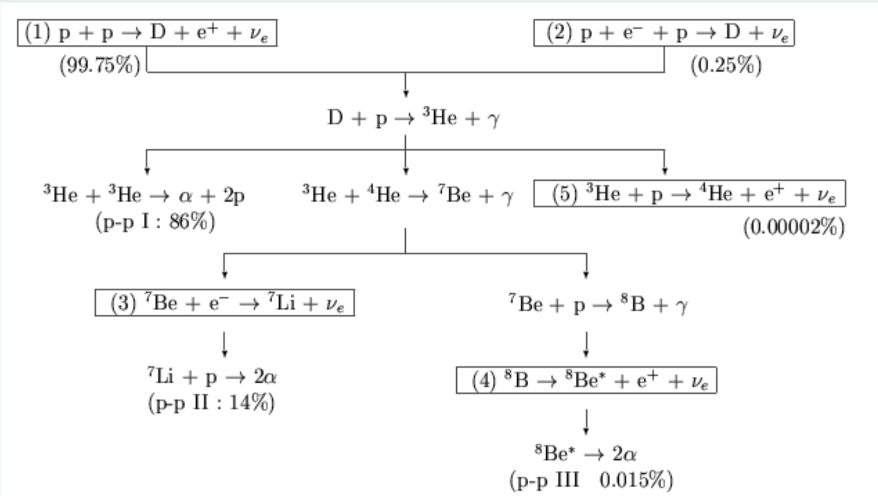
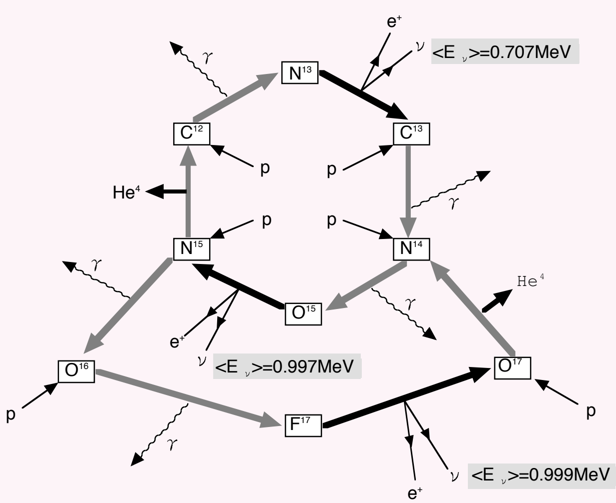
Solar Neutrinos: Fluxes

Concha Gonzalez-Garcia

pp chain



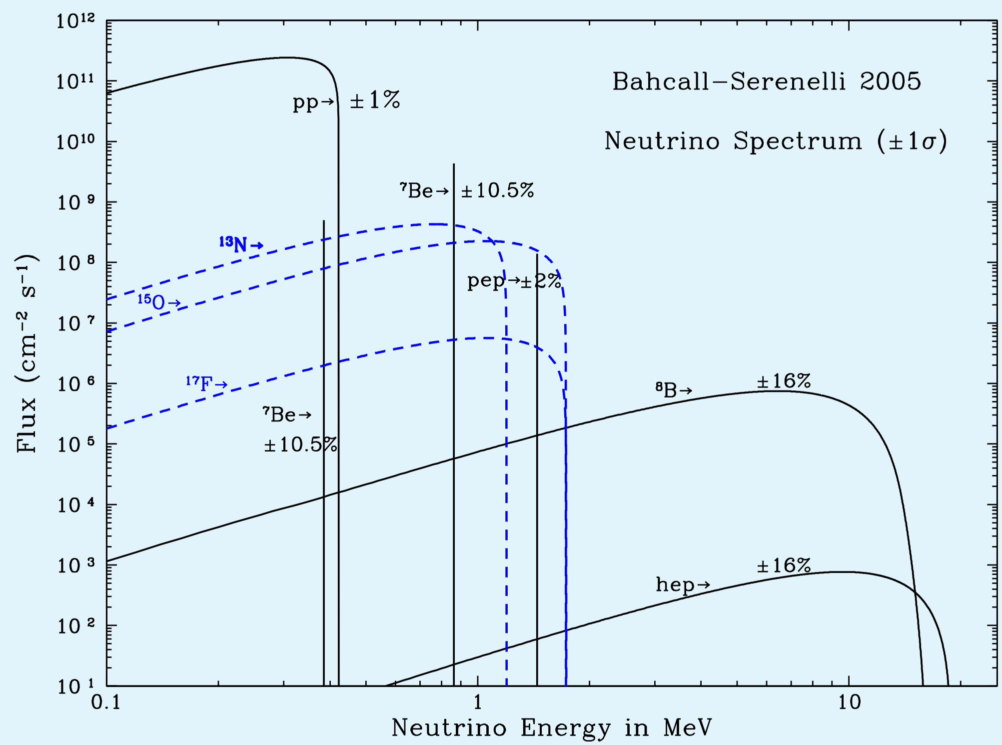
CNO cycle



- Sun shines by :

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

Solar Standard Model Fluxes



Neutrinos in The Sun : MSW Effect

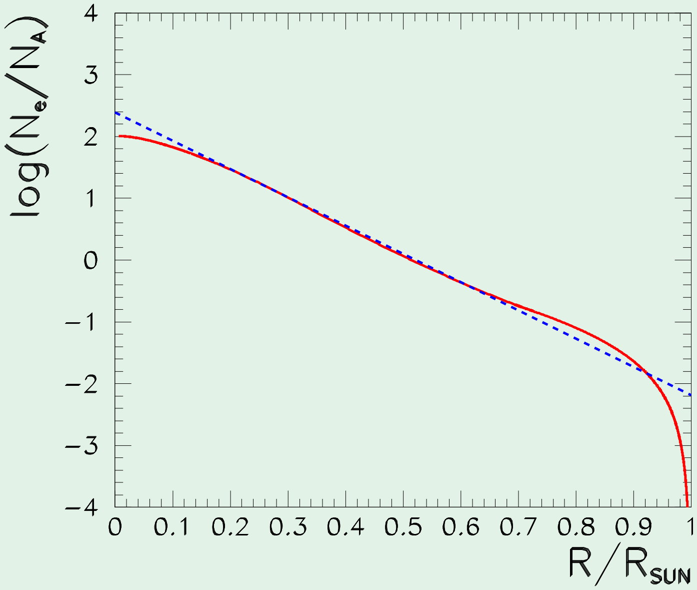
Neutrinos in The Sun : MSW Effect

- Solar neutrinos are ν_e produced in the core ($R \lesssim 0.3 R_\odot$) of the Sun

Neutrinos in The Sun : MSW Effect

- Solar neutrinos are ν_e produced in the core ($R \lesssim 0.3 R_\odot$) of the Sun

The solar matter density



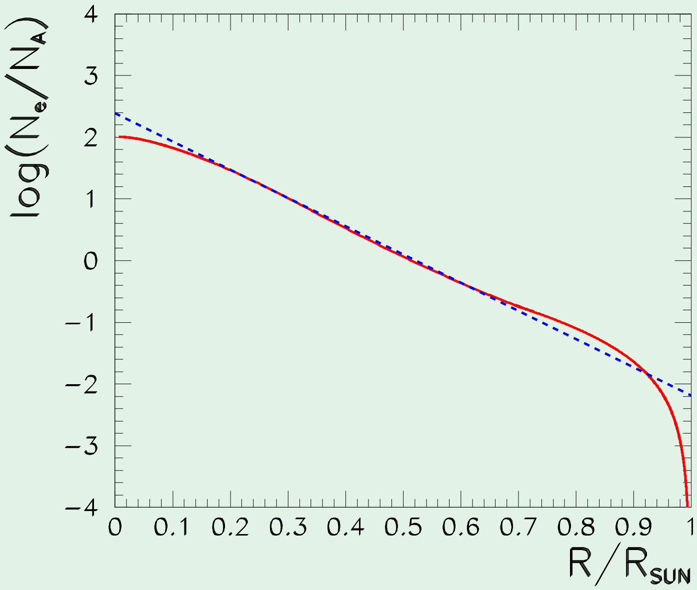
$$V_{CC} = \sqrt{2} G_F N_e \sim 10^{-14} \frac{N_e}{N_A} \text{ eV}$$

At core: $V_{CC,0} \sim 10^{-14}$–10^{-12} eV

Neutrinos in The Sun : MSW Effect

- Solar neutrinos are ν_e produced in the core ($R \lesssim 0.3 R_\odot$) of the Sun

