Matter-Antimatter asymmetry of the Universe and Leptogenesis

Koichi Hamaguchi (Tokyo U.)

@TGSW 2021, September 11, 2021.

Mostly review

+ partially based on
  K. Asai, KH, N. Nagata, S. Tseng [arXiv:2005.01039], JCAP **11** (2020) 013.

Plan

90% of the talk
= review

- Leptogenesis
  - Baryon Asymmetry of the Universe
  - Why "Lepto"genesis?
  - Seesaw and Leptogenesis in a "big picture"

- Example: Leptogenesis in the minimal gauged $U(1)_{\mu-\tau}$ model.

- Summary

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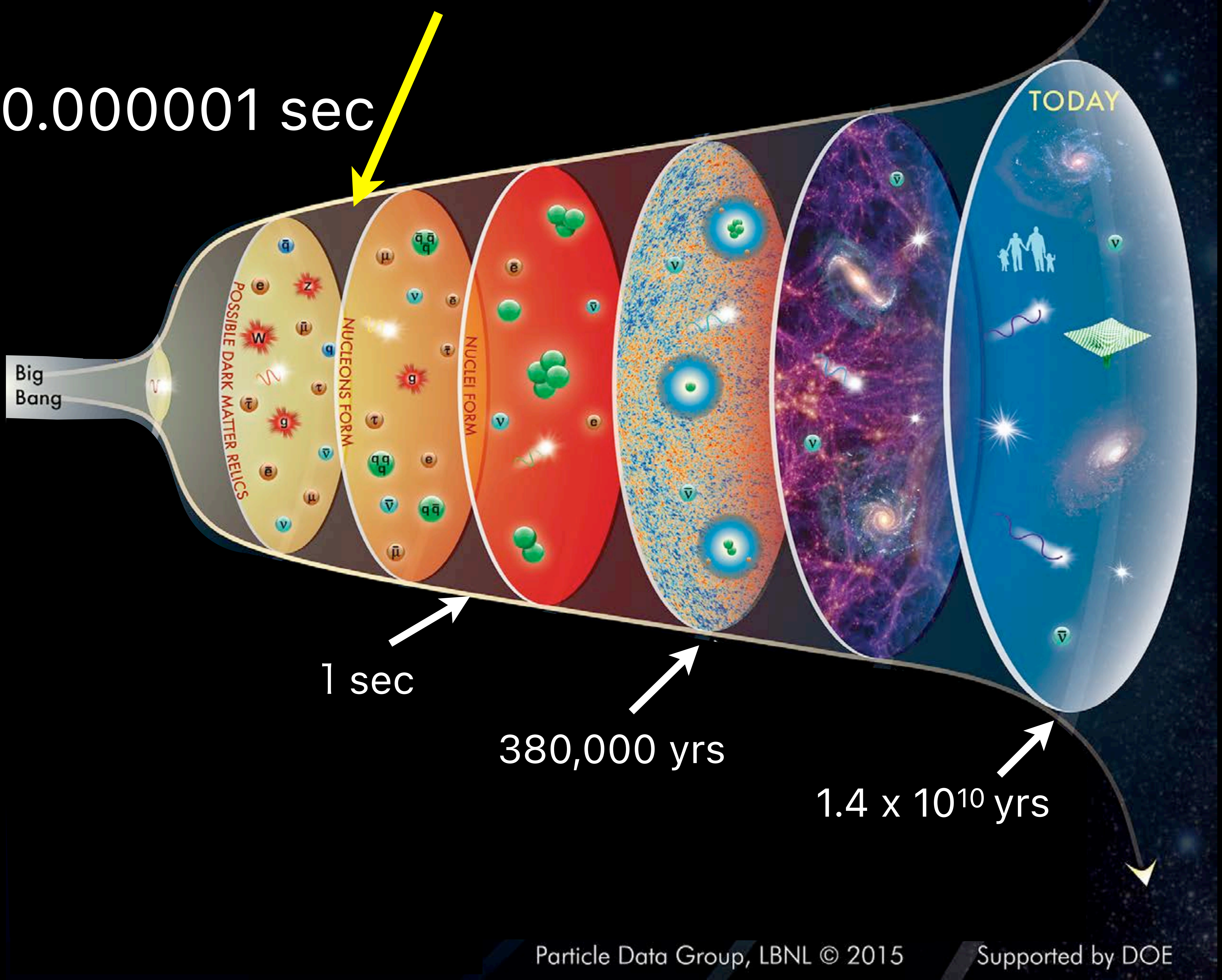
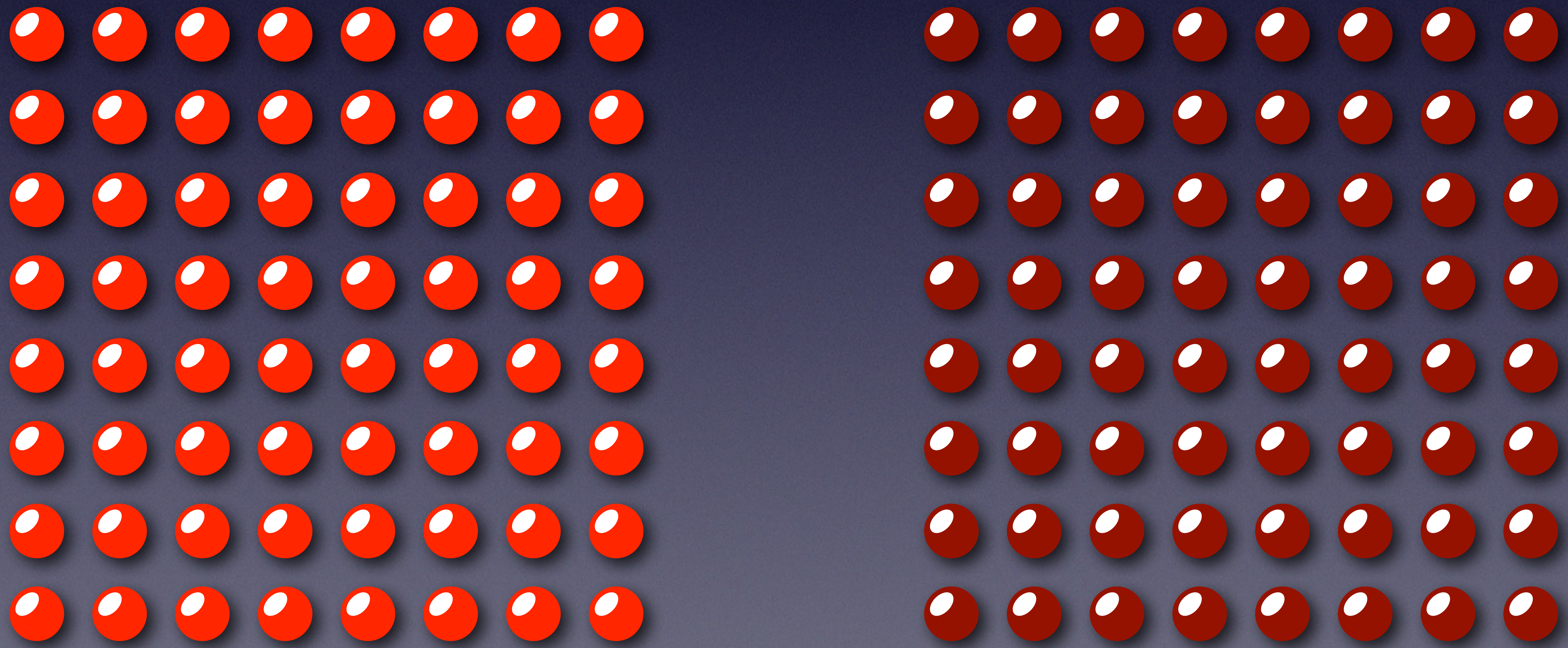
In the very early Universe,....



In the very early Universe,....

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

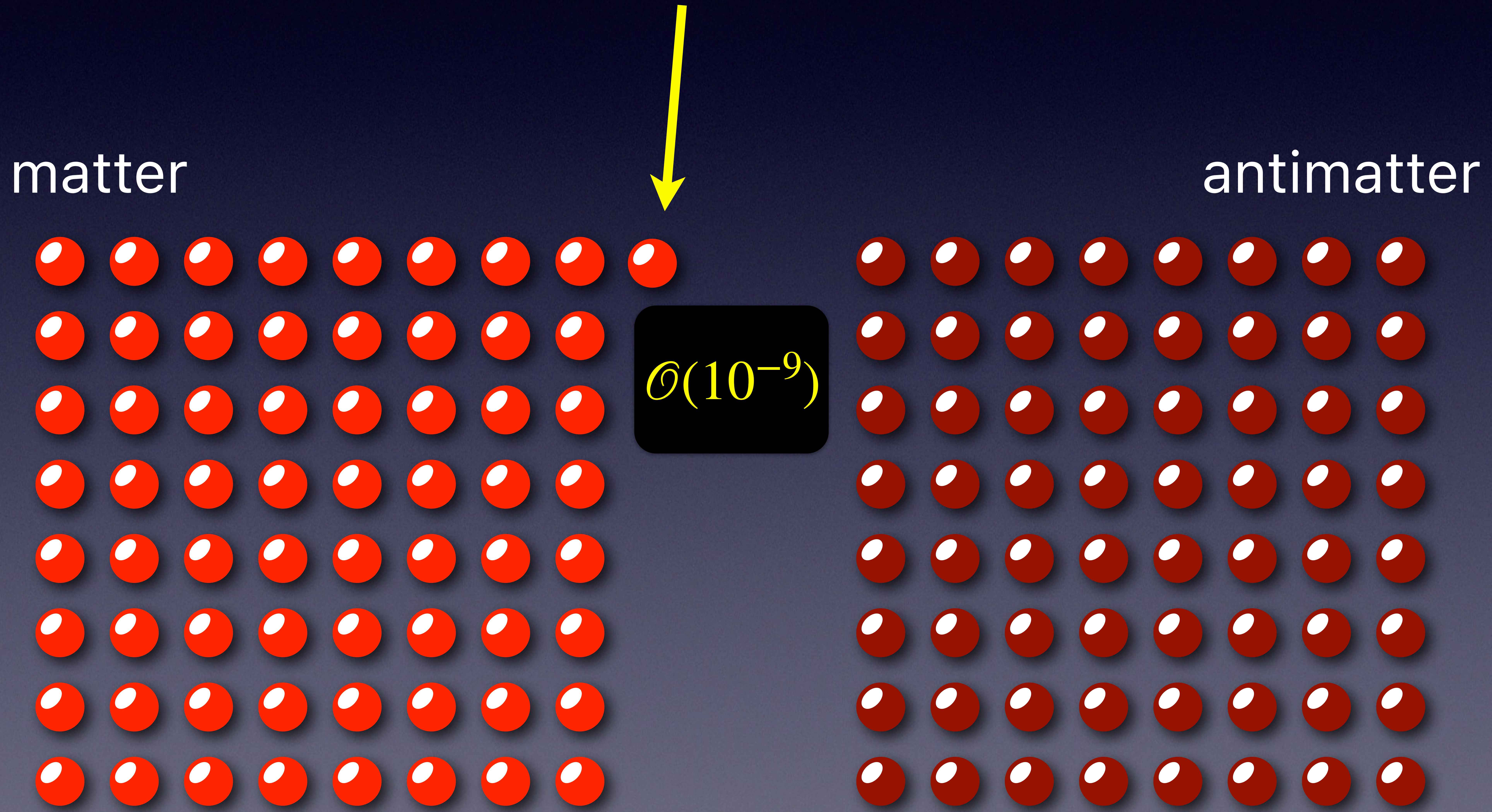
matter antimatter



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.



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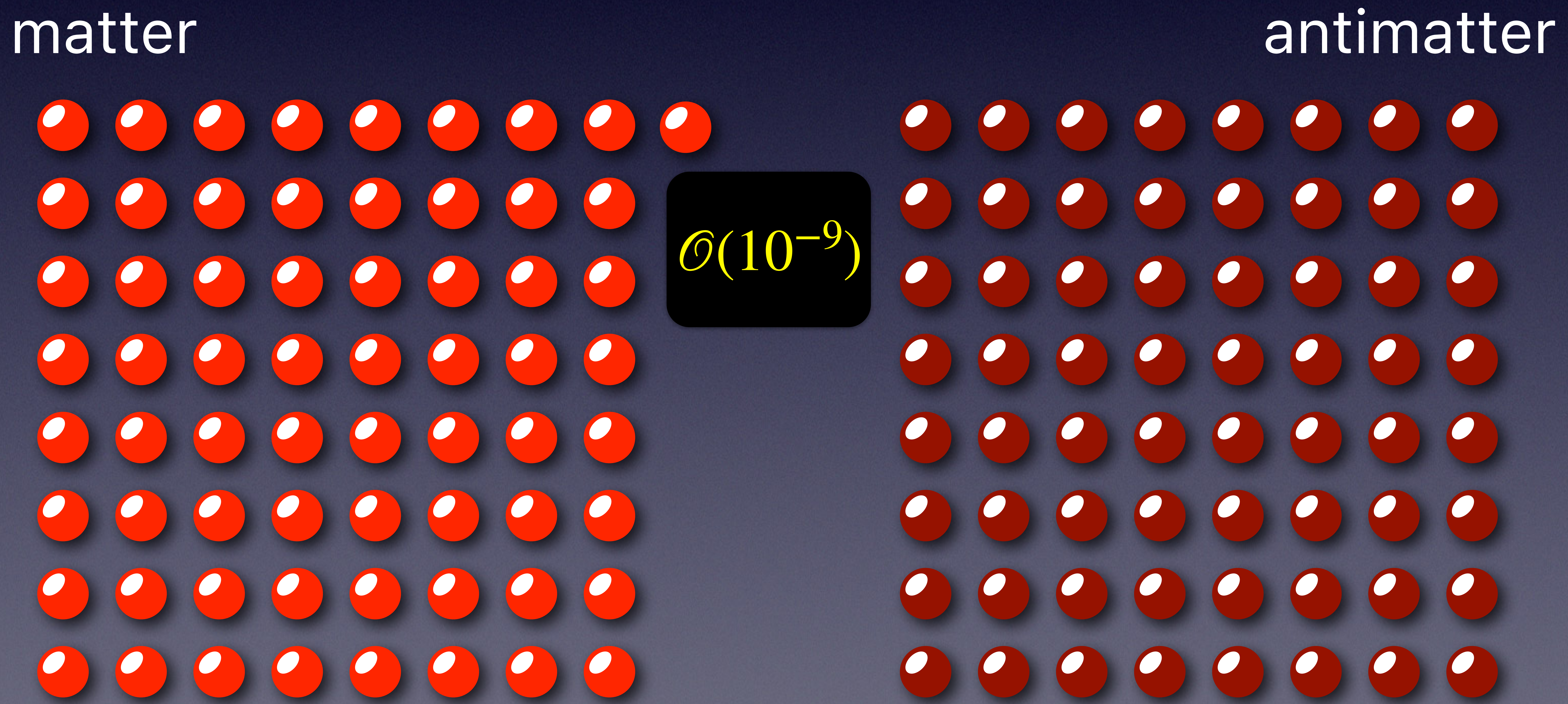
The number of particles and anti-particles were almost the same.

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



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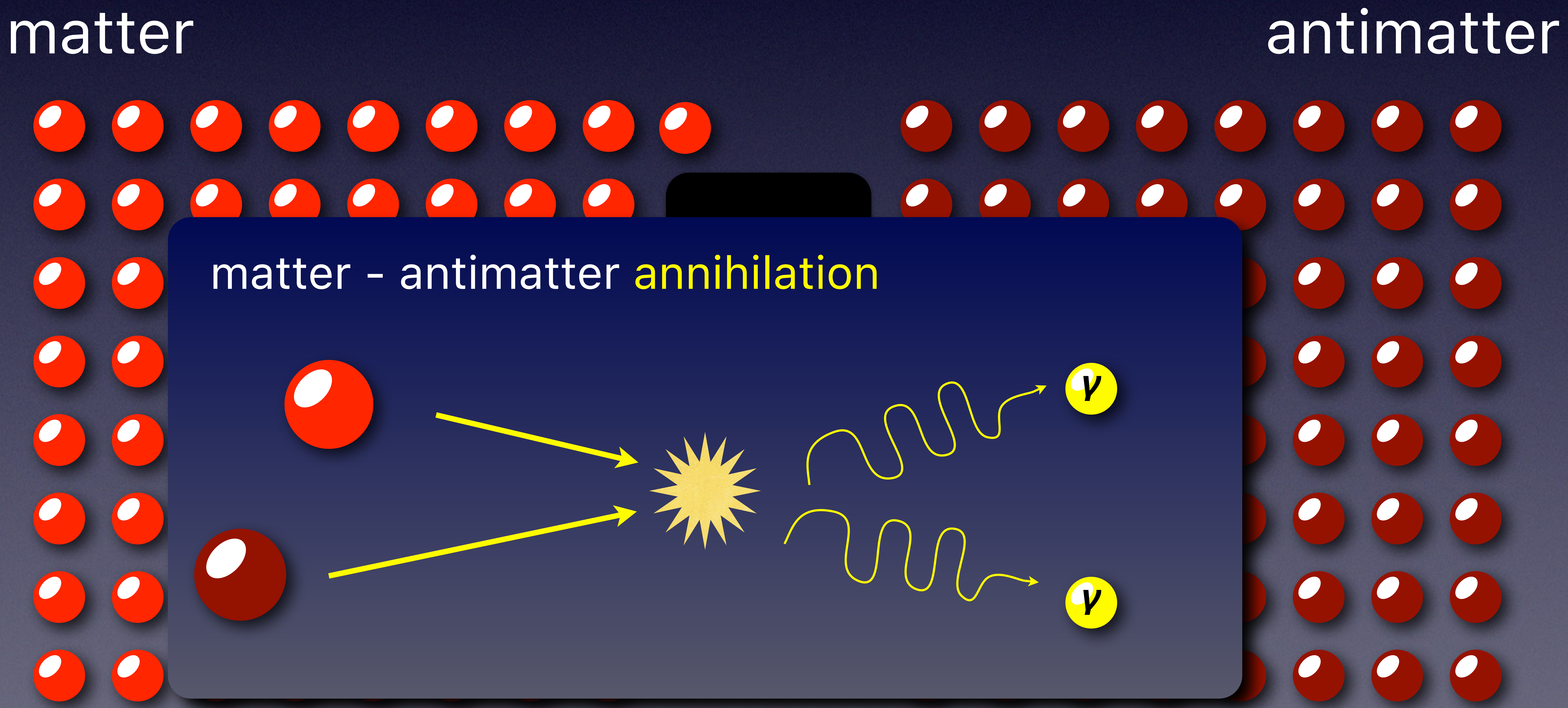


In the very early Universe,....

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

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

matter

antimatter

$\mathcal{O}(10^{-9})$

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

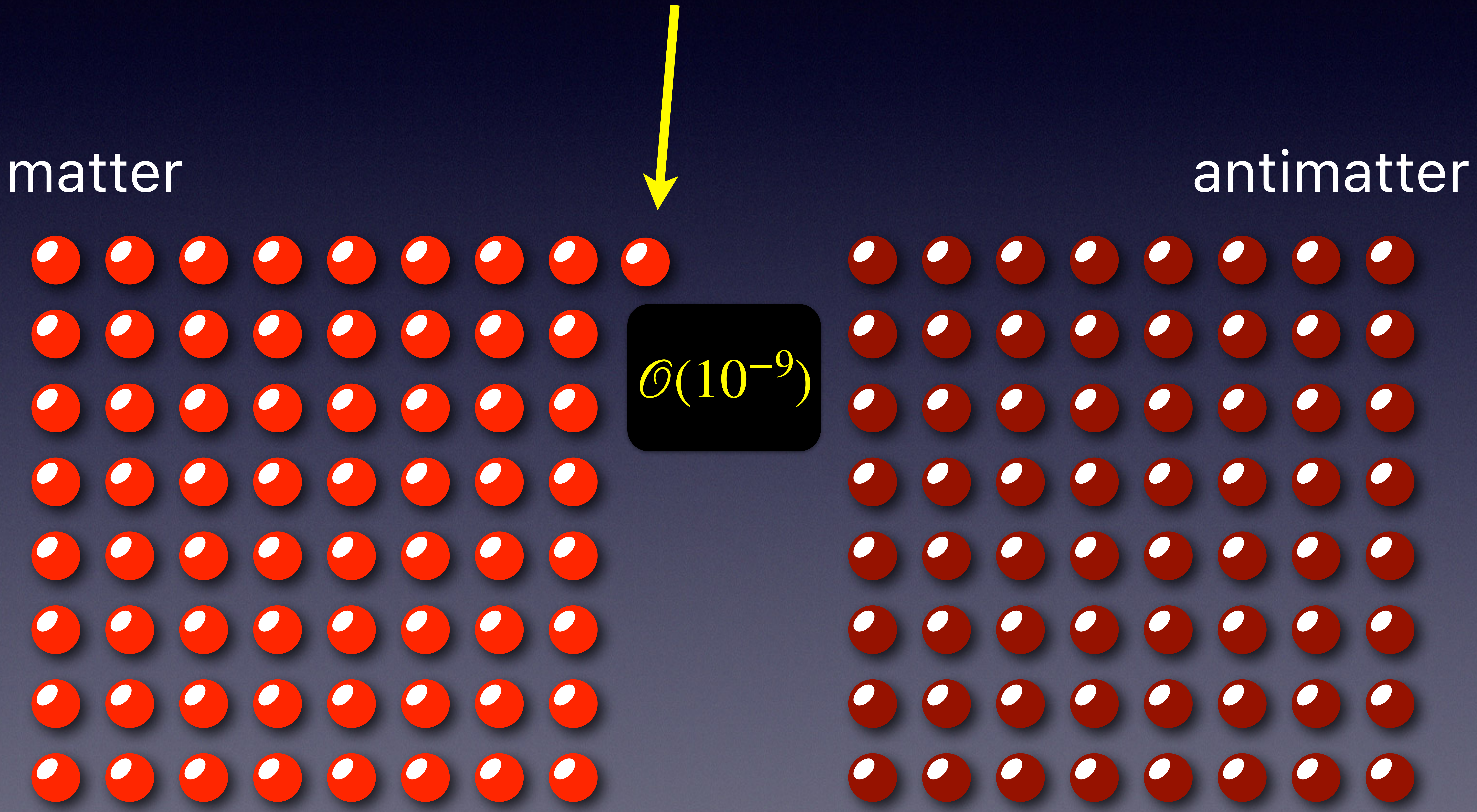
(no antimatter)

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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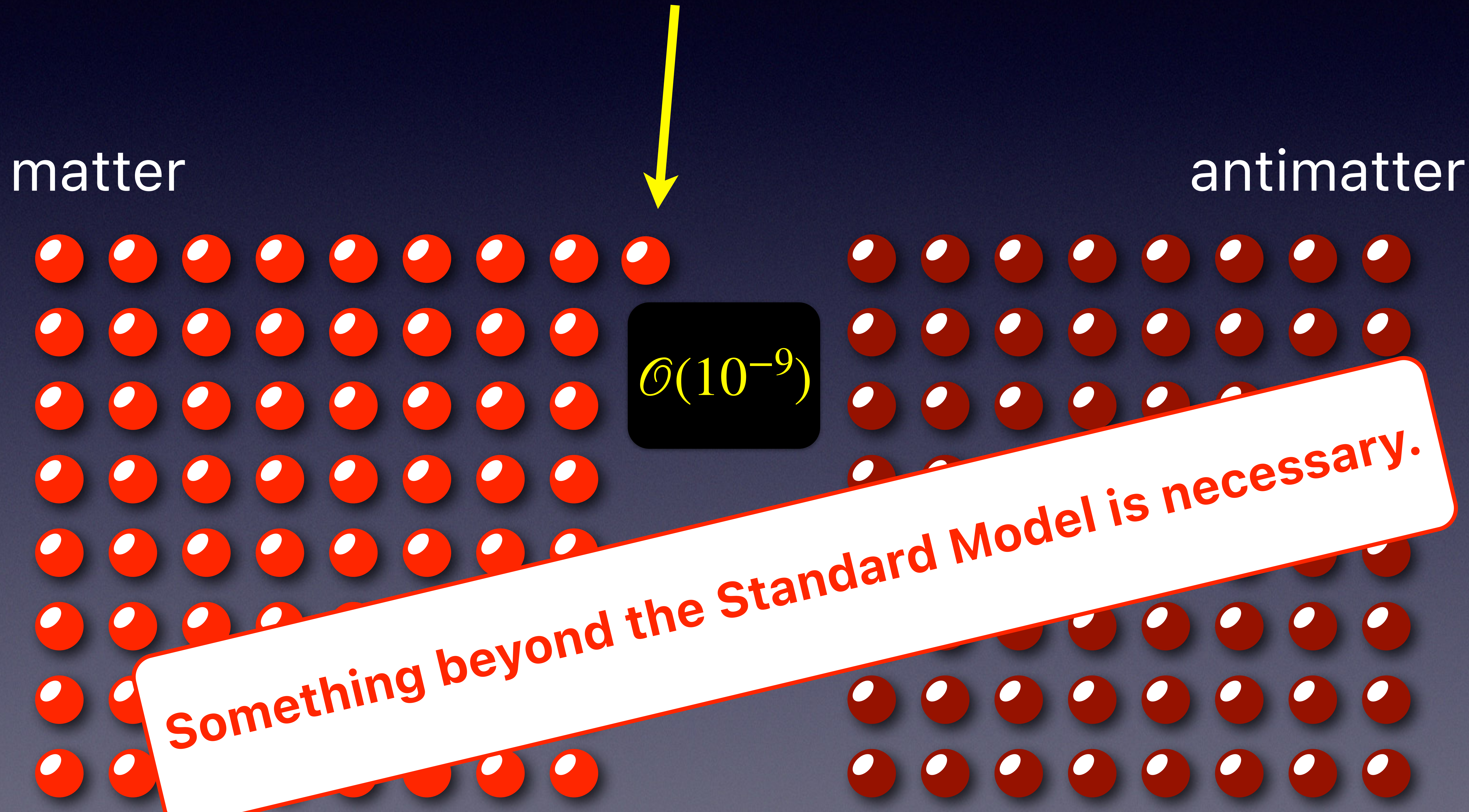
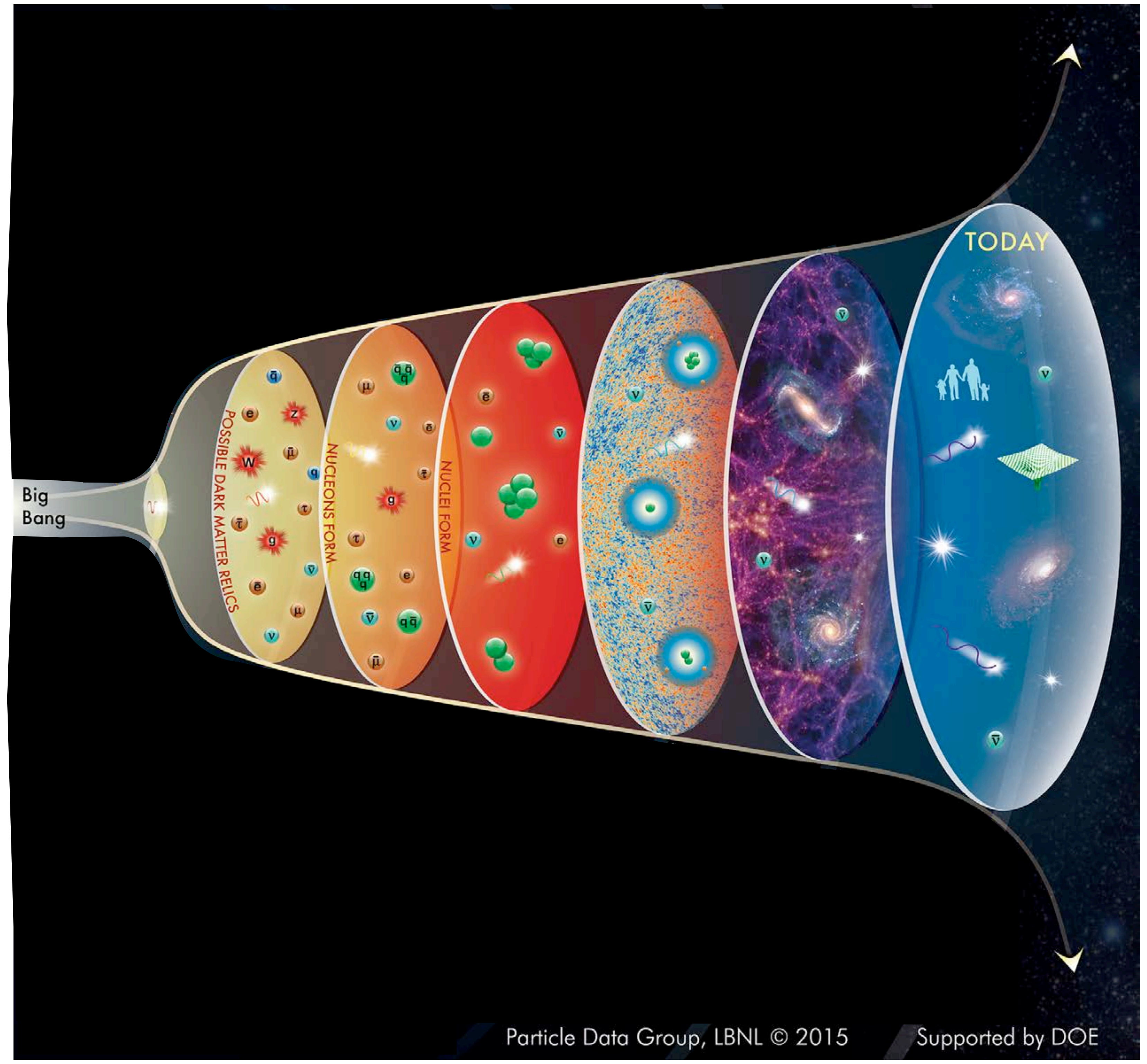


Observations (two independent evidences)



