Neutrino Physics

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Outline

- Neutrino Physics I: Basics and phenomenology
- Neutrino Physics II: Neutrino mass models

References

Links

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Recent reviews

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- G. G. Raffelt, “Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles,” Chicago, USA: Univ. Pr. (1996) 664 p.

Neutrino Physics I Outline

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   - Motivation and properties of ν's
   - ν masses in QFT and in the SM

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   - Limit on N_ν
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5. Summary and outlook

Why neutrino physics in 2012?

Very rich physics: from their invention by Pauli in 1930's to the last results on θ_{13} this year many exciting discoveries:

Why neutrino physics in 2012?

- Fermi theory
- Majorana theory
- μ decay
- $\nu_{e,\mu,\tau}$ discoveries
- neutrino oscillations
- Solar ν problem
- MSW
- Atmospheric ν problem
- SN1987A
- Invisible Z-boson decay width
- Oscillations in solar ν's confirmed
- Oscilations in atmospheric ν's confirmed

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There are experiments!

Planned experiments can answer many of them in a near future

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Implications in cosmology

- Contribution to the mass of the universe (Ω_ν)
- Effects in the cosmic microwave backgroud radiation (CMB)
- Effects in the large scale sctructure formation (LSS)
- Effects primordial nucleosyntesis (BBN)
- Possible explanation of the baryonic assymetry of the univers (BAU) with the leptogenesis mechanism

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Implications in astrophysics

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Technological implications

- Communications in dense matter (underwater)
- Neutrino-graphies: earth core (search of oil, minerals $\cdots$)
- $\cdots$

Intrinsic properties of neutrinos

Before oscillation experiments

- Three types of neutrinos ν_e, ν_μ, ν_τ
- Lepton numbers L_e, L_μ, L_τ conserved separately
  - ν_e produces e's and no μ's
  - No $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to e\gamma$, $\mu \to 3e$
- Total lepton number $L = L_e + L_\mu + L_\tau$ conserved (no $0\nu\beta\beta$)
- ν masses much smaller than charged lepton masses

$$m_{\nu_e} < 2\,\mathrm{eV}\,, \quad m_{\nu_\mu} < 170\,\mathrm{KeV}\,, \quad m_{\nu_\tau} < 18\,\mathrm{MeV} \quad \sum_a m_a \lesssim 14\,\mathrm{eV}$$

- ν's helicity $-1/2$ and $\bar{\nu}$'s helicity $+1/2$
- Magnetic moments very small: $\mu_\nu < 10^{-10}\mu_B\,, \quad \mu_\nu < 10^{-12}\mu_B)$

After oscillation experiments

- Neutrinos must be massive ($m_\nu \sim 1\,\mathrm{eV}$)
- They mix (with large mixings)
- LFV processes must exist (still not observed)

Dirac fermions reducible representation

$$\psi_L = P_L\psi = \begin{pmatrix} \xi \\ 0 \end{pmatrix}, \quad \psi_R = P_R\psi = \begin{pmatrix} 0 \\ \eta \end{pmatrix}$$

$$\xi \to \exp(-i\theta\vec{n}\cdot\vec{\sigma}\text{-}\vec{\beta}\cdot\vec{\sigma})\xi\,, \quad \eta \to \exp(-i\theta\vec{n}\cdot\vec{\sigma}+\vec{\beta}\cdot\vec{\sigma})\eta$$

In QFT the fundamental fields are two component spinors ψ_L and ψ_R and not the complete Dirac field ψ!

$$\mathscr{L} = i\overline{\psi_L}\partial\!\!\!/\psi_L + i\overline{\psi_R}\partial\!\!\!/\psi_R - m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L) =$$

$$= i\xi^\dagger\bar{\sigma}^\mu\partial_\mu\xi + i\eta^\dagger\sigma^\mu\partial_\mu\eta - m(\eta^\dagger\xi + \xi^\dagger\eta)$$

$$= i\xi_1^\dagger\bar{\sigma}^\mu\partial_\mu\xi_1 + i\xi_2^\dagger\bar{\sigma}^\mu\partial_\mu\xi_2 - m(\xi_2^T i\sigma_2\xi_1 - \xi_1^\dagger i\sigma_2\xi_2^*)$$

with $\xi_1 \equiv \xi$, $\xi_2 = i\sigma_2\eta^*$ (ξ_2 transforms like ξ_1)

Fermions vs scalars

$$\mathscr{L} = i\xi_1^\dagger \bar{\sigma}^\mu \partial_\mu \xi_1 + i\xi_2^\dagger \bar{\sigma}^\mu \partial_\mu \xi_2$$

$$-\frac{i}{2}\left(m_1 \xi_1^T \sigma_2 \xi_1 + m_2 \xi_2^T \sigma_2 \xi_2 + 2m_{21} \xi_2^T \sigma_2 \xi_1 + \mathrm{h.c.}\right)$$

Kinetic terms invariant under $\xi_{1,2} \to e^{i\alpha_{1,2}}\xi_{1,2}$. $m_{1,2}$ break it
If $m_{1,2} = 0$, $\alpha_2 = -\alpha_1$ conserved $\to$ Dirac fields

$$\mathscr{L} = i\overline{\psi}\partial\!\!\!/ \psi - m\overline{\psi}\psi\,, \quad \psi = \psi_L + \psi_R$$

Invariant under $\psi \to e^{i\alpha}\psi$

$$\mathscr{L} = \frac{1}{2}\partial\phi_1 \cdot \partial\phi_1 + \frac{1}{2}\partial\phi_2 \cdot \partial\phi_2 - \frac{1}{2}\left(m_1^2\phi_1^2 + m_2^2\phi_2^2 + 2m_{21}^2\phi_1\phi_2\right)$$

If $m_{21} = 0$ and $m_1 = m_2 \equiv m$. Invariant under rotations of (ϕ_1, ϕ_2)

$$\mathscr{L} = \partial_\mu\phi^*\partial^\mu\phi - m^2\phi^*\phi\,, \quad \phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

Invariant under $\phi \to e^{i\alpha}\phi$

Weyl and Majorana Fields

ξ_2 no necessary if there are no conserved charges: fermion fields can be massive with only two components (Majorana)

$$\mathscr{L}_{\mathrm{M}} = i\xi^\dagger \bar{\sigma}^\mu \partial_\mu \xi - \frac{i}{2}\left(m\xi^T \sigma_2 \xi + \mathrm{h.c.}\right)$$

$$i\bar{\sigma}^\mu \partial_\mu \xi - im\sigma_2 \xi^* = 0$$

If $m = 0$ (in momentum representation) $(E + \vec{p}\cdot\vec{\sigma})\xi(\vec{p}) = 0$, $E = \pm|\vec{p}|$

$$\frac{\vec{p}\cdot\vec{\sigma}}{|\vec{p}|}\xi(\vec{p}) = \begin{cases} -\xi(\vec{p}) & E > 0 \\ +\xi(\vec{p}) & E < 0 \end{cases}$$

