Kam
LAND

Results from KamLAND

Atsuto Suzuki

KamLAND Collaboration

Outline

1. KamLAND Experiment
2. Reactor Neutrino Detection
3. Solar $\bar{\nu}_e$ Search
4. Geoneutrino Detection
5. Plan: ^{7}Be Solar Neutrino Detection
6. Conclusions

1. KamLAND Experiment

1,000 ton liquid scintillator neutrino detector

1st phase experiment

(E_{th} = 1.8 MeV)

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

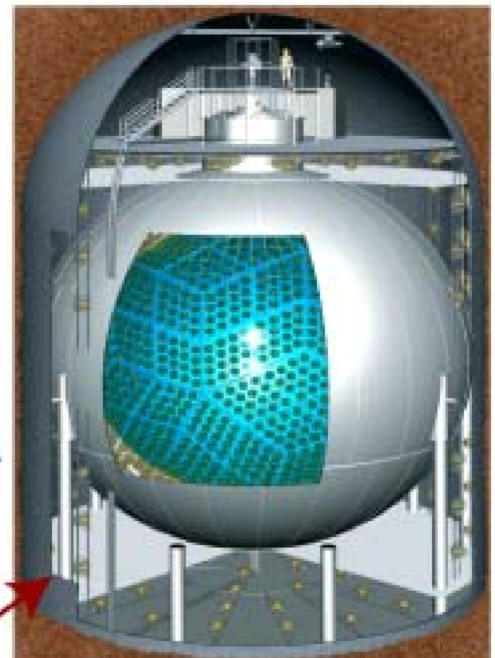
○ Neutrino Oscillation Search by Reactor Anti-neutrinos

180 km

$\bar{\nu}_e$

○ Terrestrial Anti-neutrino Detection

$\bar{\nu}_e$



2nd phase experiment

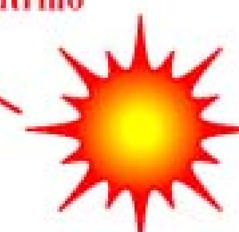
(E_{th} = 300 keV)

$\nu_e + e^- \rightarrow \nu_e + e^-$

○ Solar neutrino Detection

^{7}Be Neutrino

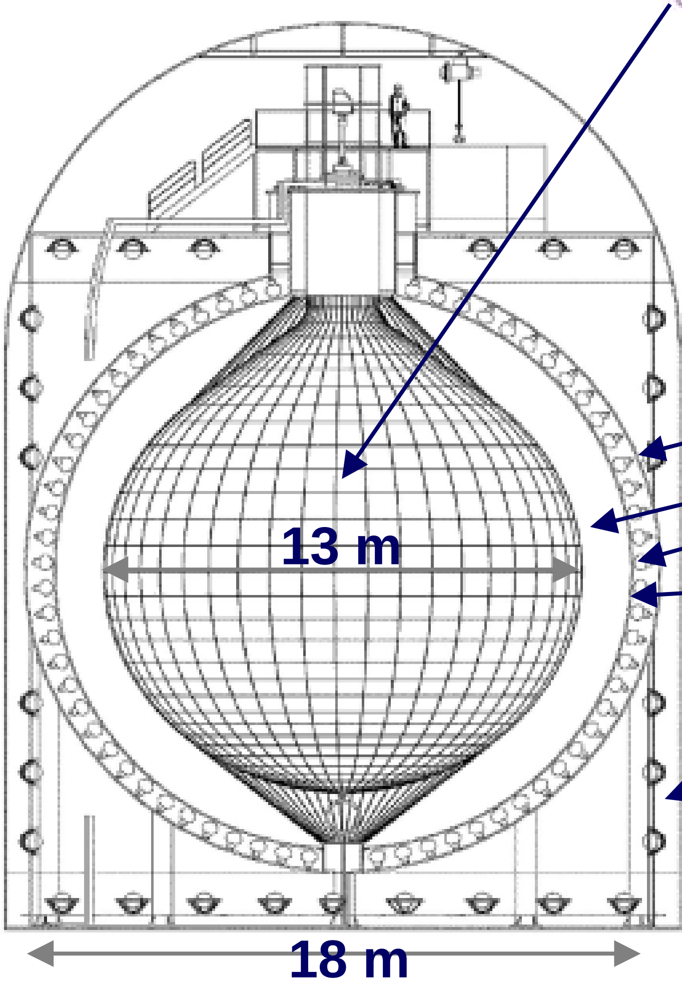
ν_e



supernova-burst ν, relic supernova ν,
atmospheric ν, Proton Decays, ・・・

KamLAND Detector

- Detector site : Old Kamiokande site (2700 m.w.e.)
- 1,000 ton Liquid Scintillator
  - 80%: dodecane, 20%: pseudocumene, 1.5 g/liter: PPO (ρ = 0.78)
  - housed in spherical balloon (13m diameter) of transparenet nylon/EVOH composite film (135μm)
  - supported by cargo net structure
- 3,000 m^3 Scintillation Light Detector
  - 18m diameter stainless steel tank filled with paraffin oil ($\Delta\rho$ = 0.04%, lighter than LS)
  - 1,325 17-inch+554 20-inch PMT's photosensitive coverage ~ 34 %
  - 3mm thick acrylic wall (120 plates) : Rn barrier
- Water Cherenkov Outer Detector
  - 225 Kamiokande 20-inch PMT's



Present analysis ~ 22%

inner view of spherical vessel

KamLAND Site

* **KamLAND construction started : April, 1997**

* **Operation started : January, 2002**

Detector Calibrations

:

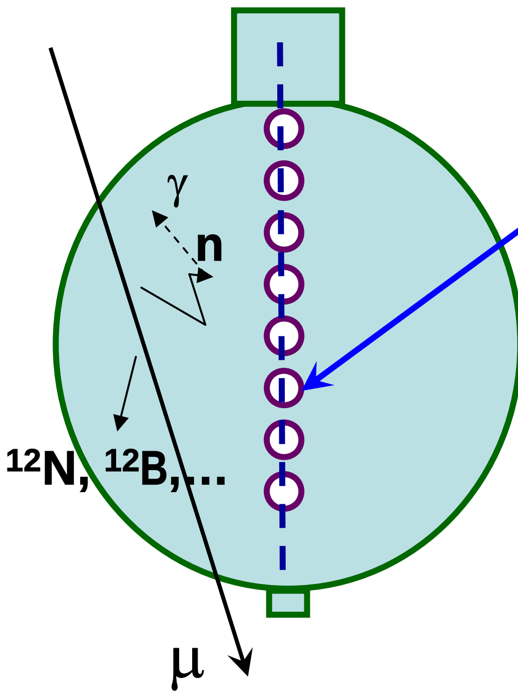
Energy scale, Timing, γ detection efficiency,

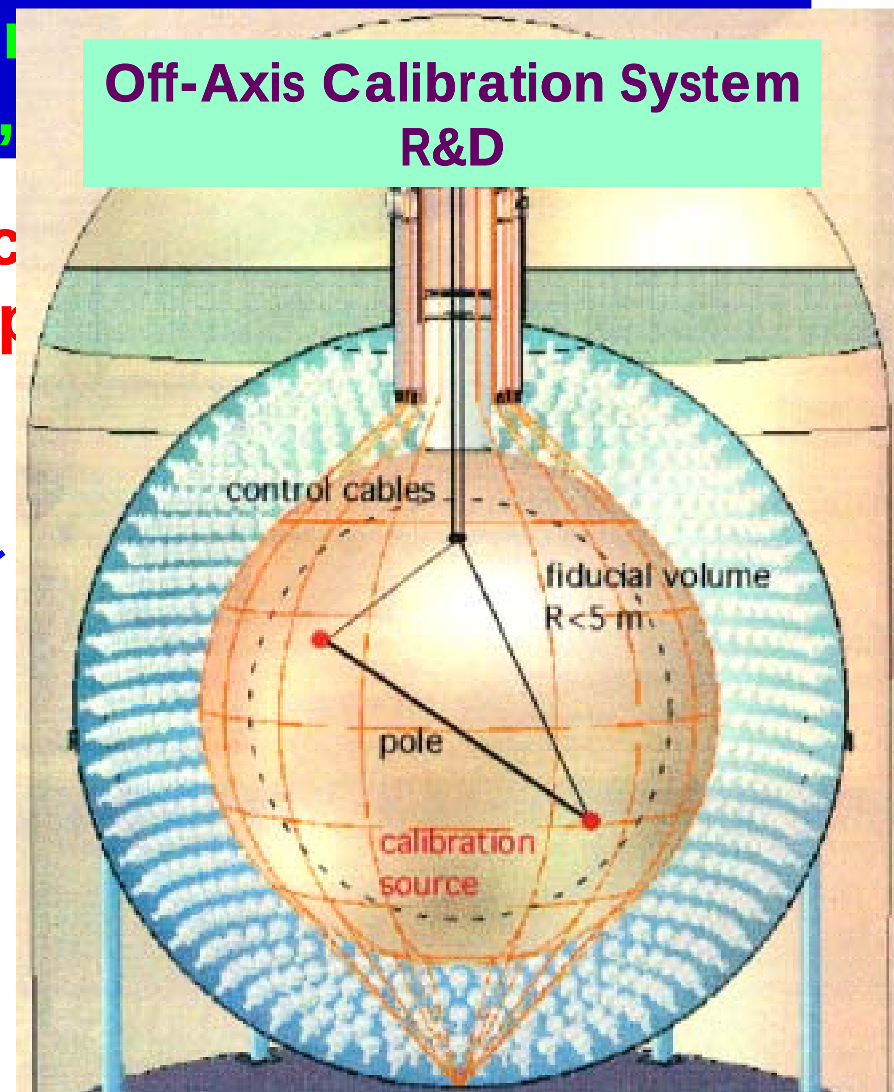
n capture time,

Trigger efficiency,

Radioactive Sourc

Cosmic-ray μ, μ sp





Radioactivity inside Liquid Scintillator

^{238}U : $^{214}Bi \xrightarrow{\beta+\gamma} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$

