Neutrino Physics II

Neutrino Phenomenology

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Neutrino Physics II Outline

1. Neutrino oscillations phenomenology
    - Solar neutrinos and KamLAND
    - Atmospheric neutrinos and MINOS
    - Results on θ_{13} and global fits
    - (Close) future: measurement of $\mathrm{sign}(\Delta m^2_{31})$ and δ

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   - Beta and double beta decays

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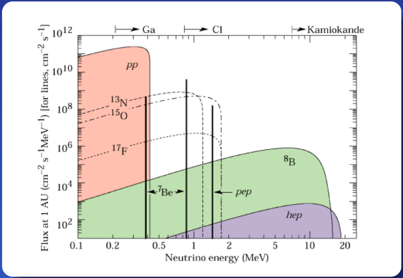
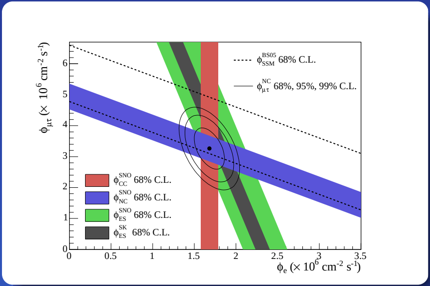
Solar neutrino experiments

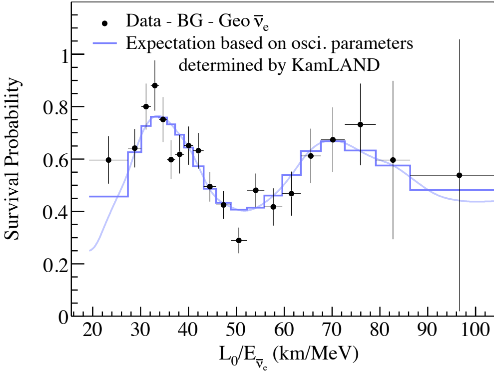
Experiment	Reaction	Threshold
Homestake	$\nu_e {}^{37}\mathrm{Cl} \to e\, {}^{37}\mathrm{Ar}$	$E > 0.814$ MeV
SAGE, Gallex/GNO	$\nu_e {}^{71}\mathrm{Ga} \to e\, {}^{71}\mathrm{Ge}$	$E > 0.233$ MeV
Super-Kamiokande	$\nu_{e,x} e \to \nu_{e,x} e$	$E > 5.5$ MeV
SNO	ES: $\nu_{e,x} e \to \nu_{e,x} e$ CC: $\nu_e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



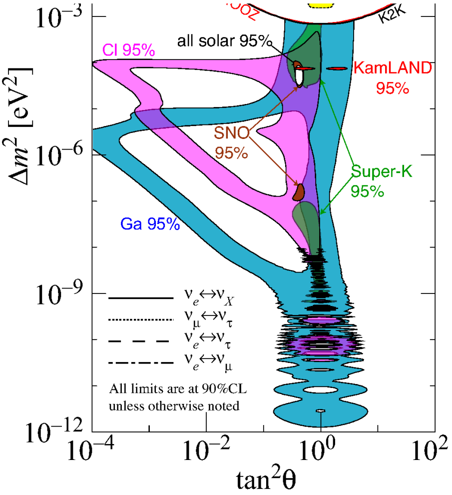


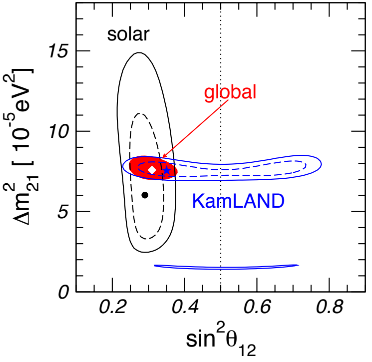
Tests with reactor neutrinos: KamLAND

Terrestrial anti-neutrinos from nuclear reactors in Japan with $E \sim 1$ MeV and average $L \sim 180\,\mathrm{Km}$ $(\Delta m^2_{21} L/(4E) \sim 1)$
$\overline{\nu}_e p \to e^+ n, \qquad E_{\nu_e} = E_{e^+} + m_n - m_p$
Measurement of $P(\bar{\nu}_e \to \bar{\nu}_e)$ as a function of the energy!



