Leptogenesis

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Technische Universität München

Sangam@HRI
25-30 March 2013

What is leptogenesis?

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

[*] This is the original leptogenesis mechanism. Many variants exist, though.

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Outline:

- Evidence for a matter-antimatter asymmetry.

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- Dynamical generation of a matter-antimatter asymmetry: Sakharov conditions.
- Neutrino masses and its origin.
- Leptogenesis in three steps.

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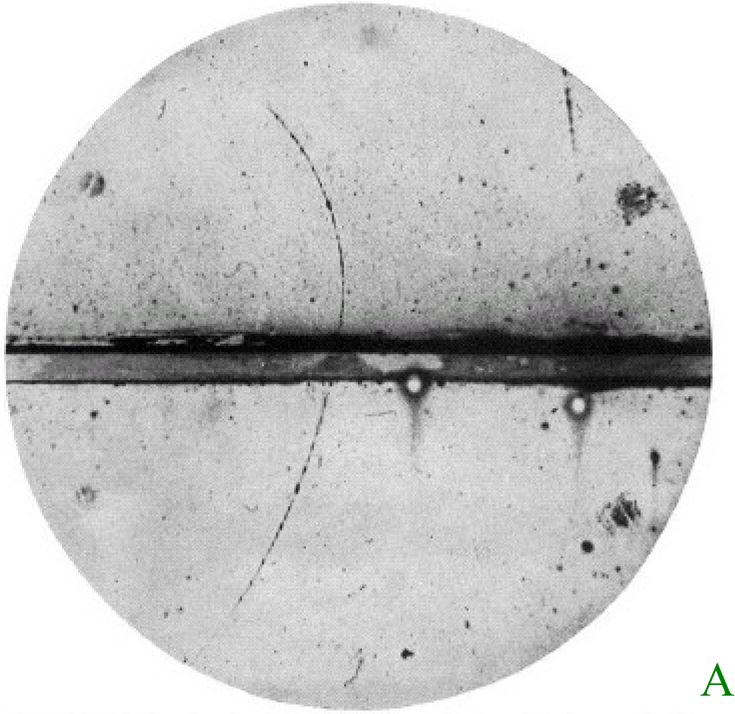
Evidence for a baryon asymmetry

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

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

It is produced in cosmic rays.



Anderson 1932

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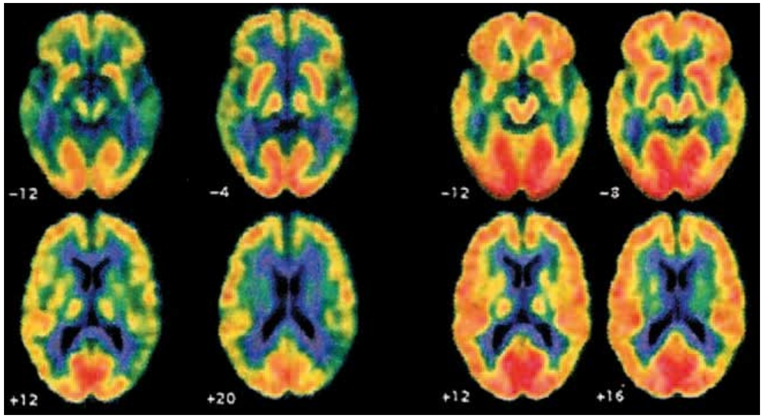

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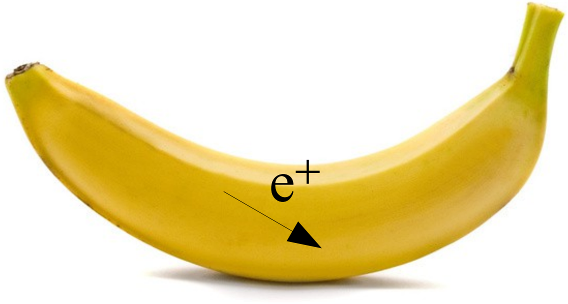
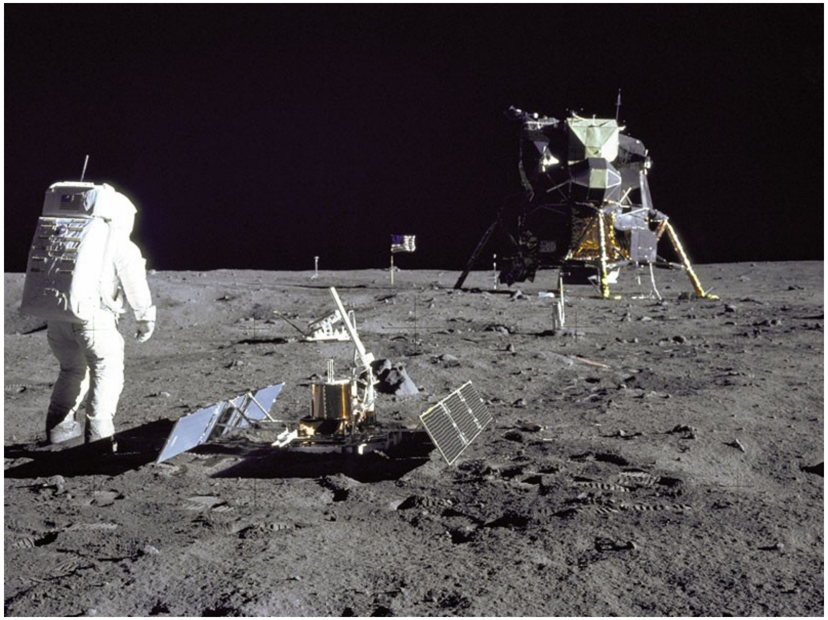
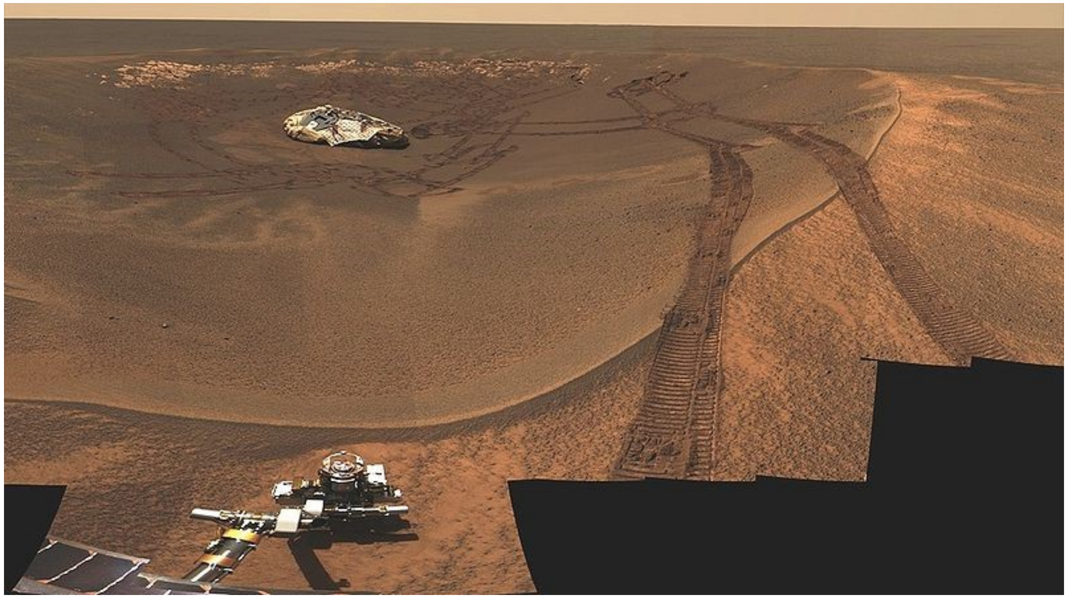


One positron every 75 minutes

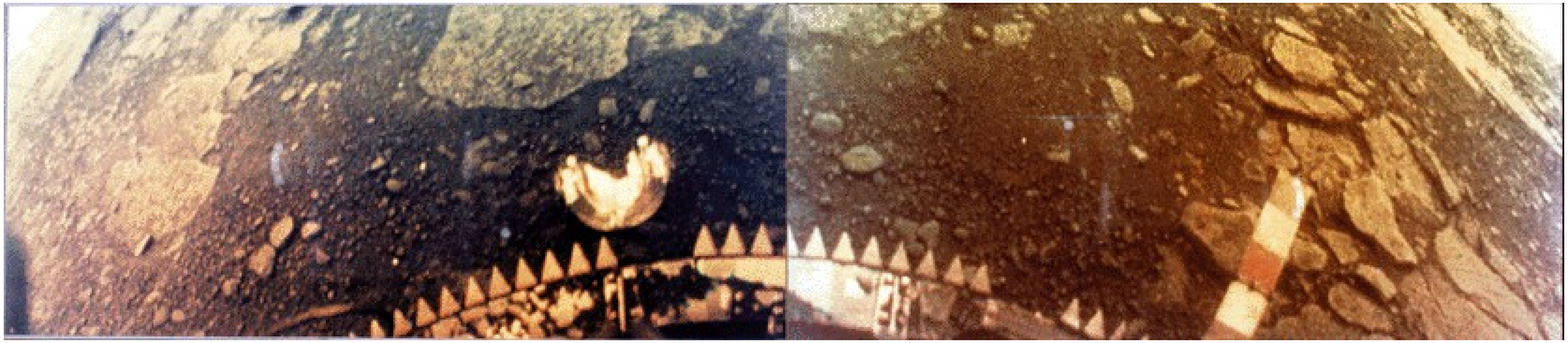
The bodies of the solar system are also composed almost entirely by matter and not by antimatter



Apollo 11

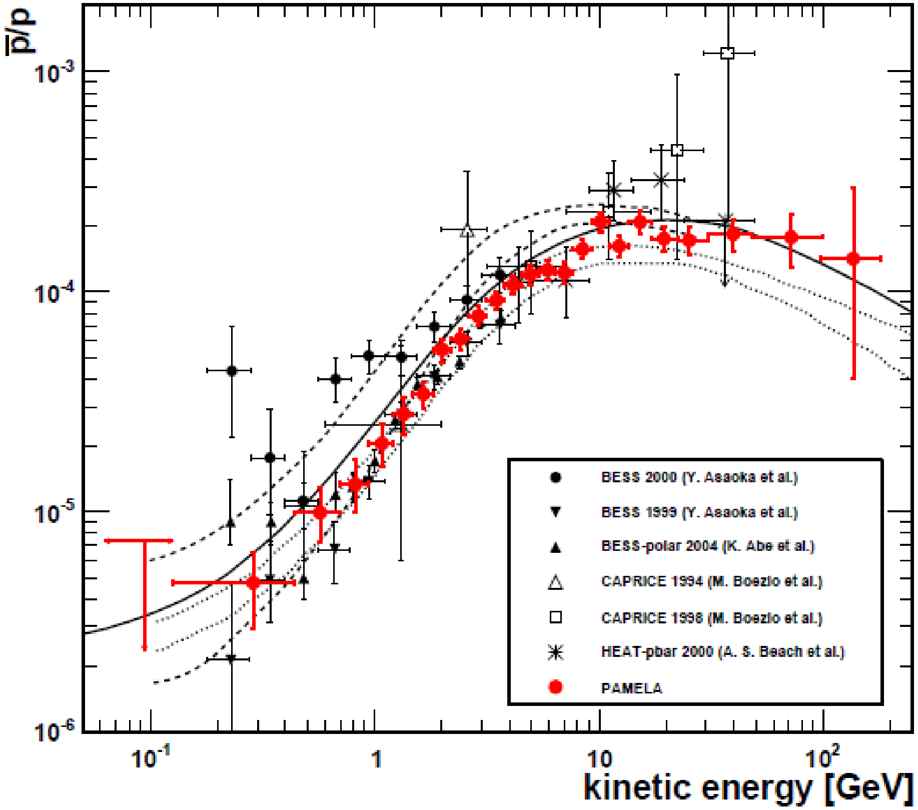


Mars Exploration Rover



Venera 13

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



Antiproton-to-proton ratio

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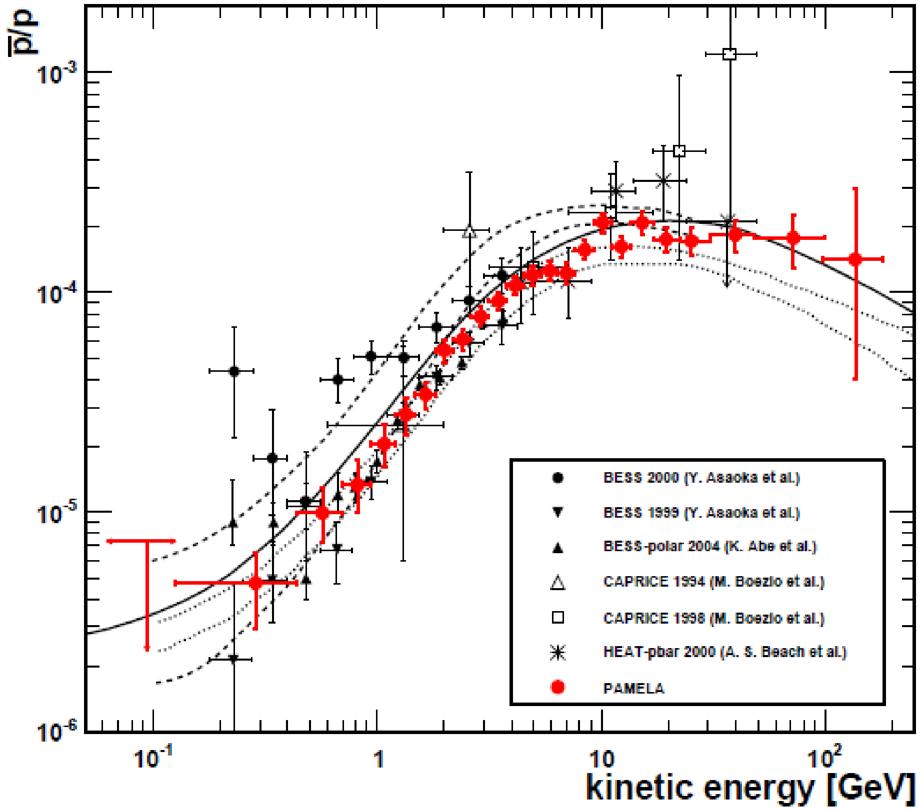
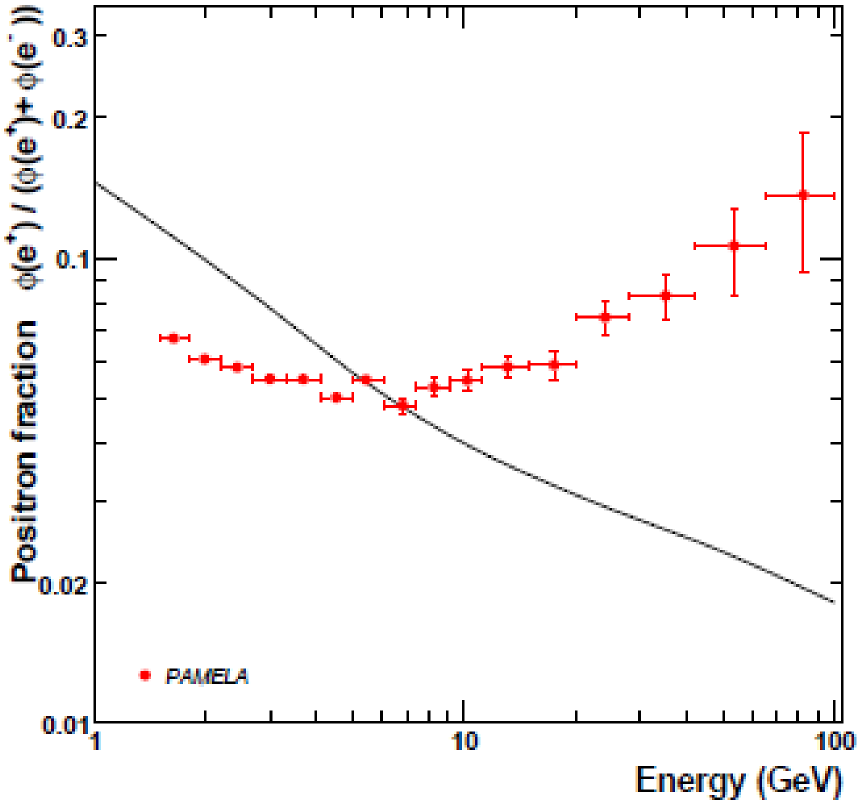


Antiproton-to-proton ratio

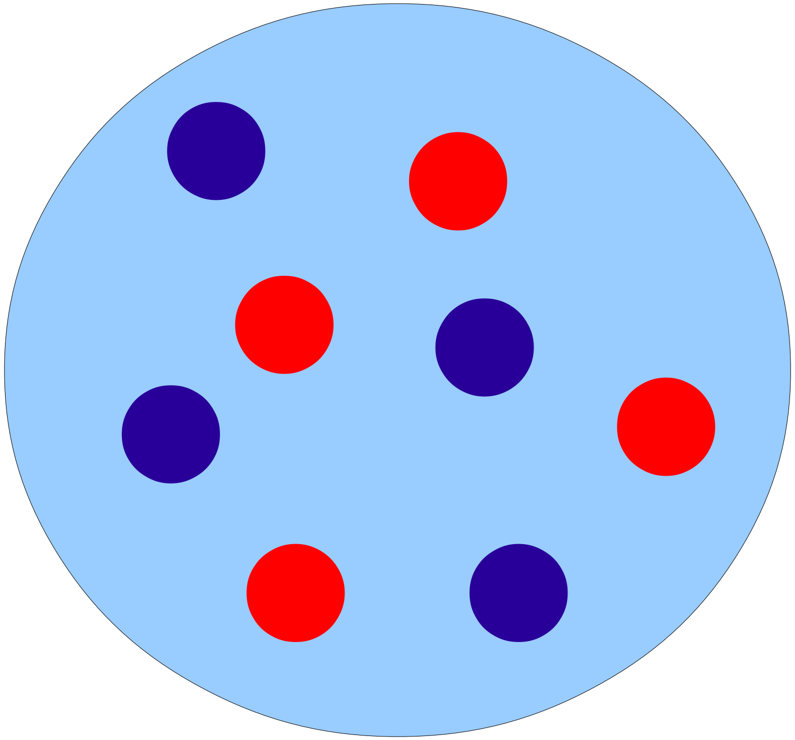


Positron fraction

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

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

Could the Universe be baryon symmetric?



NO!!

The nucleon-antinucleon annihilation cross section is rather large

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

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

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

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

Too small!

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

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

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

How many baryons?

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

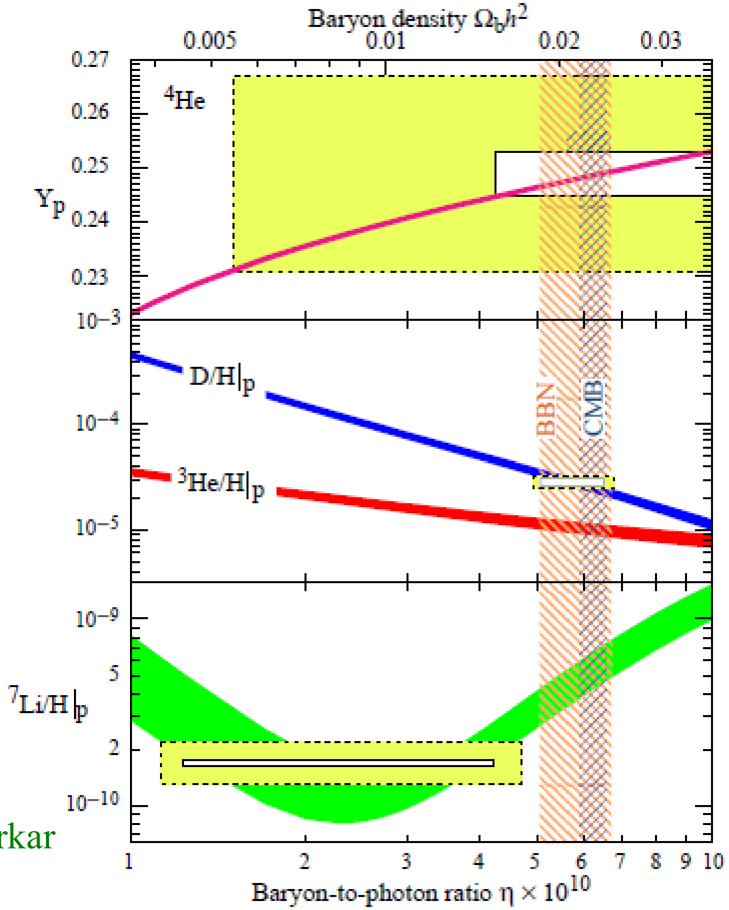
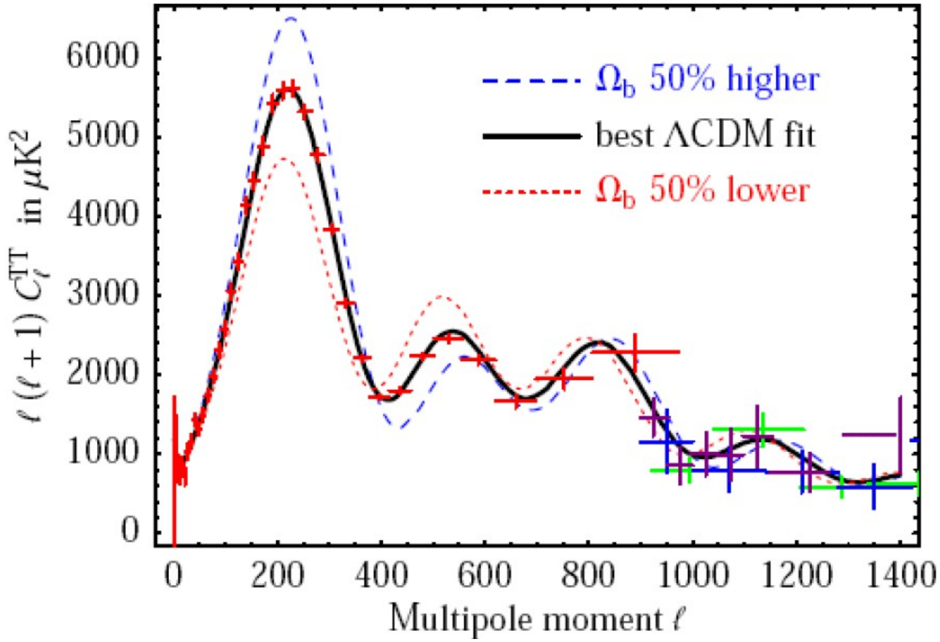


Fig. from Fields, Sarkar

Fig. from Strumia



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

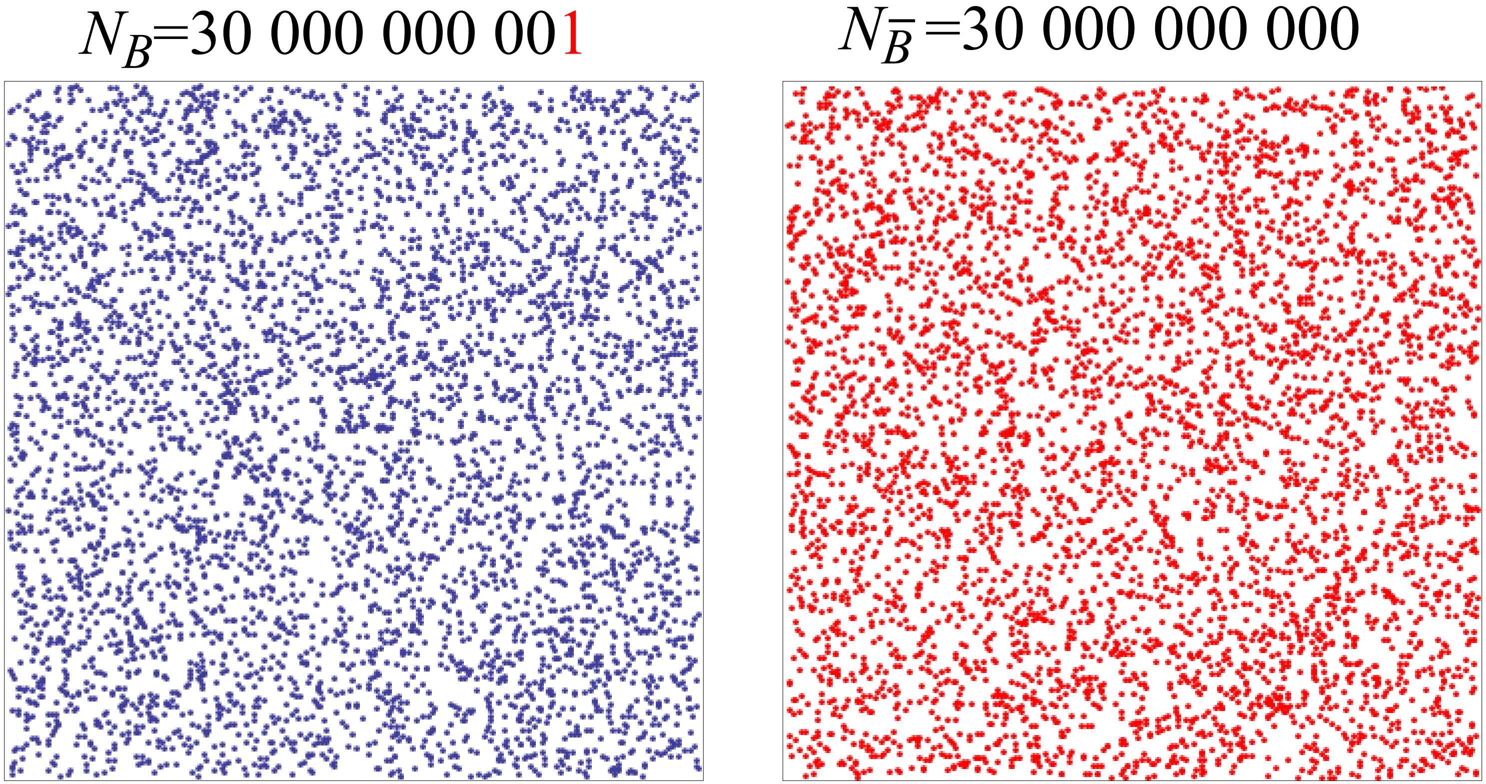
Baryon asymmetry

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!!

