Fourteenth Lomonosov Conference
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Leptogenesis

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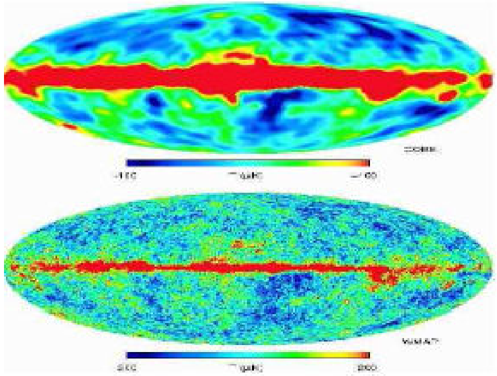
Cosmological observations

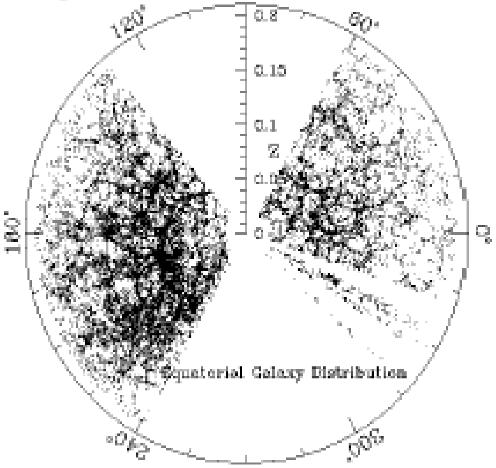
CMBR anisotropies

COBE

WMAP

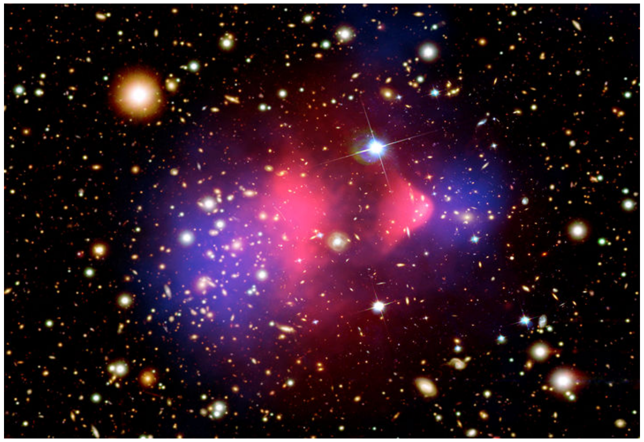


Large Scale Structure

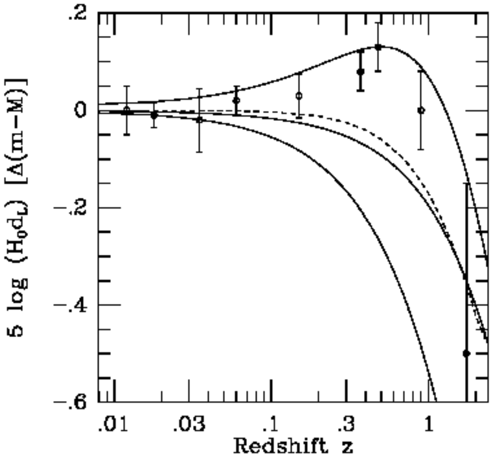


SLOAN
DIGITAL
SKY
SURVEY

Clusters of galaxies



Supernovae type Ia



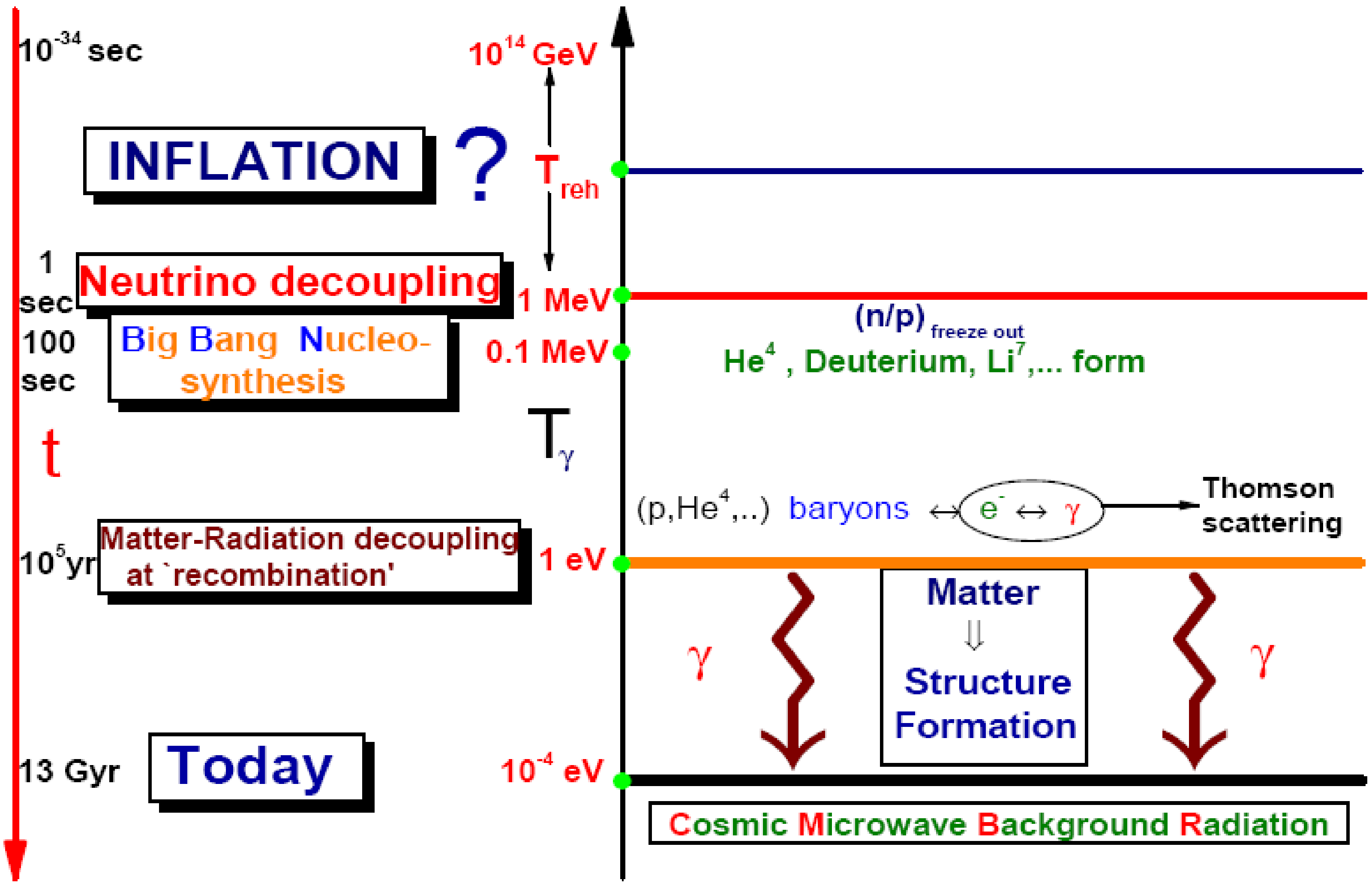
+ many others (weak lensing, BAO, Ly-a, ...)

ΛCDM: a cosmological SM ?

(Tegmark et al. 2005)

Parameter	WMAP 3 years + SDSS	Description
Ω_0	$1.003^{+0.010}_{-0.009}$	Density parameter
	$\Omega_0 = 1$ (Flat Universe prior)	
h	$0.730^{+0.019}_{-0.019}$	Present expansion rate
q_0	-0.66 ± 0.1	Deceleration parameter
$t_0\,(\mathrm{Gyr})$	13.76 ± 0.15	Age of the Universe
$T_0\,(K)$	2.725 ± 0.001	CMB temperature
Ω_{B}	0.0416 ± 0.0019	Baryon Density
Ω_{CDM}	0.197 ± 0.016	Cold Dark Matter Density
Ω_Λ	0.761 ± 0.017	Dark Energy Density
w	$-0.941^{+0.087}_{-0.101}$	Dark Energy Equation of State
n_s	$0.948^{+0.014}_{-0.018}$	Scalar index
$\sum_i m_{\nu_i}$	$< 0.94\,\mathrm{eV}(95\%CL)$	Sum of neutrino masses

Thermal history of the Universe



10^{-34} sec

10^{14} GeV

INFLATION ?

T_{reh}

1 sec

Neutrino decoupling

1 MeV

100 sec

Big Bang Nucleo-synthesis

0.1 MeV

$(n/p)_{\text{freeze out}}$

He^4 , Deuterium, Li^7,... form

t

T_γ

$(p,He^4,..)$ baryons ↔ $e^- \leftrightarrow \gamma$ → Thomson scattering

10^5yr

Matter-Radiation decoupling at `recombination'

1 eV

γ

Matter
⇓
Structure Formation

γ

13 Gyr

Today

10^{-4} eV

Cosmic Microwave Background Radiation

Puzzles of Modern Cosmology

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

Leptogenesis

$\Longrightarrow$ clash between the SM and ΛCDM !

