Absolute Neutrino Masses

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Solar $\nu_e \to \nu_\mu, \nu_\tau$ + Atmospheric $\nu_\mu \to \nu_\tau \Longrightarrow$ 3-ν Mixing

Tritium β Decay

Cosmological Bound on Neutrino Masses

Neutrinoless Double-β Decay $\Longleftrightarrow$ Majorana Mass

Three-Neutrino Mixing

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k} \, \nu_{kL} \qquad (\alpha = e, \mu, \tau)$$

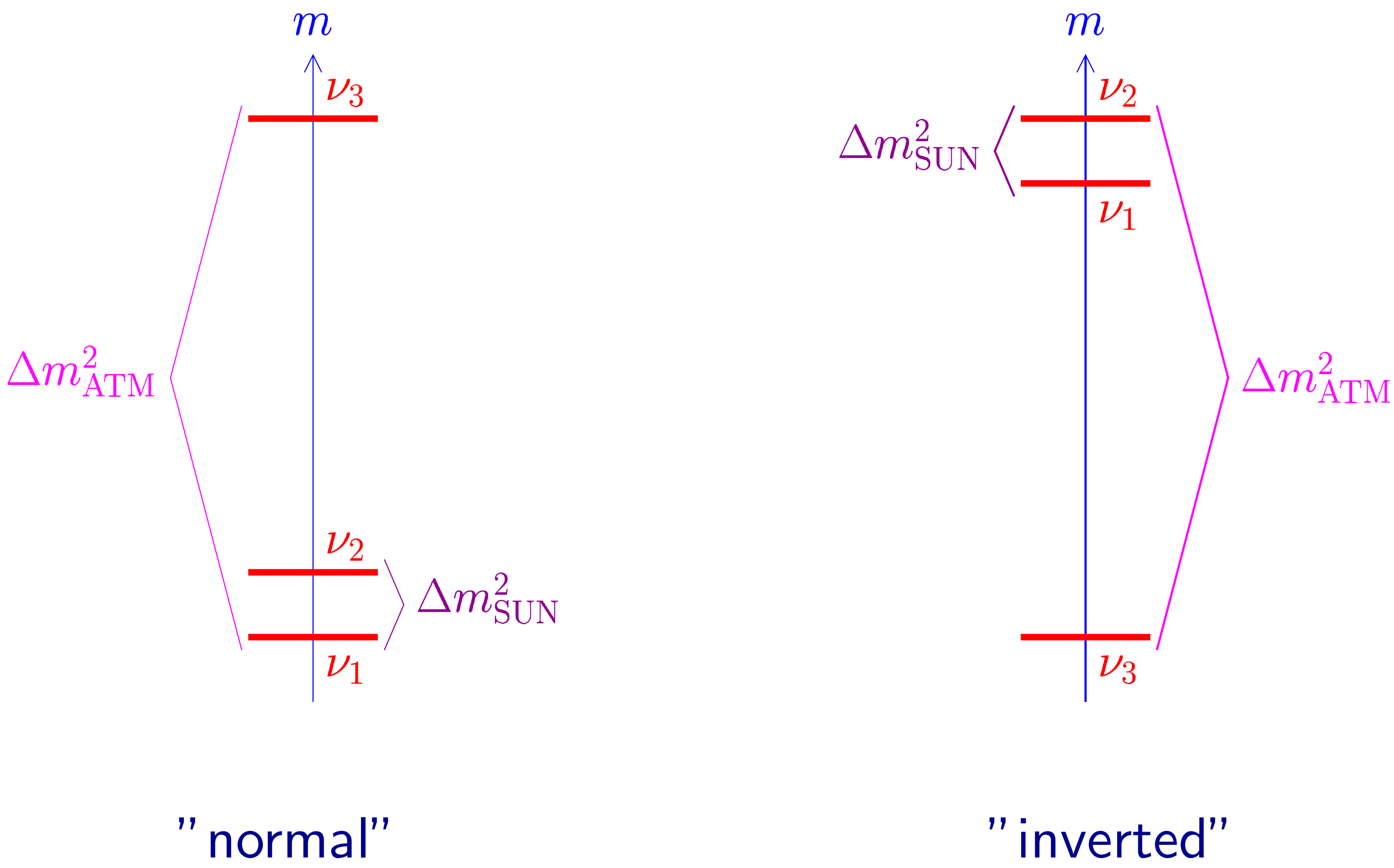
three flavor fields ν_e, ν_μ, ν_τ

three massive fields ν_1, ν_2, ν_3

$$\Delta m^2_{\text{SUN}} = \Delta m^2_{21} \simeq 8.2 \times 10^{-5} \, \text{eV}^2$$

