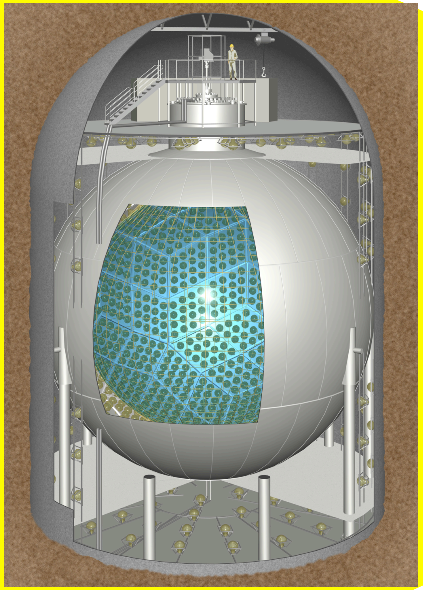
“New KamLAND Results”



Kam
LAND
Kamioka Liquid scintillator Anti-Neutrino Detector

Junpei Shirai
(for the KamLAND Collaboration)
Research Center for Neutrino Science
Tohoku University

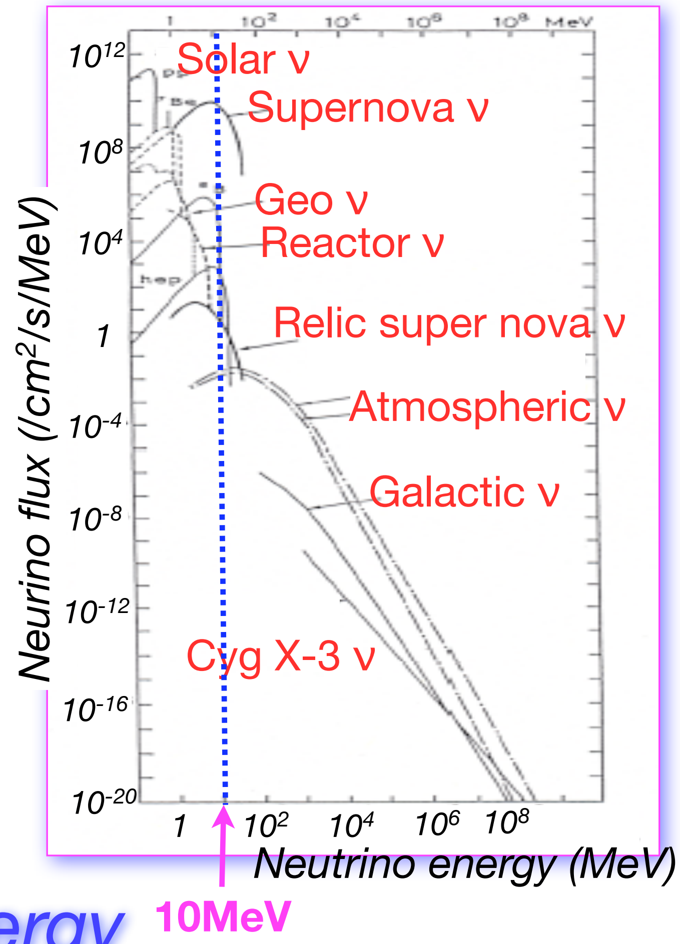
IV International Workshop on Neutrino Oscillation in Venice,
April 17, 2008

Low energy neutrinos provide lots of physics !

Neutrino properties
Neutrino generation mechanisms

Real time detection of low energy neutrinos is very important !

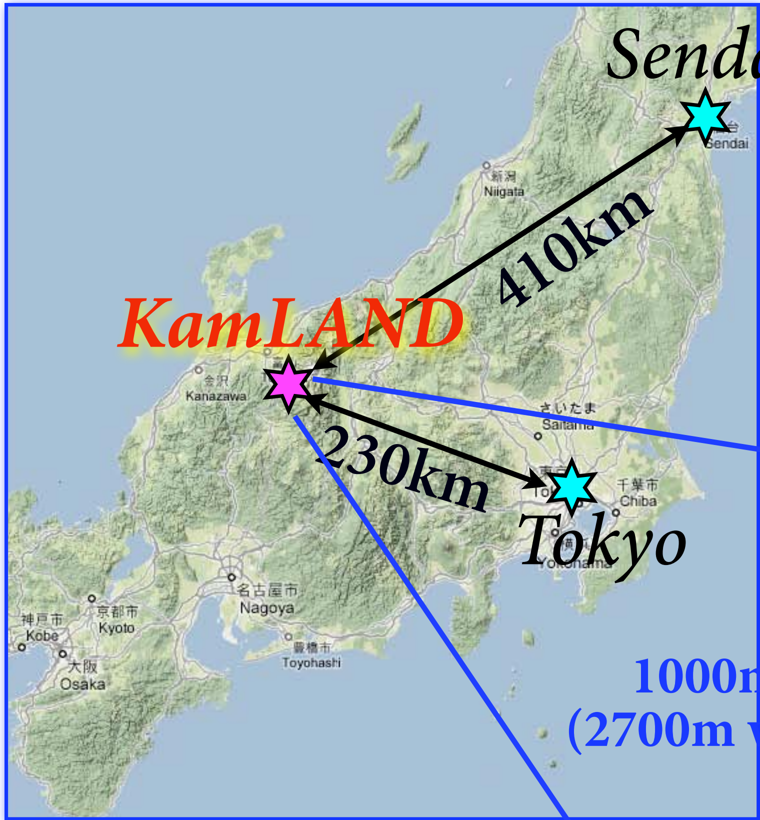
Expected spectra of various νs



KamLAND has explored low energy neutrino physics with great sensitivity !

Location of KamLAND

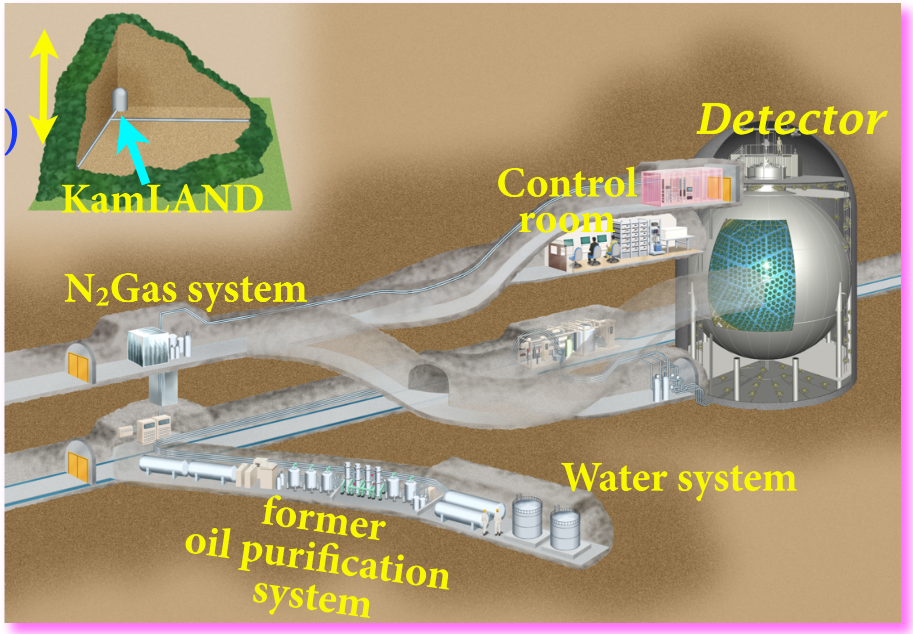
KamLAND area:
Kamioka mine in Gifu prefecture,
Former Kamiokande site.
1000m (2700m w.e.) rock overburden
Cosmic ray μon rate is 1/100,000 of the earth level.

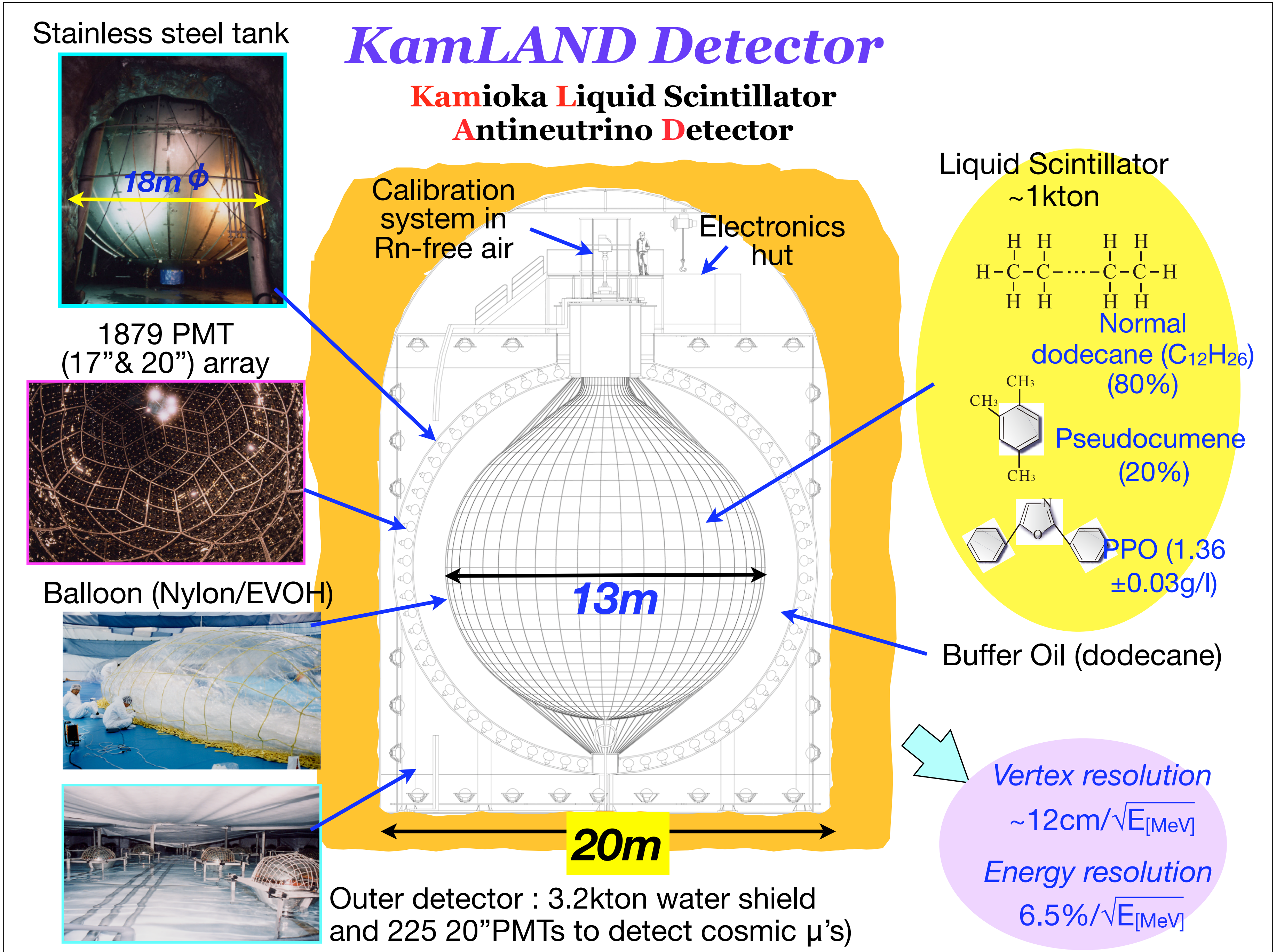


KamLAND Mozumi office

Mt. Ikenyama

1000m
(2700m w.e.)




KamLAND Detector
Kamioka Liquid Scintillator
Antineutrino Detector
Stainless steel tank
18m ϕ
1879 PMT
(17"& 20") array
Balloon (Nylon/EVOH)
Calibration system in Rn-free air
Electronics hut
13m
20m
Outer detector : 3.2kton water shield and 225 20"PMTs to detect cosmic μ's)
Liquid Scintillator
~1kton
Normal dodecane (C12H26) (80%)
CH3
Pseudocumene (20%)
N
O
PPO (1.36 ±0.03g/l)
Buffer Oil (dodecane)
Vertex resolution
~12cm/√E[MeV]
Energy resolution
6.5%/√E[MeV]

KamLAND Collaboration

~80 physicists
14 institutes

RCNS, Tohoku University
University of Alabama
Univeristy of California, Berkeley/Lawrence Berkeley National Laboratory
California Institute of Technology
Colorado State University
Drexel University
University of Hawaii
Kansas State University
Louisiana State University
Stanford University
University of Tennessee
Triangle Universities Nuclear Laboratory/North Carolina Central University/
University of North Carolina
University of Wisconsin
CEN Bordeaux-Gradignan/IN2P3-CNRS/University of Bordeaux I

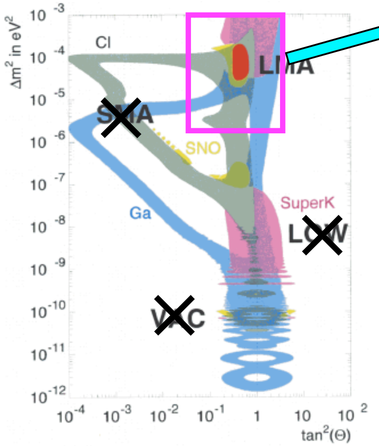
Reactor $\overline{\nu}_e$ analysis
E_{vis}: 2.6~8.5MeV

Challenging the SNP by man-made neutrinos !