Global results

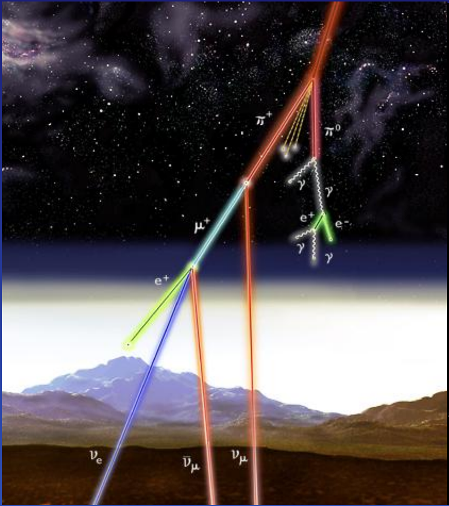


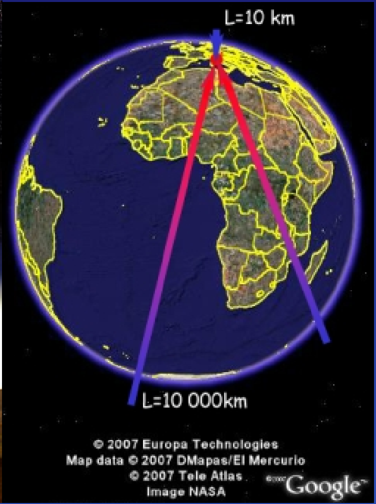


LMA MSW solution

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 $\nu_{e_i} + N \to e_i + N'$ detects e_i by Cherenkov:

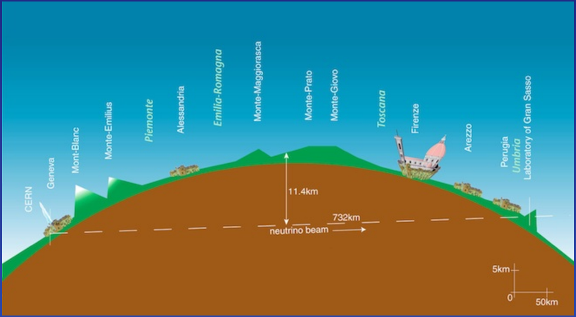
- It does not see the charge
- It allows to obtain the direction of ν_{e_i} its energy and the flavour

Results:

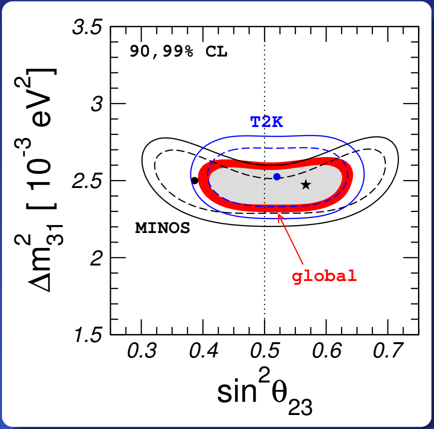
- ν_e flux not changed and no dependence in L
- Oscillations $\nu_\mu \to \nu_x$
- $x \sim \tau$ (no much space for steriles or ν decays)

Test in accelerators

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



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



Two solutions:
$\Delta m^2_{31} > 0$
Normal hierarchy (NH)
$\Delta m^2_{31} < 0$
Inverted hierarchy (IH)

