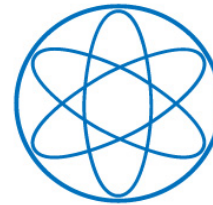


Neutrinos in cosmology

Alejandro Ibarra

Technische Universität München

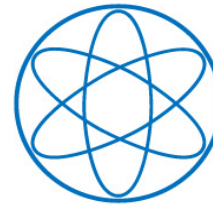


Munich
25 April 2016

Lepton number violation and baryogenesis

Alejandro Ibarra

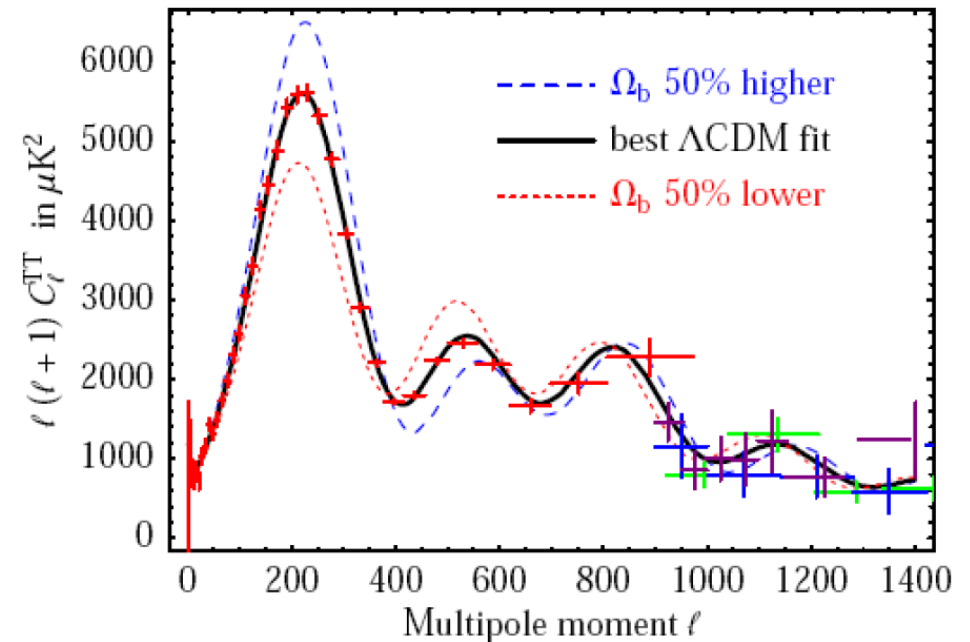
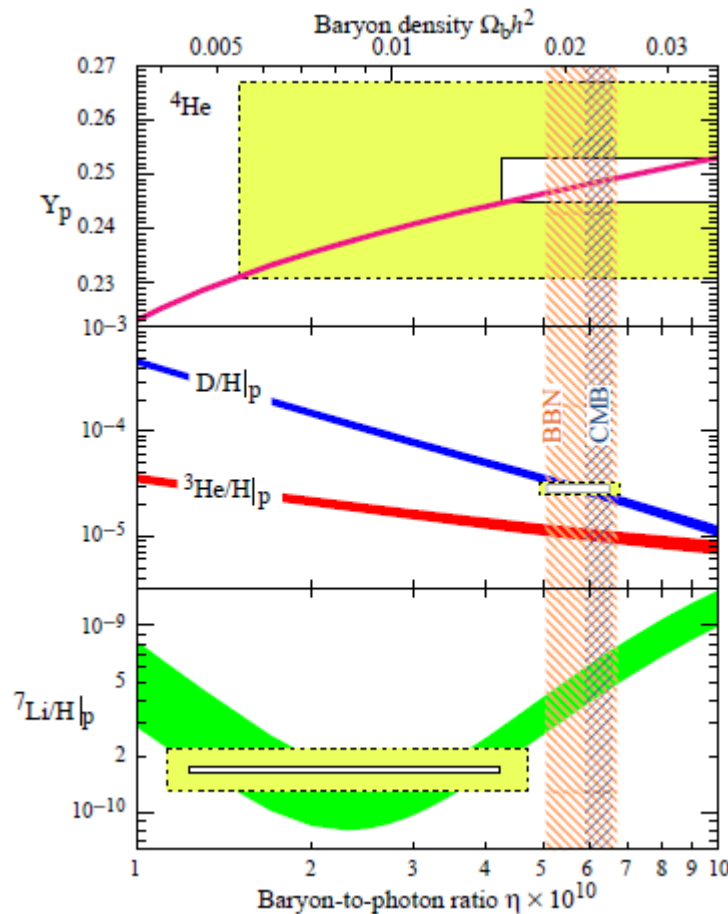
Technische Universität München



Munich
25 April 2016

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.



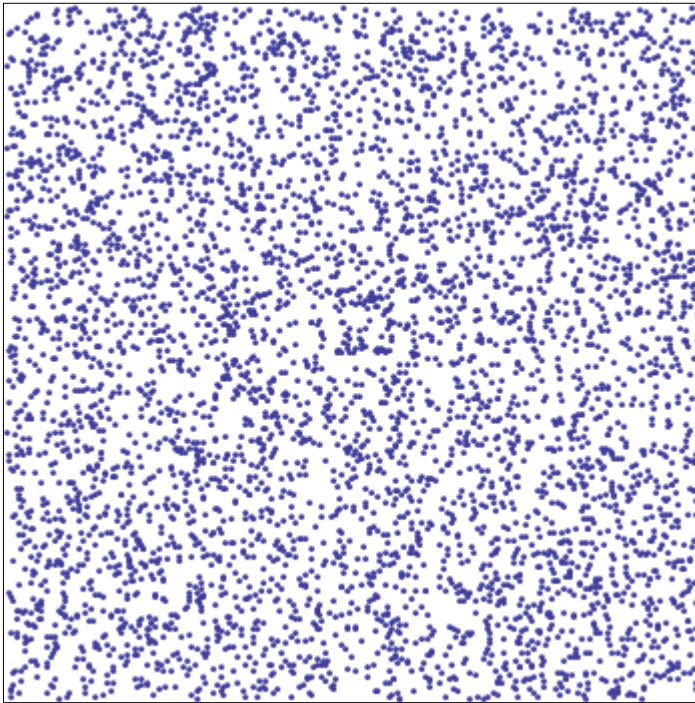
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.11 \pm 0.19) \times 10^{-10}$$

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

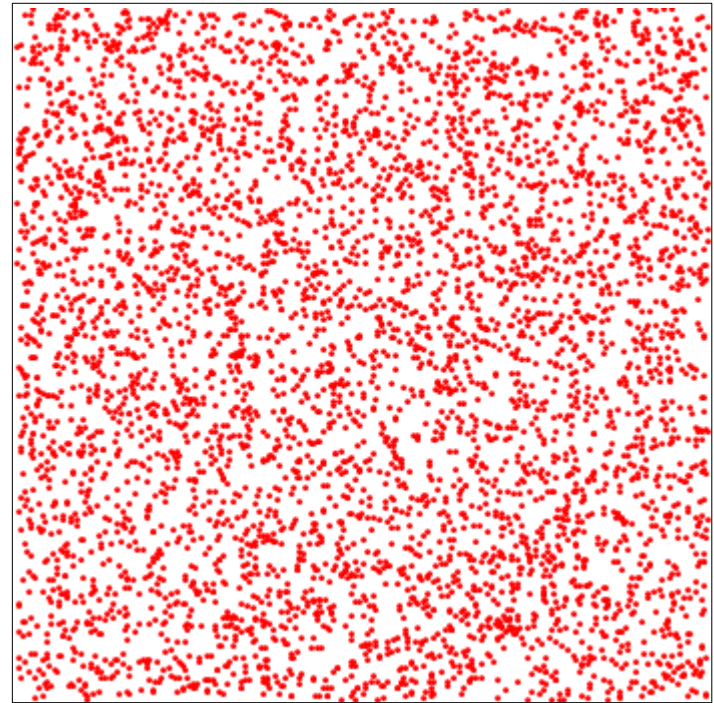
But this is a very small number!!

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

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



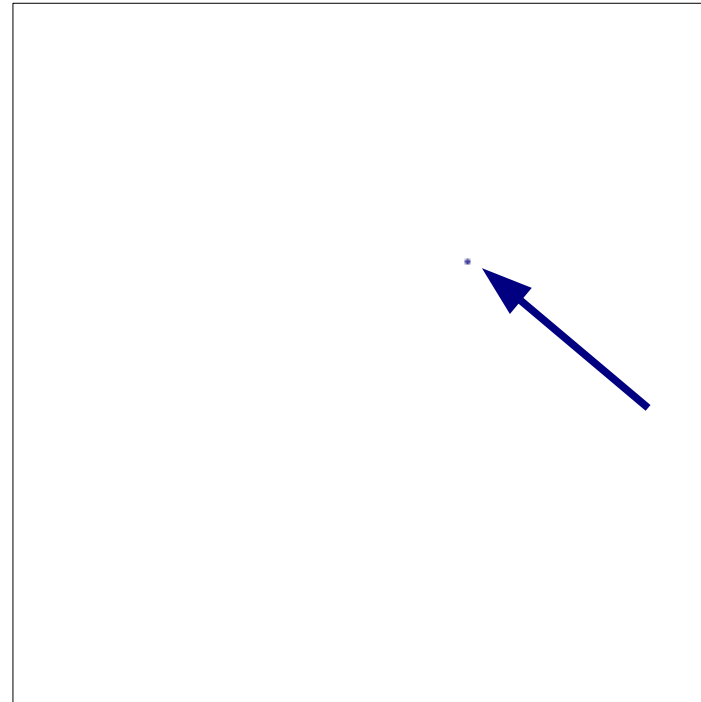
$$N_{\bar{B}} = 30\,000\,000$$



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

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

now



Why was there in the very early Universe a tiny excess of baryons?

Baryogenesis

Dynamical generation of a BAU: Sakharov conditions

The baryon asymmetry can be dynamically generated in particle decays 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

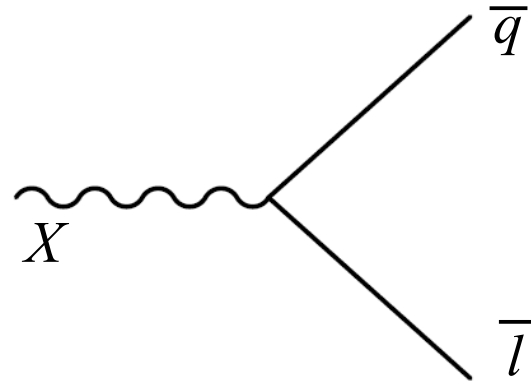
Department of Physics, Tohoku University, Sendai 980, Japan

(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.

