KamLAND

[Kamioka Liquid scintillator Anti-Neutrino Detector]

Neutrinos from Reactors to the Sun and the Earth

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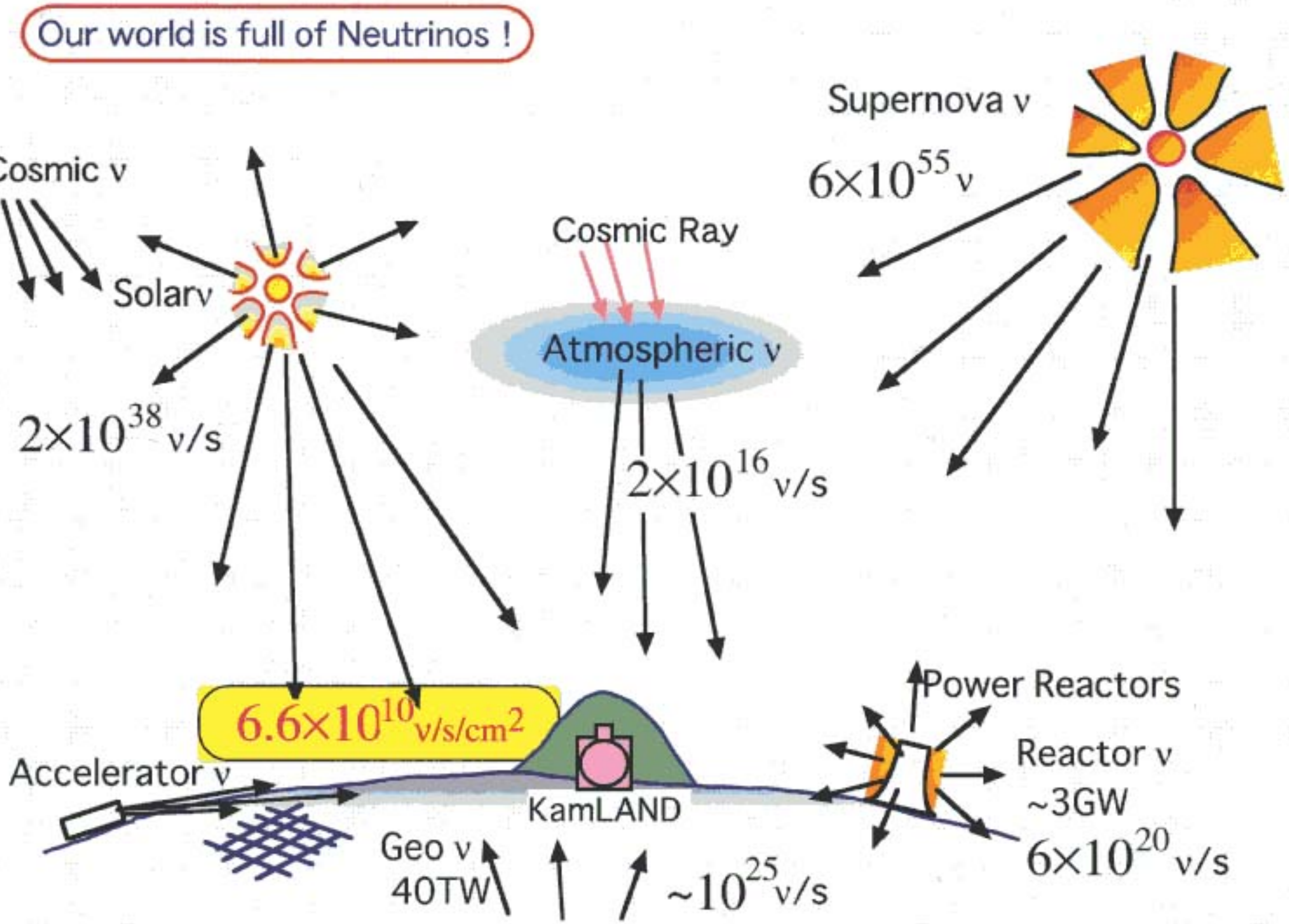
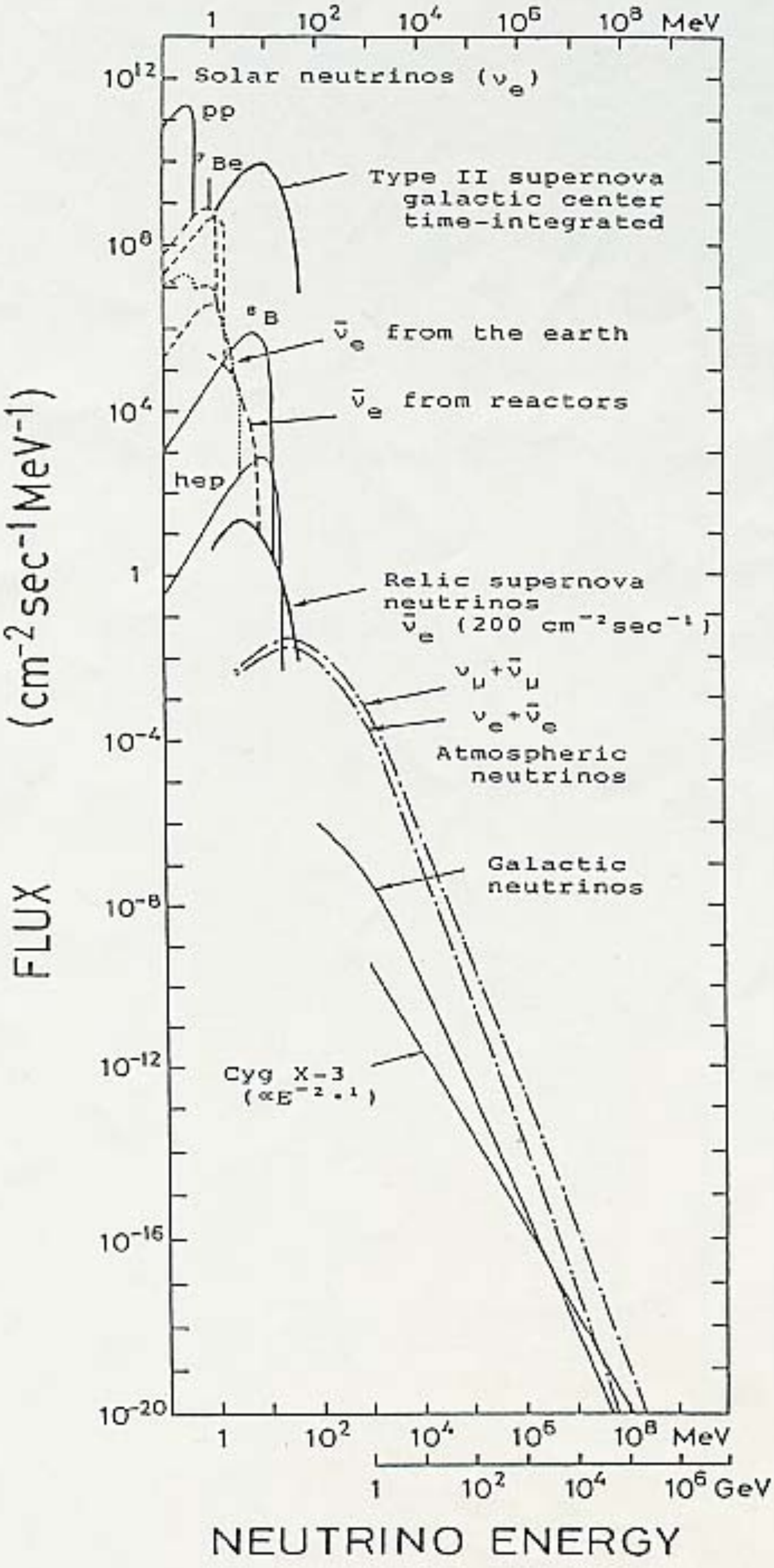
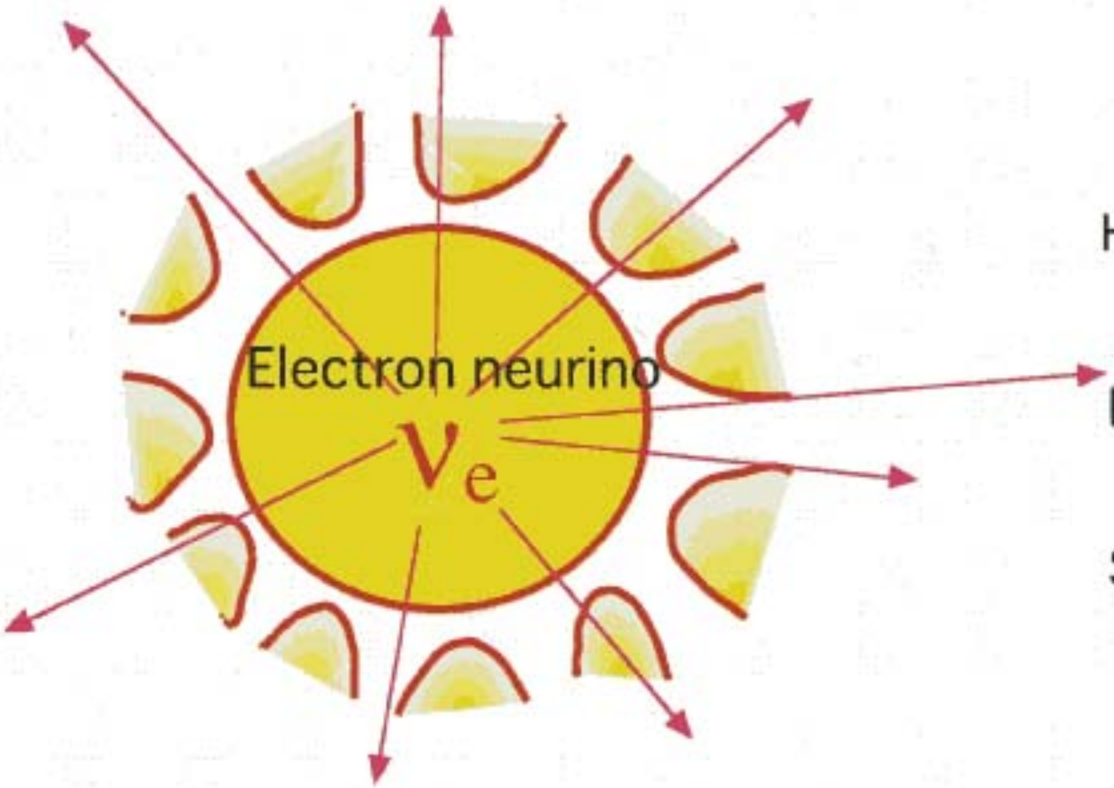


Our world is full of Neutrinos !
Supernova ν
6×10^{55} ν
Cosmic ν
Solarν
2×10^{38} ν/s
Cosmic Ray
Atmospheric ν
2×10^{16} ν/s
6.6×10^{10} ν/s/cm^2
Power Reactors
Reactor ν
~3GW
6×10^{20} ν/s
Accelerator ν
KamLAND
Geo ν
40TW
$\sim10^{25}$ ν/s



Expected neutrino energy spectra from various sources.