Weyl field:

- Limit $m = 0$ of the Majorana field
- Particle helicity $-1/2$, antiparticle helicity $+1/2$.
- A U(1) charge conserved (invariance $\xi \to e^{i\alpha}\xi$)

Quantization

$$\xi(x) = \sum_{\sigma=\pm} \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p} \left(a_\sigma(\vec{p}) u_\sigma(\vec{p}) e^{-ip\cdot x} + a_\sigma^\dagger(\vec{p}) v_\sigma(\vec{p}) e^{ip\cdot x} \right)$$

Two helicities but particle and antiparticle are the same
In the limit $m \to 0$ $u_+(\vec{p}) = v_-(\vec{p}) = 0$

$$\xi(x) = \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p} \left(a_-(\vec{p}) u_-(\vec{p}) e^{-ip\cdot x} + a_+^\dagger(\vec{p}) v_+(\vec{p}) e^{ip\cdot x} \right)$$

Particle has helicity $-1/2$ and antiparticle helicity $+1/2$
In four components define $\psi_L^c = (\psi_L)^c = C\overline{\psi_L}^T$ (is right-handed)

$$\mathscr{L}_M = i\overline{\psi_L}\partial\!\!\!/ \psi_L - m\frac{1}{2}(\overline{\psi_L^c}\psi_L + \overline{\psi_L}\psi_L^c) = i\frac{1}{2}\overline{\psi_M}\partial\!\!\!/ \psi_M - \frac{1}{2}m\overline{\psi_M}\psi_M$$

with $\psi_\mathrm{M} = \psi_L + \psi_L^c$ that satisfies $\left(i\partial\!\!\!/ - m\right)\psi_M = 0$

$$\psi_\mathrm{M}(x) = \sum_s \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p} \left(a(\vec{p},s) u(\vec{p},s) e^{-ip\cdot x} + a^\dagger(\vec{p},s) v(\vec{p},s) e^{ip\cdot x} \right)$$

Two helicities but particle and antiparticle equal

Generalization to several fields

$$\overline{\psi_i^c}\psi_j = \overline{\psi_j^c}\psi_i \quad \rightarrow \quad \text{Symmetric mass matrices}$$

$$\overline{\psi_i^c}\gamma^\mu\psi_j = -\overline{\psi_j^c}\gamma^\mu\psi_i \quad \rightarrow \quad \text{Antisymmetric vector current}$$

$$\overline{\psi_i^c}\gamma^\mu\gamma_5\psi_j = \overline{\psi_j^c}\gamma^\mu\gamma_5\psi_i \quad \rightarrow \quad \text{Symmetric axial current}$$

$$\overline{\psi_i^c}\sigma^{\mu\nu}\psi_j = -\overline{\psi_j^c}\sigma^{\mu\nu}\psi_i \quad \rightarrow \quad \text{Antisymmetric magnetic moments}$$

$$\mathscr{L} = i\overline{\Psi_L}\partial\!\!\!/\Psi_L - \frac{1}{2}\left(\overline{\Psi_L^c}M\Psi_L + \text{h.c.}\right)$$

with $\Psi_L = \text{column}(\psi_{1L}, \psi_{1L}, \cdots \psi_{NL})$ and M symmetric

$$M = V^T M_{\text{diag}} V\,, \quad \Psi_M = V\Psi_L + V^*\Psi_L^c$$

$$\mathscr{L} = \frac{i}{2}\overline{\Psi_{\rm M}}\partial\!\!\!/\Psi_{\rm M} - \frac{1}{2}\overline{\Psi_{\rm M}}M_{\text{diag}}\Psi_{\rm M}$$

Masses of neutrinos in the SM

Simpler solution: add ν_R like in the quark sector

$$\mathscr{L}_{YL} = -\bar{L}_L Y_e \Phi e_R - \bar{L}_L Y_\nu \tilde{\Phi} \nu_R + \text{h.c.}$$

But

- Why m_ν are so small?
- Why omit terms of the form $\overline{\nu_R^c} \nu_R$ in the Lagrangian?

Solution to the two questions: they are not omitted!

$$\mathscr{L}_{YL} \to \mathscr{L}_{YL} = -\bar{L}_L Y_e \Phi e_R - \bar{L}_L Y_\nu \tilde{\Phi} \nu_R - \frac{1}{2} \overline{\nu_R^c} M \nu_R + \text{h.c.}$$

$$\mathscr{L}_{\nu M} = -\frac{1}{2} \left(\bar{\nu}_L, \overline{\nu_R^c} \right) \begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

if $M \gg M_D$ ("see-saw" mechanism):

- 3 **Heavy** Majorana neutrinos $\sim \nu_R$ with masses $\sim M$
- 3 **Light** Majorana neutrinos $\sim \nu_L$ with masses $\sim M_D^2/M$

Dirac: if $M = 0$, $(M_\nu = M_D)$

$$\mathscr{L}_{\rm Dirac} = i\overline{\nu_L}\partial\!\!\!/\nu_L + \overline{\nu_R}\partial\!\!\!/\nu_R - (\overline{\nu_R}M_\nu\nu_L + {\rm h.c.})$$

- 4 degrees of freedom
- Conserve total lepton number (NO $0\nu\beta\beta$ decay)
- Less natural (why m_ν are so small)

Dirac and Majorana neutrinos

Dirac: if $M = 0$, ($M_\nu = M_D$)

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- 4 degrees of freedom
- Conserve total lepton number (NO $0\nu\beta\beta$ decay)
- Less natural (why m_ν are so small)

Majorana: if $M \gg M_D$, ($M_\nu = -M_D M^{-1} M_D^T$)

$$\mathscr{L}_{\rm Majorana} = i\overline{\nu_L}\partial\!\!\!/\nu_L - \frac{1}{2}\left(\overline{\nu_L^c}M_\nu\nu_L + {\rm h.c.}\right)$$

- 2 degrees of freedom
- Do not conserve total lepton number ($0\nu\beta\beta$ decay)
- More natural and more CP violating phases

