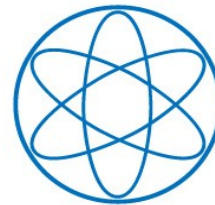


Leptogenesis

Alejandro Ibarra

Technische Universität München



Warsaw
February 2010

Outline

- Evidence for a baryon asymmetry
- Sakharov conditions
- GUT baryogenesis
- Sphalerons
- Neutrino masses and its origin
- Leptogenesis in three steps

Evidence for a baryon asymmetry

In the Universe there seems to be much more matter than antimatter.

Obviously, there is not much antimatter around us. However, we know that it exists:

It is produced in particle physics laboratories.



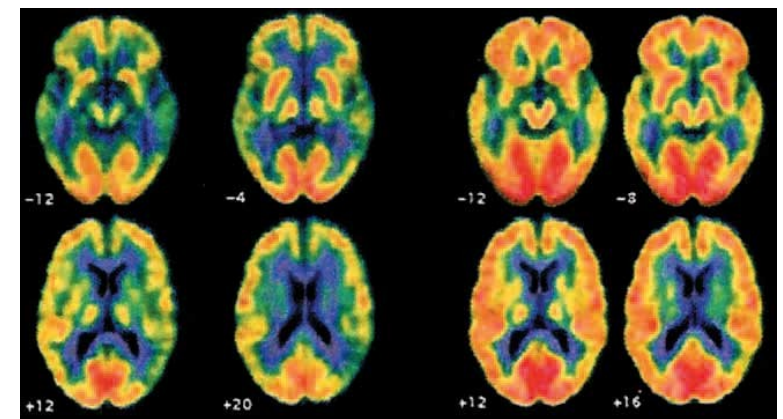
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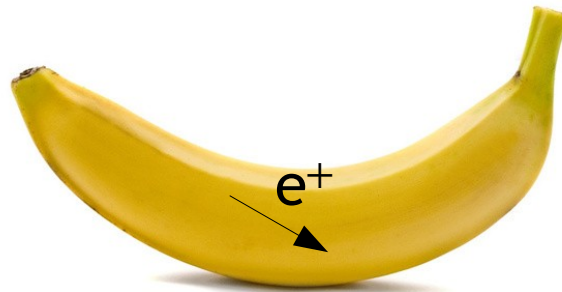
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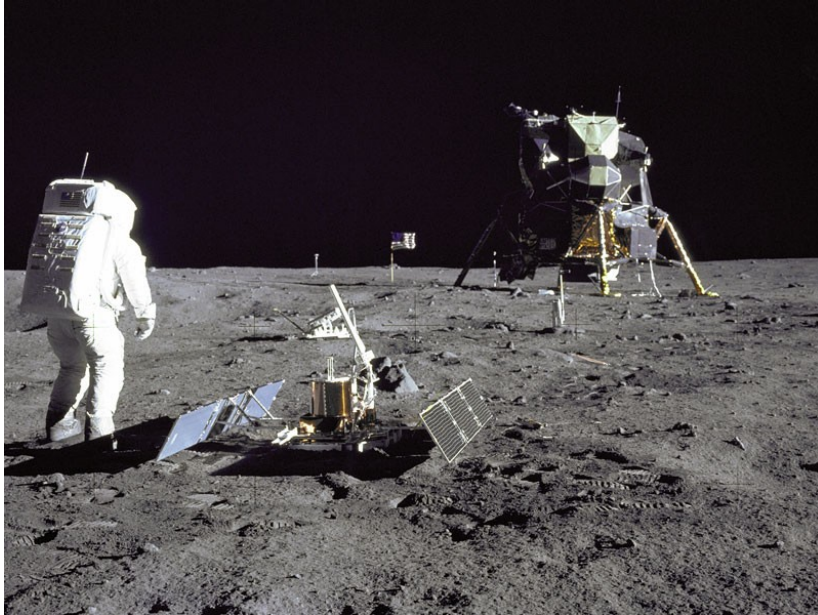
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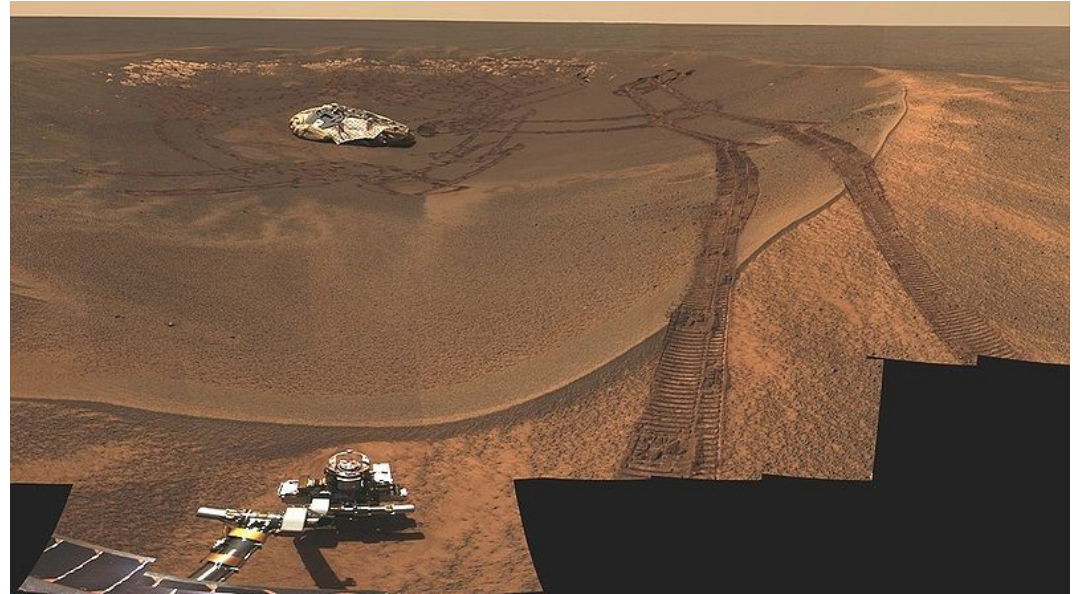


One positron every 75 minutes

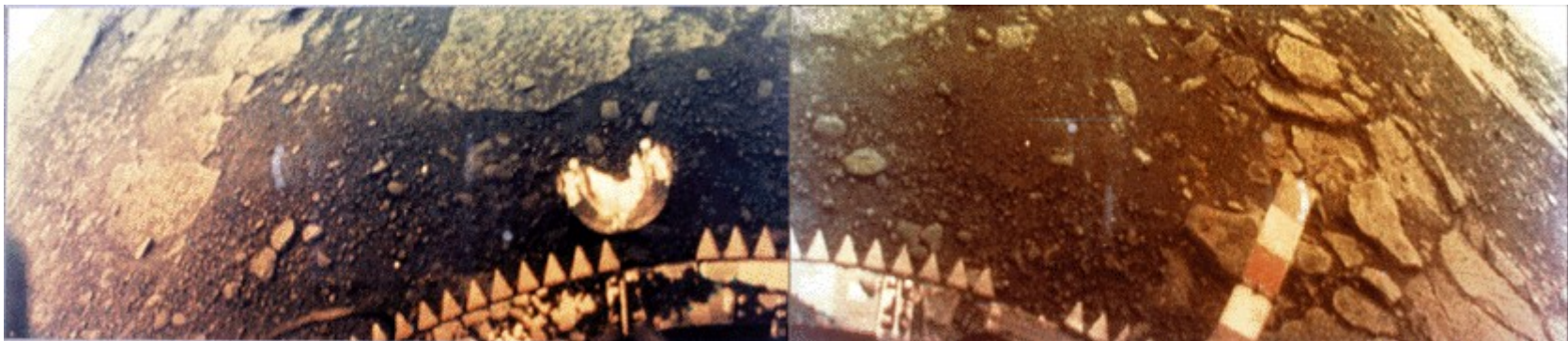
The bodies of the solar system are also composed almost entirely by matter and not by antimatter



Apollo 11

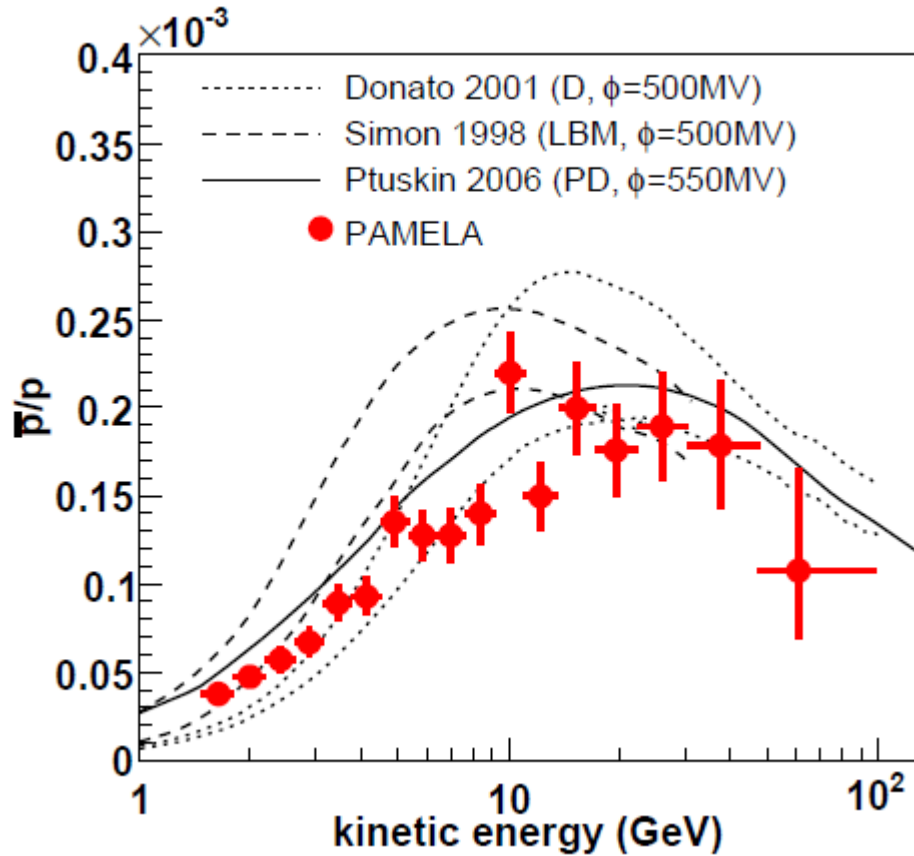


Mars Exploration Rover



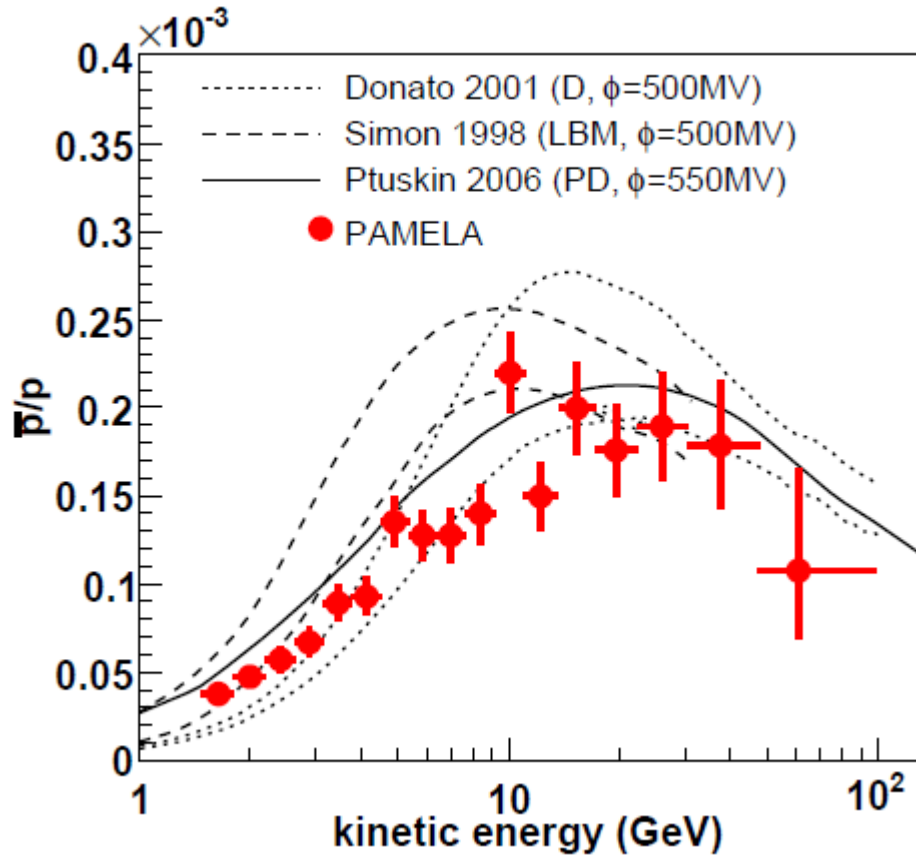
Venera 13

However, there is antimatter in the interplanetary and in the interstellar medium of our Galaxy

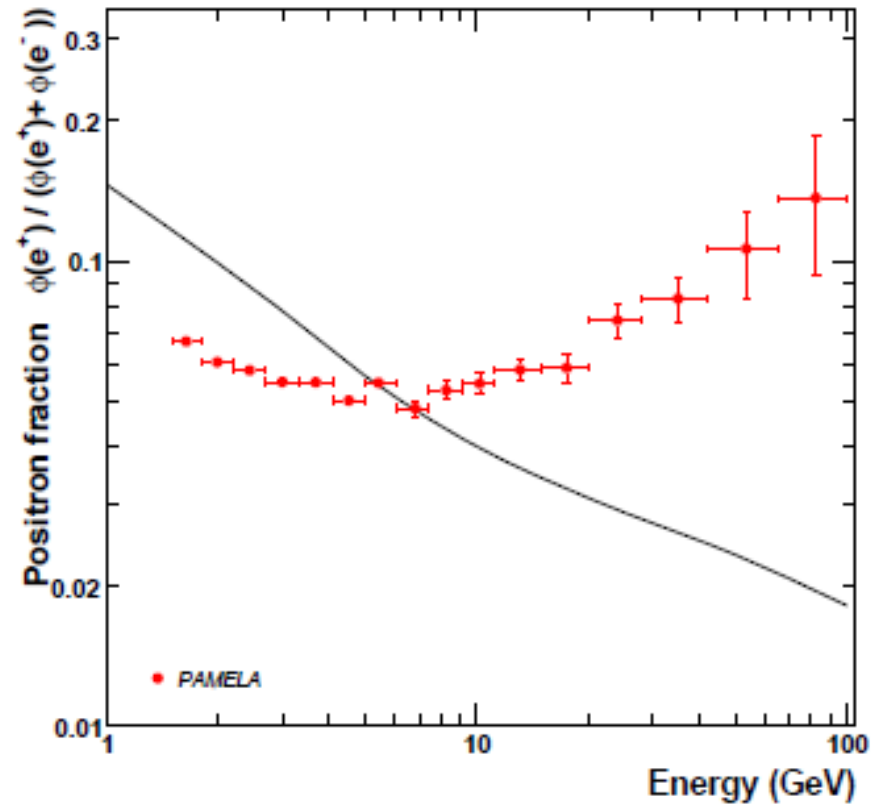


Antiproton-to-proton ratio

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Antiproton-to-proton ratio

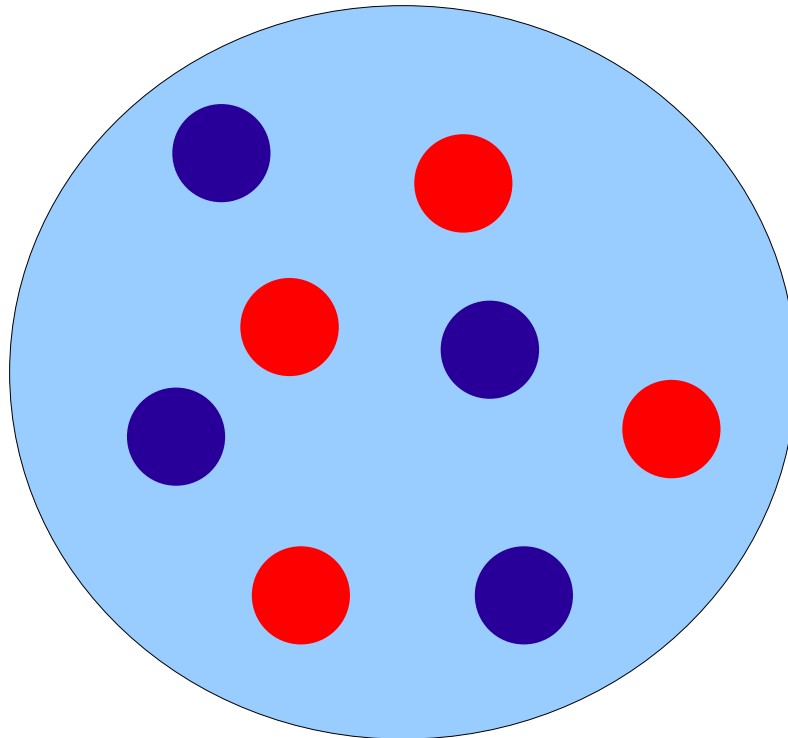


Positron fraction

At larger scales there are also indications that there is more matter than antimatter. Many clusters of galaxies contain gas. If there were in the same cluster galaxies and antigalaxies, we would see a strong γ -ray emission from annihilations.

Observations indicate that clumps of matter are as large as 10^{12} – $10^{14} M_{\odot}$. Beyond that, we don't know...

Could the Universe be baryon symmetric?



NO!!

The nucleon-antinucleon annihilation cross section is rather large

$$\langle \sigma_A |v| \rangle \sim m_\pi^2 \quad \text{with } m_\pi = 135 \text{ MeV.}$$

Annihilations of nucleons and antinucleons are in thermal equilibrium until very low temperatures, $T \sim 22 \text{ MeV}$.

Then, the relic abundance of antinucleons (the number of antinucleons that survive annihilations)

$$\frac{n_B}{s} = \frac{n_{\bar{B}}}{s} \simeq 7 \times 10^{-20}$$

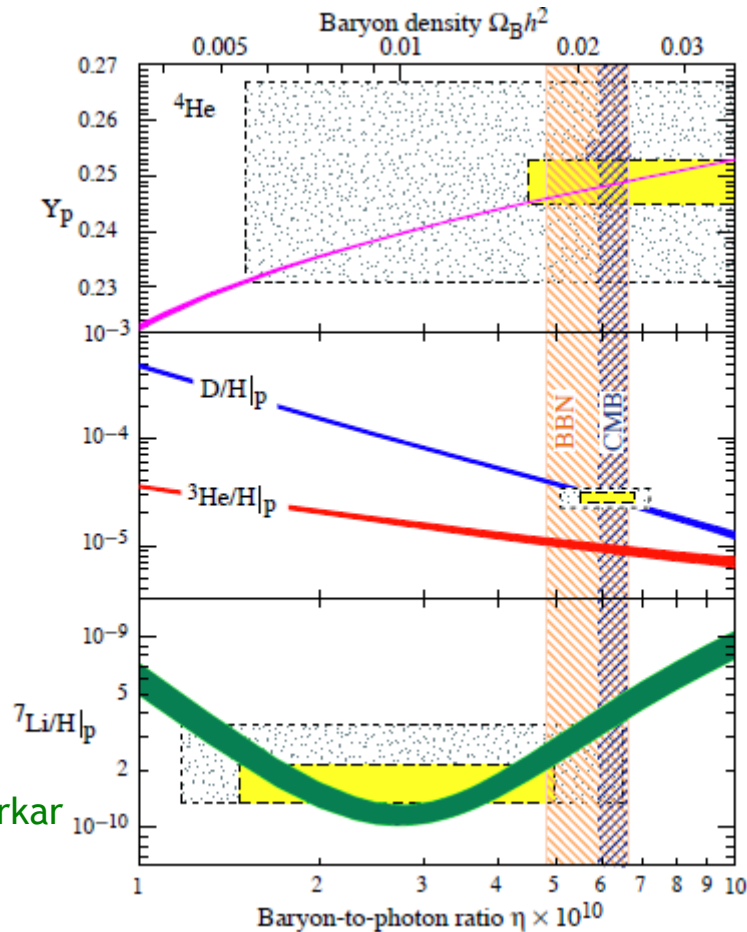
Some mechanism at temperatures larger than 38 MeV must have existed, separating nucleons and antinucleons. But which?

The most natural solution: the Universe is *not* baryon symmetric

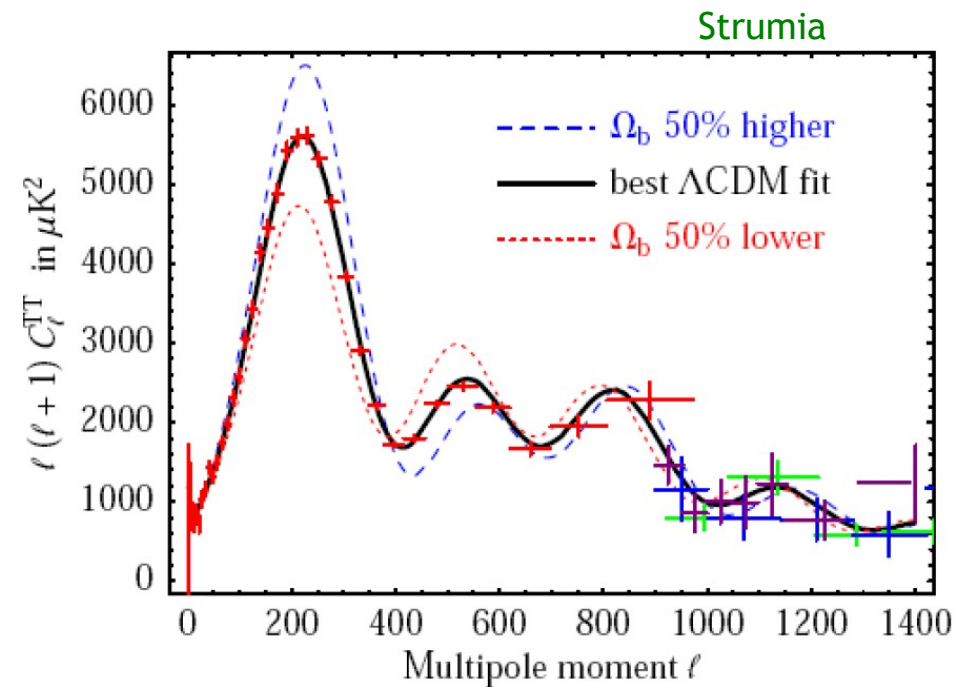
Assumption: in the very early Universe there was already a tiny excess of baryons over antibaryons. These annihilated leaving a small excess of baryons.

How many baryons?

The abundances of the primordial elements and the height of the peaks of the CMB power spectrum depend on the ratio of baryons-to-photons.



Fields, Sarkar



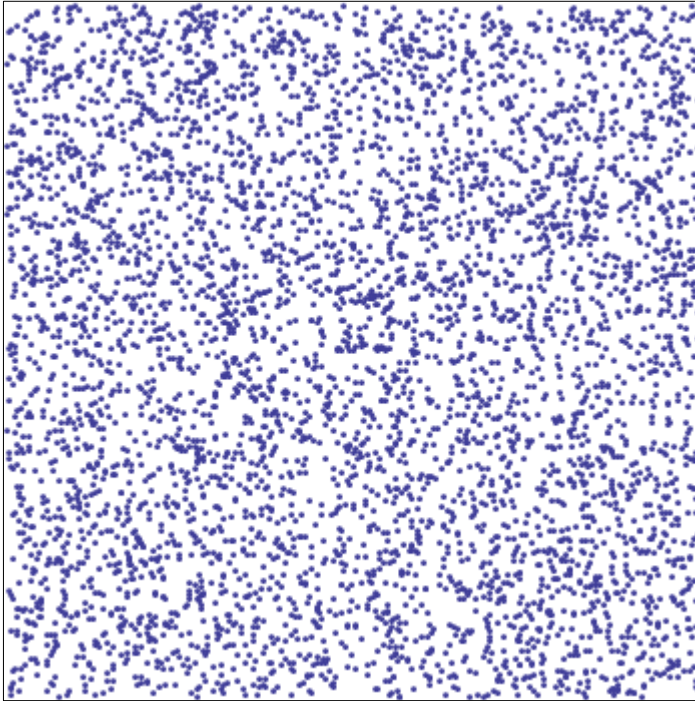
$$\eta_B = (6.11 \pm 0.19) \times 10^{-10}$$

Assumption: in the very early Universe there was already a tiny excess of baryons over antibaryons. These annihilated leaving a small excess of baryons.

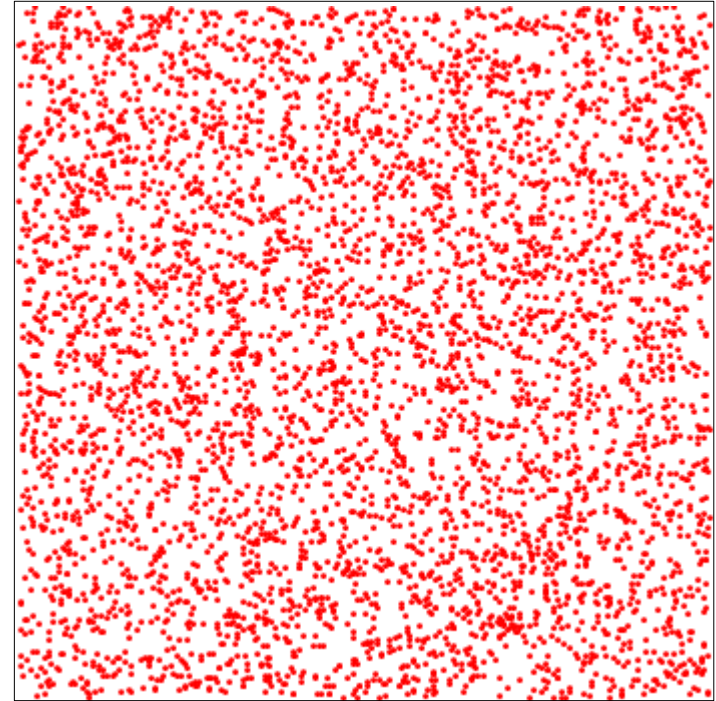
But this is a very small number!!

$$\eta_B = (6.11 \pm 0.19) \times 10^{-10}$$

$$N_B = 30\,000\,000\,001$$



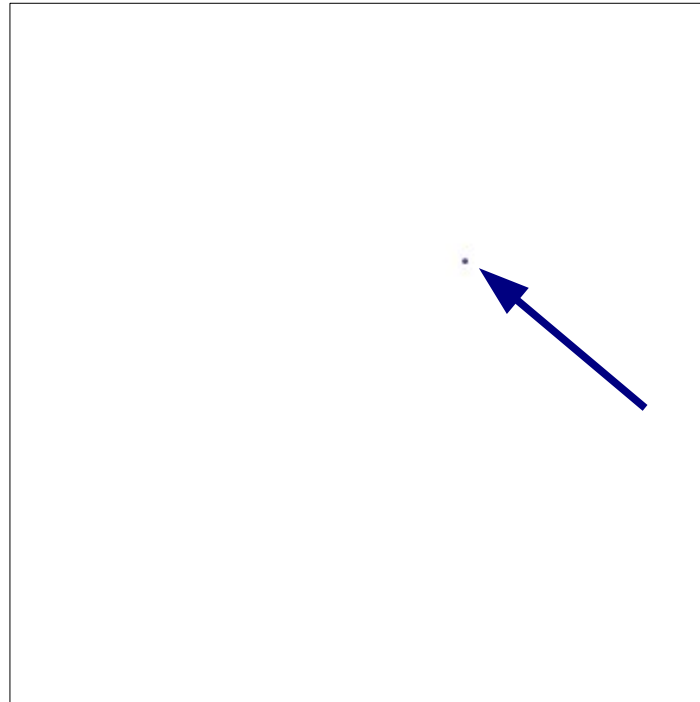
$$N_{\bar{B}} = 30\,000\,000\,000$$



$$t \lesssim 10^{-6} \text{ s}$$

$$N_B=1 \quad N_{\bar{B}}=0$$

now



Now the question is: why was there in the very early Universe an excess of baryons

Baryogenesis

Dynamical generation of a BAU: Sakharov conditions

The baryon asymmetry can be dynamically generated if the following three conditions are satisfied:

- Baryon number violation

If baryon asymmetry is conserved, no baryon number can be dynamically generated. There must exist $X^{B=0} \rightarrow Y^{B=0} + B^{B \neq 0}$

- C and CP violation

If C or CP are conserved, $\Gamma(X \rightarrow Y+B) = \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B}) \Rightarrow$ No net effect

- Departure from thermal equilibrium

In thermal equilibrium, the production rate of baryons is equal to the destruction rate: $\Gamma(X \rightarrow Y+B) = \Gamma(Y+B \rightarrow X) \Rightarrow$ No net effect.

