Baryogenesis Confronts Experiment

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Flavored thermal leptogenesis

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Outline

- ★ Motivation for thermal leptogenesis
    - ☐ See-saw
- ★ Unflavored thermal leptogenesis
    - ☐ Implications
- ★ Flavored thermal leptogenesis
    - ☐ New ingredients
    - ☐ Revised implications
    - ☐ Condition of validity of the Boltzmann equations
    - ☐ Role of low-energy phases, in particular the Dirac phase
- ★ Summary and conclusion

Motivation for thermal leptogenesis

1. A cosmological puzzle :

   To avoid the famous „baryon annihilation catastrophe“, a baryon asymmetry must be dynamically generated in the early Universe.

   Even it contains a priori all necessary elements, our SM provides no solution.

2. A particle physics puzzle:

   A fact: neutrinos have masses and mix.

   Sol.+ Reac. $\sqrt{\Delta m^2_{\text{sol}}} \simeq 0.009$ eV

   Atm.+ Acc. $\sqrt{\Delta m^2_{\text{atm}}} \simeq 0.05$ eV

   The absolute neutrino mass scale is still unknown…But there are different ways to probe it!

Motivation for thermal leptogenesis

- Direct measurement (Tritium β-decay)

Mainz exp.

$$m_{ee} \lesssim 2.3 \text{ eV}$$

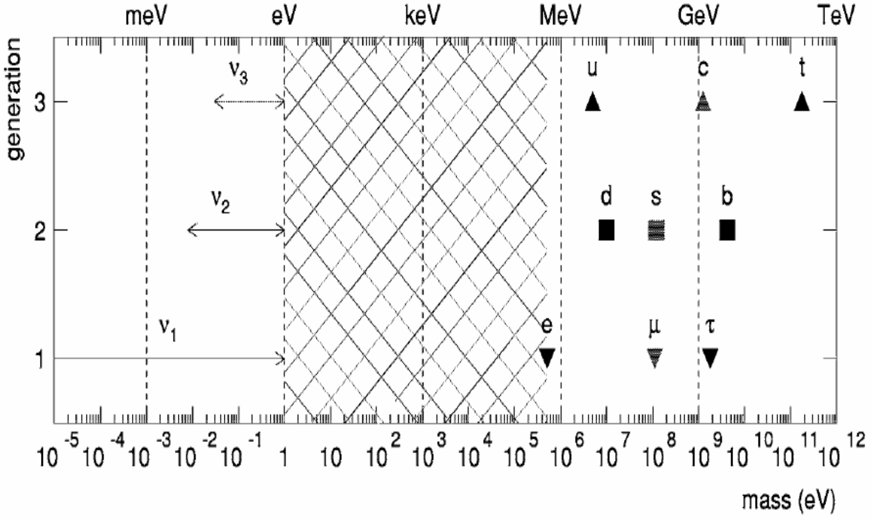
- Neutrinoless Double-β-Decay

Heidelberg-Moscow exp.

$$m_{\beta\beta} \lesssim 0.3 - 1 \text{ eV}$$

- Cosmology (CMB+LSS)

$$\sum_i m_i \lesssim 0.6 \text{ eV}$$



Bottom line: neutrinos involve a scale much smaller than all other mass scales in the SM!

→ Two seemingly unrelated problems find their solution in the same simple extension of the Standard Model...

The (type-I) see-saw mechanism

- ★ The see-saw mechanism originates from the following extension of the SM Lagrangian:

$$\boxed{\delta L = \overline{N}_i i\partial_\mu\gamma^\mu N_i - \underbrace{h_{i\alpha}\overline{N}_i\Phi L_\alpha}_{\text{Yukawa coupling}} - \underbrace{\frac{1}{2}M_i\overline{N}_i N_i^c}_{\text{Majorana mass term}} + h.c.}$$

  where $\Phi = (\phi^0, \phi^+)$ and $L_\alpha = (\nu_{L\alpha}, \alpha_L^-)$, $\alpha = e, \mu, \tau$ are the Higgs and left-handed lepton doublets, respectively, and $N_i,\ i = 1, 2, 3$ are RH neutrinos.

- ★ This extension is clearly acceptable on grounds of gauge invariance and renormalizability, and is minimal in its particle content (here: 3 new particles).

The (type-I) see-saw mechanism

- ★ The masses of the singlet neutrinos are essentially free parameters, and thus can be taken to be very large

➡ See-saw! (type I) [Minkowski, 77]

- ★ After spontaneous symmetry breaking, the vev $\langle\Phi\rangle$ of the Higgs leads to a Dirac mass term $m_{\rm D} = h\langle\Phi\rangle$. The see-saw assumes $M \gg m_{\rm D}$ so that the neutrino mass term can be block-diagonalized as:

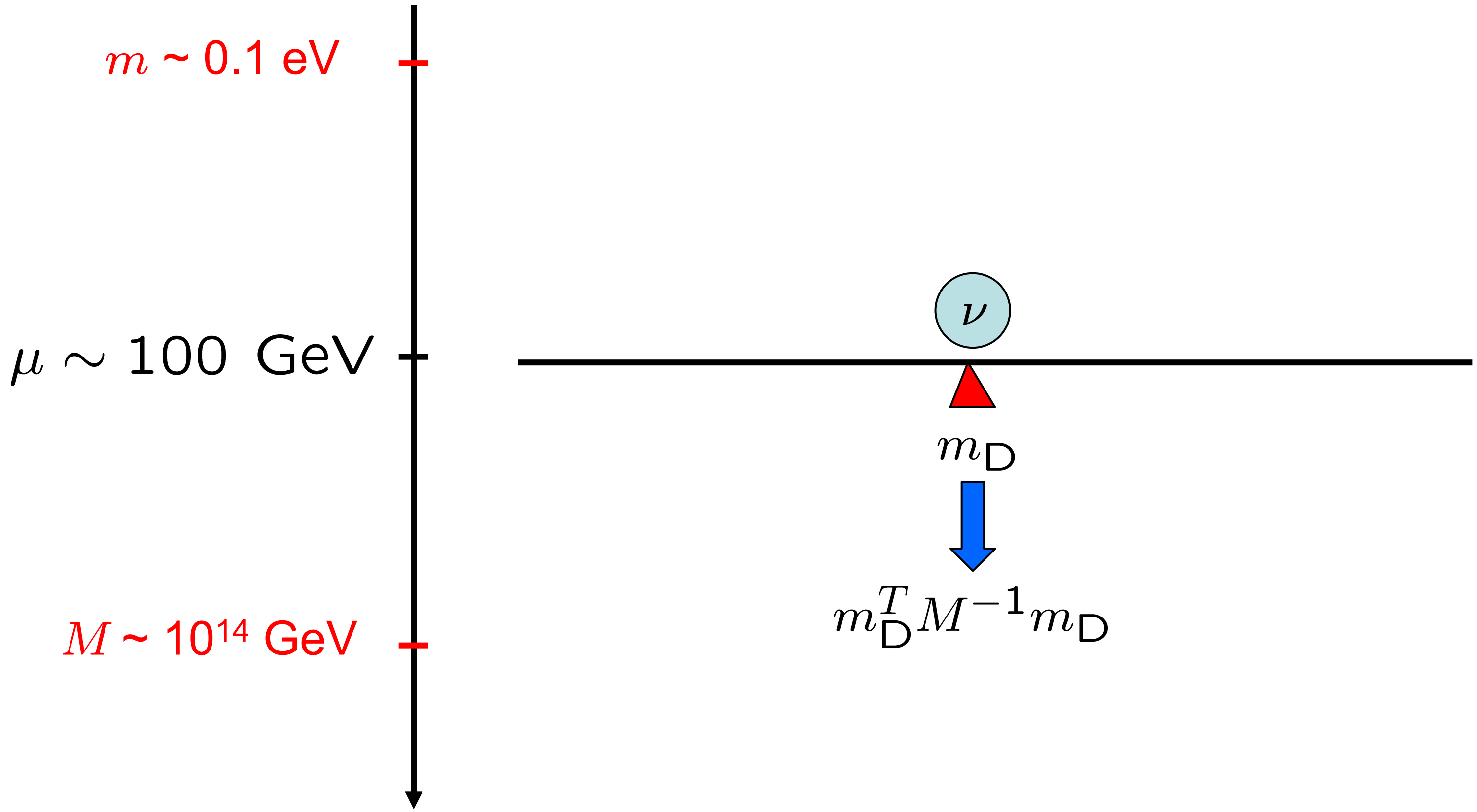
$$\begin{pmatrix} 0 & m_{\rm D}^{\rm T} \\ m_{\rm D} & M \end{pmatrix} \xrightarrow{\text{1st order}} \begin{pmatrix} m_{\rm D}^{\rm T} M^{-1} m_{\rm D} & 0 \\ 0 & M \end{pmatrix}$$

