Neutrino oscillation

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Neutrino propagation

- Neutrino mass eigenstate propagation Hamiltonian

$$H = E = \sqrt{p^2 + m^2}$$

$$= p(1 + \frac{m^2}{p^2})^{1/2}$$

$$\simeq p(1 + \frac{m^2}{2p^2})$$

-

$$\simeq E + \frac{m^2}{2E}$$

Neutrino mixing

- Flavor (weak) eigenstate not needed to be the same as mass eigenstate
- $$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U^* \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$\begin{bmatrix} \nu_\mathrm{e} \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- U is the PMNS matrix
    - Pontecorvo–Maki–Nakagawa–Sakata matrix
- The mass Eigenstate satisfy the free Schrodinger equation
- $$\frac{d}{dt}|\nu_i\rangle = -iH|\nu_i\rangle$$

Neutrino vacuum mixing (two flavour)

- $\frac{d}{dt}|\nu_i\rangle = -iH|\nu_i\rangle$
- $|\nu_i\rangle = e^{-iHt}|\nu_i\rangle$
- $|\nu_i\rangle = e^{-i(E+\frac{m^2}{2E})t}|\nu_i\rangle$
- $\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$
- $c = \cos\theta$
- $s = \sin\theta$
- $|\nu_e(t)\rangle = c|\nu_1(t)\rangle + s|\nu_2(t)\rangle$
- $|\nu_e(L=ct)\rangle = e^{-iEt}\left(ce^{-i\frac{m_1^2L}{2E}}|\nu_1(0)\rangle + se^{-i\frac{m_2^2L}{2E}}|\nu_2(0)\rangle\right)$
- $|\nu_e(L=ct)\rangle = e^{-iEt}e^{-i\frac{m_1^2L}{2E}}\left(c|\nu_1(0)\rangle + se^{-i\frac{\left(m_2^2-m_1^2\right)L}{2E}}|\nu_2(0)\rangle\right)$

Neutrino vacuum mixing (two flavour)

- $|\nu_e(L=ct)\rangle = e^{-iEt}e^{-i\frac{m_1^2 L}{2E}}\left(c\,|\nu_1(0)\rangle + s e^{-i\frac{\left(m_2^2-m_1^2\right)L}{2E}}|\nu_2(0)\rangle\right)$
- $P_{ee} = |\langle \nu_e | \nu_e(L)\rangle|^2$
- $P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
- $P_{ee} = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E}\right)$

$\sin^2 2\theta$: Amplitude

$\theta = 45°$: maximal mixing

$\Delta m^2 = |m_2^2 - m_1^2|$

- no mass ordering

- no absolute mass scale

ATM observation
Angular distribution

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Evidence for Oscillation of Atmospheric Neutrinos

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We present an analysis of atmospheric neutrino data from a 33.0 kton yr (535-day) exposure of the Super-Kamiokande detector. The data exhibit a zenith angle dependent deficit of muon neutrinos which is inconsistent with expectations based on calculations of the atmospheric neutrino flux. Experimental biases and uncertainties in the prediction of neutrino fluxes and cross sections are unable to explain our observation. The data are consistent, however, with two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2 at 90% confidence level. [S0031-9007(98)06975-0]

$$P_{a\to b} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right),$$

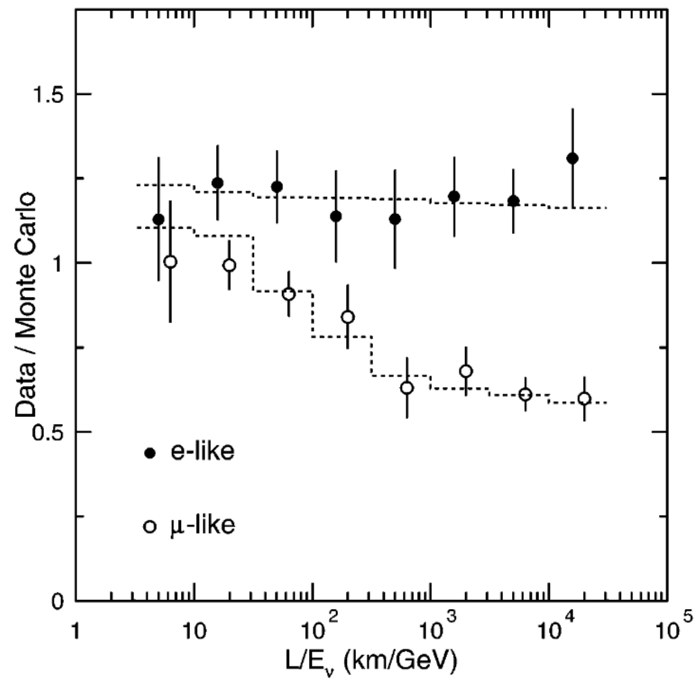

FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2–7%) of ν_μ CC interactions.

Reactor neutrino experiments

- First detection of neutrinos
  - Electron anti-neutrinos

A detector consisting of two tanks of water was employed, offering a huge number of potential targets in the protons of the water. At those rare instances when neutrinos interacted with protons in the water, neutrons and positrons were created:

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

The additional detection of the neutron from the neutrino interaction provided a second layer of certainty. Cowan and Reines detected the neutrons by dissolving cadmium chloride, $CdCl_2$, in the tank. Cadmium is a highly effective neutron absorber and gives off a gamma ray when it absorbs a neutron.

$$n + {}^{108}Cd \rightarrow {}^{109m}Cd \rightarrow {}^{109}Cd + \gamma$$

The arrangement was such that after a neutrino interaction event, the two gamma rays from the positron annihilation would be detected, followed by the gamma ray from the neutron absorption by cadmium several microseconds later.

Cowan–Reines neutrino experiment

12 languages

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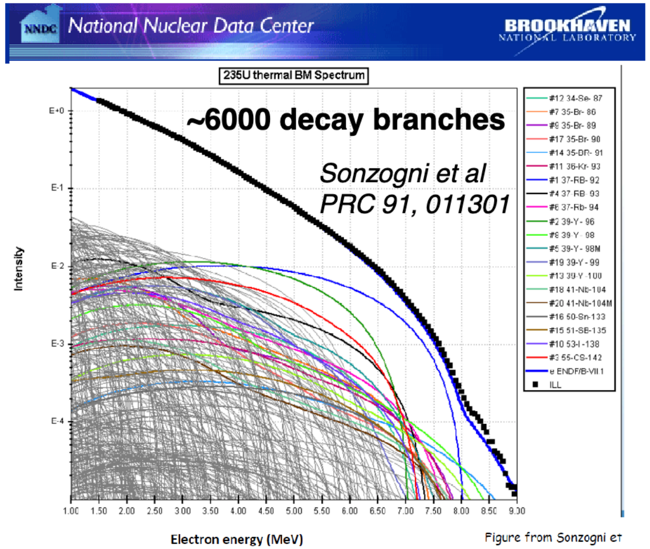
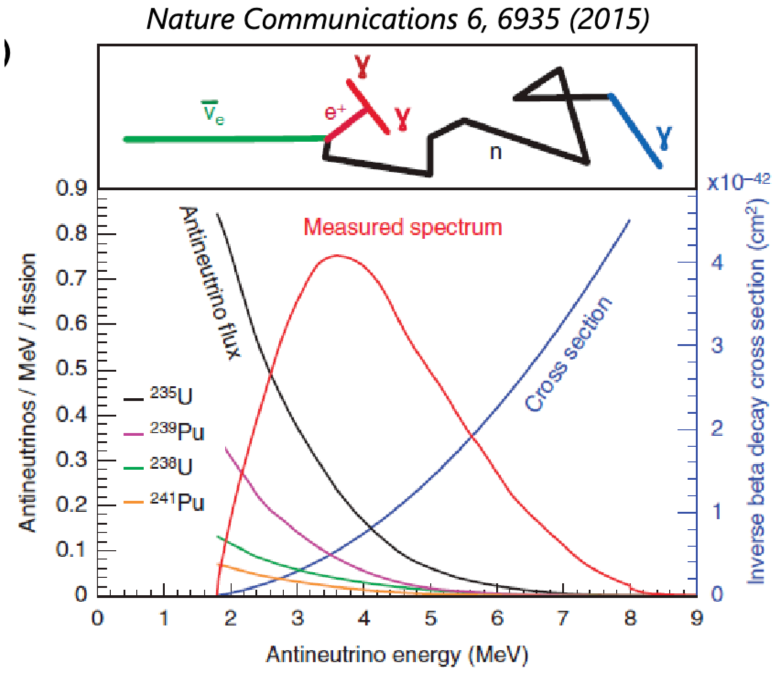
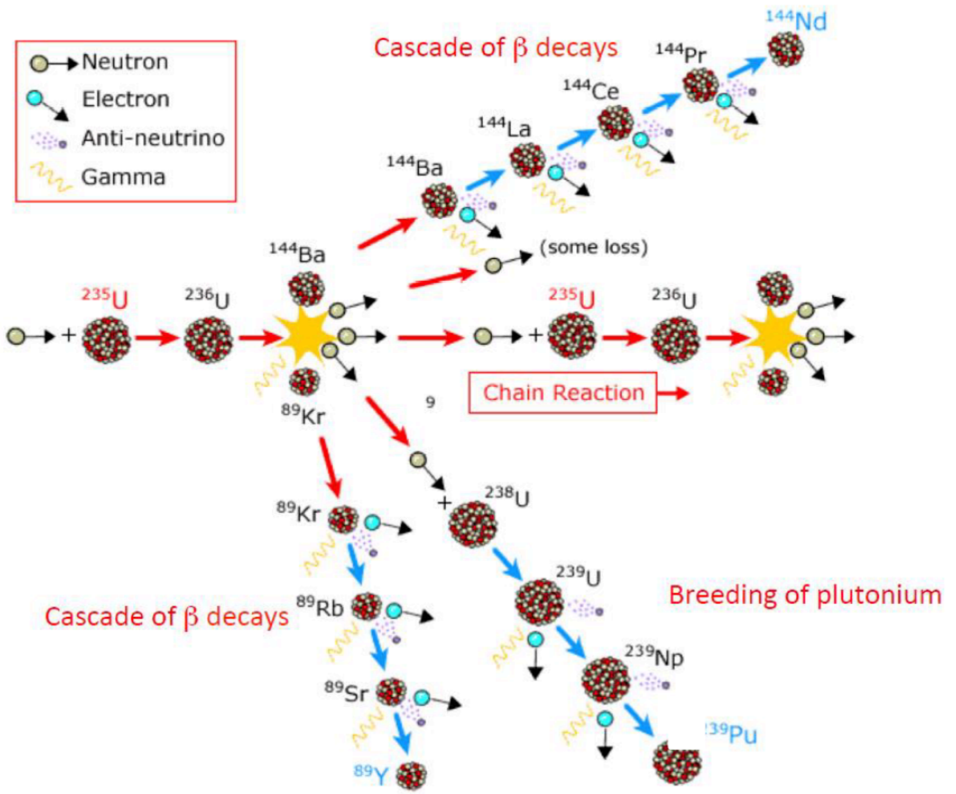
The **Cowan–Reines neutrino experiment** was conducted by physicists Clyde Cowan and Frederick Reines in 1956. The experiment confirmed the existence of neutrinos. Neutrinos, subatomic particles with no electric charge and very small mass, had been conjectured to be an essential particle in beta decay processes in the 1930s. With no charge and minuscule mass, such particles appeared to be impossible to detect. The experiment exploited a huge flux of (then hypothetical) electron antineutrinos emanating



- Summation (*ab initio*) method
  - Calculate the spectrum of each beta-decay branch using **nuclear databases**: fission yields, decay schemes
  - ~10% uncertainty

Reactor neutrino experiments

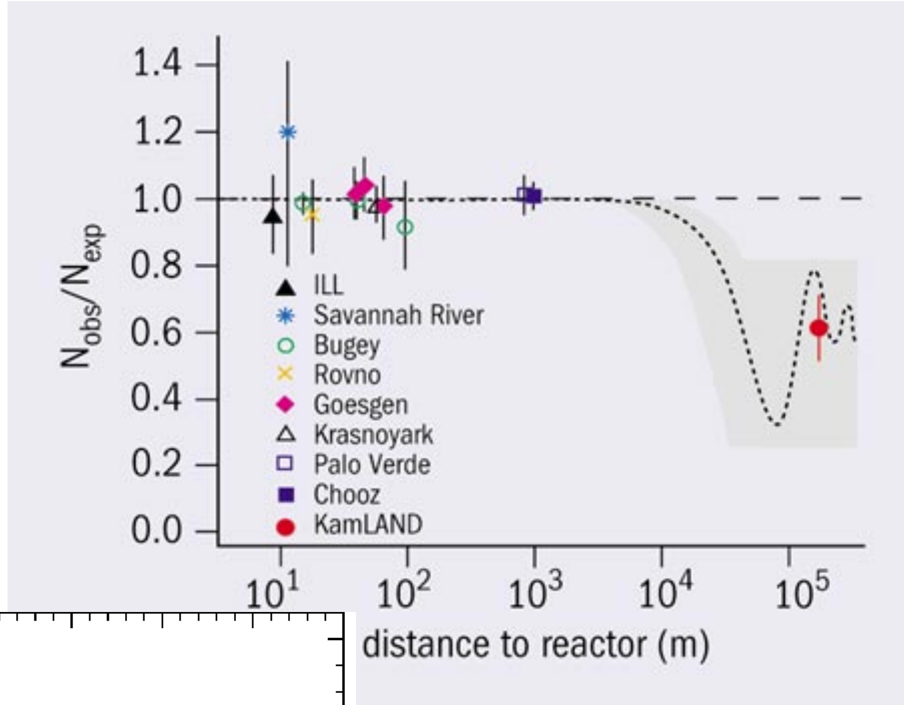


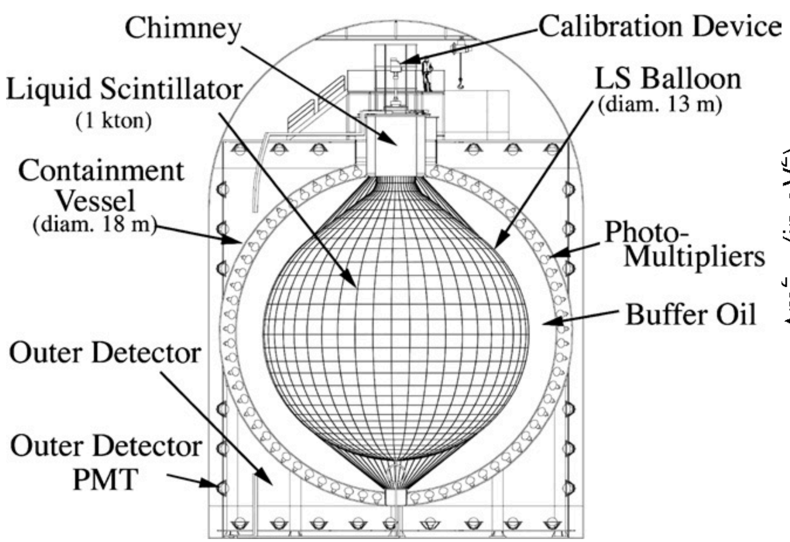


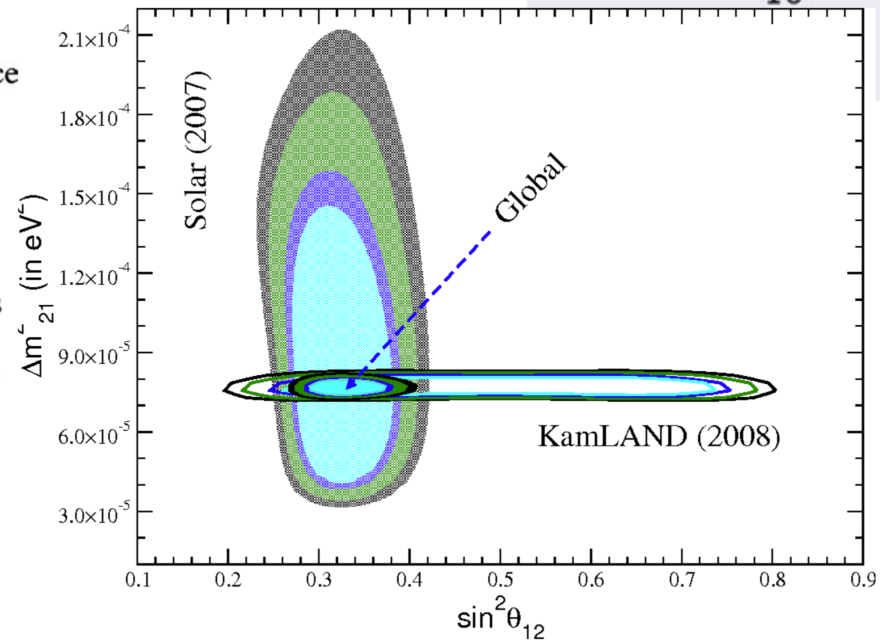
- Nuclear reactors produce pure $\overline{\nu}_e$ from beta decays of fission daughters
  - Low energy: < 10 MeV
- ~6 $\overline{\nu}_e$ / fission
- 2 x 10^{20} $\overline{\nu}_e$ / sec per GW_{th} (free for physicists)

Kamland Neutrino detector

- Kamioka Liquid Scintillator antineutrino detector
- Reactor experiment to be at the right distance and energy!







