$\beta\beta_{0\nu}$ Decay Phenomenology

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- Experimental Evidences of ν Oscillations $\Rightarrow$ 3-ν Mixing. [Pascoli]
- Tritium β Decay and Cosmological Limit on Neutrino Masses. [Pascoli]
- Majorana Neutrino Mass $\Leftrightarrow$ $\beta\beta_{0\nu}$ Decay. [Hirsch, Pascoli]
- The Problem of $\mathcal{M}_{0\nu}$. [Simkovic, Vergados, Suhonen, Kortelainen]
- Experimental Status and Perspectives. [Avignone, Thomas, Zuber]
- Neutrino Oscillations Bounds for $\beta\beta_{0\nu}$ Decay. [Hirsch, Pascoli]
- Beyond Neutrino Mass. [Hirsch, Pilaftsis]

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$: Homestake, Kamiokande, GALLEX, SAGE, GNO, Super-Kamiokande, SNO

Reactor $\bar{\nu}_e$ disappearance (KamLAND)

$\Longrightarrow$

$$\Delta m^{2\,\text{best-fit}}_{\text{SUN}} = 6.9 \times 10^{-5}$$

$$5.4 \times 10^{-5} < \Delta m^2_{\text{SUN}} < 9.4 \times 10^{-5}$$

$$\left[\text{eV}^2\right] \qquad \text{(99.73\% C.L.)}$$

[Maltoni, Schwetz, Tortola, Valle, PRD 68 (2003) 113010]

Atmospheric $\nu_\mu \to \nu_\tau$: Kamiokande, IMB, Super-Kamiokande, MACRO, SOUDAN 2

Accelerator ν_μ disappearance (K2K)

$\Longrightarrow$

$$\Delta m^{2\,\text{best-fit}}_{\text{ATM}} = 2.6 \times 10^{-3}$$

$$1.4 \times 10^{-3} < \Delta m^2_{\text{ATM}} < 5.1 \times 10^{-3}$$

$$\left[\text{eV}^2\right] \qquad \text{(99.73\% C.L.)}$$

[Fogli, Lisi, Marrone, Montanino, PRD 67 (2003) 093006]

Three-Neutrino Mixing

flavor fields ν_α

$\alpha = e, \mu, \tau$

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

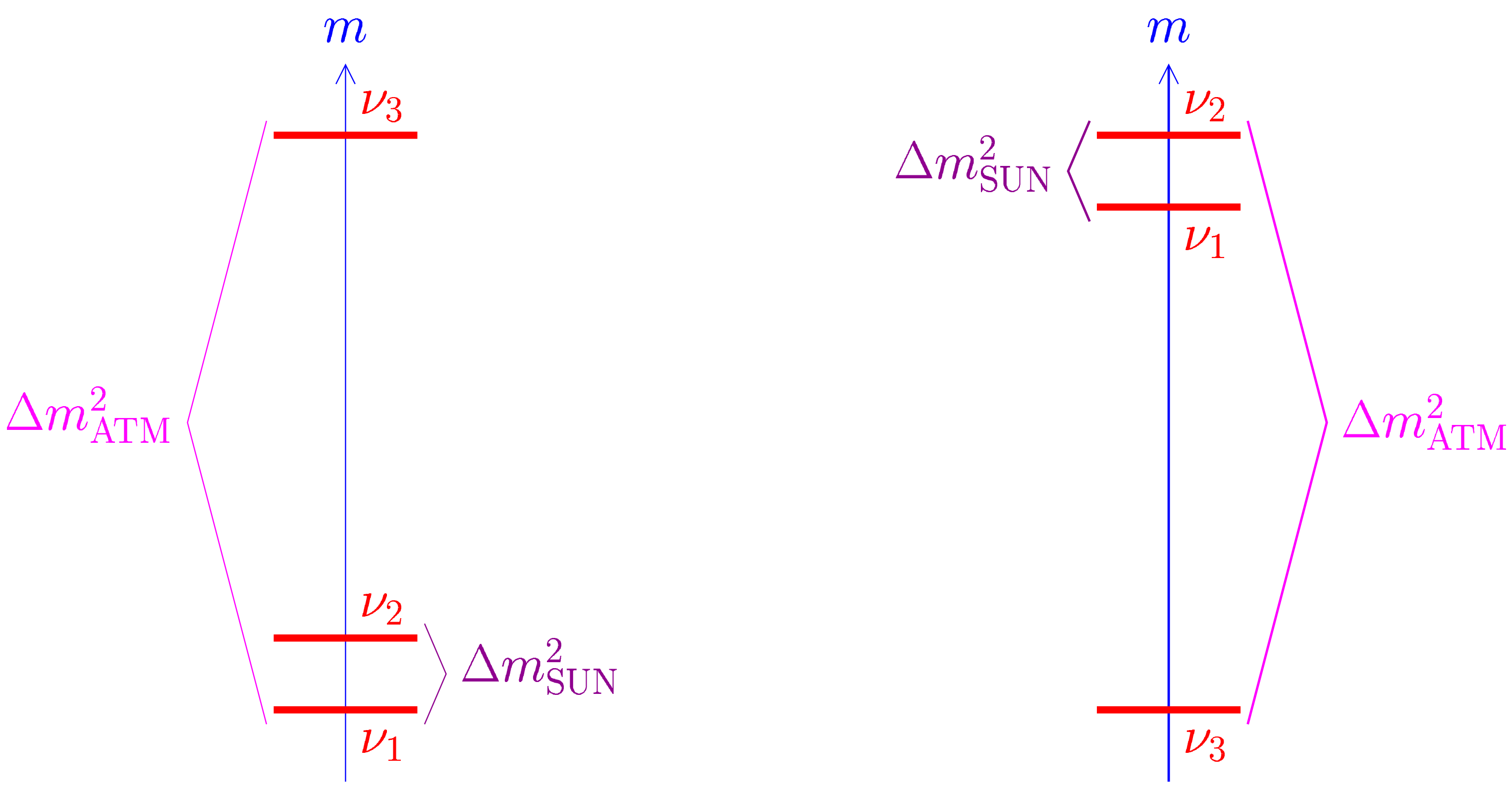
massive fields ν_k

$k = 1, 2, 3$

$$\boxed{\Delta m^2_{\text{SUN}} = \Delta m^2_{21} \simeq 7 \times 10^{-5}\,\text{eV}^2}$$

$$\boxed{\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2}$$

normal



inverted

$$\boxed{\Delta m^2_{21} \ll |\Delta m^2_{31}|}$$

$$\begin{array}{l} \text{SUN} \rightarrow \\ \\ \\ \end{array} U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

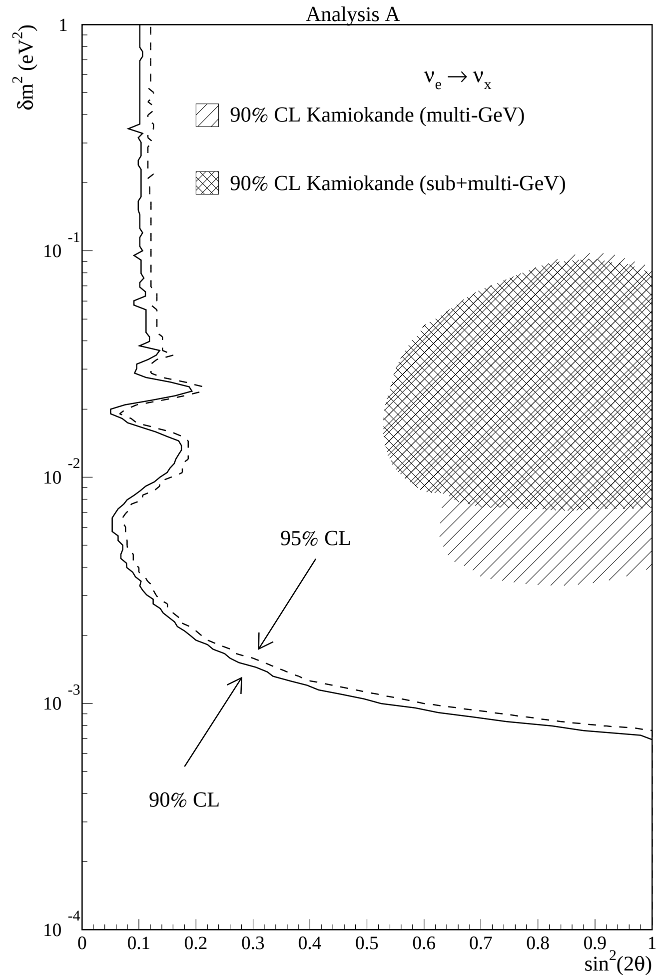
$$\begin{array}{r} \uparrow \\ \text{ATM} \end{array}$$

CHOOZ: $\begin{cases} \Delta m^2_{\text{CHOOZ}} = \Delta m^2_{31} = \Delta m^2_{\text{ATM}} \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1 - |U_{e3}|^2) \end{cases}$

$$\Downarrow$$

$$\boxed{|U_{e3}|^2 < 5 \times 10^{-2} \ (99.73\% \text{ C.L.})}$$

[Fogli et al., PRD 66 (2002) 093008]



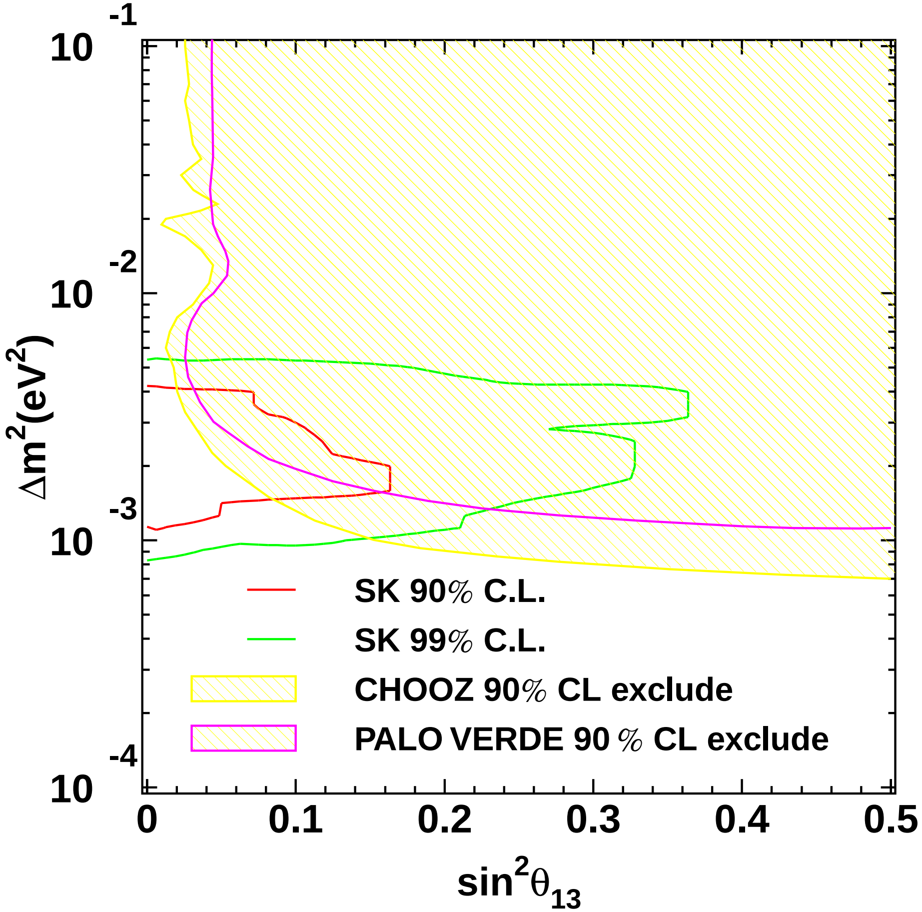
[CHOOZ, PLB 466 (1999) 415]
see also [Palo Verde, PRD 64 (2001) 112001]

SOLAR AND ATMOSPHERIC ν OSCILLATIONS
ARE PRACTICALLY DECOUPLED!