These three conditions are fulfilled in the simplest grand unified models.

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PHYSICAL REVIEW LETTERS

31 JULY 1978

Unified Gauge Theories and the Baryon Number of the Universe

Motohiko Yoshimura

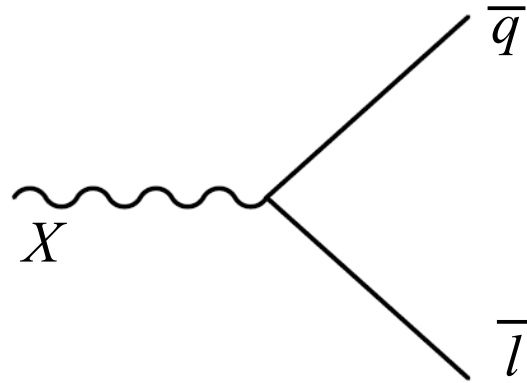
Department of Physics, Tohoku University, Sendai 980, Japan

(Received 27 April 1978)

I suggest that the dominance of matter over antimatter in the present universe is a consequence of baryon-number-nonconserving reactions in the very early fireball. Unified gauge theories of weak, electromagnetic, and strong interactions provide a basis for such a conjecture and a computation in specific SU(5) models gives a small ratio of baryon- to photon-number density in rough agreement with observation.

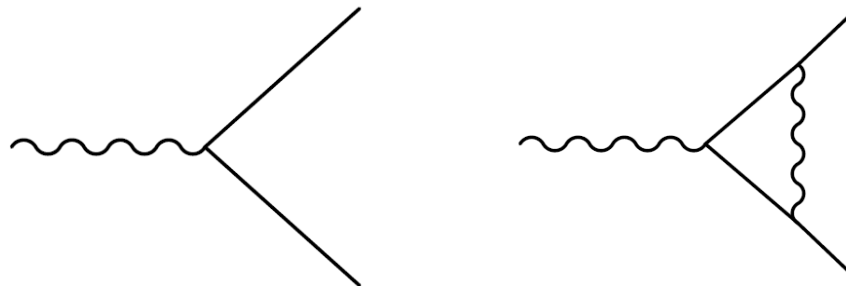
These three conditions are fulfilled in the simplest grand unified models.

In SU(5) models, quarks and leptons are in the same representation



This scenario could generate dynamically a baryon asymmetry:

- Baryon number violation
- C and CP violation. At one loop level



- Departure from thermal equilibrium, due to the expansion of the Universe

process	branching ratio	B
$X \rightarrow q q$	r	$2/3$
$X \rightarrow \bar{q} \bar{l}$	$1 - r$	$-1/3$
$\bar{X} \rightarrow \bar{q} \bar{q}$	\bar{r}	$-2/3$
$\bar{X} \rightarrow q l$	$1 - \bar{r}$	$1/3$

If C and CP are violated, $\Gamma(X \rightarrow q q) \neq \Gamma(\bar{X} \rightarrow \bar{q} \bar{q}) \implies r \neq \bar{r}$

Mean net baryon number produced in the decay of X

$$B_X = (2/3)r + (-1/3)(1 - r)$$

Mean net antibaryon number produced in the decay of X

$$B_{\bar{X}} = (-2/3)\bar{r} + (1/3)(1 - \bar{r})$$

The resulting baryon asymmetry is:

$$B = \gamma_*(B_X - B_{\bar{X}}) = \gamma_*(r - \bar{r})$$

Very attractive!!

Very attractive!!

But ruled out...

A new player in the baryogenesis game: sphalerons

In the Standard Model, lepton and baryon number conservation are accidental symmetries. However, it was discovered by 't Hooft that non-perturbative effects can violate B and L: **instantons**. Furthermore, the violation of B and L induced by instantons is very peculiar...

Baryon and lepton number are defined as:

$$B = \int d^3x J_0^B(x), \quad L = \int d^3x J_0^L(x)$$

where the currents associated to the B and L are

$$J_\mu^B = \frac{1}{3} \sum_i \left(\bar{q}_{L_i} \gamma_\mu q_{L_i} - \bar{u}_{L_i}^c \gamma_\mu u_{L_i}^c - \bar{d}_{L_i}^c \gamma_\mu d_{L_i}^c \right)$$

$$J_\mu^L = \sum_i \left(\bar{\ell}_{L_i} \gamma_\mu \ell_{L_i} - \bar{e}_{L_i}^c \gamma_\mu e_{L_i}^c \right) .$$

At the classical level, B and L are preserved:

$$\partial^\mu J_\mu^B = 0, \quad \partial^\mu J_\mu^L = 0$$

For these two currents, the Adler-Bell-Jackiw triangular anomalies do not cancel. **B and L are anomalous at the quantum level**

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2} \left(g^2 W_{\mu\nu}^p \widetilde{W}^{p\mu\nu} - g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu} \right)$$

Where $W_{\mu\nu}$ and $B_{\mu\nu}$ are the $SU(2)_L$ and $U(1)_Y$ field strengths:

$$W_{\mu\nu}^p = \partial_\mu W_\nu^p - \partial_\nu W_\mu^p$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

and N_F = number of fermion generations

As a consequence, B and L are violated at the quantum level. However, B-L is preserved:

$$\partial^\mu (J_\mu^B - J_\mu^L) = 0$$

The orthogonal combination, B+L, is of course non preserved at the quantum level,

$$\partial^\mu (J_\mu^B + J_\mu^L) = 2N_F \partial_\mu K^\mu$$

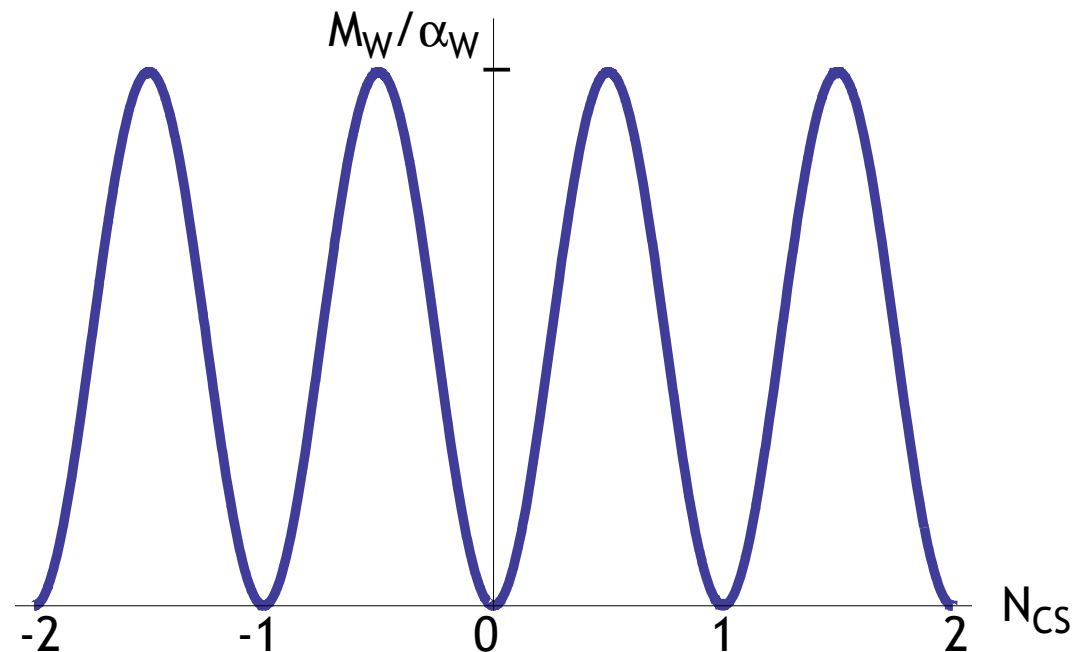
$$K^\mu = -\frac{g^2}{32\pi^2} 2\epsilon^{\mu\nu\rho\sigma} W_\nu^p (\partial_\rho W_\sigma^p + \frac{g}{3} \epsilon^{pqr} W_\rho^q W_\sigma^r) + \frac{g'^2}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} B_\nu B_{\rho\sigma}$$

The violation of B+L is due to the non-trivial structure of non-abelian gauge theories. The change in B and L are related to the change in the topological charge (the Chern-Simons number):

$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3x \partial^\mu J_\mu^B = N_f [N_{cs}(t_f) - N_{cs}(t_i)]$$

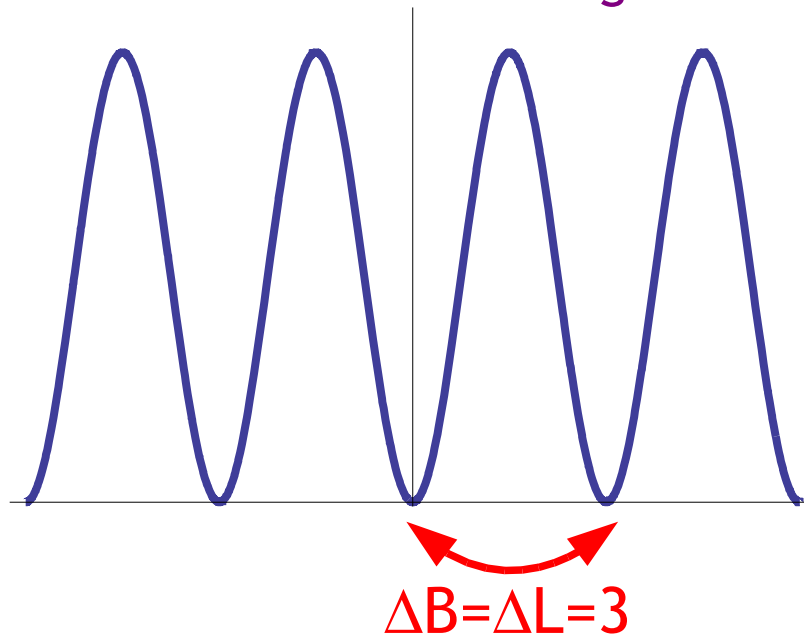
$$N_{cs}(t) = \frac{g^3}{96\pi^2} \int d^3x \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$$

There is an infinite number of degenerate vacuum states with different Chern-Simons numbers (different baryon numbers) separated by a barrier



$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3x \partial^\mu J_\mu^B = N_f |N_{cs}(t_f) - N_{cs}(t_i)|$$

3 generations $\Delta N_{cs} = \pm 1, \pm 2 \dots$

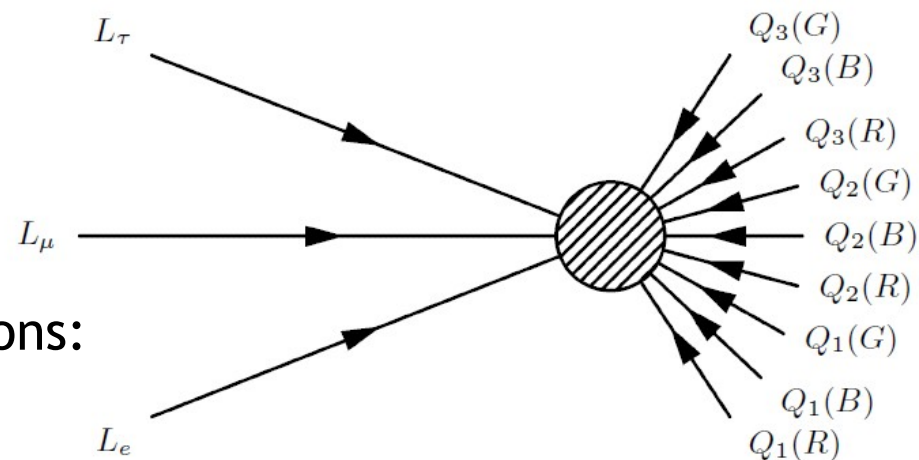


Transitions from one vacuum to another vacuum are possible, with a change of ΔB and ΔL by three units.

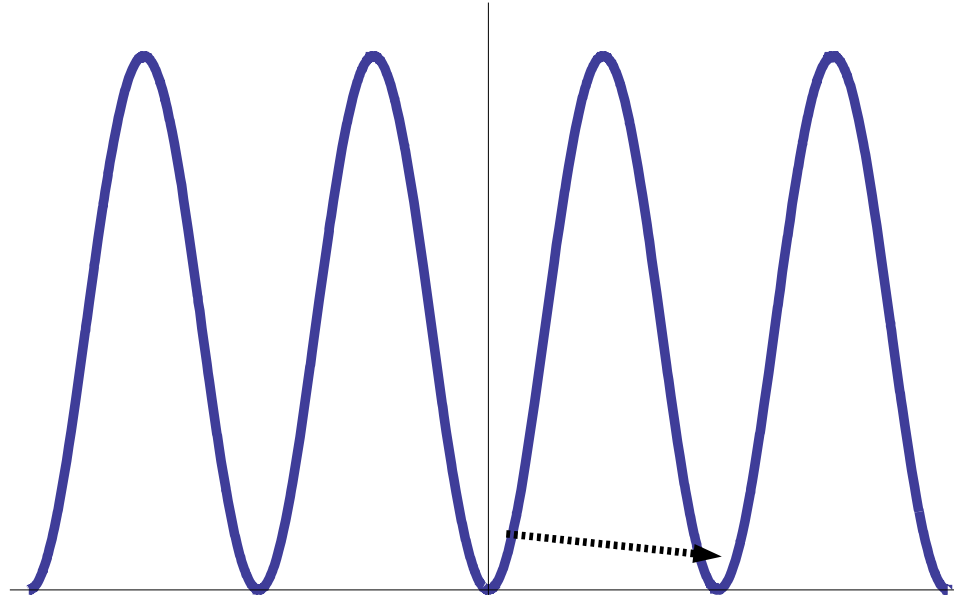
There is an effective operator

$$\mathcal{O}_{B+L} = \prod_{i=1,2,3} (q_{L_i} q_{L_i} q_{L_i} \ell_{L_i})$$

which gives interactions involving 12 fermions:

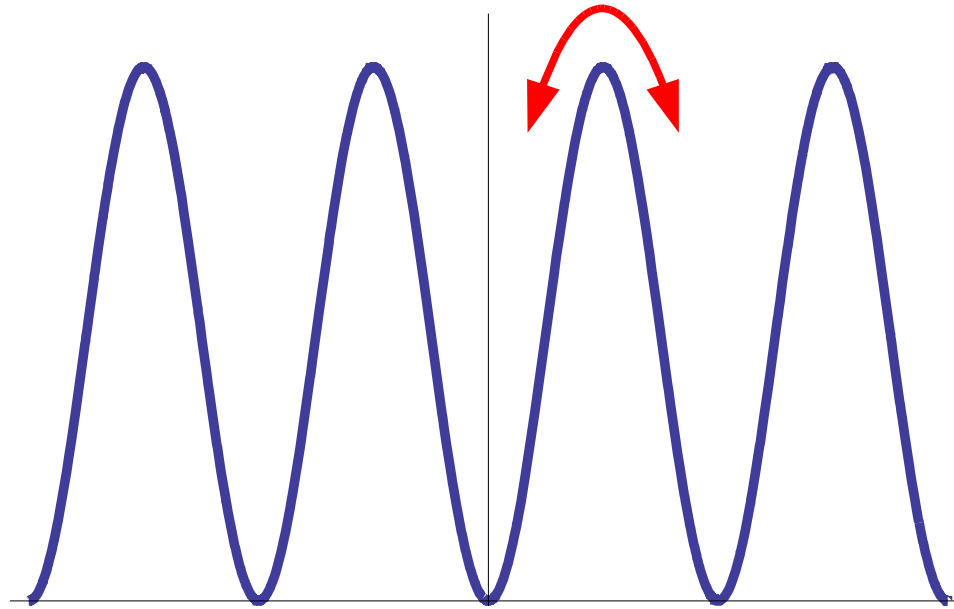


At $T=0$, transitions among vacua by tunnelling



$$\Gamma \sim e^{-S_{int}} = e^{-4\pi/\alpha} = \mathcal{O}(10^{-165})$$

At high temperatures, the barrier can be crossed



$$T < T_{EW} \quad \frac{\Gamma_{B+L}}{V} = k \frac{M_W^7}{(\alpha T)^3} e^{-\beta E_{ph}(T)} \sim e^{-\frac{M_W}{\alpha k T}}$$

$$T > T_{EW} \quad \frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln \alpha^{-1} T^4$$

At large temperatures, transitions violating B+L (and preserving B-L) occur very often.

SPHALERONS

ON ANOMALOUS ELECTROWEAK BARYON-NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE

V.A. KUZMIN, V.A. RUBAKOV

Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow, USSR

and

M.E. SHAPOSHNIKOV¹

International Centre for Theoretical Physics, Trieste, Italy

Received 8 February 1985

We estimate the rate of the anomalous electroweak baryon-number non-conserving processes in the cosmic plasma and find that it exceeds the expansion rate of the universe at $T > (\text{a few}) \times 10^2$ GeV. We study whether these processes wash out the baryon asymmetry of the universe (BAU) generated at some earlier state (say, at GUT temperatures). We also discuss the possibility of BAU generation by the electroweak processes themselves and find that this does not take place if the electroweak phase transition is of second order. No definite conclusion is made for the strongly first-order phase transition. We point out that the BAU might be attributed to the anomalous decays of heavy ($M_F \gtrsim M_W/\alpha_W$) fermions if these decays are unsuppressed.

than M_W . For instance, at $\lambda = g_W^2$ one finds $B = 2.1$, $T_c \approx 340$ GeV [19] and $T^* \approx 0.6 T_c \approx 200$ GeV.

There is one point which has been missed in the above discussion. Namely, in the pure Yang–Mills theory the “magnetic” gauge bosons seem to acquire the magnetic mass M_{magn} of the order $\alpha_W T$ [19,14]. [The electric field of the configuration (3) is zero, so we need not discuss the electric mass.] For our results to be valid, the magnetic mass should be much less than $M_W(T)$. At $T = T^*$ this is indeed the case, $M_{\text{magn}}/M_W(T^*) \approx 2B/\ln(M_{\text{Pl}}/T^*) \ll 1$. At higher temperatures, in particular at $T > T_c$, the magnetic mass cannot be neglected. However, the weight of the configurations of the form (3a) are believed to be unsuppressed at these temperatures [14], so that the fermion-number non-conserving rate is large, although it cannot be calculated within the semiclassical approach utilized here.

Turning to the possibility of the first order electroweak phase transition, we note that the estimate (6) remains valid for the stage *after* the phase transition. On the other hand, the above discussion implies that before the phase transition, when $\langle \varphi \rangle = 0$, the fermion-number non-conserving processes are rapid even at low temperature (which is possible because of the super-

$$B(T_c) = \frac{1}{2} (B_{\text{in}} - L_{\text{in}}) + \frac{1}{2} (B_{\text{in}} + L_{\text{in}}) e^{-A},$$

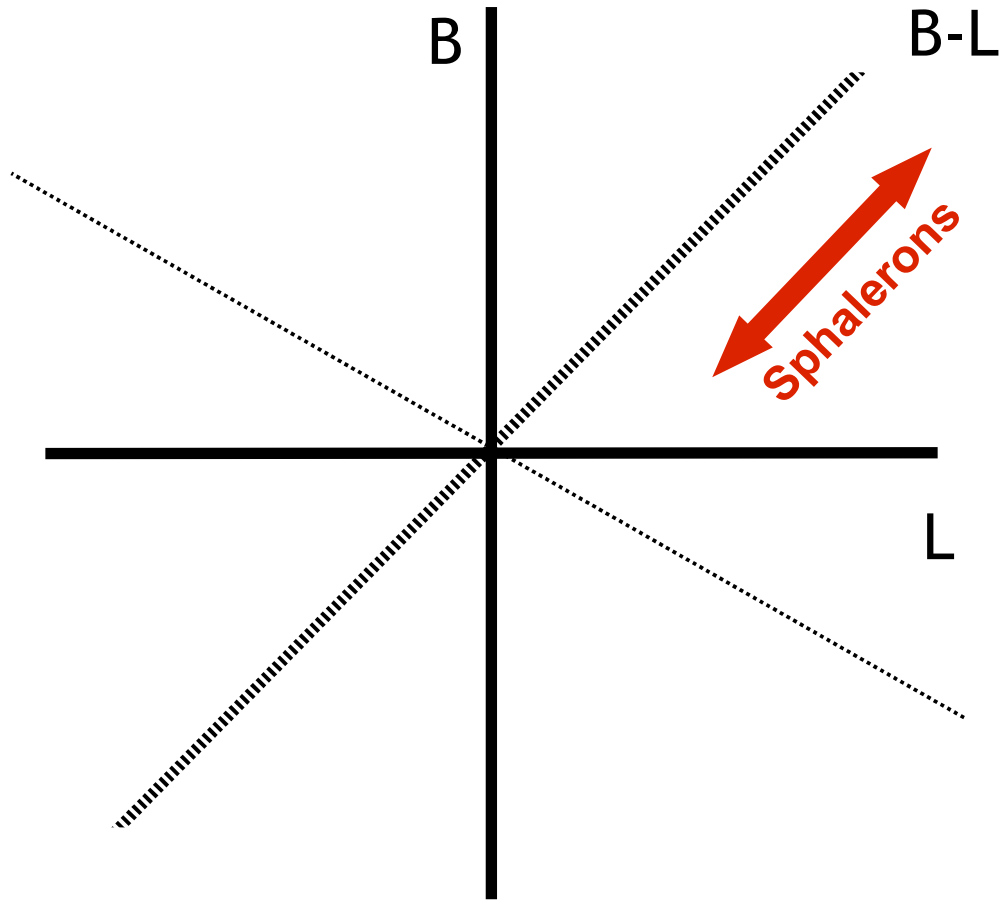
$$A \sim \beta M_{\text{Pl}}/T_c \sqrt{N_{\text{eff}}} \sim \beta \times 10^{15} \quad (9)$$

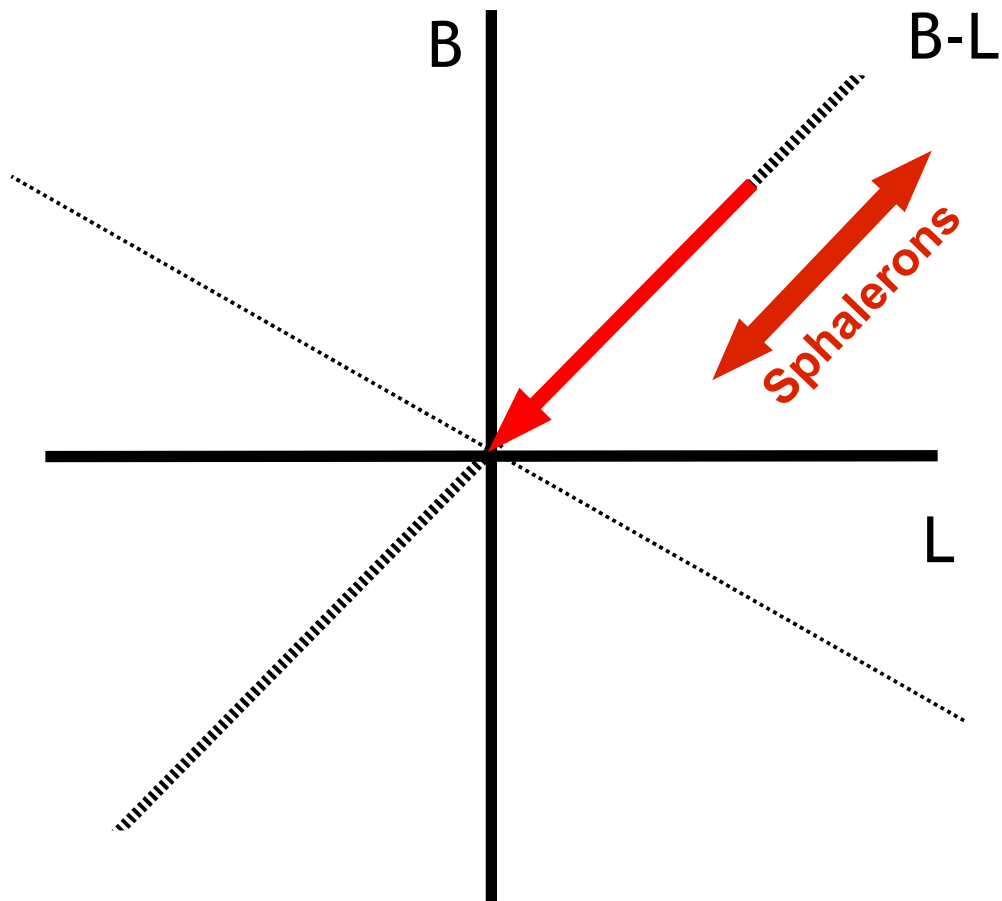
Clearly, $B(T_c) = \frac{1}{2} (B_{\text{in}} - L_{\text{in}})$ with great precision;

this means that if the primordial baryon asymmetry is generated by the $(B - L)$ conserving processes (which is the case in the minimal SU(5) model [22]), it is completely washed out by the moment of the electroweak phase transition.

