Neutrinos in cosmology

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25 April 2016

Lepton number violation and baryogenesis

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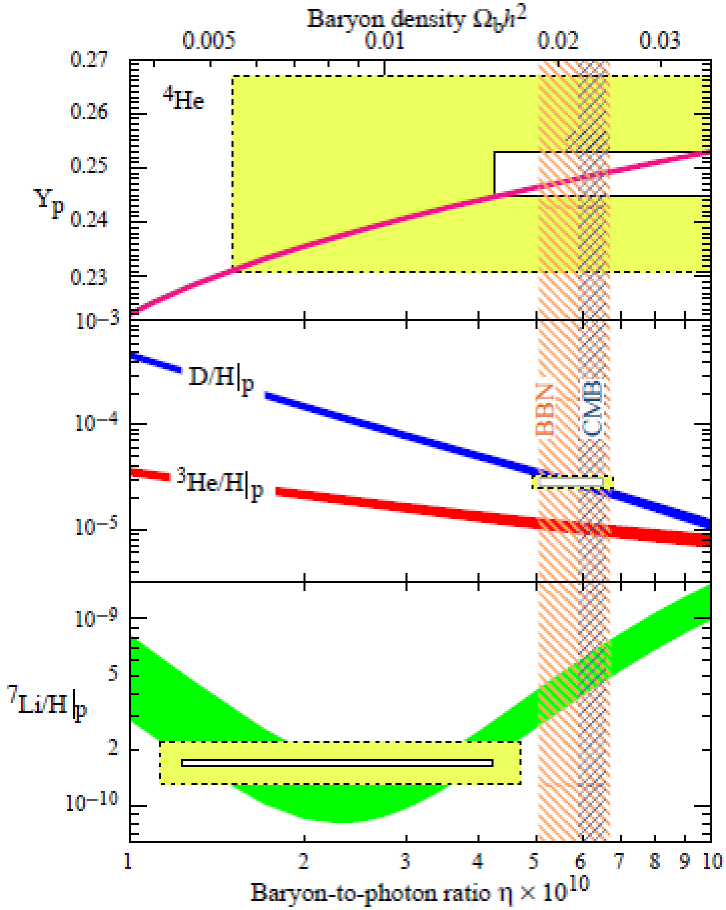
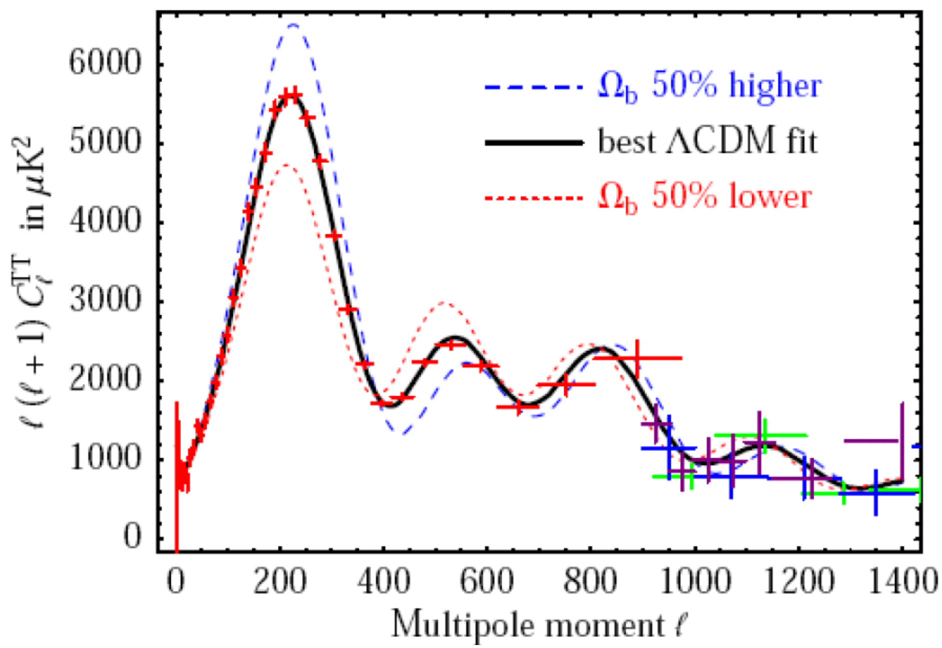
How many baryons?

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.





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

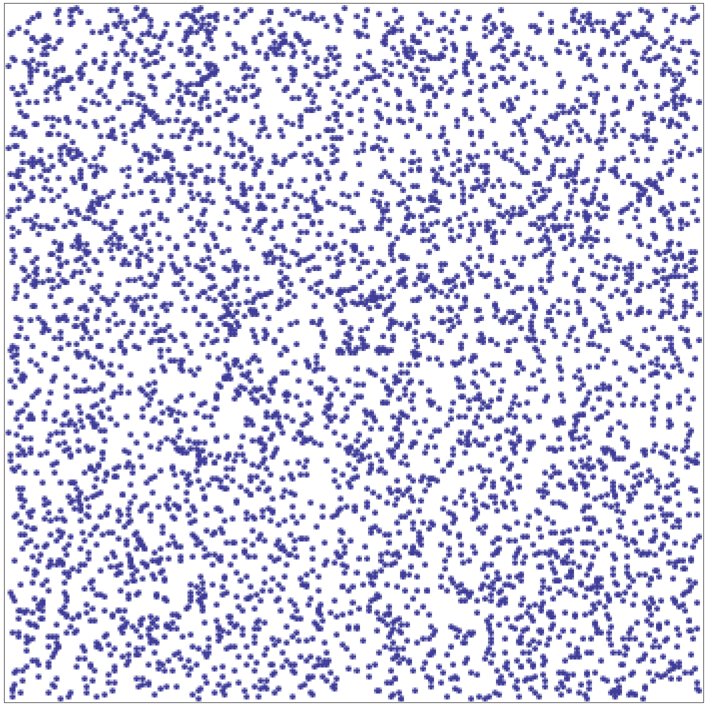
Assumption: in the very early Universe there was already a tiny excess of baryons over antibaryons. These annihilated leaving a small excess of baryons.

But this is a very small number!!

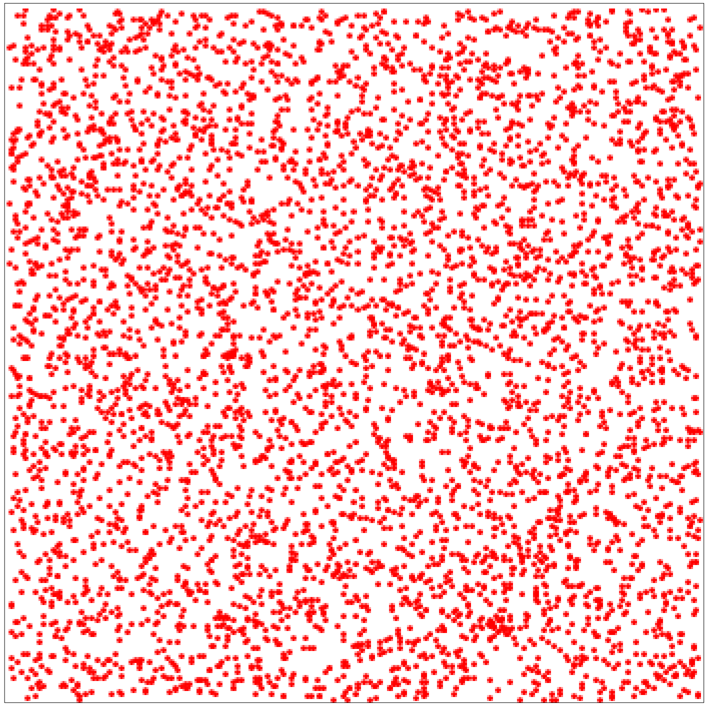
$$\eta_B = (6.11 \pm 0.19) \times 10^{-10}$$

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

N_B=30 000 001

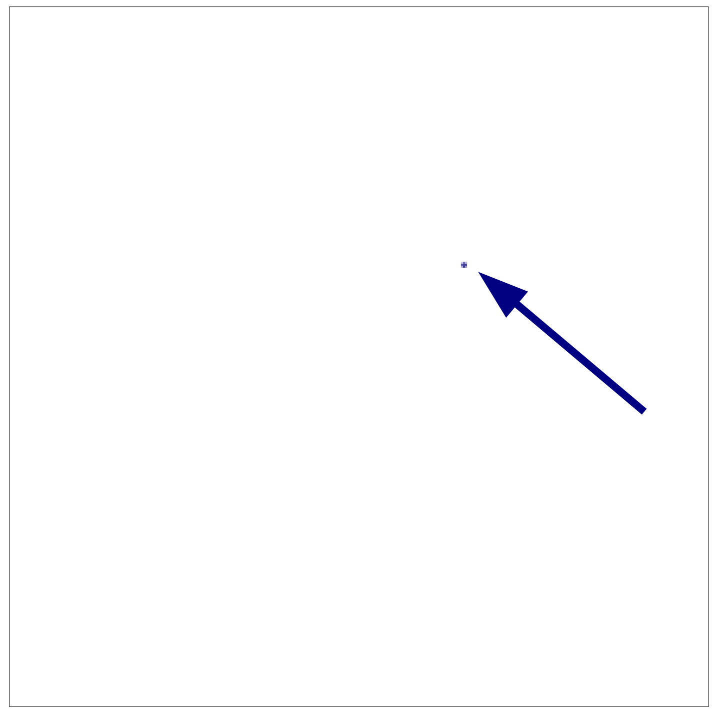


$N_{\overline{B}}$=30 000 000



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

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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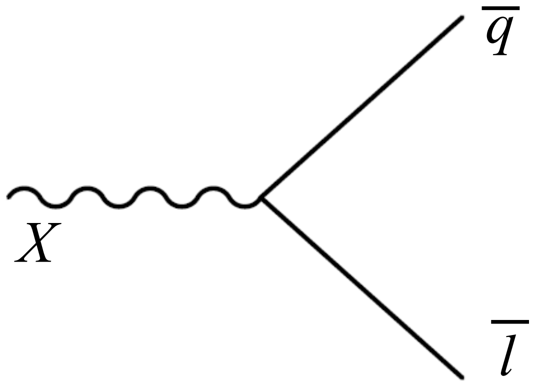
Unified Gauge Theories and the Baryon Number of the Universe

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.

