Neutrinoless double beta decay, Leptogenesis, and gauged U(1)$\mu - \tau$ models.

Koichi Hamaguchi (University of Tokyo)

"Double beta decay and underground science" (DBD18)

October 21-23, 2018 @Hawaii

Neutrinoless double beta decay,

Leptogenesis,

(mostly review)

and gauged $U(1)_{\mu-\tau}$ models.

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"Double beta decay and underground science" (DBD18)

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Plan

90% of the talk
= review

cf. Murayama-san's talk on Sunday

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

- Leptogenesis and 0νββ decay
- gauged U(1) $\mu - \tau$

- Summary

Plan

90% of the talk
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- Leptogenesis
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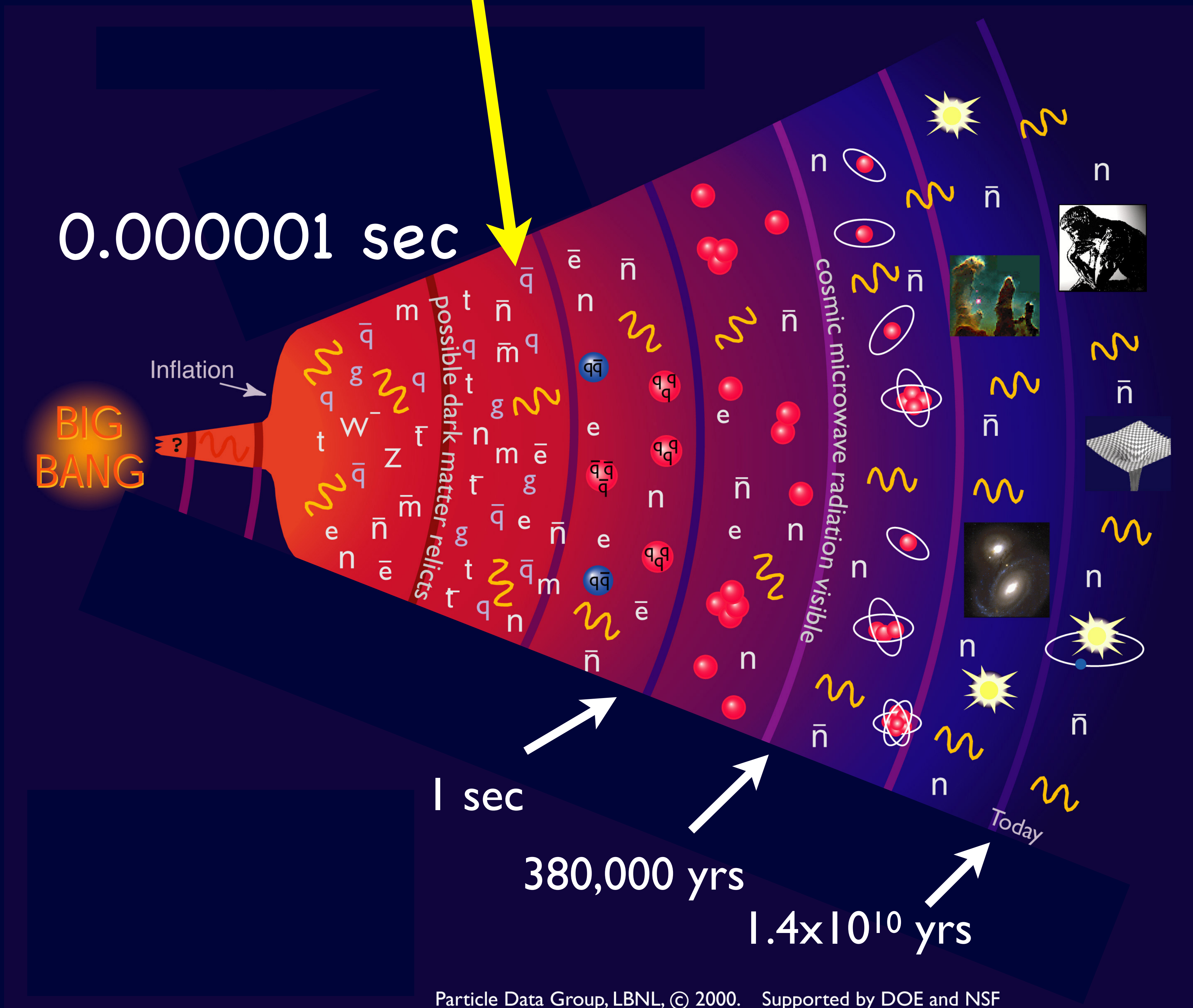
- Summary

Baryon Asymmetry of the Universe

In the very early Universe,....

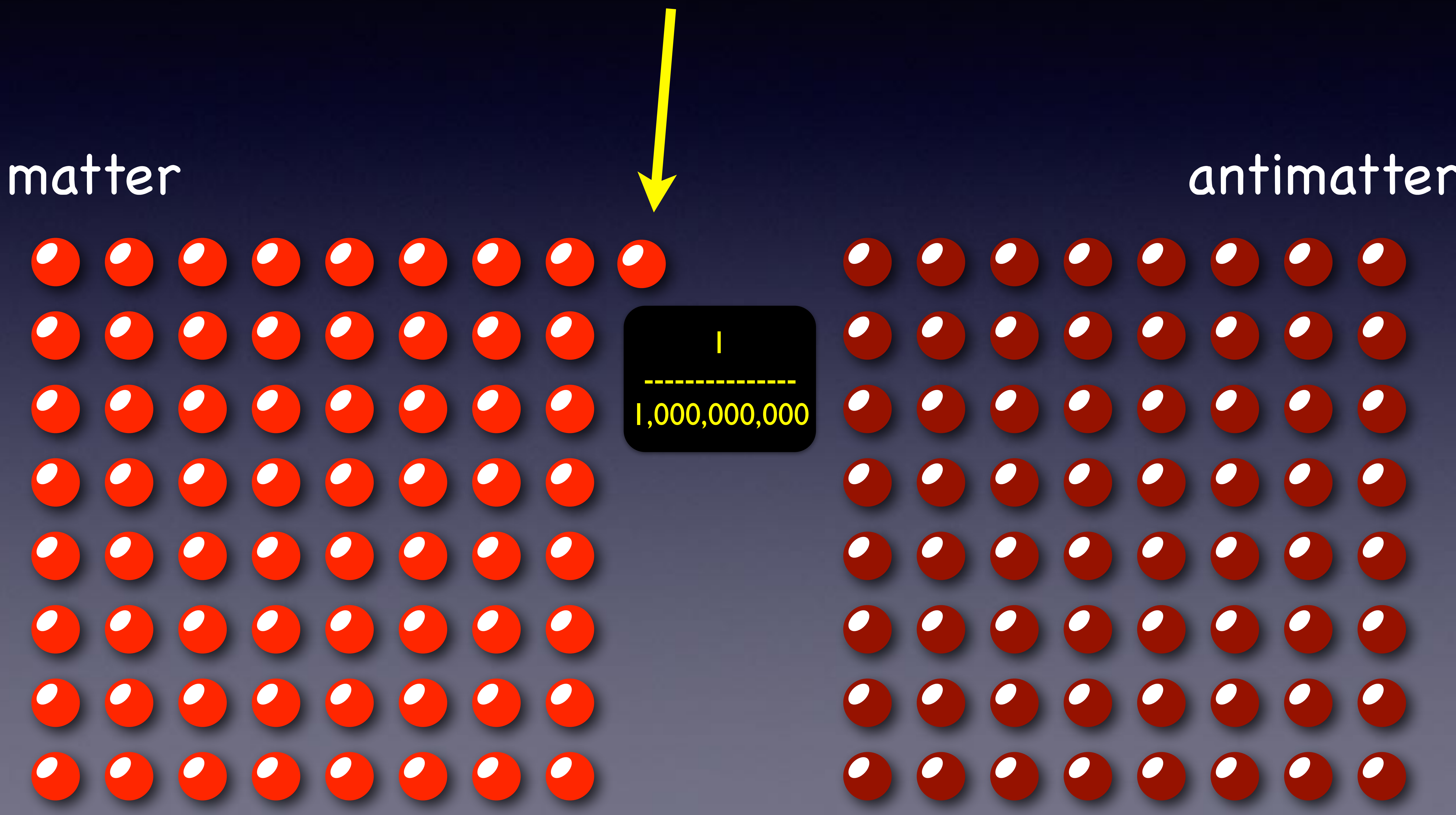


http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

In the very early Universe,....

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

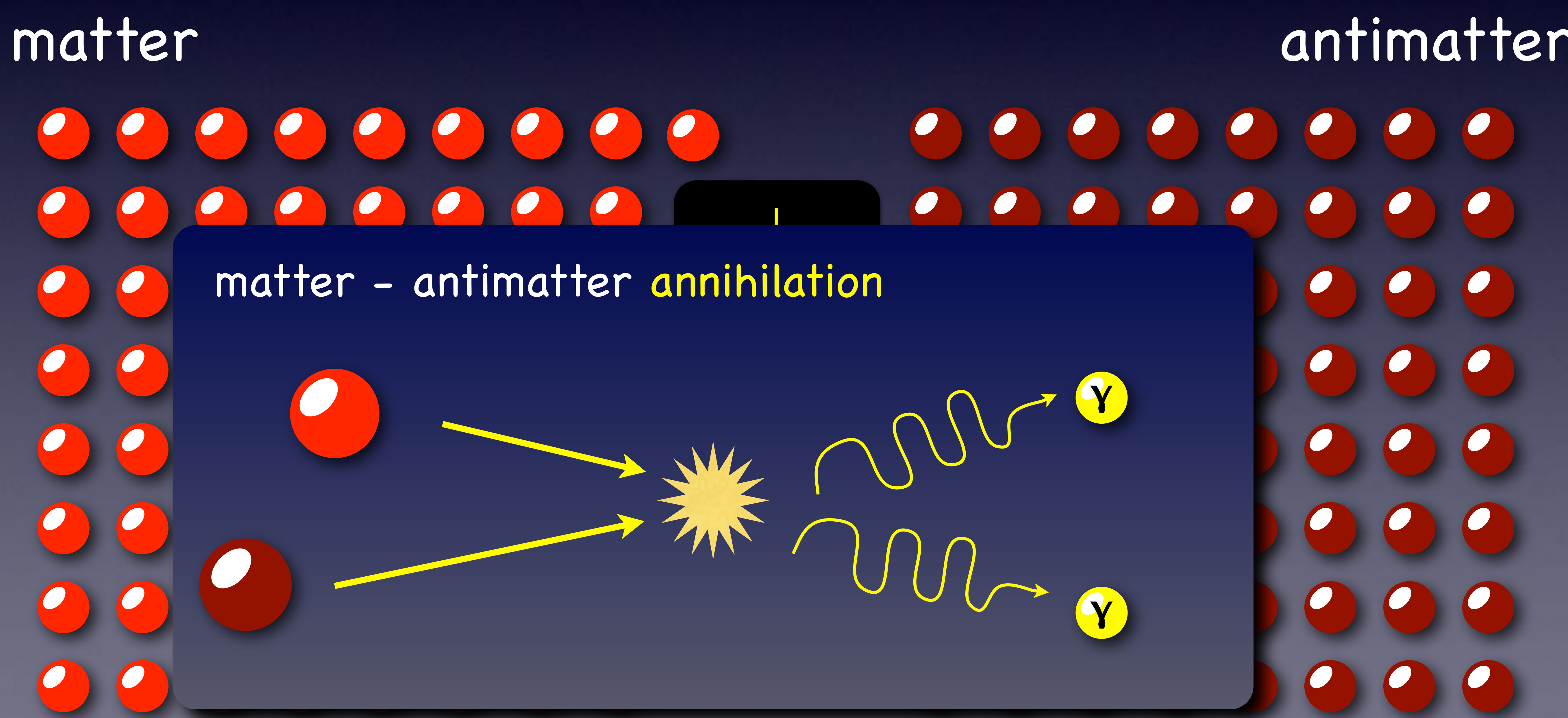
But there was tiny excess of matter over anti-matter.