TWO-NEUTRINO SOLAR and ATMOSPHERIC ν OSCILLATIONS ARE OK!

$$\sin^2 \vartheta_{\text{SUN}} = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2} \simeq |U_{e2}|^2 \qquad \sin^2 \vartheta_{\text{ATM}} = |U_{\mu 3}|^2$$

[Bilenky, Giunti, PLB 444 (1998) 379]
[Guo, Xing, PRD 67 (2003) 053002]



[Nakaya (SK), hep-ex/0209036]

FUTURE

MINOS: sensitivity $|U_{e3}|^2 \sim 10^{-2}$

JHF-Kamioka: sensitivity $|U_{e3}|^2 \sim 2 \times 10^{-3}$ ($|U_{e3}|^2 \sim 10^{-4}$ with Hyper-Kamiokande) [hep-ex/0106019]

Reactor Experiments: sensitivity $|U_{e3}|^2 \sim 3 \times 10^{-3}$ [NuFact 03, `http://www.cap.bnl.gov/nufact03`]

Neutrino Factory: sensitivity $|U_{e3}|^2 \sim 10^{-5}$

$|U_{e3}| > 0 \Rightarrow$ normal or inverted scheme (Earth matter effects) and (maybe) CP violation

Standard Parameterization of Mixing Matrix for Majorana Neutrinos

$$U = R_{23}\, W_{13}\, R_{12}\, D(\lambda)$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$\vartheta_{23} \simeq \vartheta_{\text{ATM}}$ $\vartheta_{13} = \vartheta_{\text{CHOOZ}}$ $\vartheta_{12} = \vartheta_{\text{SUN}}$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\lambda_{21}} & s_{13}e^{i(\lambda_{31}-\delta_{13})} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}e^{i\lambda_{21}} - s_{12}s_{23}s_{13}e^{i(\lambda_{21}+\delta_{13})} & s_{23}c_{13}e^{i\lambda_{31}} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}e^{i\lambda_{21}} - s_{12}c_{23}s_{13}e^{i(\lambda_{21}+\delta_{13})} & c_{23}c_{13}e^{i\lambda_{31}} \end{pmatrix}$$

$\delta_{13} \neq 0$ or $\lambda_{21} \neq 0, \dfrac{\pi}{2}$ or $\lambda_{31} \neq 0, \dfrac{\pi}{2}$ $\Rightarrow$ $\text{CP}\,\mathcal{L}^{\text{CC}}\text{CP}^{-1} \neq \mathcal{L}^{\text{CC}}$ $\Leftrightarrow$ CP violation

Bilarge Mixing

$$\sin^2\vartheta_{\rm SUN} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2} \qquad \sin^2\vartheta_{\rm ATM} = |U_{\mu 3}|^2 \qquad \sin^2\vartheta_{\rm CHOOZ} = |U_{e3}|^2$$

$$\tan^2\vartheta_{\rm SUN}^{\text{best-fit}} = 0.43 \qquad 0.30 < \tan^2\vartheta_{\rm SUN} < 0.64 \quad (99.73\%\ \text{C.L.})$$

[Maltoni, Schwetz, Tortola, Valle, hep-ph/0309130]

$$\sin^2 2\vartheta_{\rm ATM}^{\text{best-fit}} = 1 \qquad \sin^2 2\vartheta_{\rm ATM} > 0.86 \quad (99.73\%\ \text{C.L.})$$

[Fogli, Lisi, Marrone, Montanino, PRD 67 (2003) 093006]

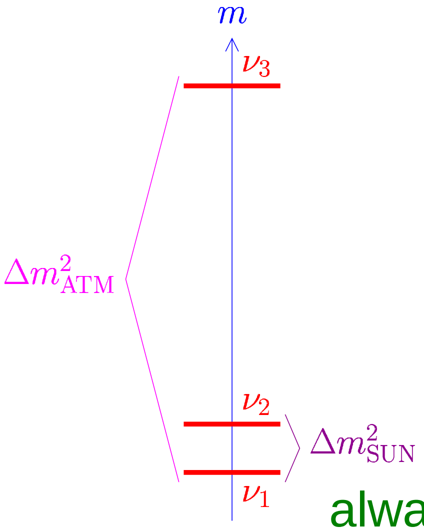
$$\sin^2 2\vartheta_{\rm CHOOZ}^{\text{best-fit}} = 0 \qquad \sin^2 2\vartheta_{\rm CHOOZ} < 5\times 10^{-2} \quad (99.73\%\ \text{C.L.})$$

[Fogli et al., PRD 66 (2002) 093008]

$$U_{\rm bf} \simeq \begin{pmatrix} 0.84 & 0.55 & 0.00 \\ -0.39 & 0.59 & 0.71 \\ 0.39 & -0.59 & 0.71 \end{pmatrix}$$

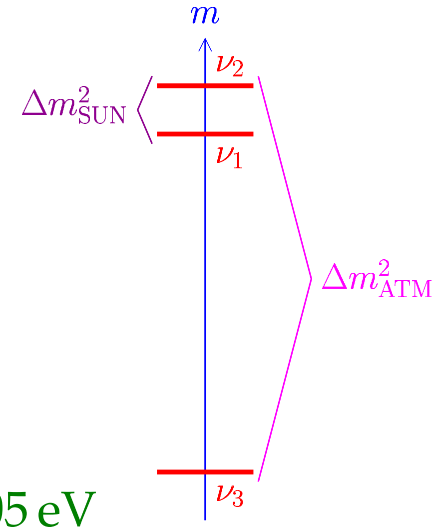
$$|U| \simeq \begin{pmatrix} 0.76-0.88 & 0.47-0.62 & 0.00-0.22 \\ 0.09-0.62 & 0.29-0.79 & 0.55-0.85 \\ 0.11-0.62 & 0.32-0.80 & 0.51-0.83 \end{pmatrix}$$

Absolute Scale of Neutrino Masses

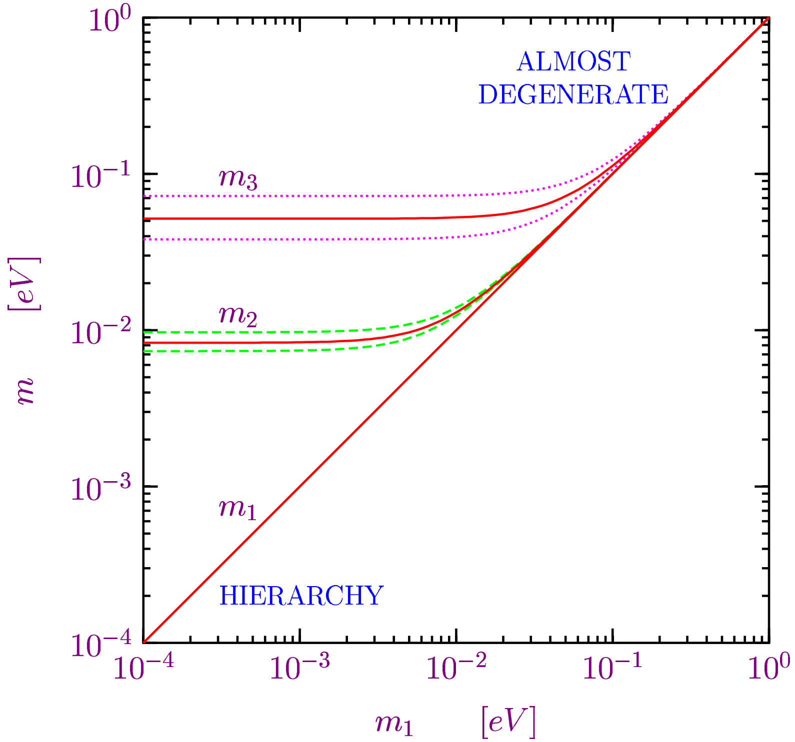


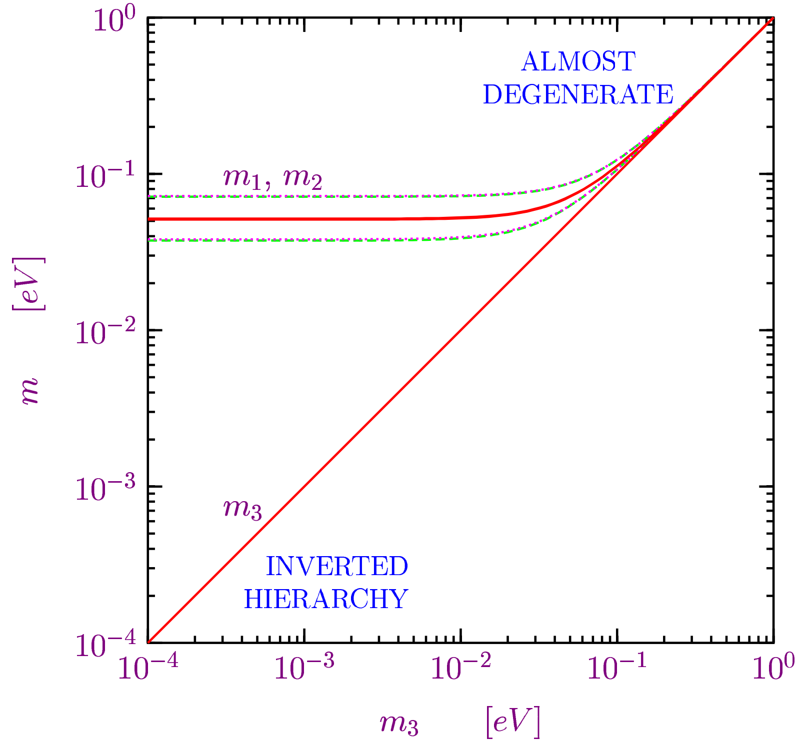
normal

inverted



always almost degenerate for $m_1 \gg \sqrt{\Delta m^2_{\mathrm{ATM}}} \simeq 0.05\,\mathrm{eV}$





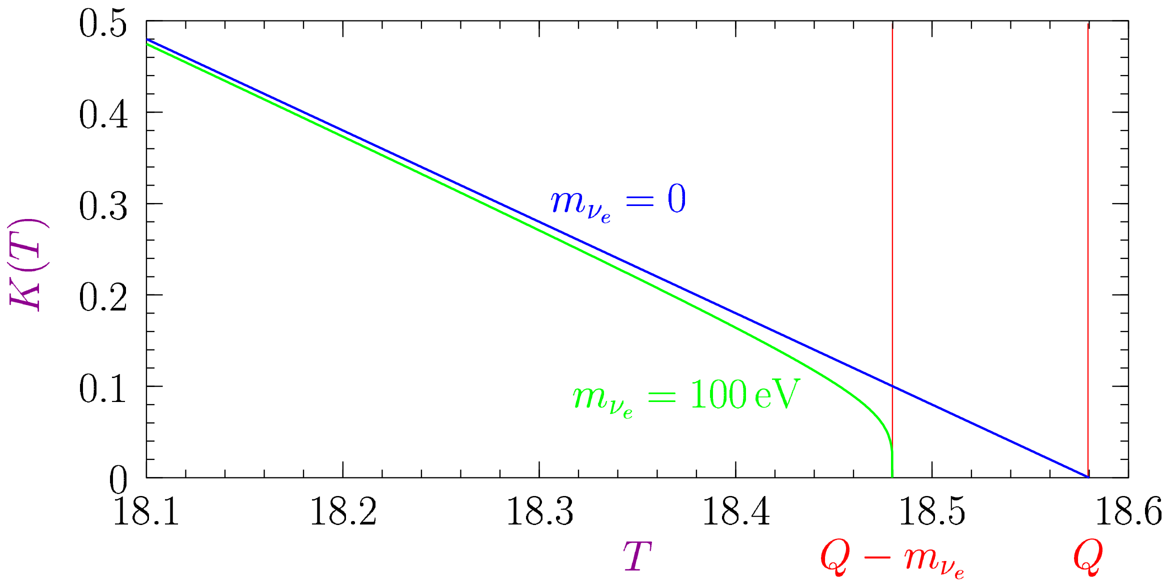
Tritium β Decay

$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}T} = \frac{(\cos\vartheta_C G_\mathrm{F})^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE\, (Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

Kurie plot: $$K(T) = \sqrt{\frac{\mathrm{d}\Gamma/\mathrm{d}T}{\frac{(\cos\vartheta_C G_\mathrm{F})^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$$



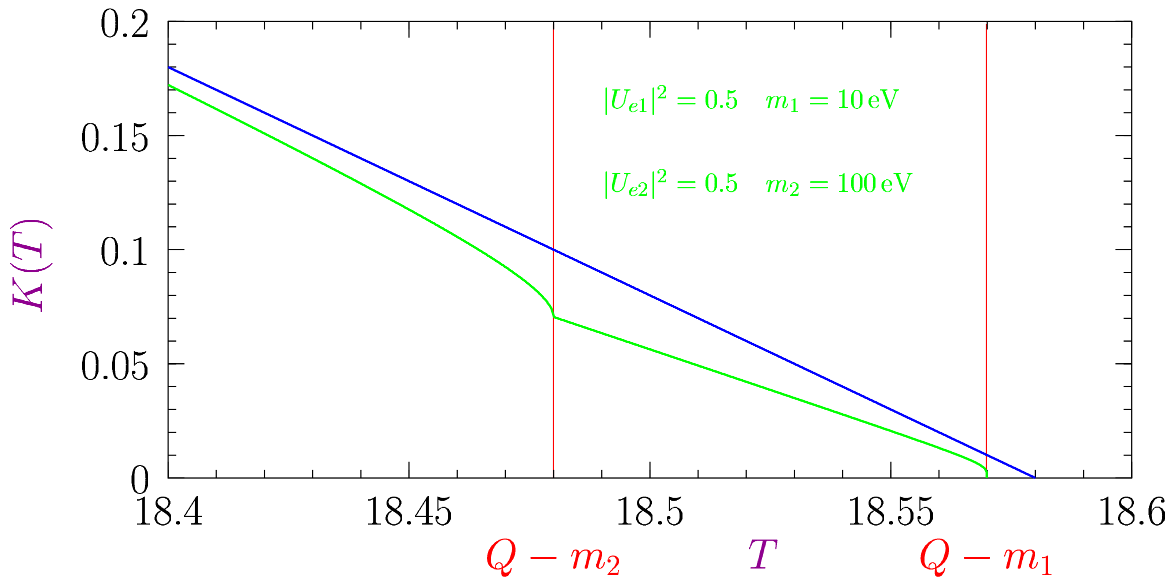
$\boxed{m_{\nu_e} < 2.2\,\mathrm{eV} \quad \text{(95\% C.L.)}}$