Can the additional BAU be generated *after* this phase transition? In spite of the fact that the necessary conditions for the BAU generation are satisfied at $T = T^*$, the answer is negative for the following reason. As shown in ref. [23], the most effective BAU generation takes place at the time when the kinetic equilibrium between the relevant particles is violated (and not just at the time when the processes with $\Delta B \neq 0$ come out of the equilibrium). In our case the kinetic equilibrium persists up to $T \sim M_W/\ln(M_{\text{Pl}}/M_W)$, but at this temperature the anomalous electroweak processes are inoperative. An estimate for the BAU generated at $T \sim T^*$ is ($\Delta \equiv n_B/n_\gamma$, n_B and n_γ are baryon and photon number densities respectively)

$$\Delta \sim \frac{1}{2} (B_{\text{in}} - L_{\text{in}}) e^{-A} \quad (10)$$





“Revised” Sakharov conditions

The baryon asymmetry can be dynamically generated if the following three conditions are satisfied:

- ~~Baryon~~ ^{B-L} number violation

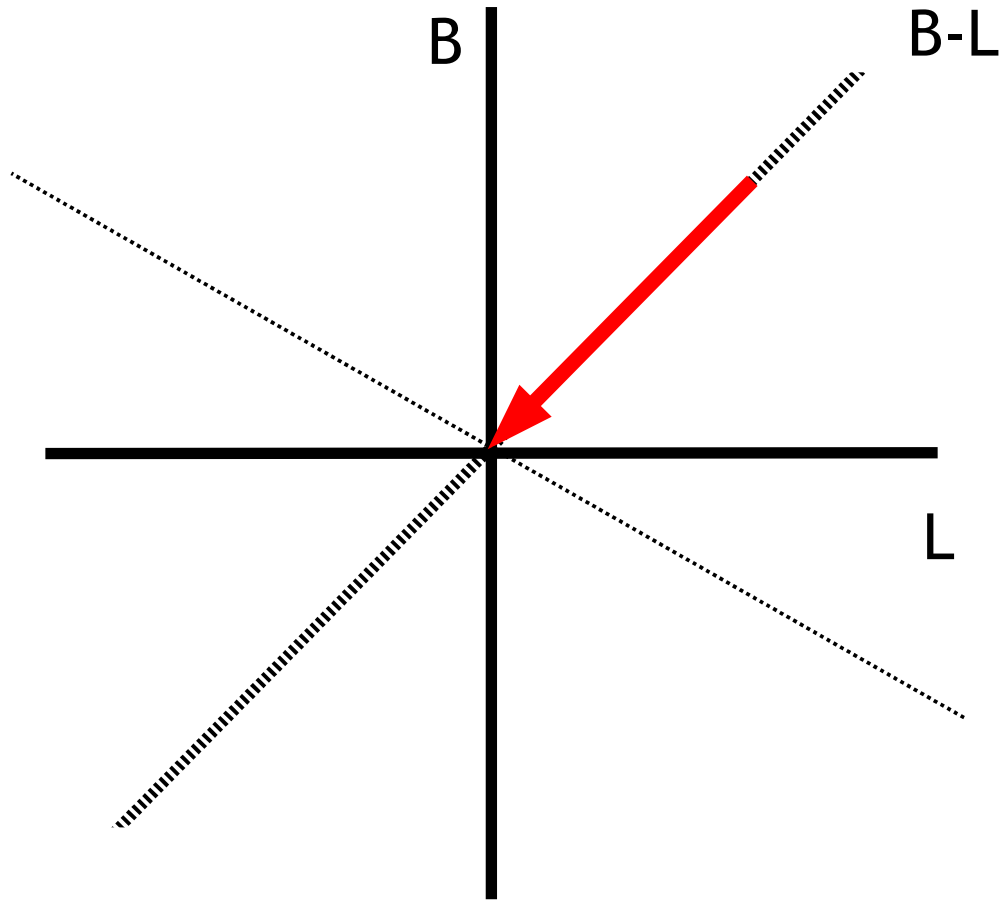
If baryon asymmetry is conserved, no baryon number can be dynamically generated. There must exist $X^{B=0} \rightarrow Y^{B=0} + B^{B \neq 0}$

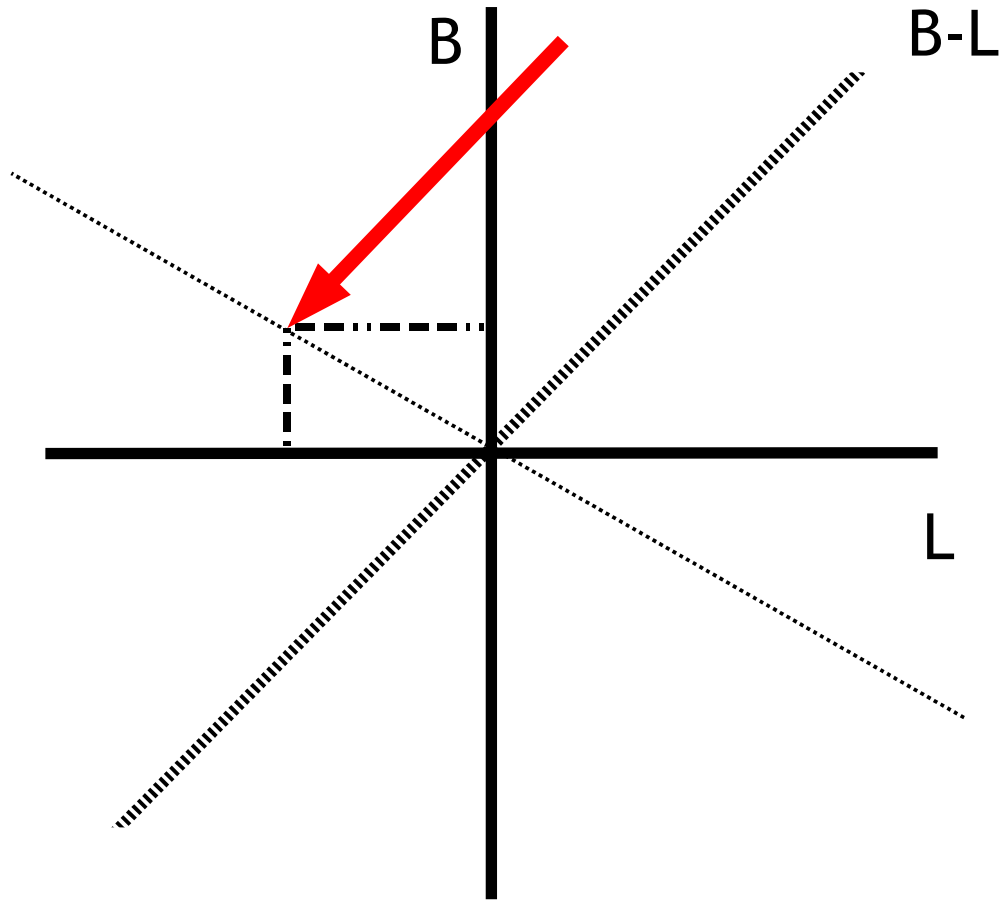
- C and CP violation

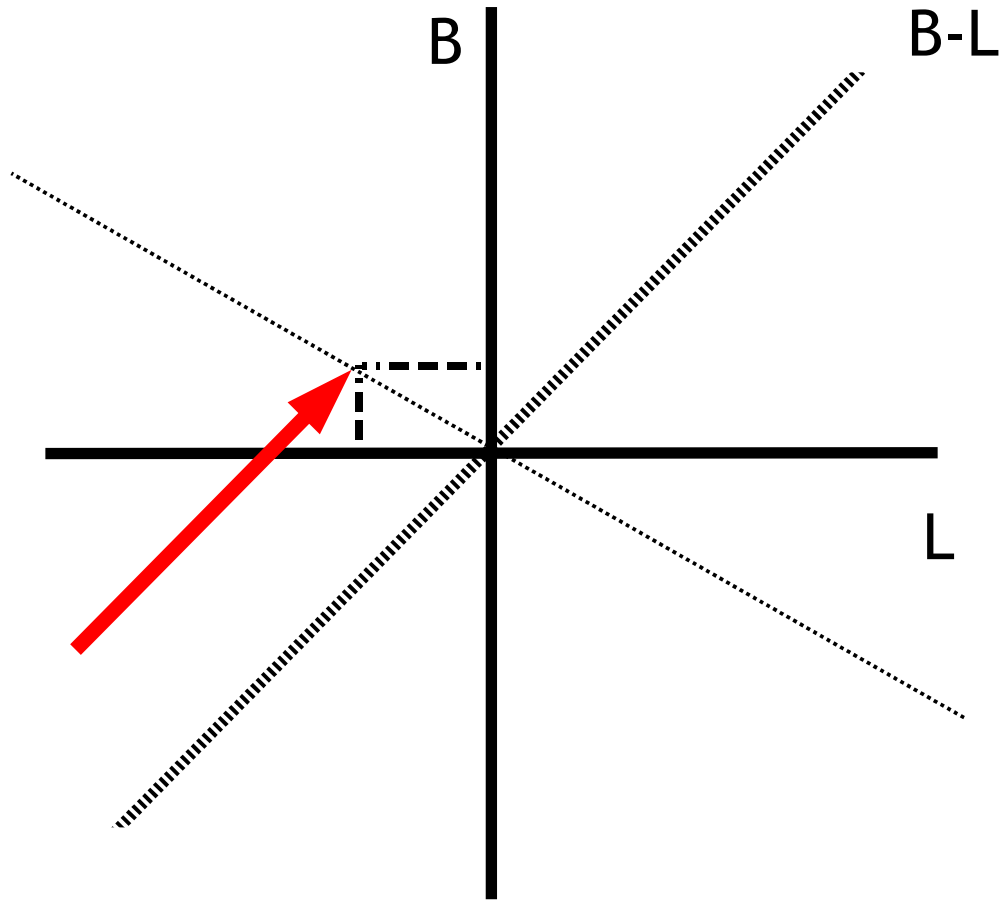
If C or CP are conserved, $\Gamma(X \rightarrow Y+B) = \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B}) \Rightarrow$ No net effect

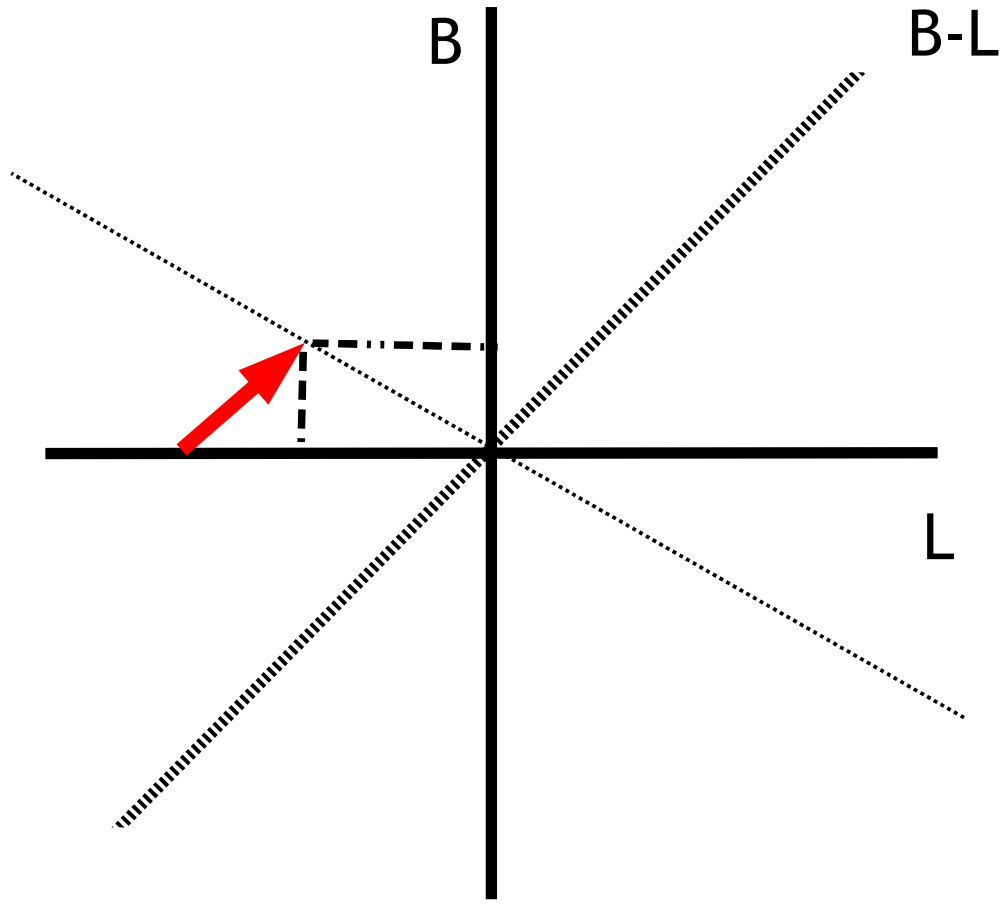
- Departure from thermal equilibrium

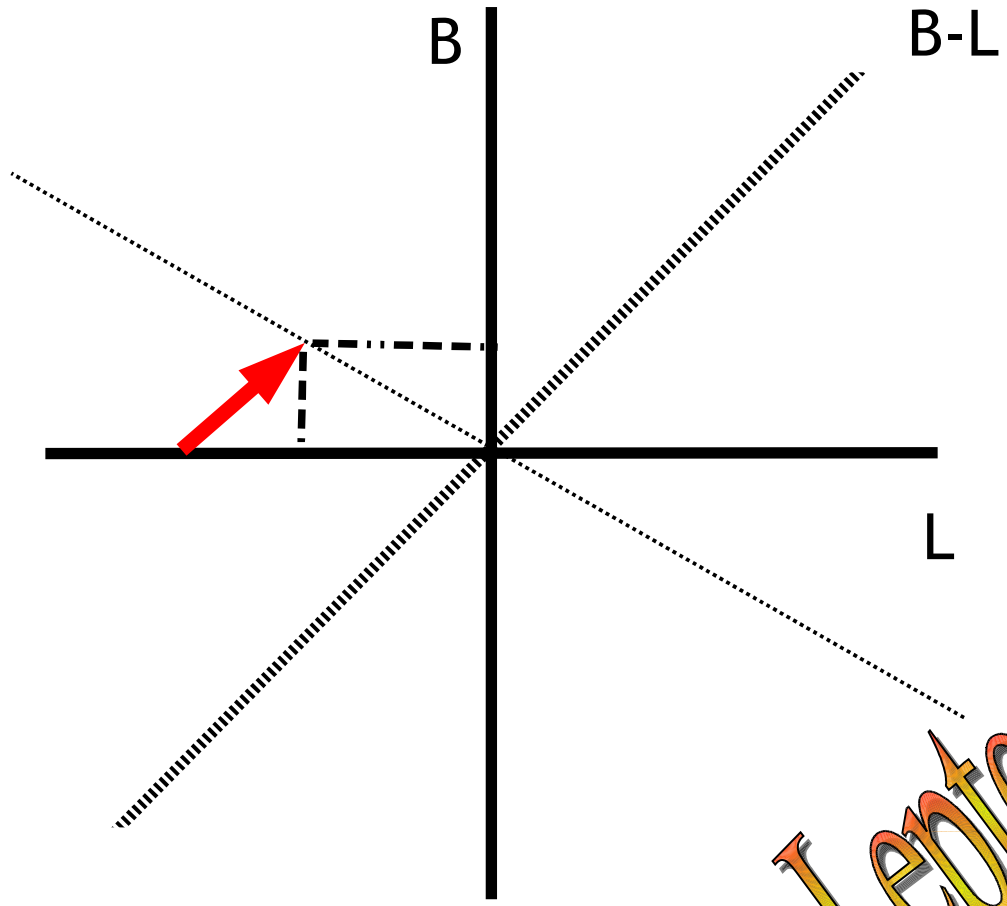
In thermal equilibrium, the production rate of baryons is equal to the destruction rate: $\Gamma(X \rightarrow Y+B) = \Gamma(Y+B \rightarrow X) \Rightarrow$ No net effect.











Leptogenesis

VERY SIMPLE IDEA:

“Baryogenesis Without Grand Unification”, Phys.Lett.B174:45,1986, by Fukugita and Yanagida.

Volume 174, number 1

PHYSICS LETTERS B

26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

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and

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Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms, first transforms into the baryon number excess through the unappressed baryon number violation of electroweak processes at high temperature.

The current view ascribes the origin of cosmological baryon excess to the microscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interaction is regarded as the standard candidate to account for this baryon number violation. The theory can give the correct order of magnitude for baryon to entropy ratio, if the Universe undergoes the inflation epoch after the baryogenesis, however, generated baryon number is diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A more interesting problem is that no evidence are given so far experimentally for the baryon number violation, which might cast some doubt on the GUT idea.

Some time ago 't Hooft suggested that the instanton-like effect violates baryon number in the Weinberg-Salam theory through the anomaly term, although the effect is suppressed by a large factor [3]. It has been pointed out, however, that this effect is not suppressed and can be efficient at high temperatures above the Weinberg-Salam energy scale [4]. This baryon number violating process conserves $B-L$, but it creates rapidly the baryon asymmetry which would have been generated at the early Universe with $B-L$

conserving baryon number violation processes as in the standard SU(5) GUT. (Baryon number would remain, if the baryon production takes place at low temperatures $T \lesssim O(100 \text{ GeV})$, e.g., after reheating [5,6].) The process itself can not produce the baryon asymmetry, since it is unlikely to suppose a particular mechanism leading to departures from equilibrium [4].

In this letter, we point out that the electroweak baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch, can generate the cosmological baryon asymmetry without resorting to the GUT scenario. The lepton number excess in the earlier stage can efficiently be transferred into the baryon number excess. It is rather easy to find an agent leading to the lepton number generation. A candidate is the decay process involving Majorana mass terms.

Let us present a specific model which gives lepton number generation. We assume the presence of a right-handed Majorana neutrino N_R^c ($c = 1, \dots, n$) in addition to the conventional leptons. We take the Lagrangian to be

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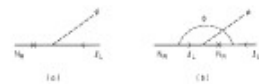


Fig. 1. The simplest diagrams giving rise to a net lepton number production. The cross denotes the Majorana mass insertion.

$$\mathcal{L} = \bar{L}_i \gamma_{\mu} \partial_{\mu} L_i + N_R^c \bar{N}_R^c + M_i N_R^c N_R^c + \text{h.c.} + h_{ij} N_R^c \bar{L}_i \psi_j + \text{h.c.}, \quad (1)$$

where \mathcal{L}_{SM} is the standard Weinberg-Salam Lagrangian, and ψ the standard Higgs doublet. For simplicity we assume three generations of flavors and the mass hierarchy $M_1 < M_2 < M_3$ in the decay of N_R^c .

$$N_R^c = \psi_L + \bar{\psi}, \quad (2a)$$

$$= \bar{\psi}_L + \bar{\psi}, \quad (2b)$$

there appears a difference between the branching ratios for (2a) and (2b), if CP is violated, through the one-loop radiative correction by a Higgs particle. The net lepton number production due to the decay of a lightest right-handed neutrino N_R^c arises from the interference of the two diagrams in fig. 1, and its magnitude is calculated as [7]

$$e = (9/4\pi) \ln(h_{ij} h_{ik}^* h_{kl}^* h_{lj}) / (M_i^2 M_k^2 / (M_j^4))_{11}, \quad (3)$$

with

$$f(x) = x^{3/2} [1 + (1+x) \ln|x/(1+x)|].$$

If we assume h_{33} to be the largest entry of the Yukawa coupling matrix and $M_3 \gg M_1$, (3) reduces to

$$e \approx (9/8\pi) |h_{31}|^2 (M_1/M_3)^2, \quad (4)$$

with δ the phase causing CP violation.

We apply the delayed decay mechanism [8] to generate the baryon asymmetry in the Universe. The out-of-equilibrium condition is satisfied, if the temperature T is smaller than the mass M_1 so that the inverse decay is blocked at the time when the decay rate $\Gamma = (M_1^5/16\pi) |h_{11}|^2$ is equal to the expansion rate of the Universe $\dot{a} \approx 1.7\sqrt{g} T^2 / (m_{\text{pl}} g = \text{numbers of degrees of freedom})$, i.e.,

$$(\Gamma/m_{\text{pl}} g^{-1/2})^{1/2} < M_1, \quad (5)$$

To obtain numerical factors for this condition, one has to solve the Boltzmann equation. Let us borrow the results of ref. [9], to obtain a rough number. The lepton number to entropy ratio is given as

$$R(\Delta L)_i/x = 10^{-3} e K^{-1/2}, \quad (6)$$

with $K = \frac{1}{2} \Gamma(\delta/\pi)$ for $K \gg 1$. The parameters in (4) and in the expression of Γ are not directly constrained by low-energy experiments. One may have an idea, however, on the mass scale M_1 as follows. With the parameter in a reasonable range, one may obtain $e \lesssim 10^{-6}$. Then to obtain our required number for $R(\Delta L)_i/x = 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives $M_1 \gtrsim 2.4 \times 10^{14} \text{ GeV} (M_1)_{11}$. If we assume $|h_{12}|^2 \lesssim |h_{11}|^2$ and take $(M^2)_{11} \approx |h_{11}|^2 \sim (10^{-2})^2$, then we are led to $M_1 \gtrsim 2 \times 10^4 \text{ GeV}$. This constant can also be expressed in terms of the left-handed Majorana neutrino mass M_1^L as $m_{\nu_1} \approx M_1^L (\phi^2/M_1) \lesssim 0.1 \text{ eV}$. If the lightest left-handed neutrino has a Majorana mass smaller than this value, the required asymmetry can be generated.

Now let us discuss the generation of the baryon asymmetry. In the presence of an instanton-like electroweak effect the baryon asymmetry changes as [4]

$$\Delta B(t) = \frac{1}{2} \Delta(B-L) + \frac{1}{2} \Delta(B+L) \exp(-\gamma t), \quad (7)$$

with $\gamma \sim 7$. At the time of the Weinberg-Salam epoch the exponent is $m_{\text{pl}}^2/\gamma g \sim 10^{16}$ and the second term practically vanishes. Therefore we obtain

$$\Delta B = -(\Delta L)/2, \quad (8)$$

which survives up to the present epoch, and should give $\Delta B/\Delta t \sim 10^{-10.8}$.

¹¹ Here we assumed the dominance of the diagonal matrix element. More precisely speaking, the matrix element constraint by our condition differs from that, which appears in the observed neutrino mass: the left-handed neutrino mass matrix given by $(m_{\nu})_{ij} = y_{ij} v^2 / (M_i M_j)$ [10]. The double beta decay experiment constrains the matrix element $|(m_{\nu})_{11} + (M_1^2/M_1) + y_{11}^2 v^2 / (M_1^2)|$, while eq. (5) refers to $(y_{11}^2 v^2 / (M_1^2) + y_{12}^2 v^2 / (M_1 M_2))$ and $y_{12} \neq y_{21}$ in general. Once we took the base where the charged-lepton mass matrix is diagonal. Therefore, the double beta decay experiment does not constrain directly the parameters in eq. (5). The stream beta decay experiment constrains the eigenvalue of the mass matrix (see ref. [11]).

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26 June 1986

A primordial lepton number excess existed before the epoch of the right-handed neutrino mass scale should have been washed out by the equilibrium of process (2) and its inverse process, if the Yukawa coupling $(M^2)_{22}$ or $(M^2)_{33}$ is large enough. The equilibrium condition $\Gamma_i \exp(-M_i/T) \gtrsim 1.7\sqrt{g} T^2 / (m_{\text{pl}} g = 2$ or 3) leads to a constraint similar to (5) but with the inequality reversed. The net baryon number destruction factor behaves as $\sim \exp(-\delta/\pi) (g = O(1))$ [9]. For $K \gtrsim 20-30$, the equilibrium practically erases the whole pre-existing lepton number excess. This condition is expressed as $(m_{\nu_1})_c > 0.1 \text{ eV}$ for the largest entry of the Majorana mass matrix.

In the presence of unappressed instanton-like electroweak effects, the lepton number equilibrium implies that the baryon excess which existed at this epoch should also be washed out, even if it was produced in the process with $B-L \neq 0$. Namely, if there are matrices with the Majorana mass heavier than $\sim 0.1 \text{ eV}$ both baryon and lepton numbers which existed before the epoch are washed out irrespective of their $B-L$ properties.

In summary, we have the following possible scenarios for the cosmological baryon number excess:

- (1) At a temperature above the mass scale M (= scale of right-handed Majorana neutrino), we started with $\Delta B = \Delta L = 0$. (The inflationary universe would give this initial condition.) Then the lepton number is generated through the Majorana mass term, and is transformed into the baryon number due to the unappressed instanton-like electroweak effect.
- (2) At the scale M , baryon and lepton numbers are generated by the grand unification, or alternatively we start with a $\Delta B \neq 0$, $\Delta L \neq 0$ Universe. The equilibrium of N_R^c ($\phi + \bar{\psi}_L + \psi + \bar{\psi}_L$) together with the electroweak process washes out both baryon and lepton numbers. Then the lepton number is newly generated by the out-of-equilibrium scenario, and it turns into the baryon number.
- (3) The baryon number with $B-L \neq 0$ is generated by the grand unification (e.g., the SU(5) model [12]). If the scale M is too large to establish the equilibrium of N_R^c and $\phi + \bar{\psi}_L$, then the initial $\Delta(B-L)$ will not be erased. The electroweak process does not affect $B-L$, and hence the initial baryon

number remains. This case is the original GUT baryon number generation scenario. To achieve this, however, all neutrino mass matrix elements (Majorana mass) should be smaller than $\sim 0.1 \text{ eV}$. If the double beta experiment would observe a Majorana mass greater than this value, this scenario fails.

In conclusion, we have suggested a mechanism of cosmological baryon number generation without resorting to grand unification. In our scenario the cosmological baryon number can be generated, even if proton decay does not happen at all.

One of us (M.F.) would like to thank V.A. Rubakov for discussions on baryon number nonconservation in electroweak processes.

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VERY SIMPLE IDEA:

“Baryogenesis Without Grand Unification”, Phys.Lett.B174:45,1986, by Fukugita and Yanagida.

BARYOGENESIS WITHOUT GRAND UNIFICATION

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A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms, now transforms into the baryon number excess through the unappressed baryon number violation of electroweak processes at high temperatures.

The current view ascribes the origin of cosmological baryon excess to the macroscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interaction is regarded as the standard candidate to account for this baryon number violation. The theory can give the correct order of magnitude for baryon to entropy ratio, if the Universe undergoes the inflation epoch after the baryogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A more intriguing problem is that no evidences are given so far experimentally for the baryon number violation, which might cast some doubt on the GUT idea.

Some time ago 't Hooft suggested that the instanton-like effect violates baryon number in the Weinberg-Salam theory through the anomaly term, although the effect is suppressed by a large factor [3]. It has been pointed out, however, that this effect is not suppressed and can be efficient at high temperatures above the Weinberg-Salam energy scale [4]. This baryon number violating process conserves $B-L$, but it creates rapidly the baryon asymmetry which would have been generated at the early Universe with $B-L$

conserving baryon number violation processes as in the standard SU(5) GUT. (Baryon numbers were zero, if the baryon production takes place at low temperatures $T \lesssim O(100 \text{ GeV})$, e.g., after reheating [5,6].) The process itself can not produce the baryon asymmetry, since it is unlikely to suppose a particular mechanism leading to departures from equilibrium [4].

In this letter, we point out that the electroweak baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch, can generate the cosmological baryon asymmetry without resorting to the GUT scenario. The lepton number excess in the earlier stage can efficiently be transformed into the baryon number excess. It is rather easy to find an agent leading to the lepton number generation. A candidate is the decay process involving Majorana mass terms.

Let us present a specific model which gives lepton number generation. We assume the presence of a right-handed Majorana neutrino N_R^c ($c = 1, \dots, n$) in addition to the conventional leptons. We take the Lagrangian to be

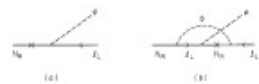


Fig. 1. The simplest diagram giving rise to a net lepton number production. The cross denotes the Majorana mass insertion.

$$L = L_{\text{SM}} + N_R^c \bar{N}_R^c + M_N^c N_R^c N_R^c + \text{h.c.} + h_{ij} N_R^c \bar{L}_i \phi^j + \text{h.c.}, \quad (1)$$

where L_{SM} is the standard Weinberg-Salam Lagrangian, and ϕ the standard Higgs doublet. For simplicity we assume three generations of flavors and the mass hierarchy $M_1 < M_2 < M_3$. In the decay of N_R^c ,

$$N_R^c \rightarrow \bar{\nu}_L + \phi, \quad (2a)$$

$$- \bar{\nu}_L + \phi, \quad (2b)$$

there appears a difference between the branching ratios for (2a) and (2b), if CP is violated, through the one-loop radiative correction by a Higgs particle. The net lepton number production due to the decay of a lightest right-handed neutrino N_R^c arises from the interference of the two diagrams in fig. 1, and its magnitude is calculated as [7]

$$e = (9/4\pi) \ln(h_{ij} h_{kl}^* h_{lm}^* h_{kn}) / (4\pi^2 M_N^c M_N^k) |h_{11}|^{-2}, \quad (3)$$

with

$$f(x) = x^{-3/2} [1 + (1+x) \ln|x/(1+x)|].$$

If we assume h_{33} to be the largest entry of the Yukawa coupling matrix and $M_3 \gg M_1$, (3) reduces to

$$e \approx (9/8\pi) |h_{31}|^2 (M_1/M_3)^2, \quad (4)$$

with δ the phase causing CP violation.

We apply the delayed decay mechanism [8] to generate the baryon asymmetry in the Universe. The out-of-equilibrium condition is satisfied, if the temperature T is smaller than the mass M_1 so that the inverse decay is blocked at the time when the decay rate $\Gamma = (|h_{11}|^2/16\pi)$ is equal to the expansion rate of the Universe $\dot{\epsilon} \approx 1.7\sqrt{g}T^2/(m_{\text{pl}} g)$ (= number of degrees of freedom), i.e.,

$$(\Gamma/\dot{\epsilon})^{1/2} \approx (|h_{11}|^2/16\pi)^{1/2} < M_1. \quad (5)$$

To obtain numerical factors for this condition, one has to solve the Boltzmann equation. Let us borrow the result of ref. [9] to obtain a rough guess. The lepton number to entropy ratio is given as

$$R(\Delta L)_L/x = 10^{-3} e K^{-1/2}, \quad (6)$$

with $K = \frac{1}{2} \Gamma/\dot{\epsilon}$ for $K \gg 1$. The parameters in (4) and in the expression of Γ are not directly constrained by low-energy experiments. One may have an idea, however, on the mass scale M_1 as follows. With the parameter in a reasonable range, one may obtain $e \lesssim 10^{-6}$. Then to obtain our required number for $R(\Delta L)_L/x = 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives $M_1 \gtrsim 2.4 \times 10^{14} \text{ GeV} (M_1/10^{14})$. If we assume $|h_{11}|^2 \lesssim |h_{33}|^2$ and take $(M_N^c)^2 \approx |h_{11}|^2 \approx (10^{-2})^2$, then we are led to $M_1 \gtrsim 2 \times 10^4 \text{ GeV}$. This constant can also be expressed in terms of the left-handed Majorana neutrino mass $m_{N_L}^c$ as $m_{N_L}^c \approx h_{11}^2 (\phi^2/M_1) \lesssim 0.1 \text{ eV}$. If the lightest left-handed neutrino has a Majorana mass smaller than this value, the required asymmetry can be generated.