Matter-antimatter asymmetry of the Universe

- Symmetric Universe with matter- anti matter domains ?

  Excluded by CMB + cosmic rays (Cohen, De Rujula, Glashow '96)

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

(barring the possibility of anti-matter "hidden" in compact objects: talk by Dolgov)

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

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

(Sakharov '67)

- A Standard Model Solution ?

  $\eta_B^{SM} <<< \eta_B^{CMB}$ by far 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

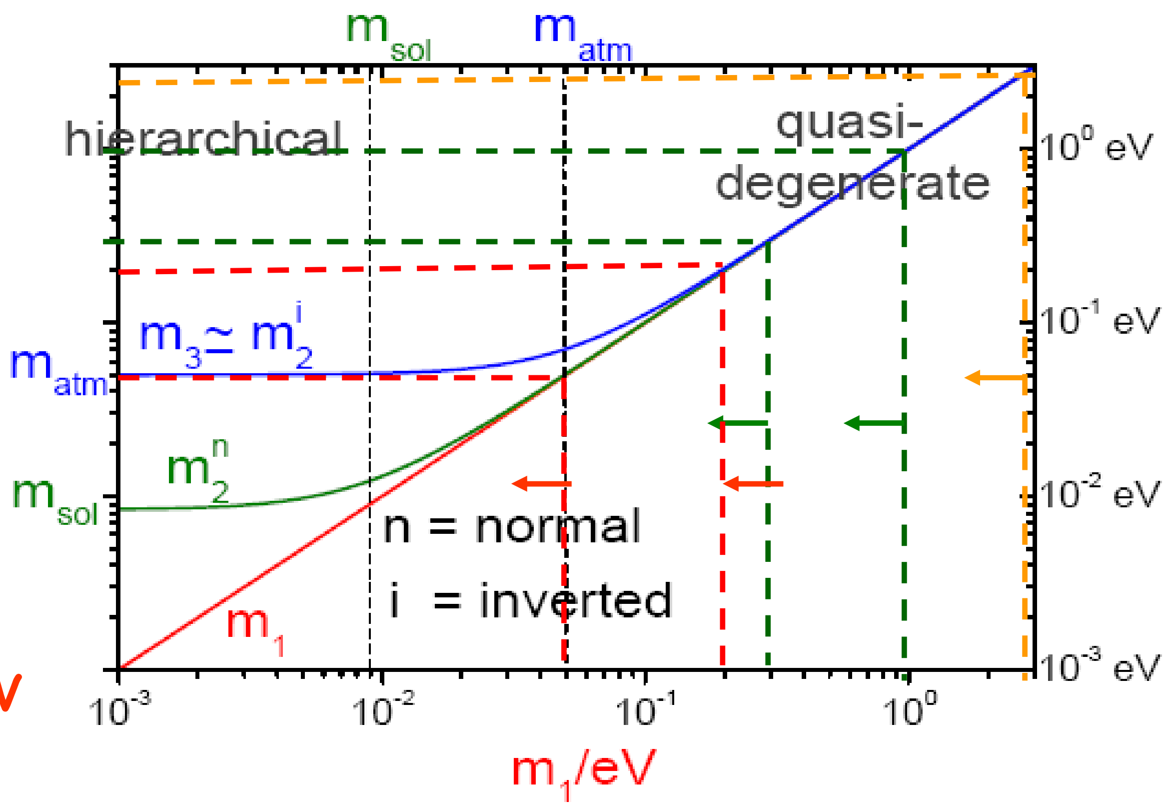
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

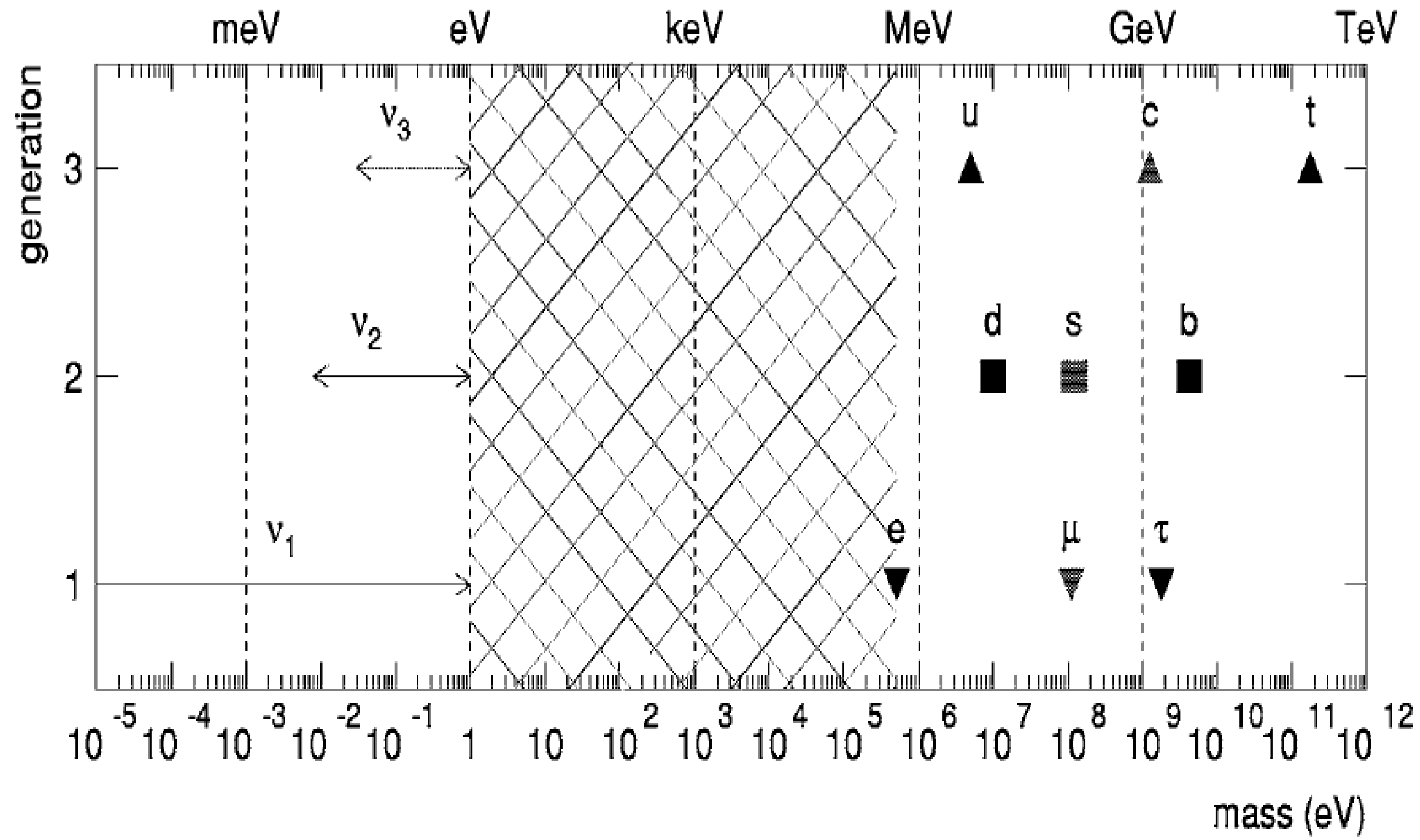
Tritium β decay : $m_e < 2.3$ eV
(Mainz 95% CL)

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

using the flat prior (Ω_0=1):
CMB+BAO : $\Sigma\, m_i < 0.61$ eV
(WMAP5+SDSS)
CMB+LSS + Lyα : $\Sigma\, m_i < 0.17$ eV
(Seljak et al.)



Neutrinos are much lighter than all other fermions !



A minimal extension of the SM

- Adding right-handed neutrinos with Yukawa couplings h and a Majorana mass term M after spontaneous symmetry breaking $\Rightarrow m_D = v\,h \quad (v \equiv \langle\phi_0\rangle)$

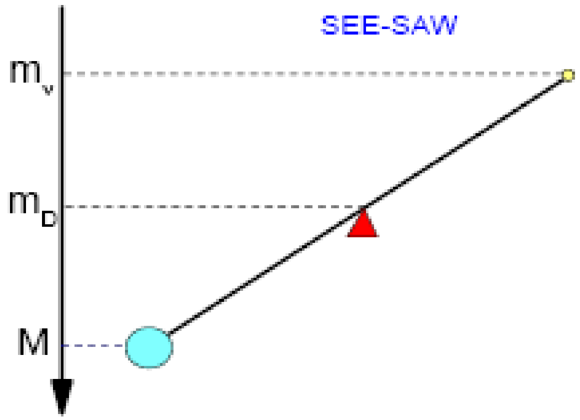
$$\mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2}\left[(\bar\nu^c_L, \bar\nu_R)\begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix}\right] + h.c.$$

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 $m_1 \leq m_2 \leq m_3$ given by:

$$\boxed{\mathrm{diag}(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3) = -U^\dagger\, m_D\, \frac{1}{M}\, m_D^T\, U^\star}$$

(U is the leptonic mixing matrix U_{PMNS} !)