Solar Neutrino Problem (SNP)



$$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.73\,MeV - E_\nu$$

Solar neutrino:
Thermo-nuclear fusion in the center of the sun

Neutrino Flux Φ_ν

(PDG'02)

	$\dfrac{\Phi_\nu[\text{Experiment}]}{\Phi_\nu[\text{Theory}]}$
Homestake(1960's~) $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ (>814keV)	$0.337 * (1^{+.193}_{-.170})$
Kamiokande('80) H_2O: $\nu_e e^- \rightarrow \nu_e e^-$ (>7MeV)	$0.554 * (1^{+.242}_{-.210})$
SAGE/GALLEX('90) $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ (>233keV)	$0.525 * (1^{+.138}_{-.126})$ $0.605 * (1^{+.120}_{-.114})$

⇓

Both (Experiments and Theory[SSM]) are OK!

⇓

Unknown neutrino properties ?

Neutrino Mass ⟹ Neutrino Oscillation

Weak eignenstates $\neq$ Mass eigenstates

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

Time evolution (rest frame):

$$\begin{aligned} |\nu_e(\tau)\rangle &= \cos\theta\, e^{-iM_1\tau}|\nu_1\rangle + \sin\theta\, e^{-iM_2\tau}|\nu_2\rangle \\ &= e^{-iM_1\tau}\left[\cos\theta\,|\nu_1\rangle + \sin\theta\, e^{-i(M_2-M_1)\tau}|\nu_2\rangle\right] \end{aligned}$$

$$P(\nu_e \rightarrow \nu_e) = \left|\langle \nu_e(0)|\nu_e(\tau)\rangle\right|^2 = 1-\sin^2 2\theta \sin^2\left(\frac{\Delta M}{2}\tau\right) \quad <1$$

$$\frac{\Delta M^2 L}{4E}$$ (Lab. frame)

(M_1, $M_2 << E$)

SNO [D_2O]: ^{8}B solar ν detection

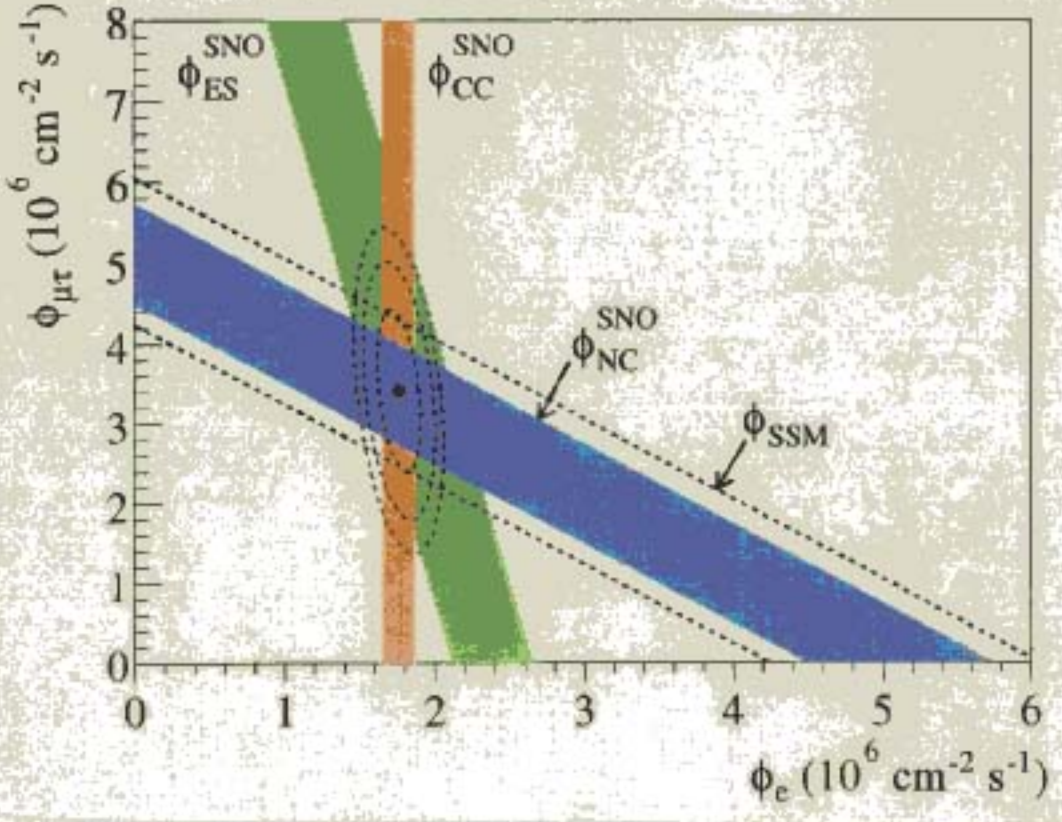
$\Phi[\nu_e]$: $\nu_e d \to e^- pp$ [CC]

$\Phi[\nu_e+\nu_\mu+\nu_\tau]$: $\nu_x d \to \nu_x pn$ [NC]

Discovery of $\nu_e \to \nu_x$!! ['01]

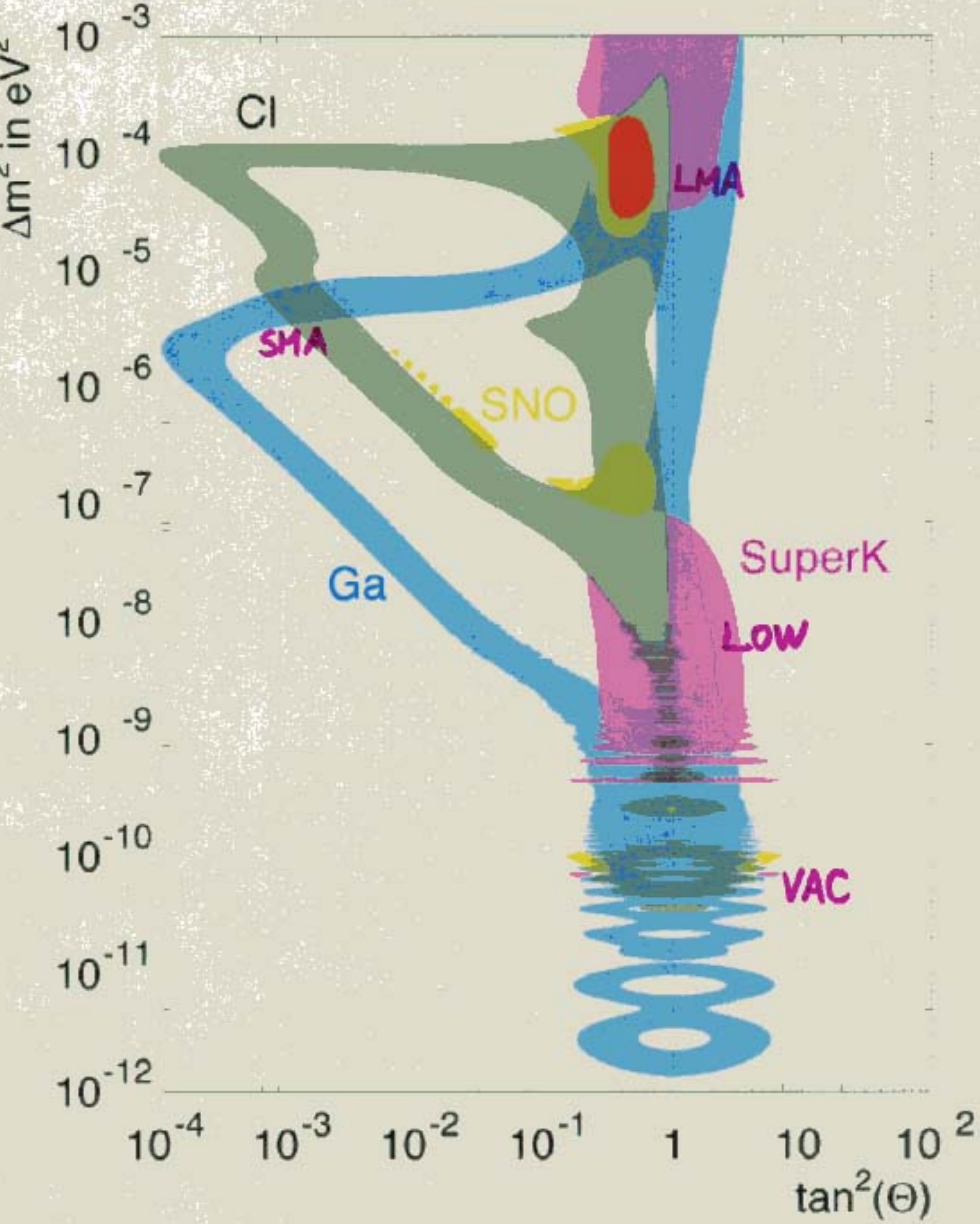
If oscillation, several solutions to SNP for θ and ΔM^2.

Large Mixing Angle (LMA) is most promising...



*Matter oscillation effect (MSW)

$$\sin^2 2\theta \leftarrow \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\frac{2\sqrt{2}E_\nu G_F N_e}{\Delta m^2} - \cos 2\theta\right)^2}$$



Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Cl
LMA
SMA
SNO
SuperK
Ga
LOW
VAC
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

KamLAND

Reactor Neutrino Experiment

!! Big Challenge to SNP by man-made neutrinos !!

Search for $\bar{\nu}_e$ oscillation of LMA ;

$\Delta M^2 \sim 10^{-5} eV^2$ @ $\sin^2 2\theta \sim 1$

KamLAND Collaboration

13 Institutes
92 physicists

- **Tohoku University** : K.Eguchi, S.Enomoto, K.Furuno, Y.Gando, H.Ikeda, K.Ikeda, K.Inoue, Y.Kishimoto, M.Koga, Y.Koseki, T.Maeda, T.Mitsui, M.Motoki, K.Nakajima, H.Ogawa, K.Owada, F.Piquemal, J.Ricol, I.Shimizu, J.Shirai, F.Suekane, A.Suzuki, K.Tada, K.Tamae, H.Watanabe, T.Araki, K.Ichimura, Y.Tsuda
- **KEK** : T.Taniguchi
- **University of Alabama** : J.Busenitz, Z.Djurcic, K.McKinny, D-M.Mei, A.Piepke, E.Yakushev
- **University of California at Berkeley and Lawrence Berkeley National Laboratory**: B.E.Berger, Y.D.Chan, M.P.Decowski, D.A.Dwyer, S.J.Freedman, Y.Fu, B.K.Fujikawa, J.Goldman, K.M.Heeger, K.T.Lesko, K.-B.Luk, H.Murayama, D.R.Nygren, C.E.Okada, A.W.P.Poon, H.M.Steiner, L.A.Winslow
- **California Institute of Technology** : G.A.Horton-Smith, C.Mauger, R.D. Mckeown, B.Tipton, P.Vogel
- **Drexel University** : C.E.Lane, T.Miletic
- **University of Hawaii** : P.W.Gorham, G.Guillian, J.G.Learned, J.Maricic, S.Matsuno, S.Pakvasa
- **Louisiana State University** : S.Dazeley, S.Hatakeyama, R.Svoboda
- **University of New Mexico** : B.D.Dieterle, M.Dimauro
- **Stanford University** : J.Detwiler, G.Gratta, K.Ishii, N.Tolich, Y.Uchida
- **University of Tennessee** : M.Batygov, W.Bugg, H.Cohn, Y.Efremenko, Y.Kamyshkov, A.Kozlov, Y.Nakamura
- **Triangle Universities Nuclear Laboratory and Duke University, North Carolina State University, and the University of North Carolaina at Chapel Hill** : G.R.Gould, H.J.Karwowski, D.M.Markoff, J.A.Messimore, K.Nakamura, R.M.Rohm,W.Tornow, A.R.Young
- **Institute of High Energy Physics, Beijing** : M-J.Chen, Y-F.Wang

Reactor $\bar{\nu}_e$ Excellent neutrino source for oscillation experiment !!