Neutrinos at low energies: Dirac

$$\mathscr{L}_{\text{Dirac}} = i\overline{\nu_L}\partial\!\!\!/\nu_L + \overline{\nu_R}\partial\!\!\!/\nu_R - (\overline{\nu_R}M_\nu\nu_L + \text{h.c.}) +$$

$$-\frac{G_F}{\sqrt{2}}J^\mu J_\mu^\dagger - \frac{G_F}{\sqrt{2}}J_Z^\mu J_{Z\mu} + \mathscr{L}_{\text{MM}} + \mathscr{L}_{\text{NSI}} + \cdots$$

$$J^\mu = 2\bar{\nu}_L\gamma^\mu e_L + \cdots, \qquad J_Z^\mu = \bar{\nu}_L\gamma^\mu\nu_L + \cdots$$

diagonalization

$$\nu_{\alpha L} = V_{\alpha i}\nu_{iL}, \quad \nu_{\alpha R} = U_{\alpha i}\nu_{iR}, \quad U^\dagger M_\nu V = M_{\text{diag}}, \quad \nu_i = \nu_{iL} + \nu_{iR}$$

$$J^\mu = 2\bar{\nu}\gamma^\mu V^\dagger P_L e + \cdots, \qquad J_Z^\mu = \bar{\nu}_L\gamma^\mu\nu_L + \cdots$$

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

Neutrinos at low energies: Majorana

$$\mathscr{L}_{\text{Dirac}} = i\overline{\nu_L}\partial\!\!\!/\nu_L - \frac{1}{2}\left(\overline{\nu_L^c}M_\nu \nu_L + \text{h.c.}\right) +$$

$$-\frac{G_F}{\sqrt{2}}J^\mu J_\mu^\dagger - \frac{G_F}{\sqrt{2}}J_Z^\mu J_{Z\mu} + \mathscr{L}_{\text{MM}} + \mathscr{L}_{\text{NSI}} + \mathscr{L}_{0\nu\beta\beta} + \cdots$$

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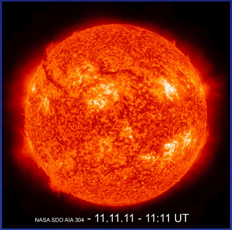
$$\nu_{\alpha L} = V_{\alpha i}\nu_{iL}\,, \quad V^T M_\nu V = M_{\text{diag}}\,, \quad \nu_i = \nu_{iL} + \nu_{iL}^c$$

$$J^\mu = 2\bar{\nu}\,V^\dagger P_L e_L + \cdots\,, \qquad J_Z^\mu = -\frac{1}{2}\bar{\nu}\gamma^\mu\gamma_5\nu + \cdots$$

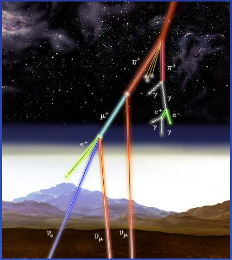
$$V_{\text{Majorana}} = V_{\text{Dirac}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Solar and atmospheric neutrino problems



The Solar neutrino problem

- The Sun produces ν_e's, whose flux can be calculated using solar models
- The flux of ν_e measured in the earth in all experiments reduced by a factor 0.3–0.5
- Explained by oscillations $\nu_e \to \nu_{\mu,\tau}$



The atmospheric neutrino problem

- π's produced in the atmosphere should give a flux of ν_μ's twice that of ν_e's
- The observed flux of ν_μ's is largely reduced
- Explained in terms of oscillations $\nu_\mu \to \nu_\tau$

Neutrino oscillacions in vacuum

Define $|\nu_e\rangle$ the state that produces e^- and $|\nu_\mu\rangle$ the one that produces μ^-. (Flavour eigenstates no energy eigenstates).

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Where $\cos\theta = \langle\nu_1|\nu_e\rangle = \langle\nu_2|\nu_\mu\rangle$ and $\sin\theta = \langle\nu_2|\nu_e\rangle = -\langle\nu_1|\nu_\mu\rangle$

$$|\nu_e, t\rangle = e^{-iE_1 t}\cos\theta\,|\nu_1\rangle + e^{-iE_2 t}\sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu, t\rangle = -e^{-iE_1 t}\sin\theta\,|\nu_1\rangle + e^{-iE_2 t}\cos\theta\,|\nu_2\rangle$$

then

$$P(\nu_e \to \nu_\mu; t) = \left|\langle\nu_\mu|\nu_e, t\rangle\right|^2 = \sin^2(2\theta)\sin^2\left(\frac{(E_2 - E_1)t}{2}\right)$$

Definite momentum ultrarelativistic neutrinos ($p \gg m_i$),
$E_i = \sqrt{m_i^2 + p^2} \approx p + m_i^2/2p$, $L \approx t$ and $p \approx E$

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(2\pi\frac{L}{\lambda}\right)$$

with λ oscillation length

$$\lambda = \frac{2\pi(E/\mathrm{GeV})}{1.27(\Delta m^2/\mathrm{eV}^2)}\mathrm{Km}\,, \quad \Delta m^2 = m_2^2 - m_1^2$$

Not valid for

- $L \gg \lambda\frac{E}{\sigma}$ (decoherence, σ wave packet width)
- $L \gg \lambda$ (Too fast oscillations: average)

$$\langle P(\nu_e \to \nu_\mu; t)\rangle = \frac{1}{2}\sin^2(2\theta)$$

Independent of L, E and Δm^2

Three neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta; t) = \left|\langle \nu_\beta | \nu_\alpha, t\rangle\right|^2 = \left|\sum_i e^{-iE_i t} \langle \nu_\beta | \nu_i \rangle \langle \nu_i | \nu_\alpha \rangle\right|^2$$

if $\langle \nu_\beta | \nu_i \rangle = V_{\beta i}$ and $E_i \approx E + m_i^2/(2E)$

$$P(\nu_\alpha \to \nu_\beta; t) = \sum_{ij} e^{-i\Delta m_{ij}^2 t/2E} V_{\beta i} V_{\alpha i}^* V_{\alpha j} V_{\beta j}^* =$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\{V_{\beta i} V_{\alpha i}^* V_{\alpha j} V_{\beta j}^*\} \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) +$$

$$+ 2 \sum_{i>j} \mathrm{Im}\{V_{\beta i} V_{\alpha i}^* V_{\alpha j} V_{\beta j}^*\} \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

Effective hamiltonian $H = M_\nu^\dagger M_\nu/(2E) = V M_{diag}^2 V^\dagger/(2E)$
Phases of Majorana irrelevant (oscillations conserve LN)

Neutrino oscillations in matter, MSW

$$\mathscr{L}_{\rm CC} = -\sqrt{2}G_F(\bar{e}\gamma_\mu P_L \nu_e)(\bar{\nu}_e\gamma^\mu P_L e) \to -\sqrt{2}G_F n_e(\bar{\nu}_e\gamma^0 P_L \nu_e)$$

$$H = C_{\rm univ} I + V \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} V^\dagger + \begin{pmatrix} \tilde{V} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$\tilde{V} = \pm b = \pm\sqrt{2}G_F n_e$ with $+$ for ν's and $-$ for $\bar{\nu}$'s