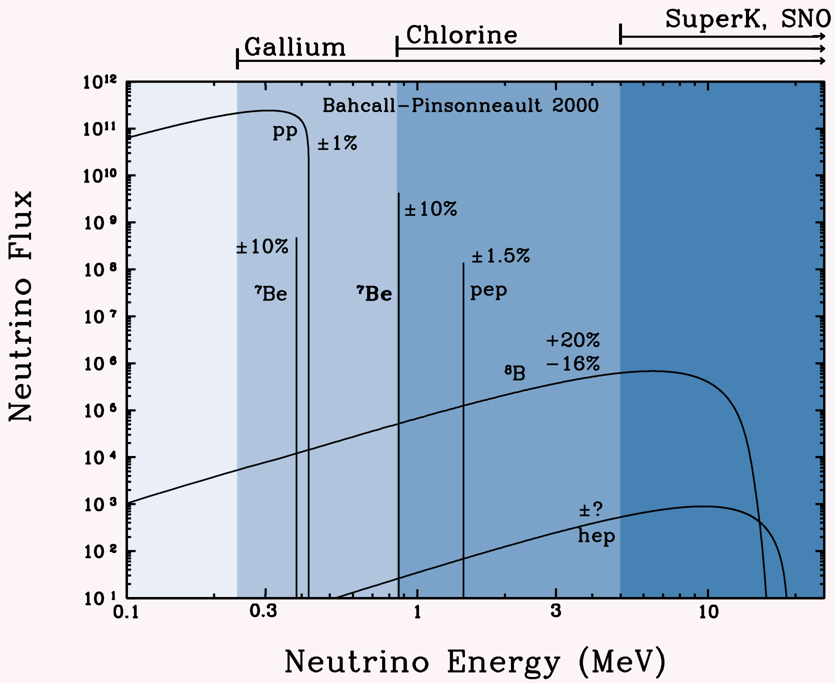
The solar matter density



$$V_{CC} = \sqrt{2} G_F N_e \sim 10^{-14} \frac{N_e}{N_A} \text{ eV}$$

At core: $V_{CC,0} \sim 10^{-14}$–10^{-12} eV

The energy spectrum of solar $\nu_e' s$

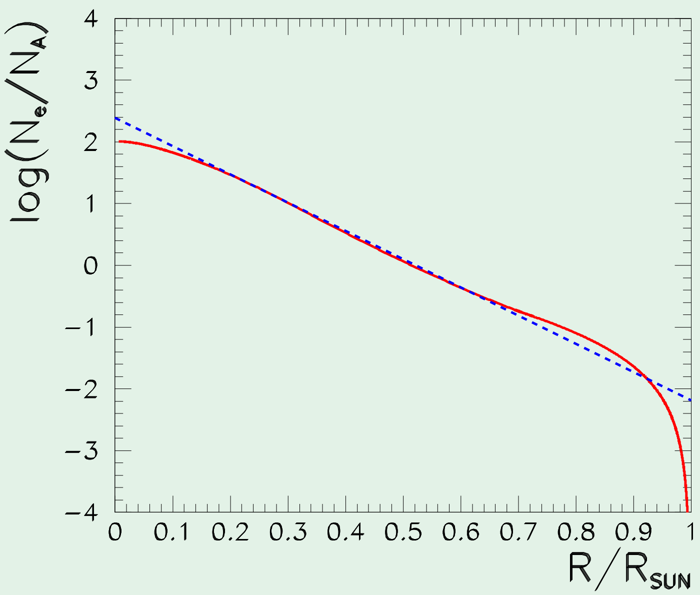


$E_\nu \sim 0.1$–10 MeV

Neutrinos in The Sun : MSW Effect

- Solar neutrinos are ν_e produced in the core ($R \lesssim 0.3 R_\odot$) of the Sun

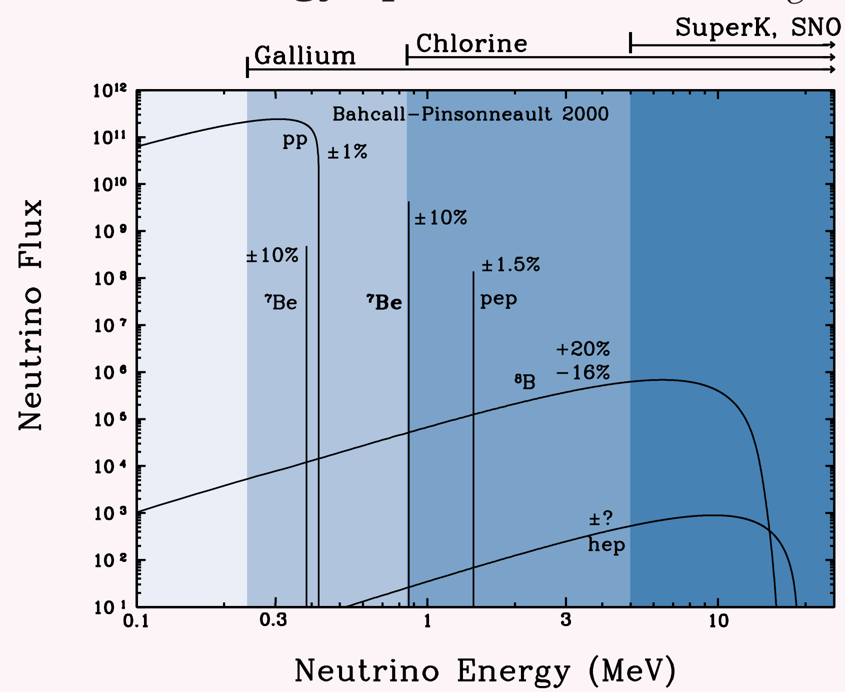
The solar matter density



$$V_{CC} = \sqrt{2} G_F N_e \sim 10^{-14} \frac{N_e}{N_A} \text{ eV}$$

At core: $V_{CC,0} \sim 10^{-14}$–10^{-12} eV

The energy spectrum of solar $\nu_e' s$



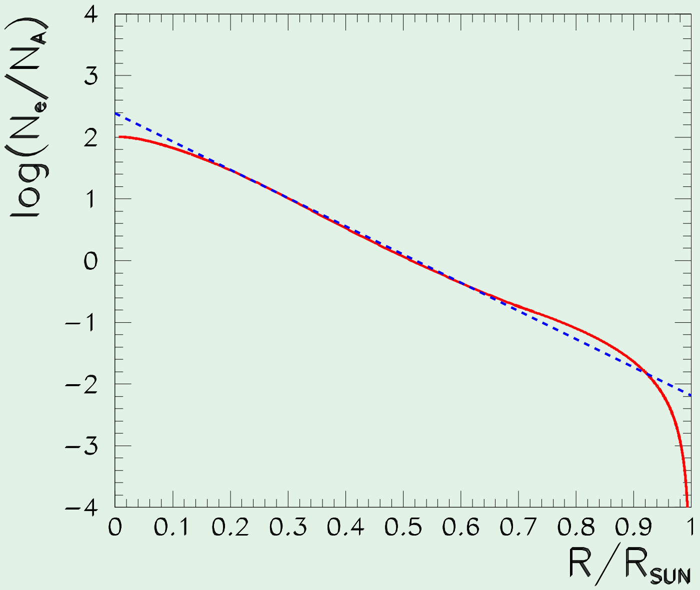
$E_\nu \sim 0.1$–10 MeV

- For $\nu_e \leftrightarrow \nu_{\mu(\tau)}$, in vacuum $\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$
- For 10^{-9} eV$^2 \lesssim \Delta m^2 \lesssim 10^{-4}$ eV^2 $\Rightarrow$ $2 E_\nu V_{CC,0} > \Delta m^2 \cos 2\theta$

Neutrinos in The Sun : MSW Effect

- Solar neutrinos are ν_e produced in the core ($R \lesssim 0.3 R_\odot$) of the Sun

