Neutrino Theory & Phenomenology (II)

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Neutrino oscillations in vacuum and in matter

Neutrino oscillations

1957: Pontecorvo suggests oscillations between neutrinos & antineutrinos (only ν_e).

B. Pontecorvo, J. Exp. Theor. Phys. 33 (1957) 549, Ibidem. 34 (1958) 247.

1962: Maki, Nakagawa and Sakata propose neutrino mixing between flavor eigenstates

$$\boxed{\begin{aligned} \nu_1 &= \nu_e \cos\delta + \nu_\mu \sin\delta, \\ \nu_2 &= -\nu_e \sin\delta + \nu_\mu \cos\delta. \end{aligned}}$$

2ν mixing

true neutrinos

weak neutrinos

Z. Maki, M. Nakagawa, S. Sakata, Prog. Theor. Phys. 28 (1962) 870.

1969: Gribov & Pontecorvo calculated the neutrino oscillation probability (in vacuum) for the first time

V. Gribov, B. Pontecorvo, Phys. Lett. B28 (1969) 493.

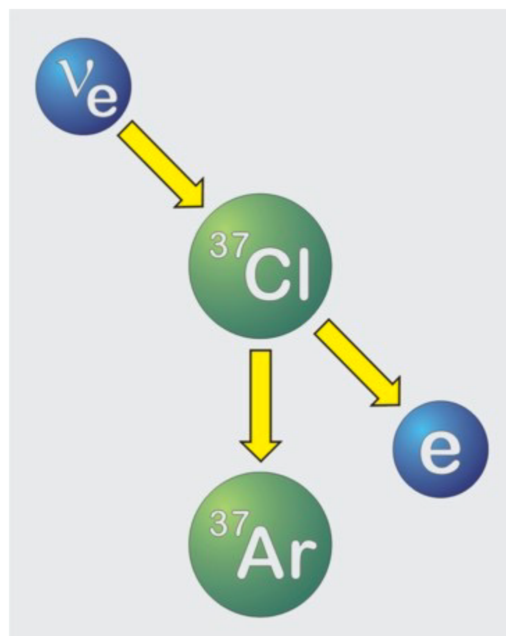
$$P\left(\nu_e \longrightarrow \nu_e\right) = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

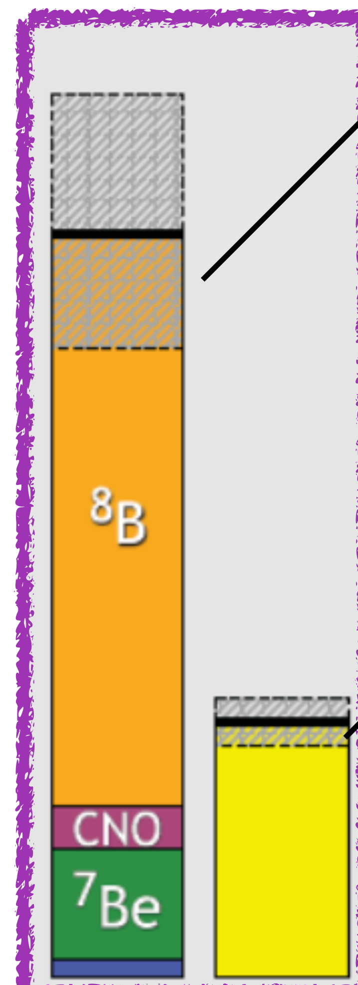
First indication of ν oscillations

Raymond Davis Jr.

1968: First observation of solar neutrinos by R. Davis in an underground experiment (Homestake gold mine, South Dakota) using 615 ton of C_2Cl_4

2002 Nobel Prize in Physics

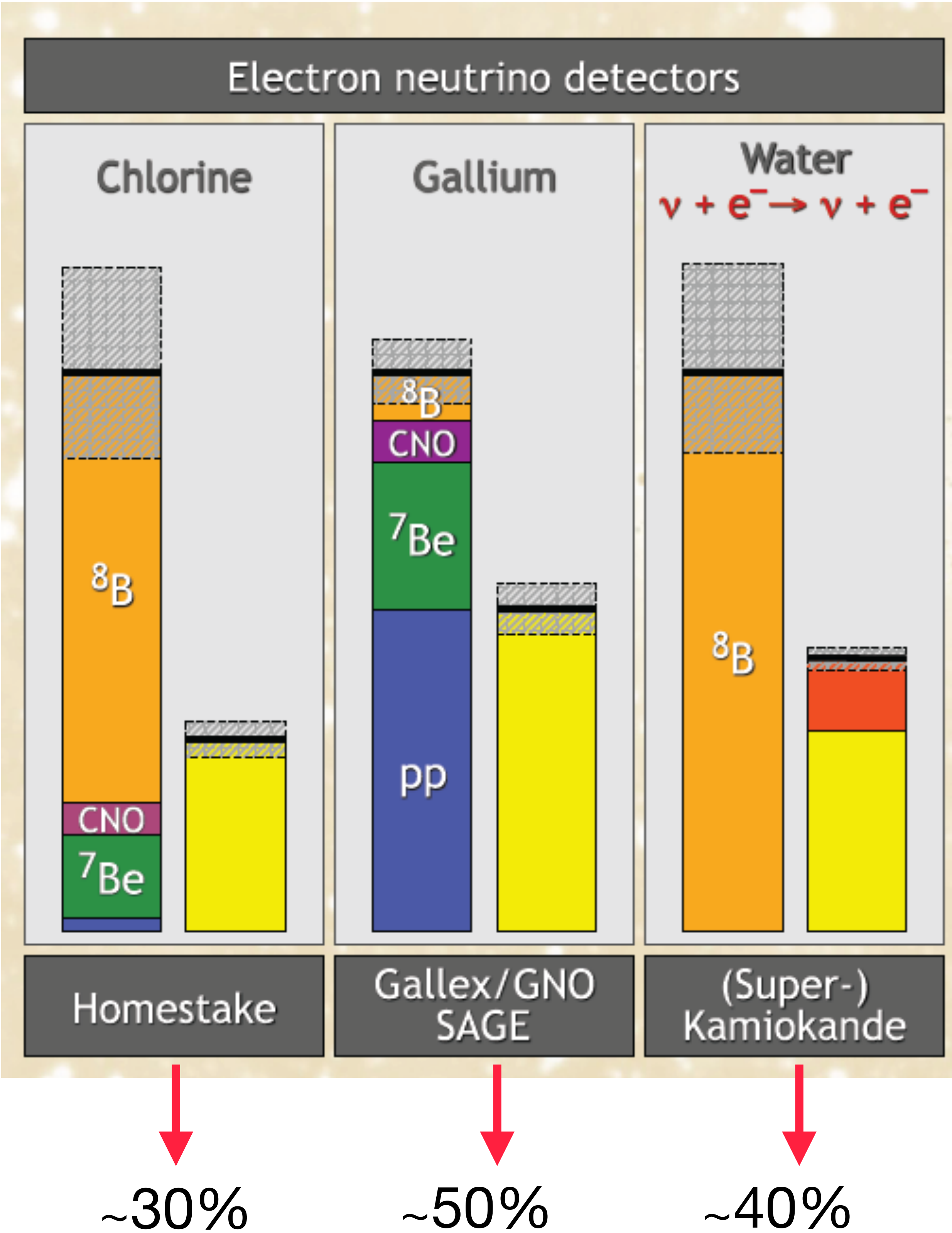




Expected neutrinos

Observed neutrinos: 30% !!

The solar neutrino problem



1980s-1990s: Confirmed by the following solar neutrino experiments

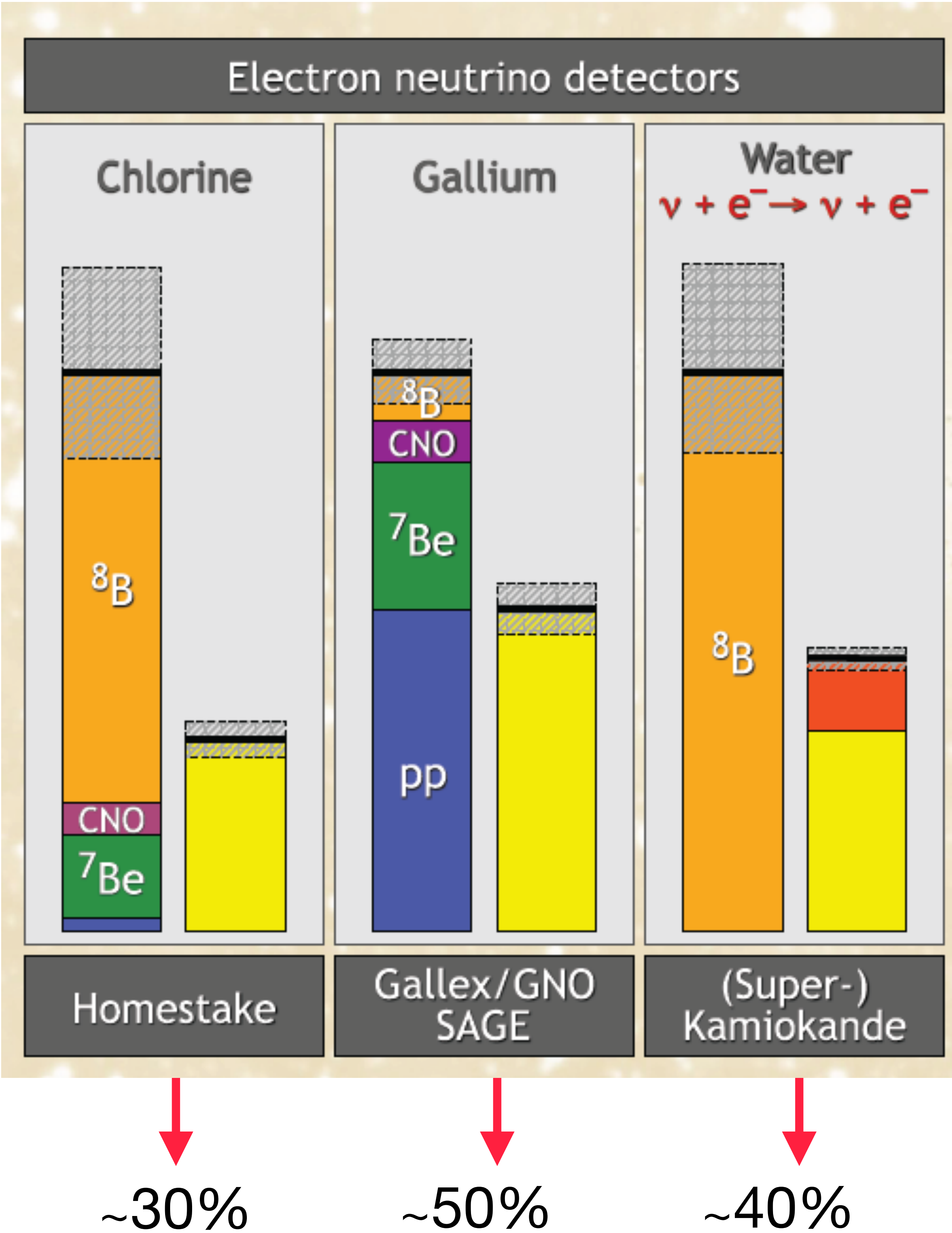
Explanation?

→ theory (SM, SSM) was wrong

→ experiments were wrong (all of them?)

→ something was happening to neutrinos

The solar neutrino problem



Why results are different?