Phys.Rev.Lett.90, 021802 (2003)

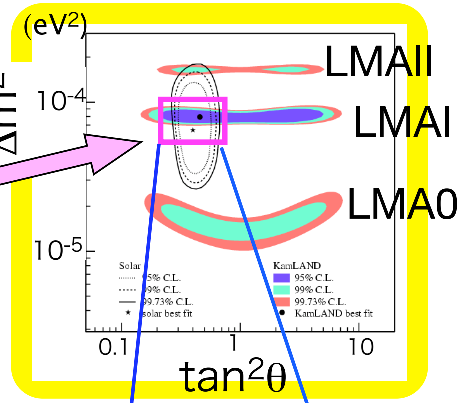
Reactor ν_e disappearance

Exclude all solutions except for LMA

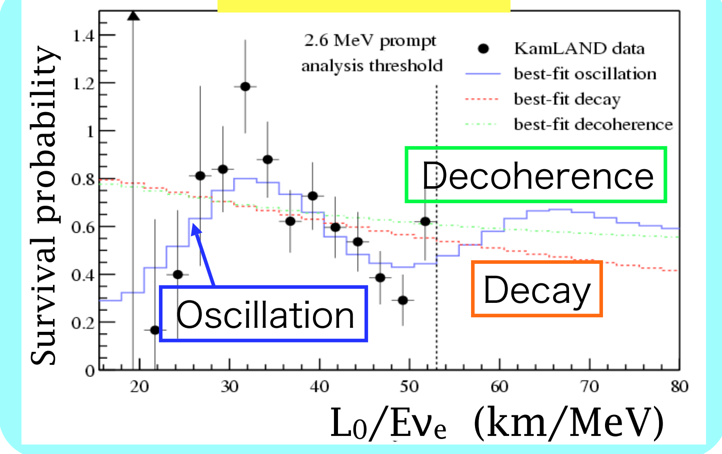


Evidence for $\overline{\nu}_e$*-oscillation*

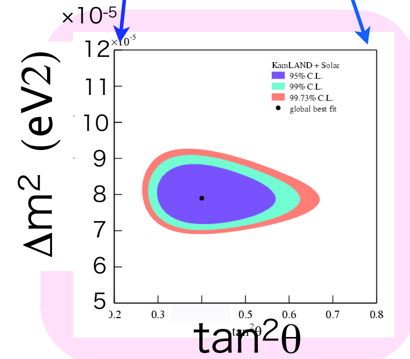
Phys.Rev.Lett.94, 081801 (2005)



L_0/E_ν distribution



Solar+KamLAND



Solar ν problem has been solved under the assumption of CPT invariance !

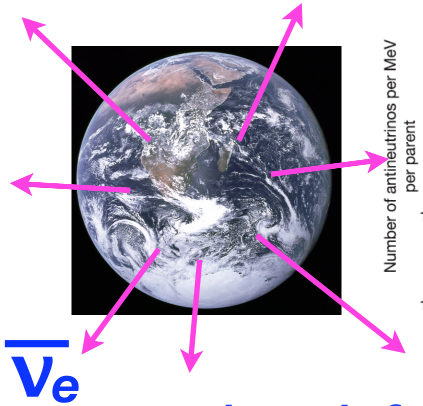
precise determination of oscillation parameters

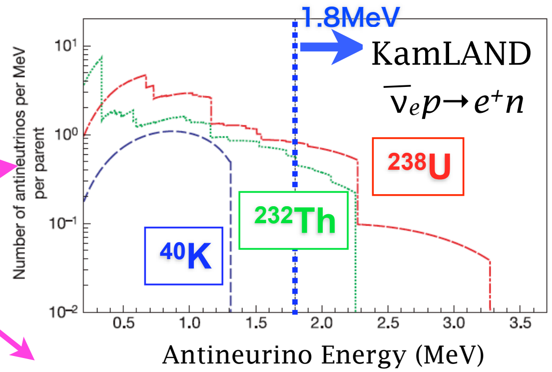
$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$eV^2

$\tan^2\theta = 0.4^{+0.10}_{-0.07}$

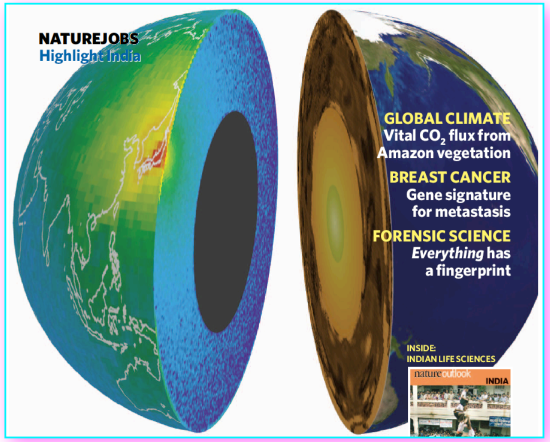
First challenge to Geo-ν detection !

Analysis for
E_{vis}= 0.9~2.6MeV

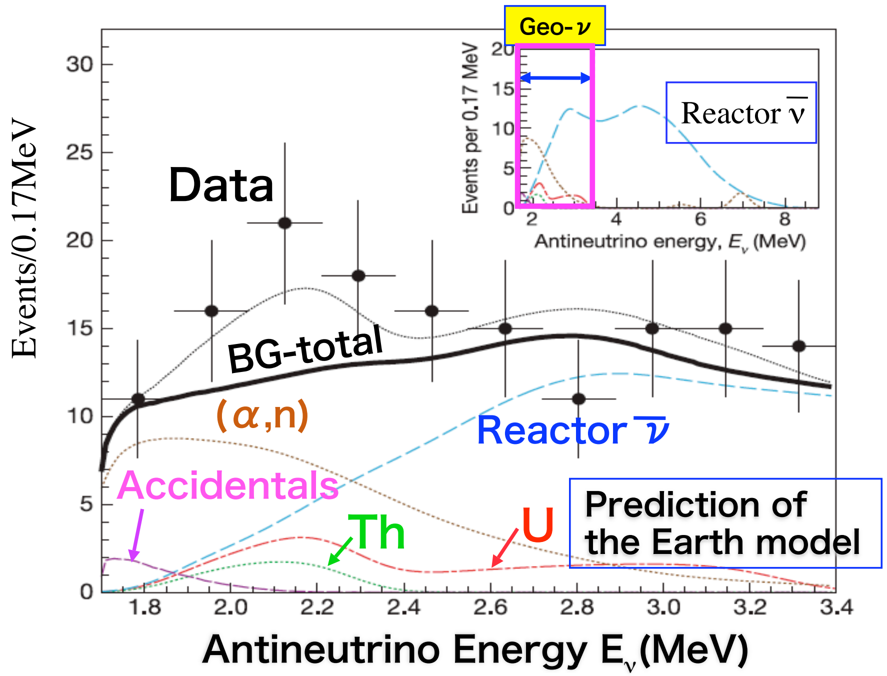




Direct information of radiogenic heat of U/Th series in the Earth.



Nature 436, 499 (2005)



Excess: 25^{+19}_{-18} events

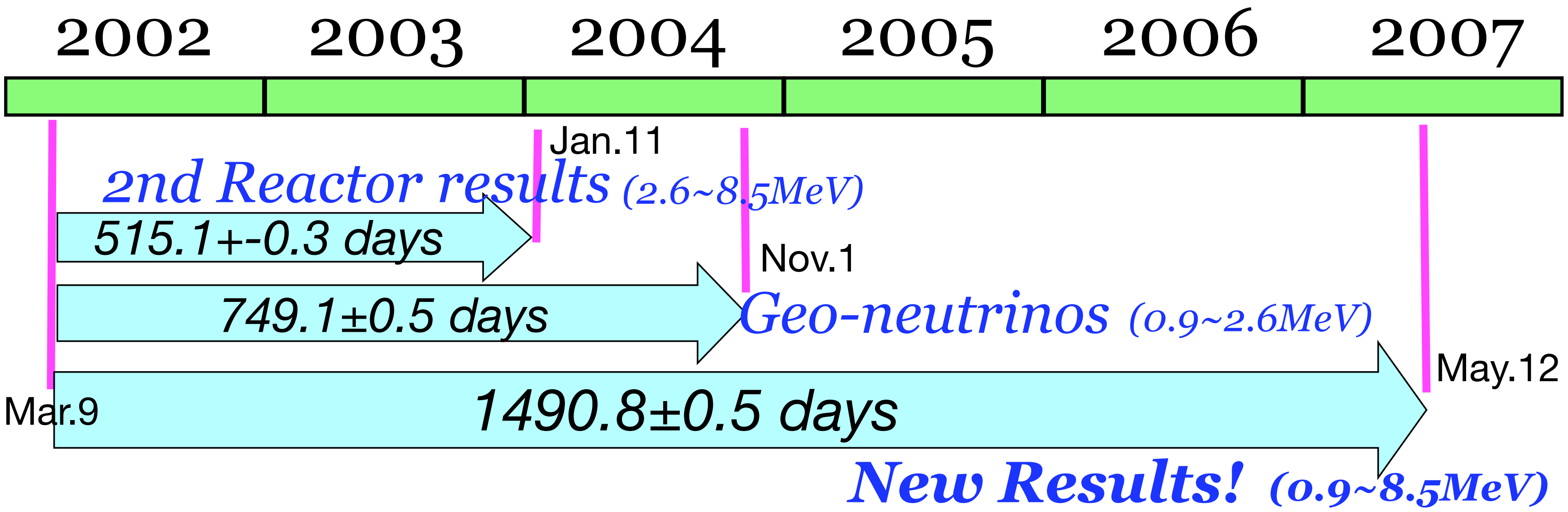
Statistically weak, but consistent with the earth model.

Neutrinos can be a probe to study the Earth interior !

Neutrino Geophysics has been opened !

New KamLAND Results on $\bar{\nu}_e$ analysis

Data Sample (Live time)

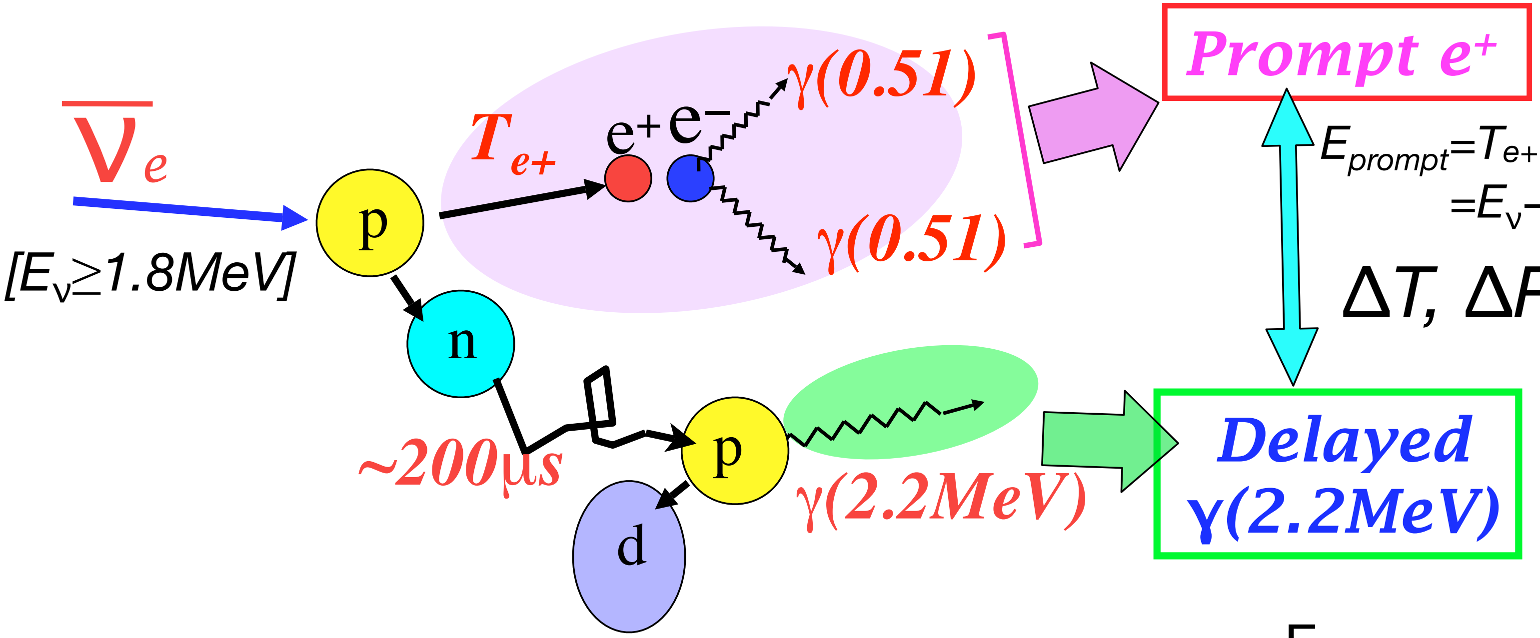


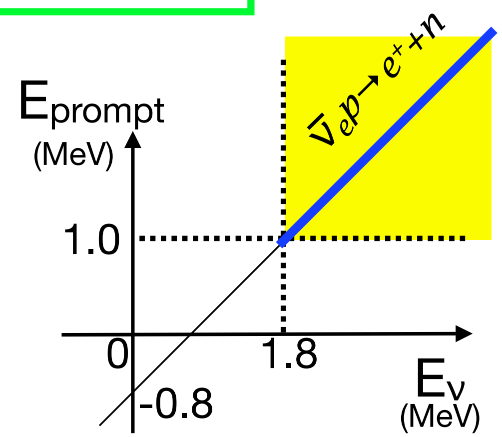
- *Expand the analysis to full reactor $\bar{\nu}_e$ energy spectrum.*
- *New analysis to enlarge fiducial volume.*
- *Reduction of systematic uncertainties in the background estimation and the fiducial volume.*

