# Leptogenesis

**Koichi Hamaguchi** (University of Tokyo)

Revealing the history of the universe
with underground particle and nuclear research 2019
@ Tohoku Univ., March. 7, 2019.

Mostly review

+ partially based on
K. Asai, KH, N. Nagata, S. Tseng, K. Tsumura, [arXiv:1811.07571]
K. Asai, KH, N. Nagata, [arXiv:1705.00419]

See the poster by
**Shih-Yen Tseng**
tomorrow!

# Plan

- Baryon Asymmetry of the Universe
- Why ``Lepto"genesis?
- Right-handed Neutrino's triple role
- Various Leptogenesis scenarios
- Predictions of minimal gauged $U(1)_{L\alpha-L\beta}$ models
- Summary

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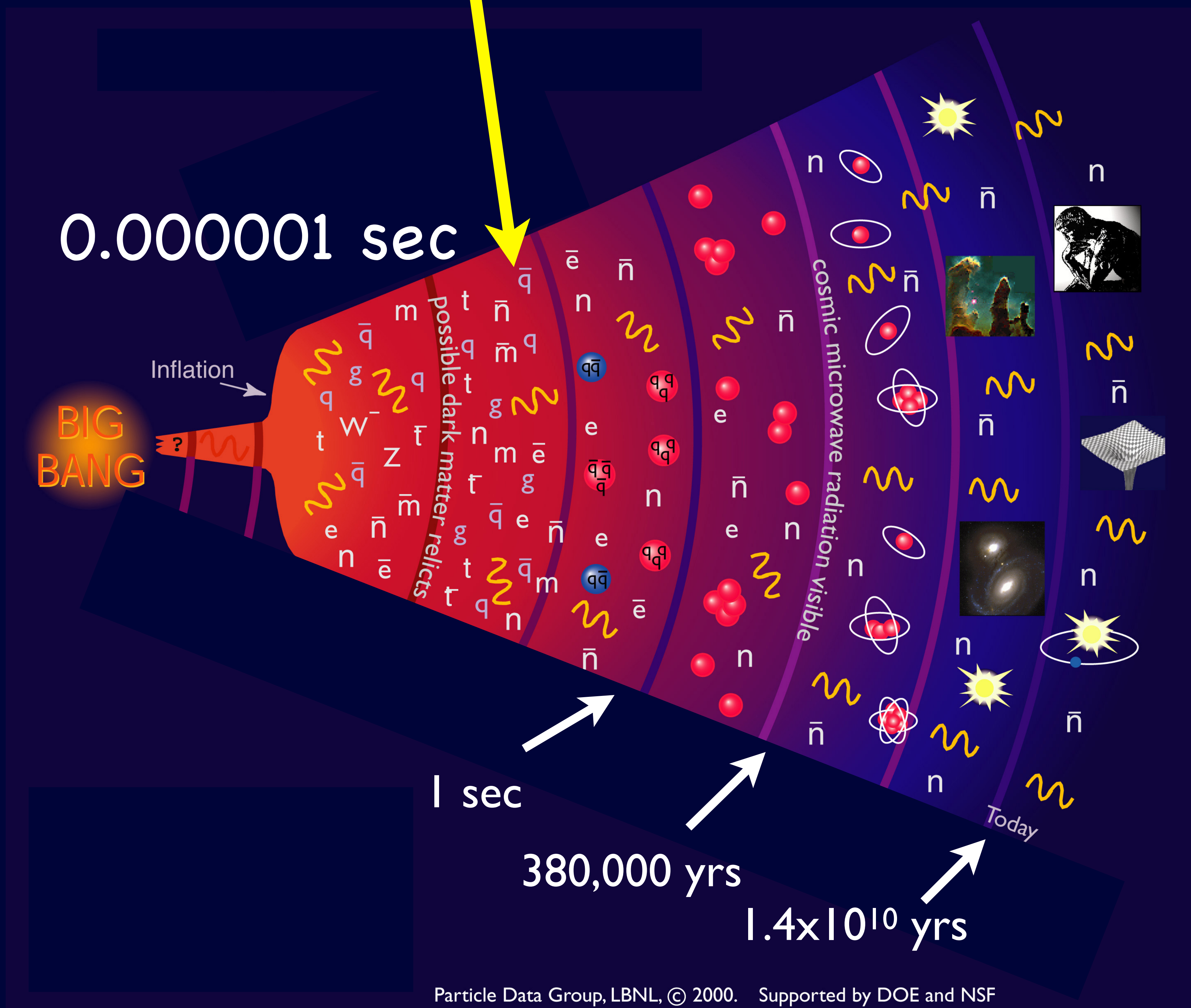
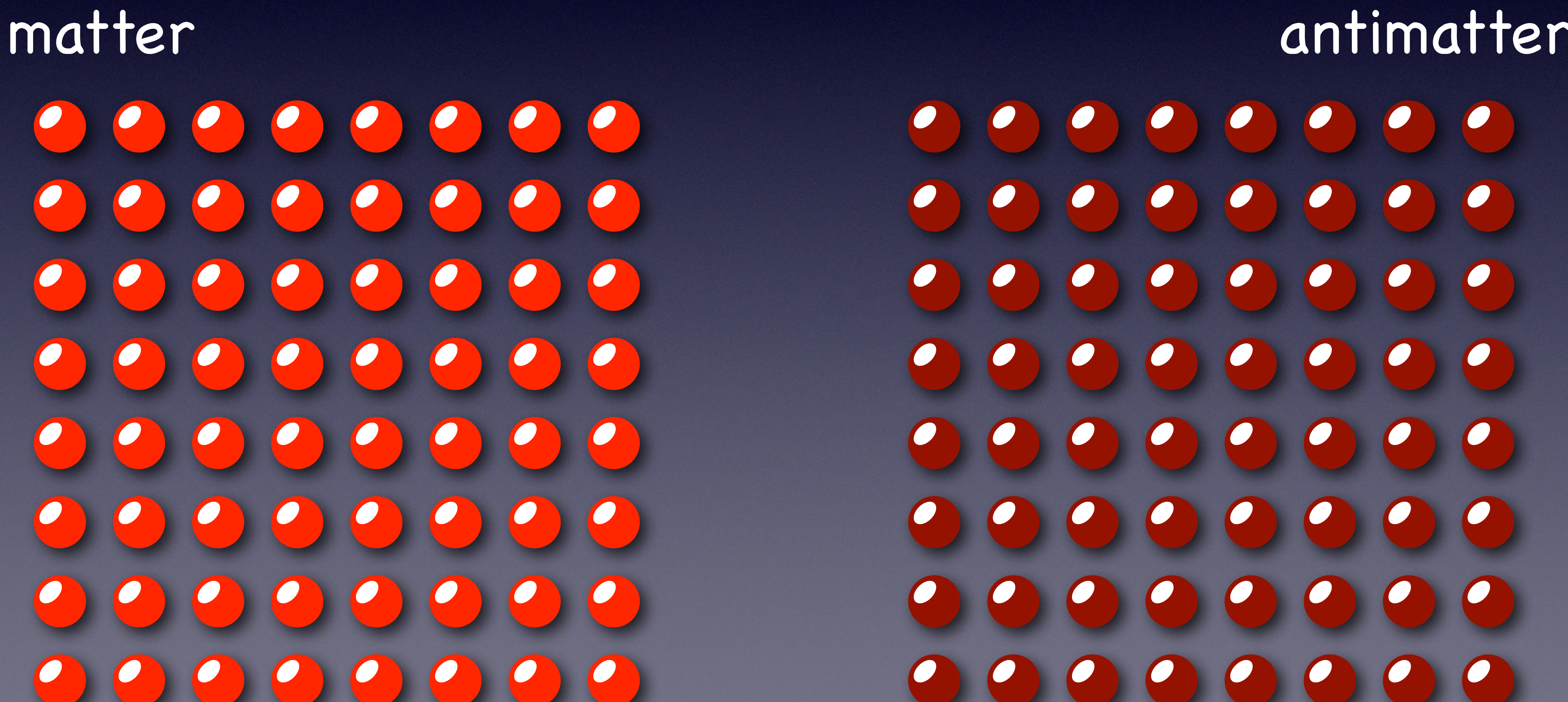
# In the very early Universe,....




http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

In the very early Universe,....

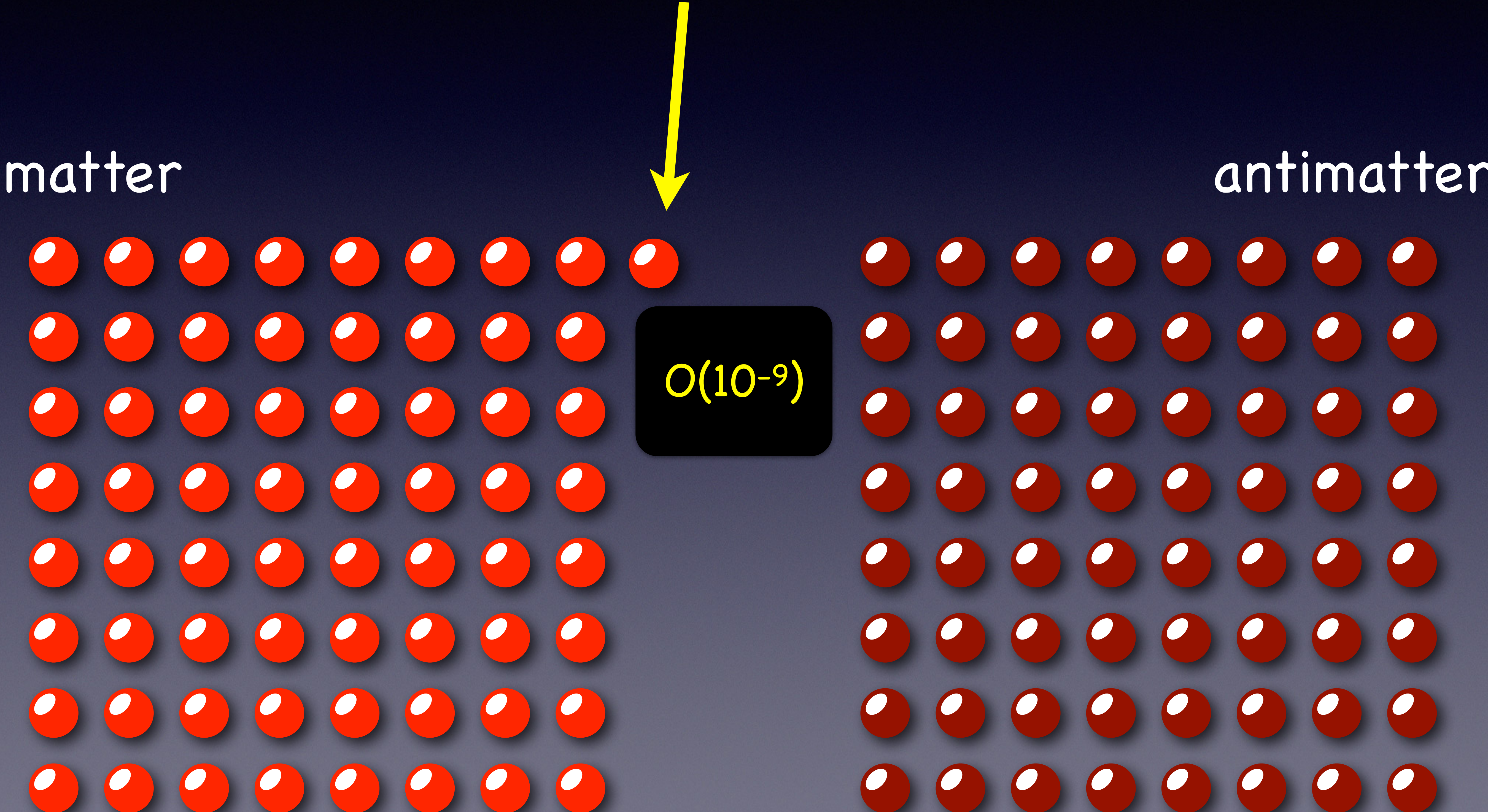
The number of particles and anti-particles were almost the same.