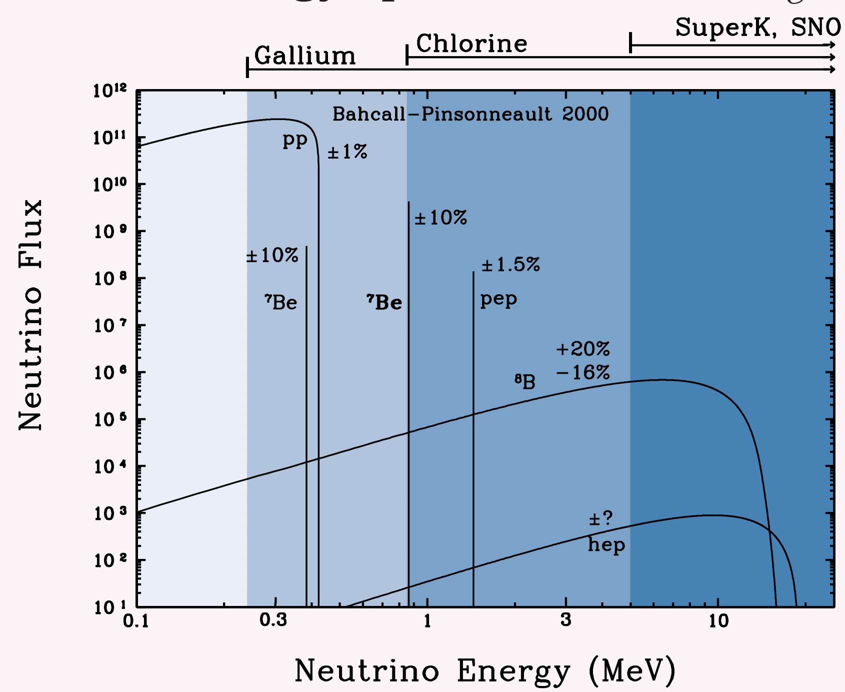
The solar matter density



$$V_{CC} = \sqrt{2} G_F N_e \sim 10^{-14} \frac{N_e}{N_A} \text{ eV}$$

At core: $V_{CC,0} \sim 10^{-14}$–10^{-12} eV

The energy spectrum of solar $\nu_e' s$



$E_\nu \sim 0.1$–10 MeV

- For $\nu_e \leftrightarrow \nu_{\mu(\tau)}$, in vacuum $\nu_e = \cos\theta\, \nu_1 \; + \; \sin\theta\, \nu_2$
- For 10^{-9} eV$^2 \lesssim \Delta m^2 \lesssim 10^{-4}$ eV^2 $\Rightarrow$ $2 E_\nu V_{CC,0} > \Delta m^2 \cos 2\theta$

$\Rightarrow$ ν can cross resonance condition in its way out of the Sun

For $\theta \ll \frac{\pi}{4}$: In vacuum $\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$ is mostly ν_1

In Sun core $\nu_e = \cos\theta_{m,0}\, \nu_1 + \sin\theta_{m,0}\, \nu_2$ is mostly ν_2

For $\theta \ll \frac{\pi}{4}$: In vacuum $\nu_e = \cos\theta\,\nu_1 + \sin\theta\,\nu_2$ is mostly ν_1

In Sun core $\nu_e = \cos\theta_{m,0}\,\nu_1 + \sin\theta_{m,0}\,\nu_2$ is mostly ν_2

If $\frac{(\Delta m^2/\mathrm{eV}^2)\sin^2 2\theta}{(E/\mathrm{MeV})\cos 2\theta} \gg 3\times 10^{-9}$

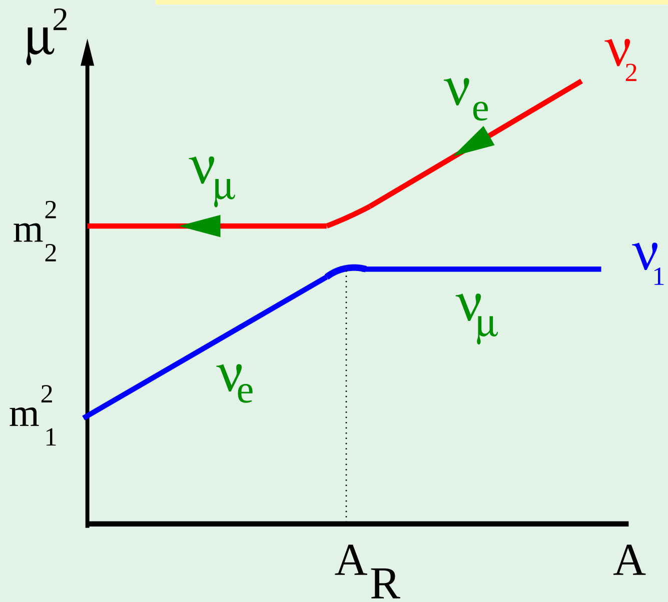
$\Rightarrow$ Adiabatic transition

* ν is mostly ν_2 before and after resonance

* $\theta_m \downarrow$ *dramatically* at resonance

$\Rightarrow \nu_e$ component $\downarrow \Rightarrow P_{ee} \downarrow$

This is the MSW effect



$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta_{m,0}\cos 2\theta\right]$$

For $\theta \ll \frac{\pi}{4}$: In vacuum $\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$ is mostly ν_1

In Sun core $\nu_e = \cos\theta_{m,0}\, \nu_1 + \sin\theta_{m,0}\, \nu_2$ is mostly ν_2

If $\frac{(\Delta m^2/\text{eV}^2)\sin^2 2\theta}{(E/\text{MeV})\cos 2\theta} \gg 3 \times 10^{-9}$

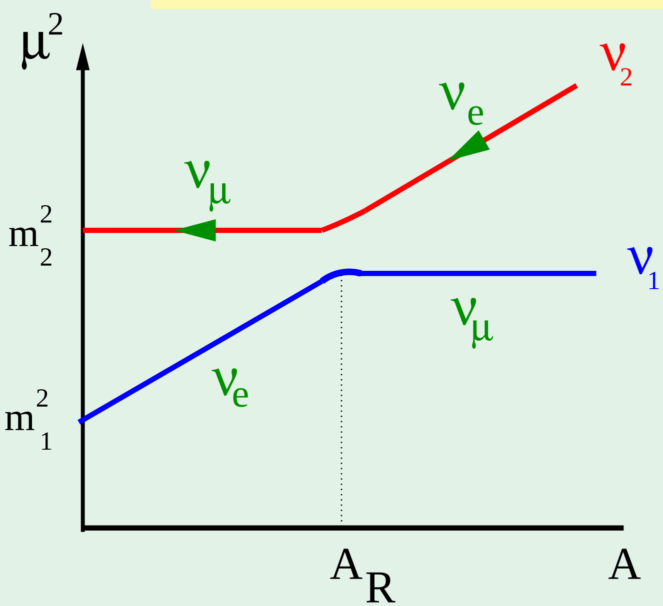
$\Rightarrow$ Adiabatic transition

$*$ ν is mostly ν_2 before and after resonance

$*$ $\theta_m \downarrow$ *dramatically* at resonance

$\Rightarrow \nu_e$ component $\downarrow \Rightarrow P_{ee} \downarrow$

This is the MSW effect



$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta_{m,0} \cos 2\theta\right]$$

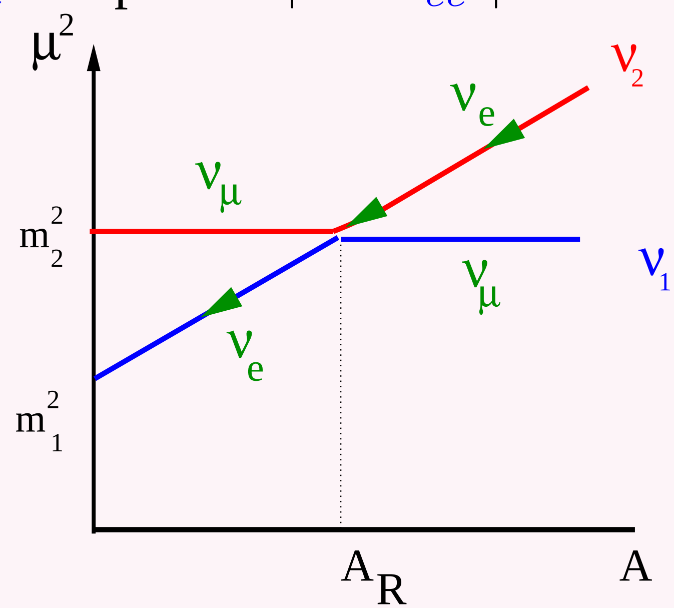
If $\frac{(\Delta m^2/\text{eV}^2)\sin^2 2\theta}{(E/\text{MeV})\cos 2\theta} \lesssim 3 \times 10^{-9}$

