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Baryogenesis in the Early Universe

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invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Outline

- Lecture I: Basics
- Lecture II: ElectroWeak Baryogenesis
- Lecture III: Leptogenesis
- Lecture IV: Affleck-Dine, etc...
- Outlook

Outline

- Introduction: GUT baryogenesis,
  See-saw mechanism and neutrino masses
- Baryogenesis through leptogenesis
- Flavored leptogenesis
- Full Quantum treatment:resonant leptogenesis
- Non-thermal leptogenesis
- Outlook

Introduction

GUT baryogenesis

The first models of baryogenesis arose in the context of Grand Unified Theories, which naturally allow for baryon number violation (and also proton decay).
In particular the minimal GUT model is based on the gauge group SU(5), which contains SU(3)xSU(2)xU(1) and has the same rank.

SU(5) Gauge bosons: $\mathbf{24}$

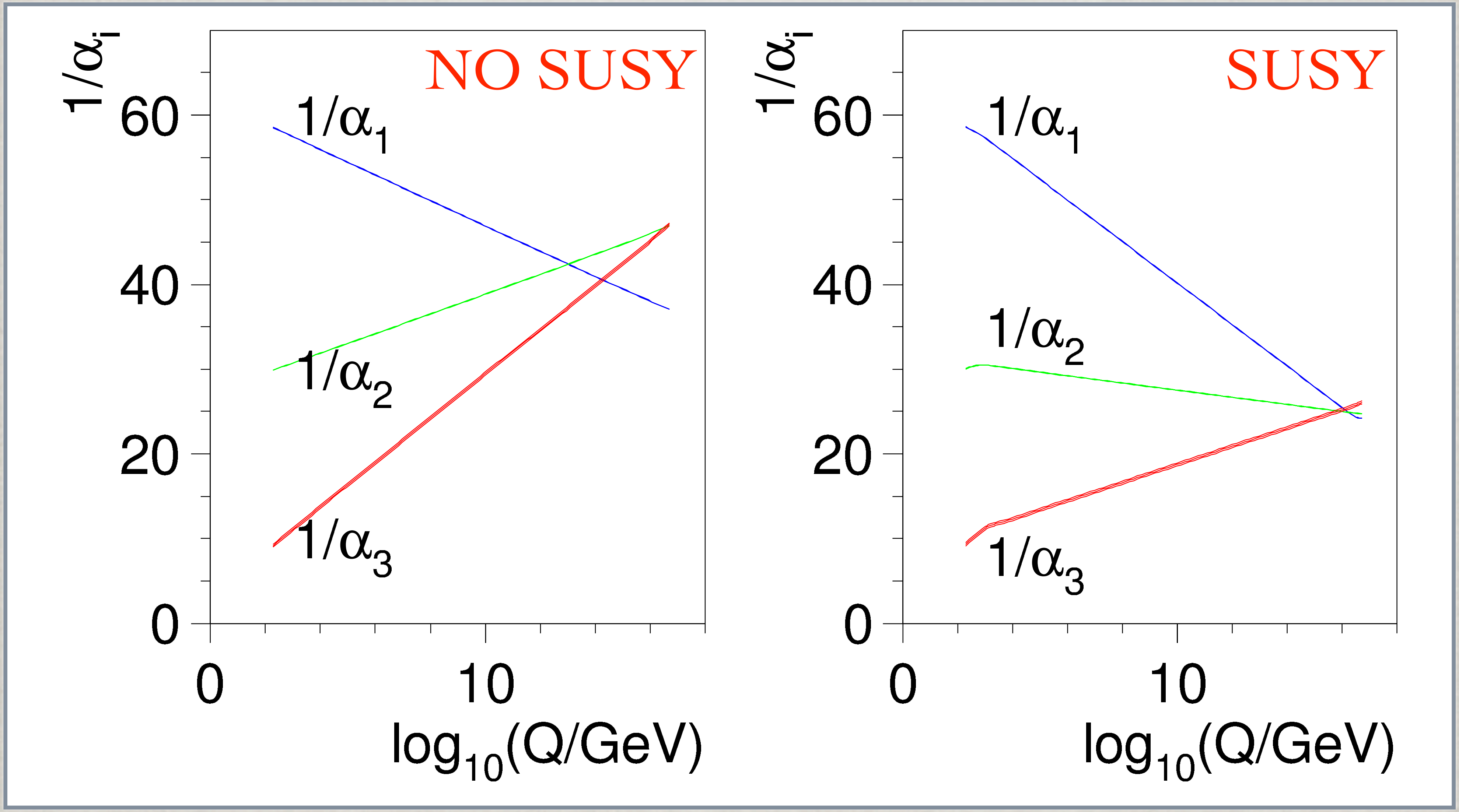
$$\begin{pmatrix} g - \sqrt{\frac{2}{15}}B & \mathcal{X} \\ \mathcal{X} & W + \sqrt{\frac{3}{10}}B \end{pmatrix}$$

12 extra gauge bosons in the SM representation $(\bar{\mathbf{3}}, \mathbf{2}, \mathbf{5/6})$

Fermions: $\bar{\mathbf{5}},\ \mathbf{10}$

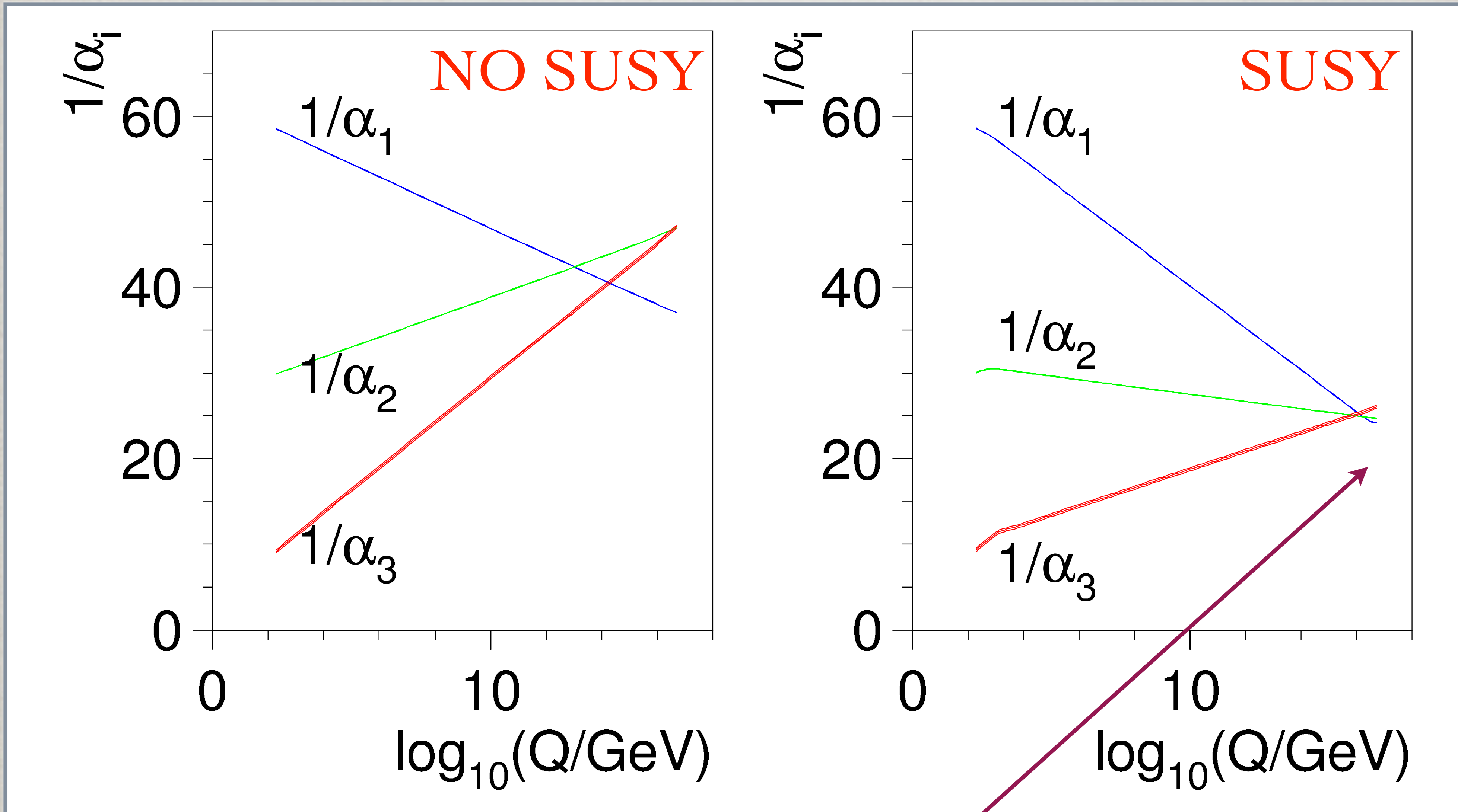
$$\begin{pmatrix} d_r^c \\ d_b^c \\ d_g^c \\ e^- \\ \nu_e \end{pmatrix}$$

UNIFICATION OF COUPLINGS



Need SUPERSYMMETRY to meet...

Unification of couplings



$M_{GUT} \sim 2 \times 10^{16}\,\mathrm{GeV}$

Need SUPERSYMMETRY to meet...