$\bar{\nu}_e$ detection in KamLAND

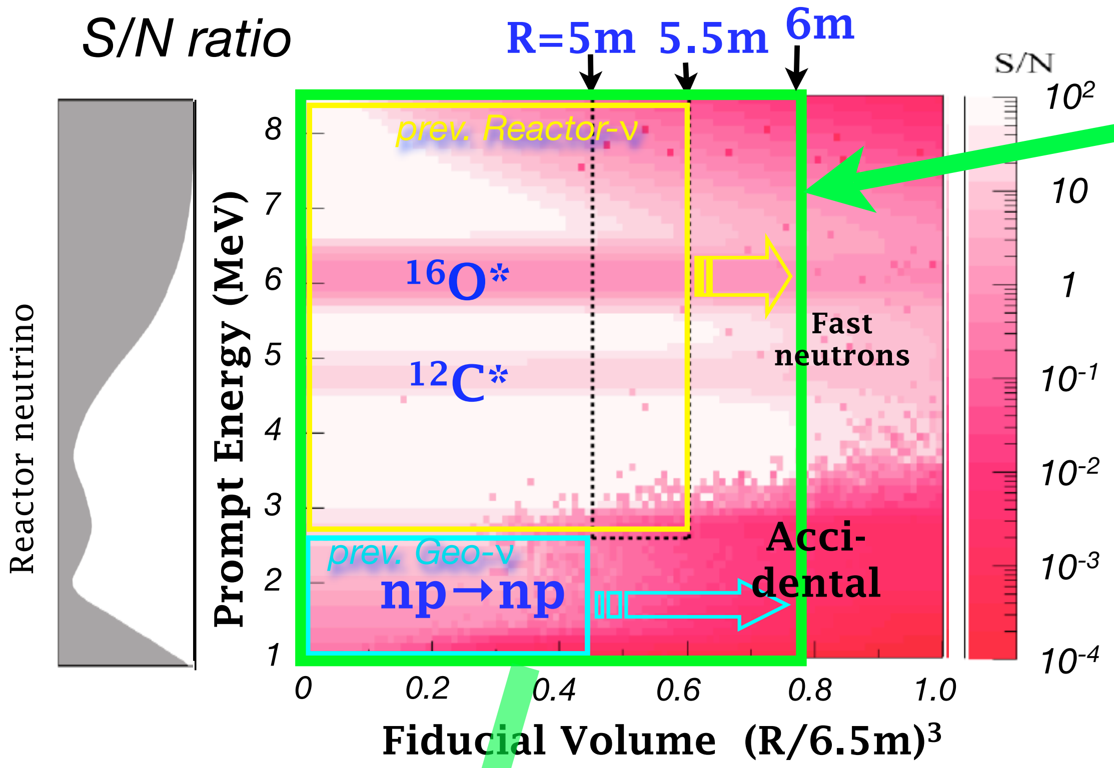
$\bar{\nu}_e + p \rightarrow e^+ + n$

Delayed coincidence of correlated events.





Cross section is precisely known within 0.2%.
Backgrounds are significantly reduced.
$\bar{\nu}_e$ energy is determined.



New Analysis

- *Enlarge the fiducial volume R=5.5m → 6.0m*
- *Enlarge prompt energy region to include reactor +Geo-ν ; E_p =0.9~8.5MeV*

Challenge the accidental (^{210}Bi, ^{40}K, ^{208}Tl) and (α,n) background !

Selection conditions (after muon cut)

	Geo-neutrinos	2nd Reactor	**New Analysis**
E_p (MeV)	0.9-2.6	2.6-8.5	**0.9**-8.5
E_d (MeV)	1.8-2.6	1.8-2.6	1.8-2.6 or **4-5.8**
R_p (m)	5.0	5.5	**6.0**
R_d (m)	5.0	5.5	**6.0**
ΔR (m)	1	2	2
ΔT (μs)	0.5-500	0.5-1000	0.5-1000

Likelihood analysis to reject accidental backgrounds

Probability density functions

$f_{acc}(E_p, E_d, R_p, R_d, \Delta R, \Delta T)$:
made by off-timing
(10ms~20s) real data.

Flat distribution in ΔR & ΔT

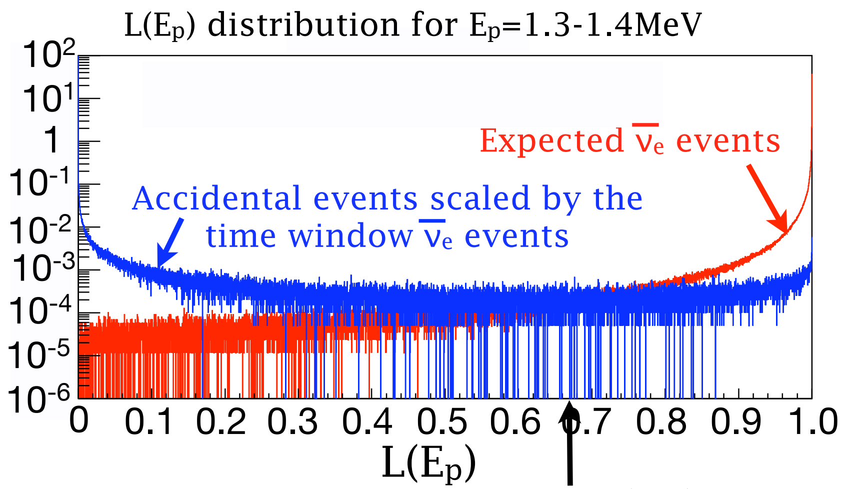
$f_{\bar{\nu}_e}(E_p, E_d, R_p, R_d, \Delta R, \Delta T)$:
GEANT4 simulation of $\bar{\nu}_e$ events using the neutron capture time and energy resolution.

Enhancement at small ΔR & ΔT

Take likelihood ratio $L(E_p)$ for selected delayed-coincidence events.

$$L(E_p) = f_{\bar{\nu}_e} / (f_{\bar{\nu}_e} + f_{acc})$$

Events with $L(E_p) > L_{cut}(E_p)$ are selected.



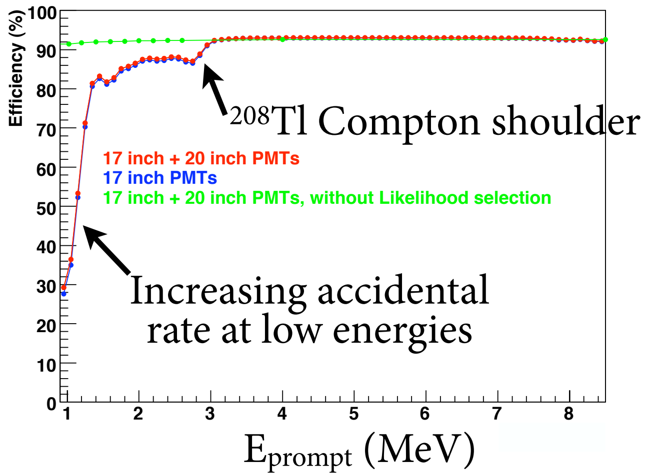
$L_{cut}(E_p)$=0.67
FOM=8.1

$L_{cut}(E_p)$ is the $L(E_p)$ which gives maximum FOM(Figure of merit=$S/\sqrt{(S+B)}$)

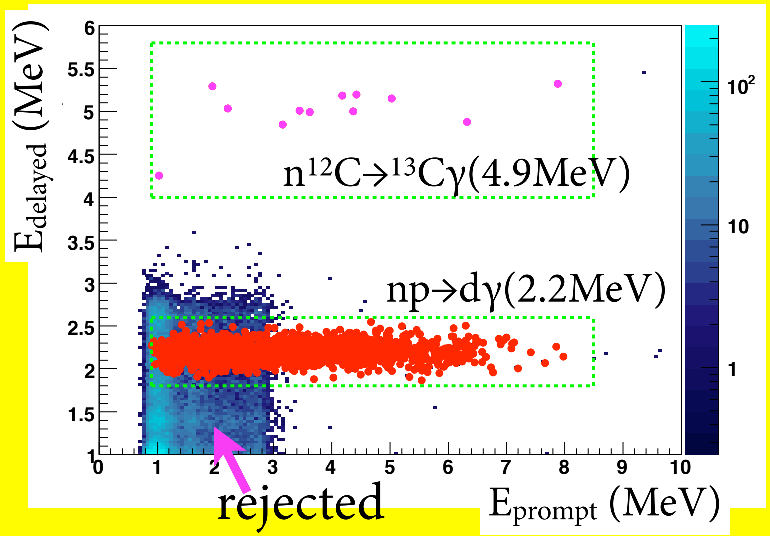
$S = \int_L^1$(# of signal events with L)dL

$B = \int_L^1$(# of accidental events with L)dL

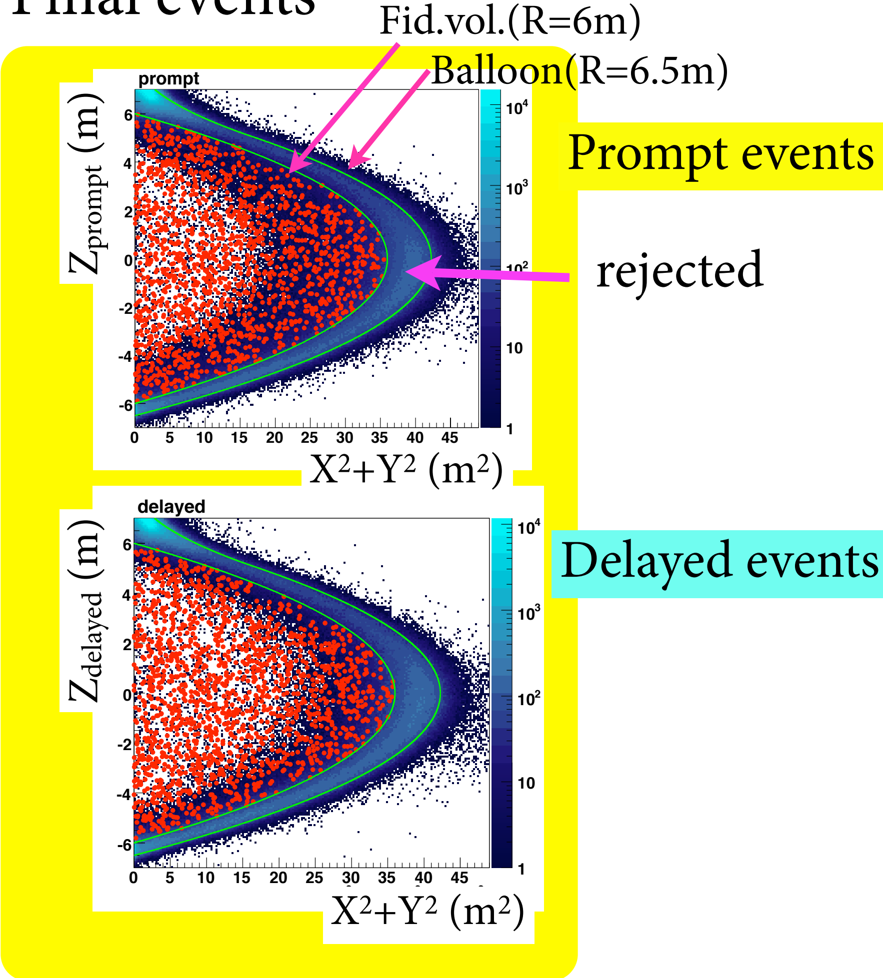
Estimated selection efficiency ε



Comparison of ^{68}Ge, ^{241}Am^{9}Be data with GEANT4 simulation
→ Average uncertainty =0.6%



Final events



Enlarge the fid. volume by 30% and significant reduction of accidental backgrounds has been made!

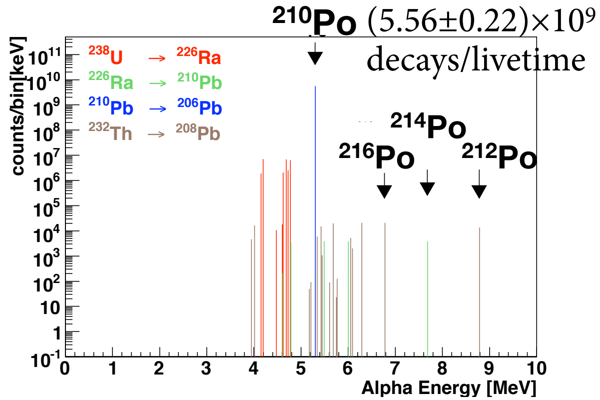
(α,n) background

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

↑ abundance =1.1%

Dominant background !