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

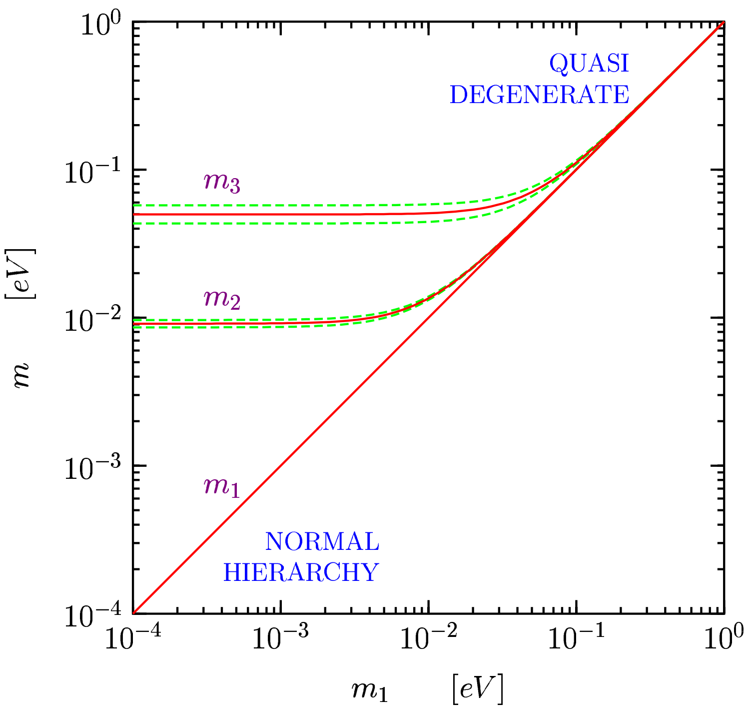
Allowed Three-Neutrino Schemes



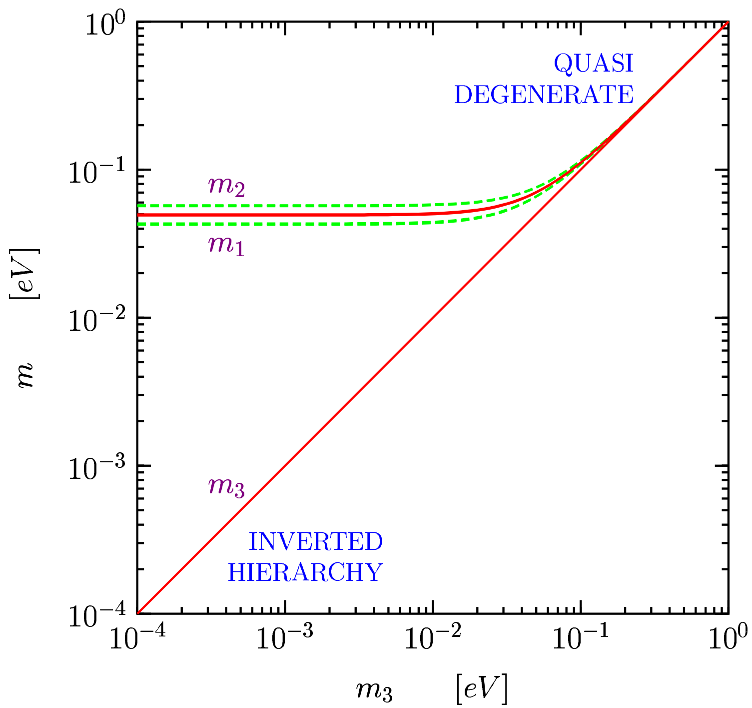
absolute scale is not determined by neutrino oscillation data

Absolute Scale of Neutrino Masses

normal scheme



inverted scheme



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_{\text{SUN}}^2$$

$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_{\text{ATM}}^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_{\text{ATM}}^2$$

$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_{\text{ATM}}^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_{\text{ATM}}^2} \simeq 5 \times 10^{-2}\,\text{eV}$

Tritium β Decay

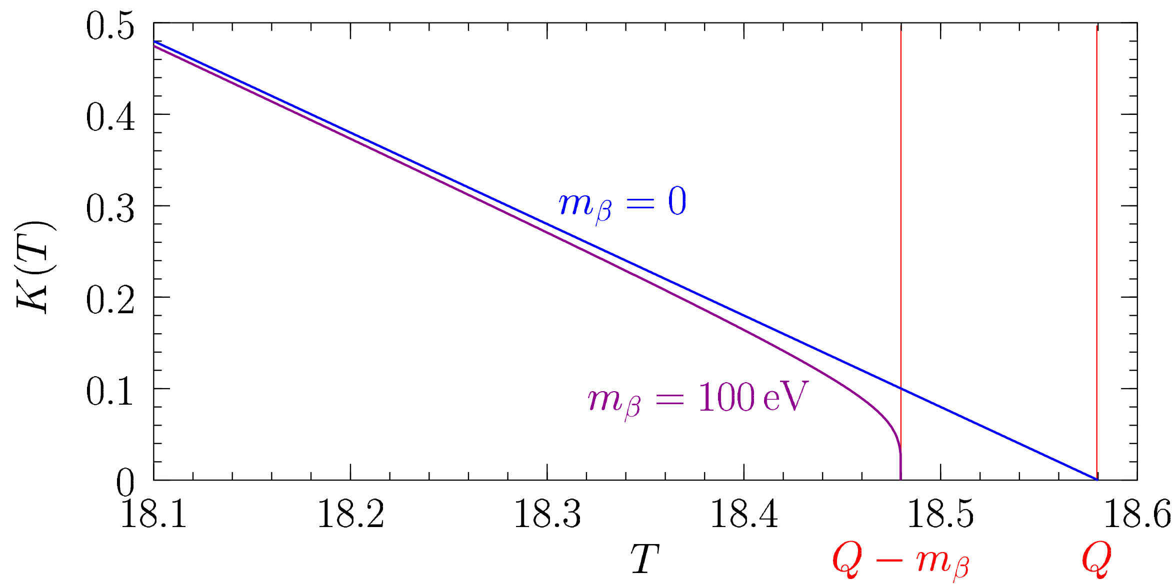
$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

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

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

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

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



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

Mainz & Troitsk

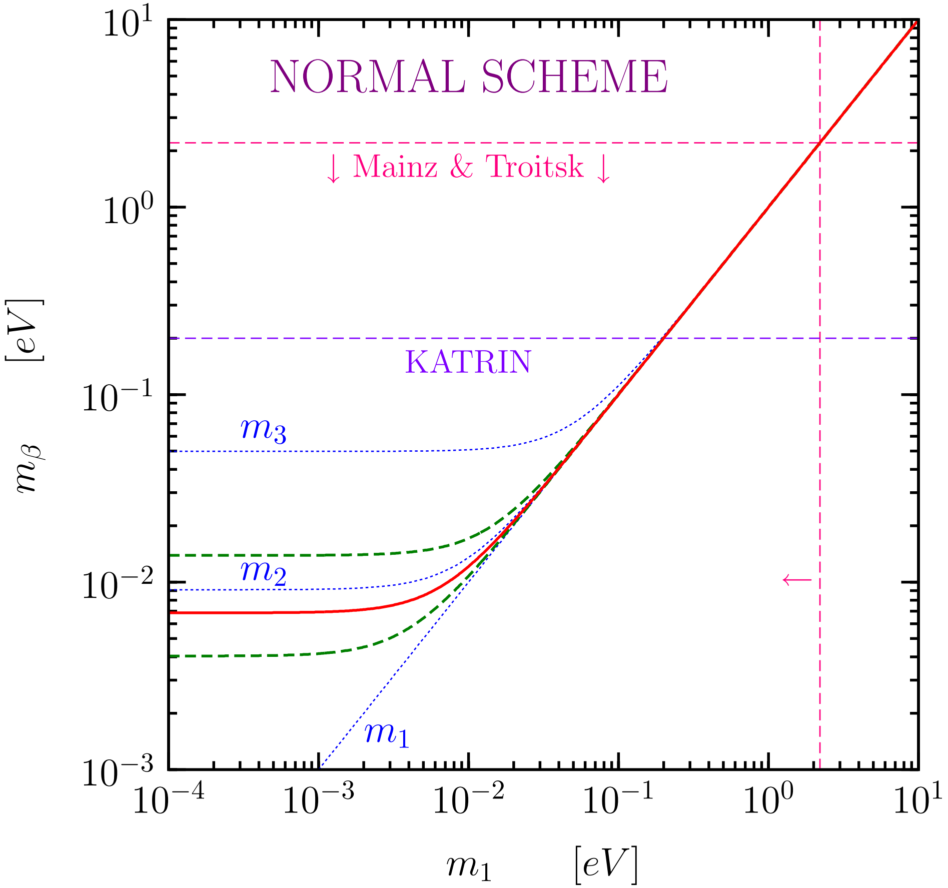
[Weinheimer, hep-ex/0210050]

