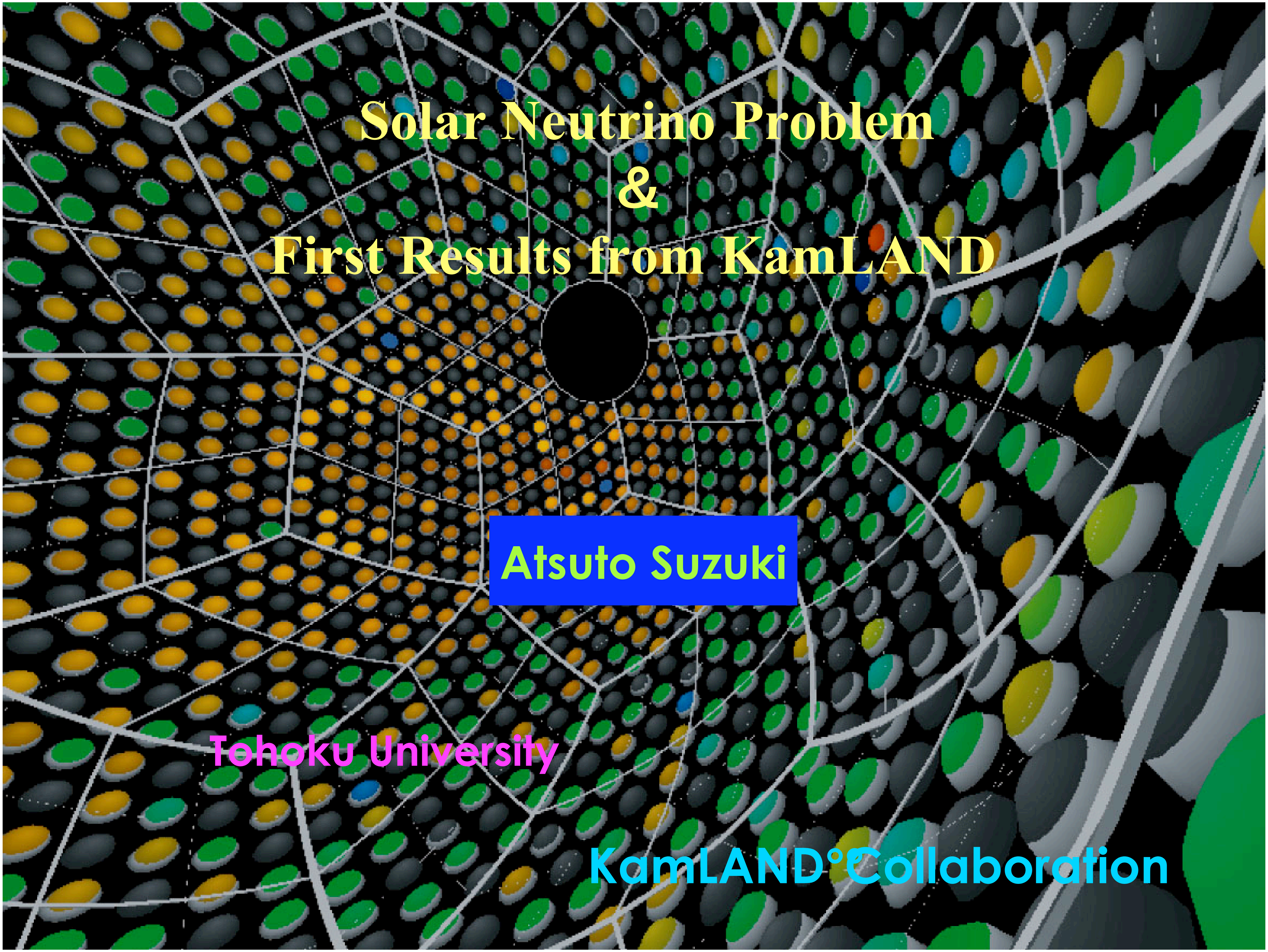
Solar Neutrino Problem
&
First Results from KamLAND

Atsuto Suzuki

Tohoku University

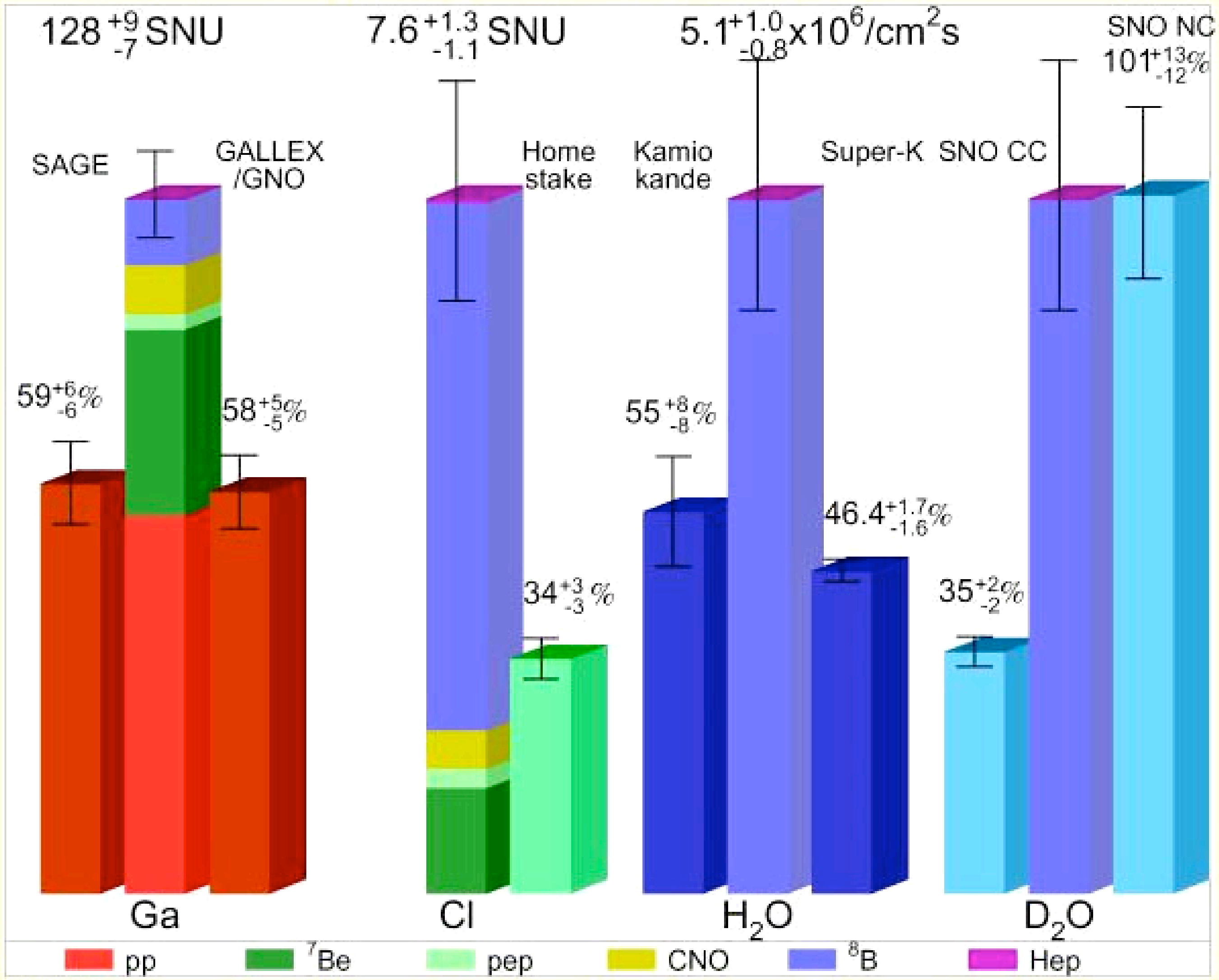
KamLAND Collaboration



Contents

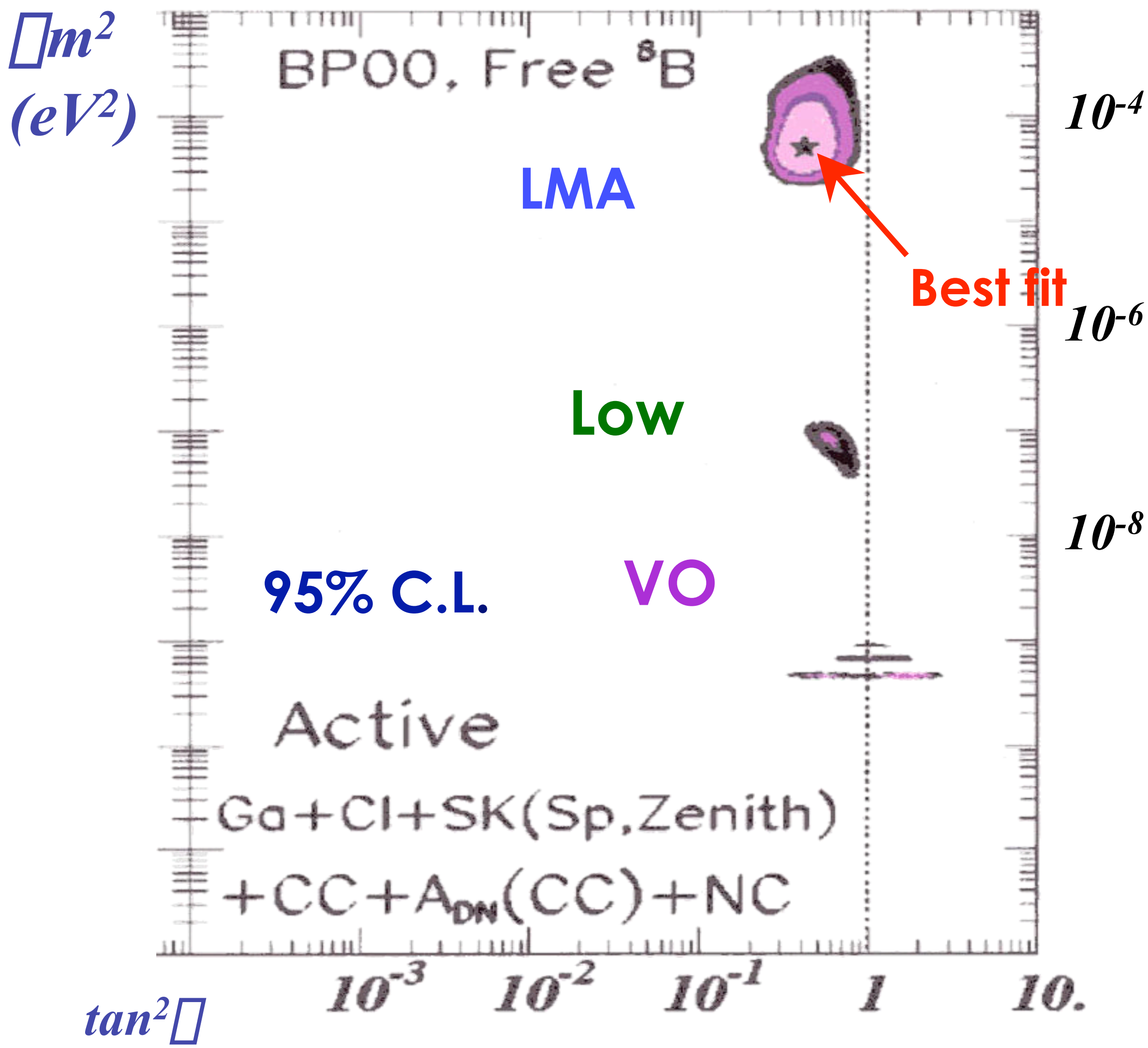
M. Smy, □2002

Solar ν Problem

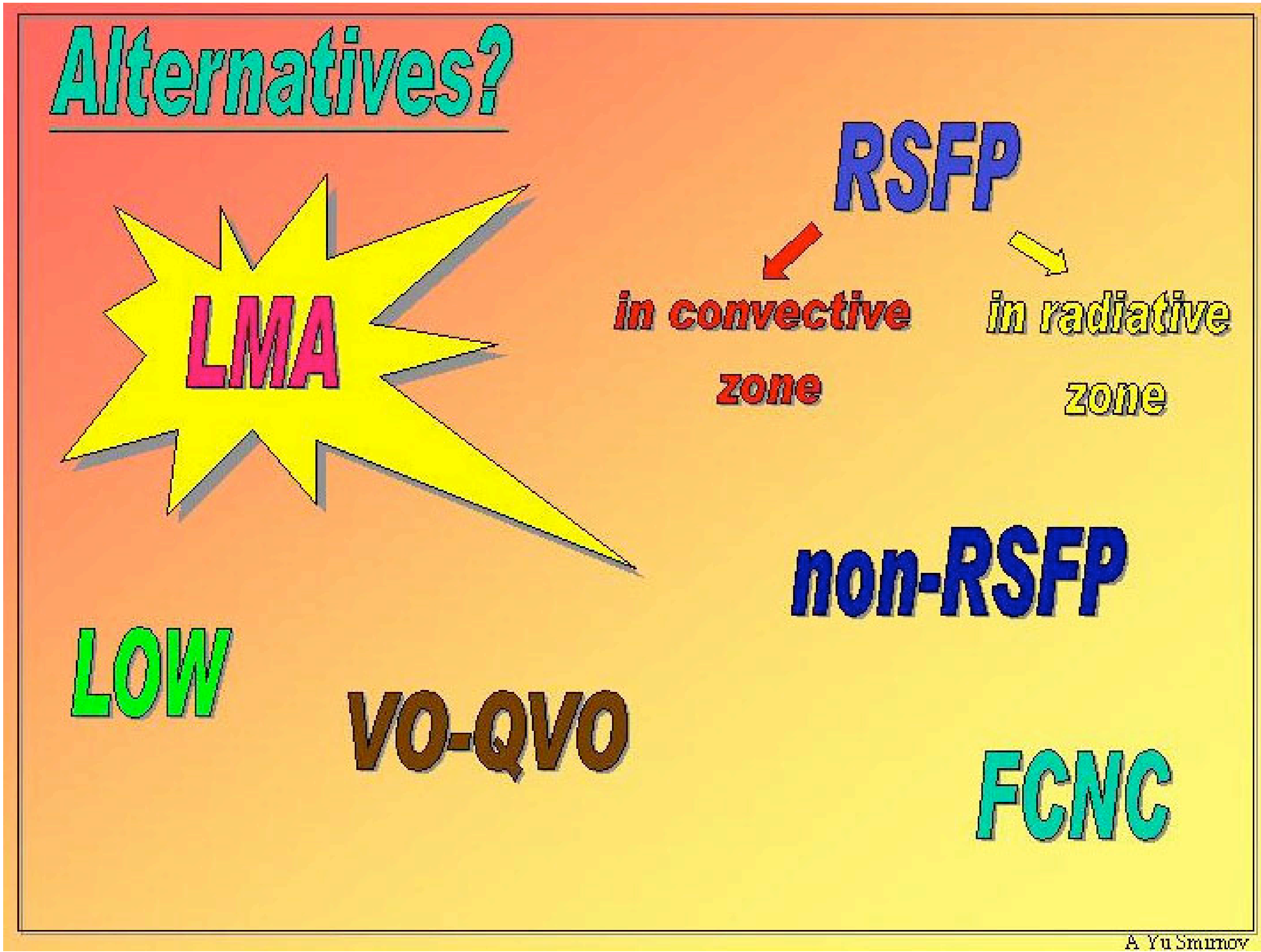


Michael Smy, UC Irvine

$\square_e \rightarrow \square_x$ ***J. Bahcall et al.**, JHEP, 07 (2002)*



A. Smirnov, □ 2002



A. Smirnov, □ 2002

KamLAND Experiment

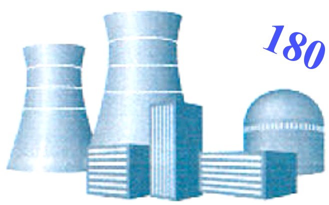
1,000 ton liquid scintillator neutrino detector