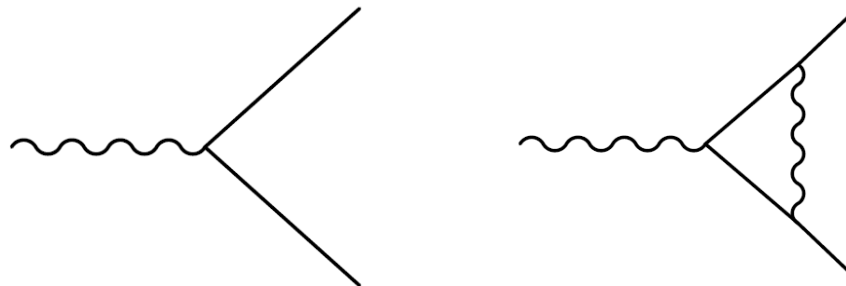
These three conditions are fulfilled in the simplest grand unified models.

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

Very attractive!!

Very attractive!!

But ruled out...

Very attractive!!

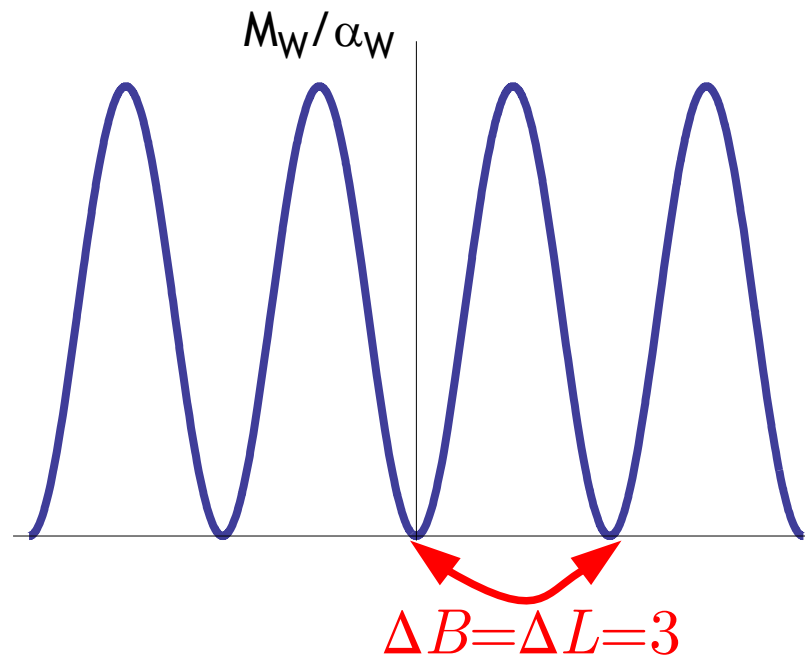
But ruled out...

The requirement of baryon number violation is not enough!

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.

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



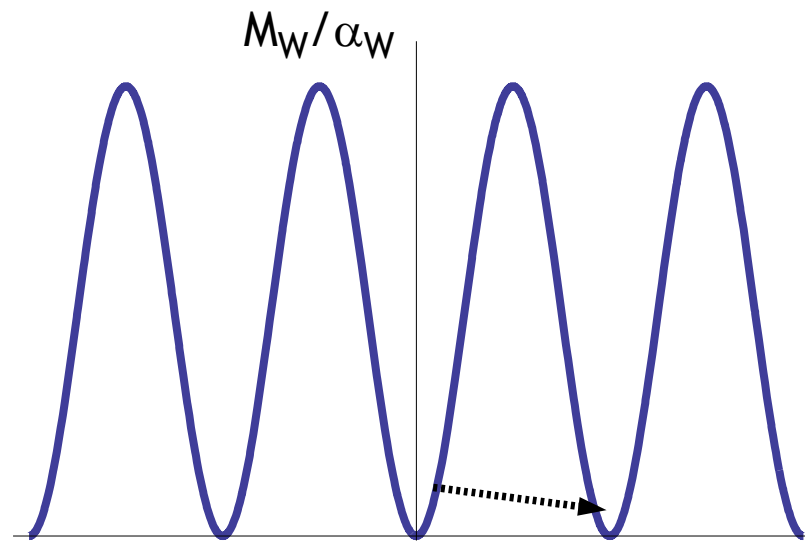
In changing from vacuum to vacuum, B and L are violated, but $B-L$ is preserved.

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At zero temperature, transitions among vacua only through tunnelling



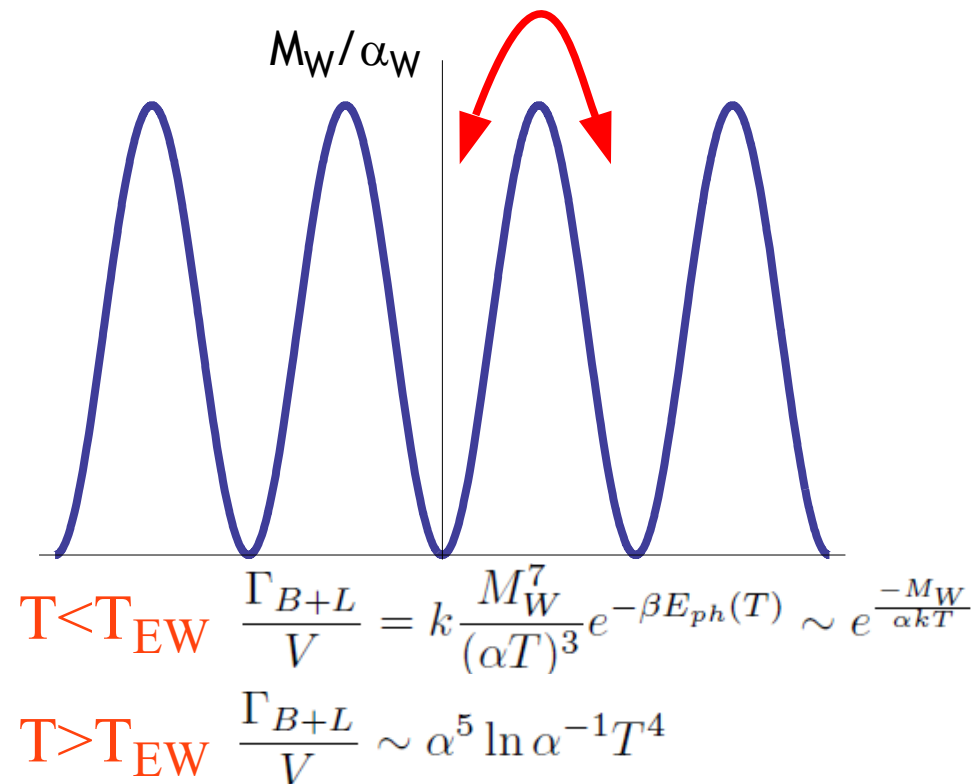
$$\Gamma \sim e^{-S_{int}} = e^{-4\pi/\alpha} = \mathcal{O}(10^{-165})$$

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At high temperature, the barrier can be easily crossed

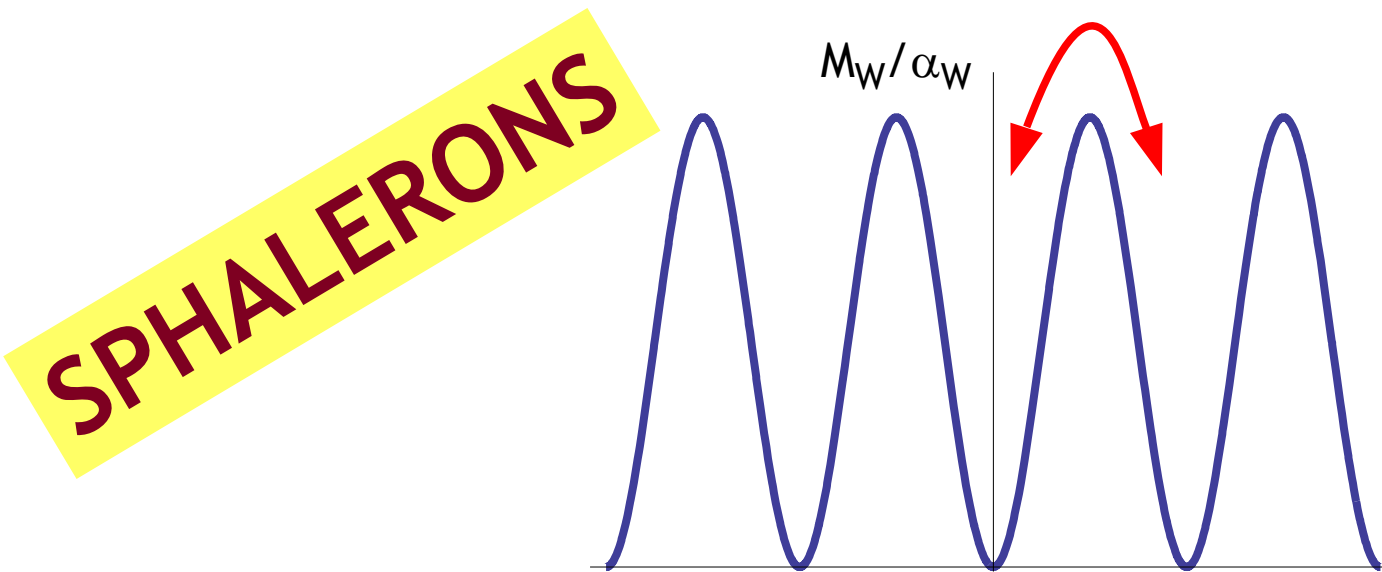


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At high temperature, the barrier can be easily crossed



