# Baryo- and leptogenesis

**Purpose : explain the current excess of matter/antimatter**

- **Is there an excess of matter?**
  - Baryons: excess directly observed;
    Antibaryons seen in cosmic rays are
    compatible with secondary production
  - Leptons: excess of electrons similar to baryons,
    - BUT WE DON'T KNOW about neutrinos,
    no direct observations + they may even be
    Majorana particles → lepton number not defined.

Today, direct observation suggests:

$$3\ 10^{-11} < n_B/n_\gamma < 6\ 10^{-8}$$

While standard cosmological constraints at the nucleosynthesis stage give the stronger, still compatible limit:

$$4\ 10^{-10} < n_B/n_\gamma < 7\ 10^{-10}$$

And the Cosmic Microwave Background estimate is in the range:

$$\eta_B^{CMB} = (6.1 \pm 0.5)10^{-10}$$

If we assume however that the asymmetry comes from earlier times, before the annihilation of most particles into photons, and assume a roughly isentropic evolution, this suggests an initial value:

$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-8}$$

This small number suggests to start from a symmetrical universe, like we expect if it arises through interaction with gravity, and to generate the asymmetry by particle physics interactions.

Program

- LEARNING EXERCISE:
  - Direct approach to baryogenesis (Sakharov Conditions)
  - Baryon number violation limits
  - CP vs TCP : how to generate the asymmetry
  - Out-of-Equilibrium transitions
  - Difficulties with the Electroweak phase transition
- LEPTOGENESIS as a solution : exploits the same mechanisms,but uses the electroweak phase transition instead of suffering from it!

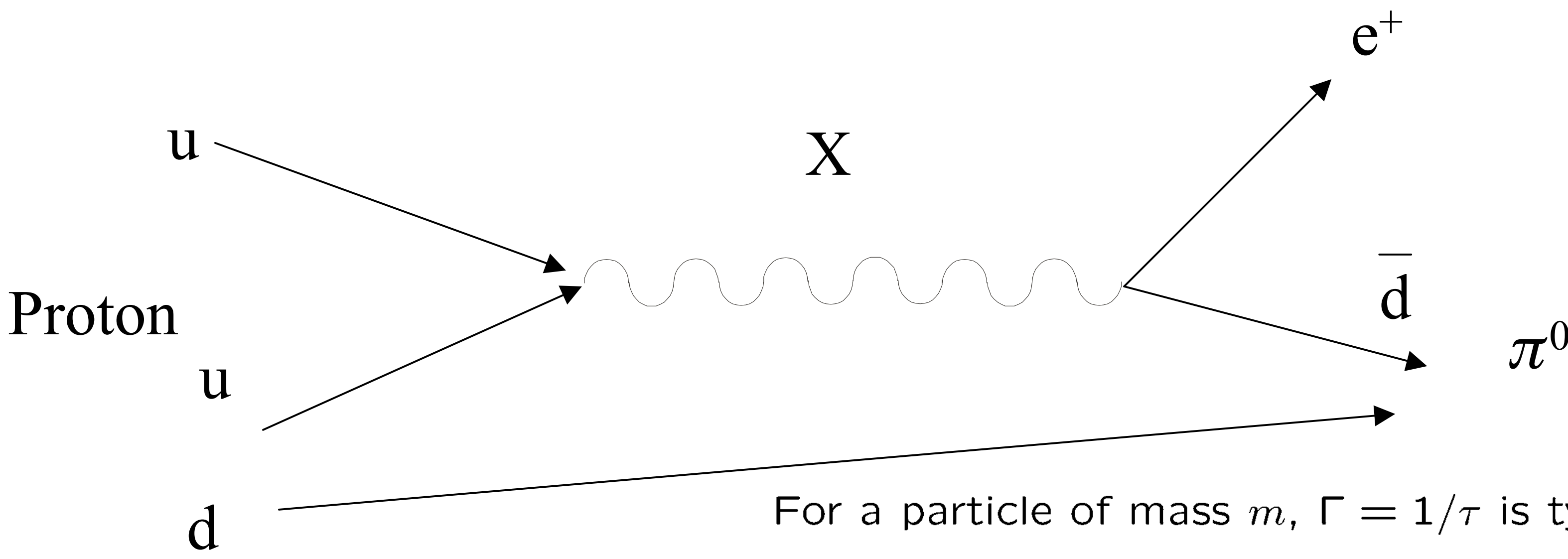
Baryogenesis

Constraints on **Baryon number** conservation

- a number just invented to « explain » or « ensure » the proton stability :

$$\tau_n \approx 15 min$$

$$\tau_p > 10^{32} years$$




For a particle of mass $m$, $\Gamma = 1/\tau$ is typically

$$\Gamma = \kappa \cdot m$$

$$\kappa \approx 1, \quad m = 1GeV \rightarrow \tau = 610^{-25}s$$

Proton decay goes through exchange X,

$$\Gamma \approx g^4 m^5_{proton}/M^4_X$$

a simple calcuation leads to

$$M_X/m_p \approx 10^{(25+32+7)/4}GeV = 10^{16}GeV$$

Typical proton instability in grand unification SU(5);

Need unification scale $10^{16}$ GeV

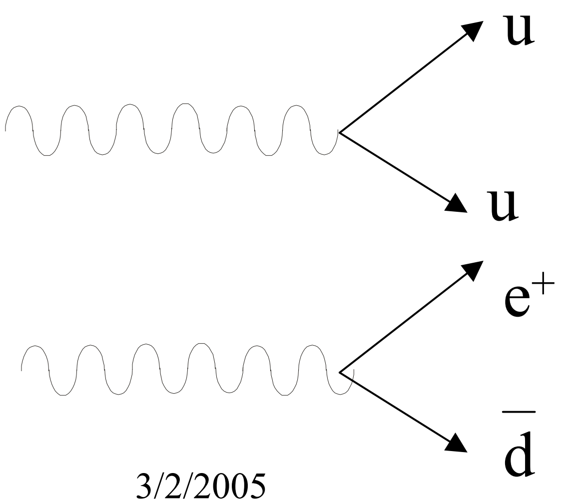
We will take SU(5) baryogenesis as an example in the next slides..