In the very early Universe,....

The number of particles and anti-particles were almost the same.

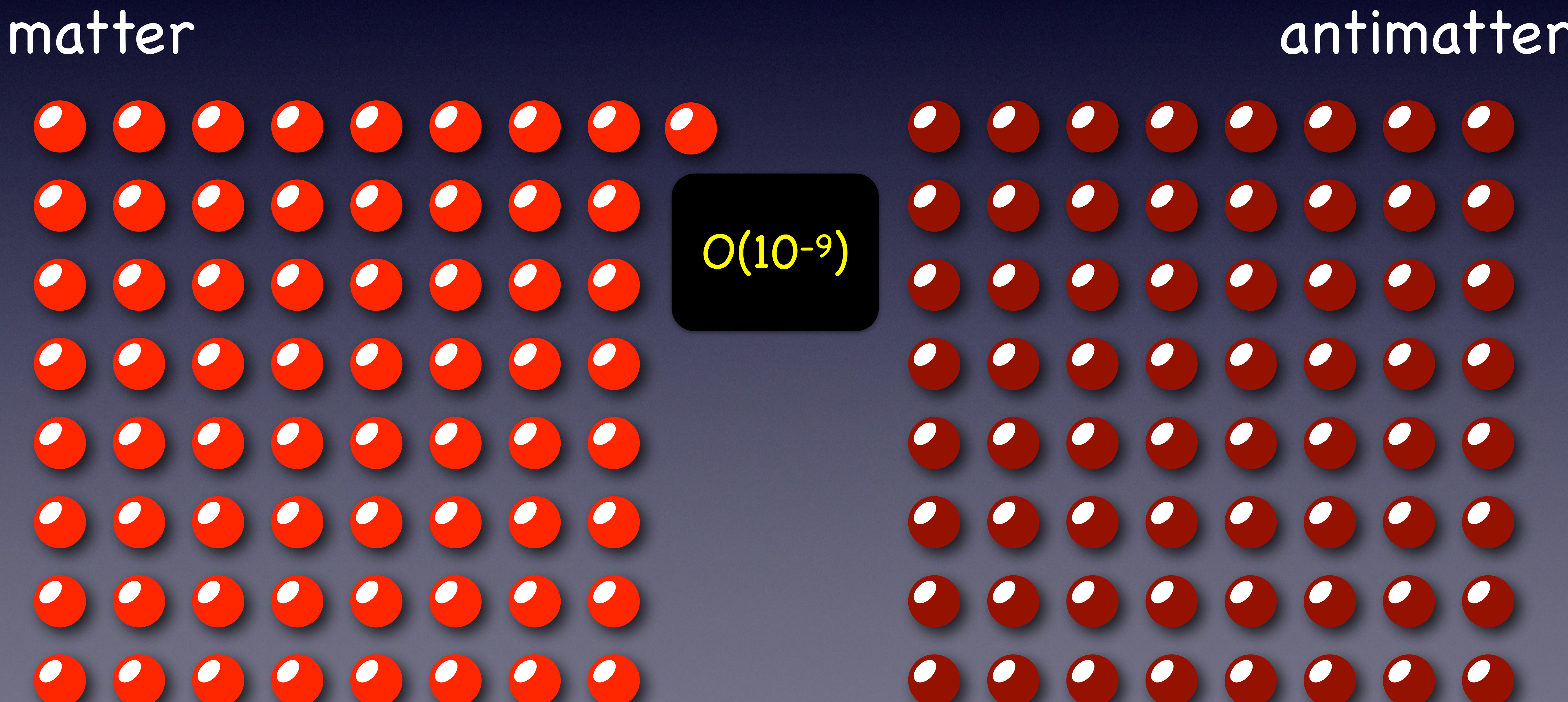
But there was tiny excess of matter over anti-matter.



In the very early Universe,....

The number of particles and anti-particles were almost the same.

When the Universe got cooler, they **pair-annihilated,..**



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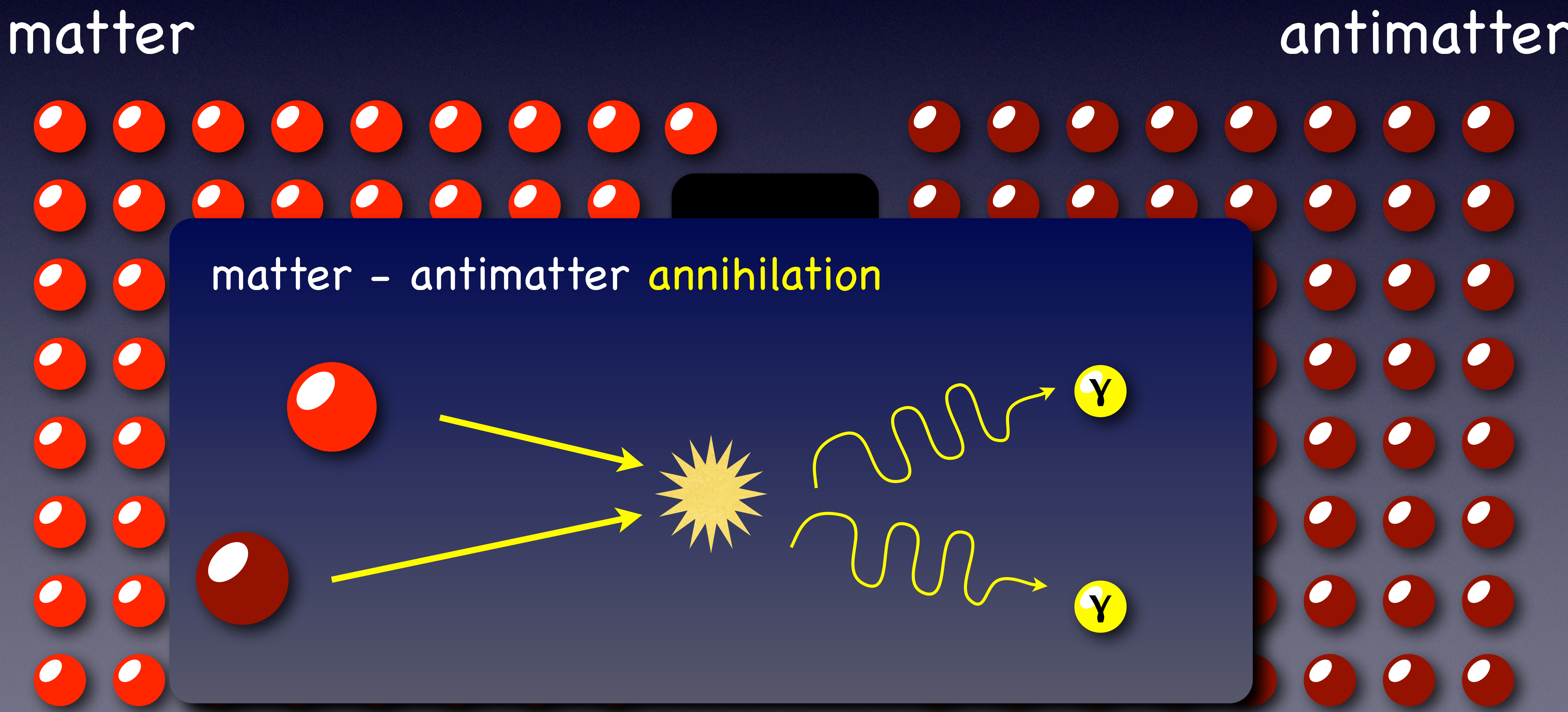


In the very early Universe,....

The number of particles and anti-particles were almost the same.

When the Universe got cooler, they **pair-annihilated,..**

matter

antimatter

$O(10^{-9})$

In the very early Universe,....

The number of particles and anti-particles were almost the same.

When the Universe got cooler, they **pair-annihilated,..**

only matter remains

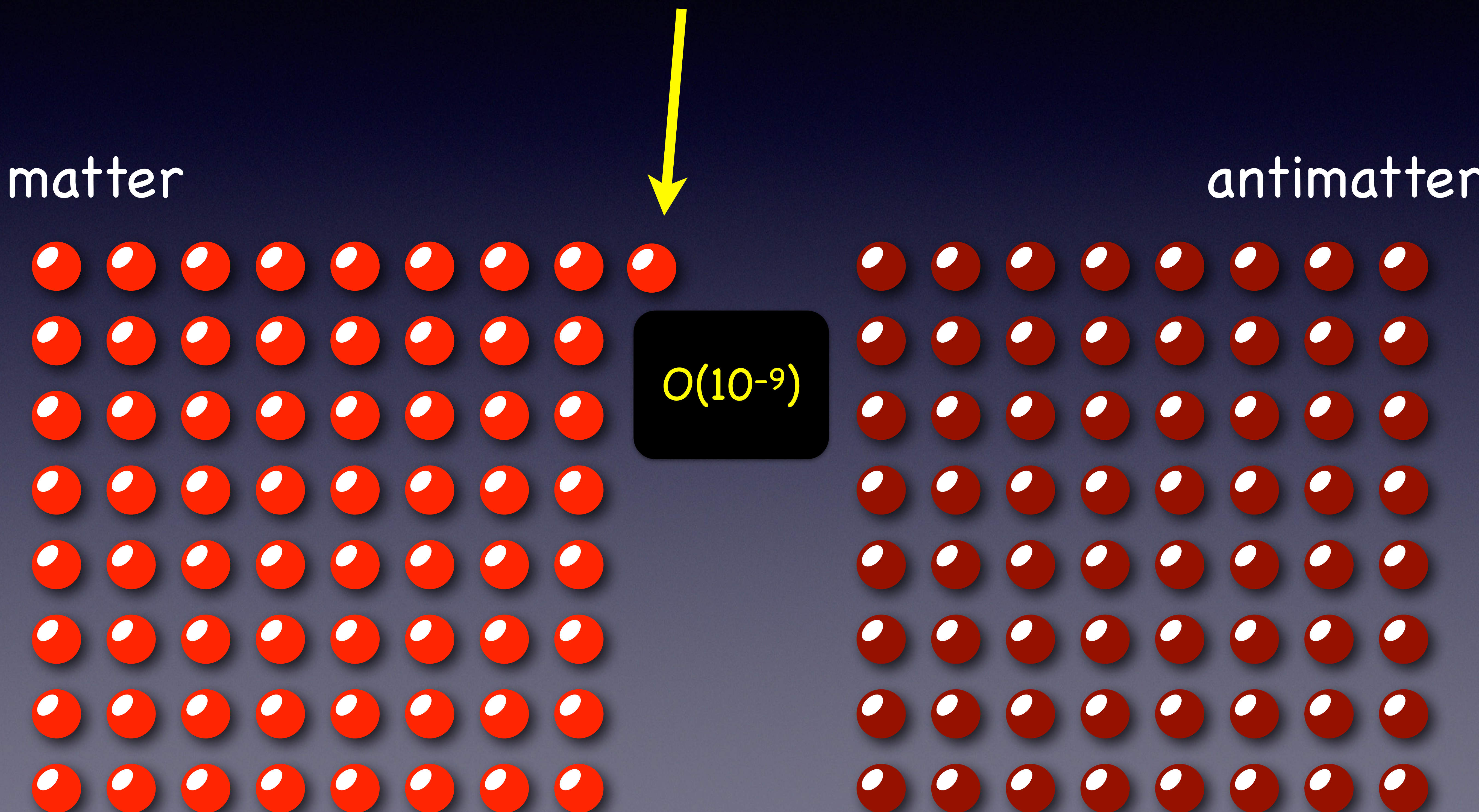
(no antimatter)

All of us (Galaxy, the Earth, the human beings,...)

are made from this leftover matter.