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

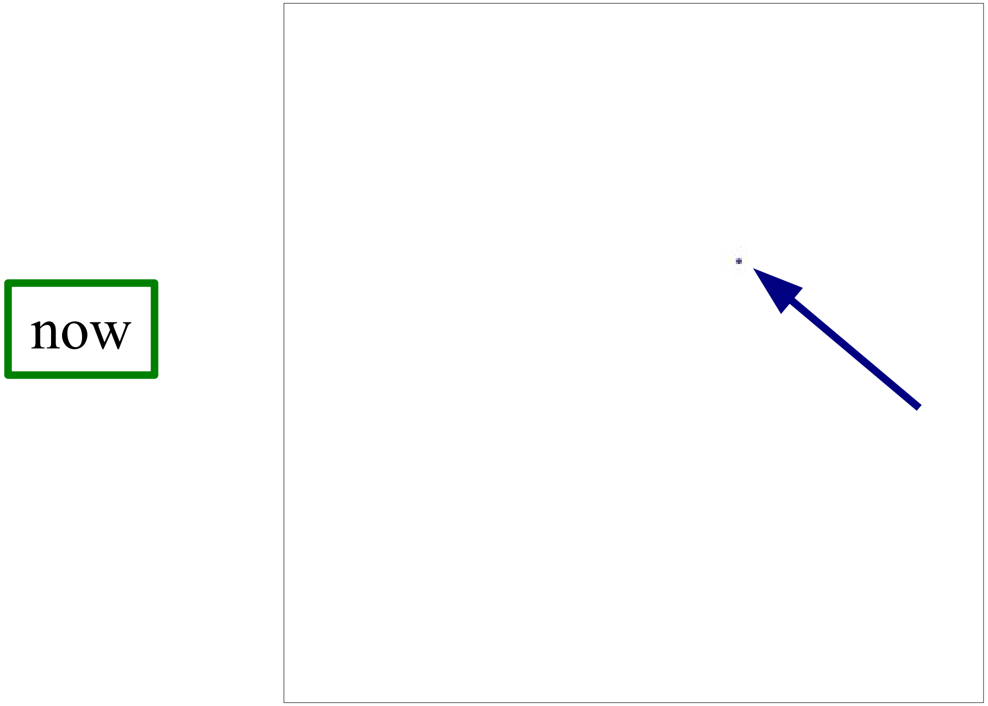
$t \lesssim 10^{-6}$ s



N_B=30 000 000 001

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

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



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

Baryogenesis

Dynamical generation of a BAU: Sakharov conditions (1967)

A baryon asymmetry can be dynamically generated if the following three conditions are *simultaneously* satisfied:

- Baryon number violation

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

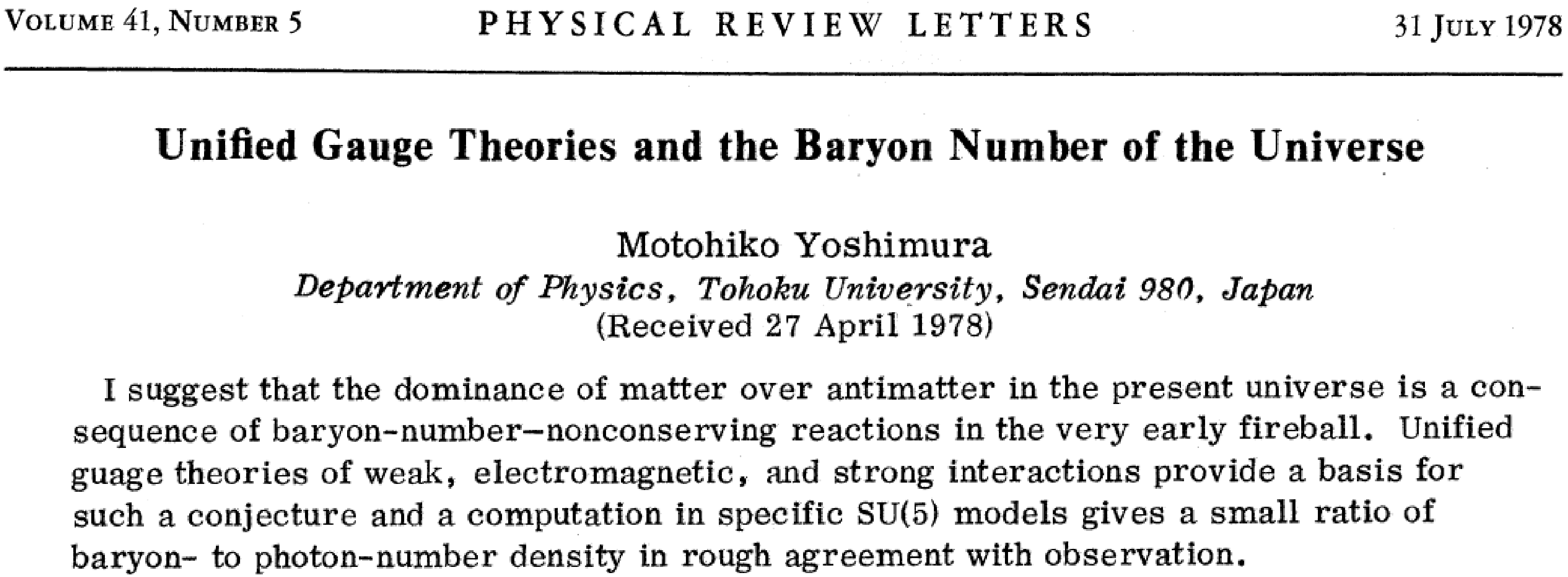
- C and CP violation

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

- Departure from thermal equilibrium

  In thermal equilibrium, the production rate of baryons is equal to the destruction rate: $\Gamma(X \rightarrow Y+B) = \Gamma(Y+B \rightarrow X)$
  ⇒ 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

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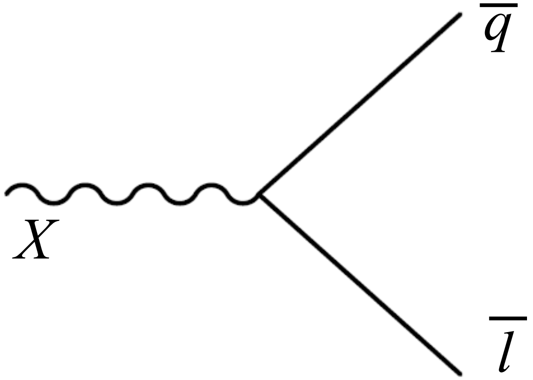
(Received 27 April 1978)

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.

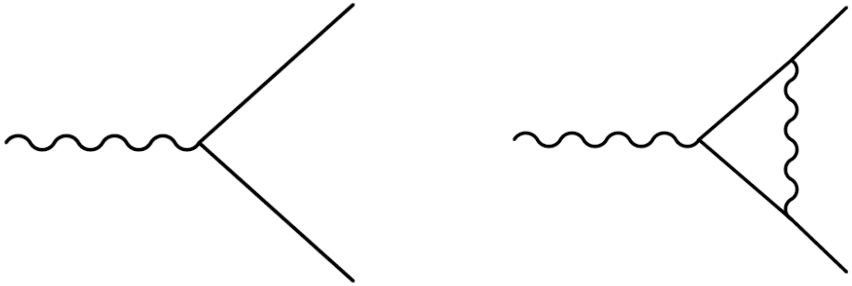
These three conditions are fulfilled in the simplest grand unified models.

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:

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

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:

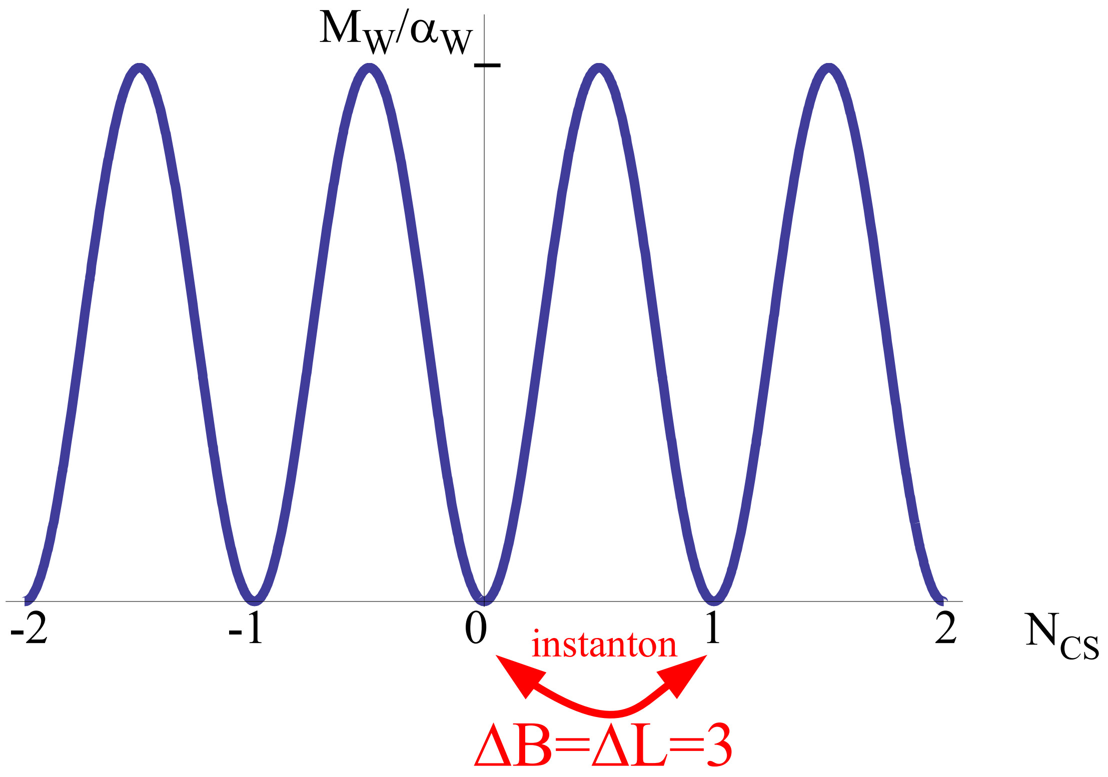
instantons

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

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

Heuristic picture of the electroweak vacuum

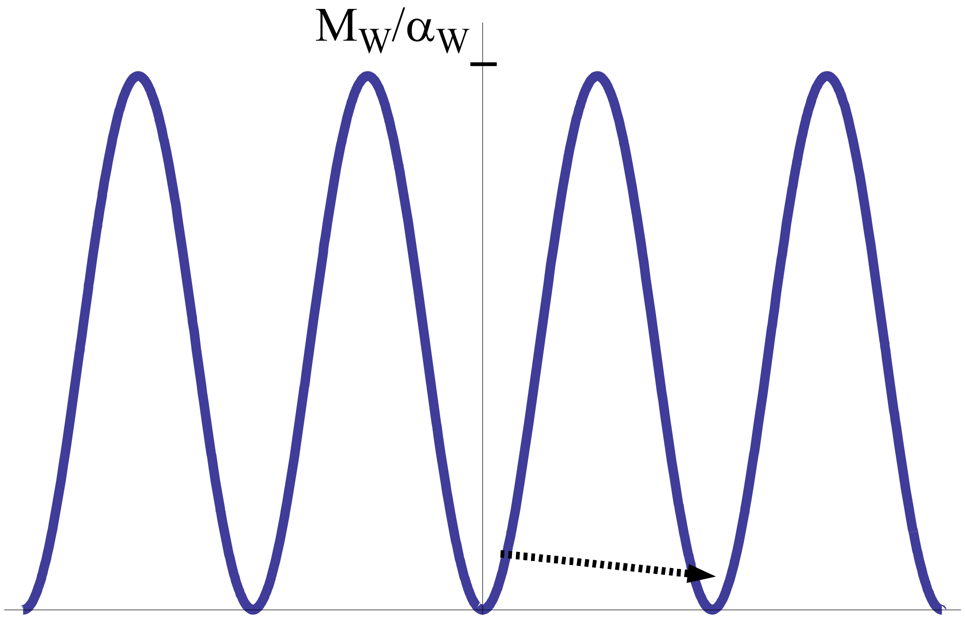
There is an infinite number of degenerate vacuum states with different "Chern-Simons" numbers separated by a barrier.



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

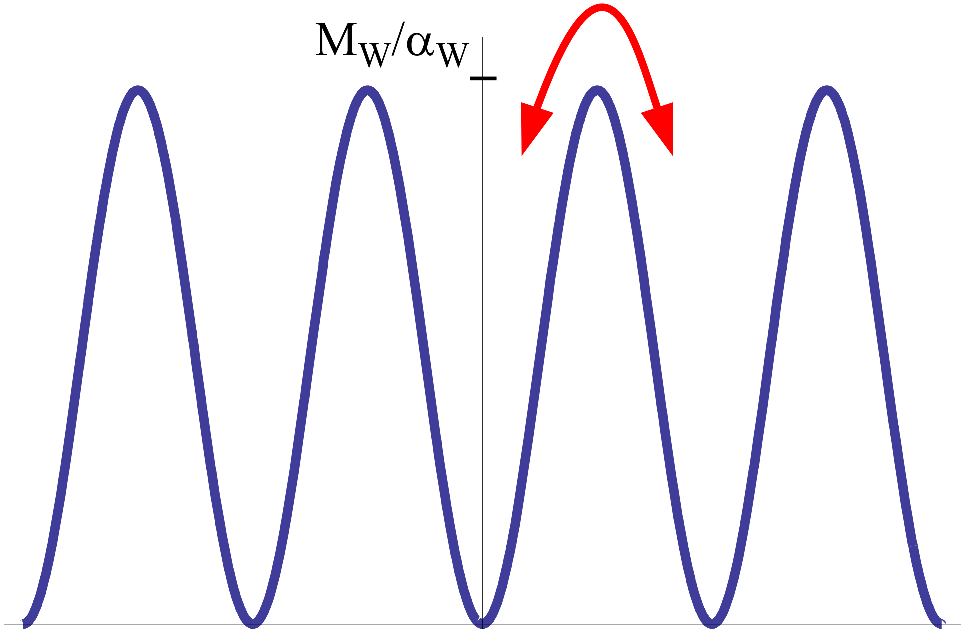
# of generations

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

SPHALERONS

Volume 155B, number 1,2 PHYSICS LETTERS 16 May 1985

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

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

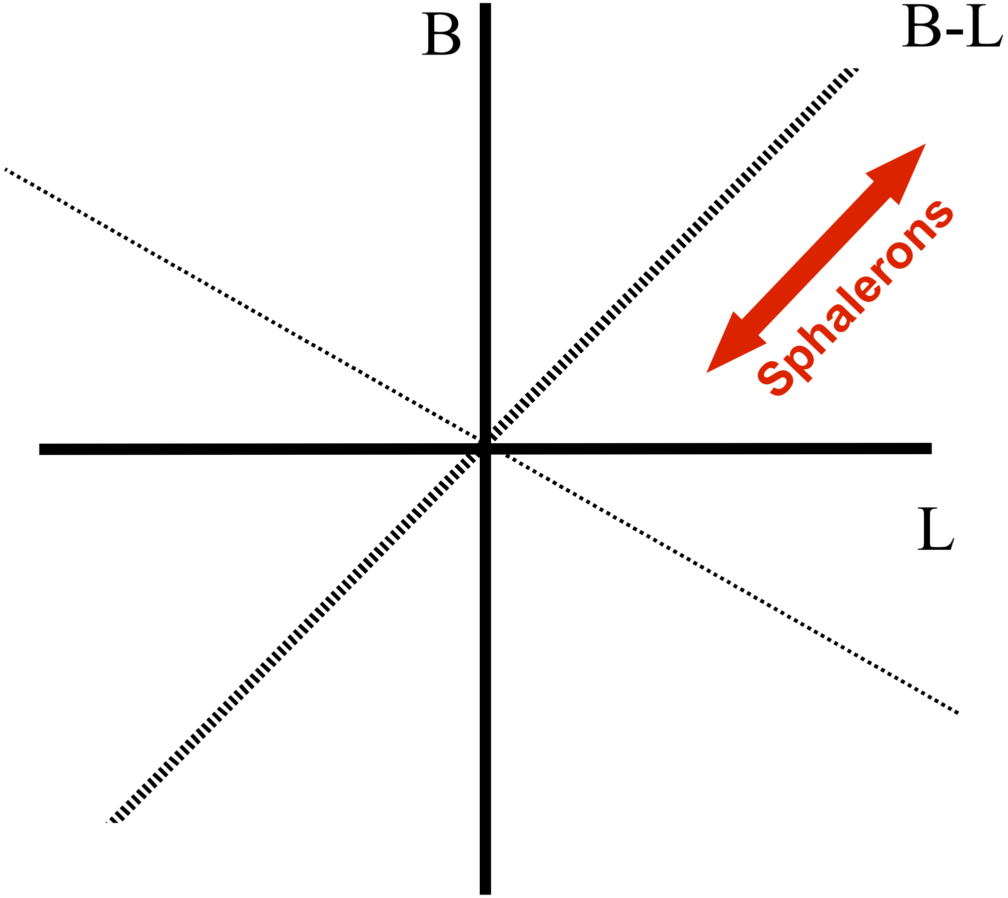
Turning to the possibility of the first order electroweak phase transition, we note that the estimate (6) remains valid for the stage *after* the phase transition. On the other hand, the above discussion implies that before the phase transition, when $\langle\varphi\rangle = 0$, the fermion-number non-conserving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

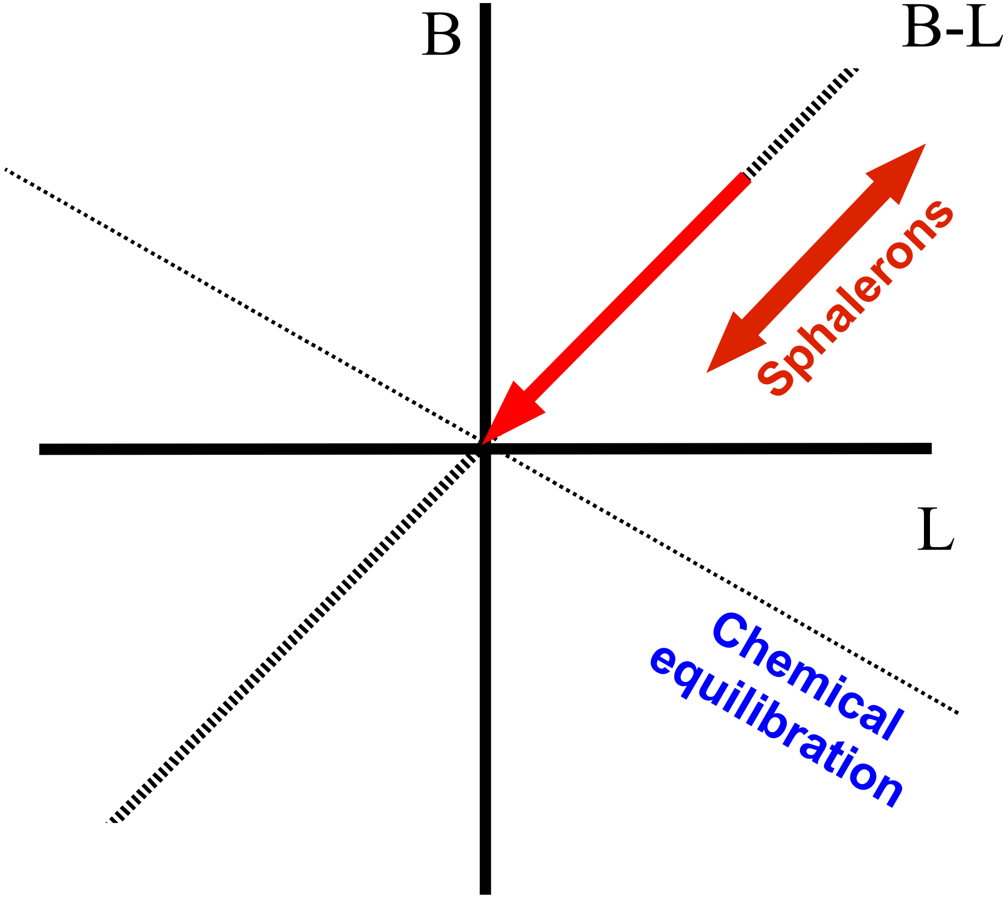
$$B(T_c) = \tfrac{1}{2}(B_{\mathrm{in}} - L_{\mathrm{in}}) + \tfrac{1}{2}(B_{\mathrm{in}} + L_{\mathrm{in}})\, \mathrm{e}^{-A}\,,$$

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

Clearly, $B(T_c) = \frac{1}{2}(B_{\mathrm{in}} - L_{\mathrm{in}})$ 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 $T \sim M_W/\ln(M_{\mathrm{Pl}}/M_W)$, 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)