Proton Decay

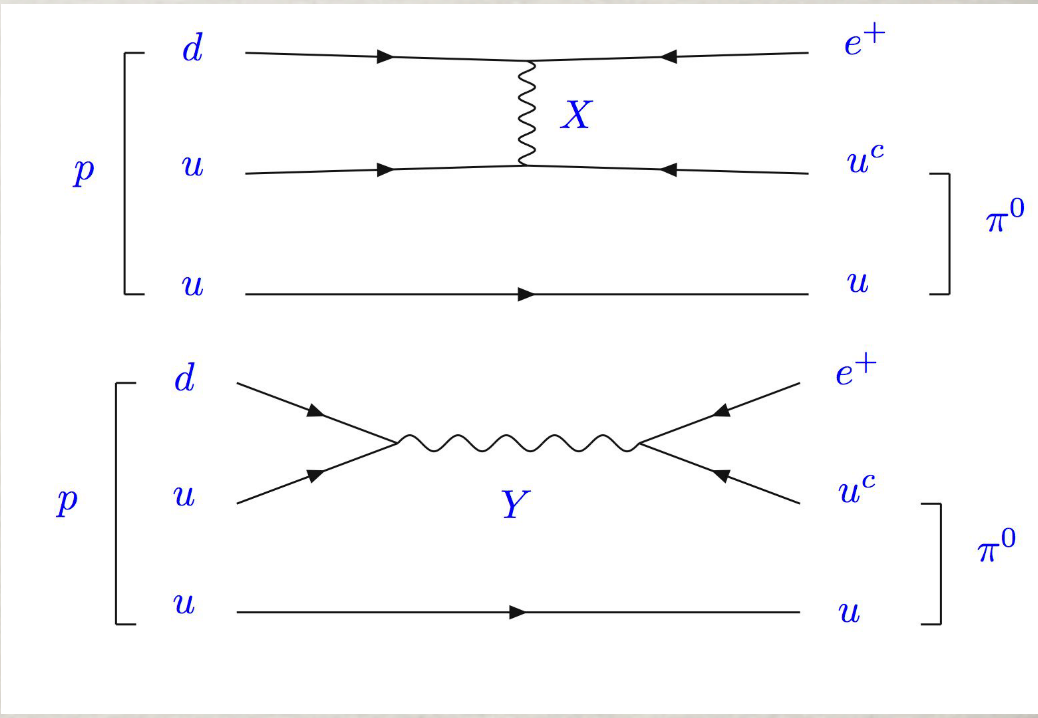
The new gauge bosons can mediate proton decay and give

$$p \to \pi^0 \ e^+$$

$$\tau_p \propto (G_p^2 m_p^5)^{-1}$$

$$G_p = \frac{g_{GUT}^2}{4\sqrt{2}M_\chi^2} \sim \frac{\alpha_{GUT}}{M_{GUT}^2}$$

$$\sim 10^{-34} GeV^{-2}$$



$$\tau_p \sim 10^{34} y$$

Very long lifetime !!!

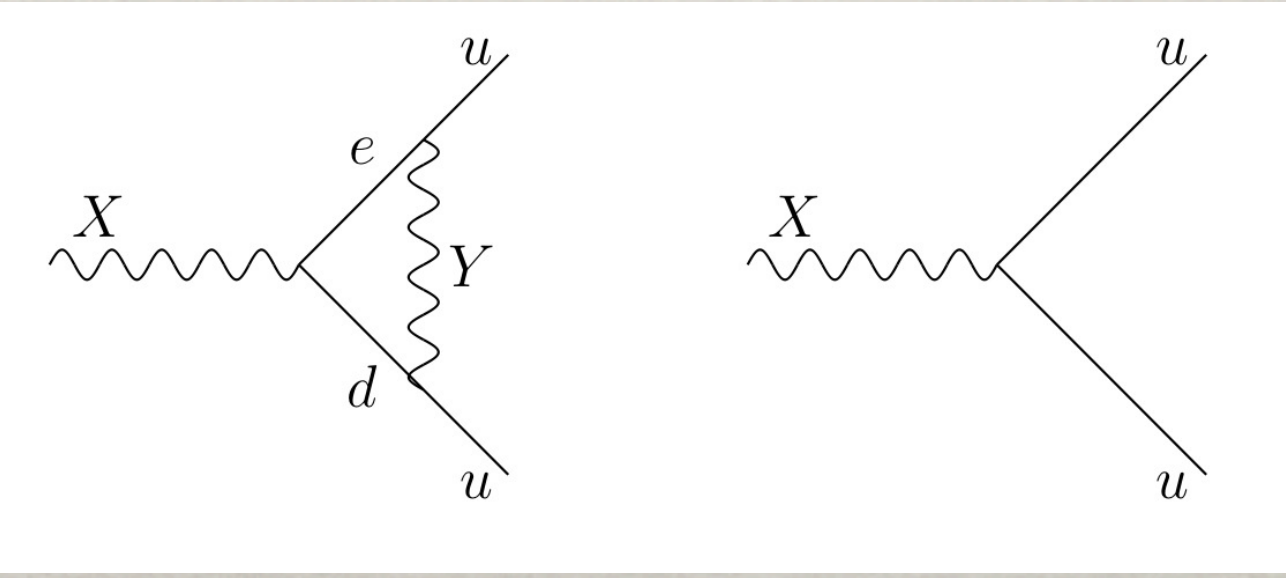
GUT BARYOGENESIS

Different decay channels: $\mathcal{X} = (X, Y)$

$$X \to u\,u,\ e^+\,\bar{d} \qquad\qquad Y \to d\,u,\ e^+\,\bar{u},\ \nu d$$

The decays violate baryon number !

C, CP violation arises from interference with the one-loop diagrams, as usual:

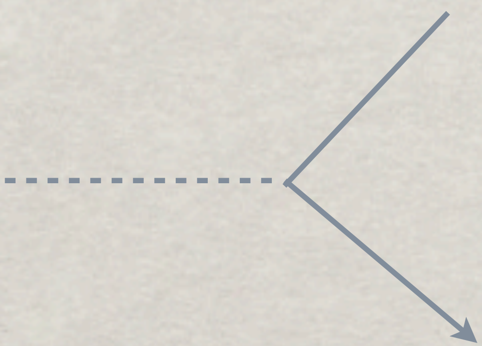


CP violation is quantum

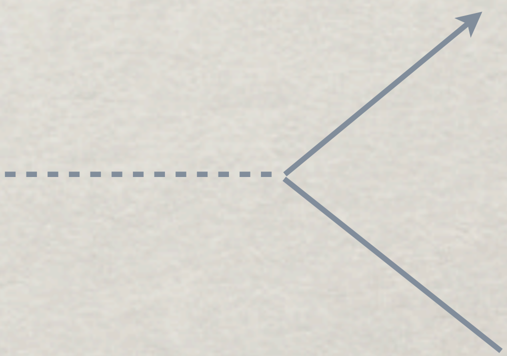
A theory violates CP if complex couplings are present, i.e.

$$\lambda\, h\bar{q}u + \lambda^*\, h^*\bar{u}q$$

If $\lambda \neq \lambda^*$ particle and antiparticle have to start with different couplings, but since $|\lambda| = |\lambda^*|$ the effect reveals itself only via quantum loops !



$i\,\lambda$



$i\,\lambda^*$

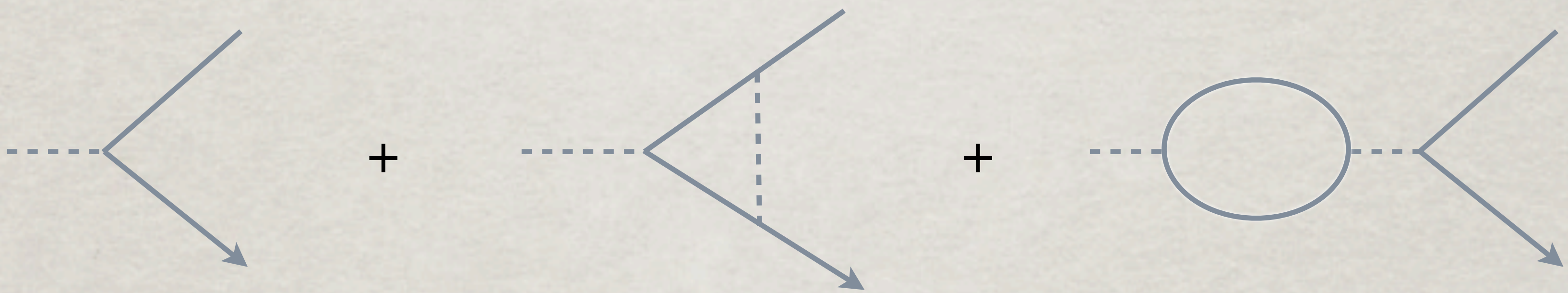
At Born level the matrix element for both decays is

$$\mathcal{M} \propto |\lambda|^2 = |\lambda^*|^2$$

No CP violation at tree level !

CP violation is quantum

At one loop level first signs of CP violation can appear, the most dominant usually the interference effect between tree-diagram and one-loop-diagrams



$i\,\lambda$ $\quad$ $i\,\lambda\, i\,\lambda^* i\,\lambda$ $\quad$ $i\,\lambda\;\; i\,\lambda^*\, i\,\lambda$

So we have for particle $\mathcal{M} \propto |\lambda|^2 + 2Re\left[\lambda\lambda^*\lambda\lambda^*\; L(x)\right] + ...$

& antiparticle: $\overline{\mathcal{M}} \propto |\lambda^*|^2 + 2Re\left[\lambda^*\lambda\lambda^*\lambda\; L(x)\right] + ...$

