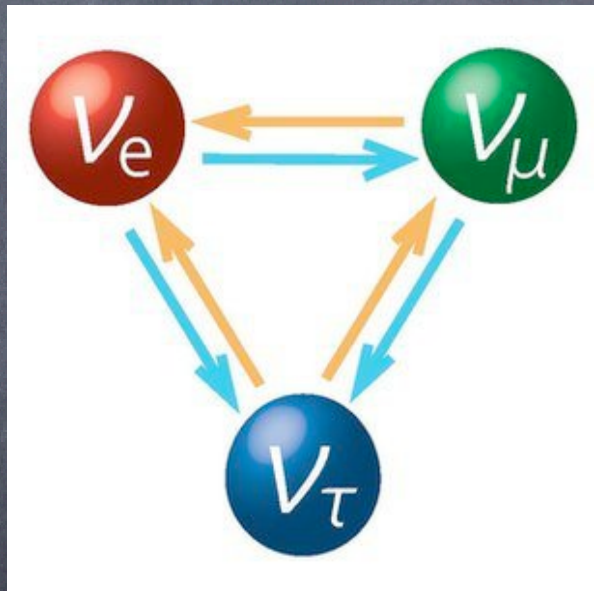
Neutrino oscillations



Neutrino mixing

- Mixing is described by the Maki-Nakagawa-Sakata (MNS) matrix:

$$\nu_{\alpha L} = \sum_k U_{\alpha i} \nu_{kL}$$

- leptonic weak charged current:

$$U = U_l^\dagger U_\nu$$

$$j_\rho^{CC\dagger} = 2 \sum_{\alpha=e,\mu,\tau} \overline{\alpha_L} \gamma_\rho \nu_{\alpha L} = 2 \sum_{\alpha=e,\mu,\tau} \sum_{k=1}^{3} \overline{\alpha_L} \gamma_\rho U_{\alpha k} \nu_{kL}$$

- NxN unitary matrix: NxN mixing parameters

→ N(N-1)/2 mixing angles + N(N+1)/2 phases

- Lagrangian invariant under global phase transformations of Dirac fields:

$$\alpha \rightarrow e^{i\theta_\alpha} \alpha, \; \nu_k \rightarrow e^{i\phi_k} \nu_k$$

$$j_\rho^{CC\dagger} \rightarrow 2 \sum_{\alpha,k} \overline{\alpha_L} e^{-i(\theta_e - \phi_1)} e^{-i(\theta_\alpha - \theta_e)} \gamma_\rho U_{\alpha k} e^{i(\phi_k - \phi_1)} \nu_{kL}$$

1 N-1 N-1

→ 2N-1 phases can be eliminated: (N-1)(N-2)/2 physical phases

Neutrino mixing

‣For Majorana neutrinos, the lagrangian is NOT invariant under global phase transformations of the Majorana fields:

$$\nu_k \to e^{i\phi_k}\nu_k \qquad \nu_{kL}^T \mathcal{C}^\dagger \nu_{kL} \to e^{2i\phi_k}\nu_{kL}^T \mathcal{C}^\dagger \nu_{kL}$$

→ only N phases can be eliminated by rephasing charged lepton fields:

$$j_\rho^{\mathrm{CC}\dagger} \to 2\sum_{\alpha,k} \overline{\alpha_L} e^{-i\theta_\alpha} \gamma_\rho U_{\alpha k}\nu_{kL}$$

N

→ N(N-1)/2 physical phases: (N-1)(N-2)/2 Dirac phases → effect in ν oscil.

(N-1) Majorana phases → relevant for 0νββ

Exercises: 1)Check number angles/phases NxN matrix
2) how many angles/phases N=2,3 ?

Neutrino mixing

- 2-neutrino mixing depends on 1 angle only (+1 Majorana phase)

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- 3-neutrino mixing is described by 3 angles and 1 Dirac (+2 Majorana) CP violating phases.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + LBL measurements	reactor disapp + LBL appearance searches	solar + KamLAND measurements

Neutrino oscillations

- flavour states are admixtures of flavor eigenstates: $$\nu_{\alpha L} = \sum_k U_{\alpha i} \nu_{kL}$$

- Neutrino evolution equation: $$-i\frac{d}{dt}|\nu\rangle = H|\nu\rangle$$

in the 2-neutrino mass eigenstates basis ν_j : $$H = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}$$

$$\rightarrow \quad |\nu_j\rangle \rightarrow e^{-iE_j t}|\nu_j\rangle$$

since neutrinos are relativistic: t = L and $$E_j \simeq p + \frac{m_j^2}{2p} \simeq p + \frac{m_j^2}{2E}$$

(equal momentum approach)

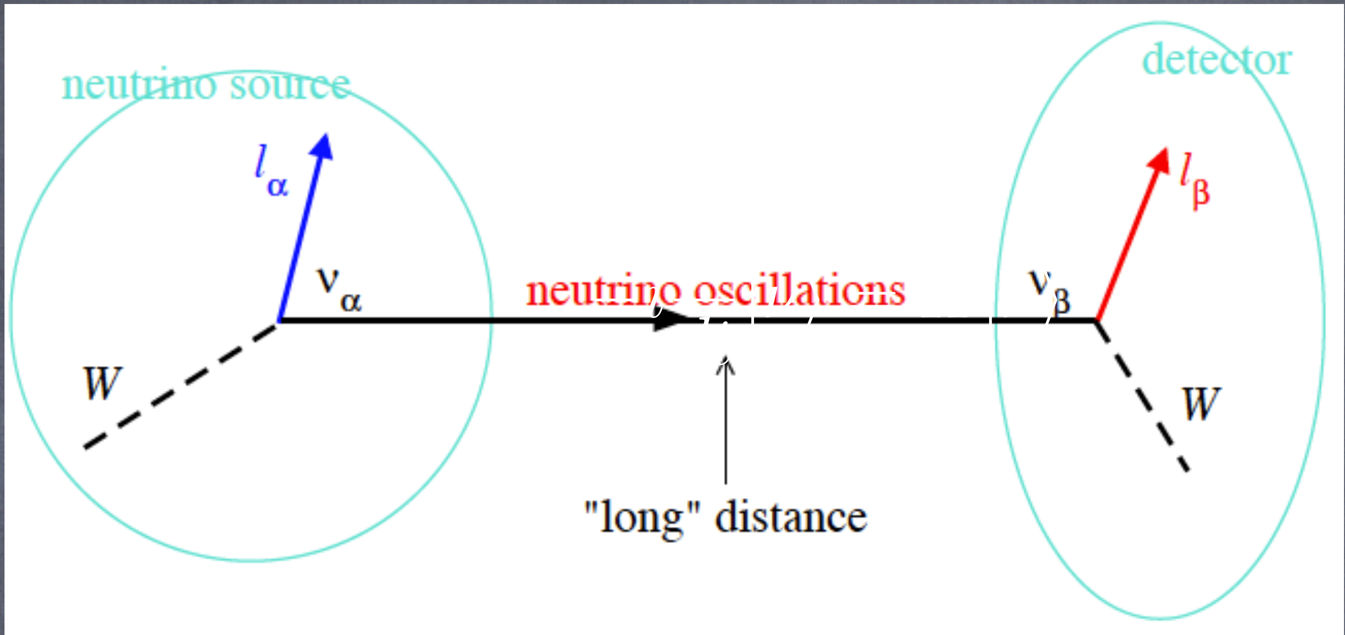
- Hamiltonian in the flavour basis:

$$H_{\text{flavour}} = U H_{\text{mass}} U^\dagger = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

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

Exercise: derive expression for H_{flavour}

Neutrino oscillations picture



Production

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle$$

coherent superposition of massive states

Propagation

$$\nu_j : e^{-iE_j t}$$

different propagation phases change ν_j composition

Detection

$$\langle\nu_\beta| = \sum_j \langle\nu_j|U_{\beta j}$$

projection over flavour eigenstates

Neutrino oscillations

Neutrino oscillation amplitude:

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta} = \langle \nu_\beta(t) | \nu_\alpha(0) \rangle = \sum_j \langle \nu_\beta | \nu_j(t) \rangle \langle \nu_j(t) | \nu_j(0) \rangle \langle \nu_j(0) | \nu_\alpha \rangle$$

$$= \sum_j U_{\beta j} e^{-i \frac{m_j^2}{2E}} U^*_{\alpha j}$$

Neutrino oscillation probability: $$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_j U^*_{\alpha j} U_{\beta j} e^{-i \frac{m_j^2}{2E}} \right|^2$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} Re(U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}) \sin^2 \left(\frac{\Delta m^2_{ij} L}{4E} \right) +$$

$$+2 \sum_{i>j} Im(U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}) \sin \left(\frac{\Delta m^2_{ij} L}{2E} \right)$$

Exercise: derive general formula for oscillation probability

General properties of neutrino oscillations

- Conservation of probability: $$\sum_{\beta} P(\nu_\alpha \to \nu_\beta) = 1$$
- For antineutrinos: U →U*
- Neutrino oscillations violate flavour lepton number conservation (expected from mixing) but conserve total lepton number
- Complex phases in the mixing matrix induce CP violation:

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$$

- Neutrino oscillations do not depend on the absolute neutrino mass scale and Majorana phases.
- Neutrino oscillations are sensitive only to mass squared differences:

$$\Delta m^2_{kj} = m^2_k - m^2_j$$

2-neutrino oscillations

- 2-neutrino mixing matrix:

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- 2-neutrino oscillation probability (α≠β):

$$P(\nu_\alpha \to \nu_\beta) = \left| U_{\alpha 1} U^*_{\beta 1} + U_{\alpha 2} U^*_{\beta 2} e^{-i \frac{\Delta m^2_{21} L}{2E}} \right|^2$$

$$= \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Exercise

- The oscillation phase:

$$\phi = \frac{\Delta m^2_{21} L}{4E} = 1.27 \frac{\Delta m^2_{21}[eV^2] L[km]}{E[GeV]}$$

Exercise

→ short distances, $\phi \ll 1$: oscillations do not develop, $P_{\alpha\beta} = 0$

→ long distance, $\phi \sim 1$: oscillations are observable

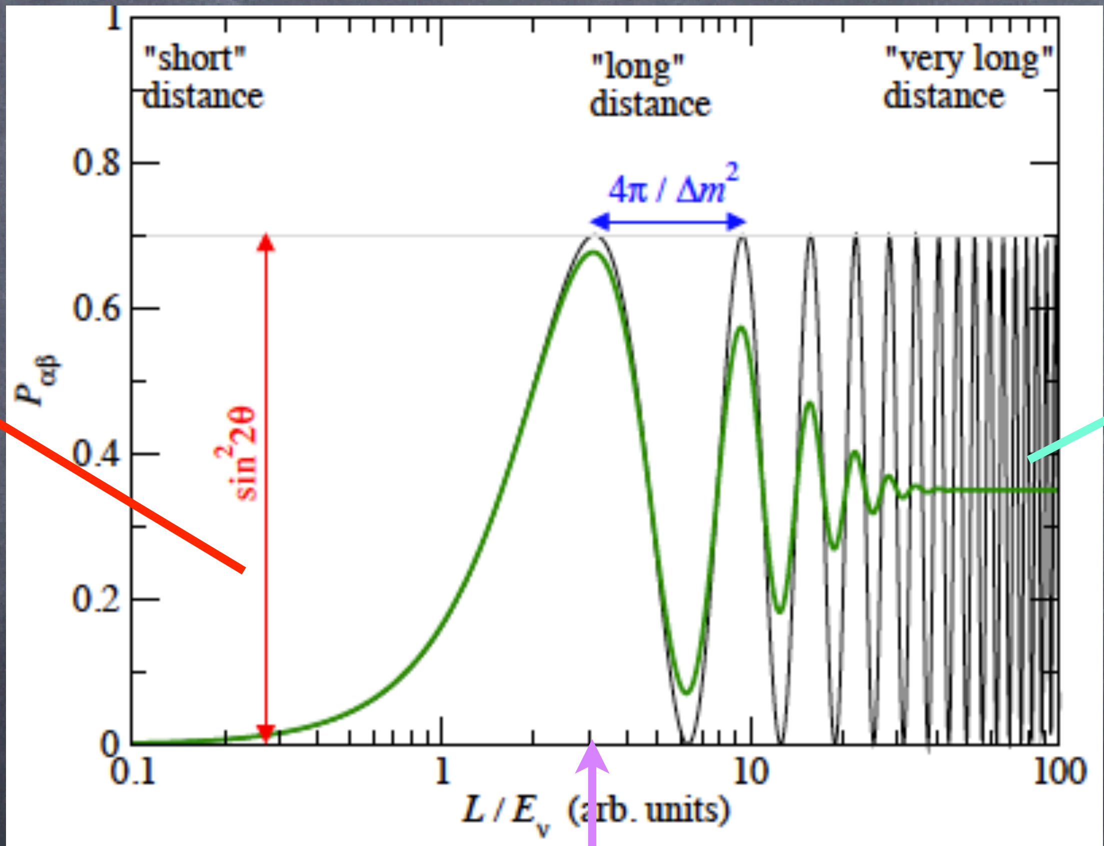
→ very long distances, $\phi \gg 1$: oscillations are averaged out:

$$P_{\alpha\beta} \simeq \frac{1}{2} \sin^2(2\theta)$$

2-neutrino oscillation probability

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

oscillation amplitude



averaged oscillations

first oscillation maximum:

oscillation length:

$$L_{osc} = \frac{4\pi E}{\Delta m^2}$$

Appearance vs disappearance experiments

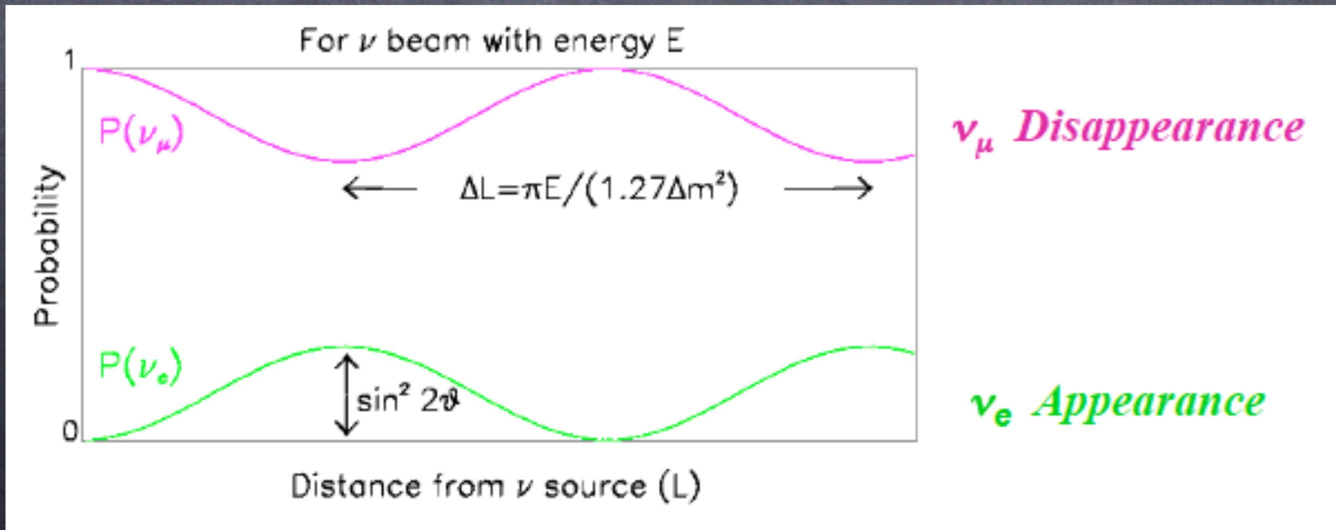
- appearance experiments: $$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

