Focus week on Neutrino Mass, 17-21 March, IPMU, Tokyo

Leptogenesis neutrino mass bounds

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Cosmological puzzles

1. Matter - antimatter asymmetry
2. Dark matter
3. Accelerating Universe
4. Inflation

❾ clash between the SM and ☹CDM !

Matter-antimatter asymmetry

- Symmetric Universe with matter- anti matter domains ?

  Excluded by CMB + cosmic rays

) $\eta_B^{CMB} = (6.3 \pm 0.3) \times 10^{-10} >> \eta_B$ -

- Pre-existing ? It conflicts with inflation ! (Dolgov '97)

) dynamical generation (baryogenesis)

(Sakharov '67)

- A Standard Model Solution ? η_B^{SM} ¿ η_B^{CMB} : too low !

New Physics is needed!

Models of Baryogenesis

- From phase transitions:
  - -Electroweak Baryogenesis:
    - * in the SM
    - * in the MSSM
    - * ……………..
- Affleck-Dine:
  - at preheating
  - Q-balls
  - ……….
- From Black Hole evaporation
- Spontaneous Baryogenesis
- ……………………………………
- From heavy particle decays:
  - GUT Baryogenesis
  - LEPTOGENESIS

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

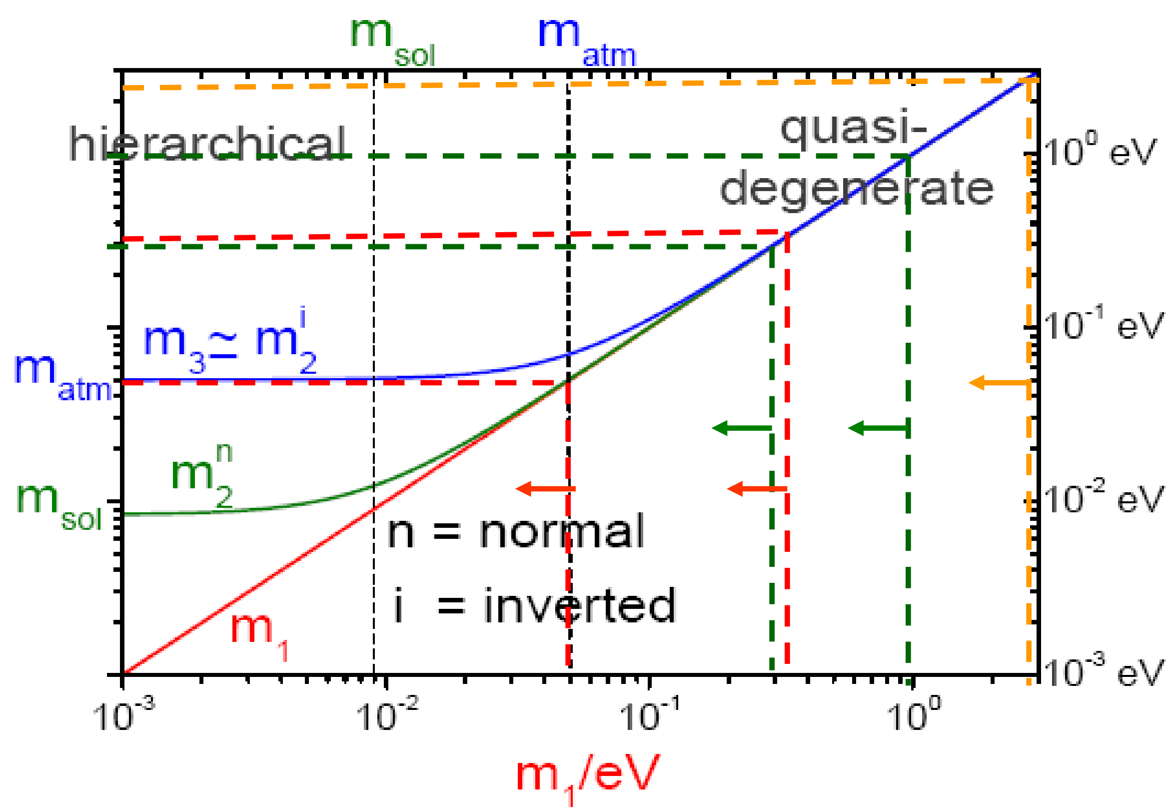
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

$$m_2^2 - m_1^2 = \Delta m^2_{\rm sol} \text{ or } \Delta m^2_{\rm atm} \qquad m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} \simeq 0.009\,{\rm eV}$$

Tritium ♌ decay : $m_e < 2.3$ eV
(Mainz 95% CL)

♌♌0■ : $m_{♌♌} < 0.3 – 1.0$ eV
(Heidelberg-Moscow 90% CL, similar result by CUORICINO)

using the flat prior ($✦_0$=1):
CMB+LSS : 🌢 $m_i < 0.94$ eV
(WMAP3+SDSS)
CMB+LSS + Ly♋ : 🌢 $m_i < 0.17$ eV
(Seljak et al.)



Minimal RH neutrino implementation

SM + RH neutrinos with Yukawa coupling and Majorana mass term:

$$\mathcal{L}_Y = -\bar{l}_L \, \phi \, h \, \nu_R - \frac{1}{2} \overline{\nu_R^c} M_R \nu_R + h.c.$$

After spontaneous symmetry breaking $\Rightarrow m_D = v\,h \quad (v \equiv \langle \phi_0 \rangle)$

$$\mathcal{L}^{\nu}_{\text{mass}} = -\frac{1}{2} \left[(\bar{\nu}^c_L, \bar{\nu}_R) \begin{pmatrix} \cancel{m_T} & {m_D}^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix} \right] + h.c.$$

3 limiting cases :

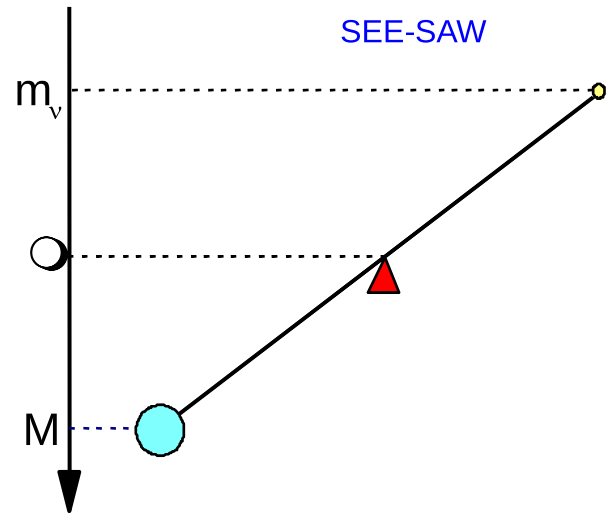
- pure Dirac: $M_R = 0$
- pseudo-Dirac : $M_R << m_D$
- see-saw limit: $M_R >> m_D$

See-saw mechanism

3 light LH neutrinos: $m_\nu = -m_D \frac{1}{M_R} m_D^T$

N❐2 heavy RH neutrinos: $N_1, N_2, \ldots$

$$max[\lambda^i_{m_D}] \equiv \mu \ll M_1 \leq M_2 \leq \ldots$$



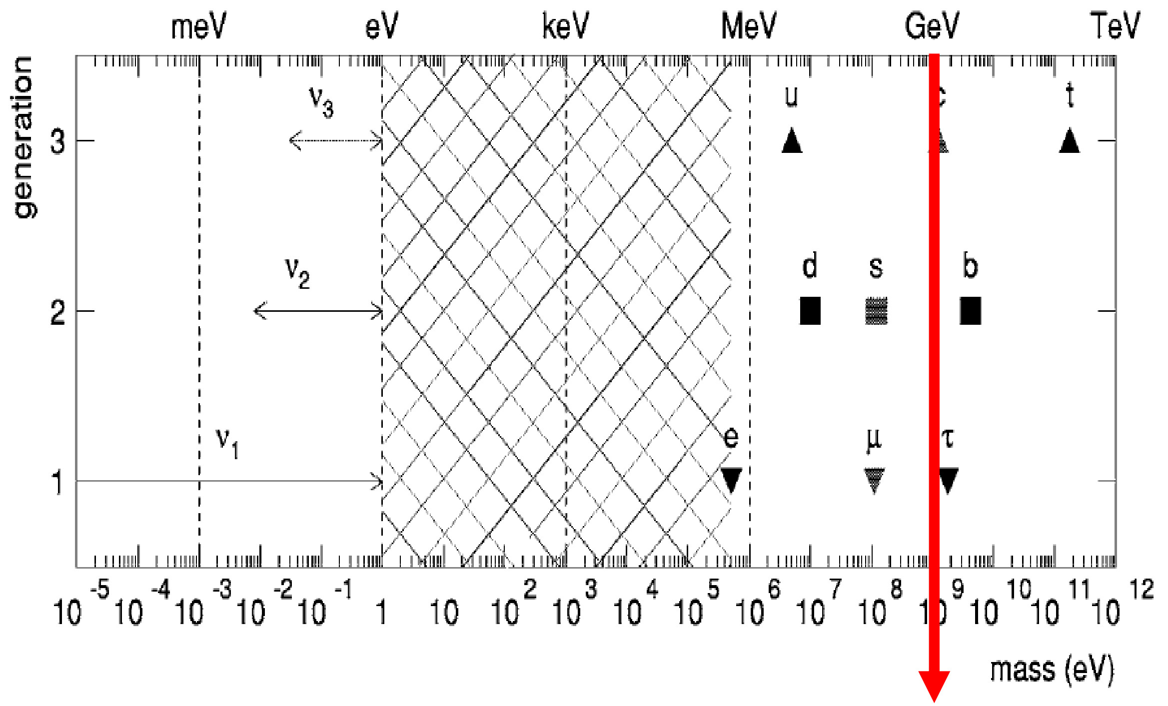
- All eigenstates (light and heavy neutrinos) are Majorana neutrinos (self-conjugate particles)

$$(N = \nu_R + \nu_R^c \;,\; \nu = \nu_L + \nu_L^c) \quad \Rightarrow \quad \beta\beta 0\nu \text{ decay}$$

Typical 1 generation example:

$$\mu \sim M_{\rm EW} \sim 100\,\text{GeV}\,,\; m_\nu \simeq m_{\rm atm} \sim 0.1\,\text{eV}$$
$$\Rightarrow M_R \sim 10^{14}\,\text{GeV} \lesssim M_{\rm GUT}$$

- the `see-saw' pivot scale ❍ is then an important quantity to understand the role of RH neutrinos in cosmology



❍$_*$ ~ 1 GeV

❍> ❍* ❾ high pivot see-saw scale ❾ `heavy’ RH neutrinos

❍< ❍* ❾ low pivot see-saw scale ❾ `light’ RH neutrinos

The see-saw orthogonal matrix

(Casas,Ibarra'01)

$$m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$$

$$\boxed{m_D} = \boxed{U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}} \qquad \begin{pmatrix} U^\dagger U & = & I \\ U^\dagger m_\nu U^\star & = & -D_m \end{pmatrix}$$

$\uparrow$ *theory* $\qquad$ $\uparrow$ *"observables"*

- parameter counting: 6 + 3 + 6 + 3 = 18
  - experiments $\Rightarrow$ information on the 9 'low energy' parameters in $m_\nu = -U\, D_m\, U^T$:

- the 9 parameters in Ω and in M_i escape conventional investigation: the dark side !

$$\Omega(\omega_{21}, \omega_{31}, \omega_{32}) = R_{12}(\omega_{21})\ R_{13}(\omega_{31})\ R_{23}(\omega_{32})\ ,$$

where

$$R_{12} = \begin{pmatrix} \sqrt{1-\omega_{21}^2} & -\omega_{21} & 0 \\ \omega_{21} & \sqrt{1-\omega_{21}^2} & 0 \\ 0 & 0 & 1 \end{pmatrix},\ R_{13} = \begin{pmatrix} \sqrt{1-\omega_{31}^2} & 0 & -\omega_{31} \\ 0 & 1 & 0 \\ \omega_{31} & 0 & \sqrt{1-\omega_{31}^2} \end{pmatrix},\ R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{1-\omega_{32}^2} & -\omega_{32} \\ 0 & \omega_{32} & \sqrt{1-\omega_{32}^2} \end{pmatrix}$$

‘Vanilla’ Leptogenesis

- **simple see-saw mechanism**

SM + RH neutrinos with Yukawa coupling and Majorana mass term:

$$\mathcal{L}_Y = -\bar{l}_L\,\phi\,h\,\nu_R - \frac{1}{2}\,\overline{\nu_R^c}\,M_R\,\nu_R + h.c.$$