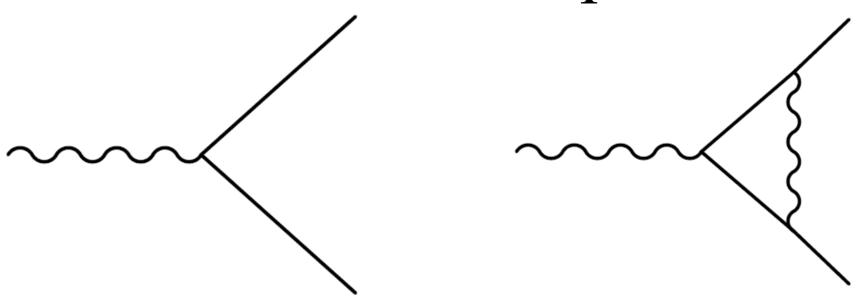
These three conditions are fulfilled in the simplest grand unified models.

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

Very attractive!!

Very attractive!!

But ruled out...

Very attractive!!

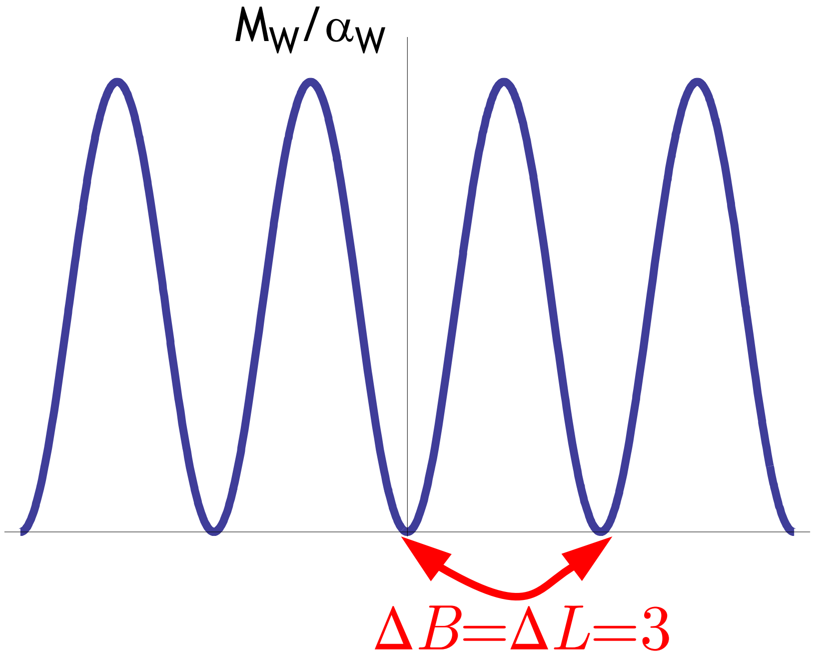
But ruled out...

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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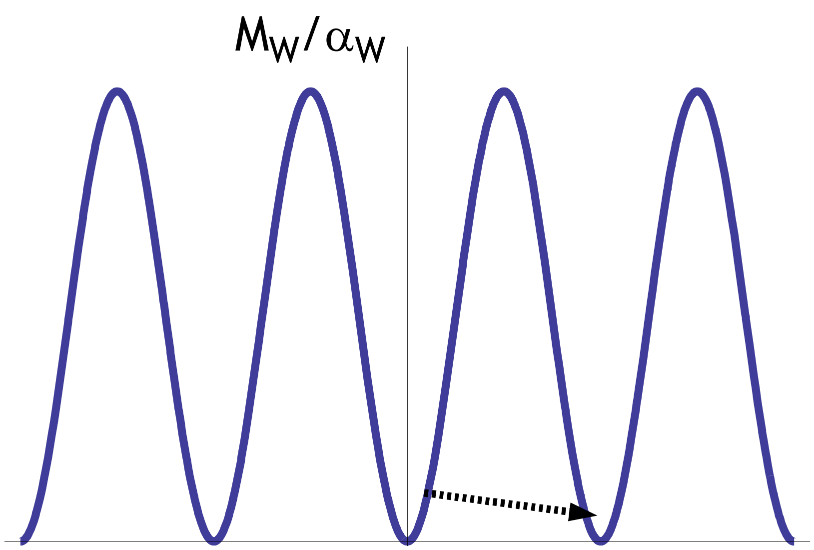
At zero temperature, transitions among vacua only through tunnelling



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

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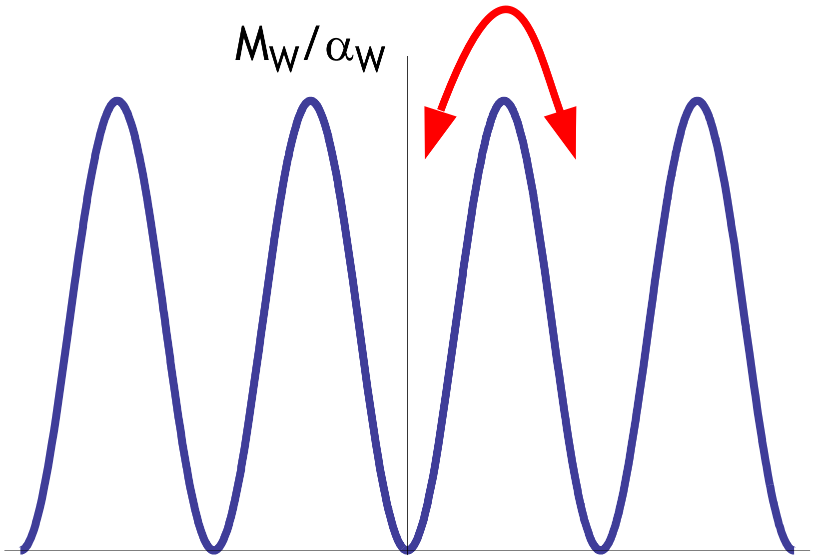
At high temperature, the barrier can be easily crossed



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

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

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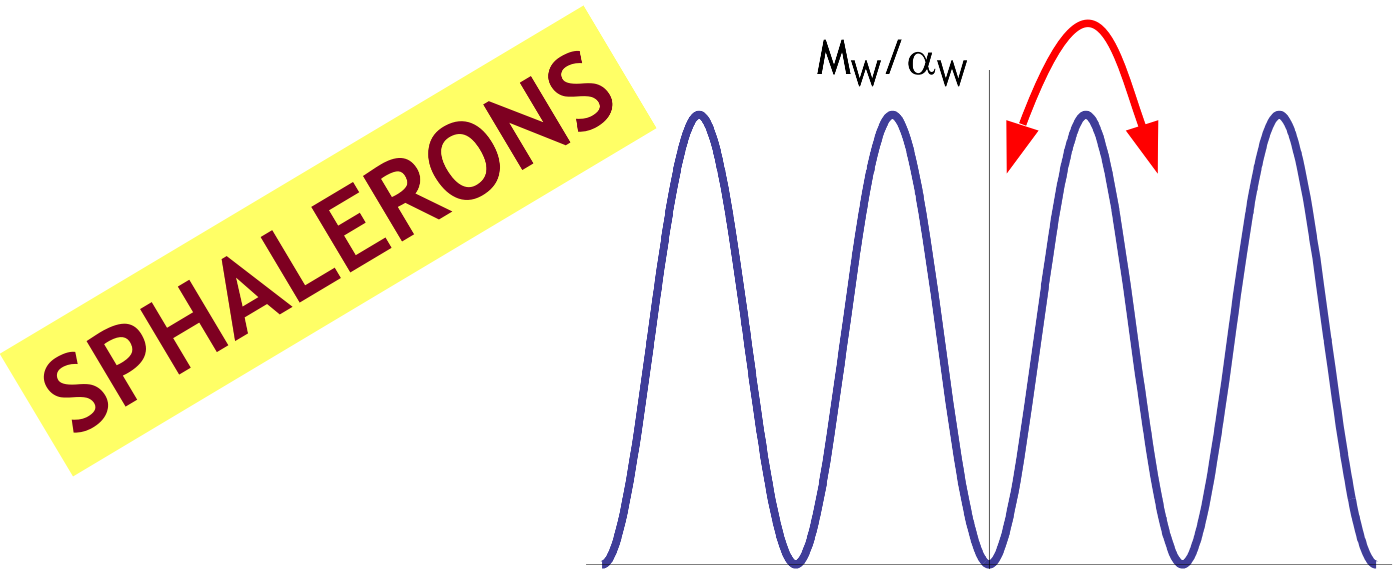

At high temperatures, transitions violating B+L (and preserving B-L) occur very often.

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.