B
B-L
Sphalerons
L


B
B-L
Sphalerons
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Chemical equilibration

“Revised” Sakharov conditions

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

- ~~Baryon~~ B-L number violation

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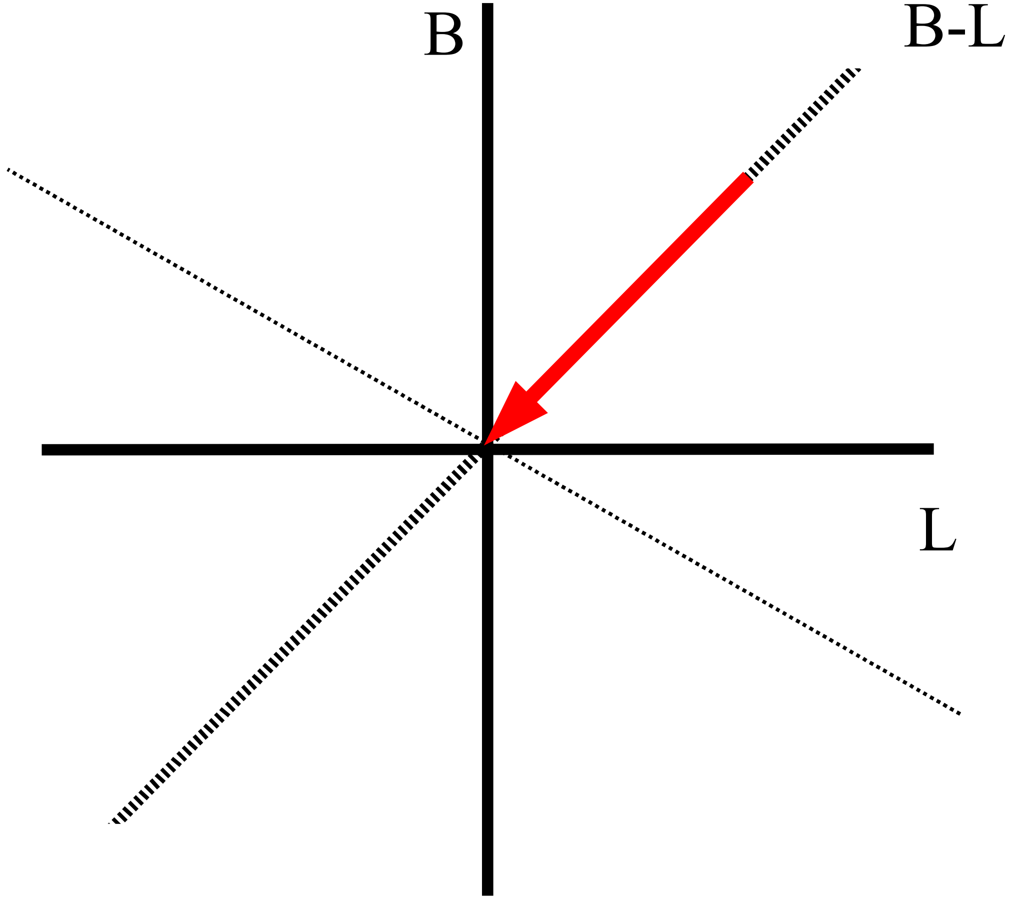
B
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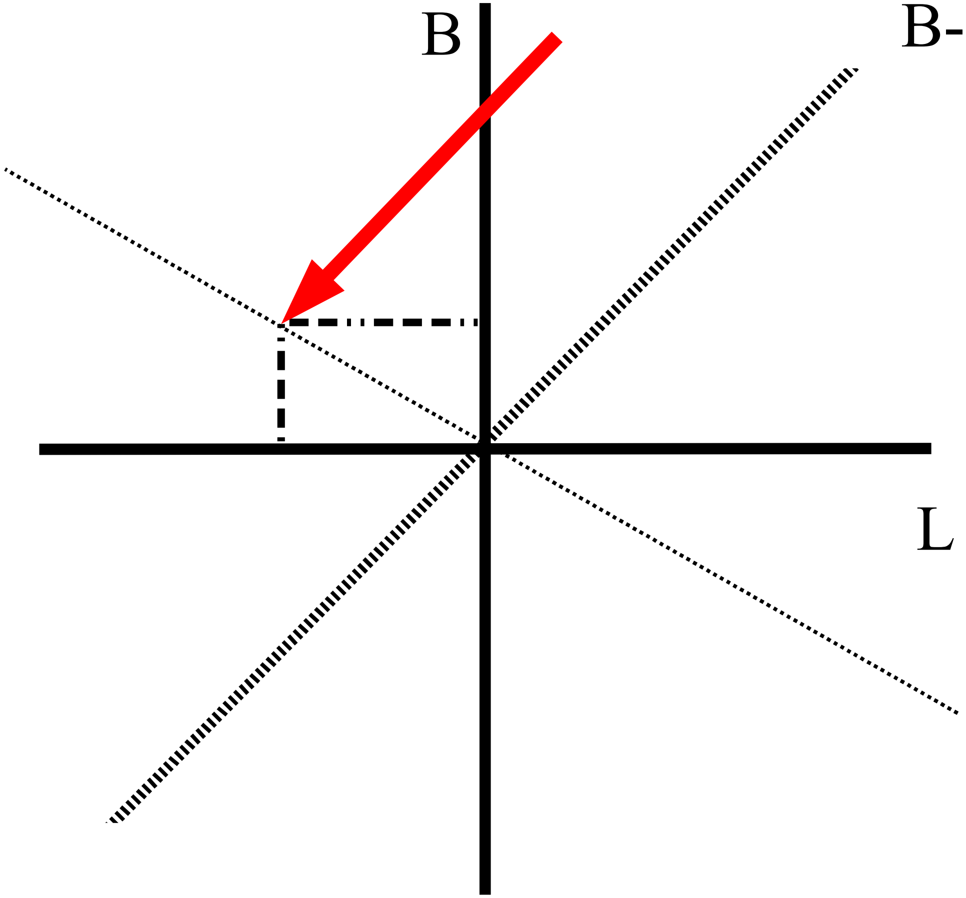
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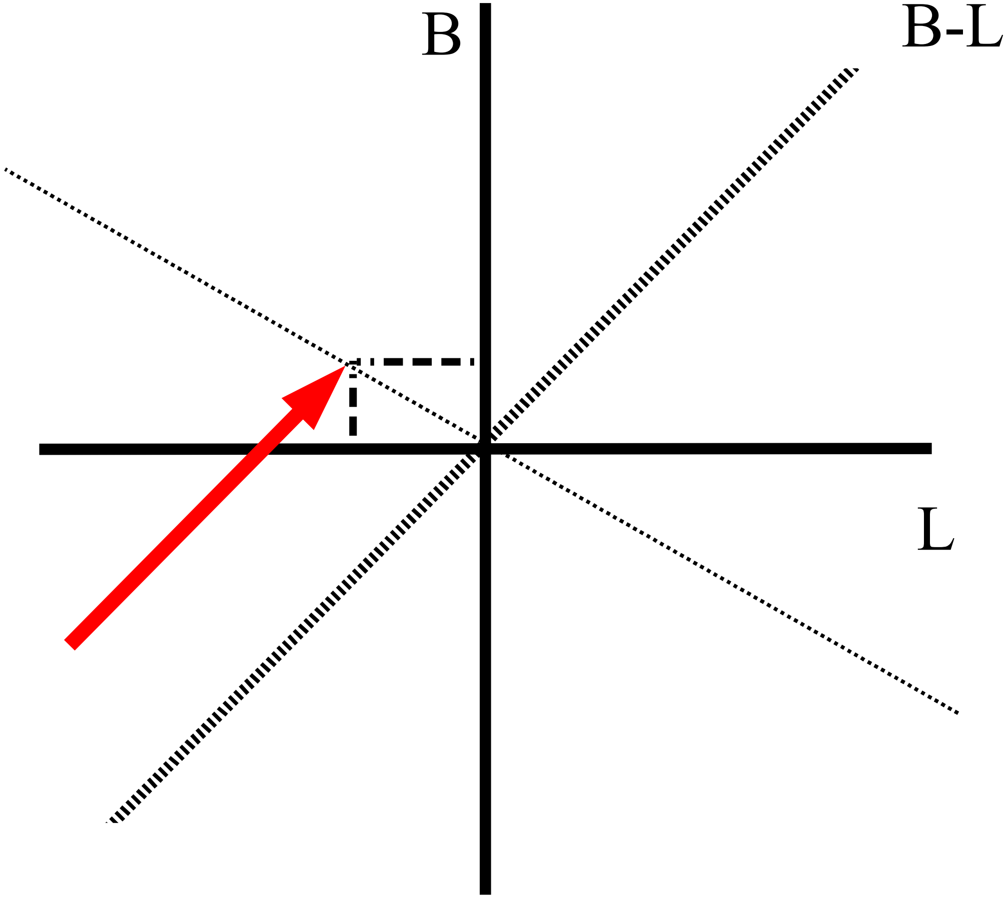
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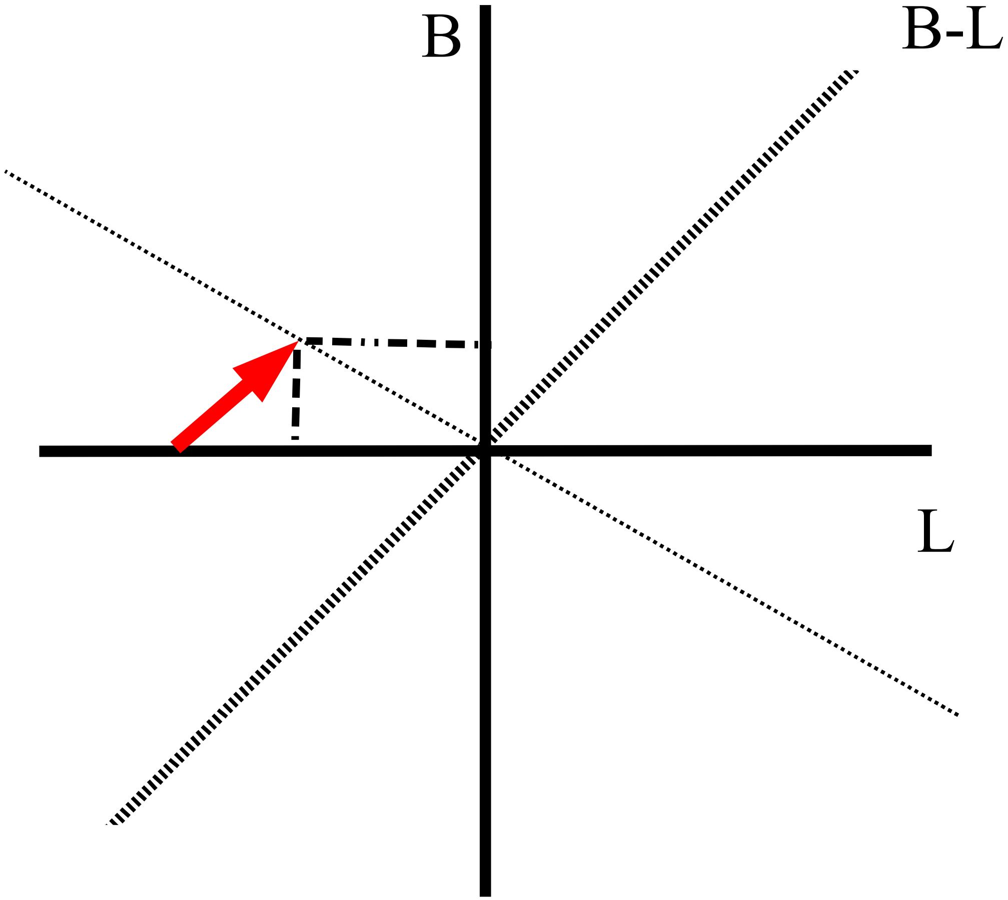
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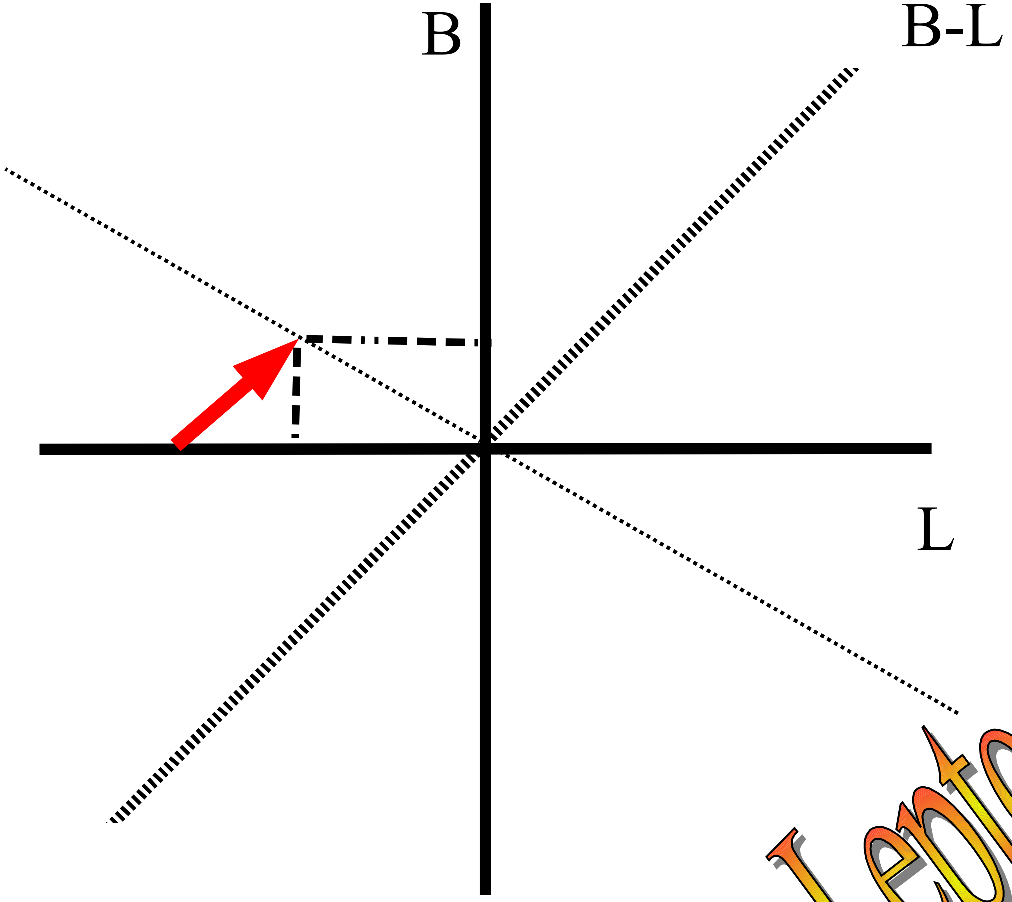
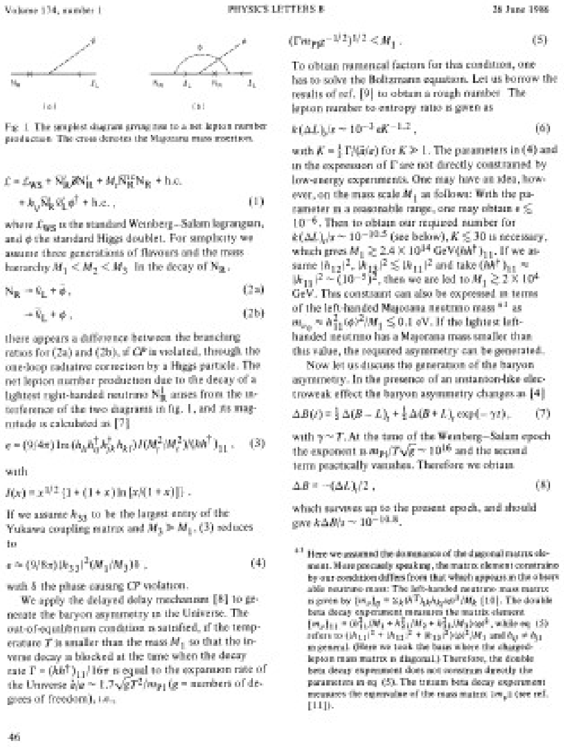
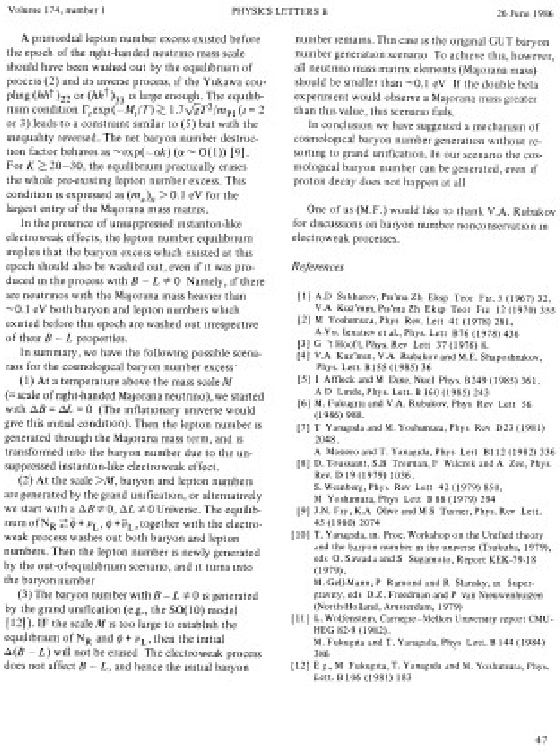


Leptogenesis

VERY SIMPLE IDEA:

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





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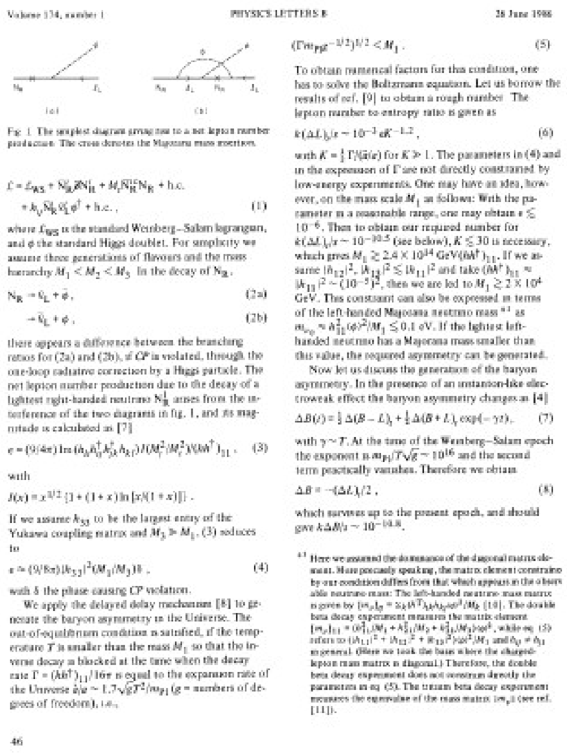
Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

M. FUKUGITA

and

T. YANAGIDA



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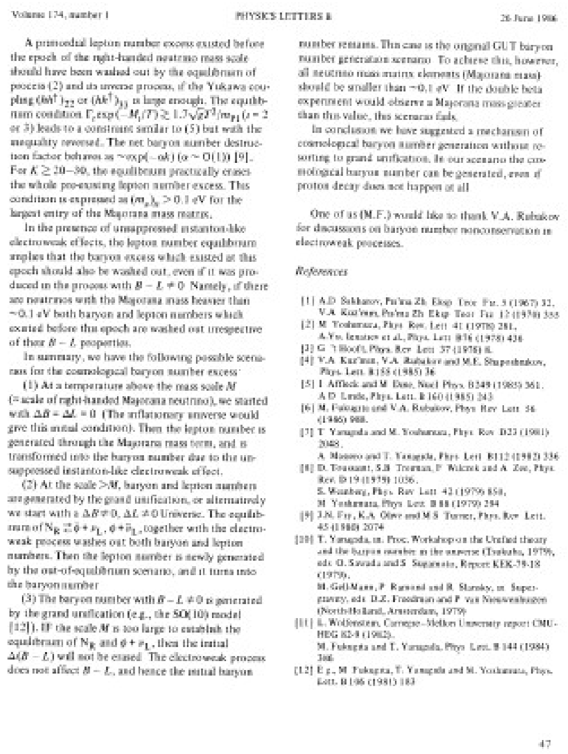
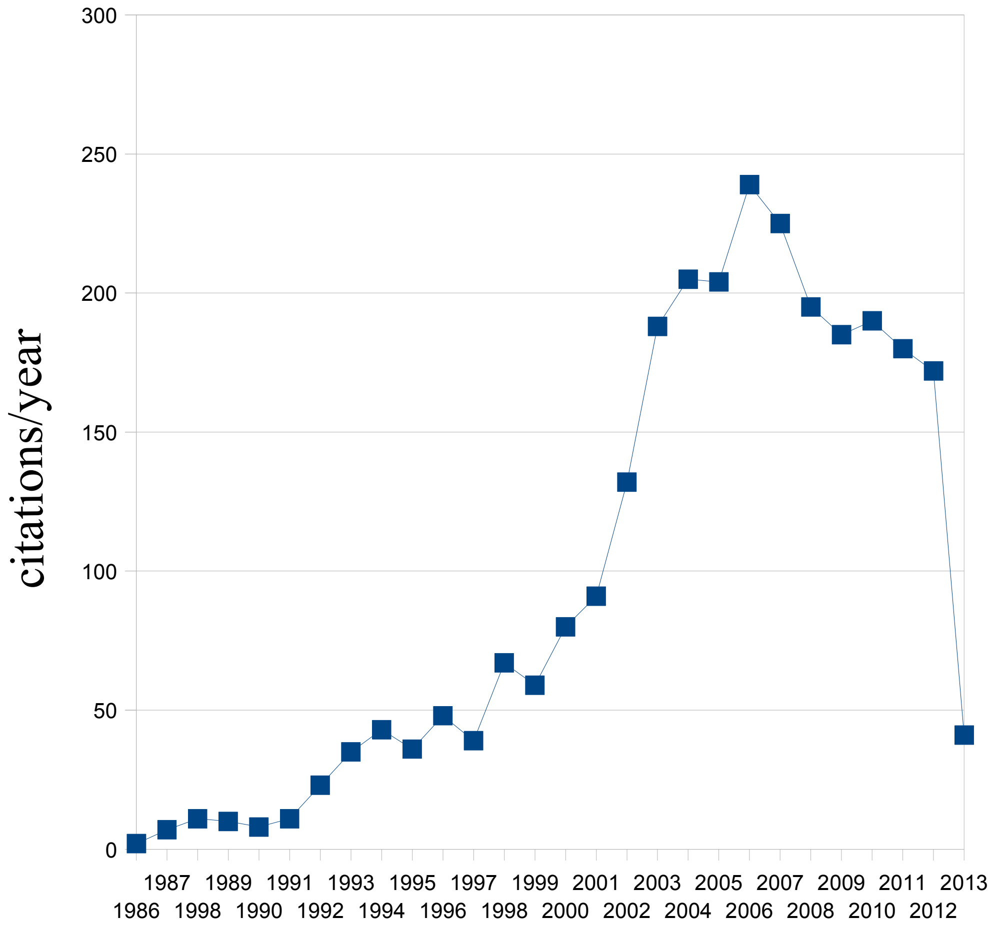


Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

And very popular...

Citations according to the SPIRES database: 1961

Why are people so excited about leptogenesis?