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

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"*

$$\boxed{m_1 \leq m_2 \leq m_3}$$

- 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

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

"Vanilla" Leptogenesis

(Fukugita, Yanagida '86)

Let us start from the simplest scenario („vanilla" leptogenesis)

1) **Flavor effects are neglected**

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

Total CP asymmetries

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

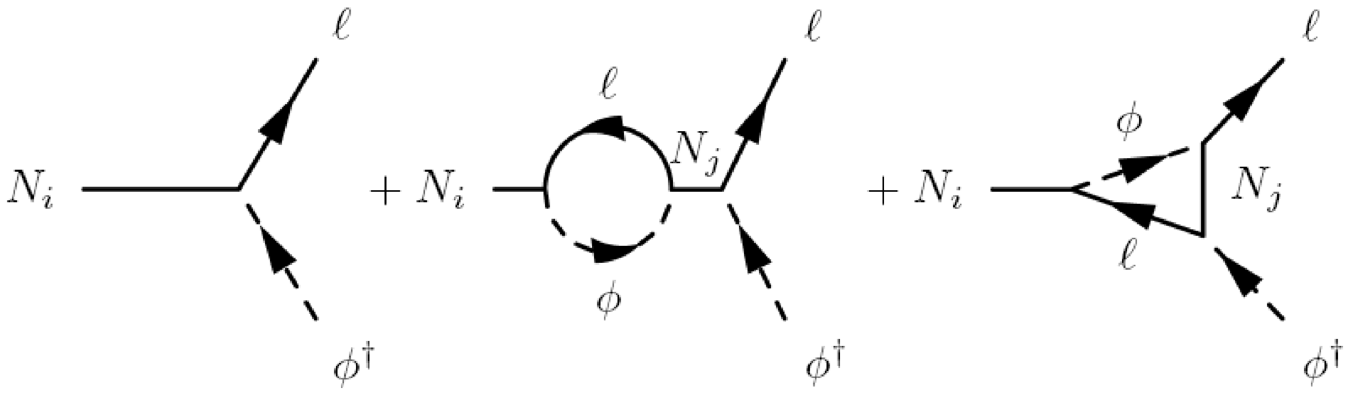
If $\varepsilon_i \neq 0$ a **lepton asymmetry** is generated from N_i decays and partly converted into a **baryon asymmetry** by sphaleron processes **if $T_{\rm reh} \gtrsim 100$ GeV !** (Kuzmin, Rubakov, Shaposhnikov, '85)

$$N_{B-L}^{\rm fin} = \sum_{i=1}^{3} \varepsilon_i\, \kappa_i^{\rm fin} \Rightarrow \eta_B = a_{\rm sph}\, \frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}}$$

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

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 the leptonic mixing matrix U !

2) Hierarchical heavy RH neutrino spectrum

$$\boxed{M_2 \gtrsim 3\, M_1}$$

(Blanchet,PDB '06)

3) N_3 does not interfere with N_2-decays:

$$(m_D^\dagger\, m_D)_{23} = 0$$

(PDB '05)

Under the last two assumptions $\Rightarrow |\varepsilon_{2,3}| \ll |\varepsilon_1|$

In the end an unflavored N_1-dominated scenario holds:

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

It does not depend on the leptonic mixing matrix U !

4) Semi-hierarchical heavy neutrino spectrum

$$\boxed{M_3 \simeq M_2 \gtrsim 3\, M_1}$$

⇒ Upper bound on ε$_1$

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

$$\boxed{\varepsilon_1 \;\; \leq \;\; \overline{\varepsilon}(M_1)\, \frac{m_{\rm atm}}{m_1 + m_3}\, f_{\rm max}(m_1)}$$

$$\boxed{\overline{\varepsilon}(M_1) \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,{\rm GeV}}\right) ,}$$

$$\boxed{0 \leq f_{\rm max}(m_1) \leq 1}$$

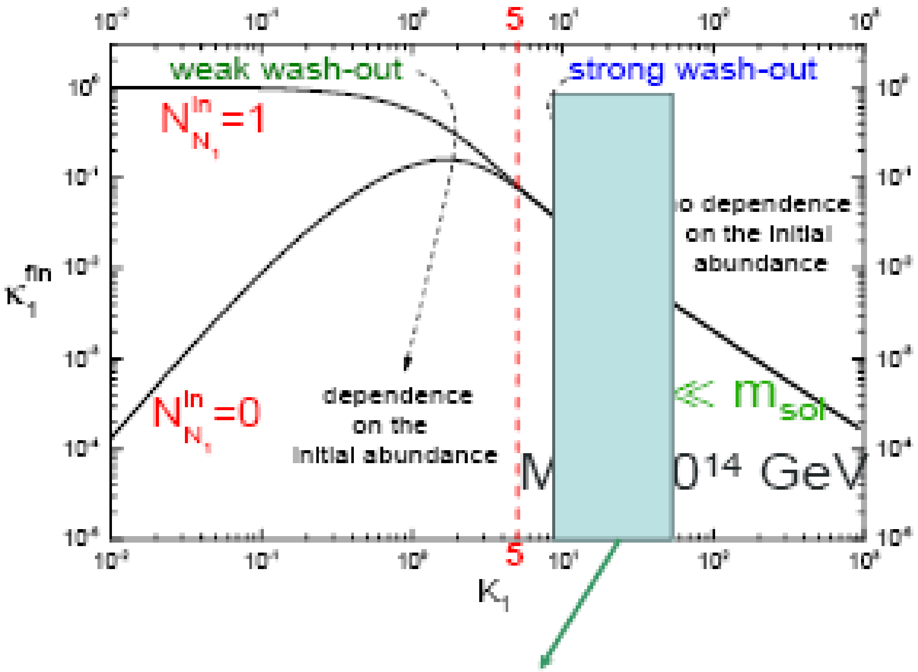
Main lessons from vanilla leptogenesis

1) The early Universe seems to „know" neutrino masses with leptogenesis: a first interesting concordance

(Buchmüller, PDB, Plümacher '04)

decay parameter

$$\eta_B \simeq 0.01\,\varepsilon_1(m_1, M_1, \Omega)\,\kappa_1^{\rm fin}(K_1) \qquad K_1 \equiv \frac{\Gamma_{N_1}}{H(T=M_1)} \sim \frac{m_{\rm sol,atm}}{m_\star \sim 10^{-3}\,{\rm eV}} \sim 10 \div 50$$



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

The measured neutrino mass scales in neutrino oscillations are such that

the wash-out is strong enough to guarantee independence of the initial conditions ....

Main lessons from vanilla leptogenesis

2) Neutrino mass bounds

...but not too strong to prevent successful leptogenesis !

$$\varepsilon_1 \leq \varepsilon_1^{\max}(m_1, M_1) \simeq 10^{-6}\,\frac{M_1}{10^{10}\,\mathrm{GeV}} \Rightarrow \eta_B < \eta_B^{\max}(m_1, M_1)$$

Upper bound on m_1 : $m_1 \lesssim 0.12$ eV

(Buchmüller,PDB,Plümacher '03;
Giudice, Raidal, Strumia,Riotto '04)

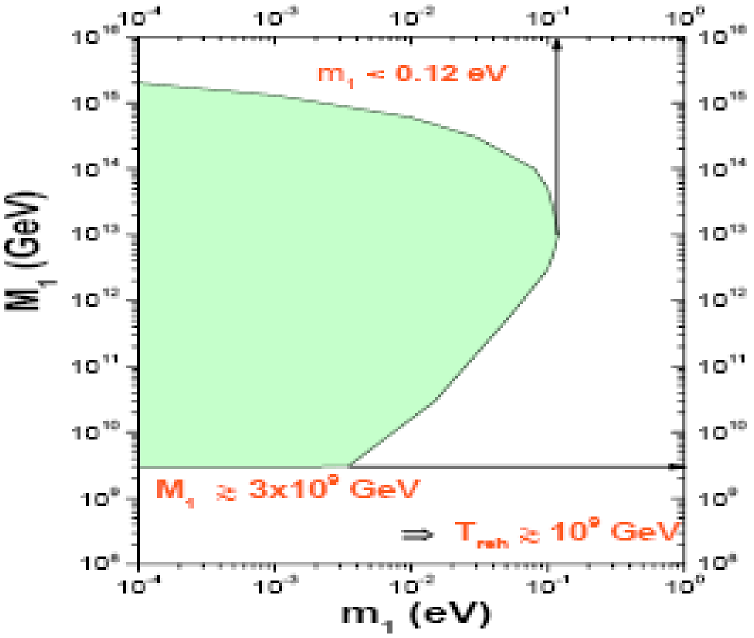
Lower bound on M_1 : $M_1 \gtrsim 3\times 10^9$ GeV