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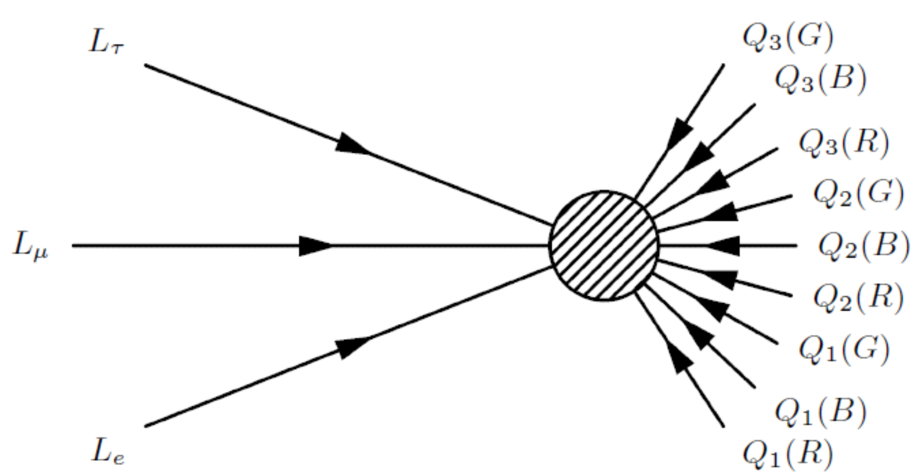
At high temperature, the barrier can be easily crossed

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

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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 $T >$ (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, $M_{magn}/M_W(T^*) \approx 2B/\ln(M_{Pl}/T^*) \ll 1$. 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 fermion-number non-conserving processes are rapid even at low temperature (which is possible because of the super-

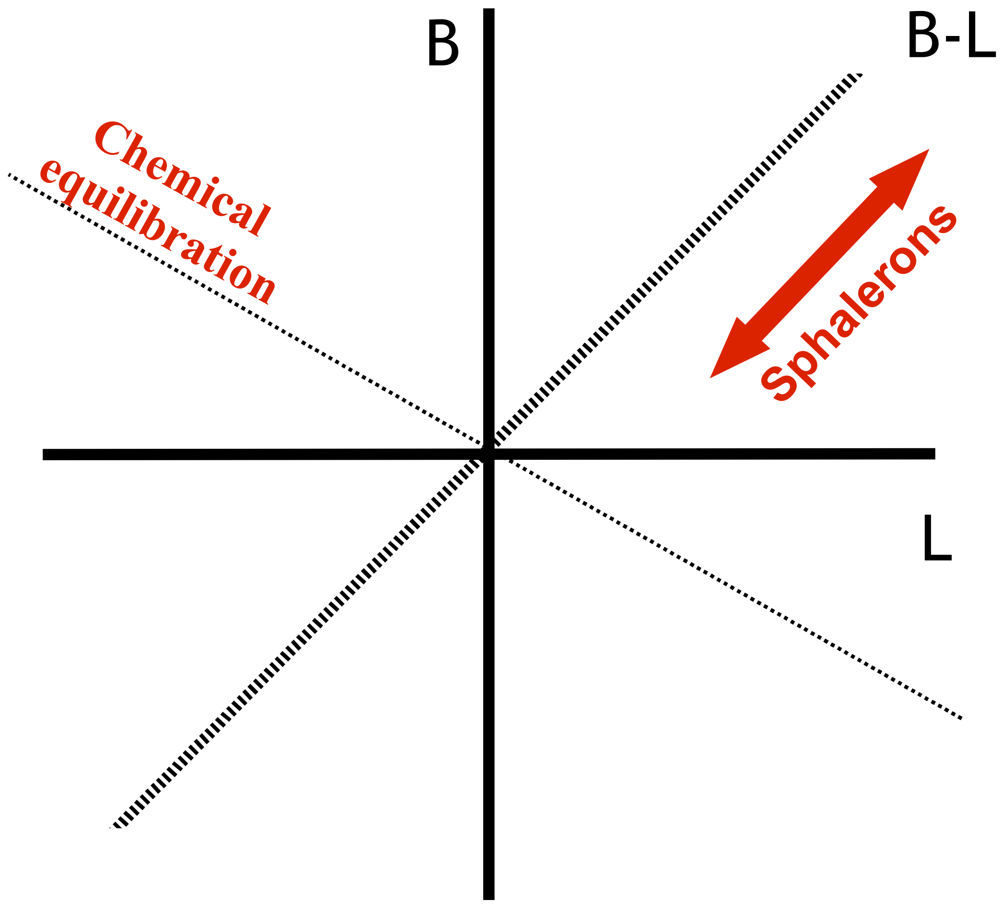
$$B(T_c) = \tfrac{1}{2}(B_{in} - L_{in}) + \tfrac{1}{2}(B_{in} + L_{in})\, e^{-A},$$

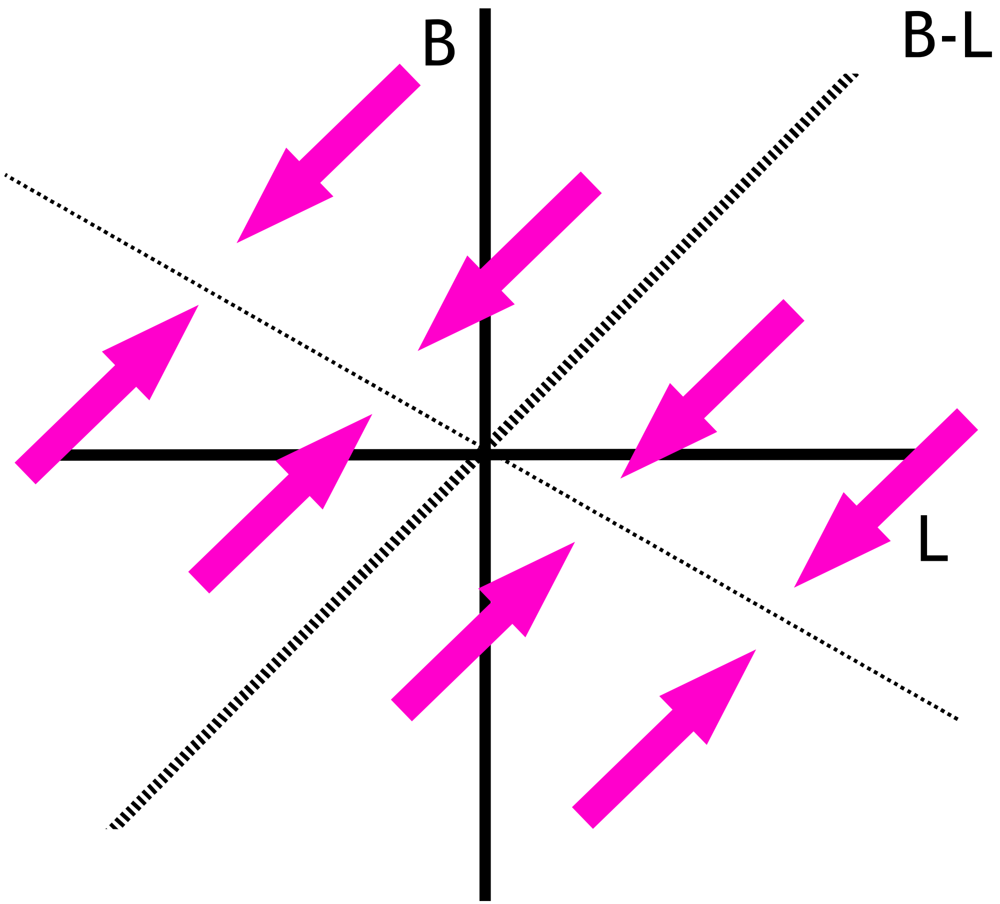
$$A \sim \beta M_{Pl}/T_c \sqrt{N_{eff}} \sim \beta \times 10^{15} \qquad (9)$$

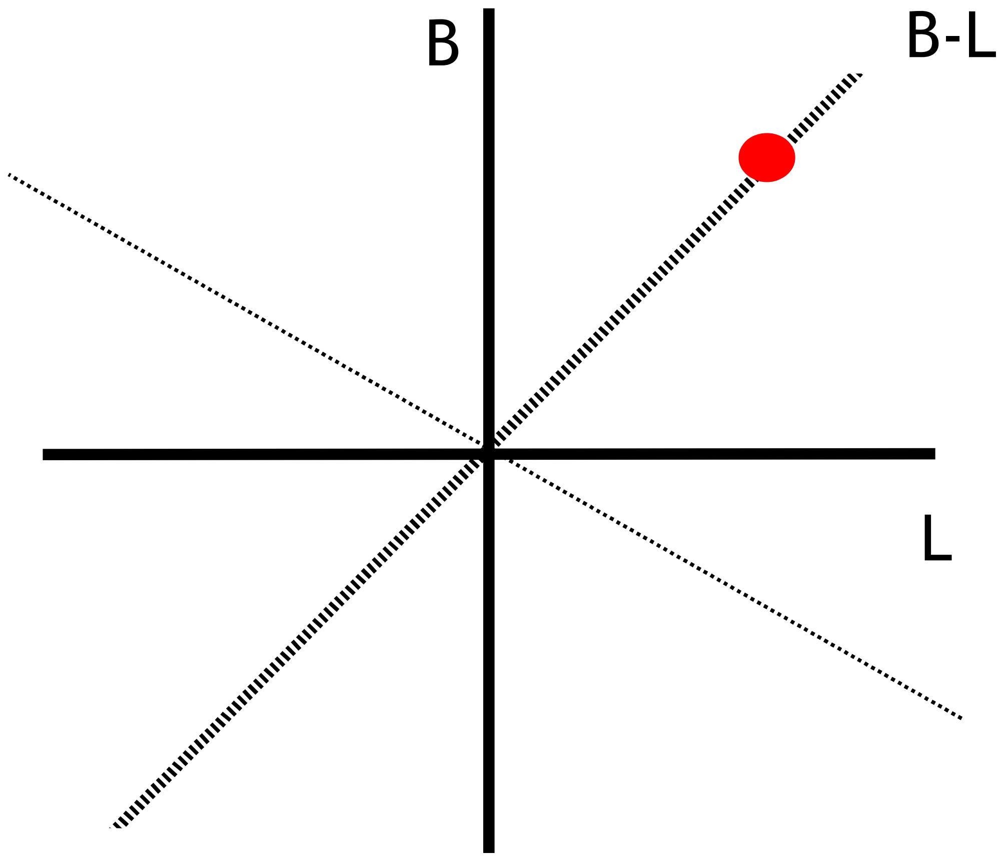
Clearly, $B(T_c) = \tfrac{1}{2}(B_{in} - L_{in})$ with great precision; this means that if the primordial baryon asymmetry is generated by the $(B - L)$ conserving processes (which is the case in the minimal SU(5) model [22]), it is completely washed out by the moment of the electroweak phase transition.

