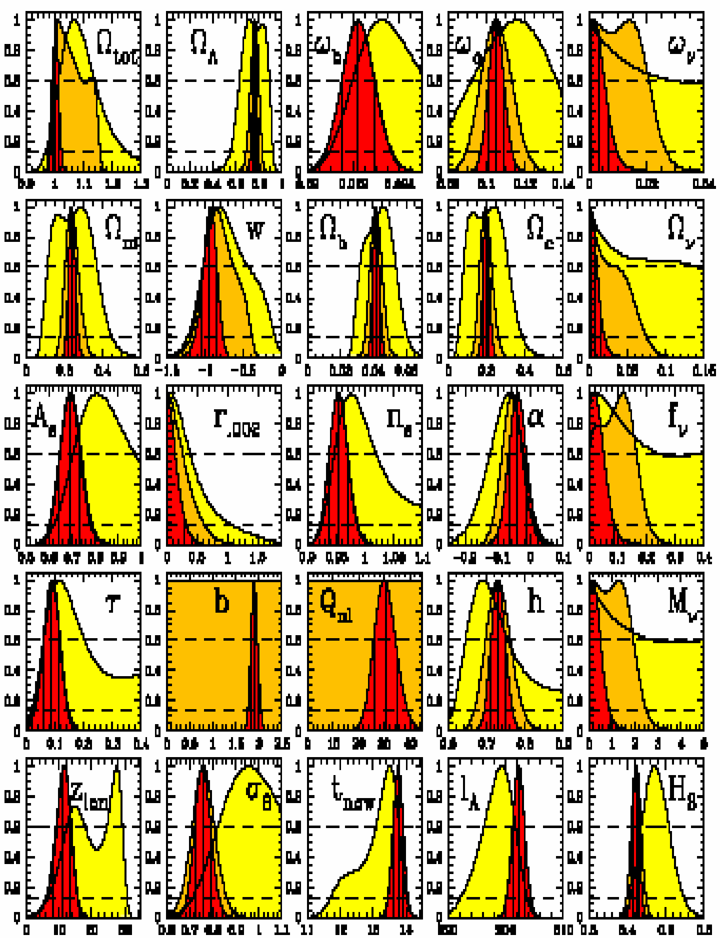
IFAE, Napoli, 12 Aprile 2007

Electroweak Baryogenesis (EWBG) versus Leptogenesis

Pasquale Di Bari
(Max Planck, Munich)

Toward a Cosmological SM ?



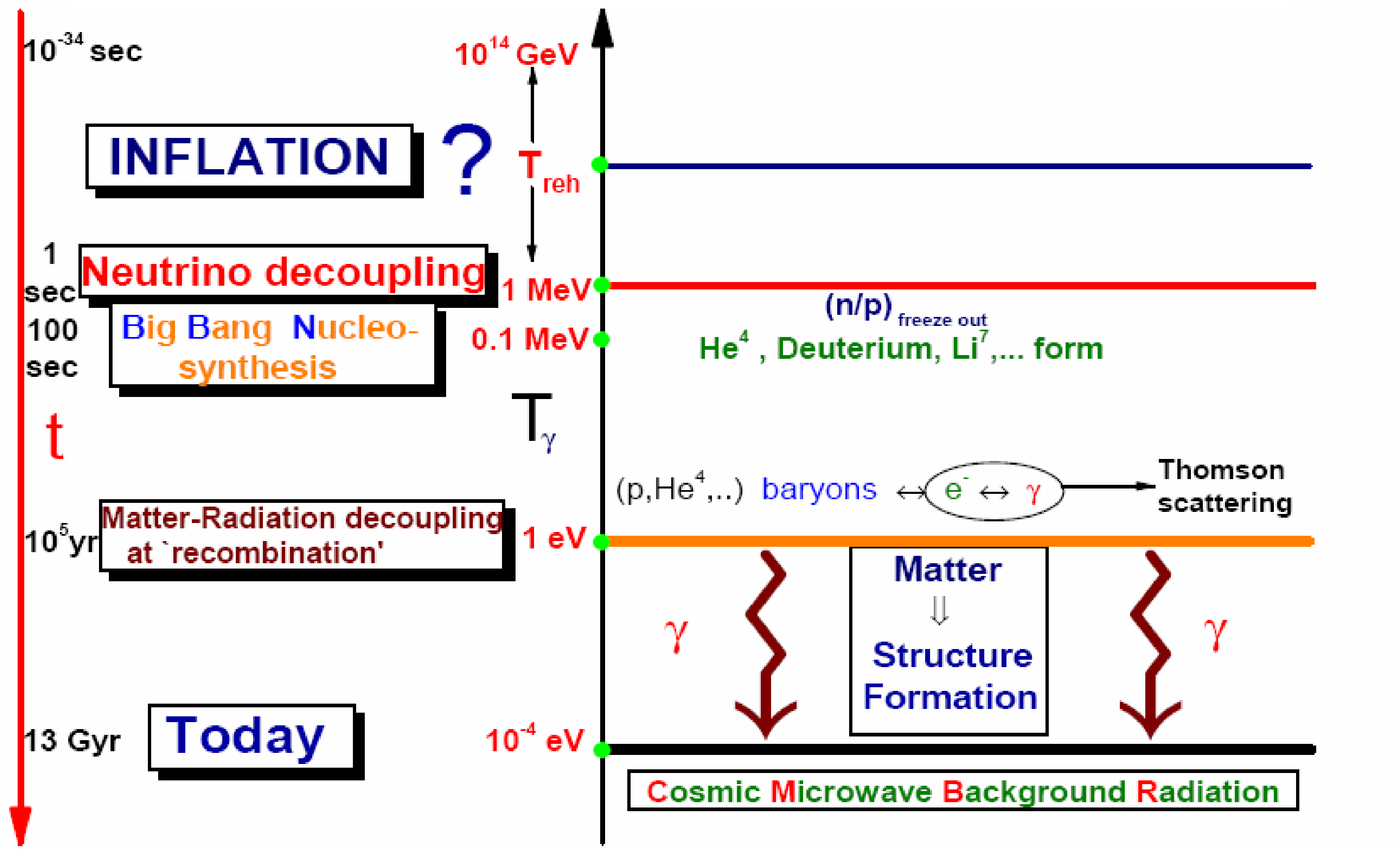
(Tegmark et al. 2005)

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

Puzzles of Modern Cosmology

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

Thermal history of the Universe



Matter-antimatter asymmetry

- Symmetric Universe with matter- anti matter domains ?
  Excluded by CMB + cosmic rays

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

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

$\Rightarrow$ dynamical generation (baryogenesis)

(Sakharov '67)

Models of Baryogenesis

- From phase transitions:
  - EWBG:
    - * in the SM
    - * **in the MSSM**
    - * in the NMSSM
    - * in the 2 Higgs model
    - * …………………
- Affleck-Dine:
  - at preheating
    - Q-balls
  - ……….
- From Black Hole evaporation
- Spontaneous Baryogenesis
- ………………………………..
- From heavy particle decays:
  - GUT Baryogenesis
  - **LEPTOGENESIS**

Baryogenesis in the SM ?

All 3 Sakharov conditions are fulfilled in the SM:

1. baryon number violation at T $\gtrsim$ 100 GeV,
2. CP violation in the quark CKM matrix,
3. departure from thermal equilibrium (an arrow

   from the expansion of the Universe

Baryon Number Violation at finite T

('t Hooft

Although at T= 0 baryon number violating processes are inhibited,
at finite T:

