NEUTRINO MIXING AND THE KAMLAND EXPERIMENT

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Manuel Franco Sevilla

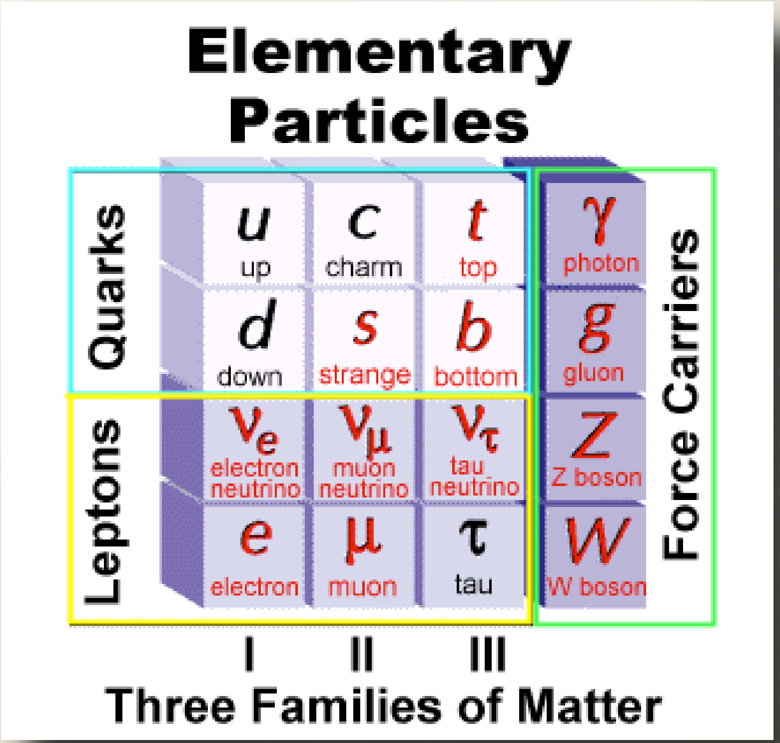
Contents

The little ν

* Suggested by Pauli in 1930
* Discovered in 1956 by Reines and Cowan

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

* ν_μ and ν_τ also found
* SM: Neutral, spin 1/2, massless

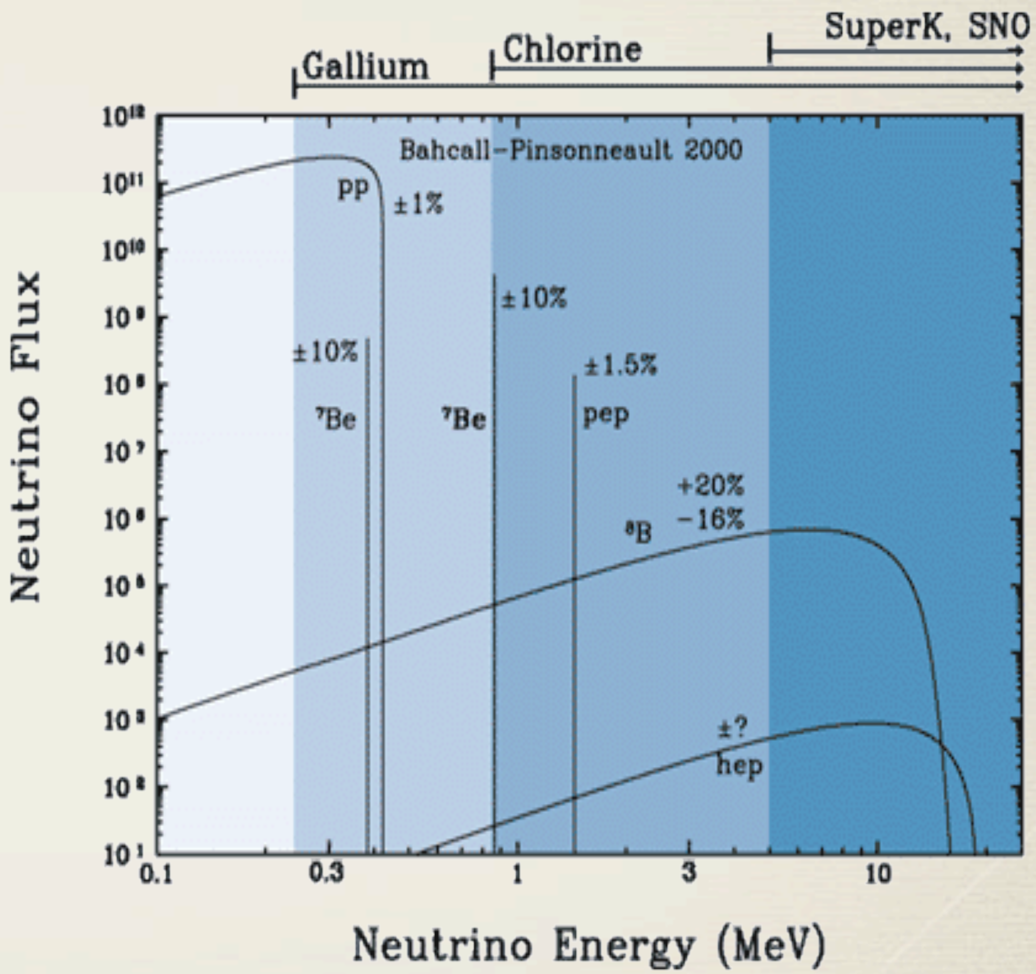


Solar neutrino problem

- Homestake experiment measured solar ν (SSM)
  - 620 m deep
  - Radiochemical detection