$\Rightarrow$ Non-Adiabatic transition

$*$ ν is mostly ν_2 till the resonance

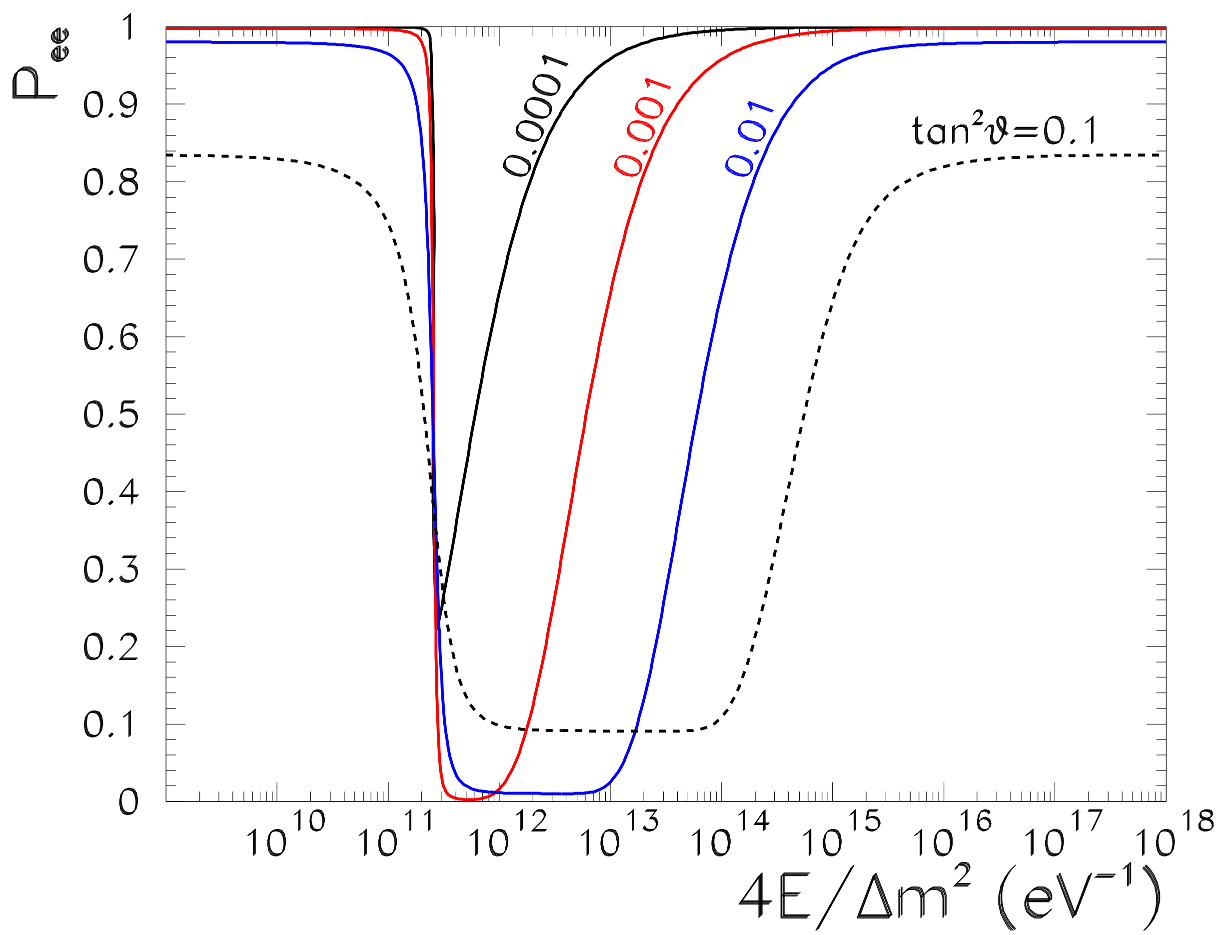
$*$ At resonance the state can jump into ν_1 (with probability P_{LZ})

$\Rightarrow \nu_e$ component $\uparrow \Rightarrow P_{ee} \uparrow$



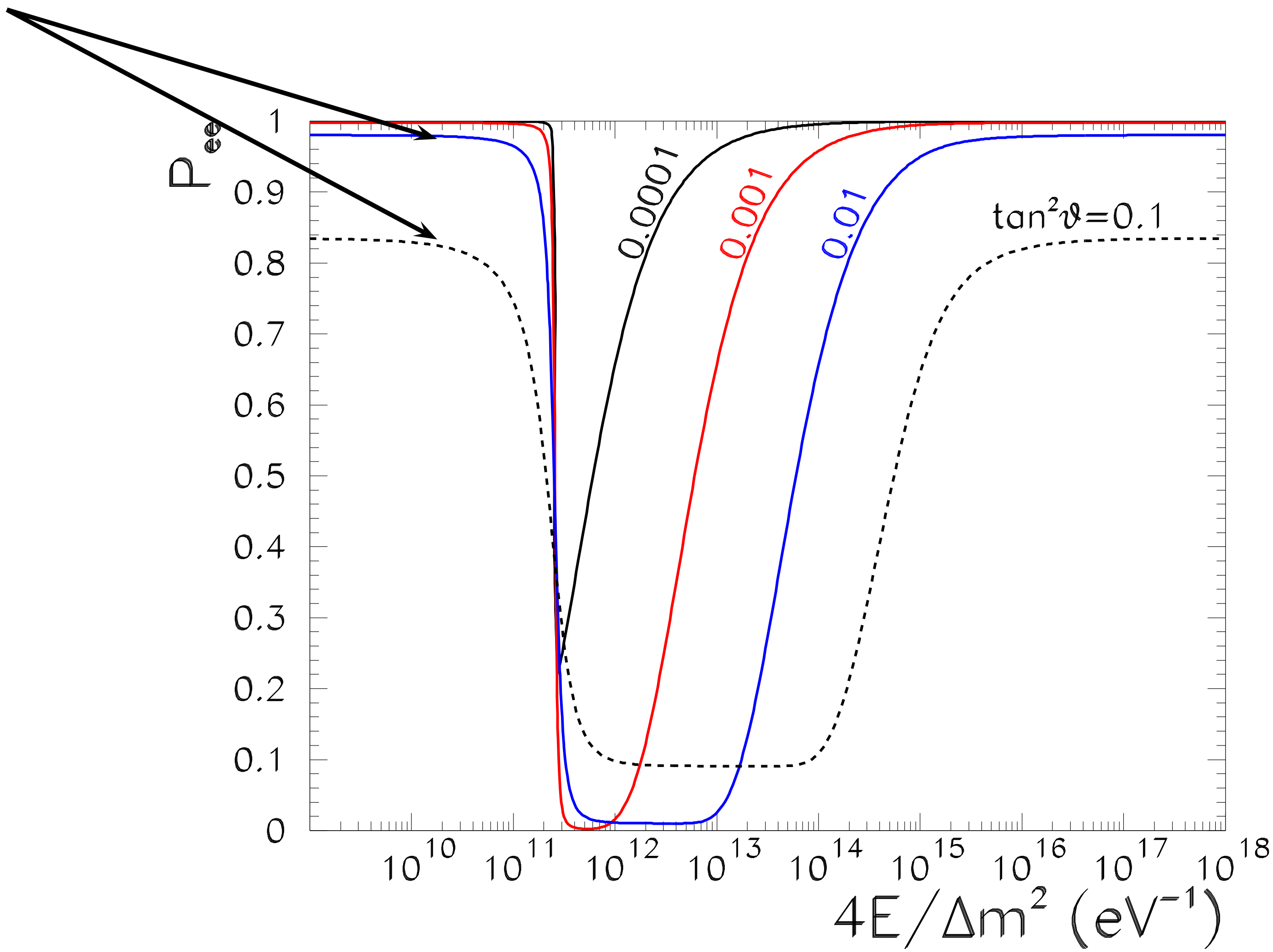
$$P_{ee} = \frac{1}{2}\left[1 + (1 - 2P_{LZ})\cos 2\theta_{m,0} \cos 2\theta\right]$$