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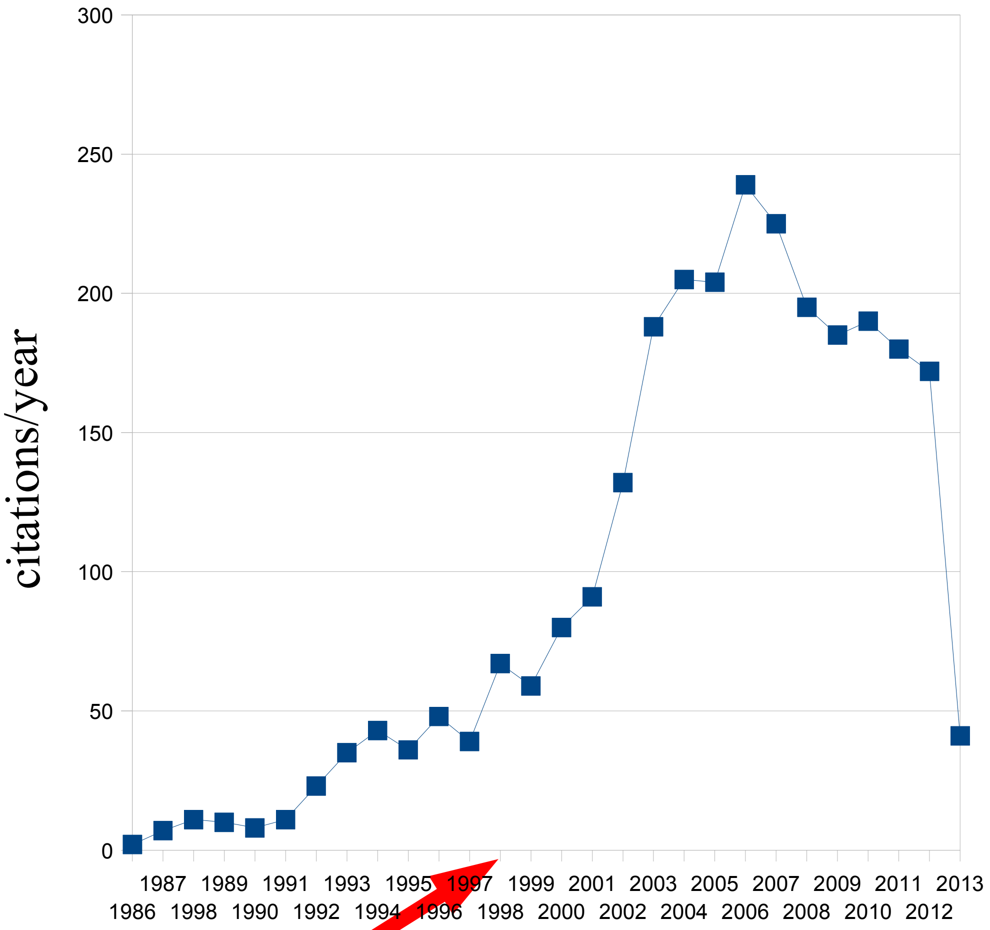

1998. Evidence for atmospheric neutrino oscillations (Super-K)

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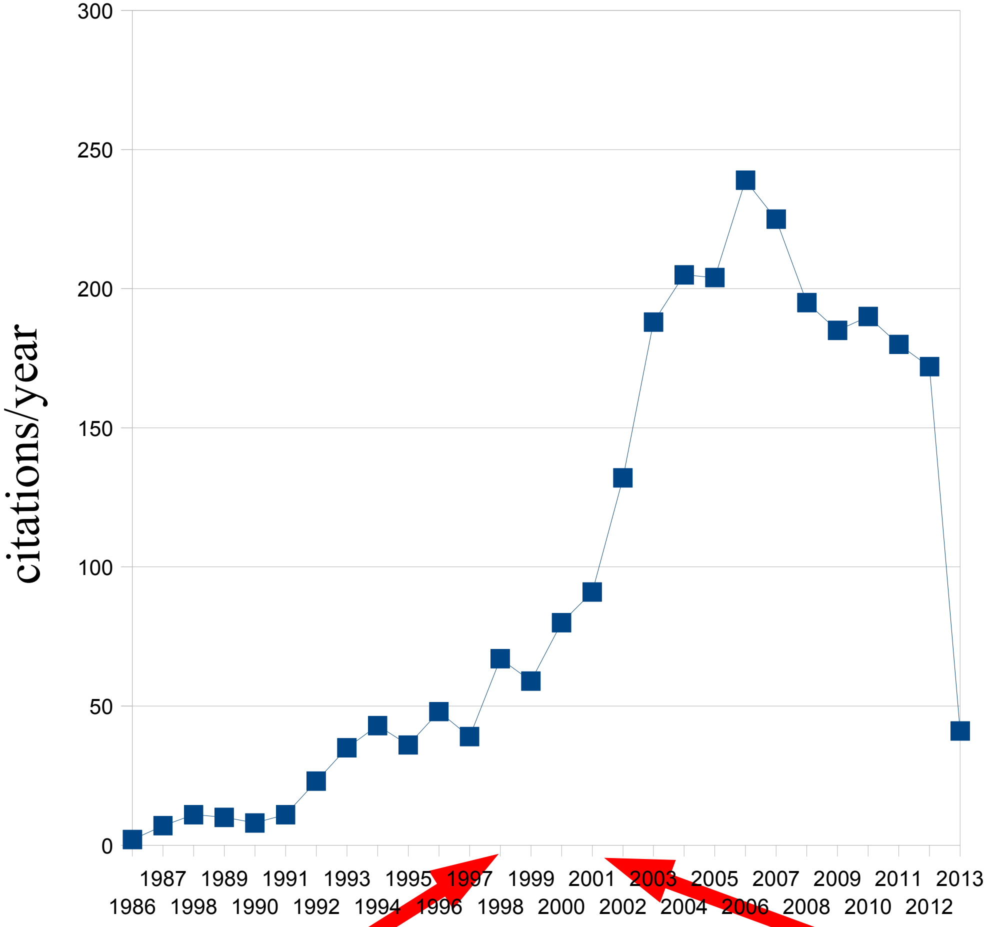
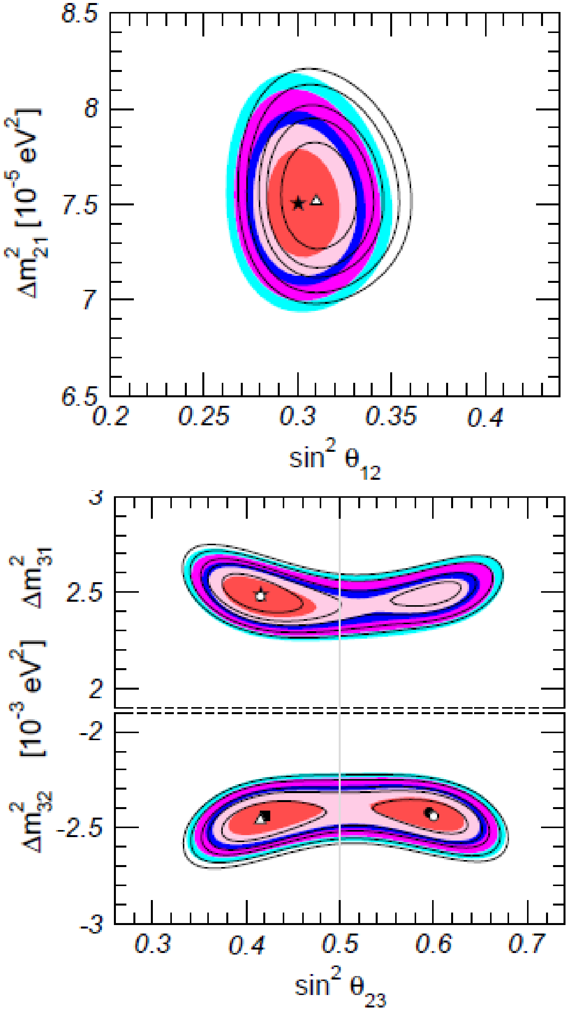


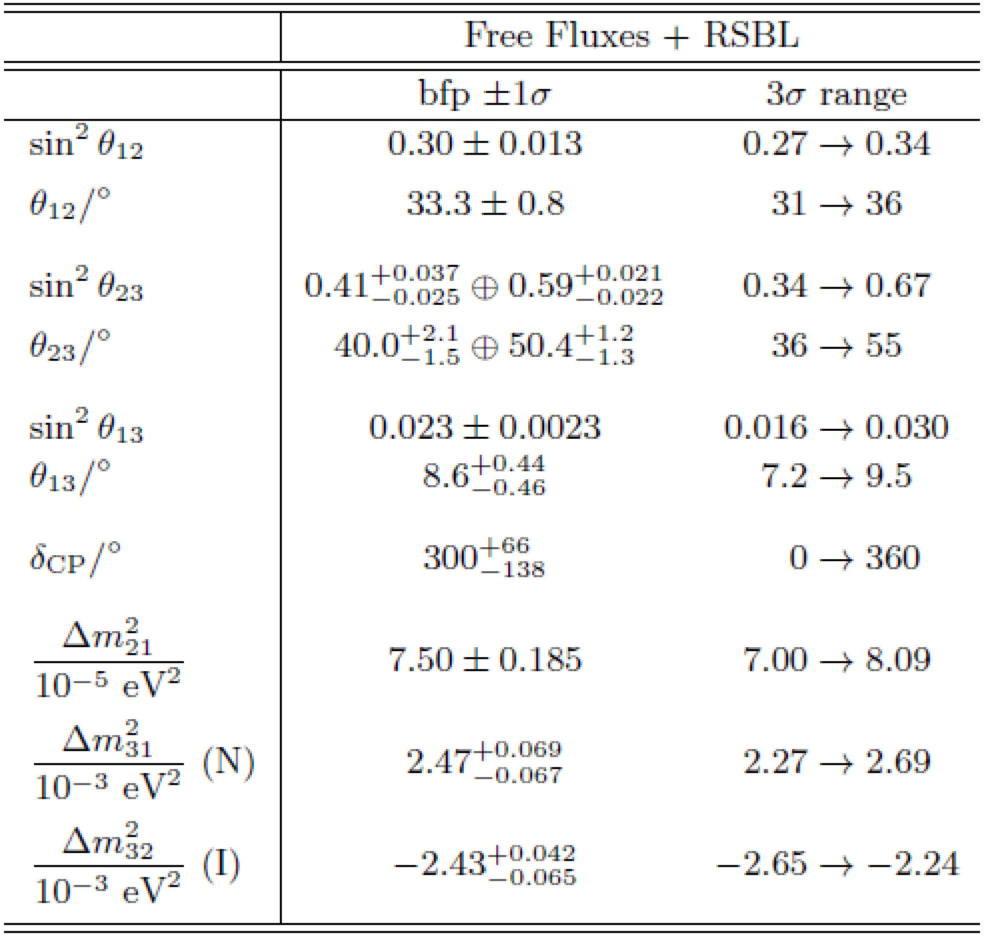
1998. Evidence for atmospheric neutrino oscillations (Super-K)

2001. Evidence for solar neutrino oscillations (SNO)

Neutrino masses

Neutrinos have mass!!





	Free Fluxes + RSBL	
	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	7.50 ± 0.185	$7.00 \to 8.09$
$\frac{\Delta m^2_{31}}{10^{-3}\ \rm eV^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$
$\frac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$

Gonzalez-Garcia, Maltoni, Salvado, Schwetz

arXiv:1209.3023

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

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

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

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

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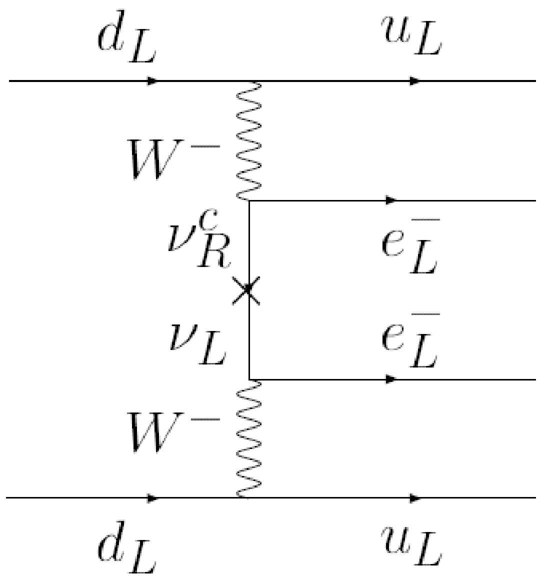
Option preferred by theorists

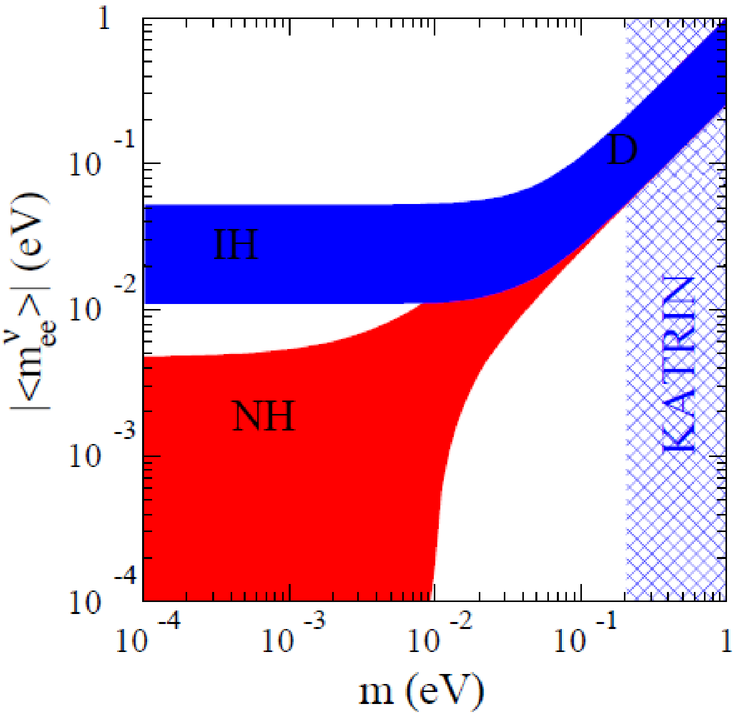
Dirac or Majorana?



The smoking gun: neutrinoless double beta decay

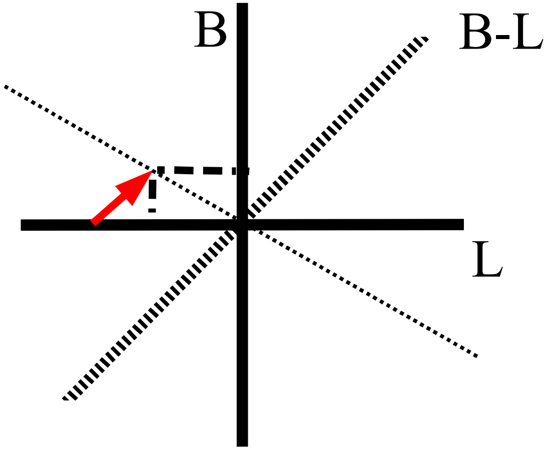
If neutrinos are Majorana particles, the nuclear process (A,Z) → (A,Z+2)+e^-+e^- is allowed

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



The rate of 0ν2β depends crucially on the spectrum. If neutrinos are degenerate or inverse hierarchical, 0ν2β could be observed in the next generation of experiments (GERDA,EXO, KamLAND-Zen, CUORE, SNO+, MAJORANA...)

- The observation of 0ν2β decay (⇒L is violated) will support the leptogenesis scenario.



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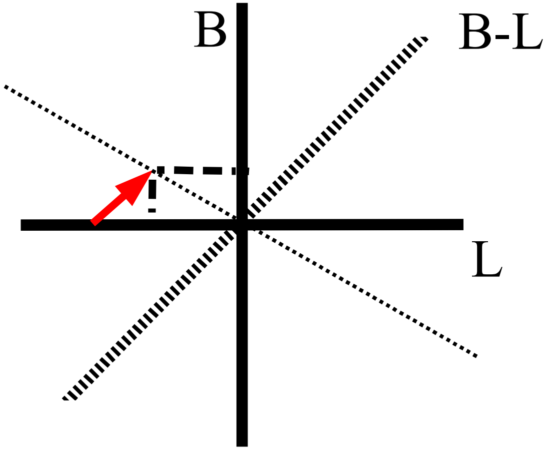
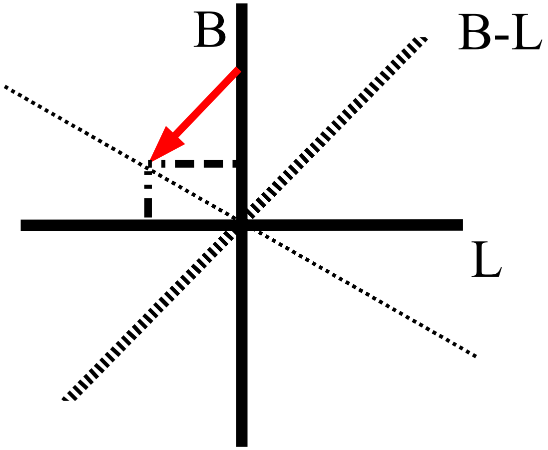
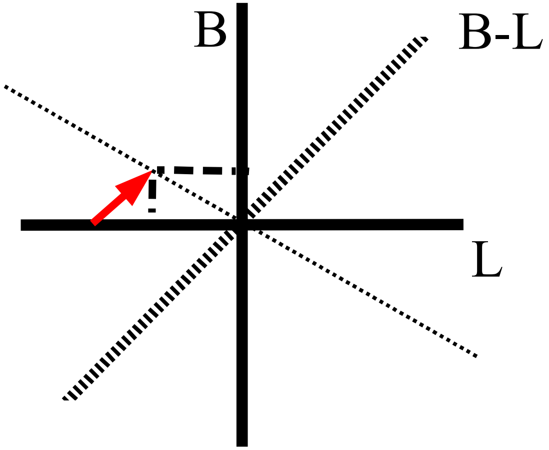


- The observation of neutron-antineutron oscillations (⇒B is violated) will support the baryogenesis scenario.



- The observation of $0\nu2\beta$ decay (⇒L is violated) will support the leptogenesis scenario.



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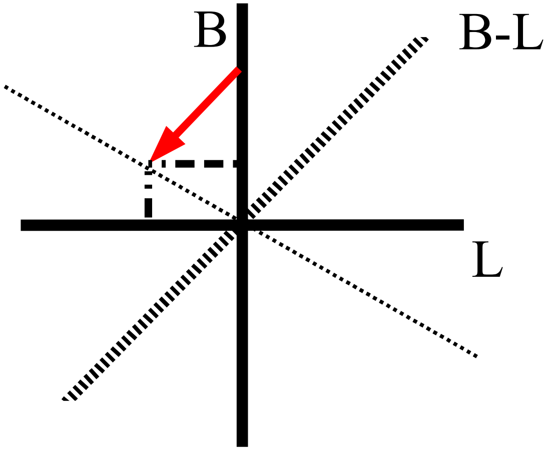
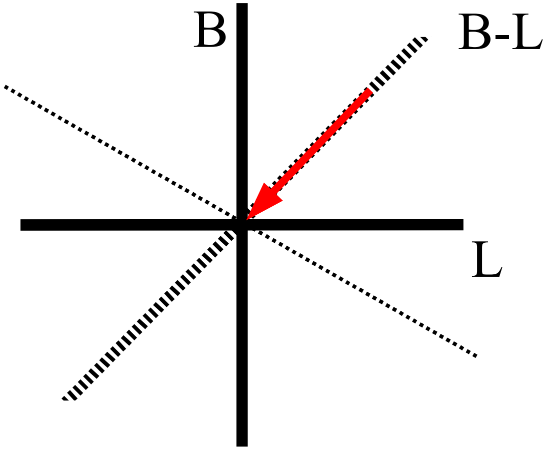


- The observation of proton decay (⇒B and L violated) will not have any implications for baryogenesis/leptogenesis (since B−L is **not** violated)



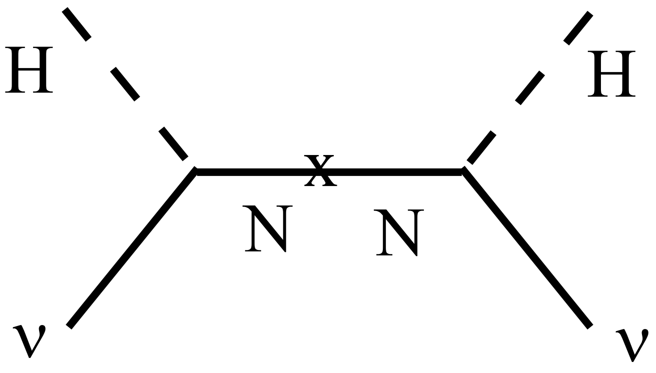
Origin of neutrino masses

Many proposals!

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

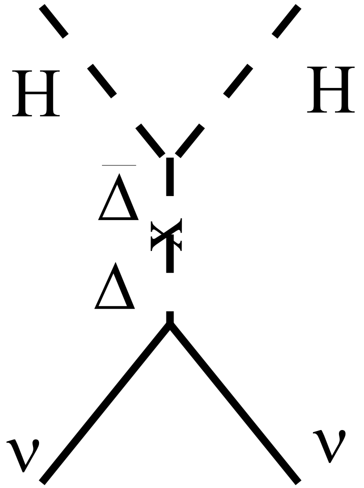
See-saw mechanism

Type I



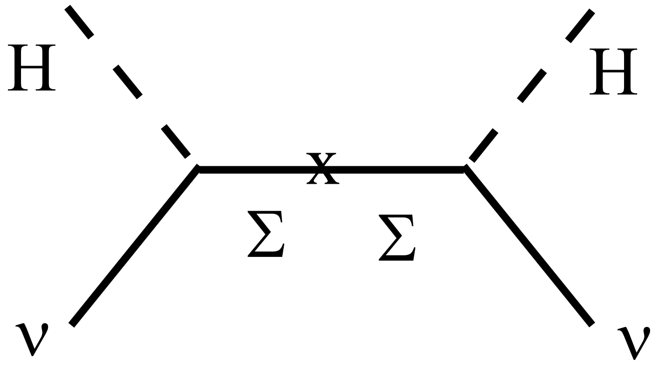
(fermion singlets)

Type II



(scalar triplets)

Type III



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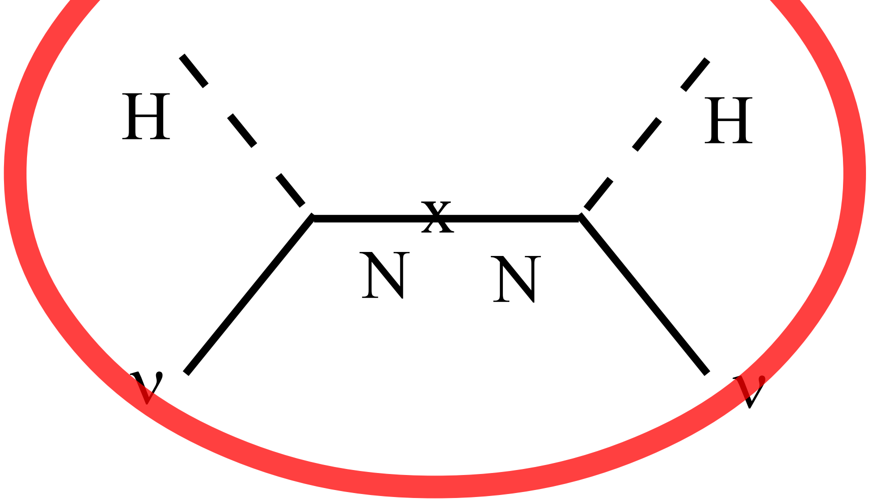

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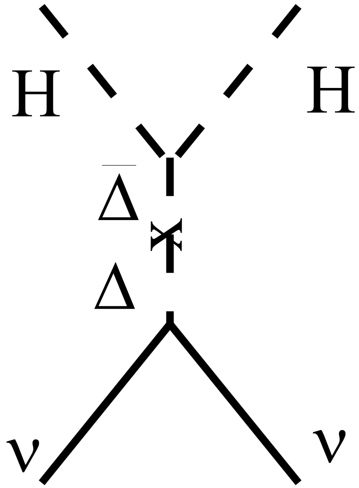

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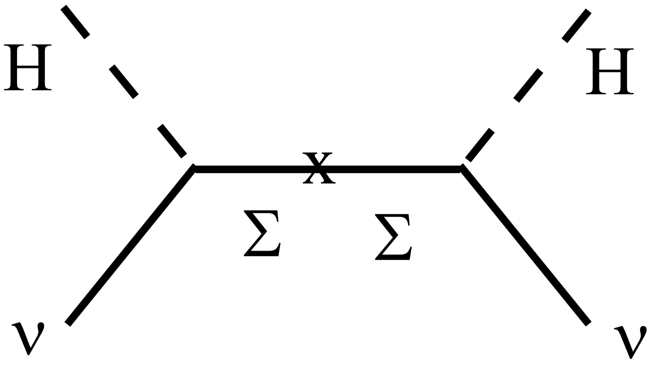

(fermion triplets)

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:

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

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

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

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

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?