❾

$$m_\nu = -m_D\,\frac{1}{M_R}\,m_D^T$$

- orthogonal parametrization (Casas,Ibarra ‘01) : $(M_1 \ll M_2 \ll M_3)$

$$m_D = U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} \qquad \begin{pmatrix} U^\dagger U & = & I \\ U^\dagger\, m_\nu\, U^\star & = & -D_m \end{pmatrix}$$

$$\Omega(\omega_{21},\omega_{31},\omega_{32}) = R_{12}(\omega_{21})\;R_{13}(\omega_{31})\;R_{23}(\omega_{32})\;,$$

where

$$R_{12} = \begin{pmatrix} \sqrt{1-\omega_{21}^2} & -\omega_{21} & 0 \\ \omega_{21} & \sqrt{1-\omega_{21}^2} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad R_{13} = \begin{pmatrix} \sqrt{1-\omega_{31}^2} & 0 & -\omega_{31} \\ 0 & 1 & 0 \\ \omega_{31} & 0 & \sqrt{1-\omega_{31}^2} \end{pmatrix}, \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{1-\omega_{32}^2} & -\omega_{32} \\ 0 & \omega_{32} & \sqrt{1-\omega_{32}^2} \end{pmatrix}$$

- **Unflavoured leptogenesis** (Fukugita,Yanagida '86)

m_D complex in general ❾ natural source of CP violation

$$N_i \xrightarrow{\Gamma} l\,H^\dagger \qquad\qquad N_i \xrightarrow{\bar{\Gamma}} \bar{l}\,H$$

Total CP asymmetries	$\varepsilon_i \equiv -\frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}$

If $\varepsilon_i \neq 0$ ❾ a **lepton asymmetry** is generated from N_i decays and partly converted into a **baryon asymmetry** by sphaleron processes

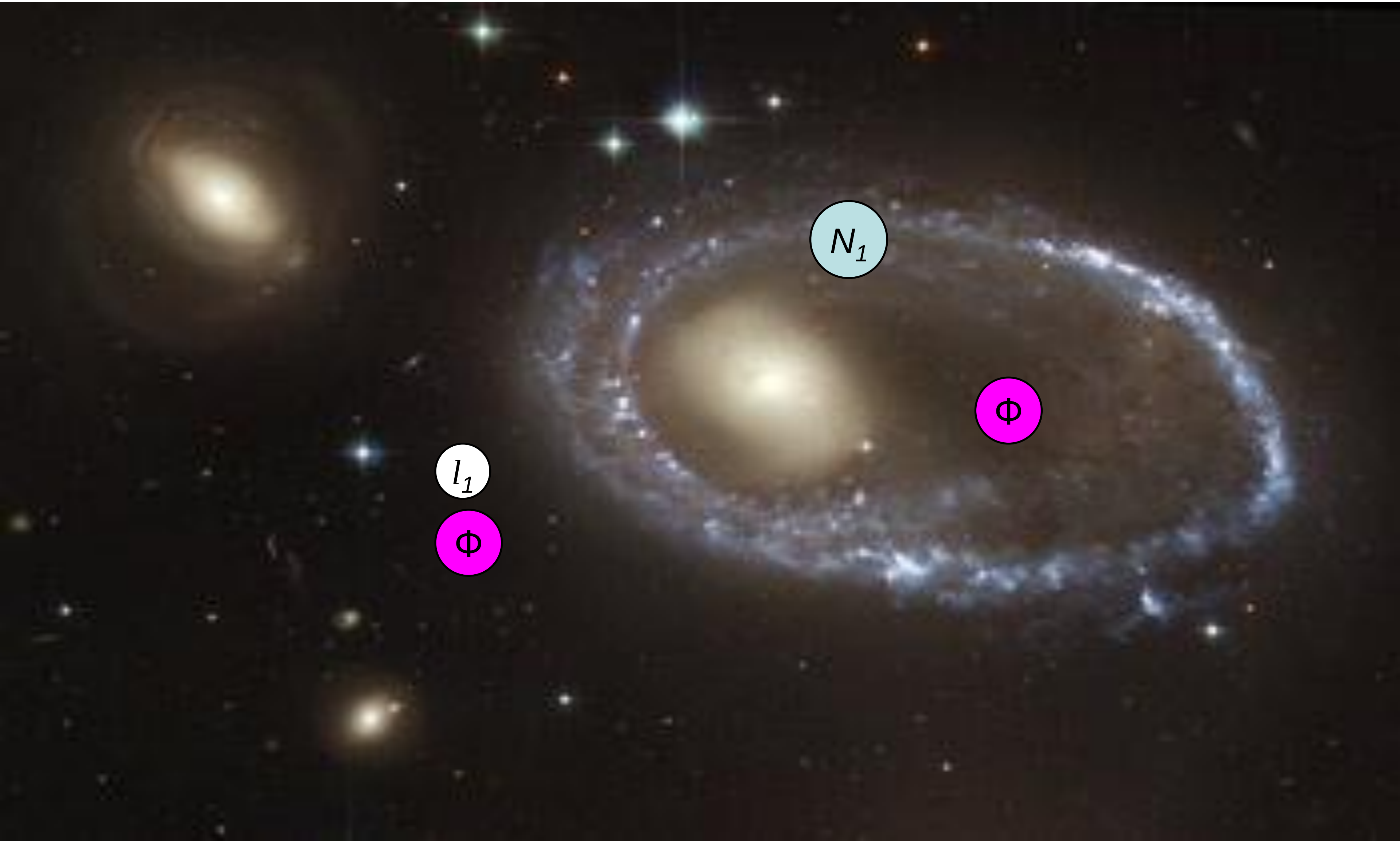
if T_{reh} ♦ 100 GeV (Kuzmin,Rubakov,Shaposhnikov, '85)

$$N_{B-L}^{\mathrm{fin}} = \sum_i \varepsilon_i\, \kappa_i^{\mathrm{fin}} \Rightarrow \eta_B = a_{\mathrm{sph}} \frac{N_{B-L}^{\mathrm{fin}}}{N_\gamma^{\mathrm{rec}}}$$

efficiency factors ✇ # of N_i decaying out-of-equilibrium

(Blanchet, PDB '06)

NO FLAVOR



- **Semi-hierarchical heavy neutrino spectrum :**

$$M_3 \simeq M_2 \gtrsim 3\, M_1$$

- **N_2 does not couple with N_3:**

$$(m_D^\dagger\, m_D)_{23} = 0 \;\Rightarrow |\varepsilon_{2,3}| \ll |\varepsilon_1|$$

❾ **1) N_1-dominated scenario :**

$$\Rightarrow \quad N_{B-L}^{\rm fin} = \sum_i \varepsilon_i\, \kappa_i^{\rm fin} \simeq \varepsilon_1\, \kappa_1^{\rm fin}$$

It does not depend on U!

2) CP asymmetry upper bound

(Davidson, Ibarra '02; Buchmüller,PDB,Plümacher'03;Hambye et al '04;PDB'05)

$$\varepsilon_1 \simeq \overline{\varepsilon}(m_1, M_1, \Omega) \equiv \overline{\varepsilon}(M_1)\, \frac{m_{\rm atm}}{m_1+m_3}\, f(m_1, \widetilde{m}_1)\, \sin\delta_L(\Omega)$$

$$\overline{\varepsilon}(M_1) \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,{\rm GeV}}\right), \quad \widetilde{m}_1 \equiv \frac{(m_D^\dagger\, m_D)_{11}}{M_1} \qquad 0 \le f(m_1, \widetilde{m}_1) \le 1$$

Efficiency factor

decay parameter

$$K_1 \equiv \frac{\Gamma(N_1 \to l\Phi^\dagger)|_{T\to 0}}{H(T=M_1)}$$

$$\frac{dN_{N_1}}{dz} = -D_1\,(N_{N_1} - N_{N_1}^{\rm eq})$$

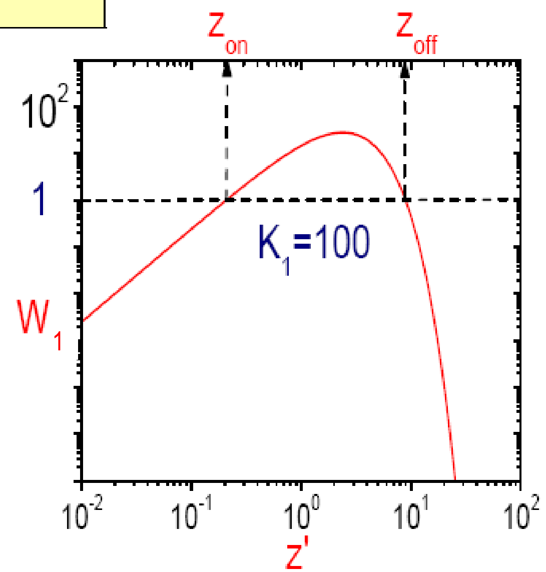
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\,\frac{dN_{N_1}}{dz} - W_1\,N_{B-L}$$

$$z \equiv \frac{M_1}{T}$$

$$D_1 = \frac{\Gamma_{D,1}}{H\,z} = K_1\,z\left\langle\frac{1}{\gamma}\right\rangle, \quad W_1 \propto D_1 \propto K_1$$

$$N_{B-L}(z;K_1,z_{\rm in}) = N_{B-L}^{\rm in}\,e^{-\int_{z_{\rm in}}^{z} dz'\,W_1(z')} + \varepsilon_1\,\kappa_1(z)$$

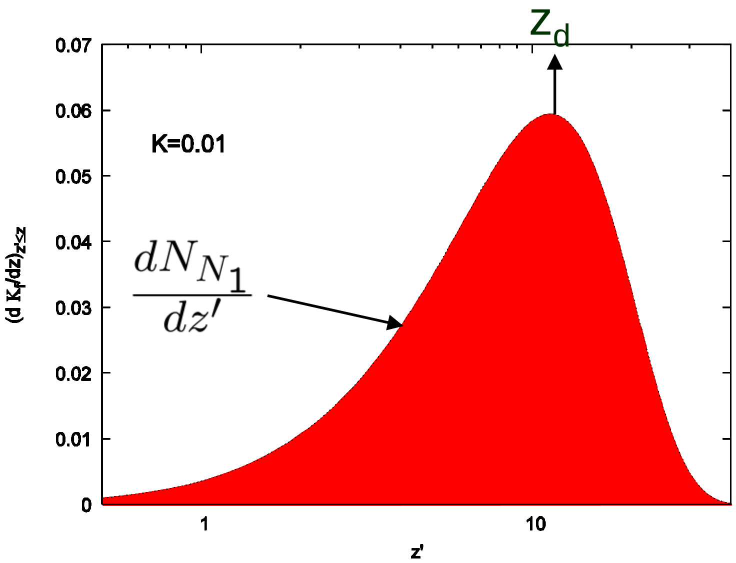
$$\kappa_1(z;K_1,z_{\rm in}) = -\int_{z_{\rm in}}^{z} dz'\left[\frac{dN_{N_1}}{dz'}\right]e^{-\int_{z'}^{z} dz''\,W_1(z'')}$$



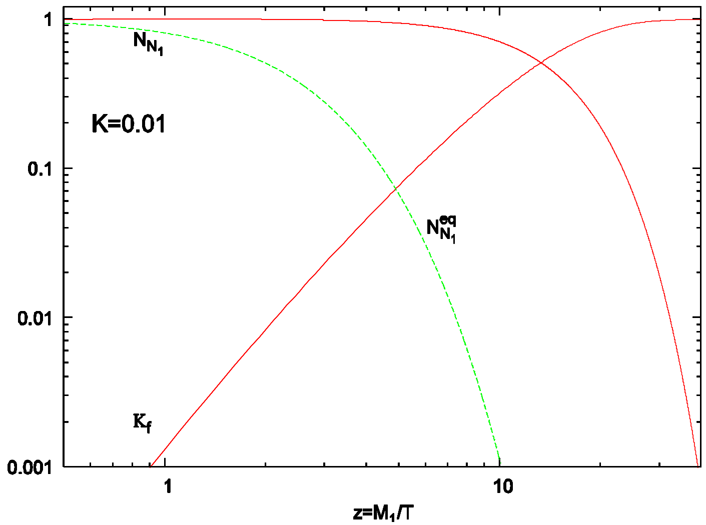
- Weak wash-out regime for $K_1 \lesssim 1$ (out-of-equilibrium picture recovered for $K_1 \to 0$)
- Strong wash-out regime for $K_1 \gtrsim 1$