1st phase experiment

(E_{th} = 1.8 MeV)

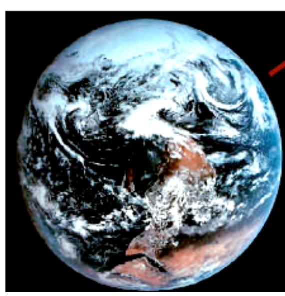
$\bar{\nu}_e + p \rightarrow e^+ + n$

○ **Neutrino Oscillation Search by Reactor Anti-neutrinos**

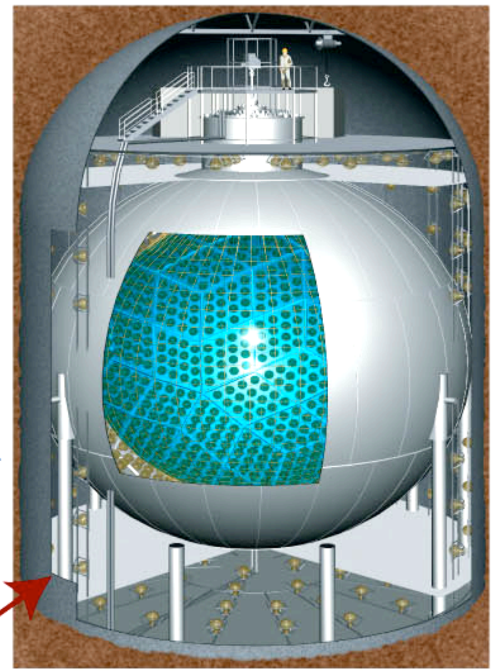


180 km $\bar{\nu}_e$

○ **Terrestrial Anti-neutrino Detection**



$\bar{\nu}_e$



2nd phase experiment

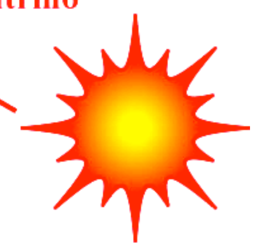
(E_{th} = 200 keV)

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

○ **Solar neutrino Detection**

^{7}Be Neutrino

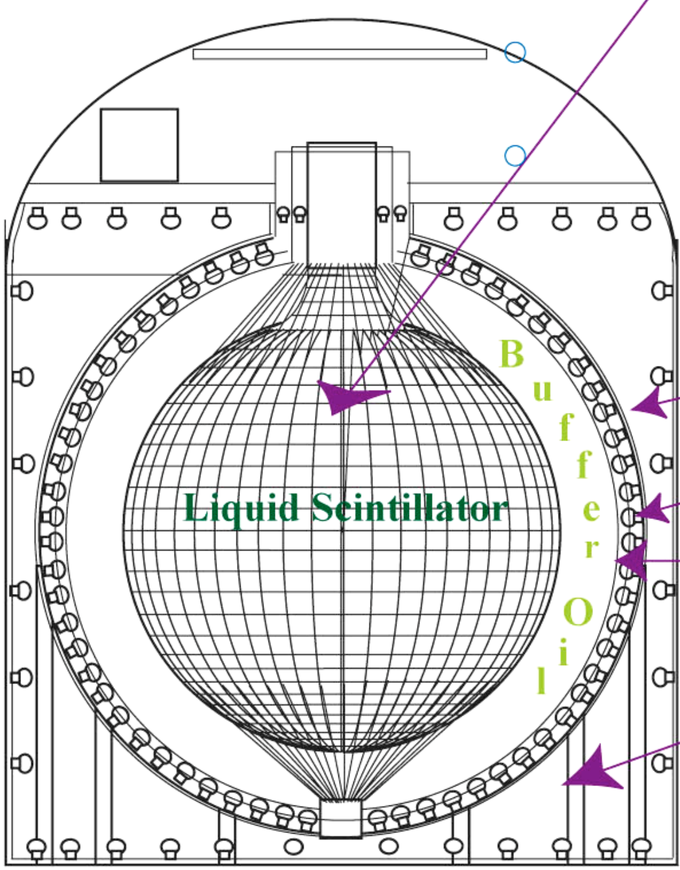
ν_e



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
  (□ = 0.78)
  housed in spherical balloon (13m diameter)
  of transparenet nylon/EVOH composite film (135□m)
  supported by cargo net structure

- 3,000 m^3 Scintillation Light Detector
  - 18m diameter stainless steel tank filled with
    paraffin oil (□□= 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

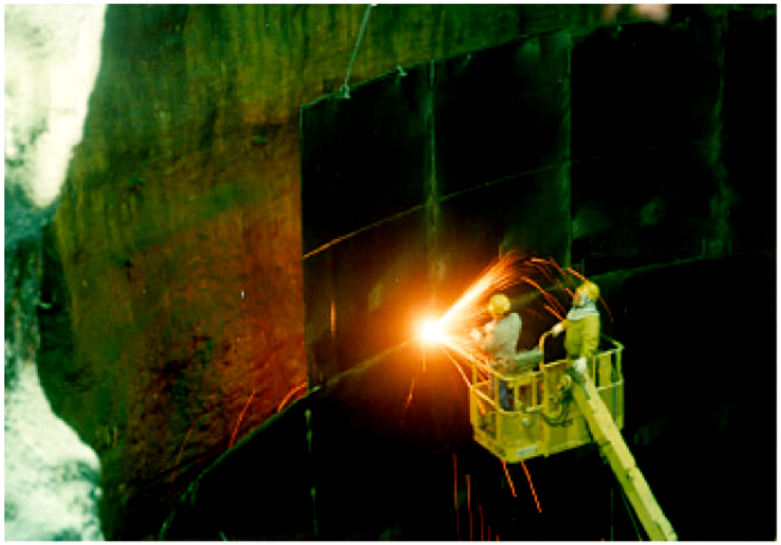
- Water Cherenkov Outer Detector
  225 Kamiokande 20-inch PMT's

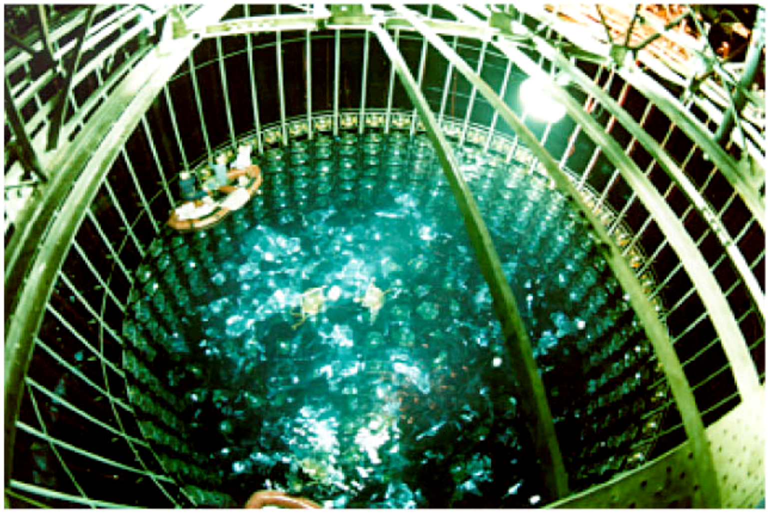
Present analysis ~ 22%

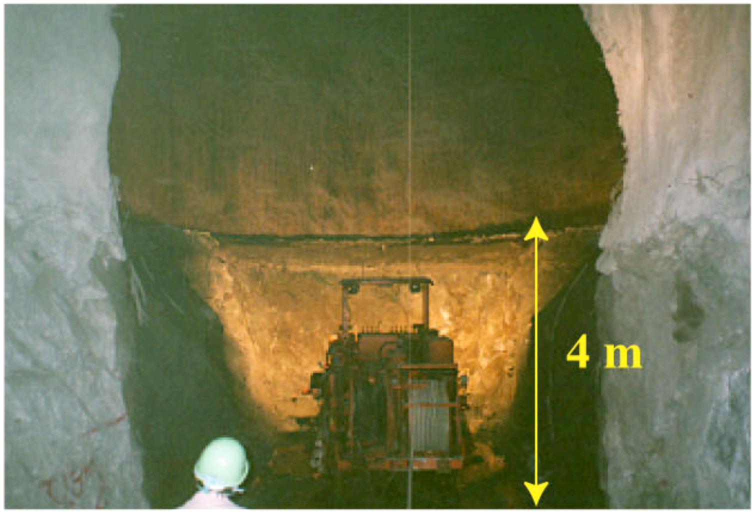
KamLAND

Detector Construction

Kamiokande Dismantling, 1998



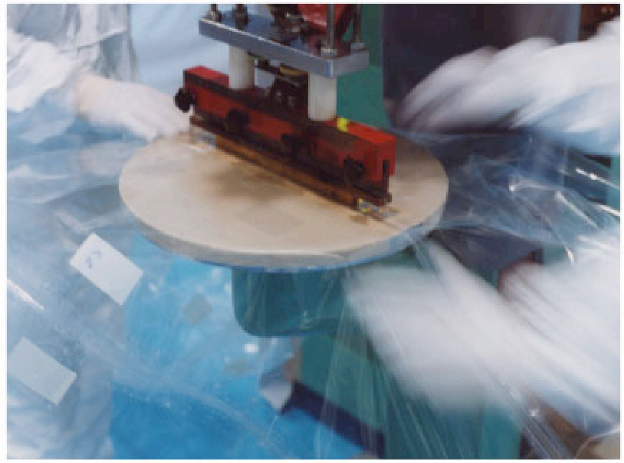




Finished in March, 2000

PMT Installation Finished (Sep. 2000)

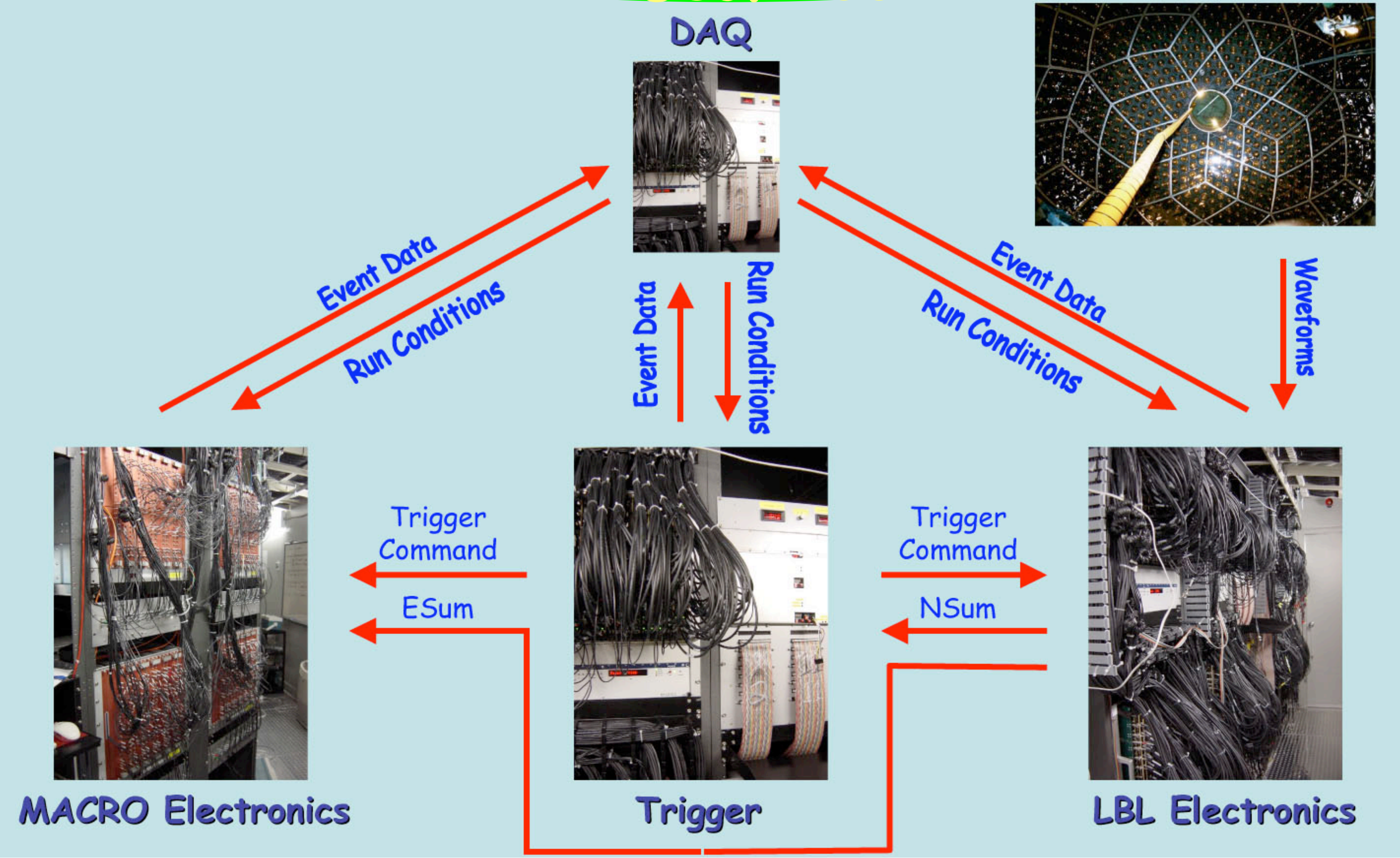
Full Size Balloon Construction
Oct. 2000 ~




March 2001

Oil Filling finished in Sept. 2001

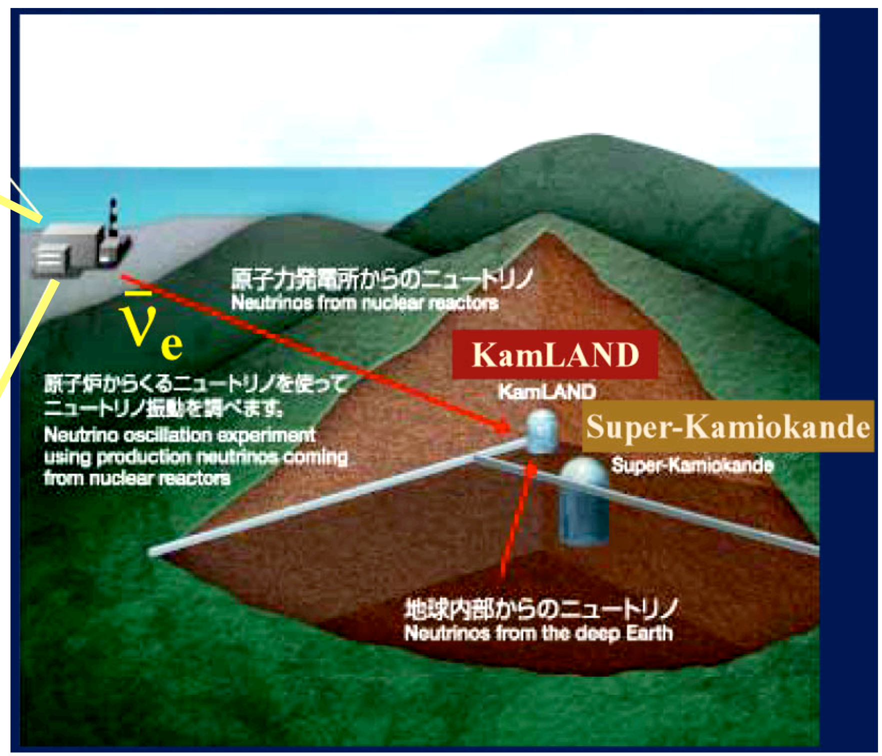
Data-Taking Electronics : Ready ~ Dec. 2001



