Neutrino Physics

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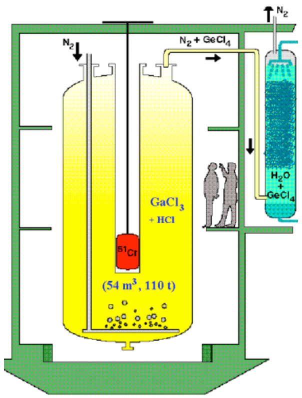
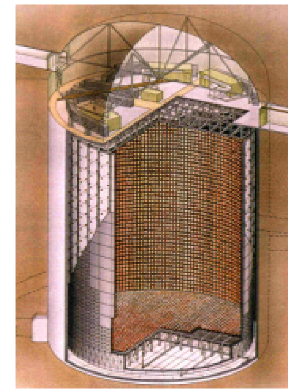
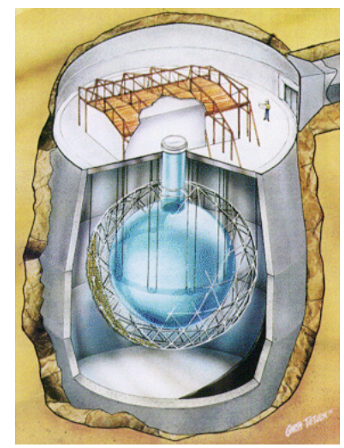
Outline

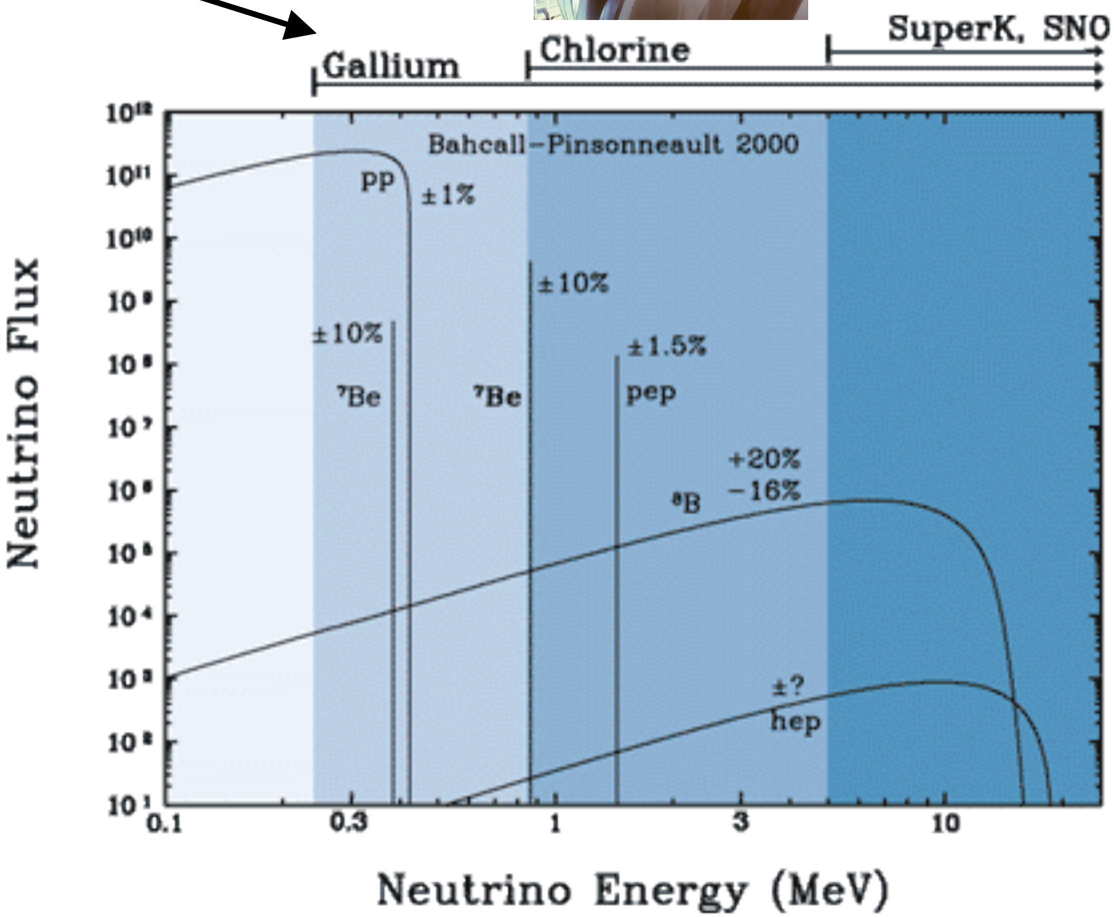
- Neutrino oscillation of 2-flavour
- KamLAND

Solar-neutrino Experiments

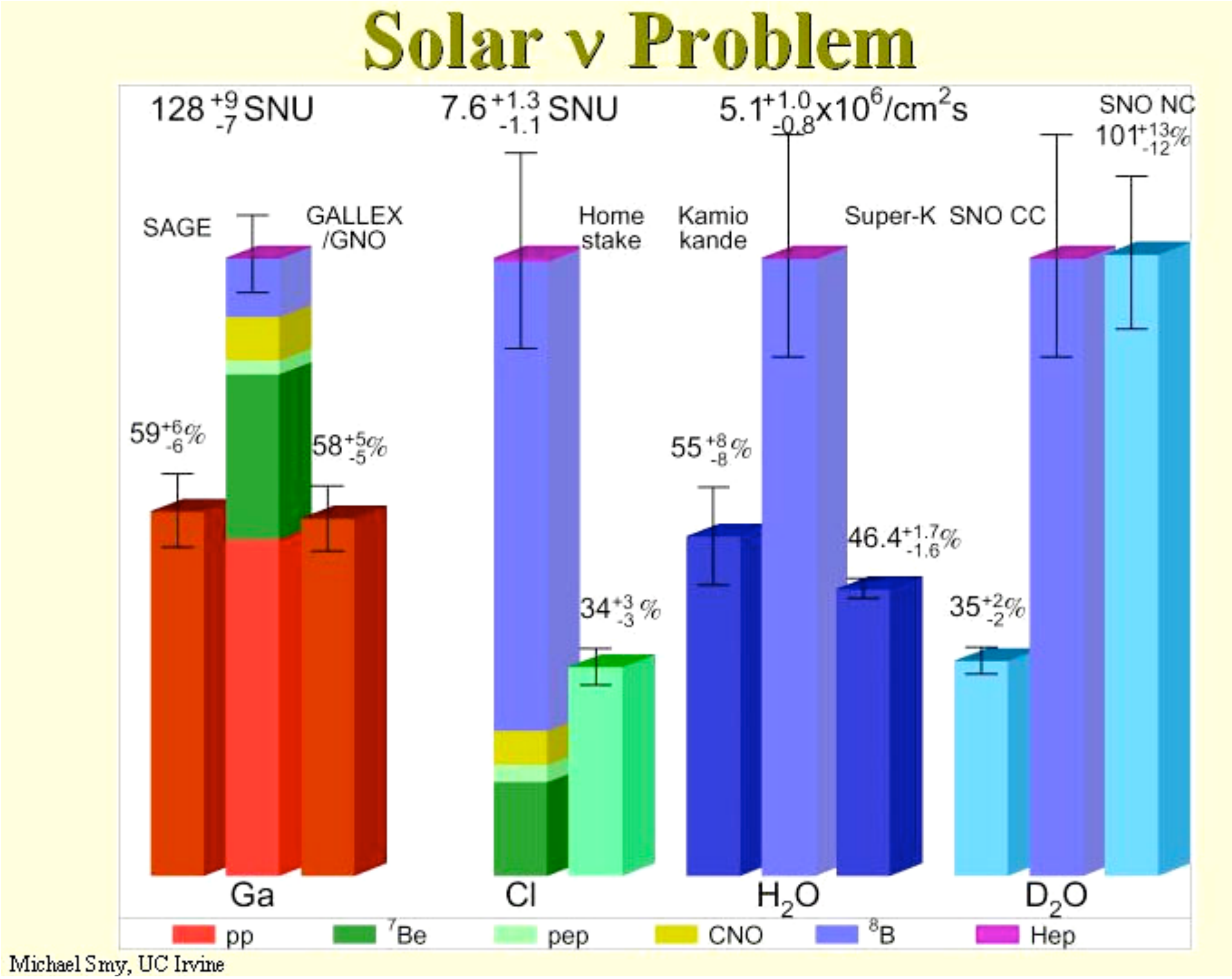








What Have Learned From Solar Neutrino



Neutrino Oscillation: Two-flavour Case

- When a neutrino is produced in a weak reaction, its identity is well defined. For example:

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

In this case, $\bar{\nu}_e$ and ν_μ are described by the weak eigenstates $|\bar{\nu}_e\rangle$ and $|\nu_\mu\rangle$ respectively.

- Once a neutrino is produced and travels as a free particle, its flavour is no longer defined until a measurement is made. Consider

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

at $t = 0$, the state vector (wavefunction) describing the neutrino is

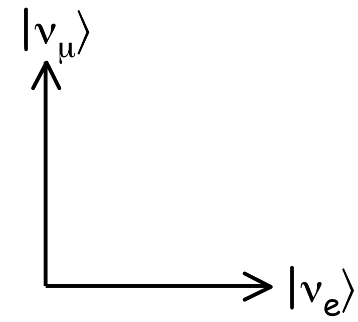
$$|\nu(0)\rangle = |\nu_\mu\rangle$$

At any other time, the state vector is given by

$$|\nu(t)\rangle = C_e(t)|\nu_e\rangle + C_\mu(t)|\nu_\mu\rangle \qquad \text{s.t. } C_e(0)=0,\ C_\mu(0)=1$$

Two-flavour Case (cont.)

The probability that the neutrino appears as ν_μ when a measurement is made is given by



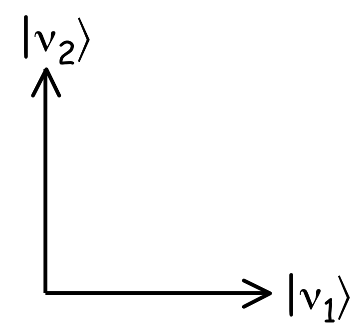
$$\langle \nu_\mu | \nu(t) \rangle = C_\mu(t)$$

Similarly, the probability that the neutrino appears as ν_μ is

$$\langle \nu_e | \nu(t) \rangle = C_e(t)$$

Clearly, $$C_\mu^2(t) + C_e^2(t) = 1$$

- Now also express the state vector as a combination of two energy eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$ such that these two states have the same momentum p (an approximation), i.e.



$$|\nu(t)\rangle = C_1(t)|\nu_1\rangle + C_2(t)|\nu_2\rangle$$

$$E_1 = \sqrt{m_1^2 + p^2} \quad \text{and} \quad E_2 = \sqrt{m_2^2 + p^2}$$

- The time evolution of the coefficients is:

$$C_1(t) = C_1(0)e^{-iE_1 t} \quad \text{and} \quad C_2(t) = C_2(0)e^{-iE_2 t}$$

Two-flavour Case (cont.)

- Since

$$|\nu(t)\rangle = C_1(t)|\nu_1\rangle + C_2(t)|\nu_2\rangle = C_e(t)|\nu_e\rangle + C_\mu(t)|\nu_\mu\rangle$$

we have

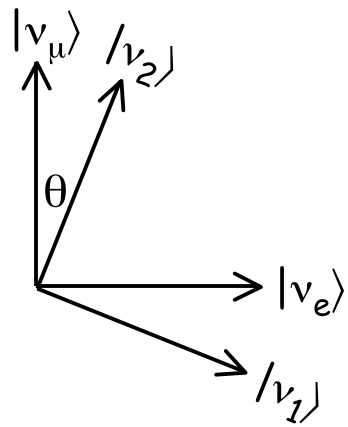
$$C_e(t) = C_1(t)\,\langle\nu_e|\nu_1\rangle + C_2(t)\,\langle\nu_e|\nu_2\rangle$$

$$C_\mu(t) = C_1(t)\,\langle\nu_\mu|\nu_1\rangle + C_2(t)\,\langle\nu_\mu|\nu_2\rangle$$

In matrix notation,

$$\begin{pmatrix} C_e(t) \\ C_\mu(t) \end{pmatrix} = \begin{pmatrix} \langle\nu_e|\nu_1\rangle & \langle\nu_e|\nu_2\rangle \\ \langle\nu_\mu|\nu_1\rangle & \langle\nu_\mu|\nu_2\rangle \end{pmatrix} \begin{pmatrix} C_1(t) \\ C_2(t) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} C_1(t) \\ C_2(t) \end{pmatrix}$$

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



- At t = 0,

$$C_1(0) = -\sin\theta \qquad \text{and} \qquad C_2(0) = \cos\theta$$

- At any time,

$$C_e(t) = \sin\theta\cos\theta\left(e^{-iE_2t} - e^{-iE_1t}\right)$$

$$C_\mu(t) = \sin^2\theta e^{-iE_1t} + \cos^2\theta e^{-iE_2t}$$

Two-flavour Case (cont.)