In the very early Universe,....

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

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



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

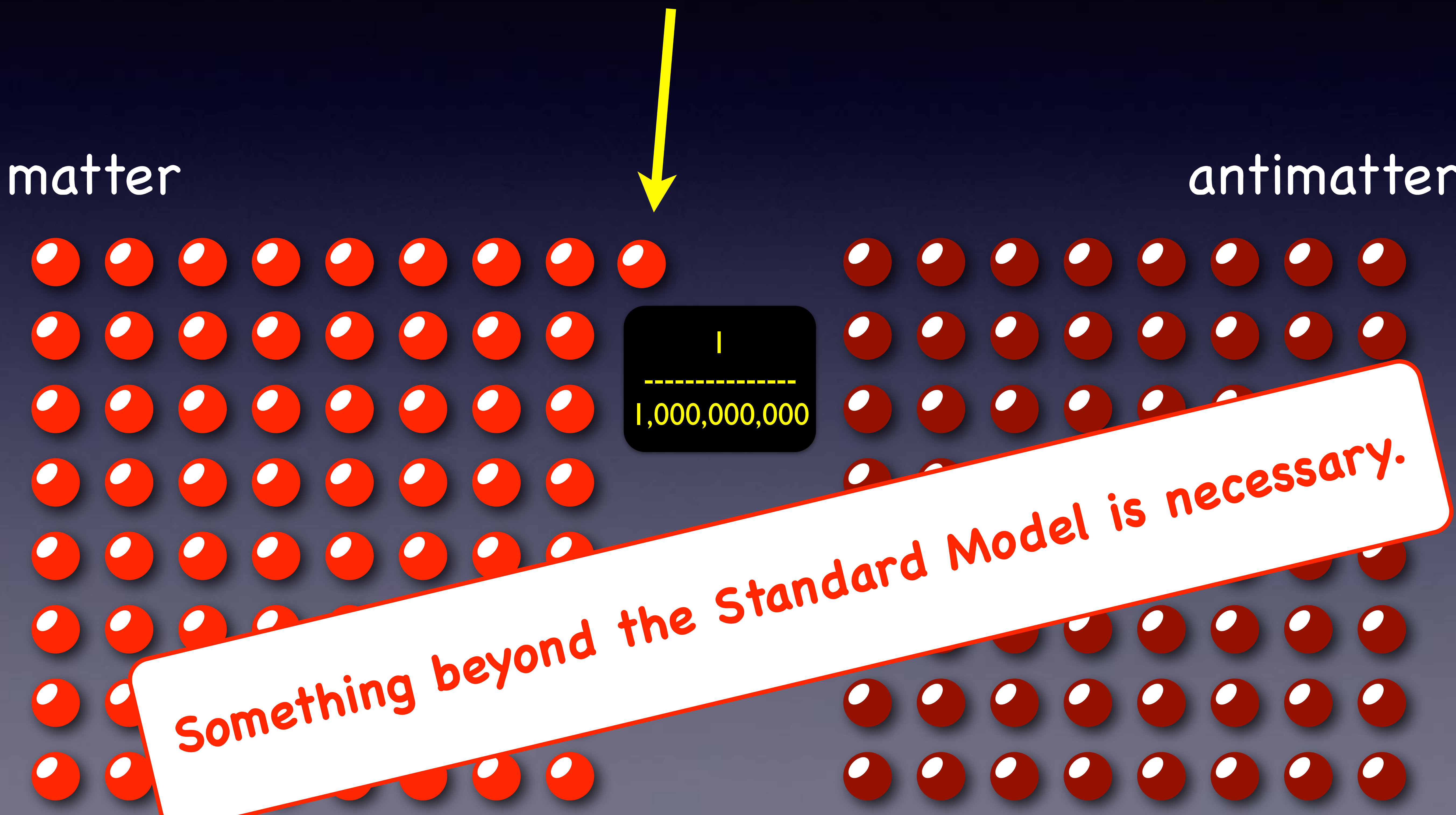
(no antimatter)

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

are made from this leftover matter.

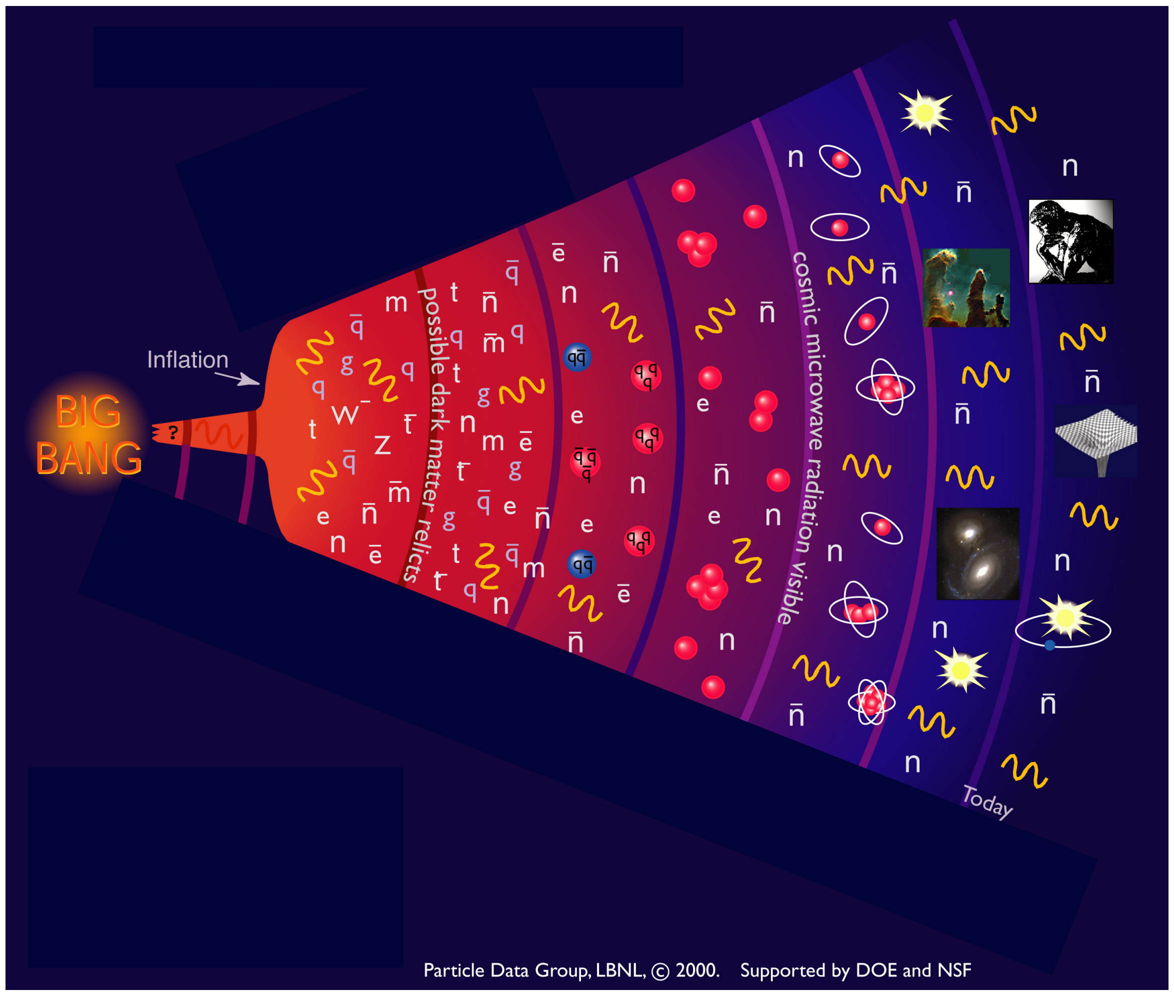
Puzzle

How was the initial excess of matter created ?

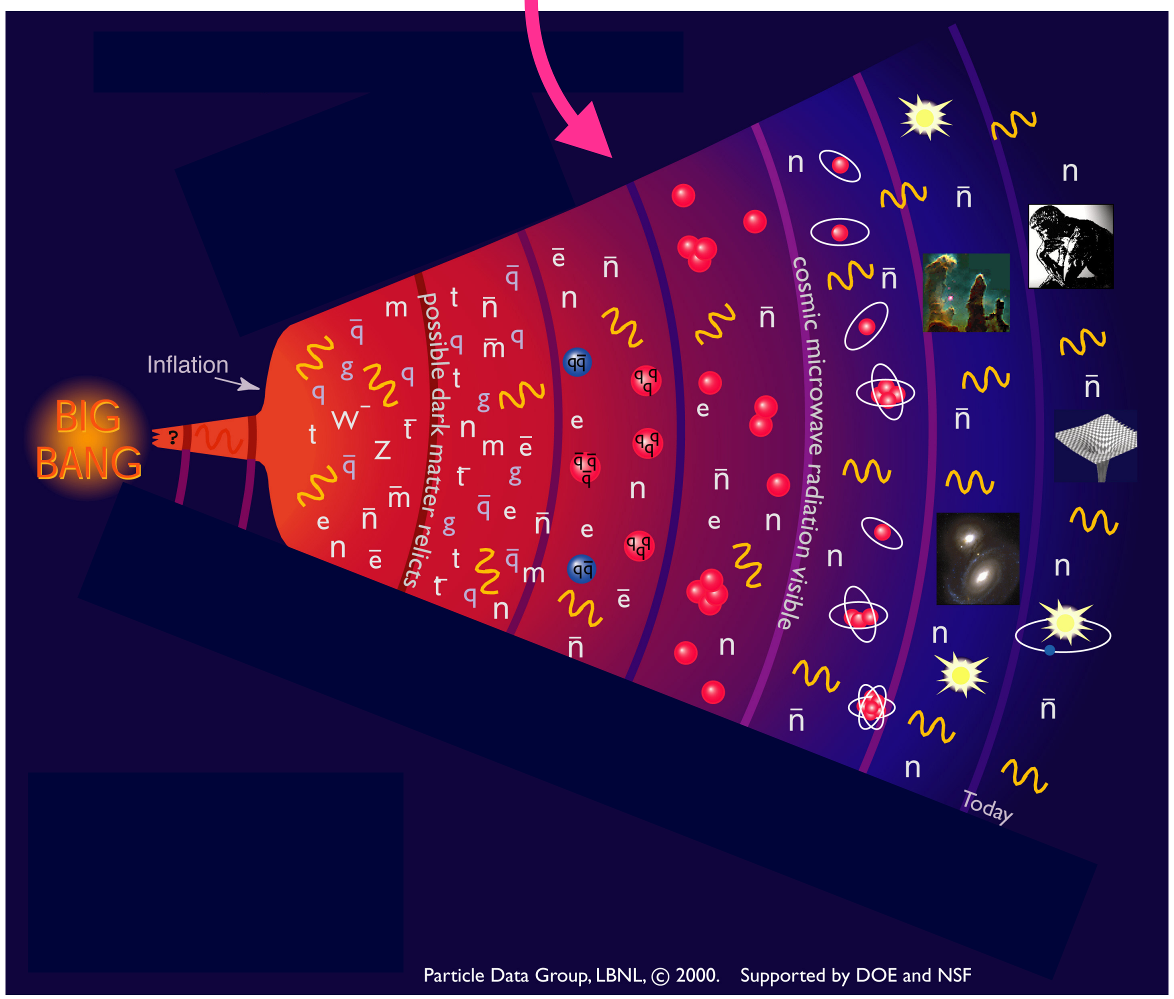


Something beyond the Standard Model is necessary.

