Neutrino Masses in Cosmology, Neutrinoless Double-Beta Decay and Direct Neutrino Masses

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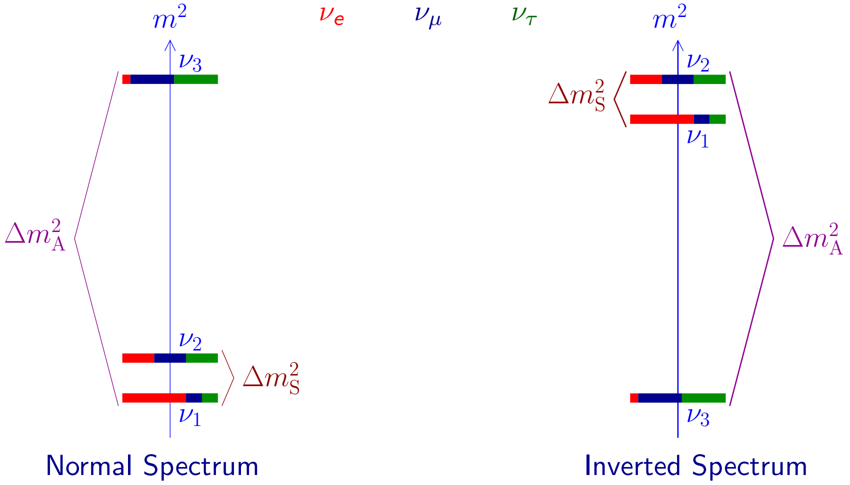
LIONeutrino2012
Neutrinos at the forefront of elementary particle physics and astrophysics

22-24 October 2012, Lyon, France

Three-Neutrino Mixing Paradigm



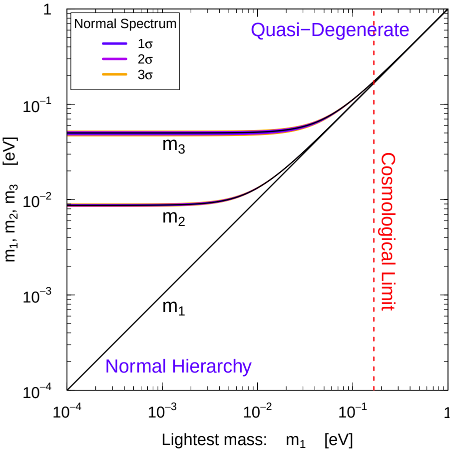
$\Delta m^2_{\mathrm{S}} \simeq 7.5 \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m^2_{\mathrm{A}} \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$

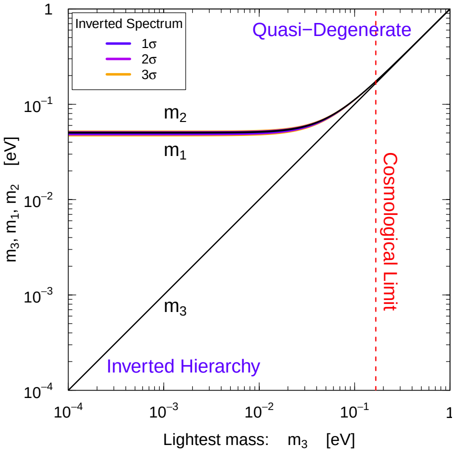
Open Problems

- CP violation ?
  - Nova, LAGUNA, CERN-GS, HyperK, ...
- Mass Hierarchy ?
  - Nova, Atmospheric Neutrinos, Day Bay II, Supernova Neutrinos, ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...

Cosmology: see Verde and Saviano talks

Absolute Scale 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 $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$

Tritium Beta-Decay

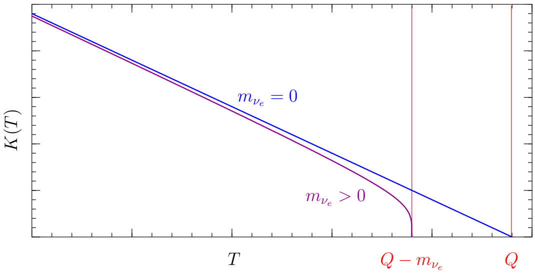
$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