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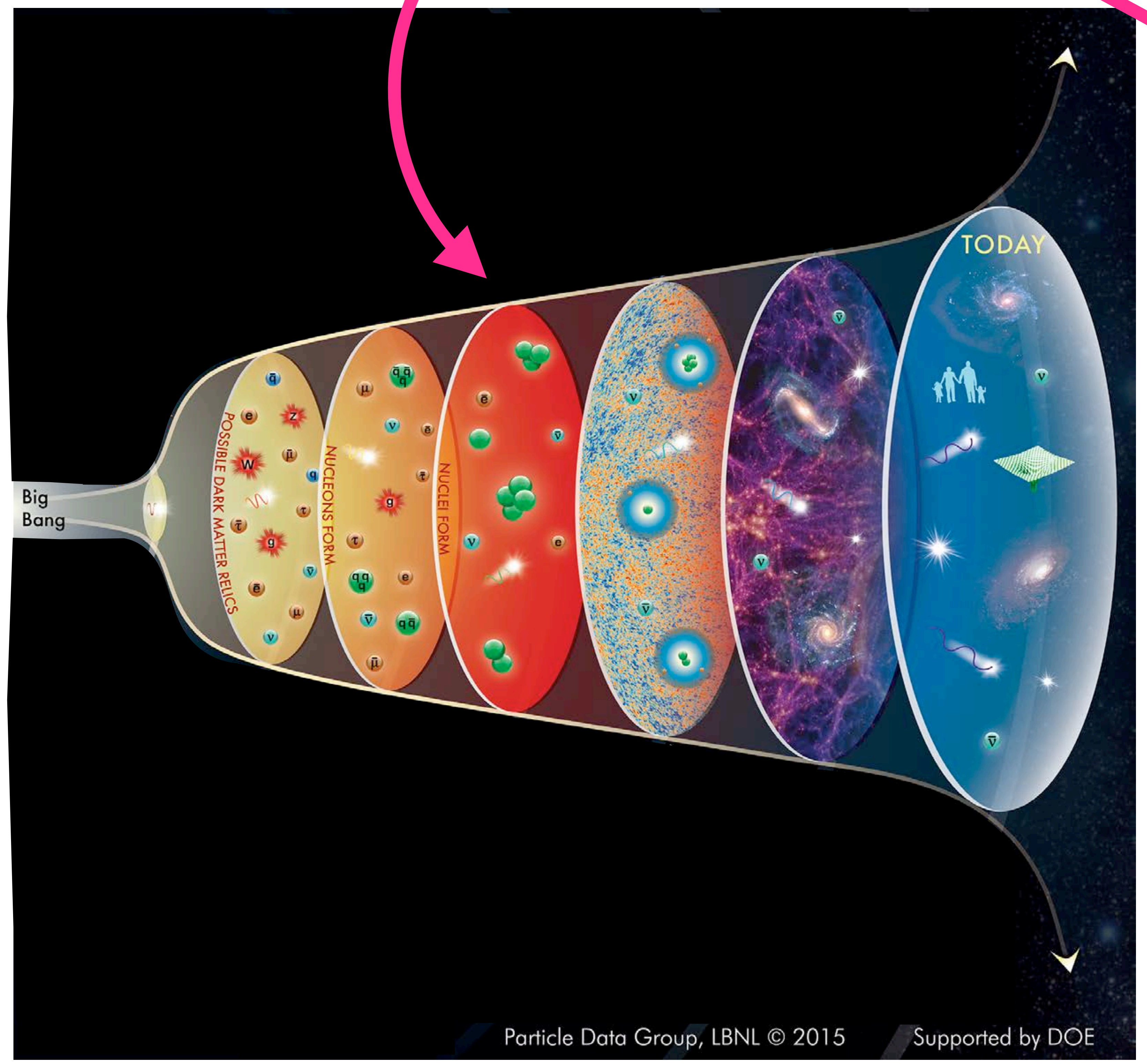

(1) Big Bang Nucleosynthesis (BBN)

(cosmic time about 1 sec)

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

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

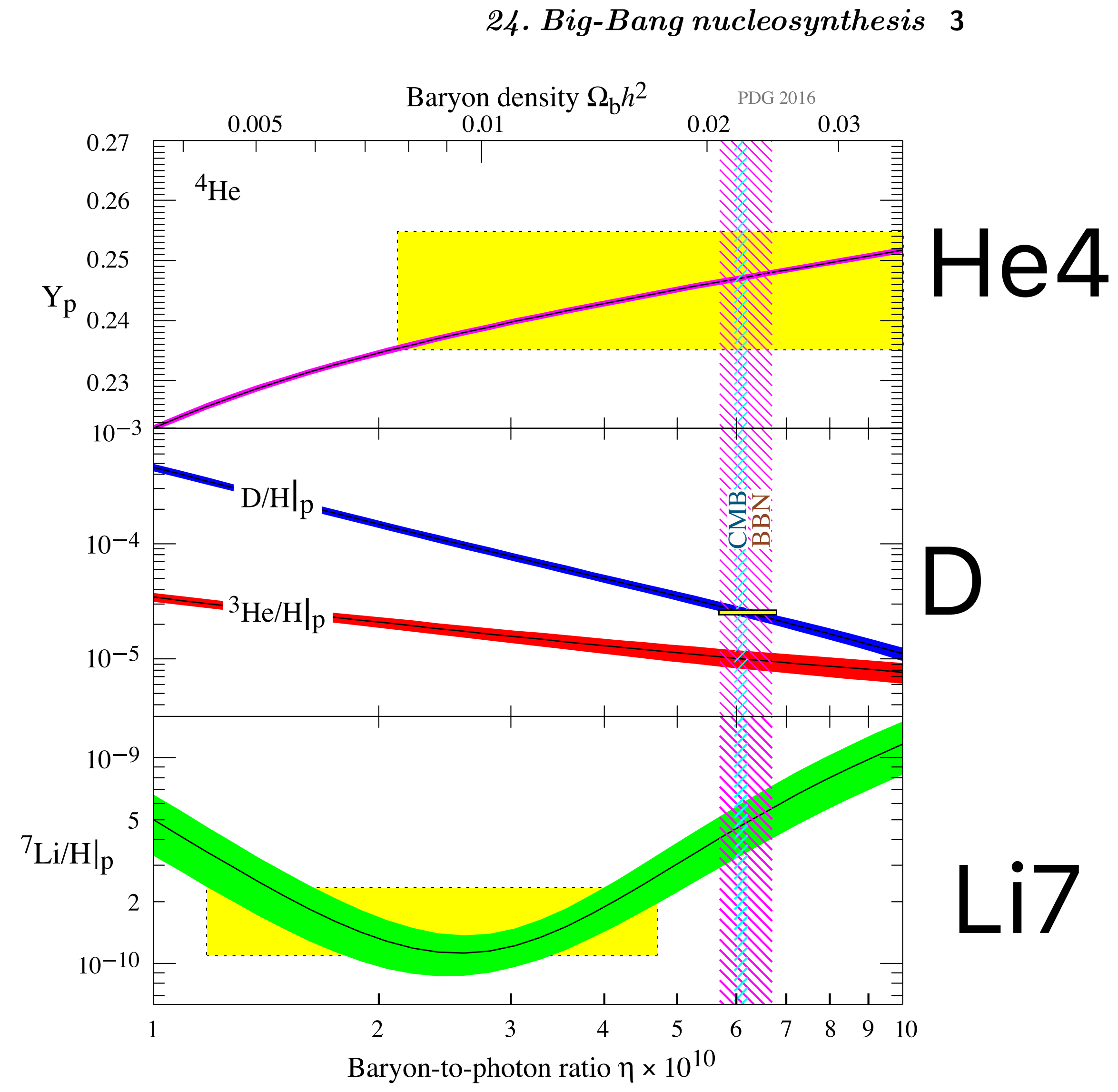

Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis—the bands show the 95% CL range [5]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density,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

[Particle Data Group]

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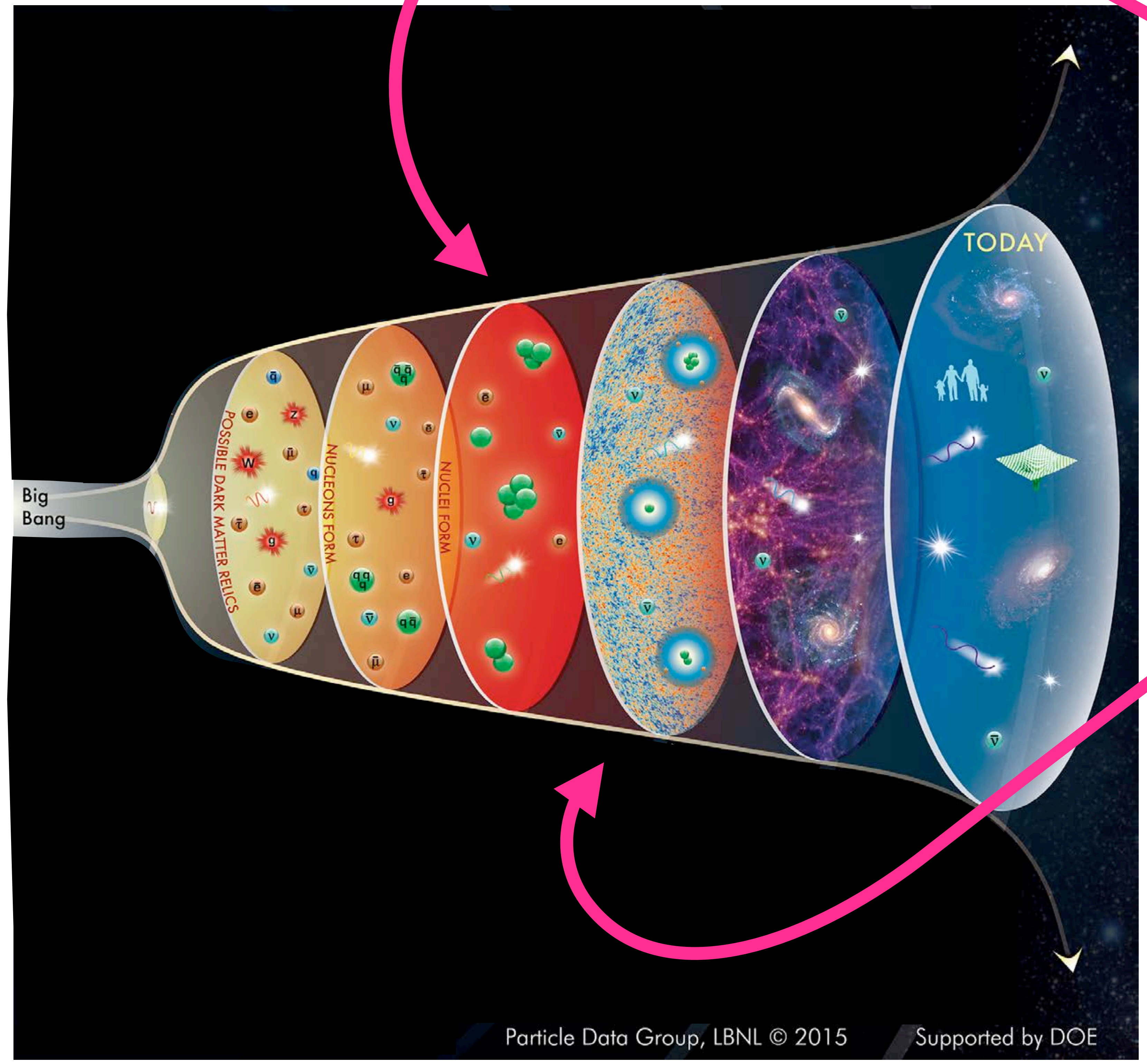

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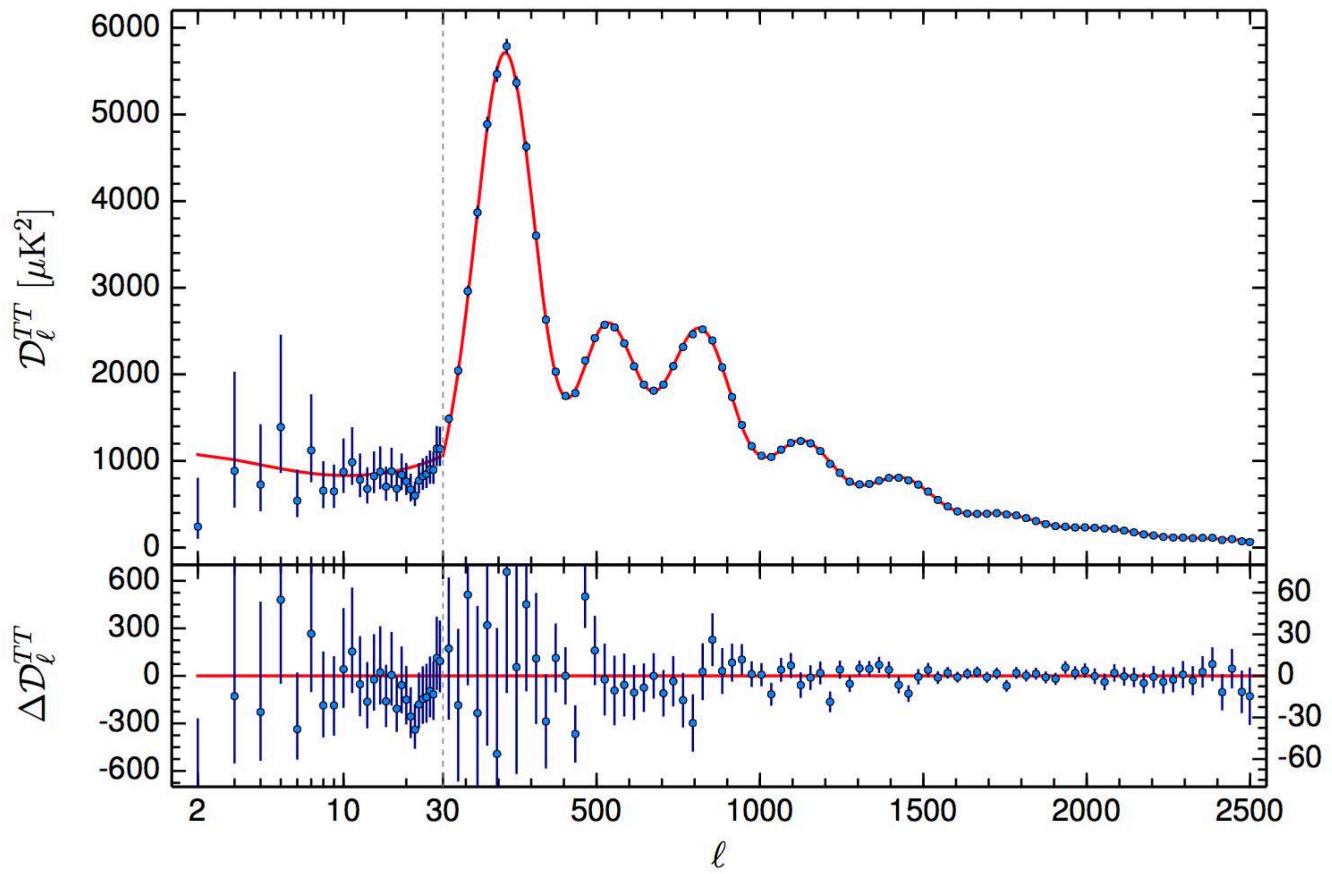
$$5.8 \leq \eta_{10} \leq 6.6 \ (95\% \ \mathrm{CL}).$$

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

(2) Cosmic Microwave background
(cosmic time about 400,000 yrs)

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

[Planck 2015]



They are consistent.
(2) has better precision.

When was the Baryon Asymmetry of the Universe generated?

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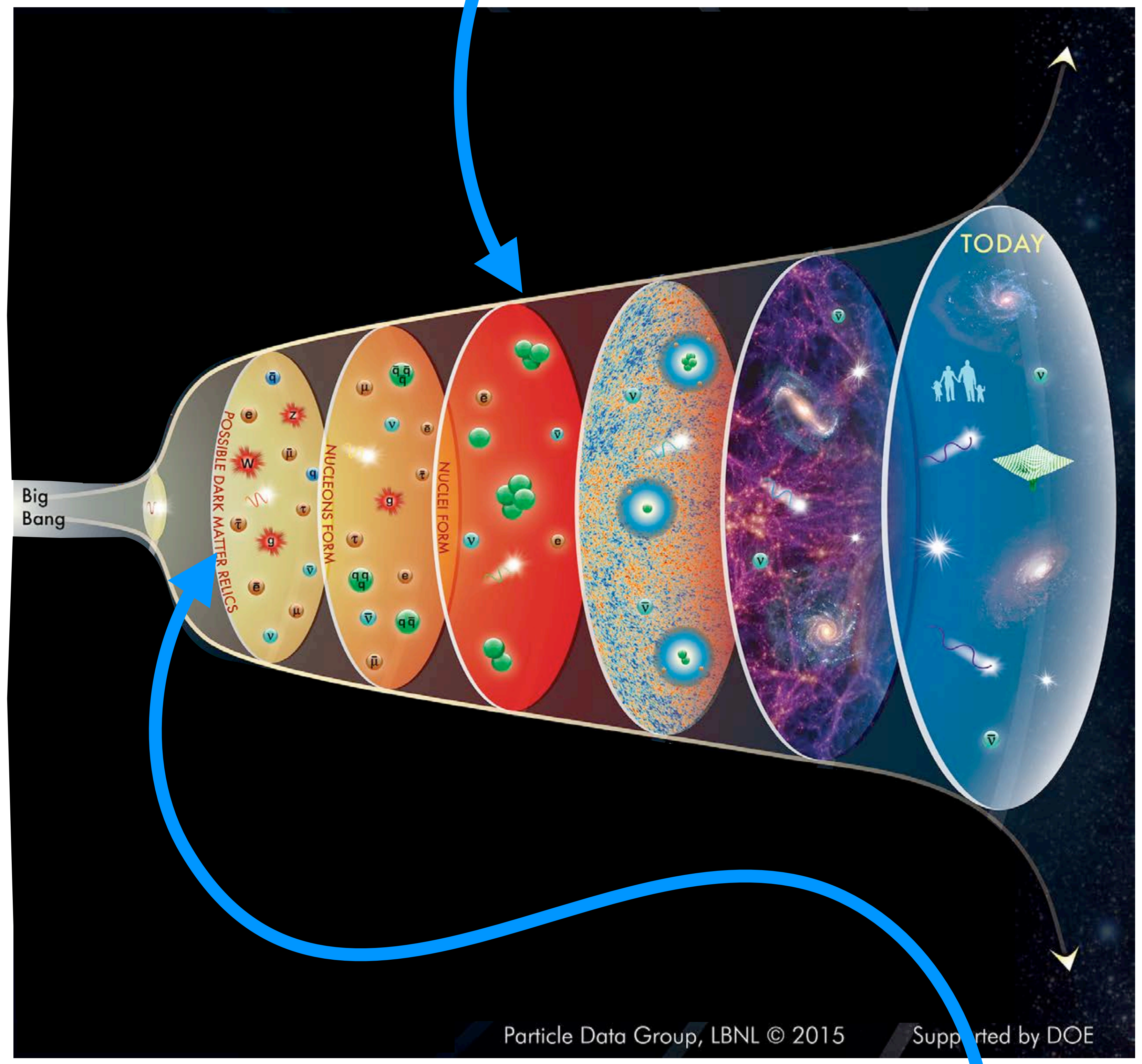


At latest, before the BBN

(before 1 sec, temperature > 1 MeV.)

It is difficult to generate the BAU just before the BBN, so usually much earlier time (much higher temperature) is considered.

(**An example** at a relatively low temperature:
Electroweak Baryogenesis, @ T∼100 GeV.)

At earliest, after the Inflation

because the inflation dilutes everything.

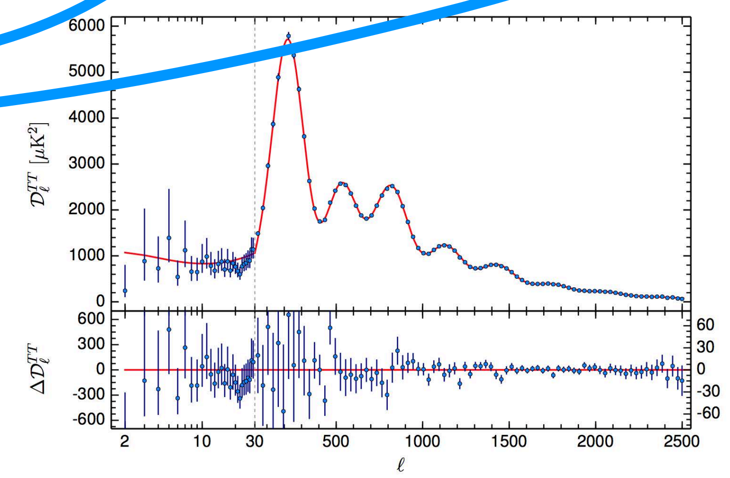
(**An example** just after the inflation: **Non-thermal Leptogenesis.**
The inflaton decays into right-handed neutrinos, which then lead to Leptogenesis.)

When was the Baryon Asymmetry of the Universe generated?

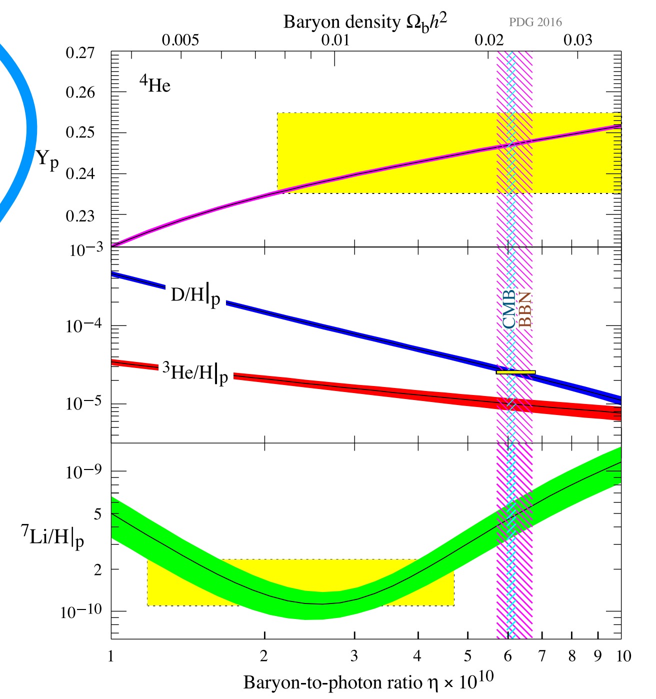
time	temperature	
??	??	Inflation
	T_R	Reheating
≈		
	100 GeV	Electroweak phase transition
	1 GeV	QCD phase transition
1 sec	1 MeV	Big Bang Nucleosynthesis
≈		
400,000 yrs	3000 K	Last Scattering Surface
≈		
14 billion yrs	3 K	Now

sometime in this range

CMB



24. Big-Bang nucleosynthesis **3**



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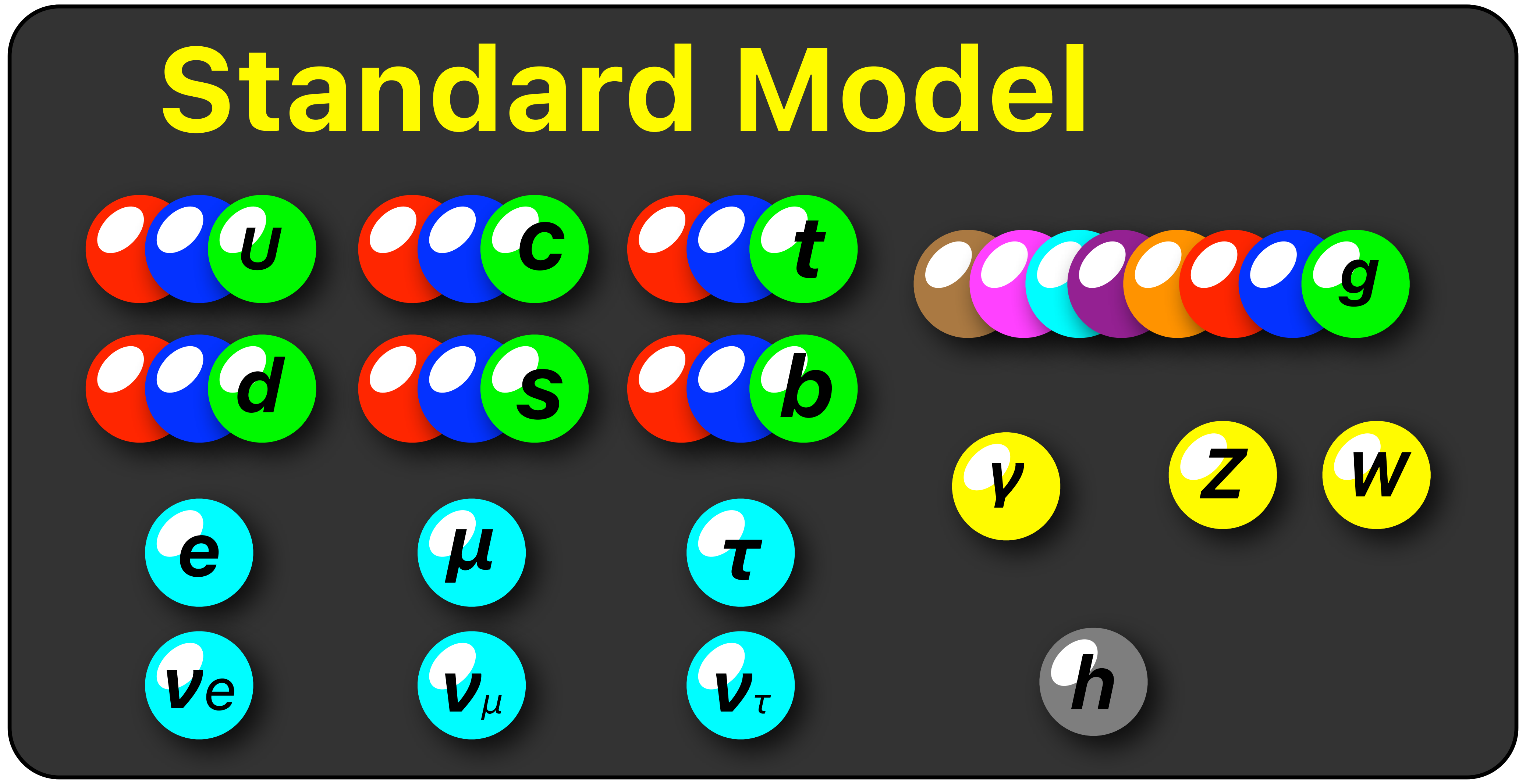

... does not work.

Sakharov's 3 conditions [Sakharov 1967]

- [x] Baryon number violation
- [x] CP-violation ... (but too small)
- [ ] out-of-equilibrium

Something beyond the Standard Model is necessary.

Plan

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Why "Lepto"genesis?

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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?

<u>Within the Standard Model,...</u>

At high temperature, T >> 100 GeV,
B and L violating processes (sphaleron)
become very rapid, and in thermal equilibrium!

[Kuzmin, Rubakov, Shaposhnikov,'85]

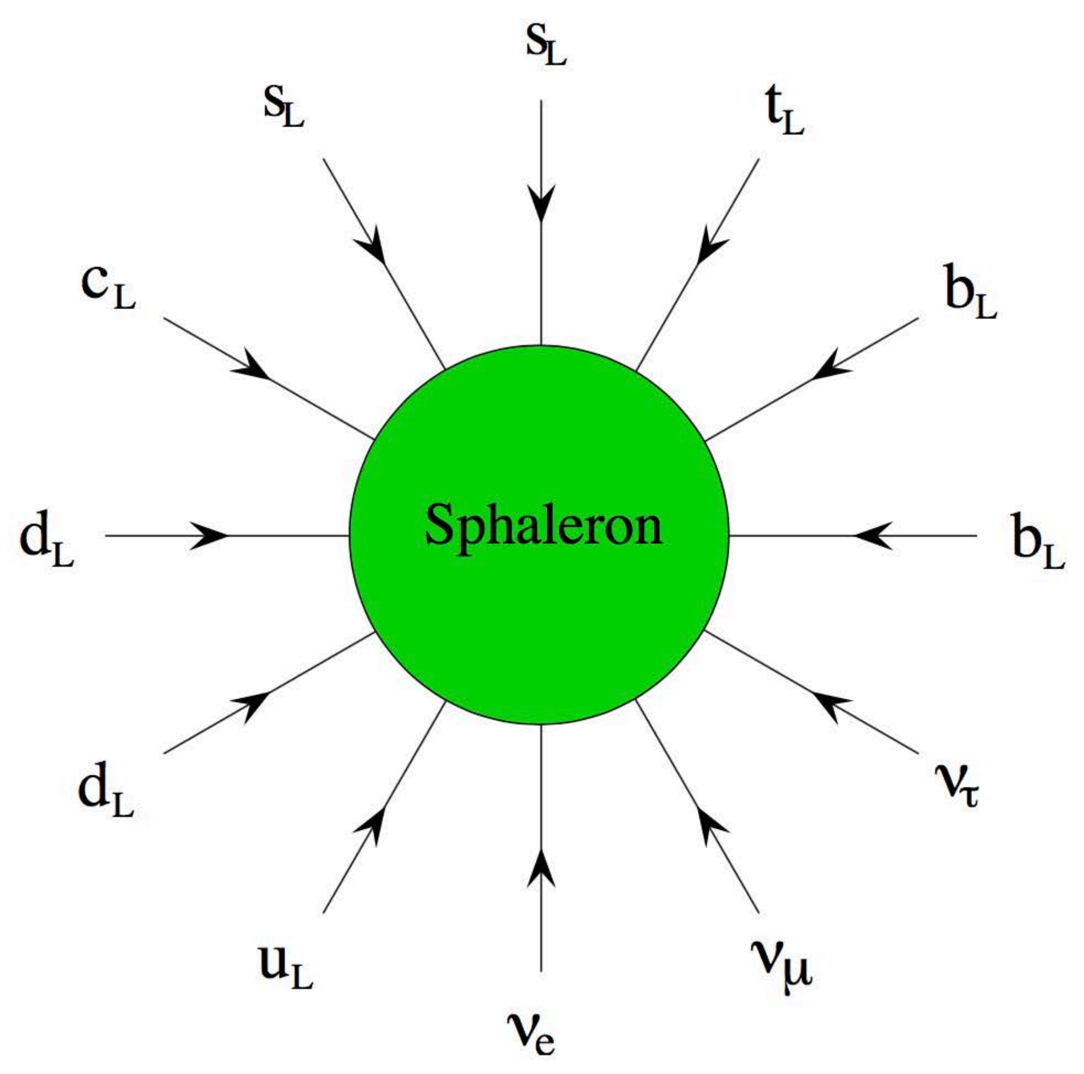


Figure 1: One of the 12-fermion processes which are in thermal equilibrium in the high-temperature phase of the Standard Model.

