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Interconnections among Baryo/Leptogenesis models

Pasquale Di Bari

UNIVERSITY OF Southampton

Puzzles of Modern Cosmology

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

$\Longrightarrow$ clash between the SM and ΛCDM !

Primordial matter-antimatter asymmetry

- Symmetric Universe with matter- anti matter domains ?

  Excluded by CMB + cosmic rays

  $$\Rightarrow \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10} \gg \bar{\eta}_B$$

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

$\Rightarrow$ **dynamical generation (baryogenesis)**

(Sakharov '67)

Models of Baryogenesis

- From phase transitions:

  - Electroweak Baryogenesis:

  * in the SM
  * in the MSSM
  * in the nMSSM
  * in the NMSSM
  * in the 2 Higgs model
  * at B-L symmetry breaking
  * in Technicolor (poster by Jarvinen)
  * ....

- Affleck-Dine:
  - at preheating
  - Q-balls
  - ....

- From Black Hole evaporation
- Spontaneous Baryogenesis
- Gravitational Baryogenesis
- ....

- From heavy particle decays:
  - maximons decays (Sakharov '67)
  - GUT Baryogenesis
  - LEPTOGENESIS

Baryogenesis in the SM ?

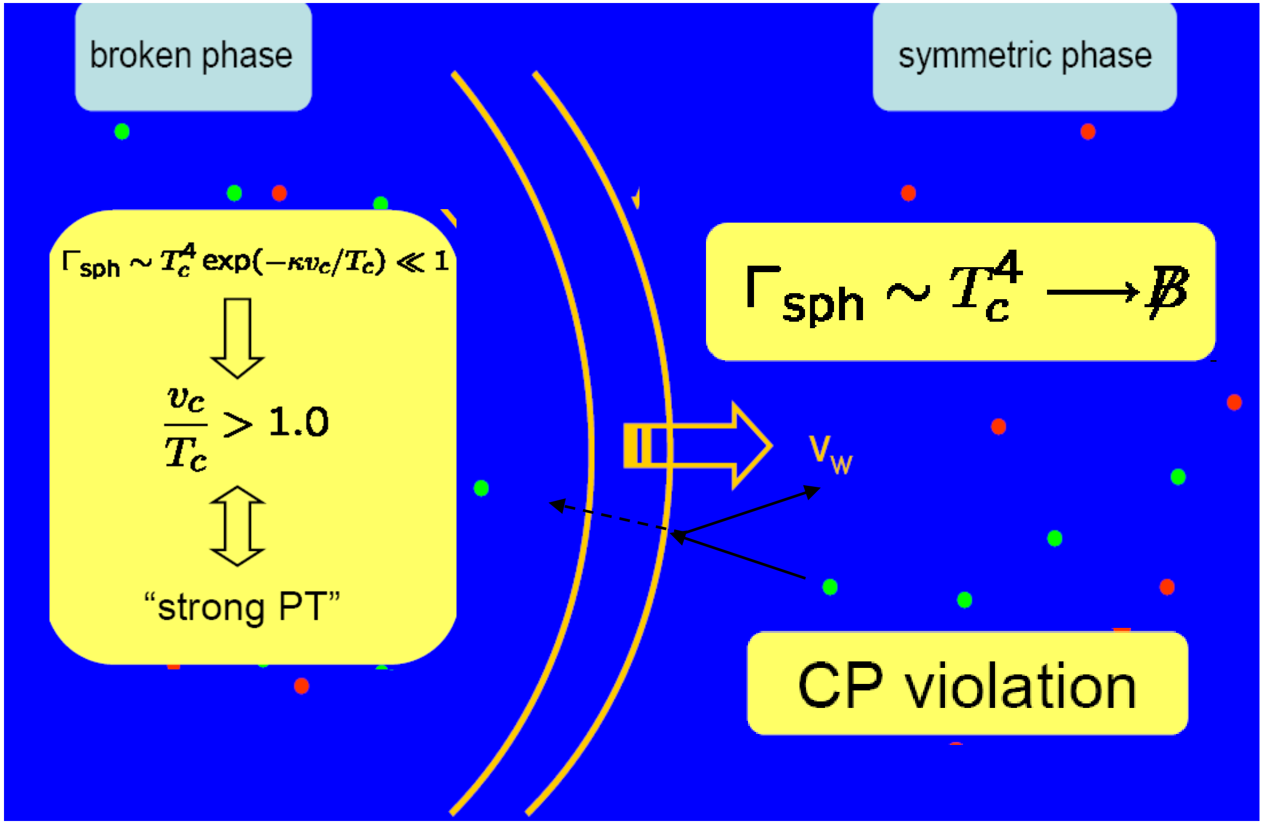
All 3 Sakharov conditions are fulfilled in the SM at some level:

1) Baryon number violation if T $\gtrsim$ 100 GeV (sphaleron transitions),
2) CP violation in the quark CKM matrix,
3) Departure from thermal equilibrium (an arrow of time) from the expansion of the Universe

EWBG in the SM

(Kuzmin, Rubakov, Shaposhnikov '85; Kajantie, Laine, Shaposhnikov '97)

If the EW phase transition (PT) is 1st order $\Longrightarrow$ broken phase bubbles nucleate



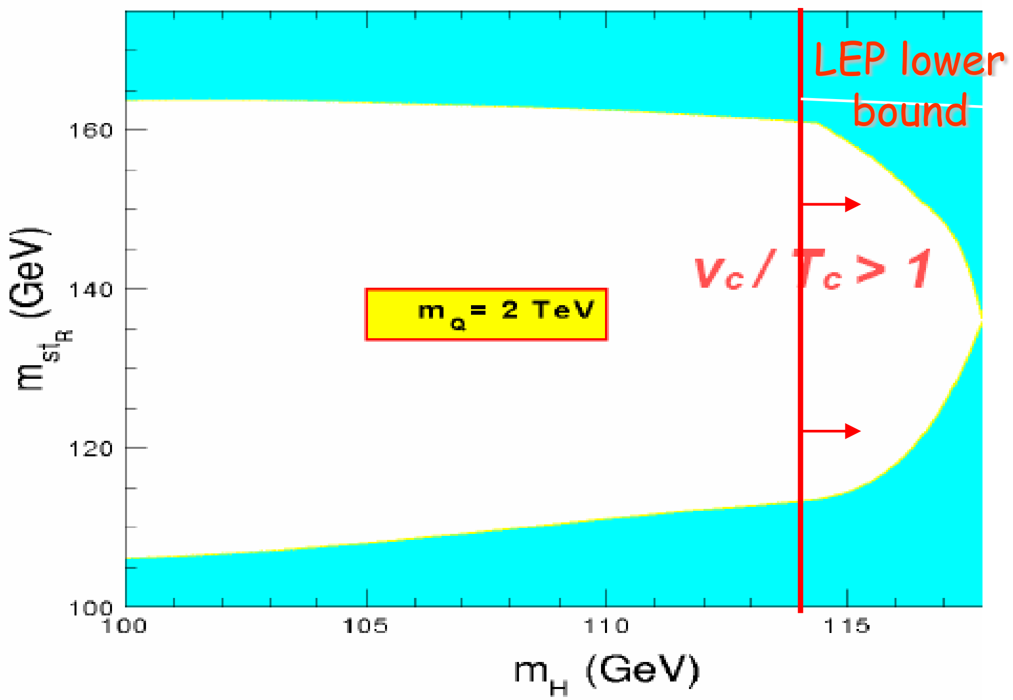
In the SM the ratio vc/Tc is directly related to the Higgs mass and only for Mh < 40 GeV one can have a strong PT $\Longrightarrow$ EW baryogenesis in the SM is ruled out by the LEP lower bound Mh $\gtrsim$ 114 GeV ! (also not enough CP)

$\Longrightarrow$ New Physics is needed!

EWBG in the MSSM

(Carena, Quiros, Wagner '98)

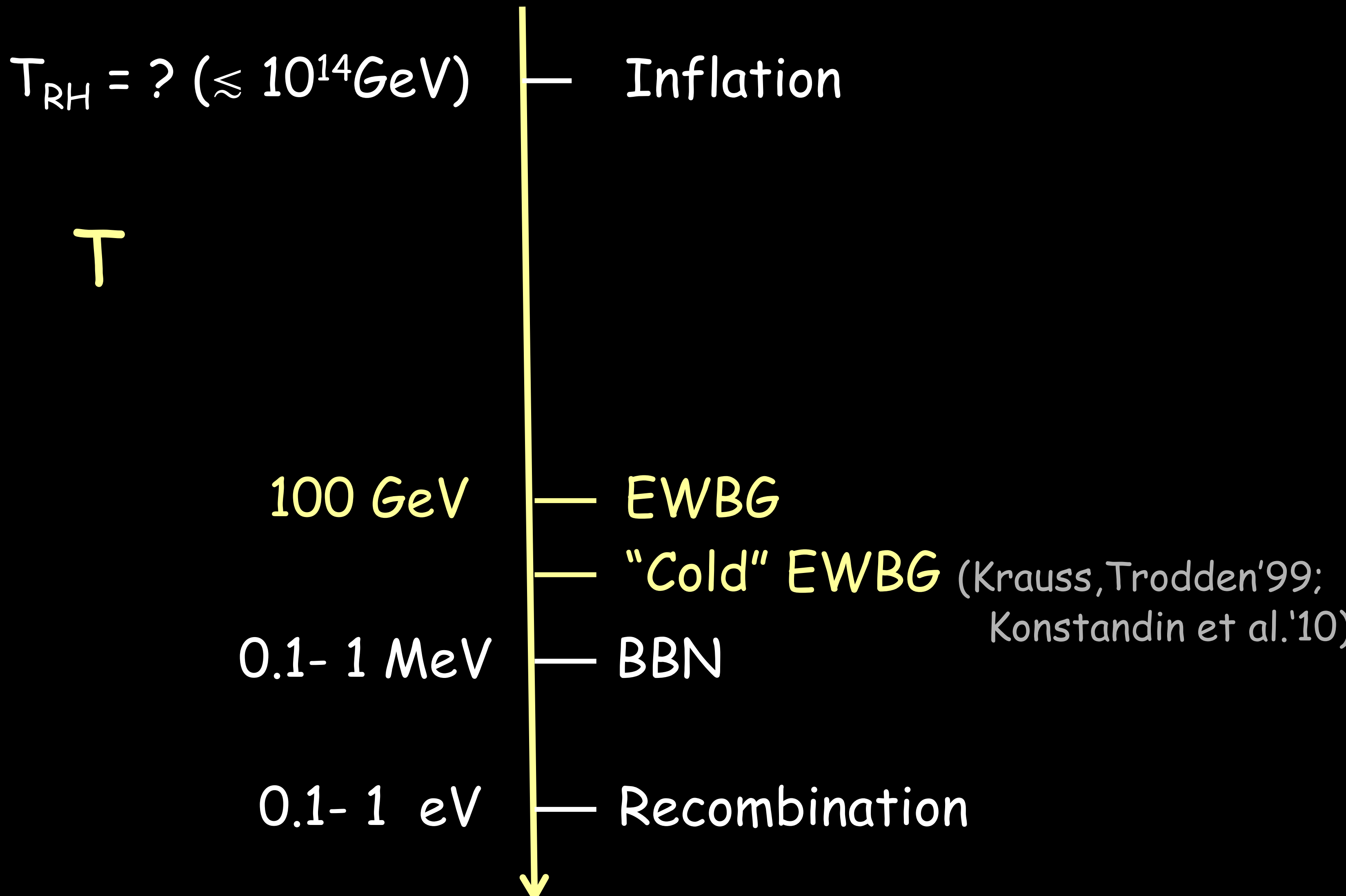
• Additional bosonic degrees of freedom (dominantly the light stop contribution) can make the EW phase transition more strongly first order if



• Notice that there is a tension between the strong PT requirement and the LEP lower bound on M_h and in particular one has to impose $5 \lesssim \tan\beta \lesssim 10$

• In addition there are severe constraints from the simultaneous requirement of CP violation in the bubble walls (mainly from charginos) without generating too large electric dipole moment of the electron

Baryogenesis and the early Universe history

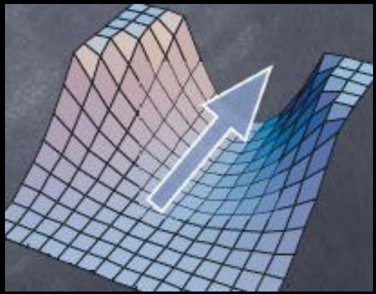


Affleck-Dine Baryogenesis

(Affleck, Dine '85)

In the Supersymmetric SM there are many "flat directions" in the space of a field composed of squarks and/or sleptons

$$V(\phi) = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + \frac{1}{2} \sum_A \left(\sum_{ij} \phi_i^* (t_A)_{ij} \phi_j \right)^2$$