Neutrinos in The Sun : MSW Effect



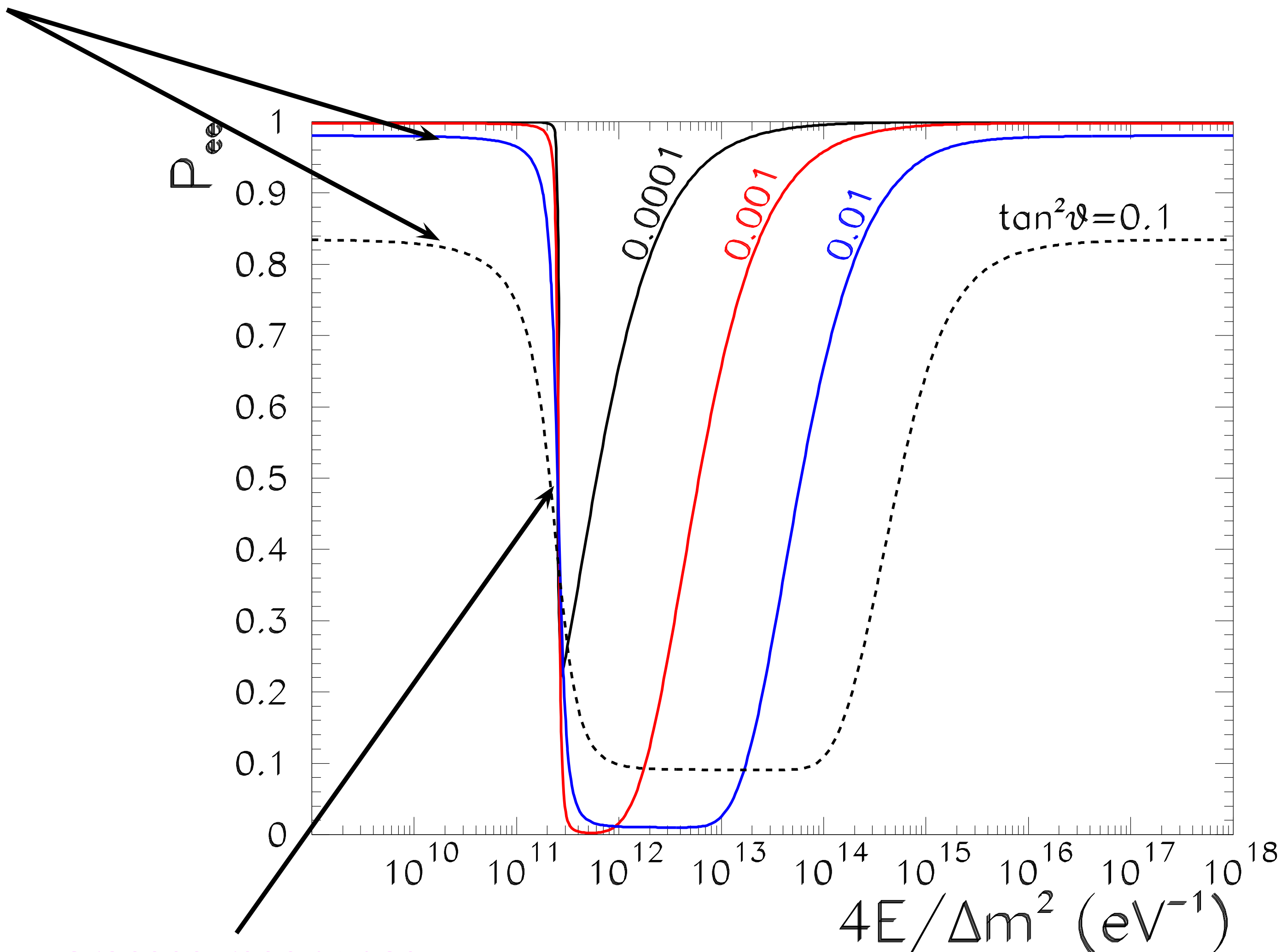
Neutrinos in The Sun : MSW Effect

ν does not cross resonance: $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$



Neutrinos in The Sun : MSW Effect

ν does not cross resonance: $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$

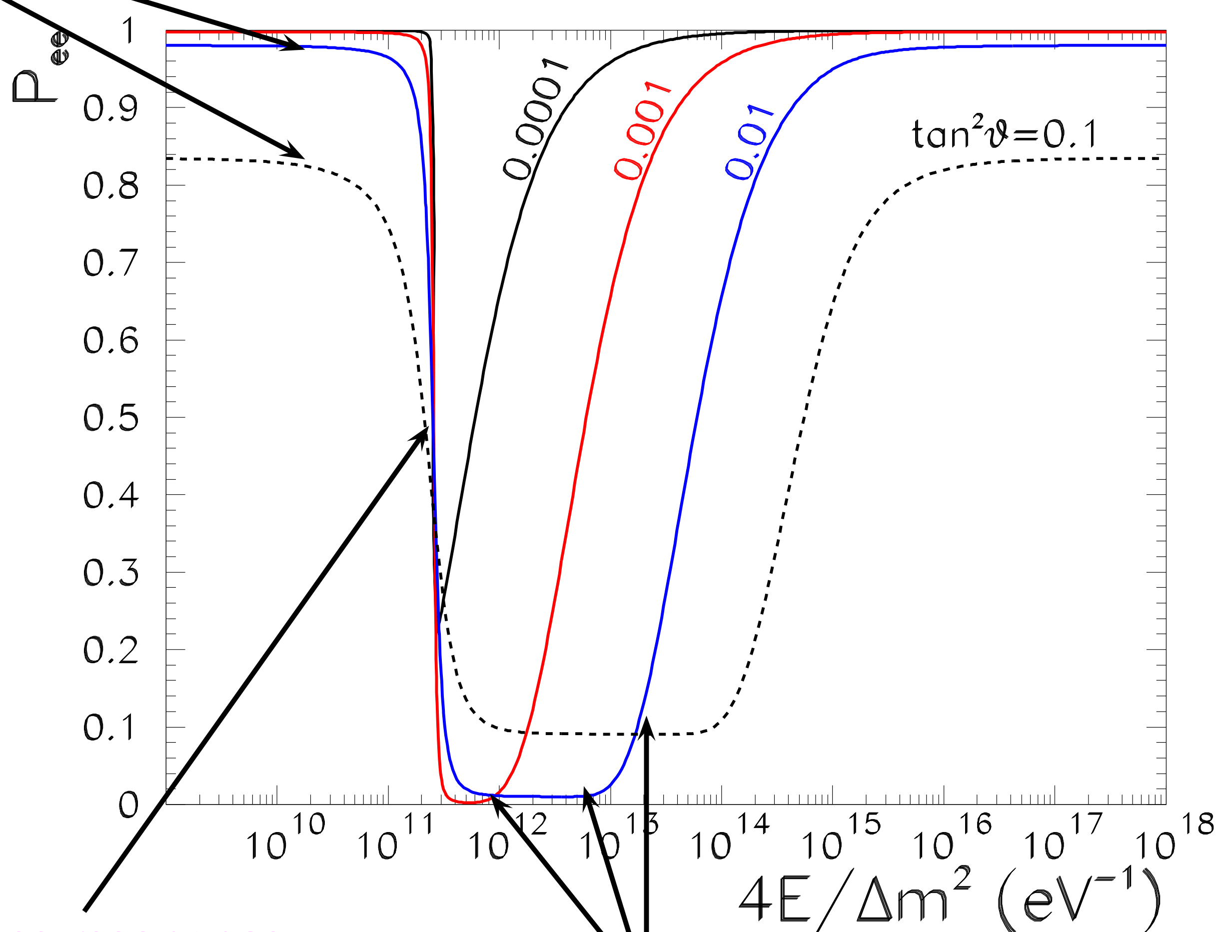


ν crosses resonance

MSW effect

Neutrinos in The Sun : MSW Effect

ν does not cross resonance: $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$



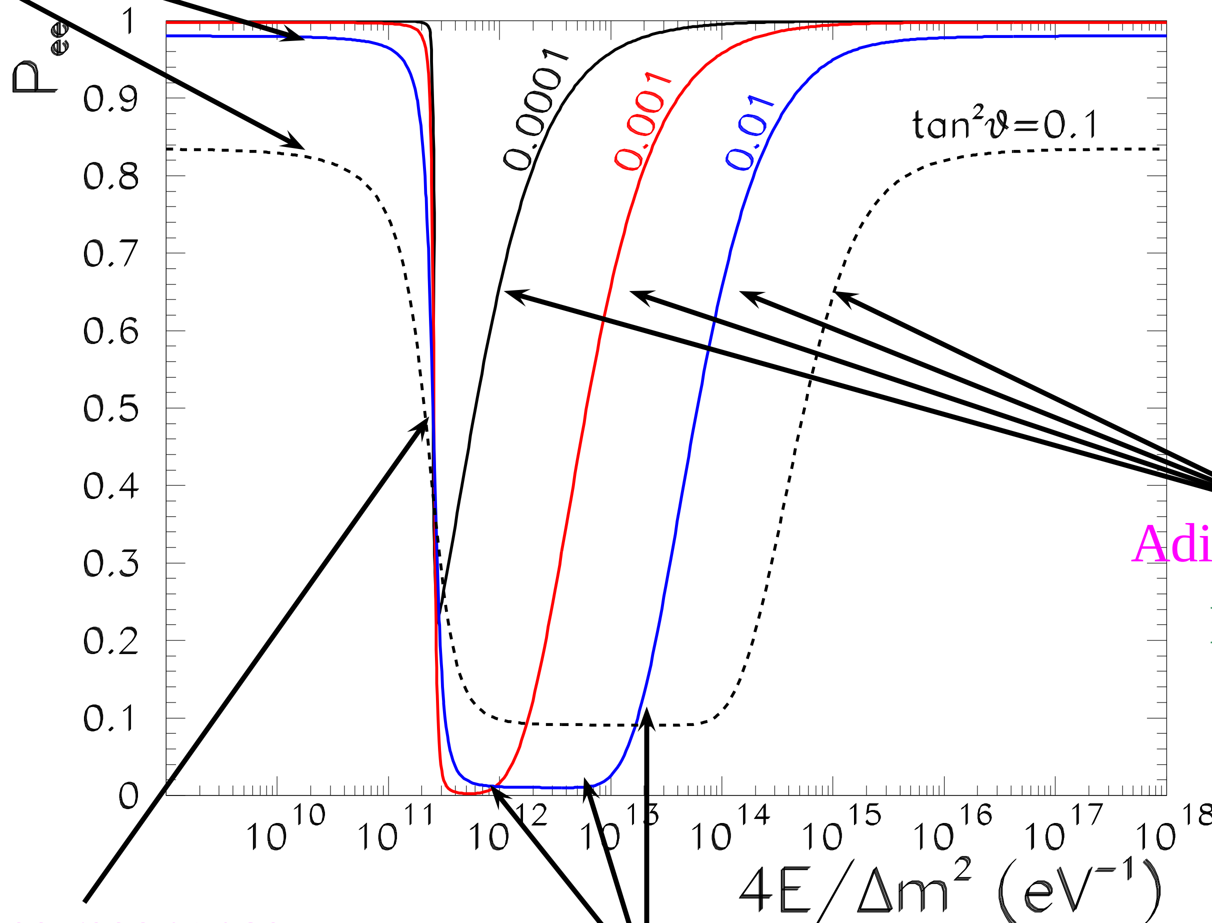
ν crosses resonance

MSW effect

Adiabatic MSW transition $P_{ee} = \sin^2\theta < \frac{1}{2}$

Neutrinos in The Sun : MSW Effect

ν does not cross resonance: $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$



