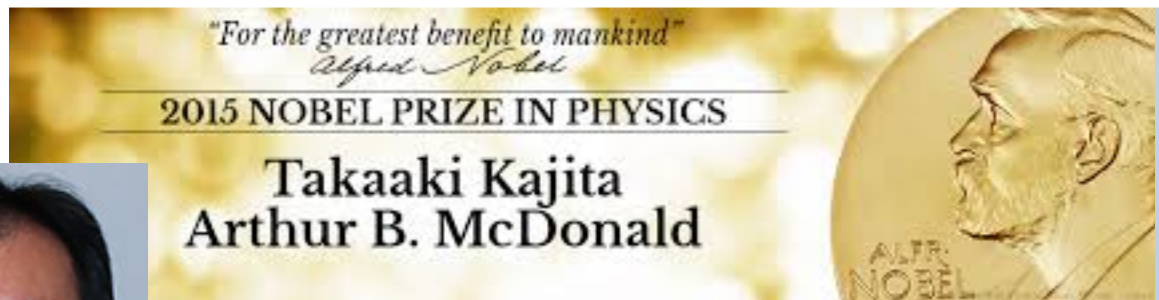
PLAN

- **Lecture I:** Neutrinos in the SM
  Neutrino masses and mixing: Majorana vs Dirac
- **Lecture II:** Neutrino oscillations and the discovery of neutrino masses and mixings
- **Lecture III:** The quest for leptonic CP violation
  A neutrino look at BSM and the history of the Universe

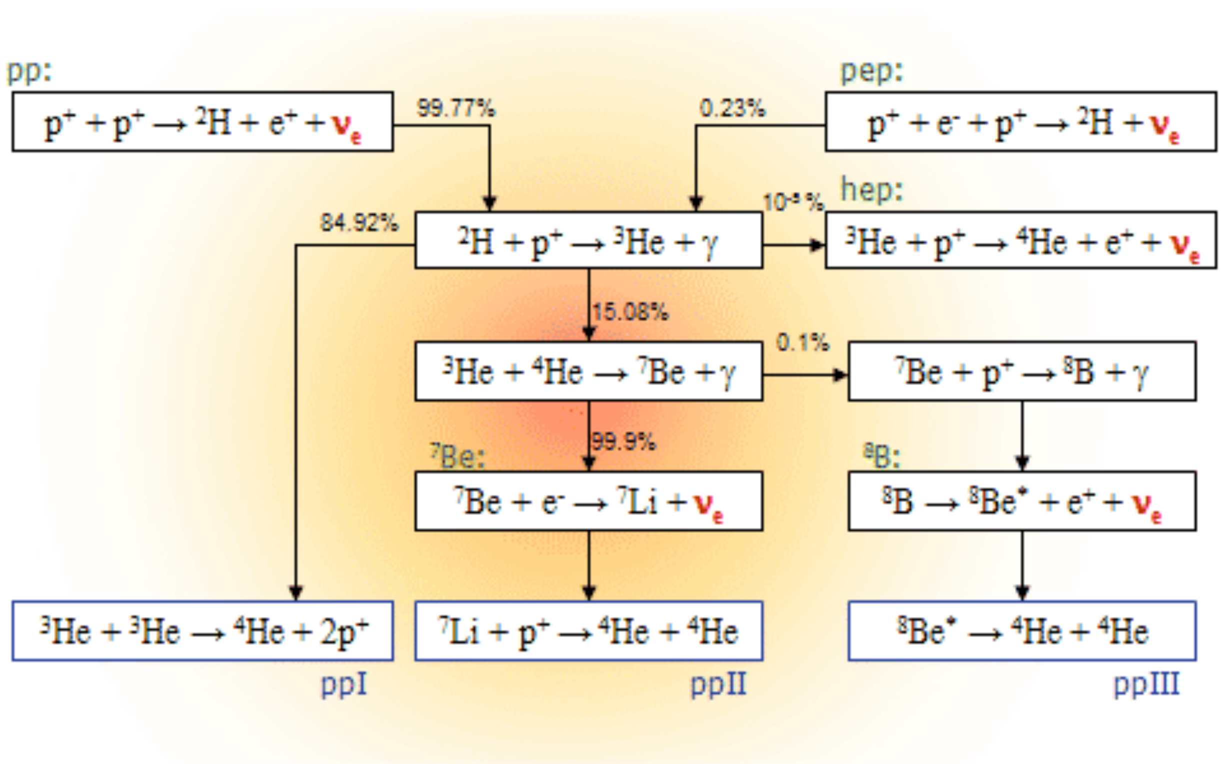
"For the discovery of neutrino oscillations,
which shows that neutrinos have mass"

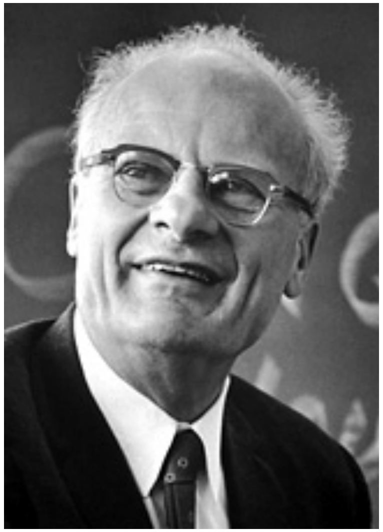


Stars shine neutrinos

1939 Bethe

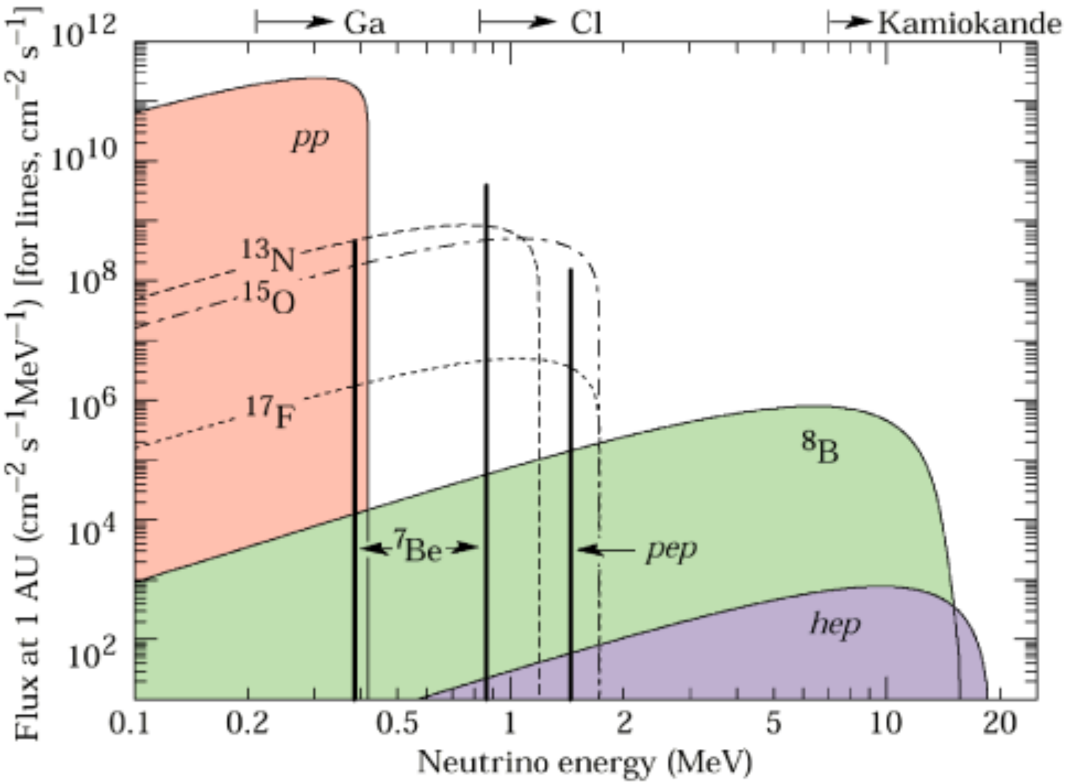
Stablishes the theory of stelar nucleosynthesis





Nobel 1967

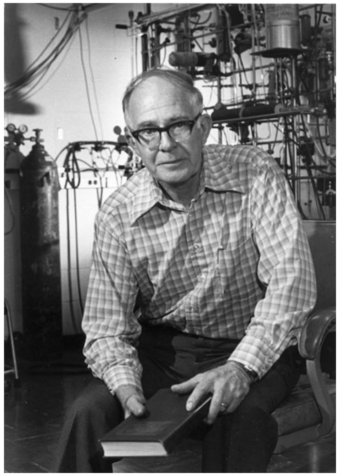
¿How many neutrinos from the Sun ?



Bahcall

The hero of the caves

1966 he detects for the first time solar neutrinos in a tank of 400000 liters 1280m underground (Homestake mine)



R. Davis
Nobel 2002

$$^{37}\mathrm{Cl} + \nu_e \rightarrow ^{37}\mathrm{Ar} + e^-$$

Did not convince because he saw 0.4 of the expected....

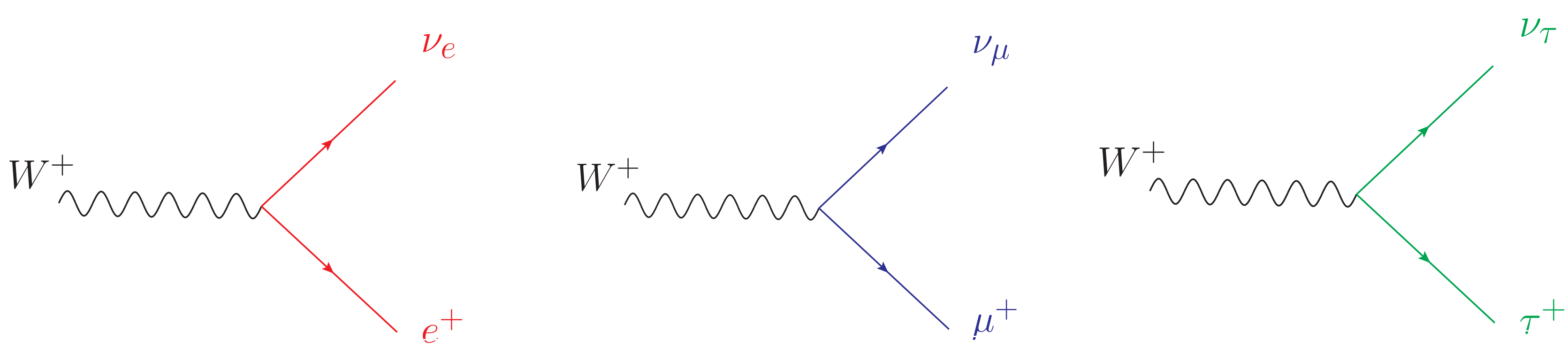
Problem in detector ? In solar model ? In neutrinos ?

Other radiochemical experiments: Gallium with lower-threshold confirmed

Lepton mixing

$$\mathcal{L}_{\rm gauge-lepton} \supset -\frac{g}{\sqrt{2}} \begin{pmatrix} \bar{e} & \bar{\mu} & \bar{\tau} \end{pmatrix} W_\mu^- \gamma_\mu P_L \, U_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} + h.c.$$

The neutrino flavour basis:



States produced in a CC interaction in combination with e, μ, τ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Eigenstates of the free Hamiltonian

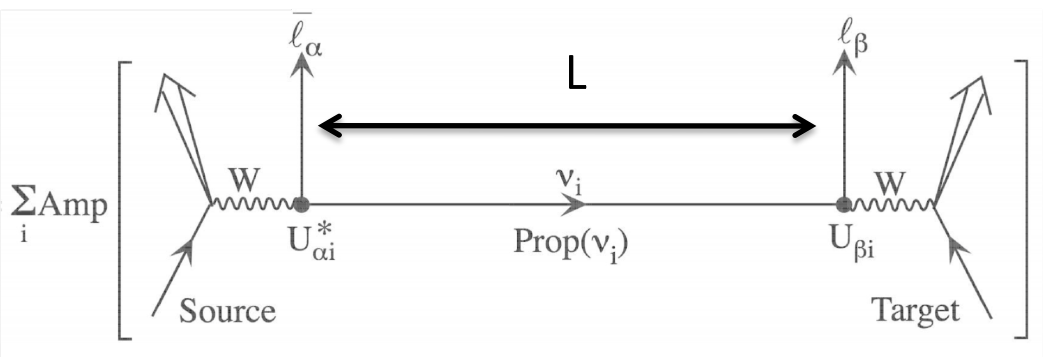
Neutrino oscillations

1968 Pontecorvo

Neutrinos are produced and detected via weak interactions as flavour states:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle, \quad \alpha = e, \mu, \tau$$

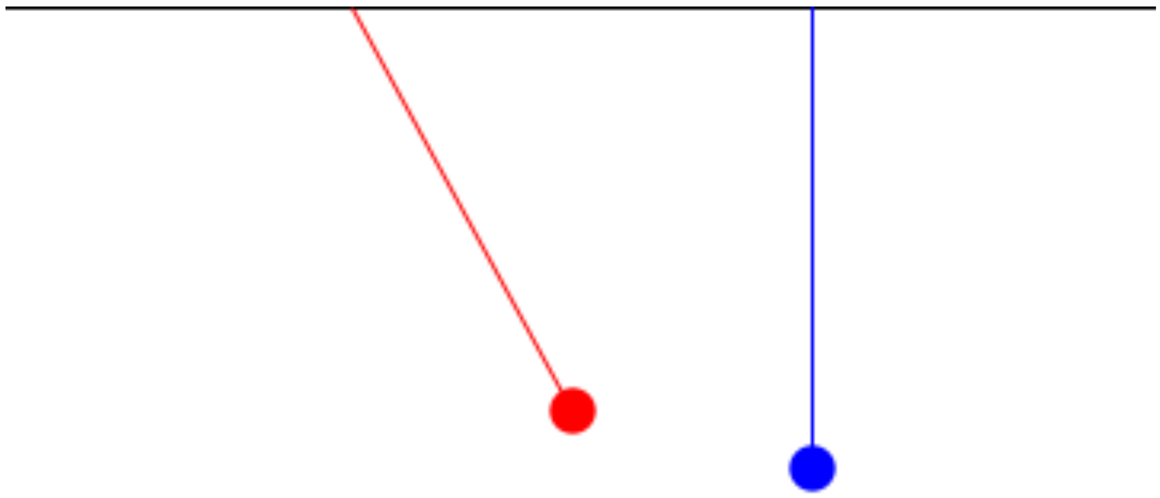
A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !



