Leptogenesis

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Warsaw
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Outline

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

Evidence for a baryon asymmetry

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

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

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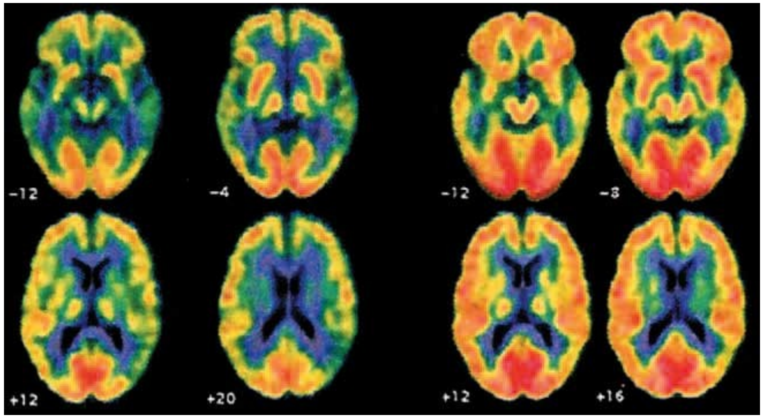

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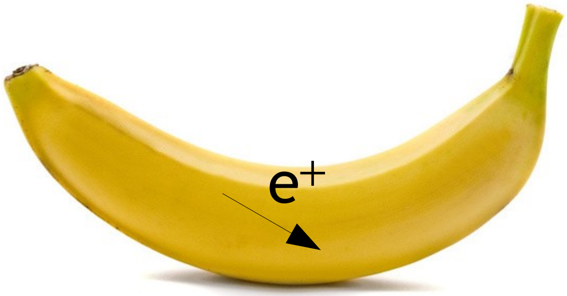
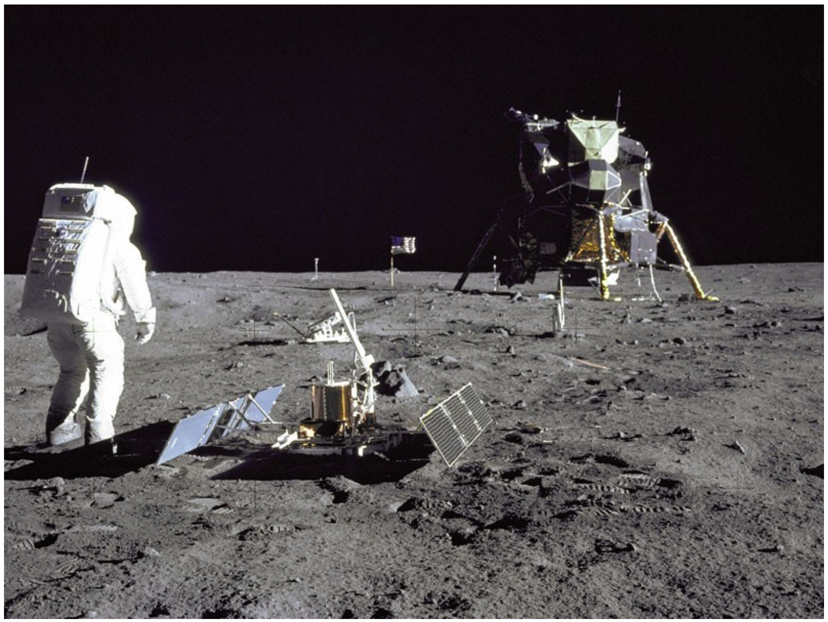
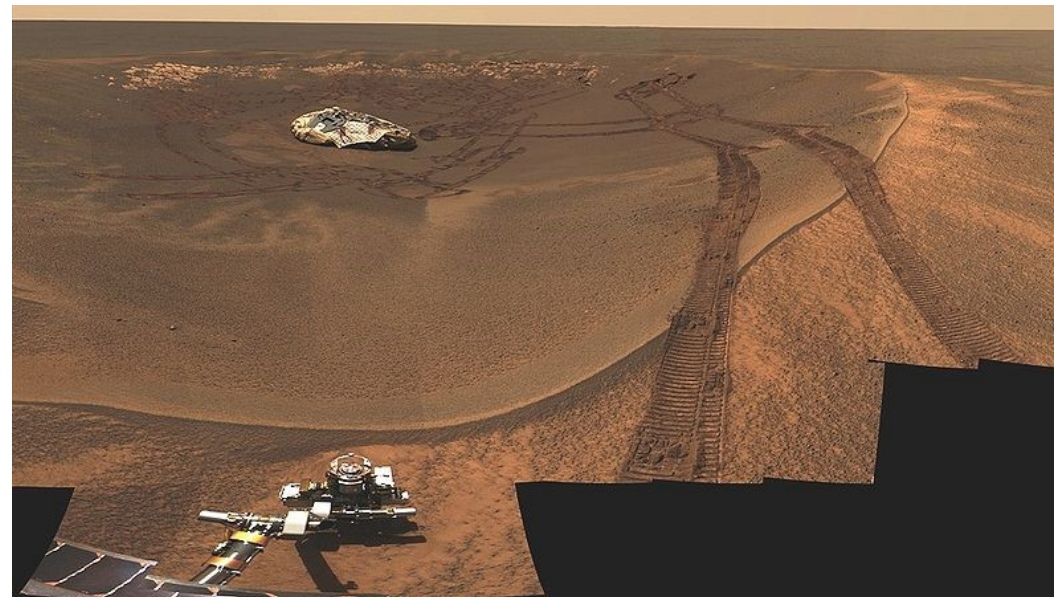


One positron every 75 minutes

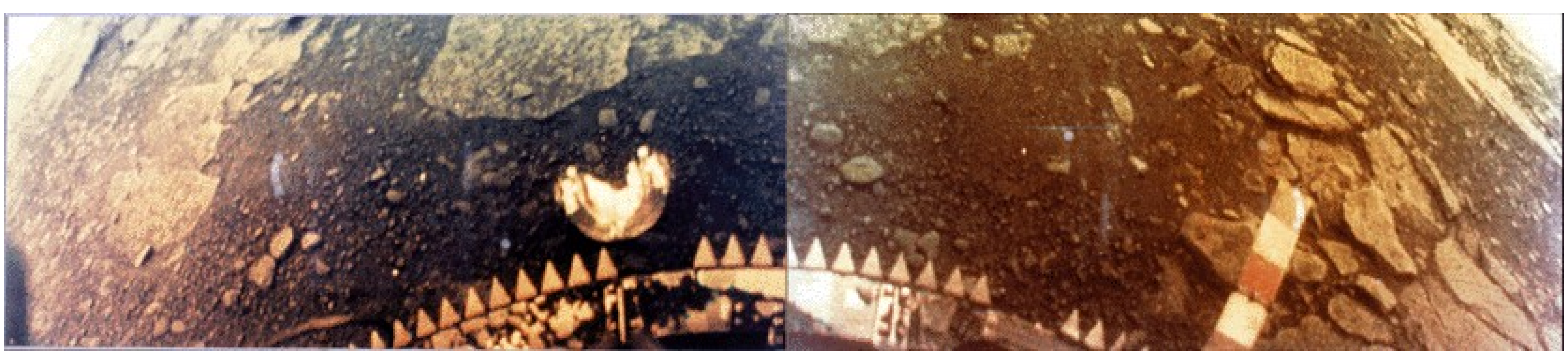
The bodies of the solar system are also composed almost entirely by matter and not by antimatter



Apollo 11

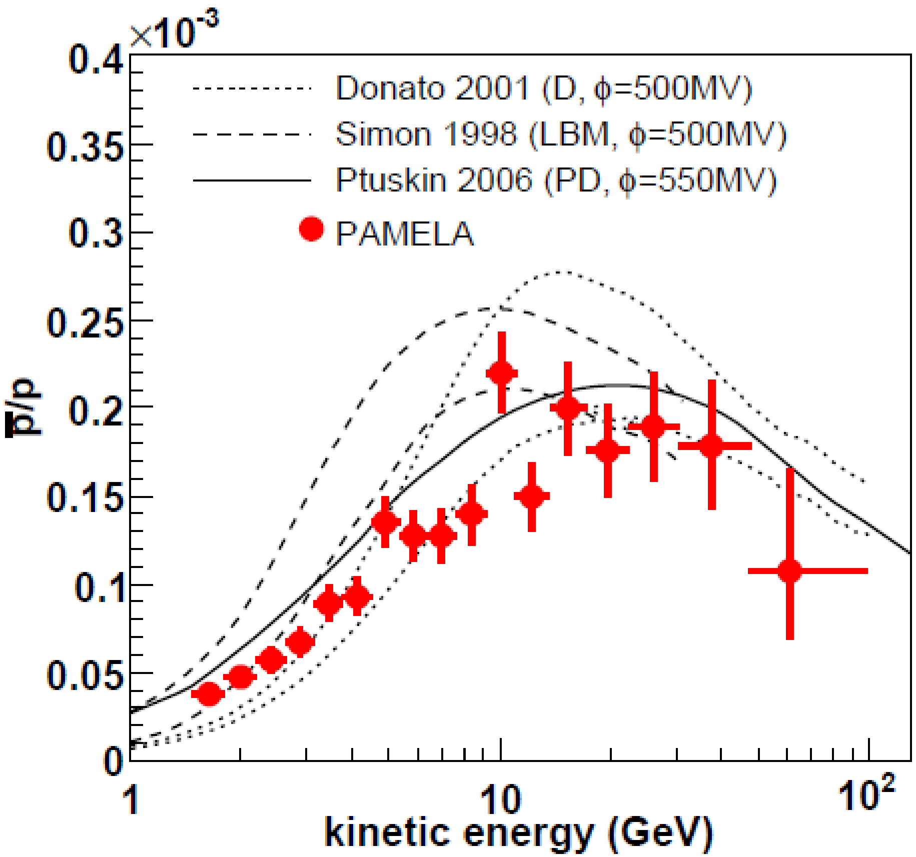


Mars Exploration Rover



Venera 13

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



Antiproton-to-proton ratio

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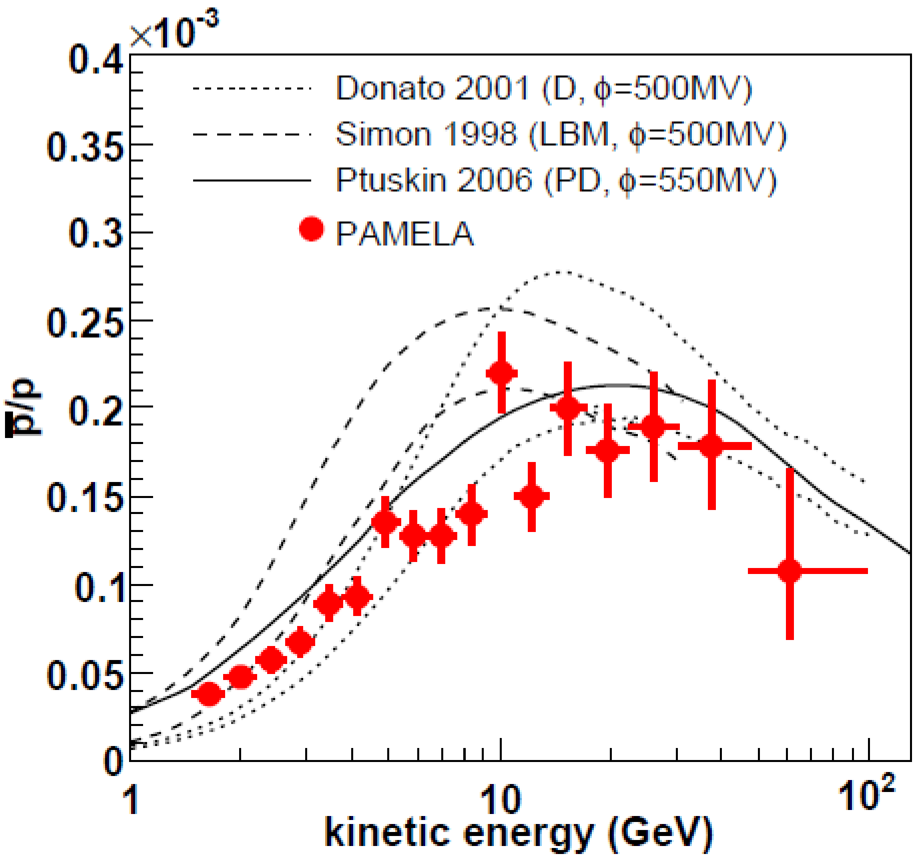

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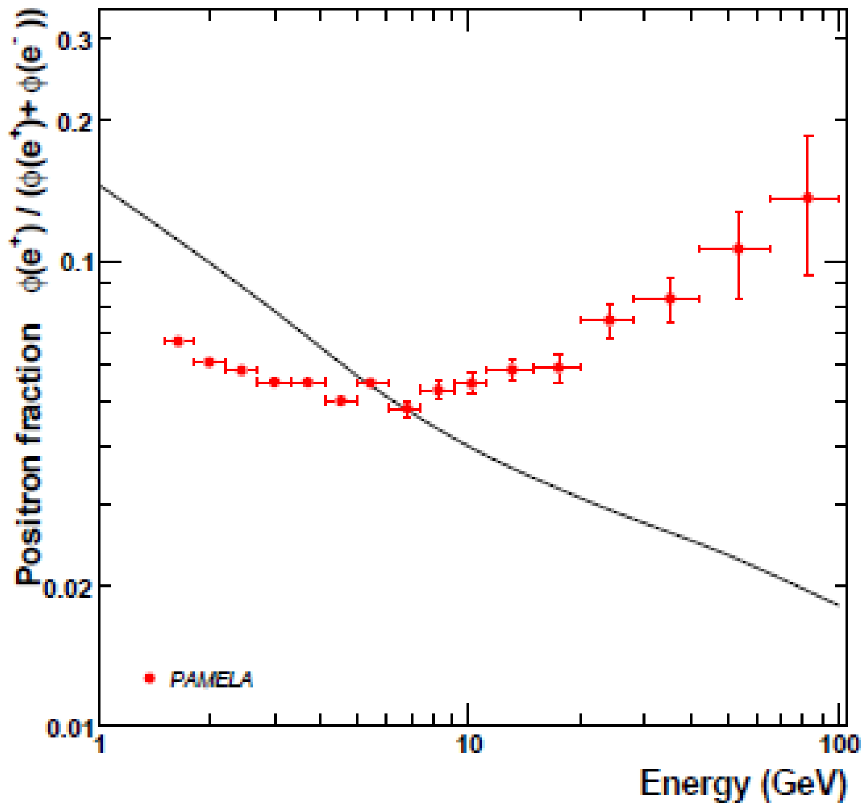
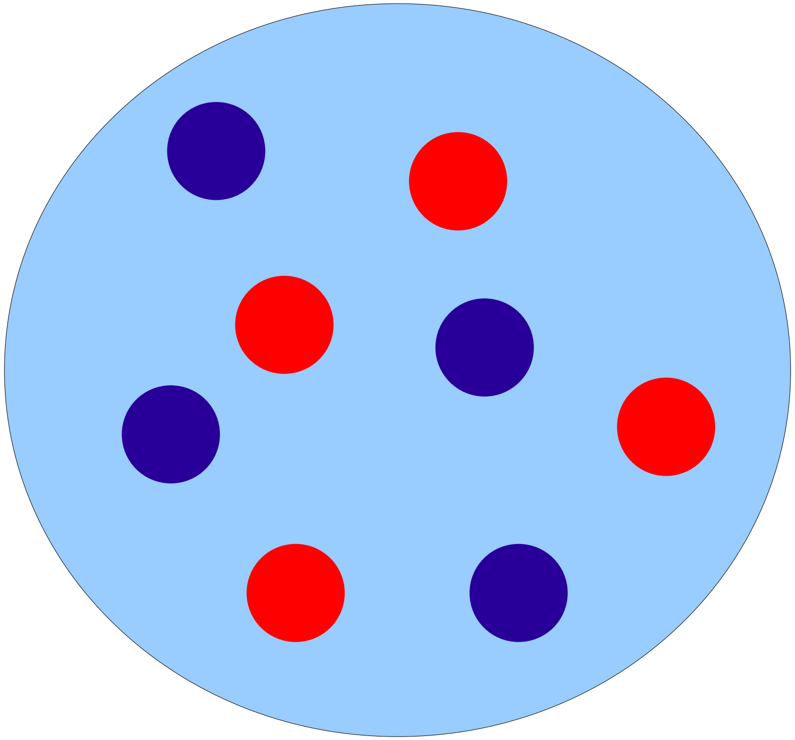


Positron fraction

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

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

Could the Universe be baryon symmetric?



NO!!

The nucleon-antinucleon annihilation cross section is rather large

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

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

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

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

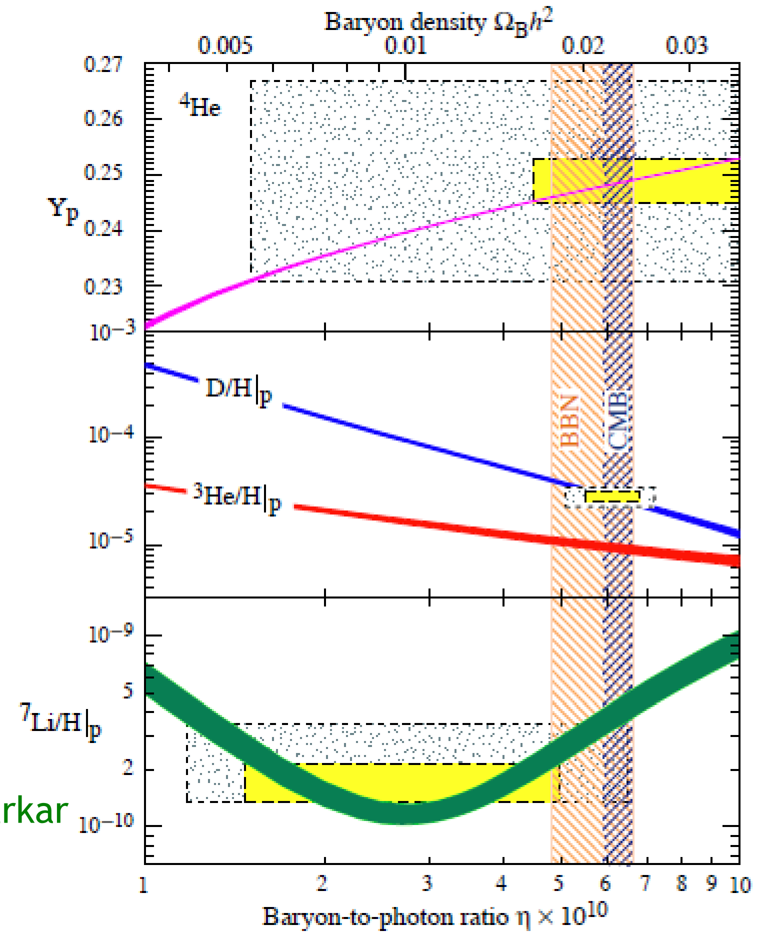
Some mechanism at temperatures larger than 38 MeV must have existed, separating nucleons and antinucleons. But which?

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

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

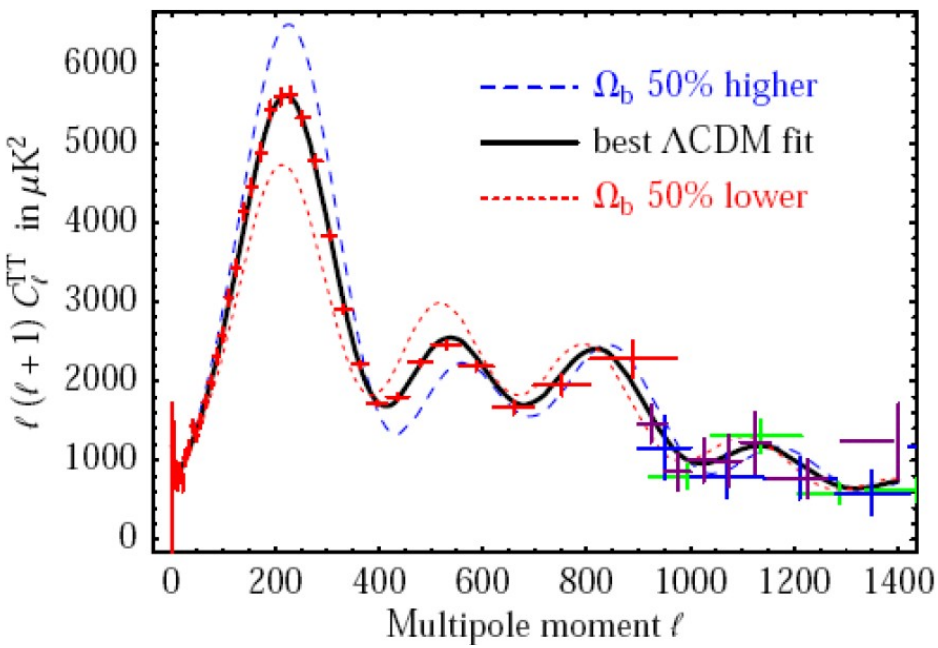
How many baryons?

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



Fields, Sarkar

Strumia



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

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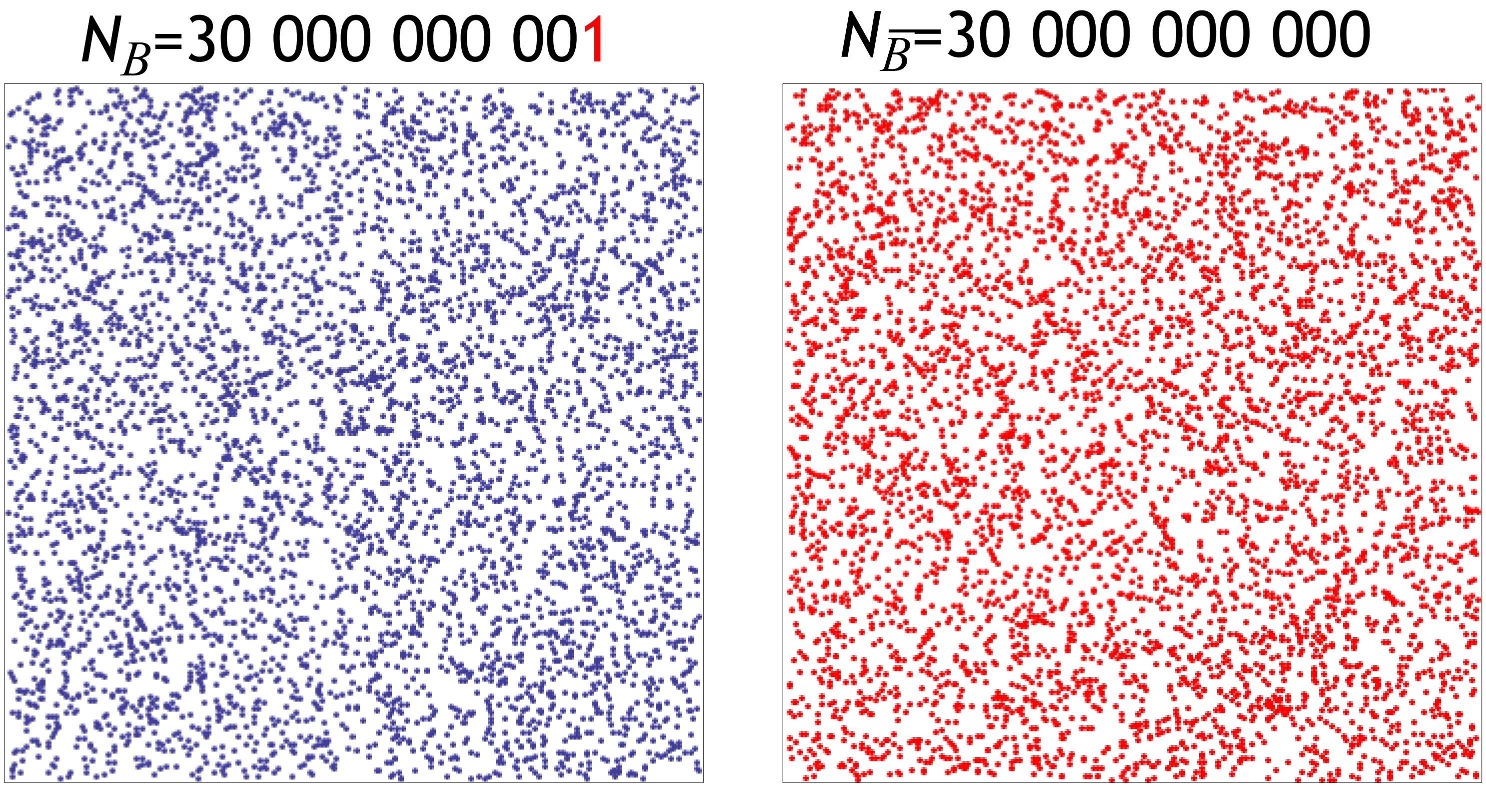
But this is a very small number!!