[Mainz, Troitsk, hep-ex/0210050]

future: KATRIN [hep-ex/0109033]

sensitivity: $m_{\nu_e} \gtrsim 0.3\,\mathrm{eV}$

Neutrino Mixing $\Longrightarrow$ $K(T) = \left[(Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$



analysis of data is different from the no-mixing case: $2N-1$ parameters

$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

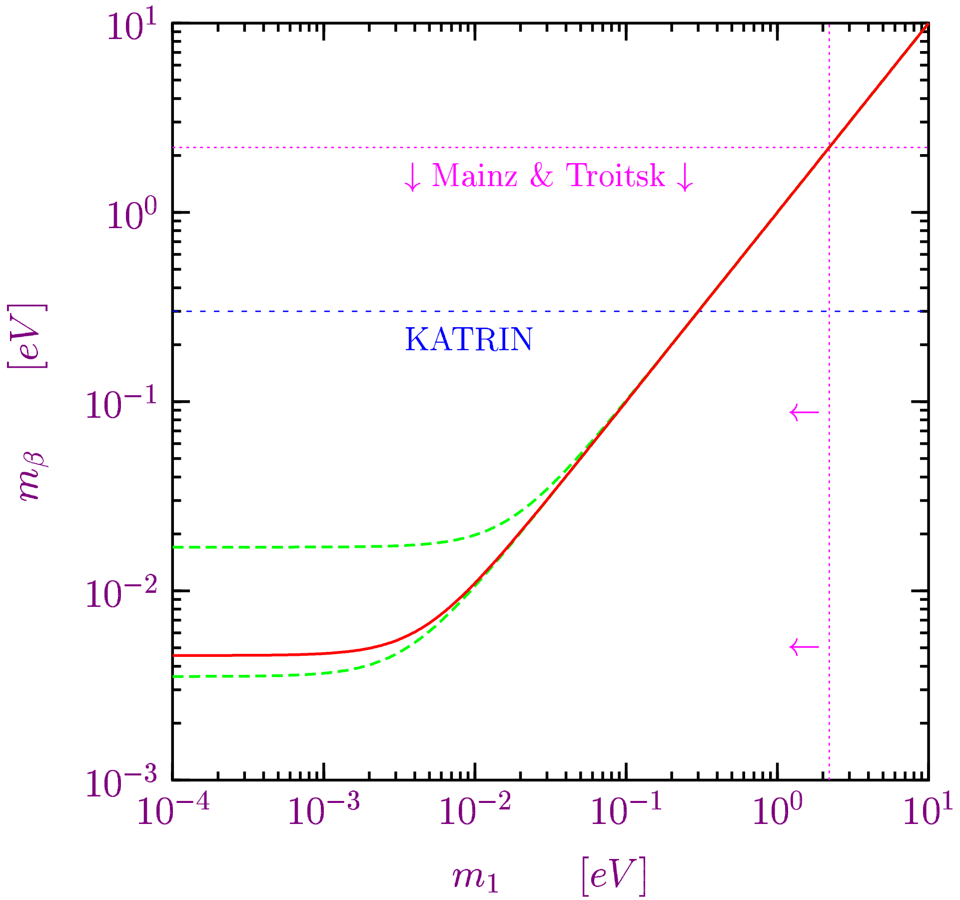
if experiment is not sensitive to masses ($m_k \ll Q - T$) $\Longrightarrow$ effective mass

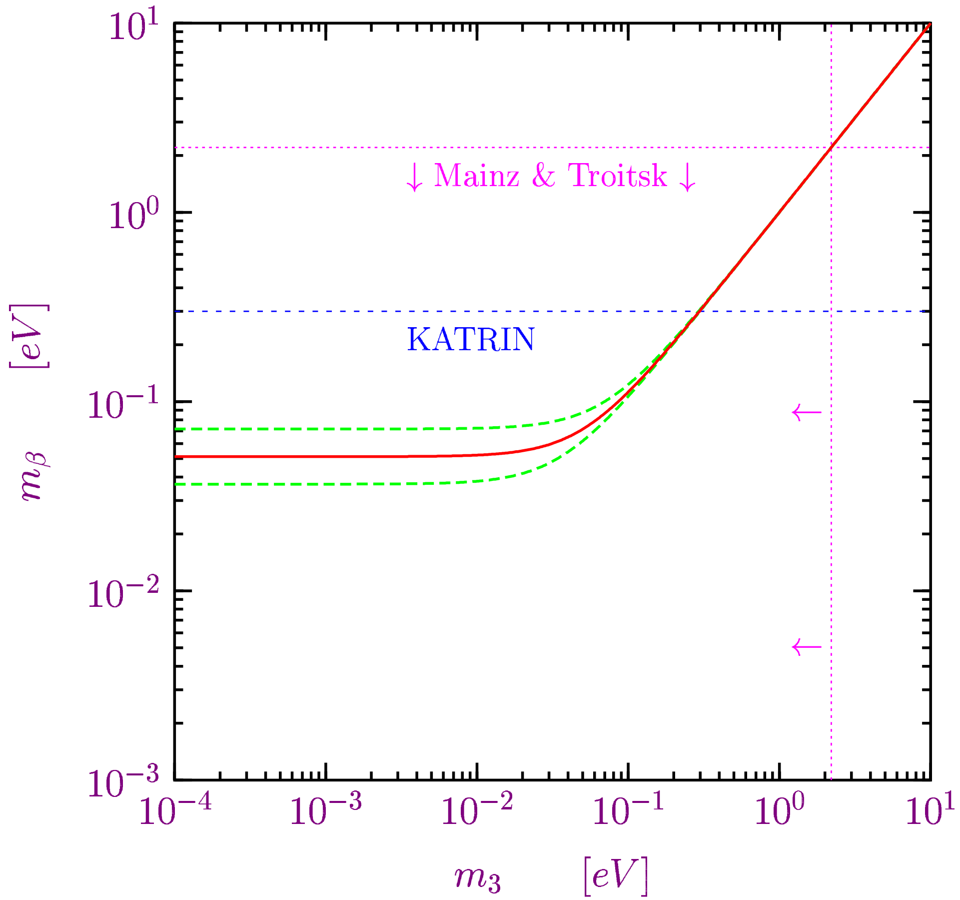
$$\boxed{m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2}$$

$$K^2 = (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2} \right]$$

$$= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2} \right] \simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2}$$

$m_{\nu_e} < 2.2\,\text{eV}$ (95% C.L.) $\Longrightarrow$ $m_\beta < 2.2\,\text{eV}$ (95% C.L.)





normal scheme

inverted scheme

almost degenerate: $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu$ $\Longrightarrow$ $m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$

VERY FAR FUTURE: IF $m_\beta \lesssim 3 \times 10^{-2}\,\text{eV} \Longrightarrow$ NORMAL HIERARCHY

Cosmological Limit on Neutrino Masses

neutrinos are in equilibrium in the primeval plasma through weak interaction reactions

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N \qquad \nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

weak interactions freeze out

$$\Gamma_{\text{weak}} = N\sigma v \sim G_{\text{F}}^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H \quad \Longrightarrow \quad T_{\text{dec}} \sim 1\,\text{MeV}$$

neutrino decoupling

Relic Neutrinos: $T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945\,\text{K} \Longrightarrow k\,T_\nu \simeq 1.676 \times 10^{-4}\,\text{eV}$ $\quad (T_\gamma = 2.725 \pm 0.001\,\text{K})$

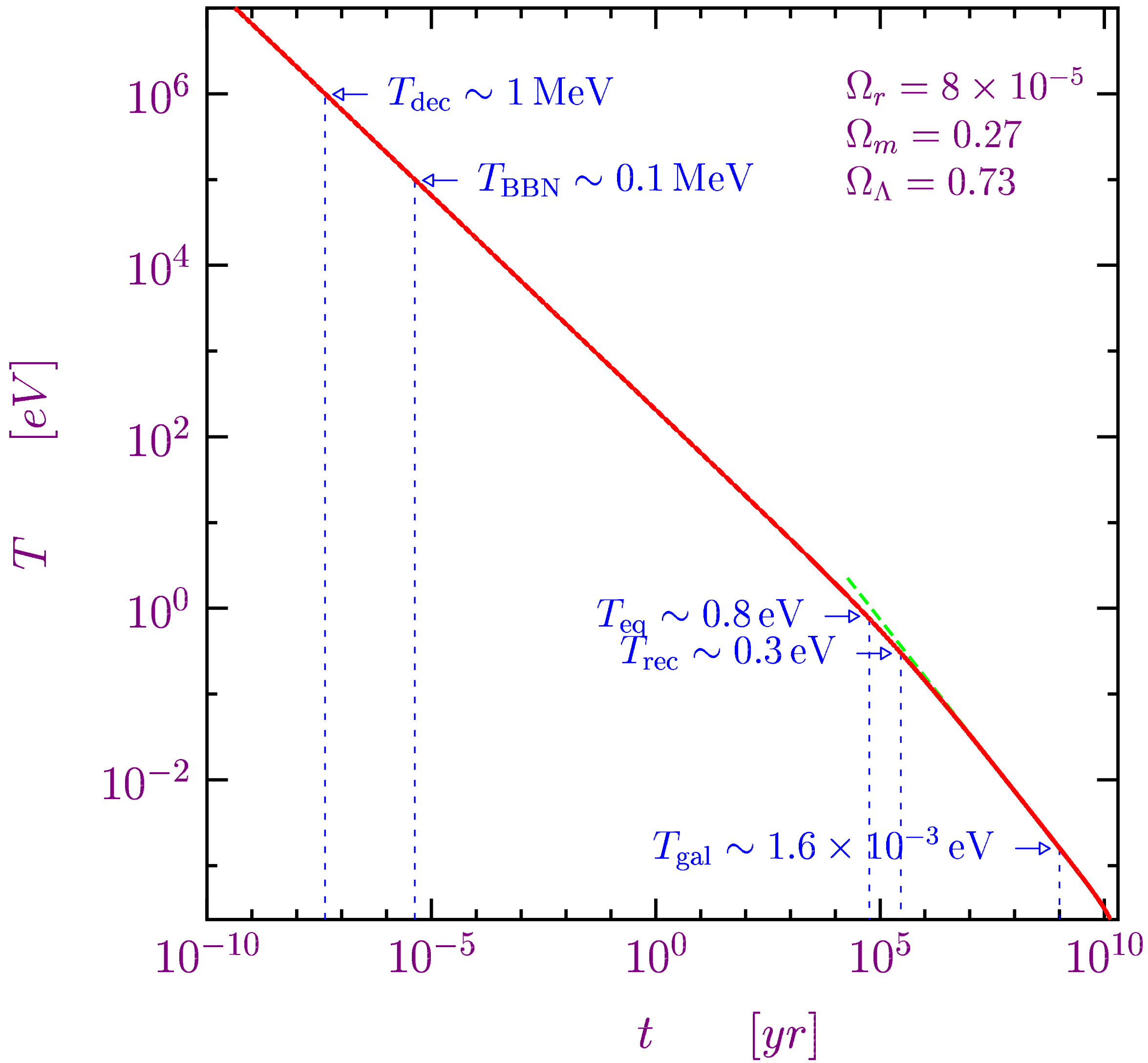
number density: $n_f = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_f T_f^3 \Longrightarrow n_{\nu_k,\bar{\nu}_k} \simeq 0.1827\,T_\nu^3 \simeq 112\,\text{cm}^{-3}$

density contribution: $\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k}\, m_k}{\rho_c} \simeq \frac{1}{h^2}\frac{m_k}{94.14\,\text{eV}} \Longrightarrow \boxed{\Omega_\nu h^2 = \frac{\sum_k m_k}{94.14\,\text{eV}}}$ $\quad \left(\rho_c = \frac{3H^2}{8\pi G_{\text{N}}}\right)$

[Gershtein, Zeldovich, JETP Lett. 4 (1966) 120] [Cowsik, McClelland, PRL 29 (1972) 669]

very weak assumptions: $h \lesssim 1$, $\Omega_\nu \lesssim 1 \quad \Longrightarrow \quad \sum_k m_k \lesssim 94\,\text{eV}$

reasonable assumptions: $h \lesssim 0.8$, $\Omega_\nu \lesssim 0.1 \quad \Longrightarrow \quad \sum_k m_k \lesssim 6\,\text{eV}$



massive neutrinos = hot dark matter

$\Updownarrow$

relativistic at matter-radiation equality

($z_{\rm eq} \sim 3000$)