This is not sufficient to generate the baryon number!
Sakharov's conditions:

- Violation of Baryon number

- Out-of-equilibrium

- Violation of C, (and CP, and ..) symmetries




B=2/3

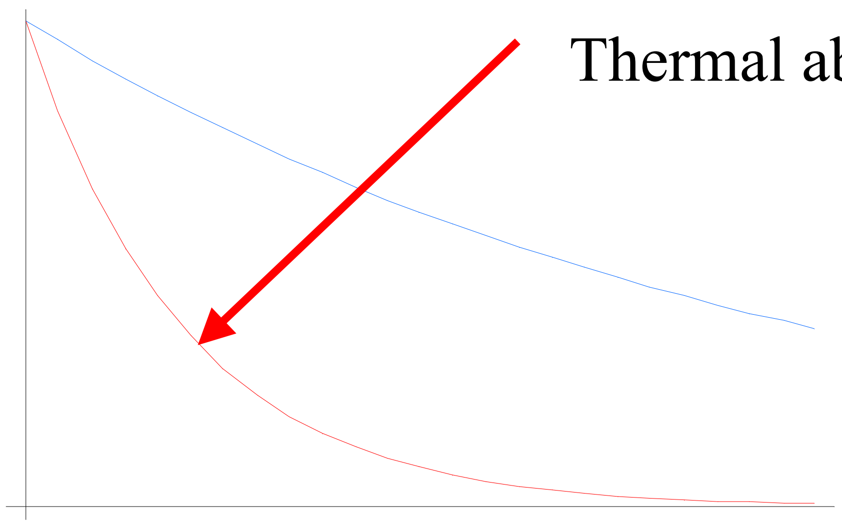
B=-1/3

The decay of X violates Baryon number…., it could generate the baryon number in the early universe!

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

Out-of equilibrium: needed to avoid « return » reaction.

Simplest approach, in case of baryogenesis (also OK for Lepto-): use the expansion of the Universe….




If the particle X decays slower than the Universe expands
→**RELIC PARTICLE**,
Decays later and
**OUT OF EQUILIBRIUM**

NEED $$\tau(X) >> H^{-1}$$

$H = \dot{a}/a$ is the Hubble constant,

$$\tau^{-1} = \Gamma \cong g^2 M$$

$$H = \sqrt{g^*}\frac{T^2}{10^{19} GeV}$$

$g^*$ is the number of degrees of freedom at the time

at decay : $T \approx M$ ,

$$\Rightarrow \quad M > 10^{16} GeV$$

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

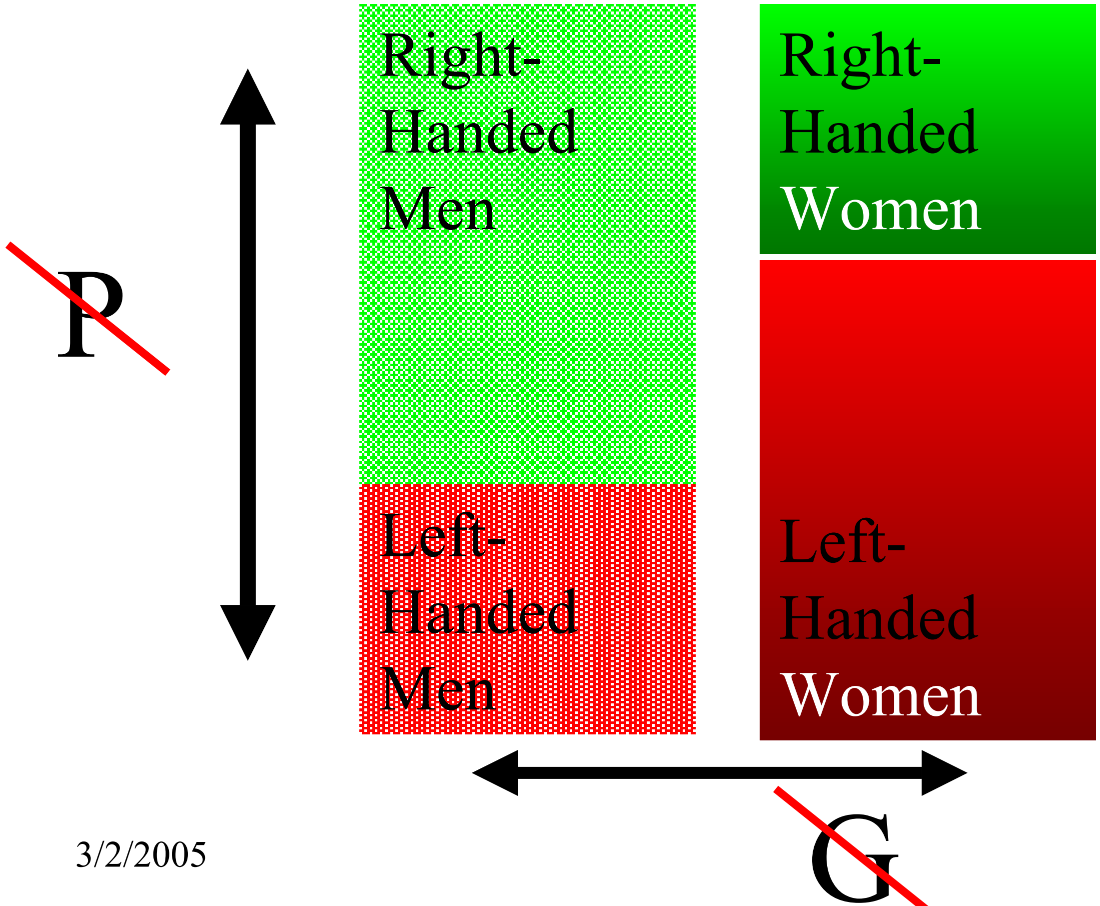
We still need one condition:
the violation of Charge conjugation

Indeed, if

The decay of X generates a baryon number B=( 2/3-1/3 )/2=1/6
BUT
The decay of anti-X will generate B=-1/6
If Charge conjugation holds….

~~C~~ is NOT sufficient , we need also to violate combined symmetries involving C , in particular CP

A toy example : replace C by G: Gender = Man ←→Woman,
P is the parity : Left-Handed ←→Right-Handed




If P and G are violated,
But PG is a valid symmetry,
→ same numbers of men and women!

**NEED CP Violation!**

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

We need CP violation , but :

- HOW is it introduced?

- HOW does it work ?

need complex coefficients

Gauge interactions ="real", CP-conserving

→ NEED scalar (Yukawa) couplings

$$\lambda \bar{\Psi} \phi^{\dagger} \xi + \lambda^{*} \bar{\xi} \phi \Psi$$

We need CP violation , but :

- HOW is it introduced?
- HOW does it work ?