✓ Sensitive to different neutrinos:

- Cl, Ga: only sensitive to ν_e

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

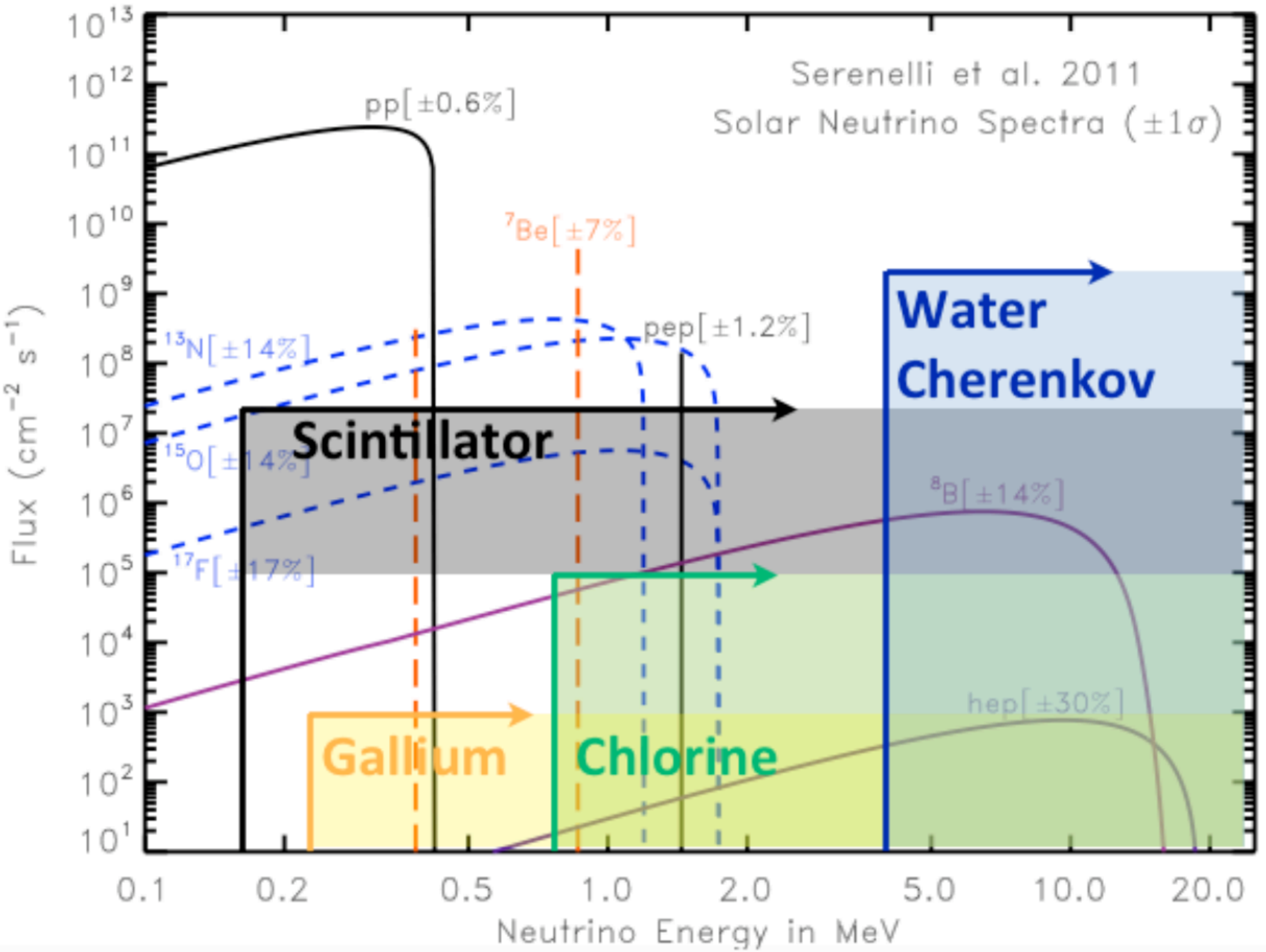
$$\boxed{\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-}$$

- Super-K: $\nu_e + \nu_\mu + \nu_\tau$

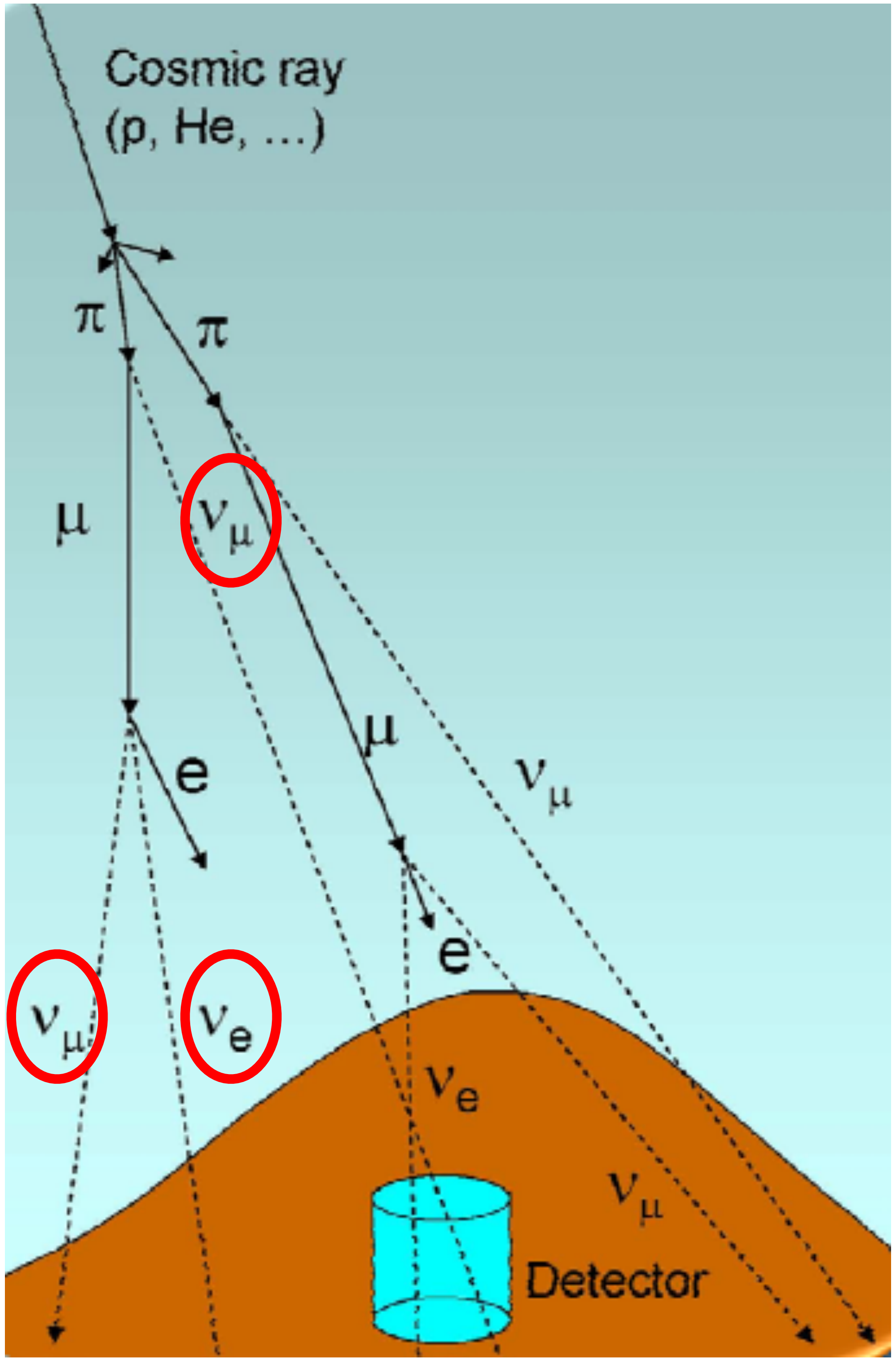
$$\boxed{\nu_x + e^- \to \nu_x + e^-}$$

✓ Sensitive to different part of the neutrino spectrum

The Solar Neutrino Spectrum



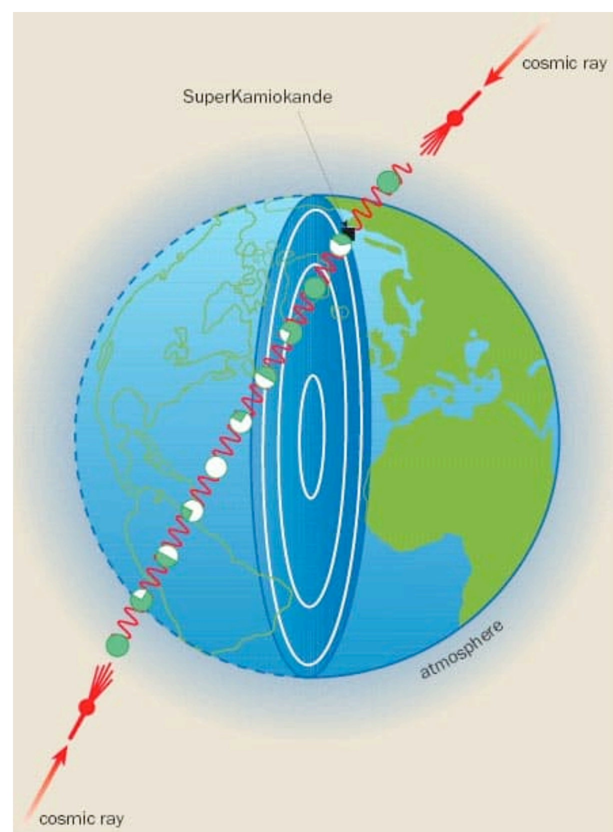
Atmospheric neutrinos



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

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

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



$$\boxed{\begin{array}{l} \nu_e + N \to e^- + N' \\ \nu_\mu + N \to \mu^- + N' \end{array}}$$

⇒ atmospheric neutrino detection in 360°

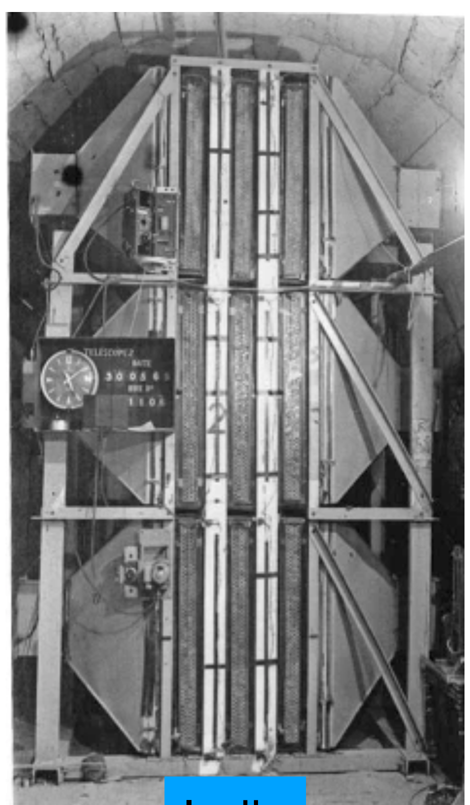
Atmospheric neutrinos

South Africa

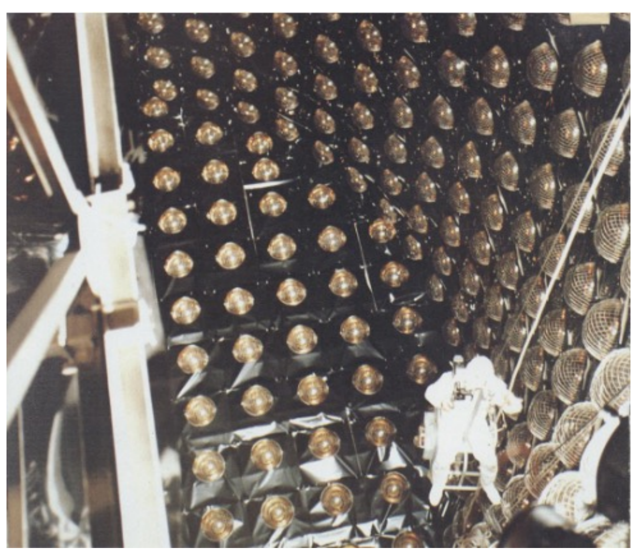
1965: First observation of **atmospheric neutrinos** in a gold mine in South Africa (F. Reines) and Kolar Gold Fields (India), at 3.2 and 2.4 km depth.

$$\boxed{\nu_\mu + N \to \mu^- + N'}$$

1980's: Proton decay experiments for which atmospheric neutrinos were a source of background.

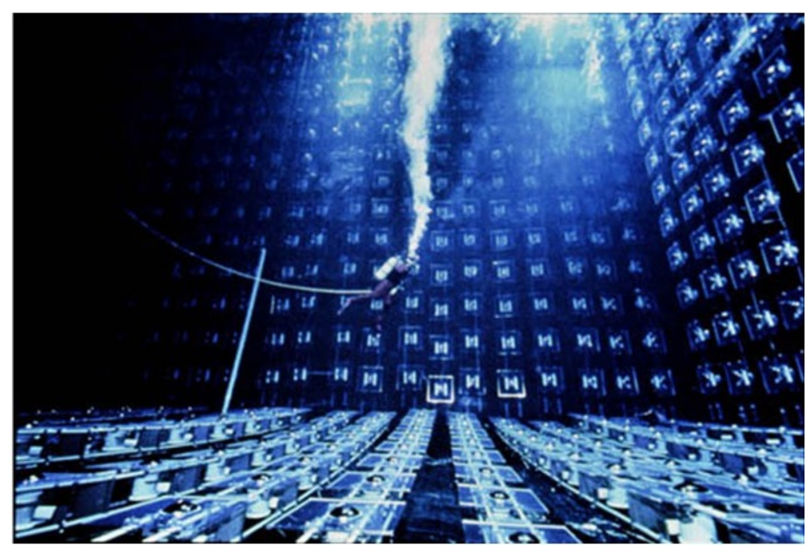


India



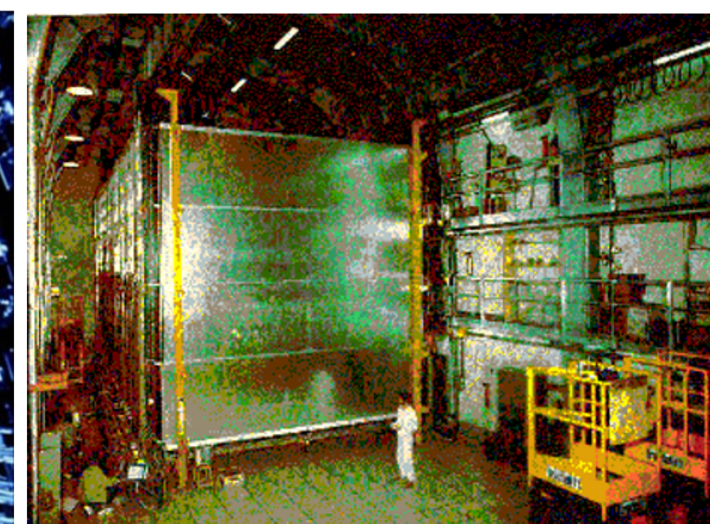
Kamiokande, Japan

[1000 ton]



