

Neutrino Mass: Overview of $\beta\beta_{0\nu}$, Cosmology and Direct Measurements

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Neutrino Unbound: <http://www.nu.to.infn.it>

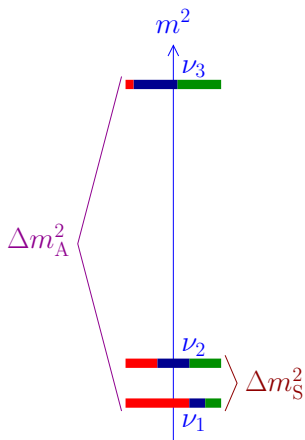
Neutrino Town Meeting

European Strategy for Neutrino Oscillation Physics - II

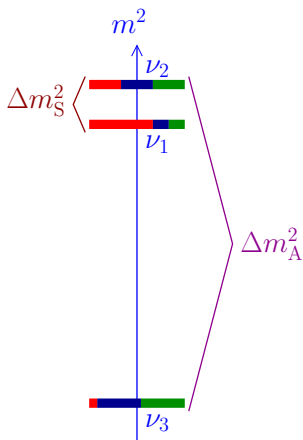
14-16 May 2012, CERN

Three-Neutrino Mixing Paradigm

ν_e ν_μ ν_τ



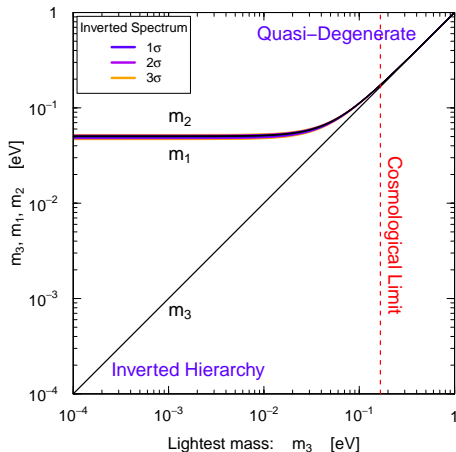
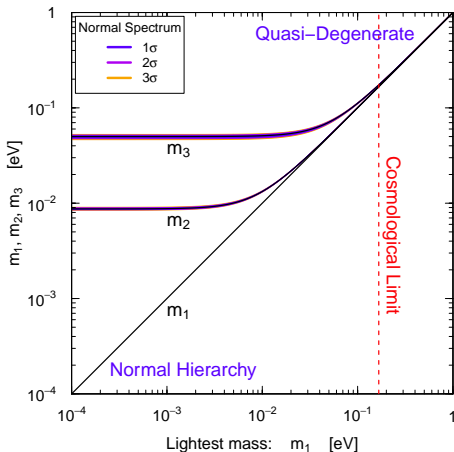
Normal Spectrum



Inverted Spectrum

absolute scale is not determined by neutrino oscillation data

Absolute Values of Neutrino Masses



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

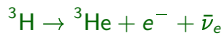
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

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

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

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

Tritium Beta-Decay

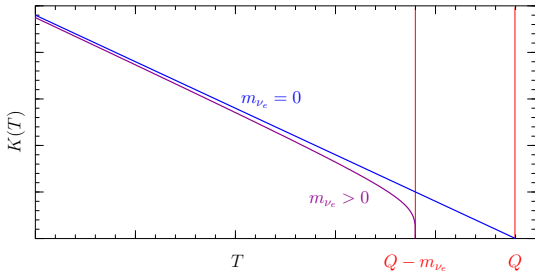


$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E (Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2}$$

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

Kurie plot

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



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

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

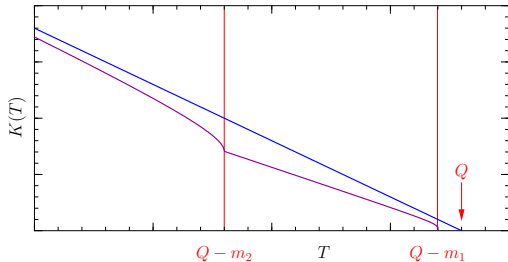
future: KATRIN

[www.katrin.kit.edu]

start data taking 2014

sensitivity: $m_{\nu_e} \simeq 0.2 \text{ eV}$

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



analysis of data is different from the no-mixing case:

$2N - 1$ parameters

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

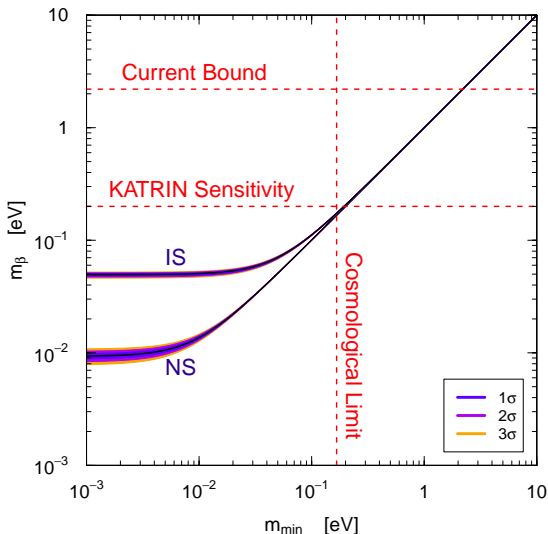
if experiment is not sensitive to masses ($m_k \ll Q - T$)

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

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

Predictions of 3ν -Mixing Paradigm

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



- ▶ Quasi-Degenerate:

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

- ▶ Inverted Hierarchy:

$$m_\beta^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2$$

- ▶ Normal Hierarchy:

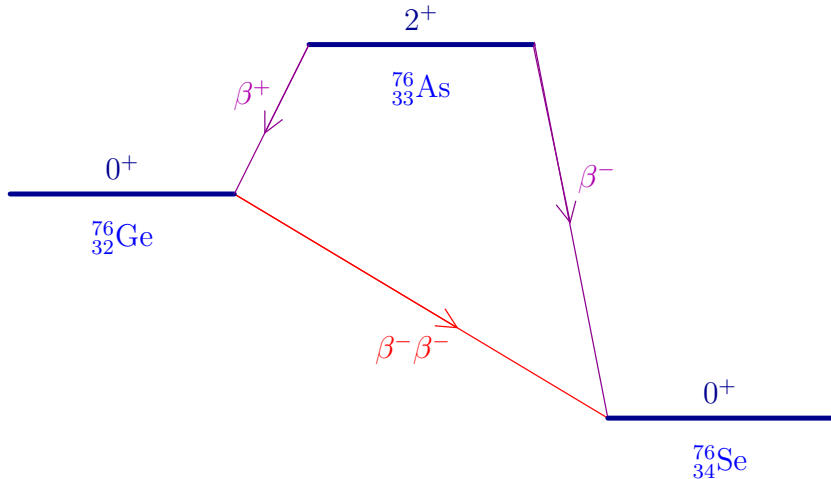
$$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2 \\ \simeq 2 \times 10^{-5} + 6 \times 10^{-5} \text{ eV}^2$$

- ▶ If $m_\beta \lesssim 4 \times 10^{-2} \text{ eV}$



Normal Spectrum

Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass:

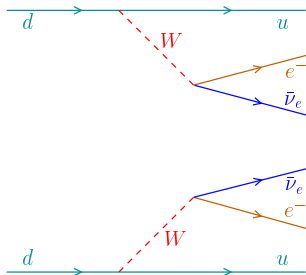
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

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

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

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

second order weak interaction process
in the Standard Model



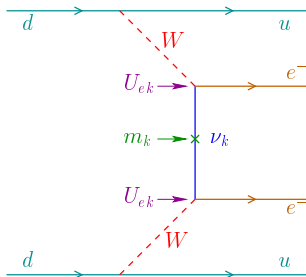
Neutrinoless Double- β Decay: $\Delta L = 2$

