DOUBLE BETA DECAY AND THE ABSOLUTE NEUTRINO MASS SCALE

Carlo Giunti

INFN, Sez. di Torino, and Dip. di Fisica Teorica, Università di Torino

giunti@to.infn.it

Solar + KamLAND & Atmospheric + K2K $\Longrightarrow$ Three-Neutrino Mixing

Direct Kinematical Limits on Neutrino Mass: Tritium β decay

Cosmology (CMB+LSS) $\Longrightarrow \sum m_{\text{light neutrinos}} \lesssim 1\,\text{eV}$

Majorana Neutrinos $\Longrightarrow$ Neutrinoless Double-β Decay

NuFact 03, 5$^{\text{th}}$ International Workshop on Neutrino Factories & Superbeams

Columbia University, New York, 5-11 June 2003

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$ $\begin{pmatrix} \text{Homestake, Kamiokande,} \\ \text{GALLEX, SAGE, GNO,} \\ \text{Super-Kamiokande, SNO} \end{pmatrix}$

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

$$\Longrightarrow \begin{cases} \Delta m^{2\,\text{best-fit}}_{\text{SUN}} = 6.9 \times 10^{-5} \\ 5.1 \times 10^{-5} < \Delta m^2_{\text{SUN}} < 9.7 \times 10^{-5} \\ 1.2 \times 10^{-4} < \Delta m^2_{\text{SUN}} < 1.9 \times 10^{-4} \\ [\text{eV}^2] \qquad (99.73\%\ \text{C.L.}) \end{cases}$$

[Maltoni, Schwetz, Valle, PRD 67 (2003) 093003]

Atmospheric $\nu_\mu \to \nu_\tau$ $\begin{pmatrix} \text{Kamiokande, IMB,} \\ \text{Super-Kamiokande,} \\ \text{MACRO, SOUDAN 2} \end{pmatrix}$

Accelerator ν_μ disappearance (K2K)

$$\Longrightarrow \begin{cases} \Delta m^{2\,\text{best-fit}}_{\text{ATM}} = 2.6 \times 10^{-3} \\ 1.4 \times 10^{-3} < \Delta m^2_{\text{ATM}} < 5.1 \times 10^{-3} \\ [\text{eV}^2] \qquad (99.73\%\ \text{C.L.}) \end{cases}$$

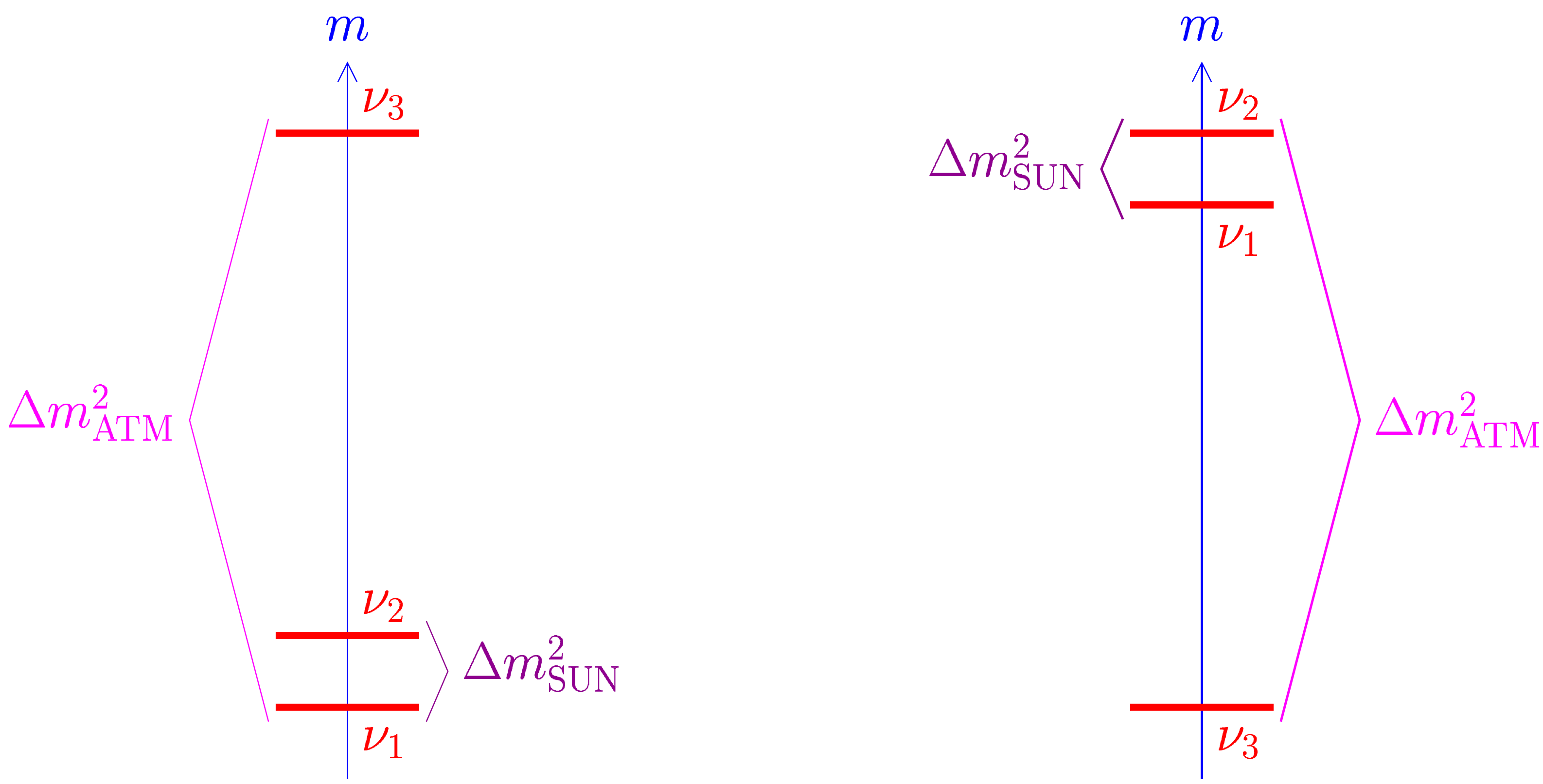
[Fogli, Lisi, Marrone, Montanino, PRD 67 (2003) 093006]

THREE-NEUTRINO MIXING

flavor fields ν_α, $\alpha = e, \mu, \tau$ $\qquad \nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k}\, \nu_{kL}$ $\qquad$ massive fields $\nu_k \to m_k$

$$\Delta m^2_{\text{SUN}} = \Delta m^2_{21} \qquad \Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$$

ALLOWED THREE-NEUTRINO SCHEMES



"normal" "inverted"

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

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

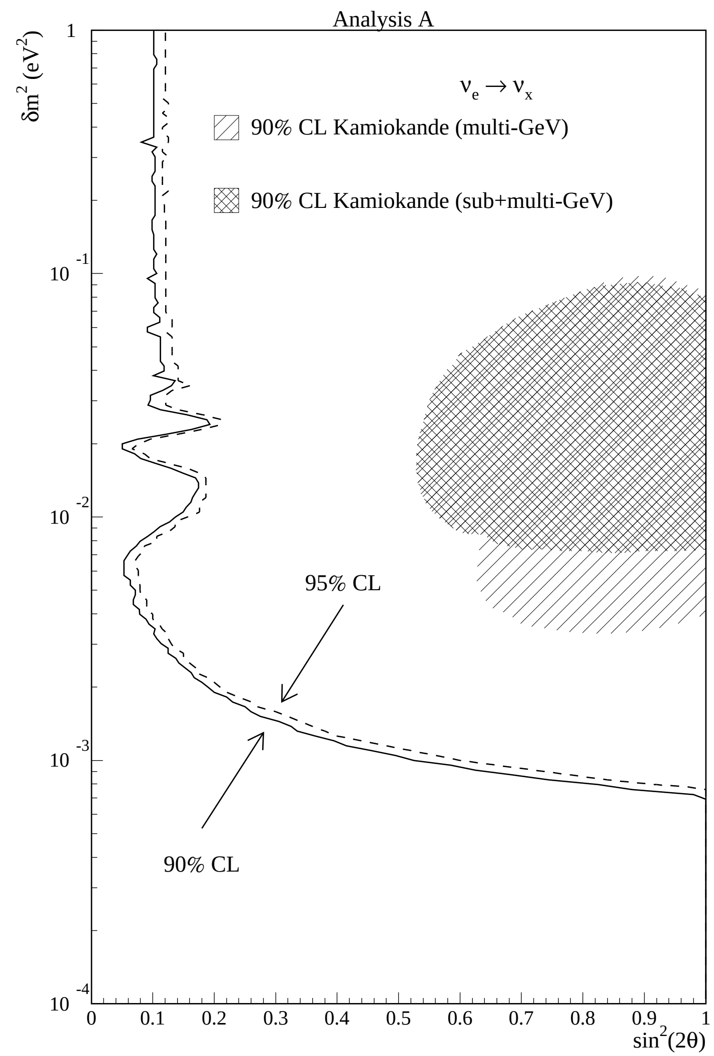
CHOOZ:
$$\begin{cases} \Delta m^2_{\text{CHOOZ}} = \Delta m^2_{31} = \Delta m^2_{\text{ATM}} \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1-|U_{e3}|^2) \end{cases}$$