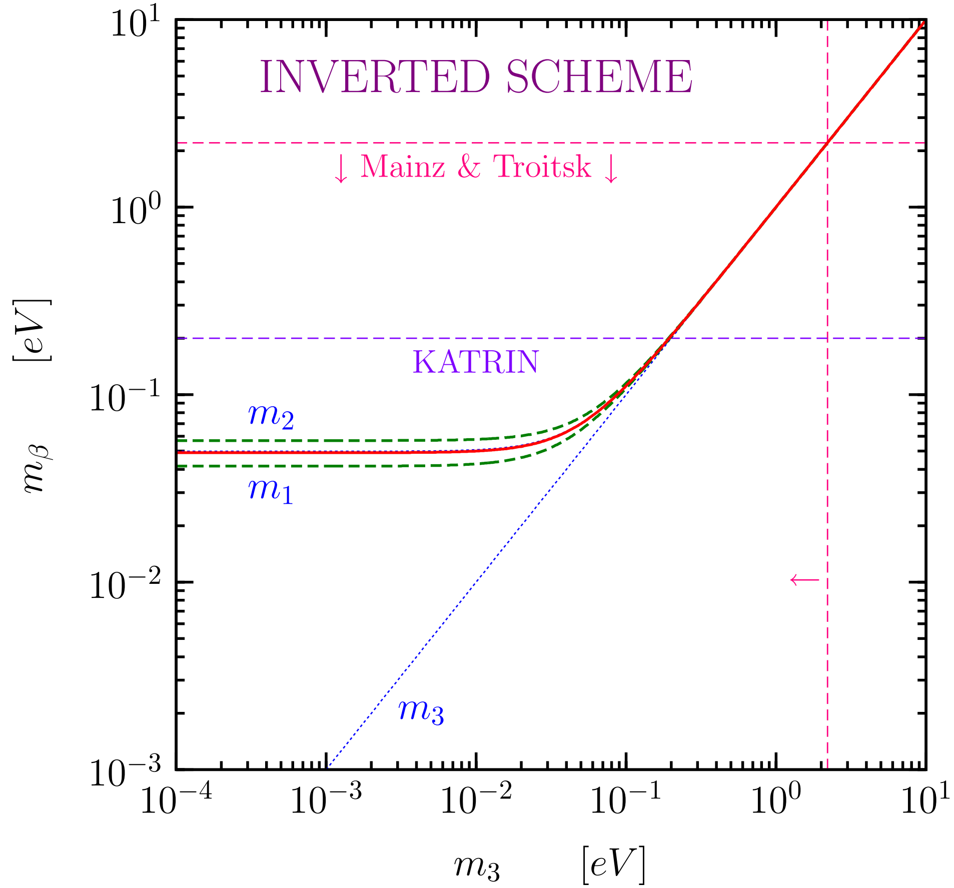
future: KATRIN

[hep-ex/0109033] [hep-ex/0309007]

sensitivity: $m_\beta \simeq 0.2 - 0.3\,\mathrm{eV}$

$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$





Quasi-Degenerate: $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \implies m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$

FUTURE: IF $m_\beta \lesssim 4 \times 10^{-2}\,\text{eV} \implies$ NORMAL HIERARCHY

Cosmological Bound on Neutrino Masses

neutrinos are in equilibrium in primeval plasma through weak interaction reactions

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

weak interactions freeze out

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

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

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

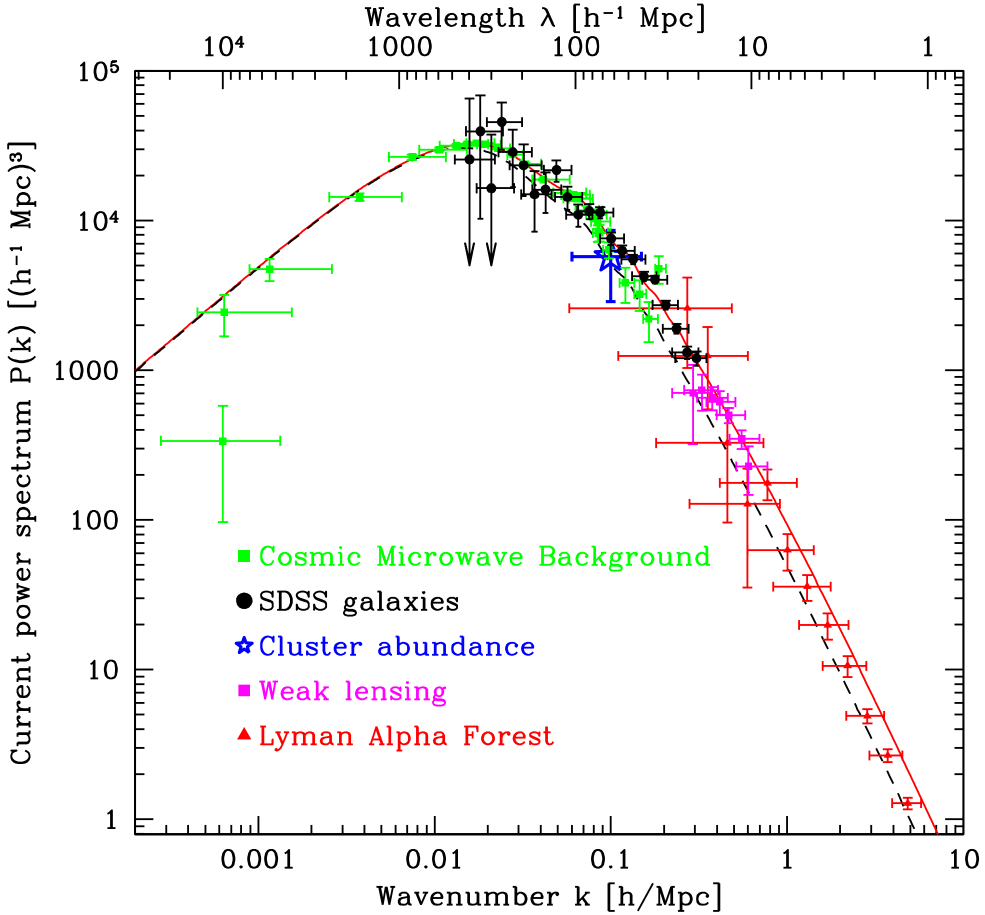
density contribution: $\Omega_k = \frac{n_{\nu_k, \bar{\nu}_k} m_k}{\rho_c} \simeq \frac{1}{h^2} \frac{m_k}{94.14\,\text{eV}} \Longrightarrow \boxed{\Omega_\nu h^2 = \frac{\sum_k m_k}{94.14\,\text{eV}}}$