$E_{max} = 3.27$ MeV $E = 7.69$ MeV

$\tau = 28.7$ min. $\tau = 237\ \mu s$

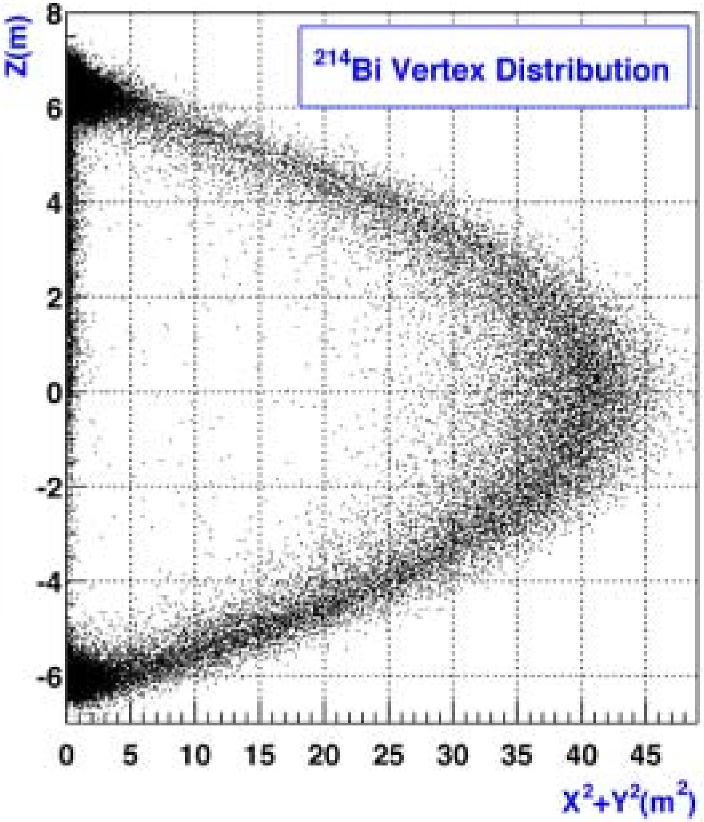
event selection

$\Delta R < 100$ cm

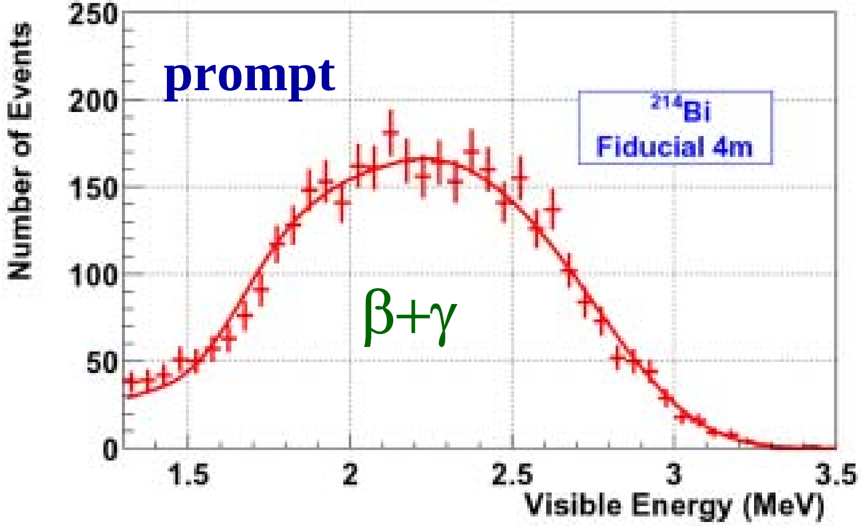
$5\ \mu s < \Delta t < 1000\ \mu s$

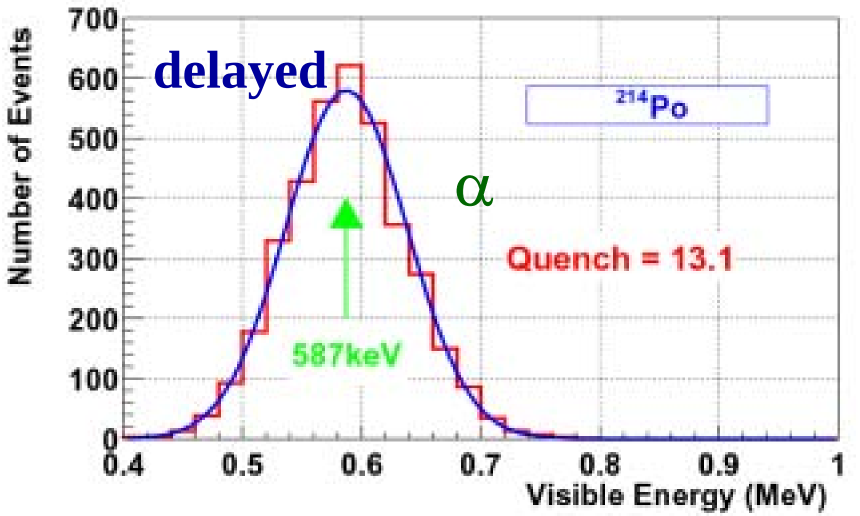
$E_{prompt} > 1.3$ MeV

$0.3 < E_{delayed} < 1$ MeV



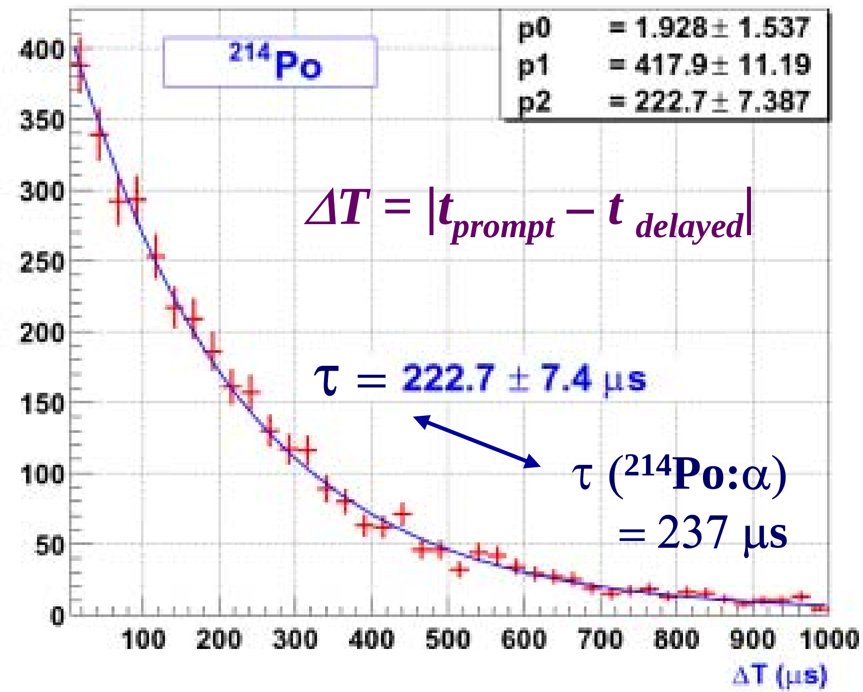
^{214}Bi – ^{214}Po – ^{210}Pb Signal





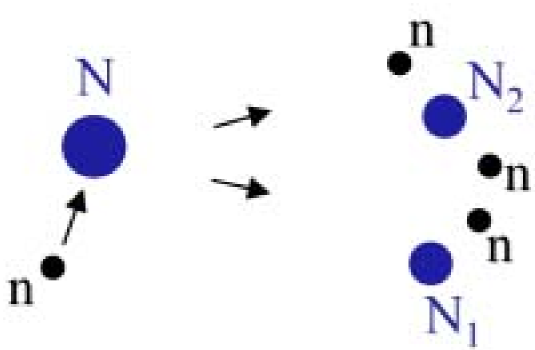
^{238}U = (3.5±0.5)x10^{-18} g/g

inside fiducial volume



2. Reactor Neutrino Detection

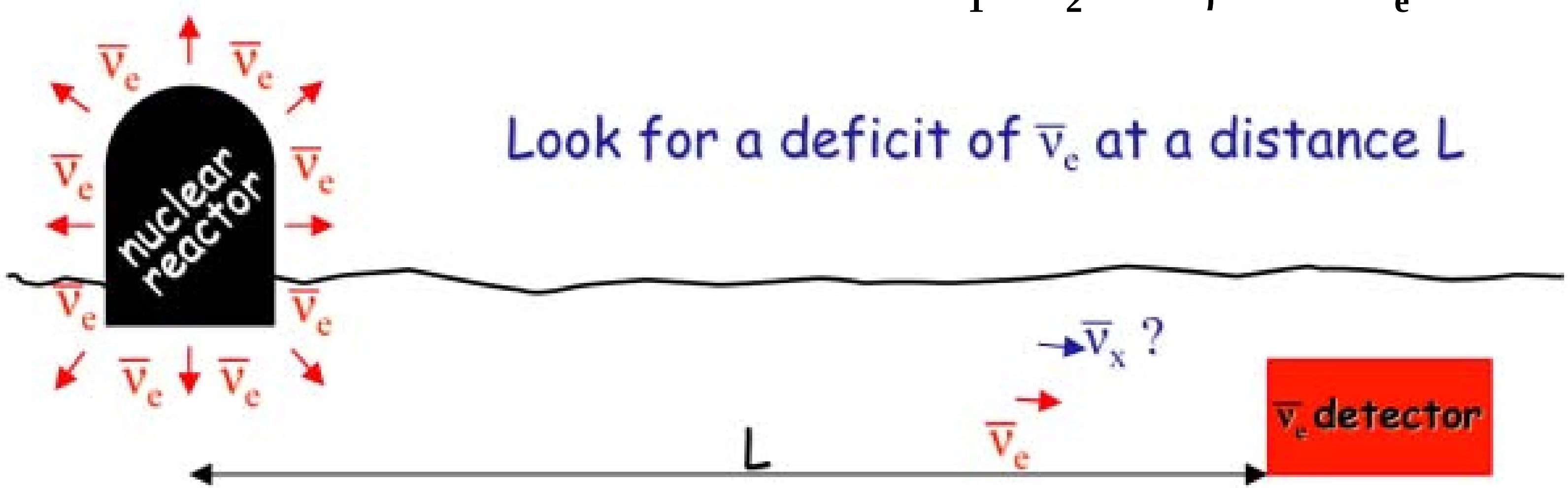
Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments



N_1 and N_2 still have too many neutrons and decay

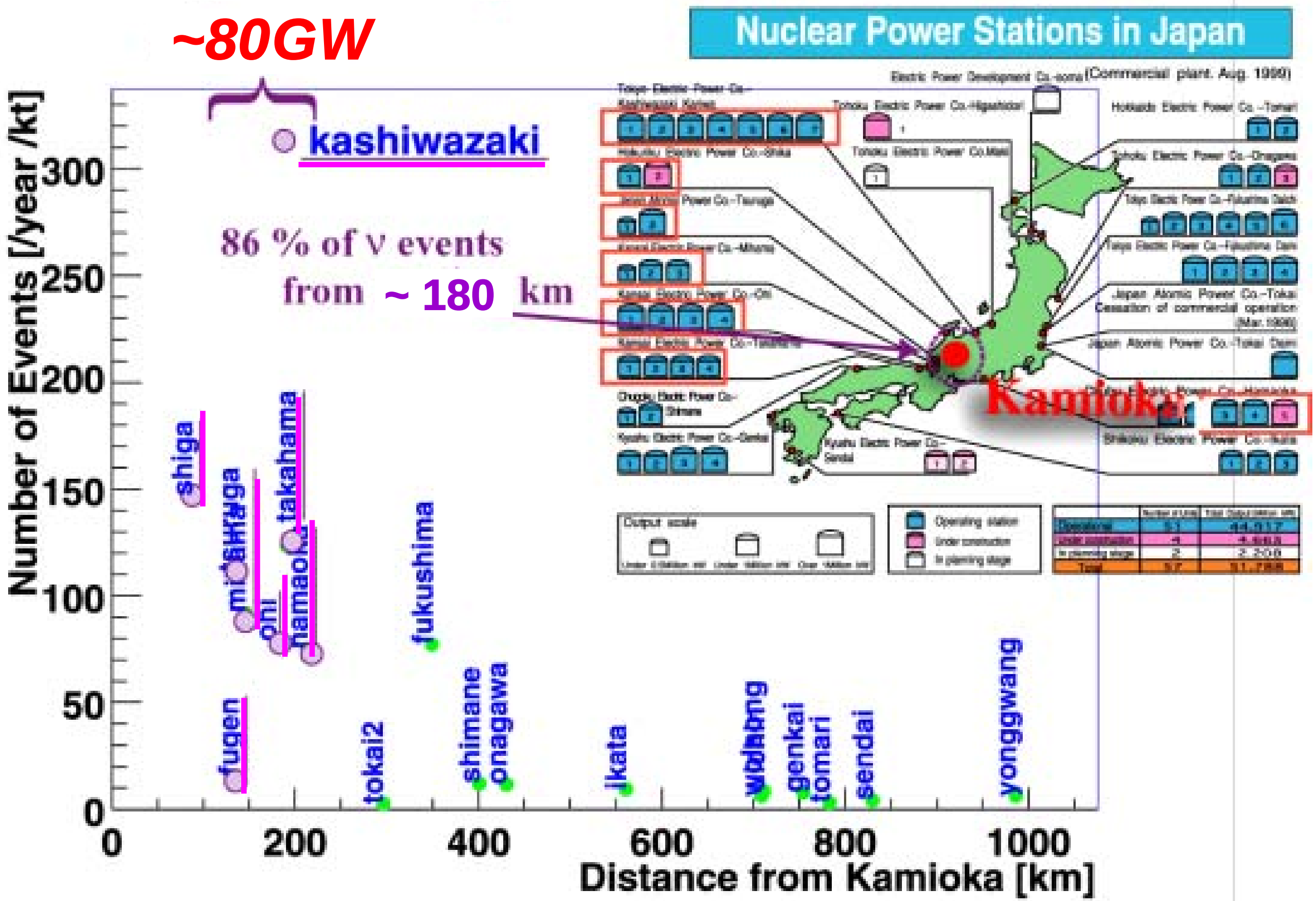
$N_2 \rightarrow N_3 + e^- + \bar{\nu}_e$

$$^{235}U + n \rightarrow N_1 + N_2 + 6.1\beta^- + 6.1\bar{\nu}_e + xn$$



Event Rate from Power-Plant Reactors

6 % of world nuclear thermal power



Investigate Solar Neutrino Anomaly Under Laboratory Conditions

2002 : 90, 95, 99, 99.73% C.L.

KamLAND :