Well known for each element

Fuel elements

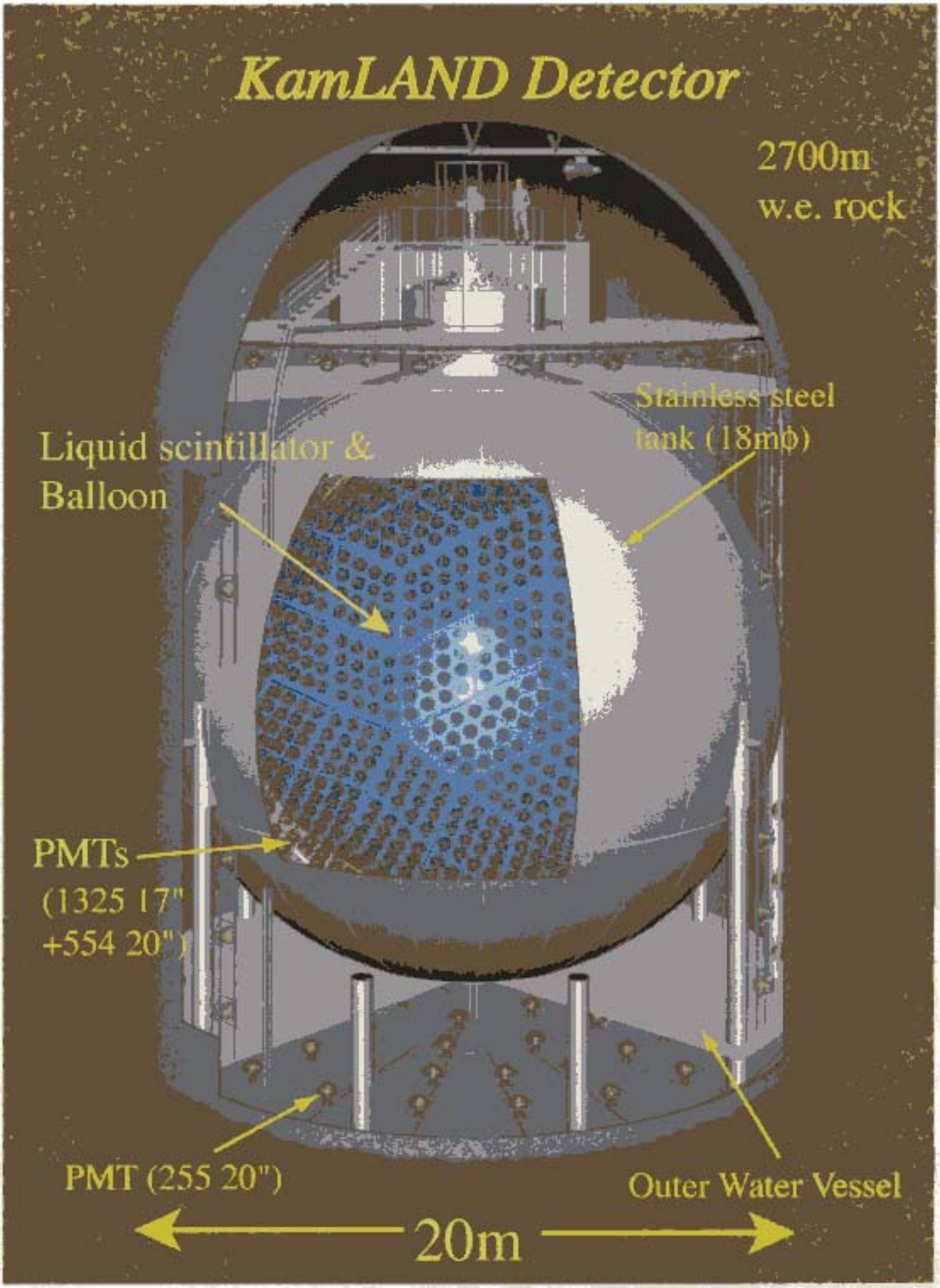
235U, 238U, 239Pu, 241Pu $+n \rightarrow$ A+B+2n+Q(~200MeV)

Numbers & spectrum of $\bar{\nu}_e$

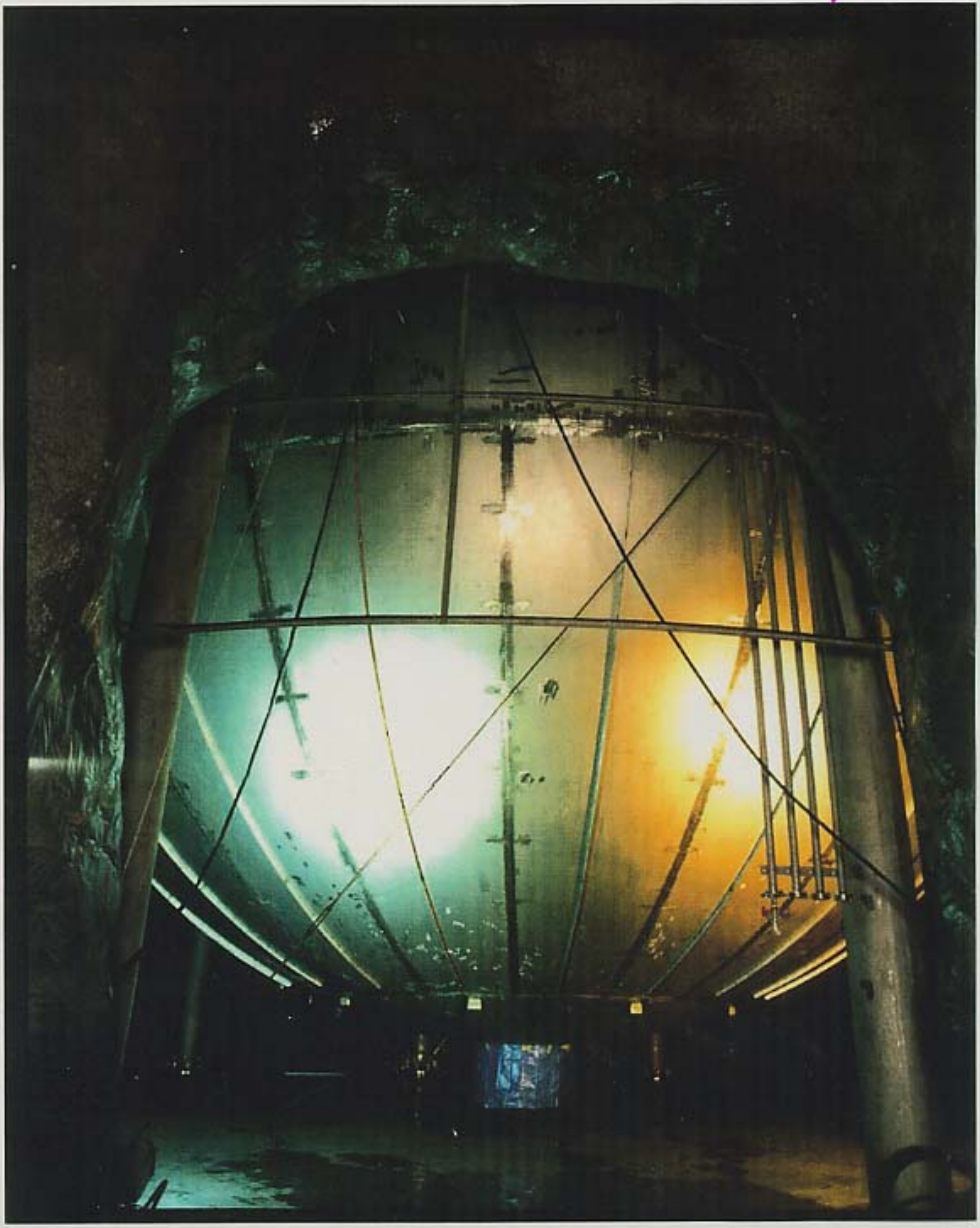
Neutron-rich ⇨ β^- decay ⇨ $\sim 6\,\bar{\nu}_e$

- Pure $\bar{\nu}_e$
- Flux and spectrum of $\bar{\nu}_e$ can be calculated ~2% precision provided the initial fuel components and the thermal power.

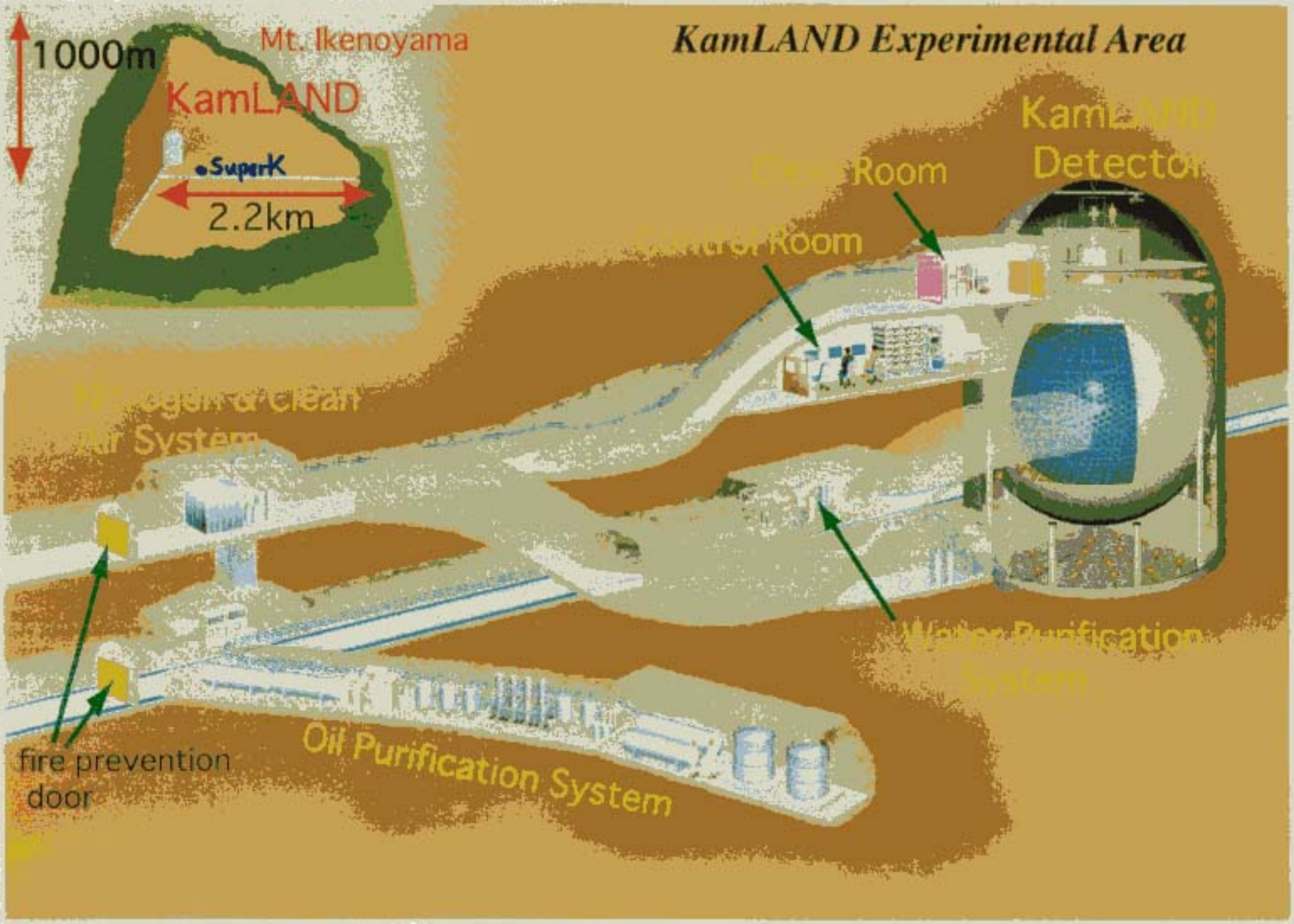
  ⇨ No front detector is needed for $\bar{\nu}_e$ flux monitoring
- Low energy ($\lesssim$8 MeV) : Large L/E ⇨ sensitive to small ΔM^2


