Fourth generation neutrinos

Heinrich Päs

Workshop on Flavor and the Fourth family, IPPP Durham 2011

- Fourth generation neutrinos

  A. Lenz, D. Schalla, H. Päs, arXiv:1104.2465

- Baryon asymmtery of the Universe and new neutrino states

  S. Hollenberg, D. Schalla, H. Päs, work in progress

Outline

- Neutrinos and the 4th generation
- Majorana-ness and double beta decay
- Baryon asymmetry washout
- A simple extra-dimensional model

Neutrino status review

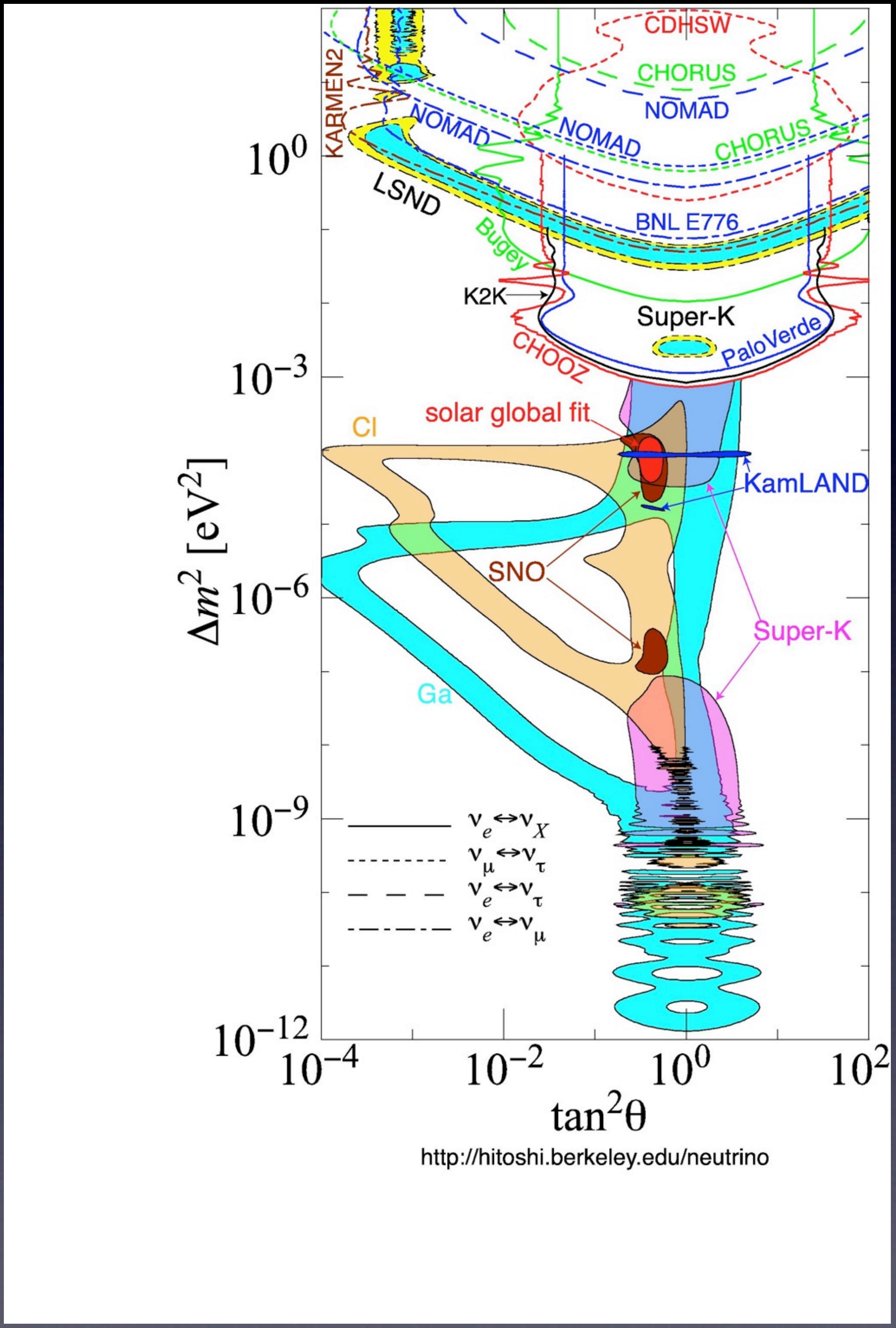
- Solar neutrino oscillations
  → large mixing
- Atmospheric neutrino oscillations
  → maximal mixing
- No short-baseline ν_e disappearance
  → small mixing

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

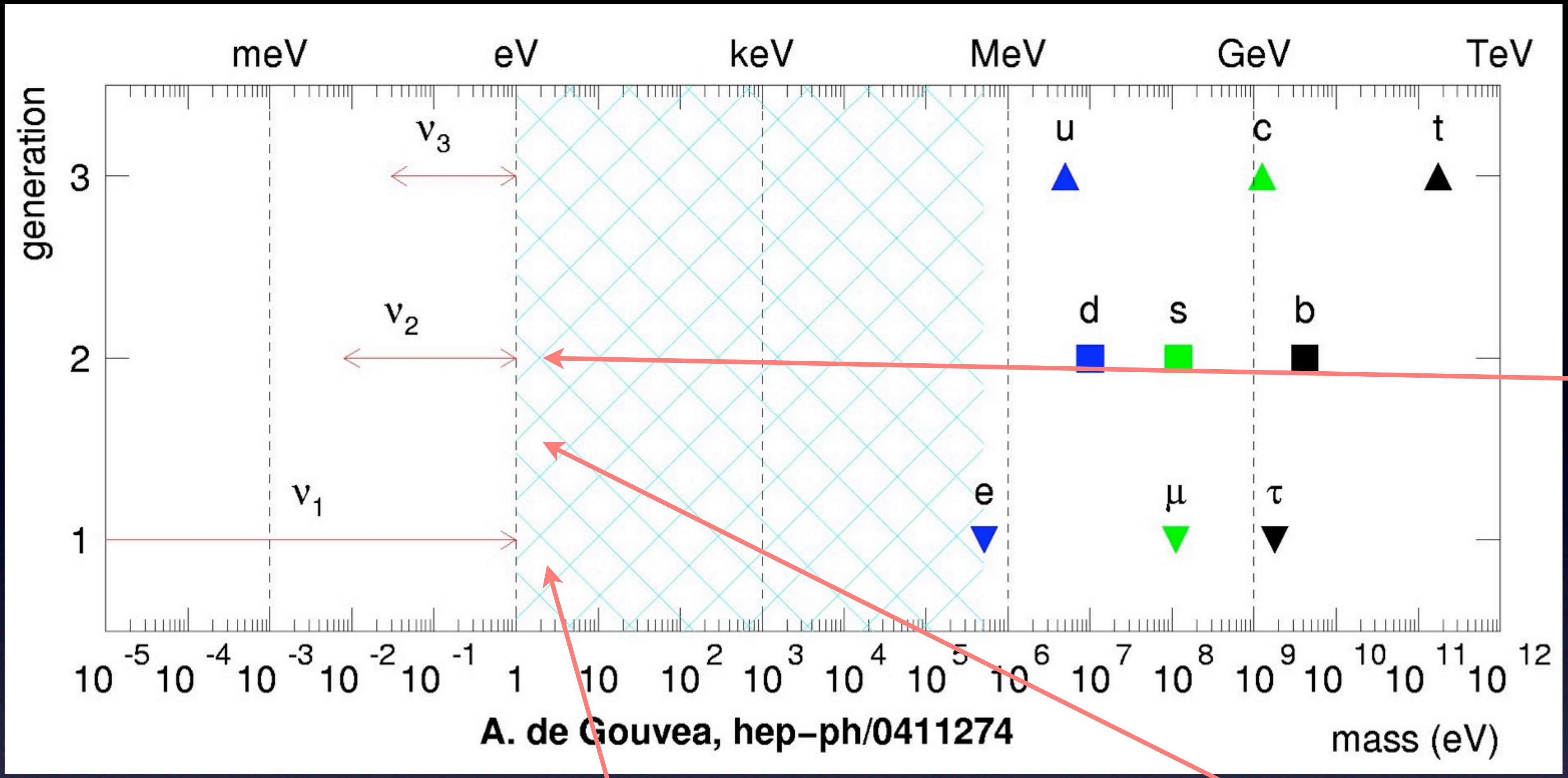
$$|U_{ij}| \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & < 0.2 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