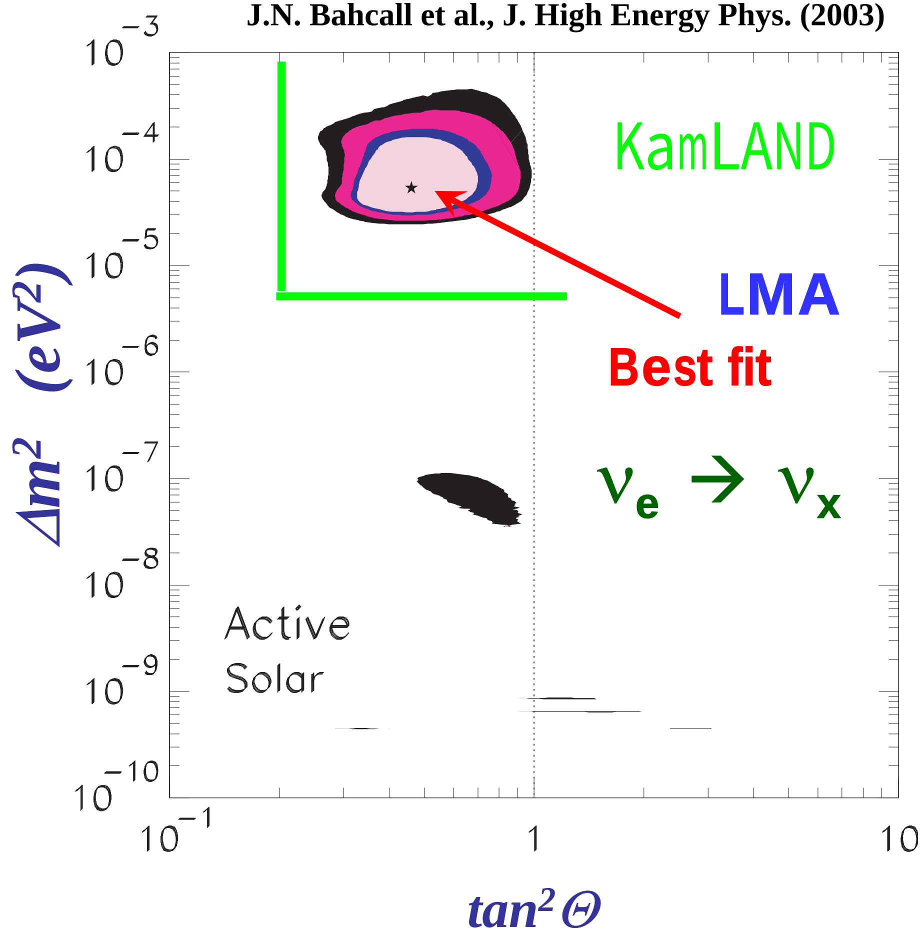
Thermal power ~ 80GW

<E> ~ 3 MeV

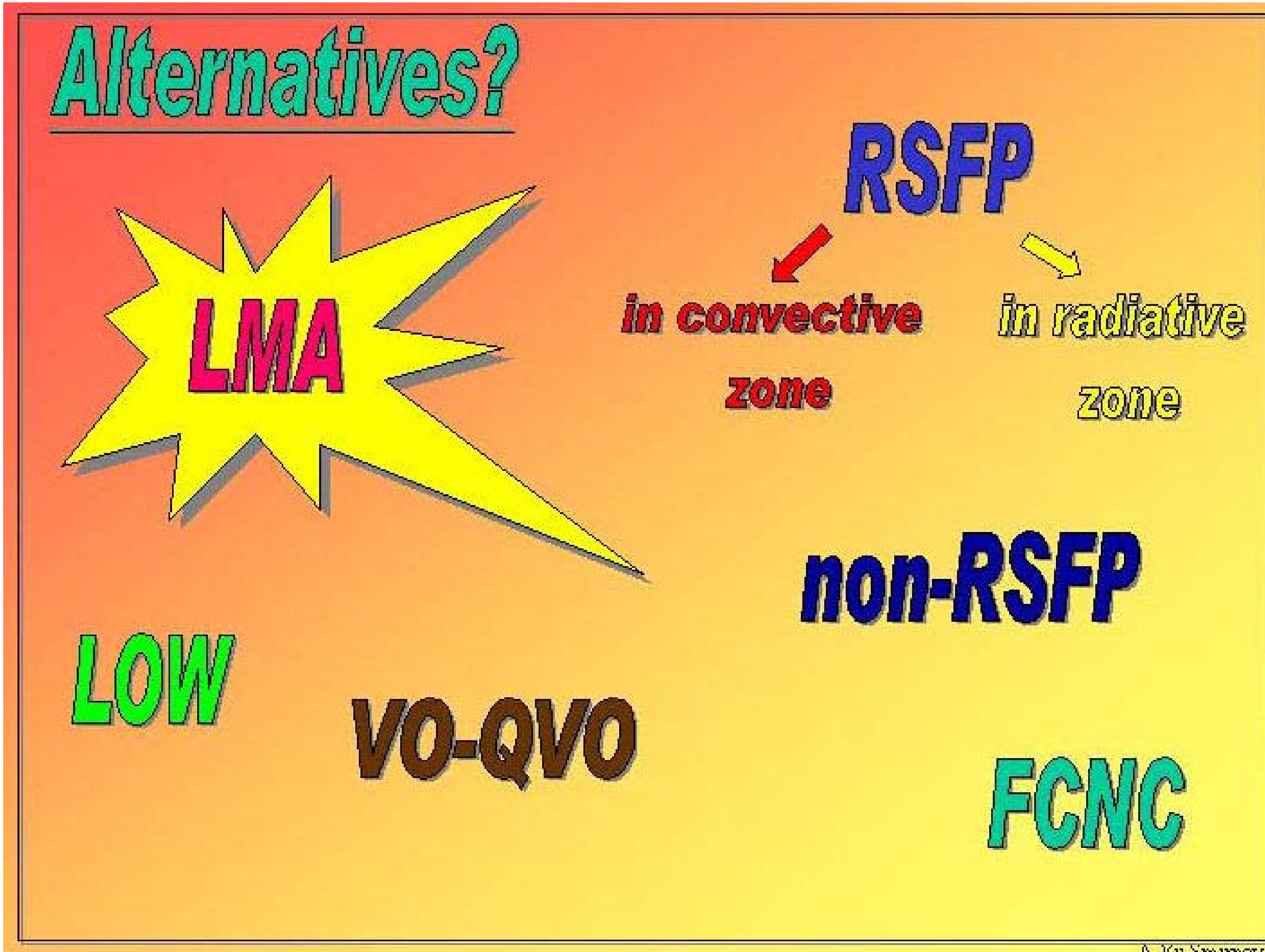
<base line> ~ 180 km

$\Delta m^2 \sim 10^{-5}\ eV^2$

J.N. Bahcall et al., J. High Energy Phys. (2003)



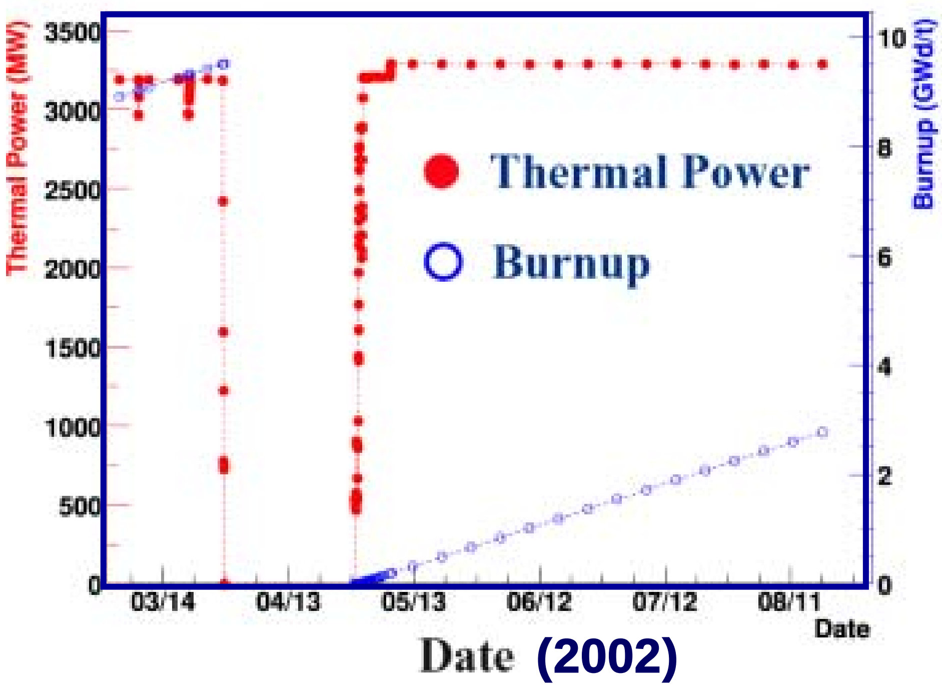
A. Smirnov, ν 2002

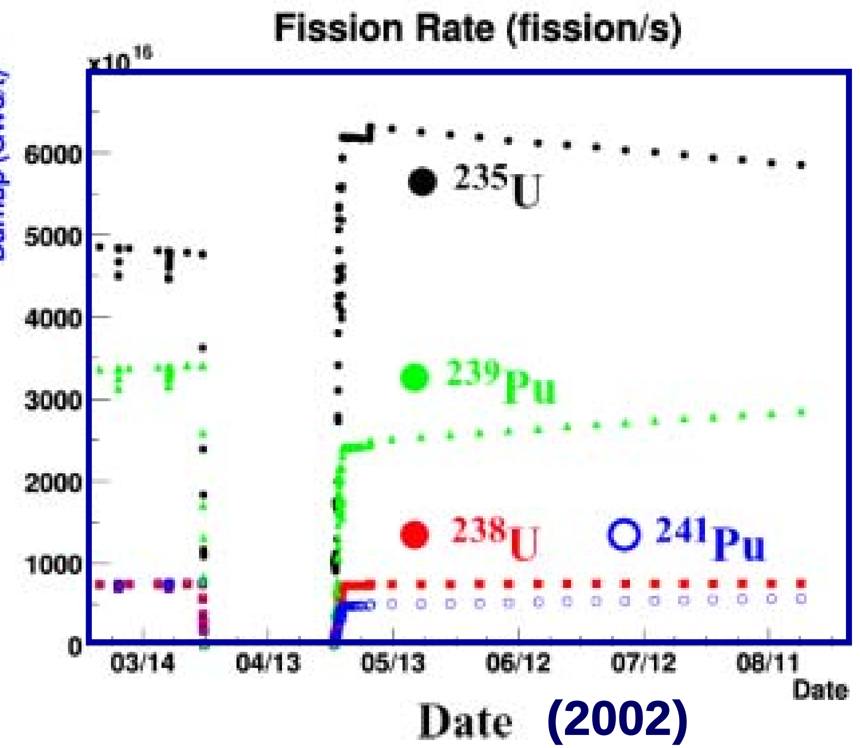


A. Smirnov, ν 2002

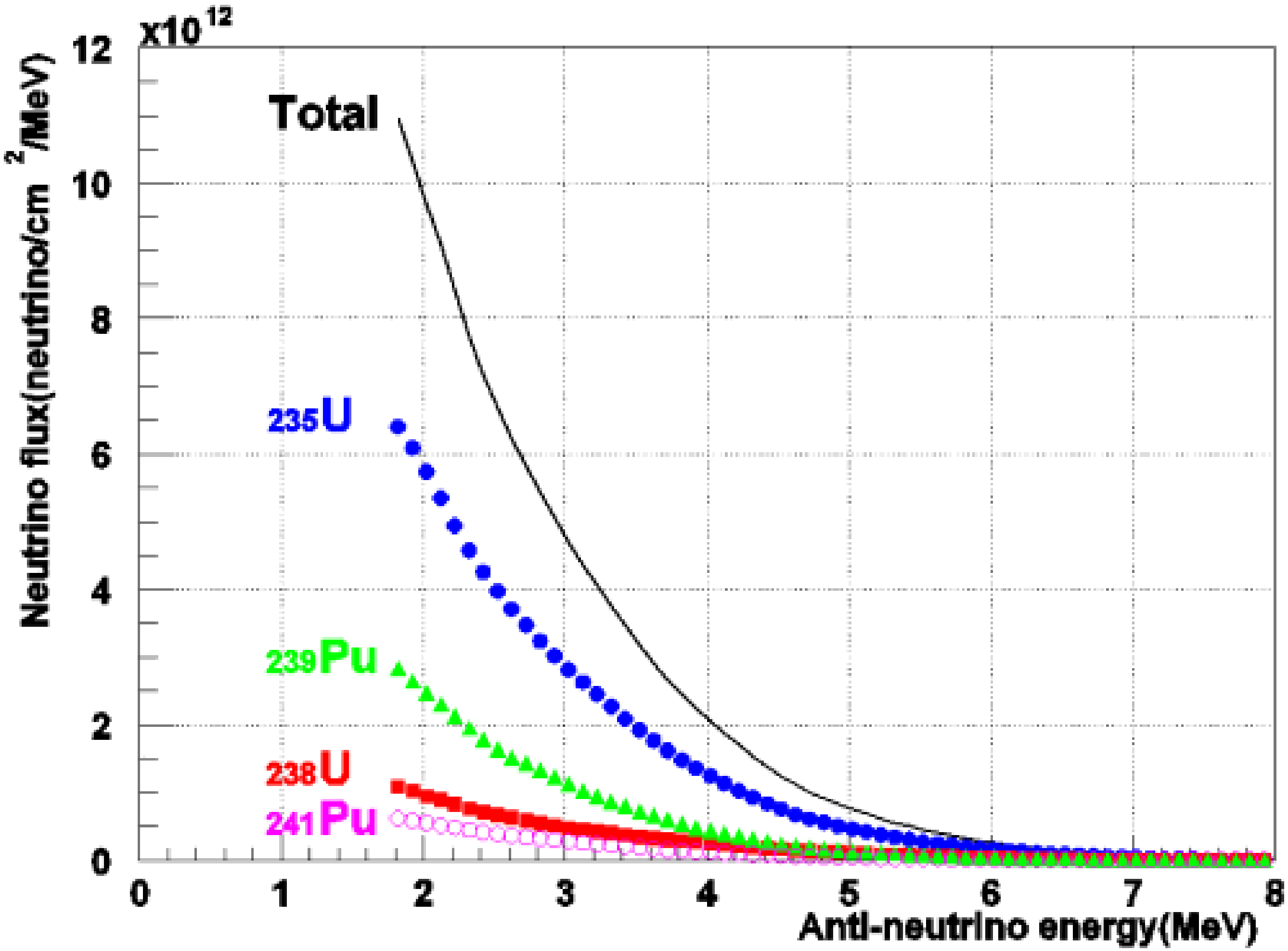
Reactor Data

One of Japanese Reactors

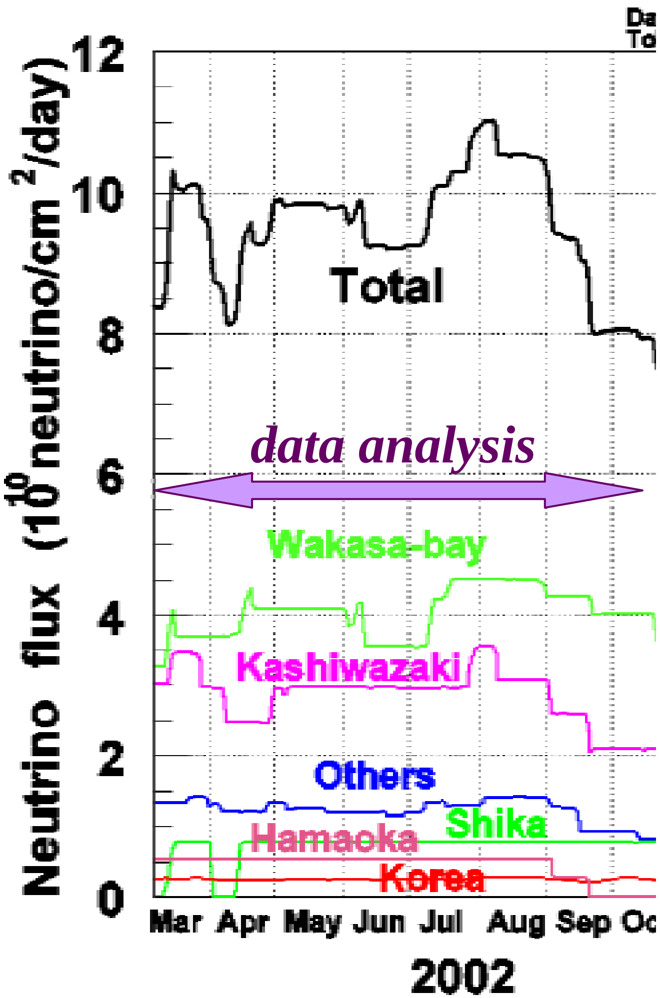




$\bar{\nu}_e$ Energy Spectrum



$\bar{\nu}_e$ Flux at Kamioka



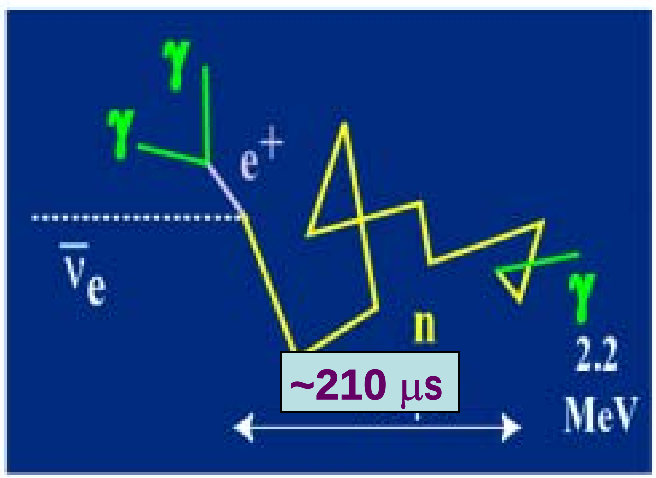
Mar. 4 – Oct. 6, 2002

Reactor $\bar{\nu}_e$ Detection in Liquid Scintillator

reaction process : inverse- β decay $(\bar{\nu}_e + p \longrightarrow e^+ + n)$

$n + p \longrightarrow d + \gamma$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- prompt part : e^+