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

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

Kurie plot

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



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

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

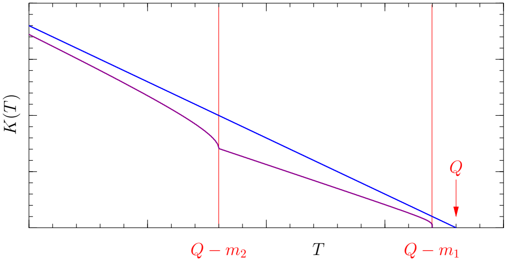
future: KATRIN

[www.katrin.kit.edu]

start data taking in 2015

sensitivity: $m_{\nu_e} \simeq 0.2\,\mathrm{eV}$

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 ($m_k \ll Q - T$)

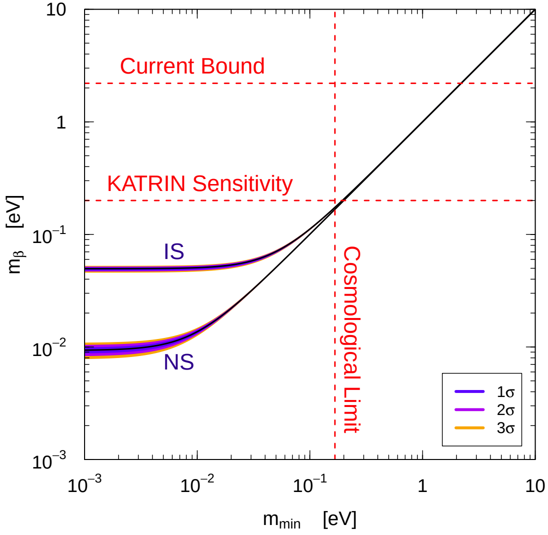
effective mass: $m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$

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

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

Predictions of 3ν-Mixing Paradigm

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

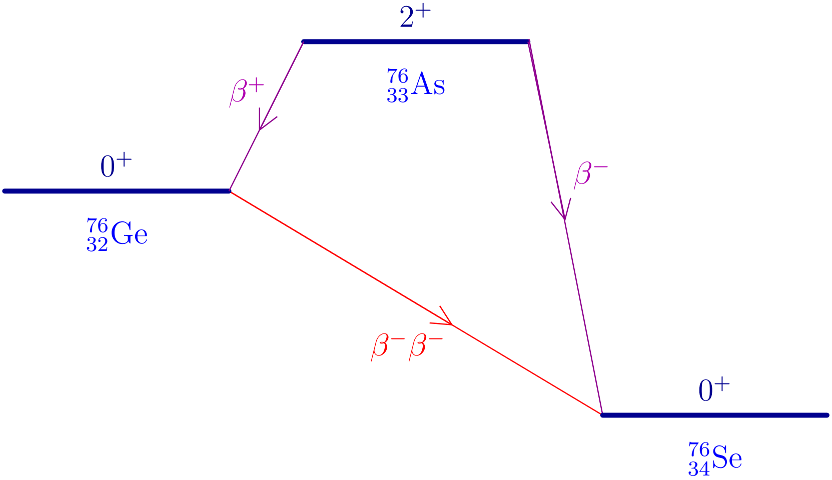


- Quasi-Degenerate:
  $$m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$$
- Inverted Hierarchy:
  $$m_\beta^2 \simeq (1 - s_{13}^2)\Delta m_{\rm A}^2 \simeq \Delta m_{\rm A}^2$$
- Normal Hierarchy:
  $$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_{\rm S}^2 + s_{13}^2 \Delta m_{\rm A}^2$$
  $$\simeq 2 \times 10^{-5} + 6 \times 10^{-5}\,{\rm eV}^2$$
- $m_\beta \lesssim 4 \times 10^{-2}\,{\rm eV}$

$\Downarrow$

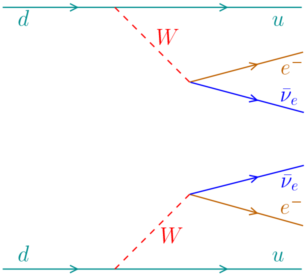
Normal Spectrum

Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass: $m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$