Kam LAND

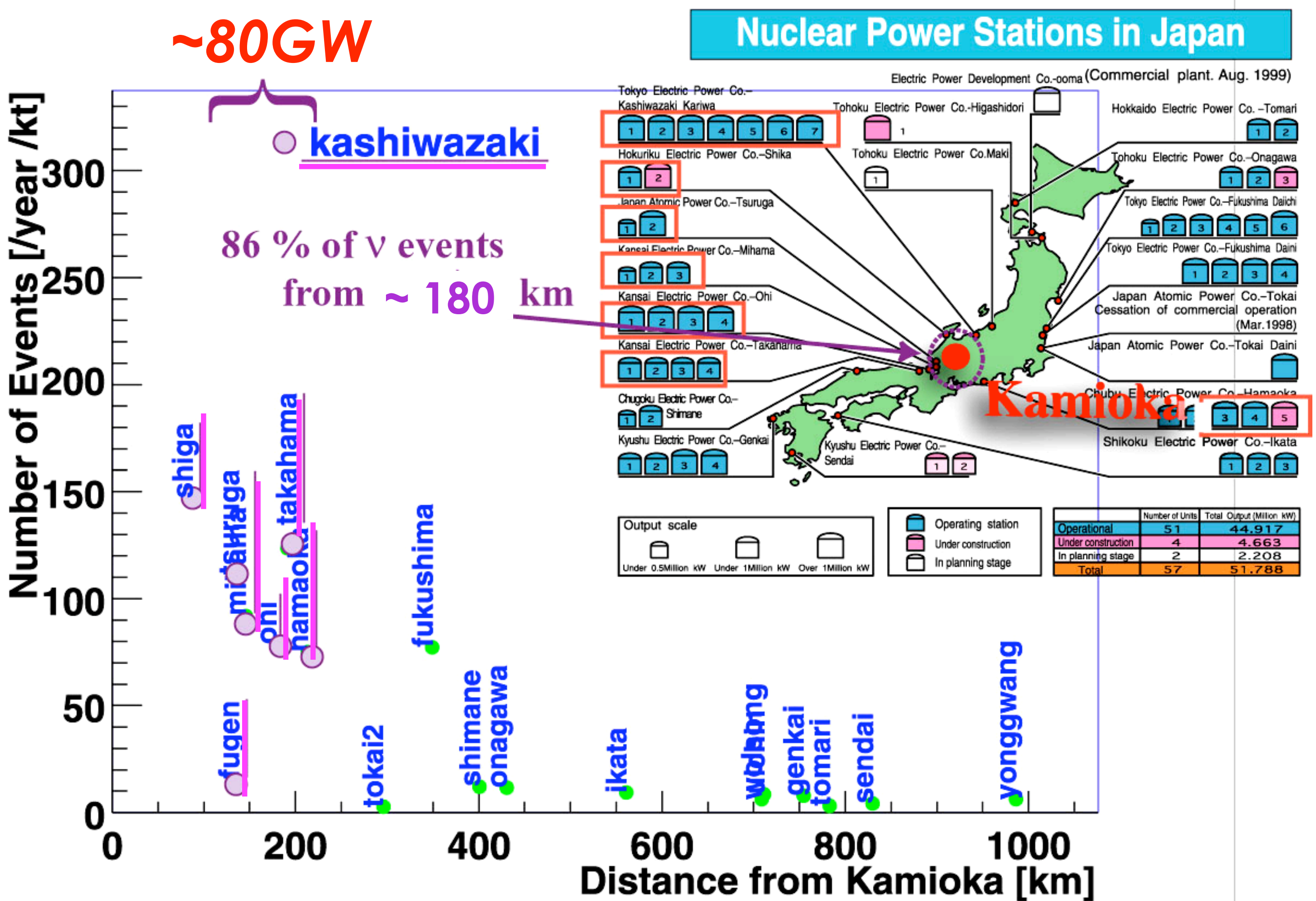
KamLAND Launch Jan. 22, 2002

Reactor Neutrino Oscillation Studies



Event Rate from Power Plant Reactors

20 % of world nuclear power



Investigate Solar Neutrino Anomaly Under Laboratory Conditions

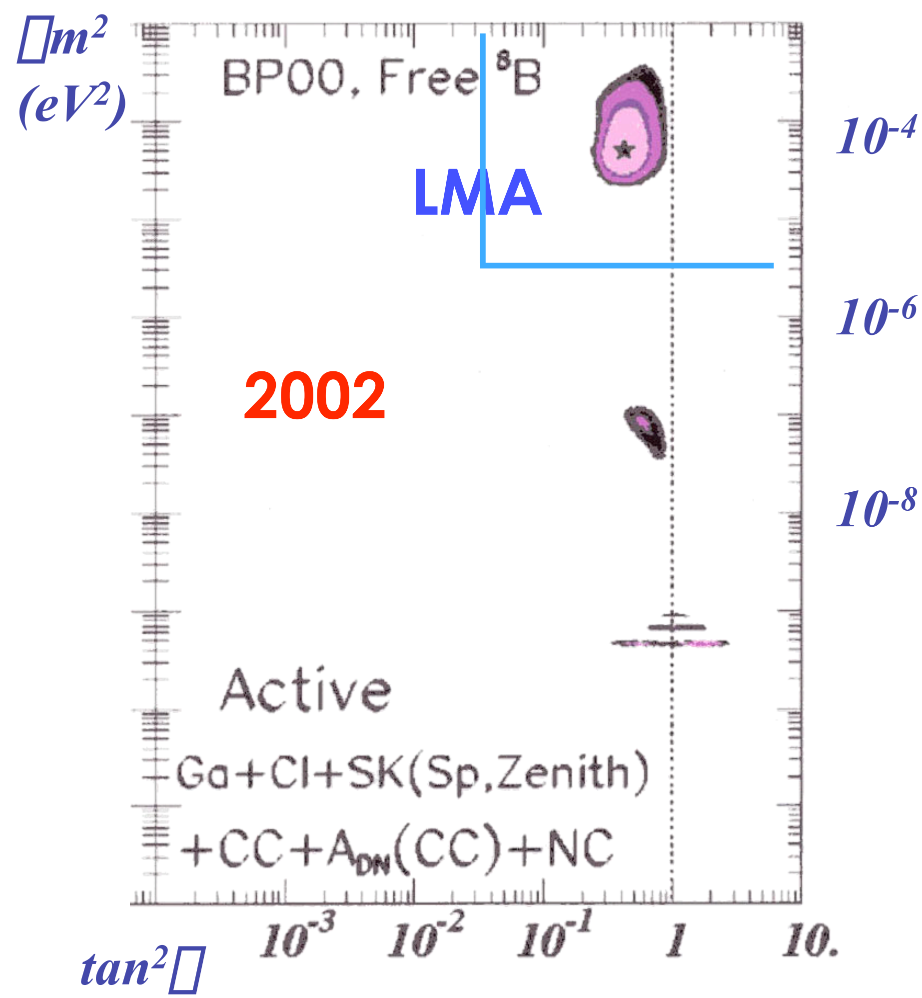
KamLAND :

Thermal power ~ 80GW

<E> ~ 3 MeV

<base line> ~ 180 km

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



ν_e Production : Fission Rate

- **Main Fuel Component :**

  4 main isotopes

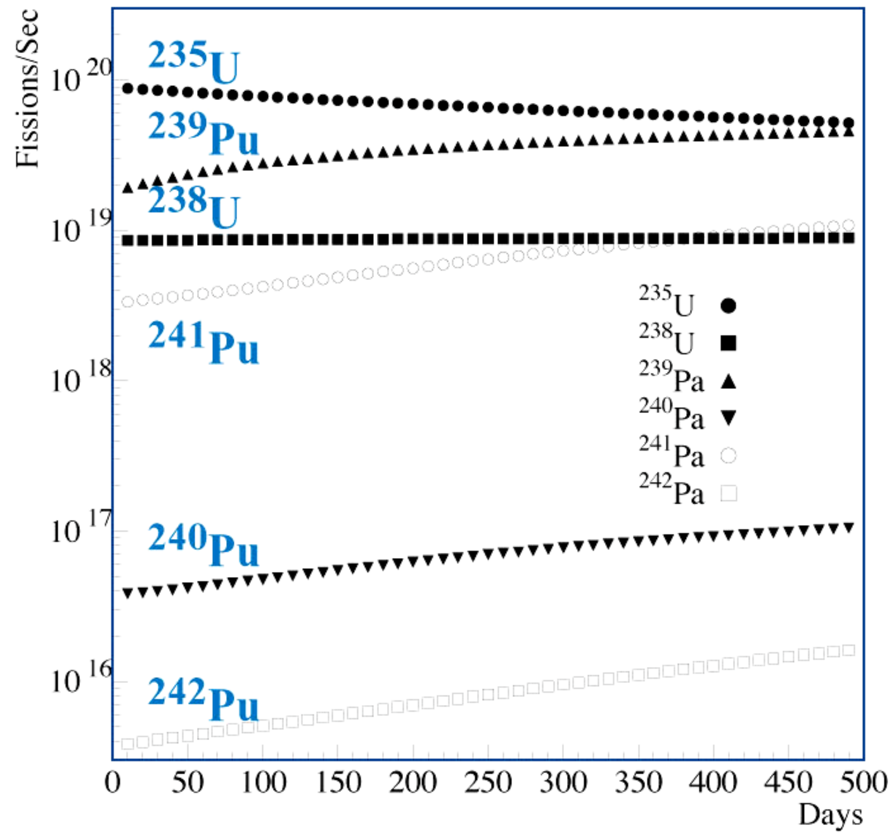
  ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu (99.9%)

  others (^{240}Pu, ^{242}Pu, ,) (< 0.1%)

- **Time evolution of fission rate :**

  Reactor thermal power

  calculation in one of the Palo Verde reactor core →

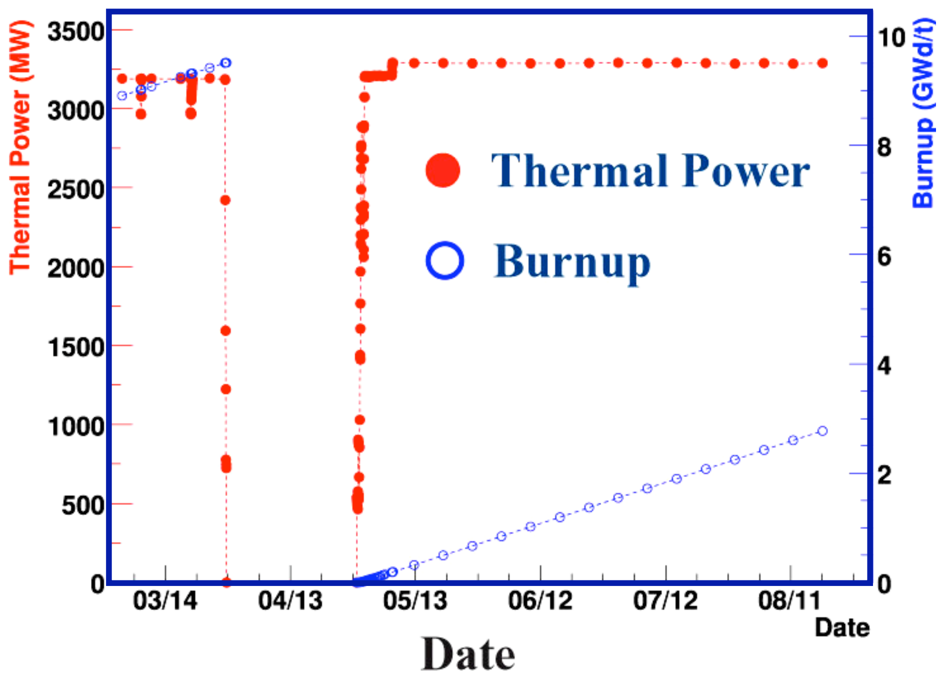


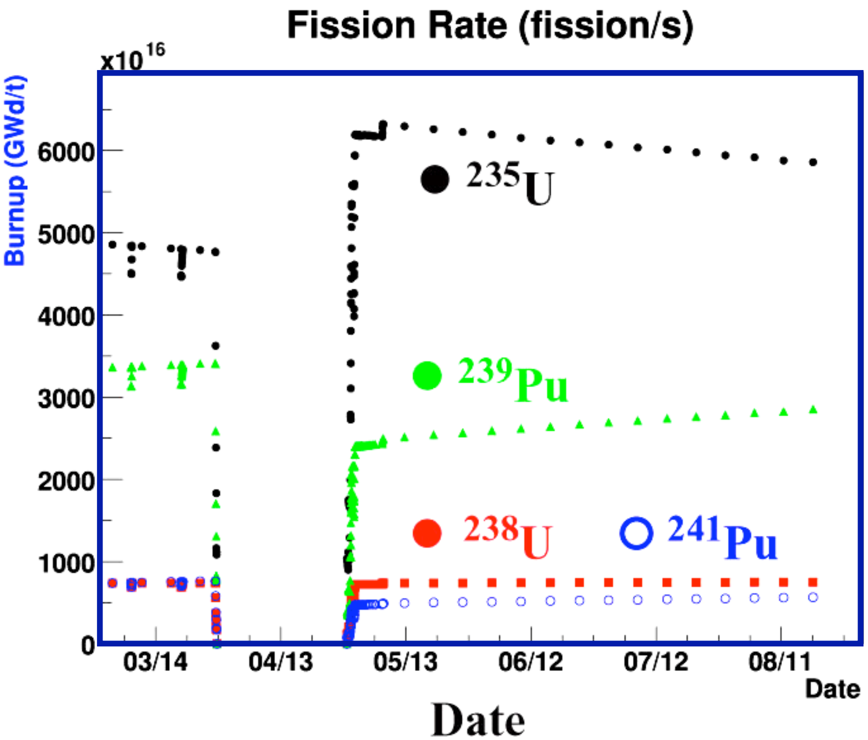
Uncertainty < 1% (neutrino yield)
: fuel-sampling & analyzing for isotopic components