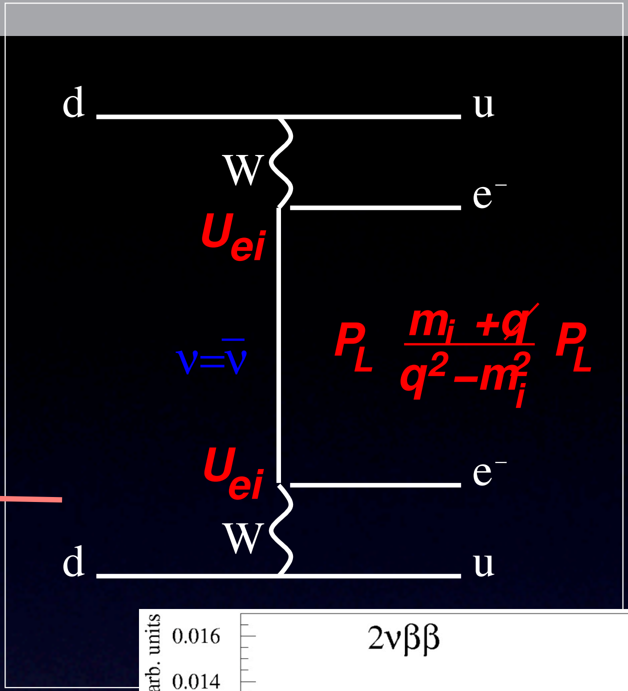
⇒Neutrinos have masses

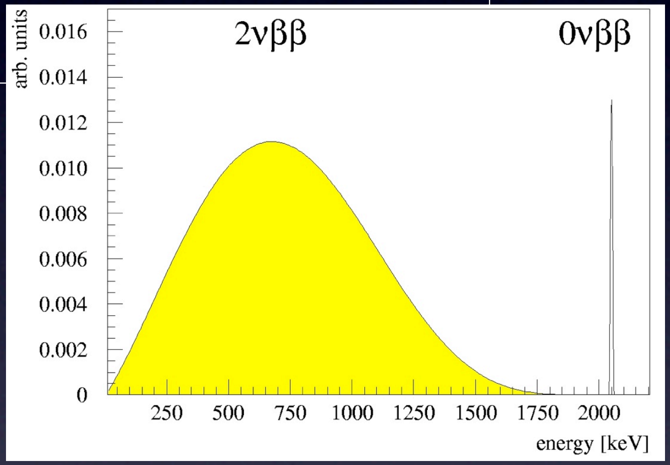
⇒Mass eigenstates ≠Flavor eigenstates

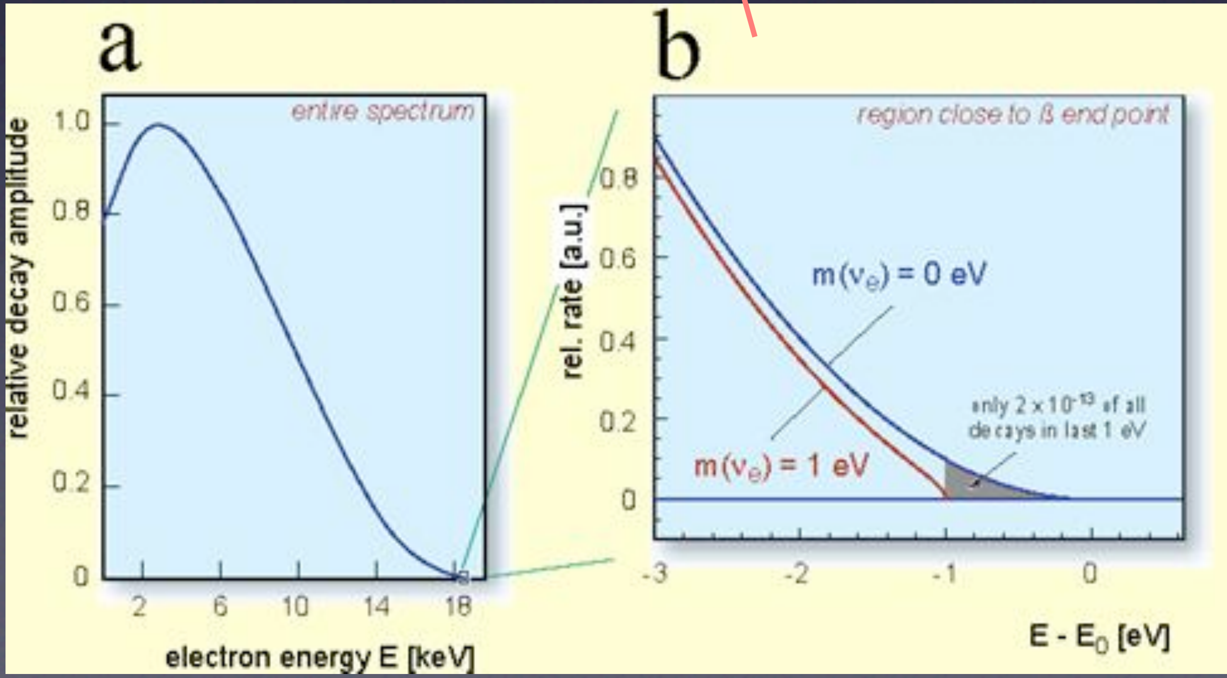


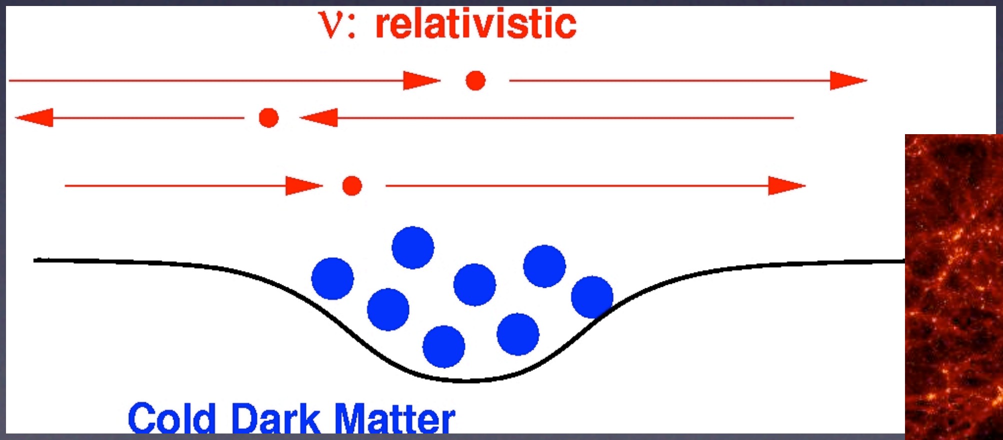
Neutrino status review

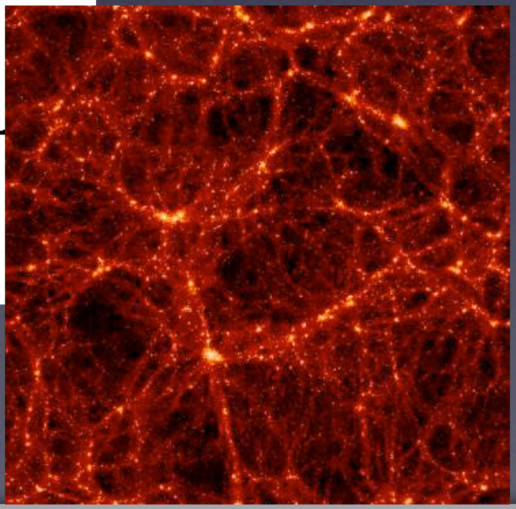










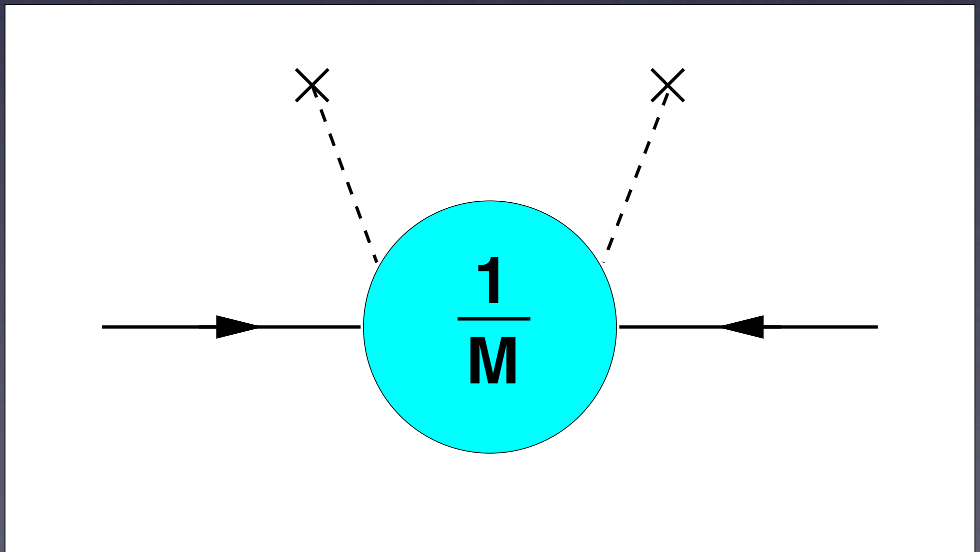


Neutrinos are special in 2 respects:

- only neutral among elementary fermions
- $m_\nu \ll m_{q,e,\mu,\tau}$

⇒ is there any connection ?

Weinberg 5D operator:



with *M* big

e.g. various Seesaws....

Seesaw I mechanism

Both Dirac and Majorana masses:

$$-\mathcal{L} = \frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{N}_L^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_R^C \\ N_R \end{pmatrix}$$

$$M_R \sim M_{GUT} \gg m_D \quad \Rightarrow \quad m_\nu = m_D^2 / M_R$$

- $\Rightarrow$ theoretical prejudice: Neutrinos are Majorana
- nice: Baryogenesis via Leptogenesis
- also nice: helps for 4th generation EW precision data (see Talk J. Rohrwild)

But - a 4th generation neutrino is different:

- an SU(2) doublet neutrino contributes to the Z decay width → LEP bound

$$m_{\nu_4} > \frac{m_Z}{2} \approx 45\,\mathrm{GeV}$$