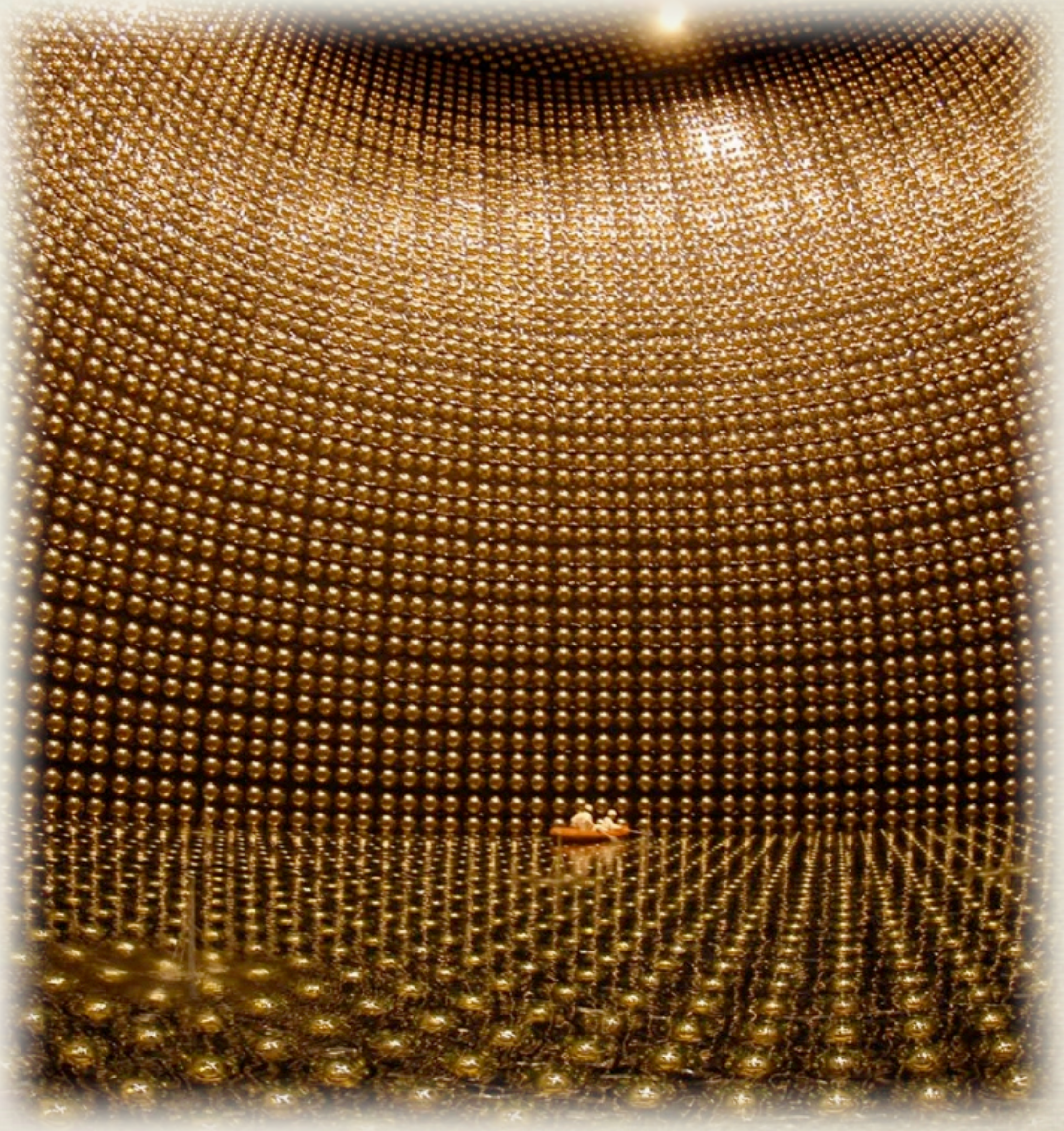
    $$\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^+$$

  - Found a ratio of 0.32 ± 0.03
- SAGE and GALLEX found similar results



Solar neutrino problem

* Real-time detection
  * Event-by-event analysis
  * Larger volumes
  * New interactions
* Kamiokande's
  * Water Cherenkov
  * Neutrino deficit



Solar neutrino problem

- SNO measures new interactions
  - Elastic Scattering (ES)

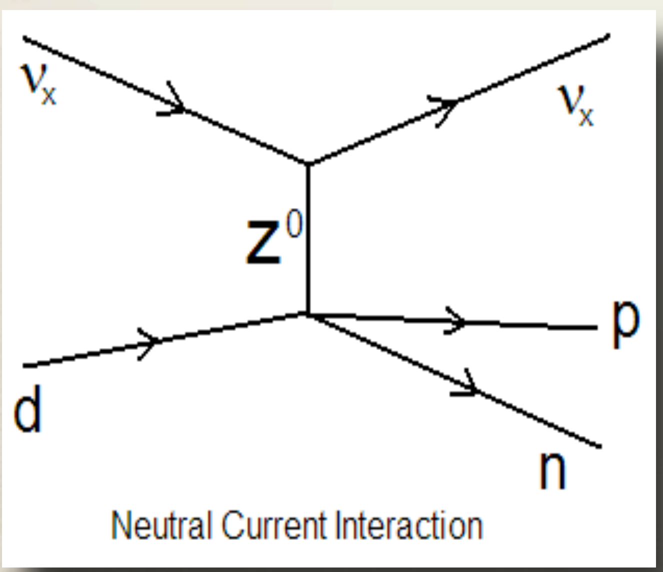
    $$\nu_x + e^- \to \nu_x + e^-$$

  - Neutral Current (NC)

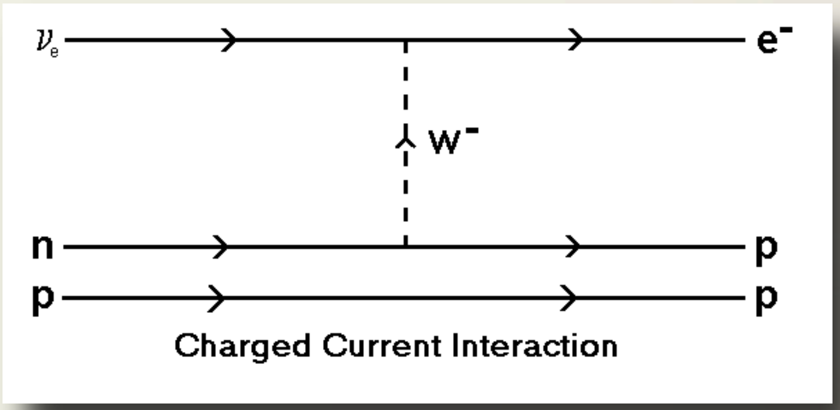
    $$\nu_x + d \to p + n + \nu_x$$

  - Charged Current (CC)