→ **No need for near detector**

Example of Thermal Power Data & Fission Rate Calculation

One of Japanese Reactors





Reactor □$_e$ Energy Spectrum

- $\overline{\nu}_e$ associated with ^{235}U, ^{239}Pu and ^{241}Pu

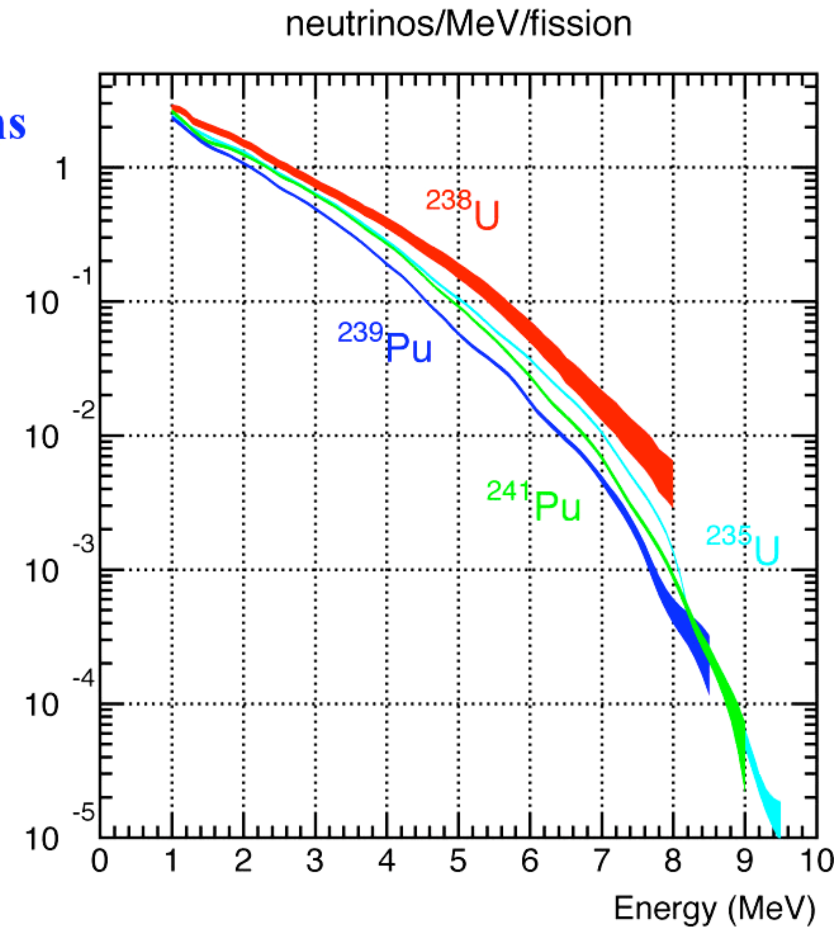
  measured β – spectra
  from thermal neutron fissions

  superposition of 30 hypothetical β-decay branches

  conversion $E_e \longrightarrow E_\nu$

- $\overline{\nu}_e$ associated with ^{238}U

  calculation based on
  744 unstable fission products

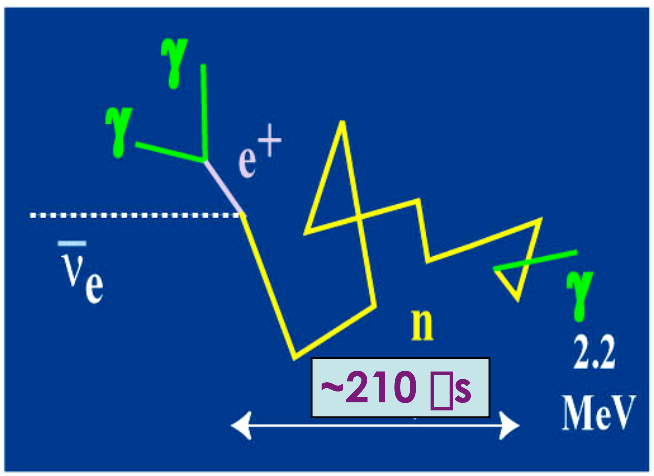


Reactor □e Detection in Liquid Scintillator

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**

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

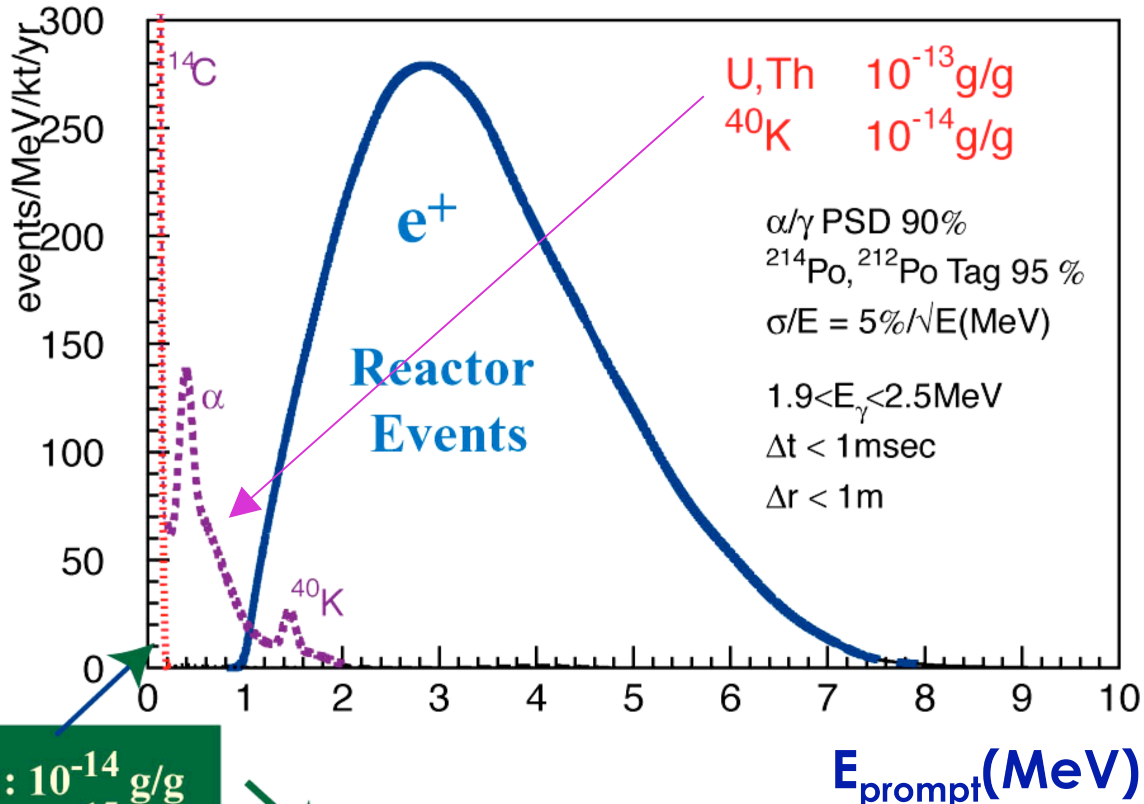
  $$\Delta = M_n - M_p$$

- **delayed part :** γ **(2.2 MeV)**

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

KamLAND e^+ Prompt Energy Spectrum

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$
$$n + p \longrightarrow d + \gamma$$



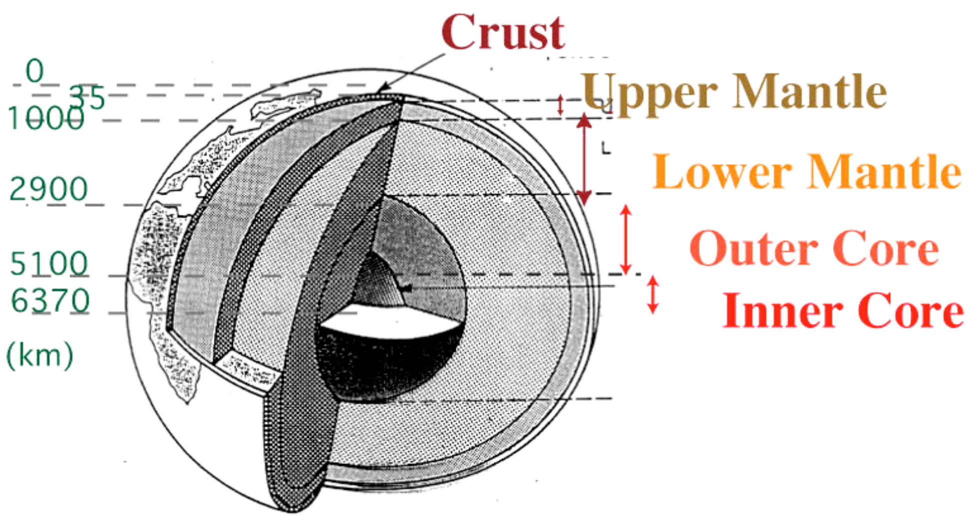
U, Th : 10^{-14} g/g
^{40}K : 10^{-15} g/g

Need radioactively ultra pure LS

Geoneutrinos

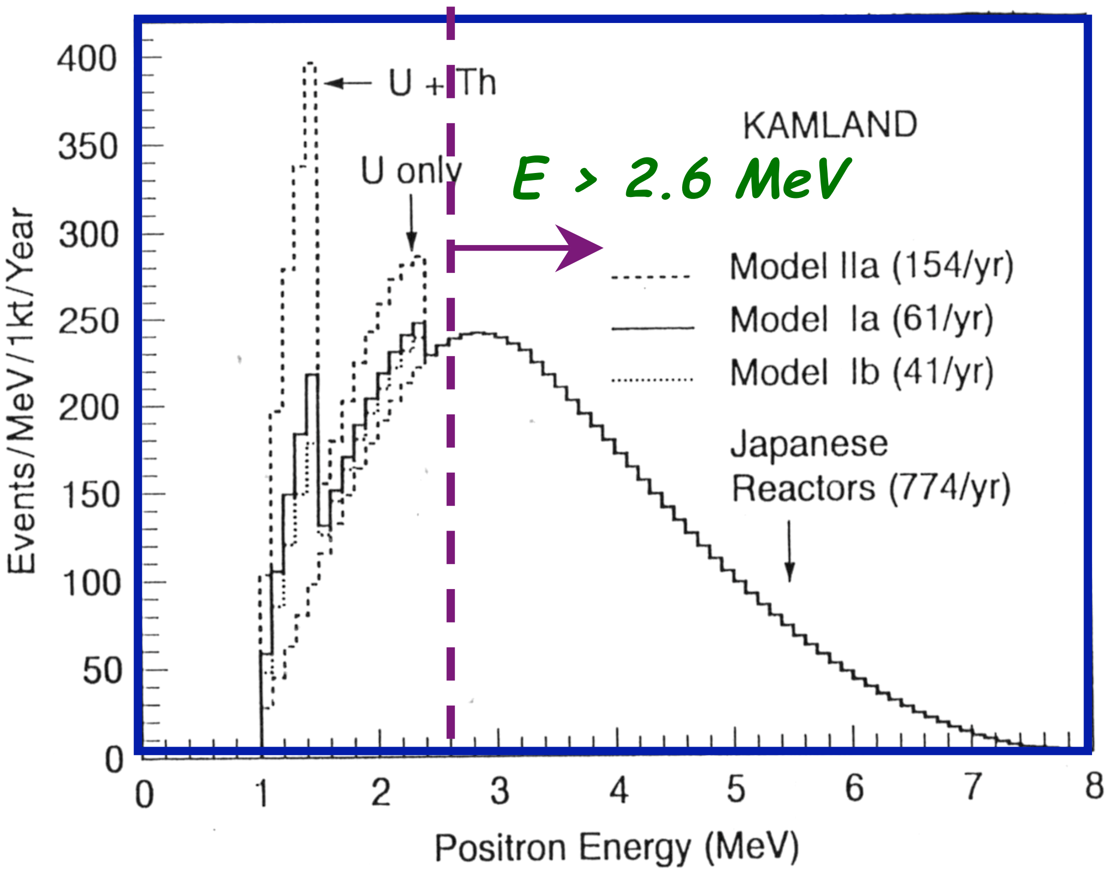
Earth is Antineutrino Star

- ◎ Radiogenic Heat (40 - 60% of 40 TW) from U / Th (Crust, Mantle) Decays
- ◎ Basic Factor in Interior Dynamics and History of the Present Earth

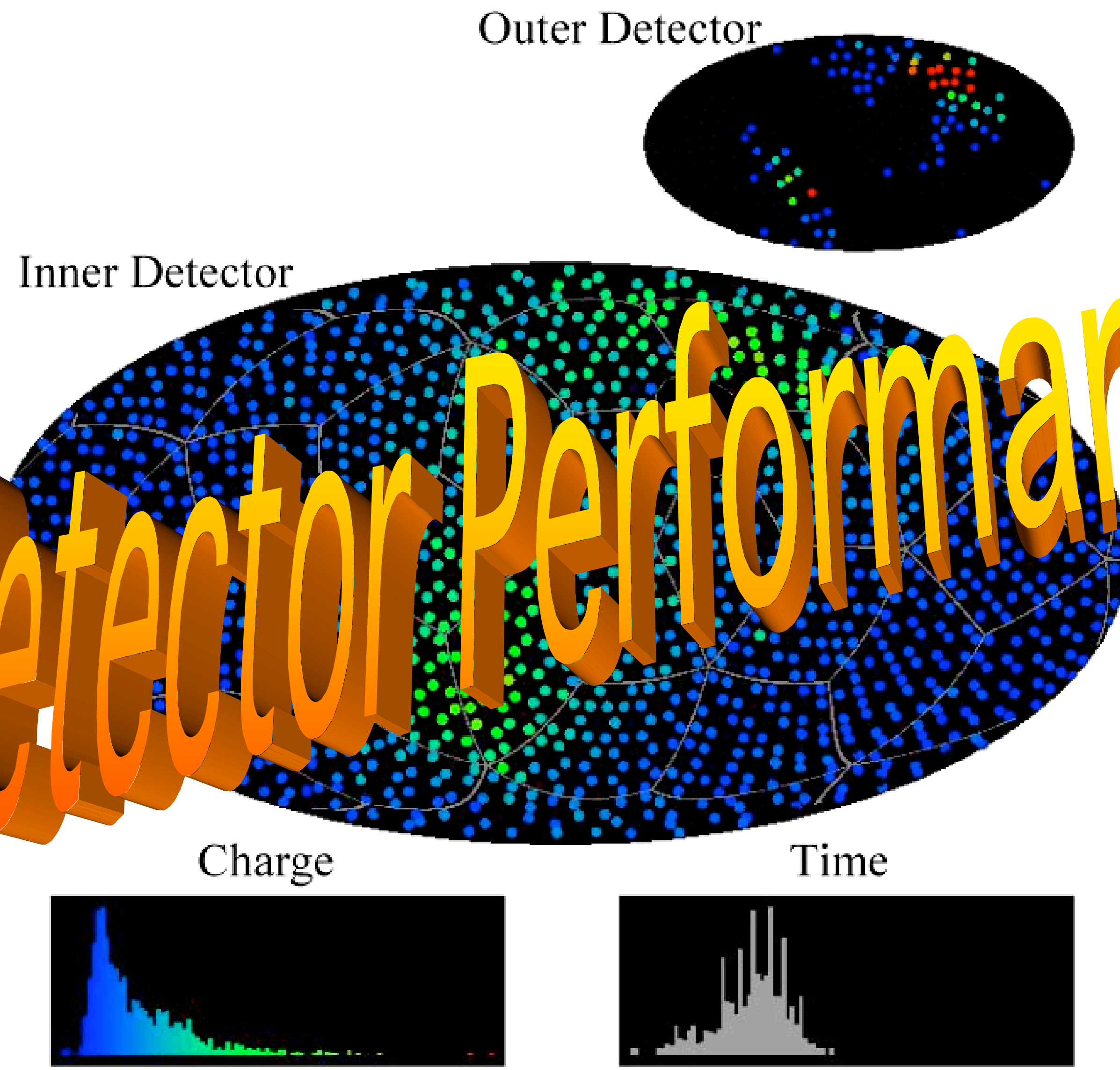


Geoneutrino Energy Spectra

Raghavan, Schoenert, Enomoto, Suekane, Shirai, A. S,
PRL 80 (1998)