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

$$\Delta \sim (\ldots)\,\delta \ldots \qquad (10)$$


B
B-L
L
Chemical
equilibration
Sphalerons


B
B-L
L



Unified Gauge Theories and the Baryon Number of the Universe

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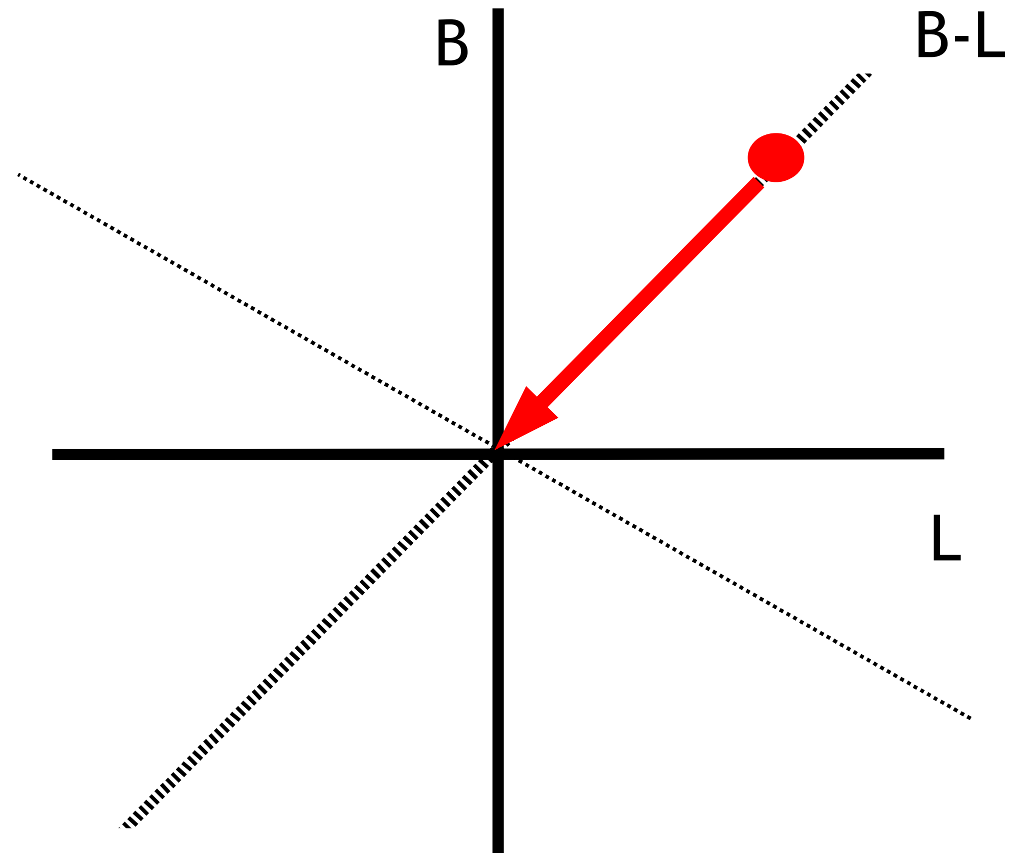

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Ruled out!

“Revised” Sakharov conditions

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- ~~Baryon~~ B-L number violation

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

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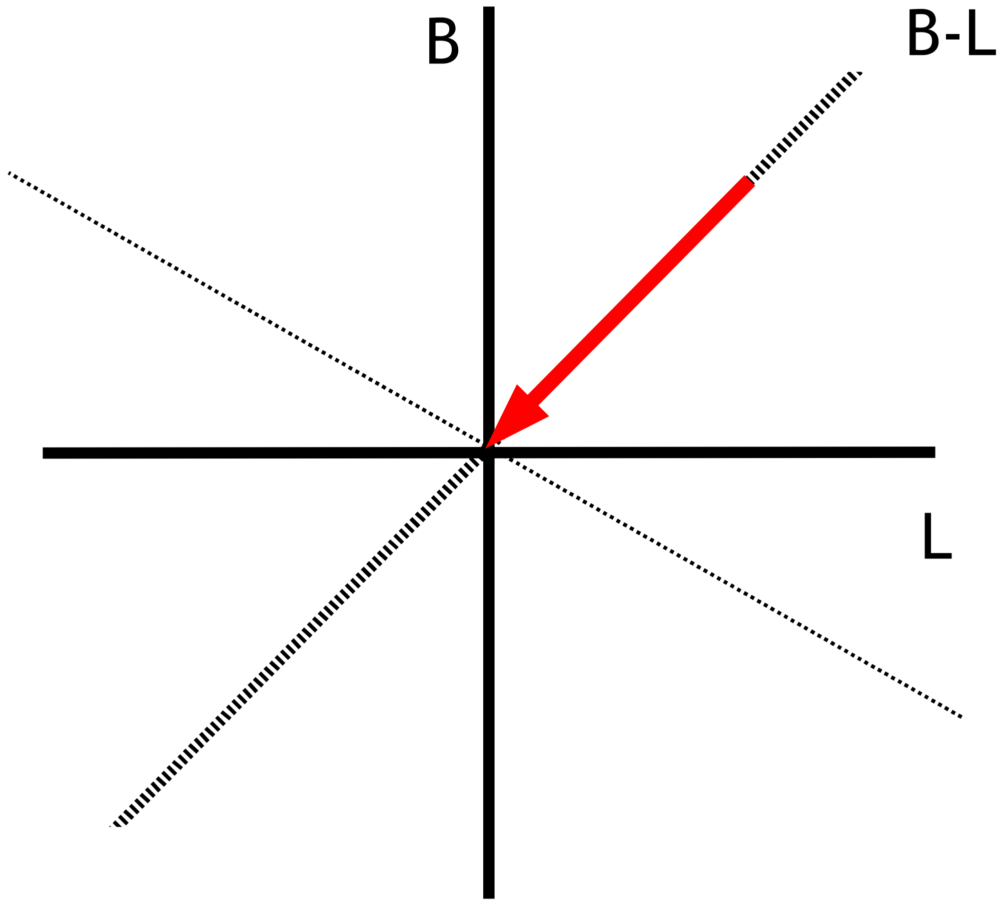
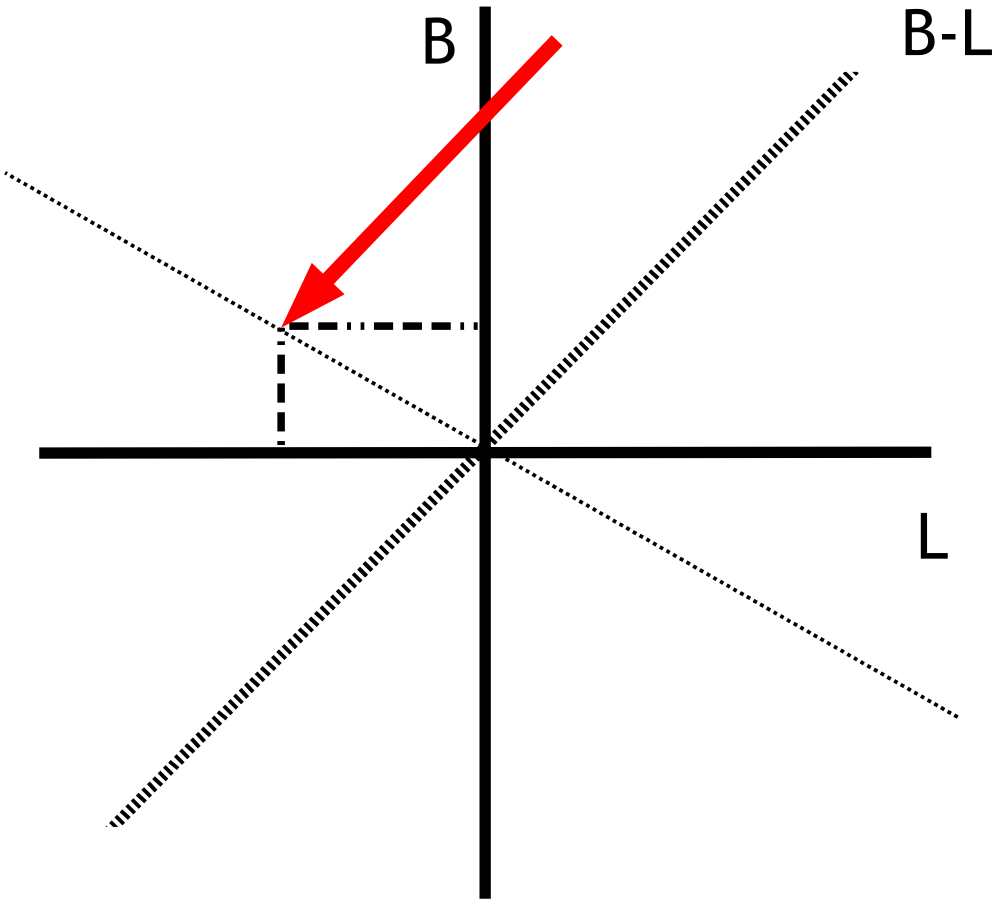
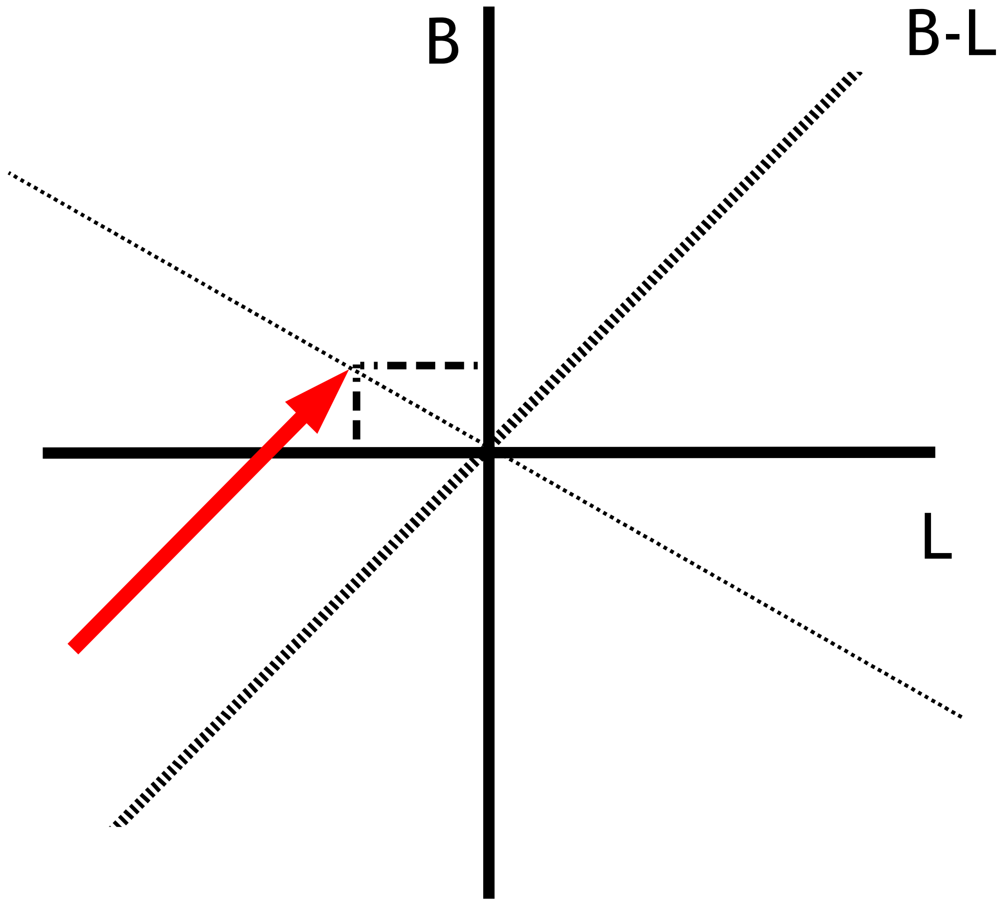