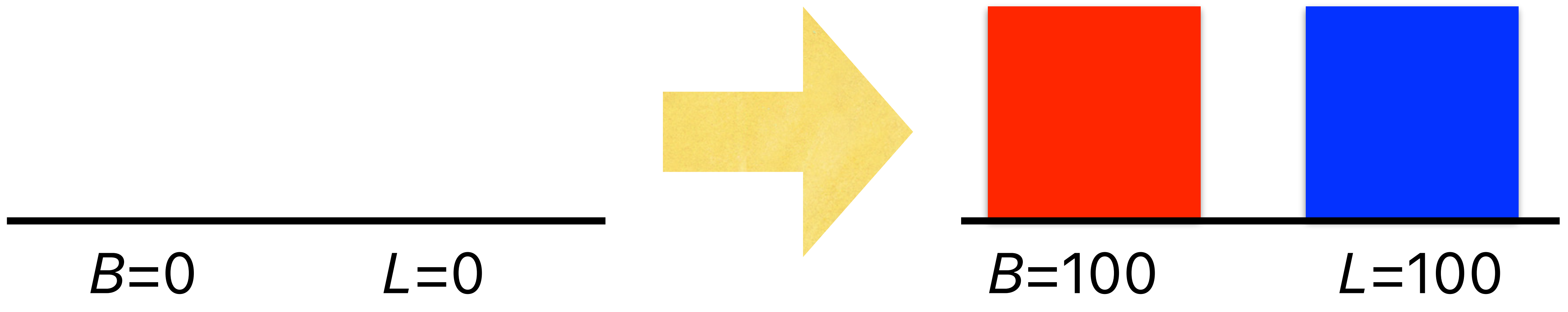
[fig. from W.Buchmuller, 1210.7758]

Sphaleron process

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

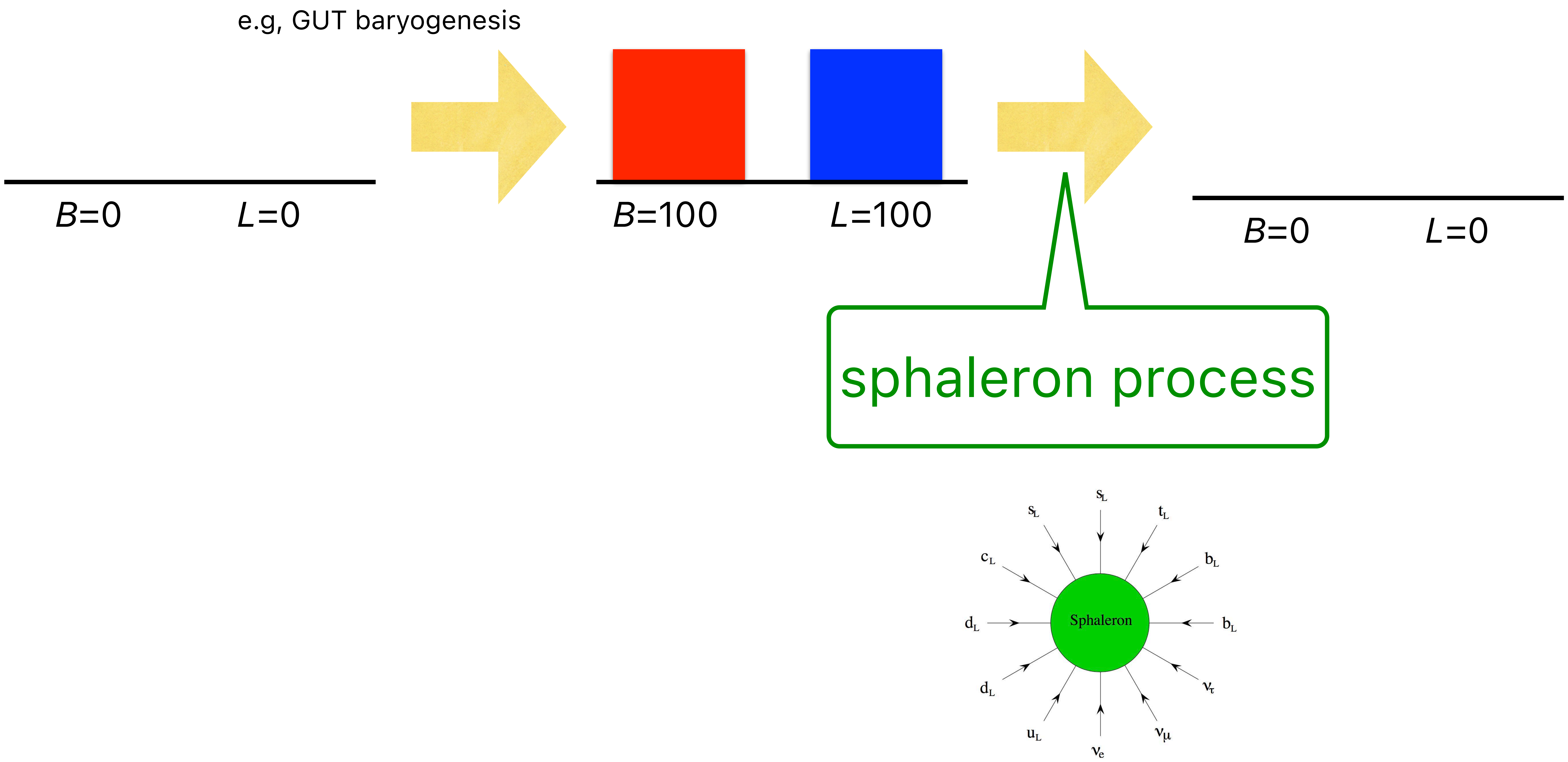
Therefore, if the Baryon asymmetry is generated via a ***B-L conserving process,...***

e.g, GUT baryogenesis



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

Finally *B*=0 at equilibrium.



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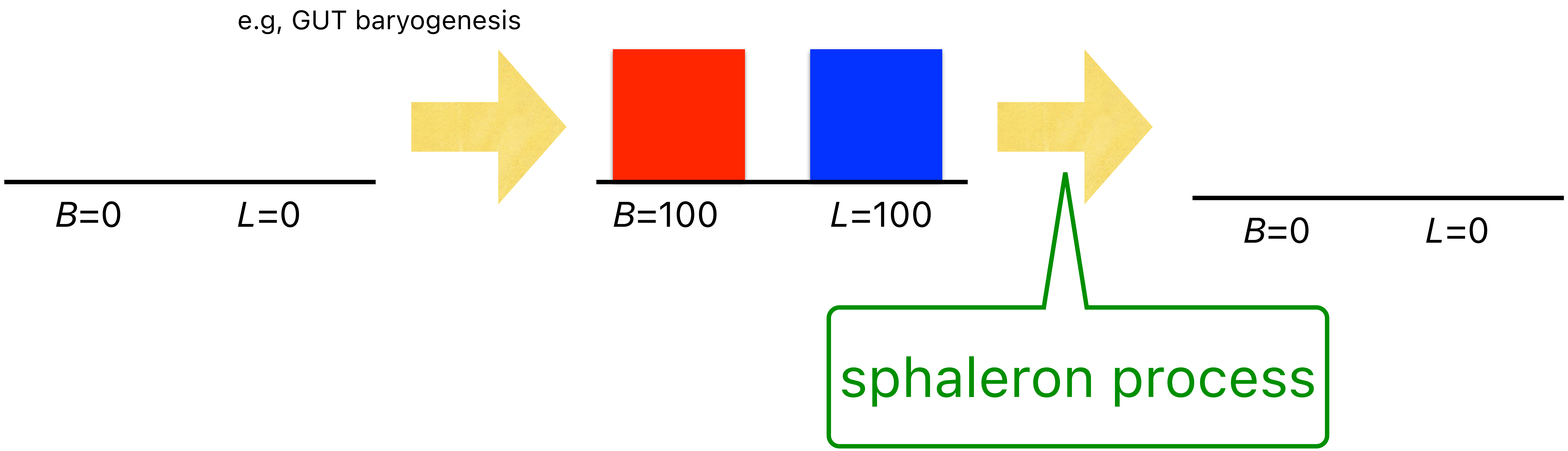
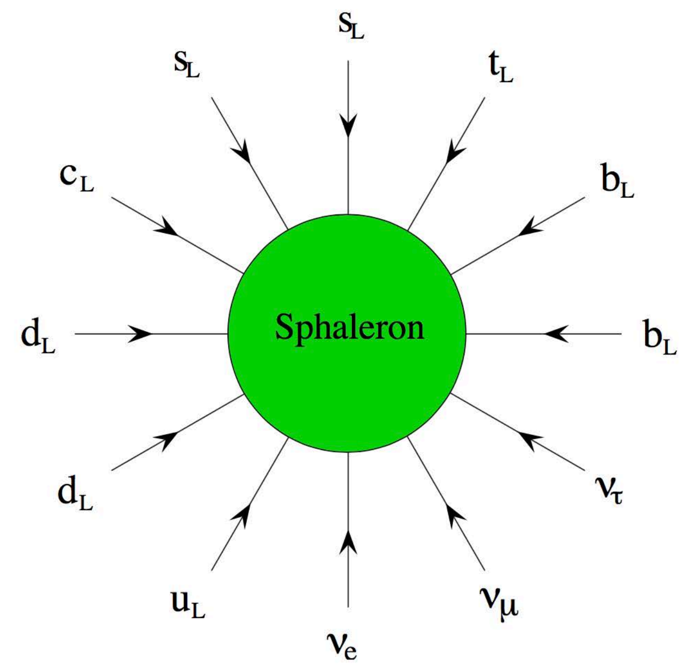


***B-L* violating process is necessary.**



Sakharov's 3 conditions

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

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On the other hand, this means that...

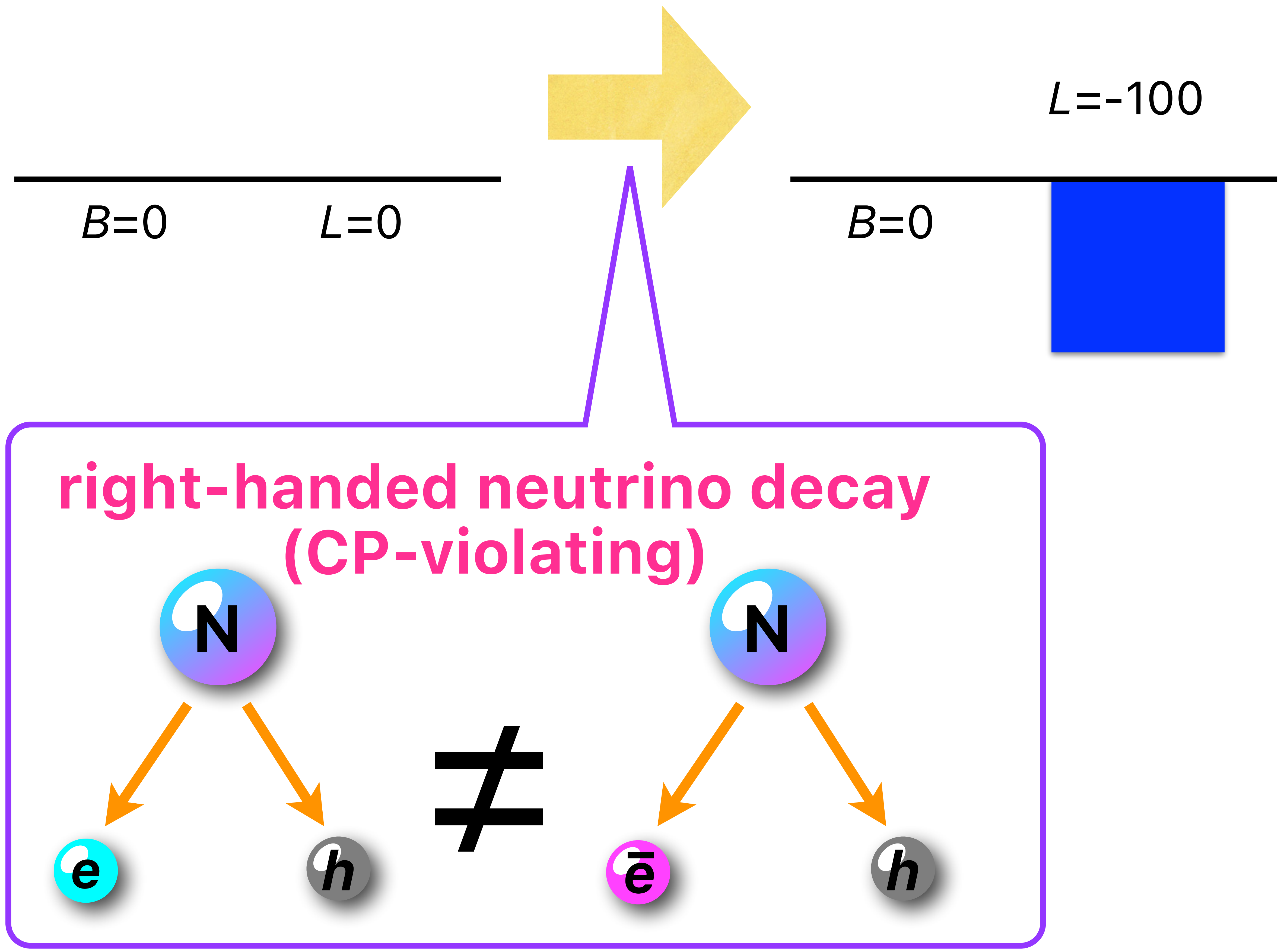
Baryogenesis can work, not only via B-violation,
but also via **L-violation.**

and L-violation implies **Majorana neutrino (and 0νββ decay).**

Leptogenesis

[Fukugita, Yanagida, '86]

generate **Lepton** asymmetry

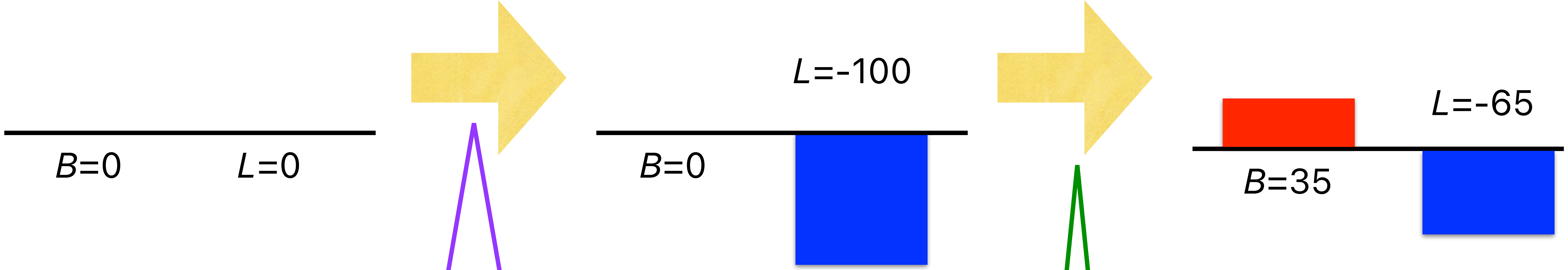


Leptogenesis

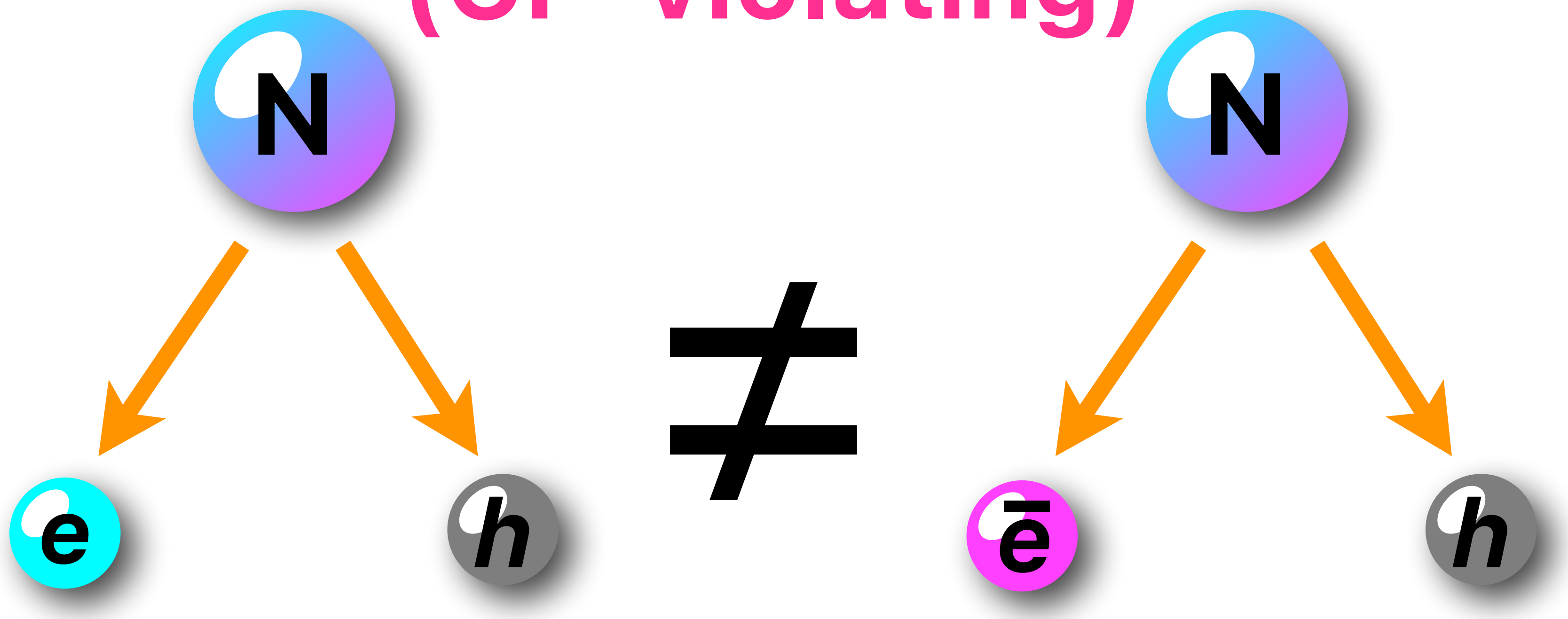
[Fukugita, Yanagida, '86]

generate **Lepton** asymmetry

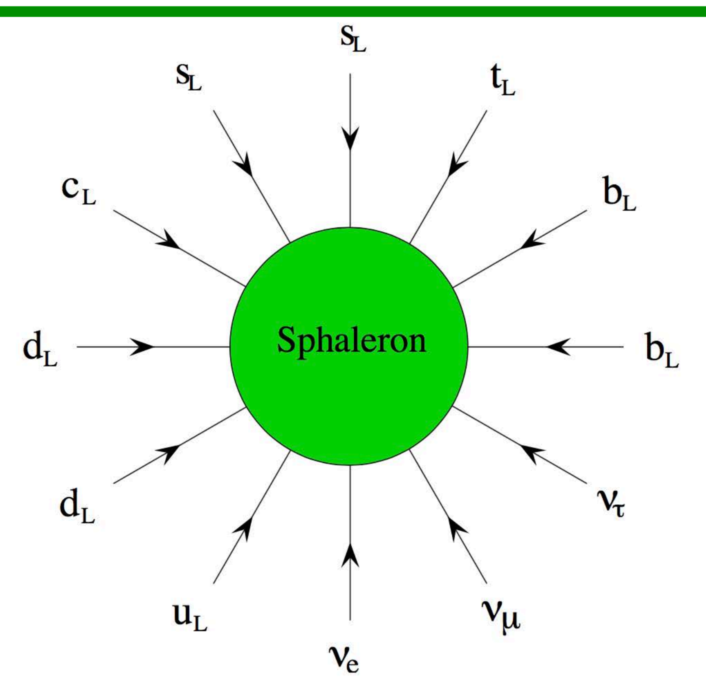
Then, ***B*≠0 remains** at equilibrium!



right-handed neutrino decay (CP-violating)



sphaleron



Leptogenesis [Fukugita, Yanagida, '86]

There are various versions…

- Thermal Leptogenesis

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

- Leptogenesis from Inflaton Decay

  […… Asaka, KH, Kawasaki, Yanagida,'99……]

- Leptogenesis from R.H.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, ……]

- via R.H.N oscillation (ν*MSM)*

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

(+ many others …)

For reviews, see e.g., arXiv:1711.02861〜 1711.02866.

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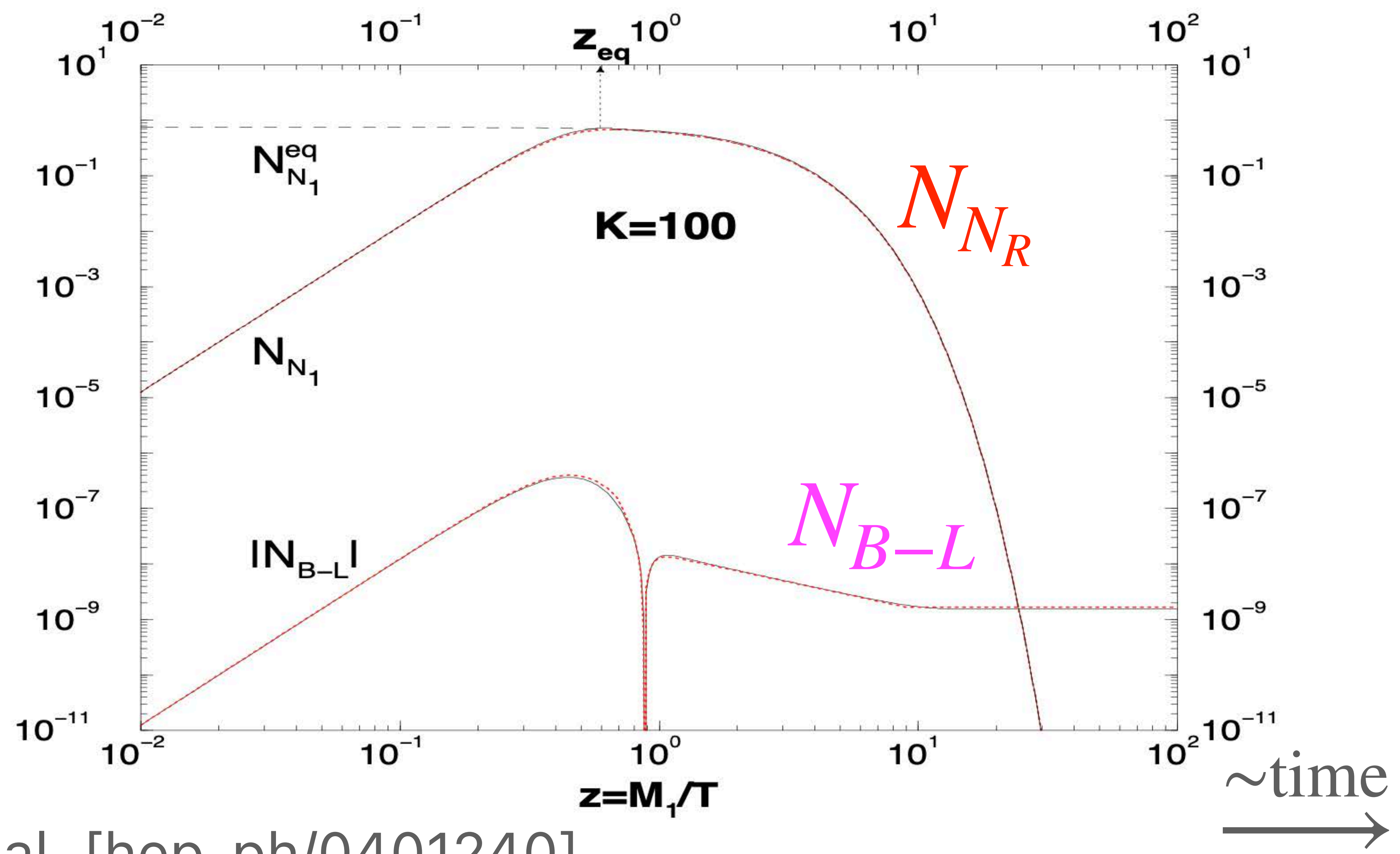
- **Model:** Standard Model + Right-handed neutrino **(very simple!)**

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\overline{N}_R(i\gamma^\mu\partial_\mu + M_{N_R})N_R + y_\nu \overline{N}_R \ell_L H + h.c.$$

- **Boltzmann eqs.**

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

$$\frac{dN_{B-L}}{dz} = \epsilon D\left(N_{N_R} - N_{N_R}^{\rm eq}\right) - WN_{B-L}$$



- The observed baryon asymmetry can be explained if $M_{N_R} \gtrsim \mathcal{O}(10^9)$ GeV.

- Fig. from Buchmuller et.al. [hep-ph/0401240]

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(+ many others …)

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※ All of them require L-number violation and predict **0νββ decay.**
cf. **talk by Umehara-san** in the previous session.

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

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Seesaw and Leptogenesis in a “big picture”

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Puzzles in the Standard Model
= Hints of Physics beyond the Standard Model

Cosmology

Dark Energy

initial condition of Universe

Dark Matter

Matter > Anti-matter

Particle Physics

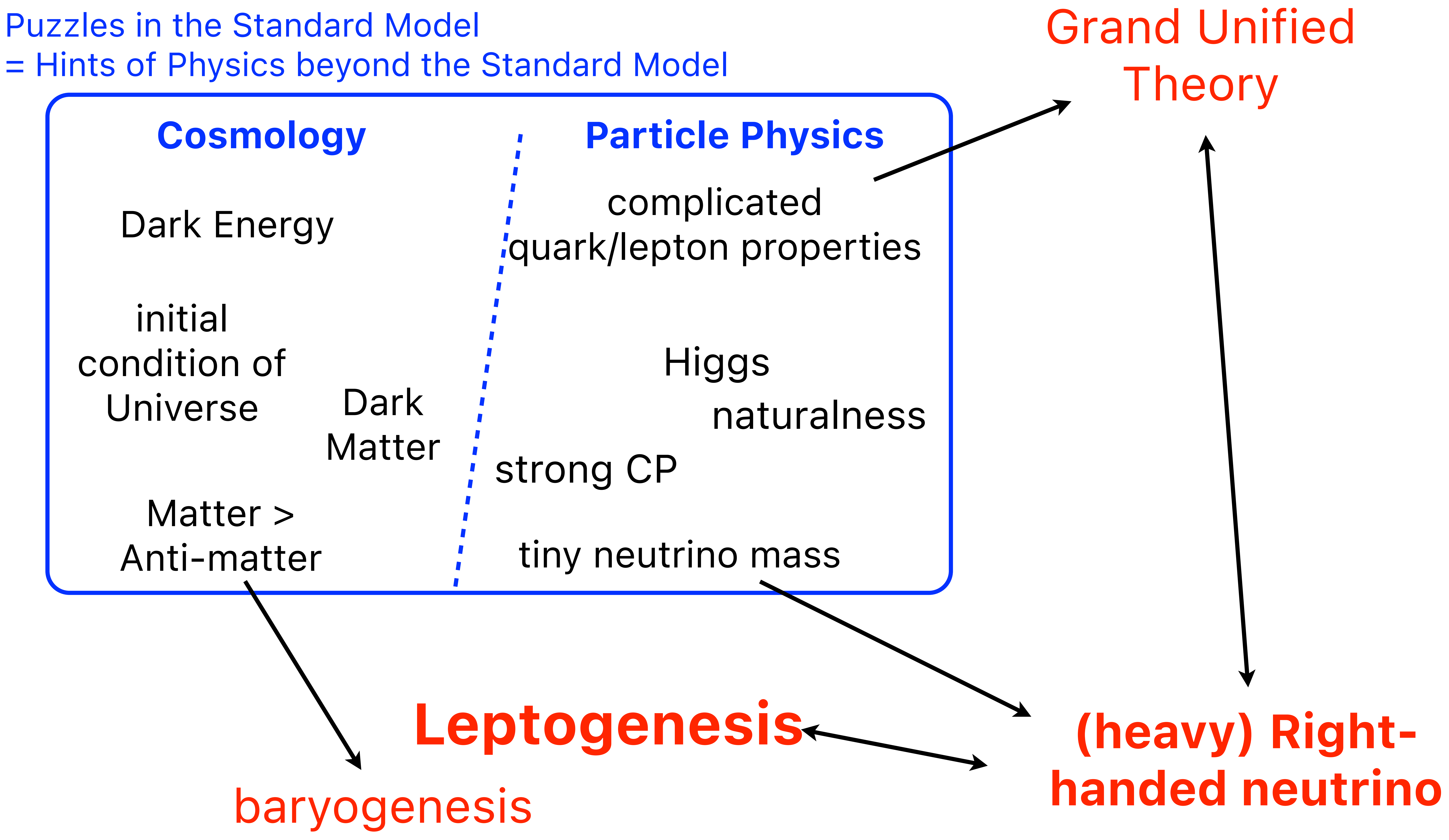
complicated quark/lepton properties

Higgs naturalness

strong CP

tiny neutrino mass

Seesaw and Leptogenesis in a “big picture”



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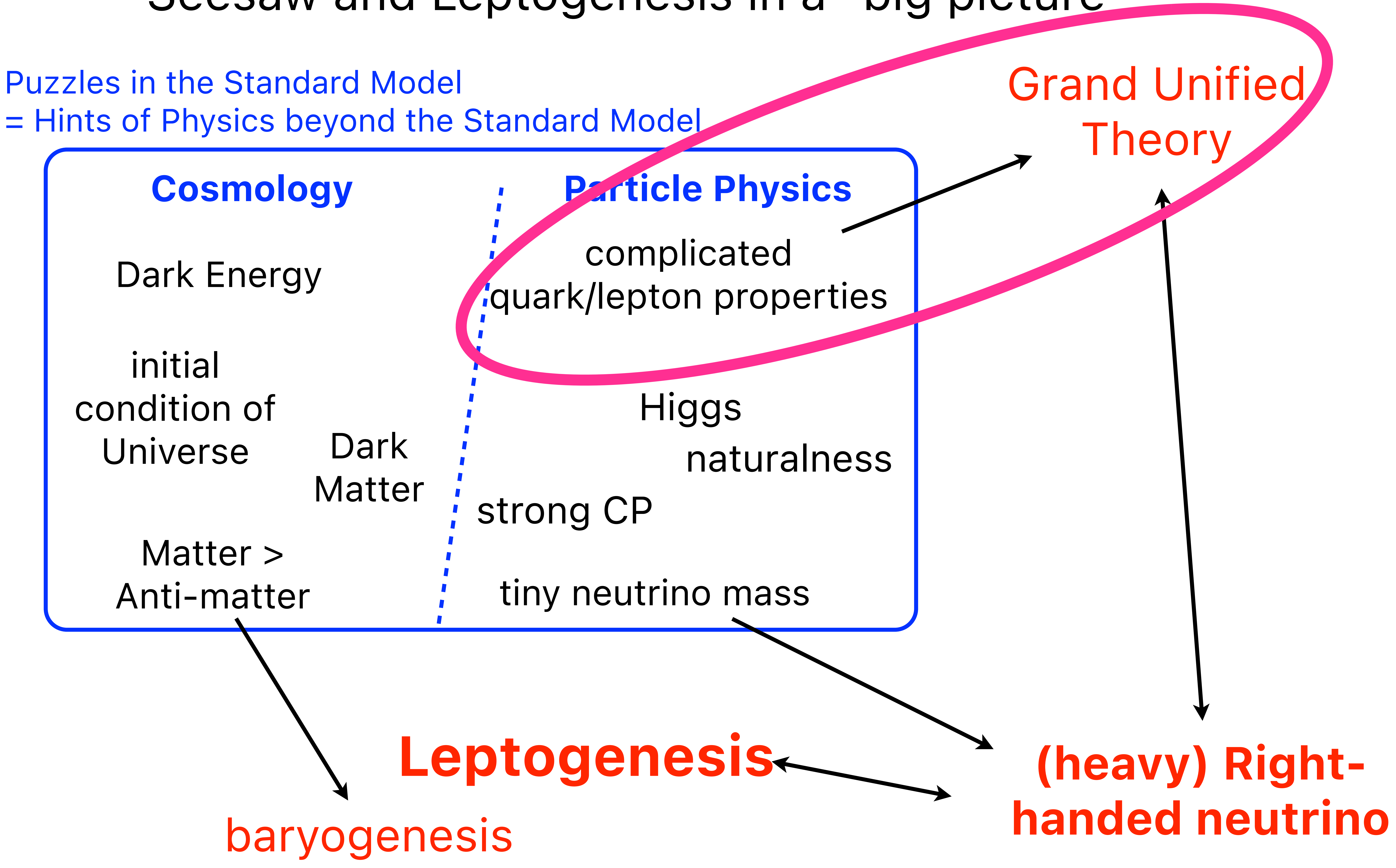


