Leptogenesis

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Leptogenesis is a mechanism to dynamically generate the matter-antimatter asymmetry of our Universe via the out-of-equilibrium decays of heavy right-handed neutrinos during the first 10⁻²⁷ s after the Big Bang.^{*}

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- Neutrino masses and its origin.

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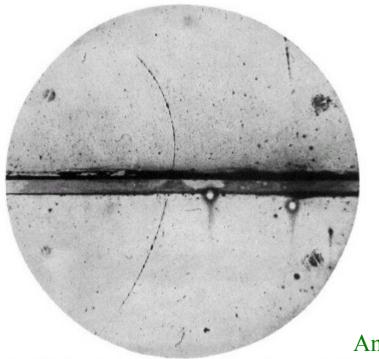
• Dynamical generation of a matter-antimatter asymmetry: Sakharov conditions.

- Neutrino masses and its origin.
- Leptogenesis in three steps.

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 cosmic rays.



Anderson 1932

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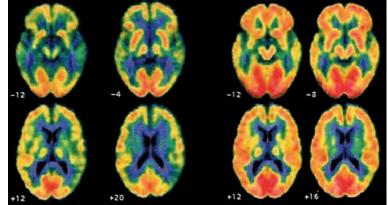


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- It is produced in the decay of some radioactive nuclei.

 $^{40}\text{K} \rightarrow ^{40}\text{Ar} + \nu + e^+$

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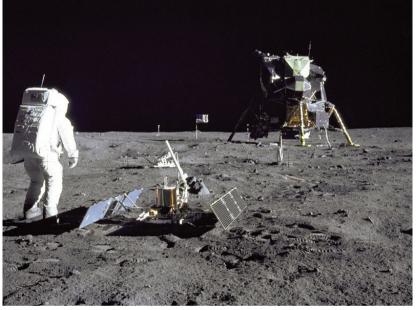
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$$e^+$$

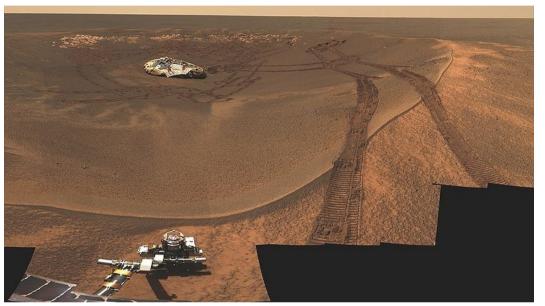
 $40\pi z$, 40 Å z + z + z +

One positron every 75 minutes

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





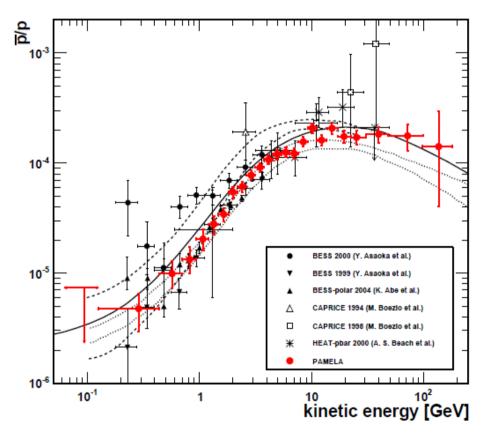


Mars Exploration Rover



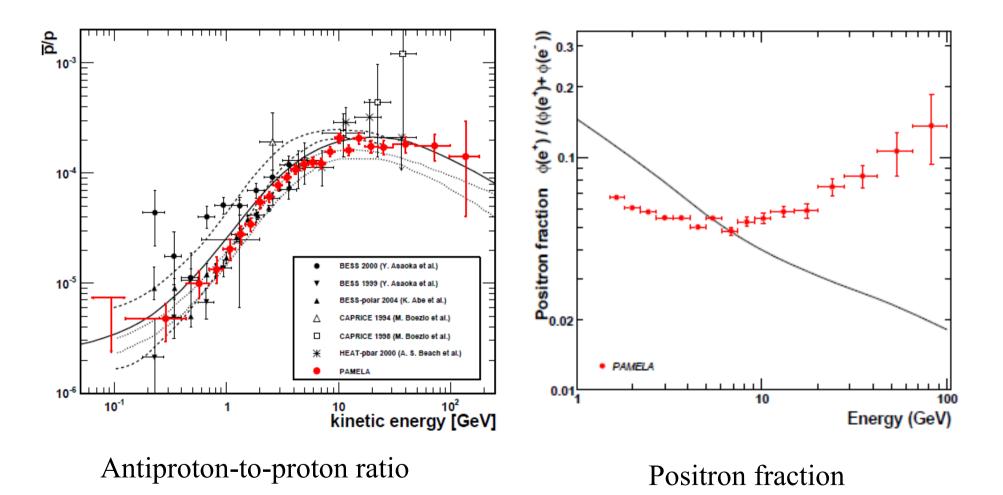
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However, there is antimatter in the interplanetary and in the interstellar medium of our Galaxy



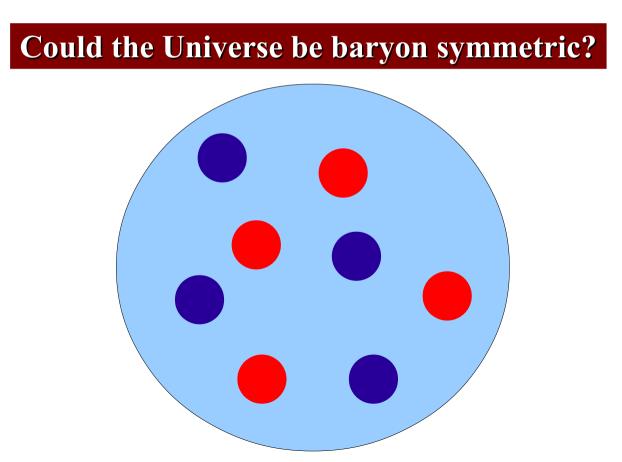
Antiproton-to-proton ratio

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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...





The nucleon-antinucleon annihilation cross section is rather large

 $\langle \sigma_A | v | \rangle \sim m_\pi^2$ with m_π =135 MeV.

Annihilations of nucleons and antinucleons are in thermal equilibrium until very low temperatures, T~22 MeV.

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

$$\frac{n_B}{s} = \frac{n_{\bar{B}}}{s} \simeq 7 \times 10^{-20} \quad \text{Too small!}$$

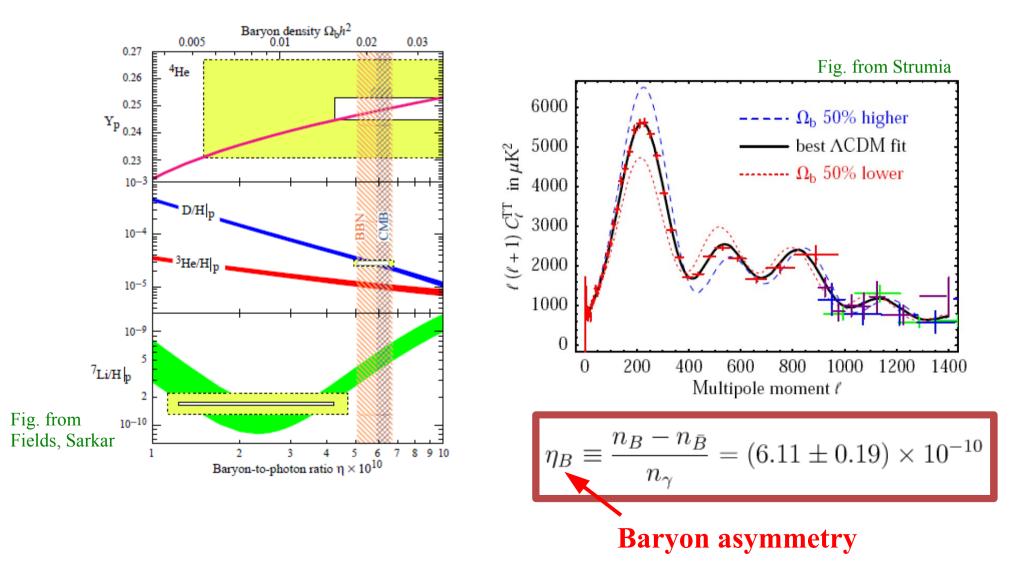
Some mechanism at temperatures larger than 38 MeV must have existed separating nucleons and antinucleons. But which?

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?

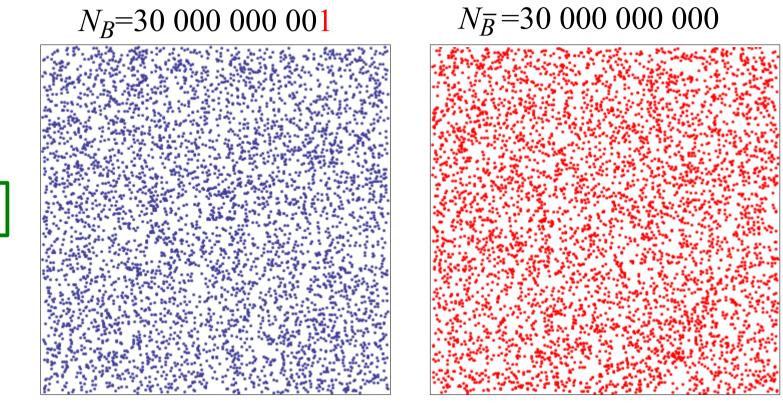
The abundances of the primordial elements and the relative height of the first two peaks of the CMB power spectrum depend on the ratio of baryons-to-photons.



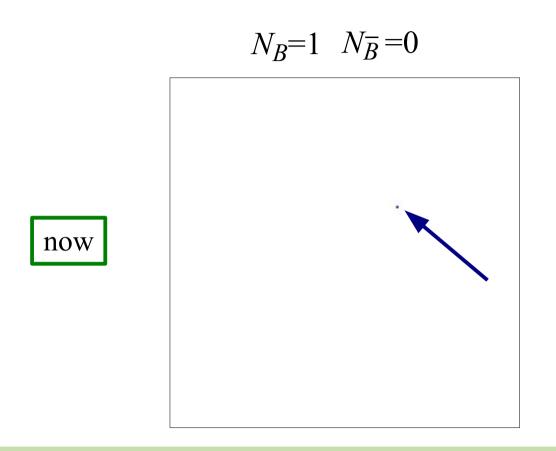
Assumption: in the very early Universe there was already a tiny excess of baryons over antibaryons. These annihilated leaving a small excess of baryons.

But this is a very small number!!

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



t ≲10⁻⁶ s



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



Dynamical generation of a BAU: Sakharov conditions (1967)

A baryon asymmetry can be dynamically generated if the following three conditions are *simultaneously* 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, $\Gamma(X \rightarrow Y+B) = \Gamma(X \rightarrow Y+B) \Rightarrow$ 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.

VOLUME 41, NUMBER 5

PHYSICAL REVIEW LETTERS

31 JULY 1978

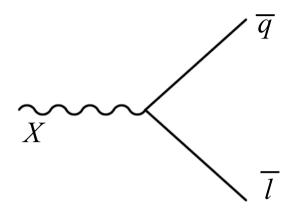
Unified Gauge Theories and the Baryon Number of the Universe

Motohiko Yoshimura

Department of Physics, Tohoku University, Sendai 980, Japan (Received 27 April 1978)

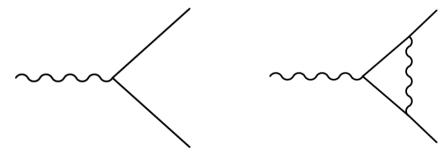
I suggest that the dominance of matter over antimatter in the present universe is a consequence of baryon-number-nonconserving reactions in the very early fireball. Unified guage theories of weak, electromagnetic, and strong interactions provide a basis for such a conjecture and a computation in specific 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	В
$X \to q q$	r	2/3
$X \to \bar{q} \bar{l}$	1 - r	-1/3
$\bar{X} \to \bar{q} \bar{q}$	$ar{r}$	-2/3
$\bar{X} \to q l$	$1-\bar{r}$	1/3

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

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:

$$B \propto (B_X + B_{\bar{X}}) = (r - \bar{r})$$





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:

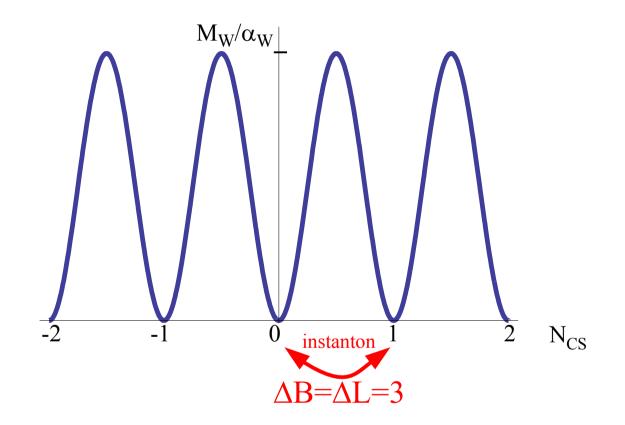


Furthermore, the violation of B and L induced by instantons is such that B–L is conserved (and B+L is violated).

Instantons change dramatically our description of the electroweak vacuum and has important implications for baryogenesis.

Heuristic picture of the electroweak vacuum

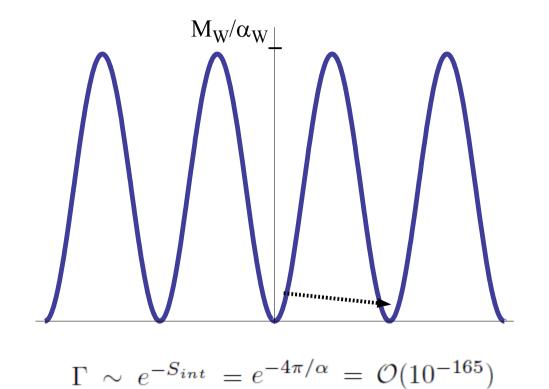
There is an infinite number of degenerate vacuum states with different "Chern-Simons" numbers separated by a barrier.