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

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

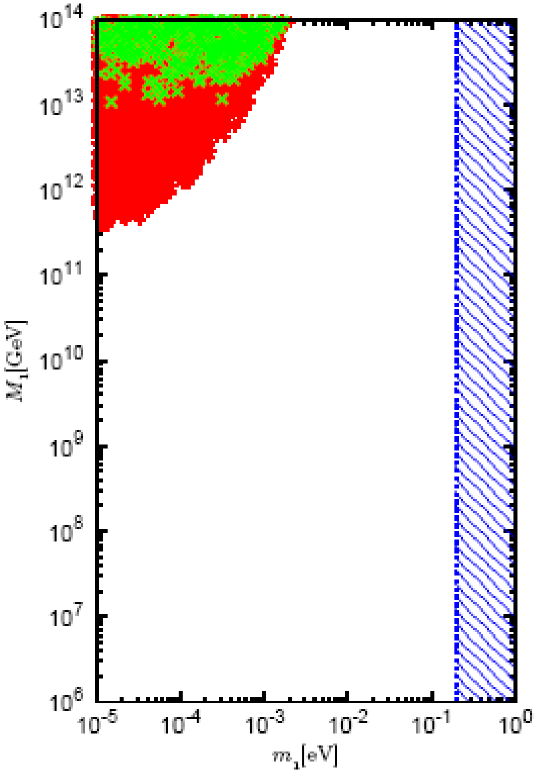
(Buchmüller,PDB,Plümacher '04)

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

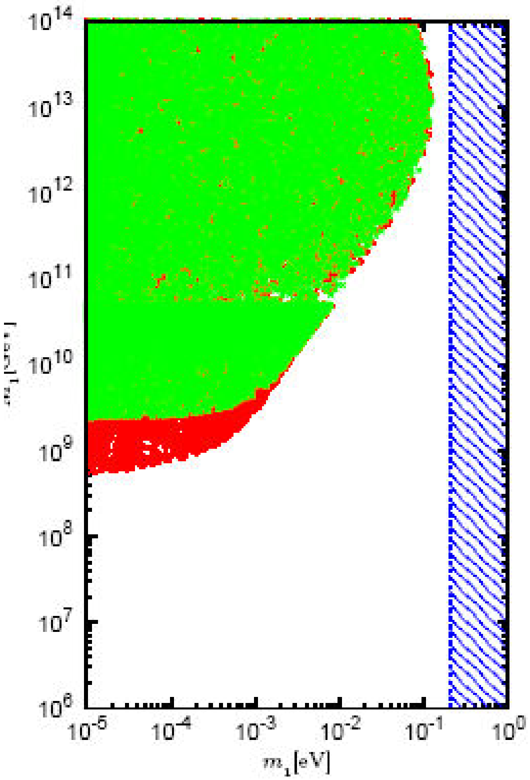


3) A second interesting concordance

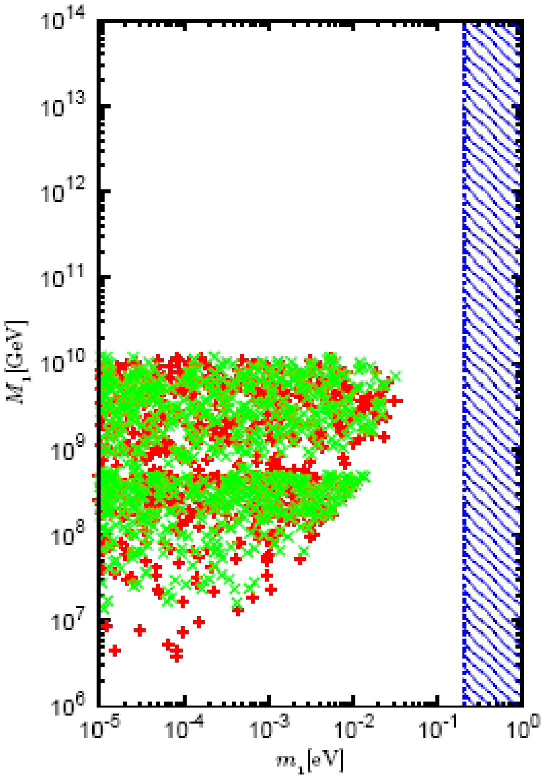
$m_{atm} = 10^{-5}\, eV$



$m_{atm} = 0.05\, eV$

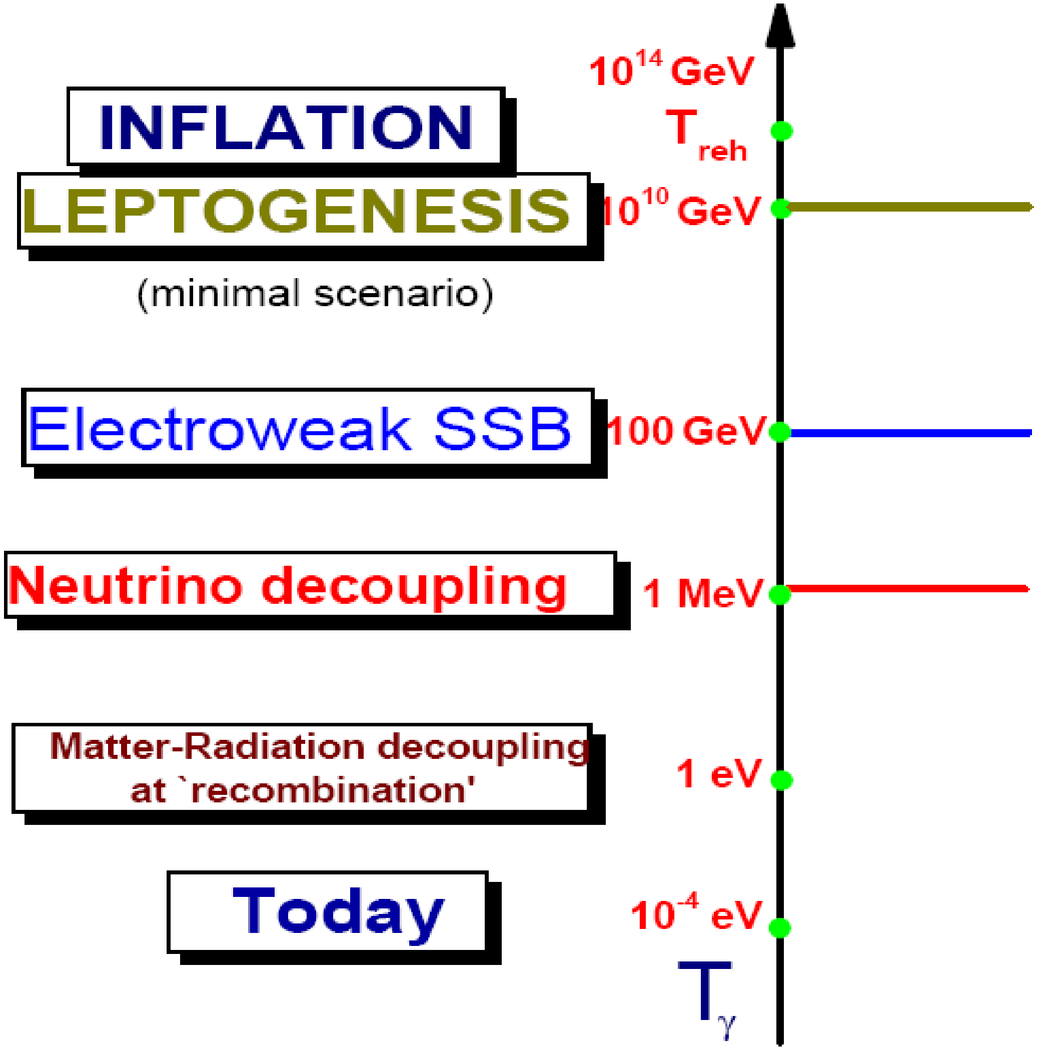


$m_{atm} = 10\, eV$



Neutrino oscillations data represent a strong positive test for leptogenesis not only in a qualitative way but also quantitavely !

A very hot Universe for leptogenesis ?



10^{14} GeV

T_{reh}

INFLATION

LEPTOGENESIS

(minimal scenario)

10^{10} GeV

Electroweak SSB

100 GeV

Neutrino decoupling

1 MeV

Matter-Radiation decoupling at `recombination'

1 eV

Today

10^{-4} eV

T_γ

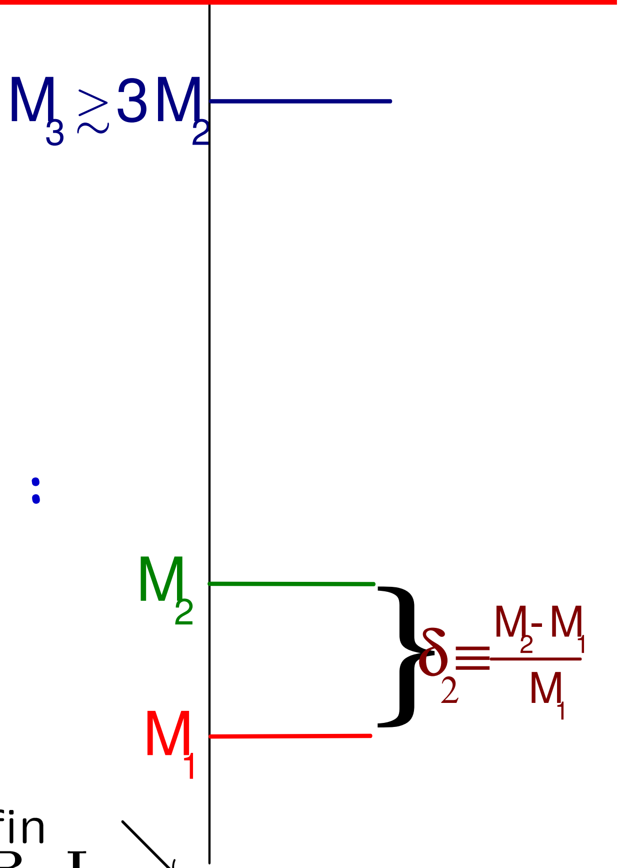
Beyond vanilla leptogenesis

- beyond the hierarchical limit
- adding flavor to vanilla leptogenesis
- N_2 - leptogenesis