Observations (two independent evidences)



Observations (two independent evidences)



(1) Big Bang Nucleosynthesis (BBN)

(cosmic time about 1 sec)

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

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

24. Big-Bang nucleosynthesis 3

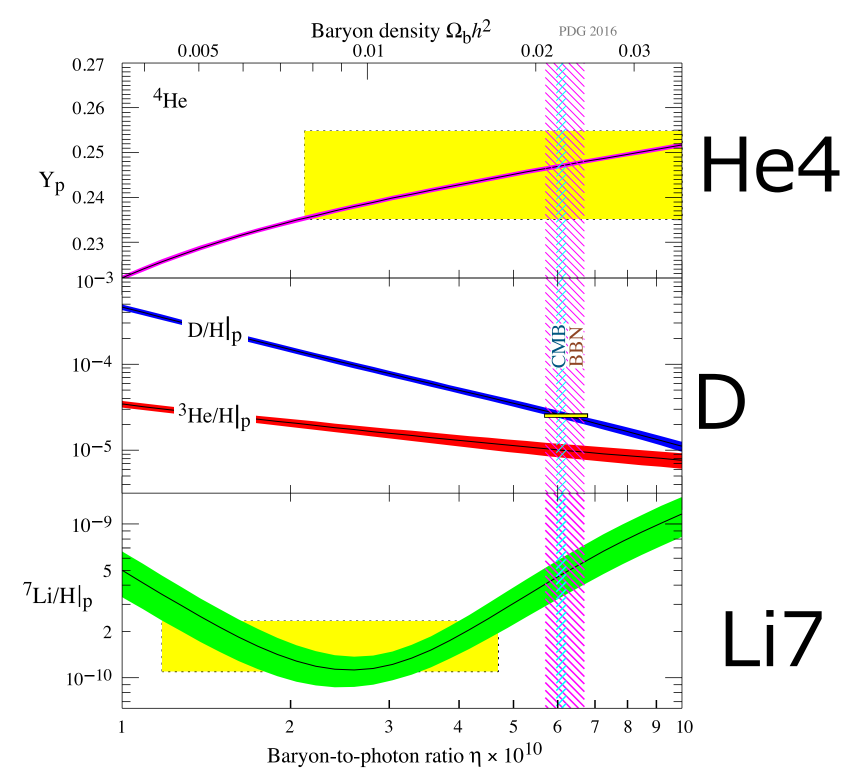
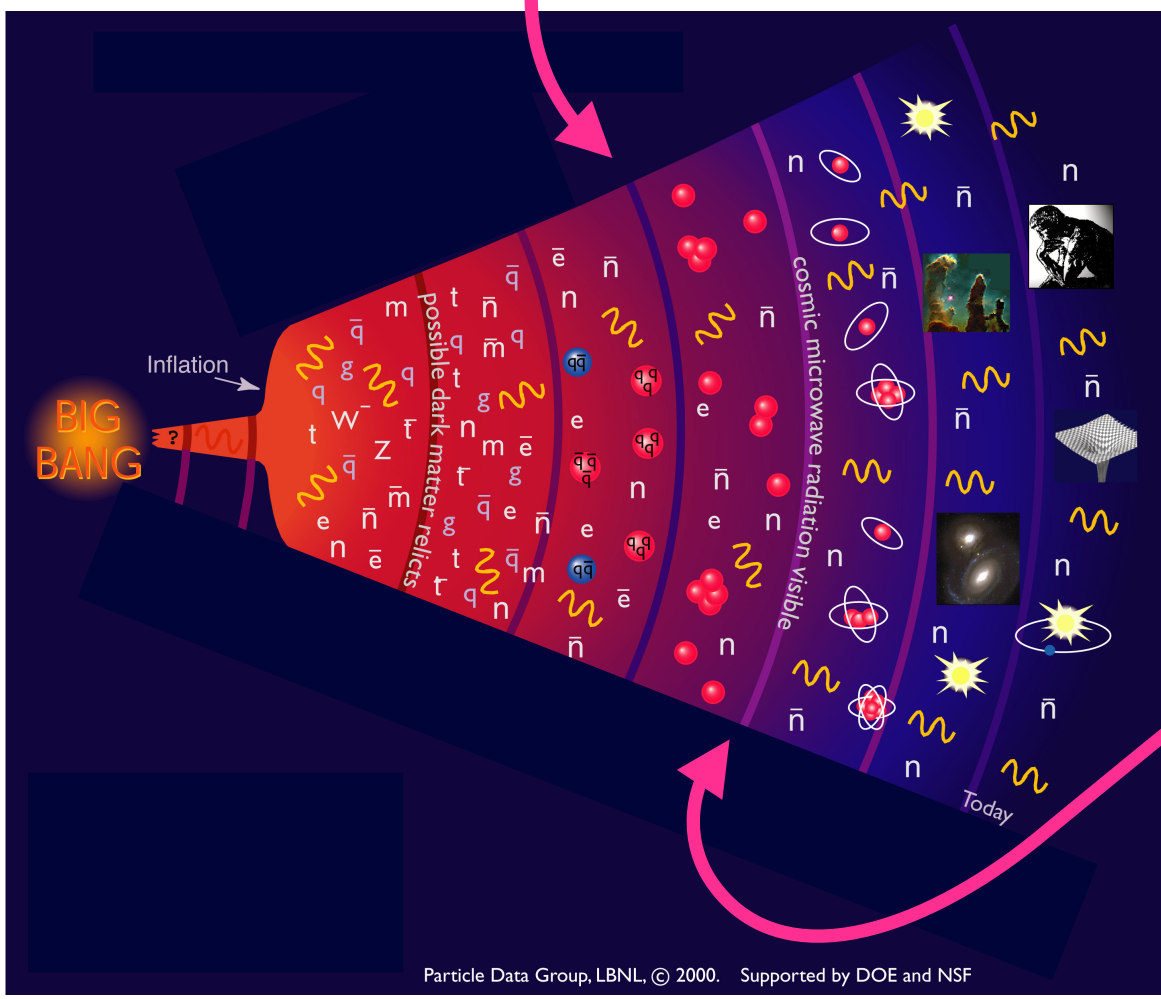


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis—the bands show the 95% CL range [5]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density,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

[Particle Data Group]

Observations (two independent evidences)



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

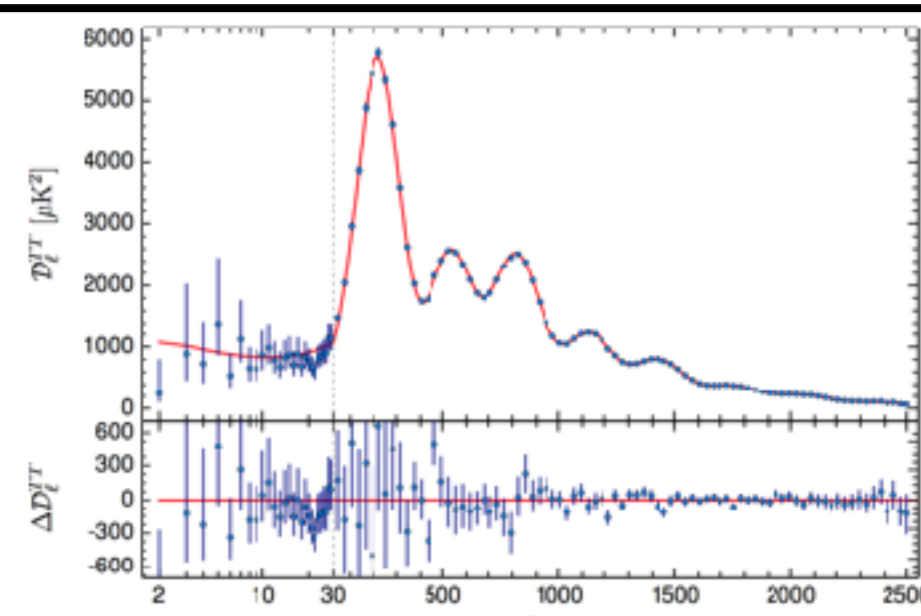
$$\longleftrightarrow \quad 0.021 \le \Omega_b h^2 \le 0.024 \ (95\% \ \mathrm{CL})$$

(2) Cosmic Microwave background

(cosmic time about 400,000 yrs)

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

[Planck 2015]

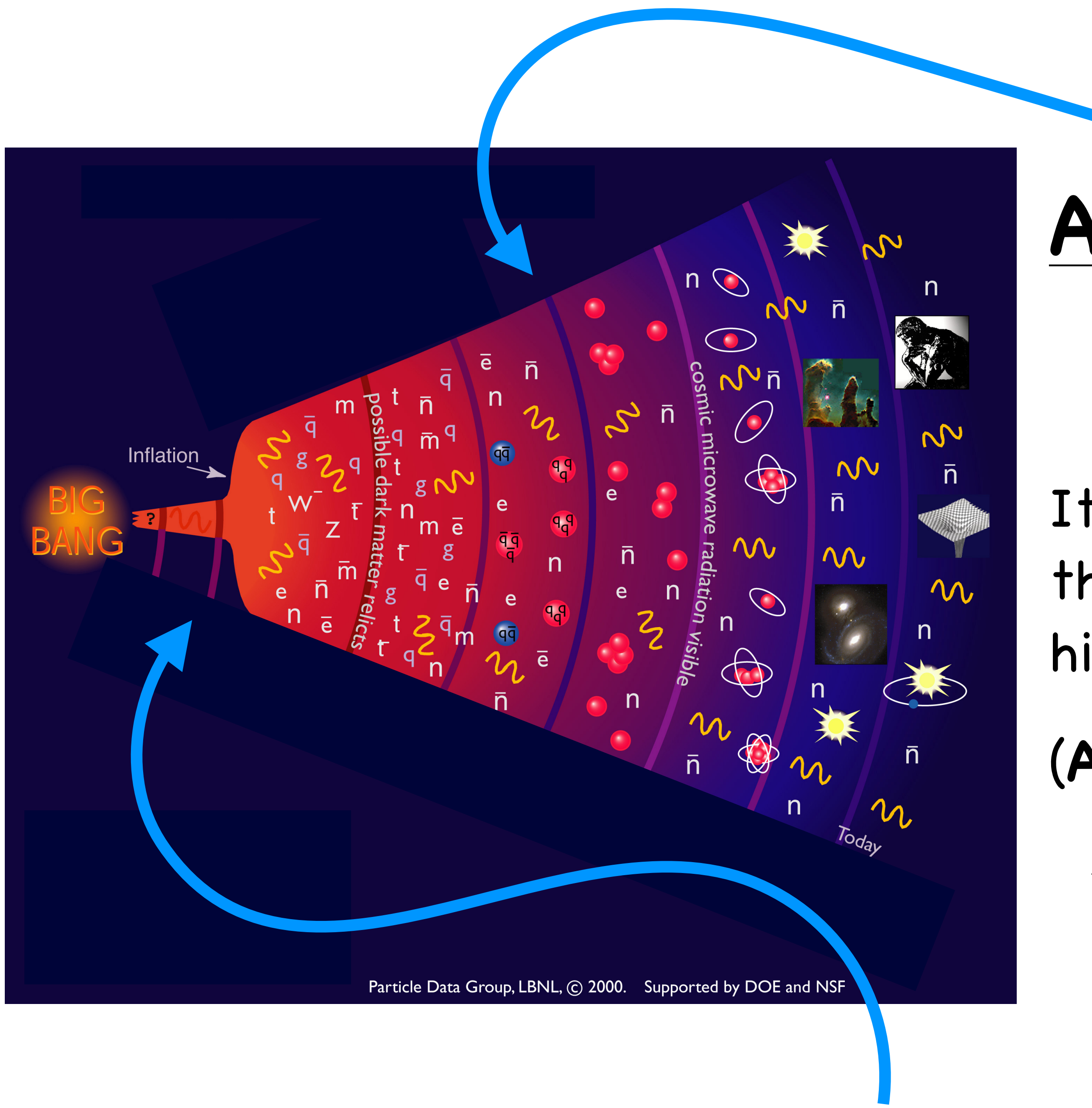


They are consistent

(2) has better precision.