After diagonalization: 3 light Majorana neutrinos, mass $m_1 \leq m_2 \leq m_3$

3 heavy Majorana neutrinos, mass $M_1 \leq M_2 \leq M_3$

The (type-I) see-saw mechanism

- ★ Conventional picture



m ~ 0.1 eV

$\mu \sim 100$ GeV

M ~ 10^{14} GeV

ν

m_{D}

$m_{\mathrm{D}}^T M^{-1} m_{\mathrm{D}}$

Unflavored thermal leptogenesis

- In order to produce a baryon asymmetry in the Early Universe, one needs to fulfill three conditions [Sakharov, 1967]
  - Baryon number violation
  - *C* and *CP* violation
  - Departure from thermal equilibrium

In thermal leptogenesis [Fukugita, Yanagida, 86] :

- Baryon number is violated in sphaleron processes
- *CP* is violated in the decay of heavy neutrinos

$$\varepsilon_i = -\frac{\Gamma(N_i \to L_i \Phi^\dagger) - \Gamma(N_i \to \bar{L}_i \Phi)}{\Gamma(N_i \to L_i \Phi^\dagger) + \Gamma(N_i \to \bar{L}_i \Phi)} \equiv -\frac{\Gamma_i - \overline{\Gamma}_i}{\Gamma_i + \overline{\Gamma}_i}$$

CP asymmetry parameter

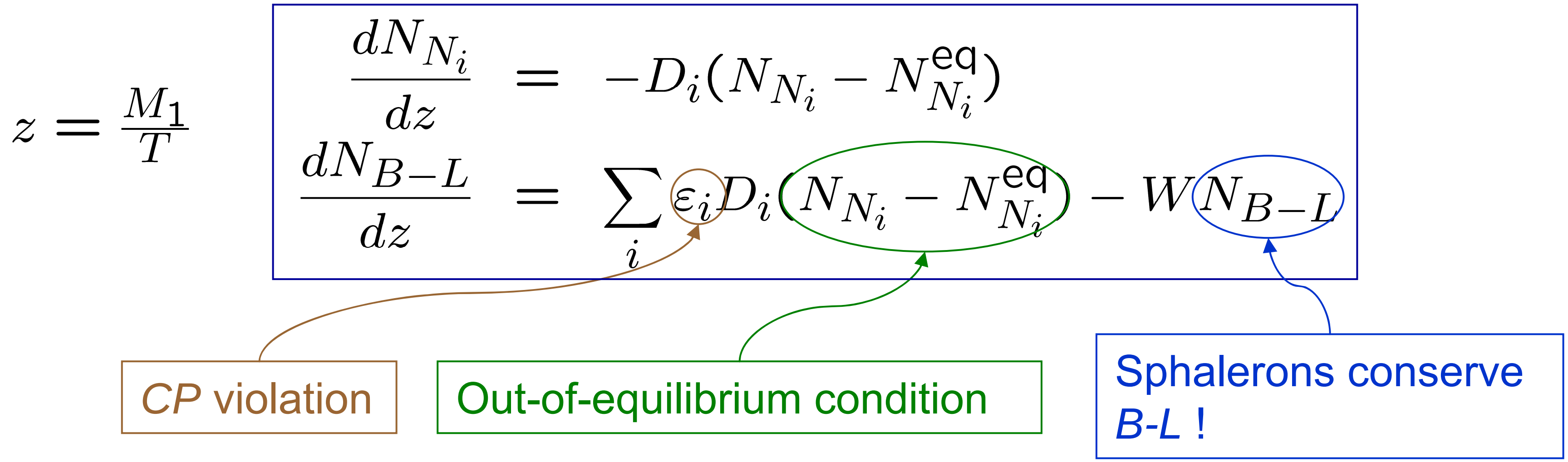
- Decays are out of equilibrium at some point, parametrized by

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

``decay parameter´´

Unflavored thermal leptogenesis

★ The (classical) Boltzmann equations are



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

$$\begin{aligned} \frac{dN_{N_i}}{dz} &= -D_i(N_{N_i} - N_{N_i}^{\text{eq}}) \\ \frac{dN_{B-L}}{dz} &= \sum_i \varepsilon_i D_i (N_{N_i} - N_{N_i}^{\text{eq}}) - W N_{B-L} \end{aligned}$$

CP violation

Out-of-equilibrium condition

Sphalerons conserve *B-L* !

- ☐ The crucial dependence on K_i enters in D_i and W.
- ☐ Strong washout when $K_i \gtrsim 1$. Weak washout when $K_i \lesssim 1$
- ☐ Assuming $M_1 \ll M_2 \ll M_3$ one typically has a N_1-dominated scenario.

Unflavored thermal leptogenesis

- ★ It is convenient to write the solution in the form

$$N_{B-L}^{\rm fin} = \varepsilon_1 \kappa_1^{\rm fin}$$

where $\kappa_1^{\rm fin}$ is the final efficiency factor.