$z\acute{}\ M_1/T$ $K_1\acute{}\ t_U(T=M_1)/\tau_1$

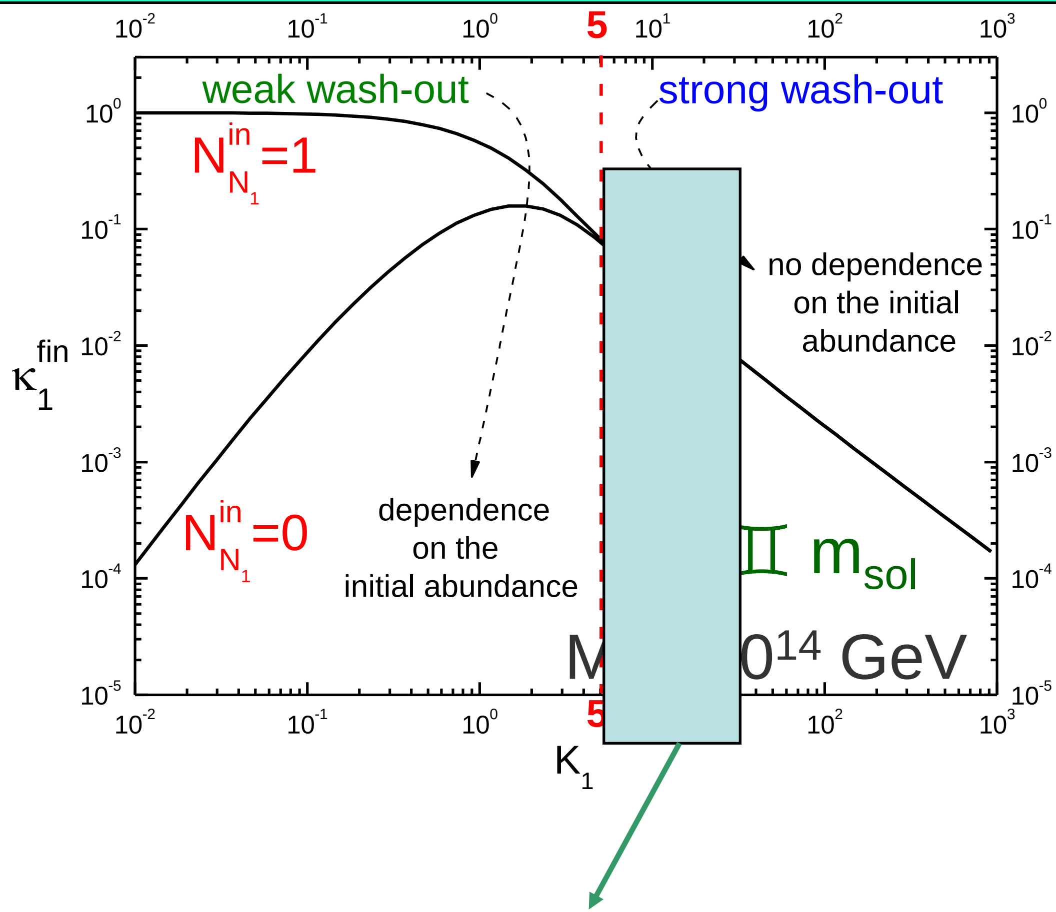
WEAK WASH-OUT



$$\left.\frac{d\kappa_1}{dz'}\right|_{z'\leq z}$$



Dependence on the initial conditions



$$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$$

Neutrino mixing data favor the strong wash-out regime !

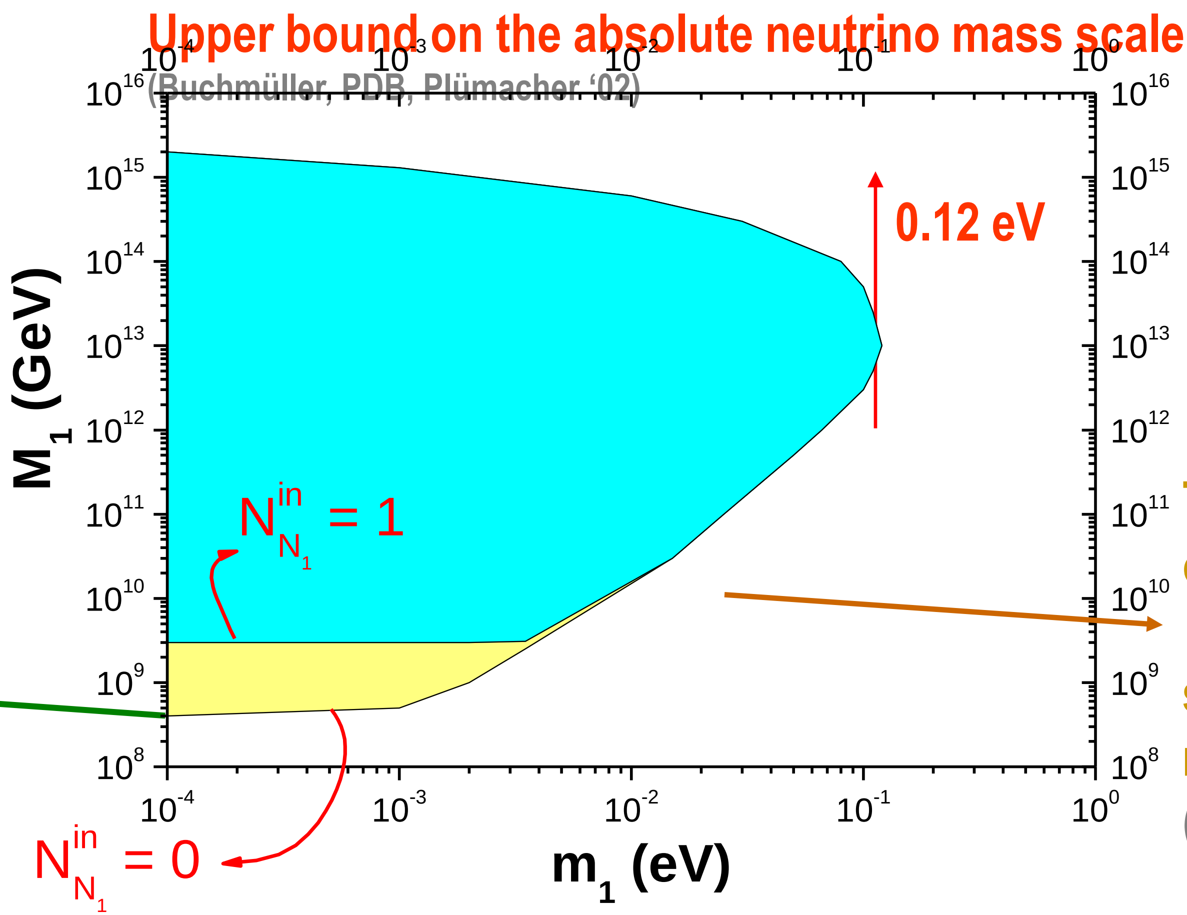
Neutrino mass bounds

$\sim 10^{-6}\,(M_1 / 10^{10}\ \mathrm{GeV})$

$$\eta_B^{\max}(m_1, \tilde{m}_1, M_1) \simeq 10^{-2}\,\bar{\varepsilon}_1(M_1)\,\frac{m_{\rm atm}}{m_3 + m_1}\,f(m_1, \tilde{m}_1)\,\kappa_{\rm f}(\tilde{m}_1)\,e^{-\frac{M_1}{10^{14}\,\mathrm{GeV}}\,\frac{\sum_i m_i^2}{m_{\rm atm}^2}} \geq \eta_B^{CMB}$$

Lower bound on M_1

(Davidson, Ibarra '02; Buchmüller, PDB, Plümacher '02)



3×10^9 GeV

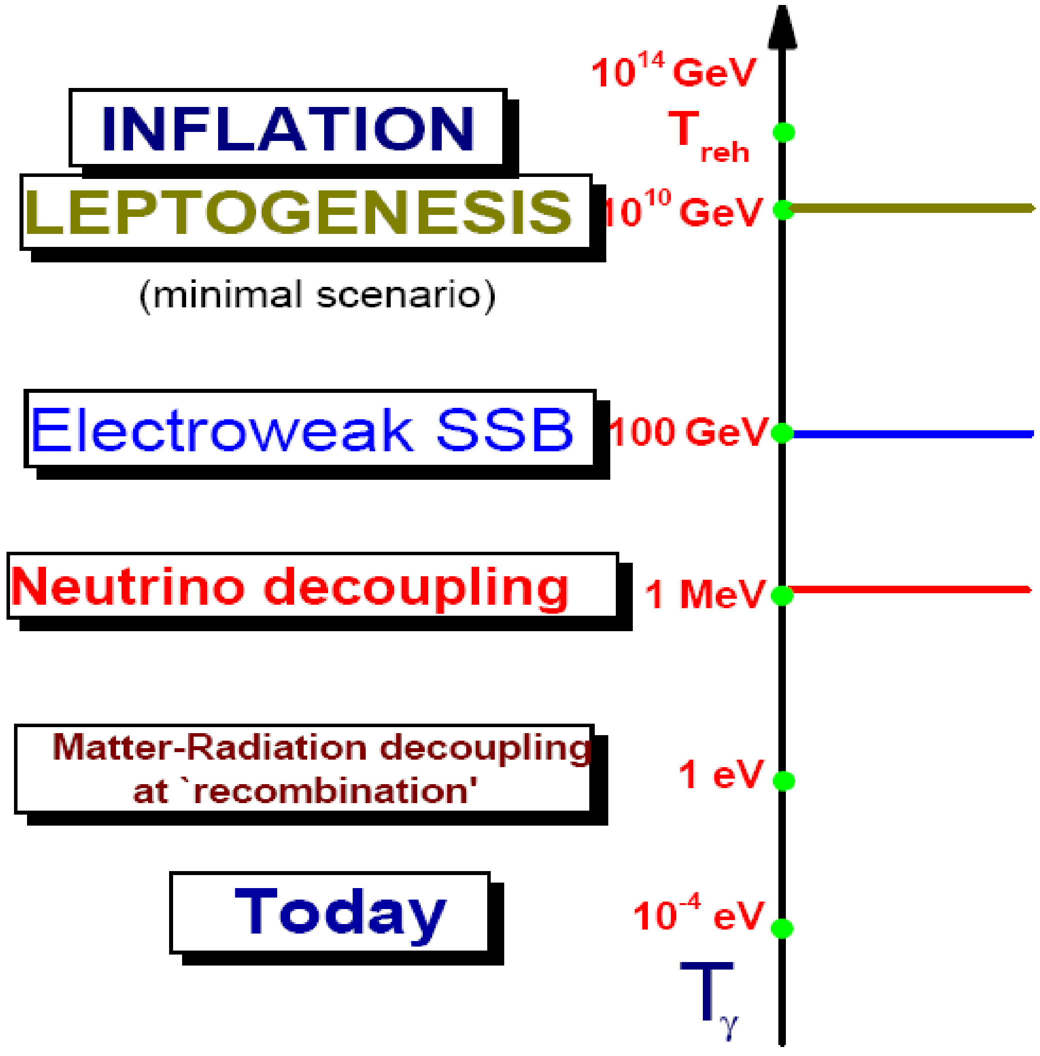
The lower bounds on M_1 and T_{reh} becomes more stringent when m_1 increases

(PDB'04)

Lower bound on T_{reh} : $T_{reh} \gtrsim 1.5 \times 10^9$ GeV

(Buchmüller, PDB, Plümacher '04; Giudice,Notari,Raidal,Riotto,Strumia'04)

A very hot Universe for leptogenesis ?



Beyond Vanilla

$$N_{B-L}^{\rm fin} = \sum_{i,\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}^{\rm fin}$$

i: heavy neutrino flavor index

α: lepton flavor index

$$x_i \equiv \frac{M_i^2}{M_1^2}, \quad N_{\rm fl} = 1, 2$$

CP asmmetry enhancement for degenerate RH neutrinos

$\xi(x_2 \gtrsim 2) \simeq 1$ Vanilla leptogenesis

$$\xi(\sqrt{x_2} - 1 \ll 1) \lesssim \xi_{\rm res} \simeq 1/\overline{\varepsilon}$$

$$N_{B-L}^{\rm fin} \simeq N_{\rm fl}\, [\xi(x_2)\, \overline{\varepsilon}(m_1, M_1, \Omega) + \Delta\varepsilon(M_1, x_2, x_3; m_1; \Omega)]\, \kappa_1^{\rm fin} + \frac{\Delta P_{1\alpha}(m_1, M_1, \Omega, U)}{2}\, [\kappa_{1\alpha}^{\rm fin} - \kappa_{1\beta}^{\rm fin}] + \sum_\alpha [\varepsilon_{2\alpha}\, \kappa_{2\alpha}^{\rm fin} + \varepsilon_{3\alpha}\, \kappa_{3\alpha}^{\rm fin}]$$