Standard Model

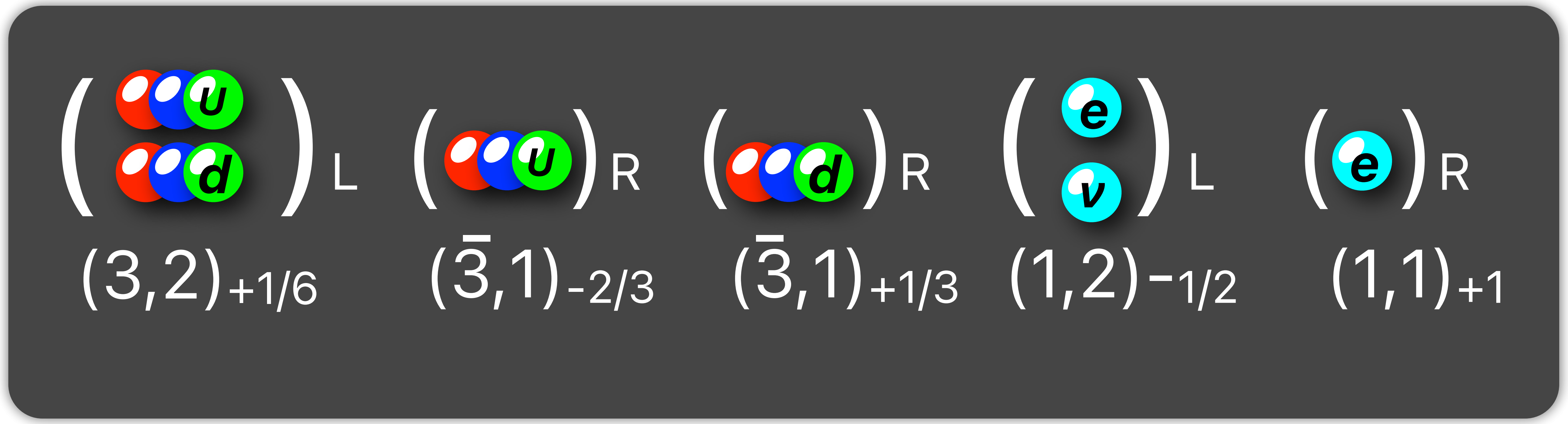
left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

right-handed lepton



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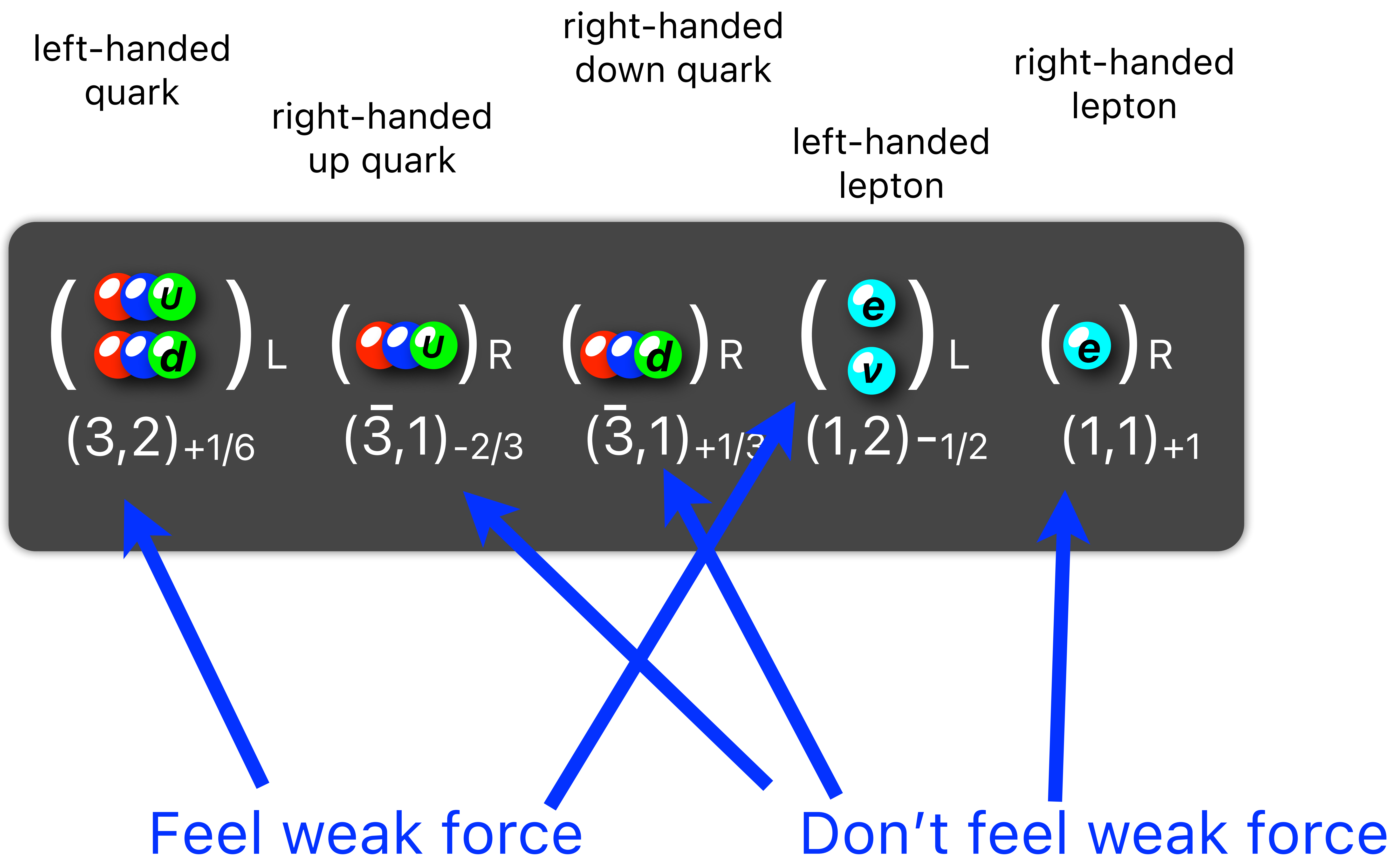

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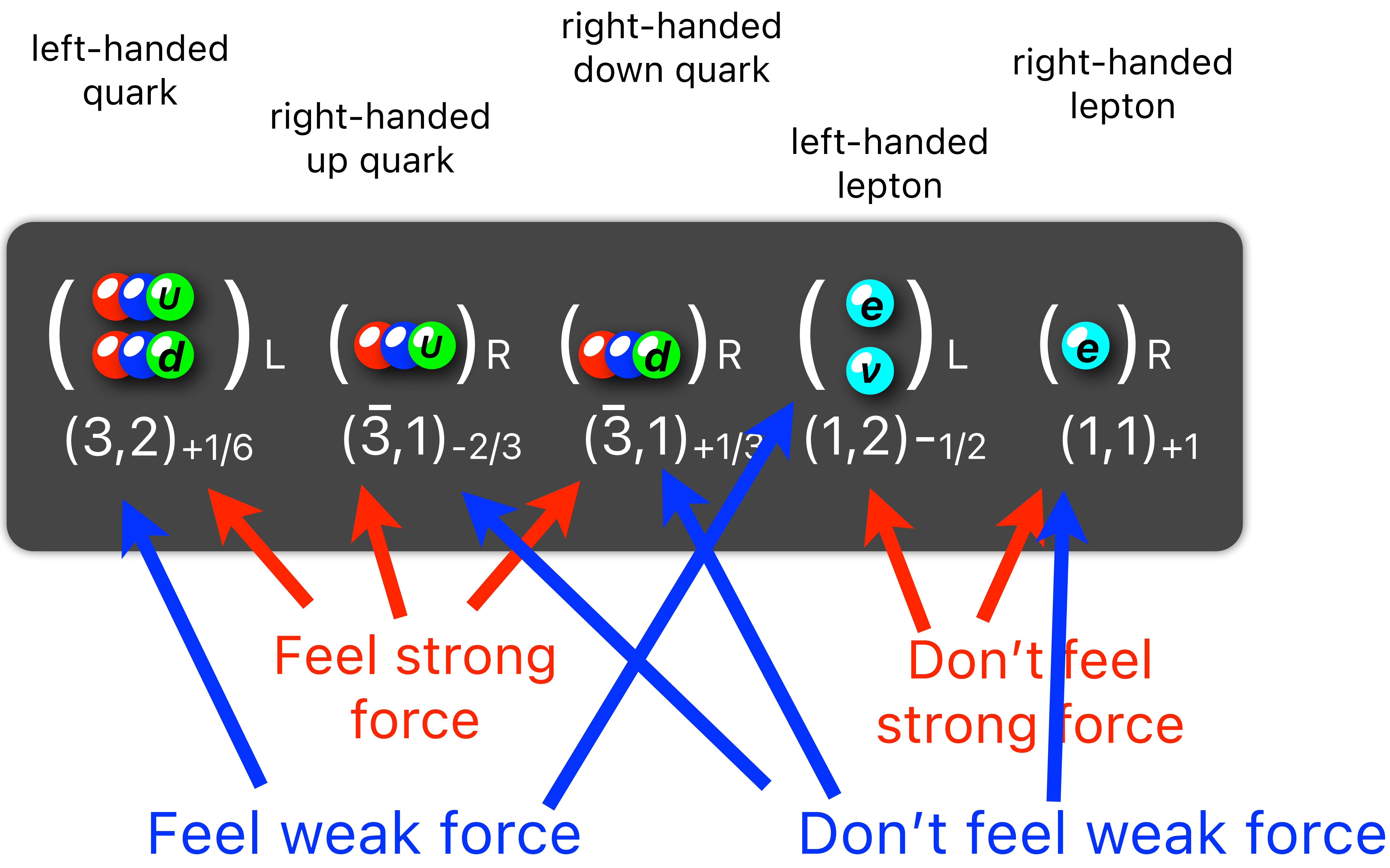

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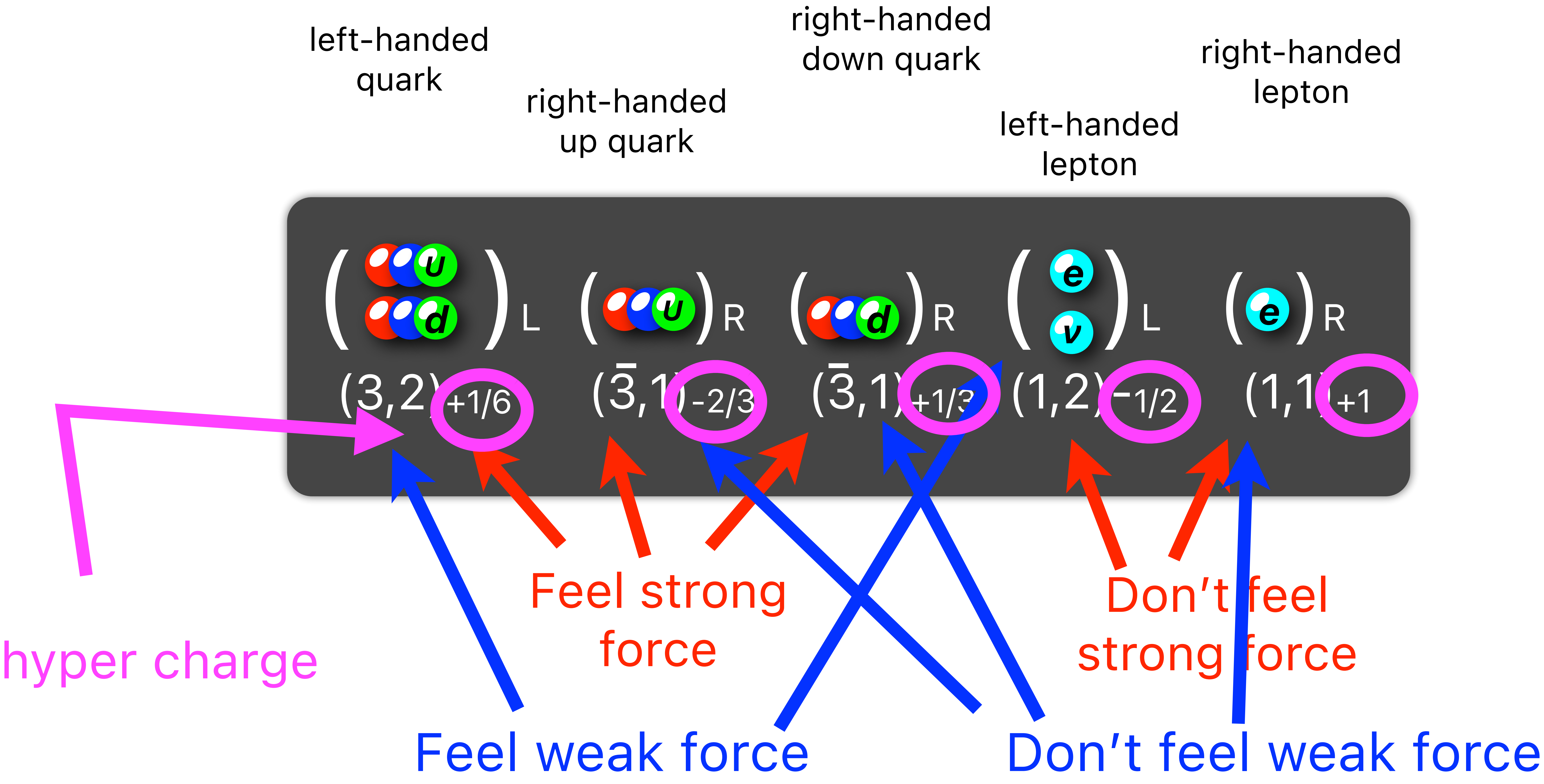

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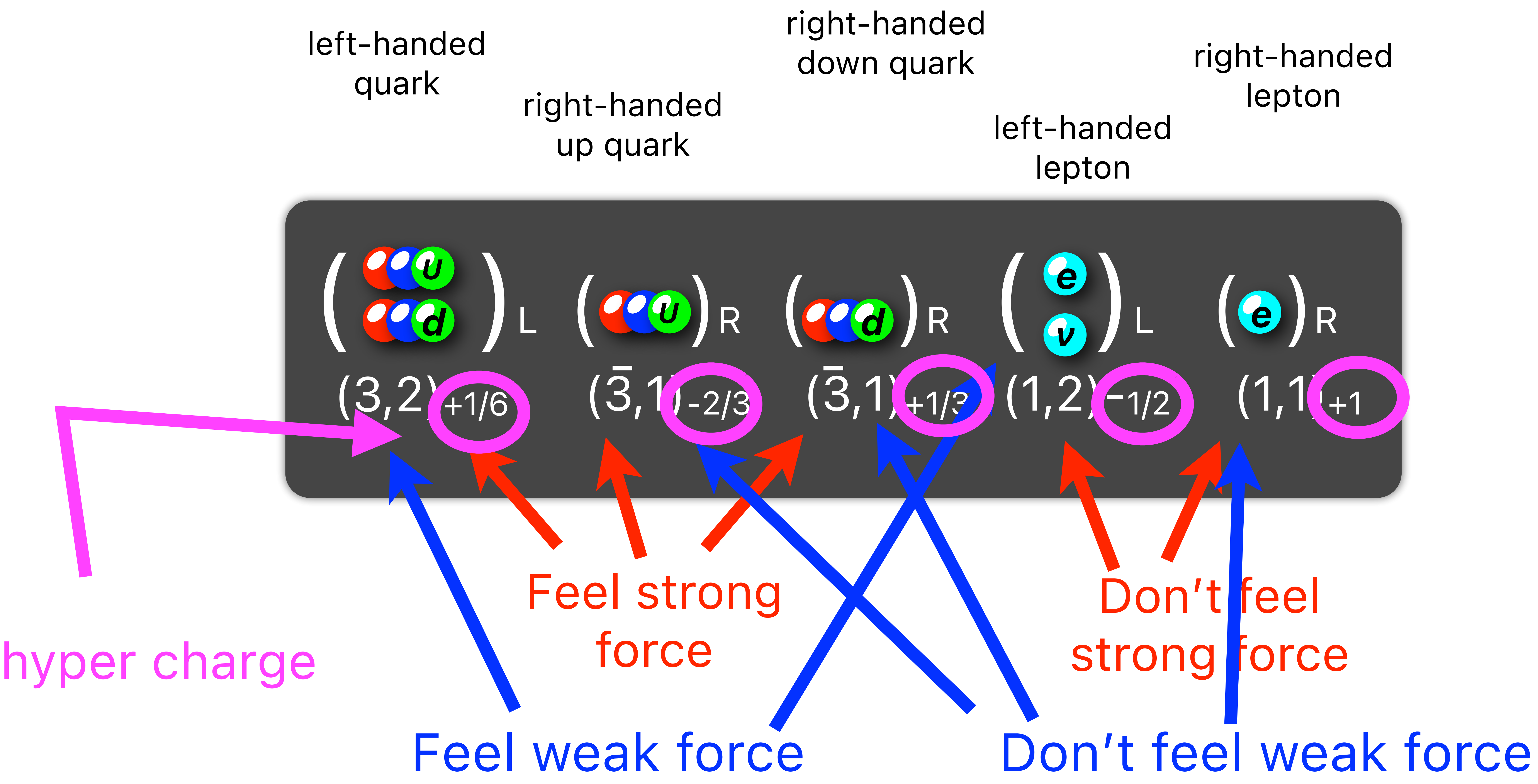
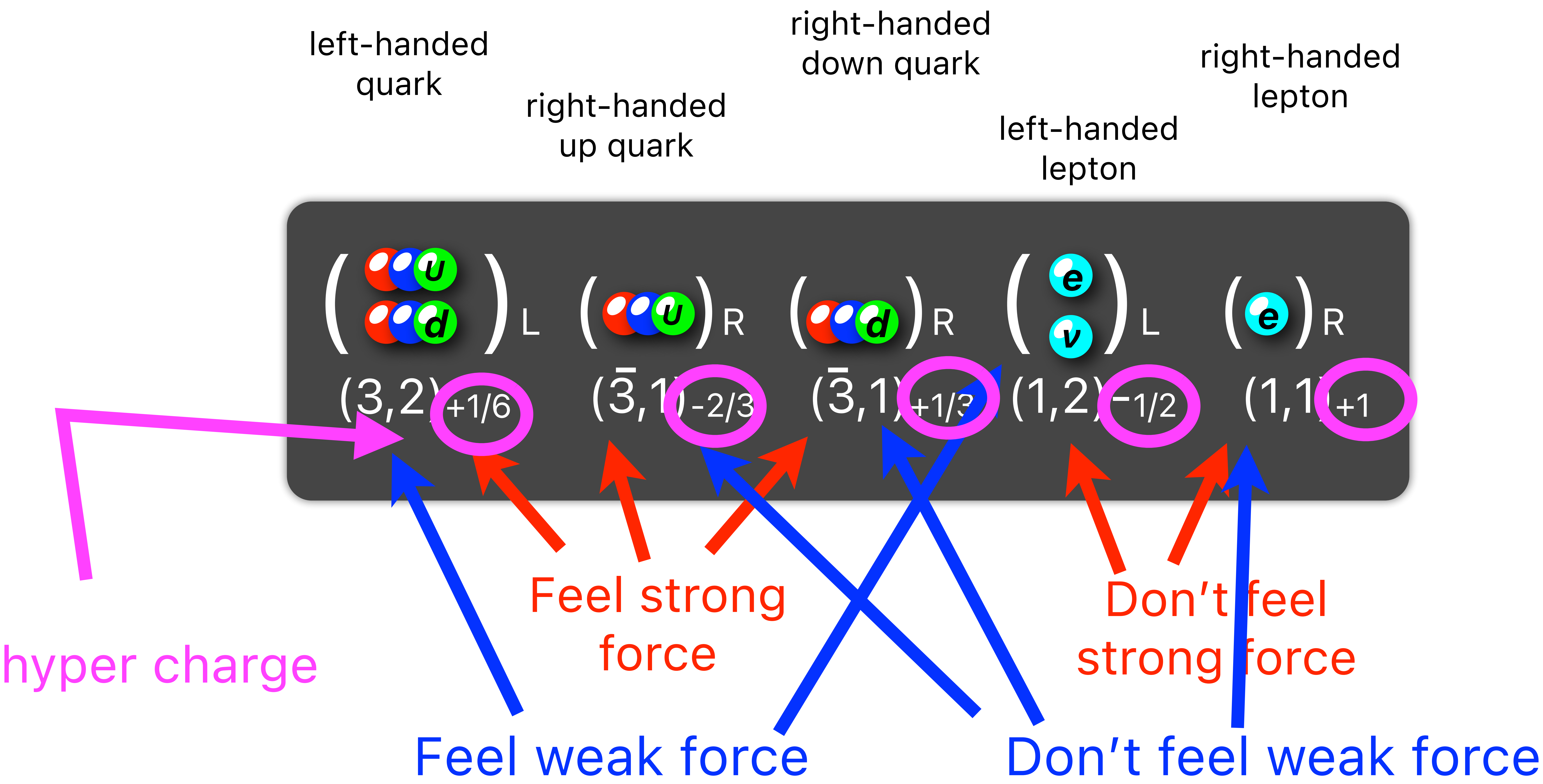


... very complicated !!

Standard Model



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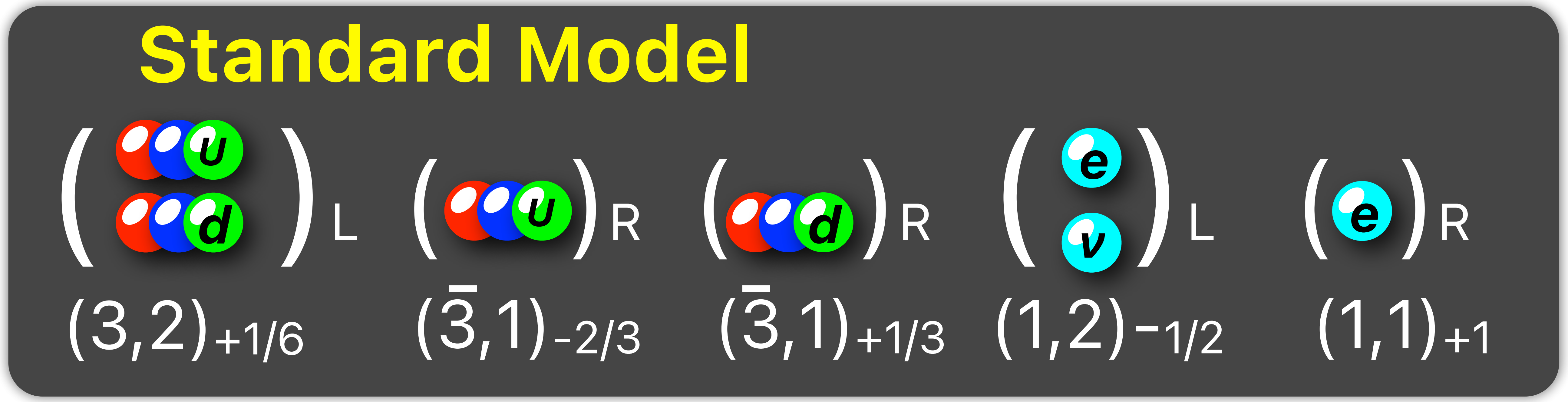

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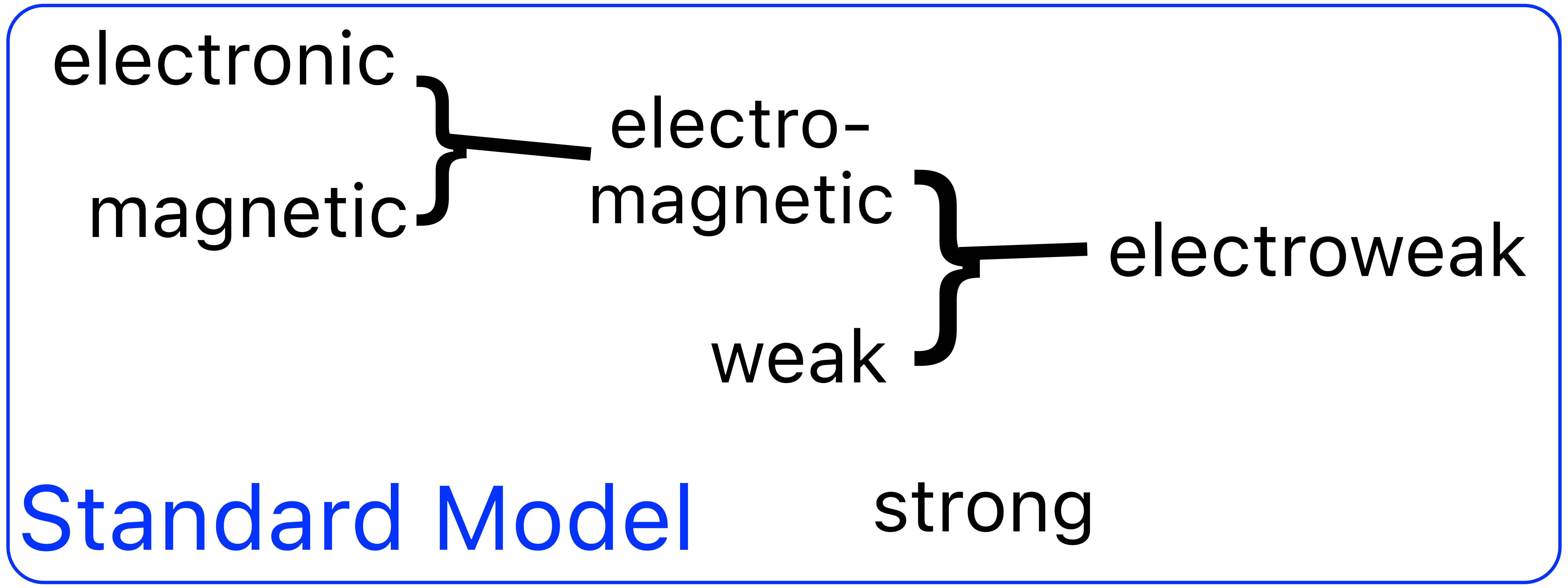

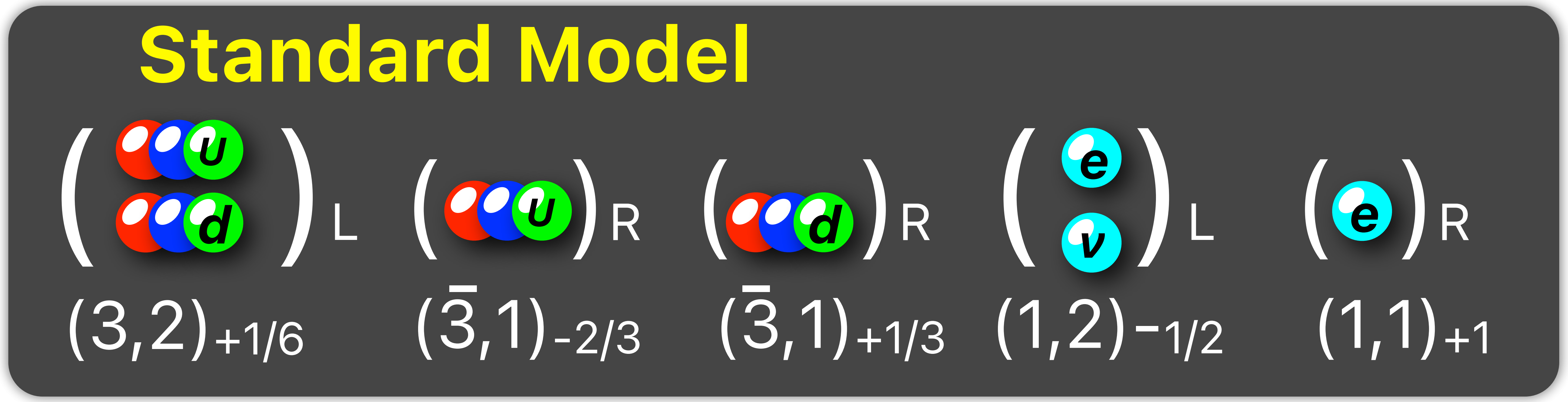

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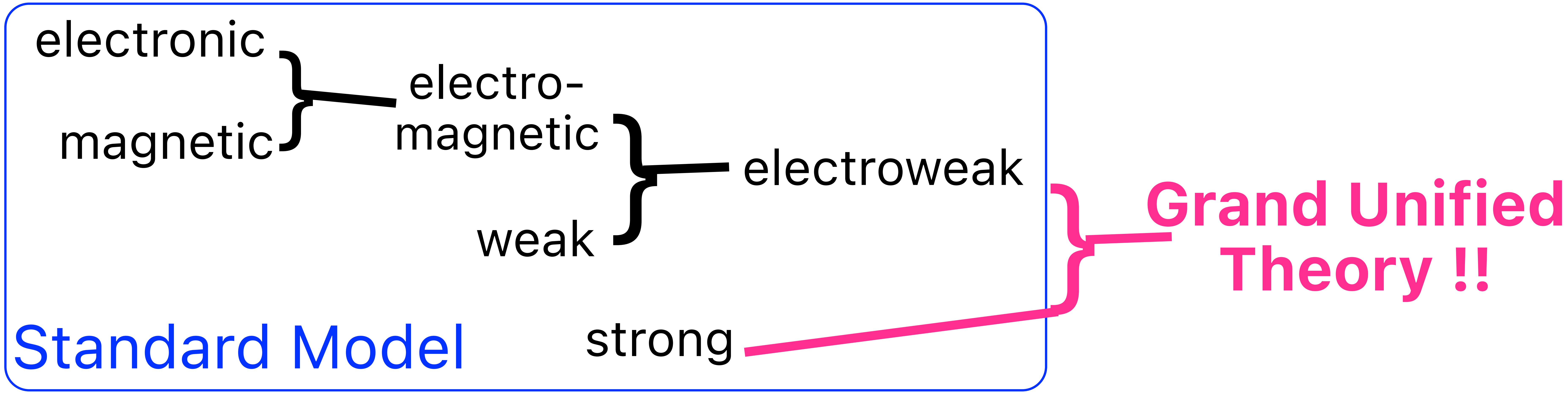