$$\Downarrow$$

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

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

SOLAR AND ATMOSPHERIC ν OSCILLATIONS ARE PRACTICALLY DECOUPLED!



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

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]

BILARGE MIXING

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

$\tan^2\vartheta_{\rm SUN}^{\text{best-fit}} = 0.46 \qquad 0.29 < \tan^2\vartheta_{\rm SUN} < 0.86$ (99.73% C.L.) [Maltoni, Schwetz, Valle, PRD 67 (2003) 093003]

$\sin^2 2\vartheta_{\rm ATM}^{\text{best-fit}} = 1 \qquad \sin^2 2\vartheta_{\rm ATM} > 0.86$ (99.73% C.L.) [Fogli, Lisi, Marrone, Montanino, PRD 67 (2003) 093006]

$|U_{e3}|^2_{\text{best-fit}} = 0 \qquad |U_{e3}|^2 < 5\times 10^{-2}$ (99.73% C.L.) [Fogli et al., PRD 66 (2002) 093008]

$$|U|_{\rm bf} \simeq \begin{pmatrix} 0.83 & 0.56 & 0.00 \\ 0.40 & 0.59 & 0.71 \\ 0.40 & 0.59 & 0.71 \end{pmatrix}$$

$$|U| \simeq \begin{pmatrix} 0.71-0.88 & 0.46-0.68 & 0.00-0.22 \\ 0.08-0.66 & 0.26-0.79 & 0.55-0.85 \\ 0.10-0.66 & 0.28-0.80 & 0.51-0.83 \end{pmatrix}$$

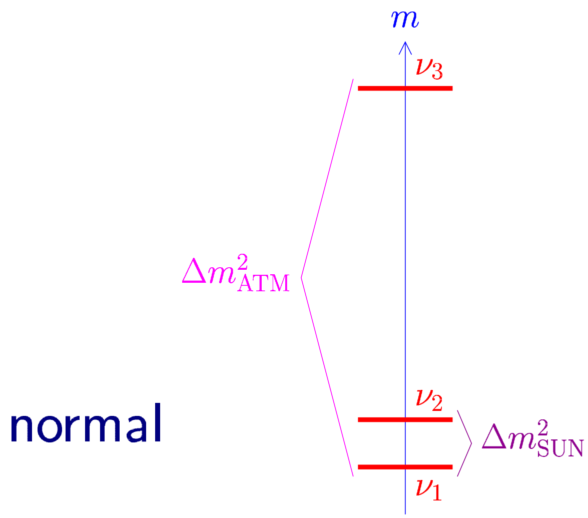
Global Analysis

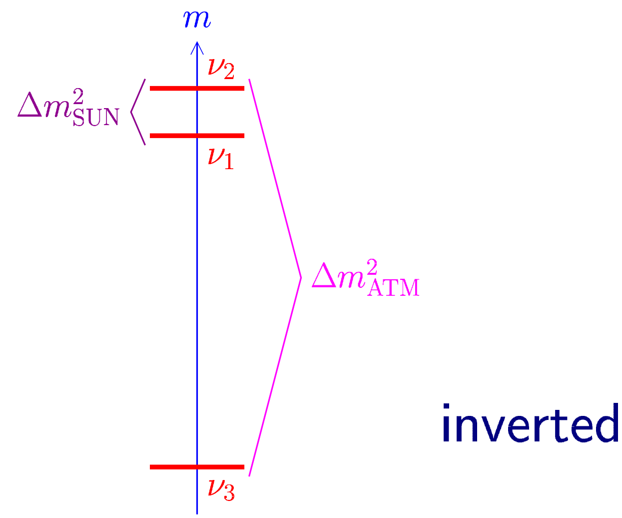
[Gonzalez-Garcia, Pena-Garay, hep-ph/0306001]

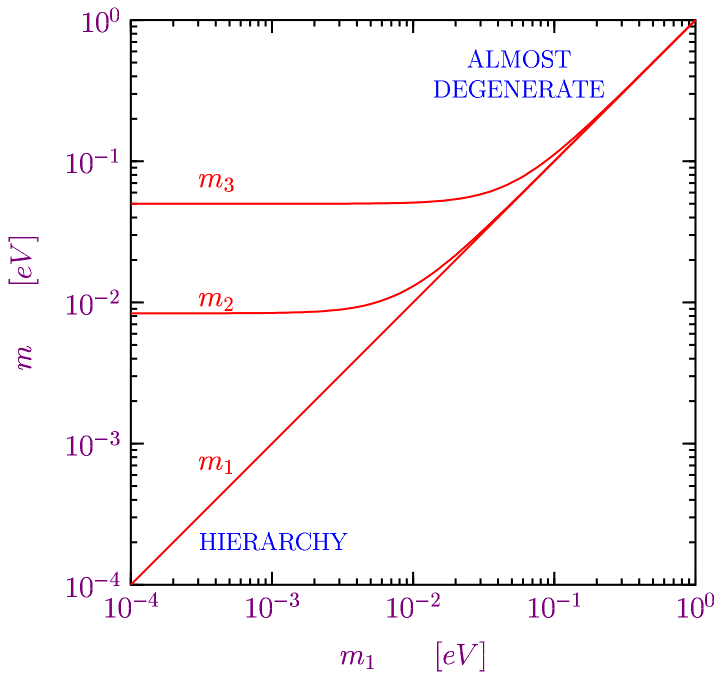
$$|U|_{\rm bf} \simeq \begin{pmatrix} 0.83 & 0.55 & 0.09 \\ 0.34-0.45 & 0.55-0.62 & 0.70 \\ 0.34-0.45 & 0.55-0.62 & 0.70 \end{pmatrix}$$

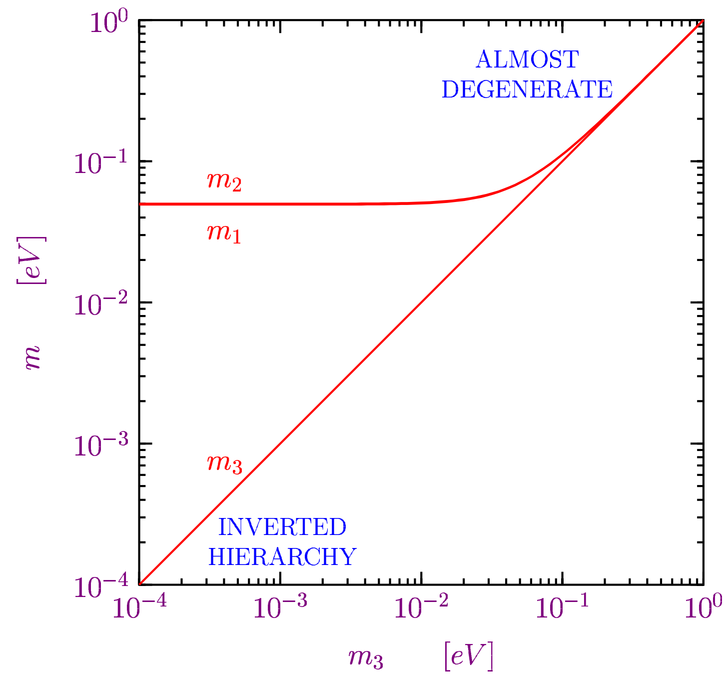
$$|U| \simeq \begin{pmatrix} 0.73-0.88 & 0.47-0.67 & 0.00-0.23 \\ 0.17-0.57 & 0.37-0.73 & 0.56-0.84 \\ 0.20-0.58 & 0.40-0.75 & 0.54-0.82 \end{pmatrix}$$