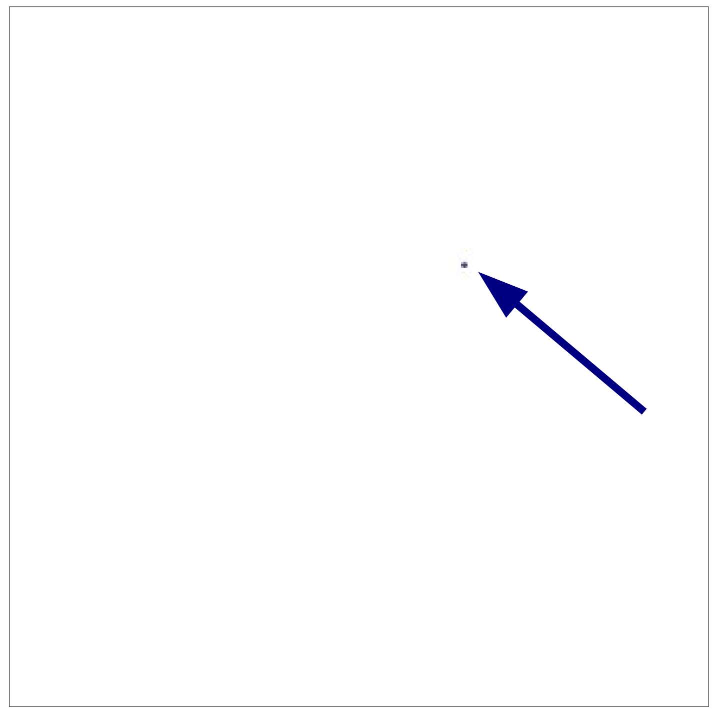
$$\eta_B = (6.11 \pm 0.19) \times 10^{-10}$$

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



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

now



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

Baryogenesis

Dynamical generation of a BAU: Sakharov conditions

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

- Baryon number violation

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

- C and CP violation

  If C or CP are conserved, $\Gamma(X \rightarrow Y+B) = \Gamma(\overline{X} \rightarrow \overline{Y}+\overline{B}) \Rightarrow$ 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.

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

VOLUME 41, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 1978

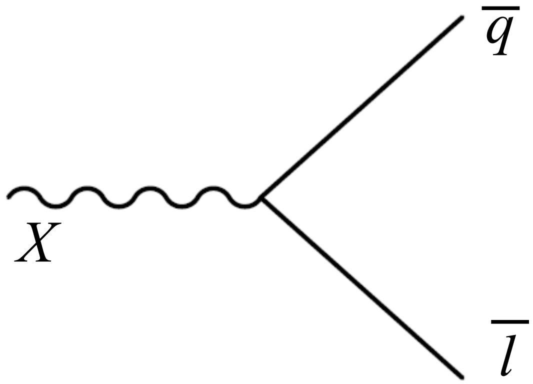
Unified Gauge Theories and the Baryon Number of the Universe

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.

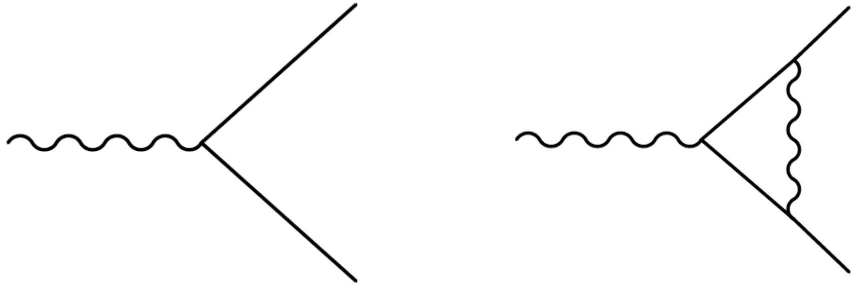
These three conditions are fulfilled in the simplest grand unified models.

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	B
$X \to q\, q$	r	$2/3$
$X \to \bar{q}\, \bar{l}$	$1 - r$	$-1/3$
$\bar{X} \to \bar{q}\, \bar{q}$	$\bar{r}$	$-2/3$
$\bar{X} \to q\, l$	$1 - \bar{r}$	$1/3$

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

Mean net baryon number produced in the decay of X

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

Mean net antibaryon number produced in the decay of X

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

The resulting baryon asymmetry is:

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

Very attractive!!

Very attractive!!

But ruled out...

A new player in the baryogenesis game: sphalerons

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

Baryon and lepton number are defined as:

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

where the currents associated to the B and L are

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

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

At the classical level, B and L are preserved:

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

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

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{N_f}{32\pi^2}\left(g^2 W^p_{\mu\nu}\widetilde{W}^{p\mu\nu} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$

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

$$W^p_{\mu\nu} = \partial_\mu W^p_\nu - \partial_\nu W^p_\mu$$

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

and N_F = number of fermion generations

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

$$\partial^\mu (J^B_\mu - J^L_\mu) = 0$$

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

$$\partial^\mu (J^B_\mu + J^L_\mu) = 2N_F \partial_\mu K^\mu$$

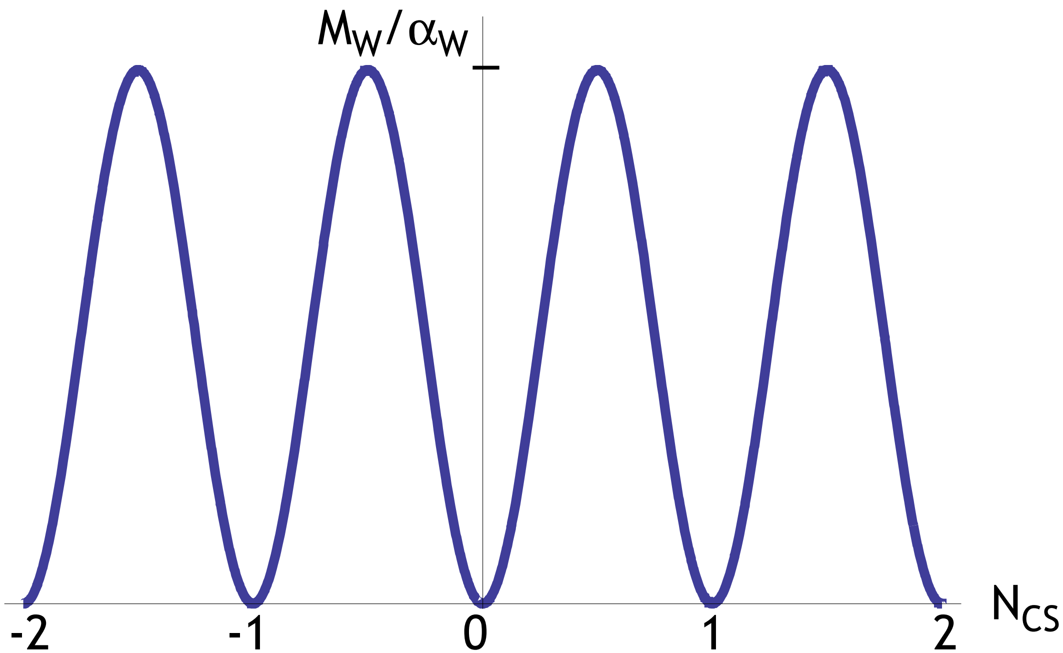
$$K^\mu = -\frac{g^2}{32\pi^2} 2\epsilon^{\mu\nu\rho\sigma} W^p_\nu (\partial_\rho W^p_\sigma + \frac{g}{3}\epsilon^{pqr} W^q_\rho W^r_\sigma) + \frac{g'^2}{32\pi^2}\epsilon^{\mu\nu\rho\sigma} B_\nu B_{\rho\sigma}$$

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

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

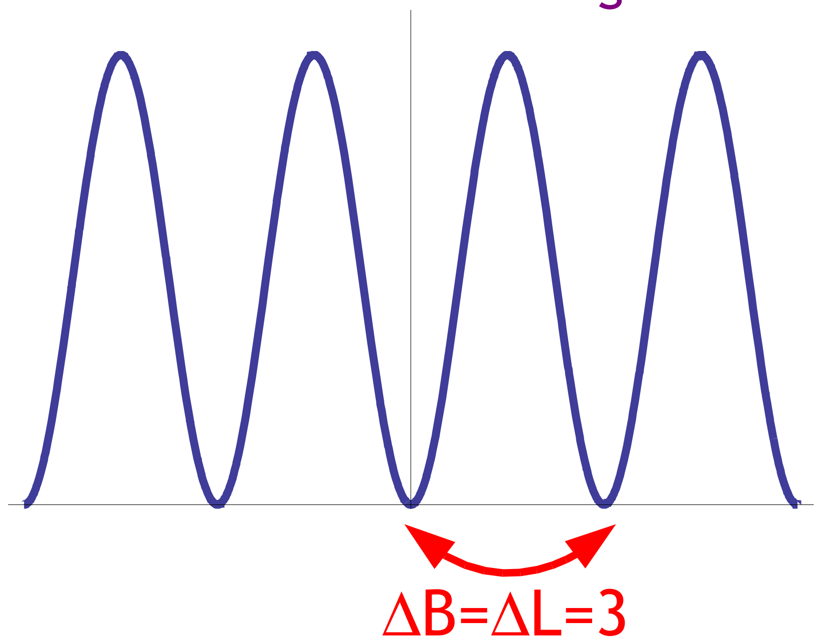
$$N_{cs}(t) = \frac{g^3}{96\pi^2} \int d^3x \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$$

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



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

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

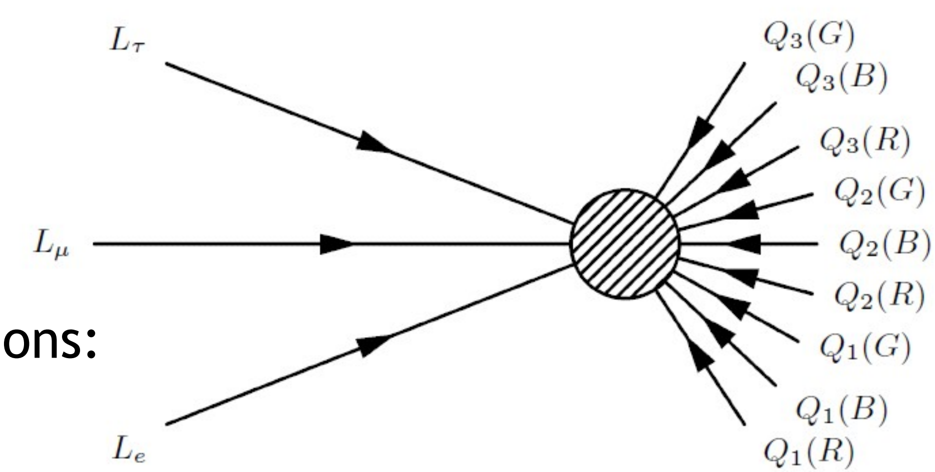


Transitions from one vacuum to another vacuum are possible, with a change of ΔB and ΔL by three units.

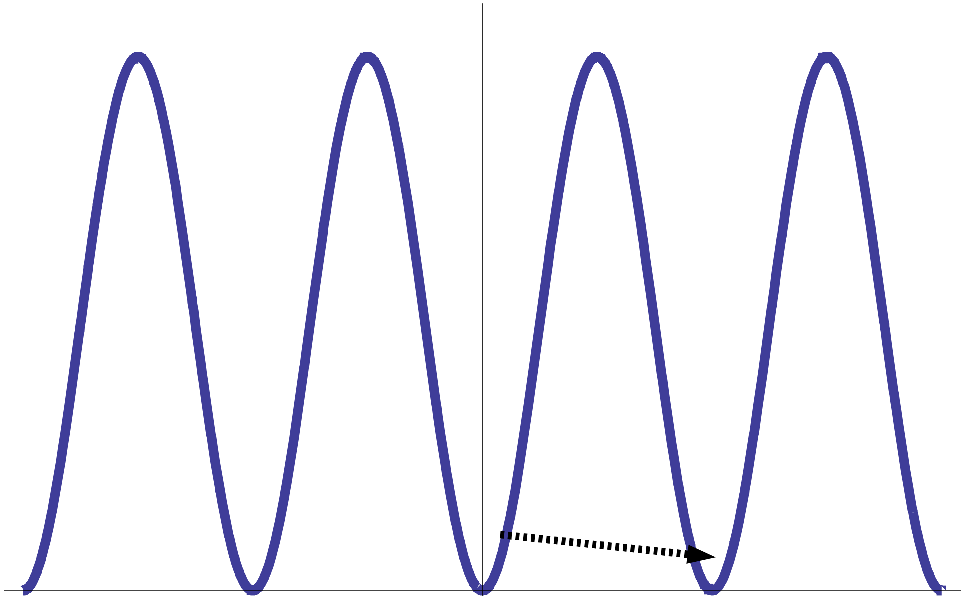
There is an effective operator

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

which gives interactions involving 12 fermions:

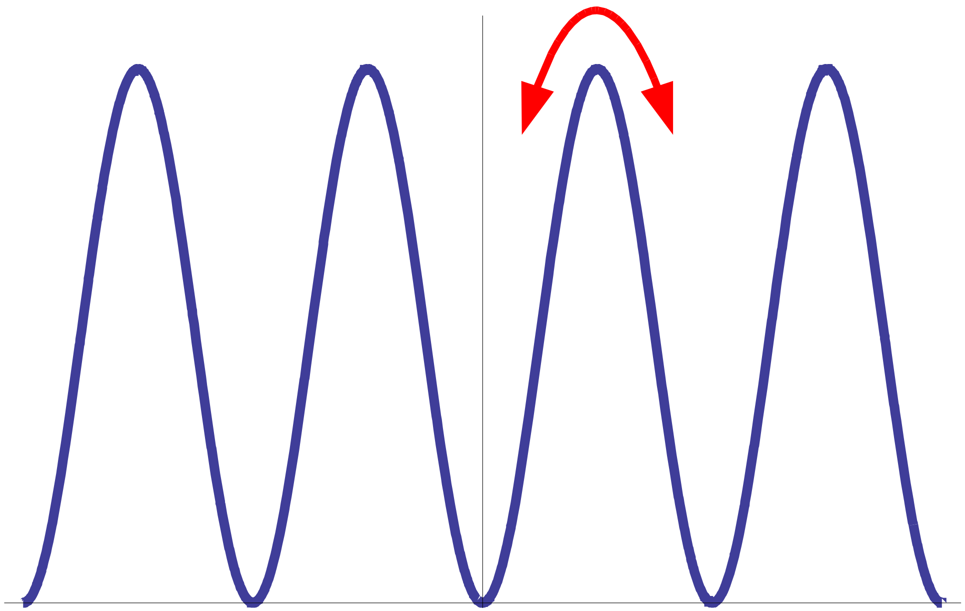


At T=0, transitions among vacua by tunnelling



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

At high temperatures, the barrier can be crossed



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

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

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

SPHALERONS

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

V.A. KUZMIN, V.A. RUBAKOV

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

and

M.E. 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 $T >$ (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-

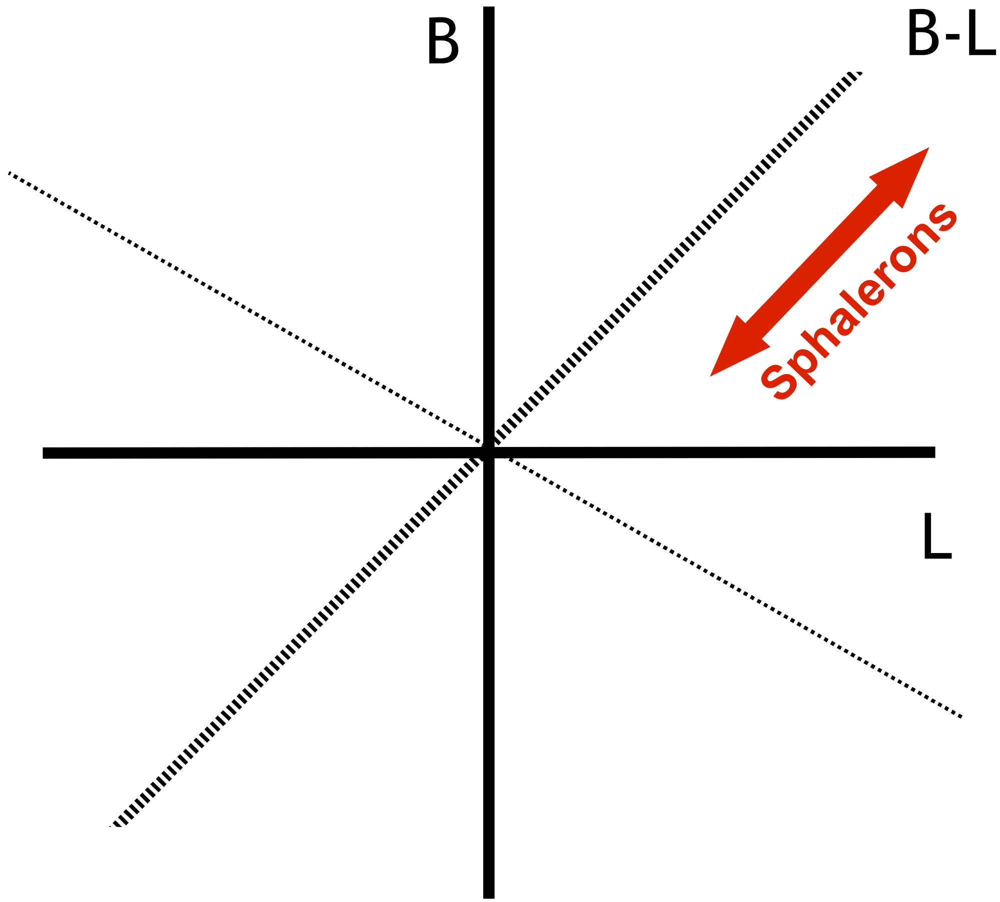
$$B(T_c) = \tfrac{1}{2}(B_{in} - L_{in}) + \tfrac{1}{2}(B_{in} + L_{in})\,e^{-A},$$

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

Clearly, $B(T_c) = \frac{1}{2}(B_{in} - L_{in})$ 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)

[illegible] (10)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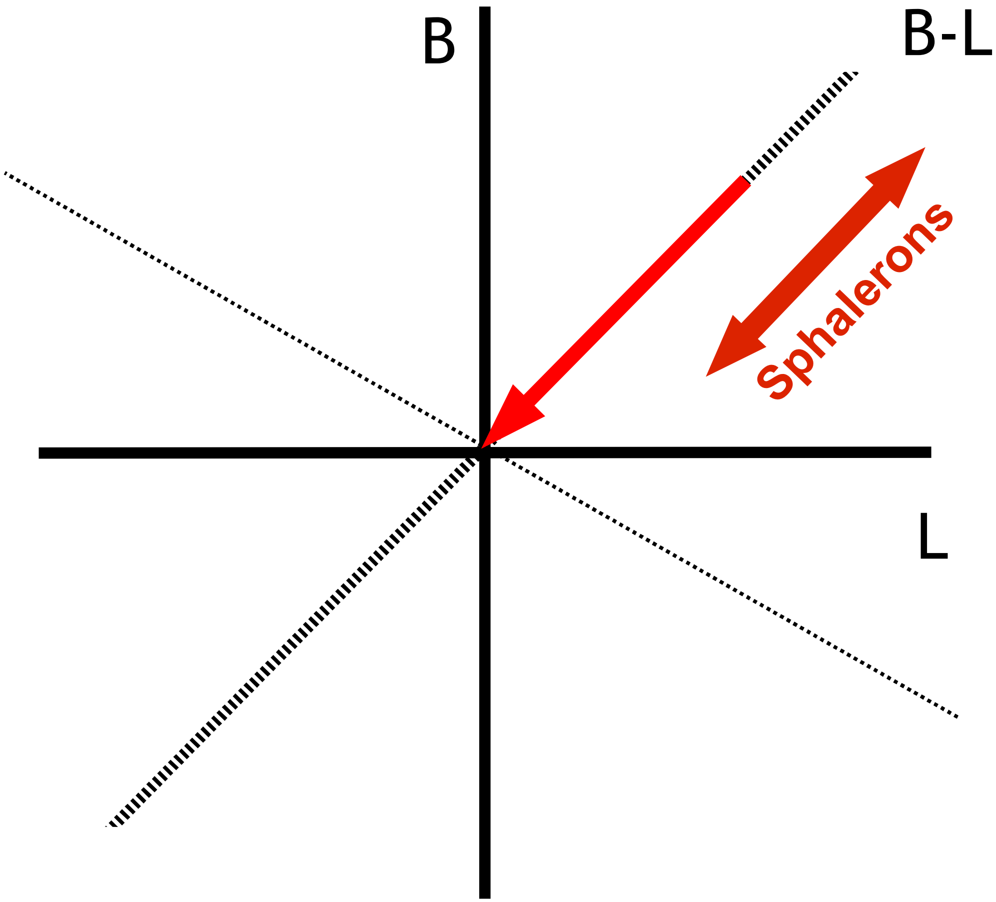
B-L
Sphalerons
L



B
B-L
Sphalerons
L

"Revised" Sakharov conditions

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

B−L

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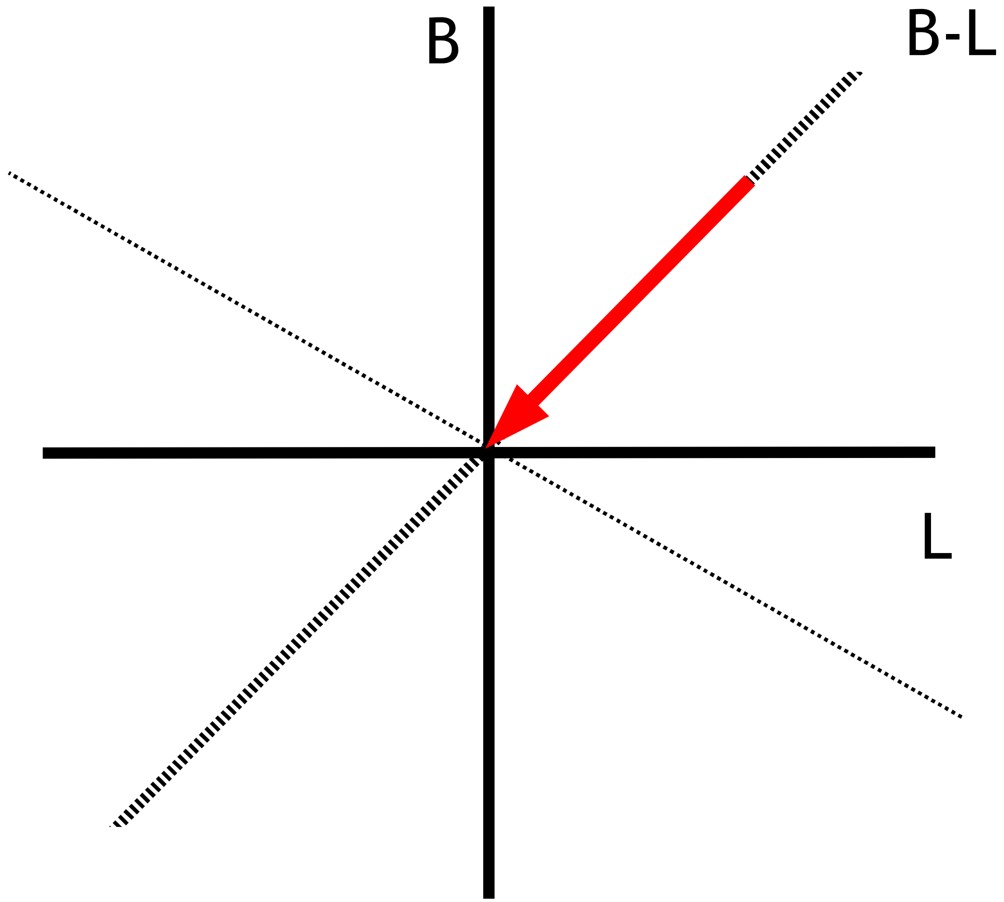