- $|m_{\ell_4} - m_{\nu_4}| < 140\,\mathrm{GeV}$ (Eberhardt, Lenz, Rohrwild: arXiv:1005.3505)

  ⇒ charged and neutral leptons have similar mass

$$\Rightarrow m_{\nu_4} \sim \mathcal{O}(100\,\mathrm{GeV})$$

Neutrinos and the 4th generation

$$-\mathcal{L} = \frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{N}_L^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_R^C \\ N_R \end{pmatrix}$$

$$m = \frac{1}{2}\left(\sqrt{4m_D^2 + M_R^2} - M_R\right) \;\&\; M = \frac{1}{2}\left(\sqrt{4m_D^2 + M_R^2} + M_R\right)$$

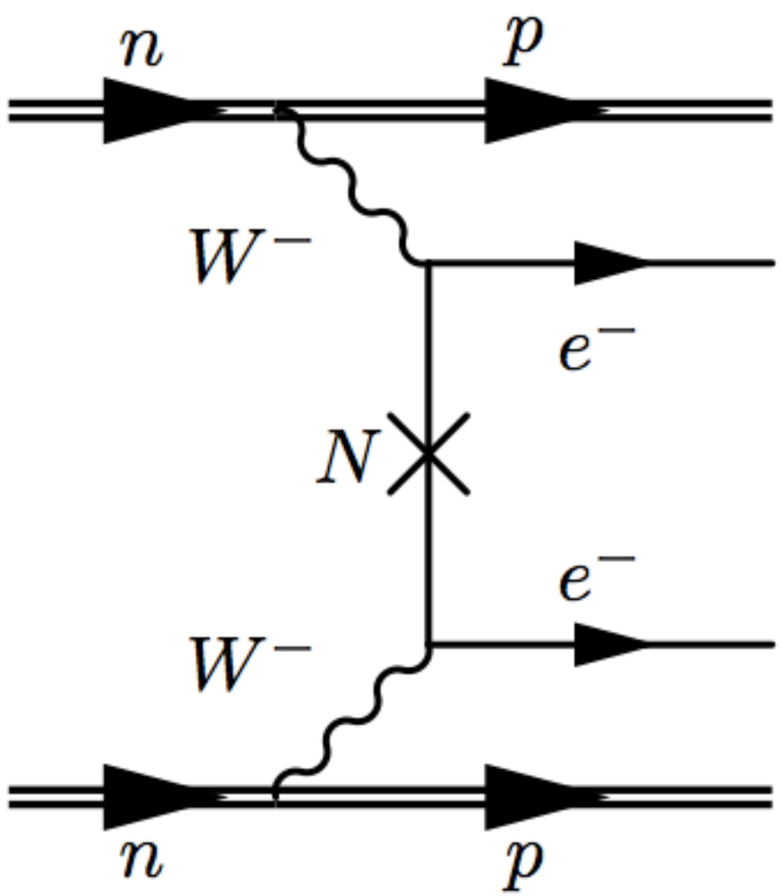
$$\Rightarrow \; m \equiv m_{\nu_4} \sim \mathcal{O}(100\,\mathrm{GeV})$$

Majorana mass free parameter

$m_D = y \cdot v \sim \mathcal{O}(100\,\mathrm{GeV}) \;\Rightarrow\; M_R$ must be small

Neutrinos and the 4th generation

Quantifying Majorana mass from $0\nu\beta\beta$:



contribution of heavy neutrino:

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\frac{m_p}{\langle m_N\rangle}\right)^2 C_{mm}^{NN}$$

with $\langle m_N\rangle^{-1} = U_{e4}^2 m^{-1}$

and using 2σ-fits from Lacker, Menzel: 1003.4532

$$0.021 \leq U_{e4} \leq 0.089$$

$\Rightarrow$ $m > \mathcal{O}(10^4\,\mathrm{GeV})$ to avoid signal in current experiments