  $\alpha \neq \beta$

→ appearance of a neutrino of a new flavour β in a beam of ν_α

- disappearance experiments: $$P_{\alpha\alpha} = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

→ measurement of the survival probability of a neutrino of given flavour

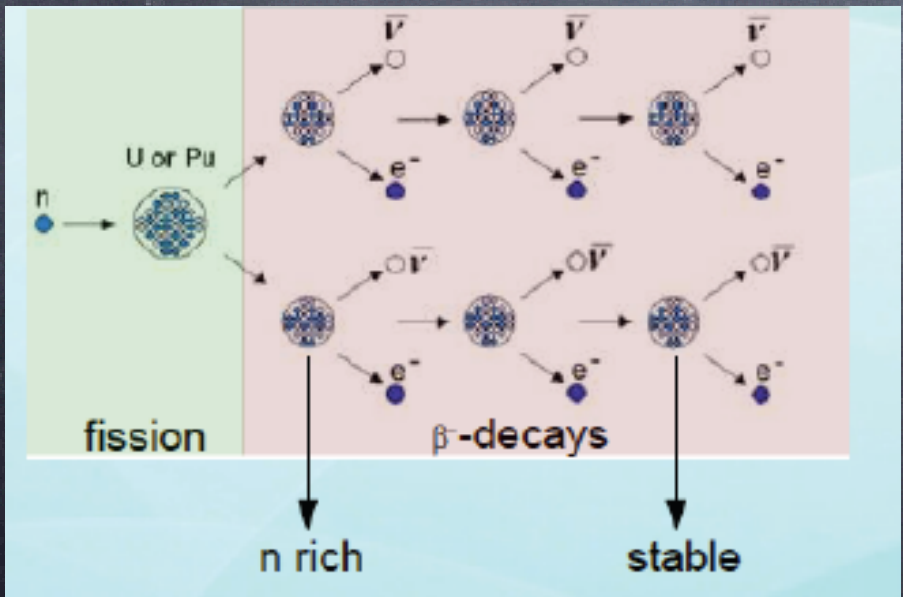


Example for 2-neutrino oscillations in vacuum: reactor experiment

Production and detection of reactor neutrinos

Emission: β-decay of fission products

- ~ 6 $\bar{\nu}_e$/ fission
- ~10^{21} $\bar{\nu}_e$/s for a 1 GW_{el} reactor



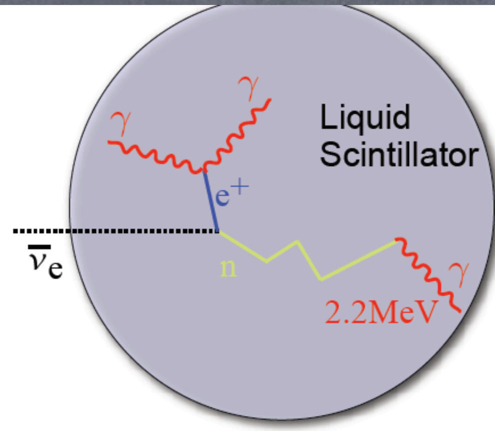
Inverse beta decay

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

207 μs

$$n + p \rightarrow d + \gamma$$

Scintillator is both target and detector



- Distinct two step process:
  - prompt event: positron

    $E_{\bar{\nu}_e} \simeq E_{prompt} + 0.8MeV$
  - delayed event: neutron capture after ~207μs
    - 2.2 MeV gamma

Delayed coincidence: good background rejection

Detection reaction cross section ~10^{-43} cm^2
→ typical ν detector masses: many 10 tons - some ktons

1ton target @ 25m of 1GW_{el} reactor gives ~4600 int./day → 1% stat within 2 days

The CHOOZ reactor experiment

- 2ν approx (Δm², θ):

$$P_{ee} = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

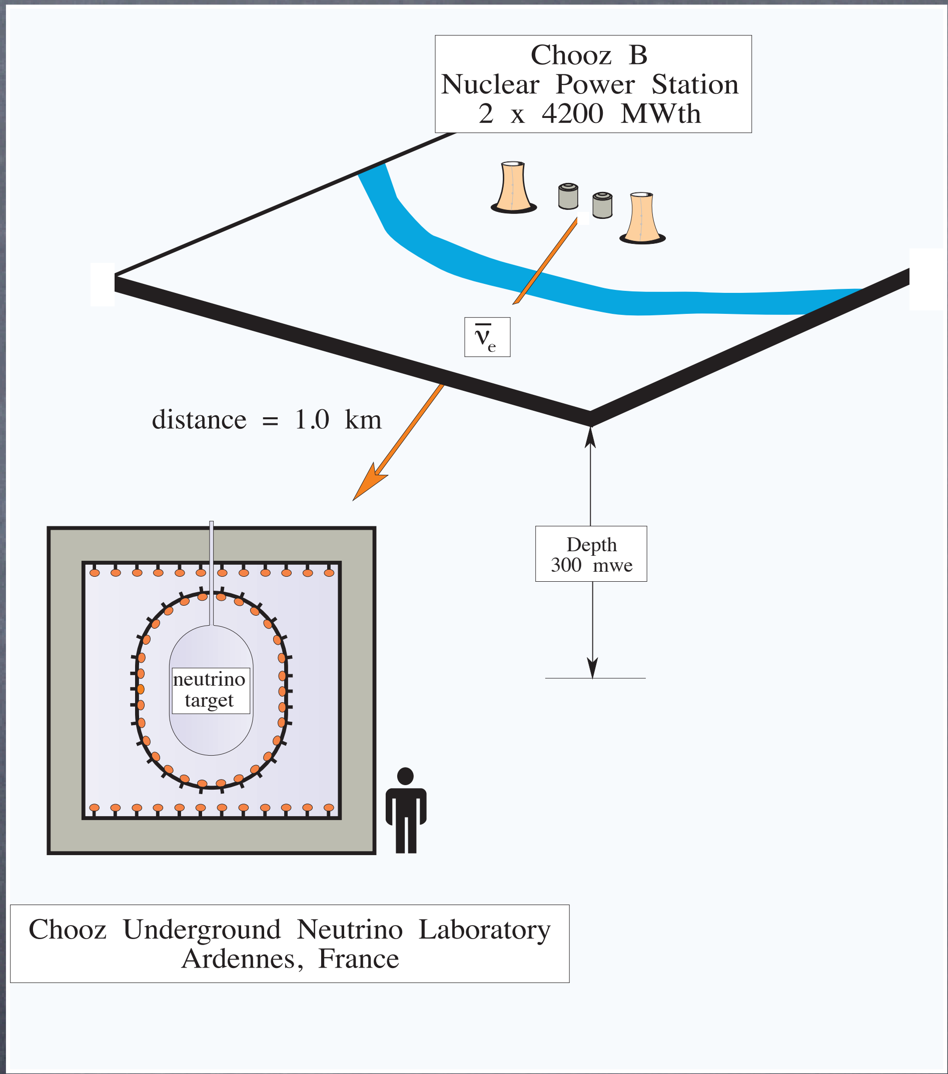
- L = 1 km, E~MeV

→ sensitive to $\Delta m^2 \sim 10^{-3}$ eV²

- non-observation of ν_e disappearance:

R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

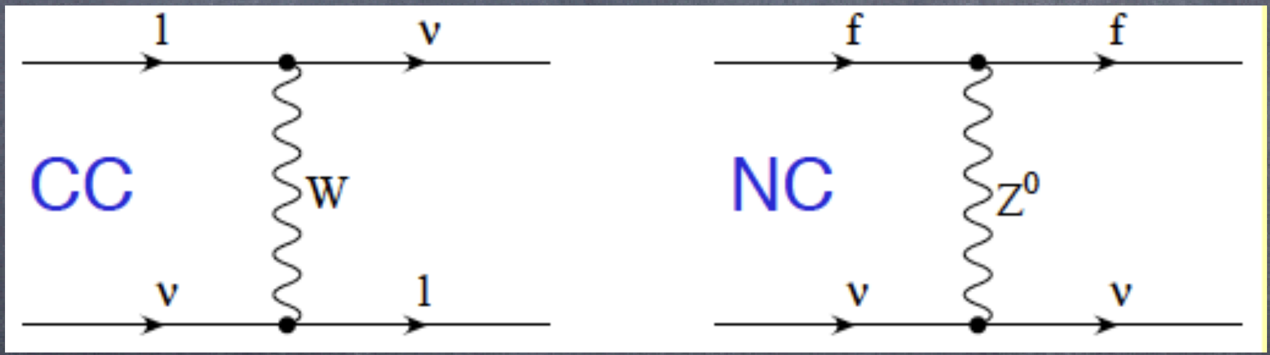
ratio between measured and expected number of events



Matter effects on neutrino oscillations

- When neutrinos pass trough matter, the interactions with the particles in the medium induce an effective potential for the neutrinos.

[→ the coherent forward scattering amplitude leads to an index of refraction neutrinos. L. Wolfenstein, 1978]



→ modifies the mixing between flavor states and propagation states as well as the eigenvalues of the Hamiltonian, leading to a different oscillation probability wrt vacuum.

Effective matter potential

- Effective four-fermion interaction Hamiltonian (CC+NC)

$$H_{\rm int}^{\nu_\alpha} = \frac{G_F}{\sqrt{2}}\overline{\nu_\alpha}\gamma_\mu(1-\gamma_5)\nu_\alpha \sum_j \underbrace{\bar{f}\gamma^\mu(g_V^{\alpha,f} - g_A^{\alpha,f}\gamma_5)f}_{J^{\mu\alpha}_{\rm matt}}$$

in ordinary matter: f=e⁻,p,n

To obtain the matter-induced potential we integrate over f-variables:

for a | non-relativistic | unpolarised | neutral | medium:

$$\langle \bar{f}\gamma^\mu f\rangle = \frac{1}{2}N_f\delta_{\mu,0}$$

$$\langle f\gamma_5\gamma^\mu f\rangle = 0$$

$$N_e = N_p$$

$$J^{\mu\alpha}_{\rm matt} = \frac{1}{2}\left[N_e(g_V^{\alpha,e} + g_V^{\alpha,p}) + N_n g_V^{\alpha,n}\right]$$

Effective matter potential

$$J^{\mu\alpha}_{\rm matt} = \frac{1}{2}\left[N_e(g_V^{\alpha,e} + g_V^{\alpha,p}) + N_n g_V^{\alpha,n}\right]$$

g_V	e^-	p	n
ν_e	$2\sin^2\Theta_W + \frac{1}{2}$	$-2\sin^2\Theta_W + \frac{1}{2}$	$-\frac{1}{2}$
$\nu_{\mu,\tau}$	$2\sin^2\Theta_W - \frac{1}{2}$	$-2\sin^2\Theta_W + \frac{1}{2}$	$-\frac{1}{2}$

$$J^{\mu\alpha}_{\rm matt} = (N_e - \frac{1}{2}N_n, -\frac{1}{2}N_n, -\frac{1}{2}N_n)$$

$$\Rightarrow \quad V_{\rm matt} = \sqrt{2}G_F\,{\rm diag}(N_e - \frac{1}{2}N_n, -\frac{1}{2}N_n, -\frac{1}{2}N_n)$$

- only νe are sensitive to CC (no μ,τ in ordinary matter)
- NC has the same effect for all flavours → it has no effect on evolution

  (however it can be important in presence of sterile neutrinos)
- for antineutrinos the potential has opposite sign

2-neutrino oscillations in matter

- 2-neutrino Hamiltonian in vacuum (mass basis): $$H^{\rm vac} = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}$$

- In the flavour basis, where effective matter potential is diagonal:

$$H_f^{\rm matt} = H_f^{\rm vac} + V_{\rm eff} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + V_{CC} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

$$V_{\rm CC} = \sqrt{2} G_F N_e$$

Diagonalizing the Hamiltonian, we identify the mixing angle and mass splitting in matter:

$$H_f^{\rm matt} = \frac{\Delta M^2}{4E}\begin{pmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{pmatrix}$$

Exercise: calculate θ_M and ΔM^2

In general: $N_e = N_e(x)$, so θ_M and ΔM^2 will be function of x as well

→ however, in some cases analytical solutions can be obtained

2-ν oscillations in constant matter

- If N_e is constant (good approximation for oscillations in the Earth crust):

  → θ_M and ΔM^2 are constant as well

  → we can use vacuum expression for oscillation probability, replacing "vacuum" parameters by "matter" parameters:

$$P_{\alpha\beta} = \sin^2(2\theta_M)\sin^2\left(\frac{\Delta M^2 L}{4E}\right)$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} \qquad A = \frac{2EV}{\Delta m^2}$$