B
B-L
L



B
B-L
L


B
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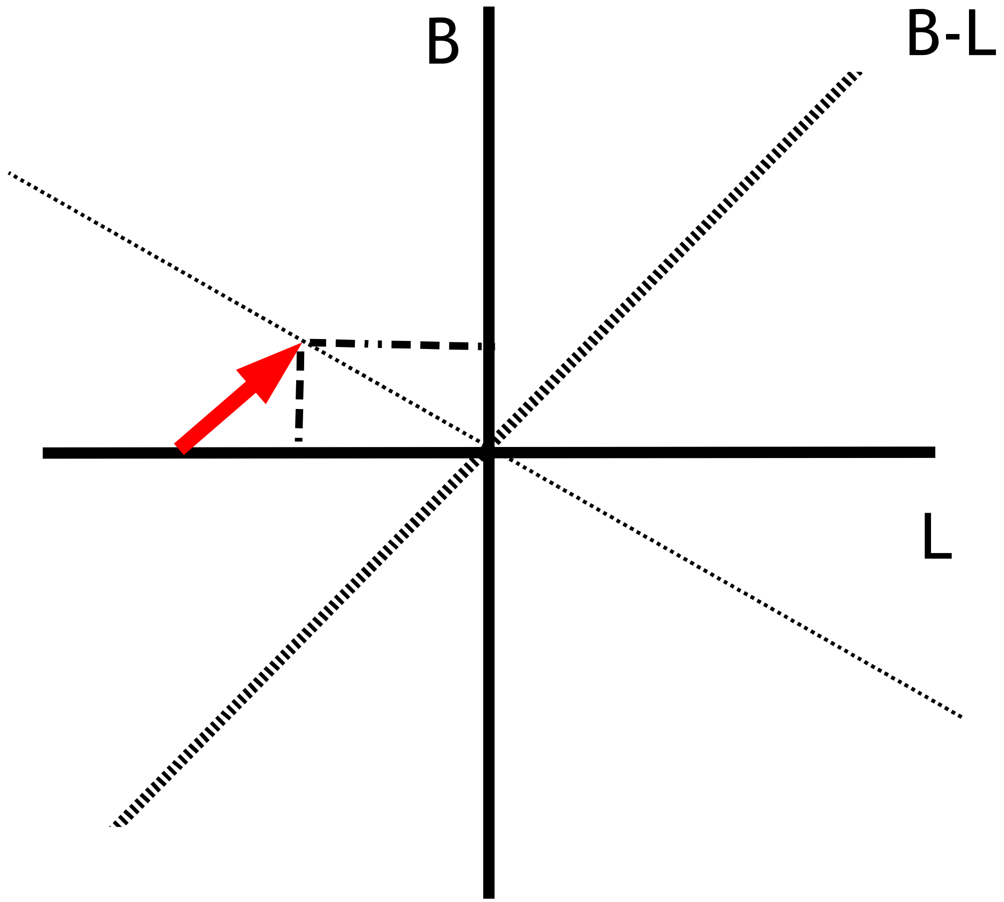
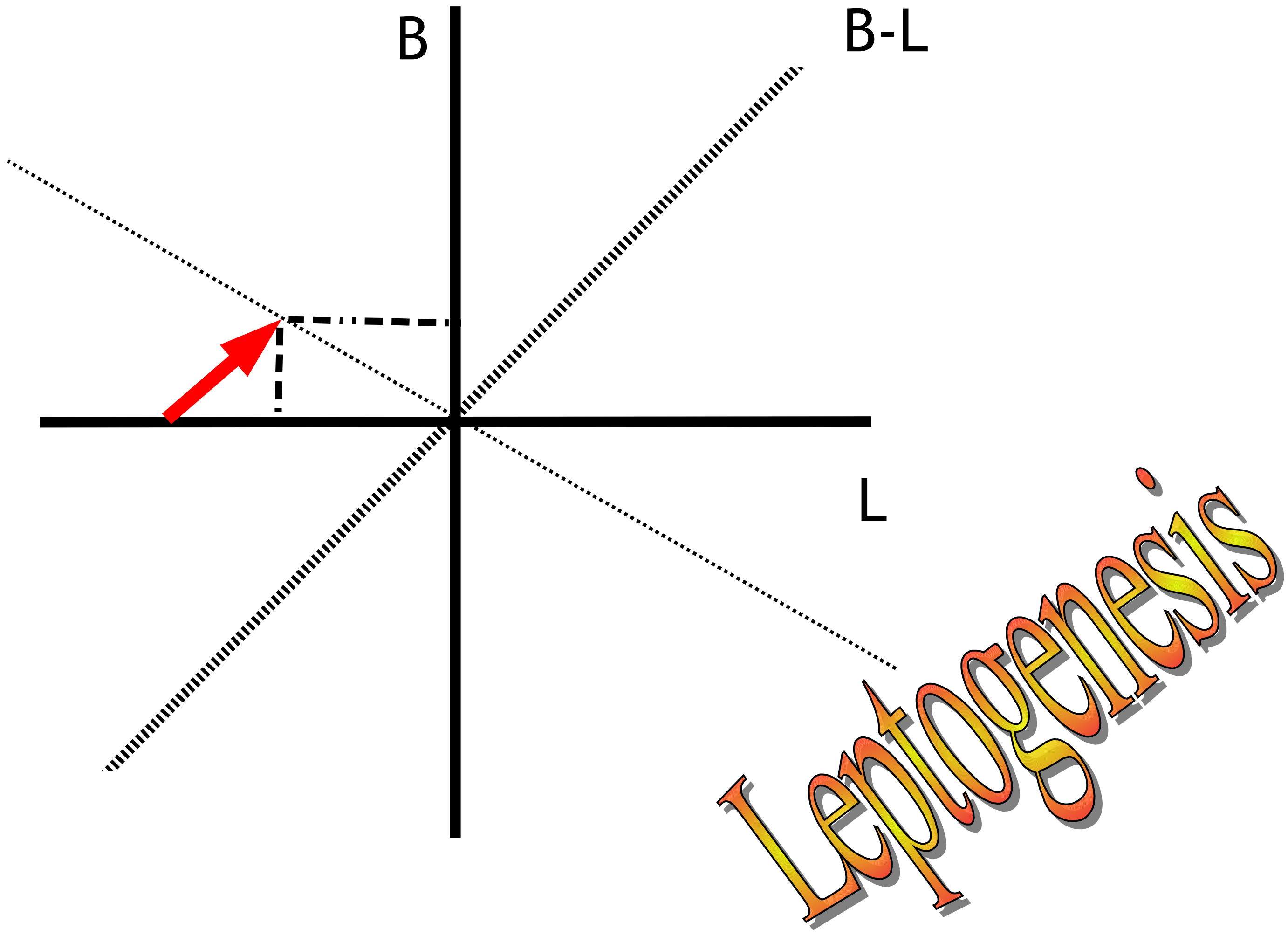
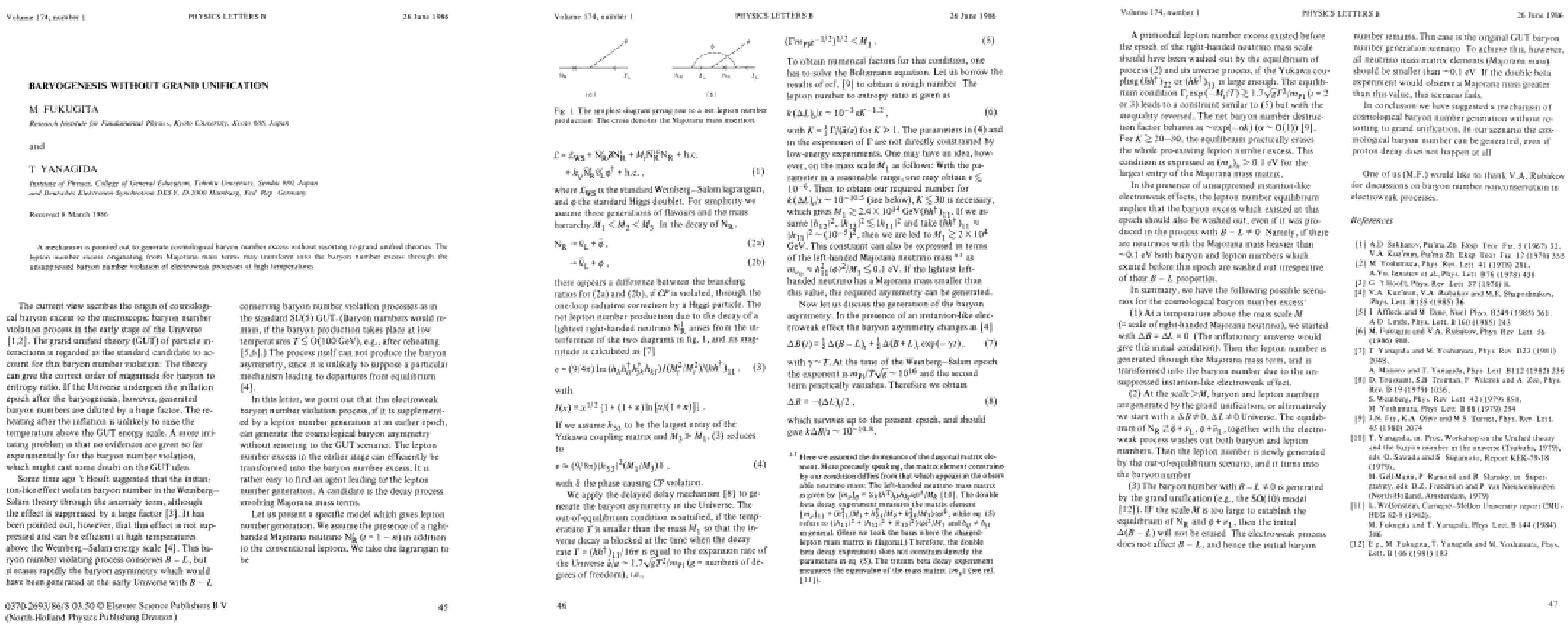