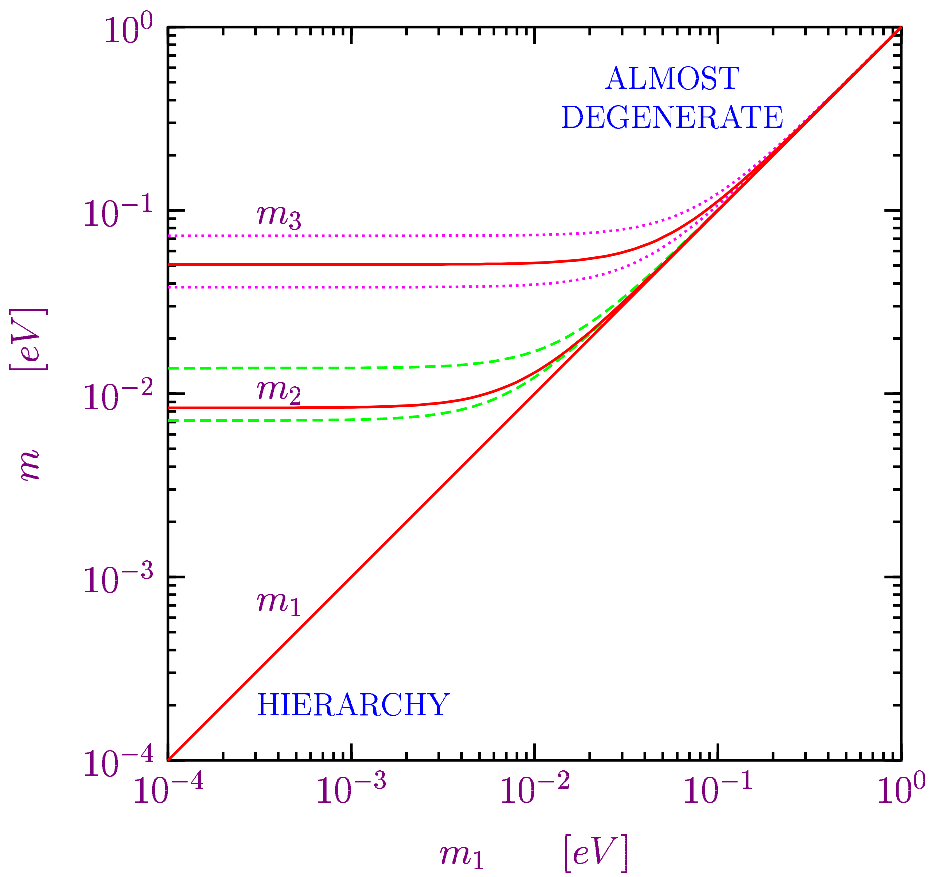
ABSOLUTE SCALE OF NEUTRINO MASSES



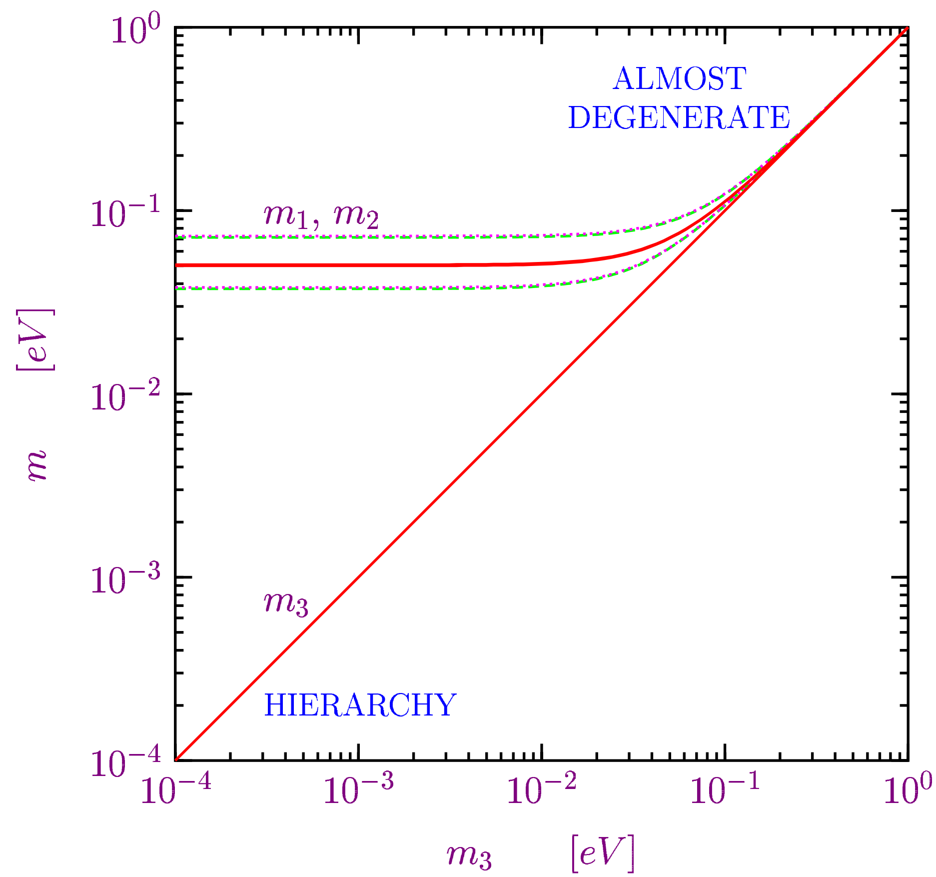








normal scheme



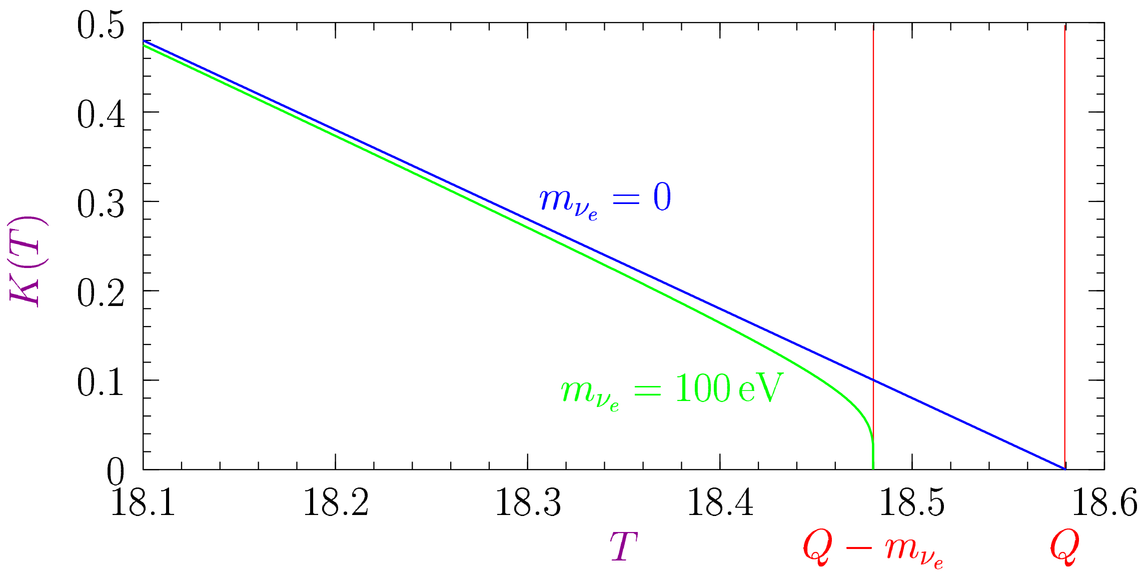
inverted scheme

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

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

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

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



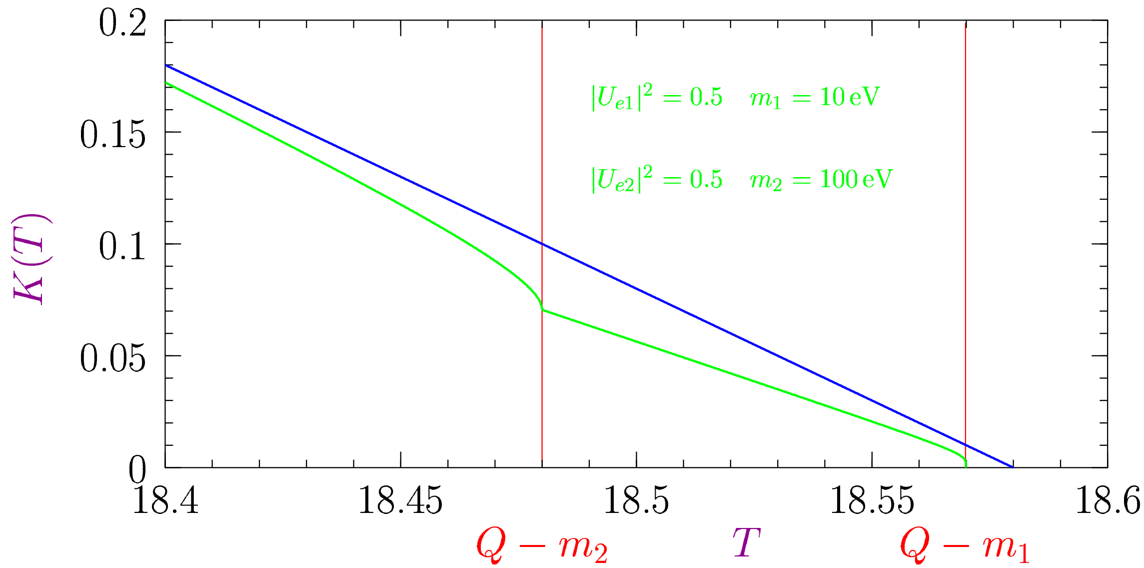
$\boxed{m_{\nu_e} < 2.2\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})}$

[Mainz, Troitsk, hep-ex/0210050]

Future: KATRIN [hep-ex/0109033]

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

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



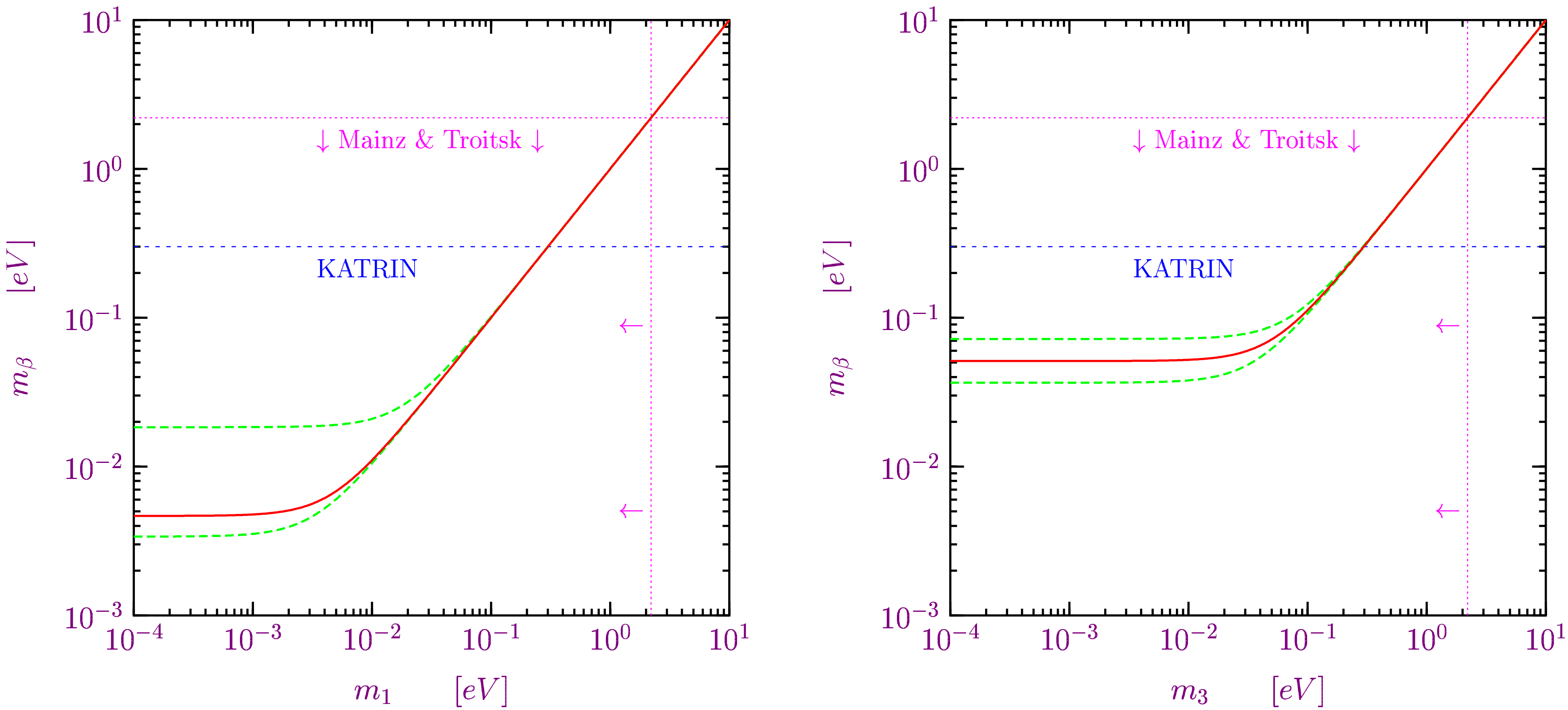
analysis of data is different from the no-mixing case: $2N-1$ parameters $\left(\sum_k |U_{ek}|^2 = 1 \right)$

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

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

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

$m_{\nu_e} < 2.2\,\text{eV}$ (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 $m_\beta < 3 \times 10^{-2}\,\text{eV} \Longrightarrow$ NORMAL HIERARCHY

COSMOLOGICAL LIMIT ON NEUTRINO MASSES

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

number density: $n_{\mathfrak{f}} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_{\mathfrak{f}} T_{\mathfrak{f}}^3 \Longrightarrow n_{\nu_k,\bar{\nu}_k} \simeq 0.1827\, T_\nu^3 \simeq 112\,\mathrm{cm}^{-3}$

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

massive neutrinos = hot dark matter ≡ relativistic at matter-radiation equality ($z_{\mathrm{eq}} \sim 3000$)