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The three Sakharov conditions are fulfilled:

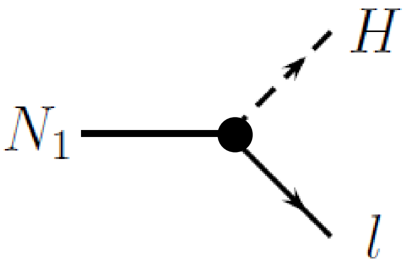
- Violation of B–L. Guaranteed if neutrinos are Majorana particles.
- C and CP violation. Guaranteed if the neutrino Yukawa couplings contain physical phases. However, it is not guaranteed that the C and CP violation are large enough for leptogenesis.
- Departure from thermal equilibrium. Guaranteed,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

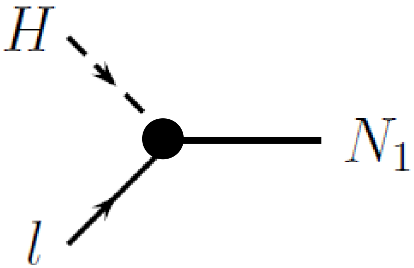
Calculate!

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

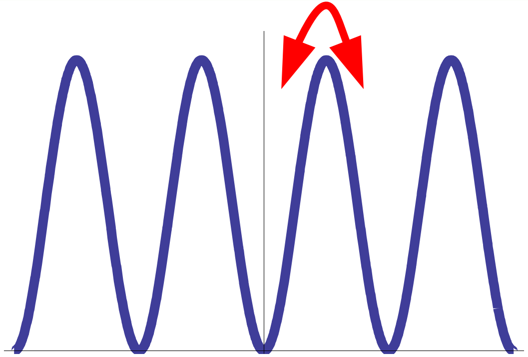
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.

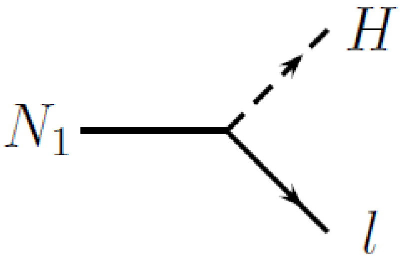


3- Conversion of the lepton asymmetry into a baryon asymmetry.



1- Generation of the lepton asymmetry

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

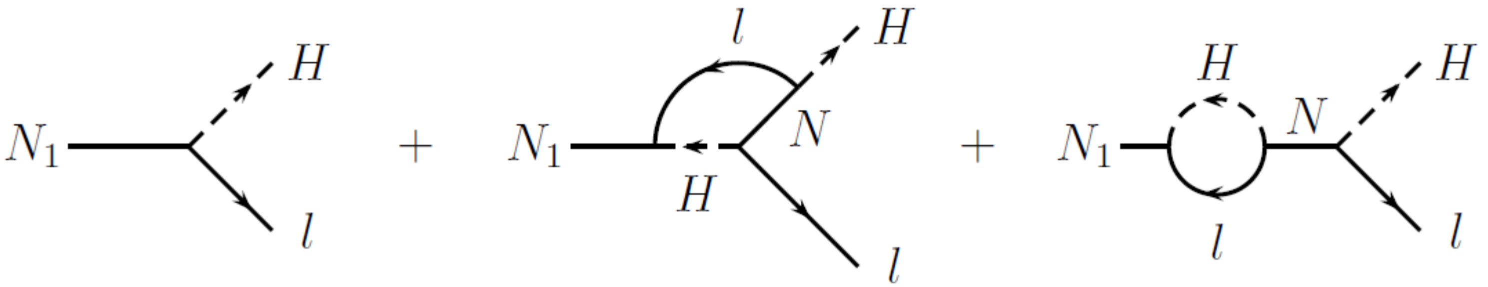


No CP asymmetry (no lepton asymmetry)

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

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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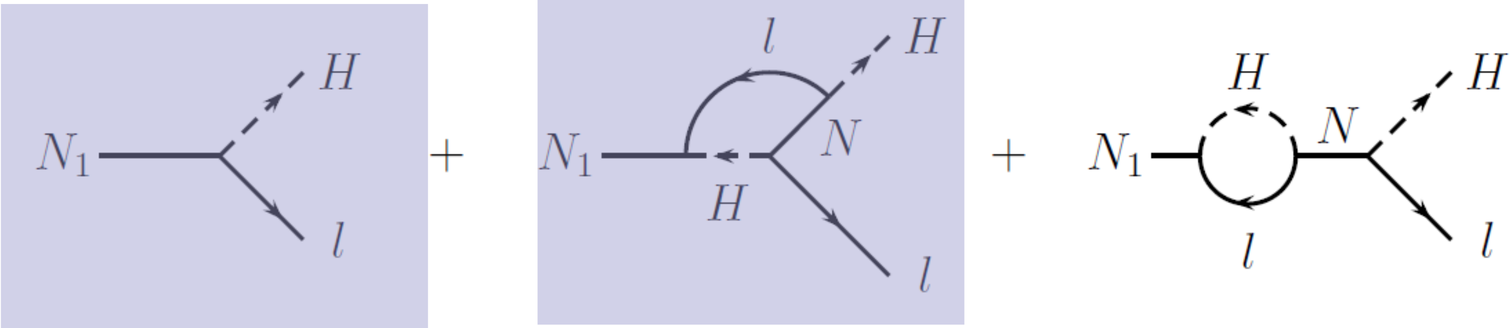

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Interference with the vertex diagram

1- Generation of the lepton asymmetry

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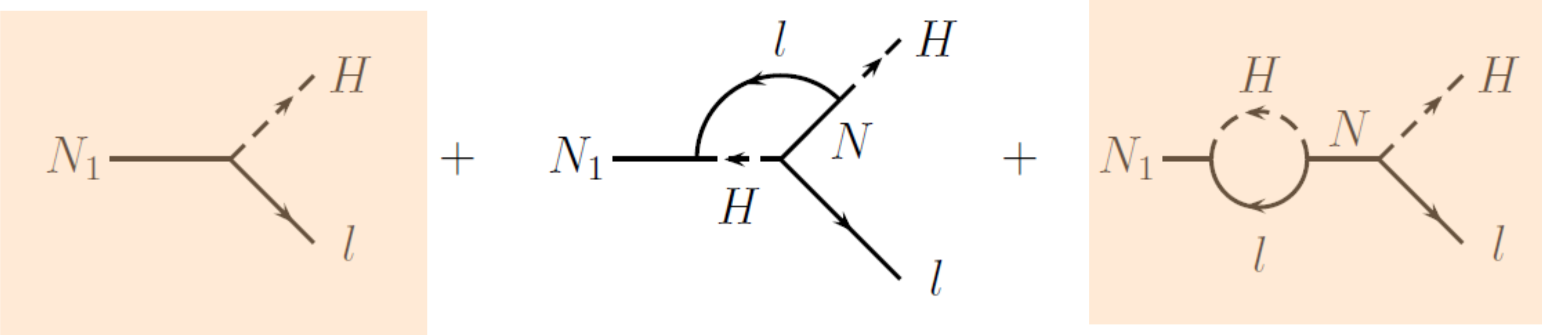

$$\begin{aligned}\epsilon_1 &= \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to l^c H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to l^c H^c)} \\ &\simeq \frac{1}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right]\left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right)\right]\end{aligned}$$

Interference with the wave-function diagram

1- Generation of the lepton asymmetry

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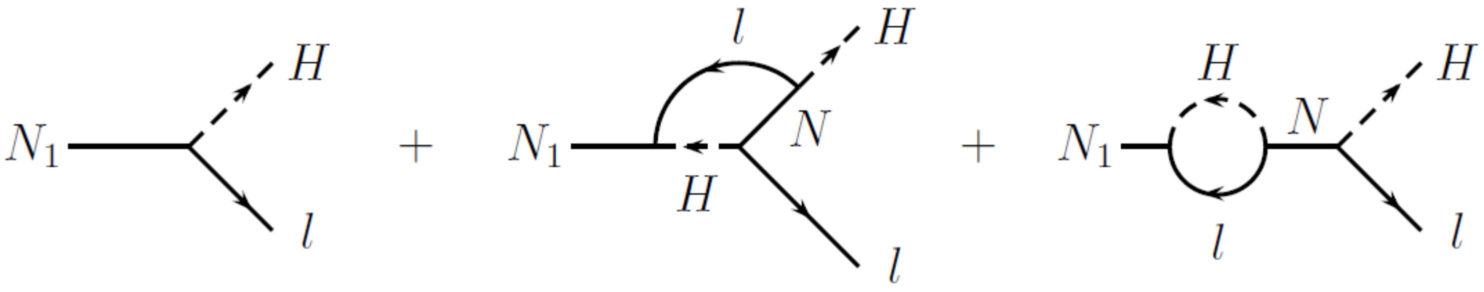

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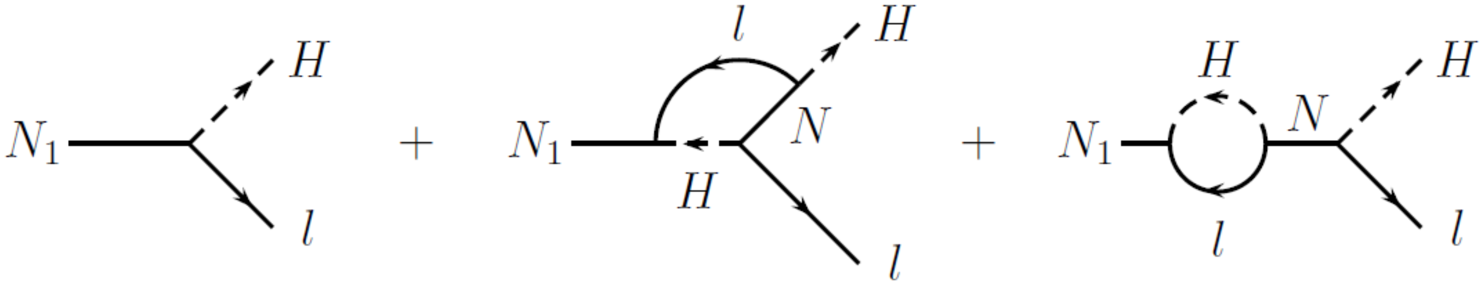
$$\simeq \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \boxed{\sum_{i=2,3} \mathrm{Im}\left[(h_\nu h_\nu^\dagger)^2_{1i}\right]} \left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right)\right]$$

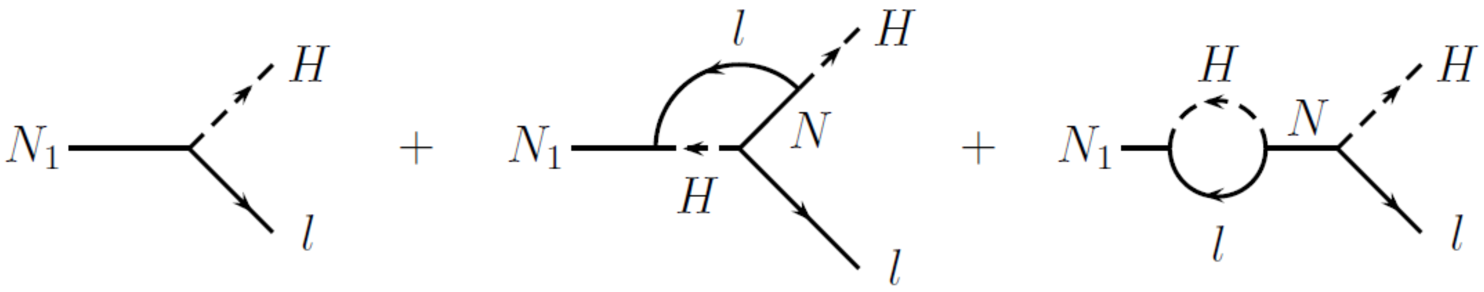
The Yukawa coupling must be complex:

C and CP violation (2nd Sakharov condition)



The CP violating decays generate instantaneously a lepton asymmetry.

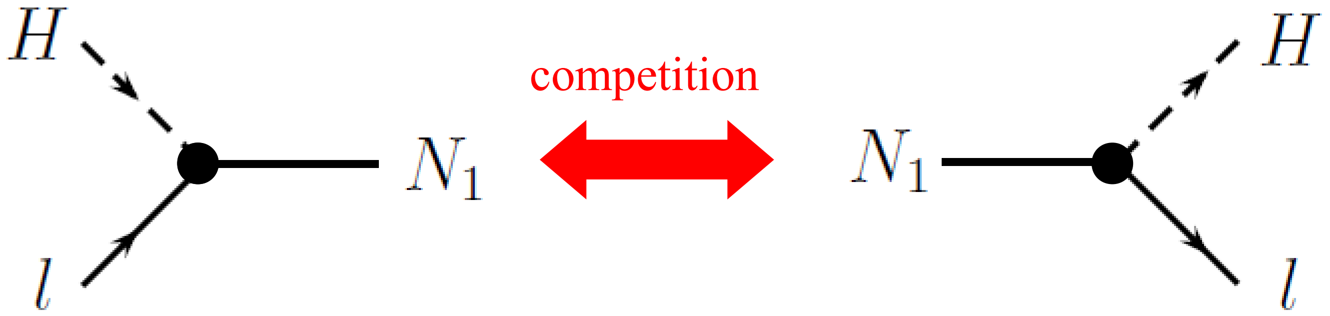
Not the end of the story...



The CP violating decays generate instantaneously a lepton asymmetry.

Not the end of the story...

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



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

2- Wash-out of the lepton asymmetry

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

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

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

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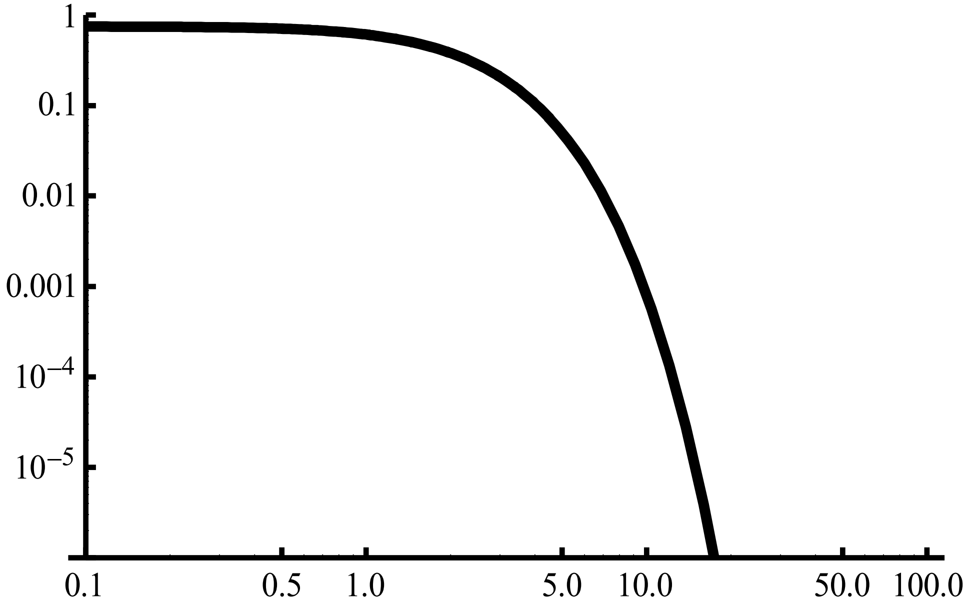
Equilibrium distribution

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



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Decay term

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

Decay rate at temperature T

Hubble rate at temperature T

***D*(*z*) measures how fast are the decays compared to the expansion to the Universe:**

$D(z) \gg 1$ → many decays/inverse decays per Hubble time at the temperature T

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

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Decay term

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

$$D(z) = K\,z\underbrace{\frac{K_1(z)}{K_2(z)}}_{\text{T-dependent}}$$

T-independent
“wash-out parameter”

$K \gg 1$ → many decays/inverse decays

$K \ll 1$ → few decays/inverse decays

2- Wash-out of the lepton asymmetry

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

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

Decay term

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

$$D(z) = K\,z\,\frac{K_1(z)}{K_2(z)}$$

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

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

"Effective neutrino mass"

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

"Equilibrium neutrino mass"

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

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

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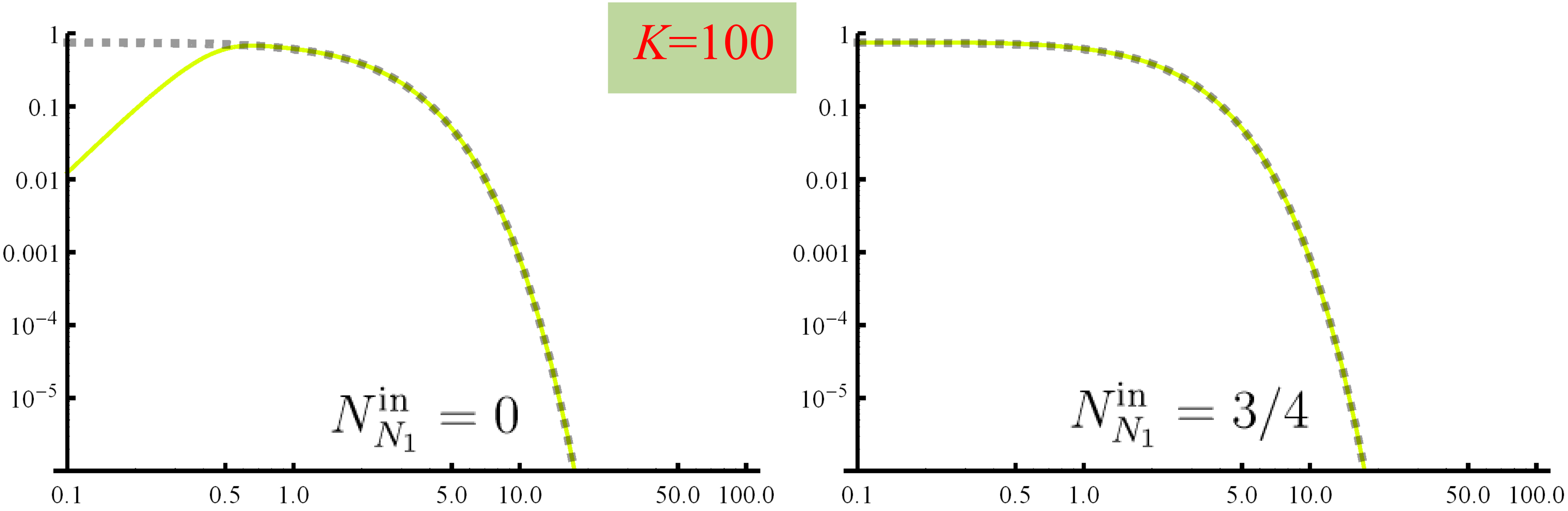
$$N_{N_1}^{\rm eq}(z) = \frac{3}{8} z^2 K_2(z)\ ,$$

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



vanishing initial abundance

thermal initial abundance

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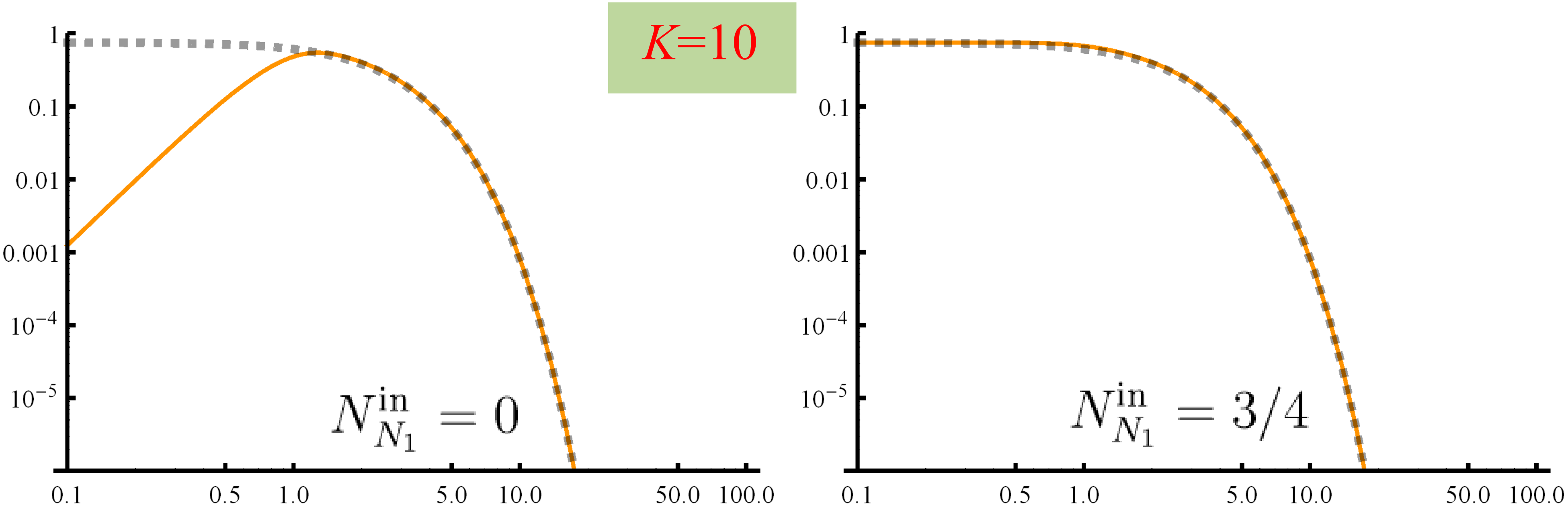

