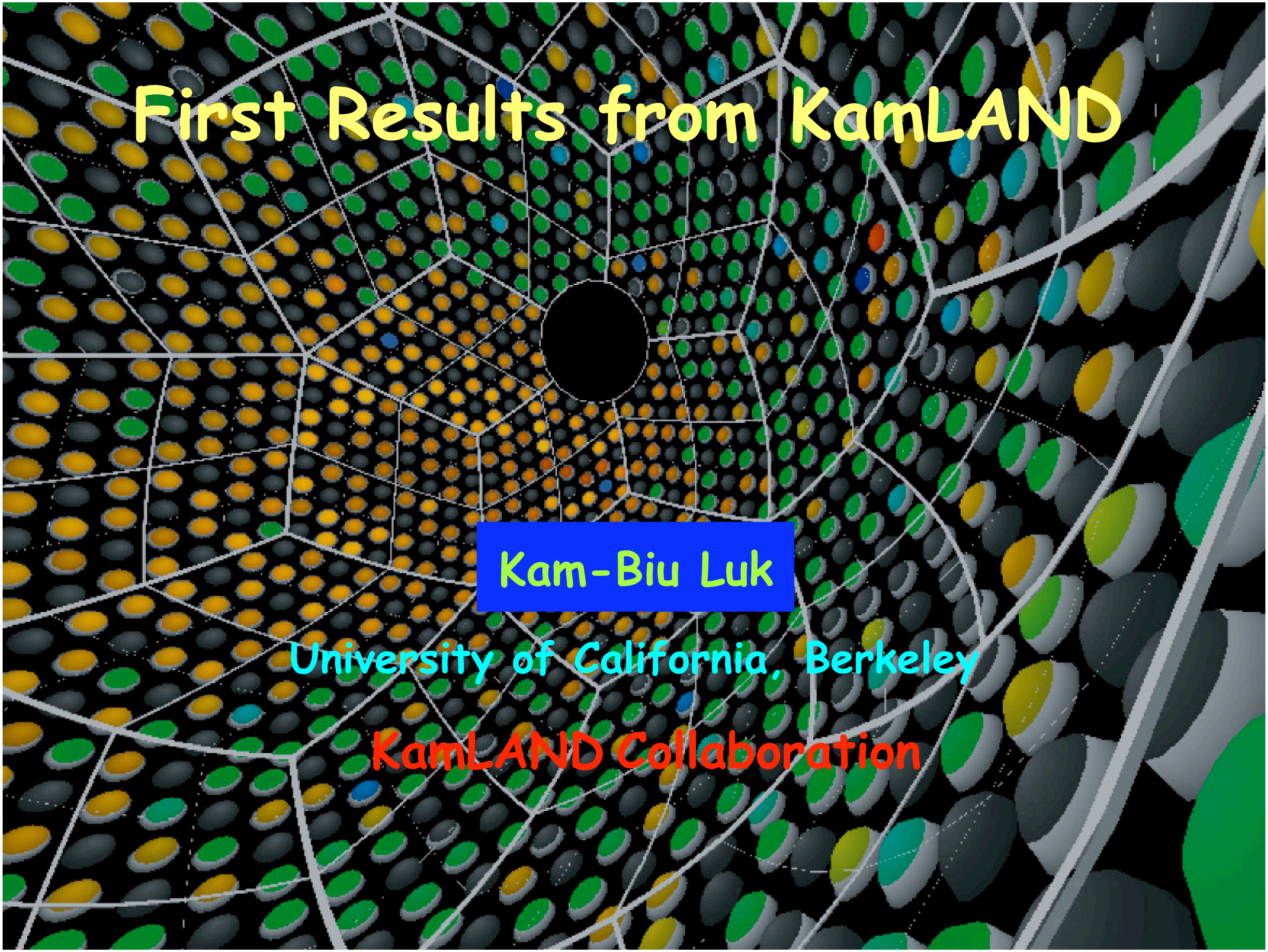


First Results from KamLAND

Kam-Biu Luk

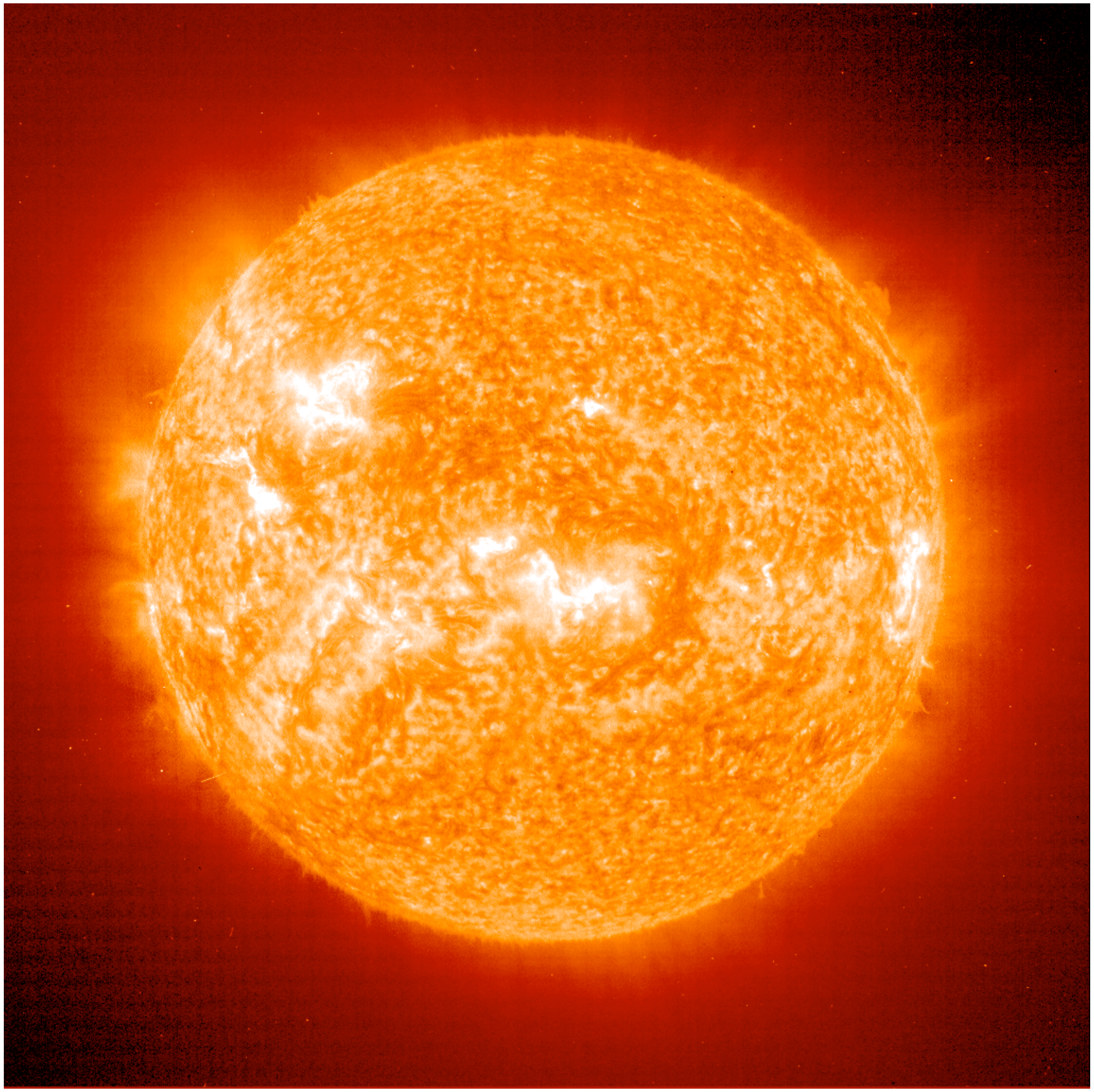
University of California, Berkeley

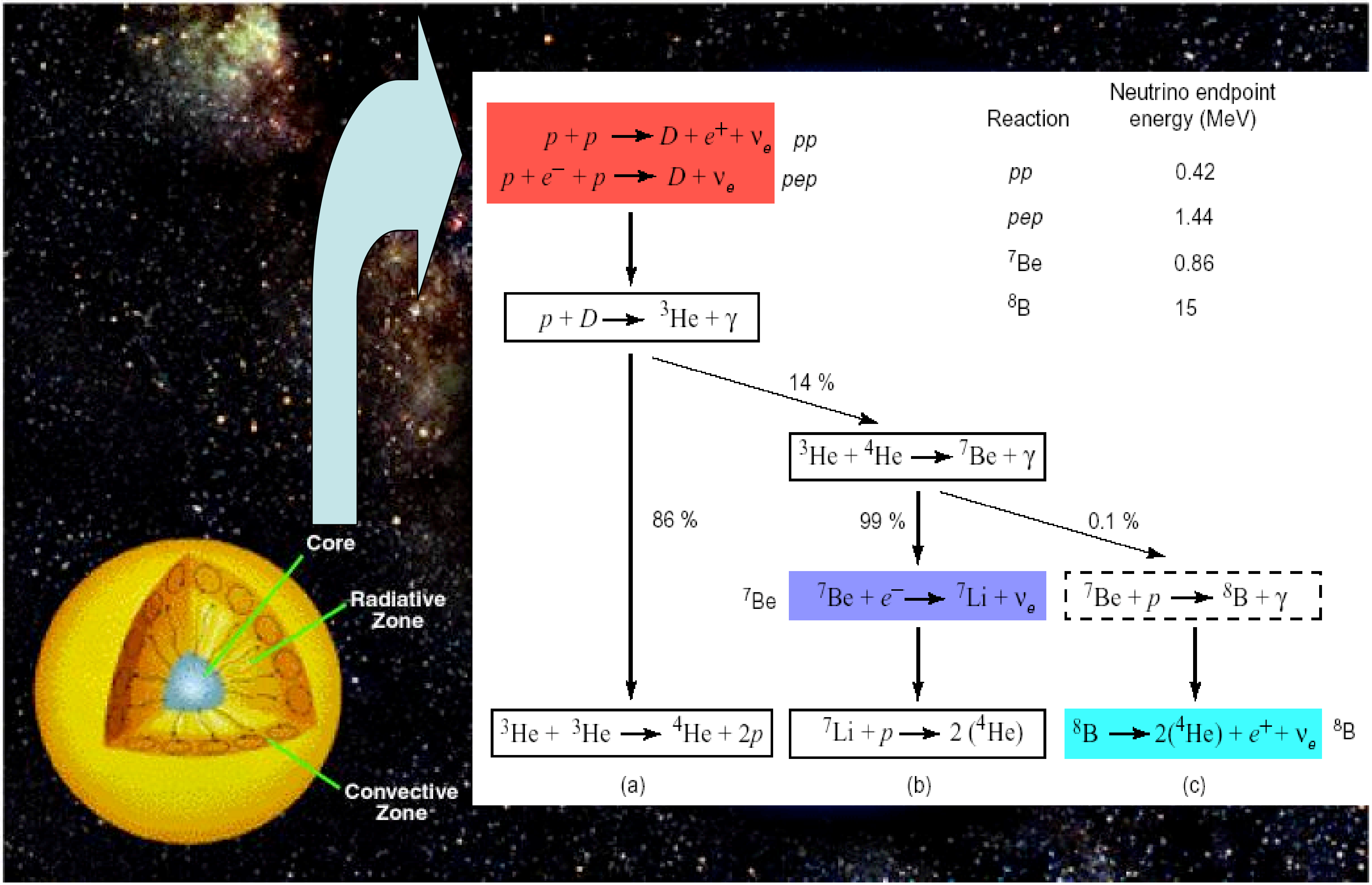
KamLAND Collaboration

Outline

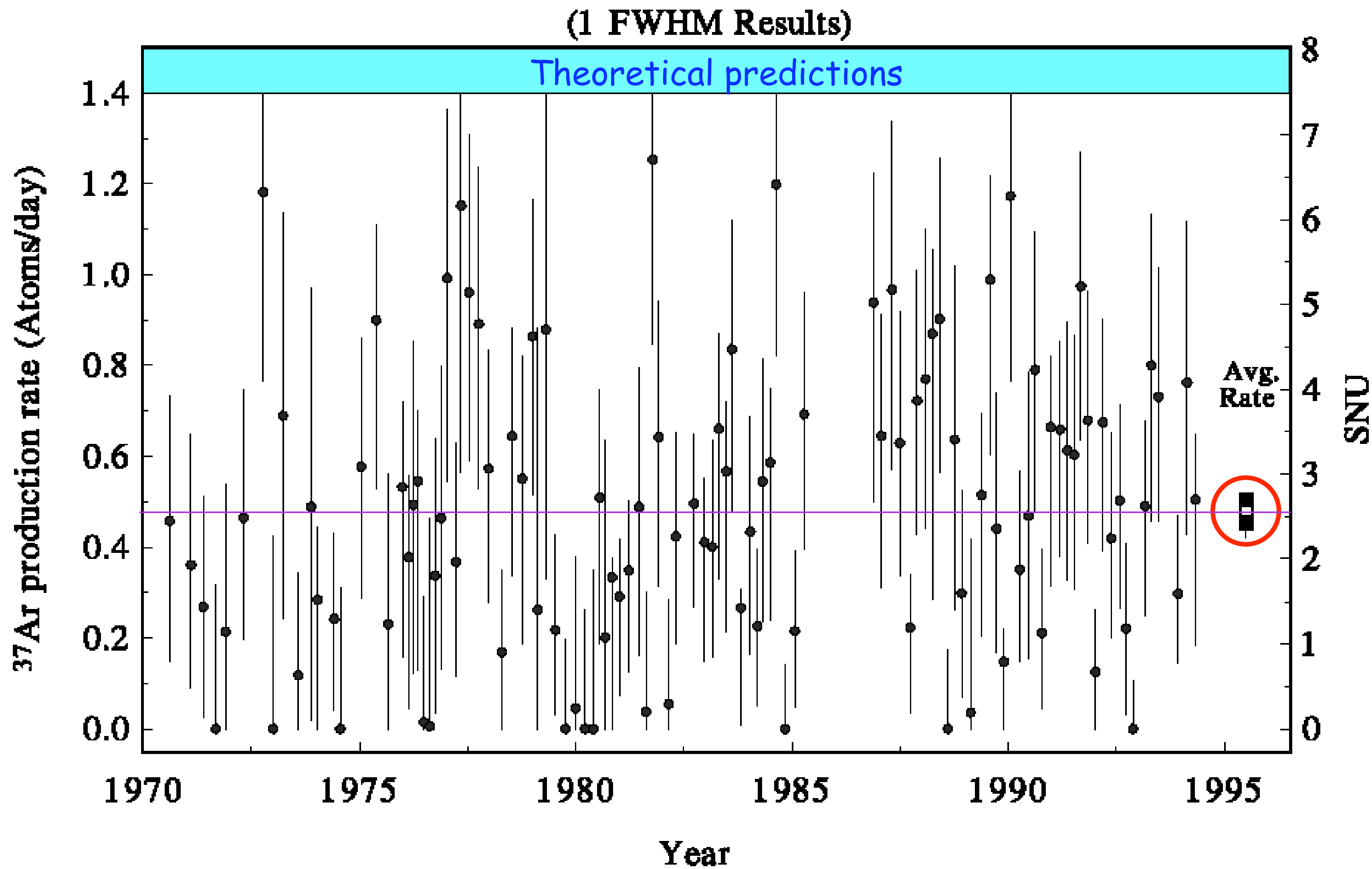
1. Solar Neutrino 'Problem'
2. KamLAND Experiment
3. Detector Construction
4. Reactor Anti-neutrinos
5. Detector Performance
6. Analysis & Results
7. Conclusions

How does the Sun shine?

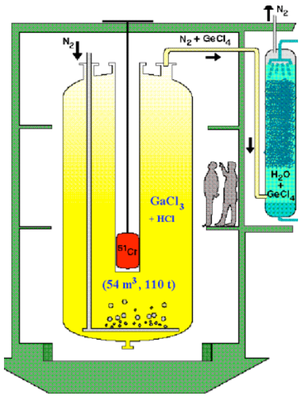


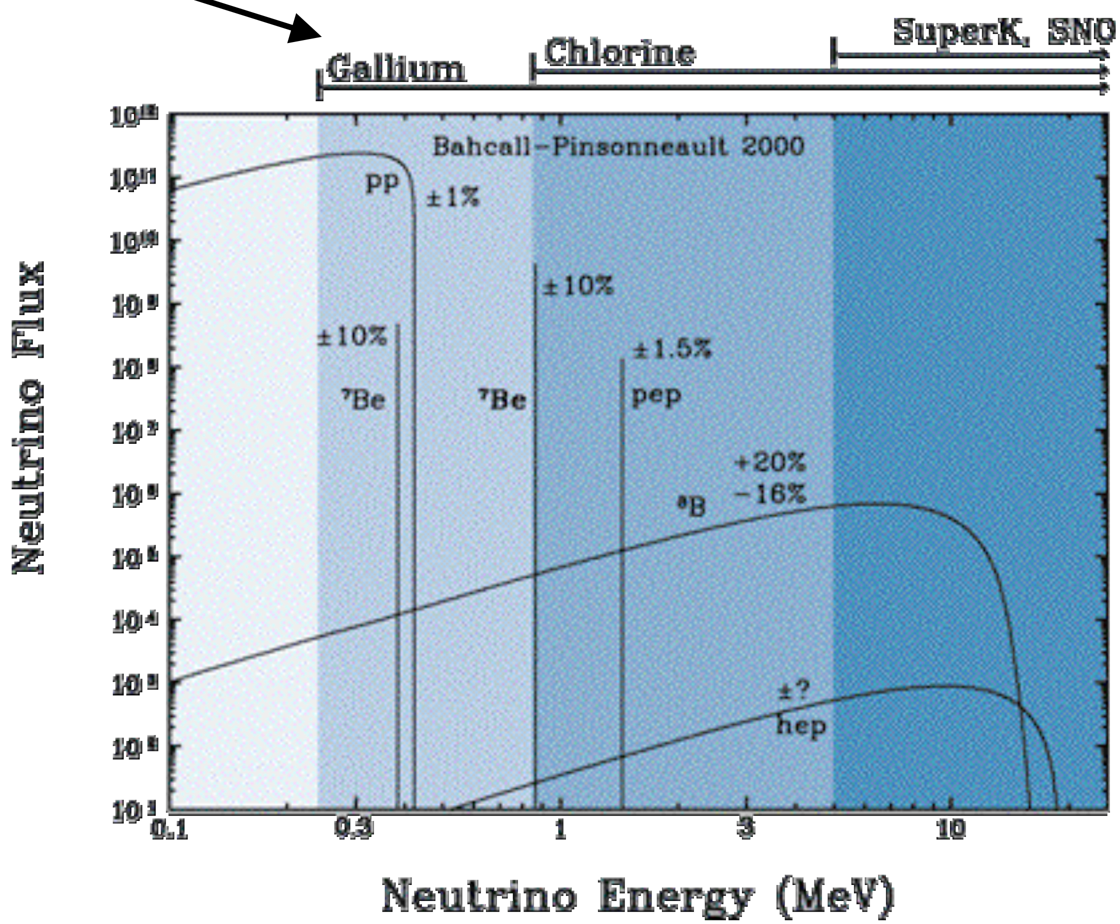

$p + p \rightarrow D + e^+ + \nu_e$ pp
$p + e^- + p \rightarrow D + \nu_e$ pep
$p + D \rightarrow {}^3He + \gamma$
14 %
86 %
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
99 %
0.1 %
${}^7Be$
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p \rightarrow {}^8B + \gamma$
${}^3He + {}^3He \rightarrow {}^4He + 2p$
${}^7Li + p \rightarrow 2({}^4He)$
${}^8B \rightarrow 2({}^4He) + e^+ + \nu_e$ ${}^8B$
(a)
(b)
(c)
Reaction
Neutrino endpoint energy (MeV)
pp 0.42
pep 1.44
${}^7Be$ 0.86
${}^8B$ 15
Core
Radiative Zone
Convective Zone

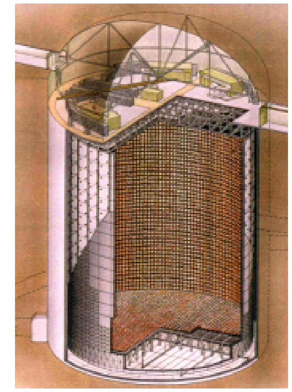
Solar Neutrino Experiment at Homestake

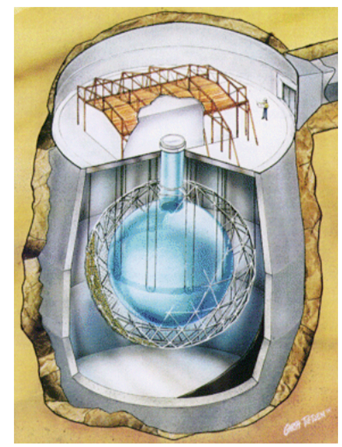


Checking the Homestake Experiment

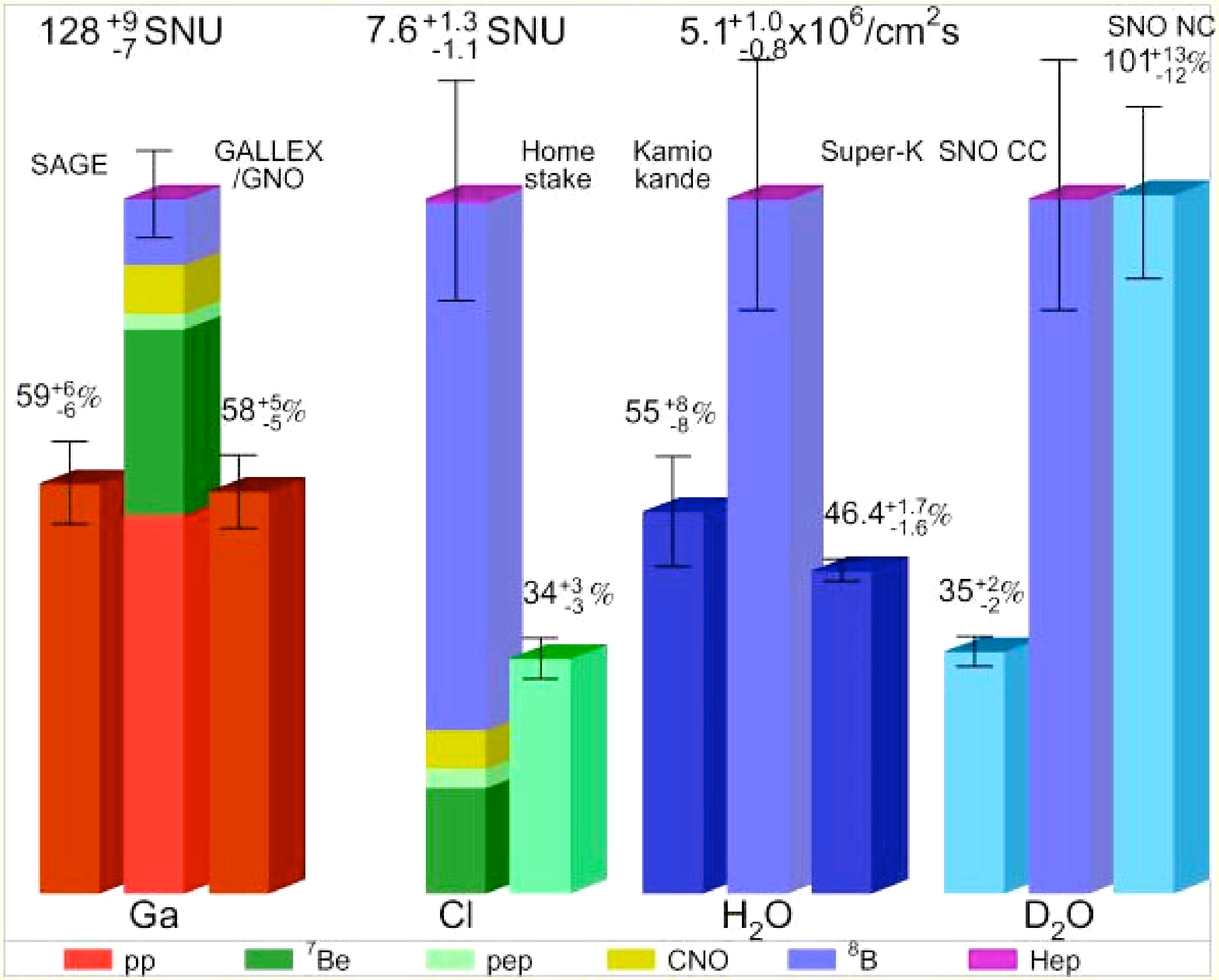








Solar ν Problem



Michael Smy, UC Irvine

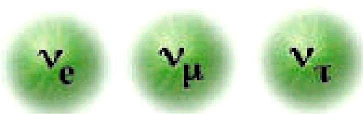
Neutrino Mixing

- If neutrinos are massive, it is possible that the weak eigenstates are not the same as the mass eigenstates:

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

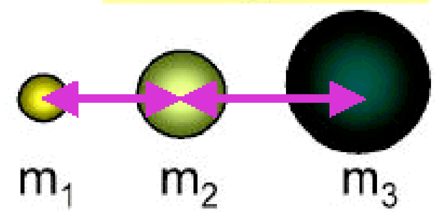
Weak eigenstates
„flavor eigenstates"



3 independent parameters
+ 1 complex phase

$\theta_{12}, \theta_{23}, \theta_{13}$
$+ \delta$

Mass eigenstates



$\Delta m^2_{12}, \Delta m^2_{23}$

Probability of Neutrino Mixing

- Parametrize the mixing matrix as:

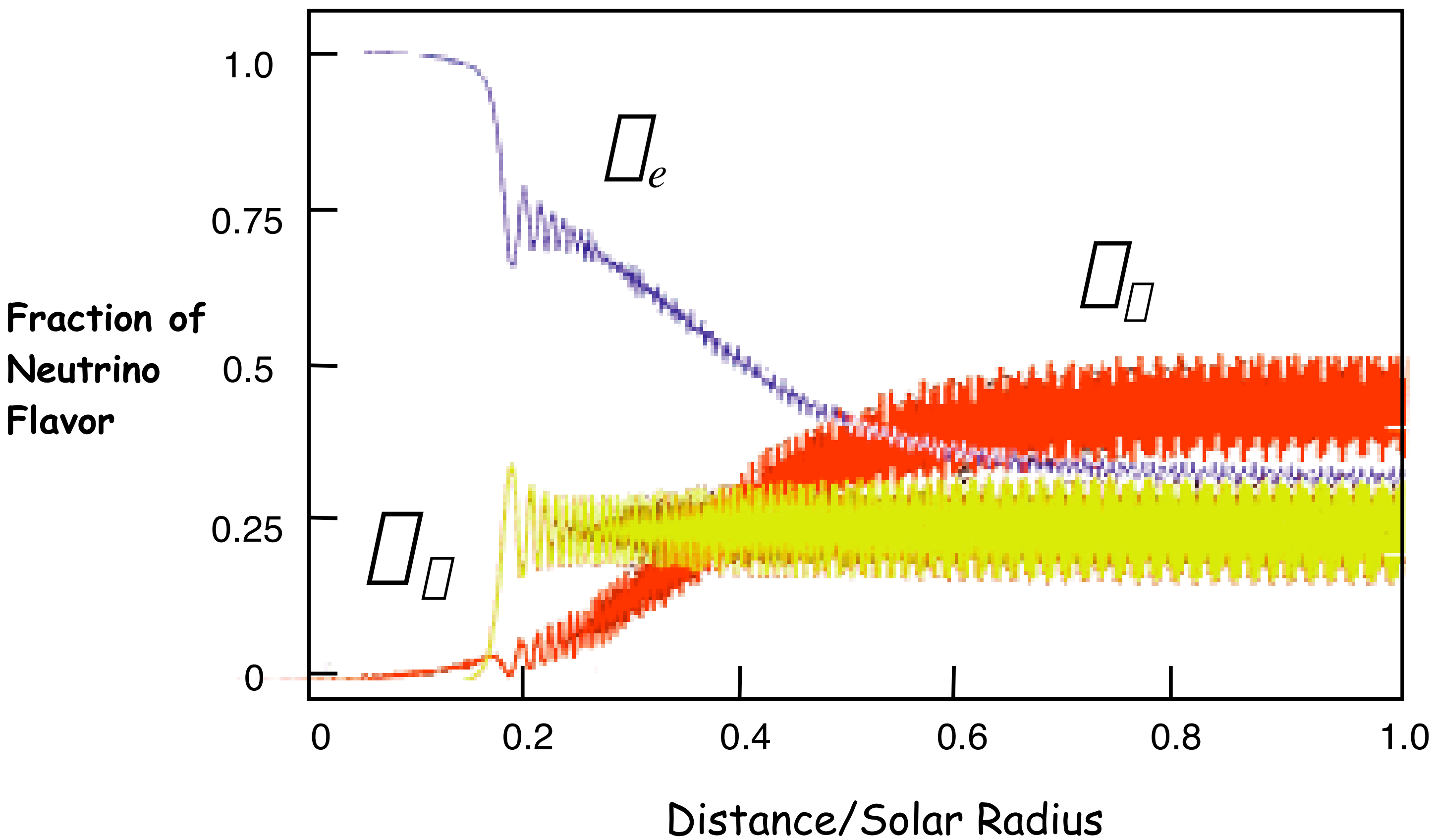
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

solar □ reactor □ atmospheric □

- The probability of $\nu_e \rightarrow \nu_e$ is:

$$P(\nu_e \rightarrow \nu_e) = \sin^4\theta_{13} + \cos^4\theta_{13}\left[1 - \sin^2(2\theta_{12}) \cdot \sin^2\left(\frac{\Delta m_{12}^2 L}{4E_\nu}\right)\right]$$

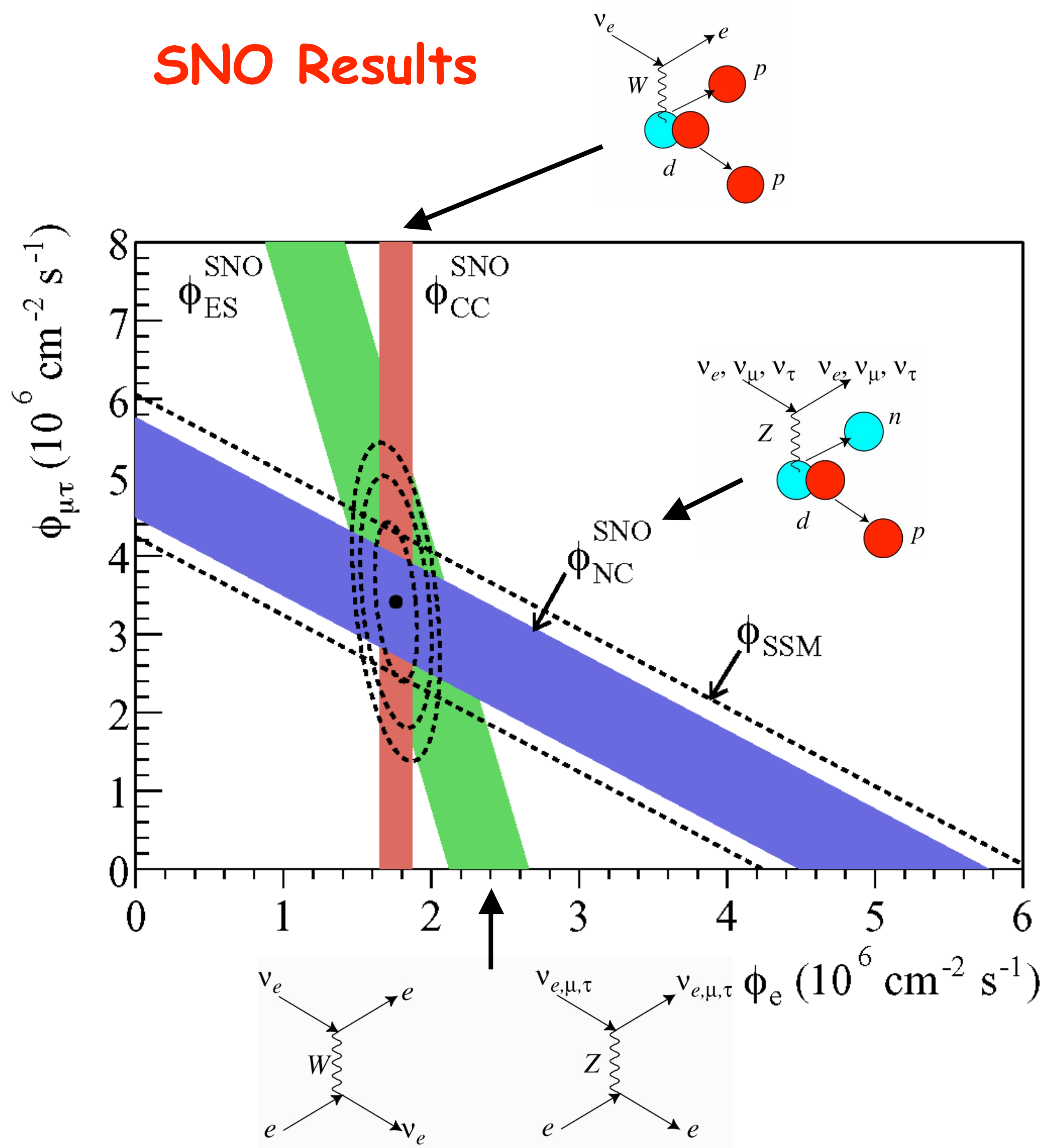
MSW Effect



ν_e NC and CC

ν_μ ν_τ NC only

SNO Results



Fluxes

(10^6 cm^{-2} s^{-1})

$\square_{e}$:	**1.76(11)**
$\square_{\square\square}$:	**3.41(66)**
$\square_{total}$:	**5.09(64)**
$\square_{SSM}$:	**5.05**

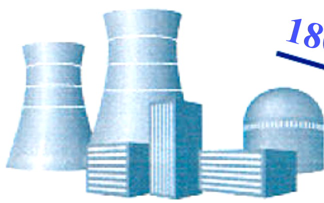
The KamLAND Experiment

1st phase experiment

(E_{th} = 1.8 MeV)

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

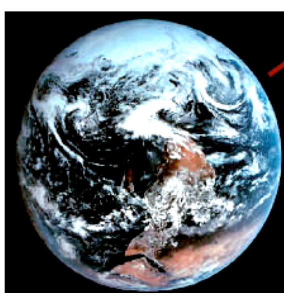
○ Neutrino Oscillation Search by Reactor Anti-neutrinos



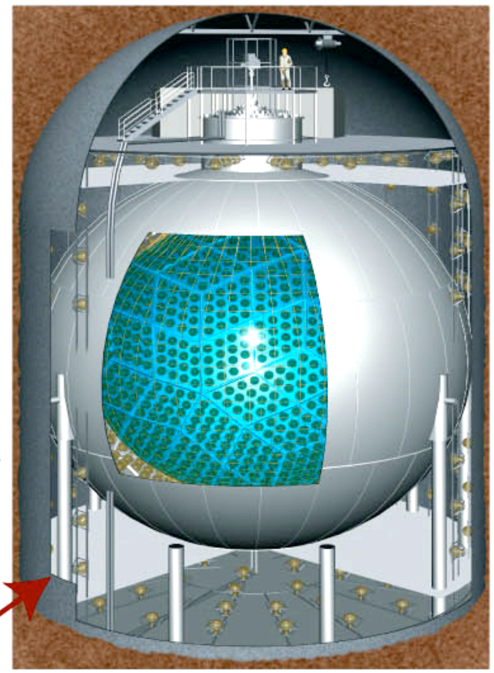
180 km

$\bar{\nu}_e$

○ Terrestrial Anti-neutrino Detection



$\bar{\nu}_e$



2nd phase experiment

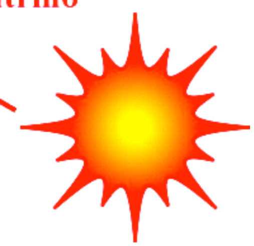
(E_{th} = 200 keV)

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

○ Solar neutrino Detection

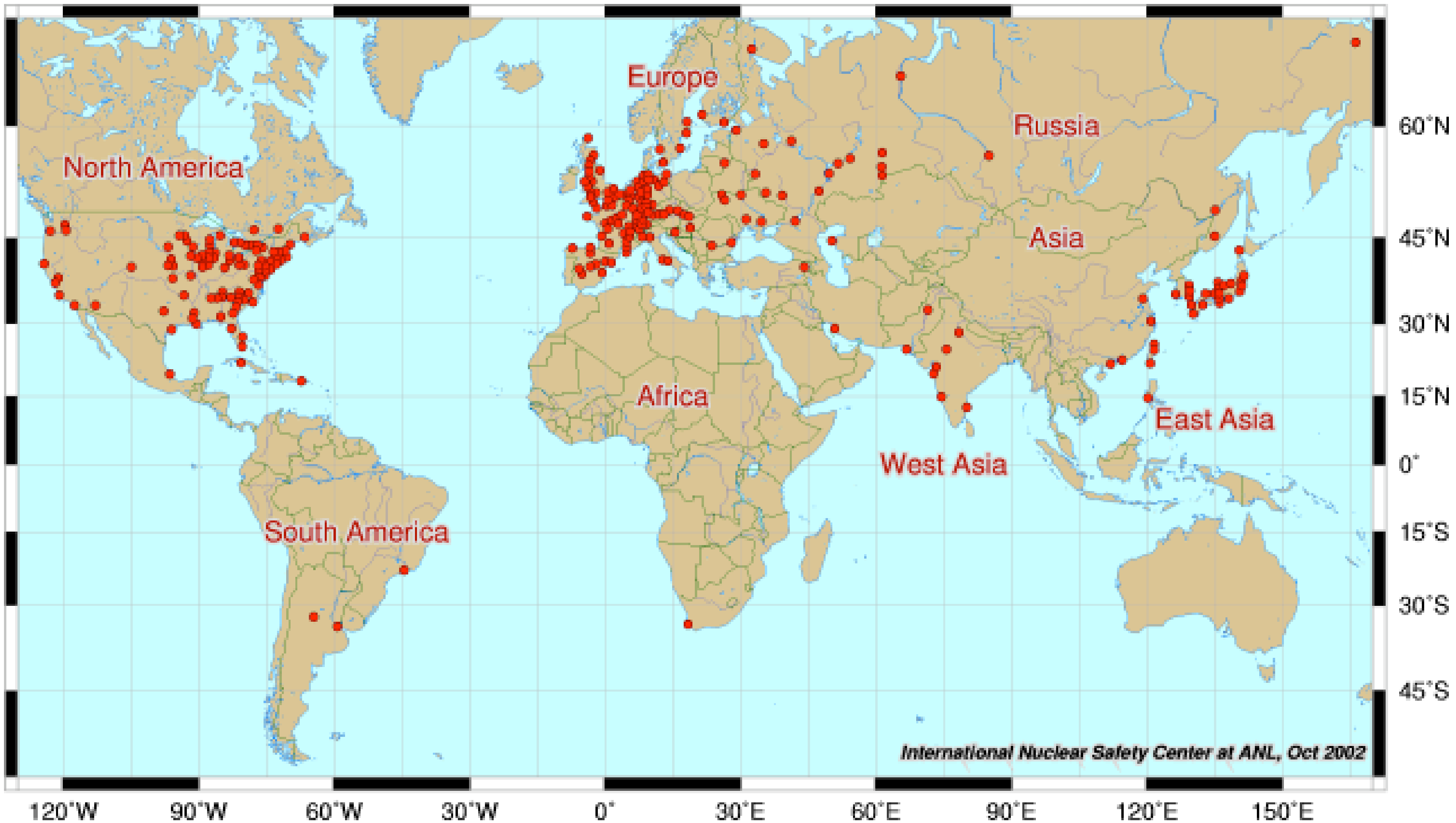
^{7}Be Neutrino

ν_e



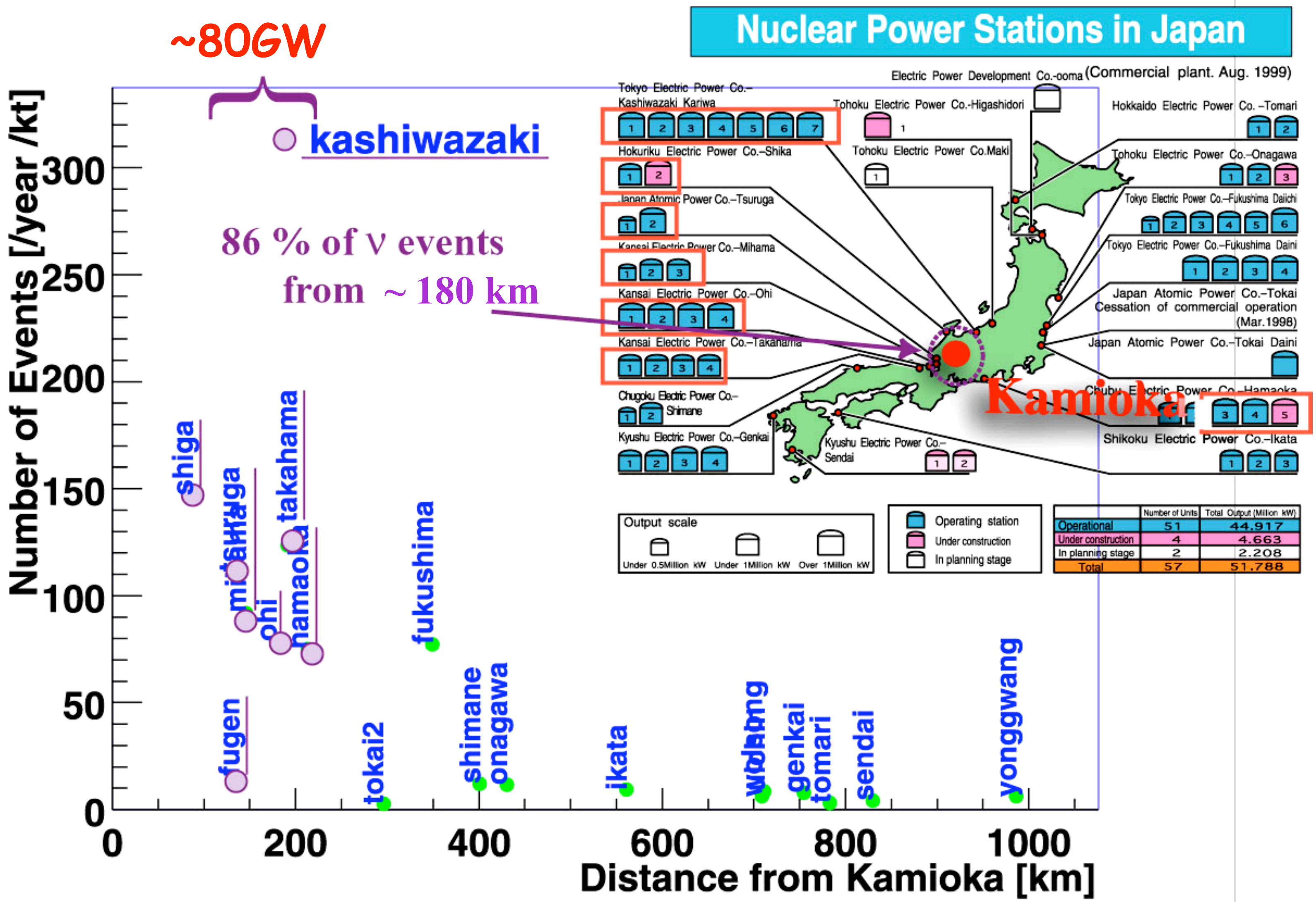
supernova-burst ν, relic supernova ν, atmospheric ν, Proton Decays, · · ·