Now let us discuss the generation of the baryon asymmetry. In the presence of an instanton-like electroweak effect the baryon asymmetry changes as [4]

$$\Delta B(t) = \frac{1}{2} (\Delta B - L)_i + \frac{1}{2} (\Delta B + L)_i \exp(-\gamma t), \quad (7)$$

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A primordial lepton number excess existed before the epoch of the right-handed neutrino mass scale should have been washed out by the equilibrium of process (2) and its inverse process, if the Yukawa coupling $(h_{11}^2)_{22}$ or $(h_{11}^2)_{33}$ is large enough. The equilibrium condition $\Gamma_i \exp(-M_i/T) \gtrsim 1.7\sqrt{g}T^2/(m_{\text{pl}} g)$ ($i = 2$ or 3) leads to a constraint similar to (5) but with the inequality reversed. The net baryon number destruction factor reduces to $\sim \exp(-\delta B) (i = 2, 3)$ [9]. For $K \gtrsim 20-30$, the equilibrium practically erases the whole pre-existing lepton number excess. This condition is expressed as $(m_{N_L}^c)_{22} > 0.1 \text{ eV}$ for the largest entry of the Majorana mass matrix.

In the presence of unappressed instanton-like electroweak effects, the lepton number equilibrium implies that the baryon excess which existed at this epoch should also be washed out, even if it was produced in the process with $B-L \neq 0$. Namely, if there are matrices with the Majorana mass heavier than $\sim 0.1 \text{ eV}$ both for baryon and lepton numbers which existed before the epoch are washed out irrespective of their $B-L$ properties.

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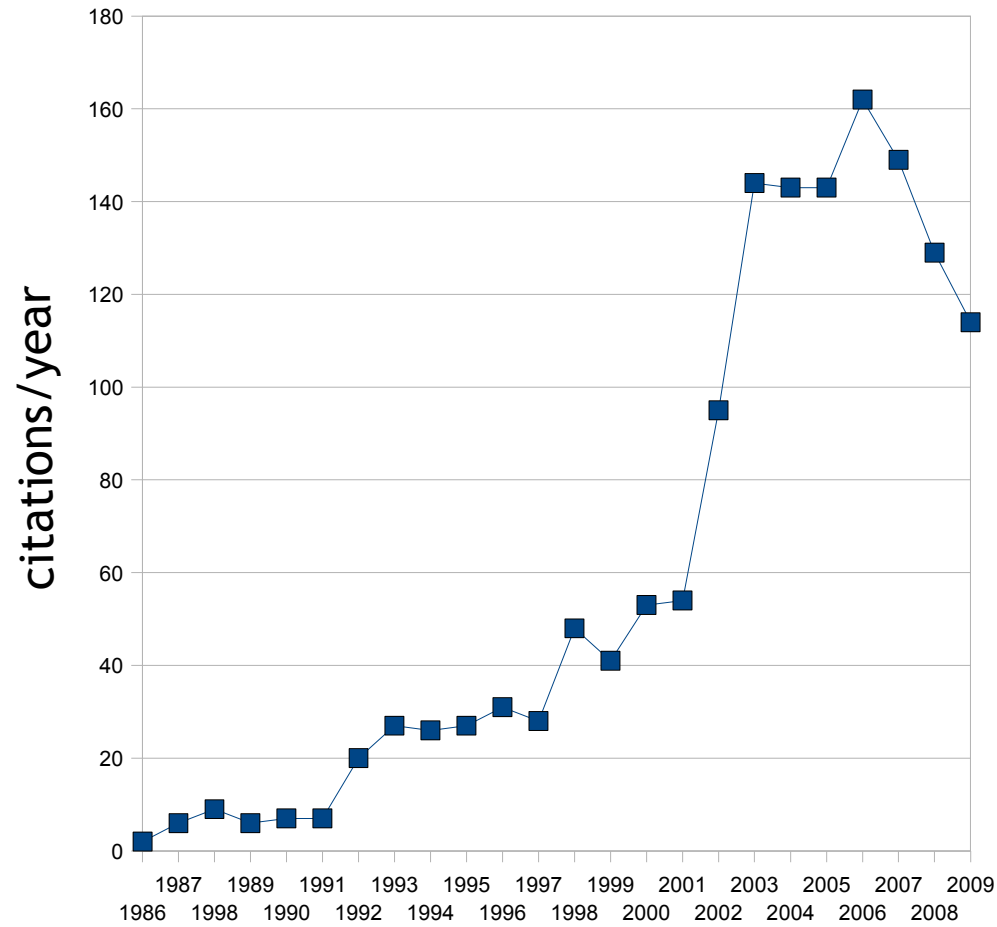
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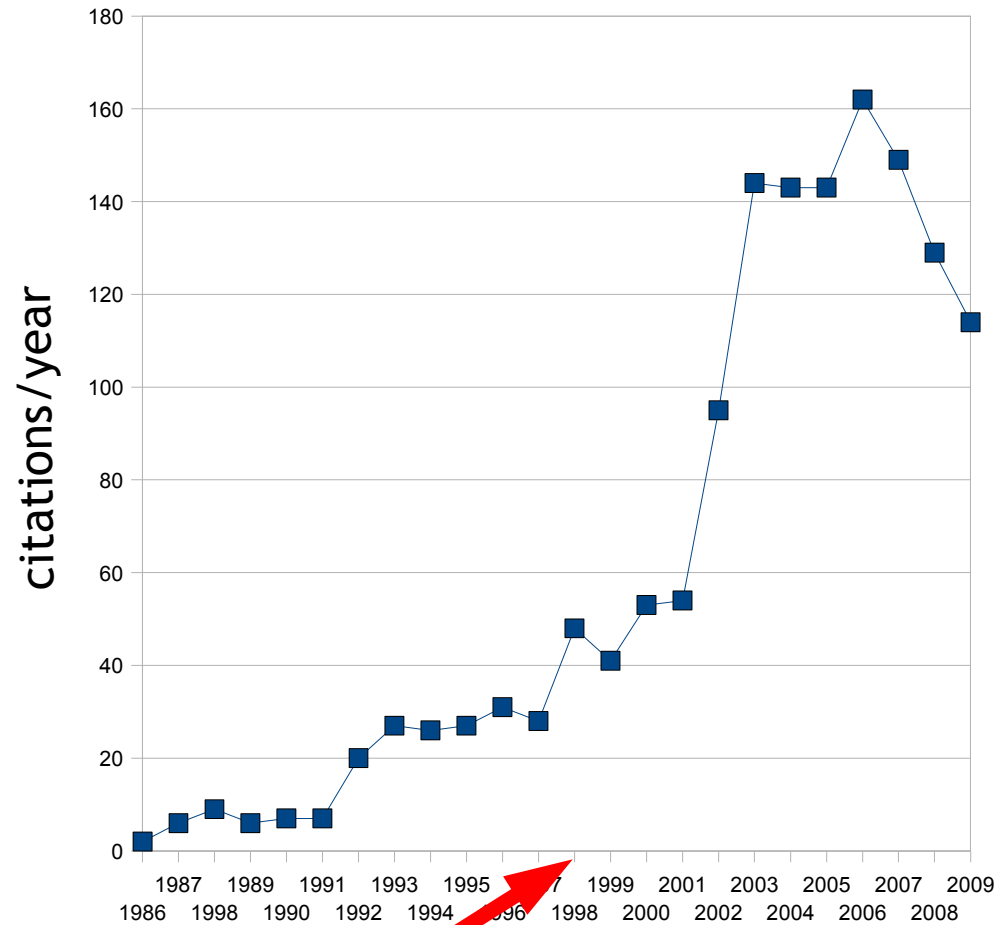
And very popular...

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Why are people so excited about leptogenesis?

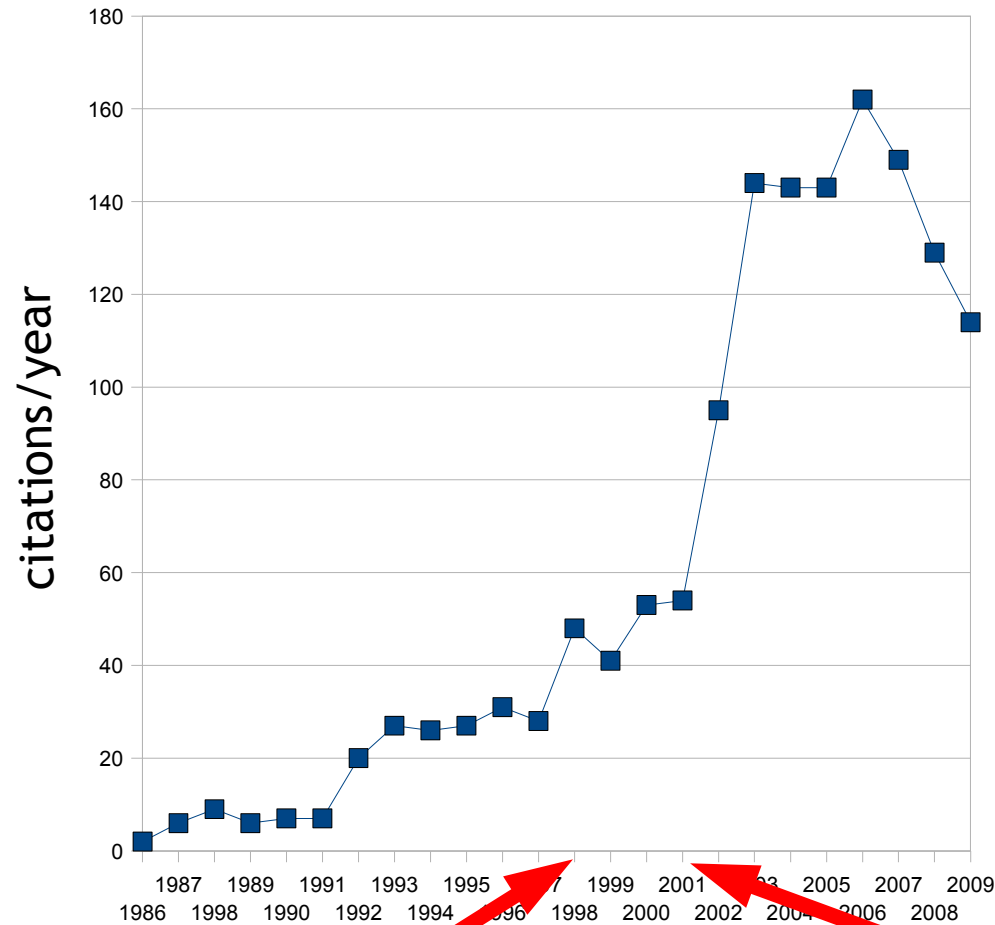


Why are people so excited about leptogenesis?



1998. Evidence of atmospheric neutrino oscillations (Super-K)

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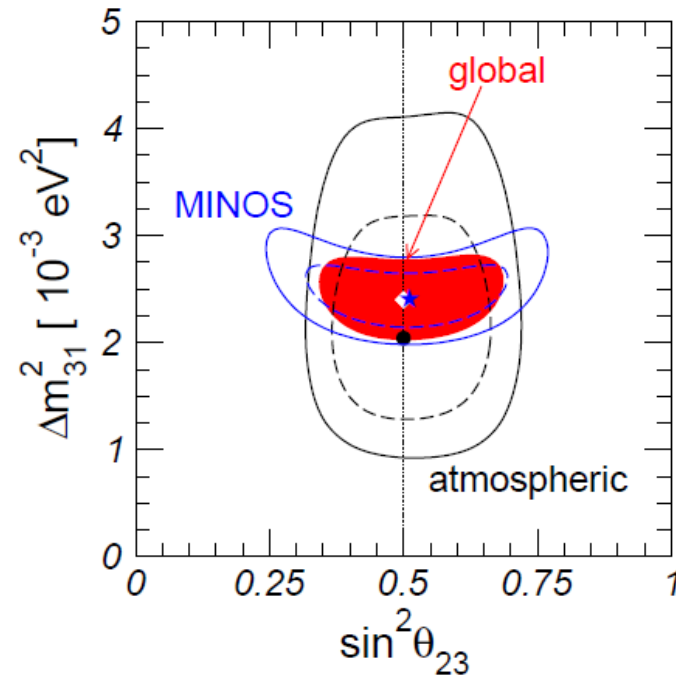
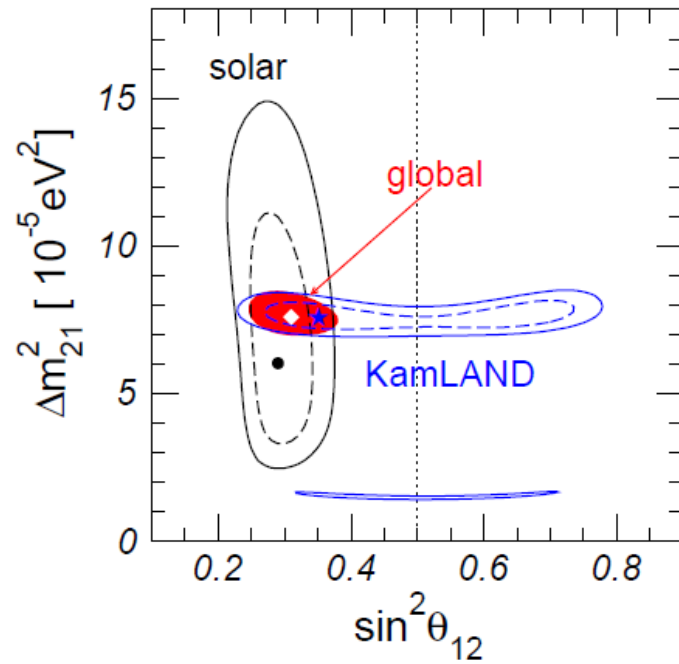


1998. Evidence of atmospheric neutrino oscillations (Super-K)

2001. Evidence of solar neutrino oscillations (SNO)

Neutrino masses

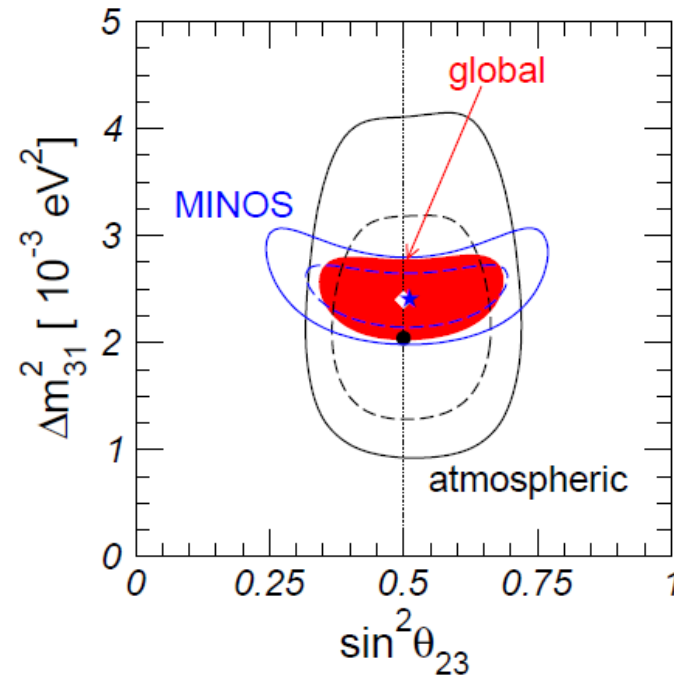
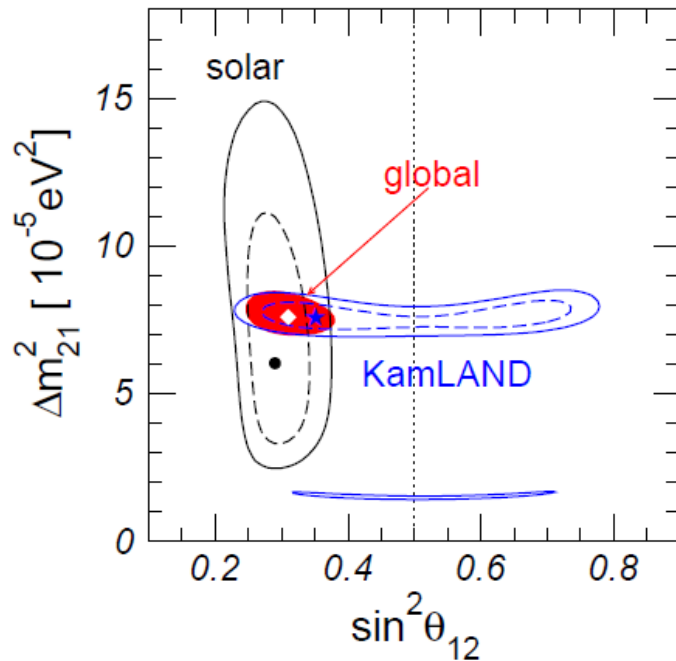
Neutrinos have mass!!



Schwetz, Tortola,
Valle

Neutrino masses

Neutrinos have mass!!



Schwetz, Tortola, Valle

parameter	best fit	2σ	3σ
Δm_{21}^2 [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$ \Delta m_{31}^2 $ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2 \theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2 \theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2 \theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

Neutrinos are very special particles: it is the only known fermion which is electrically neutral.

There are two possible new terms that can be added to the Standard Model Lagrangian to account for neutrino oscillations:

Dirac mass $-\mathcal{L} = \bar{\nu}_{Li} m_{ij}^D \nu_{Rj} + h.c.$ (L conserved)

Majorana mass $-\mathcal{L} = \frac{1}{2} \bar{\nu}_{Li}^c m_{ij}^M \nu_{Lj} + h.c.$ (L violated)

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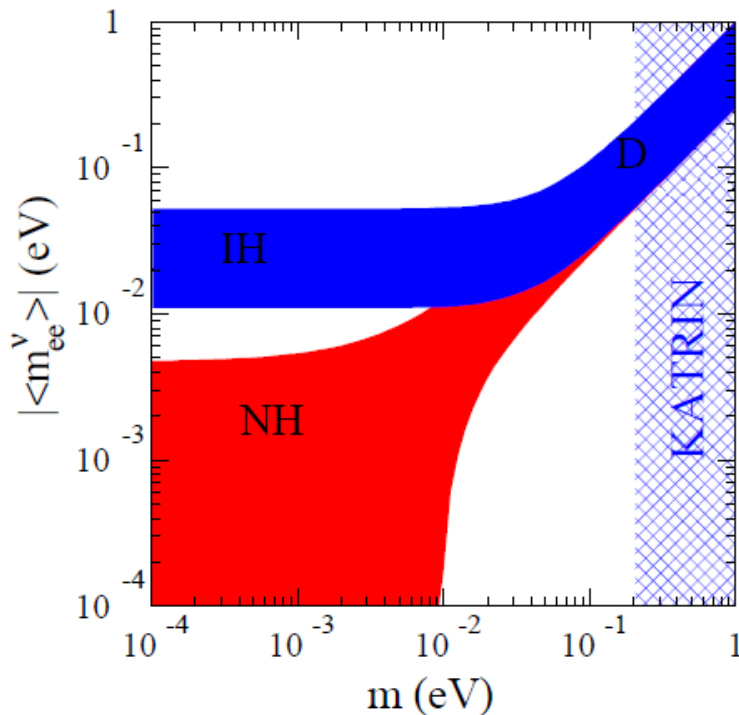
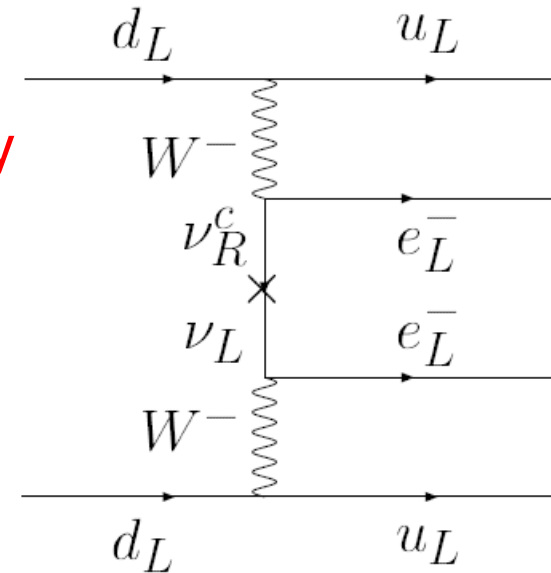
Option preferred by theorists

Dirac or Majorana?

The smoking gun: **neutrinoless double beta decay**

If neutrinos are Majorana particles, the nuclear process $(A,Z) \rightarrow (A,Z+2) + e^- + e^-$ is allowed

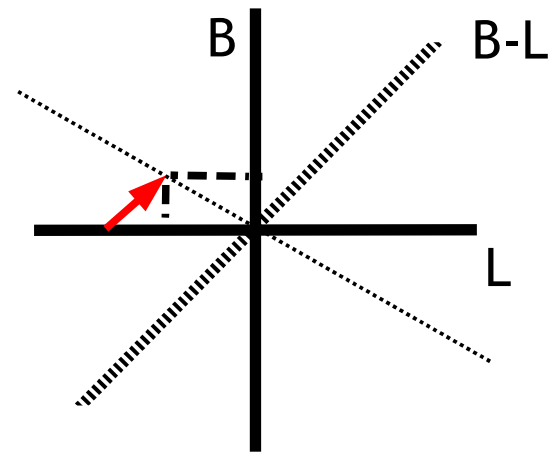
Not observed yet. Lifetime $> 10^{24} - 10^{25}$ years



The rate of $0\nu 2\beta$ depends crucially on the spectrum. If neutrinos are degenerate or inverse hierarchical, $0\nu 2\beta$ could be observed in the next generation of experiments (CUORE, GERDA...)

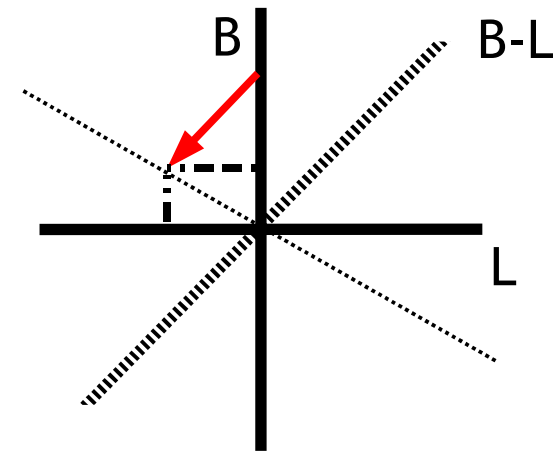
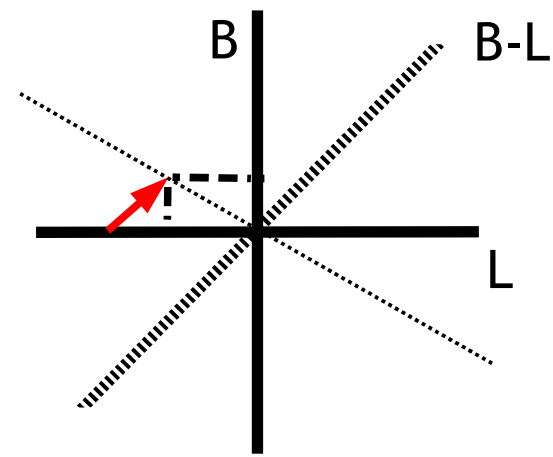
Bahcall, Murayama
Peña-Garay

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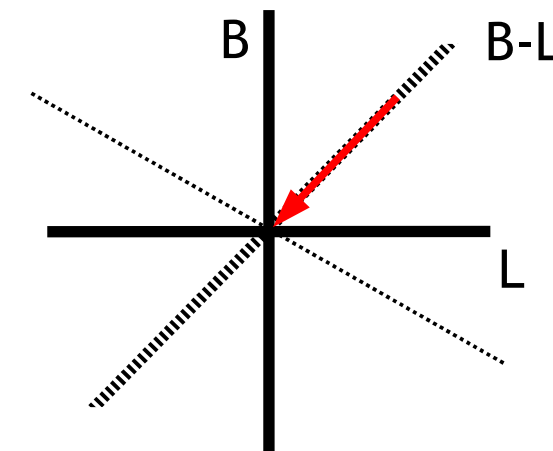
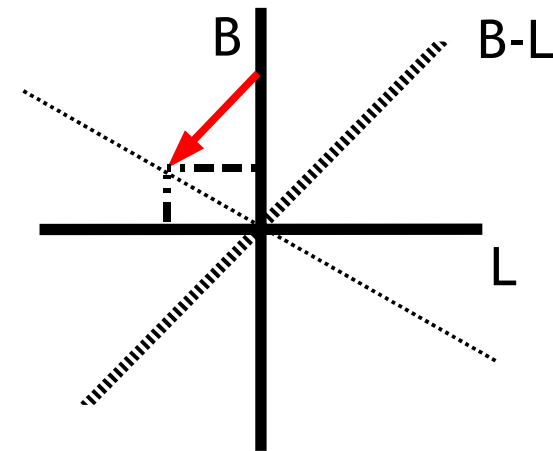
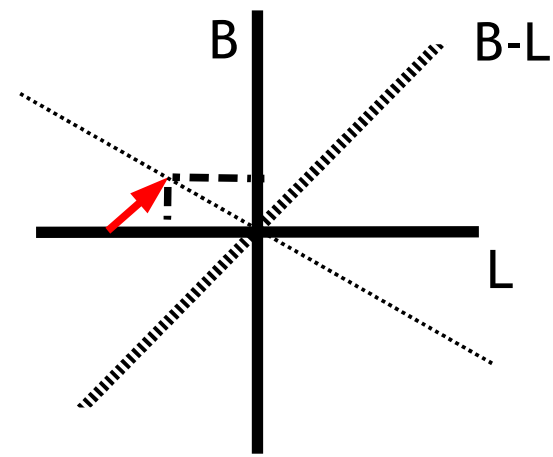
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- The observation of $0\nu 2\beta$ decay (\Rightarrow **L is violated**) will constitute a strong *hint* for leptogenesis.