$$\Gamma(\Delta B \neq 0) \propto T^4 \exp\left[-\kappa \frac{v(T)}{T}\right]$$

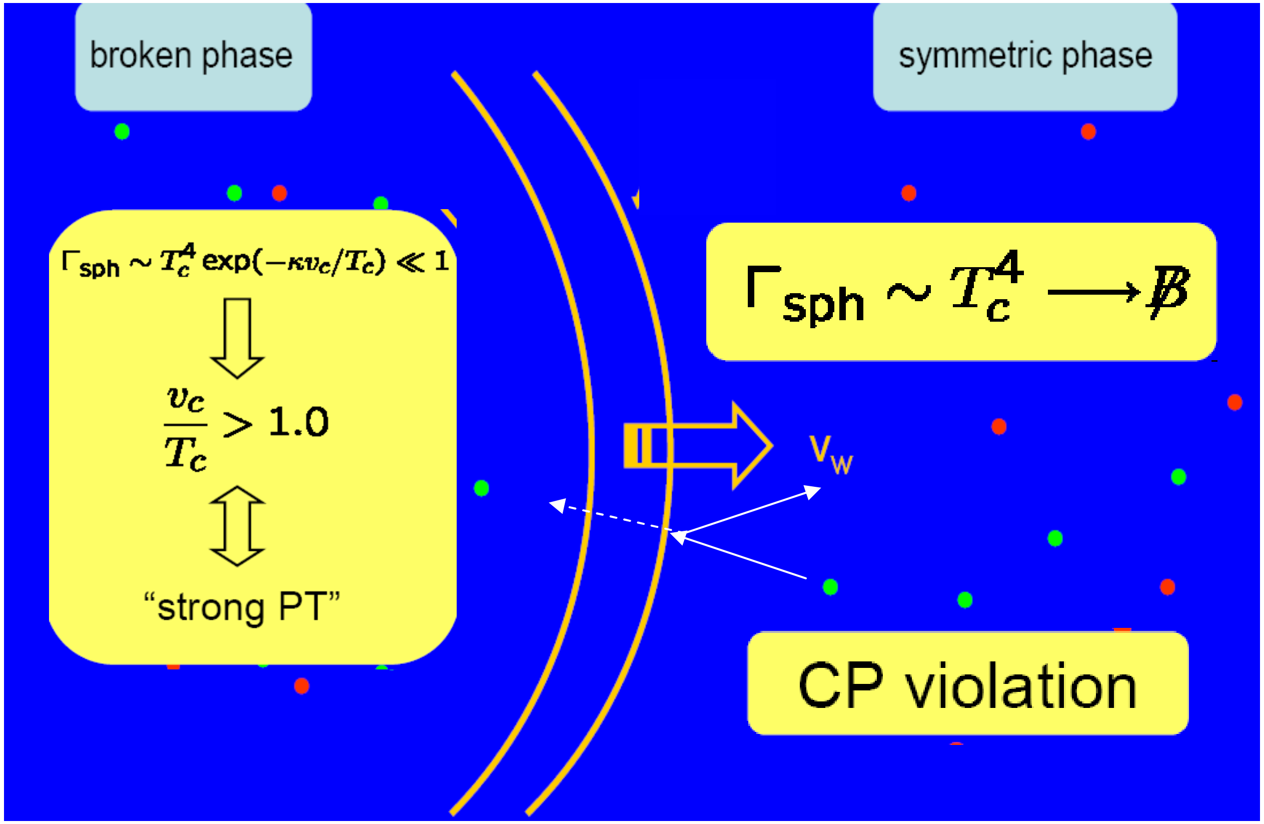
$$v \equiv \langle \Phi \rangle = \begin{cases} 0 \text{ for } T \gtrsim T_c \text{ (unbroken} \\ v(T_c) \text{ for } T \lesssim T_c \end{cases}$$

- Baryon number violating processes are unsuppressed at $T \gtrsim T_c \simeq 100$
- Anomalous processes violate lepton number as well but preserve B-L !

I **There can be enough departure from thermal equilibrium ?**

EWBG in the SM

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



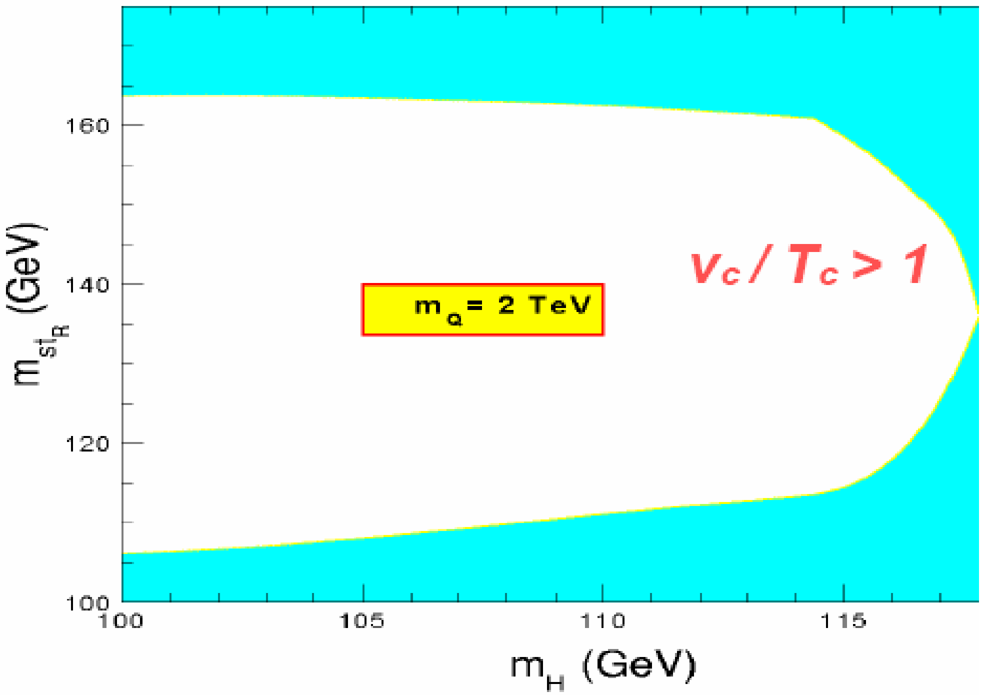
In the SM the ratio v_c/T_c is directly related to the Higgs mass and only for $M_h < 40$ GeV one can have a strong PT $\Longrightarrow$ EW baryogenesis in the SM is ruled out by the LEP lower bound $M_h \gtrsim 114$ GeV ! (also not enough $\not{CP}$)

$\Longrightarrow$ New Physics is needed!

EWBG in the MSSM

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

M.Carena, M. Quiros,C.W.' 98



- Notice that there is a tension between the strong PT requirement and the 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 CP violation in the bubble walls without generating too large electric dipole of the electron: is EWBG still alive ?

Is EWBG still alive ?

3 possible attitudes:

- Optimistic: Not only it is alive but the allowed region in the MSSM parameter space has interesting features also to solve another of the cosmological puzzles: Dark Matter

  (Carena et al. '05)
- Realistic: EWBG in the MSSM has strong constraints but these can be relaxed within other frameworks:
  - in the NMSSM

    (Pietroni '92,Davies et al. '96, Huber and Schmidt '01)
  - in the nMSSM

    (Wagner et al. '04)
  - in left-right symmetric models at B-L symmetry breaking

    (Mohapatra and Zhang '92)
  - …….
- Pessimistic: We need some other mechanism; SUSY has not yet been discovered but on the other hand ….

Neutrino masses: $m_1 < m_2 < m_3$

neutrino mixing data

2 possible schemes: normal or inverted

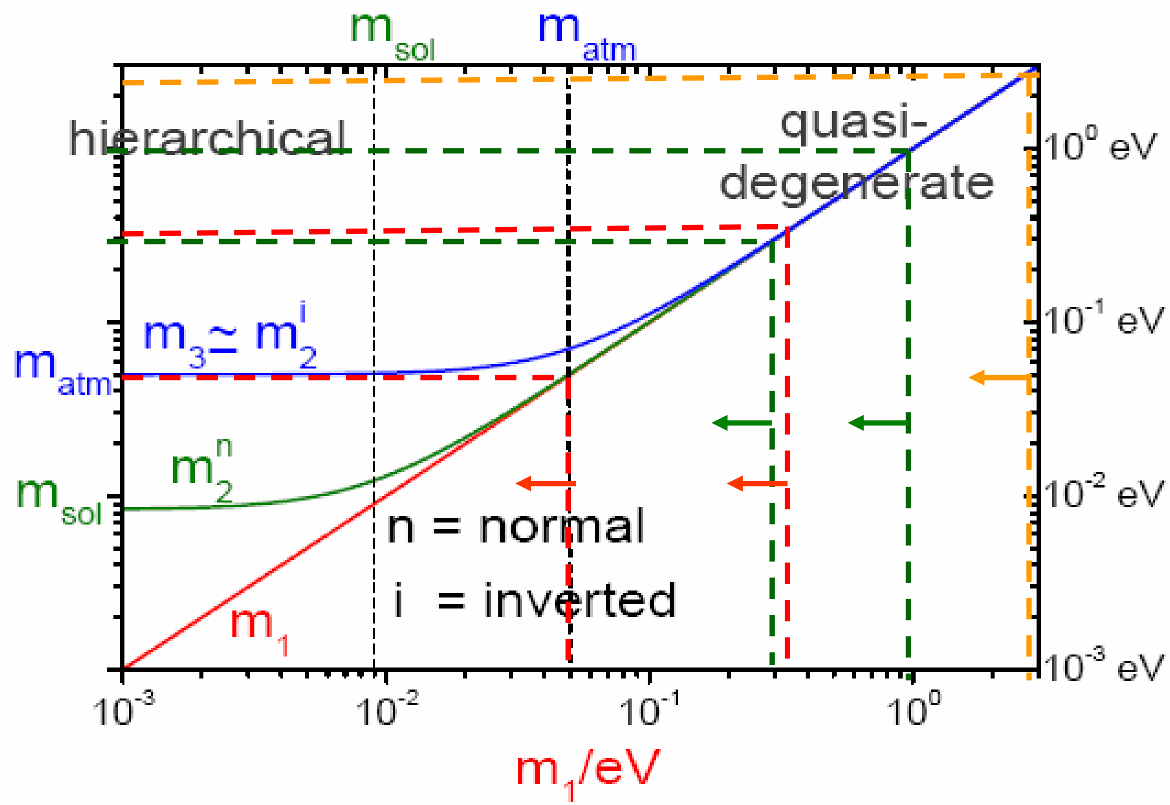
$$m_3^2 - m_2^2 = \Delta m^2_{\rm atm} \text{ or } \Delta m^2_{\rm sol} \qquad m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} \simeq 0.05\,{\rm eV}$$