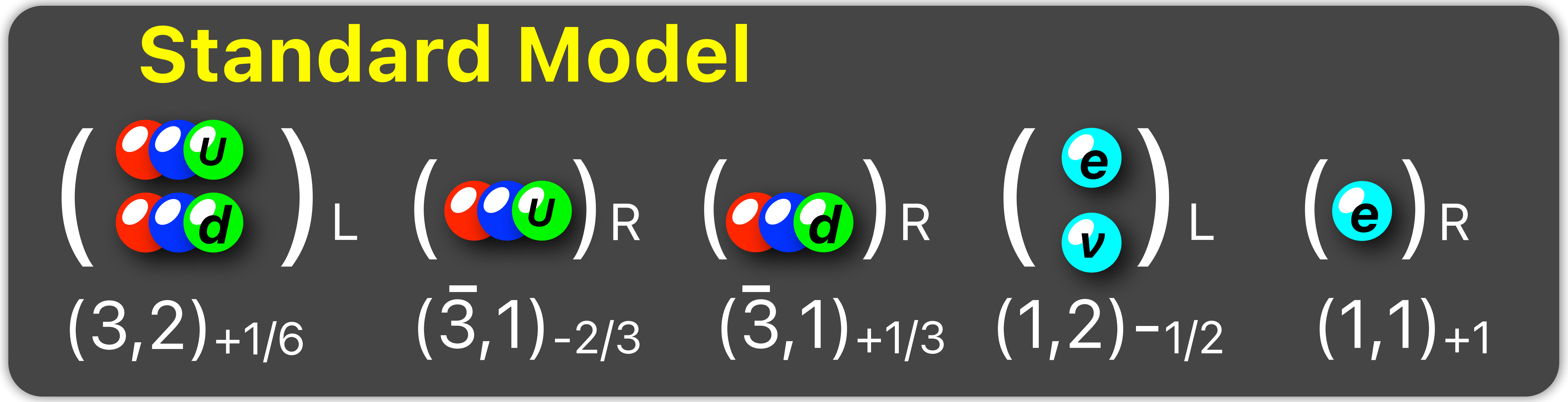

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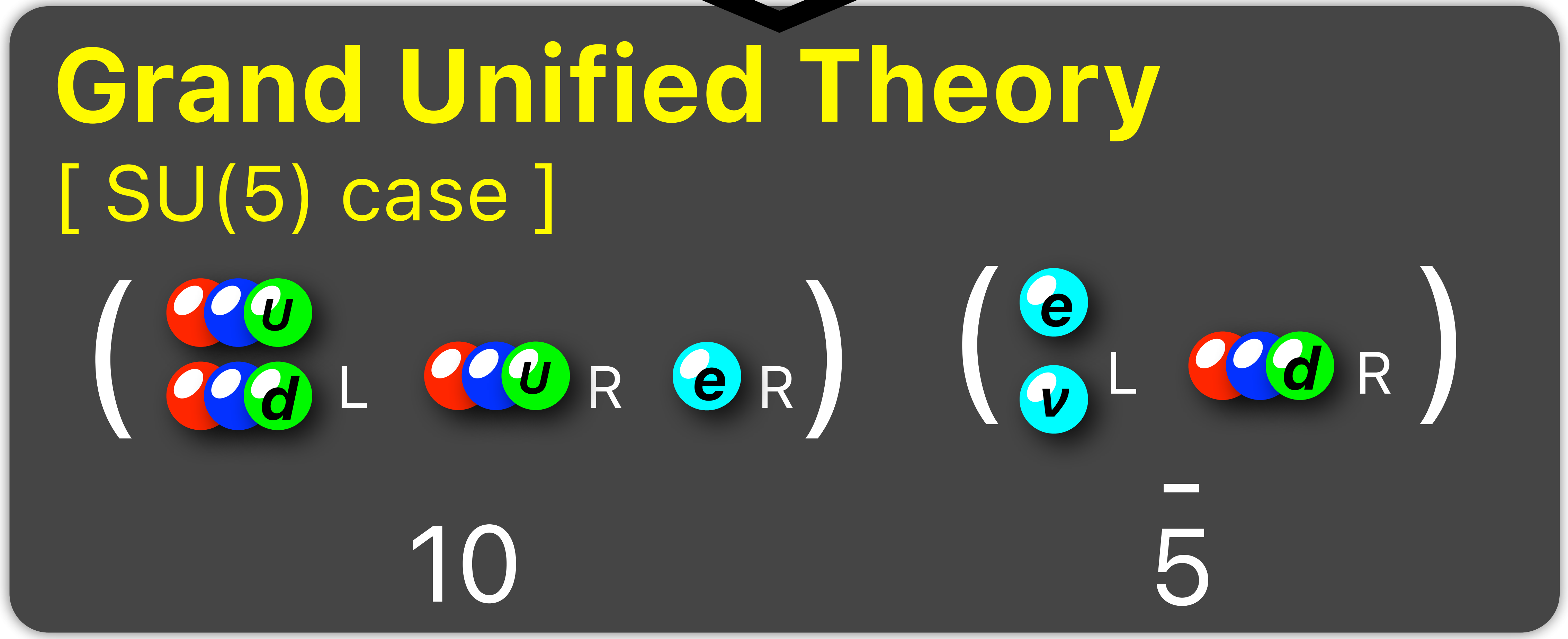
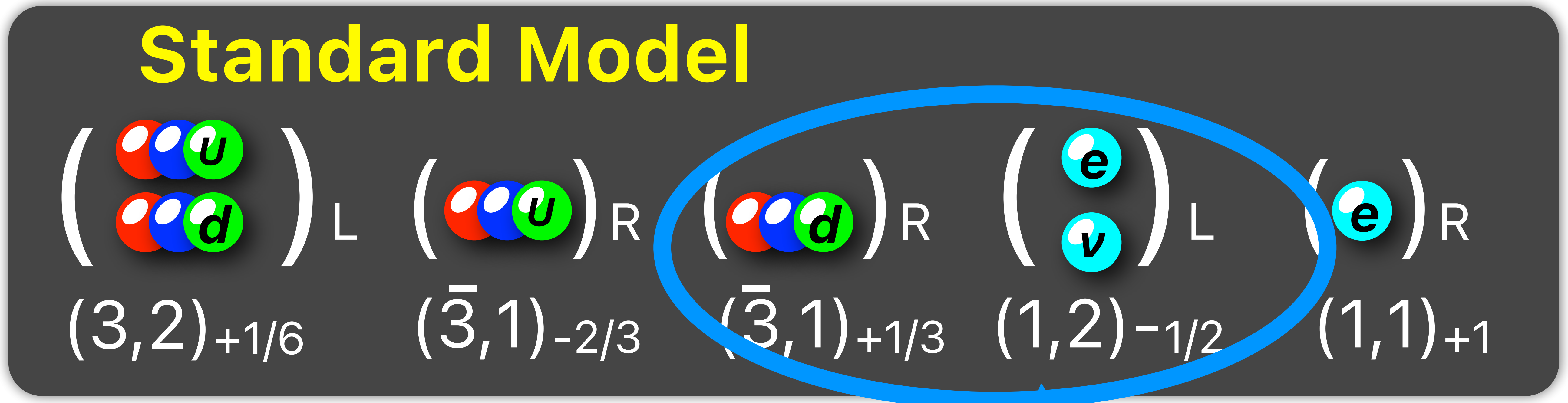


... beautifully unified
into simple SU(5)
representations !

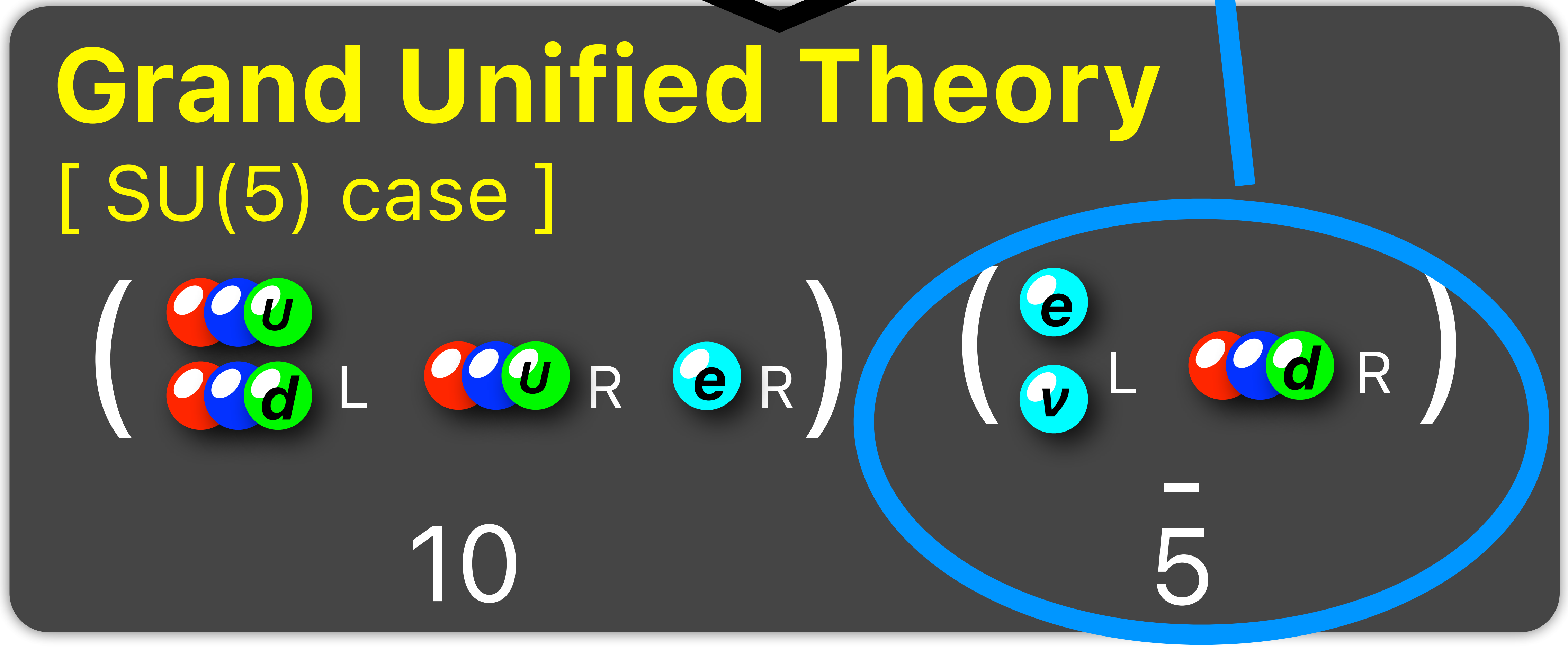
[Georgi, Glashow 1974]



Q: any simple, unified theory to explain it?

$1/3 + 1/3 + 1/3 - 1/2 - 1/2 = 0$

Complicated numbers are naturally explained !



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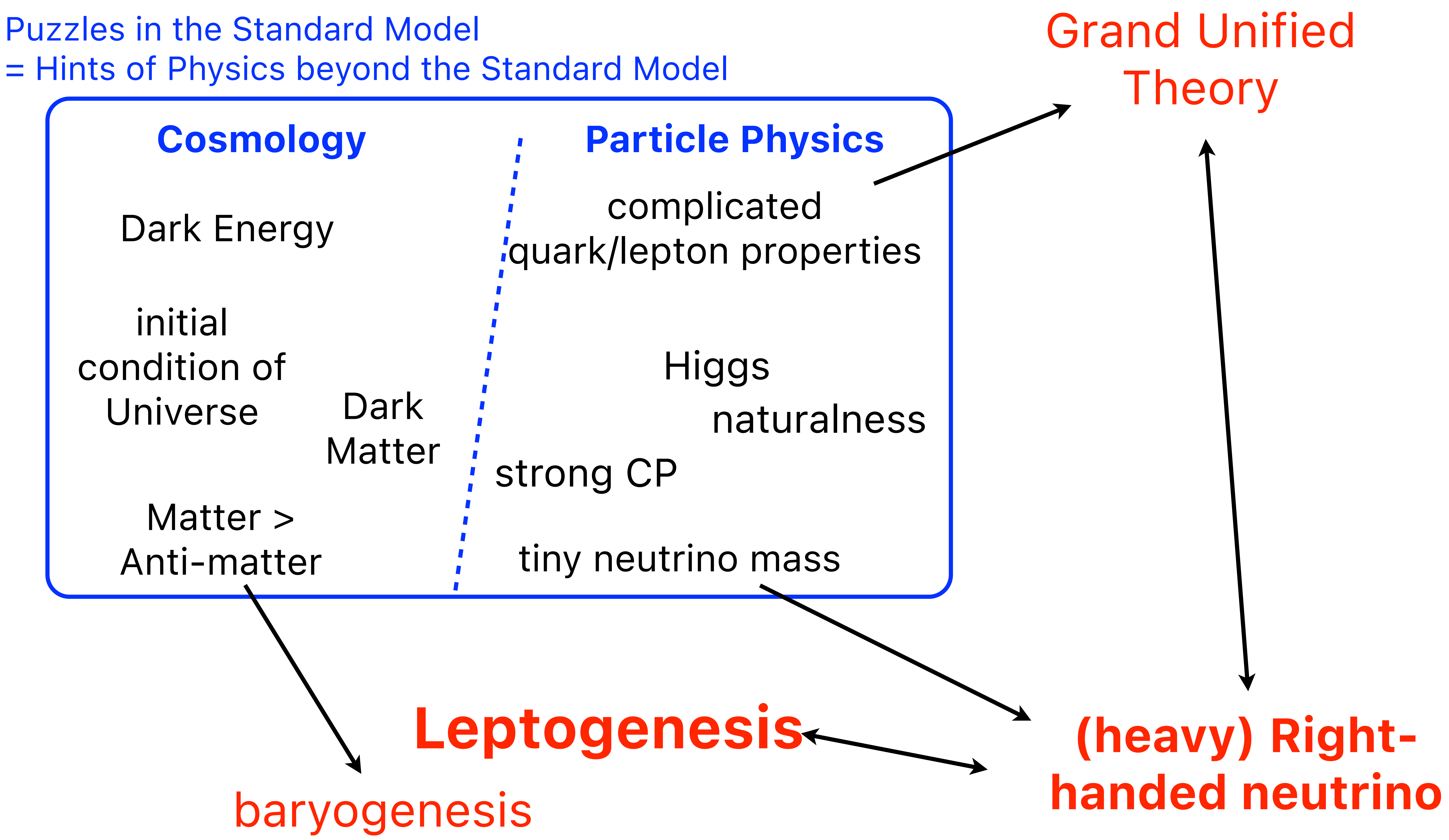
[Georgi, Glashow 1974]

Seesaw and Leptogenesis in a "big picture"



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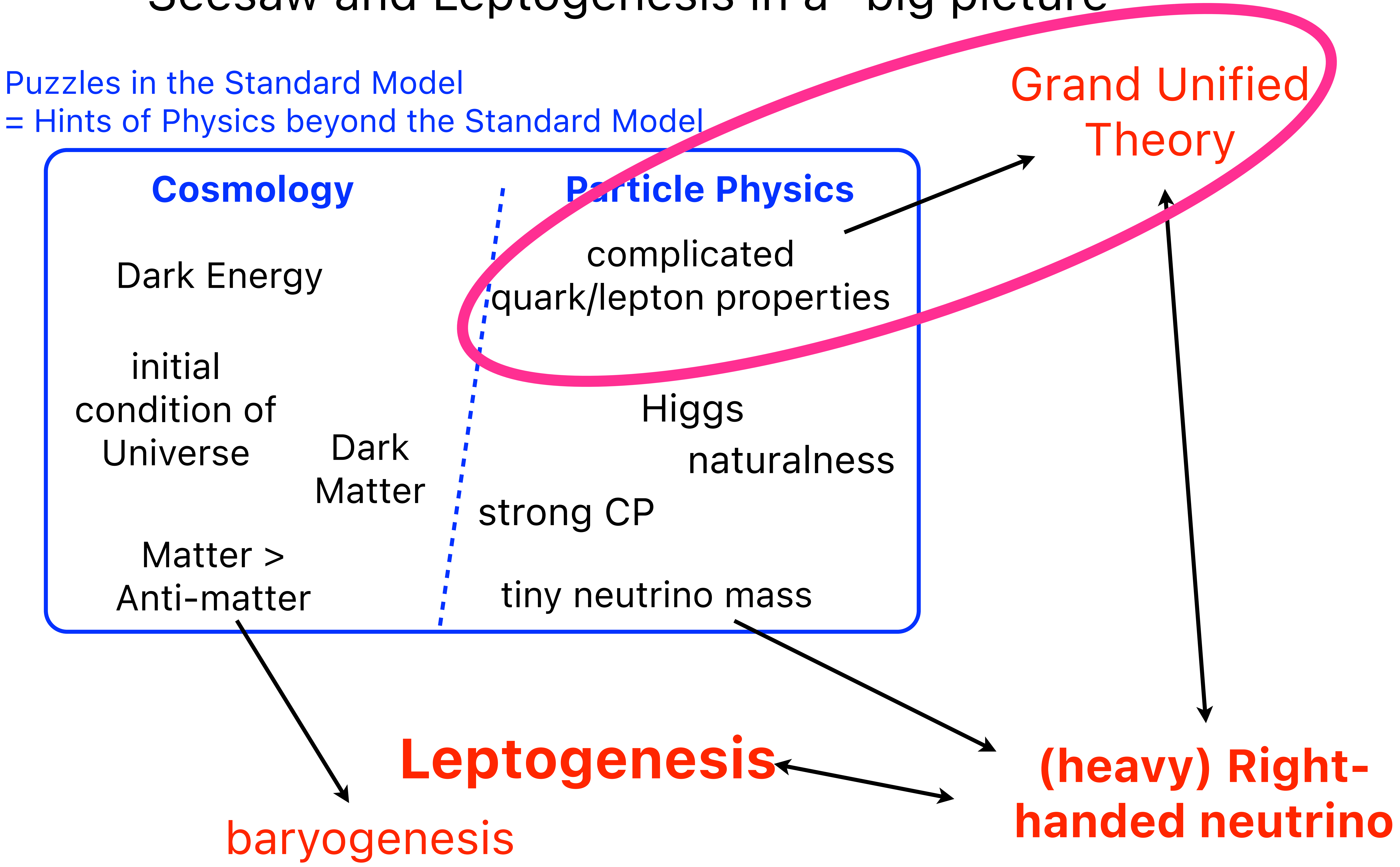
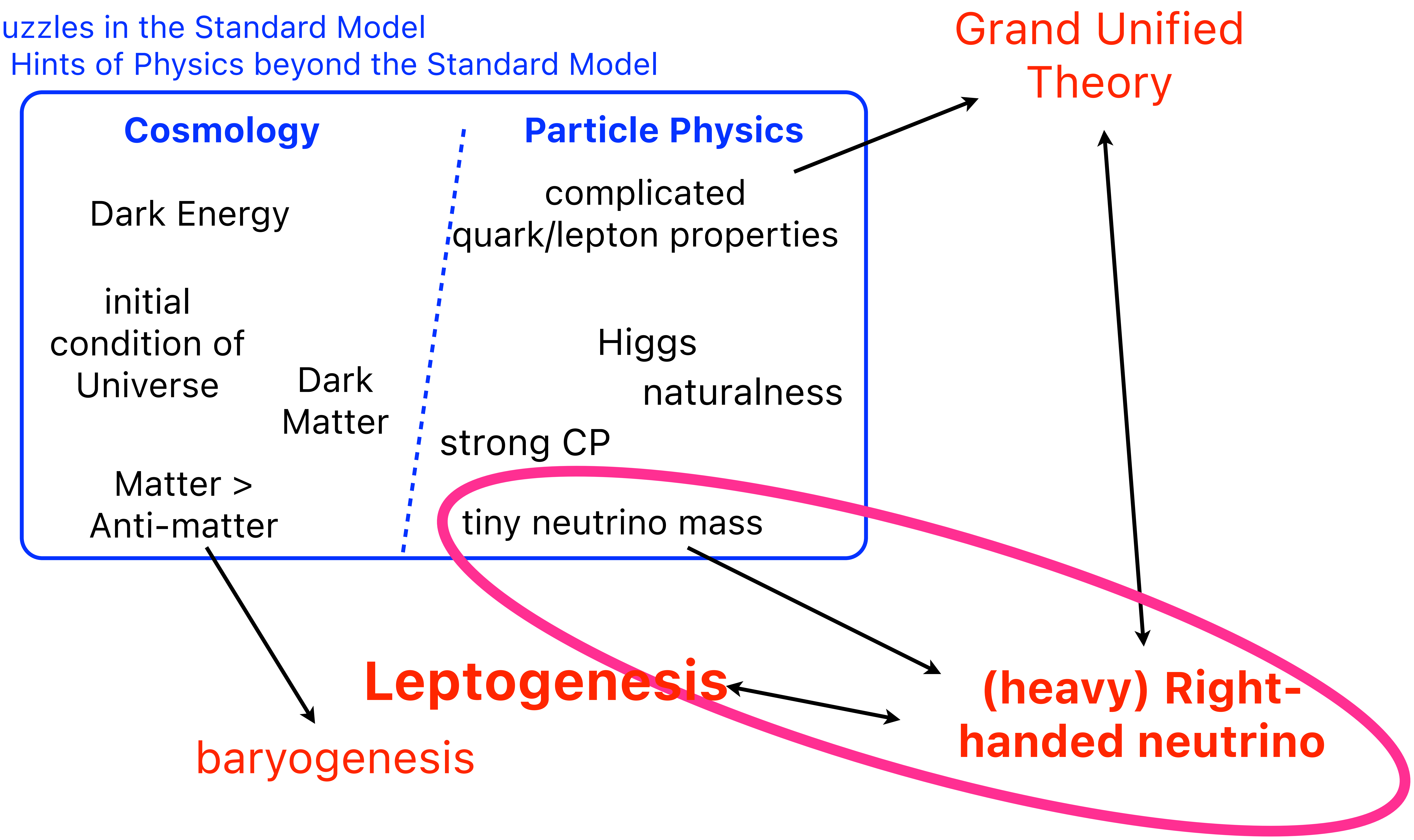
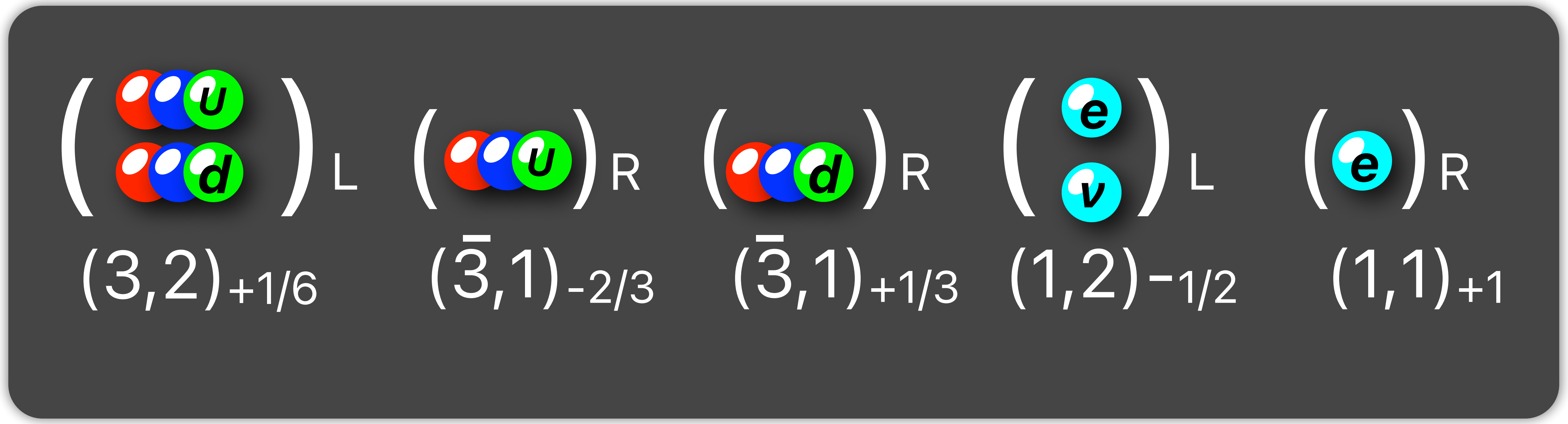


Seesaw and Leptogenesis in a "big picture"

Puzzles in the Standard Model
= Hints of Physics beyond the Standard Model



puzzle: neutrino masses



left-handed quark

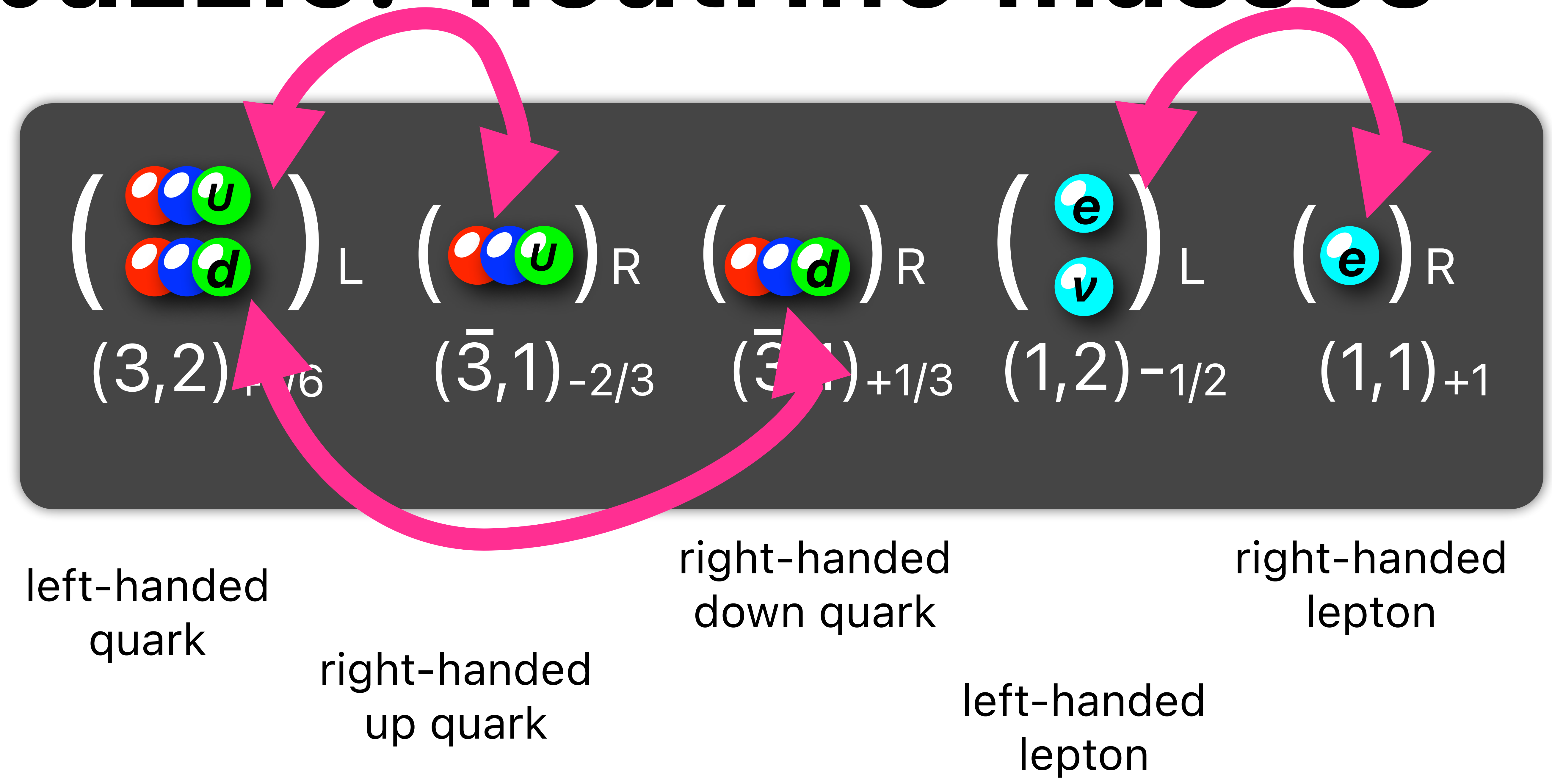
right-handed up quark

right-handed down quark

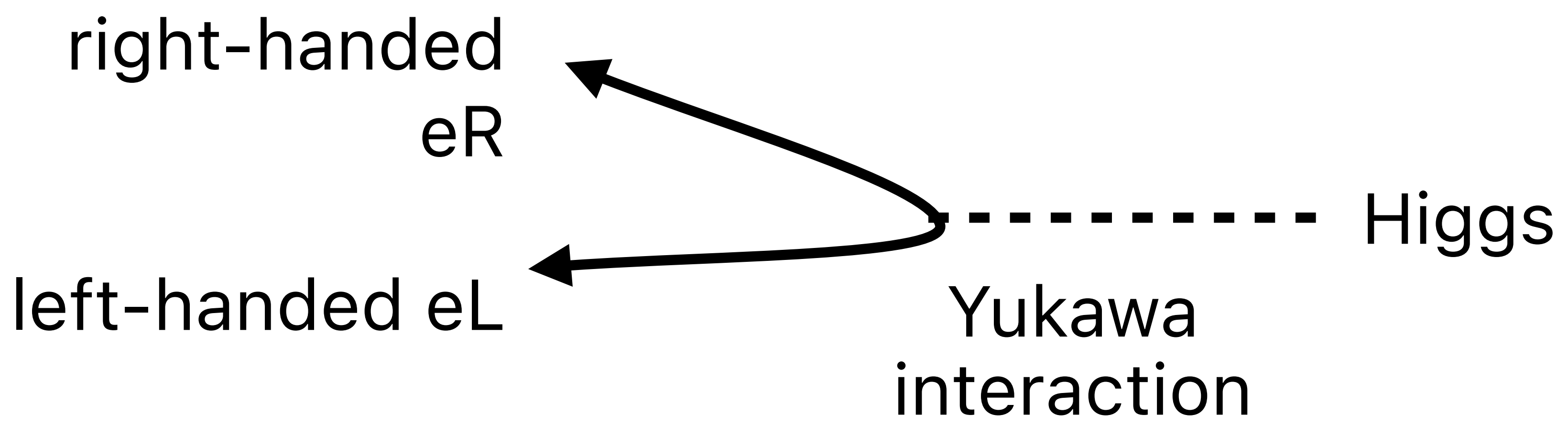
left-handed lepton

right-handed lepton

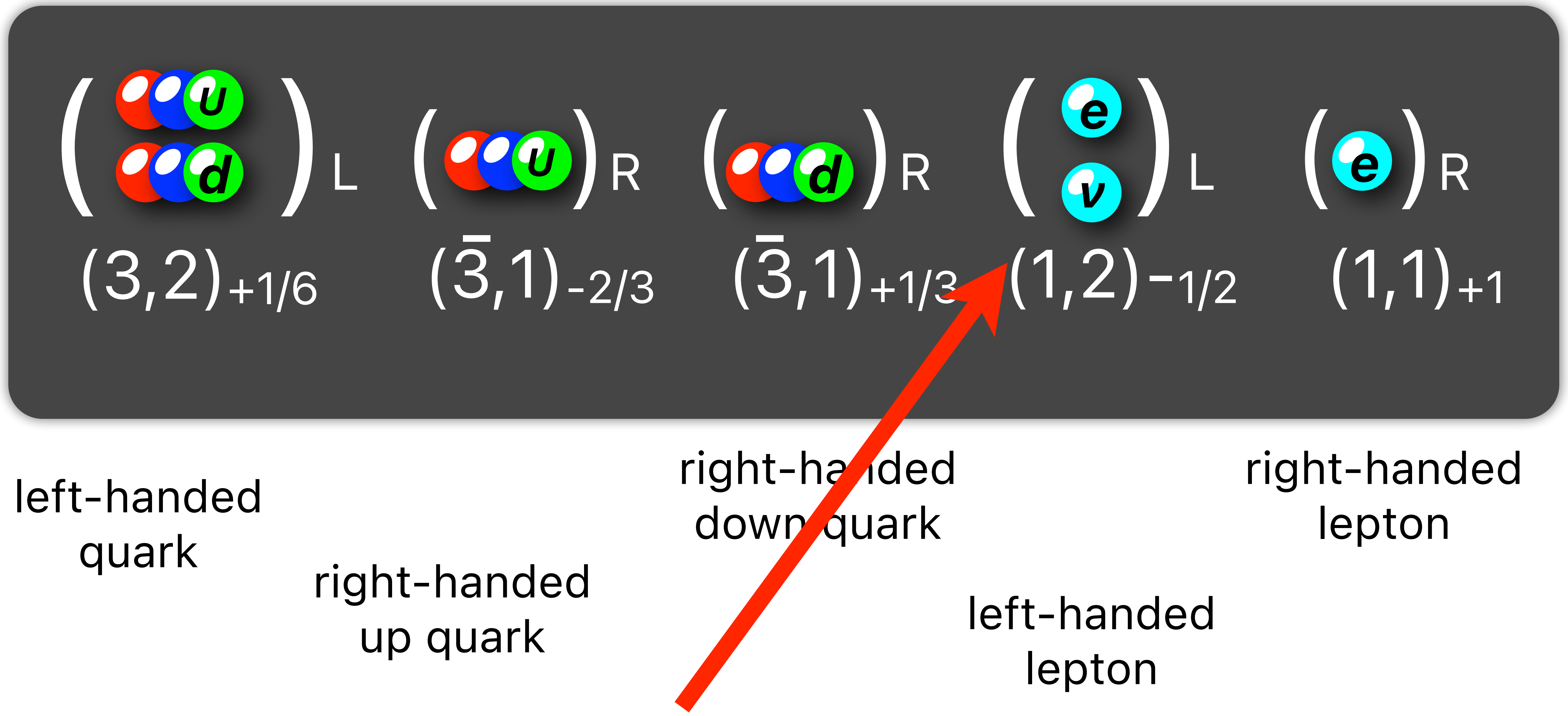
puzzle: neutrino masses



Quarks and leptons have masses by combining
left- and right-handed components (via Higgs, Yukawa interaction).



puzzle: neutrino masses

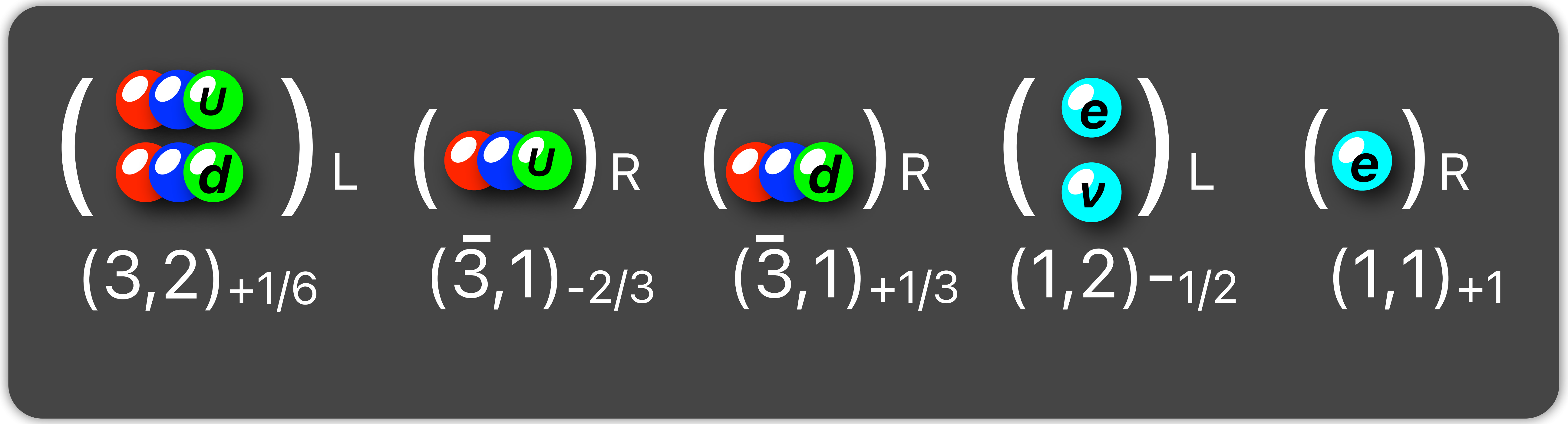


The neutrino has only left-handed component.