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- The observation of proton decay (\Rightarrow **B and L violated**) will not have any implications for baryogenesis/leptogenesis (**since B-L is not violated**)

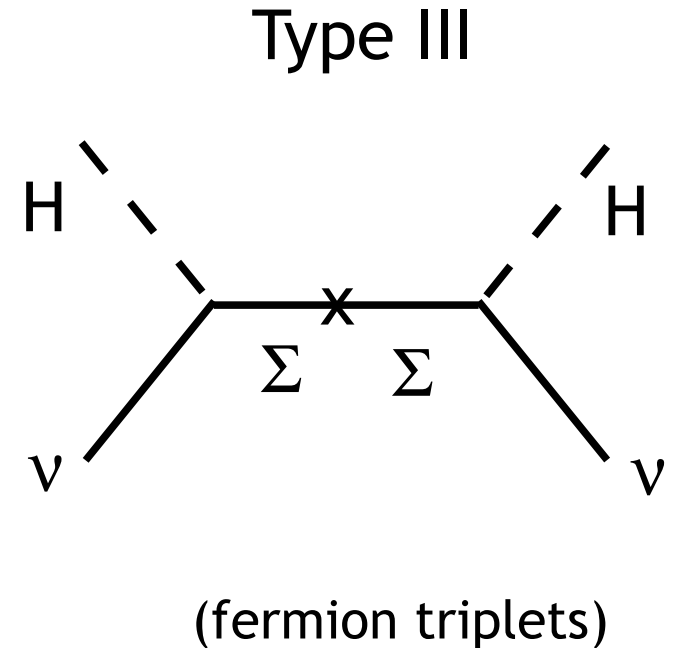
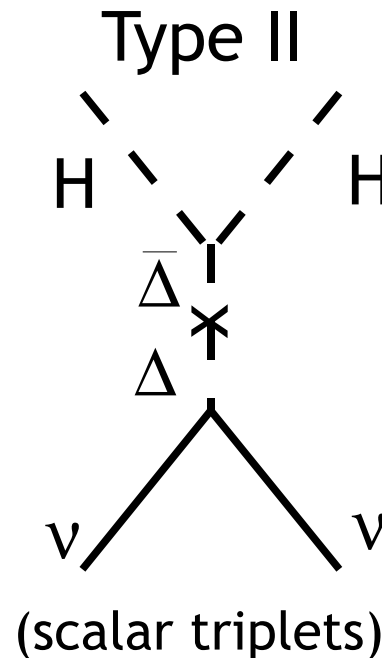
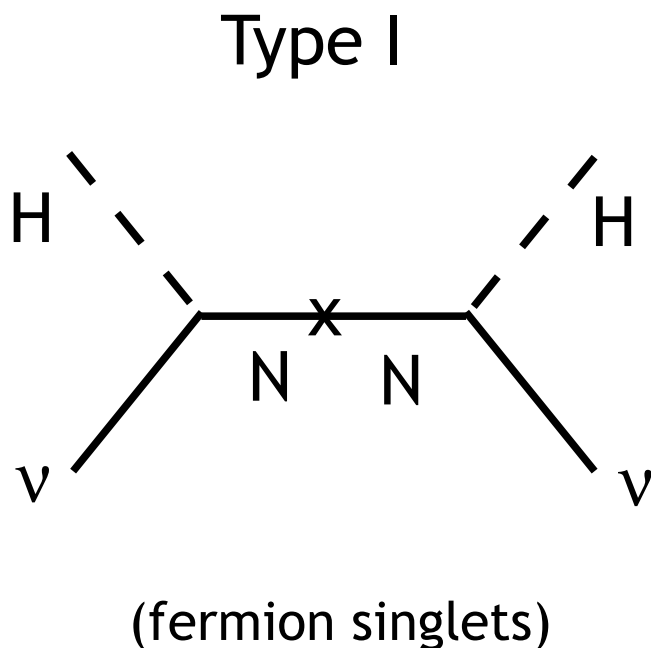


Origin of neutrino masses

Many proposals!

The most popular one (perhaps the simplest and most elegant) consists on introducing new heavy degrees of freedom:

See-saw mechanism



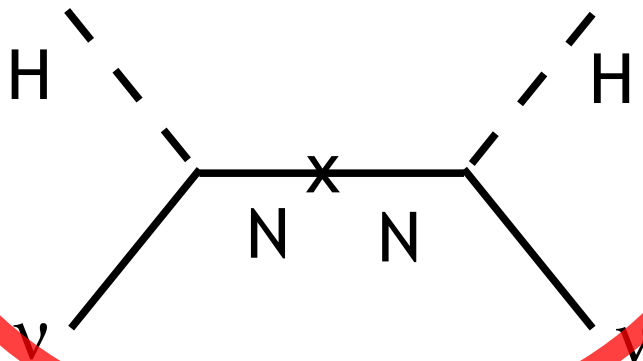
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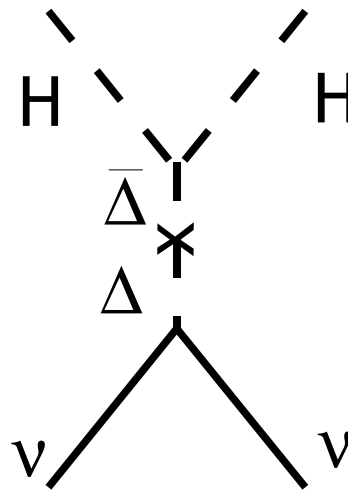
See-saw mechanism

Type I



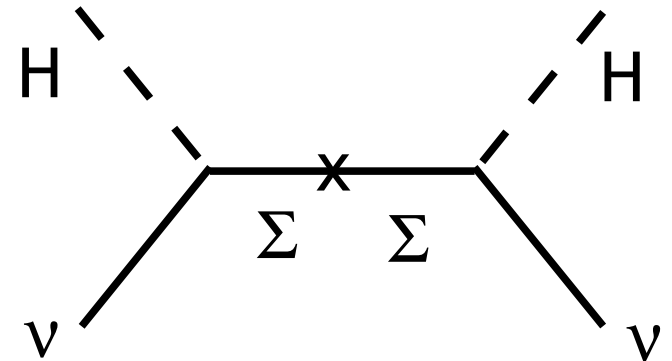
(fermion singlets)

Type II



(scalar triplets)

Type III



(fermion triplets)

Type I see-saw mechanism: Introduce heavy right-handed neutrinos (at least two).

That's it!!

The most general Lagrangian compatible with the Standard Model gauge symmetry is:

$$-\mathcal{L}_{lep} = \nu_R^{cT} h_\nu L \cdot H - \frac{1}{2} \nu_R^{cT} M \nu_R^c + \text{h.c.}$$



$$M \gg \langle H^0 \rangle$$

$$-\mathcal{L}_{\text{eff}} = -\frac{1}{2} (L \cdot H)^T \left[h_\nu^T M^{-1} h_\nu \right] (L \cdot H) + \text{h.c.}$$

$$\mathcal{M}_\nu = h_\nu^T M^{-1} h_\nu \langle H^0 \rangle^2$$

Naturally small due to the suppression by the large right-handed neutrino masses

Bonus

The decays of the right-handed neutrinos could generate the baryon asymmetry of the Universe

Leptogenesis

Mechanism to generate dynamically the baryon asymmetry through a lepton asymmetry. The simplest version consists on leptogenesis via the out of equilibrium decays of the lightest right-handed neutrino.

The three Sakharov conditions are fulfilled:

- **Violation of B–L.** Guaranteed if neutrinos are Majorana particles.
- **C and CP violation.** Guaranteed if the neutrino Yukawa couplings contain physical phases.
- **Departure from thermal equilibrium.** Guaranteed, due to the expansion of the Universe.

The generation of a baryon asymmetry is guaranteed in the leptogenesis mechanism. But, can leptogenesis generate the *observed* baryon asymmetry?

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The three Sakharov conditions are fulfilled:

- **Violation of B–L.** Guaranteed if neutrinos are Majorana particles.
- **C and CP violation.** Guaranteed if the neutrino Yukawa couplings contain physical phases. However, it is not guaranteed that the C and CP violation are large enough for leptogenesis.
- **Departure from thermal equilibrium.** Guaranteed, due to the expansion of the Universe. However, it is not guaranteed that the relevant processes are sufficiently out of equilibrium (this depends on the high-energy see-saw parameters).

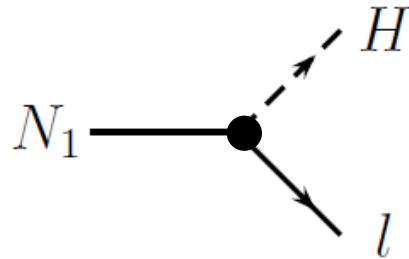
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Calculate!

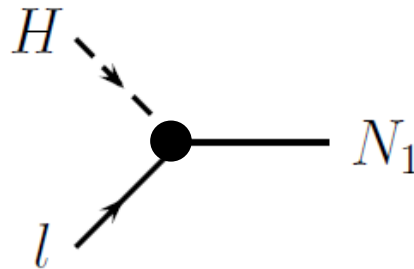


Roughly speaking, the generation of a BAU through leptogenesis proceeds in three steps:

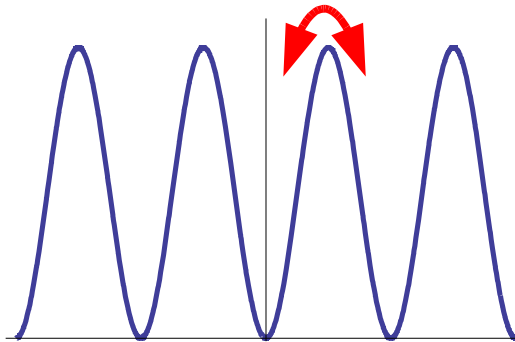
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.



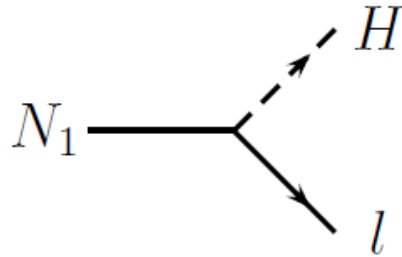
3- Conversion of the lepton asymmetry into a baryon asymmetry.



1- Generation of the lepton asymmetry

At **tree level**, the total decay rate is:

$$\Gamma_{\text{tot}} = \Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow l^c H^c) = \frac{1}{8\pi} (h_\nu h_\nu^\dagger)_{11} M_1$$

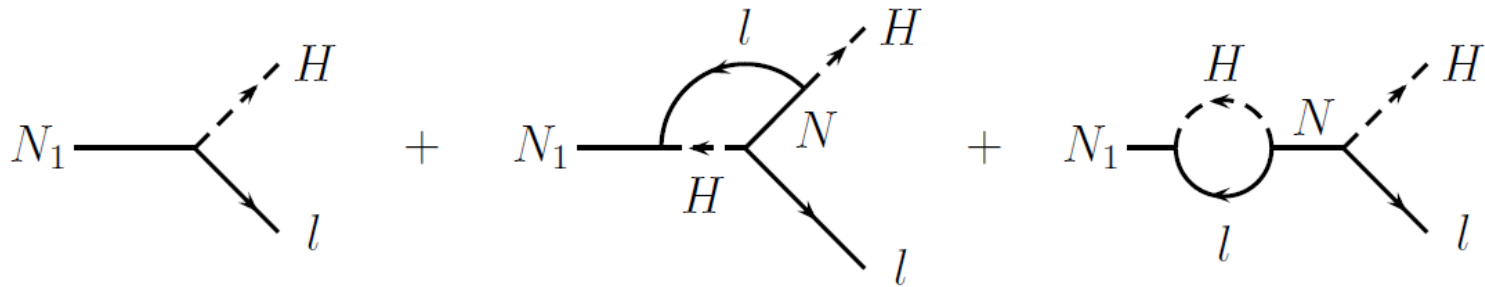


The rate for $N_1 \rightarrow lH$ and $N_1 \rightarrow l^c H^c$ are identical. **No CP asymmetry:**

$$\epsilon_1 = \frac{\Gamma(N_1 \rightarrow lH) - \Gamma(N_1 \rightarrow l^c H^c)}{\Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow l^c H^c)} = 0$$

1- Generation of the lepton asymmetry

At **one loop**, new diagrams contribute to the decay rate:

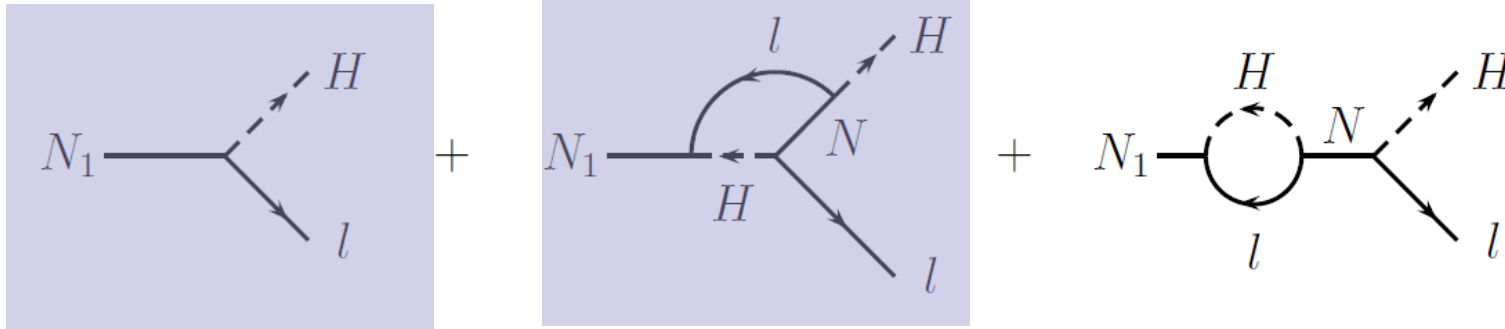


$$\epsilon_1 = \frac{\Gamma(N_1 \rightarrow lH) - \Gamma(N_1 \rightarrow l^c H^c)}{\Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow l^c H^c)}$$

$$\simeq \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \text{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \left[f \left(\frac{M_i^2}{M_1^2} \right) + g \left(\frac{M_i^2}{M_1^2} \right) \right]$$

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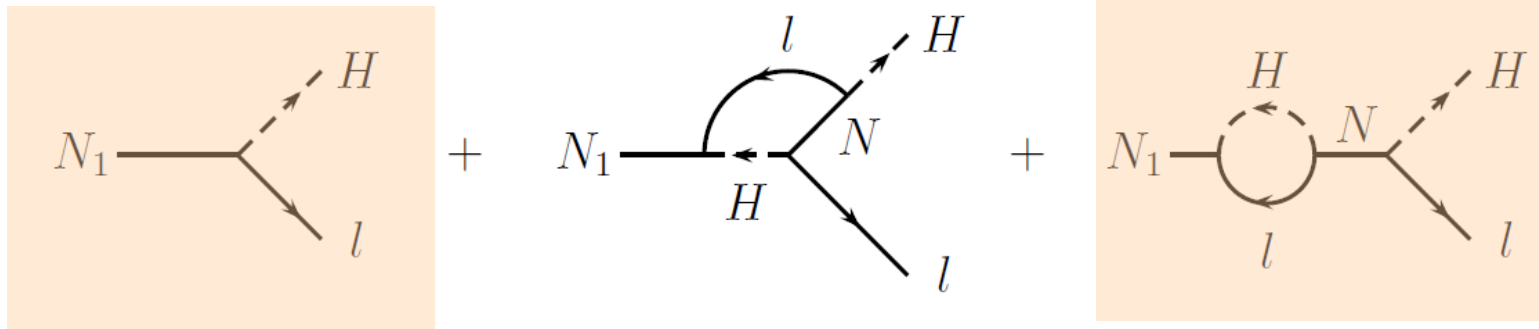
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Interference with the vertex correction

$$f(x) = \sqrt{x} \left[1 - (1+x) \ln \left(\frac{1+x}{x} \right) \right]$$

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Interference with the wave-function correction

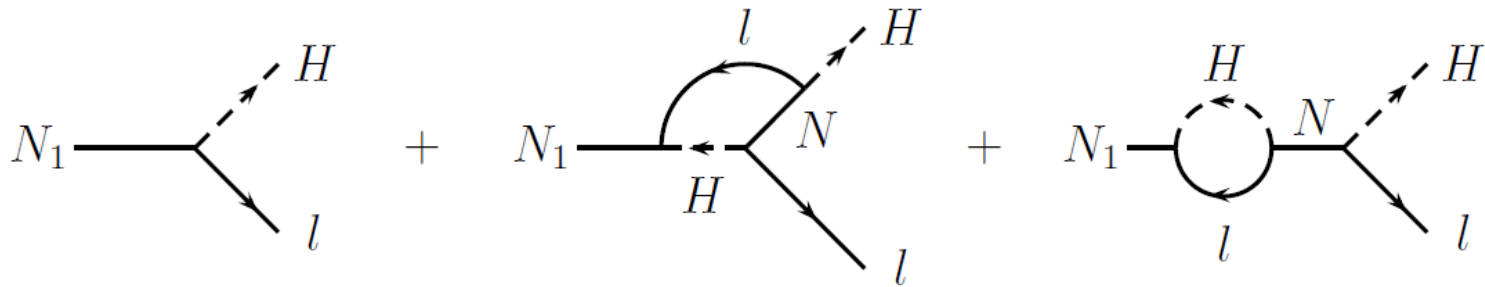
Tricky! Calculable only when $|M_i - M_1| \gg |\Gamma_i - \Gamma_1|$

$$g(x) = \frac{\sqrt{x}}{1-x}$$

Enhancement of the CP asymmetry when the right-handed neutrinos are almost degenerate

1- Generation of the lepton asymmetry

At **one loop**, new diagrams contribute to the decay rate:

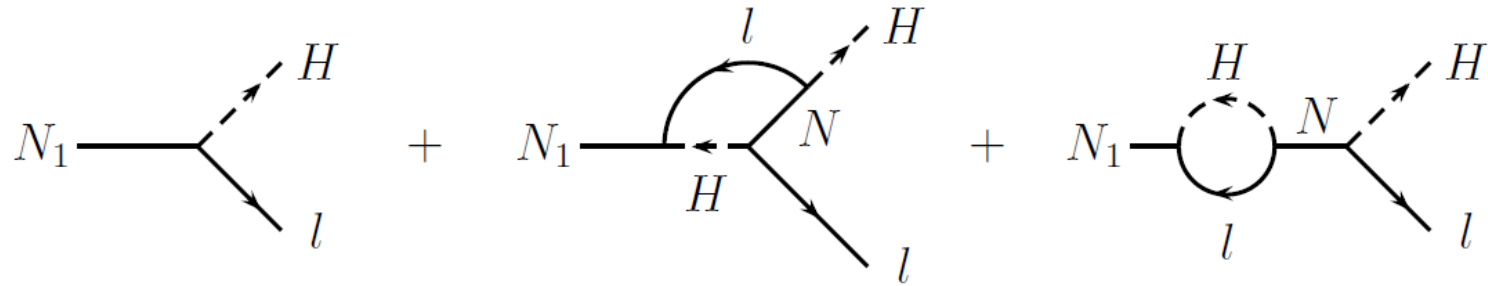


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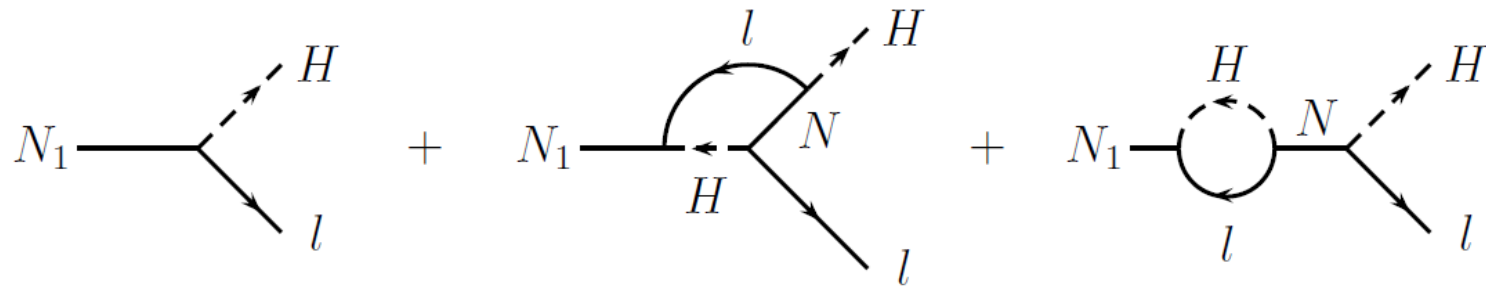


The Yukawa coupling must be complex:
C and CP violation (2nd Sakharov condition)



The CP violating decays generate instantaneously a lepton asymmetry.

Not the end of the story...



The CP violating decays generate instantaneously a lepton asymmetry.

Not the end of the story...

There are also inverse decays which wash-out the lepton asymmetry generated



If these processes are in equilibrium, there is no net effect. It is necessary a departure from thermal equilibrium (3rd Sakharov condition)

2- Wash-out of the lepton asymmetry

The abundance of right-handed neutrinos is dictated by a Boltzmann equation:

$$\frac{dN_{N_1}}{dz} = -D (N_{N_1} - N_{N_1}^{\text{eq}})$$

$$z \equiv \frac{M_1}{T} = \frac{\text{Mass of the lightest RH neutrino}}{\text{temperature}}$$

2- Wash-out of the lepton asymmetry

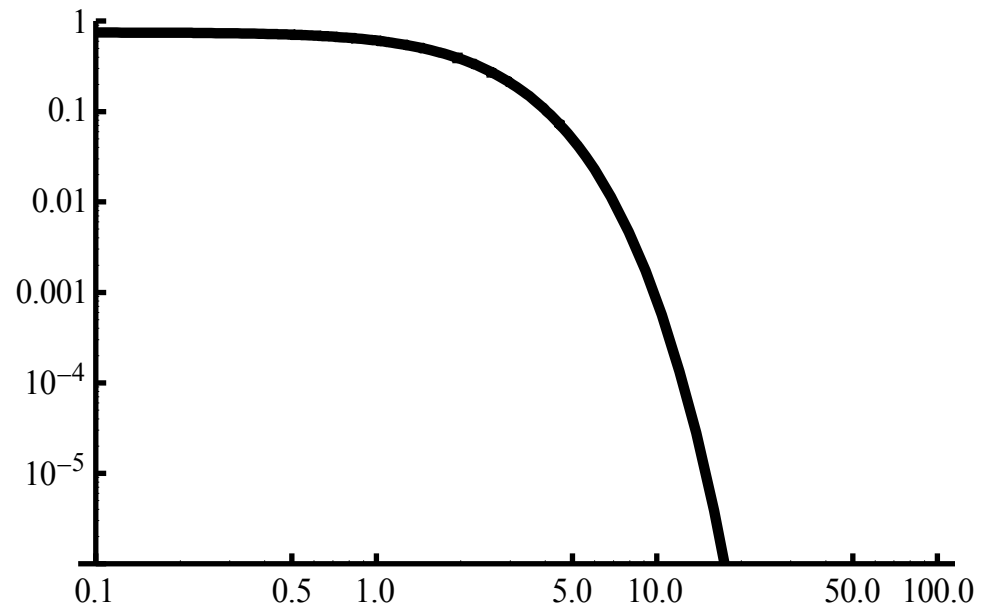
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Equilibrium distribution

$$N_{N_1}^{\text{eq}}(z) = \frac{3}{8} z^2 K_2(z)$$



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Decay term

$$D(z) = \Gamma_D(z)/(Hz)$$

Hubble rate at temperature T

$$H(T) \simeq \sqrt{\frac{8\pi^3 g_*}{90}} \frac{T^2}{M_P}$$
$$= 1.66 g_*^{1/2} \frac{M_1^2}{M_P} \frac{1}{z^2}$$

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It is convenient to write the decay term as a function of the “decay parameter” K :

$$K = \frac{\Gamma_{D_1}|_{T=0}}{H|_{T=M_1}} = \frac{\frac{1}{8\pi}(hh^\dagger)_{11}M_1}{1.66g_*^{1/2}\frac{M_1^2}{M_P}} = \frac{(hh^\dagger)_{11}\frac{v^2}{M_1}}{8\pi 1.66g_*^{1/2}\frac{v^2}{M_P}} = \frac{\tilde{m}_1}{m_*}$$

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

“Effective neutrino mass”

$$m_* = 8\pi 1.66g_*^{1/2} \frac{v^2}{M_P} \simeq 10^{-3} \text{ eV}$$

“Equilibrium neutrino mass”

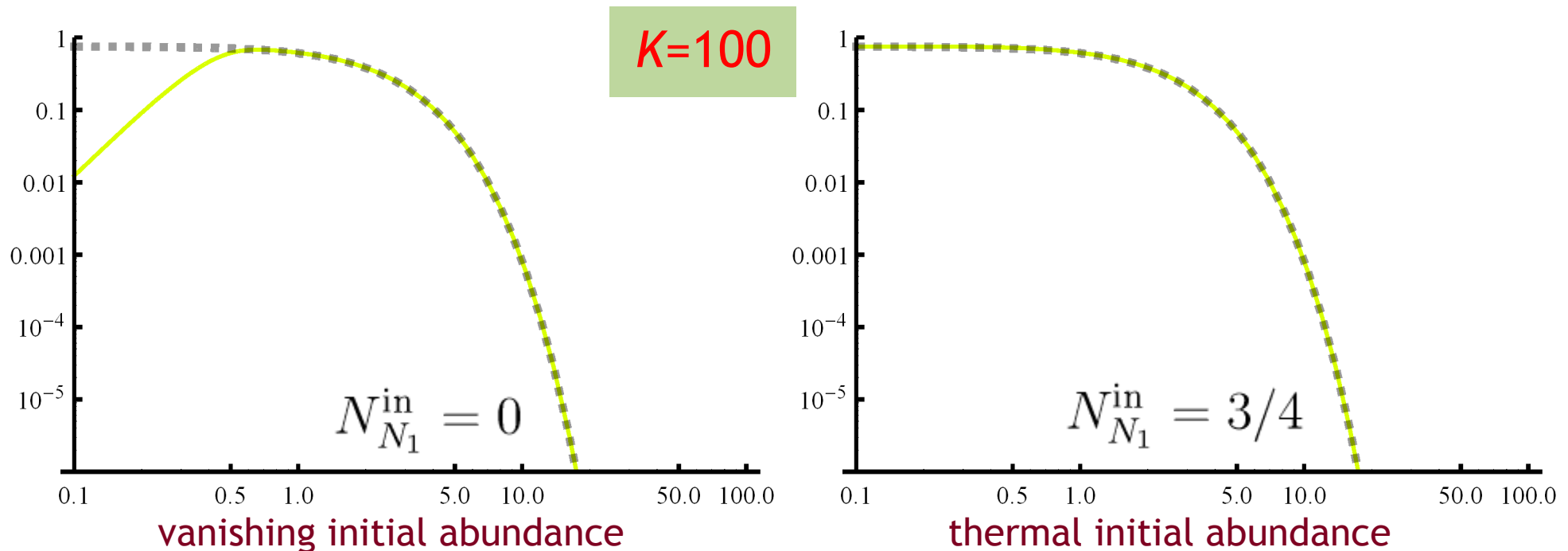
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The solution depends on the initial condition and on K (or \tilde{m}_1)