KamLAND Detector
2700m
w.e. rock
Stainless steel
tank (18mϕ)
Liquid scintillator &
Balloon
PMTs
(1325 17"
+554 20")
PMT (255 20")
Outer Water Vessel
20m

Sep. 2000



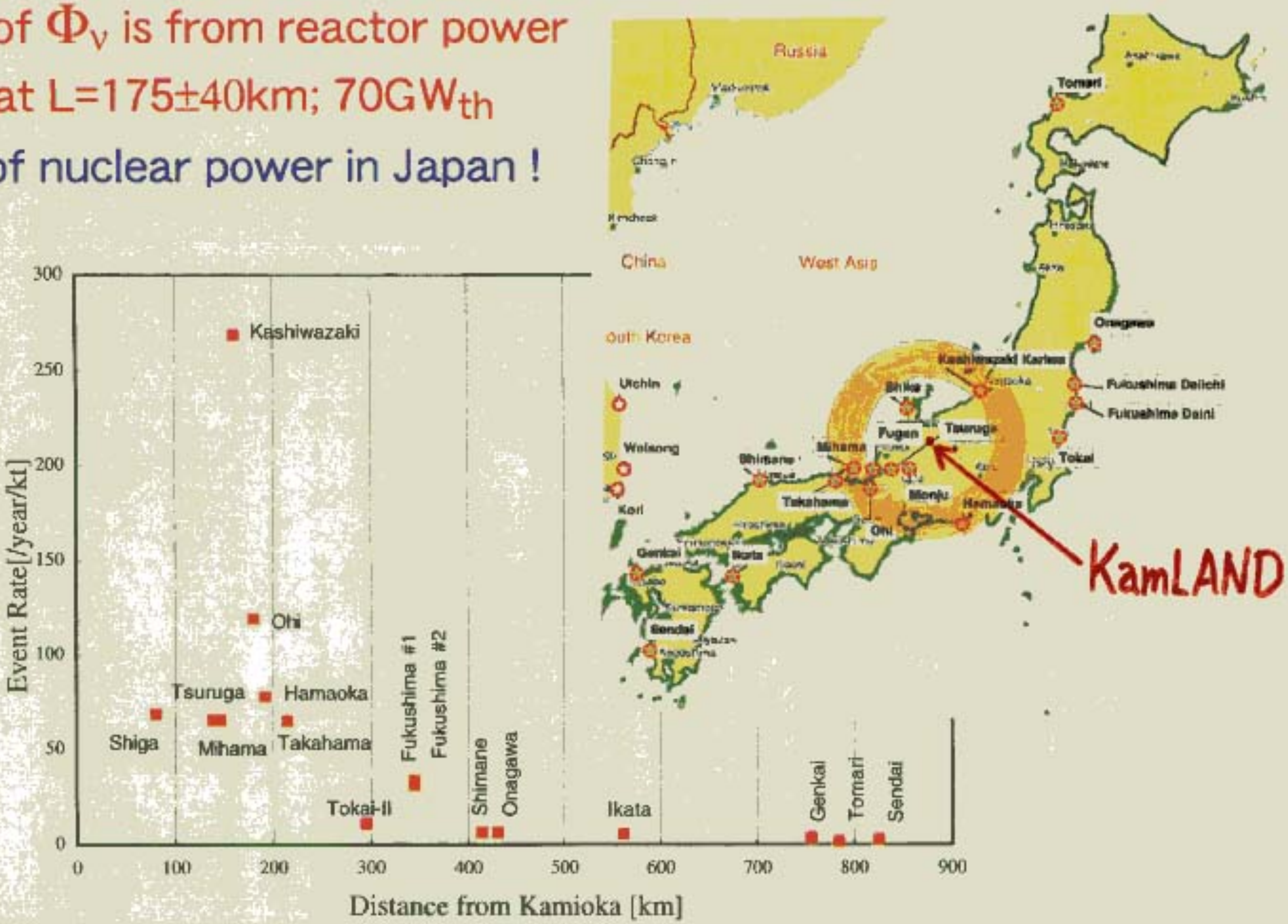
Sep 2000


KamLAND Experimental Area
1000m
Mt. Ikenoyama
KamLAND
SuperK
2.2km
KamLAND Detector
Clean Room
Control Room
Water Purification System
Oil Purification System
fire prevention door

Kamioka : Best for Long Base Line reactor $\bar{\nu}_e$ experiment !

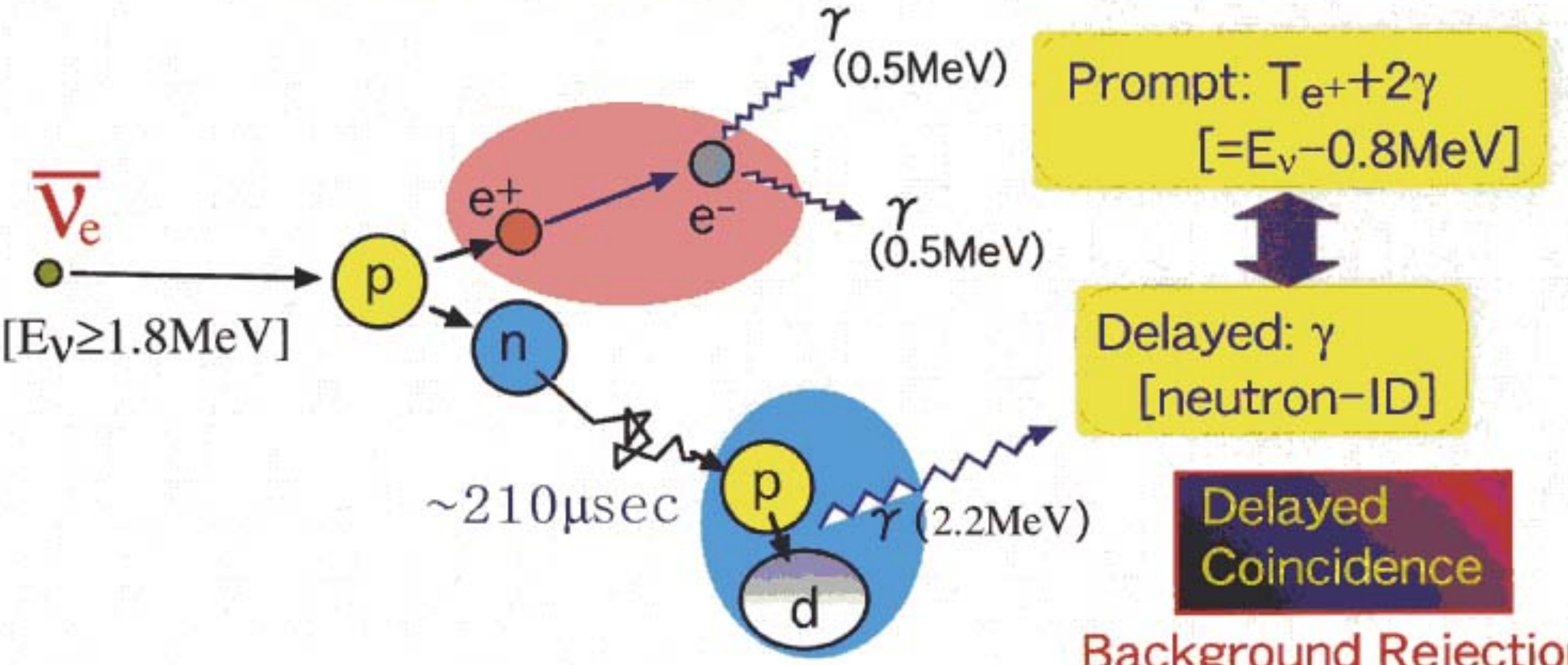
$\sim$80% of Φ_ν is from reactor power plants at L=175±40km; 70GW$_{th}$

>50% of nuclear power in Japan !