$\bar{\nu}_e$ energy measurement

$$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

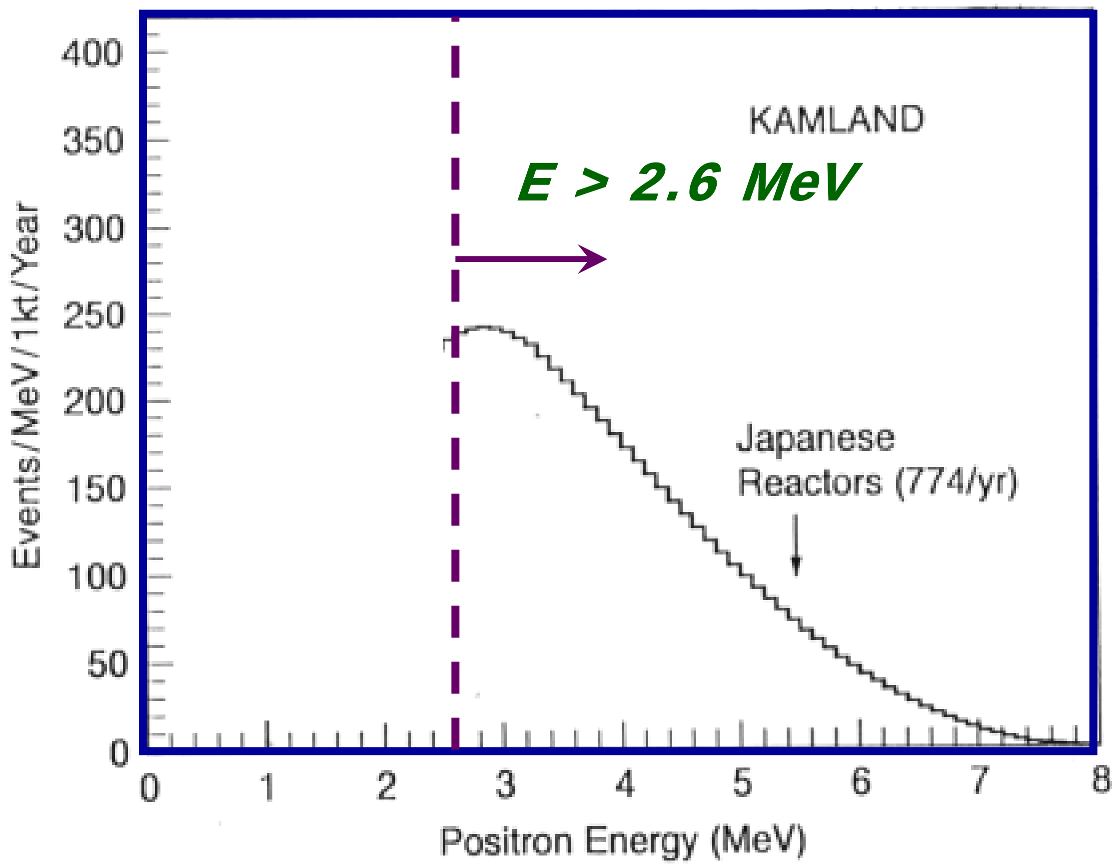
$$\Delta = M_n - M_p$$

- delayed part : γ (2.2 MeV)

- tagging : correlation of time, position and energy between prompt and delayed signal

KamLAND e^+ Prompt Energy Spectrum

PRL **80** (1998)635



$\bar{\nu}_e$ Event Selection

data sample : March 4 – Oct. 6, 2002

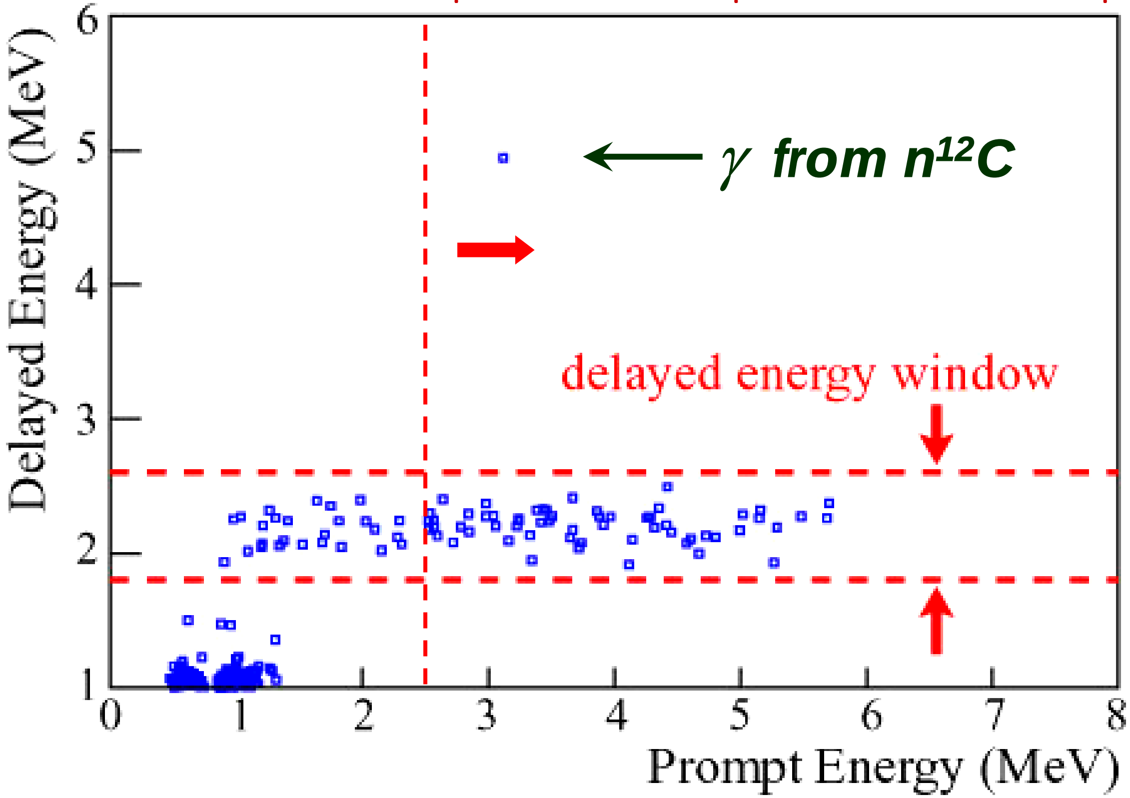
exposure time : 162 ton•yr (145.1 days)

➢ **inverse β - decay selection**

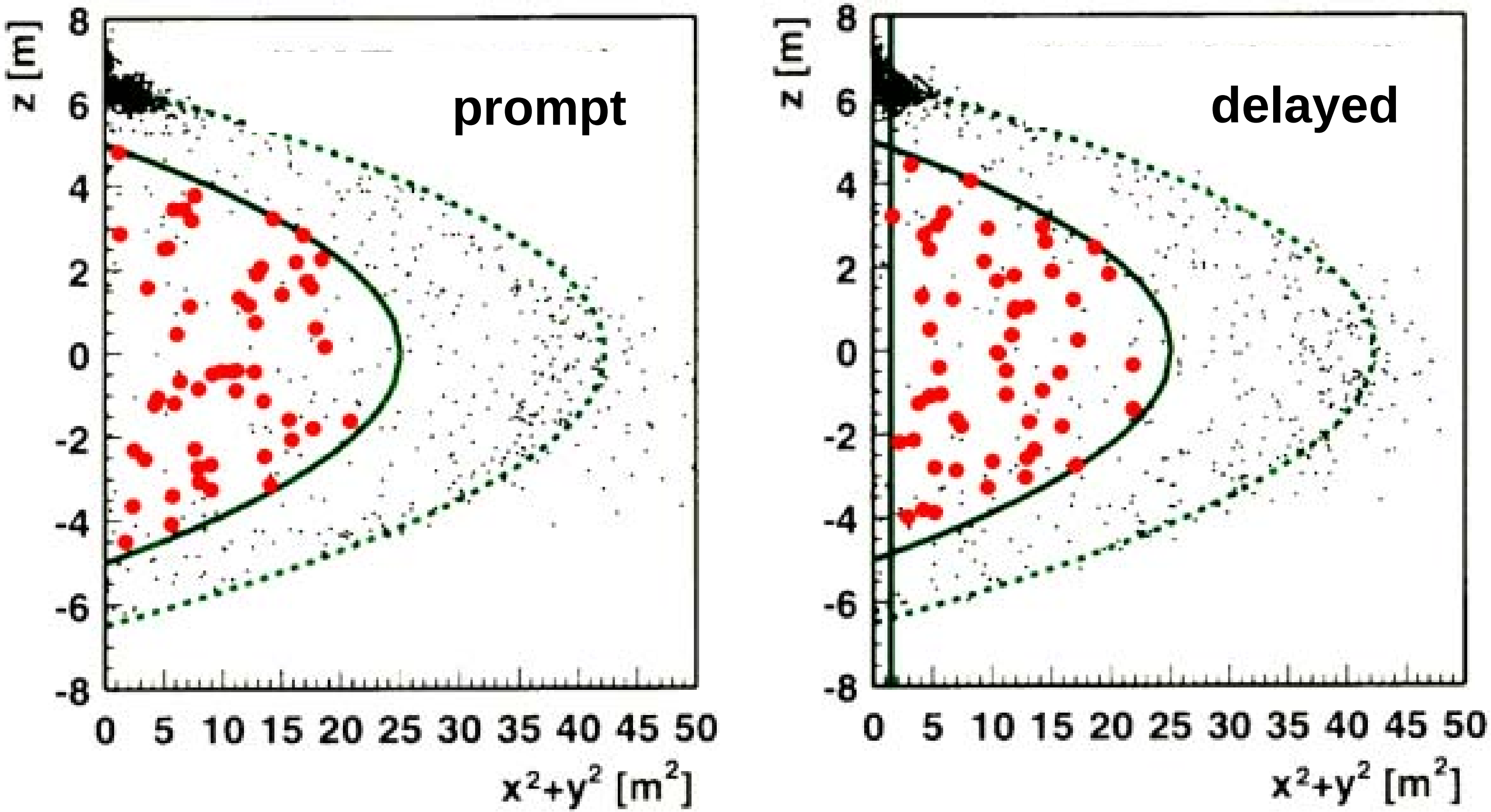
E_{prompt} > 2.6 MeV
1.8<E_{delay}<2.6 MeV
0.5 <ΔT<660 μ sec
ΔR<1.6m
no OD signals
R<5m

➢ **μ-induced spallation event cut**

ΔT_μ < 2sec , ΔE_μ >3 GeV or ΔR_μ<3m



Production Points of Candidate Events



Analysis Summary

Final sample	
162 ton•yr,	$E_{prompt} > 2.6$ *MeV*
	54 ev
Expected	**86.8 ± 5.6 ev**
Background	**0.95 ± 0.99 ev**
accidental	0.0086 ± 0.0005
$^{9}Li/^{8}He$ (β, n)	0.94 ± 0.85
fast neutron	0 ± 0.5

Deficit

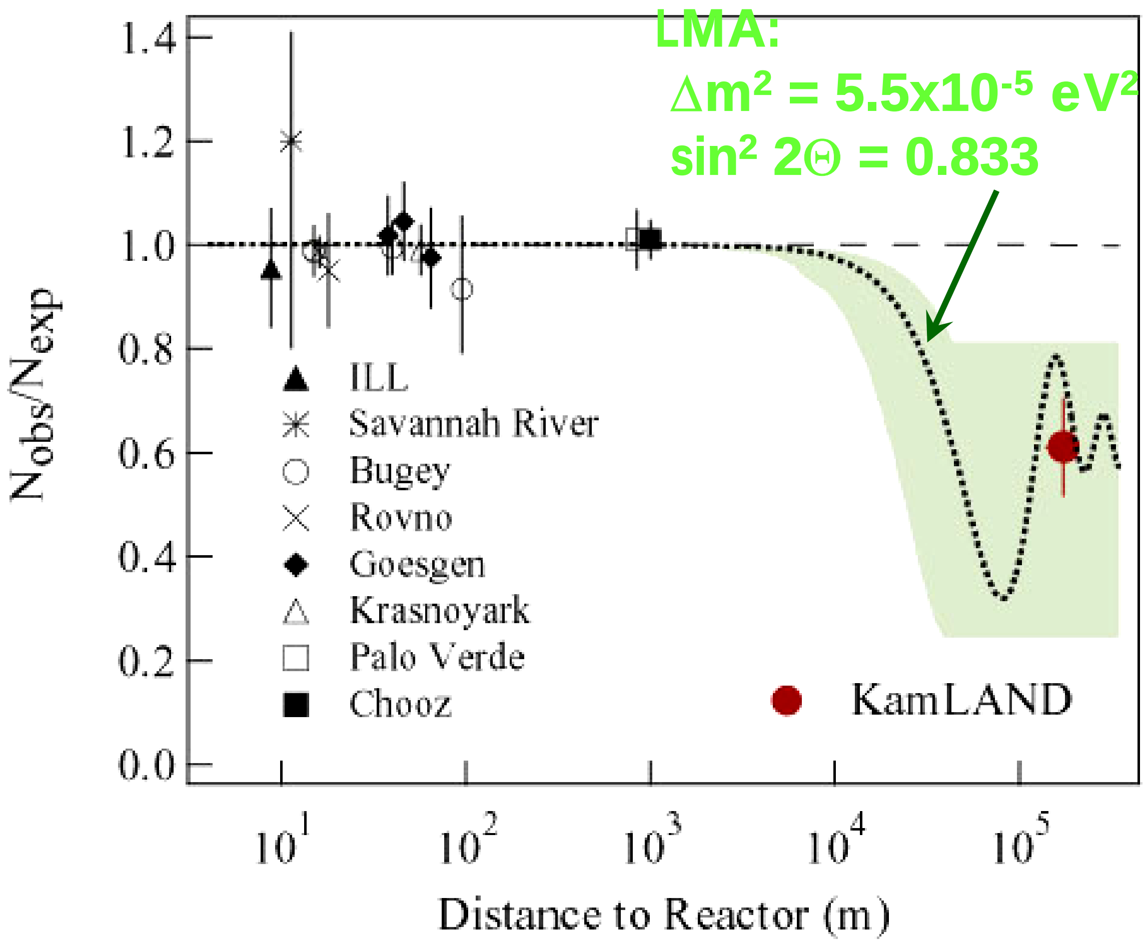
Evidence for Reactor $\bar{\nu}_e$ Disappearance

$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085\ (\text{stat}) \pm 0.041\ (\text{syst})$$

99.95 % C.L.