FLAVOR EFFECTS

Extra-term violating the 'usual' CP asymmetry upper bound

Contribution from heavier RH neutrinos

CP asymmetry bound revisited

If M_3 🕒 M_2 ♦ $3M_1$:

$$\overline{\varepsilon}(m_1, M_1, \Omega)$$

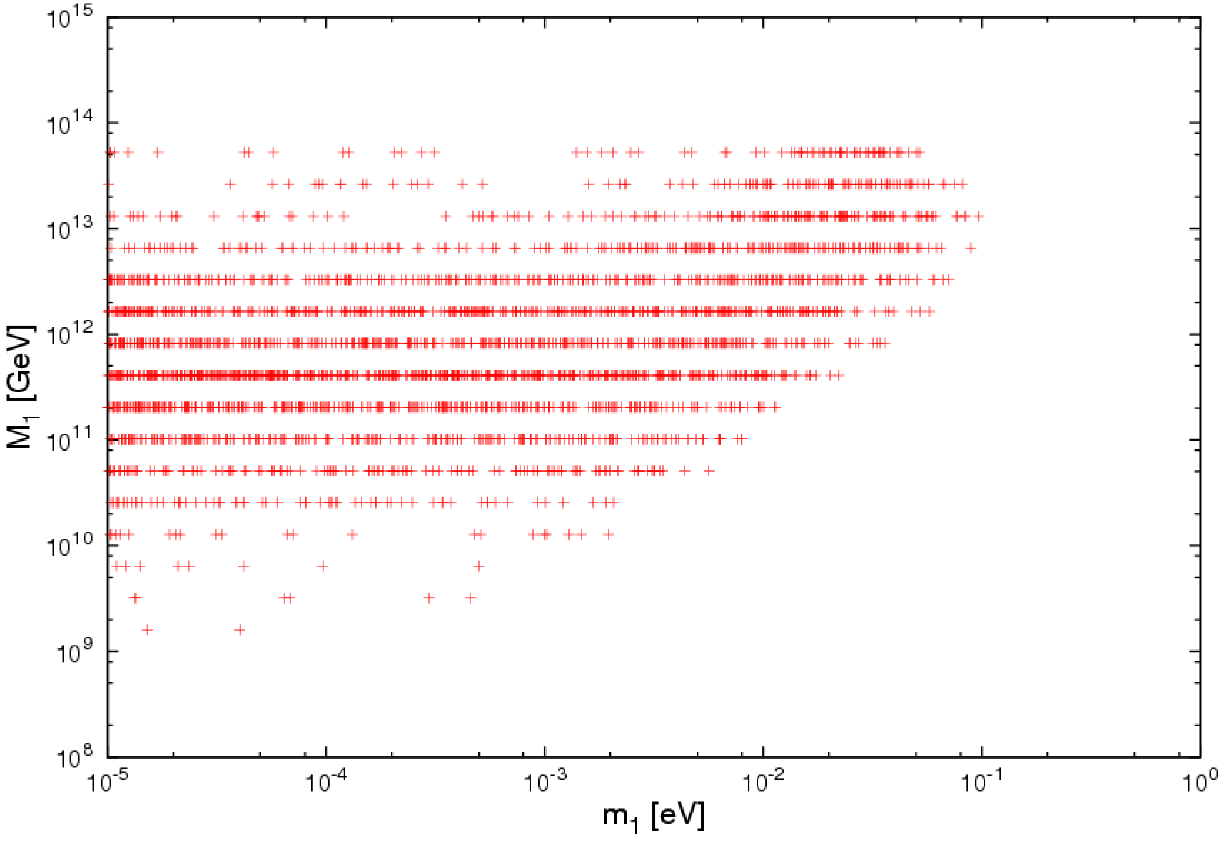
$$\varepsilon_1 \simeq \overline{\varepsilon}(M_1)\, \frac{m_{\rm atm}}{m_1+m_3}\, f(m_1,\widetilde{m}_1)\, \sin\delta_L + \overline{\varepsilon}(M_1)\,[\xi\,(x_3)-\xi\,(x_2)]\, \frac{{\rm Im}[\sum_h m_h\,\Omega^\star_{h1}\,\Omega_{h3}]^2}{m_{\rm atm}\,\widetilde{m}_1}$$

$(\xi(\infty)=1)$

(Hambye,Notari,Papucci,Strumia ’03; PDB’05; Blanchet, PDB ‘06)

$$\Delta\varepsilon(M_1, x_2, x_3; m_1, \Omega)$$

$\Phi = R_{12} R_{13}$ $M_3 \gg M_2 = 10\, M_1$



If R_{23} is switched off the extra-term does not help to relax the bounds !

Beyond the hierarchical limit

(Pilaftsis '97, Hambye et al '03, Blanchet,PDB '06)

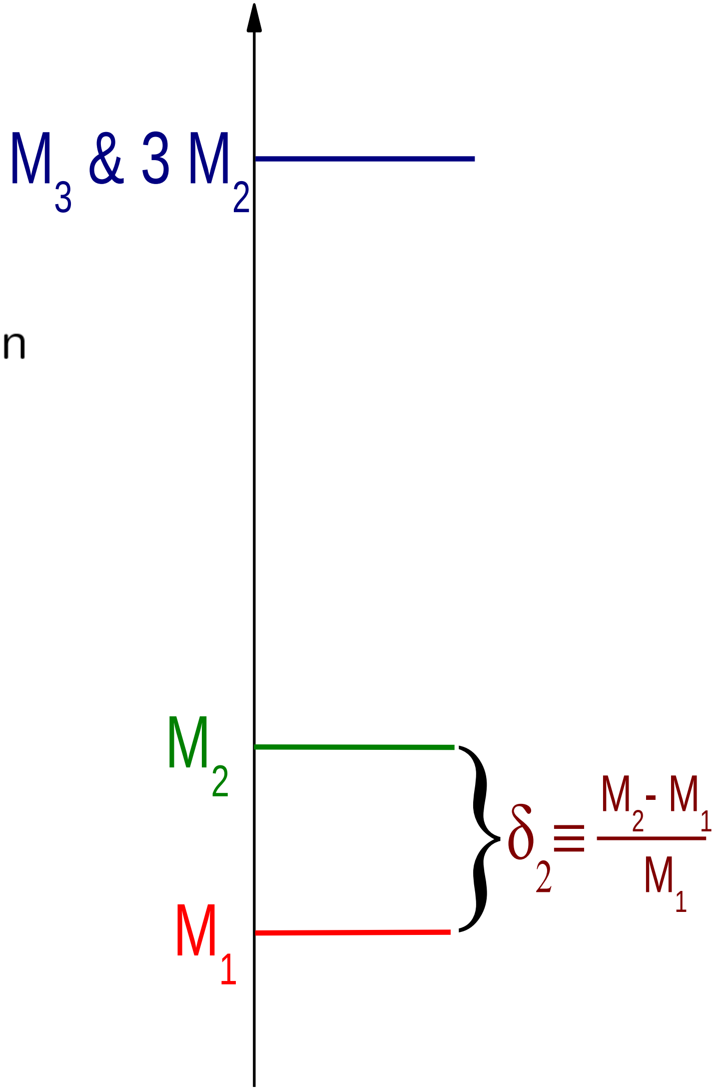
Different possibilities, for example:

• partial hierarchy: $M_3 >> M_2$, M_1

$$\Rightarrow \ |\varepsilon_3| \ll |\varepsilon_2|, |\varepsilon_1| \quad \text{and} \quad \kappa_3^{\rm fin} \ll \kappa_2^{\rm fin}, \kappa_1^{\rm fin}$$

• $M_3 >> 10^{14}$ GeV :

❾ $$\Omega = \begin{pmatrix} 0 & 0 & 1 \\ \sqrt{1-\Omega_{31}^2} & -\Omega_{31} & 0 \\ \Omega_{31} & \sqrt{1-\Omega_{31}^2} & 0 \end{pmatrix} .$$



3 Effects play simultaneously a role for ♎$_2$ ⑥ 1

1. **Asymmetries add up**

$$N_{B-L}^{\rm fin} \simeq \varepsilon_1\,\kappa_1^{\rm fin} + \varepsilon_2\,\kappa_2^{\rm fin} \Rightarrow \mathbf{N_{B-L}^{fin}} \nearrow$$

2. **Wash-out effects add up as well** $\Rightarrow \mathbf{N_{B-L}^{fin}} \searrow$

$$\kappa_1^{\rm f}(K_1,K_2,\delta_2) \simeq \kappa_1^{\rm ss}(K_1,K_2,\delta_2) \equiv -\int_0^\infty dz'\,\frac{dN_{N_1}^{\rm eq}}{dz'}\,e^{-\int_{z'}^\infty dz''\,[W_1^{\rm ID}(z'')+W_2^{\rm ID}(z'')]}$$

$$\kappa_2^{\rm f}(K_1,K_2,\delta_2) \simeq \kappa_2^{\rm ss}(K_1,K_2,\delta_2) \equiv -\int_0^\infty dz'\,\frac{dN_{N_2}^{\rm eq}}{dz'}\,e^{-\int_{z'}^\infty dz''\,[W_1^{\rm ID}(z'')+W_2^{\rm ID}(z'')]}$$

3. **CP asymmetries get enhanced**

$$\varepsilon_1 \simeq \frac{\varepsilon_1(M_2 \gg M_1)}{3\,\delta_2}\,, \qquad \varepsilon_2 = \frac{K_1}{K_2}\,\varepsilon_1 \Rightarrow \mathbf{N_{B-L}^{fin}} \nearrow$$

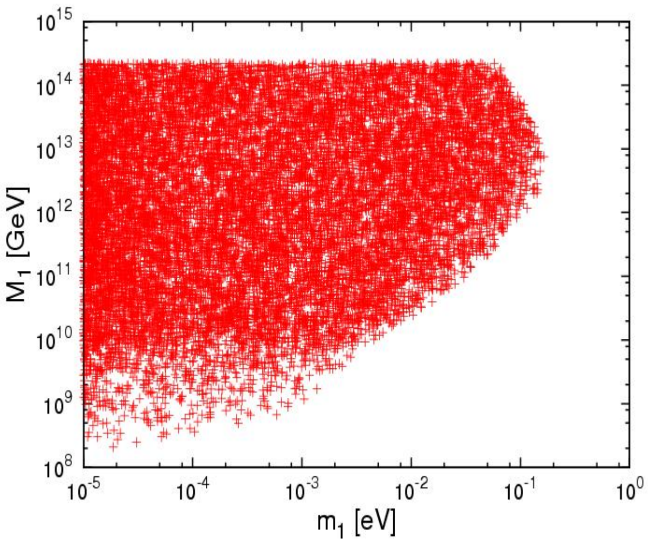
For ♎$_2$ ♎ 0.01 (**degenerate limit**) the first two effects saturate and:

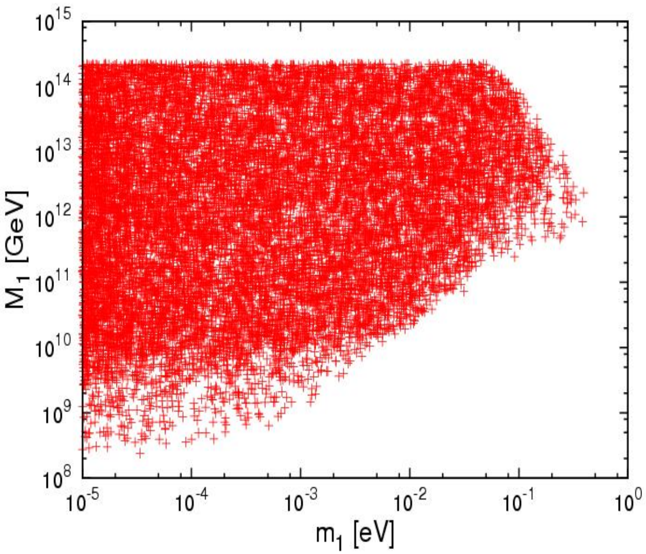
$$(M_1^{\rm min})_{\rm DL} \simeq 4\times 10^9\,{\rm GeV}\left(\frac{\delta_2}{0.01}\right) \quad \text{and} \quad (T_{\rm reh}^{\rm min})_{\rm DL} \simeq 5\times 10^8\,{\rm GeV}\left(\frac{\delta_2}{0.01}\right)$$

More generically:

$$N_{B-L}^{\rm fin} \simeq \left[\xi\,(x_2)\,\overline{\varepsilon}(m_1, M_1, \Omega) + \Delta\varepsilon(M_1, x_2, x_3; m_1; \Omega)\right]\,\kappa_1^{\rm fin}$$

$M_3 = M_2 = 1.1\,M_1$ $\qquad$ $M_3 = 10 M_2 = 1.1\,M_1$





N_2-dominated scenario

(PDB'05)

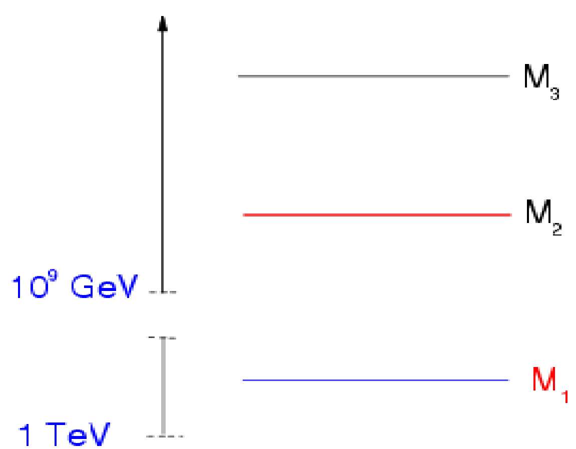
For a special choice of the see-saw orthogonal matrix:

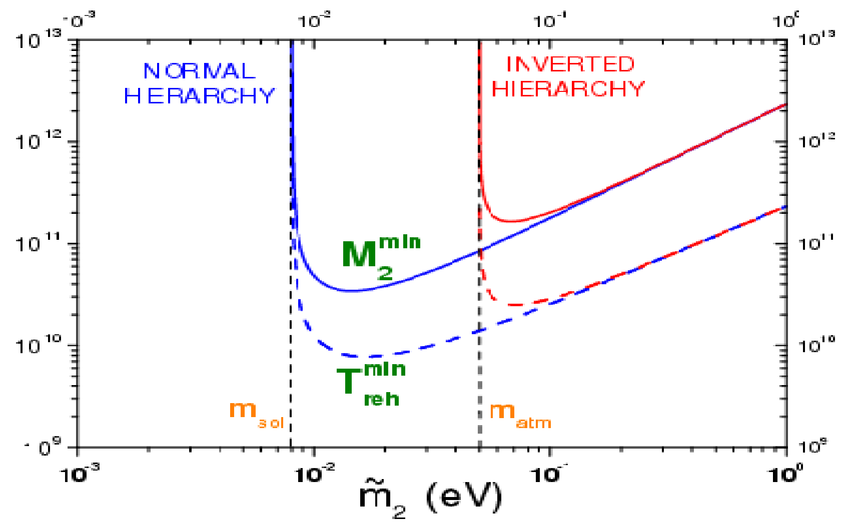
$$\Omega \simeq R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \Omega_{22} & \sqrt{1-\Omega_{22}^2} \\ 0 & -\sqrt{1-\Omega_{22}^2} & \Omega_{22} \end{pmatrix}$$

Four things happen simultaneously:

1. $\varepsilon_1 = 0 \quad \Rightarrow$ no asymmetry from N_1-decays but ...
2. $\varepsilon_2 \sim \overline{\varepsilon}(M_2) \quad \Rightarrow$ ... it can be produced from N_2-decays and ...
3. $\tilde{m}_1 = m_1 \quad \Rightarrow$ ... no washed-out if $m_1 \lesssim 10^{-3}\,\mathrm{eV}$!
4. $K_2 \geq K_{sol} \gg 1 \quad \Rightarrow$ no dependence on the initial conditions !

The lower bound on M_1 disappears and is replaced by a lower bound on M_2 …that however still implies a lower bound on T_{reh} !





Flavor effects

(Nardi,Roulet'06;Abada, Davidson, Josse-Michaux, Losada, Riotto'06)

- Flavor composition

$$N_1 \longrightarrow l_1\, H^\dagger\,, \quad |l_1\rangle = \sum_{\alpha=e,\mu,\tau} \langle l_\alpha | l_1\rangle\, |l_\alpha\rangle$$

$$N_1 \longrightarrow \bar{l}_1'\, H\,, \quad |\bar{l}_1'\rangle = \sum_{\alpha=e,\mu,\tau} \langle l_\alpha | \bar{l}_1'\rangle\, |\bar{l}_\alpha\rangle$$

- $M_1 \lesssim 10^{12}\,\mathrm{GeV}$ $\Rightarrow$ τ-Yukawa interactions ($f_{\tau\tau}\,\bar{l}_{L\tau}\,\phi\,e_{R\tau}$) are fast enough ($\Gamma_\tau \gtrsim \Gamma_{\mathrm{ID}}$) to break the coherent evolution of the $|l_1\rangle$ and $|\bar{l}_1'\rangle$ quantum states

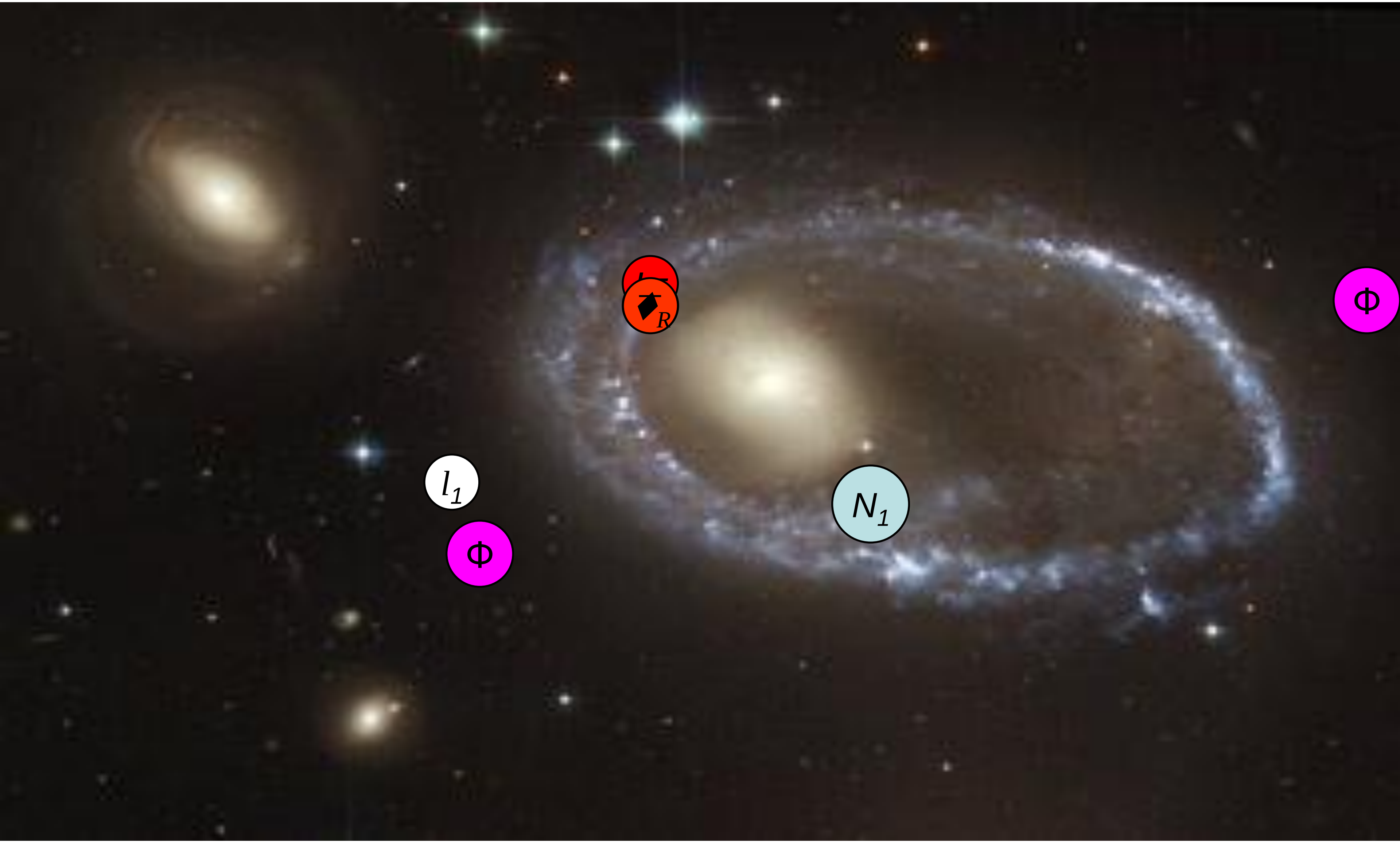
- imposing even a more restrictive condition (Blanchet,PDB, Raffelt'06)

$$M_1 \lesssim \frac{10^{12}\,\mathrm{GeV}}{2\,W_1(T_B)} \lesssim 10^{12}\,\mathrm{GeV}\,,$$

$\Rightarrow$ $|l_1\rangle$ and $|\bar{l}_1'\rangle$ are projected on the flavor basis and a fully flavored regime holds!

(Blanchet, PDB '06)

FULLY FLAVORED REGIME



Fully flavoured regime

- Projectors

$$P_{1\alpha} \equiv |\langle l_\alpha | l_1 \rangle|^2 = P^0_{1\alpha} + \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha P^0_{1\alpha} = 1 \right)$$

$$\bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}'_1 \rangle|^2 = P^0_{1\alpha} - \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha \Delta P_{1\alpha} = 0 \right)$$

These 2 terms correspond respectively to 2 different flavor effects:

1) wash-out is in general reduced: $K_1 \rightarrow K_{1\alpha} \equiv K_1 \, P^0_{1\alpha}$

2) additional CP violating contribution $\left(|\bar{l}'_1\rangle \neq CP|l_1\rangle \right)$

$$\Rightarrow \quad \varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\,\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P^0_{1\alpha}\,\varepsilon_1 + \Delta P_{1\alpha}(\Omega, U)/2$$

- Classic Kinetic Equations (in their simplest form)

$$\frac{dN_{N_1}}{dz} = -D_1 \left(N_{N_1} - N^{\rm eq}_{N_1} \right)$$

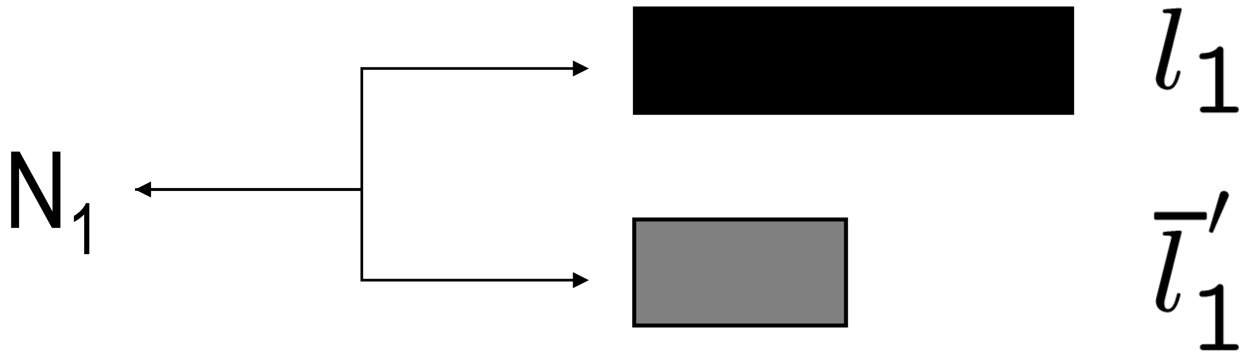
$$\frac{dN_{\Delta_\alpha}}{dz} = -\varepsilon_{1\alpha} \frac{dN_{N_1}}{dz} - P^0_{1\alpha}\, W_1\, N_{\Delta_\alpha}$$

$$\Rightarrow \quad N_{B-L} = \sum_\alpha N_{\Delta_\alpha} \qquad (\Delta_\alpha \equiv B/3 - L_\alpha)$$

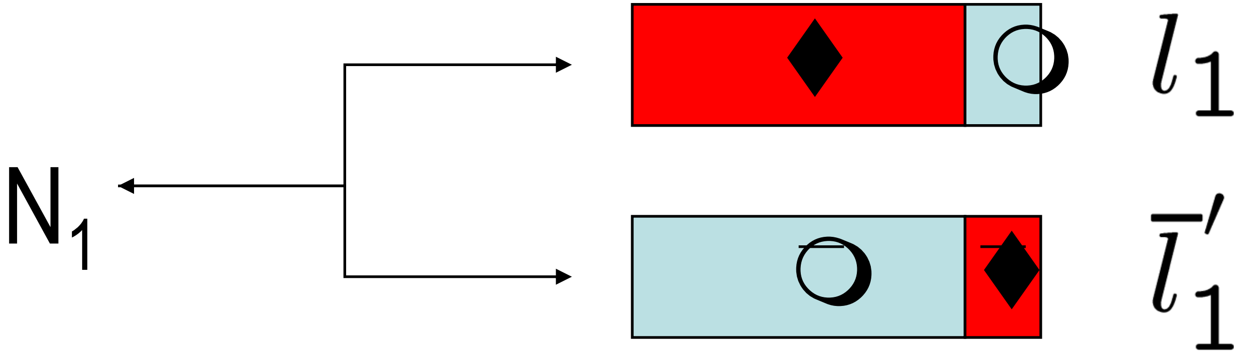
$$\Rightarrow N^{\rm fin}_{B-L} = \sum_\alpha \varepsilon_{1\alpha}\,\kappa^{\rm fin}_{1\alpha} \simeq N_{\rm fl}\,\varepsilon_1\,\kappa^{\rm fin}_1 + \frac{\Delta P_{1\alpha}}{2}\left[\kappa^{\rm fin}_{1\alpha} - \kappa^{\rm fin}_{1\beta}\right]$$

In pictures:

1) $\Gamma \neq \bar{\Gamma}$



2) $|\bar{l}'_1\rangle \neq CP|l_1\rangle$



General scenarios ($K_1 \gg 1$)

– Alignment case

$P_{1\alpha} = \overline{P}_{1\alpha} = 1$ and $P_{1\beta\neq\alpha} = \overline{P}_{1\beta\neq\alpha} = 0$ $\Longrightarrow$ $\dfrac{N^f_{B-L}}{[N^f_{B-L}]_{\text{unfl}}} = 1$

– Democratic (semi-democratic) case

$P_{1\alpha} = \overline{P}_{1\alpha} = 1/3 \quad (P_{1\alpha} = 0, P_{1\beta\neq\alpha} = 1/2)$ $\Longrightarrow$ $\dfrac{N^f_{B-L}}{[N^f_{B-L}]_{\text{unfl}}} \simeq 3$

– One-flavor dominance

$P^0_{1\alpha} \ll P^0_{1\beta\neq\alpha} \sim \mathcal{O}(1)$ and $\varepsilon_{1\alpha} \simeq \varepsilon_{1\beta\neq\alpha}$ $\Longrightarrow$ $\dfrac{N^f_{B-L}}{[N^f_{B-L}]_{\text{unfl}}} \gg 1$

Remember that: $\varepsilon_{1\alpha} = P^0_{1\alpha}\,\varepsilon_1 + \dfrac{\Delta P_{1\alpha}}{2}$

big effect!