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

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+LSS : $\Sigma\, m_i < 0.94$ eV
(WMAP+SDSS)
CMB+LSS + Lyα : $\Sigma\, m_i < 0.17$ 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 $\Rightarrow m_D = v\,h \quad (v \equiv \langle\phi_0\rangle)$

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

3 limiting cases :

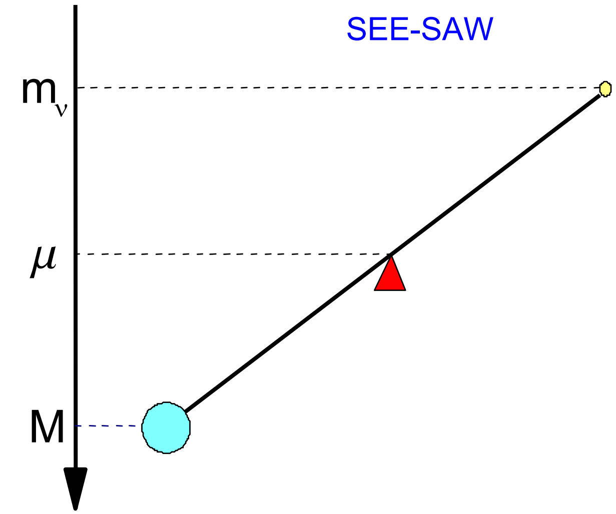
- pure Dirac: $M_R = 0$
- pseudo-Dirac : $M_R \ll m_D$
- see-saw limit: $M_R \gg m_D$

See-saw mechanism

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

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

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

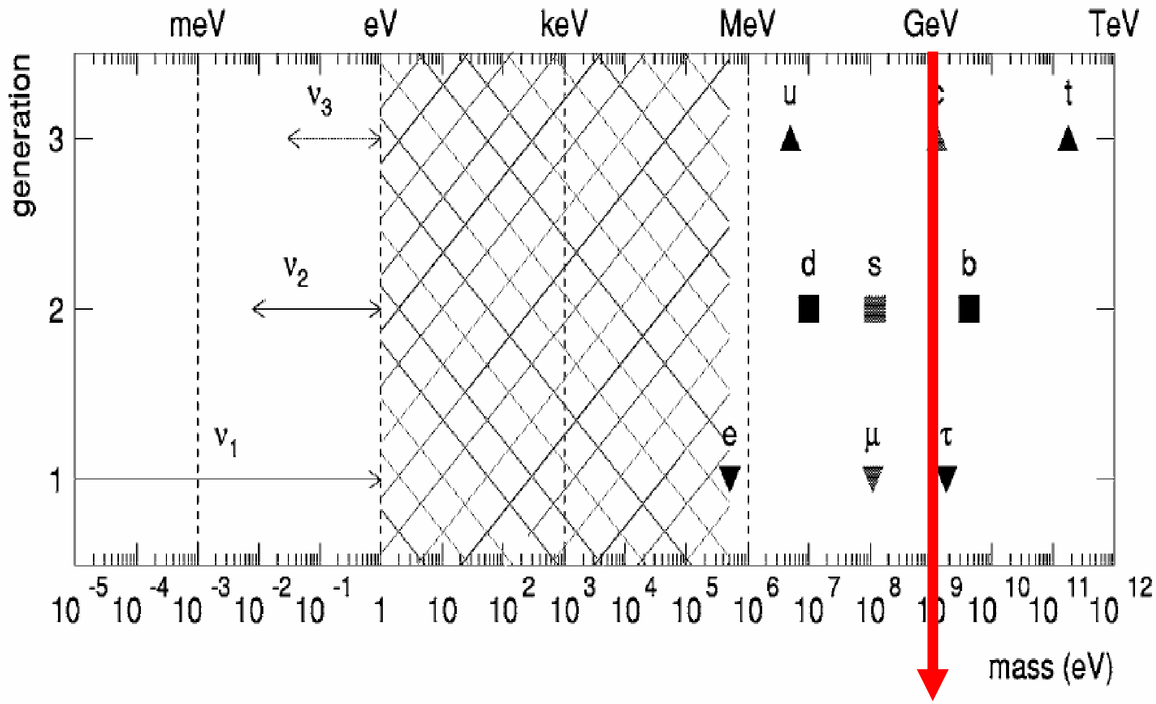


- All eigenstates (light and heavy neutrinos) are Majorana neutrinos (self-conjugate particles)

$$(N = \nu_R + \nu_R^c \;,\;\; \nu = \nu_L + \nu_L^c) \quad \Rightarrow \quad \beta\beta0\nu \text{ decay}$$

Typical 1 generation example:

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



$\mu_* \sim 1$ GeV

$\mu > \mu^* \Longrightarrow$ high pivot see-saw scale $\Longrightarrow$ \`heavy' RH neutrinos

$\mu < \mu^* \Longrightarrow$ low pivot see-saw scale $\Longrightarrow$ \`light' RH neutrinos

Basics of leptogenesis

(Fukugita,Yanagida '86)

M, m_D, m_ν are complex matrices $\Longrightarrow$ natural source of CP violation

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

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

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)

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

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

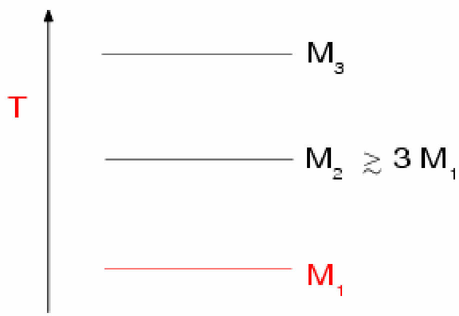
The traditional picture

- flavor composition of leptons is neglected
- hierarchical heavy neutrino spectrum
- asymmetry generated from the lightest RH neutrino decays (N_1-dominated scenario)

N_1 - dominated scenario

Assume:

1. hierarchical heavy neutrino spectrum



$$\Rightarrow N_{B-L}^{\rm fin} \simeq \left(\varepsilon_3\, \kappa_3^{T\gg M_1} + \varepsilon_2\, \kappa_2^{T\gg M_1}\right) e^{-K_1} + \varepsilon_1\, \kappa_1^{\rm fin}$$

2. • strong wash-out ($K_1 \gg 1$)

decays and inverse processes are fast compared to the expansion of the Universe

or

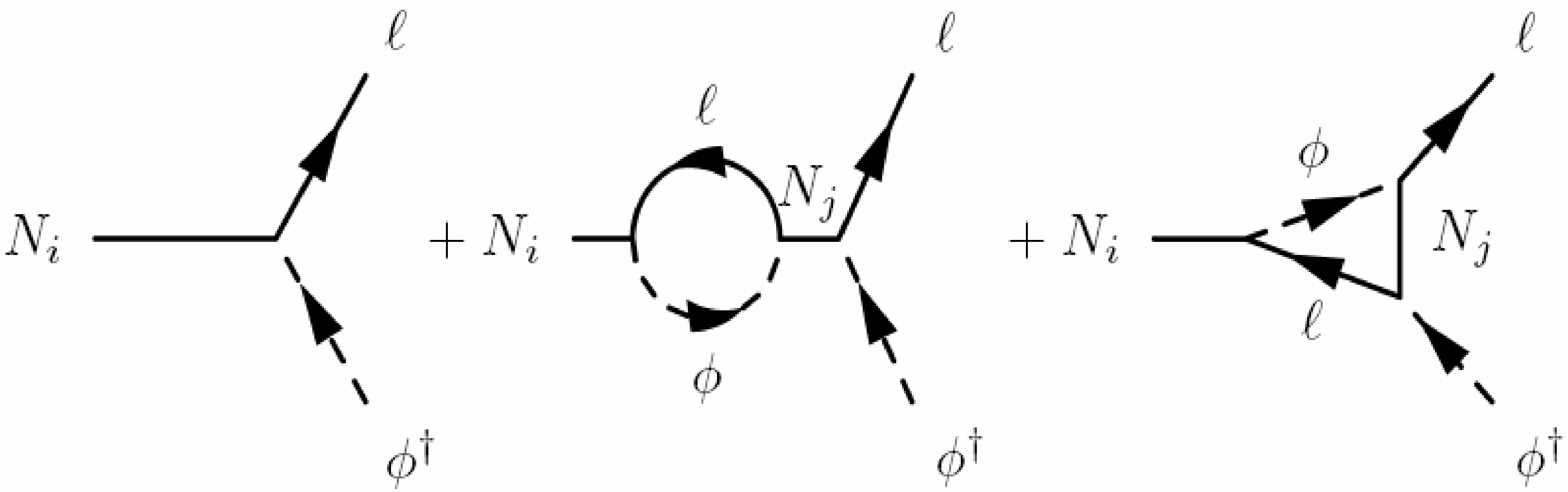
• weak wash-out ($K_1 \lesssim 1$) and $|\varepsilon_3|, |\varepsilon_2| \ll |\varepsilon_1|$

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

It does not depend on low energy phases !