===> Massless !!

But the neutrino masses are confirmed by neutrino oscillations.

puzzle: neutrino masses



left-handed quark

right-handed up quark

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left-handed lepton

right-handed lepton

a solution is ...

puzzle: neutrino masses

left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

right-handed lepton

right-handed neutrino

a solution is ...

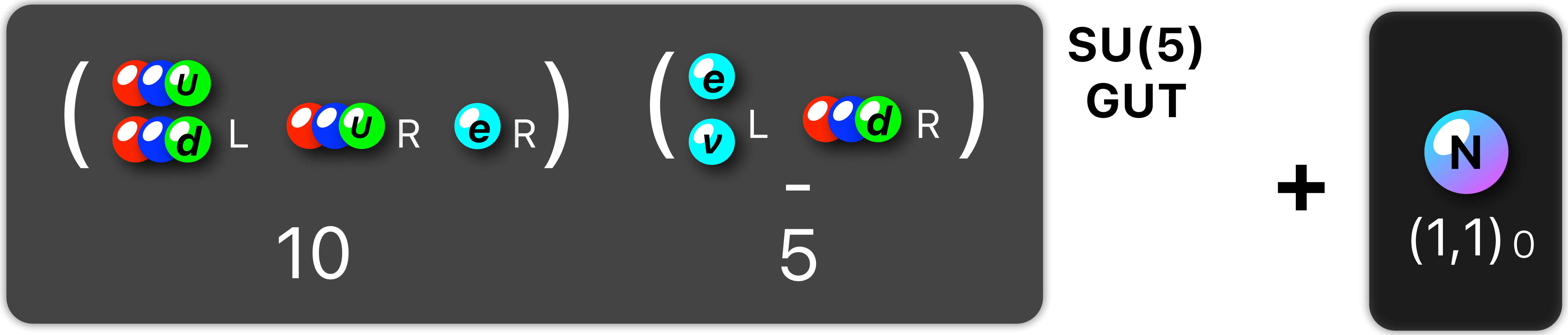
To add a right-handed neutrino !!

The right-handed neutrino 

plays a **triple role.**

The right-handed neutrino N plays a **triple role.**

① quarks and leptons completely unified



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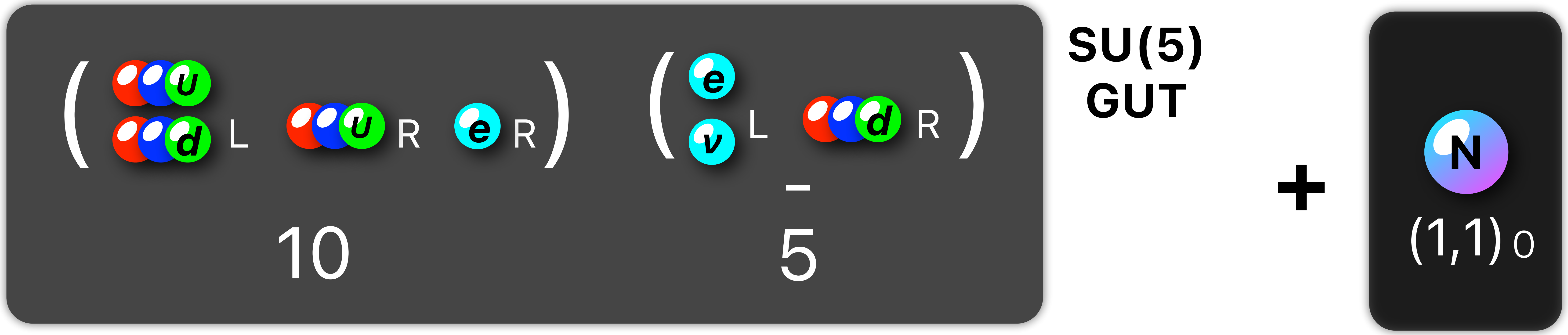

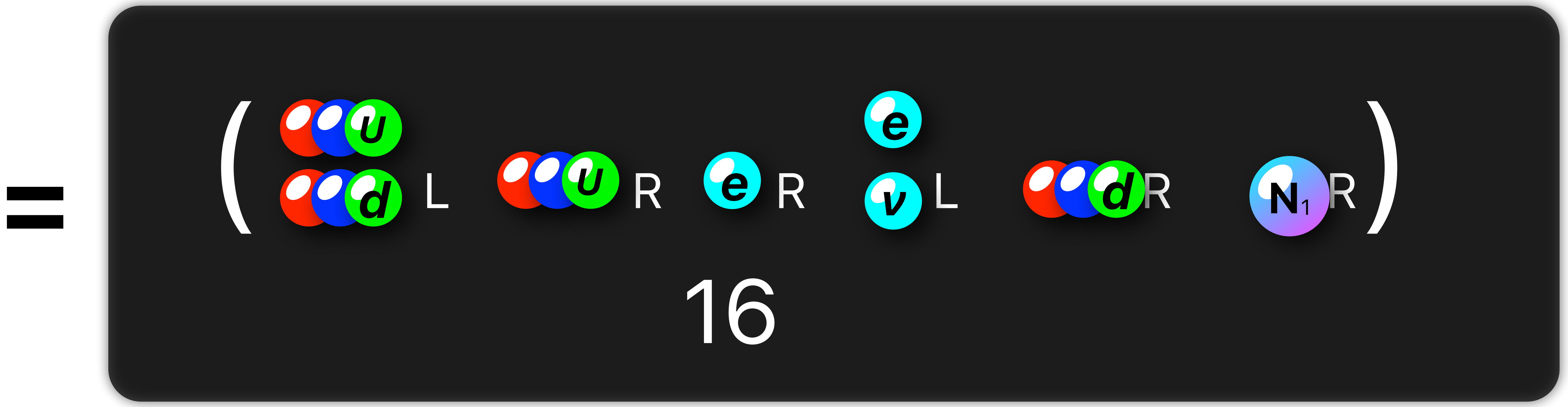

SO(10)
GUT

[Georgi,74
Fritzsch, Minkowski,75]

All quarks and leptons unified !

The right-handed neutrino N plays a **triple role.**

① quarks and leptons completely unified

$$= \left(\begin{matrix} u \\ d \end{matrix}_L \quad u_R \quad e_R \quad \begin{matrix} e \\ \nu \end{matrix}_L \quad d_R \quad N_{1R} \right) =$$

16

(↑↓ ↓↓↑)
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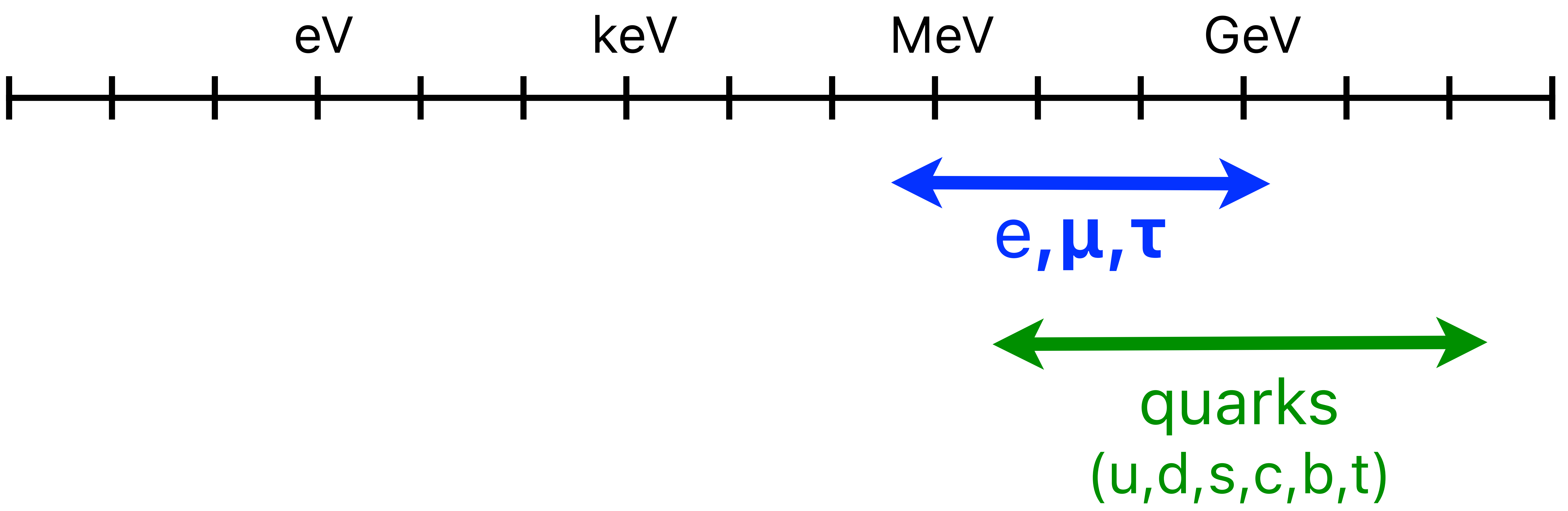
The right-handed neutrino N plays a **triple role.**

② explains **tiny** neutrino mass

masses of quarks and leptons



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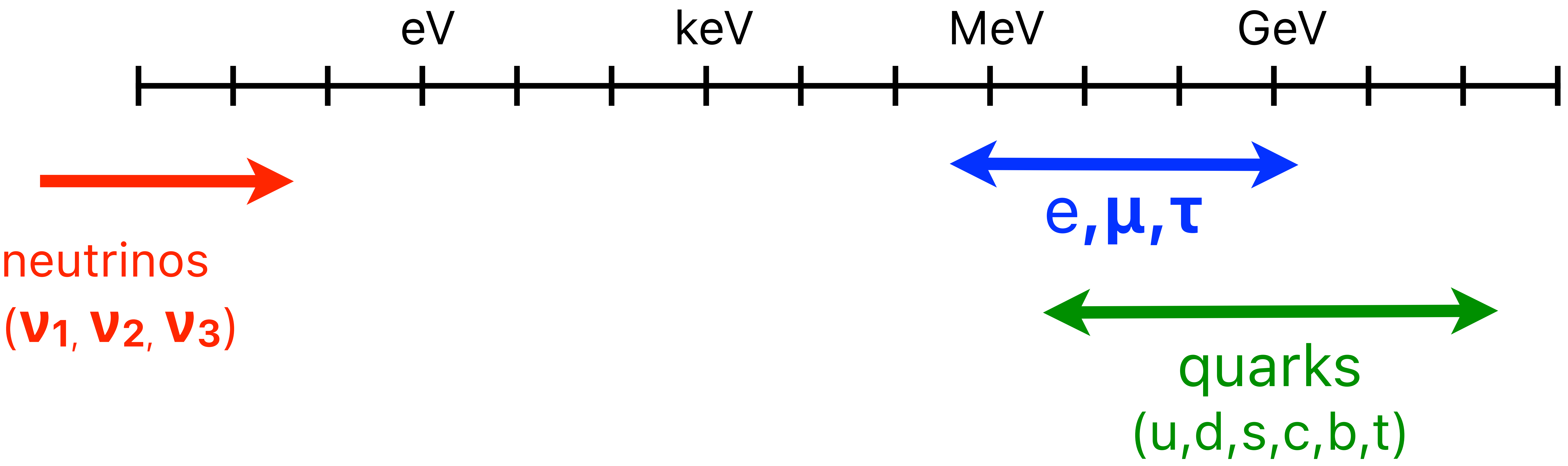

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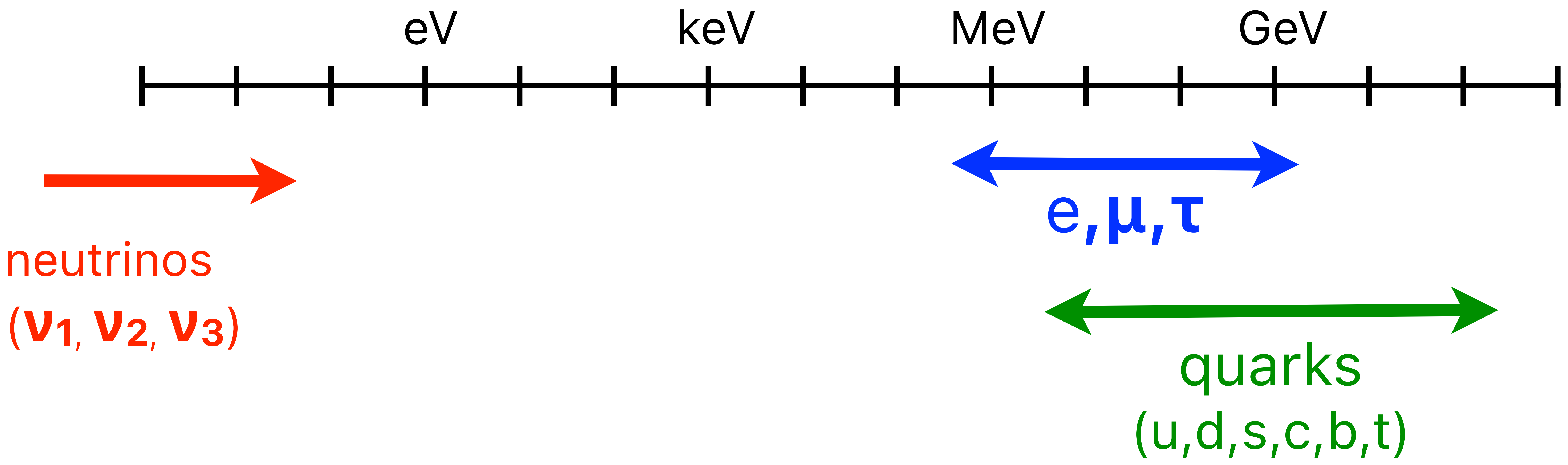

・・・**why neutrino masses are so small??**

The right-handed neutrino N plays a **triple role.**

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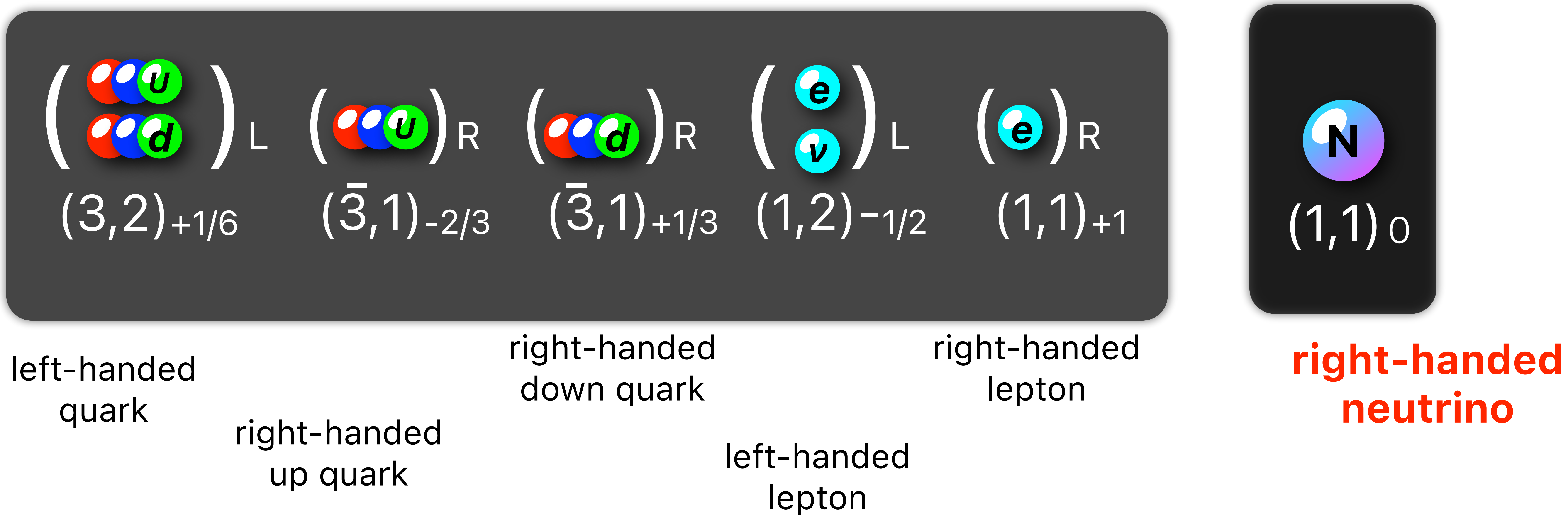

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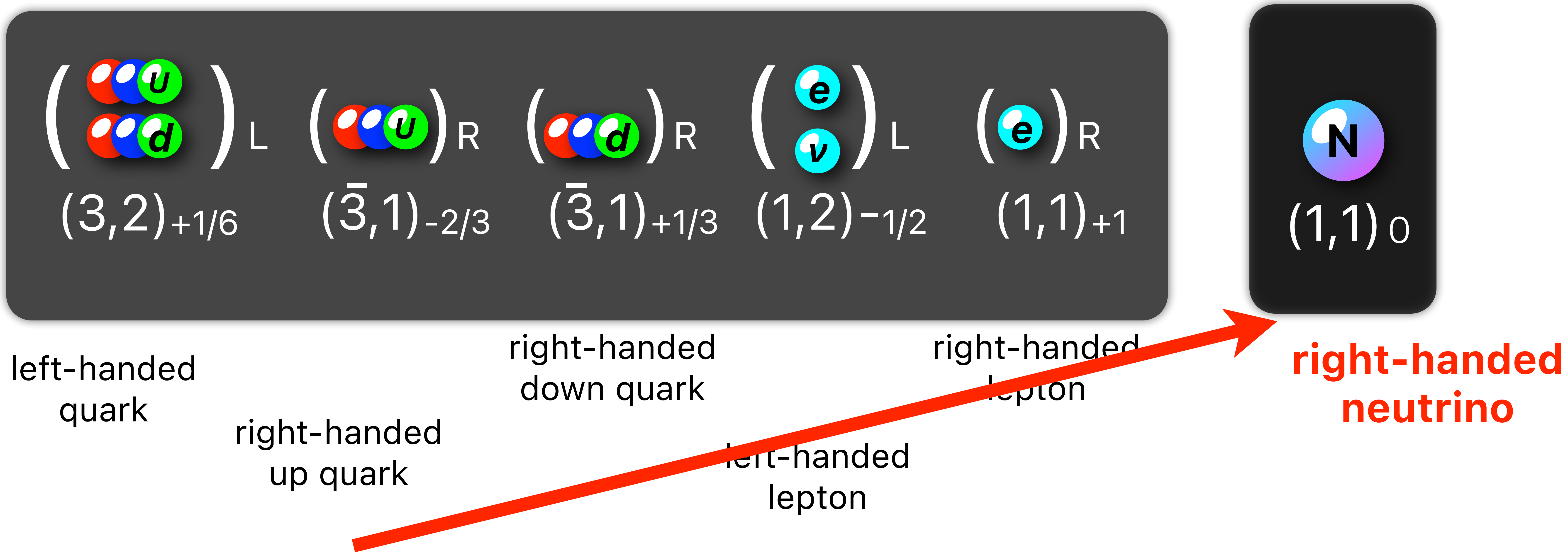

This guy is special ..... singlet (feels none of three (EM, weak, and strong) forces.)

→ it has no charge.
→ it can be its own anti-particle (Majorana particle).
→ it can have a mass without Higgs VEV.

The right-handed neutrino N plays a **triple role.**

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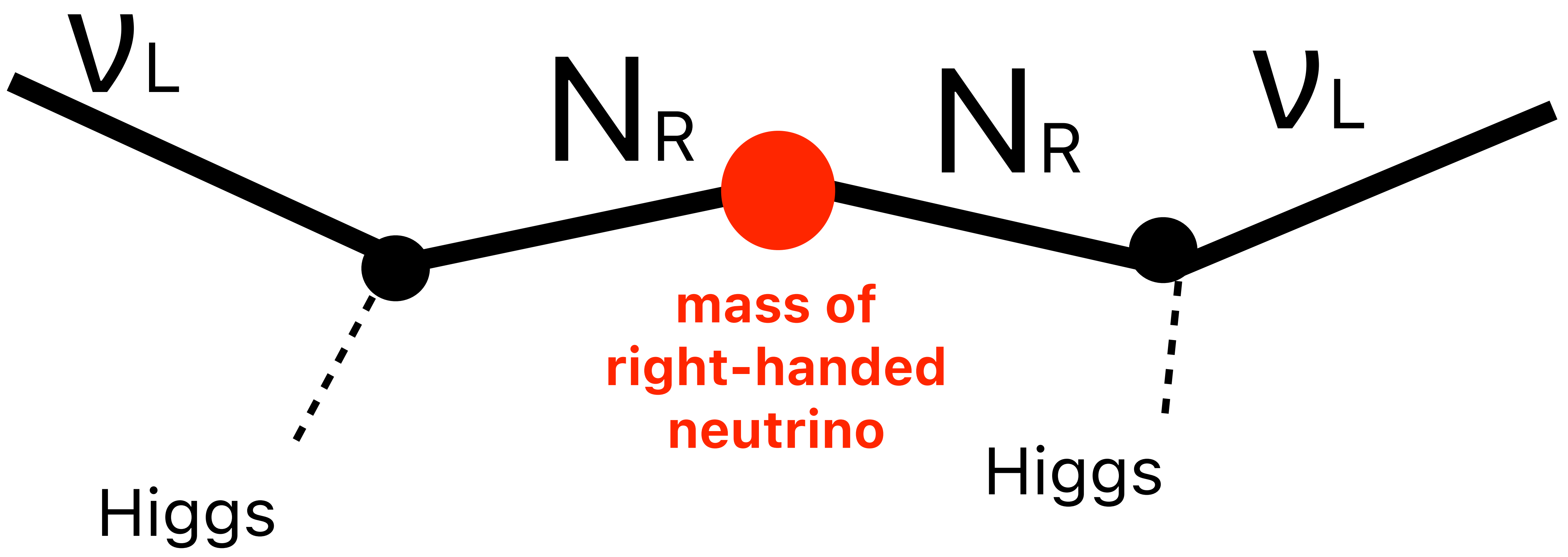

Neutrino mass (seen e.g., by oscillation exp.) = $\dfrac{(\sim \text{Higgs VEV})^2}{\text{mass of right-handed neutrino}}$

heavy R.H.ν→ small neutrino masses (“see-saw mechanism”)

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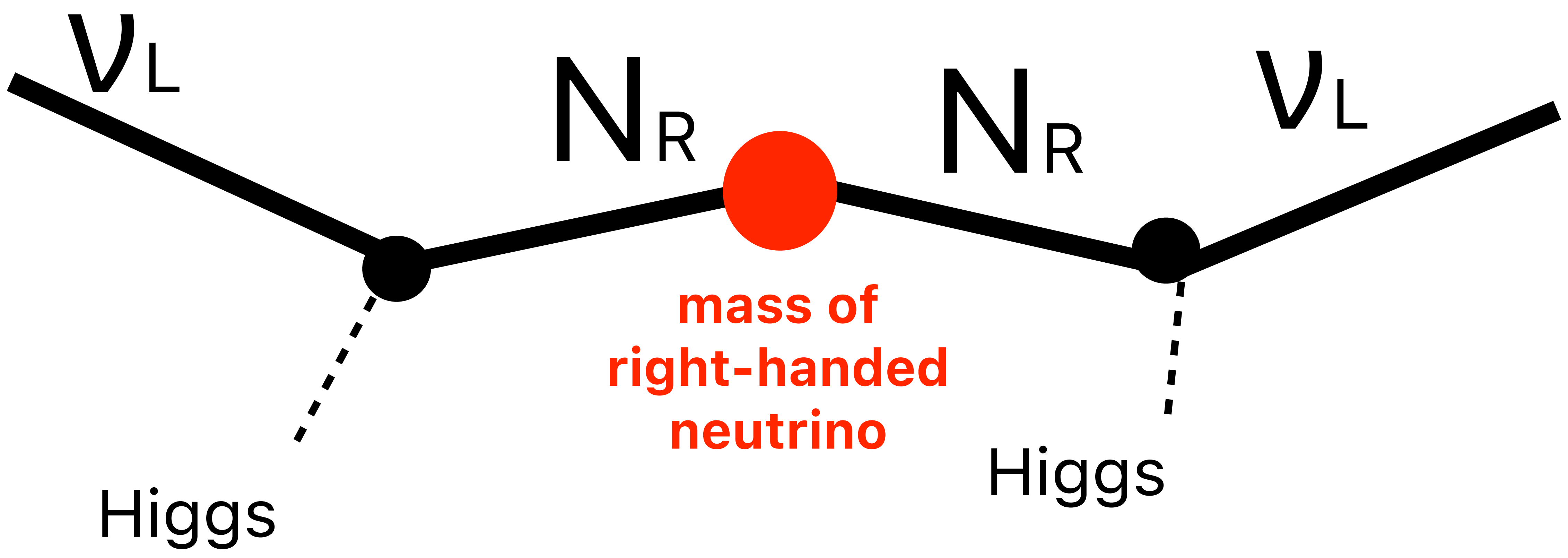

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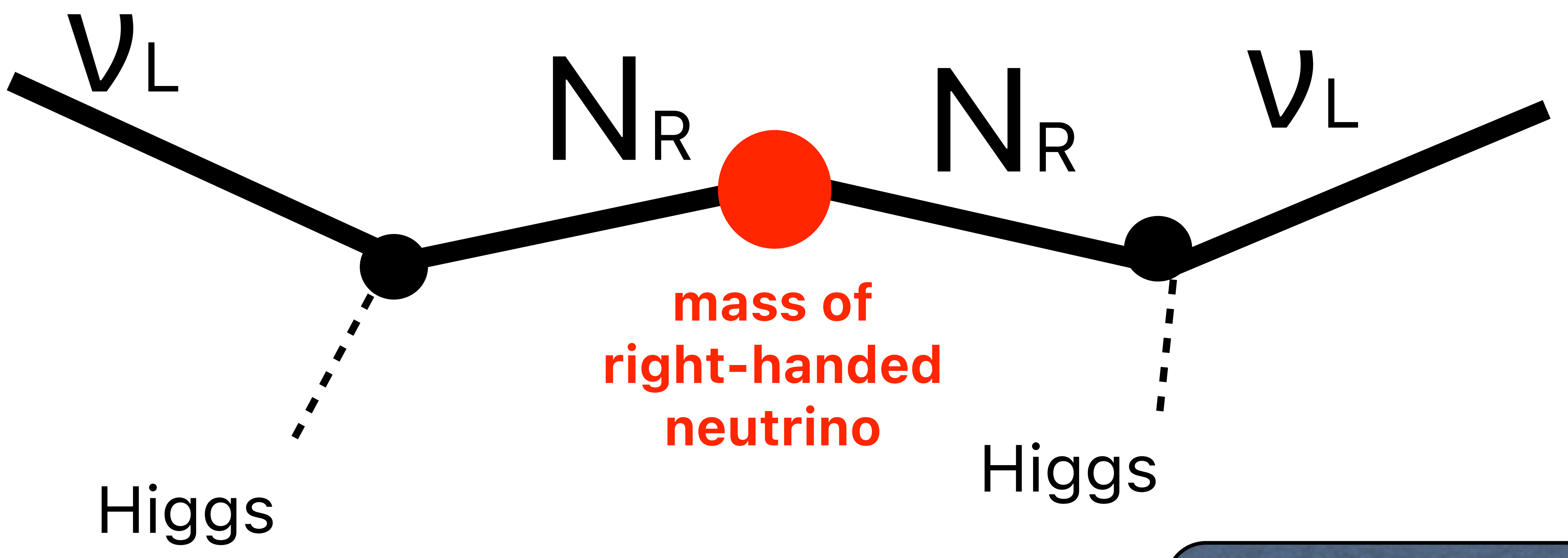

$$\text{Neutrino mass} = \frac{\text{e.g. } (100\ \text{GeV})^2}{\text{mass of right-handed neutrino}}$$