When was the Baryon Asymmetry of the Universe generated?

When was the Baryon Asymmetry of the Universe generated?



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

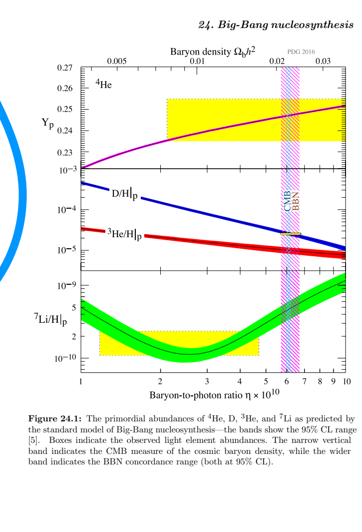
because the inflation dilutes everything.

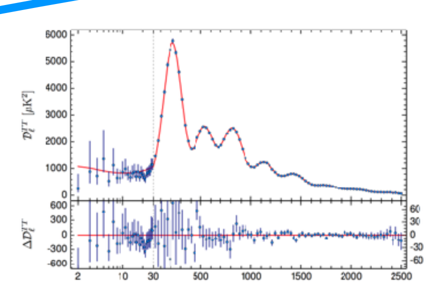
(**An example** just after the inflation: **Non-thermal Leptogenesis**.
The inflaton decays into right-handed neutrinos, which then lead Leptogenesis.

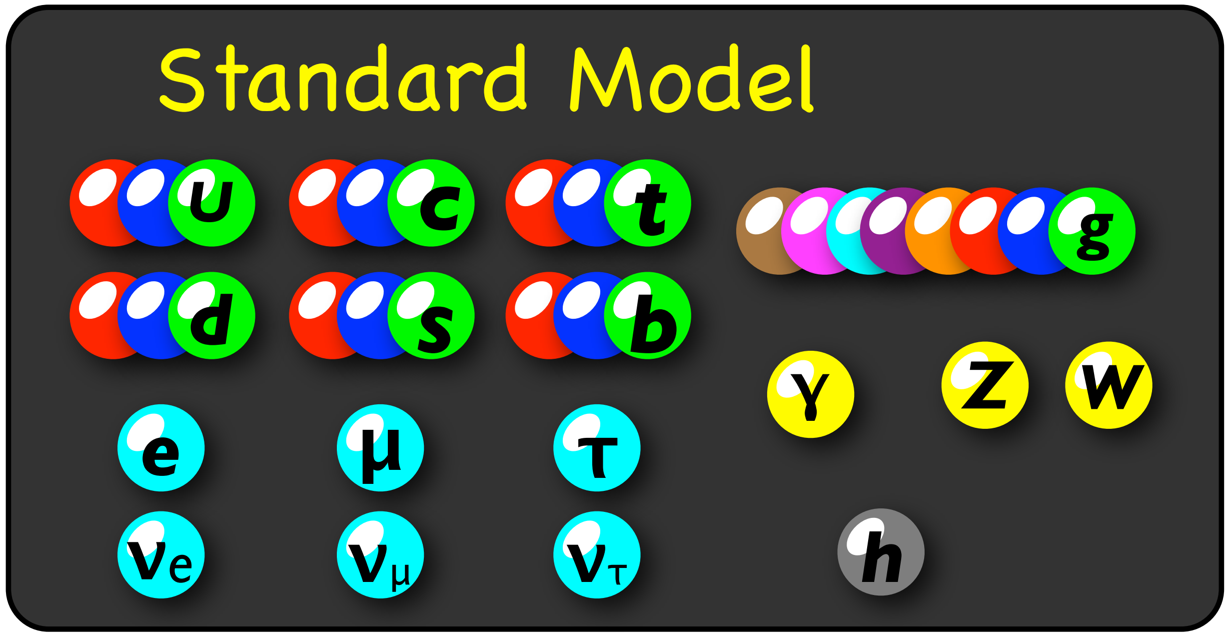
When was the Baryon Asymmetry of the Universe generated?

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
≈		CMB
14 billion yrs	3 K	Now

sometime in this range







… does not work.

Sakharov's 3 conditions [Sakharov 1967]

- ☑ Baryon number violation
- ☑ CP-violation … (but too small)
- ☐ out-of-equilibrium

Something beyond the Standard Model is necessary.

Plan

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

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- gauged $U(1)_{\mu-\tau}$

- Summary

Why ``Lepto"genesis?

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]

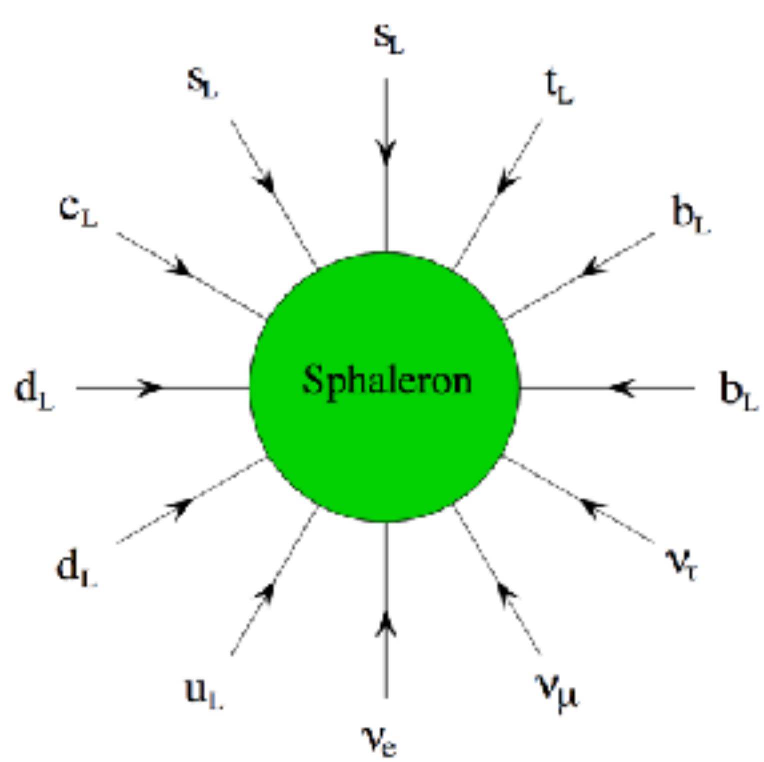


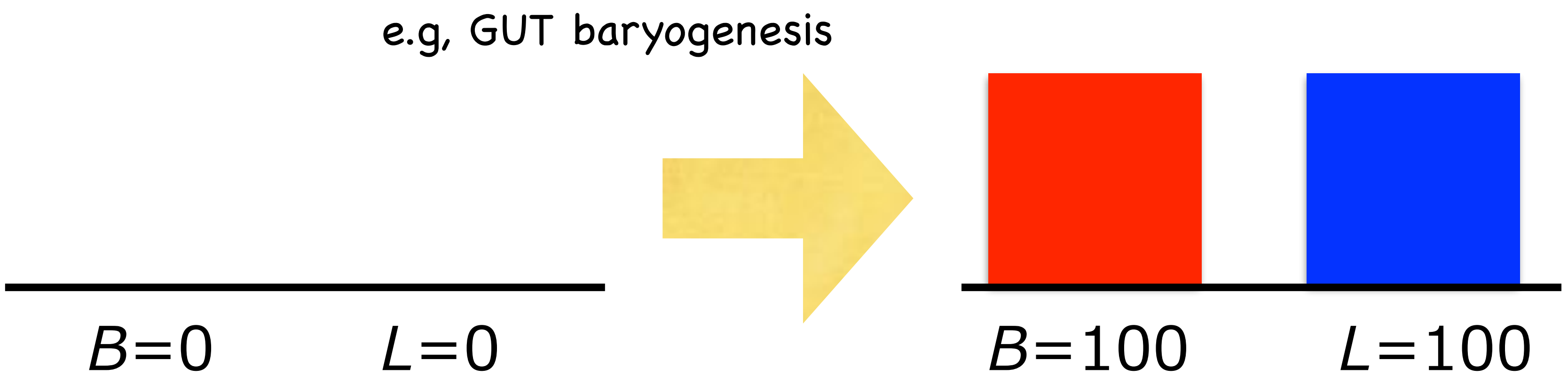
Figure 1: One of the 12-fermion processes which are in thermal equilibrium in the high-temperature phase of the Standard Model.

[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,...**

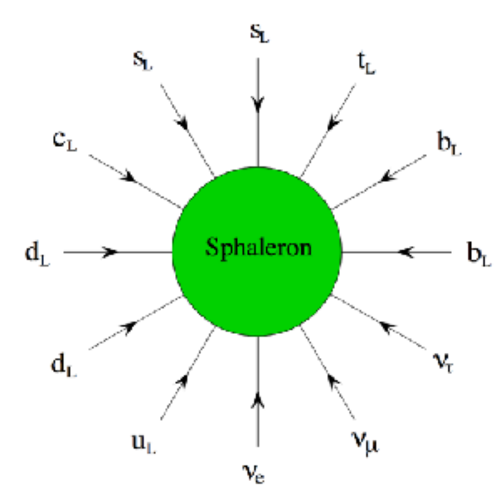
Finally B=0 at equilibrium.