# Puzzle

How was the initial excess of matter created ?



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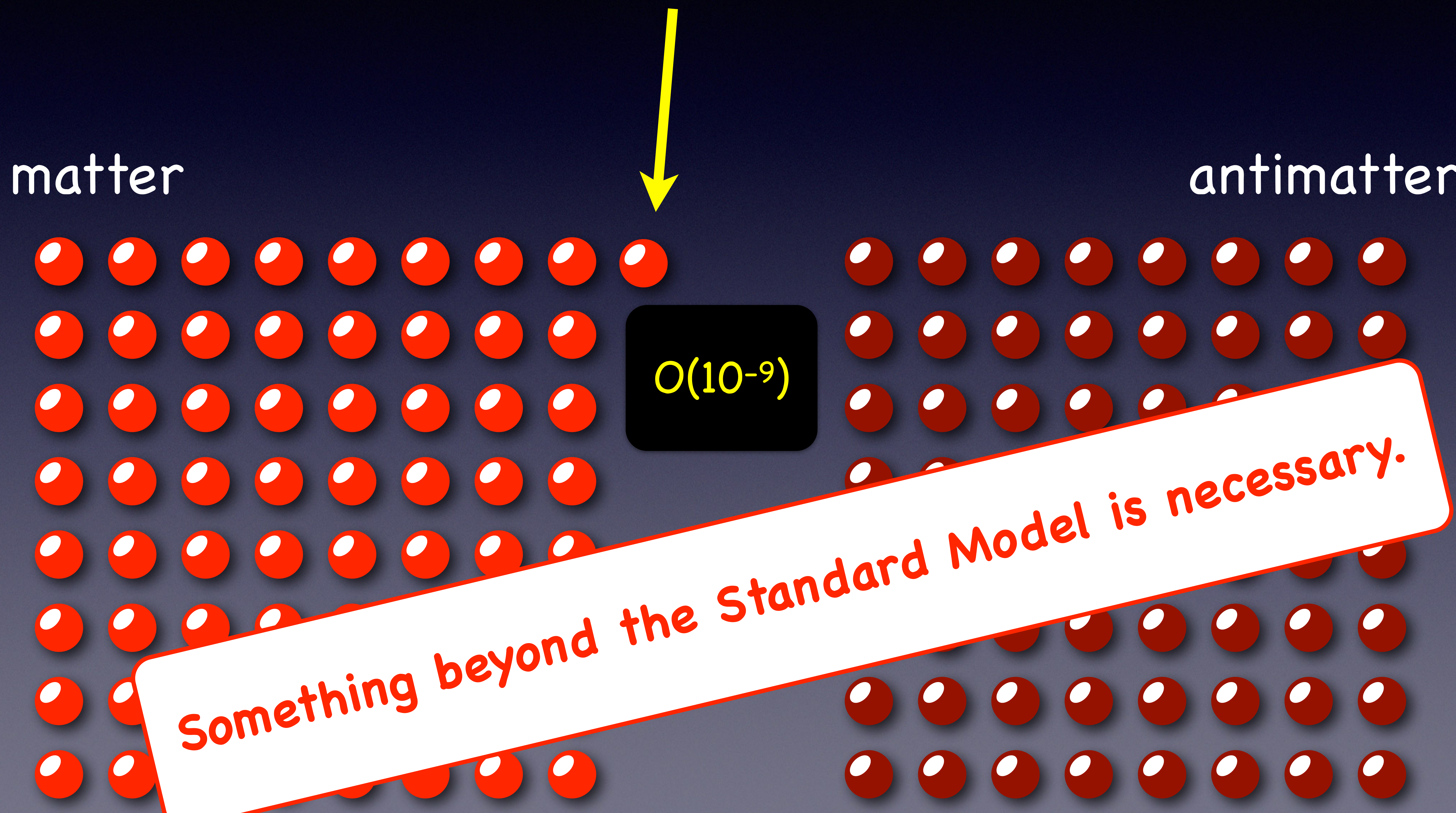


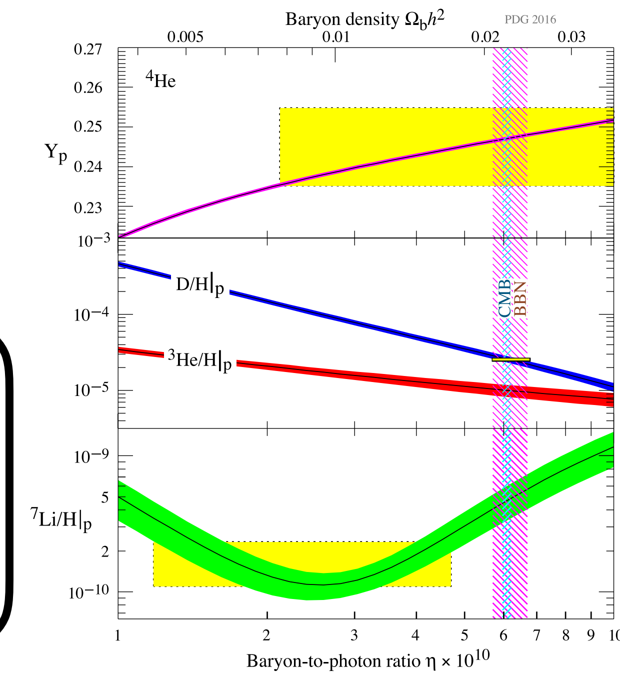
# Observations (two independent evidences)

## (1) Big Bang Nucleosynthesis (BBN)

(cosmic time about 1 sec)

$$5.8 \leq \eta_{10} \leq 6.6 \ (95\% \ \mathrm{CL}).$$

$$\longleftrightarrow \ 0.021 \leq \Omega_b h^2 \leq 0.024 \ (95\% \ \mathrm{CL})$$



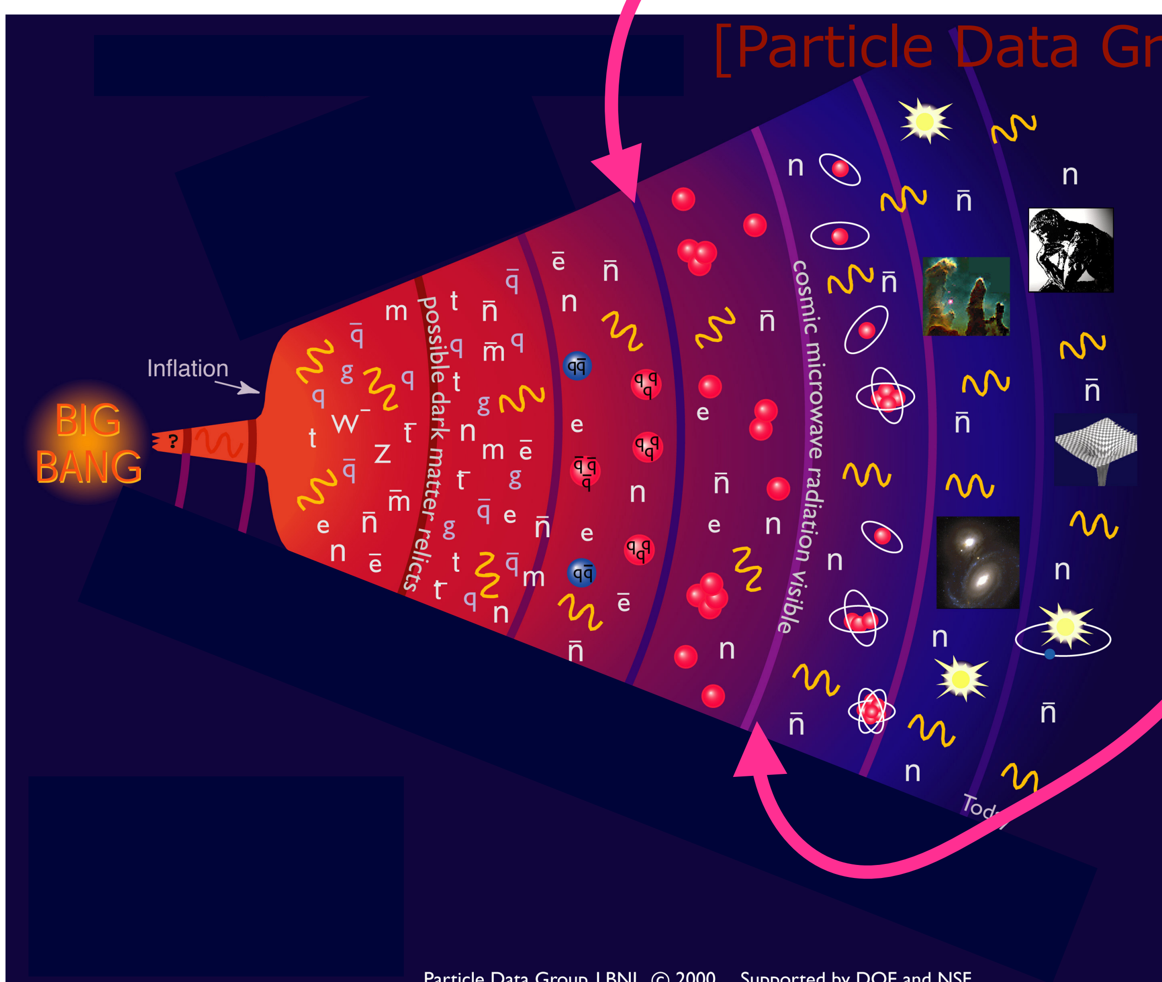

He4

D

Li7

**Figure 24.1:** The primordial abundances of $^4$He, D, $^3$He, and $^7$Li as predicted by the standard model of Big-Bang nucleosynthesis—the bands show the 95% CL range [5]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL).

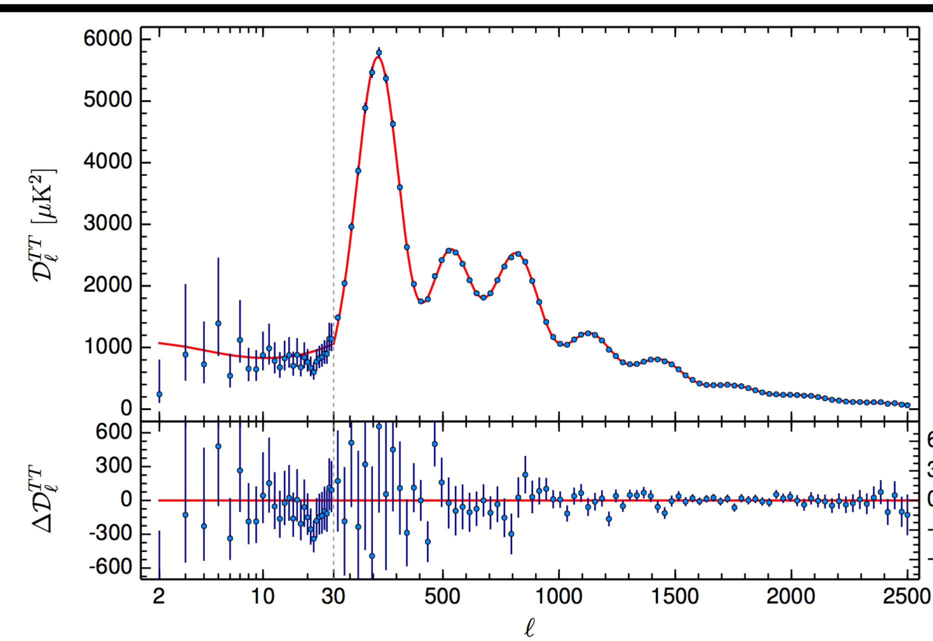
[Particle Data Group]




## (2) Cosmic Microwave background

(cosmic time about 400,000 yrs)

$$\Omega_b h^2 \ \ldots \ 0.02222 \pm 0.00023 \ (68\%)$$



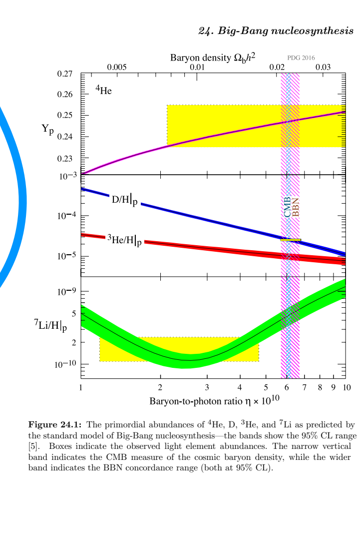

[Planck 2015]

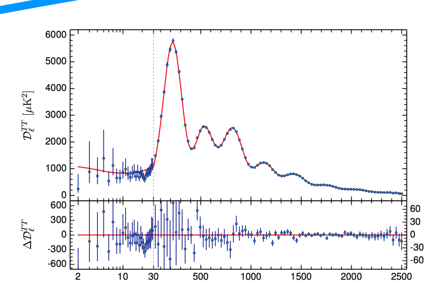
# **When** was the Baryon Asymmetry of the Universe generated?

| time | temperature | |
|---|---|---|
| ?? | ?? | Inflation |
| | $T_R$ | Reheating |
| 1 sec | 100 GeV | Electroweak phase transition |
| | 1 GeV | QCD phase transition |
| | 1 MeV | Big Bang Nucleosynthesis |
| 400,000 yrs | 3000 K | Last Scattering Surface |
| 14 billion yrs | 3 K | Now |

**sometime in this range**

CMB



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# Why "Lepto"genesis?