$\overline{\nu}_e$ detection : $\overline{\nu}_e p \rightarrow e^+ n$

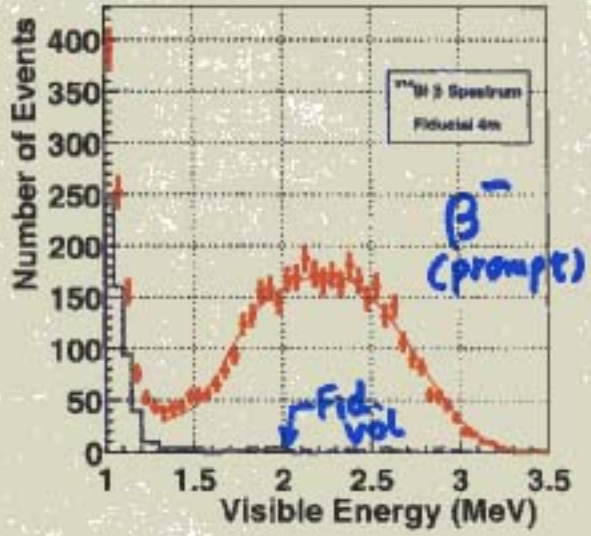
[Inverse β decay reaction]

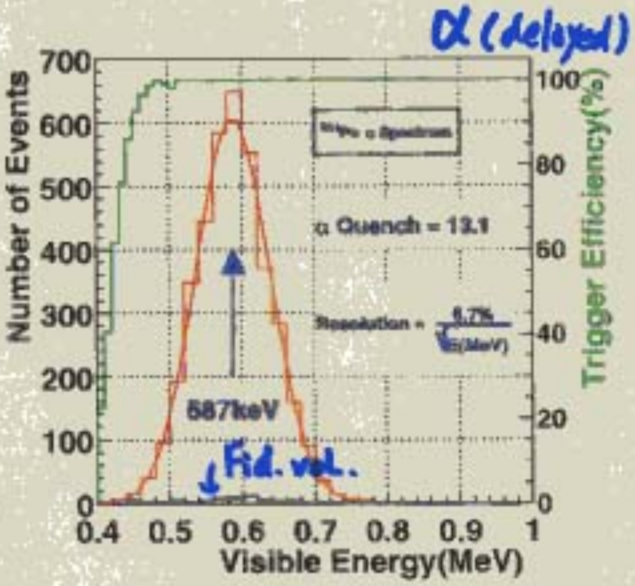


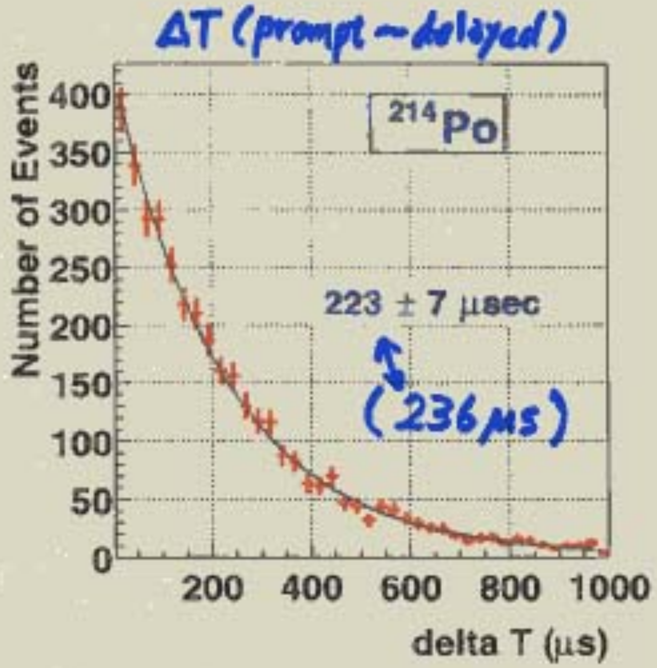
Background Rejection
Space-Time Correlation

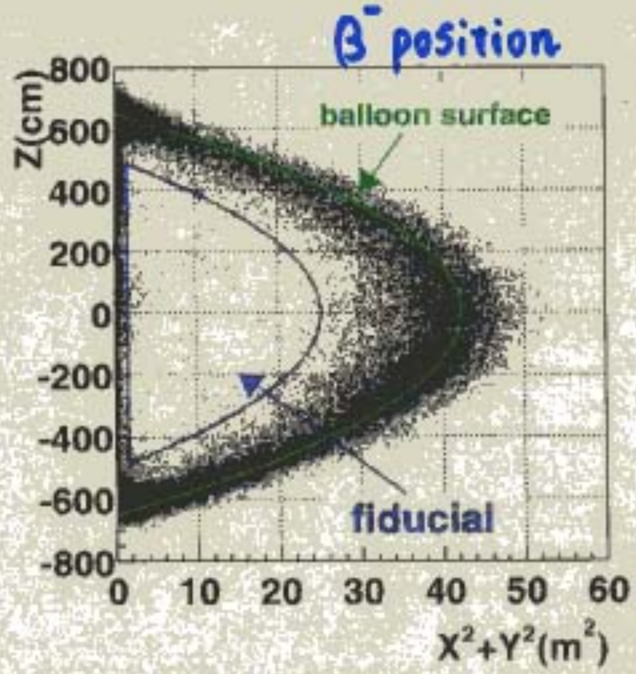
- $\overline{\nu}_e$ only
- Cross Section: Large $\sim 100 \times \sigma(\nu_e e \rightarrow \nu_e e)$,
  Precisely known $\Delta\sigma/\sigma \sim 0.2\%$

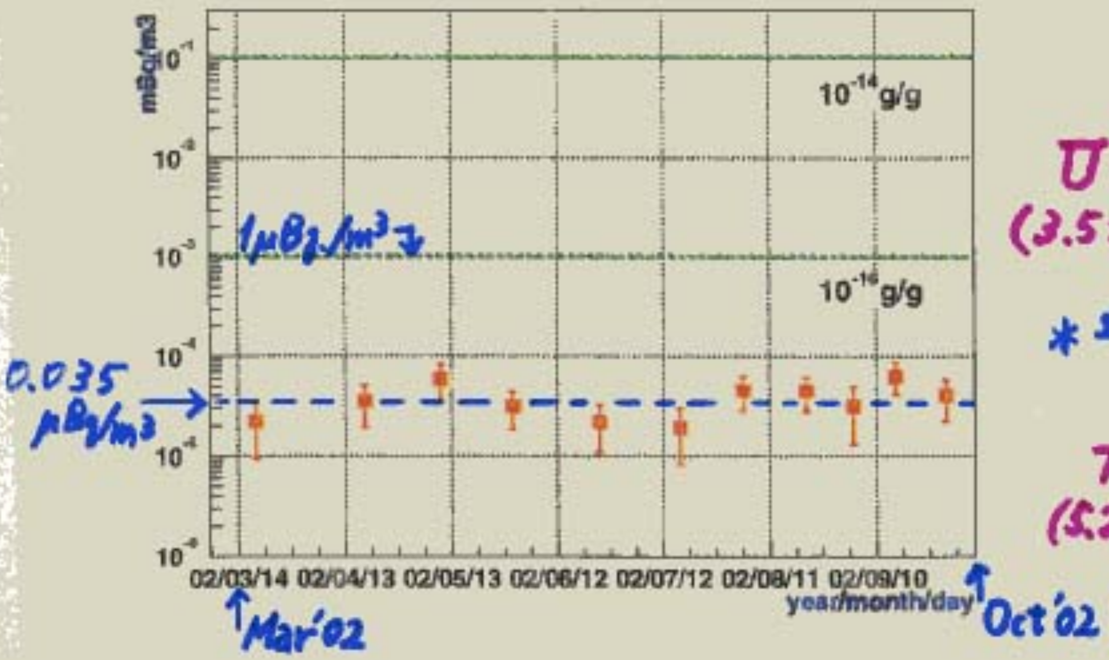
$^{214}Bi \xrightarrow[\beta^-(<3272)]{} {}^{214}Po \xrightarrow[\alpha(7687)]{} {}^{210}Pb$











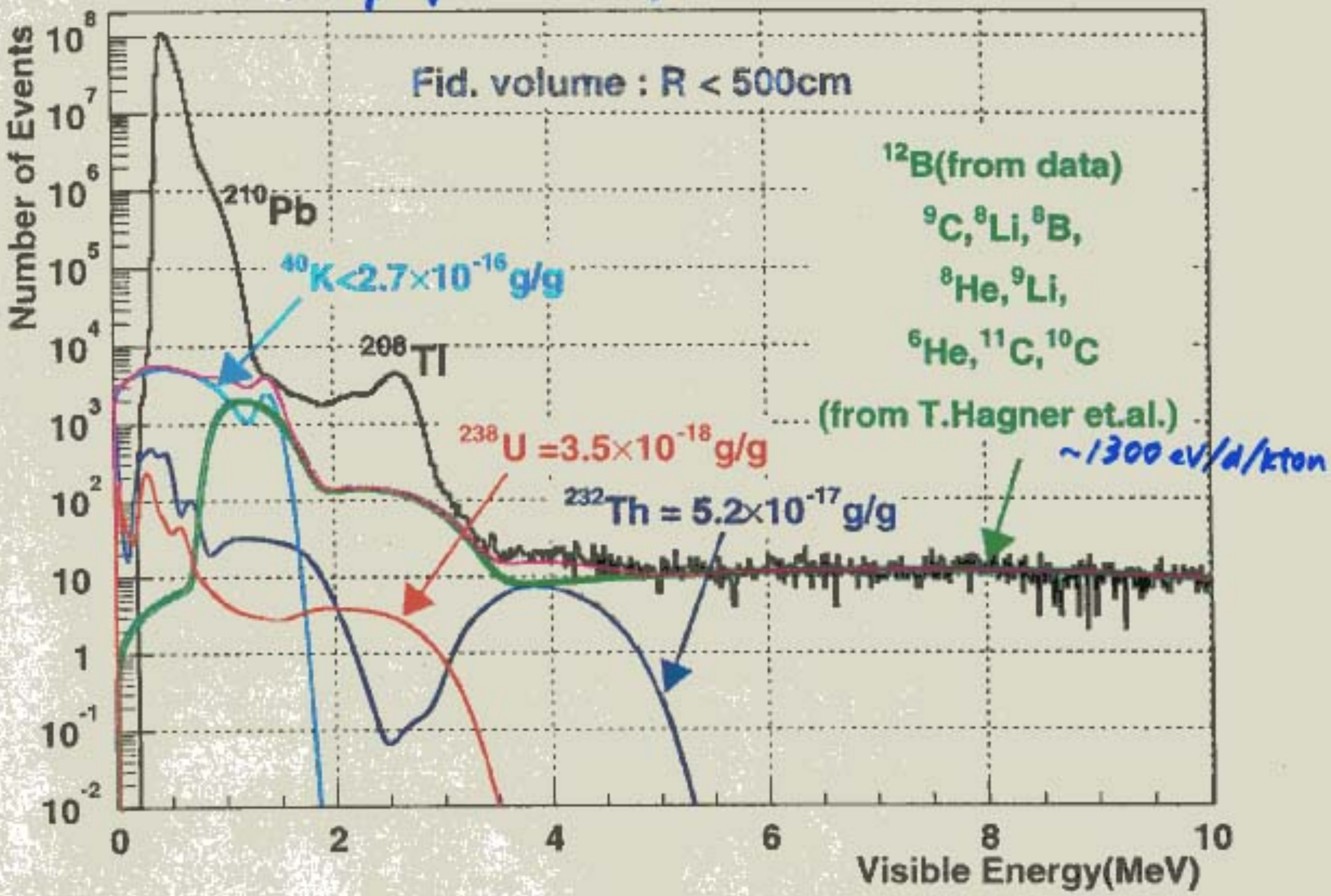
U: $(3.5 \pm 0.5) \times 10^{-18}$ g/g

* $^{212}Bi \to {}^{212}Po \to {}^{208}Pb$

0.17 μBq/m³

Th: $(5.2 \pm 0.8) \times 10^{-17}$ g/g

Energy spectrum of single events.
(before μ-spallation cut)



Event selection: (Mar. 4, '02 - Oct. 6, '02)