Potential Reactor Anti-Neutrino Sources

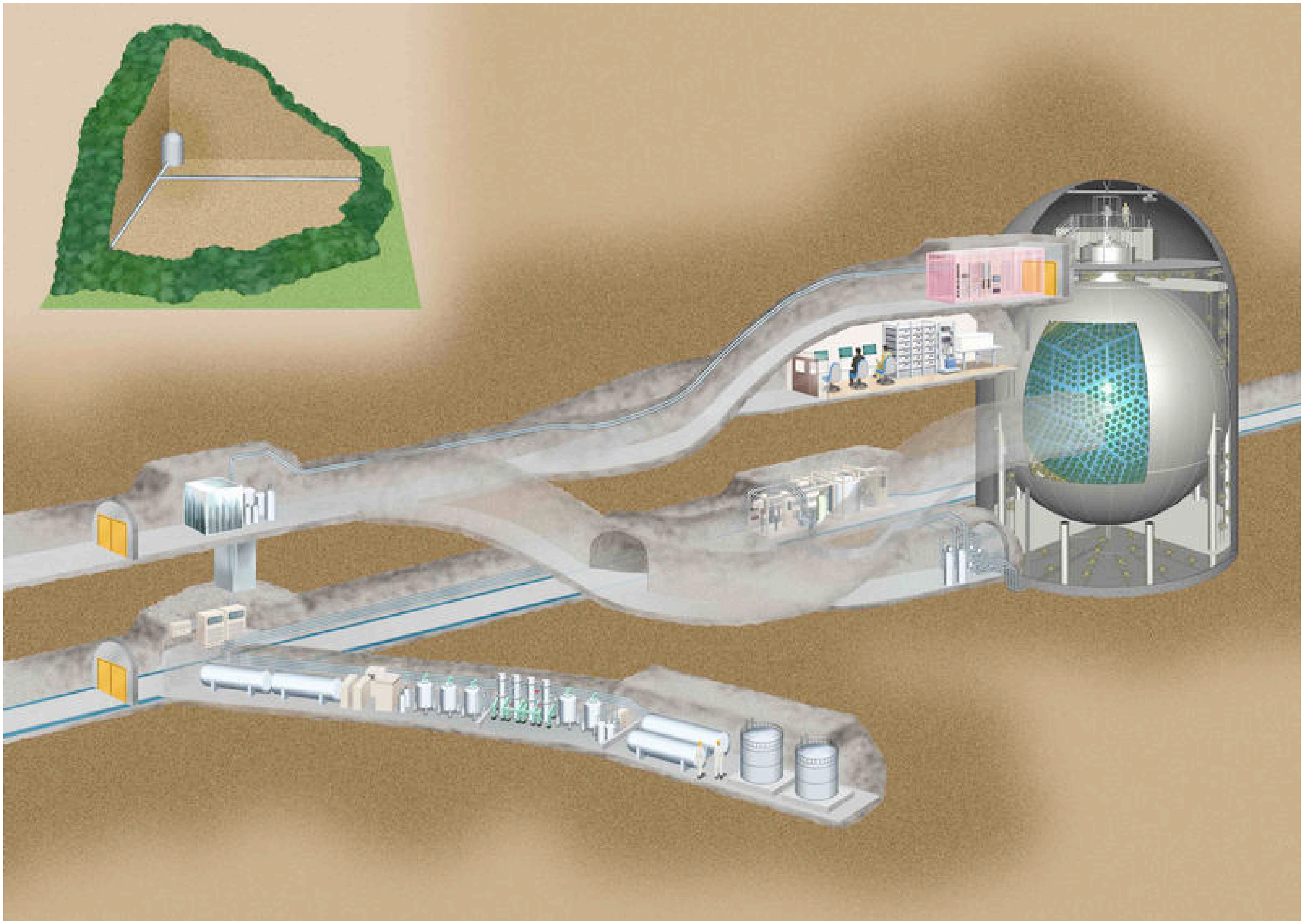


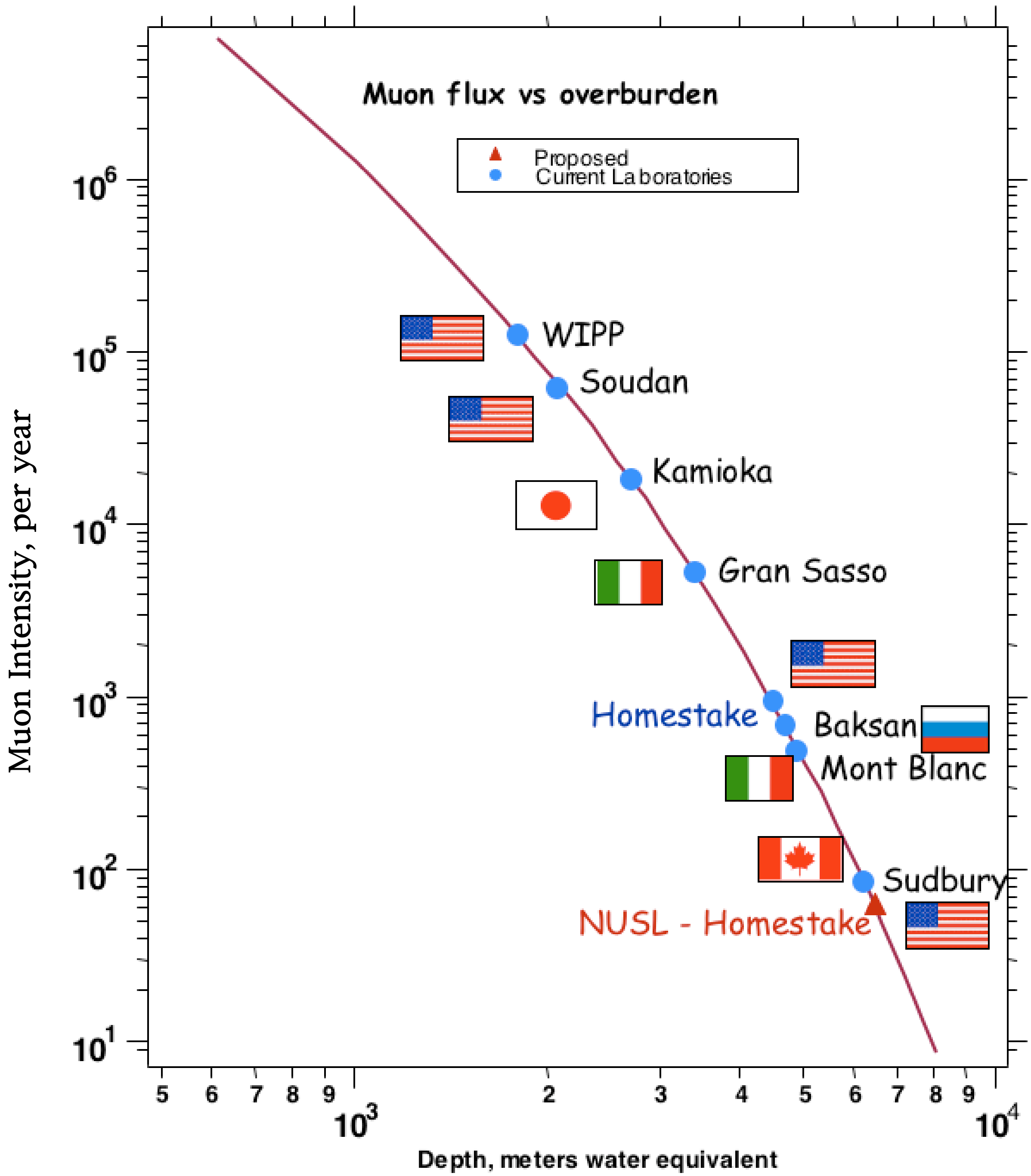
Nuclear Reactors in Japan

20 % of world nuclear power



KamLAND Is An Underground Experiment

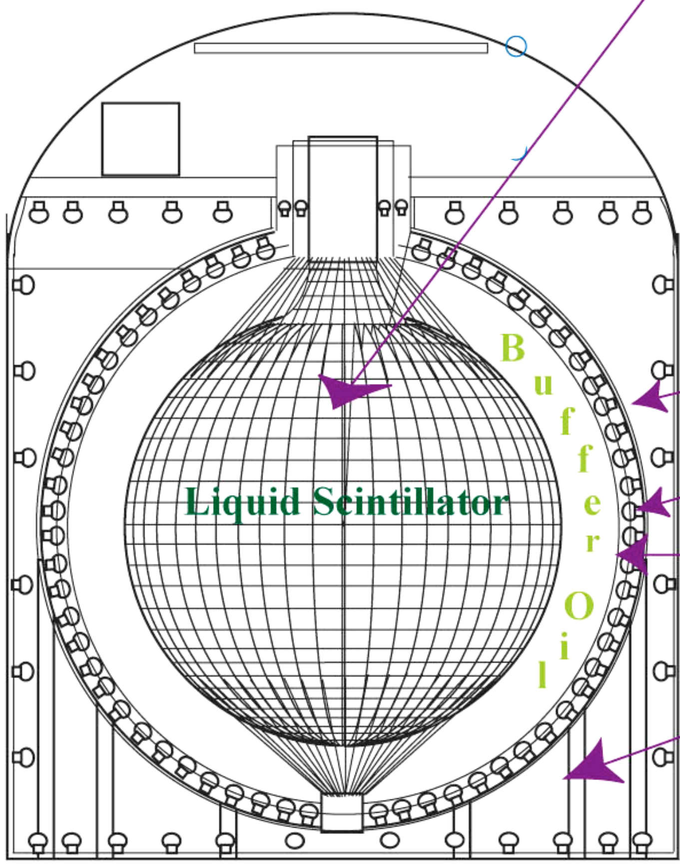




Muon flux vs overburden
Proposed
Current Laboratories
WIPP
Soudan
Kamioka
Gran Sasso
Homestake
Baksan
Mont Blanc
Sudbury
NUSL - Homestake
Muon Intensity, per year
Depth, meters water equivalent

The KamLAND Detector

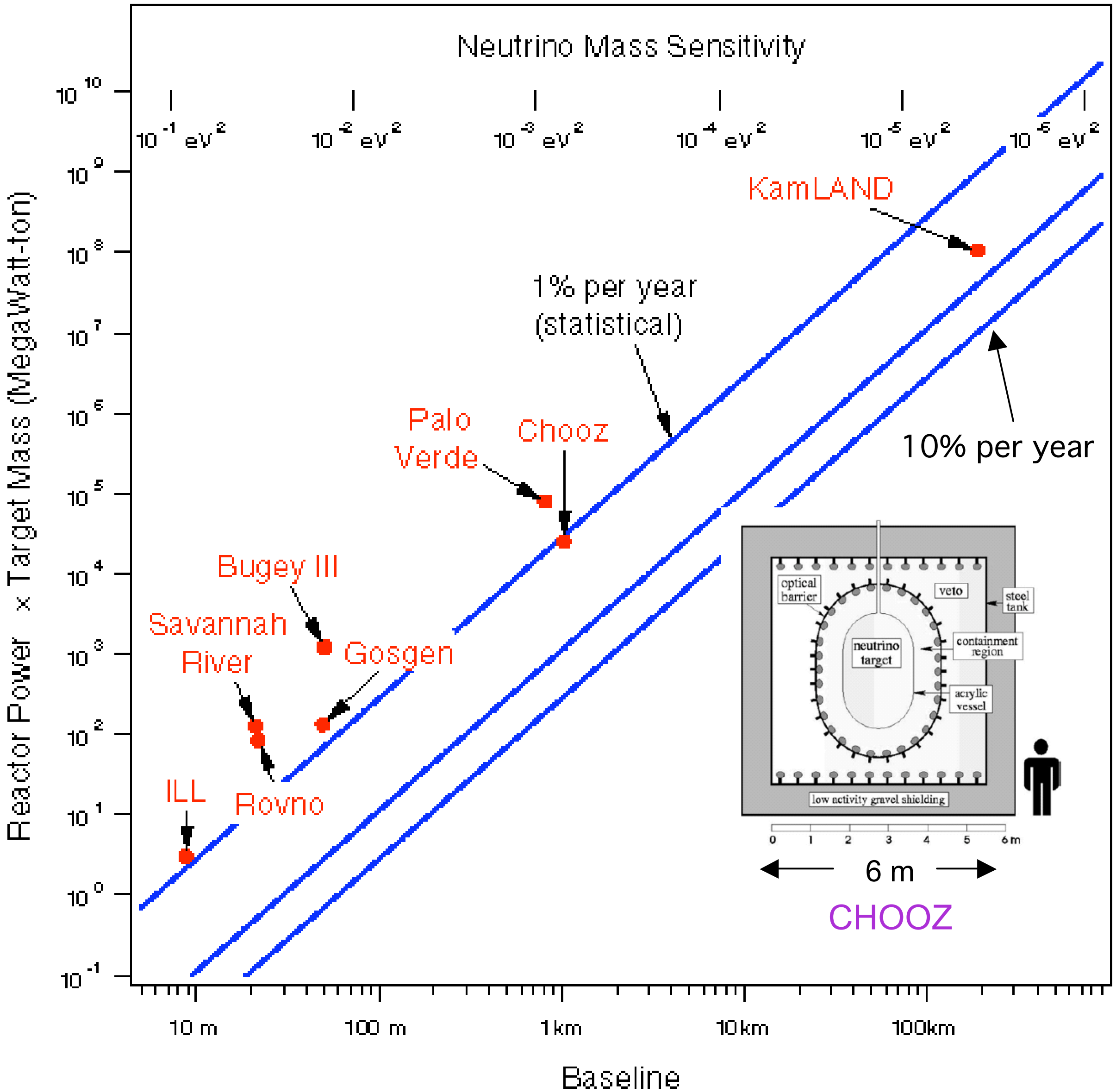
- Detector site : Old Kamiokande site (2700 m.w.e.)
- 1,000 ton Liquid Scintillator
  80%: dodecane, 20%: pseudocumene, 1.5 g/liter: PPO
  (□= 0.78)
  housed in spherical balloon (13m diameter)
  of transparenet nylon/EVOH composite film (135□m)
  supported by cargo net structure

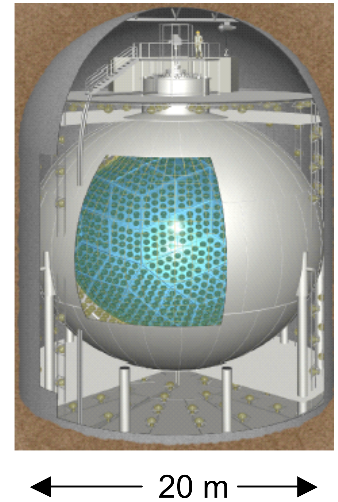


- 3,000 m^3 Scintillation Light Detector
  - 18m diameter stainless steel tank filled with paraffin oil (□□ = 0.04%, lighter than LS)
  - 1,325 17-inch+554 20-inch PMT's
    photosensitive coverage ~22%
  - 3mm thick acrylic wall (120 plates)
    : Rn barrier
- Water Cherenkov Outer Detector
  225 Kamiokande 20-inch PMT's

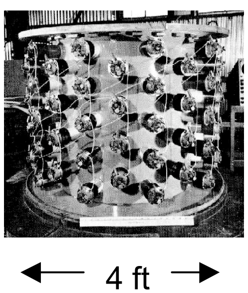
Present analysis

Reactor Anti-Neutrino Experiments





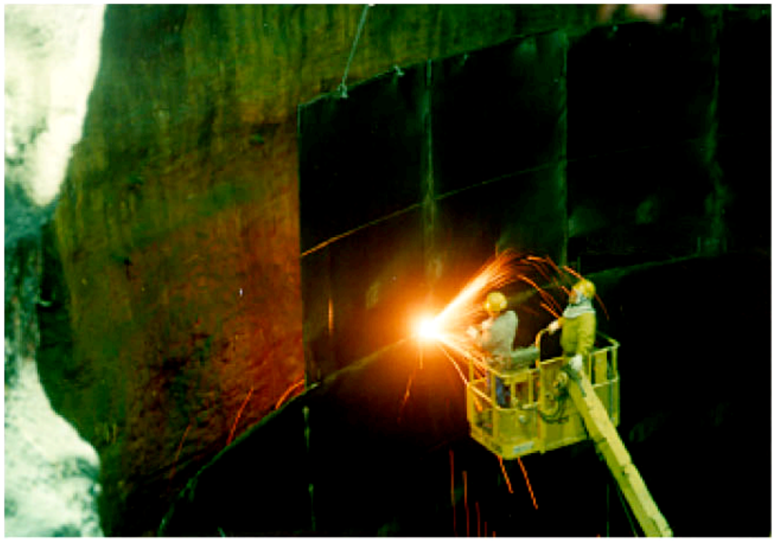
KamLAND

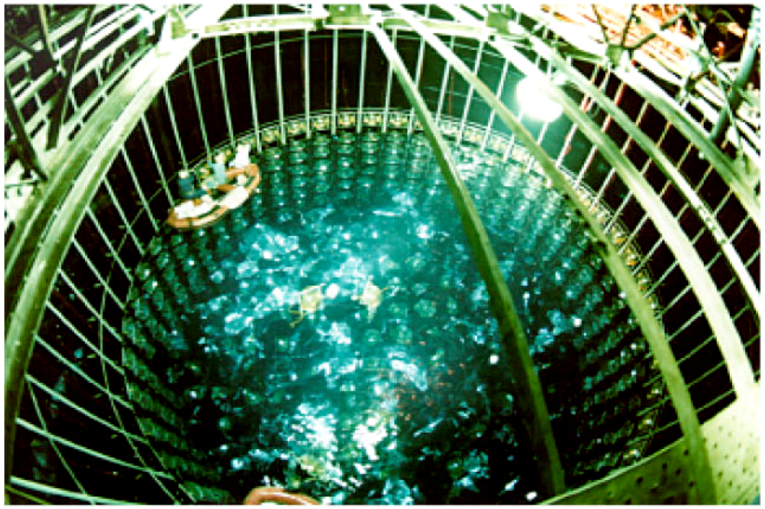


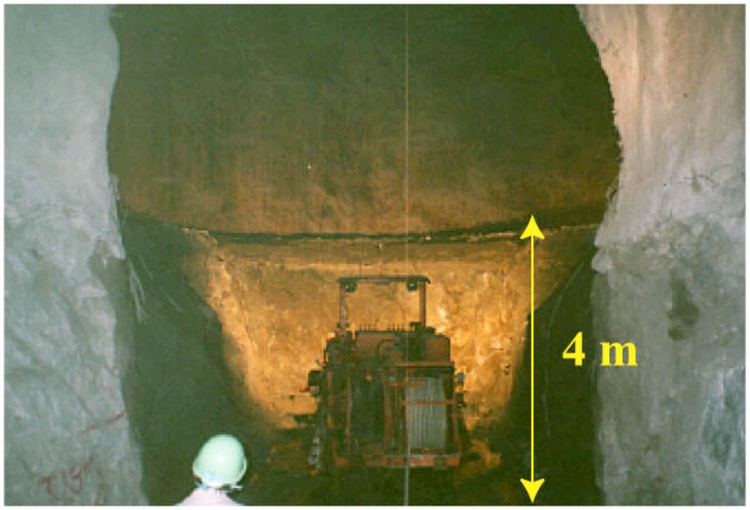
Poltergeist

Detector Construction

Dismantling Kamiokande, 1998



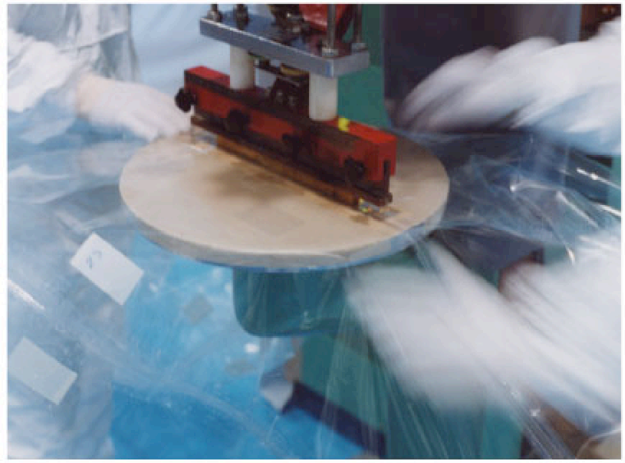





Finished in March, 2000

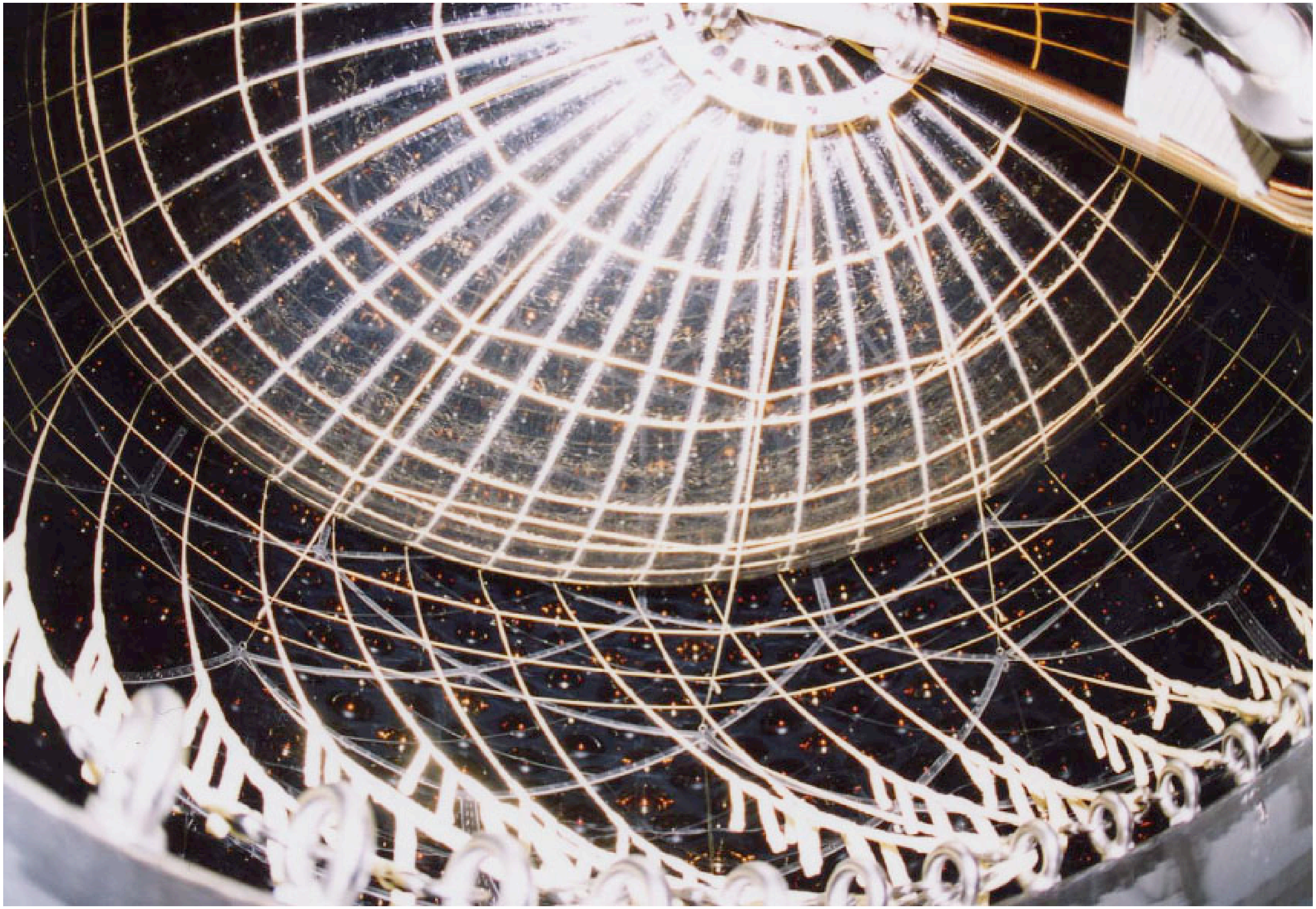
PMT Installation Finished (Sep. 2000)

Full-Size Balloon Construction
~ Oct. 2000

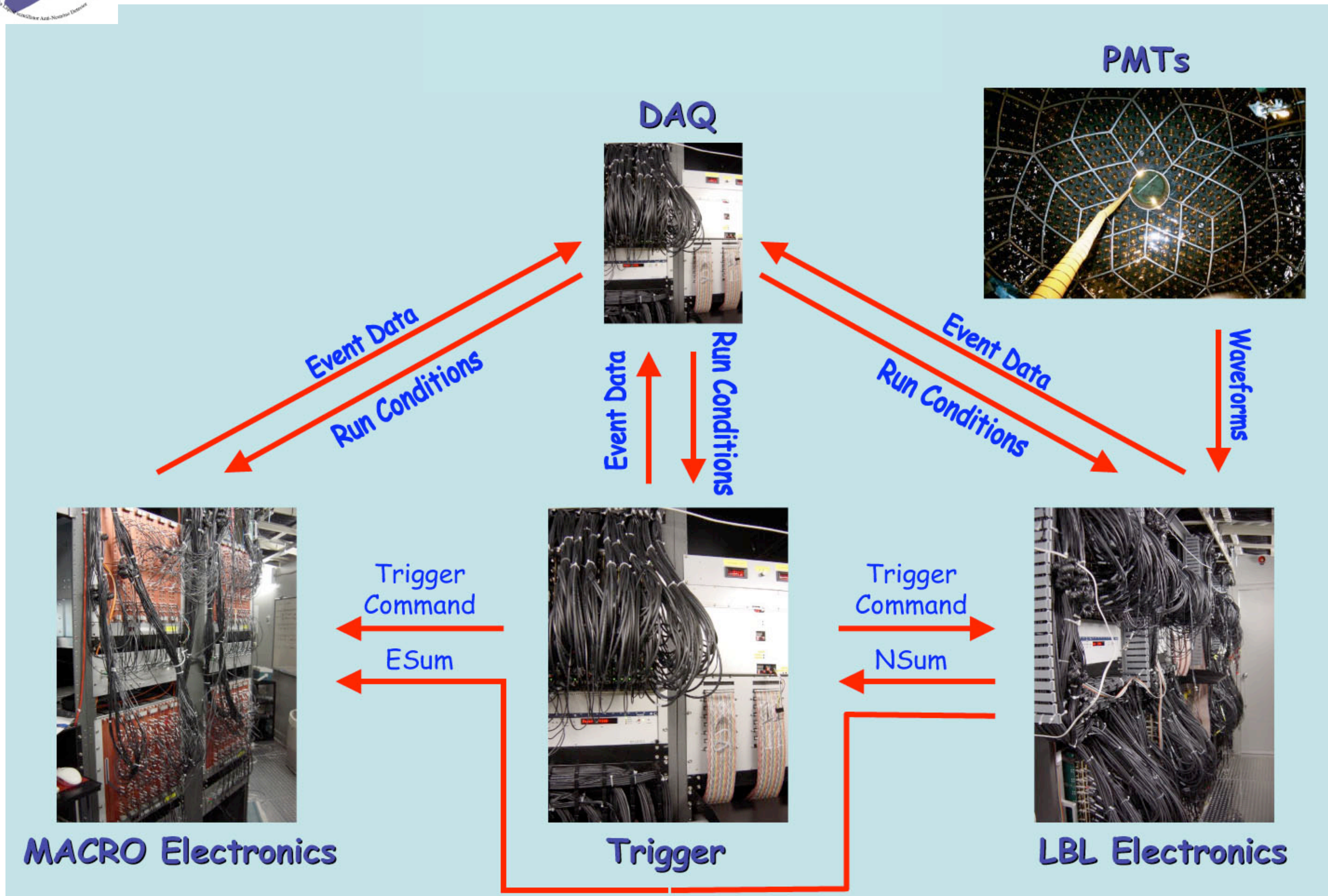


Installation of Balloon, March 2001



Oil Filling finished in Sept. 2001

Data-Acquisition Electronics
Ready in December 2001




KamLAND Launch
Jan. 22, 2002

Anti-neutrinos

Kashiwazaki Nuclear Power Station : 25 GW

KamLAND

Where Do The Anti-Neutrinos Come From?

