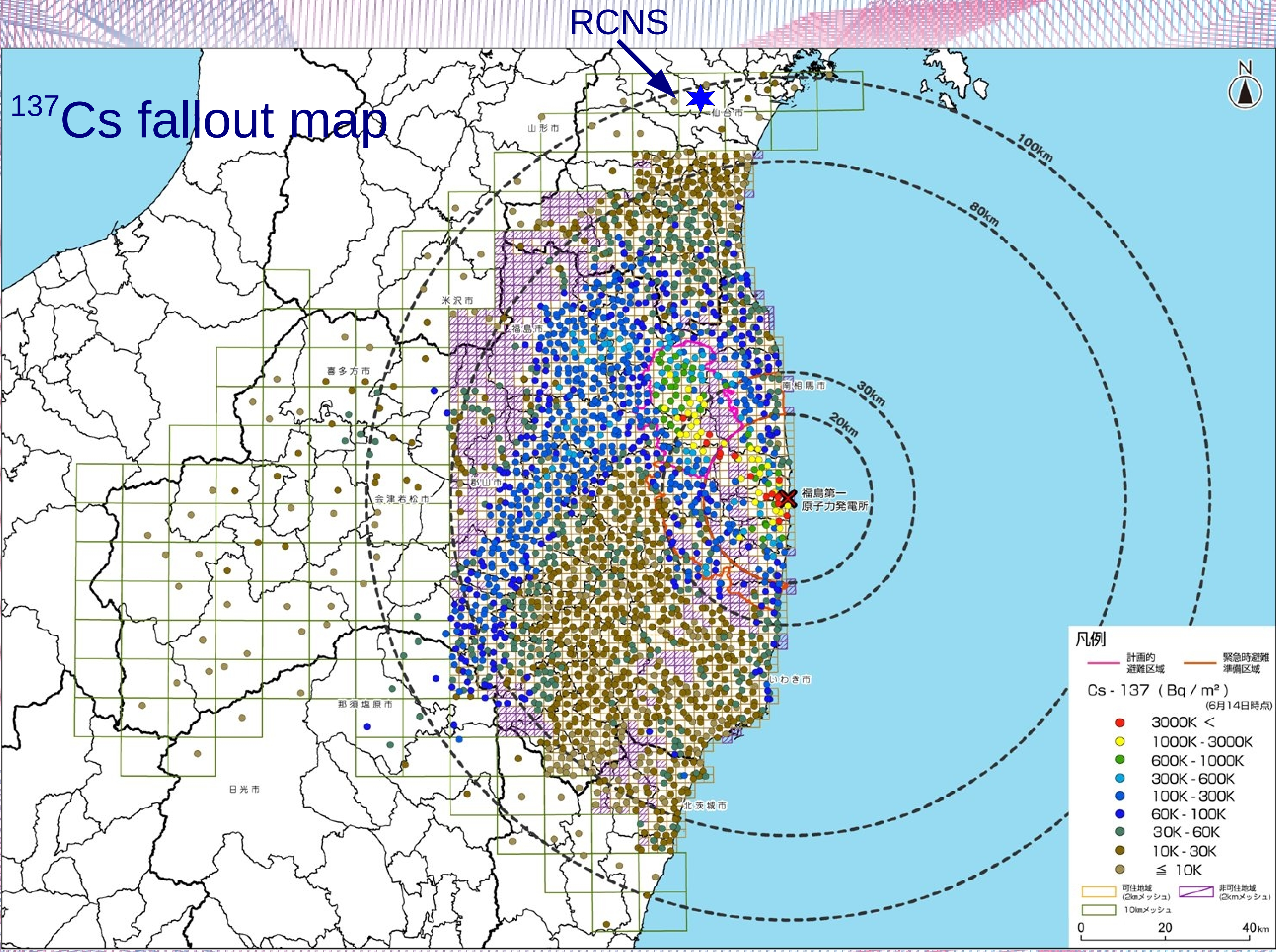


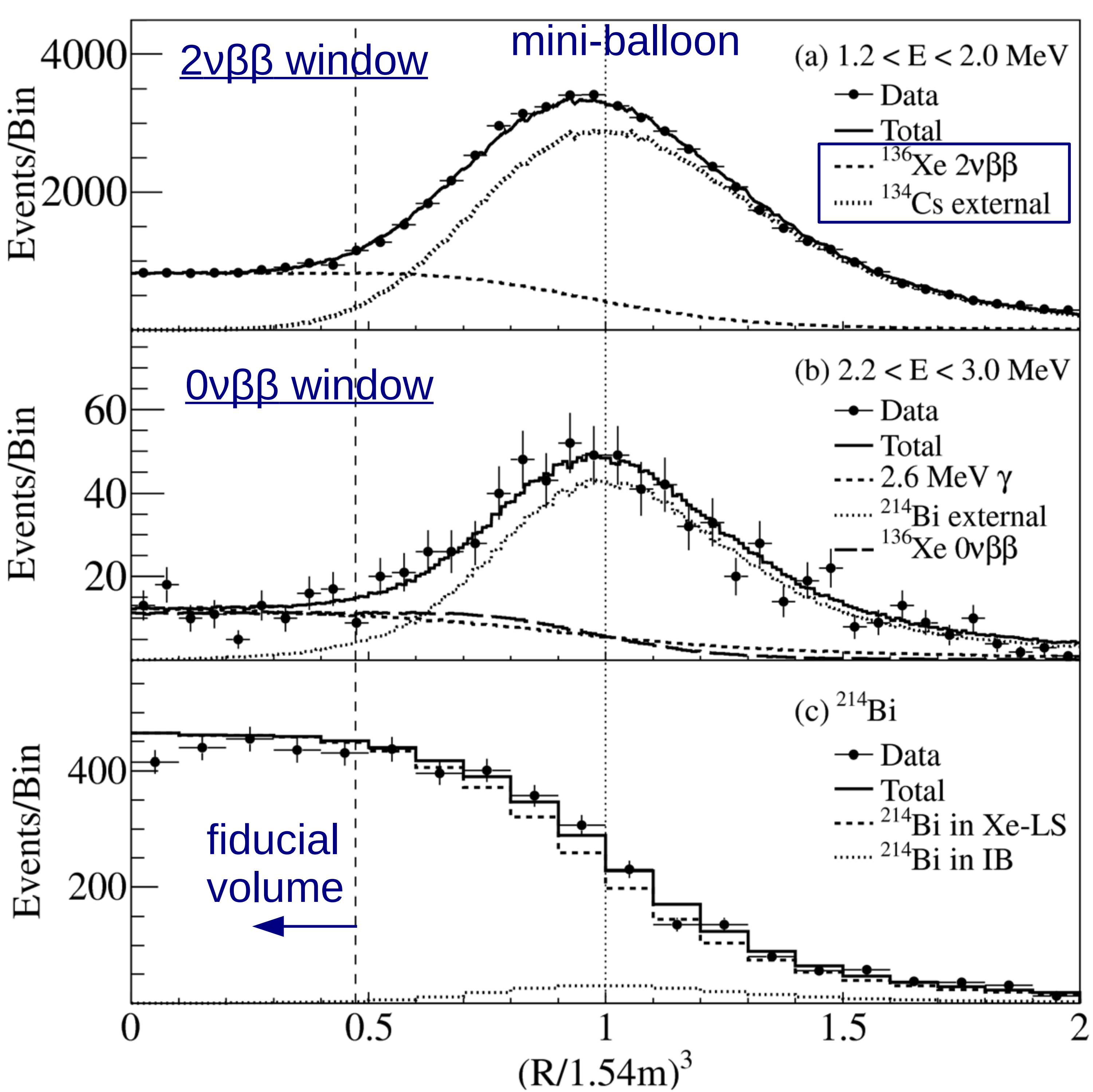
The mini-balloon surface contamination



Activity ratio (^{134}Cs / ^{137}Cs) ~ 0.8 consistent with the Fukushima accident