^{210}Po is dominant (>99%)



$(t_{1/2}=3.8d)$ (22.3y) (5.0d) (138.4d)

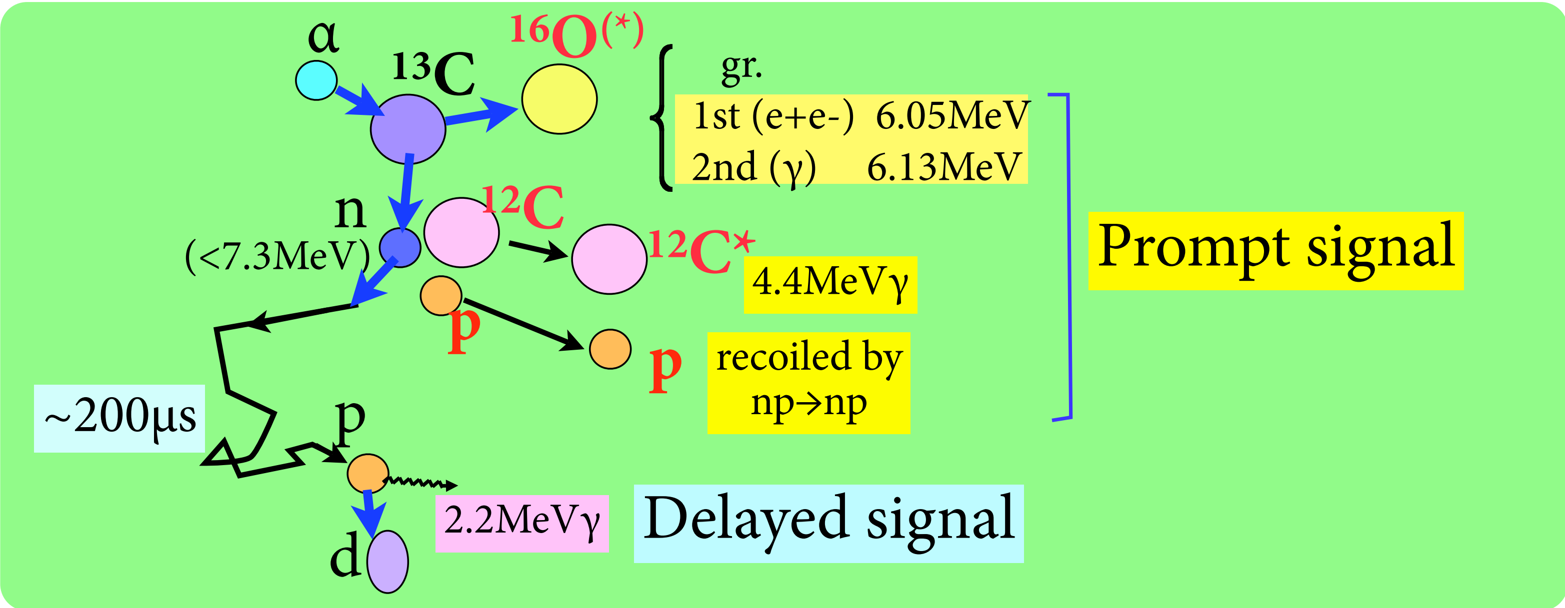
$^{222}Rn \rightarrow \bullet\bullet\bullet \rightarrow {}^{210}Pb \xrightarrow{\beta} {}^{210}Bi \xrightarrow{\beta} {}^{210}Po \rightarrow {}^{206}Pb$

(<64KeV) (<1.16MeV)

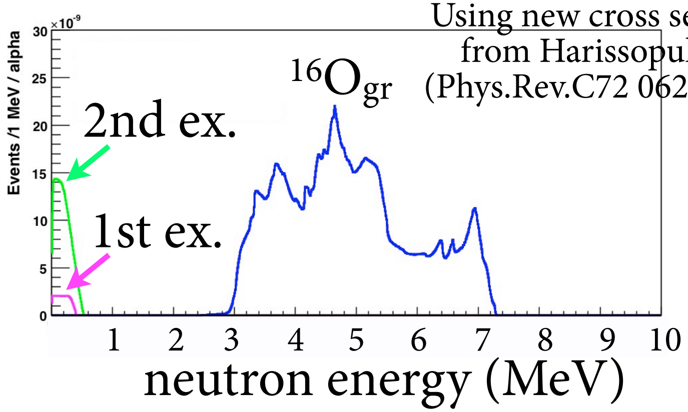
α(5.304MeV):

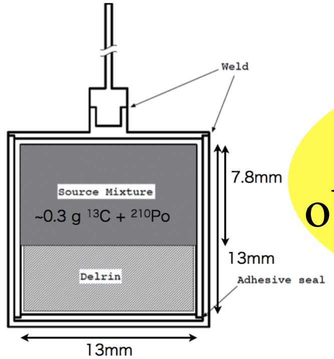
E_{vis}~300keV(quenching);

39.4±1.8 mBq/m^3

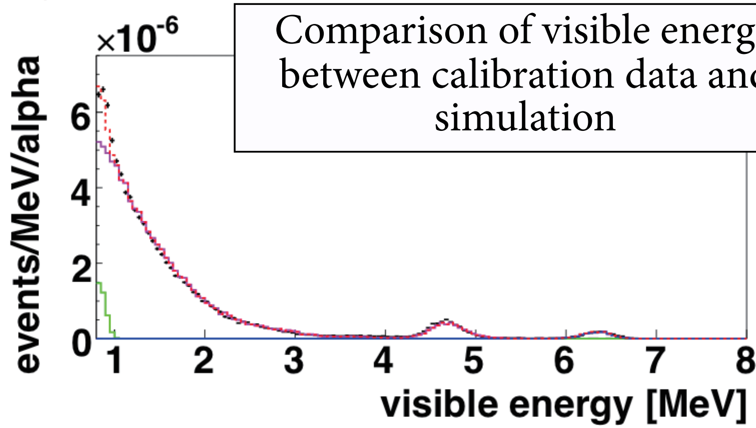


Expected neutron spectrum of $^{13}C(\alpha,n)^{16}O^{(*)}$



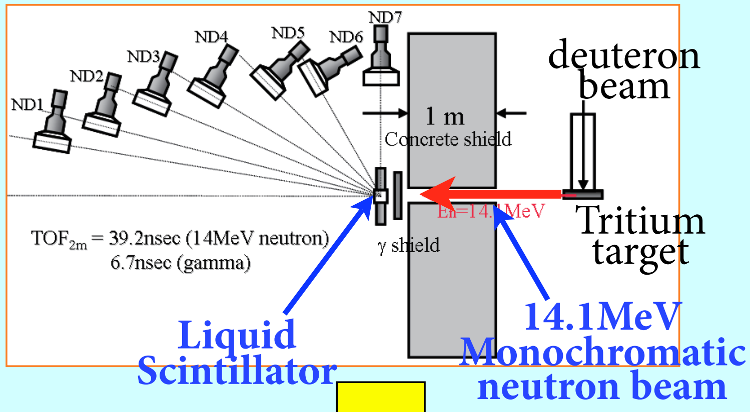


$^{210}Po^{13}C$ calibration source was deployed to obtain contribution of the ^{16}O excited states

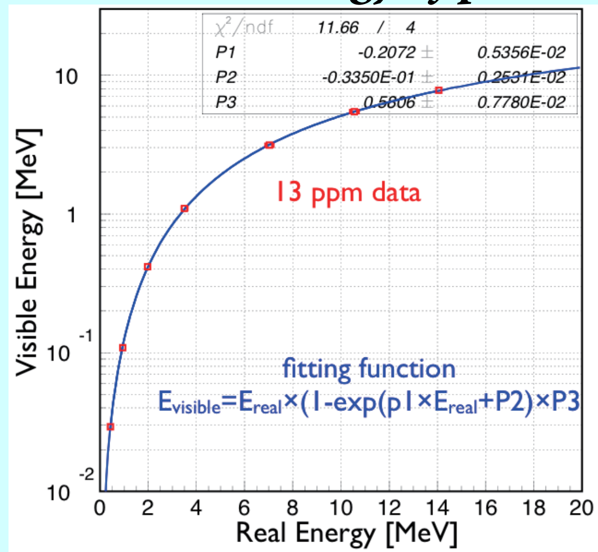


Comparison of visible energy between calibration data and simulation

Measurement of the quenching of the proton signals in LS (@ OKTAVIAN)



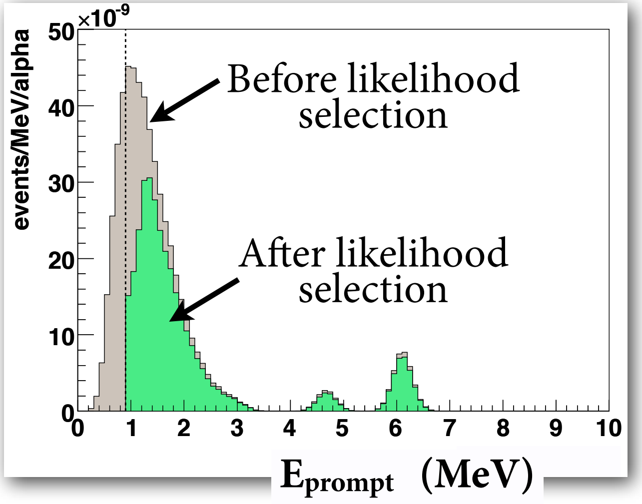
Visible vs real energy of protons



Uncertainty: ±2%

(↔ 10% in previous analysis)

Expected $^{13}C(\alpha,n)^{16}O^{(*)}$ spectrum



Estimated number of $^{13}C(\alpha,n)^{16}O^{(*)}$

$^{13}C(\alpha,n)^{16}O_{GS}$	157.2±17.3
$^{13}C(\alpha,n)^{16}O^{*}$(1st exc.)	15.2±3.5
$^{13}C(\alpha,n)^{16}O^{*}$(2nd exc.)	3.5±0.2
$^{13}C(\alpha,n)^{16}O$ $^{12}C(n,n\gamma)^{12}C^{*}(4.4)$	6.1±0.7
total	182.0±21.7

Systematic uncertainty of $^{13}C(\alpha,n)^{16}O^{(*)}$

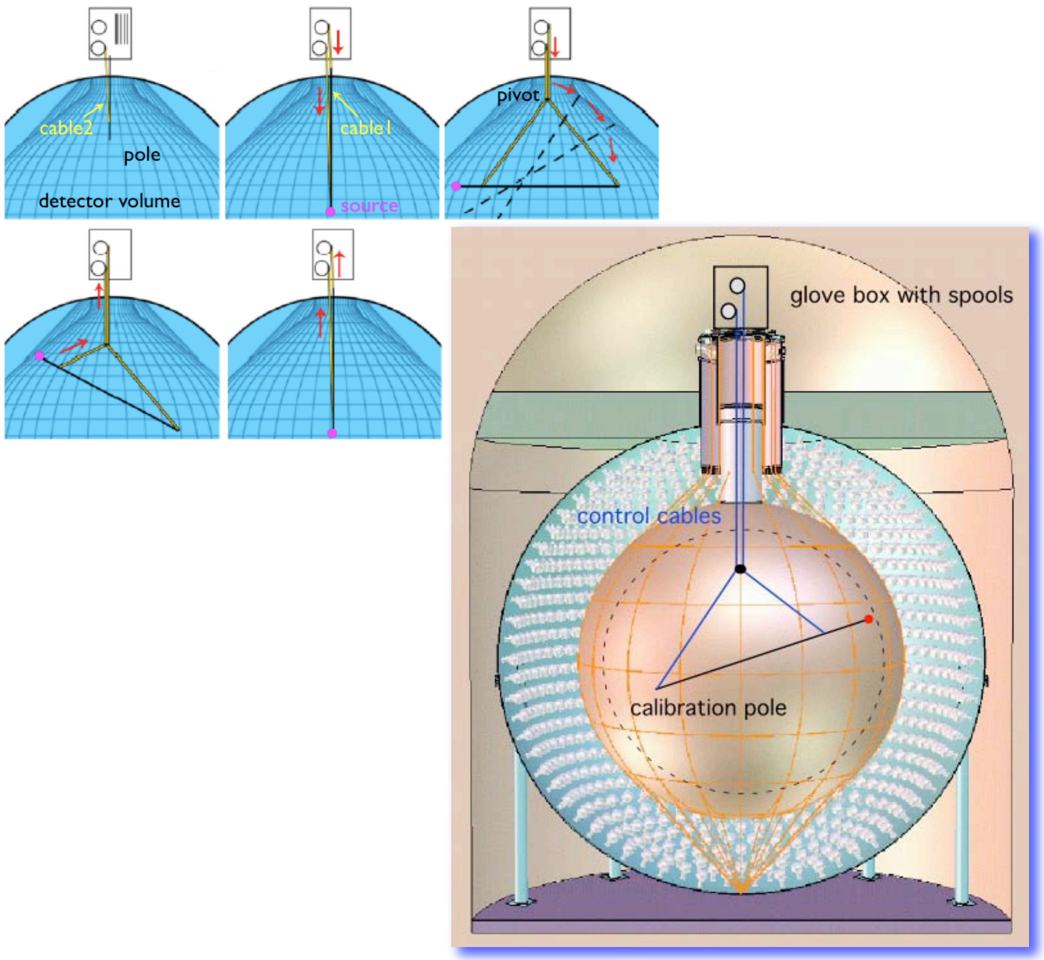
	2nd Res.	New Res.
Total	***26%***	***12%***
^{210}Po decay rate	*14%*	*4%*
$^{16}O_{GS}$	*20%*	*11%*
$^{16}O^{(1st)}+{}^{16}O^{(2nd)}$	*100%*	*20%*
Proton quench	*10%*	*2%*

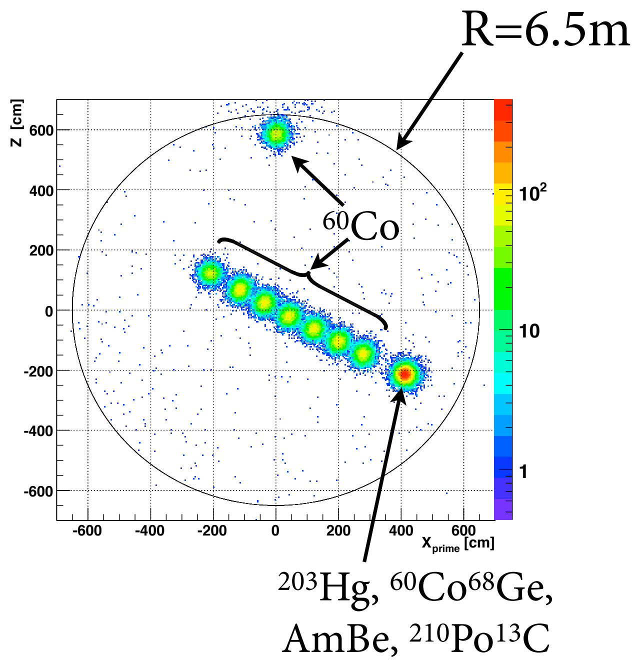
Other backgrounds

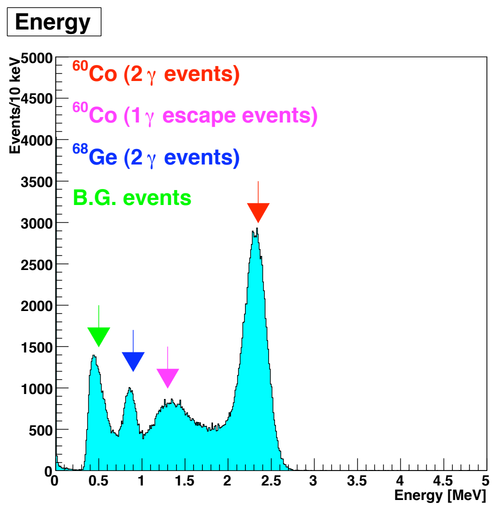
Accidentals	80.5±0.1
$^{9}Li/^{8}He$	13.6±1.0
fast neutron+Atmospheric ν	<9.0