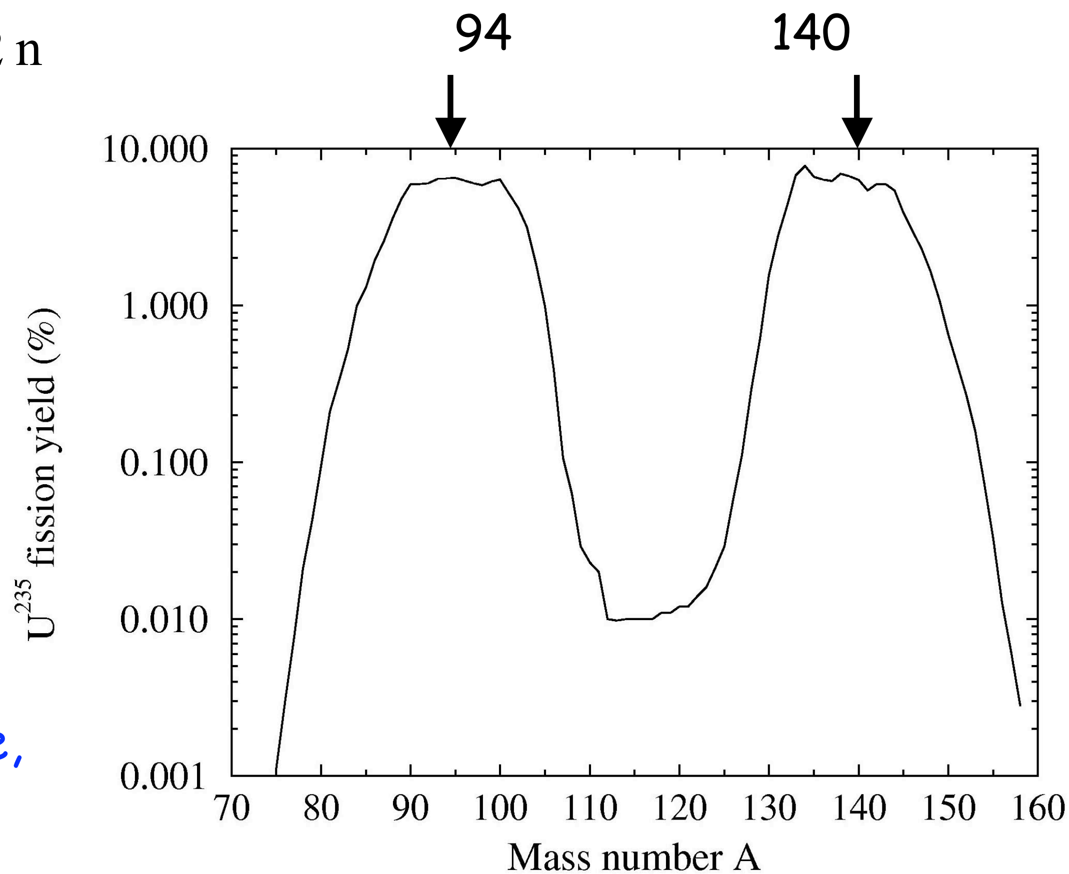
For ^{235}U fission, for instance,

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

where X_1 and X_2 are stable nuclei e.g.

$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$

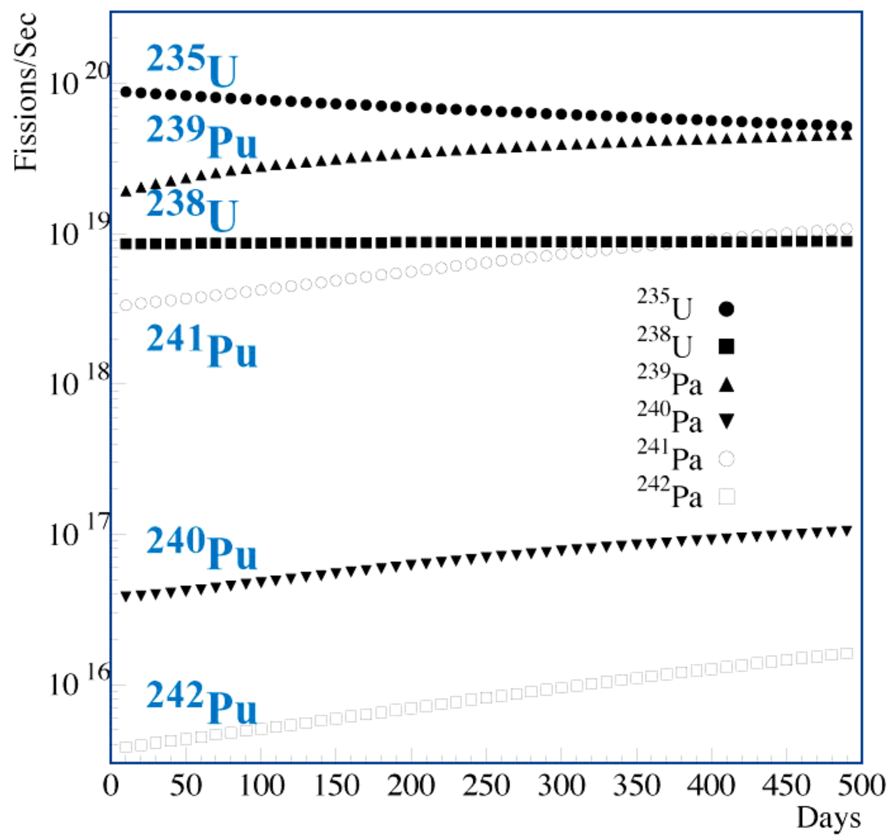
which have a total of 98 protons and 136 neutrons, whereas ^{235}U has 143 neutrons. That is, on average, 6 neutrons must beta decay, giving 6 $\bar{\nu}_e$.



Fission Rate: ν_e Production

- **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 →

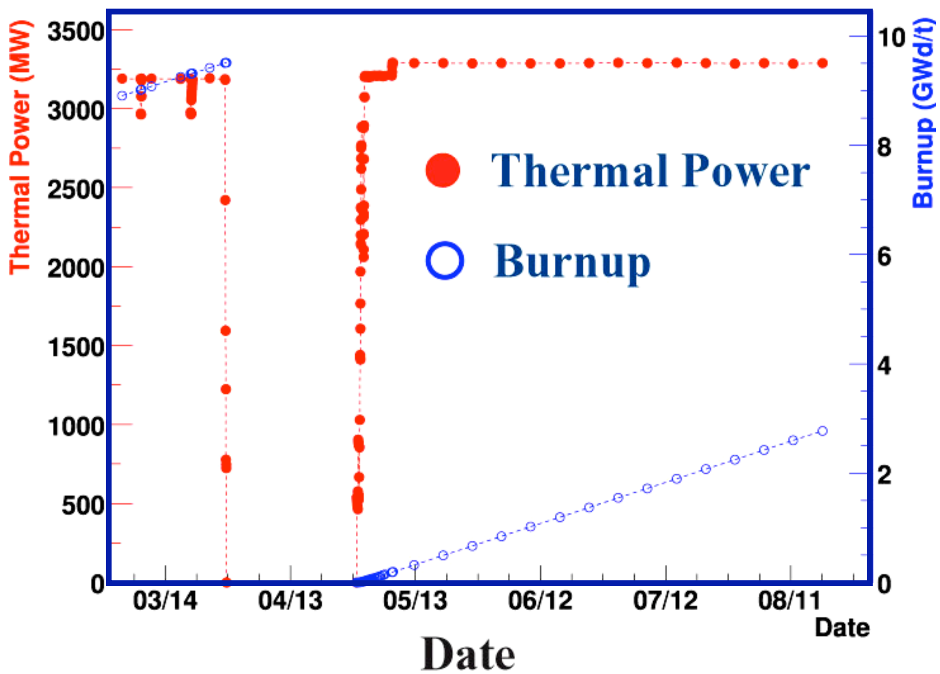


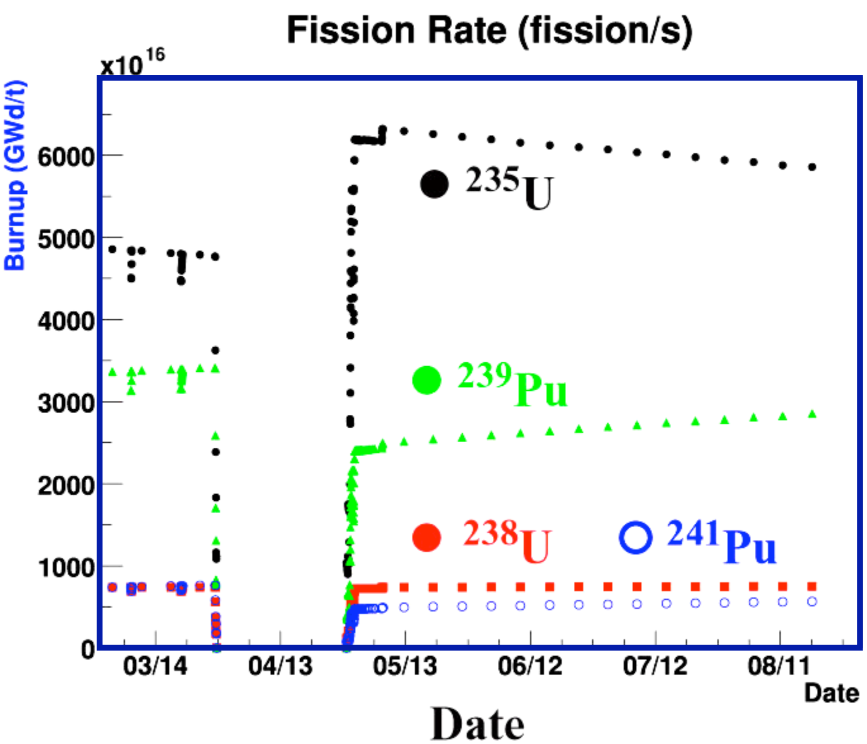
Uncertainty < 1% (neutrino yield)
: fuel-sampling & analyzing for isotopic components

→ **No need for near detector**

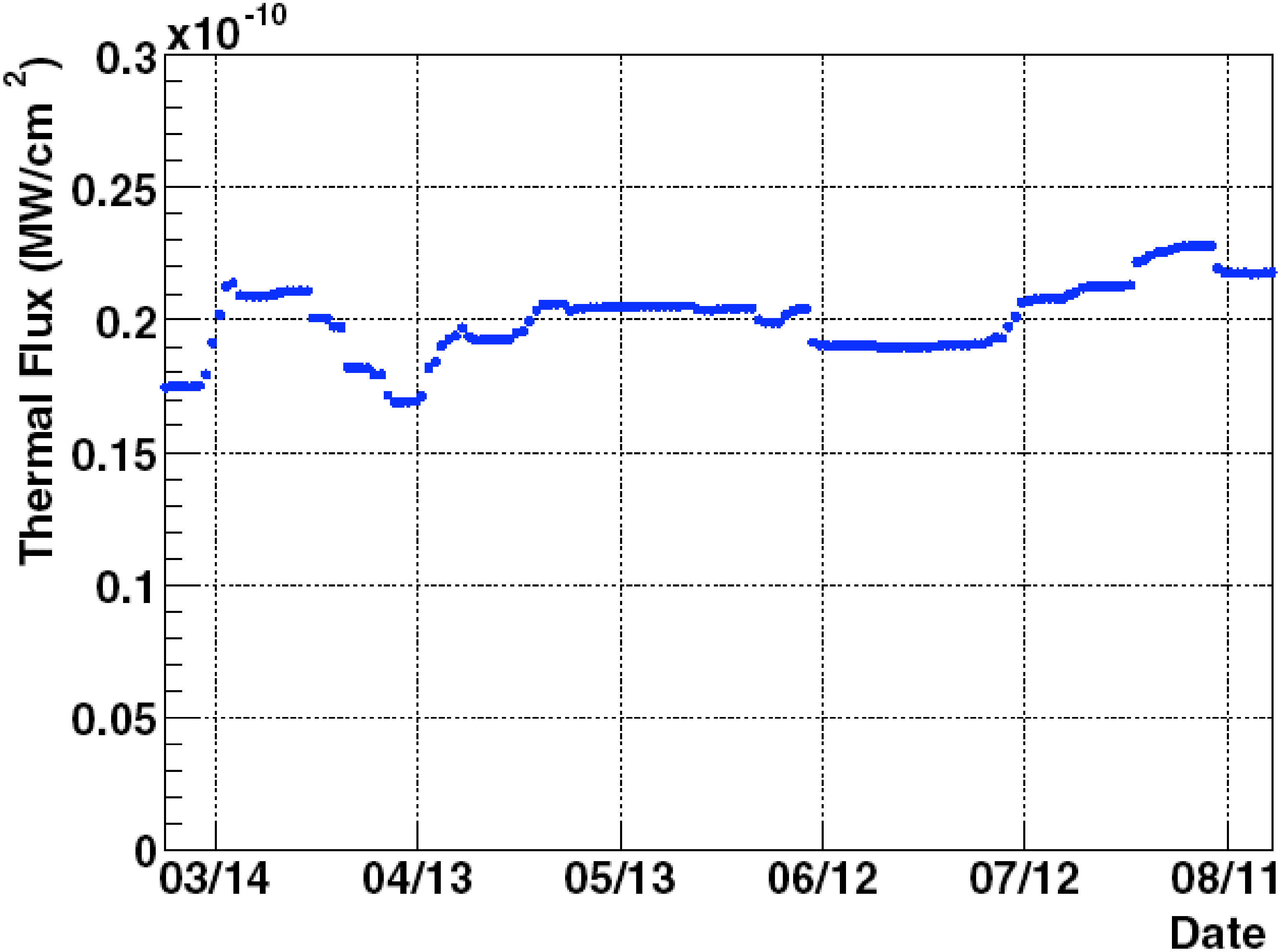
Thermal Power Data & Calculated Fission Rate

One of the Japanese Reactors

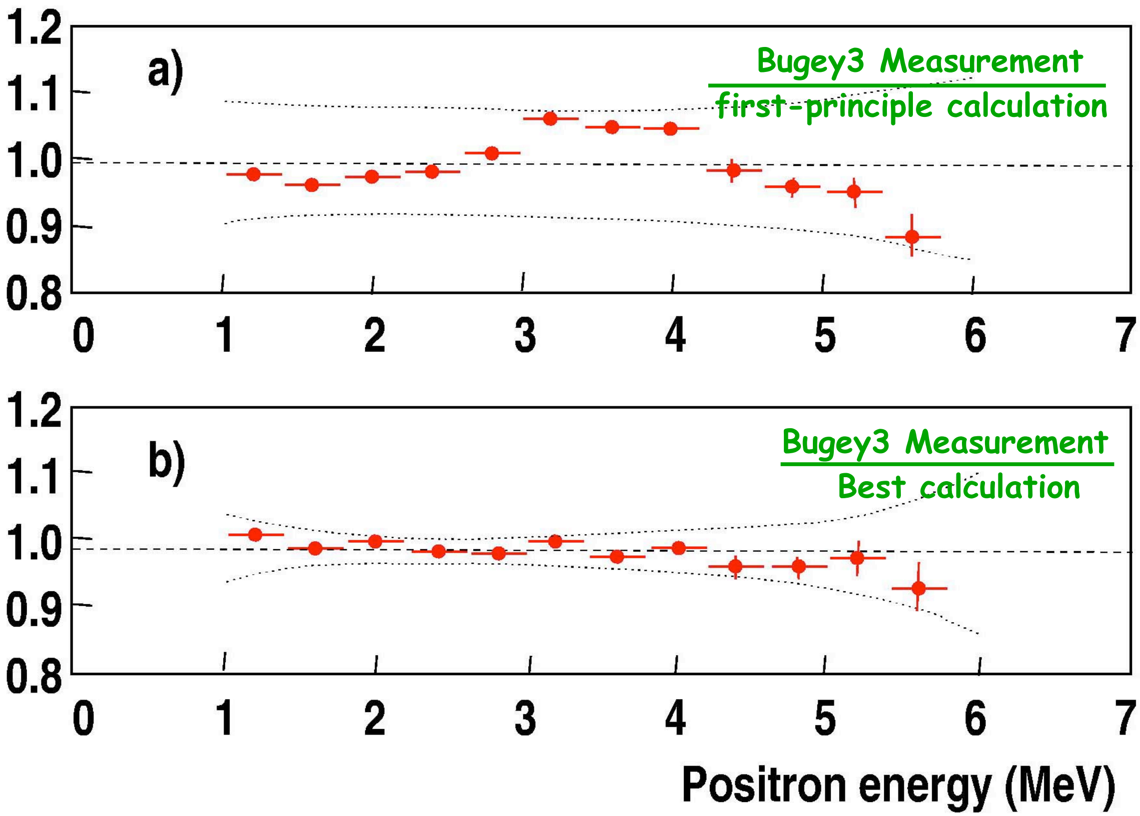


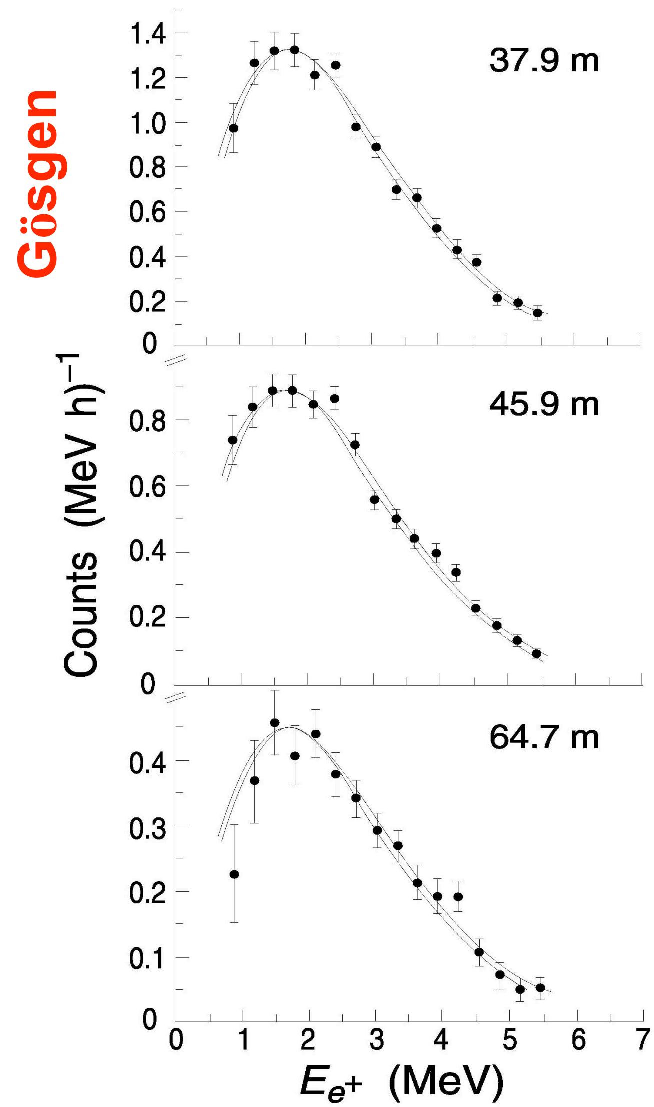


Thermal Flux from Japanese and Korean Reactors



Energy Spectrum of Reactor $\bar{\nu}_e$





- Measurements agree with expectations to ~2%:

  No near detector is needed !

Energy Spectrum of Reactor ν_e

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

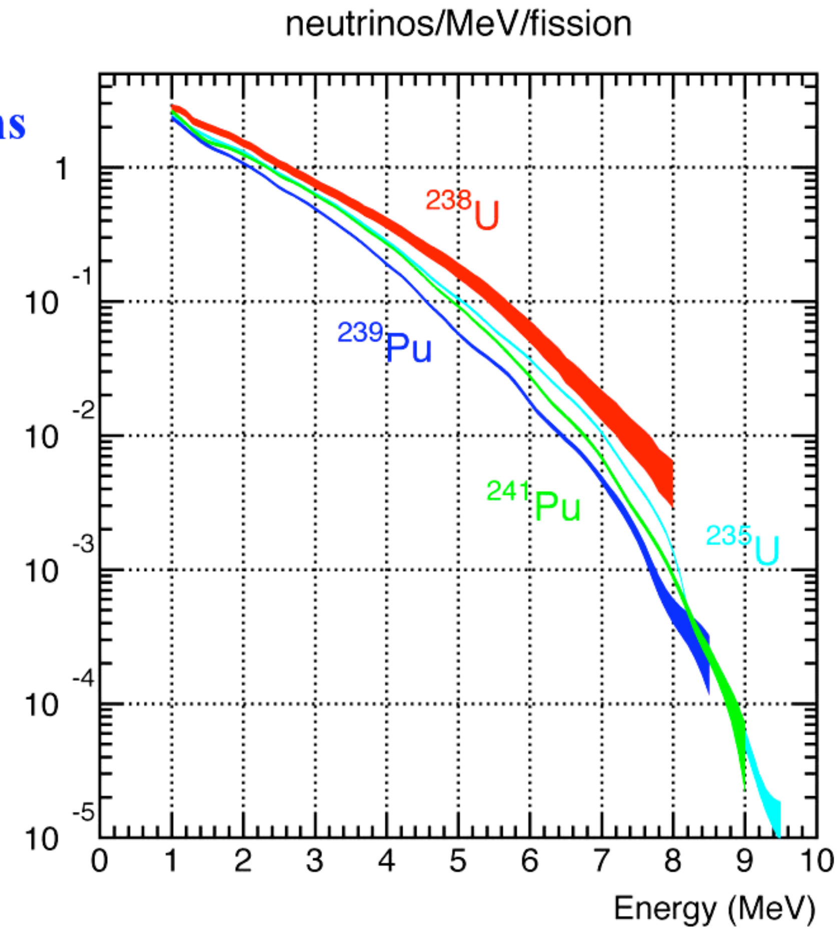
  measured β – spectra
  from thermal neutron fissions

  superposition of 30 hypothetical β-decay branches

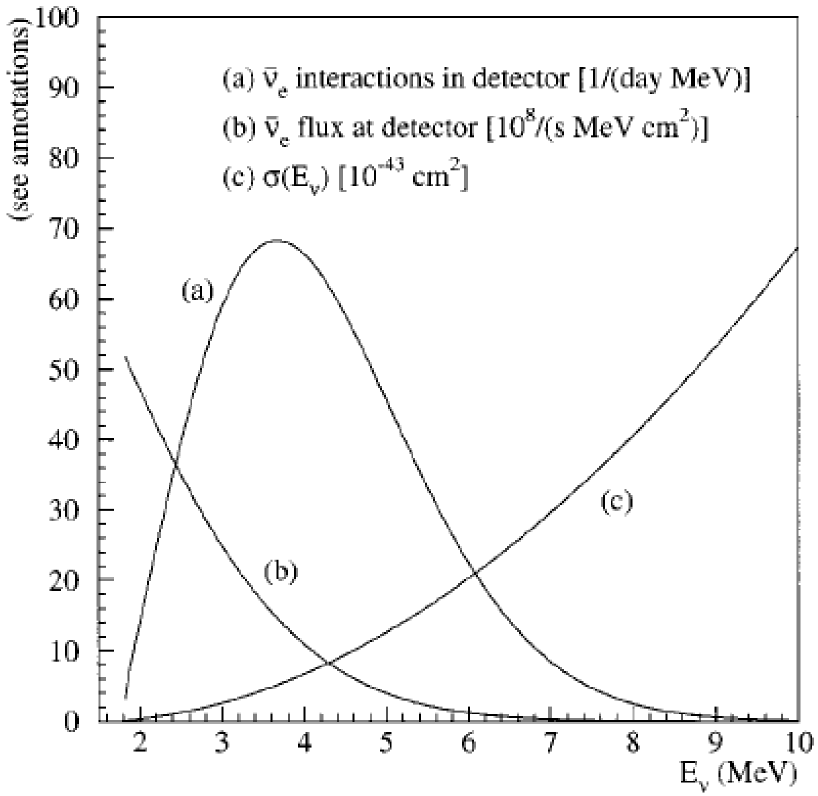
  conversion $E_e \longrightarrow E_\nu$