e.g, GUT baryogenesis

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

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

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

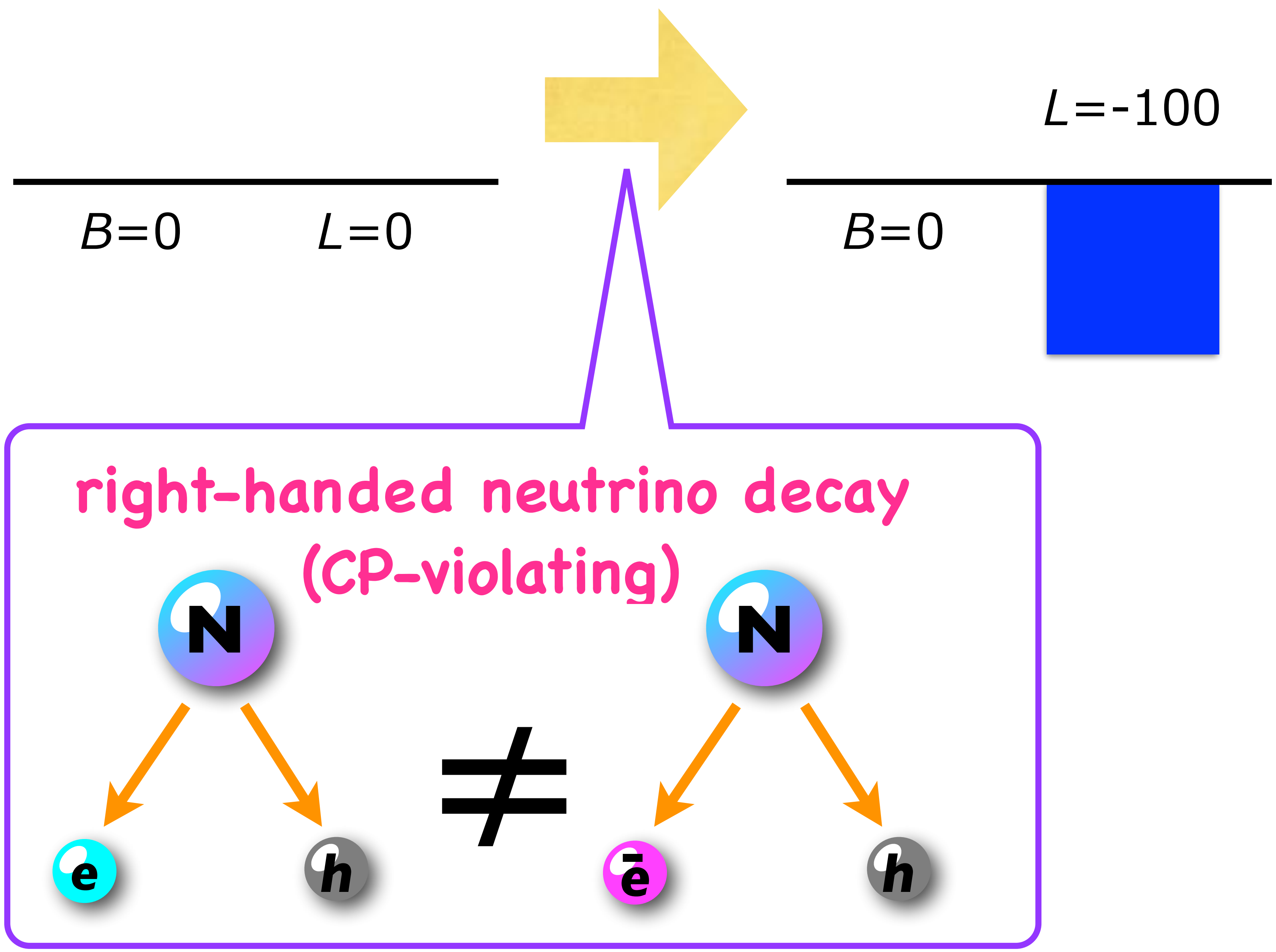
and L-violation implies,...

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

Lepgogenesis

[Fukugita, Yanagida, ’86]

generate **Lepton** asymmetry

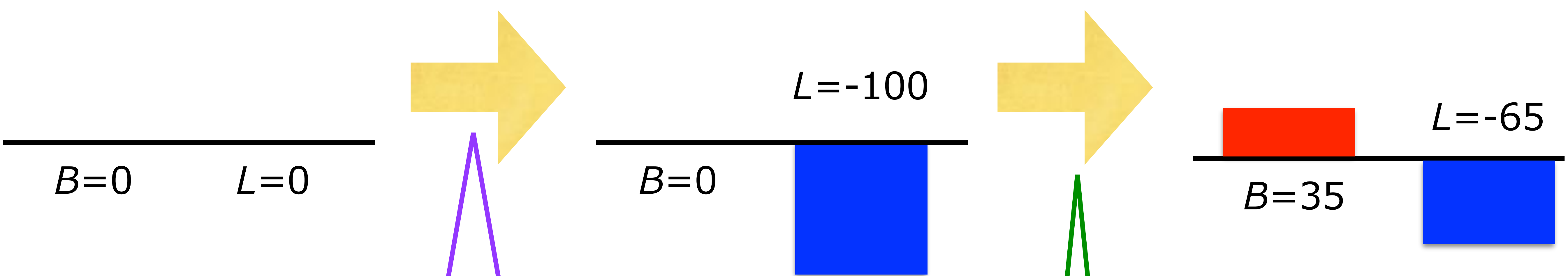


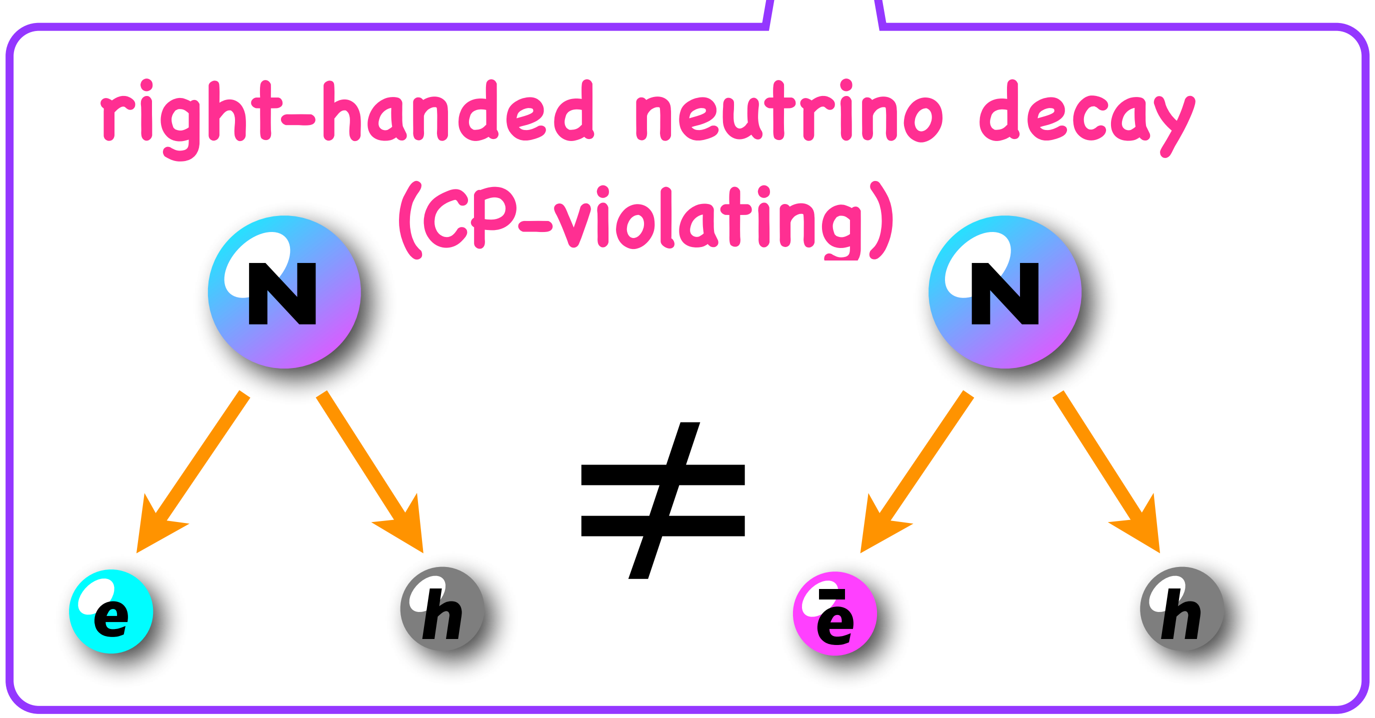
Lepgogenesis

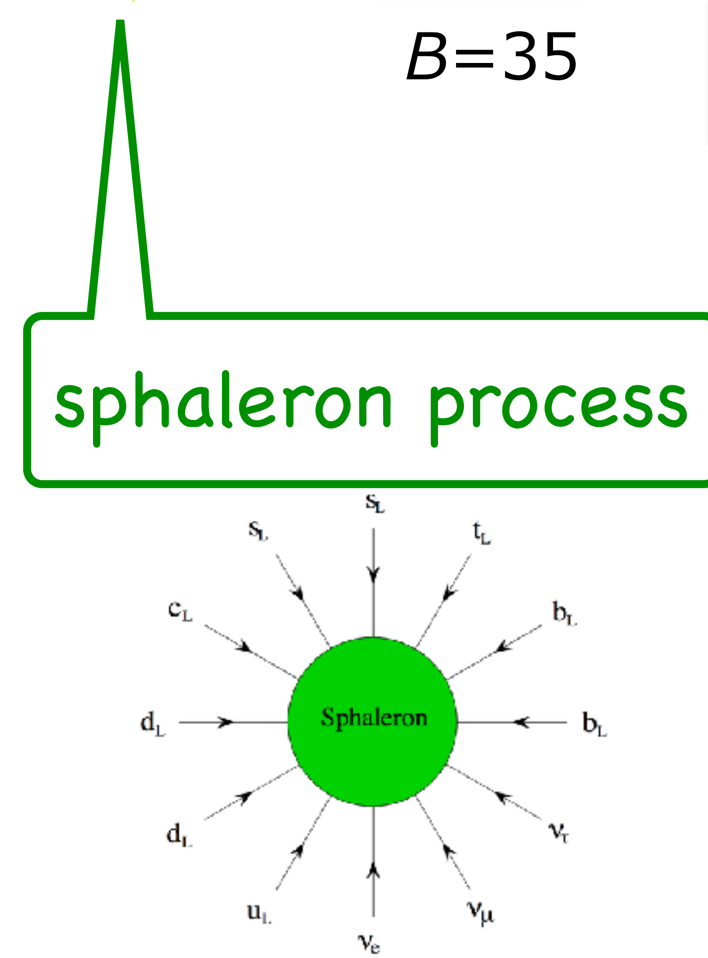
[Fukugita, Yanagida, '86]

generate **Lepton** asymmetry

Then, B≠0 remains at equilibrium!







Lepgogenesis

[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 (νMSM)

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

(+ many others ...)

and also recent progresses...

See e.g., arXiv:1711.02861～ 1711.02866.