CP asymmetry

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



Assuming $|M_{j\neq i} - M_i| \gg |\Gamma_{j\neq i} - \Gamma_i|$ (off-resonance condition),

the interference between tree level and one-loop diagrams (self energy + vertex) yields:

$$\varepsilon_i \;\simeq\; \frac{1}{8\pi\, v^2\, (m_D^\dagger\, m_D)_{ii}} \sum_{j=2,3} \mathrm{Im}\left[(m_D^\dagger\, m_D)_{ij}^2\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

$\Rightarrow$ the ε_i's depend on m_D only through $m_D^\dagger\, m_D \Rightarrow U$ cancels out !

Decays and Inverse Decays

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

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

$$K_i \equiv \frac{\Gamma(N_i\rightarrow l\Phi^\dagger)|_{T\rightarrow 0}}{H(T=M_i)} = \frac{(m_{\rm D}^\dagger m_{\rm D})_{ii}}{M_i}$$

``decay parameters´´

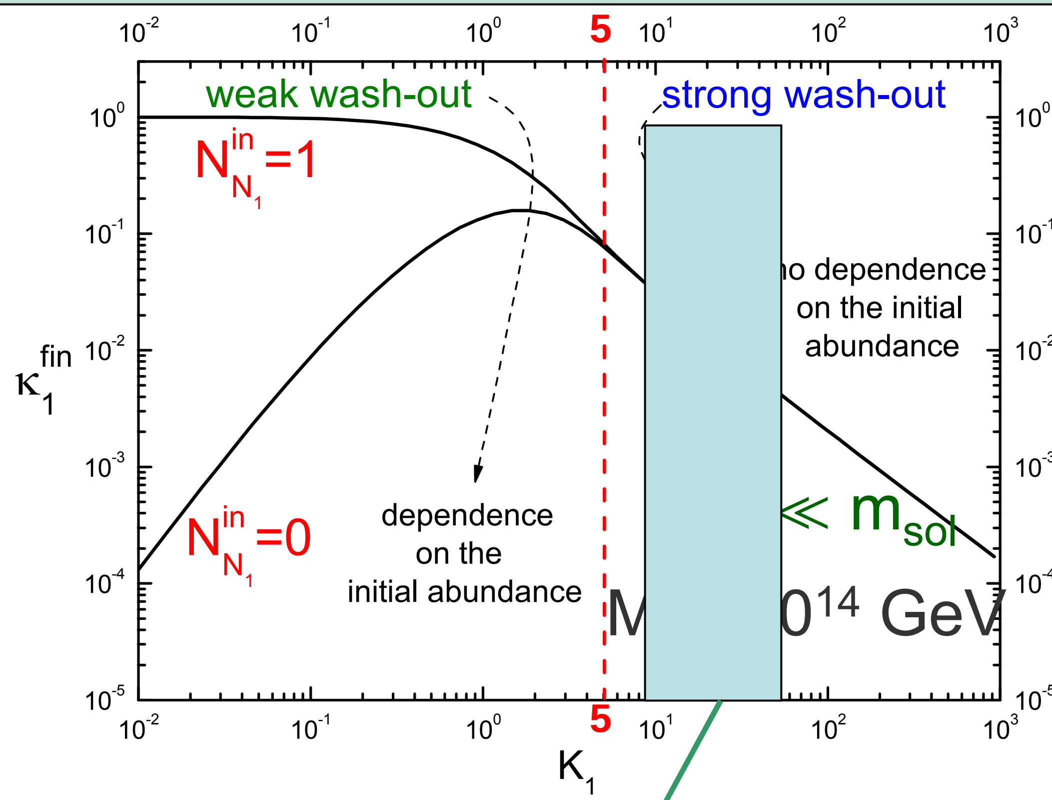
$$D_1 = \frac{\Gamma_{D,1}}{H\,z} = K_1\,z\left\langle\frac{1}{\gamma}\right\rangle, \quad W_{ID} \propto D_1 \propto K_1$$

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

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

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

Dependence on the initial conditions



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

Neutrino mixing data favor the strong wash-out regime !

Neutrino mass bounds

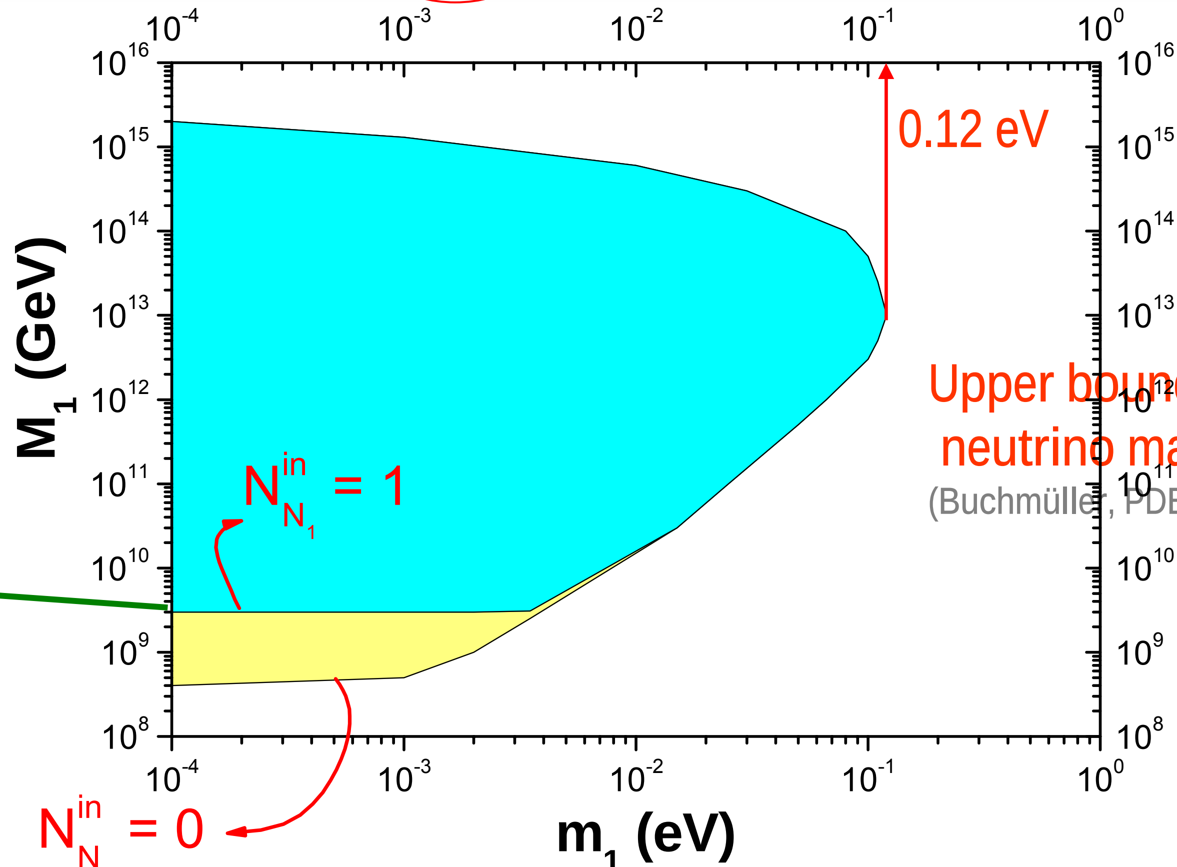
~ 10^{-6} (M_1 / 10^{10} GeV)

$$\eta_B^{\max}(m_1,\tilde{m}_1,M_1) \simeq 10^{-2}\,\varepsilon_1^{\max}(M_1)\,\frac{m_{\rm atm}}{m_3+m_1}\,f(m_1,\tilde{m}_1)\,\kappa_{\rm f}(\tilde{m}_1)\,e^{-\frac{M_1}{10^{14}\,{\rm GeV}}\frac{\sum_i m_i^2}{m_{\rm atm}^2}} \geq \eta_B^{CMB}$$