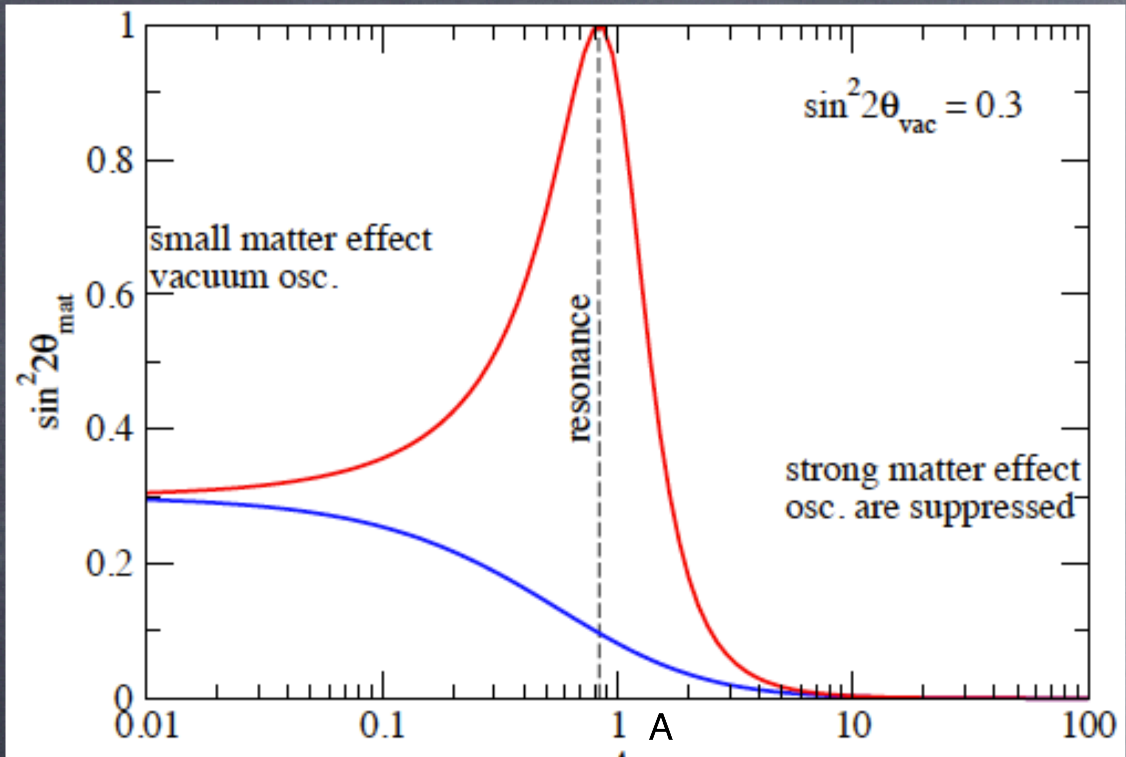
$$\Delta M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

There is a resonance effect for A = cos2θ → MSW effect

Wolfenstein, 1978

Mikheyev & Smirnov, 1986

2-ν oscillations in constant matter



mixing angle in matter:

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

$$A = \frac{2EV}{\Delta m^2}$$

- A << cos2θ, small matter effect → vacuum oscillations: $\theta_M = \theta$
- A >> cos2θ, matter effects dominate → oscillations are suppressed: $\theta_M \approx 0$
- A = cos2θ,resonance takes place→ maximal mixing $\theta_M \approx \pi/4$

→ resonance condition is satisfied for neutrinos for $\Delta m^2 > 0$

for antineutrinos for $\Delta m^2 < 0$

Solar neutrinos: the MSW effect

- neutrino oscillations in matter were first discussed by Wolfenstein, Mikheyev and Smirnov (MSW effect)

- electron neutrino is born at the center of the Sun as:

$$|\nu_e\rangle = \cos\theta_M|\nu_1^m\rangle + \sin\theta_M|\nu_2^m\rangle$$

→ ν_1^m and ν_2^m evolve adiabatically until the solar surface and propagate in vacuum from the Sun to the Earth:

$$P(\nu_e \to \nu_e) = P_{e1}^{\mathrm{prod}} P_{1e}^{\mathrm{det}} + P_{e2}^{\mathrm{prod}} P_{2e}^{\mathrm{det}}$$

$$P_{e1}^{\mathrm{prod}} = \cos^2\theta_M\,, \qquad P_{1e}^{\mathrm{det}} = \cos^2\theta$$

$$P_{e2}^{\mathrm{prod}} = \sin^2\theta_M\,, \qquad P_{2e}^{\mathrm{det}} = \sin^2\theta$$

→ $$\boxed{P_{ee} = \cos^2\theta_M\cos^2\theta + \sin^2\theta_M\sin^2\theta}$$

Solar neutrinos: the MSW effect

$$P_{ee} = \cos^2\theta_M \cos^2\theta + \sin^2\theta_M \sin^2\theta$$

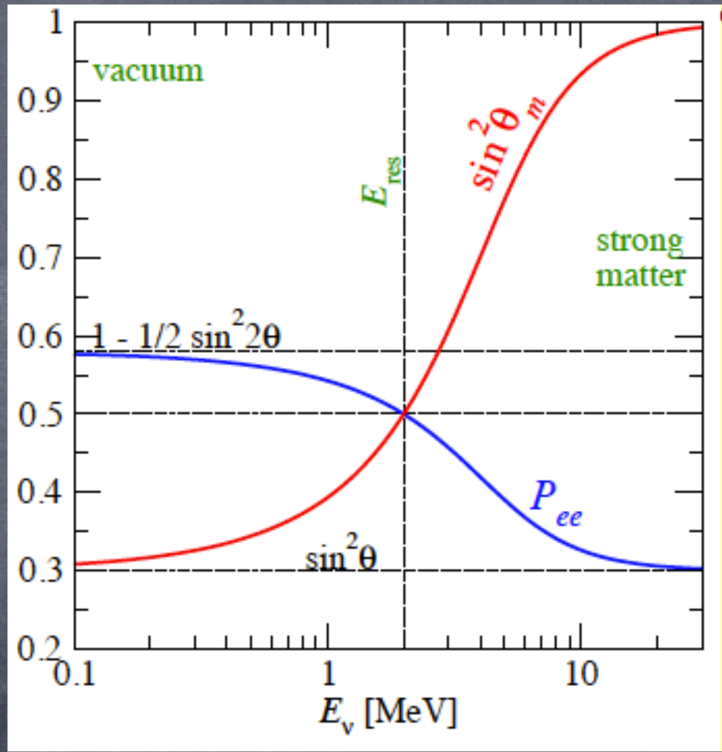
- In the center of the Sun:

$$A = \frac{2EV}{\Delta m^2} \simeq 0.2 \left(\frac{E_\nu}{\text{MeV}}\right)\left(\frac{8\times 10^{-5}\text{eV}^2}{\Delta m^2}\right)$$

Exercise: check this formula: $n_e^c \sim 100$ mol/cm^3

and resonance occurs for A = cos(2θ) = 0.4

→ $E_{res} \approx 2$ MeV



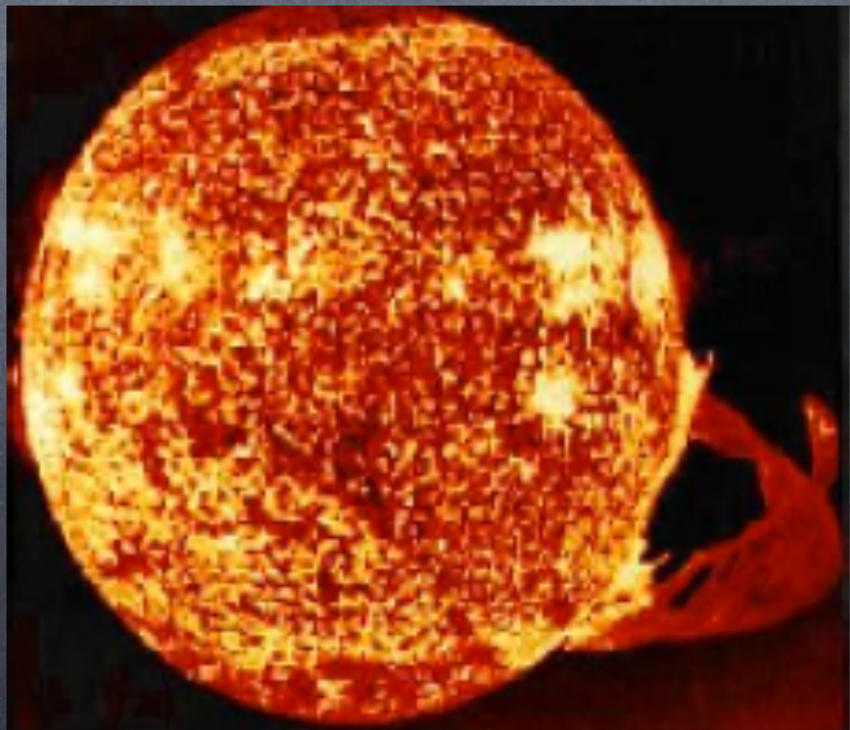
- For E < 2 MeV → vacuum osc: $\theta_M = \theta$

$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta$$

- For E > 2 MeV → strong matter effect: $\theta_M = \pi/2$ $\quad P_{ee} = \sin^2\theta$

→ P_{ee} (E) will be crucial to understand solar neutrino data

Example for 2-neutrino oscillations in matter: solar neutrinos



Solar neutrinos

* produced in nuclear reactions in the core of the Sun:

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + \gamma$$

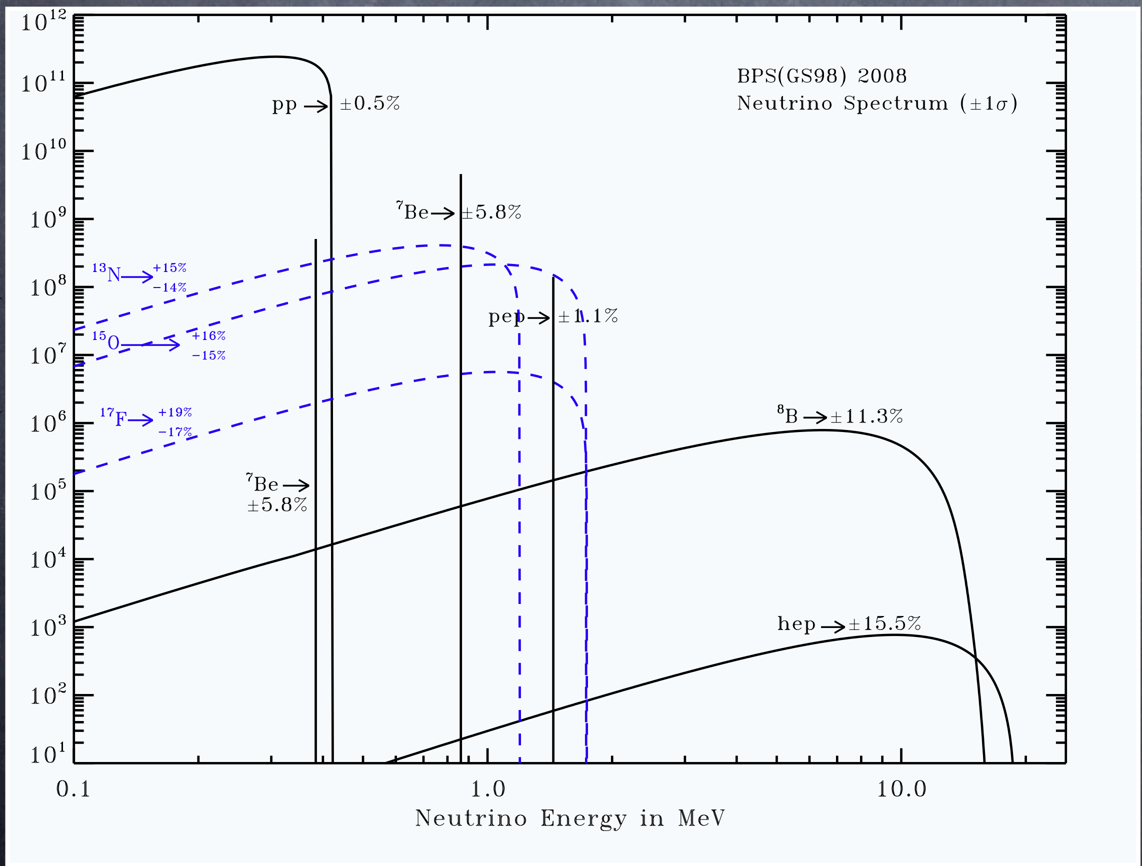
pp cycle

CNO

Reaction	source	Flux ($cm^{-2}s^{-1}$)
$p\,p \rightarrow d\,e^+\,\nu$	pp	$5.97(1 \pm 0.006)\times10^{10}$
$p\,e^-\,p \rightarrow d\,\nu$	pep	$1.41(1 \pm 0.011)\times10^{8}$
${}^3He\,p \rightarrow {}^4He\,e^+\,\nu$	hep	$7.90(1\pm 0.15)\times10^{3}$
${}^7Be\,e^- \rightarrow {}^7Li\,\nu\,\gamma$	${}^7Be$	$5.07(1 \pm 0.06)\times10^{9}$
${}^8B \rightarrow {}^8Be^*\,e^+\,\nu$	${}^8B$	$5.94(1 \pm 0.11)\times10^{6}$
${}^{13}N \rightarrow {}^{13}C\,e^+\,\nu$	${}^{13}N$	$2.88(1 \pm 0.15)\times10^{8}$
${}^{15}O \rightarrow {}^{15}N\,e^+\,\nu$	${}^{15}O$	$2.15(1 \pm {}^{0.17}_{0.16})\times 10^{8}$
${}^{17}F \rightarrow {}^{17}O\,e^+\,\nu$	${}^{17}F$	$5.82(1 \pm {}^{0.19}_{0.17})\times10^{6}$