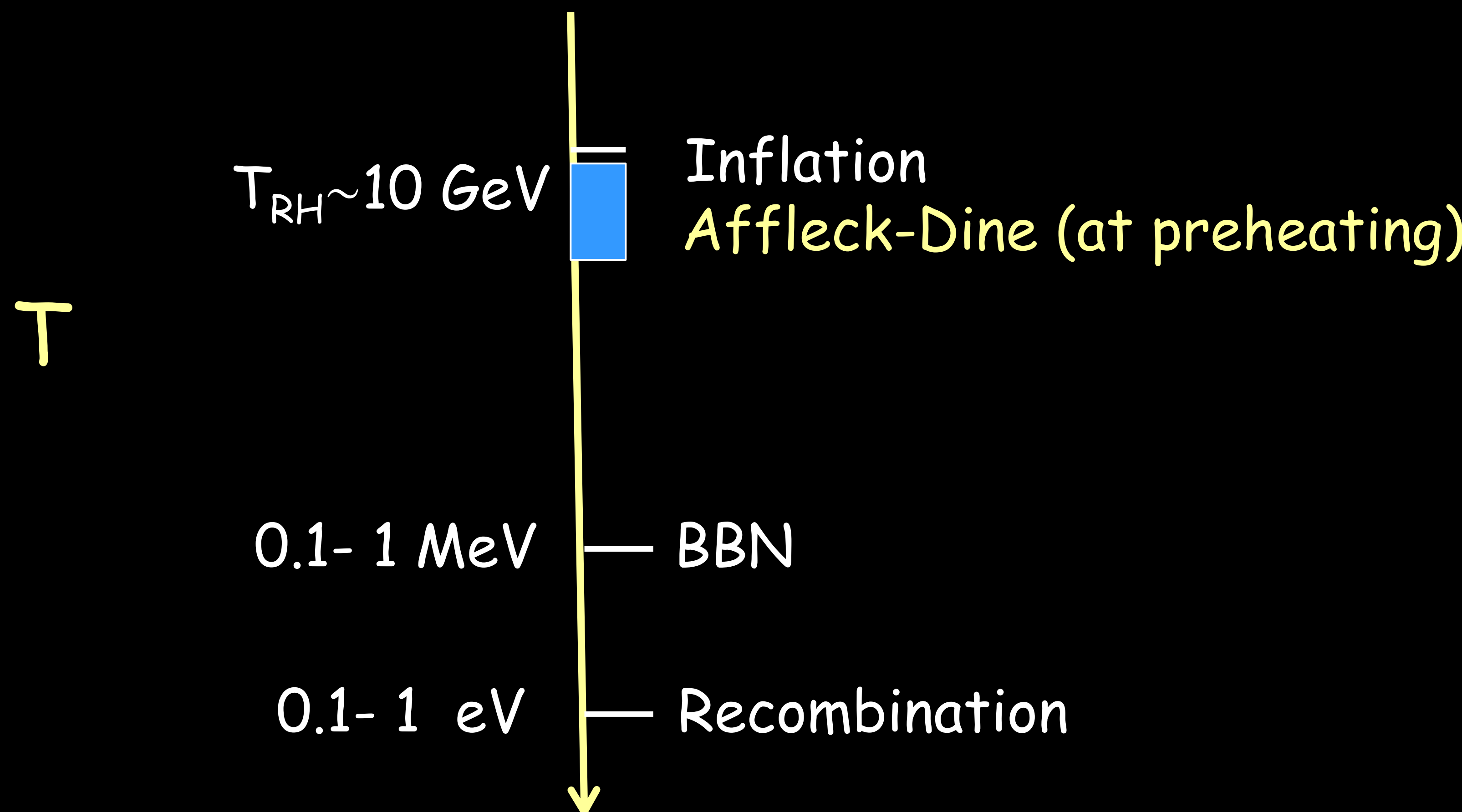
F term D term

A flat direction can be parametrized in terms of a complex field called AD field that carries a baryon number that is violated dynamically during inflation

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{m_{3/2}}{m_\Phi} \right) \left(\frac{m_\Phi}{\mathrm{TeV}} \right)^{-\frac{1}{2}} \left(\frac{M}{M_P} \right)^{\frac{3}{2}} \left(\frac{T_R}{10\,\mathrm{GeV}} \right)$$

The final asymmetry is $\propto T_{RH}$ and the observed one can be reproduced for low values $T_{RH} \sim 10$ GeV !

Baryogenesis and the early Universe history



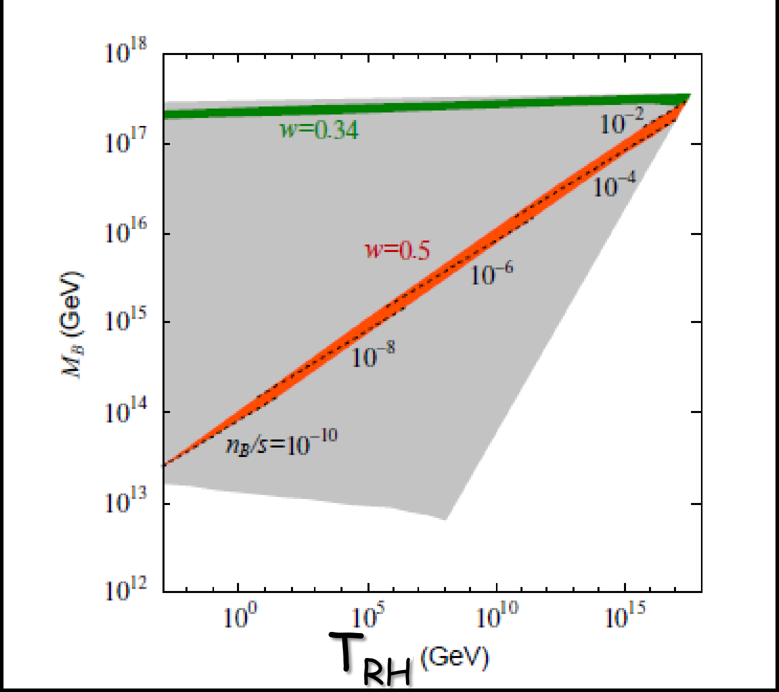
Gravitational Baryogenesis

(Davoudiasl, Kribs, Kitano, Murayama, Steinhardt '04)

The key ingredient is a CP violating interaction between the derivative of the Ricci scalar curvature $\mathcal{R}$ and the baryon number current J^μ:

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{R})J^\mu$$

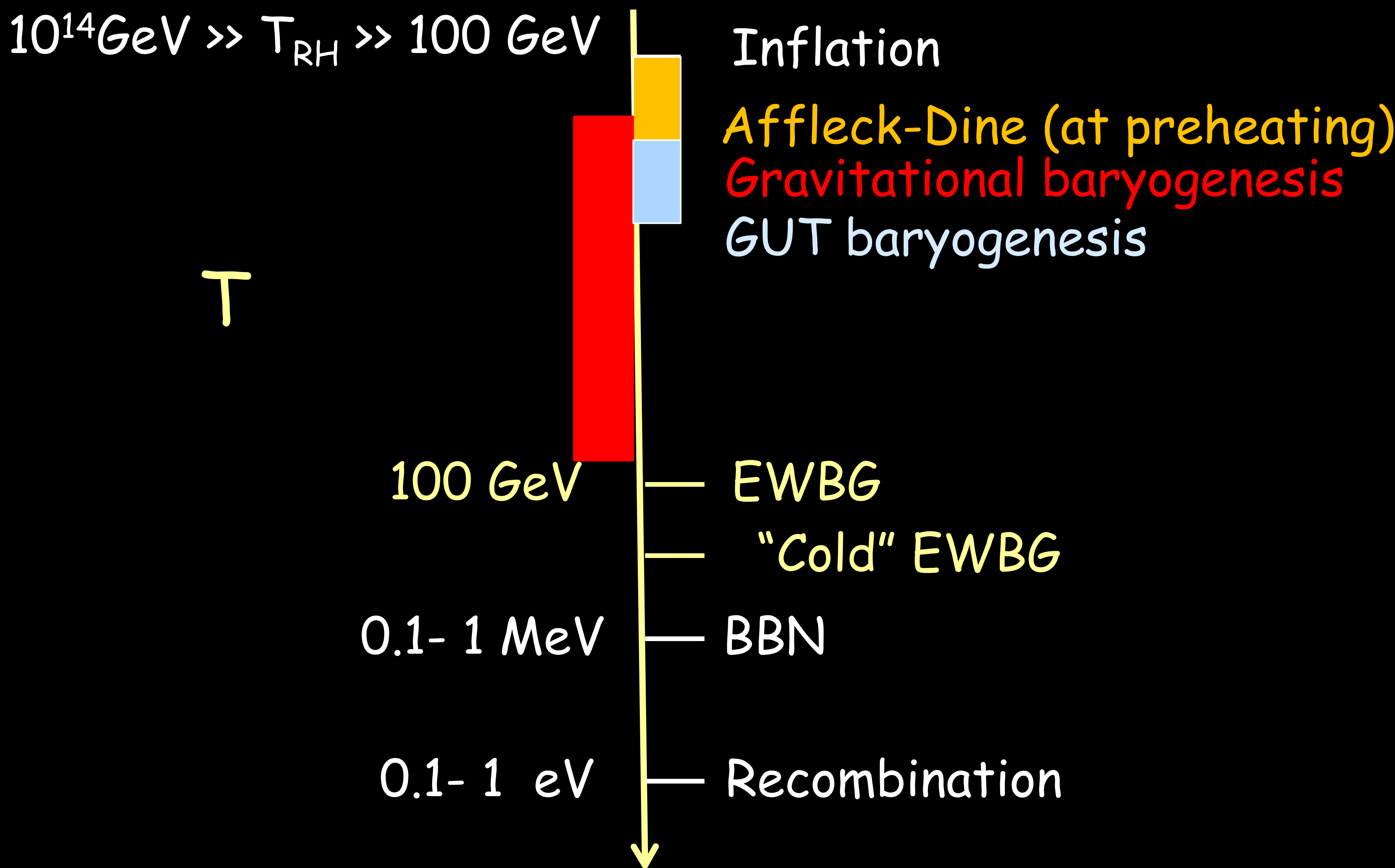
Cutoff scale of the effective theory



It is natural to have this operator in quantum gravity and in supergravity

It works (too ?) efficiently and asymmetries much larger than the observed one are generated for large T_{RH} >> 100 GeV

Baryogenesis and the early Universe history



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  - LEPTOGENESIS

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

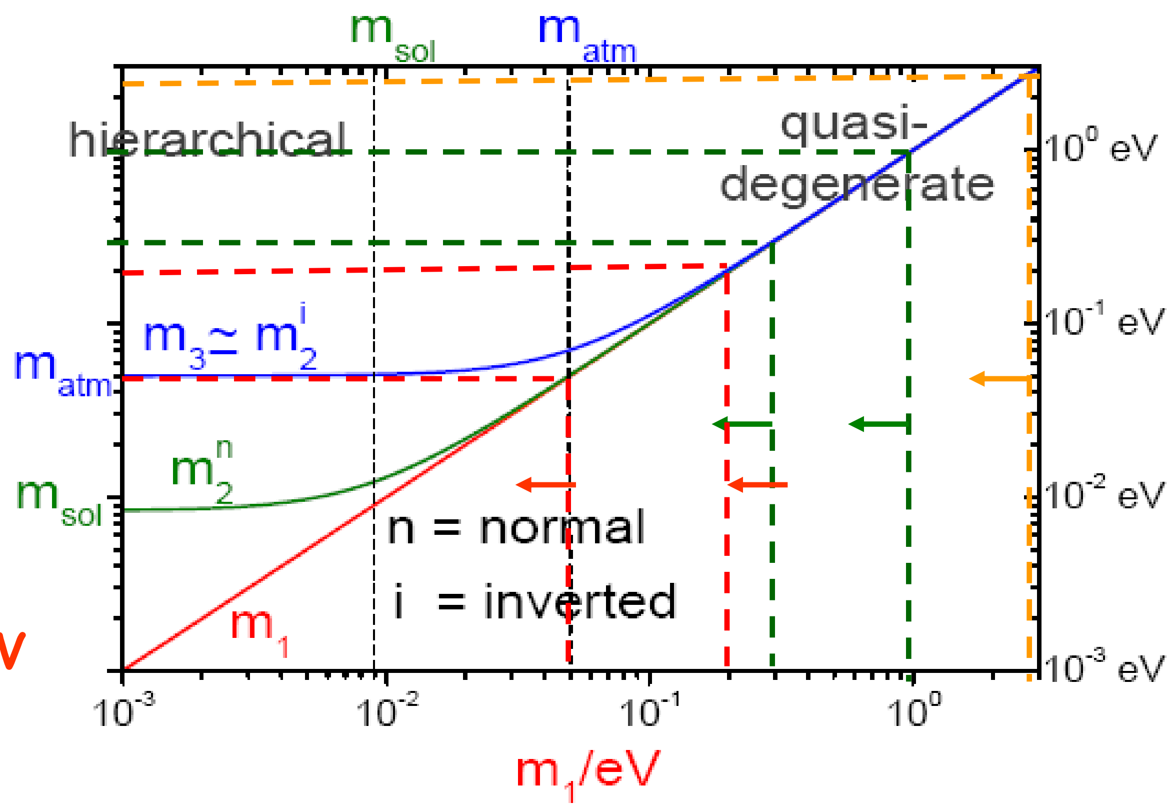
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

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

$\beta\beta 0\nu$: $m_{\beta\beta} <$ 0.3 - 1.0 eV
(Heidelberg-Moscow 90% CL,
similar result by CUORICINO)

CMB+BAO : $\Sigma\, m_i <$ 0.61 eV
(WMAP5+SDSS)
CMB+LSS + Lyα : $\Sigma\, m_i <$ 0.17 eV
(Seljak et al.)



Minimal scenario of Leptogenesis

(Fukugita, Yanagida '86)

- Type I seesaw

$$\mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2}\left[(\bar{\nu}^c_L, \bar{\nu}_R)\begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix}\right] + h.c.$$

In the see-saw limit ($M \gg m_D$) the spectrum of mass eigenstates splits in 2 sets:

- 3 light neutrinos $\nu_1,\ \nu_2,\ \nu_3$ with masses

$$\mathrm{diag}(m_1, m_2, m_3) = -U^{\dagger}\, m_D\, \frac{1}{M}\, m_D^T\, U^{\star}$$

- 3 new heavy RH neutrinos N_1,N_2,N_3 with masses $M_3 > M_2 > M_1 \gg m_D$

Total CP asymmetries

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

- Thermal production of the RH neutrinos $\Rightarrow$ $T \gtrsim M_i/5$

The importance of leptogenesis for testing the seesaw

Reconstructing M and m_D would provide a unique information on the new model embedding the seesaw addressing fundamental questions like

majorana mass M ? flavour ? How neutrino and quark Yukawa's are related ? why three families ?

But:

$$m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$$ (Casas, Ibarra '01)

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

- parameter counting: 6 + 3 + 6 + 3 = 18

Low energy neutrino experiments give information only on the 9 parameters in $m_\nu = -U\, D_m\, U^T$. The 6 parameters in the orthogonal matrix Ω (encodes the 3 life times and the 3 total CP asymmetries of the RH neutrinos and it is an invariant (King '07)) + the 3 masses M_i escape the conventional investigation !!

Leptogenesis complements low energy neutrino experiments constraining heavy neutrinos properties

Vanilla leptogenesis

1) Flavor composition of final leptons is neglected

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

Total CP asymmetries

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

If $\varepsilon_i \neq 0$ a **lepton asymmetry** is generated from N_i decays and partly converted into a **baryon asymmetry** by sphaleron processes **if $T_{reh} \gtrsim 100$ GeV !** (Kuzmin, Rubakov, Shaposhnikov, '85)

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

baryon-to-photon number ratio

efficiency factors $\simeq$ # of N_i decaying out-of-equilibrium

Successful leptogenesis : $\eta_B = \eta_B^{CMB} = (6.2 \pm 0.15) \times 10^{-10}$

Neutrino mass bounds in vanilla leptog.