Adiabacity breaking

Effect of P_{LZ}

ν crosses resonance

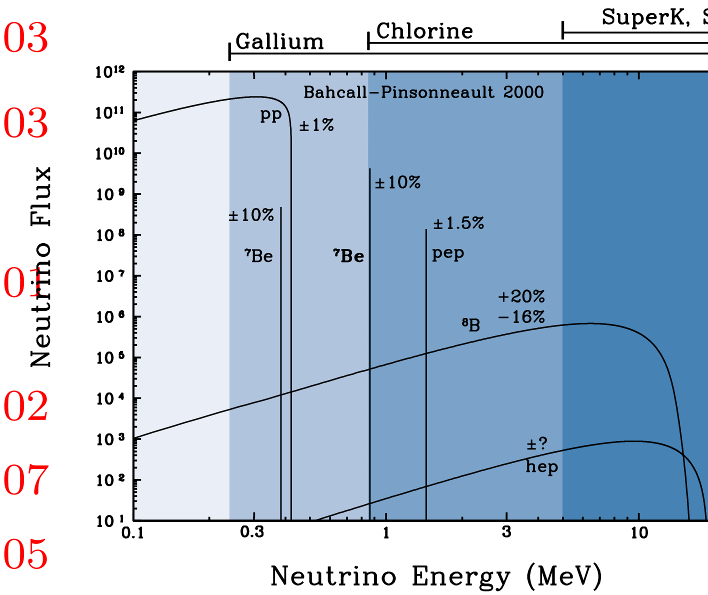
MSW effect

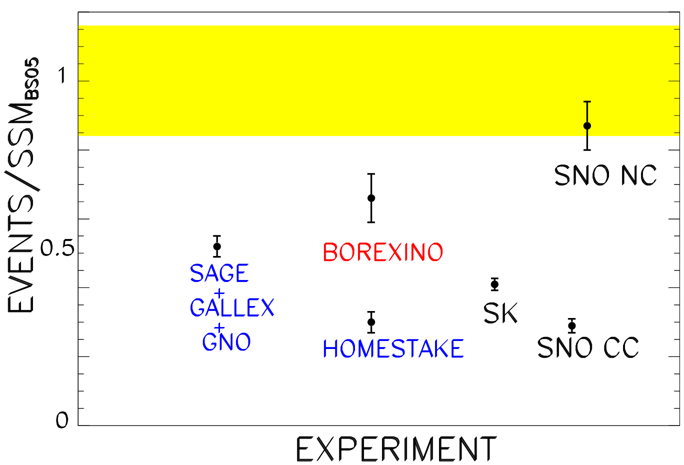
Adiabatic MSW transition $P_{ee} = \sin^2\theta < \frac{1}{2}$

Concha Gonzalez-Garcia

Solar Neutrinos: Data

	Experiment	Detection	Flavour	E_{th} (MeV)	$\frac{\text{Data}}{\text{BS05}}$
radio-chemical	Homestake	$^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$	ν_e	$E_\nu > 0.81$	0.30 ± 0.03
	Sage + Gallex+GNO	$^{71}\text{Ga}(\nu, e^-)^{71}\text{Ge}$	ν_e	$E_\nu > 0.23$	0.52 ± 0.03
real time	Kam ⇒ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$	0.41 ± 0.01
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	0.29 ± 0.02
		NC $\nu_x d \to \nu_x p\, n$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$	0.87 ± 0.07
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$	0.41 ± 0.05
	Borexino	$\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$E_\nu = 0.862$	0.66 ± 0.07