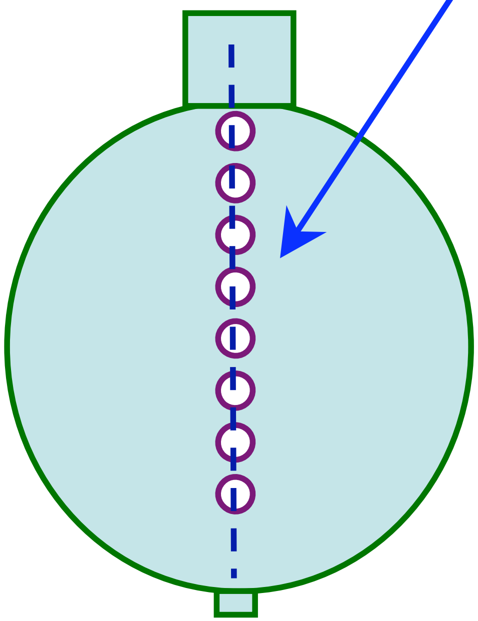
Detector Performance

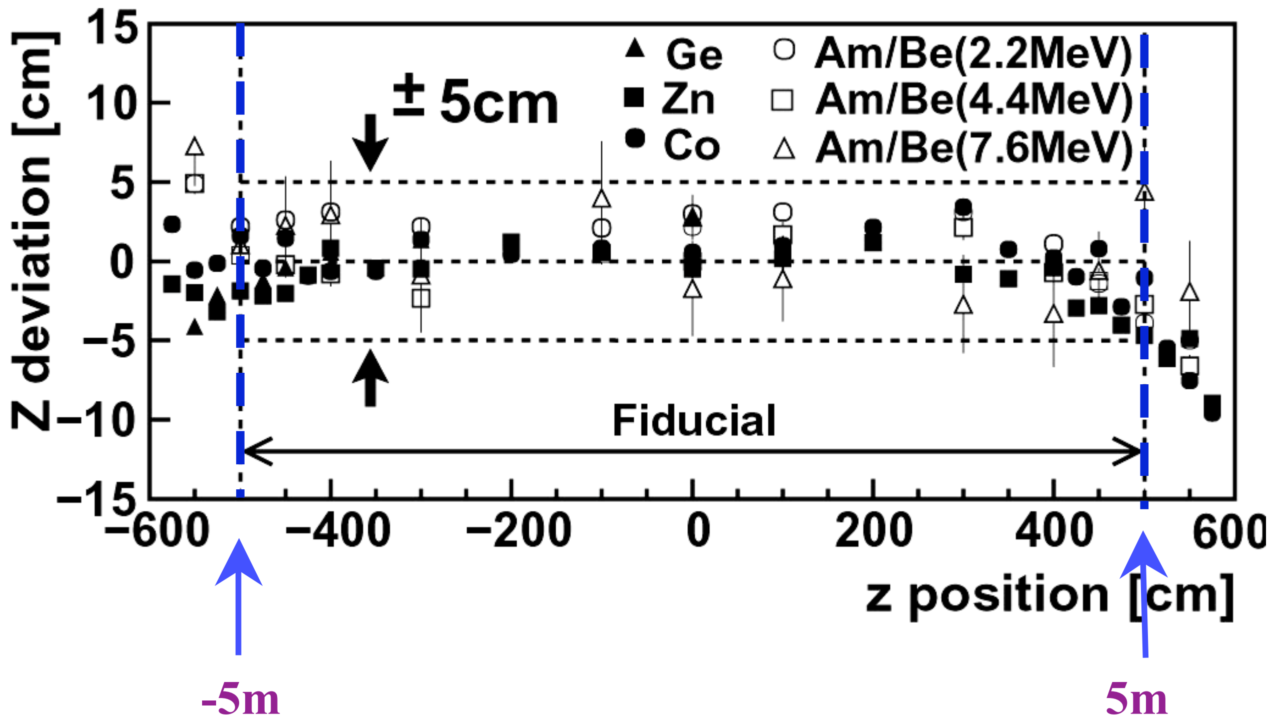


Position Reconstruction Uncertainty

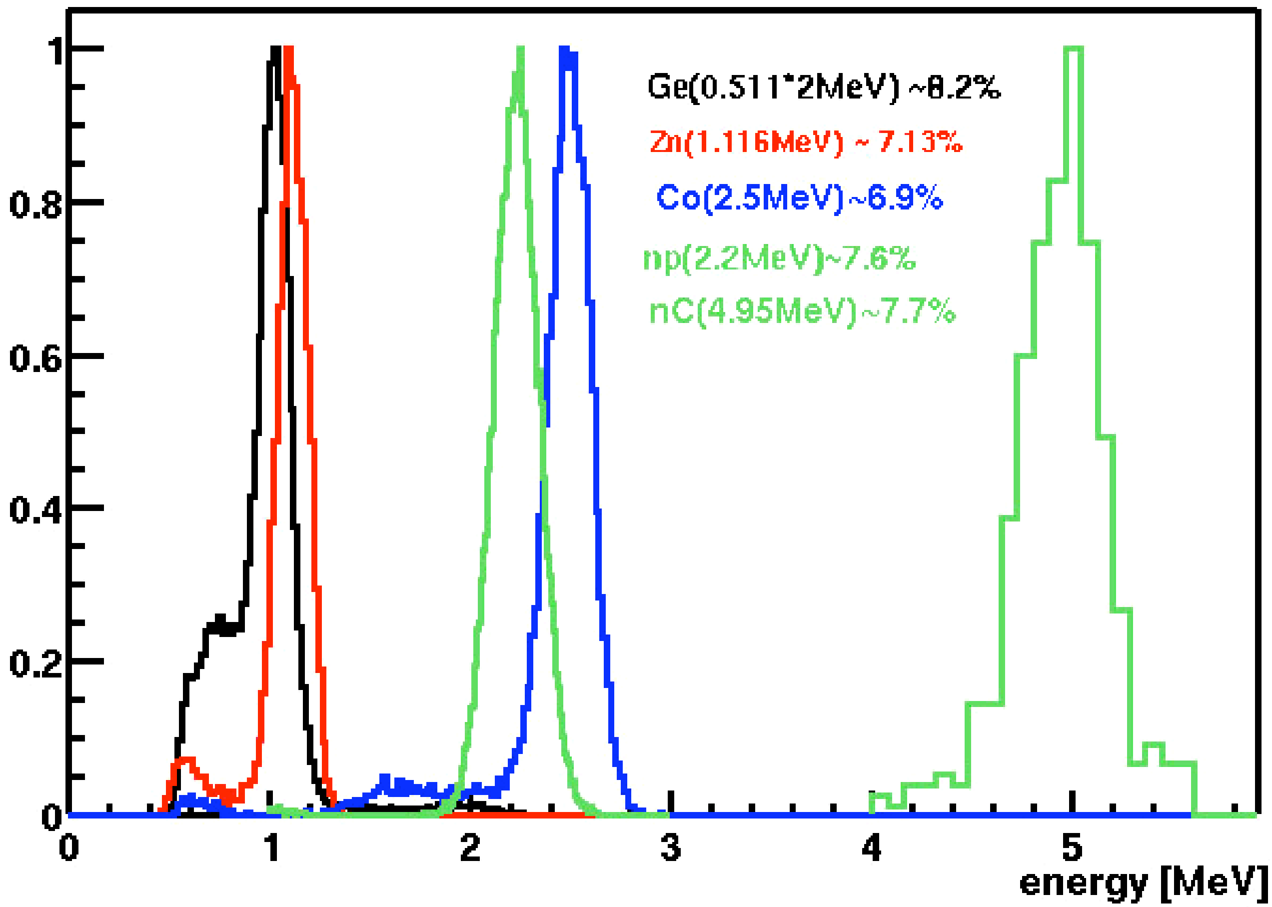
^{68}Ge : 1.012 MeV (□+ □) ^{65}Zn : 1.116 MeV (□)

^{60}Co : 2.506 MeV (□+ □) AmBe : 2.20 , 4.40, 7.6 MeV (□)





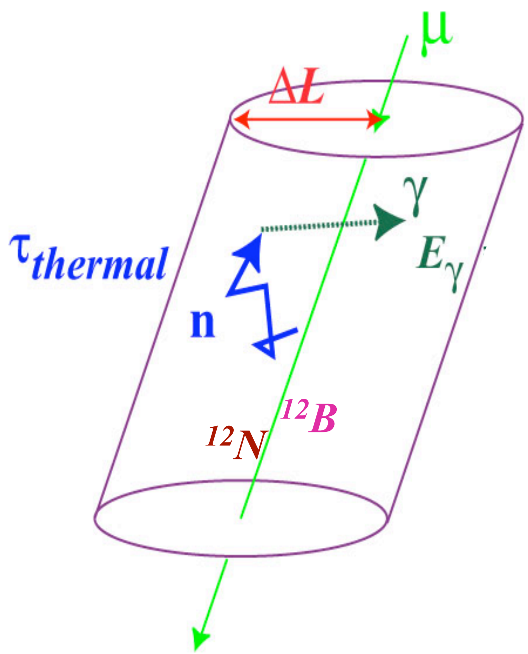
Energy Determination & Resolution

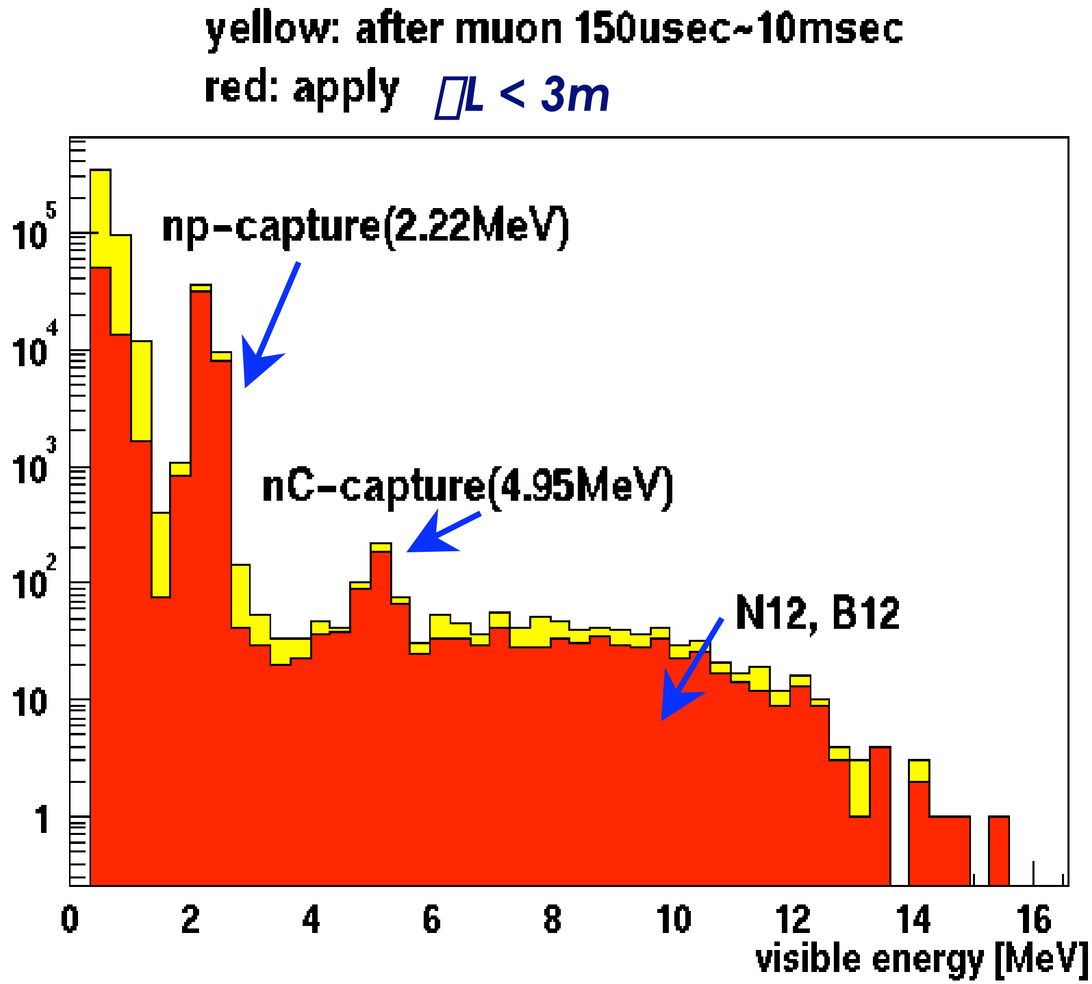


□E_{syst} = 1.91% at 2.6 MeV → 2.13 % for □$_e$

□E/E ~ 7.5% /√E , Light Yield ~ 300p.e./MeV

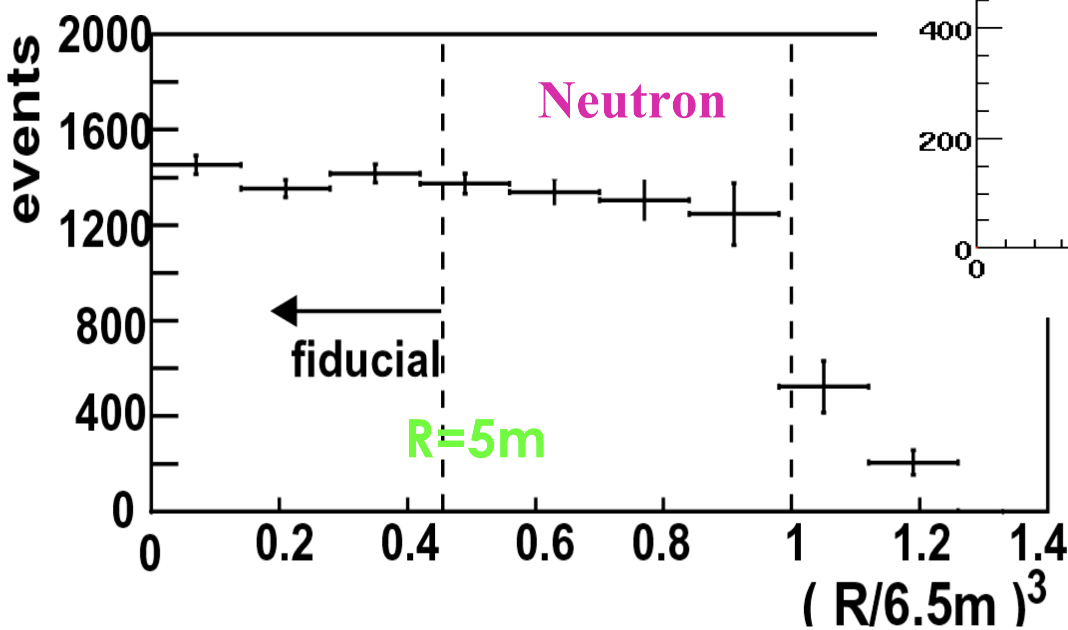
- Induced Neutrons & Spallation-$^{12}B/^{12}N$

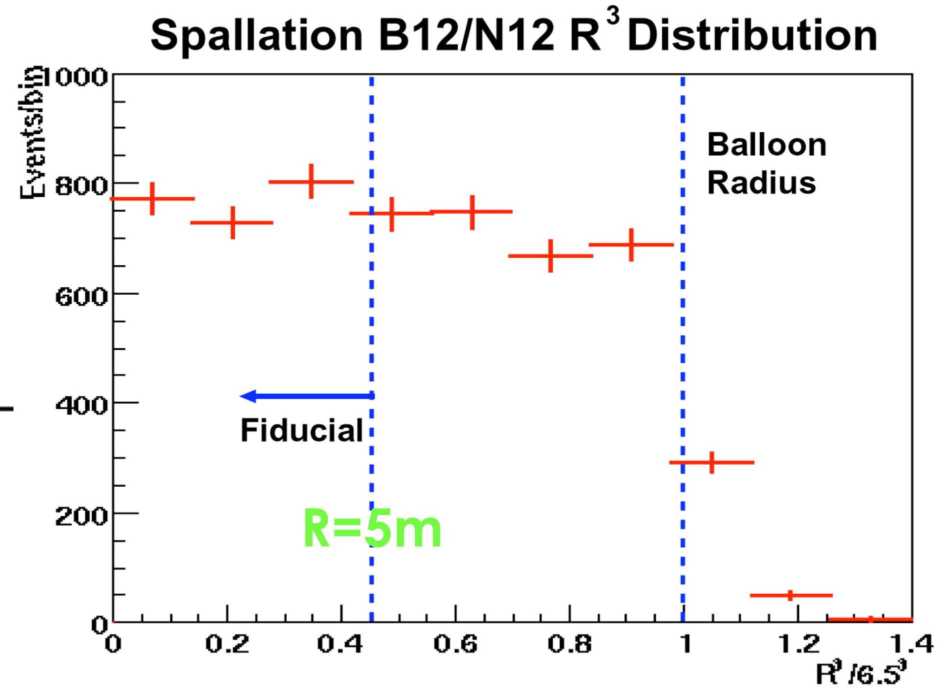




R^3 Vertex Distributions of Neutrons & $^{12}B/^{12}N$

$\Delta V_{fid}/V_{fid}$ = 4.6 %





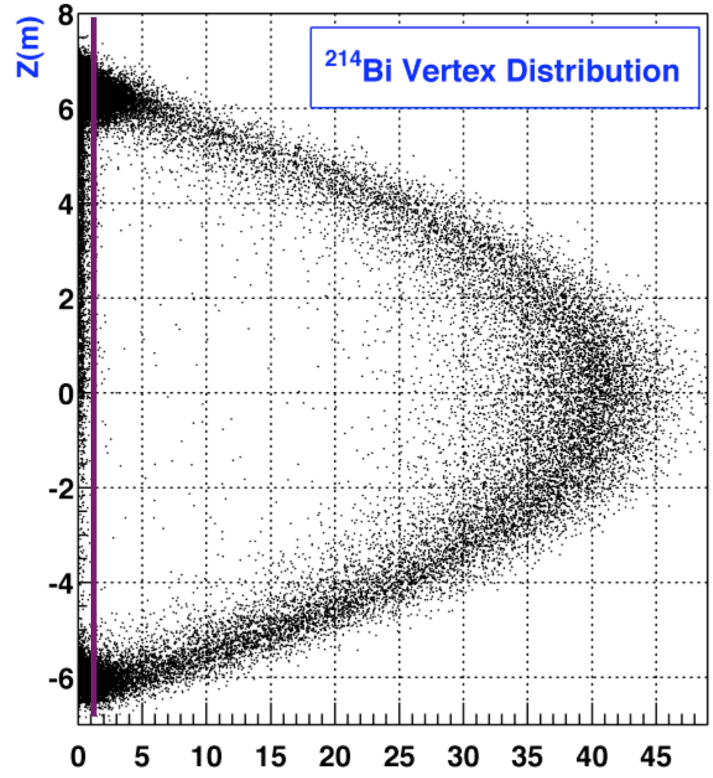
Radioactivity inside Liquid Scintillator