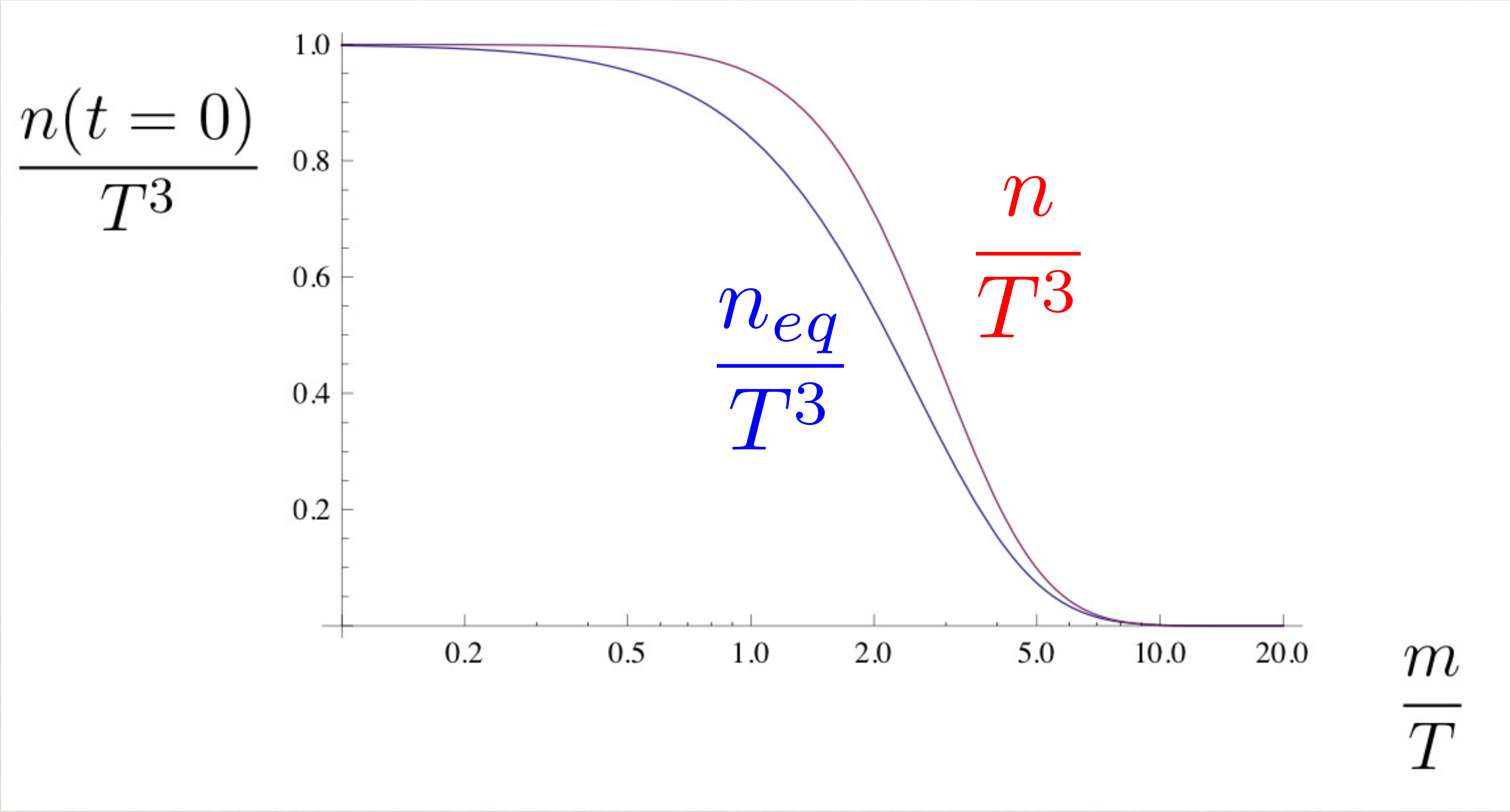
$$\Delta\mathcal{M} \propto 2Re\left[\lambda\lambda^*\lambda\lambda^*\; L(x) - \lambda^*\lambda\lambda^*\lambda\; L(x)\right] + ...$$

$$\Delta\mathcal{M} \propto -4\, Im\left[\lambda\lambda^*\lambda\lambda^*\;\right] Im[L(x)] + ...$$

NB: Vanishing for a single coupling, need flavour dependence !

GUT BARYOGENESIS

Need still a deviation from thermal equilibrium:
possible when the particle becomes non-relativistic
and its density cannot follow the Boltzmann suppression



Just a small deviation is sufficient...

GUT baryogenesis

Let us check the Sakharov conditions for GUT baryogenesis:

- B violation: OK
  Exotic gauge bosons mediate B violation
- C and CP violation: OK
  Gauge interaction and particle mixing
- Departure from thermal equilibrium: OK
  the out-of-equilibrium decay

Possible to generate the BAU ?

GUT baryogenesis

Not really ! Here some of the problems:

- B violation: ?
  In the minimal SU(5) model, B-L is conserved, therefore the sphalerons erase the produced B...

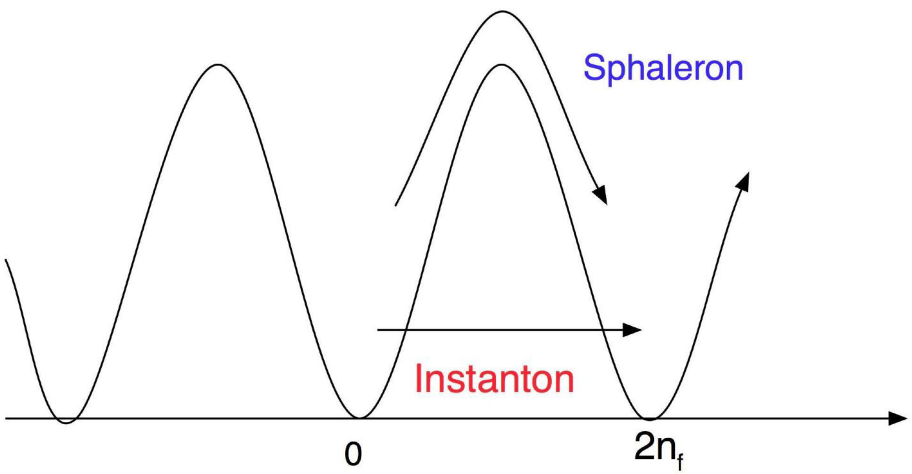
- C and CP violation: OK
  Gauge interaction and particle mixing.

- Departure from thermal equilibrium: ?
  Actually the Universe not really in equilibrium at GUT temperatures... moreover need SUSY for Unification and then the gravitino problem arises.

Spheleron Processes

$B + L$ violation in the Standard Model

In the SM the global $U(1)_{B+L}$ is anomalous. This is related to the complex vacuum structure of the theory, which contains vacua with different configurations of the gauge fields and different topological number. Non-perturbative transitions between the vacua change $B+L$ by $2n_f$.



– $T = 0$: tunneling and is suppressed by $e^{-\frac{4\pi}{\alpha_W}} \ll 1$

$\rightarrow B$ & L practically conserved!

– $T > 0$: the transition can happen via a sphaleron

with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

So at temperatures $T \geq 100$ GeV sphaleronic transitions are in equilibrium in the Universe $\rightarrow B+L$ erased if $B - L = 0$, otherwise

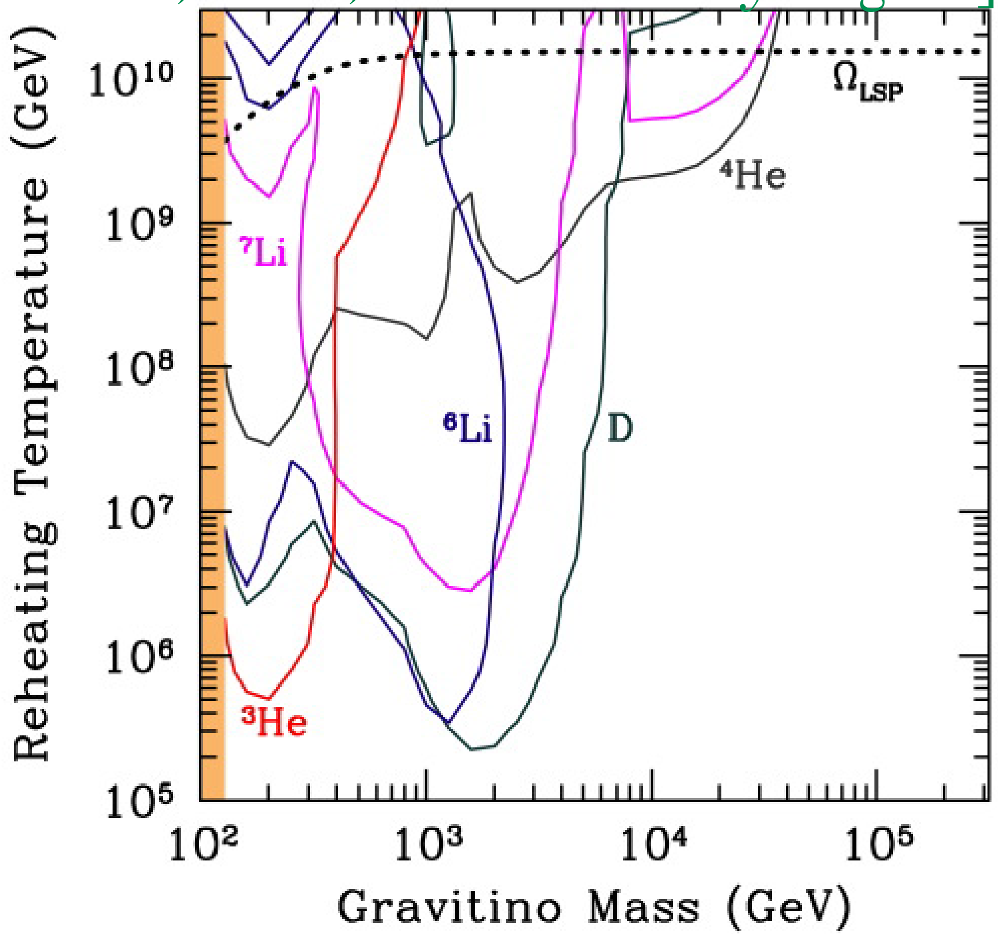
$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B-L)$$

A $B-L$ number is reprocessed into B number !

THE GRAVITINO PROBLEM

The gravitino, the spin 3/2 superpartner of the graviton, interacts only "gravitationally" and therefore decays (or "is decayed into") very late on cosmological scales.