Fiducial volume; R<5m

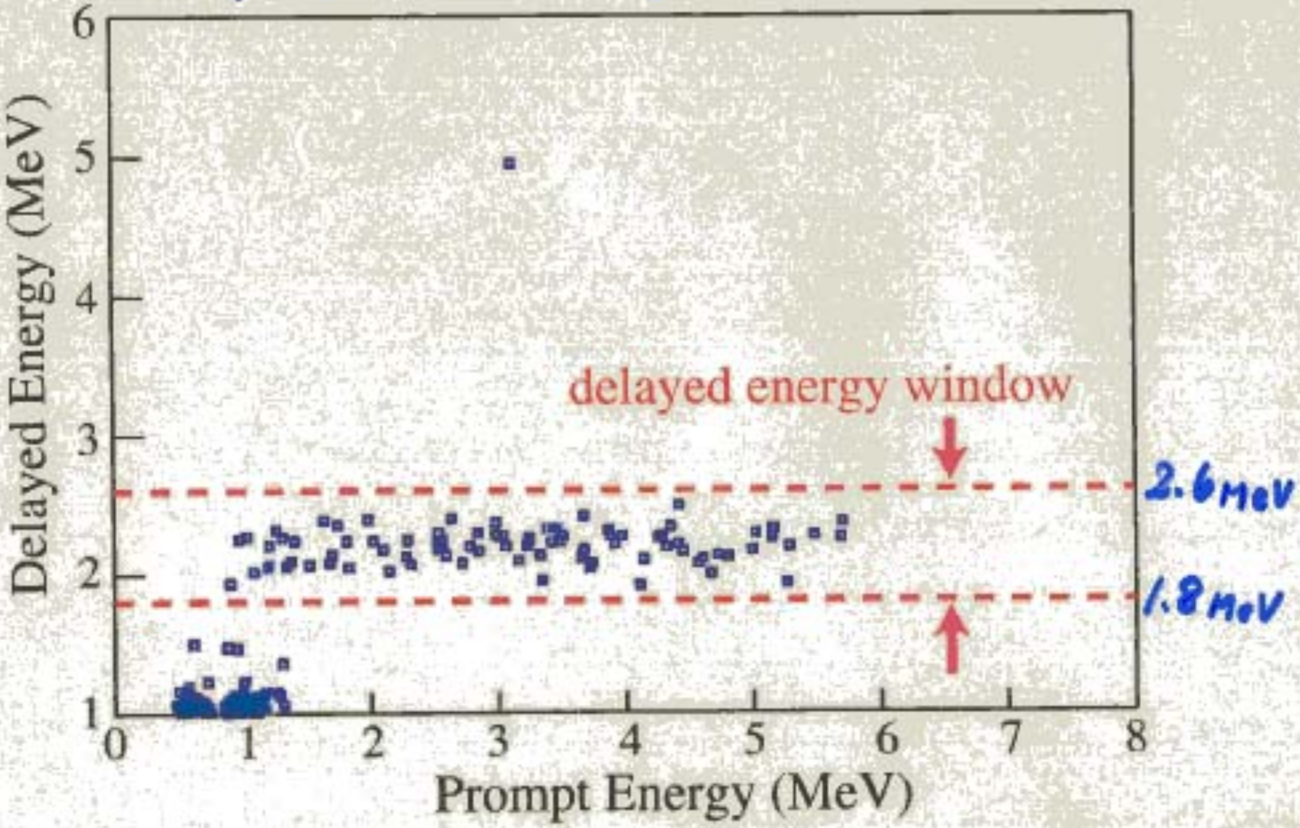
Time & Space correlation;

0.5μs<ΔT<660μs, ΔR<1.6m

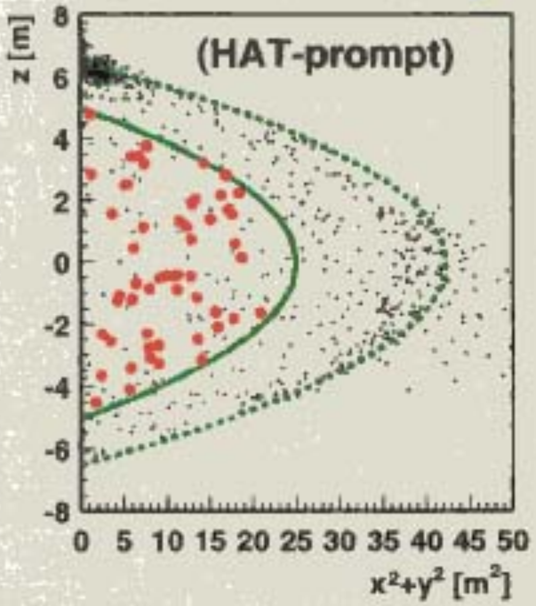
Spallation cuts

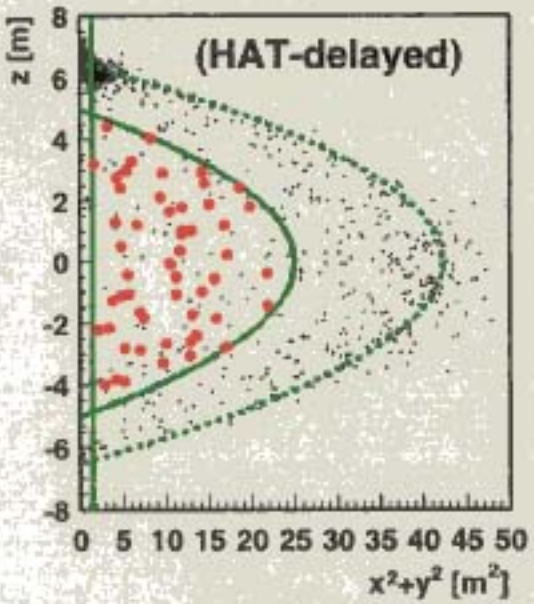
$N_{obs}(>2.6\,MeV) = 54$

$N_{BG} = 1 \pm 1$ ($^9Li/^8He$)



($E_{e^+} > 2.6\,MeV$)