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

  calculation based on
  744 unstable fission products



Cross Section and Spectrum of Inverse Beta Decay



$$\sigma_{\text{tot}}^{(0)} = \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)}$$

$$= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1\ \text{MeV}^2} \right) \times 10^{-42}\ \text{cm}^2$$

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R)$$

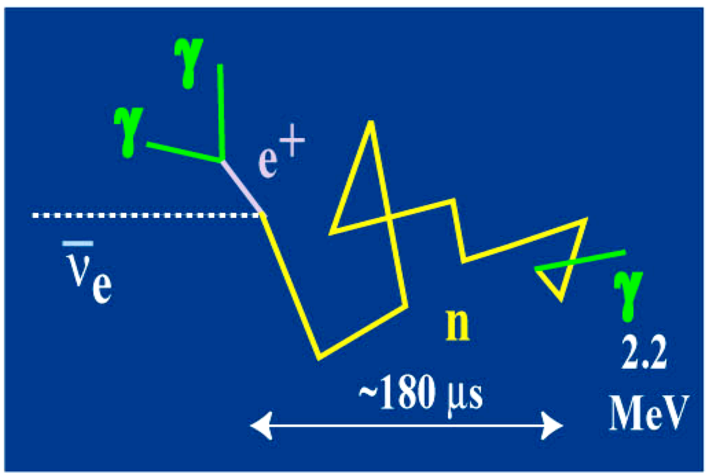
$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2 / m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

Detecting Reactor □$_e$ 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

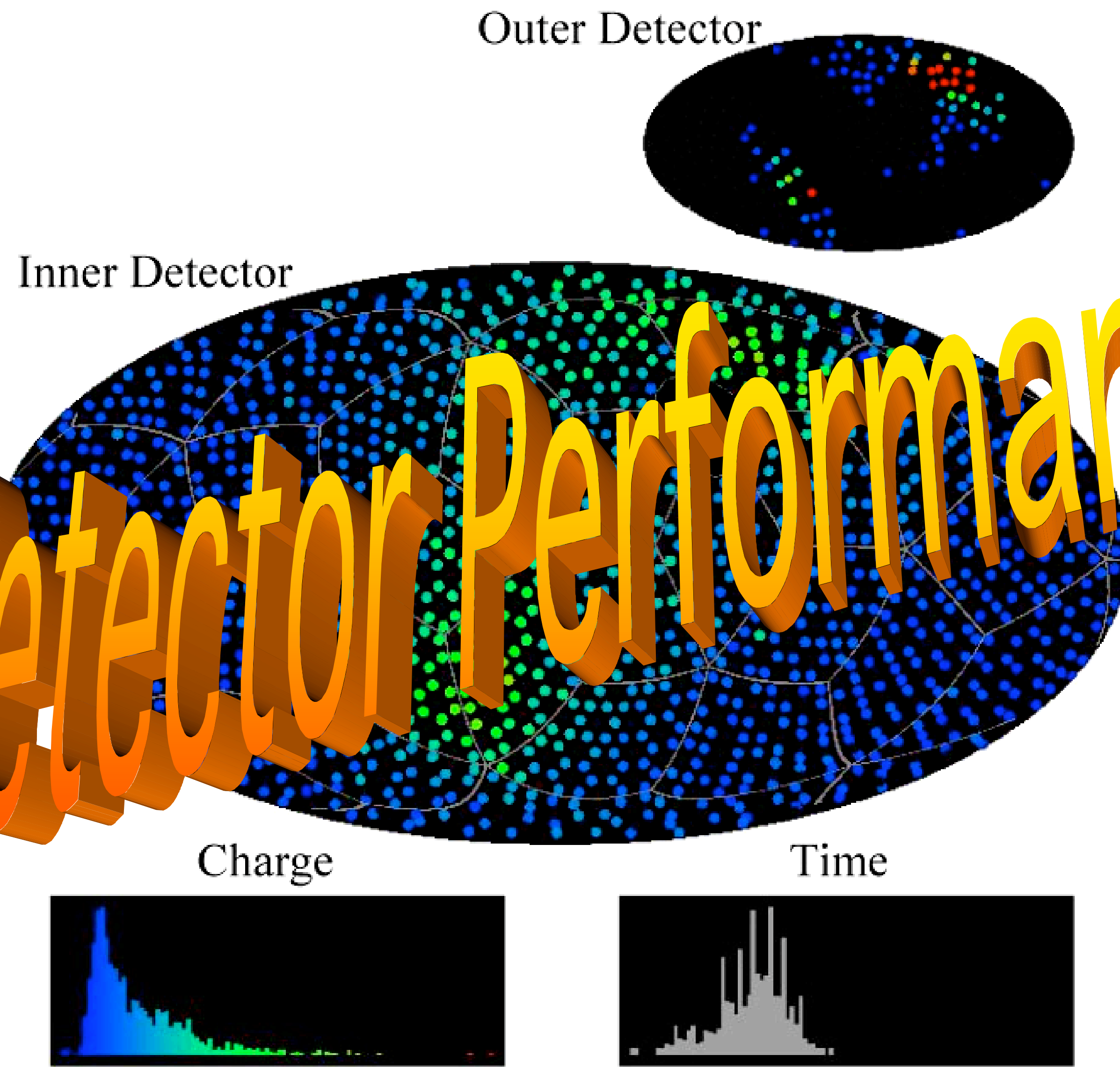
  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

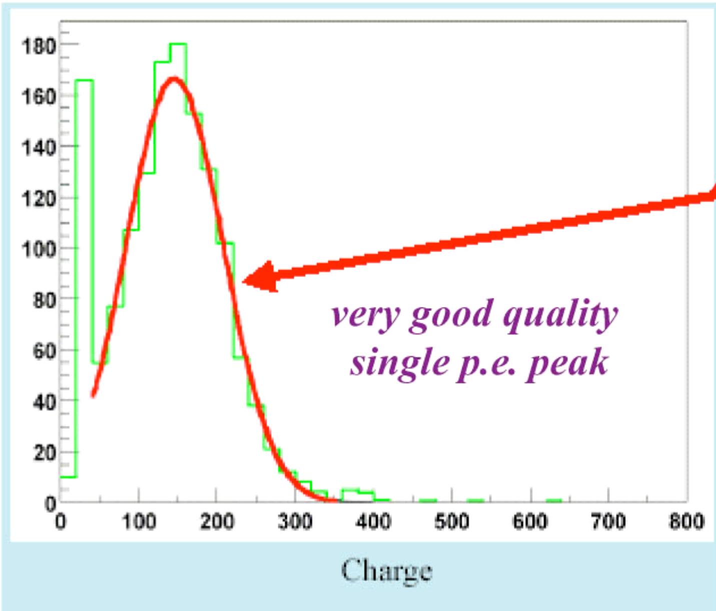
- **delayed part :** γ (2.2 MeV)

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

Detector Performance

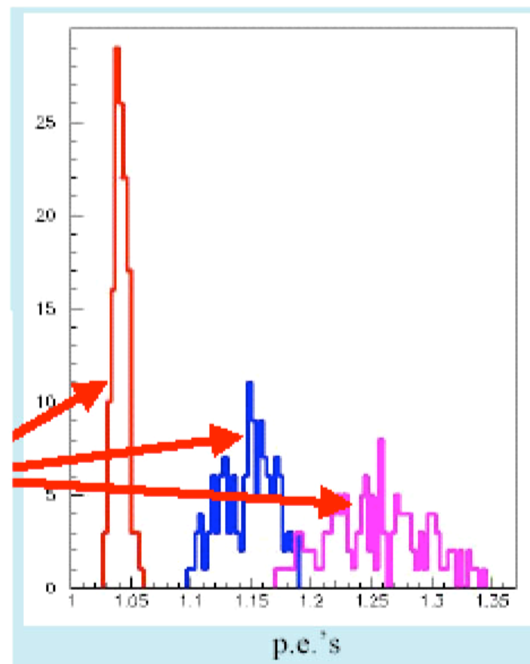


Performance of KamLAND Photodetectors



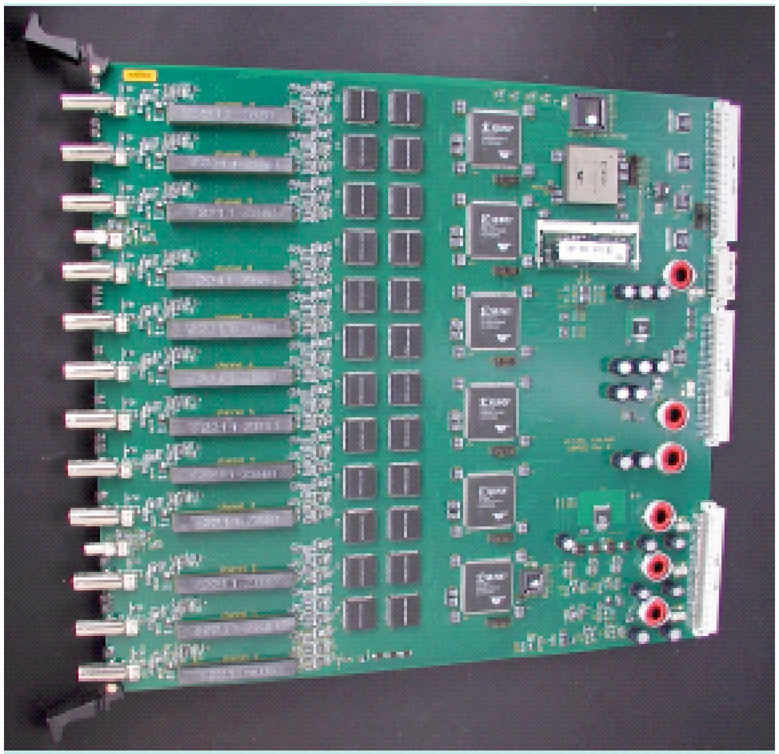
gain calibration :
single photoelectron peak
for each PMT

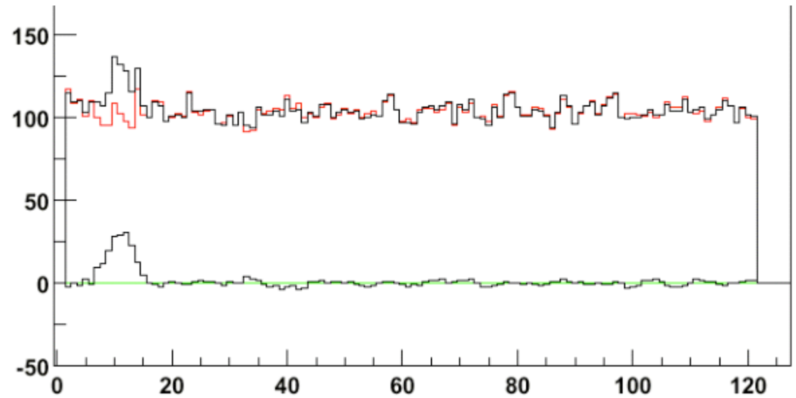
very good quality
single p.e. peak



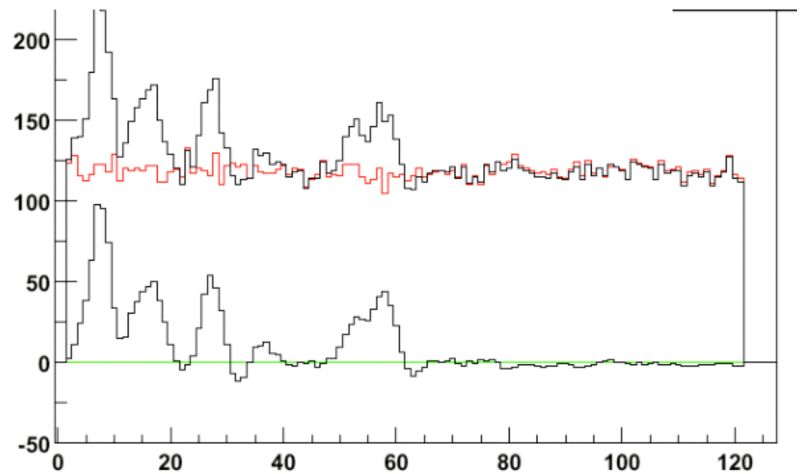
gain calibration at higher p.e.'s
: nitrogen laser
15 % intensity change with different filters

Waveform Capture Electronics





Typical single photon

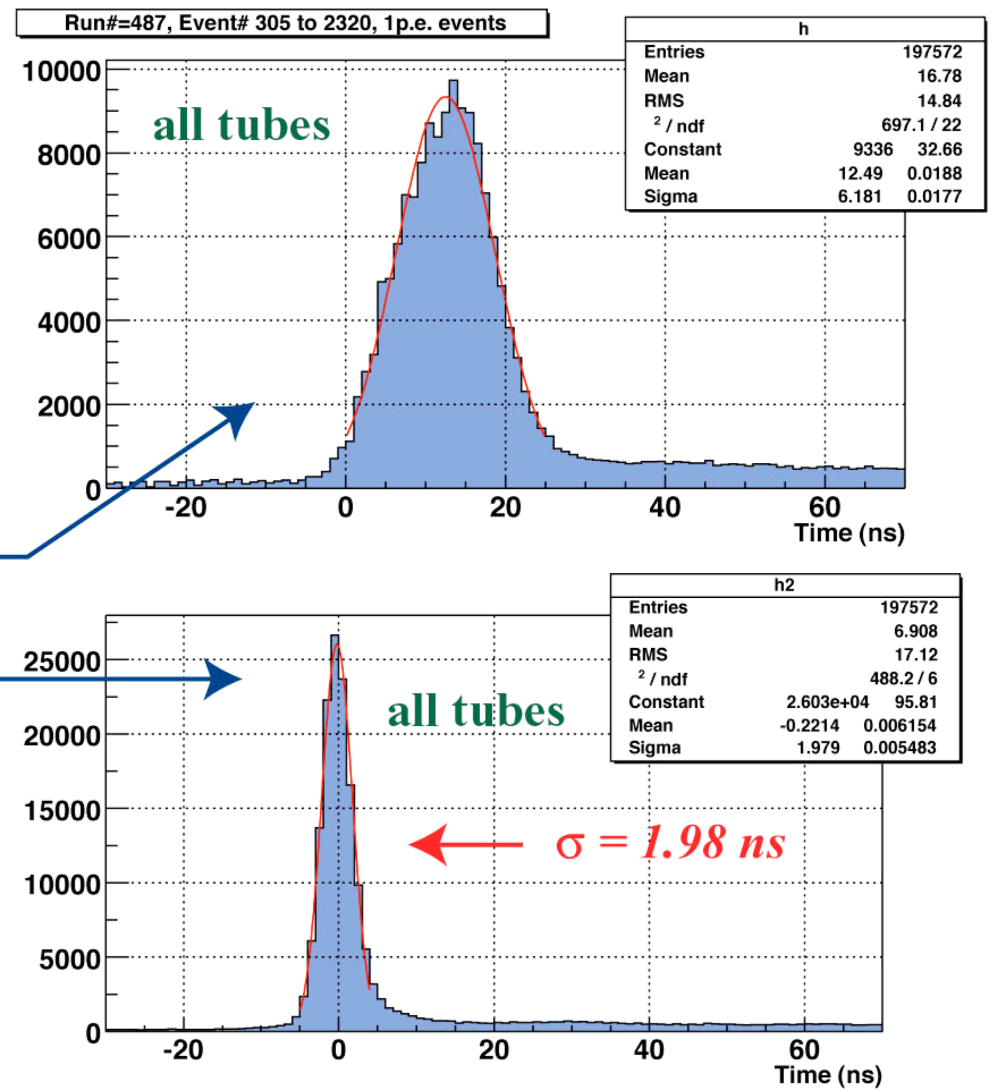


Atypical multi-pulse train

Timing Calibration of PMTs

Timing calibration was done using a dye laser (λ= 500 nm)

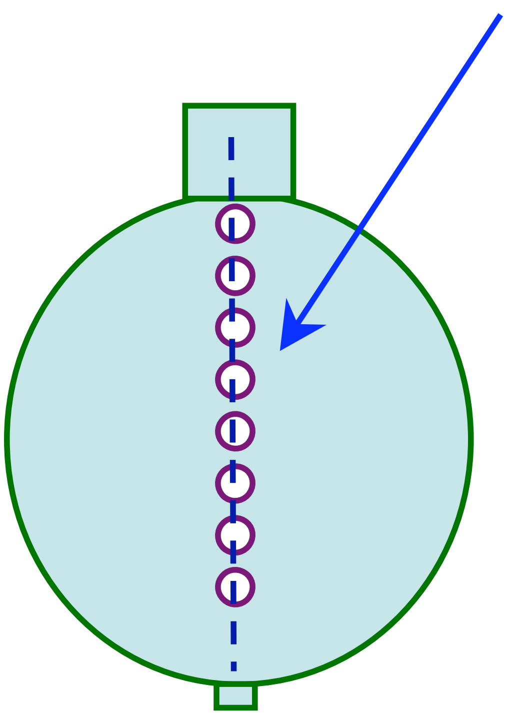
single p.e. events
before
and
after
correction

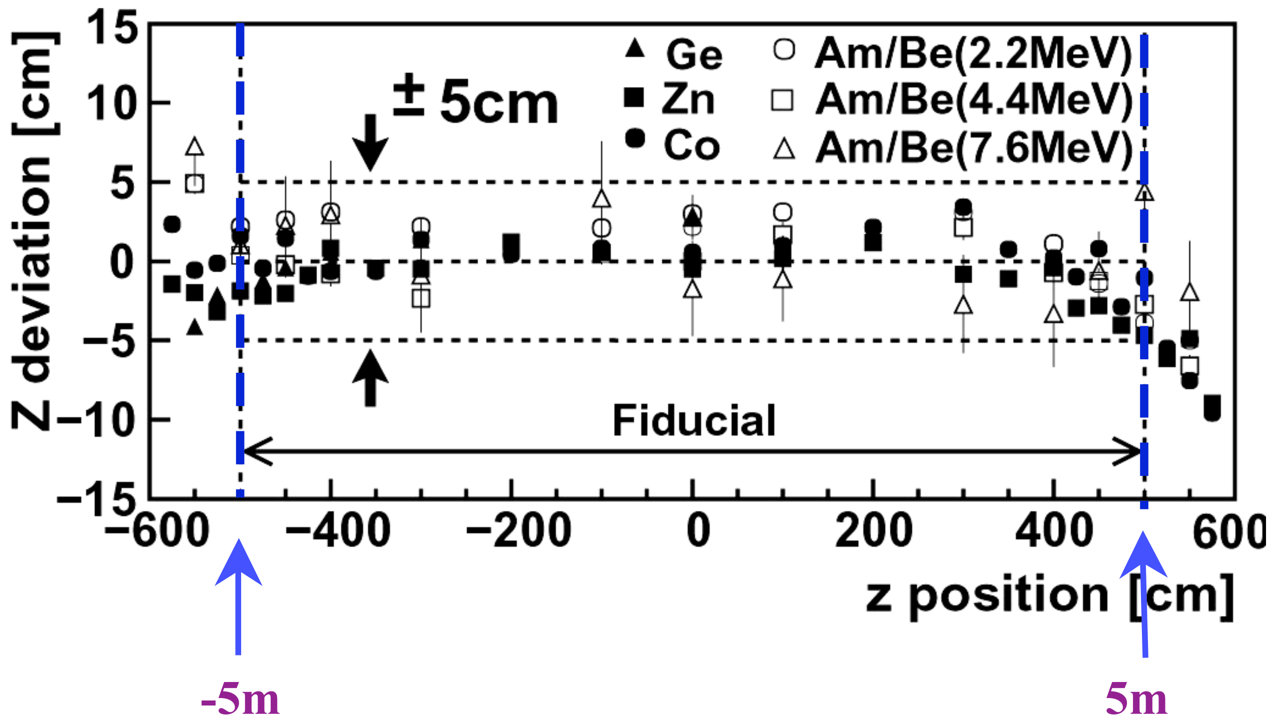


Position Reconstruction Uncertainty

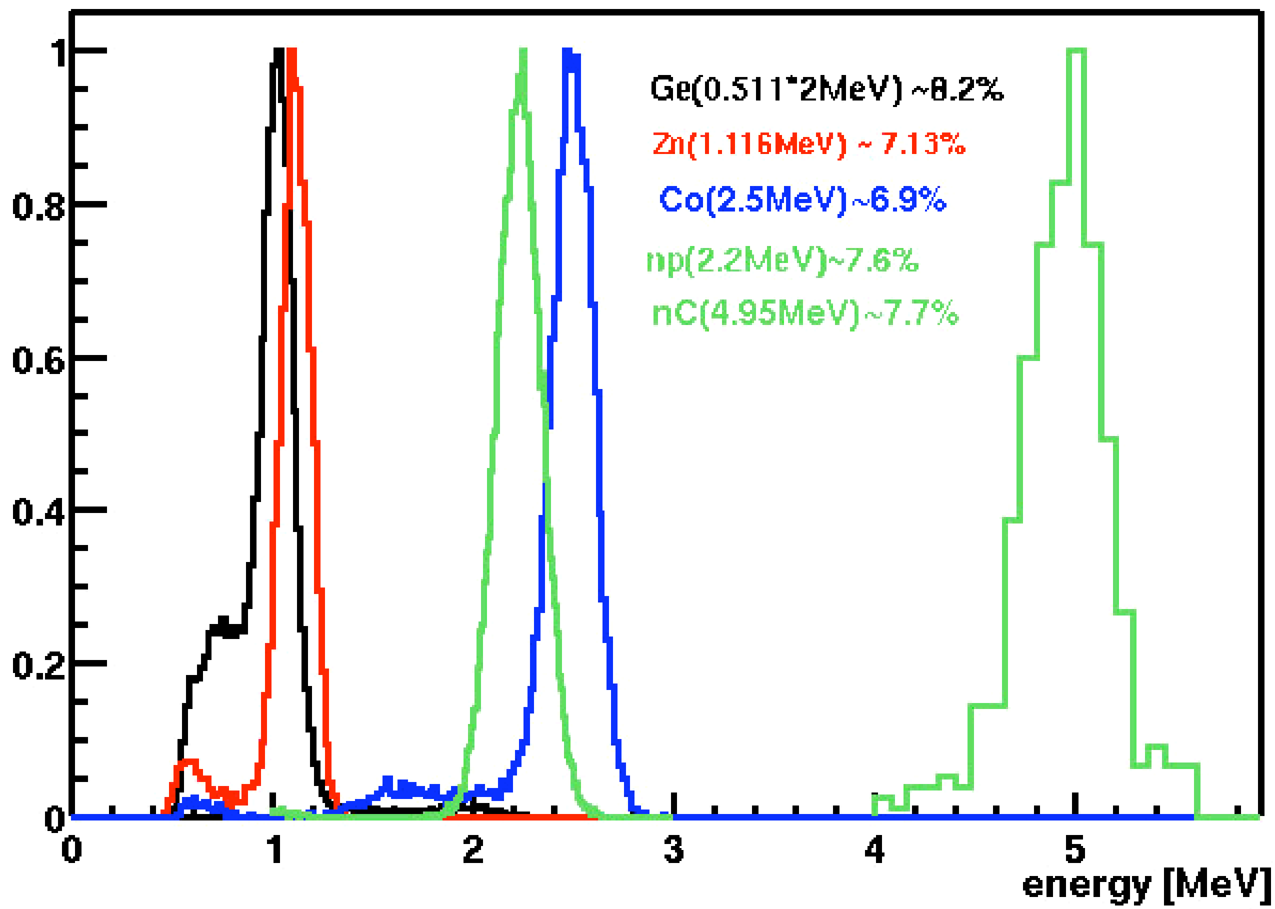
^{68}Ge : 1.012 MeV (□+ □) ^{65}Zn : 1.116 MeV (□)