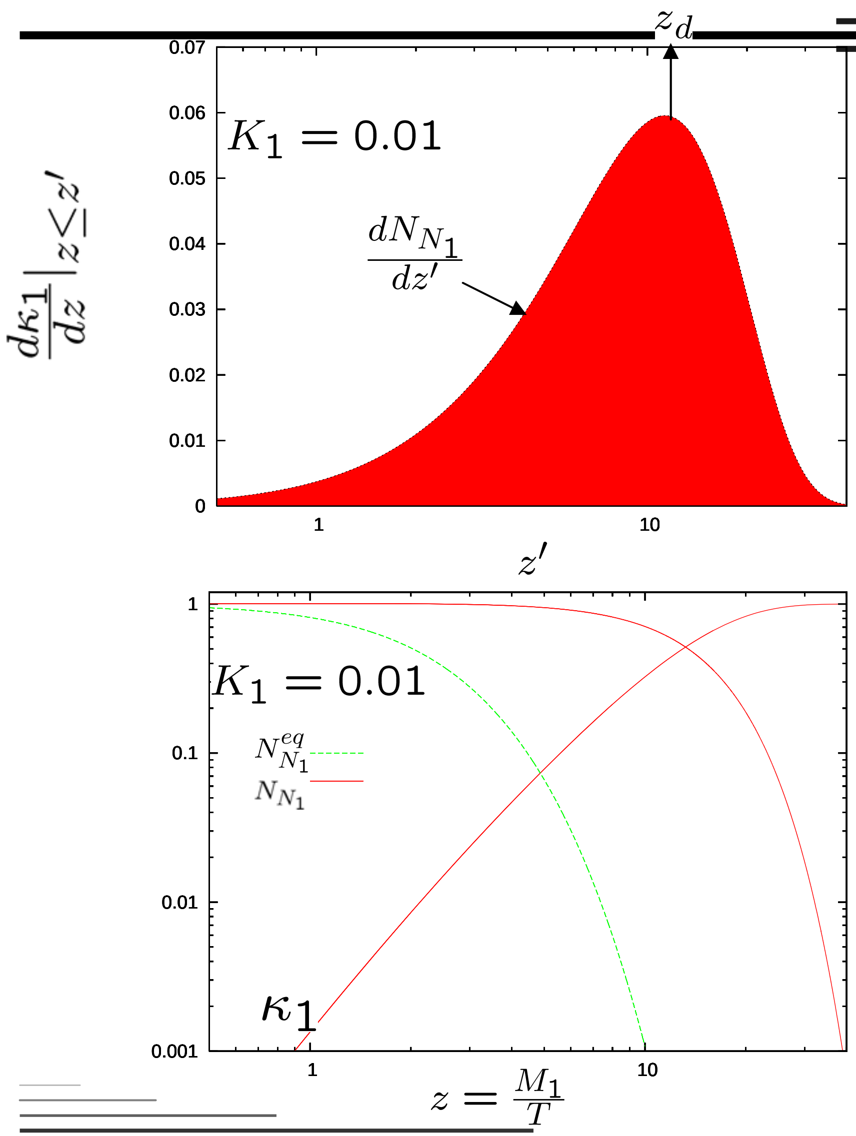
- ★ The final baryon asymmetry is given by

$$\eta_B = a_{\rm sph} \frac{N_{B-L}^{\rm fin}}{N_\gamma^{\rm rec}} \simeq 0.01 \sum_i \varepsilon_i \kappa_i^{\rm fin}$$

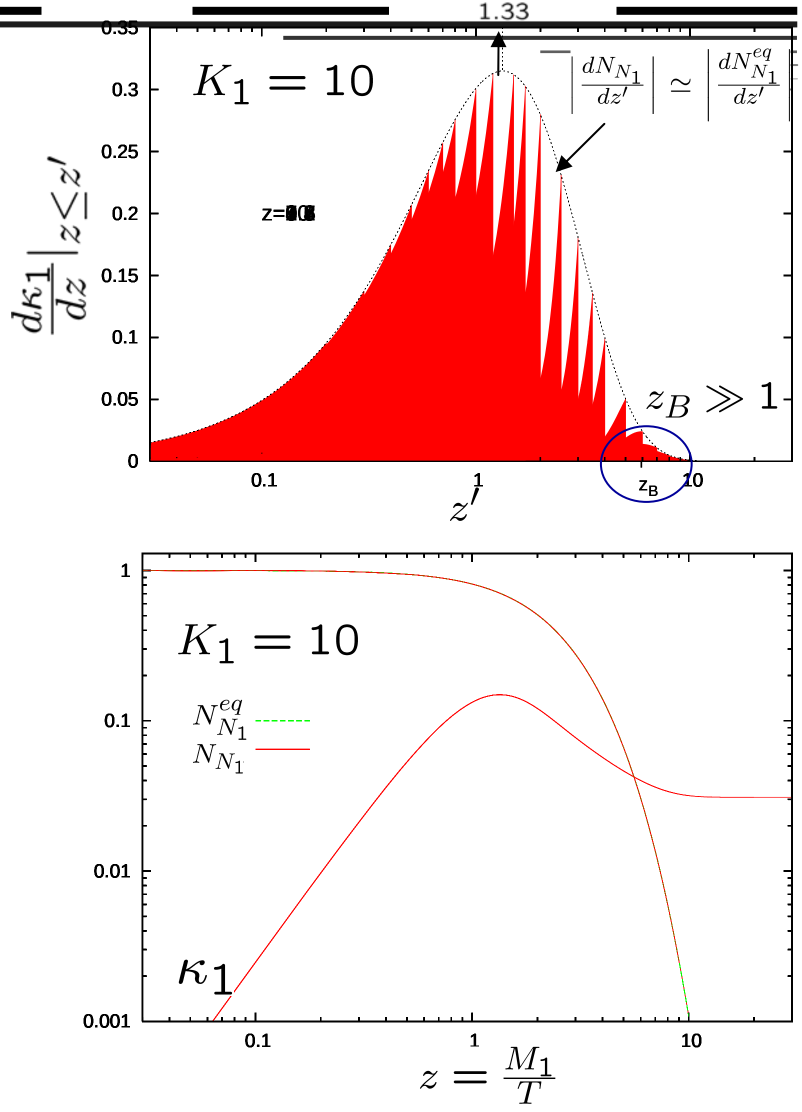
and should be compared to the measured value [WMAP,06]

$$\eta_B^{\rm CMB} = (6.11 \pm 0.22) \times 10^{-10}$$

WEAK WASHOUT



STRONG WASHOUT



Implications of unflavored Th. Lep.

- ★ From the upper bound on the *CP* asymmetry [Asaka et al., 01; Davidson, Ibarra, 02]

$$\varepsilon_1 \leq \overline{\varepsilon}(M_1) \simeq 10^{-6}\left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right)$$

one obtains a lower bound on M_1 and on the reheating temperature independent of the initial conditions [Davidson, Ibarra, 02; Buchmüller, Di Bari, Plümacher, 02] :

$$\boxed{M_1(T_{\mathrm{reh}}) \gtrsim 3(1.5) \times 10^9\,\mathrm{GeV}}$$

- ★ The suppression of the *CP* asymmetry for growing absolute neutrino mass scale leads to a stringent upper bound [Buchmüller, Di Bari, Plümacher, 02] :

$$\boxed{m_1 \lesssim 0.1\,\mathrm{eV}}$$

Flavor actually matters in Th. Lep.

- ★ When $T \lesssim 10^{12}\mathrm{GeV}$, the τ-lepton Yukawa interaction $f_{\tau\tau}\overline{L}_{\tau}\Phi E_{\tau}$ is in equilibrium, i.e. $\Gamma_{\tau} \gtrsim H$.
- ★ These interactions are then fast enough to 'measure' if the flavor of the state produced in the decay of the heavy neutrino is τ or not; a 2-flavor basis ('τ' and '$e\mu$' in the following) is defined. [Barbieri, Creminelli, Strumia, Tetradis, 99 ; Abada, Davidson, Josse-Michaux, Losada, Riotto, 06 ; Nardi, Nir, Racker, Roulet, 06]
- ★ The latter condition is necessary, however it may not be sufficient in the strong washout, i.e. when $\Gamma_{\mathrm{ID}} \gtrsim H$ because this interaction wants to preserve the direction in flavor space given by the decays (quantum Zeno effect) [SB, Di Bari, Raffelt, 06]
- ★ Let us assume for the moment that the conditions for a fully-flavored picture to hold are met.