IMB, USA

[3300 ton]



Fréjus, France

[700 ton]

The atmospheric neutrino anomaly

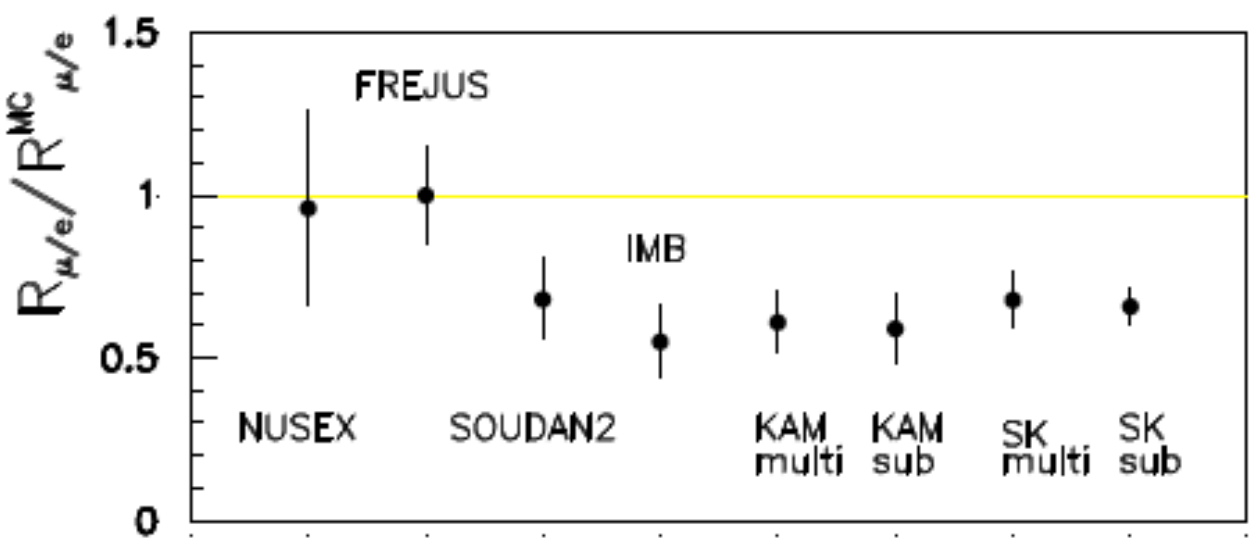
1985: First indications of a deficit in the observed number of atmospheric ν_μ at IMB.

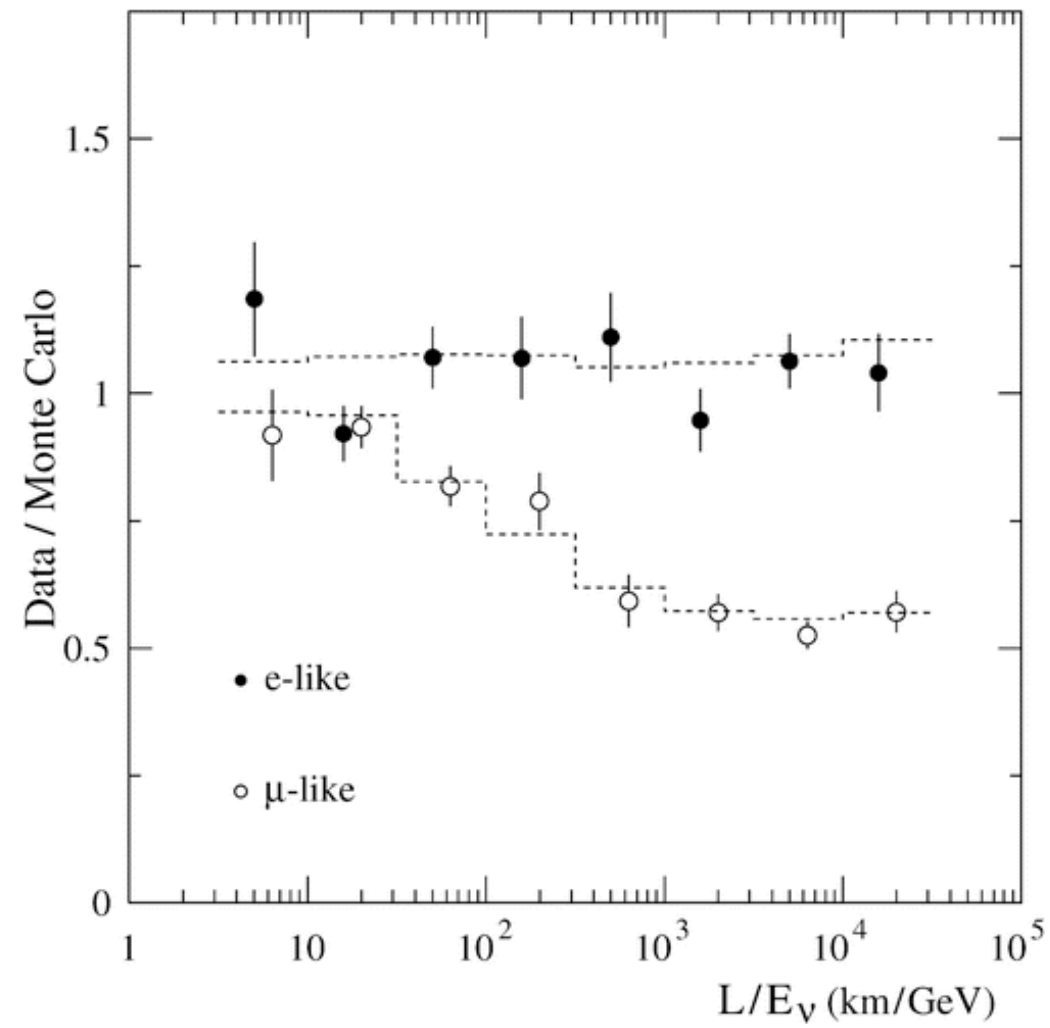
1994: **Kamiokande** finds the ν_μ deficit depends on the distance travelled by the neutrino and its energy.

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

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

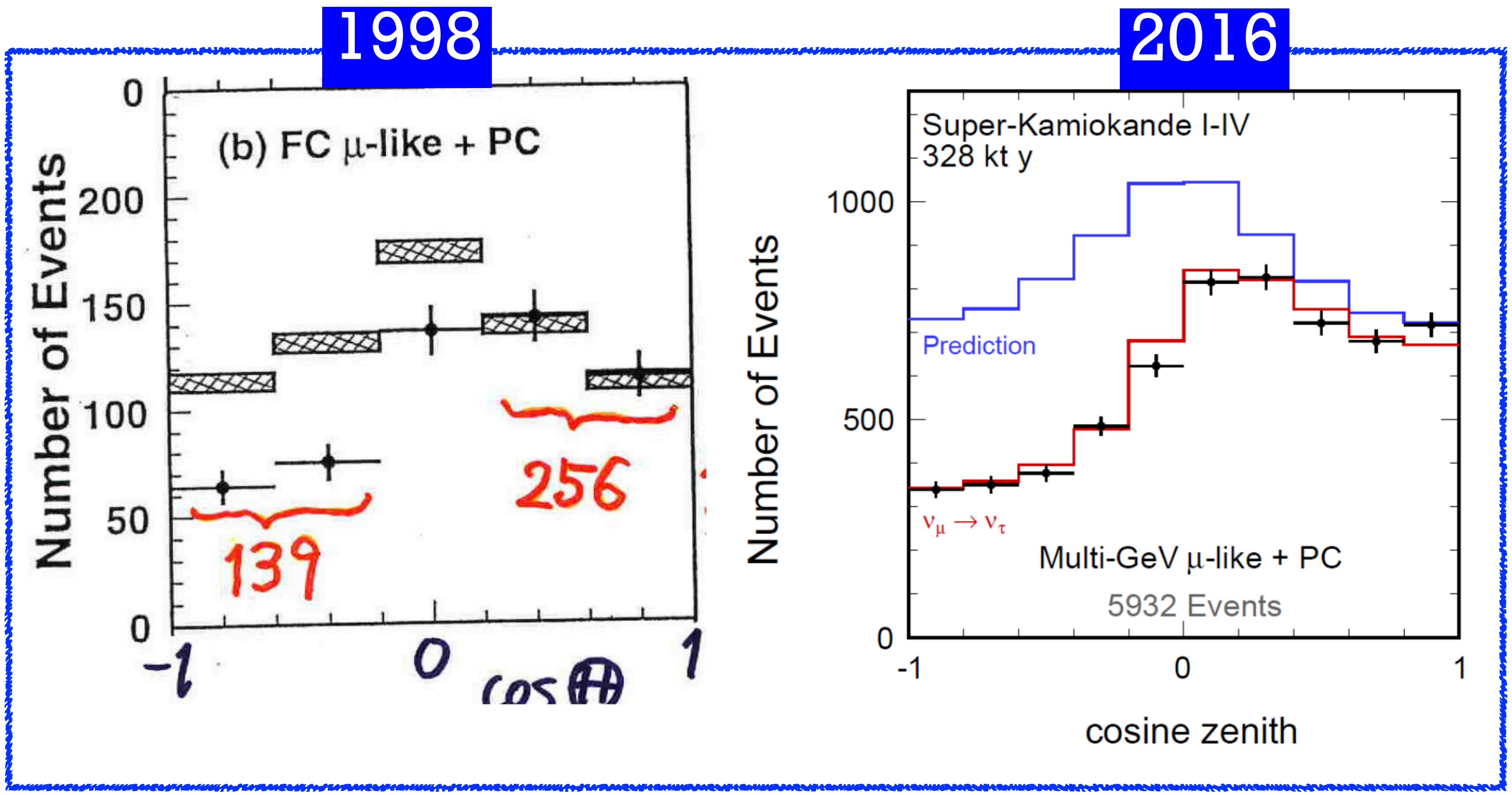
$$\boxed{R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \simeq 2}$$



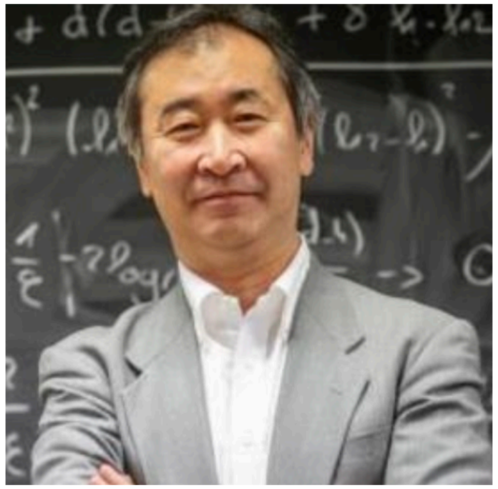


The atmospheric neutrino anomaly

1998: Discovery of atmospheric neutrino oscillations in **Super-Kamiokande**



From T. Kajita



2015 Nobel Prize in Physics

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

➡ first evidence for non-zero **neutrino masses.**

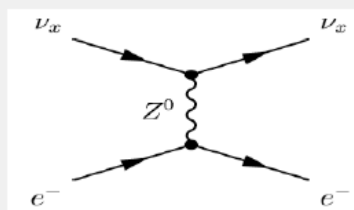
Sudbury Neutrino Observatory (SNO)

2001: Confirmation of flavor conversion in solar neutrinos in SNO (1 kton D_2O)

SNO interactions

Elastic-scattering (ES):

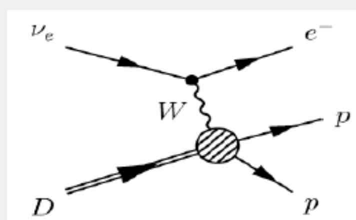
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



ν_e mainly
strong directional sensitivity

Charged-currents (CC):