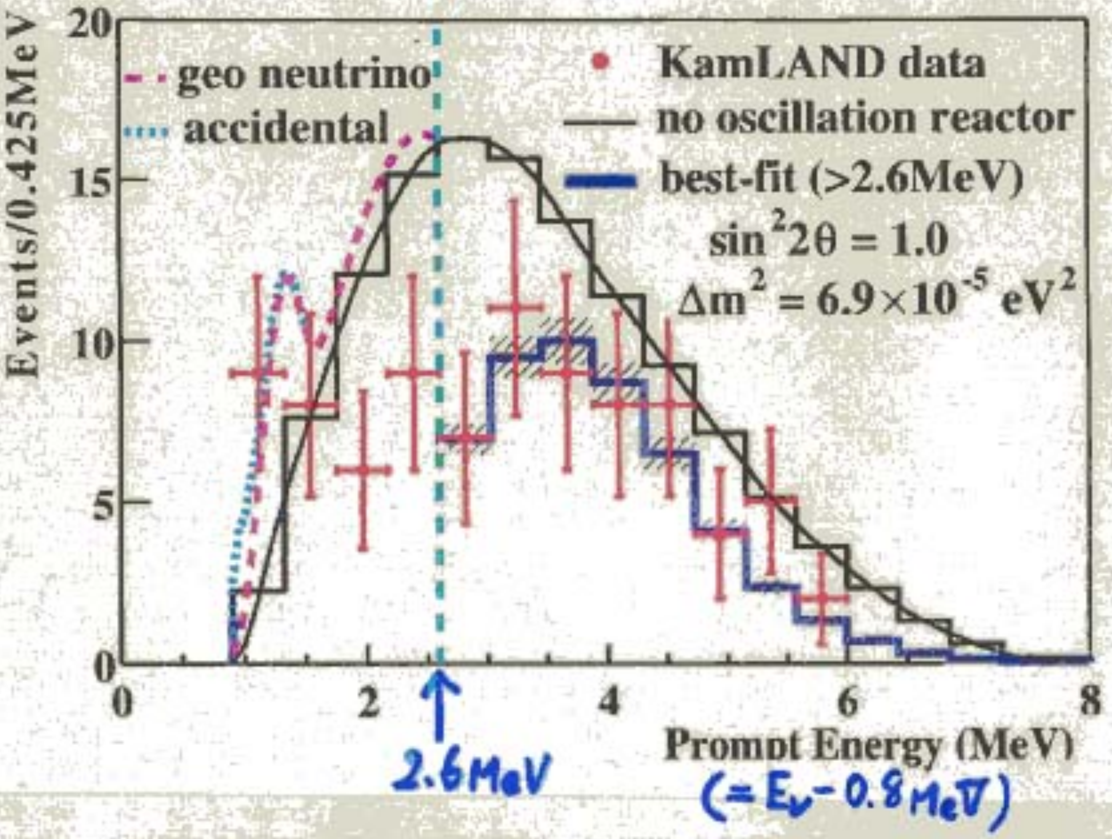


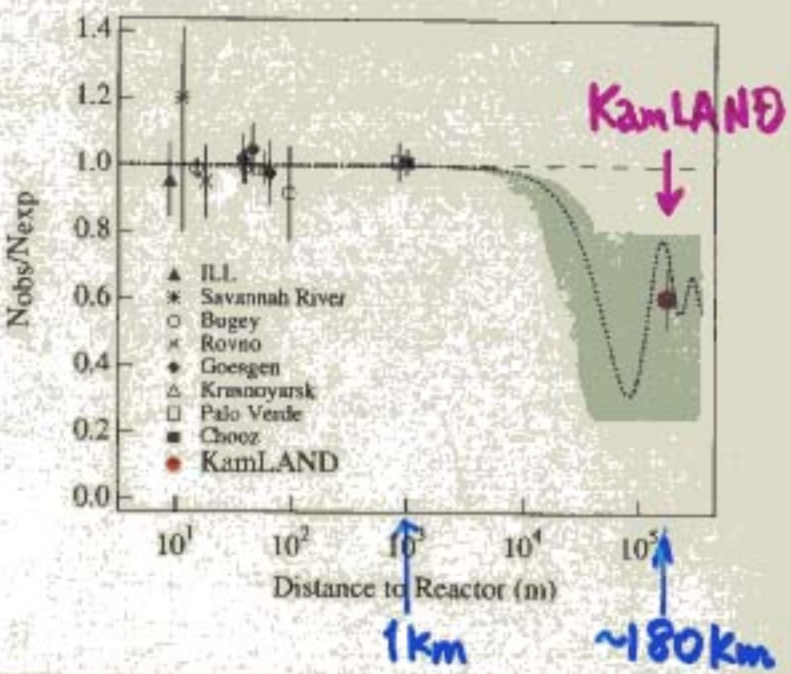


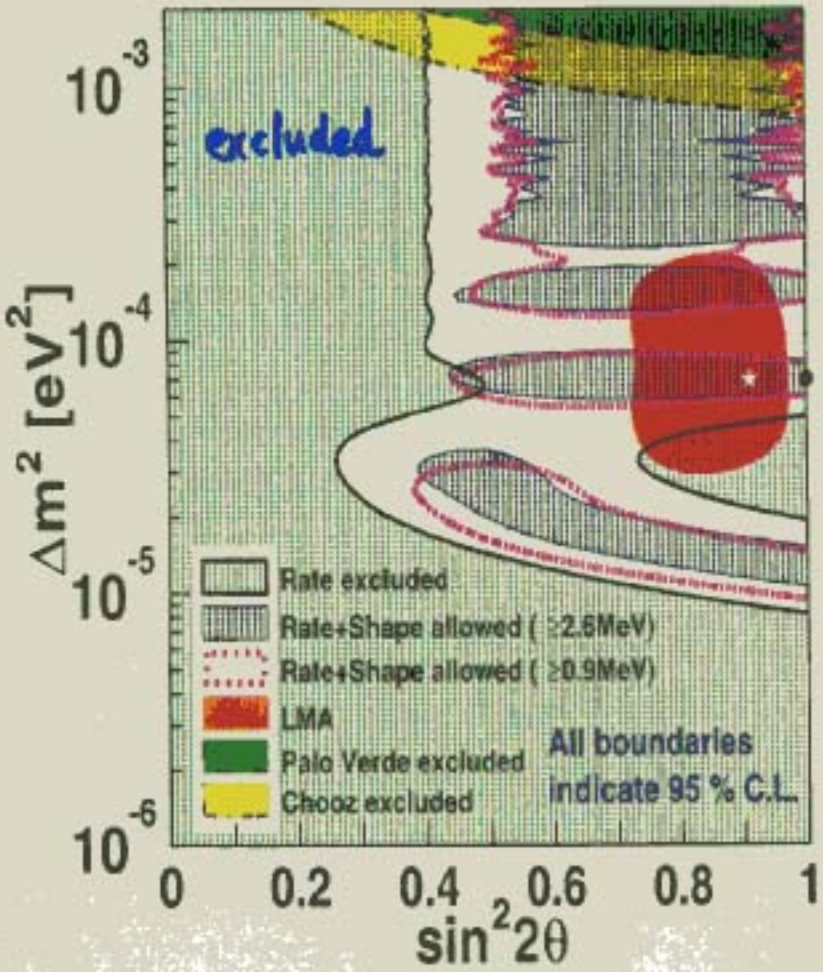
$$\frac{\text{Observed}}{\text{Expected (no-oscillation)}} = 0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{sys}) \quad <1 \ (99.95\%\text{CL})$$

[86.8±5.6]

First observation of $\overline{\nu}_e$ disappearance !







- Rate only:
  Strongly suggests neutrino oscillation is the dominant mechanism of SNP.
  All solutions to SNP except for LMA is excluded.
- Rate+ shape:
  Further restricts the allowed region.

Best fit (E_{prompt}>2.6MeV)

$\sin^2 2\theta=1.0$

$\Delta m^2=6.9\times10^{-5}$ eV^2

Best fit (E_{prompt}>0.9MeV)

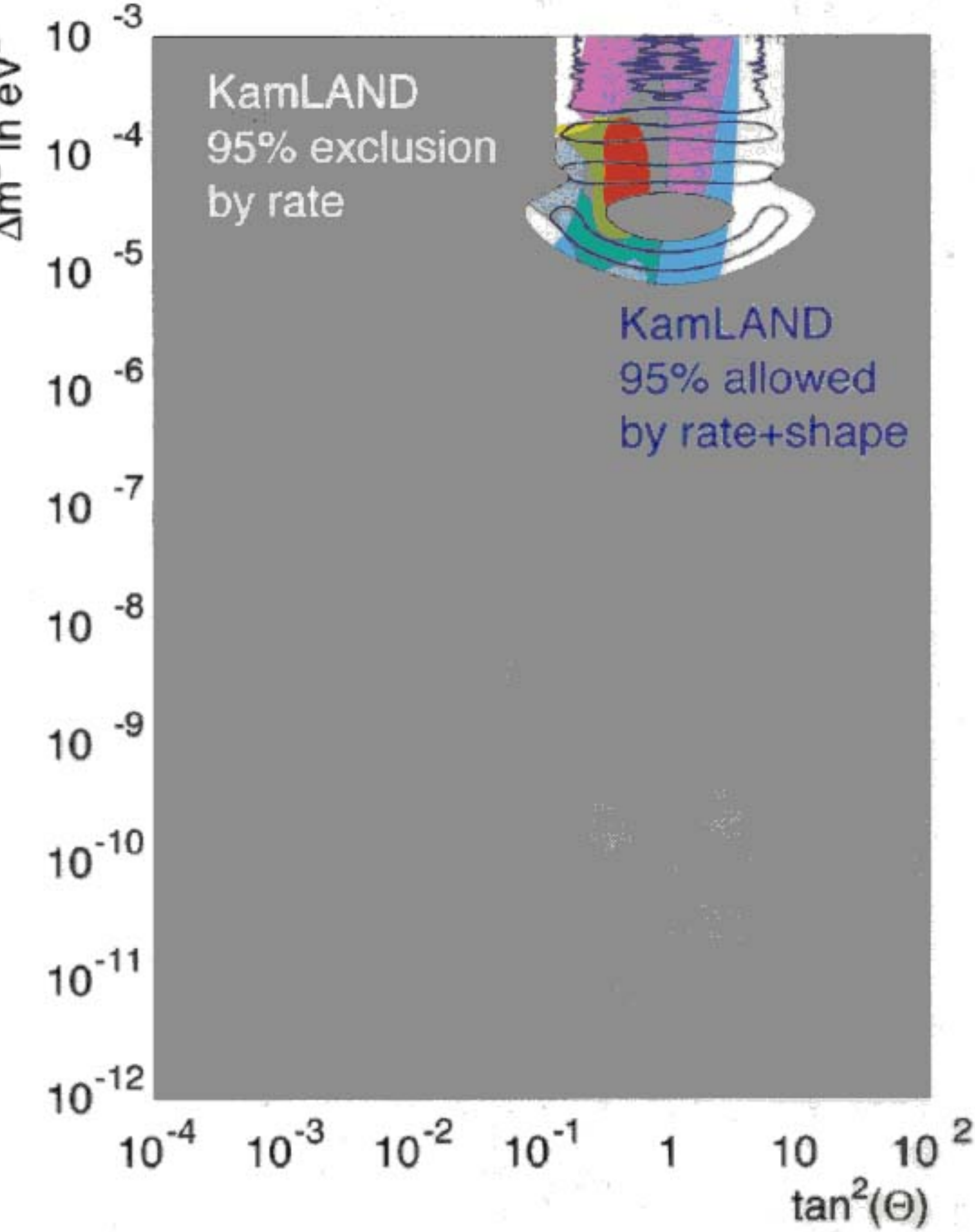
$\sin^2 2\theta=0.91$

$\Delta m^2=6.9\times10^{-5}$ eV^2

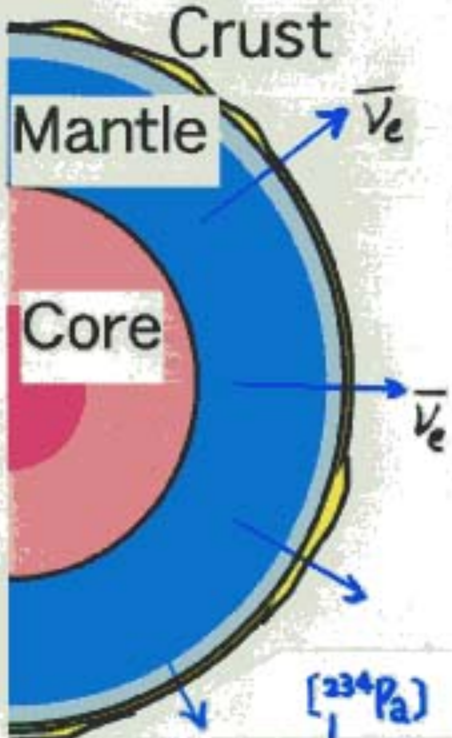
$\bar{\nu}_{geo}(^{238}U)$=4 event

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

suggesting $\bar{\nu}_{geo}$, but zero event is allowed at 95% CL.



KamLAND
95% exclusion
by rate
KamLAND
95% allowed
by rate+shape
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\Theta)$

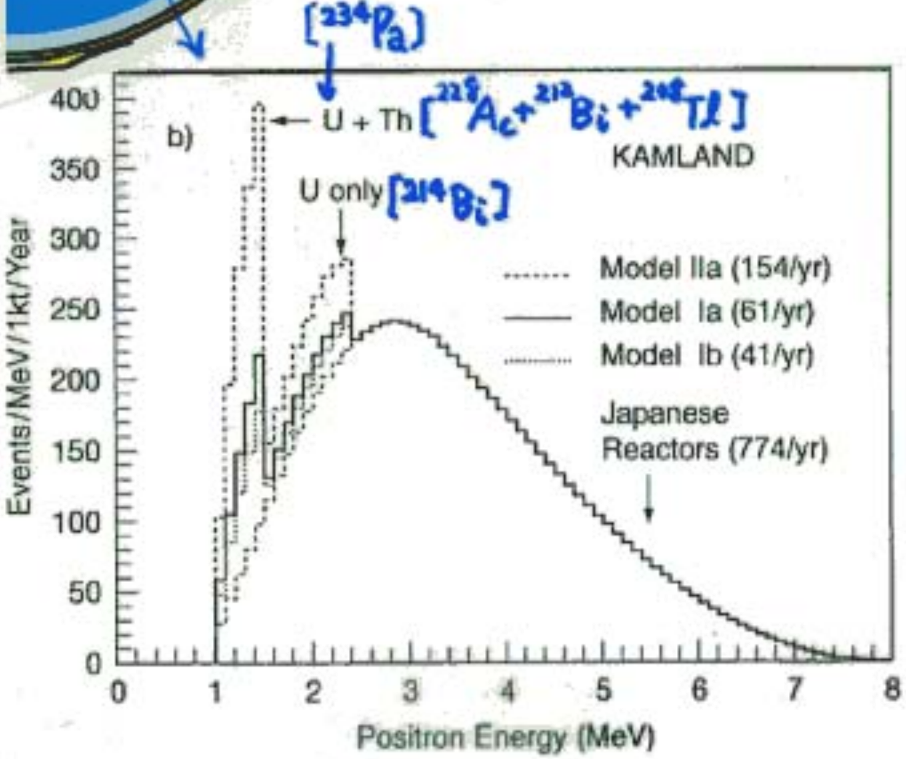


Geo-Neutrino

Radiogenic heat: 238U, 232Th decays
~16TW (~40% of total heat flow)

⇨ Interior dynamics &
Evolution of the earth

Model dependent, No direct measurement.



KamLAND: can measure the $\bar{\nu}_e$ spectrum !