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

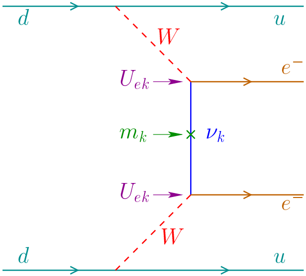


$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

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

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

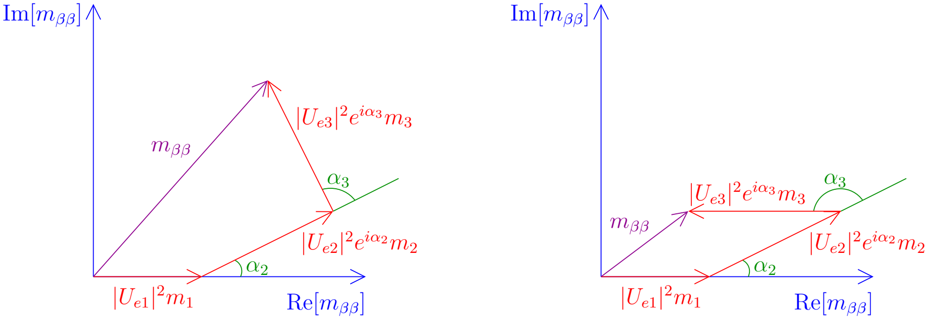
$$|m_{\beta\beta}| = \left| \sum_k U_{ek}^2 \, m_k \right|$$

Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2\, m_k$$ complex U_{ek} ⇒ possible cancellations

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

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



Experimental Bounds

EXO (^{136}Xe) [PRL 109 (2012) 032505]

$T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ y (90% C.L.) $\Longrightarrow$ $|m_{\beta\beta}| \lesssim 0.14 - 0.38\,\text{eV}$

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

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

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

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

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

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

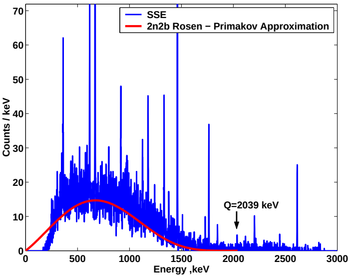
NEMO 3 (^{100}Mo) [PRL 95 (2005) 182302]

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

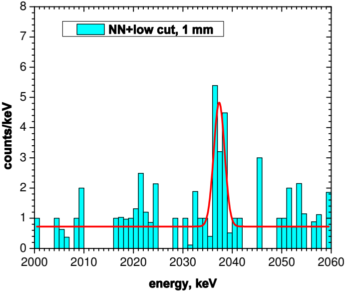
Experimental Positive Indication

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

$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25}$ y 6.5σ evidence [MPLA 21 (2006) 1547]



[PLB 586 (2004) 198]



[MPLA 21 (2006) 1547]

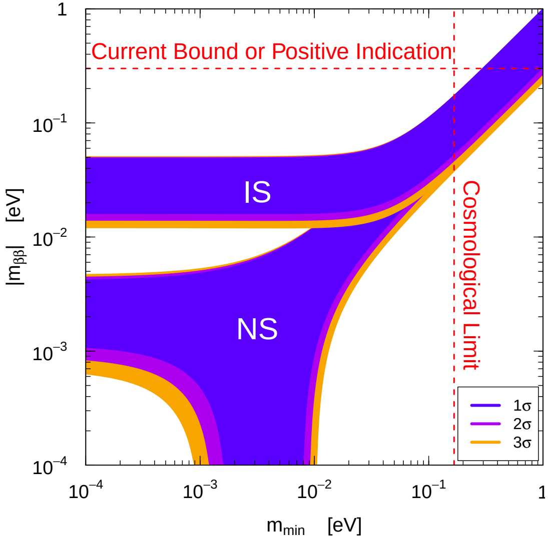
$|m_{\beta\beta}| = 0.32 \pm 0.03\,\text{eV}$ [MPLA 21 (2006) 1547]

very exciting: Majorana ν and large mass scale

partially excluded by EXO and CUORICINO

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:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2}}$$

- Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\rm A}(1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$

- Normal Hierarchy:

$$|m_{\beta\beta}| \simeq |s^2_{12}\sqrt{\Delta m^2_{\rm S}} + e^{i\alpha} s^2_{13}\sqrt{\Delta m^2_{\rm A}}|$$

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

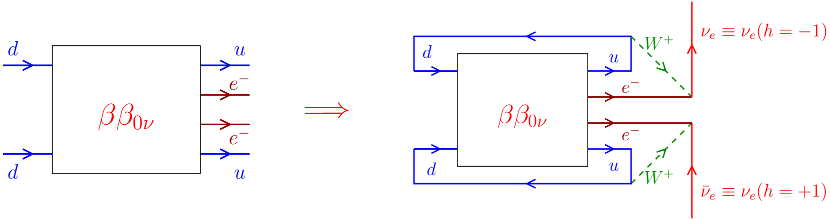
$m_1 \gtrsim 10^{-3}$ eV $\Rightarrow$ cancellation?