Fully-flavored leptogenesis

- The (classical) Boltzmann equations are

$$
\boxed{
\begin{aligned}
\frac{dN_{N_i}}{dz} &= -D_i(N_{N_i} - N^{\text{eq}}_{N_i}) \\
\frac{dN_{\Delta_\alpha}}{dz} &= \sum_i \varepsilon_{i\alpha} D_i(N_{N_i} - N^{\text{eq}}_{N_i}) - N_{\Delta_\alpha} \sum_i P^0_{i\alpha} W^{\text{ID}}_i
\end{aligned}
}
$$

Same as before!

$\alpha = e\mu, \tau$

$\Delta_\alpha = \frac{1}{3}B - L_\alpha$

- First type of effect: the rates of decay and inverse decay in each flavor are suppressed by the projectors [Barbieri et al. 99; Nardi et al., 06]

$$
\begin{aligned}
\Gamma_{i\alpha} &\equiv \Gamma(N_i \to L_\alpha \Phi^\dagger) = P_{i\alpha}\Gamma_i \quad & P_{i\alpha} &= P^0_{i\alpha} + \Delta P_{i\alpha}/2 \\
\overline{\Gamma}_{i\alpha} &\equiv \Gamma(N_i \to \overline{L}_\alpha \Phi) = \overline{P}_{i\alpha}\overline{\Gamma}_i \quad & \overline{P}_{i\alpha} &= P^0_{i\alpha} - \Delta P_{i\alpha}/2
\end{aligned}
$$

- Second type of effect: additional contribution to the individual *CP* asymmetries: [Barbieri et al., 99; Nardi et al., 06]

$$
\varepsilon_{i\alpha} \equiv -\frac{\Gamma_{i\alpha} - \overline{\Gamma}_{i\alpha}}{\Gamma_i + \overline{\Gamma}_i} = \varepsilon_i P^0_{i\alpha} + \frac{\Delta P_{i\alpha}}{2}
$$

$$
\Delta P_{i\alpha} \equiv P_{i\alpha} - \overline{P}_{i\alpha}
$$

General implications of flavor

- ★ Main scenarios in fully-flavored leptogenesis for a N_1-dominated scenario:

  - □ Alignment case [Nardi et al., 05]

$$P_{1\tau(e\mu)} = \overline{P}_{1\tau(e\mu)} = 1 \text{ and } P_{1e\mu(\tau)} = \overline{P}_{1e\mu(\tau)} = 0$$ **like unflavored case**

  - □ Democratic case

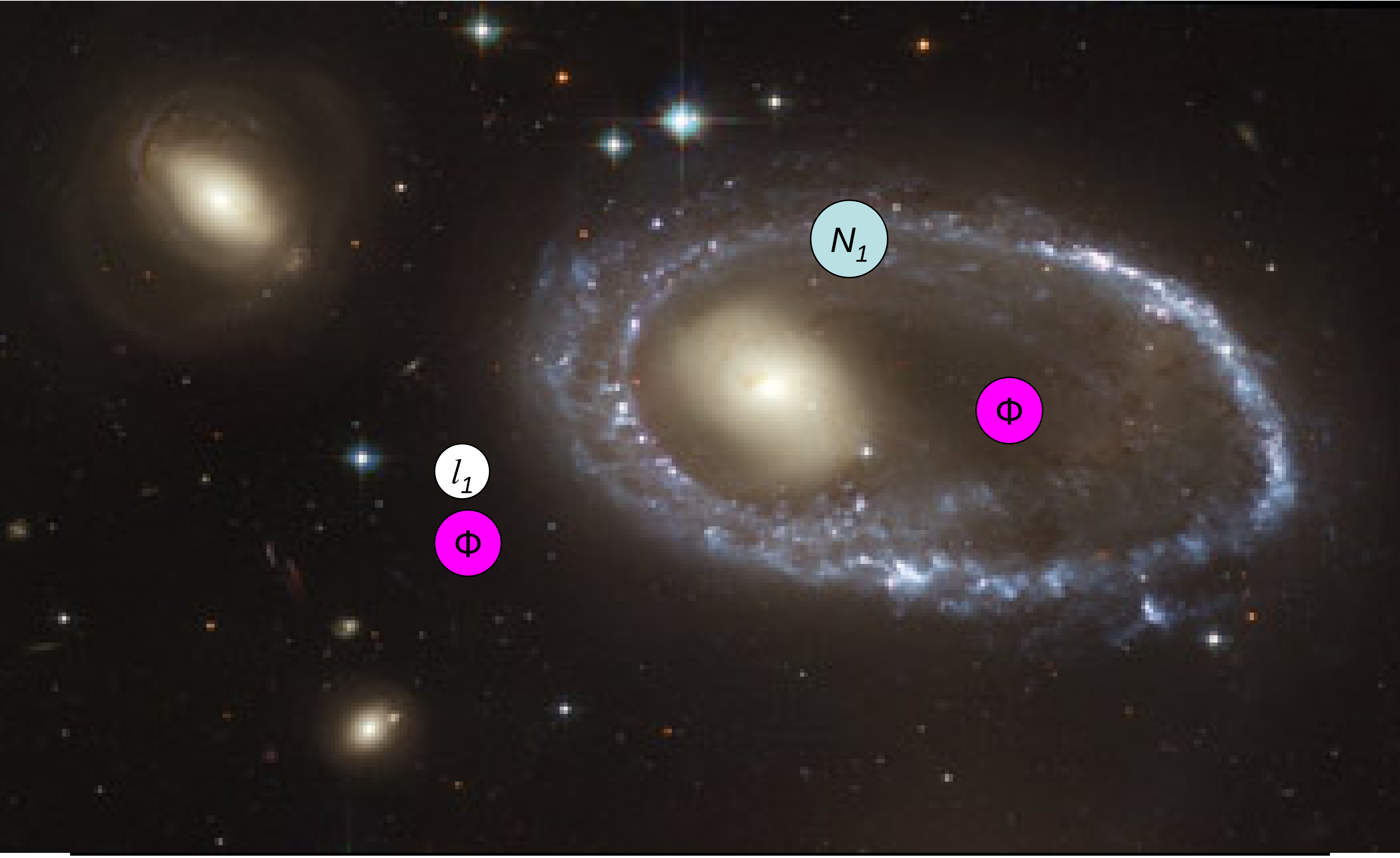
$$P_{1\tau} = P_{1e\mu} = 1/2 \quad (\Rightarrow \Delta P_{1\tau} = \Delta P_{1e\mu} = 0)$$ **factor ~2 effect**

  - □ One-flavor dominance [SB, Di Bari, 06]