Total estimated backgrounds in the data sample
276.1±23.5

Off axis calibration by system "4π" for entire detector volume (R<5.5m)

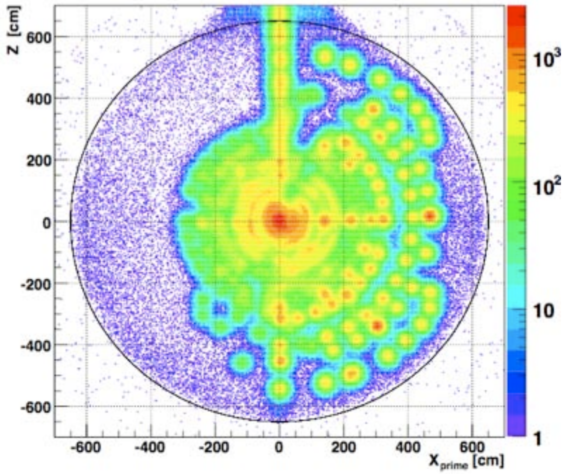


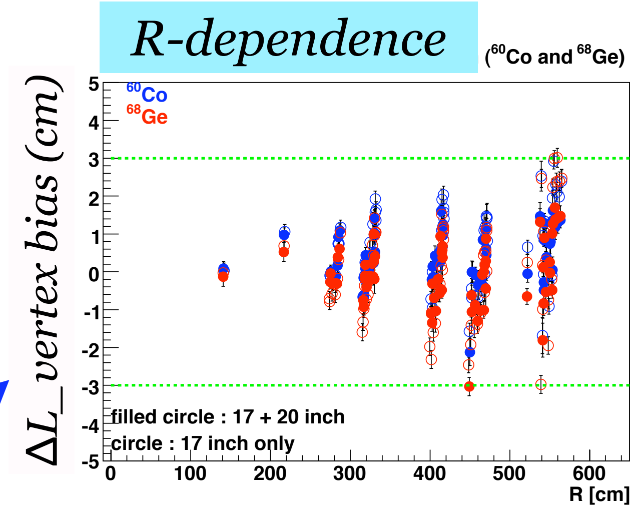




Study position dependence of reconstructed energies and vertices.

$^{60}Co^{68}Ge$ composite source

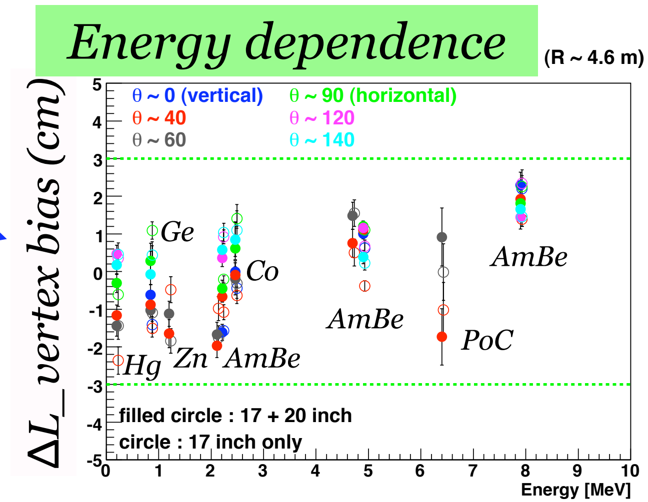




ΔL=±3cm

ΔL_vertex bias=
$L_{reconsturcted}$-$L_{expected}$

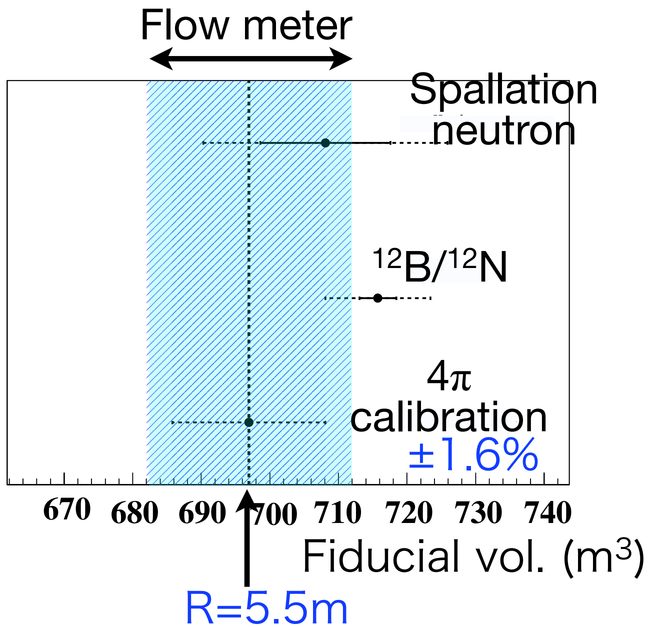
Distance between the two reconstructed source positions is compared with the expected distance.

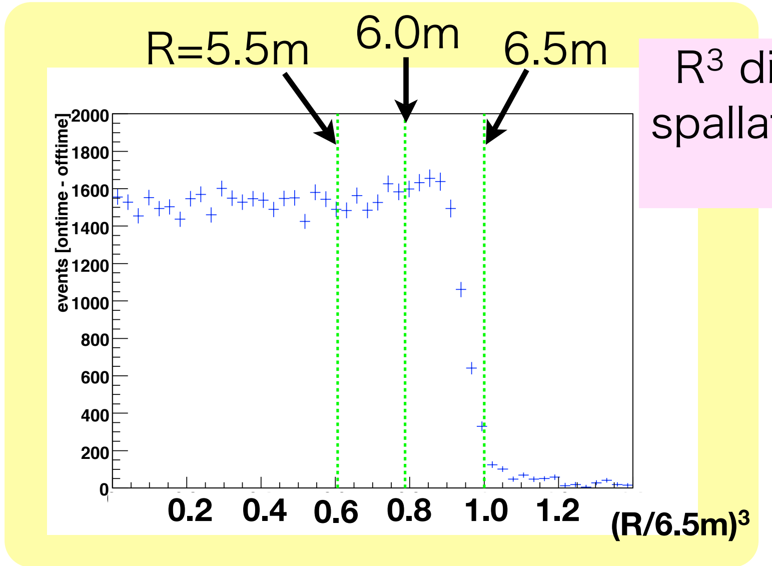


ΔL=±3cm

With various R and energy, ΔL is found <3cm.

Fid. Vol. uncertainty
$\Delta V/V = 3\times\Delta R/R =$ **1.6%** (R=5.5m)





R^3 distribution of spallation events of $^{12}B/^{12}N$

$N_{5.5m}/N_{6.0m}$=0.768±0.002(stat)

$(5.5m/6m)^3$ =0.7703 → -0.3%±0.3%

Before 4π calibration
$(\Delta V/V)$ =4.7% @R=5.5m

After 4π calibration

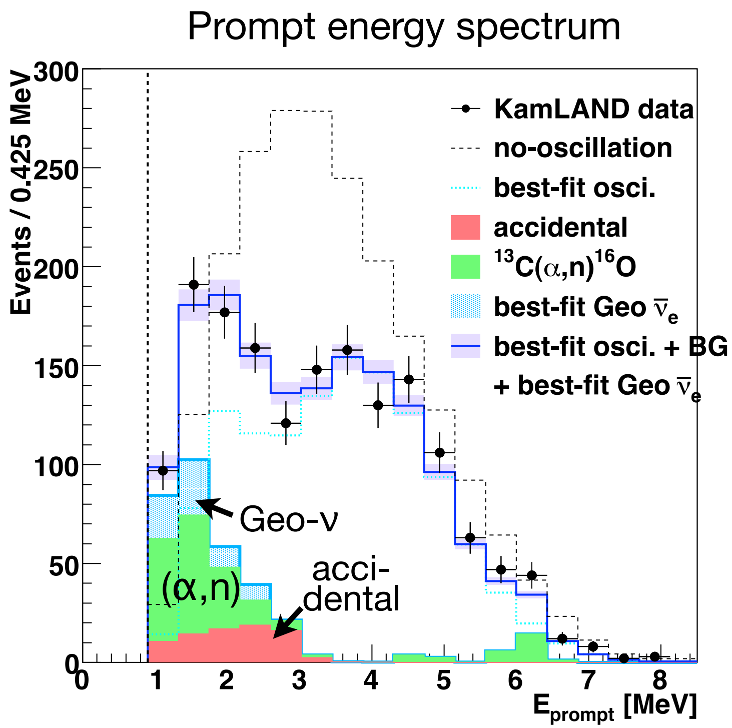
$$\Delta V/V = \sqrt{(1.6)^2+(0.6)^2} = 1.8\%$$

Summary of systematic uncertainties (rate)

	Prev. Reactor Res.(%)	New Res.(%)
Fiducial volume	4.7	1.8
Energy threshold	2.3	1.5
Efficiency of cut	1.6	0.6
Total (Detector related)	5.5	→ 2.4
Total (Detector+Reactor)	6.5	→ 4.1

Reactor related sys. uncertainty(%)

ν_e-spectra	2.4
Reactor power	2.1
Fuel composition	1.0
Long-lived nuclei	0.3
total	***3.4***



Observed : 1609

Background : 276.1±23.5

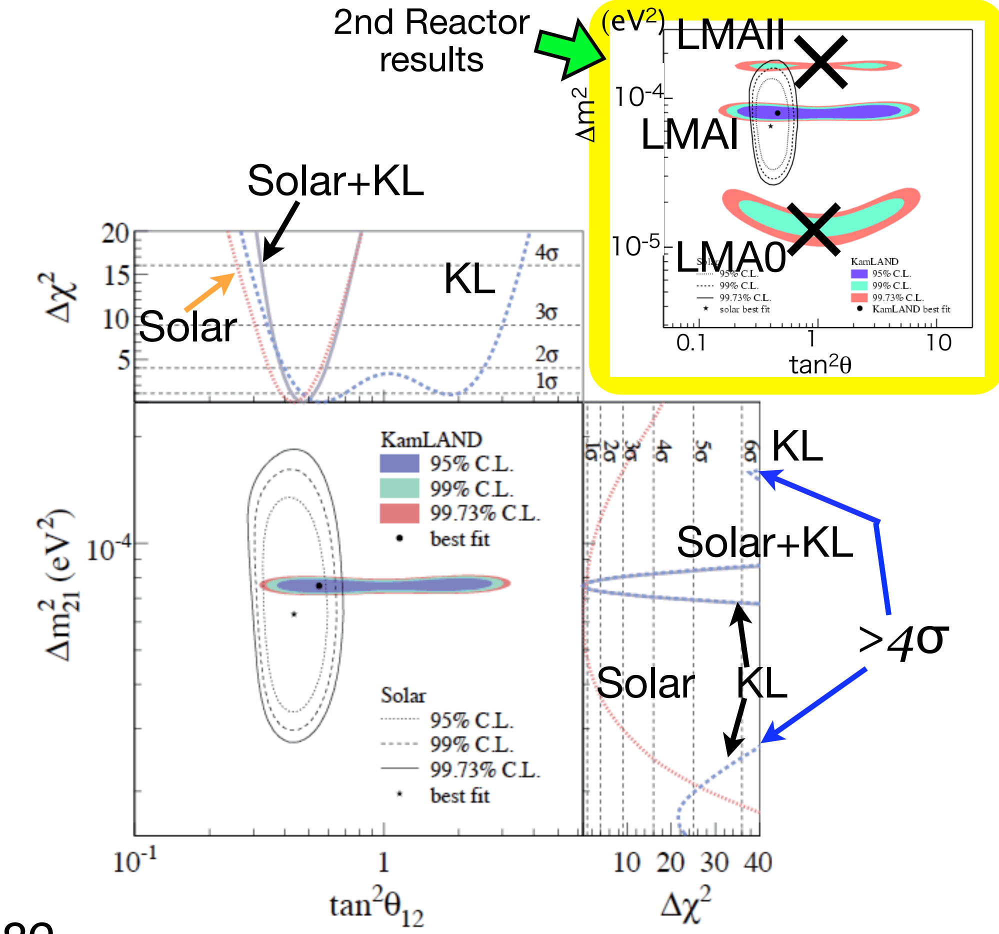
↔ *Expected (no-oscill.) : 2179±89*

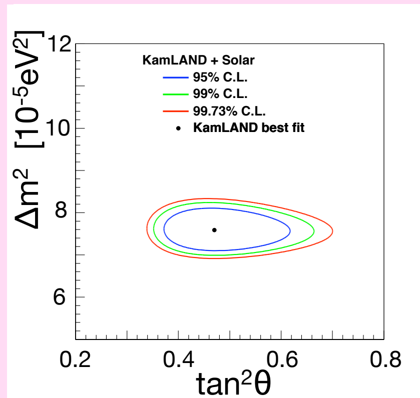
max. likelihood fit: 2 flavor ν+geo-ν
incl. event time and Earth matter oscillation