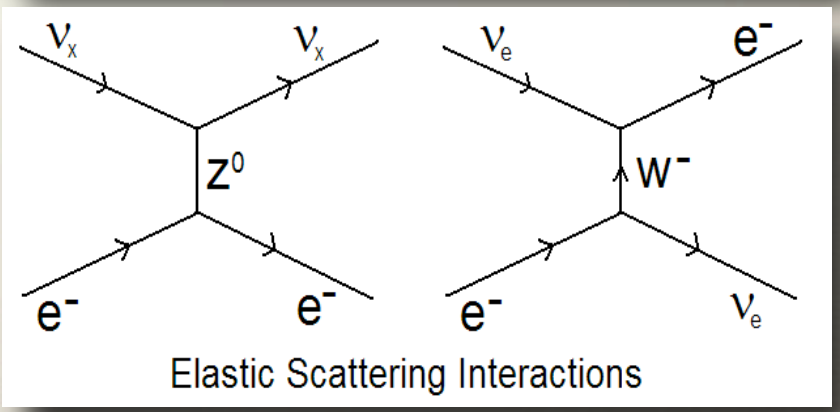
    $$\nu_e + d \to p + p + \nu_e$$



Neutral Current Interaction



Charged Current Interaction



Elastic Scattering Interactions

Solar neutrino problem

- SNO solar ν rates (Ahmad *et al.* PRL 2002)

$$\phi^{CC} = 1.76^{+0.06}_{-0.05}(stat)^{+0.09}_{-0.09}(syst) \times 10^6 cm^{-2} s^{-1}$$

$$\phi^{ES} = 2.39^{+0.24}_{-0.23}(stat)^{+0.12}_{-0.12}(syst) \times 10^6 cm^{-2} s^{-1}$$

$$\phi^{NC} = 5.09^{+0.44}_{-0.43}(stat)^{+0.46}_{-0.43}(syst) \times 10^6 cm^{-2} s^{-1}$$

Mixing proved

- SSM Prediction

$$\phi_{SSM} = 5.05^{+1.01}_{-0.81} \times 10^6 cm^{-2} s^{-1}$$

Neutrino mixing

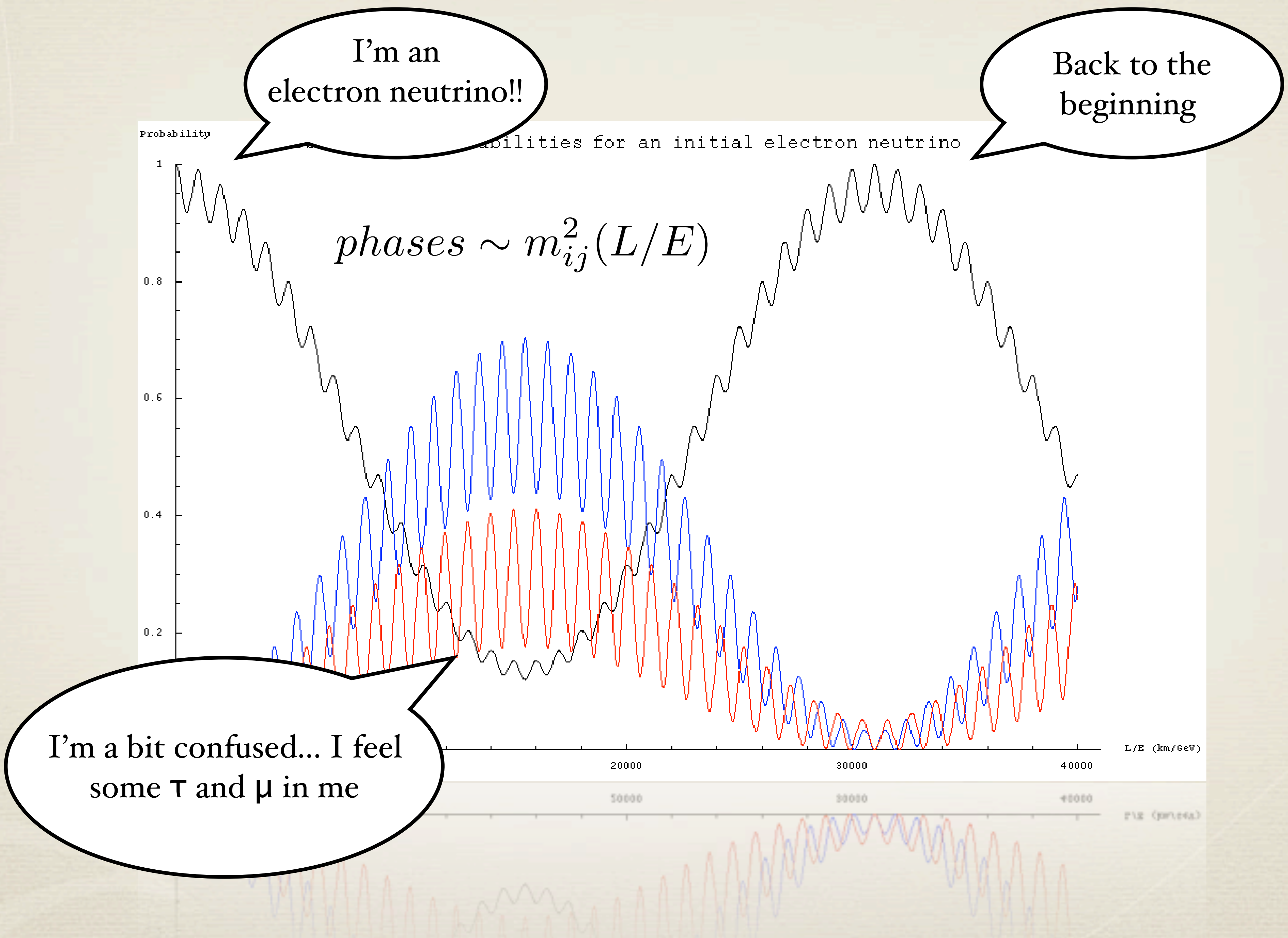
- These flavor oscillations fit in the Standard Model
  - Same lagrangian terms as the other leptons (mass $\sim m\bar{\psi}\psi$)
  - Possible additional Majorana term $\sim M_{PMNS}\psi^T C^{-1}\psi$
  - $M_{PMNS} = VK$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-\mathrm{i}\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & c_{23}c_{13} \end{pmatrix} \qquad K = \mathrm{diag}\,(1, \mathrm{e}^{\mathrm{i}\phi_1}, \mathrm{e}^{\mathrm{i}(\phi_2+\delta)})$$

- Propagation in vacuum

$$|\nu_\alpha(L)\rangle = \sum_i U^*_{\alpha i} e^{-im_i\tau_i}|\nu_i\rangle \approx \sum_i U^*_{\alpha i} e^{-i(m_i^2/2E)L}|\nu_i\rangle$$