ν_i travel at slighly different velocities in vacuum: neutrino oscillations

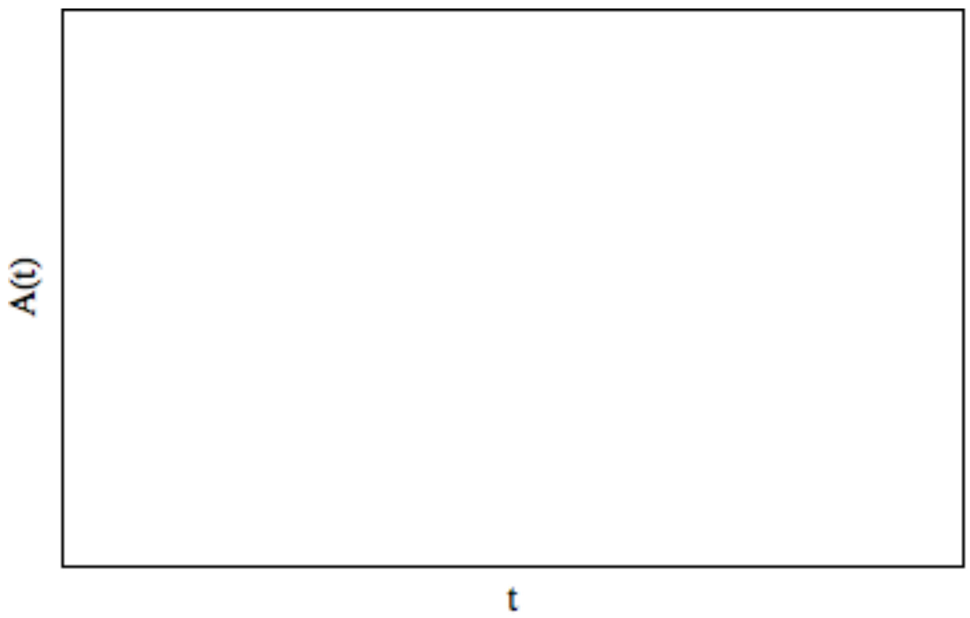
Classical analogy I: no flavour mixing

A ν_e is produced and stays a ν_e ...



ν_e

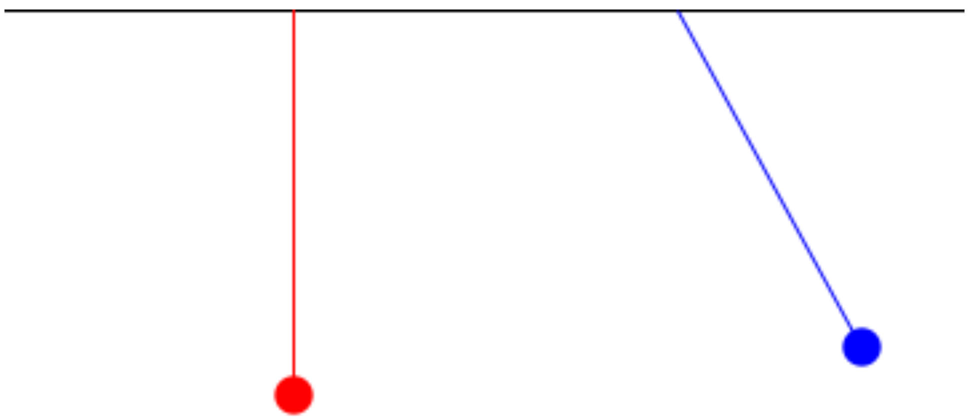
$\text{Prob}(\nu_e) = \text{Amplitude}^2$



The probability to find a ν_e at any time is the same, but the probability to find a ν_μ is zero.

No flavour mixing

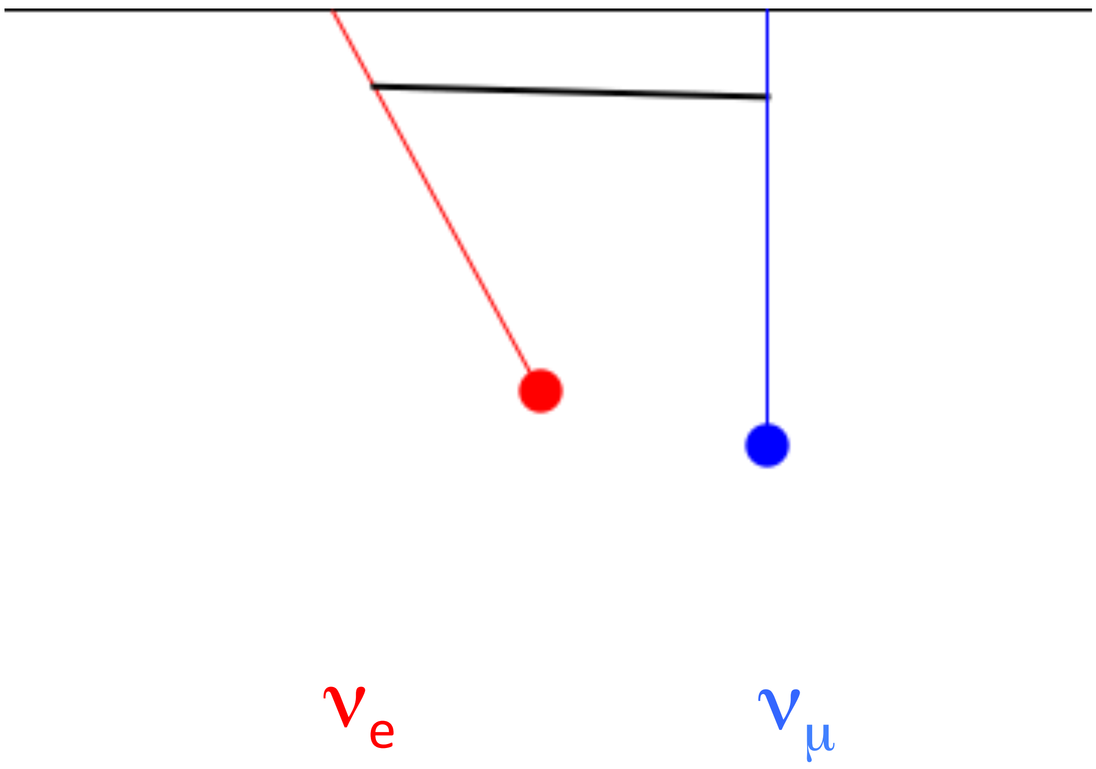
A ν_μ is produced and stays a ν_μ …

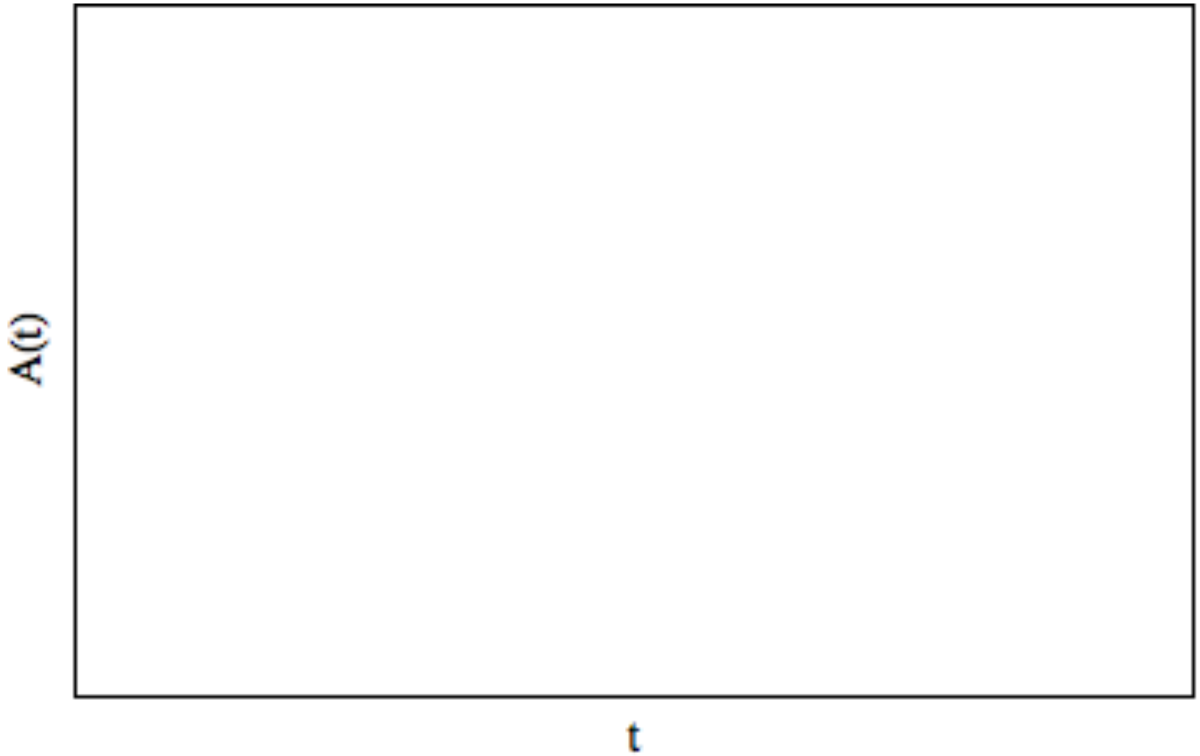


ν_μ

$\text{Prob}(\nu_\mu) = \text{Amplitude}^2$

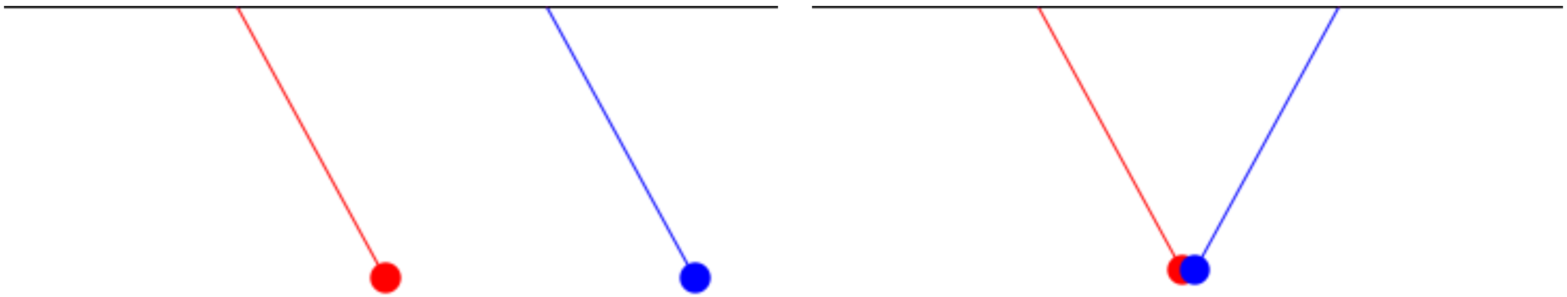
Classical analogy II: Maximal flavour mixing