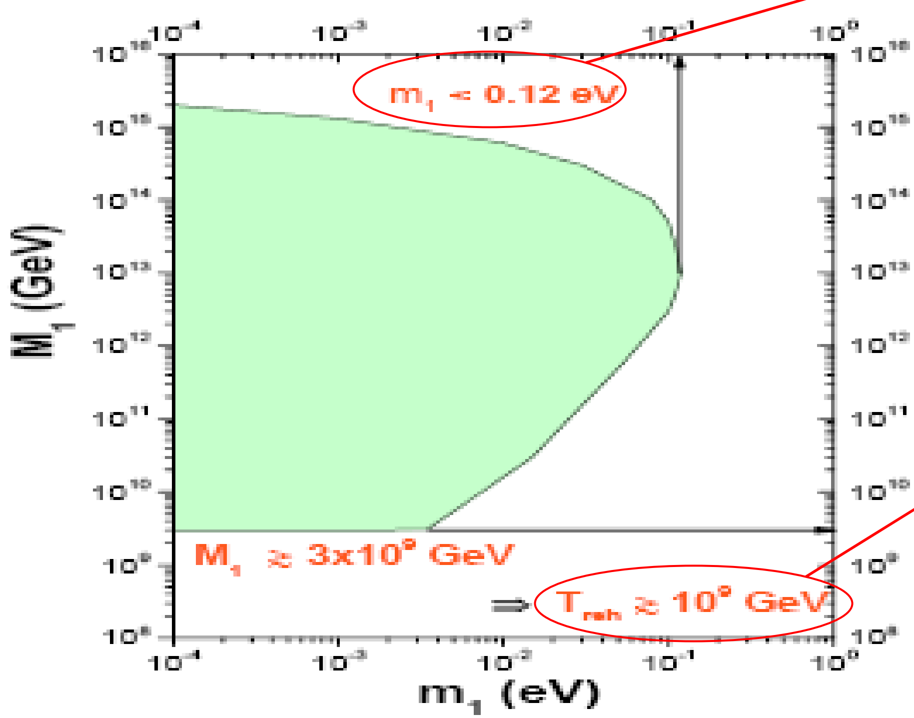
(Davidson,Ibarra '02;Buchmüller,PDB,Plümacher '02,'03,'04; Giudice et al. '04)

2) N_1 - dominated scenario

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

Imposing: $$\eta_B^{\rm max}(m_1, M_1) \geq \eta_B^{CMB}$$

No dipendence on the leptonic mixing matrix U !



Vanilla leptogenesis is not compatible with quasi-deg. neutrinos

These large temperatures in gravity mediated SUSY models suffer from the gravitino problem

SO(10)-inspired leptogenesis

(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03)

$$D_{m_D} = \mathrm{diag}\{\lambda_{D1}, \lambda_{D2}, \lambda_{D3}\}$$

$$m_D = V_L^\dagger \, D_{m_D} \, U_R$$ (bi-unitary parametrization)

assuming: 1) $\lambda_{D1} = \alpha_1 \, m_u \, , \; \lambda_{D2} = \alpha_2 \, m_c \, , \; \lambda_{D3} = \alpha_3 \, m_t \, , \quad (\alpha_i = \mathcal{O}(1))$

2) $V_L \simeq V_{CKM} \simeq I$

One typically has (there are some fine-tuned exceptions):

$$M_1 \sim \alpha_1 \, 10^5 \mathrm{GeV} \, , \; M_2 \sim \alpha_2 \, 10^{10} \, \mathrm{GeV} \, , \; M_3 \sim \alpha_3 \, 10^{15} \, \mathrm{GeV}$$

since $M_1 \ll 10^9$ GeV $\Rightarrow \eta_B(N_1) \ll \eta_B^{CMB}$!

$\Rightarrow$ failure of the N_1-dominated scenario !

Independence of the initial conditions

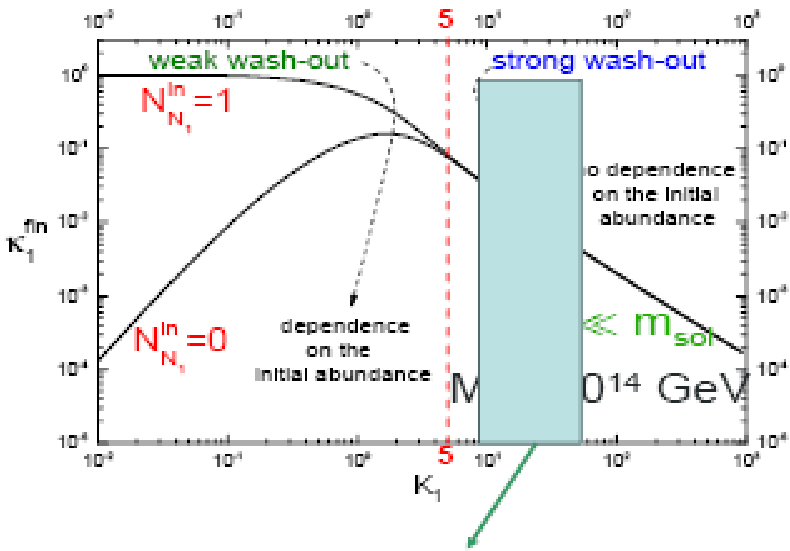
The early Universe „knows" neutrino masses ...

(Buchmüller, PDB, Plümacher '04)

$$\eta_B \simeq 0.01\, \varepsilon_1(m_1, M_1, \Omega)\, \kappa_1^{\rm fin}(K_1)$$

decay parameter

$$K_1 \equiv \frac{\Gamma_{N_1}}{H(T = M_1)} \sim \frac{m_{\rm sol,atm}}{m_\star \sim 10^{-3}\,{\rm eV}} \sim 10 \div 50$$

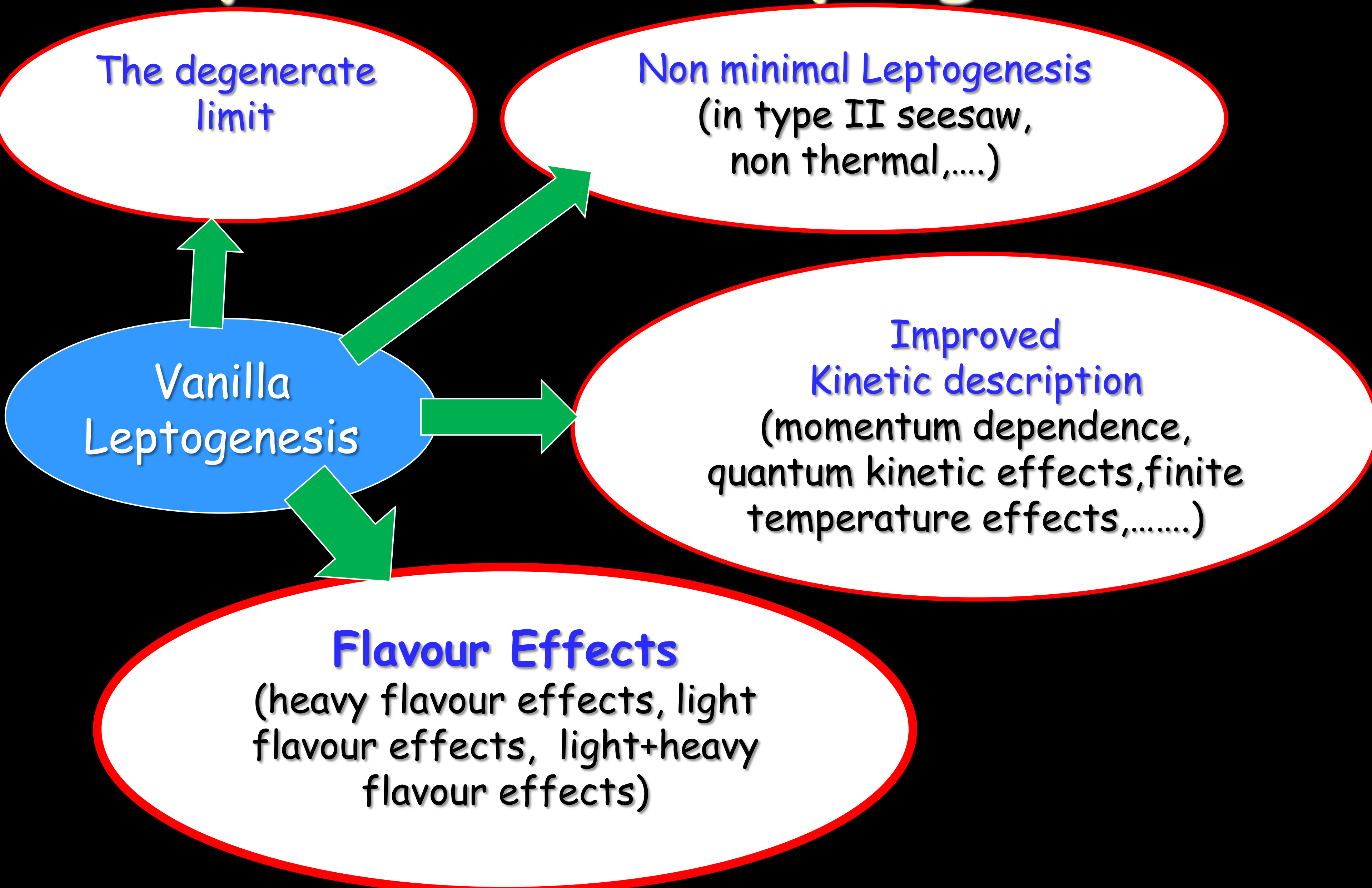


$$K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}$$

wash-out of a pre-existing asymmetry

$$N_{B-L}^{\rm p,final} = N_{B-L}^{\rm p,initial}\, e^{-\frac{3\pi}{8} K_1} \ll N_{B-L}^{\rm f,N_1}$$

Beyond vanilla Leptogenesis



Light flavour effects

(Nardi,Nir,Roulet,Racker '06;Abada,Davidson,Losada,Josse-Michaux,Riotto'06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states:

$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1\rangle \, |l_\alpha\rangle \quad (\alpha = e, \mu, \tau) \qquad P_{1\alpha} \equiv |\langle l_\alpha | l_1\rangle|^2$$

$$|\bar{l}'_1\rangle = \sum_\alpha \langle l_\alpha | \bar{l}'_1\rangle \, |\bar{l}_\alpha\rangle \qquad \bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}'_1\rangle|^2$$

It does not play any role for $M_1 \gtrsim \mathcal{O}(10^{12}\,\text{GeV})$

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

$\Longrightarrow$ become an incoherent mixture of a τ and of μ+e

If $M_1 \lesssim 10^9$ GeV then also μ- Yukawas in equilibrium $\Longrightarrow$ 3-flavor regime

$$\Rightarrow N_{B-L}^{\rm fin} = \sum_{i,\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}^{\rm fin} \quad (\alpha = e, \mu, \tau)$$

i: heavy neutrino flavor index

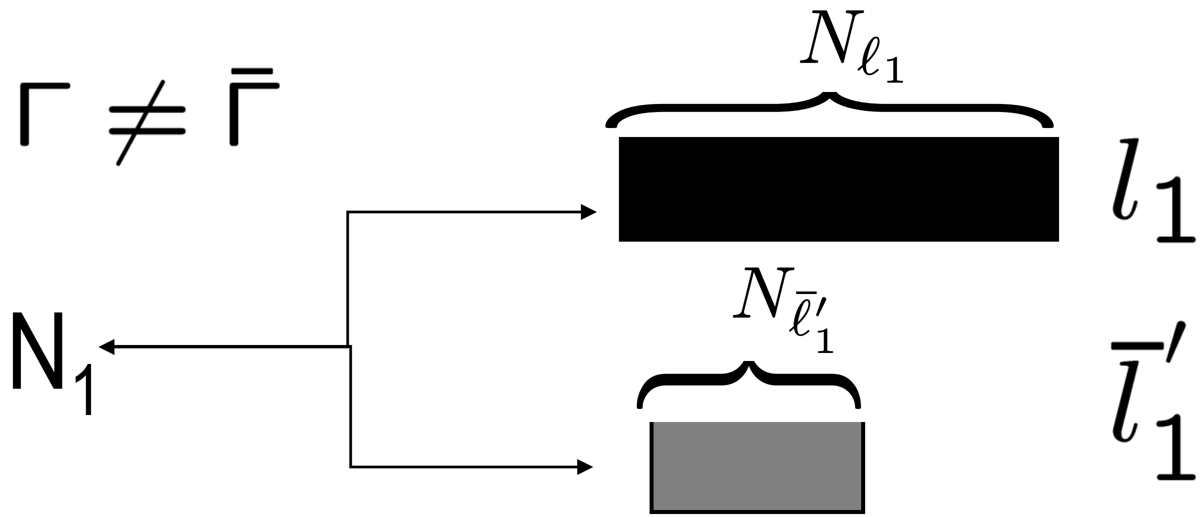
α: lepton flavor index

The additional contribution to CP violation:

$$\varepsilon_{1\alpha} = P^0_{1\alpha}\,\varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$$

depends on U !