[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]



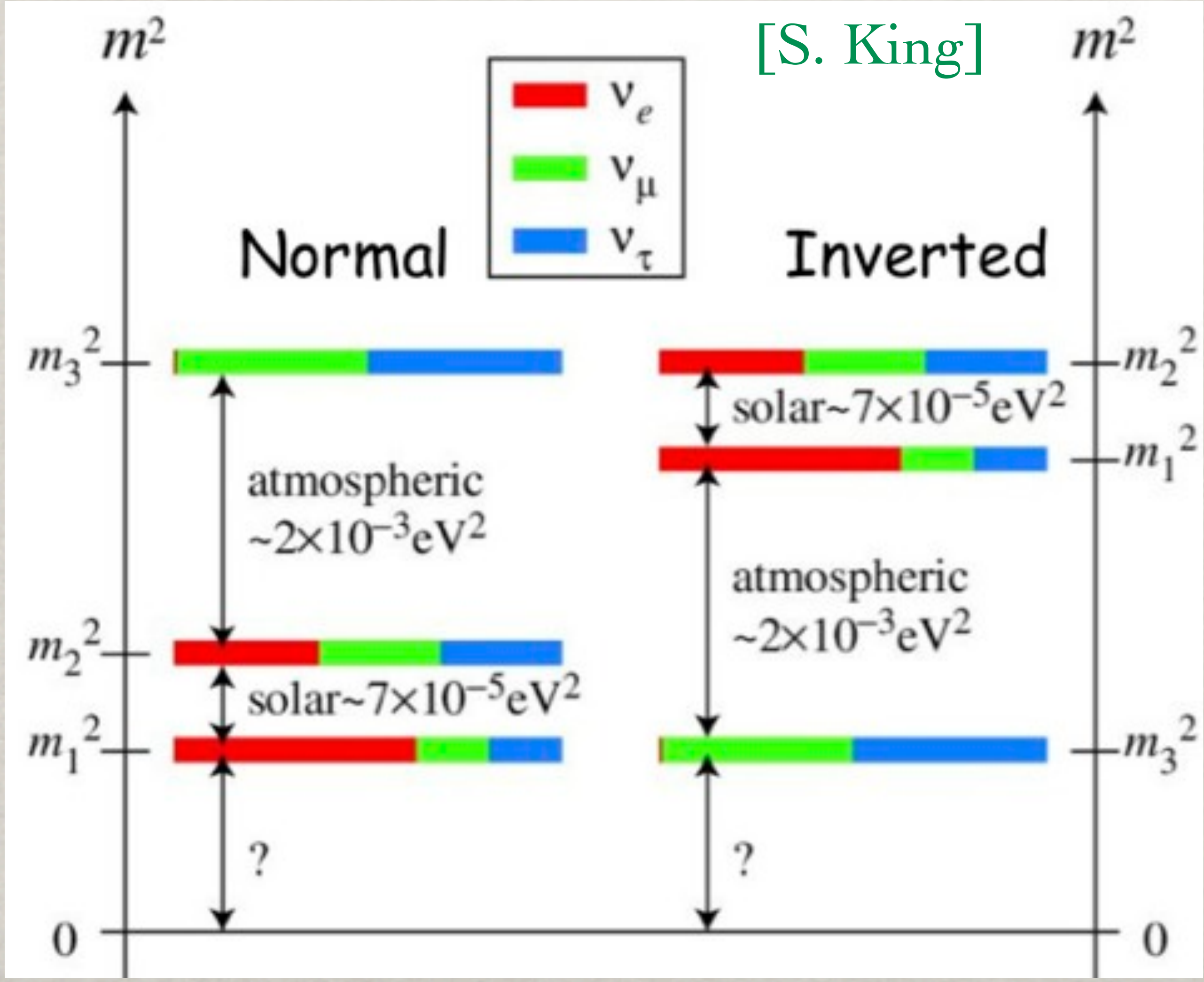
$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100\mathrm{GeV}} \right)^{-3}$$

BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is small! Indeed due to non-renormalizable coupling

$$\Omega_{3/2} \propto T_R \, M_i^2 / m_{3/2}$$

Neutrino masses

From neutrino oscillations we obtain a very good measurement not only of the mixing angles, but also of the mass differences between the three neutrino states:



Much smaller masses than all the other SM fermions !

How comes ?

Neutrino masses & seesaw

[Minkowski 77, Gell-Mann, Ramond & Slanski 79, Yanagida 80]

Try to explain why the neutrino masses are so small: via the mixing with a very heavy state, the RH neutrino N !

$$W = Y_\nu LHN + \frac{1}{2} M_R NN$$

After the EW symmetry breaking we have a mixing between the LH neutrino and N and a Majorana mass term:

$$m_{N\nu} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

Eigenvalues:

$$m_\nu = -\frac{m_D^2}{M_R}, \; m_N = M_R$$

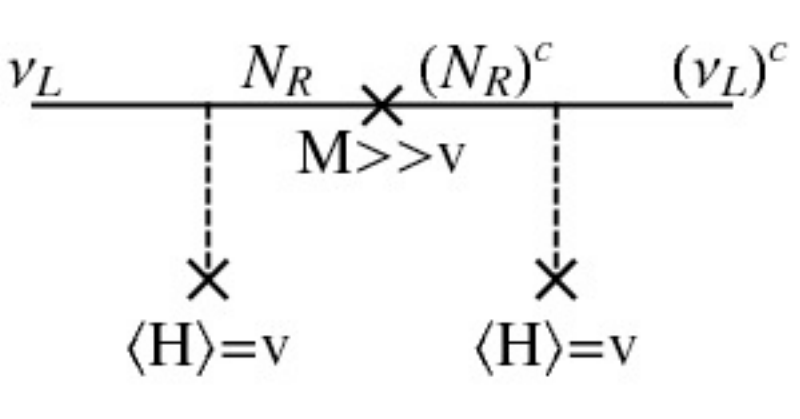
→ see-saw mechanism The larger M_R the smaller m_ν

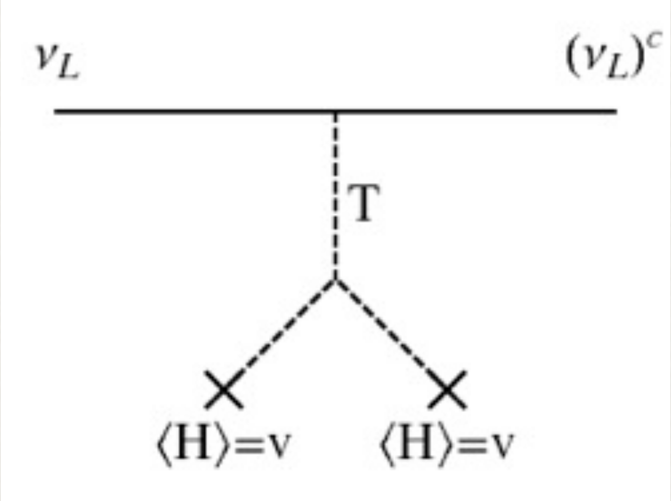
For $m_D \sim m_t$ need $M_R \sim 10^{15}\text{GeV}$

Neutrino masses & seesaw

Considering three generations, the light neutrino mass becomes a 3x3 Majorana mass matrix (type II see-saw):

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





Also other types of see-saw mechanism can be present, e.g. type I or even type III via an SU(2) triplet scalar or fermion. In all cases CP violation can arise !

Leptogenesis

Baryogenesis via Leptogenesis

[Fukugita & Yanagida '86]

Produce the baryon asymmetry from an initial lepton asymmetry reprocessed by the sphaleron transitions. Naturally possible in the case of see-saw mechanism for generating the neutrino masses.

$$W = Y_\nu LHN + \frac{1}{2} M_R NN \quad \rightarrow \quad \text{see-saw}$$

Moreover the RH Majorana neutrino can generate a lepton asymmetry via decay if the rate also violates CP

$$N \to \ell\, H \qquad N \to \bar{\ell}\, H^\star$$

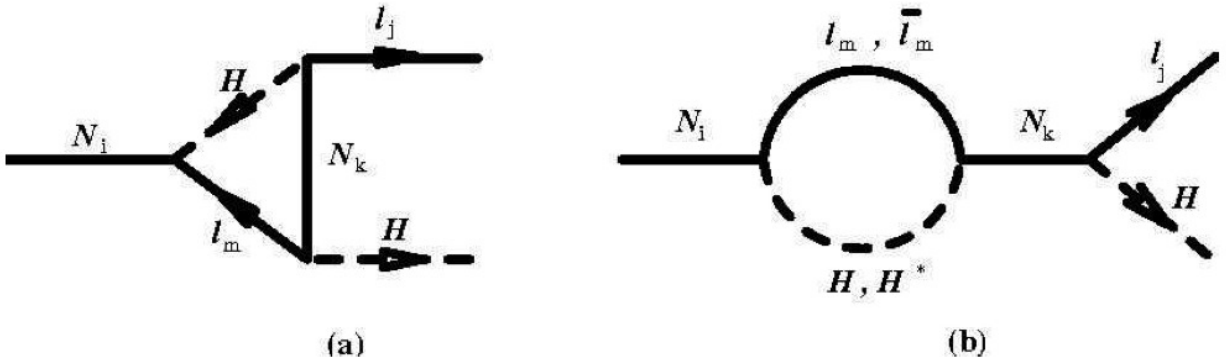
Both channel are possible due Majorana nature of N !

Thermal Leptogenesis

CP violation in N decay

We have CP in the decay of N if the couplings are complex.

CP violation always arises from an interference: tree + one-loop diagrams



We can define

$$\epsilon_i = \frac{\Gamma(N_i \to L) - \Gamma(N_i \to \bar{L})}{\Gamma(N_i \to L) + \Gamma(N_i \to \bar{L})} = -\frac{3}{16\pi} \sum_{i \neq j} \frac{M_i}{M_j} \frac{\Im[(Y_\nu^\dagger Y_\nu)^2_{ji}]}{(Y_\nu^\dagger Y_\nu)_{ii}} \text{ for } M_i \ll M_j$$

It is bounded !

$\rightarrow$relation to neutrino masses via Y_ν...

$$\epsilon \leq 10^{-6} \left(\frac{M_1}{10^{10}\ \mathrm{GeV}} \right) \frac{m_{atm}}{m_1 + m_3}$$

[Davidson & Ibarra 02]

Thermal Leptogenesis

The "back of the envelope" computation:

Out of equilibrium decay

To generate the lepton asymmetry we need also departure from thermal equilibrium: out of equilibrium decay of the lightest N. This happens if $\Gamma_1 \leq H$ at $T \sim M_1$.

$$\Gamma_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_1 \leq H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{M_1^2}{M_P}$$

$\Rightarrow M_1 \geq \sqrt{\frac{90}{\pi^2 g_*}} \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_P$, i.e. the RH neutrino have to be sufficiently massive. Or one can refrase it as

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} \leq \sqrt{\frac{\pi^2 g_*}{90}} \frac{v^2}{M_P} \sim 10^{-3}\text{eV}$$

If this condition is satisfied, then it is trivial to see that every N gives an ϵ amount of lepton number and the final asymmetry is simply

$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3) g}{8\pi^4 g_S} \epsilon_1 \simeq 4 \times 10^{-3} \epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5 \times 10^{-3} \epsilon_1$$

Otherwise one has to solve a couple of Boltzmann equations...