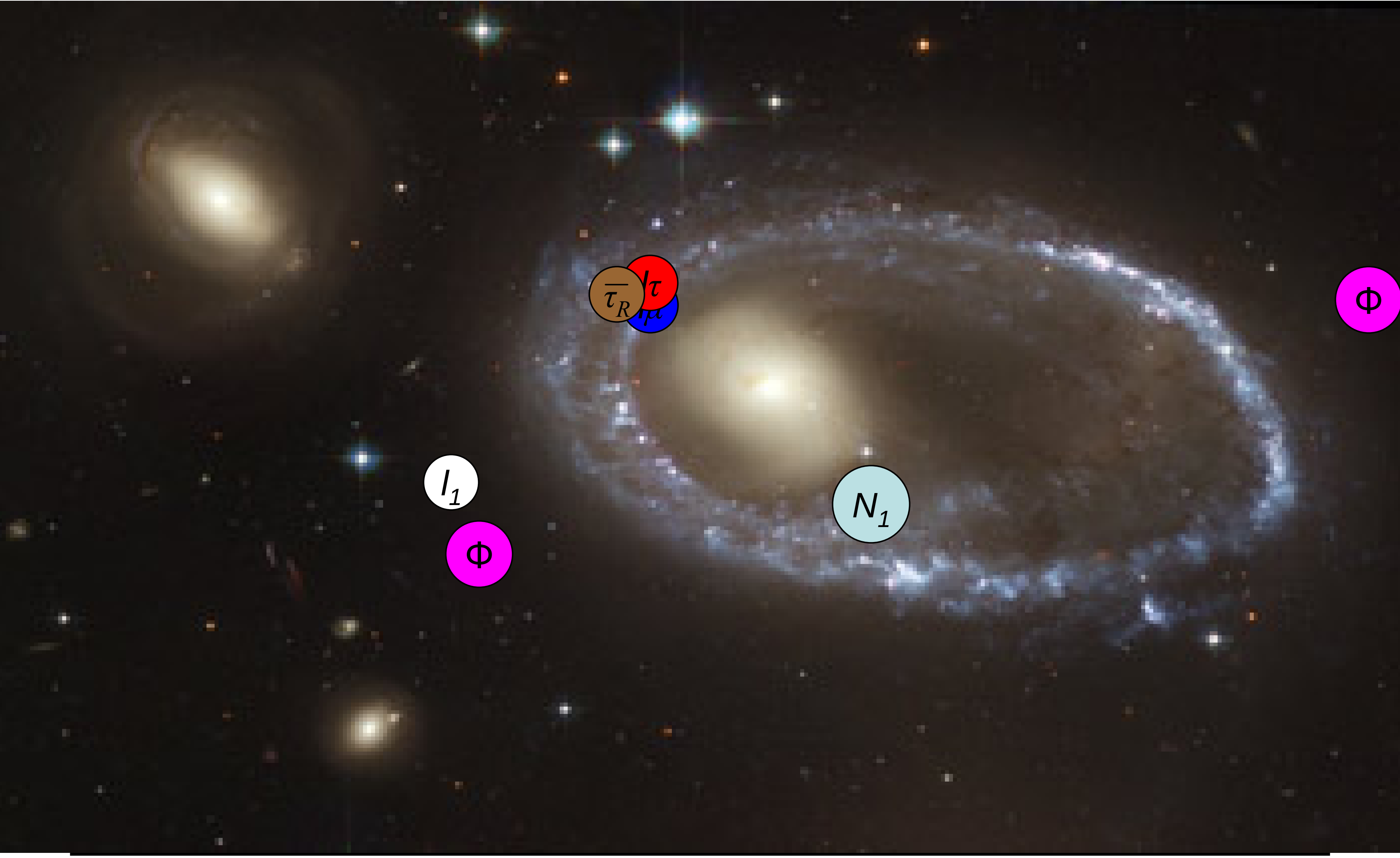
$$P_{1\tau(e\mu)} \ll P_{1e\mu(\tau)} \sim \mathcal{O}(1) \text{ and } \varepsilon_{1e\mu} \simeq \varepsilon_{1\tau}$$

potentially big effect!

NO FLAVOR EFFECTS

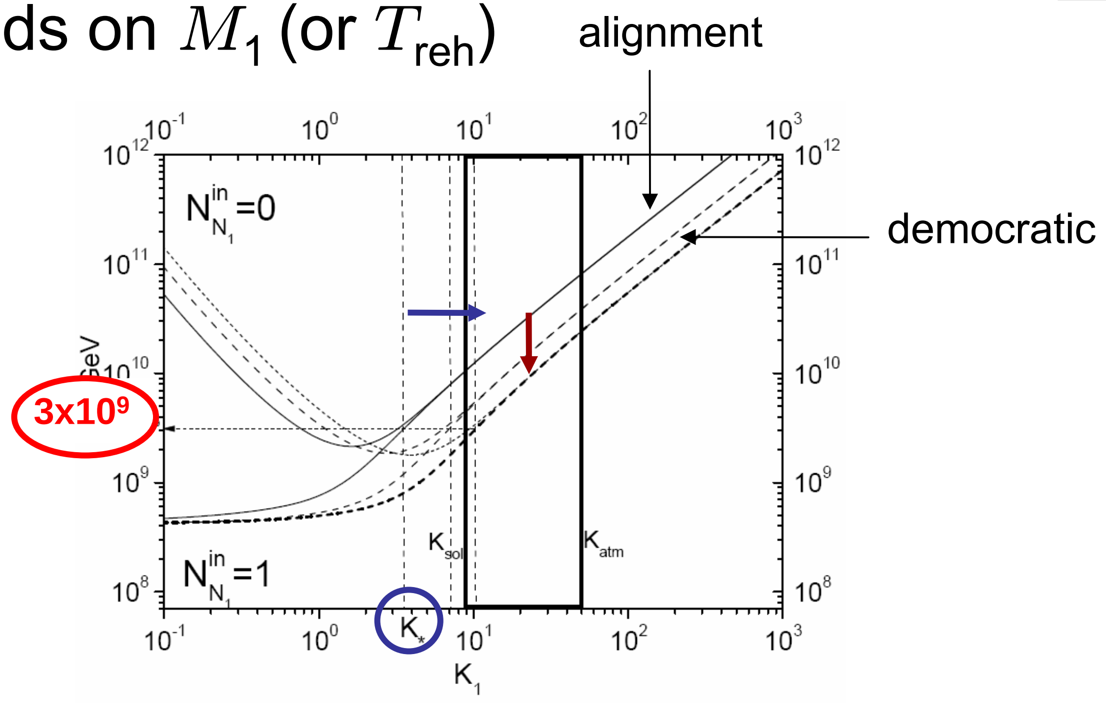


WITH FLAVOR EFFECTS (democratic case)



General implications of flavor

★ Lower bounds on M_1 (or T_{reh})



alignment

democratic

3x10^9

- The lowest bounds do not change! [SB, Di Bari, 06]
- The lower bound at fixed K_1 are relaxed.
- The region of independence of initial conditions shrinks.

General implications of flavor

- ★ There exists an upper bound on the individual *CP* asymmetries [Abada, et al., 06] :

$$|\varepsilon_{1\alpha}| < \overline{\varepsilon}(M_1)\sqrt{P^0_{1\alpha}}\boxed{\frac{m_3}{m_{\rm atm}}}\max_j(|U_{\alpha j}|)$$

It does not decrease when the active neutrino mass scale increases!

- ★ This upper bound, in combination with the fact that a one-flavor dominance is easily obtained for a quasi-degenerate light neutrino spectrum, can lead to the conclusion that the upper bound on the absolute neutrino mass scale disappears in fully-flavored leptogenesis [Abada, et al., 06] .