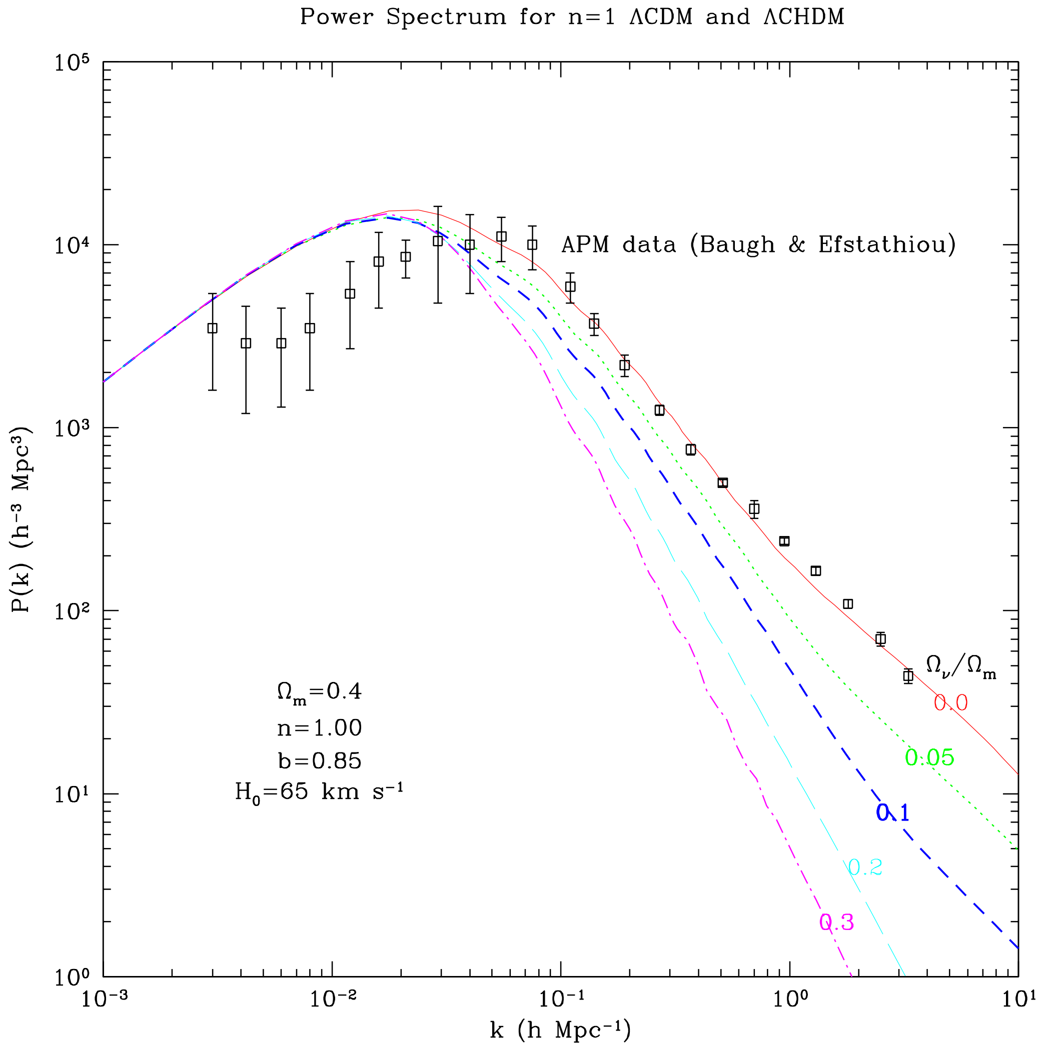
when structures start to form

last CMB Scattering (recombination)

$z_{\rm rec} \sim 1300$, $T_{\rm rec} \sim 3700\,{\rm K} \sim 0.3\,{\rm eV}$

galaxy formation at $z_{\rm gal} \sim 6.8$

Power Spectrum of Density Fluctuations



[Primack, Gross, astro-ph/0007165]

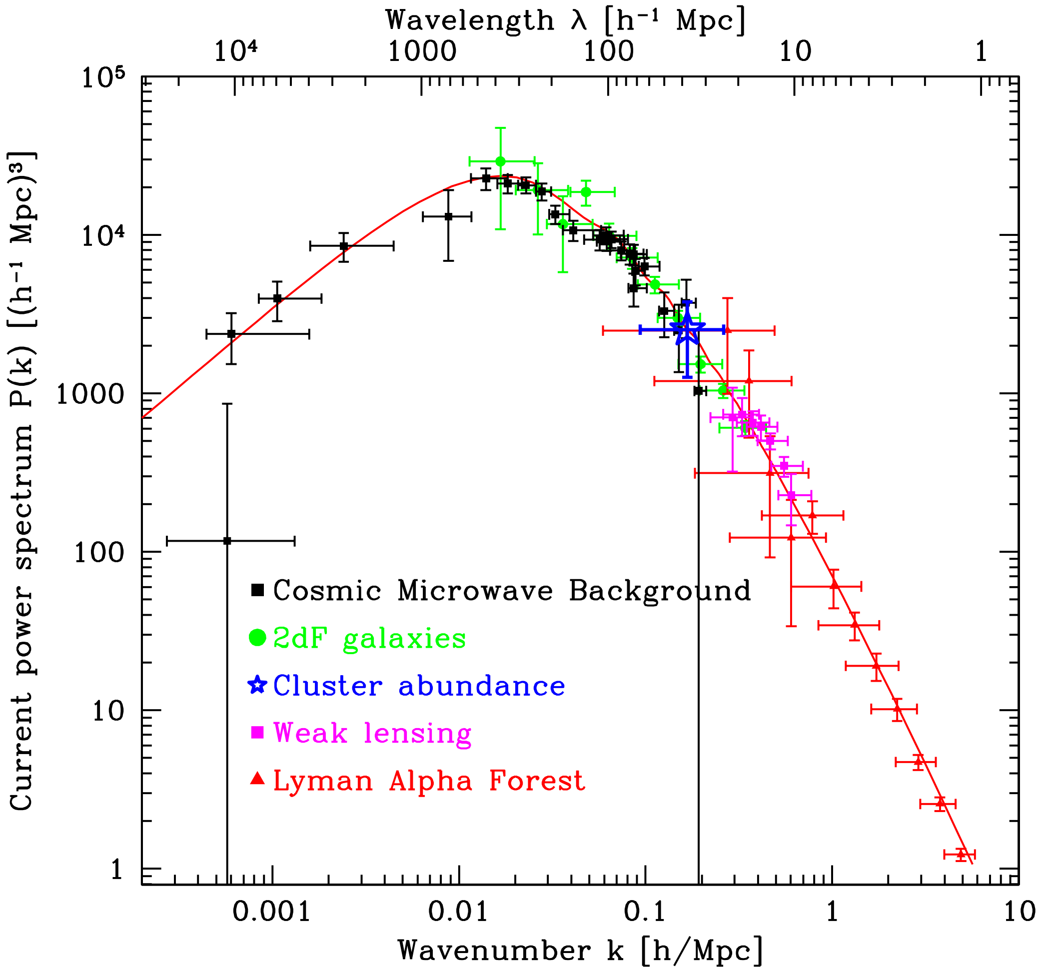
hot dark matter prevents early galaxy formation

small scale suppression

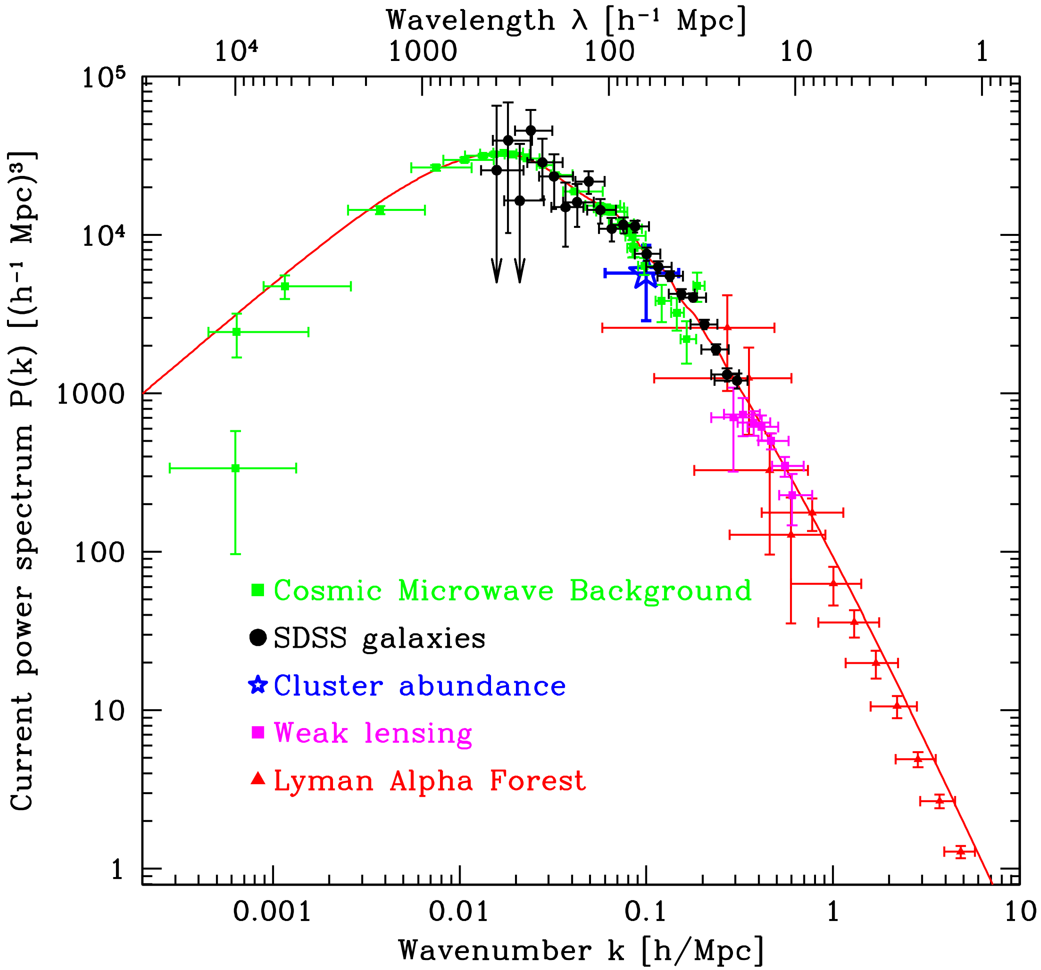
$$\frac{\Delta P(k)}{P(k)} \approx -8\,\frac{\Omega_\nu}{\Omega_m} \approx -0.8 \left(\frac{\sum_k m_k}{1\,\text{eV}}\right)\left(\frac{0.1}{\Omega_m h^2}\right)$$

for $k \gtrsim k_{\text{nr}} \approx 0.026 \sqrt{\frac{m_\nu}{1\,\text{eV}}}\,\sqrt{\Omega_m}\,h\,\text{Mpc}^{-1}$

[Hu, Eisenstein, Tegmark, PRL 80 (1998) 5255]



[Tegmark, Zaldarriaga, Phys. Rev. D66 (2002) 103508]



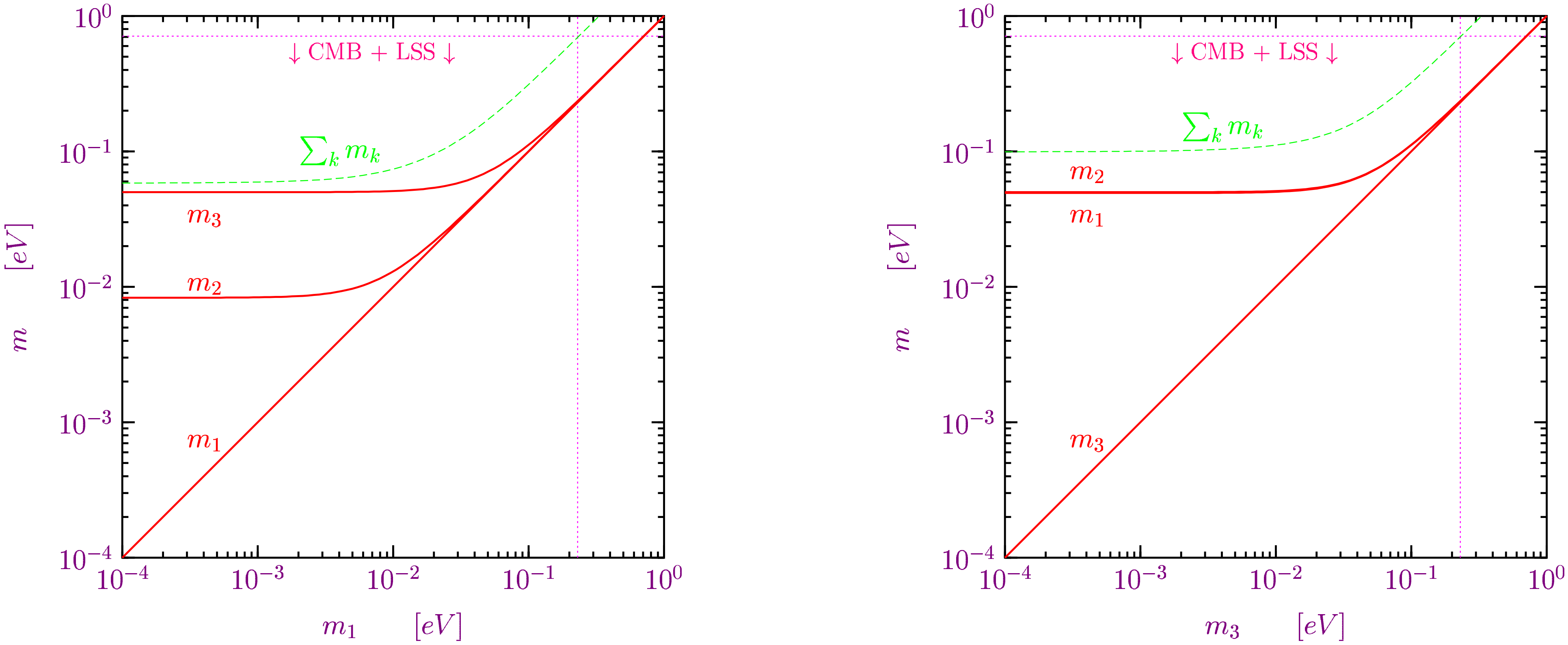
[SDSS, astro-ph/0310725]