Neutrino mixing

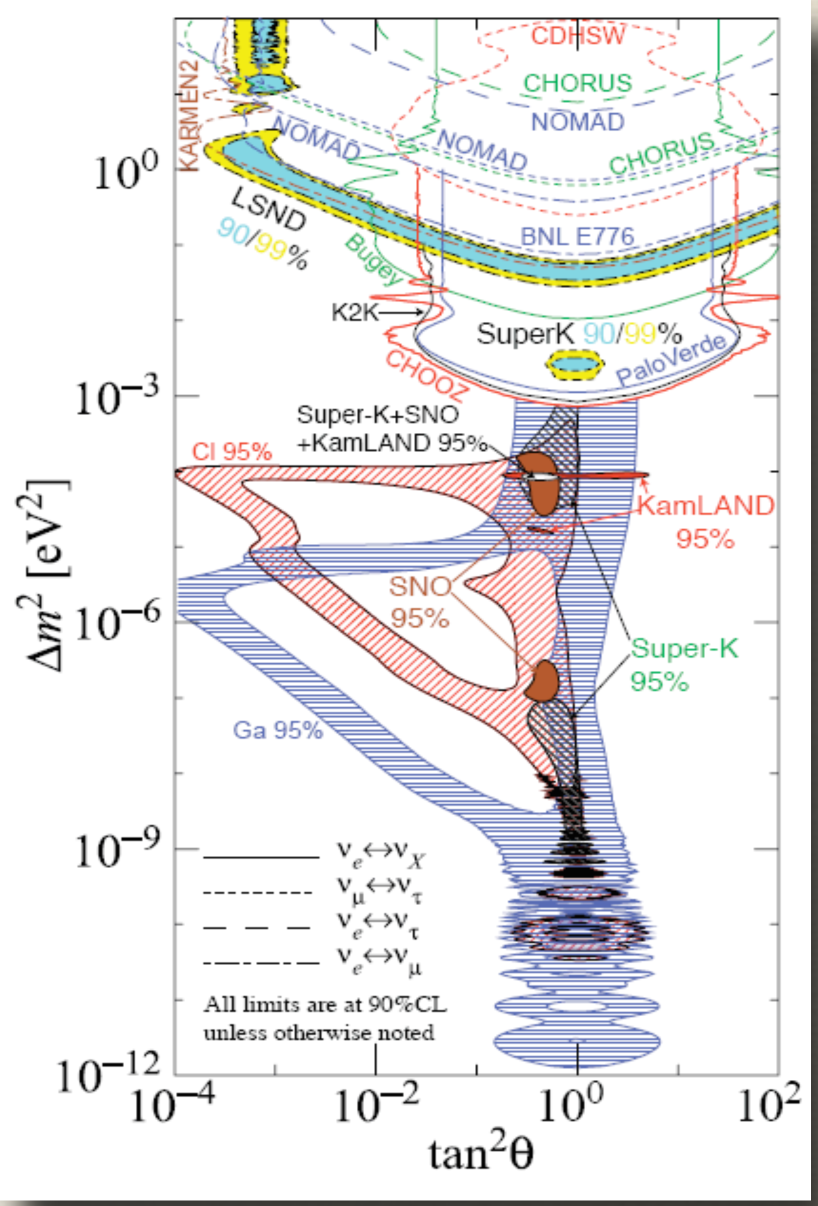


Results

- All solar and atmospheric experiments are consistent with this theory
- The global fit is

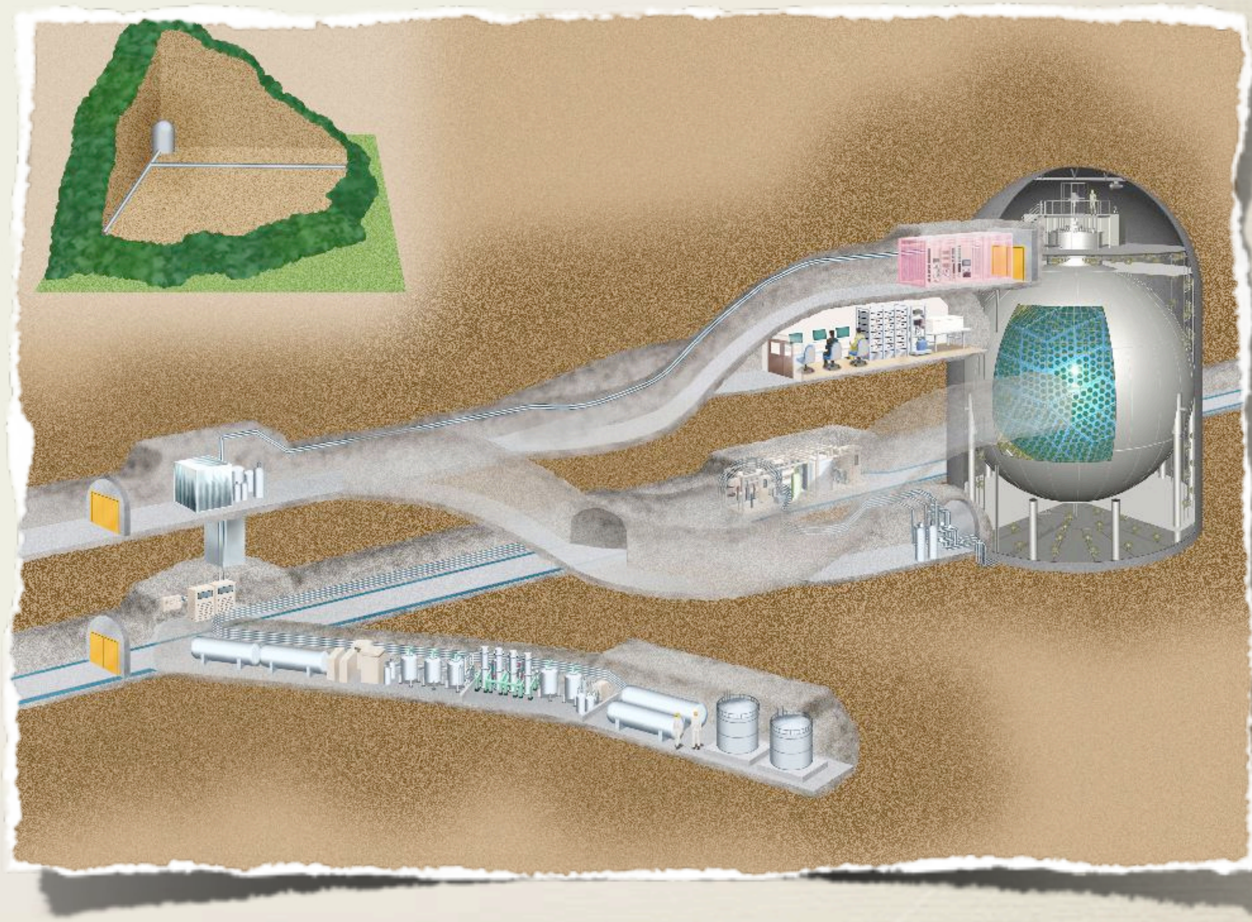
$$\Delta m^2 = 6.5^{+4.4}_{-2.3} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta = 0.45^{+0.09}_{-0.08}$$