$|m_{\beta\beta}| \lesssim 10^{-2}$ eV $\Longrightarrow$ Normal Spectrum

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

$|m_{\beta\beta}|$ can vanish because of unfortunate cancellations among m_1, m_2, m_3 contributions or because neutrinos are Dirac

$\beta\beta_{0\nu}$ decay can be generated by another mechanism beyond SM



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

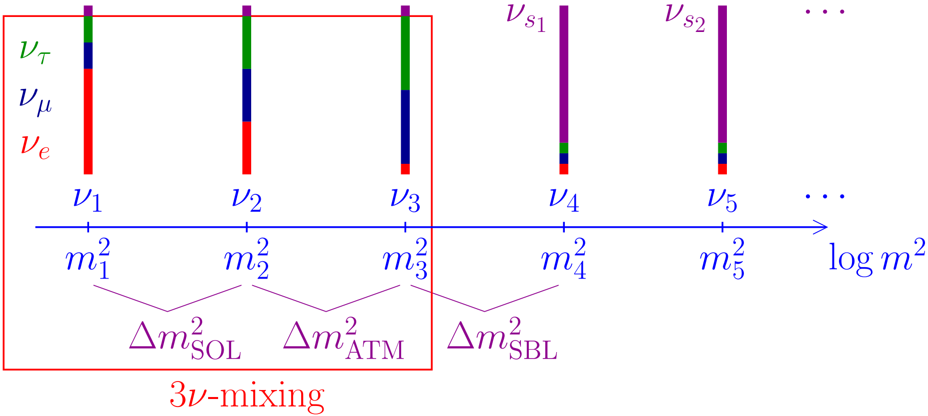
Majorana Mass Term: $\mathcal{L}_{eL}^{\mathrm{M}} = -\frac{1}{2}\, m_{ee} \left(\overline{\nu_{eL}^{c}}\, \nu_{eL} + \overline{\nu_{eL}}\, \nu_{eL}^{c} \right)$

four-loop diagram calculation: $m_{ee} \sim 10^{-24}\,\mathrm{eV}$ [Duerr, Lindner, Merle, JHEP 06 (2011) 091]

- In any case finding $\beta\beta_{0\nu}$ decay is important information to solve the Dirac-Majorana question in favor of Majorana

- On the other hand, it is not possible to prove experimentally that neutrinos are Dirac.
  A Dirac neutrino is equivalent to 2 Majorana neutrinos with the same mass.
  Impossible to prove experimentally that mass splitting is exactly zero.

Beyond Three-Neutrino Mixing



[see Schwetz and Cribier talks]

Sterile Neutrinos

- Sterile means no standard model interactions (e.g. $\nu_R^c = \nu_{sL}$)
- Oscillation observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccc} & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \dots \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \dots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \dots \end{array}$$

- Neutrino number and mass observable:
  - Number of thermalized relativistic particles in early Universe (BBN, CMB, BAO)
  - m_4 effects in cosmology (CMB, LLS), direct β-decay neutrino mass measurements and neutrinoless double-β decay (if Majorana)

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

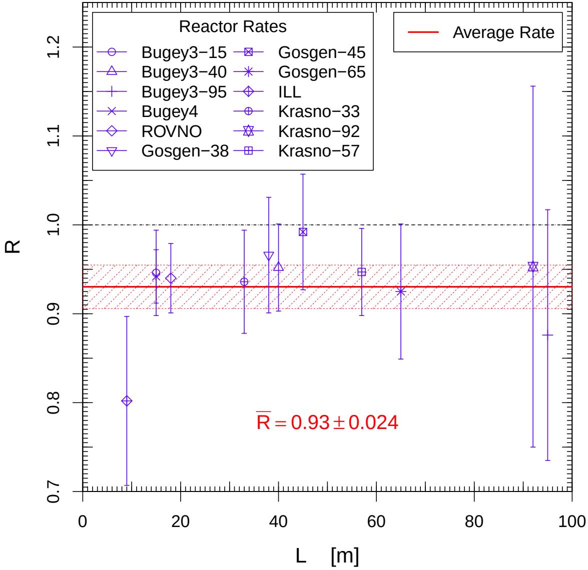
[update in White Paper, arXiv:1204.5379

new reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

2.8σ anomaly



Gallium Anomaly

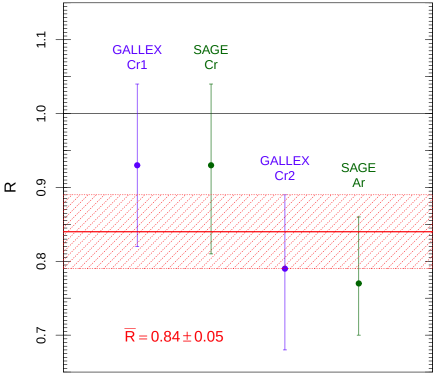
Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