❾ the one-flavor dominance scenario can be realized only if the 🖓P$_1$ ♋ term dominates !

A relevant specific case

- **Consider:** (Blanchet,PDB'06)

$$\Omega = R_{13} = \begin{pmatrix} \sqrt{1-\omega_{31}^2} & 0 & -\omega_{31} \\ 0 & 1 & 0 \\ \omega_{31} & 0 & \sqrt{1-\omega_{31}^2} \end{pmatrix}$$

- The projectors and the flavored asymmetries depend also on **U**

➒ one has to plug the information from neutrino mixing experiments

- For $m_1=0$ (fully hierarchical light neutrinos)

➒ $P^0_{1e} \simeq 0, \quad P^0_{1\mu} \simeq P^0_{1\tau} \simeq 1/2\,, \quad \Delta P_{1\alpha} = 0$

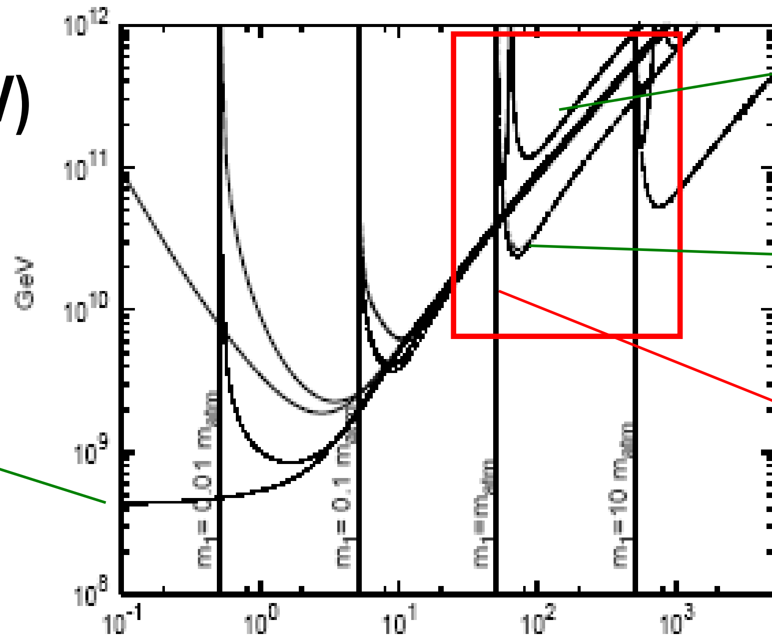
➒ Semi-democratic case

Flavor effects represent just a correction in this case !

Do flavour effects relax the bounds on neutrino masses ?

Hierarchical limit ($M_3 \gg M_2 \gg M_1$)

M_1^{min} (GeV)



K_1

$\alpha_1 = \alpha_2 = \delta = 0$

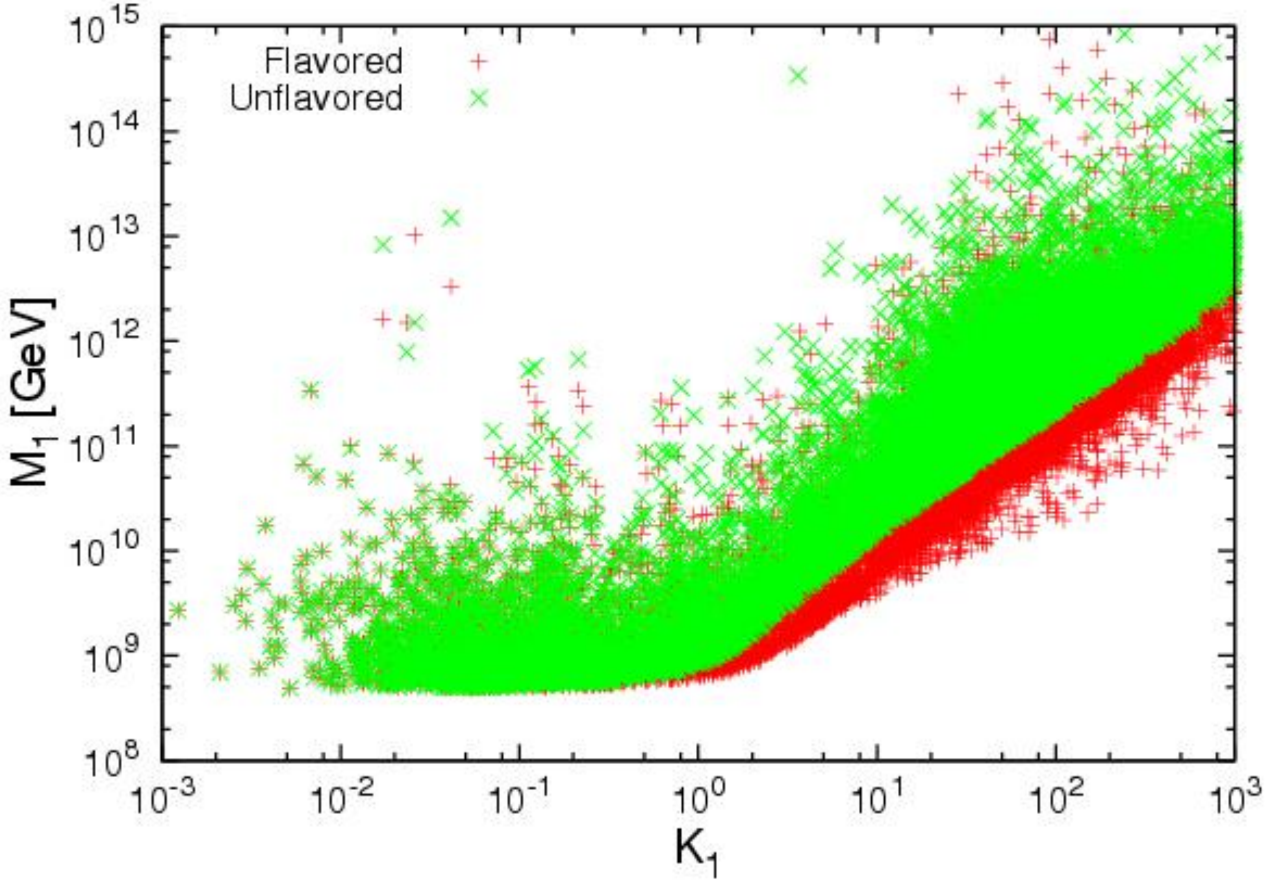
$\alpha_1 = -\pi$

$m_1 = m_{atm} \simeq 0.05$ eV

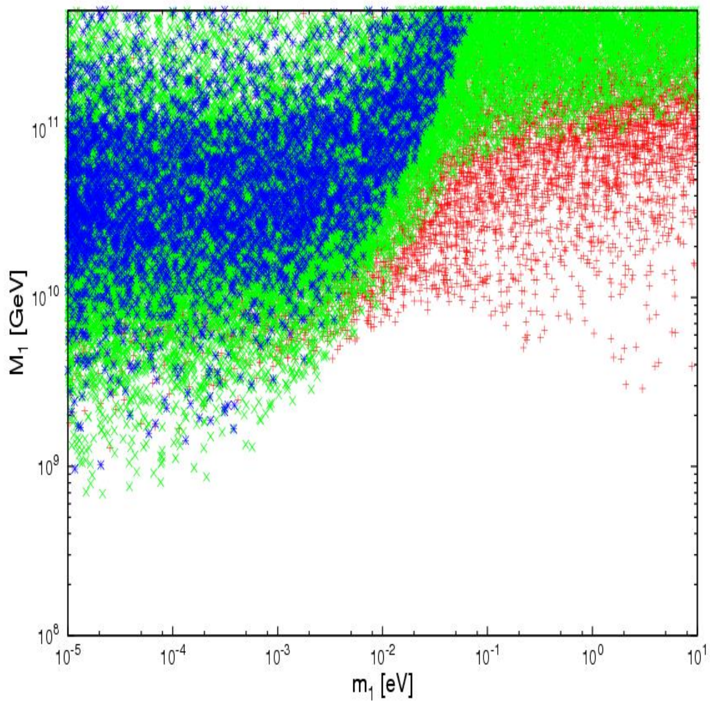
The usual lowest bounds are not relaxed !

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\,\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\,\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\,\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\,\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\,\delta} & c_{23}\,c_{13} \end{pmatrix} \times \mathrm{diag}(\mathrm{e}^{\mathrm{i}\,\frac{\Phi_1}{2}}, \mathrm{e}^{\mathrm{i}\,\frac{\Phi_2}{2}}, 1)\,,$$

For an arbitrary Φ and $m_1 = 0$:

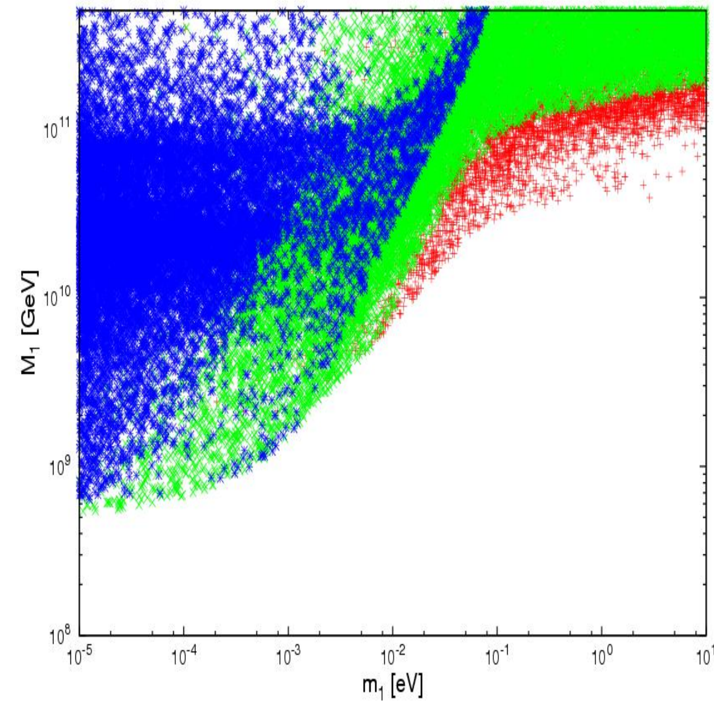


Arbitrary Φ



PMNS phases off

$\Phi = R_{13}$



Red: $P^0_{1\tau}$ or $P^0_{1e} + P^0_{1\mu} < 0.1$

Green: $0.1 < P^0_{1\tau} < 0.45$ or $0.1 < P^0_{1e} + P^0_{1\mu} < 0.45$

Blue : $0.45 < P^0_{1\tau}, P^0_{1e} + P^0_{1\mu} < 0.55$

Are Classic Kinetic Equations enough ? NO !