CMB (WMAP, CBI, ACBAR) + LSS (2dFGRS, L-α) + HST + SN-Ia

[WMAP, astro-ph/0302207, astro-ph/0302209]

$$\Lambda\text{CDM:} \quad \left\{ \begin{array}{l} T_0 = 13.7 \pm 0.1\,\text{Gyr}, \quad h = 0.71^{+0.04}_{-0.03}, \\ \Omega_{\text{tot}} = 1.02 \pm 0.02, \quad \Omega_b h^2 = 0.0224 \pm 0.0009, \quad \Omega_m h^2 = 0.135^{+0.008}_{-0.009} \end{array} \right.$$

$$\Omega_\nu h^2 < 0.0076 \text{ (95\% confidence)} \Longrightarrow \sum_k m_k < 0.71\,\text{eV} \Longrightarrow m_k < 0.23\,\text{eV}$$



Hannestad [astro-ph/0303076]

$$\sum_k m_k < 1.01\,\mathrm{eV}$$ (95% confidence) [WMAP+CBI+2dFGRS+HST+SN-Ia]

$$\sum_k m_k < 1.20\,\mathrm{eV}$$ (95% confidence) [WMAP+CBI+2dFGRS]

$$\sum_k m_k < 2.12\,\mathrm{eV}$$ (95% confidence) [WMAP+2dFGRS]

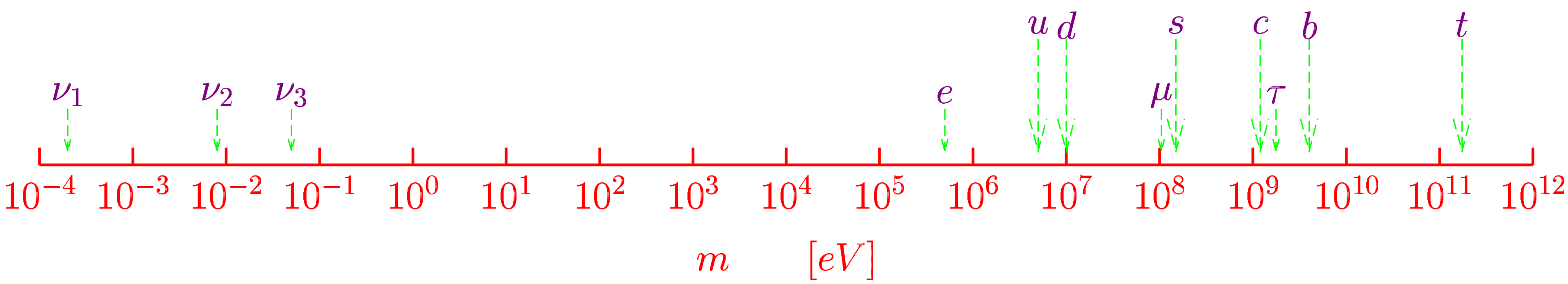
Elgaroy and Lahav [astro-ph/0303089]

$$\sum_k m_k < 1.1\,\mathrm{eV}$$ (95% confidence) [WMAP+2dFGRS+HST]

WMAP + SDSS [astro-ph/0310723]

$$h \approx 0.70^{+0.04}_{-0.03} \qquad \Omega_m \approx 0.30 \pm 0.04 \quad (1\sigma) \qquad \sum_k m_{\nu_k} < 1.7\,\mathrm{eV}$$ (95% confidence)

Majorana Neutrino Mass?



known natural explanations of smallness of ν masses:

- ★ See-Saw Mechanism
- ★ 5-D Non-Renormalizable Effective Operator

both imply

- ★ Majorana ν masses $\Longleftrightarrow$ $|\Delta L| = 2$ $\Longleftrightarrow$ $\beta\beta_{0\nu}$ decay
- ★ see-saw type relation $m_\nu \sim \dfrac{\mathcal{M}_{\text{EW}}^2}{\mathcal{M}}$
- ★ new high energy scale $\mathcal{M}$

Majorana neutrino masses provide the most accessible window on New Physics Beyond the Standard Model

In Neutrino Oscillations Dirac $\sim$ Majorana

Evolution of Amplitudes: $$\frac{\mathrm{d}\nu_\alpha}{\mathrm{d}t} = \frac{1}{2E}\left(UM^2U^\dagger + 2EV\right)_{\alpha\beta}\nu_\beta$$

difference: $$\begin{cases} \text{Dirac:} & U^{(\mathrm{D})} \\ \text{Majorana:} & U^{(\mathrm{M})} = U^{(\mathrm{D})}D(\lambda) \end{cases}$$

$$D(\lambda) = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{i\lambda_{21}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{i\lambda_{N1}} \end{pmatrix} \quad \Rightarrow \quad D^\dagger = D^{-1}$$

$$M^2 = \begin{pmatrix} m_1^2 & 0 & \cdots & 0 \\ 0 & m_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_N^2 \end{pmatrix} \quad \Longrightarrow \quad DM^2 = M^2D \quad \Longrightarrow \quad DM^2D^\dagger = M^2$$

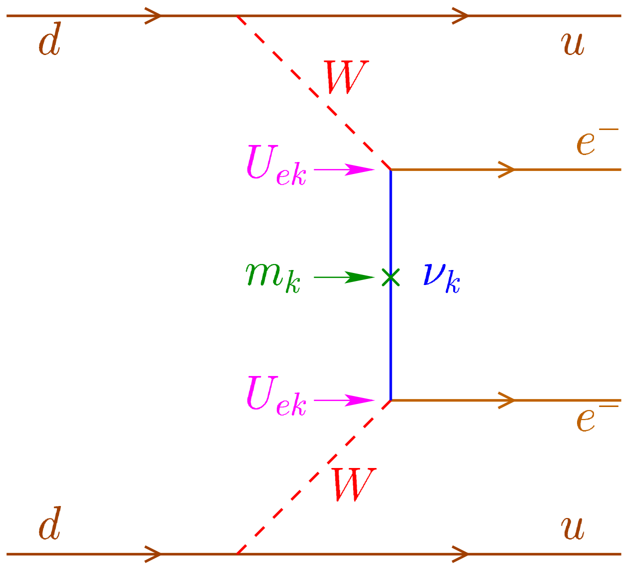
$$U^{(\mathrm{M})}M^2(U^{(\mathrm{M})})^\dagger = U^{(\mathrm{D})}DM^2D^\dagger(U^{(\mathrm{D})})^\dagger = U^{(\mathrm{D})}M^2(U^{(\mathrm{D})})^\dagger$$

Neutrinoless Double-β Decay: $\Delta L = 2$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu} \, |\mathcal{M}_{0\nu}|^2 \, |m_{\beta\beta}|^2$$

effective Majorana mass $\quad m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$



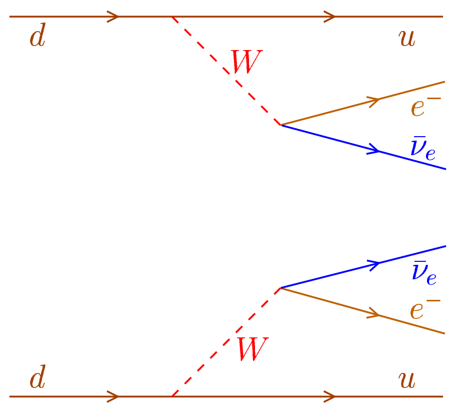
Two-Neutrino Double-β Decay: $\Delta L = 0$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu} \, |\mathcal{M}_{2\nu}|^2$$

second order weak interaction process

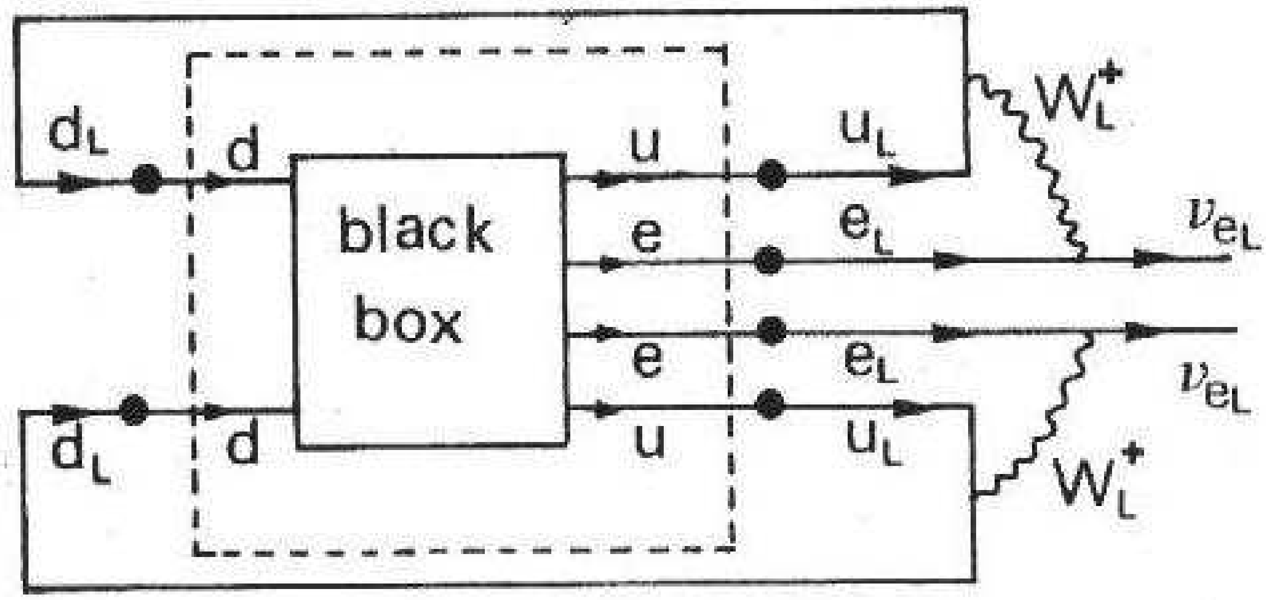
in the Standard Model



Majorana Neutrino Mass $\Leftrightarrow$ $\beta\beta_{0\nu}$ Decay

[Hirsch]

[Schechter, Valle, PRD 25 (1982) 2951] [Takasugi, PLB 149 (1984) 372]



Majorana Mass Term:
$$\boxed{\mathcal{L}_L^{\mathrm{M}} = -\frac{1}{2}\, m \left(\overline{\nu_L^c}\, \nu_L + \overline{\nu_L}\, \nu_L^c \right) = \frac{1}{2}\, m \left(\nu_L^T\, \mathcal{C}^\dagger\, \nu_L + \nu_L^\dagger\, \mathcal{C}\, \nu_L^* \right)}$$

two conditions:
- u, d, e are massive
- standard left-handed weak interaction exists

cancellations with other diagrams are very unlikely (unstable under perturbations)

The Problem of Nuclear Matrix Elements

[Simkovic, Vergados, Suhonen, Kortelainen]

Theoretically evaluated $\beta\beta(0\nu)$ half-lives (units of 10^{28} years for $\langle m_\nu \rangle = 10$ meV).