Anomaly supported by new ${}^{71}\mathrm{Ga}({}^{3}\mathrm{He}, {}^{3}\mathrm{H}){}^{71}\mathrm{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7\,\mathrm{MeV}$

$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\,\mathrm{m}$

$\langle L \rangle_{\mathrm{SAGE}} = 0.6\,\mathrm{m}$

2.9σ anomaly

3+1 SBL ν_e and $\bar{\nu}_e$ Survival Probability

$$P_{\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e} = 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

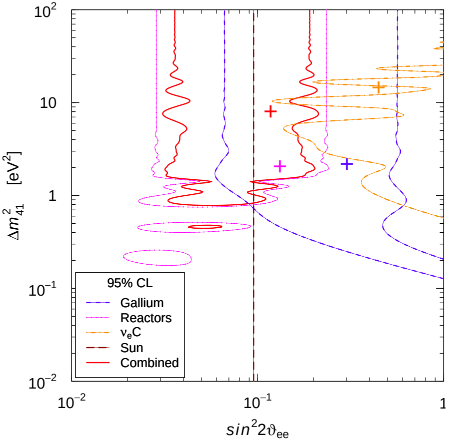
standard parameterization

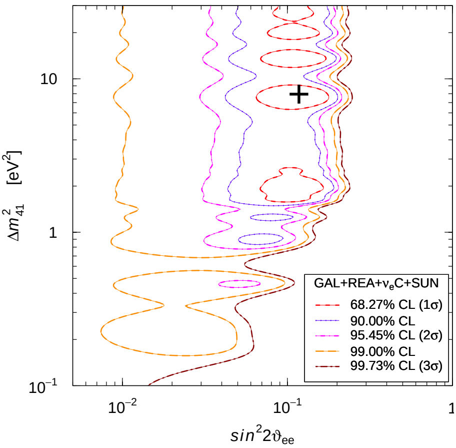
$$U_{e1} = c_{12}c_{13}c_{14} \quad U_{e2} = s_{12}c_{13}c_{14} \quad U_{e3} = s_{13}c_{14}e^{-i\delta_{13}} \quad U_{e4} = s_{14}e^{-i\delta_{14}}$$

$$\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$$

Global ν_e and $\bar{\nu}_e$ Disappearance

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, arXiv:1210.5715]





$\nu_e + {}^{12}C \to {}^{12}N_{g.s.} + e^-$

KARMEN + LSND

[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

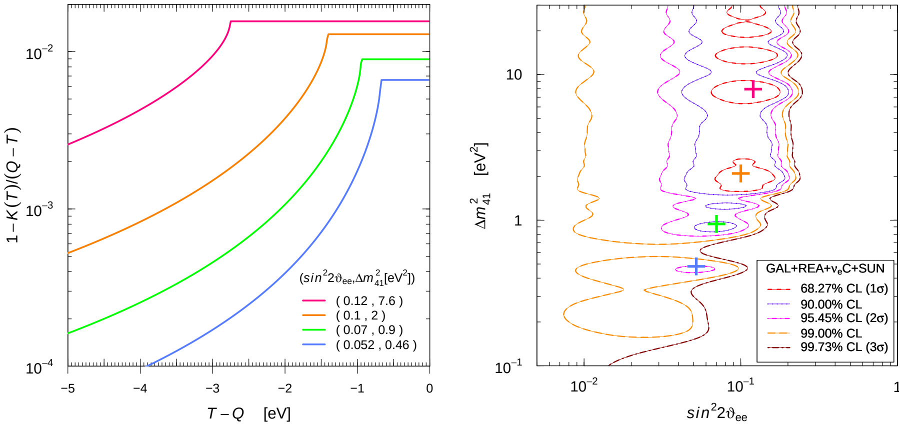
The existence of ν_4 with $m_4 \gtrsim 1\,\text{eV}$ can have dramatic effects not only on neutrino oscillations but also on all phenomena sensitive to the absolute value of neutrino masses:

- direct β-decay neutrino mass measurements
- neutrinoless double-β decay (if Majorana)
- cosmology

Information on ν_e and $\bar{\nu}_e$ disappearance is crucial for β decay and neutrinoless double-β decay

- ν_e and $\bar{\nu}_e$ disappearance depends on $\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$
- In β decay and neutrinoless double-β decay ν_4 contribution depends on $|U_{e4}|^2$

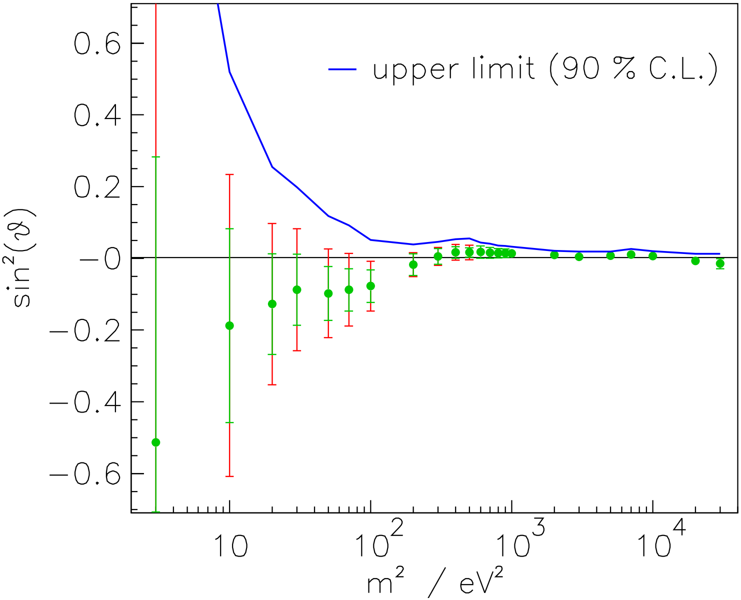
Direct β-Decay Neutrino Mass Measurements



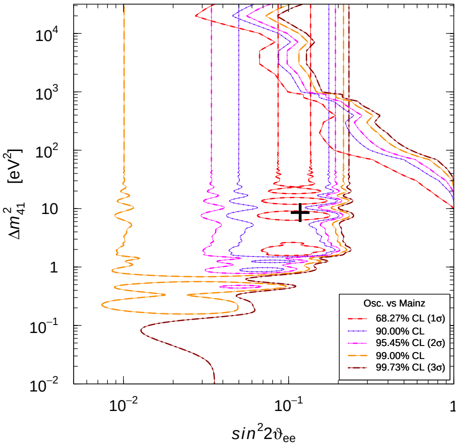
$$\left(\frac{K(T)}{Q-T}\right)^2 = 1 - |U_{e4}|^2 + |U_{e4}|^2 \sqrt{1 - \frac{m_4^2}{(Q-T)^2}}\,\theta(Q - T - m_4)$$