# CP vs TCP

TCP implies

$$< X \mid S \mid Y > = < \bar{Y} \mid S \mid \bar{X} >$$

$$< X \mid S \mid X > = < \bar{X} \mid S \mid \bar{X} >$$

$X$ and $\bar{X}$ have the same lifetime ...but they may die differently

consider:

$$\Gamma_{X \to uu} = r_u \quad n_B = 2/3; \quad n_L = 0$$

$$\Gamma_{X \to e^+ \bar{d}} = r_d \quad n_B = -1/3 \quad n_L = -1$$

$$\Gamma_{\bar{X} \to \bar{u}\bar{u}} = \bar{r}_u \quad n_B = -2/3 \quad n_L = 0$$

$$\Gamma_{\bar{X} \to e^- d} = \bar{r}_d \quad n_B = 1/3 \quad n_L = 1$$

TCP only implies

$$\Gamma(X) = \Gamma(\bar{X})$$

but we may have

$$r_u \neq \bar{r_u}$$

provided it is compensated by another channel:

$$r_u + r_d = \bar{r_u} + \bar{r_d}$$

This is sufficient to generate a NET BARYON NUMBER:

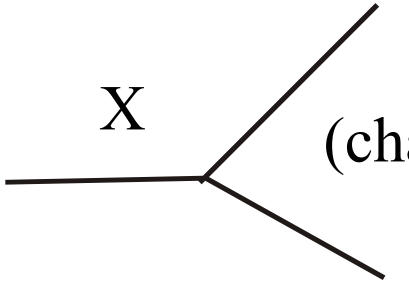
Take the decay of a pair $X + \bar{X}$, it gives

$$n_B = 2/3\ (r_u - \bar{r_u}) - 1/3\ (r_d - \bar{r_d}) \neq 0$$

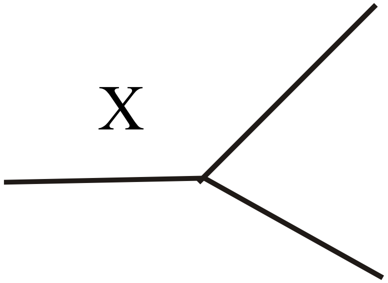
Thus, we can generate baryon number despite TCP, provided the branching ratios of X and anti-X are different, but compensate for the total lifetime

**HOW is this compensation implemented in the calculation?**

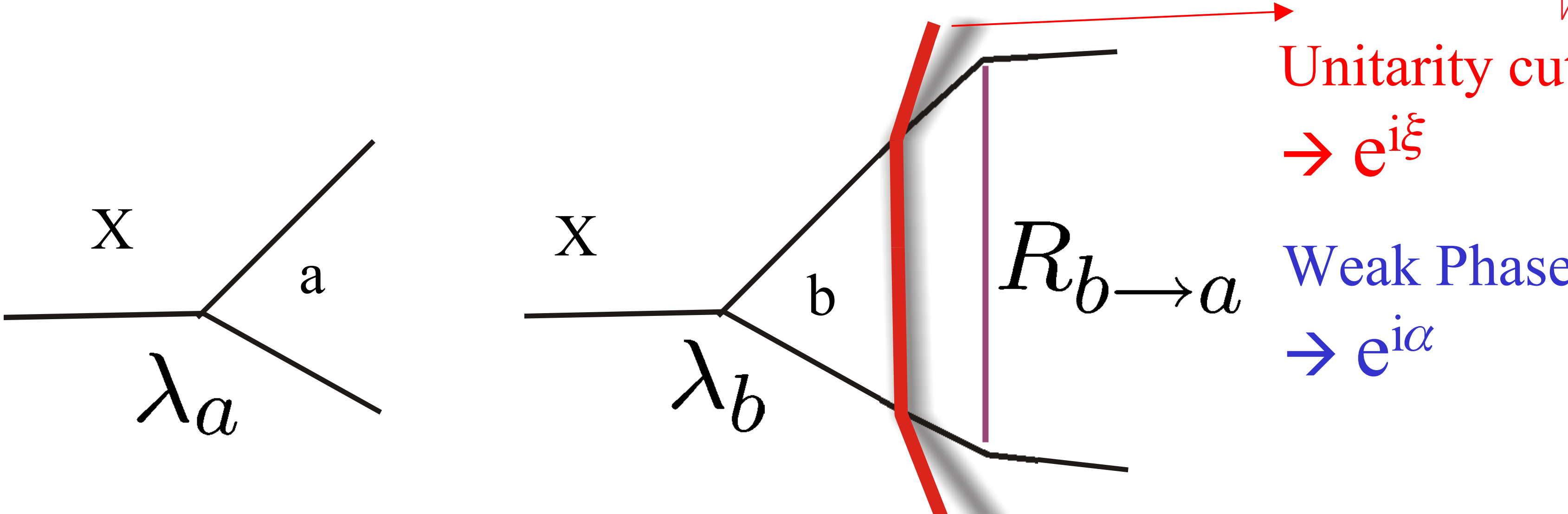
Consider 2 decay channels (say, a and b) for the particle X, and the conjugate channels for the anti-X




(channel a)




(channel b)




One channel learns about the compensation by the other through interference …

$$\Gamma(X \to a) \sim |\lambda_a + \lambda_b e^{i\alpha} R_{b\to a} e^{i\xi}|$$

$$\Gamma(\bar{X} \to \bar{a}) \sim |\lambda_a + \lambda_b e^{-i\alpha} R_{\bar{b}\to\bar{a}} e^{i\xi}|$$

$$\Gamma(X \to a) - \Gamma(\bar{X} \to \bar{a}) \sim \lambda_a \lambda_b R_{b\to a} sin(\alpha) sin(\xi)$$

- Violation of Baryon number
- Out-of-equilibrium
- Violation of C, CP and … symmetries

We have thus met all the conditions to generate baryon number through « thermal  baryogenesis », i.e., through the baryon-number violating decay of relic particles from SU(5).
Yet, this scenario is no longer favored !

WHY ?

• Need to introduce CP violation « by hand »,
through new complex scalar fields → no relation to low energy pheno

• We assumed standard big-bang cosmo: the baryon number would be diluted in an inflation scheme, or we would need re-heating to re-create the X  particles

•More importantly : the electroweak phase transition would destroy the B number just created  (although this is a specific SU(5) problem)

•the electroweak phase transition would destroy the B number just created (although this is a specific SU(5) problem)

We have seen indeed that SU(5) violates Baryon number by processes like

$$u + u \rightarrow \bar{d} + e^{+}$$

where $\Delta B = -1/3 - 2/3 = \Delta L = -1 - 0$

in other terms, SU(5) baryogenesis keeps (B-L) conserved !

# Quantum anomalies can destroy/create B and L

considering the fermionic Lagrangian,

$$L = \bar{\psi}_L D^{\mu} \gamma_{\mu} \psi_L$$

the transformation $\psi_L \to e^{i\alpha}\psi_L$ implies, at the classical level, the conservation

$$\partial_{\mu} {j_L}^{\mu} = 0$$

where ${j_L}^{\mu} = \bar{\psi}_L \gamma^{\mu} \psi_L$, and similarly for the baryons

The existence of extended (topological) solutions for the gauge fields (instantons) or, in the electroweak breaking scheme, the existence of a barrier measured by the "Sphaleron" mass, DESTROYS this conservation. For instance:

$$\partial_{\mu} j^{\mu}_{lepton,L} + \partial_{\mu} j^{\mu}_{baryon,L} = \kappa \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

(we have neglected fermion masses effects here, and concentrated to the Left-handed part, which is coupled to the gauge group $SU(2)_L$).

$$\partial_\mu j^\mu_{lepton,L} + \partial_\mu j^\mu_{baryon,L} = \kappa \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

allows to "exchange" some Baryon number for Lepton number and a change in the vacuum fields configuration

Observe that in this process,
one unit of B is exchanged for – 1 unit of L, which means that the exchange is permitted provided B-L is conserved (technically, their left-handed part)

These processed are normally extremely weak at current energies, but, are assumed to become fast if the temperature approaches the »sphaleron » Or the electroweak phase transition, at T ≈ 100 GeV

$$e^{-M_{sphaleron}/kT}$$

# Possible situations if the Electroweak phase transition takes place

## Out of Equilibrium

Independently of previous B or L, a new creation of B is possilbe, (but with B-L=0 for the new contribution)

Electroweak Baryogenesis ??