For two generations

$$H = \begin{pmatrix} \sin^2\theta + \frac{2E\tilde{V}}{\Delta m^2} & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \cos^2\theta \end{pmatrix} \frac{\Delta m^2}{2E} + \text{universal}$$

$$\sin 2\tilde{\theta} = \sin 2\theta \frac{\Delta m^2}{\Delta \tilde{m}^2}, \quad \Delta\tilde{m}^2 = \Delta m^2 \sqrt{1 + \left(\frac{2E\tilde{V}}{\Delta m^2}\right)^2 - 2\cos 2\theta \frac{2E\tilde{V}}{\Delta m^2}}$$

The resonance

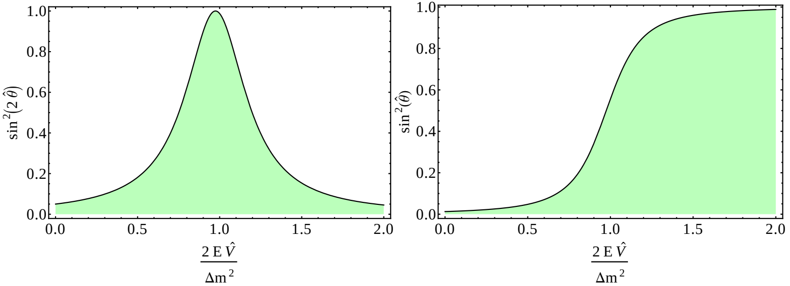
$$\Delta m^2 \cos 2\theta = \pm 2E\sqrt{2}G_F n_e \rightarrow \begin{cases} \Delta\tilde{m}^2 = \Delta m^2 \sin 2\theta \\ \sin^2 2\tilde{\theta} = 1 \end{cases}$$

$\Delta m^2 \cos 2\theta > 0$ for ν's and $\Delta m^2 \cos 2\theta < 0$ for $\bar{\nu}$'s

Ordering of H eigenvalues such that $\Delta\tilde{m}^2 > 0$ implies

$$2E\tilde{V}/\Delta m^2 \ll 1 \;, \Delta\tilde{m}^2 \approx \Delta m^2,\ \tilde{\theta} \approx \theta \text{ and } |\tilde{\nu}_2\rangle \approx |\nu_2\rangle$$

$$2E\tilde{V}/\Delta m^2 \gg 1 \;\; \Delta\tilde{m}^2 \gg \Delta m^2,\ \tilde{\theta} = \tfrac{\pi}{2} \text{ and } |\tilde{\nu}_2\rangle \approx |\nu_e\rangle$$



Adiabatic approximation in the Sun

If $n_e(x)$ changes slowly we can use the adiabatic theorem:
"If in $t = 0$ the system is in one of the instantaneous eigenstates of $H(t = 0)$, $H(t)|n, t\rangle = E_n(t)|n, t\rangle$ it will remain in the state $|n, t\rangle$ for $t > 0$"

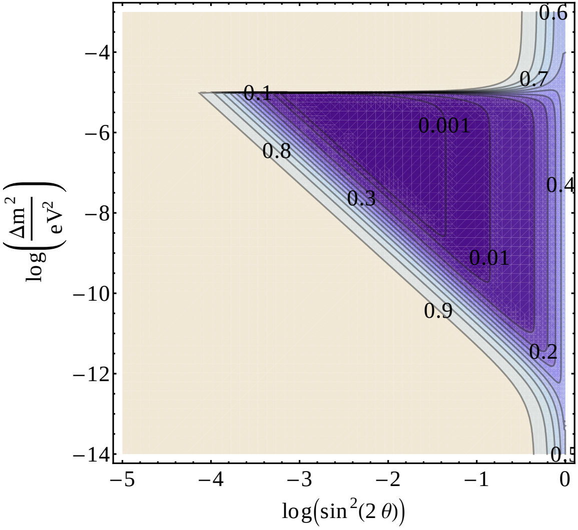
$$|\nu_e\rangle \overset{n_e \gg}{\approx} |\tilde{\nu}_2\rangle \xrightarrow{\text{Adiabat}} |\tilde{\nu}_2, t\rangle \xrightarrow{\text{Adiabat}} |\nu_2\rangle \overset{n_e \ll}{=} \sin\theta\,|\nu_e\rangle + \cos\theta\,|\nu_\mu\rangle$$

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

If $\theta \ll 1$ all the ν_e are transformed in ν_μ! (MSW)
General case

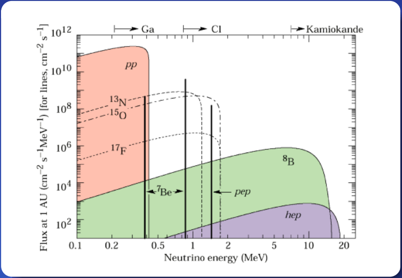
$$P(\nu_e \to \nu_e) = \frac{1}{2} + (\frac{1}{2} - P_{\rm LZ})\cos 2\hat{\theta}_0 \cos 2\theta$$

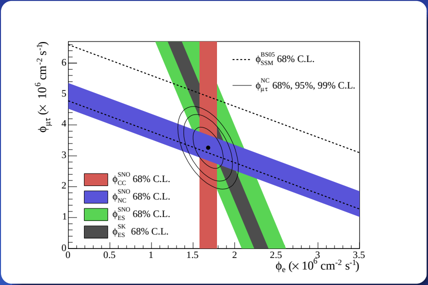
$$P_{\rm LZ} \approx e^{-\gamma}, \qquad \gamma \equiv \frac{\pi \Delta m^2}{4E|(n_e'/n_e)_{\rm res}|}\frac{\sin^2 2\theta}{\cos 2\theta}$$


0.6
0.7
0.1
0.001
0.8
0.4
0.3
0.01
0.9
0.2
0.5
−4
−6
−8
−10
−12
−14
−5
−4
−3
−2
−1
0
$\log\left(\frac{\Delta m^2}{eV^2}\right)$
$\log(\sin^2(2\theta))$