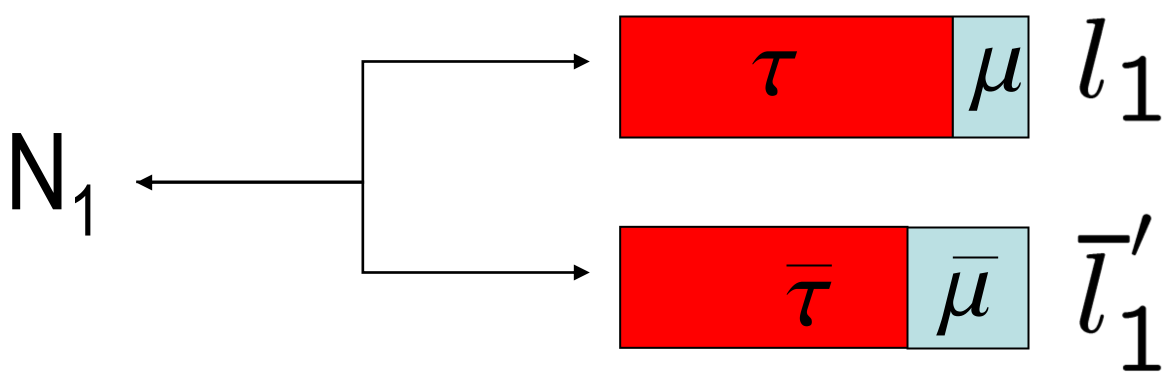
1) $\Gamma \neq \bar{\Gamma}$



$\Rightarrow \; P^0_{1\alpha}\,\varepsilon_1$

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

+



$\Rightarrow \; \frac{\Delta P_{1\alpha}}{2}$

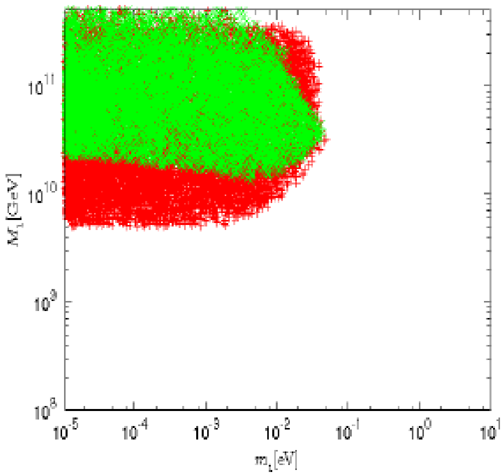
Low energy phases as the only source of CP violation

(Nardi et al; Blanchet,PDB, '06; Pascoli, Petcov, Riotto; Anisimov, Blanchet, PDB '08)

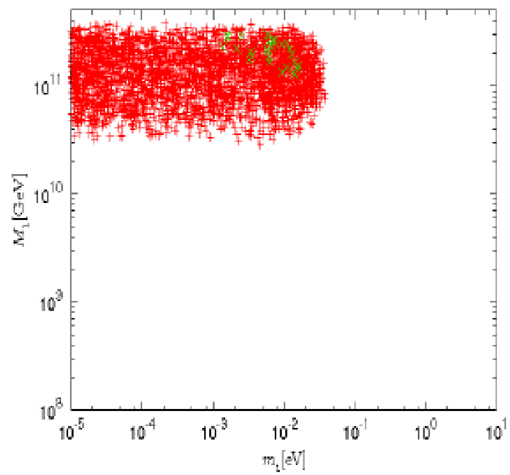
The whole CP violation can stems just from low energy phases (Dirac, Majorana phases) and still it is possible to have successful leptogenesis !

(Blanchet, PDB '09)

initial thermal N_1 abundance



independent of initial N_1 abundance



Green points: only Dirac phase with sin θ_{13}= 0.2

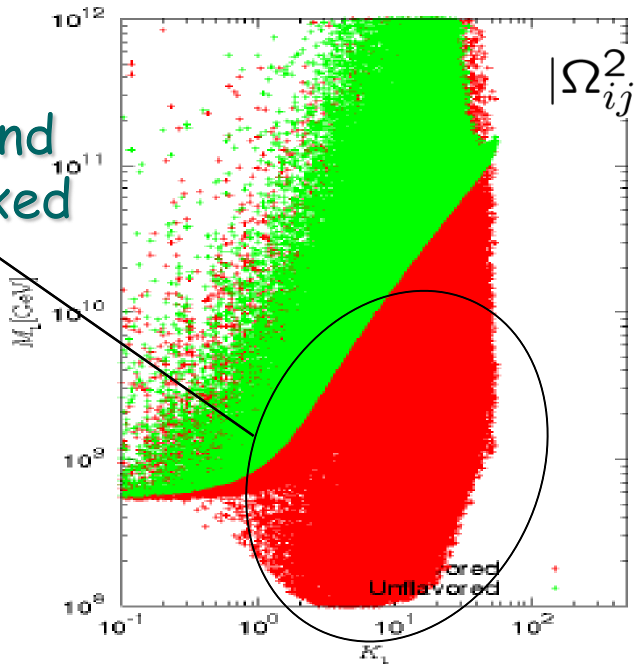
Red points: only Majorana phases

However, in general, we cannot constraint the low energy phases with leptogenesis and viceversa we cannot test leptogenesis just measuring CP violation at low energies: we need to add some further condition !

The lower bounds on M_1 and on T_{reh} get relaxed:

(Blanchet, PDB '08)

The usual lower bound gets relaxed



$|\Omega_{ij}^2| \lesssim 10$

Heavy flavour effects: N_2-dominated scenario

(PDB '05; Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)

If light flavour effects are neglected the asymmetry from the next-to-lightest (N_2) RH neutrinos is typically negligible:

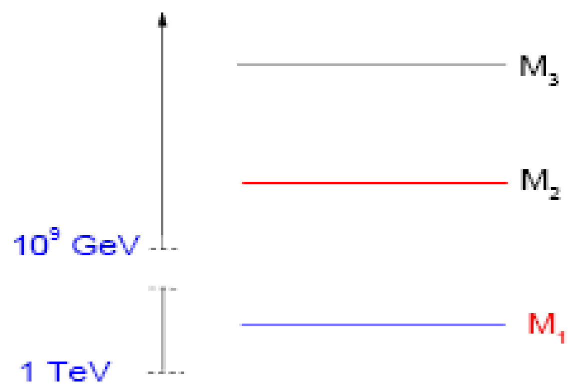
$$N_{B-L}^{\mathrm{f},\mathrm{N}_2} = \varepsilon_2 \cdot (K_2)\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\mathrm{f},\mathrm{N}_1} = \varepsilon_1 \cdot (K_1)$$

...except for a special choice of $\Omega=R_{23}$ when $K_1= m_1/m_* \ll 1$ and $\varepsilon_1=0$:

$$\Rightarrow \boxed{N_{B-L}^{\mathrm{fin}} = \sum_i \varepsilon_i\, \kappa_i^{\mathrm{fin}} \simeq \varepsilon_2\, \kappa_2^{\mathrm{fin}}}$$

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} !



N_2-flavored leptogenesis

(Vives '05; Blanchet, PDB '06; Blanchet, PDB '08)

If light and heavy flavour effects are combined together:

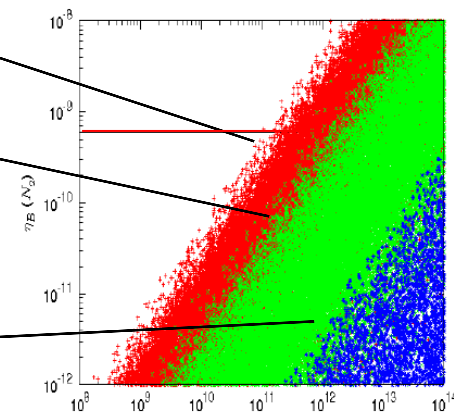
$$N_{B-L}^{\rm f}(N_2) = P_{2e}^0\,\varepsilon_2\cdot(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P_{2\mu}^0\,\varepsilon_2\cdot(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P_{2\tau}^0\,\varepsilon_2\cdot(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}$$

Notice that $K_1 = K_{1e} + K_{1\mu} + K_{1\tau}$

Wash-out is neglected

Wash-out and flavor effects are both taken into account

Unflavored case



η_B^{CMB}

η_B

M_2

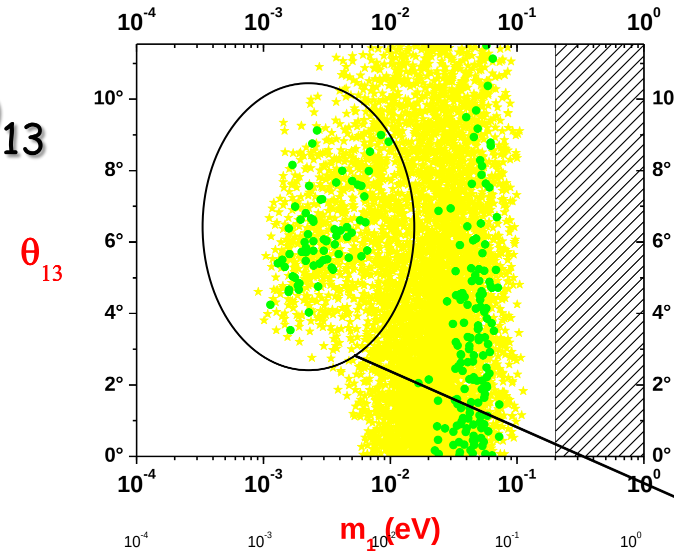
Thanks to flavor effects the domain of applicability extends much beyond the particular choice $\Omega = R_{23}$!

The N_2-dominated scenario rescues SO(10) inspired models ! (PDB, Riotto '08)

$$N^{\rm f}_{B-L} \simeq \varepsilon_{2e}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1e}} + \varepsilon_{2\mu}\,\kappa(K_{2e+\mu})\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + \varepsilon_{2\tau}\,\kappa(K_{2\tau})\,e^{-\frac{3\pi}{8}\,K_{1\tau}}\,.$$

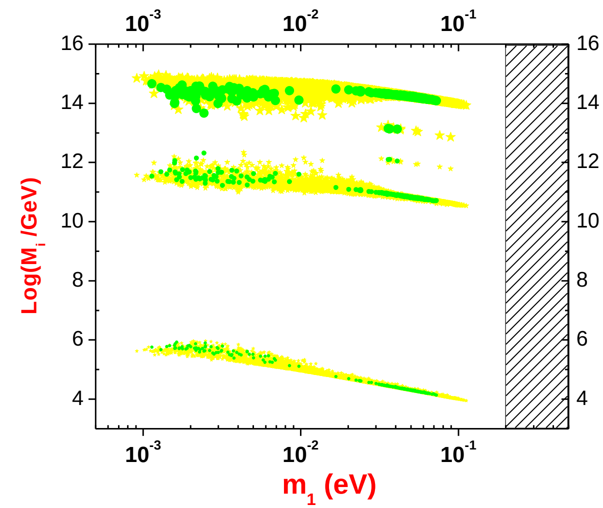
The green points correspond to $\eta_B > \eta_B^{CMB}$ at 2σ:

Θ_{13}

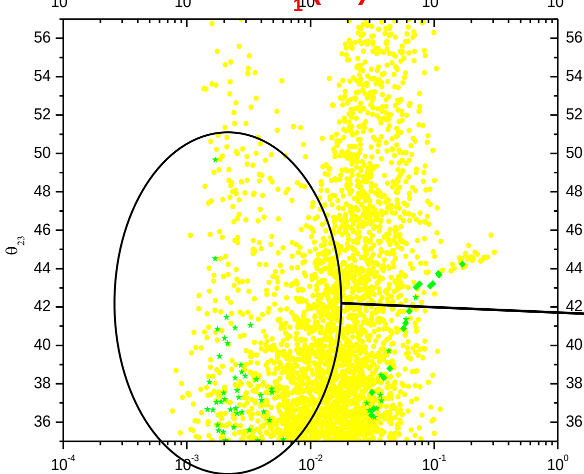


α_2=5

V_L= I



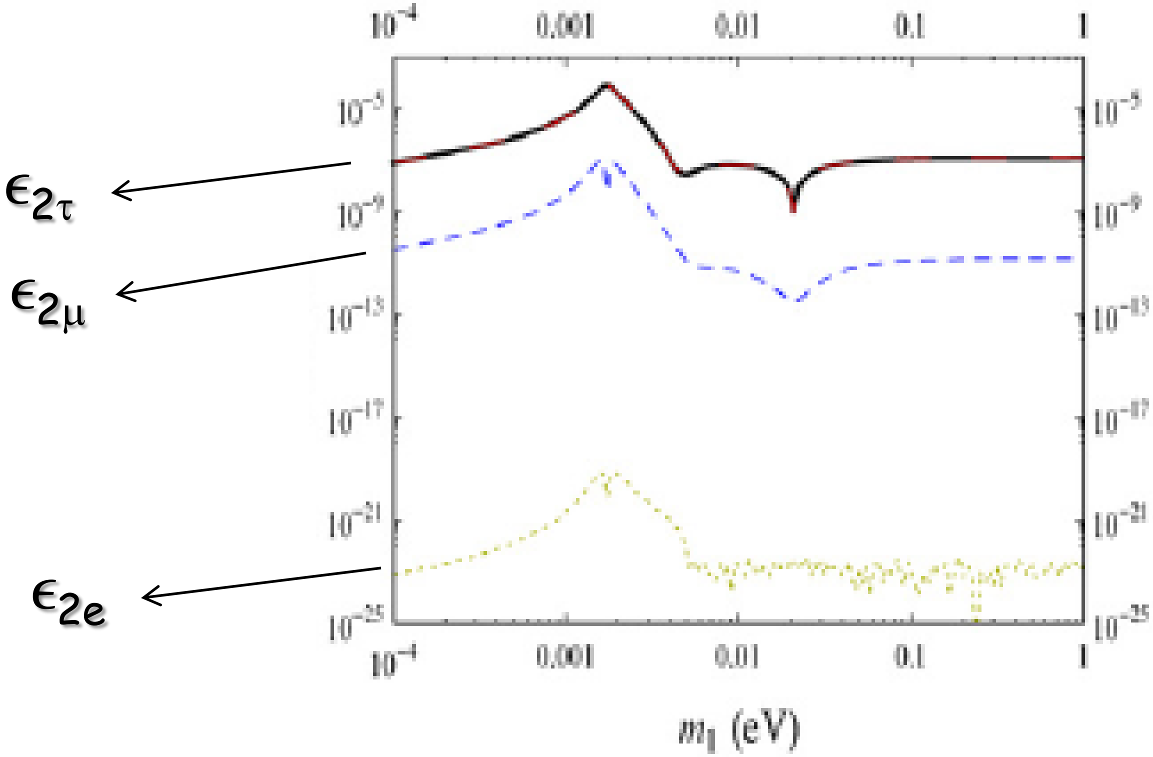
Θ_{23}



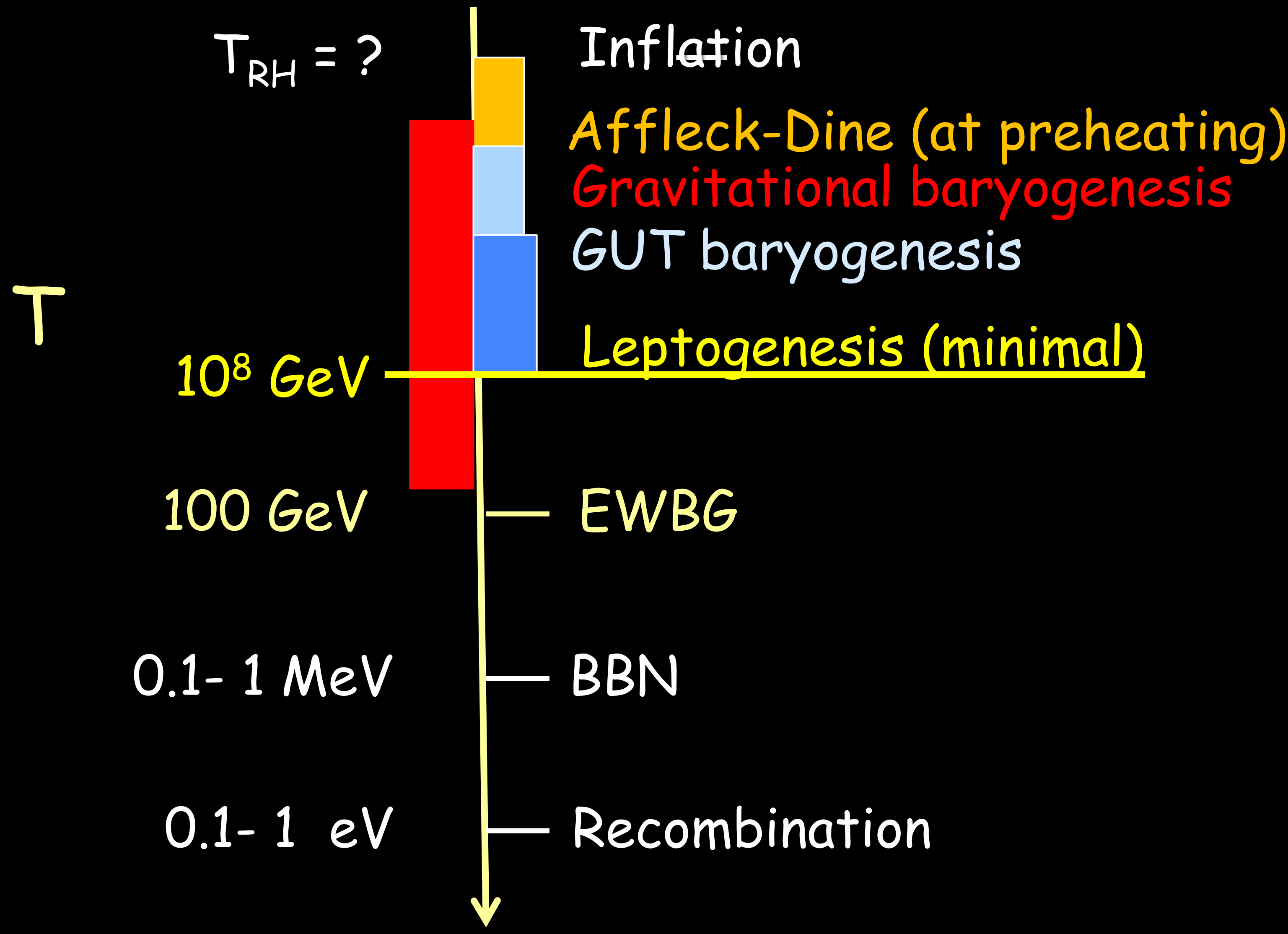
A lower bound on Θ_{13} ?

An upper bound on Θ_{23} ?

For the solution with $m_1 \sim 3\times10^{-3}$ eV the asymmetry is dominantly produced in the tauon flavour since $\epsilon_{2\tau,\mu,e} \propto (m_{t,c,u})^2$



Baryogenesis and the early Universe history



The problem of the initial conditions in flavoured leptogenesis

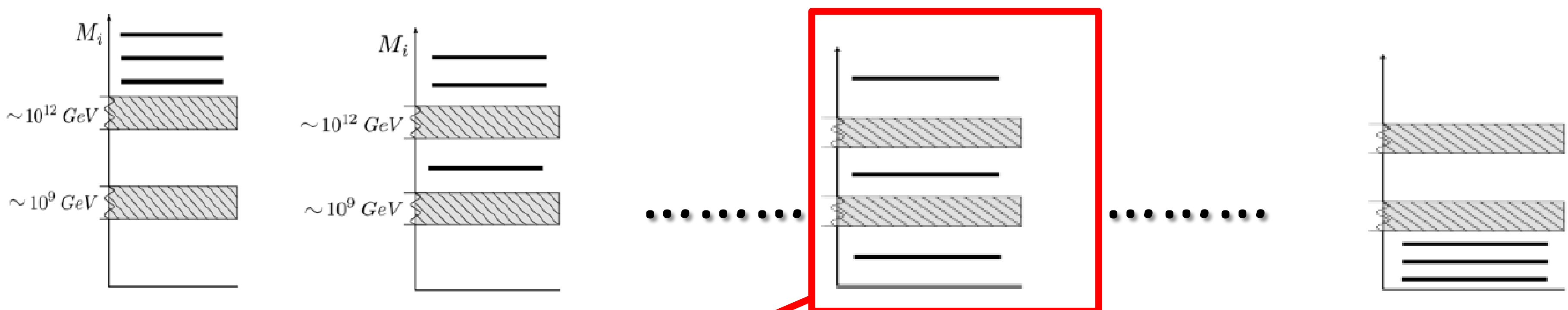
(Bertuzzo,PDB,Marzola '10)

Residual "pre-existing" asymmetry possibly generated by some external mechanism

$$N_{B-L}^{\rm f} = N_{B-L}^{\rm p,f} + N_{B-L}^{\rm lep,f}$$

Asymmetry generated from leptogenesis

One has to distinguish 10 different RH neutrino mass patterns:



The wash-out of a pre-existing asymmetry is guaranteed only in a tauon N_2-dominated scenario!

Important loophole: in supersymmetric models (Antusch,King,Riotto'06) also in N_1 dominated scenarios with $\tan^2\beta \gtrsim 20$

Flavour coupling

(Buchmuller, Plumacher '01; Barbieri et al.'01; Nardi et al.'06;Blanchet, PDB '08)

Taking into accounts that an Higgs boson asymmetry is also produced in the decays of the RH neutrinos and that the lepton asymmetries are redistributed by gauge interactions into quarks and charged leptons as well, the set of kinetic equations becomes:

$$\frac{dN_{N_i}}{dz} = -D_i\left(N_{N_i} - N_{N_i}^{\rm eq}\right) \quad (i=1,2,3),$$

$$\frac{dN_{\Delta_\alpha}}{dz} = \sum_i \varepsilon_{i\alpha} D_i\left(N_{N_i} - N_{N_i}^{\rm eq}\right) - \sum_{i,\beta} P_{i\alpha}^0 \left(C_{\alpha\beta}^{\ell} + C_{\beta}^{H}\right) W_i^{\rm ID} N_{\Delta_\beta},$$

$$\Delta_\alpha \equiv B/3 - L_\alpha \; (\alpha = e, \mu, \tau)$$

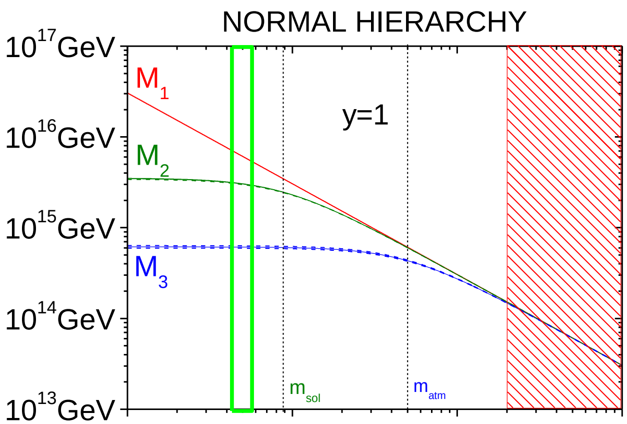
The flavored asymmetries dynamics couple !

Flavor coupling does not relevantly affect the final asymmetry In N_1-leptogenesis (Abada, Josse-Michaux '07) but a strong enhancement is possible in N_2-leptogenesis !

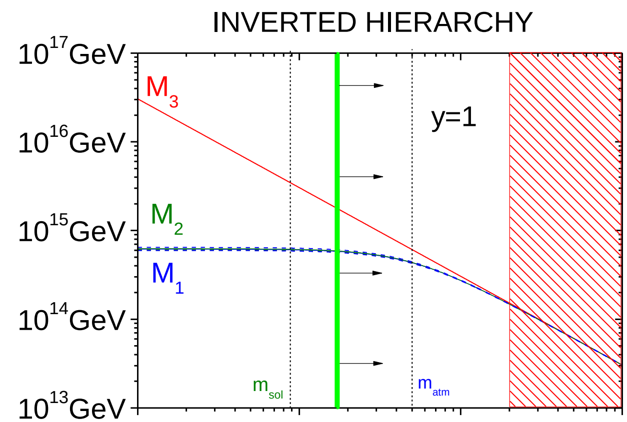
(Antusch, PDB, Jones, King '10)

Leptogenesis and discrete flavour symmetries: A4

(Ma '04; Altarelli, Feruglio '05; Bertuzzo, Di Bari, Feruglio, Nardi '09;Hagedorn,Molinaro,Petcov '09)

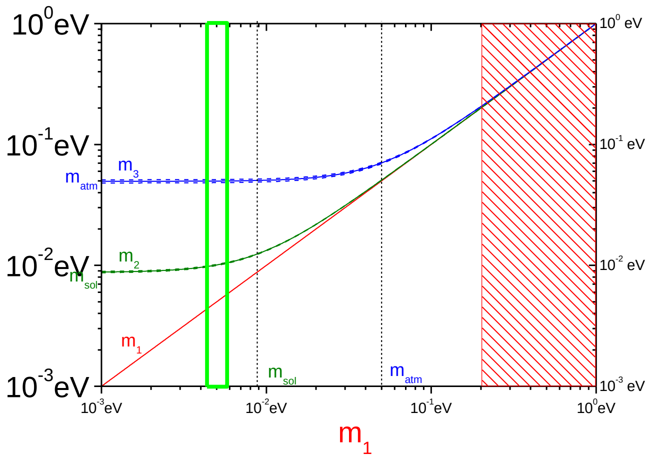


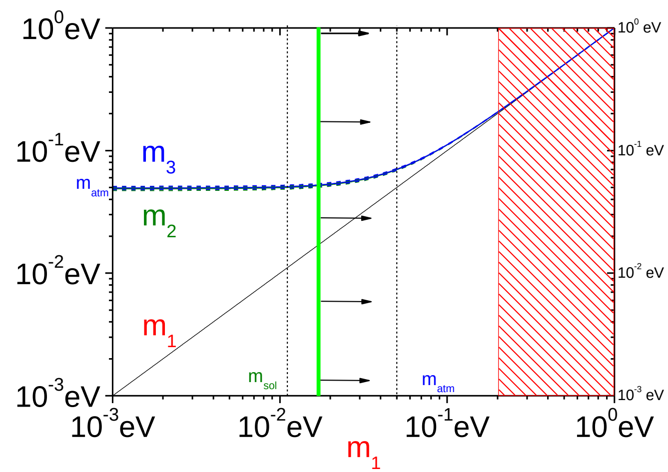
$$m_i = \frac{y^2\, v_u^2}{M_j}$$



$$m_1 \simeq 5 \times 10^{-3}\,\mathrm{eV}$$

$$m_1 \gtrsim 0.017\,\mathrm{eV}$$





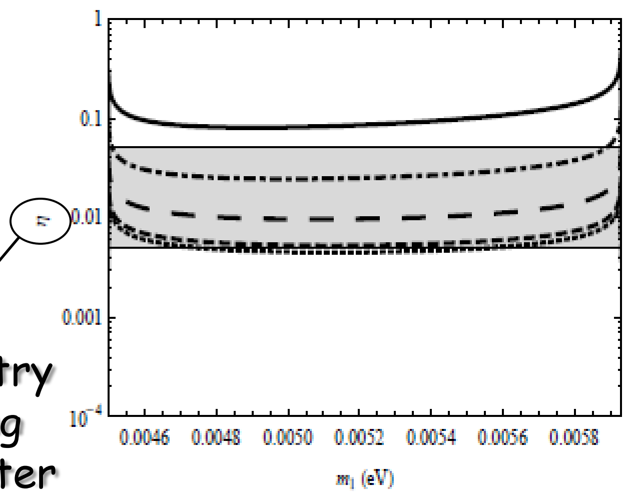
The situation is less attractive than in SO(10) inspired models because the RH neutrino mass spectrum first requires very high temperatures, second it does not allow a wash-out of a pre-existing asymmetry

Leptogenesis in A4 models

(Ma '04; Altarelli, Feruglio '05; Bertuzzo, Di Bari, Feruglio, Nardi '09)

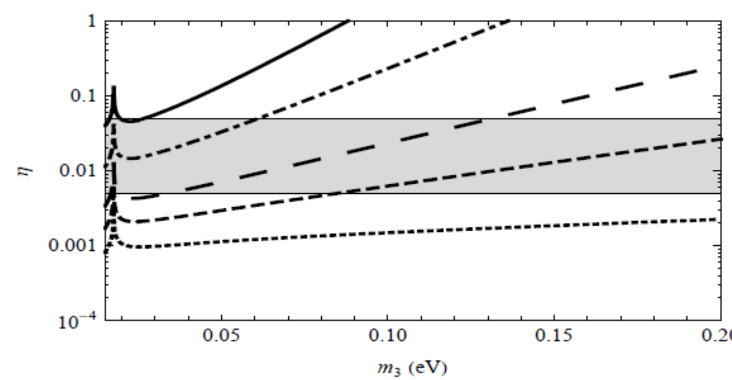
However successful leptogenesis seems to be possible (better in the normal hierarchical case) just for the best values of the symmetry breaking parameters

Normal ordering



Symmetry Breaking parameter

Inverted ordering



The different lines correspond to values of y between 0.3 and 3

Conclusions

Baryogenesis is not only a missing stage in the early Universe history but also an important tool for BSM investigation. A very long list of proposed models, some of which even able to produce much larger asymmetries than the observed one.

EWB seems at the moment in "stand by" but it could become again a viable solution if e.g. supersymmetry is discovered.