Exclude scaled no-oscillation >5σ

$\Delta m^2_{21}=7.58^{+0.14}_{-0.13}(\text{stat})^{+0.15}_{-0.15}(\text{sys})\times10^{-5}\ \text{eV}^2$

$\tan^2\theta_{12}=0.56^{+0.10}_{-0.07}(\text{stat})^{+0.10}_{-0.06}(\text{sys})$ (for $\tan^2\theta_{12}<1$)



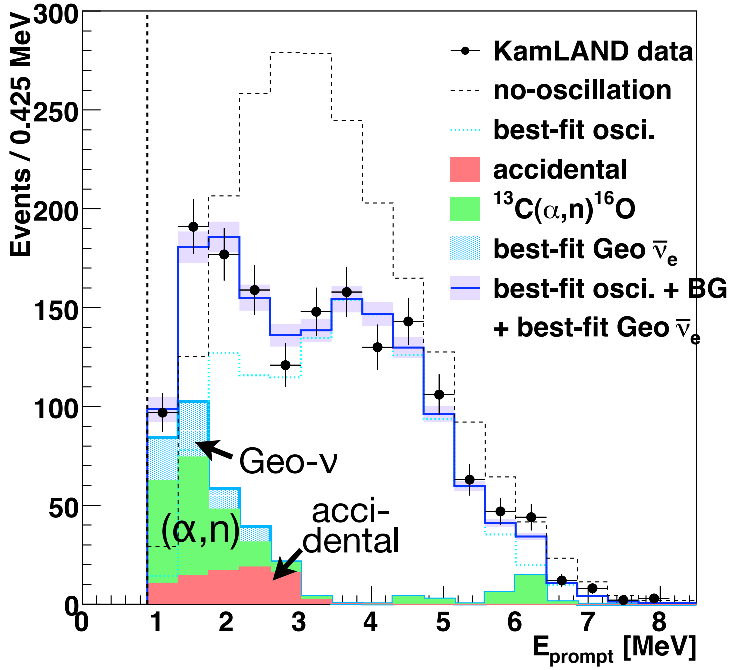


Solar+KL

$\Delta m^2_{21}=$
$7.59^{+0.21}_{-0.21}\times10^{-5}\text{eV}^2$

$\tan^2\theta_{12}=0.47^{+0.06}_{-0.05}$

Prompt energy spectrum



Observed : 1609

Background : 276.1±23.5

⟺ *Expected (no-oscill.) : 2179±89*

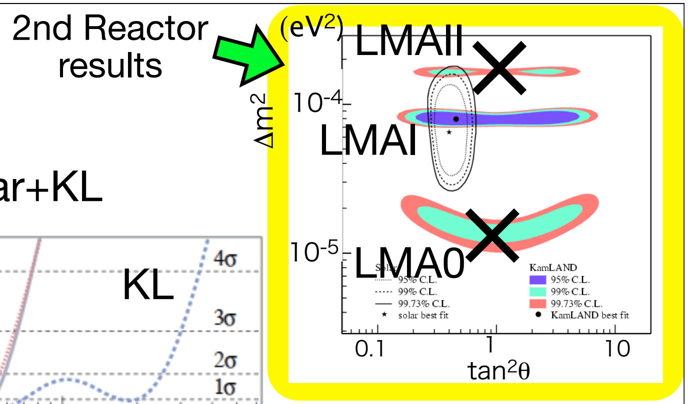
max. likelihood fit: 2 flavor ν+geo-ν

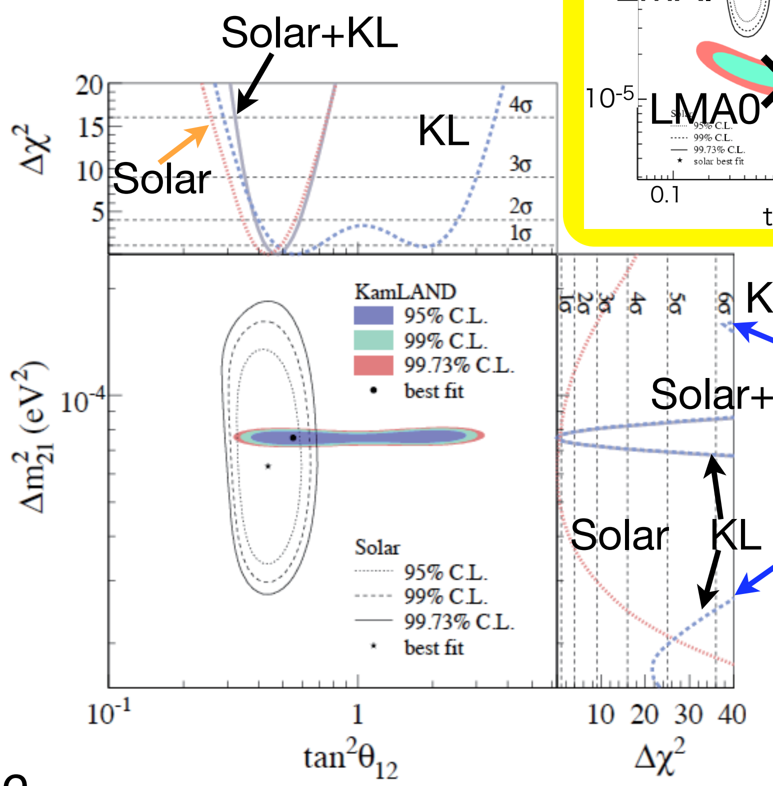
incl. event time and Earth matter oscillation

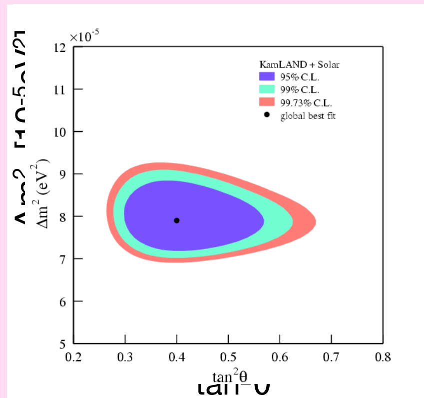
Exclude scaled no-oscillation >5σ

$\Delta m^2_{21}=7.58^{+0.14}_{-0.13}(stat)^{+0.15}_{-0.15}(sys)\times10^{-5}$ eV^2

$\tan^2\theta_{12}=0.56^{+0.10}_{-0.07}(stat)^{+0.10}_{-0.06}(sys)$ (for $\tan^2\theta_{12}<1$)





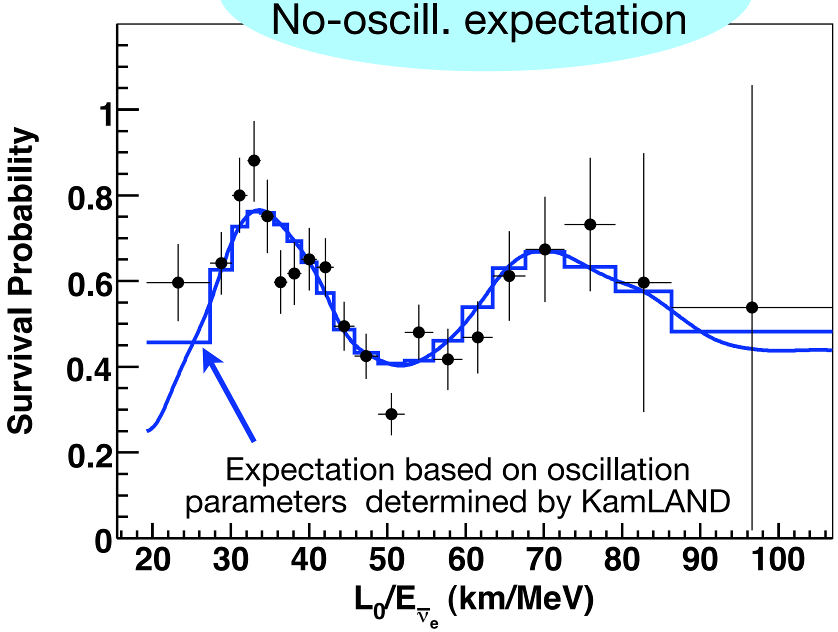


Previous Solar+KL

$\Delta m^2_{21}=$
$7.9^{+0.6}_{-0.5}\times10^{-5}$eV^2

$\tan^2\theta_{12}=0.4^{+0.10}_{-0.07}$

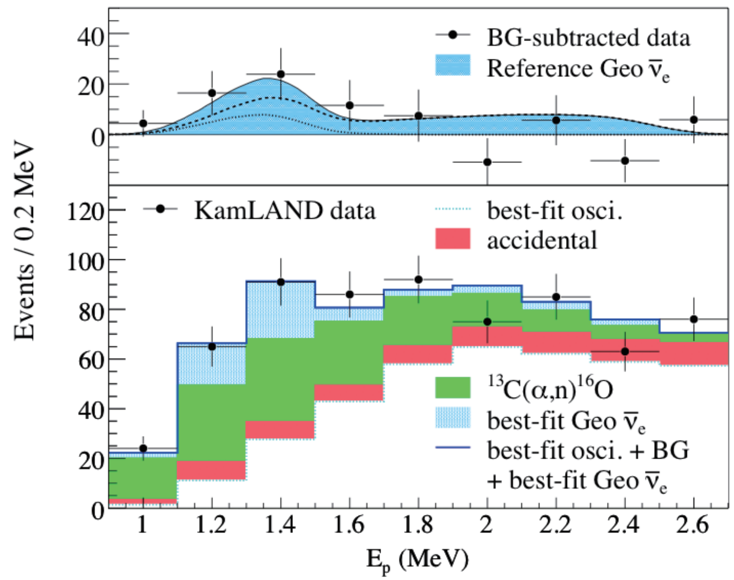
$\frac{\text{Data-(BG+Geo\_}\nu\text{)}}{\text{No-oscill. expectation}}$



L_0: flux-weighted average distance (=180km)

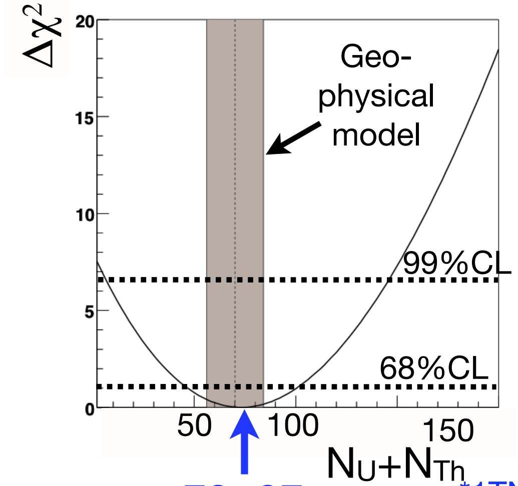
~2 cycles of Oscillation behavior is observed !

Geo-ν from U and Th



Best fit Geo-ν events; N_U=25, N_{Th}=36

Fix Th/U mass ratio to 3.9,



N_U+N_{Th}=73±27

Geo-ν flux=

$(4.4\pm1.6)\times10^6(cm^{-2}s^{-1})$

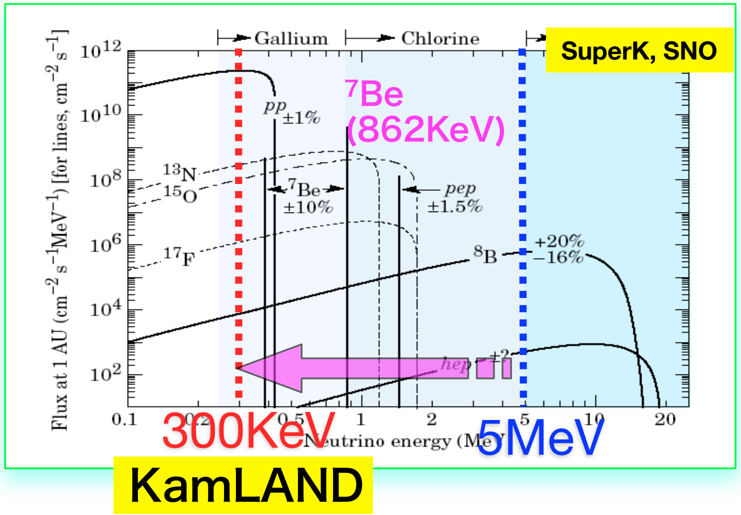
=39.4±14.3 TNU

(prev.res.=$57.4^{+32.0}_{-20.0}$TNU)

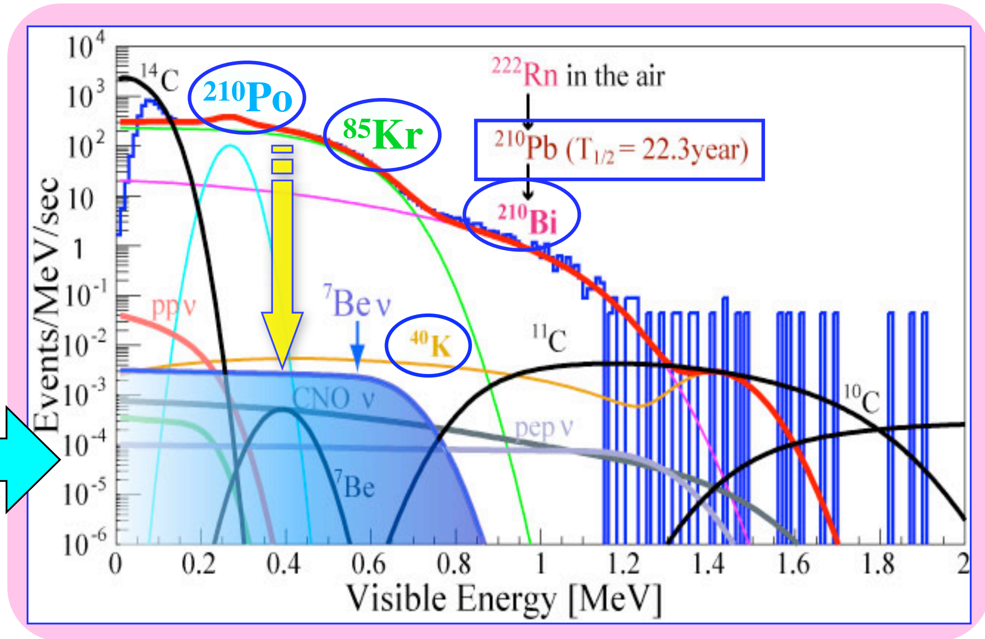
Consistent with the Earth reference model (36.5TNU, U+Th=16TW).