All experiments measuring mostly ν_e observed a deficit

Deficit is energy dependent

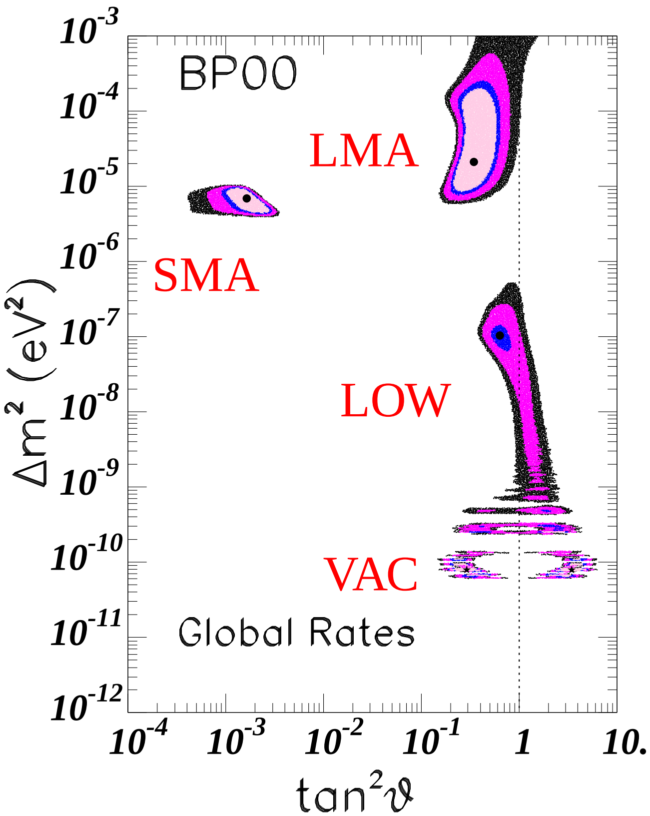
Deficit disappears in NC

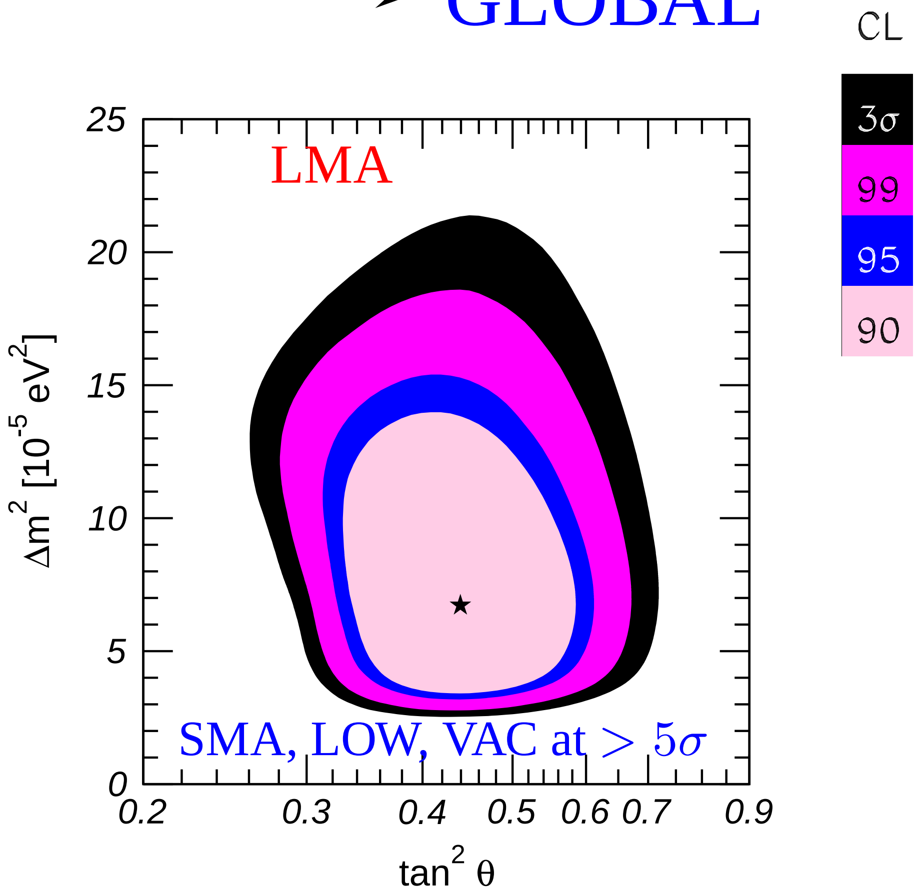
Concha Gonzalez-Garcia

Solar Neutrinos: Oscillation Solutions

RATES ONLY → GLOBAL

SK and SNO E and t dependence





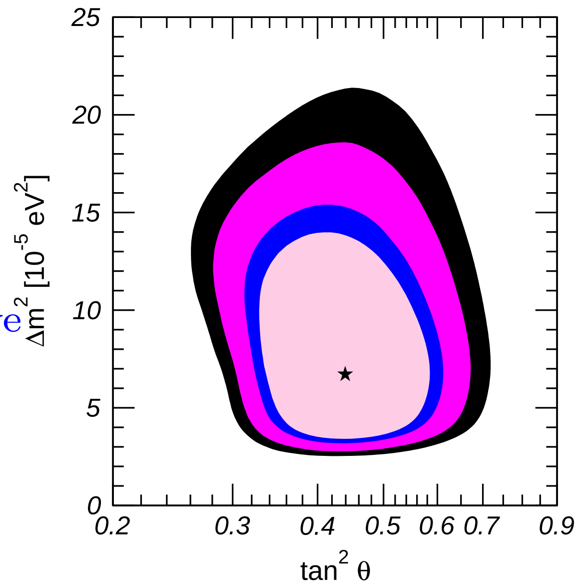
Best fit

$$\Delta m^2 = 6.8 \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta = 0.43$$

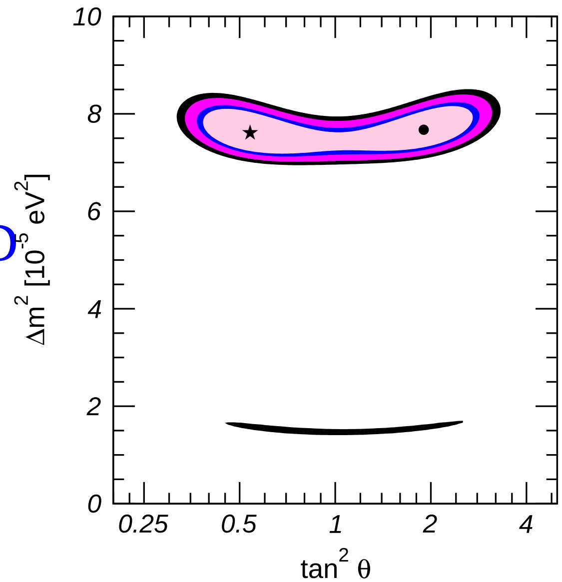
Solar

$\nu_e \longrightarrow \nu_{\rm active}$



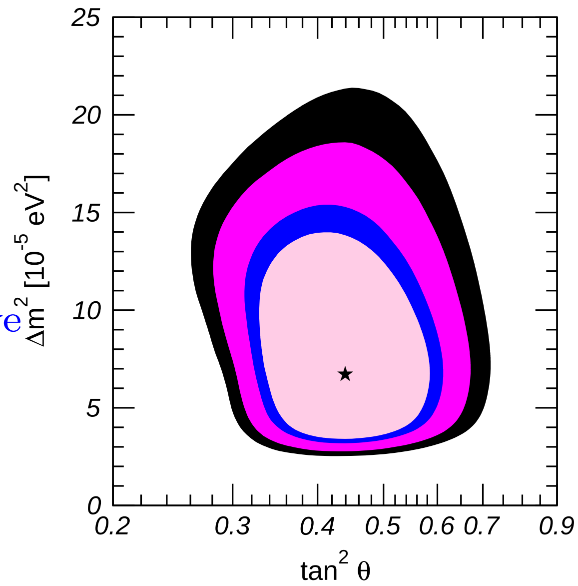
+ KamLAND

$\bar{\nu}_e \not\rightarrow \bar{\nu}_e$



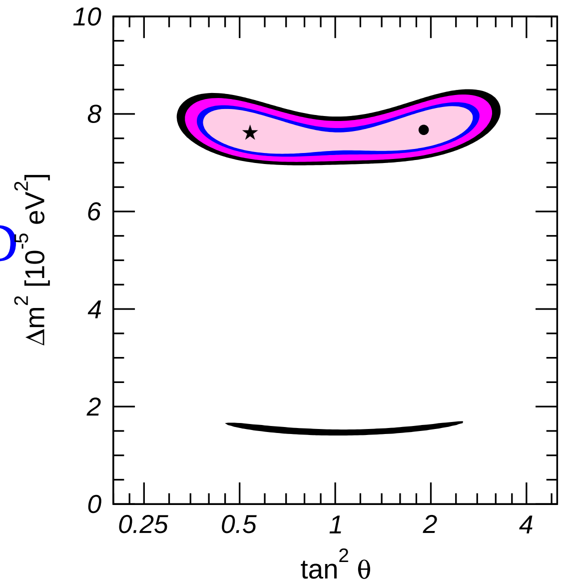
Solar

$\nu_e \to \nu_{\text{active}}$

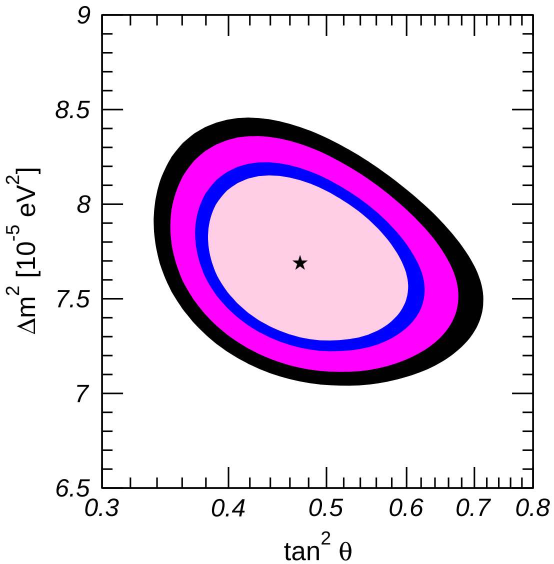


+ KamLAND

$\bar{\nu}_e \not\to \bar{\nu}_e$



ν_e oscillation parameters compatible with $\overline{\nu}_e$: *Sensible* to assume CPT: $P_{ee} = P_{\bar{e}\bar{e}}$



$\Delta m^2 = 7.7 \times 10^{-5}\ \text{eV}^2$

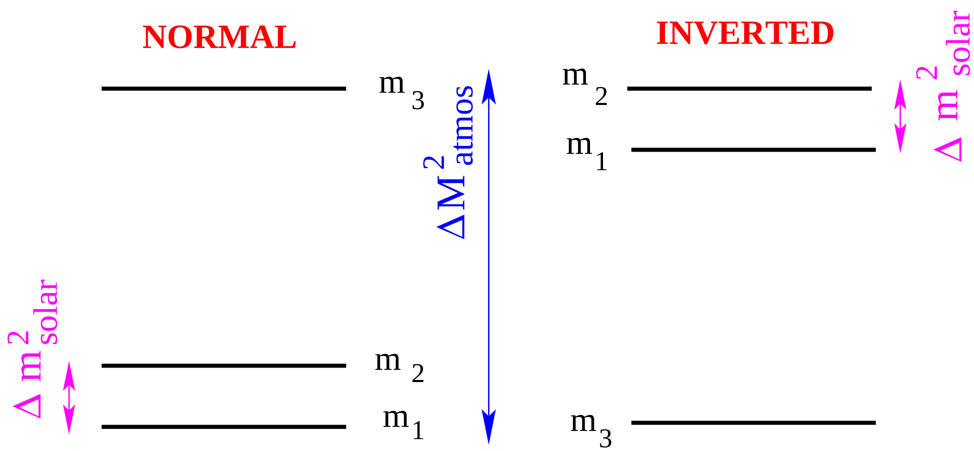
$\tan^2\theta = 0.43$

Solar+Atmospheric+Reactor+LBL 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