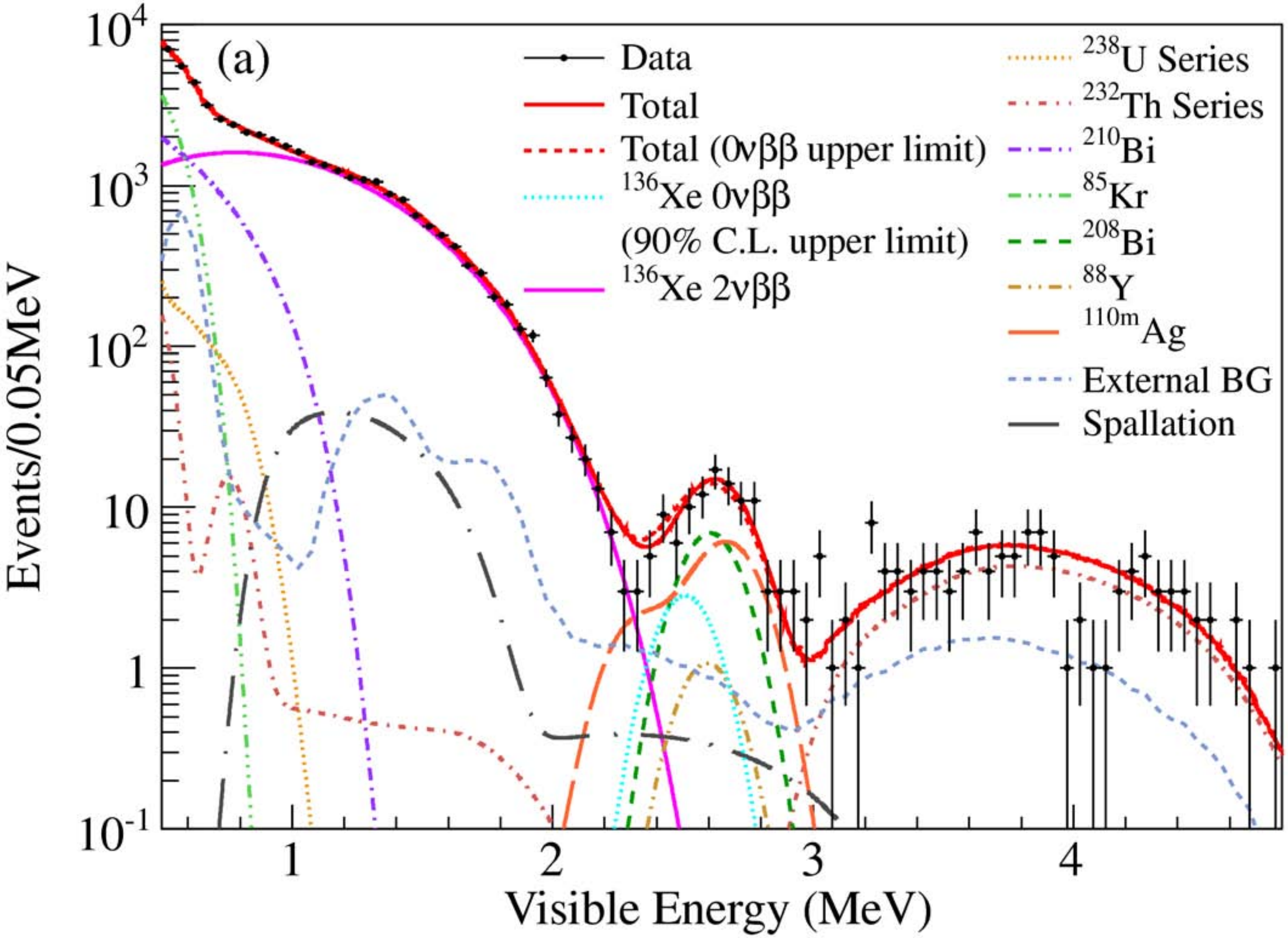
^{137}Cs fallout map





2νββ window
mini-balloon
(a) 1.2 < E < 2.0 MeV
Data
Total
136Xe 2νββ
134Cs external
0νββ window
(b) 2.2 < E < 3.0 MeV
Data
Total
2.6 MeV γ
214Bi external
136Xe 0νββ
(c) 214Bi
Data
Total
214Bi in Xe-LS
214Bi in IB
fiducial
volume
Events/Bin
4000
2000
60
40
20
400
200
0
0.5
1
1.5
2
(R/1.54m)3