$\left(\rho_c = \frac{3H^2}{8\pi G_N}\right)$

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

$$h \sim 0.7, \quad \Omega_\nu \lesssim 0.3 \quad \Longrightarrow \quad \sum_k m_k \lesssim 14\,\text{eV}$$

Power Spectrum of Density Fluctuations



[Tegmark, hep-ph/0503257]

Solid Curve: flat scalar scale-invariant ΛCDM model ($\Omega_M^0 = 0.28$, $h = 0.72$, $\Omega_B^0/\Omega_M^0 = 0.16$)

Dashed Curve: $\sum_k m_k = 1\,\text{eV}$

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]

WMAP, AJ SS 148 (2003) 175, astro-ph/0302209

CMB (WMAP, CBI, ACBAR) $+$ LSS (2dFGRS) $+$ Lyα $+$ HST $+$ SN-Ia

ΛCDM

$$T_0 = 13.7 \pm 0.1\,\text{Gyr} \qquad h = 0.71^{+0.04}_{-0.03}$$

$$\Omega_{\text{tot}} = 1.02 \pm 0.02 \qquad \Omega_b h^2 = 0.0224 \pm 0.0009 \qquad \Omega_m h^2 = 0.135^{+0.008}_{-0.009}$$

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

Hannestad, JCAP 0305 (2003) 004, astro-ph/0303076

$\sum_k m_k < 1.01\,\text{eV}$ (95% conf.) WMAP+CBI+2dFGRS+HST+SN-Ia

$\sum_k m_k < 1.20\,\text{eV}$ (95% conf.) WMAP+CBI+2dFGRS

$\sum_k m_k < 2.12\,\text{eV}$ (95% conf.) WMAP+2dFGRS

Elgaroy and Lahav, JCAP 04 (2003) 004, astro-ph/0303089

$\sum_k m_k < 1.1\,\text{eV}$ (95% conf.) WMAP+2dFGRS+HST

SDSS, PRD 69 (2004) 103501, astro-ph/0310723

CMB(WMAP)+LSS(SDSS)+SN-Ia

$h = 0.70^{+0.04}_{-0.03}$ $\Omega_m = 0.30 \pm 0.04$ $\sum_k m_k < 1.7\,\text{eV}$ (95% conf.)

SDSS, PRD 71 (2005) 043511, astro-ph/0406594

CMB(WMAP)+LSS(SDSS)+bias(SDSS) $P_g(k) = b^2\, P_m(k)$

$\Omega_m = 0.25 \pm 0.03$ $\sum_k m_k < 0.54\,\text{eV}$ (95% conf.)

SDSS, PRD 71 (2005) 103515, astro-ph/0407372

CMB(WMAP)+LSS(SDSS)+bias(SDSS)+Lyα(SDSS)+SN-Ia

$\Omega_\Lambda = 0.72 \pm 0.02$ $\sum_k m_k < 0.42\,\text{eV}$ (95% conf.)

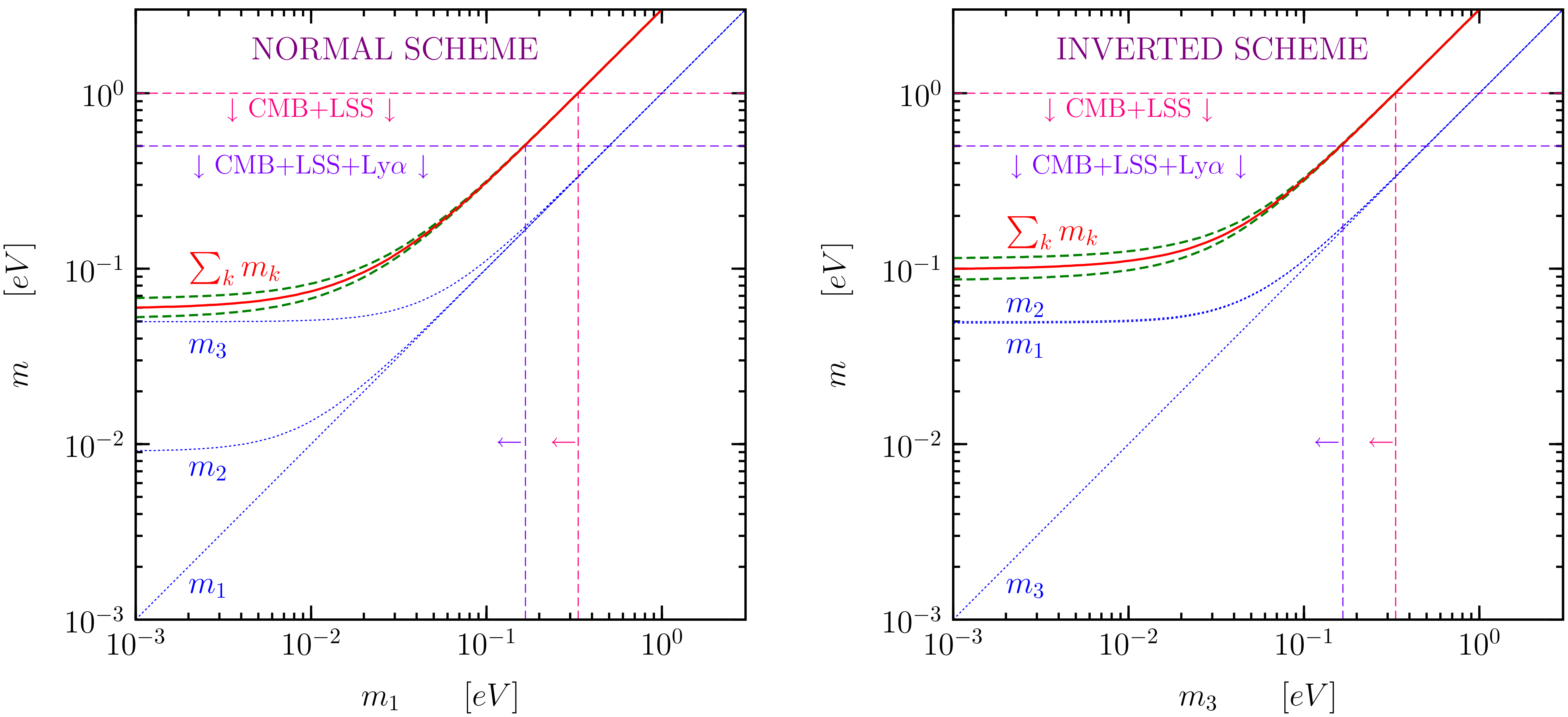
Fogli et al., PRD 70 (2004) 113003, hep-ph/0408045