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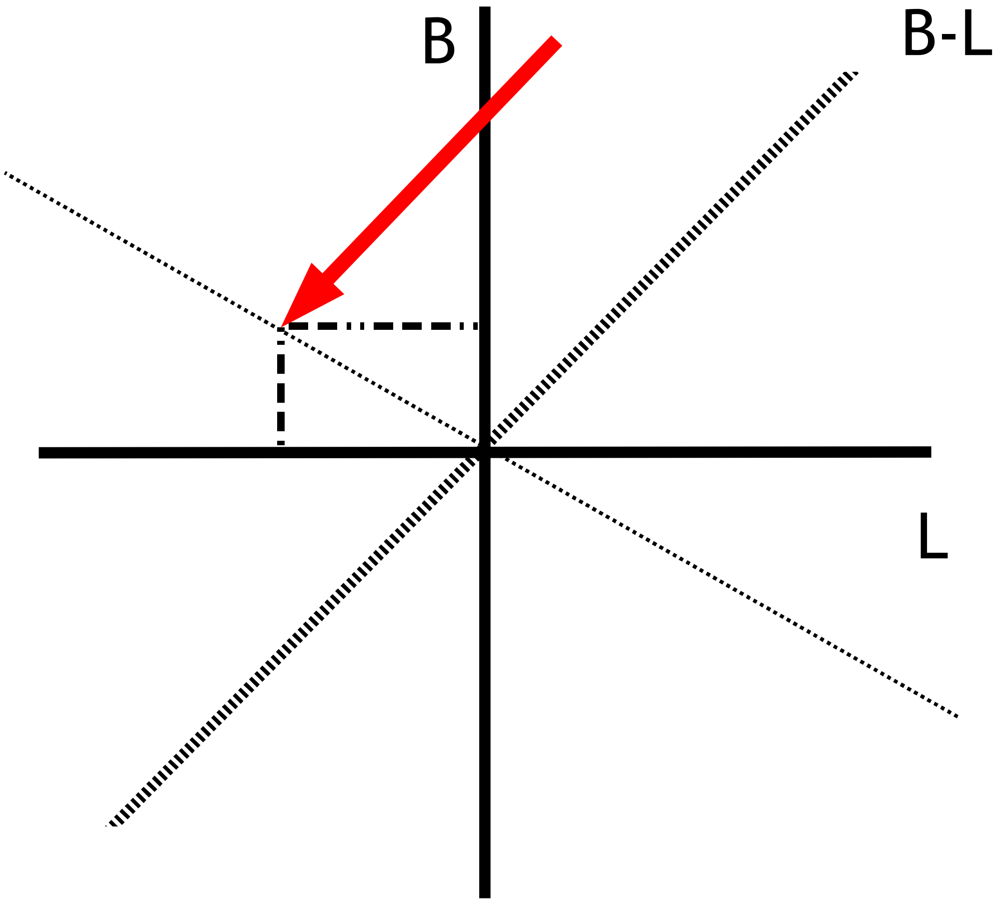
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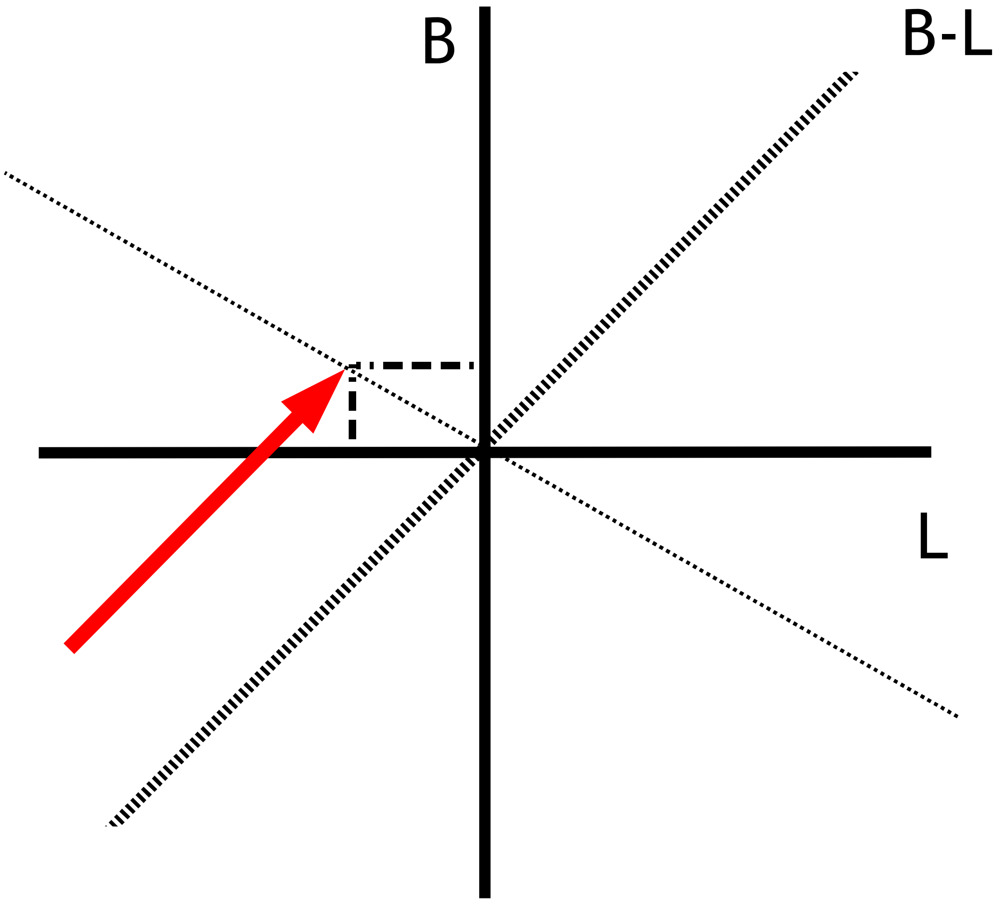
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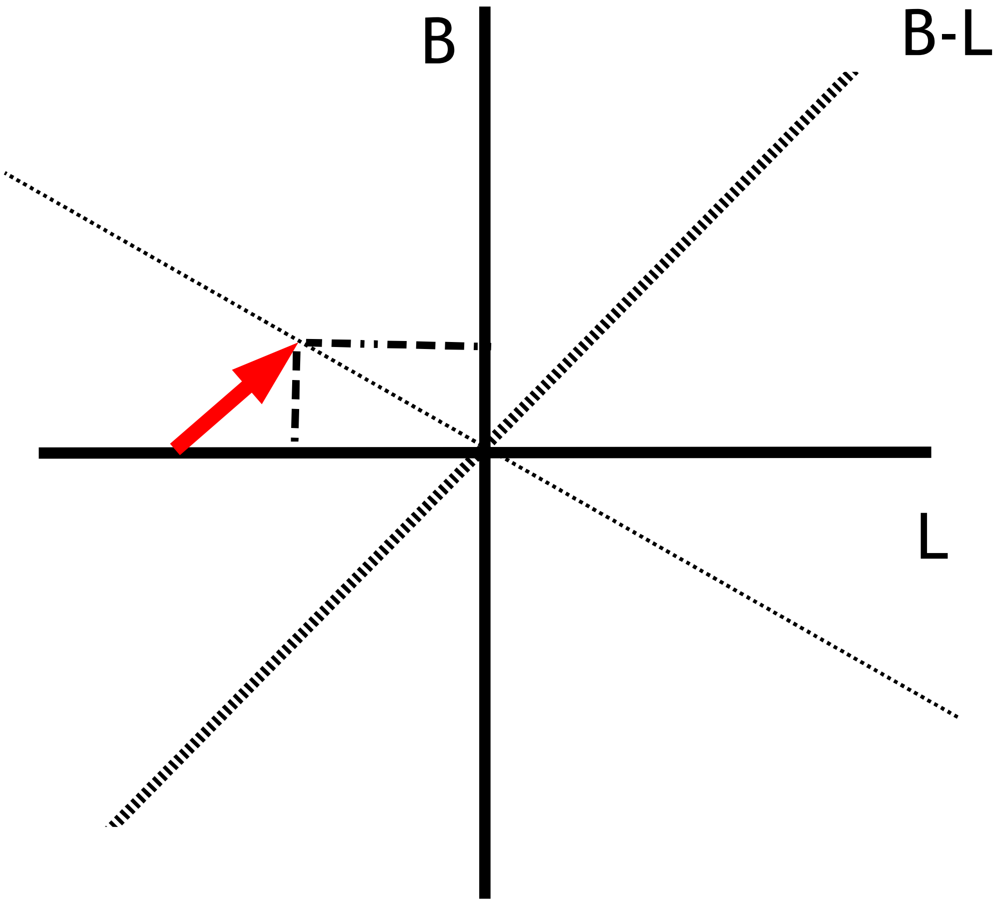
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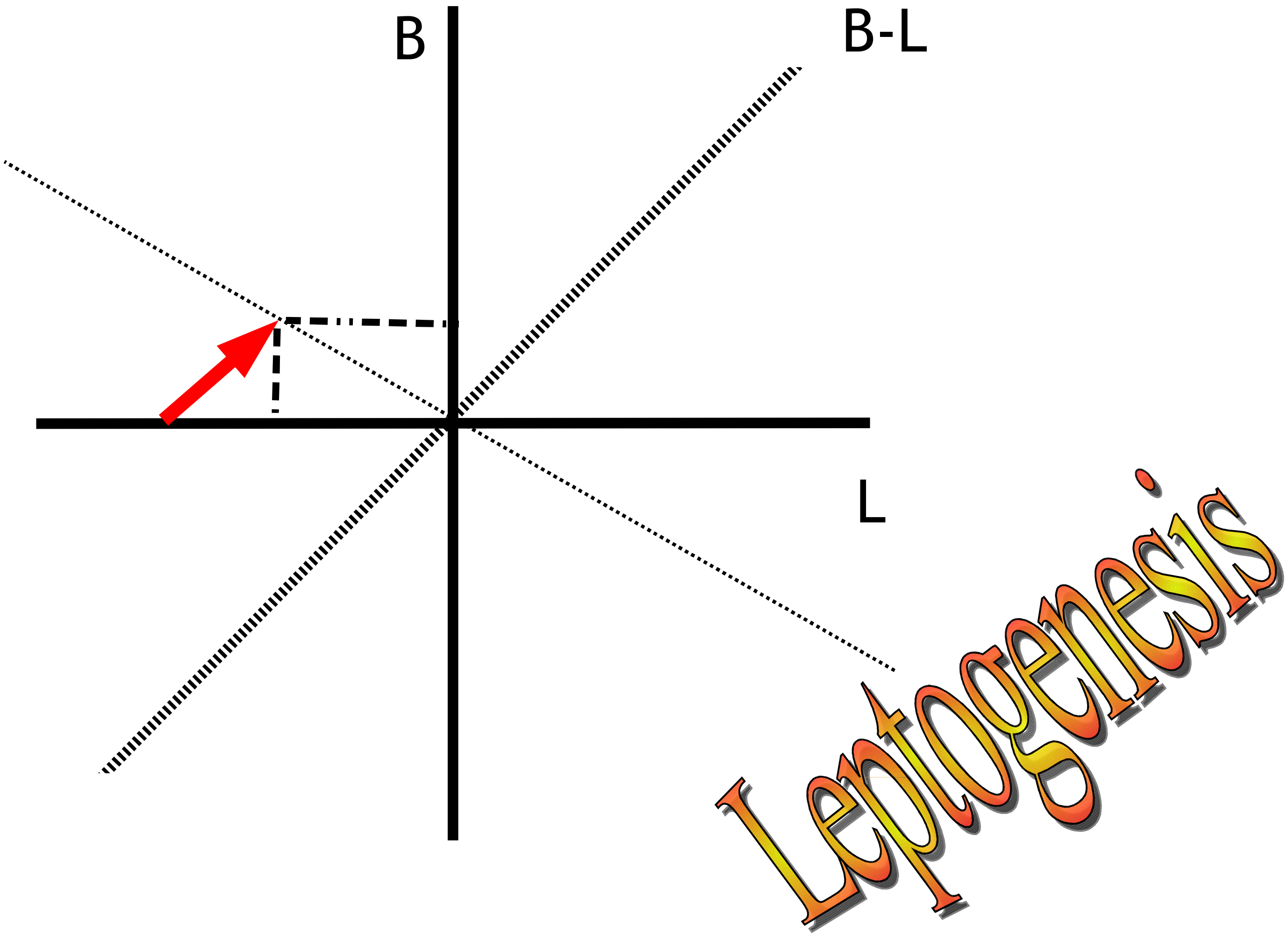
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B-L
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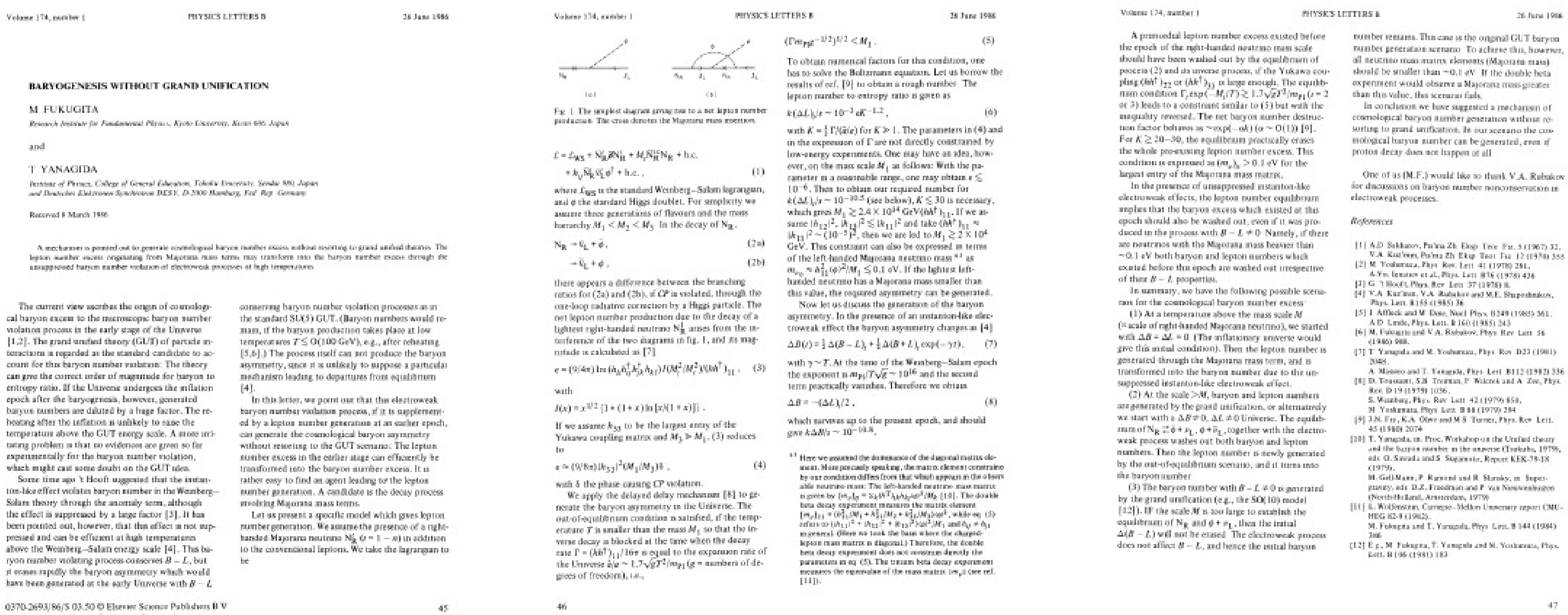
Leptogenesis

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

and

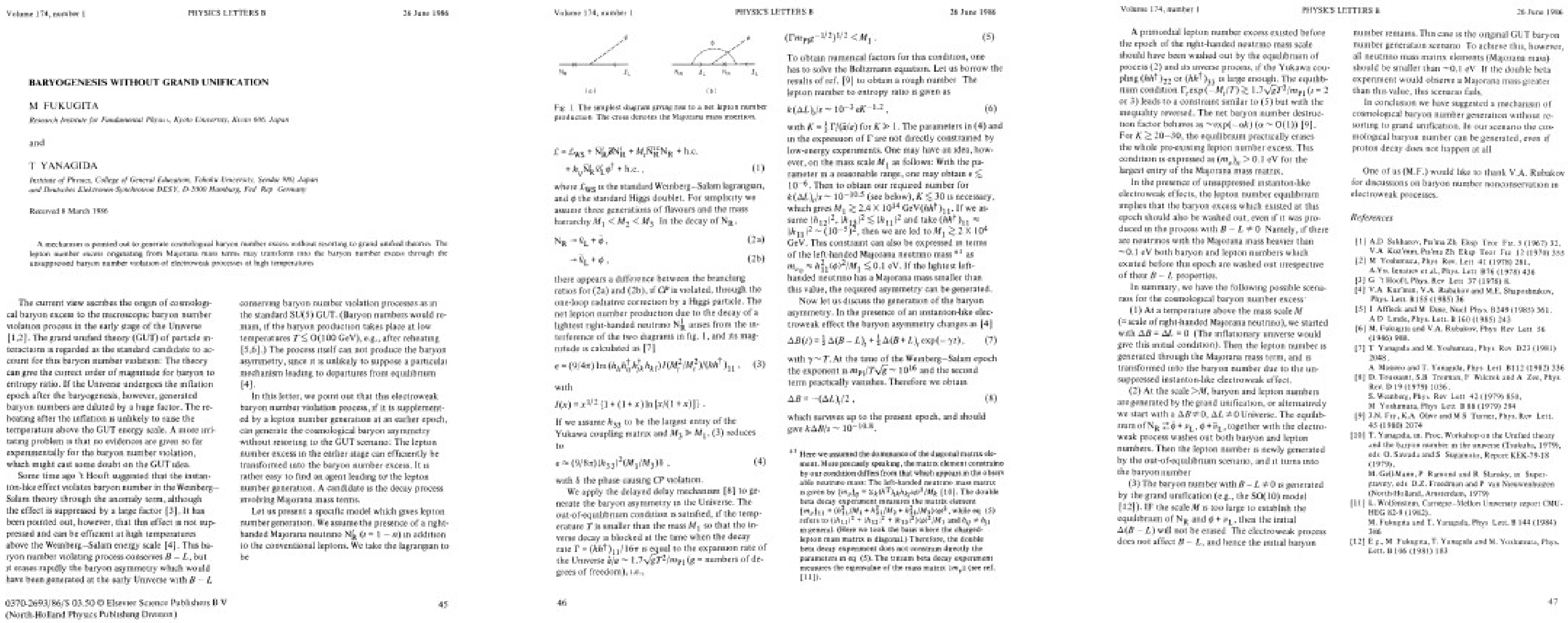
T. YANAGIDA

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.

VERY SIMPLE IDEA:

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

M. FUKUGITA

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Received 8 March 1986

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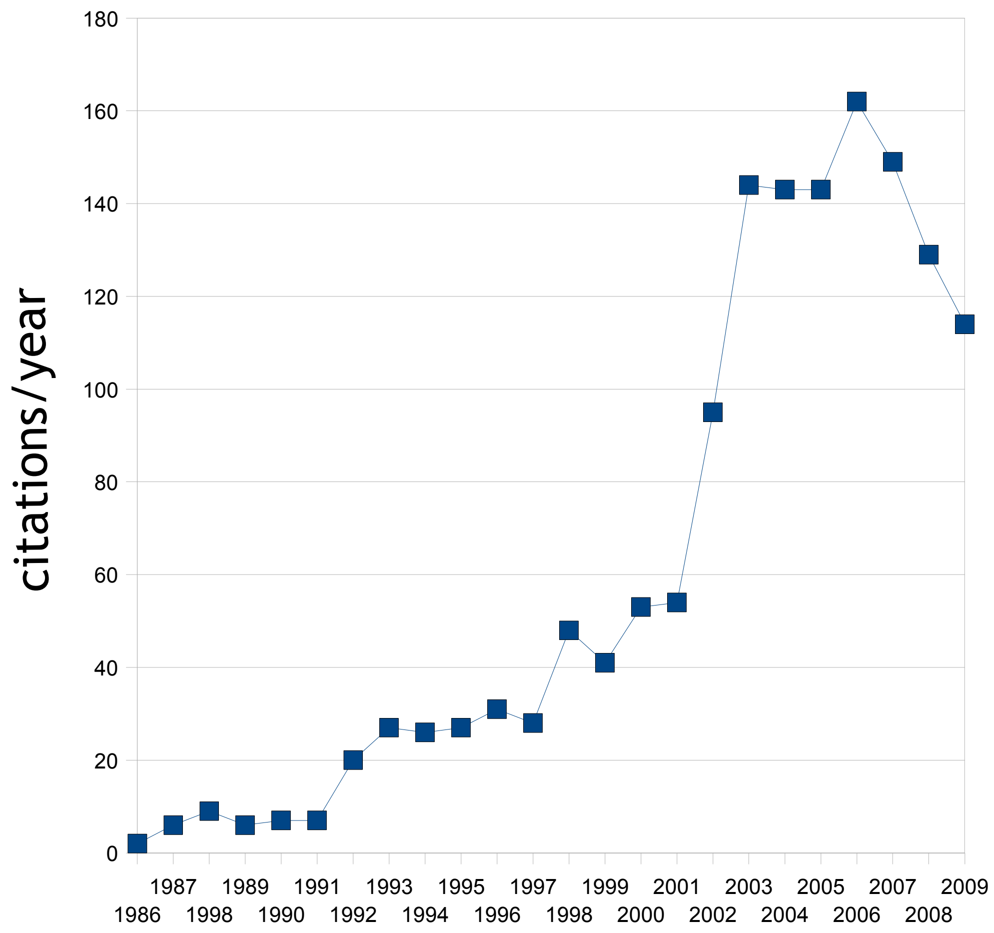
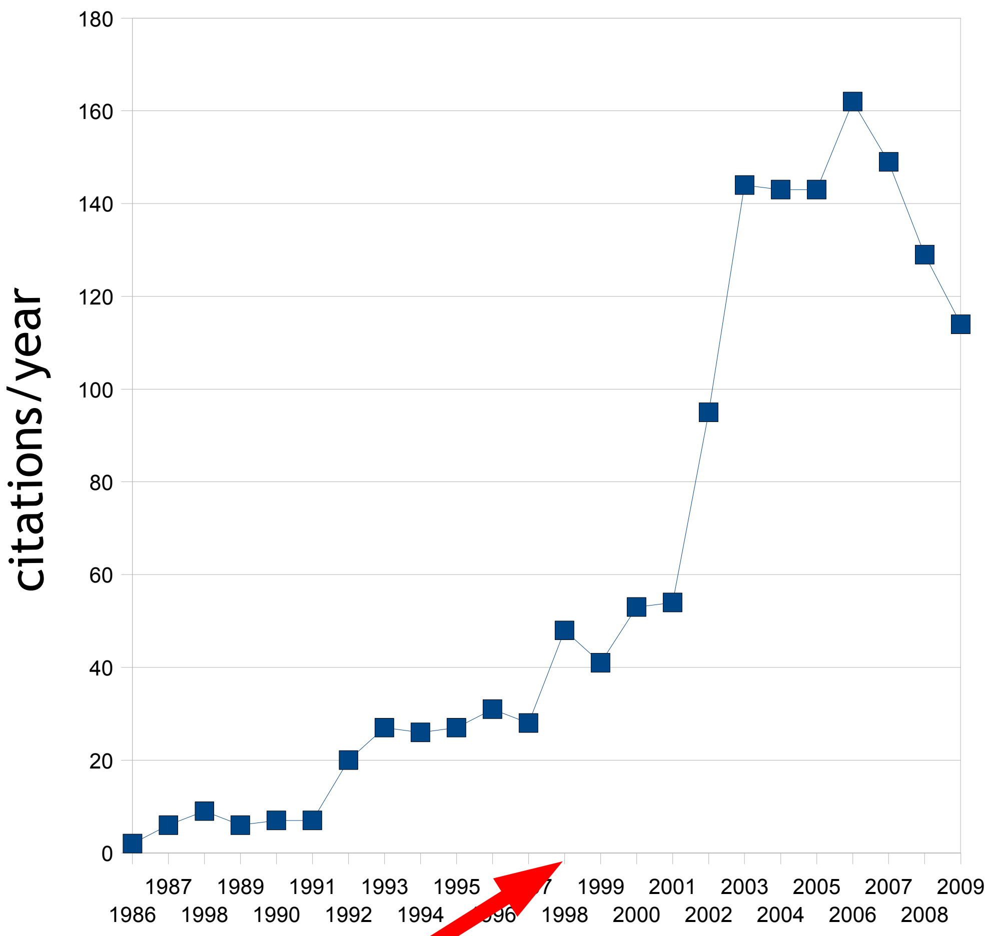
And very popular...

Citations according to the SPIRES database: 1492

Why are people so excited about leptogenesis?

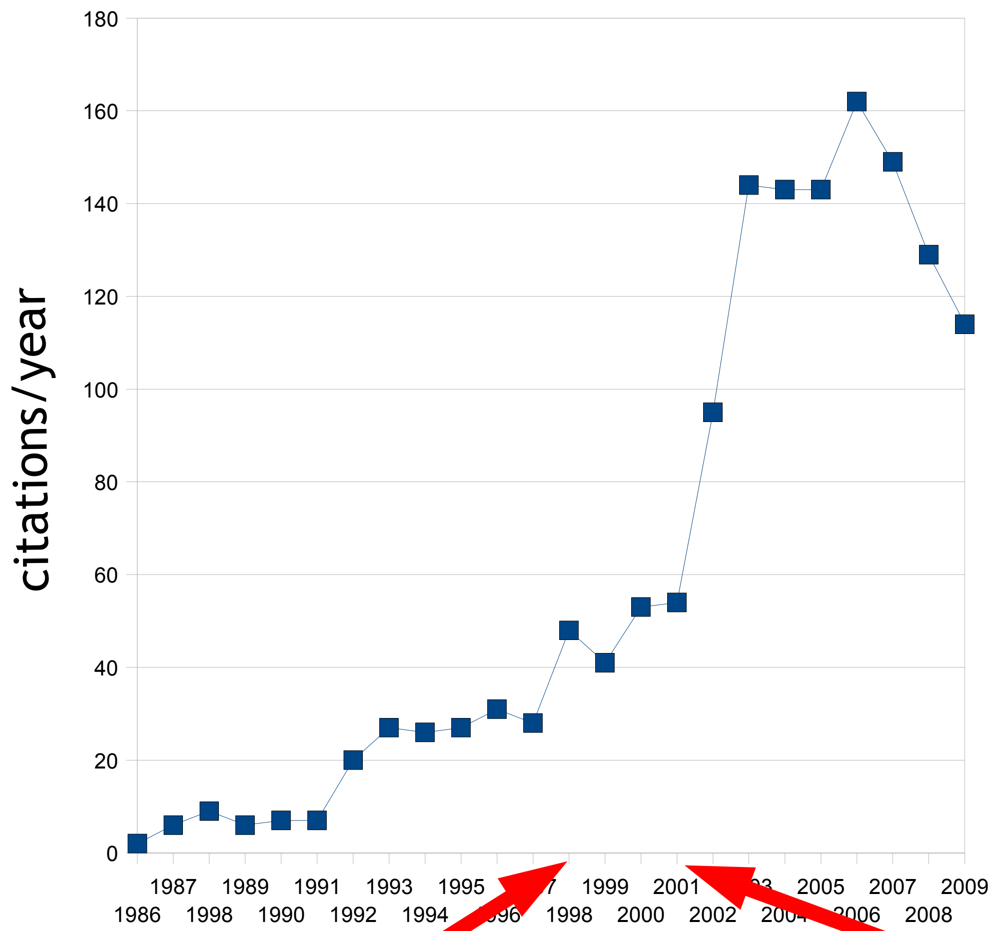


Why are people so excited about leptogenesis?



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

Why are people so excited about leptogenesis?