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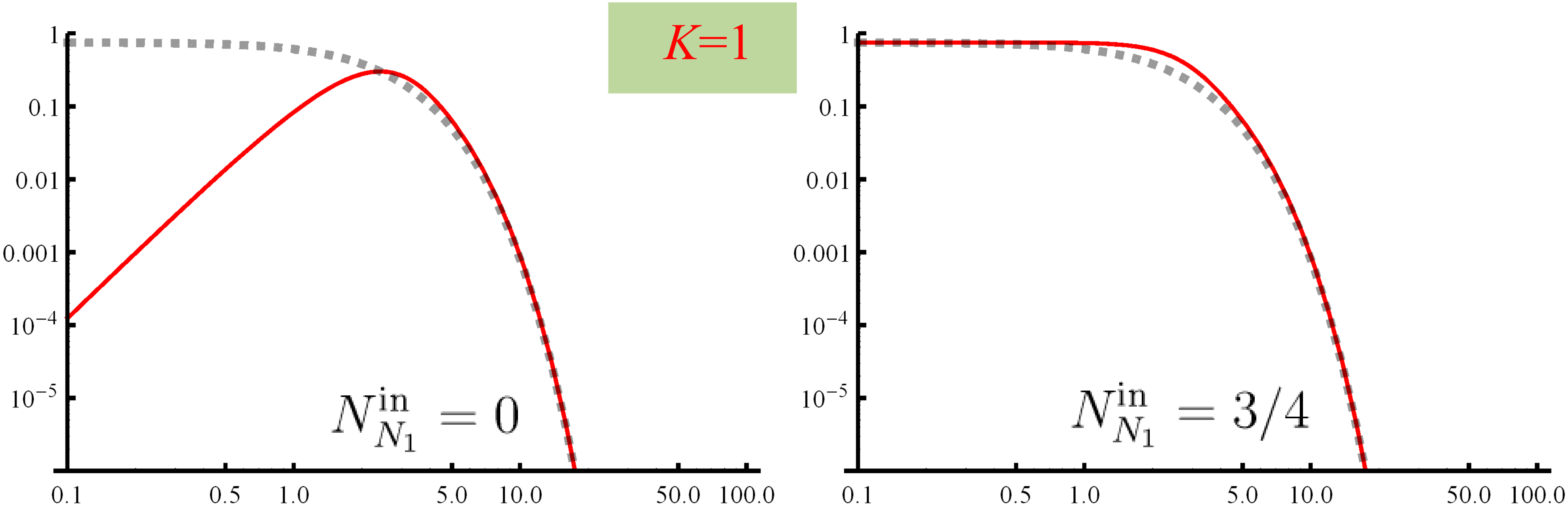

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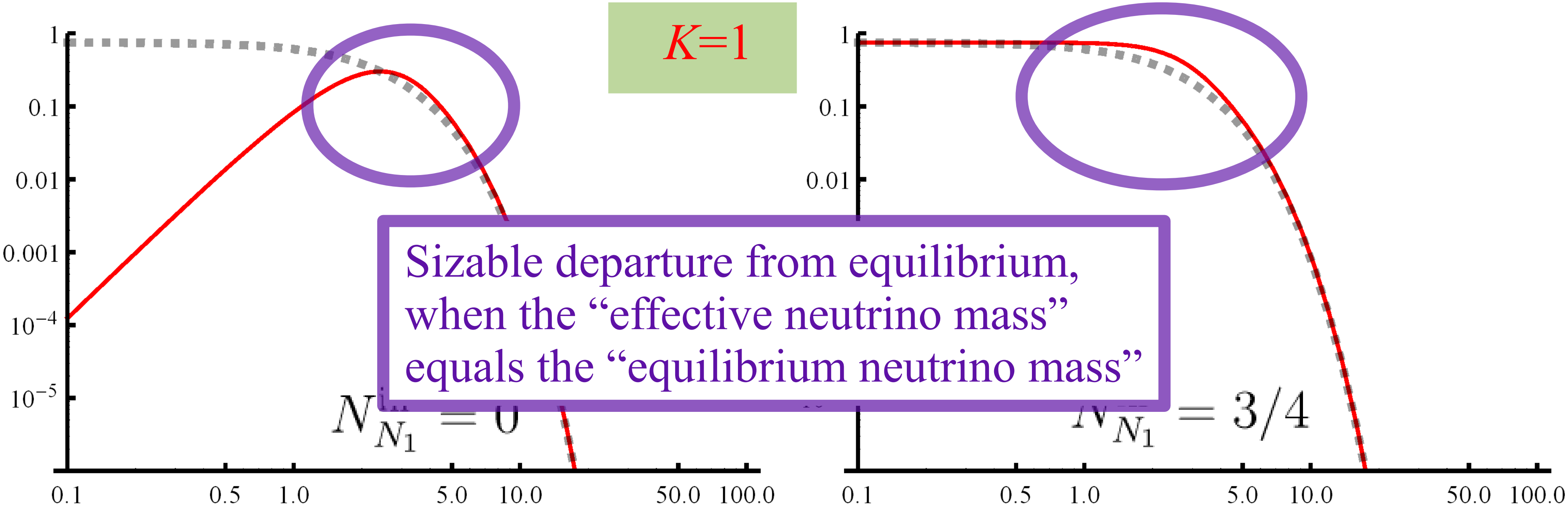

Sizable departure from equilibrium, when the "effective neutrino mass" equals the "equilibrium neutrino mass"

vanishing initial abundance

thermal initial abundance

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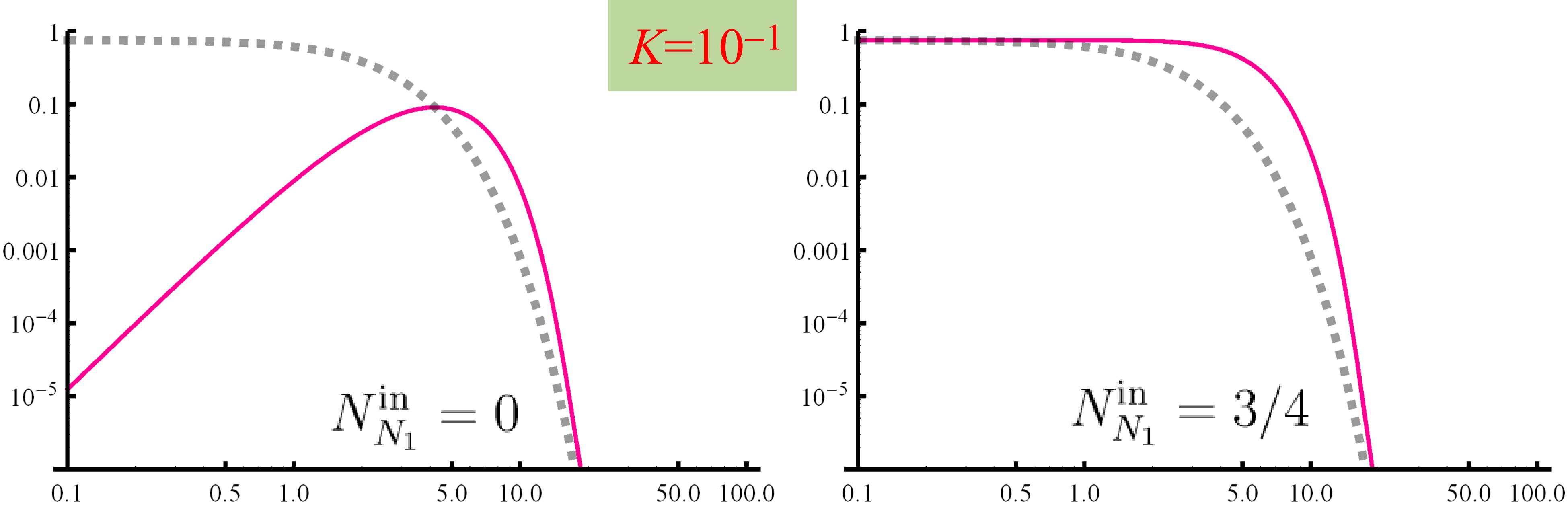

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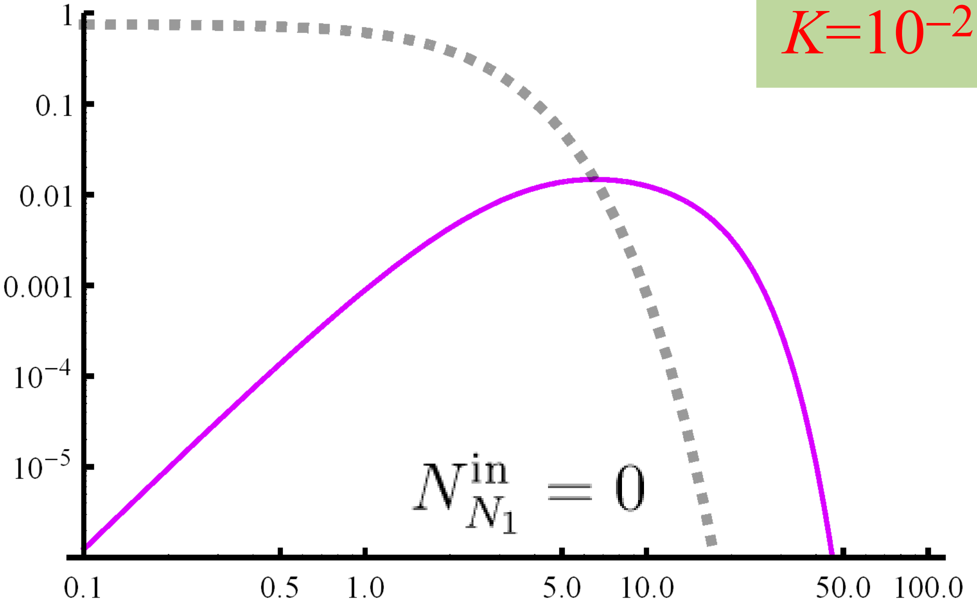
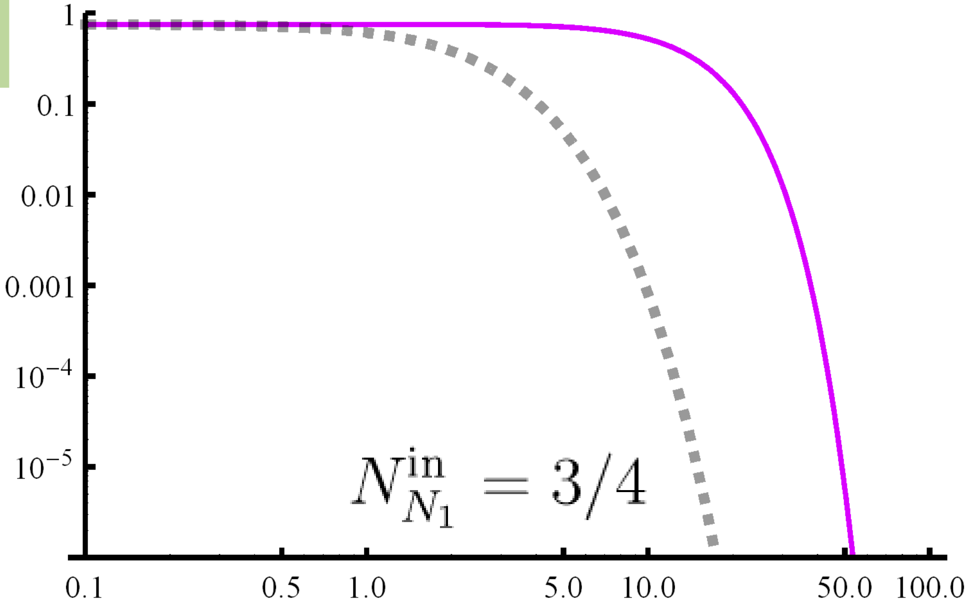
The solution depends on the initial condition and on K (or $\widetilde{m}_1$)

K=10^{-2}



vanishing initial abundance



thermal initial abundance

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

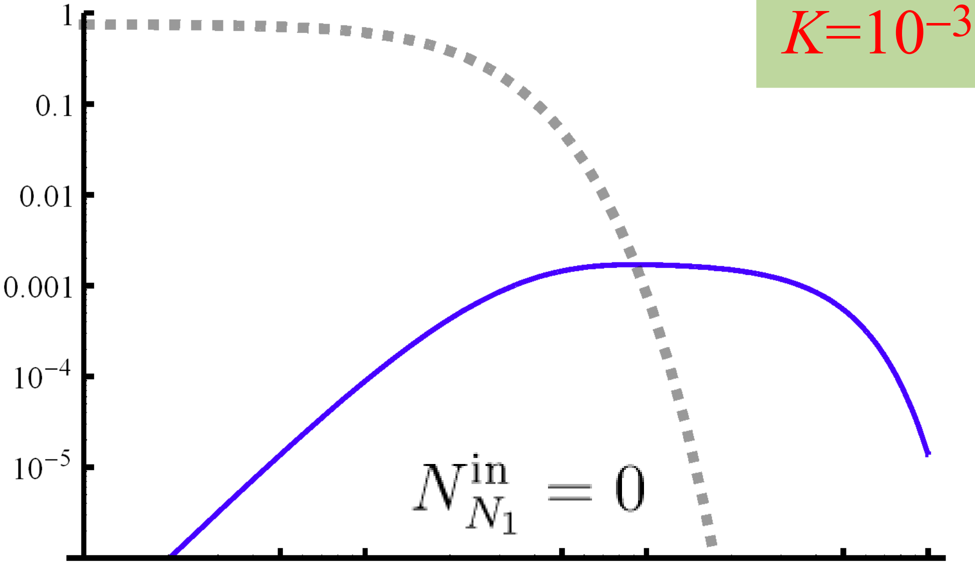
$$\boxed{\frac{dN_{N_1}(z)}{dz} = -K\, z\, \frac{K_1(z)}{K_2(z)}\left(N_{N_1}(z) - N_{N_1}^{\rm eq}(z)\right)}$$

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

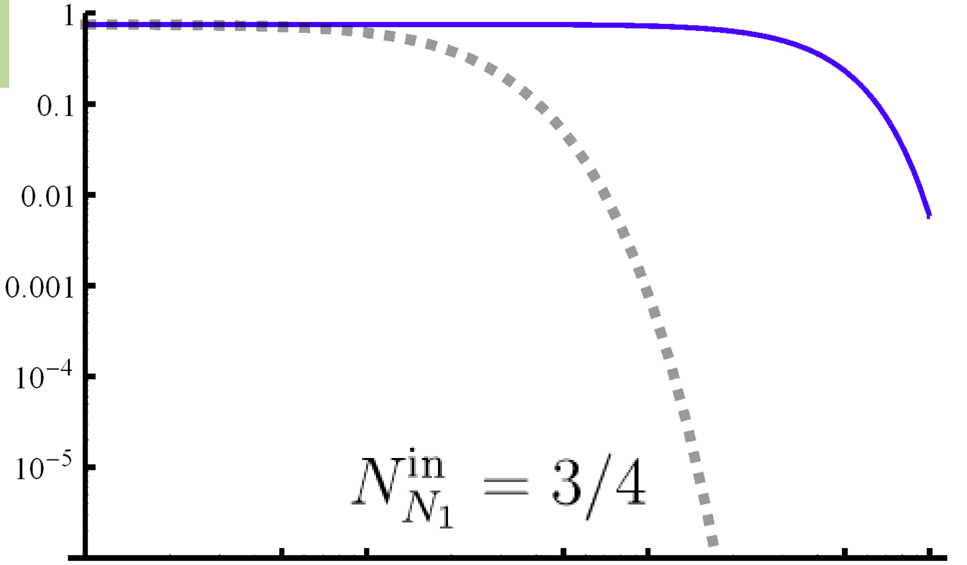
$$N_{N_1}^{\rm eq}(z) = \frac{3}{8} z^2 K_2(z)\ ,$$

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

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?

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

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

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.

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

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

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

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

Set of Boltzmann equations

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

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

Set of Boltzmann equations

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

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

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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

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

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

Set of Boltzmann equations

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

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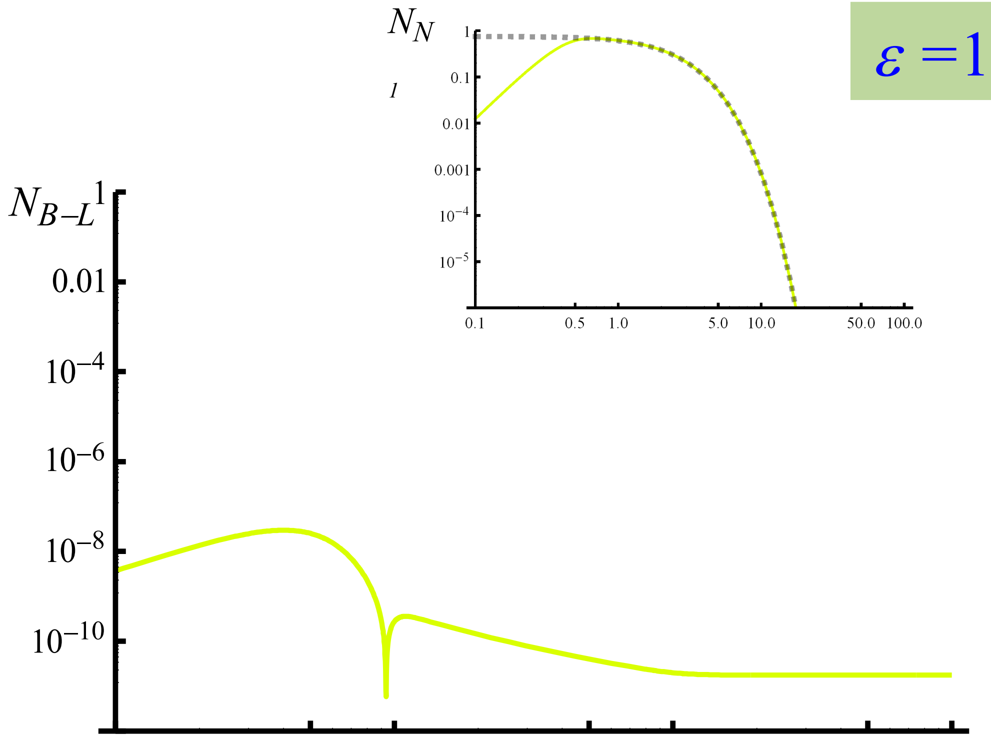
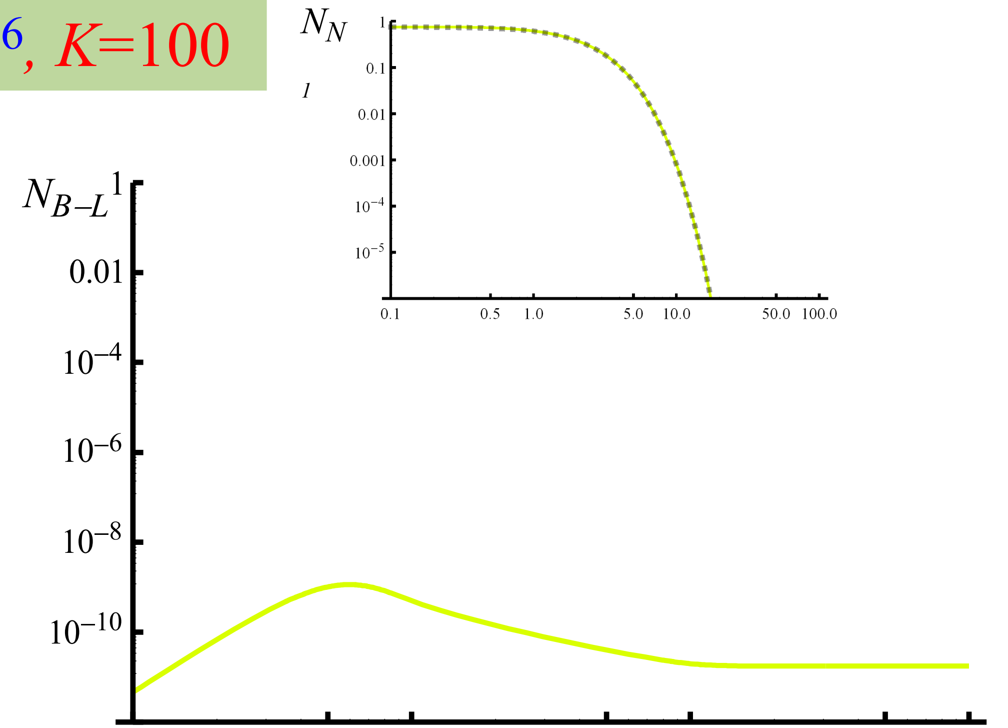
$\varepsilon = 10^{-6}$, K=100



$N^{\rm in}_{N_1} = 0$

vanishing initial abundance



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

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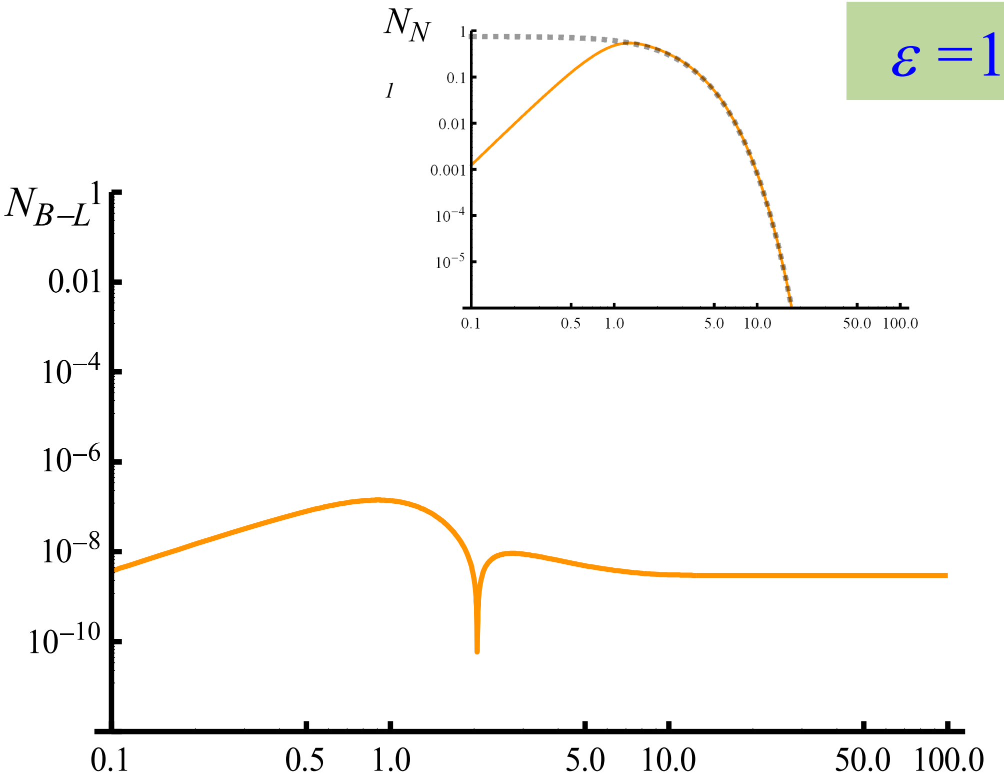
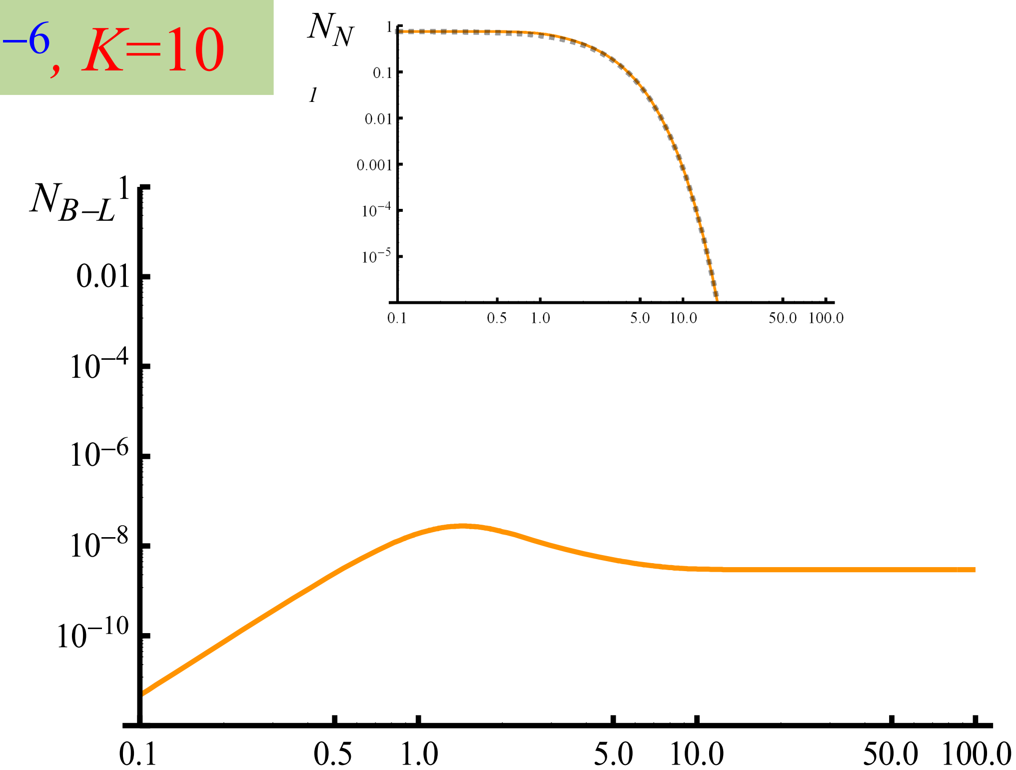
$\varepsilon = 10^{-6}$, K=10