$\sum_k m_k < 1.4\,\text{eV}$ (2σ) CMB+LSS+HST+SN-Ia

$\sum_k m_k < 0.47\,\text{eV}$ (2σ) CMB+LSS+HST+SN-Ia+Lyα(SDSS)

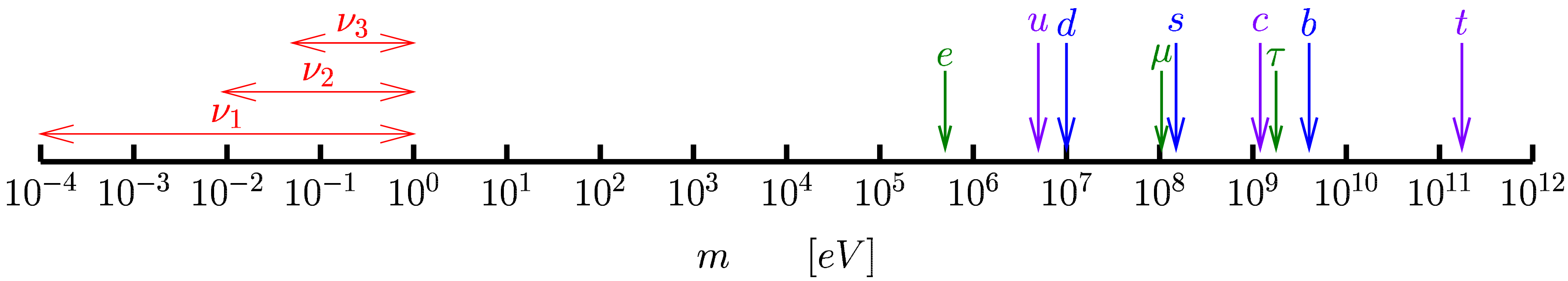
$$\sum_k m_k \lesssim 1\,\text{eV} \qquad (\sim 2\sigma) \qquad \text{CMB+LSS+HST+SN-Ia}$$

$$\sum_k m_k \lesssim 0.5\,\text{eV} \qquad (\sim 2\sigma) \qquad \text{CMB+LSS+HST+SN-Ia+Ly}\alpha$$



FUTURE: IF $\sum_k m_k \lesssim 8 \times 10^{-2}\,\text{eV} \Longrightarrow$ NORMAL HIERARCHY

Majorana Neutrino Mass?



known natural explanation of smallness of ν masses

New High Energy Scale $\mathcal{M}$ $\Rightarrow$
- See-Saw Mechanism (if ν_R's exist)
- 5-D Non-Renormaliz. Eff. Operator

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

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

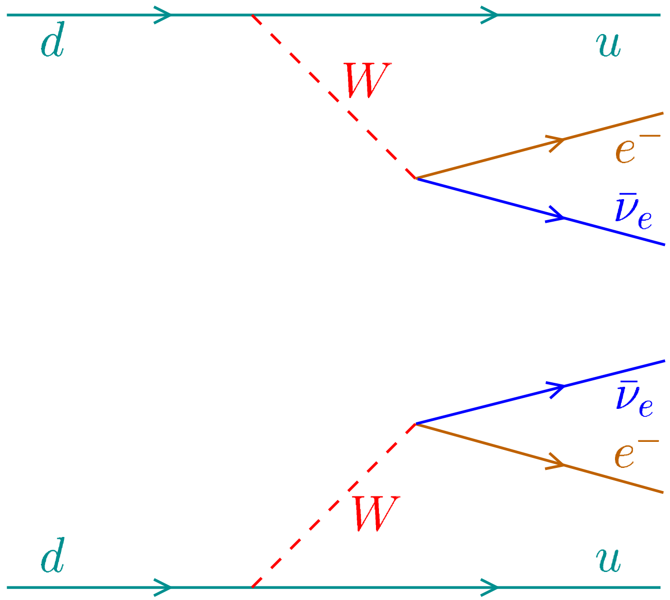
Two-Neutrino Double-β Decay: $\Delta L = 0$