Kamland Neutrino detector

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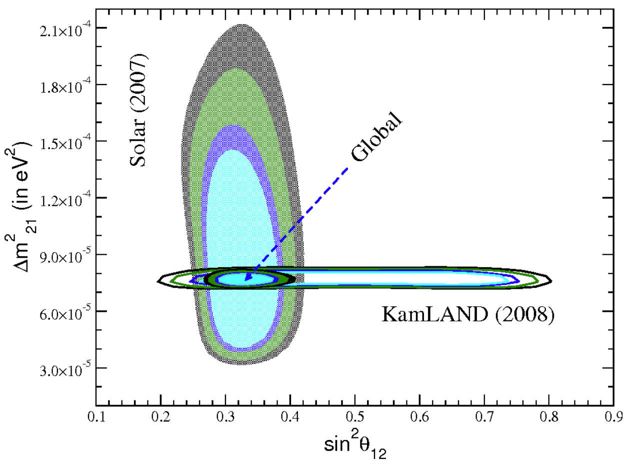
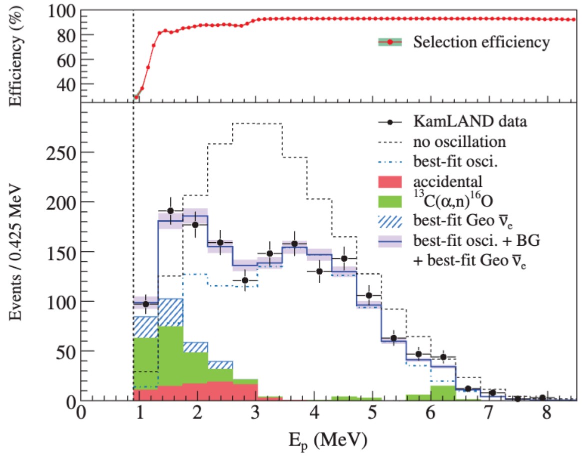
PRL **100,** 221803 (2008) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2008

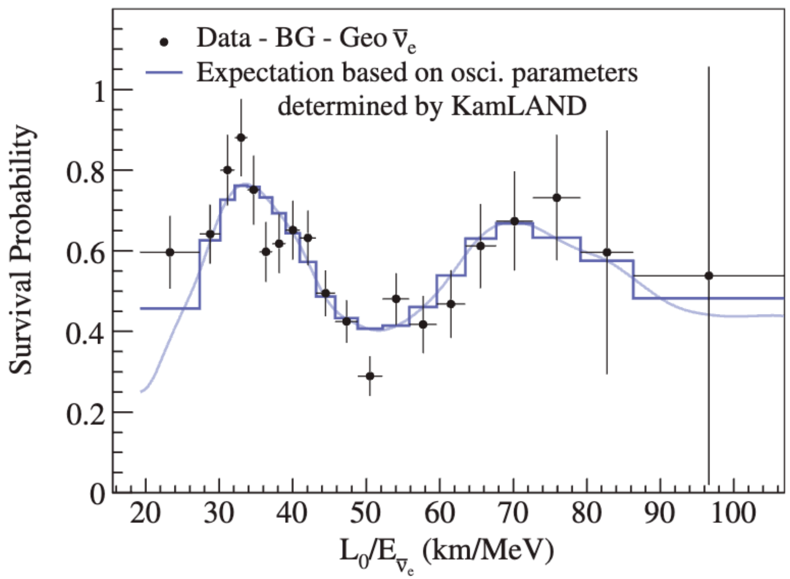
Precision Measurement of Neutrino Oscillation Parameters with KamLAND

S. Abe,[1] T. Ebihara,[1] S. Enomoto,[1] K. Furuno,[1] Y. Gando,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] Y. Kibe,[1] Y. Kishimoto,[1] M. Koga,[1] A. Kozlov,[1] Y. Minekawa,[1] T. Mitsui,[1] K. Nakajima,[1,*] K. Nakajima,[1] K. Nakamura,[1] M. Nakamura,[1] K. Owada,[1] I. Shimizu,[1] Y. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] Y. Takemoto,[1] K. Tamae,[1] A. Terashima,[1] H. Watanabe,[1] E. Yonezawa,[1] S. Yoshida,[1] J. Busenitz,[2] T. Classen,[2] C. Grant,[2] G. Keefer,[2] D. S. Leonard,[2] D. McKee,[2] A. Piepke,[2] M. P. Decowski,[3] J. A. Detwiler,[3] S. J. Freedman,[3] B. K. Fujikawa,[3] F. Gray,[3,†] E. Guardincerri,[3] L. Hsu,[3,‡] R. Kadel,[3] C. Lendvai,[3] K.-B. Luk,[3] H. Murayama,[3] T. O'Donnell,[3] H. M. Steiner,[3] L. A. Winslow,[3] D. A. Dwyer,[4] C. Jillings,[4,§] C. Mauger,[4] R. D. McKeown,[4] P. Vogel,[4] C. Zhang,[4] B. E. Berger,[5] C. E. Lane,[6] J. Maricic,[6] T. Miletic,[6] M. Batygov,[7] J. G. Learned,[7] S. Matsuno,[7] S. Pakvasa,[7] J. Foster,[8] G. A. Horton-Smith,[8] A. Tang,[8] S. Dazeley,[9,∥] K. E. Downum,[10] G. Gratta,[10] K. Tolich,[10] W. Bugg,[11] Y. Efremenko,[11] Y. Kamyshkov,[11] O. Perevozchikov,[11] H. J. Karwowski,[12] D. M. Markoff,[12] W. Tornow,[12] K. M. Heeger,[13] F. Piquemal,[14] and J.-S. Ricol[14]

(The KamLAND Collaboration)







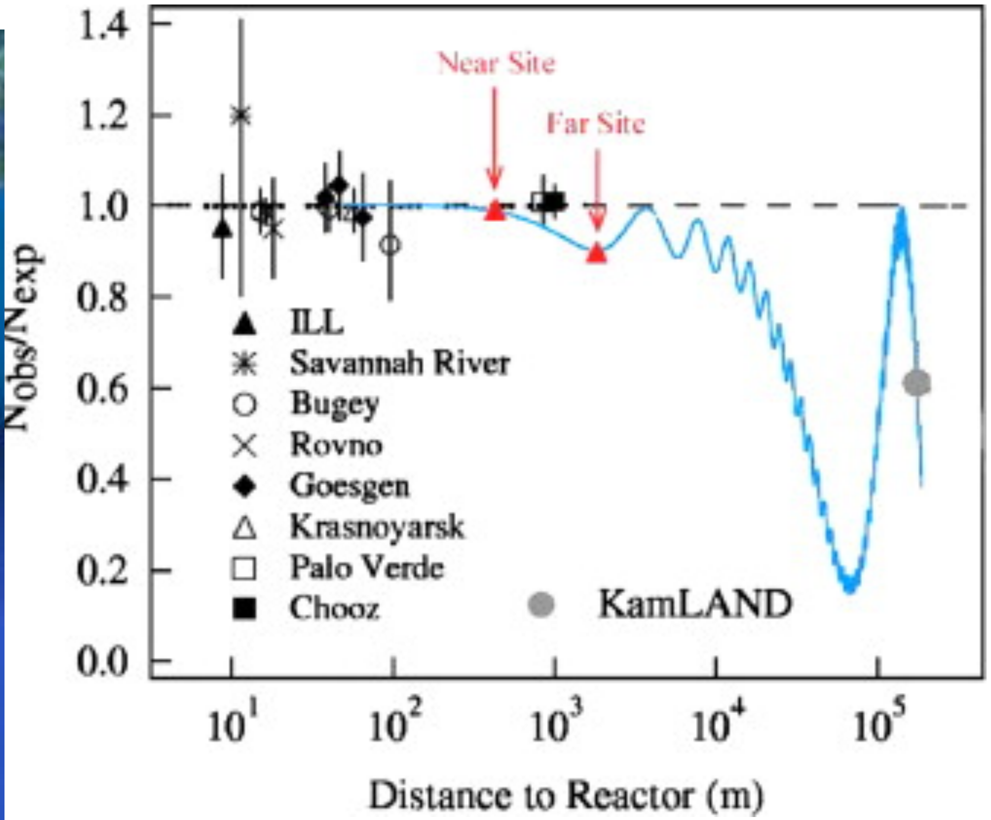
Neutrino mixing parameters

- $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$.[28] This corresponds to $\theta_{\rm sol}$ (solar), obtained from KamLand, solar, reactor and accelerator data.
- $\sin^2(2\theta_{23}'') > 0.92$ at 90% confidence level, corresponding to $\theta_{23} \equiv \theta_{\rm atm} = 45 \pm 7.1°$ (atmospheric)[29]
- $\Delta m^2_{21} \equiv \Delta m^2_{\rm sol} = (0.753 \pm 0.018) \times 10^{-4}\ ({\rm eV}/c^2)^2$[28]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = (24.4 \pm 0.6) \times 10^{-4}\ ({\rm eV}/c^2)^2$ (normal mass hierarchy)[28]
- δ, α_1, α_2, and the sign of Δm^2_{32} are currently unknown.

- For a long time, we dont know what is the value of θ_{13}

Daya Bay experiment

- For a long time, we dont know what is the value of θ_{13}
- Roughly know what is Δm^2_{13}




The Daya Bay Reactor Neutrino Experiment Collaboration Meeting
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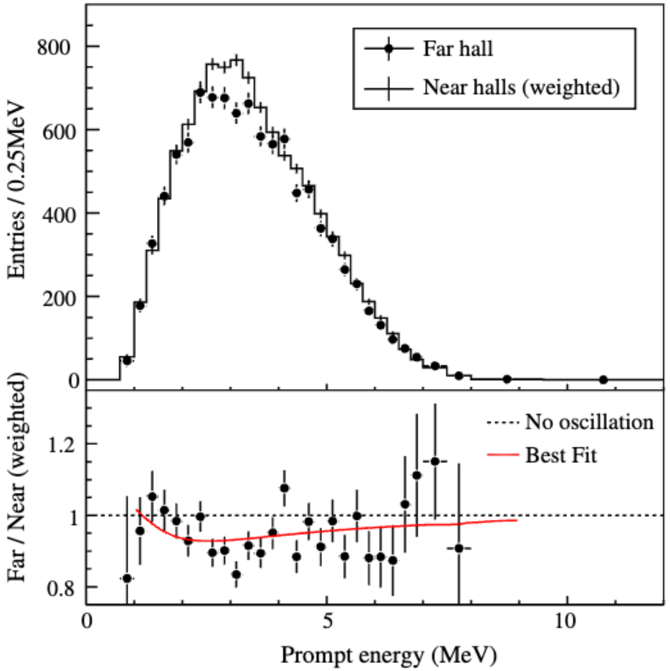

Selected for a Viewpoint in *Physics*

PRL **108,** 171803 (2012) PHYSICAL REVIEW LETTERS week ending 27 APRIL 2012

Observation of Electron-Antineutrino Disappearance at Daya Bay

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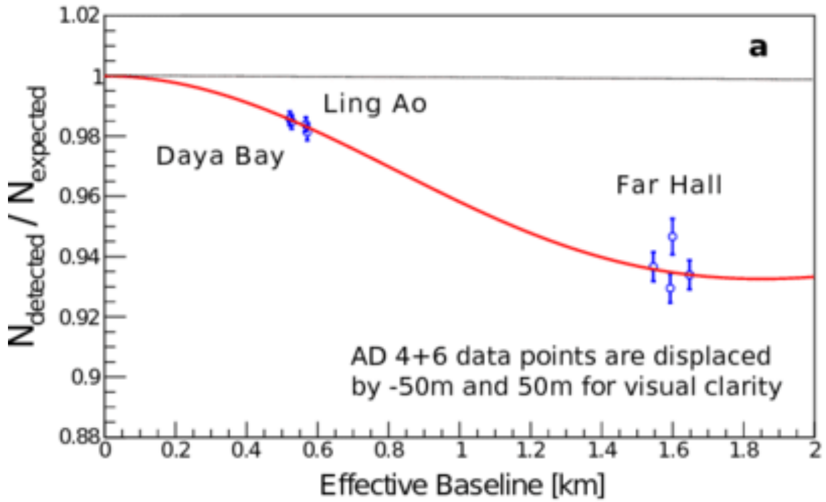

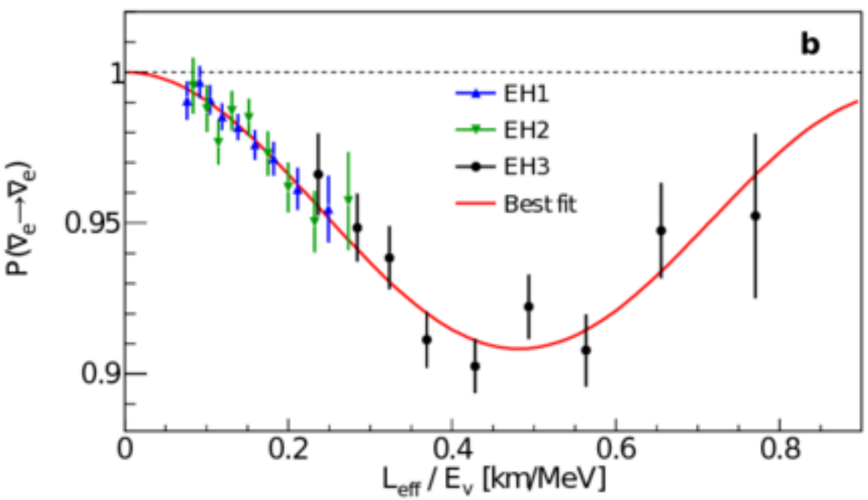

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- δ, α_1, α_2, and the sign of Δm^2_{32} are currently unknown.

- For a long time, we dont know what is the value of θ_{13}

The Daya Bay Reactor Neutrino Experiment has measured a nonzero value for the neutrino mixing angle θ_{13} with a significance of 5.2 standard deviations. Antineutrinos from six 2.9 $\mathrm{GW_{th}}$ reactors were detected in six antineutrino detectors deployed in two near (flux-weighted baseline 470 m and 576 m) and one far (1648 m) underground experimental halls. With a 43 000 ton–$\mathrm{GW_{th}}$–day live-time exposure in 55 days, 10 416 (80 376) electron-antineutrino candidates were detected at the far hall (near halls). The ratio of the observed to expected number of antineutrinos at the far hall is $R = 0.940 \pm 0.011(\mathrm{stat.}) \pm 0.004(\mathrm{syst.})$. A rate-only analysis finds $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})$ in a three-neutrino framework.

Neutrino oscillation with Matter effect

Neutrino Hamiltonian in flavour basis

- $$\frac{d}{dt}|\nu_i\rangle = -iH|\nu_i\rangle$$
- $$\frac{d}{dt}|\nu_i\rangle = -i\frac{1}{2E}\begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}|\nu_i\rangle$$
- Let's move to flavor basis
- $$\frac{d}{dt}|\nu_\beta\rangle = -iU_{\beta i}\frac{m_i^2}{2E}U^*_{\alpha i}|\nu_\alpha\rangle$$
- $$\frac{d}{dt}|\nu_\beta\rangle = -i\frac{1}{2E}\begin{pmatrix} c & s \\ -s & c \end{pmatrix}\begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}\begin{pmatrix} c & -s \\ s & c \end{pmatrix}|\nu_\alpha\rangle$$
- $$\frac{d}{dt}|\nu_\beta\rangle = -i\frac{1}{2E}\begin{pmatrix} c^2m_1^2 + s^2m_2^2 & cs(m_2^2 - m_1^2) \\ cs(m_2^2 - m_1^2) & s^2m_1^2 + c^2m_2^2 \end{pmatrix}|\nu_\alpha\rangle$$ (then $-Im_1^2$)
- $$\frac{d}{dt}|\nu_\beta\rangle = -i\Delta\begin{pmatrix} s^2 & cs \\ cs & c^2 \end{pmatrix}|\nu_\alpha\rangle \ , \ \Delta = \frac{m_2^2 - m_1^2}{2E}$$

Note that adding an identity matrix term doesnt affect the transition probability!

Neutrino Hamiltonian in flavour basis

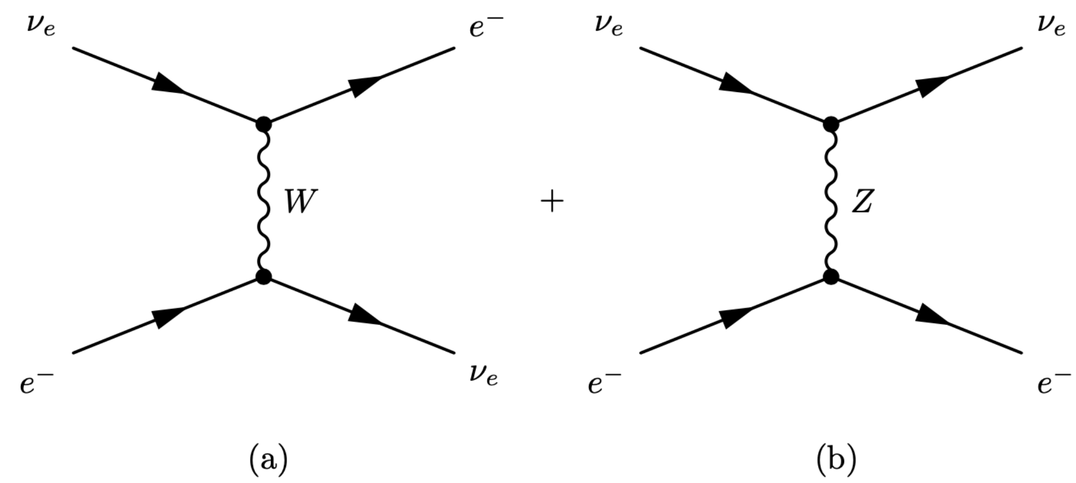
- $\frac{d}{dt}|\nu_\beta\rangle = -i\Delta \begin{pmatrix} s^2 & cs \\ cs & c^2 \end{pmatrix} |\nu_\alpha\rangle$, $\Delta = \frac{m_2^2 - m_1^2}{2E}$
- Take away another factor ($\frac{1}{2}$ x Identity) from the matrix
- $\frac{d}{dt}|\nu_\beta\rangle = -i\frac{\Delta}{2} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} |\nu_\alpha\rangle$

When $\theta \sim 0$
=> diagonal terms dominate
=> $\nu_e = \nu_1$

- If this is what you are given, what to do?
  - Diagonalize the matrix to find the mass engines values (tho only know the diff.)
  - The rotation matrix defines a mixing angle between flavour and mass eigenstates

Neutrino propagation in matter

- Matter has protons, neutrons, electrons.



$$\mathscr{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_e\gamma^\rho\left(1-\gamma^5\right)e\right]\left[\bar{e}\gamma_\rho\left(1-\gamma^5\right)\nu_e\right]+$$

- $$-\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_e\gamma^\rho\left(1-\gamma^5\right)\nu_e\right]\left[\bar{e}\gamma_\rho\left(g_V-g_A\gamma^5\right)e\right]$$

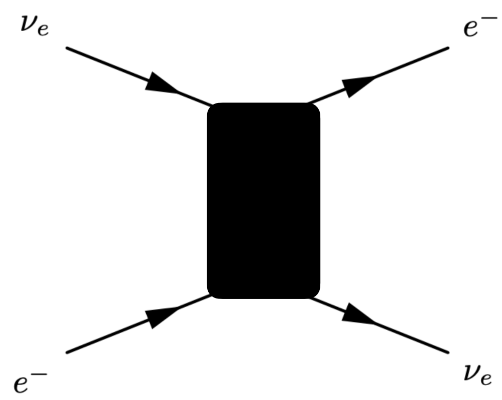
- However, only electron neutrino has the charged current diagram!