- The probabilities of observing the neutrino as a ν_e or ν_μ are:

$$P(\nu_\mu \rightarrow \nu_e) = C_e^*(t)C_e(t) = \sin^2 2\theta \sin^2\left[\frac{(E_2 - E_1)t}{2}\right]$$

$$P(\nu_\mu \rightarrow \nu_\mu) = C_\mu^*(t)C_\mu(t) = 1 - \sin^2 2\theta \sin^2\left[\frac{(E_2 - E_1)t}{2}\right]$$

- If m_1 and m_2 << p, the neutrino is moving at approximately c, thus

$$ct = L, \quad E_1 \approx p + m_1^2/2p, \quad E_2 \approx p + m_2^2/2p, \; E_1 \approx E_2 \approx p = E$$

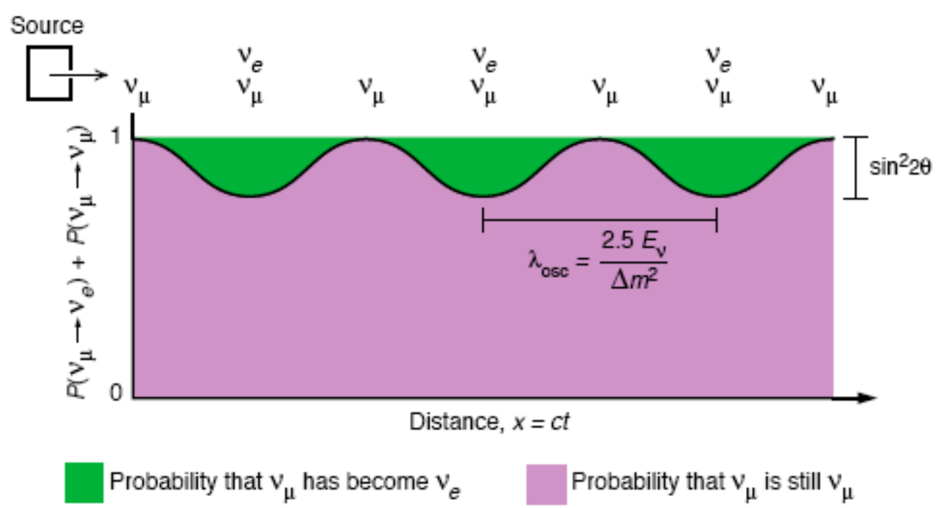
Hence,

Appearance probability:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right]$$

Disappearance probability (chance that it will survive):

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right]$$



A Few Facts About Neutrino Oscillation

- Oscillation is only possible if

$$\Delta m^2 = m_2^2 - m_1^2 \neq 0$$

  - the neutrinos must have different masses
  - at least one of the neutrinos must have mass

- For a given energy E, the wavelength of the oscillation is given by

$$\lambda = \frac{4E}{\Delta m^2}$$

- The amplitude of the oscillation is determined by

$$A = \sin^2 2\theta$$

The amplitude grows with the mixing angle θ

- Both the mixing angle θ and Δm^2 are not calculable.

Determining Mixing Angle And Δm^2

- Use statistical methods to compare observed events and expectation at each combination of $\sin^2 2\theta$ and Δm^2 values:
- For the elementary approach, form a likihood function:

$$L\,(N_{\exp}, N_{obs}) = \prod_{n=1} \frac{\exp(-N^n_{\exp})(N^n_{\exp})^{N^n_{obs}}}{N^n_{obs}!}$$

Prob. of observed no. of events in n-th bin

where N_{obs} is the observed number of events

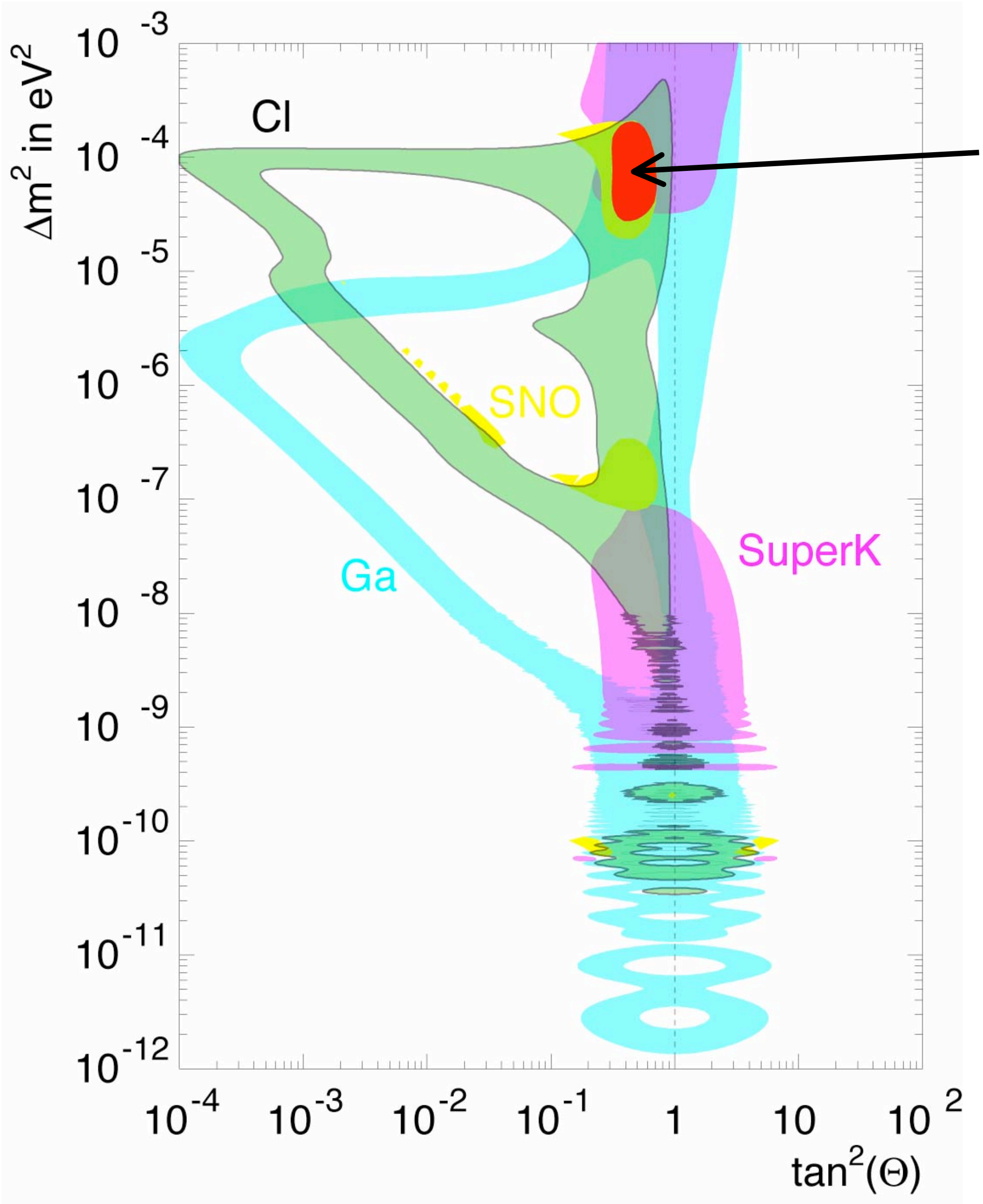
N_{exp} is the expectation number of events

$$N_{\exp} = N_{MC} \cdot P(\nu_e \to \nu_e)$$

$$\chi^2 \equiv -2\ln\left(\frac{L\,(N_{\exp}, N_{obs})}{L\,(N_{obs}, N_{obs})}\right) = \sum_{n=1}\left[2(N^n_{\exp} - N^n_{obs}) + 2N^n_{obs}\ln\left(\frac{N^n_{obs}}{N^n_{\exp}}\right)\right]$$

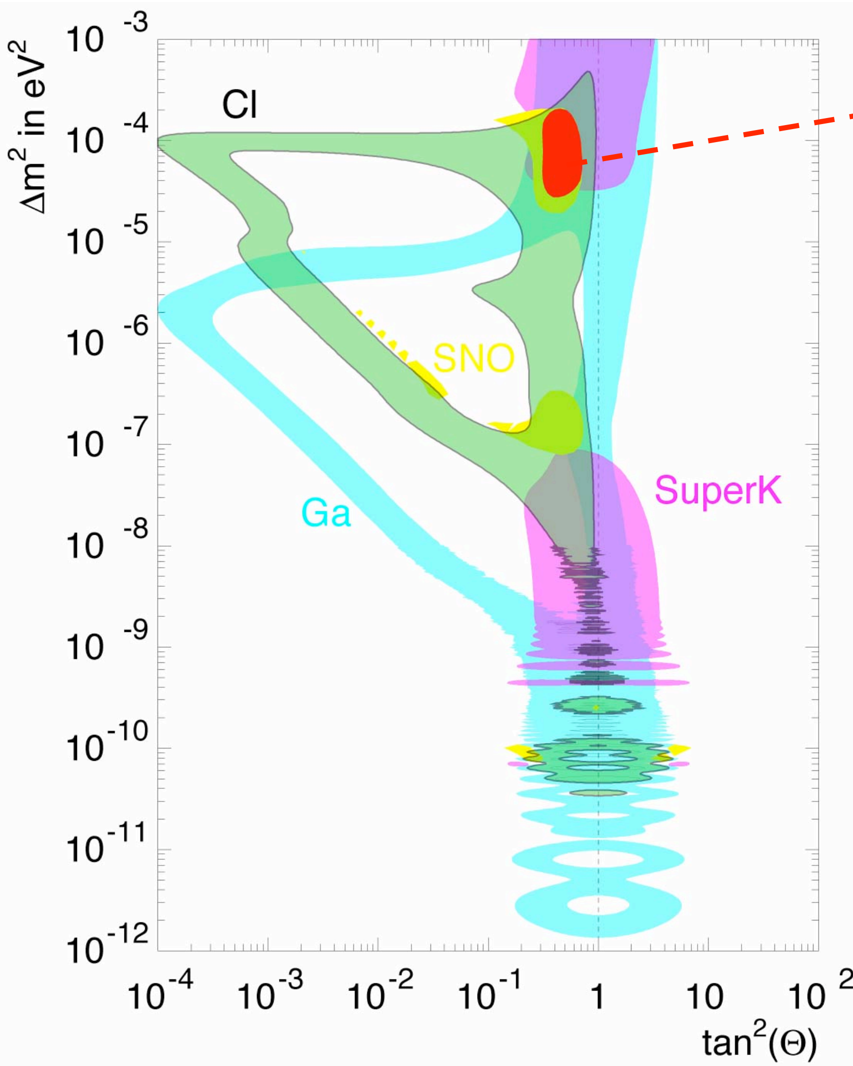
- Calculate the χ^2 value for each combination (Δm^2, $\sin^2 2\theta$, …).
- The most likely answer of Δm^2 and $\sin^2 2\theta$ is the combination that gives the smallest χ^2 value.