K. Eguchi et al., Phys. Rev. Lett. 90, 021802 (2003)

Ratio of Measured to Expected $\bar{\nu}_e$ Flux from Reactor Neutrino Experiments

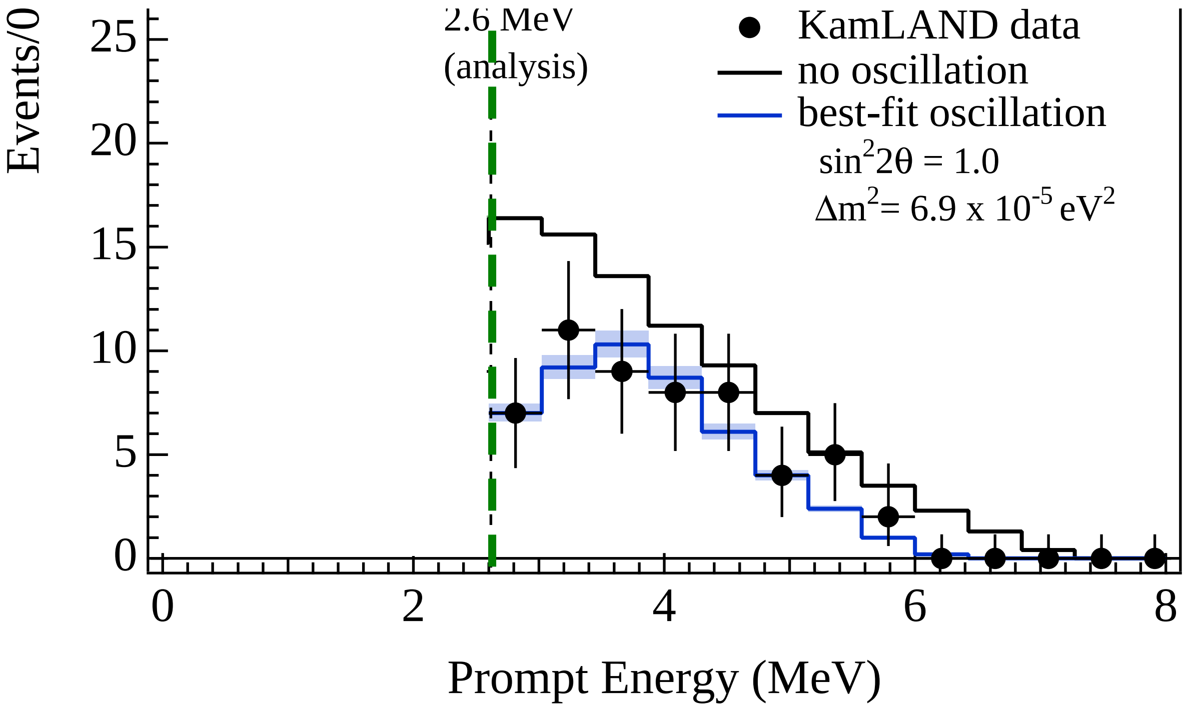


G.Fogli et al., PR D66, 010001-406, (2002)

Energy Spectrum (E_{prompt} > 2.6 MeV)

data : consistent with

distorted shape at 93 % C.L.
&
no oscillation shape at 53% C.L.



Neutrino Oscillation Study, Combining Event Rate & Energy Spectrum

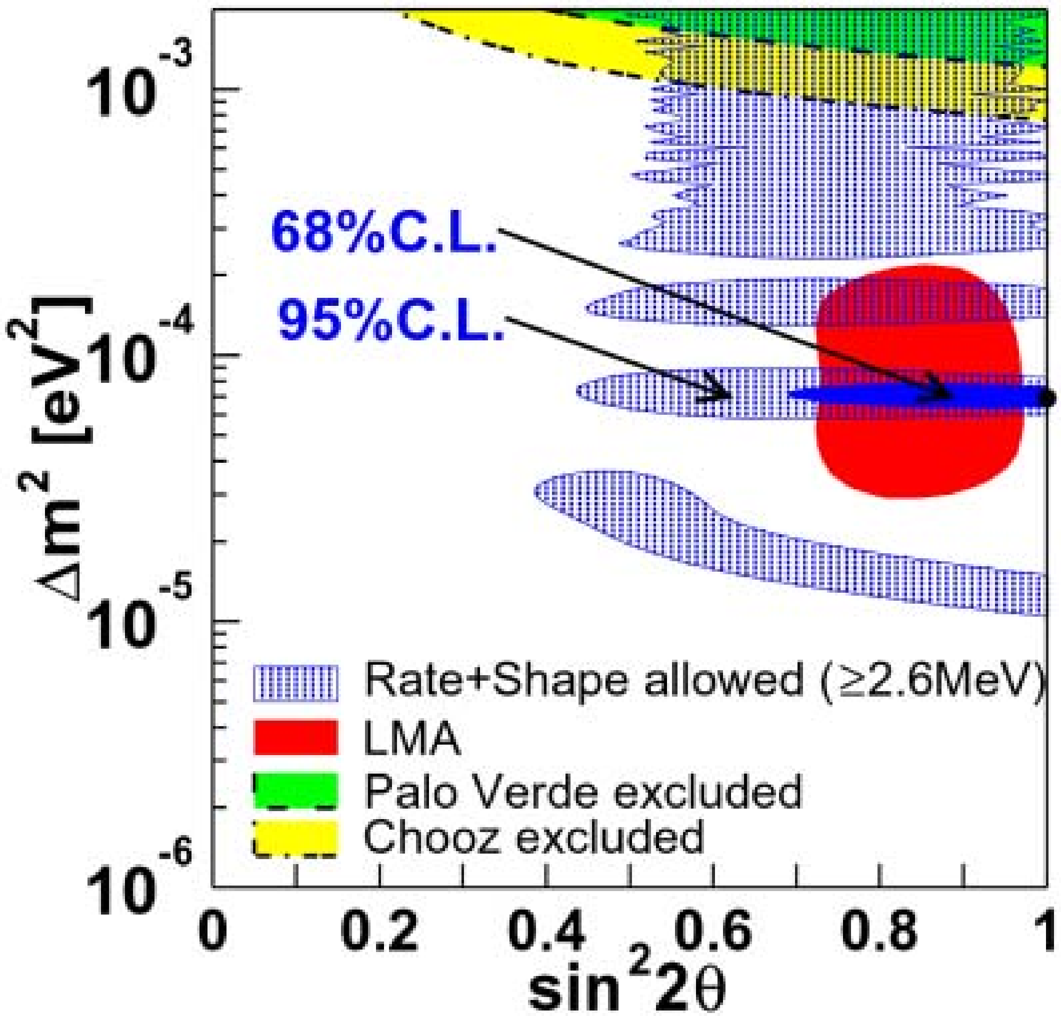
$E_{prompt} > 2.6$ MeV

Best fit :

$\Delta m^2 = 6.9 \times 10^{-5}\ eV^2$

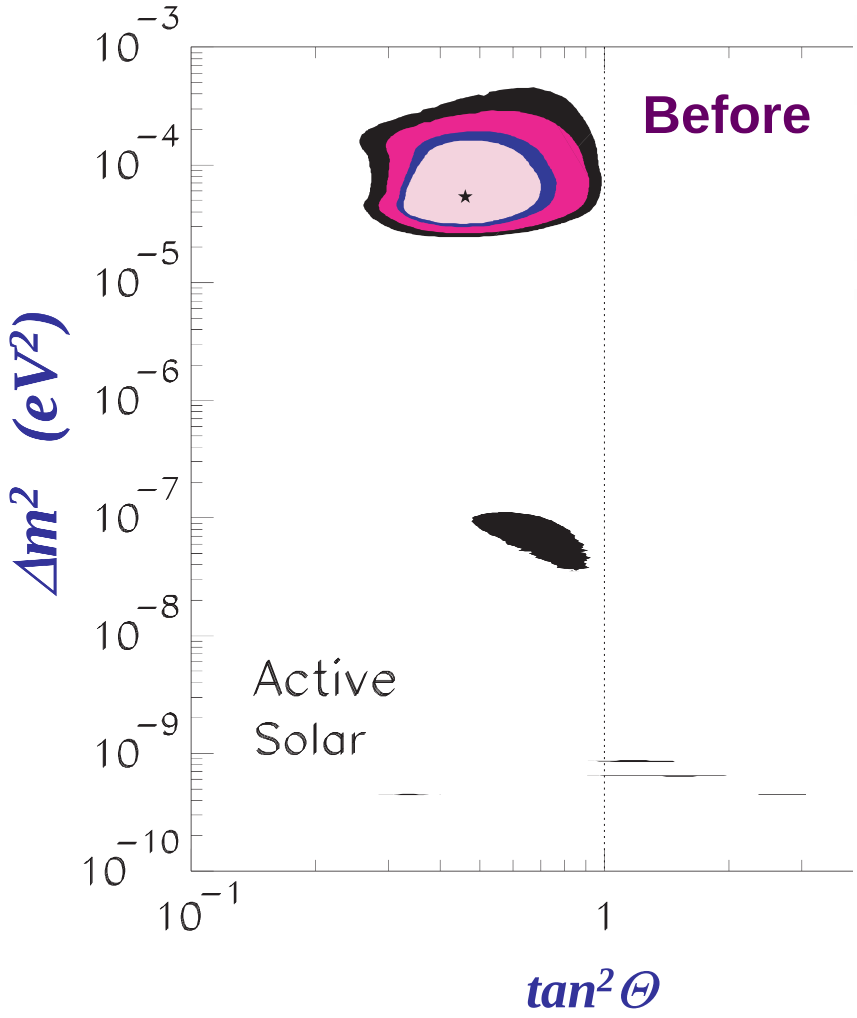
$\sin^2 2\theta = 1.0$

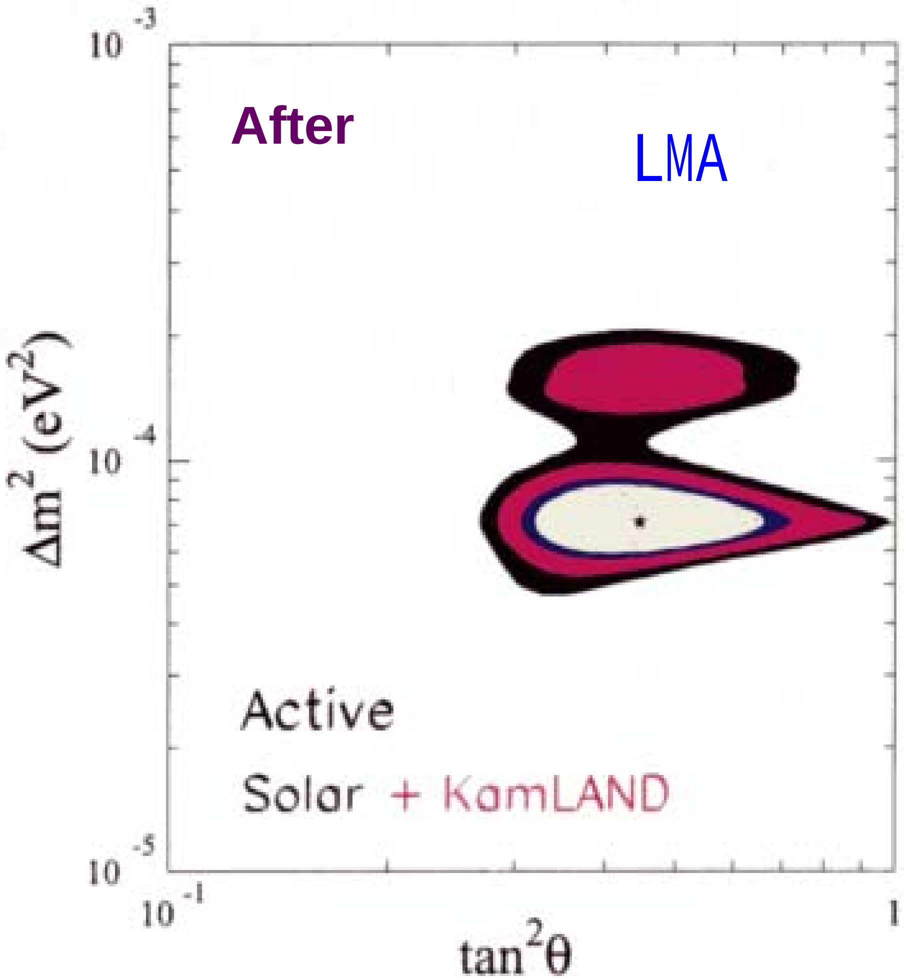
$\nu_e \rightarrow \nu_x$



Before & After KamLAND : 90, 95, 99, 99.73% C.L.

J.N. Bahcall et al., J. High Energy Phys. (2003)





KamLAND + Solar

Exclusion C.L.