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





Energy Determination & Resolution

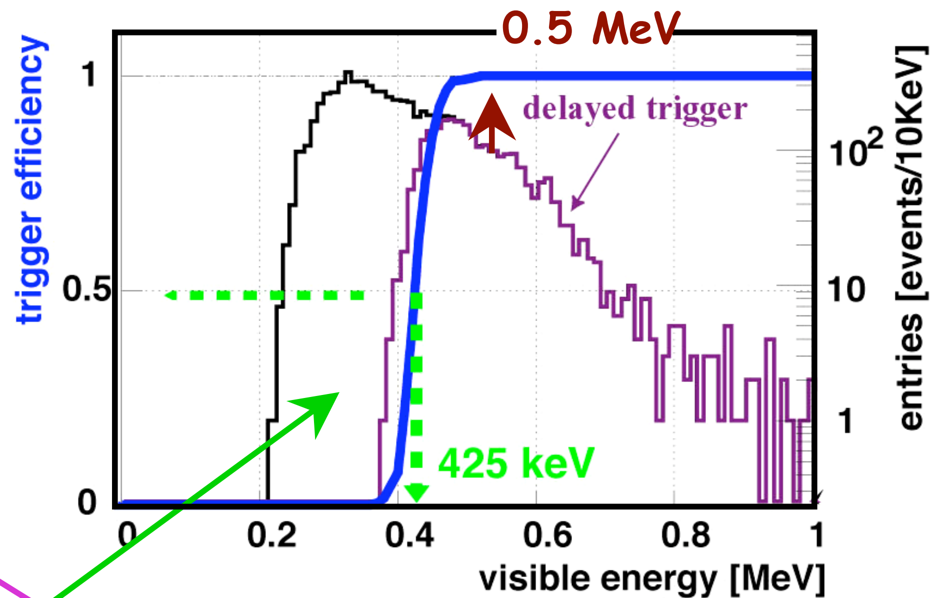


□E_{syst} = 1.91% at 2.6 MeV → 2.13% for □$_e$

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

Energy scale stable to 0.6% through out the period

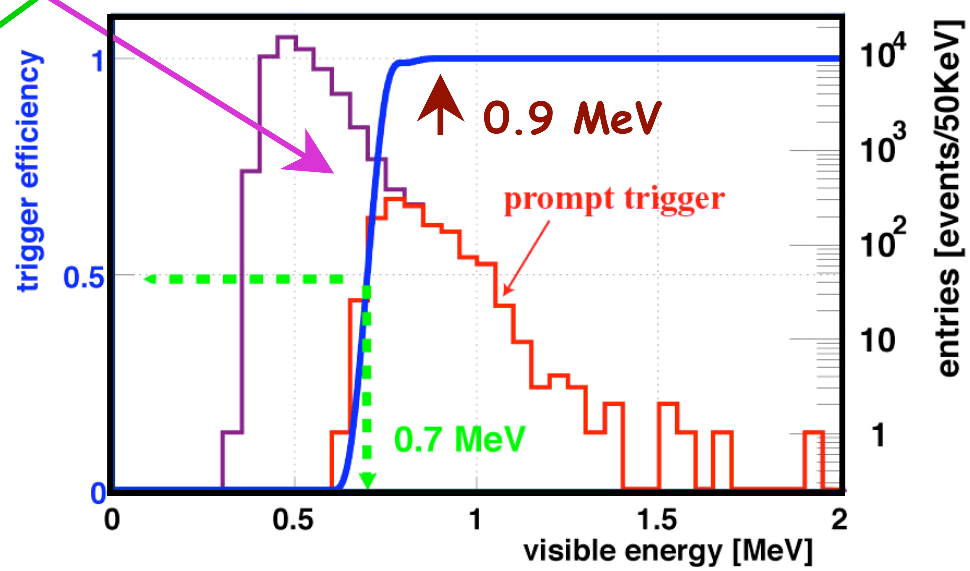
Trigger Efficiency



KamLAND Trigger Scheme

prompt trigger:
200 PMT hits (0.7 MeV)

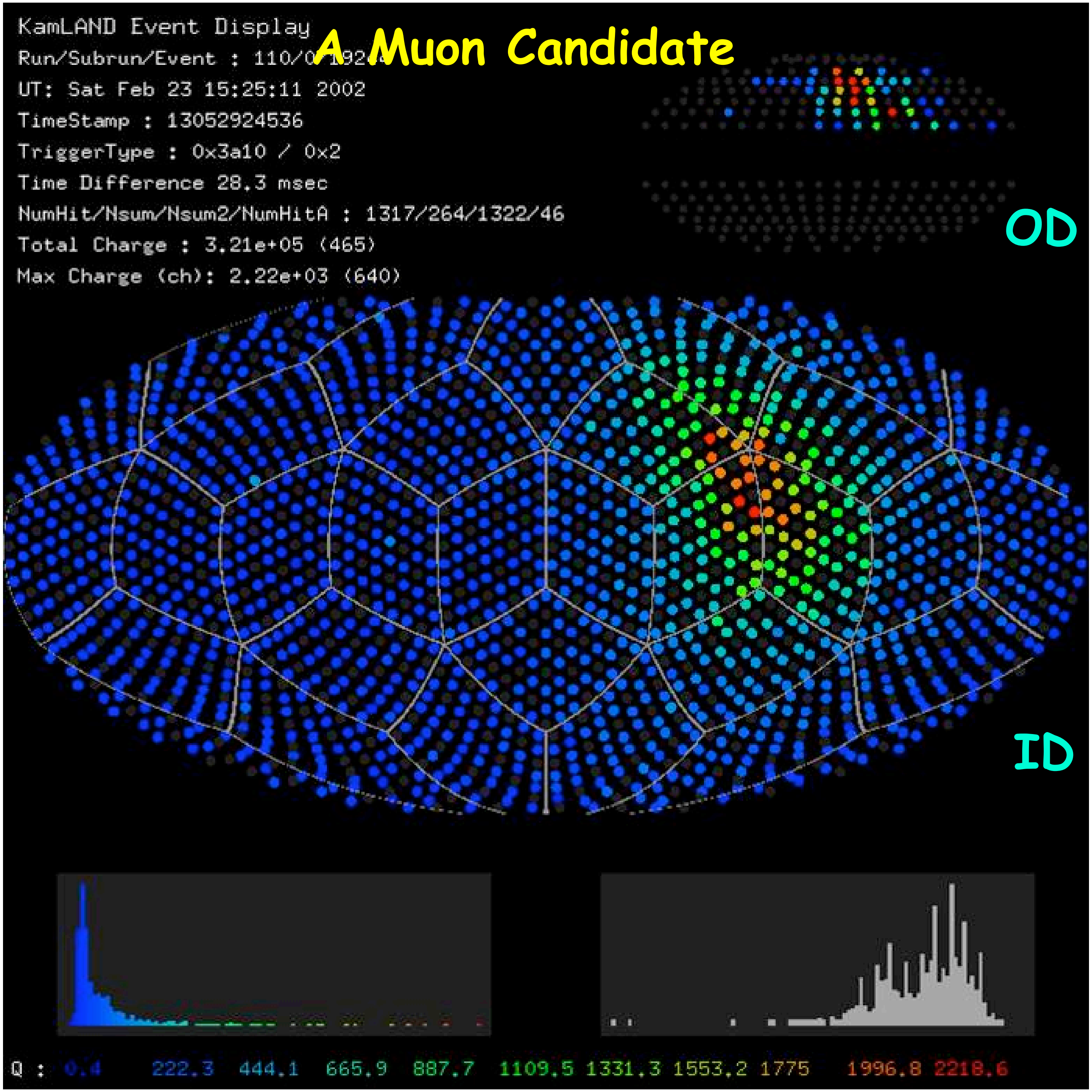
delayed trigger:
120 hits for 1 msec. after primary trigger



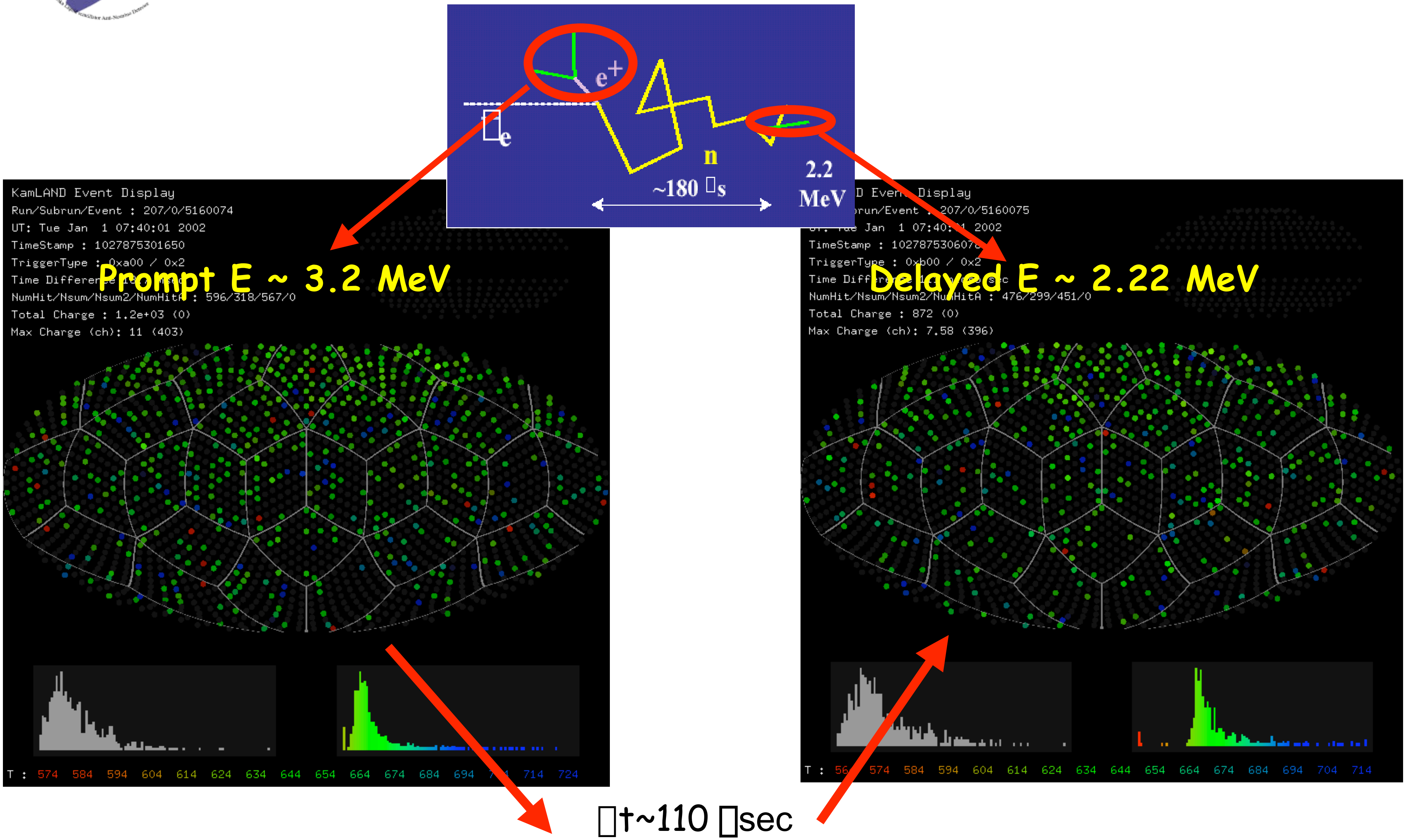
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

$$+ p \longrightarrow d + \gamma$$

A Muon Candidate



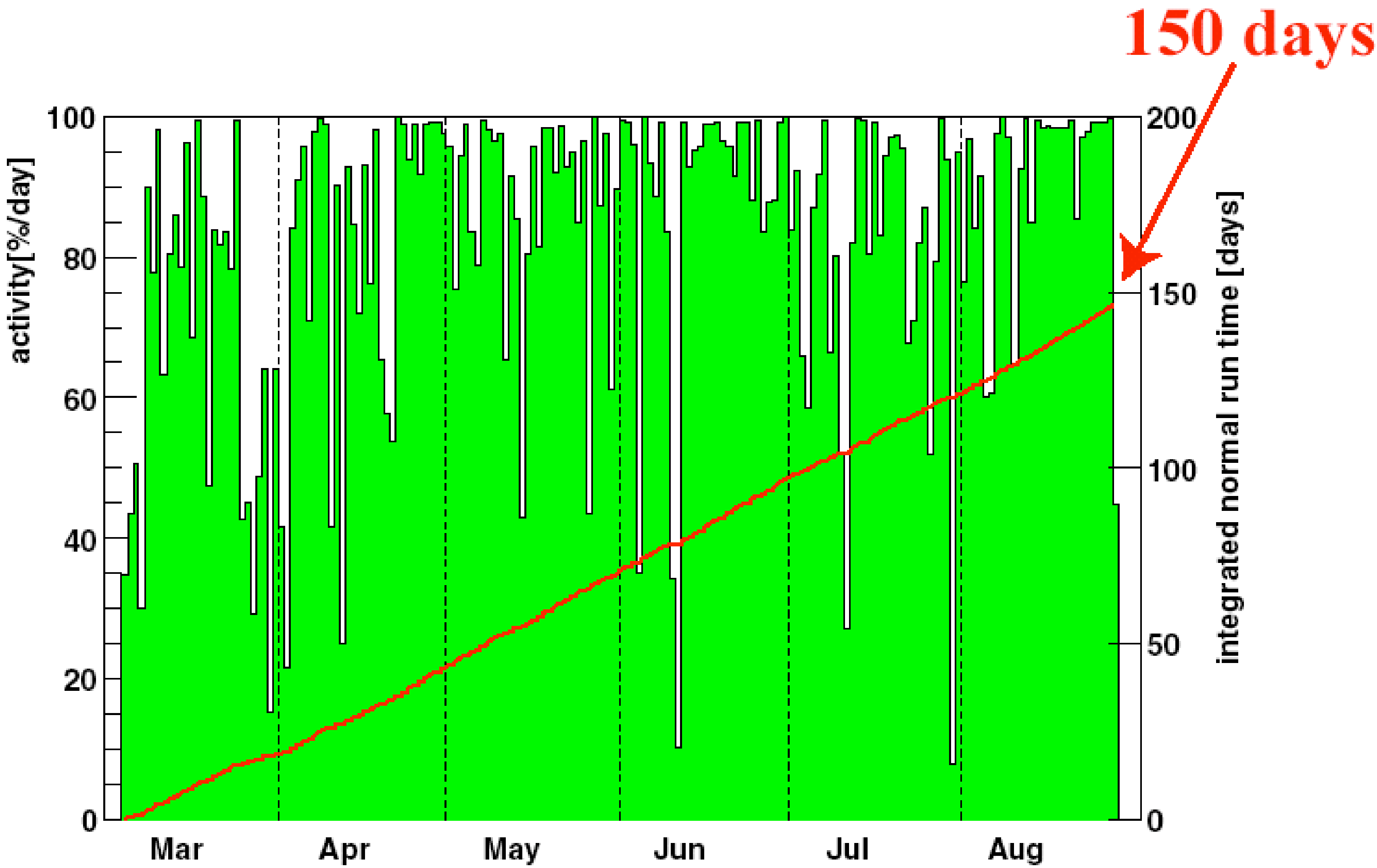
An Anti-neutrino Candidate



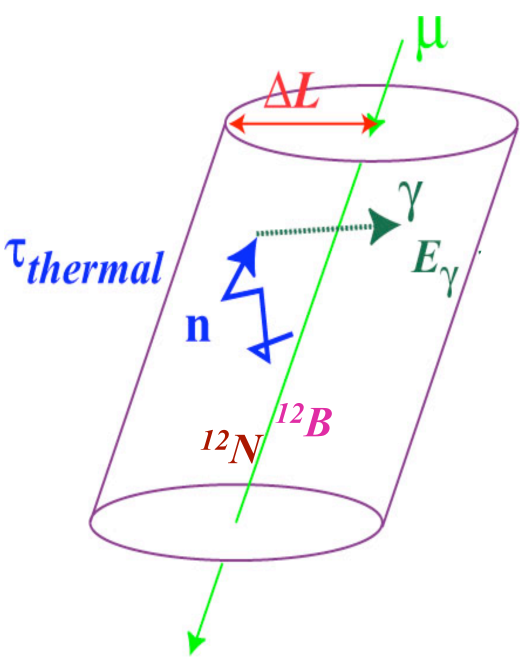
Δt~110 μsec

ΔR~0.35 m

Data-Collection Up Time

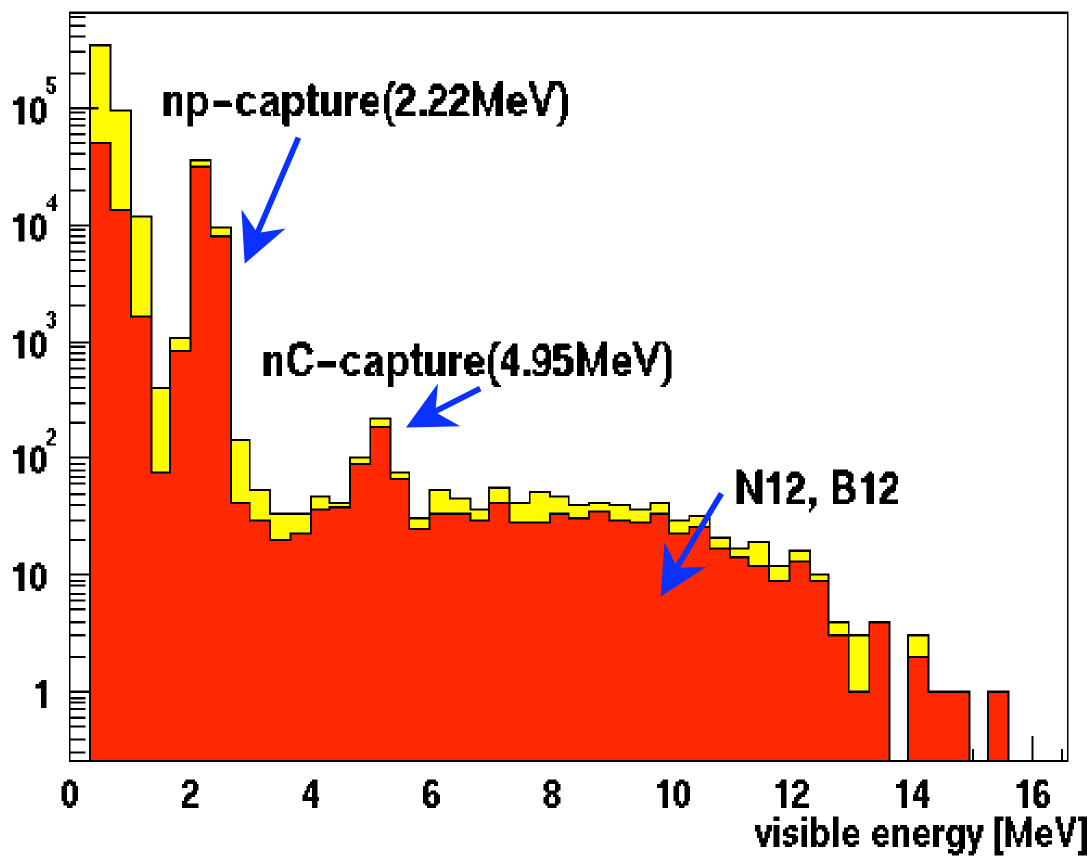


□-Induced Neutrons & Spallation-$^{12}B/^{12}N$



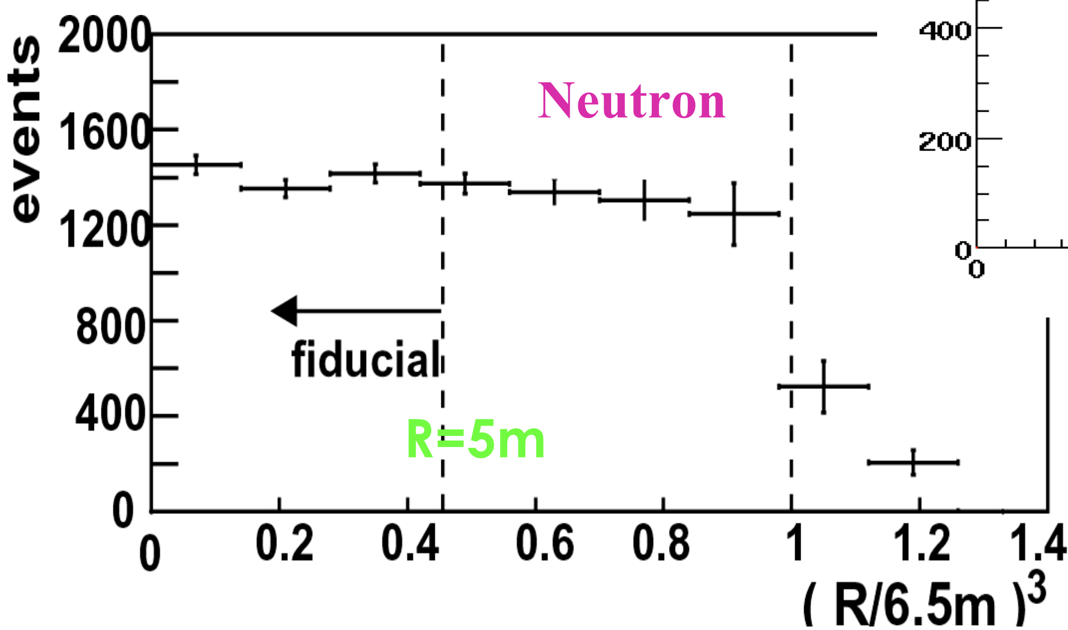
yellow: after muon 150usec~10msec

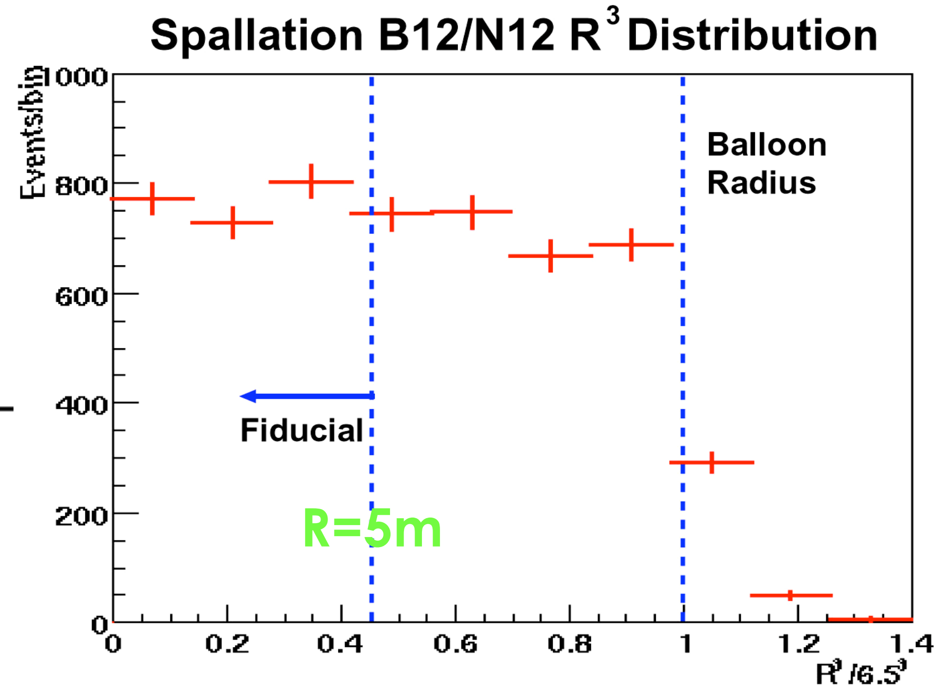
red: apply □L < 3m



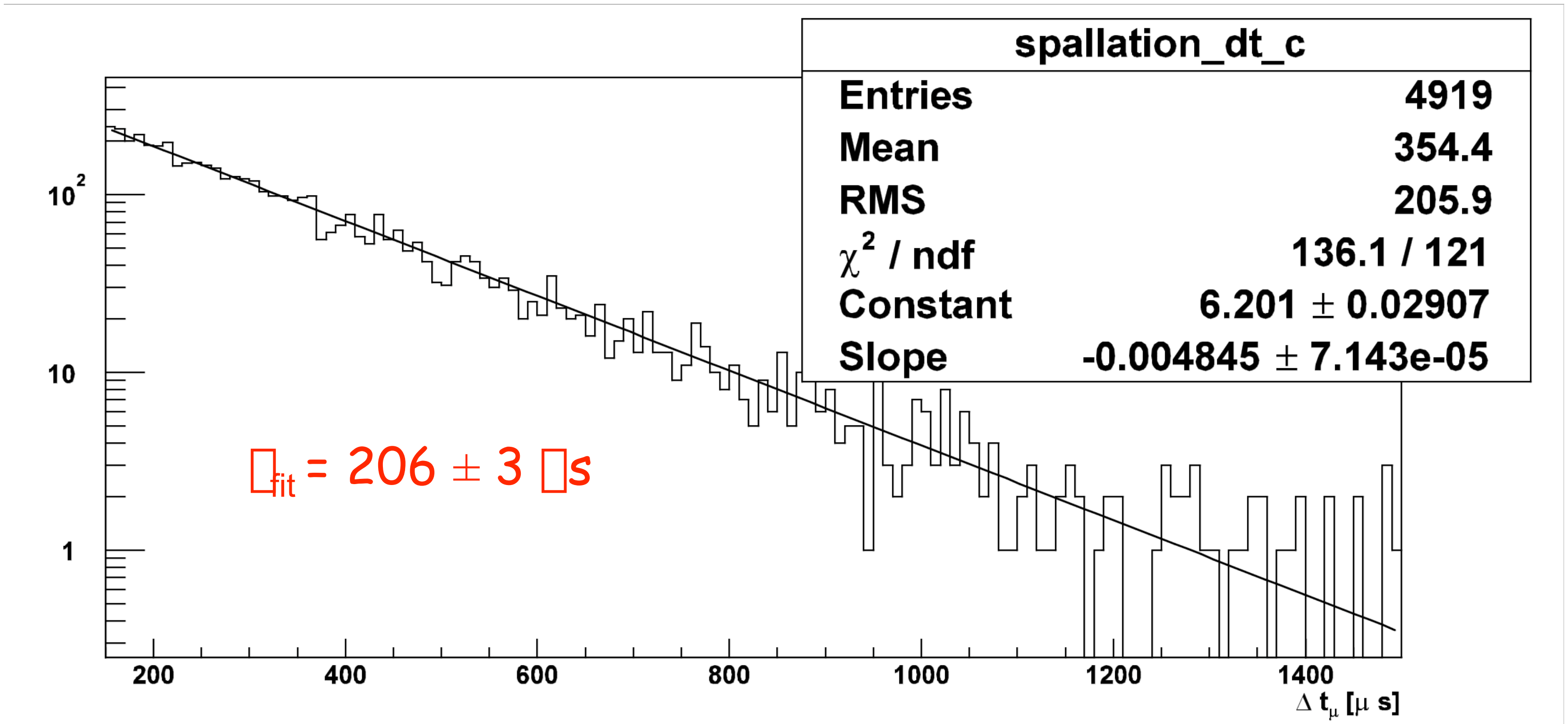
R^3 Vertex Distributions of Neutrons & $^{12}B/^{12}N$