## At (or near) Equilibrium

Pre-existing B or L can be erased, but B-L is conserved

For SU(5) baryo, B-L=0, so B and L can be totally erased.

IF B-L ≠0, the proportions of B and L are simply changed;
In particular, if only L was generated,
it can be changed into B →
**Leptogenesis**

# Electroweak Baryogenesis ??

- **NOT favoured in Standard Model** :
  - 1$^{st}$ order phase transition (requires light scalar boson) excluded by LEP
  - CP violation insufficient in SM: (see next slide)
- **Possible in some extensions, like SUSY**
  - e.g. add extra scalars (including singlets and trilinear couplings to force a strong 1st order phase transition
  - Extra CP violation needed
  - Even in the best case, evaluation of the efficiency of the conversion mechanism difficult, due to extended solutions.

# Electroweak Baryogenesis – Enough CP violation?

In the Standard Model, CP violation is governed, in the Kobayashi-Maskawa mechanism, by the quantity

$$J = sin(\theta_1)sin(\theta_2)sin(\theta_3)sin(\delta) * P_u * P_d$$

$$P_u = ({m_u}^2 - {m_c}^2) * ({m_t}^2 - {m_c}^2) * ({m_t}^2 - {m_u}^2)$$

$$P_d = ({m_d}^2 - {m_s}^2) * ({m_b}^2 - {m_s}^2) * ({m_b}^2 - {m_d}^2)$$

This quantity has to be made dimensionless; for this, we can divide by $(100GeV)^{12}$, the result is $10^{-17}$, much too small for baryogenesis!

(the same result is obtained if one prefers to use the Yukawa couplings directly, instead of the quark masses)

# Leptogenesis

- Basic idea :generate L at higher temperature
- Use the electroweak phase transition near equilibrium to convert L → - B
  - Advantage: insensitive to the details of the sphaleron-based mechanism, provided the transition stays close to equilibrium until completion
- Use cheap, readily available heavy Majorana neutrinos,
  - … because their inclusion has recently become very popular

# Do we need heavy (Majorana) neutrinos?

$\nu$ oscillations → neutrino masses

Must explain how they are introduced in the Standard Model, and why they are so small

light $\nu$ masses are $\leq 1eV$

$$m_\nu/m_e \leq 10^{-6}$$

of course,such ratios are found:

$$m_e/m_t \leq 3 10^{-6}$$

but the significant comparison in the Standard Model is

$$m_\nu/m_W \leq 10^{-11}$$

## Possible ways to introduce masses for the light neutrinos IN THE STANDARD MODEL:

**Don't want to introduce $\nu_R$**

*Such (heavy) triplet is not forbidden, but its v.expectation value must be <.03 doublet vev*

need to introduce at least one scalar complex triplet field: $\chi$

$$\lambda \bar{\Psi}^c_L \tau^a \Psi_L \chi^a$$

where

$$\Psi_L = \begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$$

**Don't want to introduce $\chi$**

need at least some $\nu_R$ - will be called N from now on

*Rem: in extended models, other solutions, eg: SUSY*

## $\nu$ masses with $\nu_R$ = **N** present

Again more options:

Simplest DIRAC mass term between $\nu_L$ and $\nu_R$ = **N**

$$\bar{\Psi}_L^i \lambda_{ij} N^j + h.c.$$

$i$ is the generation index, $\lambda$ are complex coefficients

OR

Only difficulty : the Yukawa coëfficients must be very small

Allow for MAJORANA mass term for the neutrino singlet N

$$1/2 \bar{N}_i^c M^{ij} N_j$$

# Get usual See-Saw mechanism

| | $\nu_{Li}$ | $\epsilon_{ik} N^{+}_{Rk}$ |
|---|---|---|
| $\epsilon_{il} \nu_{Ll}$ | $M_1$ | $m$ |
| $N^{+}_{Ri}$ | $m'$ | $M_2$ |

VIOLATE Lepton number by 2 units

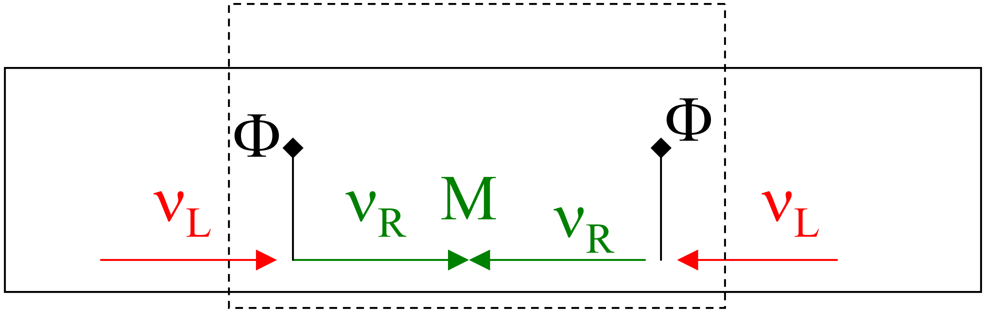
| | $\nu_{Li}$ | $\epsilon_{ik} N^+_{Rk}$ |
|---|---|---|
| $\epsilon_{il} \nu_{Ll}$ | $M_1$ | $m$ |
| $N^+_{Ri}$ | $m'$ | $M_2$ |

The diagonalisation leads to states;
For $M_1 = 0$ , and $m \ll M_2$
one gets the familiar See-Saw eigenstates and values

$$\lambda_1 \approx \nu_L - m/M \;\epsilon \cdot N^+_R \qquad |m_1| \approx m/M^2$$

$$\lambda_2 \approx N_R + m/M \;\epsilon \cdot \nu^+_L \qquad |m_2| \approx M$$

# See-saw mechanism = Poor Man's Triplet




Results in effective Majorana mass term for the light neutrino

$$\epsilon_{ij}\nu_i\nu_j \bullet \chi$$

Where the triplet is in fact simulated by 2 doublets, linked by a heavy particle, the right-handed Majorana neutrino

Thus, mixes high and low energy scales

$$m_\nu^{ab} \approx v^2/2 \sum \lambda^{ai}(\frac{1}{M})_{ij}\lambda^{\dagger jb}$$

The mass of the neutrinos comes both from some high-energy structure (the heavy Majorana terms) and from low-energy symmetry breaking

$$m_\nu^{ab} \approx v^2/2 \sum \lambda^{ai} (\frac{1}{M})_{ij} \lambda^{\dagger jb}$$

We will need to return to this formula in the next lecture, as we will see that a SIMILAR, but DIFFERENT parameter governs CP violation and Leptogenesis

$$\tilde{m}_1 = (\lambda^\dagger \lambda)_{11} v^2 / M_1$$

Nice feature: CP violation is already present in the complex couplings (total of 6 phases !)