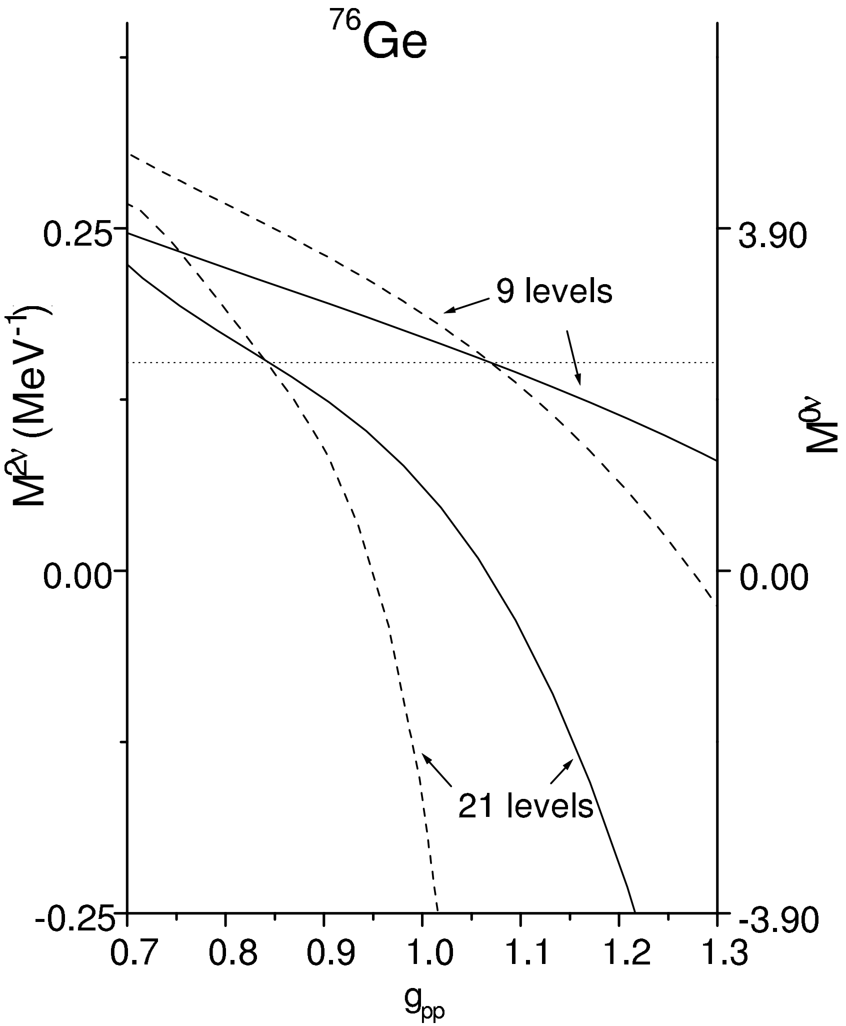
Isotope	[10]	[11]	[12]	[13]	[14]	[15]
^{48}Ca	3.18	8.83	-	-	-	2.5
^{76}Ge	1.7	17.7	14.0	2.33	3.2	3.6
^{82}Se	0.58	2.4	5.6	0.6	0.8	1.5
^{100}Mo	-	-	1.0	1.28	0.3	3.9
^{116}Cd	-	-	-	0.48	0.78	4.7
^{130}Te	0.15	5.8	0.7	0.5	0.9	0.85
^{136}Xe	-	12.1	3.3	2.2	5.3	1.8
^{150}Nd	-	-	-	0.025	0.05	-
^{160}Gd	-	-	-	0.85	-	-

[Cremonesi, NPB P.S. 118 (2003) 287]

about factor of 3 discrepancies $\Longrightarrow$ estimated uncertainty

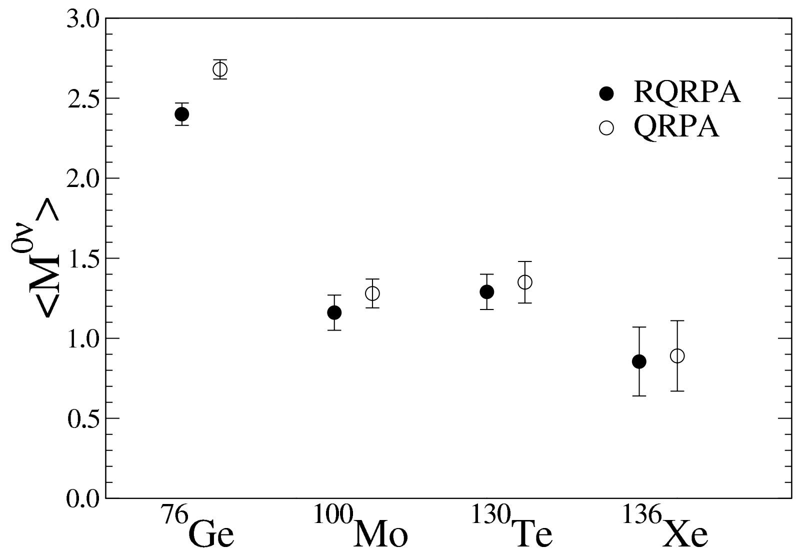
QRPA calculation of $\mathcal{M}_{0\nu}$

[Simkovic]



Nucleus	$\lvert\mathcal{M}_{0\nu}\rvert$
^{76}Ge	2.40 ± 0.07
^{100}Mo	1.16 ± 0.11
^{130}Te	1.29 ± 0.11

[Rodin, Faessler, Simkovic, Vogel, PRC 68 (2003) 044302]
[Bilenky, Faessler, Simkovic, hep-ph/0402250]



uncertainties much smaller than the traditional factor of ~ 3

Hirsch Comment on Matrix Element Uncertainty

- ★ in QRPA calculations g_{pp} is the most important parameter
- ★ increasing g_{pp} reduces both $\beta\beta_{2\nu}$ and $\beta\beta_{0\nu}$ matrix elements
- ★ if $\beta\beta_{2\nu}$ half life is known, g_{pp} can be fitted

[Rodin, Faessler, Simkovic, Vogel, PRC 68 (2003) 044302]

3 different nuclear Hamiltonians

3 different model spaces

$\Longrightarrow$

$$\mathcal{M}_{0\nu}^{\text{QRPA}} = 2.68 \pm 0.06$$

$$\mathcal{M}_{0\nu}^{\text{RQRPA}} = 2.40 \pm 0.07$$

[Muto, PLB 391 (1997) 243]

$$\mathcal{M}_{0\nu}^{\text{QRPA}} = 4.5 \qquad \mathcal{M}_{0\nu}^{\text{RQRPA}} = 3.8 \qquad \mathcal{M}_{0\nu}^{\text{EQRPA}} = 3.9$$

$$\frac{\mathcal{M}_{0\nu}^{\text{Rodin-Faessler-Simkovic-Vogel}}}{\mathcal{M}_{0\nu}^{\text{Muto}}} \sim \frac{1}{2}$$

- ★ Rodin-Faessler-Simkovic-Vogel uncertainties seem too optimistic
- ★ but factor of ~ 3 uncertainty maybe too pessimistic
- ★ necessary to exclude old or unreliable calculations
- ★ experts should join, select the best calculations and estimate uncertainty

Vergados: important to improve shell model and QRPA calculations
to reach (hopefully) convergence

Suhonen: use available $\beta^{\pm}$ decay data of intermediate nucleus
to constrain and test models

important to test and constrain model with all available data

Kortelainen: possible test with μ capture

no method can guarantee rightness of matrix element,
but important to increase confidence

$\beta\beta_{0\nu}$ Decay Experiments

[Avignone]

sensitivity: signal equal to background fluctuations

$$\Gamma^{0\nu}_{1/2}\, N_{\beta\beta}\, T\, \epsilon \sim \sqrt{B\, \Delta E\, M\, T}$$

$$T^{0\nu}_{1/2} \sim \frac{N_{\beta\beta}\, T\, \epsilon}{\sqrt{B\, \Delta E\, M\, T}} \propto \epsilon \sqrt{\frac{M\, T}{B\, \Delta E}}$$

large efficiency ϵ

large mass M

long time T

low background rate B

small energy resolution ΔE

Best limits for $\beta\beta_{0\nu}$ Decay

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\, |\mathcal{M}_{0\nu}|^2\, |m_{\beta\beta}|^2$$

RQRPA calculation of $\mathcal{M}_{0\nu}$

[Rodin, Faessler, Simkovic, Vogel, PRC 68 (2003) 044302]

[Bilenky, Faessler, Simkovic, hep-ph/0402250]

Nucleus	$G_{0\nu}$ $[10^{-25}\,\mathrm{y}^{-1}\,\mathrm{eV}^{-2}]$	$\lvert\mathcal{M}_{0\nu}\rvert$
$^{76}\mathrm{Ge}$	0.30	2.40
$^{100}\mathrm{Mo}$	2.19	1.16
$^{130}\mathrm{Te}$	2.12	1.29

Heidelberg-Moscow ($^{76}\mathrm{Ge}$)

[EPJA 12 (2001) 147]

$$\boxed{T^{0\nu}_{1/2} > 1.9 \times 10^{25}\,\mathrm{y} \quad \text{(90\% C.L.)}} \quad \Longrightarrow \quad \boxed{|m_{\beta\beta}| < 0.55\,\mathrm{eV} \quad \text{(90\% C.L.)}}$$

IGEX ($^{76}\mathrm{Ge}$)

[PRD 65 (2002) 092007]

$$\boxed{T^{0\nu}_{1/2} > 1.57 \times 10^{25}\,\mathrm{y} \quad \text{(90\% C.L.)}} \quad \Longrightarrow \quad \boxed{|m_{\beta\beta}| < 0.61\,\mathrm{eV} \quad \text{(90\% C.L.)}}$$

Best reported results on $\beta\beta$ processes. Limits are at 90% C.L. except when noted. $\beta\beta(2\nu)$ results are averaged over different experiments. The effective neutrino mass limits and ranges are those deduced by the authors ($\langle m_\nu \rangle$) or according to Table 1 ($\langle m_\nu^\dagger \rangle$).

Isotope	$T^{2\nu}_{1/2}$ (y)	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)	$\langle m_\nu^\dagger \rangle$ (eV)
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$[16]	$> 9.5 \times 10^{21}$(76%)[17]	< 8.3	$< 16 - 30$
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$[37,18]	$> 1.9 \times 10^{25}$[37]	< 0.35	$< 0.3 - 1$
		$> 1.6 \times 10^{25}$ [19,38]	$< 0.33 - 1.35$	
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$[20,21]	$> 2.7 \times 10^{22}$(68%) [20]	< 5	$< 4.6 - 14.4$
^{96}Zr	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$[22,23]			
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$[24–26]	$> 5.5 \times 10^{22}$[27]	< 2.1	$< 2.3 - 8.4$
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$[28–30]	$> 7 \times 10^{22}$[29]	< 2.6	$< 2.6 - 8.2$
^{128,130}Te		Geoch. ratio[31]	$< 1.1 - 1.5$	
^{128}Te	$(7.2 \pm 0.3) \times 10^{24}$[31,32]	$> 7.7 \times 10^{24}$ [31]	$< 1.1 - 1.5$	
^{130}Te	$(2.7 \pm 0.1) \times 10^{21}$[31]	$> 2.08 \times 10^{23}$	$< 0.9 - 2.0$	$< 0.85 - 5.3$
^{136}Xe	$> 8.1 \times 10^{20}$[33]	$> 4.4 \times 10^{23}$ [34]	$< 1.8 - 5.2$	$< 2 - 5.2$
^{150}Nd	$7.0^{+11.8}_{-0.3} \times 10^{18}$[25,35]	$> 1.2 \times 10^{21}$[25]	< 3	$< 4.6 - 6.5$
^{238}U$^{(3)}$	$(2.0 \pm 0.6) \times 10^{21}$[36]			

[Cremonesi, NPB P.S. 118 (2003) 287]

Indication of $\beta\beta_{0\nu}$ Decay in Heidelberg-Moscow Experiment

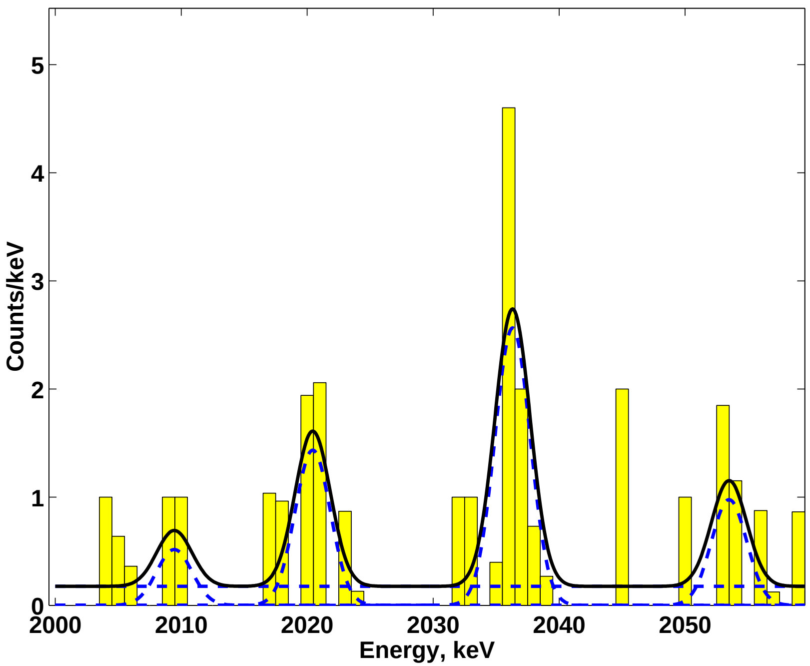
[Klapdor-Kleingrothaus, Dietz, Harney, Krivosheina, Mod. Phys. Lett. A16 (2001) 2409] [Klapdor-Kleingrothaus, Dietz, Krivosheina, Found. Phys. 32 (2002) 1181]