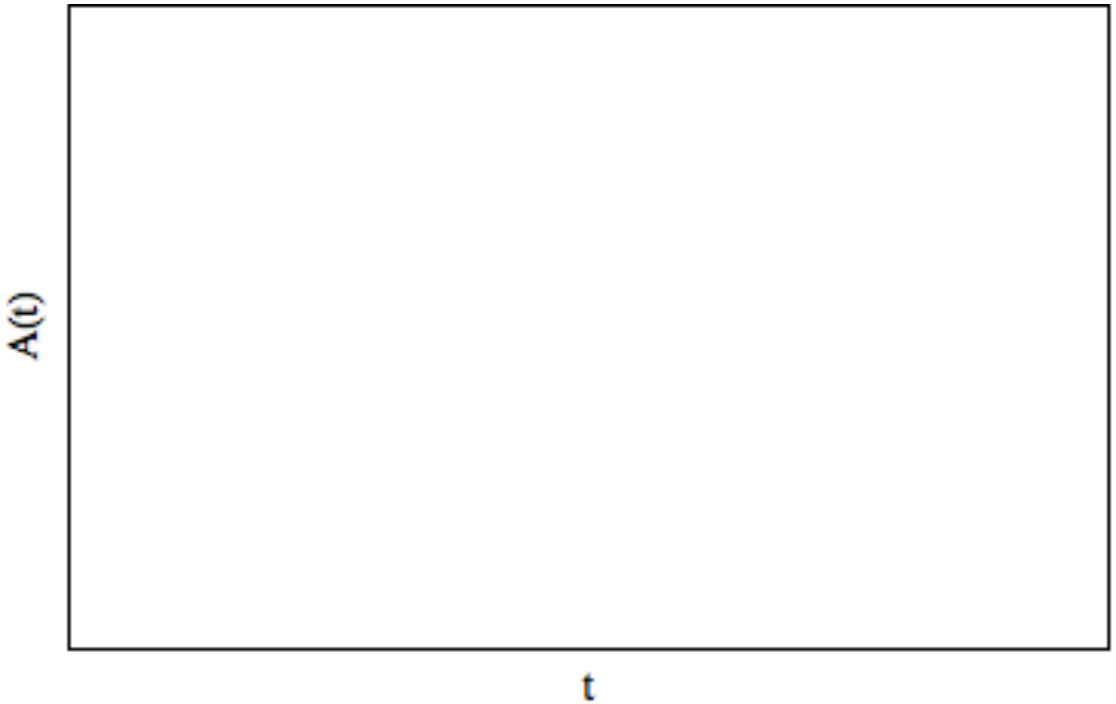




The probability to find a ν_e oscillates with time and so does that of ν_μ

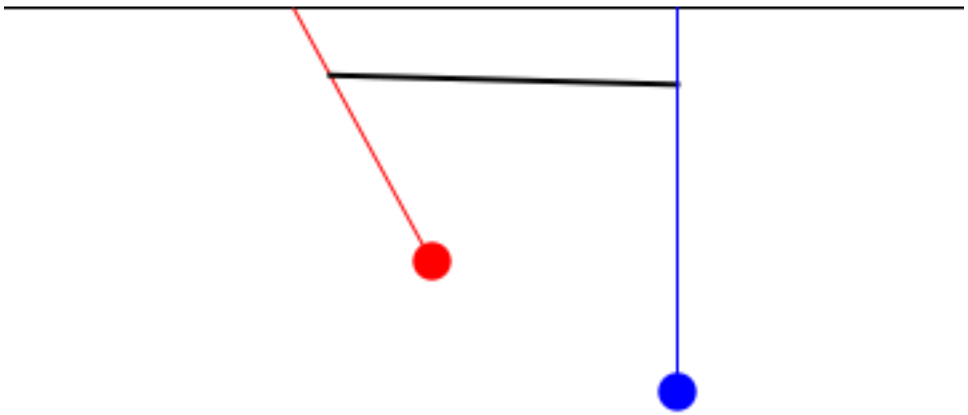
Mass eigenstates=normal modes

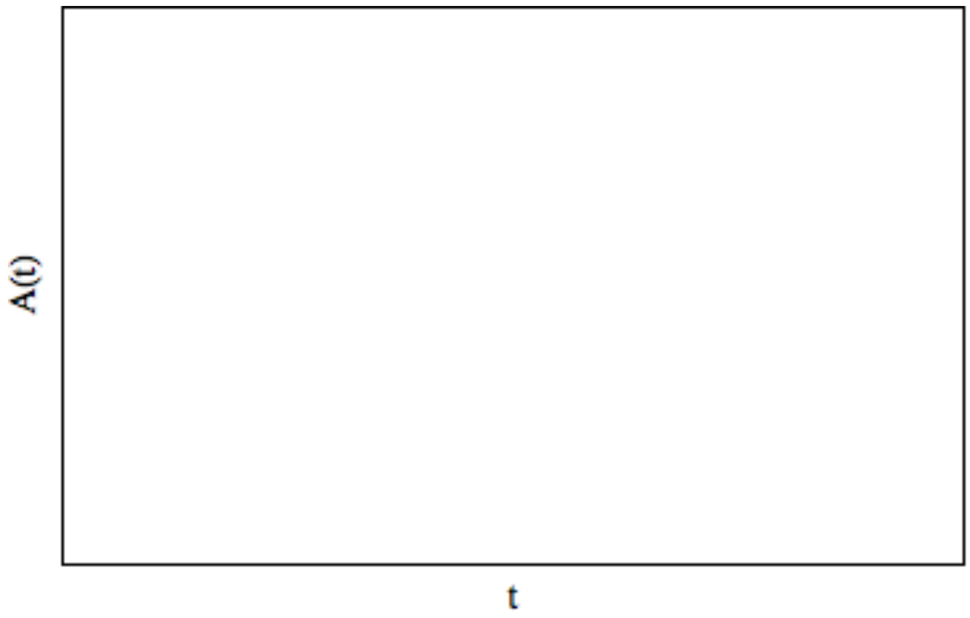




The probability to find a ν_e o ν_μ does not change with time

Classical analogy III: small flavour mixing





The probability to find a ν_e oscillates with time and so does that of ν_μ

Neutrino oscillations in vacuum

$$|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i}|\nu_i(\mathbf{p})\rangle, \qquad \hat{H}|\nu_i(\mathbf{p})\rangle = E_i(\mathbf{p})|\nu_i(\mathbf{p})\rangle, \quad \mathbf{p}^2 + m_i^2 = E_i^2(\mathbf{p})$$

$$\downarrow \text{time evolution} \equiv e^{-i\hat{H}(t-t_0)}$$

$$|\nu_\alpha(t)\rangle = \sum_i U^*_{\alpha i} e^{-iE_i(\mathbf{p})(t-t_0)}|\nu_i(\mathbf{p})\rangle \qquad |\nu_\beta\rangle = \sum_\beta U^*_{\beta i}|\nu_i(\mathbf{p})\rangle$$

$$P(\nu_\alpha \to \nu_\beta)(t) = |\langle \nu_\beta|\nu_\alpha(t)\rangle|^2 = |\sum_i U_{\beta i} U^*_{\alpha i} e^{-iE_i(t-t_0)}|^2$$

$$= \sum_{i,j} e^{-i(E_i - E_j)(t-t_0)} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}$$

$$E_i(\mathbf{p}) - E_j(\mathbf{p}) \simeq \frac{1}{2}\frac{m_i^2 - m_j^2}{|\mathbf{p}|} + \mathcal{O}(m^4) \qquad L \simeq t - t_0, v_i \simeq c$$

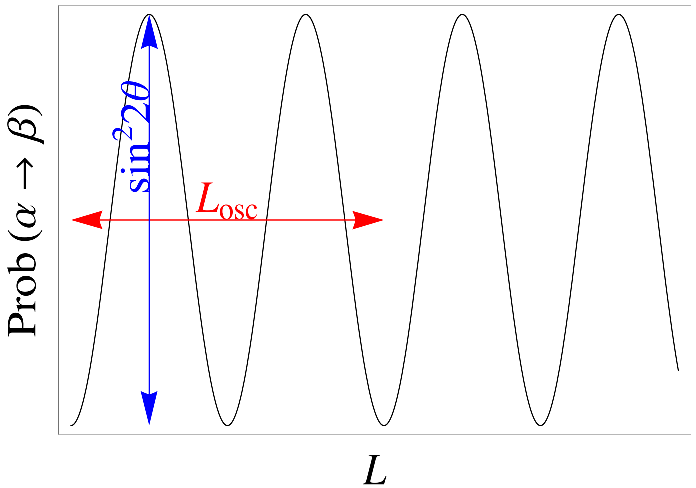
$$P(\nu_\alpha \to \nu_\beta)(L) \simeq \sum_{i,j} e^{i\frac{\Delta m^2_{ji} L}{2E}} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}$$

Neutrino Oscillation: 2ν

Only one oscillation frequency, $U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2(eV^2) L(km)}{E(GeV)}\right)$$

(appearance probability)



$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

(disappearance or survival probability)

$$L_{osc}(km) = \frac{\pi}{1.27} \frac{E(GeV)}{\Delta m^2(eV^2)}$$

Optimal experiment: $\frac{E}{L} \sim \Delta m^2$

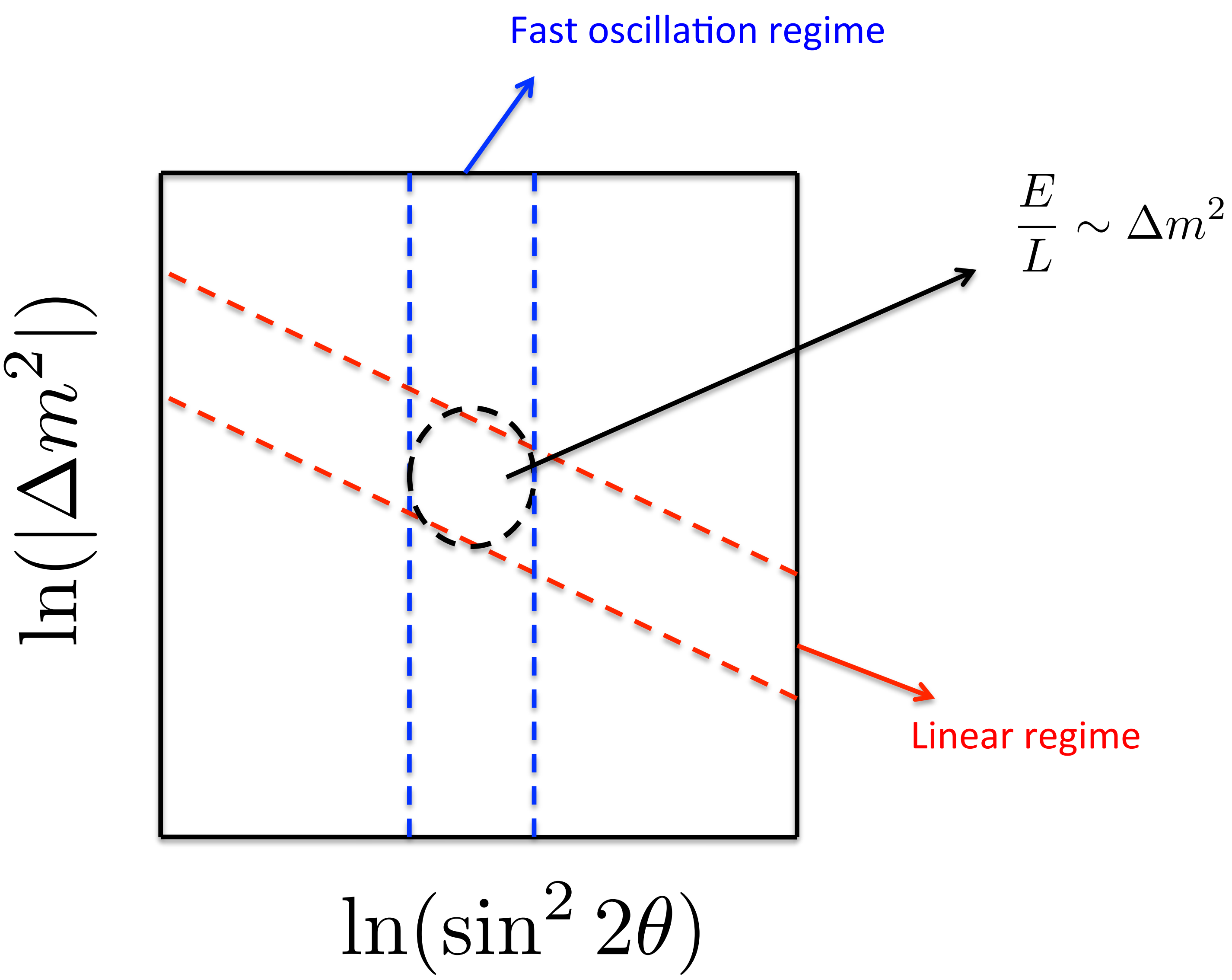
$\frac{E}{L} \gg \Delta m^2$ Oscillation suppressed

$$P(\nu_\alpha \to \nu_\beta) \propto \sin^2 2\theta \left(\Delta m^2\right)^2$$

$\frac{E}{L} \ll \Delta m^2$ Fast oscillation regime

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \, \langle \sin^2 \frac{\Delta m^2 L}{4E} \rangle \simeq \frac{1}{2} \sin^2 2\theta = |U^*_{\alpha 1} U_{\beta 1}|^2 + |U^*_{\alpha 2} U_{\beta 2}|^2$$

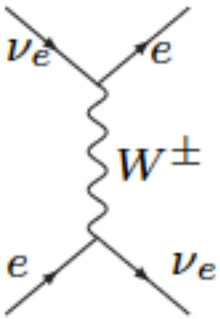
Equivalent to incoherent propagation: sensitivity to mass splitting is lost

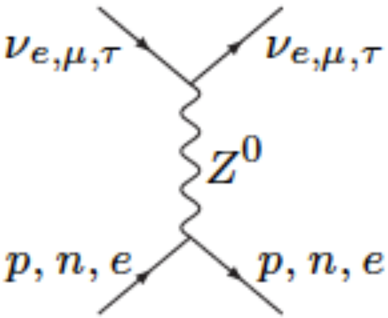


Fast oscillation regime
$\frac{E}{L} \sim \Delta m^2$
Linear regime
$\ln(|\Delta m^2|)$
$\ln(\sin^2 2\theta)$

Neutrino Oscillations in matter

Many neutrino oscillation experiments involve neutrinos propagating in matter (Earth for atmospheric neutrinos or accelerator experiments, Sun for solar neutrinos)





Wolfenstein

Index of refraction (coherent forward scattering) different for electron and μ/τ neutrinos

Neutrino propagation in matter

$$M_\nu^2 \longrightarrow \pm 2 V_m E + M_\nu^2$$

+: neutrinos, -: antineutrinos

In the flavour basis:

$$V_m = \begin{pmatrix} V_{NC} + \sqrt{2} G_F N_e & & \\ & V_{NC} & \\ & & V_{NC} \end{pmatrix}$$

Earth: $V_m \simeq 10^{-13} eV \rightarrow 2 V_m E \simeq 10^{-4} eV^2 \left[\frac{E}{1GeV}\right]$