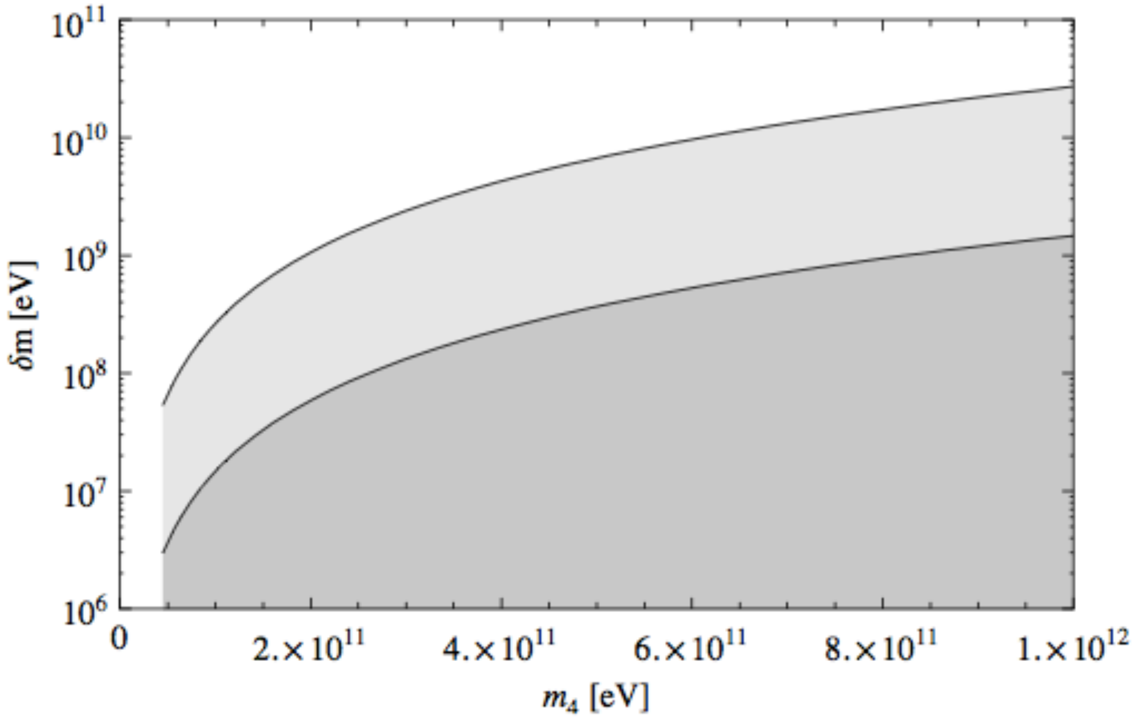
contributions from light neutrinos too small

$\Rightarrow$ M must cancel contribution of m

Neutrinos and the 4th generation

efficient cancellation $\Leftrightarrow$ $m \sim M$ $\Leftrightarrow$ M_R small

$$\Rightarrow \left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\frac{m_p}{\langle m \rangle} - \frac{m_p}{\langle M \rangle}\right)^2 C_{mm}^{NN}$$

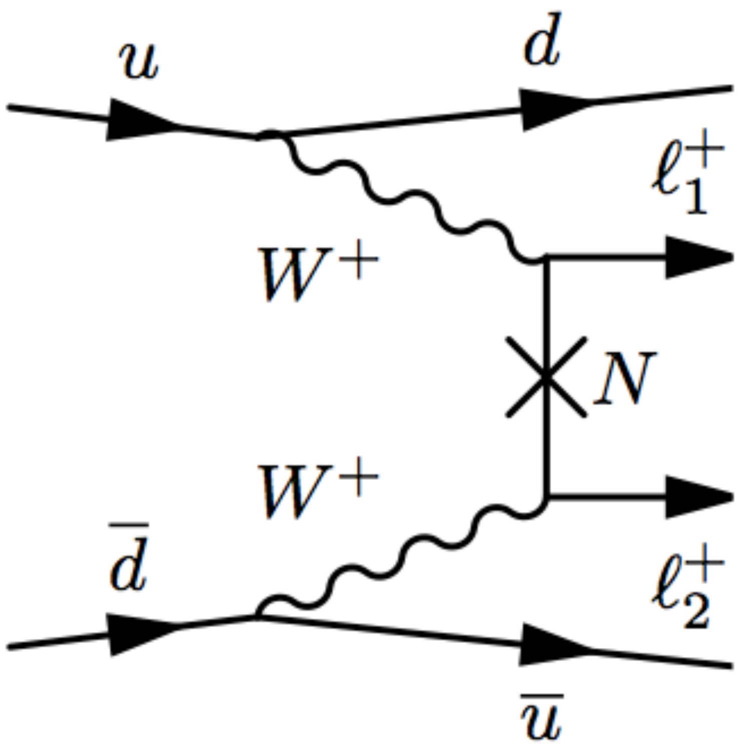


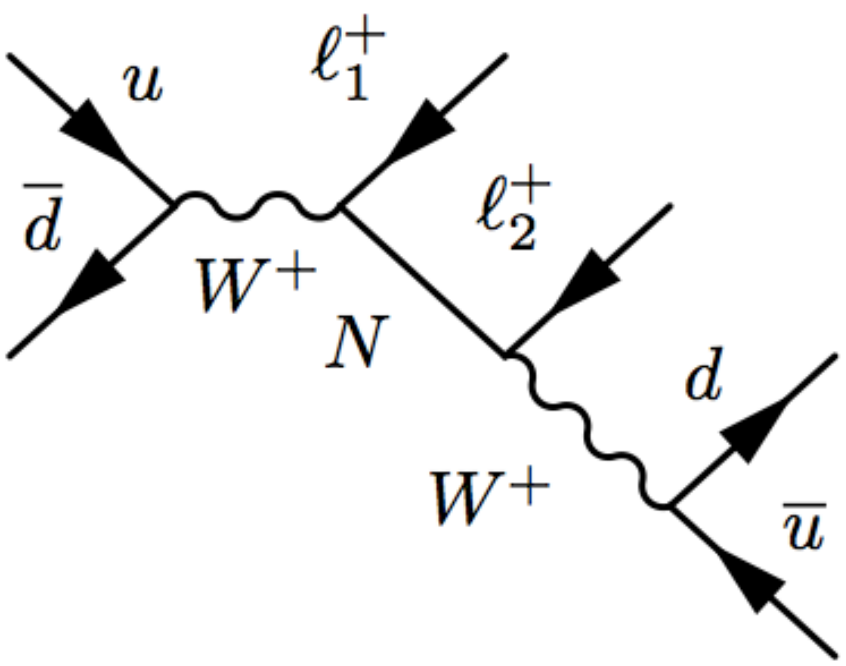
$$\Rightarrow \delta m \equiv M - m < \mathcal{O}(1\,\mathrm{GeV})$$

thus a fourth generation neutrino must be either a pure Dirac or a pseudo-Dirac particle

$\Rightarrow$ lepton number violating processes are allowed but suppressed

$$pp \to \ell_1^+ \ell_2^+ X$$





single heavy Majorana neutrino:

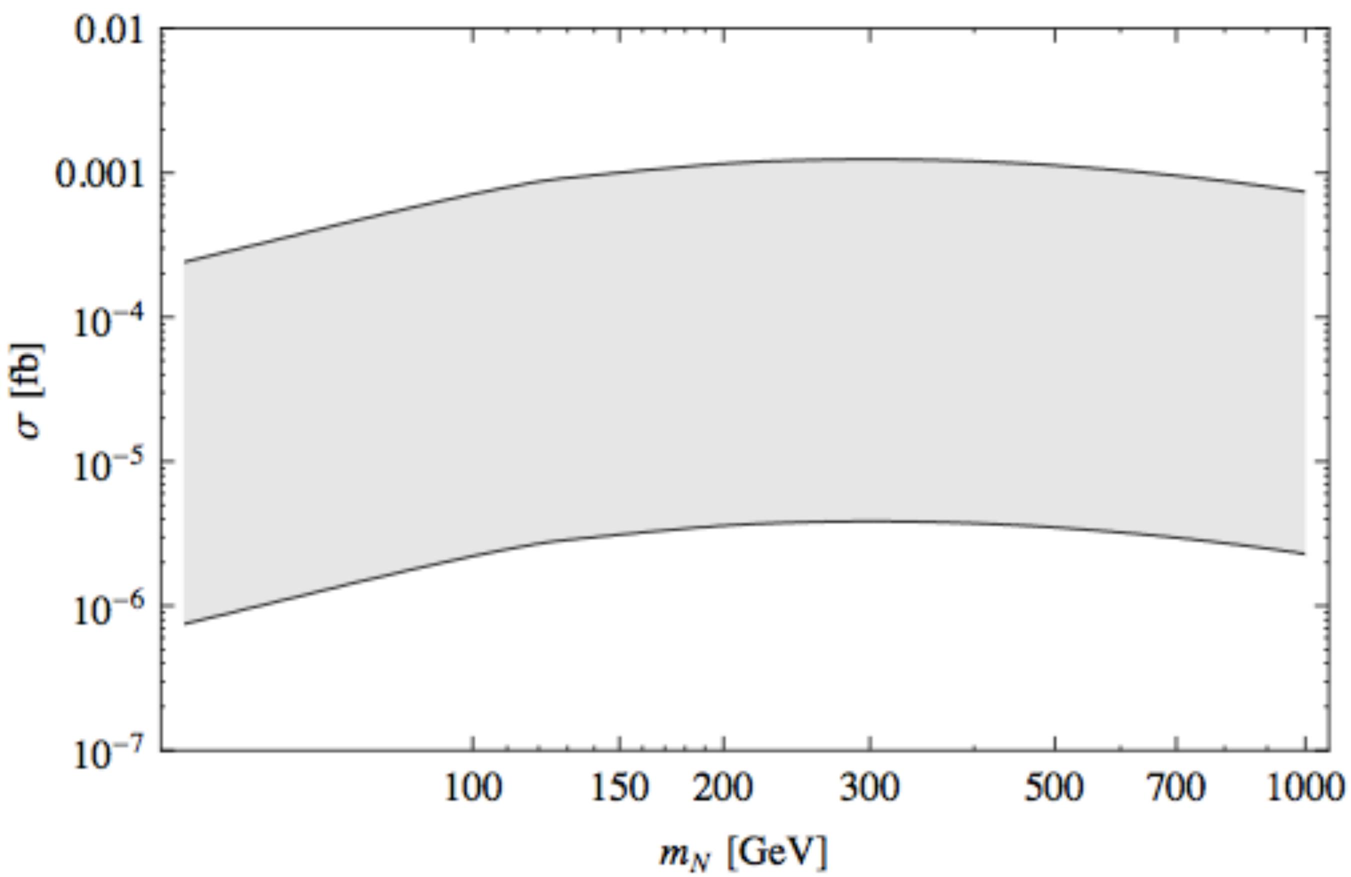
$$\sigma_{single}\left(pp \to \ell_1^+ \ell_2^+ X\right) = \frac{G_F^4 m_W^6}{8\pi^5}\left(1 - \frac{1}{2}\delta_{\ell_1 \ell_2}\right)\left|U_{\ell_1 N} U_{\ell_2 N}\right|^2 F\left(E, m_N\right)$$

Ali, Eur. Phys. J. C21. 123 (2001)

Δ_{pD} reduces like-sign dilepon production drastically

like-sign dielectron production

Majorana neutrino
(w/o $0\nu\beta\beta$ constraints)