SO(10) has furthermore many nice features, like having each family in a single representation, or an automatic cancellation of anomalies….

In fact, giving a Majorana mass to the SU(5) singlet N is precisely
the simplest way to break SO(10) intoSU(5) !

$$SU(5) \subset SO(10)$$

and the fermions come in nice representations

$$16 = \bar{5} \oplus 10 \oplus 1$$

where "1" is precisely $N_R$

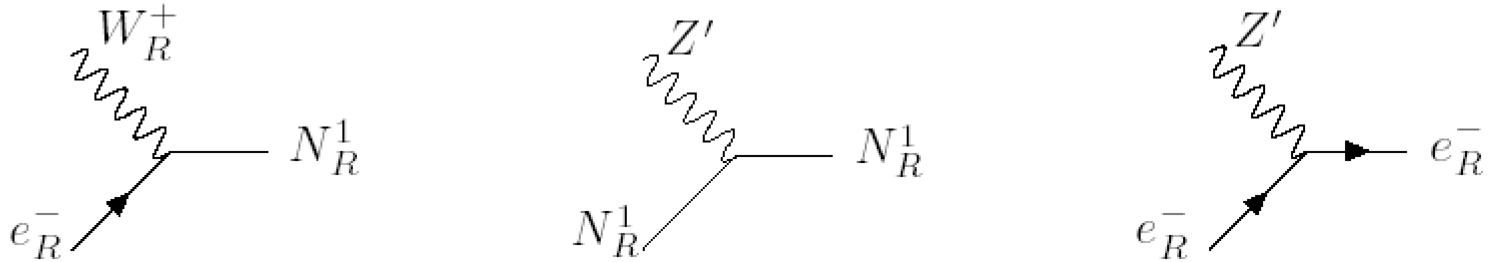
# A few more words about SO(10)…

In fact, the breaking of SO(10) into SU(5)

- breaks also the conservation of B-L  (usefull for leptogenesis)

- gives mass to extra gauge bosons associated to $SU(2)_R$

- the masses of WR and Z' are similar to M, the mass of the heavy Majorana fermions.



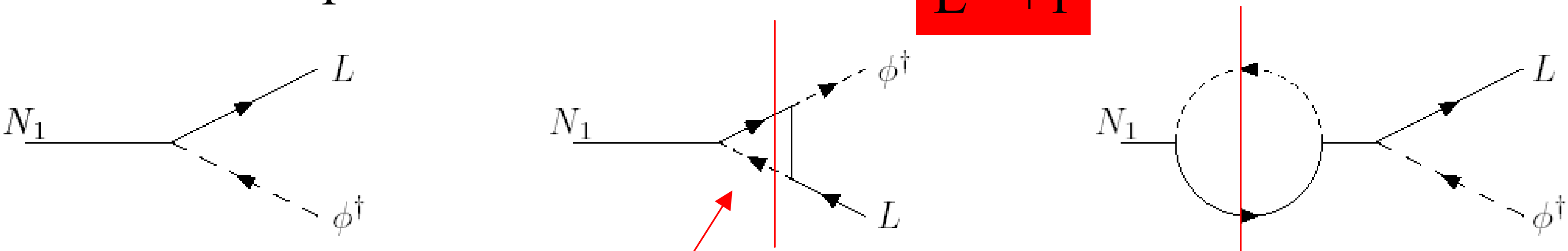

These extra bosons must not be forgotten, and change the conclusions

# How leptogenesis works….

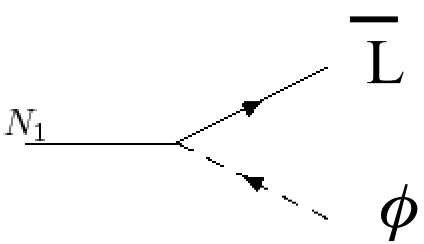
Assume that we have some population of heavy N particles…
*(either initial thermal population, or re-created after inflation) ; due to their heavy mass and relatively small coupling, N become easily relic particles.*

Generation of lepton number

L =+1




N can decay to Lepton L + $\phi^\dagger$ as above, or to the opposite channel $\overline{L}\phi$

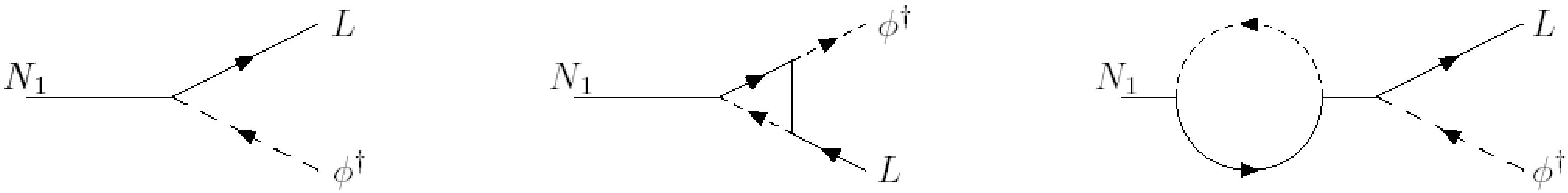



Interference term

L =-1

Possible unitarity cuts

$$\lambda_\nu = v M^{1/2} R \,\mathrm{diag}\,(m_1, m_2, m_3)\, U^\dagger, \quad M = \mathrm{diag}\,(M_1, M_2, M_3),$$




If the heavy Majorana particles N are very different in mass, it is sufficient to consider the lightest (any asymmetry created by the others would be washed out by the remaining ones.
– by convention it is called $N_1$

Define the asymmetry:

$$\varepsilon_i^\phi = \frac{\Gamma(N_i \to l\,\phi) - \Gamma(N_i \to \bar{l}\,\phi^\dagger)}{\Gamma(N_i \to l\,\phi) + \Gamma(N_i \to \bar{l}\,\phi^\dagger)},$$

Non-degenerate case: get approx.

$$\varepsilon_i^\phi = -\frac{3}{16\pi} \frac{1}{[\lambda_\nu \lambda_\nu^\dagger]_{ii}} \sum_{j \neq i} \mathrm{Im}\left( [\lambda_\nu \lambda_\nu^\dagger]_{ij}^2 \right) \frac{M_i}{M_j}.$$