Sun: $V_m \simeq 10^{-12} eV \rightarrow 2 V_m E \simeq 10^{-6} eV^2 \left[\frac{E}{1MeV}\right]$

Neutrino oscillations in constant matter

Effective mixing angles and masses depend on energy

$$\begin{pmatrix} \tilde{m}_1^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} = \tilde{U}^\dagger_{\rm PMNS} \left(M_\nu^2 \pm 2E \begin{pmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{pmatrix} \right) \tilde{U}_{\rm PMNS}$$

+: neutrinos
-: antineutrinos

For two families :

$$\sin^2 2\tilde{\theta} = \frac{\left(\Delta m^2 \sin 2\theta\right)^2}{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\Delta\tilde{m}^2 = \sqrt{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2} E\, G_F\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

-: neutrinos
+: antineutrinos

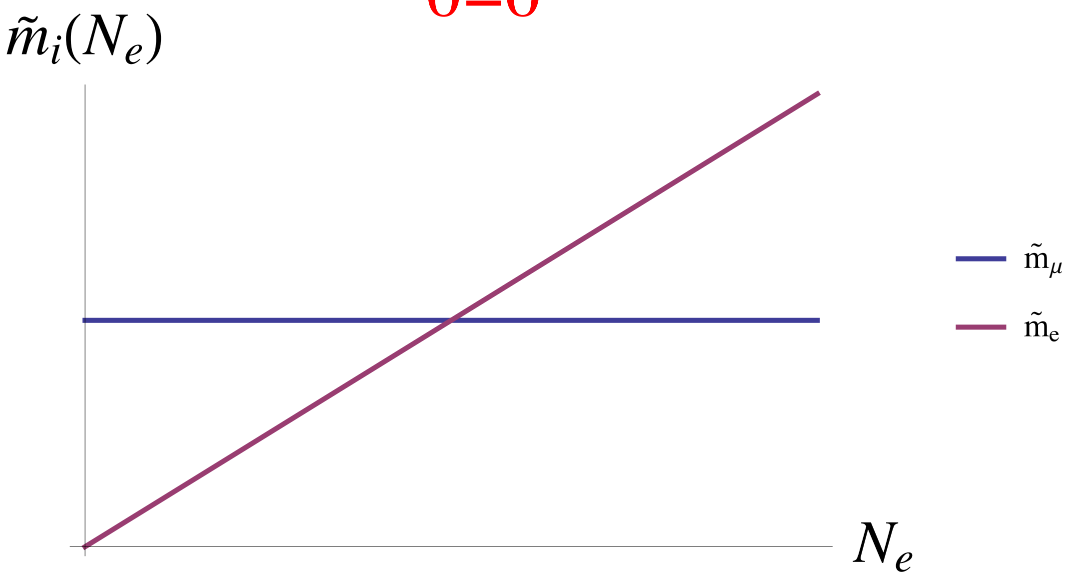
Resonant condition: $\sin^2 2\tilde{\theta} = 1, \quad \Delta\tilde{m}^2 = \Delta m^2 \sin 2\theta$

$$\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e = 0$$

MSW resonance

Mikheyev, Smirnov '85

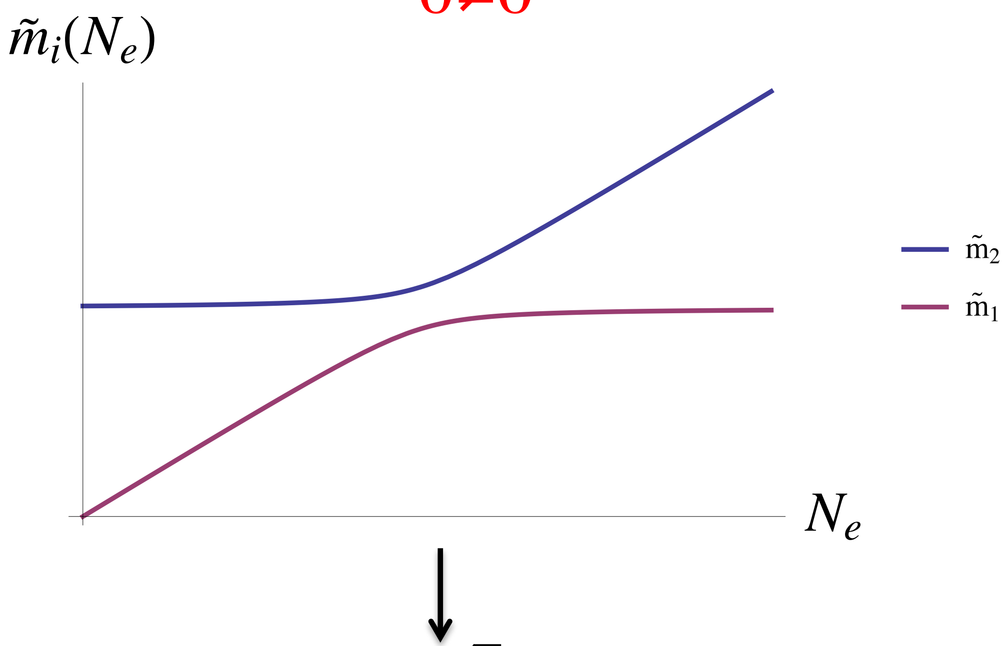
$\theta=0$



MSW resonance

Mikheyev, Smirnov '85

$\theta \neq 0$



$$\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e = 0$$

MSW Resonance:

-Only for ν or $\overline{\nu}$, not both

-Only for one sign of $\Delta m^2 \cos 2\theta$

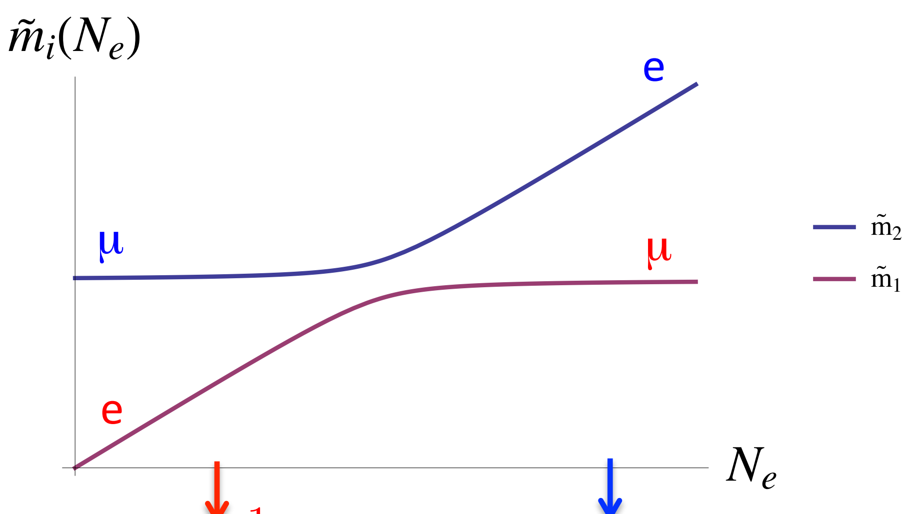
Neutrinos in variable matter

Solar neutrinos propagate in variable matter:

$$N_e(r) \propto N_e(0)e^{-r/R}$$

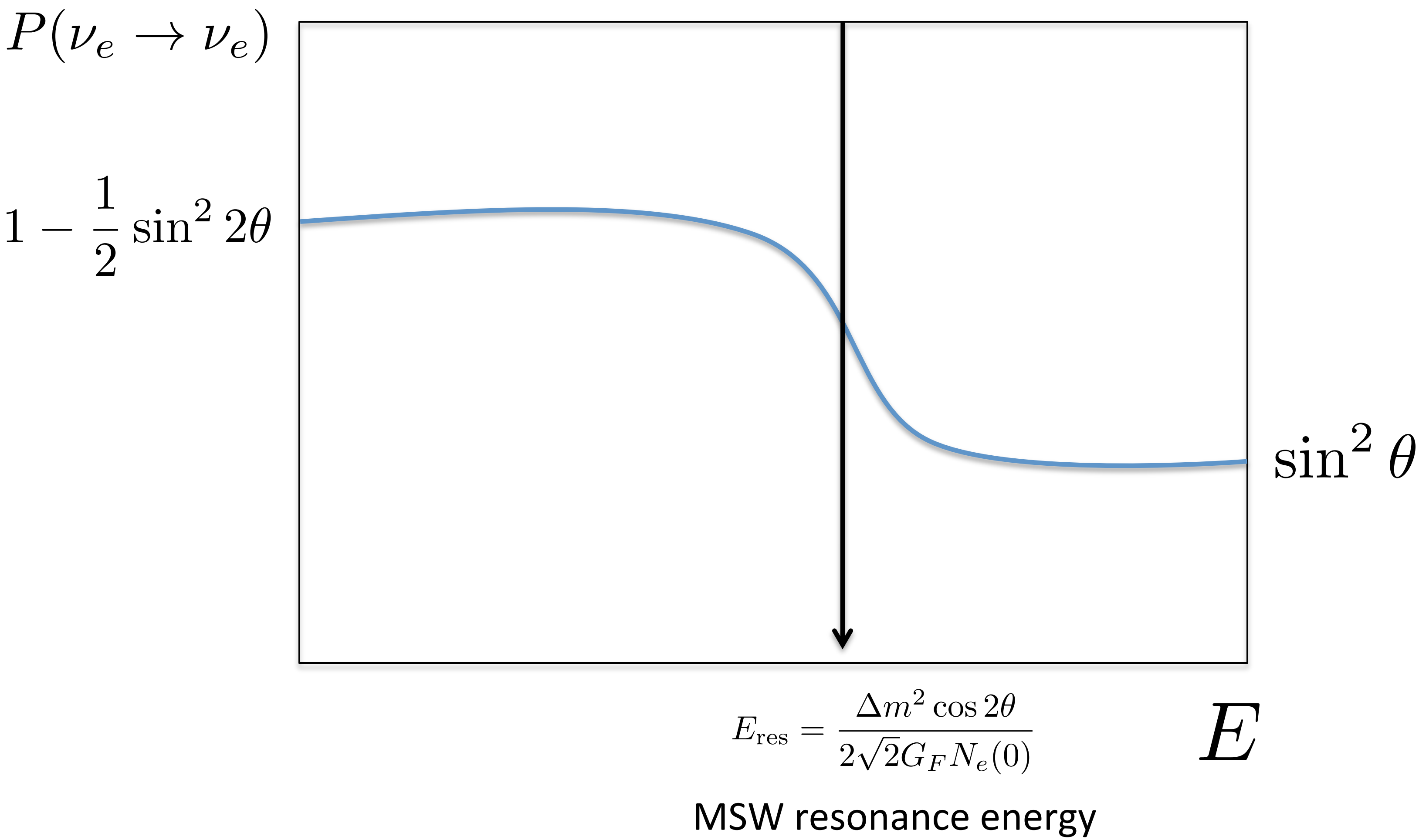
If the variation is slow enough: adiabatic approximation (if a state is at r=0 in an eigenstate $\tilde{m}_i^2(0)$ it remains in the i-th eigenstate until it exits the sun)

$$P(\nu_e \to \nu_e) = \sum_i |\langle \nu_e | \tilde{\nu}_i(\infty)\rangle|^2 |\langle \tilde{\nu}_i(0)|\nu_e\rangle|^2$$



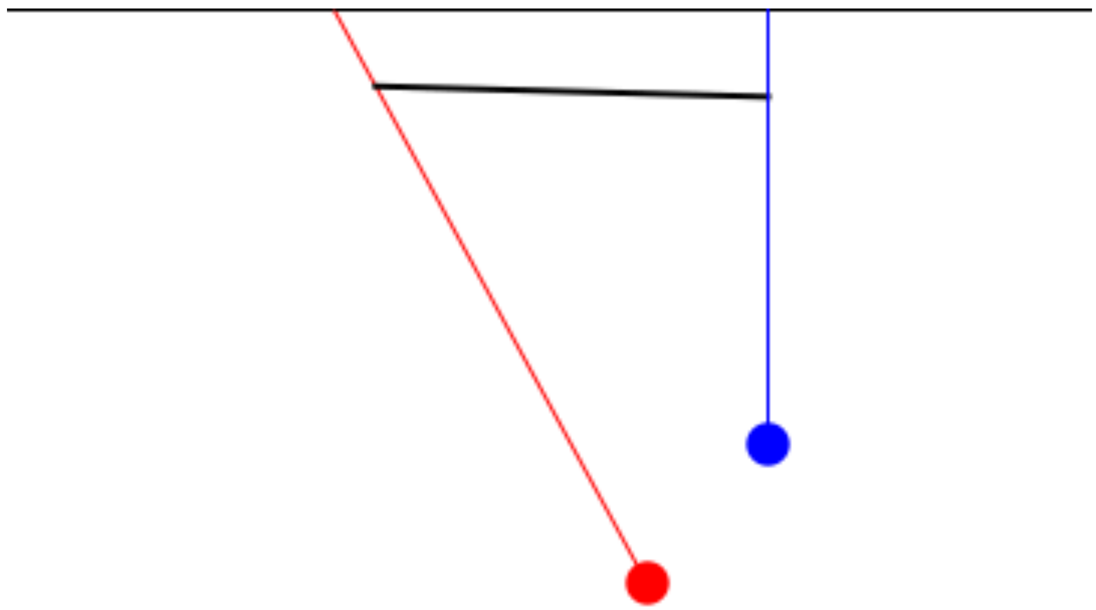
$P(\nu_e \to \nu_e) \simeq 1 - \frac{1}{2}\sin^2 2\theta$ $P(\nu_e \to \nu_e) \simeq \sin^2\theta$