Mixing Angle And Δm^2 From Solar Neutrino



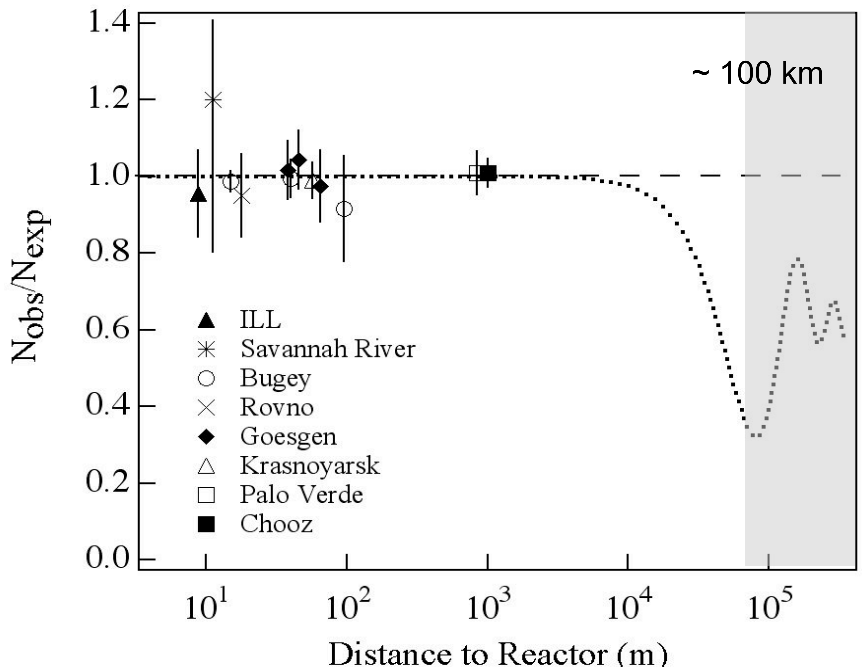
The most likely answer that can account for the results from all solar-neutrino expts

Checking The Results



- This region can be explored with reactor $\bar{\nu}_e$. For a mean energy E of 4 MeV, the wavelength of the oscillation is roughly

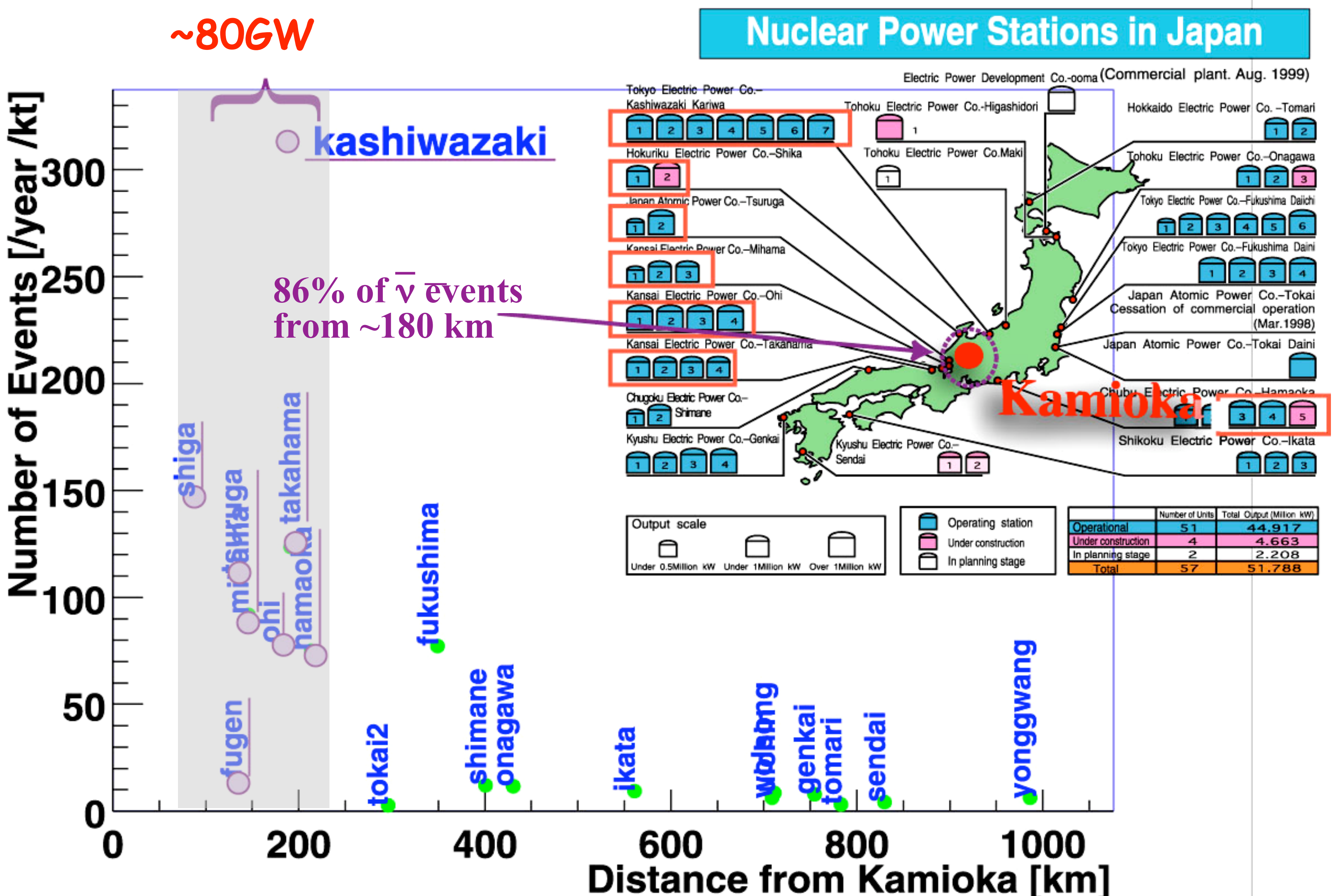
$$\lambda = \frac{4E}{\Delta m^2} \approx \frac{2.5 \times 4}{10^{-4}} m = 100 \text{ km}$$