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

$$x = \frac{M_1}{T} \qquad Y_i = \frac{n_i}{s}$$

[Buchmüller, Di Bari & Plümacher '04]

$$\begin{cases} \dfrac{dY_{N_1}}{dx} = -(\Gamma + \sigma)(Y_{N_1} - Y_{N_1}^{eq}) \\ \dfrac{dY_{B-L}}{dx} = -\epsilon_1 \Gamma (Y_{N_1} - Y_{N_1}^{eq}) - W\, Y_{B-L} \end{cases}$$

Decay+Scattering

Asymmetry in the Decay   Wash-out term

Final result: $$Y_{B-L} = \epsilon_1\, \kappa\, Y_{N_1}(x \sim 1)$$

Efficiency factor

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

[Buchmüller, Di Bari & Plümacher '04]

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Decay+Scattering

Asymmetry in the Decay   Wash-out term

Source of Lepton number

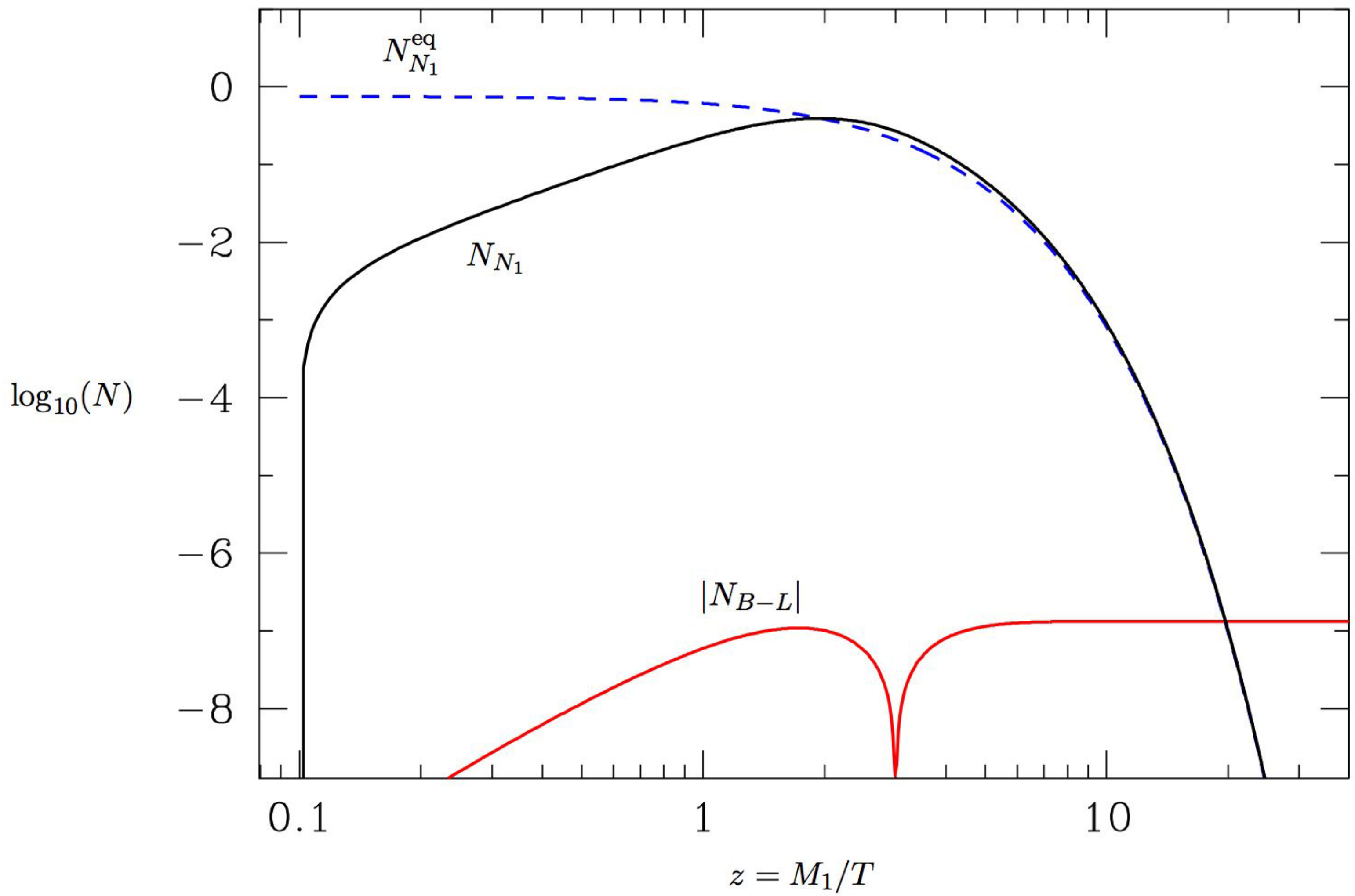
Final result: $Y_{B-L} = \epsilon_1\, \kappa\, Y_{N_1}(x \sim 1)$

Efficiency factor

Thermal Leptogenesis

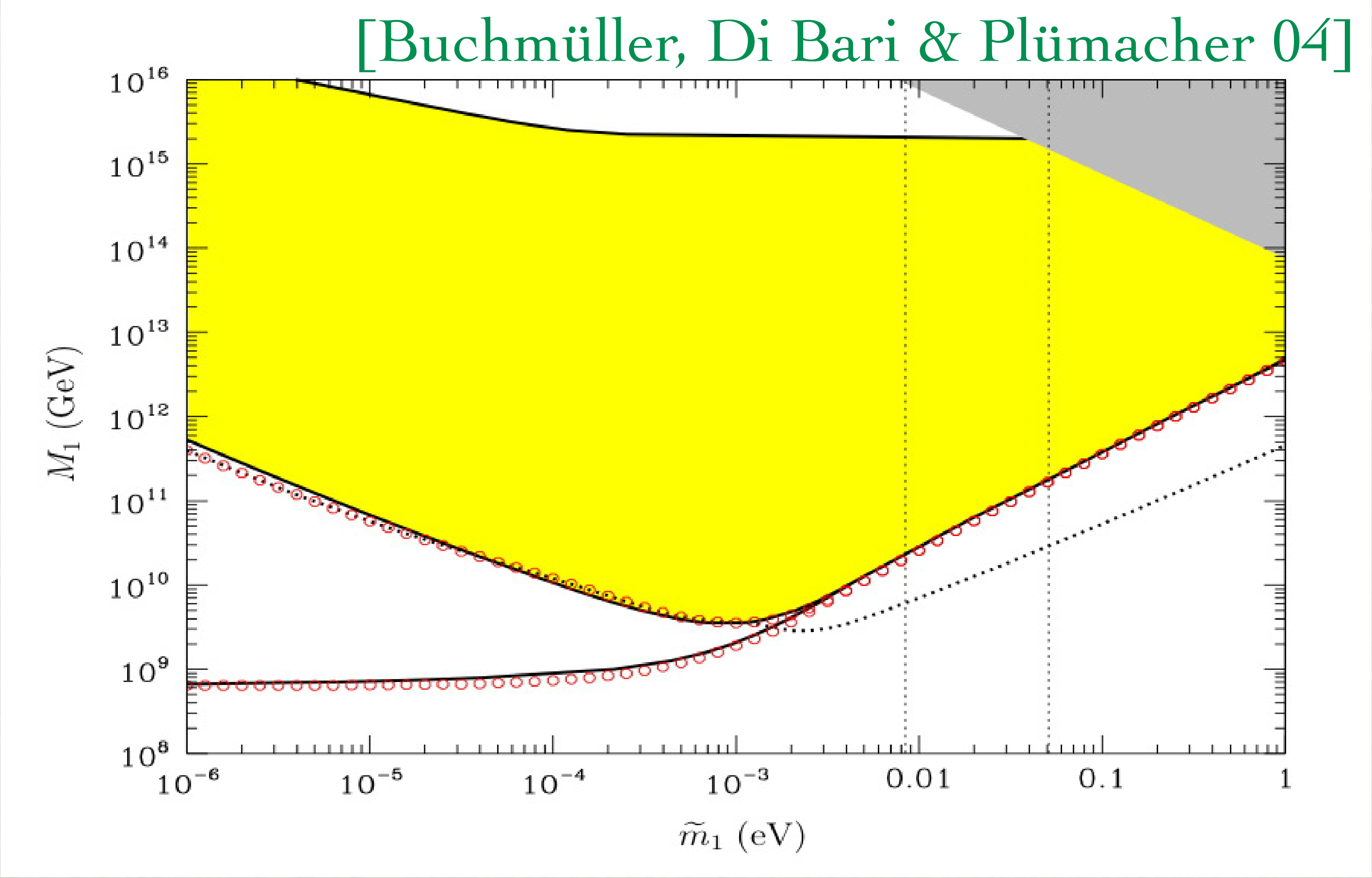
The solution of the coupled Boltzmann equations:

[Buchmüller, Di Bari & Plümacher '04]



Thermal Leptogenesis

M_1 must be large enough to generate the baryon asymmetry, for small M_1 the CP violation is just too small. Need large T_{RH} to produce the RH neutrino...



Ways out: enhanced CP violation due to degenerate N's, non-thermal leptogenesis, etc...

Low E vs high E CP ?

One important question is if the low energy leptonic CP violation observables are related to the CP violation in leptogenesis... Unfortunately not directly !

Simple parameter counting:

the 3x3 Majorana (low energy) mass matrix contains 9 real parameters, i.e. 3 masses, 3 mixings and 3 phases (1 Dirac & 2 Majorana phases), while the (high energy) Yukawa matrix & RH neutrino mass matrix amount instead to 18 real parameters.

In general the measurable low-energy Dirac phase in the neutrino sector is given by a complicated of the high energy parameters ! Nevertheless in specific models definite predictions are possible, e.g. 2 RH neutrino case or some flavoured leptogenesis cases...

Flavored Leptogenesis

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

In the early universe the charged leptons have different thermal equilibration time due to the different Yukawa couplings, so the coherence of the light neutrino combination coupling to N_1 is not always ensured.

$T > 10^{12}\mathrm{GeV}$	Single flavour: all leptons NEQ	
$T \sim 5 \times 10^{11}\mathrm{GeV}$	Tau Yukawa is in equilibrium	2Flav
$T \sim 2 \times 10^{9}\mathrm{GeV}$	Muon Yukawa is in equilibrium	3Flav
$T \sim 4 \times 10^{4}\mathrm{GeV}$	Electron Yukawa is in equilibrium	

Depending on the epoch of leptogenesis, one may have to consider flavour effects !