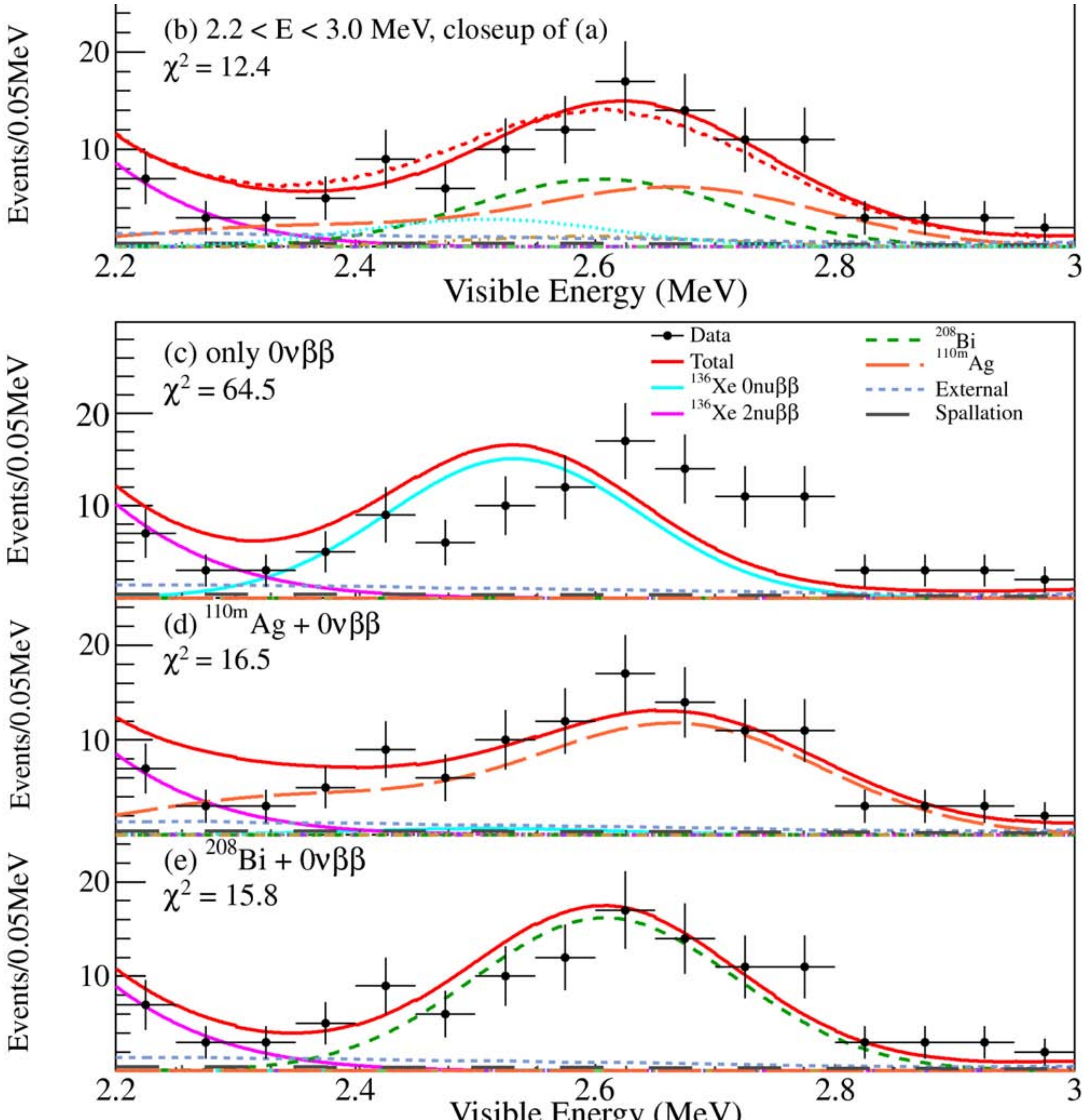
The KamLAND-Zen first published result



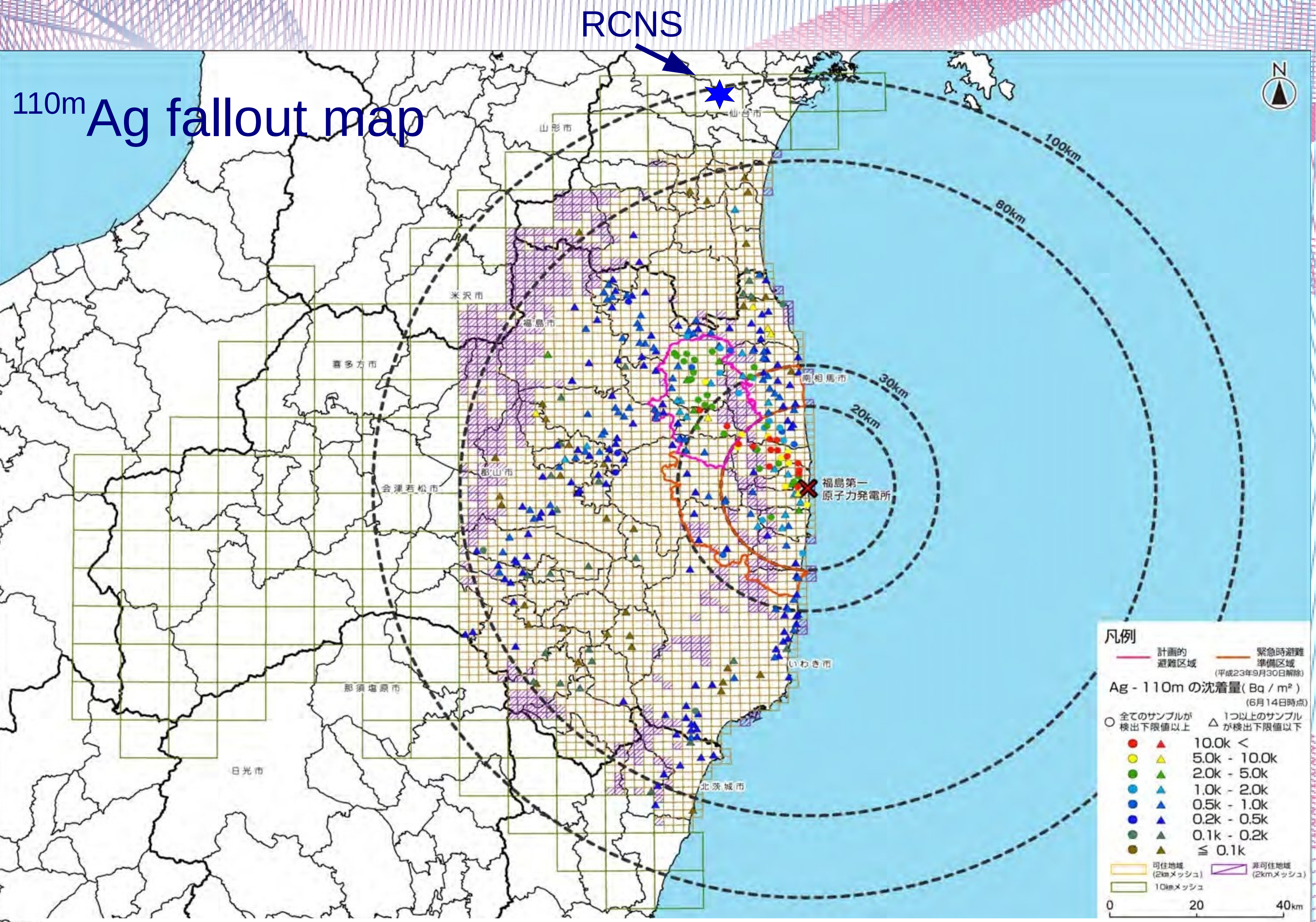
129kg of ^{136}Xe isotope; 78 day exposure; 36000 $2\nu\beta\beta$ events detected

$T_{1/2}(2\nu) = 2.38 \pm 0.02(\text{stat}) \pm 0.14(\text{syst}) \cdot 10^{21}$ y; $T_{1/2}(0\nu) > 5.7 \cdot 10^{24}$ y (90%CL)

The 0νββ background candidates



^{110m}Ag fallout map



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

KamLAND-Zen: what to do next

- Between February 10 and 28 Xenon-loaded LS was circulated through a 50nm filter in attempt to remove nano-particles containing Ag or Bi isotopes. Currently we take data in a normal operation mode and so far no rise in background was detected. This fact indicates that in present condition Xenon system is not a source of background near the expected $0\nu2\beta$ peak location
- We might try to use a 15nm filter if filtration had some effect on background (not determined yet)
- We plan to replace scintillator in the mini-balloon to a newly distilled one
- We consider possibility to make another mini-balloon in a place not contaminated by the Fukushima fallout