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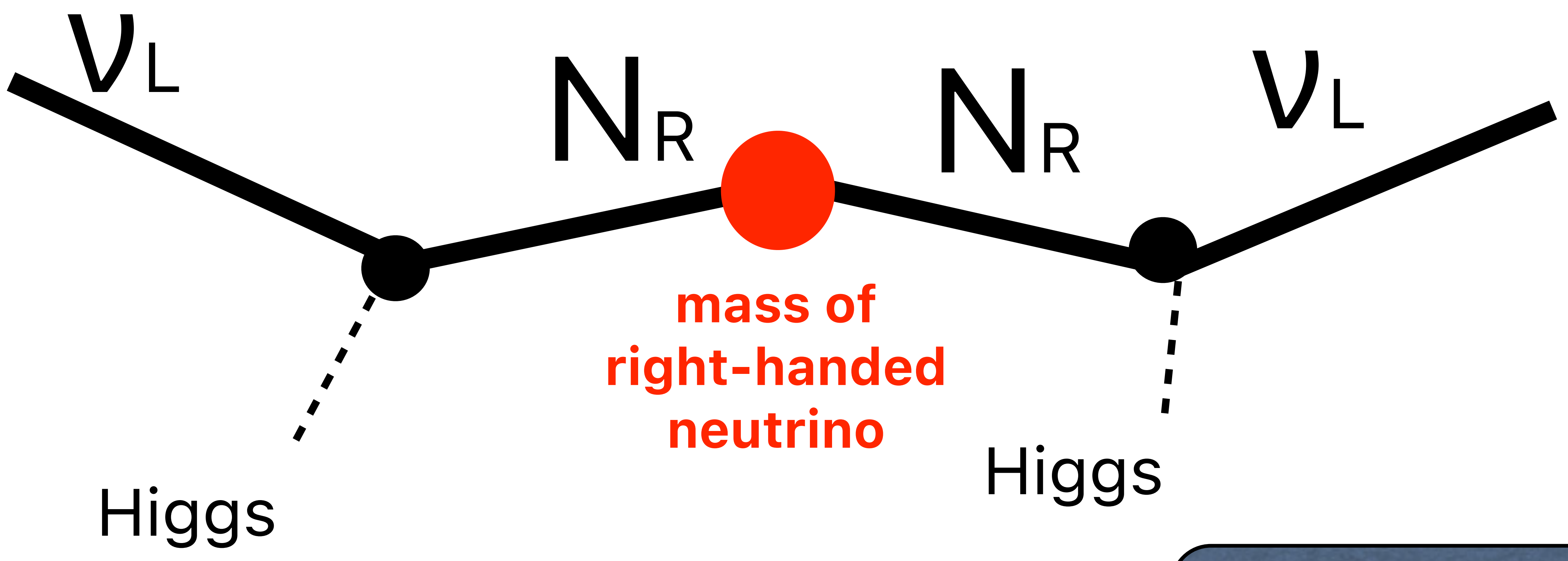
② explains **tiny** neutrino mass



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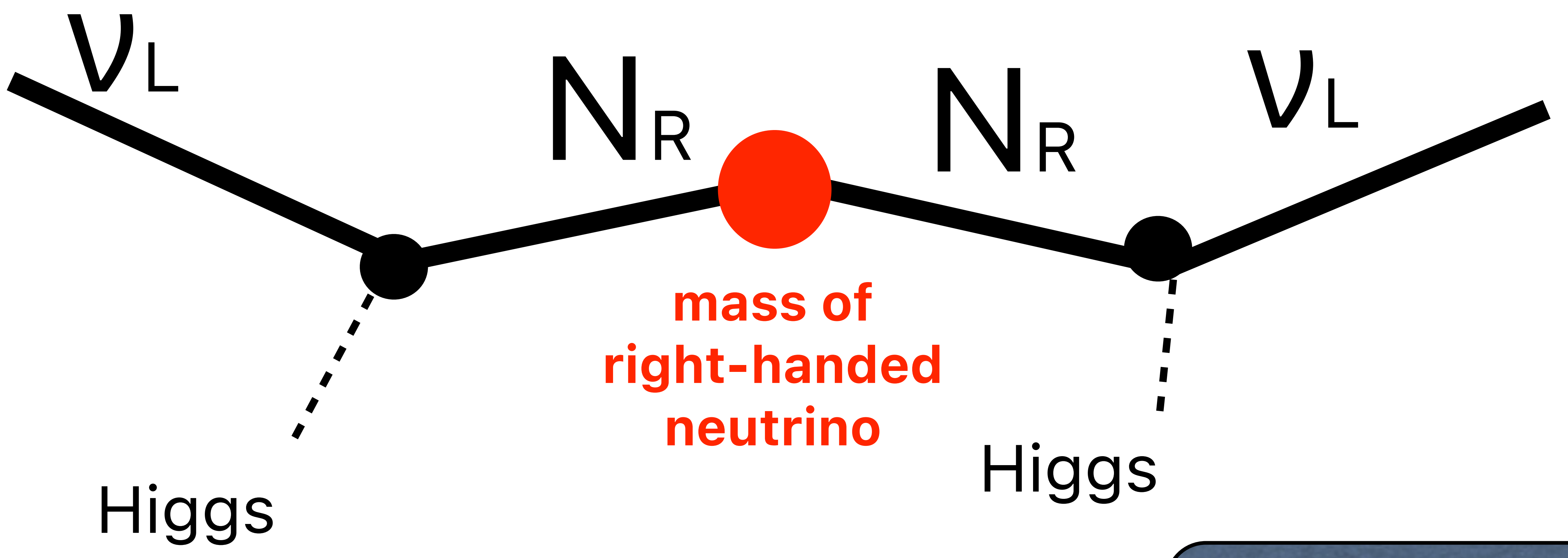

Neutrino mass = $\dfrac{\text{e.g. } (100\ \text{GeV})^2}{\text{e.g. } 10^{15}\ \text{GeV}}$

0.01 eV

heavy R.H.ν→ small neutrino masses（"see-saw mechanism"）

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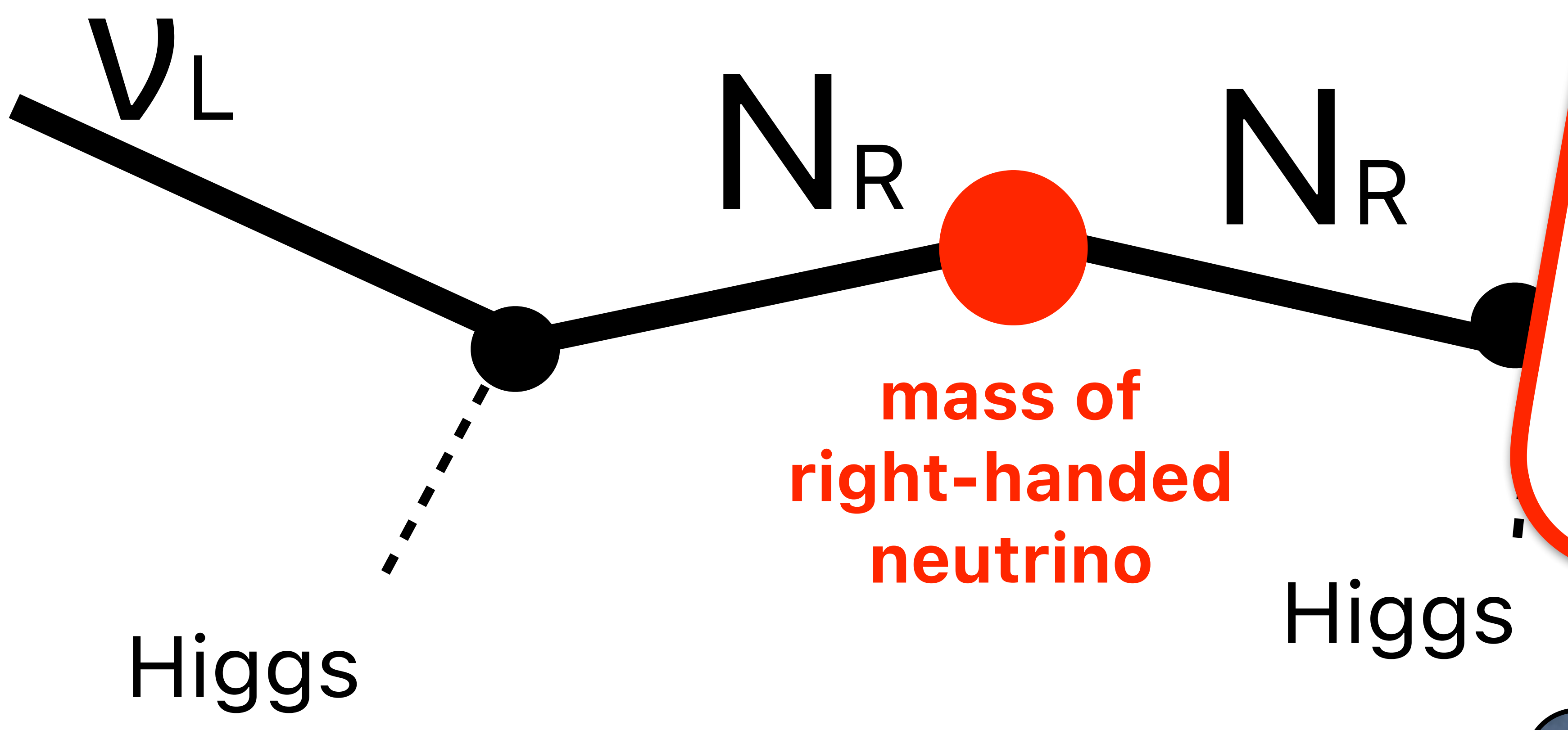


… and neutrinos become Majorana
-> predicts 0νββ decay!!
cf. talk by Umehara-san in the previouse session

Neutrino mass = e.g. (100 GeV)^2 / e.g. 10^{15} GeV

$$\underset{0.01\ \text{eV}}{\text{Neutrino mass}} = \frac{\text{e.g. } (100\ \text{GeV})^2}{\text{e.g. } 10^{15}\ \text{GeV}}$$

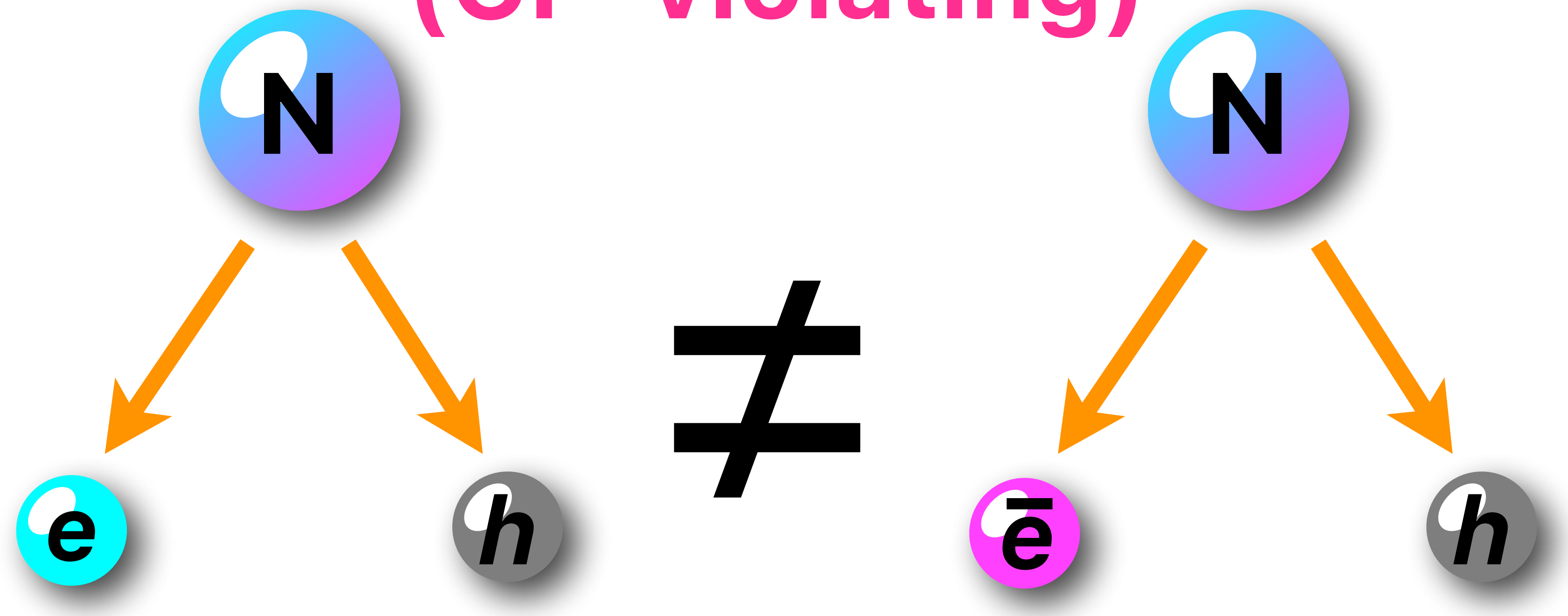
heavy R.H.ν→ small neutrino masses（“see-saw mechanism”)

The right-handed neutrino N plays a triple role.

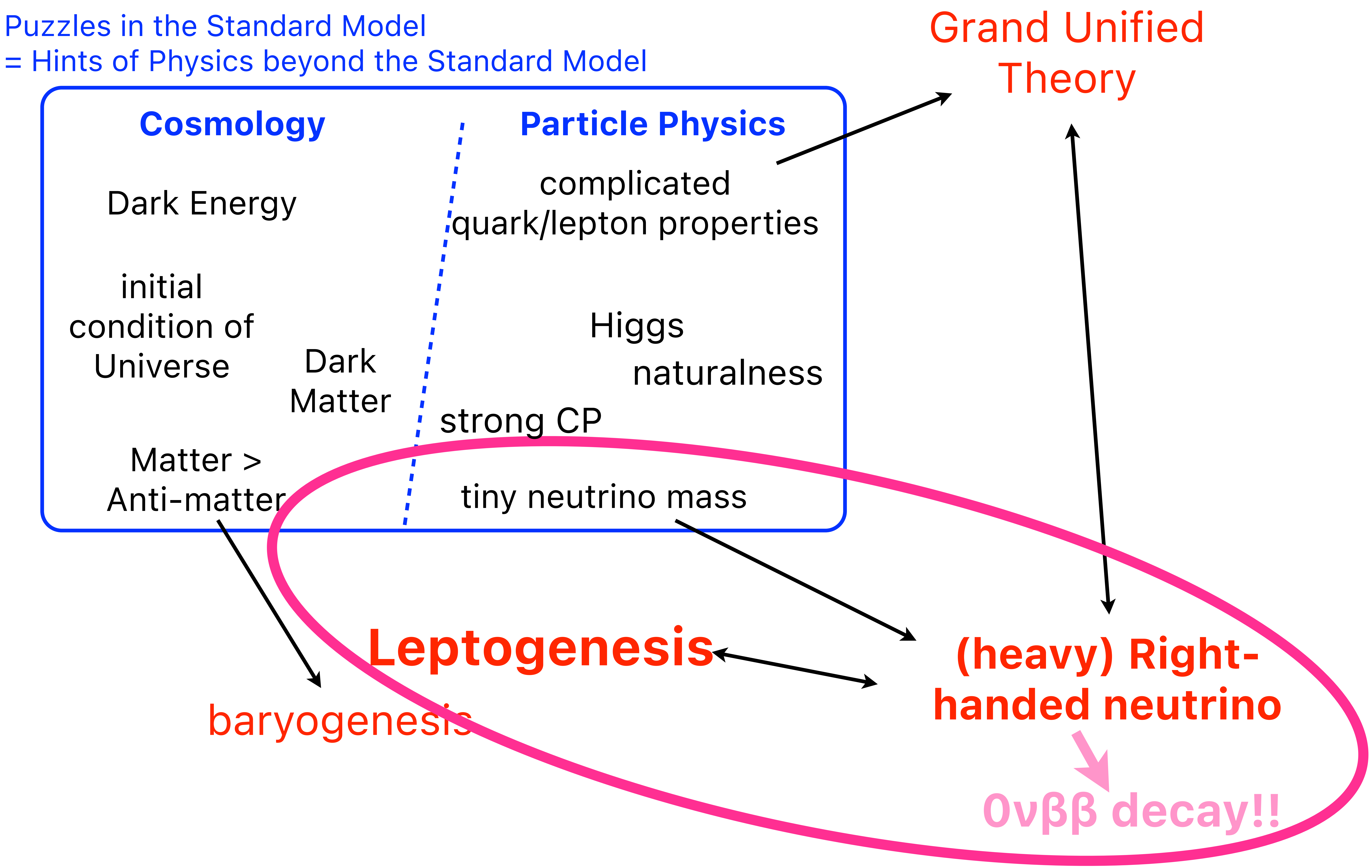
③ explains matter > anti-matter asymmetry of the universe.

-----> Leptogenesis !!

right-handed neutrino decay
(CP-violating)



Seesaw and Leptogenesis in a “big picture”



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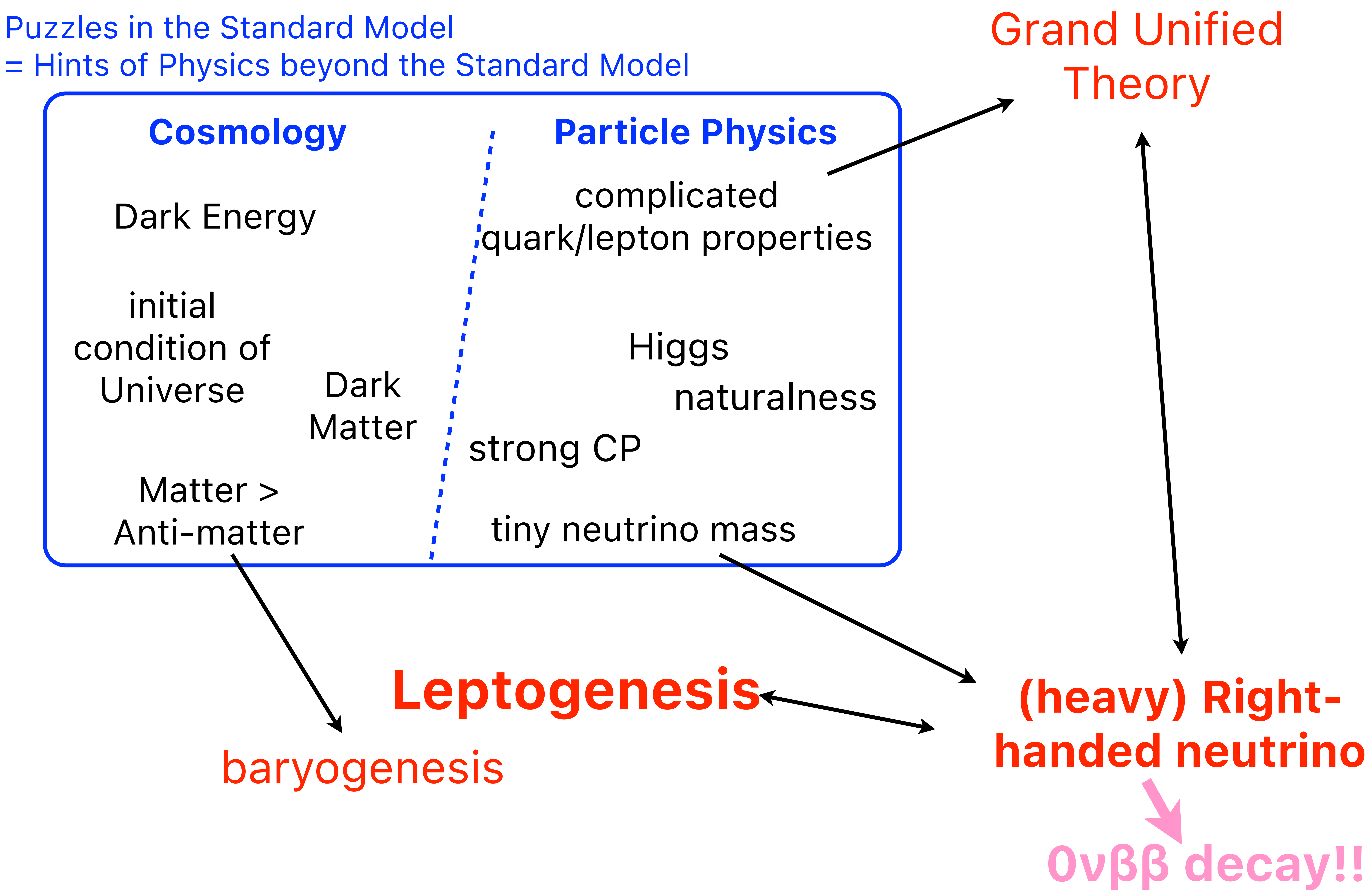

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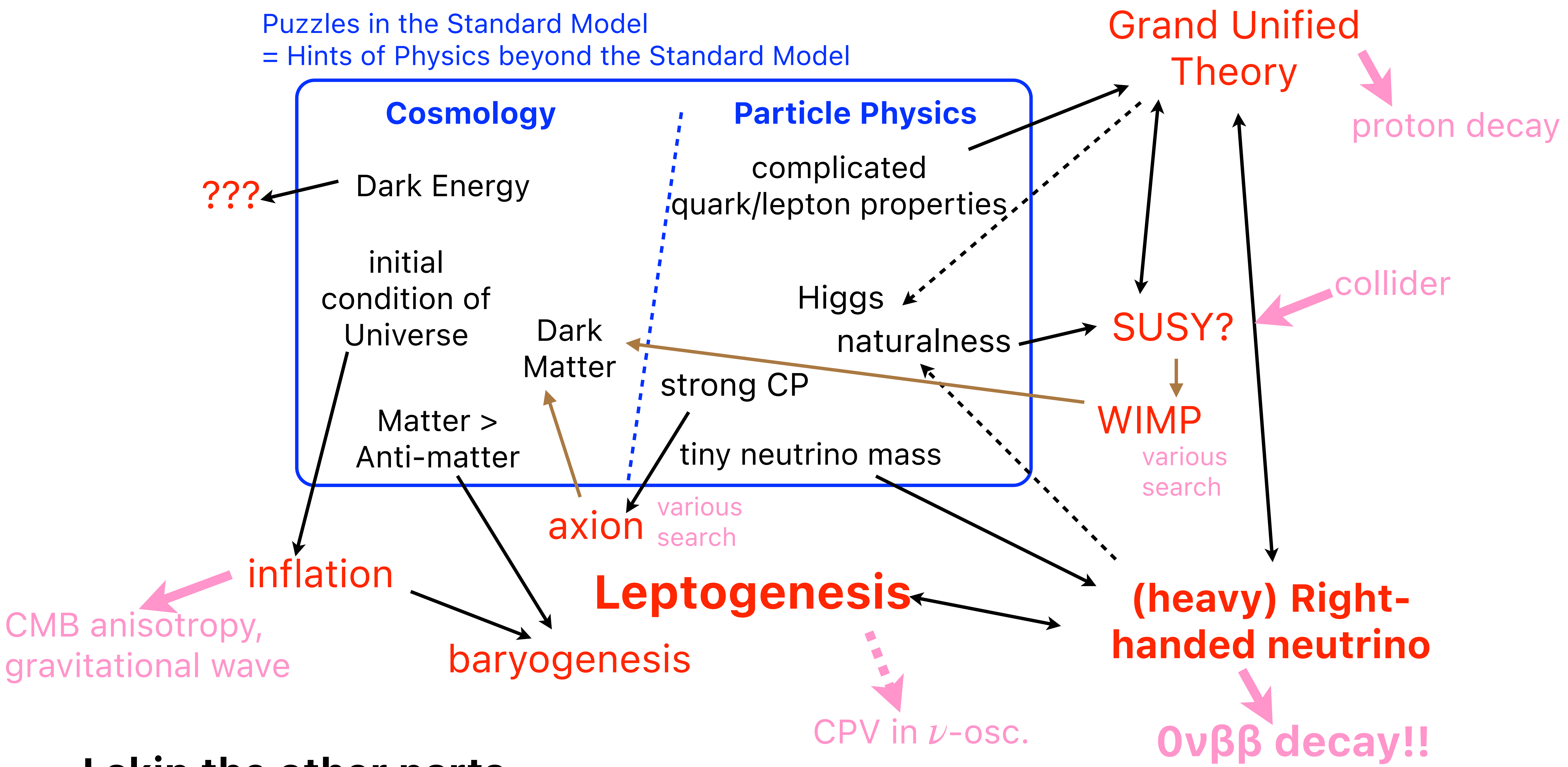

I skip the other parts...

Seesaw and Leptogenesis in a “big picture”

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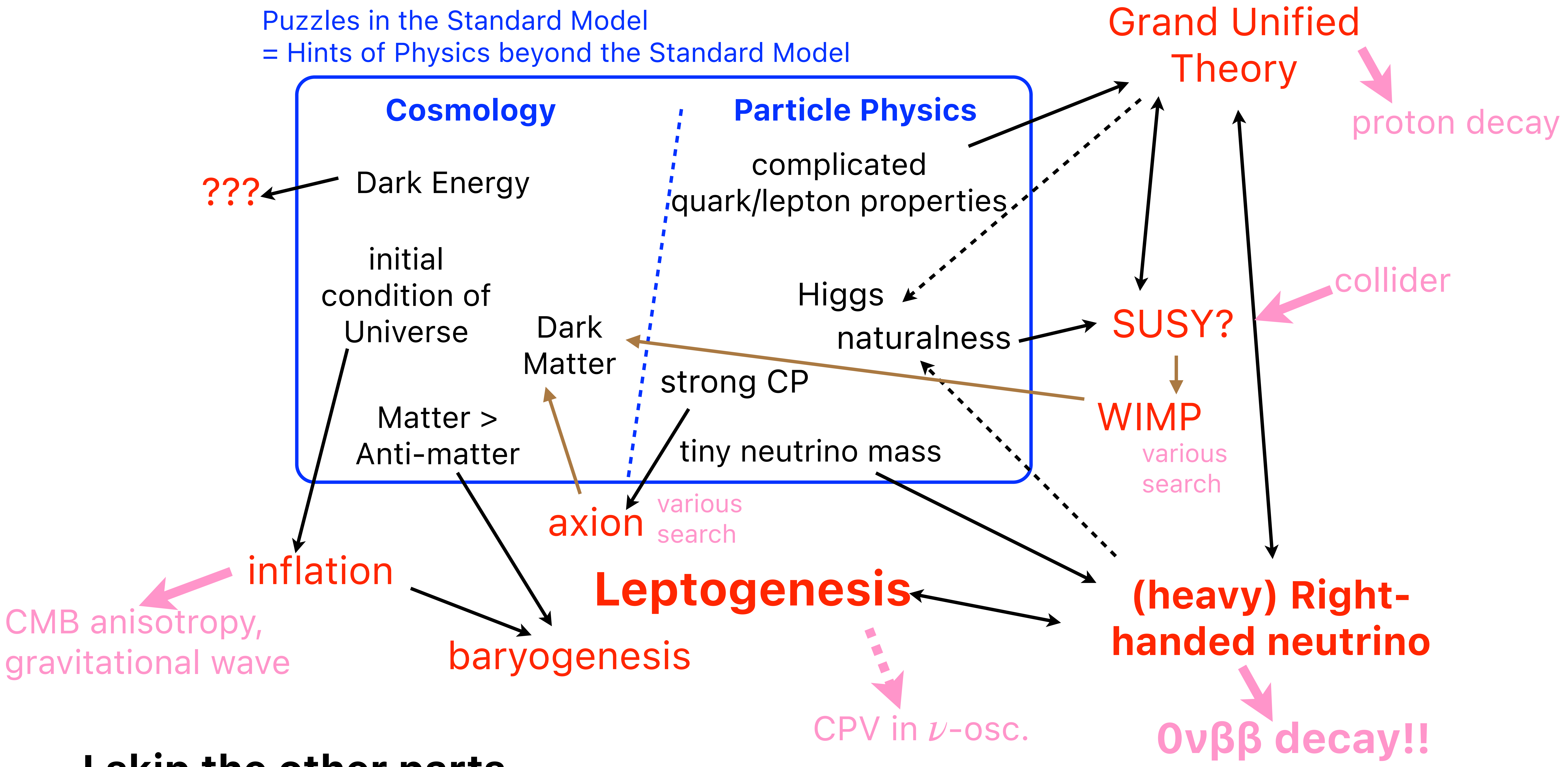
Seesaw and Leptogenesis in a "big picture"



I skip the other parts...

Plan

- Leptogenesis
  - Baryon Asymmetry of the Universe
  - Why "Lepto"genesis?
  - Seesaw and Leptogenesis in a "big picture"

- Example: Leptogenesis in the minimal gauged $U(1)_{\mu-\tau}$ model.
- Summary

Example: Leptogenesis in the minimal gauged $U(1)_{\mu-\tau}$ model.

K. Asai, KH, N. Nagata, S. Tseng [arXiv:2005.01039] JCAP **11** (2020) 013

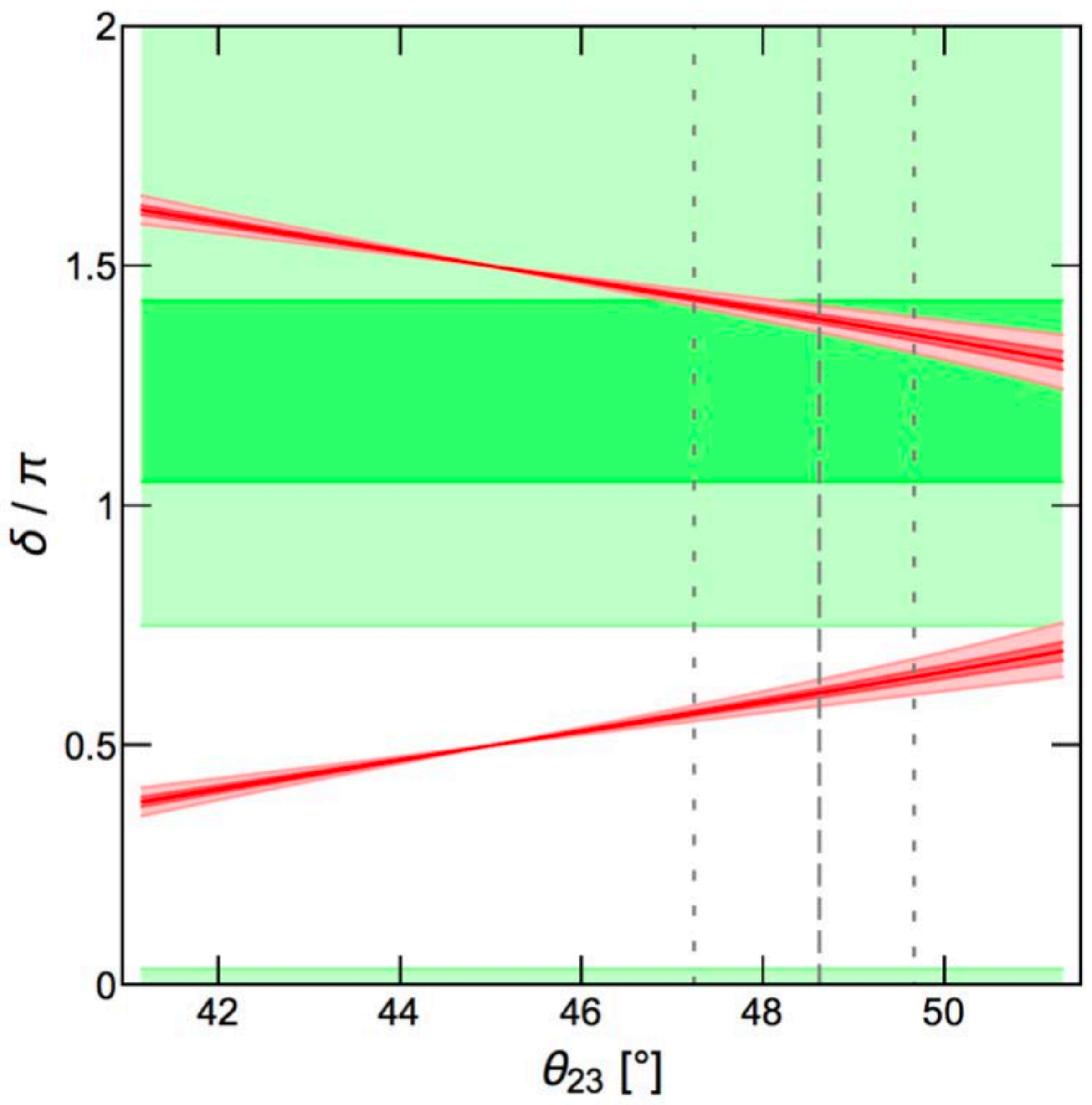
cf. K. Asai, KH, N. Nagata, S. Tseng, K. Tsumura, [arXiv:1811.07571] Phys.Rev. **D99** (2019) 055029

K. Asai, KH, N. Nagata, [arXiv:1705.00419] Eur.Phys.J. **C77** (2017) 763

- gauged $U(1)_{\mu-\tau}$ model: one of the simplest, anomaly-free extension of the Standard Model.
- In minimal models (with just one scalar) neutrino mass matrix is constrained. $m_\nu^{-1} = \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$

-> predictions!