LOW : 4.8 σ
VAC : 4.9 σ

With the results from KamLAND, one can confidently state that the solar neutrino problem was solved, if CPT is invariant

V. Berger et al., Phys. Lett. B555 (2003)

3. Solar $\bar{\nu}_e$ Searches

185.5 days data : March 4 – December 1, 2002

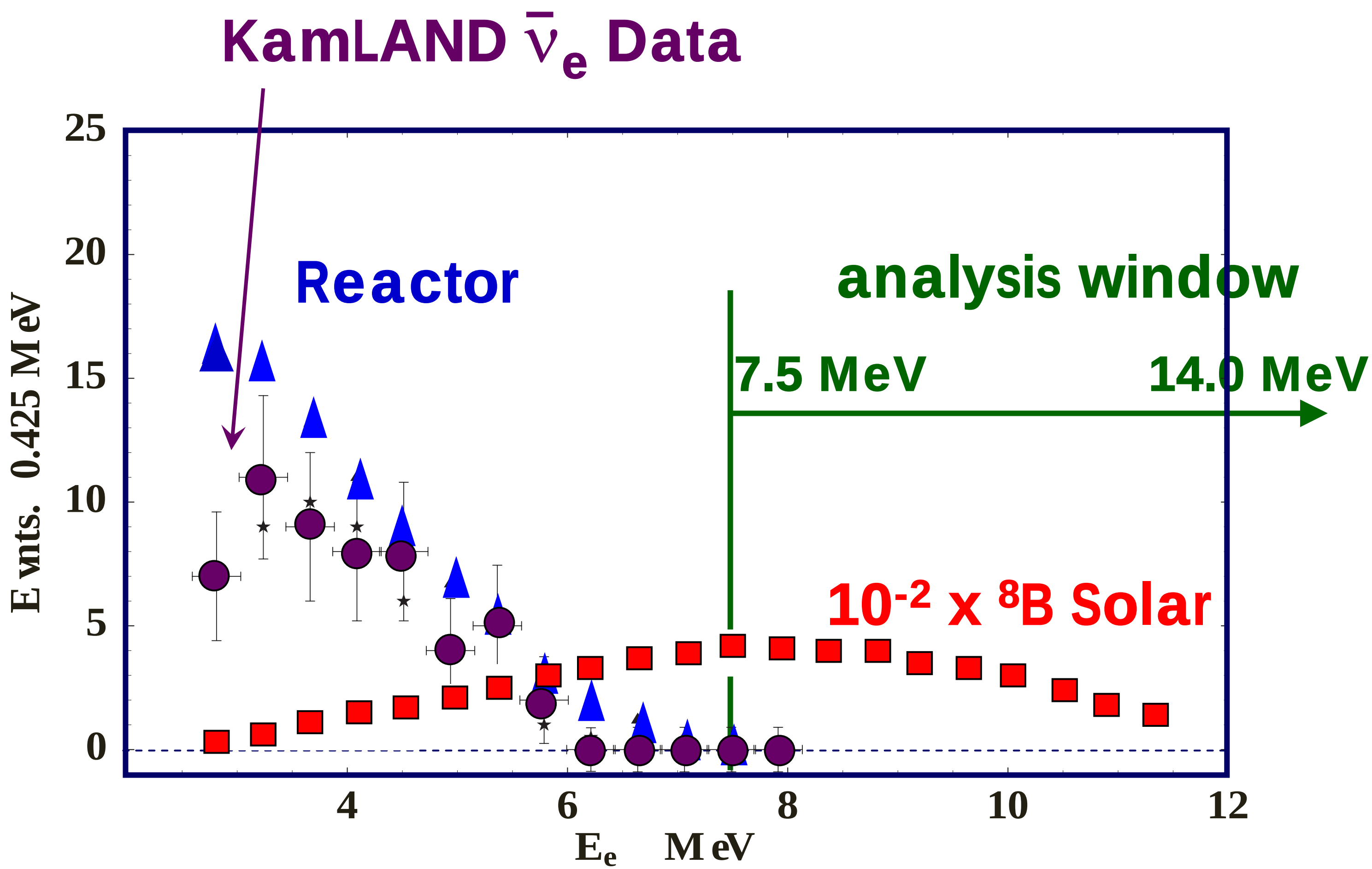
* **Spin-Flavor Precession**
  (μ_ν with solar magnetic field)

$$\nu_e \xrightarrow{\text{SFP}} \bar{\nu}_\mu \xrightarrow{\text{OSC}} \bar{\nu}_e$$

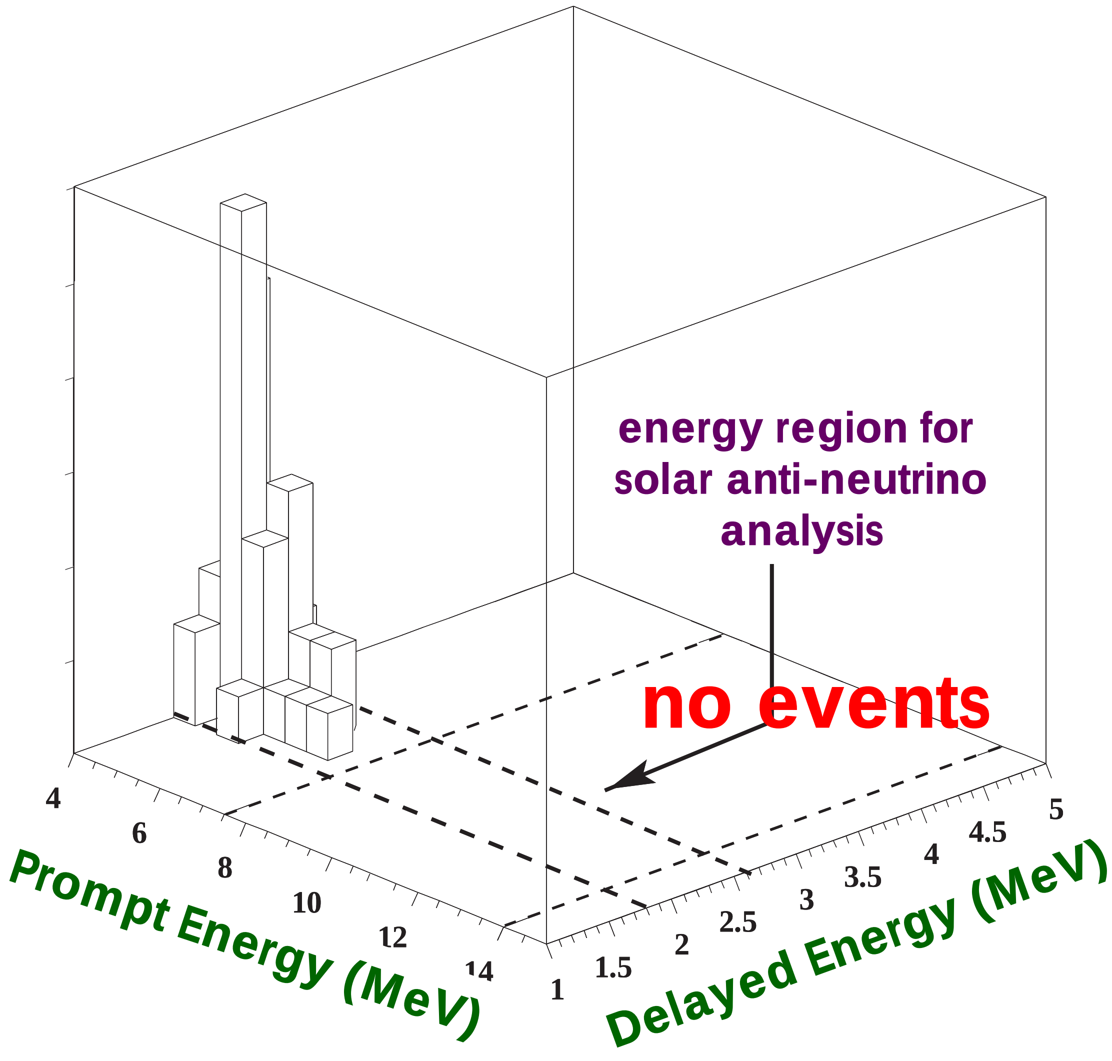
: majorana ν

* **Neutrino Decay**

$$\nu_e\ (\nu_2) \longrightarrow \bar{\nu}_e\ (\bar{\nu}_1) + \text{Majoron}$$


KamLAND $\bar{\nu}_e$ Data
Reactor
analysis window
7.5 MeV
14.0 MeV
10^{-2} x ^{8}B Solar
Events. 0.425 MeV
0
5
10
15
20
25
4
6
8
10
12
E_e MeV

Energy Distributions of Prompt & Delayed Events



Kam-LAND

90 % C.L. limit

$\Phi_{\bar{\nu}}$ < 3.7 x 10^{2} cm^{-2}s^{-1}

< 0.028 %

of $^{8}B_{\nu}$ (8.3 < E_{ν} < 14.8 MeV)

K. Eguchi et al., Phys. Rev. Lett. 92, 071301 (2004)

a factor 30 improvement

over previous best measurement (SK)

Spin-Flavor Precession :

$$\nu_e \xrightarrow[\text{SFP}_{R_\odot}]{} \bar{\nu}_\mu \xrightarrow[\text{LMA}_{S-E}]{} \bar{\nu}_e$$

(E.Kh. Akhmedov and J. Pulido, Phys. Lett. B553, 2003)

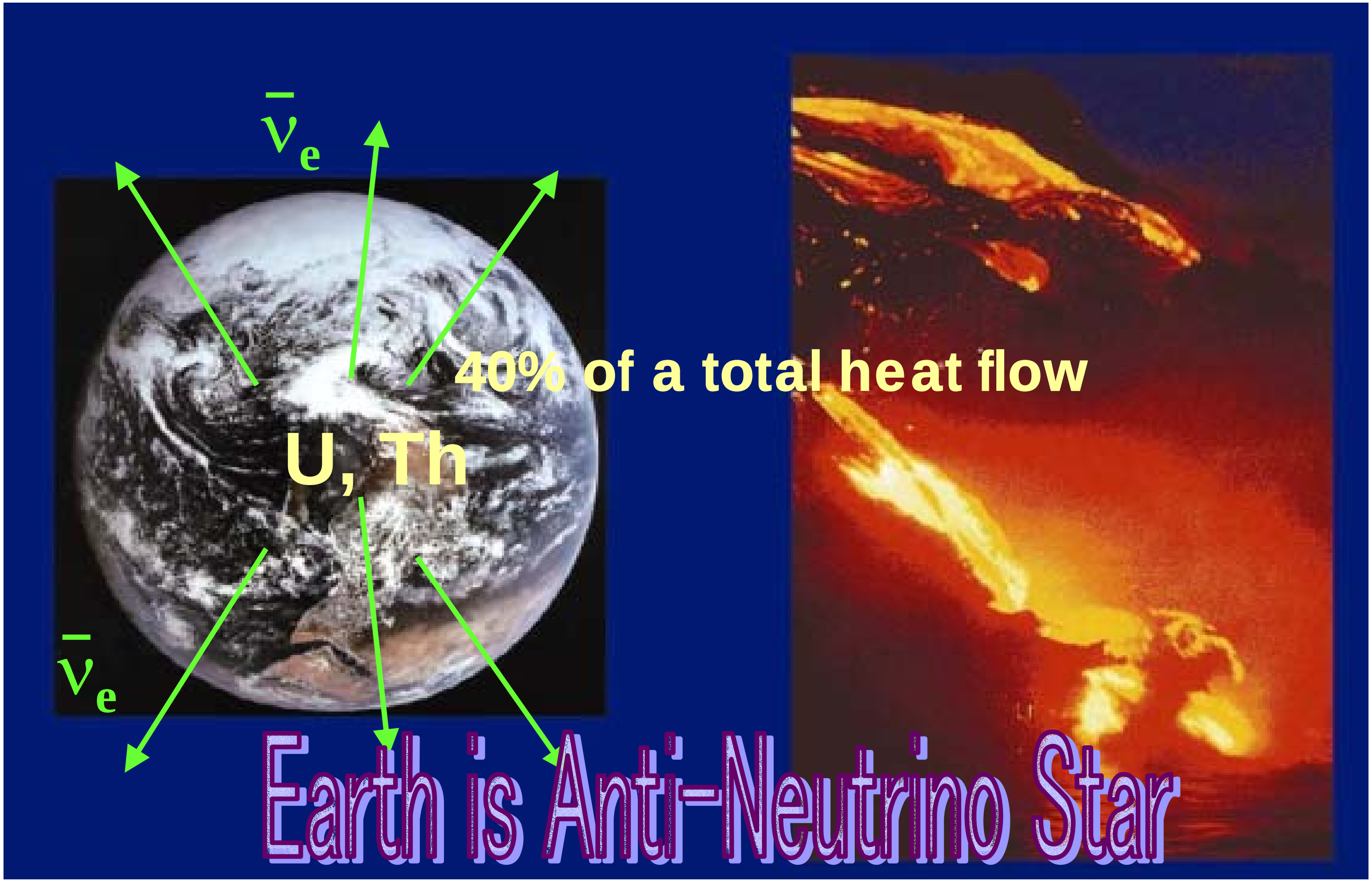
$\mu_{\bar{\nu}} <$ **1.3 x 10**$^{(-9 \text{ to } -11)}$ μ_B (90 % C.L.)

for $B_T(0.05R_\odot) = (10\text{-}1000)$ kG

within present astrophysical expectatives

$\mu_{\bar{\nu}} < 1.0 \times 10^{-10}\ \mu_B$: current best limit from MUNU

4. Geoneutrino Detection



Geoneutrino Generation

- **Heat Generation inside the Earth**
  -- total heat flow ~ 40 TW ?
  -- U/Th contribution ~ 16 TW ???

$$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He + 6\,e^{-} + 6\,\bar{\nu}_e + 51.7\ MeV$$

$$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^{4}He + 4\,e^{-} + 4\,\bar{\nu}_e + 42.7\ MeV$$

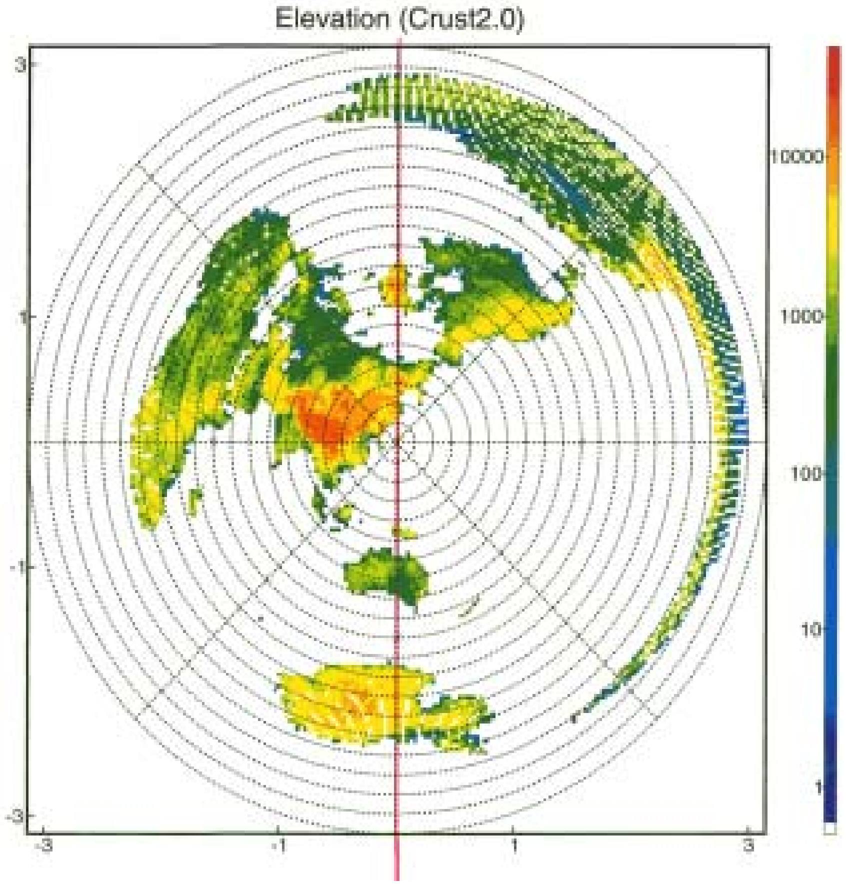
- **Geochemical Earth Model**
  -- no reliable values of U/Th concentration in Crust, Mantle and Core