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

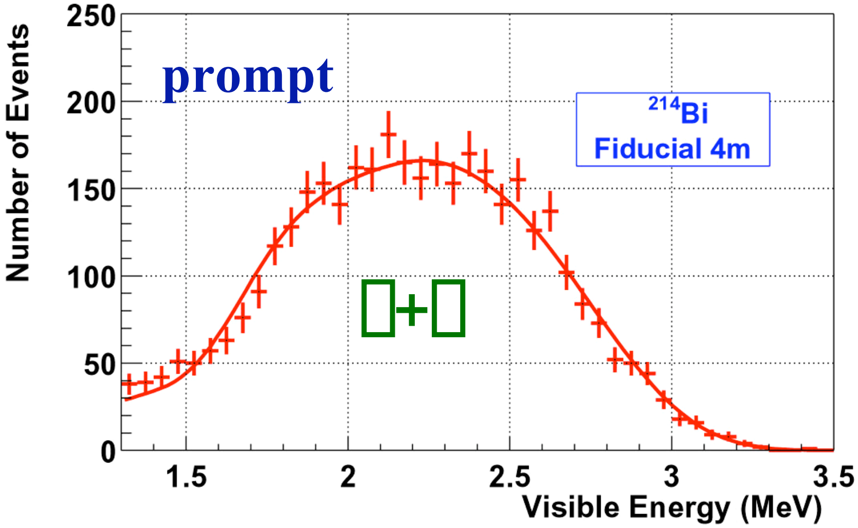
$E = 3.27$ MeV, $\tau = 28.7$ min. $E = 7.69$ MeV, $\tau = 237\ \mu s$

event selection

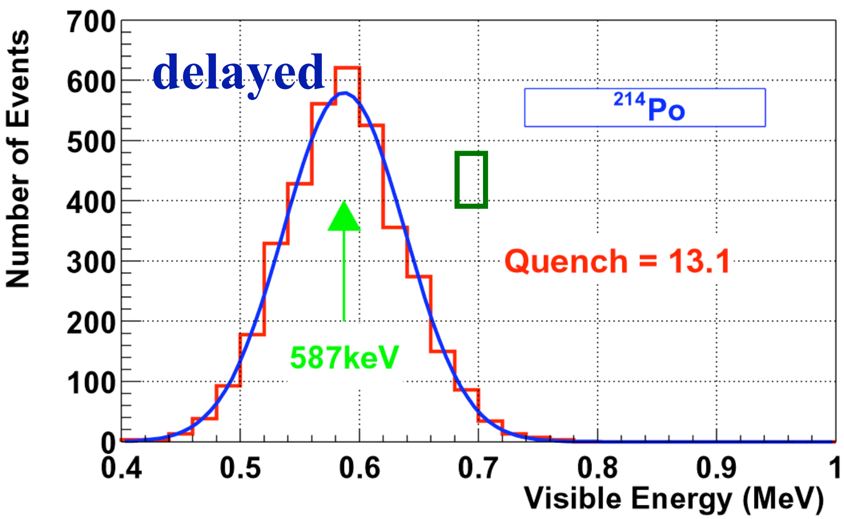
- $\Delta R < 100$ cm
- $5\ \mu s < \Delta t < 1000\ \mu s$
- $E_{prompt} > 1.3$ MeV
- $0.3 < E_{delayed} < 1$ MeV

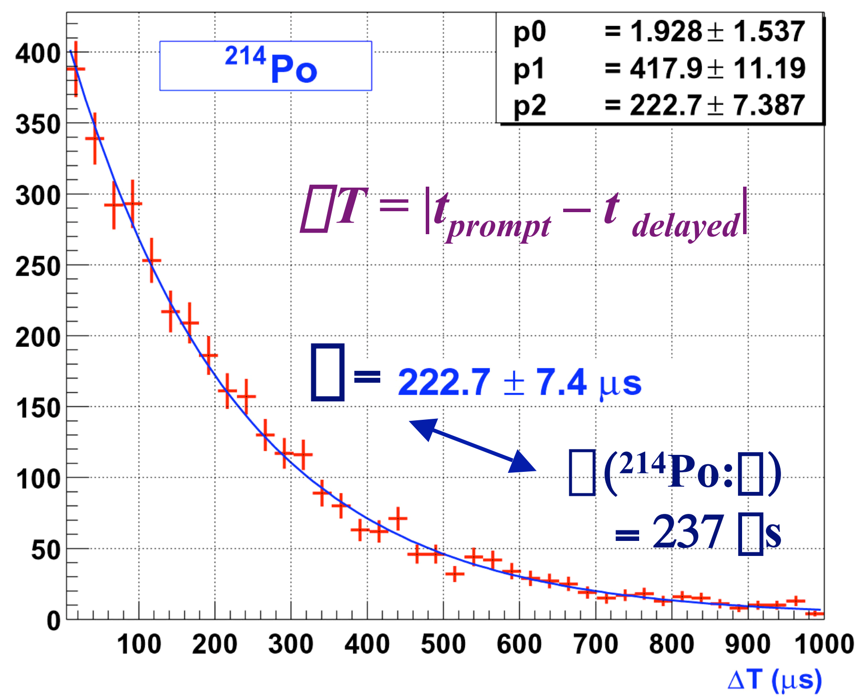


^{214}Bi – ^{214}Po – ^{210}Pb Signal



^{238}U = (3.5±0.5)×10^{-18} g/g





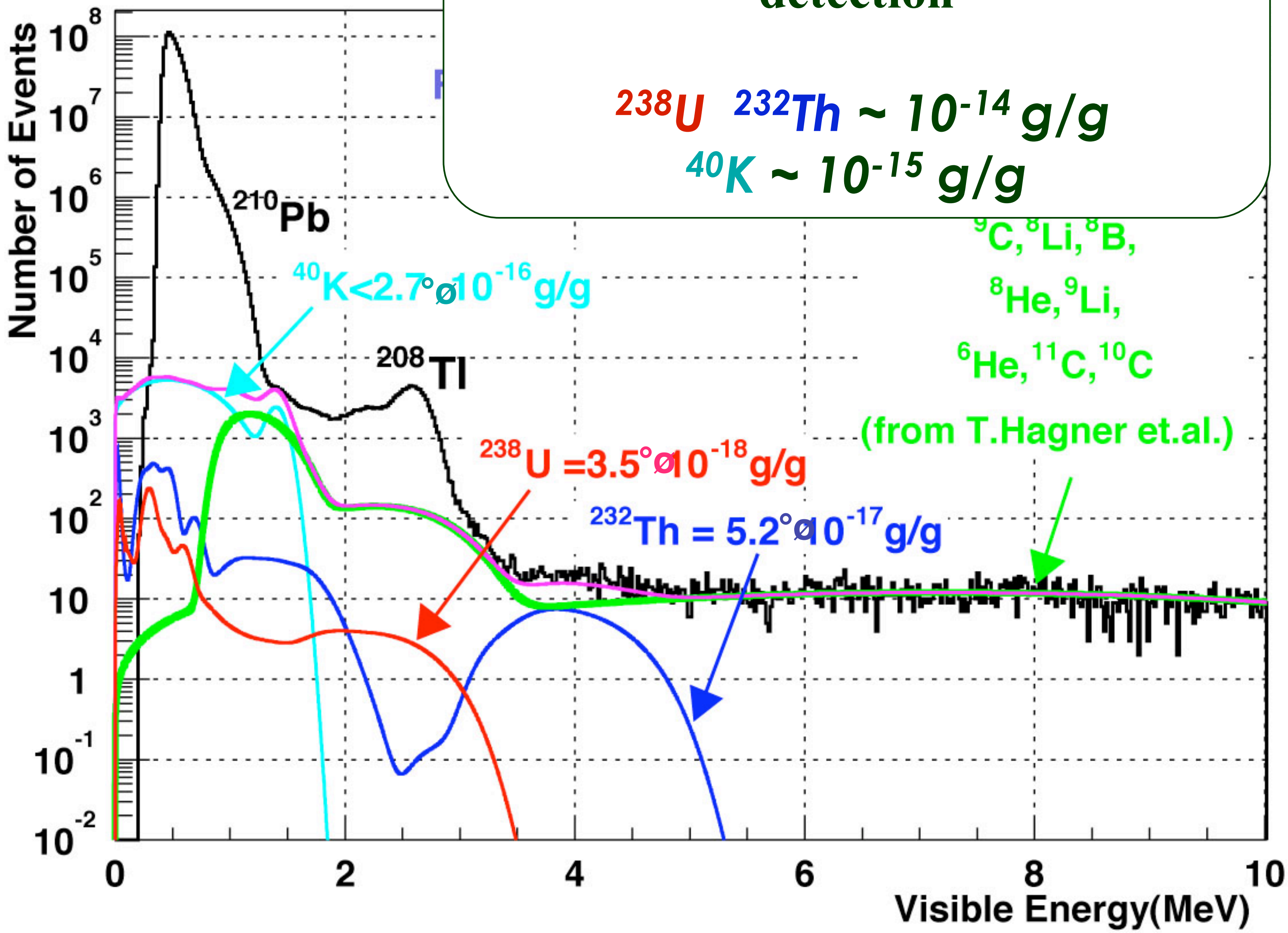
$^{212}Bi - ^{212}Po$ Sequential Decay

^{232}Th : $(5.2 \pm 0.8) \times 10^{-17}$ g/g

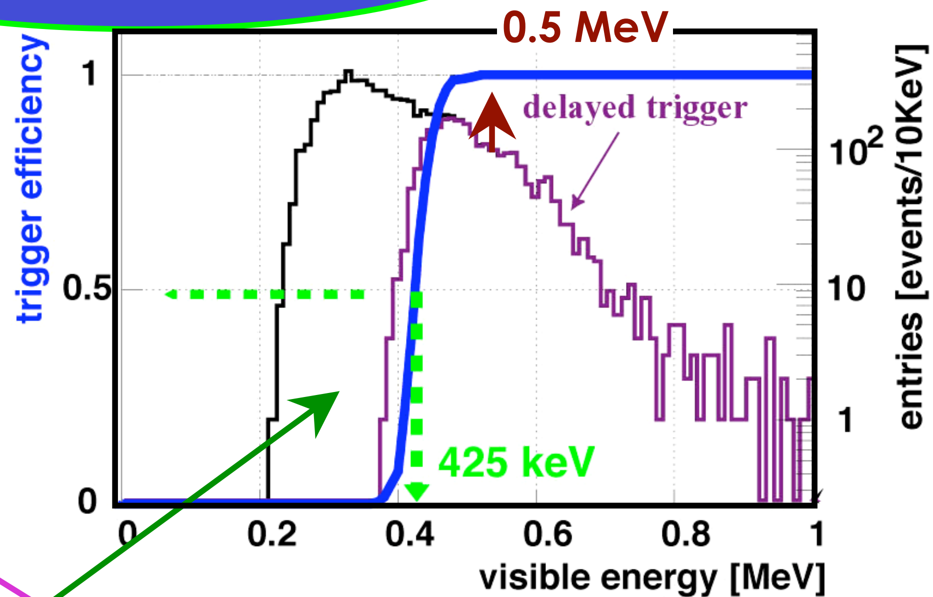
Requirements for reactor $\bar{\nu}_e$ detection

^{238}U ^{232}Th ~ 10^{-14} g/g

^{40}K ~ 10^{-15} g/g



Trigger Efficiency



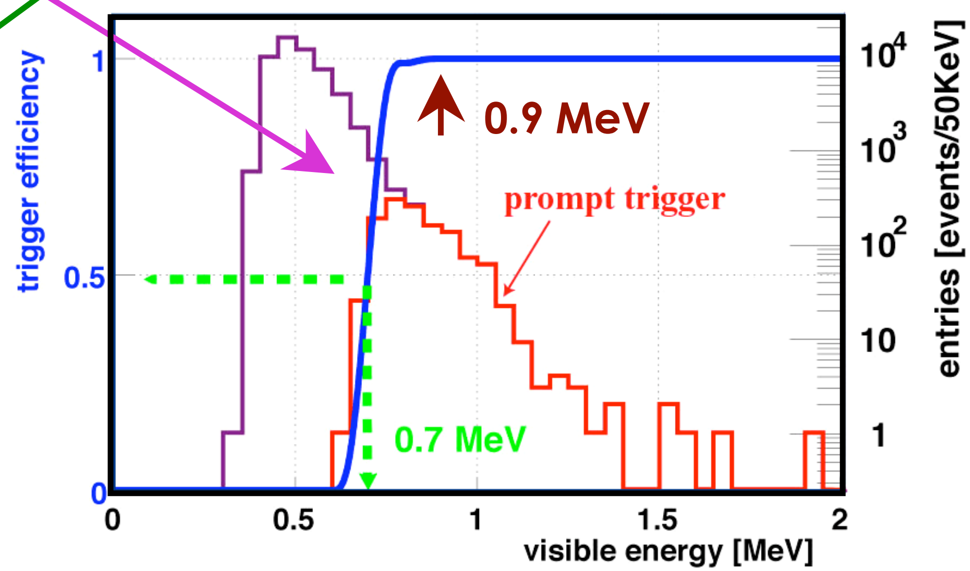
KamLAND Trigger Scheme

prompt trigger:
200 PMT hits (0.7 MeV)

delayed trigger:
120 hits for 1 msec. after primary trigger

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

$+ p \longrightarrow d + \gamma$



Estimated Systematic Uncertainties

E > 2.6 MeV

	%	
Total LS mass	2.13	4. 60 (Total LS mass + Fiducial mass ratio)
Fiducial mass ratio	4.06	
Energy threshold	2.13	
Tagging efficiency	2.06	
Live time	0.07	
Reactor power	2.05	
Fuel composition	1.00	
Time lag	0.28	
ν_e spectra	2.48	
Cross section	0.2	
Total error	**6.42 %**	

Analysis Results

$\bar{\nu}_e$ Event Selection

Data Sample

Mar. 4 – Oct. 6, 2002   162 ton•yr (145.1 days)