Lower bound on M_1

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

3x10^9 GeV



$N_{N_1}^{in} = 0$

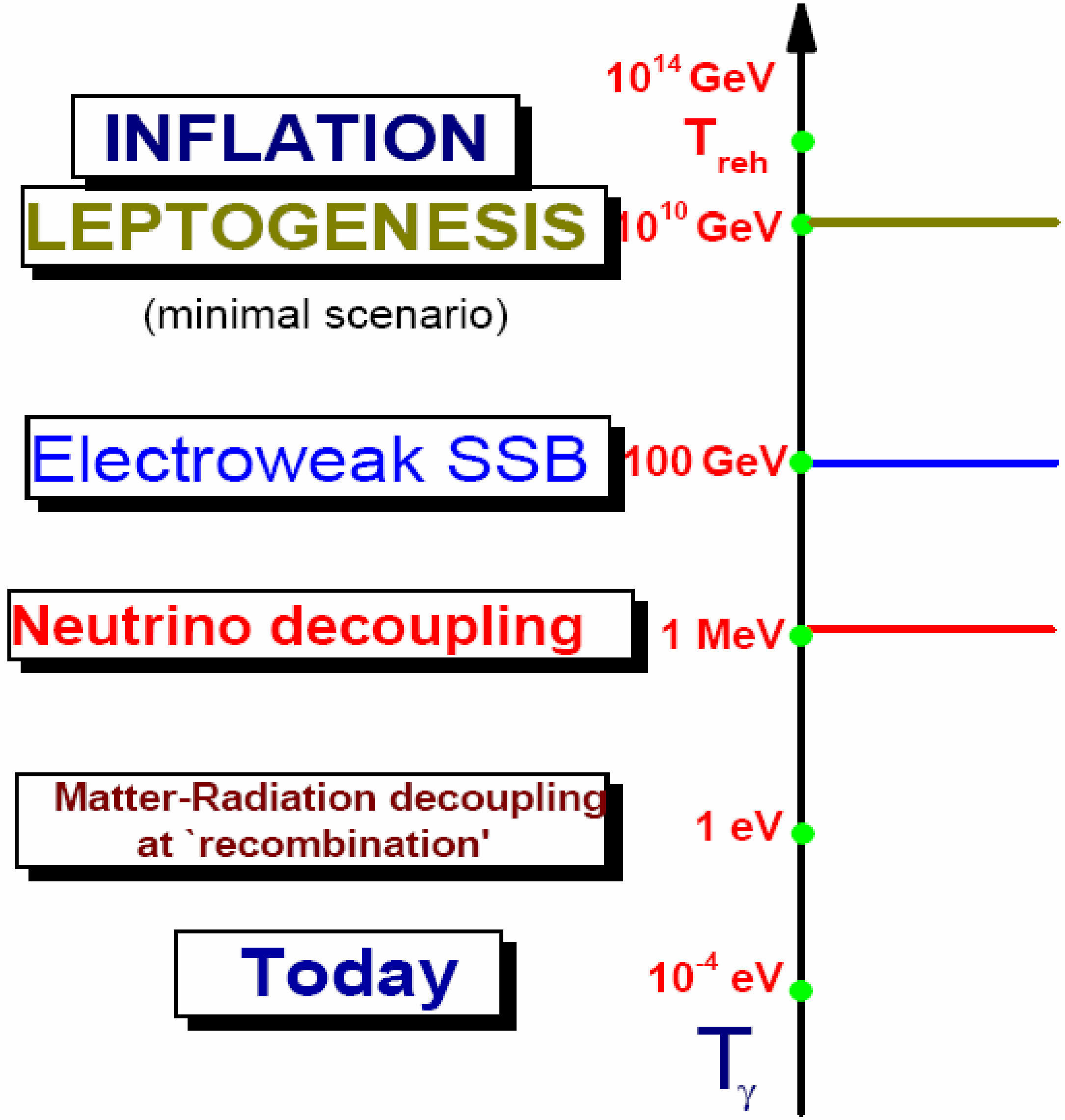
Upper bound on the absolute neutrino mass scale

(Buchmüller, PDB, Plümacher '02)

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

(Buchmüller, PDB, Plümacher '04)

The need of a very hot Universe for Leptogenesis



Beyond the traditional picture

- N_2-dominated scenario
- beyond the hierarchical limit
- flavor effects

N_2-dominated scenario

(PDB'05)

See-saw orthogonal matrix:

(Casas, Ibarra'01)

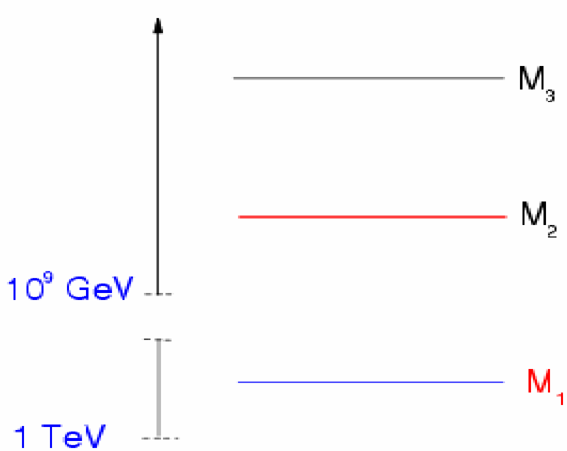
$$m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$$

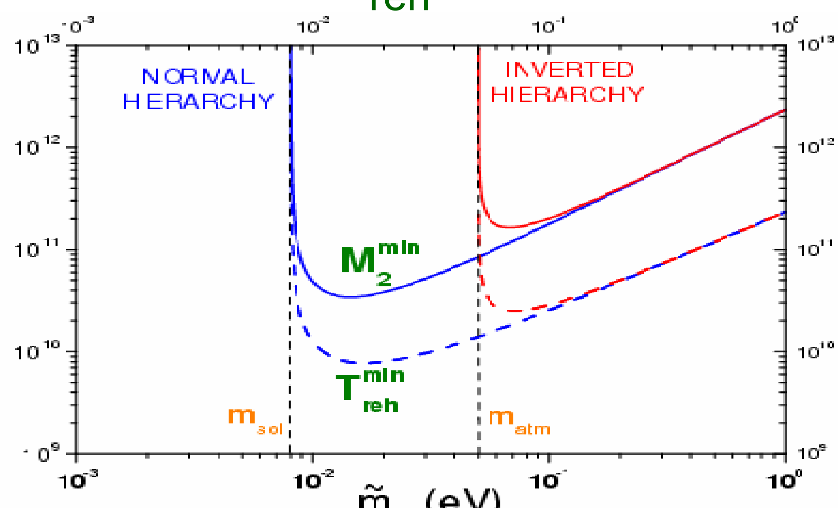
$$\boxed{m_D} = \boxed{U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}}$$

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

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

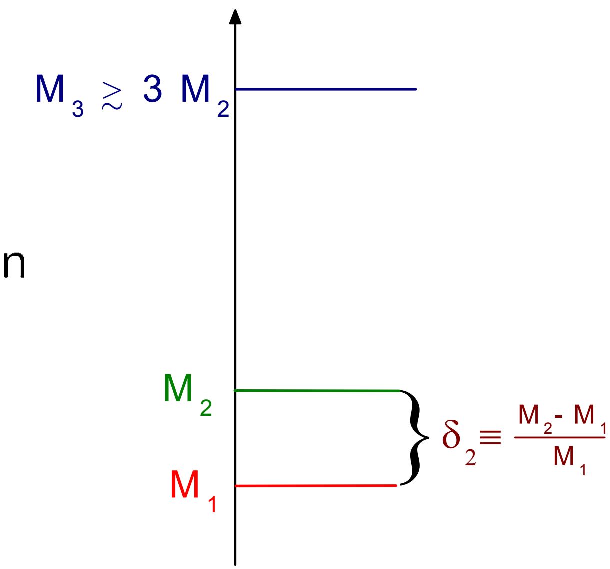
The lower bound on M_1 disappears and is replaced by a lower bound on M_2. The lower bound on T_{reh} remains





Beyond the hierarchical limit

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



Assume:

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

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

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

- heavy N_3: $M_3 >> 10^{14}$ GeV

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

1) the two wash-out add up $\Rightarrow \mathbf{N}_{\mathbf{B-L}}^{\rm fin} \searrow$

2) $\varepsilon_2\, \kappa_2^{\rm fin} \sim \varepsilon_1\, \kappa_1^{\rm fin} \Rightarrow \mathbf{N}_{\mathbf{B-L}}^{\rm fin} \nearrow$

3) both $\varepsilon_1, \varepsilon_2 \propto \delta_2^{-1}$ for $\delta_2 \ll 0.1 \Rightarrow \mathbf{N}_{\mathbf{B-L}}^{\rm fin} \nearrow$

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

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

Flavor effects

(Nardi,Roulet'06;Abada et al.'06;Blanchet,PDB'06)

$$N_1 \longrightarrow l_1\, H^\dagger\,, \qquad\qquad N_1 \longrightarrow \bar{l}'_1\, H$$

Flavour composition:

$$|l_{\rangle} = \sum_\alpha \langle l_\alpha | l_1 \rangle\, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau)$$

$$|\bar{l}'_1\rangle = \sum_\alpha \langle l_\alpha | \bar{l}'_1 \rangle\, |\bar{l}_\alpha\rangle$$

Does it play any role ? No if $M_1 > \mathcal{O}(10^{12}\,\mathrm{GeV})$

However for lower values of M_1 the τ-Yukawa interactions,

$$-\bar{l}_{L\alpha}\, \phi\, f_{\alpha\alpha}\, e_{R\alpha}\,, \qquad (\alpha = \tau)$$

are fast enough to break the coherent evolution of the $|l_1\rangle$ and $|\bar{l}'_1\rangle$ quantum states that are projected on the flavor basis!

projectors:

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

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

these 2 terms correspond to 2 different flavor effects :

- In each inverse decay $H^\dagger + l_\alpha \rightarrow N_1$ the Higgs interacts now with incoherent flavor eigenstates !