- **Dirac CP phase**



- **$0\nu\beta\beta$ double beta decay.**

$$\langle m_{\beta\beta} \rangle \gtrsim \begin{cases} 0.027\ \mathrm{eV} & \text{for } \theta_{23} \lesssim 50.1^\circ \quad [1\sigma, \mathrm{NuFit5.0}] \\ 0.017\ \mathrm{eV} & \text{for } \theta_{23} \lesssim 51.7^\circ \quad [3\sigma, \mathrm{NuFit5.0}] \end{cases}$$

※ The other parameters are fixed to be the best fit value.

===> testable in the next-generation $0\nu\beta\beta$ experiments.

Example: Leptogenesis in the minimal gauged $U(1)_{\mu-\tau}$ model.

K. Asai, KH, N. Nagata, S. Tseng [arXiv:2005.01039] JCAP **11** (2020) 013

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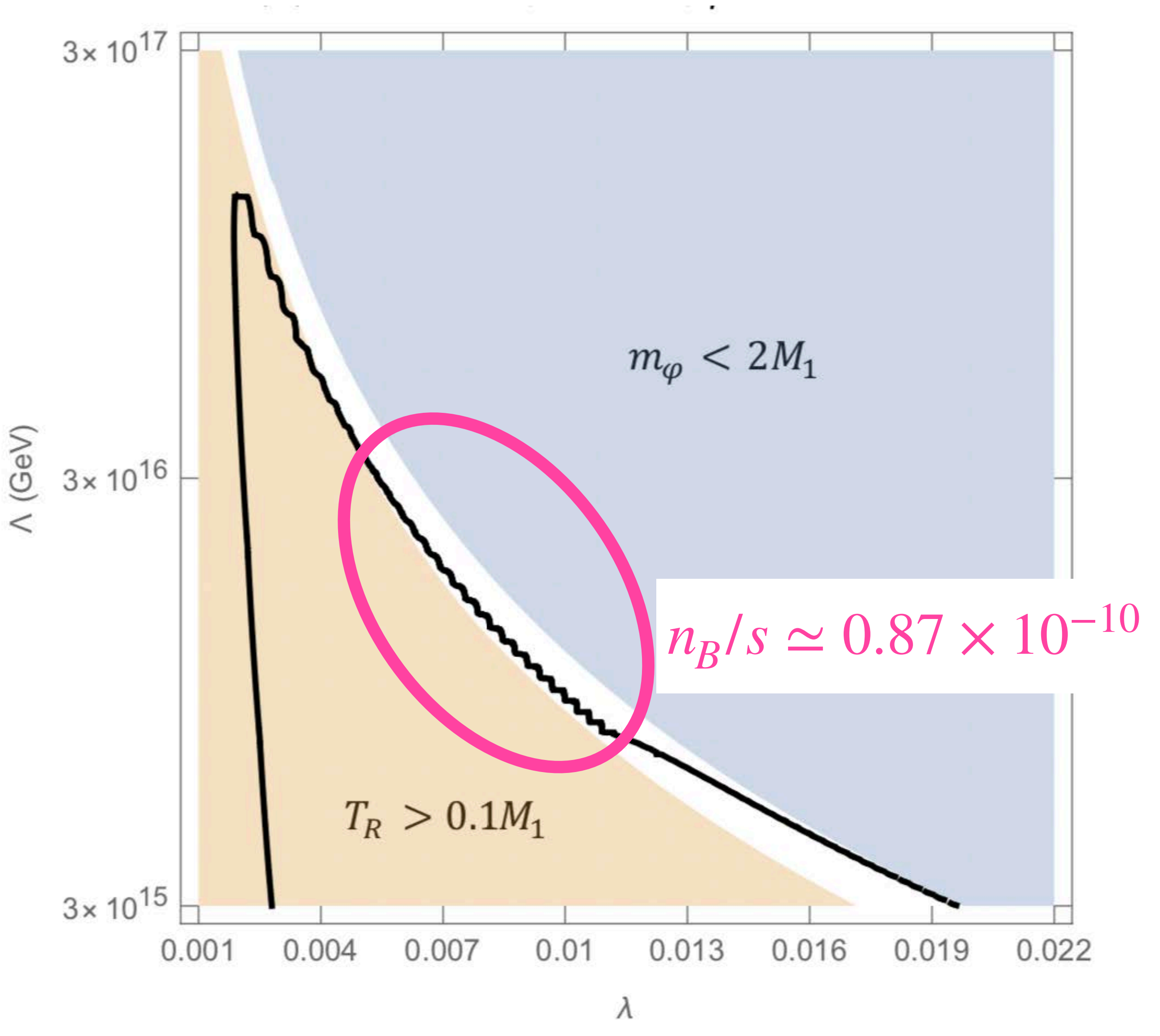
$$m_\nu{}^{-1} = \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

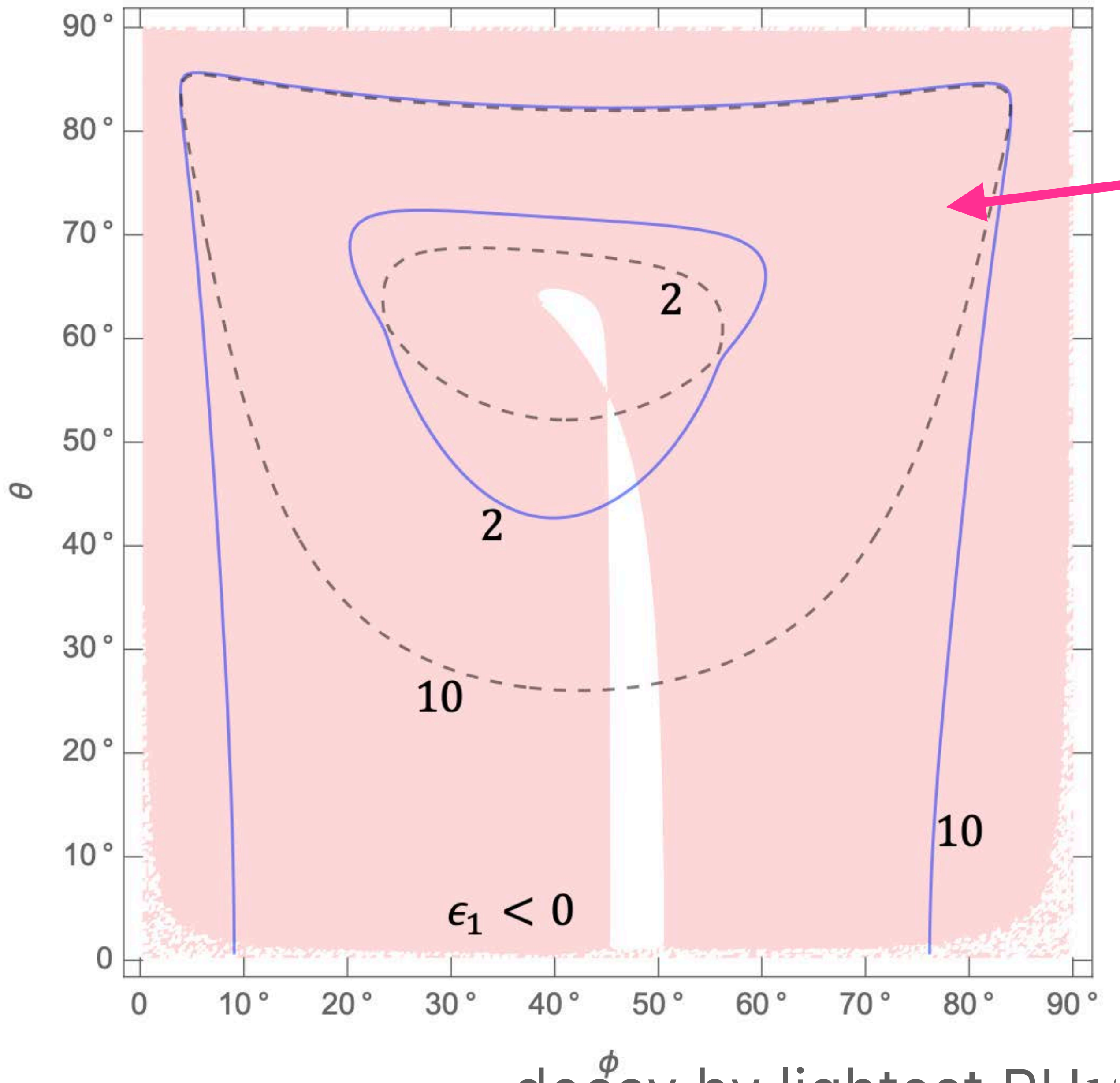
-> predictions!

- **Leptogenesis works.**

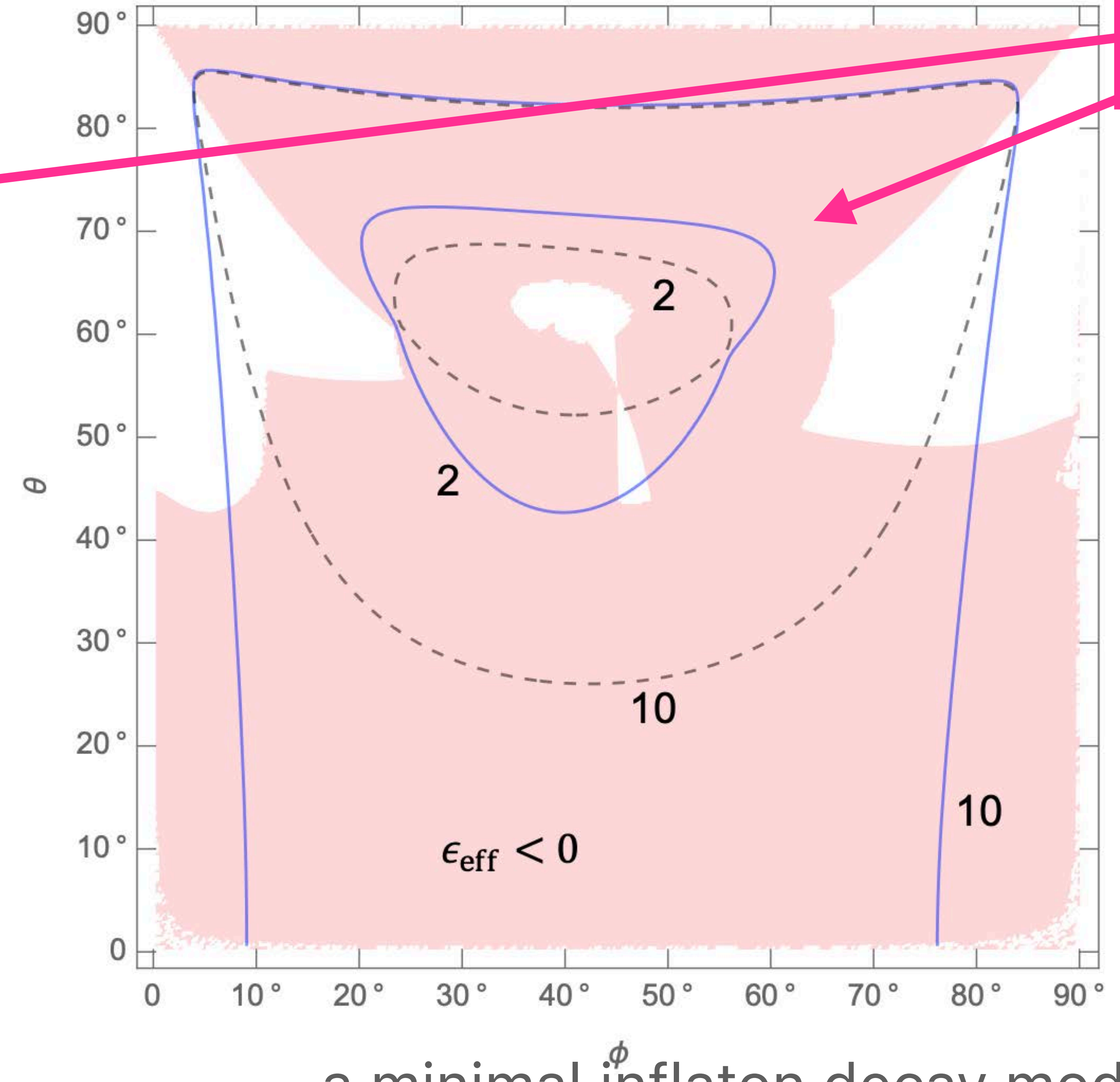


- **Correlation between the cosmological sign of baryon asymmetry and the Dirac CP phase of neutrino oscillation.**

$\delta > \pi \rightarrow$ matter remains
$\delta < \pi \rightarrow$ anti-matter remains



decay by lightest RHν.



a minimal inflaton decay model.

T2K (global fit) suggests $\delta > \pi$.

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)

- There are various kinds of Leptogenesis. (Most of them predict **0νββ decay.)**

- An example: the minimal gauged $U(1)_{\mu-\tau}$ model. Predictions for neutrino physics.

Backup

What is necessary

to generate the Baryon Asymmetry of the Universe?

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Sakharov's 3 conditions [Sakharov 1967]

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

What is necessary

to generate the Baryon Asymmetry of the Universe?

Sakharov's 3 conditions [Sakharov 1967]

- Baryon number (B) violation

  If all processes conserve B, then impossible to have $n_B = 0 \to n_B \neq 0$.

- C and CP violation

- Out-of-equilibrium

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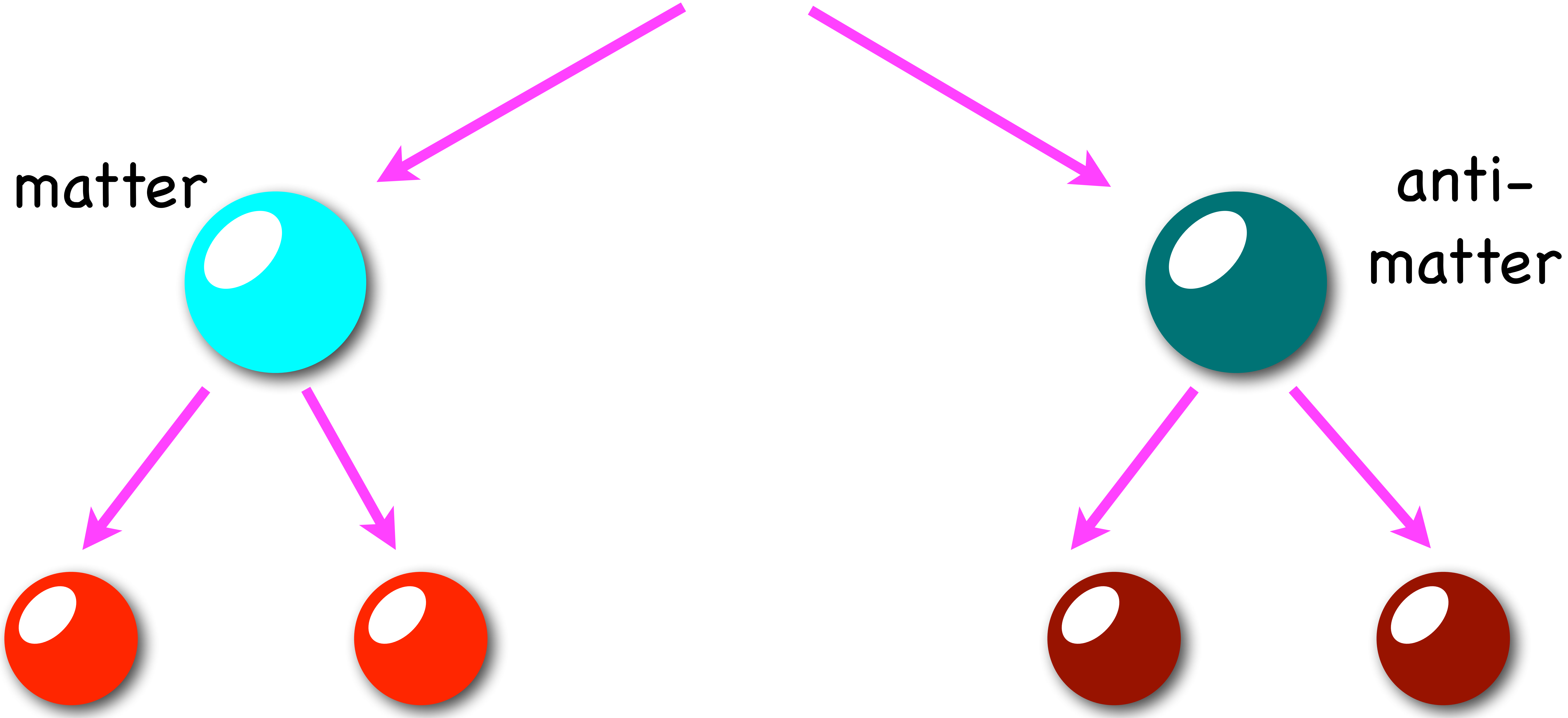
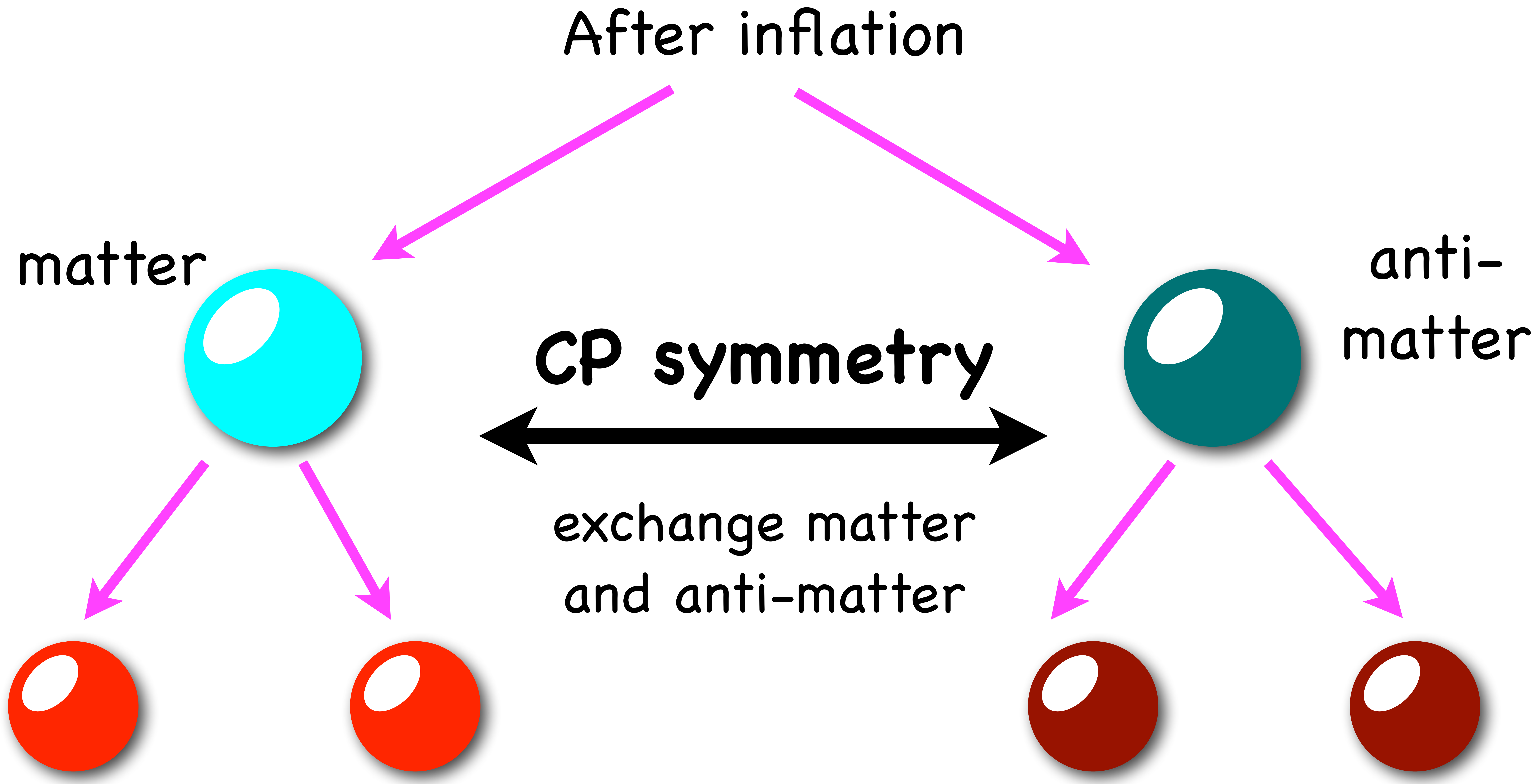
  If all processes conserve CP, then impossible to have $n_B = 0 \rightarrow n_B \neq 0$.

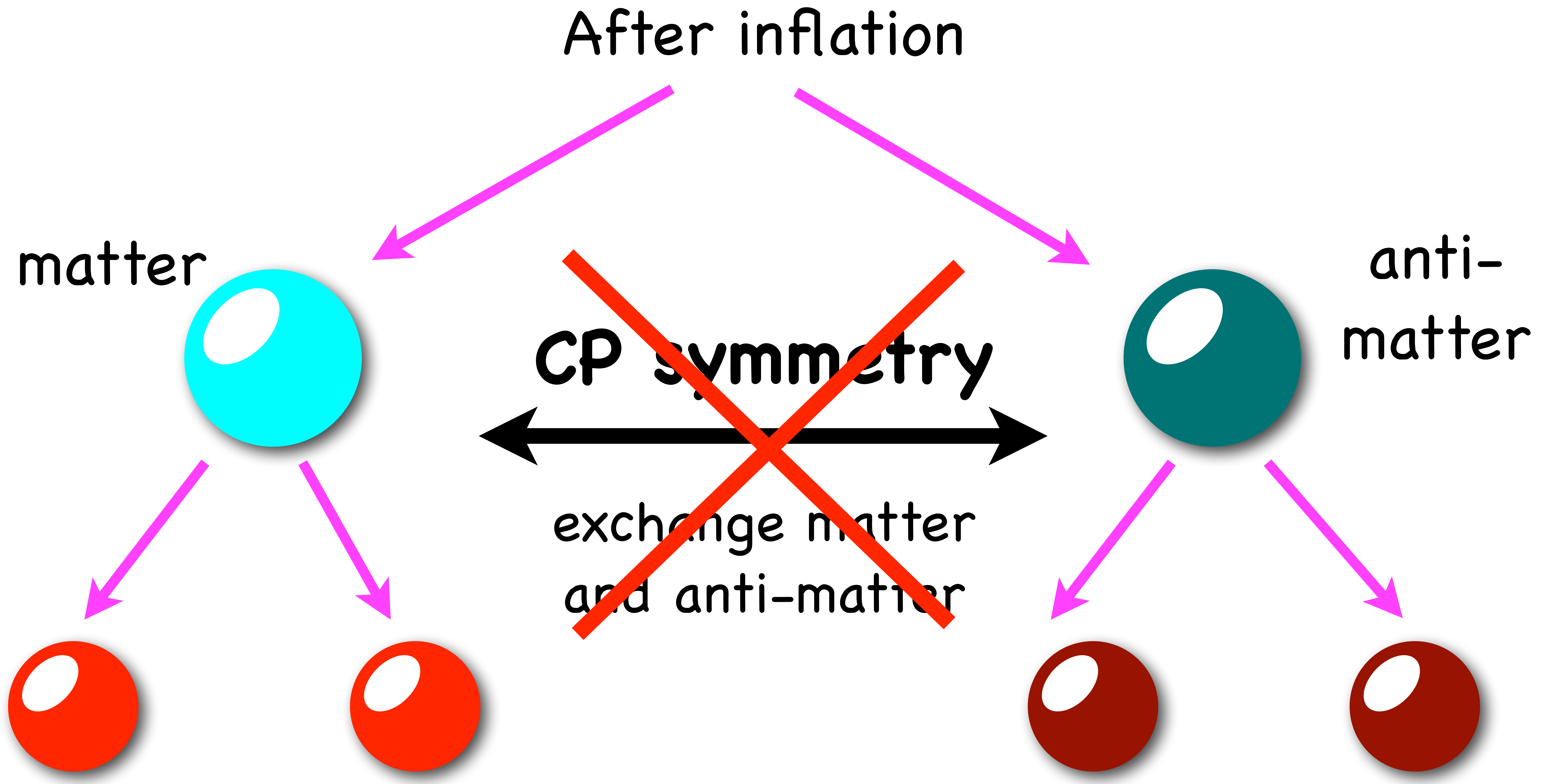
- Out-of-equilibrium

After inflation





As far as **CP is conserved,** there is
no difference between matter and anti-matter.



If CP is violated, there can be
a difference between matter and anti-matter.

What is necessary

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Sakharov's 3 conditions [Sakharov 1967]

- Baryon number (B) violation

  If all processes conserve B, then impossible to have $n_B = 0 \to n_B \neq 0$.

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- **C and CP violation**

  If all processes conserve CP, then impossible to have $n_B = 0 \rightarrow n_B \neq 0$.

- **Out-of-equilibrium**

  If the processes $n_B < 0 \leftrightarrow n_B = 0 \leftrightarrow n_B > 0$ are in thermal equilibrium,
  then the system arrives at the equilibrium state ($n_B = 0$).

  The system must be out-of-equilibrium, such that $n_B = 0 \rightleftarrows n_B > 0$.

Leptogenesis

Leptogenesis

[Fukugita, Yanagida,1986]

Model: Standard Model + R.H. ν

Cosmology: Standard thermal cosmology

Extremely simple!
No complicated model/cosmology required.

Leptogenesis

[Fukugita, Yanagida,1986]

scenario

Leptogenesis

[Fukugita, Yanagida,1986]

scenario

temperature RH ν 's mass

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

Leptogenesis

[Fukugita, Yanagida,1986]

scenario

temperature　　RH ν's mass

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

step 2: $T \sim M_R$: N_1 decay. (CP violation + out-of-eq.)

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

Leptogenesis

[Fukugita, Yanagida,1986]

<u>scenario</u>

temperature → T, RH ν's mass → M_R

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

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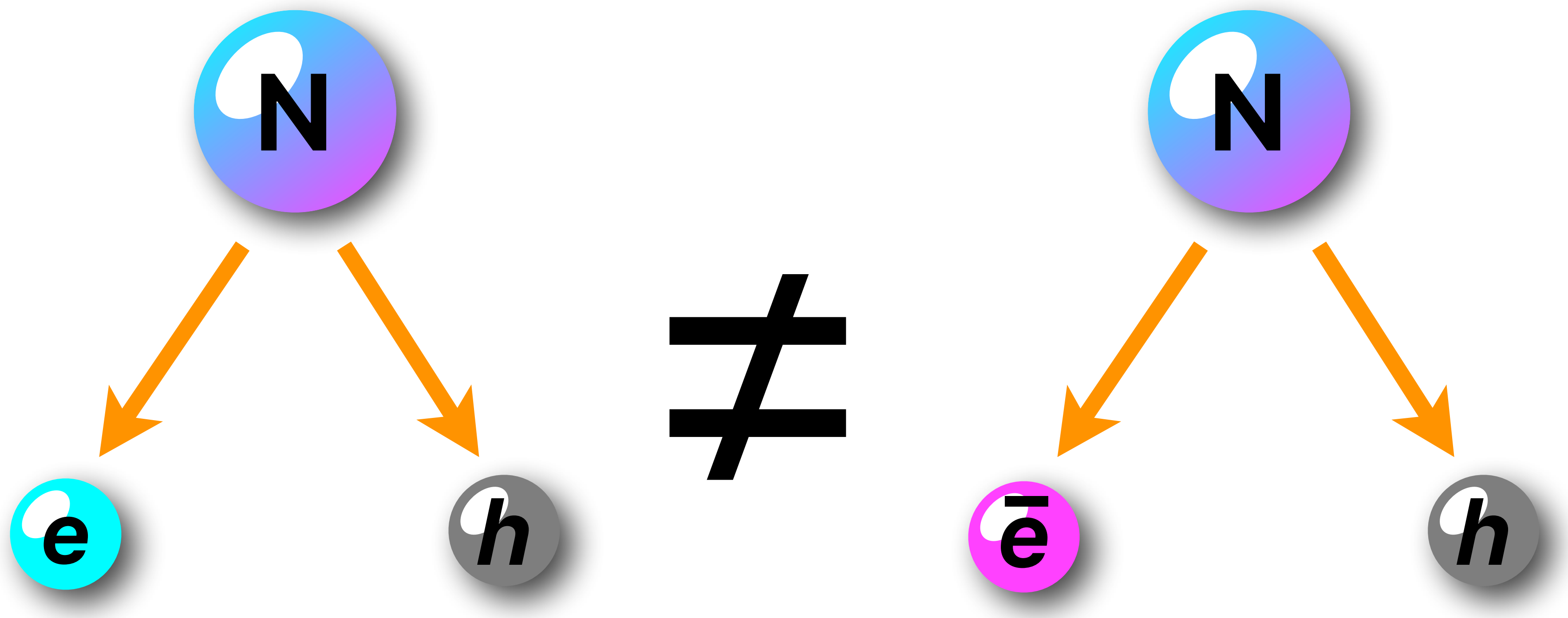

CP violation
is essential.

Leptogenesis

[Fukugita, Yanagida, 1986]

scenario

temperature — RH ν's mass

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step 2: $T \sim M_R$: N_1 decay. (CP violation + out-of-eq.)

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

step 3: Lepton asymmetry ---> Baryon asymmetry

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

(automatic in SM ! thanks to "sphaleron")

[Kuzmin, Rubakov, Shaposhnikov, 1985]

Leptogenesis

[Fukugita, Yanagida,1986]

Result: (I skip all the details of the calculation...

For derivations and references, see, e.g., KH: hep-ph/0212305)

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

Leptogenesis

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final baryon asymmetry

RH ν's mass

heaviest neutrino mass ($\sim$ atmospheric)

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

Leptogenesis

[Fukugita, Yanagida,1986]

Result: (I skip all the details of the calculation…
For derivations and references, see, e.g., KH: hep-ph/0212305)

final baryon asymmetry

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Predictable / Calculable in terms of [SM + R.H. ν] Lagrangian !

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[PDG, 2012]

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