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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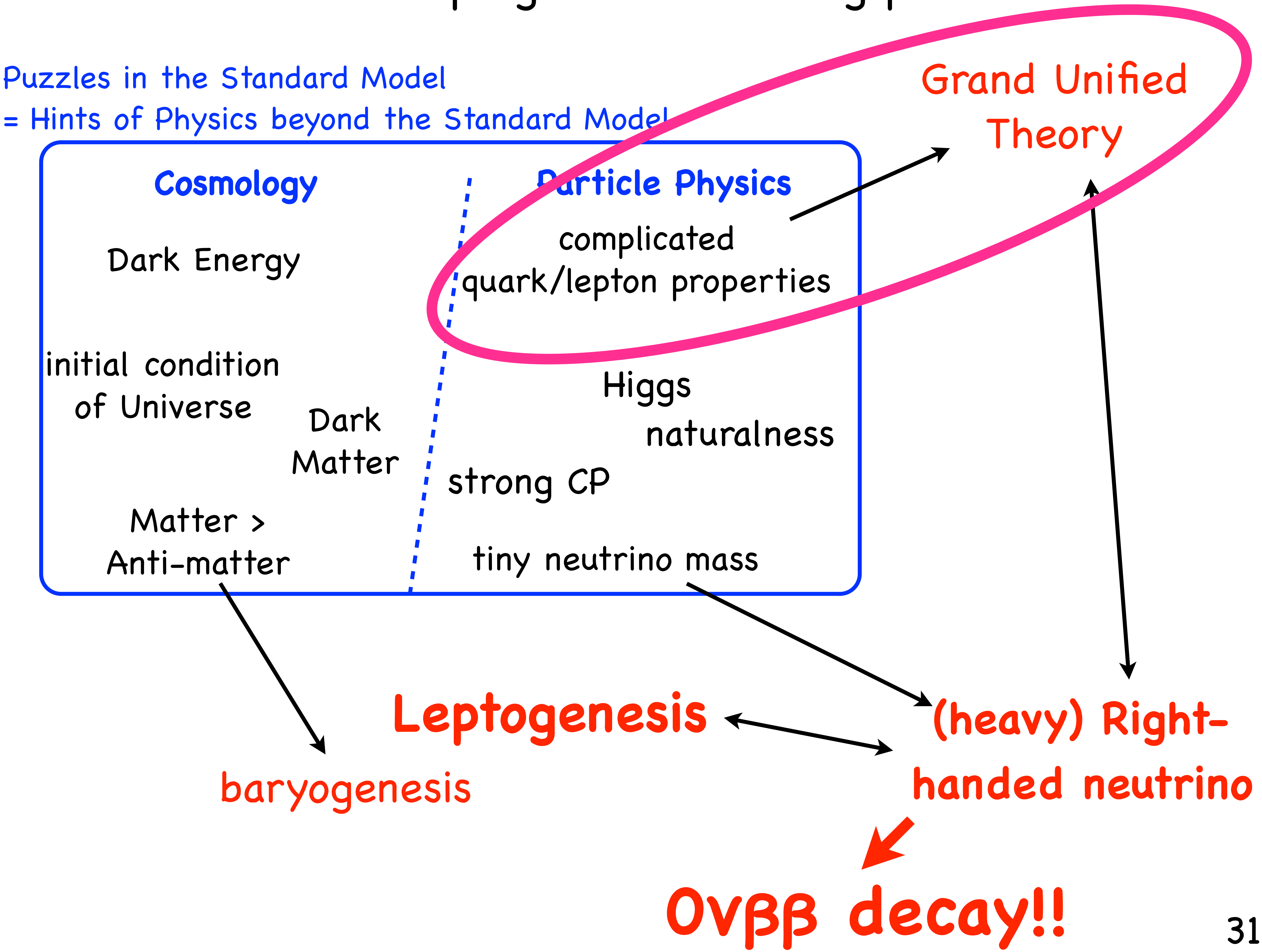
Seesaw and Leptogenesis in a ``big picture”

Seesaw and Leptogenesis in a ``big picture”

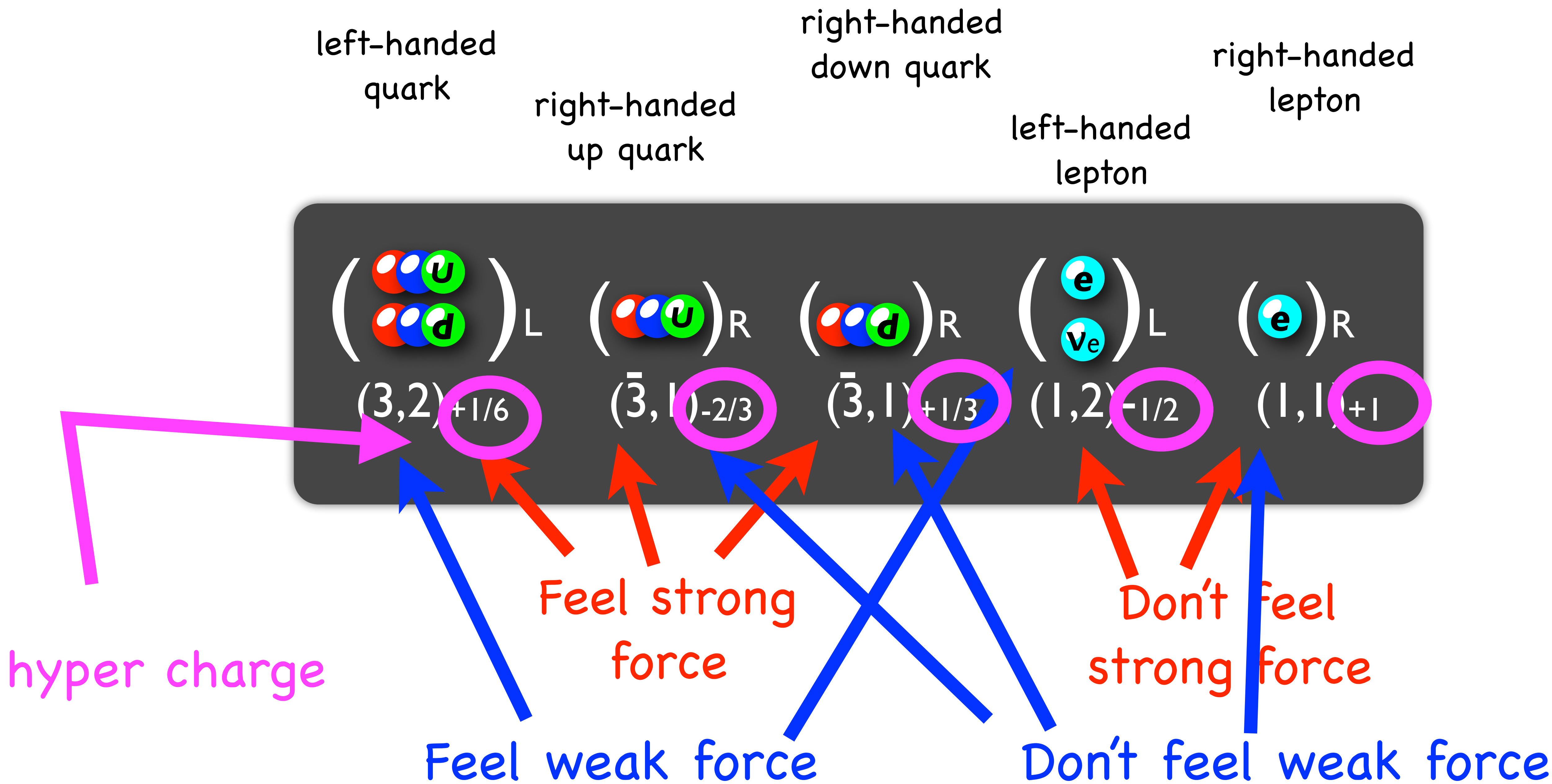
Puzzles in the Standard Model
= Hints of Physics beyond the Standard Model

Cosmology	**Particle Physics**
Dark Energy	complicated quark/lepton properties
initial condition of Universe	Higgs
Dark Matter	naturalness
Matter > Anti-matter	strong CP
	tiny neutrino mass

Seesaw and Leptogenesis in a ``big picture"

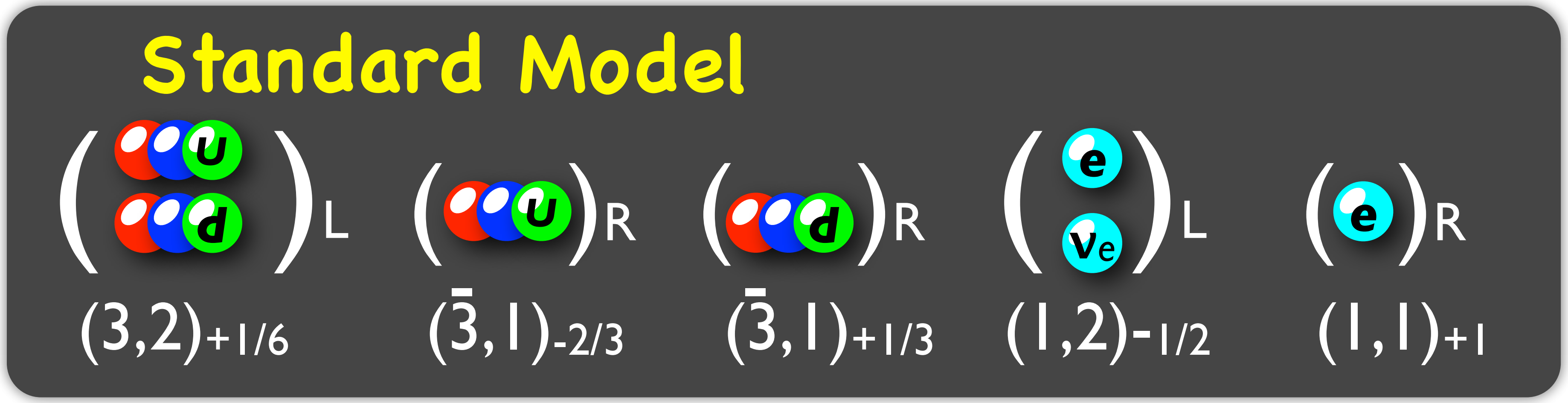


Standard Model



... very complicated !!

Q: any simple, unified theory to explain it?