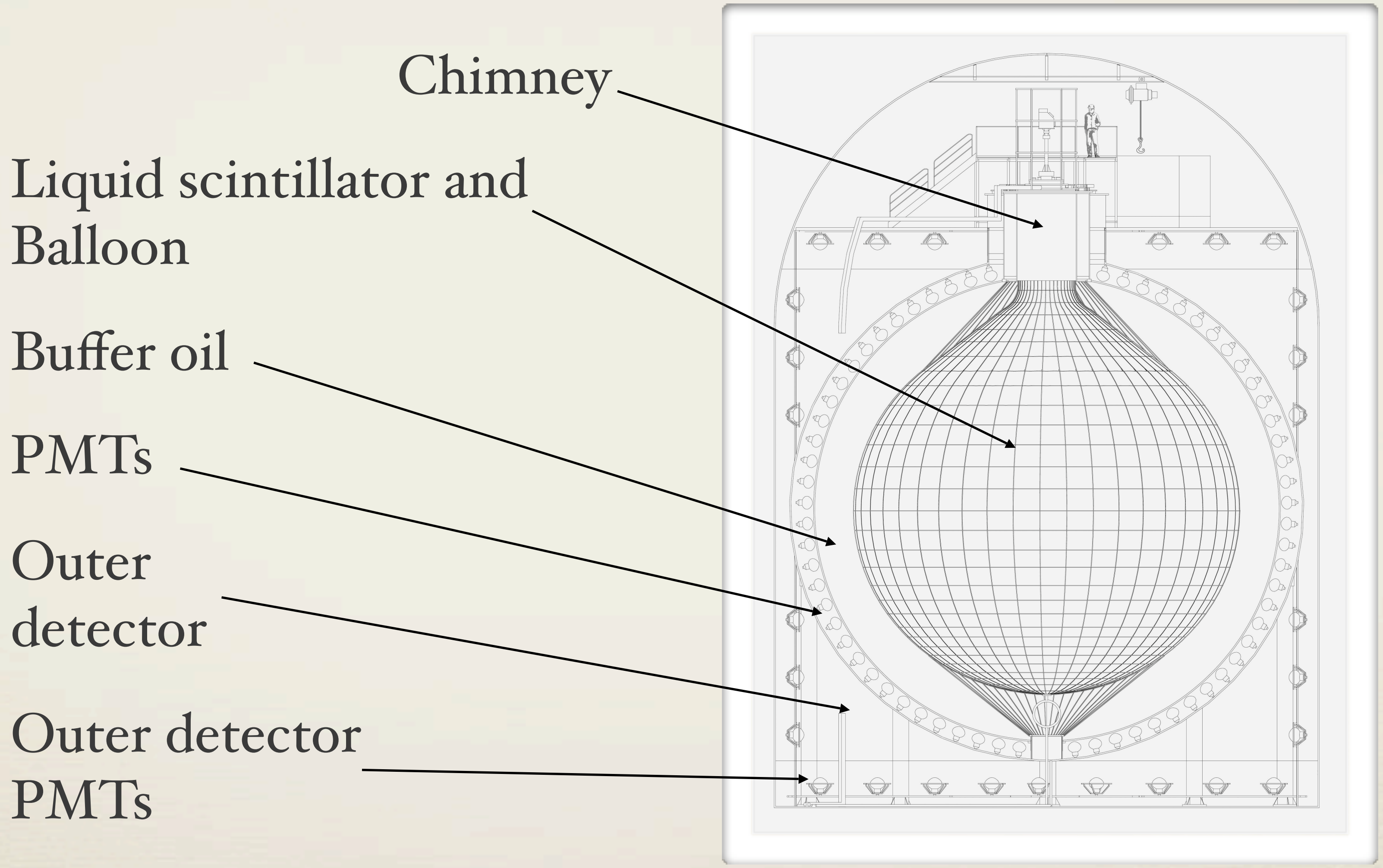
The KamLAND experiment

- Kamioka observatory, Japan
  - 2,700 m water equivalent underground
  - Reactor neutrinos
  - Since 2002



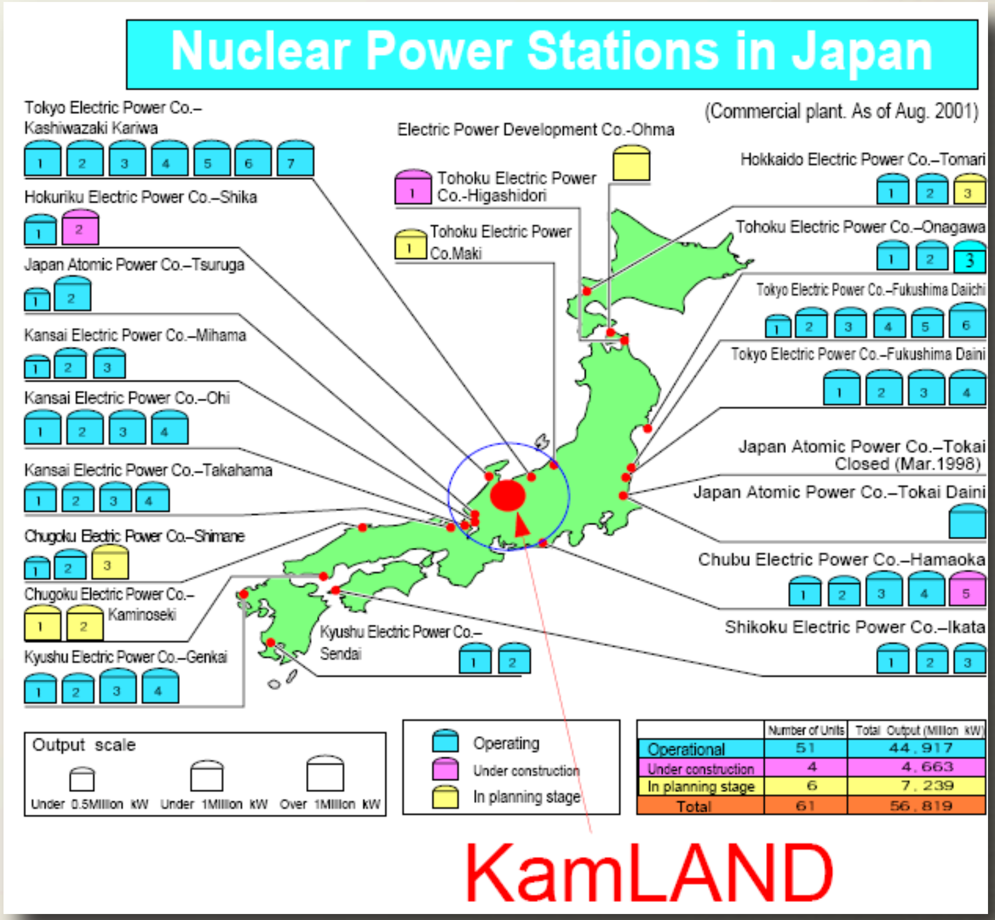
The KamLAND experiment

* Main components



The KamLAND experiment

* Power companies provide power output and burn-up data of each reactor
* Decays of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu are modeled
* Experimental checks: β-decays and reactor experiments
* Error of 3%