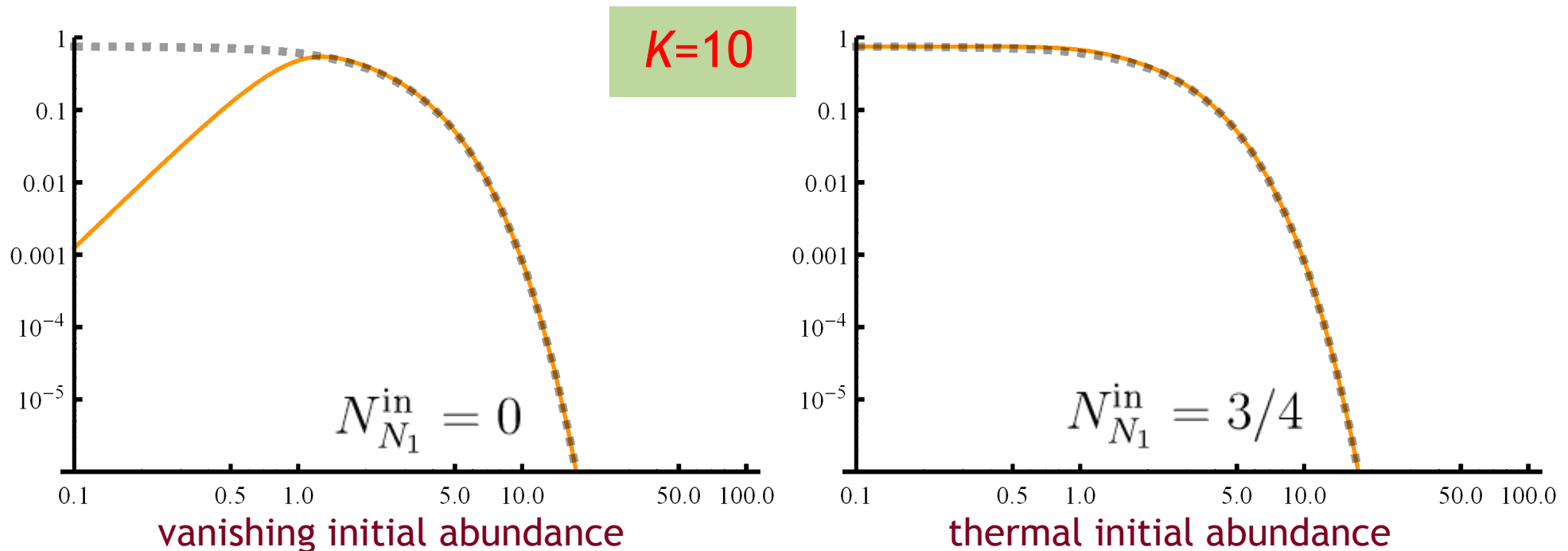
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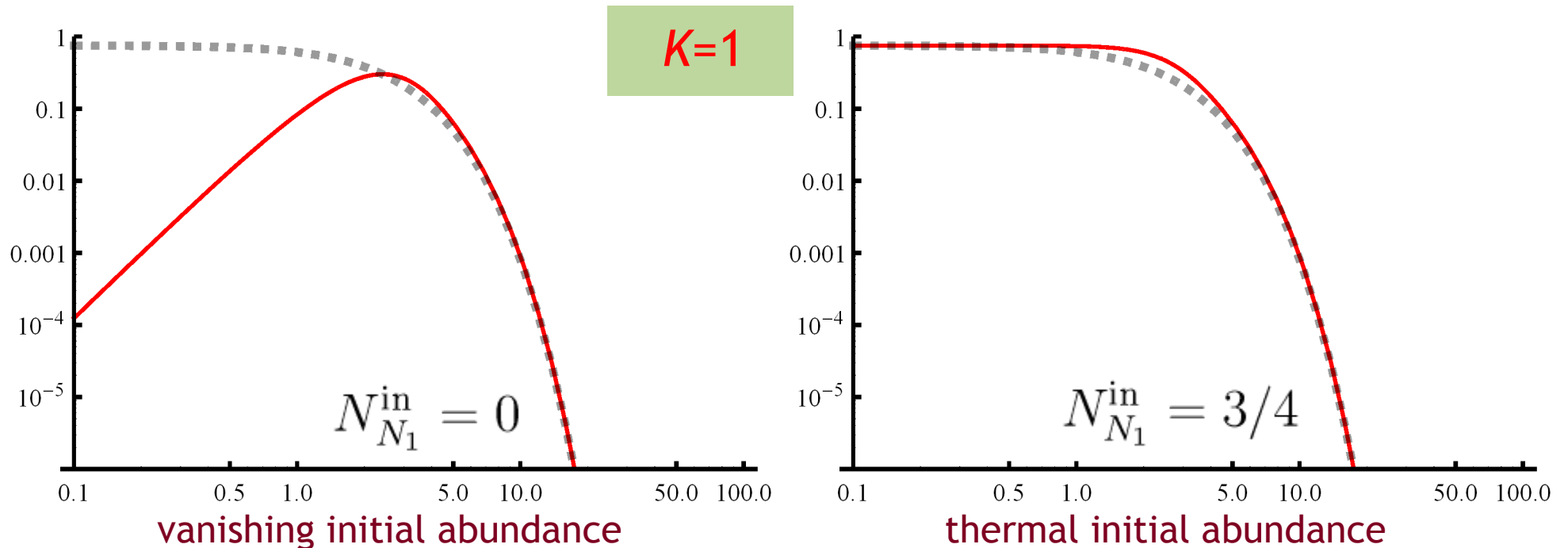
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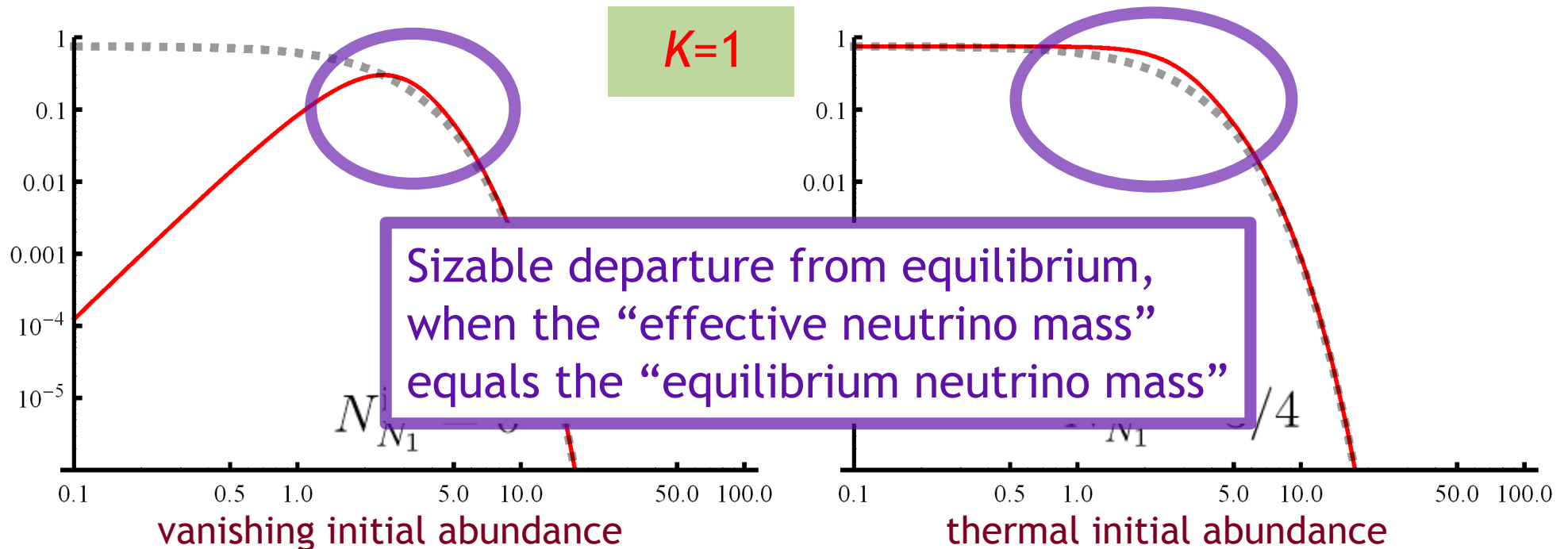
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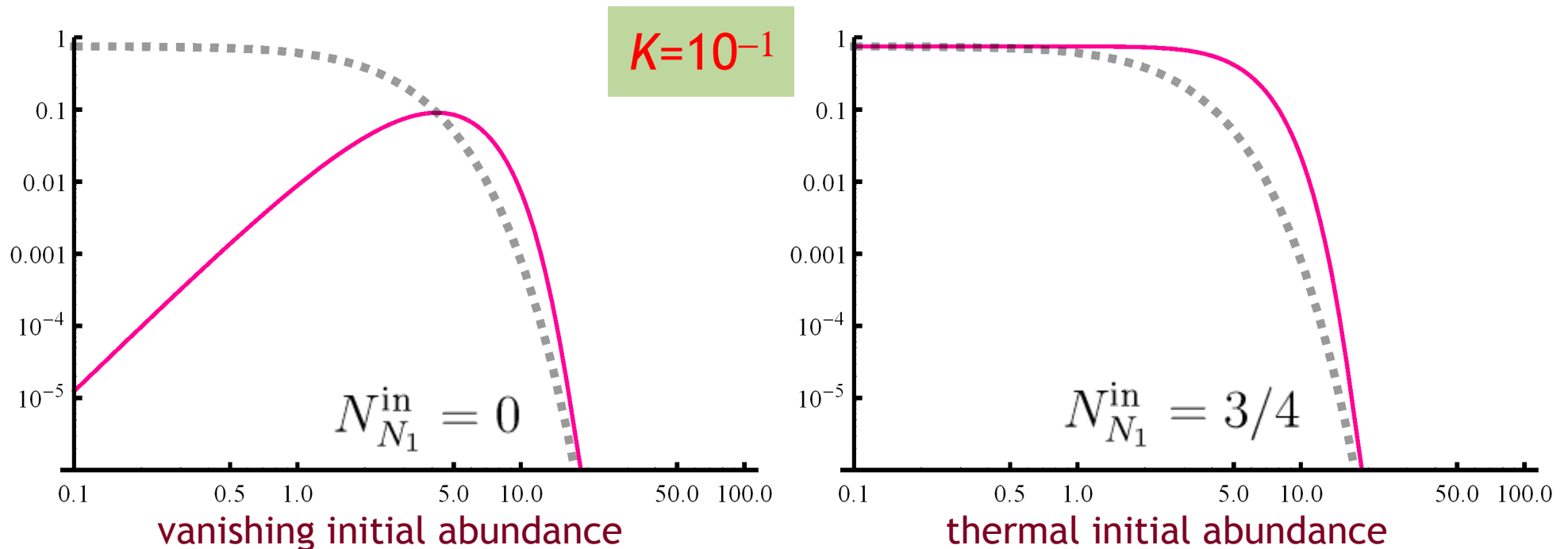
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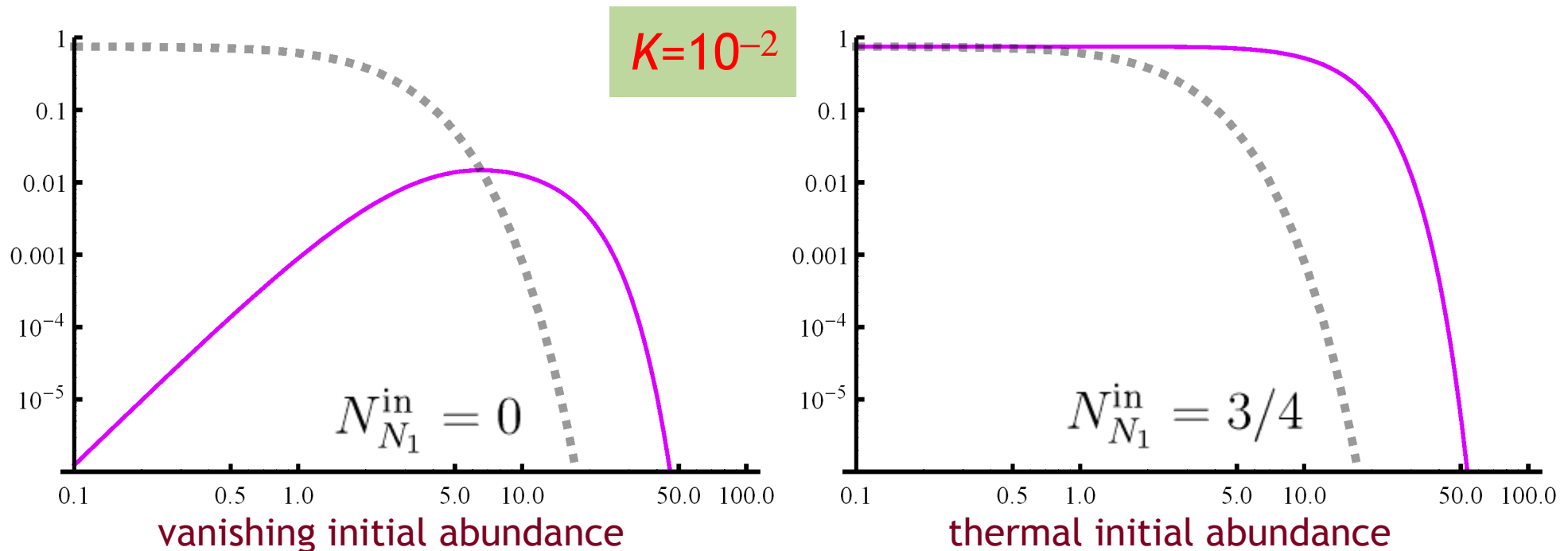
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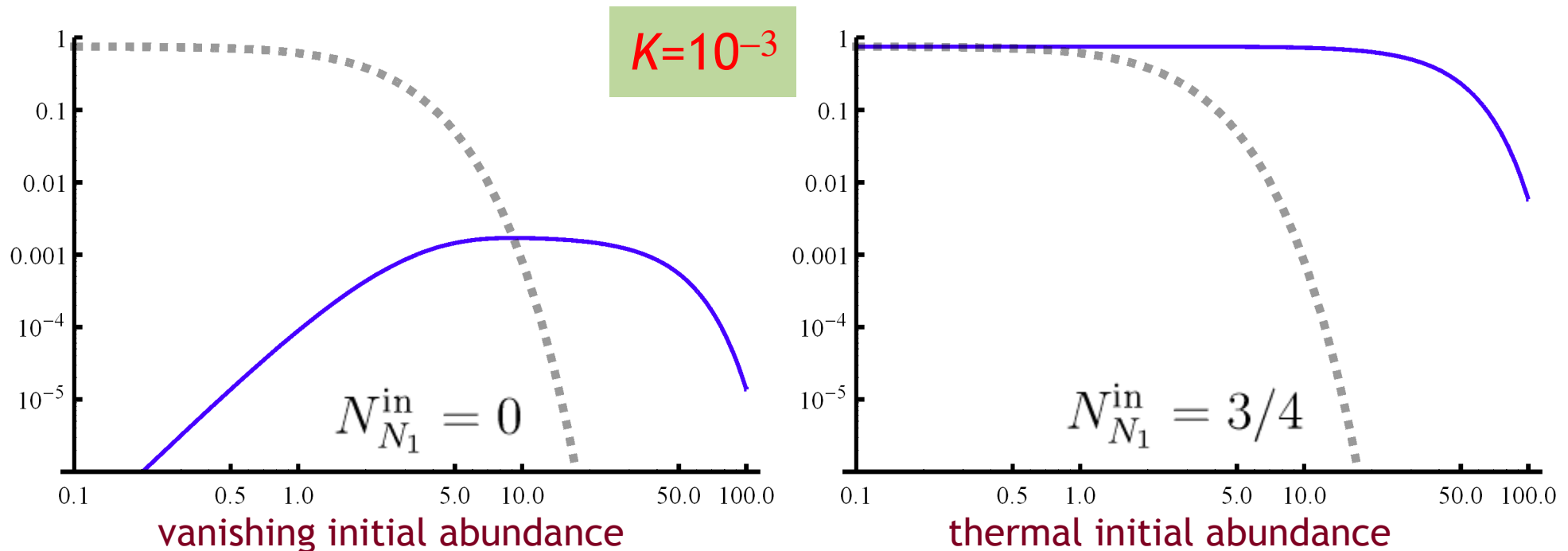
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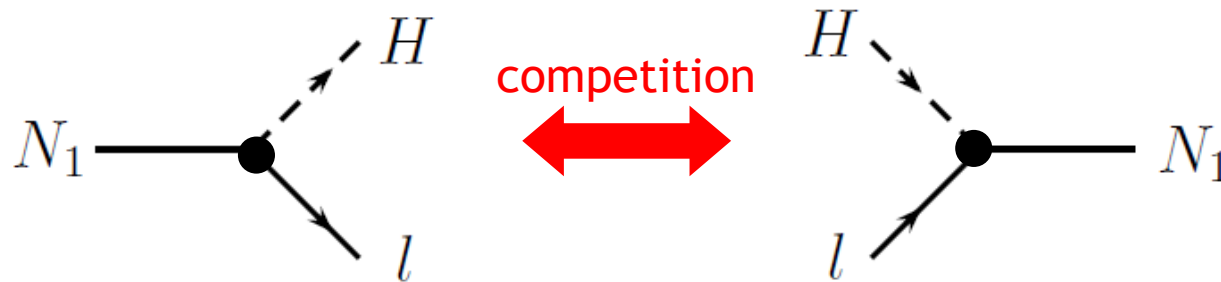
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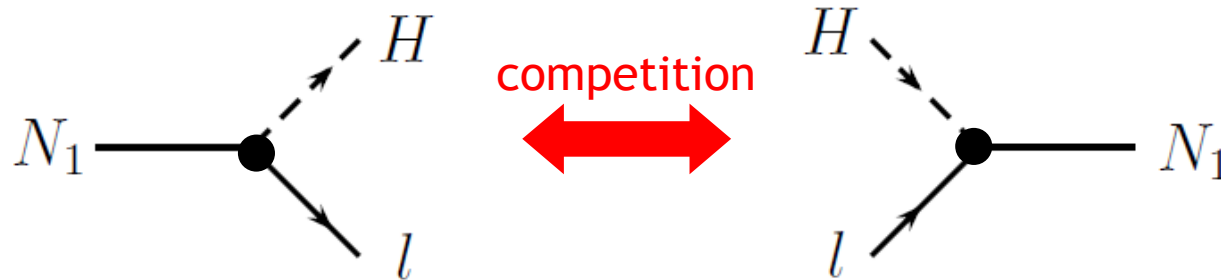
Remember: leptogenesis is a competition between decays (which generate an asymmetry) and inverse decays (which erase the asymmetry)



We have seen the conditions to keep these processes out of equilibrium. What is the effect on the B-L asymmetry?

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - W_{ID} N_{B-L}$$

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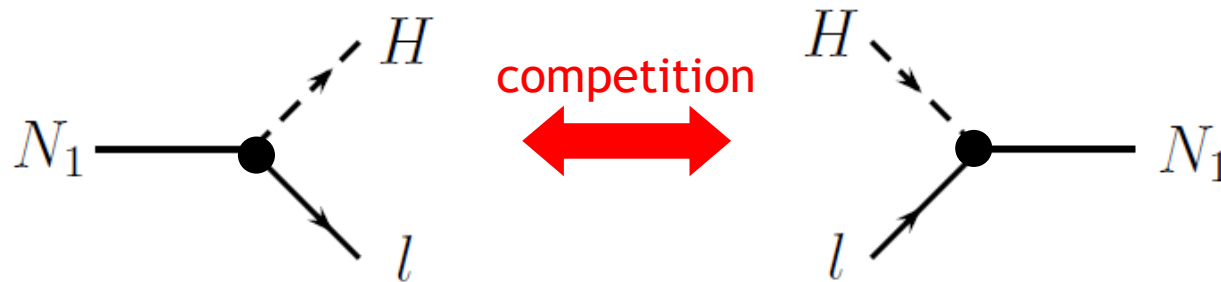
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Generates a B-L asymmetry.

The size depends on the CP asymmetry,
on the decay rate and on how many
right-handed neutrinos are out of equilibrium

Remember: leptogenesis is a competition between decays (which generate an asymmetry) and inverse decays (which erase the asymmetry)

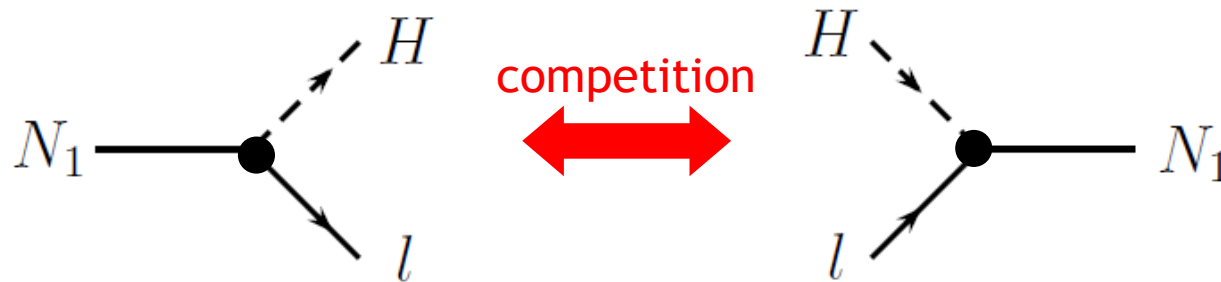


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$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - W_{ID} N_{B-L}$$

Washes-out the B-L asymmetry.
Depends on how large is the B-L asymmetry itself and is proportional to the rate of inverse decays.

Remember: leptogenesis is a competition between decays (which generate an asymmetry) and inverse decays (which erase the asymmetry)



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$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - W_{ID} N_{B-L}$$

$$W_{ID}(z) = \Gamma_W(z)/(Hz)$$

The washout rate is related to the rate of inverse decay, which is in turn related to the rate of decay:

$$\Gamma_{ID}(z) = \Gamma_D(z) \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}}$$

$$N_{N_1}^{\text{eq}}(z) = \frac{3}{8} z^2 K_2(z)$$

$$N_l^{\text{eq}} = \frac{3}{4}$$

Then,

$$W_{ID}(z) = \frac{1}{2} D(z) \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}}$$

Set of Boltzmann equations

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - W_{ID} N_{B-L}$$

$$\frac{dN_{N_1}}{dz} = -D (N_{N_1} - N_{N_1}^{\text{eq}})$$

Set of Boltzmann equations

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} K z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$

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The solution depends on:

- Initial abundance of right-handed neutrinos

$$N_{N_1}^{\text{in}} = 0 \quad \text{or} \quad N_{N_1}^{\text{in}} = 3/4$$

- “Effective neutrino mass”, \tilde{m}_1 , through $K = \frac{\tilde{m}_1}{m_*}$

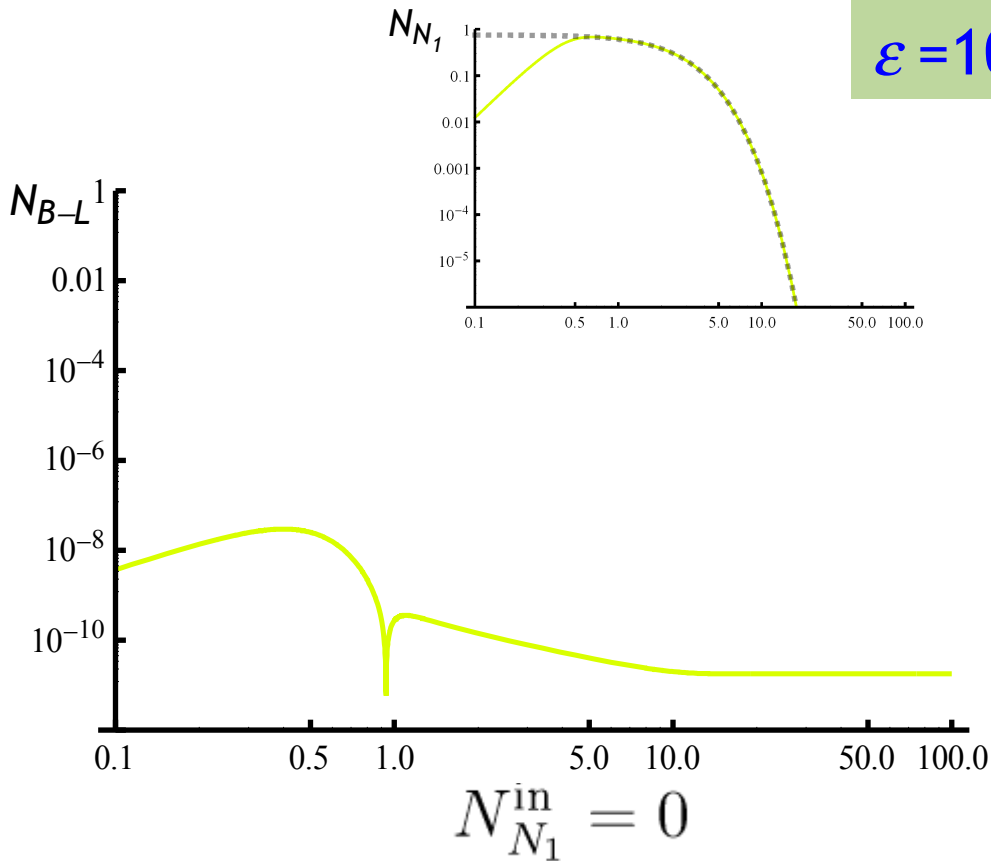
- CP asymmetry, ϵ

Set of Boltzmann equations

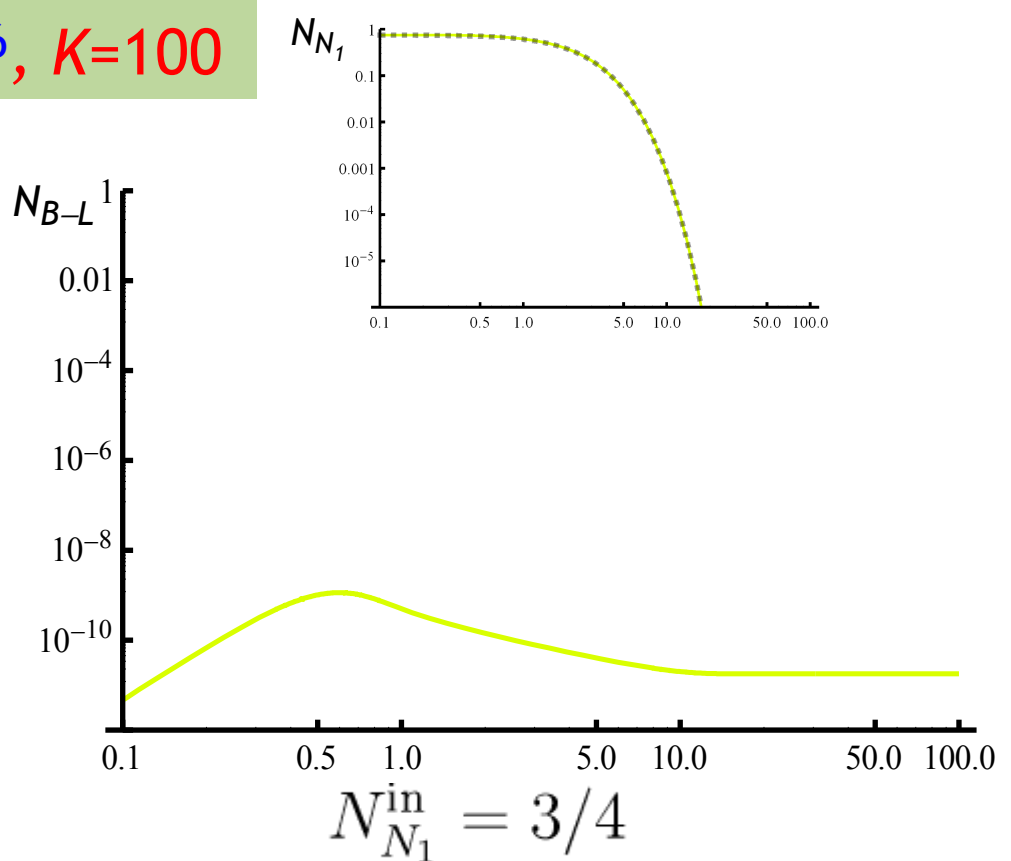
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$\epsilon = 10^{-6}, K = 100$



vanishing initial abundance



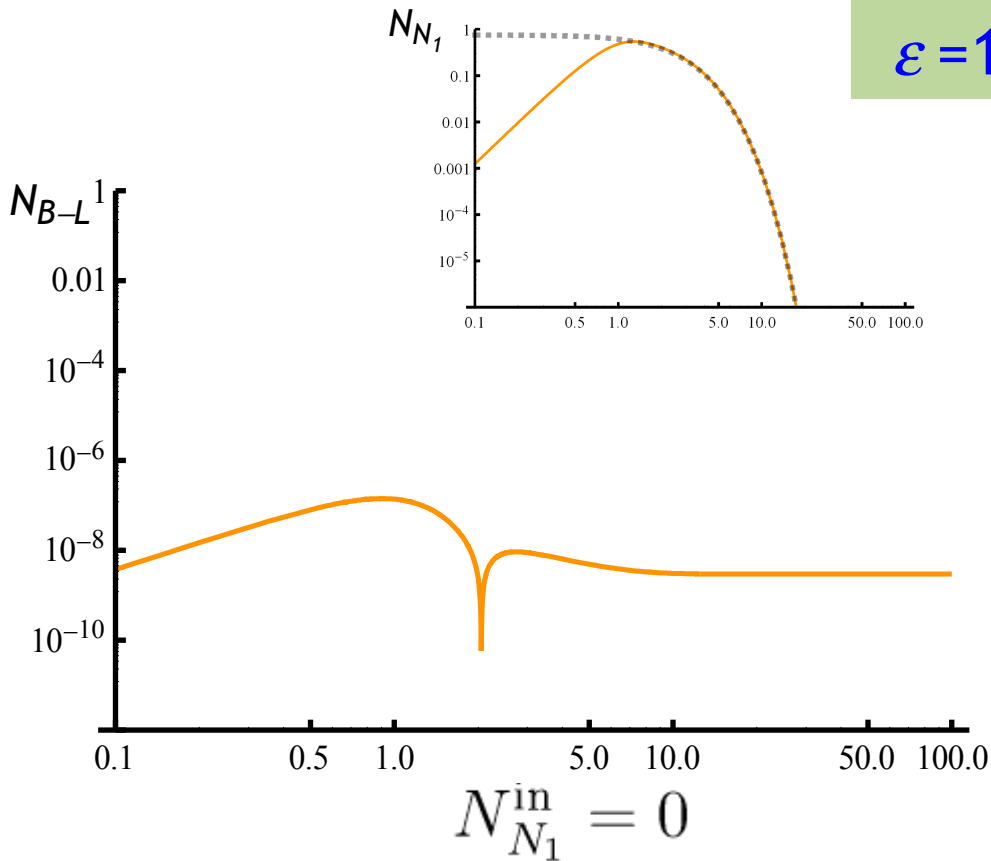
thermal initial abundance

Set of Boltzmann equations

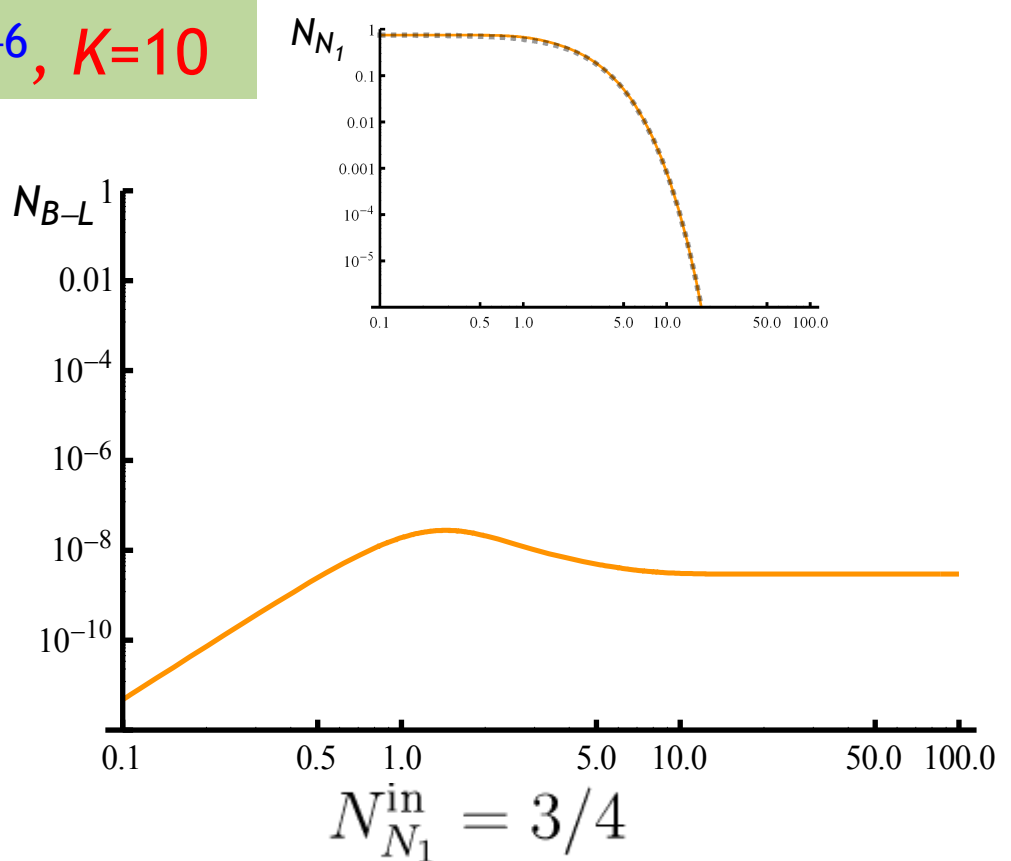
$$\frac{dN_{B-L}(z)}{dz} = -\epsilon K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} K z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$