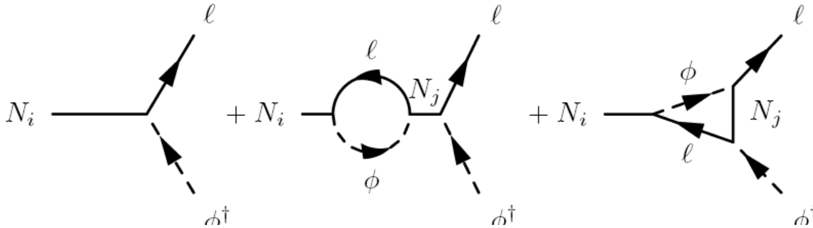
In Leptogenesis on the other hand the necessary BSM condition has been already found (neutrino masses) and we are seeking a way to (dis)prove it !

In minimal leptogenesis (type I + thermal), flavour effects make the N_2 dominated scenario as quite an attractive option: it rescues SO(10)-inspired scenarios providing a well motivated framework testable (to some extent) at future low energy neutrino experiments.

It is quite intriguing that SO(10)-inspired leptogenesis fulfil those quite specific requirements necessary for a complete independence of the initial conditions! Constraints on low energy neutrino parameters become then more robust

Leptogenesis is an interesting guidance for the identification of the theory responsible for neutrino masses and mixing underlying the seesaw mechanism (GUT's ? Flavor symmetries ? Either ? Neither ?)

The total CP asymmetries can be calculated from :



(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 !

It holds if:

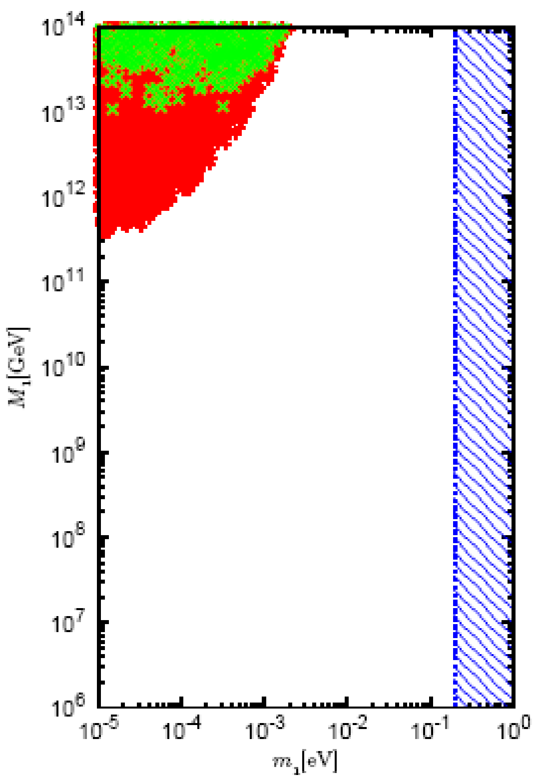
Hierarchical RH neutrino spectrum $\quad M_2 \gtrsim 100\, M_1$

N_3 does not interfere with N_2-decays: $\quad (m_D^\dagger\, m_D)_{23} = 0$ (PDB '05)

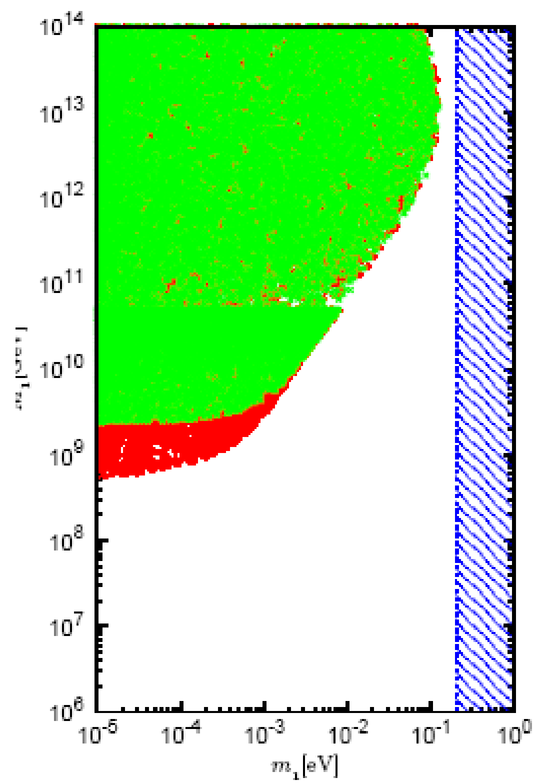
under these two conditions $\quad \Rightarrow |\varepsilon_{2,3}|^{\max} \ll |\varepsilon_1|^{\max}$

Leptogenesis "conspiracy" (2)

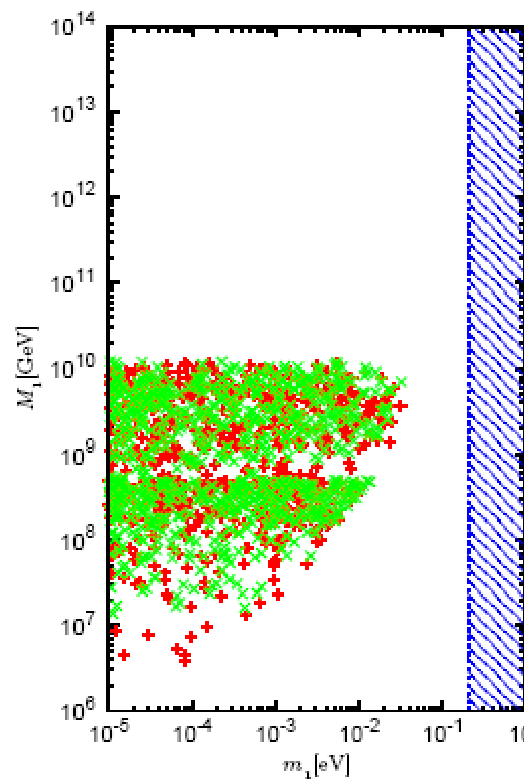
$m_{atm} = 10^{-5}\, eV$



$m_{atm} = 0.05\, eV$



$m_{atm} = 10\, eV$



Green points: Unflavored

Red points: Flavored

Flavoured Boltzmann equations

- $$P_{1\alpha} \equiv |\langle l_\alpha | l_1 \rangle|^2 = P^0_{1\alpha} + \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha P^0_{1\alpha} = 1 \right)$$
  $$\bar{P}_{1\alpha} \equiv |\langle \bar{l}_\alpha | \bar{l}'_1 \rangle|^2 = P^0_{1\alpha} - \Delta P_{1\alpha}/2 \qquad \left(\sum_\alpha \Delta P_{1\alpha} = 0 \right)$$

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)

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

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

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

The double side of Leptogenesis

Cosmology (early Universe)

Neutrino Physics, New Physics

- ***Cosmological Puzzles*** :

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

- ***New stage in early Universe history*** :

T

T	
< 10^{14} GeV	Inflation
	Leptogenesis
100 GeV	EWSSB
0.1- 1 MeV	BBN
0.1- 1 eV	Recombination

Leptogenesis complements
low energy neutrino experiments
testing the
high energy parameters
of the seesaw mechanism

$\Rightarrow$ It provides a precious guidance to try to understand what kind of new physics is responsible for the neutrino masses and mixing

Beyond the type I seesaw

It is motivated typically by two reasons:

- Again avoid the reheating temperature lower bound
- In order to get new phenomenological tests….the most typical motivation in this respect is quite obviously whether we can test the seesaw and leptogenesis at the LHC

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

Many different proposals to circumvent the problem:

- additional gauged $U(1)_{B-L}$ (King,Yanagida '04)
- leptogenesis with Higgs triplet (type II seesaw mechanism) (Ma,Sarkar '00 ; Hambye,Senjanovic '03; Rodejohann'04; Hambye,Strumia '05; Antusch '07)
- leptogenesis with three body decays (Hambye '01)
- see-saw with vector fields (Losada,Nardi '07)
- inverse seesaw mechanism and leptogenesis

(talk by R. Mohapatra)

Efficiency factor

decay parameter

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

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

decays

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

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

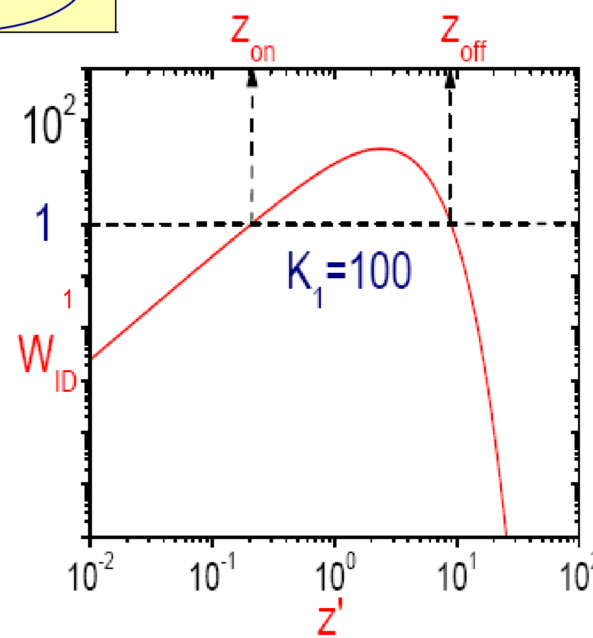
inverse decays

wash-out

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

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

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



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

Non minimal leptogenesis

Non thermal leptogenesis

The RH neutrino production is non-thermal and typically associated to inflation. They are often motivated in order to obtain successful leptogenesis with low reheating temperature.

- RH neutrino production from inflaton decays (Shafi,Lazarides' 91)

- Leptogenesis from RH sneutrinos decays (Murayama,Yanagida ' 93)

- RH neutrinos can also be produced at the end of inflation during the pre-heating stage (Giudice,Peloso,Riotto,Tkachev99)

-The connections with low energy neutrino experiments become even looser in these scenarios, while they can be made with properties of CMBR anisotropies (Asaka, Hamaguchi,Yanagida '99)

Improved kinetic description

- Momentum dependence in Boltzmann equations

  (Hannestad ' 06; Hahn-Woernle, M. Plümacher, Y.Wong '09; Pastor, Vives'09)

- Kadanoff-Baym equations

  (Buchmüller,Fredenhagen '01; De Simone,Riotto '07; Garny,Hohenegger, Kartavtsev,Lindner '09; Anisimov,Buchmüller,Drewes,Mendizibal '09; Beneke, Garbrecht, Herranen, Schwaller '10)

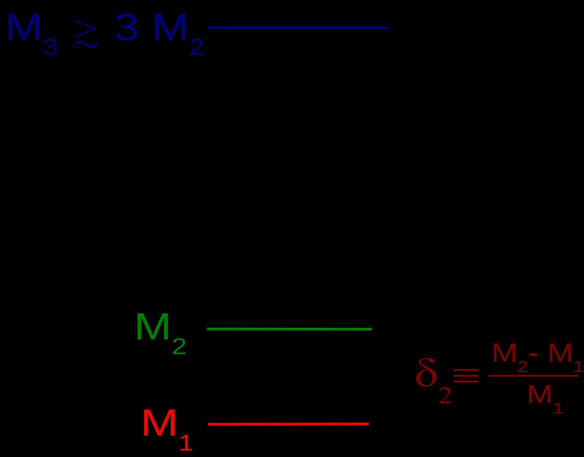
  The asymmetry is directly calculated in terms of Green functions instead than in terms of number densities and they account for off-shell , memory and medium effects in a systematic way

At the moment all these analyses confirm what also happens for other effects (e.g. inclusion of scatterings) and that is expected: large theoretical uncertainties in the weak wash-out regime, limited corrections ($\mathcal{O}(1)$) in the strong wash-out regime where the asymmetry is produced in a narrow range of temperatures for T « M_i (Buchmüller,PDB,Plümacher

The degenerate limit

(Covi, Roulet, Vissani '96; Pilaftsis ' 97; Blanchet, PDB '06)

Different possibilities, for example: :



- partial hierarchy: $M_3 \gg M_2\ ,\ M_1$

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

CP asymmetries get enhanced $\propto 1/\delta_2$

$$\Rightarrow N_{B-L}^{\text{fin}} \nearrow$$

For $\delta_2 \lesssim 0.01$ (**degenerate limit**) :

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

The reheating temperature lower bound is relaxed

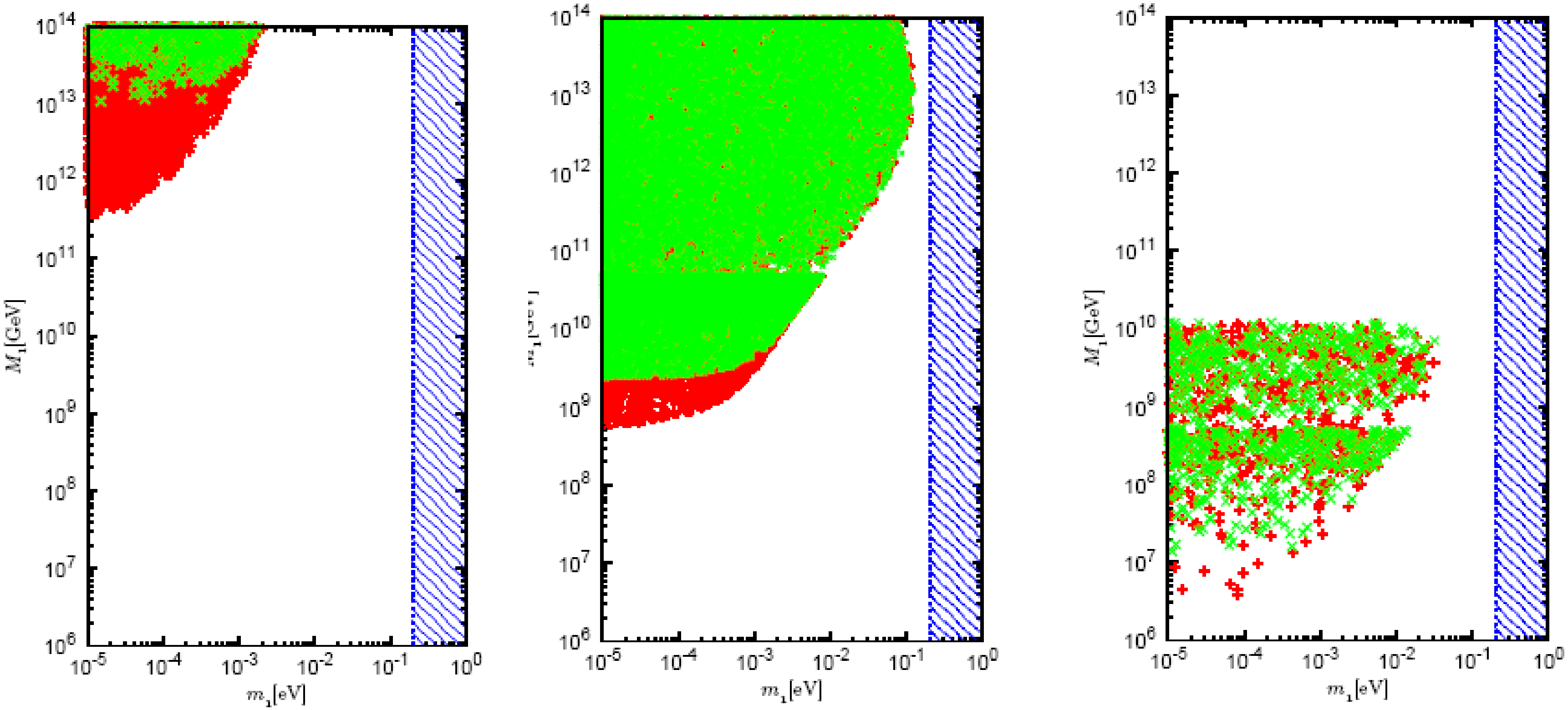
The required tiny value of δ_2 can be obtained e.g. in ***radiative leptogenesis*** (Branco, Gonzalez, Joaquim, Nobre'04,'05)