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

In presence of flavour, Yukawa scattering processes destroy coherence and project the lepton combination down to the flavour eigenstates. One can then define a CP asymmetry for every relevant flavour:

$$\epsilon_{1\alpha} = \frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1}$$

Similarly also wash-out processes can be different for the different flavours. So the possibility arises to store lepton number in the flavour with smaller wash-out rate !

More successful leptogenesis regions open up in general, but the prediction become flavour model-dependent.

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

Different formalisms can be used to take into account flavour, depending on the regime.
Away from the transition between 1 - 2 flavours, one can use a flavoured Boltzmann equation, but this cannot take into account oscillations effects !

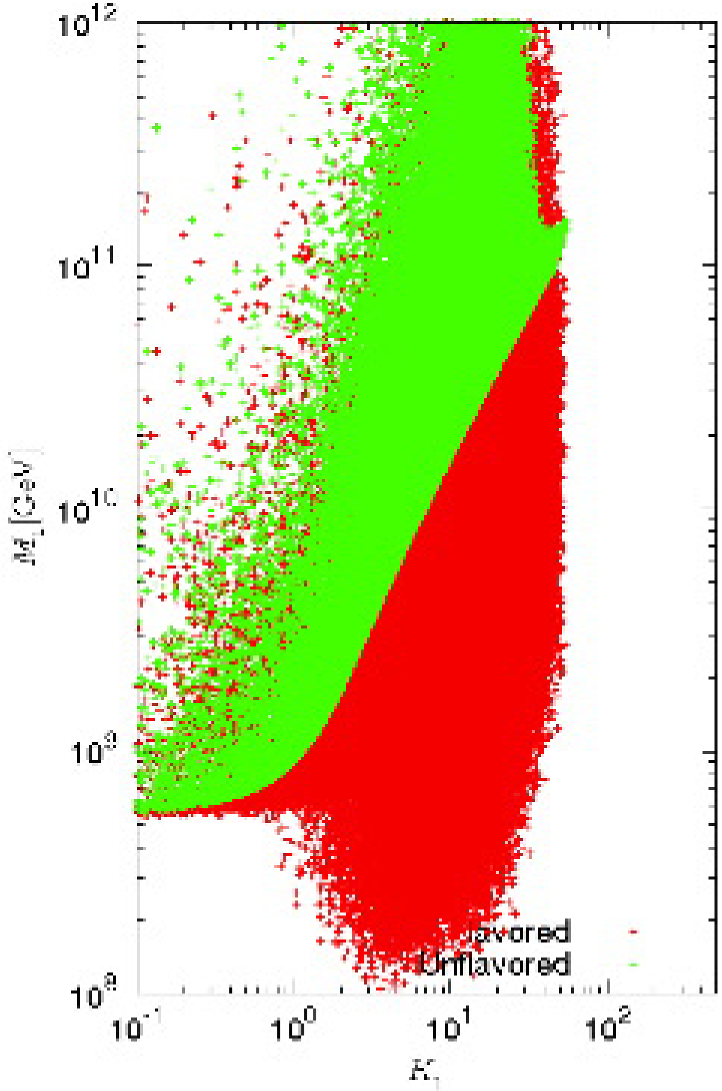
Another formalism is based on the full density matrix in flavour space and takes into account also the off-diagonal part, not included in the Boltzmann equations.

$$i\hbar \frac{\partial \rho}{\partial t} = [H, \rho]$$

Flavored Leptogenesis

One important issue is if flavour allows to extend the parameter region, where leptogenesis works.
Indeed, there are additional contributions to the Lepton asymmetry that cancel in the single flavour case !
Nevertheless not all is possible, thermal leptogenesis still works only at high temperature !

[Di Bari 1206.3168]

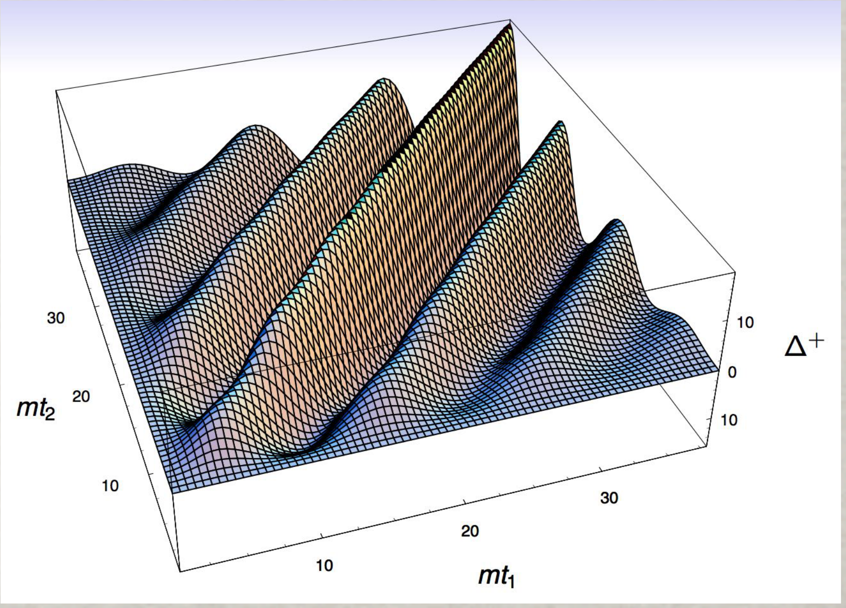


Quantum Leptogenesis

Quantum Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al....]

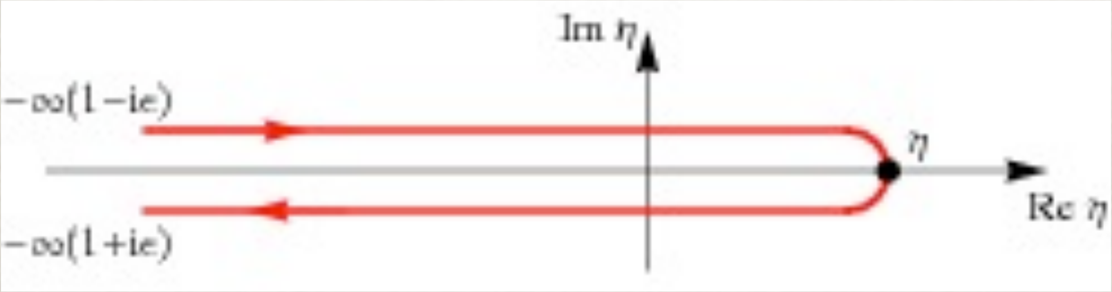
- Full quantum mechanical description of the process using Kadanov-Baym equations (2nd order) instead of the Boltzmann equations... No double counting and more effects (e.g. memory effects) arise !
- Different statistical/spectral propagators depending on two time variables and solutions include full particle width and coherence !



Quantum Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al....]

To describe the full non-equilibrium quantum evolution, exploit QFT in Closed-Time-Path formalism in order to compute in-in transition amplitudes



Propagators and Self-Energies become 2x2 Matrices

$$G = \begin{pmatrix} G^{++} & G^{+-} \\ G^{-+} & G^{--} \end{pmatrix} \qquad \Sigma = \begin{pmatrix} \Sigma^{++} & \Sigma^{+-} \\ \Sigma^{-+} & \Sigma^{--} \end{pmatrix}$$

Quantum Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al....]

To obtain the kinetic equations, start from the Schwinger-Dyson equation for the propagator:

$$G = G^0 + G^0 * \Sigma * G$$

From this one obtains the Kadanov-Baym equations for two combinations of the propagators: $G^{>,<} = G^{++} \mp G^{--}$

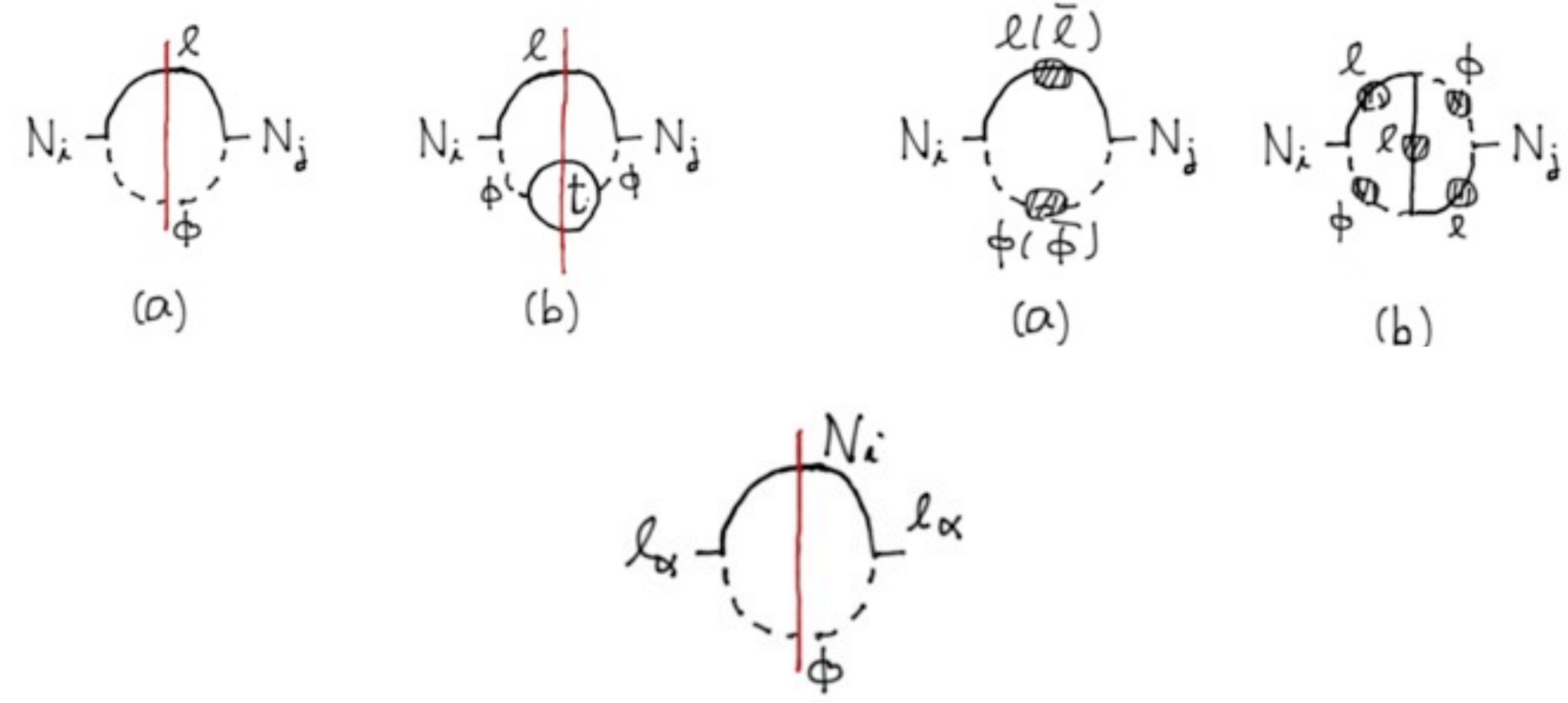
$$(i\gamma^\mu \partial_\mu - M_1) G^> = -\Sigma^> * G^>$$

$$(i\gamma^\mu \partial_\mu - M_1) G^< = \Sigma^> * G^< - \Sigma^< * G^>$$

This equations can then be expanded in gradient and perturbative series.