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

vanishing initial abundance



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thermal initial abundance

Set of Boltzmann equations

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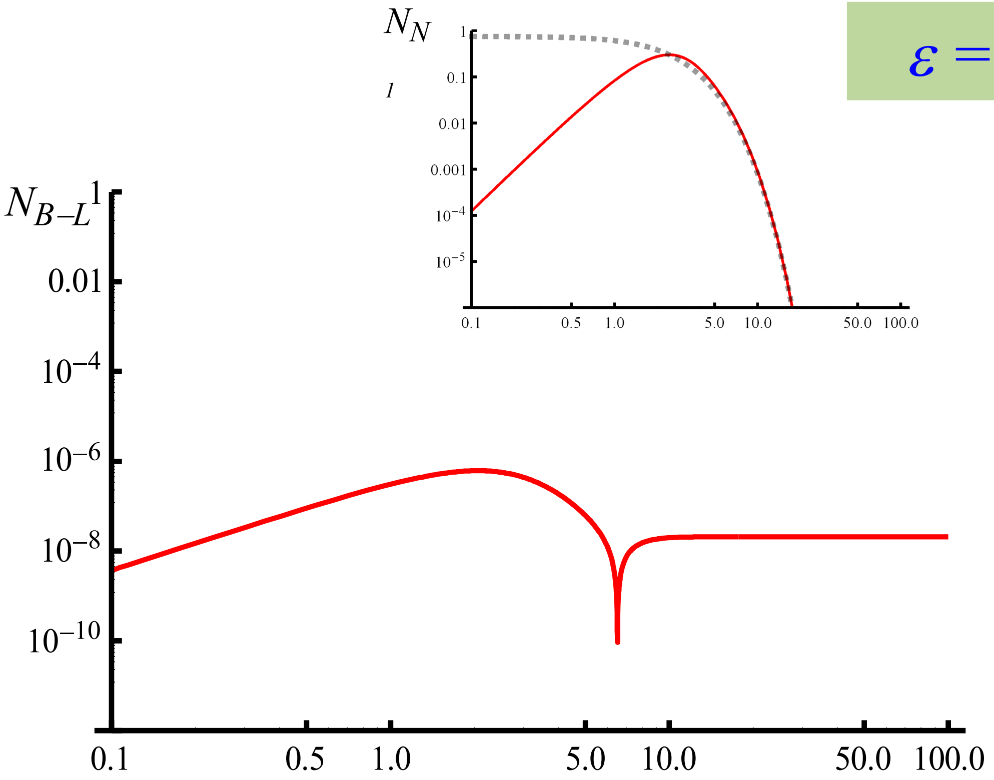
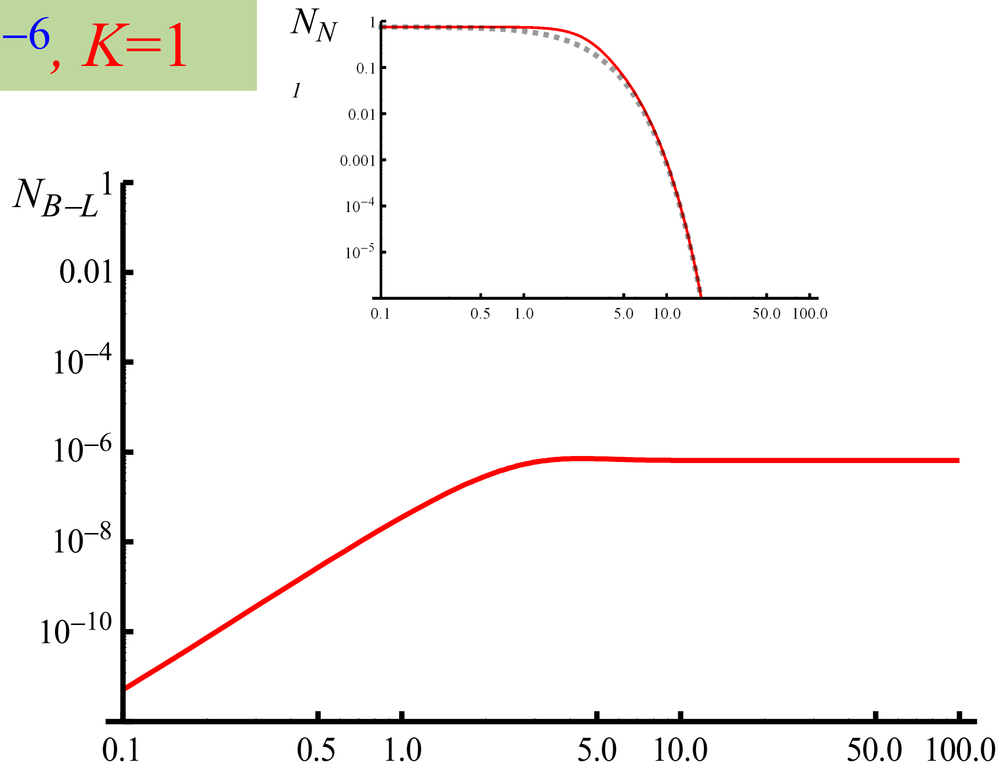
$\varepsilon = 10^{-6}$, $K = 1$



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

vanishing initial abundance



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thermal initial abundance

Set of Boltzmann equations

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

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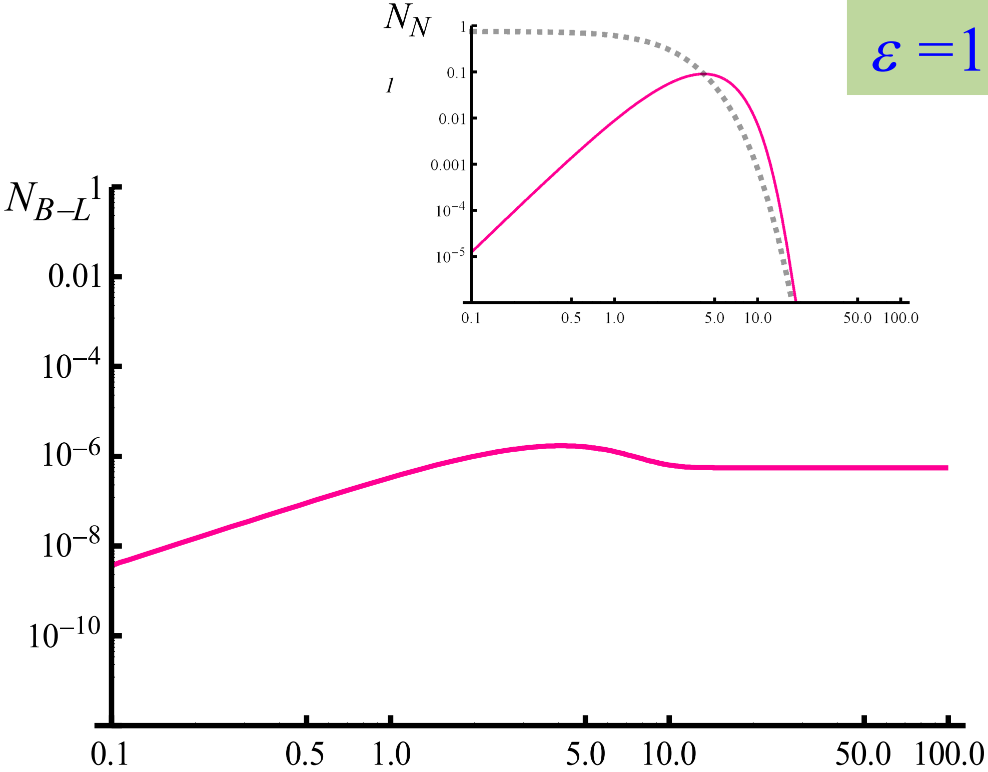
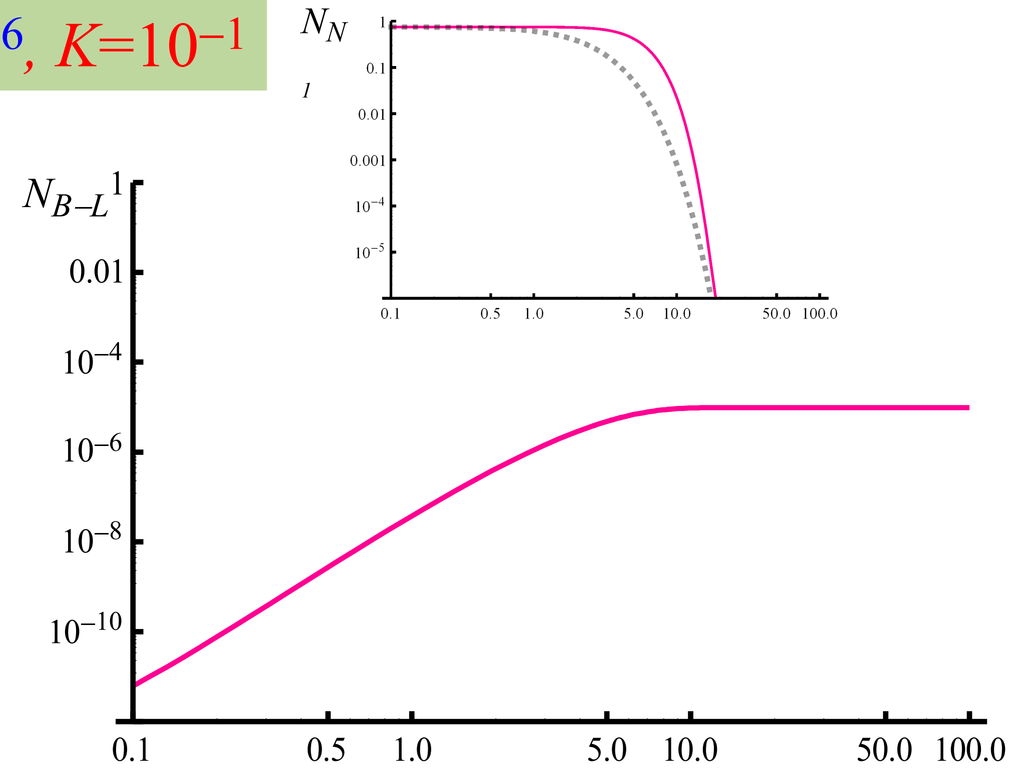


$N^{\mathrm{in}}_{N_1} = 0$

vanishing initial abundance



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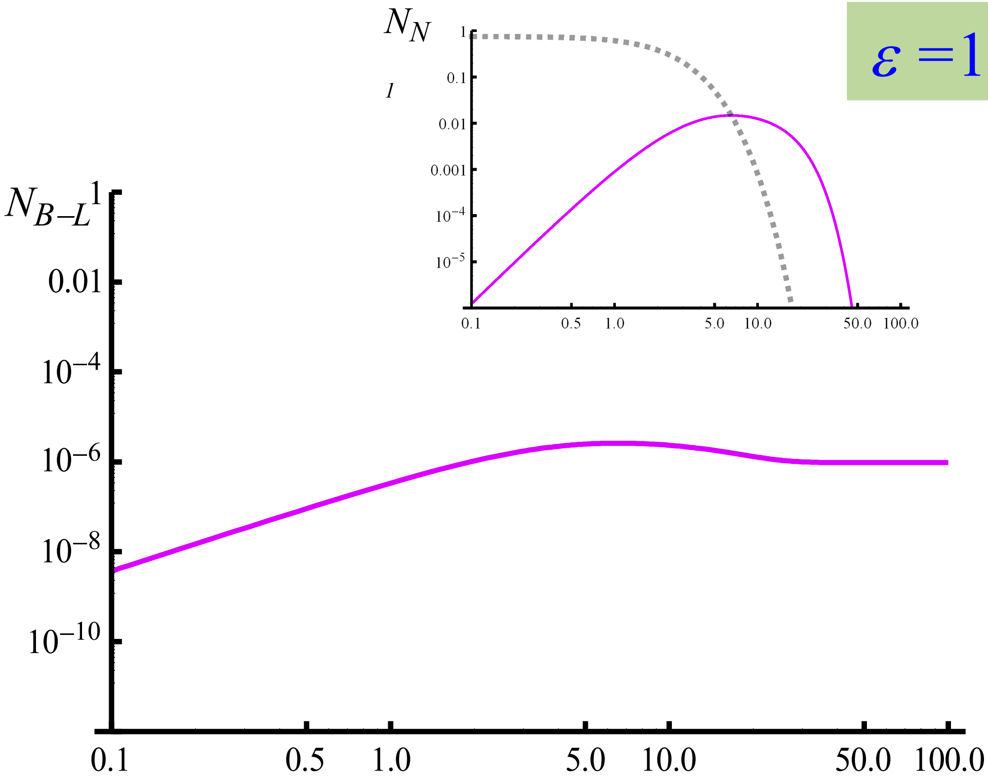
thermal initial abundance

Set of Boltzmann equations

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

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

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



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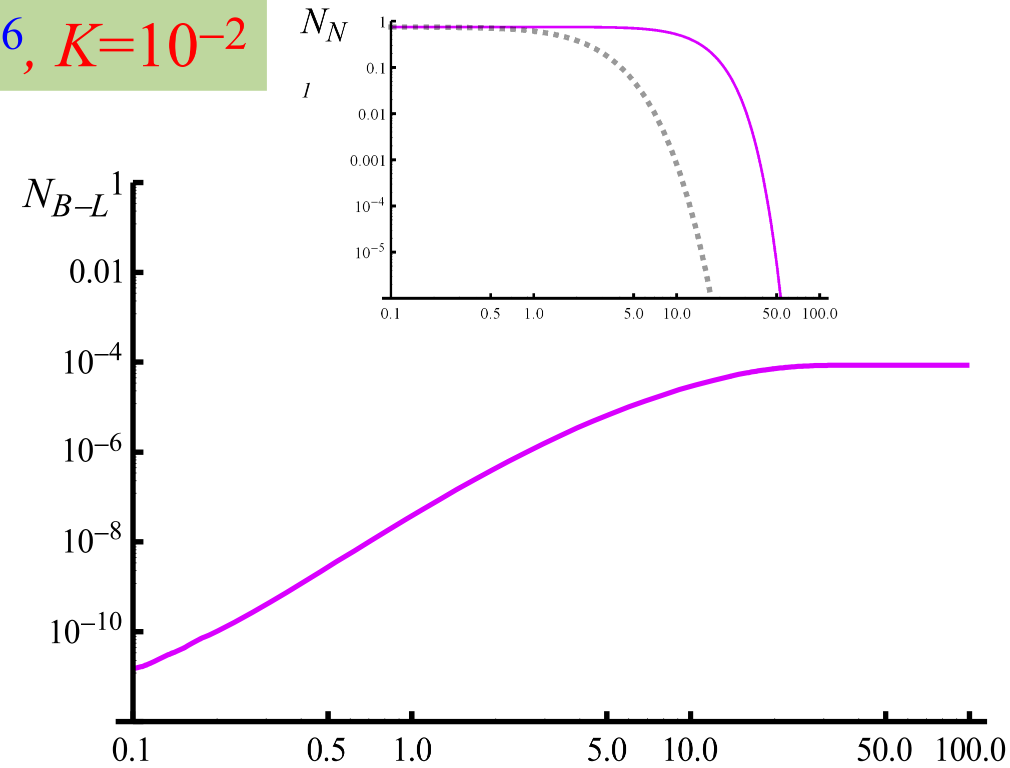

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Set of Boltzmann equations

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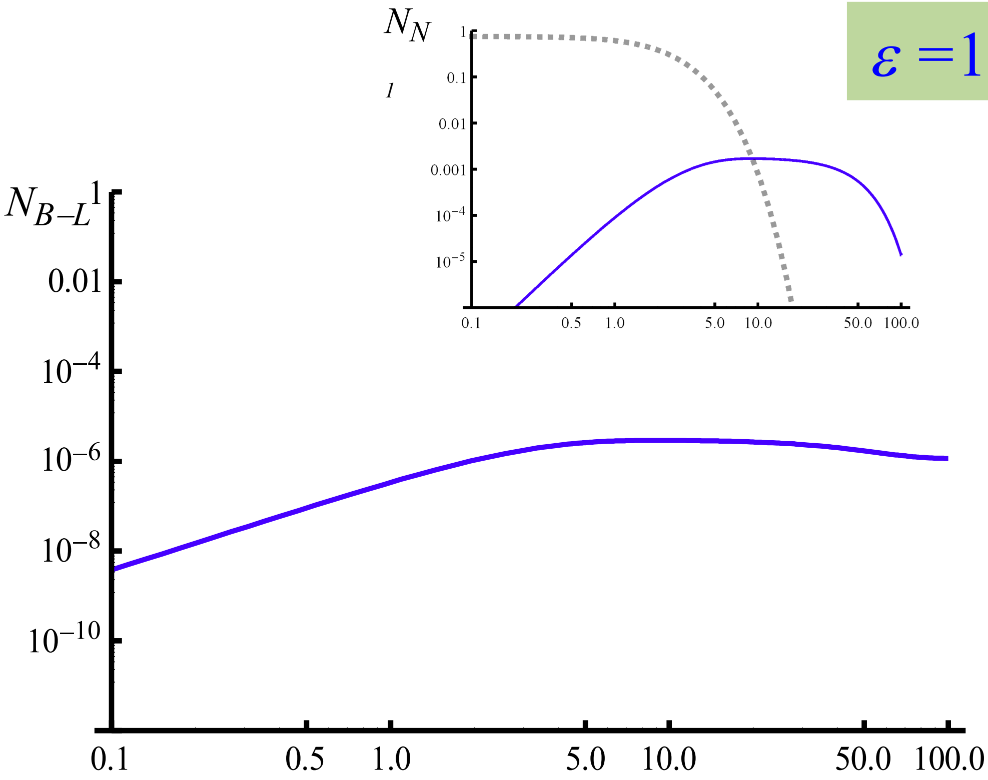
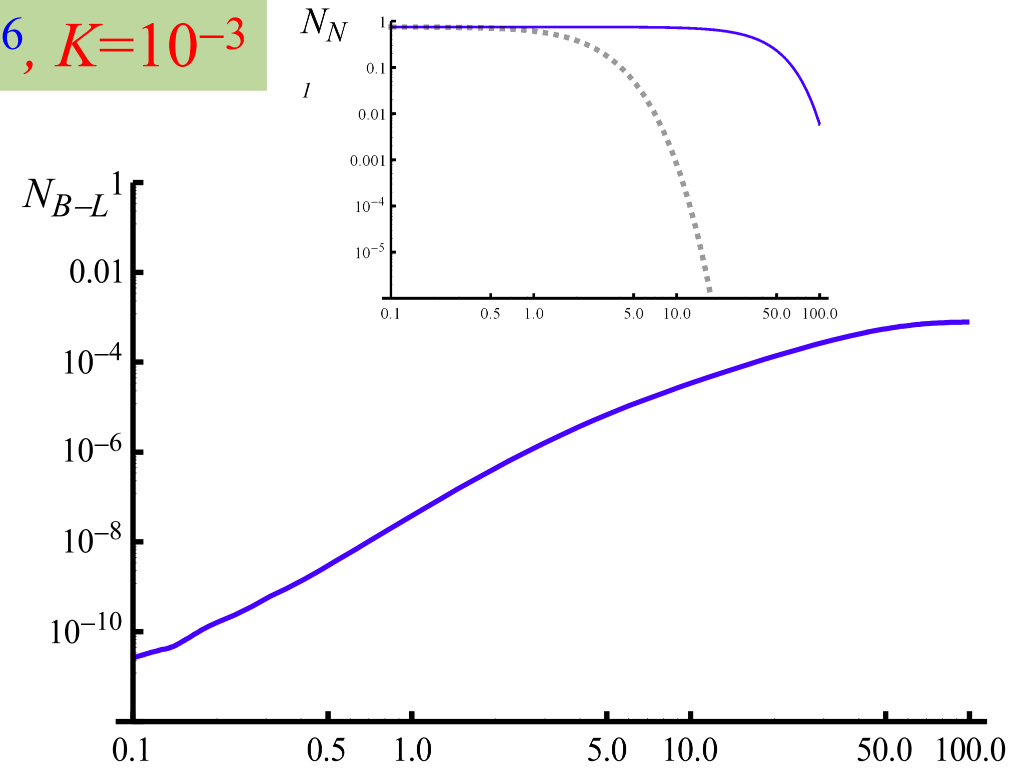
$$\frac{dN_{N_1}(z)}{dz} = -K\, z\frac{K_1(z)}{K_2(z)}(N_{N_1}(z) - N_{N_1}^{\rm eq}(z))$$