- **Inverse β - decay selection**

  E_{prompt} > 2.6 MeV

  no OD signals

  0.5 < ΔT < 660 μsec

  ΔR < 1.6m, 1.8 < E_{delay} < 2.6 MeV

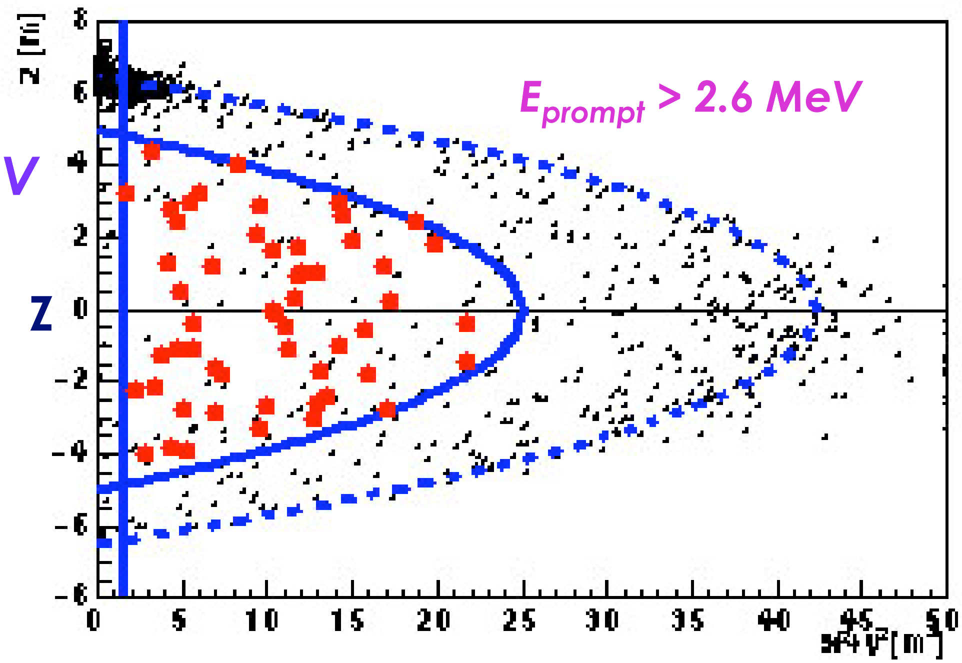
  tagging efficiency 78.3% (AmBe, LED)

- **Spallation event cut**

  ΔT_{μ} < 2sec , ΔE_{μ} > 3 GeV or ΔR_{μ} < 3m

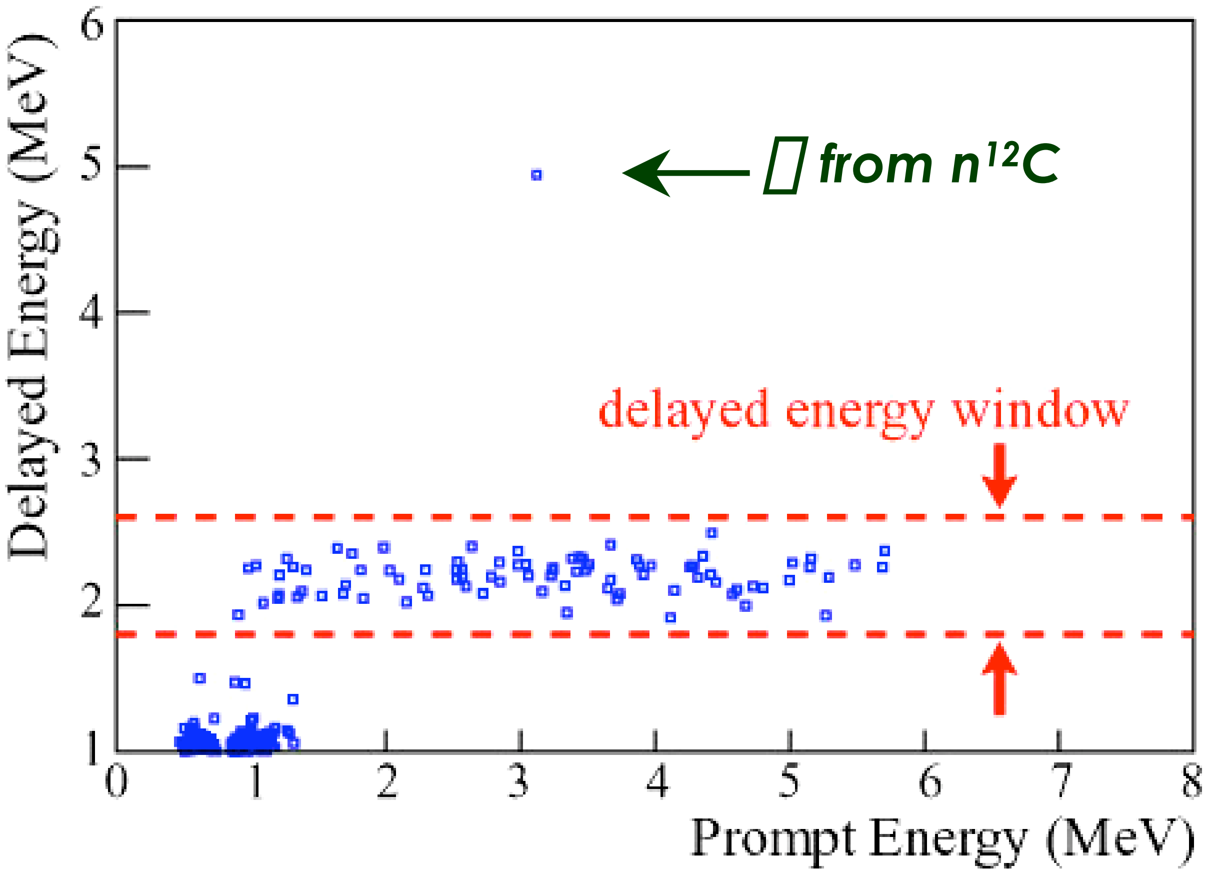
- **Fiducial selection**

  R<5m : 408 ton, 3.46×10^{31} free protons

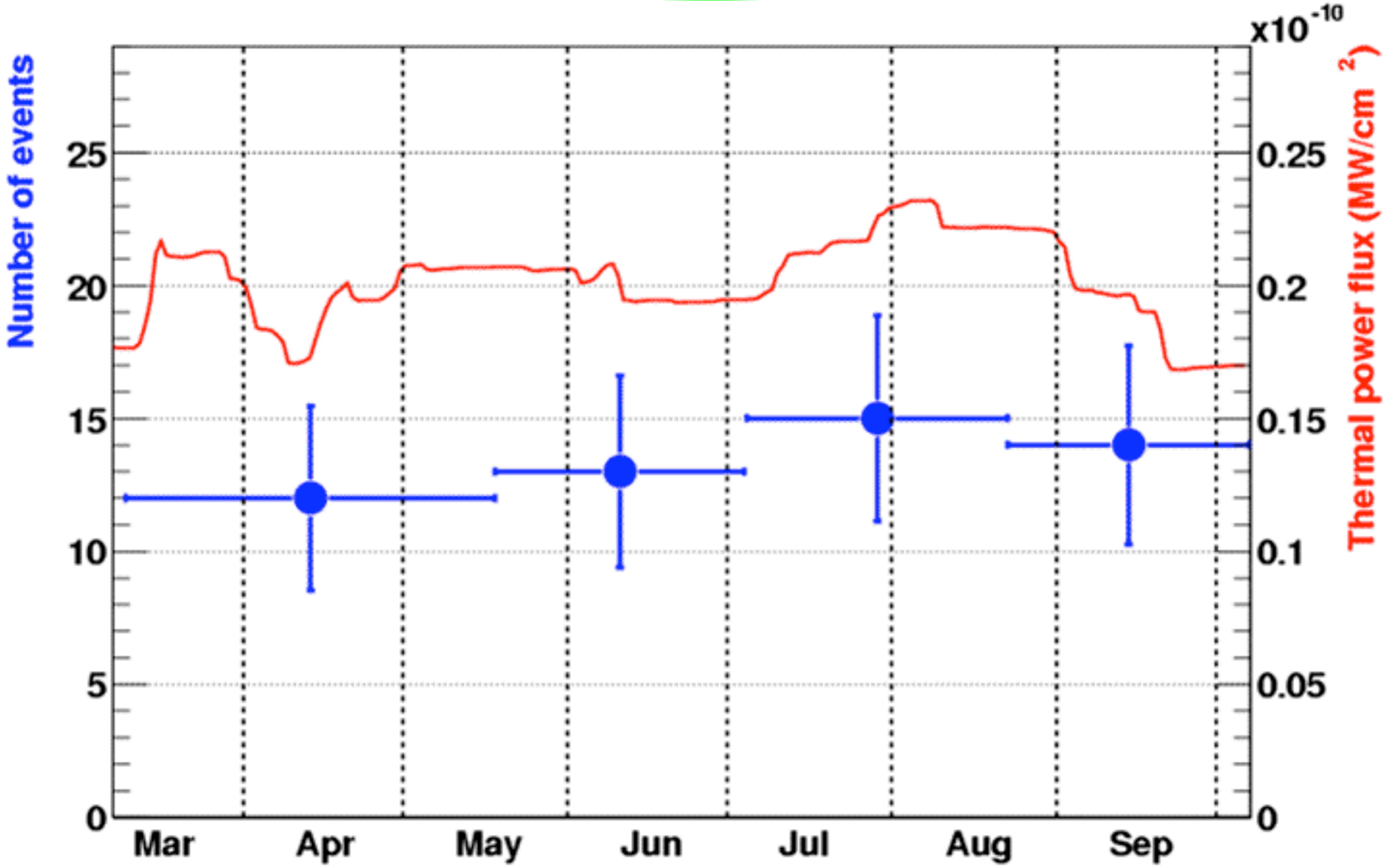


X² + y² (m²)

Scatter Plot of Prompt and Delayed Energies



Time Variations of Reactor Power and Signals



2002

Observed Event Rates

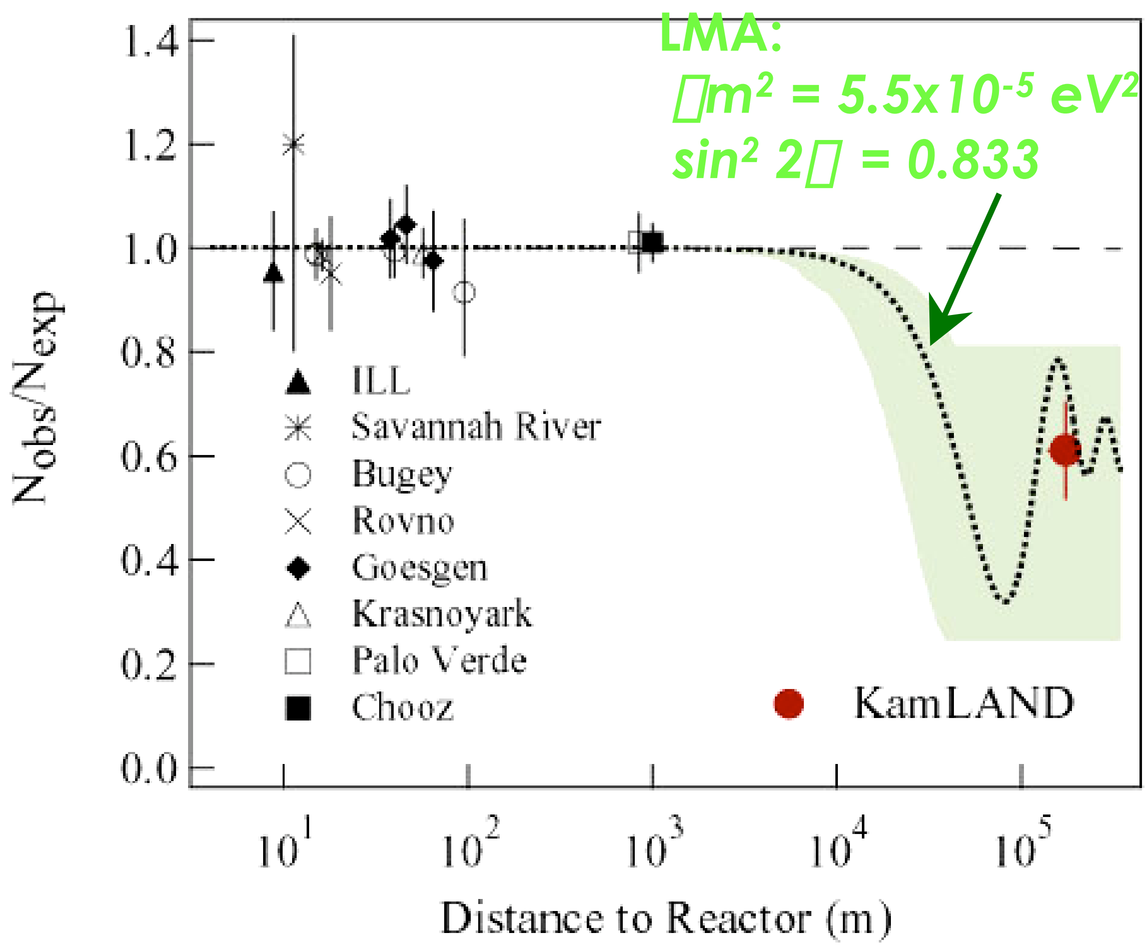
Final sample	
162 ton•yr,	$E_{prompt} > 2.6$ MeV
	54 ev
Expected	86.8 ± 5.6 ev
Background	0.95 ± 0.99 ev
accidental	*0.0086 ± 0.0005*
^{9}Li/^{8}He (□, n)	*0.94 ± 0.85*
fast neutron	*< 0.5*

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

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

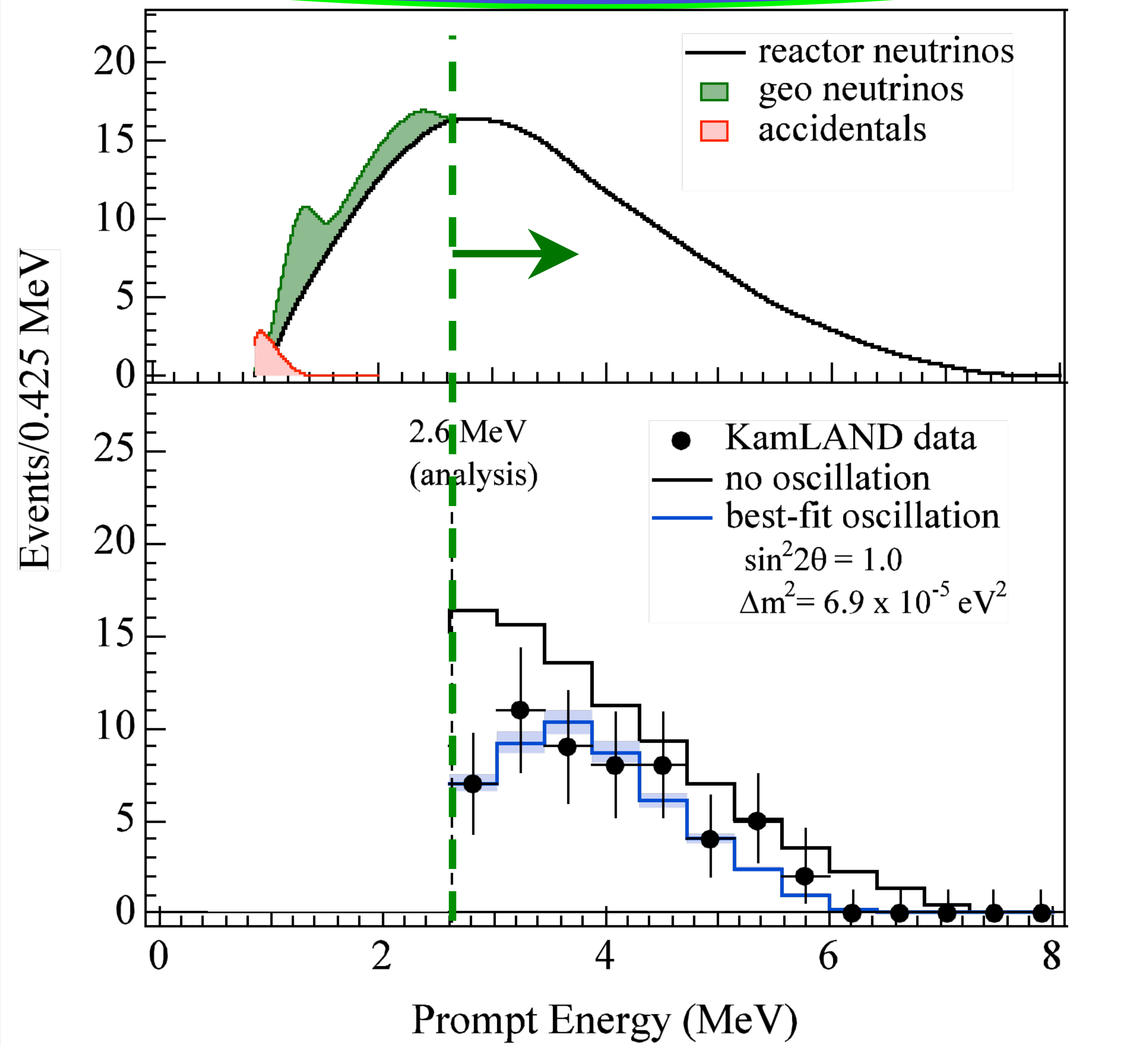
99.95 % C.L.