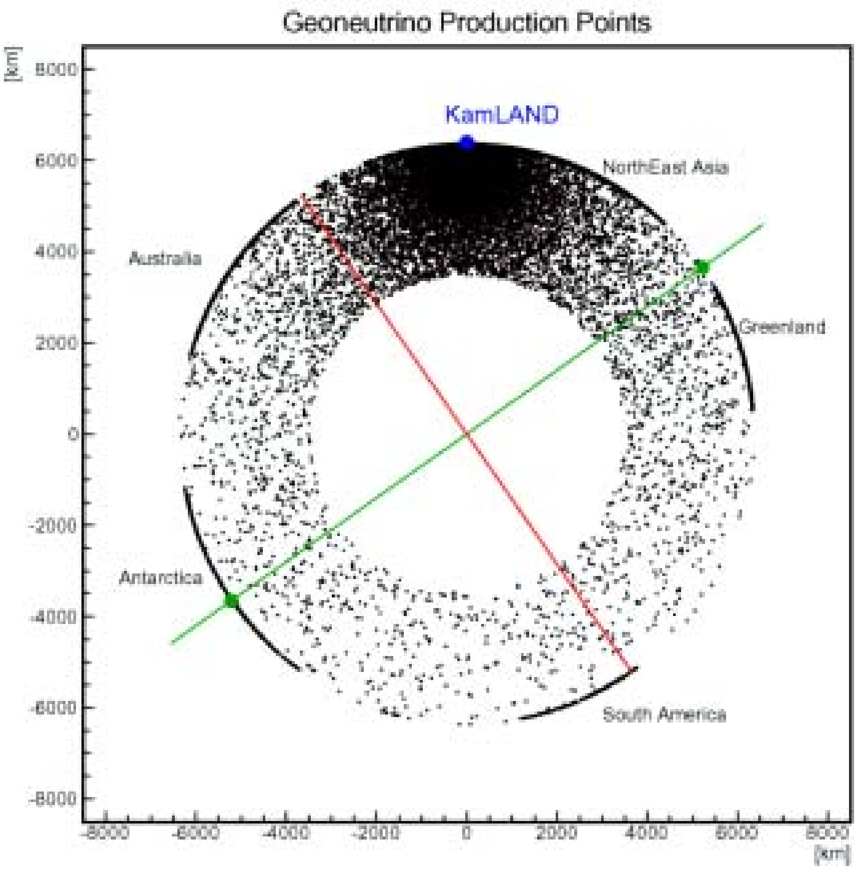
⇓

$\bar{\nu}_e$ detection is essential

Geoneutrino Production Points

[U] : 2.7 ppm (C.C.), 0.08 ppm (O.C.), 0.01 ppm (Mantle), 0 (Core)
[Th] : 4[U]



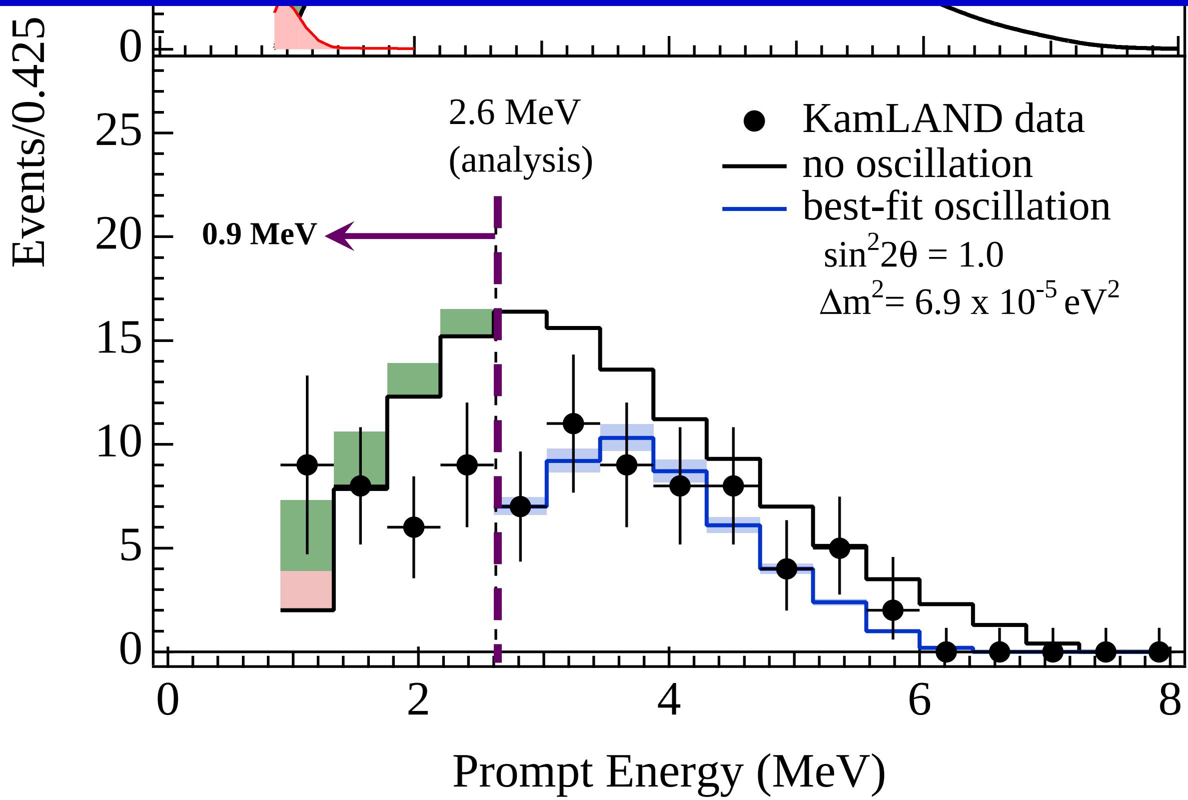


Geoneutrino Flux ?

$\sim 4\,\bar{\nu}_e$: ^{238}U $\sim 5\,\bar{\nu}_e$: ^{232}Th

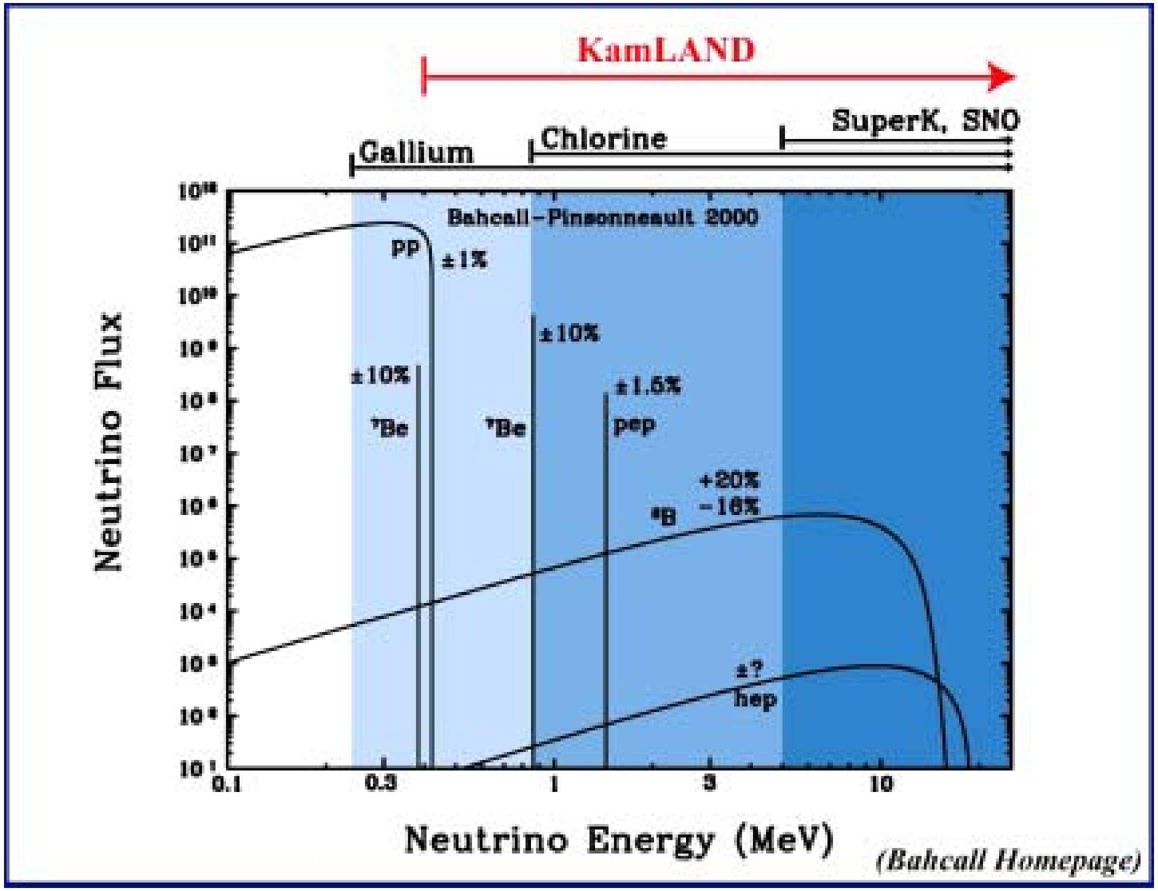
Radiogenic heat：～40TW (model-dependent)

(0 – 110) TW at 95 % C.L.



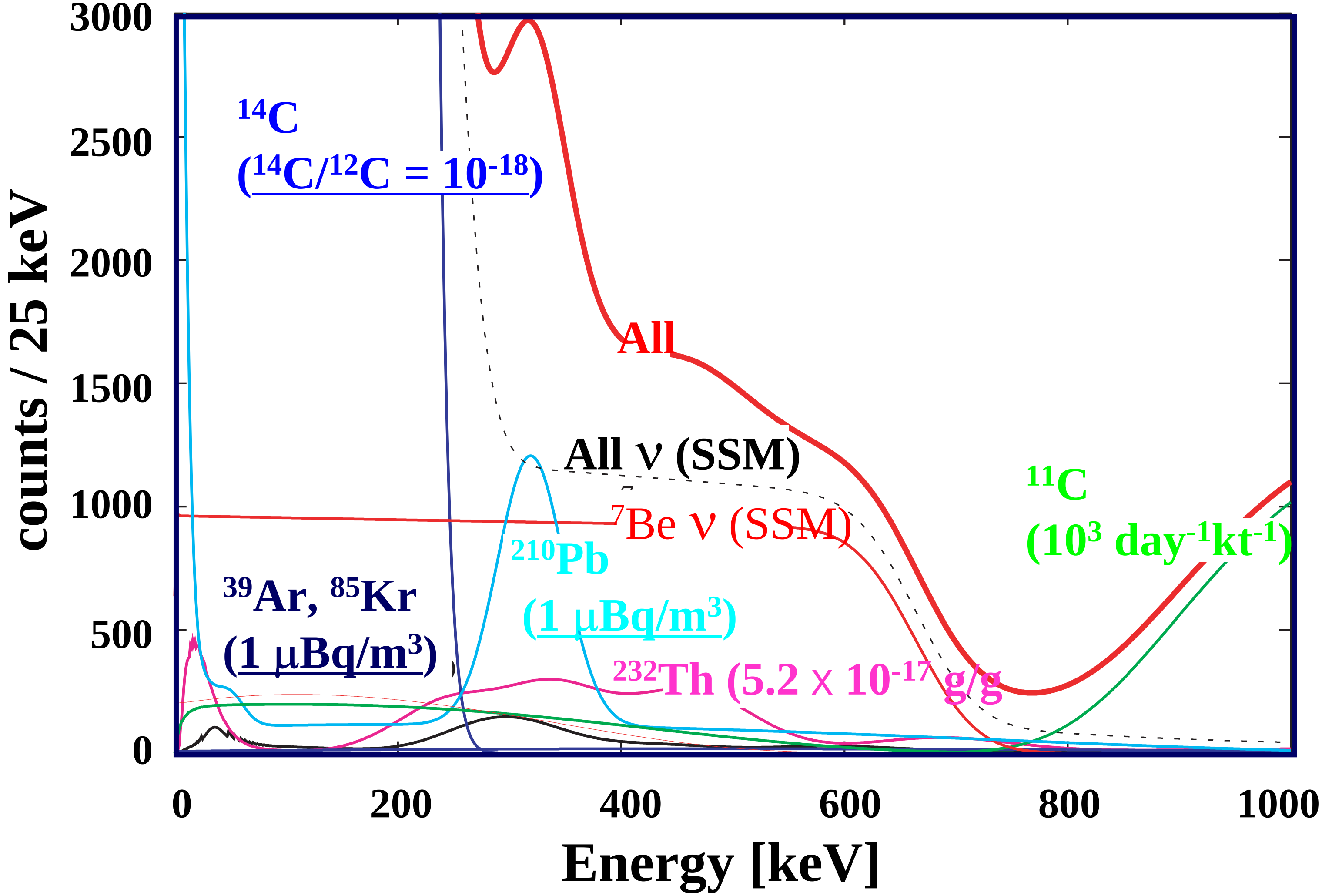
5. Plan : ^{7}Be Solar Neutrino Detection