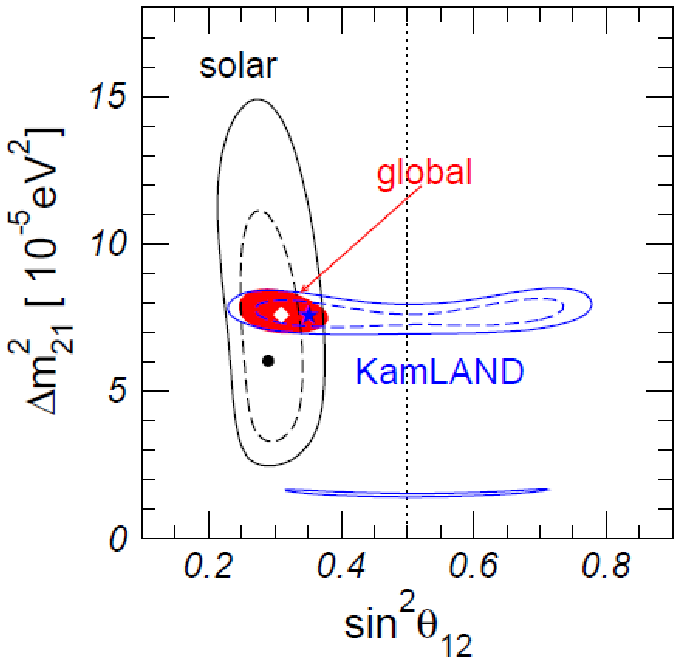


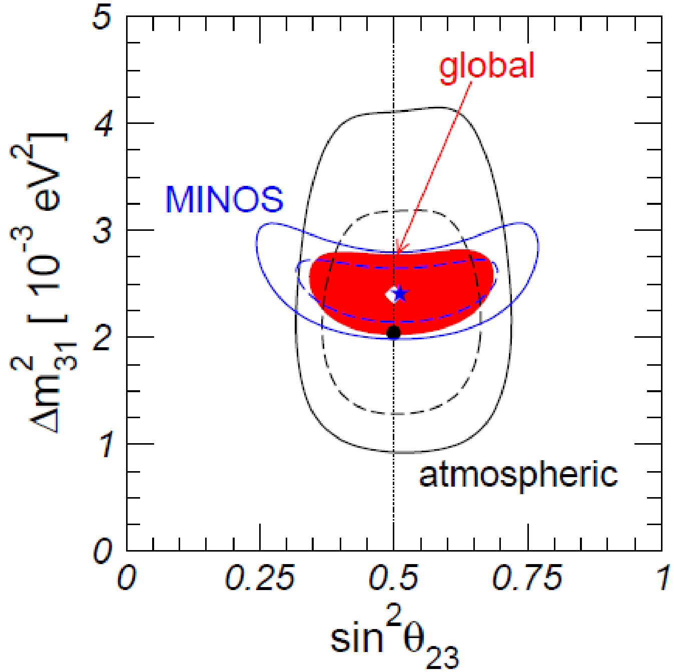
1998. Evidence of atmospheric neutrino oscillations (Super-K)

2001. Evidence of solar neutrino oscillations (SNO)

Neutrino masses

Neutrinos have mass!!





Schwetz, Tortola, Valle

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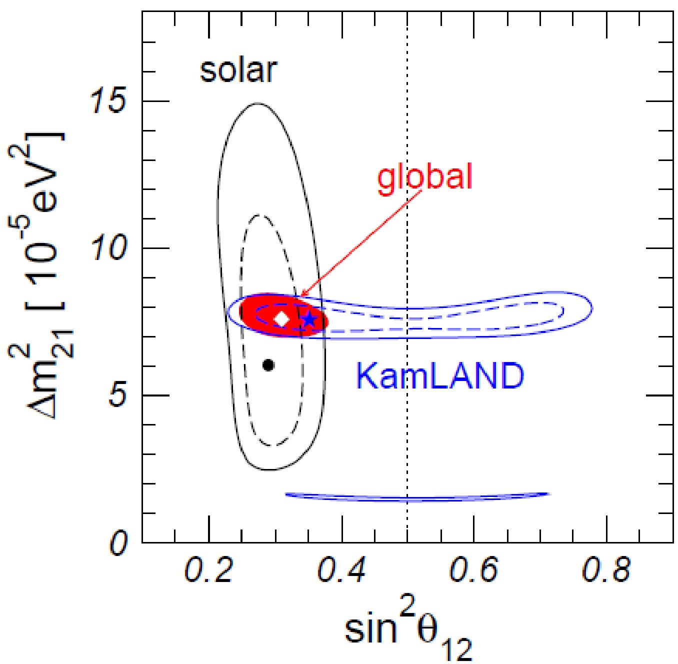

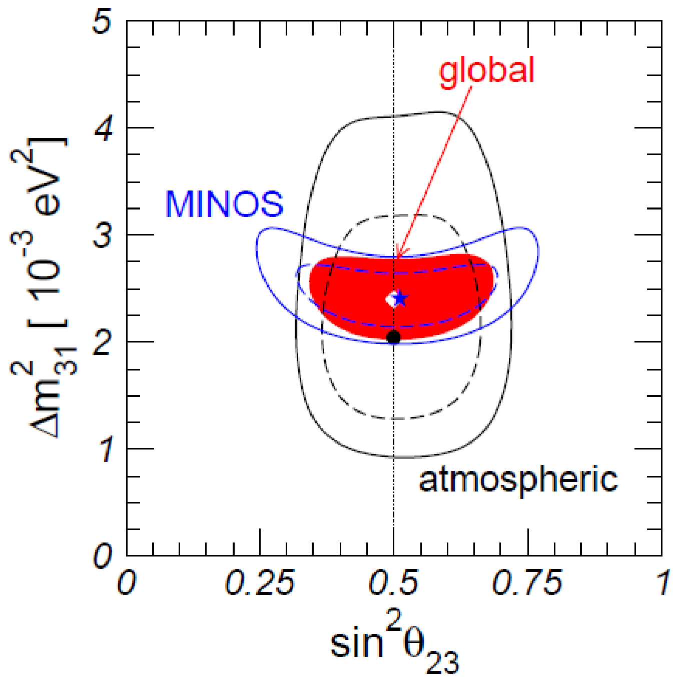

Schwetz, Tortola, Valle

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

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

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

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

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

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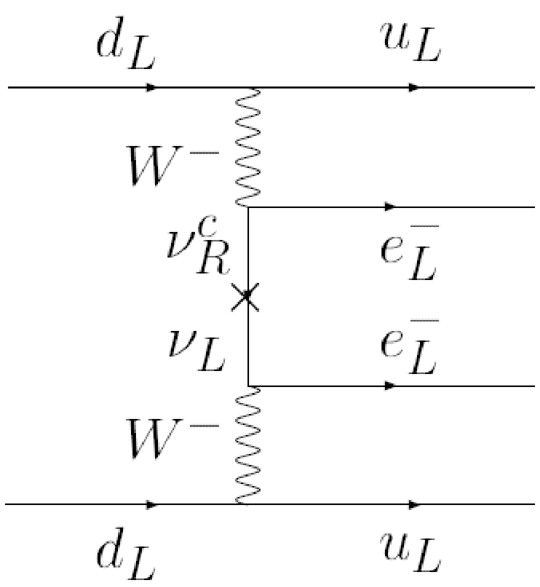
Option preferred by theorists

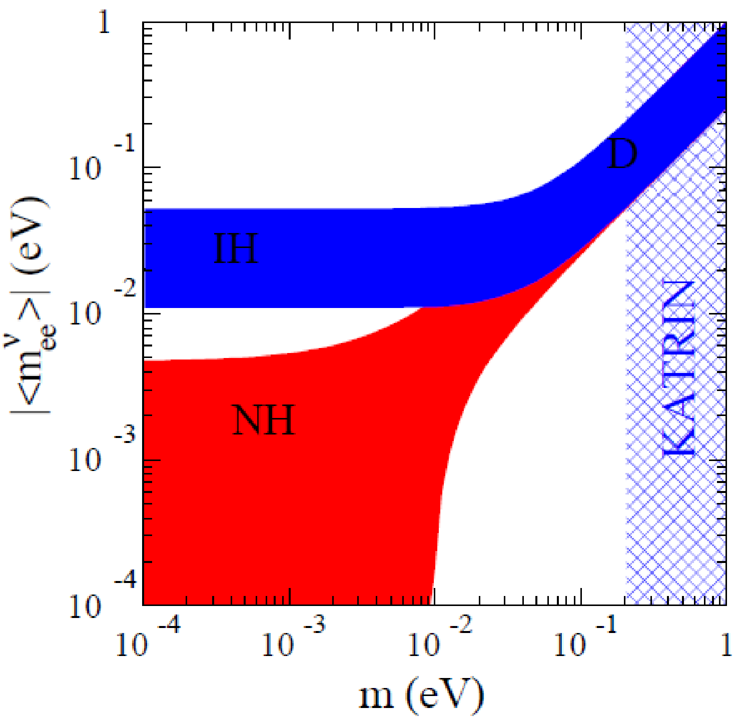
Dirac or Majorana?

The smoking gun: neutrinoless double beta decay

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



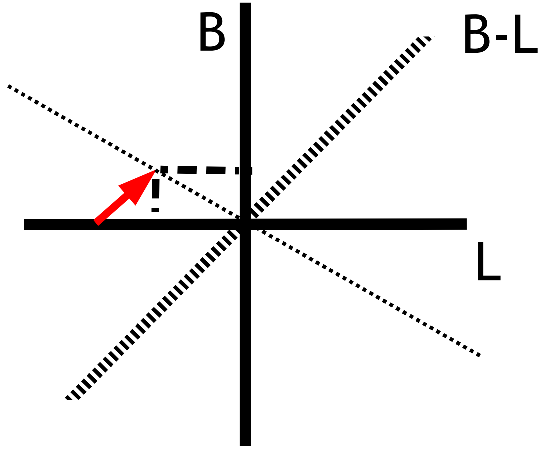
Not observed yet. Lifetime $>10^{24}$–10^{25} years



Bahcall, Murayama
Peña-Garay

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 (CUORE, GERDA…)

● The observation of $0\nu2\beta$ decay (⇒L is violated) will constitute a strong *hint* for leptogenesis.



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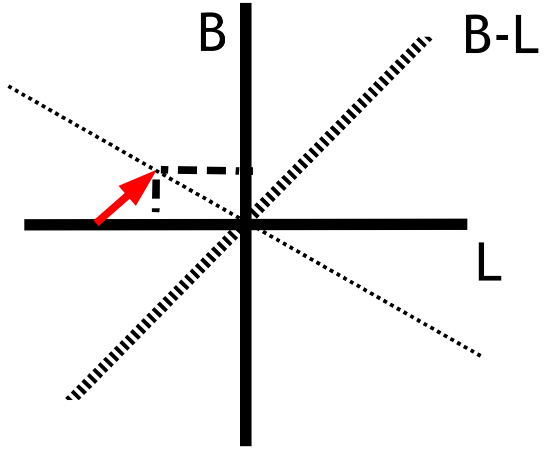
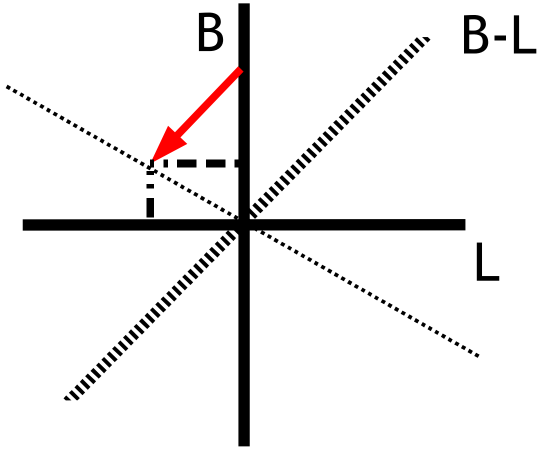


• The observation of neutron-antineutron oscillations (⇒B is violated) will constitute a strong *hint* for baryogenesis.



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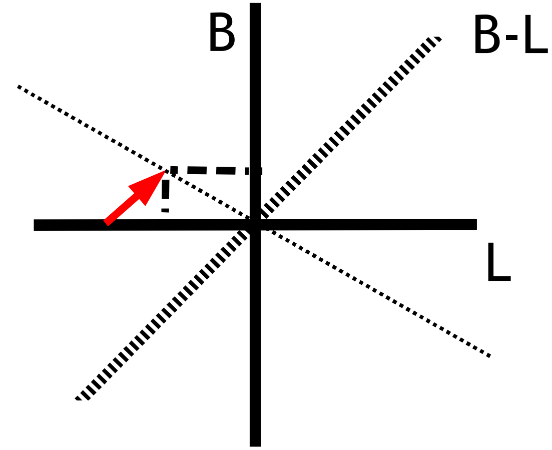

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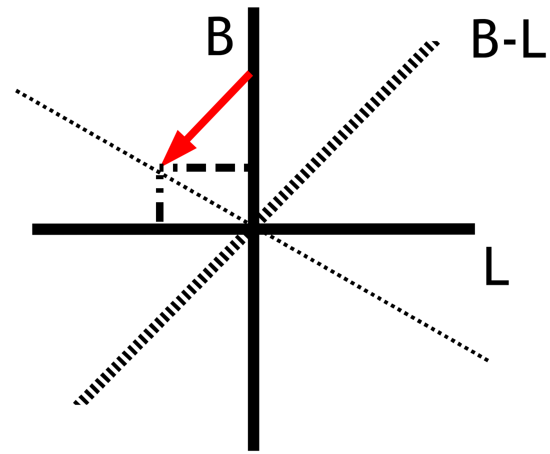
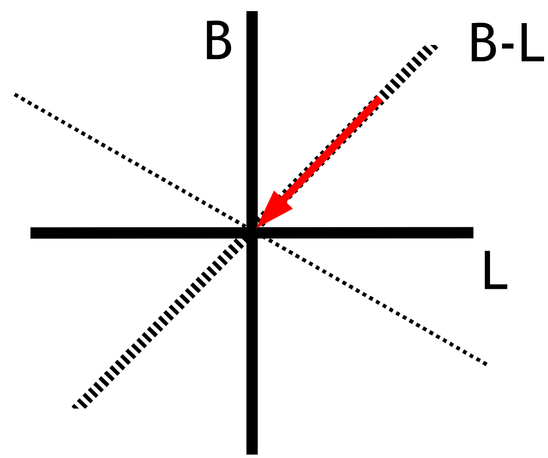


• The observation of proton decay (⇒B and L violated) will not have any implications for baryogenesis/leptogenesis (since B−L is **not** violated)



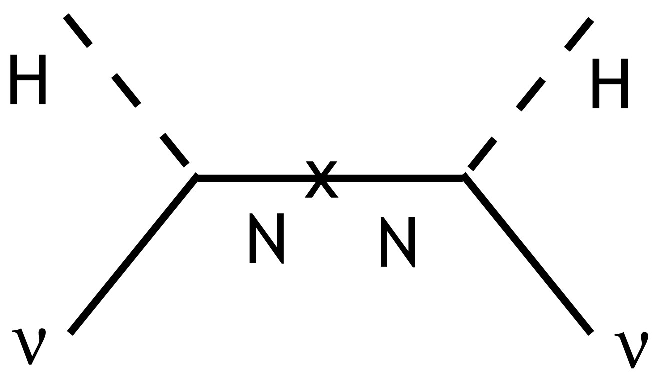
Origin of neutrino masses

Many proposals!

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

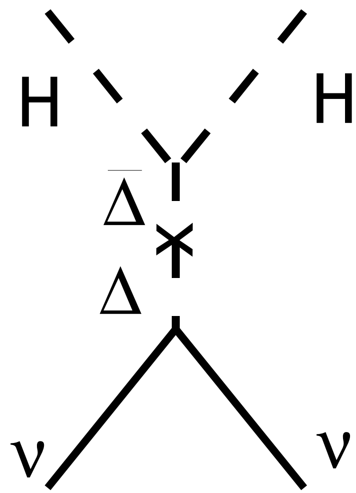
See-saw mechanism

Type I



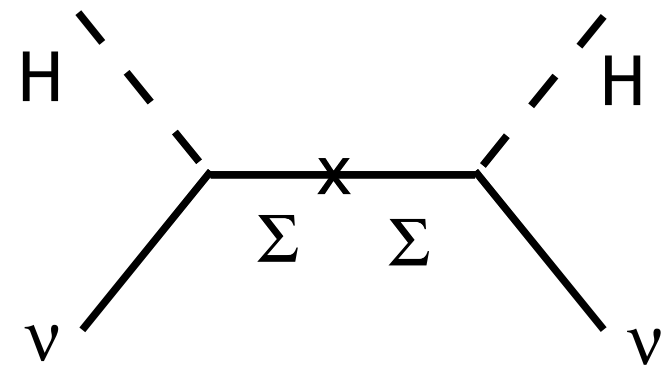
(fermion singlets)

Type II



(scalar triplets)

Type III



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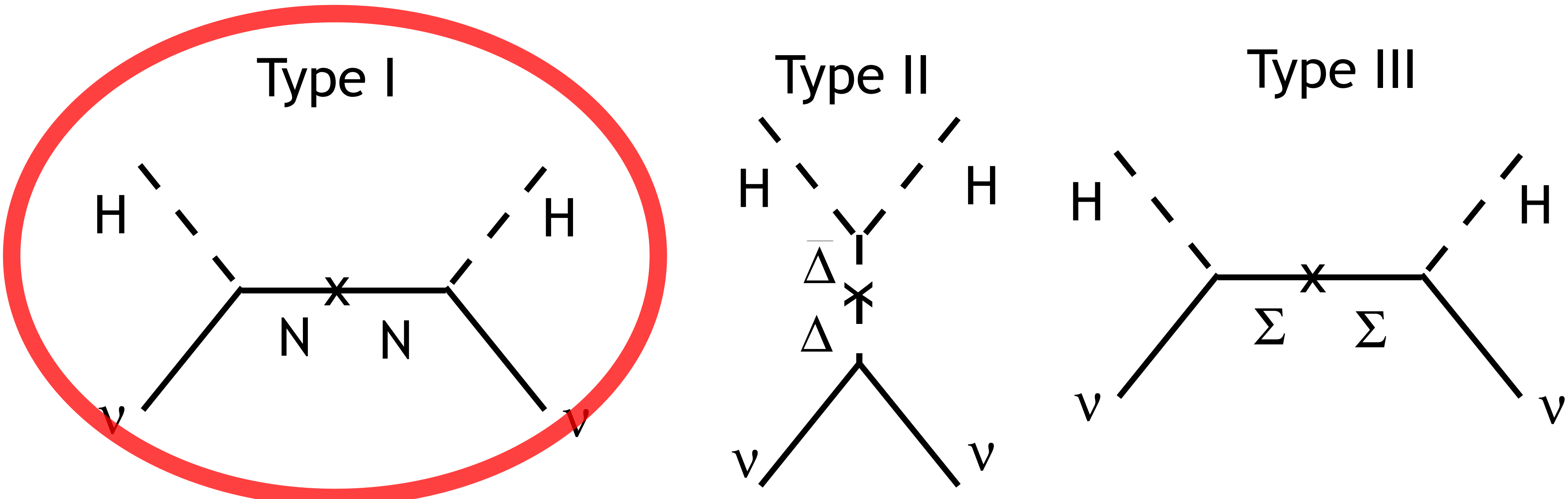

(fermion singlets) (scalar triplets) (fermion triplets)

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

That's it!!

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

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

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

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

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

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

Bonus

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

Leptogenesis

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

The three Sakharov conditions are fulfilled:

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

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

Leptogenesis

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The three Sakharov conditions are fulfilled:

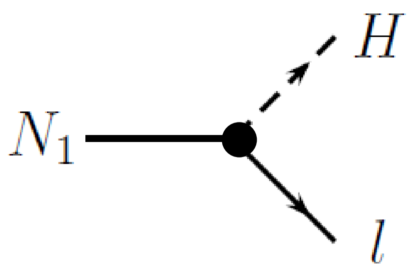
- Violation of B–L. Guaranteed if neutrinos are Majorana particles.
- C and CP violation. Guaranteed if the neutrino Yukawa couplings contain physical phases. However, it is not guaranteed that the C and CP violation are large enough for leptogenesis.
- Departure from thermal equilibrium. Guaranteed,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

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

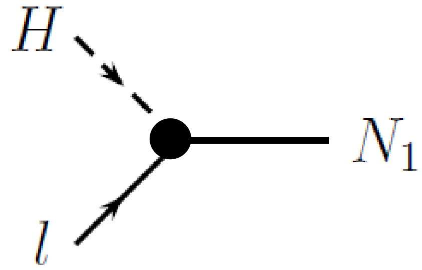
Calculate!

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

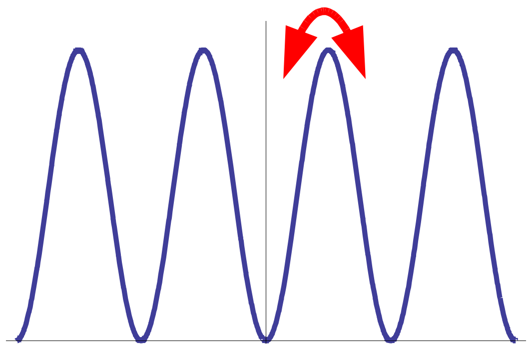
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.



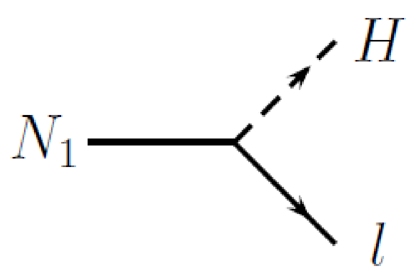
3- Conversion of the lepton asymmetry into a baryon asymmetry.



1- Generation of the lepton asymmetry

At tree level, the total decay rate is:

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

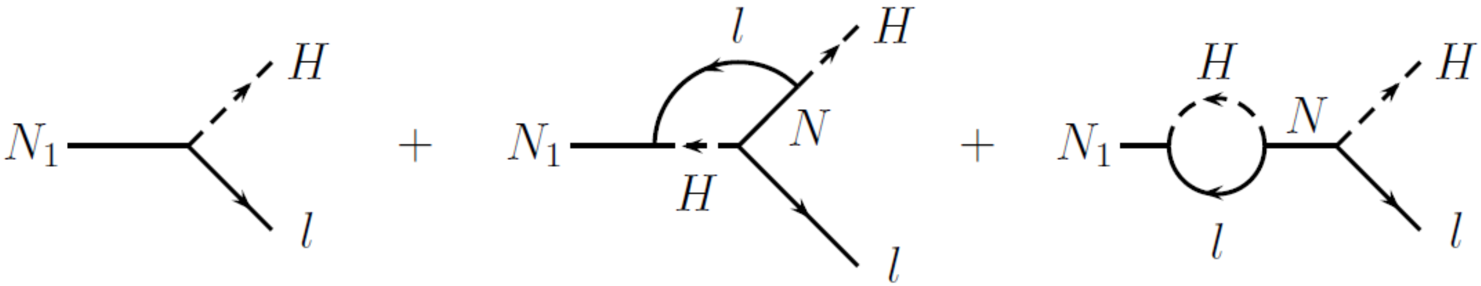


The rate for $N_1 \to lH$ and $N_1 \to l^c H^c$ are identical. **No CP asymmetry**:

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

1- Generation of the lepton asymmetry

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



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

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

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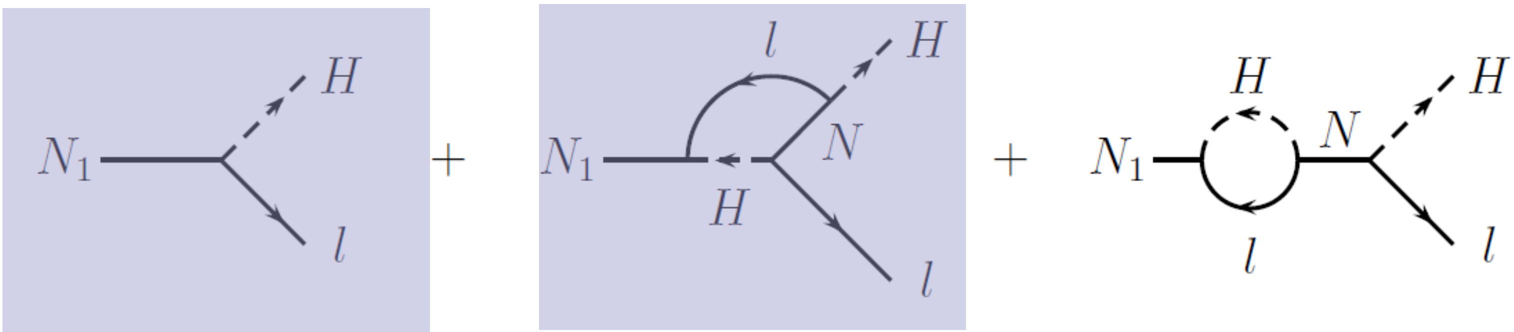

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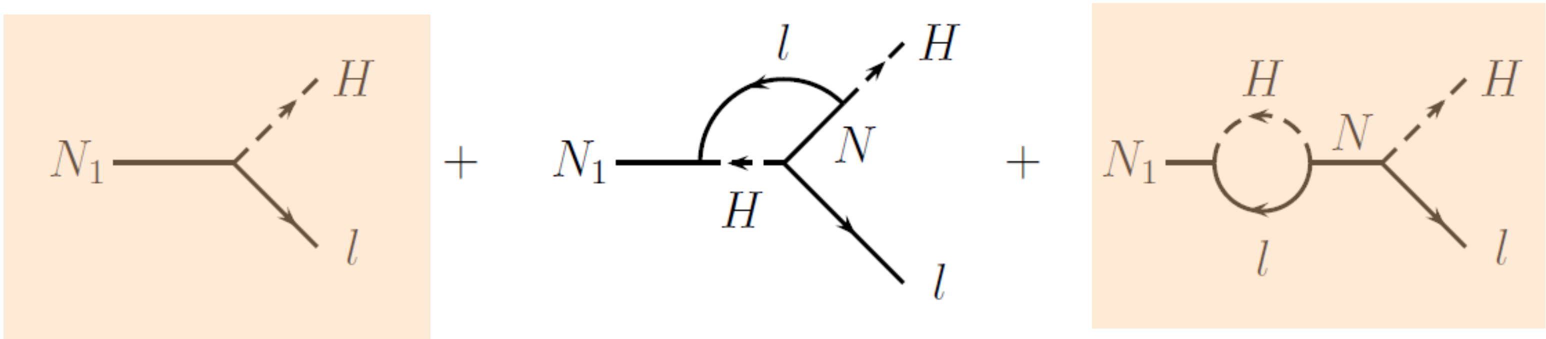
Interference with the vertex correction