(Abada et al. '06; Blanchet, PDB, Raffelt '06; De Simone, Riotto '06)

- Unflavored regime holding for $M_1 \gtrsim 10^{12}\,\mathrm{GeV}$

$$\frac{dN_{N_1}}{dz} = -D_1\,(N_{N_1} - N_{N_1}^{\rm eq})$$

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\,\frac{dN_{N_1}}{dz} - W_1\,N_{B-L}$$

- Fully flavored regime holding for $M_1 \lesssim 10^{12}\,\mathrm{GeV}/W_1(T_B)$

$$\frac{dN_{N_1}}{dz} = -D_1\,(N_{N_1} - N_{N_1}^{\rm eq})$$

$$\frac{dN_{\Delta_\alpha}}{dz} = -\varepsilon_{1\alpha}\,\frac{dN_{N_1}}{dz} - P^0_{1\alpha}\,W_1\,N_{\Delta_\alpha} \Rightarrow N_{B-L} = \sum_\alpha N_{\Delta_\alpha}$$

- the possibility to have $\frac{[N^{\rm fin}_{B-L}]_{\rm fl}}{[N^{\rm fin}_{B-L}]_{\rm unfl}} \gg 1$ implies $W_1(T_B) \gg 1$

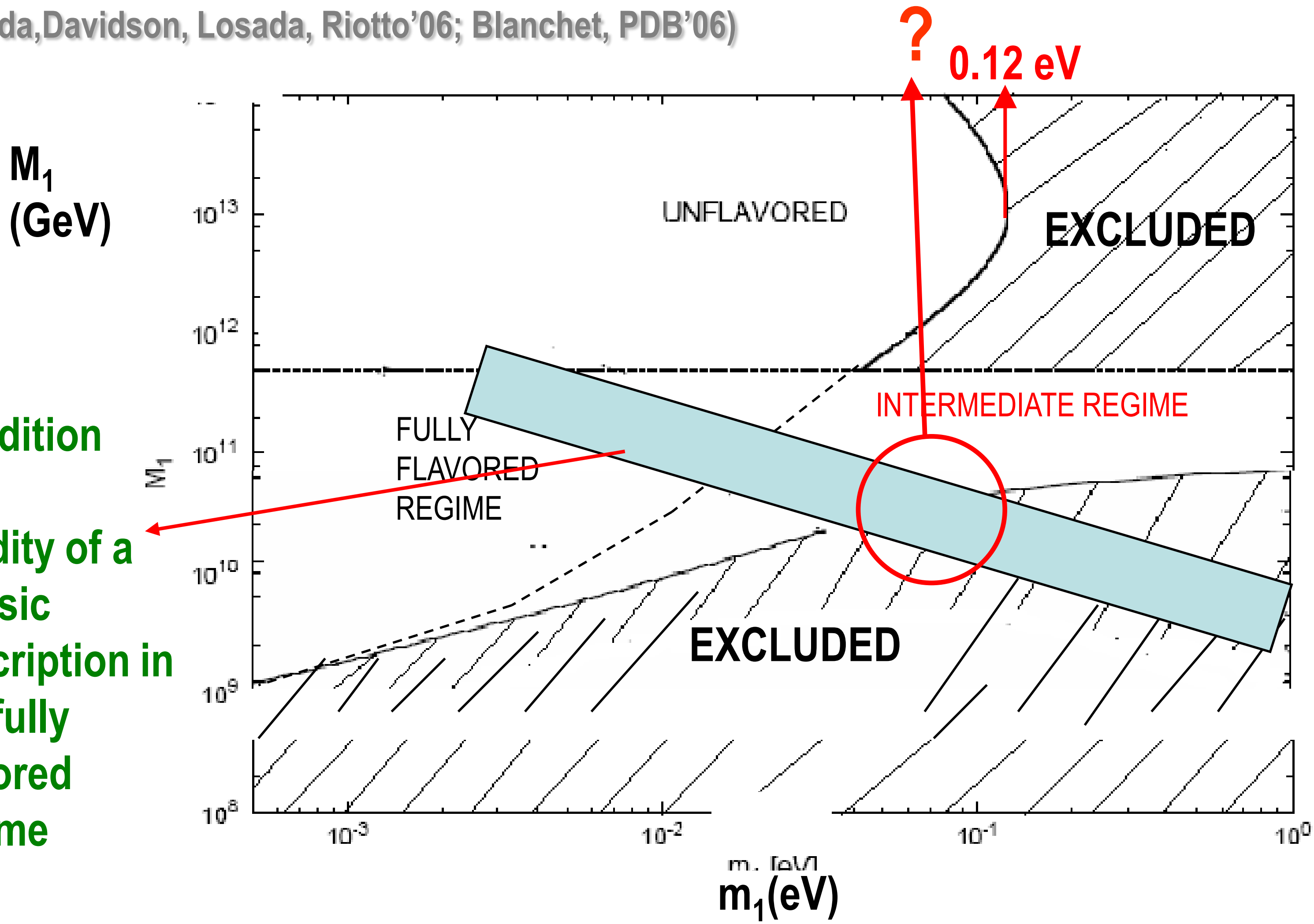
$\Rightarrow$ there is an intermediate regime that requires a (not fully developed !)

quantum kinetic treatment in terms of density matrix equations

A description of this intermediate regime is important to answer some questions !

Neutrino mass bounds

(Abada,Davidson, Losada, Riotto'06; Blanchet, PDB'06)



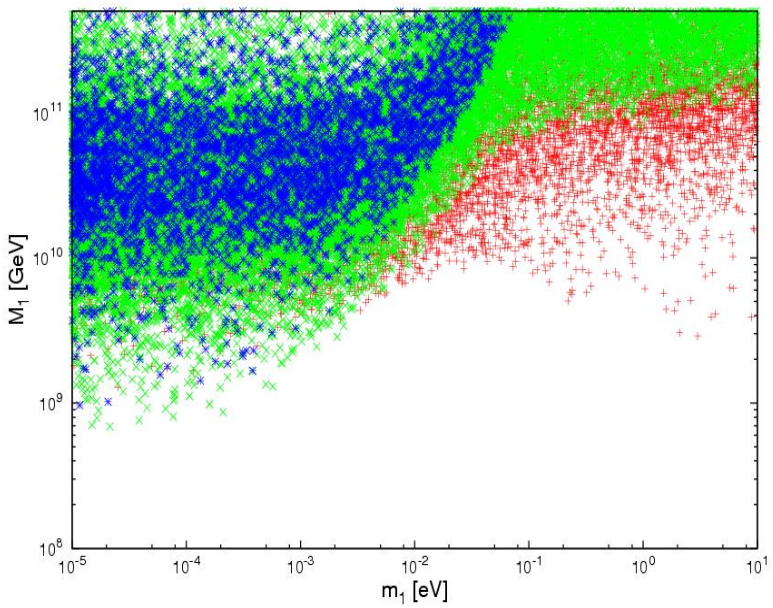
Condition of validity of a classic description in the fully flavored regime

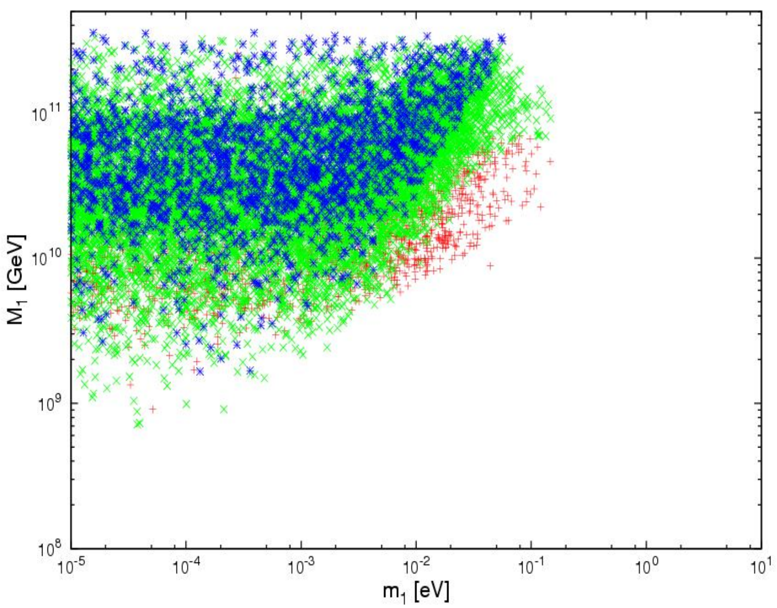
Is the fully flavoured regime suitable to answer the question ?

No ! There is an intermediate regime where a full quantum kinetic description is necessary !

(Blanchet,PDB,Raffelt '06)

$M_1 \lesssim 10^{12}\,\mathrm{GeV}/W_1(T_B)$





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Green: $0.1 < P^0_{1\tau}$ or $P^0_{1e} + P^0_{1\mu} < 0.45$

Blue : $0.45 < P^0_{1\tau}$ or $P^0_{1e} + P^0_{1\mu} < 0.5$

The importance of the A-matrix for the m_1 upper bound

(De Simone,Riotto'06)

The condition $M_1 \lesssim 10^{12}\,\mathrm{GeV}/W_1(T_B)$ cuts away especially one-flavor dominated cases where one projector is much smaller than the other

On the other hand IF $P_{1e+❍}$ ☺ $P_{1♦}$ ☺ 0.5 when m_1 increases one has

☆$_1$ ✹ 0 ❾ ☆$_{1e+❍}$ = - ☆$_{1♦}$ and using:

$$\frac{dN_{N_1}}{dz} = -D(N_{N_1} - N_{N_1}^{\rm eq})$$

$$\frac{dN_{\Delta_{e+\mu}}}{dz} = \varepsilon_{1e+\mu}\,D\,(N_{N_1} - N_{N_1}^{\rm eq}) - P^0_{1e+\mu}\,W^{\rm ID}\,N_{\Delta_{e+\mu}},$$

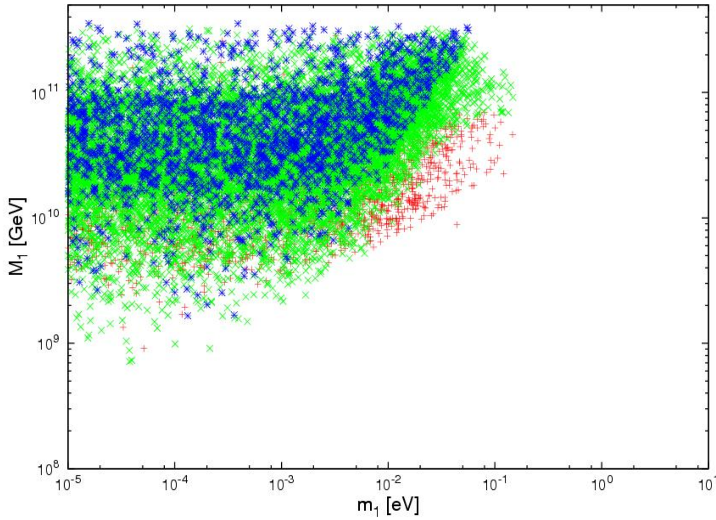
$$\frac{dN_{\Delta_\tau}}{dz} = \varepsilon_{1\tau}\,D\,(N_{N_1} - N_{N_1}^{\rm eq}) - P^0_{1\tau}\,W^{\rm ID}\,N_{\Delta_\tau},$$

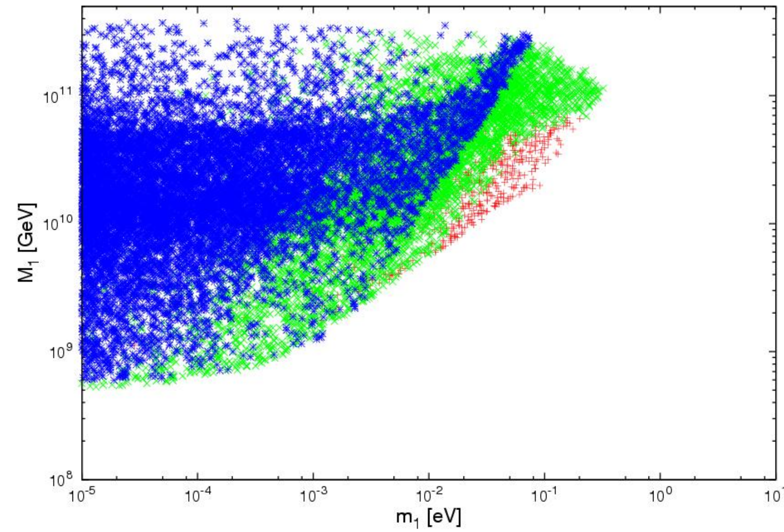
one obtains ♒$_B$ ✹ 0 and this contributes to lower the upper bound !