Quantum Leptogenesis

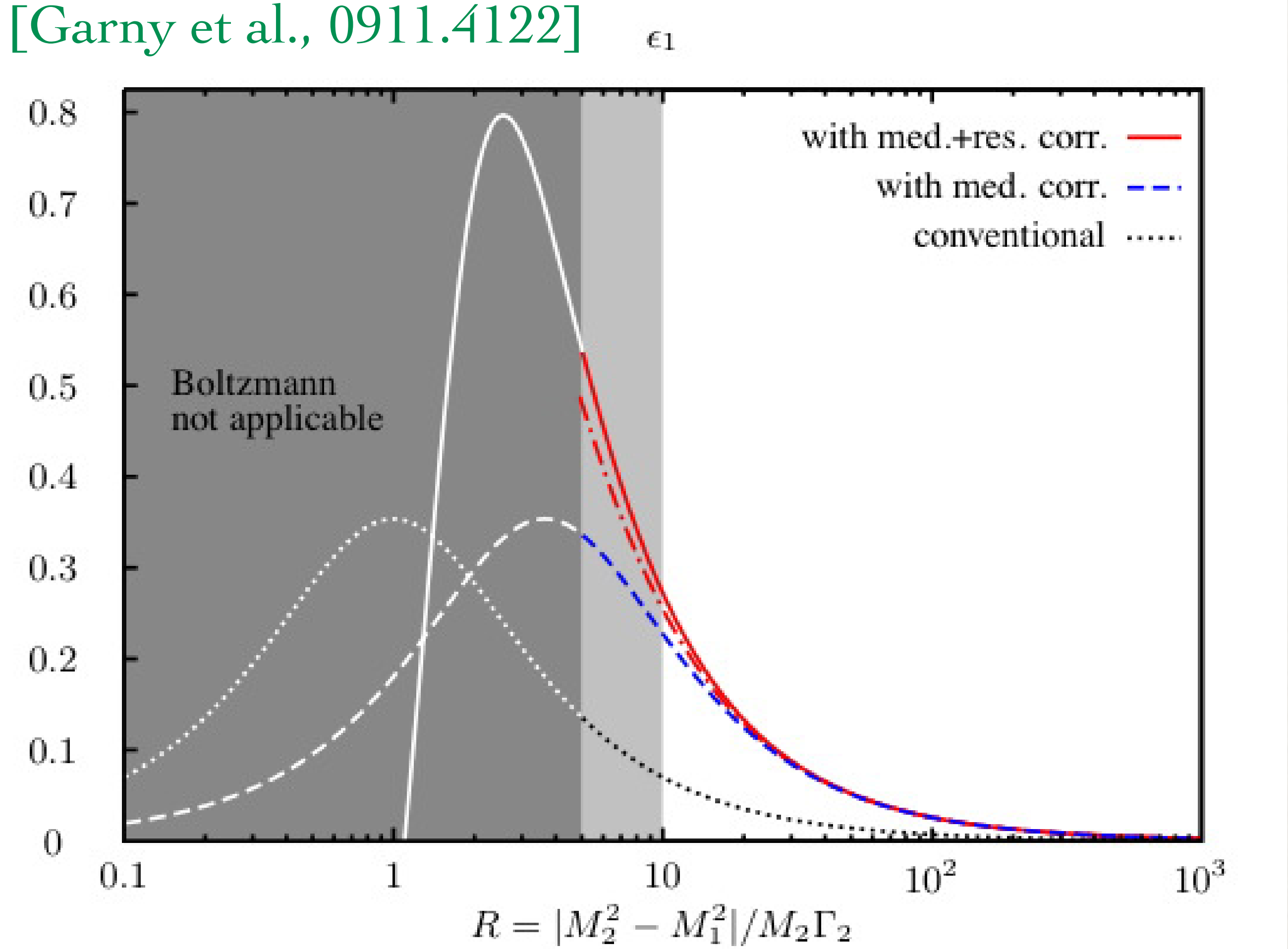
Where is the CP violation ??? In the self-energy !!!
Also includes scatterings and all possible processes with real/virtual particles automatically.



Quantum resonant Leptogenesis

[Garny et al.., Garbrecht et al...]

[Garny et al., 0911.4122]

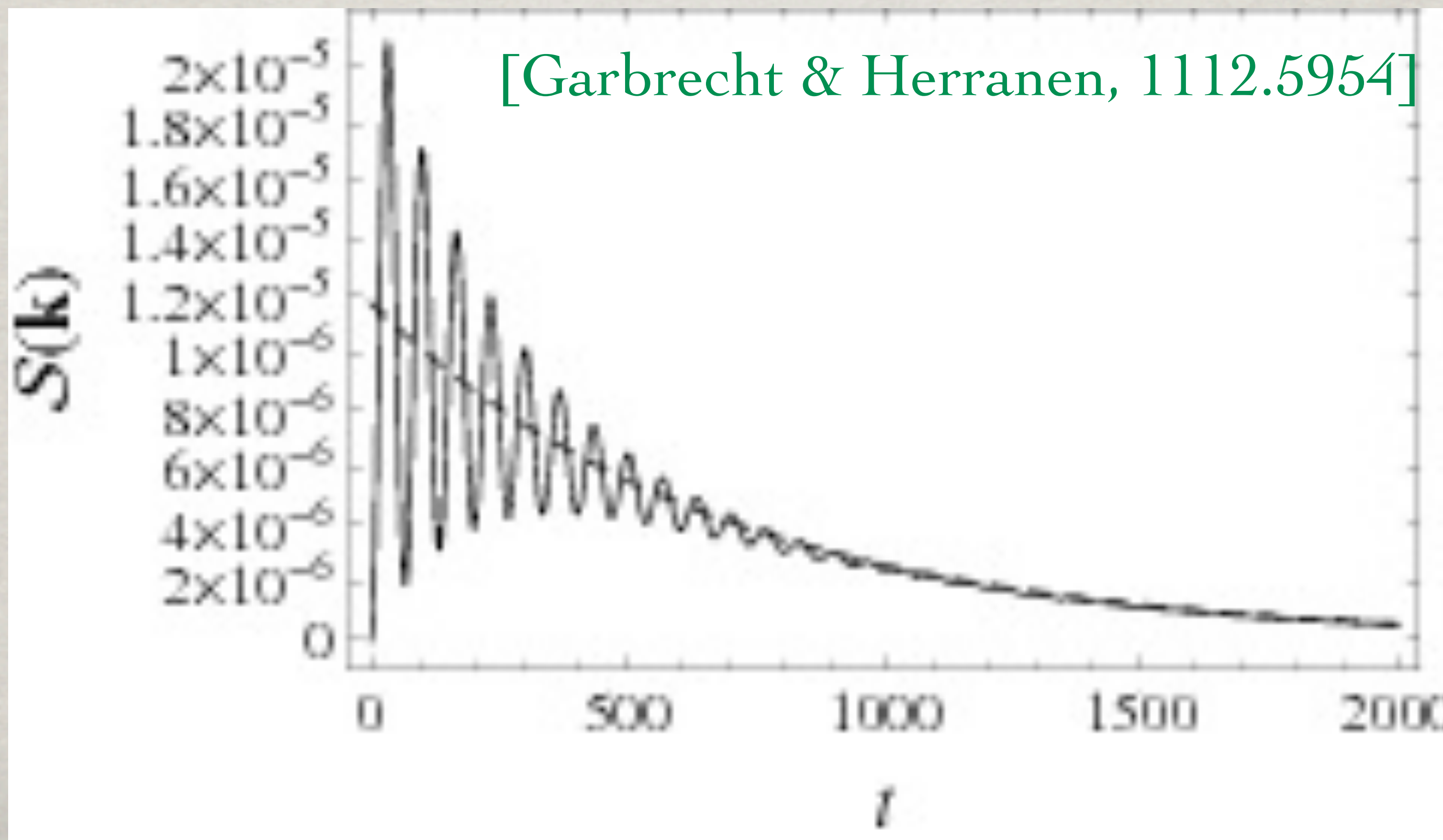


Resonant leptogenesis : the CP violation is enhanced if the mass difference is of the same order as the decay width.