Neutrino propagation in matter

This matrix is useful in discussions of quantum mechanical chirality. For example, a Dirac field can be projected onto its left-handed and right-handed components by:

$$\psi_{\mathrm{L}} = \frac{I - \gamma^5}{2}\,\psi, \qquad \psi_{\mathrm{R}} = \frac{I + \gamma^5}{2}\,\psi\,.$$

- $\mathscr{H}_{\text{eff}} = +\frac{G_{\mathrm{F}}}{\sqrt{2}}\left[\bar{\nu}_e\gamma^{\rho}\left(1-\gamma^5\right)e\right]\left[\bar{e}\gamma_{\rho}\left(1-\gamma^5\right)\nu_e\right]$
- Can be shown using gamma-matrix properties (Fierz transformation)
- $\mathscr{H}_{\text{eff}} = +\frac{G_{\mathrm{F}}}{\sqrt{2}}\left[\bar{\nu}_e\gamma^{\rho}\left(1-\gamma^5\right)\nu_e\right]\left[\bar{e}\gamma_{\rho}\left(1-\gamma^5\right)e\right]$



(a)

- Effective potential experience by neutrinos
- $\langle \nu_e e \,|\, \mathscr{H} \,|\, \nu_e e \rangle$

Neutrino propagation in matter

- $\mathscr{H}_{\text{eff}} = + \frac{G_{\text{F}}}{\sqrt{2}} \left[\bar{\nu}_e \gamma^\rho \left(1 - \gamma^5\right) \nu_e \right] \left[\bar{e} \gamma_\rho \left(1 - \gamma^5\right) e \right]$
- $\langle \nu_e e \,|\, \mathscr{H} \,|\, \nu_e e \rangle$
- Effective matter potential in matter due to electrons, for electron neutrinos
  - Averaged over the distribution of the background neutrinos, over their spins
  - We will not go into details here.
- $\langle \mathscr{H} \rangle = \sqrt{2} G_F N_e$
- Note that here you get (-2) for anti-neutrinos

Neutrino propagation in matter

- $$i\frac{d}{dt}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \left[\frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} \sqrt{2}G_F N_e & 0 \\ 0 & 0 \end{pmatrix}\right]\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}$$

- $$i\frac{d}{dt}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \left[\frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos 2\theta + 2A & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta \end{pmatrix}\right]\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}$$

- $A = 2E \times \sqrt{2}G_F N_e$

- If this is what you are given, what to do?
  - Diagonalize the matrix to find the mass engines values (tho only know the diff.)
  - The rotation matrix defines a mixing angle between flavour and mass eigenstates

Diagonalize the matrix

- $\dfrac{m_{1m}^2}{2E} = \dfrac{1}{2E}\left(\dfrac{A}{2} - \dfrac{1}{2}\sqrt{\left(\Delta m^2 \cos 2\theta - A\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}\right)$
- $\dfrac{m_{2m}^2}{2E} = \dfrac{1}{2E}\left(\dfrac{A}{2} + \dfrac{1}{2}\sqrt{\left(\Delta m^2 \cos 2\theta - A\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}\right)$
- $\Delta m_m^2 = m_2^2 - m_1^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - A\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$

- The rotation matrix is defined by a 'matter mixing angle'
- $\tan 2\theta_m = \dfrac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$
-

Diagonalize the matrix

- $\Delta m_m^2 = m_2^2 - m_1^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - A\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$
- $\tan 2\theta_m = \dfrac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$
- $P_{\alpha\beta} = \sin^2 2\theta_m \sin^2\left(\dfrac{\Delta m_m^2 L}{4E}\right)$

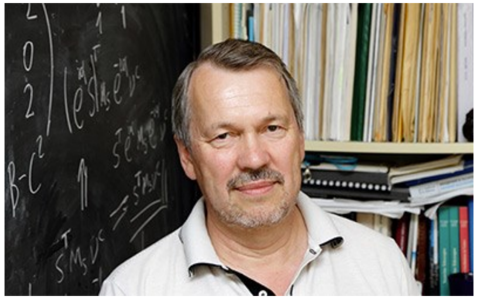
$$A = 2E \times \sqrt{2} G_F N_e$$

- For $A \ll \Delta m^2$, get back the vacuum case
- For $A \gg \Delta m^2$, θ_m mixing angle $\to \pi/2$, now $\nu_e \sim \nu_2$

Disgonalize the matrix

- $\tan 2\theta_m = \dfrac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$
- If $A = \Delta m^2 \cos 2\theta$
- => Resonance, mixing is enhanced, even if θ is tiny!

- Wolfenstein (1978, 1979)
- Mikheyev, Smirnov (1985)



- Smirnov

- I have mostly followed Bethe 1986, who explained this and fixed a minus sign at the age of 80!

Possible Explanation of the Solar-Neutrino Puzzle

H. A. Bethe

Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853,[a] *and Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106*

(Received 27 December 1985; revised manuscript received 27 January 1986)

Mikheyev and Smirnov have shown that electron neutrinos above a certain minimum energy E_m may all be converted into μ neutrinos on their way out through the sun. We assume here that this is the reason why Davis and collaborators, in their experiments, find many fewer solar neutrinos than predicted. The minimum energy E_m is found to be about 6 MeV, the mass m of the μ neutrino must be greater than that of the electron neutrino, $m_2^2 - m_1^2 = 6 \times 10^{-5}$ eV^2, and there is a very minor restriction on the neutrino mixing angle.

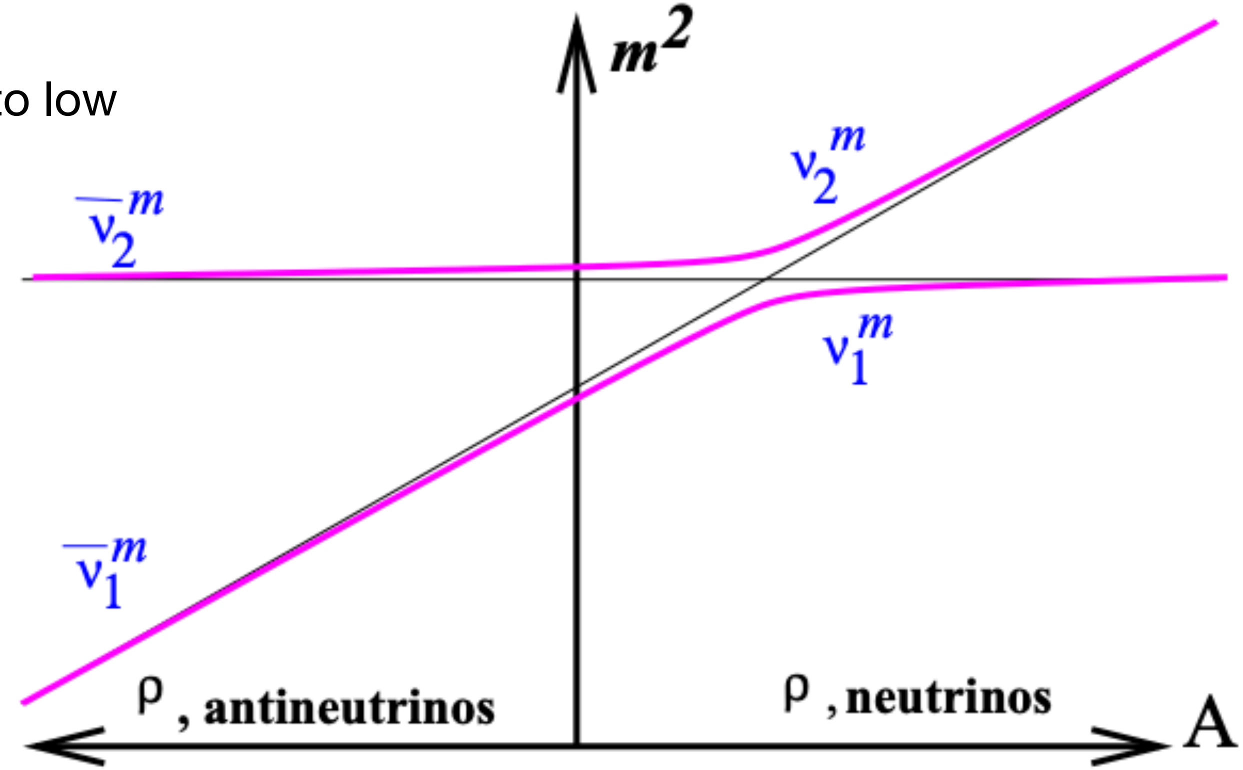
PACS numbers: 96.60.Kx, 12.15.Ff, 14.60.Gh

Matter effect

- Solar neutrinos comes from high density to low density (vacuum)
    - From large A to small A.

- Adiabatic (no level crossing)
- ν_e leaves the sun as ν_2
    - ν_e detection probability = $\sin^2\theta$

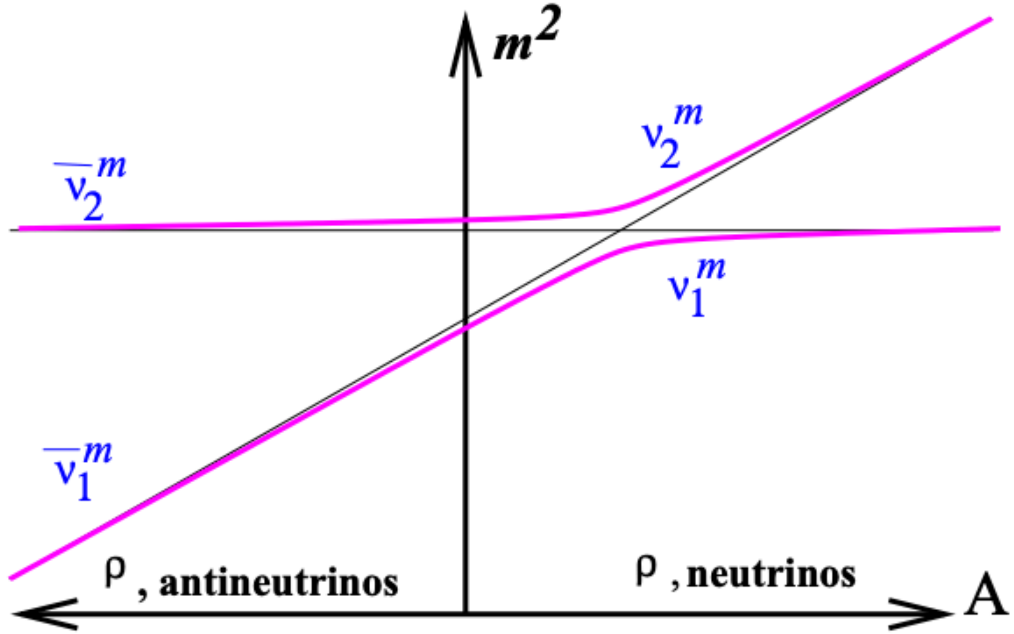
- Level crossed
- ν_e leaves the sun as ν_1
    - ν_e detection probability = $\cos^2\theta$



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

Matter effect

- In general
- Probability of level crossing P_L
- $P(\nu_e \to \nu_e e) = P_L \cos^2\theta + (1 - P_L)\sin^2\theta$



Neutrino propagation in matter

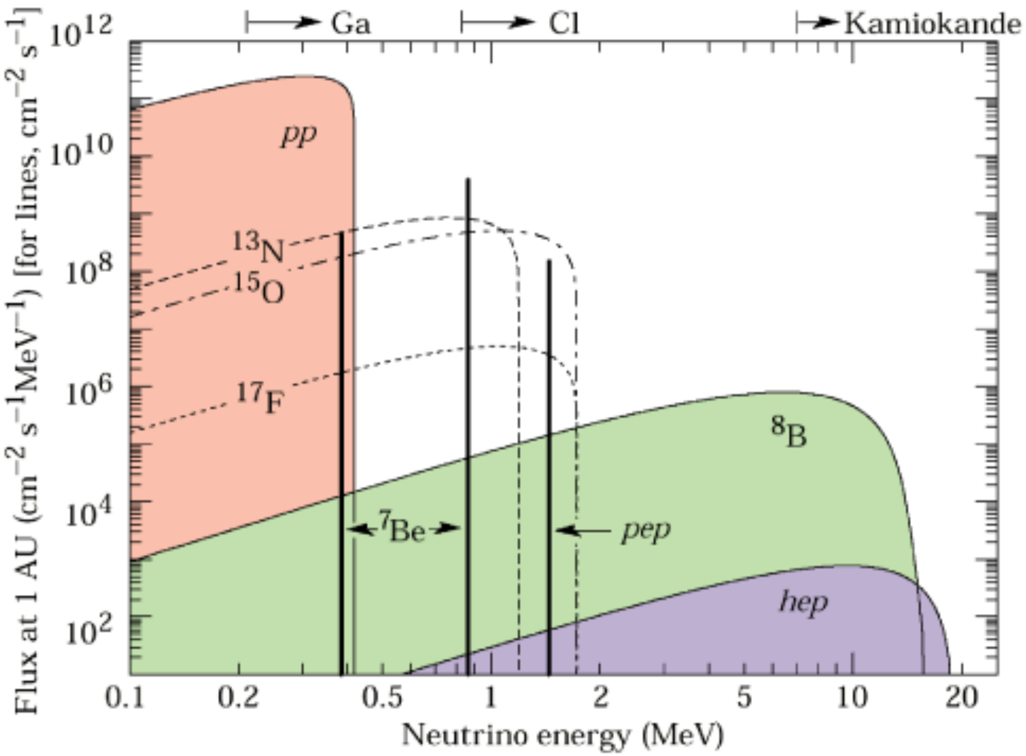
- $$i\frac{d}{dx}\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} = i\frac{d}{dx}U^*(\theta_m)\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\end{pmatrix}$$
- $$i\frac{d}{dx}\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} = i\frac{dU^*}{dx}(\theta_m)\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\end{pmatrix} + iU^*(\theta_m)\frac{d}{dx}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\end{pmatrix}$$
- Use the Schrodinger equations
- $$i\frac{d}{dx}\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} = i\frac{dU^*}{dx}(\theta_m)U(\theta_m)\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} + U^*(\theta_m)H_fU(\theta_m)\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix}$$
- Explicitly differentiating the mixing matrix
-

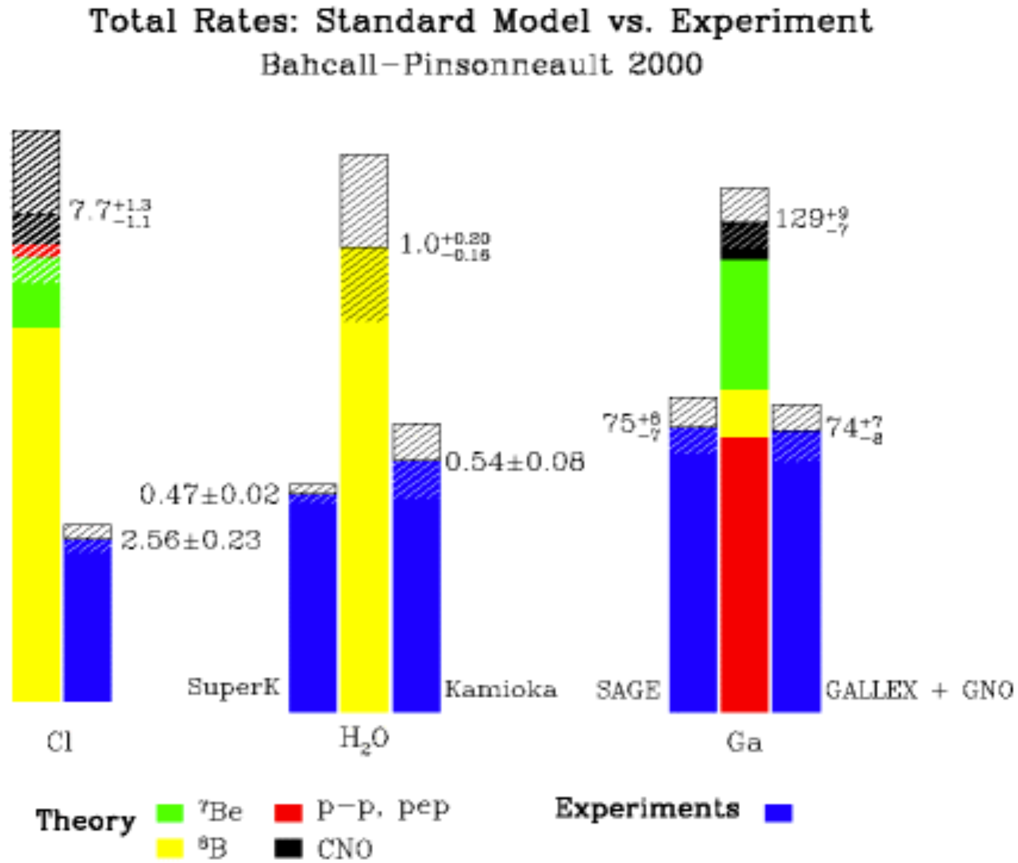
Neutrino propagation in matter

- $i\dfrac{d}{dx}\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} = i\dfrac{dU^*}{dx}(\theta_m)U(\theta_m)\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} + U^*(\theta_m)H_f U(\theta_m)\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix}$
- Use the Schrodinger equations
- $i\dfrac{d}{dx}\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix} = \left[\begin{pmatrix}\frac{m_{1m}^2}{2E} & -i\frac{d\theta_m}{dx}\\ i\frac{d\theta_m}{dx} & \frac{m_{1m}^2}{2E}\end{pmatrix}\right]\begin{pmatrix}|\nu_{1m}\rangle\\|\nu_{2m}\rangle\end{pmatrix}$
- The off-diagonal terms, which depends on how fast matter density changes, determines whether level-crossing happened or not
- The level cross problem is described by the Landau-Zener formula
    - We will omit the detailed treatment here
    - Basically, the transition is more likely to happen when density changes rapidly
    - $P_L = \exp(-\dfrac{\pi}{2}\gamma), \quad \gamma = \dfrac{\delta m^2 \sin^2 2\theta}{2E\cos 2\theta(1/n_e)(dn_e/dr)}$

Solar neutrino problem

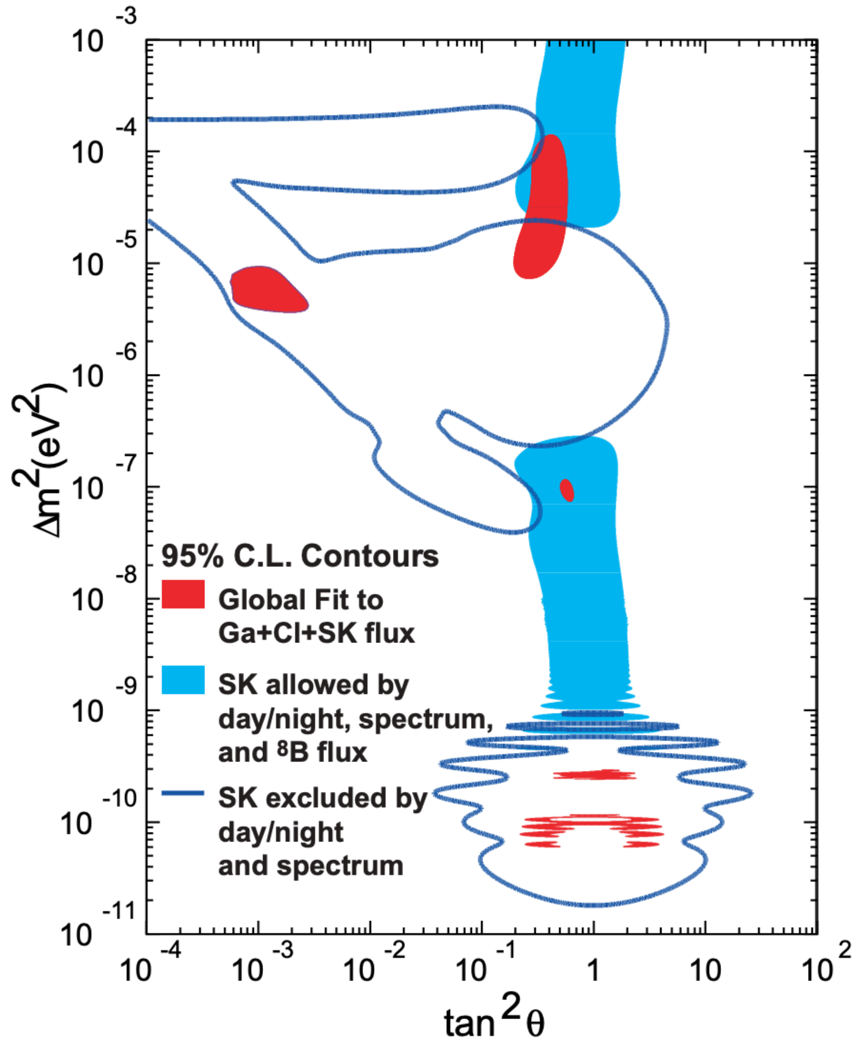
- Different experiment saw different amount of deficits.