Solar neutrino experiments

Experiment	Reaction	Threshold
Homestake	$\nu_e{}^{37}\mathrm{Cl} \to e\,{}^{37}\mathrm{Ar}$	$E > 0.814$ MeV
SAGE, Gallex/GNO	$\nu_e{}^{71}\mathrm{Ga} \to e\,{}^{71}\mathrm{Ge}$	$E > 0.233$ MeV
Super-Kamiokande	$\nu_{e,x}e \to \nu_{e,x}e$	$E > 5.5$ MeV
SNO	ES: $\nu_{e,x}e \to \nu_{e,x}e$ CC: $\nu_e D \to ppe$ NC: $\nu_x D \to \nu_x pn$	$E > 5.5$ MeV



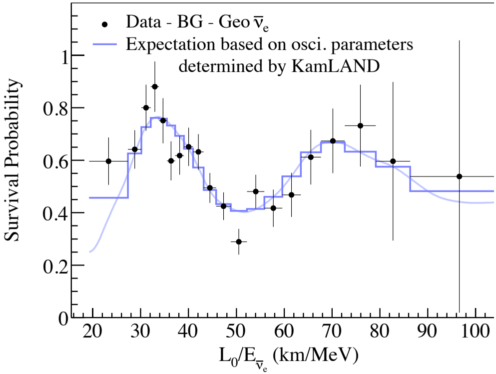


Tests with reactor neutrinos: KamLAND

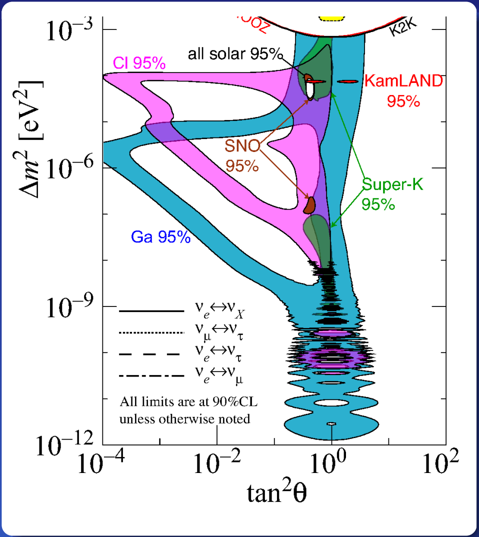
Terrestrial anti-neutrinos from nuclear reactors in Japan with $E \sim 1$ MeV and average $L \sim 180$ Km $(\Delta m^2_{21} L/(4E) \sim 1)$

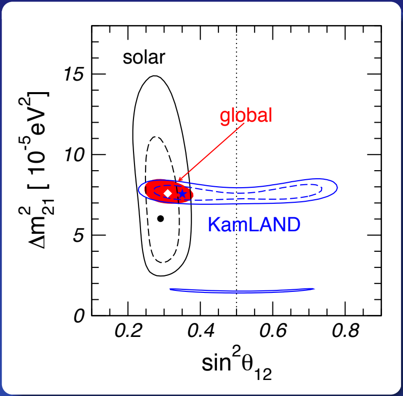
$\overline{\nu}_e p \to e^+ n, \qquad E_{\nu_e} = E_{e^+} + m_n - m_p$

Measurement of $P(\bar{\nu}_e \to \bar{\nu}_e)$ as a function of the energy!



Global results

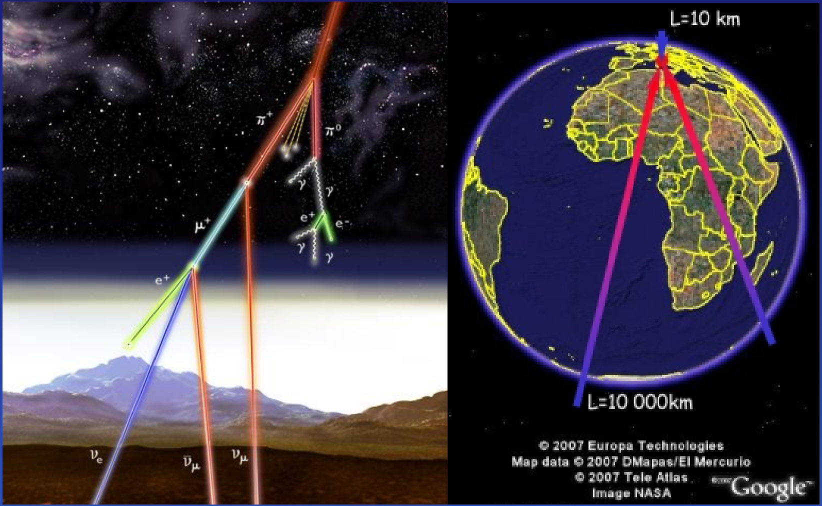




LMA MSW solution

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

Atmospheric neutrino: SuperKamiokande



$\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$. Same with π^-.

If ν's are not distinguished from $\bar{\nu}'s$: $2\nu_\mu$ for each ν_e

$L \sim 10$ Km to 10^4 Km and $E \sim 0.1$ GeV To 10 GeV.
Ideal to have oscillations with $\Delta m^2 \sim 10^{-3}\,\mathrm{eV}^2$.
SuperKamiokande $\nu_{e_i} + N \rightarrow e_i + N'$ detects e_i by Cherenkov:

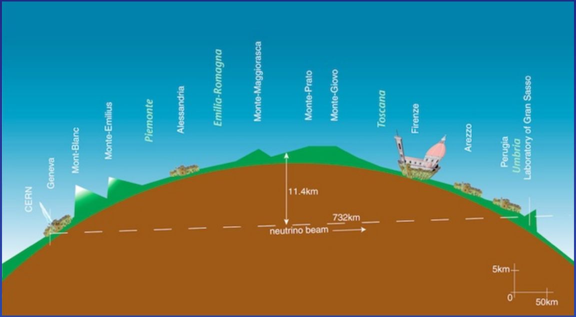
- It does not see the charge
- It allows to obtain the direction of ν_{e_i} its energy and the flavour

Results:

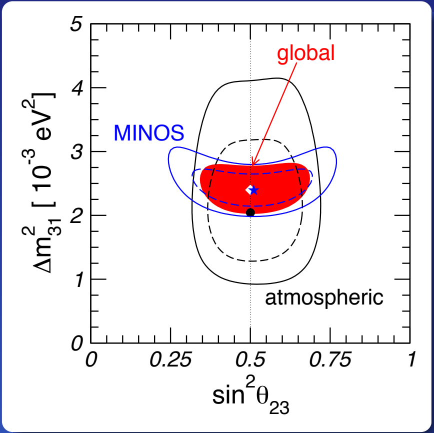
- ν_e flux not changed and no dependence in L
- Oscillations $\nu_\mu \rightarrow \nu_x$
- $x \sim \tau$ (no much space for steriles or ν decays)