However one has to take into account that (Barbieri et al. '99)

$$N_{l_\alpha} = A\,N_{\Delta_\alpha}\ , \qquad A = \begin{pmatrix} 417/589 & -120/589 \\ -30/589 & 390/589 \end{pmatrix}$$

$M_1 \lesssim 10^{12}\,\mathrm{GeV}/W_1(T_B)$ and A-matrix into account and no PMNS phases





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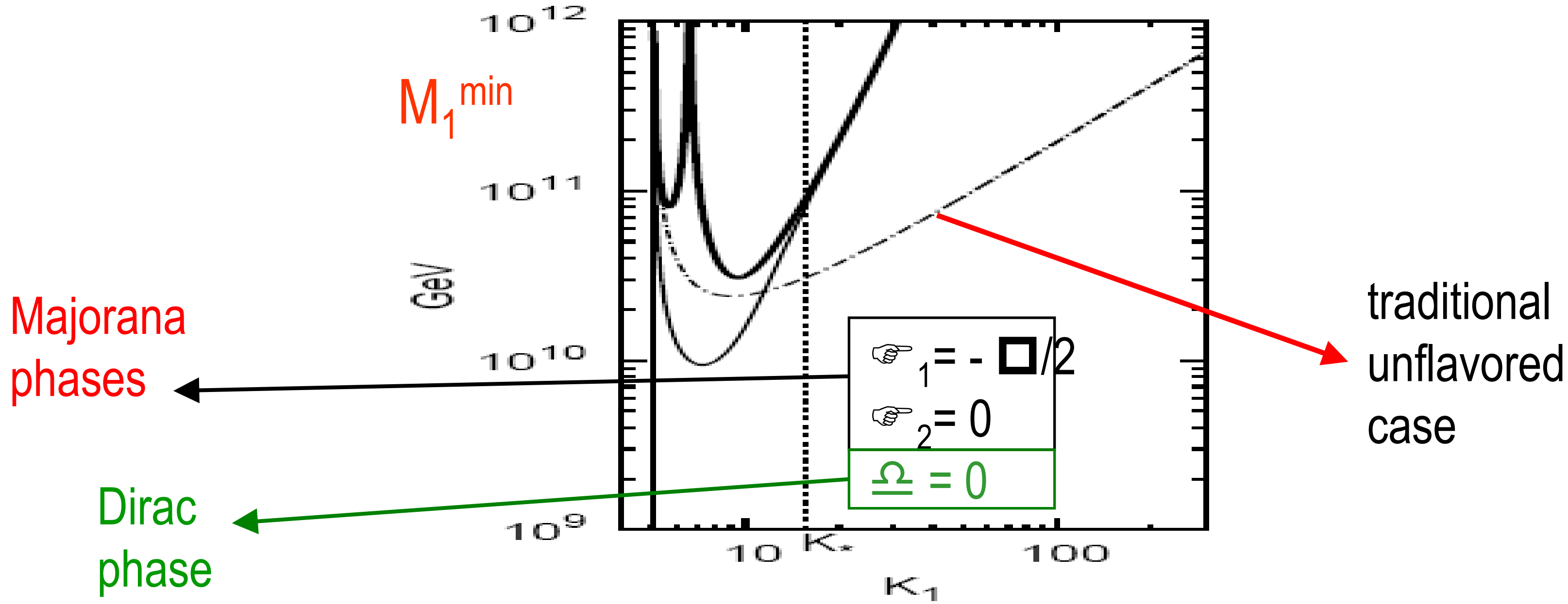
Blue : $0.45 < P^0_{1\tau}$ or $P^0_{1e} + P^0_{1\mu} < 0.5$

Leptogenesis from low energy phases ?

(Blanchet, PDB '06)

Let us now further impose ⌖ real setting Im(◆$_{13}$)=0 ❾ ☆$_1$= 0

$$N^{\rm fin}_{B-L} \sim \sout{N_{\rm fl}\,\varepsilon_1\,\kappa_1^{\rm fin}} + \frac{\Delta P_{1\alpha}}{2}\left[\kappa^{\rm fin}_{1\tau} - \kappa^{\rm fin}_{1,e+\mu}\right]$$



- The lower bound gets more stringent but still successful leptogenesis is possible just with CP violation from 'low energy' phases that can be tested in ♌♌0■ decay (Majorana phases) (difficult) and more realistically in neutrino mixing (Dirac phase)

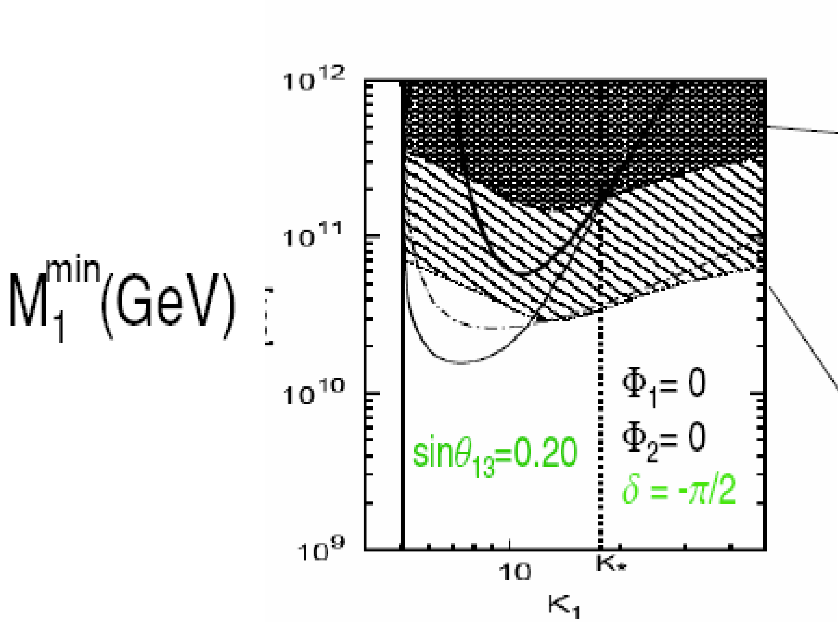
Dirac phase leptogenesis

(Abada et al. '06; Blanchet, PDB '06; Pascoli, Petcov, Riotto '06; Branco et al. '06; Blanchet, PDB '07)

- Assume Ω matrix real $\Rightarrow \varepsilon_{1\alpha} = P^0_{1\alpha}\,\cancel{\varepsilon_1} + \Delta P_{1\alpha}/2$
- Assume furthermore $\Phi_1 = \Phi_2 = 0 \;\Rightarrow\; \delta$ is the only source of CP violation !

Is it still possible to explain $\eta_B^{\rm CMB}$? Yes, but with severe limitations

- Hierarchical Limit ($M_2 \gtrsim 3\, M_1$)



In this region the results from the full flavored regime are expected to undergo severe corrections that tend to reduce the allowed region

Here some minor corrections are also expected

- a quantum kinetic description is strongly required
- only a marginally allowed region with strong dependence on initial conditions

Full degenerate limit: M_1 ⊛ M_2 ⊛ M_3

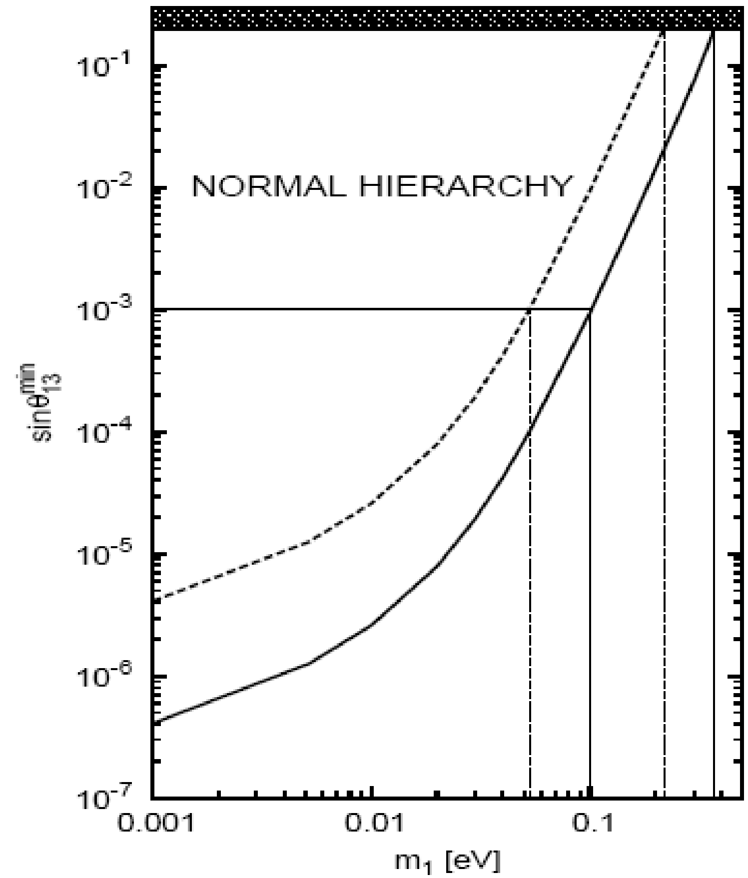
$$\delta_{31} \equiv \frac{M_3 - M_1}{M_1}$$

$$M_1 \gtrsim 5 \times 10^9\,\text{GeV}\,\frac{\delta_{31}}{|\sin\theta_{13}\sin\delta|} \qquad (\delta_{31} \lesssim 0.01)$$

The **maximum enhancement of the CP asymmetries** is obtained in so called **resonant leptogenesis**:

$$\delta_{31}^{\text{res}} \simeq (1 \div 10)\,\frac{\overline{\varepsilon}(M_1)}{3}$$

❾ lower bound on **sin ❑$_{13}$** and upper bound on **m_1**



Some remarks on ♎-leptogenesis :

- there is no theoretical motivation

- …however, within a generic model where all 6 phases are present,

it could be regarded as an approximate scenario if the contribution from ♎ dominates ❾ it is interesting to know that something we could discover in neutrino mixing experiments is sufficient to explain (in principle) a global property of the Universe

- On the other hand notice that:

if we do not discover CP violation in neutrino mixing it does not disprove leptogenesis

Some remarks on the N_2 - dominated scenario in the flavored regime

The N_2 dominated scenario relies on two conditions:

1) A large enough asymmetry has to be generated by N_2 decays at $T \sim M_2$
2) It has not to be washed-out afterwards, at $T \sim M_1$, by N_1- inverse processes (at least not too much)

Flavor effects make much easier to satisfy 2) in different ways..
(Vives'06; Engelhard,Grossman,Nardi'06;Shindou,Yamashita'07)
and in some respects also 1) **(Blanchet,PDB'06)** but still it is not trivial to satisfy simultaneously 1) and 2)
(Example: in Ω-leptogenesis it is like in the unflavored case: the N_2 dominated scenario is realized in the end for $\Omega \sim R_{23}$)

Unflavored vs. flavored leptogenesis

	Unflavored	Flavored
Lowest bounds on M_1 and T_{reh}	~ 10^9 GeV	Unchanged
Upper bound on m_1	0.12 eV	? **(QKE needed !)**
N_2 - dominated scenario	for Φ ~ R_{23}	Domain is enlarged but no drastic changes
Leptogenesis from low energy phases	Non-viable	Viable only marginally in the HL ❾ DL is needed **(QKE needed !)**

Can we detect RH neutrinos at LHC ?

Typically lowering the RH neutrino scale at TeV , the RH neutrinos decouple and they cannot be efficiently produced in colliders

Different **claimed** possibilities to circumvent the problem:

- ♦ - resonant leptogenesis (Pilaftsis, Underwood '05)
- additional gauged $U(1)_{B-L}$ (King,Yanagida '04)

Going beyond the usual type I see-saw :

- leptogenesis with Higgs triplet

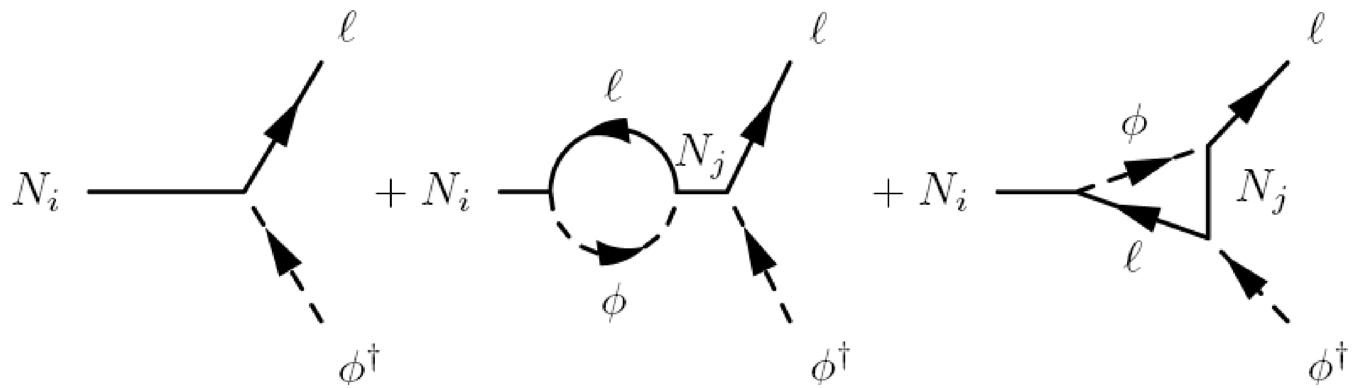
  (Ma,Sarkar '00 ; Hambye,Senjanovic '03; Rodejohann'04; Hambye,Strumia '05)
- leptogenesis with three body decays (Hambye '01)
- see-saw with vector fields (Aristizabal,Losada,Nardi '07)
- ……………………………….

A wish list for future

- Higgs discovery at LHC !
- $T_{\rm reh} \gtrsim 100\,{\rm GeV}$
- non viable Electro-weak Baryogenesis
- CP violation in neutrino mixing
- $\beta\beta0\nu$ decay
- SUSY discovery with the right features:
  - non viable electro-weak baryogenesis
  - LFV processes
- the dream: production of heavy RH neutrinos at LHC

Total CP asymmetries

(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)



$$\varepsilon_i \simeq \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(m_D^\dagger\, m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

It does not depend on U !