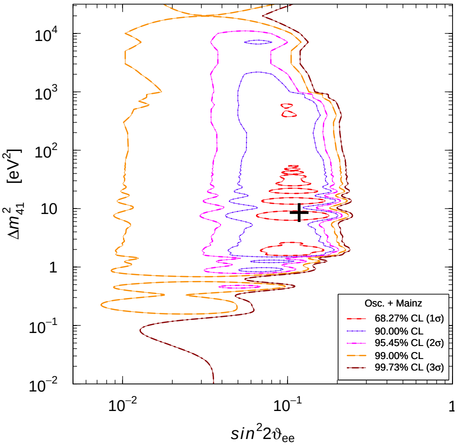
Mainz Neutrino Mass Experiment

[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

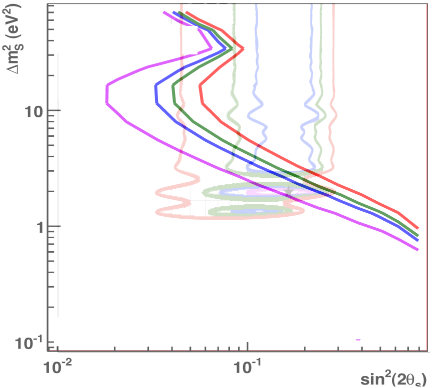


Δm^2_{41} Upper Bound

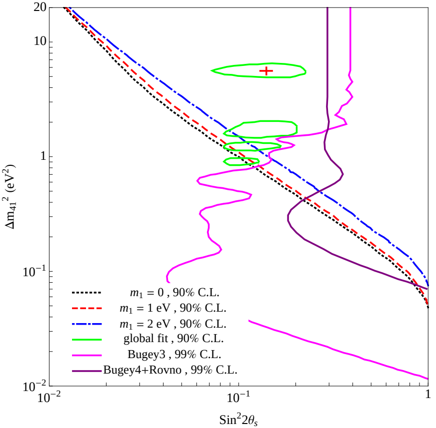




KATRIN Sensitivity



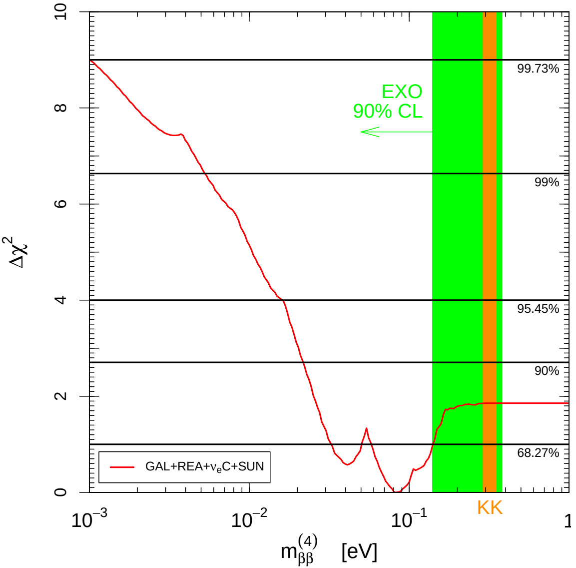
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



$$|m_{\beta\beta}| = \left|\sum_{k=1}^{4} U_{ek}^2 \, m_k\right|$$

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

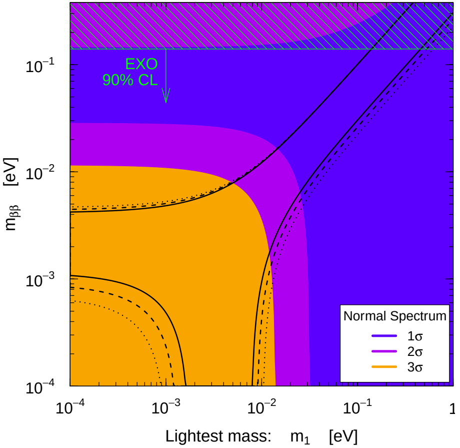
Cancellation with $m_{\beta\beta}^{(\mathrm{light})}$?

[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]; Li, Liu, PLB 706 (2012) 406; Rodejohann, arXiv:1206.2560]

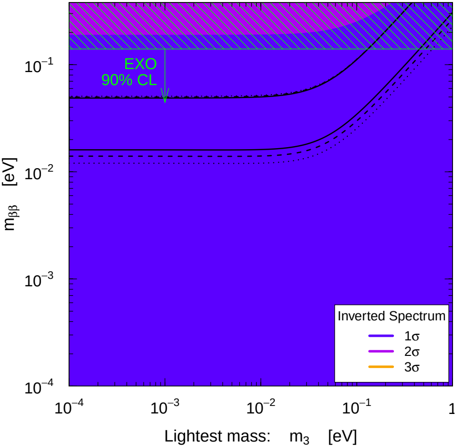
$$m_{\beta\beta}^{(\mathrm{light})} = \left| \sum_{k=1}^{3} U_{ek}^2 \, m_k \right| \qquad m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = m_{\beta\beta}^{(\mathrm{light})} + e^{i\alpha_4} m_{\beta\beta}^{(4)} \qquad m_{\beta\beta}^{(4)} \gtrsim 10^{-2}\,\mathrm{eV}$$

- **Normal Hierarchy:** $m_{\beta\beta}^{(\mathrm{light})} \lesssim 4.5 \times 10^{-3}\,\mathrm{eV}$ (95% CL)
  no cancellation is possible
- **Inverted Hierarchy:** $1.4 \times 10^{-2} \lesssim m_{\beta\beta}^{(\mathrm{light})} \lesssim 5.0 \times 10^{-2}\,\mathrm{eV}$ (95% CL)
  cancellation is possible
- **Quasi-Degenerate:** $m_{\beta\beta}^{(\mathrm{light})} \gtrsim 5.0 \times 10^{-2}\,\mathrm{eV}$ cancellation is possible