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



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

vanishing initial abundance



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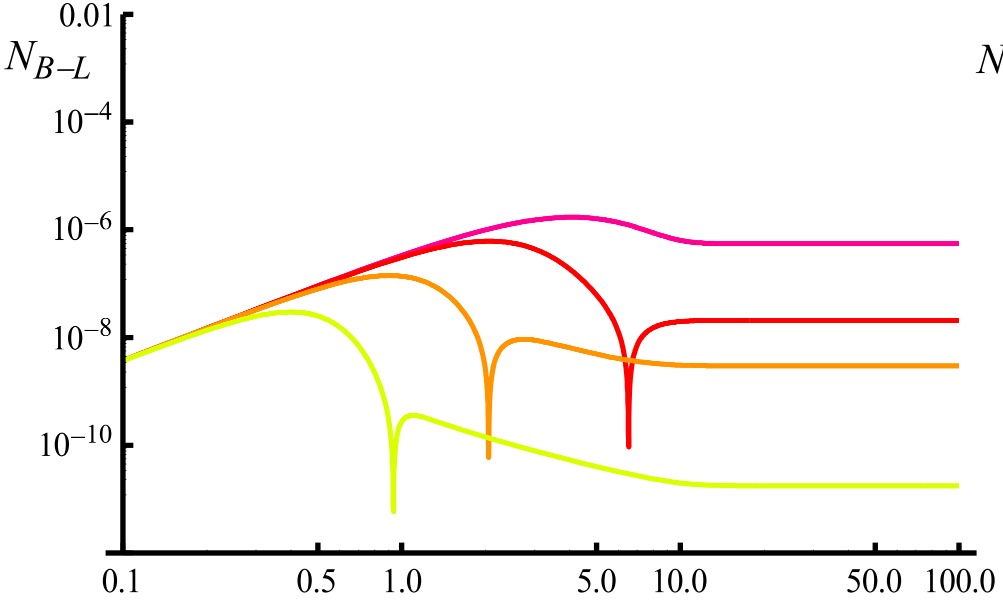
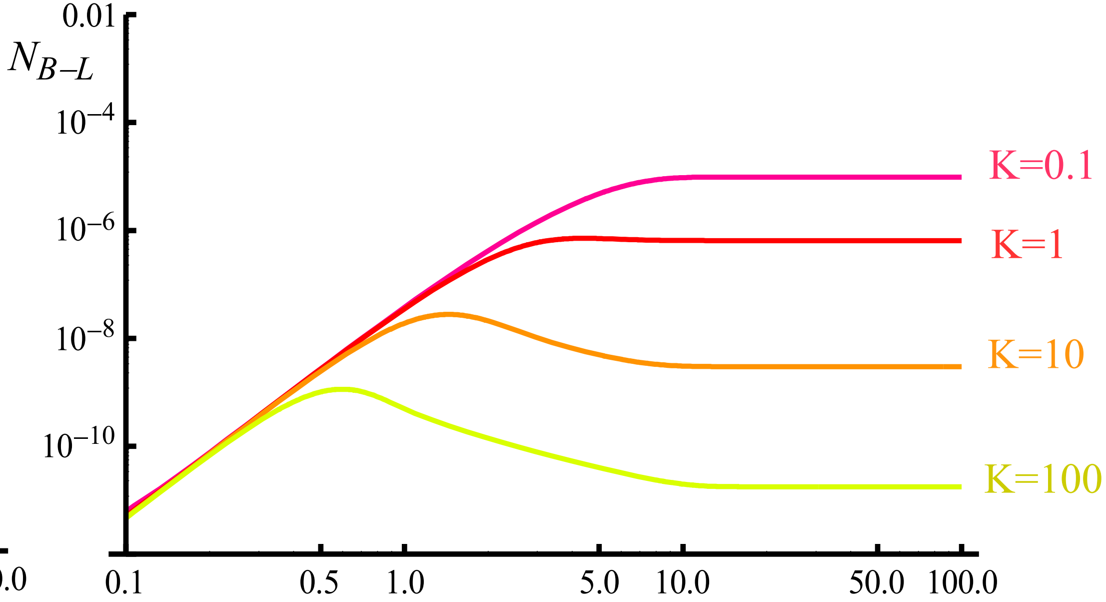
thermal initial abundance

Fixed $\varepsilon = 10^{-6}$



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

vanishing initial abundance



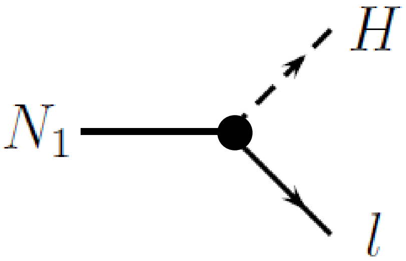
$$N_{N_1}^{\text{in}} = 3/4$$

thermal initial abundance

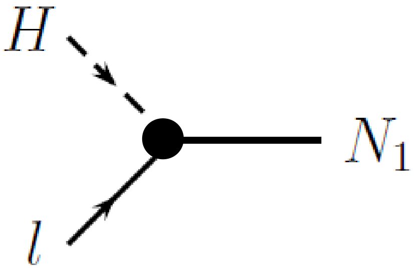
Recapitulation

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

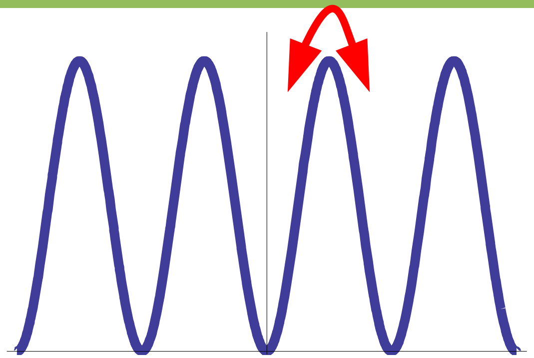
1- Generation of a lepton asymmetry in the decay of the lightest right-handed neutrino.



2- Washout of the lepton asymmetry.



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



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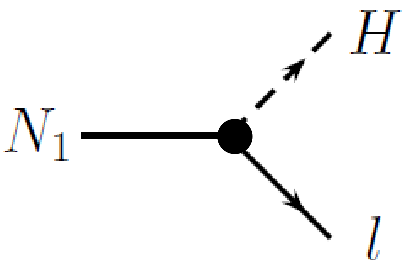
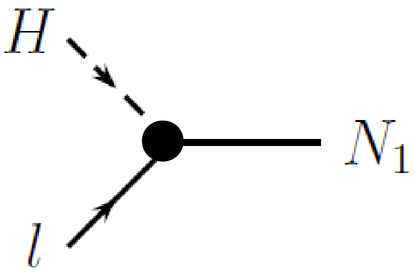


Done!

2- Washout of the lepton asymmetry.



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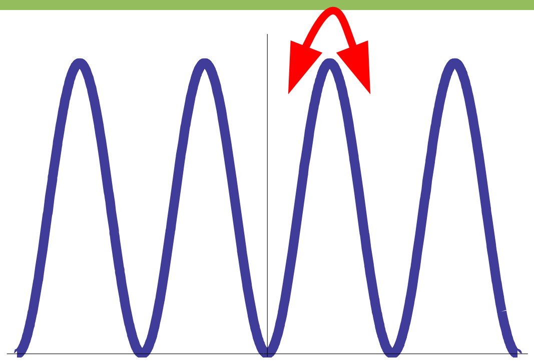

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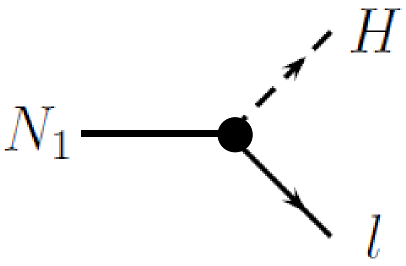
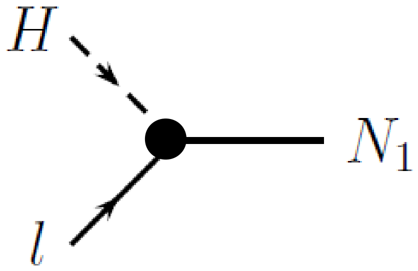


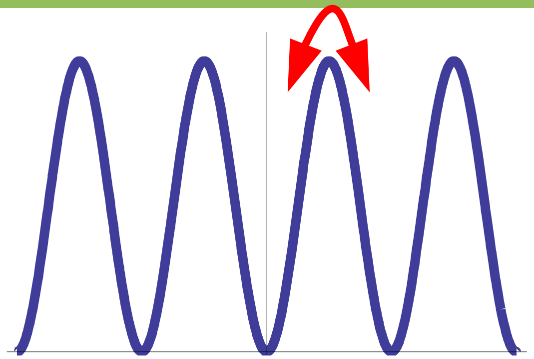
Done!

2- Washout of the lepton asymmetry.



Done!

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



3- Conversion of the lepton asymmetry into a baryon asymmetry

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

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

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

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

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

In equilibrium there are relations among the chemical potentials

- The effective 12-fermion interactions $O_{\mathrm{B+L}}$ 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:

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

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

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

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

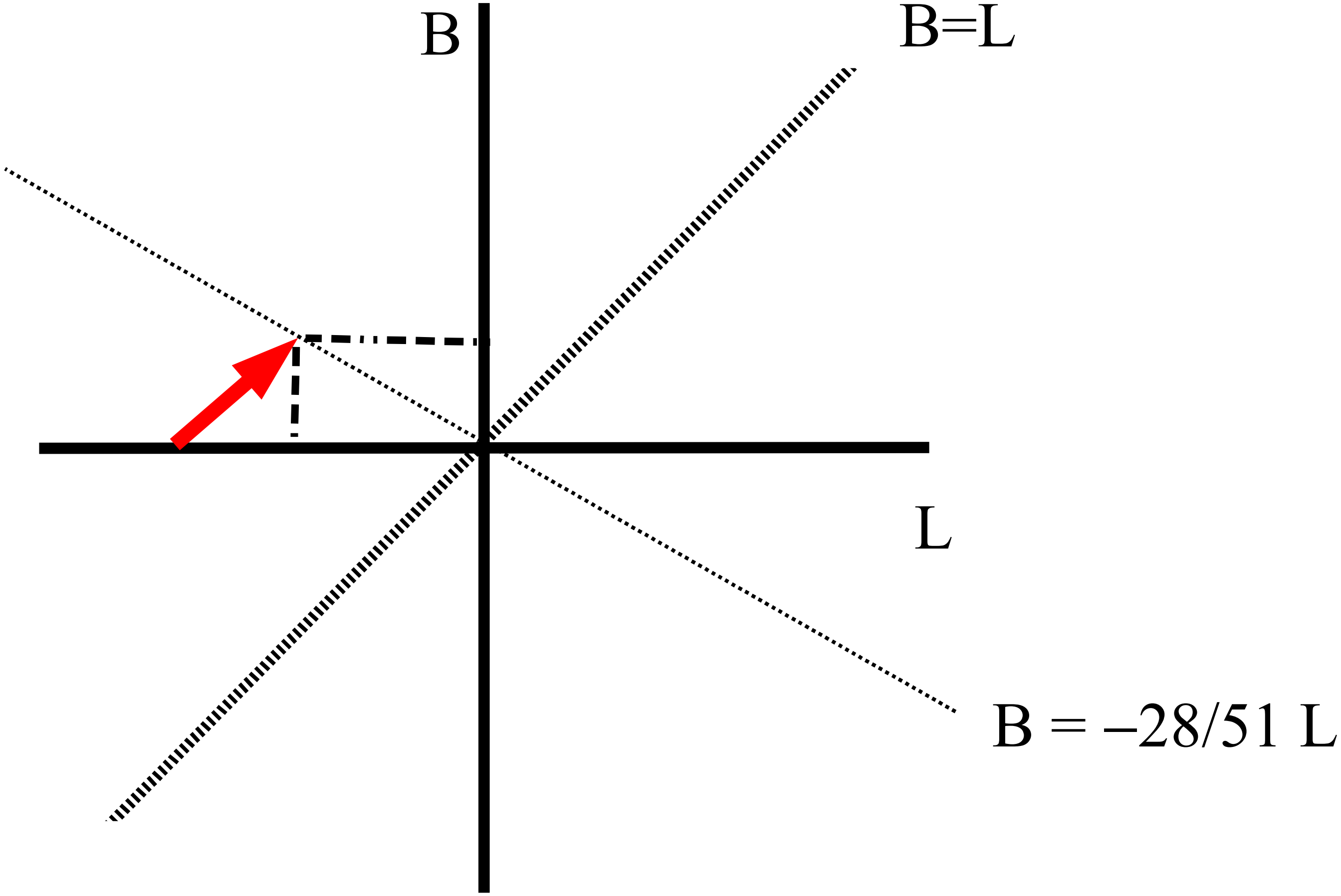
Then $$B = -\frac{4}{3}N_f\mu_\ell\,,\; L = \frac{14N_f^2+9N_f}{6N_f+3}\mu_\ell$$

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

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

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

c=28/79 in the SM with three generations


B
B=L
L
B = –28/51 L

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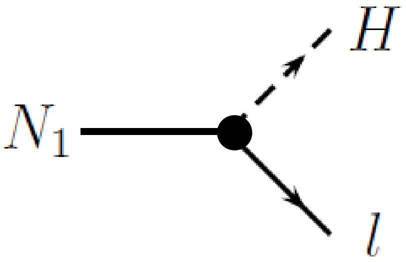
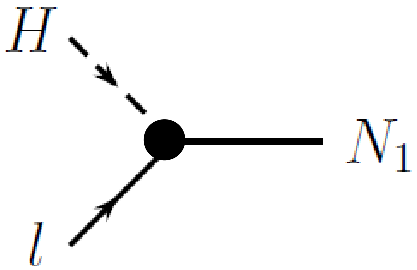


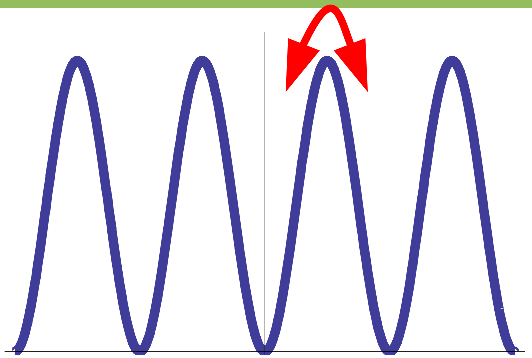
Done!

2- Washout of the lepton asymmetry.



Done!

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



Done!

Recipe to cook a baryon asymmetry

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

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2- Calculate $\epsilon, \quad K = \frac{\widetilde{m}_1}{m_*}$

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

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

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

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

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Recipe to cook a baryon asymmetry

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

2- Calculate $\epsilon, \quad K = \frac{\widetilde{m}_1}{m_*}$

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

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

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

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4-Calculate the baryon-to-photon ratio

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

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

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Sphaleron conversion

$f = N_\gamma^{\mathrm{rec}}/N_\gamma^* = 2387/86$

Dilution factor due to photon production between leptogenesis and recombination

Recipe to cook a baryon asymmetry

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

A CRUCIAL QUESTION...

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

See-saw parameters

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

Neutrino masses and mixing angles

Leptogenesis

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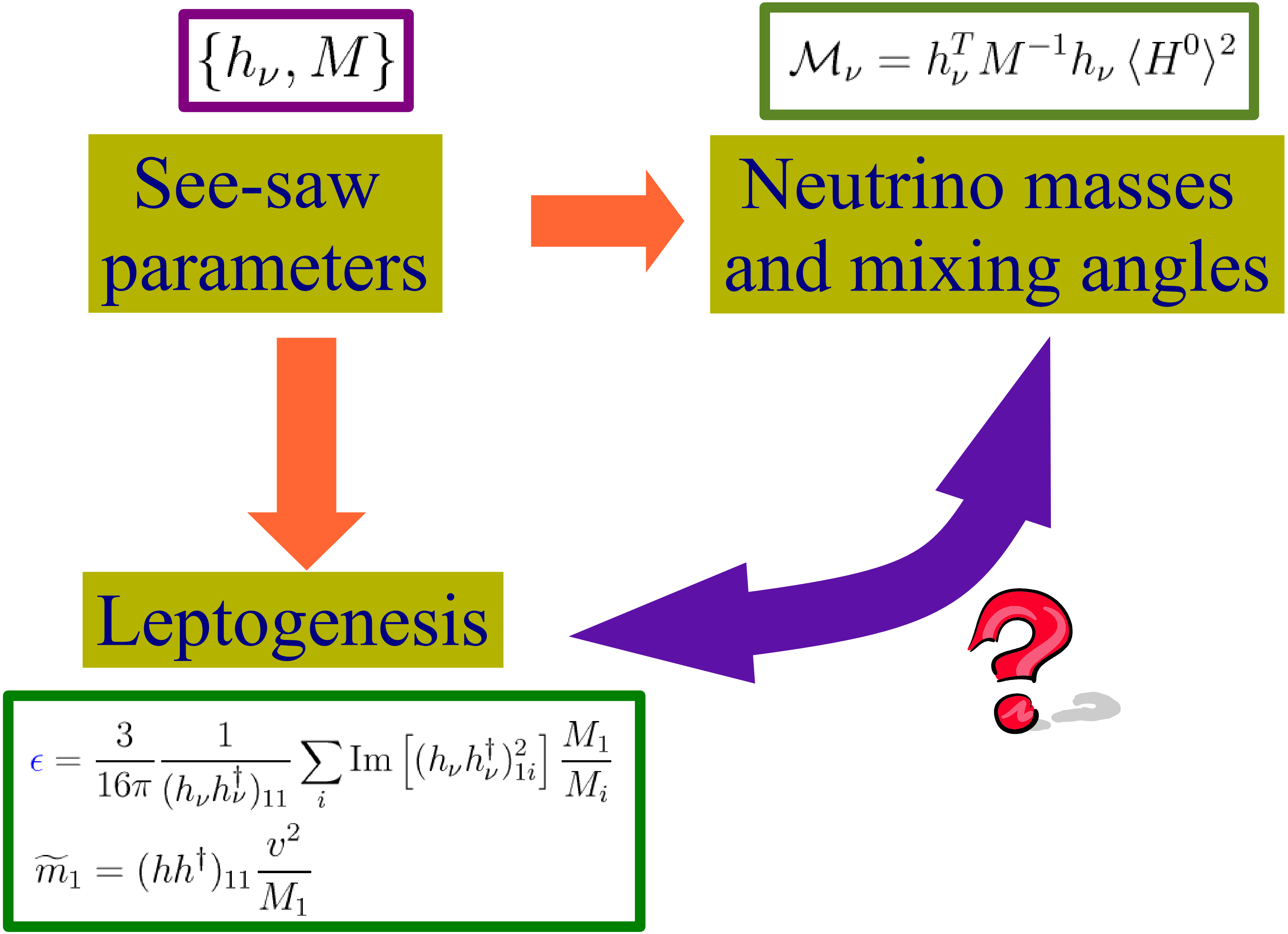

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The connection is not simple...

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

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

M has 3 real parameters

h_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

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

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

Does leptogenesis make any prediction?

How to test/rule-out leptogenesis?

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How to test/rule-out leptogenesis?

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

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

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

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

1- Upper bound on the CP asymmetry

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

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

Davidson, AI

If the light neutrino spectrum is also hierarchical

$$\boxed{|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m^2_{\rm atm}}}{\langle H^0 \rangle^2}}$$

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

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

The baryon asymmetry from leptogenesis can be approximated by:

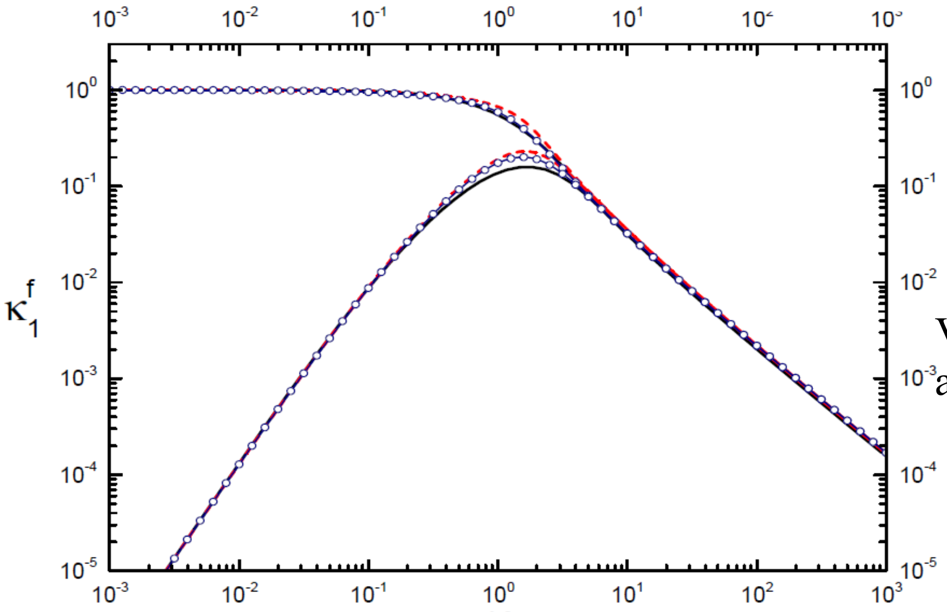
$$\eta_B \simeq 0.96 \times 10^{-2}\, \epsilon_1 \kappa$$

where η_B=(6.11±0.19)×10^{-10} (WMAP) and κ is an “efficiency factor”

From the upper bound on the CP asymmetry $$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1 \sqrt{\Delta m^2_{\rm atm}}}{\langle H^0 \rangle^2}$$

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

$$M_1 \gtrsim \frac{6 \times 10^8\,\mathrm{GeV}}{\kappa}$$



thermal initial abundance

$\kappa \lesssim 1$ ➡ $\boxed{M_1 \gtrsim 6 \times 10^8\,\mathrm{GeV}}$

Vanishing initial abundance

$\kappa \lesssim 0.2$ ➡ $\boxed{M_1 \gtrsim 3 \times 10^9\,\mathrm{GeV}}$

Davidson, AI

Neutrino masses are generated at VERY high energies

2- Upper bound on the neutrino mass

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

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

The larger the scale of neutrino masses, the smaller the CP asymmetry.

For large neutrino masses, it is more difficult to generate a BAU!

- Furthermore, the washout rate due to ΔL=2 scatterings goes as:

$$\Delta W \propto M_1 \overline{m}^2$$

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

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

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For $\overline{m}$>0.20 eV, leptogenesis is no longer possible.
This corresponds to m_i>0.11 eV

Buchmüller, Di Bari, Plümacher

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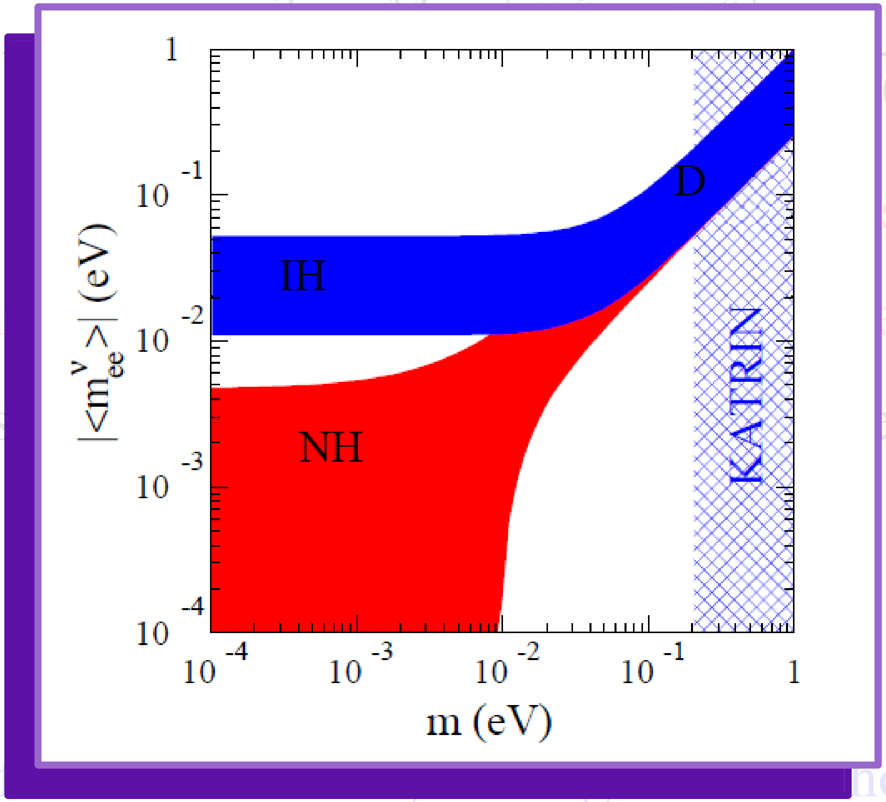

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Conclusions

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

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

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

- How to test leptogenesis? The observation of $\nu 0\beta\beta$ decay would give support to the leptogenesis scenario, however a "smoking gun" for leptogenesis is still lacking.