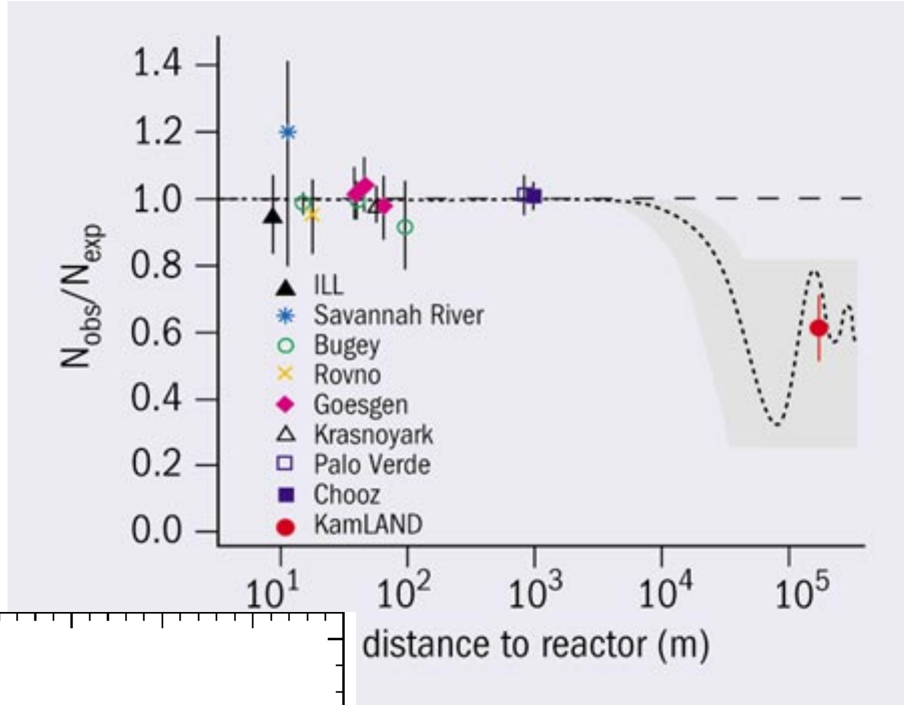
Solution to the solar neutrino problem

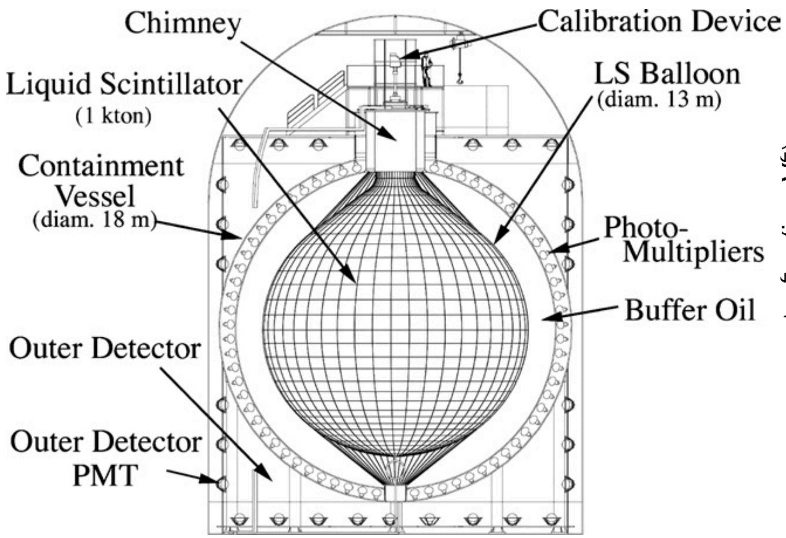
- There were several possibilities
- Vacuum solution
    - $\Delta m^2 \sim 10^{-10}$
- Small mixing angle $P_L \sim 1, \quad \theta \sim 0$
- Large mixing angle $P_L \sim 0, \quad \theta \sim 1$

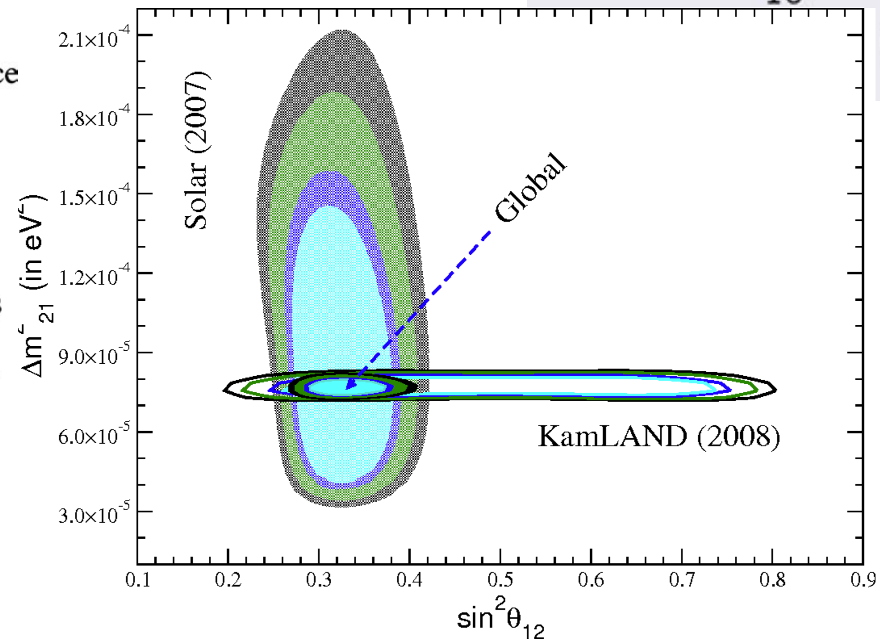


Kamland Neutrino detector

- Kamioka Liquid Scintillator antineutrino detector
- Reactor experiment to be at the right distance and energy!

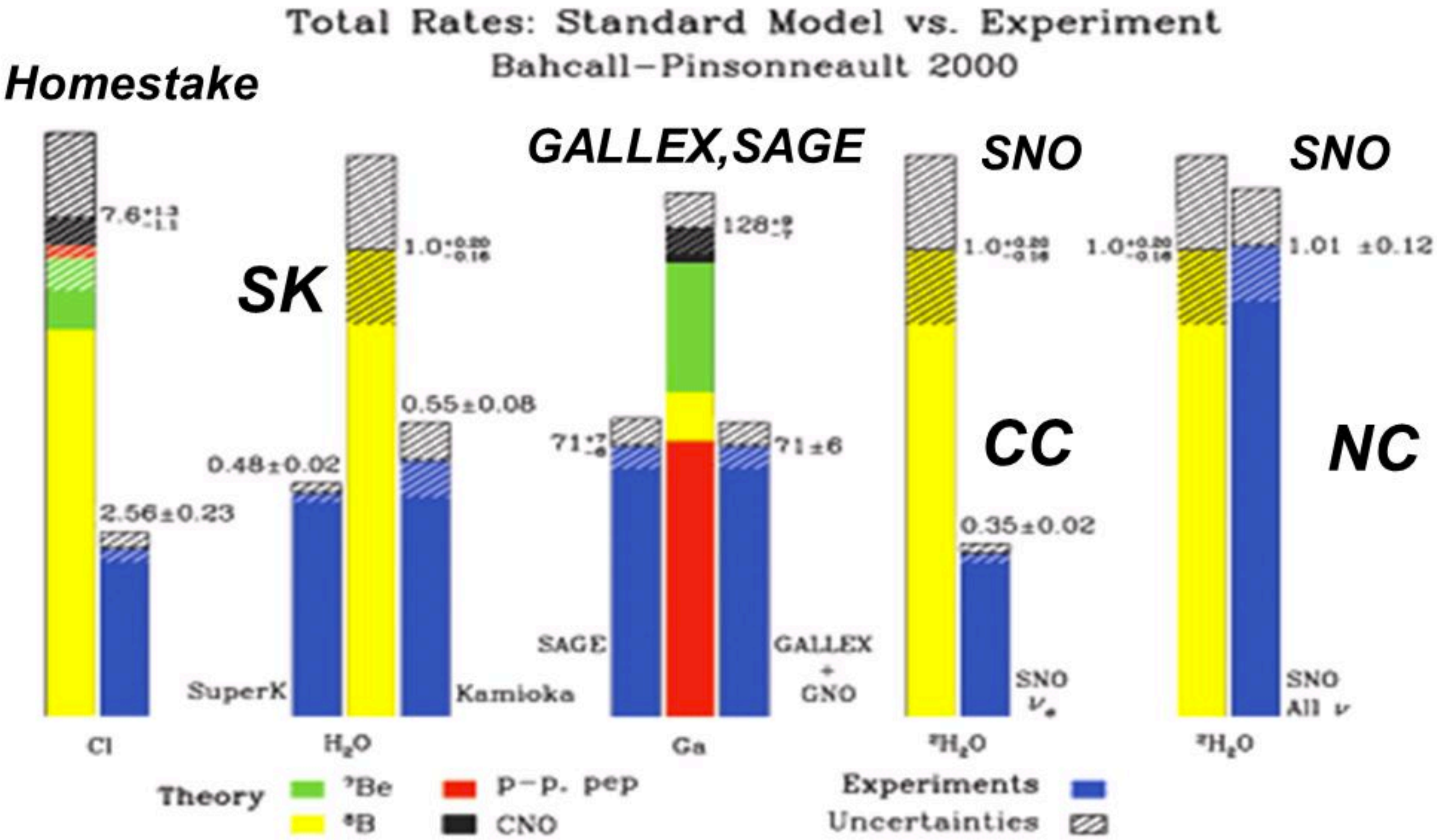






Solar Neutrino Problem : Data/SSM

Observed solar neutrino flux/Expected flux from solar < 1.0

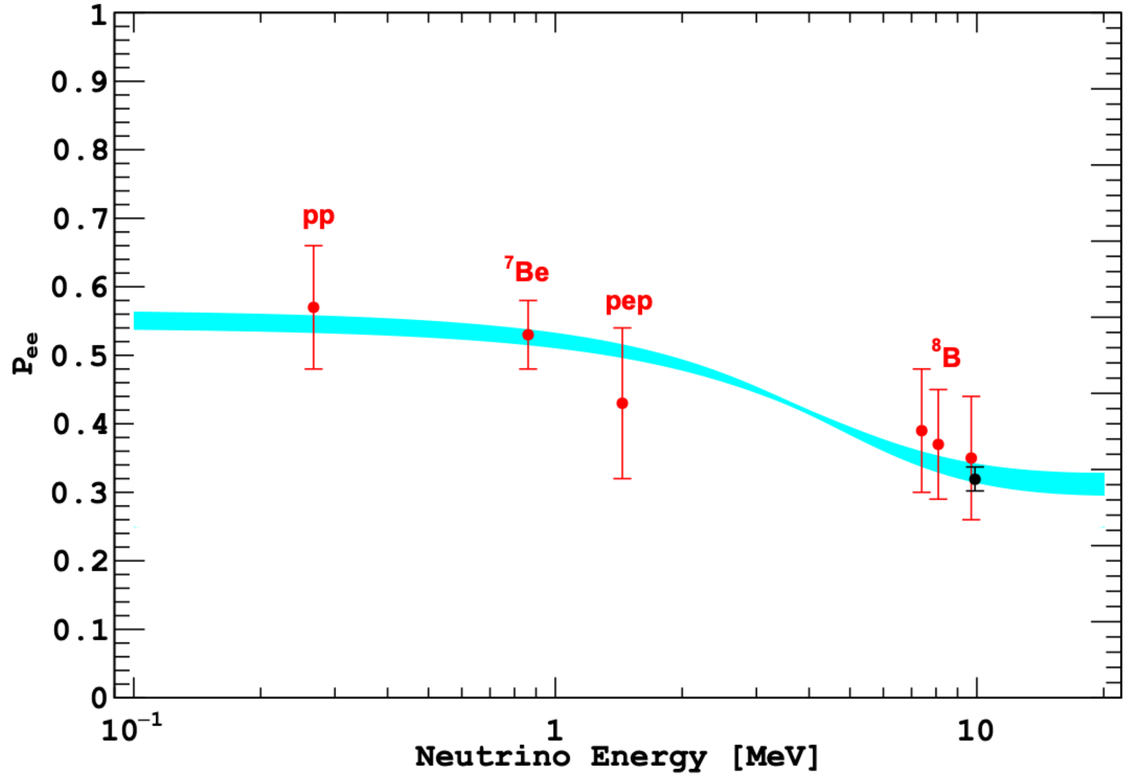


http://www.sns.ias.edu/~jnb

- **At the end, the Large mixing angle solution provide the best fit**
- Data vs the LMA solution

- Below 1 MeV
- Vacuum oscilaltion dominates

- Above 1 MeV
- Matter effect dominates



Sudbury Neutrino Observatory

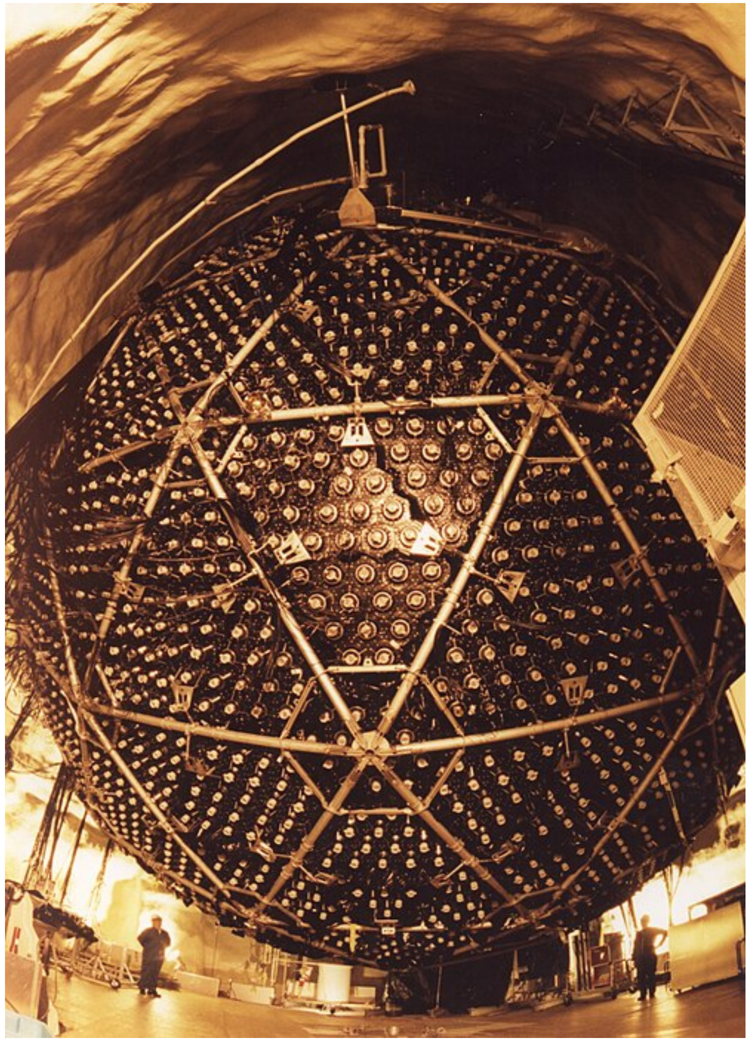
In 1984, Herb Chen of the University of California at Irvine first pointed out the advantages of using heavy water as a detector for solar neutrinos.[2] Unlike previous detectors, using heavy water would make the detector sensitive to two reactions, one reaction sensitive to all neutrino flavours, the other reaction sensitive to only electron neutrino. Thus, such a detector could measure neutrino oscillations directly. A location in Canada was attractive because Atomic Energy of Canada Limited, which maintains large stockpiles of heavy water to support its CANDU reactor power plants, was willing to lend the necessary amount (worth CA$330,000,000 at market prices) at no cost.[3][4]

- 1 kilo ton of heavy water
  - D2O

SNO detected ^{8}B solar neutrinos via the reactions

$$\nu_e + {}^2H \rightarrow e^- + p + p \quad \text{(CC)}$$
$$\nu_x + {}^2H \rightarrow \nu_x + p + n \quad \text{(NC)}$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

- Sensitivity to both electron flavor, and all flavor!