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

1- Generation of the lepton asymmetry

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



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

Interference with the wave-function correction

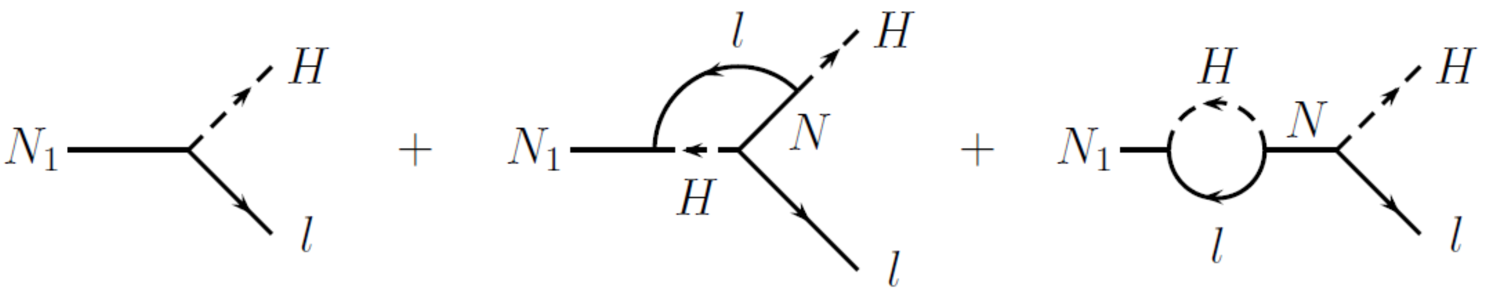
Tricky! Calculable only when $|M_i - M_1| \gg |\Gamma_i - \Gamma_1|$

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

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

1- Generation of the lepton asymmetry

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

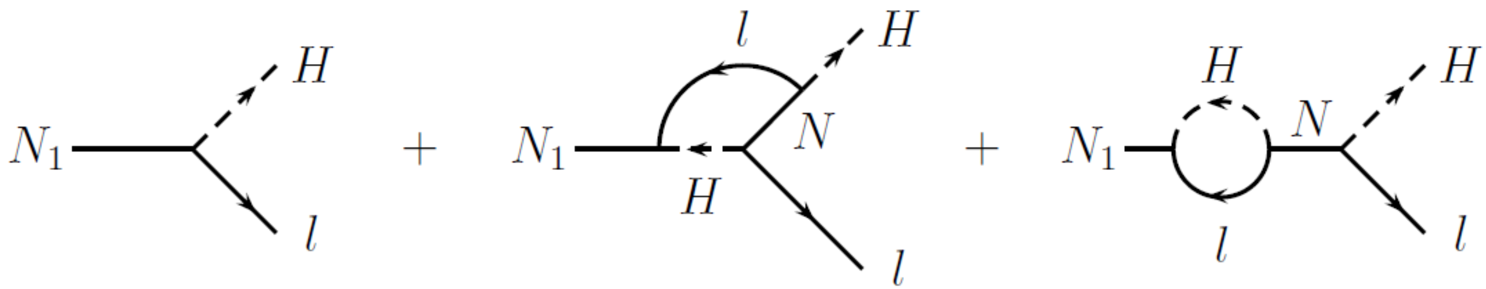


$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to l^c H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to l^c H^c)}$$

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

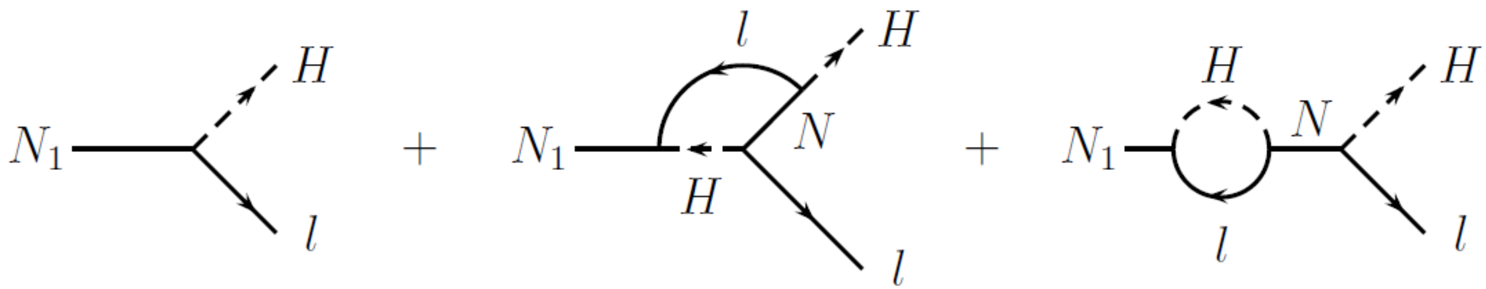
⚠ The Yukawa coupling must be complex:

C and CP violation (2nd Sakharov condition)



The CP violating decays generate instantaneously a lepton asymmetry.

Not the end of the story…



The CP violating decays generate instantaneously a lepton asymmetry.

Not the end of the story...

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

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

2- Wash-out of the lepton asymmetry

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

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

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

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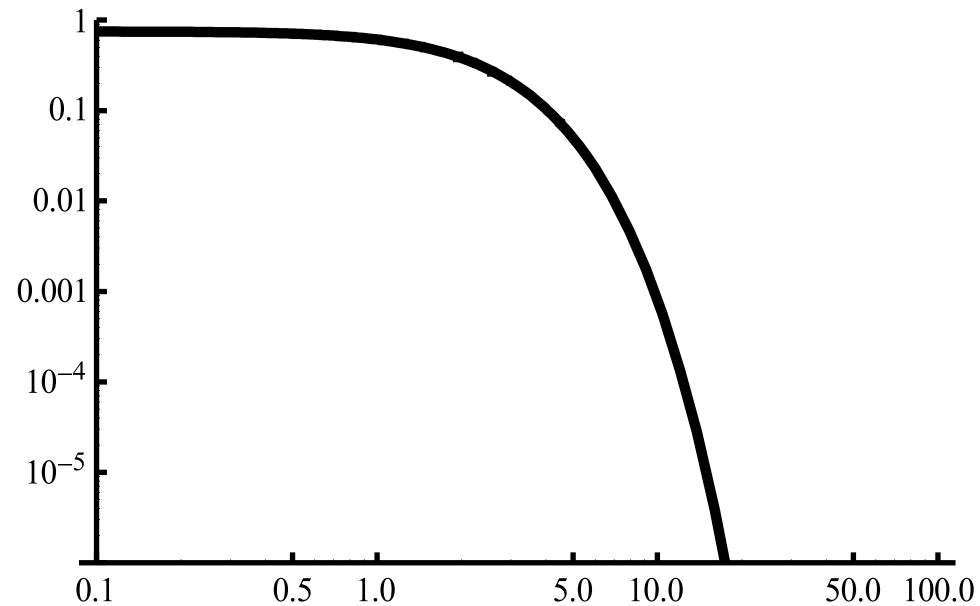
$$z \equiv \frac{M_1}{T}$$

Equilibrium distribution

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



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Decay term

$$D(z) = \Gamma_D(z)/(H\,z)$$

Hubble rate at temperature T

$$H(T) \simeq \sqrt{\frac{8\pi^3 g_*}{90}}\,\frac{T^2}{M_P}$$

$$= \quad 1.66 g_*^{1/2}\,\frac{M_1^2}{M_P}\,\frac{1}{z^2}$$

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$$z \equiv \frac{M_1}{T}$$

Decay term

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

Decay rate at temperature T

$$\Gamma_D(z) = \Gamma_D|_{z=\infty} \langle \frac{1}{\gamma} \rangle$$

$$\langle \frac{1}{\gamma} \rangle = \frac{K_1(z)}{K_2(z)}$$

$$\Gamma_D|_{z=\infty} = \frac{1}{8\pi}(hh^\dagger)_{11} M_1$$

Hubble rate at temperature T

$$H(T) \simeq \sqrt{\frac{8\pi^3 g_*}{90}}\frac{T^2}{M_P}$$

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

$$z \equiv \frac{M_1}{T}$$

Decay term

$$D(z) = \Gamma_D(z)/(H\,z)$$

Decay rate at temperature T

$$\Gamma_D(z) = \Gamma_D|_{T=0}\langle\frac{1}{\gamma}\rangle$$

$$\langle\frac{1}{\gamma}\rangle = \frac{K_1(z)}{K_2(z)}$$

$$\Gamma_D|_{T=0} = \frac{1}{8\pi}(hh^\dagger)_{11}M_1$$

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$$D(z) = \Gamma_D(z)/(H\,z)$$

- Substituting, $D(z) = \dfrac{\Gamma_D(z)}{H\,z} = \dfrac{\Gamma_D|_{T=0}}{H\,z}\langle\dfrac{1}{\gamma}\rangle = \dfrac{\Gamma_D|_{T=0}}{H|_{T=M_1}}\,z\,\langle\dfrac{1}{\gamma}\rangle$

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$$z \equiv \frac{M_1}{T}$$

Decay term

$$D(z) = \Gamma_D(z)/(H\,z)$$

- Substituting, $D(z) = \dfrac{\Gamma_D(z)}{H\,z} = \dfrac{\Gamma_D|_{T=0}}{H\,z}\langle\dfrac{1}{\gamma}\rangle = \dfrac{\Gamma_D|_{T=0}}{H|_{T=M_1}}z\,\langle\dfrac{1}{\gamma}\rangle$

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

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

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

"Effective neutrino mass"

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

"Equilibrium neutrino mass"

To summarize: the abundance of right-handed neutrinos is dictated by a Boltzmann equation:

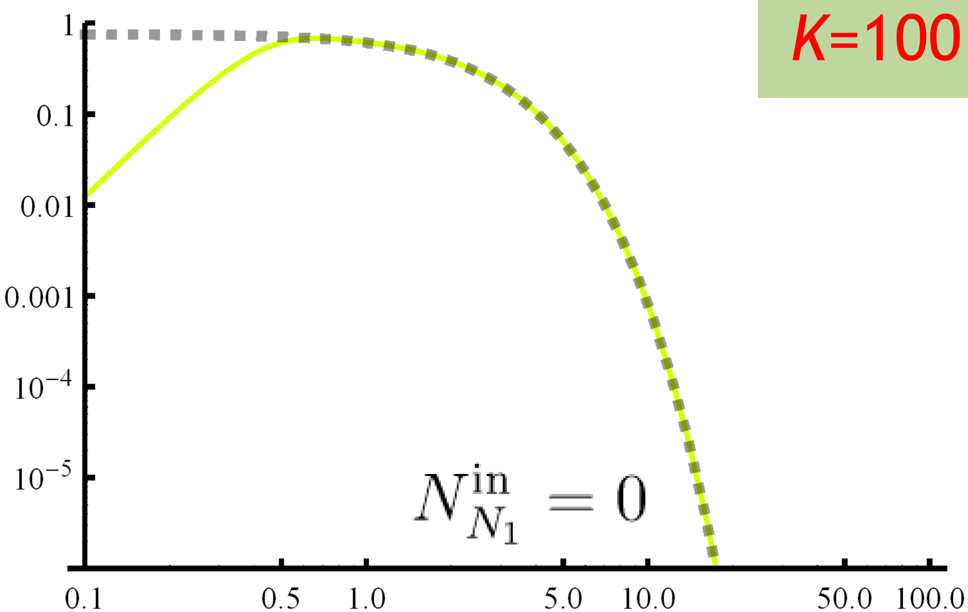
$$\frac{dN_{N_1}(z)}{dz} = -K\, z\, \frac{K_1(z)}{K_2(z)} \left(N_{N_1}(z) - N_{N_1}^{\rm eq}(z)\right)$$

$$K = \frac{\widetilde{m}_1}{m_*}$$

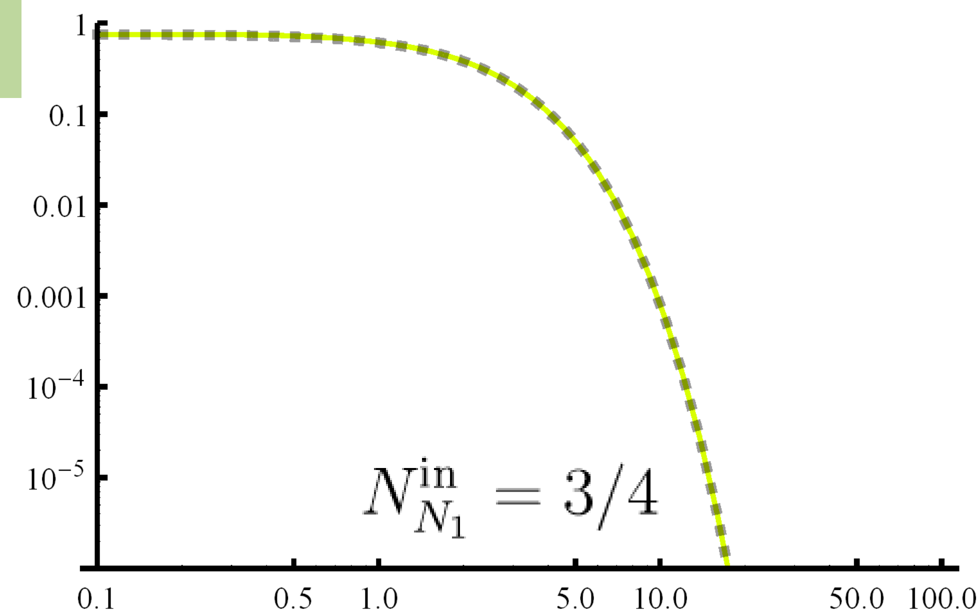
$$N_{N_1}^{\rm eq}(z) = \frac{3}{8} z^2 K_2(z) \,,$$

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

K=100



vanishing initial abundance



thermal initial abundance

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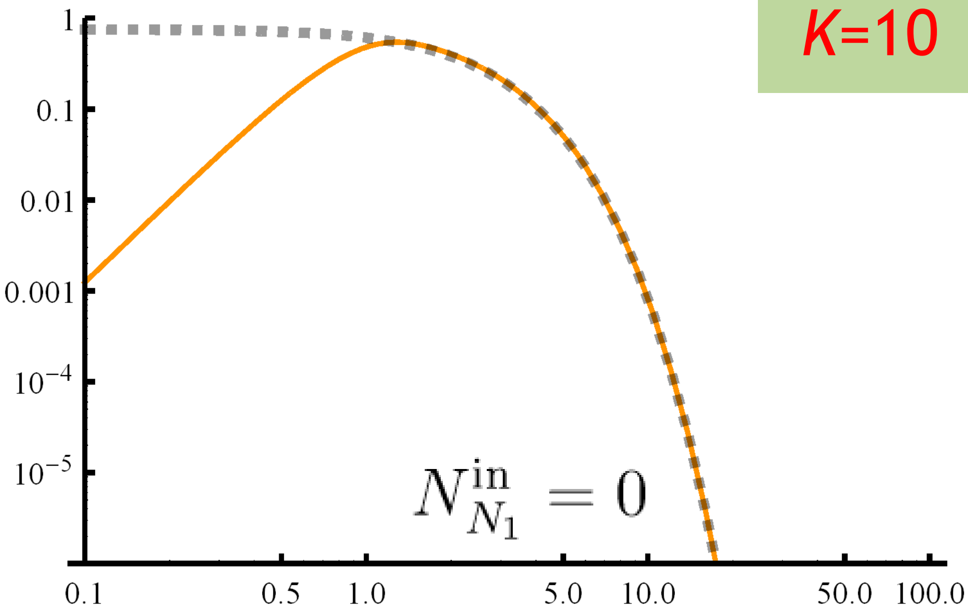
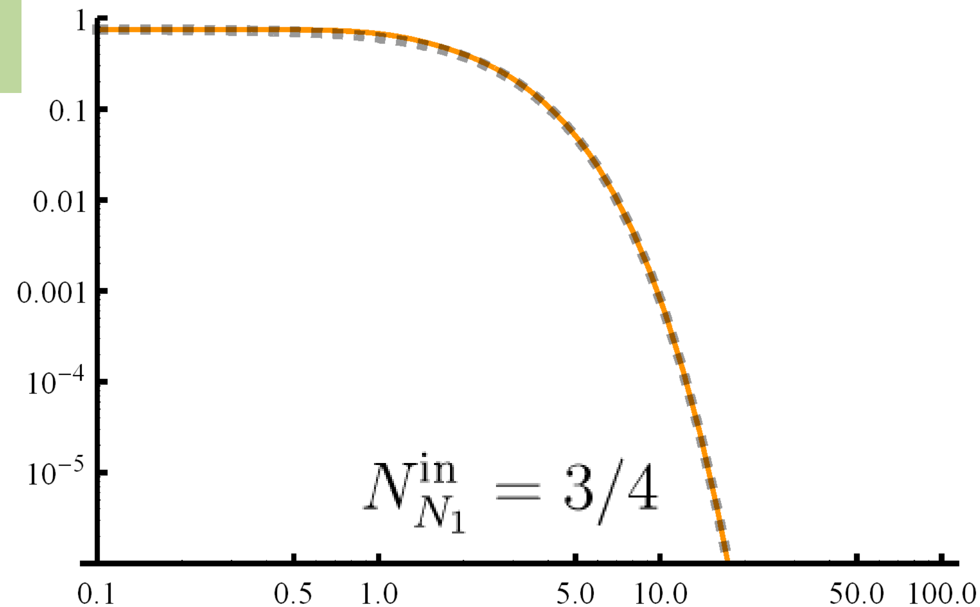
K=10



vanishing initial abundance



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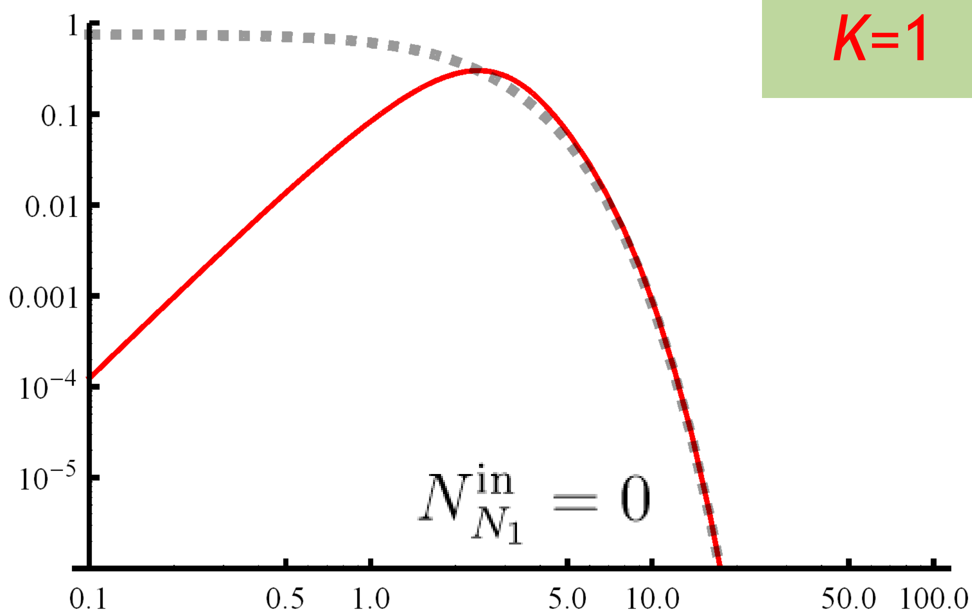
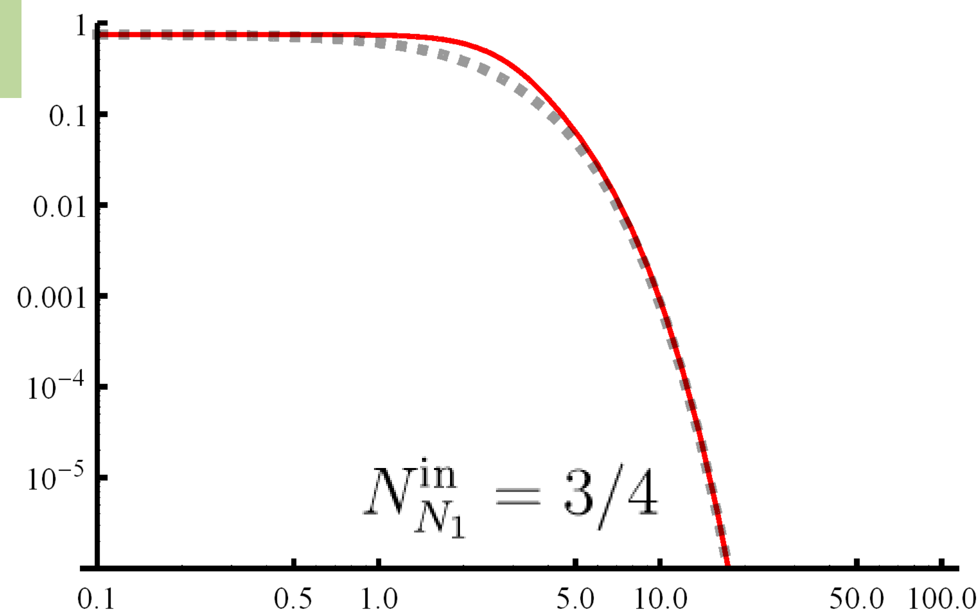
$$K = \frac{\widetilde{m}_1}{m_*} \qquad N_{N_1}^{\rm eq}(z) = \frac{3}{8} z^2 K_2(z) \,,$$

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



vanishing initial abundance

K=1



thermal initial abundance

To summarize: the abundance of right-handed neutrinos is dictated by a Boltzmann equation:

$$\frac{dN_{N_1}(z)}{dz} = -K\, z\, \frac{K_1(z)}{K_2(z)} \left(N_{N_1}(z) - N_{N_1}^{\mathrm{eq}}(z)\right)$$

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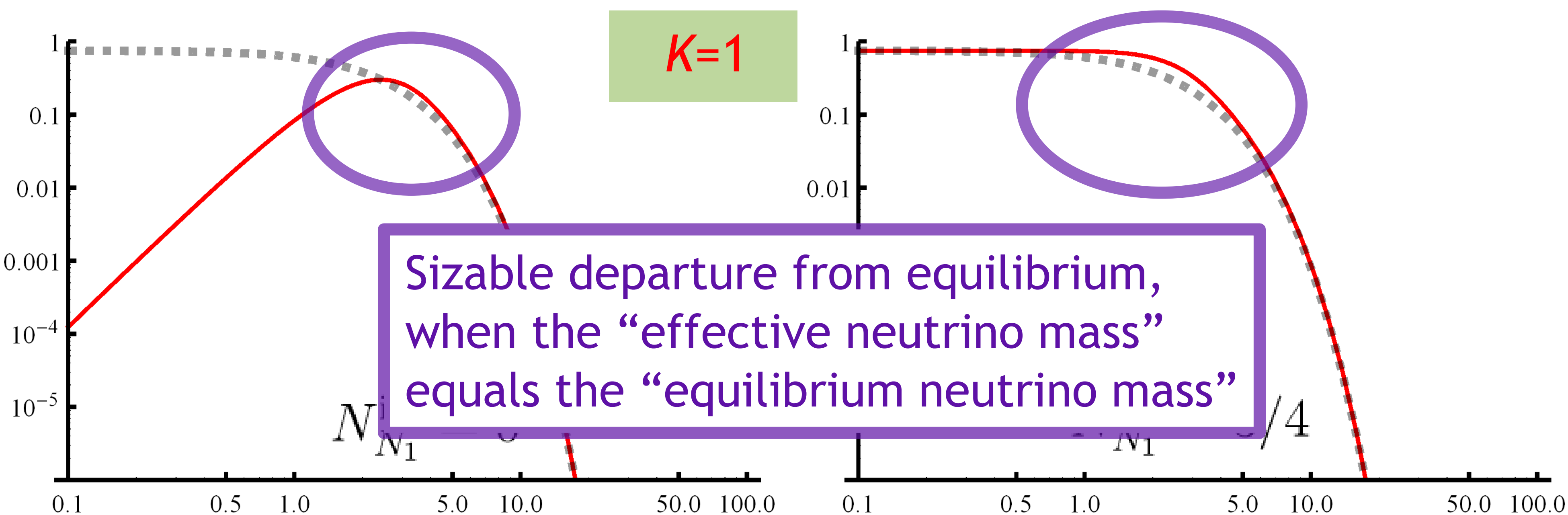