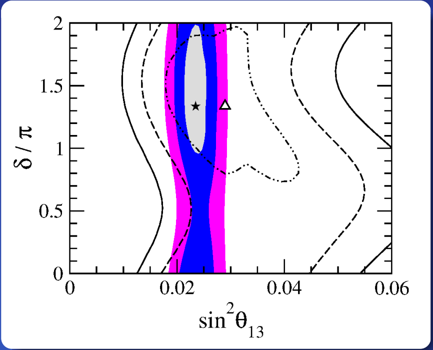
Octant ambiguity in θ_{23}

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

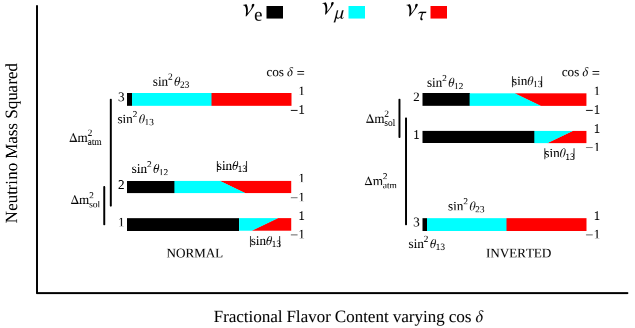
Results on θ_{13} and δ

θ_{13} has been measured since 2012 to be different from zero by using reactor anti-neutrino disappearance (Daya Bay and RENO) as well as accelerator appearance and disappearance (MINOS and T2K)

From Global fits some indirect information on δ



The two mass orderings



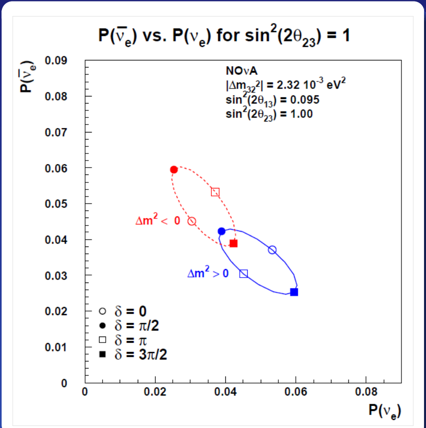
$$\Delta m^2_{21} = \quad 7.6\times 10^{-5}\,\mathrm{eV}^2 \quad (2.5\% \qquad \sin^2\theta_{12} = 0.32\ (4\%)$$

$$\Delta m^2_{31} = \begin{cases} 2.48\times 10^{-3}\,\mathrm{eV}^2 \\ -2.38\times 10^{-3}\,\mathrm{eV}^2 \end{cases} \quad (2.5\%) \qquad \begin{array}{l} \sin^2\theta_{23} = 0.57\ (11\%) \\ \sin^2\theta_{13} = 0.021\ (5\%) \end{array}$$

Octant ambiguity in θ_{23}

δ still not well determinded from the fits but a hint for $\delta \approx 3\pi/2$

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



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

- $\mathrm{sign}(\Delta m^2_{31})$ (Earth 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
$A^{\mathrm{CP}}_{\alpha\beta} \equiv (P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta))/(P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta))$
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_{31}

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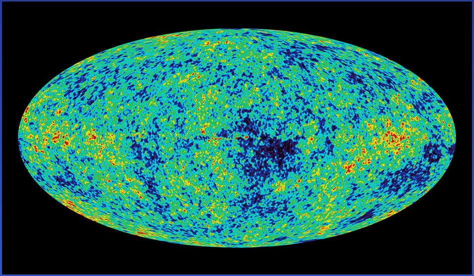
Cosmic Neutrino Background

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)

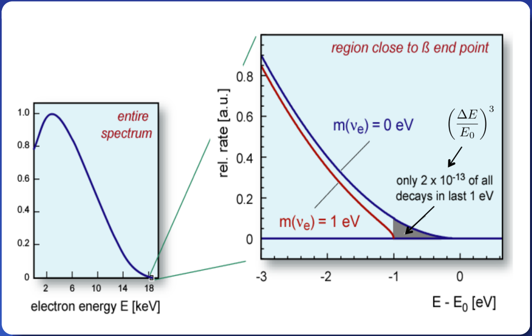
$$\sum_i m_{\nu_i} < 0.2\text{–}2\,\mathrm{eV}$$