Last CMB Scattering (recombination): $z_{\mathrm{rec}} \sim 1300$, $T_{\mathrm{rec}} \sim 3700\,\mathrm{K} \sim 0.3\,\mathrm{eV}$

hot dark matter prevents early galaxy formation

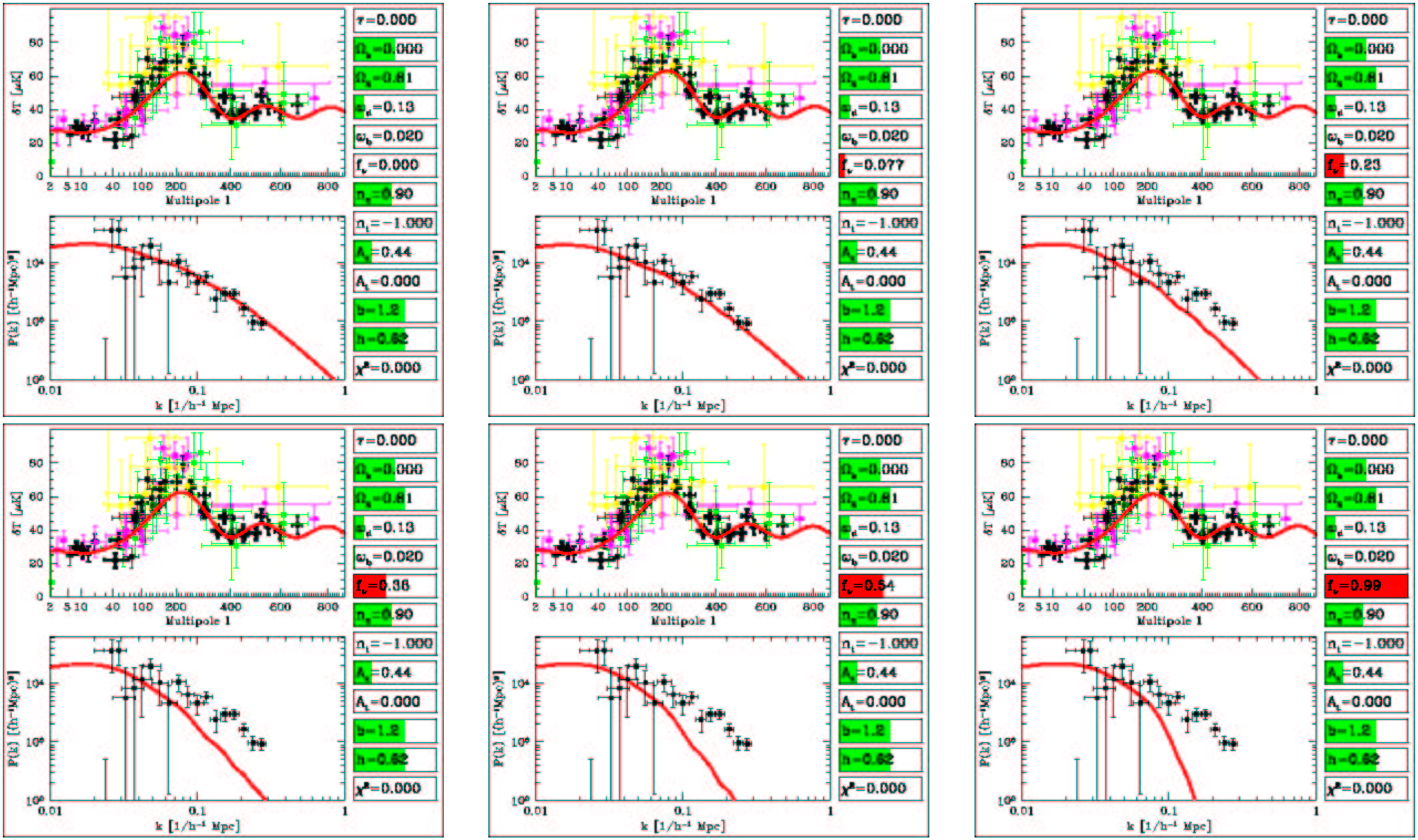
small scale suppression: $\frac{\Delta P(k)}{P(k)} \approx -8\,\frac{\Omega_\nu}{\Omega_m} \approx -0.8 \left(\frac{\sum_k m_k}{1\,\mathrm{eV}}\right)\left(\frac{0.1}{\Omega_m\, h^2}\right)$

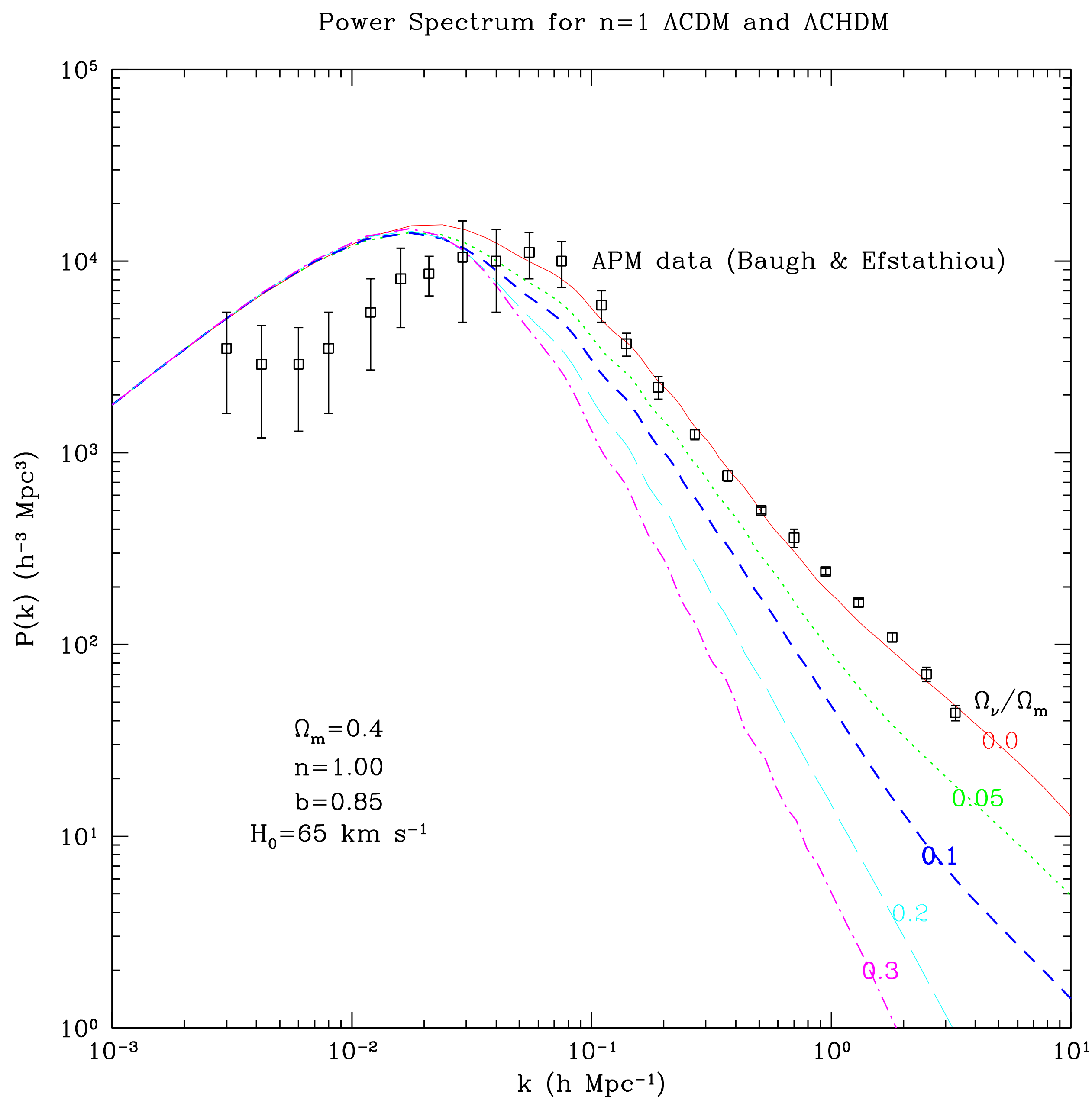
for $k \gtrsim k_{\mathrm{nr}} \approx 0.026 \sqrt{\frac{m_\nu}{1\,\mathrm{eV}}}\sqrt{\Omega_m}\, h\,\mathrm{Mpc}^{-1}$

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

Max Tegmark's Cosmic Cinema

[http://www.hep.upenn.edu/~max/cmb/movies.html]