Rem : if the N’s are degenerate, the « self- energy » may lead to large enhancement of this asymmetry… but it is difficult to handle consistently the initial composition of the plasma --

# Asymmetry for non-degenerate Ni– only i=1 is important

$$\varepsilon_i^{\phi} = -\frac{3}{16\pi}\frac{1}{[\lambda_\nu \lambda_\nu^\dagger]_{ii}} \sum_{j\neq i} \mathrm{Im}\left([\lambda_\nu\lambda_\nu^\dagger]^2_{ij}\right)\frac{M_i}{M_j}.$$

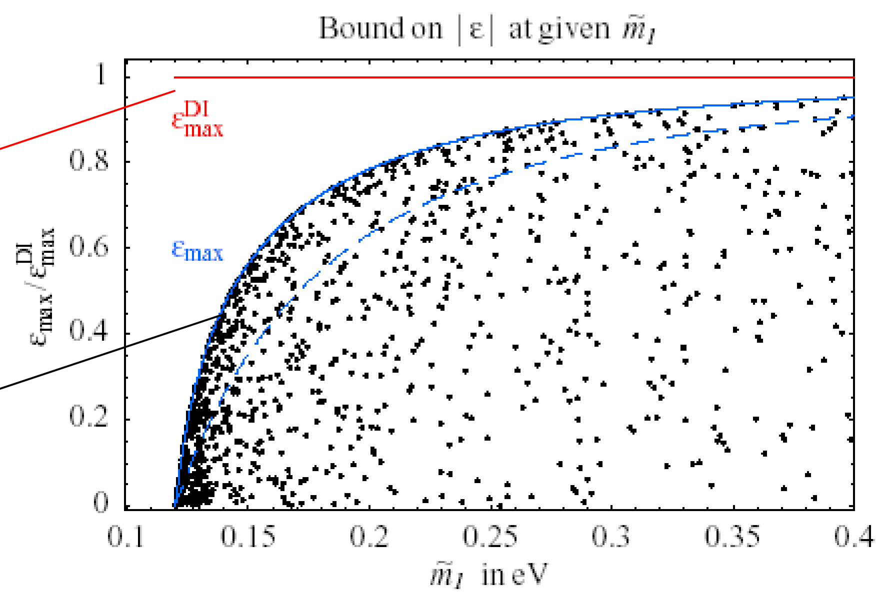
Involves 6 phases, and 3 M, while low energy only gives access to (1 osc + 2 maj ph

Look for bounds …

$$|\varepsilon_1^{\phi}| \leq \varepsilon_{DI}^{\phi} = \frac{3}{16\pi}\frac{M_1}{v^2}\left(m_3 - m_1\right).$$

$$|\varepsilon_1^{\phi}| \leq \frac{\varepsilon_{DI}^{\phi}}{2}\sqrt{1-\left[\frac{(1-a)\tilde{m}_1}{(m_3-m_1)}\right]^2}\sqrt{(1+a)^2-\left[\frac{(m_3+m_1)}{\tilde{m}_1}\right]^2}$$

$$a = 2\mathrm{Re}\left[\frac{m_1 m_3}{\tilde{m}_1^2}\right]^{1/3}\left[-1 - i\sqrt{\frac{(m_1^2+m_3^2+\tilde{m}_1^2)^3}{27 m_1^2 m_3^2 \tilde{m}_1^2}-1}\,\right]^{1/3}$$



# Other decay channels…

$$\varepsilon_i^{\phi} = \frac{\Gamma(N_i \to l\,\phi) - \Gamma(N_i \to \bar{l}\,\phi^{\dagger})}{\Gamma(N_i \to l\,\phi) + \Gamma(N_i \to \bar{l}\,\phi^{\dagger})},$$

Remember that the asymmetry parameter used this far is NOT the whole story…

$$\Gamma_{N_1}^{tot} = [\Gamma(N_1 \to l\,\phi) + \Gamma(N_1 \to \bar{l}\,\phi^{\dagger})]\,(1 + X)$$

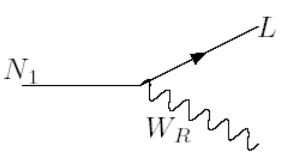
For instance

$$\epsilon_1 = \frac{\epsilon_1^0}{1 + X}$$

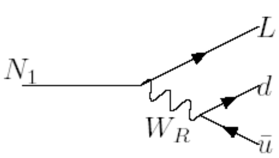
diluted CP asymmetry

Gauge-mediated decays are mostly CP conserving

$M_{W_R} < M_{N_1}$




$M_{W_R} > M_{N_1}$



Dilution factor $X$ ?