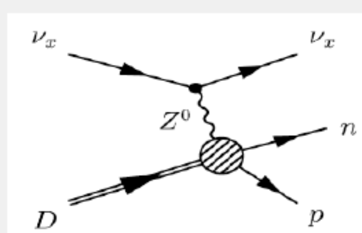
$$\nu_e + d \rightarrow p + p + e^-$$



ν_e only
E_e well correlated with E_ν

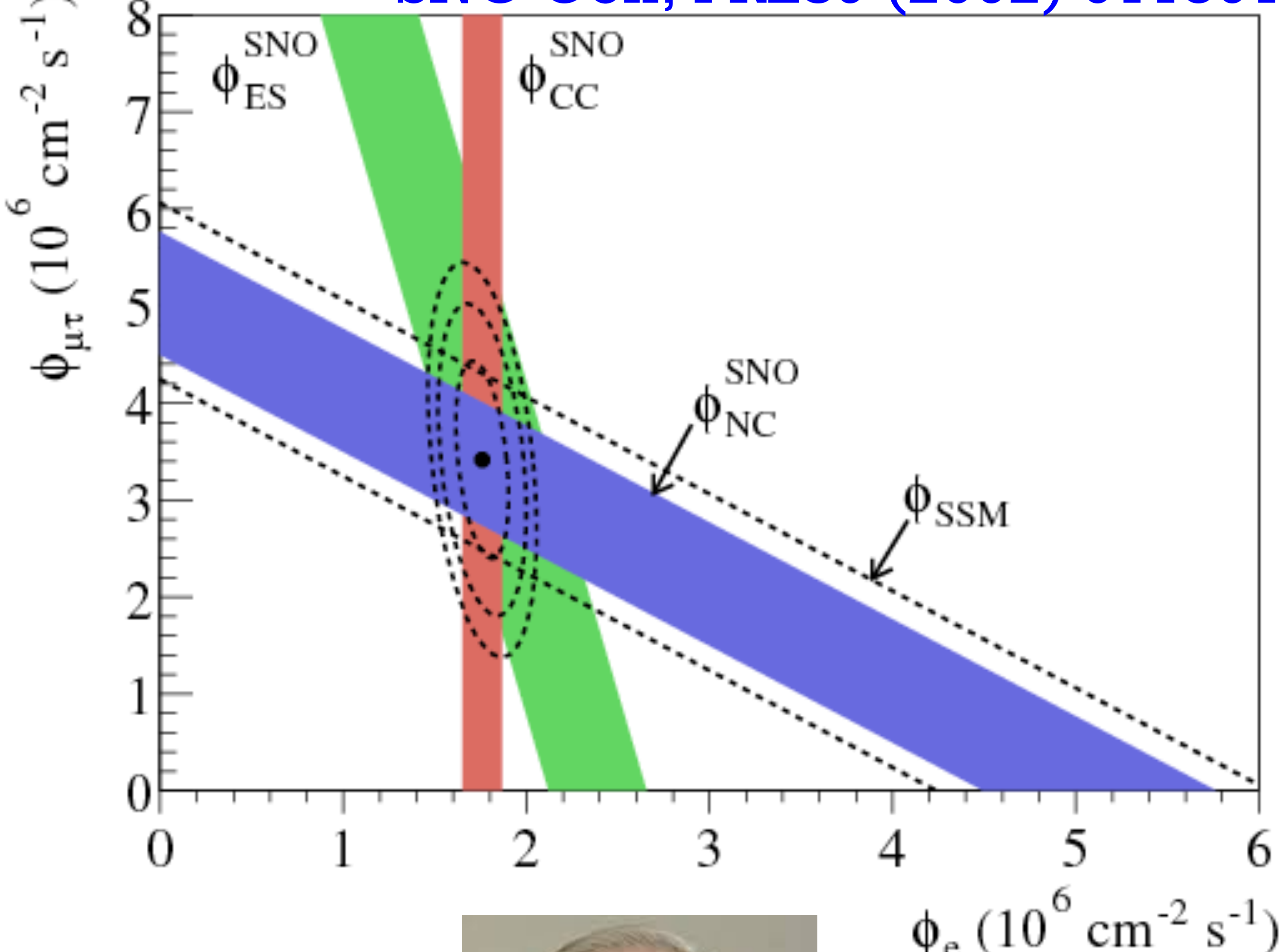
Neutral-currents (NC):

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



All flavors equally
Total neutrino flux

SNO Coll, PRL89 (2002) 011301

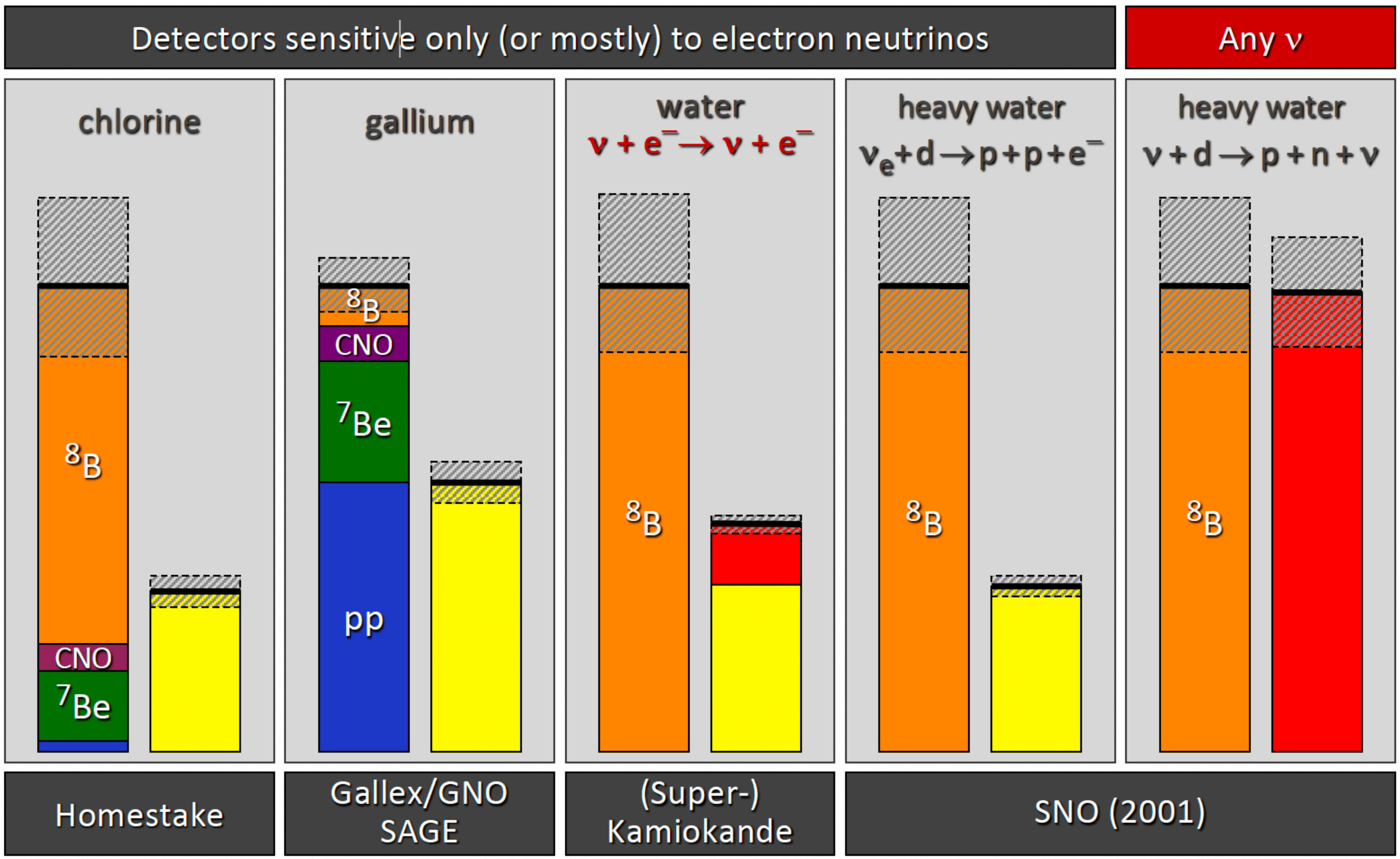


$$\frac{\phi^{\rm SNO}_{\rm CC}}{\phi^{\rm SNO}_{\rm NC}} = 0.301 \pm 0.033$$ → 30% of solar neutrinos are detected as ν_e

$$\phi^{\rm SNO}_{\rm NC} \simeq \phi^{\rm SSM}_{^8\rm B}$$ → $\boxed{\text{conversion } \nu_e \rightarrow \nu_\mu, \nu_\tau}$

2015 Nobel Prize in Physics

The solar neutrino ~~problem~~



All solar neutrinos predicted by the SSM are detected

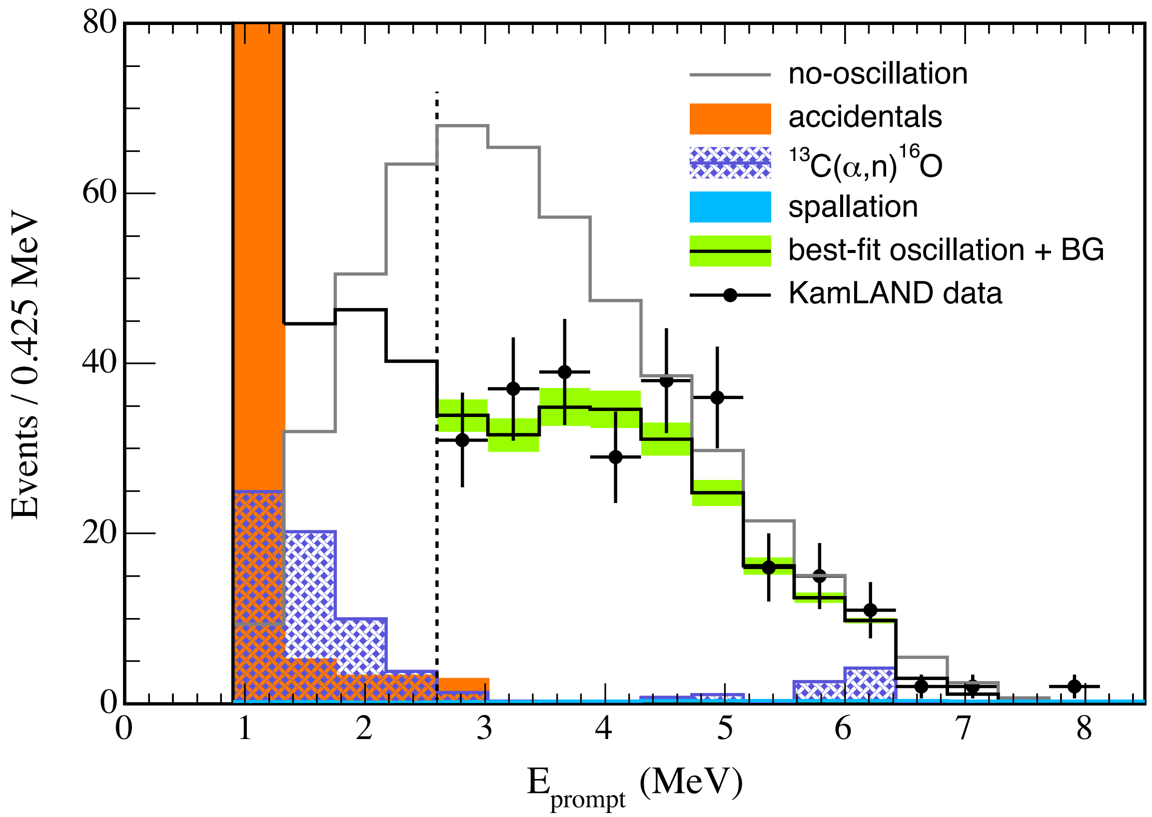
SNO confirms the conversion

$\boxed{\nu_e \to \nu_\mu, \nu_\tau}$

Conversion mechanism??

Other important results

2002: The reactor experiment KamLAND observed neutrino oscillations consistent with the solar anomaly.



KamLAND Coll, PRL 90 (2003) 021802

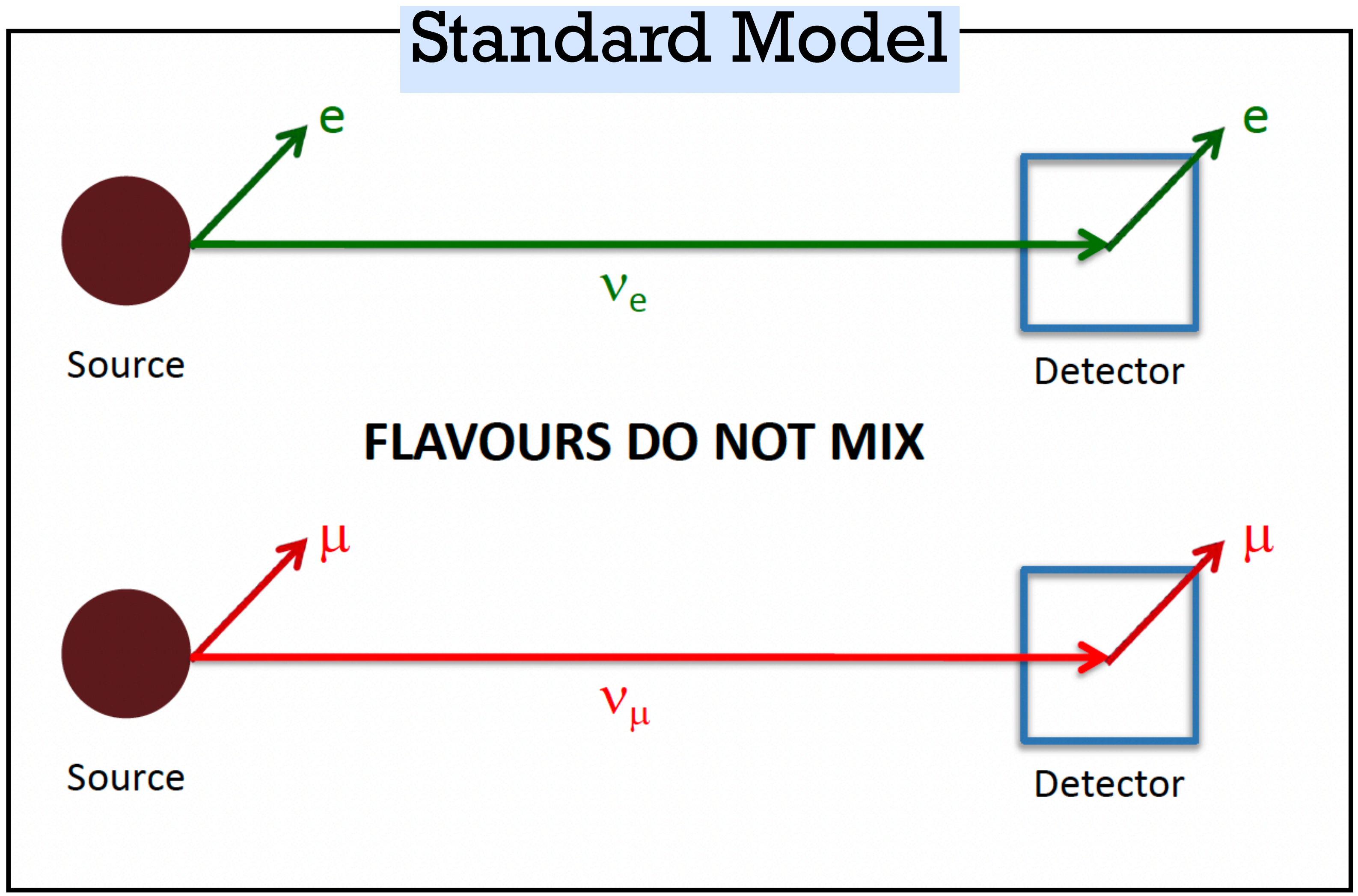
2002: Results of the accelerator experiment K2K consistent with ν_μ oscillations as in the atmospheric anomaly (MINOS, T2K, NOvA).