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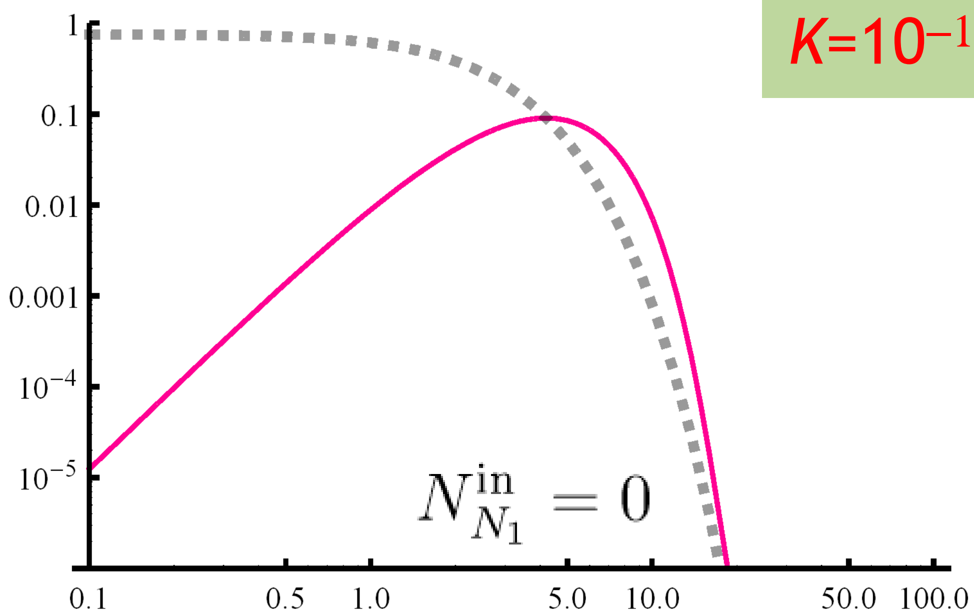
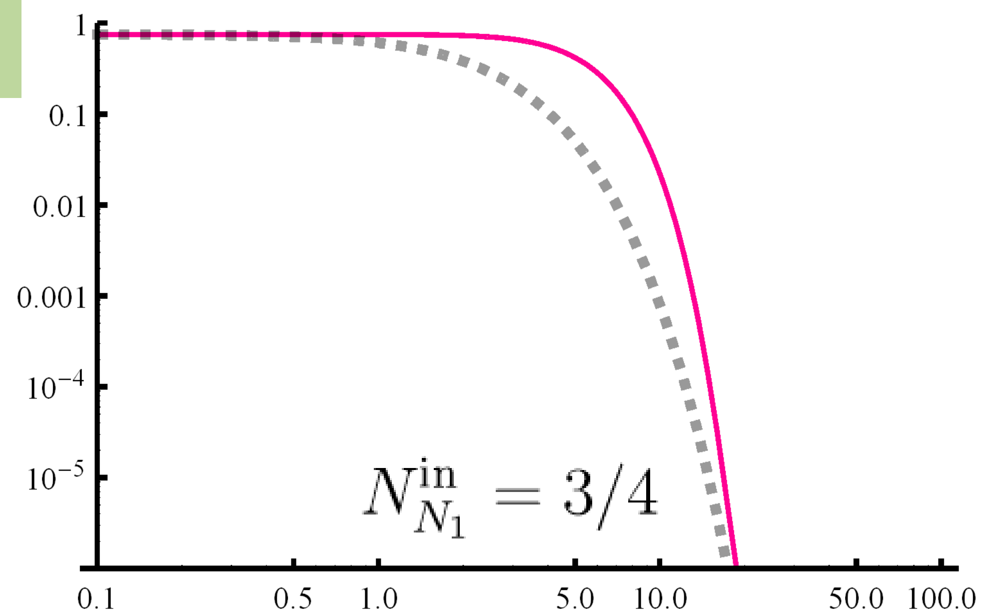
K=10^{-1}



vanishing initial abundance



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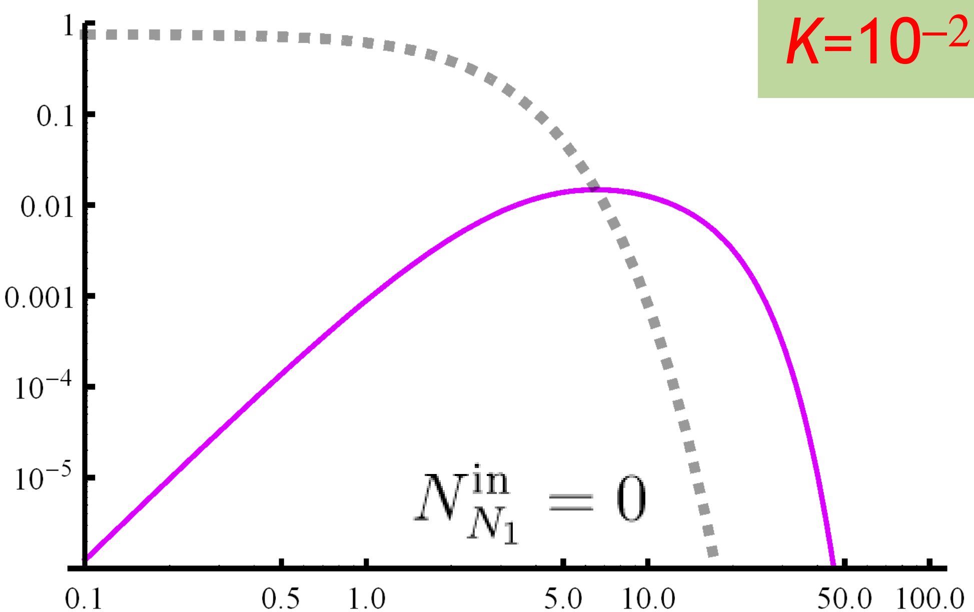
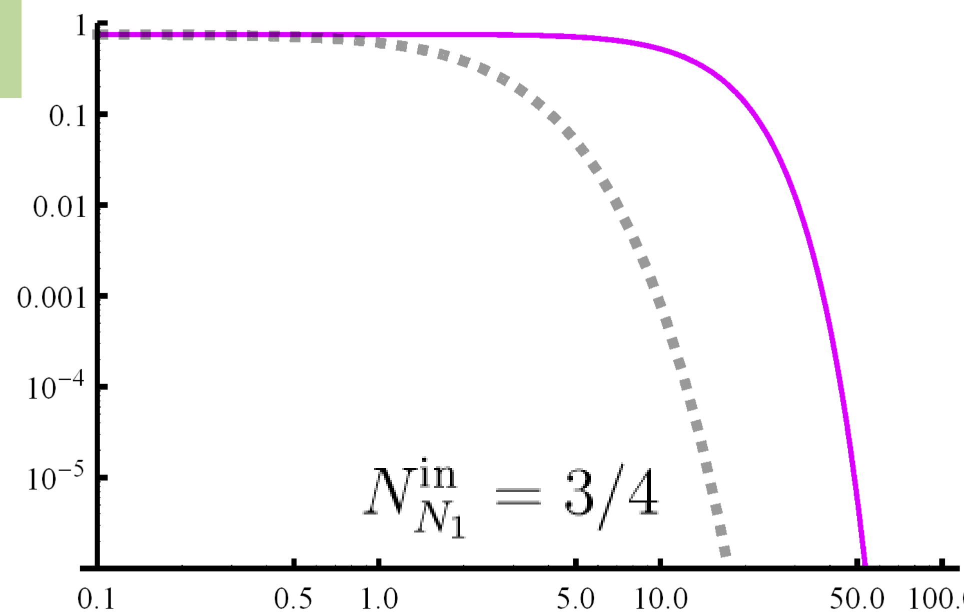
K=10^{-2}



vanishing initial abundance



thermal initial abundance

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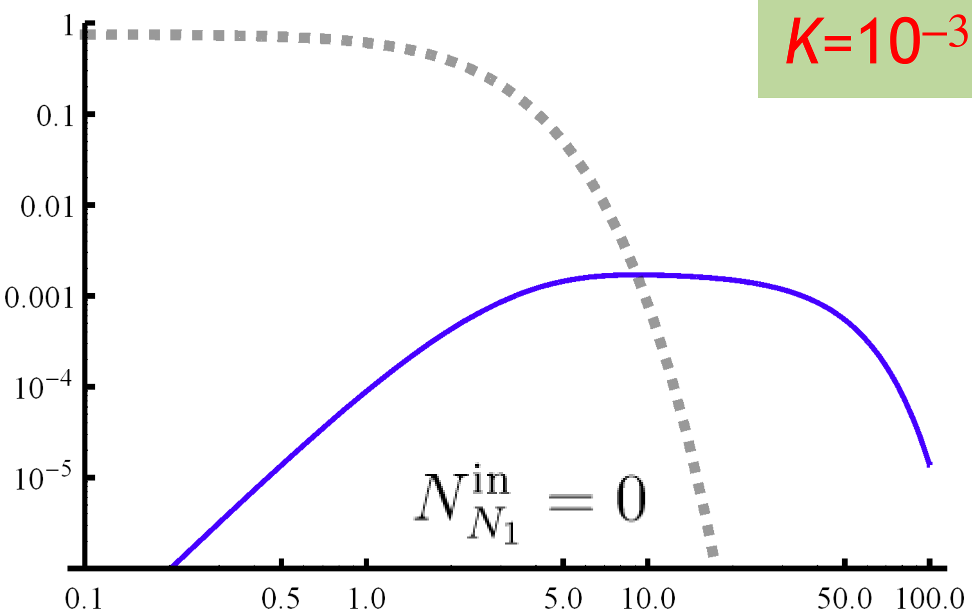
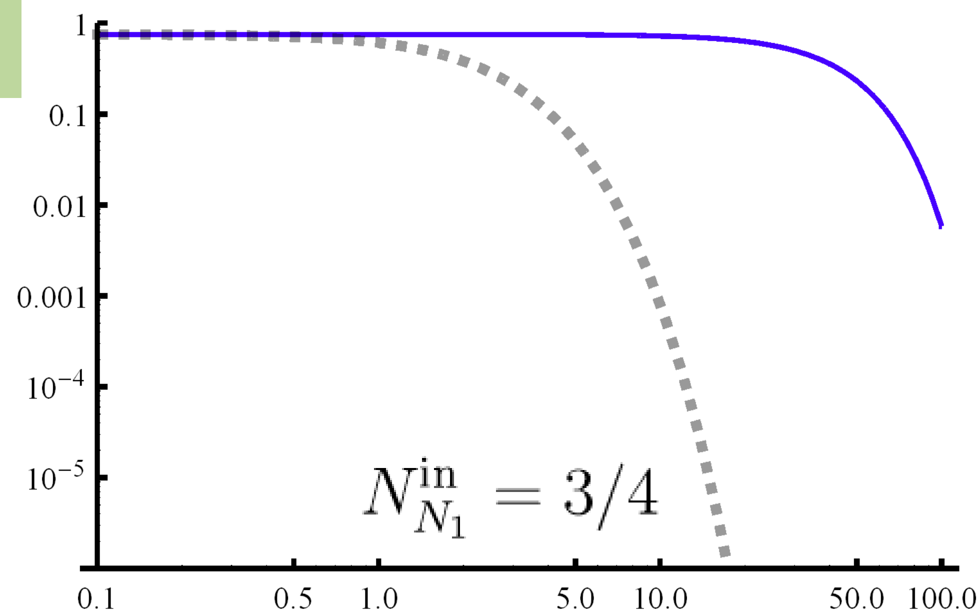
The solution depends on the initial condition and on K (or $\tilde{m}_1$)

K=10^{-3}



vanishing initial abundance



thermal initial abundance

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

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

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

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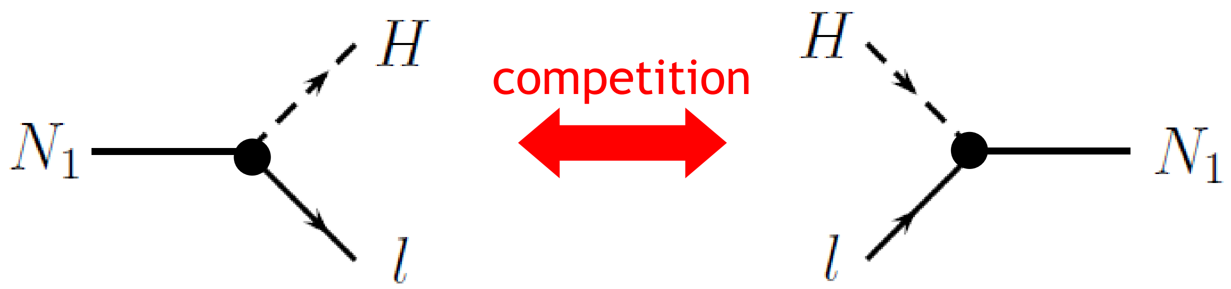

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$$\frac{dN_{B-L}}{dz} = -\epsilon_1 \, D \left(N_{N_1} - N_{N_1}^{\mathrm{eq}}\right) - W_{ID} N_{B-L}$$

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

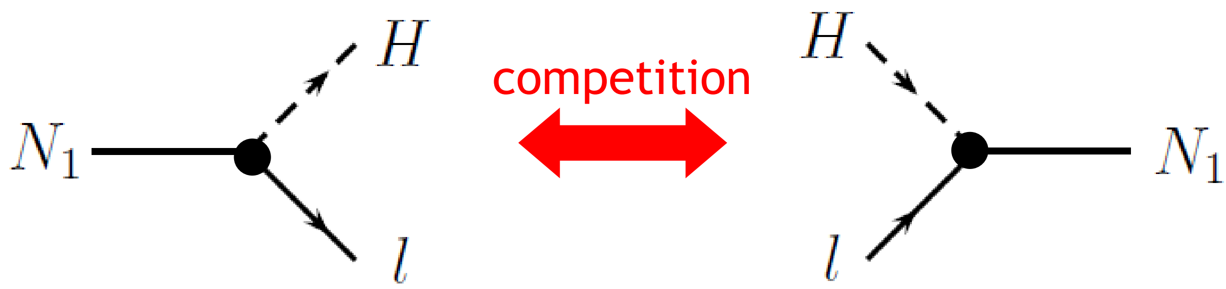
Remember: leptogenesis is a competition between decays (which generate an asymmetry) and inverse decays (which erase the asymmetry)

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

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

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

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



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

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

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

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

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

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

Then,

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

Set of Boltzmann equations

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

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

Set of Boltzmann equations

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

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

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

The solution depends on:

- Initial abundance of right-handed neutrinos

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

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

- CP asymmetry, ϵ

Set of Boltzmann equations

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

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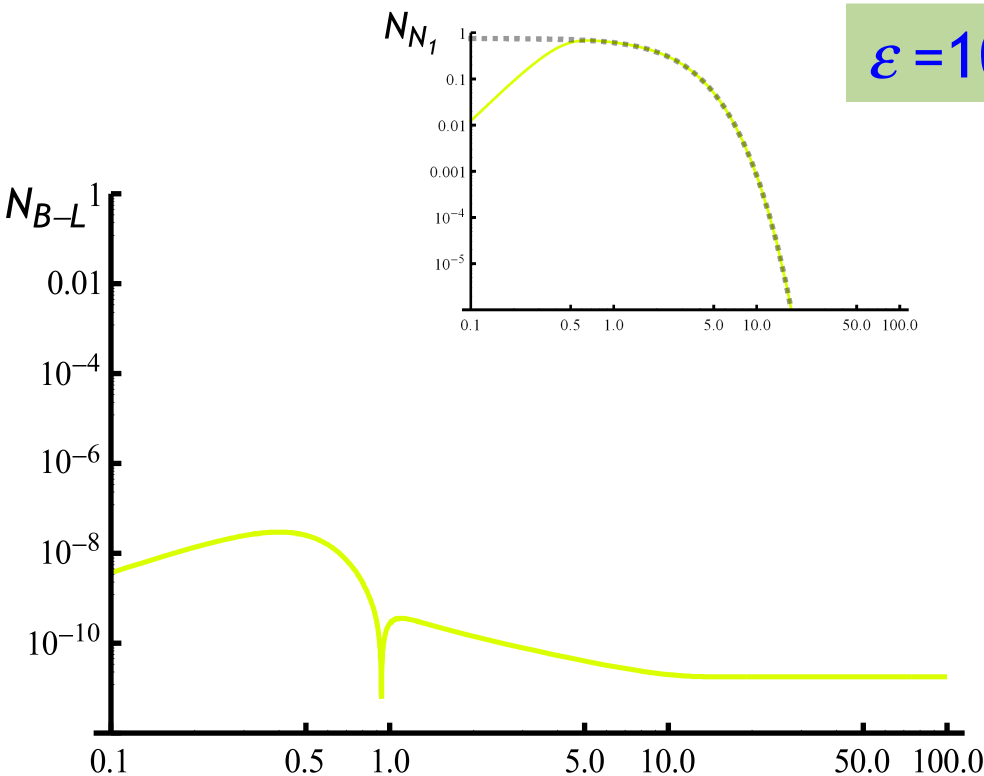
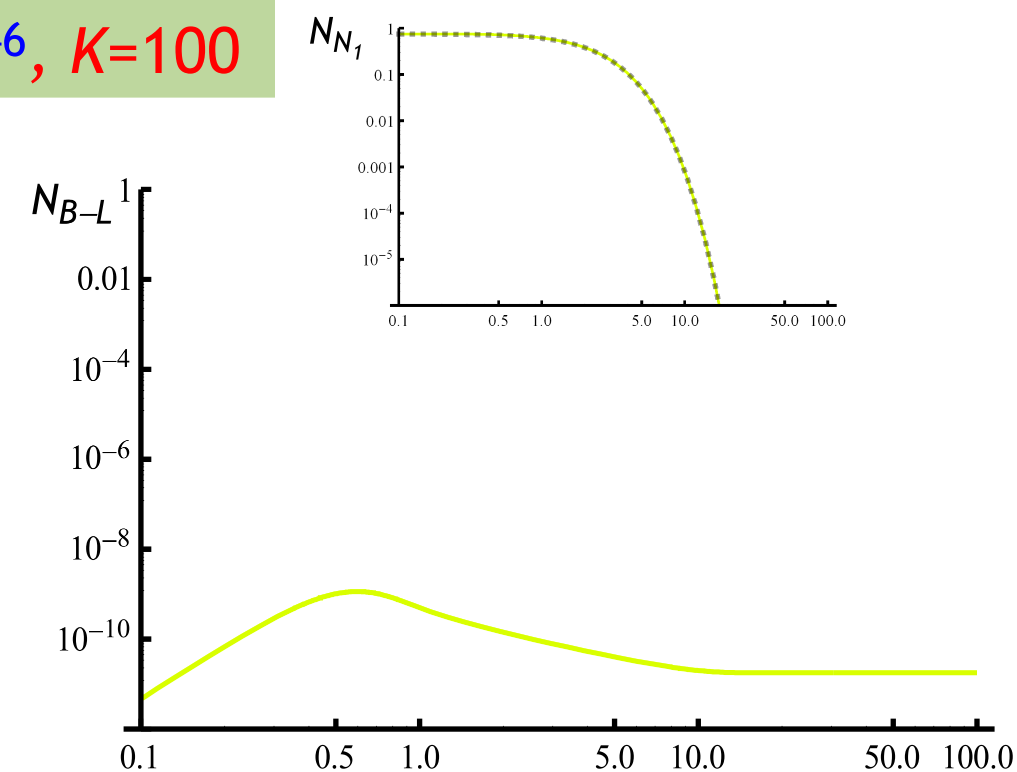
$\varepsilon = 10^{-6}$, K=100



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

vanishing initial abundance



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

thermal initial abundance

Set of Boltzmann equations

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

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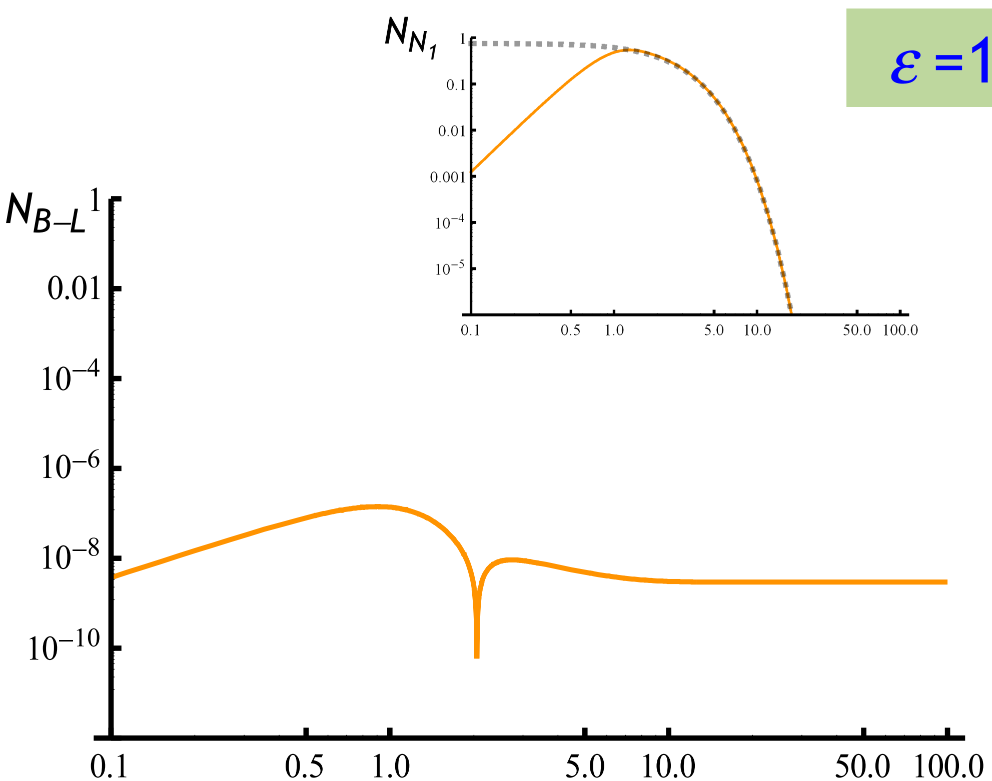
$\varepsilon = 10^{-6}$, $K = 10$



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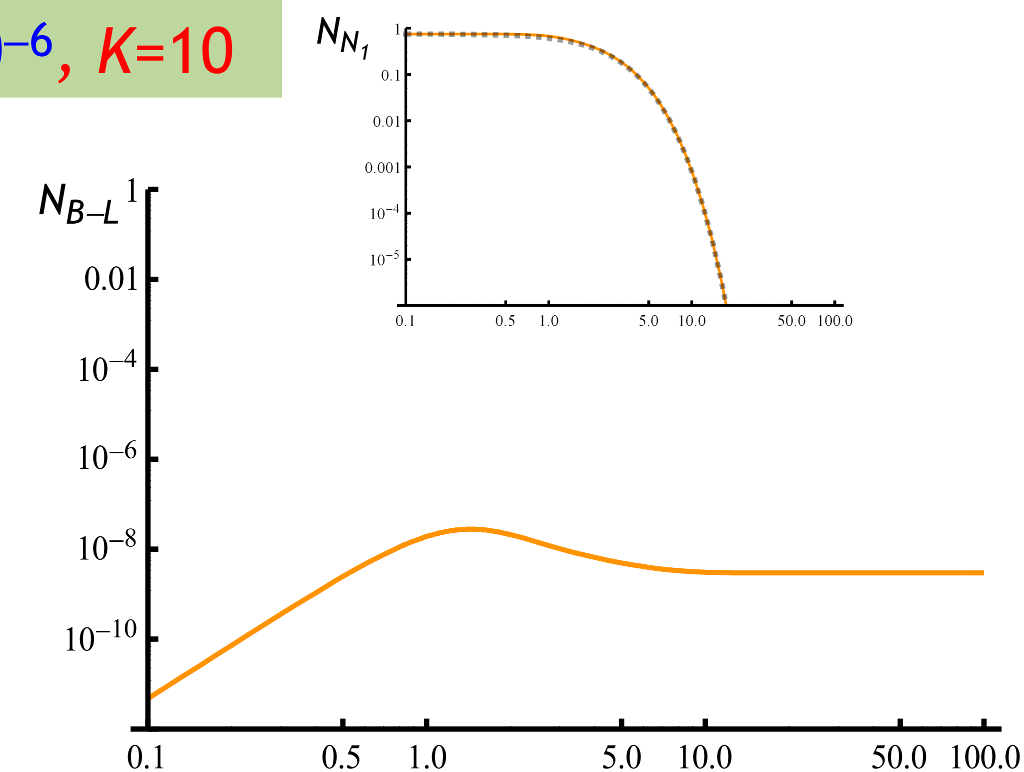

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thermal initial abundance

Set of Boltzmann equations

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

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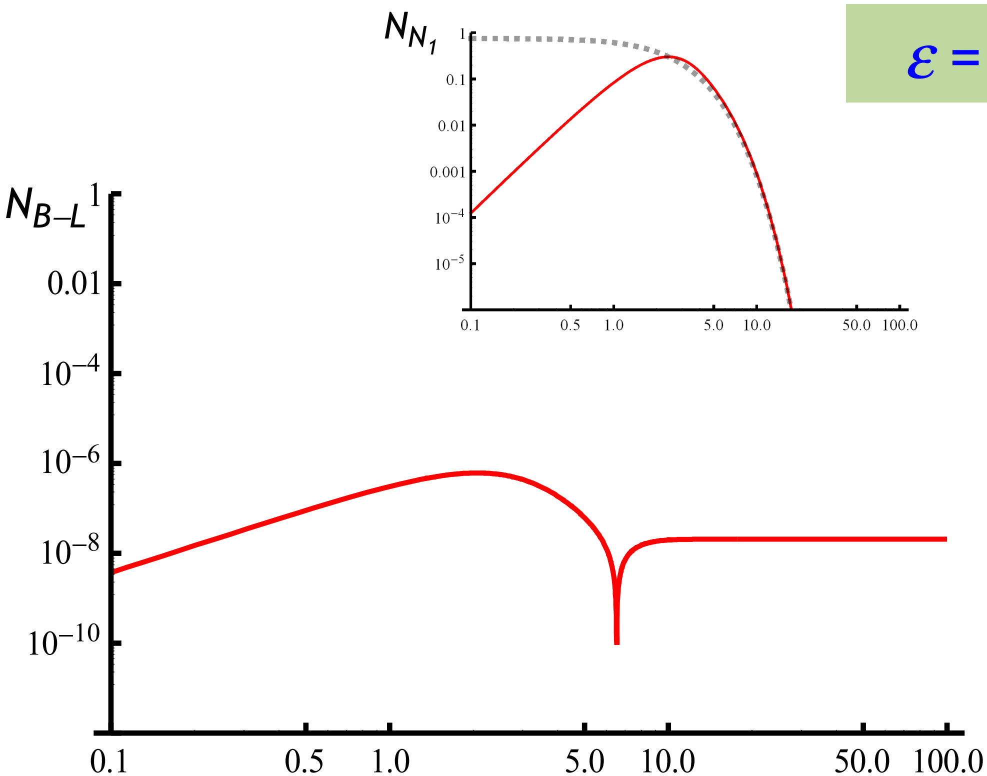
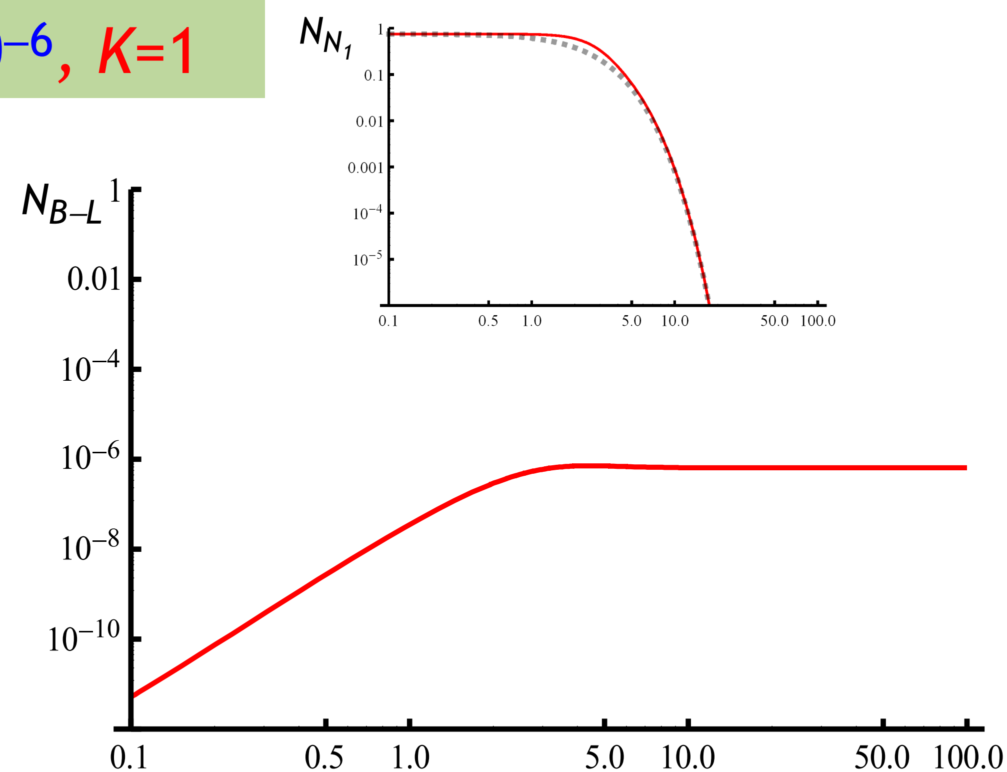