ν fluxes

SSM predictions



ν energy spectra

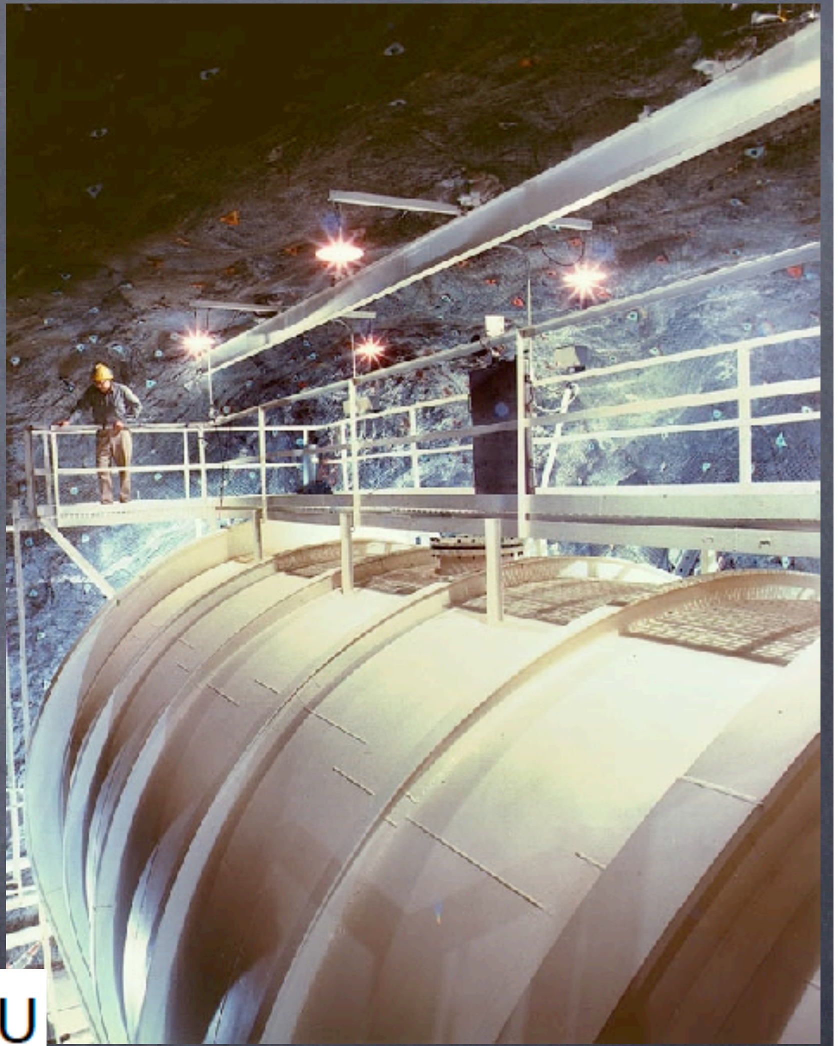
Radiochemical solar experiments

Homestake (Cl) experiment: 1967-2002

- gold mine in Homestake (South Dakota)
- 615 tons of perchloro-ethylene (C_2Cl_4)
- detection process (radiochemical)

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

$E_{th} = 0.814$ MeV



- only 1/3 of SSM prediction detected:

$$R_{Cl}^{SSM} = 8.12 \pm 1.25 \text{ SNU}$$

$$R_{Cl} = 2.56 \pm 0.16 \text{ (stat.)} \pm 0.16 \text{ (syst.) SNU}$$

Gallium radiochemical experiments:

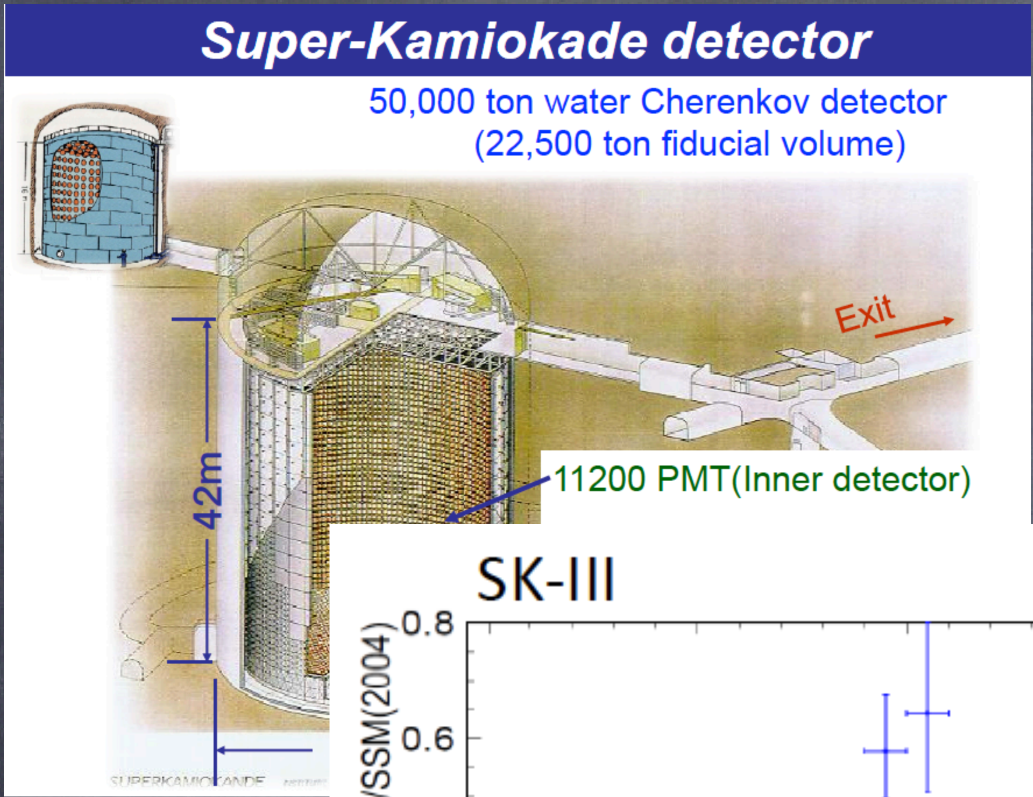
$$R_{SAGE} = 66.9 \pm 3.9 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

$$R_{GALLEX/GNO} = 69.3 \pm 4.1 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

$$R_{Ga}^{SSM} = 126.2 \pm 8.5 \text{ SNU}$$

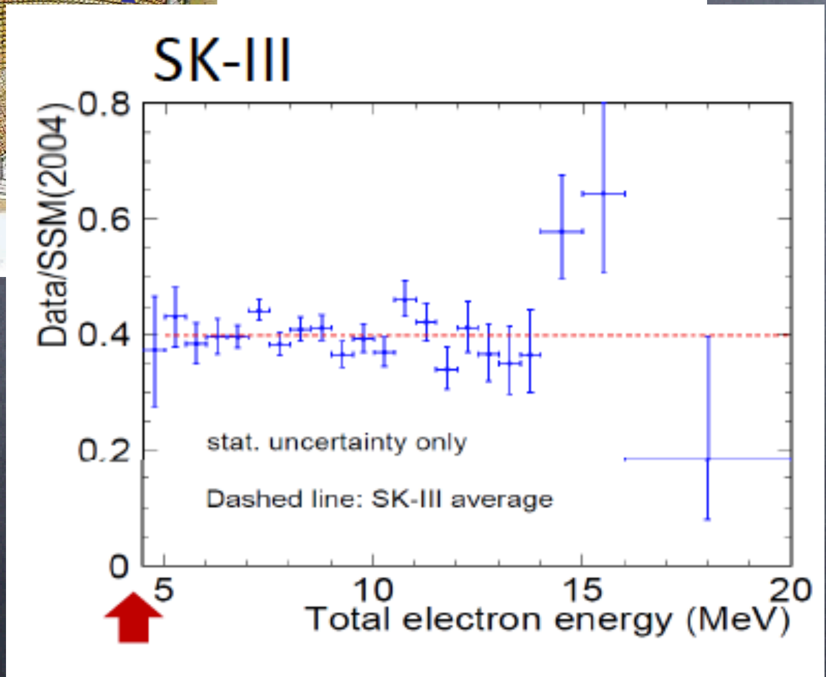
→ 50% deficit

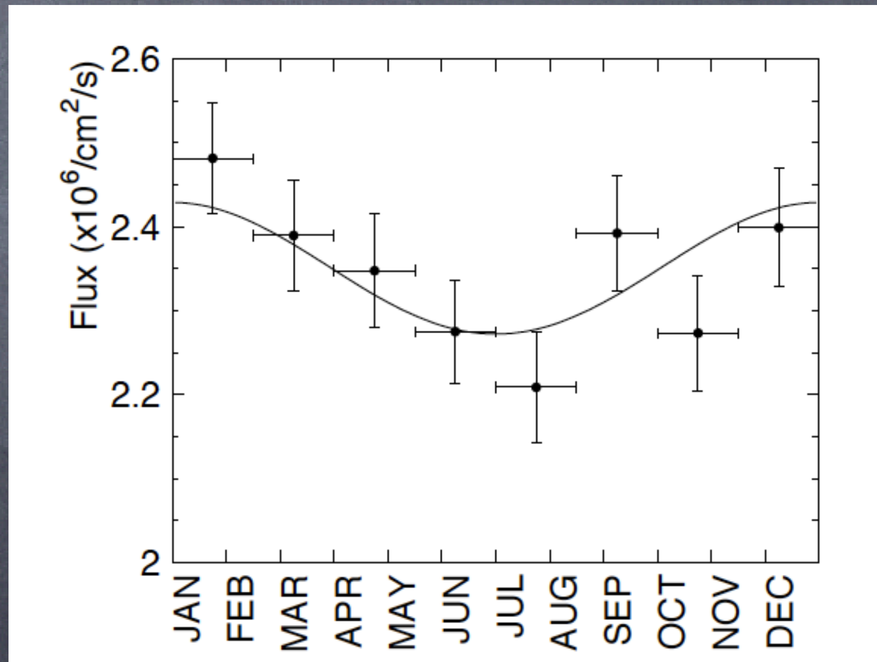
Solar neutrinos in Super-Kamiokande



- water cherenkov detector
- sensitive to all neutrino flavors:

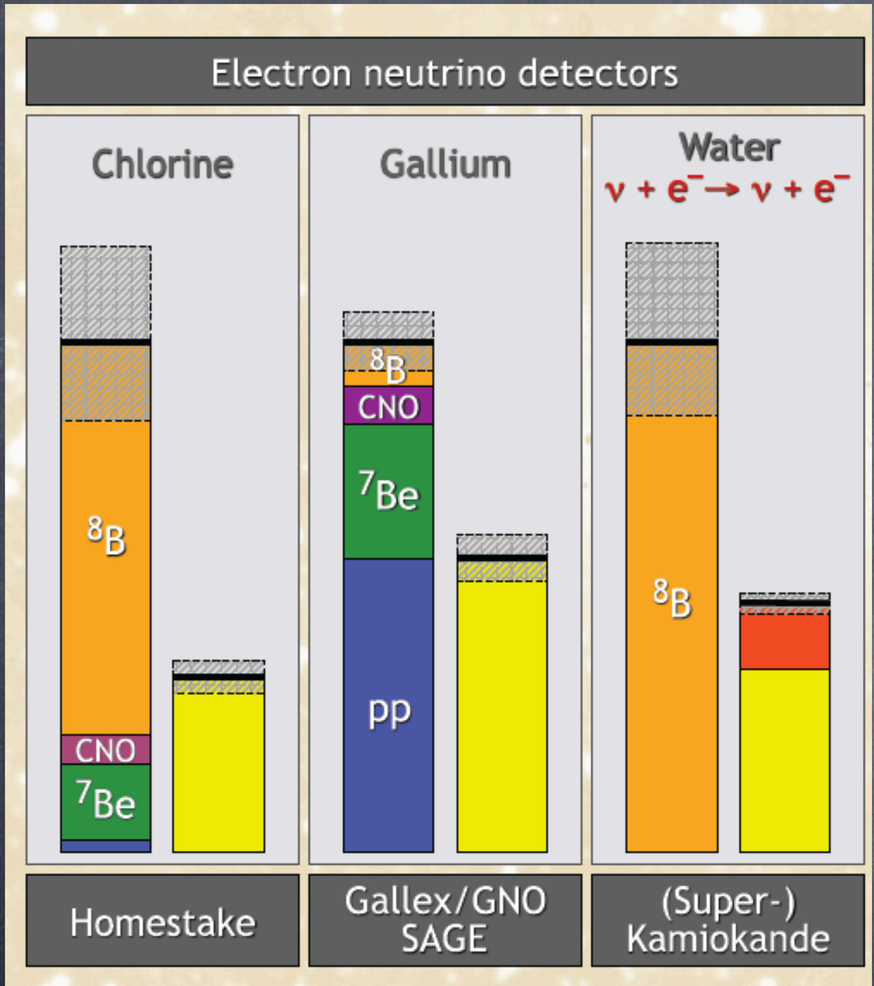
  $\nu_x\ e^- \rightarrow \nu_x\ e^-$
- threshold energy ~ 4-5 MeV
- real-time detector: (E, t)





➡ Super-Kamiokande detects less neutrinos than expected according to the SSM (40%)

The solar neutrino problem



~30% ~50% ~40%

➡ All the experiments detect less neutrinos than expected (30-50%)

Why the deficit observed is different?