## Within the Standard Model,...

Both Baryon # (B) and Lepton # (L) are conserved at classical level.

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 0$$

However, B and L are violated at quantum level! ['t Hooft,'76]

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = N_f \frac{g_2^2}{32\pi^2} \epsilon_{\mu\nu\rho\sigma} \mathrm{Tr} F^{\mu\nu} F^{\rho\sigma} \neq 0$$

**Note:** B-L is conserved

$$\partial_\mu (J_B^\mu - J_L^\mu) = 0$$

Although there is essentially no effect at low energy,...

$$\Gamma_{\not B, \not L} \sim e^{-16\pi^2/g_2^2} \sim 10^{-170}$$

# Why "Lepto"genesis?

## Within the Standard Model,...

**At high temperature, T >> 100 GeV,**

**B and L violating processes (sphaleron)**

**become very rapid, and in thermal equilibrium!**

[Kuzmin, Rubakov, Shaposhnikov,'85]

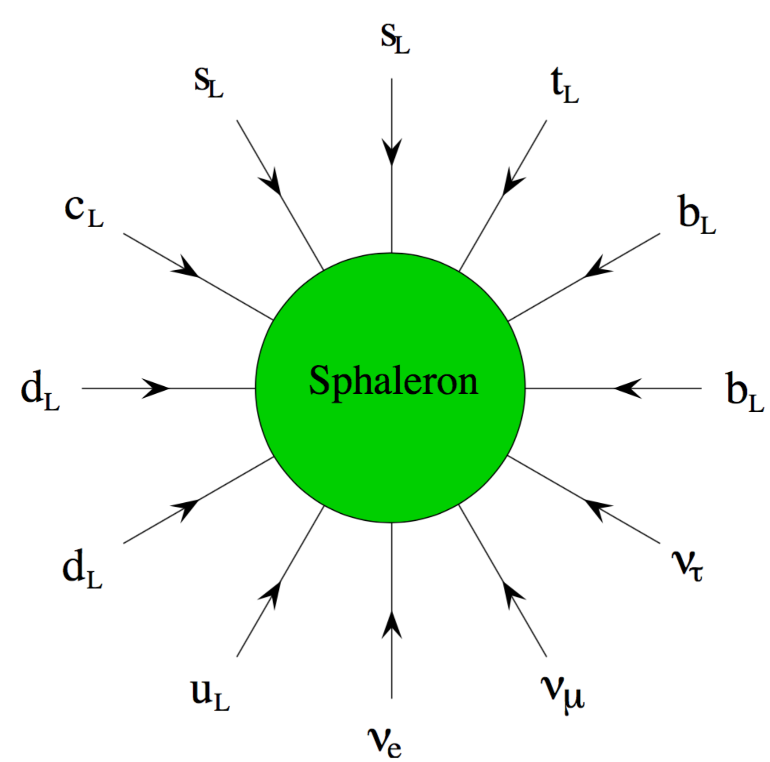


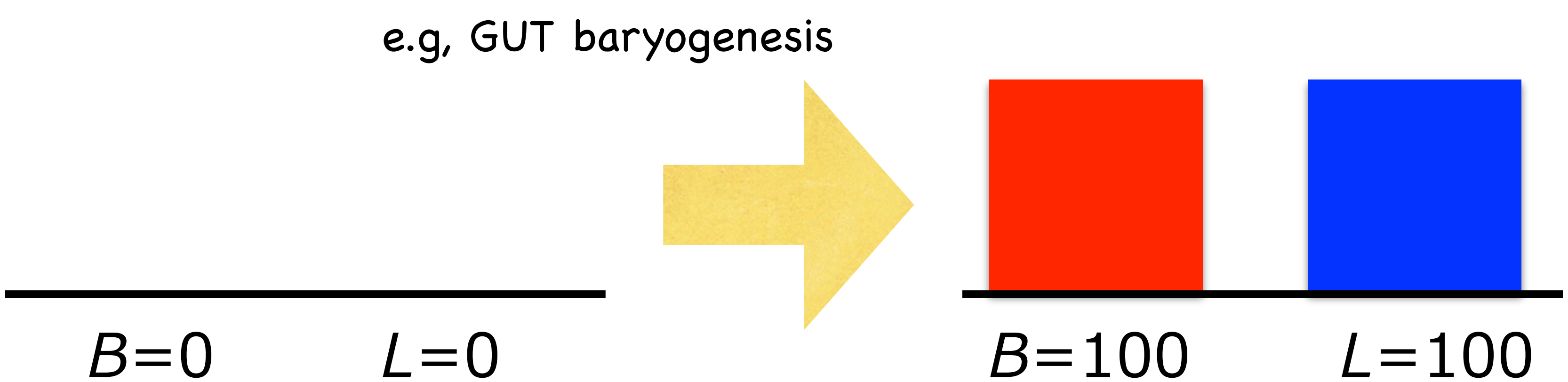

Figure 1: One of the 12-fermion processes which are in thermal equilibrium in the high-temperature phase of the Standard Model.

[fig. from W.Buchmuller, 1210.7758]

**Sphaleron process**

processes involving 9 quarks (B=3) and 3 leptons (L=3).
Note that B-L is conserved.

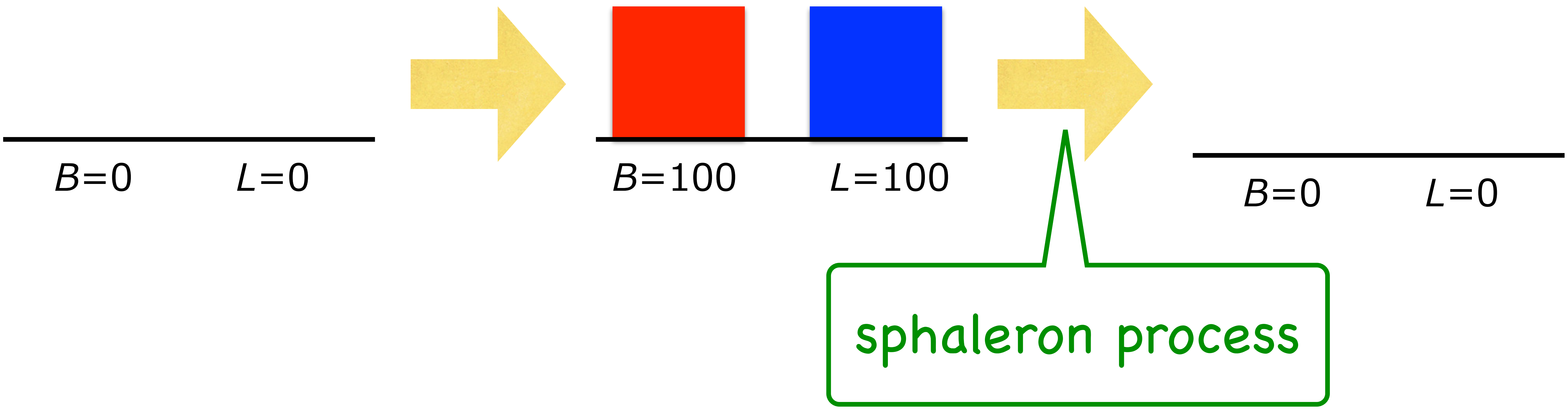
Therefore, if the Baryon asymmetry is generated via a **B-L conserving process,...**

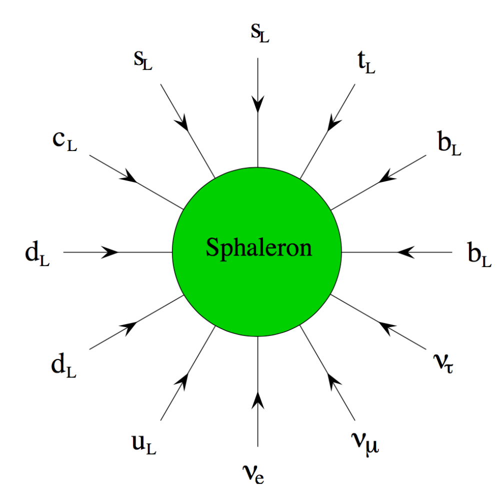


Therefore, if the Baryon asymmetry is generated via a **B-L conserving process,...**

**Finally B=0 at equilibrium.**

e.g, GUT baryogenesis



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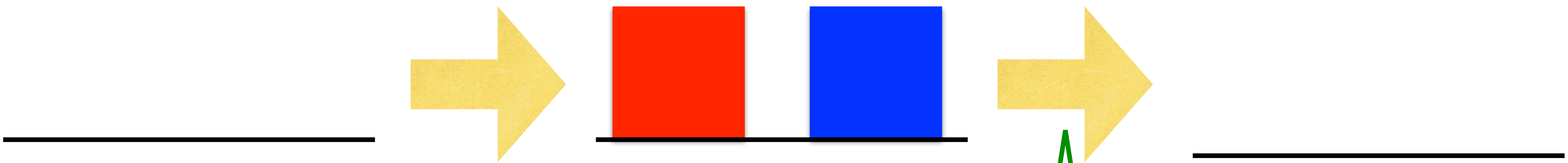
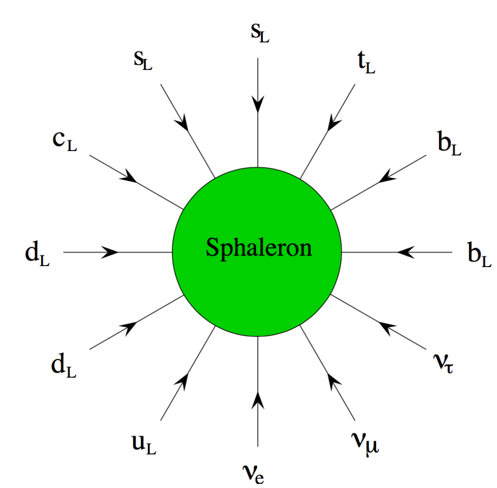


$B$=0 $L$=0 $B$=100 $L$=100 $B$=0 $L$=0

sphaleron process

**B-L violating process is necessary.**



**Sakharov's 3 conditions**

- ~~Baryon number (B) violation~~ B-L violation
- C and CP violation
- Out-of-equilibrium

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- ~~Baryon number (B) violation~~ **B-L violation**
- C and CP violation
- Out-of-equilibrium