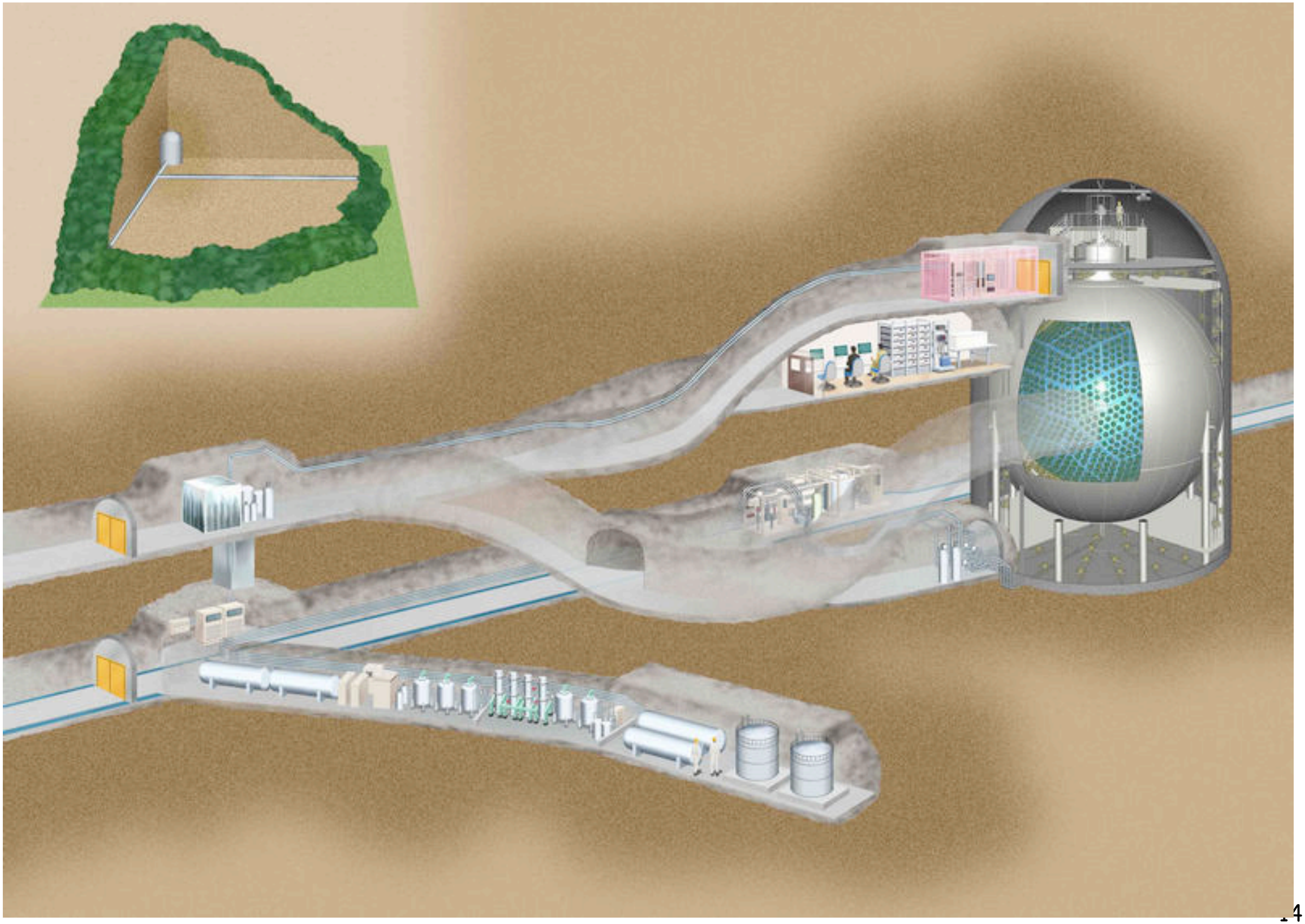
Nuclear Reactors In Japan

20 % of world nuclear power

~80GW

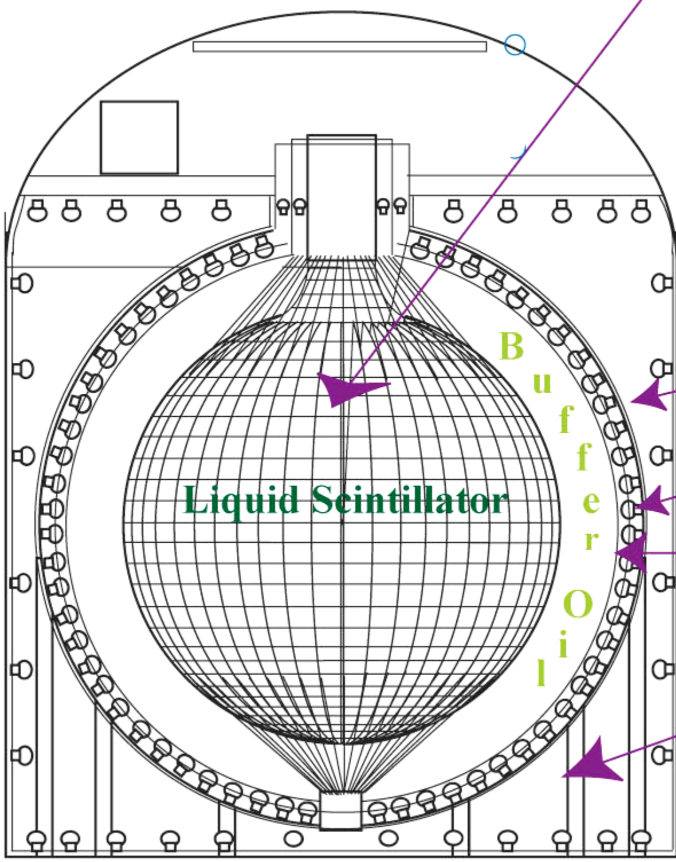


The KamLAND Experiment



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

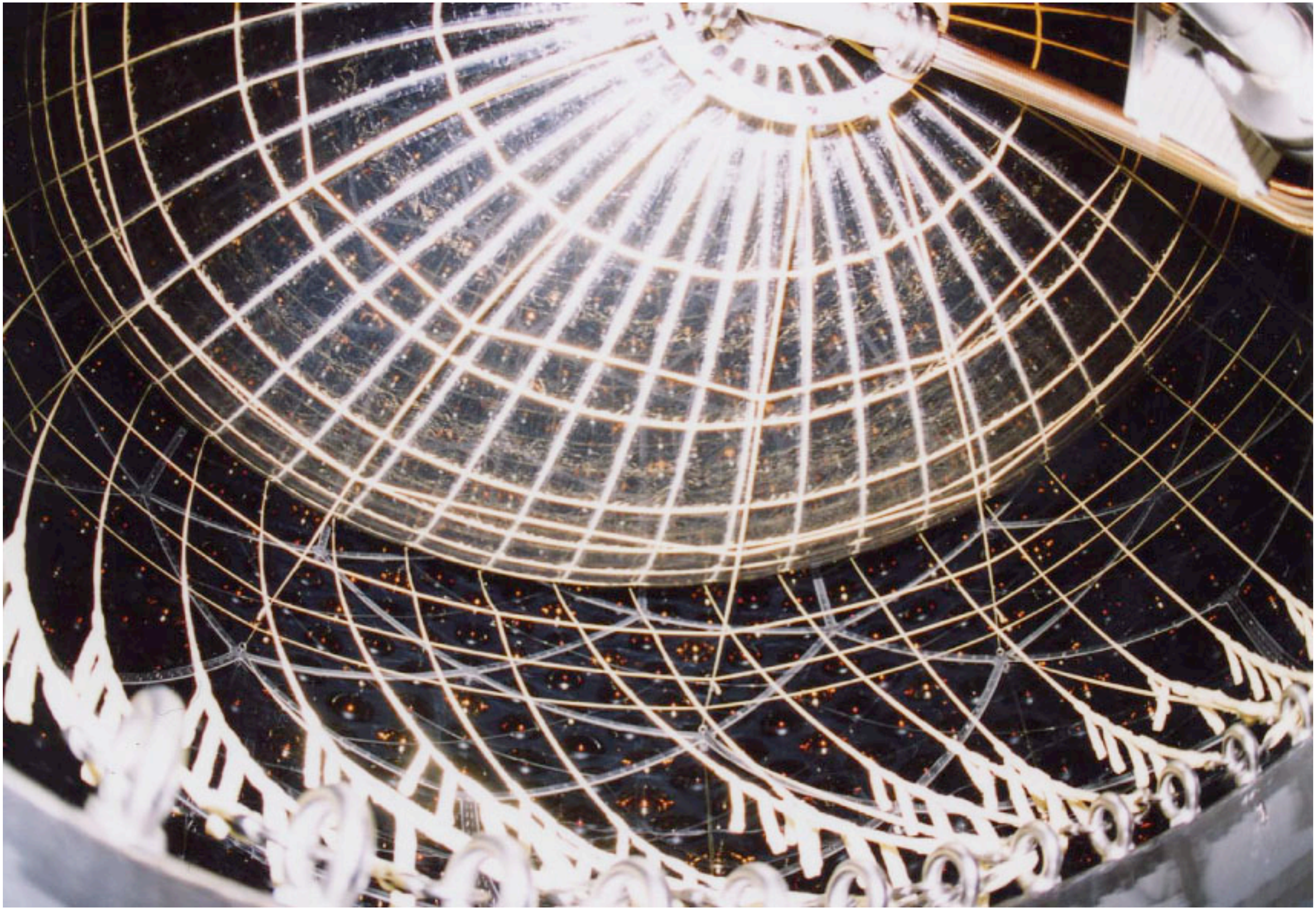
○ 3,000 m^3 Scintillation Light Detector

- 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 (3.2 kton)

225 Kamiokande 20-inch PMT's

Looking Inside The KamLAND Detector

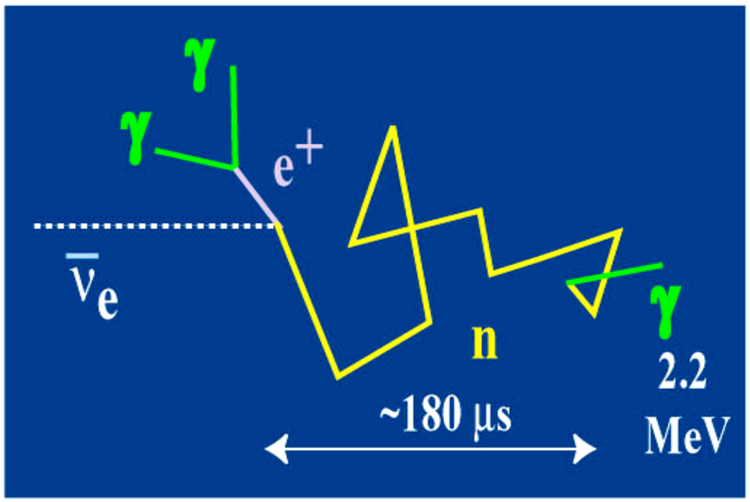


Detecting Reactor $\bar{\nu}_e$ in Liquid Scintillator

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

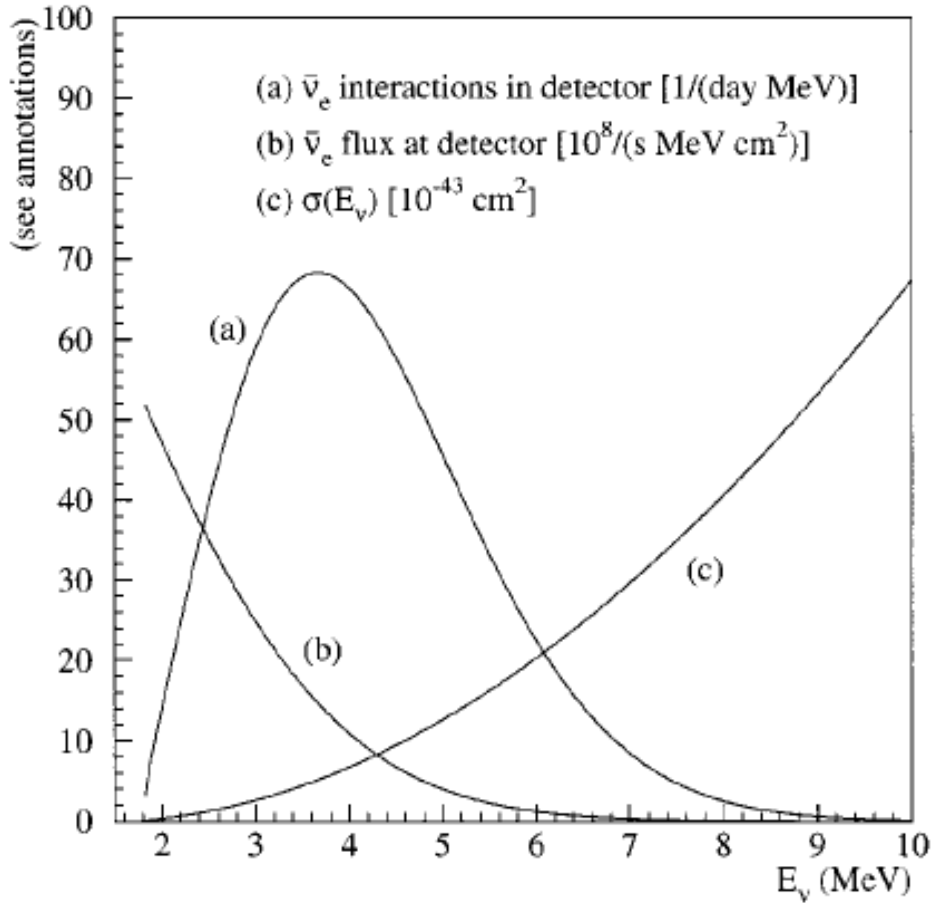
  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

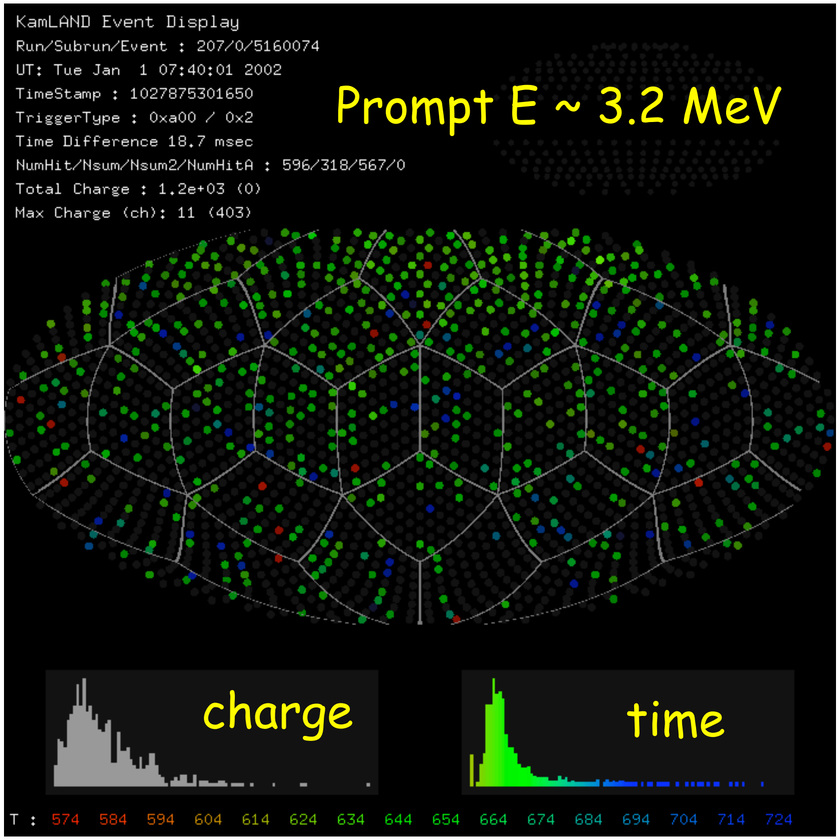
- **delayed part : γ (2.2 MeV)**

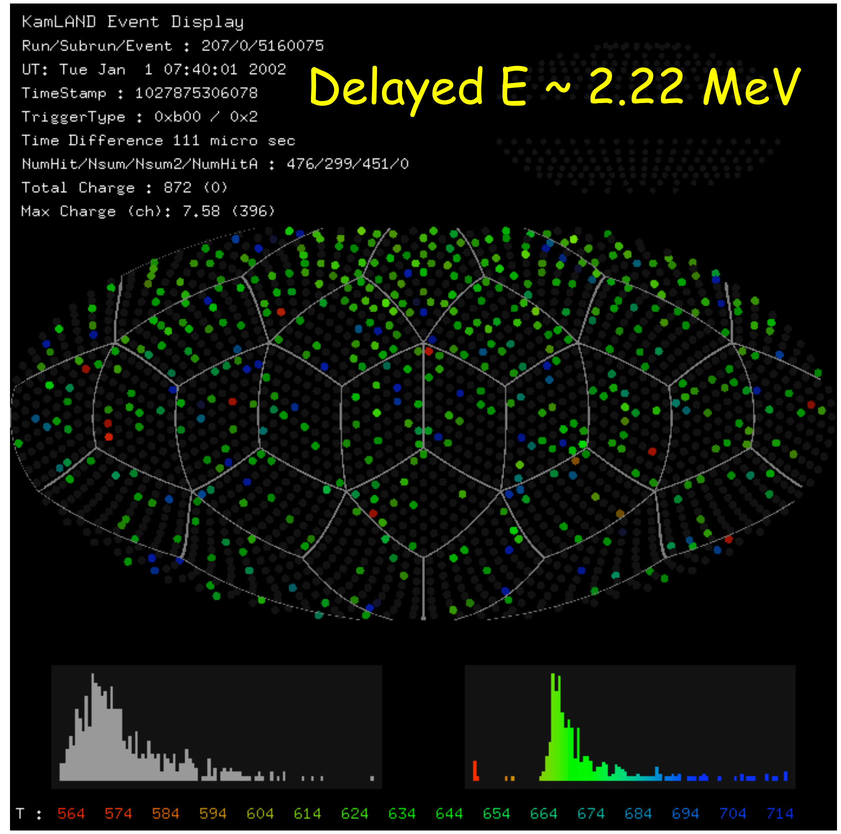
- **tagging : correlation of time, position and energy between prompt and delayed signal**