Flavor effects do not spoil the conspiracy

Green points: Unflavored

Red points: Flavored

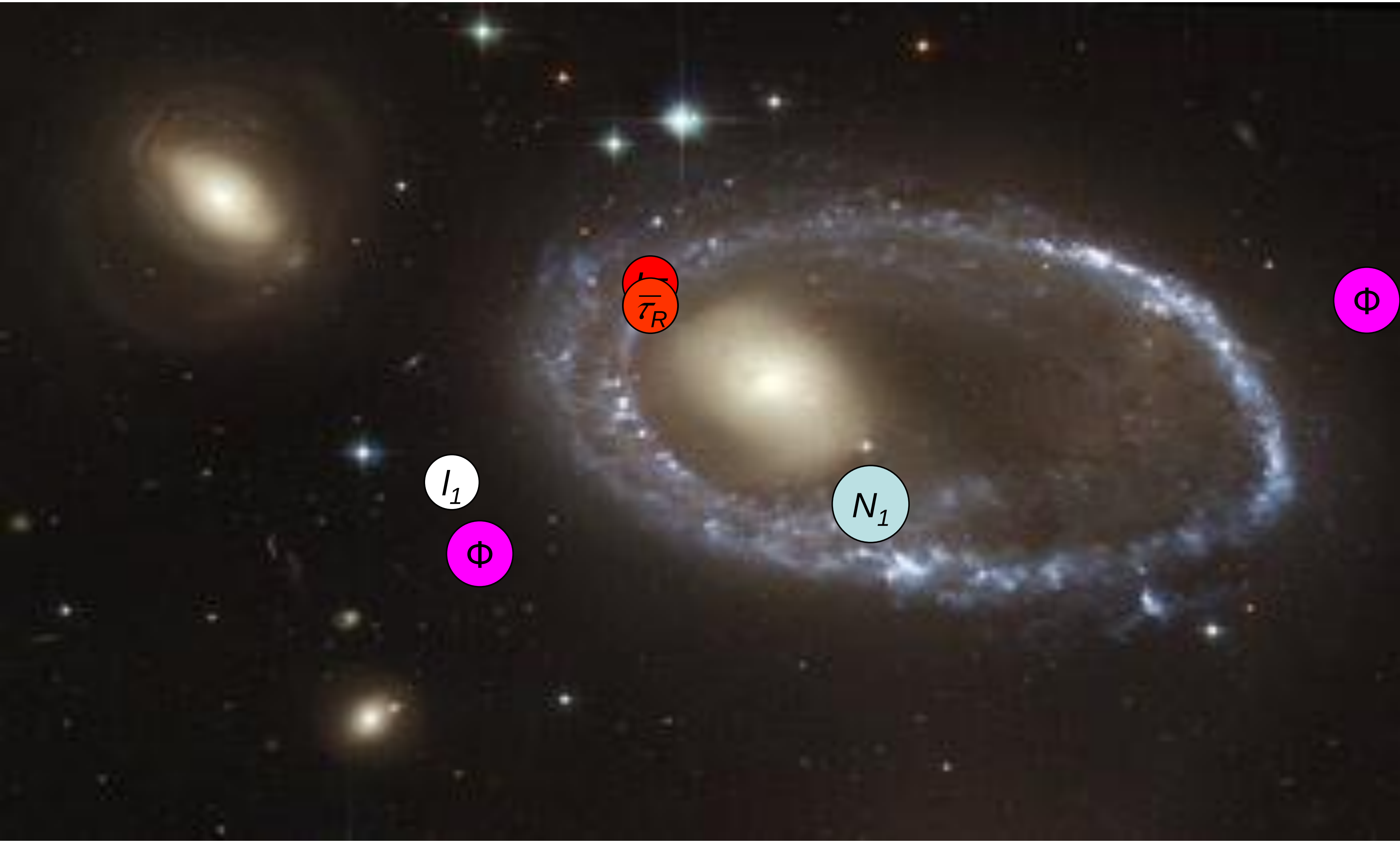
$m_{atm} = 10^{-5}\, eV$ $m_{atm} = 0.05\, eV$ $m_{atm} = 10\, eV$



….but they yield two interesting results:

(Blanchet, PDB '06)

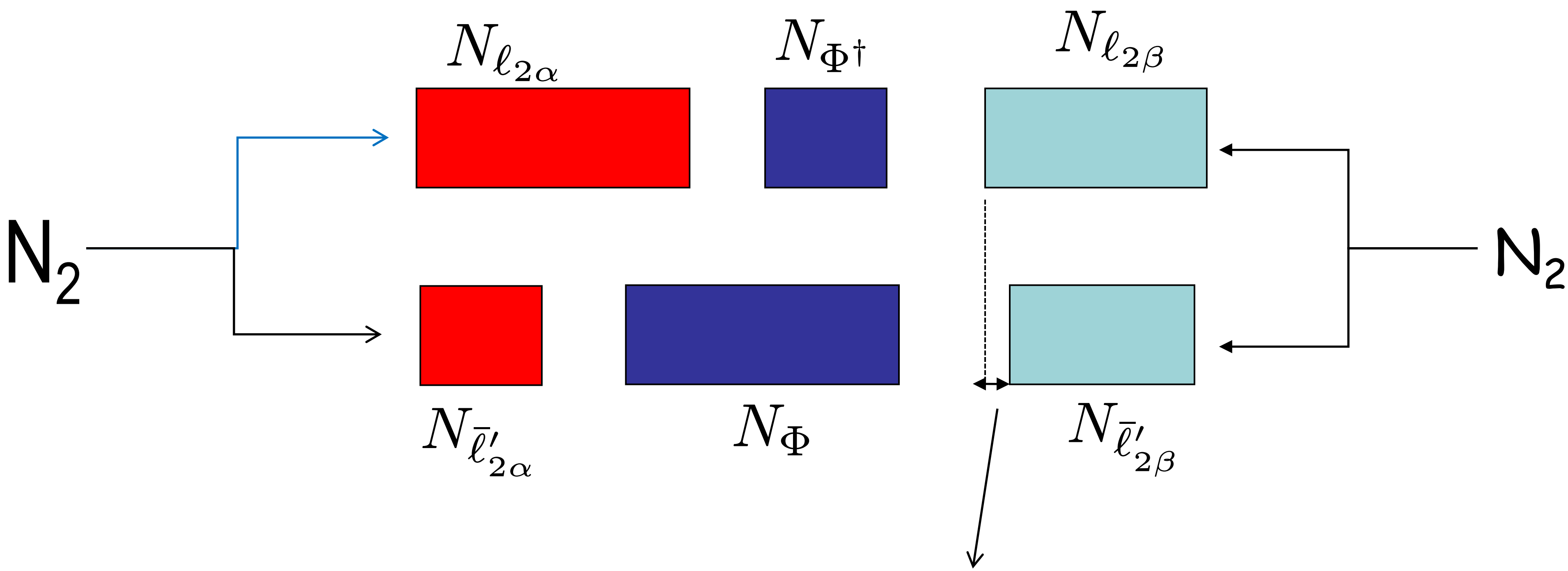
FULLY TWO-FLAVORED REGIME



A pictorial representation

Let us give a pictorial description focusing on the dominant Higgs asymmetry and disregarding the asymmetries in quarks and charged lepton singlets

Assume $K_{2\alpha} \lesssim 1$ while $K_{2\beta} \gg 1$



This β-asymmetry is induced by the "thermal contact" with the α-leptons via the Higgs

Production stage

We have to solve :

$$
\begin{aligned}
\frac{dN_{N_2}}{dz_2} &= -D_2\,(N_{N_2} - N_{N_2}^{\rm eq})\,, \\
\frac{dN_{\Delta_\gamma}}{dz_2} &= \varepsilon_{2\gamma}\,D_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\gamma}^0\,W_2 \sum_{\alpha=\gamma,\tau} C_{\gamma\alpha}^{(2)}\,N_{\Delta_\alpha}\,, \\
\frac{dN_{\Delta_\tau}}{dz_2} &= \varepsilon_{2\tau}\,\Delta_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\tau}^0\,W_2 \sum_{\alpha=\gamma,\tau} C_{\tau\alpha}^{(2)}\,N_{\Delta_\alpha}\,.
\end{aligned}
$$

Defining U as the matrix that diagonalizes: $P_2^0 \equiv \begin{pmatrix} P_{2\gamma}^0\,C_{\gamma\gamma}^{(2)} & P_{2\gamma}^0\,C_{\gamma\tau}^{(2)} \\ P_{2\tau}^0\,C_{\tau\gamma}^{(2)} & P_{2\tau}^0\,C_{\tau\tau}^{(2)} \end{pmatrix}$

$$
U\,P_2^0\,U^{-1} = {\rm diag}(P_{2\gamma'}^0, P_{2\tau'}^0)
$$

The asymmetry at T ~ M_2 is then given by :

$$
\begin{aligned}
N_{\Delta_\gamma}^{T\sim M_2} &= U_{\gamma\gamma'}^{-1}\,[U_{\gamma'\gamma}\,\varepsilon_{2\gamma} + U_{\gamma'\tau}\,\varepsilon_{2\tau}]\cdot(K_{2\gamma}) + U_{\gamma\tau'}^{-1}\,[U_{\tau'\gamma}\,\varepsilon_{2\gamma} + U_{\tau'\tau}\,\varepsilon_{2\tau}]\cdot(K_{2\tau})\,, \\
N_{\Delta_\tau}^{T\sim M_2} &= U_{\tau\gamma'}^{-1}\,[U_{\gamma'\gamma}\,\varepsilon_{2\gamma} + U_{\gamma'\tau}\,\varepsilon_{2\tau}]\cdot(K_{2\gamma}) + U_{\tau\tau'}^{-1}\,[U_{\tau'\gamma}\,\varepsilon_{2\gamma} + U_{\tau'\tau}\,\varepsilon_{2\tau}]\cdot(K_{2\tau})\,, \\
N_{B-L}^{T\sim M_2} &= N_{\Delta_\gamma}^{T\sim M_2} + N_{\Delta_\tau}^{T\sim M_2}\,.
\end{aligned}
$$

Flavour coupling in the N_2-dom.scenario

(Antusch, PDB, Jones, King '10)

Flavor coupling does not relevantly affect the final asymmetry In N_1-leptogenesis (Abada, Josse-Michaux '07) but a strong enhancement is possible in N_2-leptogenesis because here now there are three stages to be taken into account:

1) Production at 10^{12} GeV >> T ~ $M_2 \gtrsim 10^9$ GeV (2-flavour regime):

$$\frac{dN_{N_2}}{dz_2} = -D_2\,(N_{N_2} - N_{N_2}^{\rm eq})\,,$$

$$\frac{dN_{\Delta_\gamma}}{dz_2} = \varepsilon_{2\gamma}\,D_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\gamma}^0\,W_2 \sum_{\alpha=\gamma,\tau} C_{\gamma\alpha}^{(2)}\,N_{\Delta_\alpha}\,,(\gamma \equiv e+\mu)$$

$$\frac{dN_{\Delta_\tau}}{dz_2} = \varepsilon_{2\tau}\,\Delta_2\,(N_{N_2} - N_{N_2}^{\rm eq}) - P_{2\tau}^0\,W_2 \sum_{\alpha=\gamma,\tau} C_{\tau\alpha}^{(2)}\,N_{\Delta_\alpha}\,.$$

2) Decoherence at T ~ 10^9 GeV : $N_{\Delta_\gamma}^{T\sim M_2}$ splits into $N_{\Delta_\mu}^{T\sim M_2}$ and $N_{\Delta_e}^{T\sim M_2}$

3) Lightest RH neutrino wash-out at T ~ M_1 << 10^9 GeV (3-fl. regime):

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P_{1\alpha}^0 \sum_\beta C_{\alpha\beta}^{(3)}\,W_1\,N_{\Delta_\beta}\,, \qquad (\alpha,\beta = e,\mu,\tau)$$

Lightest RH neutrino wash-out

We have to solve

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha} \sum_\beta C^{(3)}_{\alpha\beta} W_1 N_{\Delta_\beta} , \qquad (\alpha, \beta = e, \mu, \tau)$$

using as initial conditions $N^{\rm in}_{\Delta\beta} = N^{T\sim M_2}_{\Delta\beta}$

If we first neglect the flavour coupling using the approximation $C^{(3)} = I$, then

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha} W_1 N_{\Delta_\alpha} , \qquad (\alpha, \beta = e, \mu, \tau)$$

This can be straightforwardly solved finding:

$$N^{\rm f}_{B-L} = N^{T\sim T_{M_2}}_{\Delta_e} e^{-\frac{3\pi}{8} K_{1e}} + N^{T\sim M_2}_{\Delta_\mu} e^{-\frac{3\pi}{8} K_{1\mu}} + N^{T\sim M_2}_{\Delta_\tau} e^{-\frac{3\pi}{8} K_{1\tau}}$$