Beyond the hierarchical limit

(Blanchet,PDB '06)

For example:



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

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

3 Effects play simultaneously a role for $\delta_2 \ll 1$:

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** $\Rightarrow \mathbf{N_{B-L}^{fin}} \searrow$

3. ***CP* asymmetries get enhanced: $|\varepsilon_{1,2}| \propto 1/\delta_2$** $\Rightarrow \mathbf{N_{B-L}^{fin}} \nearrow$

For $\delta_2 \lesssim 0.01$ (degenerate limit) the first two effects saturate:

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

Flavor effects

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

Flavor composition:

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

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

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

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 $|\bar{l}'_1\rangle$

$\Longrightarrow$ $|l_1\rangle$ and $|\bar{l}'_1\rangle$ „tend" to be projected on a 2-flavor basis: along the τ and a coherent over-position of μ+e

For $M_1 \lesssim 10^9$ GeV the μ-Yukawas are also in equilibrium $\Longrightarrow$ 3-flavor regime

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

heavy neutrino flavor index

lepton flavor index

1) Low energy phases can be the only source of CP violation!

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

Assume that all CP violation stems from low energy phases:

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

This implies that the total CP asymmetries vanish and :

$$N_{B-L}^{\mathrm{fin}} \sim \cancel{N_{\mathrm{fl}}\, \varepsilon_1\, \kappa_1^{\mathrm{fin}}} + \frac{\Delta P_{1\alpha}}{2}\,[\kappa_{1\tau}^{\mathrm{fin}} - \kappa_{1,e+\mu}^{\mathrm{fin}}]$$

Assume that even the Majorana phases vanish $\Longrightarrow$ the only possible source of CP violation for leptogenesis is then the same we could observe in neutrino oscillations and that is described by $\sin\theta_{13} \sin\delta$: would such a source be sufficient to have successful leptogenesis ? YES ! (though with severe restrictions on the RH neutrino mass spectrum)

NOTE: (un-)discovery of CP violation in neutrino oscillations would not (dis-)prove leptogenesis but it would however certainly represent an additional strong experimental support (or a missed opportunity) !

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

(Blanchet,PDB '08)

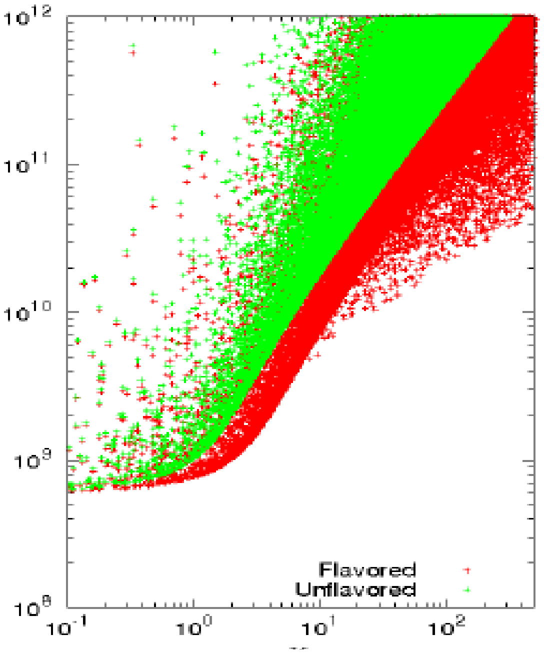
$$\frac{\Delta P_{i\alpha}}{2} \simeq \frac{1}{8\,\pi\,(h^\dagger\,h)_{ii}} \sum_{j\neq i} \left\{ \mathrm{Im}\left[h^\star_{\alpha i}\, h_{\alpha j} \left(\frac{3}{2\,\sqrt{x_j}} (h^\dagger h)_{ij} + \qquad \right] \right\}$$

$$\boxed{x_j = \frac{M_j^2}{M_1^2}}$$

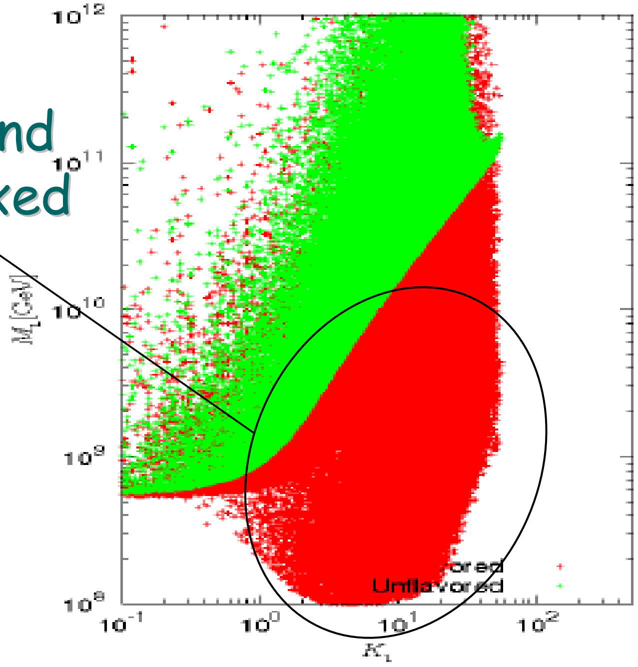
It dominates for $|\Omega_{ij}| \lesssim 1$ but is upper bounded because of Ω orthogonality:

$$\left|\frac{\Delta P_{1\alpha}}{2}\right| < \overline{\varepsilon}(M_1)\,\sqrt{P^0_{1\alpha}}$$

It is usually neglected but since it is not upper bounded by orthogonality, for $|\Omega_{ij}| \gtrsim 1$ it can be important



The usual lower bound gets relaxed



N_2-dominated scenario

(PDB'05)

For a special choice of $\Omega=R_{23}$

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

3 things happen simultaneously:

- $\varepsilon_1 = 0 \;\Rightarrow$ no asymmetry from N_1-decays
- $\varepsilon_2 \lesssim \varepsilon^{\max}(m_1, M_2)$

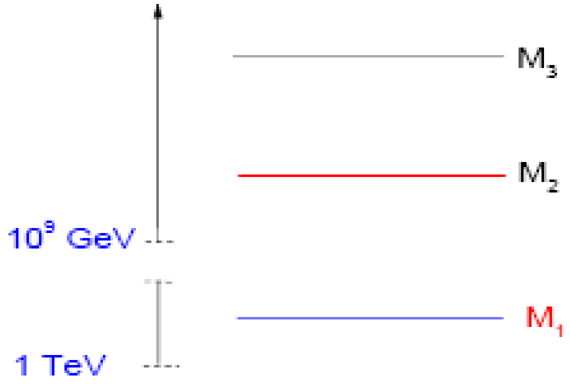
  $\Rightarrow$ asymmetry from N_2-decays
- $K_1 = m_1/m_\star$ AND IF $m_1 \lesssim m_\star \simeq 10^{-3}\,\mathrm{eV}$

  $\Rightarrow$ negligible wash-out from N_1-inverse decays

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

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} !



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

(Vives '05; Blanchet, PDB '06; Nardi,Nir '07; Blanchet, PDB '08)

N_2-flavored leptogenesis

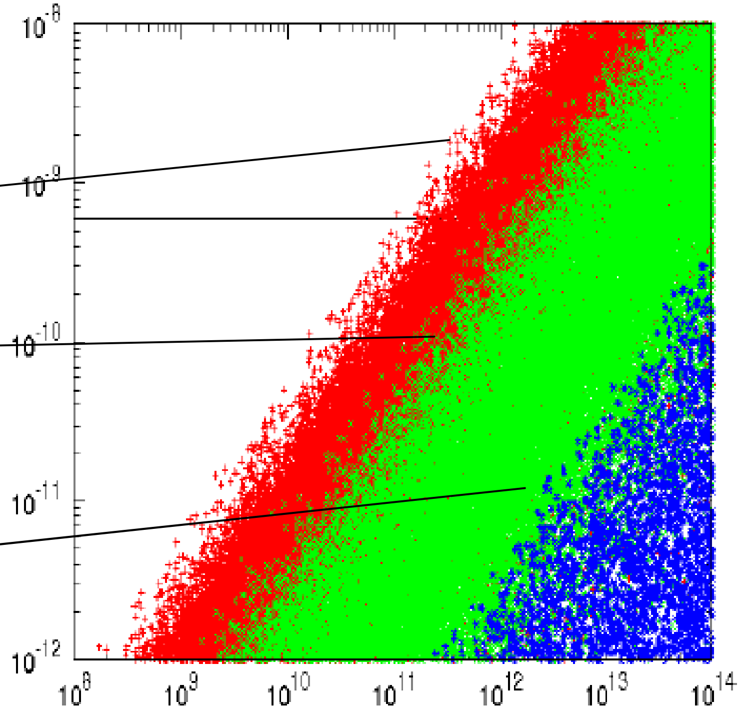
(Vives '05; Blanchet, PDB '06; Nardi,Nir '07; Blanchet, PDB '08)