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



At T=0, transitions among vacua by tunnelling



At high temperatures, the barrier can be crossed M_W/α_W $\mathbf{T} < \mathbf{T}_{\mathrm{EW}} \quad \frac{\Gamma_{B+L}}{V} = k \frac{M_W^7}{(\alpha T)^3} e^{-\beta E_{ph}(T)} \sim e^{\frac{-M_W}{\alpha kT}}$ $T > T_{EW}$ $\frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln \alpha^{-1} T^4$

At high 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

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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 $T > (a \text{ few}) \times 10^2$ 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 ($M_F \ge M_W/\alpha_W$) fermions if these decays are unsuppressed Volume 155B, number 1,2

PHYSICS LETTERS

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, $M_{magn}/M_W(T^*) \approx 2B/\ln (M_{Pl}/T^*) \ll 1$ 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.

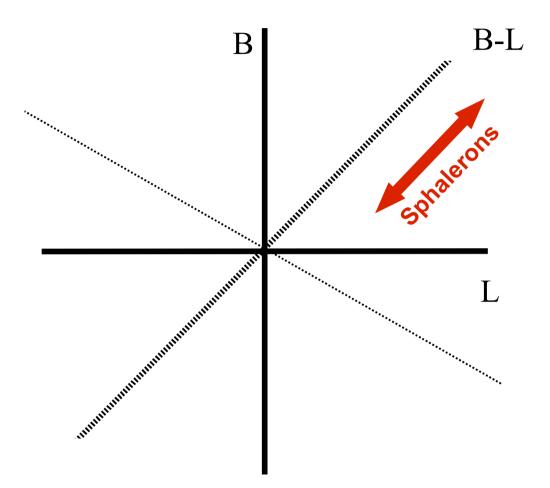
Turning to the possibility of the first order electroweak phase transition, we note that the estimate (6) remains valid for the stage *after* the phase transition. On the other hand, the above discussion implies that before the phase transition, when $\langle \varphi \rangle = 0$, the fermionnumber non-conserving processes are rapid even at low temperature (which is possible because of the super $B(T_{\rm c}) = \frac{1}{2} (B_{\rm 1n} - L_{\rm 1n}) + \frac{1}{2} (B_{\rm 1n} + L_{\rm 1n}) e^{-A},$ $A \sim \beta M_{\rm Pl} / T_{\rm c} \sqrt{N_{\rm eff}} \sim \beta \times 10^{15}$ (9) Clearly, $B(T_{\rm c}) = \frac{1}{2} (B_{\rm 1n} - L_{\rm 1n})$ with great precision;

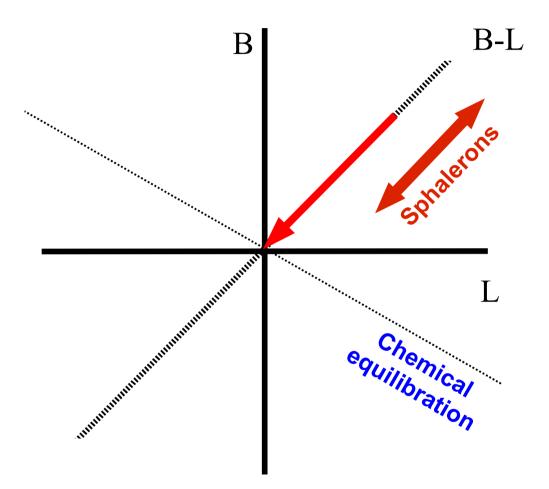
this means that if the primordial baryon asymmetry is generated by the (B-L) conserving processes (which is the case in the minimal SU(5) model [22]), it is completely washed out by the moment of the electroweak phase transition.

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 equilibnum 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 $T \sim M_W/\ln(M_{Pl}/M_W)$, 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)

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"Revised" Sakharov conditions

A baryon asymmetry can be dynamically generated at $T>T_{EW}$ if the following three conditions are *simultaneously* satisfied:

B-L Deryca number violation

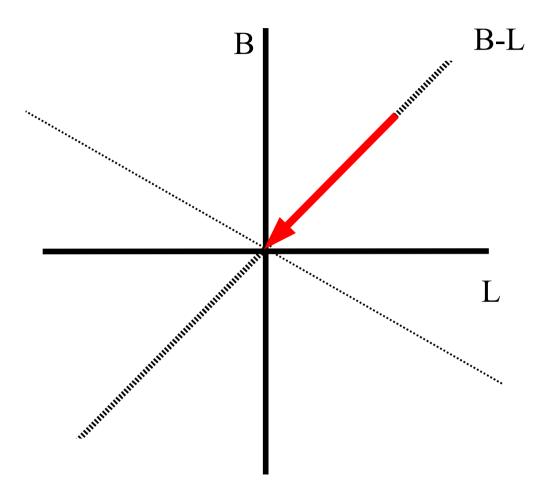
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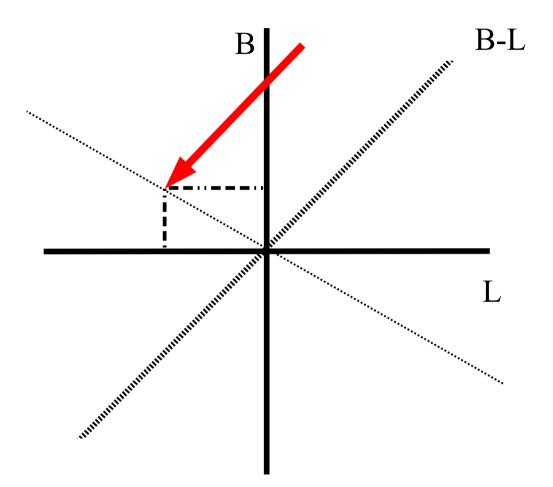
• C and CP violation

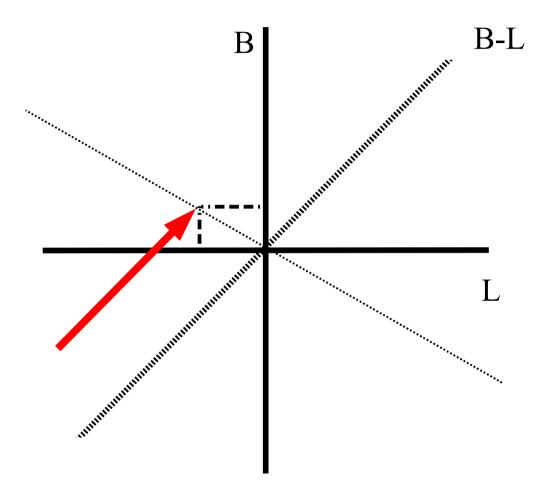
If C or CP are conserved, $\Gamma(X \rightarrow Y+B) = \Gamma(\overline{X} \rightarrow \overline{Y}+\overline{B}) \Rightarrow$ No net effect

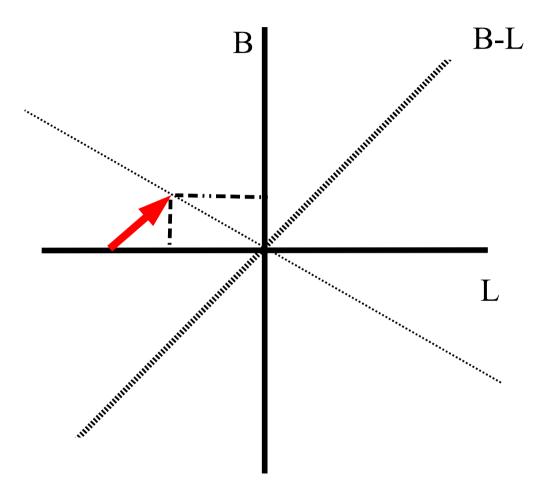
• Departure from thermal equilibrium

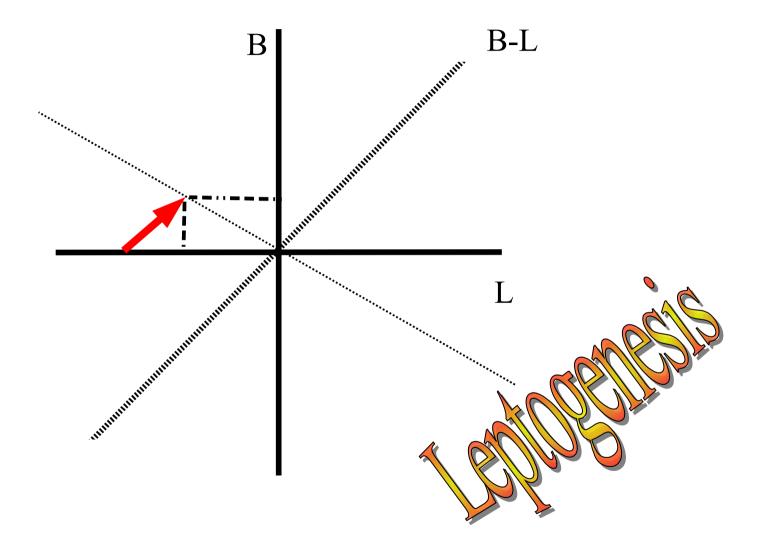
In thermal equilibrium, the production rate of baryons is equal to the destruction rate: $\Gamma(X \rightarrow Y+B)=\Gamma(Y+B \rightarrow X)$ \Rightarrow No net effect.











VERY SIMPLE IDEA:

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

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BARYOGENESIS WITHOUT GRAND UNIFICATION

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Received & March 1986

A mechanism is pensied out to generate cosmological harves number excess softext resorting to grand antibid theories. The lepton number excess originating from Majorana main terms may transform must the baryon number excess through the anappropriated barrow number substant of electroweak processes at high termenutares.

PHYSICS LETTERS B

The current view ascribes the origin of cosmologcal harvon excess to the microscoric baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle mteractions is regarded as the standard candidate to account for this baryon number violation: The theory can area the correct order of manutude for harvon to entropy ratio. If the Universe undergoes the inflation eroch after the barvogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to suse the terroperature above the GUT energy scale. A more unitating problem is that no evidences are given so far experimentally for the baryon number violation, which mucht cast some doubt on the GUT siles.

Some time ago 't Hooft suggested that the instanton-like effect violates baryon number in the Weinberg-Salars 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 st erases rapidly the baryon asymmetry which would have been generated at the early Universe with B - L

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conserving baryon number violation processes as in the standard SL(5) GUT, (Baryon numbers would remam, if the baryon production takes place at low reperatures T \$\le O(100 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

In this letter, we point out that this electroweak baryon number violation process, if it is supplement ed by a lepton number generation at an eacher spoch, 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 lewton number generation. A candidate is the decay process greelying Masorana mass terms.

Let us present a specific model which gives lepton number generation. We assume the presence of a rightbanded Majorana neutrino N'_{k} (l = 1 - n) in addition to the conventional leptons. We take the lagrangian to Volume 124, number 1

(6)

Fig. 1. The semplest diagram group rost to a net lepton number sequences. The cross denotes the Massaura mass rottion.

 $\mathcal{L} = \mathcal{L}_{WS} + \tilde{N}_{R}^{i} \tilde{\mathcal{S}} N_{R}^{i} + M_{i} \tilde{N}_{R}^{ic} N_{R} + h.c.$ $+k_0 \tilde{N}_R \tilde{S}_L^{\dagger} \phi^{\dagger} + h.c.$

where Lugs is the standard Weinberg-Salam lagrangun, and e the standard Higos doublet. For simplicity we assume three generations of flavours and the mass hararchy $M_1 < M_2 < M_3$ in the decay of Ng.

 $N_R = \hat{v}_L + \phi$, + R_ + \$

there oppears 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 Ng arises from the interference of the two diagrams in fig. 1, and its magrutade is calculated as [7]

 $e = (9/4\pi) \ln{(h_h h_0^{\dagger} h_{hk}^{\dagger} h_{kl})} I(M_e^2/M_e^2)/(kh^{\dagger})_{11}, \quad (3)$

 $I(x) = x^{\frac{1}{2}} \left\{ 1 + (1+x) \ln \left[x/(1+x) \right] \right\}.$

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

 $s \simeq (9/8\pi) |k_{2,2}|^2 (M_3/M_3) b$.

with & the phase causing CP violation. We apply the delayed dolay mechanism [8] to geoccute 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 inyerse docuy in blocked at the time when the decay rate $\Gamma = (hh^{\dagger})_{11}/16\pi$ is equal to the expansion rate of the Universe $\dot{a}/a \sim 1.7 \sqrt{g}T^2/m_{P1}$ (g = numbers of degrees of freedom), i.e.,

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(1)

(2a)

(26)

(4)



 $(\Gamma m_{PR}^{-1/2})^{1/2} < M_1$ 751 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 epton number to entropy ratio is given as

28 June 1988

 $k(\Delta L)/s \sim 10^{-3} eK^{-1.2}$ (6)

with $K = \frac{1}{2} \Gamma/(\hat{a}(x))$ for $K \ge 1$. The parameters in (4) and in the extrement of Face not directly constrained by low-energy experiments. One may have an idea, however, on the mass scale M1 as follows: With the parameter in a reasonable range, one may obtain e S 10-6. Then to obtain our required number for $k(\Delta L)/r \sim 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives M1 2 2.4 × 1014 GeV(hA[†])11. If we assame $|h_{12}|^2$, $|k_{13}|^2 \le |k_{11}|^2$ and take $(hh^{\dagger})_{11} \approx |k_{11}|^2 \sim (10^{-5})^2$, then we are led to $M_1 \ge 2 \times 10^4$ $|k_{11}|^2 \sim (10^{-5})^2$, then we are led to $M_1 \leq c \sim \infty$ GeV. This constraint can also be expressed in terms $m_{\rm ex} \approx h_{11}^2 (\phi)^2 / M_1 \leq 0.1$ eV. If the lightest leftanded 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]

 $\Delta B(t) = \frac{1}{2} \Delta (B - L)_{t} + \frac{1}{2} \Delta (B + L)_{t} \exp(-\gamma t)_{t}$ (7) with y~T. At the time of the Weinberg-Salam epoch

the exponent is $m_{\rm Pl}/T\sqrt{g} \simeq 10^{16}$ and the second term practically vanishes. Therefore we obtain $\Delta B = -(\Delta L)/2 ,$ (8)

which survives up to the present epoch, and should gwe k AB/a ~ 10-10.8

41 Here we assumed the dominance of the diagonal matrix element. More precisely speaking, the matrix element constraints be our condition differs from that which appears in the observ by our conduction diffest from that which appears in the obset also narrows examines The disbundled matrixes must market approximation ($|\mathbf{n}_{1,1}| = \mathbf{x}_{2,1} h^2_{1,1} h^$ lepton man matrix n diagonal). Therefore, the double bein decay expression does not constrain devily the parameters in eq. (5). The tream beta docay expression meanances the experivalise of the mass matrix law, if the ref.