Quantum resonant Leptogenesis

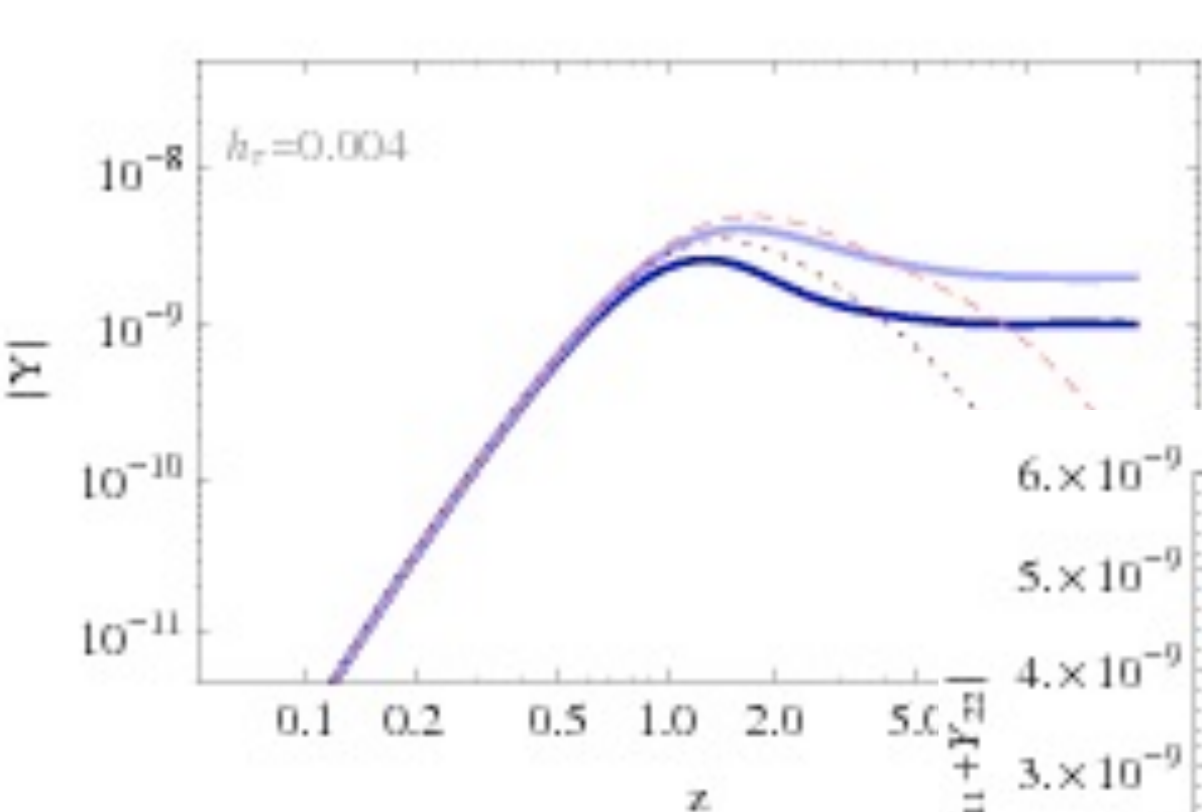
[Garny et al.., Garbrecht et al...]

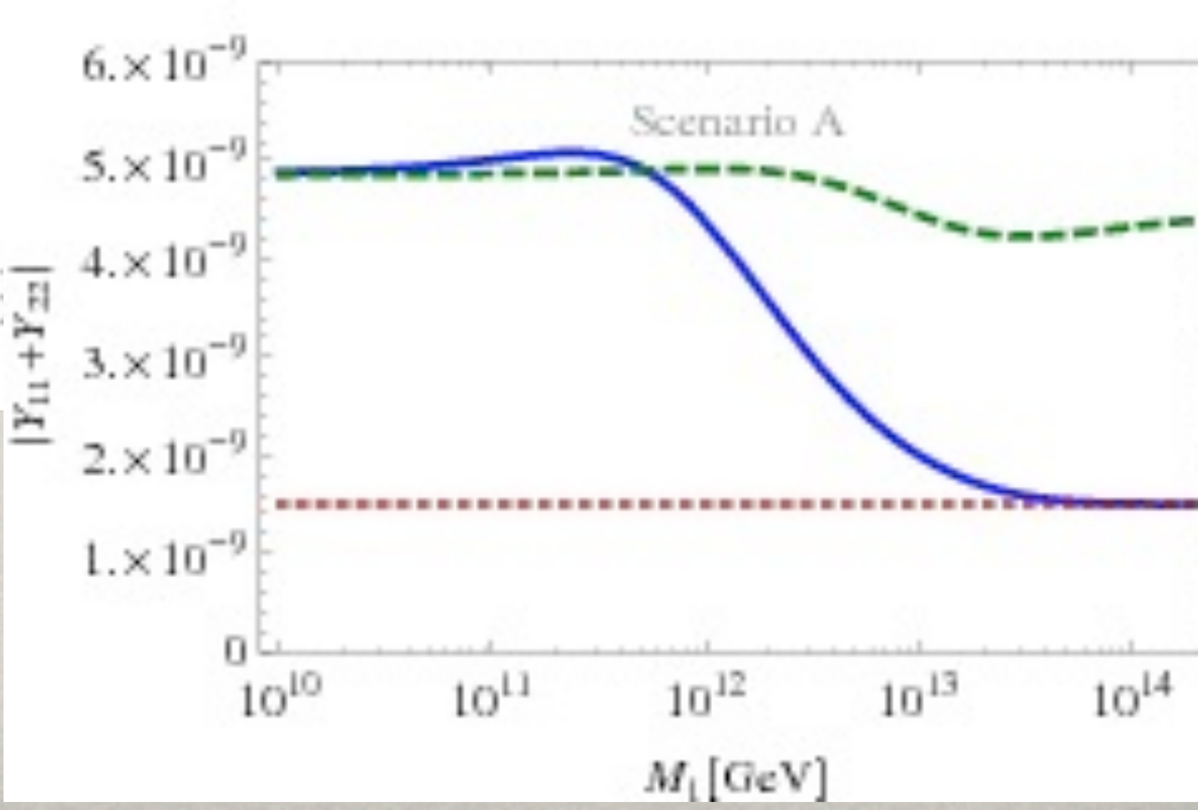
Resonant leptogenesis if two RH neutrinos are degenerate: oscillatory source term for the lepton asymmetry !



Quantum flavored Leptogenesis

[Beneke et al, 1007.4783]





Non thermal Leptogenesis

Non-thermal leptogenesis

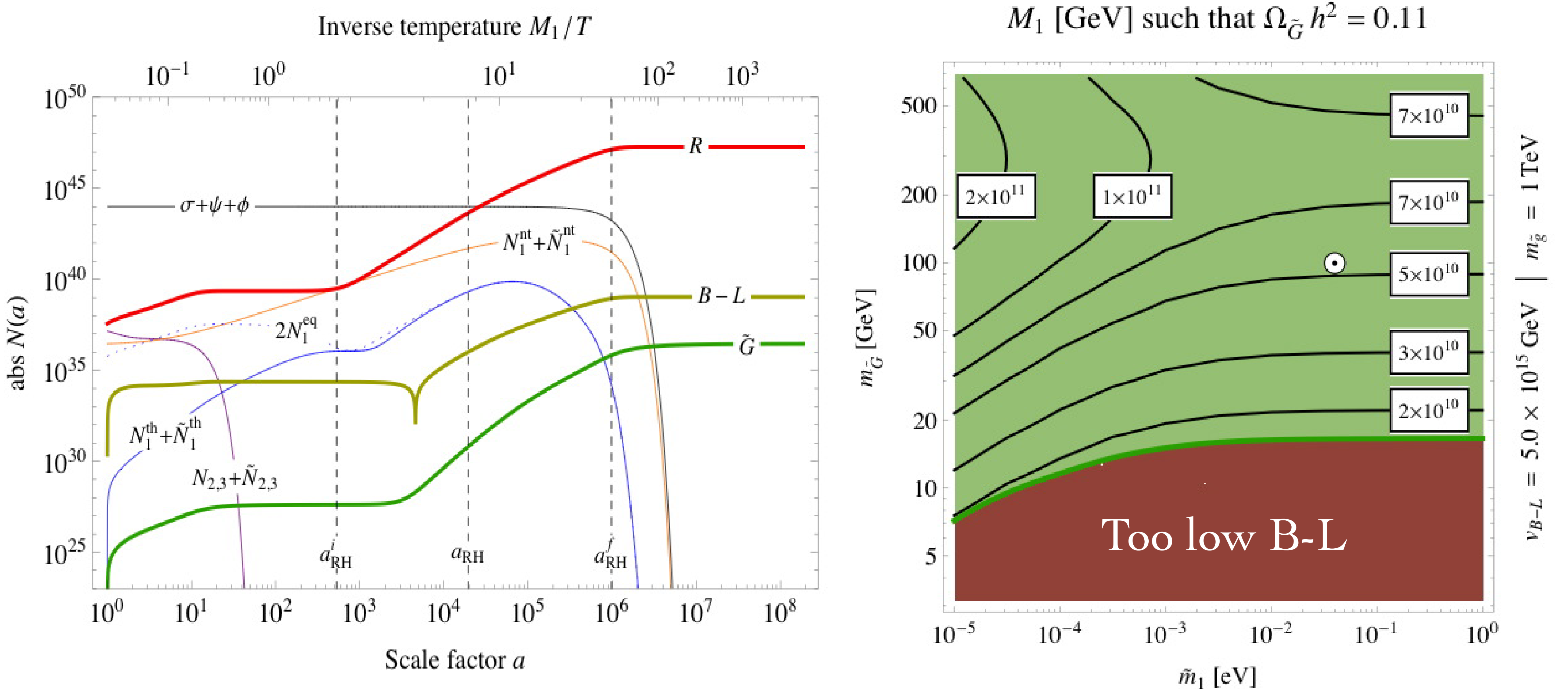
We have considered so far the case of thermal leptogenesis, where the initial state for the heavy RH neutrinos is thermal equilibrium (so no dependence on initial conditions !).

Many more possibilities open up, if we relax this assumption, in particular:

- Leptogenesis from inflaton decay (e.g. if inflaton is the RH sneutrino...)
- Leptogenesis at reheating/preheating
- Cogenesis of DM+leptons

B-L from reheating

[W. Buchmuller, V. Domcke, K. Schmitz 12]



Gravitino DM and B-L may be produced both from heavy RH neutrino decay during reheating: then there is a relation with the neutrino sector parameters and a lower bound on $m_{\tilde{G}}$

Outlook

Conclusions & Outlook

- Leptogenesis offers an elegant mechanism to generate the baryon asymmetry of the Universe
- The parameters can be connected to neutrino masses and mixing, but unfortunately not always directly...
- Predictions: CP violation in the neutrino sector, neutrinoless double beta decay
- In the resonant case possible to lower the scale, but unclear if down to EW...

References

- E. Kolb & M. Turner - The Early Universe - Front. Phys. 69 (1994) - Westview Press
- C. S. Fong, E. Nardi and A. Riotto - Leptogenesis in the Universe - arXiv:1301.3062
- S. Davidson, E. Nardi and Y. Nir - Leptogenesis - arXiv:0802.2962