$\nu_e + e^- \rightarrow \nu_e + e^-$ ～200 ν/kton•day

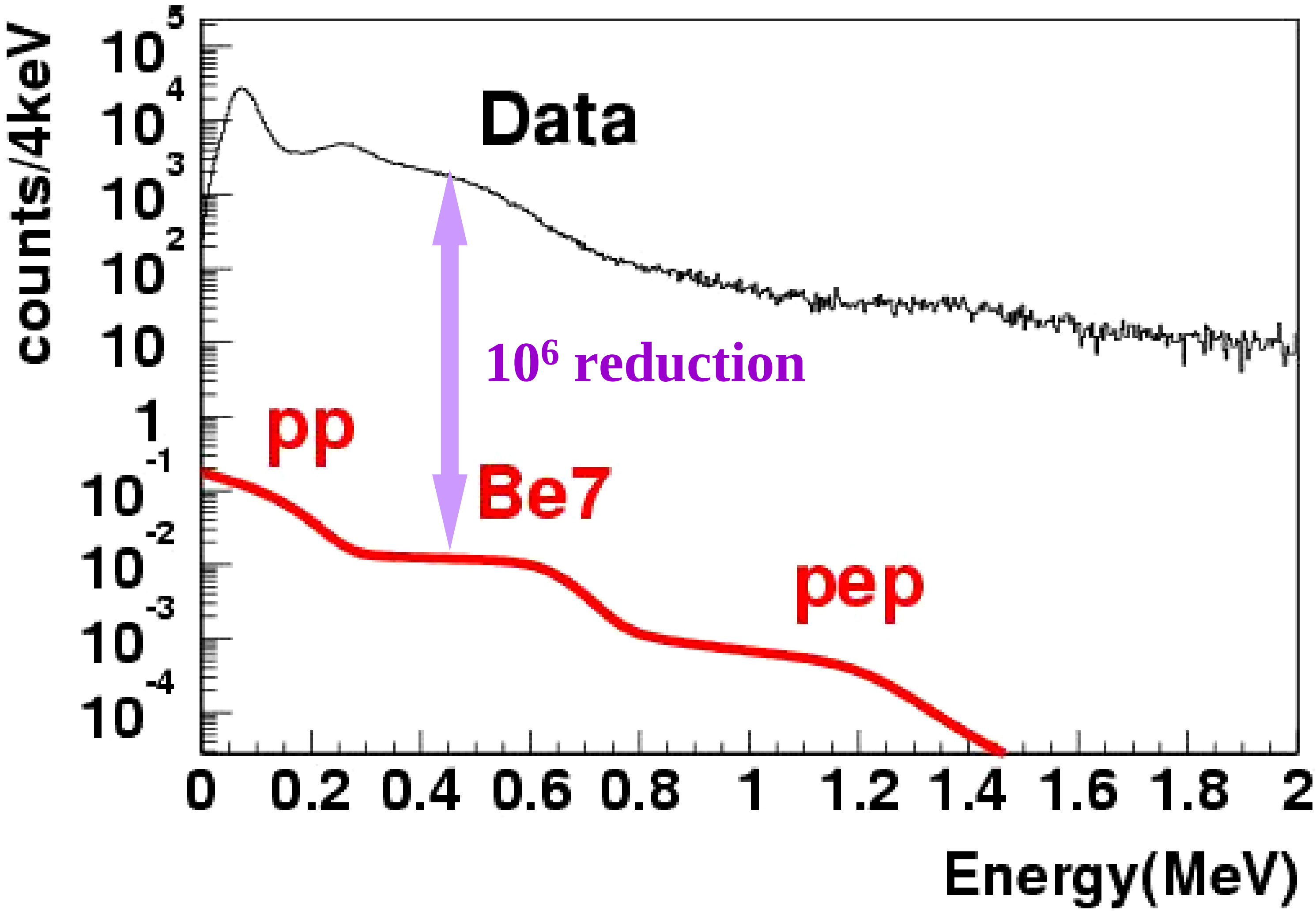


(Bahcall Homepage)

KamLAND Goal



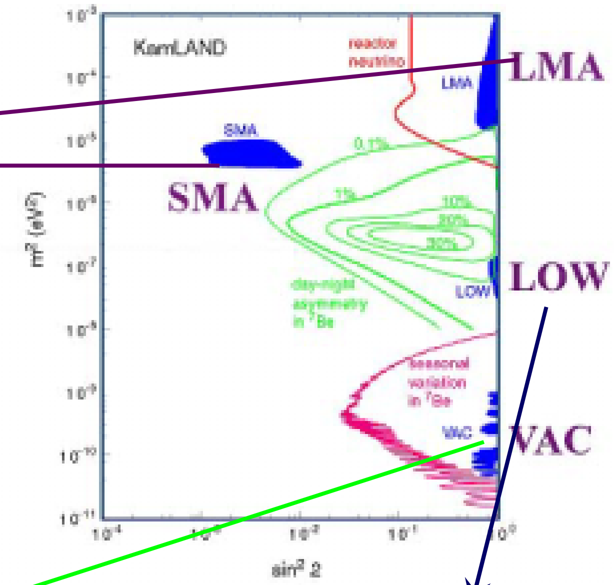
Present KamLAND



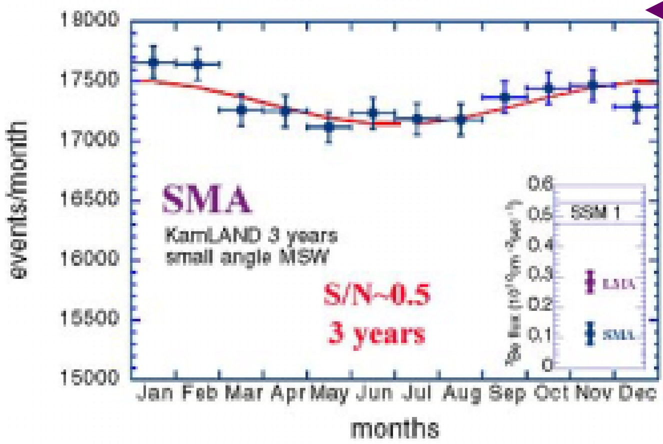
Requirements & Achievements of Radioactive Impurities in Liquid Scintillator

impurities	present	goal	reduction
^{238}U	$(3.5 \pm 0.5) \times 10^{-18}$ g/g	10^{-16} g/g	☺
^{232}Th	$(5.2 \pm 0.8) \times 10^{-17}$ g/g	10^{-16} g/g	☺
^{40}K	$< 2.7 \times 10^{-16}$ g/g	10^{-18} g/g	$\sim 10^{-2}$
^{85}Kr	~ 1 Bq/m^3	~ 1 μBq/m^3	10^{-6}
^{210}Pb	~ 100 Bq/m^3	~ 1 μBq/m^3	10^{-6}

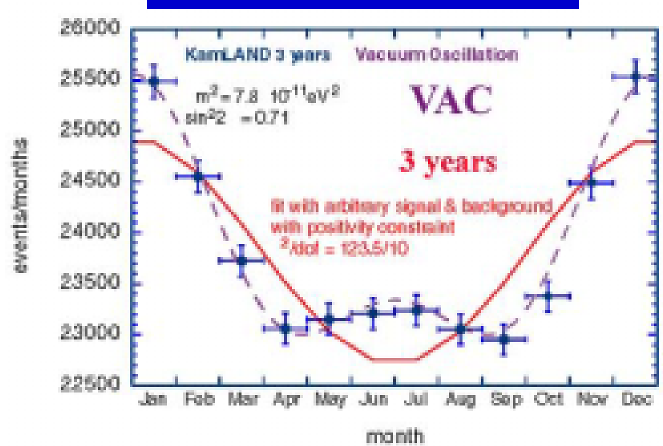
Physics 1 : Reconfirmation of Oscillation Solution



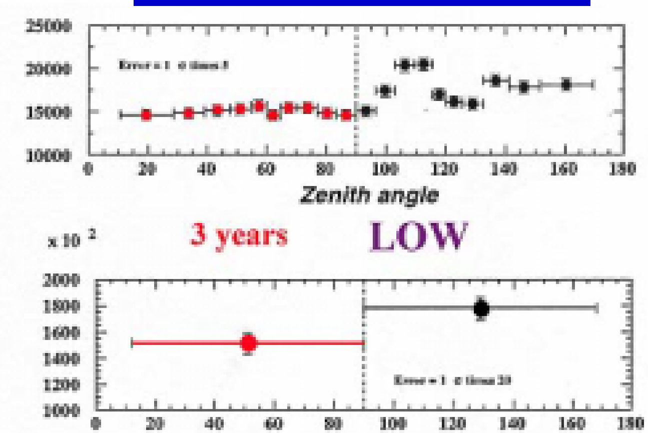
Seasonal Variation



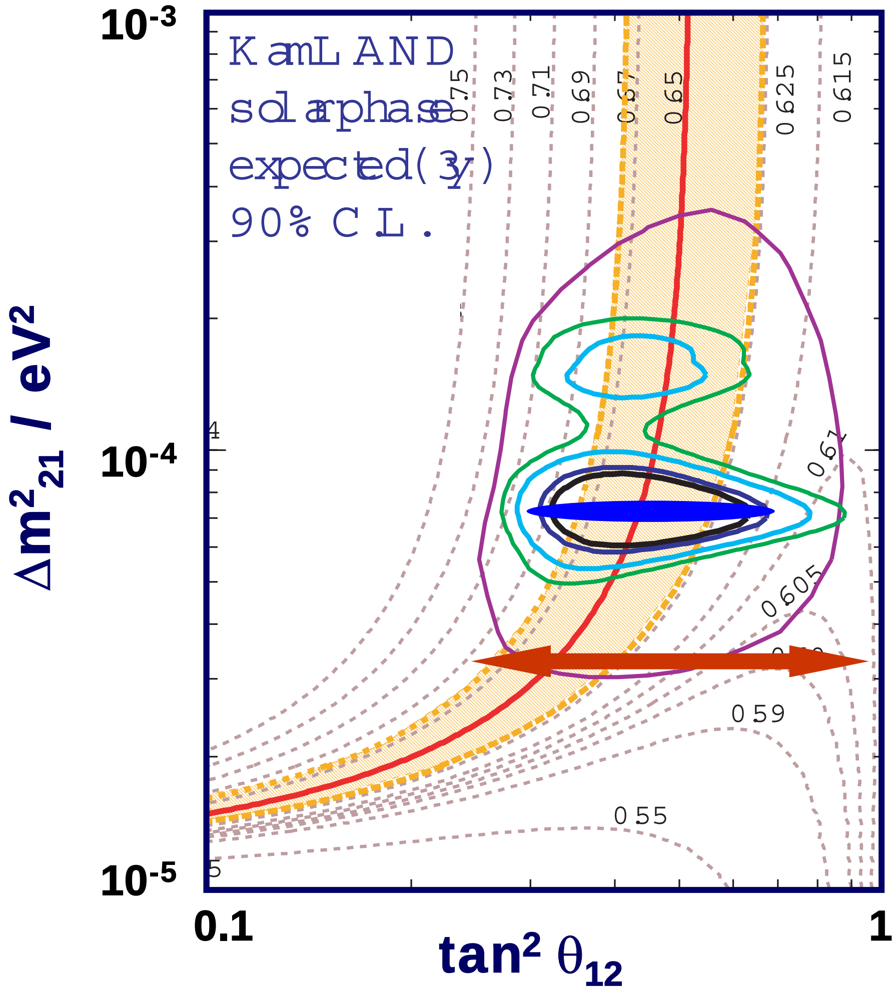
Just So Resonance



Day / Night Variation



Physics 2 : Determination of Θ_{12} ?

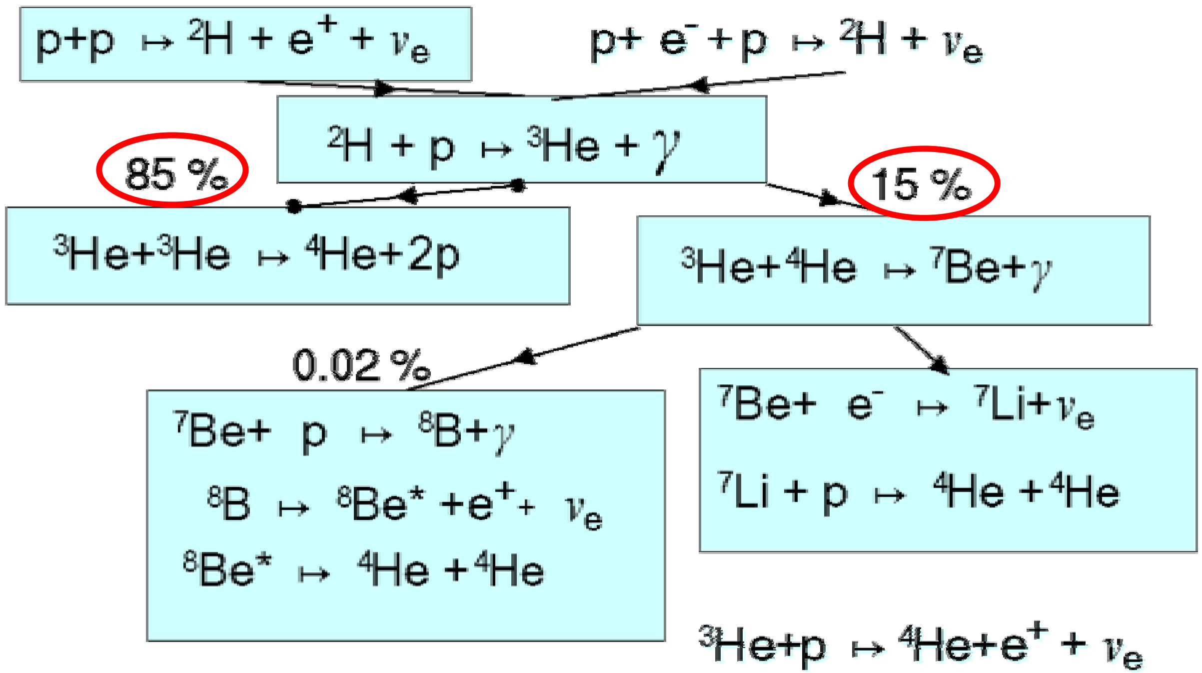


A.Bandyopadhyay et al., hep-ph/0302243 (2003)

KamLAND reactor

flux uncertainties ± 10 %

Physics 3 :
Test of Standard Solar Model



$$\frac{< {}^{3}\mathrm{He} + {}^{4}\mathrm{He} >}{< {}^{3}\mathrm{He} + {}^{3}\mathrm{He} >} = \frac{2\phi({}^{7}\mathrm{Be})}{\phi(pp) - \phi({}^{7}\mathrm{Be})}$$

6. Conclusions

- Reactor neutrino detection
  - strong evidence on disappearance
  - more data for convincing energy deformation
- Geoneutrino detection
  - more data
- Solar neutrino detection
  - R&D: final stage
  - more funding