Volume 124, member 1

PHYSICS LETTIRS &

26 June 1986

A premordial lepton number excess existed before the moch of the multi-hunded neutrino mass scale. should have been washed out by the equilibrium of process (2) and its inverse process, if the Yukawa cou plug $(bh^{\dagger})_{22}$ or $(hk^{\dagger})_{13}$ is large enough. The equilibrium condition $\Gamma_c \exp(-M_c/T) \gtrsim 1.7 \sqrt{g}T^2/m_{Pl}(s=2)$ or 3) leads to a constraint similar to (5) but with the menuality presented. The net baryon number destroys son factor behaves as $\sim exp(-\alpha k)$ ($\alpha \sim O(1)$) [9]. For $K \ge 20-30$, the equilibrium practically erase the whole pro-existing lepton number excess. This condition is expressed as (m_), > 0.1 eV for the largest entry of the Majorana mass matrix.

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

In summary, we have the following possible scenarates for the cosmological baryon number excess (1) At a termograture above the mass scale M

(= scale of right-handed Majorana neutrino), we started with $\Delta B = \Delta L = 0$ (The inflationary inverse would give this metal condition). Then the lepton number is generated through the Masoraro mass term, and is transformed into the baryon number due to the unsuppressed 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 $\Delta R \neq 0$, $\Delta L \neq 0$ linewerse. The souldmum of $N_R \equiv \phi + \nu_L$, $\phi + \bar{\nu}_L$, together with the electro-weak process washes out both baryon and lepton numbers. Then the lepton number is newly generated by the out-of-equilibrium scenario, and it turna into the baryon number

(3) The baryon number with $B - L \neq 0$ is generated by the grand unification (e.g., the SO(10) model [12]). IF the scale M is too large to establish the adibraan of N_R and $\phi + \mu_L$, then the initial $\Delta(B - L)$ will not be erased. The electroweak process does not affect H = L, and hence the initial baryon.

all neutrino mass mating elements (Majorana essail). should be smaller than ~0.1 eV. If the double beta experiment would observe a Majorana mass greater than this value, this scenario field. In conclusion we have suggested a mechanism of cosmological baryon number generation without resofting to grand unification. In our scenario the conmological buryon number can be generated, even if

proton decay does not happen at all

number remains. This case is the original GUT baryon

number generation scenario. To achieve this, however,

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

References

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47

VERY SIMPLE IDEA:

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

PRIVACE LETTERS P

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Volume 174, number 1

26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

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and

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Received & March 1986

A mechanism is pensied out to generate cosmological harves number excess softext resorting to grand antibid theories. The lepton number excess originating from Majorana main terms may transform must the baryon number excess through the anappropriated barrow number substant of electroweak processes at high termenutares.

PHYSICS LETTERS B

The current view ascribes the origin of cosmological harvon excess to the microscoric baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle mteractions is regarded as the standard candidate to account for this baryon number violation: The theory can area the correct order of manutude for harvon to entropy ratio. If the Universe undergoes the inflation eroch after the barvogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to suse the terroperature above the GUT energy scale. A more unitating problem is that no evidences are given so far experimentally for the baryon number violation, which mucht cast some doubt on the GUT siles.

Some time ago 't Hooft suggested that the instanton-like effect violates baryon number in the Weinberg-Salars 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 st erases rapidly the baryon asymmetry which would have been generated at the early Universe with B - L

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conserving baryon number violation processes as in the standard SL(5) GUT, (Baryon numbers would remam, if the baryon production takes place at low reperatures T \$\le O(100 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

In this letter, we point out that this electroweak baryon number violation process, if it is supplement ed by a lepton number generation at an eacher spoch, 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 lewton number gameration. A candidate is the decay process greelying Masorana mass terms.

Let us present a specific model which gives lepton number generation. We assume the presence of a rightbanded Majorana neutrino N'_{k} (l = 1 - n) in addition to the conventional leptons. We take the lagrangian to

45

Volume 124, number 1

(6)

Fig. 1. The semplest diagram group rost to a net lepton number sequences. The cross denotes the Massaura mass rottion.

 $\mathcal{L} = \mathcal{L}_{WS} + \tilde{N}_{R}^{i} \tilde{\mathcal{S}} N_{R}^{i} + M_{i} \tilde{N}_{R}^{ic} N_{R} + h.c.$ $+k_0 \tilde{N}_R \tilde{N}_L \phi^{\dagger} + h.c.$

where Lugs is the standard Weinberg-Salam lagrangun, and e the standard Higos doublet. For simplicity we assume three generations of flavours and the mass hararchy $M_1 < M_2 < M_3$ in the decay of Ng.

 $N_R = \hat{v}_L + \phi$, + R_ + \$

there oppears 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 Ng arises from the interference of the two diagrams in fig. 1, and its magrutade is calculated as [7]

 $e = (9/4\pi) \ln{(h_h h_0^{\dagger} h_{hk}^{\dagger} h_{kl})} I(M_e^2/M_e^2)/(kh^{\dagger})_{11}, \quad (3)$

 $I(x) = x^{\frac{1}{2}} \left\{ 1 + (1+x) \ln \left[x/(1+x) \right] \right\}.$

south

46

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

 $s \simeq (9/8\pi) |k_{2,3}|^2 (M_3/M_3) \delta$.

with & the phase causing CP violation. We apply the delayed dolay mechanism [8] to geoccute 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 inyerse docuy in blocked at the time when the decay rate $\Gamma = (hh^{\dagger})_{11}/16\pi$ is equal to the expansion rate of the Universe $\dot{a}/a \sim 1.7 \sqrt{g}T^2/m_{P1}$ (g = numbers of degrees of freedom), i.e.,

 $(\Gamma m_{PR}^{-1/2})^{1/2} < M_1$ 751 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 opton number to entropy ratio is given as

28 June 1988

 $k(\Delta L)_{\rm c}/s = 10^{-3} \, eK^{-1.2}$ (6) with $K = \frac{1}{4} \Gamma/(\hat{a}(g))$ for $K \ge 1$. The parameters in (4) and in the extrement of Face not directly constrained by low-energy experiments. One may have an idea, however, on the mass scale M1 as follows: With the pa-

rameter in a reasonable range, one may obtain e S 10-6. Then to obtain our required number for $k(\Delta L)/r \sim 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives M1 2 2.4 × 1014 GeV(hA[†])11. If we assame $|h_{12}|^2$, $|k_{13}|^2 \le |k_{11}|^2$ and take $(hh^{\dagger})_{11} \approx |k_{11}|^2 \sim (10^{-5})^2$, then we are led to $M_1 \ge 2 \times 10^4$ sume $(n_{12}, n_{23})^2$, then we are led to $M_1 \leq c \leq \infty$ $|k_{13}|^2 \sim (10^{-3})^2$, then we are led to $M_1 \leq c < \infty$ GeV. This constraint can also be expressed in terms GeV and $M_1 \leq c < \infty$ $m_{\rm ex} \approx h_{11}^2 (\phi)^2 / M_1 \leq 0.1$ eV. If the lightest leftanded 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]

 $\Delta B(t) = \frac{1}{2} \Delta (B - L)_{t} + \frac{1}{2} \Delta (B + L)_{t} \exp(-\gamma t)_{t}$ (7) with y~T. At the time of the Weinberg-Salam epoch the exponent is $m_{\rm Pl}/T\sqrt{g} \simeq 10^{16}$ and the second

term practically vanishes. Therefore we obtain $\Delta B = -(\Delta L)_1/2 ,$ (8)

which survives up to the present epoch, and should gwe k AB/a ~ 10-10.8

41 Here we assumed the dominance of the diagonal matrix elemant. More precisely speaking, the matrix element constraints be our condition differs from that which appears in the observ by our conduction diffest from that which appears in the obset also narrows examines The disbundled matrixes must market approximation ($|\mathbf{n}_{1,1}| = \mathbf{x}_{2,1} h^2_{1,1} h^$ lepton man matrix n diagonal). Therefore, the double bein decay expression does not constrain devily the parameters in eq. (5). The tream beta docay expression meanances the experivalise of the mass matrix law, if the ref.

Volume 124, number 1

PHYSICS LETTIRS &

26 June 1986

A premordial lepton number excess existed before the moch of the multi-hunded neutrino mass scale. should have been washed out by the equilibrium of process (2) and its inverse process, if the Yukawa cos plug $(bh^{\dagger})_{22}$ or $(hk^{\dagger})_{13}$ is large enough. The equilibrium condition $\Gamma_c \exp(-M_c/T) \gtrsim 1.7 \sqrt{g}T^2/m_{Pl}(s=2)$ or 3) leads to a constraint smillar to (5) but with the menuality presented. The net baryon number destroys son factor behaves as $\sim exp(-\alpha k)$ ($\alpha \sim O(1)$) [9]. For $K \ge 20-30$, the equilibrium practically erase the whole pro-existing lepton number excess. This condition is expressed as (m_), > 0.1 eV for the largest entry of the Majorana mass matrix.

In the presence of unsuppressed instanton-like electroweak effects, the lepton number equilibrium amplies that the baryon excess which existed at this epoch should also be washed out, even if it was pro duced in the process with $B - L \neq 0$ Namely, if there are neutrinos with the Majorana mass heavier than ~0.1 eV both baryon and lepton numbers which exated before this epoch are washed out irrespective of their B - L properties.

In summary, we have the following possible scenarates for the cosmological baryon number excess (1) At a termograture above the mass scale M

(= scale of right-handed Majorana neutrino), we started with $\Delta B = \Delta L = 0$ (The inflationary inverse would give this mitual condition). Then the lepton number is generated through the Masoraro mass term, and is transformed into the baryon number due to the unsuppressed 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 $\Delta R \neq 0$, $\Delta L \neq 0$ linewerse. The souldmum of $N_R \equiv \phi + \nu_L$, $\phi + \bar{\nu}_L$, together with the electro-weak process washes out both baryon and lepton numbers. Then the lepton number is newly generated by the out-of-equilibrium scenario, and it turna into the baryon number

(3) The baryon number with $B - L \neq 0$ is generated by the grand unification (e.g., the SO(10) model [12]). IF the scale M is too large to establish the adibraan of N_R and $\phi + \mu_L$, then the initial $\Delta(B - L)$ will not be erased. The electroweak process does not affect H = 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 mating elements (Majorana essail). should be smaller than ~0.1 eV. If the double beta experiment would observe a Majorana mass greater than this value, this scenario field.

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

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

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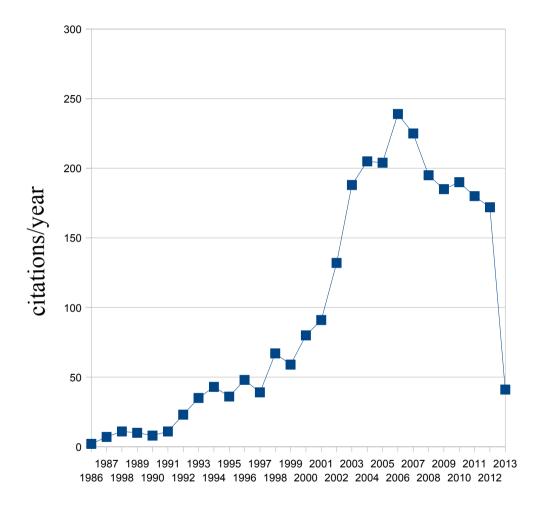
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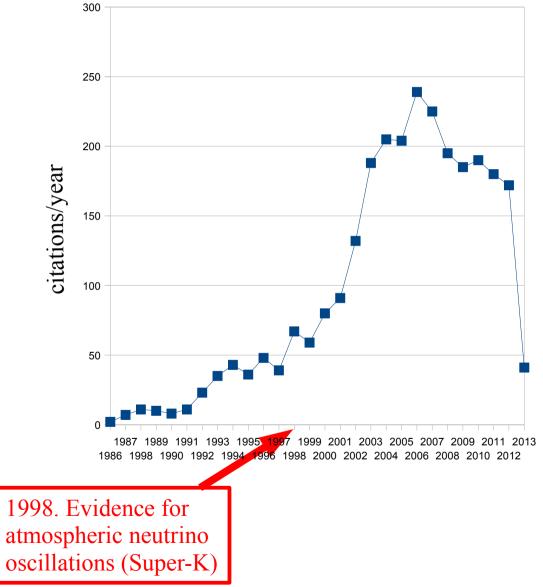


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Why are people so excited about leptogenesis?