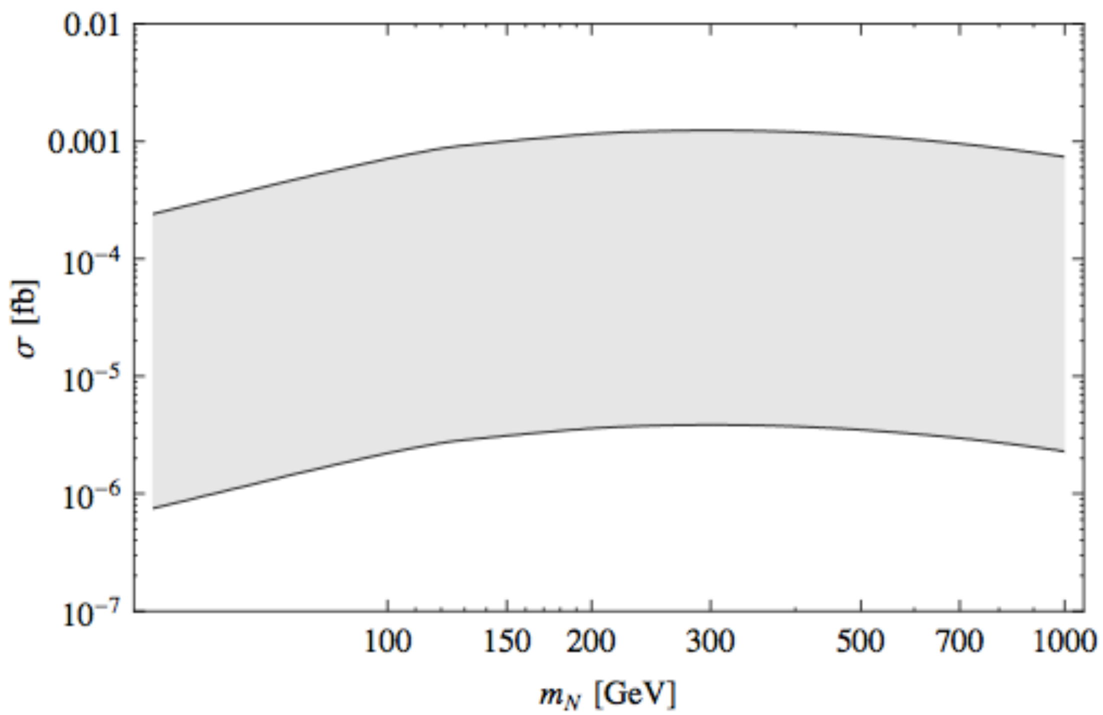


Neutrinos and the 4th generation

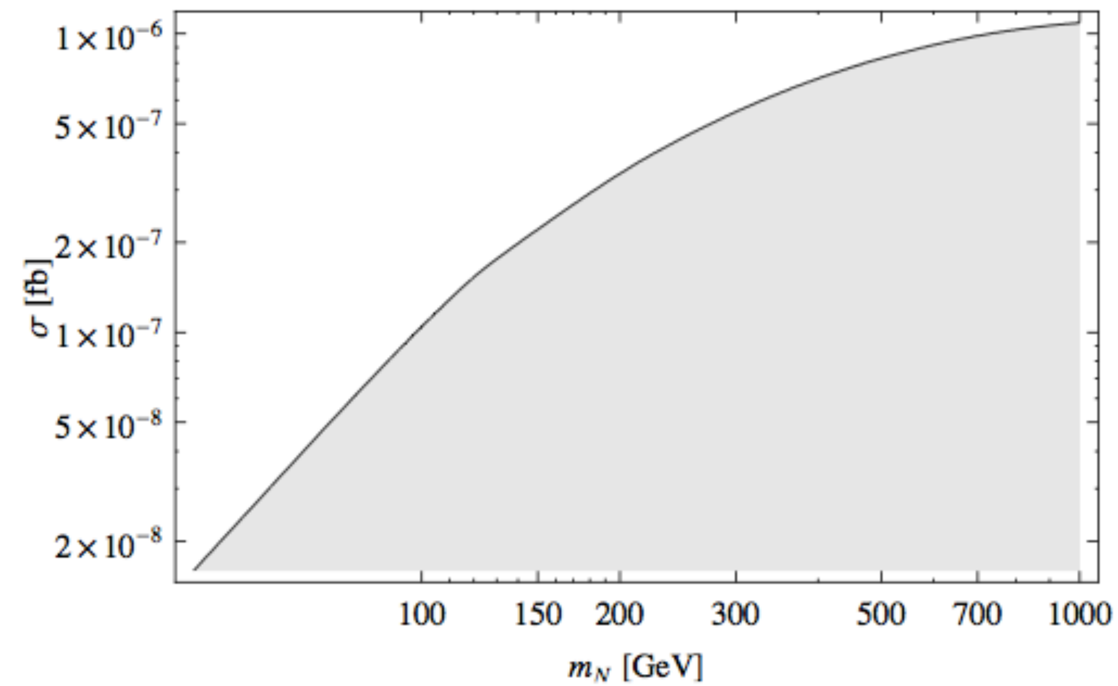
Δ_{pD} reduces like-sign dilepon production drastically

like-sign dielectron production

Majorana neutrino
(w/o $0\nu\beta\beta$ constraints)



pseudo-Dirac neutrino
(with $0\nu\beta\beta$ constraints)



$\Rightarrow$ observation from $0\nu\beta\beta$ gives hard constraints on collider experiments

Neutrinos and the 4th generation

Our universe today:

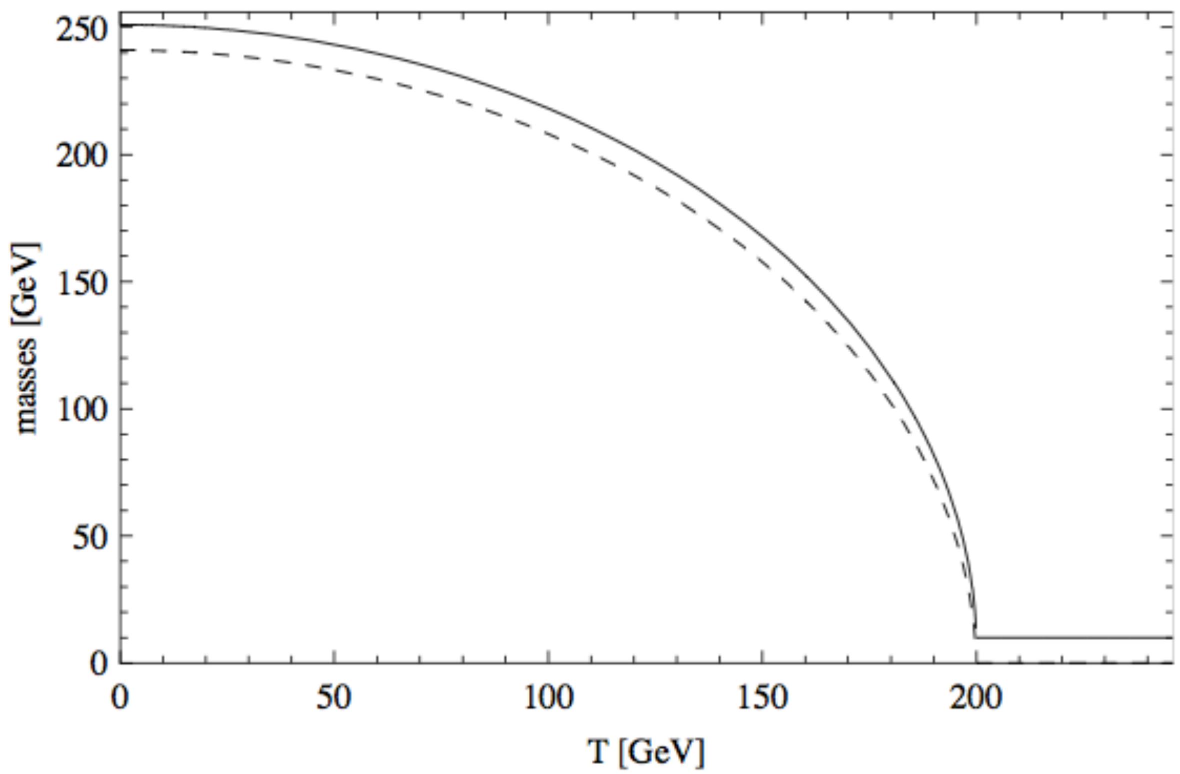
number of baryons $\neq$ number of antibaryons

$$Y_{\Delta B} \equiv \frac{n_B - n_{\overline{B}}}{s} = (8.75 \pm .23) \cdot 10^{-11}$$

numerous viable models to explain this value
($\rightarrow$ Baryogenesis/Leptogenesis scenarios)
most of them create this asymmetry at high temperatures $\sim T_{GUT}$
The fourth generation neutrino is too light/freezes out too early to actively produce this asymmetry, but might erase any pre-existing asymmetry in the early universe due to their lepton number violating interactions.

Neutrinos and the 4th generation

above the electroweak phase transition the Higgs-vev vanishes and the two mass eigenstates decouple



$$m \xrightarrow{T>T_{EW}} 0$$

$$M \xrightarrow{T>T_{EW}} M_R$$

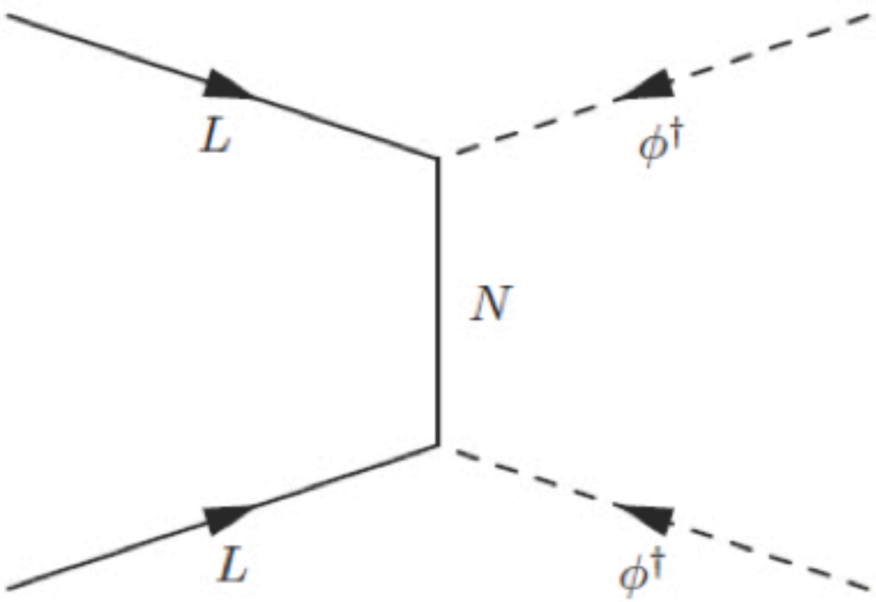
the mass splitting is unaffected:

$$\delta m = M_R = \text{const.}$$

$\Rightarrow$ above the EW phase transition a heavy pseudo-Dirac and a light sterile neutrino with mass δm are indistinguishable
$\Rightarrow$ following discussion not solely applies to fourth generation neutrinos