$\Longrightarrow$ the wash-out is reduced and $K_1 \rightarrow K_{1\alpha} \equiv P^0_{1\alpha} K_1$

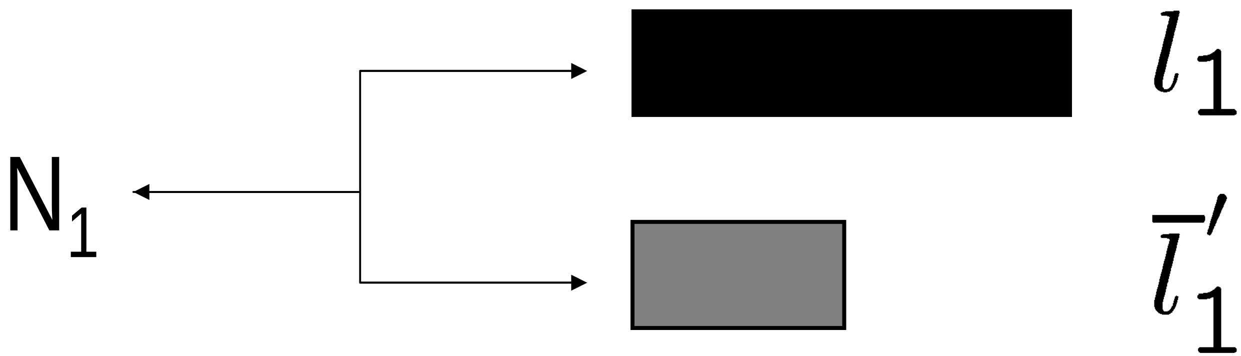
- In general $|\bar{l}'_1\rangle \neq CP|l_1\rangle$ and this produces an additional CP violating contribution to the flavoured CP asymmetries

$$\varepsilon_{1\alpha} \equiv -\frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = P^0_{1\alpha}\,\varepsilon_1 + \frac{\Delta P_{1\alpha}}{2}$$

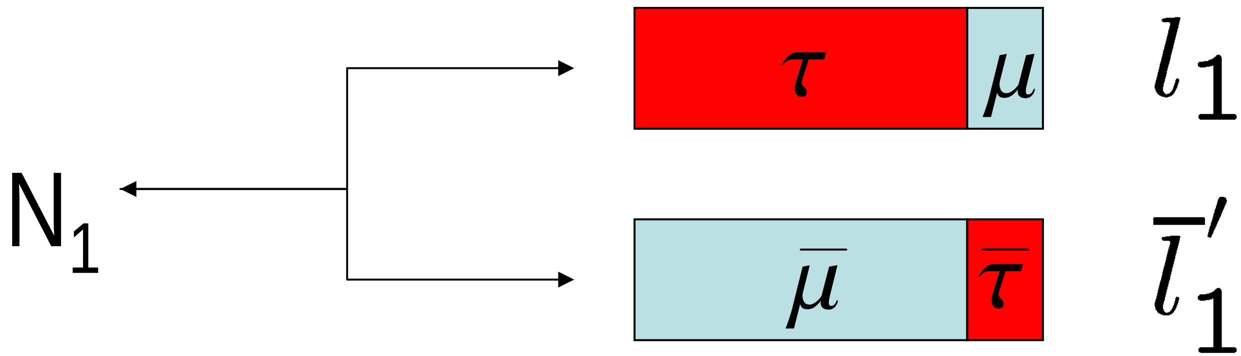
Interestingly one has that this additional contribution depends on U !

In pictures:

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



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



Flavoured Kinetic Equations

It is then necessary to track the asymmetries separately in each flavor:

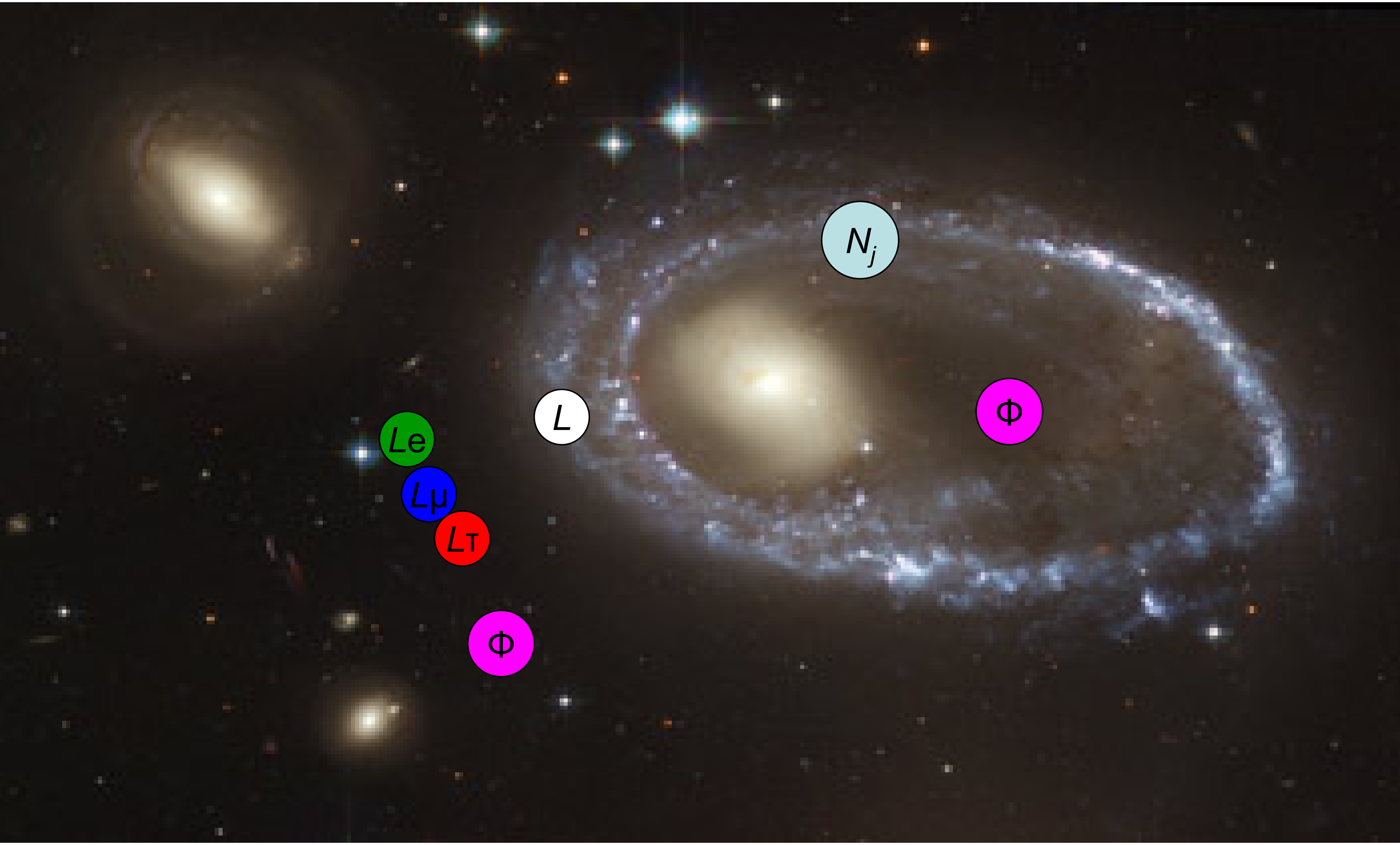
$$\Delta_\alpha \equiv \frac{B}{3} - L_\alpha$$