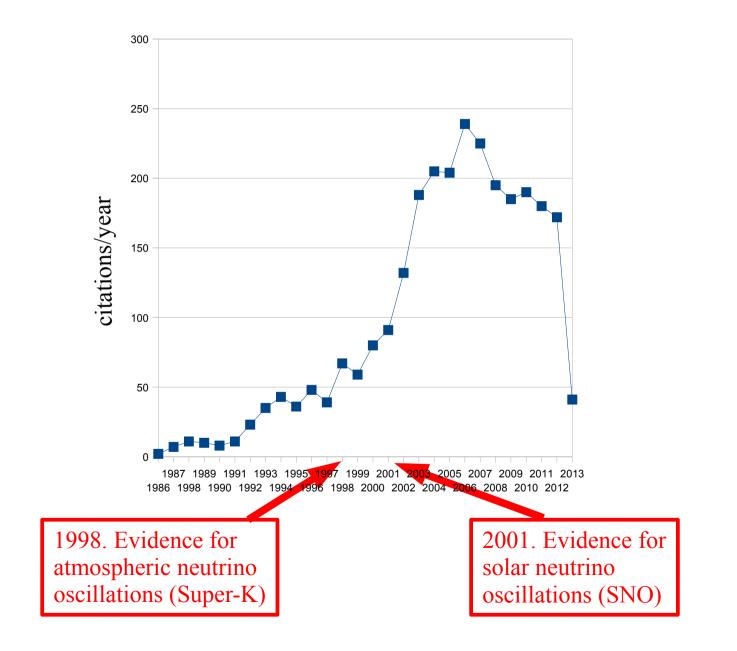


Why are people so excited about leptogenesis?



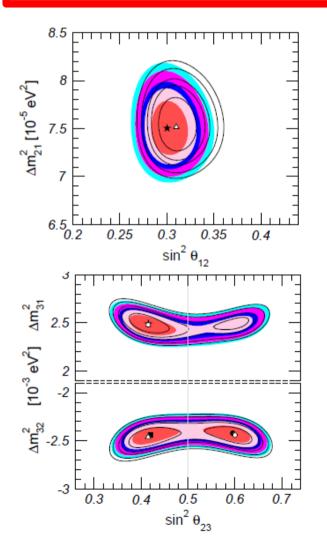
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Why are people so excited about leptogenesis?



Neutrino masses

Neutrinos have mass!!



	Free Fluxes $+$ RSBL	
	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	0.30 ± 0.013	$0.27 \rightarrow 0.34$
$\theta_{12}/^{\circ}$	33.3 ± 0.8	$31 \rightarrow 36$
$\sin^2 \theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \rightarrow 0.67$
$ heta_{23}/^{\circ}$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \rightarrow 55$
$\sin^2 \theta_{13}$	0.023 ± 0.0023	$0.016 \rightarrow 0.030$
$ heta_{13}/^{\circ}$	$8.6\substack{+0.44\\-0.46}$	$7.2 \rightarrow 9.5$
$\delta_{ m CP}/^{\circ}$	300^{+66}_{-138}	$0 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \ {\rm eV}^2}$	7.50 ± 0.185	7.00 ightarrow 8.09
$\frac{\Delta m_{31}^2}{10^{-3} \ {\rm eV}^2} \ ({\rm N})$	$2.47^{+0.069}_{-0.067}$	$2.27 \rightarrow 2.69$
$\frac{\Delta m_{32}^2}{10^{-3} \ {\rm eV}^2} \ ({\rm I})$	$-2.43^{+0.042}_{-0.065}$	$-2.65 \rightarrow -2.24$

Gonzalez-Garcia, Maltoni, Salvado, Schwetz arXiv:1209.3023 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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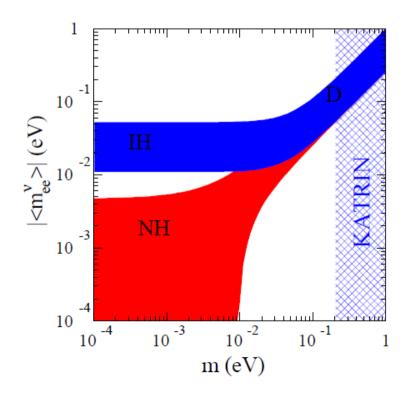
Majorana mass
$$\mathcal{L} = \frac{1}{2} \bar{\nu}_{Li}^c m_{ij}^M \nu_{Lj} + h.c$$
 (L violated)
Option preferred by theorists

Dirac or Majorana?

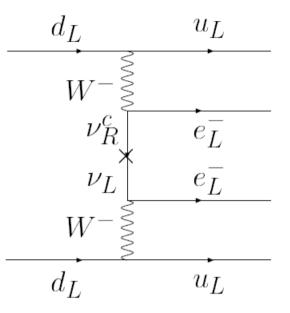
The smoking gun: neutrinoless double beta decay

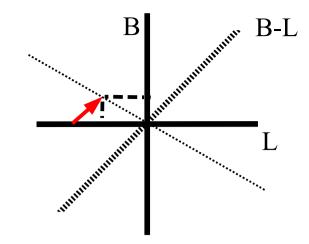
If neutrinos are Majorana particles, the nuclear process $(A,Z) \rightarrow (A,Z+2)+e^-+e^-$ is allowed





The rate of $0\nu2\beta$ depends crucially on the spectrum. If neutrinos are degenerate or inverse hierarchical, $0\nu2\beta$ could be observed in the next generation of experiments (GERDA,EXO, KamLAND-Zen, CUORE, SNO+, MAJORANA...)

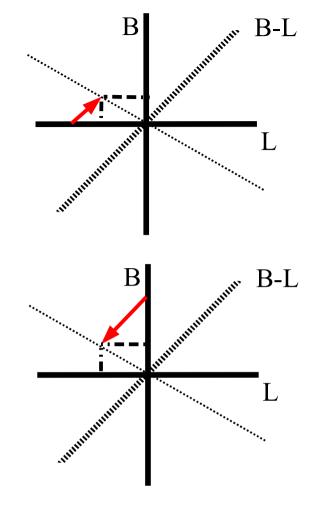




• The observation of $0v2\beta$ decay (\Rightarrow L is violated) will support the leptogenesis scenario.

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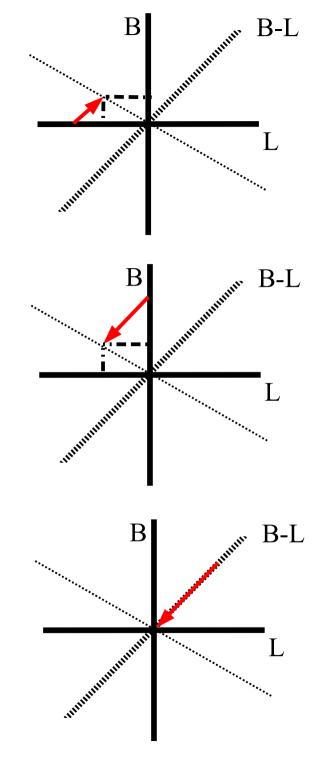
• The observation of neutron-antineutron oscillations (\Rightarrow B is violated) will support the baryogenesis scenario.



• The observation of $0v2\beta$ decay (\Rightarrow L is violated) will support the leptogenesis scenario.

• The observation of neutron-antineutron oscillations (⇒B is violated) will support the baryogenesis scenario.

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

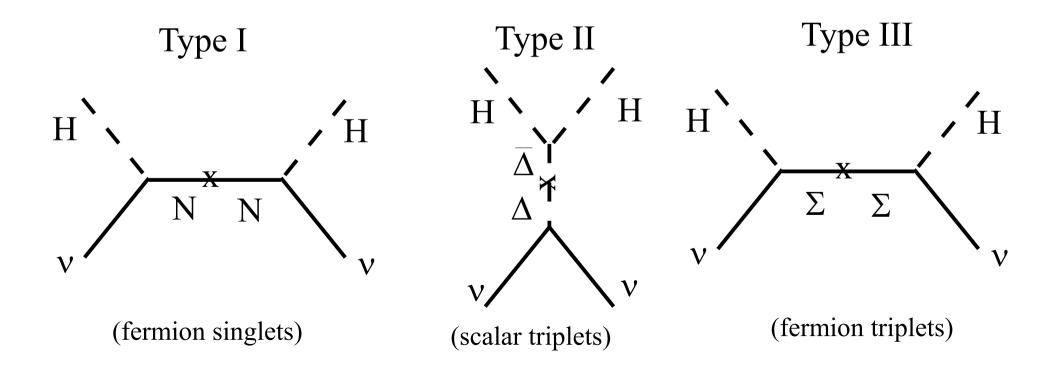


Origin of neutrino masses

Many proposals!

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

See-saw mechanism

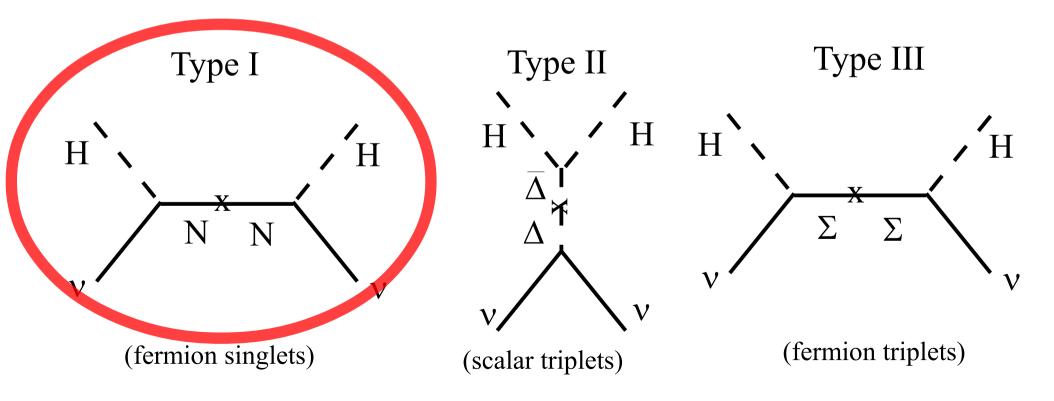


Origin of neutrino masses

Many proposals!

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

See-saw mechanism



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



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

$$-\mathcal{L}_{lep} = \nu_R^{c T} h_{\nu} L \cdot H - \frac{1}{2} \nu_R^{c T} M \nu_R^c + \text{h.c.}$$
$$M \gg \langle H^0 \rangle$$
$$-\mathcal{L}_{eff} = -\frac{1}{2} (L \cdot H)^T \left[h_{\nu}^T M^{-1} h_{\nu} \right] (L \cdot H) + \text{h.c.}$$
$$\mathcal{M}_{\nu} = h_{\nu}^T M^{-1} h_{\nu} \langle H^0 \rangle^2$$

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



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



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?

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. 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).

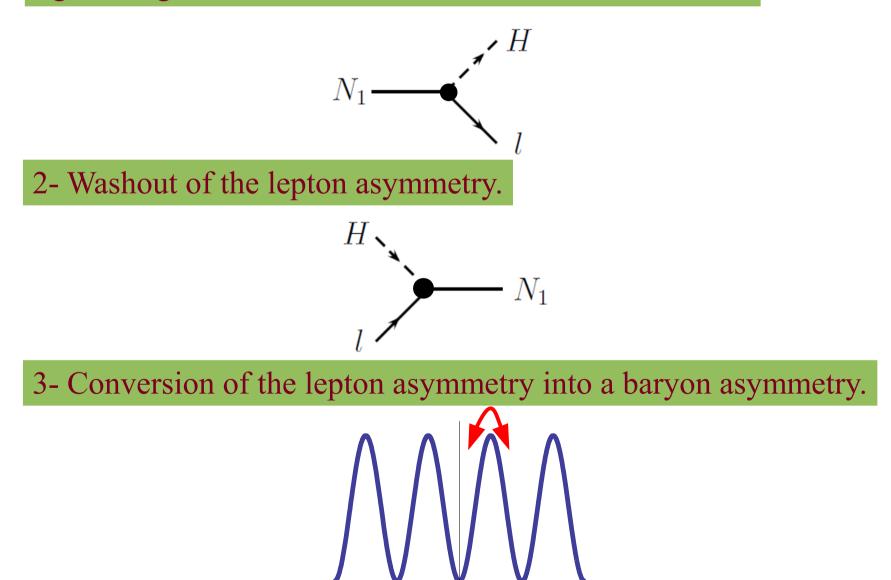
The generation of a baryon asymmetry is guaranteed in the leptogenesis mechanism. But, can leptogenesis generate the *observed* baryon asymmetry?



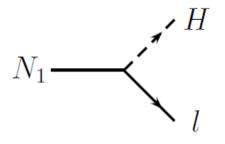


Roughly speaking, the generation of a BAU through leptogenesis proceeds in three steps:

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



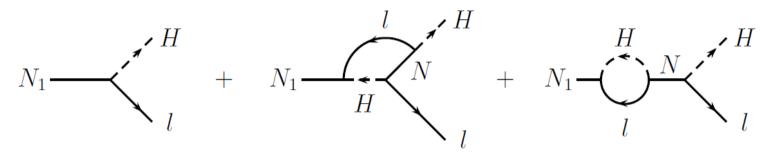
At tree level, the rates of the decays $N_1 \rightarrow lH$ and $N_1 \rightarrow l^c H^c$ are identical.