$$a_w = \frac{M_{W_R}^2}{M_1^2}$$

- $M_{W_R} < M_1 \quad \Rightarrow \quad$ 2-body decay

  $\Rightarrow$ $X$ Large $\sim 10^4 - 10^5$

  $\Rightarrow$ too much dilution

  $\Big\}$ ×

- $M_{W_R} > M_1 \quad \Rightarrow \quad$ 3-body decay

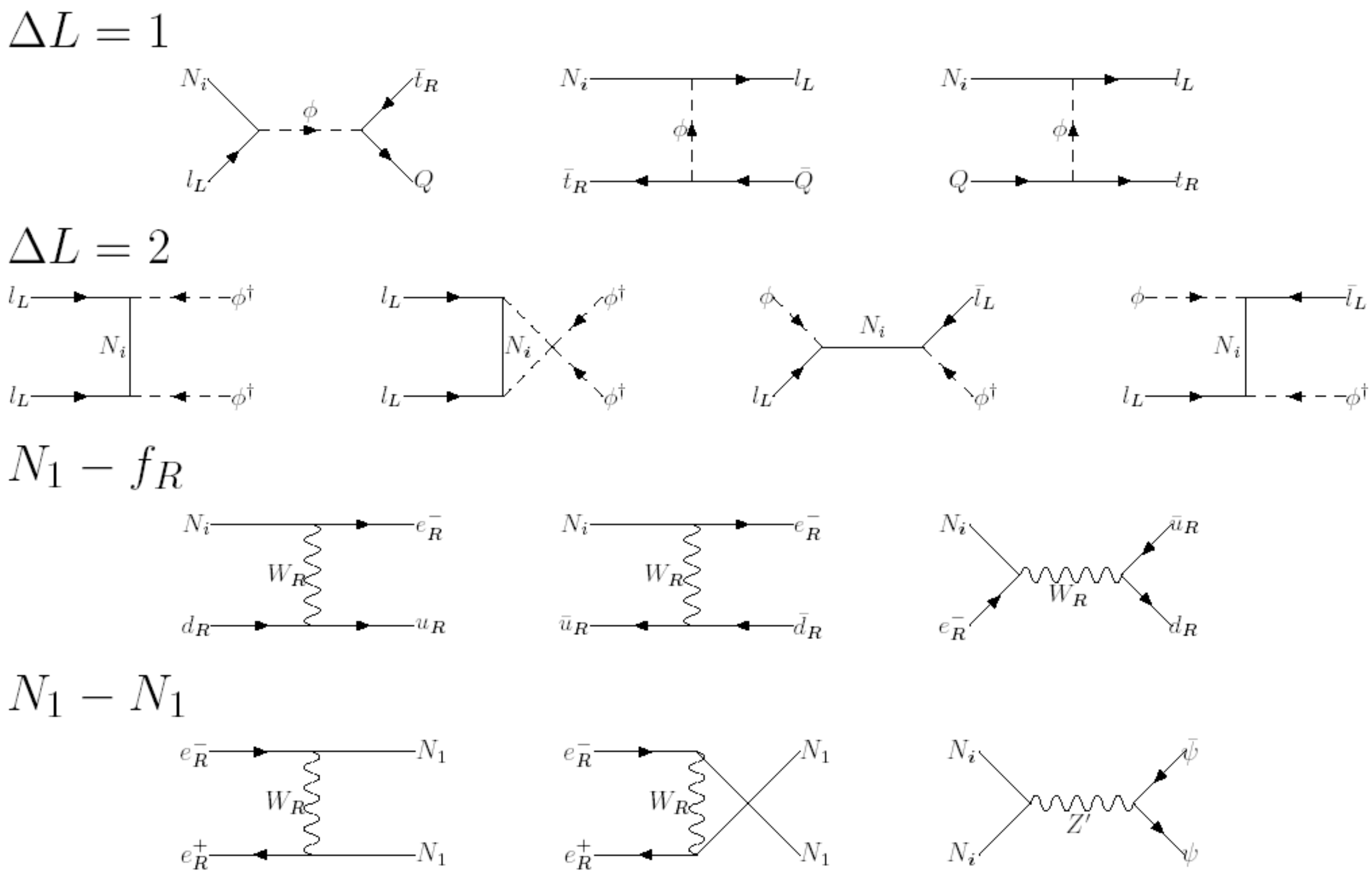
  $\Rightarrow \; X = \frac{3g^4v^2}{2^7\pi^2} \frac{1}{\tilde{m}_1 M_1 a_w^2}$

  $\Rightarrow \; a_w \sim 10 \Rightarrow X \sim 10$

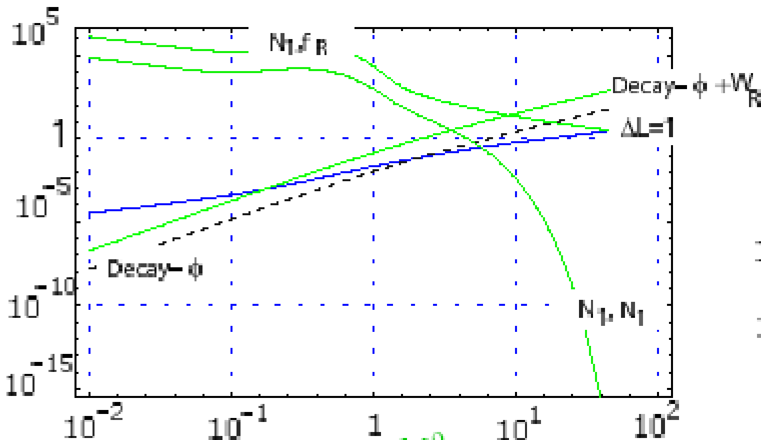
  $\Big\}$ √

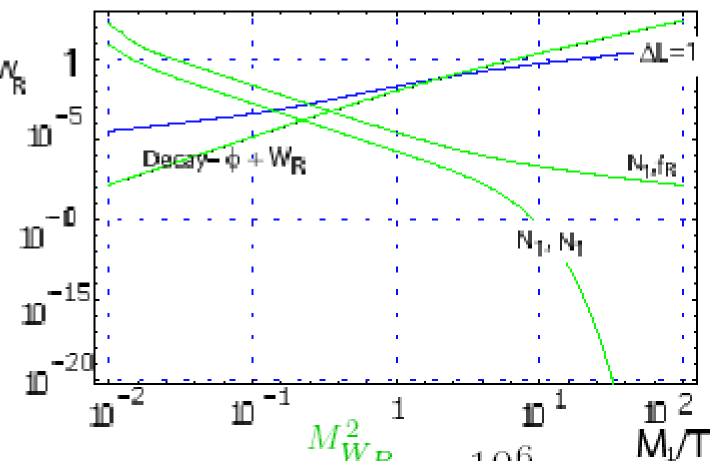
In fact, the presence of WR will prove beneficial in some cases (re-heating after inflation )

# Diffusion equations….also contribute to the wash-out of lepton number…



(Reaction Rate/ Expansion Rate) should be < 1:




$a_w = \frac{M^2_{W_R}}{M^2_1} = 10^2$ $\qquad$ $a_w = \frac{M^2_{W_R}}{M^2_1} = 10^6$

$\tilde{m}_1 = 10^{-5} eV, M_1 = 10^{10} GeV$

All these effects are incorporated into the « efficiency »

$$n_b/n_\gamma \propto \epsilon_1 Y^{eq}_{N_1}(0)\eta_{\mathsf{eff}}$$

L violation

Initial abundance

efficiency

# Initial conditions:

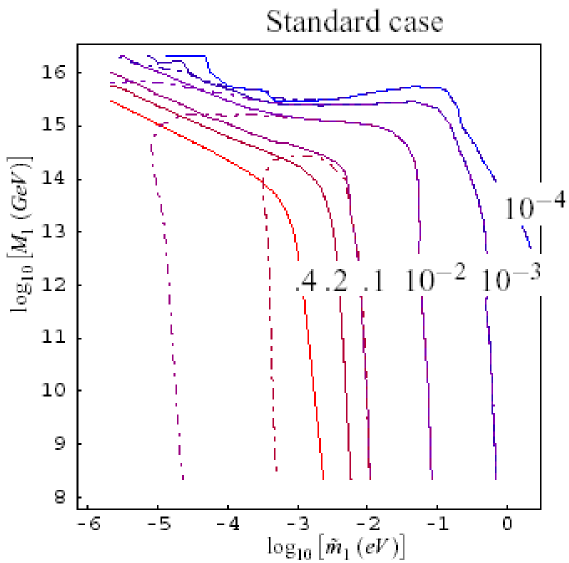
Cf previous study:
assume scalar field
produces asym. via virtual
Majoranas
→ simpler formulation
of initial state for degenerate N

- Thermal leptogenesis :
  high- temperature N distribution

- Inflation followed by re-heating
  - Various scenarios depending on inflation scheme:
    - Inflation attributed to scalar field (inflaton,…) which may couple only to light modes, N must be re-created after inflation
    - New developments:
      - inflation field linked to dark matter
      - Might even have inflation field preferably coupled to heavy Majorana …