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

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

effective
Majorana
mass

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

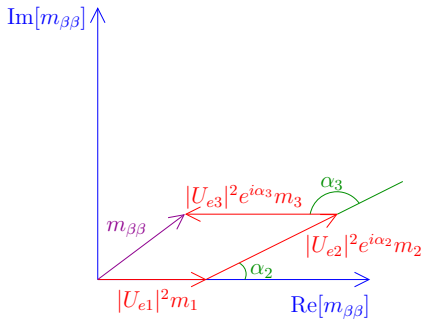
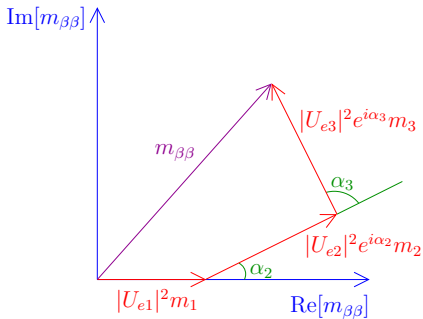


Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k \quad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$

$$\alpha_2 = 2\lambda_2 \quad \alpha_3 = 2(\lambda_3 - \delta_{13})$$



Experimental Bounds

CUORICINO (^{130}Te) [AP 34 (2011) 822]

$$T_{1/2}^{0\nu} > 2.8 \times 10^{24} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.3 - 0.7 \text{ eV}$$

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

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

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

$$T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.33 - 1.35 \text{ eV}$$

NEMO 3 (^{100}Mo) [PRL 95 (2005) 182302]

$$T_{1/2}^{0\nu} > 4.6 \times 10^{23} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.7 - 2.8 \text{ eV}$$

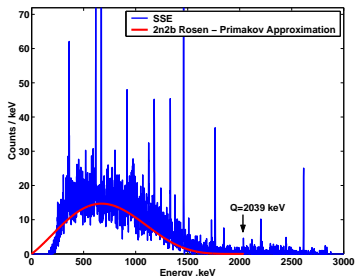
Experimental Positive Indication

[Klapdor et al., MPLA 16 (2001) 2409]

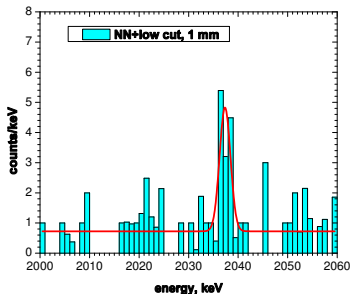
$$T_{1/2}^{0\nu} = (2.23_{-0.31}^{+0.44}) \times 10^{25} \text{ y}$$

6.5 σ evidence

[MPLA 21 (2006) 1547]



[PLB 586 (2004) 198]



[MPLA 21 (2006) 1547]

the indication must be checked by other experiments

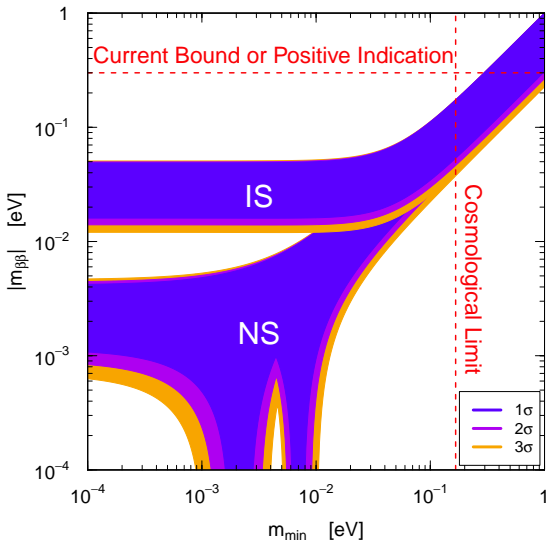
$$|m_{\beta\beta}| = 0.32 \pm 0.03 \text{ eV}$$