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

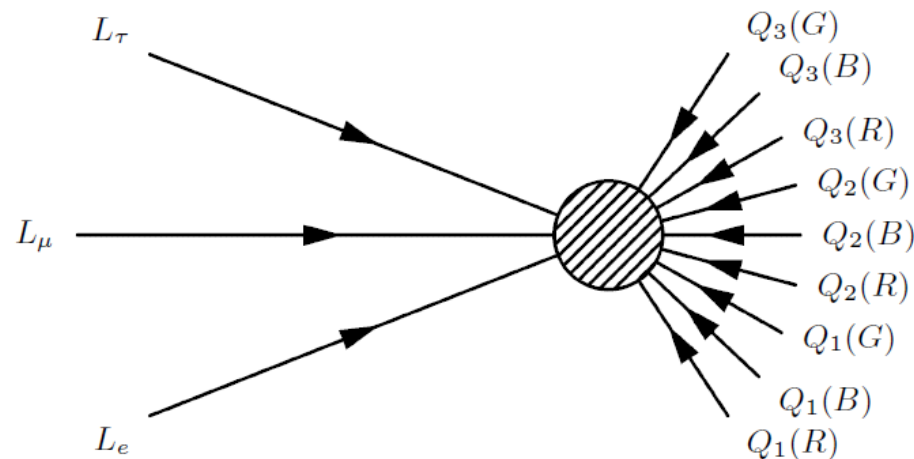
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At high temperature, the barrier can be easily crossed

SPHALERONS



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

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. SHAPOSHNIKOV ¹

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-

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

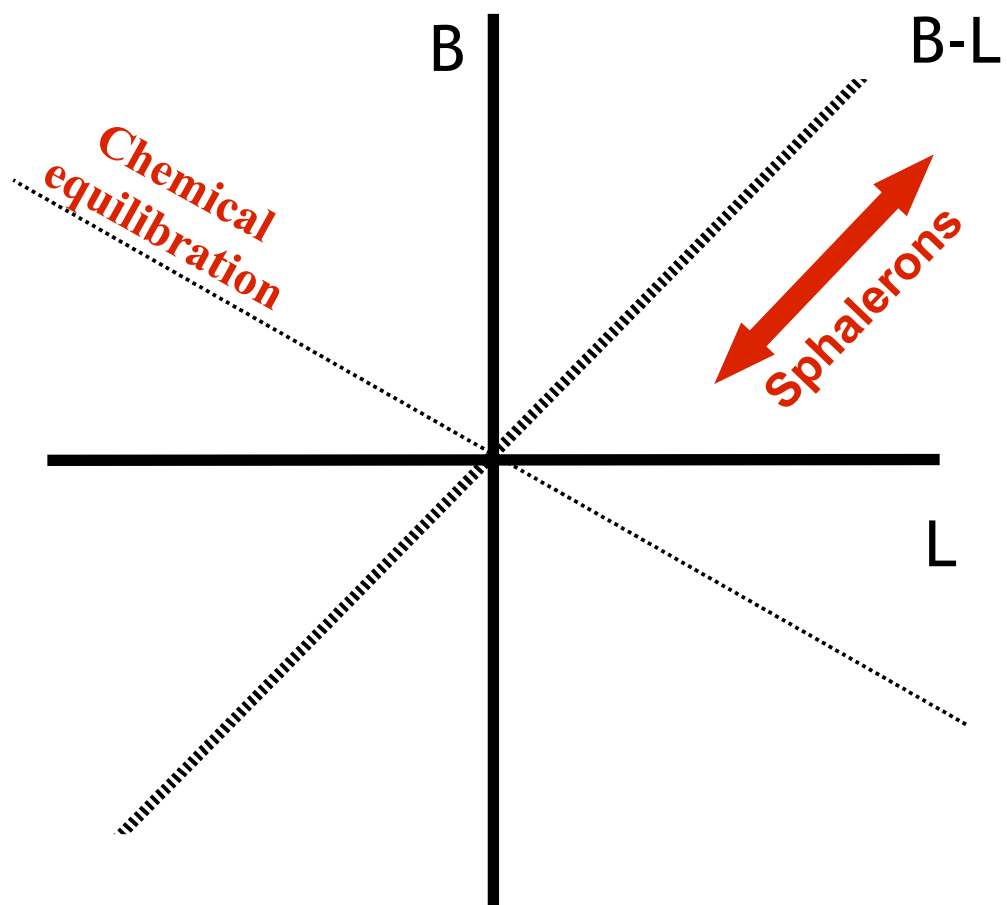
$$A \sim \beta M_{\text{Pl}}/T_c \sqrt{N_{\text{eff}}} \sim \beta \times 10^{15} \quad (9)$$

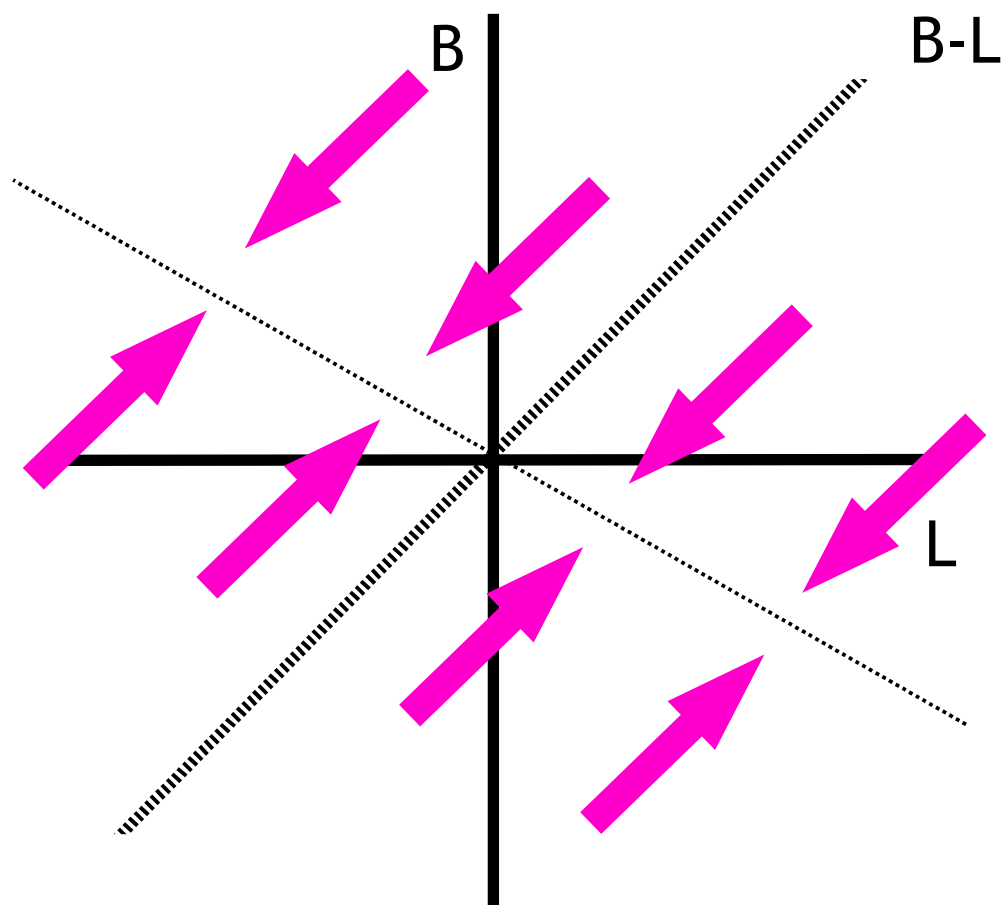
Clearly, $B(T_c) = \frac{1}{2} (B_{\text{in}} - L_{\text{in}})$ with great precision;

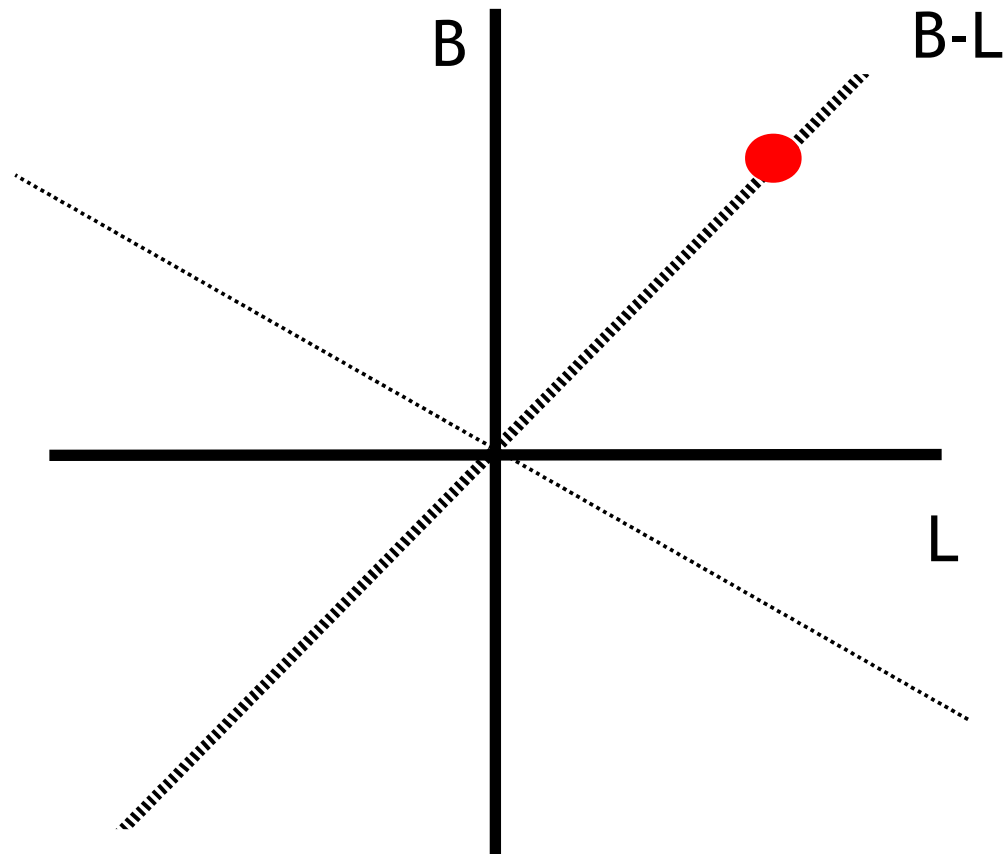
this means that if the primordial baryon asymmetry is generated by the $(B - L)$ conserving processes (which is the case in the minimal SU(5) model [22]), it is completely washed out by the moment of the electroweak phase transition.