Neutrinos and the 4th generation

We will not specify the mechanism of baryogenesis
$\rightarrow$ assume pre-existing asymmetry of the right amount at T_{GUT}.
LNV processes mediated by additional neutrino species may dilute such asymmetry



$$\Delta L = 2$$

$$\langle \sigma |v| \rangle \sim \frac{\delta m^2}{(T^2 + \delta m^2)^2} = \frac{1}{\delta m^2} \frac{z^4}{(1+z^2)^2}$$

with $z \equiv \delta m / T$

Such processes are efficient in thermal equilibrium

Neutrinos and the 4th generation

The strongest constraint is obtained by demanding that no washout should occur at all.
$\Rightarrow$ Process should not reach equilibrium while sphaleron transitions are effective

$$\Rightarrow \; H(T) > \Gamma(T) \text{ for } T_{EW} < T < T_{GUT}$$

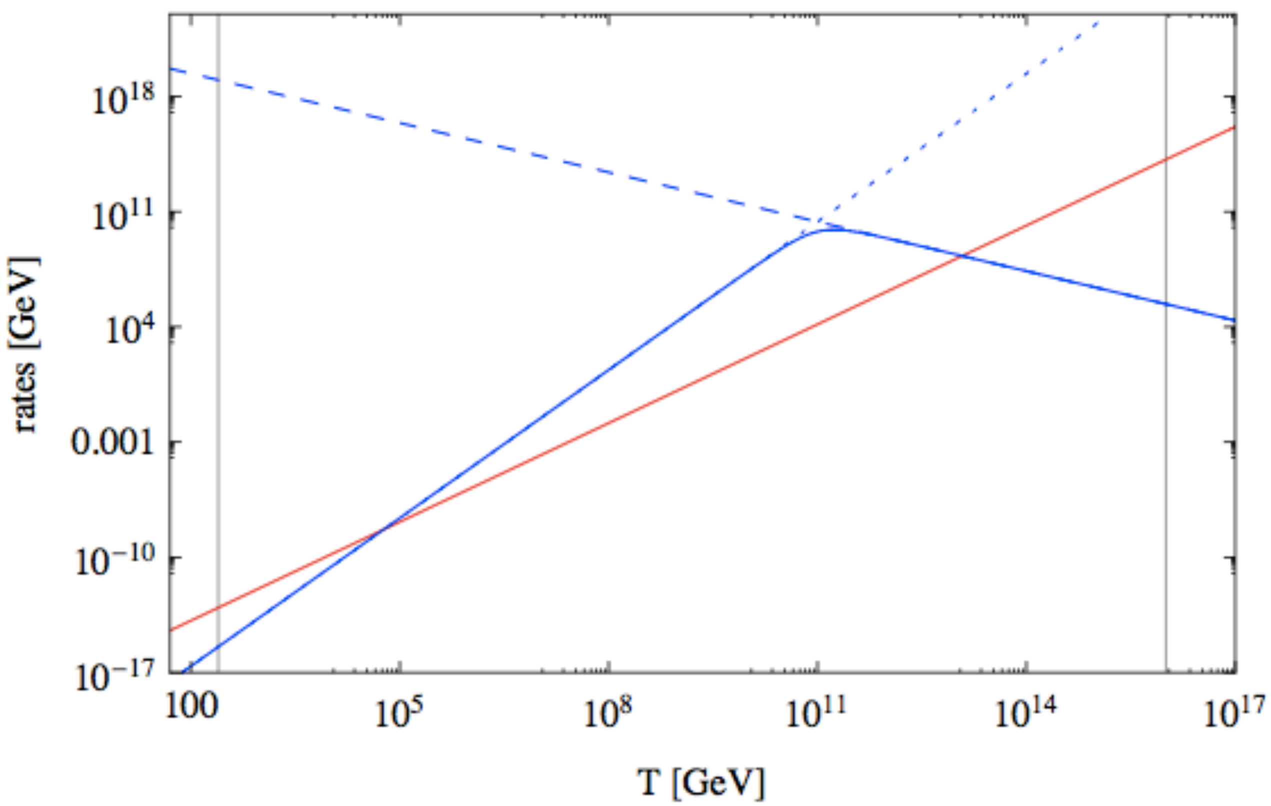
$$H(T) = \sqrt{\frac{8\pi^3 g_*}{90}} \frac{T^2}{m_{Pl}} \qquad \Gamma(T) \sim n_\phi \langle \sigma |v| \rangle \text{ with } n_\phi \approx 2\zeta(3) T^3/\pi^2$$

$$\Rightarrow \left(\frac{\delta m}{10\,\mathrm{keV}} \right)^2 < 1 \times \left(\frac{T}{246\,\mathrm{GeV}} \right)^3$$

Neutrinos and the 4th generation

When the scattering rate exceeds the expansion rate while sphaleron transitions are effective LNF depletes the existing asymmetry