Double-beta decay search summary

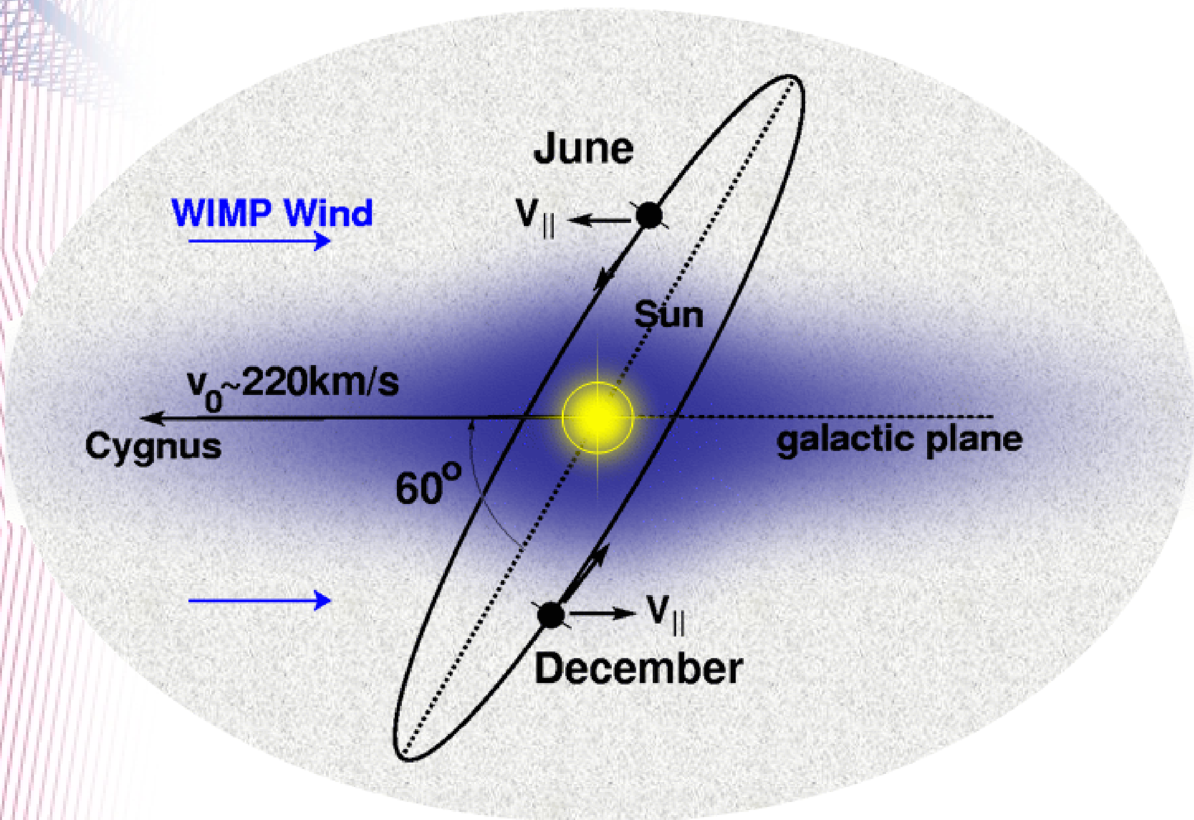
• During the last few years search for the neutrinoless double beta decay experienced a transition from table size setups to large scale dedicated (and expensive) experiments