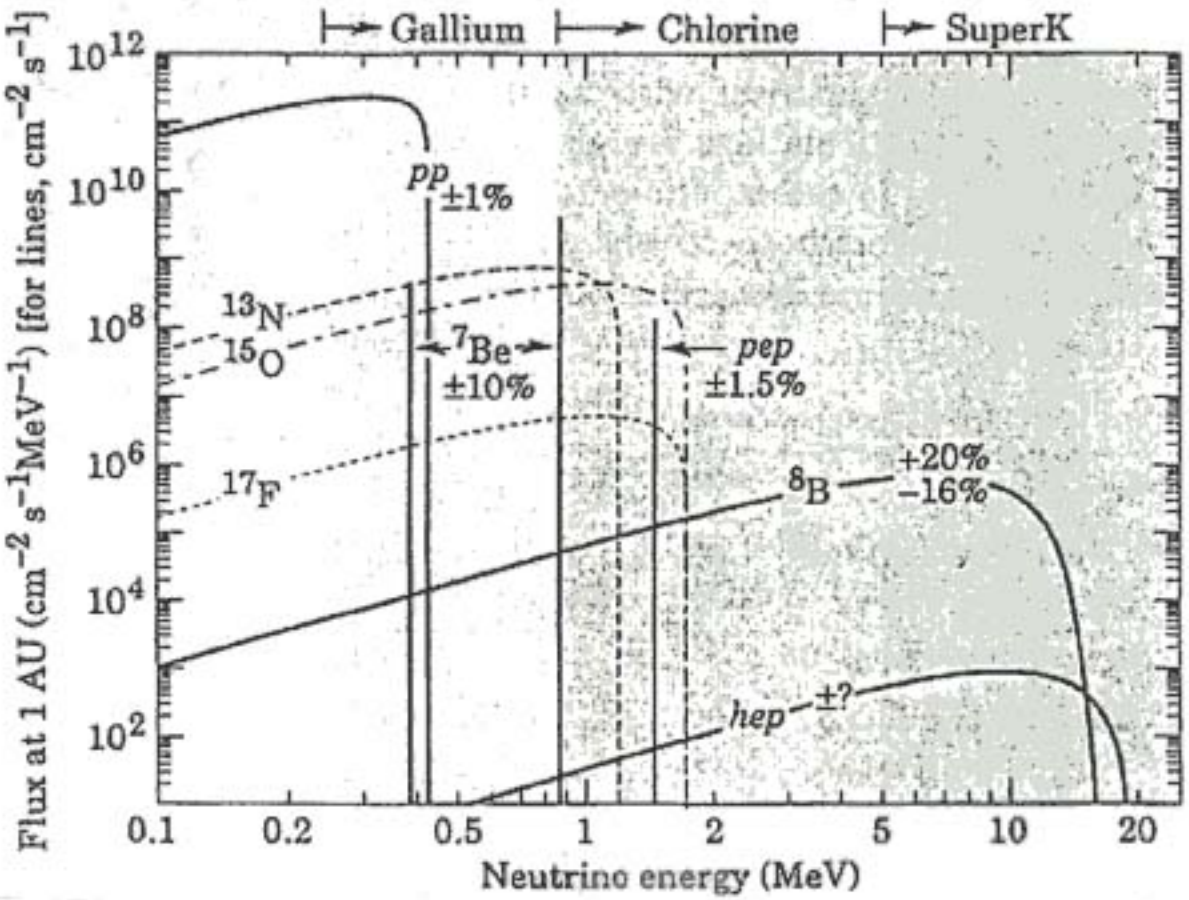
⇨ U,Th and the ratio
~60 events/kt/yr

New approach to geo-physics may be opened by ν!

New Challenge to Solar Neutrino !

Solar ν spectrum measurement:

Only E>5.5MeV [^{8}B, SK/SNO] (< 0.01% of the total flux)



Lower energy region:

7Be, pp, CNO, etc.

Much more intense and smaller uncertainty!

- **Particle Physics:** ν properties; θ, ΔM^2, μ_ν, decay, ...
- **Solar-/Astro-physics:** Burning mech., Internal structure of the sun

KamLAND : ^{7}Be solar ν measurement

[SSM]

$\Phi_{\nu}[^{7}\mathrm{Be}]$:

4.77(±10% error)×10^{9} /cm²/s

7.3% of the total flux

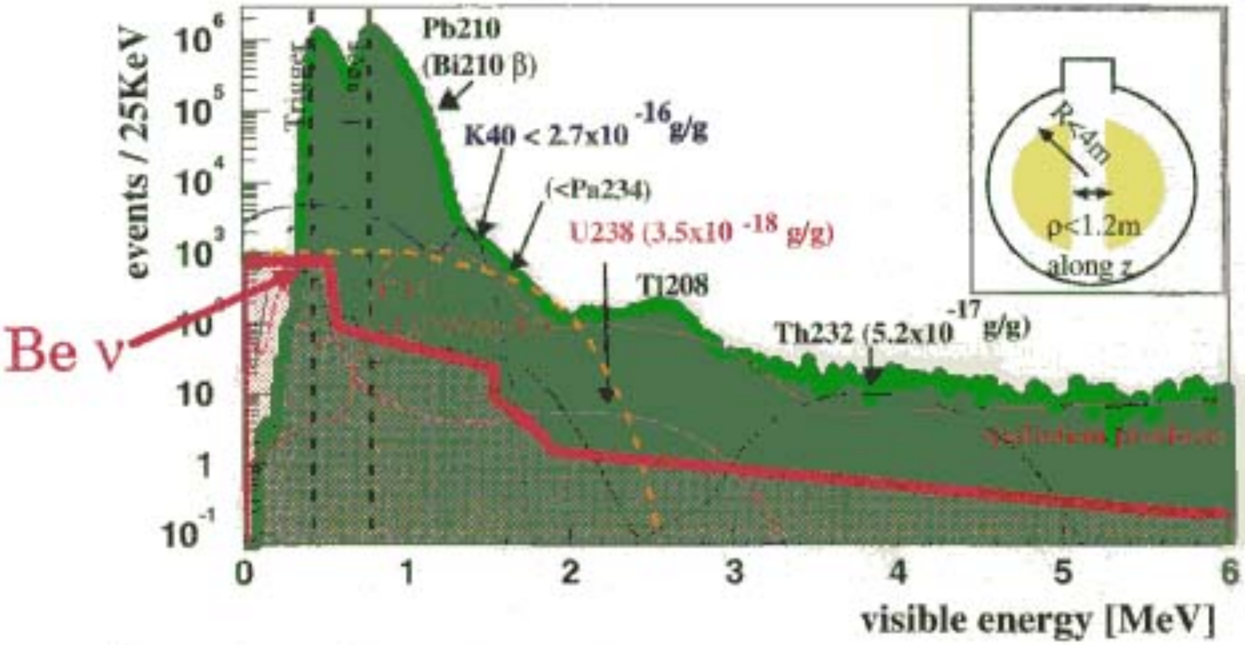
Monochromatic: $^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li}^{(*)} + \nu_e + (\gamma)$

862keV(90%), 384keV(10%)

$\Phi_{\nu}[^{8}\mathrm{B}]$:

5.05(+20%,−16% error) ×10^{6}/cm²/s, 0.008% of the total flux

Continuous: <15MeV



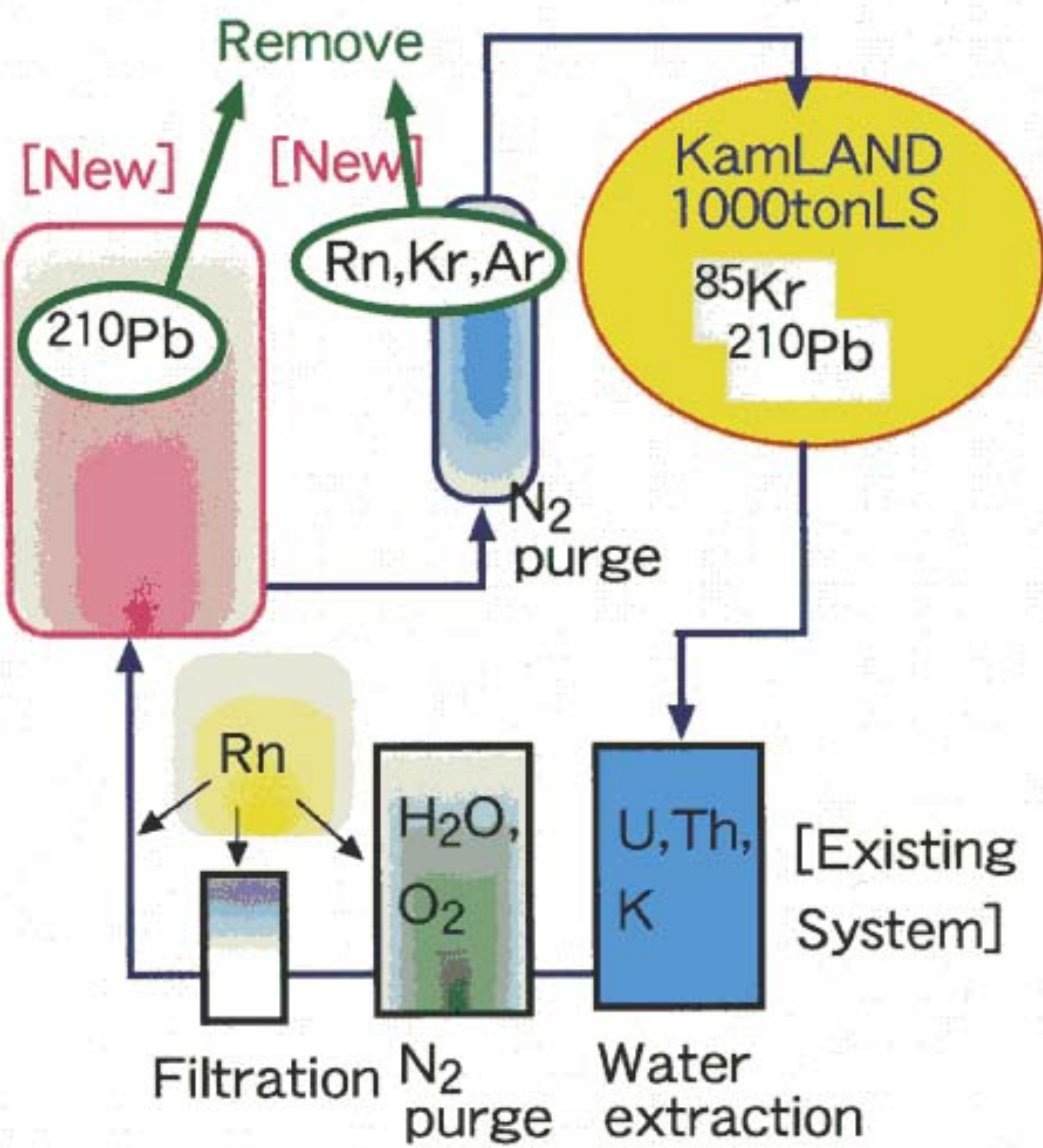
KamLAND: νe →νe

; ~260/day [LMA]

[single hit]

Background reduction by 10^{5}~10^{6} !!

Big Challenge !!



Radio-impurities with Long-life (>10yr);

^{85}Kr, ^{39}Ar; 1Bq/m^3

($^{222}Rn \rightarrow$) ^{210}Pb; 0.1Bq/m^3

⇩

Goal:1μBq/m^3

R&D for efficient purification methods underway;

Distillation, Adsorption, Filtration, Water extr., N_2-purge with reduced press., etc.

Summary KamLAND: With 1000ton ultra-pure Liq.Scintillator,

$\bar{\nu}_e \rightarrow \bar{\nu}_x$ firstly observed by KamLAND!

We expect: $\bar{\nu}_e$ oscillation by spectrum distortion.

First observation of geo-neutrino.

We challenge: ^{7}Be solar ν detection

Lots of Physics are awaiting !

ν is exciting!