↳ BUT… Is fully-flavored leptogenesis the whole story?

From unflavored to fully-flavored lep.

- ★ The ‘old’ unflavored leptogenesis and the ‘new’ fully-flavored one rely both on classical Boltzmann equations. One expects, however, that in the transition regime a more correct quantum kinetic treatment (density matrix) should be used [Abada et al., 06].
- ★ Such a density-matrix equation should contain the two asymptotic limits we know: unflavored and fully flavored.

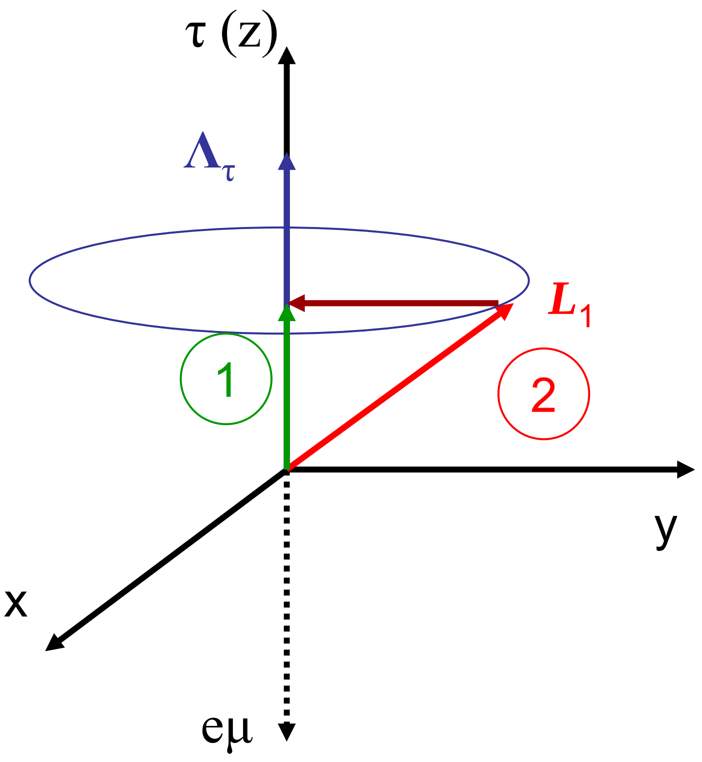
Q: Under which condition does one expect to recover one or the other?

From unflavored to fully-flavored lep.

★ Precession formula [Stodolsky, 87]

$$\frac{\partial \vec{L_1}}{\partial t} = \vec{\Lambda}_\tau \times \vec{L}_1 - D_\tau \vec{L}_1^{\perp}$$

Refractive index　　Damping rate



① When the lepton state is (on average or effectively) fully projected on the z-axis, the fully-flavored Boltzmann equations can be used.

② When the lepton state remains in its original direction (L_1), then the unflavored Boltzmann equations can be used.

Condition of validity for each picture

- ★ For the unflavored picture to hold, one needs that the lepton Yukawa interactions is slower than the inverse-decay washout at the time when the asymmetry is produced in the unflavored case [Barbieri et al., 99].

$$\Gamma_\tau(z_B) \lesssim \Gamma_{\rm ID}(z_B) \sim H \Rightarrow \boxed{M_1 \gtrsim 5 \times 10^{11}\,{\rm GeV}}$$

- ★ For the fully-flavored picture to hold, one needs that the lepton Yukawa interactions is faster than the inverse-decay washout at the time when the asymmetry is produced in the fully-flavored case [SB, Di Bari, Raffelt, 06].

$$\Gamma_\tau(z_{B\alpha}) \gtrsim \Gamma_{\rm ID}(z_{B\alpha})$$

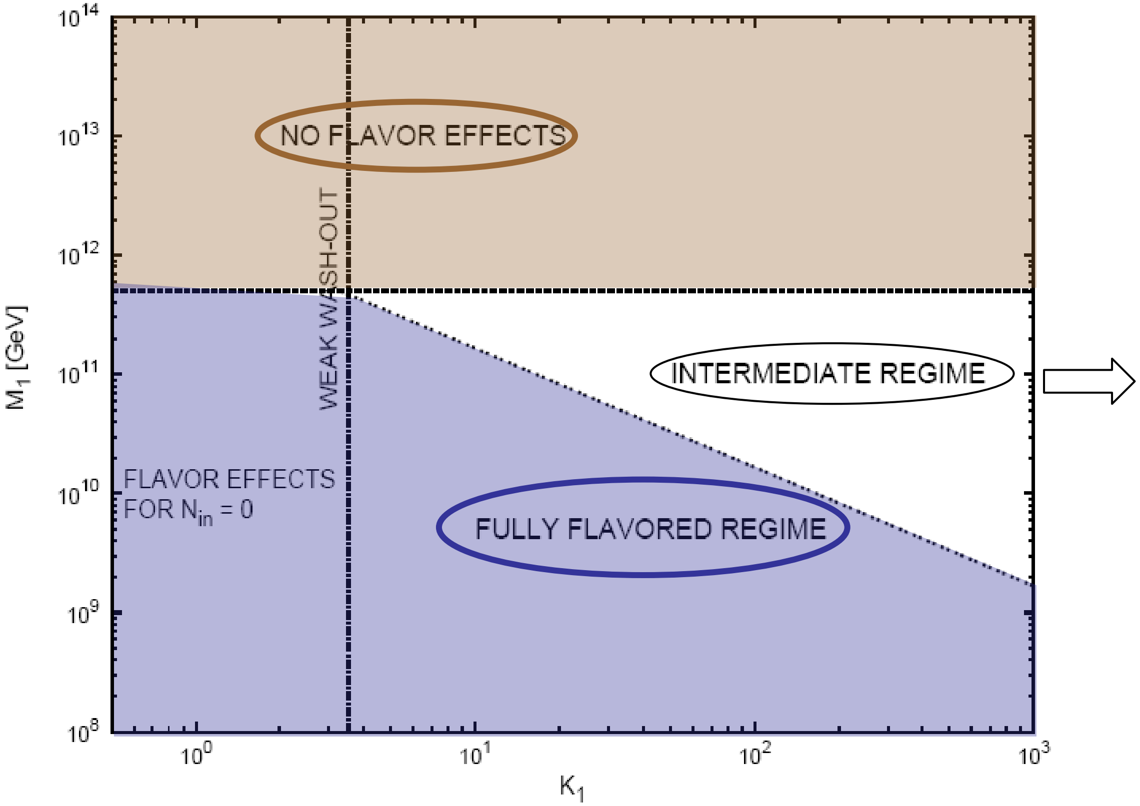
Condition of validity for each picture

- ★ The important point here is that the asymmetry in the fully-flavored regime is produced before, i.e. $z_{B\alpha} \leq z_B$, and at this z, the inverse-decay rate can be much larger than H.
- ★ Assuming an extreme one-flavor dominance, the fully-flavored regime is valid for:

$$\boxed{M_1 \lesssim \frac{2\times 10^{12}\mathrm{GeV}}{K_1}}$$

Condition of validity for each picture

[SB, Di Bari, Raffelt, 06]