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

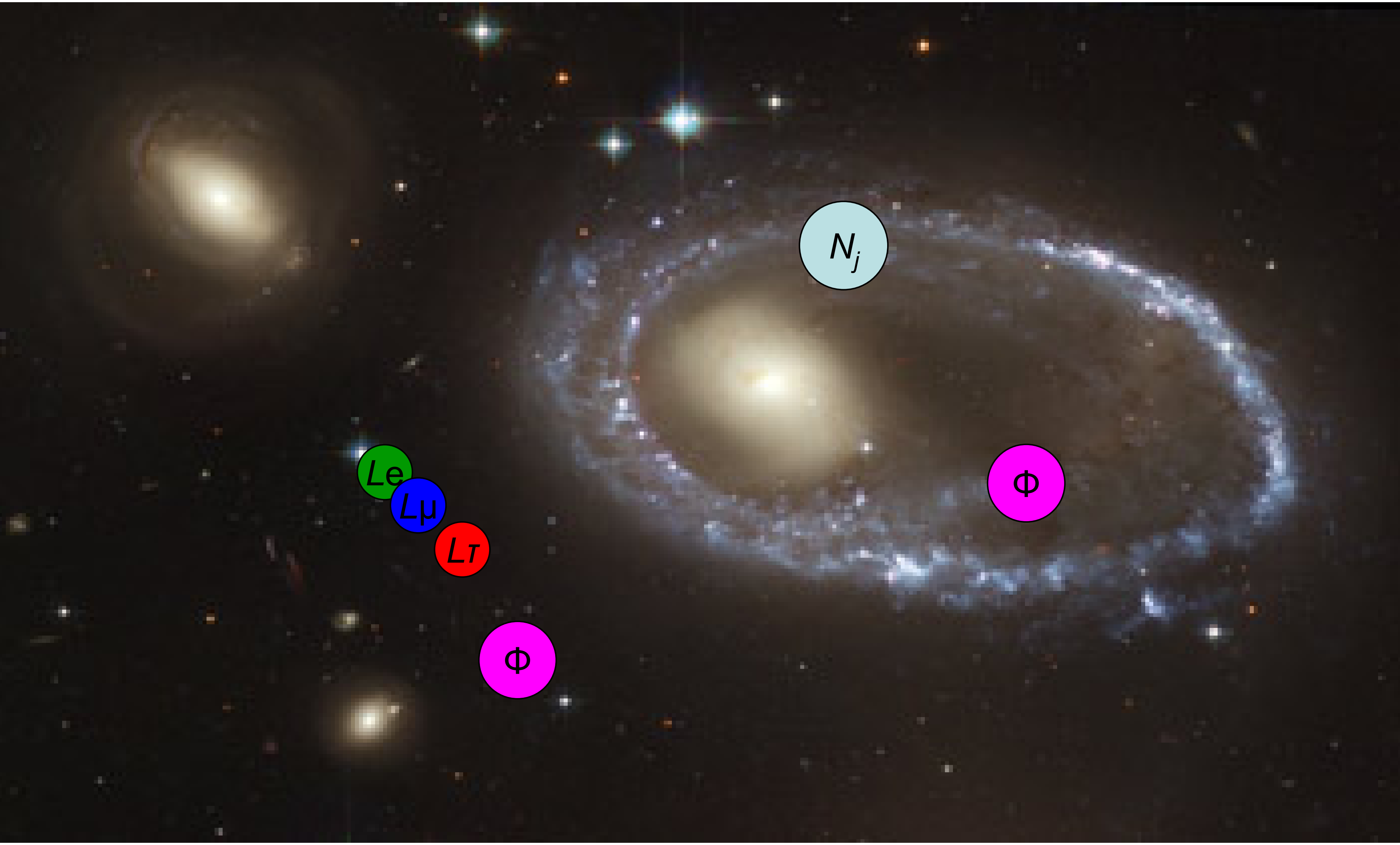
$$\frac{dN_{\Delta_\alpha}}{dz} = -\varepsilon_{1\alpha}\,\frac{dN_{N_1}}{dz} - P_{1\alpha}^0\,W_{ID}\,N_{\Delta_\alpha}$$

$$N_{B-L} = \sum_\alpha N_{\Delta_\alpha}$$

NO FLAVOR



WITH FLAVOR



General scenarios ($K_1 >> 1$)

– Alignment case

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

– Democratic (semi-democratic) case

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

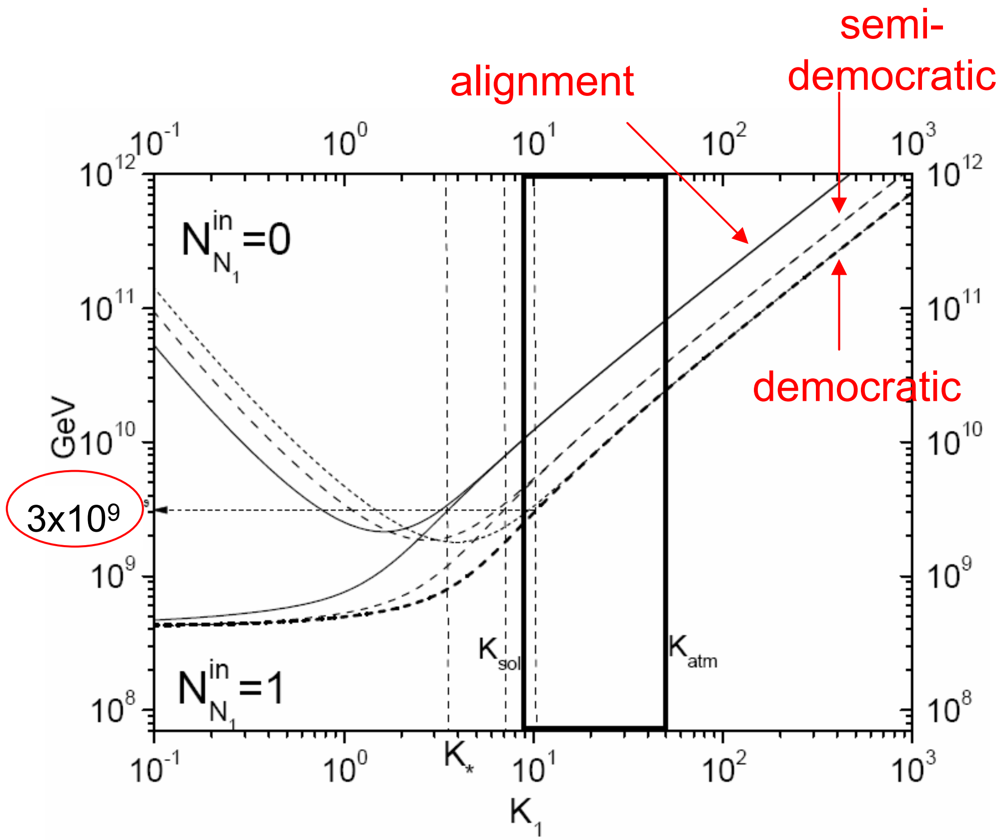
– One-flavor dominance

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

big effect!

Lower bound on M_1

(Blanchet,PDB'06)



⟹ The lowest bounds independent of the initial conditions (at $K_1=K_*$) don't change! (Blanchet, PDB '06)

But for a fixed K_1, there is a relaxation of the lower bounds of a factor 2 (semi-democratic) or 3 (democratic), but it can be much larger in the case of one flavor dominance.

A relevant specific case

- Let us consider:

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

•Since the projectors and flavored asymmetries depend on U
$\Longrightarrow$ one has to plug the information from neutrino mixing experiments

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

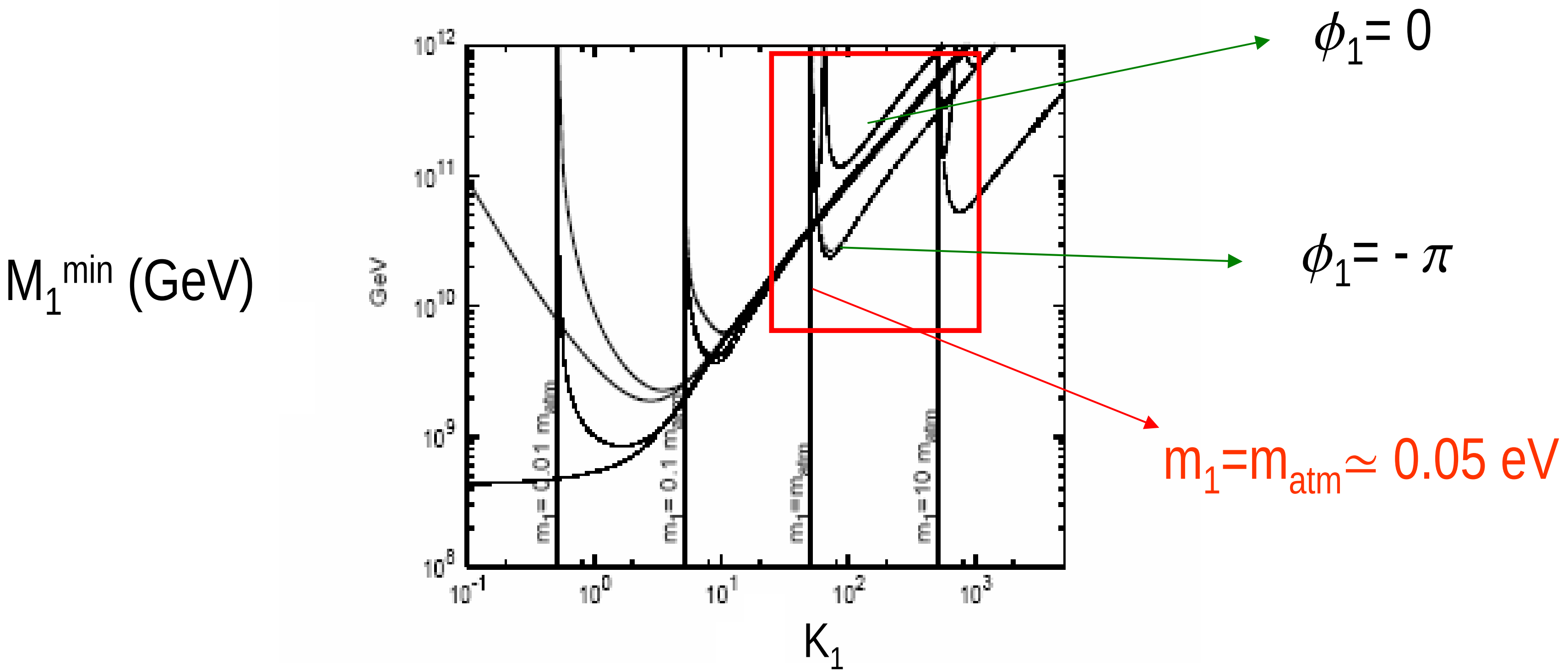
$$\Longrightarrow \quad P^0_{1e} \simeq 0, \quad P^0_{1\mu} \simeq P^0_{1\tau} \simeq 1/2\,, \quad \Delta P_{1\alpha} = 0$$

$\Longrightarrow$ Semi-democratic case

Flavor effects represent just a correction in this case !