Baryogenesis can work, not only via B-violation, but also via **L-violation.**

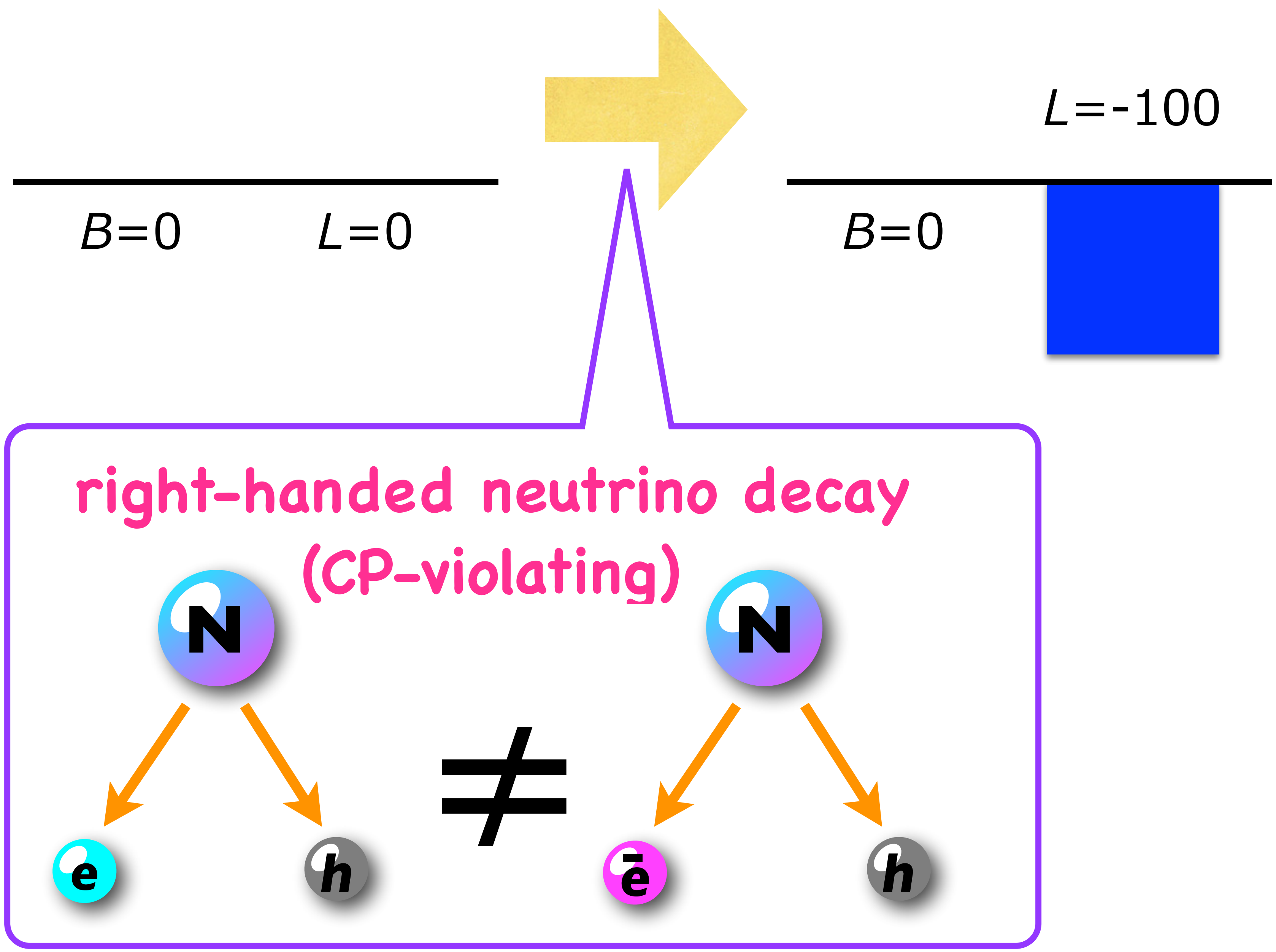
and L-violation implies,...

**Majorana neutrino, and $0\nu\beta\beta$ decay!!**

# Lepgogenesis

[Fukugita, Yanagida, '86]

generate **Lepton** asymmetry

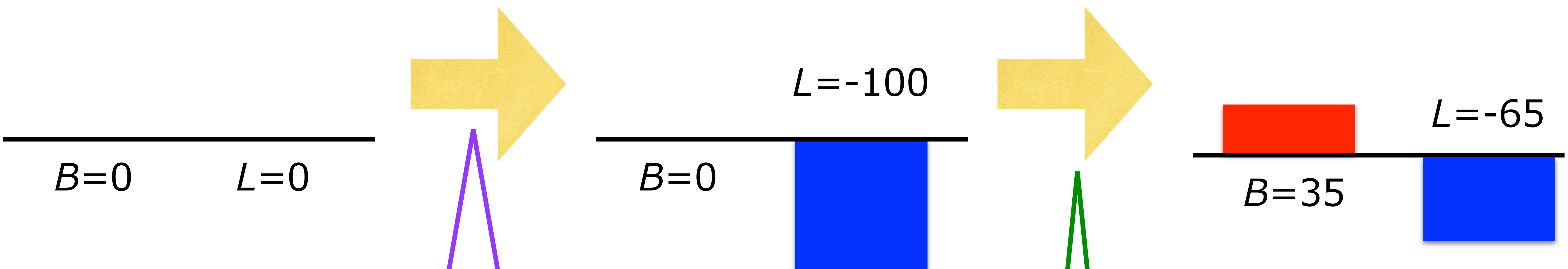


# Lepgogenesis

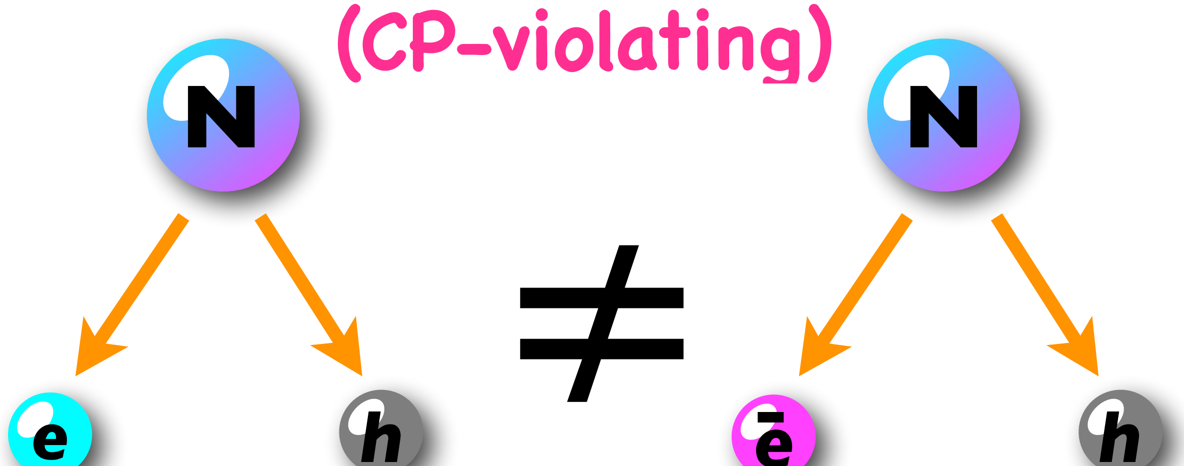
[Fukugita, Yanagida, '86]

generate **Lepton** asymmetry

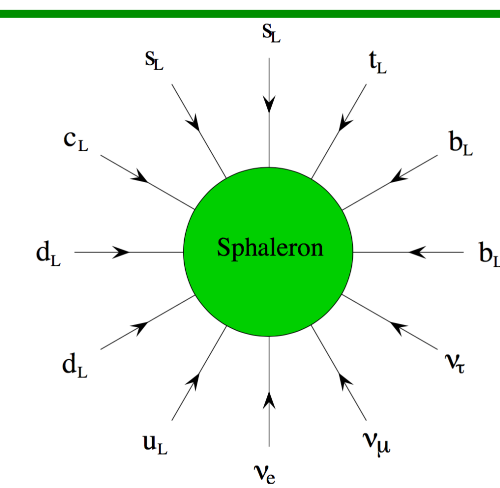
**Then, B≠0 remains at equilibrium!**




right-handed neutrino decay
(CP-violating)




sphaleron process



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# Right-handed Neutrino's triple role

Just by adding (2 or) 3 heavy right-handed neutrinos
to the Standard Model,...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underbrace{\frac{1}{2}\overline{N_R}(i\partial\!\!\!/ + M_R)N_R + y_\nu \overline{N_R}\ell_L {\color{blue}H} + h.c.}_{\text{New Physics}}$$

Higgs

RH neutrino

# Right-handed Neutrino's triple role

Just by adding (2 or) 3 heavy right-handed neutrinos
to the Standard Model,...

(1) small neutrino masses

(2) matter unification
in 16 of SO(10)

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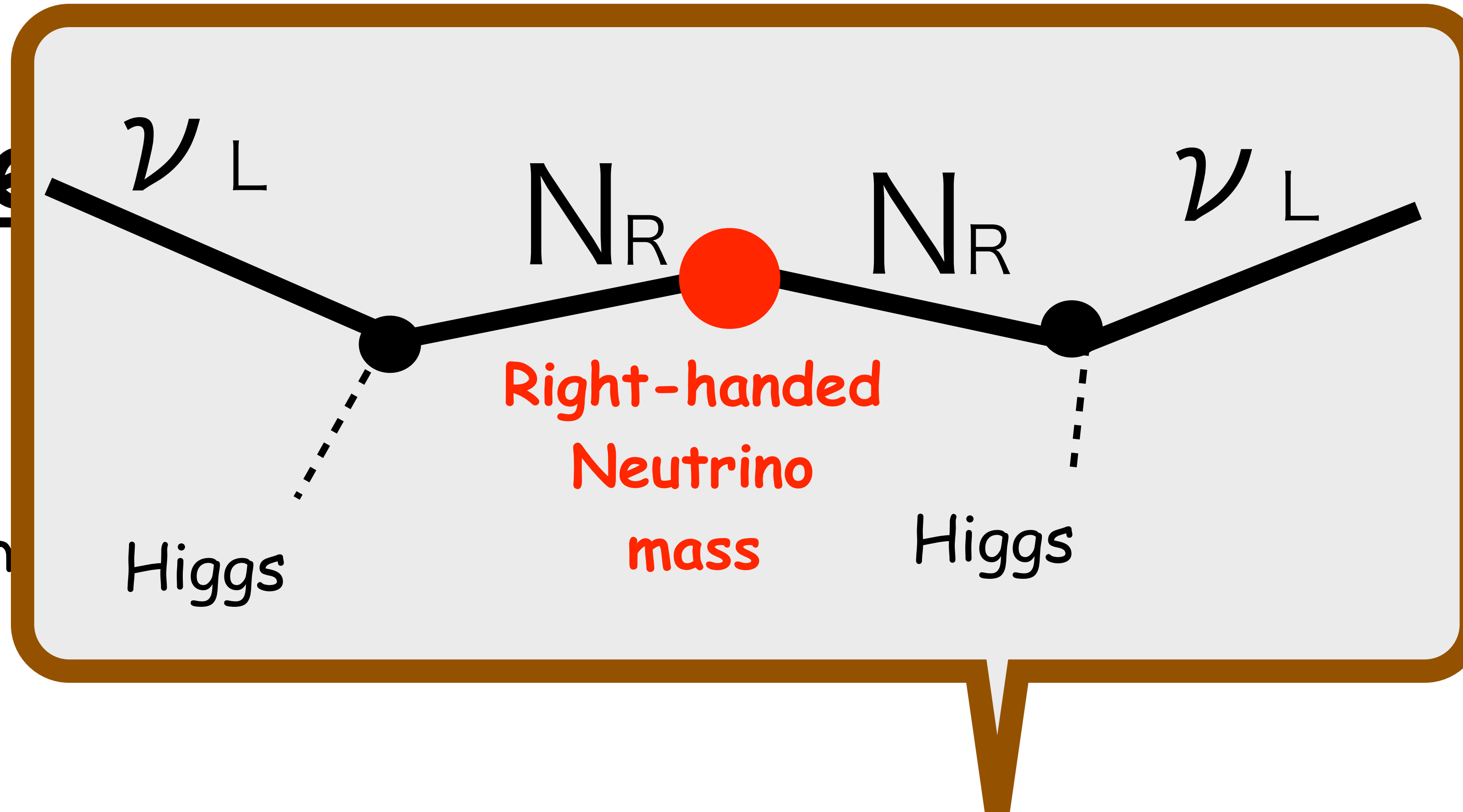
(3) Leptogenesis