2011: $\nu_\mu \to \nu_e$ oscillations observed in long-baseline accelerator experiments.

2011: Double Chooz confirmed reactor antineutrino oscillations in a baseline of ~1 km (Daya Bay, RENO).

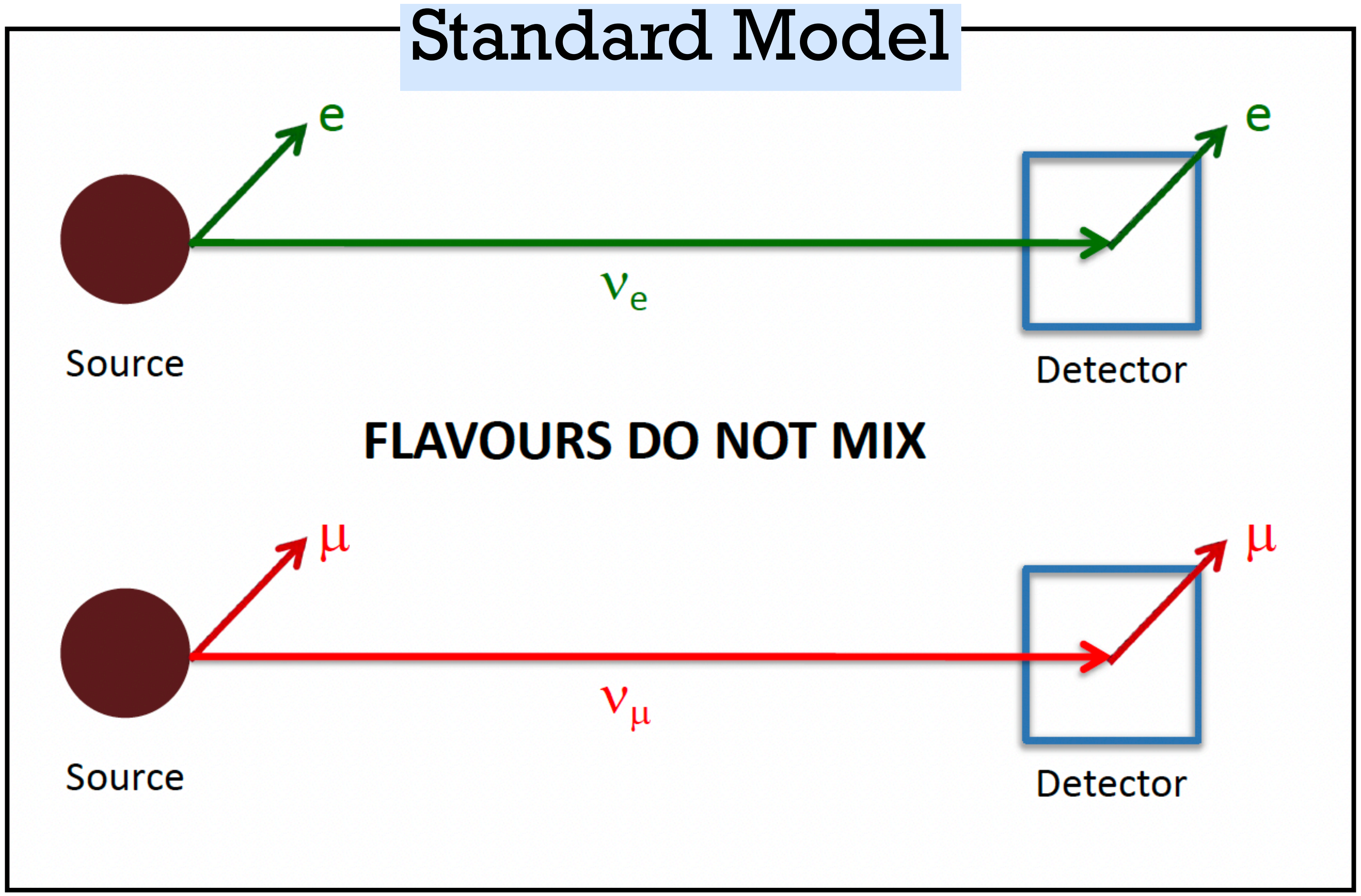
neutrino oscillations have been observed in solar, atmospheric, reactor and accelerator neutrino experiments.

Neutrino oscillations

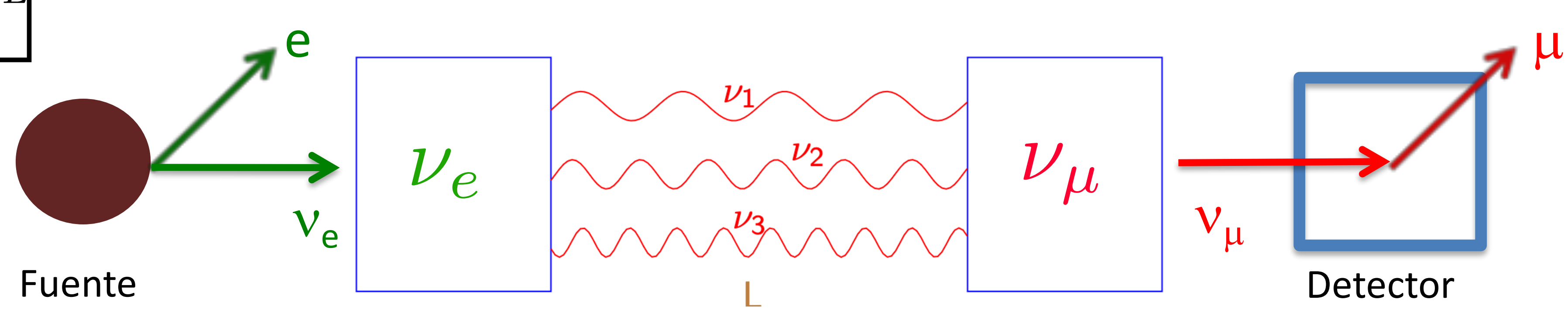


However

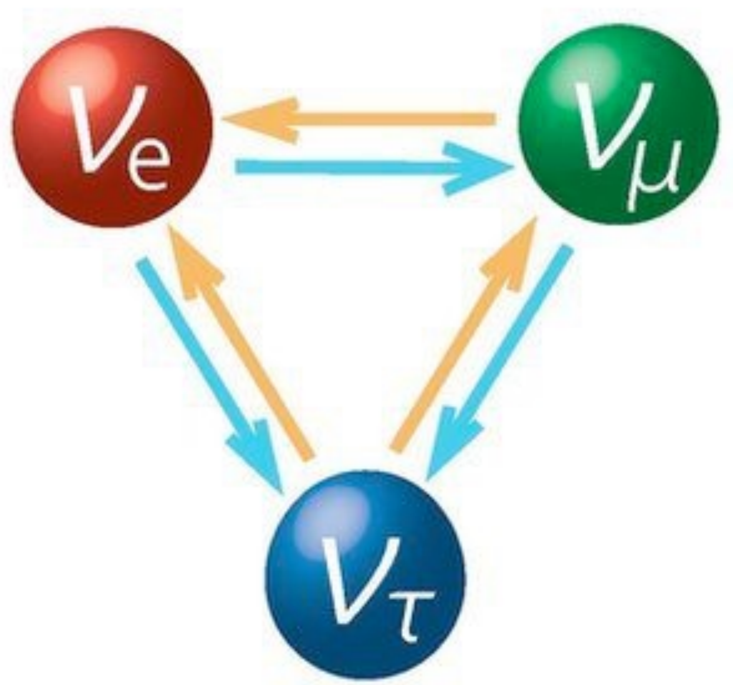
Neutrino oscillations



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



Neutrino oscillations: formalism



Neutrino mixing

✦ Mixing described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

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

✦ NxN unitary matrix: NxN real parameters

→ N(N-1)/2 mixing angles + N(N+1)/2 phases (not all observables!)

✦ Leptonic weak charged current:

N(N+1)/2 phases

$$J^\rho = 2 \sum_\alpha \overline{l_{\alpha L}} \gamma^\rho \nu_{\alpha L} = \sum_\alpha \sum_k \overline{l_{\alpha L}} \gamma^\rho U_{\alpha k} \nu_{kL}$$

✦ Lagrangian invariant under global phase transformations of Dirac fields:

$$l_\alpha \to e^{i\theta_\alpha} l_\alpha \,, \quad \nu_k \to e^{i\phi_k} \nu_k$$

$$J^\rho \to 2 \sum_{\alpha,k} \overline{l_{\alpha L}} e^{-i(\underbrace{\theta_\alpha - \phi_1}_{\mathrm{N}})} \gamma^\rho U_{\alpha k} e^{i(\underbrace{\phi_k - \phi_1}_{\mathrm{N-1}})} \nu_{kL}$$

(2N-1) phases from U reabsorbed in the fields

(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:

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

→ only N phases can be eliminated by rephasing charged lepton fields (neutrino fields can not be rephased!!):

$$J^\rho \to 2 \sum_{\alpha,k} \overline{l_{\alpha L}} \underset{\mathbf{N}}{e^{-i\theta_\alpha}} \gamma^\rho U_{\alpha k} \nu_{kL}$$

N(N+1)/2 - N = N(N-1)/2 physical phases for Majorana neutrinos

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

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

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   reactor + LBL   solar + KamLAND

Neutrino oscillations

- Flavour states are admixtures of mass eigenstates: $$\nu_{\alpha L} = \sum_j U_{\alpha j}\nu_{kL}$$

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

in the neutrino mass eigenstates basis ν_j :

$$H = \begin{pmatrix} E_i & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}$$

$\rightarrow$ neutrino mass eigenstates evolve as planes waves *:

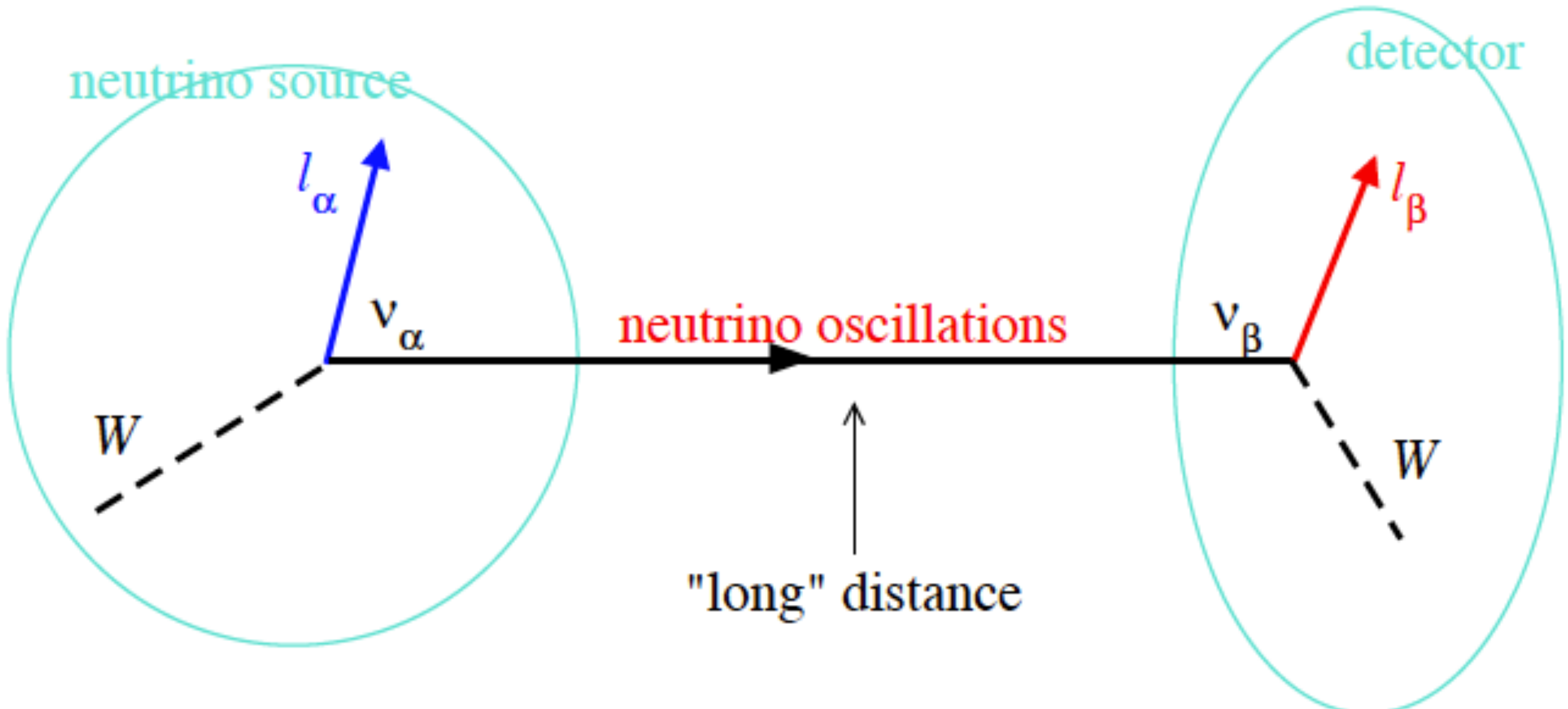
$$|\nu_j(t,L)\rangle = e^{-i(E_j t - p_j L)}|\nu_j\rangle$$