‣different type of neutrinos observed

→ radiochemical: ν_e while Super-K: ν_α

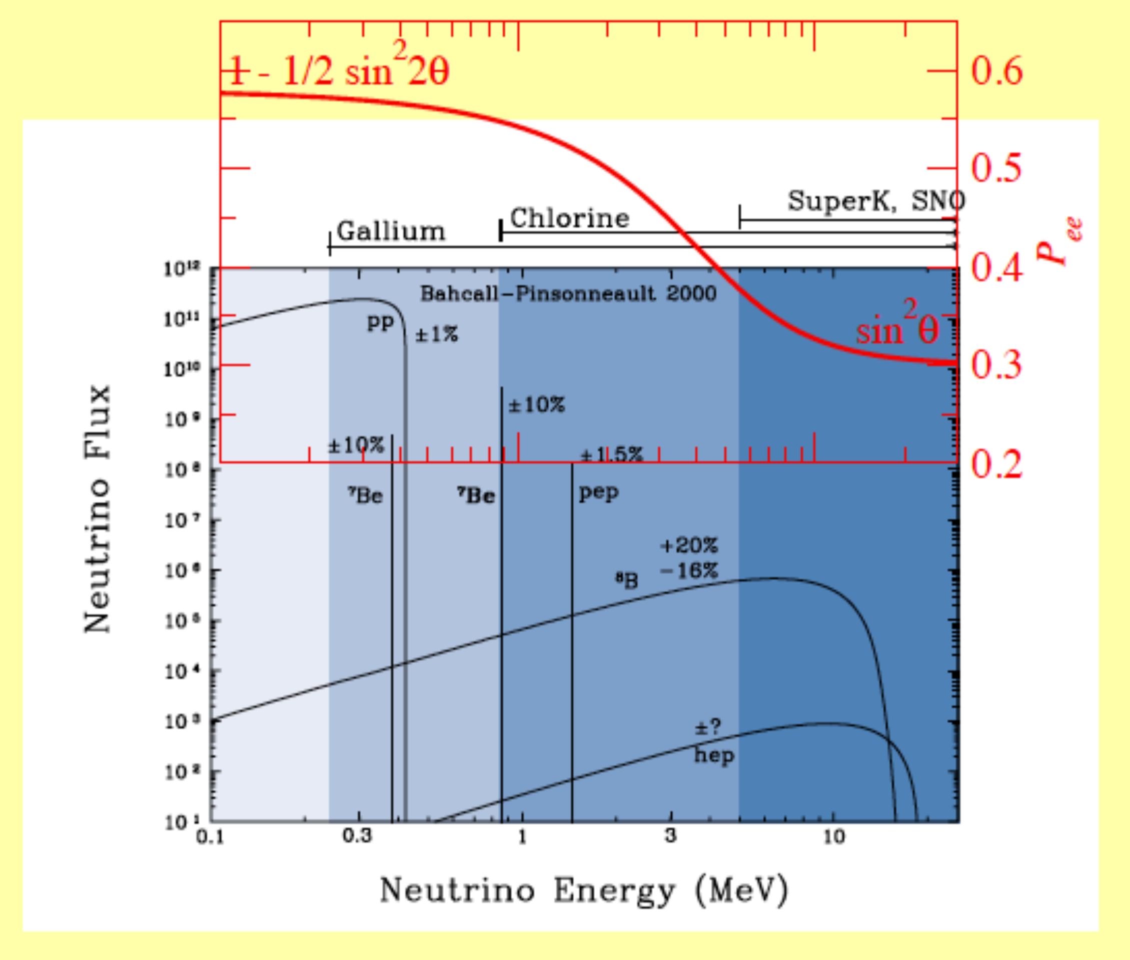
‣different E-range sensitivity:

→ Cl: E > 0.814 MeV

→ Ga: E > 0.233 MeV

→ Super-K: E > 5 MeV

Different energy suppression of solar fluxes



- Ga experiments: pp neutrinos

$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta$$

with $\sin^2 2\theta \simeq 0.84$ Pee > 0.5

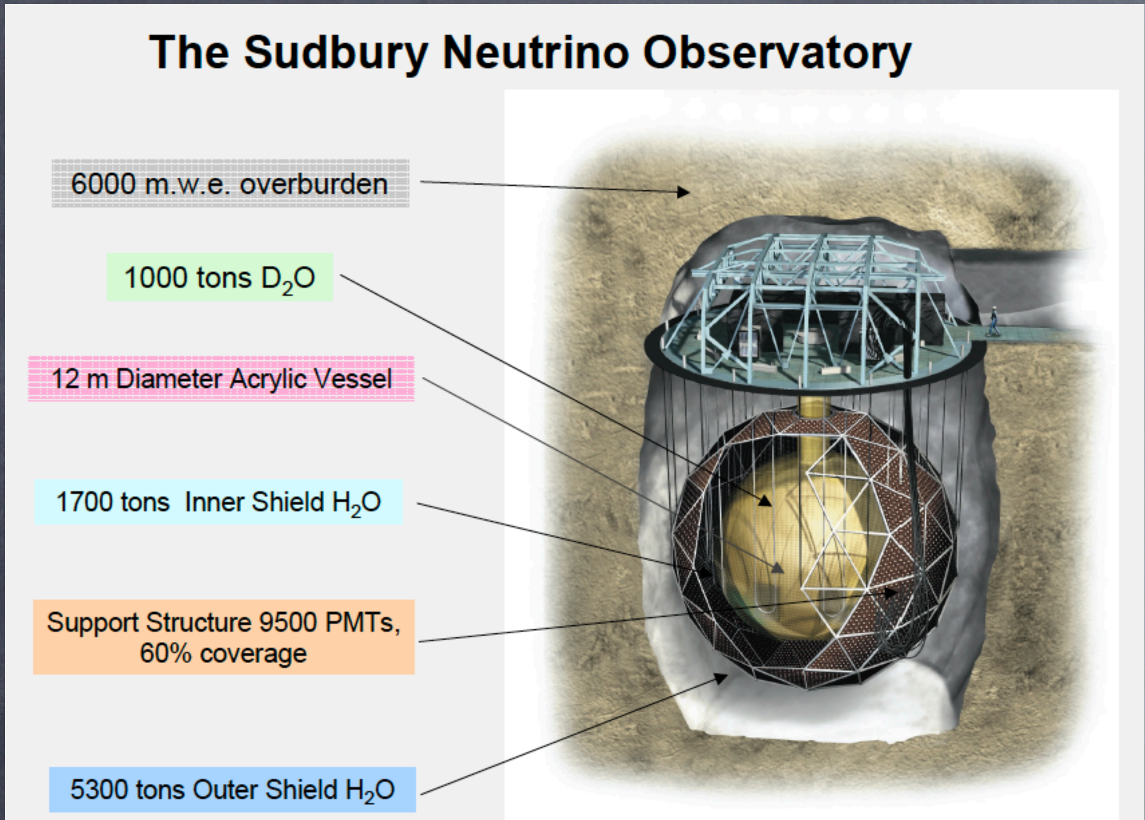
- Cl + Super-K: ^{8}B neutrinos

$$P_{ee} = \sin^2\theta$$

→ Pee ~ 0.3

→ stronger neutrino deficit is expected

The Sudbury Neutrino Observatory, SNO

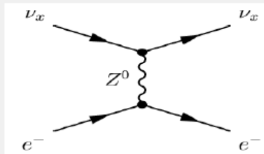


SNO is sensitive to all ν flavors:

SNO interactions

Elastic-scattering (ES):

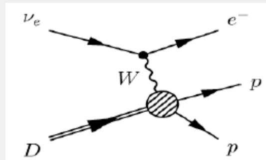
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



ν_e mainly
strong directional sensitivity

Charged-currents (CC):

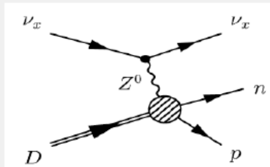
$$\nu_e + d \rightarrow p + p + e^-$$



ν_e only
E_e well correlated with E_ν

Neutral-currents (NC):

$$\nu_x + d \rightarrow p + n + \nu_x$$



All flavors equally
Total neutrino flux

3 phases:

D_2O phase:

$n + d \rightarrow t + \gamma + 6.25$ MeV

Salt phase (D_2O + 2 tons of NaCl):

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$'s $+ 8.6$ MeV

NCD phase (^3He proportional counters):

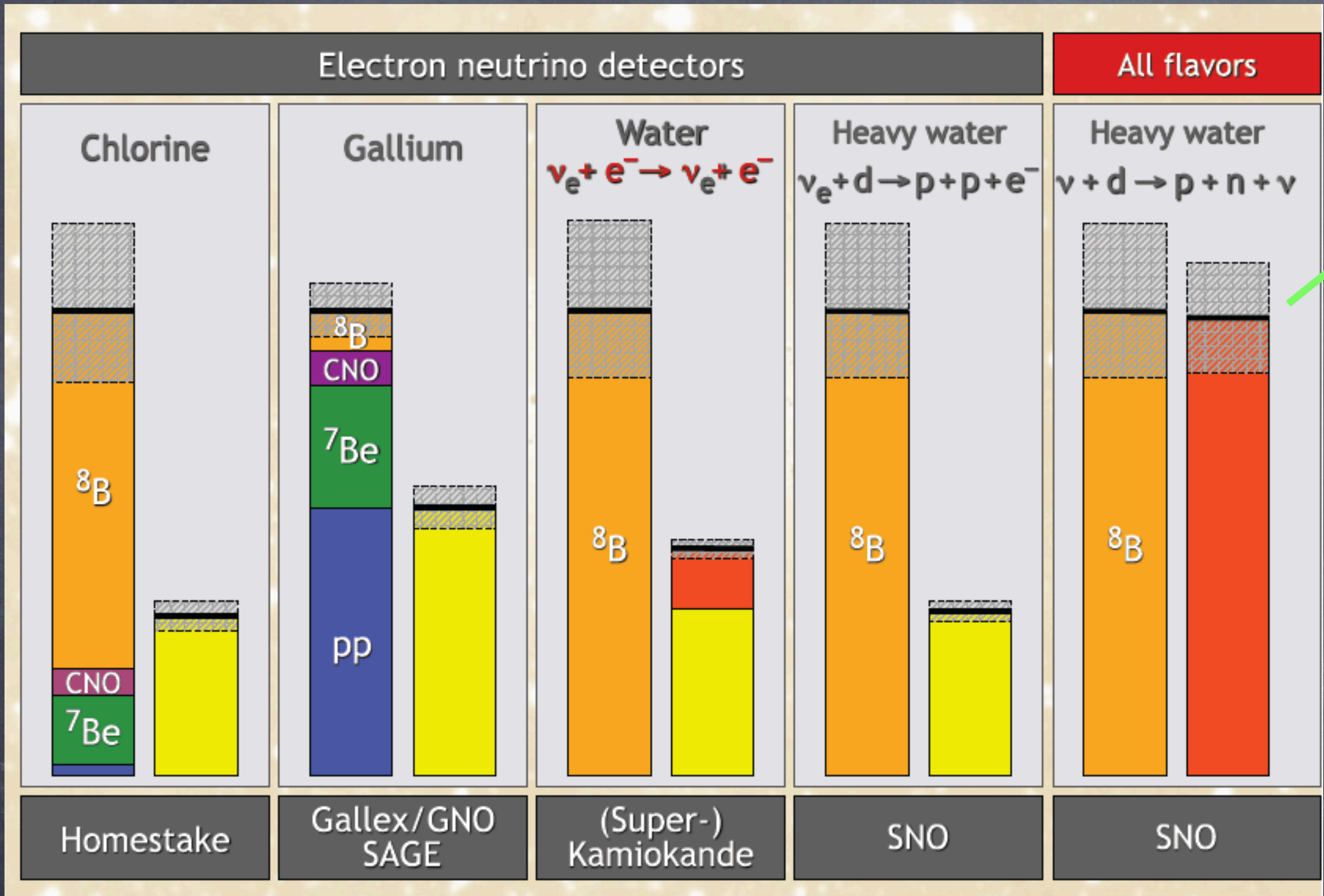
$n + {}^3He \rightarrow p + t + 0.76$ MeV

ν_e flux (CC): $$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$$ 30%

total ν flux (NC): $$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst})$$

100% !!

The solar neutrino ~~problem~~



All neutrinos are there!!

The Sun produces ν_e that arrive to the Earth as $1/3\ \nu_e + 1/3\ \nu_\mu + 1/3\ \nu_\tau$

➡ flavor conversion: $\nu_e \rightarrow \nu_x$

Conversion mechanism ?
Neutrino oscillations ??

Solar neutrino oscillations

Homestake (E_ν > 0.814 MeV)

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

SAGE/GALLEX-GNO (E_ν >0.233 MeV)

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Super-Kamiokande ($E_e \gtrsim 5$ MeV)

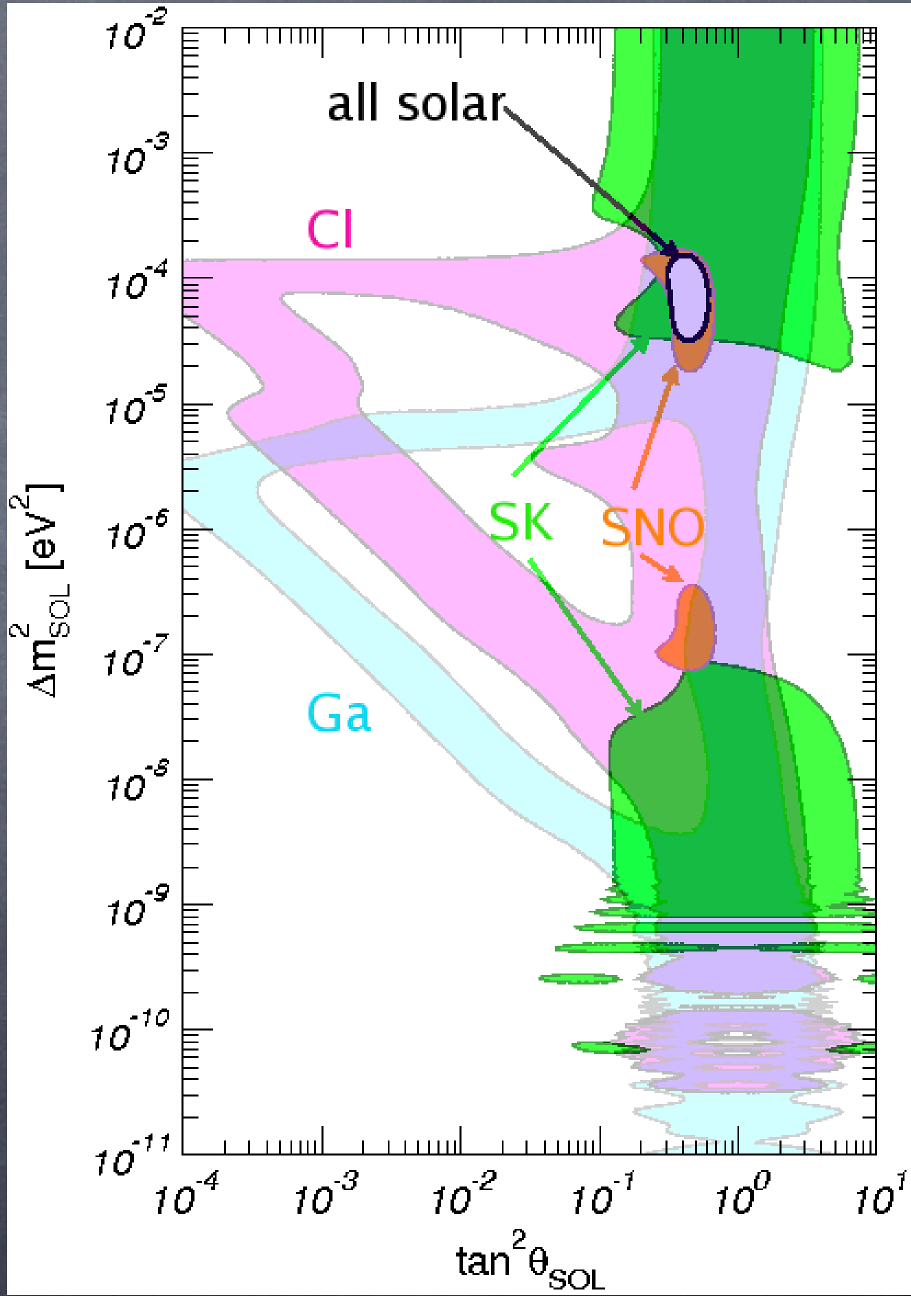
$\nu_x + e^- \rightarrow \nu_x + e^-$

SNO ($E_e \gtrsim 5$ MeV)