No CP asymmetry (no lepton asymmetry)

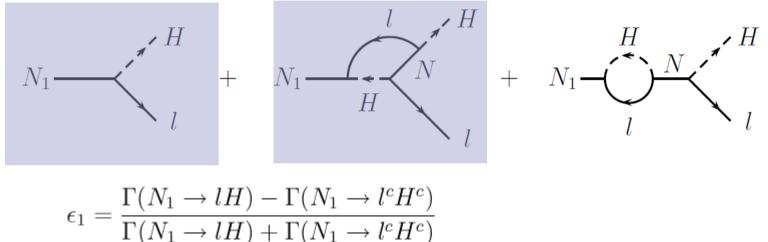
$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to l^c H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to l^c H^c)} = 0$$

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



$$\begin{split} \epsilon_1 &= \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to l^c H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to l^c H^c)} \\ &\simeq \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \operatorname{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right) \right] \end{split}$$

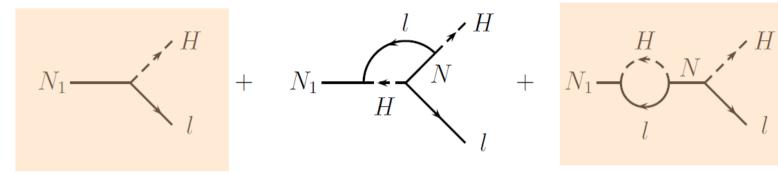
At one loop, new diagrams contribute to the decay rate:



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

Interference with the vertex diagram

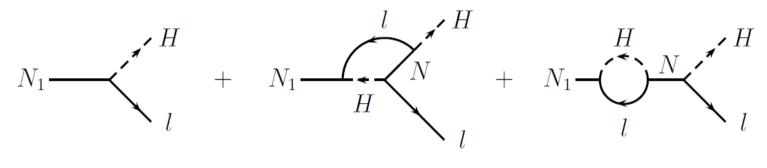
At one loop, new diagrams contribute to the decay rate:



$$\epsilon_{1} = \frac{\Gamma(N_{1} \to lH) - \Gamma(N_{1} \to l^{c}H^{c})}{\Gamma(N_{1} \to lH) + \Gamma(N_{1} \to l^{c}H^{c})}$$
$$\simeq \frac{1}{8\pi} \frac{1}{(h_{\nu}h_{\nu}^{\dagger})_{11}} \sum_{i=2,3} \operatorname{Im}\left[(h_{\nu}h_{\nu}^{\dagger})_{1i}^{2}\right] \left[f\left(\frac{M_{i}^{2}}{M_{1}^{2}}\right) + g\left(\frac{M_{i}^{2}}{M_{1}^{2}}\right)\right]$$

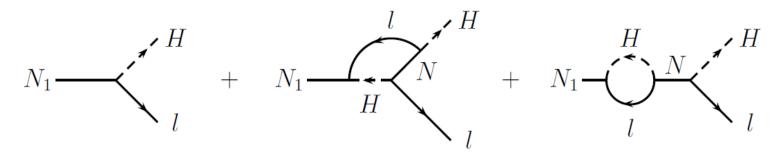
Interference with the wave-function diagram

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



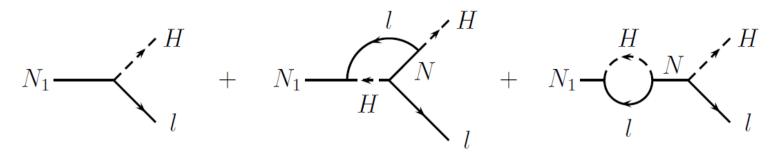
$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to l^c H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to l^c H^c)}$$
$$\simeq \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \operatorname{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right) \right]$$

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



The CP violating decays generate instantaneously a lepton asymmetry.

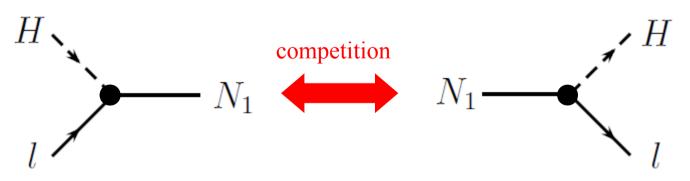
Not the end of the story...



The CP violating decays generate instantaneously a lepton asymmetry.

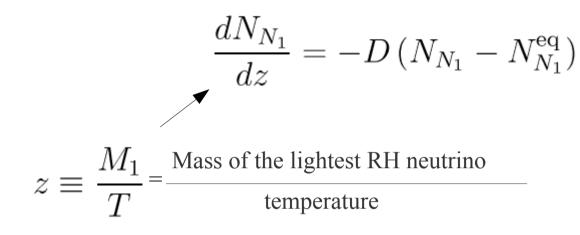
Not the end of the story...

There are also inverse decays which deplete the number of right-handed neutrinos and wash-out the lepton asymmetry generated

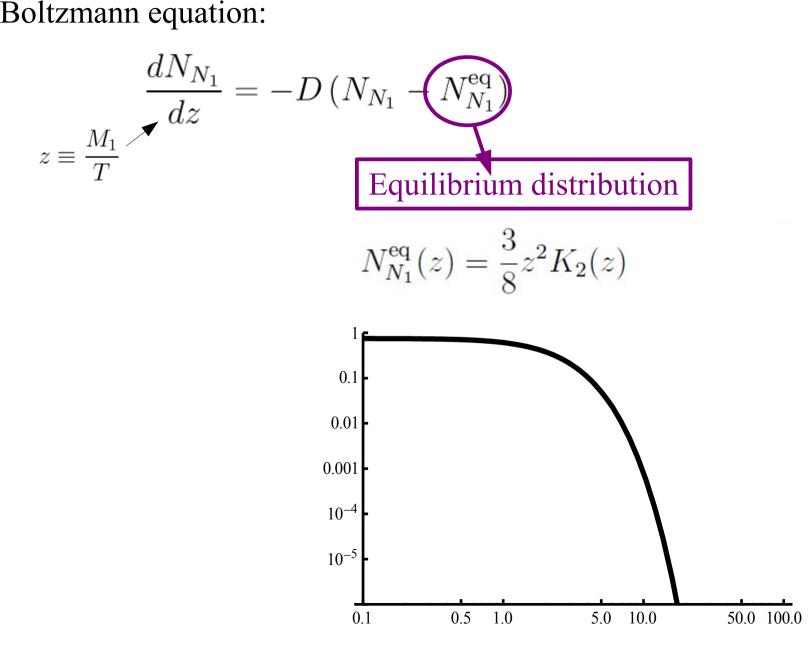


If these processes are in equilibrium, there is no net effect. It is necessary a departure from thermal equilibrium (3rd Sakharov condition)

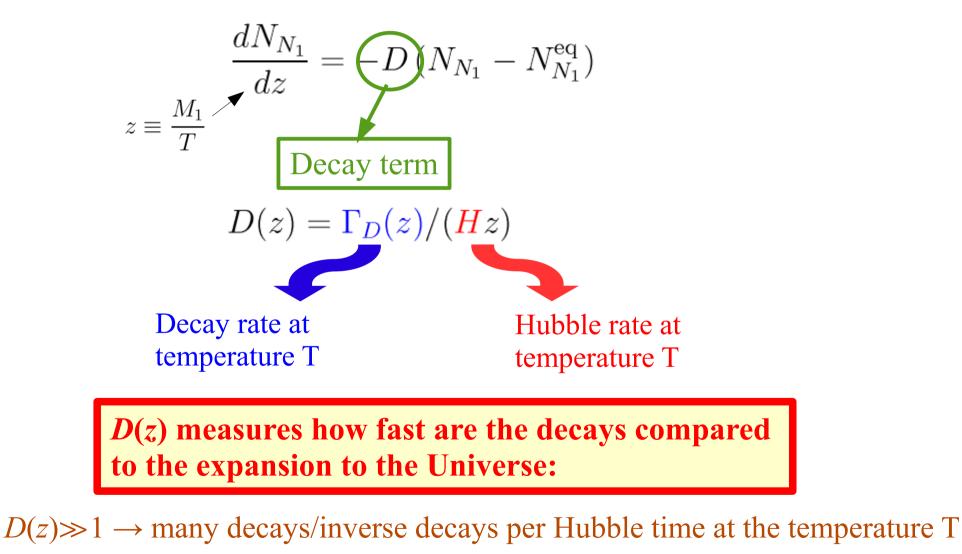
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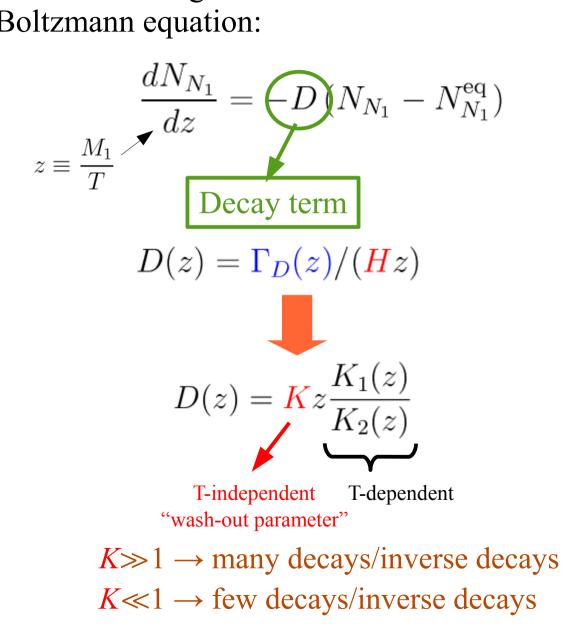


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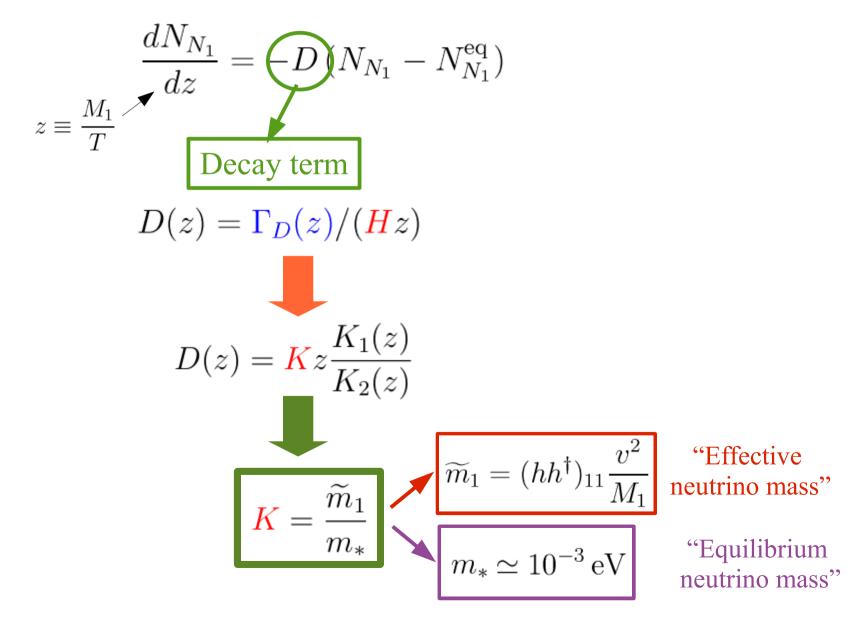
 $D(z) \ll 1 \rightarrow$ few decays/inverse decays per Hubble time at the temperature T

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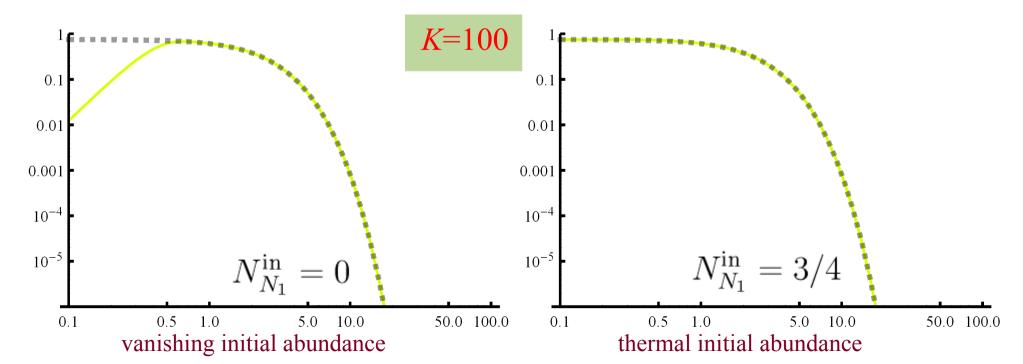


2- Wash-out of the lepton asymmetry

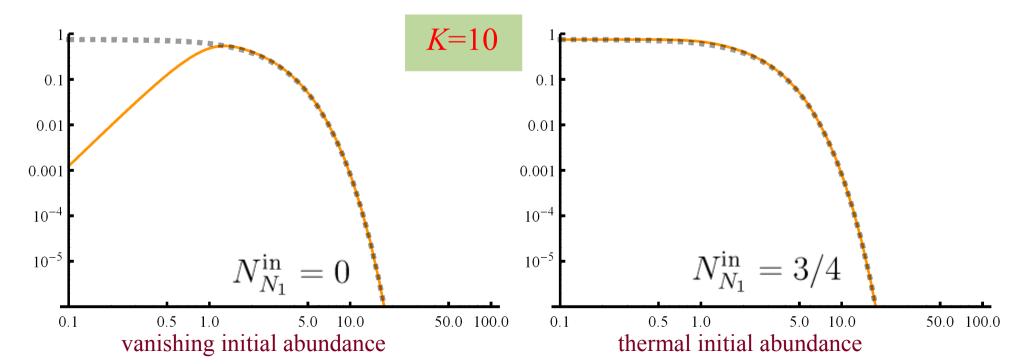
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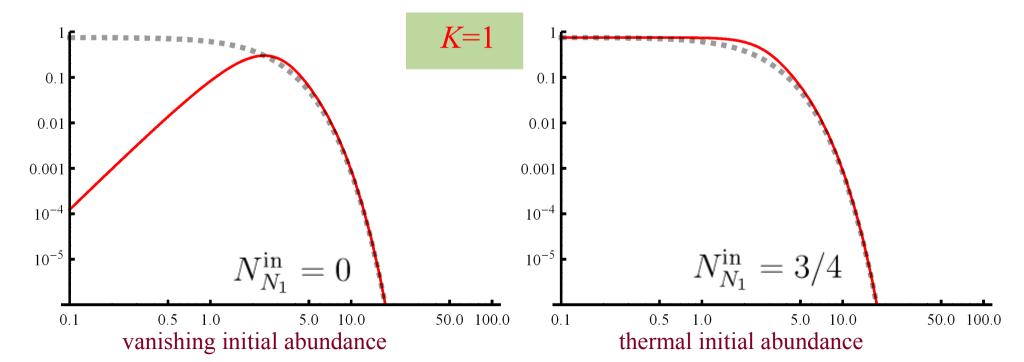
$$\frac{dN_{N_1}(z)}{dz} = -\frac{K}{K_2(z)} \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z))$$
$$K = \frac{\widetilde{m}_1}{m_*} \qquad N_{N_1}^{\text{eq}}(z) = \frac{3}{8} z^2 K_2(z) ,$$