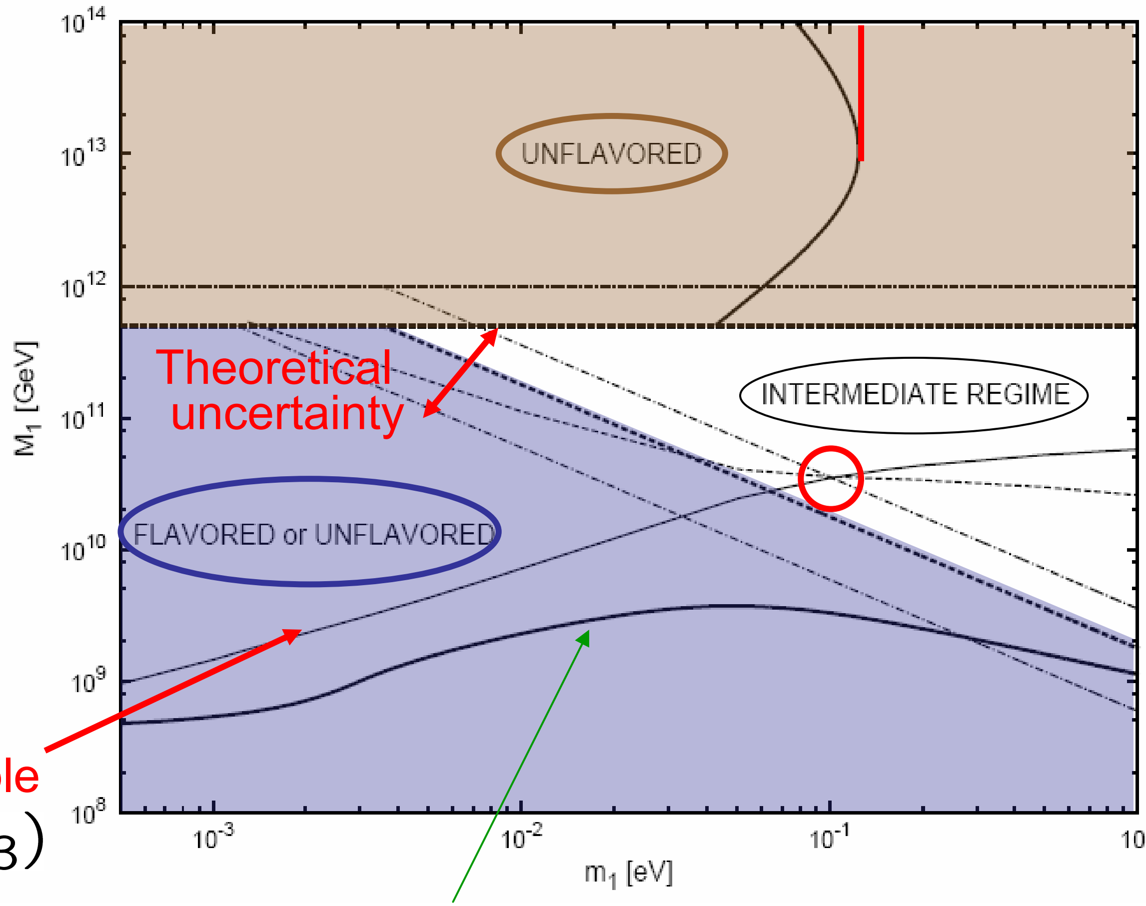


Full density matrix calculation required…

★ For a quasi-degenerate light neutrino spectrum, $m_1 \propto K_1$… So what about the upper bound on m_1?

Upper bound on m_1?

Well-known bound: 0.12 eV



Theoretical uncertainty

Density matrix…

Real example $(\Omega = R_{13})$

Bound: 0.1 eV

Bound: ~2 eV

‘Academic’ lower bound (never saturated!)

CP violation and leptogenesis

★ The projectors [Barbieri, Creminelli, Strumia, Tetradis, 99] are given by

$$\begin{aligned} P_{1\alpha} &\equiv |\langle l_\alpha | l_1 \rangle|^2 = P^0_{1\alpha} + \Delta P_{1\alpha}/2 \\ \bar{P}_{1\alpha} &\equiv |\langle \bar{l}_\alpha | \bar{l}'_1 \rangle|^2 = P^0_{1\alpha} - \Delta P_{1\alpha}/2 \end{aligned}$$

New source of *CP* violation!

★ The flavored *CP* asymmetries can indeed be written as

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

⇨ Even when the total *CP* asymmetry, ε_1, is 0, the flavored ones can be non-zero.

⇨ This new source of *CP* violation depends on the lepton mixing matrix, contrary to ε_1 !

CP violation and leptogenesis

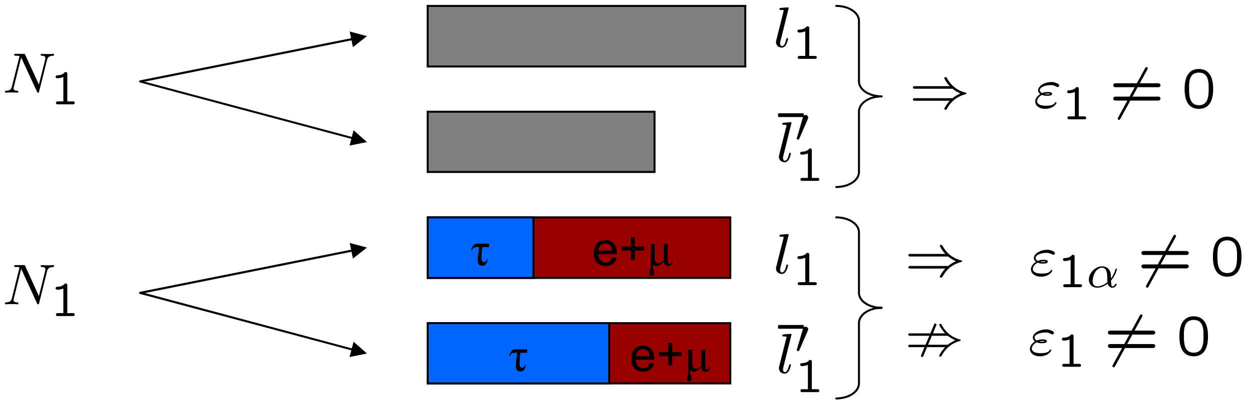
- ★ Very interestingly, in fully-flavored leptogenesis, the *CP* phases in the PMNS matrix can be uniquely responsible for the generation of the BAU!

  [SB, Di Bari, 06; Pascoli, Petcov, Riotto, 06; Branco, Gonzalez Felipe, Joaquim, 06]

- ★ Pictorially, the two sources of *CP* violation can be seen as follows

1) $\Gamma_1 \neq \bar{\Gamma}_1$

2) $P_{1\alpha} \neq \bar{P}_{1\alpha}$



CP violation and leptogenesis

- ★ The see-saw has many new parameters (18!) compared to the Standard Model, among which 6 are *CP*-violating phases.