B
B-L
L



B
B-L
L
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

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and

T. YANAGIDA

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.

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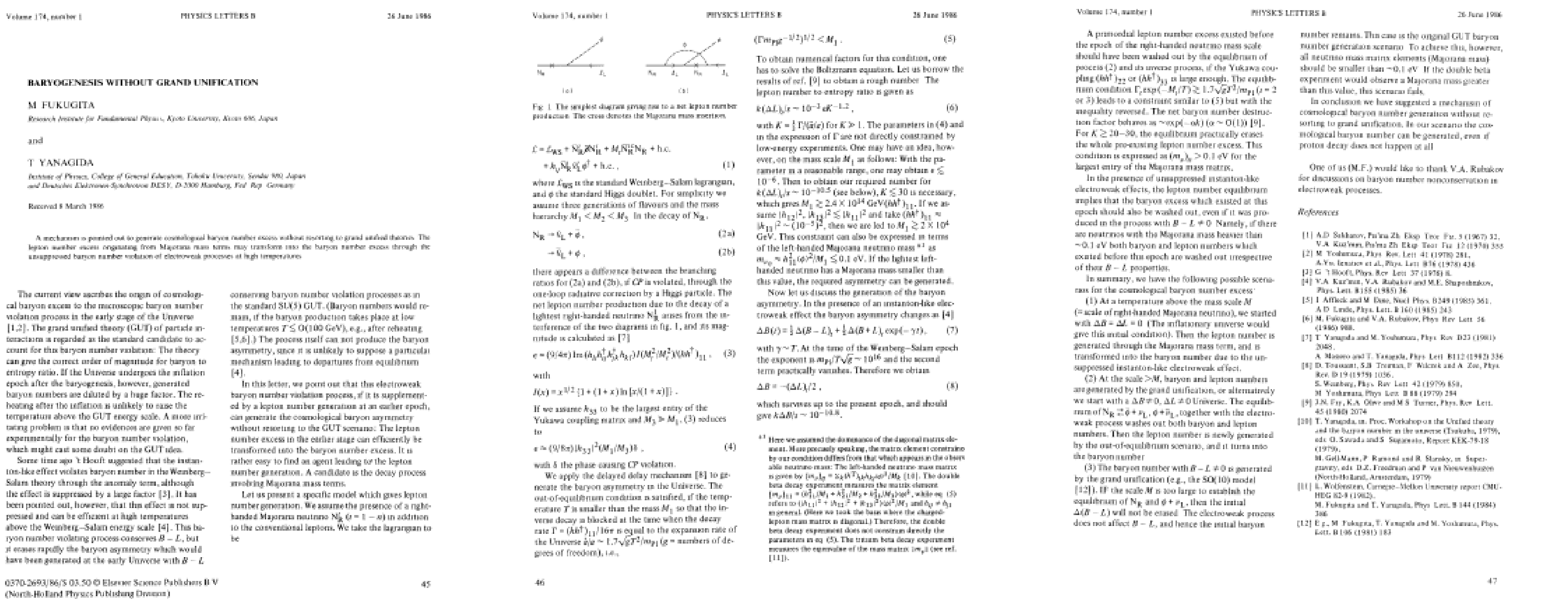

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

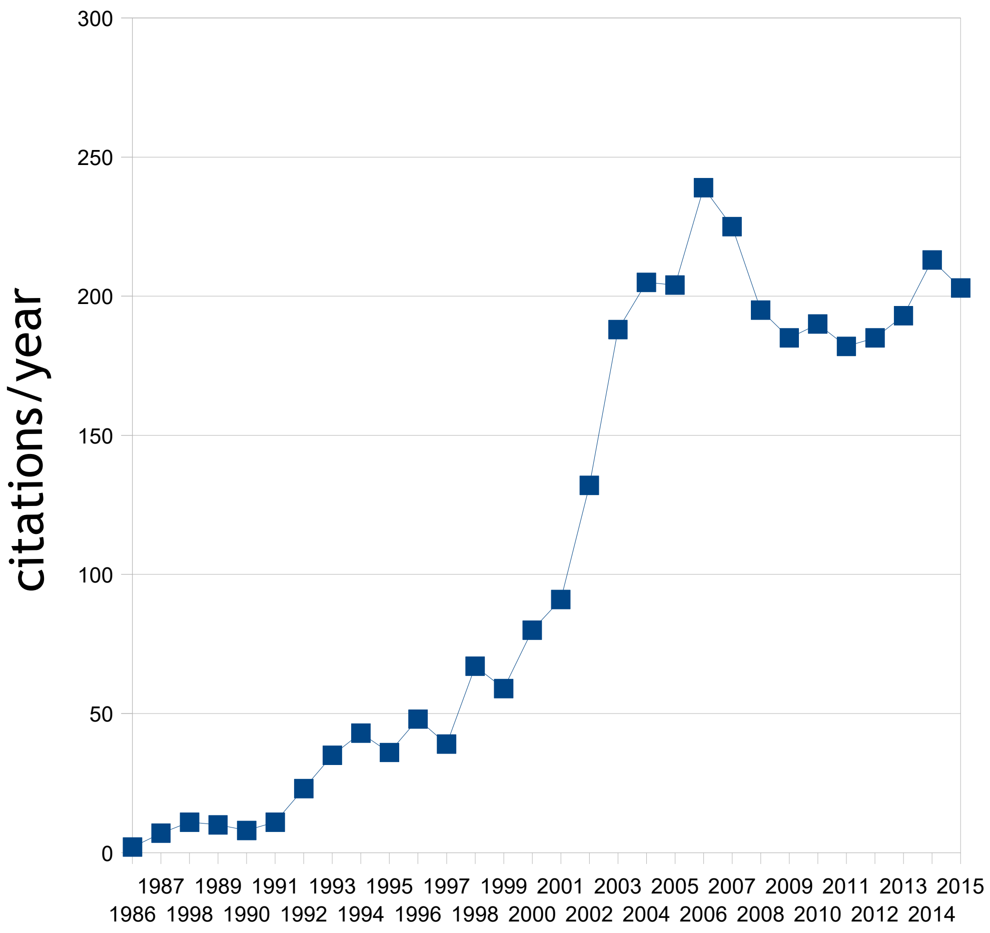
M. FUKUGITA

T. YANAGIDA

And very popular...