Sudbury Neutrino Observatory

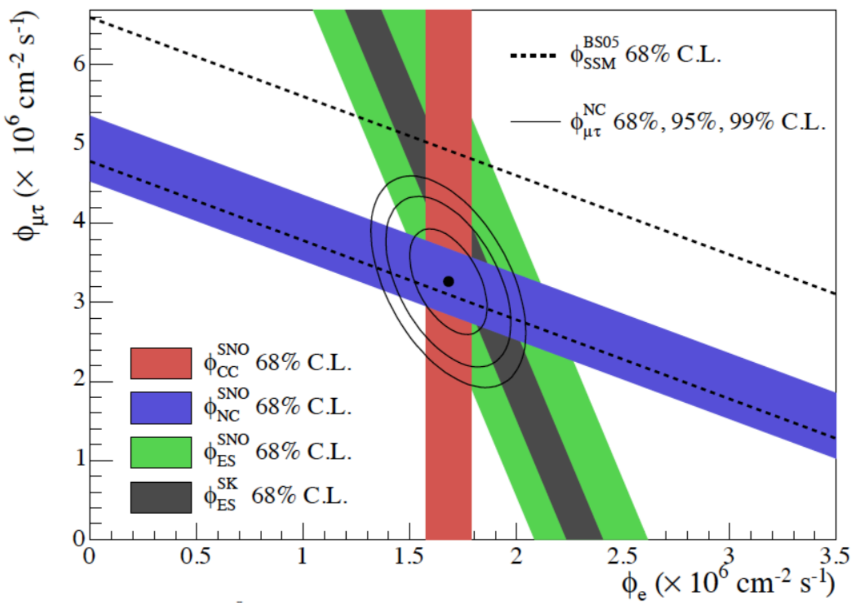
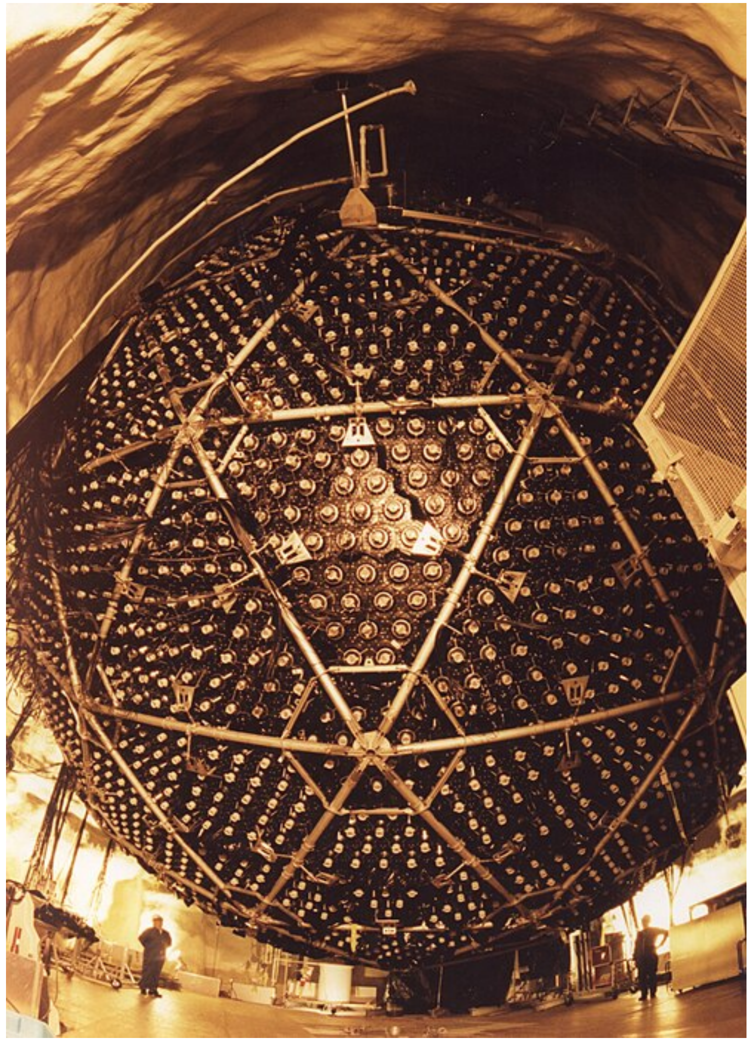


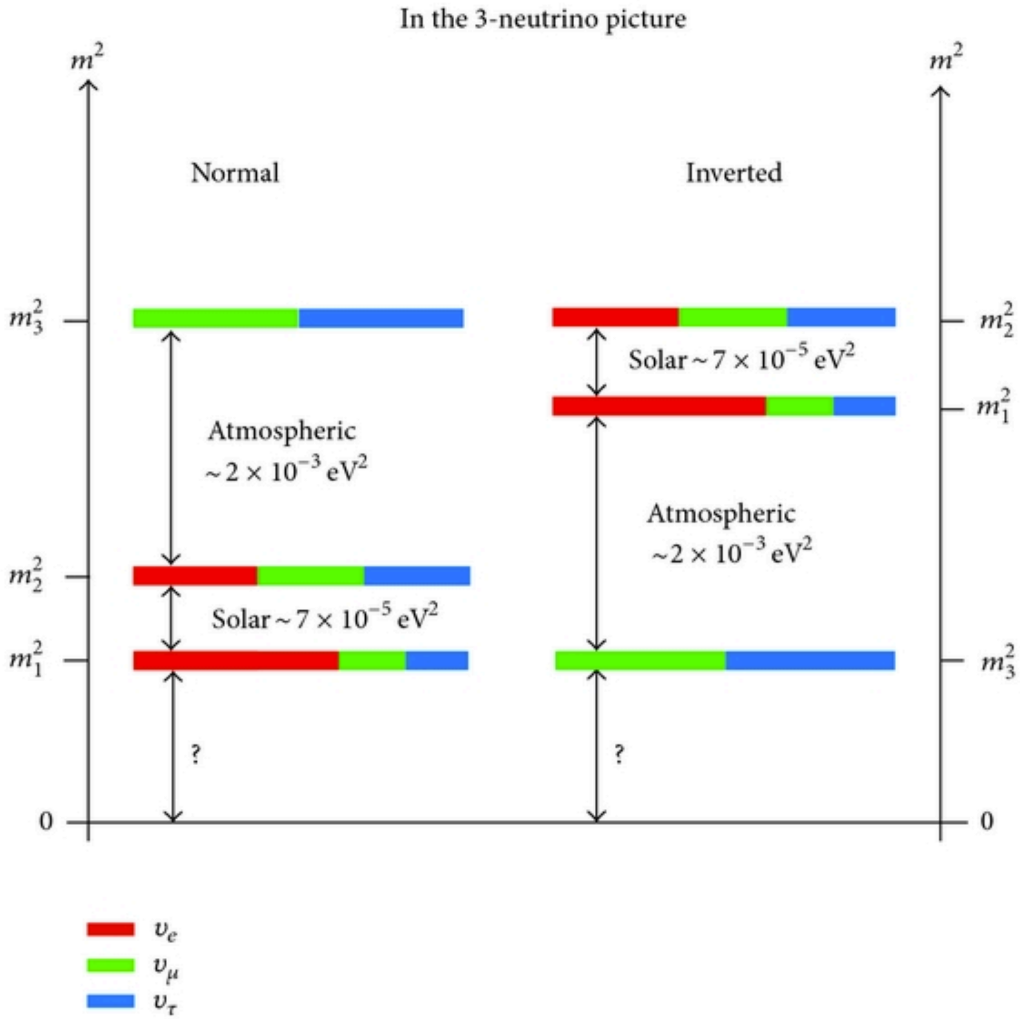
Figure 4: Fluxes of ^{8}B solar neutrinos from SNO and Super-Kamiokande. The SSM BS05 [38] prediction is shown as a range between the dashed lines. C.L. stands for confidence level. From [36] and references therein.



- Confirming that neutrino only changed “flavors”, but didnt disappear!
  - (Neutrino decay was one possible idea to SNP)

What we (don’t) know about neutrino

- 3 angles
  - Atmospheric neutrino mixing
  - Solar neutrino + reactor
  - Reactor neutrino (Daya Bay)
- Solar neutrino, m2 > m1
- One mass hierarchy unknown
- CP phase unknown
- Total mass unknown



Story of the Solar neutrino problem

- Bahcall 2004

- First prediction ~ 1960
- Finally resolved in ~200

Bahcall 2004: Howard Georgi and Michael Luke wrote as the opening sentences in a paper on possible particle physics effects in solar neutrino experiments:
"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of 8B neutrinos to within a factor of 2 or 3..."

The Nobel Prize in Physics 2015

Takaaki Kajita

Prize share: 1/2

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

For me I think of all of the walks or conversations I have had in my professional life, that was the most important, because I was a young man without tenure, and [while] I'd done many calculations by that time, this was the one that was most visible and people had paid the most attention to, and it looked like it was wrong. I really was feeling very, very, very discouraged. And for a person whom I so enormously admired, Dick Feynman, to tell me "You haven't done anything that's visibly wrong, maybe you've done something important"—for me that was a huge boost.

3 Flavor mixing, and CP violation

Neutrino vacuum mixing (3 flavours)

- In general
- $P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2$
- $P_{\alpha\beta} = |\sum_i \sum_j U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(L) \rangle|^2$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin^2 X_{ij} +$$

$$X_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

- $$2 \sum_{i<j} \mathrm{Im}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin 2X_{ij}$$

Neutrino vacuum mixing (3 flavours)

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin^2 X_{ij} +$$

- $$2\sum_{i<j} \mathrm{Im}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin 2X_{ij}$$

- For neutrino -> antineutrino $|\nu_\alpha\rangle = U^*|\nu_i\rangle$ $->$ $|\bar{\nu}_\alpha\rangle = U|\bar{\nu}_i\rangle$
- The first line is CP conserving
- The second line violates CP, if, of course, U is complex.

3 - Flavor neutrinos

- Degrees of freedom counting

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle \, ,$$

- U is a 3x3 dimensional Unitary matrix
  - 18 variables
- $U^\dagger U = 1$ (9 equations)
- From weak interactions, ν_α couples to the lepton l_α through Charged Current interactions.
- Each ν_α and l_α and absorbed a complex phase factor $e^{i\theta}$ without changing the physics, BUT not an overall common phase (5 phases)
- 4 parameters left.
- A 3x3 real Unitary (orthogonal) matrix
  - Only has 3 degrees of freedom
- **U could be complex**

3 Flavor neutrinos

- 3 angles to be determined.
- 1 CP violating phase
- Neutrino oscillation only care about mass differences
- 3 mass differences =
  - 2 mass differences + 2 signs
  - Solar neutrino tells us 1 sign (MSW effect)
- Solar neutrino, atm neutrino, each determined 1 angle and 1 mass difference

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle\,,$$

$C_{13} = \cos\theta_{13}$

$S_{13} = \sin\theta_{13}$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$\left.\begin{matrix}\theta_{12}\\ \theta_{23}\\ \theta_{13}\end{matrix}\right\}$

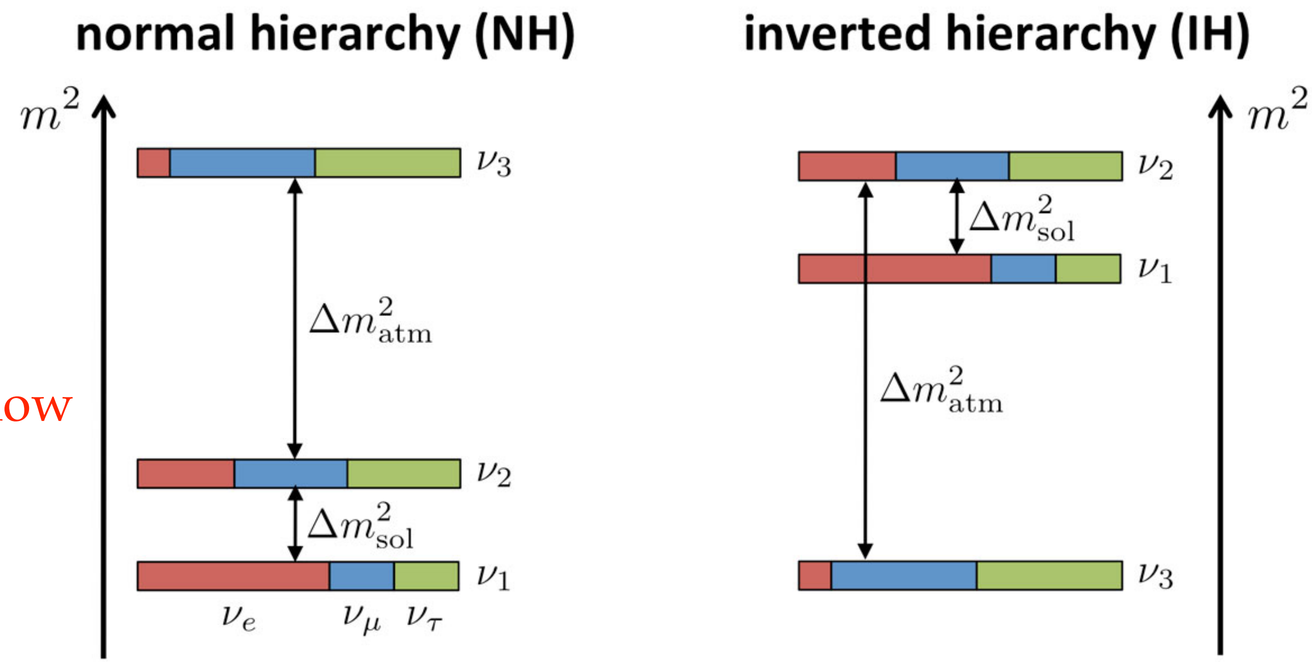
$+\ \delta$

Observed values of oscillation parameters [edit]

- $\sin^2(2\theta_{13}) = 0.093 \pm 0.008$.[24] PDG combination of Daya Bay, RENO, and Double Chooz results.
- $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$.[24] This corresponds to θ_{sol} (solar), obtained from KamLand, solar, reactor and accelerator data.
- $\sin^2(2\theta_{23}) > 0.92$ at 90% confidence level, corresponding to $\theta_{23} \equiv \theta_{atm} = 45 \pm 7.1°$ (atmospheric)[25]
- $\Delta m^2_{21} \equiv \Delta m^2_{sol} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$[24]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{atm} = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$ (normal mass hierarchy)[24]
- δ, α_1, α_2, and the sign of Δm^2_{32} are currently unknown.

Unknown in neutrino mixing

- 3 angles to be determined. All known
- 1 CP violating phase Dont know
- Neutrino oscillation only care about mass differences
- 3 mass differences = 1 sign dont know
  - 2 mass differences + 2 signs
  - Solar neutrino tells us 1 sign (MSW effect)
- Solar neutrino, atm neutrino, each determined 1 angle and 1 mass difference



The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

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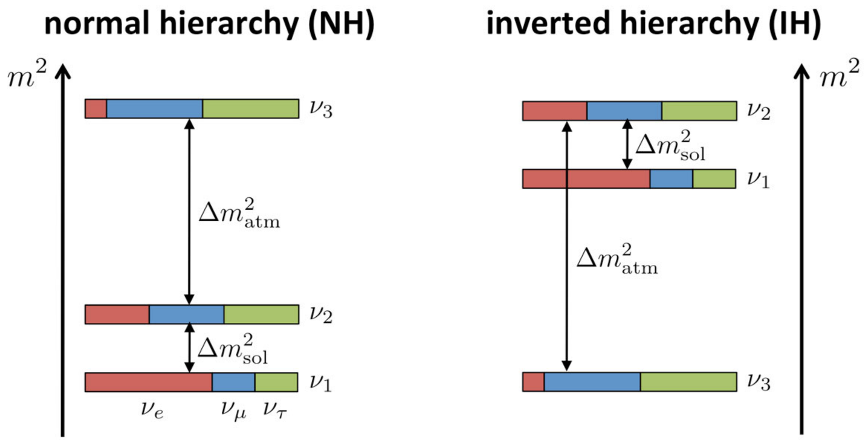
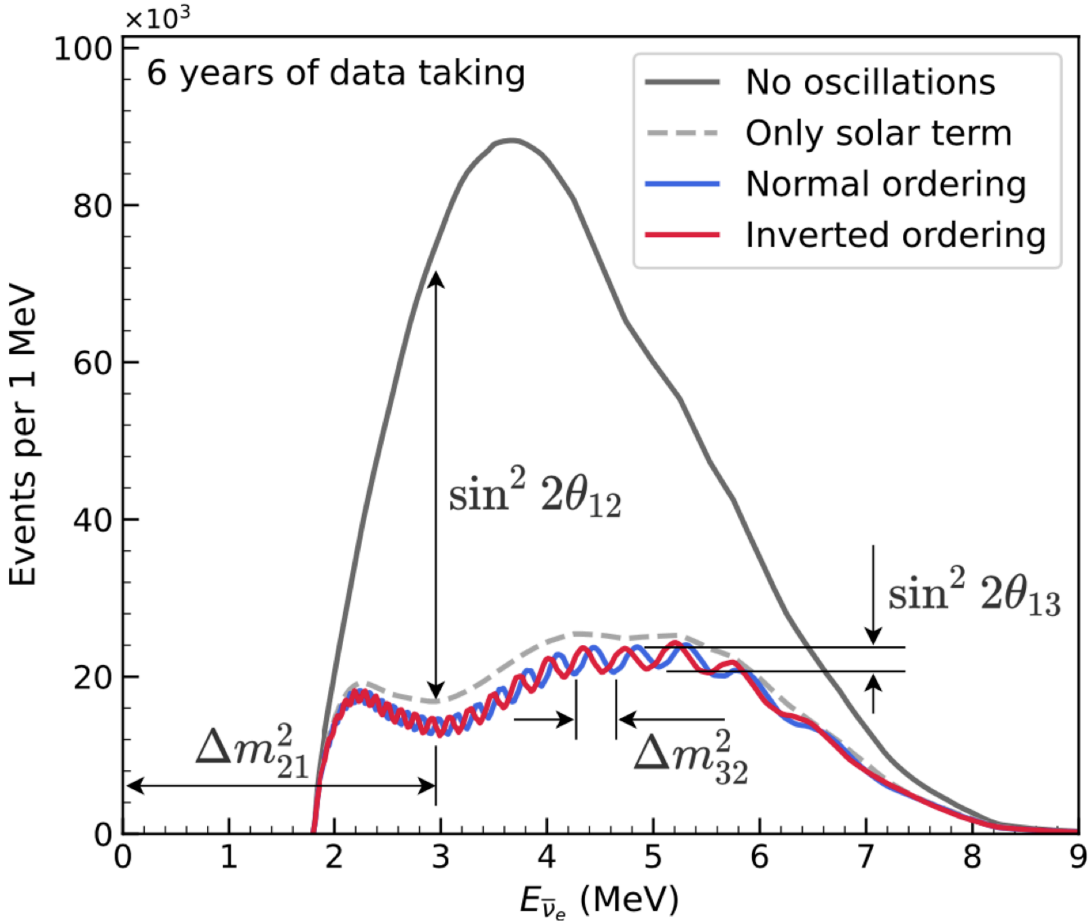
Mass Hierarchy