- ★ A useful parametrization is given by [Casas,Ibarra, 01]

$$h = U_{\mathrm{PMNS}} \sqrt{D_m}\, \Omega \sqrt{D_M} / v$$

3 low-energy (measurable) phases: 2 Majorana phases and 1 Dirac phase δ

3 high-energy (unmeasurable) phases

- ★ The Ω matrix can be parametrized by three complex rotations:

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

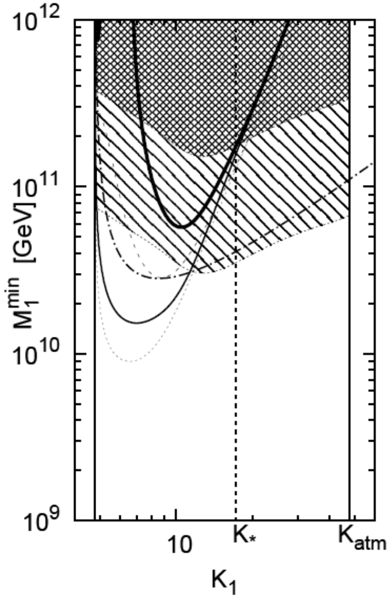
δ-leptogenesis [Anisimov, SB, Di Bari, arXiv:0707.3024]

- ★ Assume from now on that only the Dirac phase δ is turned on. This is a minimal condition on the necessary *CP* violation for successful leptogenesis because this phase appears only in combination with the small θ_{13} angle (<0.2 at 3σ).

- ★ In the hierarchical limit $M_1 \ll M_2 \ll M_3$ it is possible to explain the BAU only with this source of *CP* violation [Pascoli, Petcov, Riotto, 06]

Example:

$$\Omega = R_{13}$$
$$m_1/m_{\rm atm} = 0.1$$



➡ Problem: it is quite constrained and in the weak wash-out!

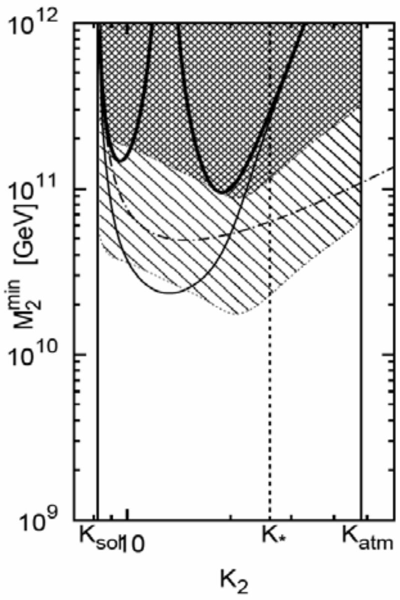
δ-leptogenesis in the hierar. limit

- ★ The generation of the BAU from the second RH neutrino, N_2, is also possible:

$$\underbrace{\Omega = R_{23} \qquad m_1 = 0}$$

$$\Big\downarrow \text{[Di Bari, 05]}$$

$$\varepsilon_1 = 0, \qquad K_1 = 0$$



➡ The asymmetry is given by the second RH neutrino:

$$N^{\rm f}_{B-L} = \sum_\alpha \varepsilon_{2\alpha} \kappa(K_{2\alpha})$$

- ★ The situation is as constrained as in the previous case…

δ-leptogenesis in the deg. limit

- ★ In the degenerate limit (DL), $M_1 \simeq M_2 \simeq M_3$, the *CP* asymmetry can be enhanced [Covi, Roulet, Vissani, 96] ,

$$\varepsilon_{i\alpha} = \frac{1}{8\pi(h^\dagger h)_{ii}} \sum_{j\neq i} (h^\dagger h)_{ij} \mathrm{Im}[h^\star_{\alpha i} h_{\alpha j}] \delta_{ji}^{-1} \qquad \delta_{ji} \equiv \frac{M_j - M_i}{M_i}$$

until one hits a resonance [Pilaftsis, 99] (RL) when

$$\delta_{ji} \simeq 3 \times 10^{-7} \left(\frac{M_1}{10^{10}\mathrm{GeV}}\right)$$

- ★ Note that in the DL, contrary to the HL, all three RH neutrinos contribute to the asymmetry and the wash-out from each of them must be taken into account:

$$N^{\mathrm{f}}_{B-L} = \sum_\alpha (\varepsilon_{1\alpha} + \varepsilon_{2\alpha} + \varepsilon_{3\alpha}) \kappa(\underbrace{K_{1\alpha} + K_{2\alpha} + K_{3\alpha}}_{\Rightarrow \text{ strong wash-out}})$$

δ-leptogenesis in the resonant limit

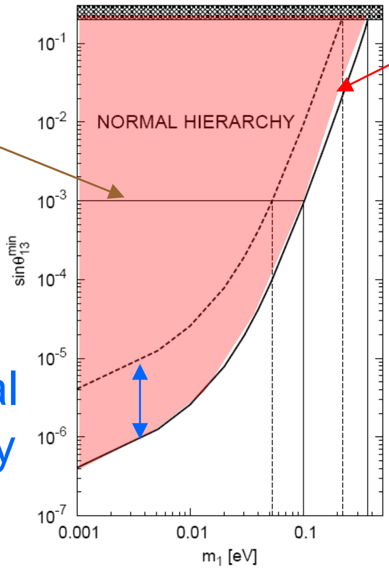
- ★ In the RL, the final asymmetry is essentially independent of the RH neutrino mass ⇒ TeV scale possible! [Pilaftsis, 99]
- ★ We found a nice link between low-energy parameters (θ_{13}, mass hierarchy, absolute neutrino mass scale, Dirac phase) and the BAU. [Anisimov, SB, Di Bari, 07]

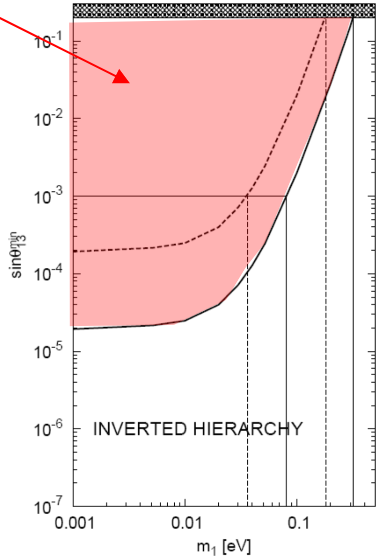
Allowed regions

(Far) future sensitivity

$$\Omega = R_{13}$$

Theoretical uncertainty





Flavored vs. Unflavored leptogenesis

	Unflavored	Flavored
Lower bound on M_1 and T_{reh}	~10^9 GeV (assuming HL)	Same!
Upper bound on m_1	0.12 eV (assuming HL)	? (QKE needed)
N_2-dominated scenario	$\Omega = R_{23}$	Domain enlarged
From low-energy phases	Non-viable	Viable (mainly in the DL)

Conclusions

- ★ Thermal leptogenesis is an attractive way to explain the BAU.
- ★ The latest developments (flavor effects) impose a new description of leptogenesis where low-energy phases play an important role.
- ★ When the Dirac phase acts as the only source of *CP* violation (δ-leptogenesis), the DL is favored, with a large range of viability and independence from the initial conditions.
- ★ Very interestingly, in the extreme case of resonant lep., in order to produced the BAU, an upper bound on m_1 which depends on the angle θ_{13} was obtained.

Test of see-saw and leptogenesis?

- ★ Reheating temperature larger than 100 GeV.
- ★ Discovery of *CP* violation in neutrino oscillations.
- ★ Discovery of $0\nu\beta\beta$ decay.
- ★ Discovery of lepton flavor violation and electric dipole moment (mainly for the supersymmetric see-saw).
- ★ Discovery of RH neutrinos at colliders.