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

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

second order weak interaction process

in the Standard Model

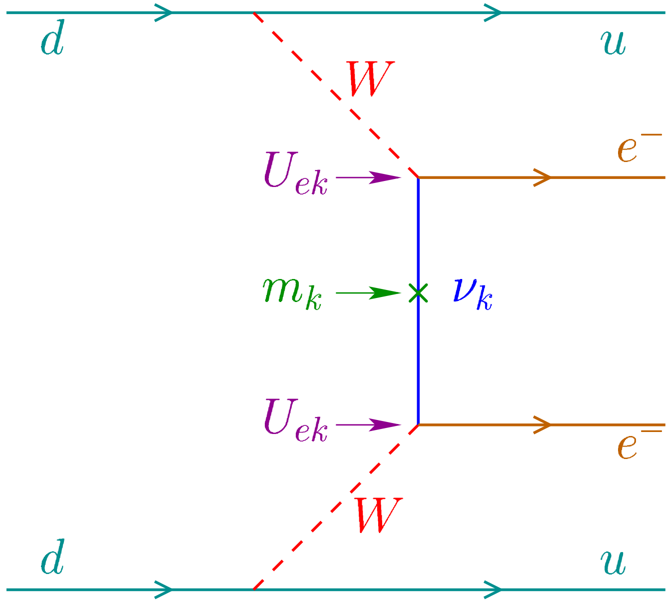


Neutrinoless Double-β Decay: $\Delta L = 2$

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

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

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

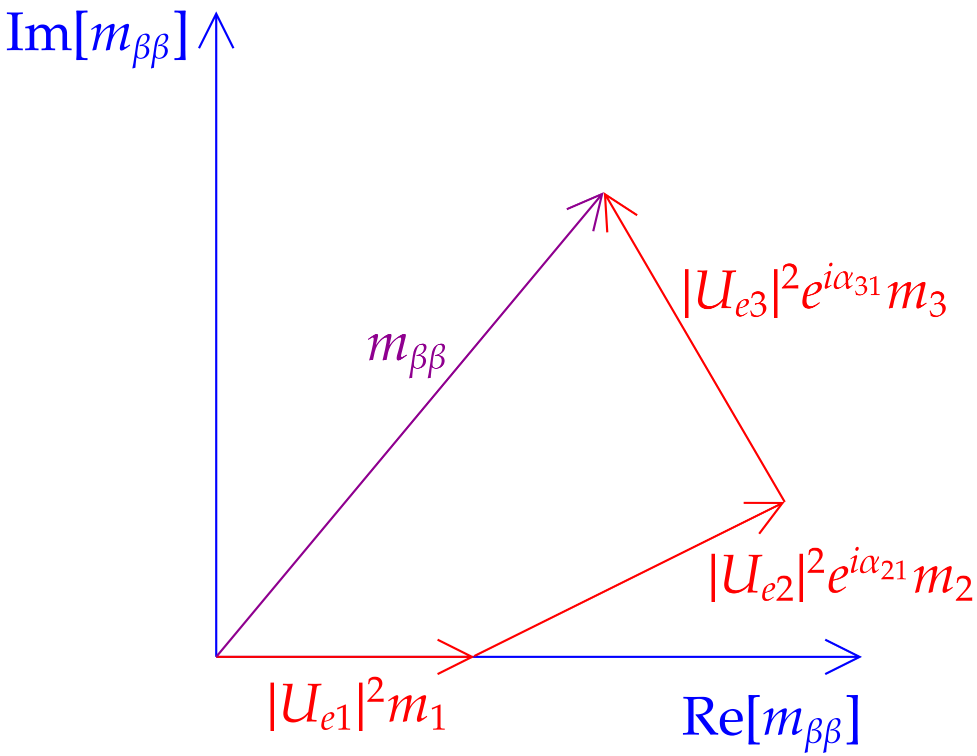


Effective Majorana Neutrino Mass in $\beta\beta_{0\nu}$ Decay

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

complex U_{ek} $\Rightarrow$ possible cancellations

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_{21}} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_{31}} \, m_3$$



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

Heidelberg-Moscow ^{76}Ge [EPJA 12 (2001) 147]

$$\boxed{T^{0\nu}_{1/2} > 1.9 \times 10^{25}\,\text{y} \quad (90\%\ \text{C.L.})} \Longrightarrow \boxed{|m_{\beta\beta}| \lesssim 0.32 - 1.0\,\text{eV}}$$

IGEX ^{76}Ge [PRD 65 (2002) 092007]

$$\boxed{T^{0\nu}_{1/2} > 1.57 \times 10^{25}\,\text{y} \quad (90\%\ \text{C.L.})} \Longrightarrow \boxed{|m_{\beta\beta}| \lesssim 0.35 - 1.1\,\text{eV}}$$

FUTURE EXPERIMENTS

NEMO3, CUORICINO, COBRA, XMASS, CAMEO, CANDLES

$|m_{\beta\beta}| \sim$ few 10^{-1} eV

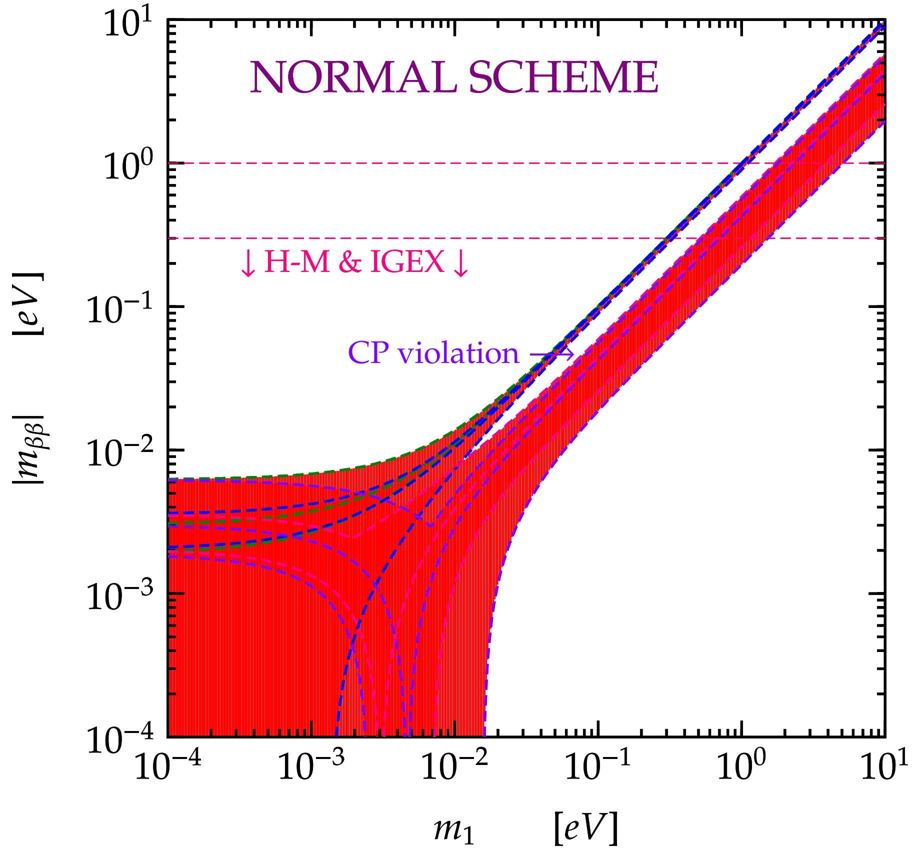
EXO, MOON, Super-NEMO, CUORE, Majorana, GEM, GERDA