# Right-hande

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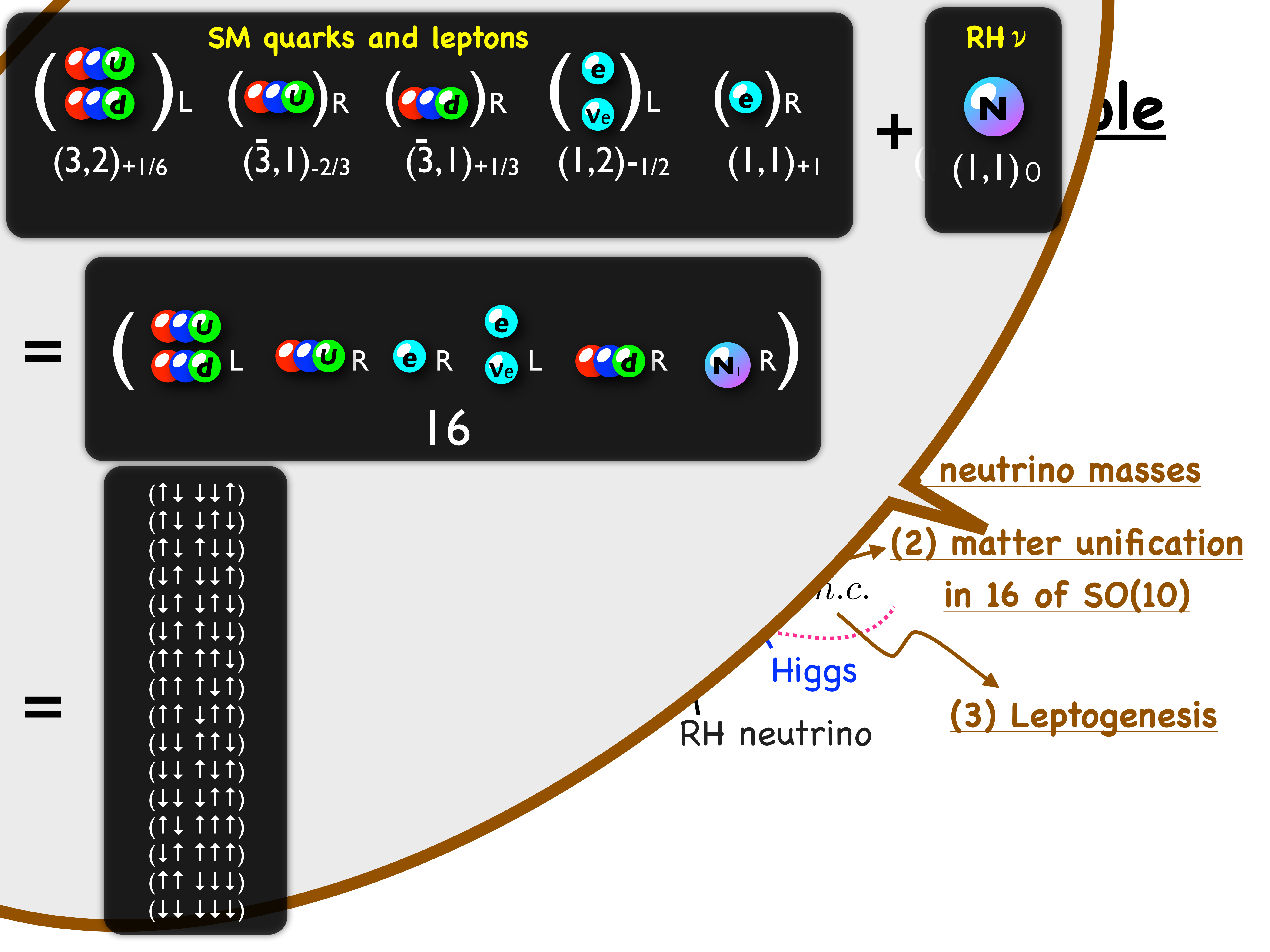
SM quarks and leptons
( u d )L (u)R (d)R ( e νe )L (e)R
(3,2)+1/6 (3̄,1)-2/3 (3̄,1)+1/3 (1,2)-1/2 (1,1)+1
+
RH ν
N
(1,1)0
=
( u d L u R e R e νe L d R N1 R )
16
=
(↑↓ ↓↓↑)
(↑↓ ↓↑↓)
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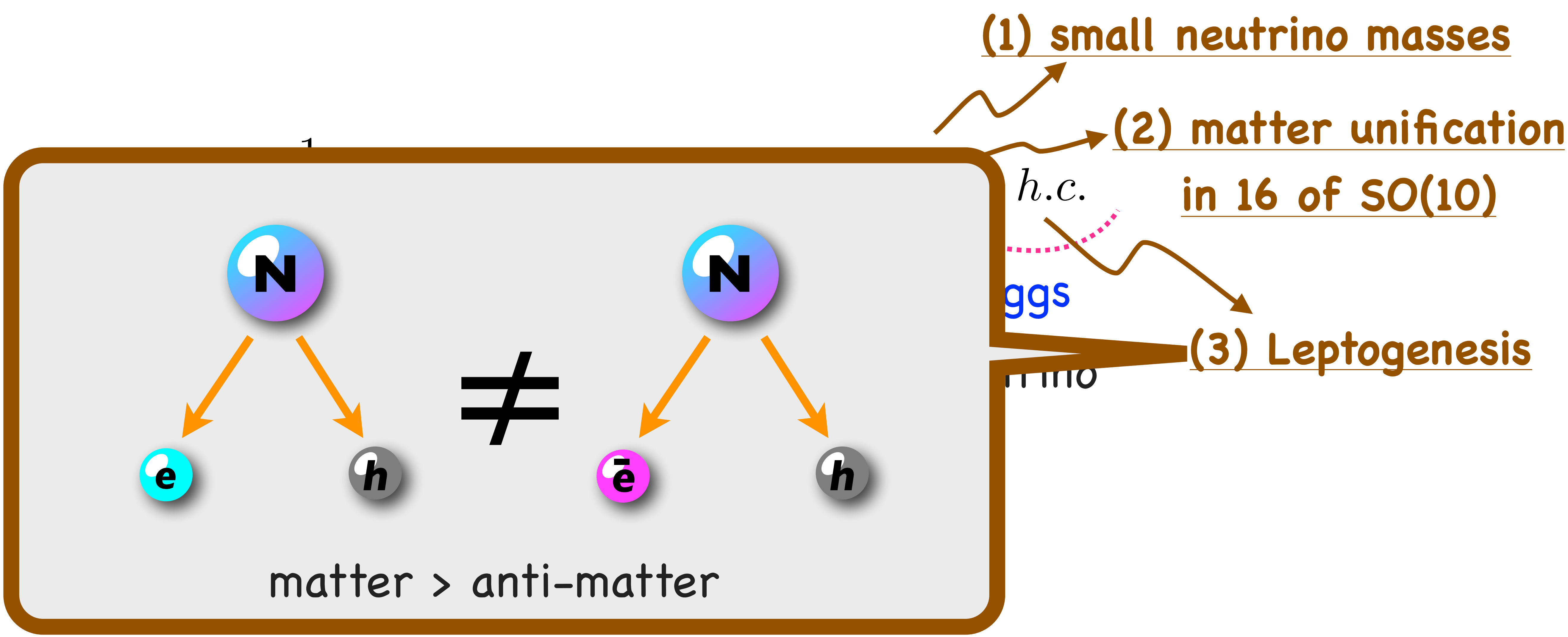

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New Physics

Higgs

RH neutrino

(3) Leptogenesis

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# Various Leptogenesis scenarios

- Thermal Leptogenesis

  [Fukugita, Yanagida,'86, …… Buchmuller, Plumacher, Di Bari,……]

- via RH$\nu$ oscillation ($\nu$MSM)

  [Akhmedov, Rubakov, Smirnov,'98, Asaka, Shasposhnikov,'05……]

- via neutrino oscillation (with the LHLH operators)

  […, Hamada, Kitano, Yin ,'18……]

- Leptogenesis from Inflaton Decay

  […… Kumekawa, Moroi, Yanagida,'94,… Asaka, KH, Kawasaki, Yanagida,'99……]

- Leptogenesis from RH-Sneutrino dominated Universe

  [Murayama, Yanagida,'93, …… KH, Murayama, Yanagida,'01……]

  [Murayama, Suzuki, Yanagida, Yokoyama,'93,… … ]

- Affleck-Dine Leptogenesis

  [Murayama, Yanagida,'93, …… Asaka, Fujii, KH, Yanagida,'00, Fujii, KH, Yanagida,'01, ……]

**+ many others …**

**All of them require L-number violation, and predict $0\nu\beta\beta$ decay!!**

Exception: "Dirac leptogenesis".
[Dick, Lindner, Ratz, Wright, 99,
Murayama, Pierce, 02]

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- Thermal Leptogenesis

[Fukugita, Yanagida,'86, …… Buchmuller, Plumacher, Di Bari,……]

**Model**: Standard Model + RH$\nu$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{N_R}(i\partial\!\!\!/ + M_R)N_R + y_\nu \overline{N_R}\ell_L H + h.c.$$

**Cosmology**: Standard thermal cosmology

**Extremely simple!**
**No complicated model/cosmology required.**

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scenario

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## scenario

temperature RH$\nu$'s mass

**step 1**: $T > M_R$ : $N_I$ are in thermal bath.

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temperature   RH$\nu$'s mass

**step 1**: $T > M_R$ : $N_I$ are in thermal bath.

**step 2**: $T \sim M_R$ : $N_I$ decay. (CP violation + out-of-eq.)

--> generate Lepton asymmetry, $\Delta L \neq 0$.

# Various Leptogenesis scenarios

- Thermal Leptogenesis

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scenario

temperature RH$\nu$'s mass

**step 1**: $T > M_R$ : $N_1$ are in thermal bath.

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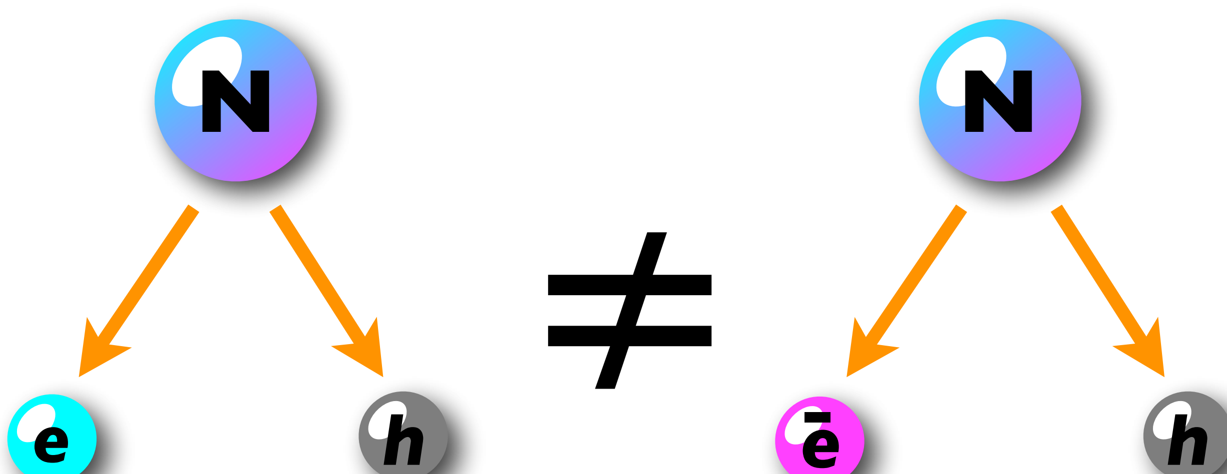


CP violation
is essential.