The JUNO project





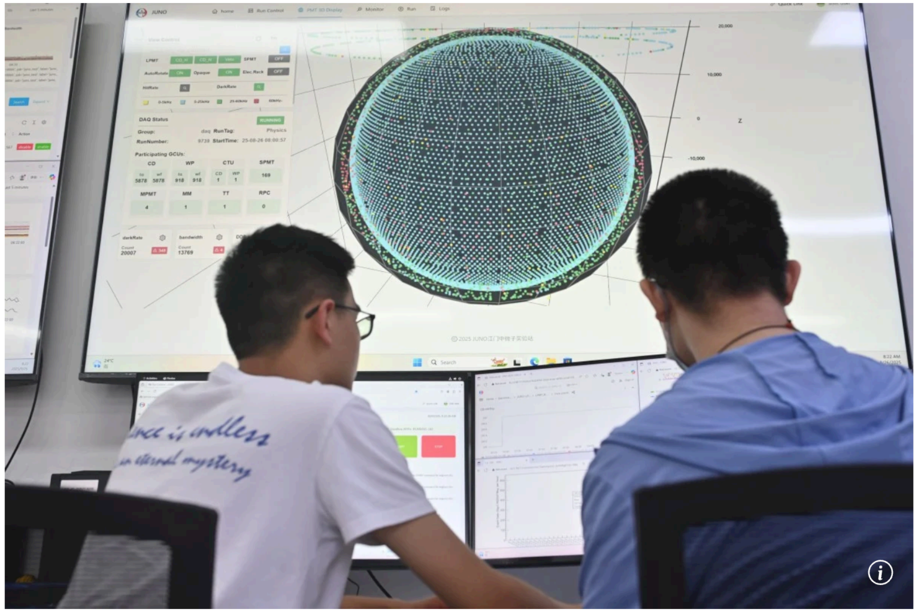
JUNO site

- Guangdong Province
- 53 km to Yangjiang and Taishan NPP
  - **Yangjiang**: 6 * 2.9 GW_{th} (PWR)
  - **Taishan**: 4 * 4.6 GW_{th} (EPR)
  - **19.1 GW_{th} online now**
  - **26.6 GW_{th} since 2020**
- 700m underground lab

China launches Juno, the world’s most powerful detector for ‘ghost particles’

In ‘historic milestone’, massive underground facility in Guangdong province has begun collecting data to track mysterious neutrinos

Reading Time: **3 minutes**



Holly Chik

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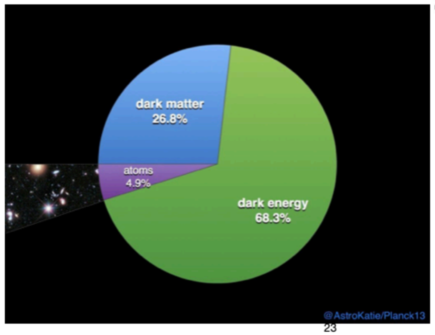
Baryogenesis

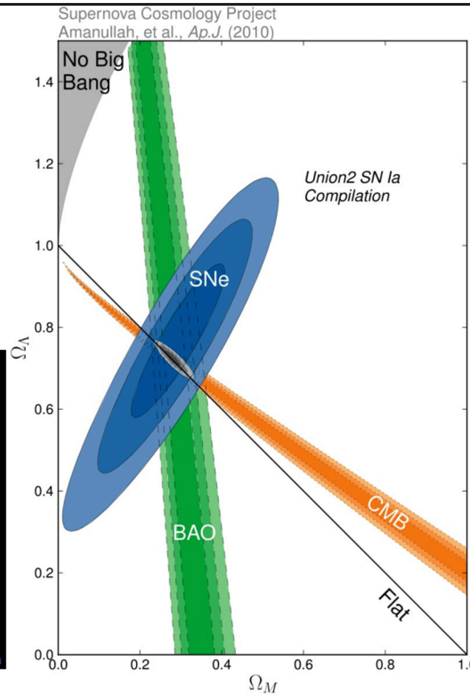
The Baryon part of the Universe

- $\eta \simeq 6 \times 10^{-10}$
- $\rho_b \simeq m_p \times \eta \times n_\gamma = 2.4 \times 10^{-7}$ GeV/cc
- $\rho_{cr} \simeq 1.05 h^2 \times 10^{-5}\,\mathrm{GeV cm}^{-3}$
- $\Omega_b \sim 0.05$!

Cosmological parameters

- h ~ 0.67
- $\Omega_\gamma \simeq 0.5 \times 10^{-5}$
- $\Omega_\nu h^2 = \dfrac{m_\nu}{94\mathrm{eV}}$
- $\Omega_b \sim 0.05$
- Flat
- $\Omega_\Lambda \simeq 0.7$
- $\Omega_M \simeq 0.3$





Symmetric Universe

- $\bar{p} + p \leftrightharpoons \gamma + \gamma$, … …
- Strong reaction!
- Freezeout until T ~ 20 MeV
- $\dfrac{n_p}{n_\gamma} \sim \dfrac{n_{\bar{p}}}{n_\gamma} \sim \left(\dfrac{m_p}{T}\right)^{3/2} e^{-\frac{m_p}{T}} \sim 10^{-19}$
- Much smaller than BBN value!

Baryogenesis

- inflation
    - Set the initial condition, make the Universe, flat, homogeneous, and symmetric
- …
- …   Some thing happened
- …

- BBN, ~ 1MeV,   The Universe is asymmetric

Sakharnov Conditions

- Baryon Number violation
  - $n + \nu_e \to p^+ + e^-$ [x]
  - $N \to B$ (creation of net baryon number)
- CP and C violation ($N \to B$)
  - Asymmetric Universe is odd under C and CP
  - $\Gamma_N \neq \Gamma_{\bar{N}}$ ($N \to B \neq \bar{N} \to \bar{B}$)
  - $\Gamma_{N_L} \neq \Gamma_{\bar{N}_R}$ (otherwise, $\Gamma_{N_L} + \Gamma_{N_R} = \Gamma_{\bar{N}_L} + \Gamma_{\bar{N}_R}$)
- Out of thermal equilibrium
  - Thermal equilibrium drives $B \to N$ reactions

- Peace Price 1975

Leptogenesis

https://arxiv.org/pdf/hep-ph/0502169.pdf

- Heavy right-handed neutrino decay (Condition 3)

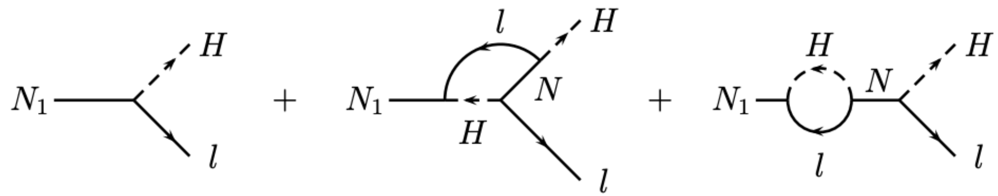


Figure 1: Tree level and one-loop diagrams contributing to heavy neutrino decays whose interference leads to Leptogenesis.

- The loop correction breaks lepton number L and CP (Condition 2)
- High temperature Standard model interactions, L -> B (Condition 1)
-
- If one of the right-handled neutrinos is keV, could be dark matter
- Neutrinos Mass via seesaw mechanism
- Baryon asymmetry

Search For CP

Neutrino vacuum mixing (3 flavours)

- There are two kinds of oscillation experiment
- Disappearance
- CPT[$P(\nu_e \rightarrow \nu_e)$] $= P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
- appearance
- CPT[$P(\nu_e \rightarrow \nu_\mu)$] $= P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- There appearance is related by CPT, ‘should’ be the same
- CP[$P(\nu_e \rightarrow \nu_\mu)$] $= P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$
- Now you can search for CP!

3 Flavor neutrinos

- The flavour conversion probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}]\sin^2 X_{ij}$$

$$+ 2\sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}]\sin 2X_{ij}\,,$$

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.267\,\frac{\Delta m_{ij}^2}{\mathrm{eV}^2}\,\frac{L/E}{\mathrm{m/MeV}}\,.$$

- P($\nu_{e,L} \rightarrow \nu_{\mu,L}$)
- Through a CP (charge conjugate + Parity) operation
- P($\bar{\nu}_{e,R} \rightarrow \bar{\nu}_{\mu,R}$)
- These two probabilities could be different **if U is complex**

- IF
    - P($\nu_{e,L} \rightarrow \nu_{\mu,L}$) - P($\bar{\nu}_{e,R} \rightarrow \bar{\nu}_{\mu,R}$) $\neq 0$
    - **It implies CP is violated**

Accelerator neutrinos

Accelerator neutrinos

- 3 research frontier in particle physics

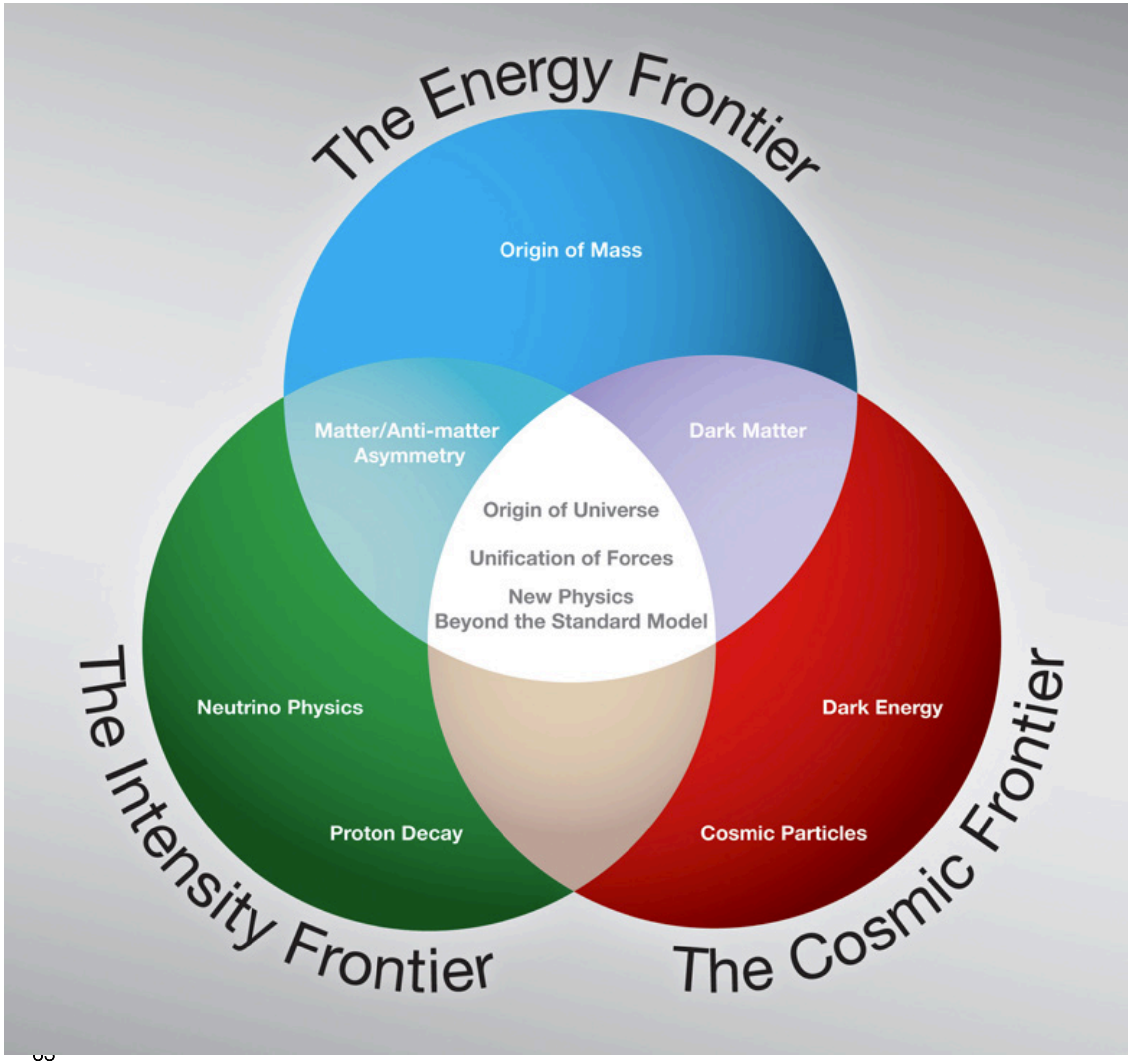
- Energy frontier
  - e.g., LHC

- Cosmic frontier
  - Cosmic rays, cosmological probes

- Intensity frontier
  - High-intensity, precision experiments.

    http://cds.cern.ch/record/1448568/files/arXiv:1205.2671.pdf

  - or, means lots of events/ large detector for precision study

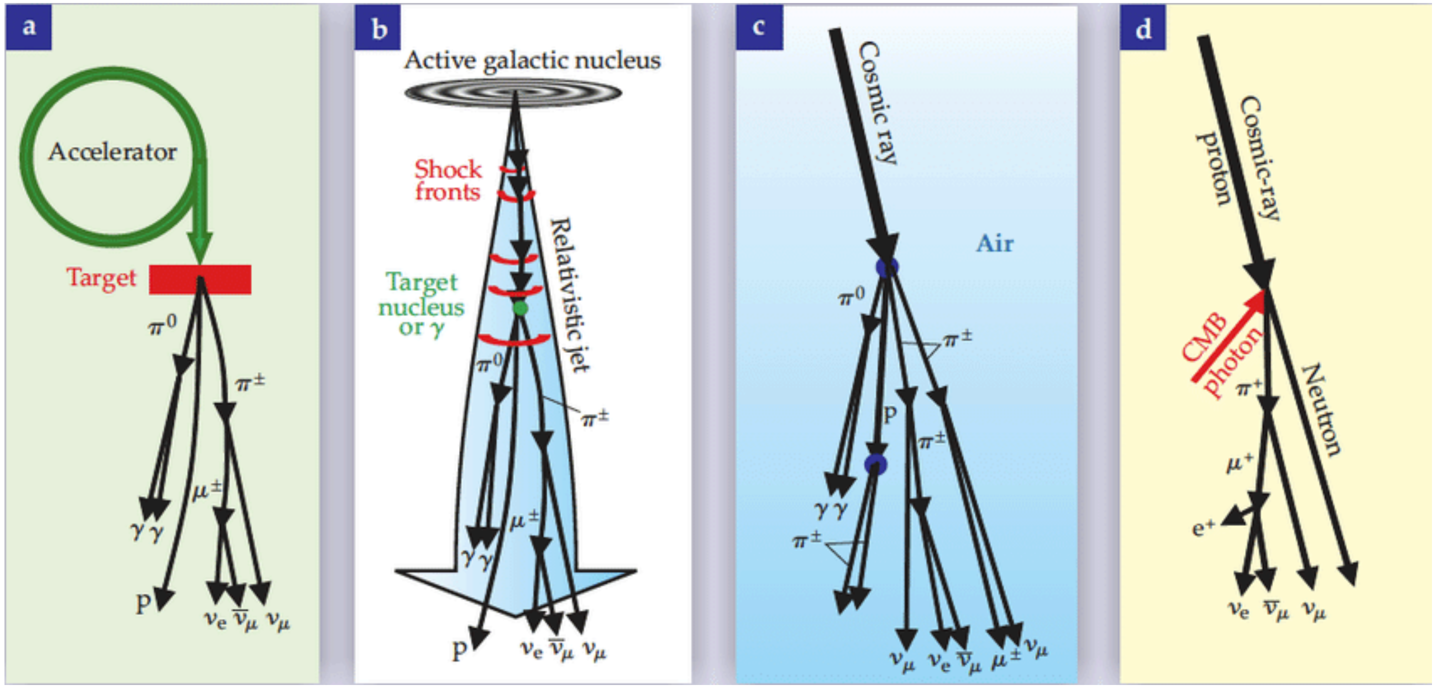


Accelerator neutrinos

- man-made neutrinos.
- Good control of
  - timing (to make sure that you are detecting neutrinos)
  - Energy
  - baseline

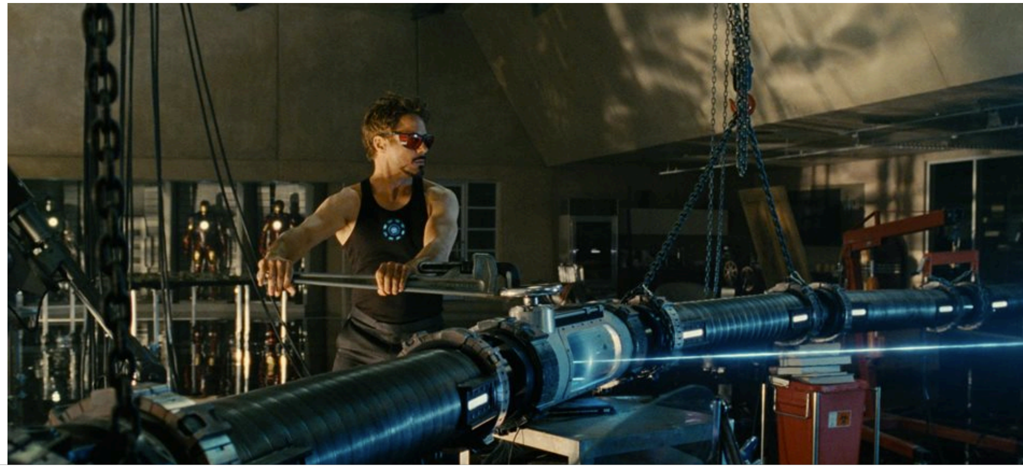
Neutrino production

- accelerate protons in particle accelerators
- Smash into a target (nucleons)
- Pions decay into neutrinos

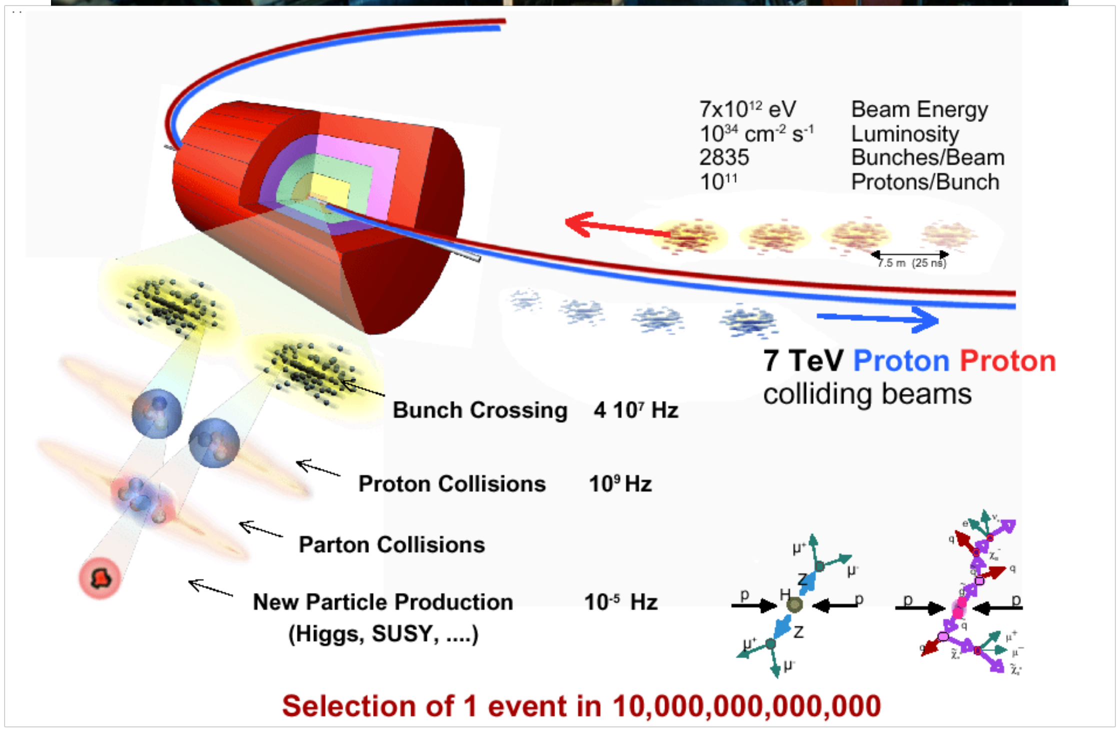


Timing

- particle beams looks like continuous (e.g., in movies)