The Observed Energy Spectrum Of Reactor $\bar{\nu}_e$



An Anti-neutrino Candidate





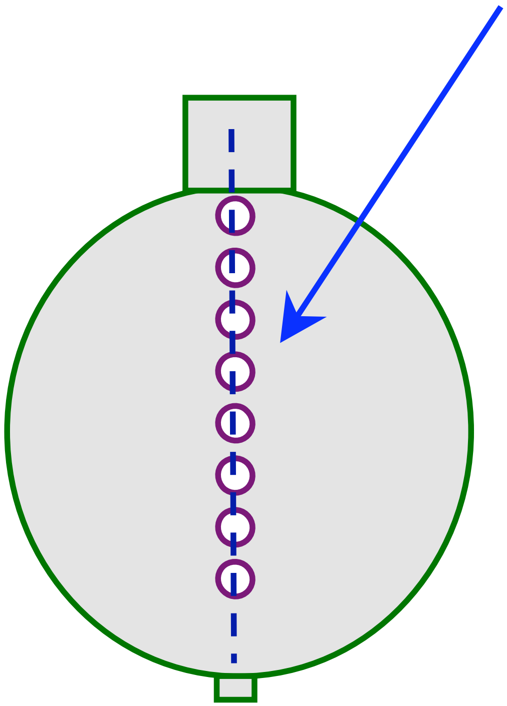
$\Delta t \sim 110\ \mu sec$

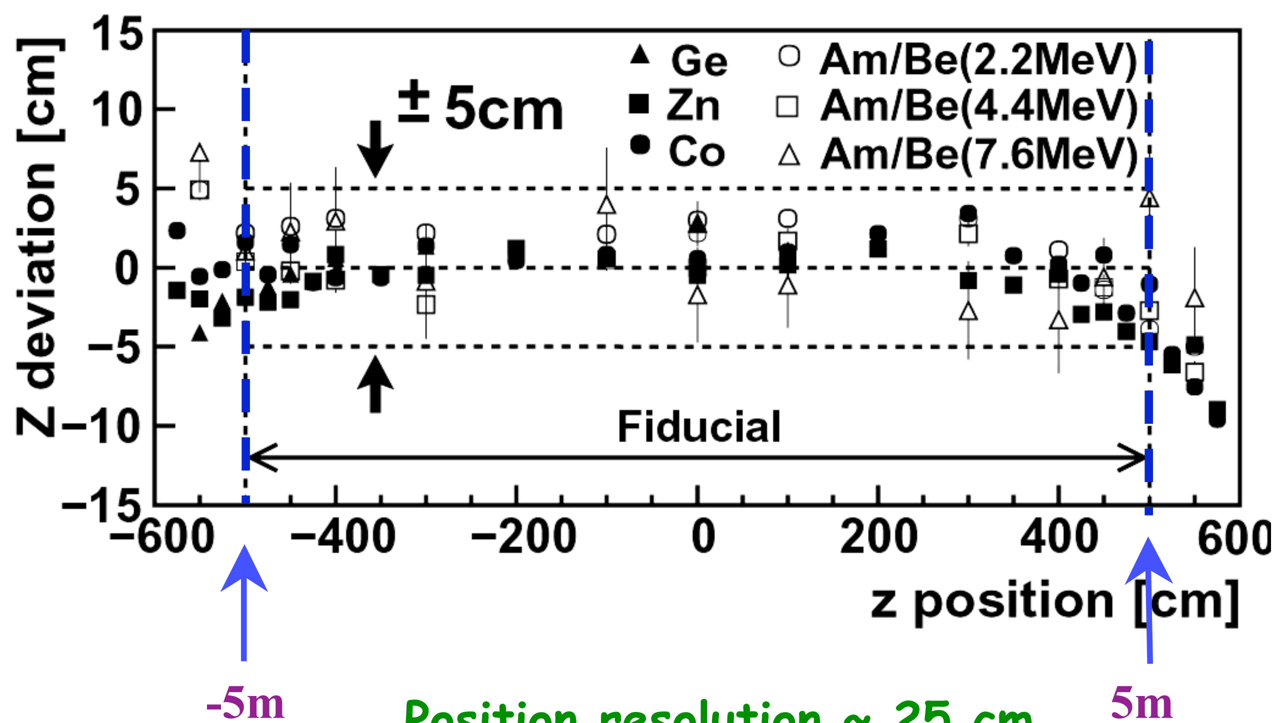
$\Delta R \sim 0.35$ m

Reconstructing Position

^{68}Ge : 1.012 MeV ($\gamma + \gamma$)
^{60}Co : 2.506 MeV ($\gamma + \gamma$)

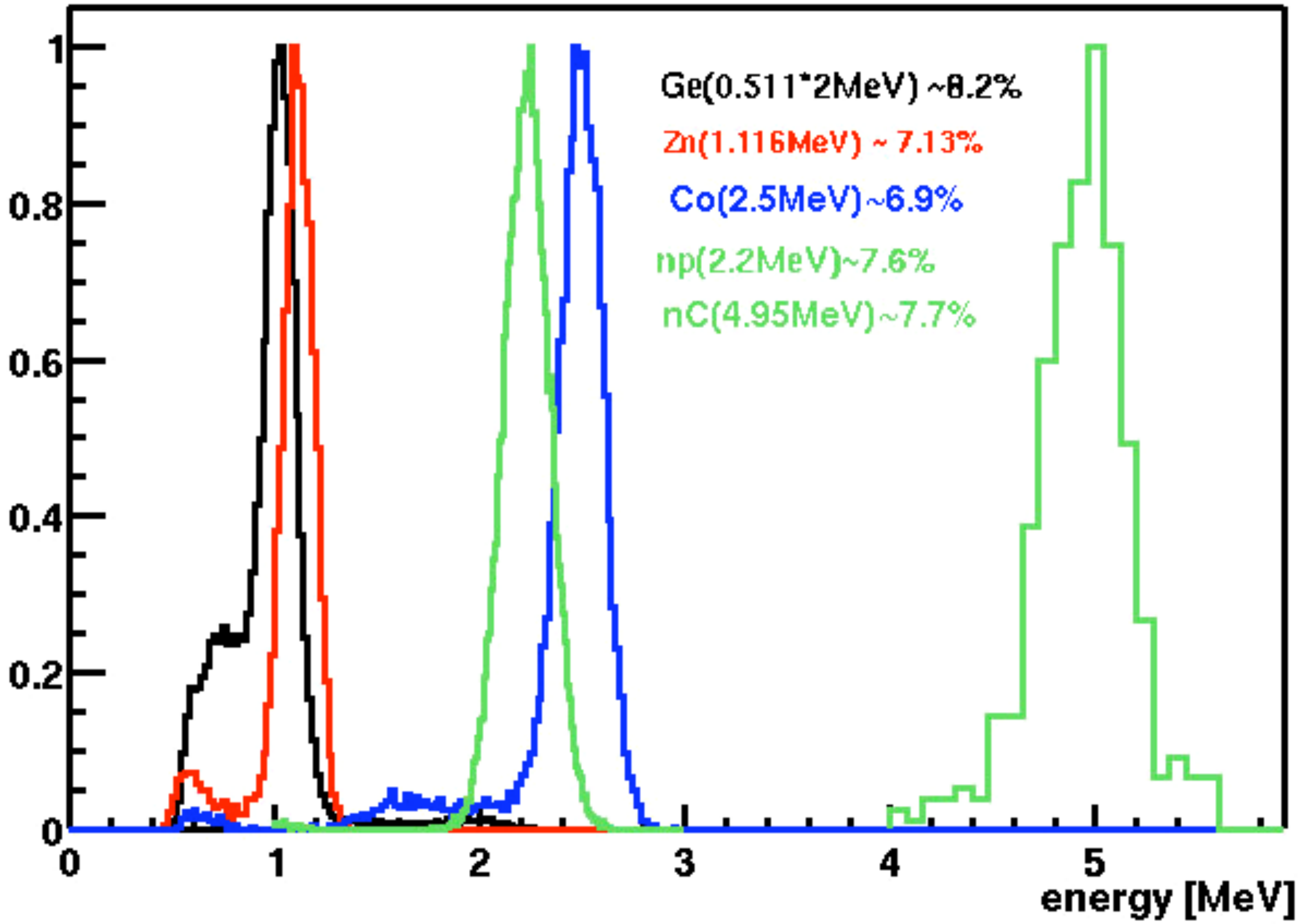
^{65}Zn : 1.116 MeV (γ)
AmBe : 2.20 , 4.40, 7.6 MeV (γ)





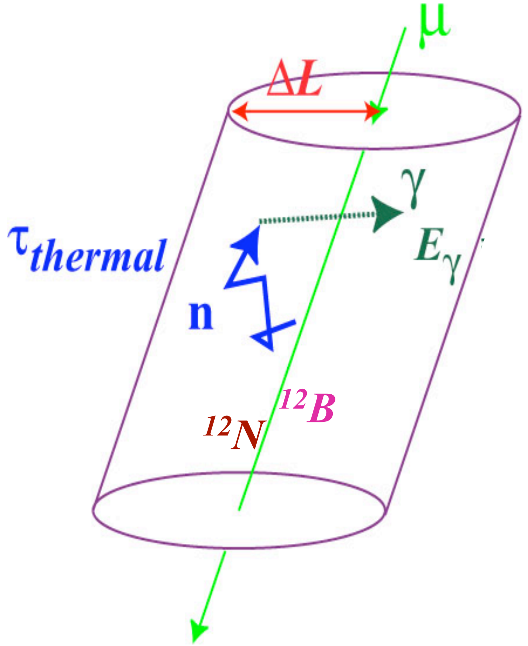
Position resolution ~ 25 cm

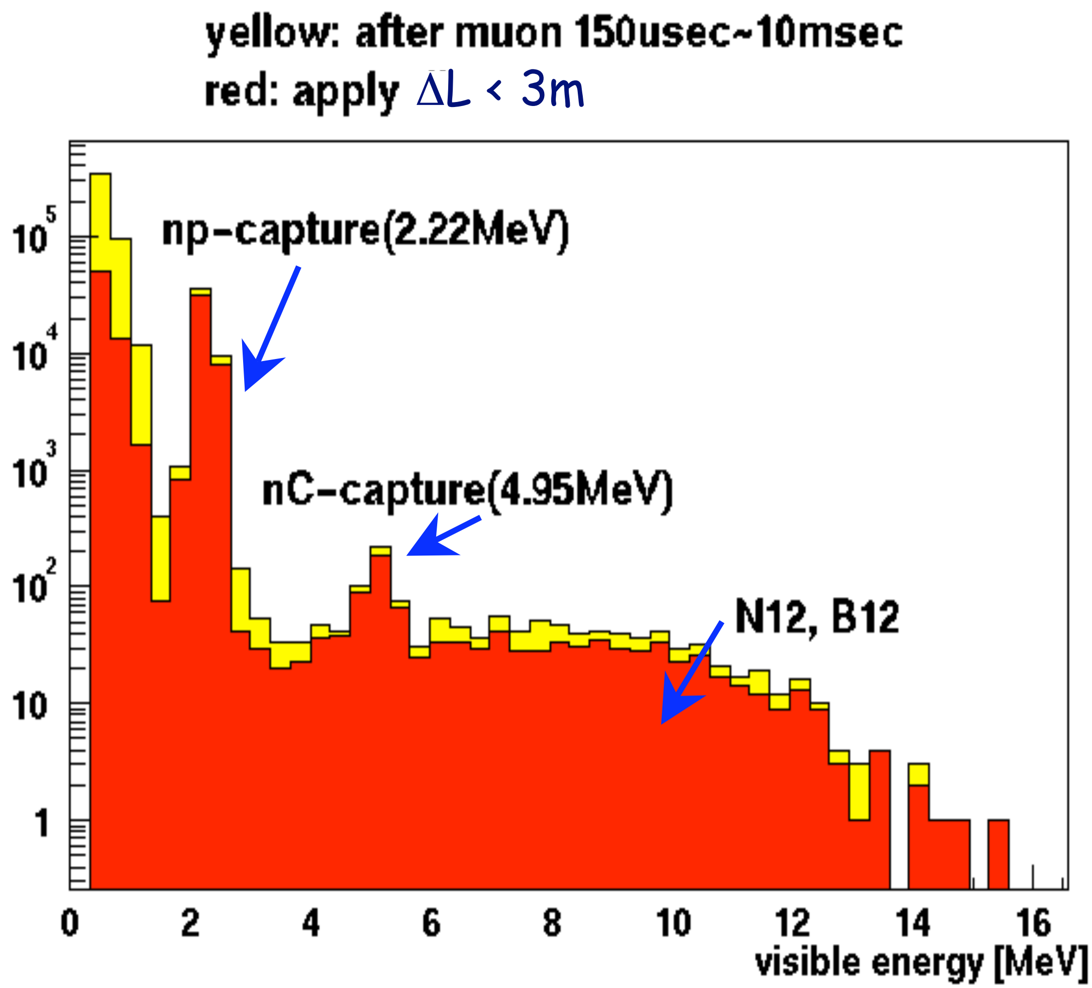
Determining Energy



- Light Yield: ~ 300 p.e./MeV
- Energy resolution: $\Delta E/E \sim 7.5\% /\sqrt{E}$