Test in accelerators

SuperK results confirmed by neutrinos produced in accelerators: MINOS, K2K,Opera



Opera:	$\nu_\mu \to \nu_\tau$	$L = 732$ Km	$E \sim 17$ GeV
K2K:	$\nu_\mu \to \nu_\mu$	$L = 250\,$km	$E \sim 1$ GeV
MINOS:	$\nu_\mu \to \nu_\mu$	$L = 735\,$km	$E \sim 3$ GeV



Two solutions:

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

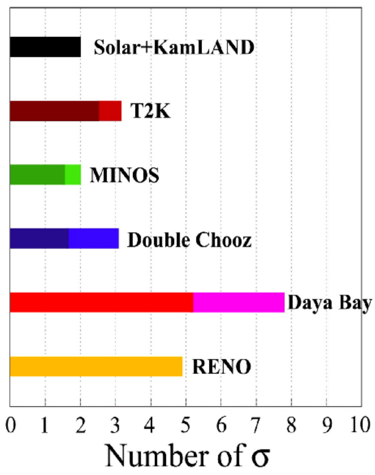
Normal hierarchy (NH)

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

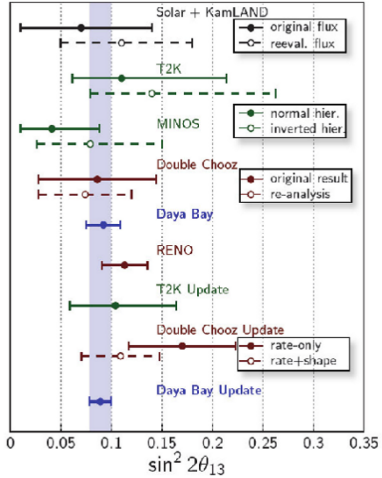
Inverted hierarchy (IH)

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

Results on θ_{13}

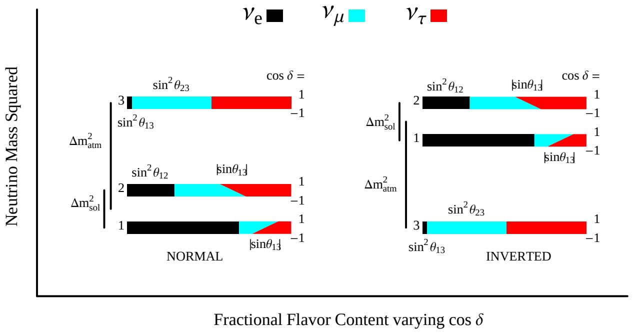


Exclusion of non-zero θ_{13}



By S. Jetter

The two mass orderings

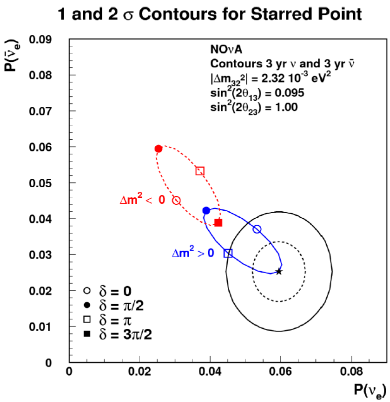


$$\Delta m^2_{21} = 7.5 \times 10^{-5}\,\mathrm{eV}^2 \quad (2.4\% \qquad \sin^2\theta_{12} = 0.3\ (4\%)$$

$$\Delta m^2_{31} = \begin{cases} 2.45 \times 10^{-3}\,\mathrm{eV}^2 \\ -2.43 \times 10^{-3}\,\mathrm{eV}^2 \end{cases} \quad (2.8\%) \qquad \begin{array}{l} \sin^2\theta_{23} = 0.42\ (11\%) \\ \sin^2\theta_{13} = 0.023\ (10\%) \end{array}$$

δ still not well determinded from the fits

(Close) future: measurement of $\mathrm{sign}(\Delta m^2_{31})$ and δ



Nova ($\nu_\mu \to \nu_e$ And $\bar{\nu}_\mu \to \bar{\nu}_e$) begins in 2013:

- $\mathrm{sign}(\Delta m^2_{31})$ (MSW effects)
- δ (ν_e vs $\bar{\nu}_e$)
- Strong dependece on θ_{23}

Also: ν-Factories (NF), Super Beams (SB), Beta Beams (BB)

Direct CP asymmetry

$A^{\rm CP}_{\alpha\beta} \equiv (P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta))/(P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta))$

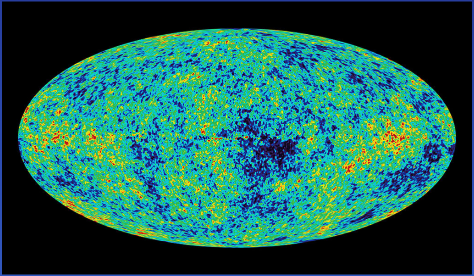
difficult: depends on $J = s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$ and the two mass differences Δm^2_{21} and Δm^2_{32}

ν's decouple at $T_f \sim 1\,\mathrm{MeV}$ and present ν density is

$$n_\nu = \frac{3\zeta(3) g_\nu}{4\pi^2} T_\nu^3 \approx 112\,\mathrm{cm}^{-3}, \qquad kT_\nu \sim 10^{-4}\,\mathrm{eV}$$

if $m_\nu \neq 0$, ν's contribute to the mass density of the universe

$$\Omega_{\nu_i} = \frac{n_{\nu_i} m_{\nu_i}}{\rho_c} \to \Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94\,\mathrm{eV}}, \xrightarrow{h\sim 0.7,\,\Omega \lesssim 0.3} \sum_i m_{\nu_i} \lesssim 14\,\mathrm{eV}$$



Refined using CMB and LSS (depends on hypothesis)

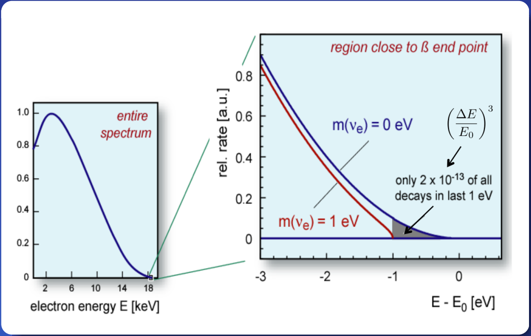
$$\sum_i m_{\nu_i} < 0.2\text{–}2\,\mathrm{eV}$$