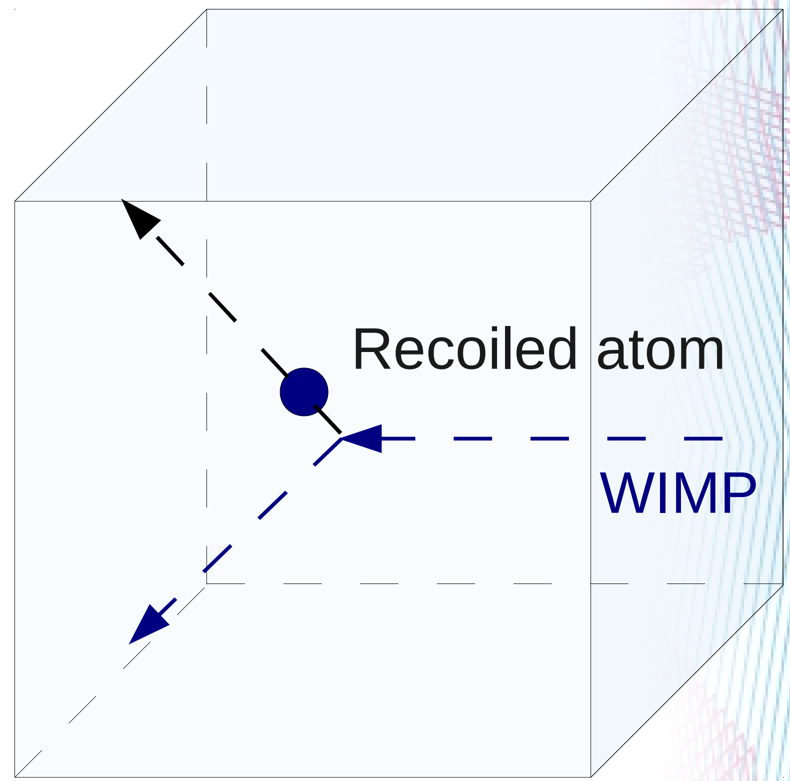
• Wide use of enriched isotopes (^{76}Ge, ^{136}Xe): GERDA, MOJARANO, EXO-200, KamLAND-Zen, SuperNEMO became a normal practice

• 100kg-class experiments started data taking (EXO, KamLAND-Zen)

• EXO and KamLAND-Zen have potential to be upgraded to ton-class experiments in several years. Currently the KamLAND-Zen collaboration received 530kg of ^{136}Xe, more Xe will be delivered soon.

Direct Dark Matter detection

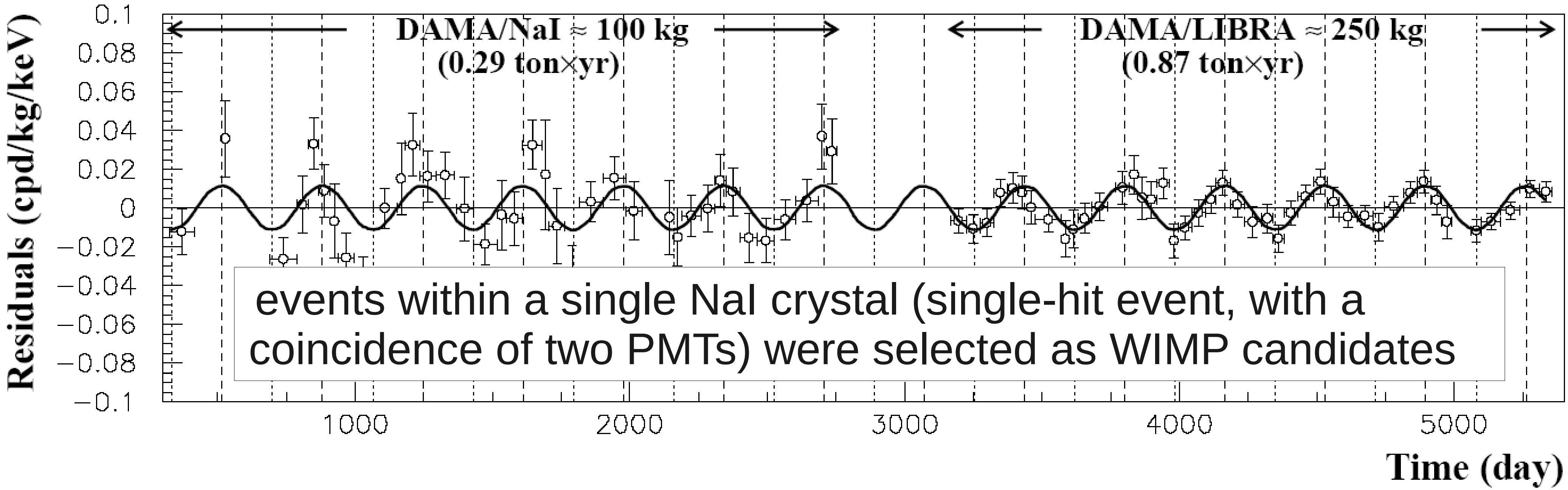




Kinetic energy of recoiled atoms is converted into heat and light in the target material. The local mass density needed to explain the rotation curve of our Galaxy is ρ ~0.3GeV/cm^3. Due to the Sun motion the DM velocity relative to the Earth is V~220km/s. In case if DM consists of WIMPs with a mass M_{DM}~100GeV we get $\rho \times V/ M_{DM}$ ~ 66,000 particles/cm^2/s passing through a detector.