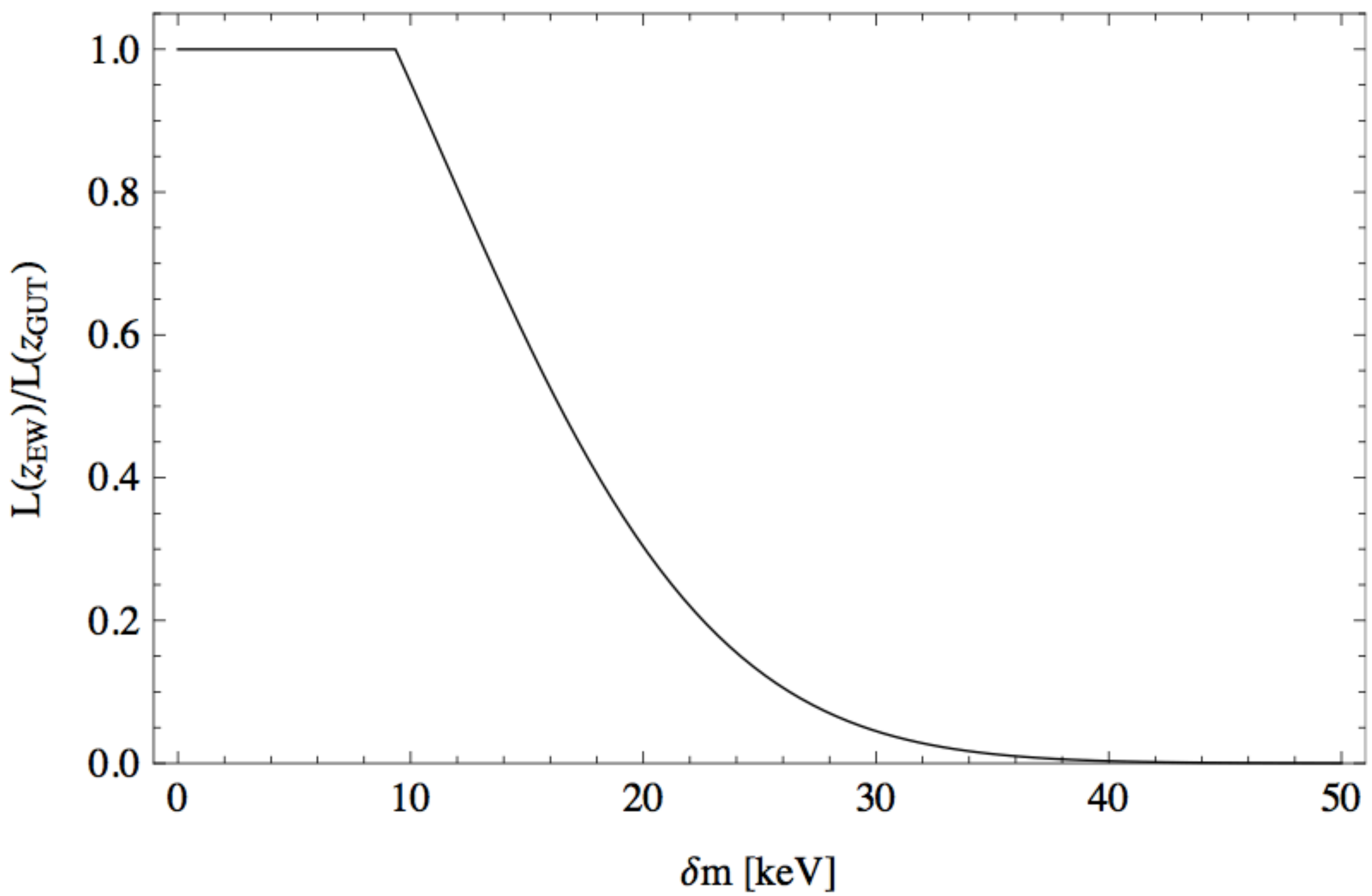
$$\ln\left(\frac{L(z_{EW})}{L(z_{GUT})}\right) = -\frac{1}{H(z=1)}\int_{z_{GUT}}^{z_{EW}} dz'\, z' n_\gamma \langle \sigma\,|\,v\,|\rangle (z')$$



careful treatment of integration limits crucial

Neutrinos and the 4th generation

combined washout for small neutrino masses

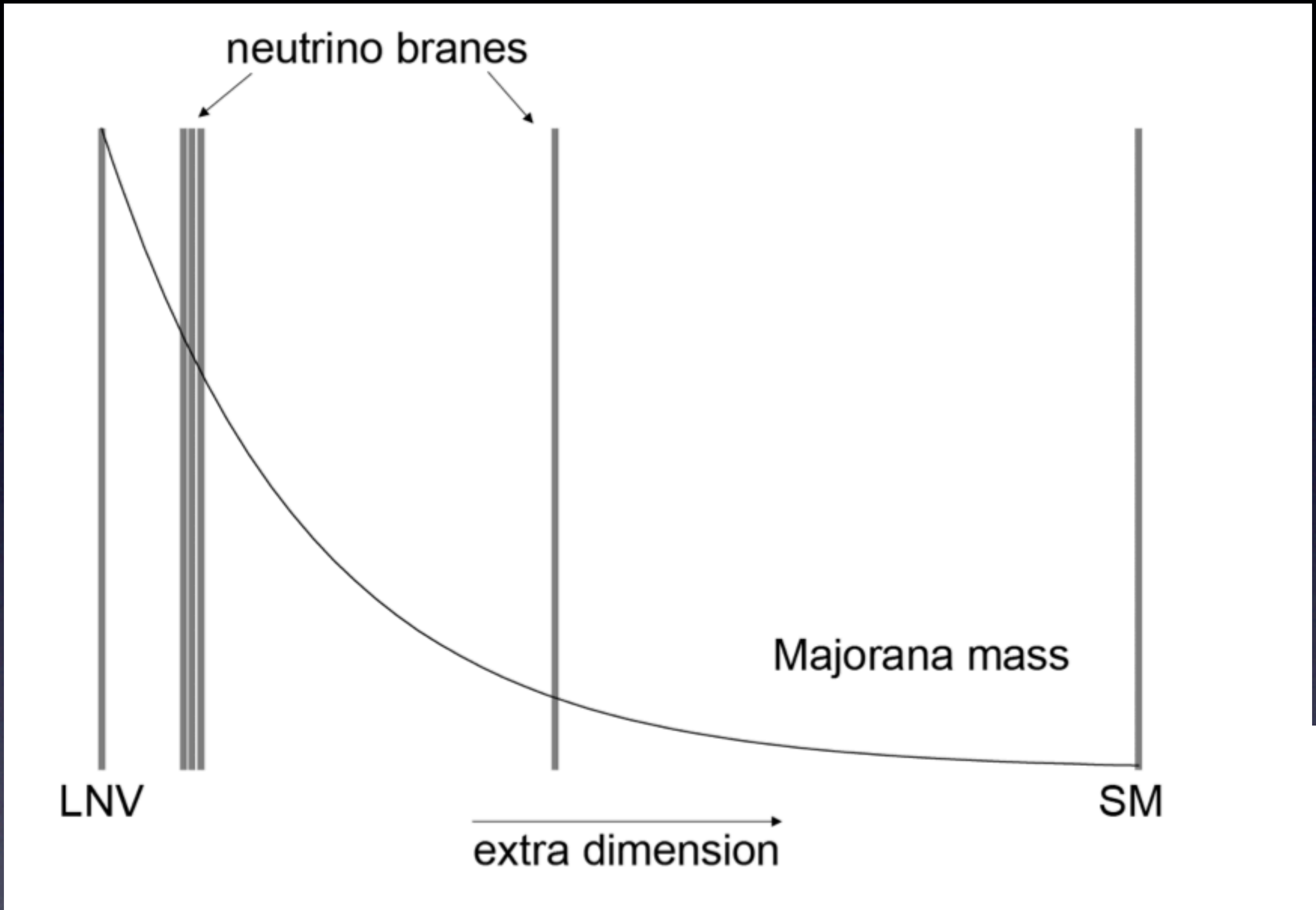


Amount of allowed washout depends on capability of model

constrained to $< 10\,\mathrm{keV}$

A simple extra-dimensional realization

Breaking of lepton number on a distant brane



See e.g. [Arkani-Hamed, Dvali, Dimopoulos, March-Russell, 1998]

$$< \chi > \propto e^{-mr}$$

$$M_{Ri} = \Lambda_{LNV} e^{-\alpha_i}$$

i	α_i	m_i [GeV]	M_i [GeV]
4	~ 43.7	246	247
3	9.6	$5.0 \cdot 10^{-11}$	$6.7 \cdot 10^{14}$
2	8.7	$9.1 \cdot 10^{-12}$	$1.7 \cdot 10^{15}$
1	$\lesssim 7.9$	$\lesssim 4.1 \cdot 10^{-12}$	$\gtrsim 3.7 \cdot 10^{15}$

TABLE II: Localizations of the neutrino branes in the extradimensional bulk and corresponding mass eigenvalues for $\Lambda_{LNV} = 10^{19}$ GeV.

Conclusions

- Fourth generation neutrinos are heavier
- → bound from double beta decay
- → bound from washout of baryon asymmetry
- 4G ν's are Dirac or Pseudo-Dirac
- Simple realization: Extra-dimensional breaking of lepton number
- Also: radiative ν masses for 3G due to 4th & 5th G neutrinos (see Talk by A. Aparici)