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

Thanks to flavor effects the domain of applicability extends much beyond the particular choice **Ω=R$_{23}$** !

$$|\omega_{13}|\,,|\omega_{12}| \leq 1$$

$$\Omega = R_{12}(\omega_{12})\,R_{13}(\omega_{13})$$



Wash-out is neglected

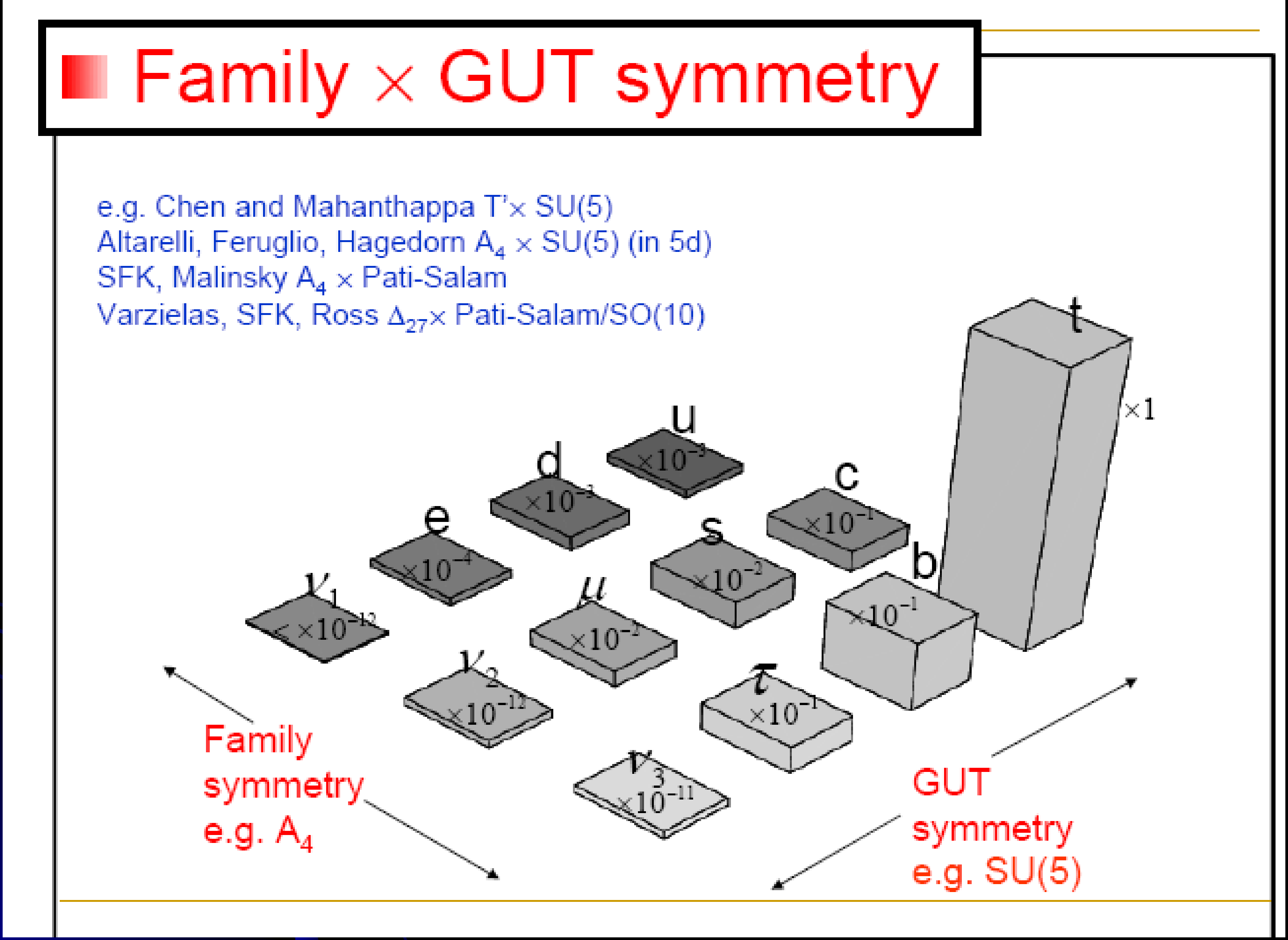
Wash-out and flavor effects are both taken into account

Unflavored case

Testing Models of New Physics with Leptogenesis

2 examples:

1. GUT's
2. Flavor symmetries



Family × GUT symmetry

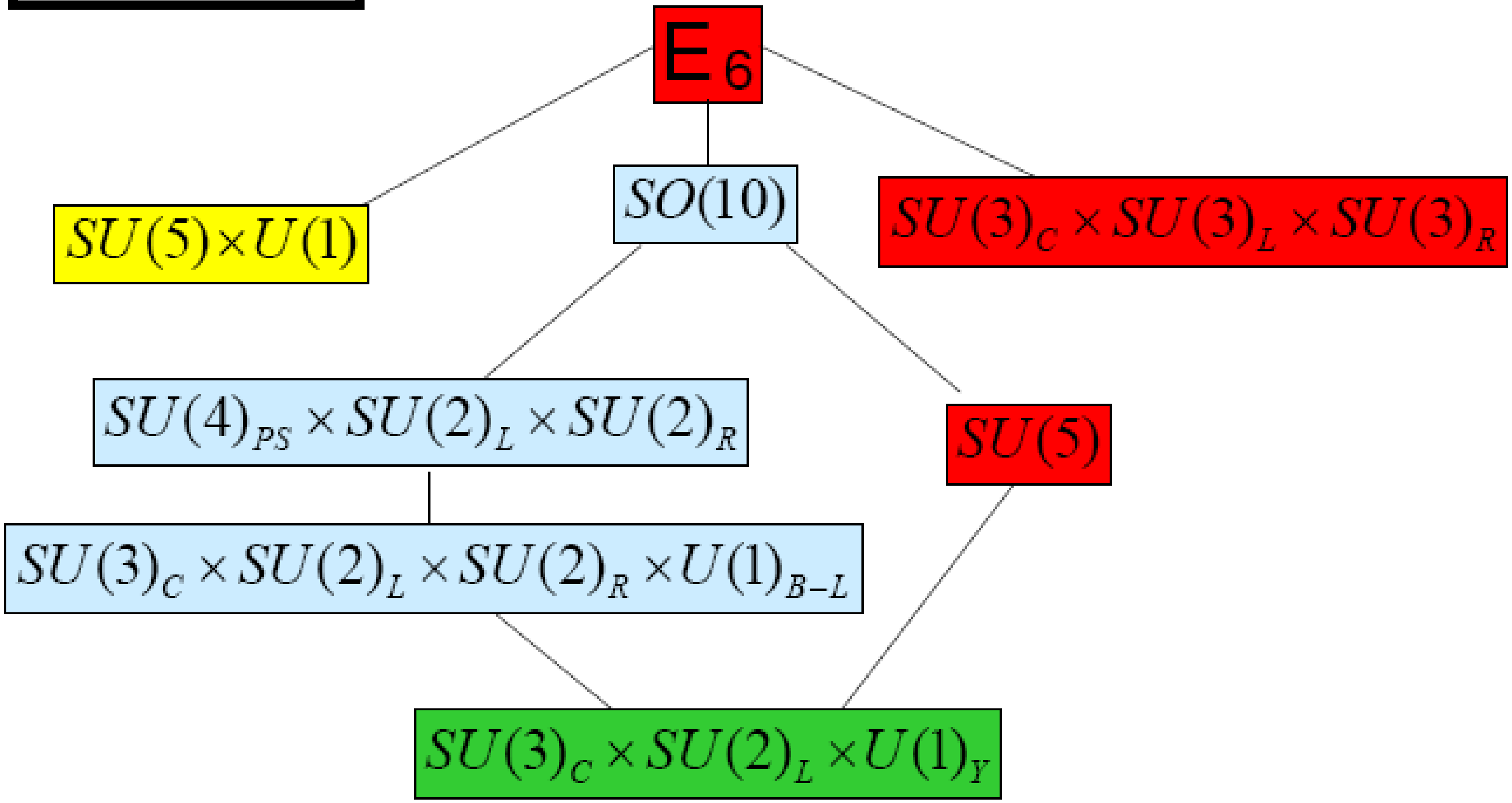
e.g. Chen and Mahanthappa T'× SU(5)
Altarelli, Feruglio, Hagedorn A_4 × SU(5) (in 5d)
SFK, Malinsky A_4 × Pati-Salam
Varzielas, SFK, Ross Δ_{27}× Pati-Salam/SO(10)

Family symmetry e.g. A_4

GUT symmetry e.g. SU(5)