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)

$$\Delta \sim (C - L_{\text{in}}) e^{-A} \sim 10^{-15} \quad (10)$$







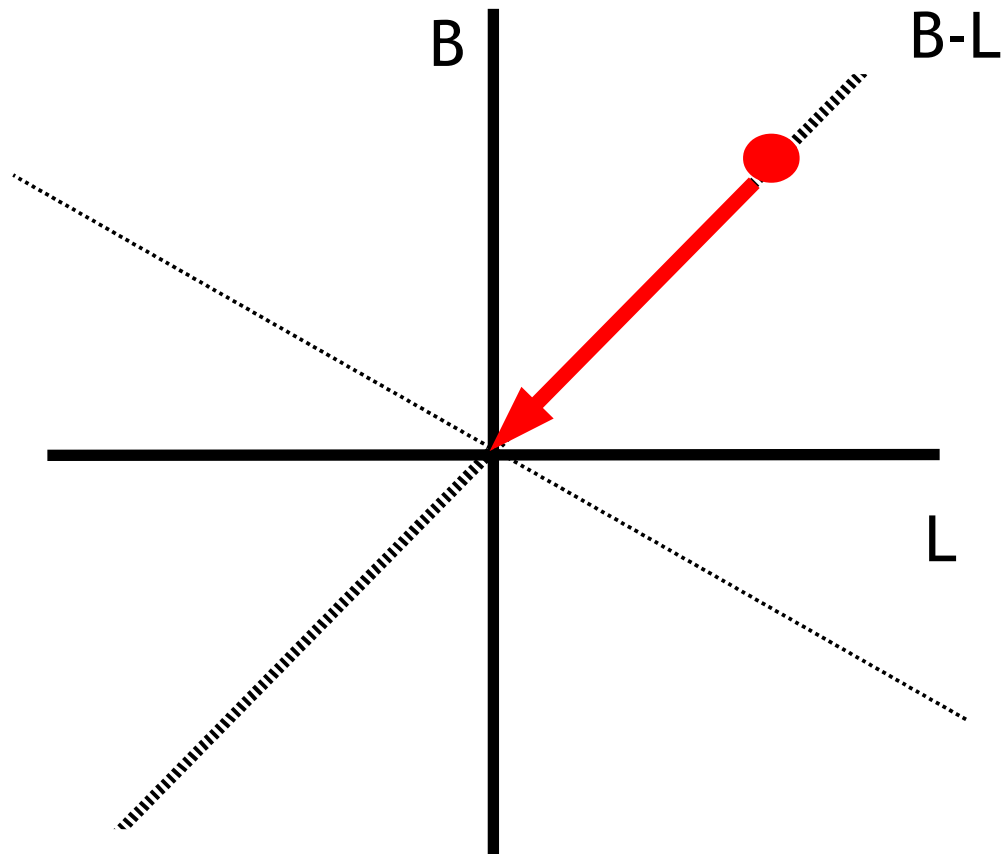
Unified Gauge Theories and the Baryon Number of the Universe

Motohiko Yoshimura

Department of Physics, Tohoku University, Sendai 980, Japan

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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.



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“Revised” Sakharov conditions

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

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

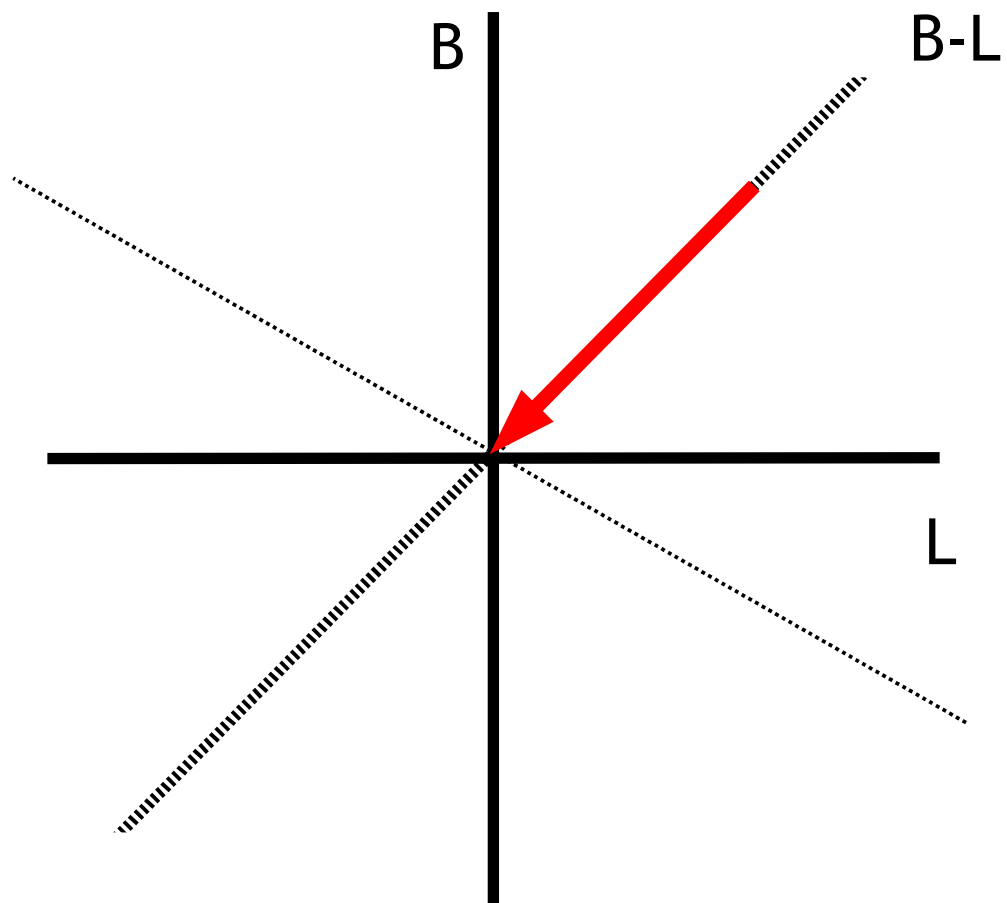
If baryon asymmetry is conserved, no baryon number can be dynamically generated. There must exist $X^{B=0} \rightarrow Y^{B=0} + B^{B \neq 0}$

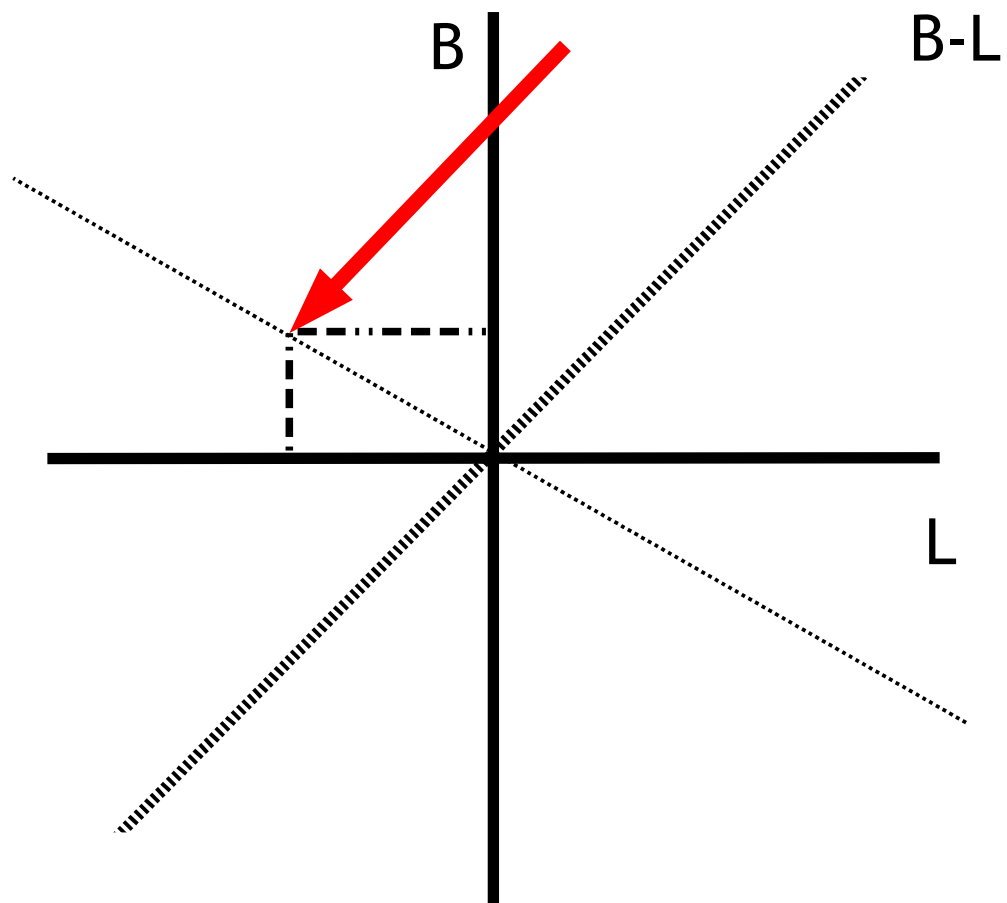
- C and CP violation

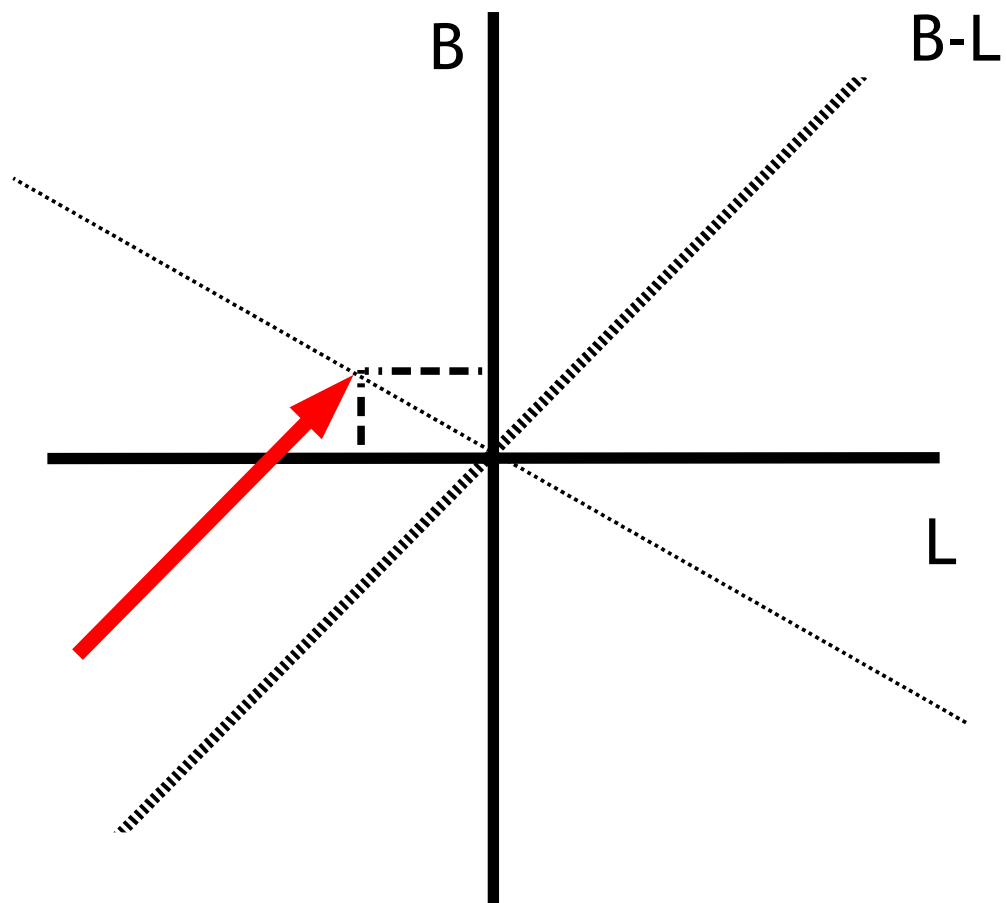
If C or CP are conserved, $\Gamma(X \rightarrow Y+B) = \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B}) \Rightarrow$ No net effect