[MPLA 21 (2006) 1547]

if confirmed, very exciting: Majorana ν and large mass scale

Predictions of 3ν -Mixing Paradigm

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$



▶ Positive indication:
tension with cosmology

▶ Quasi-Degenerate:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s_{2\theta_{12}}^2 s_{\alpha_2}^2}$$

▶ Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m_A^2 (1 - s_{2\theta_{12}}^2 s_{\alpha_2}^2)}$$

▶ Normal Hierarchy:

$$|m_{\beta\beta}| \simeq |s_{12}^2 \sqrt{\Delta m_S^2} + e^{i\alpha} s_{13}^2 \sqrt{\Delta m_A^2}|$$

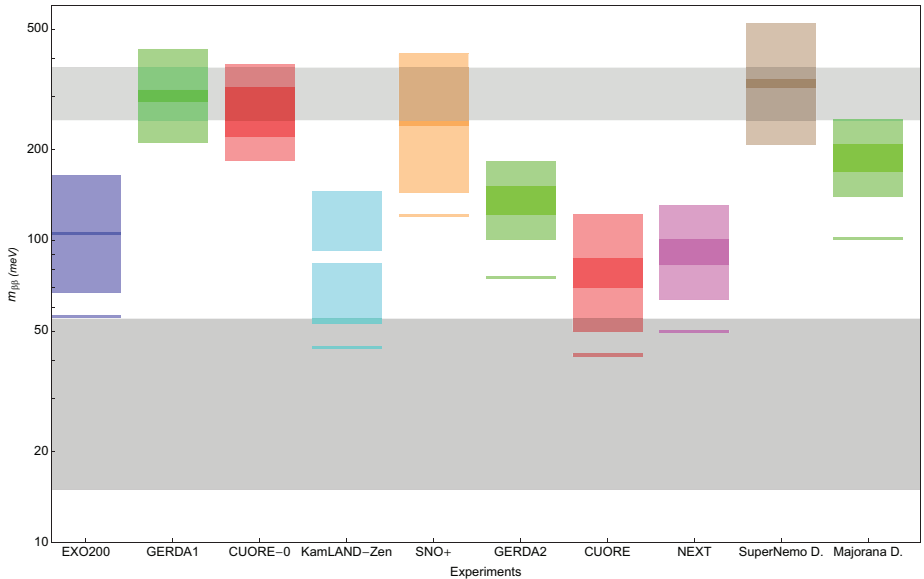
$$\simeq |2.7 + 1.2e^{i\alpha}| \times 10^{-3} \text{ eV}$$