Solar neutrinos

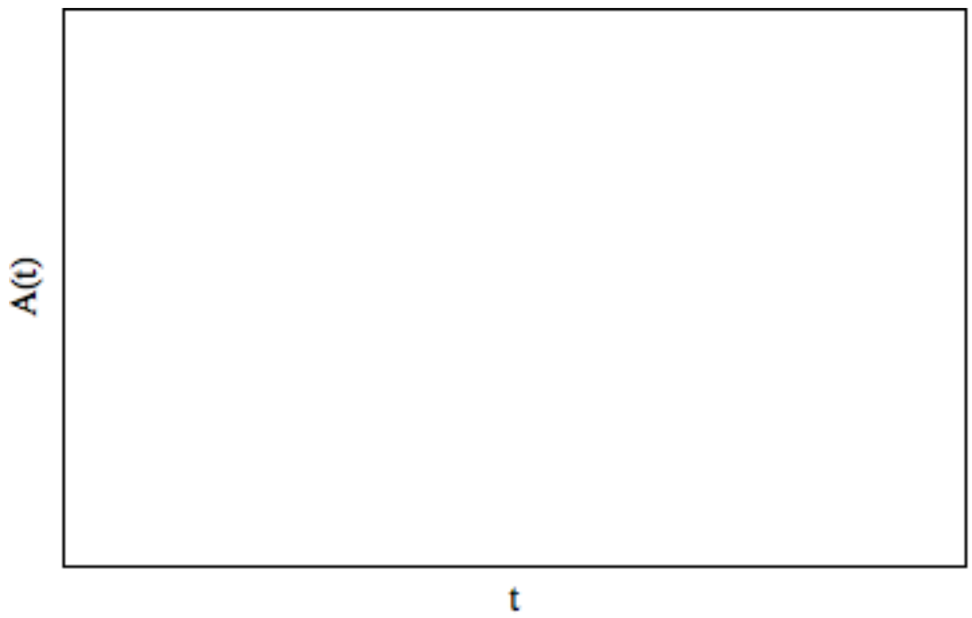


In most physical situations: piece-wise constant matter or adiabatic approx. good enough

Classical analogy IV:MSW resonance

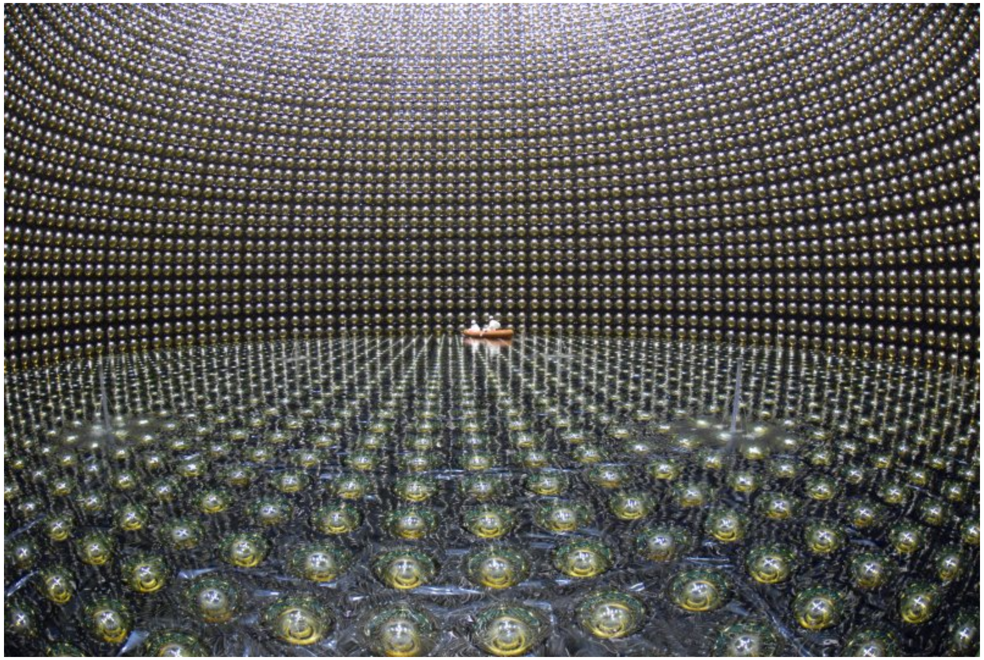


Classical analogy IV:MSW resonance

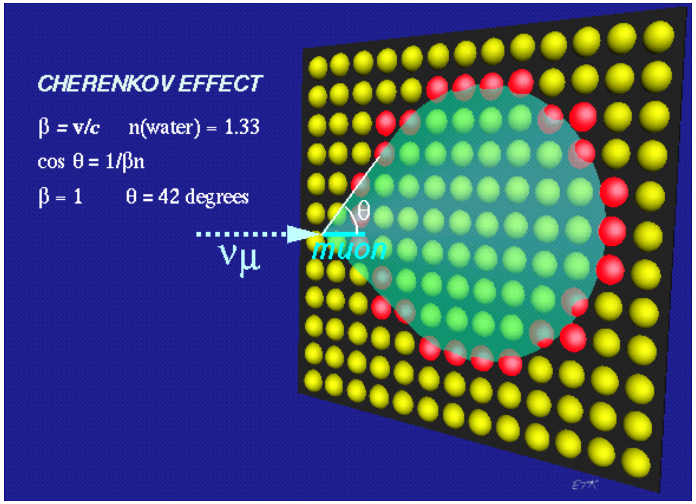


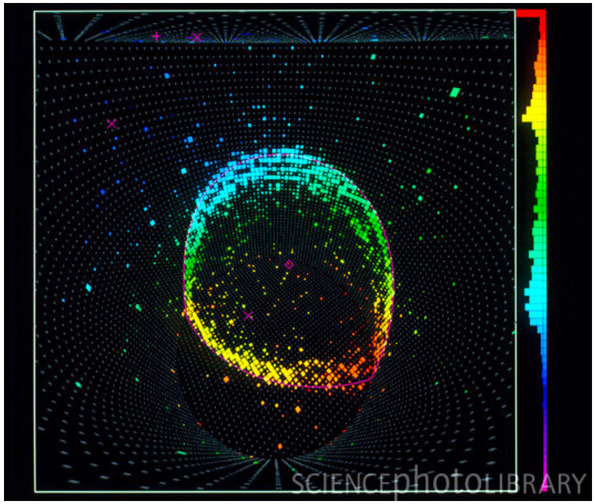
As we cross the resonance (when the two lengths are the same), there is a maximal flavour conversion: what was mostly ν_e is now mostly ν_μ

Underground cathedrals of light



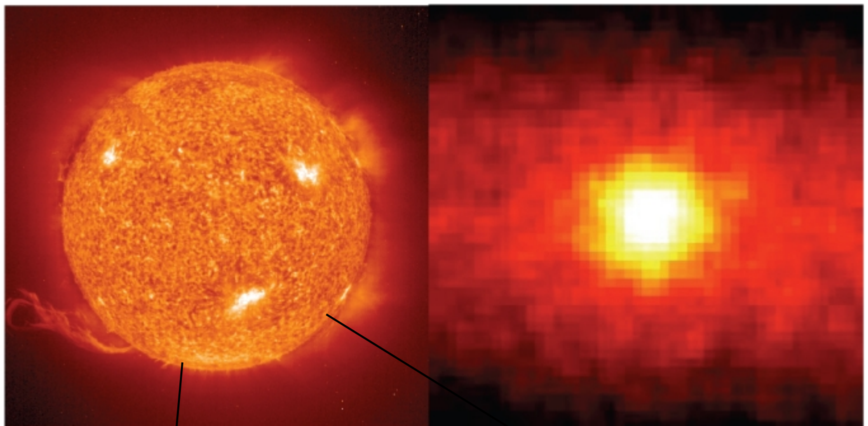
Koshiba (Nobel 2002)





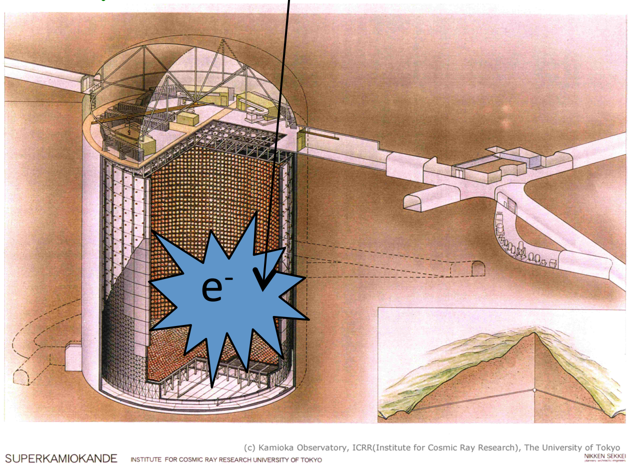
Allows to reconstruct velocity and direction, e/μ particle identification

Solar Neutrinos



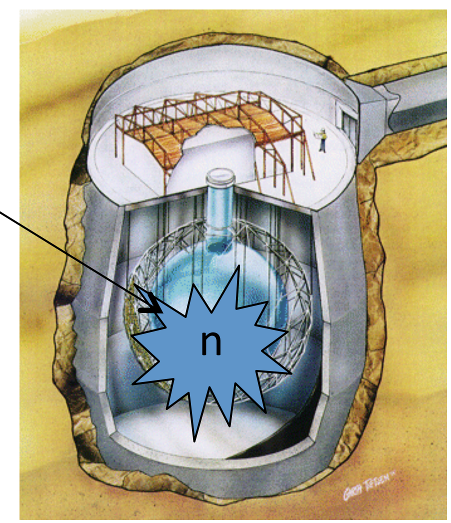
Neutrinography of the sun

SuperKamiokande (22.5 kton!)



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

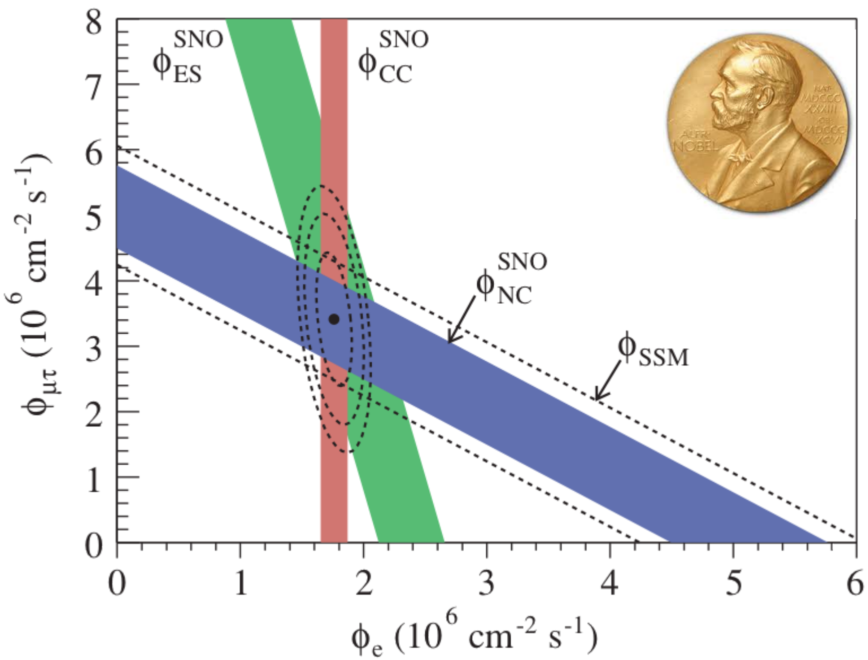
SNO

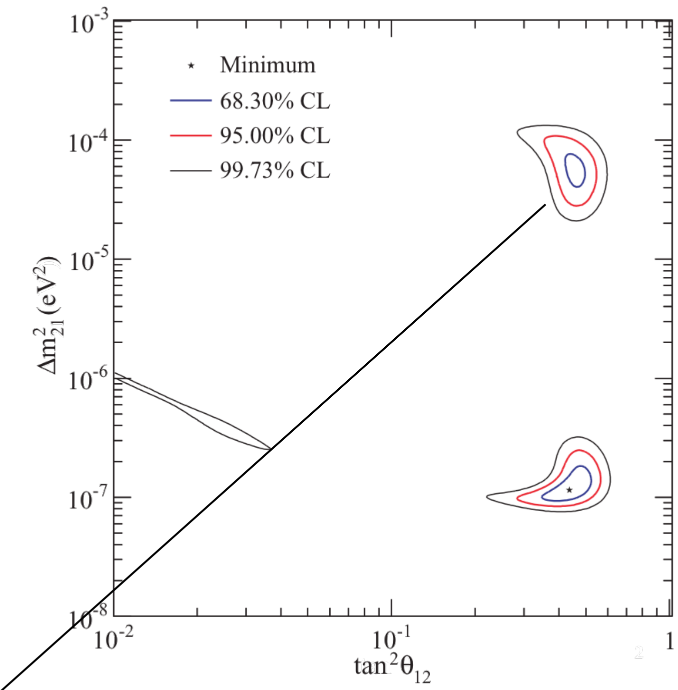


$$NC: \quad \nu_i + d \rightarrow p + n + \nu_i$$

$$CC: \quad \nu_e + d \rightarrow p + p + e^-$$

Flavour of solar neutrinos





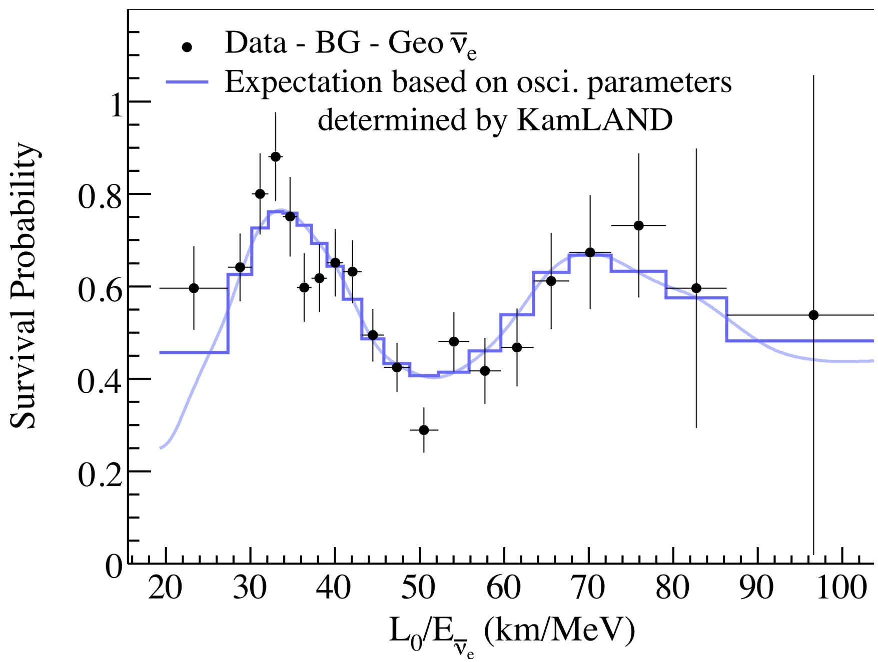
$$|\Delta m^2|^{-1} \sim \frac{O(100Km)}{O(MeV)}$$

Can be tested in the Earth with Reines&Cowen experiment !