[CC] $\nu_e + d \rightarrow p + p + e^-$

[NC] $\nu_x + d \rightarrow \nu_x + n + p$

[ES] $\nu_x + e^- \rightarrow \nu_x + e^-$



→ only LMA allowed at 3σ

→ max. mixing excluded at 5σ

The KamLAND reactor experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector

- reactor experiment:

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

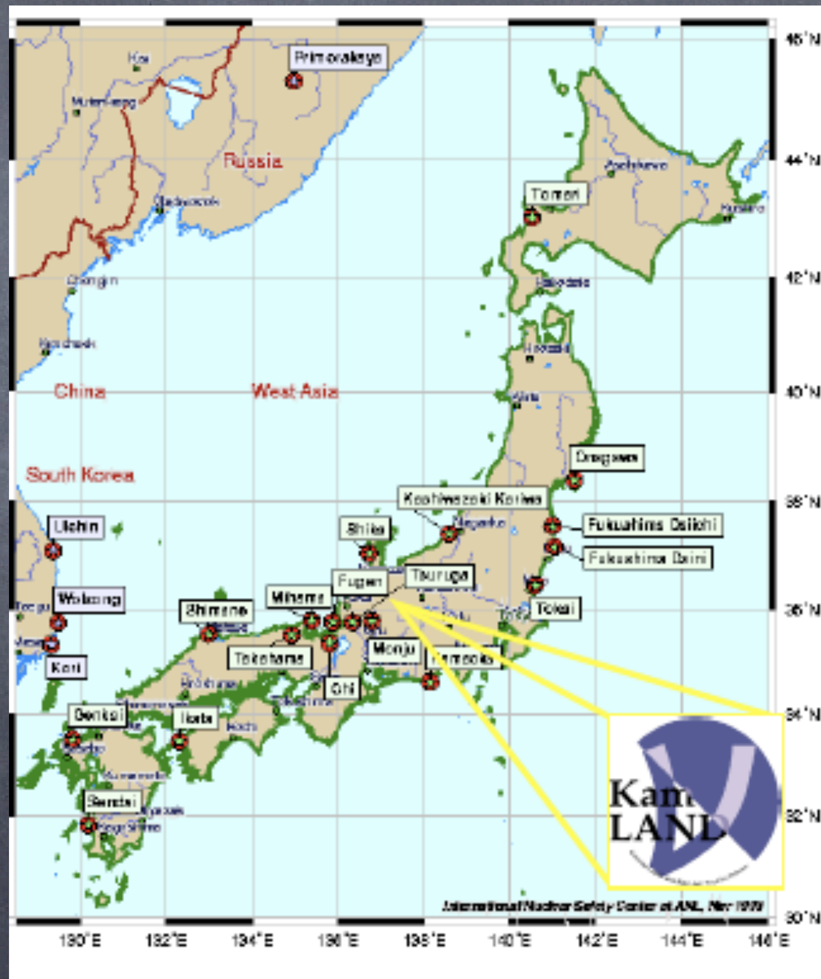
- 55 commercial power reactors

- average distance ~ 180 km

→ E_ν/L sensitivity range: $\Delta m^2 \sim 10^{-5}$ eV^2

→correct order of magnitude to test solar neutrino oscillations in LMA region

- CPT invariance: same oscillation channel as solar ν_e (Δm^2_{21} , θ_{12})



Results from KamLAND

2002: First evidence $\bar{\nu}_e$ disappearance

→ confirmation of solar LMA ν oscillations

KamLAND Coll, PRL 90 (2003) 021802

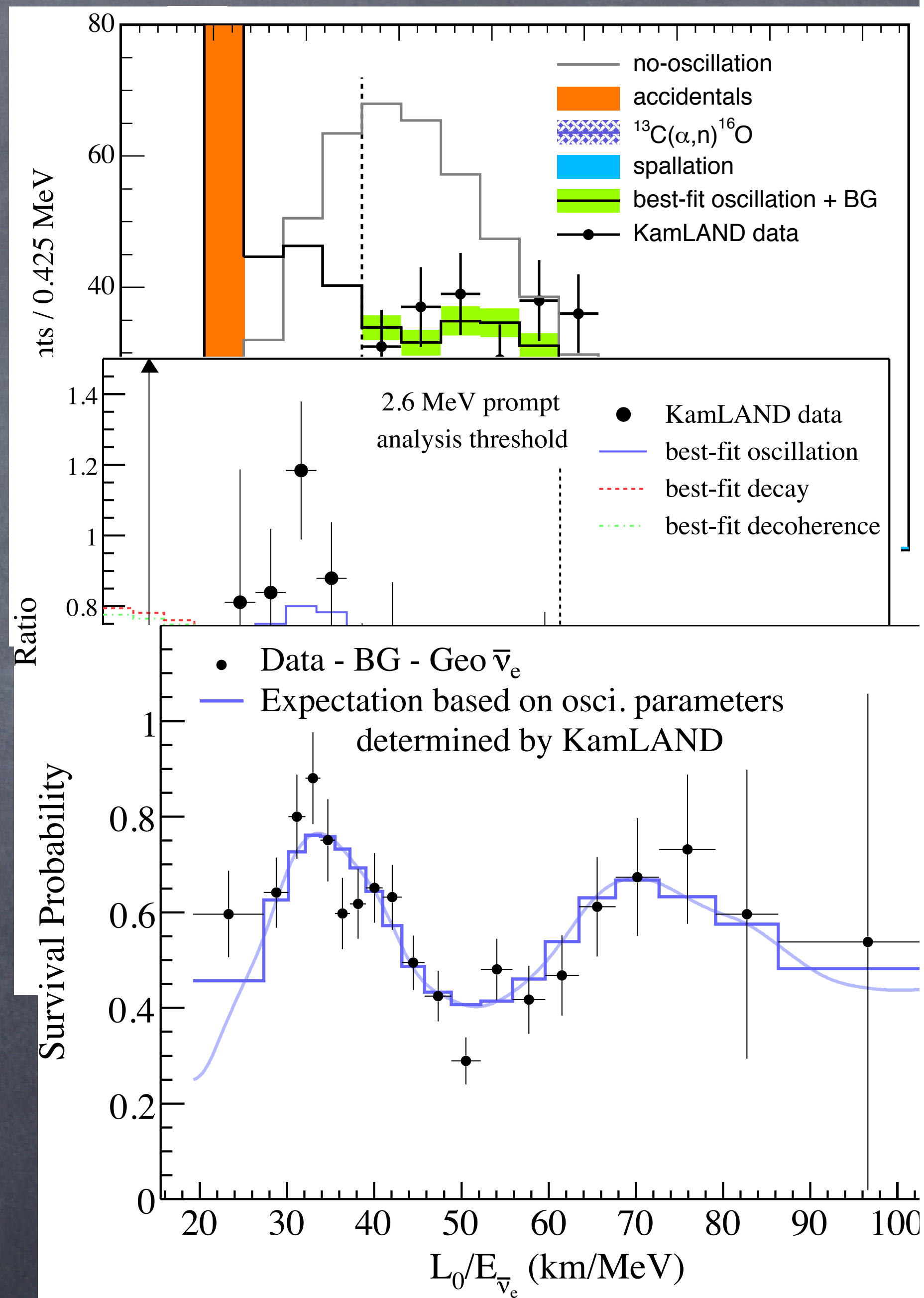
2004: spectral distortions (L/E)

KamLAND Coll, PRL 94 (2005) 081801

2008: 1-period oscillations observed

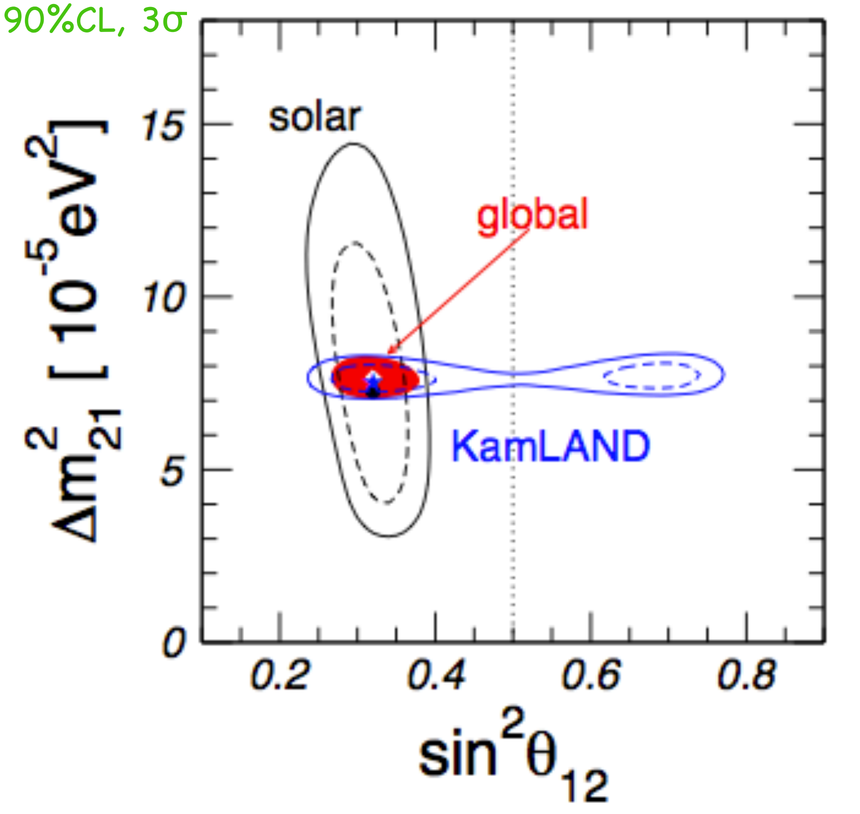
→ high precision determination Δm^2_{21}

KamLAND Coll, PRL 100 (2008) 221803



Combined analysis solar + KamLAND

90%CL, 3σ



- KamLAND confirms solar neutrino oscillations.
- Best fit point:

  $\sin^2\theta_{12} = 0.320^{+0.016}_{-0.017}$

  $\Delta m^2_{21} = 7.62 \pm 0.19 \times 10^{-5}$ eV^2
- max. mixing excluded at more than 7σ

Forero, M.T., Valle, PRD86, 073012 (2012)
arXiv:1205.4018 [hep-ph]

➡ Bound on θ_{12} dominated by solar data.

➡ Bound on Δm^2_{21} dominated by KamLAND.

The atmospheric neutrino sector

The atmospheric neutrino anomaly

Cosmic rays interacting with the Earth atmosphere producing pions and kaons, that decay generating neutrinos:

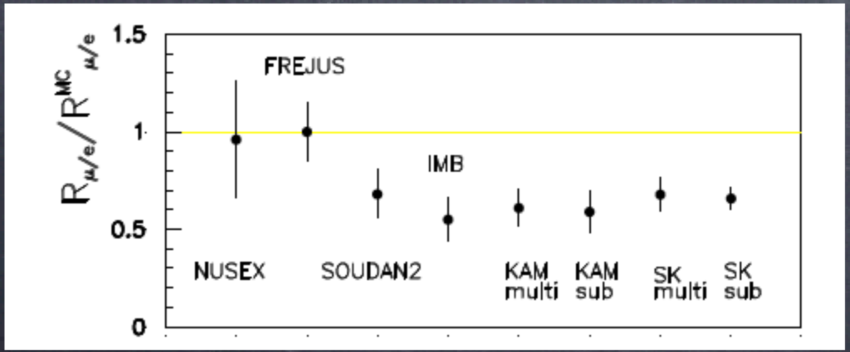
$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

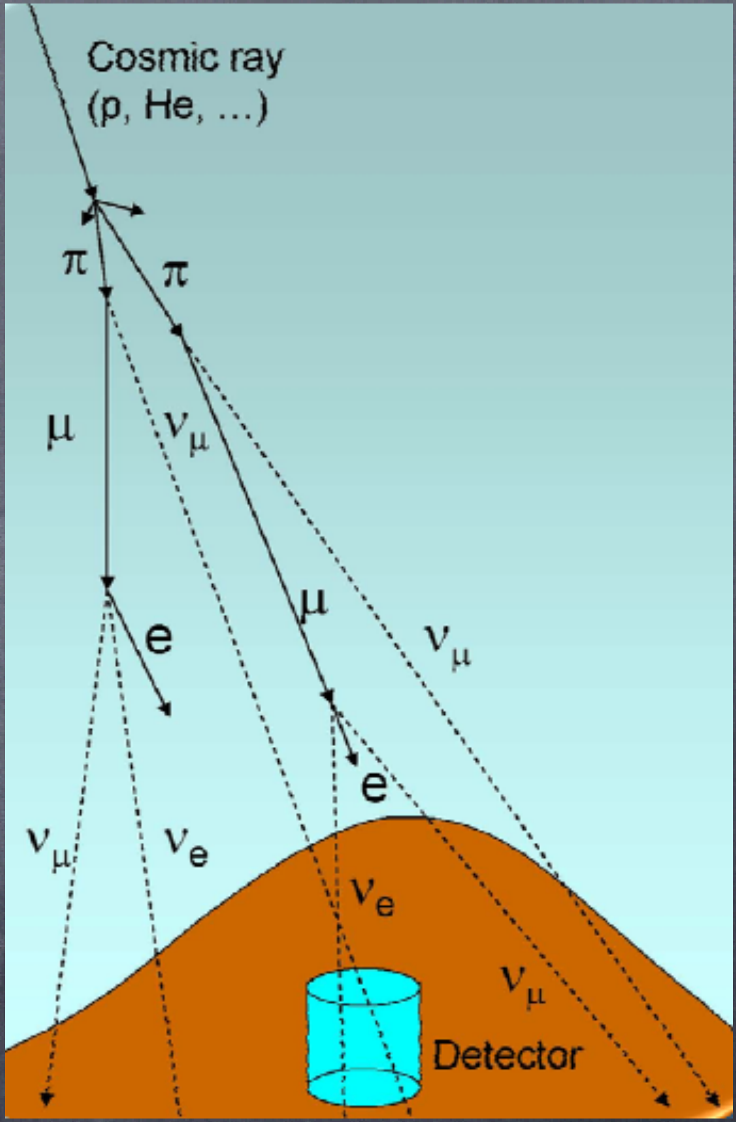
$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

then, one expects:

$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \simeq 2$$

However, this prediction is in disagreement with the experimental results:



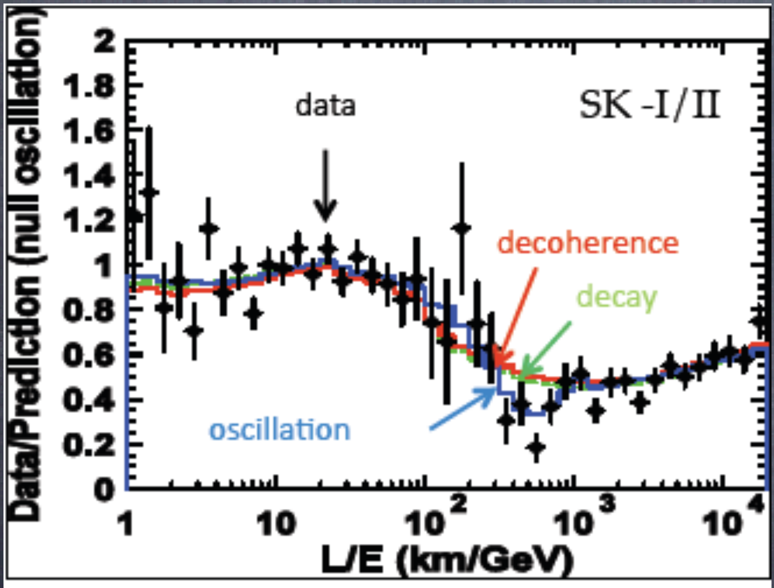


Atmospheric neutrinos

1998: Evidence ν_μ oscillations at Super-K

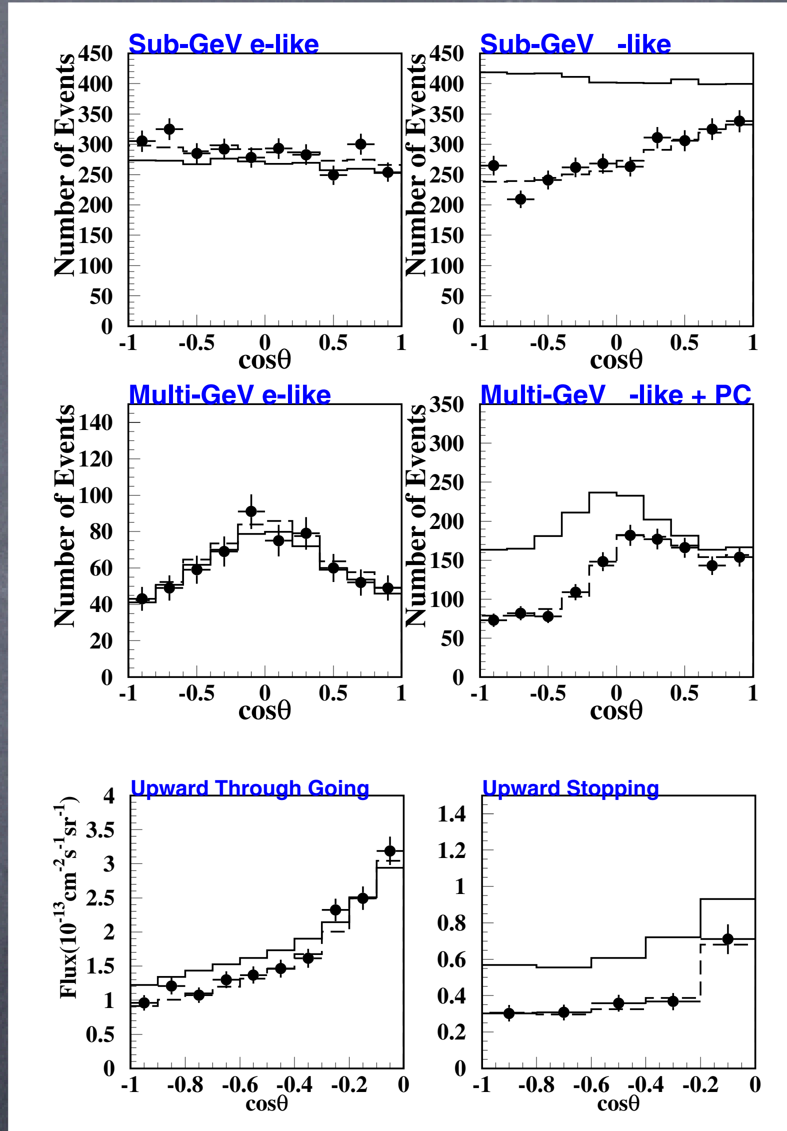
oscillation channel $\nu_\mu \rightarrow \nu_\tau$

2004: oscillatory L/E pattern



Super-K Coll, PRL93, 101801 (2004)

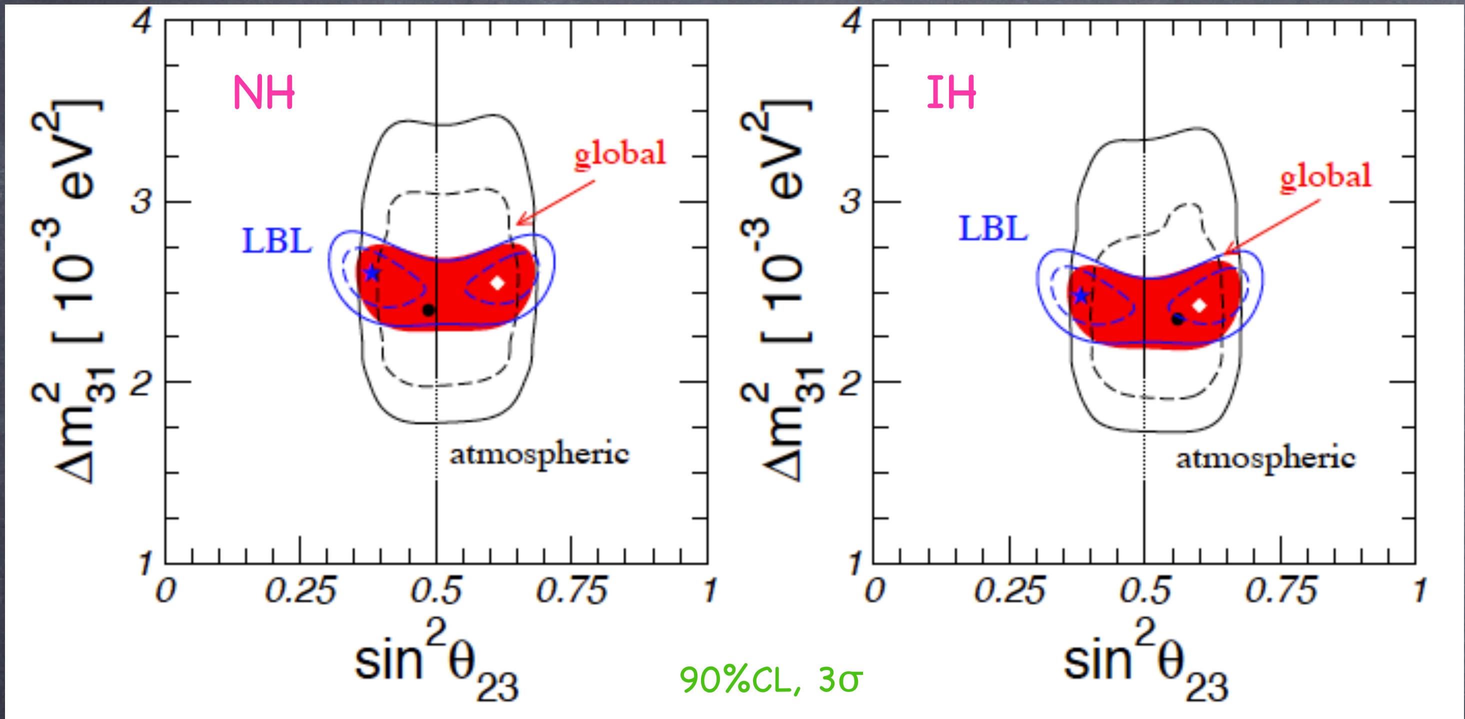
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32}}{4} \frac{L}{E_\nu} \right)$$



Super-K Coll., PRL 8 (1998) 1562.

Combined analysis atmospheric + LBL data

➡ Super-Kamiokande (I + II + III) + K2K + MINOS + T2K LBL data



➡ Determination of θ_{23} and Δm^2_{31} is now dominated by LBL data

Forero, M.T., Valle, 2012

- Best fit point:

$\sin^2\theta_{23} = 0.613^{+0.022}_{-0.040}$ *local bf in 0.427

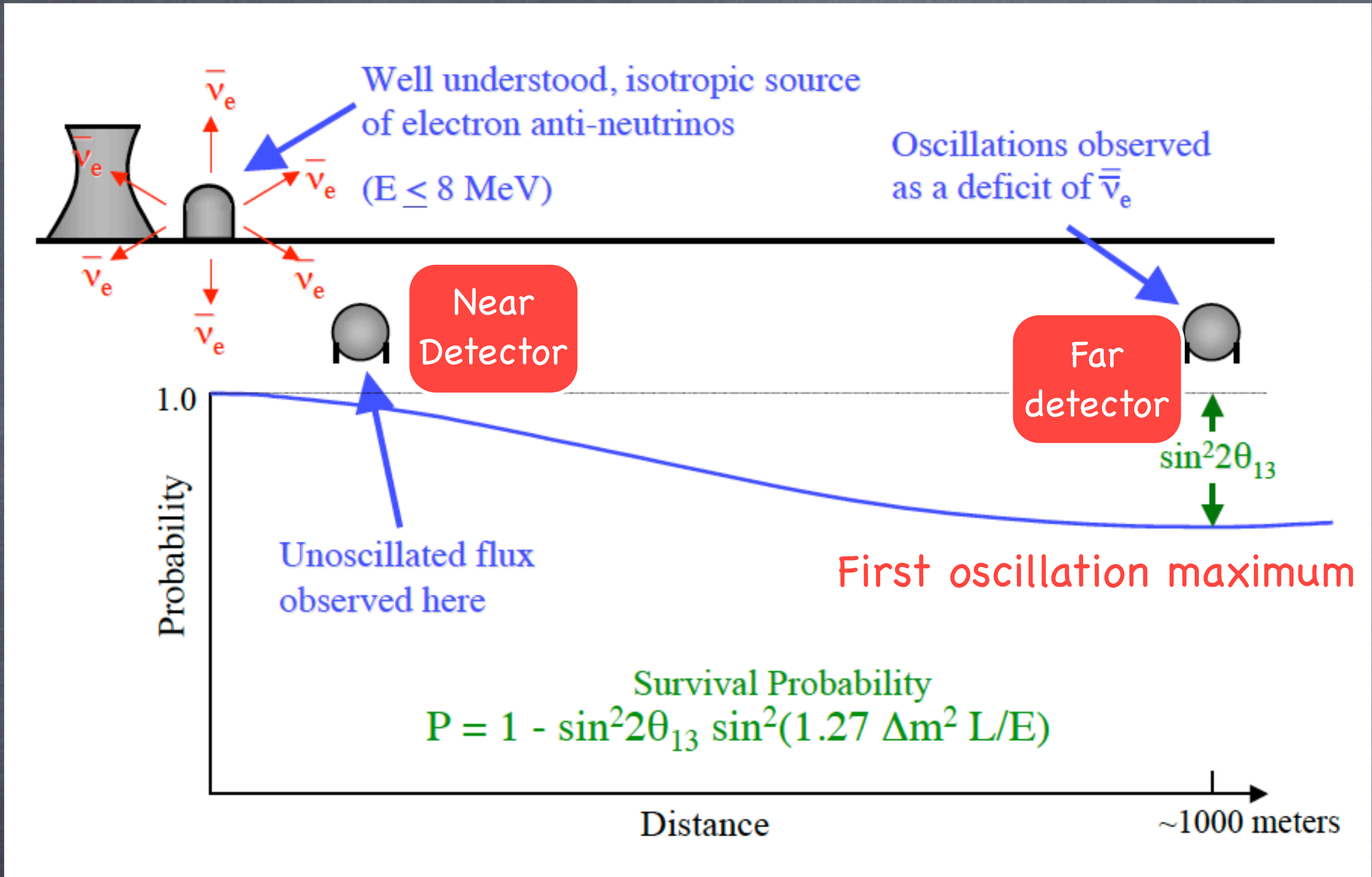
$\Delta m^2_{31} = 2.55^{+0.06}_{-0.08} \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.600^{+0.026}_{-0.031}$

$\Delta m^2_{31} = -(2.43^{+0.07}_{-0.06} \times 10^{-3})$ eV^2

Short-baseline reactor experiments

New generation of reactor experiments



* more powerful reactors (multi-core)
* larger detector volume
* 2-6 detectors at 100 m - 1 km.