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vanishing initial abundance



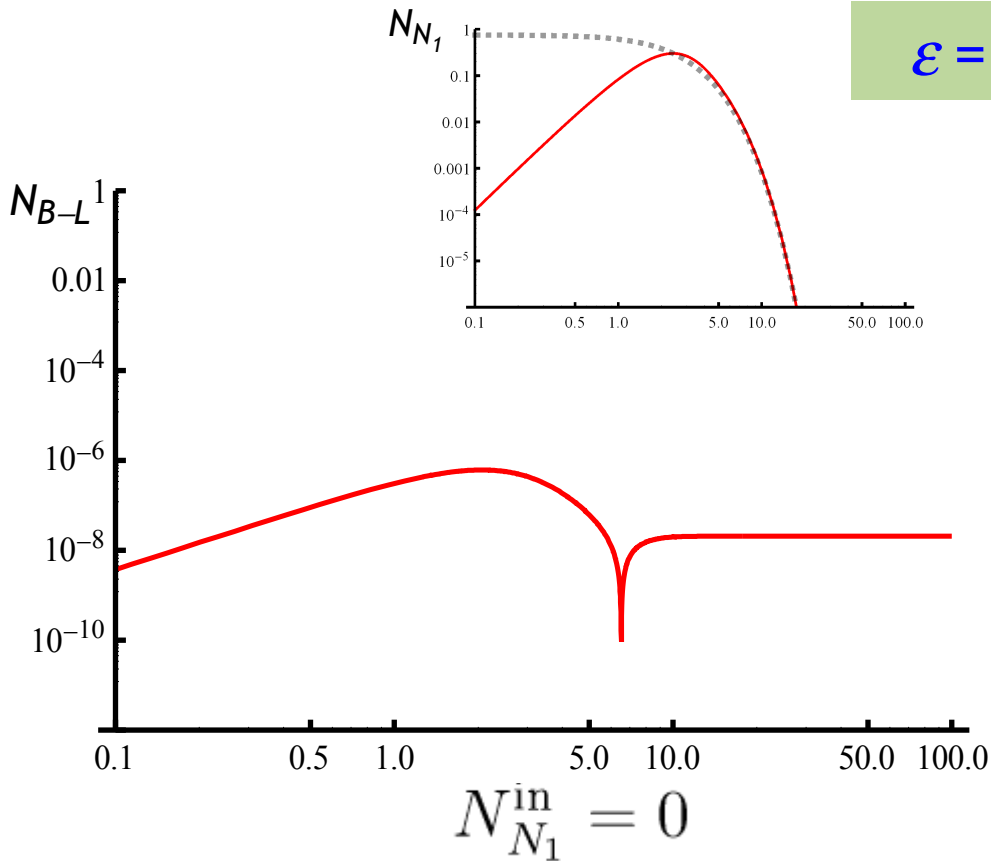
thermal initial abundance

Set of Boltzmann equations

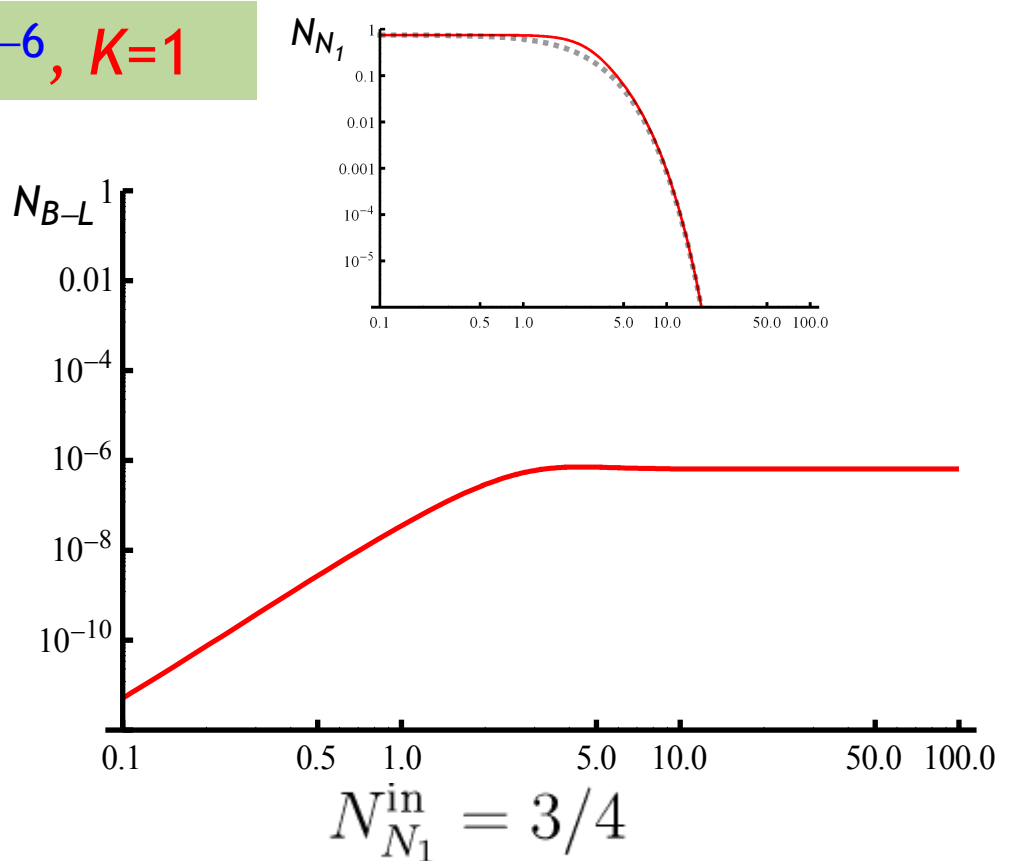
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vanishing initial abundance



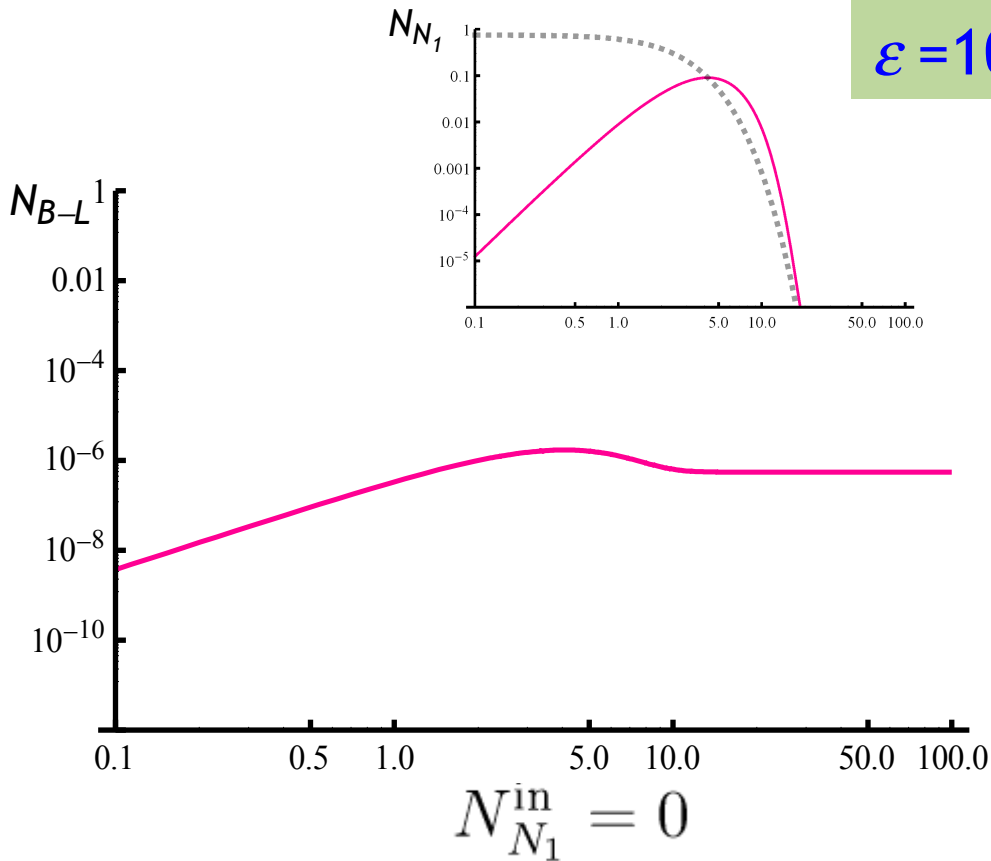
thermal initial abundance

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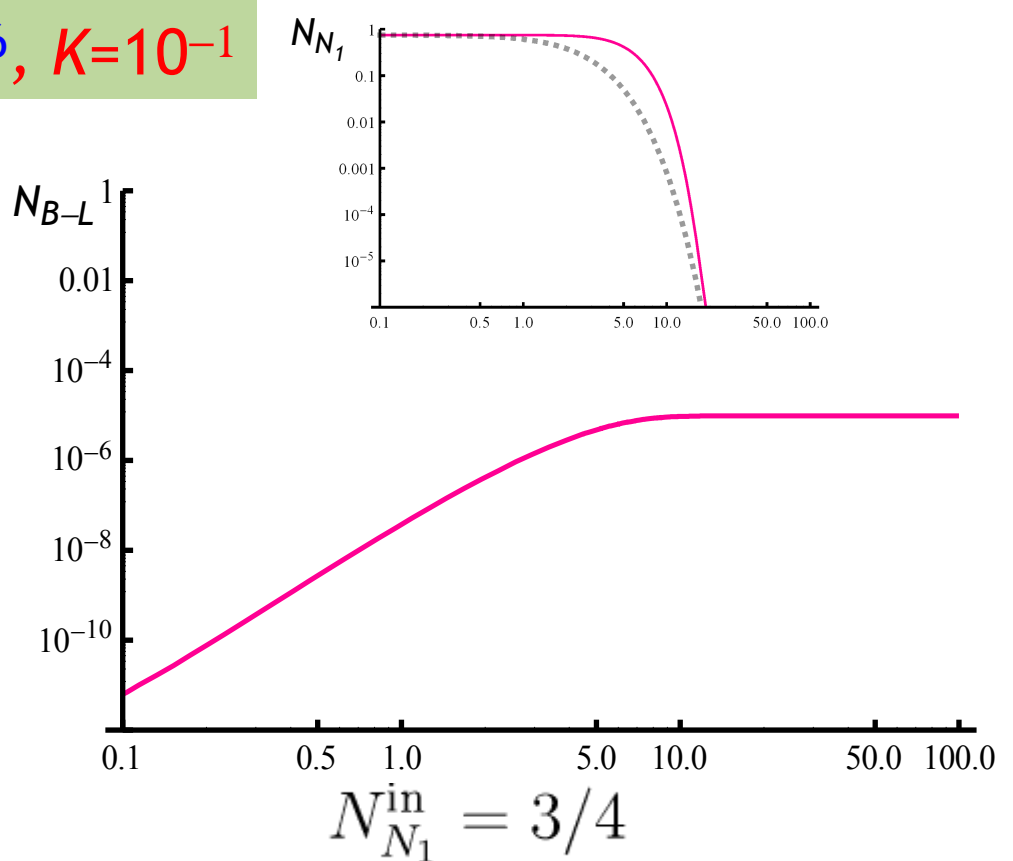
$$\frac{dN_{B-L}(z)}{dz} = -\epsilon K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} K z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$

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vanishing initial abundance



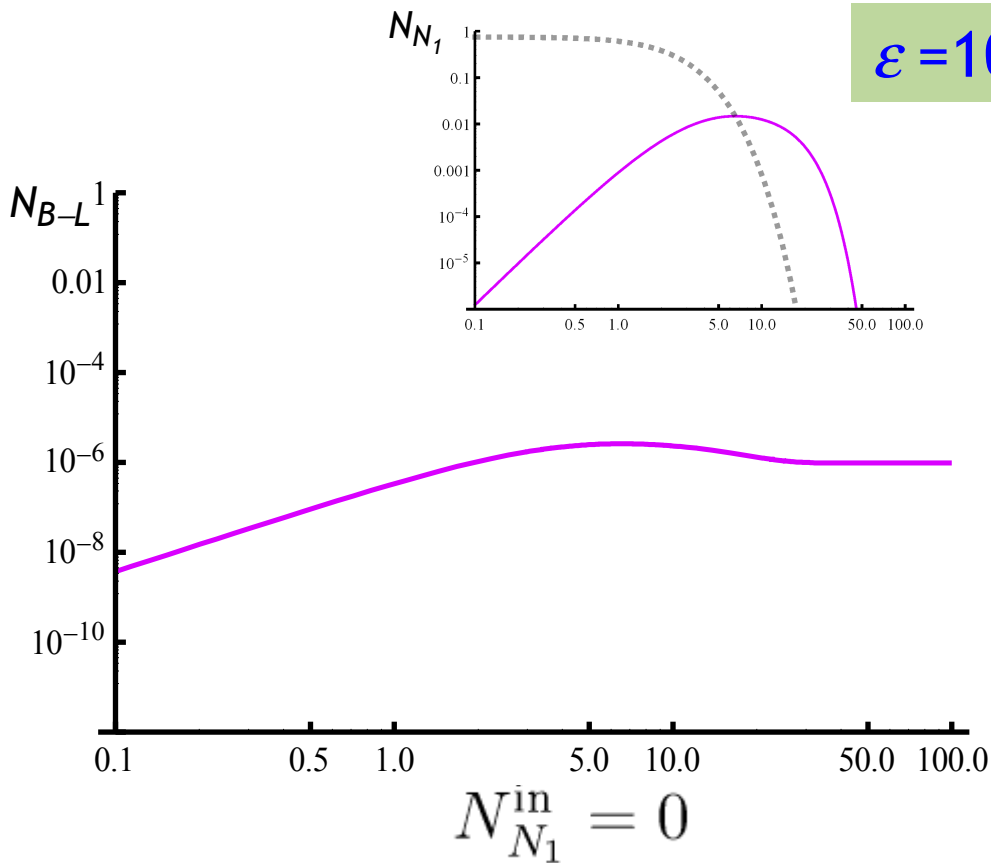
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Set of Boltzmann equations

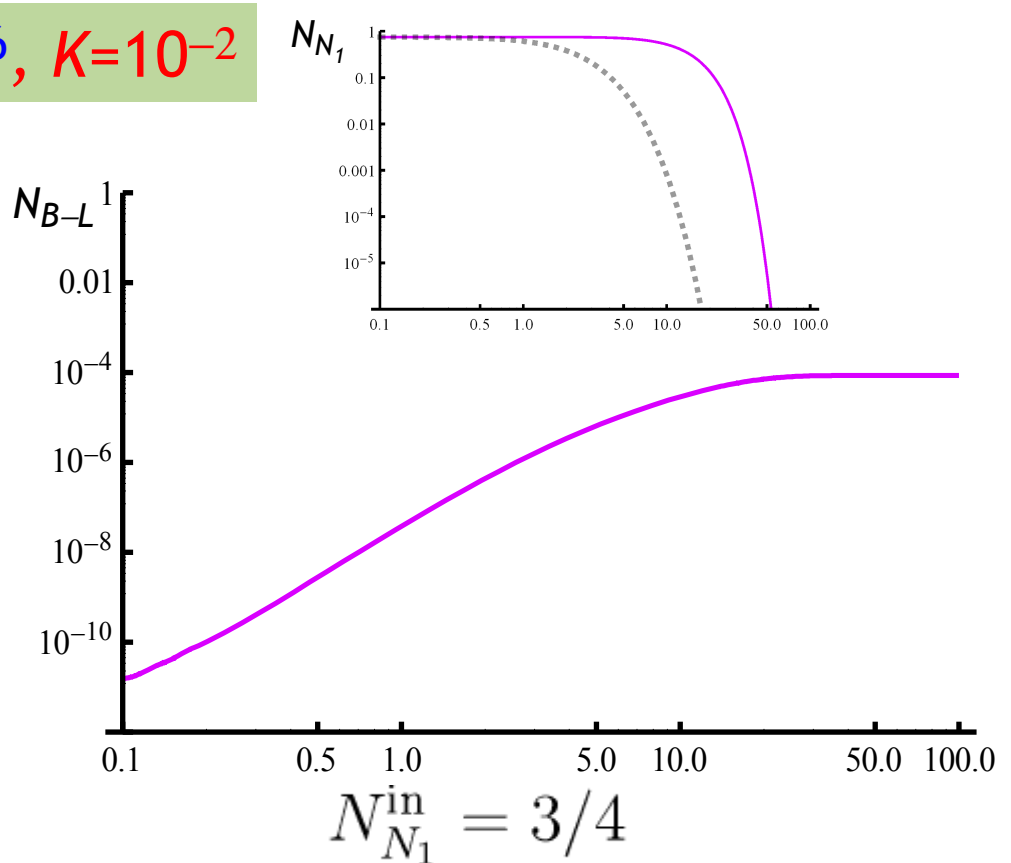
$$\frac{dN_{B-L}(z)}{dz} = -\epsilon K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} K z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$

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$$\epsilon = 10^{-6}, K = 10^{-2}$$



vanishing initial abundance



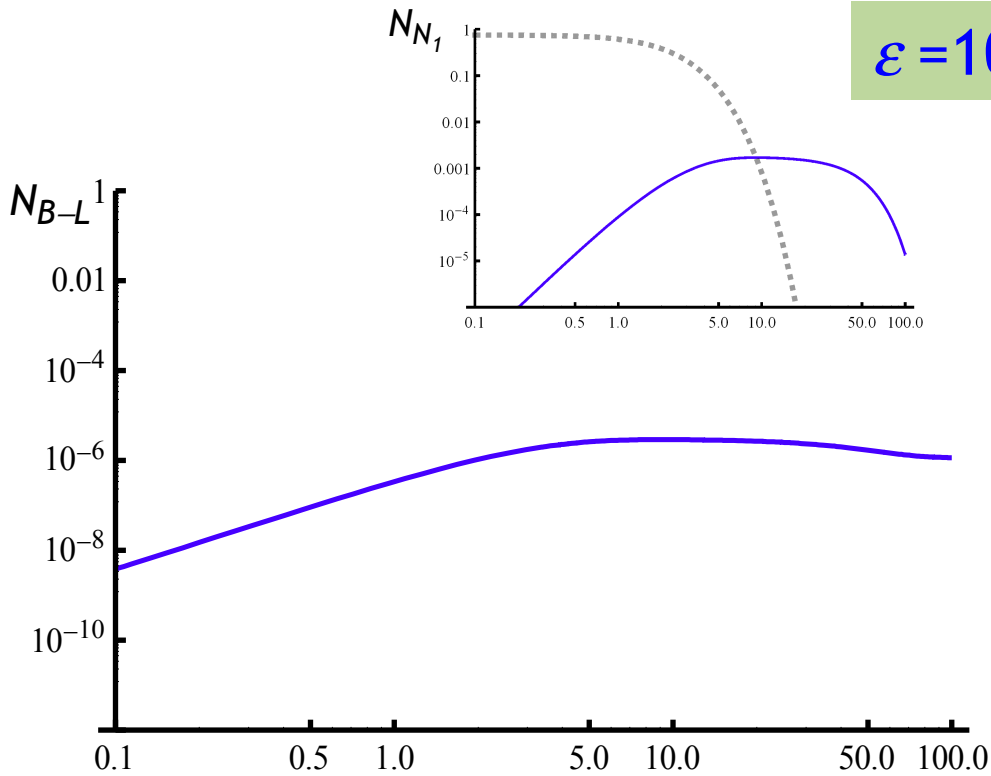
thermal initial abundance

Set of Boltzmann equations

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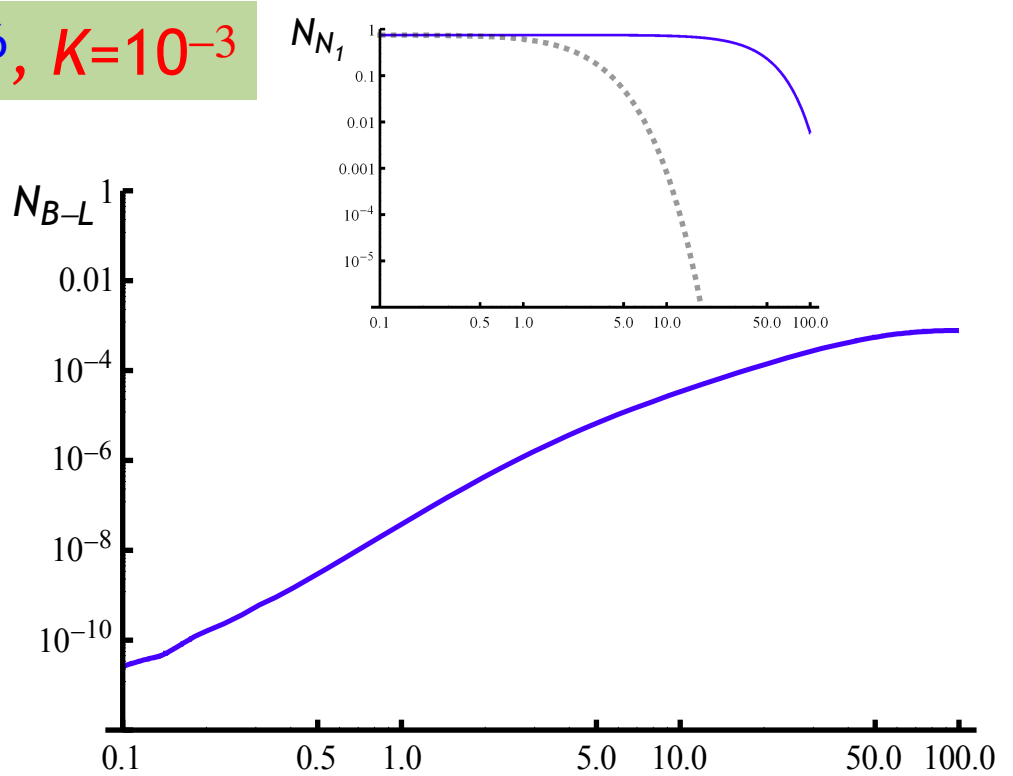
$$\frac{dN_{N_1}(z)}{dz} = -K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z))$$

$$\epsilon = 10^{-6}, K = 10^{-3}$$



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

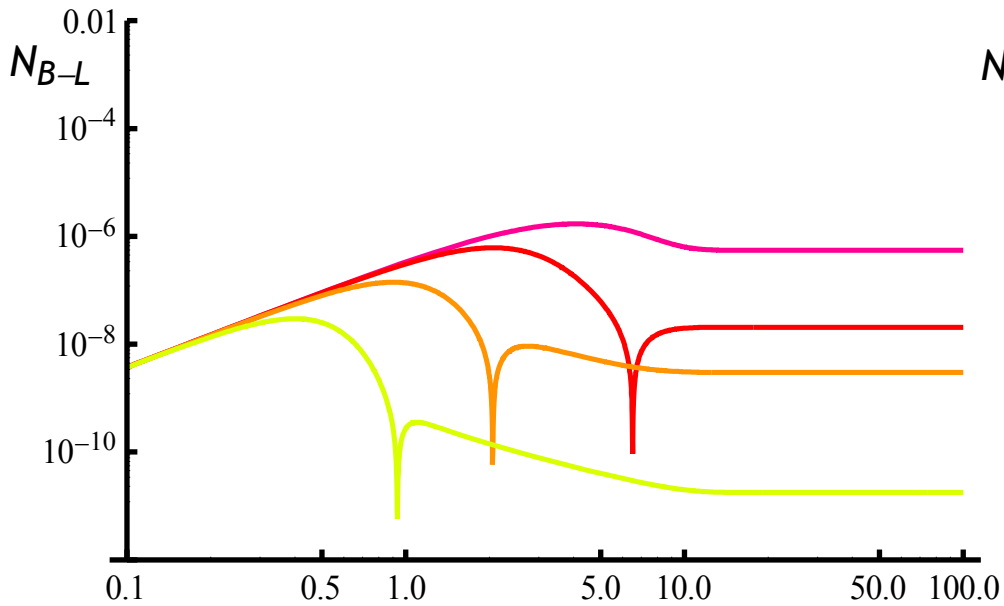
vanishing initial abundance



$$N_{N_1}^{\text{in}} = 3/4$$

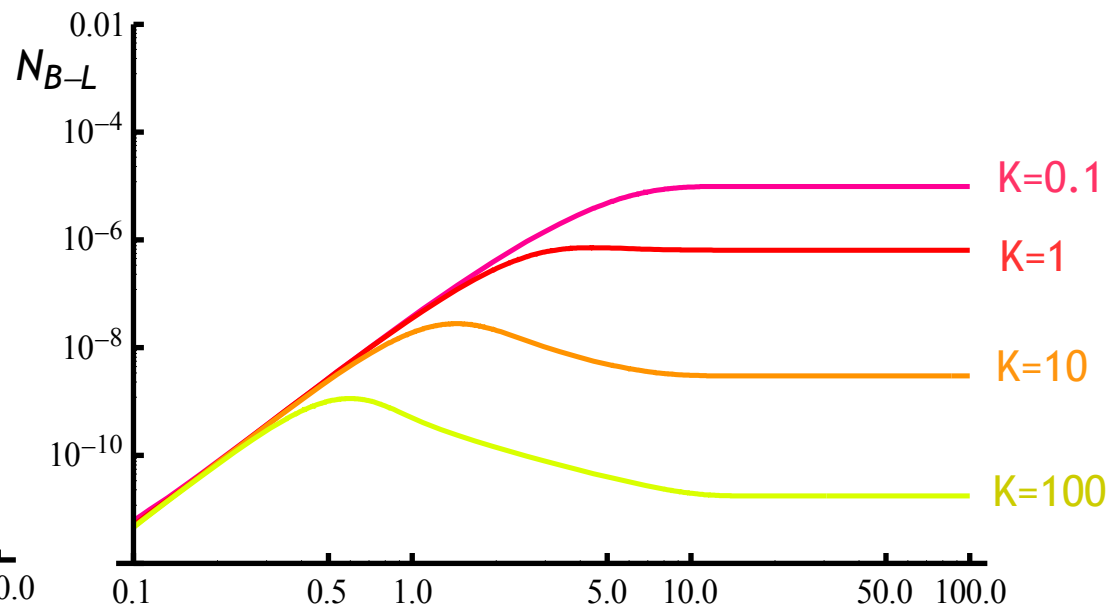
thermal initial abundance

Note that when $K \gg 1$ (strong washout) the final asymmetry is the same, independently of the initial condition:



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

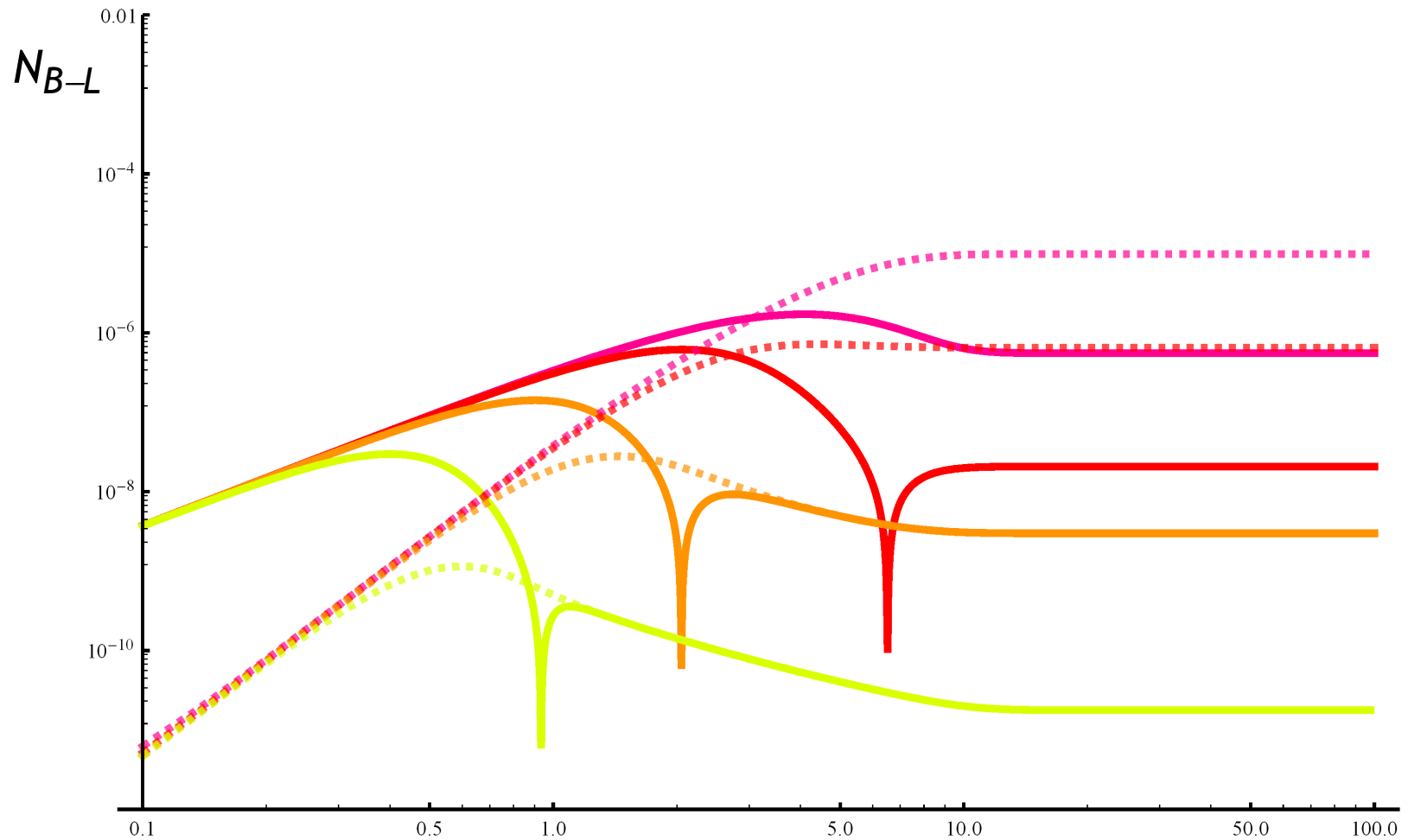
vanishing initial abundance



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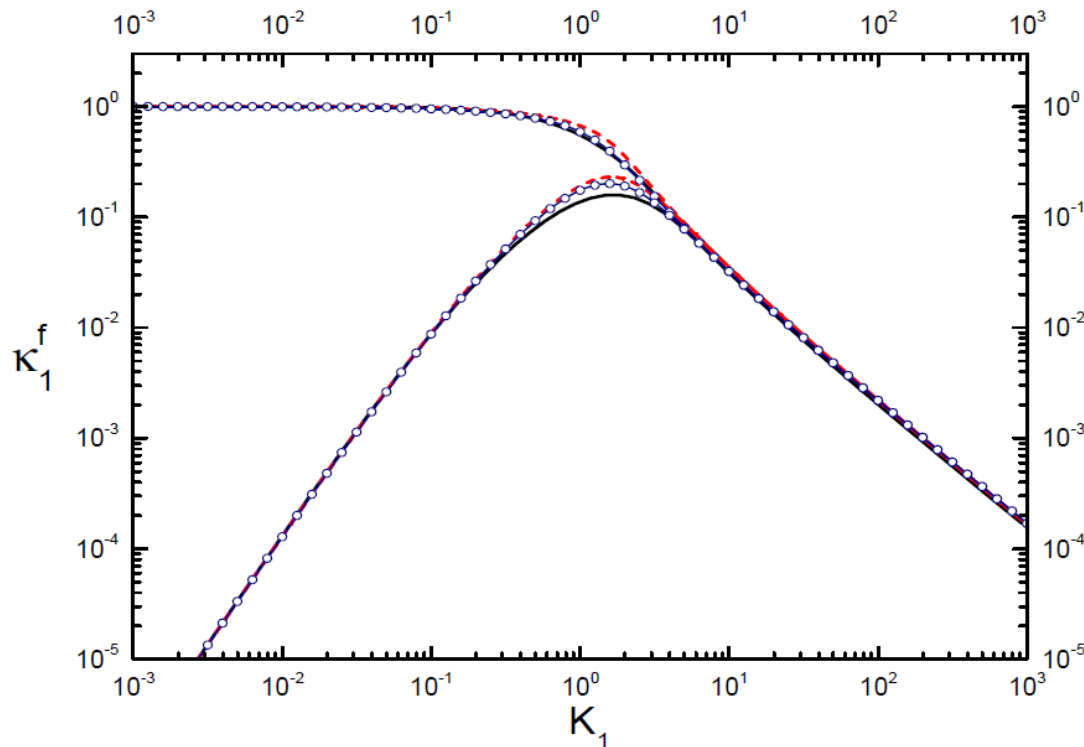
Note that when $K \gg 1$ (strong washout) the final asymmetry is the same, independently of the initial condition:



The solution is usually expressed in terms of an “efficiency factor” (assuming that initially there is no B-L asymmetry)

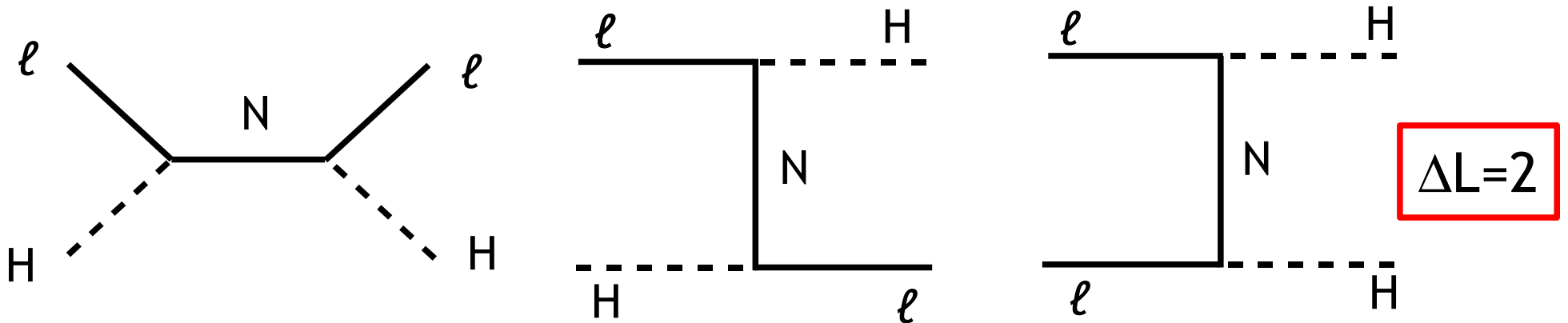
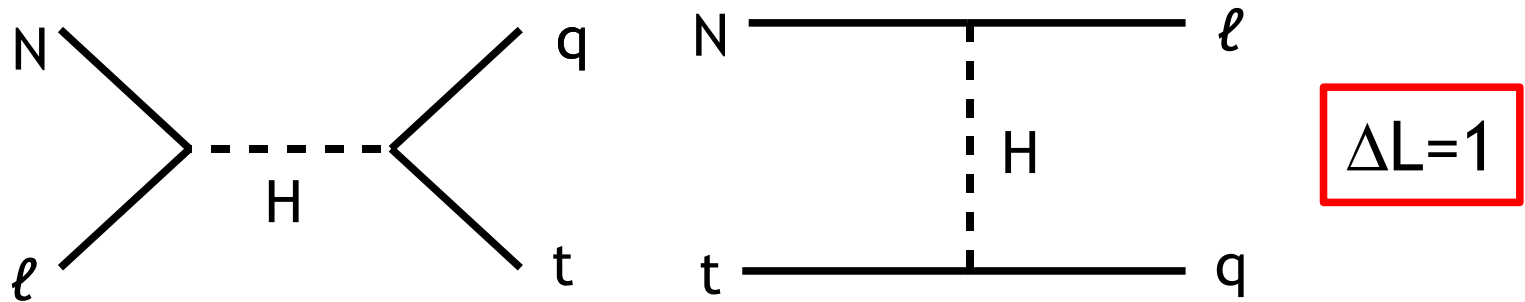
$$N_{B-L}(z) = -\frac{3}{4} \epsilon_1 \kappa(z_i, z, \tilde{m}_1)$$

$$\kappa(z_i, z, \tilde{m}_1) = \frac{4}{3} \int_{z_i}^z dz' D(N_{N_1} - N_{N_1}^{\text{eq}}) e^{-\int_{z'}^z dz'' W_{ID}(z'')}$$



An additional effect on leptogenesis: scatterings

In addition to decays and inverse decays, scatterings can also bring the right-handed neutrinos into equilibrium or washout the B-L asymmetry, through:

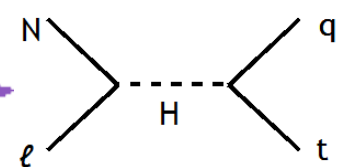
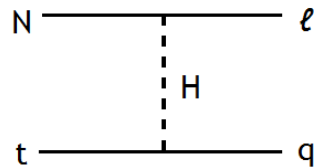


Including these effects, the Boltzmann equations read:

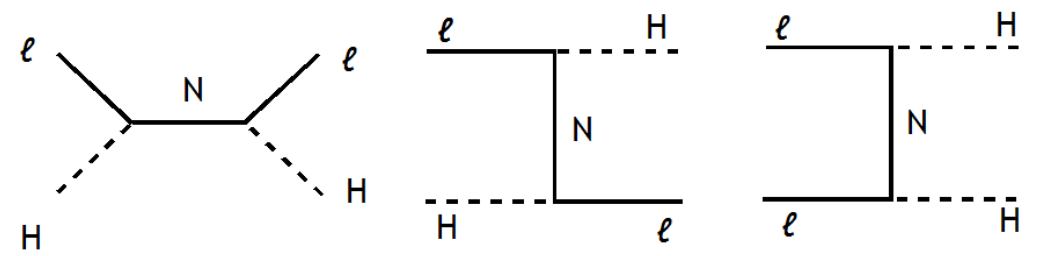
$$\frac{dN_{N_1}}{dz} = -(D + S) (N_{N_1} - N_{N_1}^{\text{eq}})$$

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - (W_{ID} + W_{\Delta L=2}) N_{B-L}$$

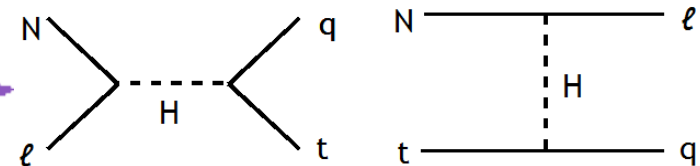
Including these effects, the Boltzmann equations read:

$$\frac{dN_{N_1}}{dz} = -(D + S)(N_{N_1} - N_{N_1}^{\text{eq}})$$



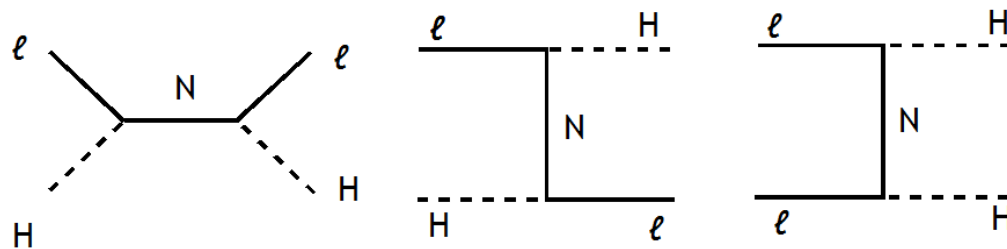
$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - (W_{ID} + W_{\Delta L=2}) N_{B-L}$$



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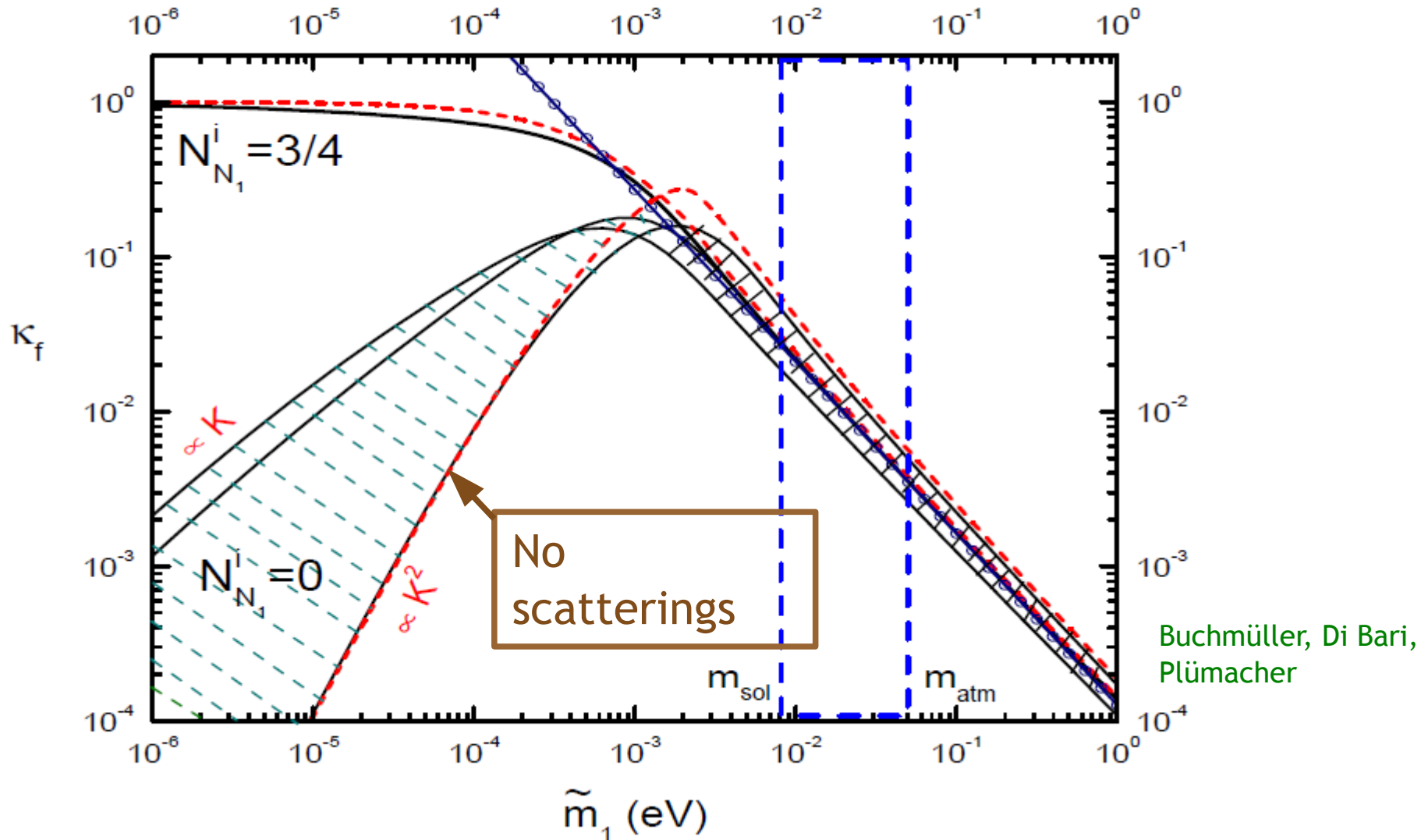
Similar diagrams to the one giving neutrino masses:

$$W_{\Delta L=2} \simeq \frac{0.186}{z^2} \left(\frac{M_1}{10^{10} \text{ GeV}} \right) \left(\frac{\bar{m}}{1 \text{ eV}} \right)^2$$

$$\bar{m}^2 = m_1^2 + m_2^2 + m_3^2$$

The solution can still be written in the form:

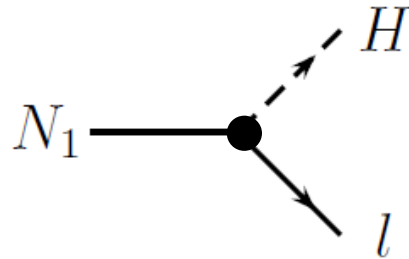
$$N_{B-L}(z) = -\frac{3}{4} \epsilon_1 \kappa(z_i, z, \tilde{m}_1)$$



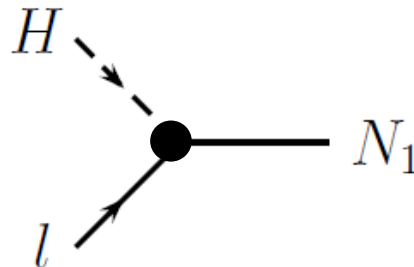
Recapitulation

Roughly speaking, the generation of a BAU through leptogenesis proceeds in three steps:

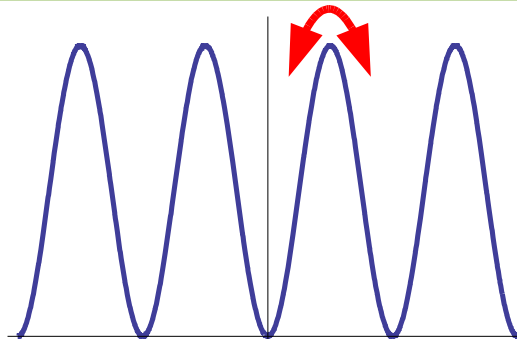
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.

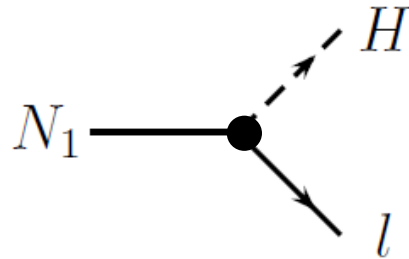


3- Conversion of the lepton asymmetry into a baryon asymmetry.



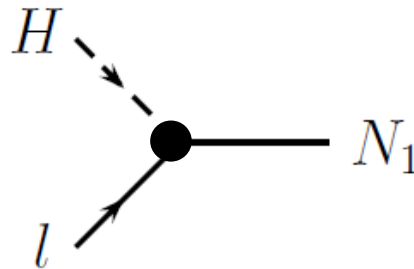
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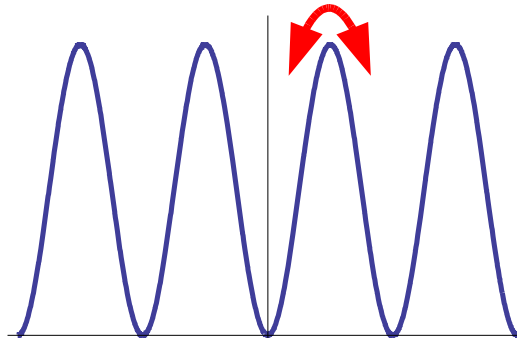


Done!

2- Washout of the lepton asymmetry.

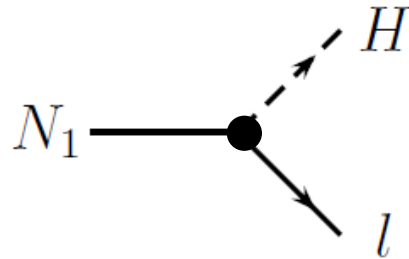


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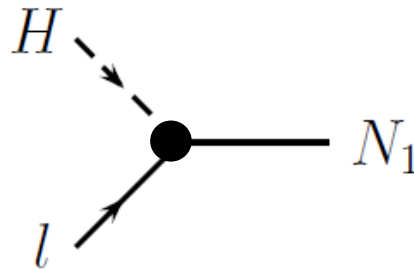
Roughly speaking, the generation of a BAU through leptogenesis proceeds in three steps:

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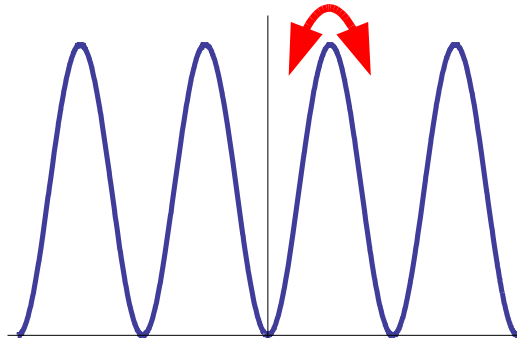
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3- Conversion of the lepton asymmetry into a baryon asymmetry

In a weakly coupled plasma, it is possible to assign a chemical potential to each particle specie

$$n_i - \bar{n}_i = \frac{gT^3}{6} \begin{cases} \beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) & \text{fermions} \\ 2\beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) & \text{bosons} \end{cases}$$

Thus, the asymmetry between the number of baryons (leptons) and antibaryons (antileptons) is:

$$n_B - n_{\bar{B}} = \frac{1}{6} g T^2 \sum_{i=1}^{N_f} (2\mu_{Q_i} + \mu_{u_i} + \mu_{d_i})$$
$$n_L - n_{\bar{L}} = \frac{1}{6} g T^2 \sum_{i=1}^{N_f} (2\mu_{\ell_i} + \mu_{e_i})$$

In thermal equilibrium there are relations among the chemical potentials

- The effective 12-fermion interactions O_{B+L} induced by sphalerons leads to:

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

- The SU(3) QCD instanton processes lead to interactions between LH and RH quarks, described by the operator $\prod_i (q_{L_i} q_{L_i} u_{R_i}^c d_{R_i}^c)$. When they are in equilibrium, they lead to:

$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0$$

- The total hypercharge of the plasma must vanish, leading to:

$$\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f} \mu_H) = 0$$

- If the Yukawa interactions are in thermal equilibrium, the chemical potentials satisfy:

$$\mu_{q_i} - \mu_H - \mu_{d_j} = 0 ,$$

$$\mu_{q_i} + \mu_H - \mu_{u_j} = 0 ,$$

$$\mu_{\ell_i} - \mu_H - \mu_{e_j} = 0 .$$

Assuming equilibrium among different generations, all the chemical potentials can be written in terms of μ_ℓ .

$$\mu_e = \frac{2N_f + 3}{6N_f + 3}\mu_\ell, \quad \mu_d = -\frac{6N_f + 1}{6N_f + 3}\mu_\ell, \quad \mu_u = \frac{2N_f - 1}{6N_f + 3}\mu_\ell$$

$$\mu_q = -\frac{1}{3}\mu_\ell, \quad \mu_H = \frac{4N_f}{6N_f + 3}\mu_\ell.$$

Then $B = -\frac{4}{3}N_f\mu_\ell$, $L = \frac{14N_f^2 + 9N_f}{6N_f + 3}\mu_\ell$

Leptogenesis produces a B-L asymmetry. The equilibration, leads to a baryon asymmetry and to a lepton asymmetry given by:

$$B = c(B - L)$$

$$L = (c - 1)(B - L)$$

where $c = \frac{8N_f + 4}{22N_f + 13}$ $\left(c = \frac{8N_f + 4N_H}{22N_f + 13N_H}$ in models with N_H higgses)

$$c = 28/79 \text{ in the SM with three generations}$$

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν, M)

Recipe to calculate the BAU in leptogenesis

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2- Calculate ϵ , $K = \frac{\tilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \text{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \frac{M_1}{M_i}$$

$$\tilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \quad m_* \simeq 10^{-3} \text{ eV}$$

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$$\frac{dN_{N_1}}{dz} = -D (N_{N_1} - N_{N_1}^{\text{eq}})$$

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4- Calculate the baryon-to-photon ratio

$$\eta_B = \frac{c}{f} N_{B-L}^{T=0}$$

$$c = 28/79 \quad f = N_\gamma^{\text{rec}}/N_\gamma^* = 2387/86$$

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Sphaleron conversion

Dilution factor due to photon production between leptogenesis and recombination

Recipe to calculate the BAU in leptogenesis

1- Take your favourite neutrino model (h_ν, M)

2- Calculate ϵ , $K = \frac{\tilde{m}_1}{m_*}$

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \text{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \frac{M_1}{M_i}$$

$$\tilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \quad m_* \simeq 10^{-3} \text{ eV}$$

3- Solve the Boltzmann equations to obtain $N_{B-L}^{T=0}$

$$\frac{dN_{B-L}(z)}{dz} = -\epsilon K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} K z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$

$$\frac{dN_{N_1}(z)}{dz} = -K z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z))$$

4- Calculate the baryon-to-photon ratio

$$\eta_B = \frac{c}{f} N_{B-L}^{T=0}$$

$$c = 28/79 \quad f = N_\gamma^{\text{rec}}/N_\gamma^* = 2387/86$$

5- Compare with the experimental value! $\eta_B = (6.11 \pm 0.19) \times 10^{-10}$

Tomorrow

See-saw
parameters



Neutrino masses
and mixing angles



Leptogenesis

Tomorrow

See-saw
parameters



Neutrino masses
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Leptogenesis