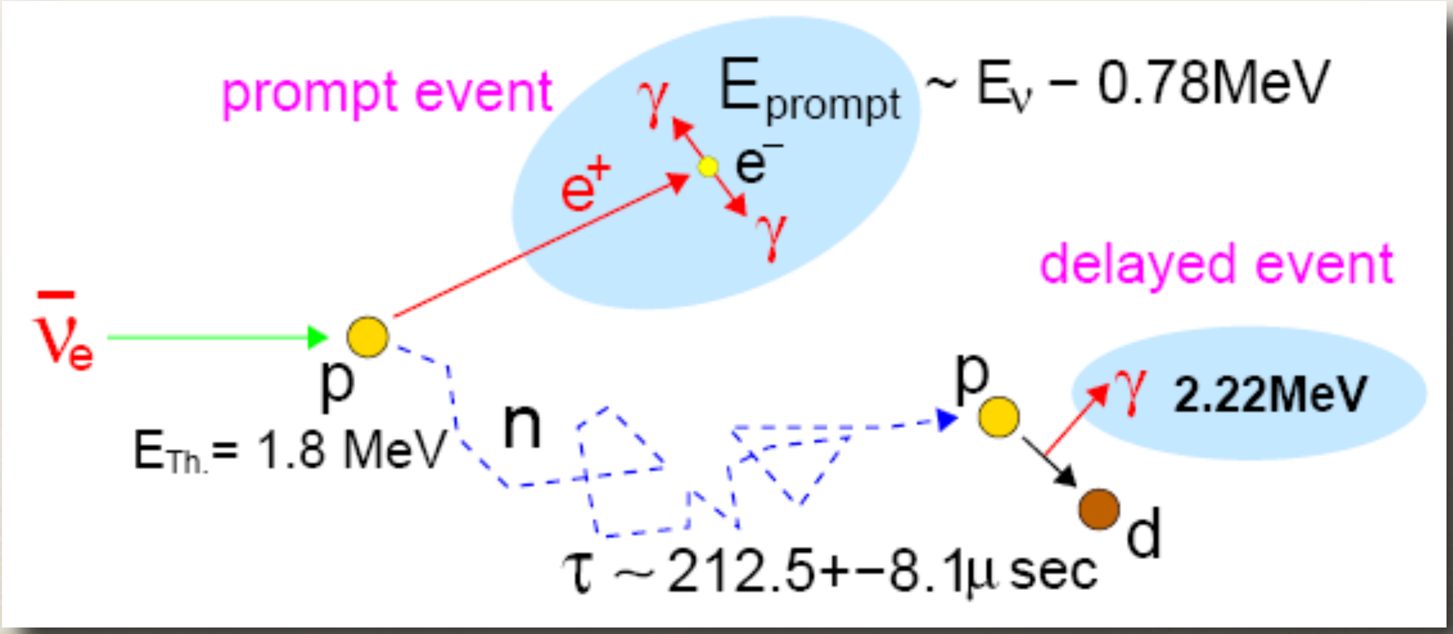
	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	6	7.239
Total	61	56.819

The KamLAND experiment

- Neutrinos are detected via

  $\bar{\nu}_e + p \rightarrow n + e^+ (E_{threshold} = \Delta m_{np} + m_e = 1.804\,\mathrm{MeV})$

- The e⁺ annihilates
- The neutron is thermalized and in 210 μs is absorbed



KamLAND results

* Latest results
  * S. Abe *et al.*, hep-ex/0801.4589v2
* Signal region
  * $0.5\ \mu s < \Delta T < 1000\ \mu s$
  * $\Delta R < 2$ m
  * 2.6 MeV $< E_{prompt} < 8.5$ MeV
  * 1.8 MeV $< E_{delayed} < 2.6$ MeV
* ~92% efficiency

KamLAND results

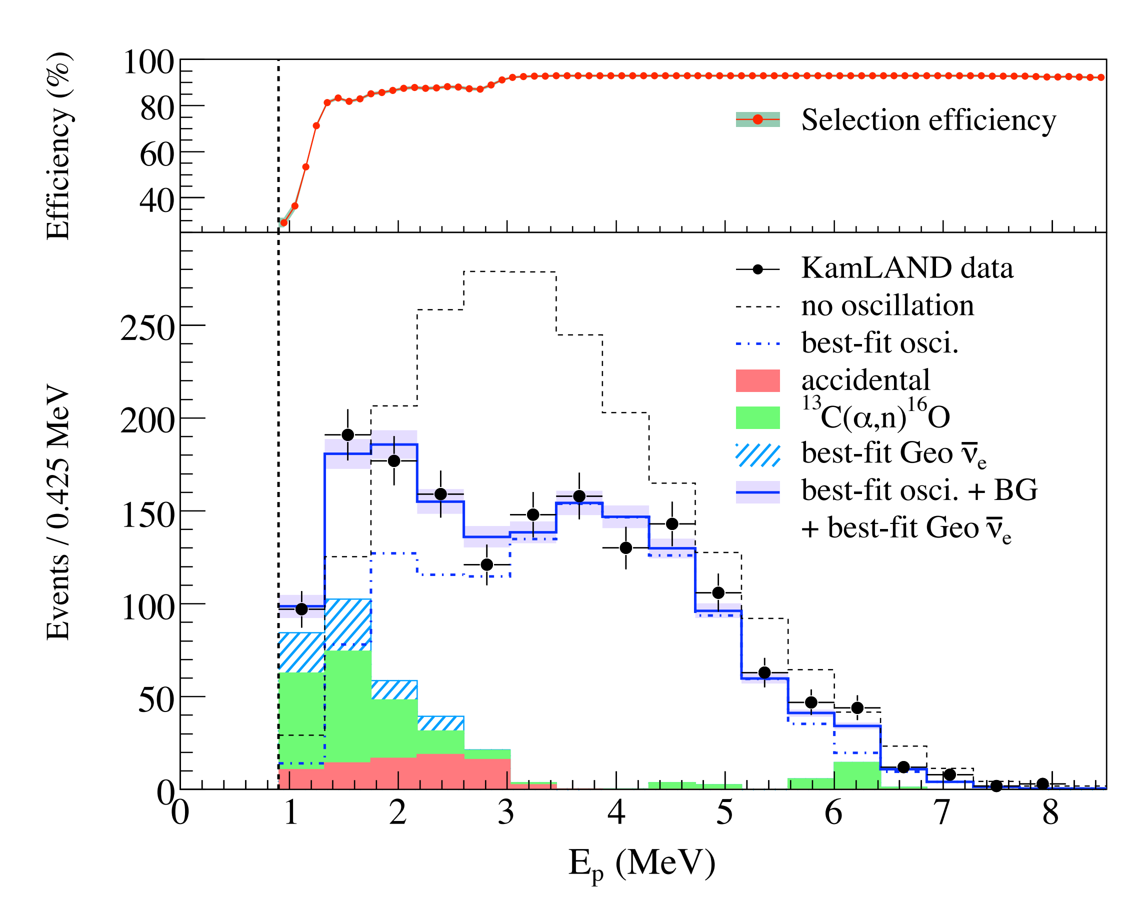
- Backgrounds
  - Muons interacting with nuclei that release neutrons
    - Mimic the signal shape
    - 2ms veto of the full volume
    - Less than 9 events in data sample
  - Muons also create β + neutron emitters $^{9}Li/^{8}He$
    - Long lifetimes
    - 2 s veto
      - Whole volume for poorly tracked or high energy μ
      - 3 m radius cylinder otherwise
    - 13.6 ± 1.0 $^{9}Li/^{8}He$ events