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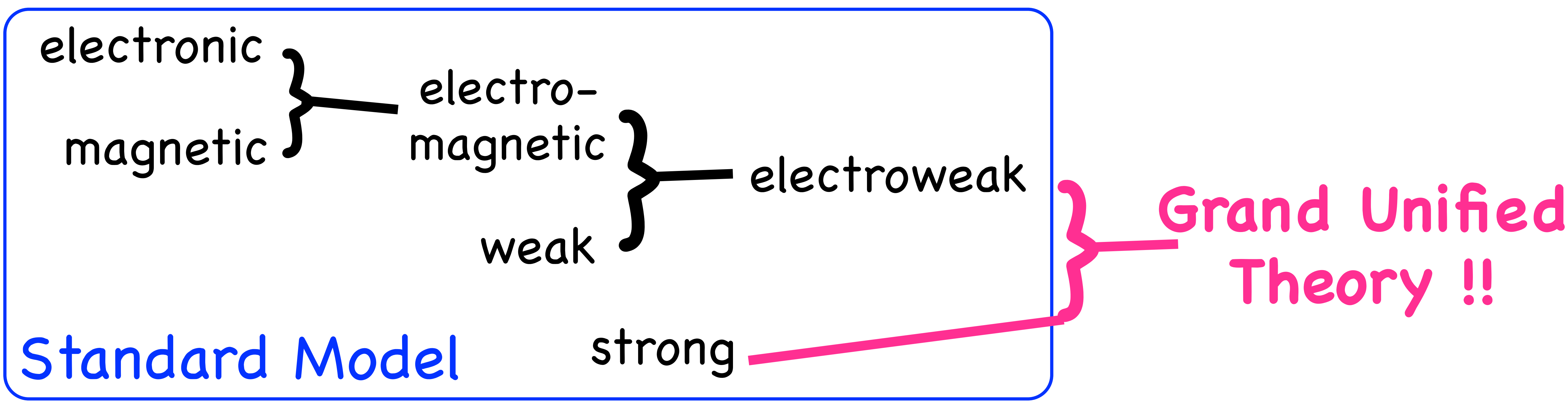
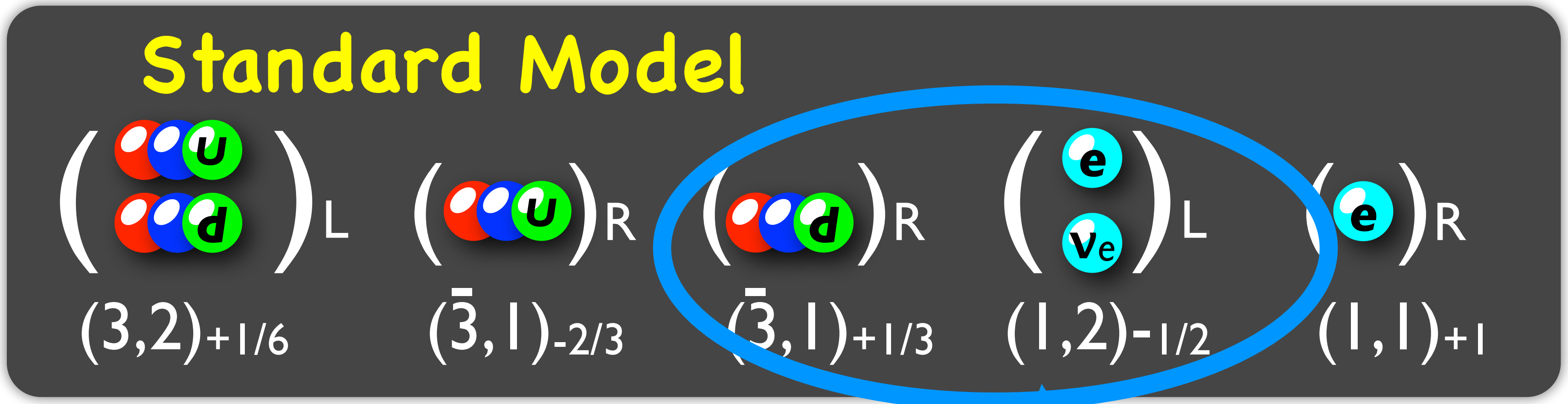
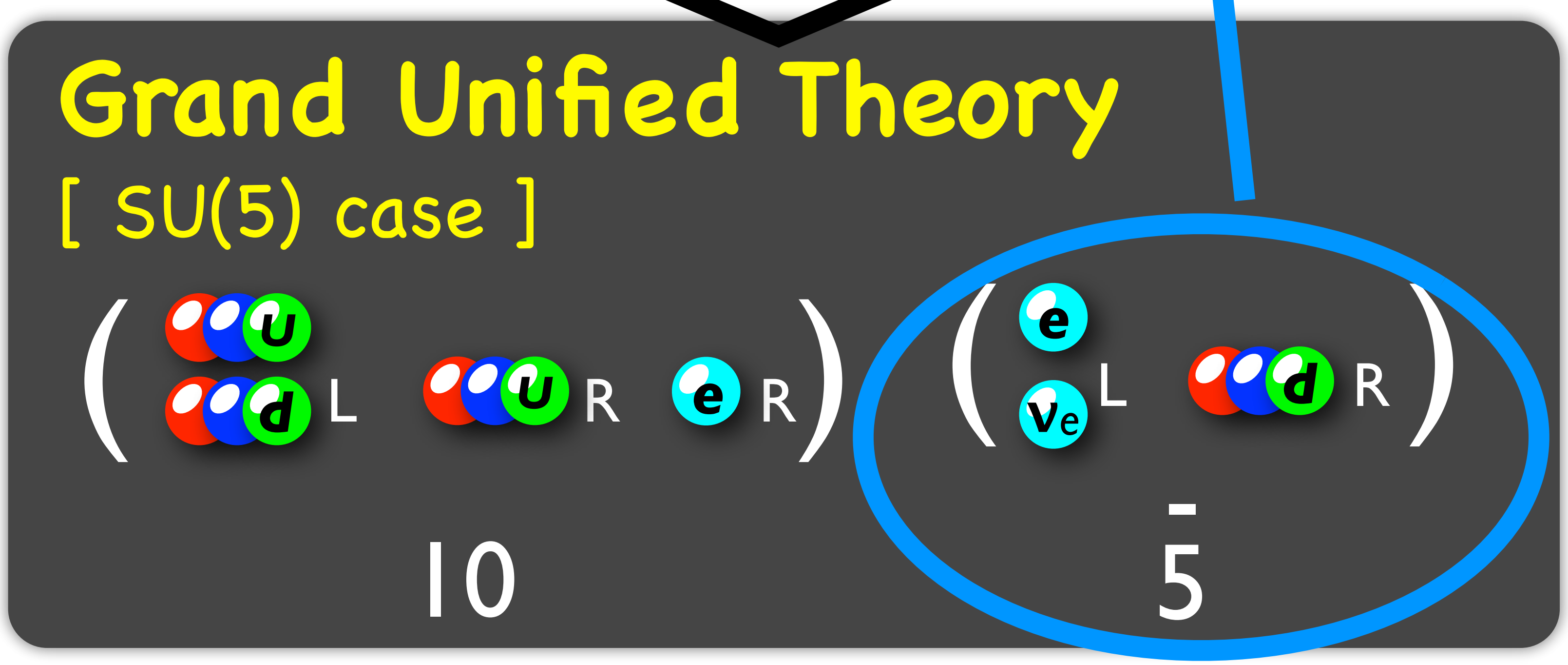




Q: any simple, unified theory to explain it?

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

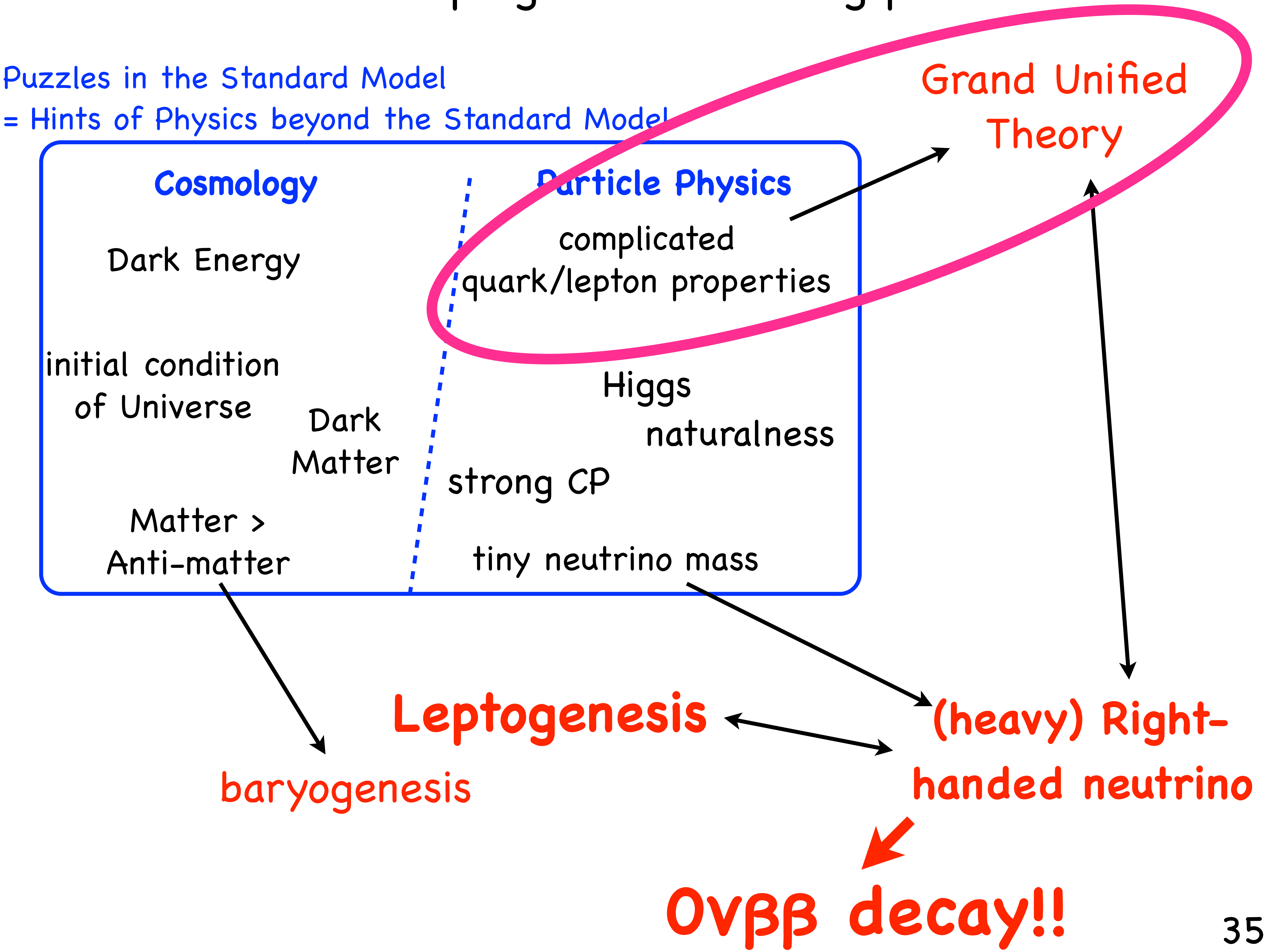
Complicated numbers are naturally explained !



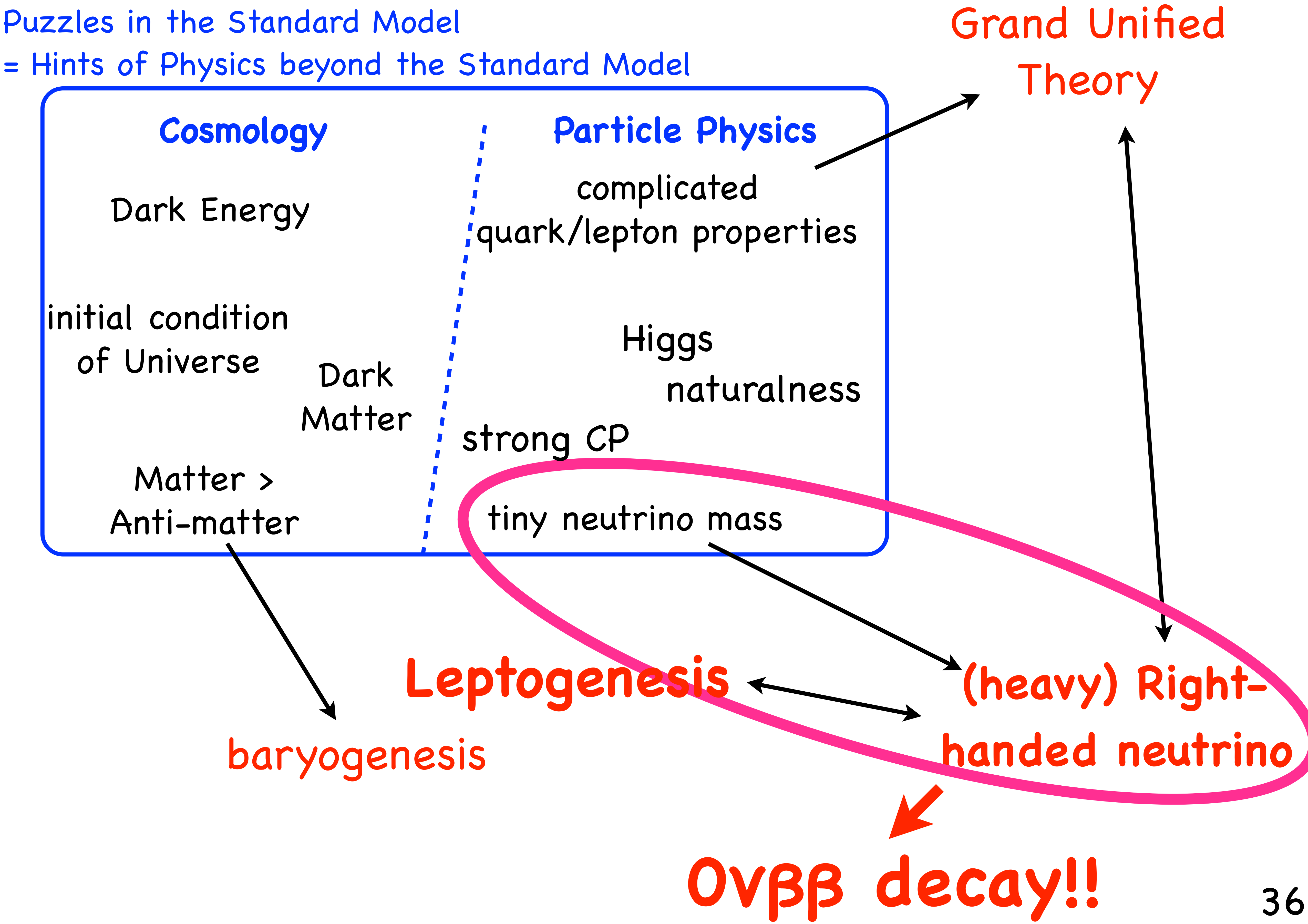
... beautifully unified into simple SU(5) representations !