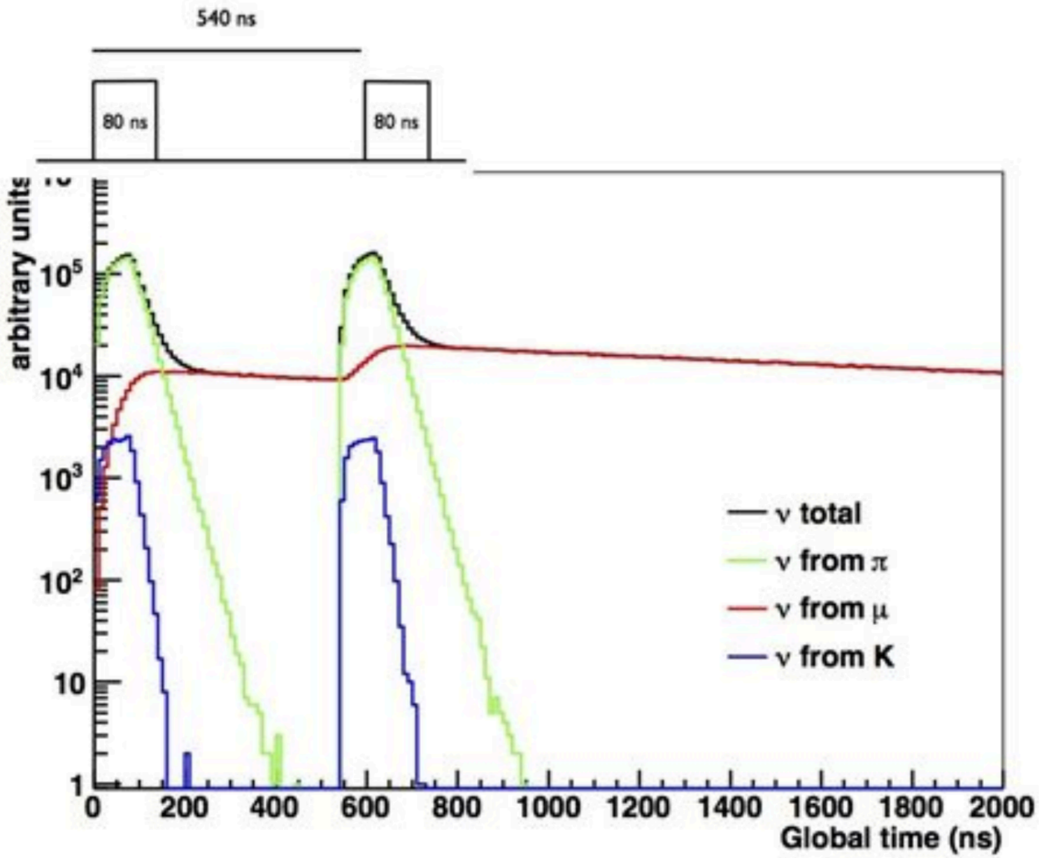


- In practice, particles comes in bunches



Timing

- Neutrinos bunches correlates with proton bunches
- Completely eliminates background from cosmic and environmental sources
- Example in the right.
- Pions are stopped in the beam target, and decay rapidly. (decay is slowed by time dilation)
- Muons travel long distance, and decay.



Side track: The OPERA experment

- Oscillation Project with Emulsion-tRacking Apparatus (OPERA)
- 2012
- Goal of the experiment: detecting tau neutrinos

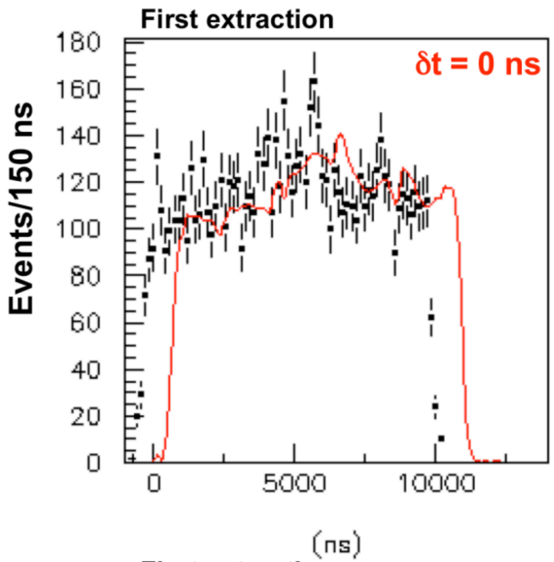
Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

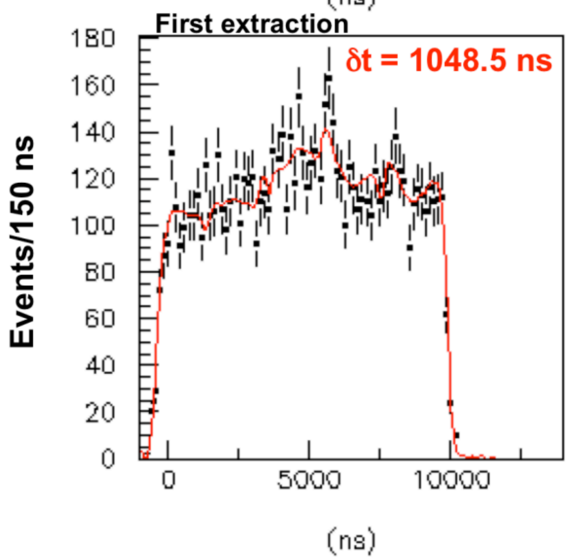
The OPERA Collaboration: T. Adam, N. Agafonova, A. Aleksandrov, O. Altinok, P. Alvarez Sanchez, S. Aoki, A. Ariga, T. Ariga, D. Autiero, A. Badertscher, A. Ben Dhahbi, A. Bertolin, C. Bozza, T. Brugiére, F. Brunet, G. Brunetti, S. Buontempo, F. Cavanna, A. Cazes, L. Chaussard, M. Chernyavskiy, V. Chiarella, A. Chukanov, G. Colosimo, M. Crespi, N. D'Ambrosios, Y. Déclais, P. del Amo Sanchez, G. De Lellis, M. De Serio, F. Di Capua, F. Cavanna, A. Di Crescenzo, D. Di Ferdinando, N. Di Marco, S. Dmitrievsky, M. Dracos, D. Duchesneau, S. Dusini, J. Ebert, I. Eftimiopolous, O. Egorov, A. Ereditato, L.S. Esposito, J. Favier, T. Ferber, R.A. Fini, T. Fukuda, A. Garfagnini, G. Giacomelli, C. Girerd, M. Giorgini, M. Giovannozzi, J. Goldberga, C. Göllnitz, L. Goncharova, Y. Gornushkin, G. Grella, F. Griantia, E. Gschewentner, C. Guerin, A.M. Guler, C. Gustavino, K. Hamada, T. Hara, M. Hierholzer, A. Hollnagel, M. Ieva, H. Ishida, K. Ishiguro, K. Jakovcic, C. Jollet, M. Jones, F. Juget, M. Kamiscioglu, J. Kawada, S.H. Kim, M. Kimura, N. Kitagawa, B. Klicek, J. Knuesel, K. Kodama, M. Komatsu, U. Kose, I. Kreslo, C. Lazzaro, J. Lenkeit, A. Ljubicic, A. Longhin, A. Malgin, G. Mandrioli, J. Marteau, T. Matsuo, N. Mauri, A. Mazzoni, E. Medinaceli, j, F. Meisel, A. Meregaglia, P. Migliozzi et al. (75 additional authors not shown)

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light $(v-c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$.

The OPERA anomaly

- Neutrinos travle faster than light?
- Einstein finally wrong?
- Hundreds of papers written

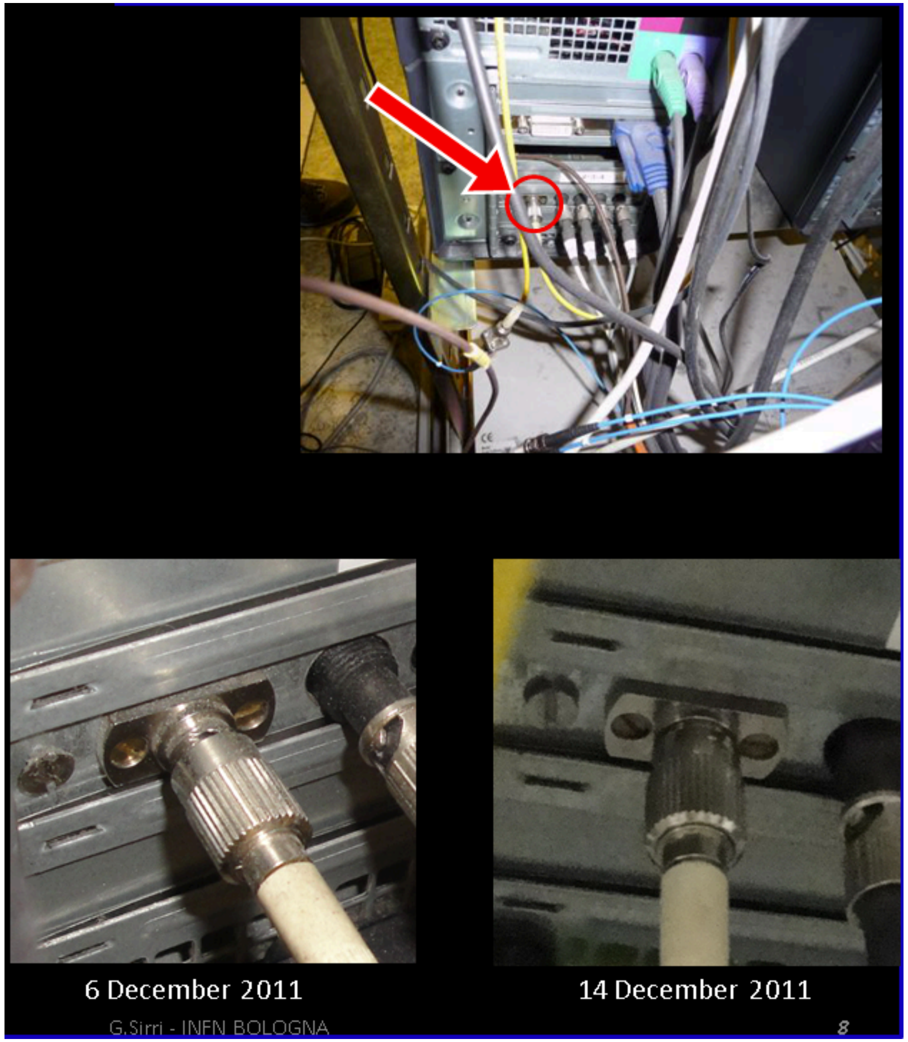




The OPERA anomaly, solved

- Turns out, it was a loose optical cable
- -> Delay in light intensity
- -> Delay in charge build up
- -> Delay in time

https://profmattstrassler.com/articles-and-posts/particle-physics-basics/neutrinos/neutrinos-faster-than-light/opera-what-went-wrong/



- PI reigned in 2012

Legacy of OPERA

- Search for Lorentz invariance violation (LIV) in neutrinos.
- neutrinos has the largest γ factor in all know propagating particles.
- May be the place to find LIV if LIV exists.

arXiv.org > hep-ph > arXiv:1109.6562

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High Energy Physics – Phenomenology

[Submitted on 29 Sep 2011]

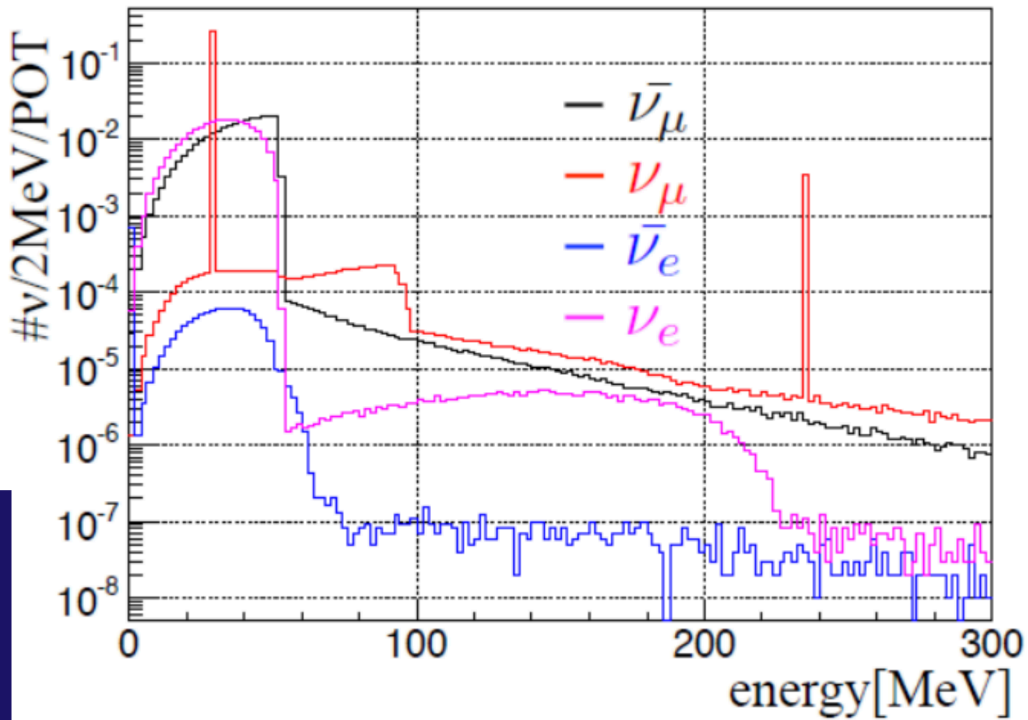
New Constraints on Neutrino Velocities

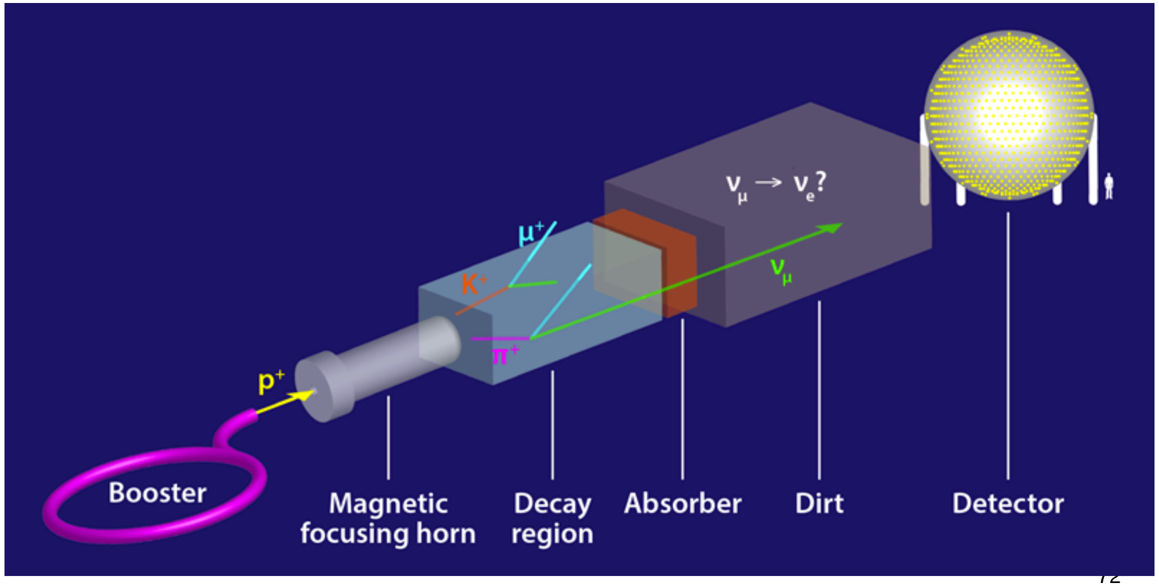
Andrew G. Cohen, Sheldon L. Glashow

The OPERA collaboration has claimed that muon neutrinos with mean energy of 17.5 GeV travel 730 km from CERN to the Gran Sasso at a speed exceeding that of light by about 7.5 km/s or 25 ppm. However, we show that such superluminal neutrinos would lose energy rapidly via the bremsstrahlung of electron–positron pairs ($\nu \to \nu + e^- + e^+$). For the claimed superluminal neutrino velocity and at the stated mean neutrino energy, we find that most of the neutrinos would have suffered several pair emissions en route, causing the beam to be depleted of higher energy neutrinos. Thus we refute the superluminal interpretation of the OPERA result. Furthermore, we appeal to Super-Kamiokande and IceCube data to establish strong new limits on the superluminal propagation of high-energy neutrinos.