Citations according to the SPIRES database: 2573

Why are people so excited about leptogenesis?



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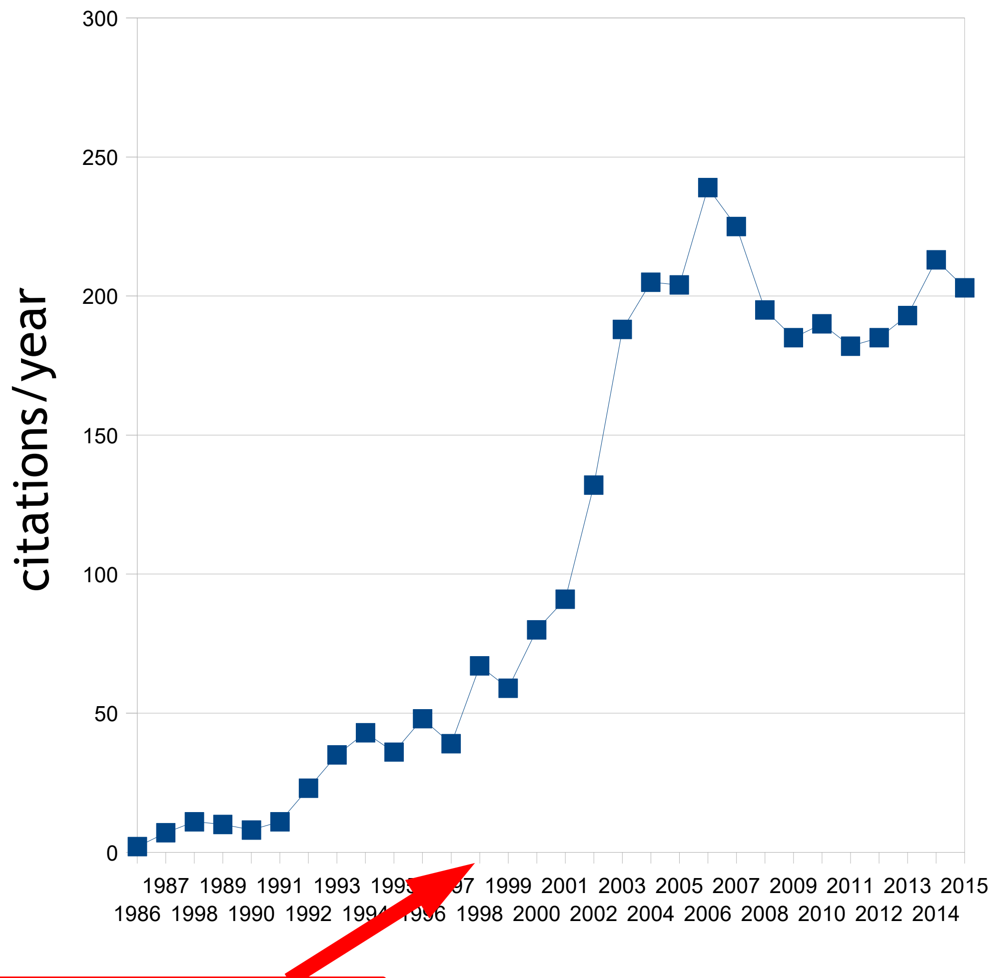

1998. Evidence of atmospheric neutrino oscillations (Super-K)

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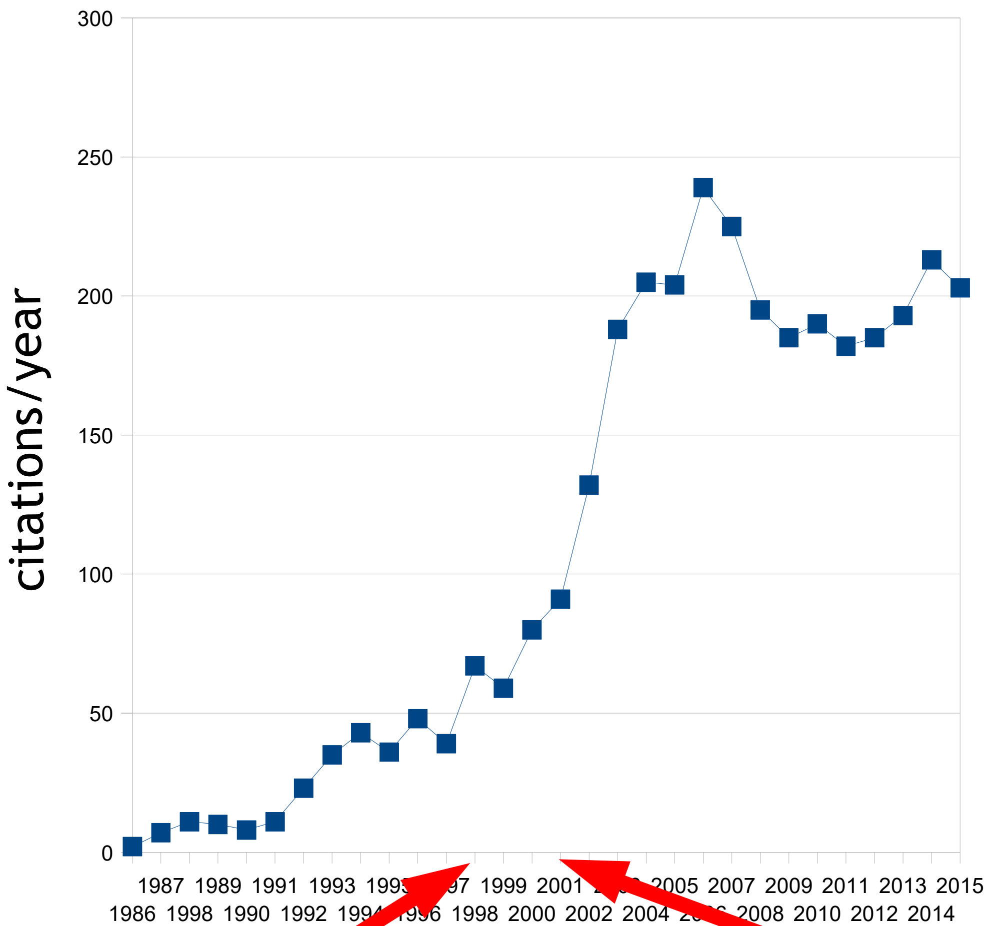


1998. Evidence of atmospheric neutrino oscillations (Super-K)

2001. Evidence of solar neutrino oscillations (SNO)

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:

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

$$\Big\downarrow \quad M \gg \langle H^0 \rangle$$

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

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

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:

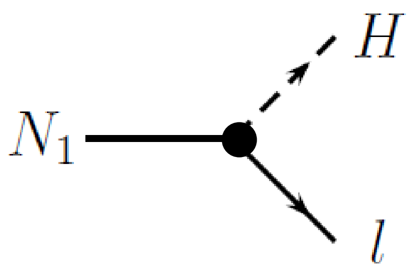
- Violation of B-L. Guaranteed if neutrinos are Majorana particles.
- C and CP violation. Guaranteed if the neutrino Yukawa couplings contain physical phases. However, it is not guaranteed that the C and CP violation are large enough for leptogenesis.
- Departure from thermal equilibrium. Guaranteed, 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?

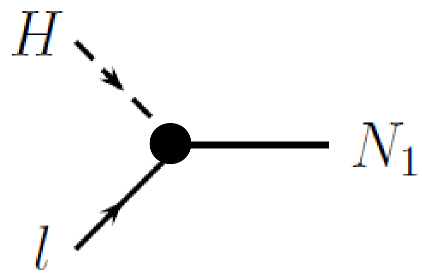
Calculate!

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

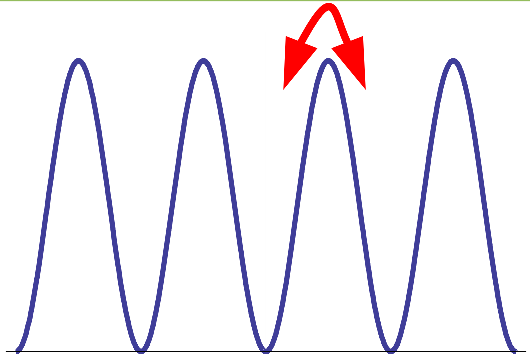
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.