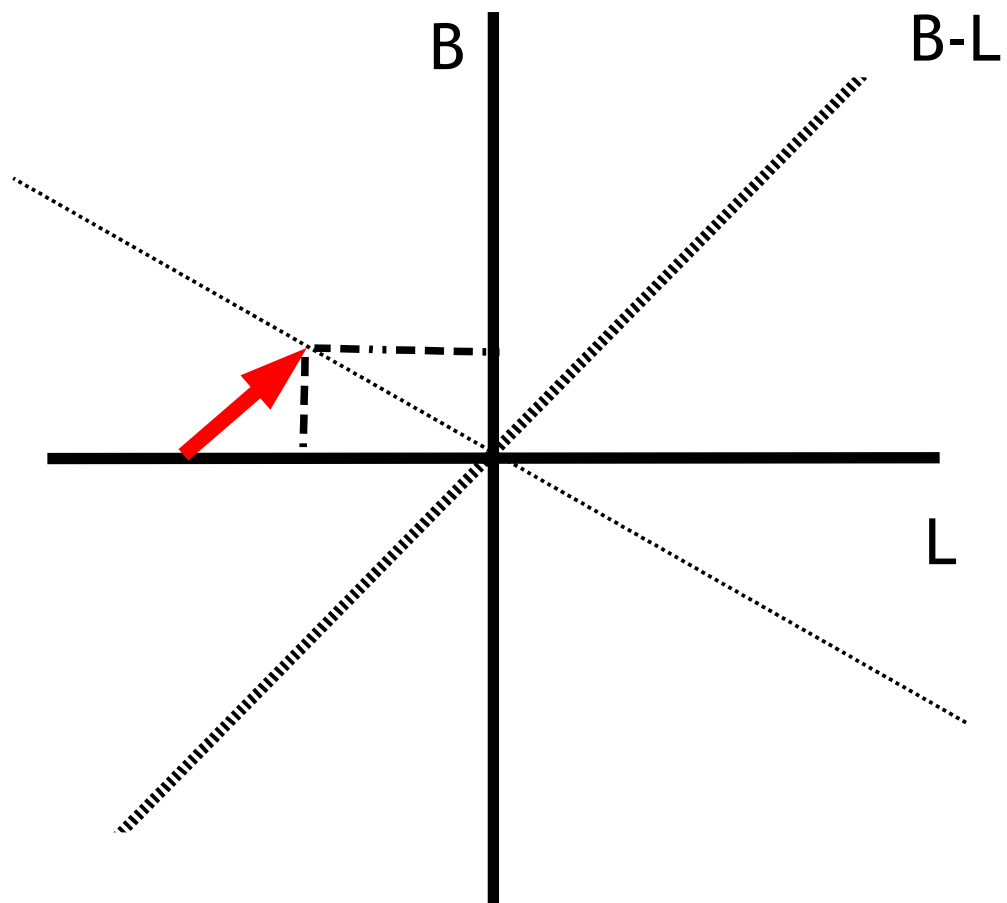
- Departure from thermal equilibrium

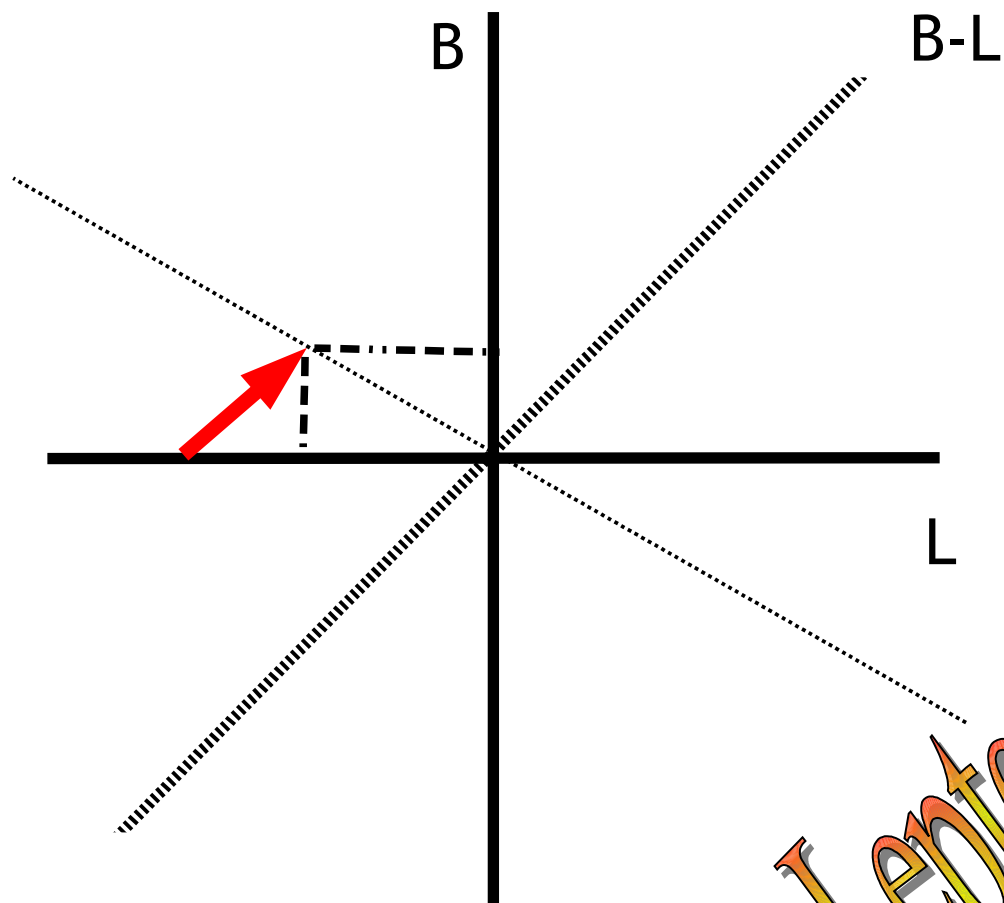
In thermal equilibrium, the production rate of baryons is equal to the destruction rate: $\Gamma(X \rightarrow Y+B) = \Gamma(Y+B \rightarrow X) \Rightarrow$ No net effect.











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

M. FUKUGITA

Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

and

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and Deutscher Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

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 may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.

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 numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A serious interesting problem is that no evidence is 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 erases 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 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 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 ($\phi = 1 - n$) in addition to the conventional leptons. We take the Lagrangian to be

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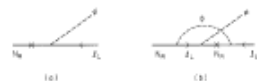


Fig. 1. The simplest diagrams giving rise to a net lepton number production. The cross denotes the Majorana mass insertion.

$$\mathcal{L} = \bar{L}_R \gamma_\mu D_\mu L_R + \bar{N}_R^c \gamma_\mu D_\mu N_R^c + \bar{L}_R \gamma_\mu N_R^c + \text{h.c.} + h_L \bar{N}_R^c \tilde{\phi}^c + \text{h.c.}, \quad (1)$$

where \mathcal{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 ,

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

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

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]

$$e = (9/8\pi) \ln(h_{11}^2 h_{21}^2 h_{31}^2 / h_{12}^2 h_{22}^2 h_{32}^2) / (M_1^2 M_2^2 M_3^2) \quad (3)$$

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

$$e \approx (9/8\pi) |h_{21}|^2 (M_1/M_3)^2, \quad (4)$$

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 $\Gamma = (M_1^2/16\pi)$ [10] is equal to the expansion rate of the Universe $H \approx 1.7\sqrt{g}T^2/m_{\text{pl}}$ (g = number of degrees of freedom), i.e.,

$$(\Gamma m_{\text{pl}}^{-2})^{1/2} \lesssim M_1. \quad (5)$$

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

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

with $K = \frac{1}{2} \Gamma/\tilde{\Gamma}$ for $K \gg 1$. The parameters in (4) and in the expression of $\tilde{\Gamma}$ 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 $R(\Delta L)_L/x \approx 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives $M_1 \gtrsim 2.4 \times 10^{14} \text{ GeV} (M_1^2/h_{11}^2)$. If we assume $|h_{21}|^2 \sim (10^{-2})^2$, 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_{ν_L} as $m_{\nu_L} \approx h_{11}^2 \phi^2/M_1 \lesssim 0.1 \text{ eV}$. If the lighter 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]

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

with $\gamma \sim T$. At the time of the Weinberg-Salam epoch the exponent is $m_{\text{pl}} T/\sqrt{g} \sim 10^{16}$ 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 $\Delta B/\Delta S \sim 10^{-10.8}$.

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 observable neutrino mass. The left-handed neutrino mass matrix is given by $(m_{\nu_L})_{ij} = \sum_k h_{ki}^2 h_{kj}^2 \phi^2/M_k$ [10]. The double beta decay experiment constrains the matrix element $|(m_{\nu_L})_{11}| = (h_{11}^2/M_1 + h_{21}^2/M_2 + h_{31}^2/M_3)/\phi^2$, while eq. (5) refers to $(h_{11}^2/M_1 + h_{21}^2/M_2 + h_{31}^2/M_3)/\phi^2$ and h_{11}^2/M_1 in general. Others 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 instant beta decay experiment constrains the eigenvalue of the mass matrix (m_{ν_L}) (see ref. [11]).