[Klapdor-Kleingrothaus, Dietz, Chkvorez, Krivosheina, NIMA 522 (2004) 371] [Klapdor-Kleingrothaus, Krivosheina, Dietz, Chkvorets, PLB 586 (2004) 198]

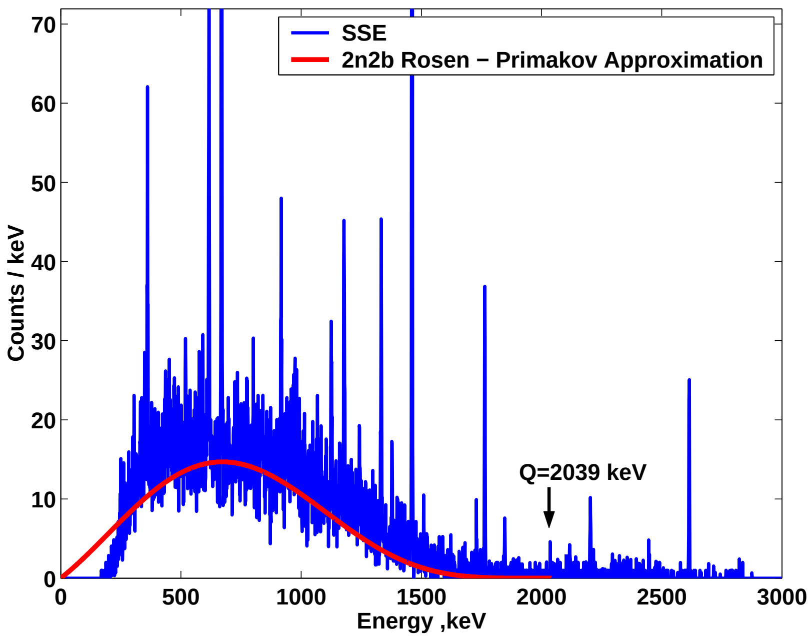
$T^{0\nu}_{1/2} = (0.69 - 4.18) \times 10^{25}\,\mathrm{y}$ (99.73% C.L.) $\qquad T^{0\nu\,\mathrm{best-fit}}_{1/2} = 1.19 \times 10^{25}\,\mathrm{y}$

4.2σ evidence (99.9973% C.L.)

$|m_{\beta\beta}| = 0.37 - 0.92\,\mathrm{eV}$ (99.73% C.L.) $\qquad |m_{\beta\beta}|^{\mathrm{best-fit}} = 0.70\,\mathrm{eV}$



pulse-shape selected spectrum



3.8σ evidence [PLB 586 (2004) 198]

the claim must be tested by independent experiment (NEMO-3, CUORICINO)

Experimental Perspectives for $\beta\beta_{0\nu}$ Decay

[Avignone, Thomas, Zuber]

Expected 5 y sensitivities of future projects. NME are from ref. [13] except when noted.

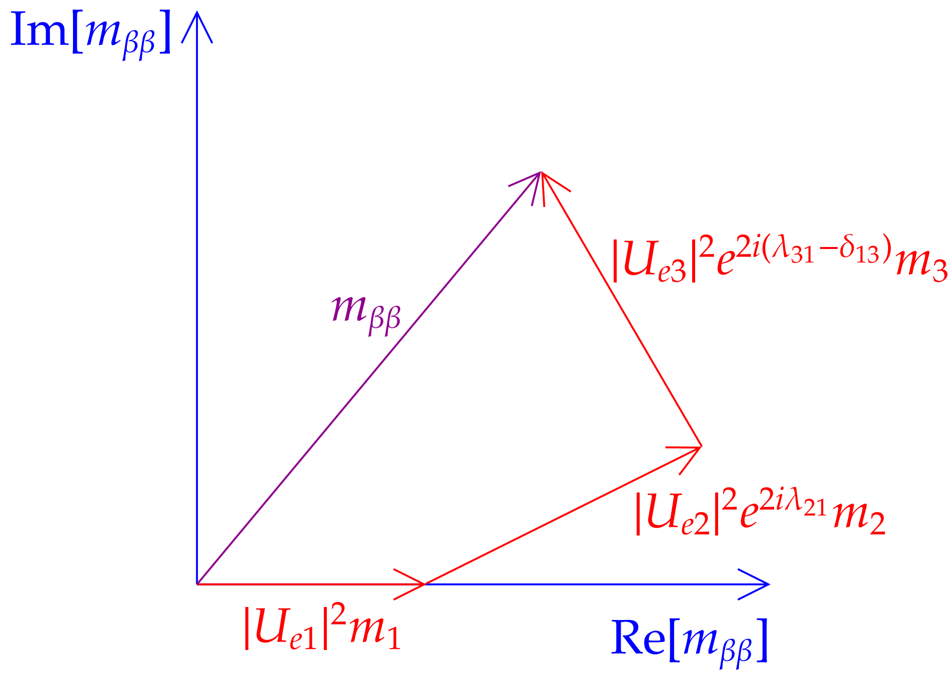
Experiment	Isotope	$T^{0\nu}_{1/2}$ (10^{26} y)	$\langle m_\nu \rangle$ (meV)
CUORE[47]	^{130}Te	7	27
CUORICINO[47]	^{130}Te	0.15	184
EXO[48]	^{136}Xe	8	52
GENIUS[49]	^{76}Ge	100	15
MAJORANA[50]	^{76}Ge	40	25
GEM[51]	^{76}Ge	70	18
MOON[52]	^{100}Mo	10	36
XMASS[53]	^{136}Xe	3	86
COBRA[54]	^{130}Te	0.01	240
DCBA[55]	^{150}Nd	0.15	190
NEMO 3[56]	^{100}Mo	0.04	560
CAMEO[57]	^{116}Cd	> 1	69
CANDLES[58]	^{48}Ca	1	158[15]

[Cremonesi, NPB P.S. 118 (2003) 287]

Neutrino Oscillations Bounds for $\beta\beta_{0\nu}$ Decay

[Hirsch, Pascoli]

$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$



complex U_{ek} $\Rightarrow$ possible cancellations among m_1, m_2, m_3 contributions!

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\lambda_{21}} m_2 + |U_{e3}|^2 e^{2i(\lambda_{31}-\delta_{13})} m_3$$

conserved CP $\Longrightarrow$ $\delta_{13} = 0 \quad \lambda_{kj} = 0 \, , \frac{\pi}{2}$ $\Longrightarrow$ $e^{2i\lambda_{kj}} = \pm 1$

opposite CP parities of ν_k and ν_j $\Longrightarrow$ $e^{2i\lambda_{kj}} = -1$ $\Longrightarrow$ maximal cancellation!

Mass Hierarchy Without Fine-Tuned Cancellations

$$|\langle m \rangle| \simeq \max_k |\langle m \rangle|_k \qquad |\langle m \rangle|_k \equiv |U_{ek}|^2 m_k$$

$$|U_{e2}|^2 \simeq \sin^2 \vartheta_{\text{SUN}} \qquad m_2 \simeq \sqrt{\Delta m^2_{\text{SUN}}} \qquad |U_{e3}|^2 \simeq \sin^2 \vartheta_{\text{CHOOZ}} \qquad m_3 \simeq \sqrt{\Delta m^2_{\text{ATM}}}$$

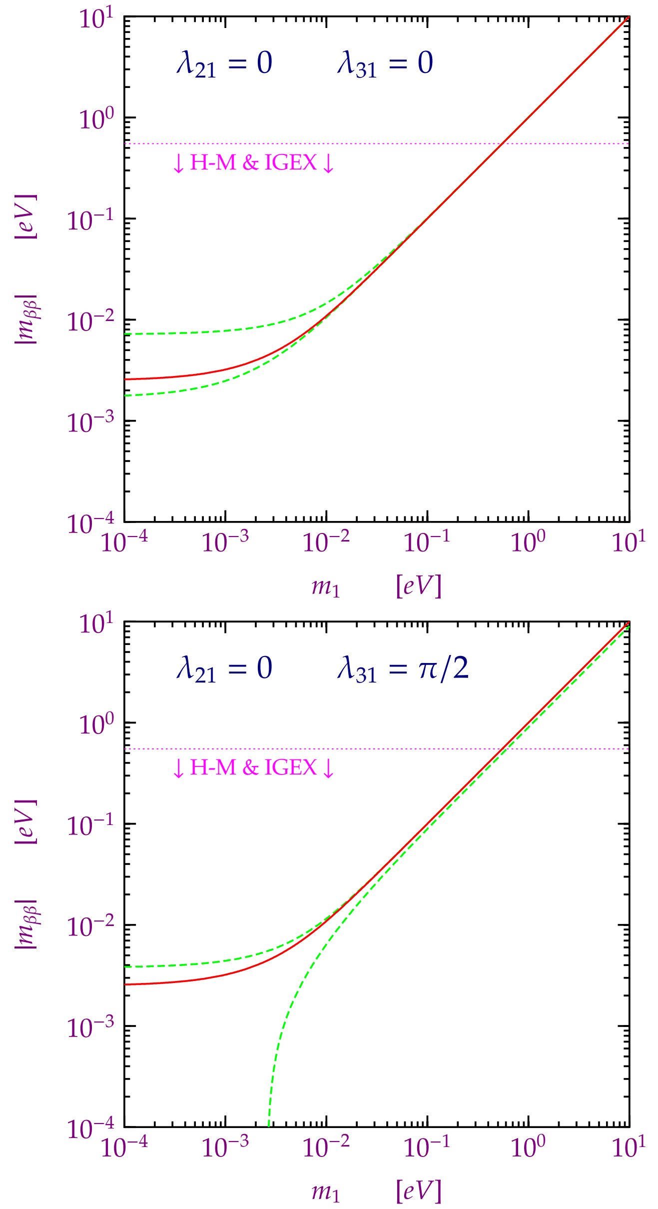
$$\left.\begin{array}{c} |U_{e2}|^2_{\text{best-fit}} = 0.30\,, \qquad \sqrt{\Delta m^{2\,\text{best-fit}}_{\text{SUN}}} = 8.3 \times 10^{-3} \\ 0.22 \lesssim |U_{e2}| \lesssim 0.38 \\ 7.3 \times 10^{-3} \lesssim \sqrt{\Delta m^2_{\text{SUN}}} \lesssim 9.7 \times 10^{-3} \end{array}\right\} \Longrightarrow \left\{\begin{array}{c} |\langle m \rangle|_2^{\text{best-fit}} = 2.5 \times 10^{-3} \\ 1.6 \times 10^{-3} \lesssim |\langle m \rangle|_2 \lesssim 3.7 \times 10^{-3} \end{array}\right.$$

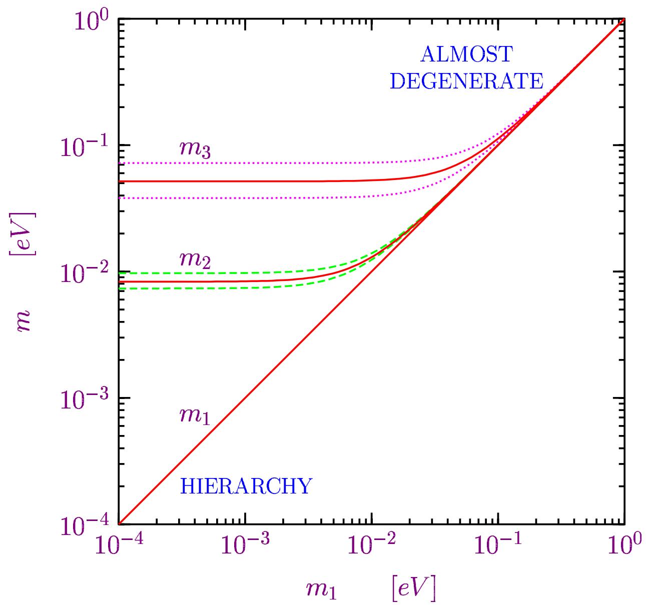
$$\left.\begin{array}{c} |U_{e3}|^2_{\text{best-fit}} = 0\,, \qquad \sqrt{\Delta m^{2\,\text{best-fit}}_{\text{ATM}}} = 5.1 \times 10^{-2} \\ |U_{e2}| \lesssim 0.05 \\ 3.7 \times 10^{-2} \lesssim \sqrt{\Delta m^2_{\text{ATM}}} \lesssim 7.1 \times 10^{-2} \end{array}\right\} \Longrightarrow \left\{\begin{array}{c} |\langle m \rangle|_3^{\text{best-fit}} = 0 \\ |\langle m \rangle|_3 \lesssim 3.6 \times 10^{-3} \end{array}\right.$$