(Steve King at Neutrino Telescopes ´09)

G_{GUT}



E_6

$SU(5)\times U(1)$

$SO(10)$

$SU(3)_C \times SU(3)_L \times SU(3)_R$

$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$

$SU(5)$

$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(3)_C \times SU(2)_L \times U(1)_Y$

(Steve King at Neutrino Telescopes ´09)

Leptogenesis and SO(10) models

Using the parameterization: (PDB, Riotto '08)

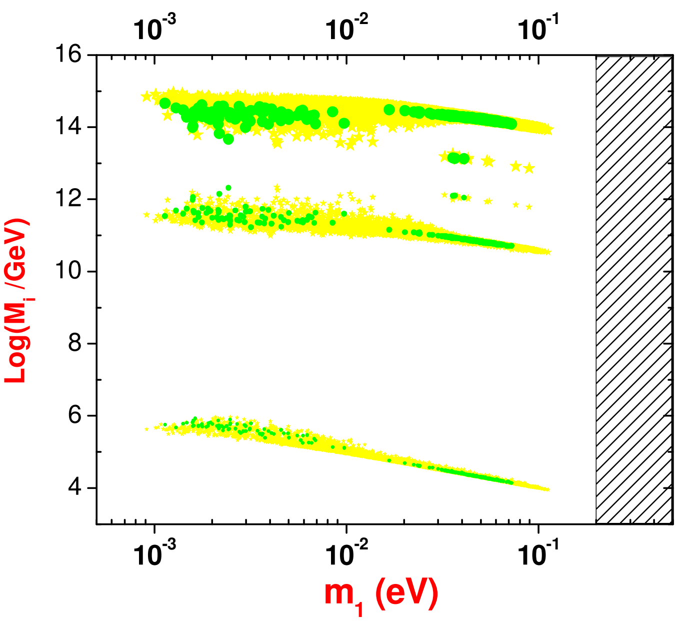
$$m_D = V_L^\dagger \, D_{m_D} \, U_R \, , \quad \lambda_{D1} = \alpha_1 \, m_u , \quad \lambda_{D2} = \alpha_2 \, m_c , \quad \lambda_{D3} = \alpha_3 \, m_t \, ,$$

and assuming `SO(10)-inspired relations´ : V_L=1 and $\boxed{\alpha_i = \mathcal{O}(1)}$.

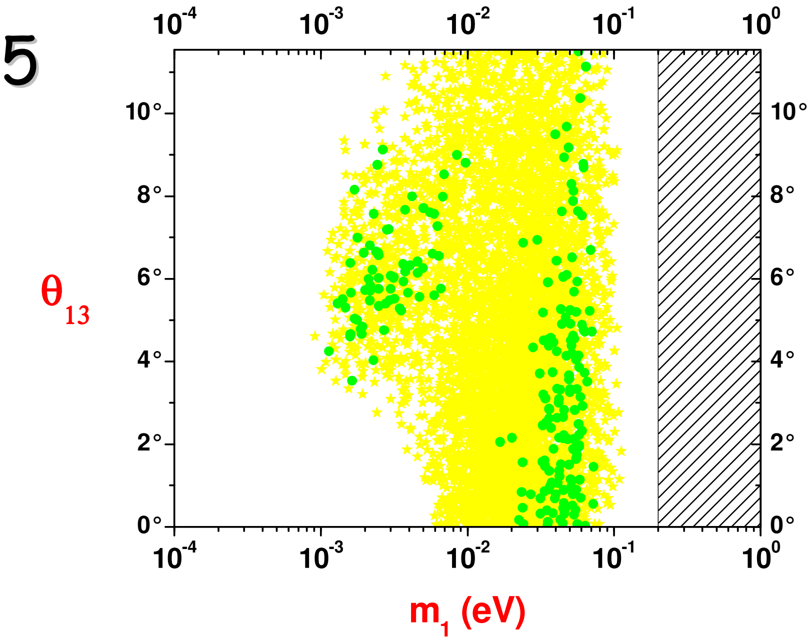
$$\Longrightarrow \quad M_1 \sim 10^5 \, \mathrm{GeV} \, , \;\; M_2 \sim 10^{10} \, \mathrm{GeV} \, , \;\; M_3 \sim 10^{14-16} \, \mathrm{GeV}$$

$\Longrightarrow$ the asymmetry produced from the lightest RH neutrino is negligible and the N_2-dominated scenario is realized !

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



α_2=5



Flavor Symmetries

Some basic features

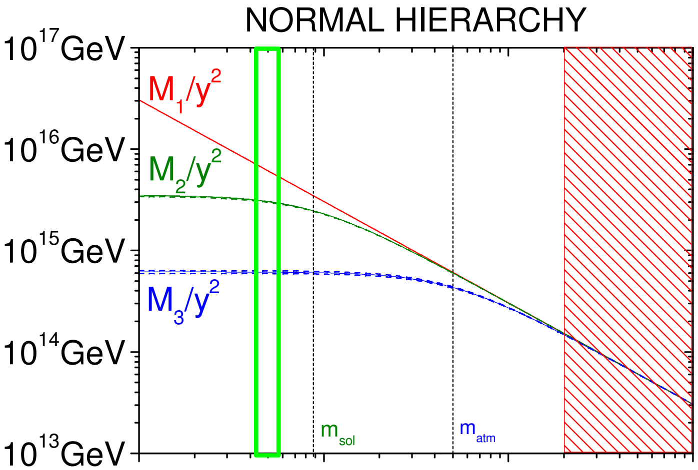
- Assume that the theory is invariant under transformations of a flavour symmetry group G (discrete or continuous)
- ...and that this is spontaneously broken to a subgroup H through the VEV 's of a set of scalar fields φ (flavons)
- $\eta = \langle\varphi\rangle/\Lambda \ll 1$
- flavor symmetries can well embed the see-saw mechanism !
- In this case the matrices M and m_D become functions of η and in the limit $\eta \to 0$ they have special forms enforced by the symmetry. For example defining $m_D^\dagger m_D = \mathcal{Y}\langle\phi\rangle^2$ one has:

$$\Omega_N^\dagger(g)\,\mathcal{Y}^0\,\Omega_N(g) = \mathcal{Y}^0$$

Example: A_4-symmetry ⟹ approximate tri-bimaximal mixing after symmetry breaking (Ma `04)

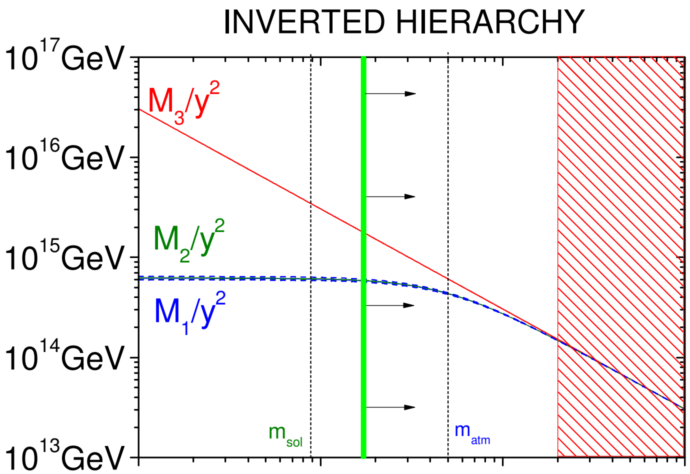
A popular example: A4 × Z_3 × $U(1)_{FN}$