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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_{21}^2) or (h_{31}^2) is large enough. The equilibrium condition $\Gamma_{\text{eq}} \exp(-M_1/T) \gtrsim 1.7\sqrt{g}T^2/m_{\text{pl}}$ ($\nu = 2$ or 3) leads to a constraint similar to (5) but with the inequality reversed. The net baryon number destruction factor behaves as $\sim \exp(-\delta B)$ ($\delta = O(1)$) [9]. For $K \gtrsim 20-30$, the equilibrium practically erases the whole pre-existing lepton number excess. This condition is expressed as $(m_{\nu_L})_1 > 0.1 \text{ eV}$ for the largest entry of the Majorana mass matrix.

In the presence of unsuppressed 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 this epoch are washed out irrespective of their $B-L$ properties.

In summary, we have the following possible scenario 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 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 $\Delta B \neq 0$, $\Delta L = 0$ Universe. The equilibrium of N_R^c and $\phi + \bar{\nu}_L$, 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 $\phi + \bar{\nu}_L$, 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.

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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 may transform 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 microscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interactions 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 interesting 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 erases 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 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 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

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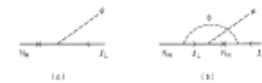


Fig. 1. The striped diagrams giving rise to a net lepton number production. The cross denotes the Majorana mass insertion.

$$\mathcal{L} = \mathcal{L}_{\text{WS}} + \sum_{\alpha} \bar{N}_R^{\alpha} N_R^{\alpha} + M_N^{\alpha} \bar{N}_R^{\alpha} N_R^{\alpha} + \text{h.c.} + h_{\alpha} \bar{N}_R^{\alpha} \psi_L^{\alpha} \phi + \text{h.c.}, \quad (1)$$

where \mathcal{L}_{WS} 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 ,

$$N_R \rightarrow \psi_L + \bar{\phi}, \quad (2a)$$

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

there appear 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^1 arises from the interference of the two diagrams in fig. 1, and its magnitude is calculated as [7]

$$\epsilon = (9/8\pi) \ln(h_{11}^2/h_{21}^2) (M_2^2/M_1^2) (\text{Im } h_{11}^2)_{11}, \quad (3)$$

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

$$\epsilon \approx (9/8\pi) |h_{33}|^2 (M_3/M_1)^2, \quad (4)$$

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 $\Gamma = (M_1^2/12\pi) \ln$ (for ϵ equal to the expansion rate of the Universe $H \approx 1.7\sqrt{g}T^2/m_{\text{Pl}}$ (g = number of degrees of freedom), i.e.,

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

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

$$R(\Delta L)_1/x = 10^{-3} \epsilon K^{-1/2}, \quad (6)$$

with $K = \frac{1}{2} \Gamma/\tilde{\Gamma}$ for $K \gg 1$. The parameters in (4) and in the expansion 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 $\epsilon \lesssim 10^{-6}$. Then to obtain our required number for $R(\Delta L)_1/x = 10^{-10.5}$ (see below), $K \lesssim 30$ is necessary, which gives $M_1 \gtrsim 2.4 \times 10^{14} \text{ GeV} (M_1^2/h_{11}^2)$. If we assume $|h_{11}|^2 \sim (10^{-2})^2$, 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_{ν}^L as $m_{\nu}^L \approx h_{11}^2 \phi^2/M_1 \lesssim 0.1 \text{ eV}$. 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]

$$\Delta B(\nu) = \frac{1}{2} \Delta(B-L)_1 + \frac{1}{2} \Delta(B+L)_1 \exp(-\gamma), \quad (7)$$

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

$$\Delta B = -(\Delta L)_1/2, \quad (8)$$

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

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 observable neutrino mass: The left-handed neutrino mass matrix is given by $(m_{\nu}^L)_{ij} = \sum_{\alpha} h_{\alpha i} h_{\alpha j} \phi^2/M_{\alpha}$ [10]. The doublet lepton decay experiment constrains the matrix element $(m_{\nu}^L)_{11} = (h_{11}^2/M_1 + h_{21}^2/M_2 + h_{31}^2/M_3)/\phi^2$, while eq. (5) refers to $(h_{11}^2/M_1 + h_{21}^2/M_2 + h_{31}^2/M_3)/\phi^2$ and $\delta_{11} = \delta_{31}$ in general. Others we took the case where the charged-lepton mass matrix is diagonal. Therefore, the doublet lepton decay experiment does not constrain directly the parameters in eq. (5). The instanton lepton decay experiment requires the eigenvalue of the mass matrix (m_{ν}^L) (see ref. [11]).

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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 (M_1^2/h_{11}^2) or (M_1^2/h_{21}^2) is large enough. The equilibrium condition $\Gamma \exp(-M_1/T) \gtrsim 1.7\sqrt{g}T^2/m_{\text{Pl}}$ ($g = 2$ or 3) leads to a constraint similar to (5) but with the inequality reversed. The net baryon number destruction factor behaves as $\sim \exp(-\delta B)$ ($\delta = O(1)$) [9]. For $K \gtrsim 20-30$, the equilibrium practically erases the whole pre-existing lepton number excess. This condition is expressed as $(m_{\nu}^L)_{11} > 0.1 \text{ eV}$ 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 neutrinos with the Majorana mass heavier than $\sim 0.1 \text{ eV}$ both baryon and lepton numbers which existed before this epoch are washed out irrespective of their $B-L$ properties.

In summary, we have the following possible scenario 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 $N_R^c \rightleftharpoons \psi_L + \bar{\phi} + \bar{\nu}_L$, 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(10) model [12]). If the scale M is too large to establish the equilibrium of N_R^c and $\phi + \psi_L$, 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.

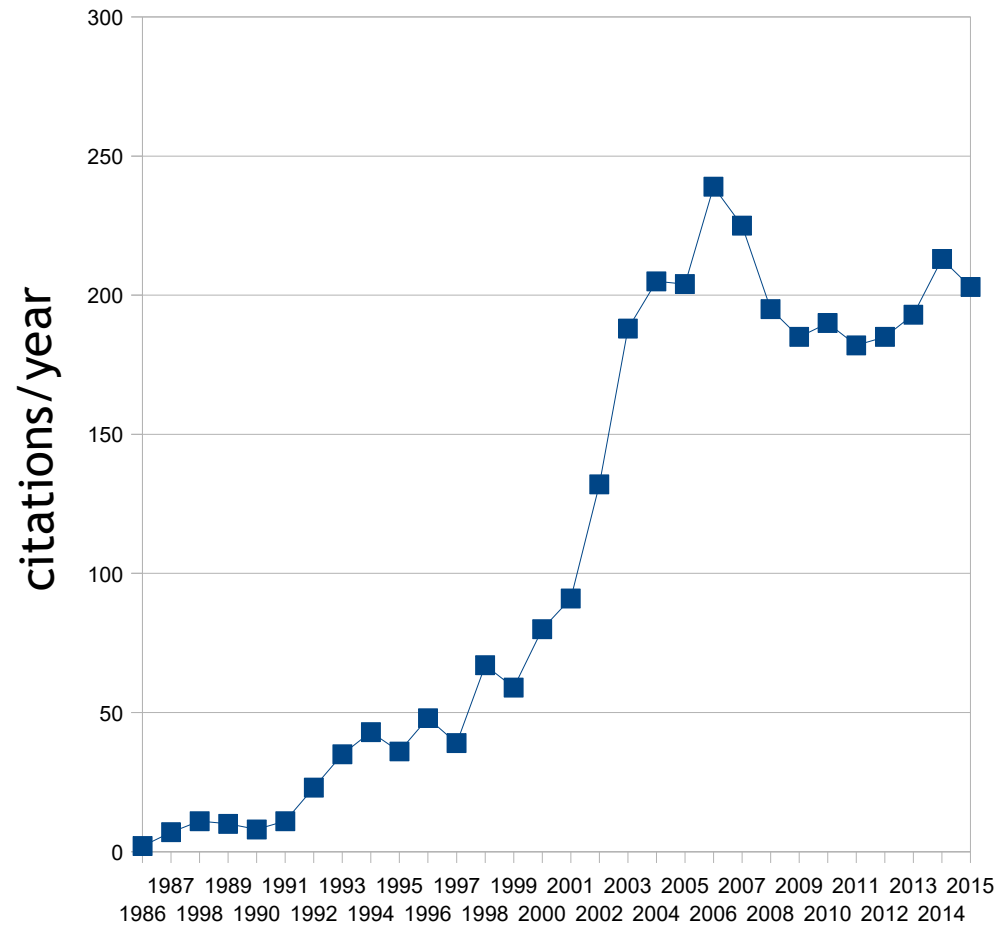
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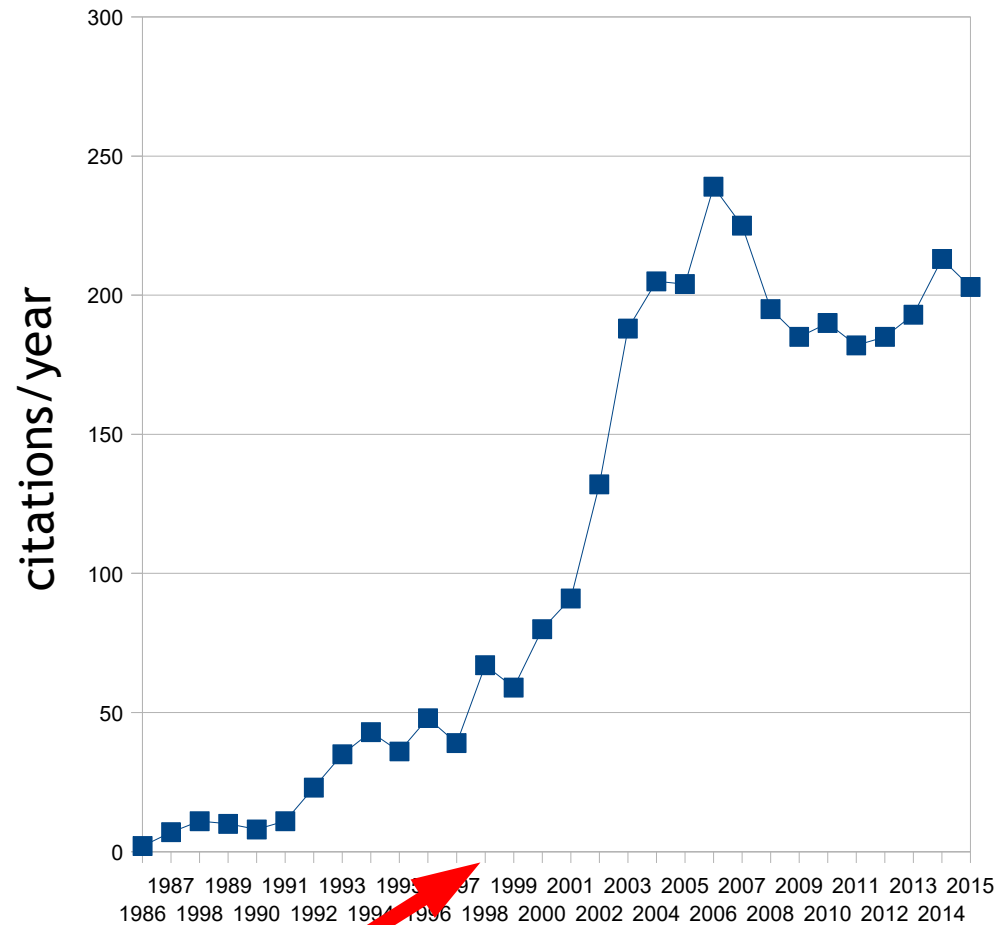
And very popular...