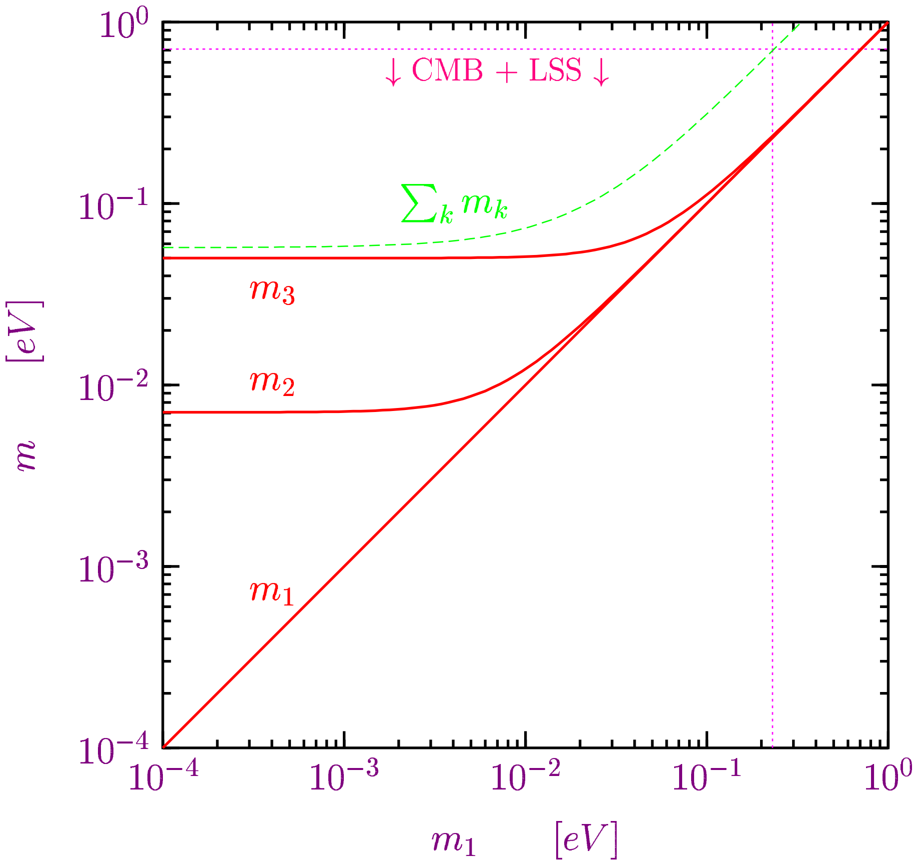
[Primack, Gross, astro-ph/0007165]

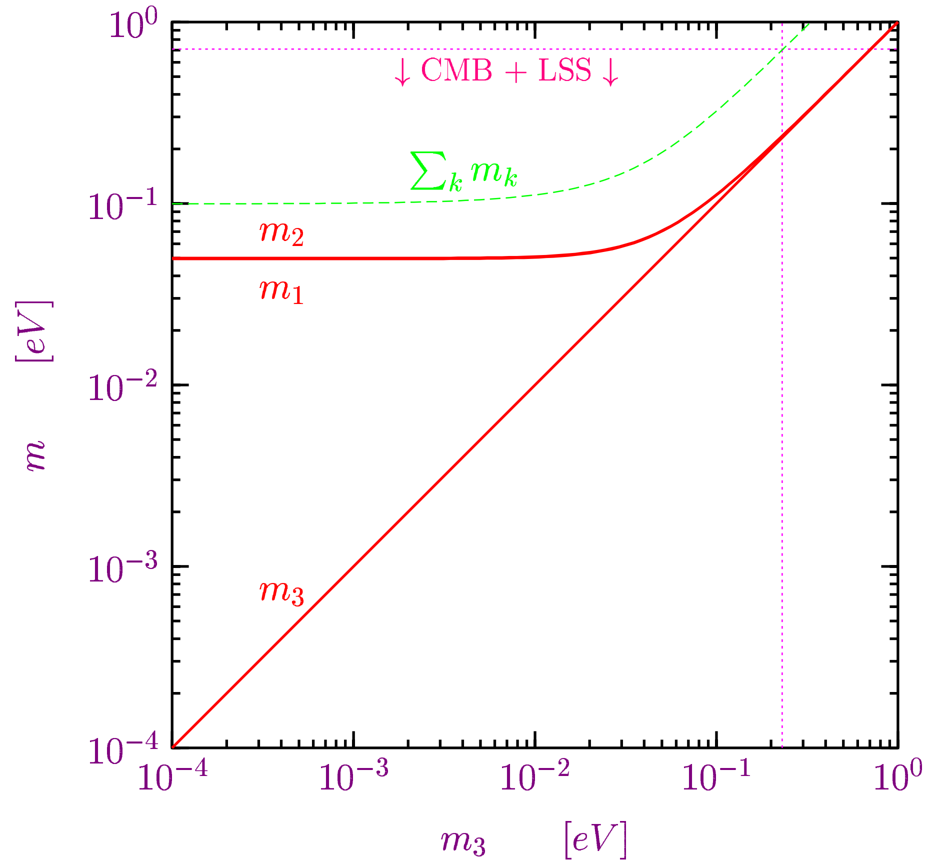
CMB (WMAP, CBI, ACBAR) + LSS (2dFGRS, Lyman-α)

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

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

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





Other Analyses of Cosmological Data

Hannestad [astro-ph/0303076]

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

$\sum_k m_k < 1.20\,\mathrm{eV}$ (WMAP+CBI+2dFGRS)

$\sum_k m_k < 2.12\,\mathrm{eV}$ (WMAP+2dFGRS)

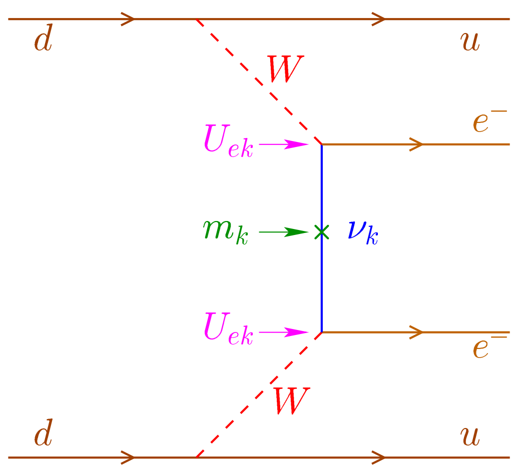
Elgaroy and Lahav [astro-ph/0303089]

$$\sum_k m_k < 1.1\,\mathrm{eV} \quad \text{(WMAP+2dFGRS+HST)}$$

"The linear matter power spectrum inferred from the Lyman-α forest probes smaller scales than the 2dFGRS and therefore has considerable power in constraining neutrino masses.
...the Lyman-α forest power spectrum plays a role in pushing the constraint on $\sum_k m_k$ below 1 eV."

MAJORANA NEUTRINOS? $\Longleftrightarrow$ $\beta\beta_{0\nu}$ decay

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



effective Majorana mass $\quad |\langle m \rangle| = \left| \sum_k U_{ek}^2 m_k \right|$

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

$$|\langle m \rangle| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 \right|$$

conserved CP

$\alpha_{21} = 0, \pi \qquad \alpha_{31} = 0, \pi$

$\eta_{kj} = e^{i\alpha_{kj}}$ relative CP parity

Heidelberg-Moscow ($^{76}\mathrm{Ge}$) $\quad |\langle m \rangle|_{\mathrm{exp}} < 0.35\,\mathrm{eV}$ (90% C.L.) $\quad$ [EPJA 12 (2001) 147]

IGEX ($^{76}\mathrm{Ge}$) $\quad |\langle m \rangle|_{\mathrm{exp}} < 0.33 - 1.35\,\mathrm{eV}$ (90% C.L.) $\quad$ [PRD 65 (2002) 092007]

catch: about factor 3 theoretical uncertainty on nuclear matrix element!