$N_{N_1}^{\rm in} = 0$

vanishing initial abundance



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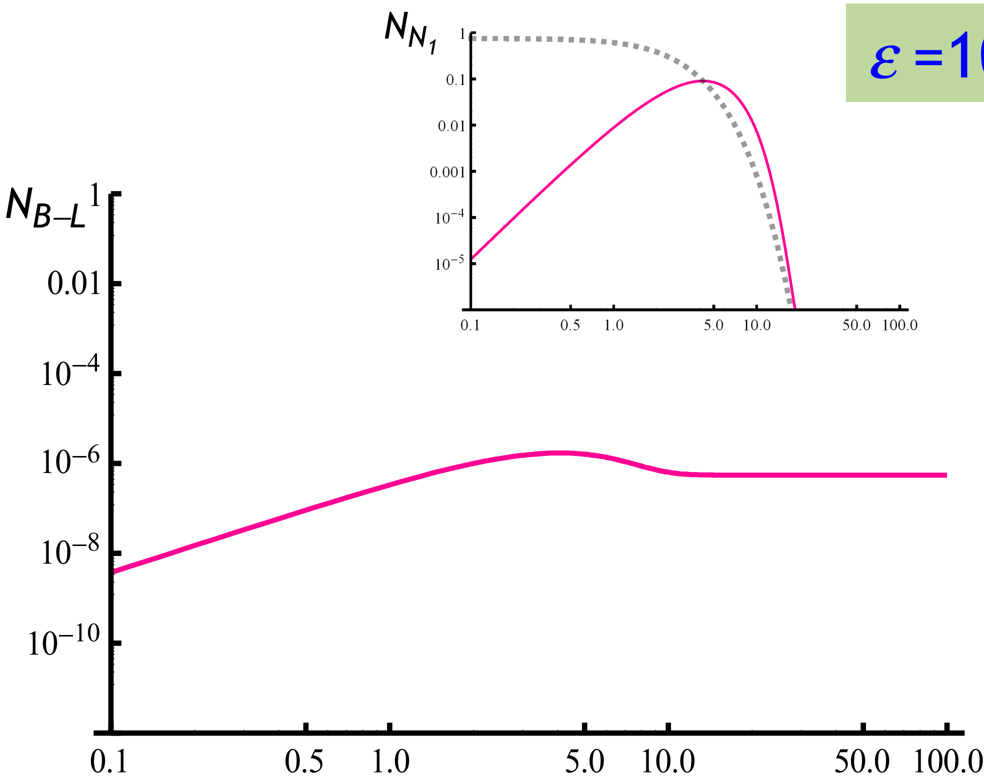
$\varepsilon = 10^{-6}$, $K = 10^{-1}$



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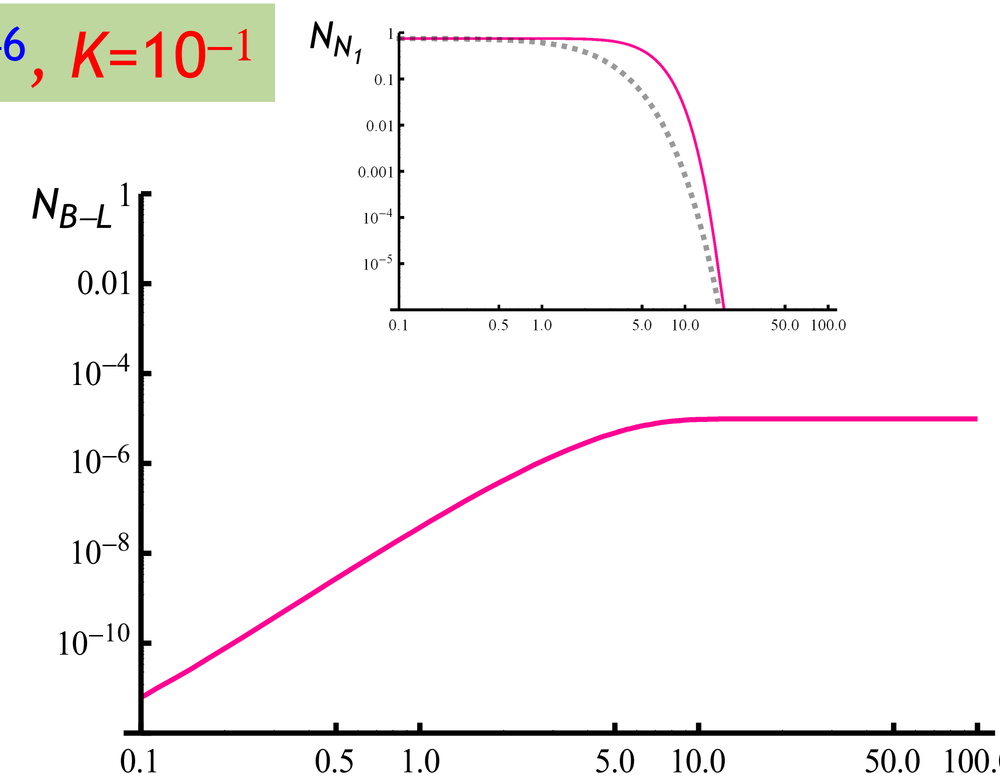

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thermal initial abundance

Set of Boltzmann equations

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

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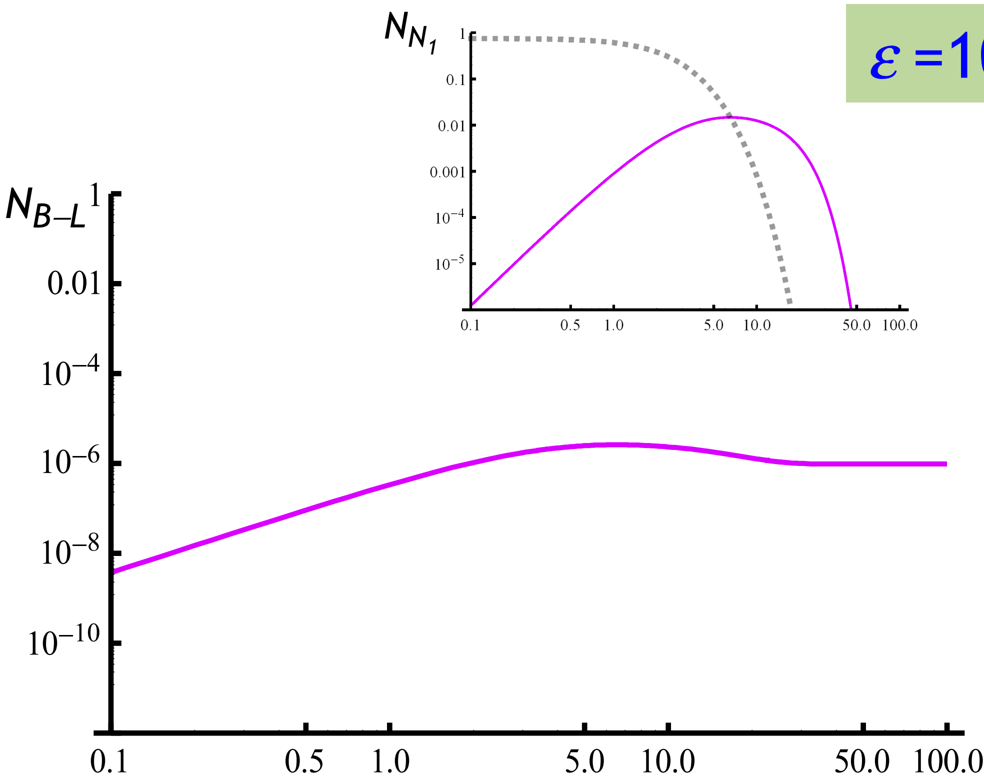
$\varepsilon = 10^{-6}$, $K = 10^{-2}$



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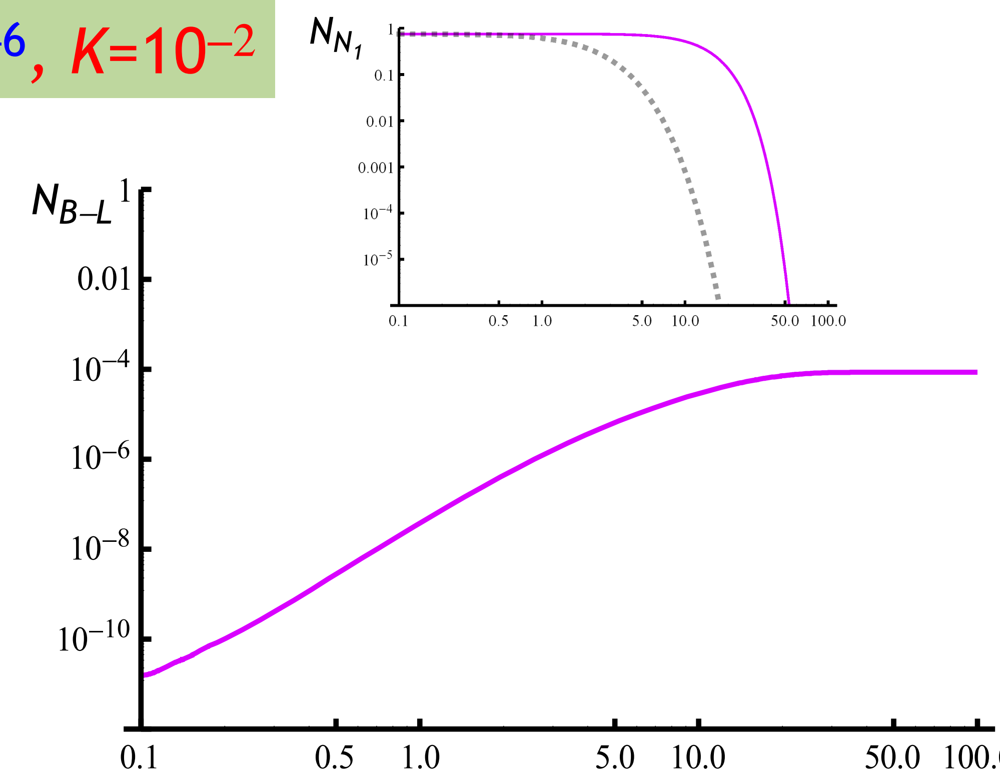

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thermal initial abundance

Set of Boltzmann equations

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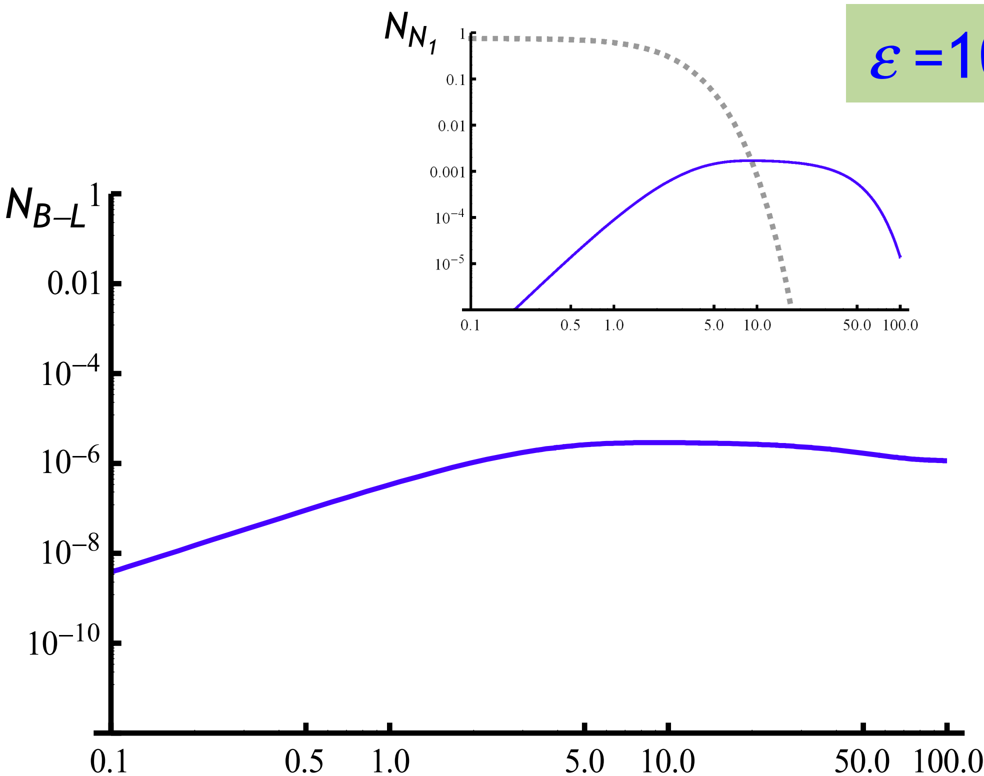

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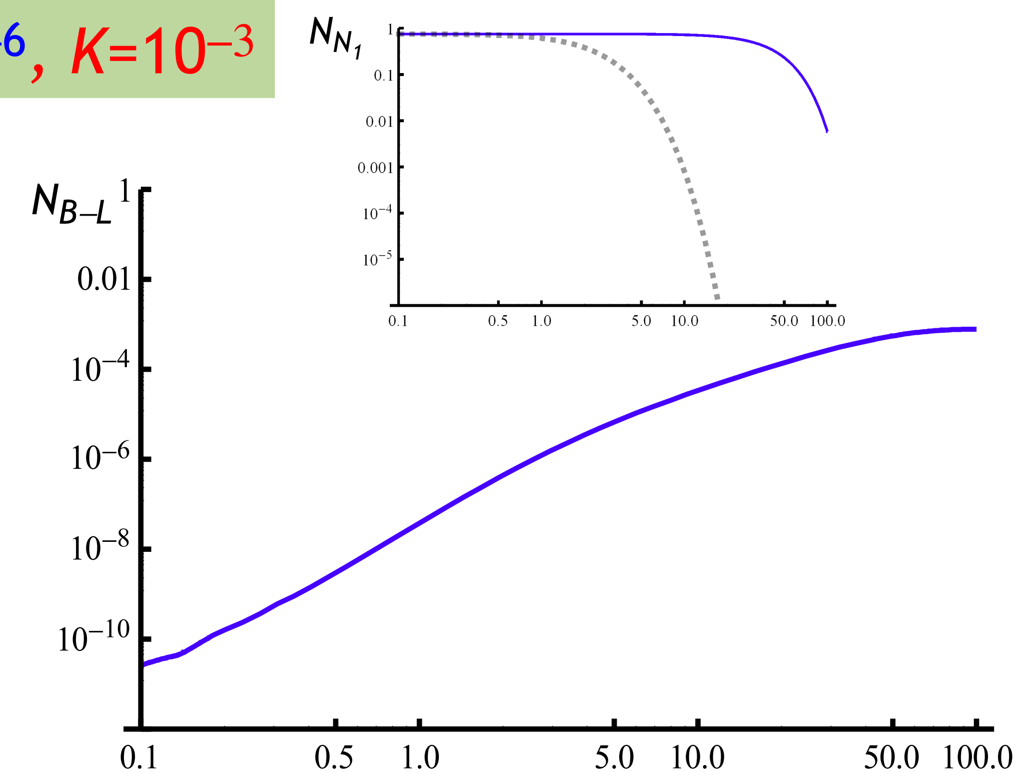

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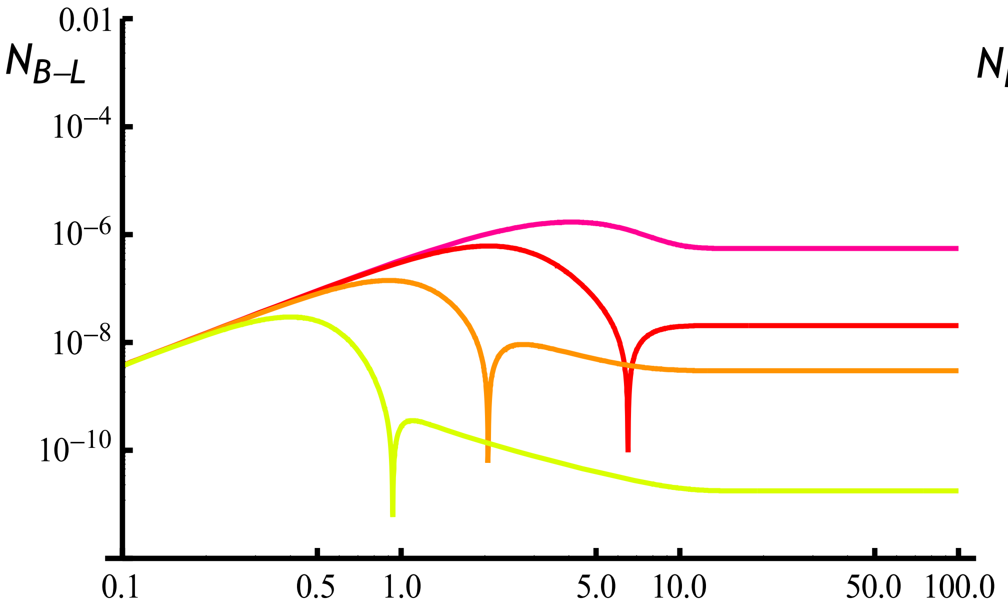
thermal initial abundance

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



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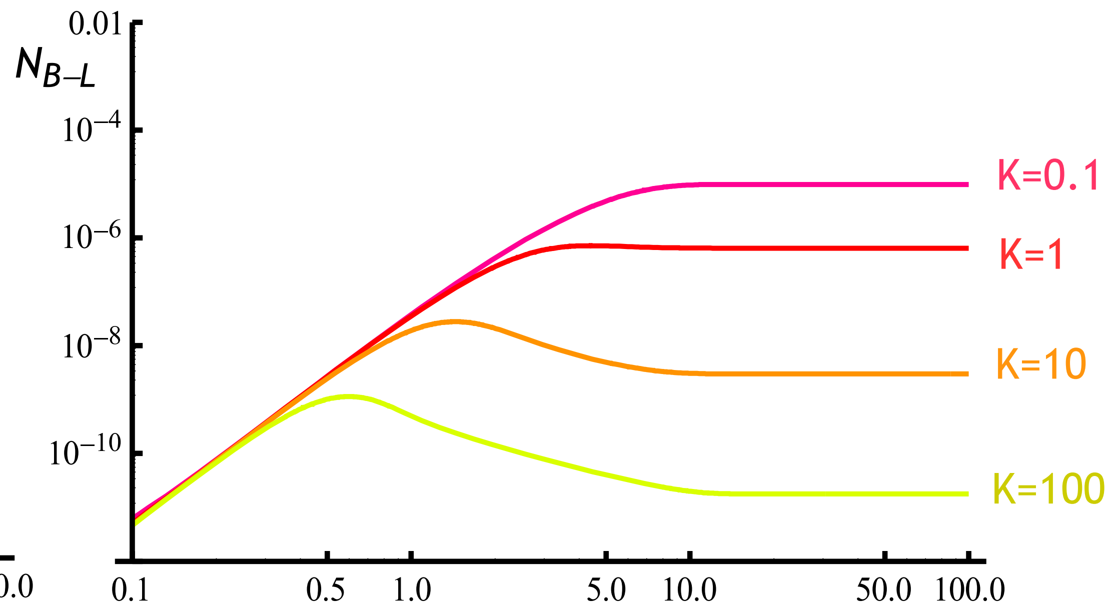

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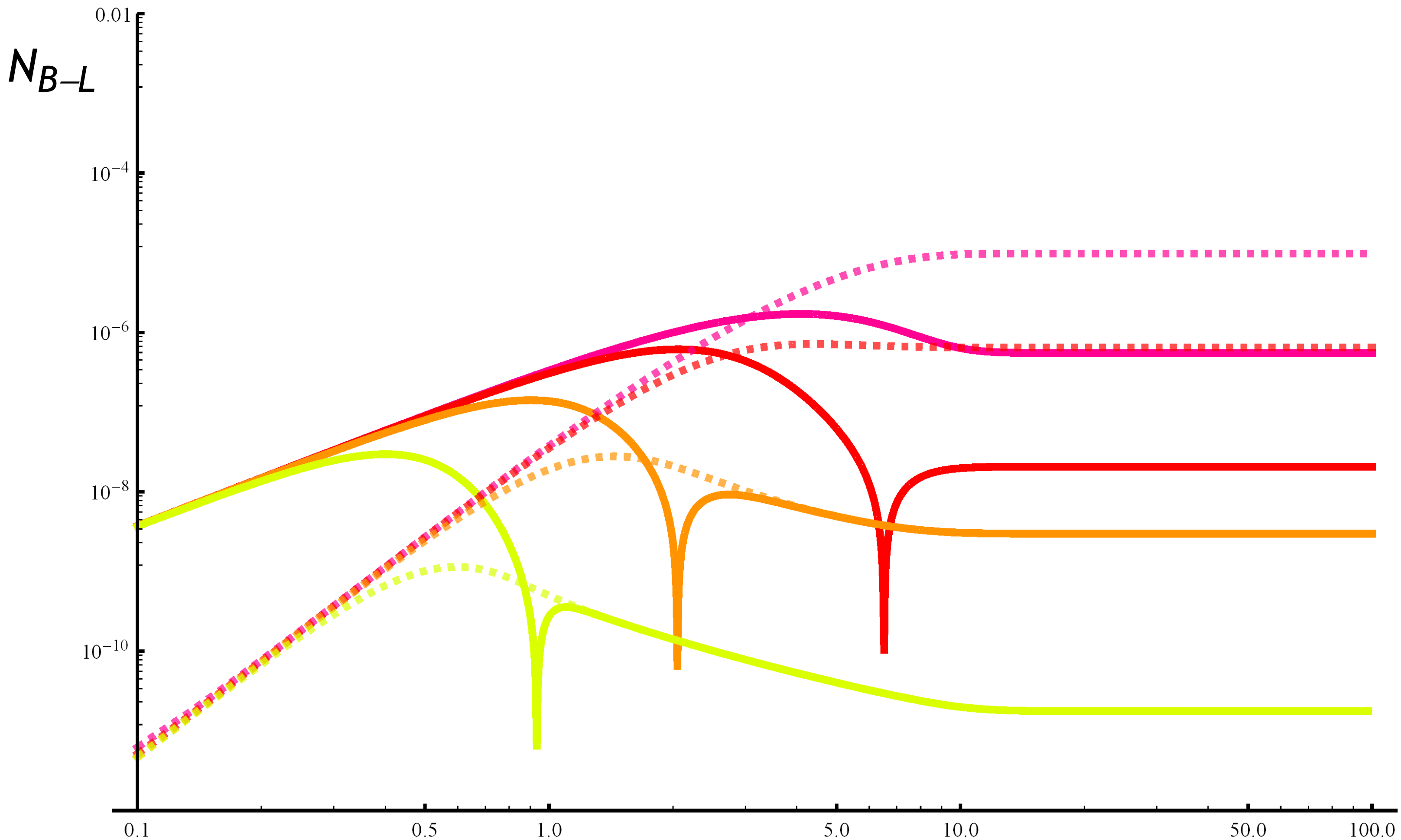
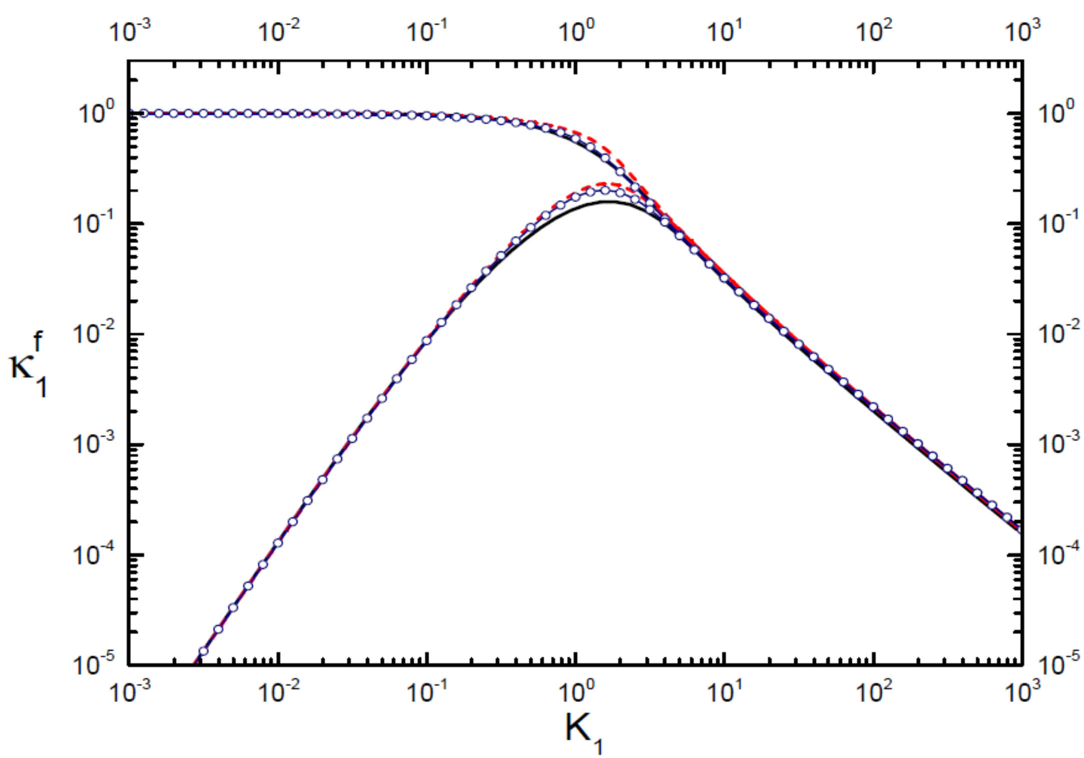