# Efficiencies

## $W_R$ neglected

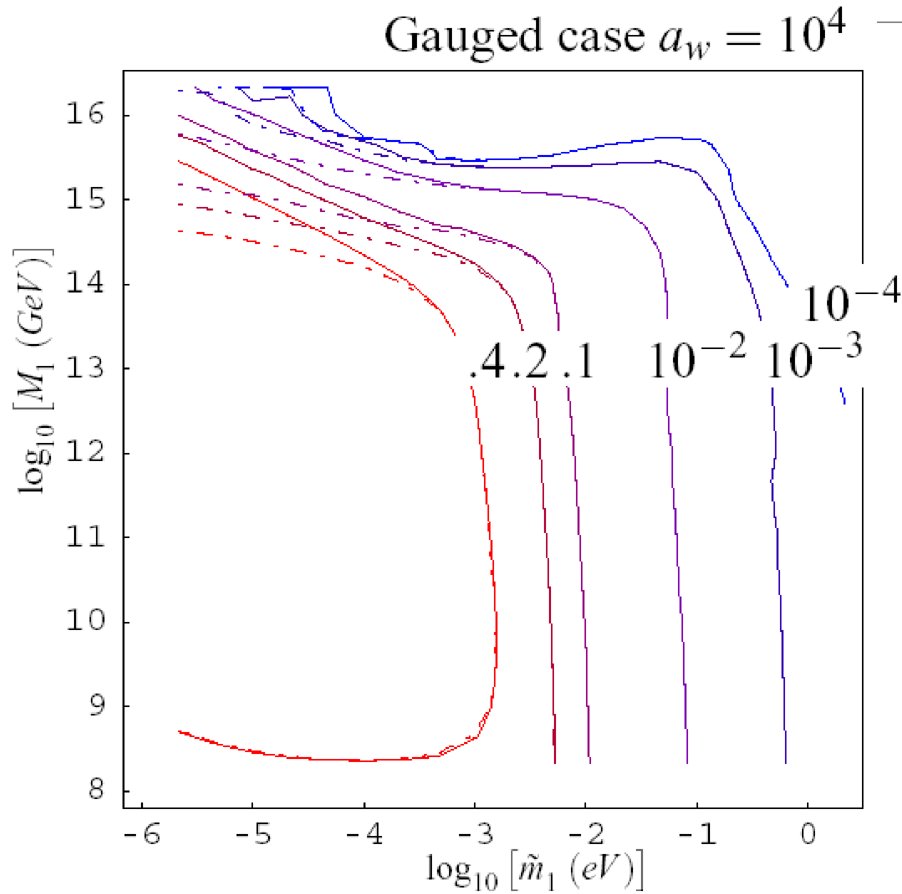



$$Y_{N_1}^{init.} = Y_{N_1}^{eq.}$$

$$Y_{N_1}^{init.} = 0$$

$$a_w = \frac{M_{W_R}^2}{M_1^2}$$

## $M(W_R) = 100\ M_N$




$$a_W = \frac{M_{W_R}^2}{M_1^2}$$

# Also include Leptonic to Baryonic number conversion at the electroweak phase transition.

Initial situation :

$$B_i = 0 \; L_i = L_0 \rightarrow (B-L)_i = -L_0 = -(B+L)_i$$

If the transition is complete, $B+L$ is completely suppressed, while (B-L) is conserved

$$(B+L)_f = 0 \; (B-L)_f = -L_0$$

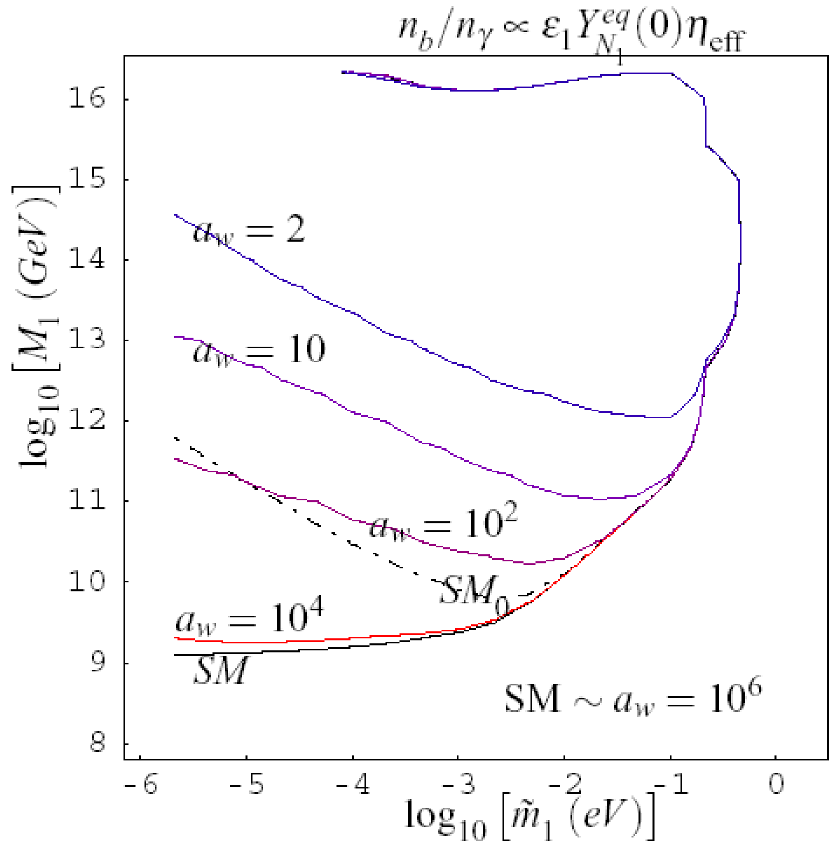
thus

$$B_f = -1/2 \quad L_0$$

(much) more elaborate calculations claim:

$$B_f = -28/79 \; L_0$$

# Baryon density




Allowed contours in $M_1 - \tilde{m}_1$ plane,

solid line = thermal Majorana initial population

dashed line = Majorana population rebuilt after reheating

$$a_W = \frac{M^2_{W_R}}{M^2_1}$$

# Conclusions : Leptogenesis

• Valid scheme, simple processes;

  •Weakest point may remain L to B conversion at the Electroweak transition, but less critical than other schemes (only assumes completion of transition close to equilibrium)

• Quite some freedom left – 6 phases at high energy, while only 3 (difficult to observe) at low energy

  • 1 phase observable (?) in oscillations,

  • 1 combination of remaining 2 phases and masses plays in neutrinoless double beta decay

  • Full comparison with observed light neutrino masses depends on explicit mass model

• Must include realistic high energy scheme, not just Massive Neutrinos (for instance, $W_R$ ..)