- For ultrarelativistic neutrinos: $$(E_j - p_j)L = \frac{E_j^2 - p_j^2}{E_j + p_j}L \simeq \frac{m_j^2}{2E}L$$

(t=L)

$$\rightarrow \quad |\nu_j(t,L)\rangle = e^{-i\frac{m_j^2 L}{2E}}|\nu_j\rangle$$

Neutrino oscillations picture



Production

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

coherent superposition of massive states

Propagation

$$\nu_j : e^{-i\frac{m_j^2 L}{2E}}$$

different propagation phases change ν_j composition

Detection

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

projection over flavour eigenstates

Neutrino oscillation probability

Neutrino oscillation amplitude:

$$\mathcal{A}_{\nu_\alpha\to\nu_\beta} = \langle\nu_\beta(t)|\nu_\alpha(0)\rangle = \sum_j \underbrace{\overbrace{\langle\nu_\beta|\nu_j(t)\rangle}^{\text{detection}}\underbrace{\langle\nu_j(t)|\nu_j(0)\rangle}_{\text{propagation}}\overbrace{\langle\nu_j(0)|\nu_\alpha\rangle}^{\text{production}}}_{}$$

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

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

* For a realistic derivation considering uncertainties in E and L and wave packet treatment see:

Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics. Oxford University Press, 2007.

Neutrino oscillation properties

✦ Conservation of probability: $$\sum_{\beta} P(\nu_\alpha \to \nu_\beta) = 1$$

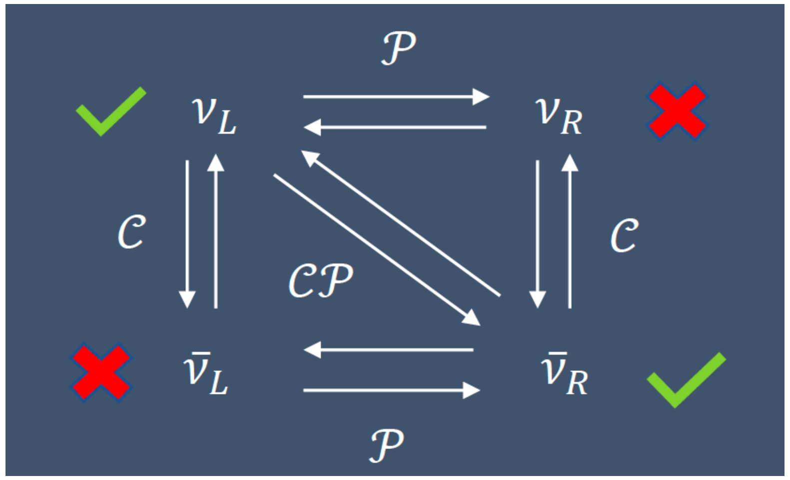
✦ Neutrino oscillations are sensitive only to **mass squared differences**:

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

✦ For **antineutrinos**: U →U*

✦ Phases in the mixing matrix induce **CP violation**:

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

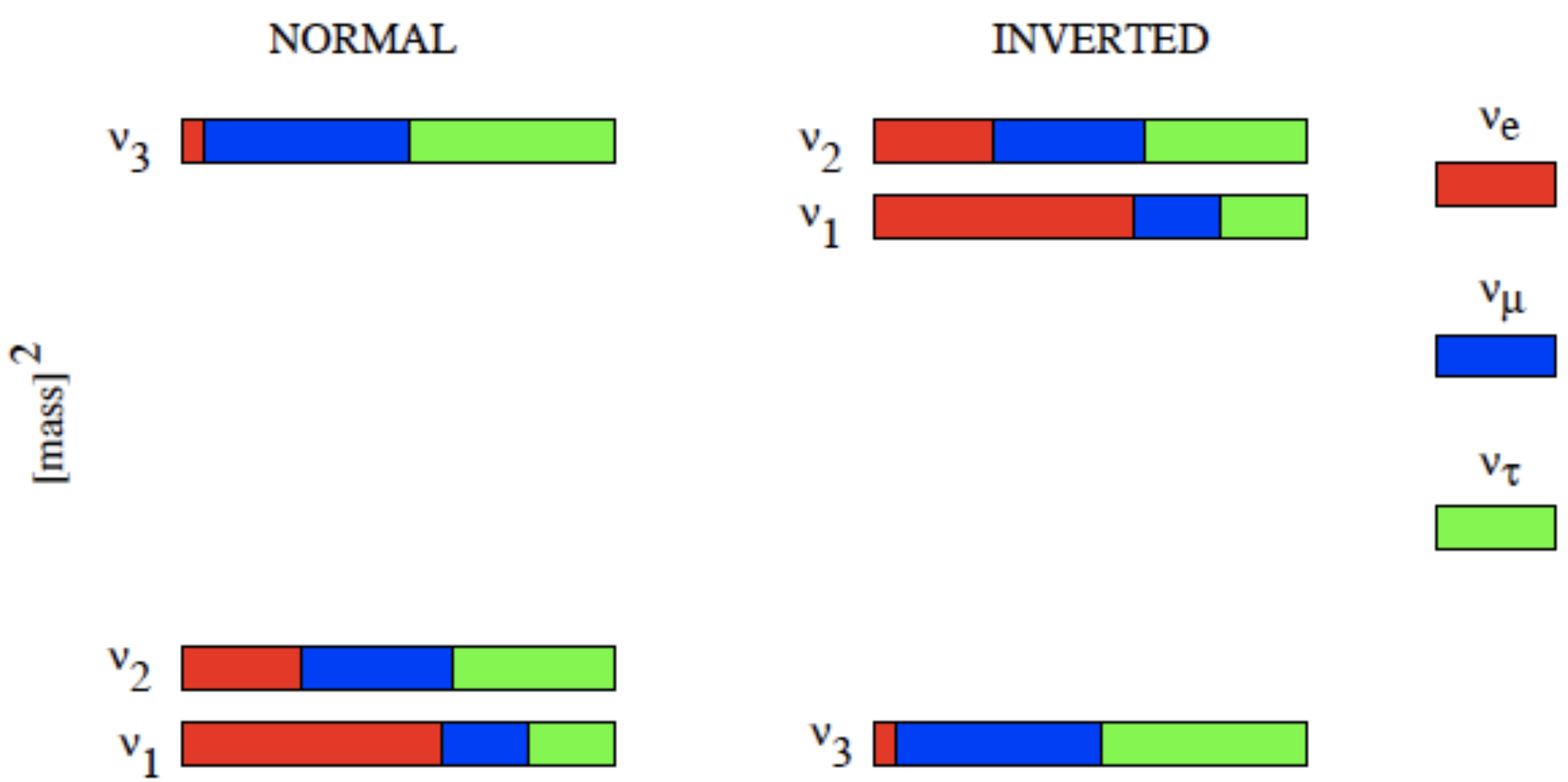


✦ Neutrino oscillations do not depend on the absolute neutrino mass scale and Majorana phases.

✦ Neutrino oscillations violate flavour **lepton number conservation** but conserve total lepton number.

Two possible mass orderings

- Δm^2_{21} : solar + KamLAND (positive)
- Δm^2_{31} : atmospheric + LBL accelerator + SBL reactor (sign?)



$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

Two-neutrino oscillations

- Two-neutrino mixing matrix: $\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

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

$$P(\nu_\alpha \to \nu_\beta) = \left| U_{\alpha 1} U^*_{\beta 1} + U_{\alpha 2} U^*_{\beta 2} e^{-i\frac{\Delta m^2_{21} L}{2E}} \right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- The **oscillation phase**:

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

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

→ long distance, ϕ ~ 1: oscillations are observable

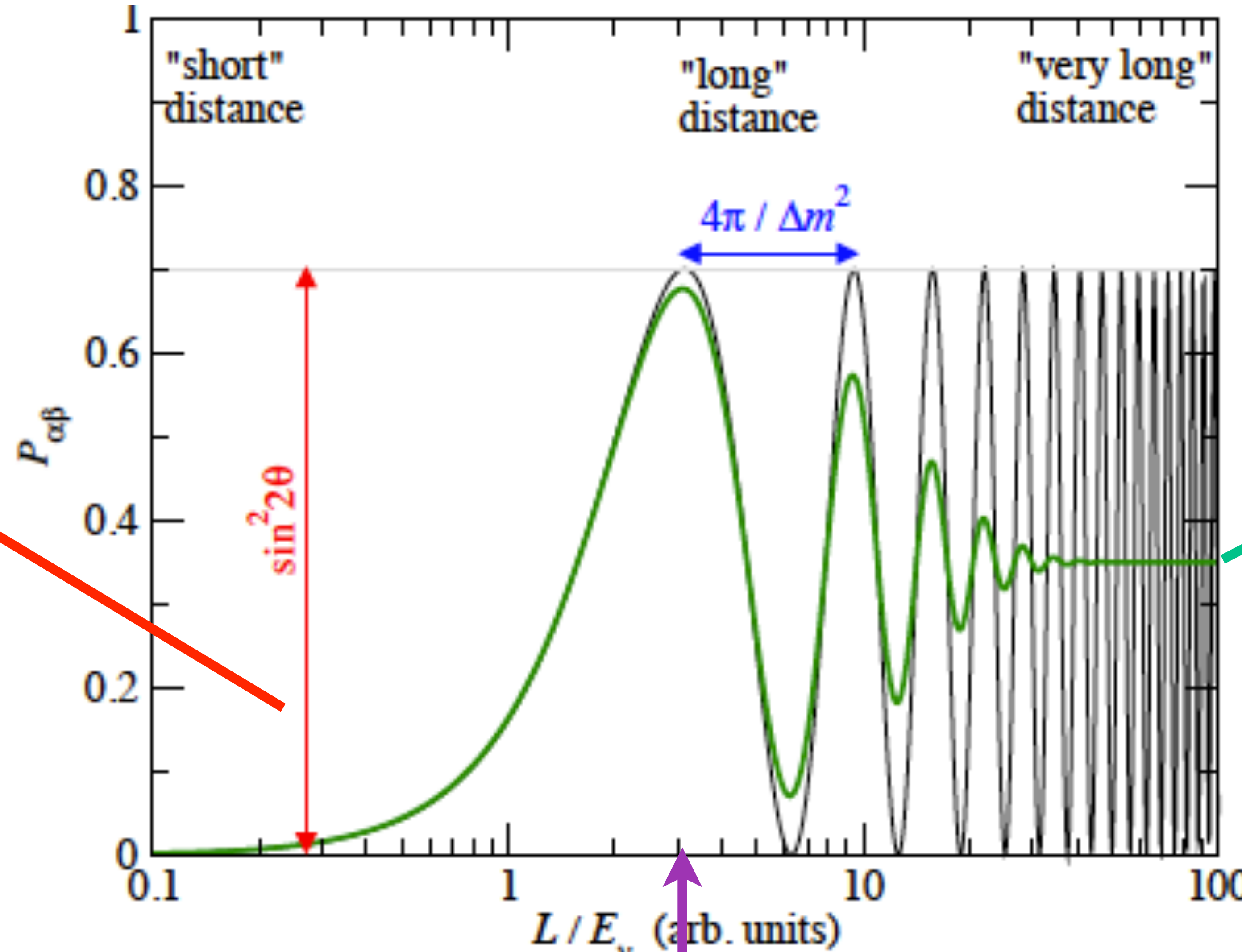
→ very long distances, ϕ >> 1: oscillations are averaged out:

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

2-neutrino oscillation probability

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

oscillation amplitude



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

averaged oscillations

oscillation length:

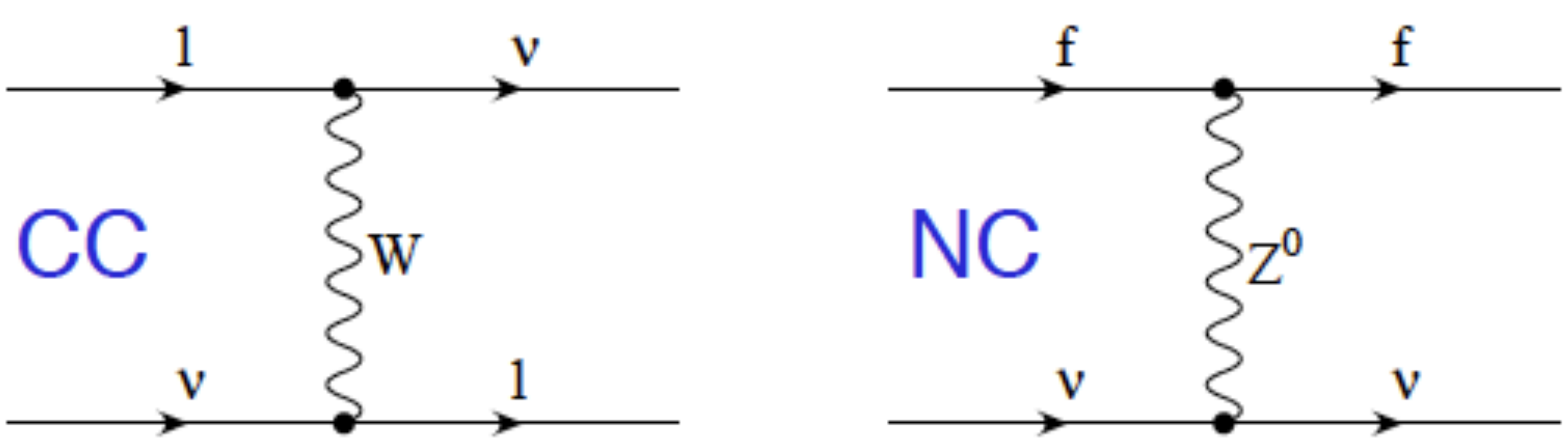
$$L_{\rm osc} = \frac{4\pi E}{\Delta m^2}$$

first oscillation maximum

Matter effects on neutrino oscillations

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

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



→ modifies the **mixing between flavor states and mass eigenstates** as well as the eigenvalues of the Hamiltonian, leading to a different oscillation probability with respect to vacuum oscillations.

Effective matter potential

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

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

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

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

✦ only ν_e 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-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:

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

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

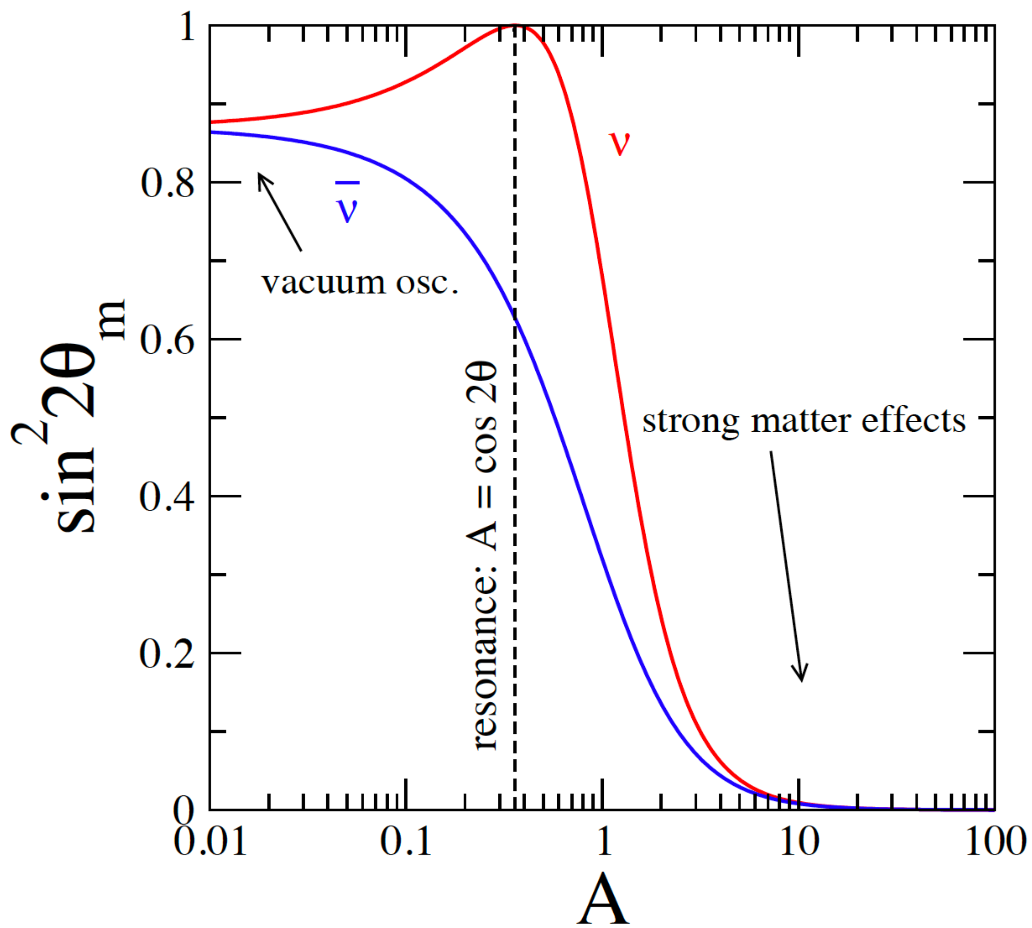
$$A = \frac{2EV}{\Delta m^2}$$

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

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:

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

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

for antineutrinos

✦ $A << \cos2\theta$, small matter effect → vacuum oscillations: $\theta_M = \theta$

✦ $A >> \cos2\theta$, matter effects dominate → oscillations suppressed: $\theta_M \approx \pi/2$

✦ $A = \cos2\theta$, resonance takes place → maximal mixing $\theta_M \approx \pi/4$

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

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

2-ν oscillations in varying matter

- If N_e varies with time (nu beam propagating through the Earth or the Sun)

  → diagonalization of H_{matt} at every instant to obtain $\theta_M(t)$ and $\Delta M^2(t)$

  → evolution of the **instantaneous eigenstates in matter** $\boldsymbol{\nu_i^m}$:

$$i\frac{d}{dt}\nu_\alpha = i\frac{d}{dt}\left[U(\theta_M)\nu_i^m\right] = i\frac{d}{dt}U(\theta_M)\nu_i^m + U(\theta_M)i\frac{d}{dt}\nu_i^m$$

On the other hand:

$$i\frac{d}{dt}\nu_\alpha = H_f\nu_\alpha = U(\theta_M)H_{\text{diag}}\left(\frac{\Delta M^2}{4E}\right)U(\theta_M)^\dagger\nu_\alpha = U(\theta_M)H_{\text{diag}}\left(\frac{\Delta M^2}{4E}\right)\nu_i^m$$

$$\Rightarrow \quad i\frac{d}{dt}\begin{pmatrix}\nu_1^m\\ \nu_2^m\end{pmatrix} = \begin{pmatrix}-\Delta M^2/4E & -i\dot{\theta}_M\\ i\dot{\theta}_M & \Delta M^2/4E\end{pmatrix}\begin{pmatrix}\nu_1^m\\ \nu_2^m\end{pmatrix}$$

→ the presence of off-diagonal terms induce the **mixing of ν_i^m states**

Adiabatic evolution

$$i\frac{d}{dt}\begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix} = \begin{pmatrix} -\Delta M^2/4E & -i\dot{\theta}_M \\ i\dot{\theta}_M & \Delta M^2/4E \end{pmatrix}\begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

- For small off-diagonal terms: $|\dot{\theta}_M| \ll \Delta M^2/4E$

→ the transitions between the instantaneous eigenstates ν_1^m and ν_2^m are suppressed: **adiabatic approximation**.

- Adiabaticity condition:

$$\gamma^{-1} \equiv \frac{2\dot{\theta}_M}{\Delta m^2/2E} = \frac{\sin 2\theta \Delta m^2/2E}{(\Delta M^2/2E)^3}|\dot{V}_{CC}| \ll 1$$

adiabaticity parameter

from the instantaneous expression of θ_M

the typical value in the Sun: $\gamma^{-1} \sim \frac{\Delta m^2}{10^{-9}\mathrm{eV}^2}\frac{\mathrm{MeV}}{E}$

→ adiabaticity applies up to 10 GeV

Solar neutrinos: the MSW effect

- 2nu approx: 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:

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

$$P_{e1}^{\text{prod}} = \cos^2\theta_M\,, \quad P_{1e}^{\text{det}} = \cos^2\theta$$
$$P_{e2}^{\text{prod}} = \sin^2\theta_M\,, \quad P_{2e}^{\text{det}} = \sin^2\theta$$

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

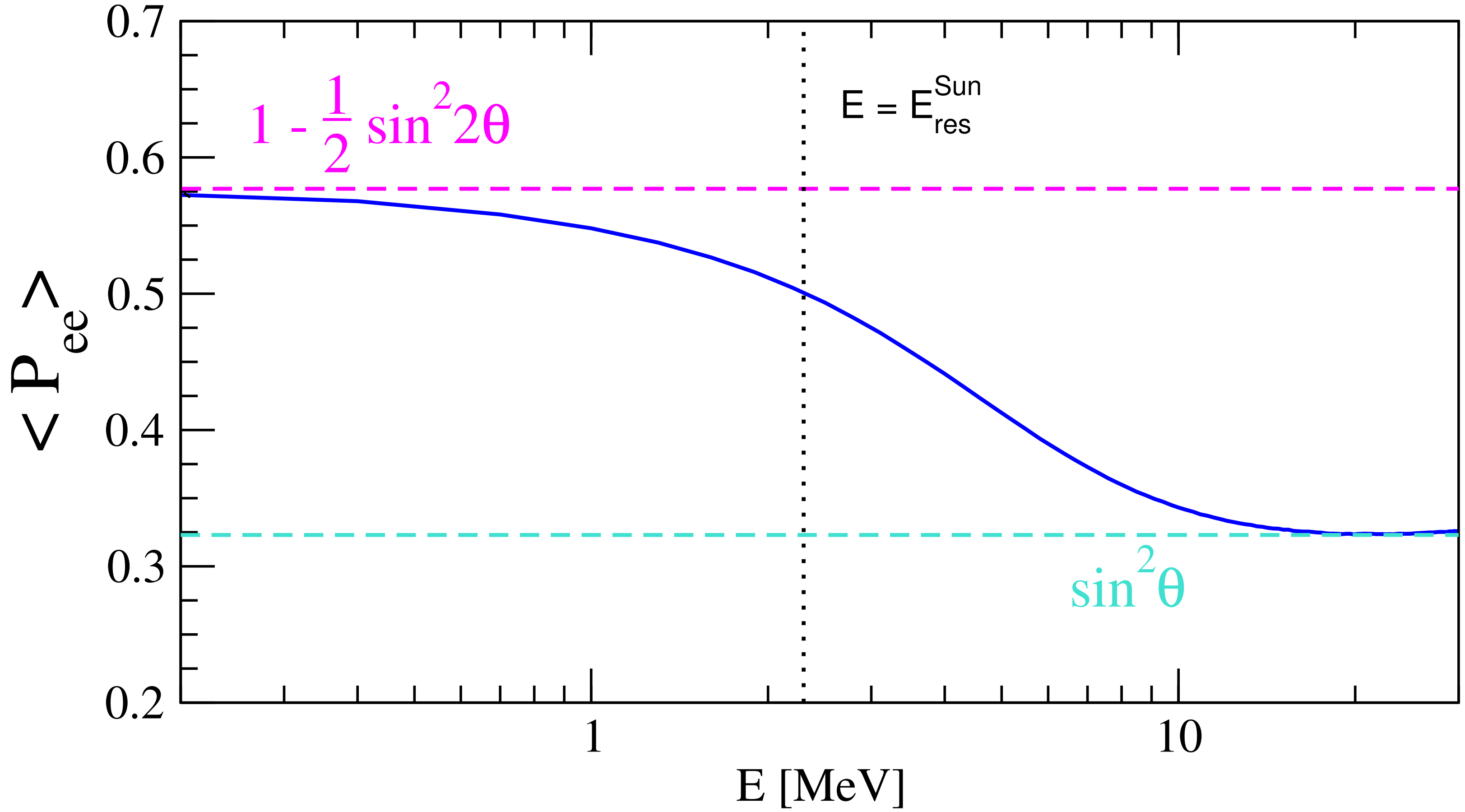
Solar neutrinos: the MSW effect

- In the center of the Sun: $A = \dfrac{2EV}{\Delta m^2} \simeq 0.2 \left(\dfrac{E}{\text{MeV}}\right)\left(\dfrac{8\times 10^{-5}\text{eV}^2}{\Delta m^2}\right)$
- Since resonance occurs for A = cos(2θ) = 0.4 $\rightarrow E_{res} \approx 2$ MeV