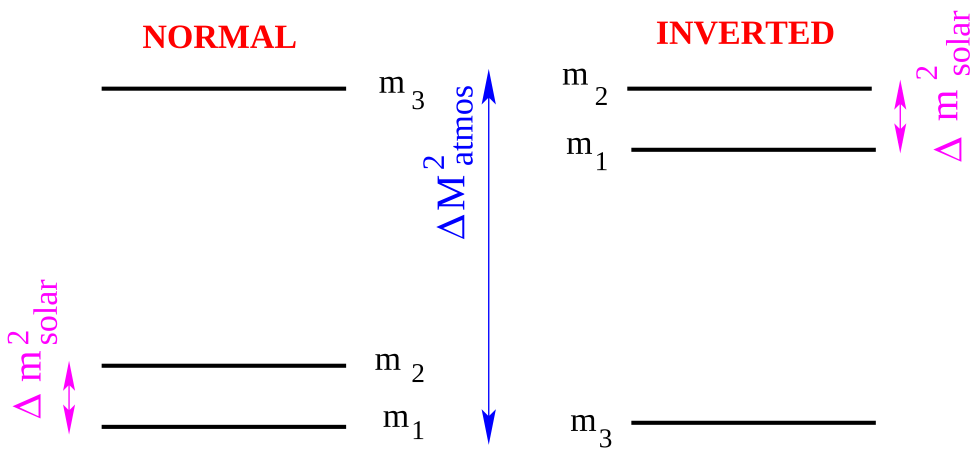
2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_{\odot} \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

Solar+Atmospheric+Reactor+LBL 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_\odot \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

Generic 3ν mixing effects:

– Effects due to θ_{13}

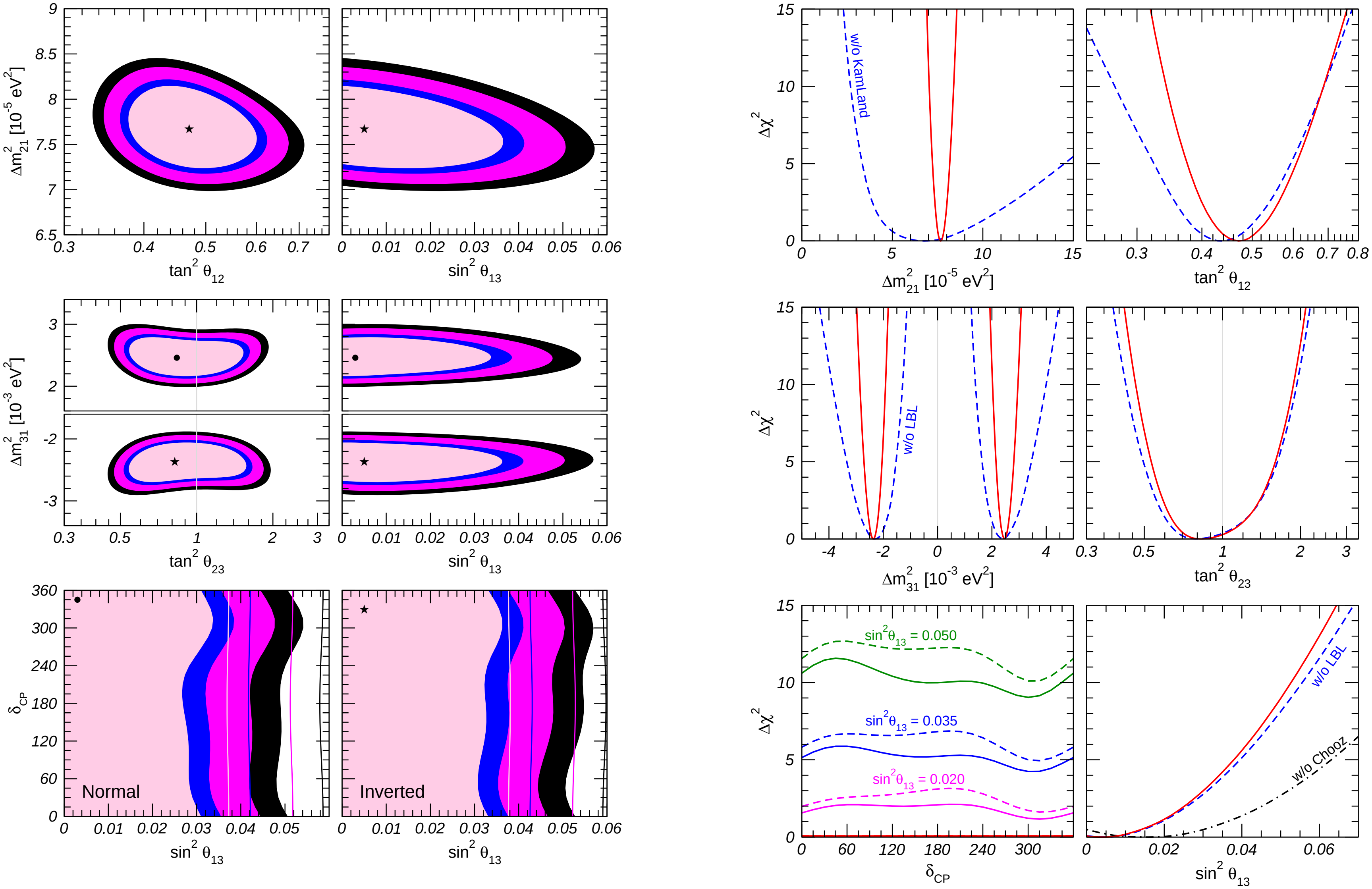
– Difference between Inverted and Normal

– Interference of two wavelength oscillations

– CP violation due to phase δ

z-Garcia

Global Analysis: Three Neutrino Oscillations



The derived ranges for the six parameters at 1σ (3σ) are:

$$\Delta m^2_{21} = 7.7\,^{+0.22}_{-0.21}\,\left({}^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| = 2.37 \pm 0.17\,(0.46) \times 10^{-3}\ \mathrm{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\ \left({}^{+4.8}_{-4.0}\right) \qquad \theta_{23} = 42.3\,^{+5.1}_{-3.3}\ \left({}^{+11.3}_{-7.7}\right)$$

$$\theta_{13} = 0\,^{+7.9}_{-0.0}\ \left({}^{+12.9}_{-0.0}\right) \qquad \delta_{\mathrm{CP}} \in [0,\ 360]$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77\text{–}0.86 & 0.50 - 0.63 & 0.00 - 0.22 \\ 0.22\text{–}0.56 & 0.44 - 0.73 & 0.57 - 0.80 \\ 0.21\text{–}0.55 & 0.40 - 0.71 & 0.59 - 0.82 \end{pmatrix}$$

The derived ranges for the six parameters at 1σ (3σ) are:

$$\Delta m^2_{21} = 7.7\,^{+0.22}_{-0.21}\,\left({}^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| = 2.37 \pm 0.17\,(0.46) \times 10^{-3}\ \mathrm{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\,\left({}^{+4.8}_{-4.0}\right) \qquad \theta_{23} = 42.3\,^{+5.1}_{-3.3}\,\left({}^{+11.3}_{-7.7}\right)$$

$$\theta_{13} = 0\,^{+7.9}_{-0.0}\,\left({}^{+12.9}_{-0.0}\right) \qquad \delta_{\mathrm{CP}} \in [0,\,360]$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77\text{–}0.86 & 0.50-0.63 & 0.00-0.22 \\ 0.22\text{–}0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21\text{–}0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix}$$

with structure

$$|U_{\mathrm{LEP}}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \quad \begin{matrix} \lambda \sim 0.2 \\ \epsilon \lesssim 0.2 \end{matrix}$$

The derived ranges for the six parameters at 1σ (3σ) are:

$$\Delta m^2_{21} = 7.7\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \text{eV}^2 \qquad \left|\Delta m^2_{31}\right| = 2.37 \pm 0.17\,(0.46) \times 10^{-3}\ \text{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\ \left(^{+4.8}_{-4.0}\right) \qquad \theta_{23} = 42.3\,^{+5.1}_{-3.3}\ \left(^{+11.3}_{-7.7}\right)$$

$$\theta_{13} = 0\,^{+7.9}_{-0.0}\ \left(^{+12.9}_{-0.0}\right) \qquad \delta_{\rm CP} \in [0,\,360]$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77\!-\!0.86 & 0.50-0.63 & 0.00-0.22 \\ 0.22\!-\!0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21\!-\!0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix}$$

with structure

$$|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \qquad \begin{matrix} \lambda \sim 0.2 \\ \epsilon \lesssim 0.2 \end{matrix}$$

very different from quark's

$$|U_{\rm CKM}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix} \qquad \lambda \sim 0.2$$

Open Questions

We still ignore:

(1) Is $\theta_{13} \neq 0$? How small?

(2) Is $\theta_{23} = \frac{\pi}{4}$? If not, is it $>$ or $<$?

(3) Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?

(4) What is the ordering of the neutrino states?

(5) Are neutrino masses:

hierarchical: $m_i - m_j \sim m_i + m_j$?

degenerated: $m_i - m_j \ll m_i + m_j$?

(6) Dirac or Majorana?