New generation reactor experiments

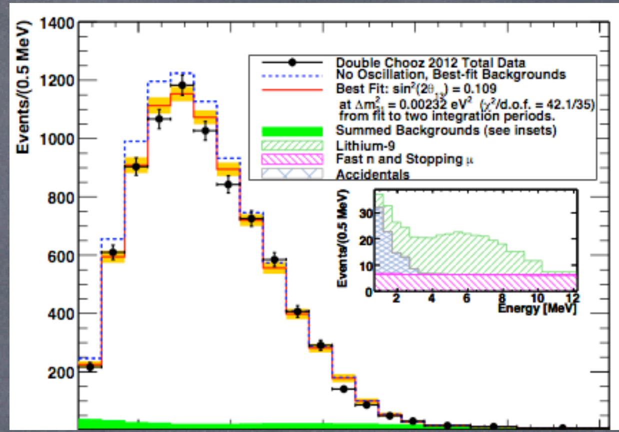
2 reactor cores + 1 FD (ND 2013)

livetime: 227.9 days

$\sin^2 2\theta_{13}$ = 0.109 ± 0.030 (stat) ±0.025 (syst)

→ $\sin^2 2\theta_{13}$ = 0 excluded at 2.9σ

Double Chooz Coll, PRD 86 (2012) 052008



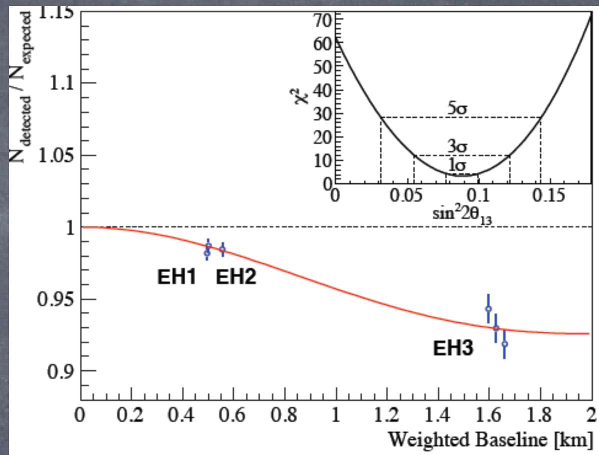
6 reactor cores + 6 detectors (3ND,3FD)

livetime: 139 days

$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ±0.005 (syst)

→ $\sin^2 2\theta_{13}$ = 0 excluded at 7.7σ

Daya Bay Coll., Chin. Phys. C 37 (2013) 011001



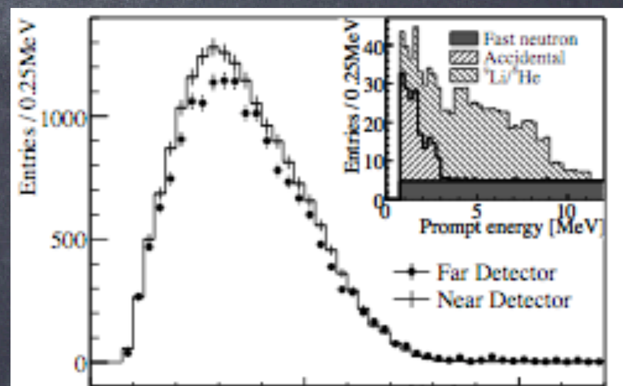
6 reactor cores + 2 detectors (ND,FD)

livetime: 229 days

$\sin^2 2\theta_{13}$ = 0.113 ± 0.013 (stat) ±0.019 (syst)

→ θ_{13}=0 excluded at 4.9σ

RENO Coll., PRL 108 (2012) 191802



3-neutrino probabilities in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

ν_e disappearance channel

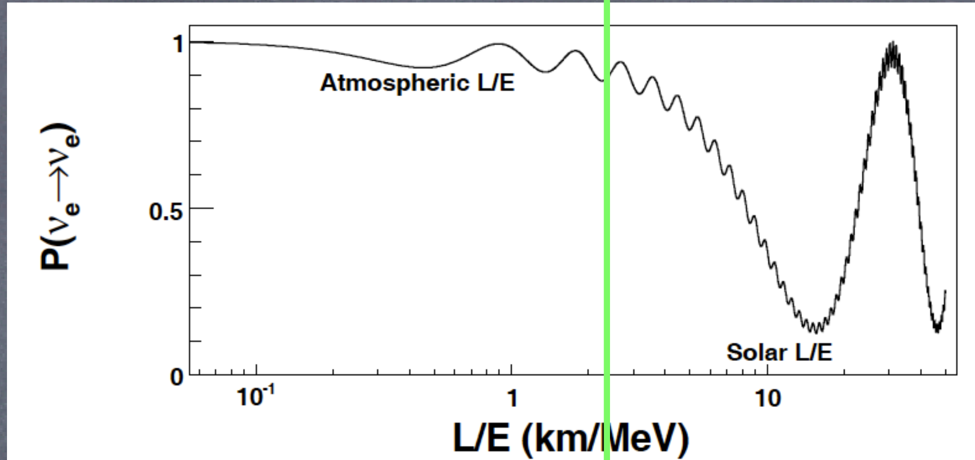
$$P(\nu_e \to \nu_e) = 1 - 4|U_{e3}|^2|U_{e1}|^2 \sin^2\Delta_{31} - 4|U_{e3}|^2|U_{e2}|^2 \sin^2\Delta_{32} - 4|U_{e2}|^2|U_{e1}|^2 \sin^2\Delta_{21}$$

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

$$P^{\text{reactor}}_{ee} \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{31} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

↓ reactor exp with atm L/E (CHOOZ)

↓ reactor exp with solar L/E (KamLAND)



$\nu_\mu \to \nu_e$ appearance channel

$$\begin{aligned} P_{\mu e} &= \left|2U^*_{\mu 3}U_{e3}\sin\Delta_{31}e^{-i\Delta_{32}} + 2U^*_{\mu 2}U_{e2}\sin\Delta_{21}\right|^2 = \\ &\approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31} + \cos^2\theta_{23}\cos^2\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} + \\ &+ \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\sin\Delta_{31}\sin\Delta_{21}\cos(\Delta_{32}+\delta) \end{aligned}$$

CP violating term: only present for appearance probabilities α≠β.
Genuine 3-flavor effect

for antineutrinos: δ →-δ

$$\Delta P = P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e) = -2\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\Delta_{21}\sin\Delta_{31}\sin\Delta_{32}\sin\delta$$

3-neutrino masses and mixings

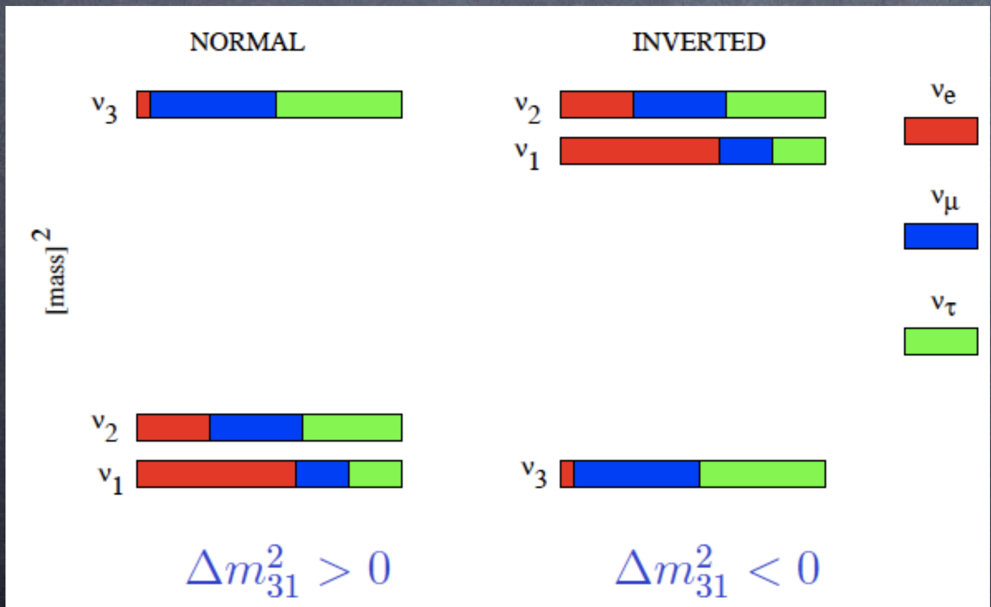
- 3-neutrino mixing is described by 3 angles and 1 Dirac (+2 Majorana) CP violating phases.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + LBL measurements

reactor disapp + LBL appearance searches

solar + KamLAND measurements



Δm^2_{31} : atmospheric + long-baseline

Δm^2_{21} : solar + KamLAND

3-neutrino masses and mixings

- 3-neutrino mixing is described by 3 angles and 1 Dirac (+2 Majorana) CP violating phases.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + LBL measurements

reactor disapp + LBL appearance searches

solar + KamLAND measurements

- From the experimental data we know:

$\Delta m^2_{31} >> \Delta m^2_{21}$ and $\theta_{13} << 1$

→ 3-flavour effects are suppressed: dominant oscillations are well described by effective 2-flavour oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Three-neutrino effects

- θ_{13} effects in oscillations with Δm^2_{21} : KamLAND + solar neutrinos

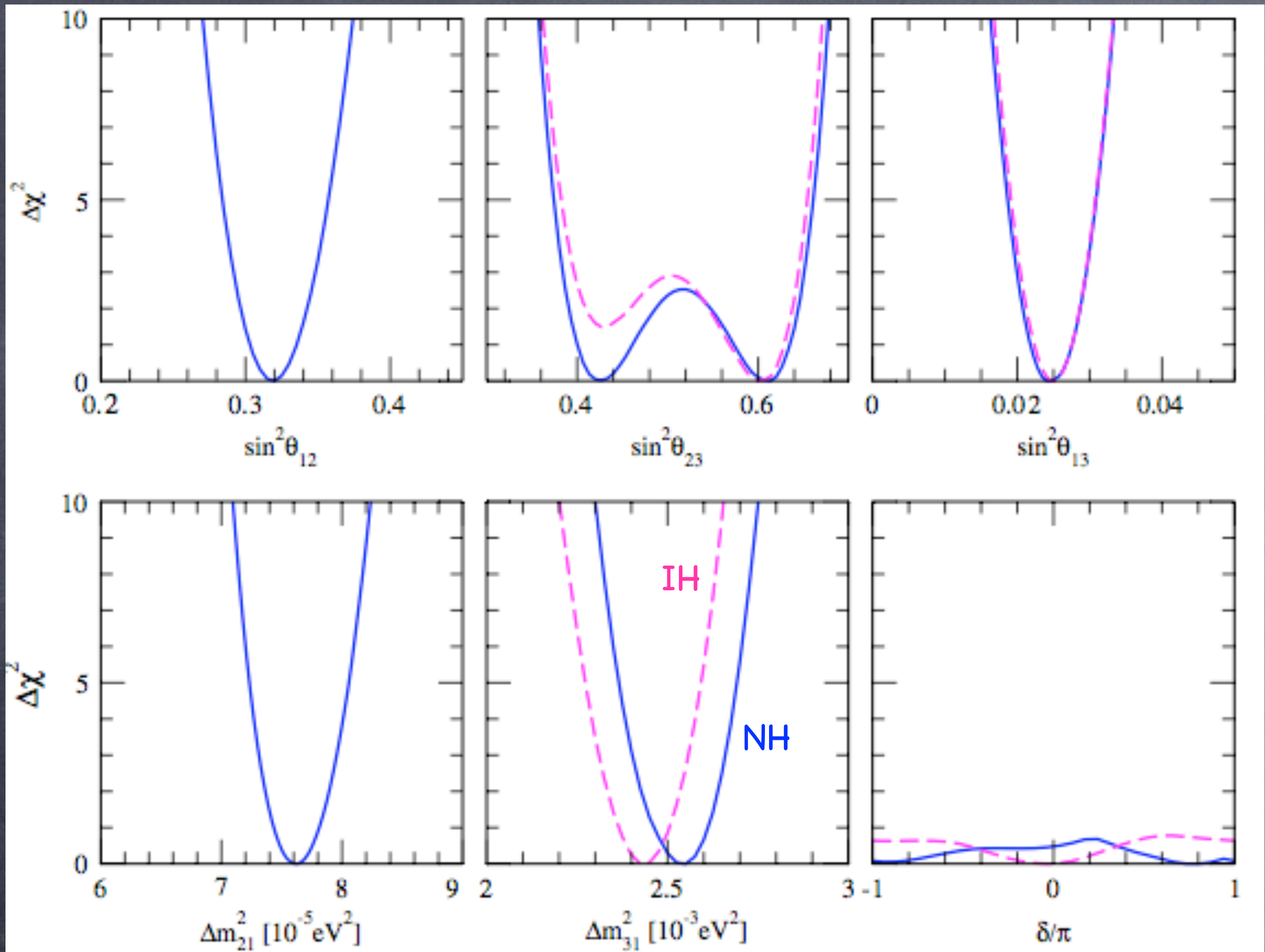
- θ_{13} effects in oscillations with Δm^2_{31} : atmospheric and accelerator experiments

  $\rightarrow$ ν_e appearance in ν_μ beam

- Δm^2_{21} effects in oscillations with Δm^2_{31}: reactor and atmospheric experiments

- effects of CP violation: atmospheric and accelerator experiments

3-flavour oscillation parameters



parameter	best fit ± 1σ	
Δm^2_{21} [10^{-5}eV^2]	7.62 ± 0.19	3%
Δm^2_{31} [10^{-3}eV^2]	$2.55^{+0.06}_{-0.09}$ $-(2.43^{+0.07}_{-0.06})$	3%
$\sin^2\theta_{12}$	$0.320^{+0.016}_{-0.017}$	5%
$\sin^2\theta_{23}$	$0.613^{+0.022}_{-0.040}$ $(0.427^{+0.034}_{-0.027})$ $0.600^{+0.026}_{-0.031}$	10%
$\sin^2\theta_{13}$	$0.0246^{+0.0029}_{-0.0028}$ $0.0250^{+0.0026}_{-0.0027}$	15%
δ	0.80π -0.03π	

- Deviations from 2-3 maximal mixing, $\theta_{23} > 45°$ preferred for IH.
- Poor sensitivity to δ_{CP}
- No indication for correct mass ordering

Forero, M.T., Valle, PRD86, 073012 (2012) arXiv:1205.4018 [hep-ph]