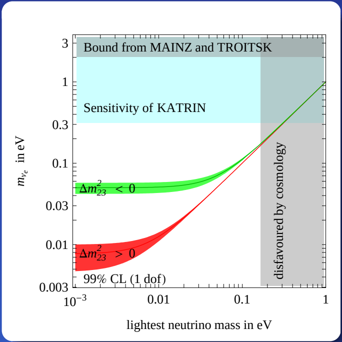
Beta decay

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

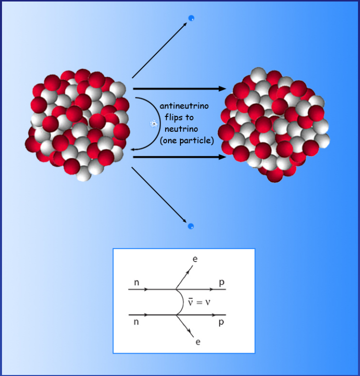
$$\frac{dN}{dE} = \sum |U_{ei}|^2 \Gamma(m_{\nu_i}^2, E) = \langle \Gamma(m_\nu^2, E) \rangle \approx \Gamma(\langle m_\nu^2 \rangle, E)$$

$$m_{\nu_e}^2 \equiv \langle m_\nu^2 \rangle = |U_{ei}|^2 m_{\nu_i}^2 = (M_\nu^\dagger M_\nu)_{ee} = c_{13}^2(m_1^2 c_{12}^2 + m_2^2 s_{12}^2) + m_3^2 s_{13}^2$$





Neutrinoless 2β decay



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

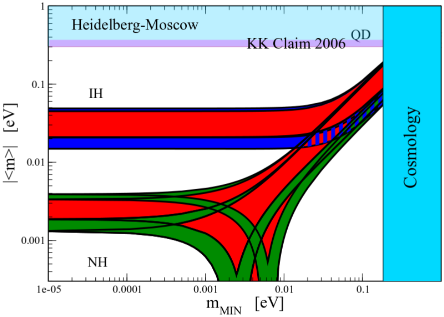
$0\nu\beta\beta$ requires Majorana ν masses (does not conserve LN)
Suppressed by m_ν but enhanced by phase space

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

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

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

Present limits (HM,IGEX) give $m_{\beta\beta} \lesssim 0.3$–$0.4\,\mathrm{eV}$.
Improved recently by KamLAND-Zen (and EXO-200)
$m_{\beta\beta} \lesssim 0.12$–$0.25\,\mathrm{eV}$
Future
(KamLAND2-Zen,nEXO,Majorana,GERDA2,CUORE,. . .):
$m_{\beta\beta} \sim 0.01\,\mathrm{eV}$



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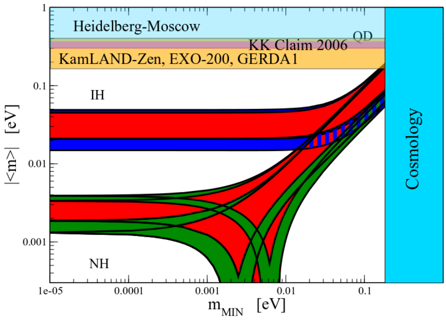

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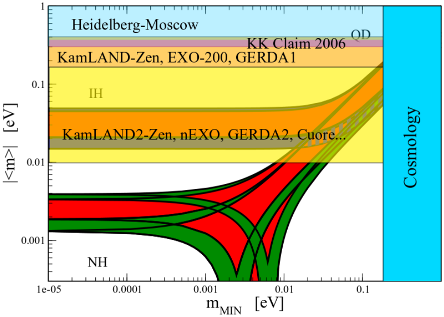