KamLAND results

- Backgrounds
  - $^{13}C(\alpha,n)^{16}O$ coming from α-decays of ^{210}Po
    - Fast neutrons
    - Special runs to measure rate of α-decays
    - Source of ^{210}Po and Monte Carlo studies yield 182.0 ± 21.7 events
  - 80.5 ± 0.1 of uncorrelated events
  - Also geoneutrinos, but those ones are fitted
  - Total of 276.1 ± 23.5 events

KamLAND results

- Expected 2179 ± 89 events
- 1609 observed
- Energy spectrum without ν-oscillation excluded at more than 5σ



KamLAND results

* The results of the solar experiments were

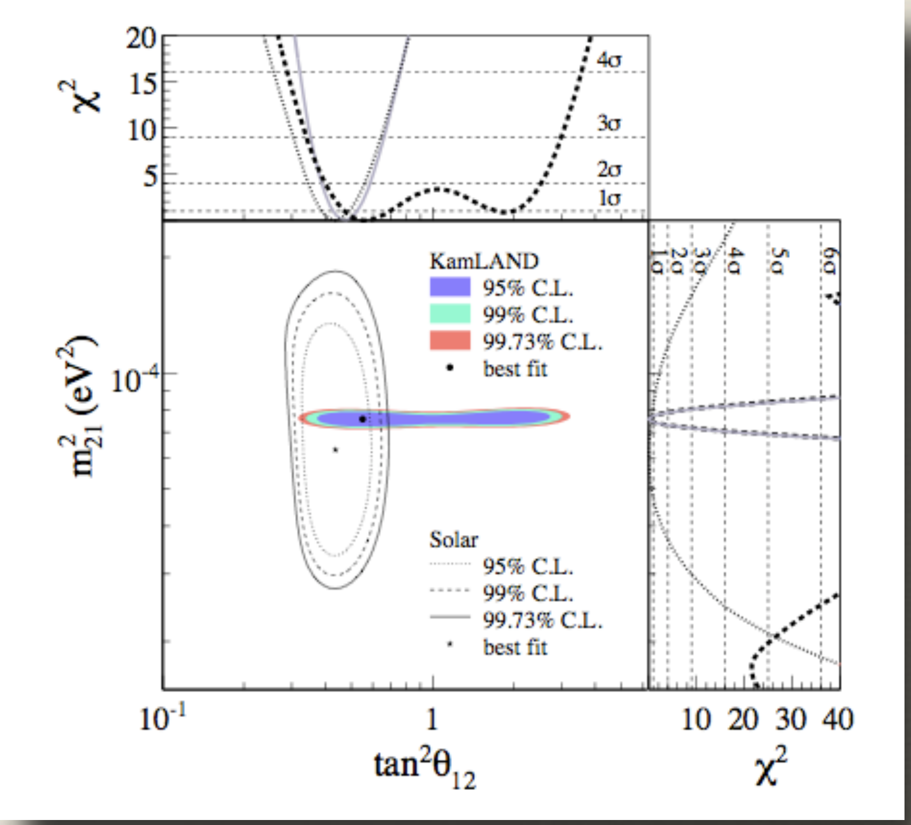
$$\Delta m^2 = 6.5^{+4.4}_{-2.3} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta = 0.45^{+0.09}_{-0.08}$$