ν_2 contribution $|\langle m \rangle|_2$ may be dominant! (lower limit for $|\langle m \rangle|$)

but overlap of allowed ranges for $|\langle m \rangle|_2$ and $|\langle m \rangle|_3$ show that strong cancellations are possible

CP Conservation: Normal Scheme





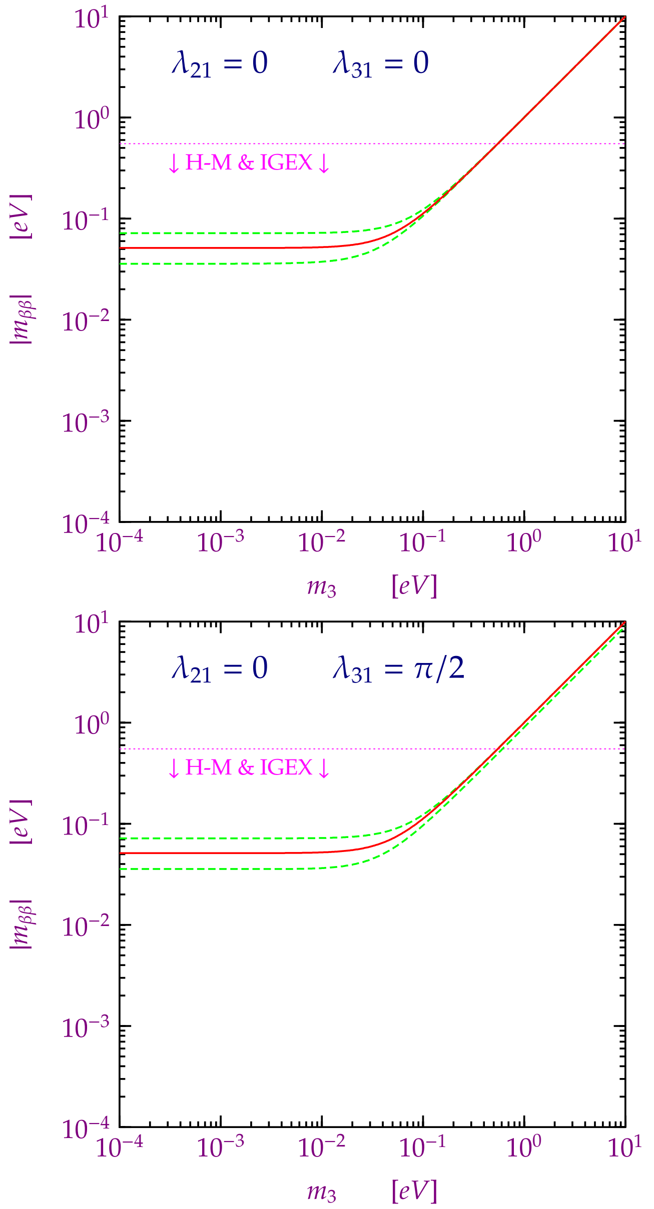
$$|U_{e1}|^2 = 0.58 - 0.77$$

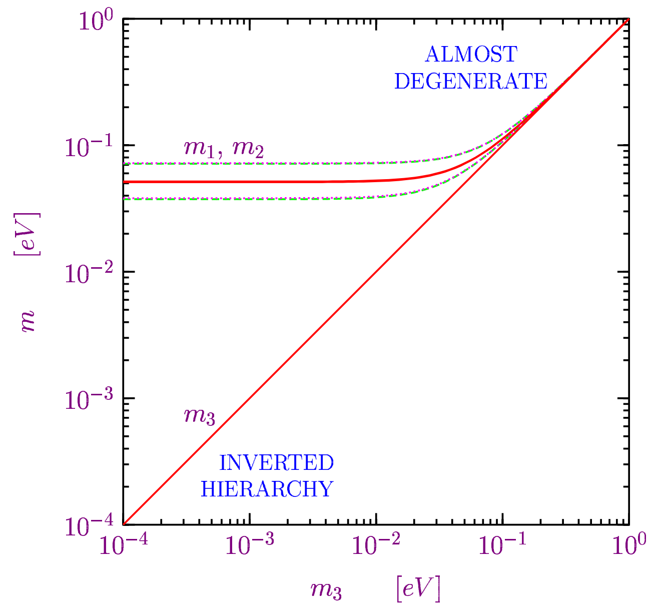
$$|U_{e2}|^2 = 0.22 - 0.38$$

$$|U_{e3}|^2 = 0.00 - 0.05$$

[Hirsch, Pascoli]

CP Conservation: Inverted Scheme





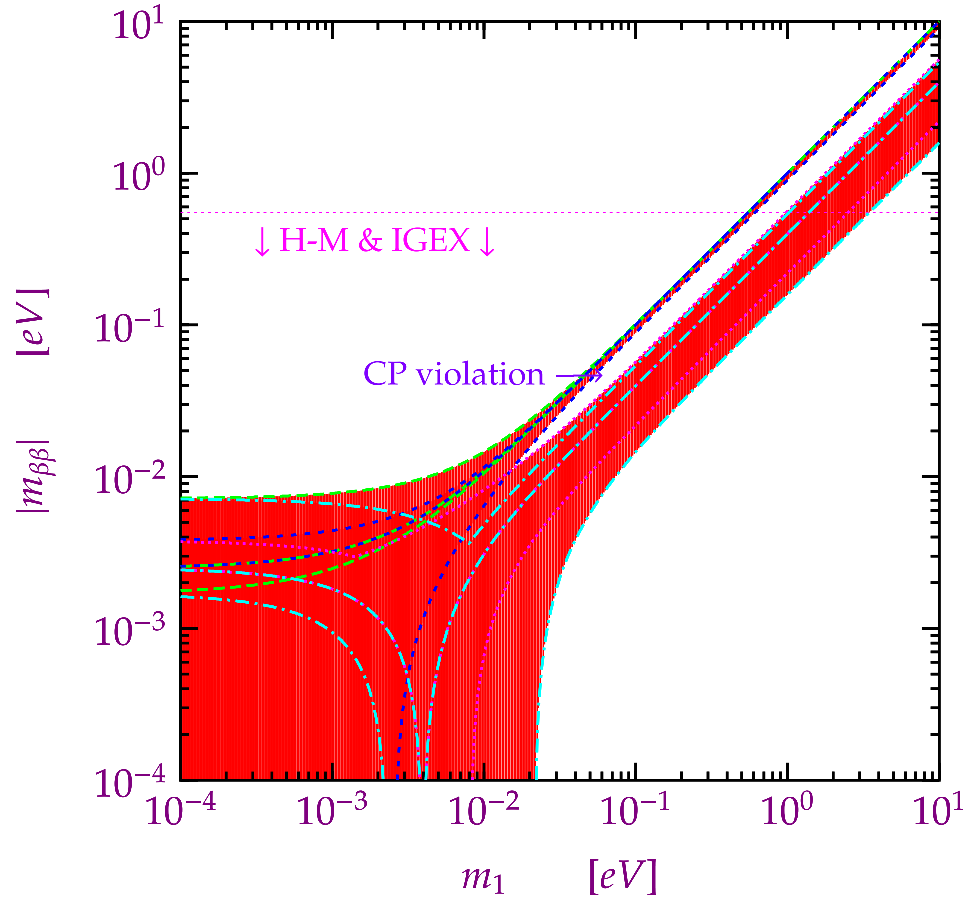
$$|U_{e1}|^2 = 0.58 - 0.77$$

$$|U_{e2}|^2 = 0.22 - 0.38$$

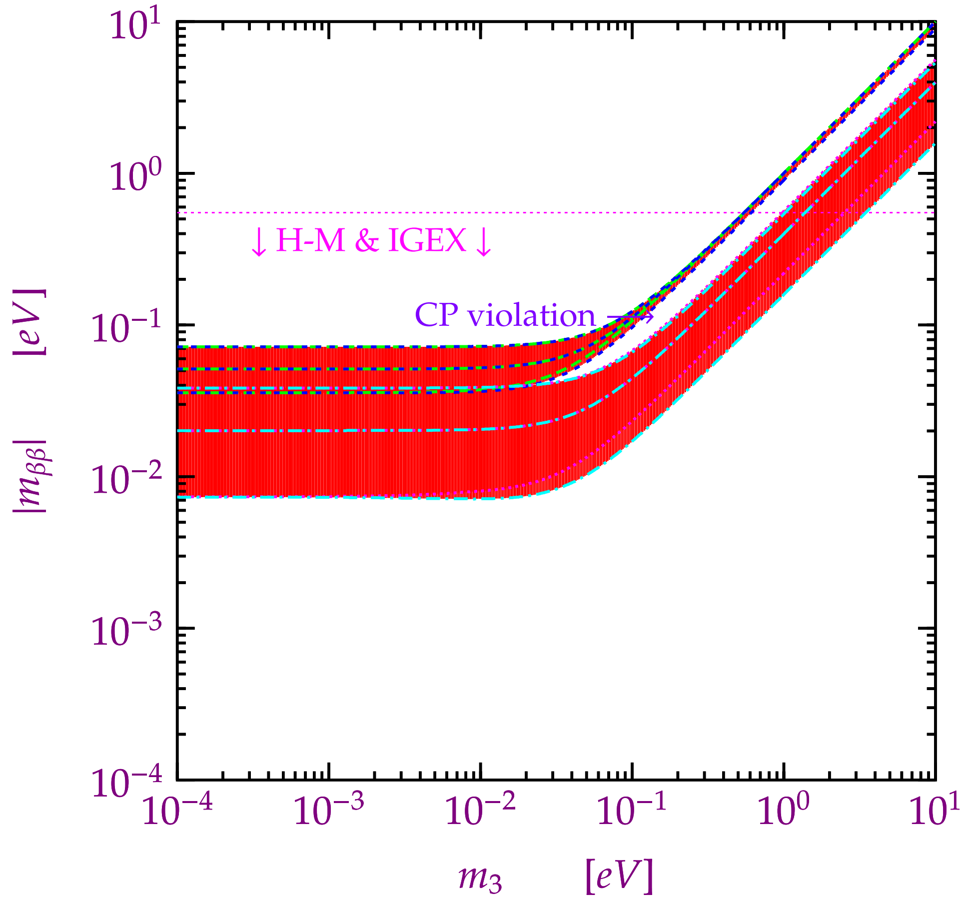
$$|U_{e3}|^2 = 0.00 - 0.05$$

[Hirsch, Pascoli]

General Neutrino Oscillations Bounds for $\beta\beta_{0\nu}$ Decay



"normal" scheme



"inverted" scheme

FUTURE: NEMO3, CUORICINO, COBRA, XMASS, CAMEO ($|m_{\beta\beta}| \sim$ few 10^{-1} eV)
EXO, MOON, Super-NEMO, CUORE, Majorana, GEM, GENIUS ($|m_{\beta\beta}| \sim$ few 10^{-2} eV)

VERY FAR FUTURE: IF $|m_{\beta\beta}| \lesssim 7 \times 10^{-3}$ eV $\Longrightarrow$ NORMAL HIERARCHY

Beyond Neutrino Mass

very interesting, but I think always important to remember

OCKHAM RAZOR

essentia non sunt multiplicanda praeter necessitatem

entities should not be multiplied unnecessarily

[William Of Ockham (near Ripley, Surrey, England), $\sim 1288 - 1348$]

a basic principle of scientific research (and common sense)

I think that until the neutrino mass contribution dominance is found insufficient

or there is independent evidence of the existence of other entities

$\beta\beta_{0\nu}$ data should be used only to place limit on other mechanisms

[Hirsch]

many possible mechanisms

heavy majorana neutrinos

left-right symmetry

R-parity conserving supersymmetry

R-parity violating supersymmetry

leptoquarks

composite neutrinos

extra-dimensions [Pilaftsis]

$\vdots$

Conclusions

- Experimental evidences of ν Oscillations $\Rightarrow$ 3-ν Mixing.
- Most important open fundamental question: which is the nature of neutrinos (Dirac or Majorana)? Theory favors Majorana neutrinos. Windows on physics beyond SM.
- Best known mechanism to reveal the Majorana nature of neutrinos is $\beta\beta_{0\nu}$ decay.
- Next generation of $\beta\beta_{0\nu}$ decay experiments with sensitivity $|m_{\beta\beta}| \sim$ few $10^{-1}\,\mathrm{eV}$ can probe the degenerate mass spectra.
- Planned $\beta\beta_{0\nu}$ decay experiments with sensitivity $|m_{\beta\beta}| \sim$ few $10^{-2}\,\mathrm{eV}$ will probe the inverted hierarchical mass spectrum.
- Eventually $\beta\beta_{0\nu}$ decay experiments with sensitivity $|m_{\beta\beta}| < 10^{-2}\,\mathrm{eV}$ may exclude the inverted hierarchical mass spectrum.
- Hope is to find $\beta\beta_{0\nu}$ decay at large $|m_{\beta\beta}|$, which may allow detailed study of neutrino properties (masses and maybe CP violation and Majorana phases).
- Big theoretical effort to understand and improve uncertainty of nuclear matrix element calculation is absolutely needed!