KamLAND: solar oscillation

$$\overline{\nu}_e \to \overline{\nu}_e$$

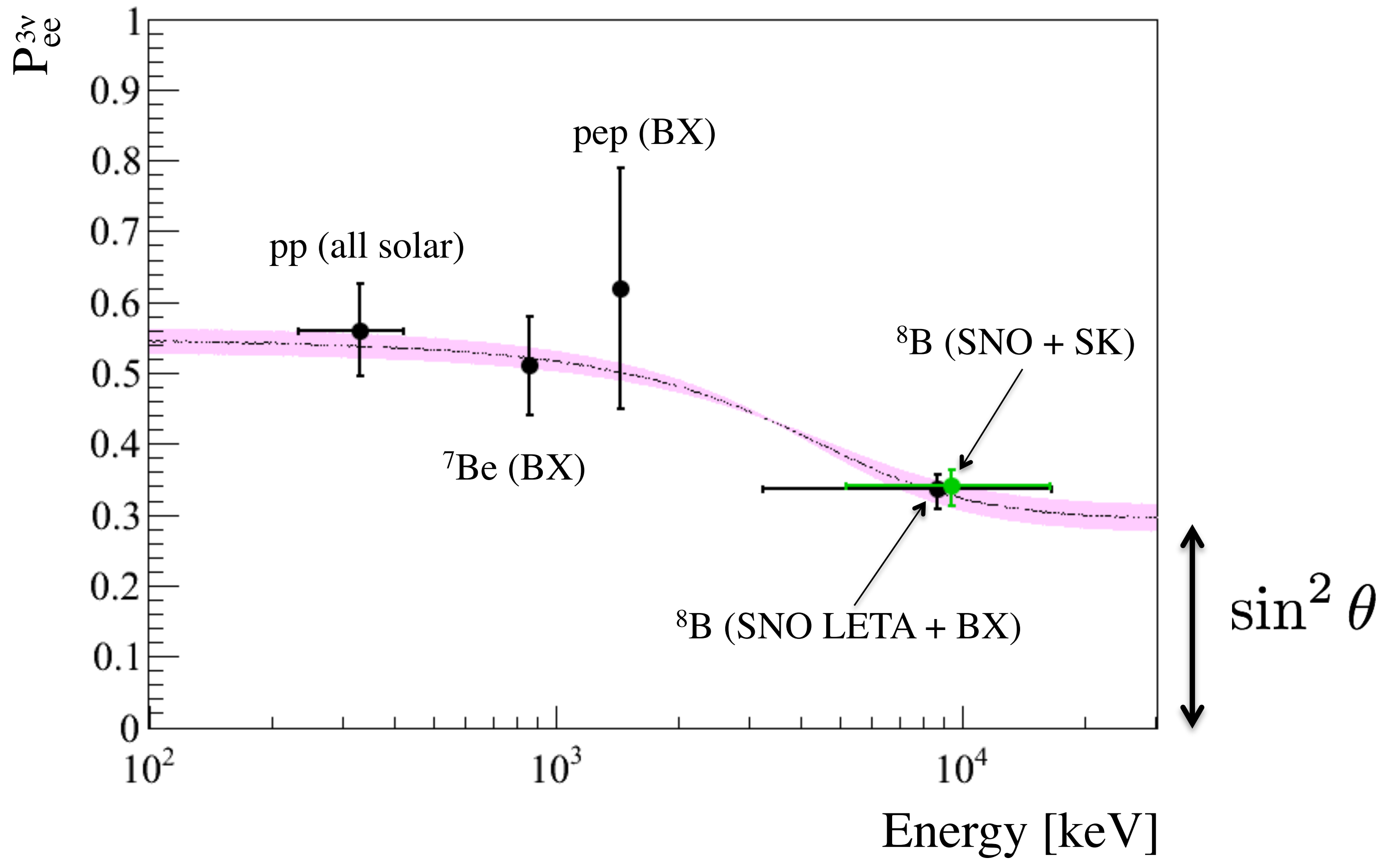
Reines&Cowan experiment ½ century later
at 170 km from Japenese reactors ...