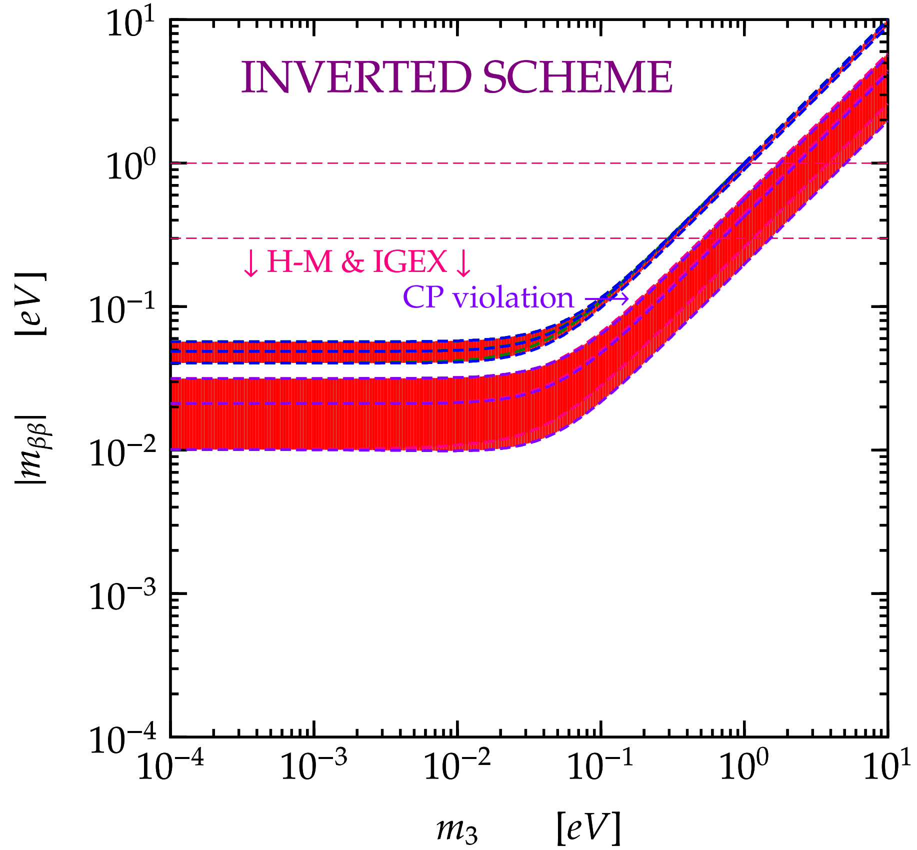
$|m_{\beta\beta}| \sim$ few 10^{-2} eV

[Zdesenko, RMP 74 (2002) 663] [Elliott,Vogel, ARNPS 52 (2002) 115] [Elliott, Engel, JPG 30 (2004) R183]

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

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3$$



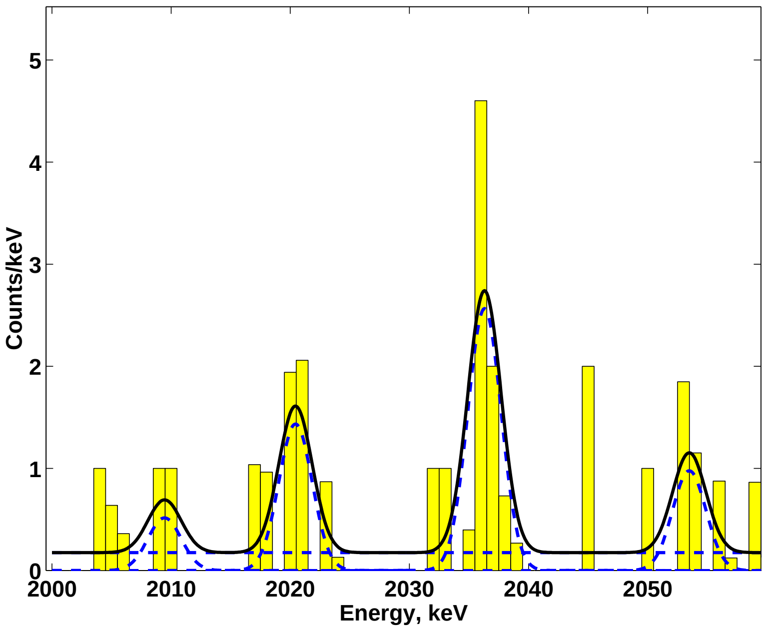


FUTURE: IF $|m_{\beta\beta}| \lesssim 10^{-2}\,\text{eV} \Longrightarrow$ NORMAL HIERARCHY

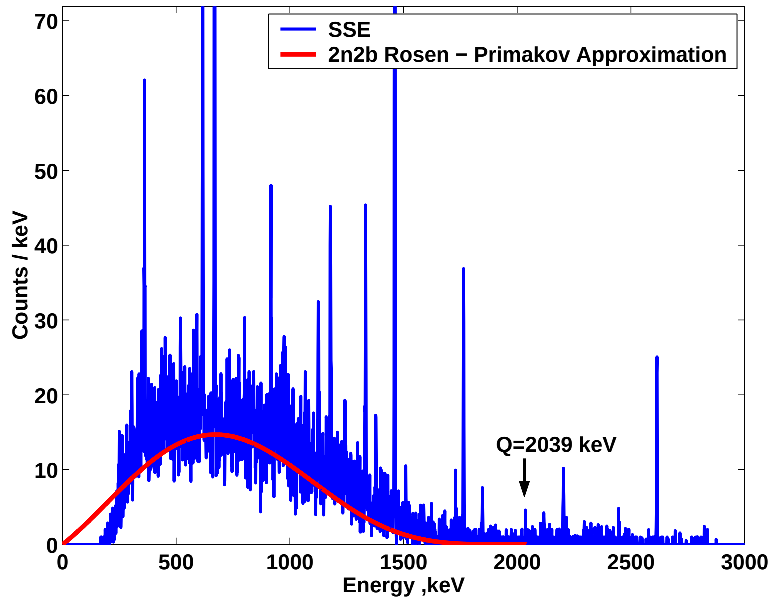
Indication of $\beta\beta_{0\nu}$ Decay

[Klapdor et al., MPLA 16 (2001) 2409; FP 32 (2002) 1181; NIMA 522 (2004) 371; PLB 586 (2004) 198]