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



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

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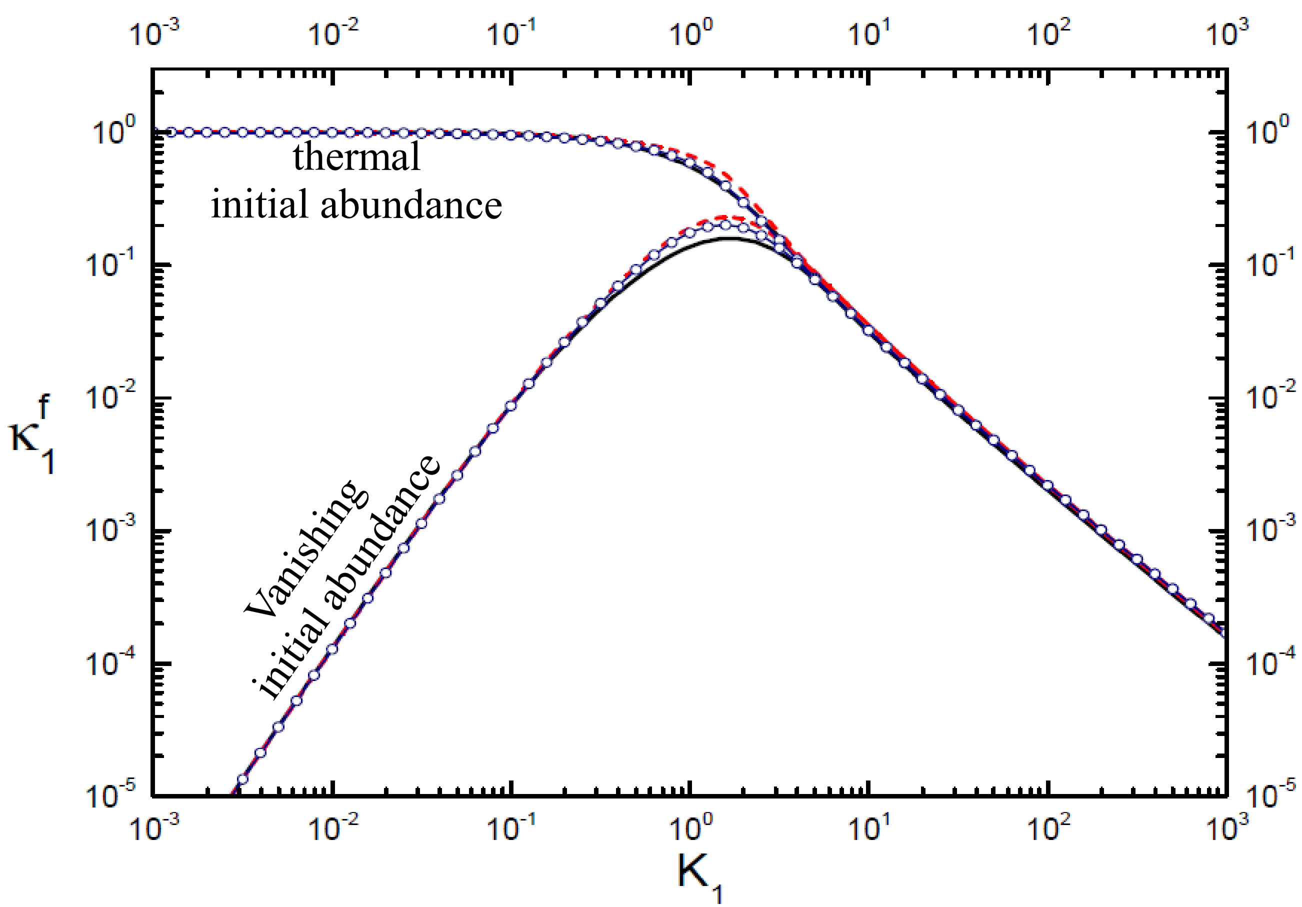
"Efficiency factor"



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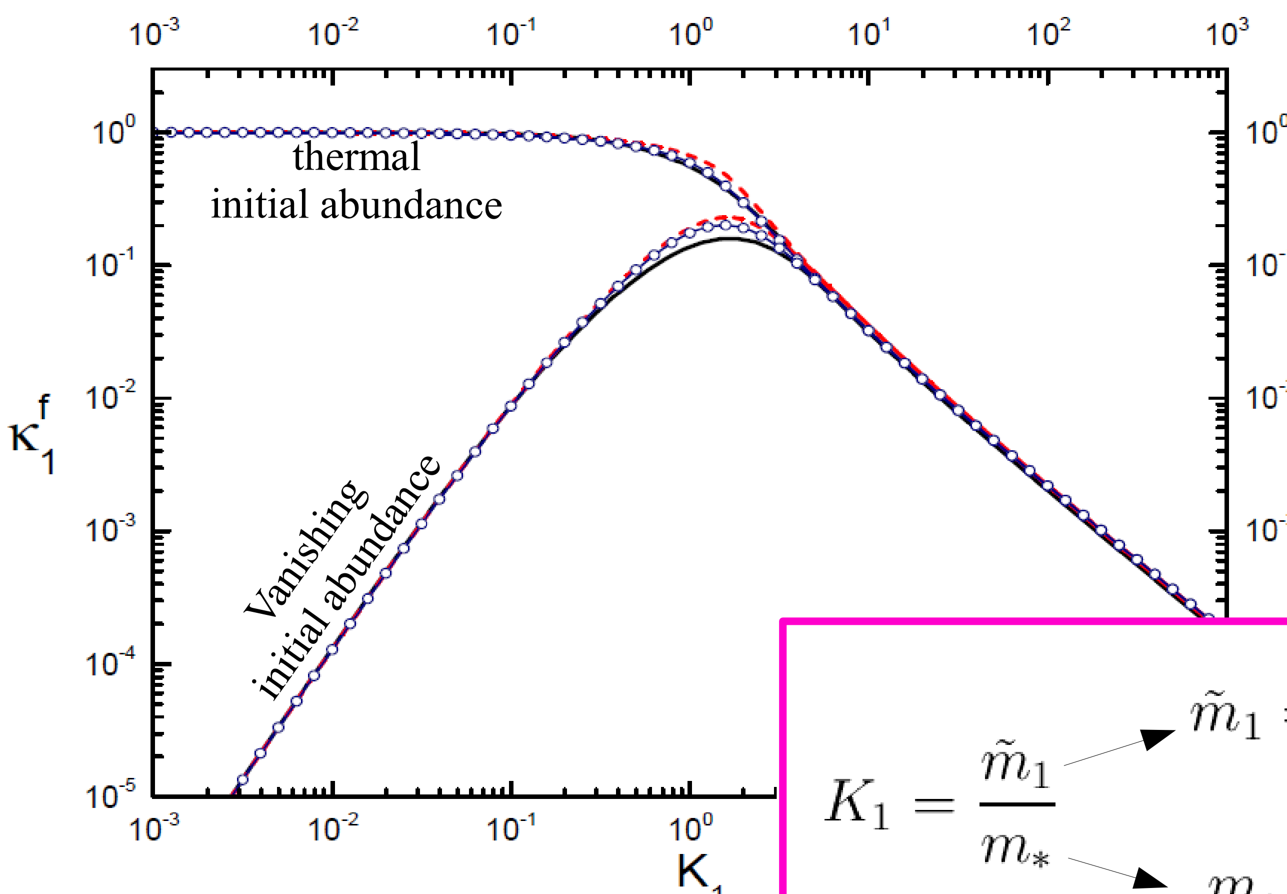
“Efficiency factor”



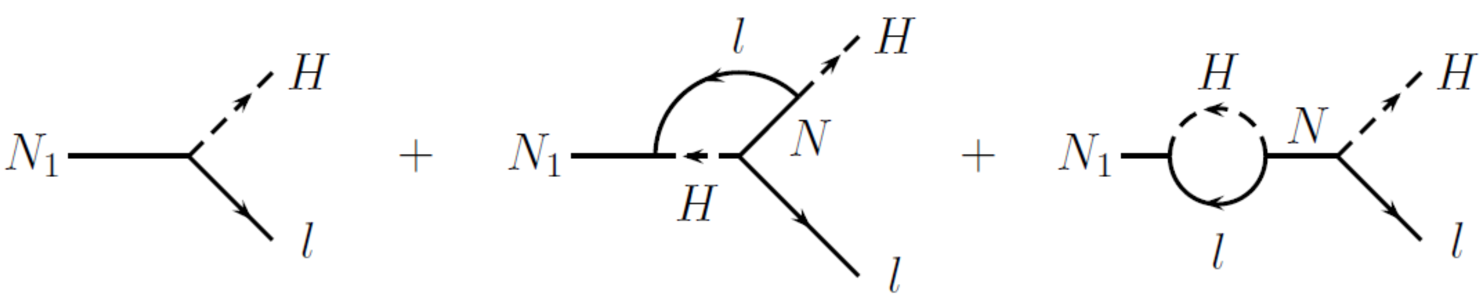
$$K_1 = \frac{\tilde{m}_1}{m_*}$$

$$\tilde{m}_1 = (h_\nu h_\nu^\dagger)_{11} \frac{\langle H^0 \rangle^2}{M_1}$$

$$m_* \approx 10^{-3}\,\mathrm{eV}$$

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

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



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

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

A CRUCIAL QUESTION...

$\{h_\nu, M\}$

See-saw parameters → **Neutrino masses and mixing angles**

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

↓

Leptogenesis

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

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

A CRUCIAL QUESTION...

$\{h_\nu, M\}$

See-saw parameters → **Neutrino masses and mixing angles**

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

↓

Leptogenesis ⟷ (Neutrino masses and mixing angles) ?

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

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

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

  $\mathcal{M}_\nu$ 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:

$$h_\nu = \frac{1}{\langle H^0 \rangle} \sqrt{D_M}\, R \sqrt{D_m}\, U^\dagger_{\rm lep}$$

Right-handed neutrino masses
3 real parameters

"Fixed" by experiments

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

Implications

1) Implications of leptogenesis for the seesaw parameters

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

$$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m^2_{\rm atm}}}{v^2}$$

$$\Downarrow$$

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

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

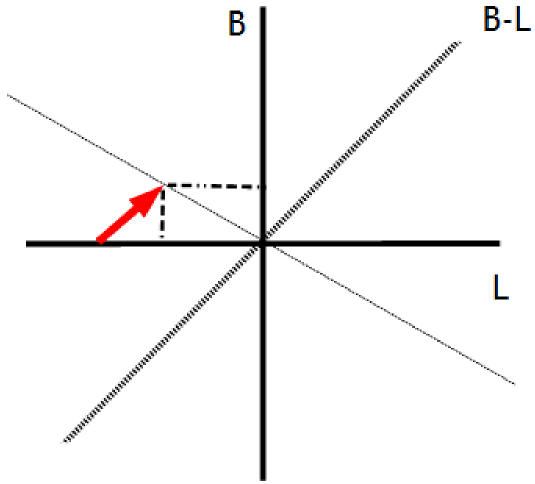
Very few and very vague:

- 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.