Neutrino Oscillations Implications for $\beta\beta_{0\nu}$ decay

$$|\langle m \rangle| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 \right|$$

mass hierarchy without fine-tuned cancellations among m_1, m_2, m_3 contributions

[Giunti, PRD 61 (2000) 036002]

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

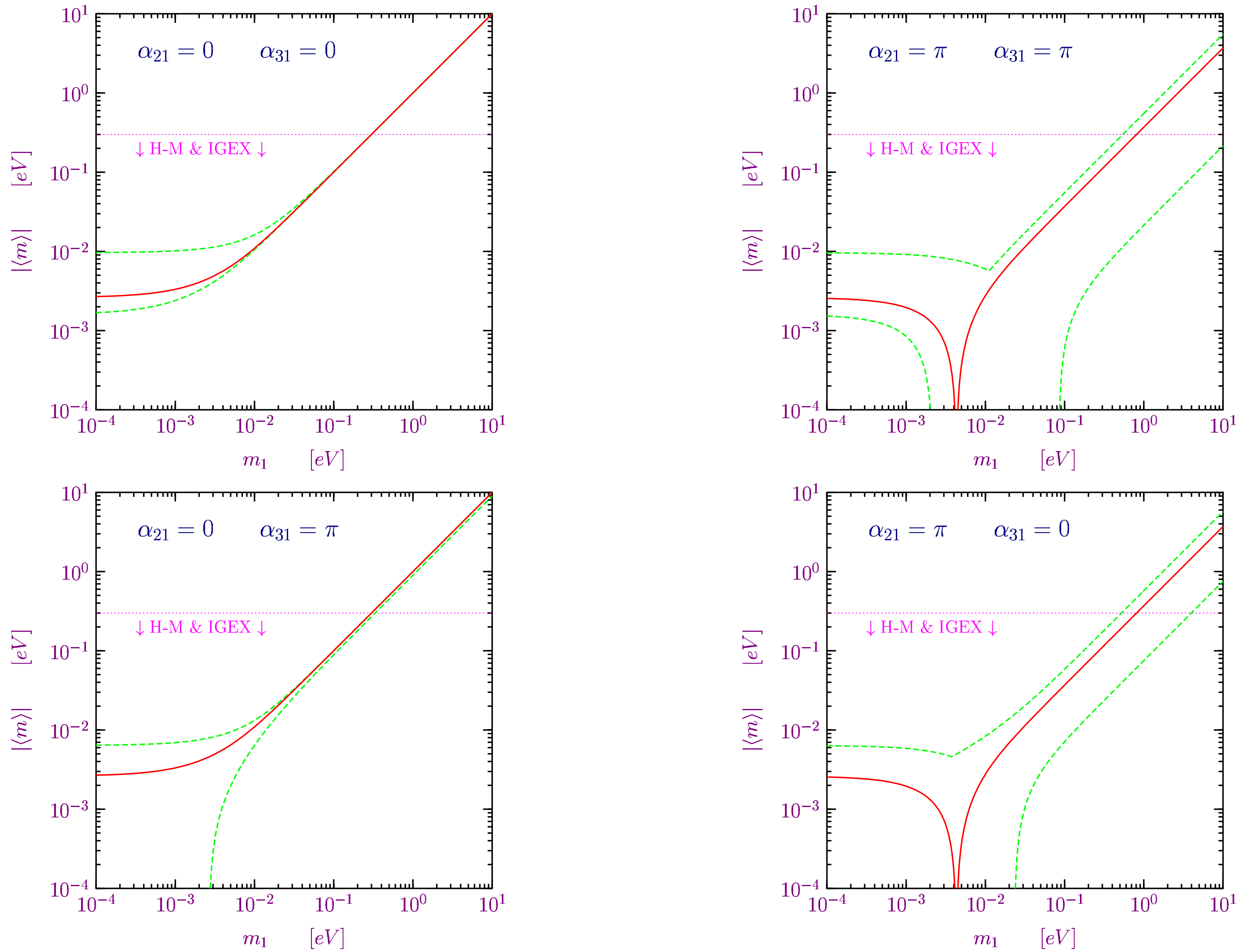
$$|U_{e2}|^2 \simeq \sin^2\vartheta_{\text{SUN}}, \; m_2 \simeq \sqrt{\Delta m^2_{\text{SUN}}} \qquad |U_{e3}|^2 \simeq \sin^2\vartheta_{\text{CHOOZ}}, \; m_3 \simeq \sqrt{\Delta m^2_{\text{ATM}}}$$

$$\left.\begin{array}{c} \Delta m^{2\,\text{best-fit}}_{\text{SUN}} = 6.9 \times 10^{-5}, \quad |U_{e2}|_{\text{best-fit}} = 0.56 \\ 5.1 \times 10^{-5} \lesssim \Delta m^2_{\text{SUN}} \lesssim 1.9 \times 10^{-4} \\ 0.46 \lesssim |U_{e2}| \lesssim 0.68 \end{array}\right\} \Longrightarrow \left\{\begin{array}{c} |\langle m \rangle|_2^{\text{best-fit}} = 2.6 \times 10^{-3} \\ 1.5 \times 10^{-3} \lesssim |\langle m \rangle|_2 \lesssim 6.4 \times 10^{-3} \end{array}\right.$$

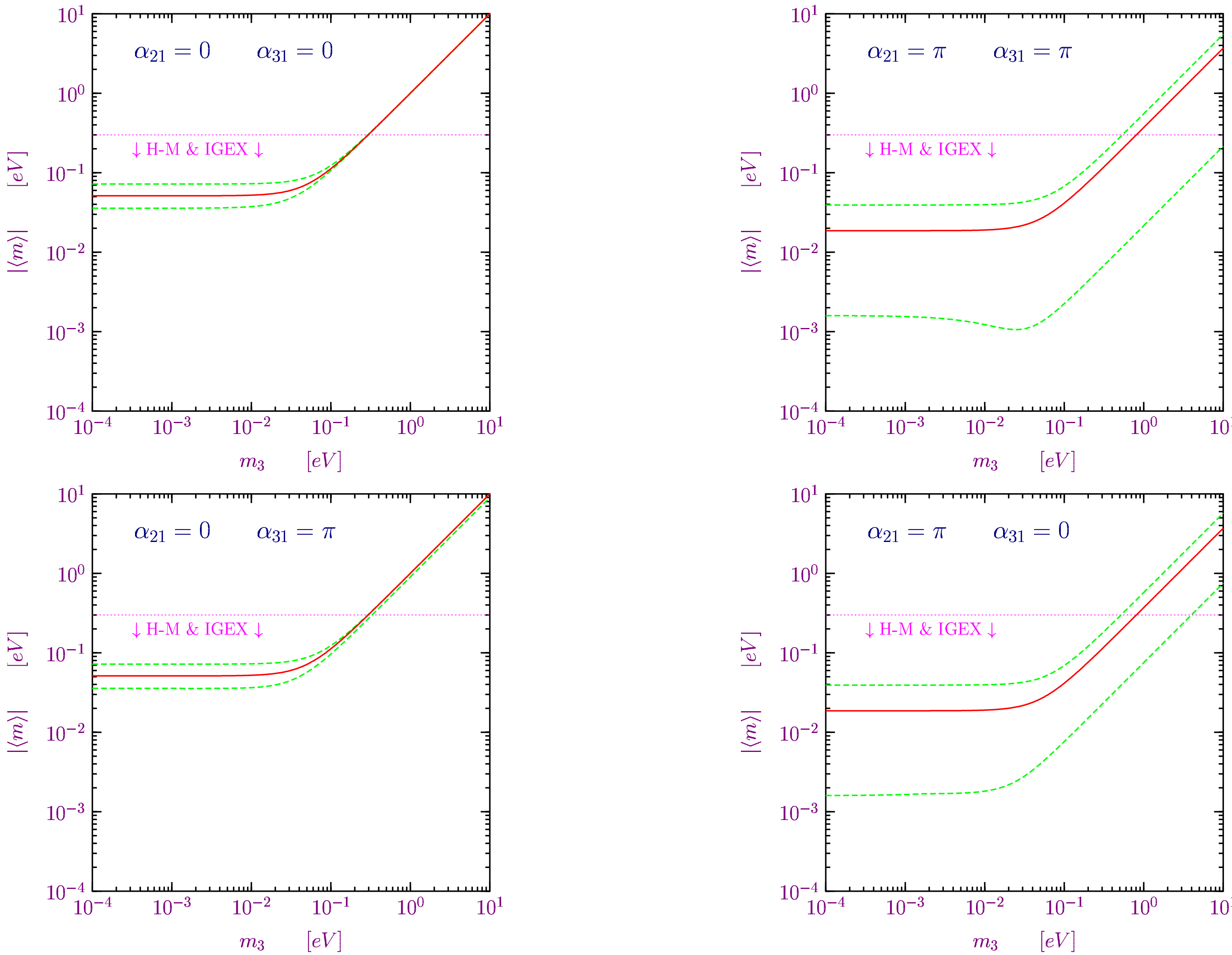
$$\left.\begin{array}{c} \Delta m^{2\,\text{best-fit}}_{\text{ATM}} = 2.6 \times 10^{-3}, \quad |U_{e3}|_{\text{best-fit}} = 0 \\ 1.4 \times 10^{-3} \lesssim \Delta m^2_{\text{ATM}} \lesssim 5.1 \times 10^{-3} \\ |U_{e2}| \lesssim 0.22 \end{array}\right\} \Longrightarrow \left\{\begin{array}{c} |\langle m \rangle|_3^{\text{best-fit}} = 0 \\ |\langle m \rangle|_3 \lesssim 3.5 \times 10^{-3} \end{array}\right.$$