$T_{1/2}^{0\nu\,\mathrm{bf}} = 1.19 \times 10^{25}\,\mathrm{y}$ $\quad T_{1/2}^{0\nu} = (0.69 - 4.18) \times 10^{25}\,\mathrm{y}\,(3\sigma)$ $\quad 4.2\sigma$ evidence



pulse-shape selected spectrum



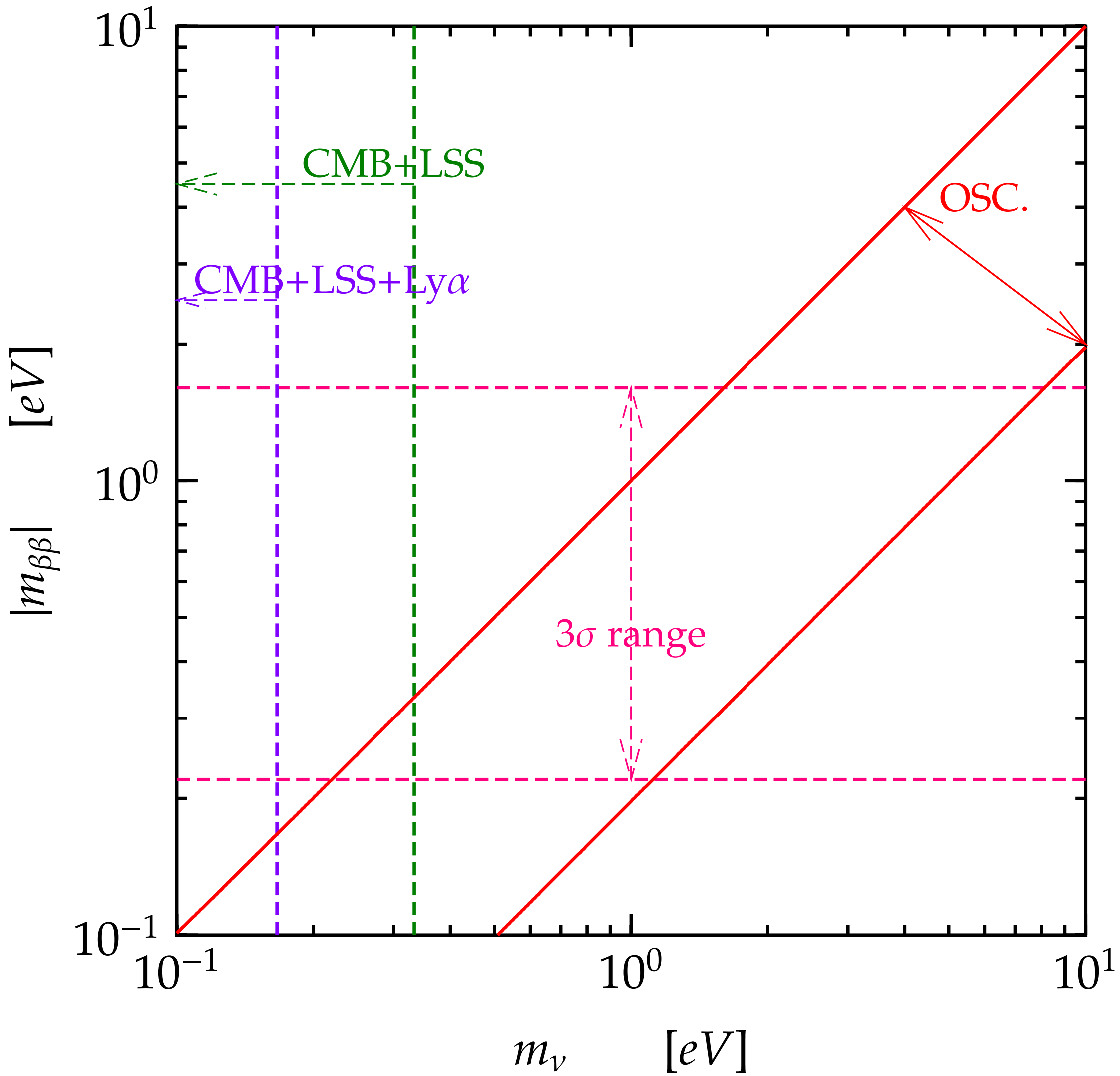
3.8σ evidence [PLB 586 (2004) 198]

the indication must be checked by other experiments

$$1.35 \lesssim |\mathcal{M}_{0\nu}| \lesssim 4.12 \quad \Longrightarrow \quad 0.22\,\mathrm{eV} \lesssim |m_{\beta\beta}| \lesssim 1.6\,\mathrm{eV}$$

if confirmed, very exciting (Majorana ν and large mass scale)

Indication of $\beta\beta_{0\nu}$ Decay: $0.22\,\text{eV} \lesssim |m_{\beta\beta}| \lesssim 1.6\,\text{eV}$ (3σ range)



tension among oscillation data, CMB+LSS+Lyα and $\beta\beta_{0\nu}$ signal

Conclusions

$\nu_e \to \nu_\mu, \nu_\tau$ with $\Delta m^2_{\text{SUN}} \simeq 8.3 \times 10^{-5}\,\text{eV}^2$ (solar ν, KamLAND)

$\nu_\mu \to \nu_\tau$ with $\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ (atmospheric ν, K2K)

$\Downarrow$

Bilarge 3ν-Mixing with $|U_{e3}|^2 \ll 1$

β Decay, Cosmology, $\beta\beta_{0\nu}$ Decay $\Longrightarrow$ $m_\nu \lesssim 1\,\text{eV}$

FUTURE

Theory: Improve calculation of $\mathcal{M}_{0\nu}$!

Exp.: β Decay: KATRIN ($m_\beta \simeq 0.2 - 0.3\,\text{eV}$), ?

Cosmology: WMAP, SDSS, Planck, ...

$\beta\beta_{0\nu}$ Decay: Many experiments ($|m_{\beta\beta}| \sim 10^{-1} \to 10^{-2}\,\text{eV}$)