Neutrons And $^{12}B/^{12}N$ Produced by Cosmic-ray Muons





Natural Radioactivity In The Detector

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

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

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

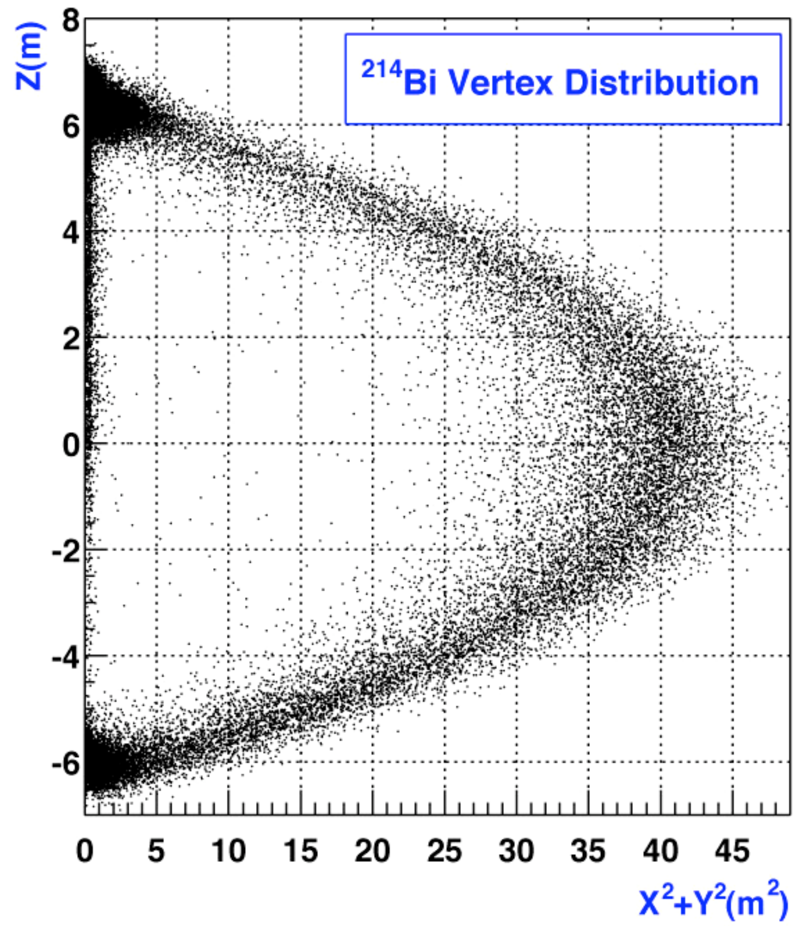
event selection

$\Delta R < 100\ cm$

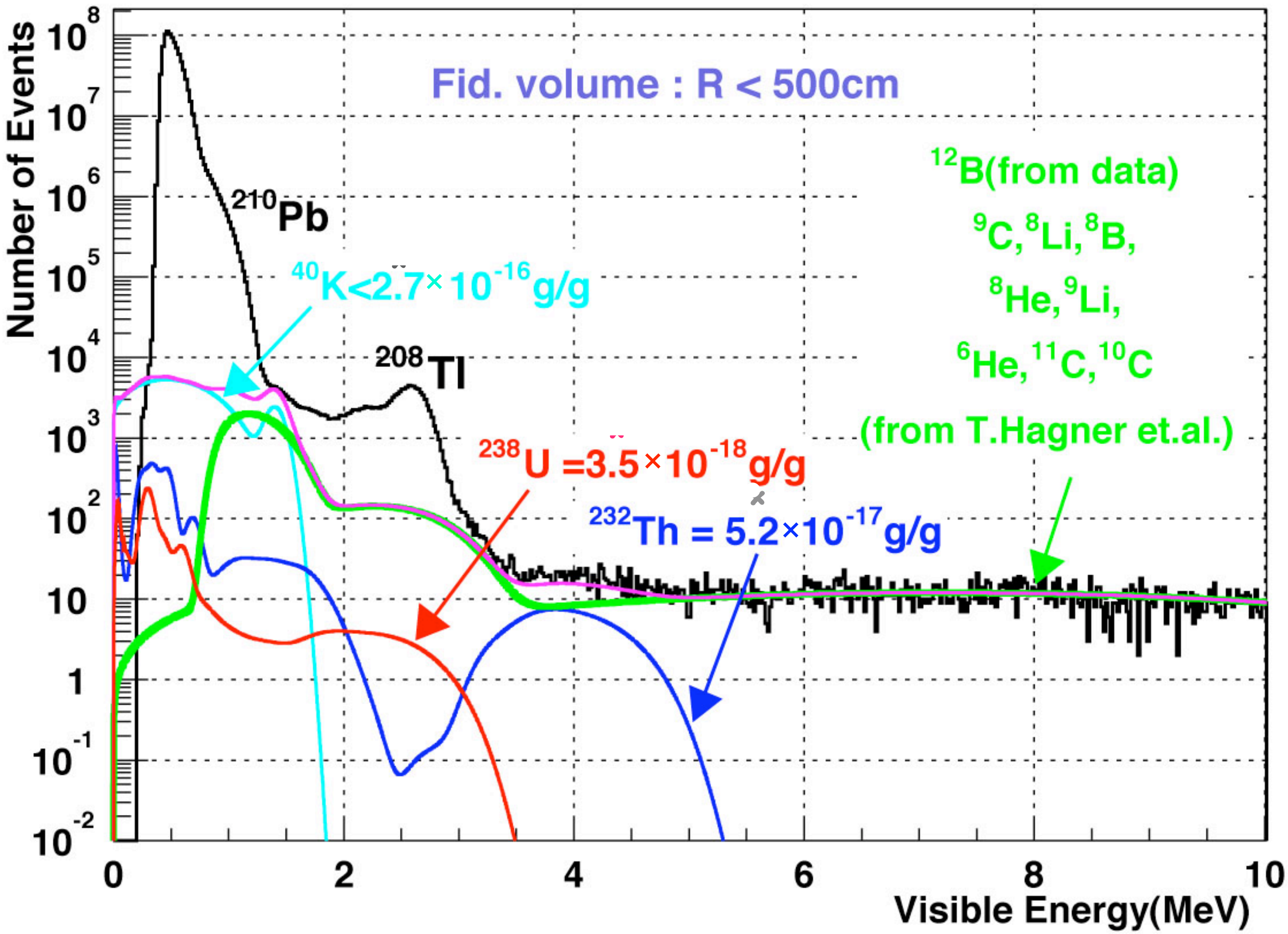
$5\ \mu s < \Delta t < 1000\ \mu s$

$E_{prompt} > 1.3\ MeV$

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



Energy Spectrum of Radioactivity inside Liquid Scintillator

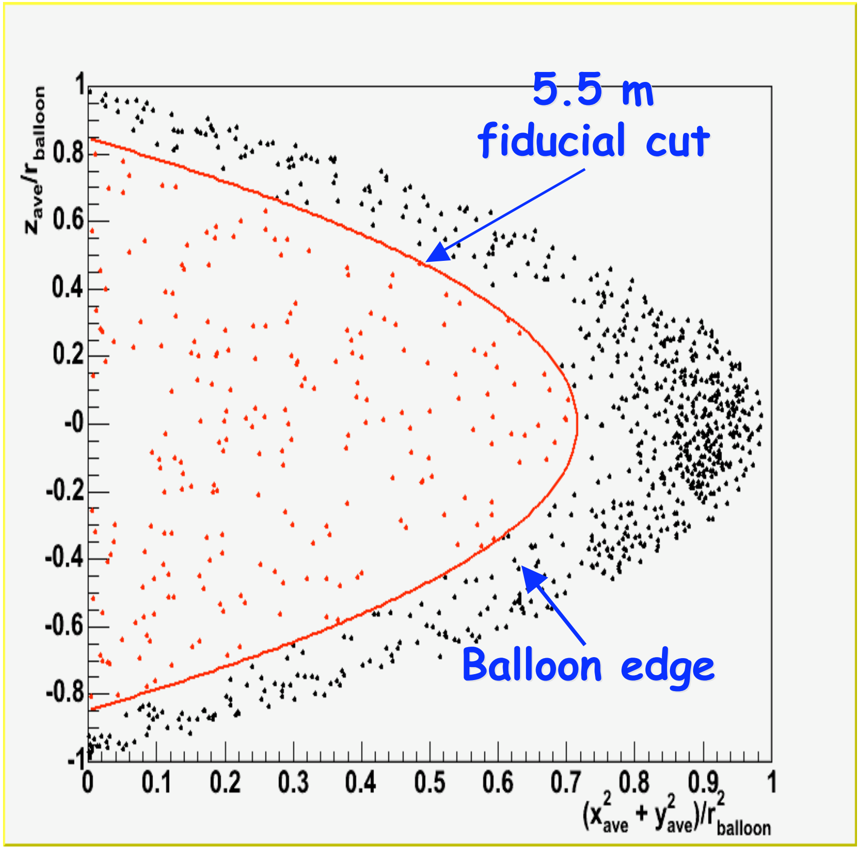


Selecting $\bar{\nu}_e$ Candidates

Requirements:

- $R_{prompt,\ delayed}$ < 5.5 m
- ΔR_{e-n} < 2 m
- 0.5 μs < ΔT_{e-n} < 1 ms
- 1.8 MeV < $E_{delayed}$ < 2.6 MeV
- 2.6 MeV < E_{prompt} < 8.5 MeV

Tagging efficiency 89.8%

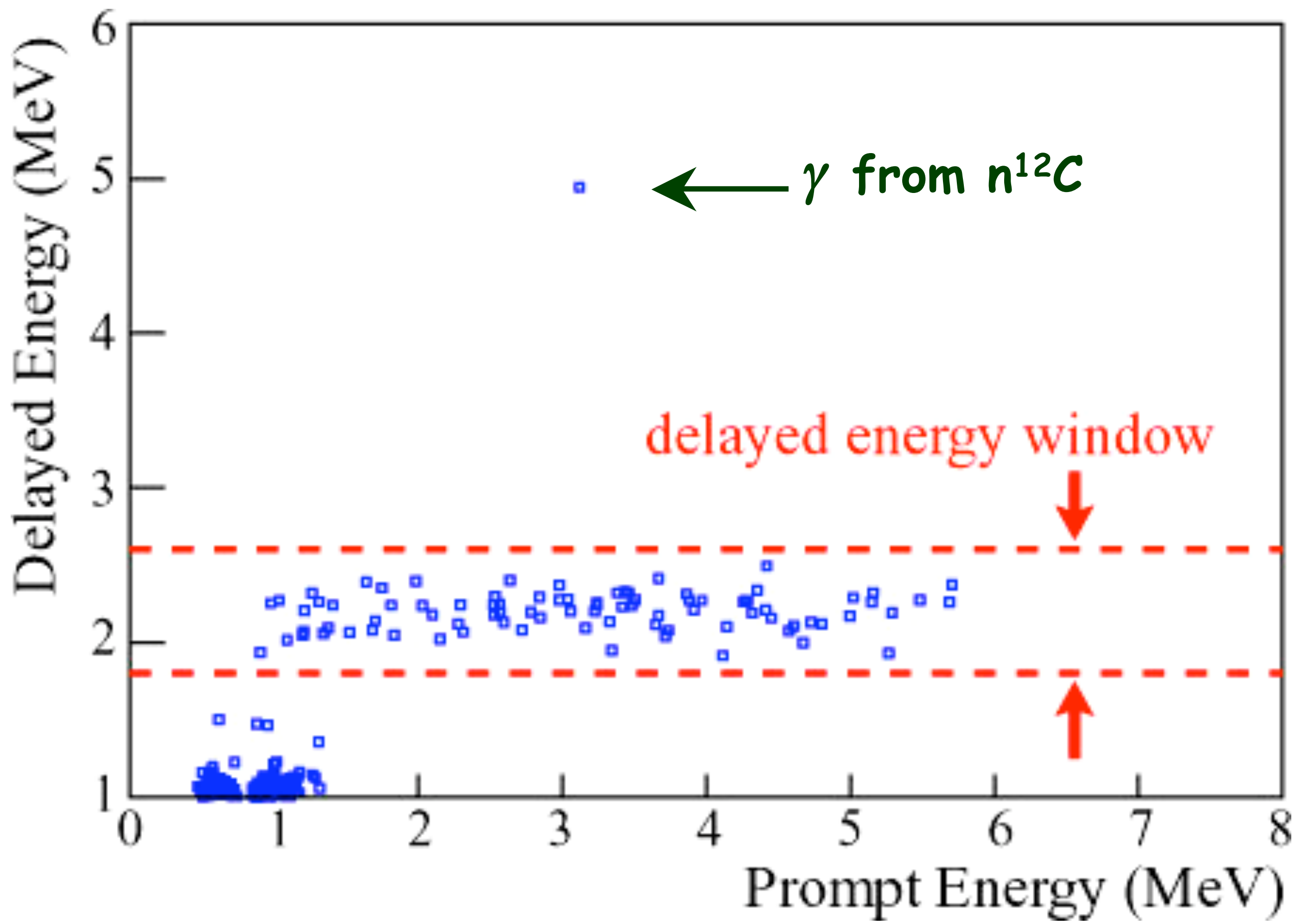


In addition:

- 2s veto for showering/bad μ
- 2s veto in a R = 3m tube along track

Dead-time 9.7%

Correlation Between Prompt and Delayed Energies



Result From KamLAND

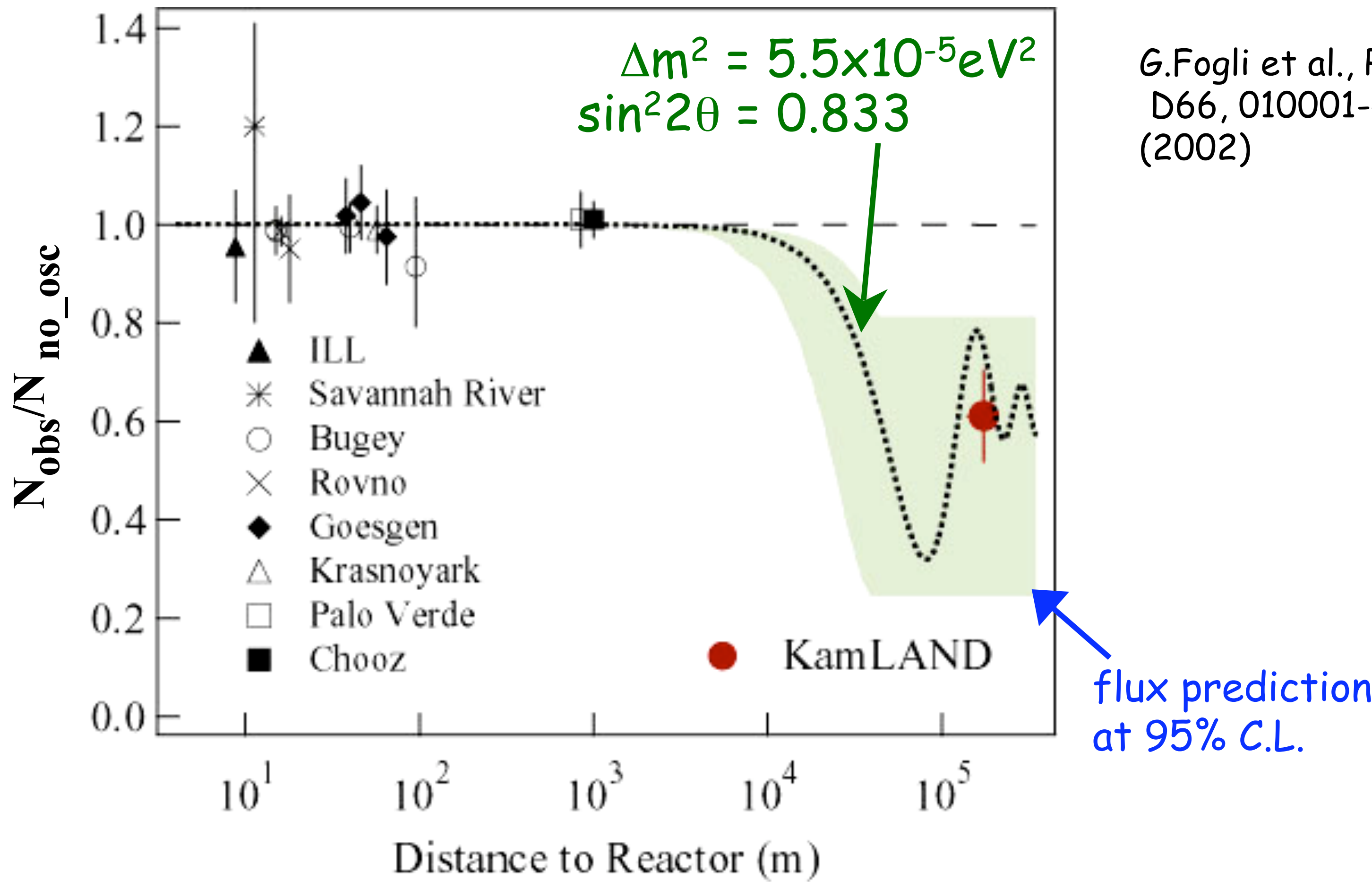
- Based on 766.3 ton·yr, with E_{prompt} > 2.6 MeV

Final sample, N_{obs}	258 events
Expected, N_{no}	365 ± 24(sys) events
Background, N_{bg}	7.5 ± 1.3 event
Accidental	2.69 ± 0.02 event
^{9}Li/^{8}He (β, n)	4.8 ± 0.9 event
μ-induced neutron	< 0.9 event

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

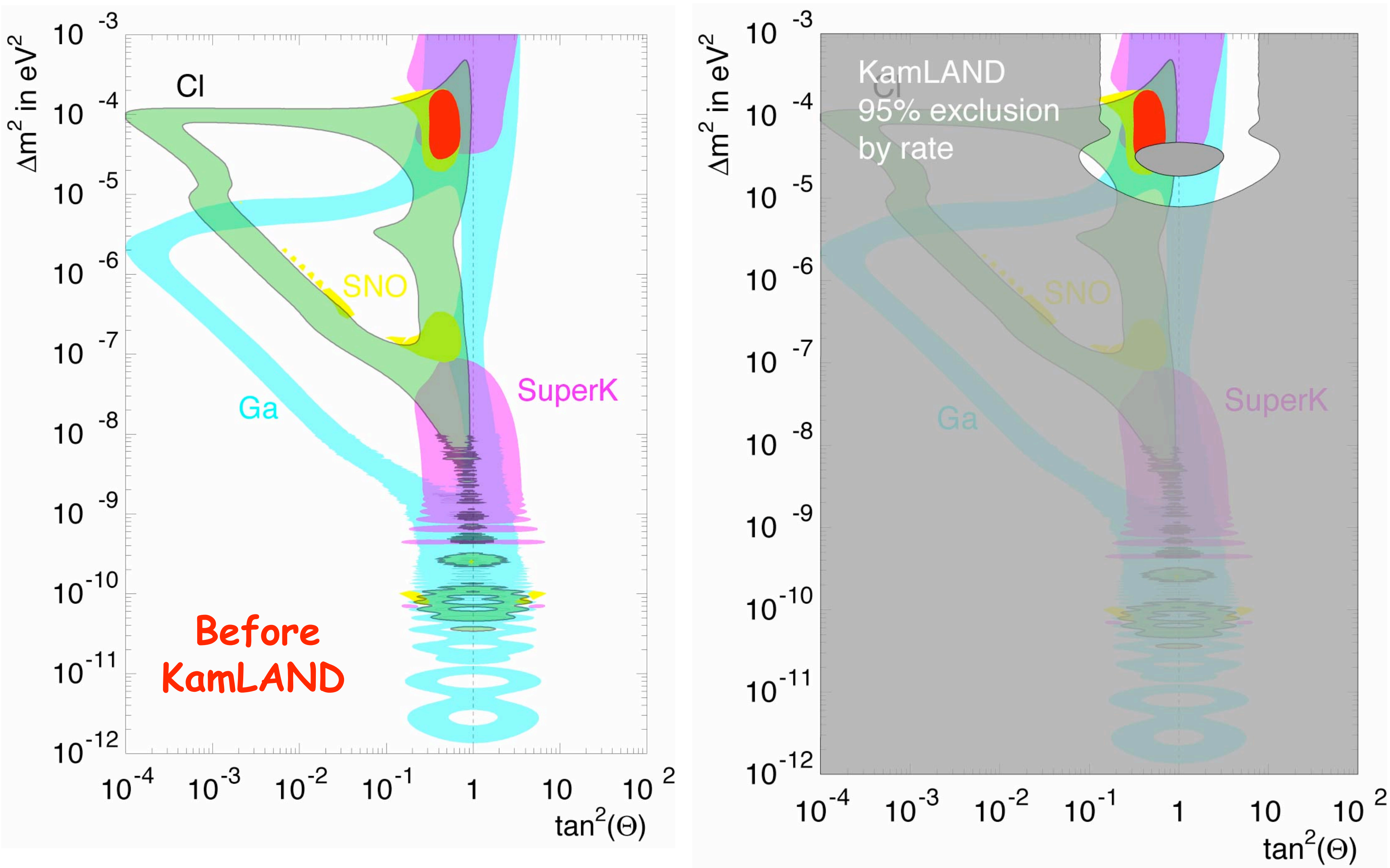
$$\frac{N_{obs} - N_{bg}}{N_{no}} = 0.686 \pm 0.044\ (stat) \pm 0.045\ (sys)$$

How Does It Compare With Expectation?

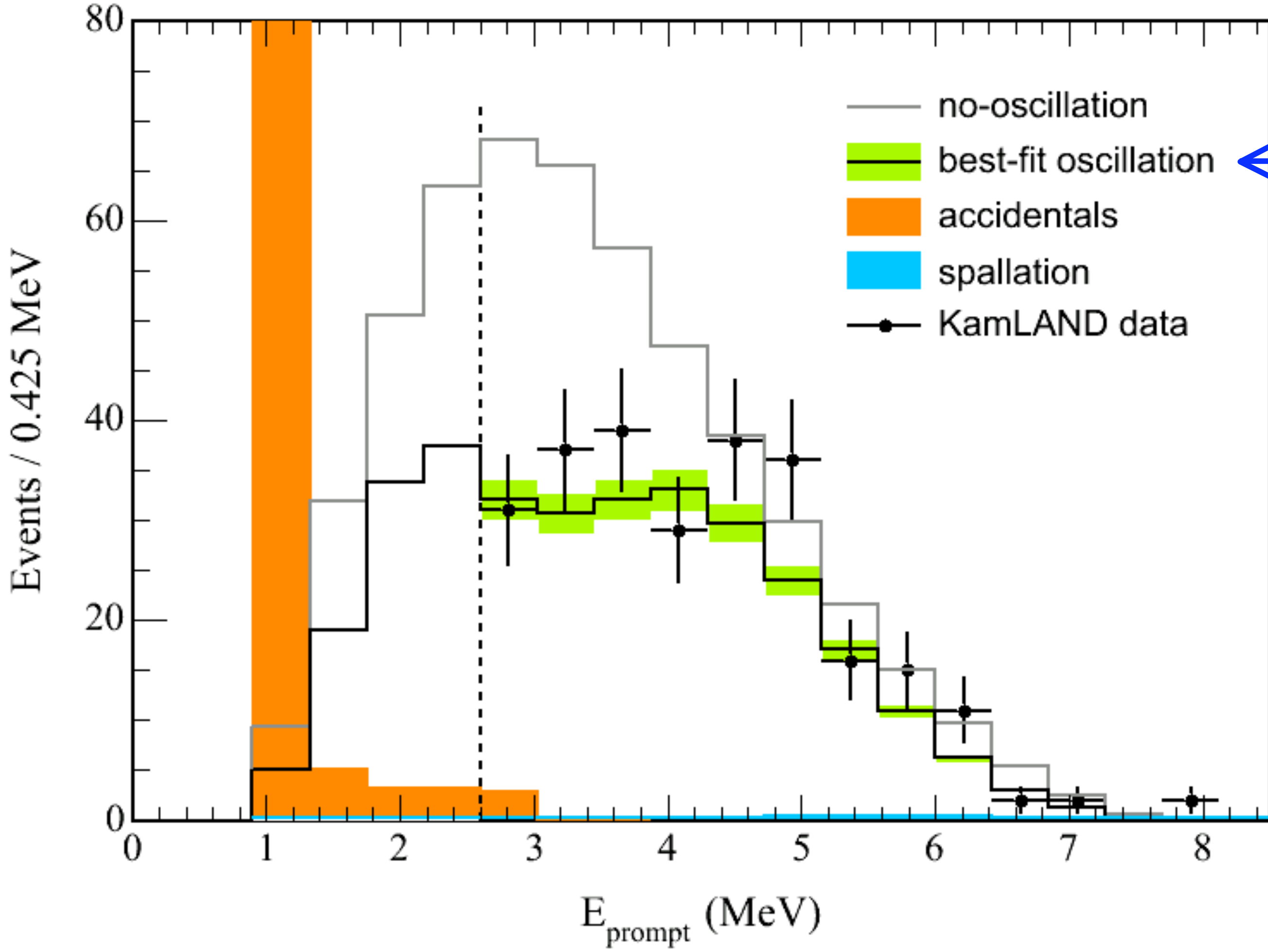


G.Fogli et al., PR D66, 010001-406, (2002)