DAMA / LIBRA result

2-6keV energy bin



events within a single NaI crystal (single-hit event, with a coincidence of two PMTs) were selected as WIMP candidates

Earth motion around the Sun allows to set several strict requirements to check if observed signal comes from WIMP interactions or belongs to some unidentified source of background. Those requirements are: modulated event rate according to cosine, a proper modulation time period (1 year) with a proper phase (June 2nd). DAMA/LIBRA collaboration which is using 25 pure crystals of NaI(Tl) at Gran Sasso laboratory claimed observation of the modulated DM signal at 8.9σC.L. (13 annual cycles).

Test of the DAMA / LIBRA result using KamLAND

- We could test the DAMA / LIBRA result using a segmented detector made of ultra-pure identical NaI(Tl) crystals deployed into KamLAND. It would serve as a massive passive shielding against external γ-rays and neutron background from the rock, and as an active muon and spallation neutron veto detector.

- In order to be sensitive in the 2-6keV region where the modulated signal was found DM detector modules must be optically isolated from the rest of KamLAND. Light collection has to be done using photo-sensors attached to each module connected to a separate data acquisition system (DAQ) synchronized with the current KamLAND DAQ.

- Radiopurity of NaI(Tl) crystals, photo-sensors and surrounding materials has to be carefully controlled and preserved.

Development of NaI(Tl) DM modules

• Combine GEANT simulations and actual measurements using several crystal prototypes to determine main background components (and improve crystals purity), fix units design (shape, mass, PMTs, surrounding materials), and then perform energy calibrations down to 1keV

• Few units have to be deployed into KamLAND for an extended period of time in order to measure background rates and check interference between units themselves, and the rest of KamLAND

• Next, one of the units are going to be used to measure light yield quenching factors using mono-energetic neutron beams capable to create low energy recoils of Na and I atoms

• The other units would remain underground to study time dependence of the background event rate caused by decay of isotopes of cosmogenic origin (e.g. ^{125}I $T_{1/2}$ ~ 60days) with a long half life

Status of a clean-room facility at KamLAND

- It is necessary to develop strict procedures to keep crystals clean from Rn daughters contamination (^{210}Pb, ^{210}Po)
- At least one of rooms located in the KamLAND Kamioka mine area is going to be upgraded into an ultra-clean room facility for Dark Matter research using NaI(Tl) crystals
- The room has an air conditioning, Radon shields, and Radon-less air supply line equipped with ULPA filters and ULPA filters for internal air circulation
- Next step would be to construct an inner clean-room inside with a standalone Radon free air supply system (10m^3/hour)
- The clean-room equipment: ultrasonic cleaners, a solid particles counter, new ULPA air filters are being prepared now
- NaI(Tl) crystals will be kept inside of a glove box equipped with a precise temperature control, and connected to a second air circulation system with a cryogenic Radon trap

Production of ultra-clean NaI crystals

Production facility will be upgraded by joined efforts of japanese research groups who plan to use clean NaI crystals.

- Oven for crystal growth
- Company agreed to impose quality control at all steps of crystals production
- 10μBq/kg of ^{214}Bi-^{214}Po were already achieved. Need more efforts to get all background under control

Conclusions

- Experimental neutrino physics program at underground facilities in Kamioka is progressing well
- Current KamLAND physics measurements will be continued boosted by unexpectedly favorable situation with the geo-neutrino detection
- The 0νββ-decay search program using 300kg of enriched ^{136}Xe was started in September 2011
- In the future, the 0νββ-decay search most likely would be upgraded into a 1 ton ^{136}Xe experiment capable to test the inverted hierarchy mass region down to the effective neutrino mass of 20meV
- Preparations for further detector modifications and upgrades including the DM search experiment using NaI crystals are underway