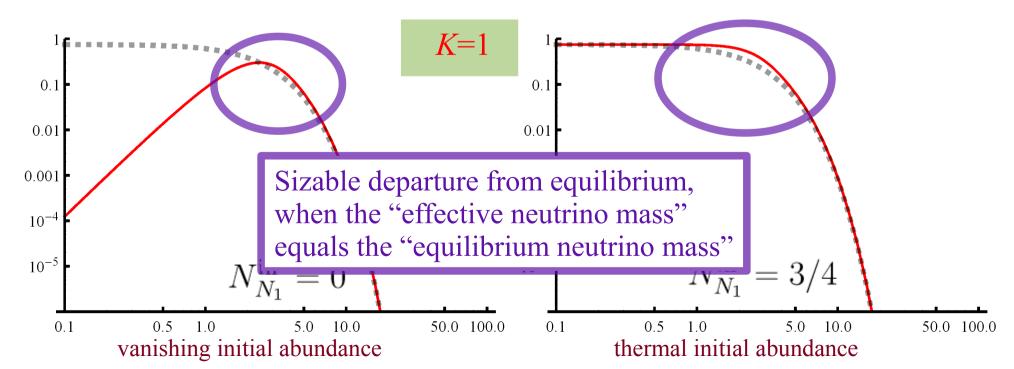
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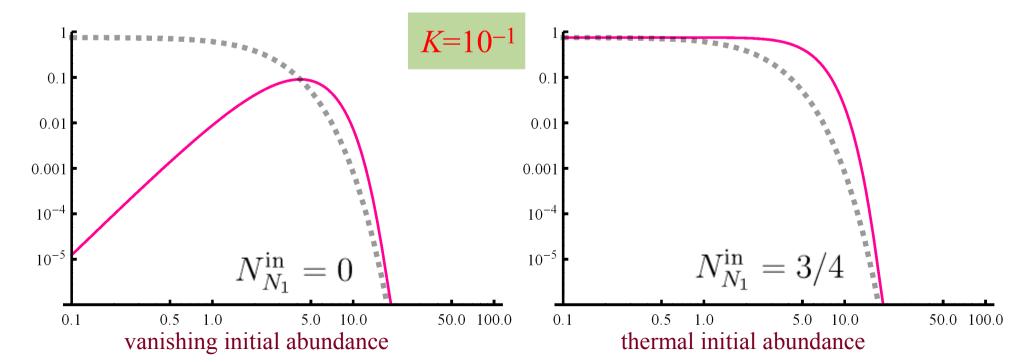
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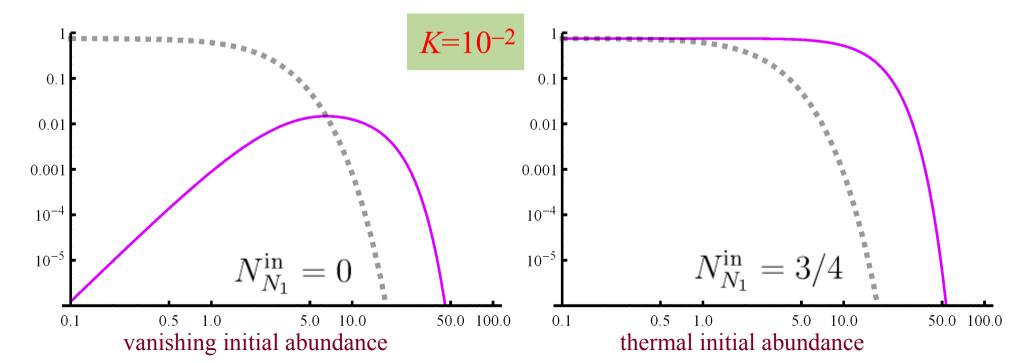
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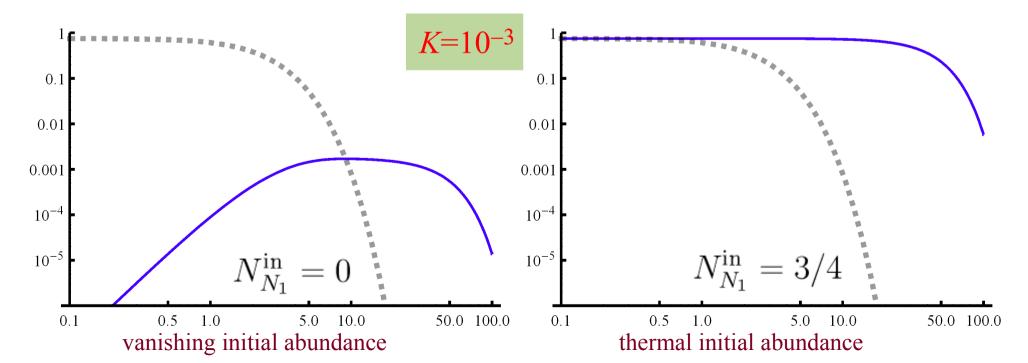


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We have seen the conditions to keep these processes out in equilibrium. What is the effect on the B-L asymmetry?

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



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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



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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.



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$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D \left(N_{N_1} - N_{N_1}^{\text{eq}} \right) - W_{ID} N_{B-L}$$
$$W_{ID}(z) = \frac{1}{2} D(z) \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}}$$

The washout rate is related to the rate of decay/inverse decay.

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

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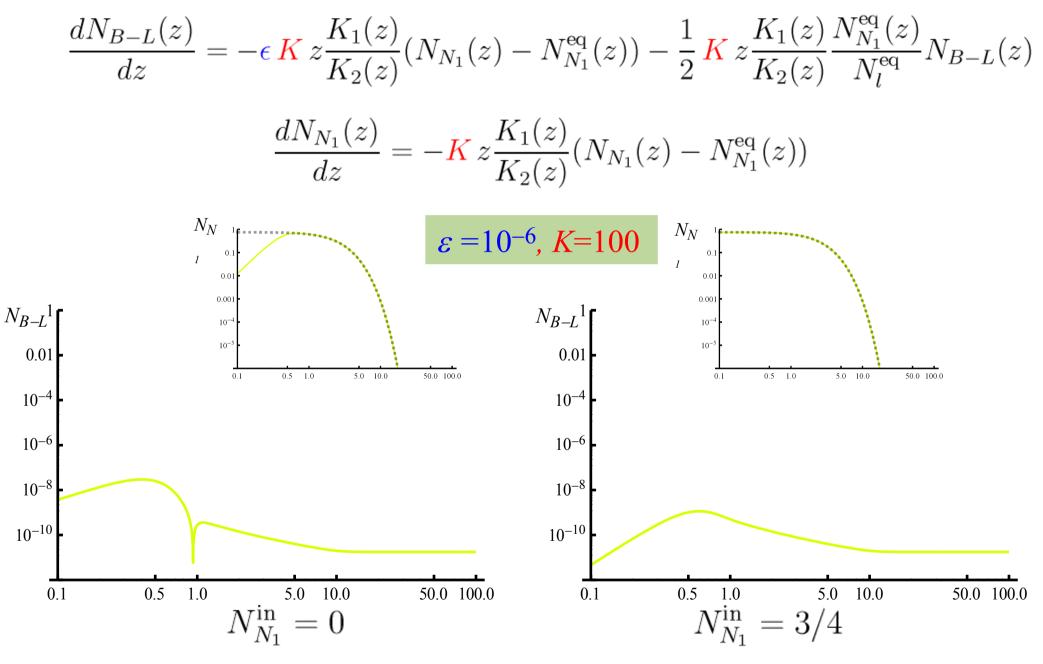
$$\frac{dN_{B-L}(z)}{dz} = -\epsilon \, \mathbf{K} \, z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} \, \mathbf{K} \, z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$
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The solution depends on:

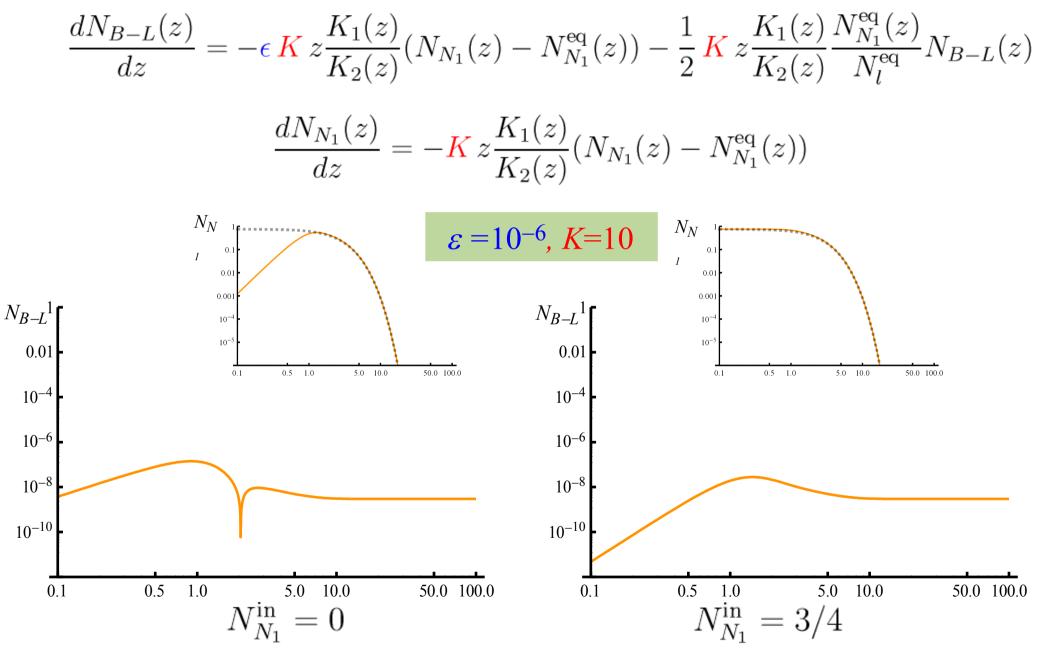
• Initial abundance of right-handed neutrinos

$$N_{N_1}^{\text{in}} = 0$$
 or $N_{N_1}^{\text{in}} = 3/4$
• "Effective neutrino mass", \widetilde{m}_1 , through $K = \frac{\widetilde{m}_1}{m_*}$