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Why are people so excited about leptogenesis?

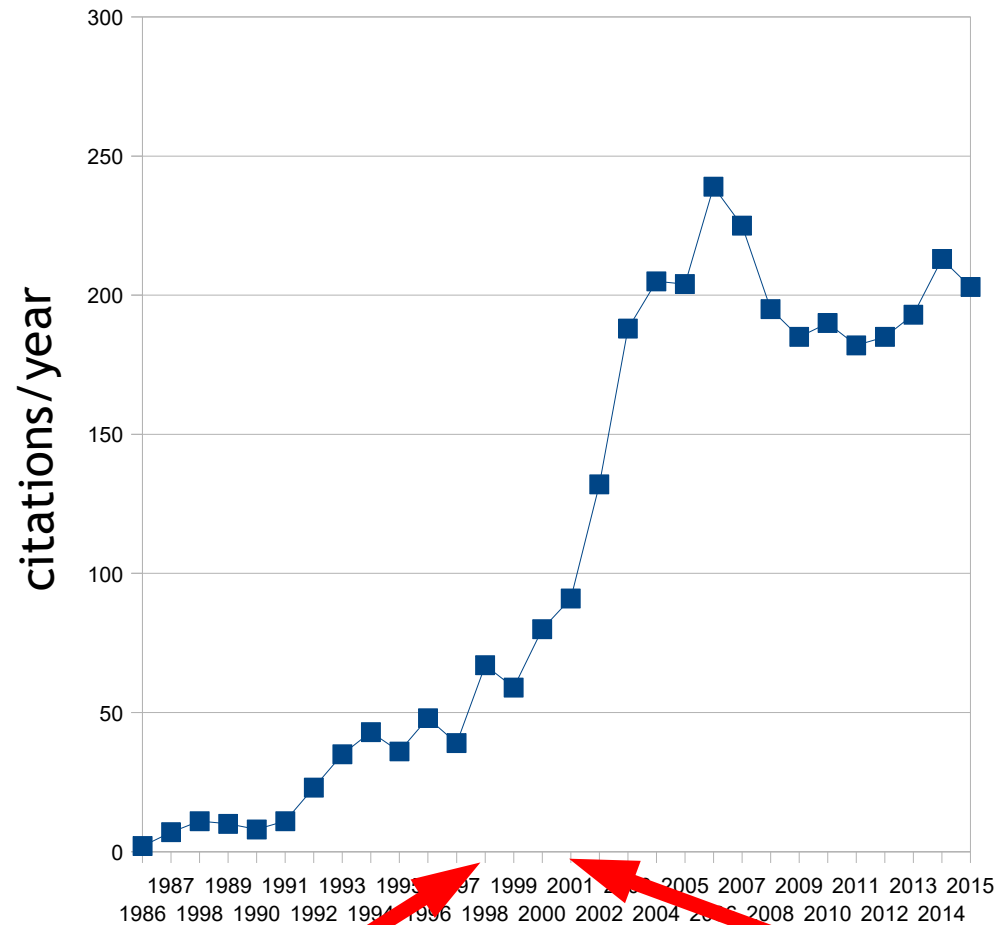


Why are people so excited about leptogenesis?



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

Why are people so excited about leptogenesis?



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

2001. Evidence of
solar neutrino
oscillations (SNO)

A simple model of neutrino masses: The type I seesaw model

Extension of the particle content of the Standard Model by heavy right-handed neutrinos (at least two).

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

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



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

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

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

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

Bonus

The out-of-equilibrium 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 three Sakharov conditions are in general 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.

Leptogenesis

Mechanism to generate dynamically the baryon asymmetry through a lepton asymmetry.

The three Sakharov conditions are in general 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.**

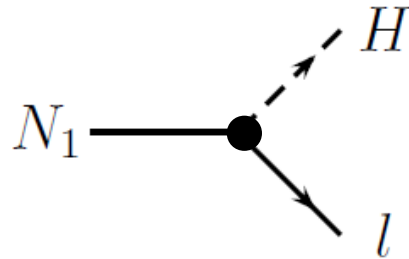
The generation of a baryon asymmetry is basically guaranteed in the leptogenesis mechanism. But, can leptogenesis generate the *observed* baryon asymmetry?

Calculate!

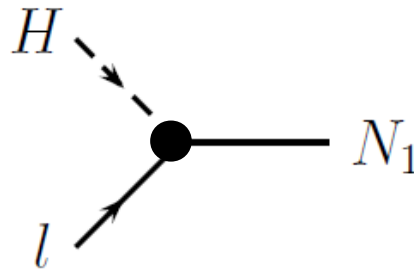


Roughly speaking, the generation of a BAU through leptogenesis proceeds in three steps:

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



2- Washout of the lepton asymmetry.



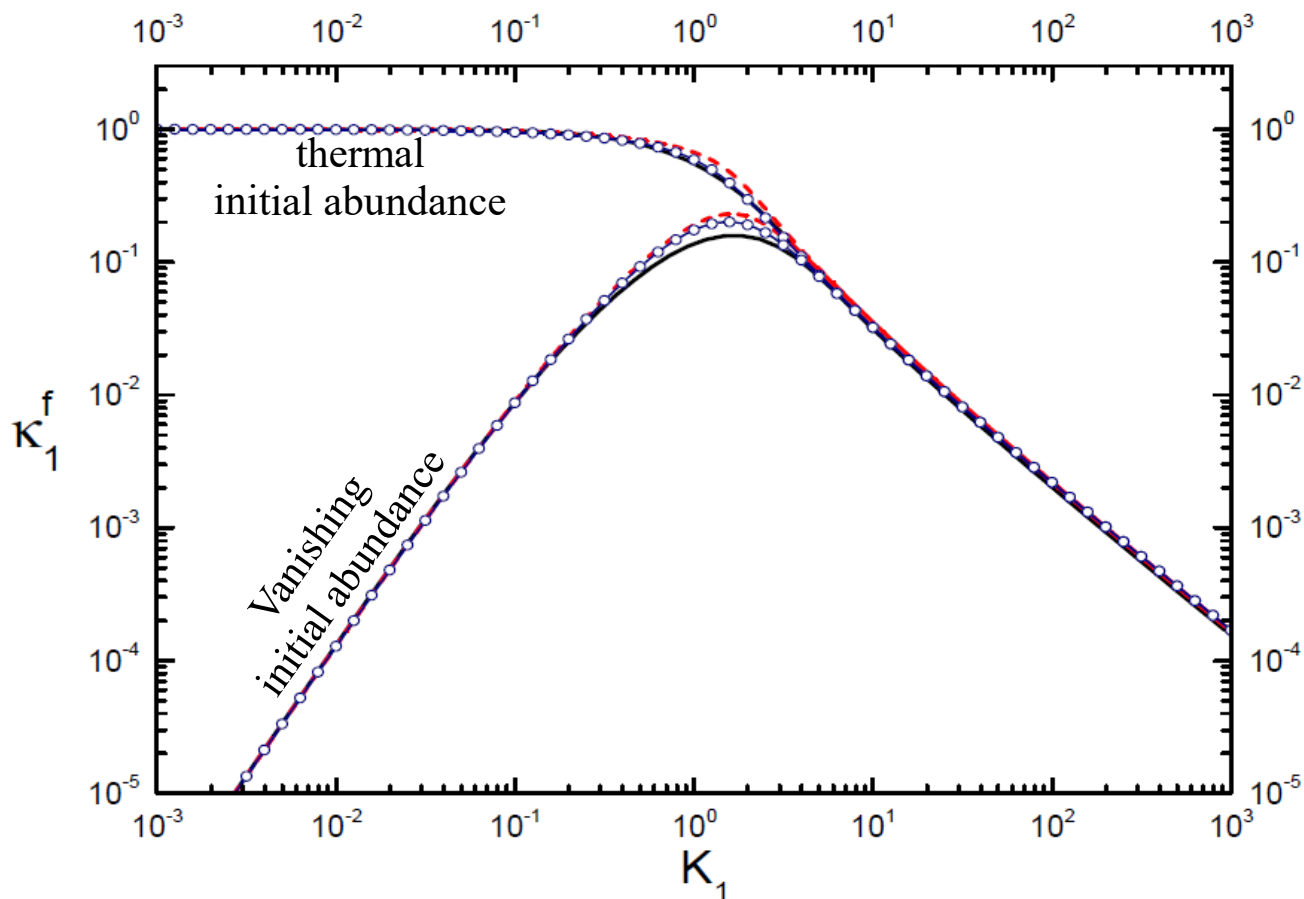
3- Conversion of the lepton asymmetry into a baryon asymmetry.