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





Test of n-Capture Time With Cosmic-ray Muon-Induced Neutrons



Requirements:

E_p > 10 MeV, E_d = 1.8-2.6 MeV, Δt_{pd} = 150-1500 μs, r_{pd} < 5 m

Radioactivity inside Liquid Scintillator

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

$\beta+\gamma$: $E = 3.27\ MeV$, $\tau = 28.7\ min.$

α: $E = 7.69\ MeV$, $\tau = 237\ \mu s$

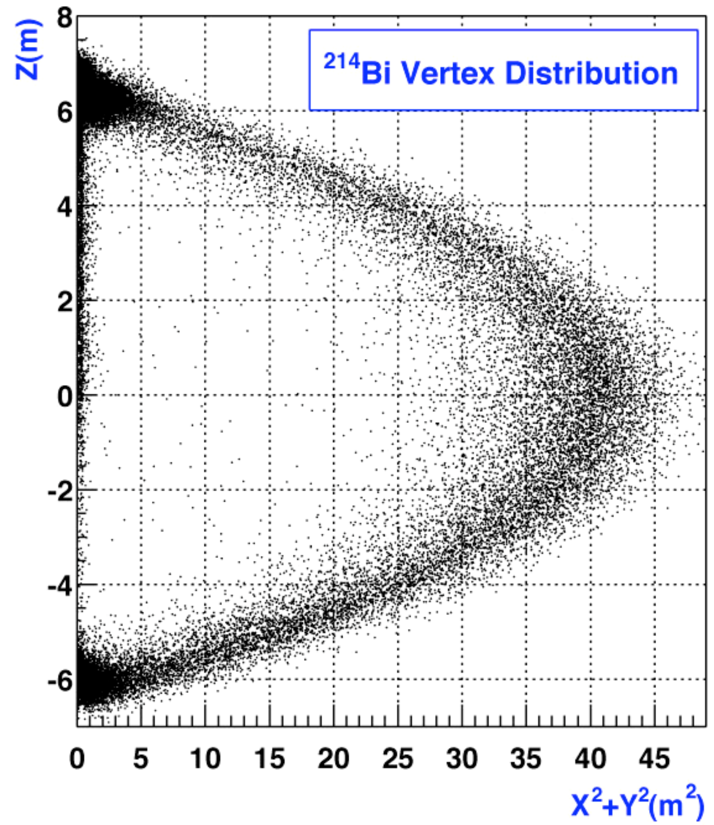
event selection

$\Delta R < 100\ cm$

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

$E_{prompt} > 1.3\ MeV$

$0.3 < E_{delayed} < 1\ MeV$

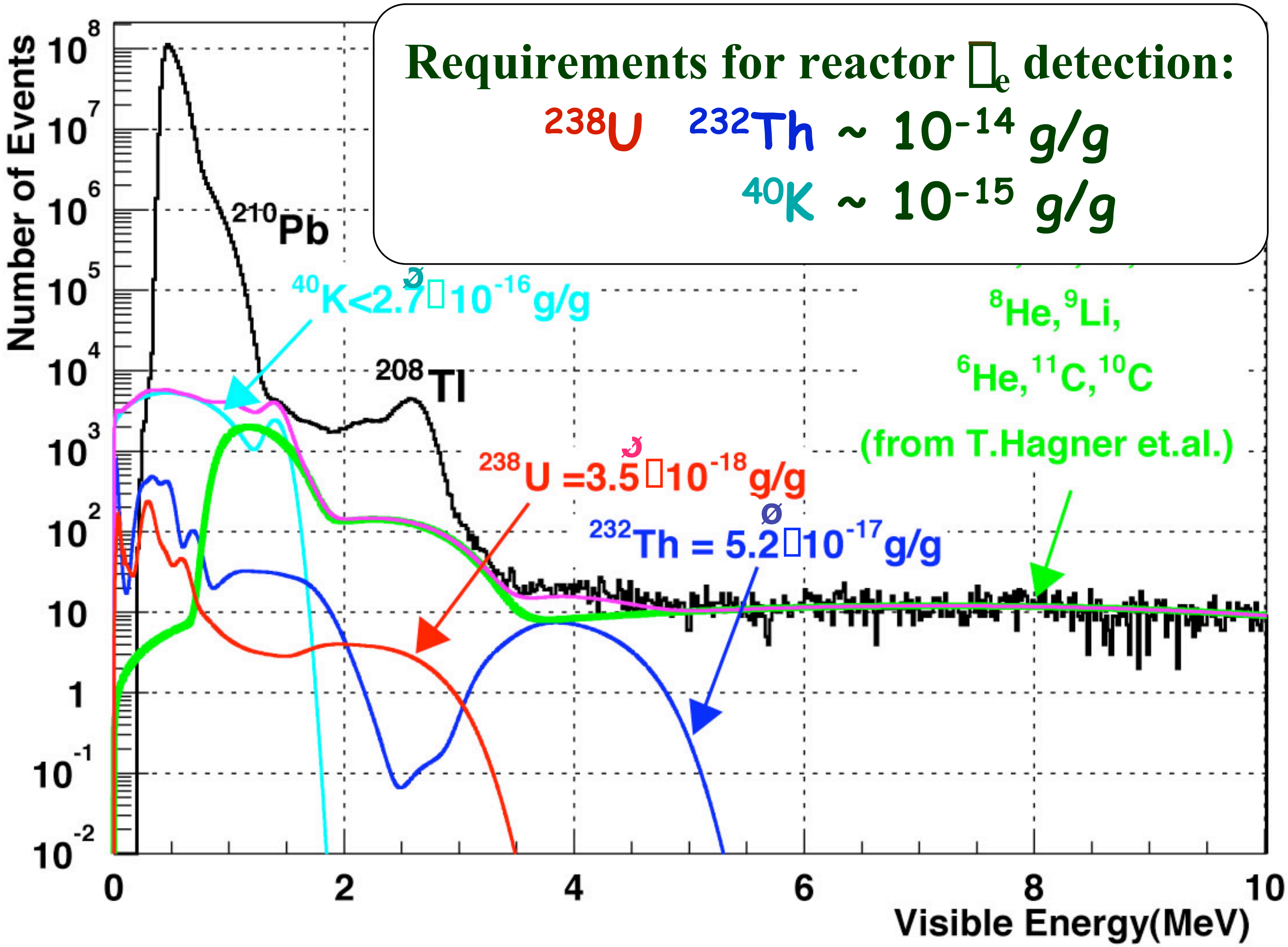


Energy Spectrum of Radioactivity inside Liquid Scintillator

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

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

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

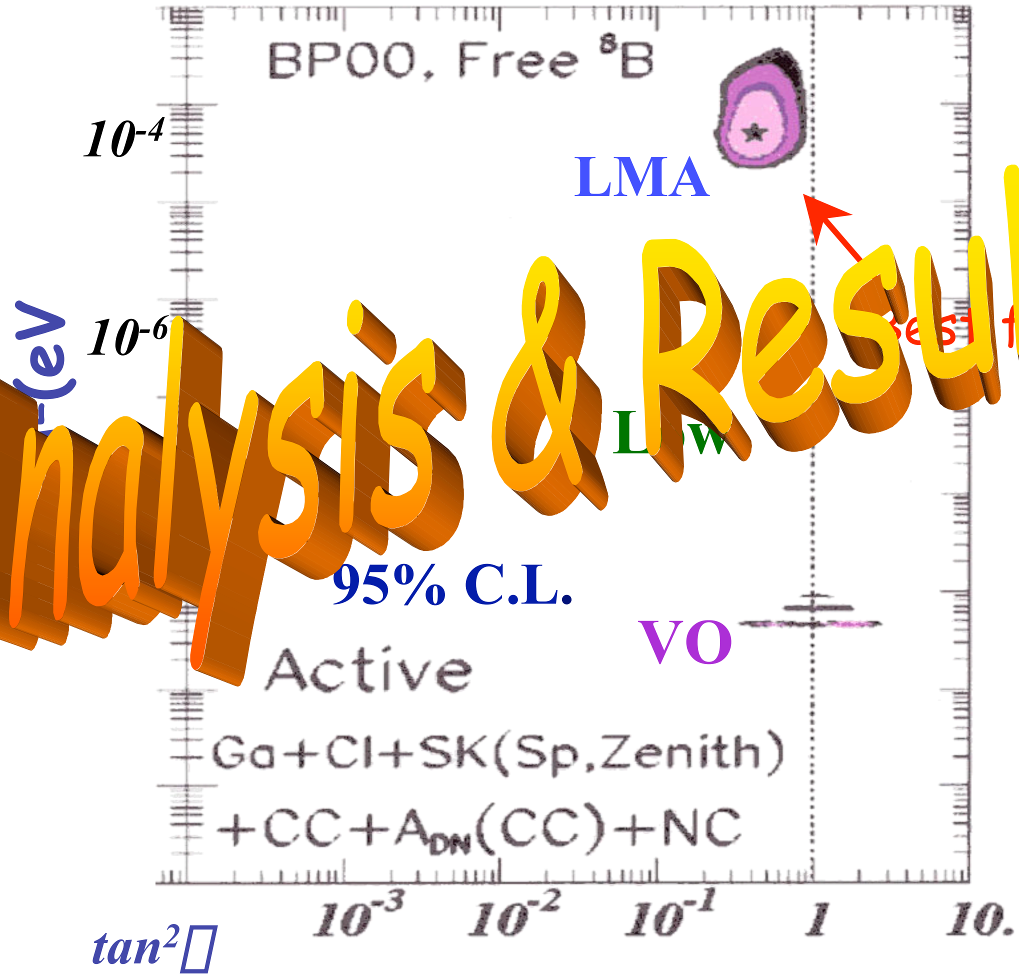


Estimated Systematic Uncertainties

E > 2.6 MeV

	%	
Total LS mass	2.13	4.60 (combined)
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	
$\bar{\nu}_e$ spectra	2.48	
Cross section	0.2	
Total Uncertainty	**6.42 %**	

Analysis & Results

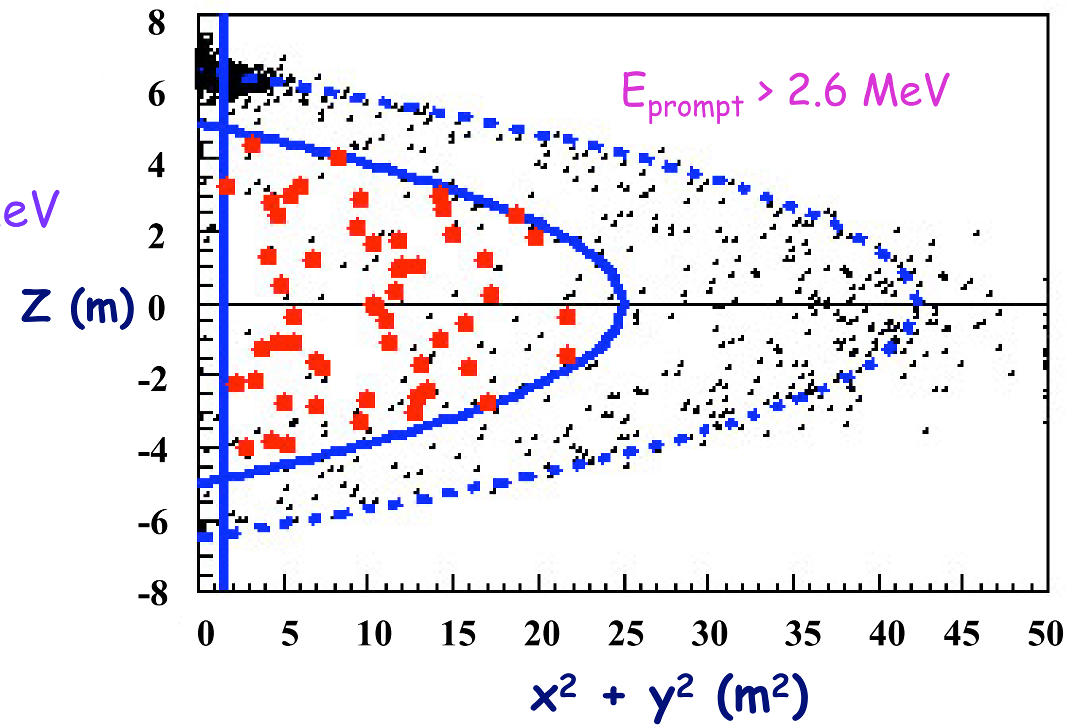


$\bar{\nu}_e$ Event Selection

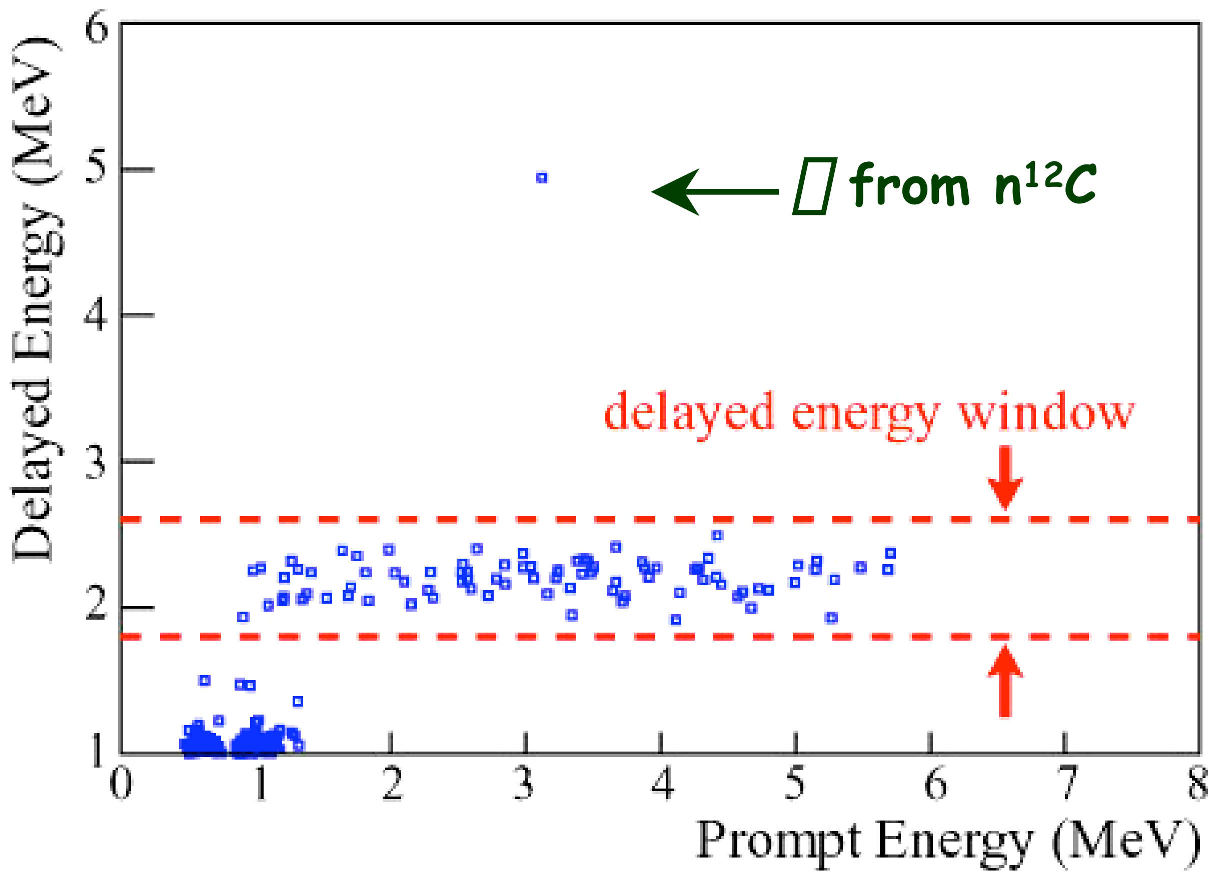
Data Sample

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

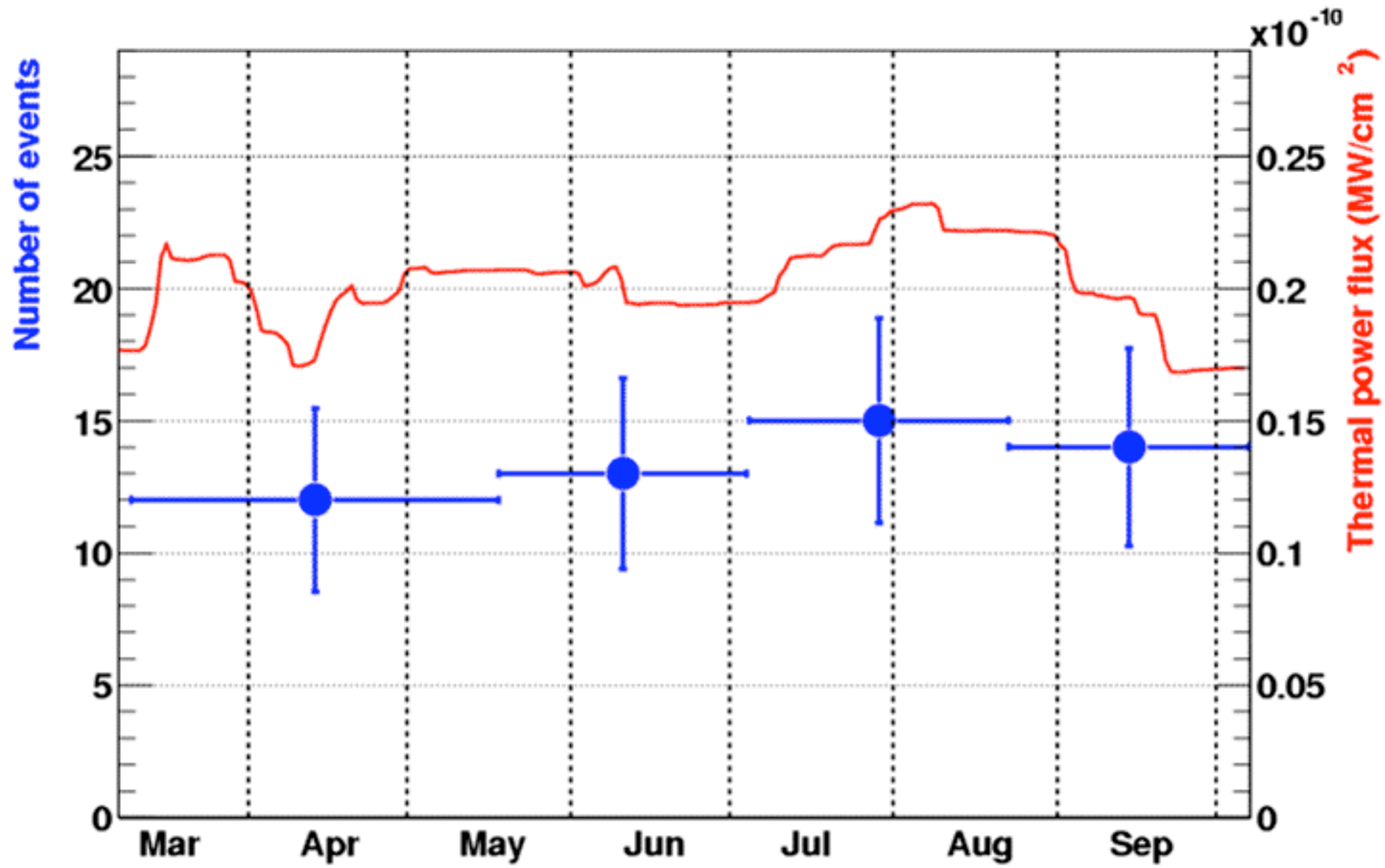
- Inverse β-decay selection
  - E_{prompt} > 2.6 MeV
  - no OD signals
  - 0.5 < ΔT < 660 μsec
  - ΔR < 1.6m, 1.8 < E_{delay} < 2.6 MeV
  - tagging efficiency 78.3% (AmBe, LED)
- Spallation event cut
  - ΔT_μ < 2sec , ΔE_μ > 3 GeV or ΔR_μ < 3m
- Fiducial selection
  - R < 5m : 408 ton, 3.46×10^{31} free protons