$$\Delta m^2_{\mathrm{solar}} \simeq 8 \times 10^{-5}\ eV^2$$

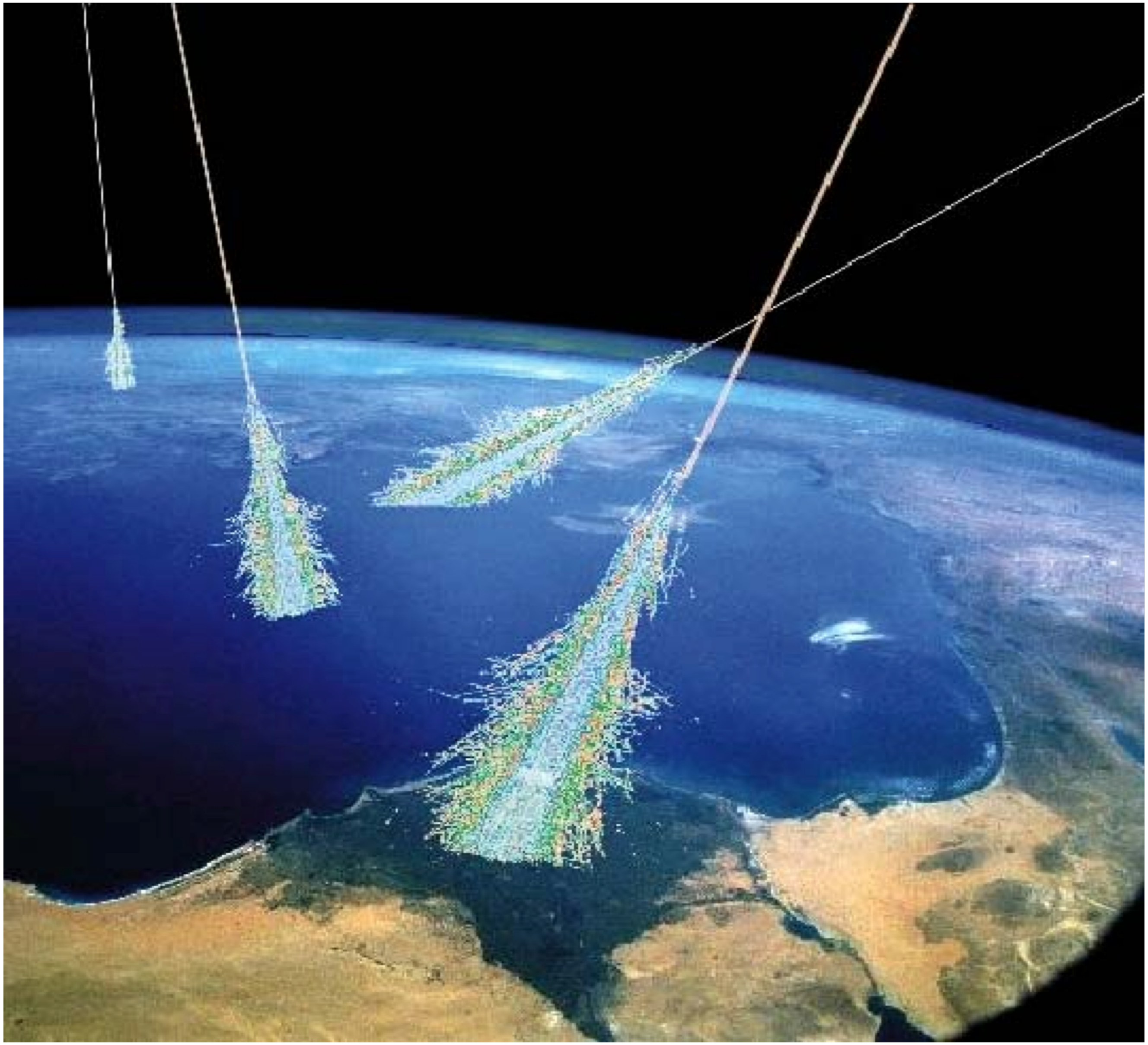
Large mixing

Solar neutrinos and MSW



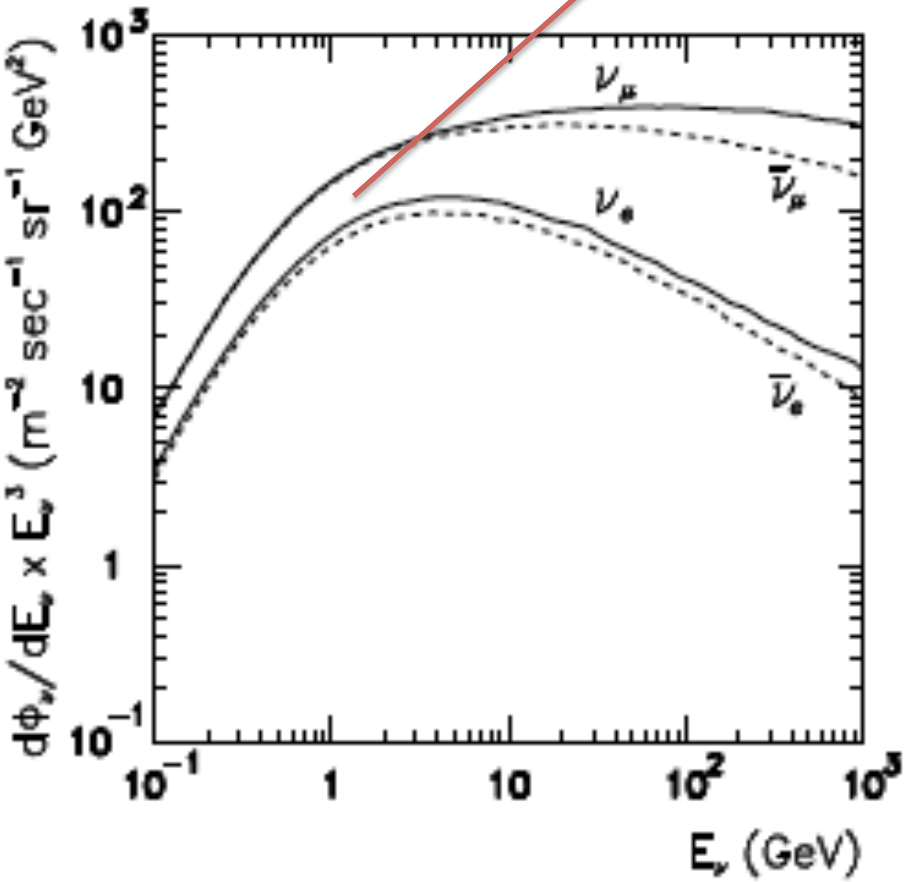
Borexino

Atmospheric Neutrinos



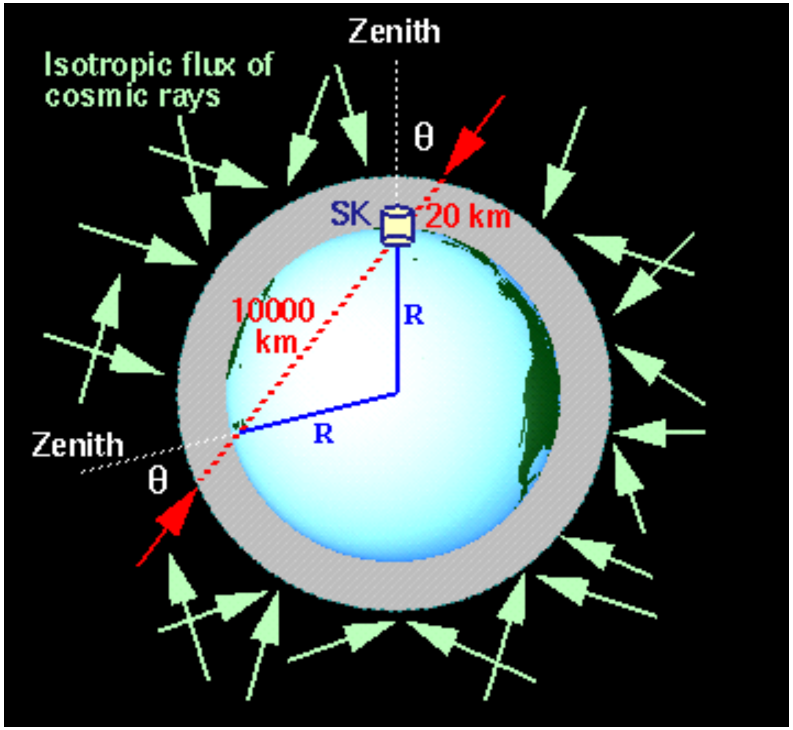
Atmospheric Neutrinos

$\nu_\mu/\nu_e \sim 2$

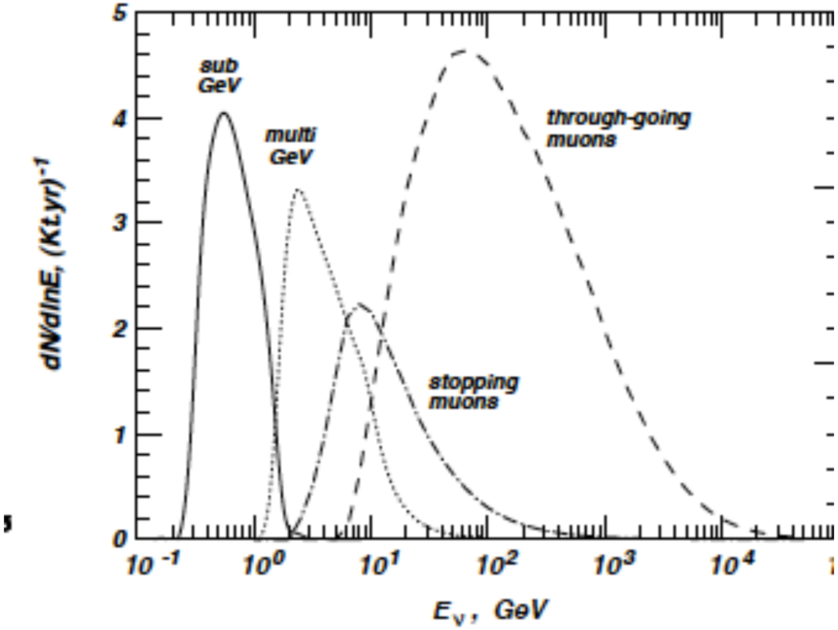


Produced in the atmosphere when primary cosmic rays collide with it, producing π, K

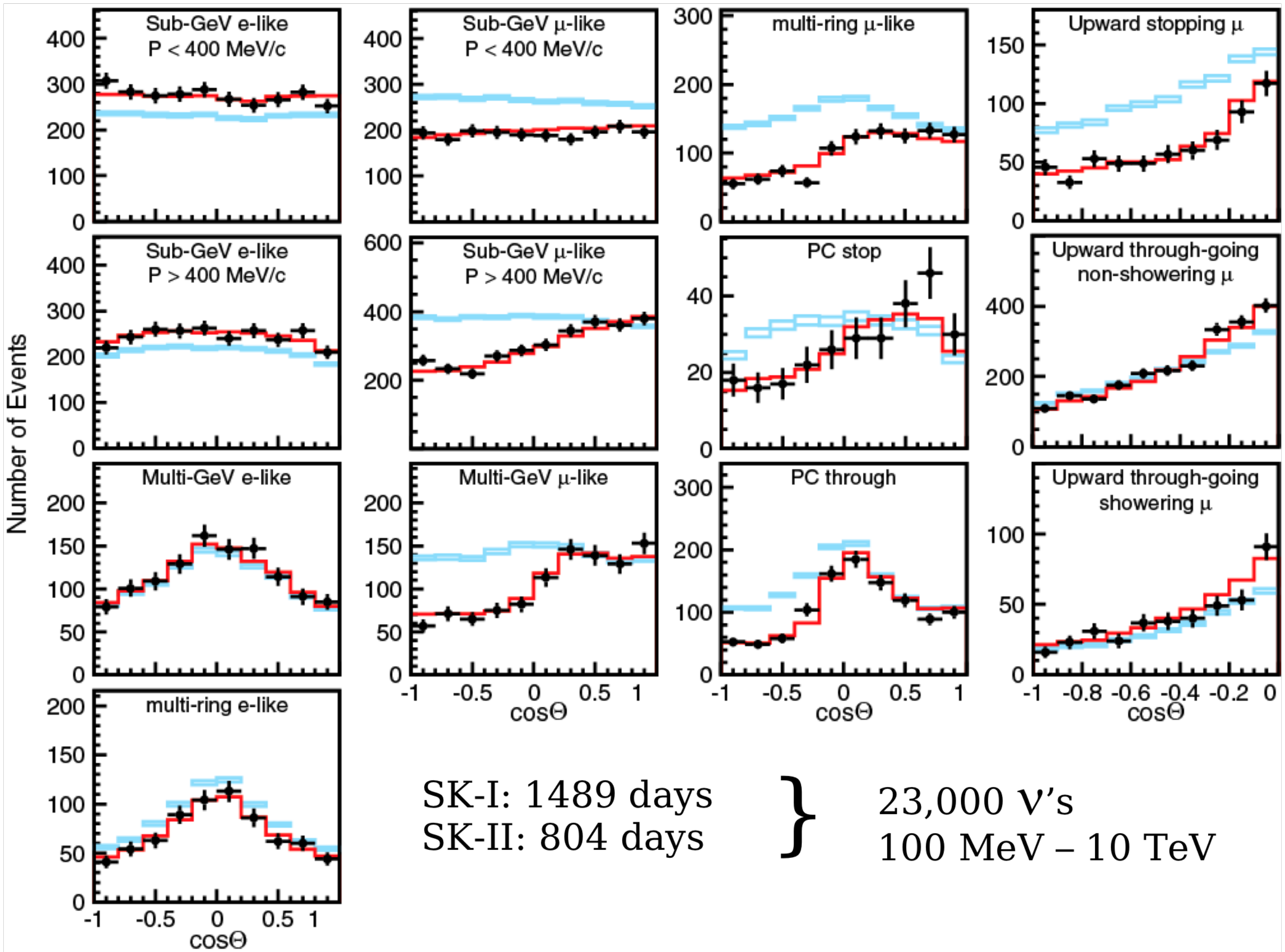
Atmospheric Neutrinos



$$L = 10 - 10^4 \text{ Km}$$



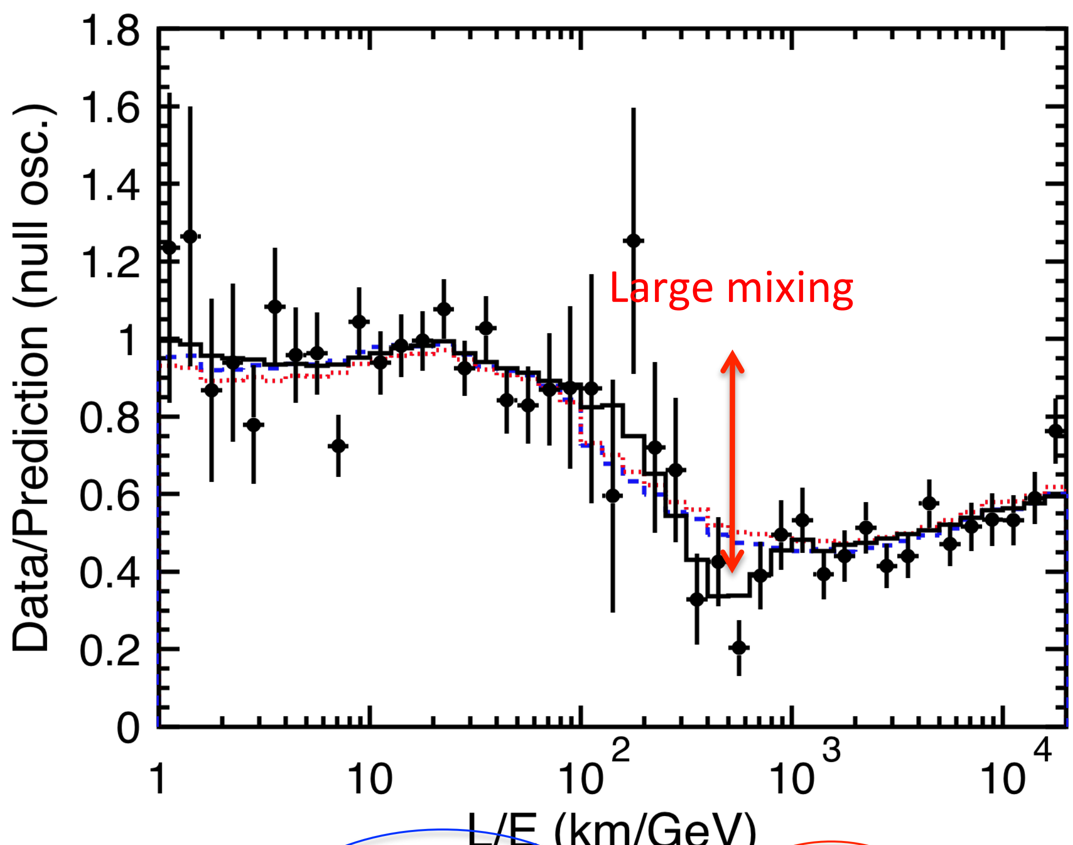
Atmospheric Neutrinos



SK-I: 1489 days
SK-II: 804 days

} 23,000 ν's
100 MeV – 10 TeV

Atmospheric Oscillation



$$\Delta m^2_{\rm atm} = 2.5 \times 10^{-3} eV^2$$

$$|\Delta m^2|^{-1} \sim \frac{O(1000Km)}{O(GeV)} \sim \frac{O(1km)}{O(MeV)}$$

Reines&Cowan experiment at 1km!

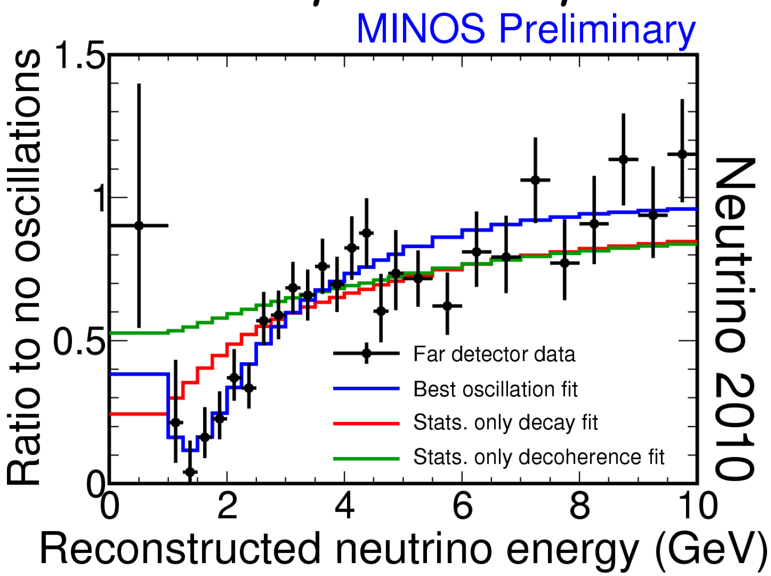
Lederman&co experiment at 1000km!