Ratio of Measured and 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)



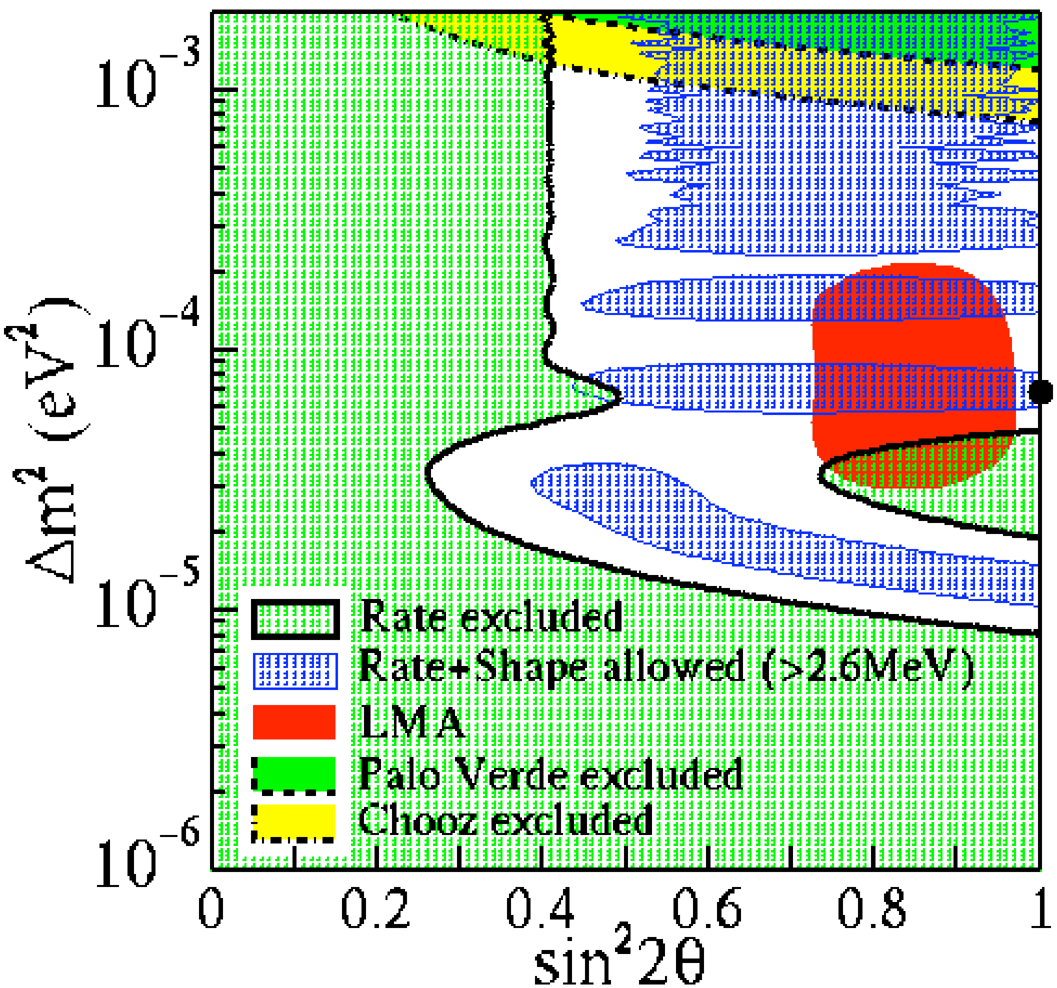
Neutrino Oscillation Study for E_{prompt} > 2.6 MeV

Best fit :

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

$\sin^2 2\theta = 1.0$

$\bar{\nu}_e \to \bar{\nu}_x$ 95 % C.L.

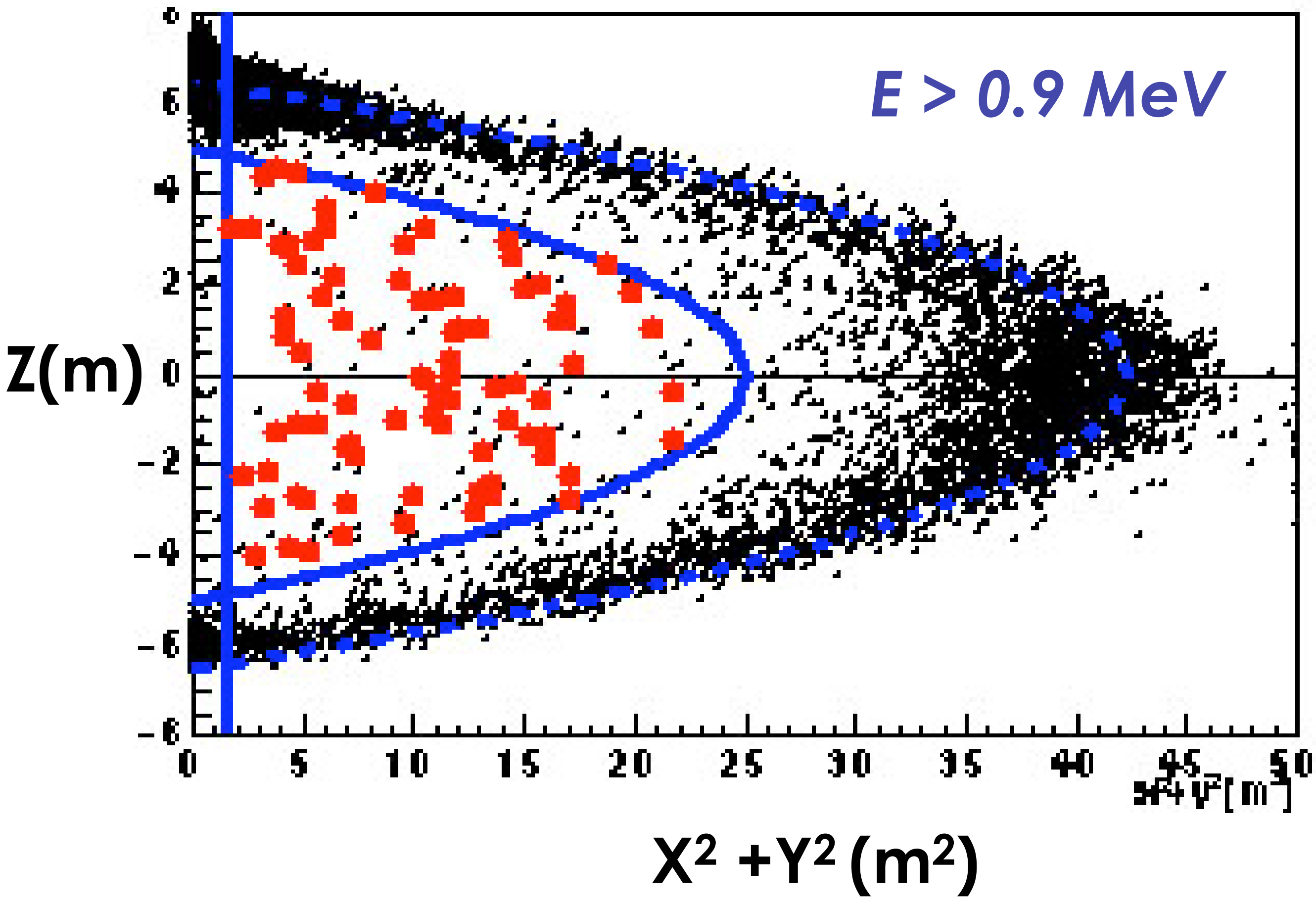


Further Analysis

- check : stability of results (*E*>2.6 MeV)
- study : sensitivity of geoneutrinos

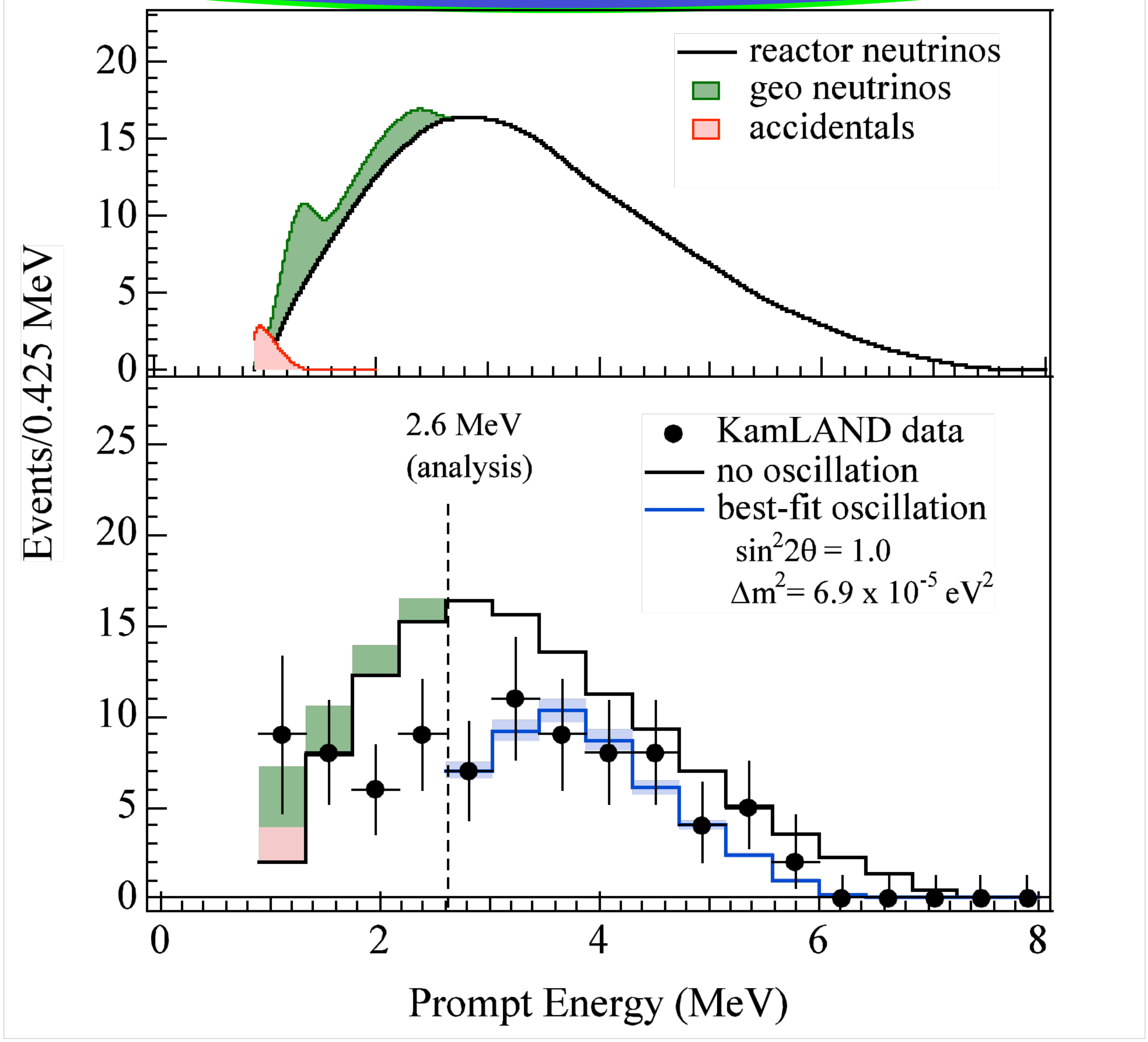
Analysis of Events with *E*>0.9 MeV

total background events = 2.91 ± 1.12
systematic error = 6.0 %



E > 0.9 MeV
Z(m)
X² +Y² (m²)

Energy Spectrum (E_{prompt} > 0.9 MeV)



Neutrino Oscillation Study for E_{prompt} > 0.9 MeV

- event rate
- spectrum deformation
- free parameters of geoneutrino fluxes

Neutrino Oscillation Study for E_{prompt} > 0.9 MeV

Best fit :

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

$\sin^2 2\theta = 0.91$

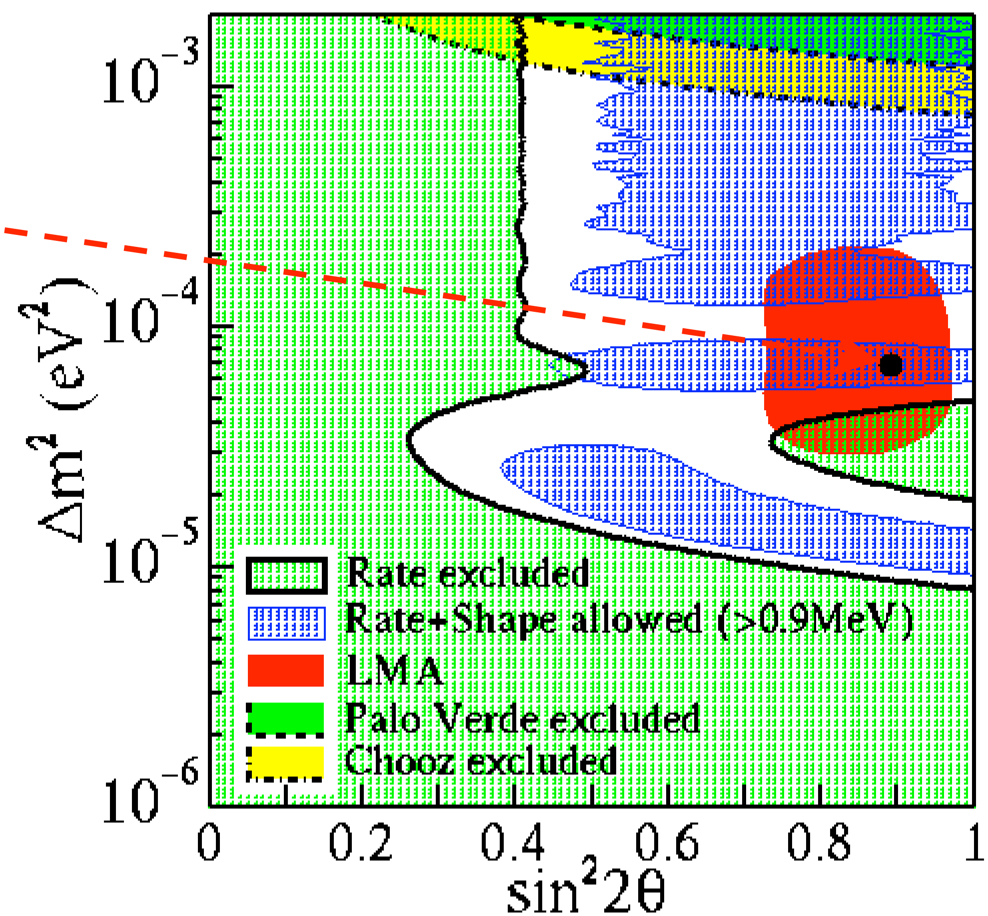
Fitted : ν_{geo} events

4 for ^{238}U

5 for ^{232}Th

0 ~ 110 TW at 95 % C.L.

$\nu_e \rightarrow \nu_x$ 95 % C.L.



Conclusions

- strong evidence for reactor $\bar{\nu}_e$ disappearance over 100 km scale

- completes a nearly 50 yr quest for this type of measurements

- solar neutrino oscillations with LMA completely consistent with the present results