▶ If $|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV}$



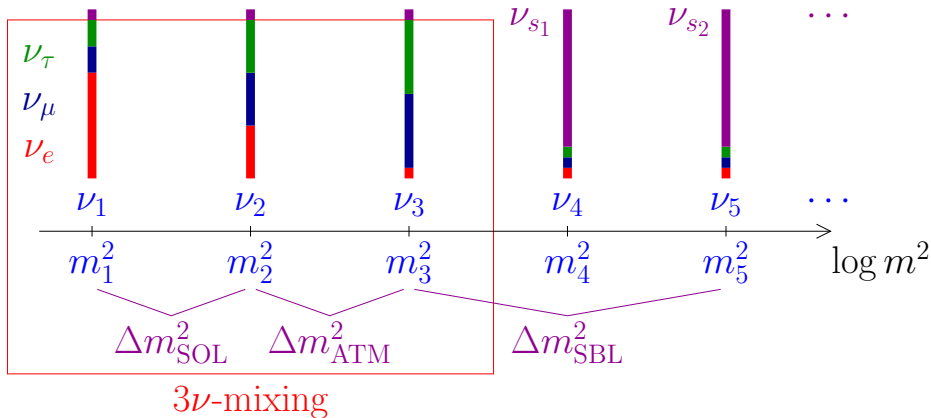
Normal Spectrum

New Experiments

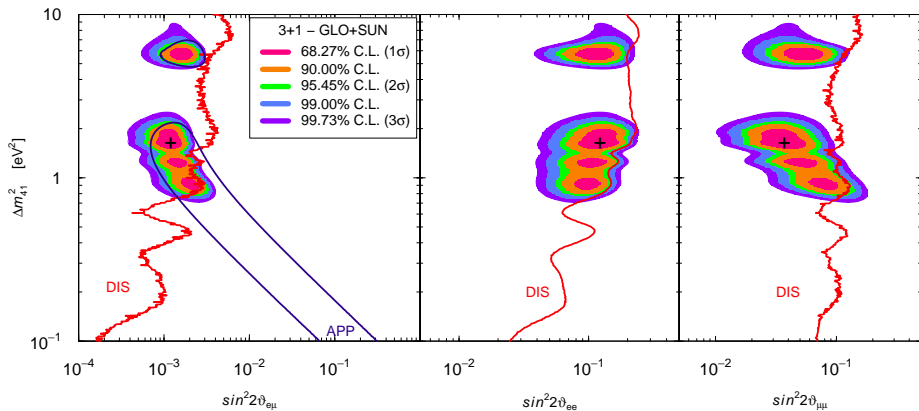


[Gomez-Cadenas, Martin-Albo, Mezzetto, Monrabal, Sorel, Riv. NC 35 (2012) 29]

Beyond Three-Neutrino Mixing



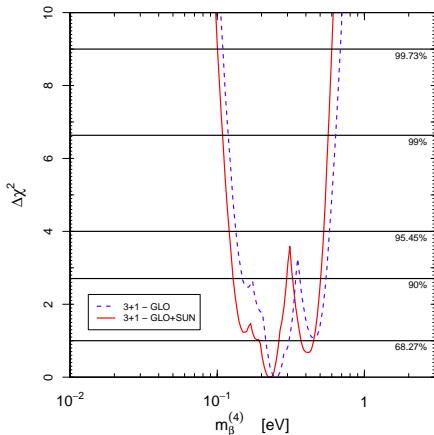
3+1



[Giunti, Laveder, Y.F. Li, in preparation]

3+1 Predictions

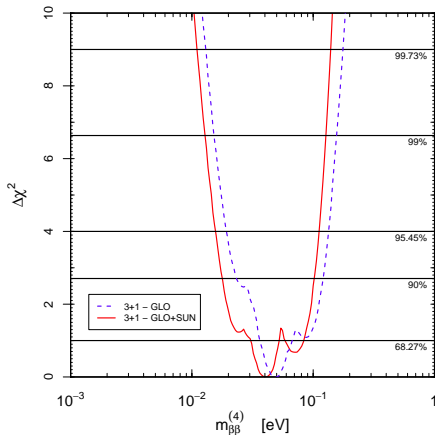
β Decay



$$m_{\beta}^{(4)} = |U_{e4}| \sqrt{\Delta m_{41}^2}$$

$$m_{\beta}^{(4)} \gg m_{\beta}^{(3\nu)} \text{ (IH)}$$

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



$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta}^{(4)} \gtrsim m_{\beta\beta}^{(3\nu)} \text{ (IH)}$$

Conclusions

D.3 – What is the likelihood of there being ~~no~~ interesting physics beyond measuring CP violation and mass hierarchy?

- ▶ Majorana Neutrinos: Very Likely

$\beta\beta_{0\nu}$ Decay; Majorana Phases; Lepton Number Violation; See-Saw Mechanism; Physics Beyond the Standard Model; Leptogenesis; ...

- ▶ Sterile Neutrinos: Possible

More Mixing Parameters: Masses, Mixing Angles, Phases; Rich Phenomenology at “Easily” Measurable eV Scale; Physics Beyond the Standard Model; ...

- ▶ ...?