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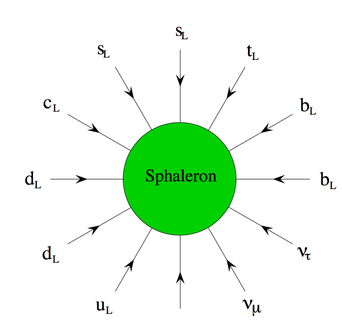
**step 3**: Lepton asymmetry　　Baryon asymmetry

$\Delta L \neq 0$ ---> $\Delta B \neq 0$

sphaleron process



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**Result:** (* the simplest case. flavor effect omitted.
for more recent progresses, See e.g., arXiv:1711.02861～ 1711.02866.)

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$$\frac{n_B}{s} \simeq 0.3 \times 10^{-10} \left(\frac{\kappa}{0.1}\right) \left(\frac{M_1}{10^9 \text{ GeV}}\right) \cdot \left(\frac{m_{\nu 3}}{0.05 \text{ eV}}\right) \delta_{\text{eff}}$$

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wash-out factor (< 1)
(calculable: by Boltzmann eq.)

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(calculable: by Boltzmann eq.)

effective CP violating phase

$$\delta_{\text{eff}} \equiv \frac{\text{Im}\left[\left(\hat{h}_{13}\right)^2 + \frac{m_{\nu 2}}{m_{\nu 3}}\left(\hat{h}_{12}\right)^2 + \frac{m_{\nu 1}}{m_{\nu 3}}\left(\hat{h}_{11}\right)^2\right]}{\left|\hat{h}_{13}\right|^2 + \left|\hat{h}_{12}\right|^2 + \left|\hat{h}_{11}\right|^2} < 1$$

Yukawa

# Various Leptogenesis scenarios

- Thermal Leptogenesis

[Fukugita, Yanagida,'86, ...... Buchmuller, Plumacher, Di Bari,......]

**Result:** (* the simplest case. flavor effect omitted.
for more recent progresses, See e.g., arXiv:1711.02861∼ 1711.02866.)

final baryon asymmetry

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**Predictable / Calculable in terms of [SM + RH$\nu$] Lagrangian !**

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$$\frac{n_B}{s}(\text{observed}) = (0.88 \pm 0.02) \times 10^{-10}$$

**It works !! (for $M_R > 10^9$–$10^{10}$ GeV).**

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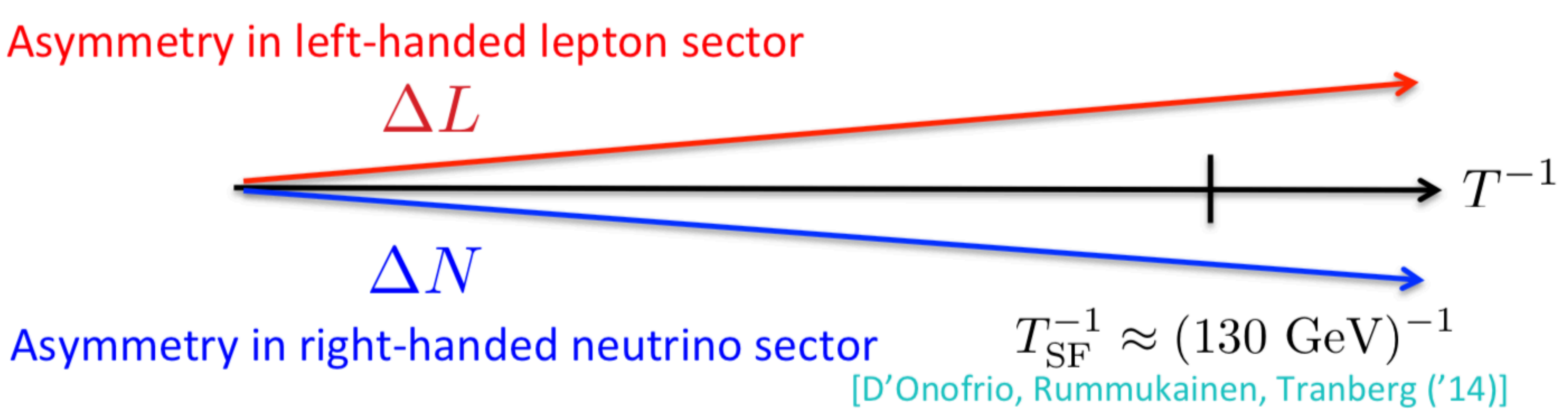


Fig. from S. Eijima's seminar (Tokyo, U. 2019)

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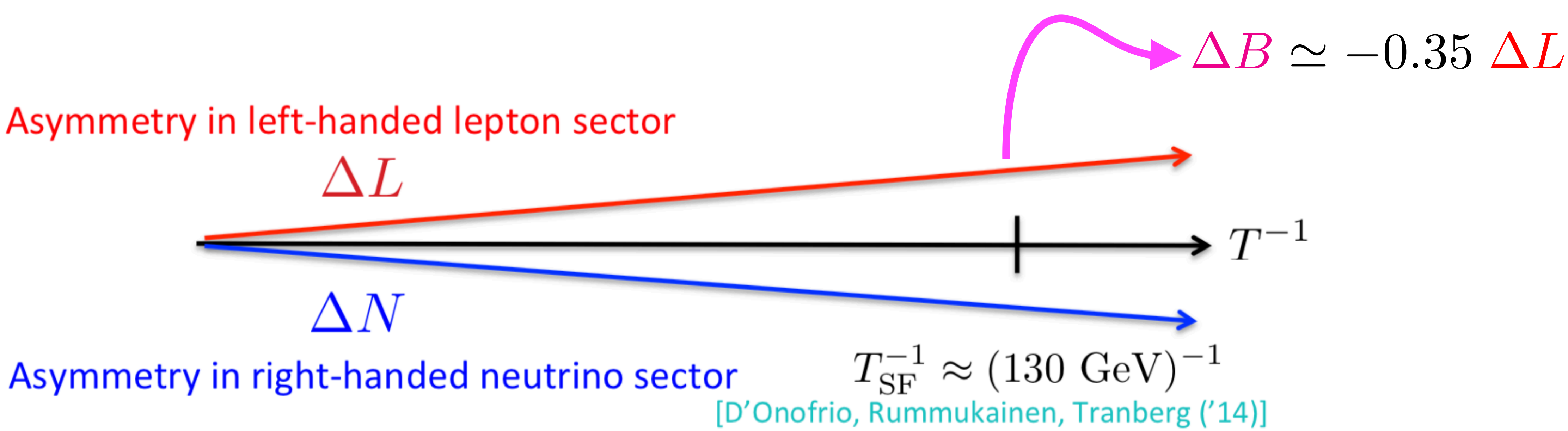


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- Target of various experiments.

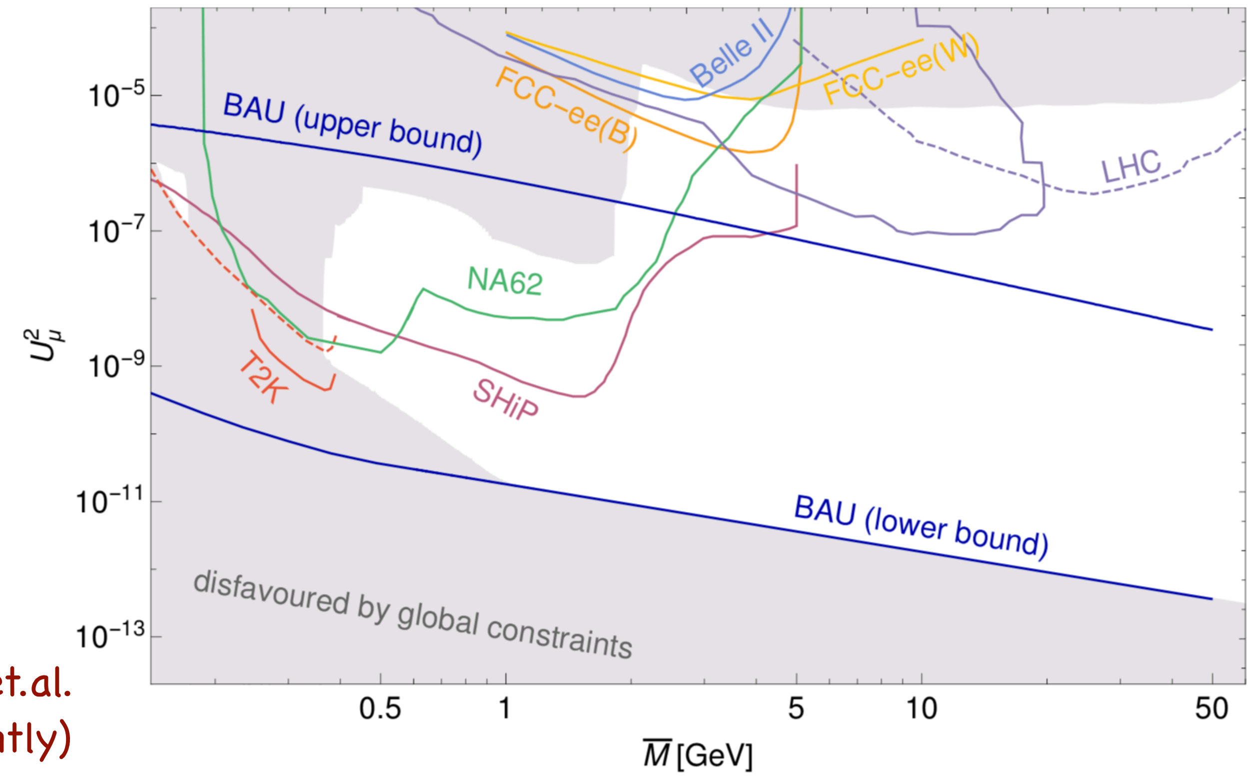


Fig. from 1609.09069, M.Drewes et.al.
(* maybe updated more recently)