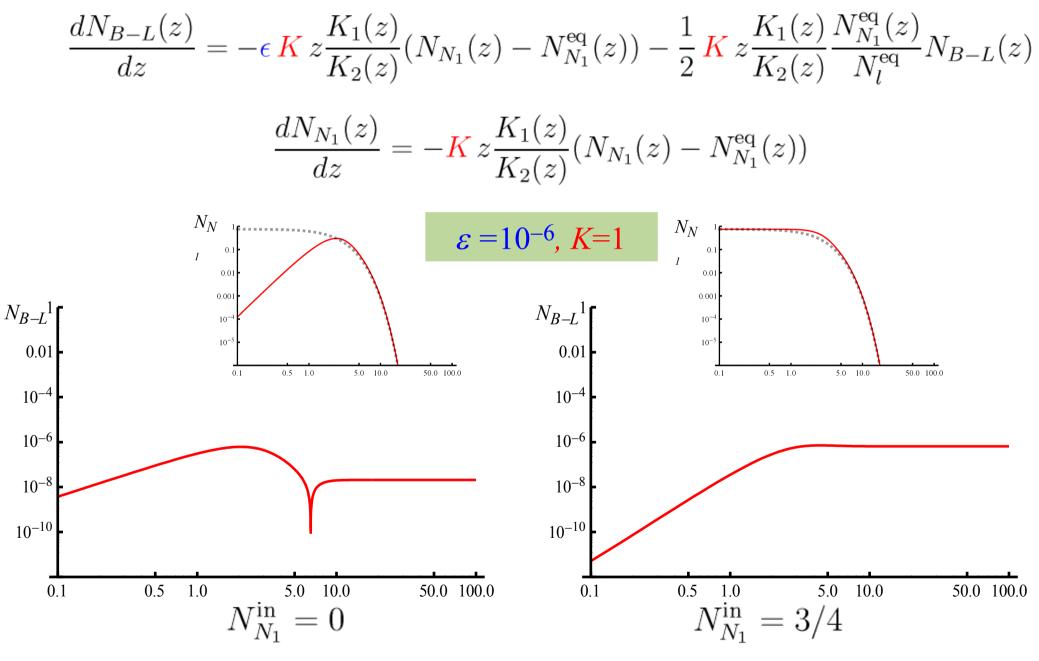
• CP asymmetry, ϵ



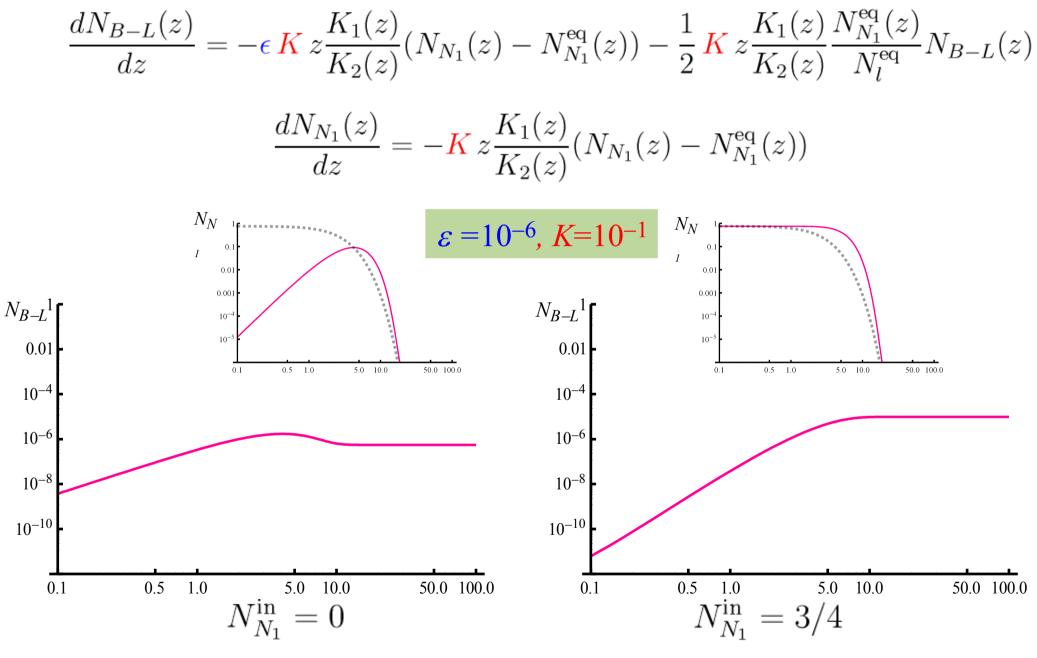
vanishing initial abundance



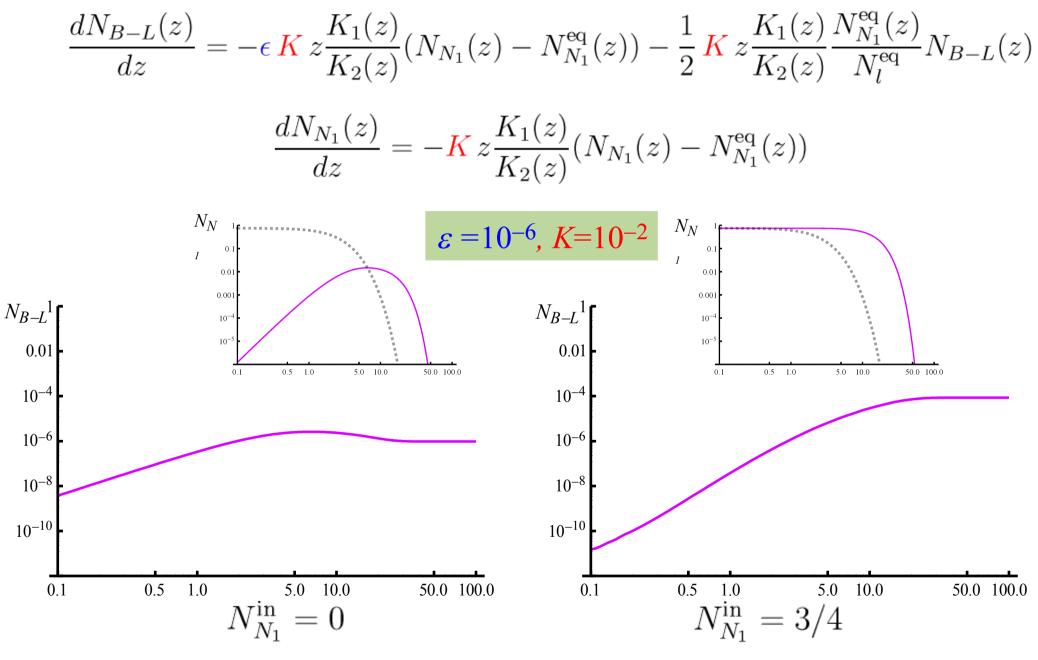
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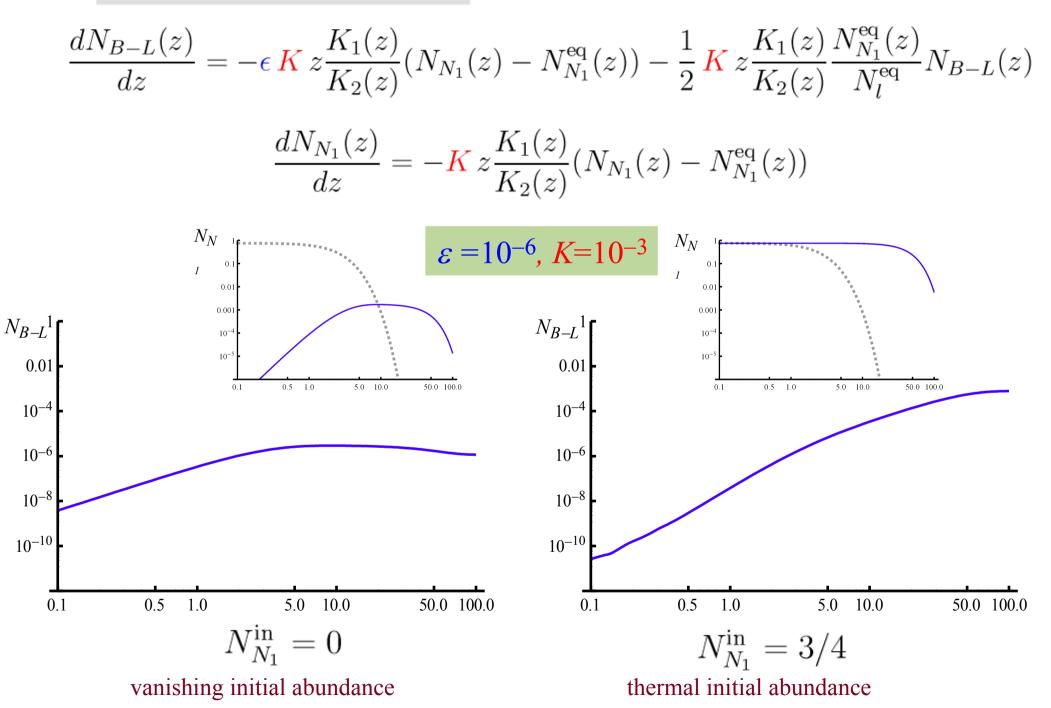
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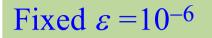


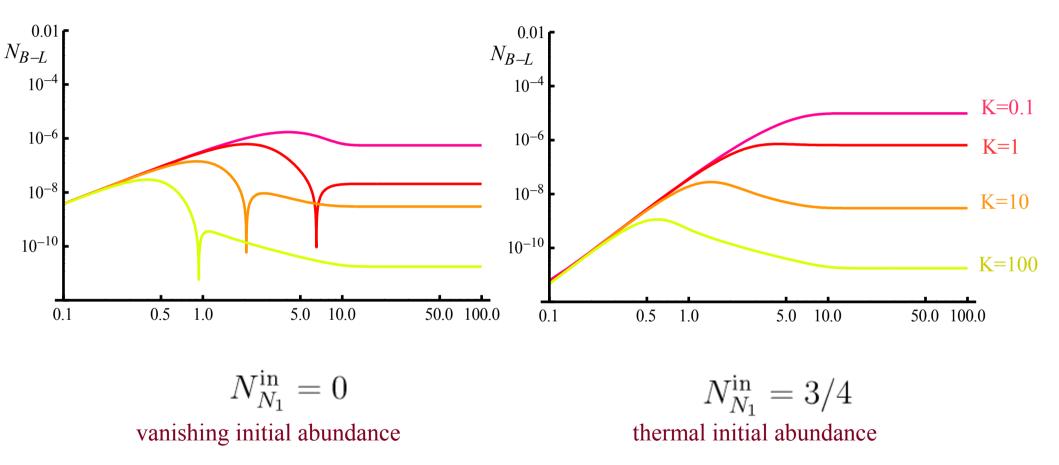
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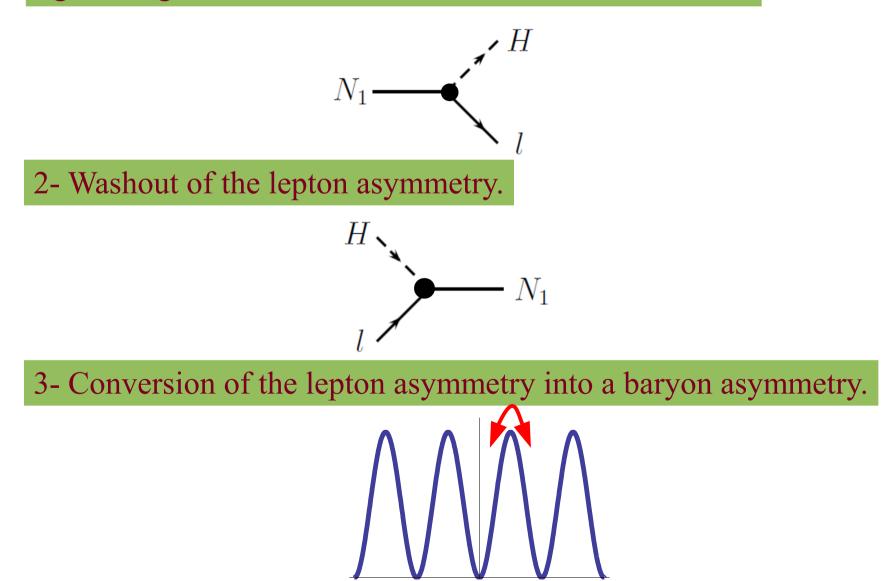
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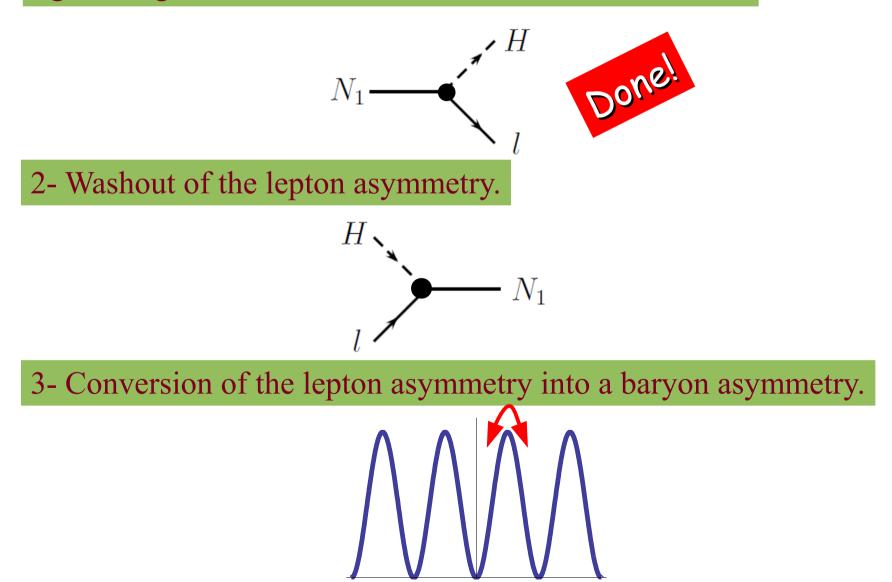


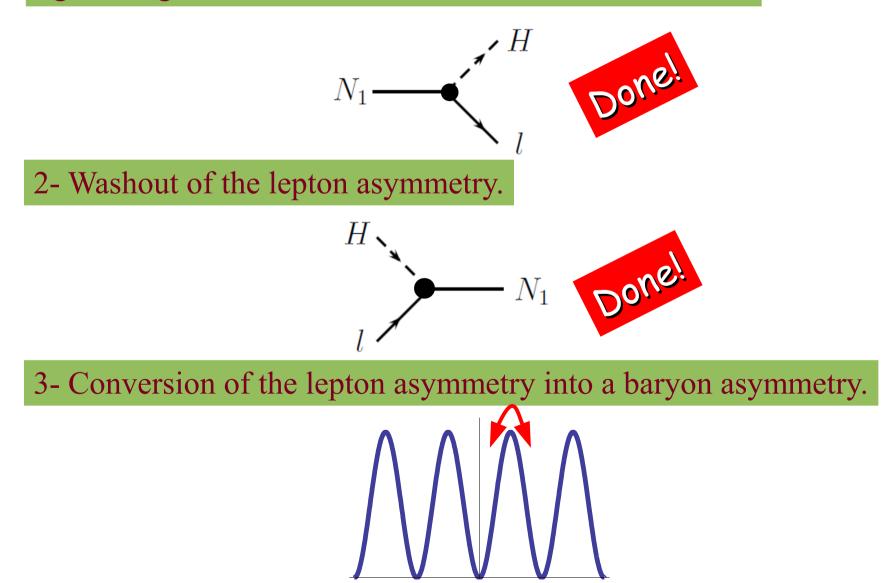












3- Conversion of the lepton asymmetry into a baryon asymmetry

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

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

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 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} .

$$\begin{split} \mu_e &= \frac{2N_f + 3}{6N_f + 3} \mu_\ell, \quad \mu_d = -\frac{6N_f + 1}{6N_f + 3} \mu_\ell, \quad \mu_u = \frac{2N_f - 1}{6N_f + 3} \mu_\ell \\ \mu_q &= -\frac{1}{3} \mu_\ell, \quad \mu_H = \frac{4N_f}{6N_f + 3} \mu_\ell \;. \end{split}$$