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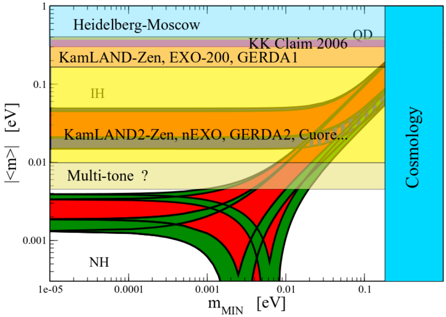

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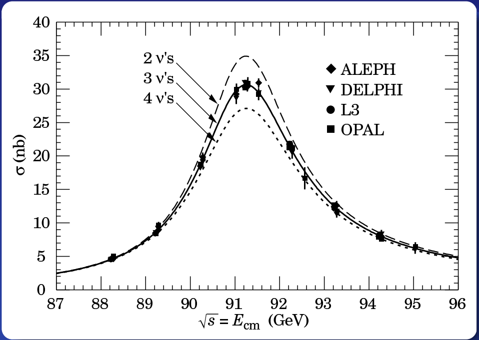
Limit on N_ν



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

- 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 $m_{\nu_4} < 45\,\mathrm{GeV}$: $\Delta N_\nu = 1$ (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 $\Delta m^2_{\text{LSND}} > \Delta m^2_{\text{ATM}}$ (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.

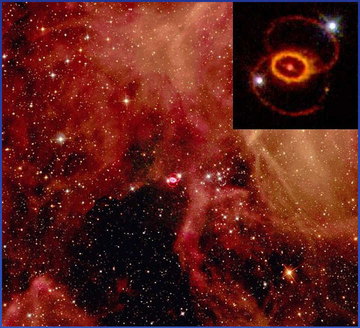
Neutrino magnetic moments

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

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

Supernova neutrinos

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.

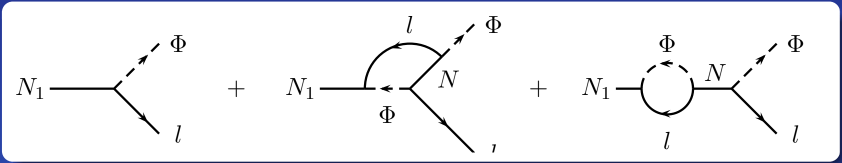


- Limit on the masses: $m_\nu < 16$ eV
- Restrictions on the neutrino velocities
- Restrictions on non-standard cooling mechanisms
  - Oscillation to steriles $\sin^2 2\theta_s \lesssim 10^{-8}$
  - Magnetic moments of neutrinos

BAU from leptogenesis

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

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



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

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

$$\eta_B = 10^{-2}\, \varepsilon_1\, \kappa \to M_1 \geq 10^9\,\mathrm{GeV}$$

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
$m_{\beta\beta} = \sum_i \lvert V_{ei}^2 m_{\nu_i} \rvert$	$\lesssim 0.2\,\mathrm{eV}$	KamLAND-Zen,EXO,HM,IGEX,...
$m_{\nu_e} = \sum_i \lvert V_{ei} \rvert^2 m^2_{\nu_i}$	$< 2.2\,\mathrm{eV}$	Mainz and Troitsk
$\sum_i m_{\nu_i}$	$\lesssim 1\,\mathrm{eV}$	Cosmology
sign(Δm^2_{31})	?	Noνa,NF,BB,SB,...
CP, δ	$3\pi/2$?	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 $(\mu \to e\gamma, \cdots)$	$< 5.7 \times 10^{-13}$	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 there 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?

Conclusions

- We have learned a lot on the neutrino properties in the last years but there is still a lot to be learned

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- We do not have a “Standard Model” of neutrino masses but have many interesting ideas
- Fortunatelly, we have many proposed experiments which can refine our knowledge on the neutrino properties and guide us in our way to a **“Standard Model of Neutrino Masses”**

Thank you

Thanks for your attention
It has been a pleasure!