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



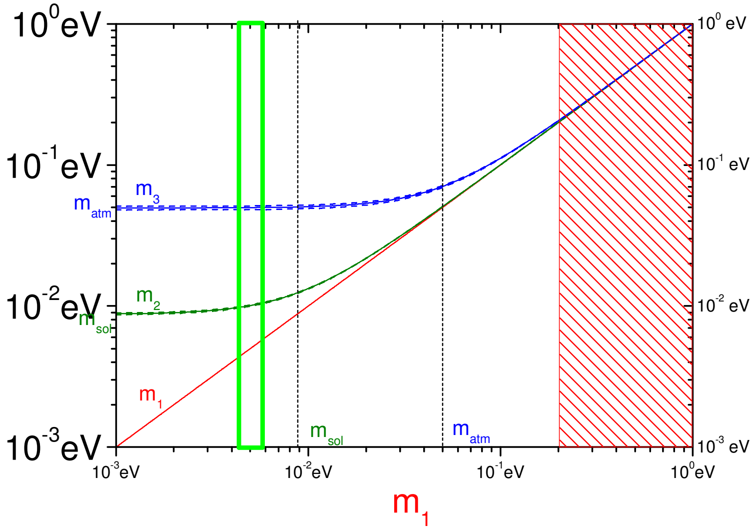
$$m_i = \frac{y^2\, v_u^2}{M_j}$$

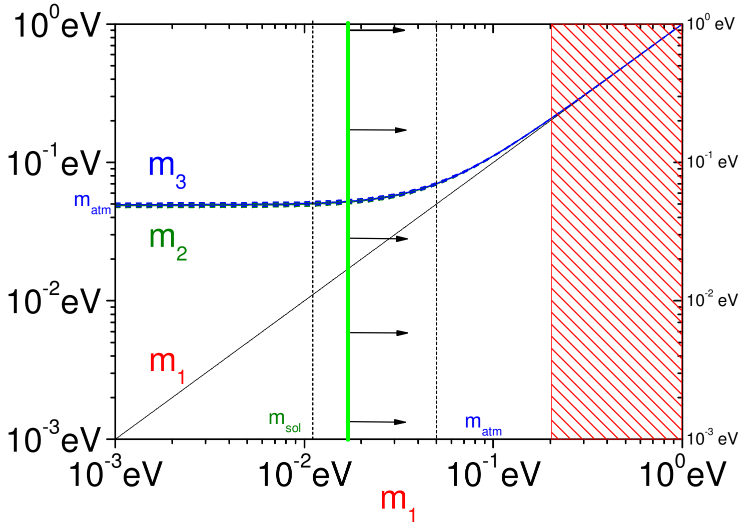
$$0.1 \lesssim y \lesssim 10$$



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

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

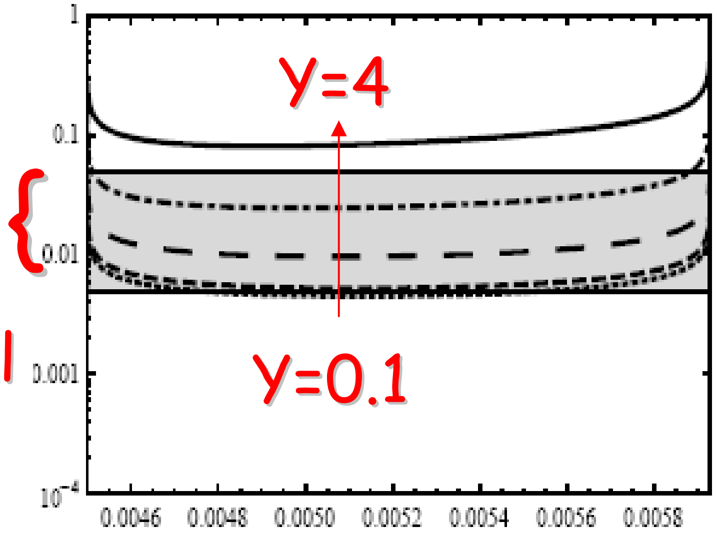




Leptogenesis in A4 x Z_3 x $U(1)_{FN}$

(Manohar, Jenkins ´08; Bertuzzo, Di Bari, Feruglio, Nardi '09;
Hagedorn, Molinaro, Petcov ´09)

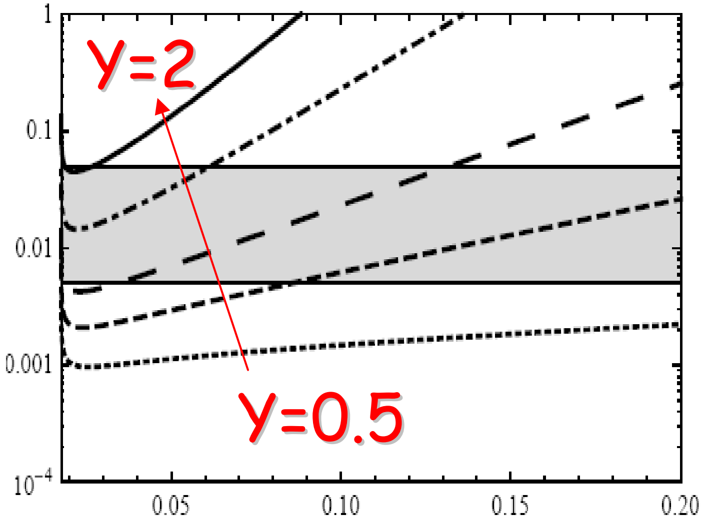
NORMAL ORDERING



Optimal range

Successful leptogenesis is realized for the natural values of the parameters without any tuning + the scale of masses (and of T_{reh}) can be lowered (lowering y)

INVERTED ORDERING



Some tuning is needed and the scale of masses (and of T_{reh}) is necessarily very high

Beyond the minimal scenario?

Many extensions have been explored that can potentially produce signals at colliders, in cosmic rays, ...

- Non-thermal leptogenesis
- Supersymmetric

$\Longrightarrow$ LFV, EDM's get enhanced and give additional constraints

- type I+type II (or type III) see-saw

- extra-gauge interactions

$\Longrightarrow$ TeV RH neutrinos get produced (and detected) more efficiently

- light (KeV) RH neutrinos

$\Longrightarrow$ can explain DM, X-ray background, pulsars kicks

- ………………………………………

...on the other hand in all these extensions of the minimal see-saw the nice matching between observed neutrino masses and matter-antimatter asymmetry is spoiled to some extent

Final remarks

- current information on neutrino masses is in very nice agreement with leptogenesis expectations !

Wish list for leptogenesis :

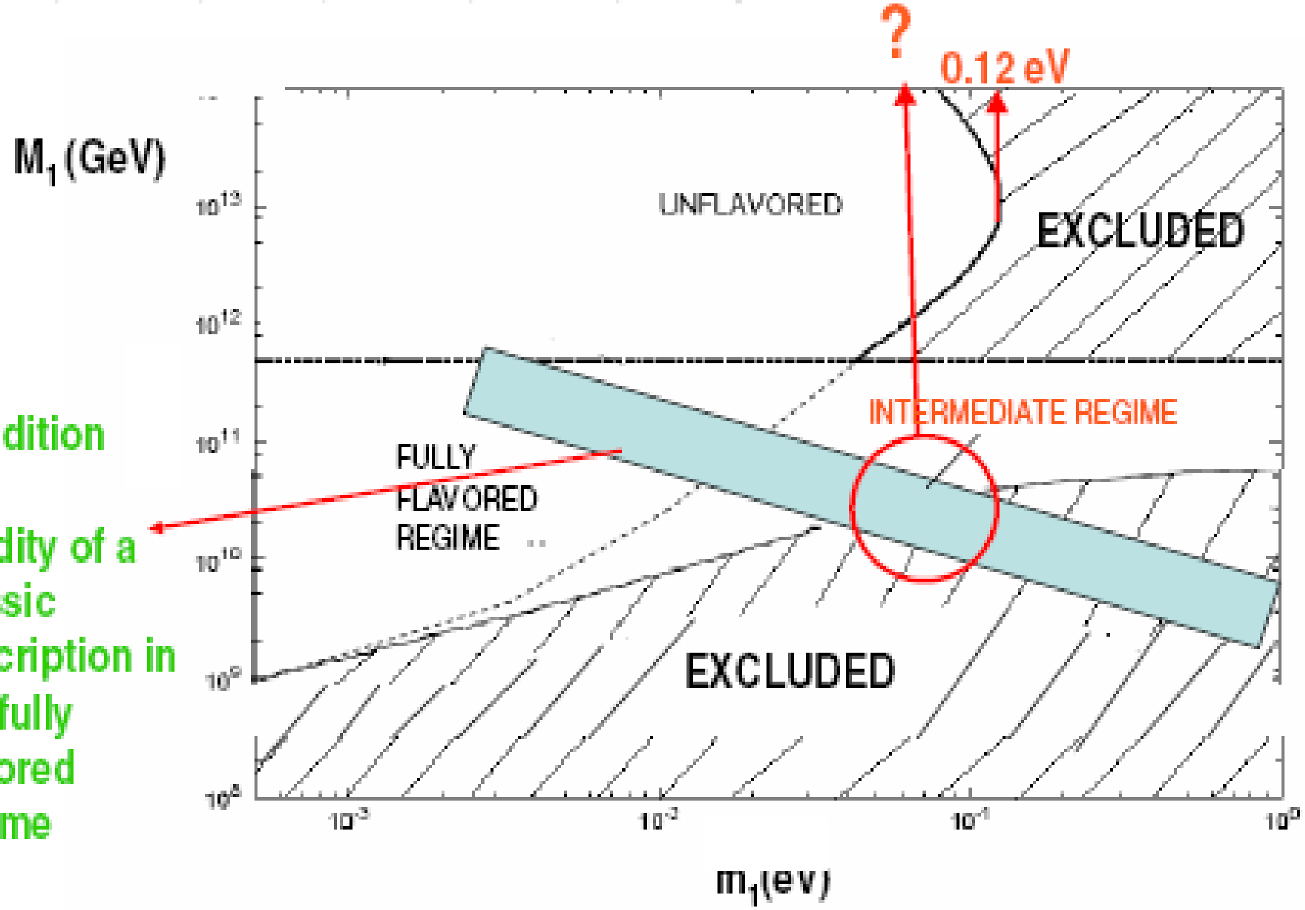
- definitive exclusion of quasi-degenerate light neutrinos
- discovery of CP violation in neutrino oscillations
- discovery of $0\nu\beta\beta$
- emergence of correlations among different data that can be explained by leptogenesis + some model of new physics
- discovery of heavy neutrinos ?

dangers :

- quasi-degenerate light neutrinos
- viable electroweak barogenesis
- $T_{reh} \lesssim 100$ GeV

There is no upper bound on m_1 in the fully flavoured regime !

(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)