*1TNU:Geo-ν flux for 1ev/10^{32} protons/y

Toward the Solar phase



Singles spectrum in KamLAND below 2MeV



^{7}Be ν, pep and CNO ν
reaction: νe→νe

^{210}Pb($T_{1/2}$=22.3yr→^{210}Bi→^{210}Po), ^{85}Kr(10.8yr)
→ 10^{-5}~10^{-4}, and ^{40}K→ 10^{-2}~10^{-1}.

A big challenge to the singles backgrounds !

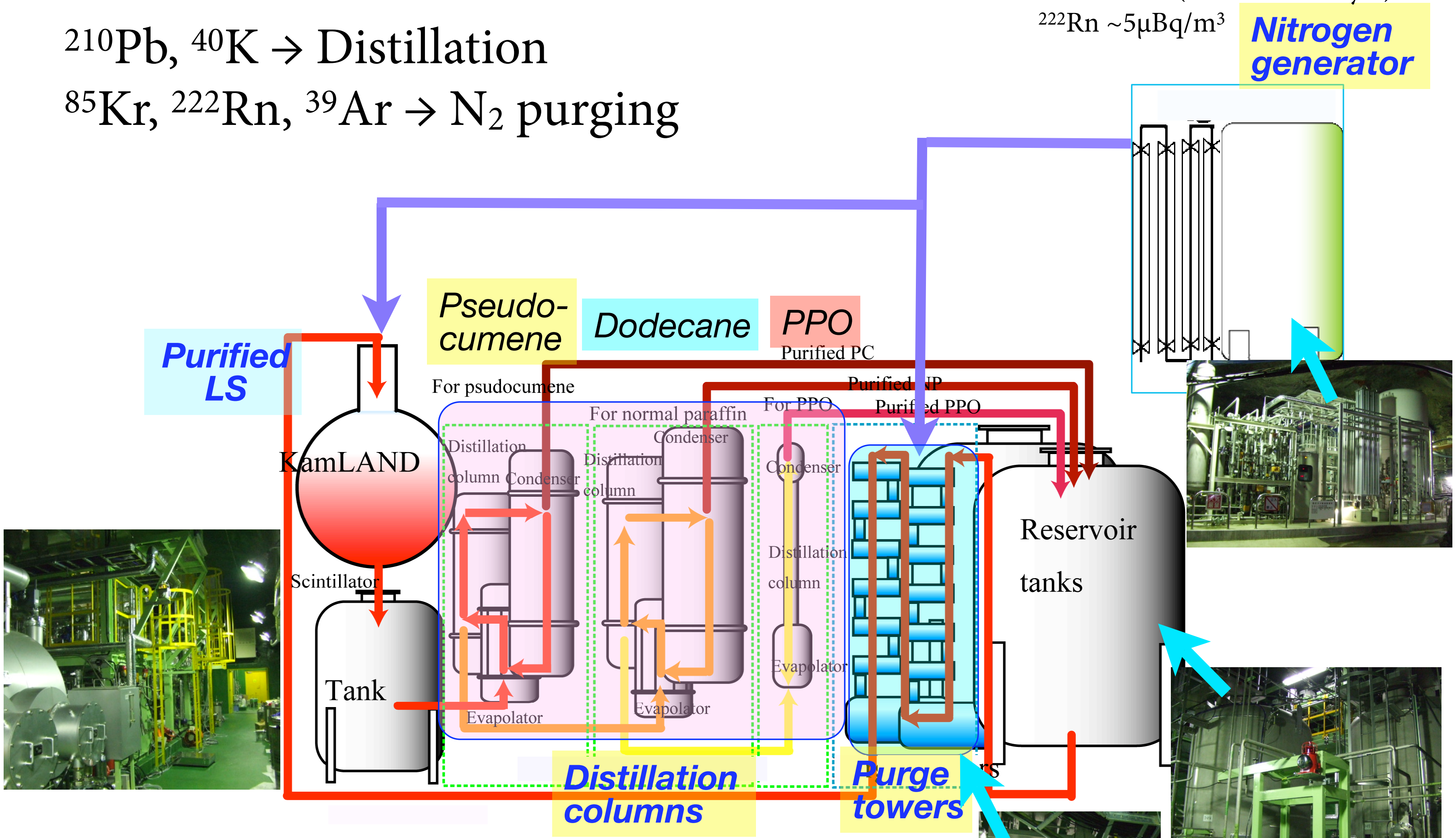
Burning mechanism of the sun !
Check the solar model ; discrepancy between studies on helio-seismology and the SSM with recent chemical components of the sun.

Purification in KamLAND (May-Aug '07):

Ar : 0.02~0.03ppm
Kr : ~10-15 (not measured yet)
^{222}Rn ~5μBq/m^3

^{210}Pb, ^{40}K → Distillation

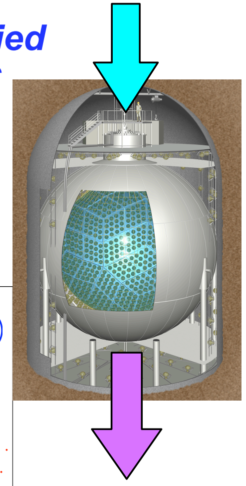
^{85}Kr, ^{222}Rn, ^{39}Ar → N_2 purging

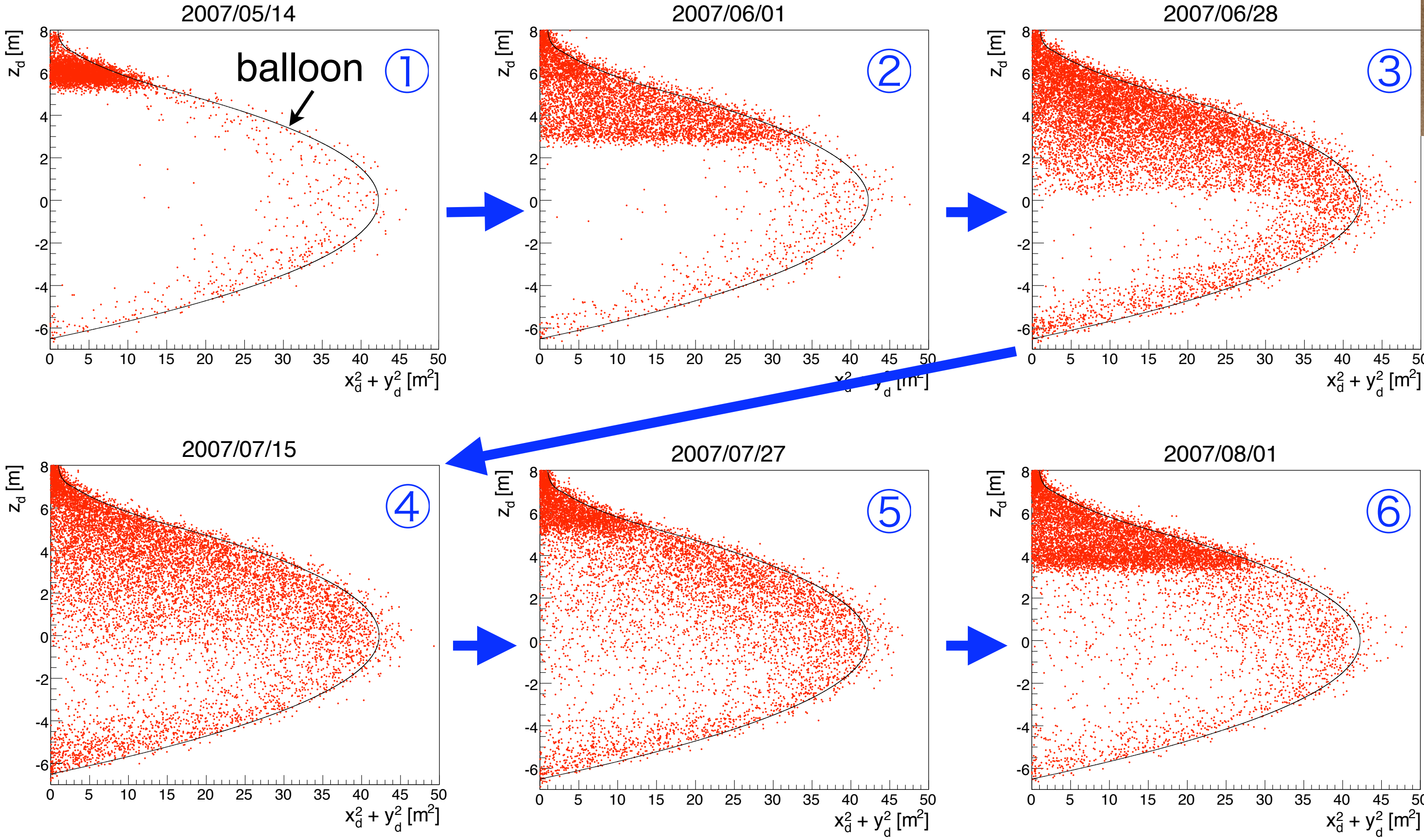


Three components of the LS are separately distilled and mixed after the distillation.

LS status during the purification

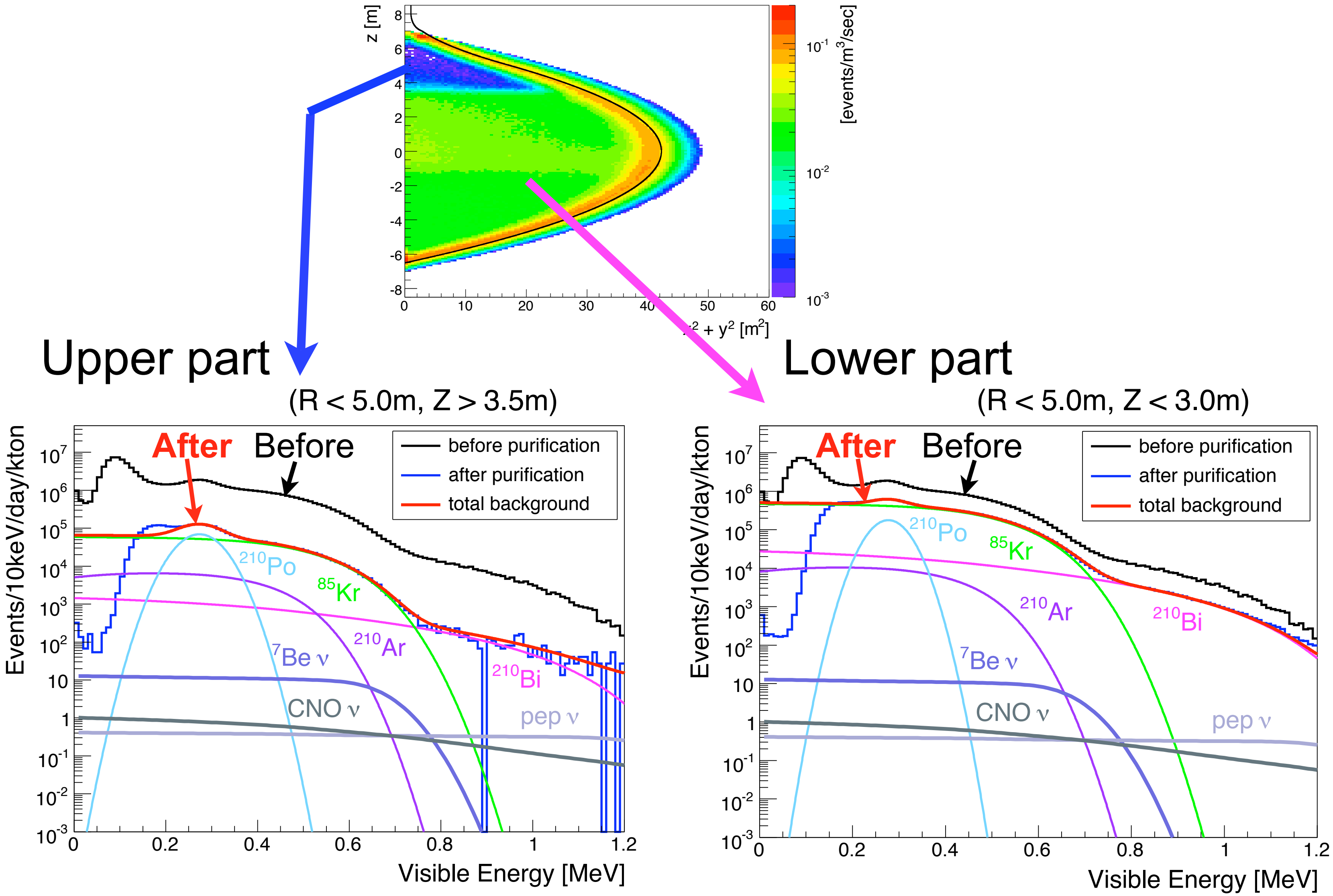
Monitored by ^{222}Rn daughters,
$^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$ (<0.8mBq/m^3, OK)





(1) Start purification → (2) Purified LS is clearly separated. → (3) A part of the LS flows down near the balloon. → (4) Purified LS goes down and mixed → (5) Make lower the LS density → (6) Finish the purification

Energy spectrum after the purification.