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

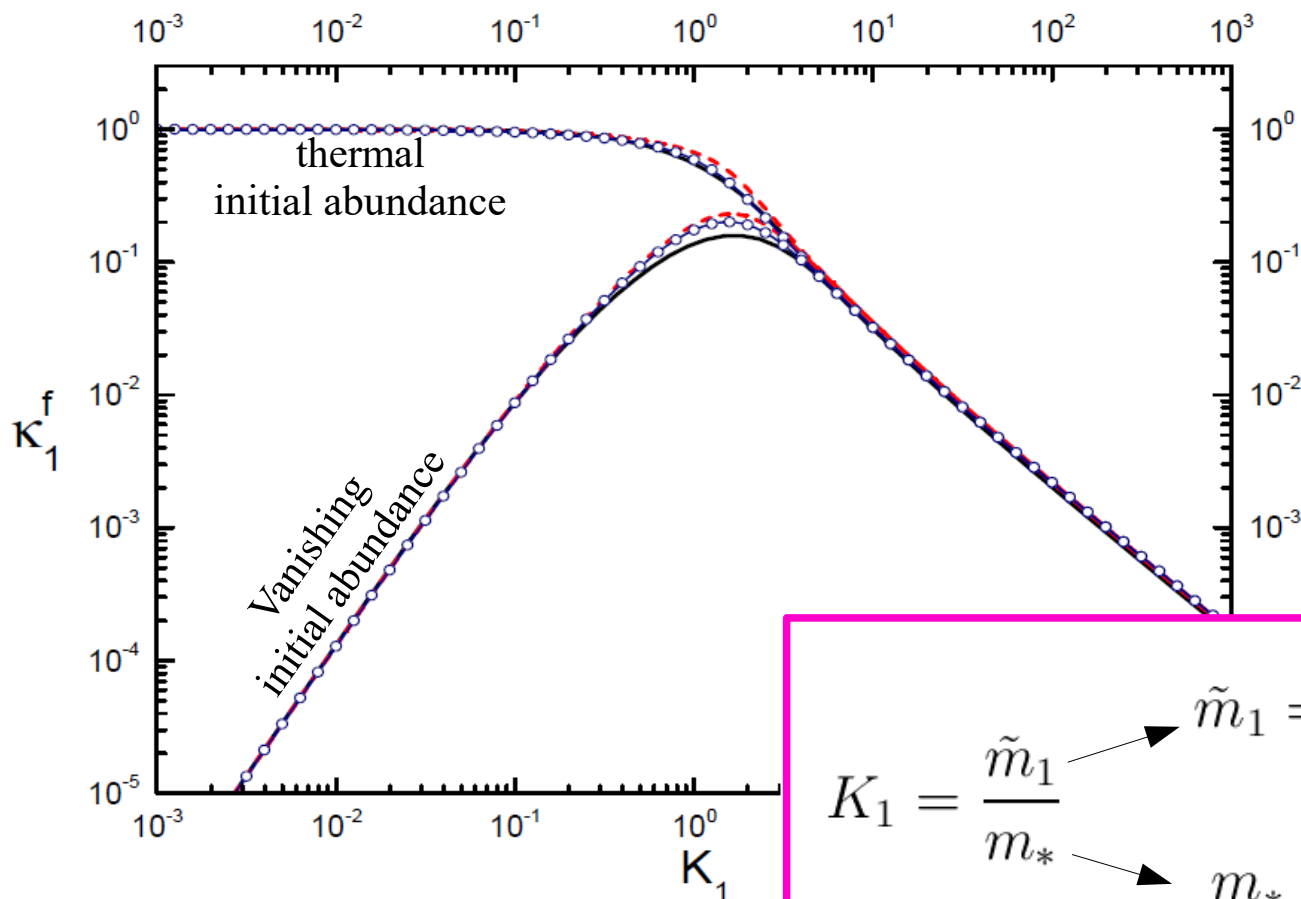
$$\eta_B \simeq 0.96 \times 10^{-2} \epsilon_1 \kappa_f$$

“Efficiency factor”



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

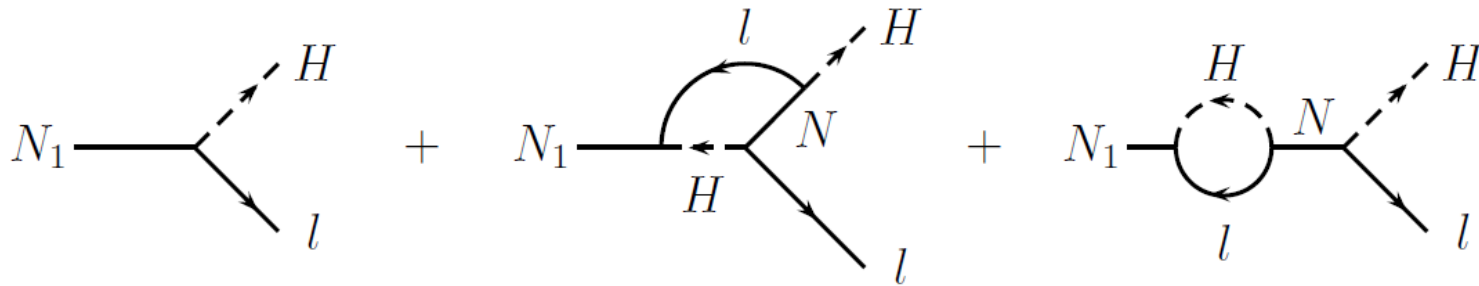
“Efficiency factor”



$$K_1 = \frac{\tilde{m}_1}{m_*} \quad \begin{array}{l} \nearrow \tilde{m}_1 = (h_\nu h_\nu^\dagger)_{11} \frac{\langle H^0 \rangle^2}{M_1} \\ \searrow m_* \approx 10^{-3} \text{ eV} \end{array}$$

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

CP asymmetry: generated through the interference between tree level and one loop decay diagrams



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

A CRUCIAL QUESTION...

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

See-saw
parameters

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

Neutrino masses
and mixing angles

Leptogenesis

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \text{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \frac{M_1}{M_i}$$
$$\widetilde{m}_1 = (h h^\dagger)_{11} \frac{v^2}{M_1}$$

A CRUCIAL QUESTION...

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

See-saw
parameters

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

Neutrino masses
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Leptogenesis

$$\epsilon = \frac{3}{16\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_i \text{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \frac{M_1}{M_i}$$
$$\widetilde{m}_1 = (h h^\dagger)_{11} \frac{v^2}{M_1}$$



The connection is not simple...

- The high energy leptonic Lagrangian contains 12+6 new parameters
 M has 3 real parameters, h_ν has 9 real parameters and 6 phases
- The effective Lagrangian contains 6+3 new parameters
 \mathcal{M}_ν has six real parameters (3 masses, 3 angles) and three phases

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

The diagram illustrates the decomposition of the Yukawa coupling h_ν into its constituent parts. The equation $h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M} R \sqrt{D_m} U_{\text{lep}}^\dagger$ is shown in a red box. Three arrows point from the terms in the equation to their physical interpretations: $\sqrt{D_M}$ points to "Right-handed neutrino masses" (3 real parameters), R points to "Orthogonal matrix: $R^T R = 1$ " (3 real parameters and 3 phases), and $\sqrt{D_m} U_{\text{lep}}^\dagger$ points to "Fixed" by experiments.

$$h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M} R \sqrt{D_m} U_{\text{lep}}^\dagger$$

Right-handed neutrino masses
3 real parameters

Orthogonal matrix: $R^T R = 1$

$$R = \begin{pmatrix} \hat{c}_2 \hat{c}_3 & -\hat{c}_1 \hat{s}_3 - \hat{s}_1 \hat{s}_2 \hat{c}_3 & \hat{s}_1 \hat{s}_3 - \hat{c}_1 \hat{s}_2 \hat{c}_3 \\ \hat{c}_2 \hat{s}_3 & \hat{c}_1 \hat{c}_3 - \hat{s}_1 \hat{s}_2 \hat{s}_3 & -\hat{s}_1 \hat{c}_3 - \hat{c}_1 \hat{s}_2 \hat{s}_3 \\ \hat{s}_2 & \hat{s}_1 \hat{c}_2 & \hat{c}_1 \hat{c}_2 \end{pmatrix}$$

3 real parameters and 3 phases

"Fixed" by experiments

Implications

1) Implications of leptogenesis for the seesaw parameters

For hierarchical right-handed neutrinos, there exists an upper limit on the CP asymmetry:

$$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m_{\text{atm}}^2}}{v^2}$$



$$M_1 \gtrsim 10^9 \text{ GeV}$$

Implications for:

- Naturalness of the electroweak symmetry breaking.
- Cosmology of supersymmetric scenarios (gravitino problem).
- Inflationary scenarios: leptogenesis requires a very high reheating temperature.

Implications

2) Implications of leptogenesis for low energy experiments

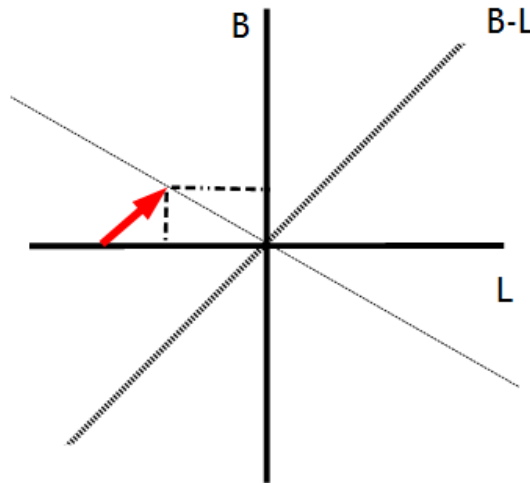
Very few and very vague:

- Non-vanishing neutrino masses
- Lepton number violation ($0\nu\beta\beta$)
- However, no direct connection with the neutrino mixing angles or CP violating phases (only in concrete scenarios)

Implications

3) Implications of low energy experiments for leptogenesis

- The observation of lepton number violation ($0\nu\beta\beta$) would provide *strong support* to leptogenesis (first Sakharov condition fulfilled)



(However, a lepton asymmetry is converted into a baryon asymmetry only at temperatures larger than a few hundreds of GeV.)

- The observation of CP violation in neutrino oscillations would provide *strong support* to leptogenesis (second Sakharov condition fulfilled)

(However, a large CP violation in neutrino oscillations does not guarantee successful leptogenesis.)

Conclusions

- Neutrino masses constitute an evidence for Physics beyond the Standard Model. Notably, **the origin of the cosmic matter-antimatter asymmetry could be related to the origin of neutrino masses** → the leptogenesis mechanism.
- In the simplest (most plausible) frameworks, leptogenesis occurs in the very first stages of the Universe and involves very heavy particles.
Leptogenesis is difficult to test!
- No smoking gun for leptogenesis as the origin of the observed baryon asymmetry has been identified. However, the discovery of $0\nu\beta\beta$ and CP violation in neutrino oscillations would provide strong support to leptogenesis.