Flavor swap scenario

(Antusch, PDB, Jones, King '10)

Suppose that at the production the e+μ (γ) flavour component of the asymmetry is weakly washed-out while the τ component is strongly washed-out. Then the latter can be considerably enhanced by flavor coupling:

$$N_{\Delta_\tau}^{T\sim M_2} \simeq \varepsilon_{2\tau}\cdot(K_{2\tau}) - C^{(2)}_{\tau\gamma}\,\varepsilon_{2\gamma}\cdot(K_{2\gamma}) \simeq C^{(2)}_{\tau\gamma}\,\varepsilon_{2\gamma}\cdot(K_{2\gamma})\,,$$

$$N_{\Delta_\gamma}^{T\sim M_2} \simeq \varepsilon_{2\gamma}\cdot(K_{2\gamma})\,,$$

At the production the total asymmetry does not relevantly change (Abada, Josse-Michaux '07) but… a "flavor-swap" can be induced at the N_1 wash-out if $K_{1e}, K_{1\mu} \gg 1\,, K_{1\tau} \ll 1$

$$\Rightarrow N_{B-L}^{\rm f} = N_{\Delta_e}^{T\sim T_{M_2}}\,e^{-\frac{3\pi}{8}\,K_{1e}} + N_{\Delta_\mu}^{T\sim M_2}\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + N_{\Delta_\tau}^{T\sim M_2}\,e^{-\frac{3\pi}{8}\,K_{1\tau}} \simeq N_{\Delta_\tau}^{T\sim M_2} \simeq C^{(2)}_{\tau\gamma}\,\varepsilon_{2\gamma}\,\kappa(K_{2\gamma})$$

In this way the strong enhancement of the τ-asymmetry at the production translates into a strong enhancement of the final asymmetry

Flavour coupling at the N_1 wash-out

Let us now take into account flavour coupling at the N_1-wash-out as well:

$$\frac{dN_{\Delta_\alpha}}{dz_1} = -P^0_{1\alpha}\, \sum_\beta C^{(3)}_{\alpha\beta}\, W_1\, N_{\Delta_\beta}\,, \qquad (\alpha,\beta = e,\mu,\tau)$$

using as initial conditions $N^{\rm in}_{\Delta\beta} = N^{T\sim M_2}_{\Delta\beta}$

We can repeat the same trick as before, i.e. introducing a matrix V that diagonalizes:

$$P^0_1 \equiv \begin{pmatrix} P^0_{1e}\, C^{(3)}_{ee} & P^0_{1e}\, C^{(3)}_{e\mu} & P^0_{1e}\, C^{(3)}_{e\tau} \\ P^0_{1\mu}\, C^{(3)}_{\mu e} & P^0_{1\mu}\, C^{(3)}_{\mu\mu} & P^0_{1\mu}\, C^{(3)}_{\mu\tau} \\ P^0_{1\tau}\, C^{(3)}_{\tau e} & P^0_{1\tau}\, C^{(3)}_{\tau\mu} & P^0_{1\tau}\, C^{(3)}_{\tau\tau} \end{pmatrix}$$

One finally finds the general solution :

$$N^{\rm f}_{\Delta_\alpha} = \sum_{\alpha''} V^{-1}_{\alpha\alpha''}\, e^{-\frac{3\pi}{8}\,K_{1\alpha''}} \left[\sum_\beta V_{\alpha''\beta}\, N^{T\sim M_2}_{\Delta_\beta}\right]\,, \qquad N^f_{B-L} = \sum_\alpha N^{\rm f}_{\Delta_\alpha}$$

with $K_{1\alpha''} \simeq K_{1\alpha}$

Circumventing the N_1 wash-out

Because of flavour coupling at the N_1 wash-out there is another interesting effect. Let us "unpack" the previous general expression for example for the τ-asymmetry:

$$
\begin{aligned}
N_{\Delta_\tau}^{\rm f} \quad \simeq \quad & V^{-1}_{\tau e''} \left[\sum_\beta V_{e''\beta}\, N_{\Delta_\beta}^{T\sim M_2} \right] e^{-\frac{3\pi}{8}\, K_{1e}} \\
+ \quad & V^{-1}_{\tau \mu''} \left[\sum_\beta V_{\mu''\beta}\, N_{\Delta_\beta}^{T\sim M_2} \right] e^{-\frac{3\pi}{8}\, K_{1\mu}} \\
+ \quad & V^{-1}_{\tau \tau''} \left[\sum_\beta V_{\tau''\beta}\, N_{\Delta_\beta}^{T\sim M_2} \right] e^{-\frac{3\pi}{8}\, K_{1\tau}}
\end{aligned}
$$

Now even though one has $K_{1\tau} \gg 1$, there is still a final τ asymmetry that manages to escape the N_1 wash-out. Why ? Again because of the Higgs asymmetry present in the thermal bath that is not exactly that one needed for a complete wash-out of the τ asymmetry

⇒ the lightest RH neutrino wash-out becomes less efficient !

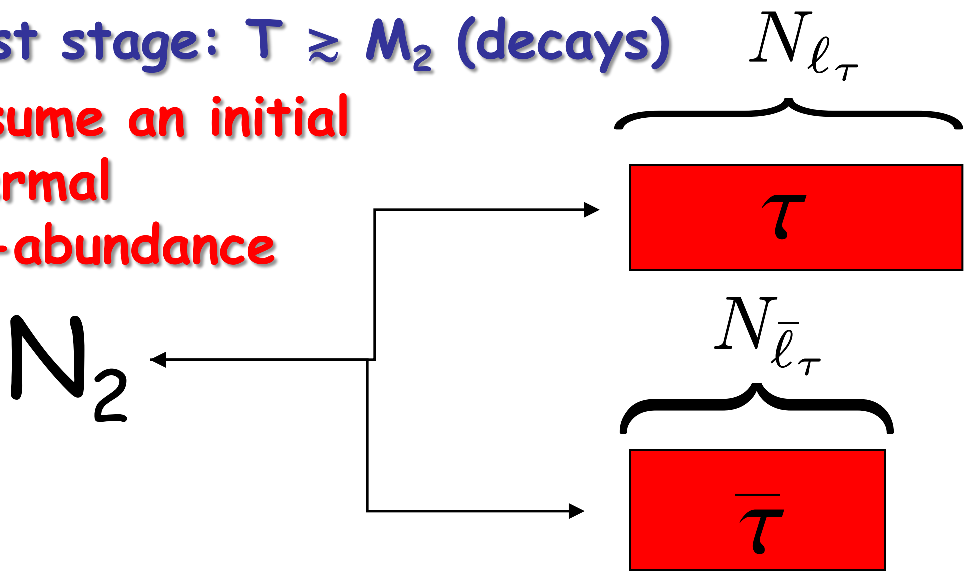
Phantom terms

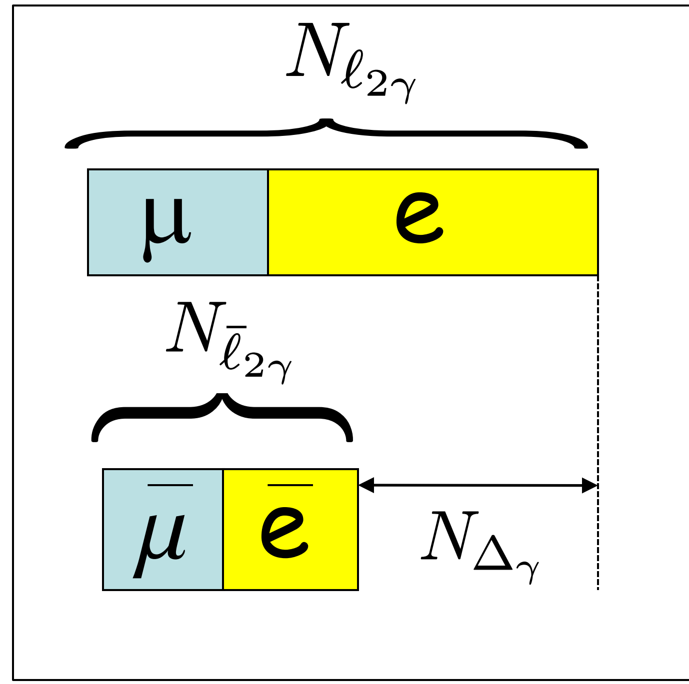
We have now to answer: how at the decoherence, at T ~ 10[9] GeV,

$$N_{\Delta_\gamma}^{T\sim M_2} \text{ splits into } N_{\Delta_\mu}^{T\sim M_2} \text{and } N_{\Delta_e}^{T\sim M_2}?$$

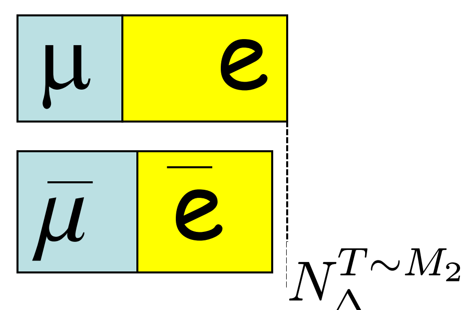
First stage: T ≳ M_2 (decays)

Assume an initial thermal N_2-abundance





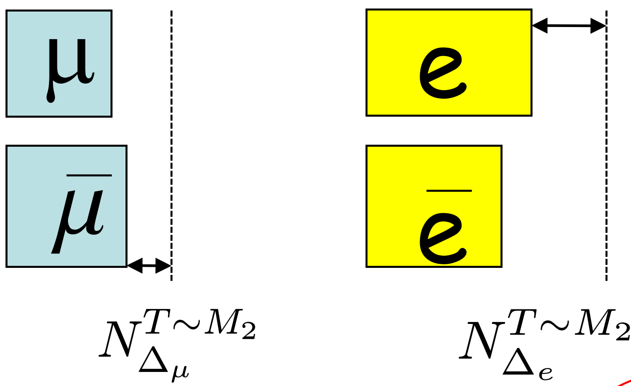
Second stage: T ~ M_2 (N_2 – washout)



The N_2 wash-out can only suppress the γ-asymmetry but it cannot change the flavour compositions of $\ell_{2\gamma}$ and $\bar{\ell}'_{2\gamma}$

Phantom terms

Third stage: 10^9 GeV $\gtrsim T' \gg M_1$ (3-flavour regime)



$$f_{2\alpha} \equiv \frac{|\langle \ell_\alpha | \ell_{2\gamma}\rangle|^2 + |\langle \bar{\ell}_\alpha | \bar{\ell}'_{2\gamma}\rangle|^2}{2}$$

$$N_{\Delta_e}(T') = p_e + \frac{f_{2e}}{f_{2e}+f_{2\mu}} N_{\Delta_\gamma}^{T\sim M_2}, \quad N_{\Delta_\mu}(T') = p_\mu + \frac{f_{2\mu}}{f_{2e}+f_{2\mu}} N_{\Delta_\gamma}^{T\sim M_2}$$

$\simeq \cdot (K_{2\gamma})\, \varepsilon_{2\gamma}$ (neglecting flavour coupling !)

Phantom terms

$$p_e = \varepsilon_{2e} - \frac{f_{2e}}{f_{2e}+f_{2\mu}} \varepsilon_2$$

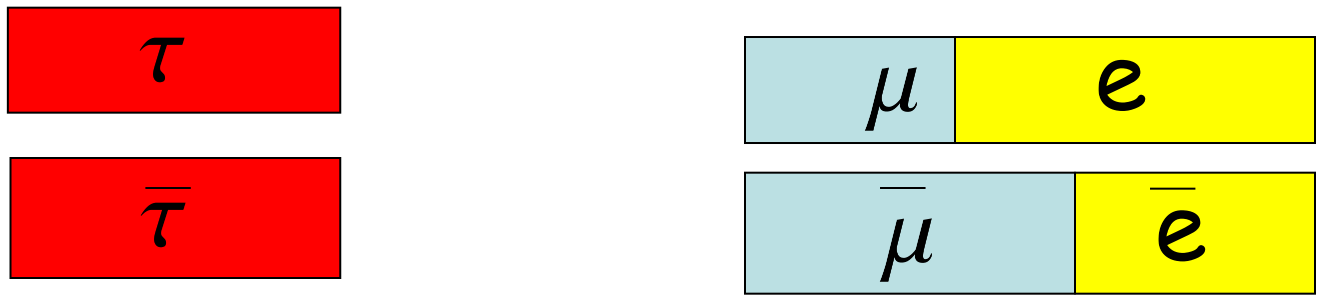
$$p_\mu = \varepsilon_{2\mu} - \frac{f_{2\mu}}{f_{2e}+f_{2\mu}} \varepsilon_2 = -p_e$$

Notice that phantom terms are not suppressed by N_2 wash-out !

Phantom Leptogenesis

We can have then a situation where $K_{2\gamma}$, $K_{2\tau}$ >> 1 so that at the End of the N_2 washout the total asymmetry is negligible:

T ~ M_2



$$N_{B-L}^{T\sim M_2} = N_{\Delta\tau}^{T\sim M_2} + N_{\Delta\gamma}^{T\sim M_2} \simeq 0\ !$$

10^9 GeV $\gtrsim$ T >> M_1

$$N_{B-L}^{T\sim M_2} = N_{\Delta\tau}^{T\sim M_2} + N_{\Delta e}^{T\sim M_2} + N_{\Delta\mu}^{T\sim M_2} \simeq 0\ !$$

T $\simeq$ M_1

Assume $K_{1e} \lesssim 1$ and $K_{1\mu}$ >> 1

$$N_{B-L}^{\rm f} = N_{\Delta e}^{T\sim M_2} \simeq p_e\ !$$

The N_1 wash-out un-reveal the phantom term and effectively it create a N_{B-L} asymmetry ! There is nothing esoteric but there is a...

Drawback of phantom Leptogenesis

We assumed an initial N_2 thermal abundance but if we were assuming An initial vanishing N_2 abundance the phantom terms were just zero !

Therefore, more generally :

$$p_e = \left(\varepsilon_{2e} - \frac{f_{2e}}{f_{2e}+f_{2\mu}}\,\varepsilon_2\right) N_{N_2}^{\rm in}$$

The reason is that phantom terms with opposite sign would be created during the N_2 production by inverse decays and exactly cancelling with the contribution generated from decays ! More generally

In conclusion ....phantom leptogenesis is more a problem for the N_2 dominated scenario since it introduces a strong dependence on the initial conditions !!