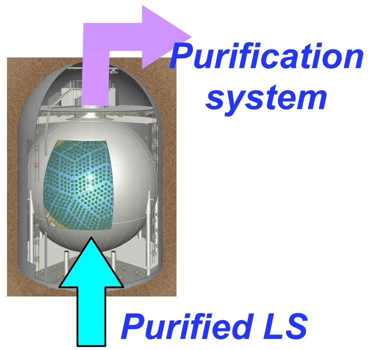


Summary of the purification effect on radio-activities.

(mBq/m^3)

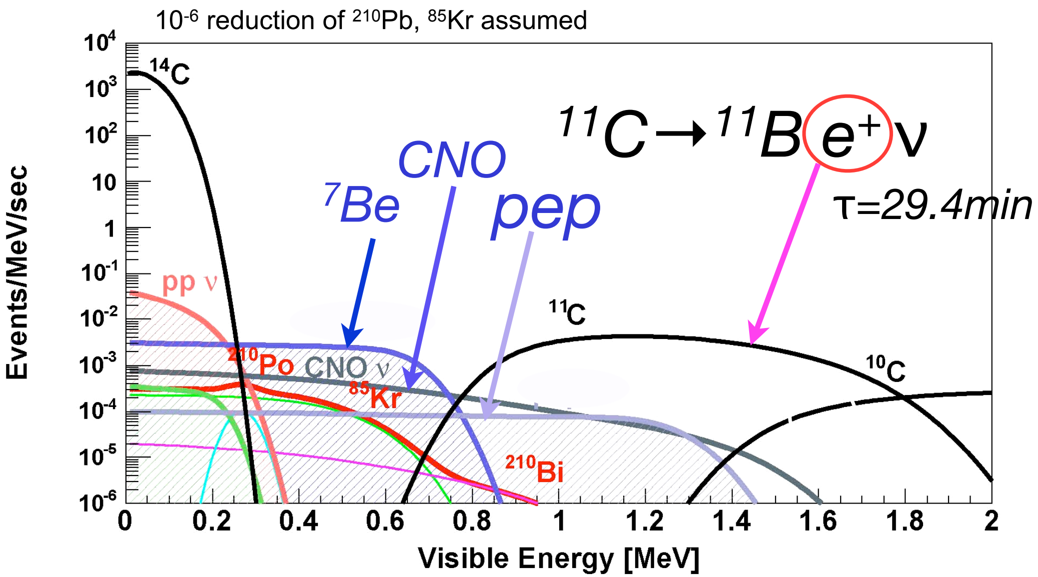
	^{210}Bi	^{210}Po	^{85}Kr	^{39}Ar	^{40}K
Before	42^{+8}_{-6}	43^{+1}_{-2}	508^{+19}_{-34}	18^{+38}_{-18}	$(44\pm4)\times10^{-3}$
After (Upper)	0.2 ± 0.1	9 ± 1	14^{+1}_{-4}	0^{+5}_{-0}	-
After (Lower)	10 ± 1	14 ± 1	185^{+1}_{-2}	0^{+2}_{-0}	$(13\pm1)\times10^{-3}$
Reduction (Upper)	$(4.8\pm2.6)\times10^{-3}$	0.21 ± 0.03	$(2.8\pm0.8)\times10^{-2}$	-	-
Reduction (Lower)	0.24 ± 0.05	0.33 ± 0.03	0.36 ± 0.02	-	0.29 ± 0.03

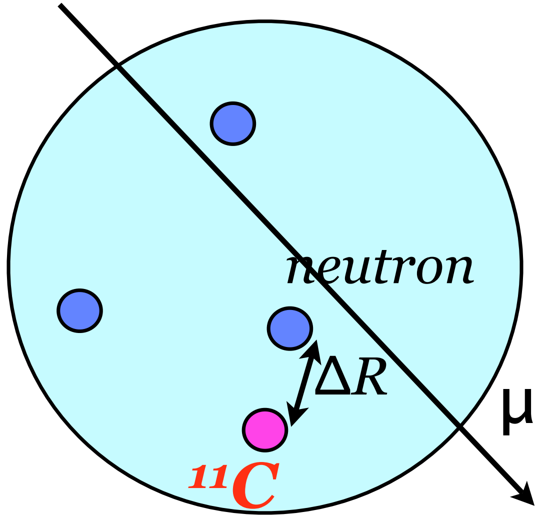
Pb and Kr are decreased, but the reduction is not enough for solar phase.
2nd purification campaign is started next month.



- Mixing is avoided between purified and un-purified LS.
  → Introduce temperature control system to cool down the purified LS and put it from the bottom.
- Improve the PPO tower to make better the distillation condition.
- Improve the air-tightness of the detector (upper part) for Kr.

If purification is successfully done, ^{11}C is a major BG for ^{7}Be/CNO/pep ν detection.

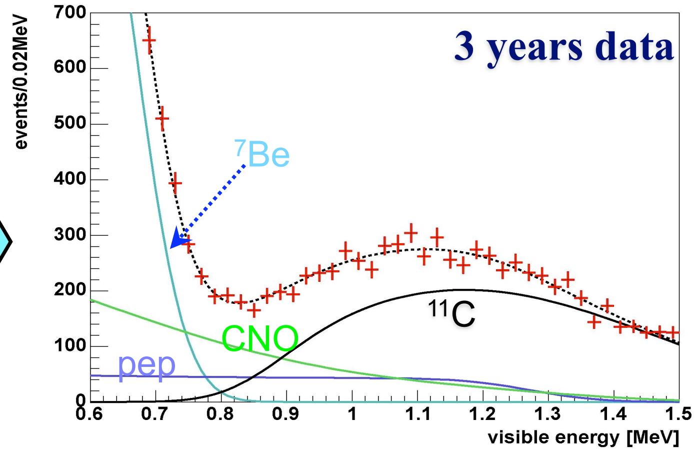




Spherical cut around 2.2 MeV γ.

~95% of ^{11}C is produced in spallation reactions by muons and associated with neutrons.

^{11}C can be vetoed by triple coincidence ; muon, n-capture γ(2.2MeV), ^{11}C decay

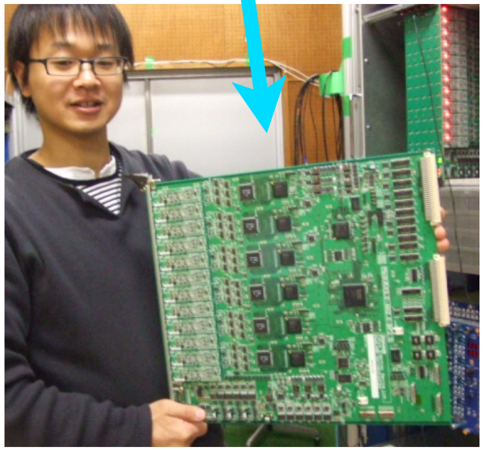


New electronics (MOGURA) to detect muon-induced neutrons for ^{11}C veto.

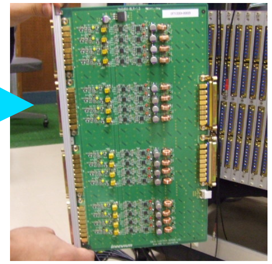
*Module for General-Use Rapid Application

Dead-time free digitization (1GHz, 3 200MHz FADCs) for up to ~60 neutrons generated by muon.
Baseline restoration to quick recovery of the overshoot after the big muon signal.

Main board for the MOGURA system



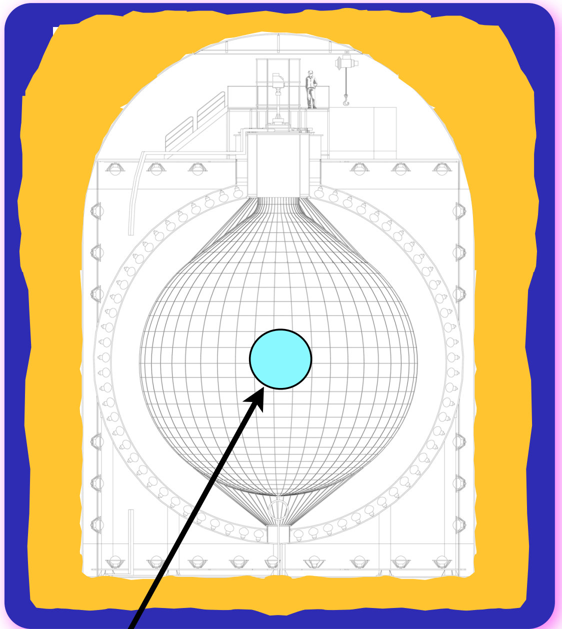
Splitter board; one for the current FBE system and the other through base-line restorer for the new MOGURA system.



All the boards are being checked in RCNS (Tohoku).

MOGURA system will be installed in KamLAND after the 2nd purification campaign.

Next Challenge: 0νββ decay search of ^{136}Xe using KamLAND



An inner balloon of ~3m ϕ, containing 10ton LS, 200kg 90%-enriched ^{136}Xe

Physics beyond the SM.

Neutrino type: Majorana? or Dirac?
Absolute Mass of neutrinos

* No signal except for KKDC claiming $m_{\beta\beta}$~0.3eV.

An experiment is considered in KamLAND using ^{136}Xe to <$m_{\beta\beta}$>~0.1eV !

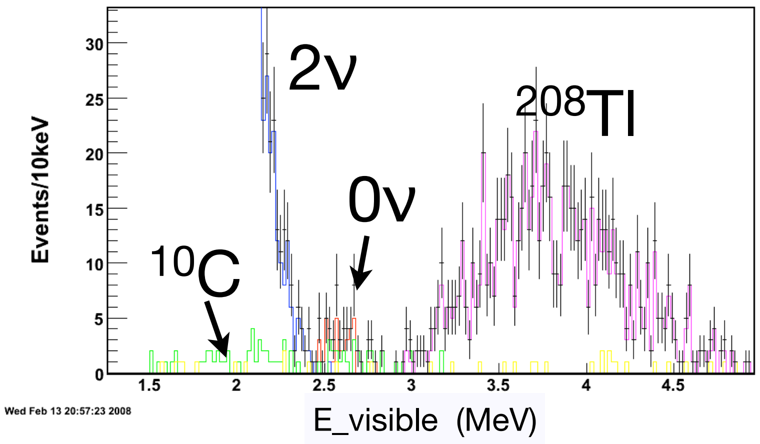
136Xe (nat. abundance=8.9%, $Q_{\beta\beta}$=2.47MeV): Large solubility (2% in mass), no harm to the LS. Blank measurement can be made easily. Current ν measurements can be simultaneously done.

KamLAND provides a large clean environment and has been in stable operation in several years and well understood.

A small modification can make the experiment !

Background estimation

200 kg, 2yrs, 0.2eV, ^{10}C 90% reduction



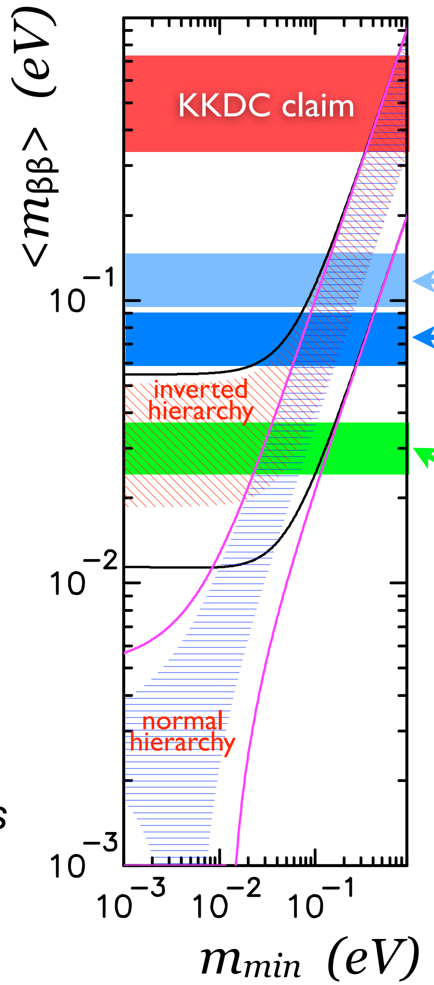
0ν signal : $T_{1/2}=3.2\times10^{25}$y→34 events/2y

^{208}Tl Background /2y
Balloon: 1kg Nylon(2×15μmt+glue)
5×10^{-11}gTh/g → ~4000 ^{208}Tl events
LS (12m^3 2wt%Xe) 4.8×10^{-17}gTh/g →
0.15μBq/m^3→~40 ^{208}Tl

^{208}Tl from balloon is dominant, but 0ν is separated.

^{10}C spallation background : ~20/d/kton→14/2y (broad)

KamLAND+^{136}Xe sensitivities



With a low radioactivity balloon KamLAND+Xe can be quickly started with low cost !

Summary

- KamLAND made a new analysis on full reactor $\overline{\nu}_e$ energies using much higher statistics data (in live time and fiducial volume) than previous analysis.

- Neutrino oscillation parameters are determined much more precisely than the previous results by significant reduction of systematic uncertainties of fiducial volume by new calibration system, and studies on (α,n) background.

- Solar ν detection in sub-MeV region is being prepared by the next purification in the next month and introduction of new electronics system.

- Next plan of ^{136}Xe o$\nu\beta\beta$ decay search is considered.