Energy information from accelerator neutrinos

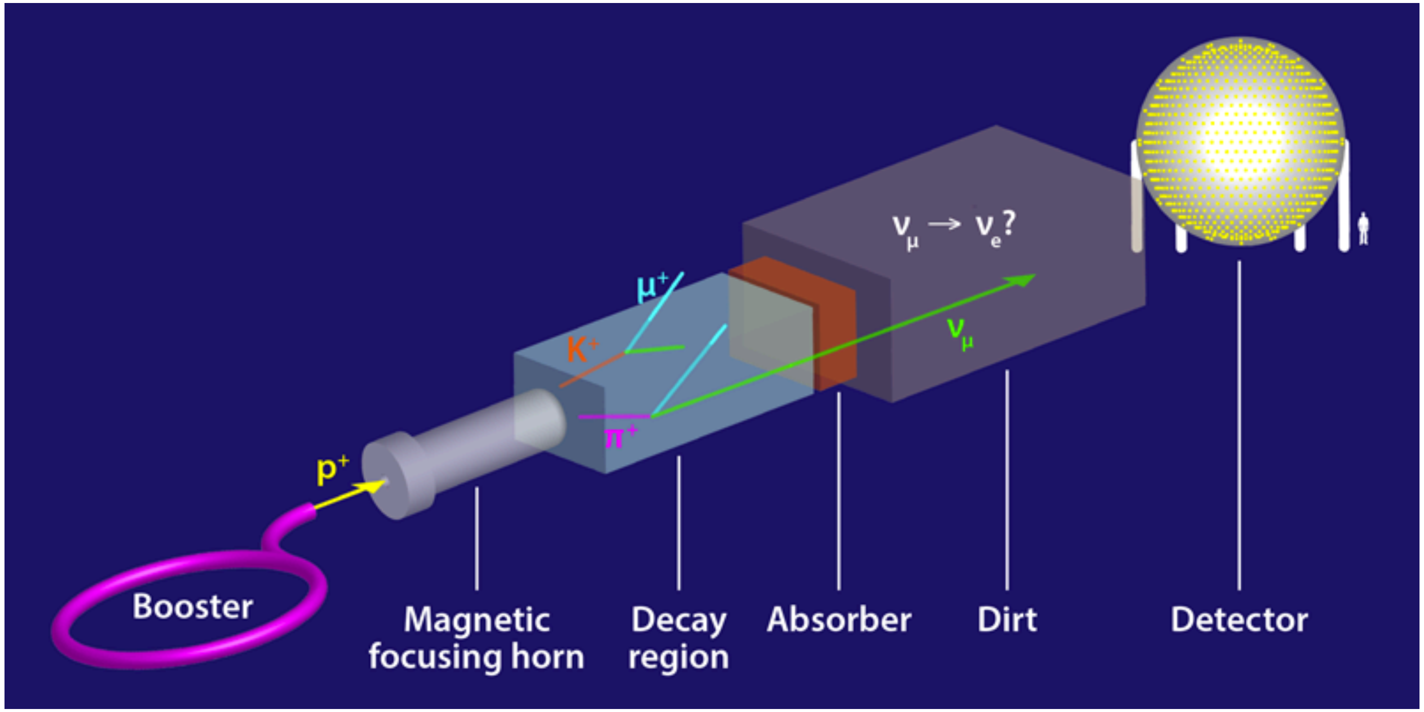
- 1st type of accel. neutrino
- Pion or muon decay-at-rest experiments
- Pion or muon are stopped by high-density materials





Energy information from accelerator neutrinos

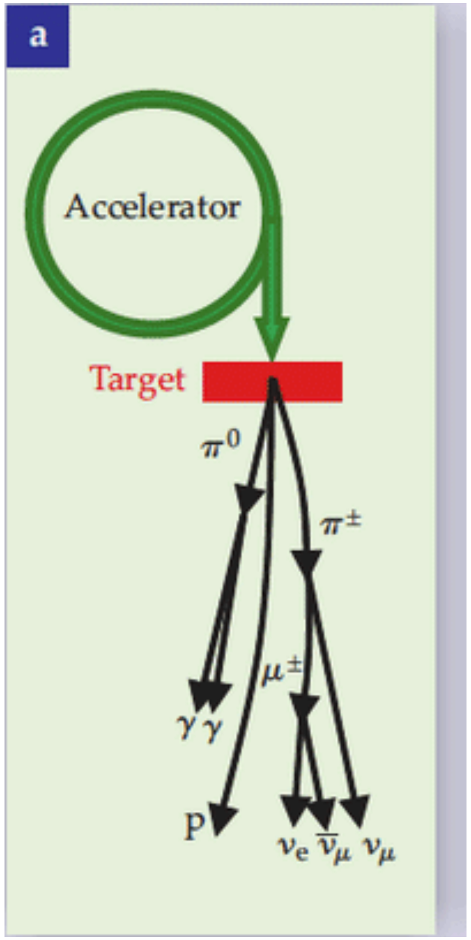
- 2nd type of accel. neutrino
- pions are allowed to travel in the decay region
- Magnets select positive or negative pions.
- Select neutrinos, or anti-neutrinos!



Energy information from accelerator neutrinos

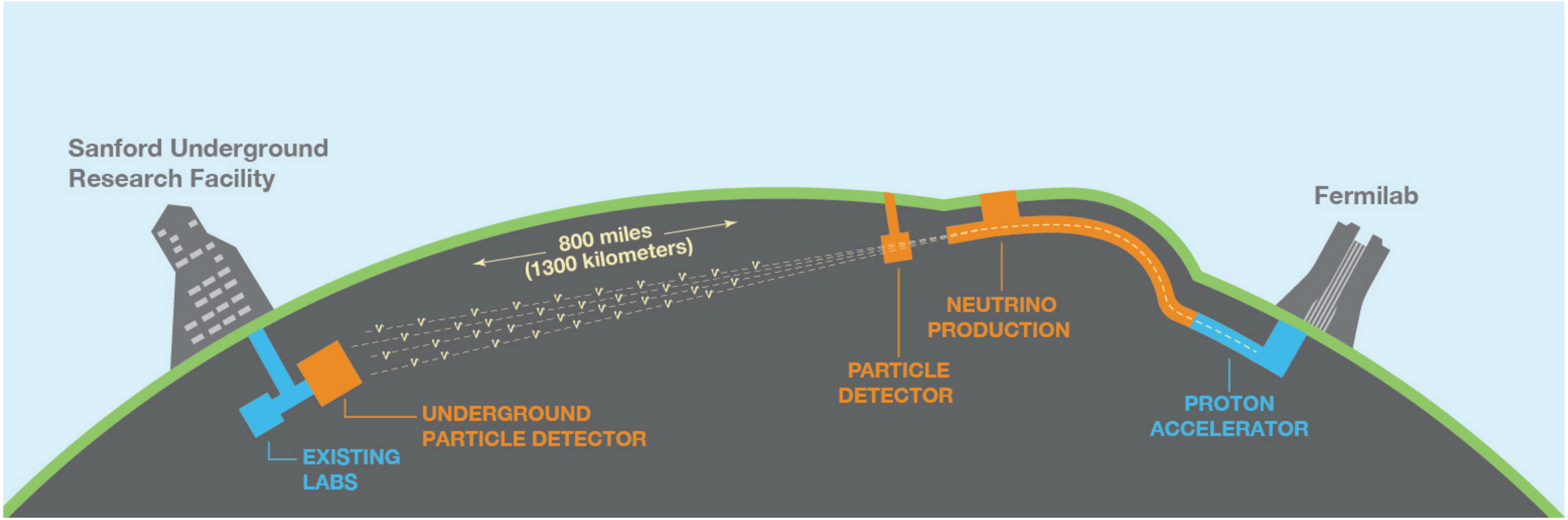
- The production of neutrinos depends on

- proton energy and amount (known)
- proton interaction in the target (messy)
    - many re-interactions
- production (messy)
    - no usable fundamental theory of proton proton interactions.



Energy information from accelerator neutrinos

- Uncertainty in flux production reduced by having a near detector



Long baseline neutrino experiment

- Path to finding CP violation
- appearance experiment.
- $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$$
\begin{array}{ccccc}
 & & \mathrm{CP} & & \\
 & \nu_\mu \to \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \to \bar{\nu}_e & \\
\mathrm{T} & \Updownarrow & & \Updownarrow & \mathrm{T} \\
 & \nu_e \to \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \to \bar{\nu}_\mu & \\
 & & \mathrm{CP} & &
\end{array}
$$

- The probability calculation is long and not very interesting, but straight forward if you know how to do two flavour oscillation.
- want

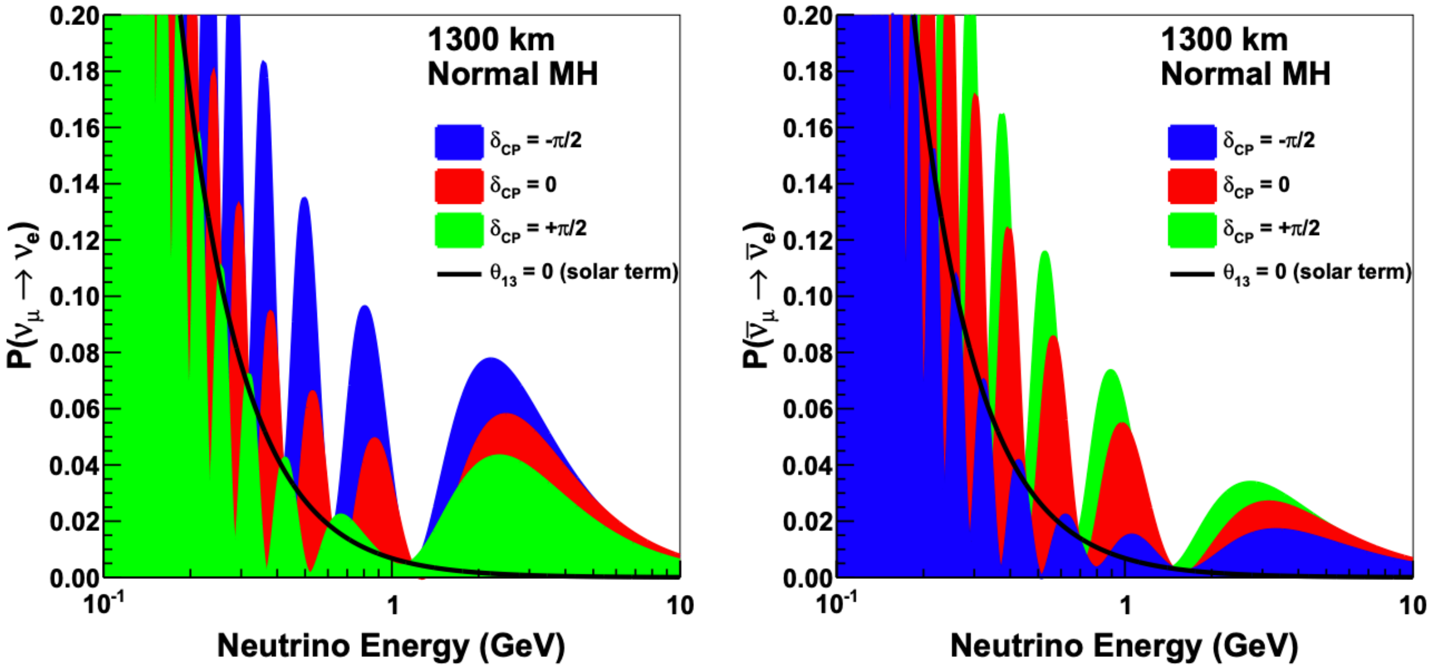
$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \to \nu_e) - \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{\mathrm{P}(\nu_\mu \to \nu_e) + \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$

- Which is proportional to $\sin \delta_{CP}$

https://arxiv.org/pdf/0710.0554.pdf

Long baseline neutrino experiment

- Path to finding CP violation
- appearance experiment.
- $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

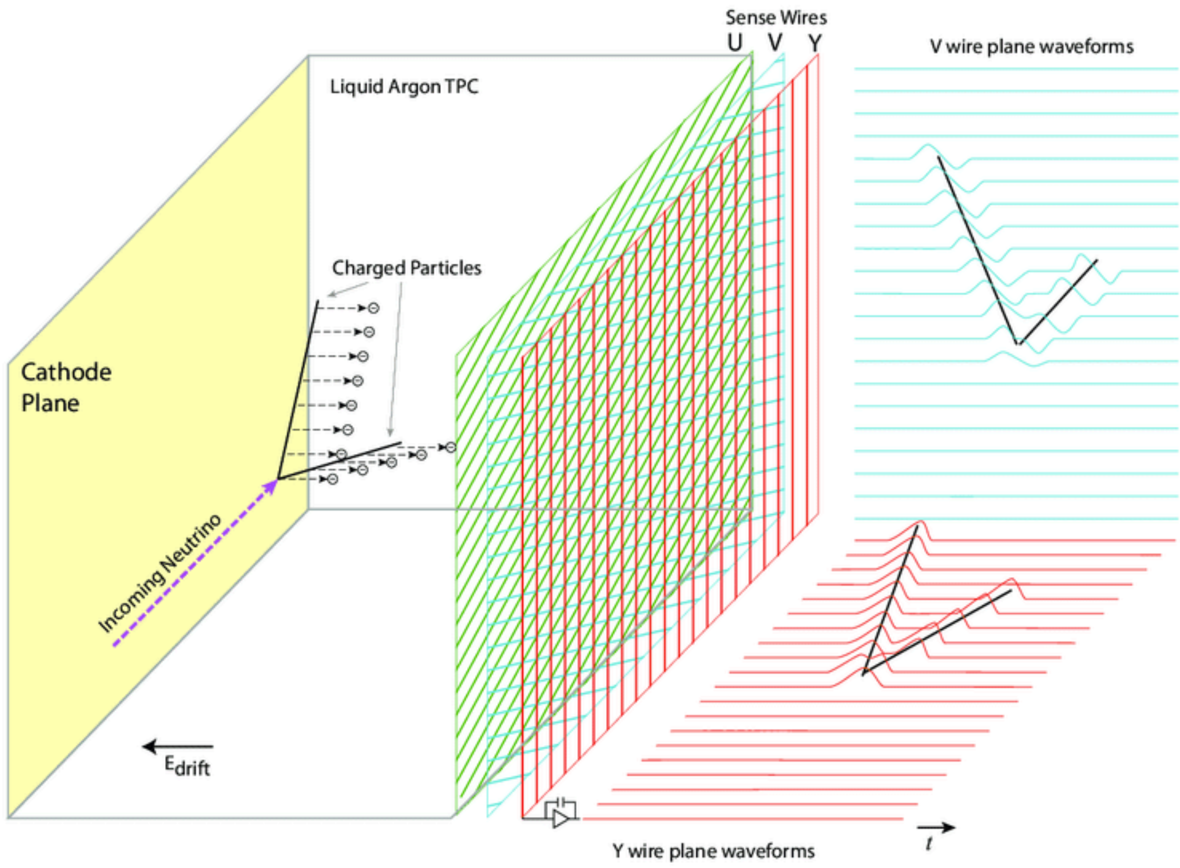


Liquid argon time projection chamber

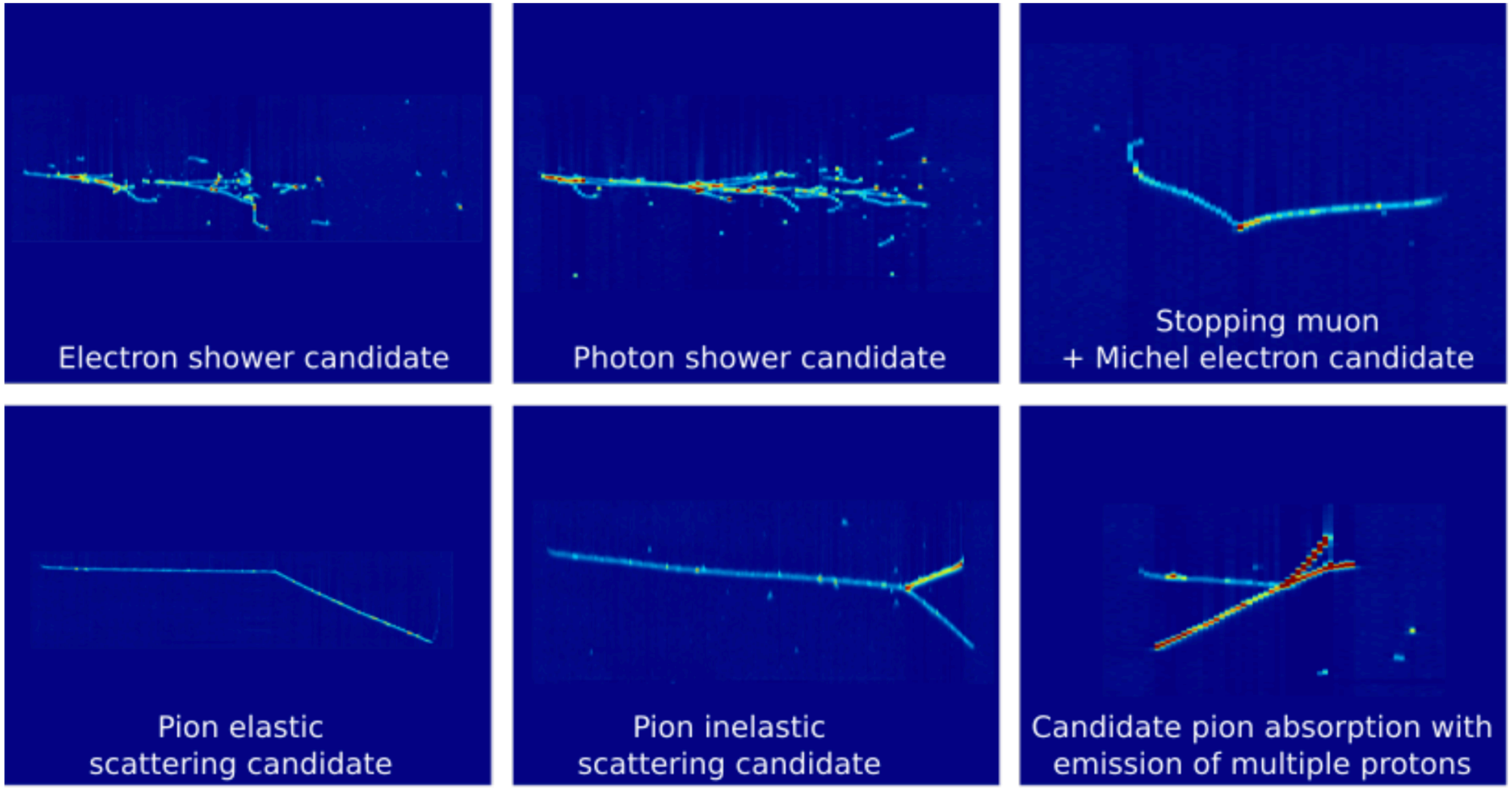
- charged particles leaves a ionisation track (floating electrons)

- Time projection chamber to reconstruct the results of the reaction.

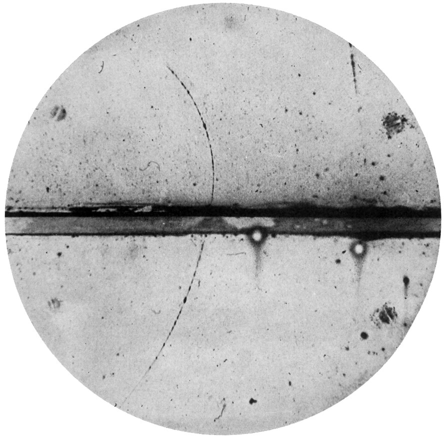
- Good neutrino energy and direction information!



Liquid argon time projection chamber



- 100 years ago



CP violation