Lederman&co neutrinos oscillate with the atmospheric wave length

Pulsed neutrino beams to 700 km baselines

MINOS

$$\nu_\mu \to \nu_\mu$$

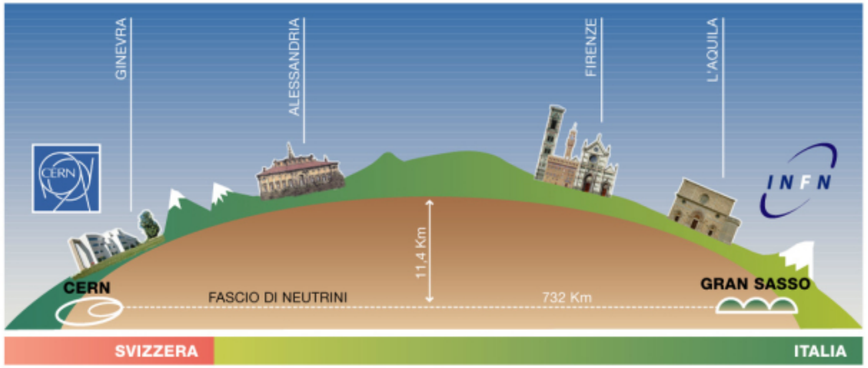


$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta_{\rm atmos} \simeq 1$$

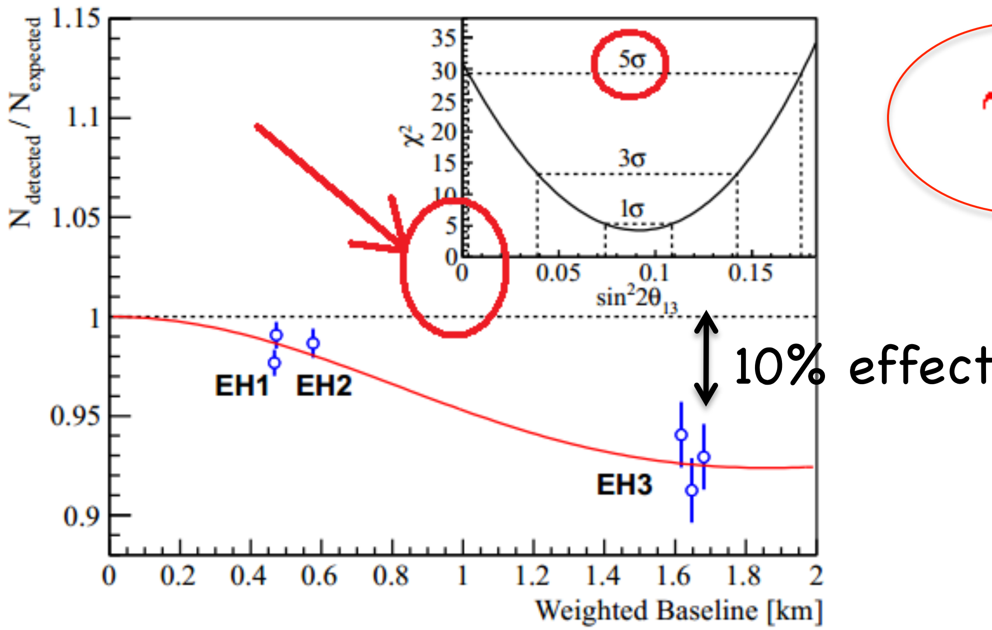
$$\nu_\mu \to \nu_\tau$$

OPERA

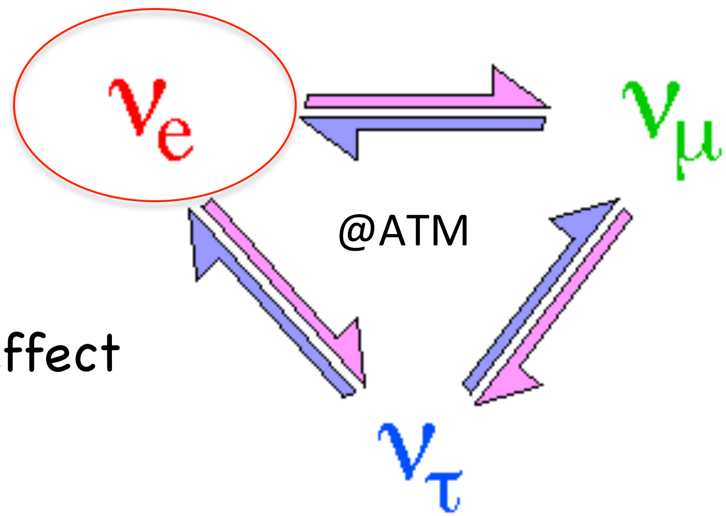


Reines&Cowan (reactor) neutrinos oscillate with atmospheric wave length

Double Chooz, Daya Bay, RENO



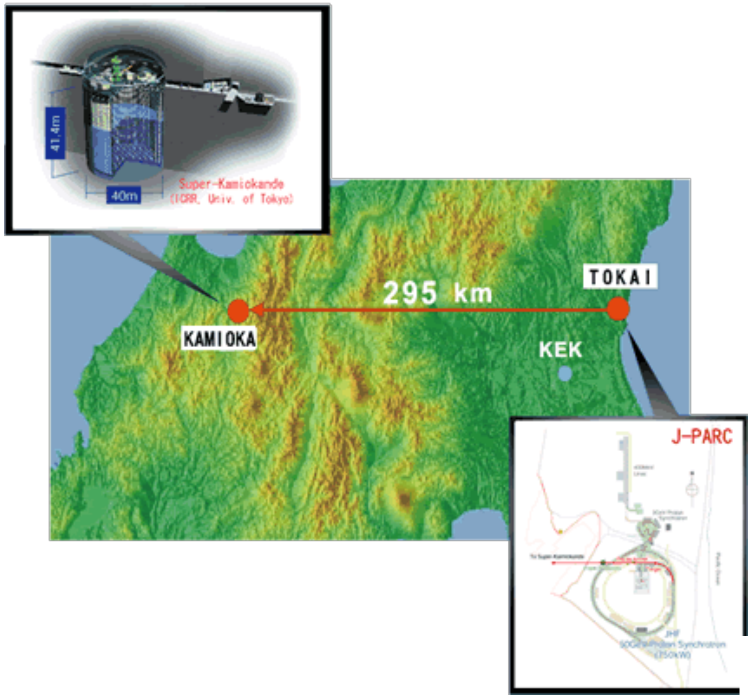
$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$

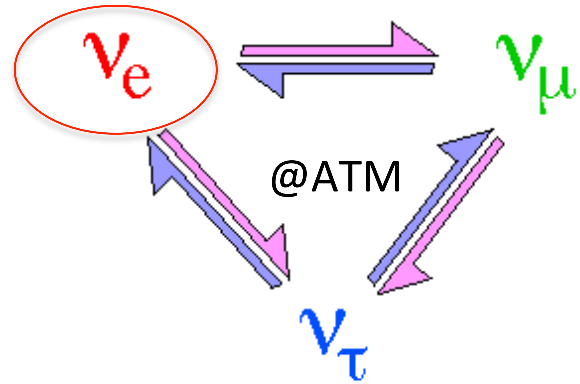


Two different wave lengths

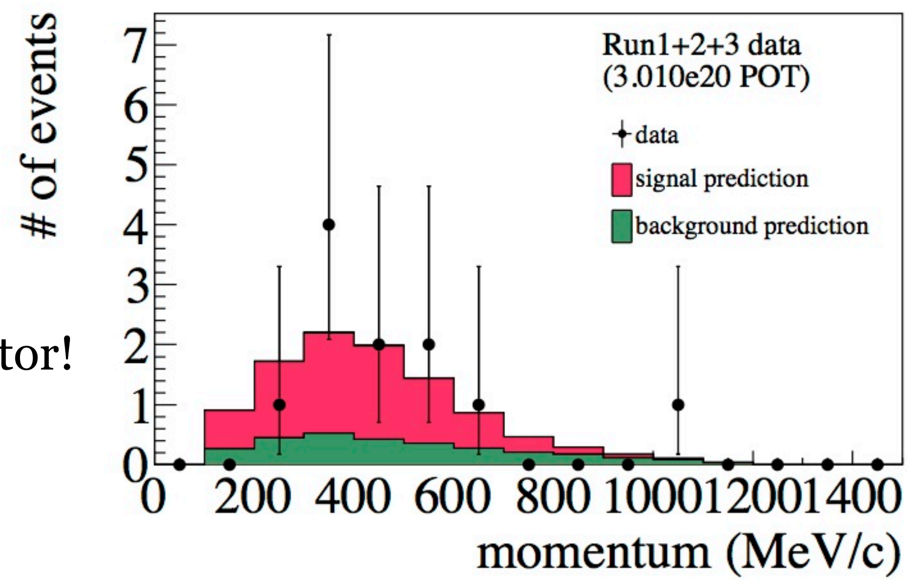
Modern copies of the influential experiment Chooz that barely missed the effect and set a limit

T2K





$$\nu_\mu \rightarrow \nu_e$$



Using the SuperKamiokande detector!

Standard 3ν scenario

$$\Delta m^2_{23} = m^2_3 - m^2_2 \equiv \Delta m^2_{atm}$$

$$\Delta m^2_{12} = m^2_2 - m^2_1 \equiv \Delta m^2_{sol}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{23}(\theta_{23}) U_{13}(\theta_{13}, \delta) U_{12}(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar and atmospheric osc. decouple as 2x2 mixing phenomena:

- hierarchy $\frac{|\Delta m^2_{atm}|}{|\Delta m^2_{sol}|} > 10$
- small θ_{13}

$$E_\nu / L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

Chooz

$$P(\nu_e \to \nu_\mu) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \approx 0$$

$$P(\nu_e \to \nu_\tau) = c^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \approx 0$$

$$P(\nu_\mu \to \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \approx 1$$

$$E_\nu / L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

$$P(\nu_e \to \nu_\mu) = 0$$

$$P(\nu_e \to \nu_\tau) = 0$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{23}}{4E} L \right)$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1$$

Experiments in the atmospheric are described approximately by 2x2 mixing with

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atm}, \theta_{atm})$$

$$E_\nu / L \sim \Delta m^2_{12} \ll \Delta m^2_{23}$$

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq c^4_{13} \left(1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{12}}{4E} L \right) \right) + s^4_{13}$$

$$E_\nu / L \sim \Delta m^2_{12} \ll \Delta m^2_{23}$$

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \qquad 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12}}{4E} L\right)$$

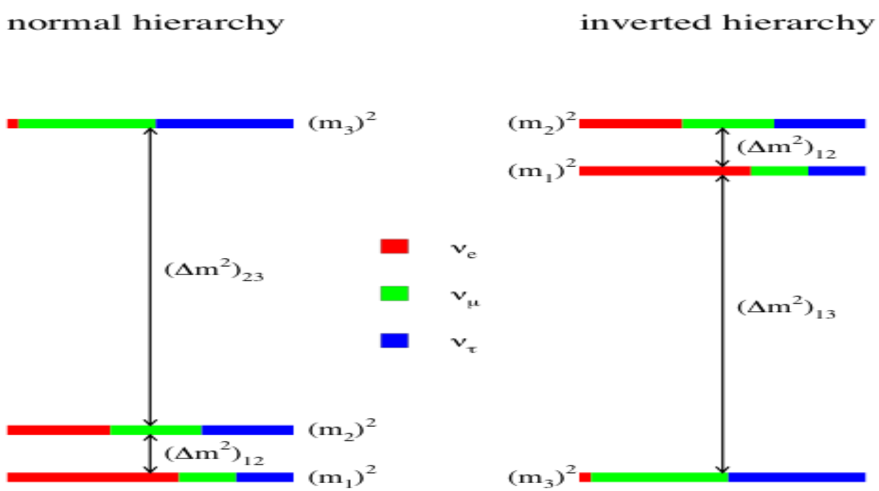
Experiments in the solar range are described approximately by 2x2 mixing with

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\rm sol}, \theta_{\rm sol})$$

The measurement of $\theta_{13} \sim 9^\circ$ implies that corrections to these approximations are sizeable and need to be included in all analyses

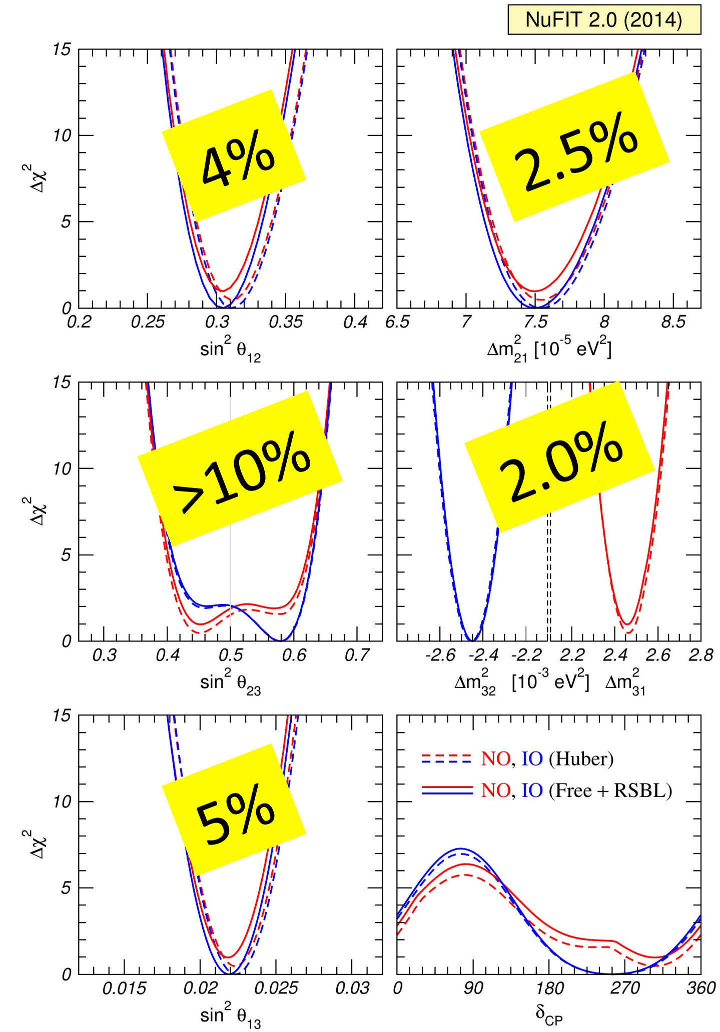
SM+3 massive neutrinos: Global Fits

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



?

$$\Delta m^2_{13} > 0 \qquad \Delta m^2_{13} < 0$$



Gonzalez-Garcia et al 1409.5439

Two state Quantum System

$$\hat{H} = E_1|\phi_1\rangle\langle\phi_1| + E_2|\phi_2\rangle\langle\phi_2|$$

@t=0 $$\Psi(0) = \frac{1}{\sqrt{2}}\left(|\phi_1\rangle + |\phi_2\rangle\right)$$

$$\Psi(t) = e^{-i\hat{H}t}\Psi(0) = \frac{1}{\sqrt{2}}\left(e^{-iE_1t}|\phi_1\rangle + e^{-iE_2t}|\phi_2\rangle\right) =$$

Probability to find the state in the same initial state:

$$|\langle\Psi(t)|\Psi(0)\rangle|^2 = \frac{1}{4}|1 + e^{-i(E_2 - E_1)t}|^2$$
$$= 1 - \sin^2\left(\frac{\Delta E\ t}{2}\right)$$