m_2 contribution $|\langle m \rangle|_2$ may be dominant! (lower limit for $|\langle m \rangle|$)

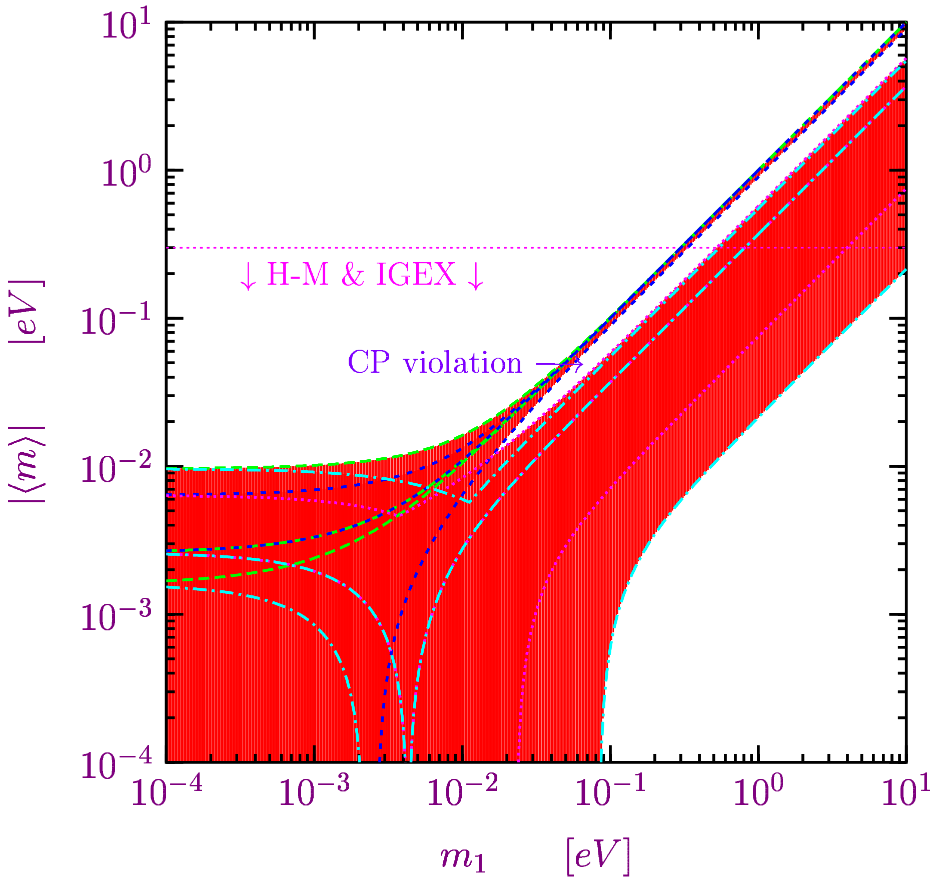
CP Conservation: Normal Scheme



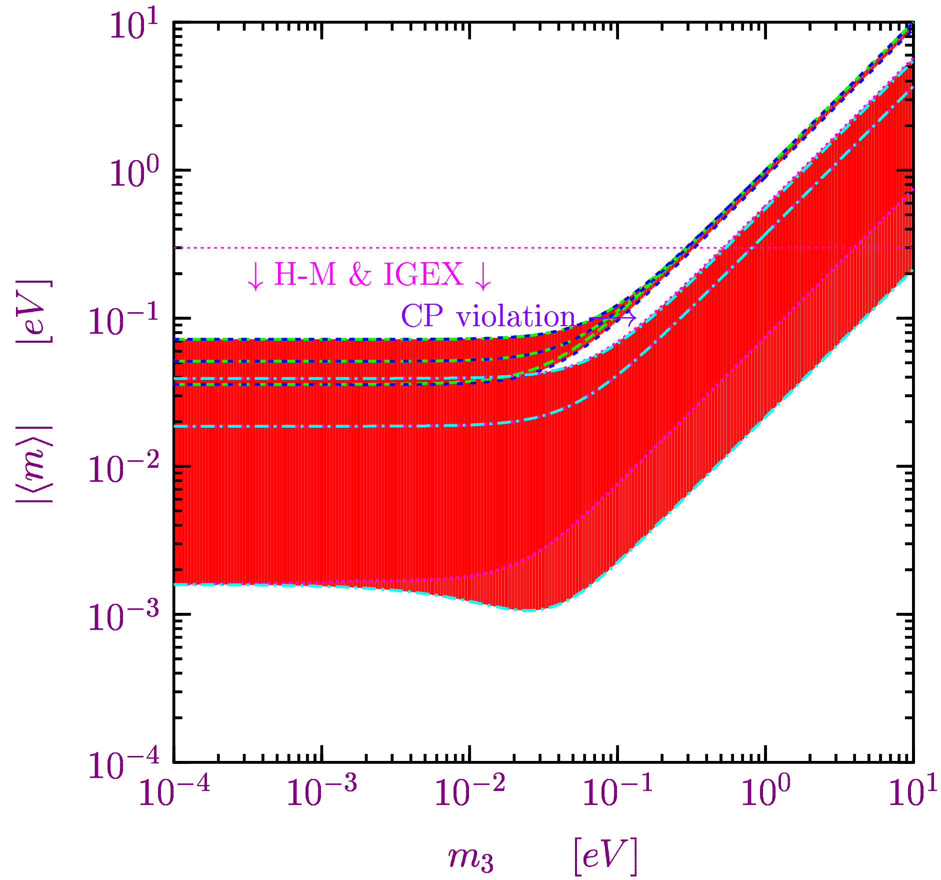
CP Conservation: Inverted Scheme



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



"normal" scheme



"inverted" scheme

FUTURE: NEMO3, CAMEO, Majorana, CUORICINO, XMASS ($|\langle m \rangle| \sim 10^{-1}\,\mathrm{eV}$)
GENIUS, CUORE, EXO, MOON, GEM ($|\langle m \rangle| \sim 10^{-2}\,\mathrm{eV}$)

VERY FAR FUTURE: IF $|\langle m \rangle| < 10^{-3}\,\mathrm{eV} \Longrightarrow$ NORMAL HIERARCHY

Conclusions

⇝ In the beginning of the high-precision era of neutrino physics the absolute scale of neutrino masses is still unknown: only upper limits (Tritium β Decay and Cosmology) $\Longrightarrow$ Important Problem!

⇝ Future: KATRIN & More Cosmological Data (WMAP, SDSS, PLANK, ...)

⇝ Other Very Important Question: Are Neutrinos Majorana? $\Longleftrightarrow$ Neutrinoless Double-β Decay (bounded by neutrino oscillation data).

⇝ Future: Many $\beta\beta_{0\nu}$ Decay Projects (often connected with dark matter searches)

Neutrino Unbound

`http://www.to.infn.it/~giunti/NU`

Carlo Giunti & Marco Laveder