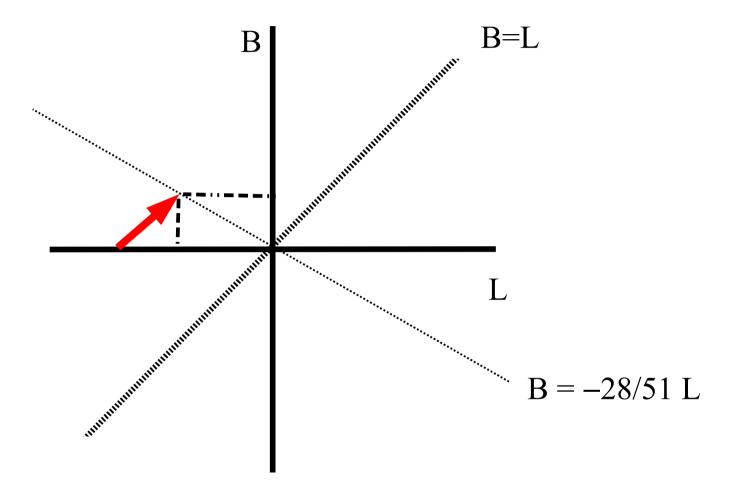
Then
$$B = -\frac{4}{3}N_f\mu_\ell$$
, $L = \frac{14N_f^2 + 9N_f}{6N_f + 3}\mu_\ell$

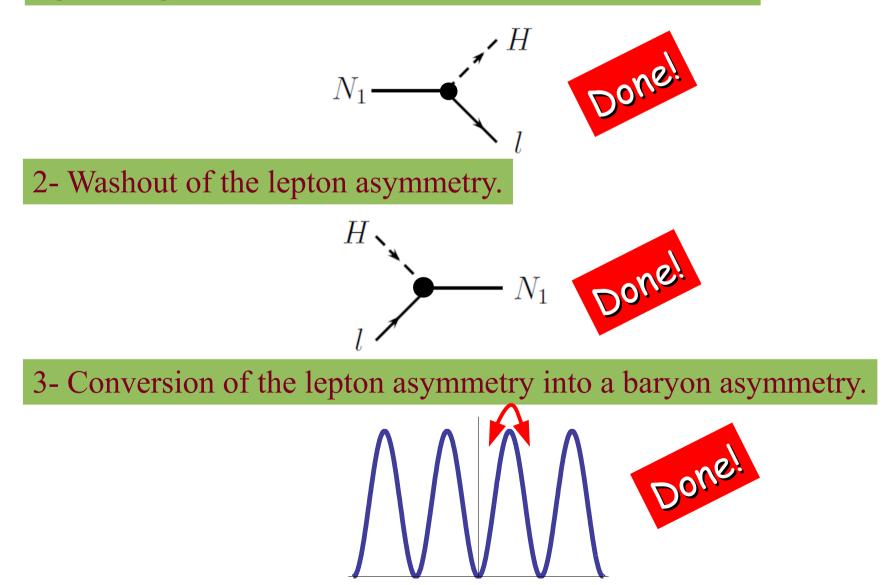
Leptogenesis produces a B-L asymmetry. The equilibration, leads to a baryon asymmetry and to a lepton asymmetry given by:

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

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

c=28/79 in the SM with three generations





1- Take your favourite neutrino see-saw model (h_v, M)

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2- Calculate
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 $\widetilde{m}_1 = (hh^\dagger)_{11} \frac{v^2}{M_1} \qquad m_* \simeq 10^{-3} \, \mathrm{eV}$

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4-Calculate the baryon-to-photon ratio

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

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

Recipe to cook a baryon asymmetry

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Sphaleron conversion

Dilution factor due to photon production between leptogenesis and recombination

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$$\frac{dN_{B-L}(z)}{dz} = -\epsilon \mathbf{K} z \frac{K_1(z)}{K_2(z)} (N_{N_1}(z) - N_{N_1}^{\text{eq}}(z)) - \frac{1}{2} \mathbf{K} z \frac{K_1(z)}{K_2(z)} \frac{N_{N_1}^{\text{eq}}(z)}{N_l^{\text{eq}}} N_{B-L}(z)$$
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$$\eta_B = \frac{c}{f} N_{B-L}^{T=0}$$

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

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

A CRUCIAL QUESTION ...

 $\{h_{\nu}, M\}$

See-saw

parameters

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

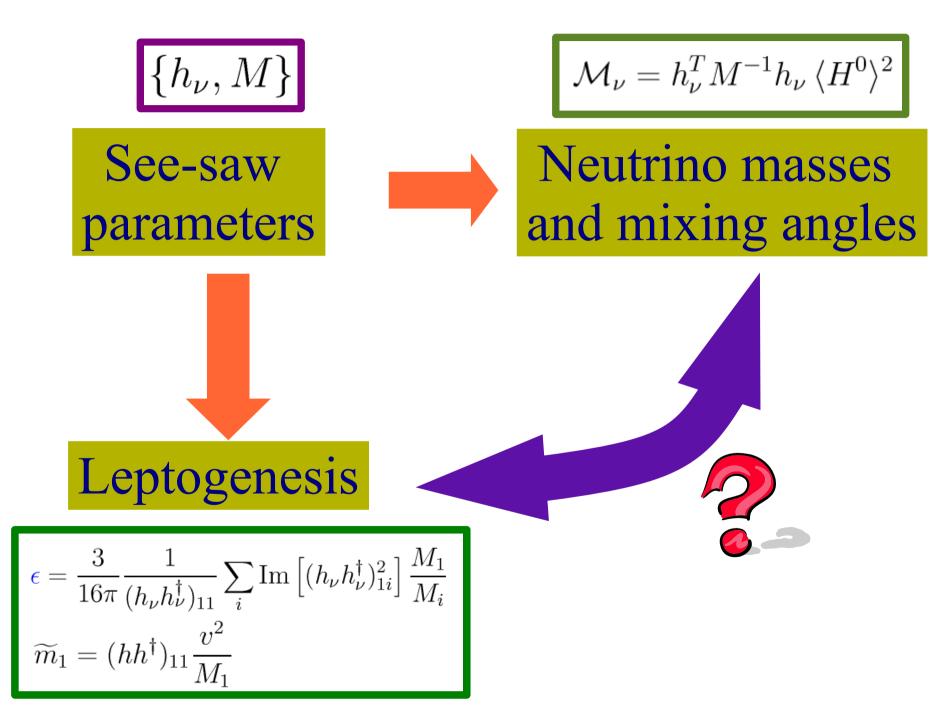




Leptogenesis

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_{\nu}h_{\nu}^{\dagger})_{11}} \sum_{i} \operatorname{Im} \left[(h_{\nu}h_{\nu}^{\dagger})_{1i}^{2} \right] \frac{M_{1}}{M_{i}}$$
$$\widetilde{m}_{1} = (hh^{\dagger})_{11} \frac{v^{2}}{M_{1}}$$

A CRUCIAL QUESTION ...



The connection is not simple...

• The high energy leptonic Lagrangian contains 12+6 new parameters

One can always choose a basis where the right-handed mass matrix is diagonal and real (but not the Yukawa coupling):

M has 3 real parameters h_v has 9 real parameters and 6 phases

• The effective Lagrangian contains 6+3 new parameters

 \mathcal{M}_{v} has six real parameters (3 masses, 3 angles) and three phases

More parameters in the high energy theory than in the effective theory

There is, compatible with the observed neutrino parameters, an infinite set of Yukawa couplings!

Does leptogenesis make any prediction?

How to test/rule-out leptogenesis?

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How to test/rule-out leptogenesis?

Even though the connection between leptogenesis and low energy neutrino data is very vague, it is possible to derive from neutrino parameters very valuable information about the leptogenesis scenario.

1) Upper bound on the CP asymmetry (\Rightarrow Lower bound on the lightest right-handed neutrino mass)

2) Upper bound on the overall neutrino mass scale (*)

(*) Depending on the impact of flavour effects on leptogenesis

1- Upper bound on the CP asymmetry

In the scenario with hierarchical right-handed neutrinos, one can show that the CP asymmetry is bounded from above by:

$$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} (m_3 - m_1)$$
 Davidson, AI

If the light neutrino spectrum is also hierarchical

$$|\epsilon_1| \le \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m_{\rm atm}^2}}{\langle H^0 \rangle^2}$$

The CP asymmetry is bounded from above by the mass of the lightest right-handed neutrino and the square root of the atmospheric mass splitting.

Direct window on the scale at which neutrino masses are generated, from the requirement of successful leptogenesis.

The baryon asymmetry from leptogenesis can be approximated by:

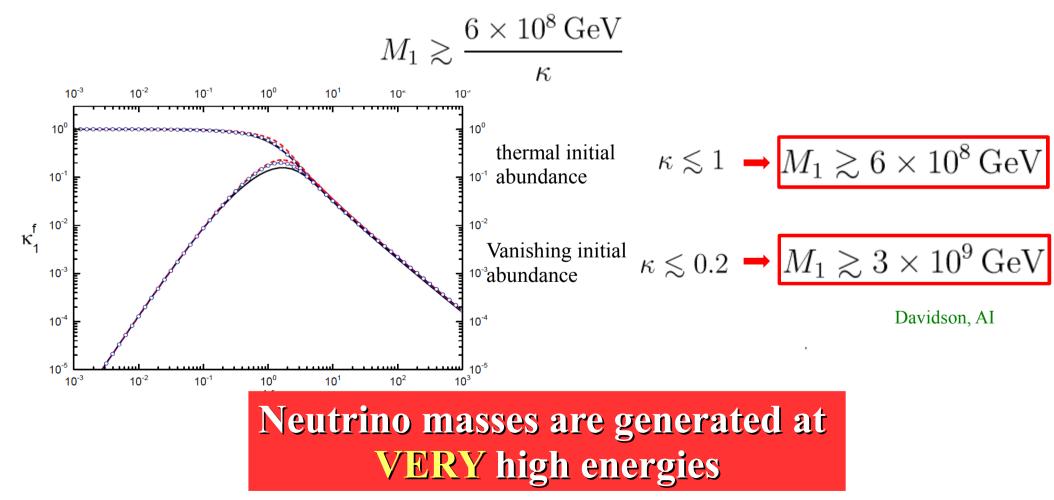
$$\eta_B \simeq 0.96 \times 10^{-2} \,\epsilon_1 \kappa$$

where $\eta_B = (6.11 \pm 0.19) \times 10^{-10}$ (WMAP) and κ is an "efficiency factor"

From the upper bound on the CP asymmetry

 $|\epsilon_1| \le \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m_{\rm atm}^2}}{\langle H^0 \rangle^2}$

a lower bound on the lightest right-handed neutrino mass follows:



2- Upper bound on the neutrino mass

• The upper bound on the CP asymmetry can be rewritten as:

$$|\epsilon_1| \le \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} (m_3 - m_1) = \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} \frac{(m_3^2 - m_1^2)}{m_3 + m_1} = \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} \frac{\Delta m_{atm}^2}{m_3 + m_1}$$

The larger the scale of neutrino masses, the smaller the CP asymmetry. For large neutrino masses, it is more difficult to generate a BAU!

• Furthermore, the washout rate due to $\Delta L=2$ scatterings goes as:

$$\Delta W \propto M_1 \overline{m}^2$$
$$\overline{m}^2 = m_1^2 + m_2^2 + m_3^2$$

The larger the scale of neutrino masses, the larger the washout.

Is there a neutrino mass at which leptogenesis just doesn't work?

2- Upper bound on the neutrino mass

• The upper bound on the CP asymmetry can be rewritten as:

$$|\epsilon_1| \le \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} (m_3 - m_1) = \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} \frac{(m_3^2 - m_1^2)}{m_3 + m_1} = \frac{3}{16\pi} \frac{M_1}{\langle H^0 \rangle^2} \frac{\Delta m_{atm}^2}{m_3 + m_1}$$

The larger the scale of neutrino masses, the smaller the CP asymmetry. For large neutrino masses, it is more difficult to generate a BAU!

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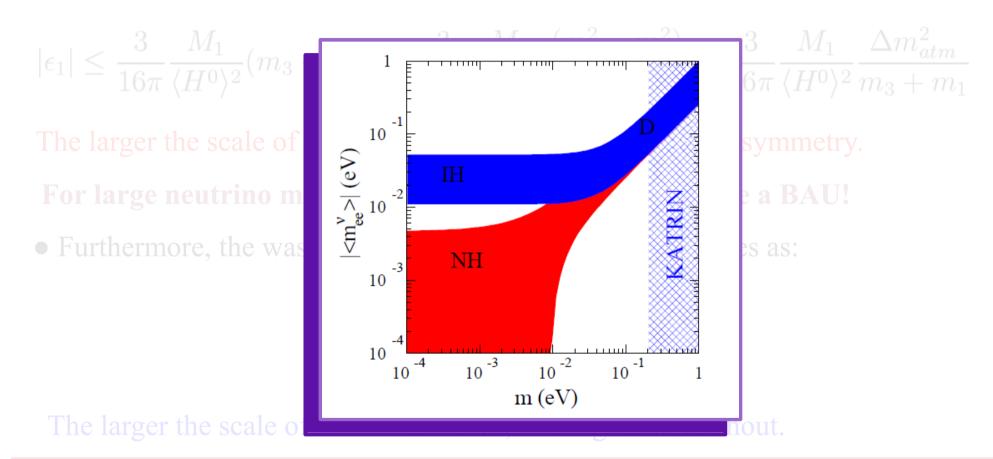
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• The observation of a matter-antimatter asymmetry in our Universe cannot be explained within the Standard Model and requires new physics.

• After the discovery of neutrino masses, leptogenesis stands as one of the most plausible explanations for the matter-antimatter asymmetry.

• Leptogenesis is very naturally implemented within the see-saw mechanism. The simplest scenario consists in the out of equilibrium decay of right-handed neutrinos with a mass $M_1 \gtrsim 10^9$ GeV.

• How to test leptogenesis? The observation of $v0\beta\beta$ decay would give support to the leptogenesis scenario, however a "smoking gun" for leptogenesis is still lacking.