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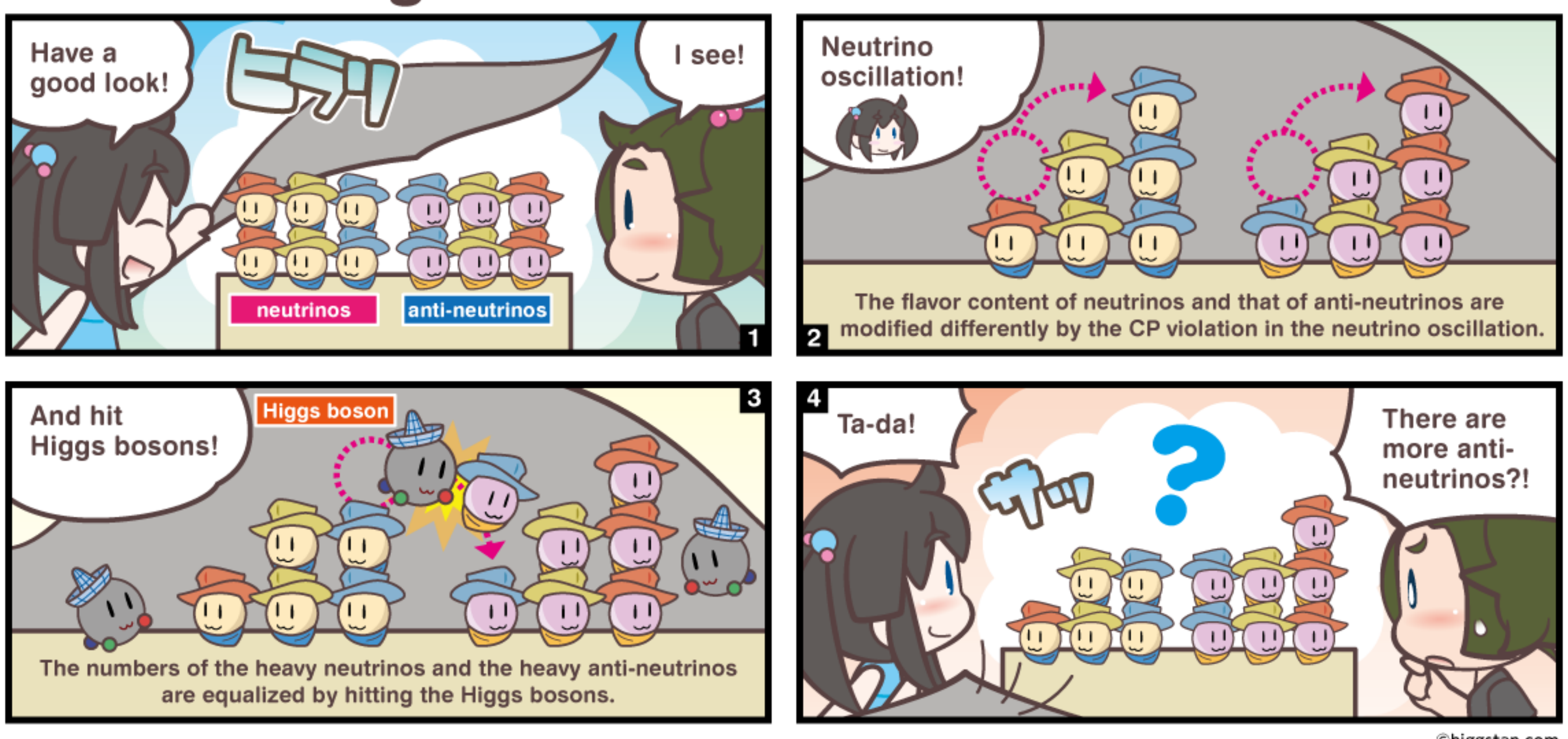
  [..., Hamada, Kitano, Yin ,'18……]

**Neutrino Magic!**




**More anti-neutrinos than neutrinos?**
Starting with the same numbers of neutrinos and anti-neutrinos, some magic under the cloth created an imbalance between them. This CP violating phenomenon, if it has really happened in the early Universe, give the reason for the Universe being made of matter rather than anti-matter.

Manga by HiggsTan（ひっぐすたん）
http://higgstan.com/

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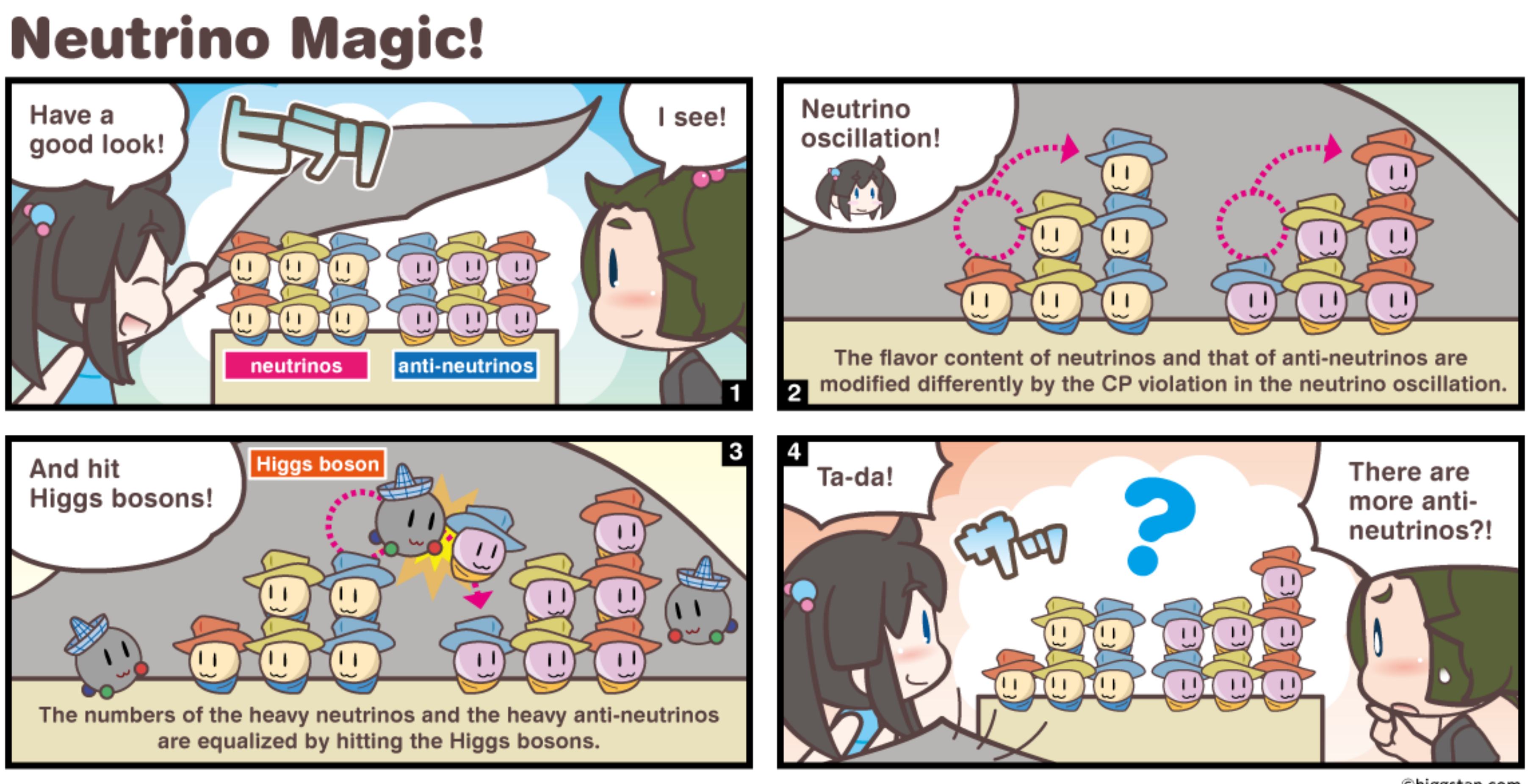
Ask **Yin-kun** for details !

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- Leptogenesis from Inflaton Decay

  […… Kumekawa, Moroi, Yanagida,'94,… Asaka, KH, Kawasaki, Yanagida,'99……]

- Leptogenesis from RH-Sneutrino dominated Universe

  [Murayama, Yanagida,'93, …… KH, Murayama, Yanagida,'01……]
  [Murayama, Suzuki, Yanagida, Yokoyama,'93,… … ]

- Affleck-Dine Leptogenesis

  [Murayama, Yanagida,'93, …… Asaka, Fujii, KH, Yanagida,'00, Fujii, KH, Yanagida,'01, ……]

**+ many others …**

**All of them require L-number violation, and predict $0\nu\beta\beta$ decay!!**

Exception: "Dirac leptogenesis".
[Dick, Lindner, Ratz, Wright, 99,
Murayama, Pierce, 02]

# Plan

- Baryon Asymmetry of the Universe
- Why ``Lepto"genesis?
- Right-handed Neutrino's triple role
- Various Leptogenesis scenarios
- Predictions of minimal gauged $U(1)_{L_\alpha - L_\beta}$ models
- Summary

# Predictions of minimal gauged $U(1)_{L_\alpha - L_\beta}$ models

K. Asai, KH, N. Nagata, [arXiv:1705.00419]
K. Asai, KH, N. Nagata, S. Tseng, K. Tsumura, [arXiv:1811.07571]
K. Asai, KH, N. Nagata, S. Tseng, + more [work in progress]

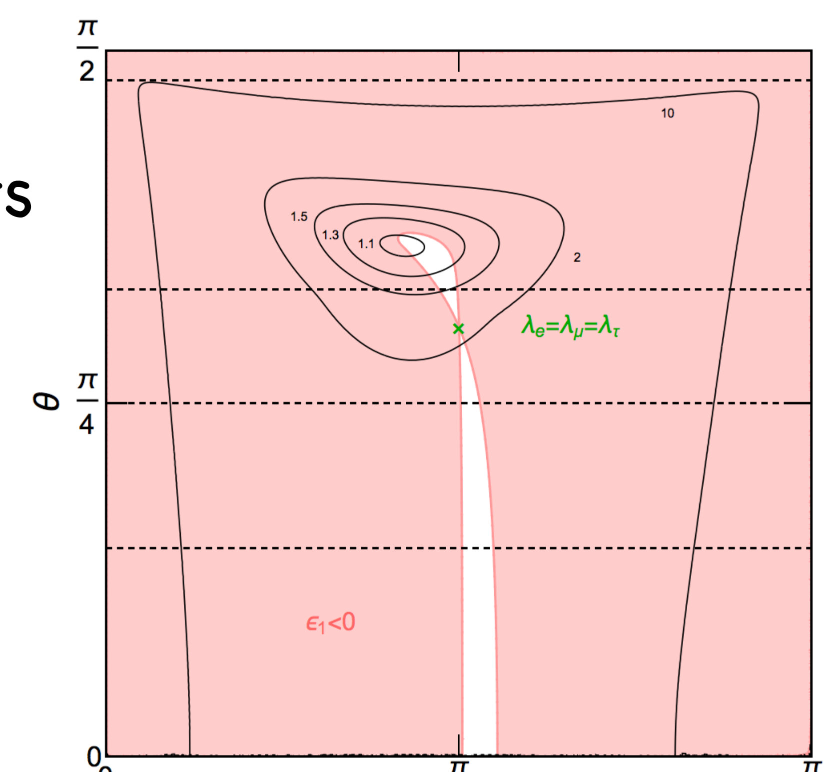
- gauged $U(1)_{L_\alpha - L_\beta}$ ($\alpha$ = e, $\mu$, $\tau$) models: anomaly-free gauge extension of the SM.
- $U(1)_{\mu-\tau}$ may explain muon g-2 anomaly.
- In minimal models (with just one scalar, either singlet or SU2 doublet)

neutrino mass matrix is constrained **-> predictions!.** **In particular,**

$$\mathbf{M}_\nu^{-1} = \begin{pmatrix} * & * & * \\ * & \boxed{0} & * \\ * & * & \boxed{0} \end{pmatrix} \qquad \mathbf{M}_\nu = \begin{pmatrix} * & \boxed{0} & * \\ 0 & \boxed{0} & * \\ * & * & * \end{pmatrix}$$

$$\boxed{\langle m_{\beta\beta} \rangle \gtrsim 0.016 \text{ eV}.}$$

- Interestingly, it also predicts the sign of the baryon asymmetry in the Universe!




For more details, see the poster by **Shih-Yen Tseng** tomorrow!

# Summary

- The Baryon Asymmetry of the Universe = one of the evidences of BSM.

- **Leptogenesis** can naturally explain it.

- **Right-handed neutrino (with large Majorana mass) plays a triple role.**

  (1). Small neutrino masses. (seesaw)

  (2). Unification of all quarks and leptons. (16 rep. of SO(10).)

  (3). **Leptogenesis.** (matter-antimatter asymmetry)

  ... and it predicts **$0\nu\beta\beta$ decay !!**

- There are various kinds of Leptogenesis. (Most of them predict **$0\nu\beta\beta$ decay**.)

- $0\nu\beta\beta$ decay will also test various other new particle physics models (e.g., gauged $U(1)_{\mu-\tau}$ model).