Correlation Between Prompt and Delayed Energies



Time Variation of Reactor Power and Signal



2002

Observed Event Statistics

Based on 162 ton·yr, with E_{prompt} > 2.6 MeV

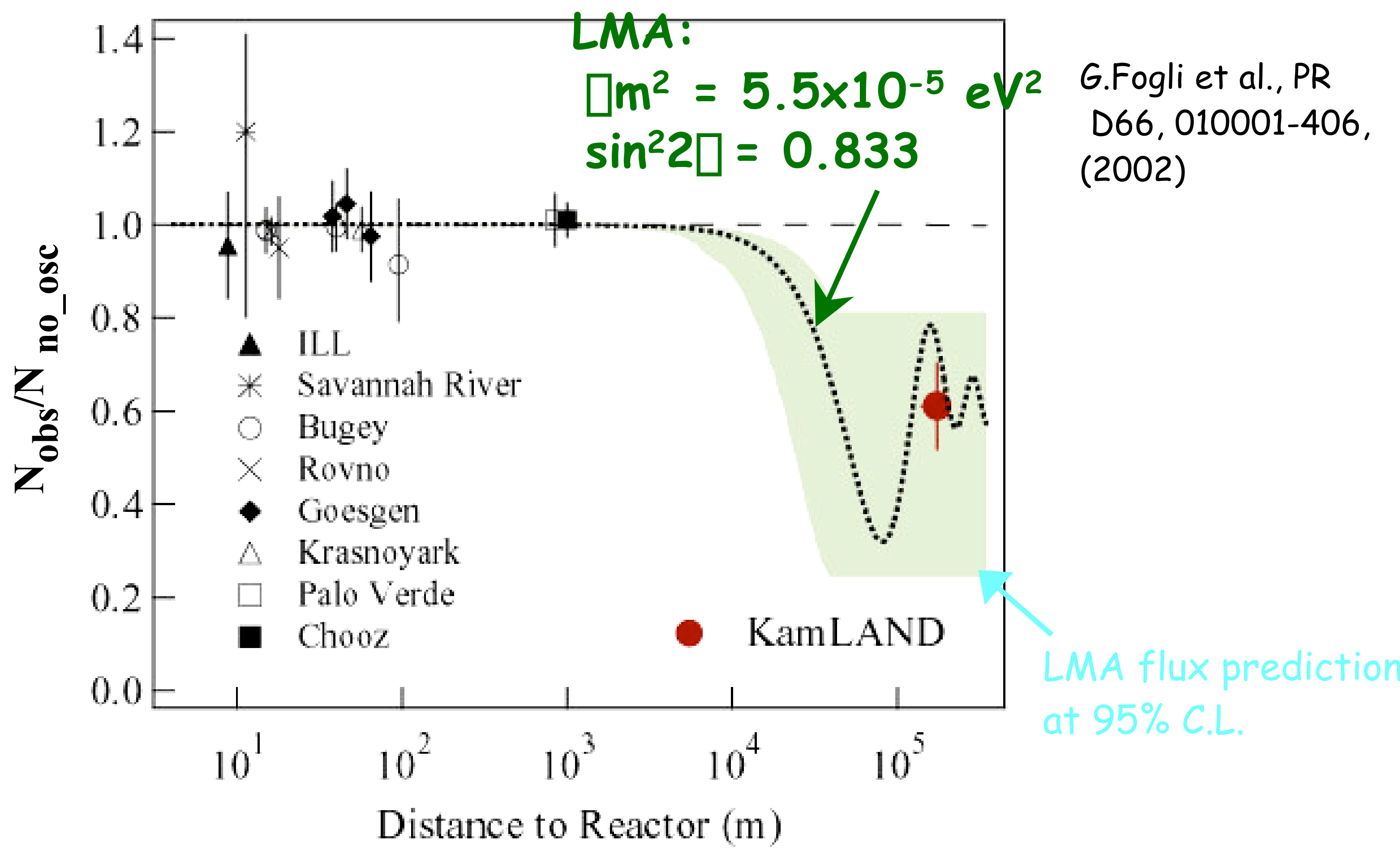
Final sample	54
Expected	86.8 ± 5.6(sys)
Background	0.95 ± 0.99
Accidental	0.0086 ± 0.0005
$^{9}Li/^{8}He$ (□, n)	0.94 ± 0.85
fast neutron	< 0.5

Evidence for Reactor ν_e Disappearance

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

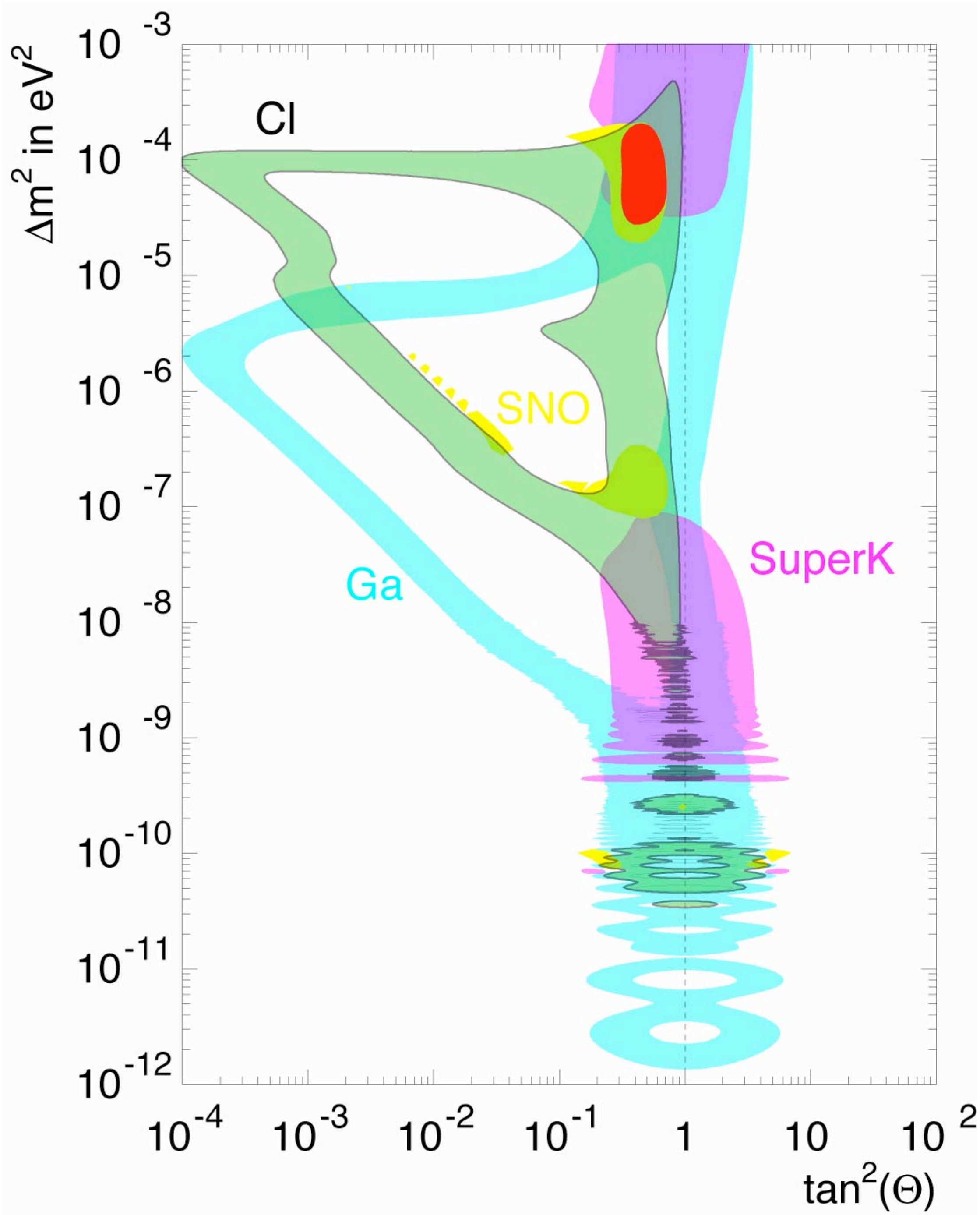
Probability of getting 54 events from 86.8 events due to a statistical fluctuation is 0.05% with Poisson statistics

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

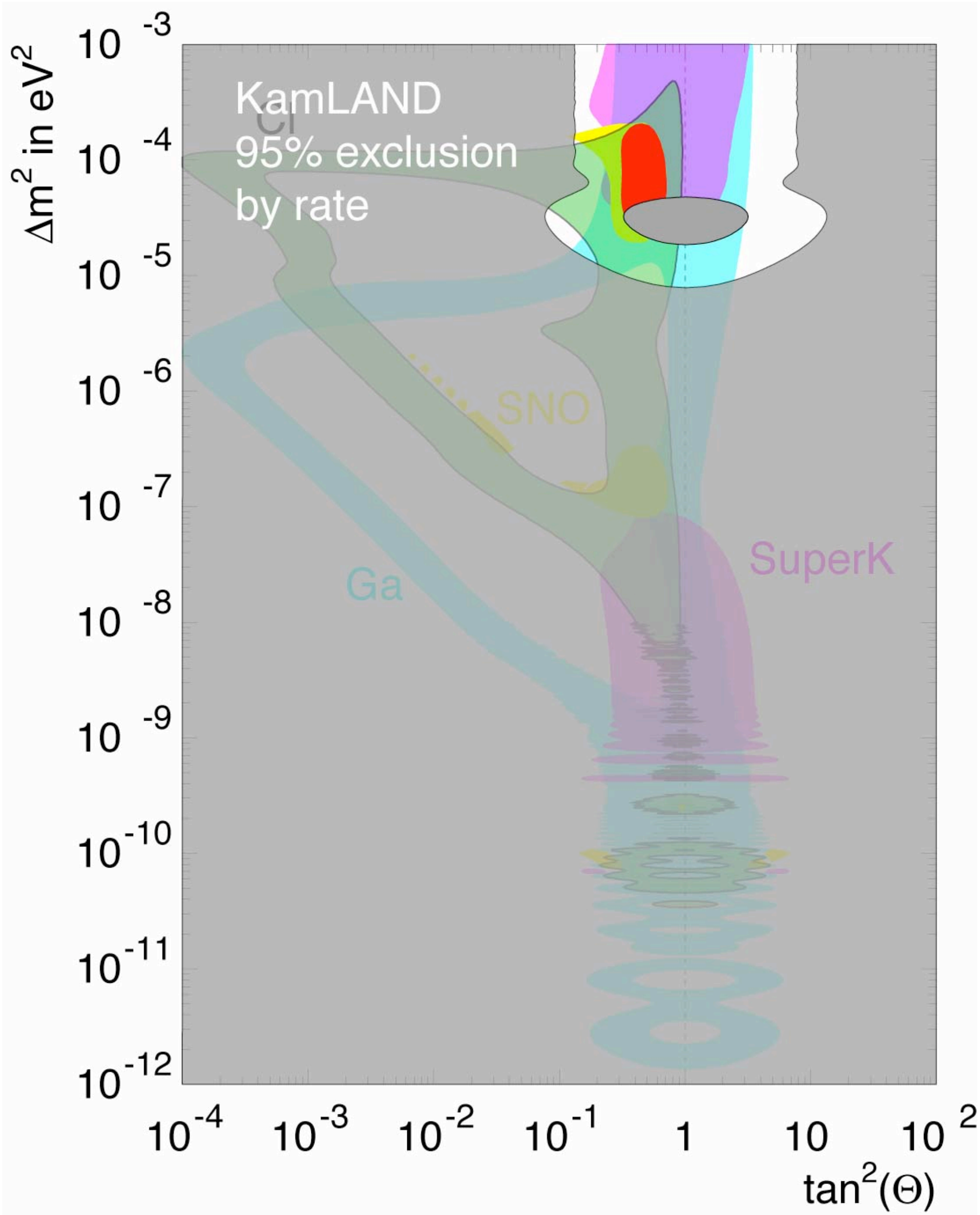


G.Fogli et al., PR D66, 010001-406, (2002)

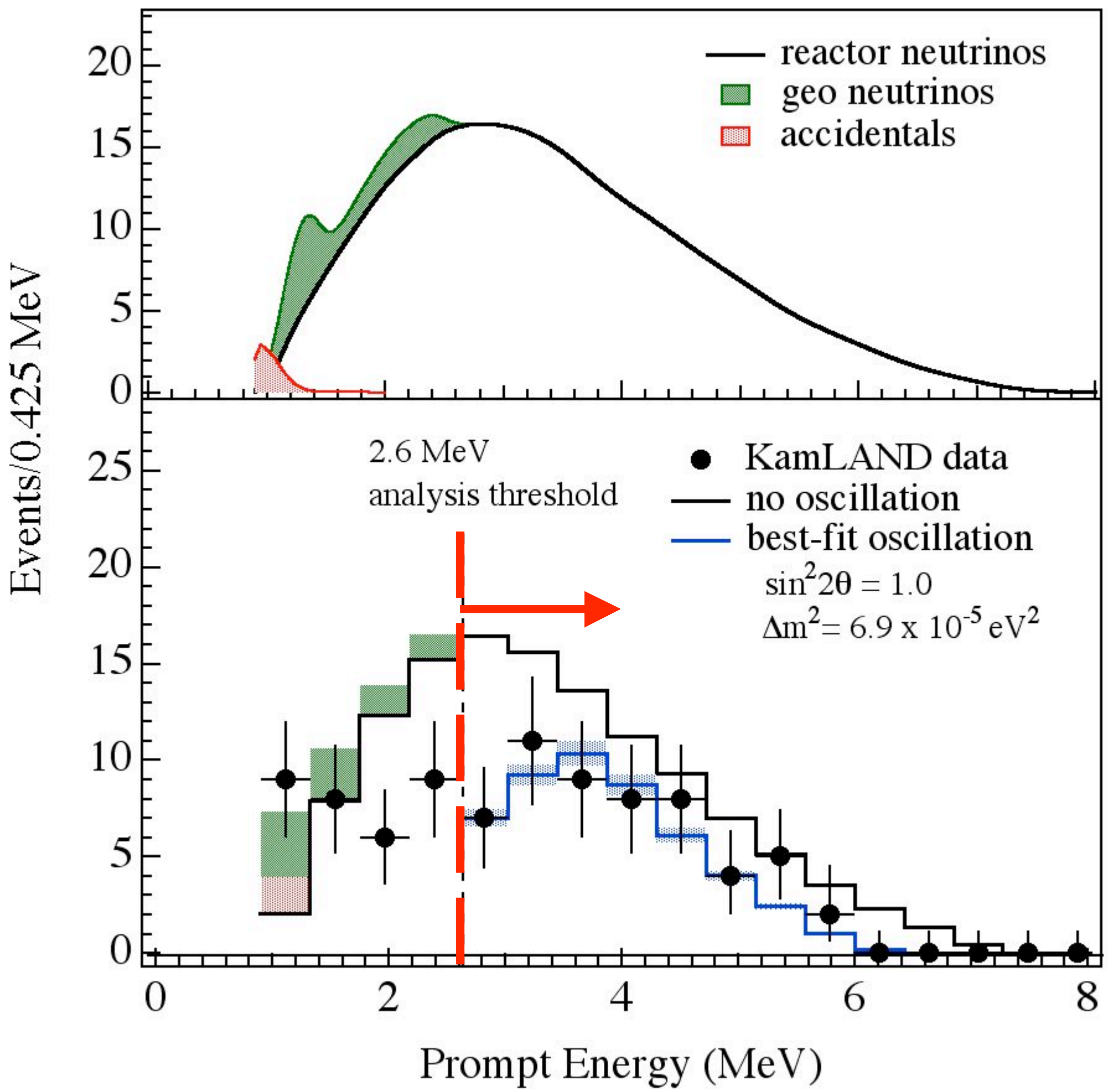
Kam
LAND



Δm² in eV²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
Cl
SNO
SuperK
Ga
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
tan²(Θ)

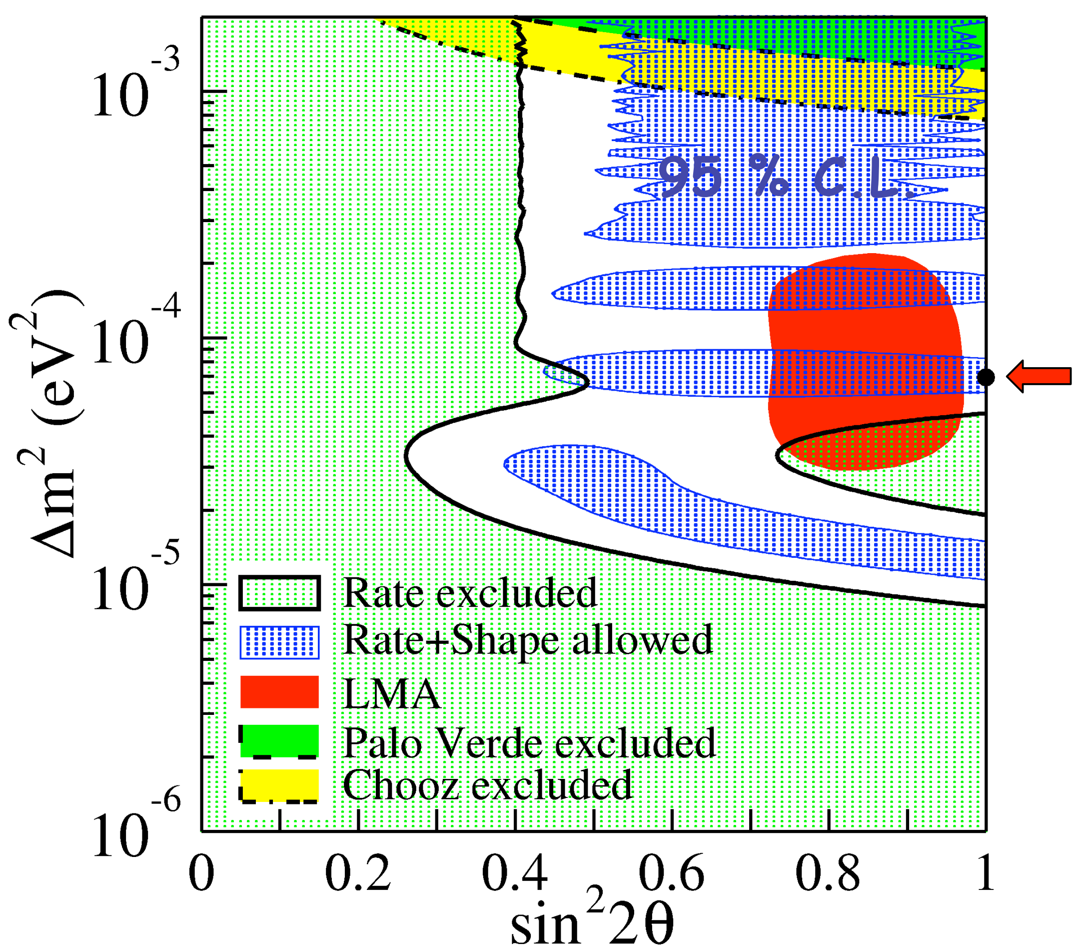

KamLAND
95% exclusion
by rate
Cl
SNO
Ga
SuperK
Δm^2 in eV^2
$\tan^2(\Theta)$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}

Energy Spectrum (E_{prompt} > 2.6 MeV)



Neutrino Oscillation Study for E_{prompt} > 2.6 MeV

$\nu_e \rightarrow \nu_x$

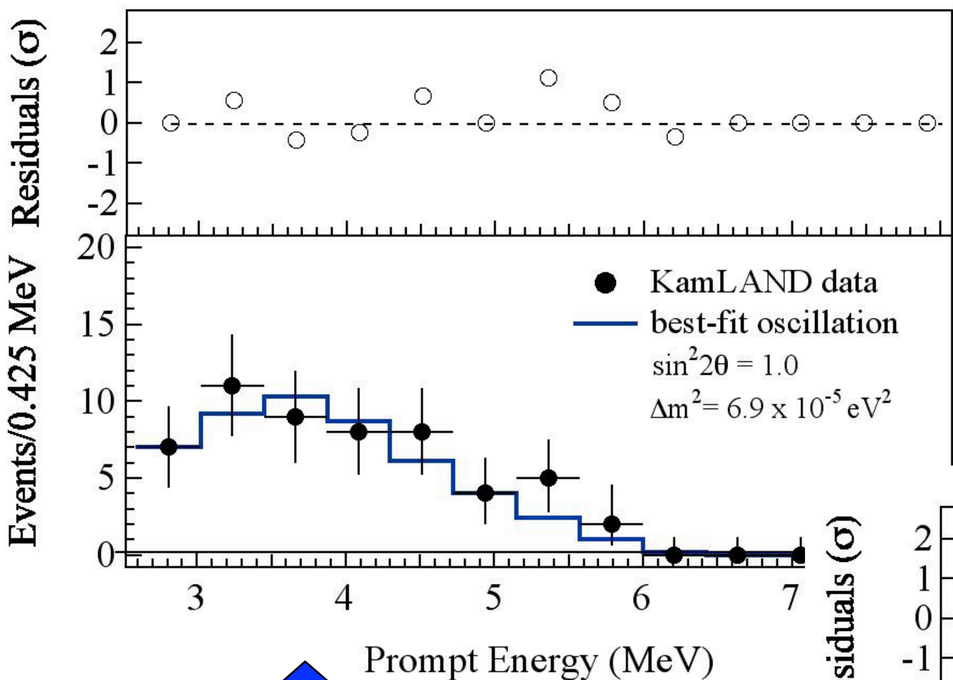


Best fit :

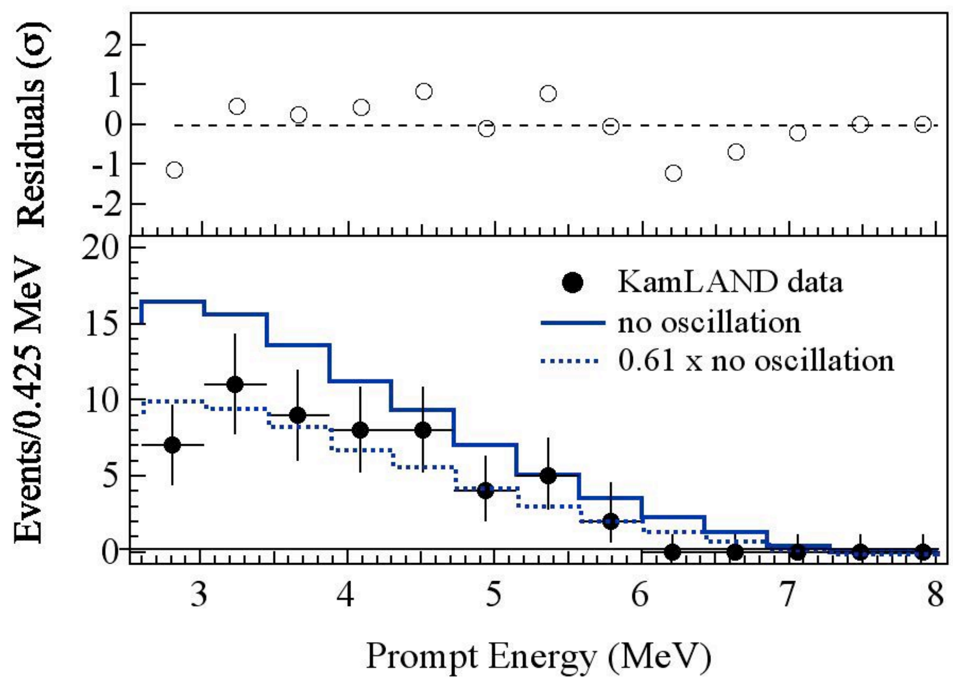
$\Delta m^2 = 6.9 \times 10^{-5}\ eV^2$

$\sin^2 2\theta = 1.0$

Spectrum of Prompt Energy



53% C.L.



χ^2 = 0.3/8 d.o.f.

93% C.L.

Conclusions

- KamLAND is routinely taking data since January 2002.
- Background and energy resolution are better than expected.
- Analysis of first 145 days of data shows clear deficit of $\bar{\nu}_e$ events. This finding is consistent with the LMA oscillation solution of the solar neutrino problem. The other solutions are strongly disfavored.
- Data taking continues. Higher statistics should allow us to probe spectral distortion and perform precise measurement of neutrino mixing parameters.