The role of Majorana phases

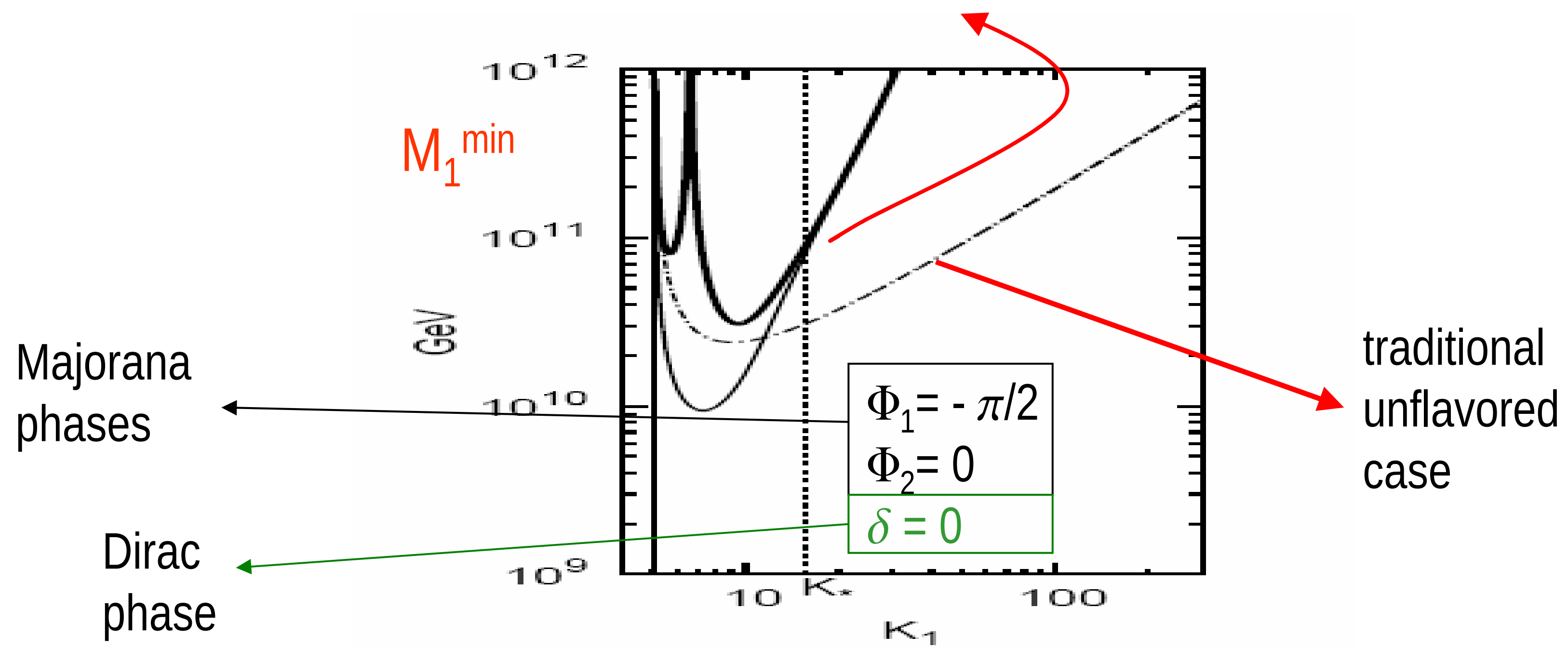
- However allowing for a non-vanishing m_1 the effects become much larger especially when Majorana phases are turned on !



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

Leptogenesis from low energy phases ?

Let us now further impose Ω real setting $Im(\omega_{13})=0$



•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 $\beta\beta0\nu$ decay (Majorana phases) and neutrino mixing (Dirac phase)

• Moreover considering the degenerate limit these lower bounds can be relaxed: this is important for `δ-leptogenesis' ! (Anisimov, Blanchet, PDB, in preparation)

Conclusions

- Leptogenesis has at the moment a clear advantage on EWBG: neutrino masses have been discovered and even in the right range; a discovery of CP violation in neutrino mixing would represent another success;
- EWBG has the nice virtue to be highly predictive (therefore also falsifiable): LHC,ILC,DM direct searches, EDM's, gravitational waves in LISA **(Riotto et al. '01)** ;
- EWBG discovery would kill leptogenesis making it useless;
- However, if nothing beyond a SM Higgs will be found then this would represent another positive test for leptogenesis and a definitive death of EWBG

The orthogonal seesaw matrix

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

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

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

- parameter counting: 6 + 3 + 6 + 3 = 18
  - experiments $\Rightarrow$ information on the 9 'low energy' parameters in $m_\nu = -U\, D_m\, U^T$:
    - we measure 4: $m_{\rm atm},\, m_{\rm sol},\, \theta_{23} \simeq 45^0,\, \theta_{12} \simeq 32^0 \simeq 45^0 - \theta_C$
    - we still miss five: $m_1 \lesssim 1\,{\rm eV},\, \theta_{13} \lesssim 14^0,\, \delta,\, \varphi_1,\, \varphi_2$
  - the 9 parameters in Ω and in M_i escape conventional investigation: the dark side !
  - leptogenesis $\Rightarrow$ information on Ω, M_i and also on m_1 but $\varepsilon_i = \varepsilon_i(m_D^\dagger\, m_D)$

    $\Rightarrow$ U cancels out: in general we cannot test leptogenesis with $\not{CP}$ in neutrino mixing !

(Unflavored) Kinetic Equations

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

$$\frac{dN_{N_i}}{dz} = -(D_i + S_i)(N_{N_i} - N_{N_i}^{\rm eq})$$

$$\frac{dN_{B-L}}{dz} = \sum_i \varepsilon_i (D_i + S_i)(N_{N_i} - N_{N_i}^{\rm eq}) - N_{B-L} \sum_i W_i^{\rm ID}$$

CP violation in decays

Wash-out term from inverse decays

$$D_i \equiv \frac{\Gamma_{D,i}}{H(z)\, z} = K_i\, z \left\langle \frac{1}{\gamma} \right\rangle , \quad W_i^{\rm ID} \propto D_i \propto K_i$$

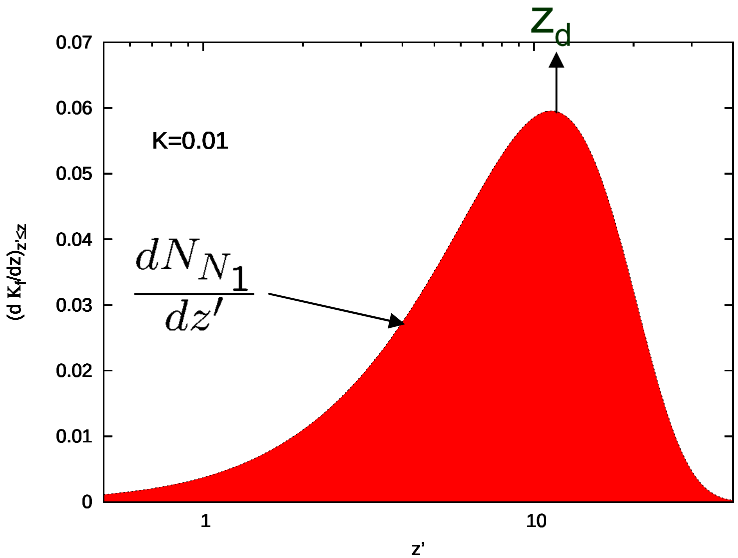
``decay parameters´´

$$K_i \equiv \frac{\Gamma(N_i \to l \Phi^\dagger)|_{T \to 0}}{H(T = M_i)} = \frac{(m_{\rm D}^\dagger m_{\rm D})_{ii}}{M_i}$$

- Strong wash-out when $K_i \gtrsim 3$
- Weak wash-out when $K_i << 3$

$z \equiv M_1 / T$ $K_1 \equiv t_U(T=M_1)/\tau_1$

WEAK WASH-OUT



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