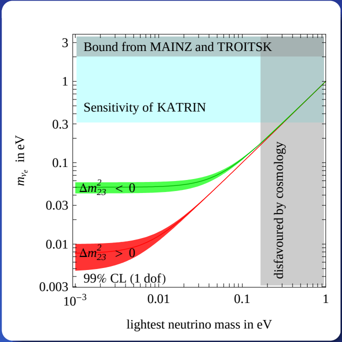
Beta decay

β decay of tritium: ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \overline{\nu}_e$
Very little available energy (order few keV) very sensitive to m_ν

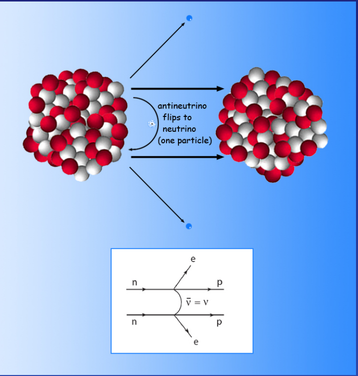
$$\frac{dN}{dE} = \sum |U_{ei}|^2 \Gamma(m^2_{\nu_i}, E) = \langle \Gamma(m^2_\nu, E) \rangle \approx \Gamma(\langle m^2_\nu \rangle, E)$$

$$m^2_{\nu_e} \equiv \langle m^2_\nu \rangle = |U_{ei}|^2 m^2_{\nu_i} = (M^\dagger_\nu M_\nu)_{ee} = c^2_{13}(m^2_1 c^2_{12} + m^2_2 s^2_{12}) + m^2_3 s^2_{13}$$





Neutrinoless 2β decay



$2\nu\beta\beta$ observed with $T_{2\nu\beta\beta} \sim 10^{20}$ year

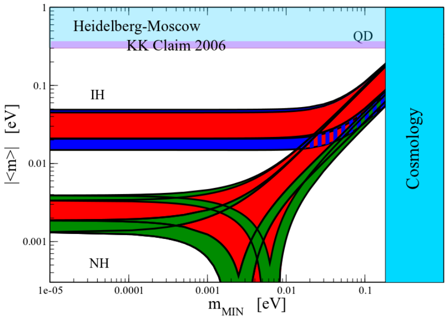
$0\nu\beta\beta$ requires Majorana ν masses (does not conserve LN)
Suppressed by m_ν but enhanced by phase space

$$\mathscr{A}_{0\nu\beta\beta} \propto G_F^2 \frac{m_{\beta\beta}}{q^2}\,, \qquad q \sim 100\,\mathrm{MeV}$$

$$m_{\beta\beta} = \left|\sum V_{ei}^2 m_i\right| = \left|\left(V M_{\mathrm{diag}} V^T\right)_{ee}\right| = \left|\left(M_\nu^\dagger\right)_{ee}\right| =$$

$$= \left|c_{13}^2 (m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\alpha}) + m_3 s_{13}^2 e^{2i(\beta-\delta)}\right|$$

Present limits (HM,IGEX) give $m_{\beta\beta} \lesssim 0.3$–$1.0$ eV.
Improved recently by EXO $m_{\beta\beta} \lesssim 0.14$–$0.38$ eV
Future (EXO,Majorana,GERDA,CUORE,...): $m_{\beta\beta} \sim 0.02$ eV



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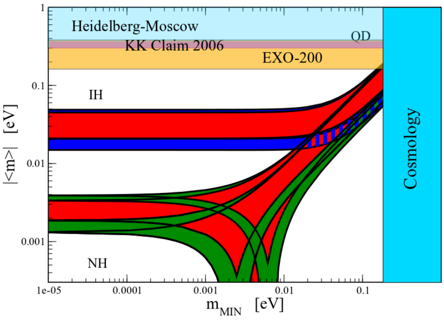

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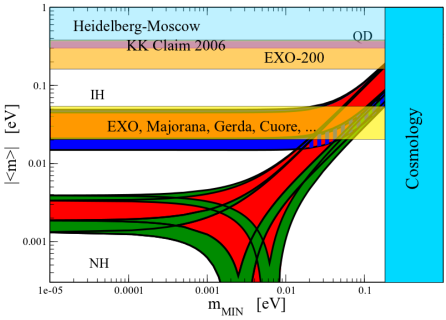

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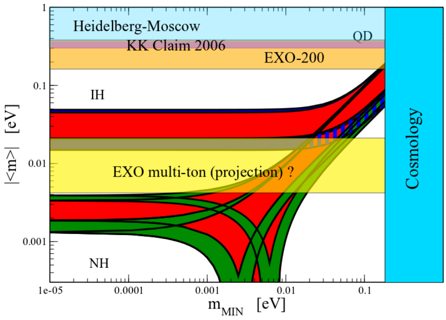


1 Introduction

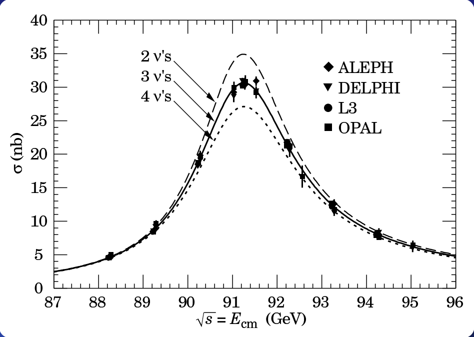
2 Neutrino oscillations

3 Absolute Mass Scale

4 Other Relevant Information
- Limit on N_ν
- Sterile ν's, NSI and magnetic moments
- Supernova neutrinos
- BAU from Leptogenesis

5 Summary and outlook

Limit on N_ν



$$N_\nu = 2.982 \pm 0.008$$

- Light ($m_\nu \lesssim 45\,\text{GeV}$)
- Active (full Z couplings)

Any other light particle coupling to the Z will contribute

- A fourth generation with $m_{\nu_4} < 45\,\text{GeV}$: $\Delta N_\nu = 1$ (excluded)
- Triplet majorons ($Y = 1$): $\Delta N_\nu = 2$ (excluded)
- Doublet majorons, light sneutrinos: $\Delta N_\nu = 1/2$ (excluded)

Light esterile (singlet) neutrinos are allowed

Sterile ν's, NSI and magnetic moments

Sterile neutrinos

LSND and MiniBoone see evidence of transitions $\overline{\nu}_\mu \to \overline{\nu}_e$ with $\Delta m^2_{\rm LSND} > \Delta m^2_{\rm ATM}$ (Also hints from reactor, Gallium anomalies and from cosmology ($N_s = 1,2$))

- Experimental situation not completely clear
- Difficult to adjust everything
- Necessary, at least, a fourth neutrino (sterile given Γ_Z)

Non-standar interactions (NSI)

$\mathscr{L}_{\rm NSI} = -\varepsilon^{fC}_{\alpha\beta} 2\sqrt{2} G_F 2 \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma^\mu P_{L,R} \bar{f}\right)$, affect ν cross sections and oscillations. Not very strong limits, typically $\varepsilon_{\alpha_\beta} < 0.01 - 10$ depending on the flavours.