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

E < 2 MeV

vacuum oscillations: $\theta_M = \theta$



E > 2 MeV

strong matter effects: $\theta_M = \pi/2$

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

Mass hierarchy in solar neutrinos

✦ Mixing angle in matter:

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

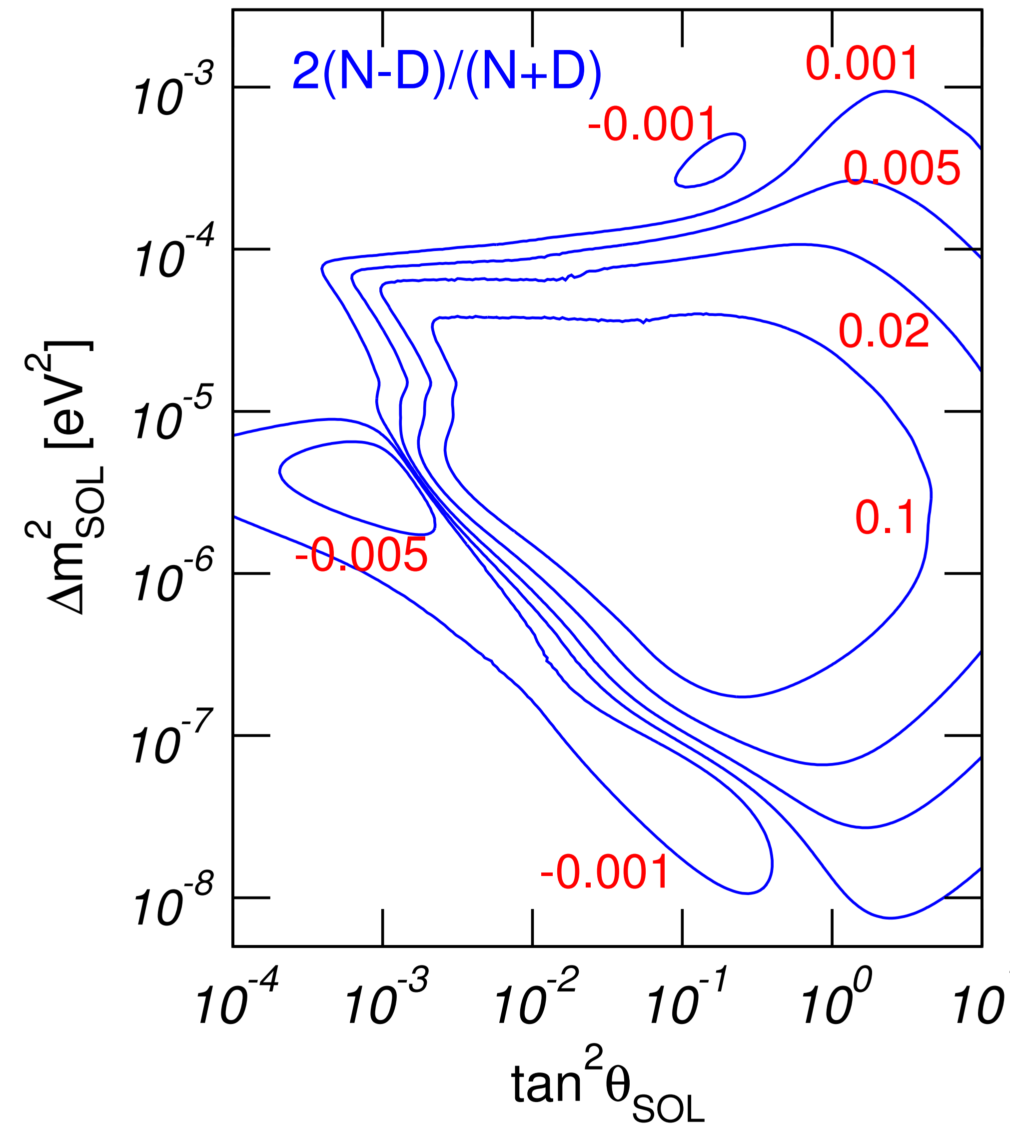
for antineutrinos

→ **resonance condition** A = cos2θ is satisfied for neutrinos for $\Delta m^2 > 0$ and for antineutrinos for $\Delta m^2 < 0$ (change of sign in Vcc)

✦ Matter effects observed in solar neutrino data are in agreement with the presence of a resonance as predicted above:

→ since solar neutrinos are ν_e: $\Delta m^2_{21} > 0 \rightarrow m_2 > m_1$

Earth regeneration effect



- Neutrinos observed at night are also affected by Earth matter effects

- If neutrinos cross only the Earth mantle, P_{2e}^{det} is well approximated by the evolution of a constant potential:

$$P_{2e}^{\text{det}} = \underbrace{\sin^2\theta}_{\text{prob. during day}} + \underbrace{f_{\text{reg}}}_{\text{regeneration term}}$$

$$f_{\text{reg}} = \frac{4EV_{CC}}{\Delta m^2} \sin^2 2\theta_E \sin^2 \frac{\pi L}{L_{\text{osc}}}$$

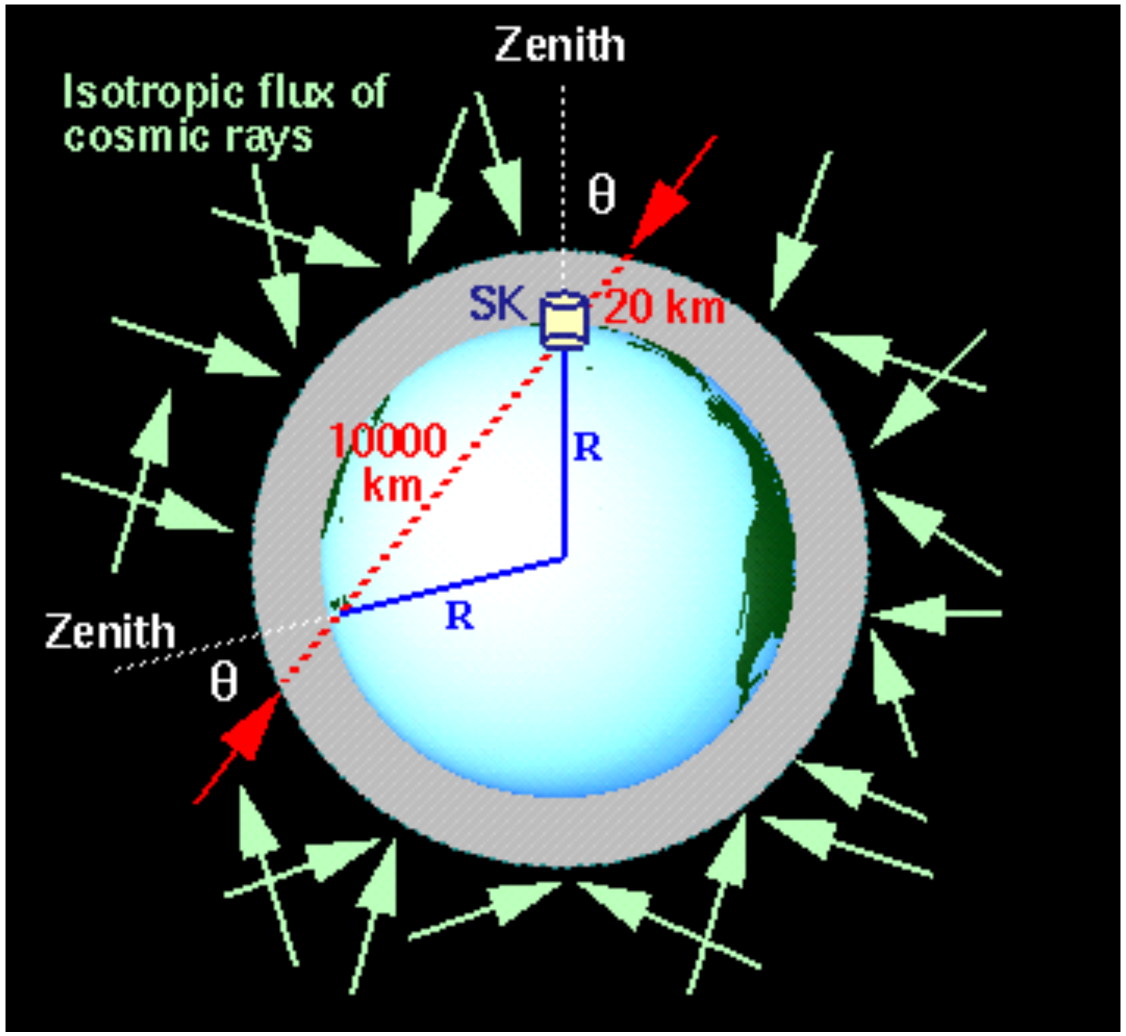
$$P_{ee}^{\text{night}} = P_{ee}^{\text{day}} - \cos 2\theta_M f_{\text{reg}}$$

→ day-night asymmetry:

$$A_{\text{DN}} \equiv 2\frac{(P_N - P_D)}{P_N + P_D}$$

- For the measured solar neutrino parameters $f_{reg} \sim +1\%$

Matter effects in atmospheric ν's



✦ Atmospheric neutrinos interact with the Earth mantle and core

✓ no matter effects in $\nu_\mu \to \nu_\tau$ channel

✓ MSW resonance in $\nu_\mu \to \nu_e$ channel

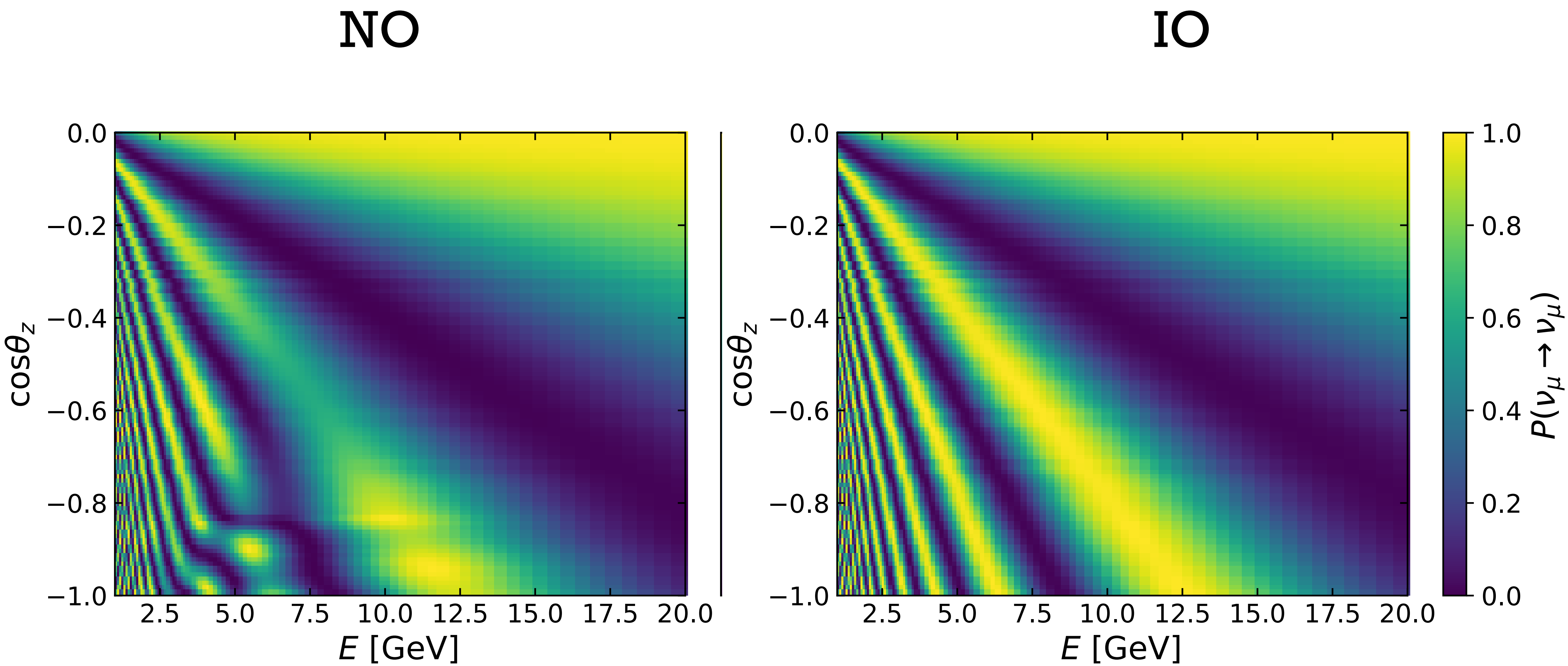
$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{4E}\sin 2\theta}{\frac{\Delta m^2}{4E}\cos 2\theta \mp \sqrt{2} G_F N_e}$$

(-) neutrinos (+)antineutrinos

➙ Matter effects on the atmospheric neutrino flux are sensitive to the mass ordering.

➙ they are harder to observe since $P_{\mu e} \propto \theta_{13}$

Matter effects in atmospheric ν's



de Salas et al, arXiv:1806.11051

At E~ 3-8 GeV: MSW resonance for neutrinos and NO mass spectrum.

For antineutrinos ⟹ the resonance appears in IO