Implication of Observed Rate Deflict

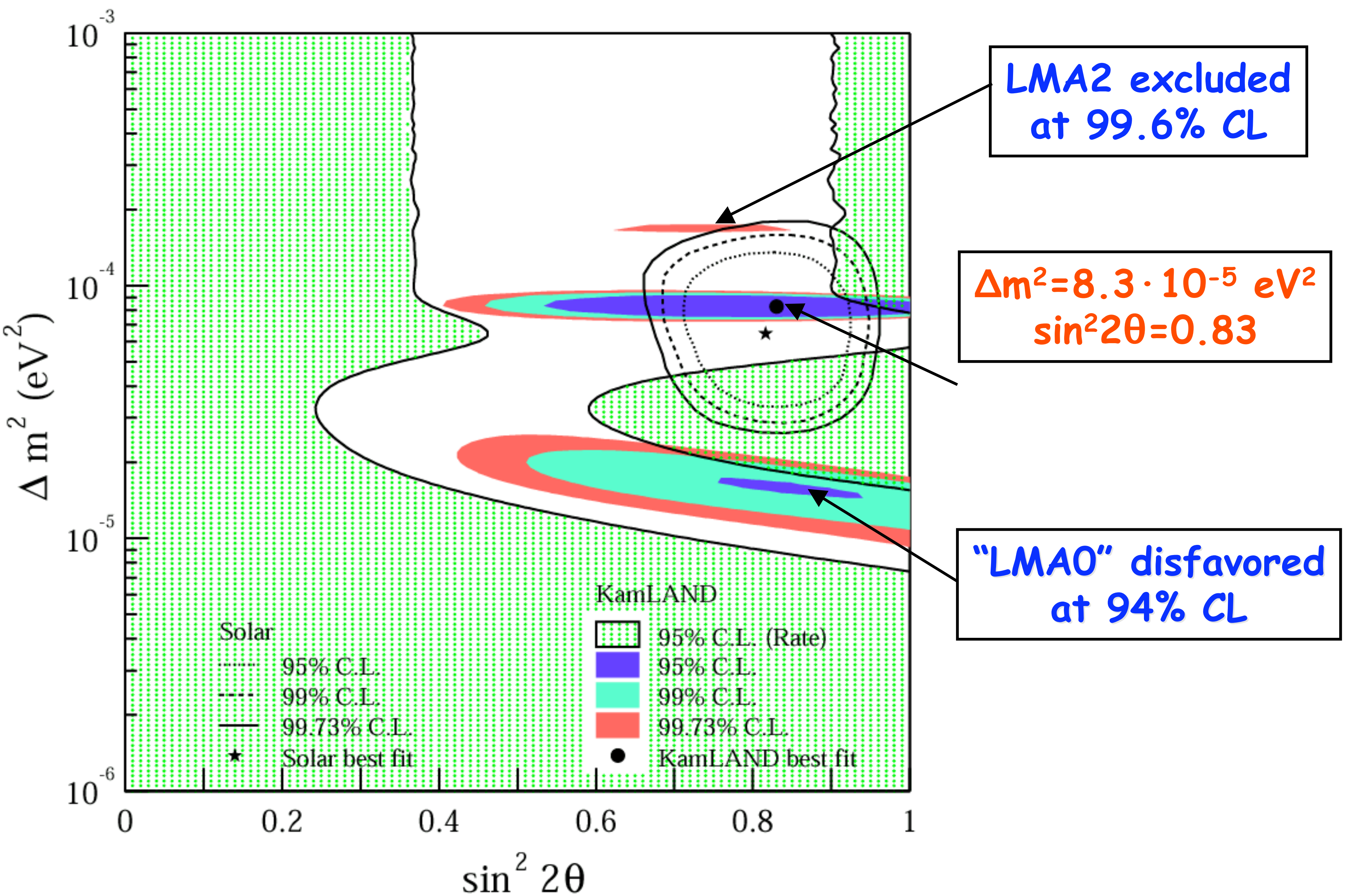


Energy Spectrum Helps



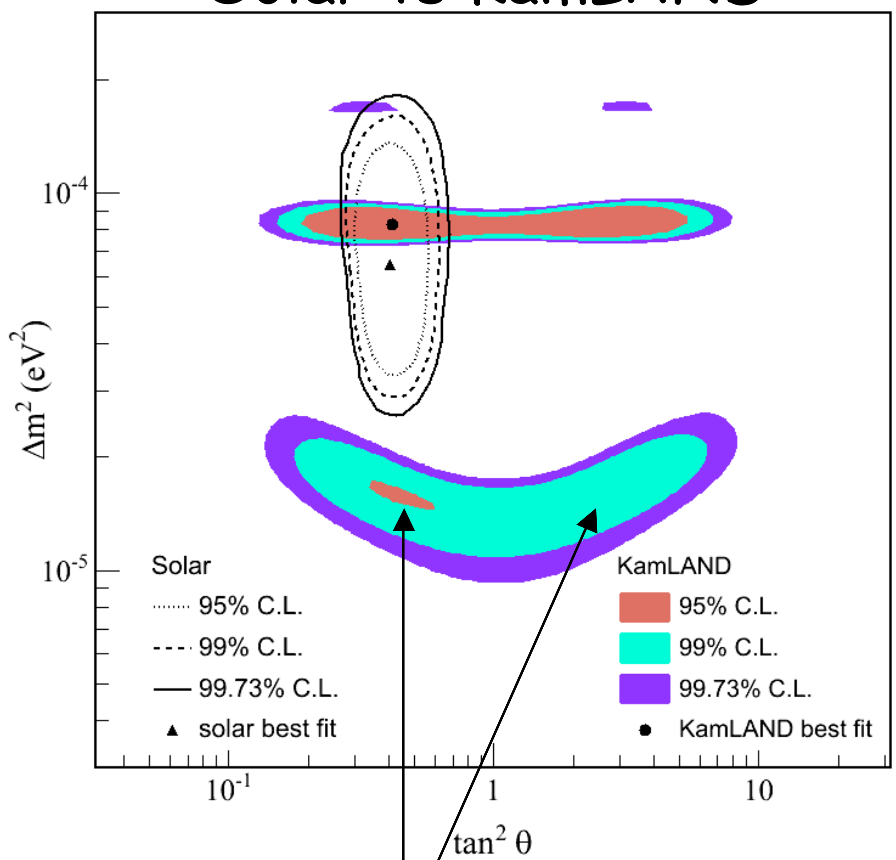
$\Delta m^2 = 8.3 \times 10^{-5}\ eV^2$
$\sin^2 2\theta = 0.83$

Likelihood Fit To 2-Flavour Oscillation

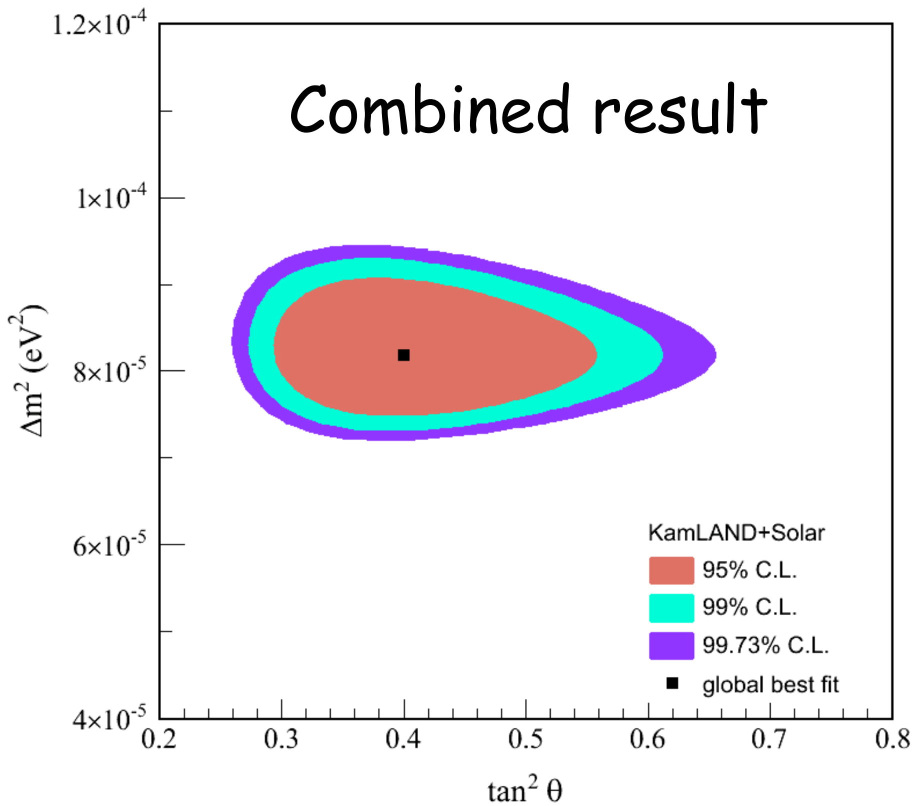


Combining Results

Solar vs KamLAND



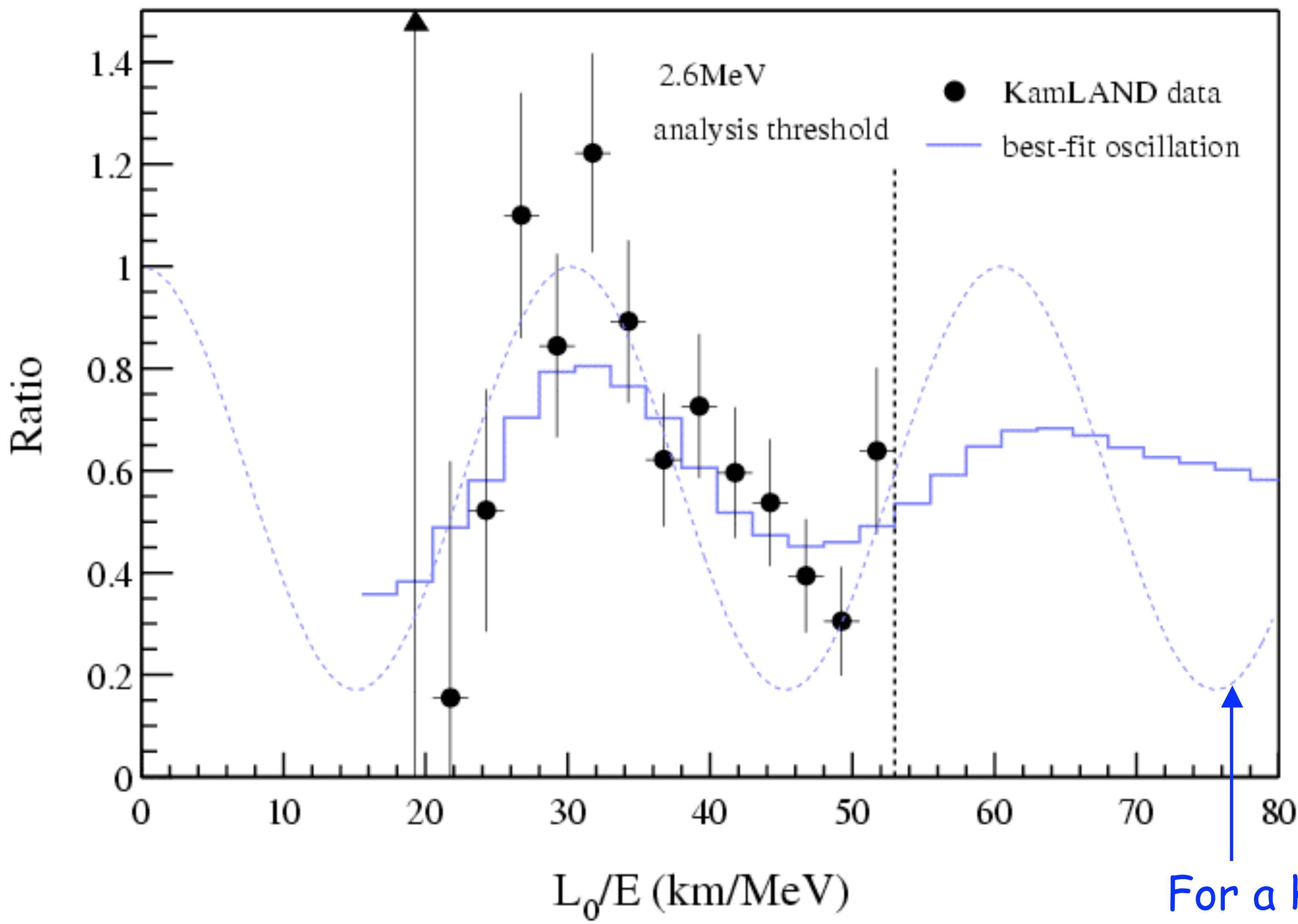
Includes small matter effects



$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2 \theta_{12} = 0.40^{+0.09}_{-0.07}$$

Observed Pattern Of Oscillation



For a hypothetical Experiment with a baseline of 180km

Summary

- Studies of solar neutrino led to the discovery of neutrino oscillation
- KamLAND using reactor confirmed neutrino oscillation
- The mixing angle θ and Δm^2 in the 2-flavour formulism are now pretty well-determined