* Using KamLAND

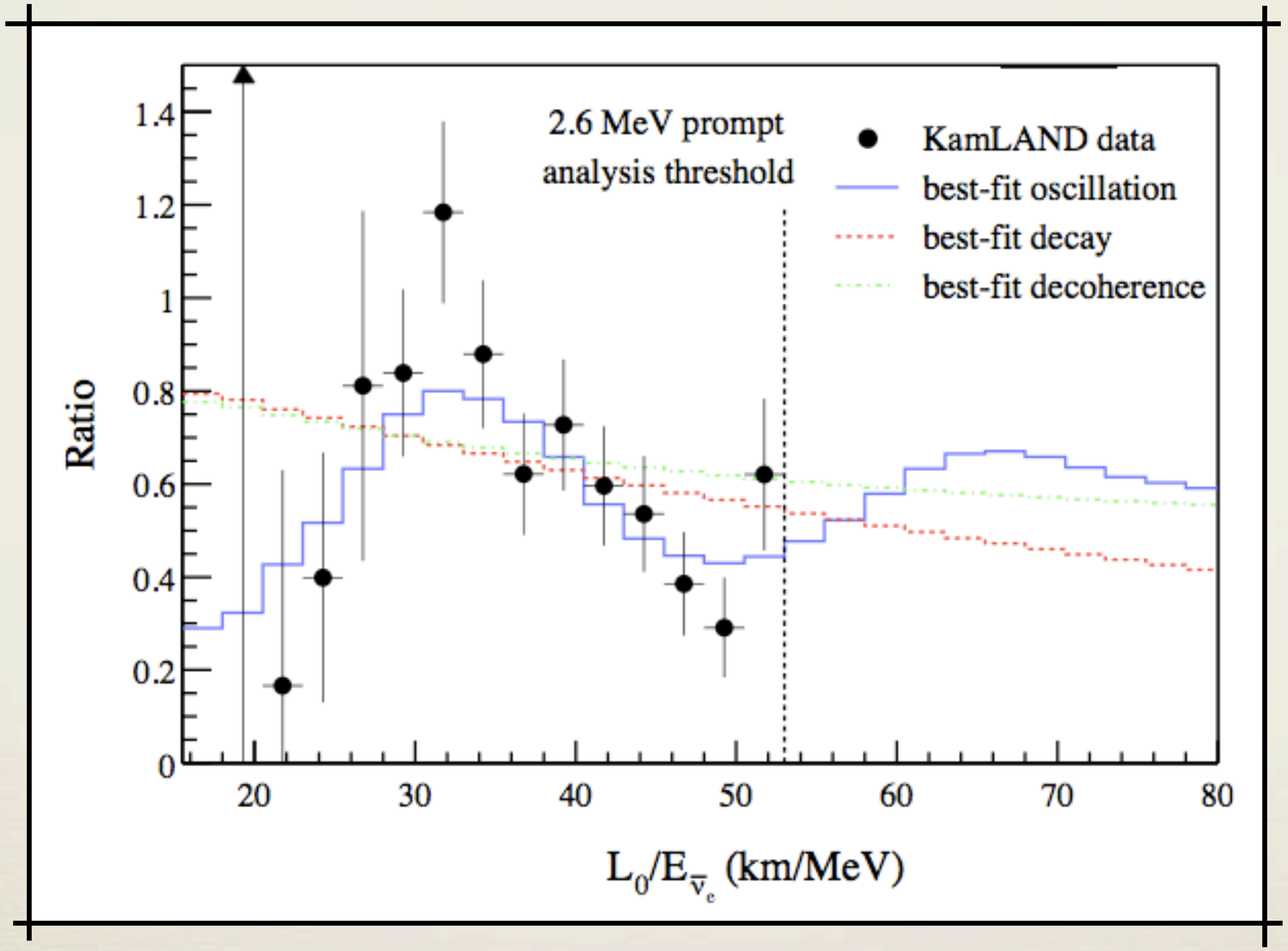
$$\Delta m^2 = 7.59^{+0.21}_{-0.25} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta = 0.47^{+0.06}_{-0.05}$$



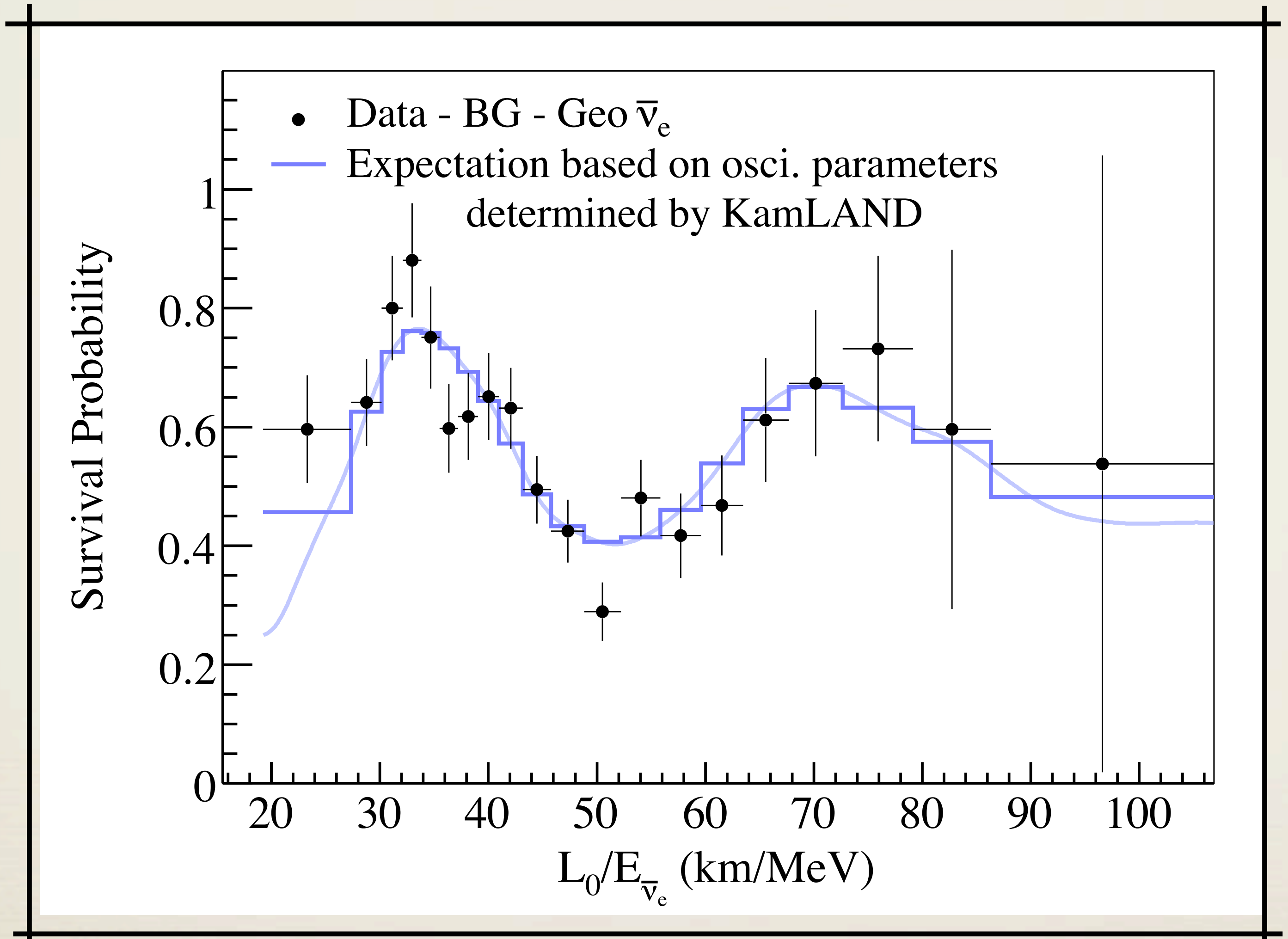
Why KamLAND *is* cool

2005



Why KamLAND *is* cool

2008



Summary

* Neutrinos oscillate
  * Mass required. New physics?
* KamLAND greatly improves Δm^2 measurement
* It *sees* the oscillations
* Still lots of physics to have fun with

Thank you all!