Neutrino magnetic moments

Change $\nu e \to \nu e$ cross section ($\mu_\nu \lesssim 10^{-10}\mu_B$) and contribute to the energy loss of stars becasue plasmon decay $\gamma_{\rm P} \to \nu\nu$. From red giant stars

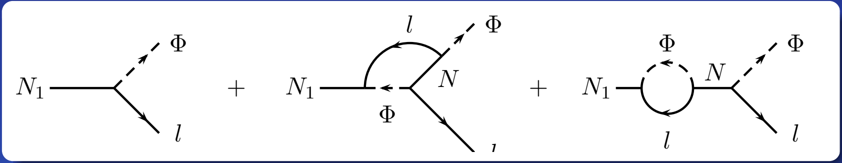
$$\mu_\nu < 3 \times 10^{-12} \mu_B \qquad 2m_\nu < \omega_{\rm P} \simeq 10\,{\rm KeV}$$

Energy released in a SN explosion $\sim 3 \times 10^{53}$ erg mainly neutrinos (99%)
E_ν $\sim$few MeV. $\Delta t \sim 10\,\mathrm{s}$. The 3 types of neutrinos are emitted.
SN1987A observed: $24\bar{\nu}$ in a $13\,\mathrm{s}$ interval.

- Limit on the masses: $m_\nu < 16$ eV
- Restrictions on the neutrino velocities
- Restrictions on non-standard cooling mechanisms
  - Oscillation to steriles $\sin^2 2\theta_s \lesssim 10^{-8}$
  - Magnetic moments of neutrinos

We exist!: $\eta_B \equiv (n_{\rm baryons} - n_{\rm antibaryons})/n_\gamma \sim 6 \times 10^{-10}$.
Need Sakharov: a) $\Delta B \neq 0$, b) out of equilibrium c) $\Delta C \neq 0$ and $\Delta(CP) \neq 0$
Possible in the SM but not enough. In seesaw $L \to B$

$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi\ell) - \Gamma(N_1 \to \Phi\bar{\ell})}{\Gamma(N_1 \to \Phi\ell) + \Gamma(N_1 \to \Phi\bar{\ell})}$$



$$|\varepsilon_1| = \left| -\frac{3}{16\pi} \sum_i \frac{\mathrm{Im}\{(\tilde{\lambda}_\nu^\dagger \tilde{\lambda}_\nu)^2_{i1}\}}{(\tilde{\lambda}^\dagger \tilde{\lambda})_{11}} \frac{M_1}{M_i} \right| \leq \frac{8}{16\pi} \frac{M_1}{v^2} |\Delta m^2_{\rm atm}|^{1/2}$$

Sphalerons conserve $B - L$ but violate B with $\Delta L = \Delta B$

Summary of parameters

$\Delta m^2_{31} \sim \pm 2.4 \times 10^{-3}\,\mathrm{eV}^2$	$\theta_{23} \sim 45^\circ$	Atmos,K2K,MINOS
$\Delta m^2_{21} \sim 7.6 \times 10^{-5}\,\mathrm{eV}^2$	$\theta_{12} \sim 35^\circ$	Solar, KamLAND
	$\theta_{13} \sim 9^\circ$	T2K,MINOS,Double Chooz Daya Bay,RENO
N_ν (active and light)	3	LEP
$m_{\beta\beta} = \sum_i \lvert V^2_{ei} m_{\nu_i} \rvert$	$\lesssim 0.4\,\mathrm{eV}$	HM,IGEX,EXO,...
$m_{\nu_e} = \sum_i \lvert V_{ei} \rvert^2 m^2_{\nu_i}$	$< 2.2\,\mathrm{eV}$	Mainz,Troitsk
$\sum_i m_{\nu_i}$	$\lesssim 1\,\mathrm{eV}$	Cosmology
$\mathrm{sign}(\Delta m^2_{31})$	?	Noνa,NF,BB,SB,...
CP, δ	?	Noνa,NF,BB,SB,...
Dirac or Majorana? (α,β)	?	HM?,$0\nu\beta\beta$
N_s (light sterile)	1,2 ?	LSND,MiniBooNE,Cosmology
μ_ν / μ_B	$< 10^{-10}, 10^{-12}$	σ_ν, red giants
NSI	$\varepsilon \lesssim 0.01$–$10$	Sun,Atm,LSND,NF,...
LFV ($\mu \to e\gamma, \cdots$)	$< 2.4 \times 10^{-12}$	MEG,COMET/Mu2e,...

Unknowns

- m_{lightest} not known (it could be zero)
- Mass ordering ($\mathrm{sign}(\Delta m^2_{31})$) now known
- Is there CP violation (δ)?
- Is LN conserved in 2β decays? Is it due to Majorana ν masses?
- Is the LFV in the charged sector ($\mu \to e\gamma, \tau \to \mu\gamma, \mu\text{-}e\,\mathrm{conversion}, \cdots$)
- Are there sterile ν's, NSI or magnetic moments?
- Why ν masses are so small?
- Why the structure of masses and mixings is so different from the quark sector?

Still we do not have a universally accepted model of ν masses

Summary of dependences

Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13} ,$\delta_{\rm cp}$
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\rm atm}$	θ_{23}
Accelerator LBL ν_e App (Minos,T2K)	$\rightarrow \delta_{\rm cp}$	θ_{13} , θ_{23}

Summary of LFV

Process	Present UL	Future UL
$\mu \to e\gamma$	2.4×10^{-12}	$\mathcal{O}(10^{-14})$, MEG upgrade
$\mu \to eee$	1.0×10^{-12}	$\mathcal{O}(10^{-16})$, Mu3e
$\mu + \mathrm{Ti} \to e + \mathrm{Ti}$	4.3×10^{-12}	$\mathcal{O}(10^{-17})$, COMET/Mu2e
$\tau \to e\gamma$	3.3×10^{-8}	$\mathcal{O}(10^{-9})$, Future B-factories
$\tau \to eee$	2.7×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$\tau \to e\mu\mu$	2.7×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$\tau \to \mu\gamma$	4.4×10^{-8}	$\mathcal{O}(10^{-9})$, Future B-factories
$\tau \to \mu\mu\mu$	2.1×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$\tau \to \mu ee$	1.8×10^{-8}	$\mathcal{O}(10^{-10})$, Future B-factories
$K \to \pi\mu e$	1.3×10^{-11}	
$K \to e\mu$	4.7×10^{-12}	