EXO
90% CL
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$m_{\beta\beta}$ [eV]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Lightest mass: m_1 [eV]
Normal Spectrum
1σ
2σ
3σ

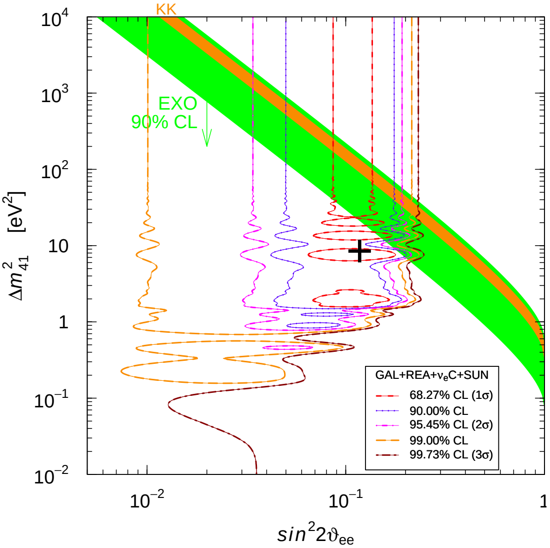


EXO
90% CL
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$m_{\beta\beta}$ [eV]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Lightest mass: m_3 [eV]
Inverted Spectrum
1σ
2σ
3σ

Assumption: no cancellation

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

$$\Delta m_{41}^2 = \left(\frac{m_{\beta\beta}^{(4)}}{|U_{e4}|^2} \right)^2 \leq \left(\frac{m_{\beta\beta}}{|U_{e4}|^2} \right)^2$$



Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer) [see Saviano talk]

- CMB and LSS in ΛCDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66\,\text{eV}$ (95% C.L.)

  [Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301]

  $N_s = 1.61 \pm 0.92$ $m_s < 0.70\,\text{eV}$ (95% C.L.)

  [Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023]

- BBN: $\begin{cases} N_s \leq 1 \text{ at } 95\% \text{ C.L.} \\ N_s = 0.0 \pm 0.5 \end{cases}$

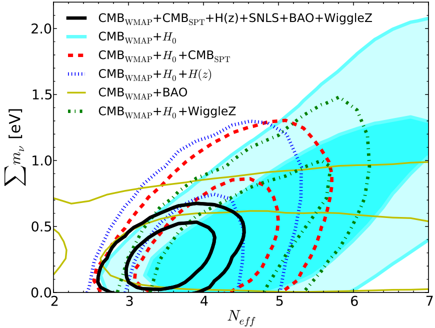
  [Mangano, Serpico, PLB 701 (2011) 296]

  [Pettini, Cooke, arXiv:1205.3785]

- CMB+LSS+BBN: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

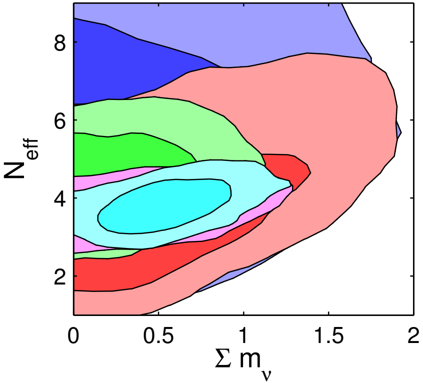
  [Hamann, Hannestad, Raffelt, Wong, JCAP 1109 (2011) 034]

- Standard ΛCDM: 3+1 allowed, 3+2 disfavored



68% and 95% CL

[Riemer-Sørensen, Parkinson, Davis, Blake, arXiv:1210.2131]



CMB (blue), CMB+WL (red)
CMB+BAO+OHD (magenta)
CMB+BAO+SNIa (green)
CMB+WL+BAO+OHD+SNIa (cyan)

[Wang et al., arXiv:1210.2136]

Conclusions

- Cosmology
  - Very powerful probe of neutrino number and masses
  - Model dependent. Thermalization loophole
  - Bright future (Plank, ...)
- Direct β-Decay Neutrino Mass Measurements
  - Model independent and robust
  - Sensitive to large neutrino masses beyond three-neutrino mixing
  - KATRIN will start in 2015
  - Unclear future (bolometers, project 8: radio-frequency)
- Neutrinoless Double-β Decay
  - Crucial for Majorana discovery
  - Sensitive to large neutrino masses beyond three-neutrino mixing
  - Many running and future experiments