The solution is usually expressed in terms of an "efficiency factor" (assuming that initially there is no B-L asymmetry)

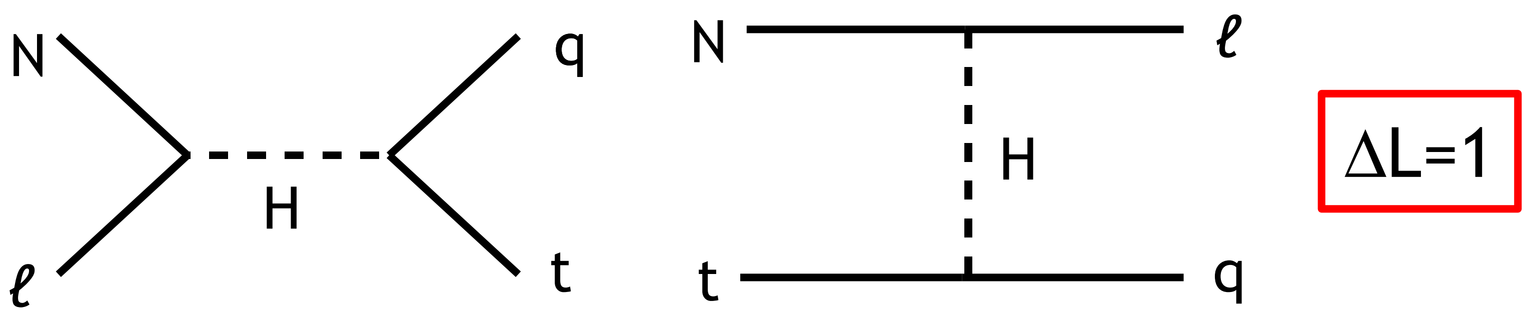
$$N_{B-L}(z) = -\frac{3}{4}\epsilon_1\, \kappa(z_i, z, \widetilde{m}_1)$$

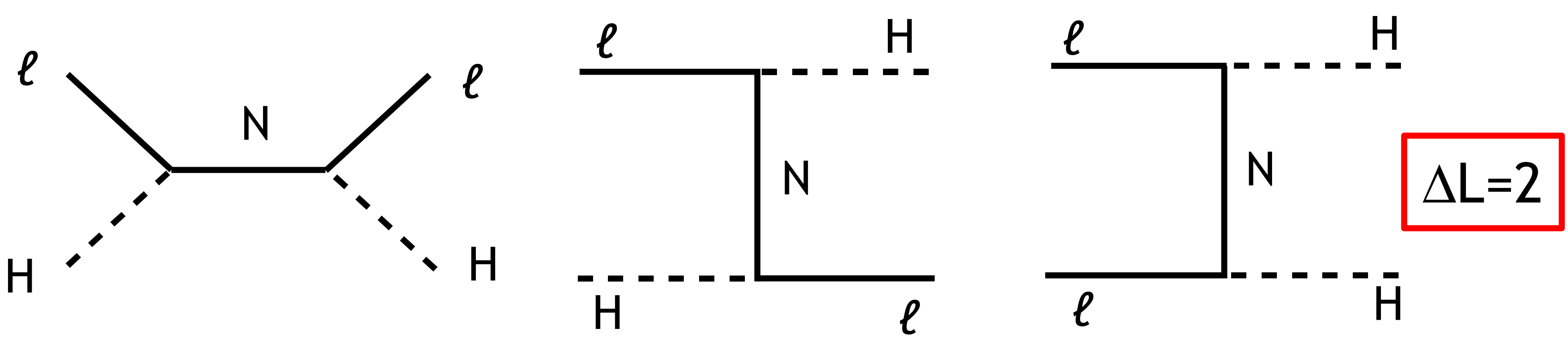
$$\kappa(z_i, z, \widetilde{m}_1) = \frac{4}{3}\int_{z_i}^{z} dz'\, D\,(N_{N_1} - N_{N_1}^{\rm eq})\, e^{-\int_{z'}^{z} dz'' W_{ID}(z'')}$$



An additional effect on leptogenesis: scatterings

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



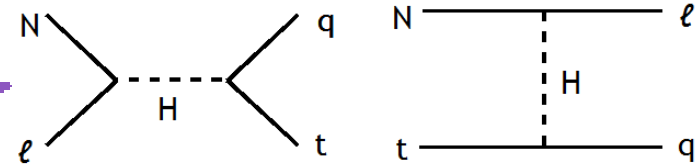


Including these effects, the Boltzmann equations read:

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

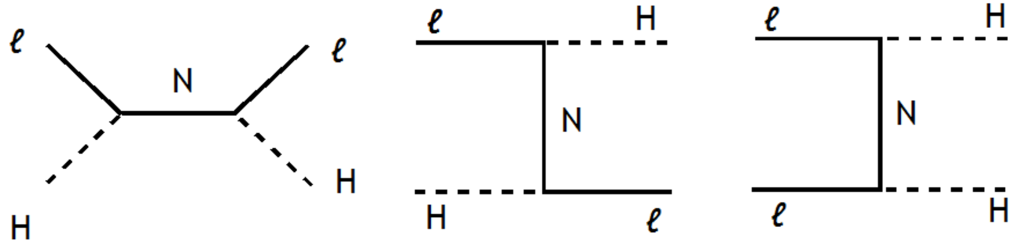
$$\frac{dN_{B-L}}{dz} = -\epsilon_1\,D\,(N_{N_1} - N_{N_1}^{\rm eq}) - (W_{ID} + W_{\Delta L=2})N_{B-L}$$

Including these effects, the Boltzmann equations read:



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

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



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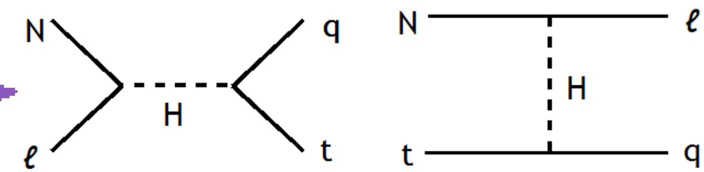

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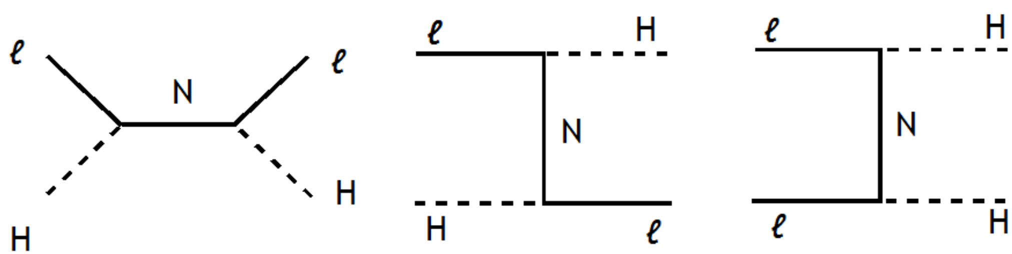


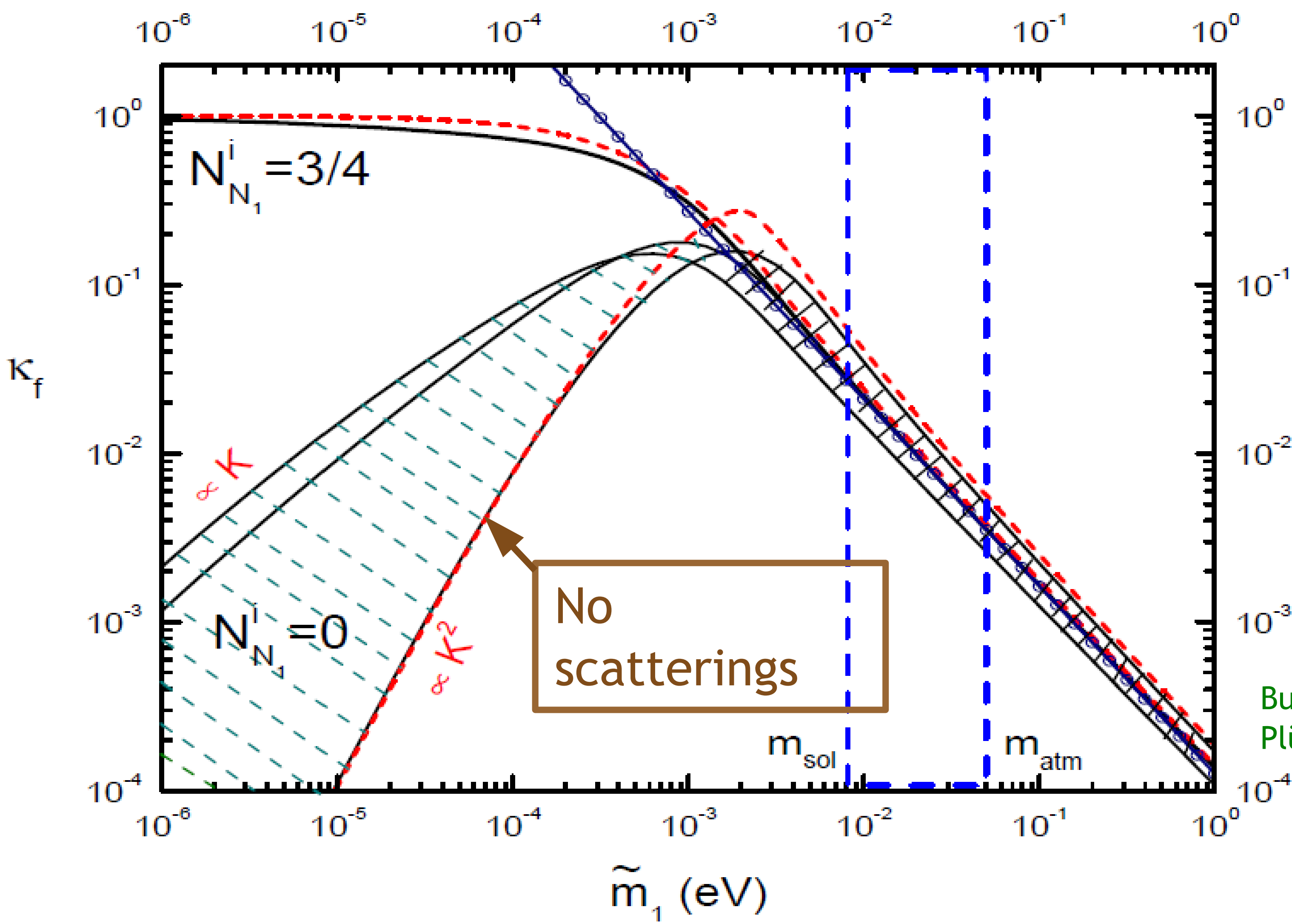
Similar diagrams to the one giving neutrino masses:

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

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

The solution can still be written in the form:

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

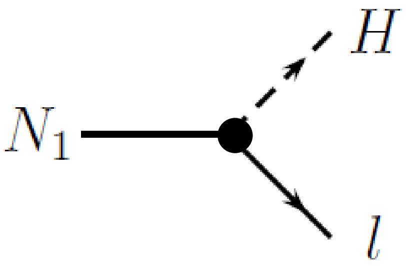


Buchmüller, Di Bari, Plümacher

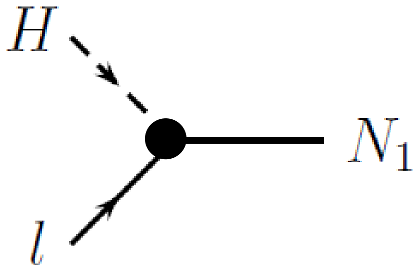
Recapitulation

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

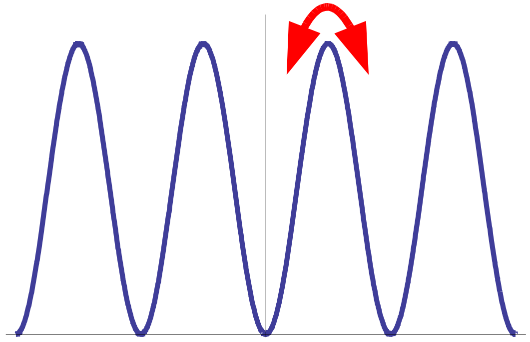
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.



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



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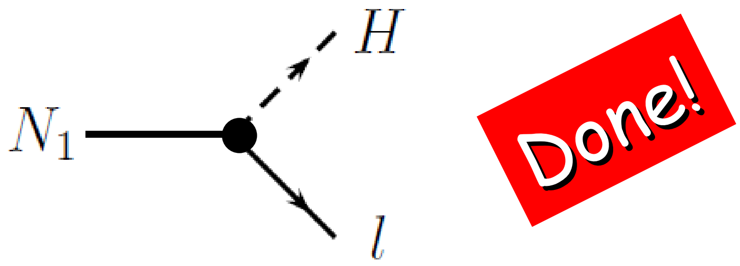
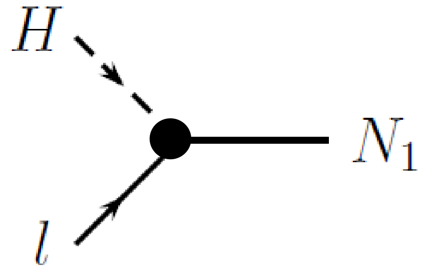
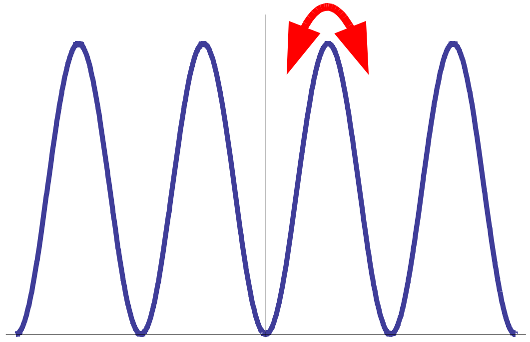


2- Washout of the lepton asymmetry.



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



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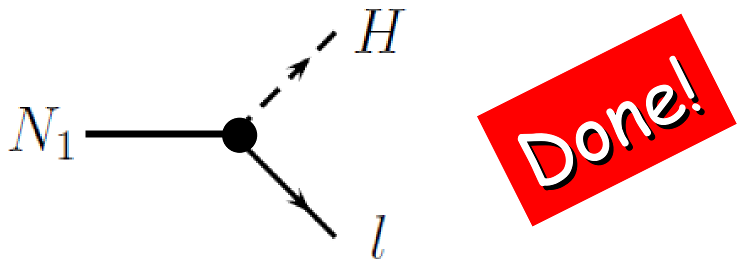

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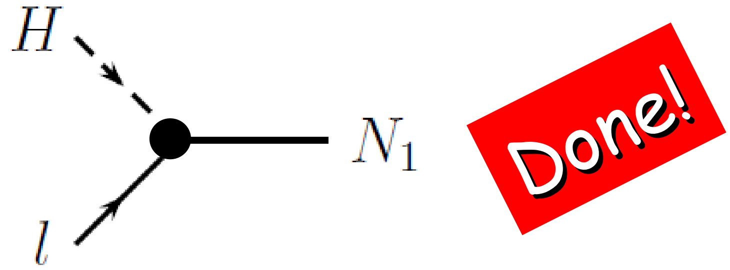

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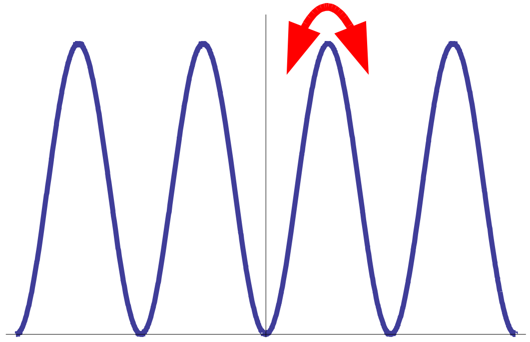

3- Conversion of the lepton asymmetry into a baryon asymmetry

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

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

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

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

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

In thermal equilibrium there are relations among the chemical potentials

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

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

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

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

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

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

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

$$\mu_{q_i} - \mu_H - \mu_{d_j} = 0 \,,$$
$$\mu_{q_i} + \mu_H - \mu_{u_j} = 0 \,,$$
$$\mu_{\ell_i} - \mu_H - \mu_{e_j} = 0 \,.$$

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

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

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

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

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

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

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

c=28/79 in the SM with three generations

Recipe to calculate the BAU in leptogenesis

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$$\frac{dN_{B-L}}{dz} = -\epsilon \;\; D\,(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W_{ID} N_{B-L}$$

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

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$f = N_\gamma^{\mathrm{rec}}/N_\gamma^* = 2387/86$ — Dilution factor due to photon production between leptogenesis and recombination

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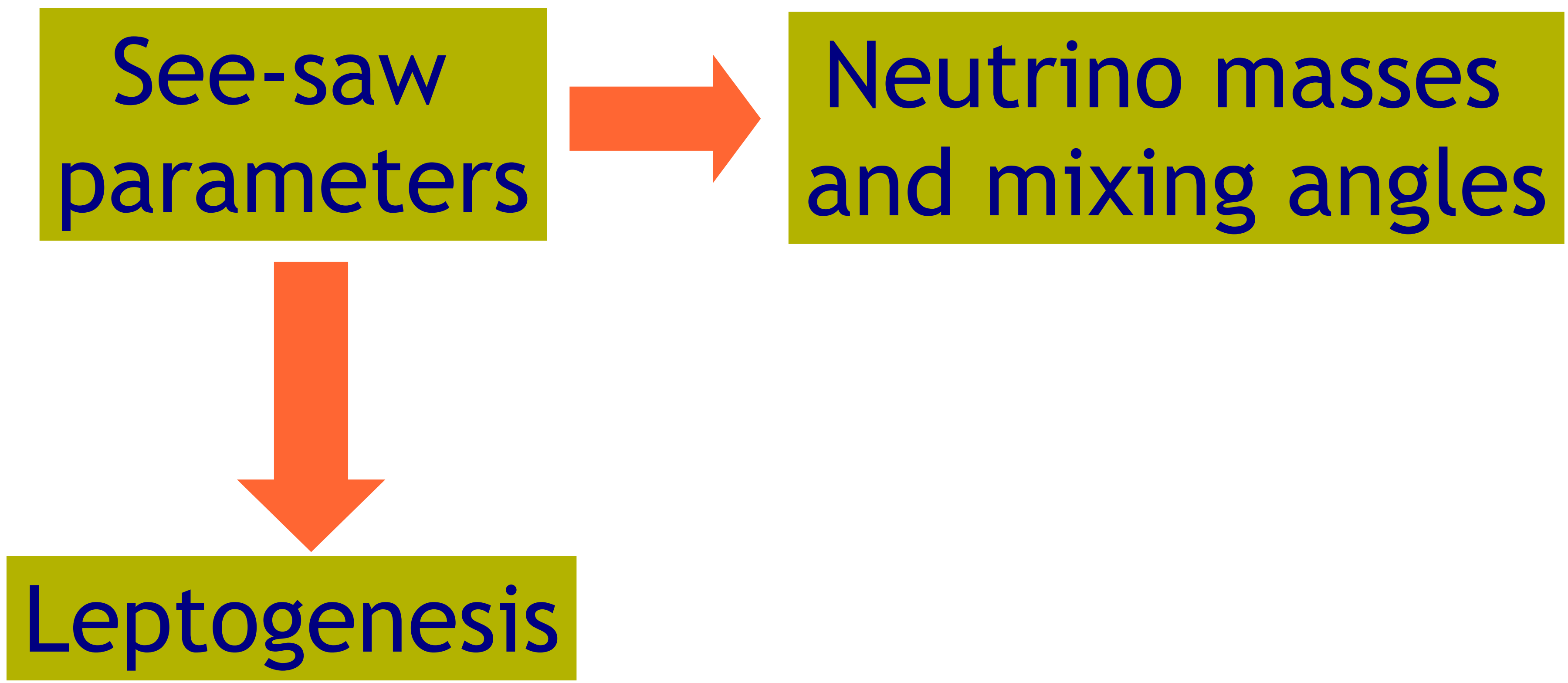
5-Compare with the experimental value! $\eta_B = (6.11 \pm 0.19)\times 10^{-10}$

Tomorrow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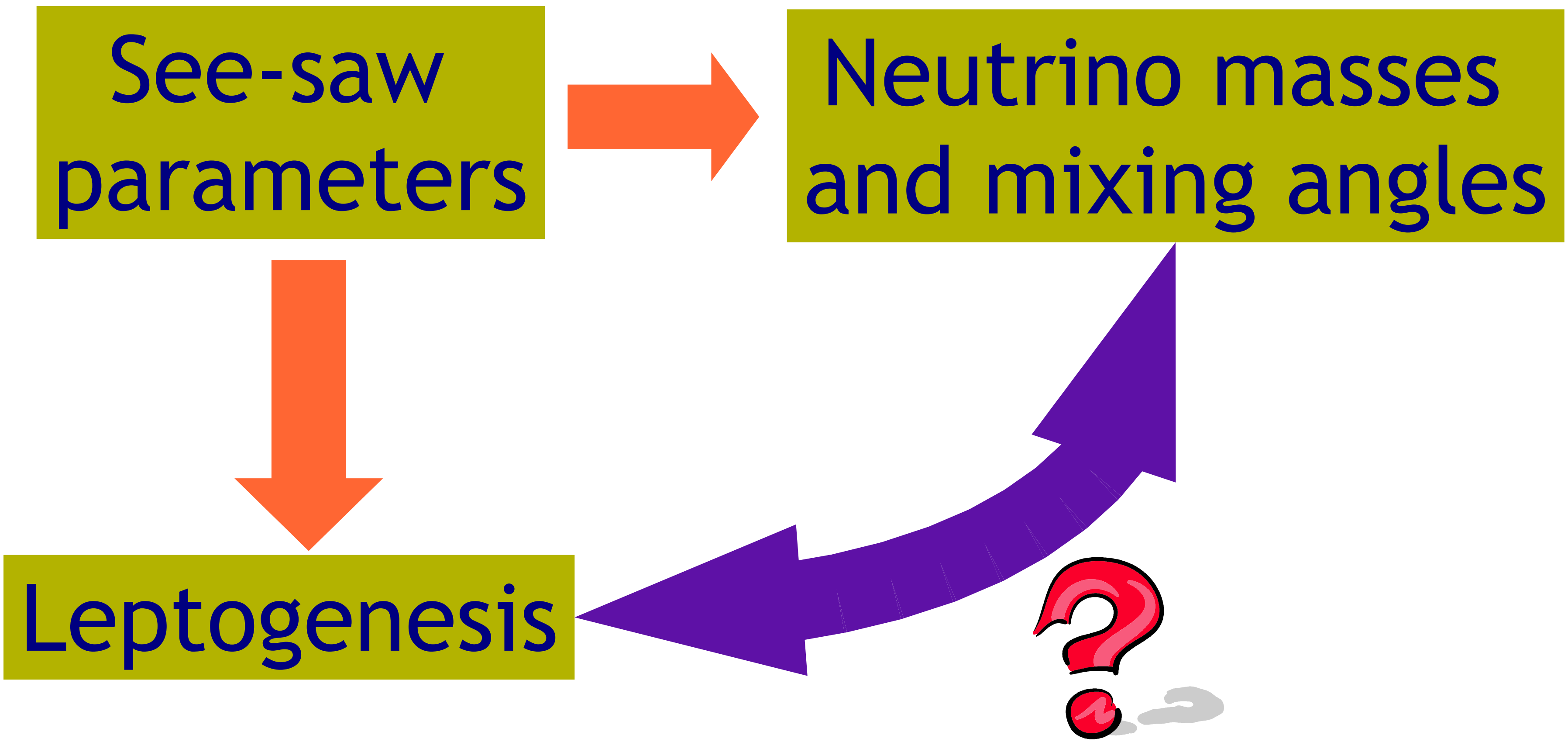
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