[Georgi, Glashow 1974]

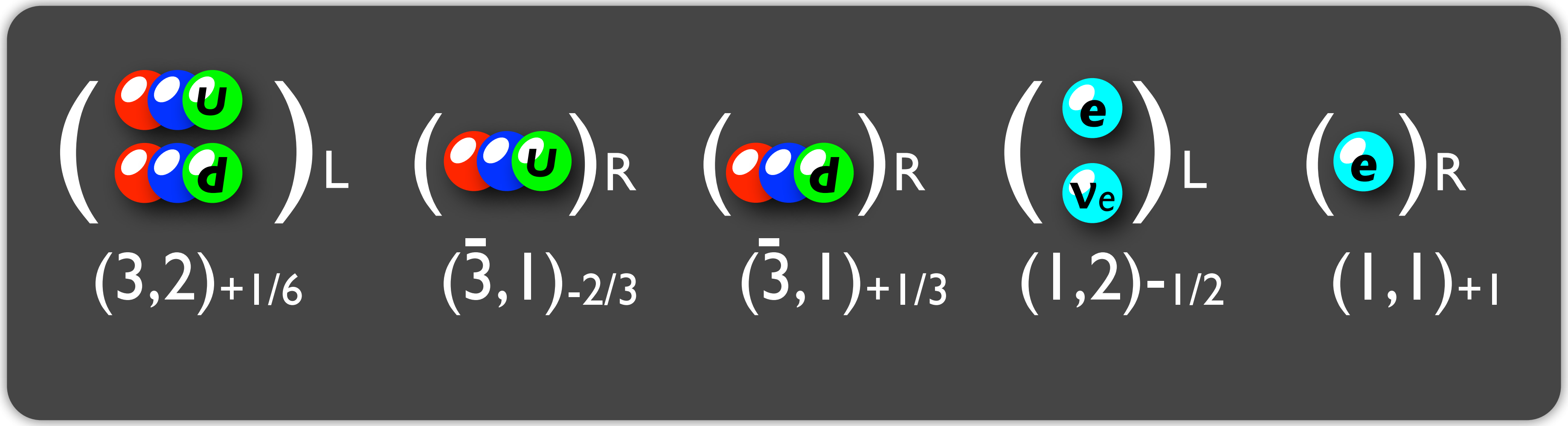
Seesaw and Leptogenesis in a ``big picture"



Seesaw and Leptogenesis in a ``big picture"



puzzle: neutrino masses



left-handed quark

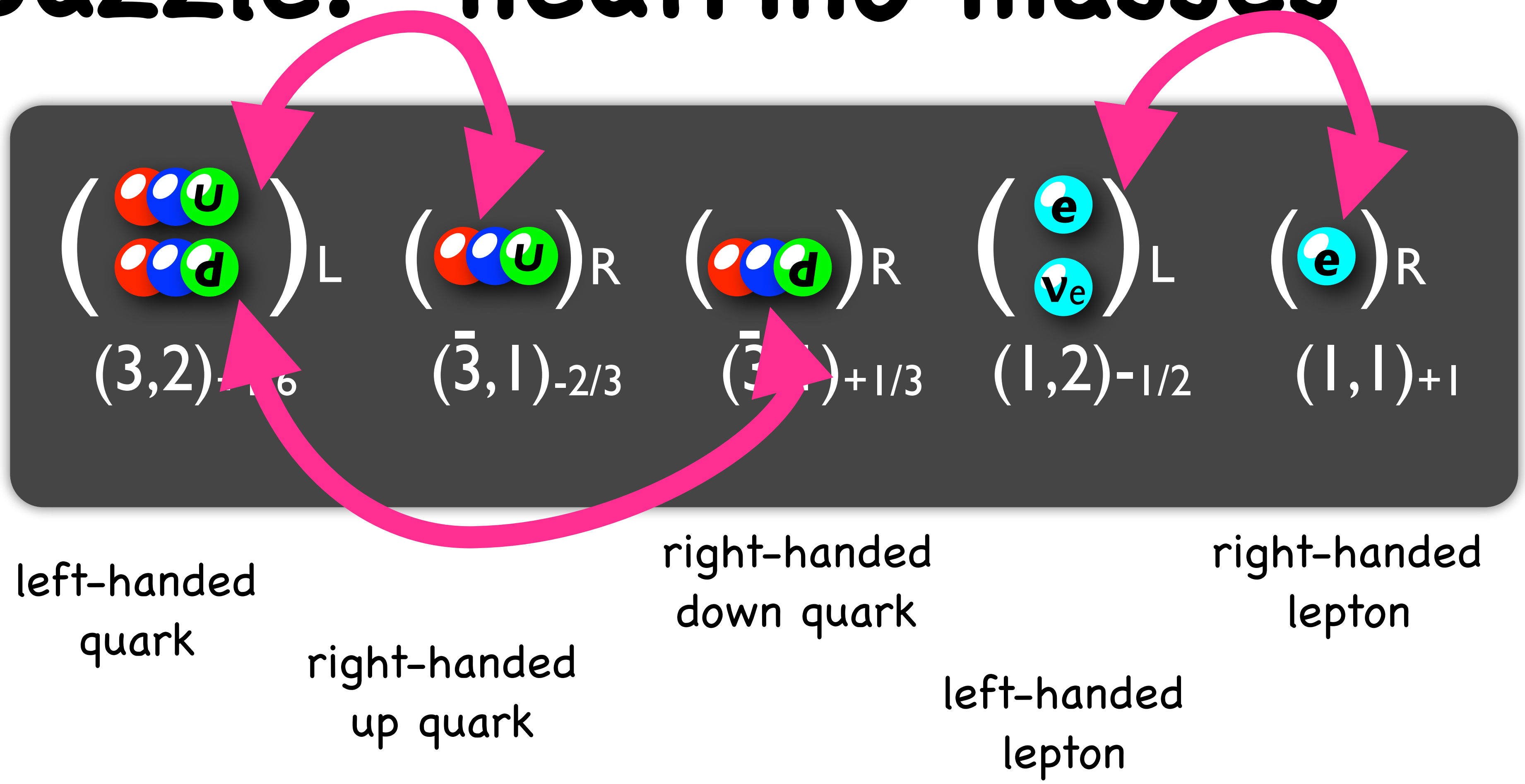
right-handed up quark

right-handed down quark

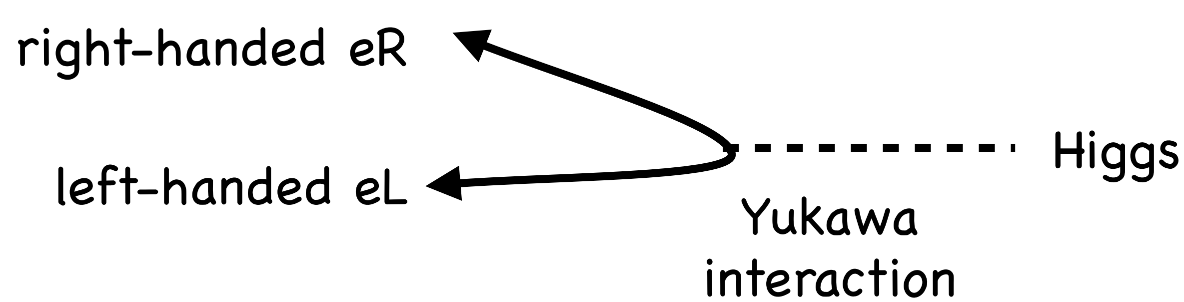
left-handed lepton

right-handed lepton

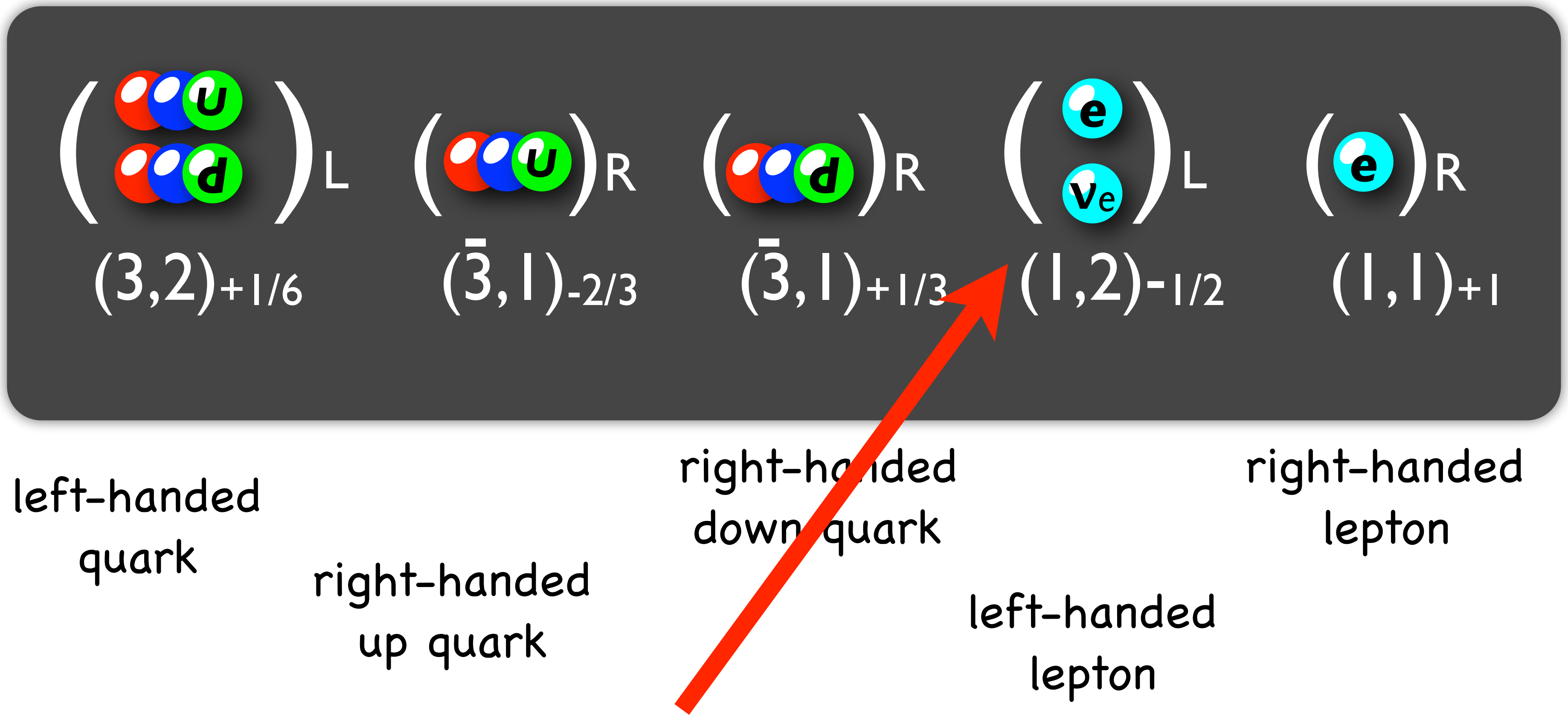
puzzle: neutrino masses



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



puzzle: neutrino masses

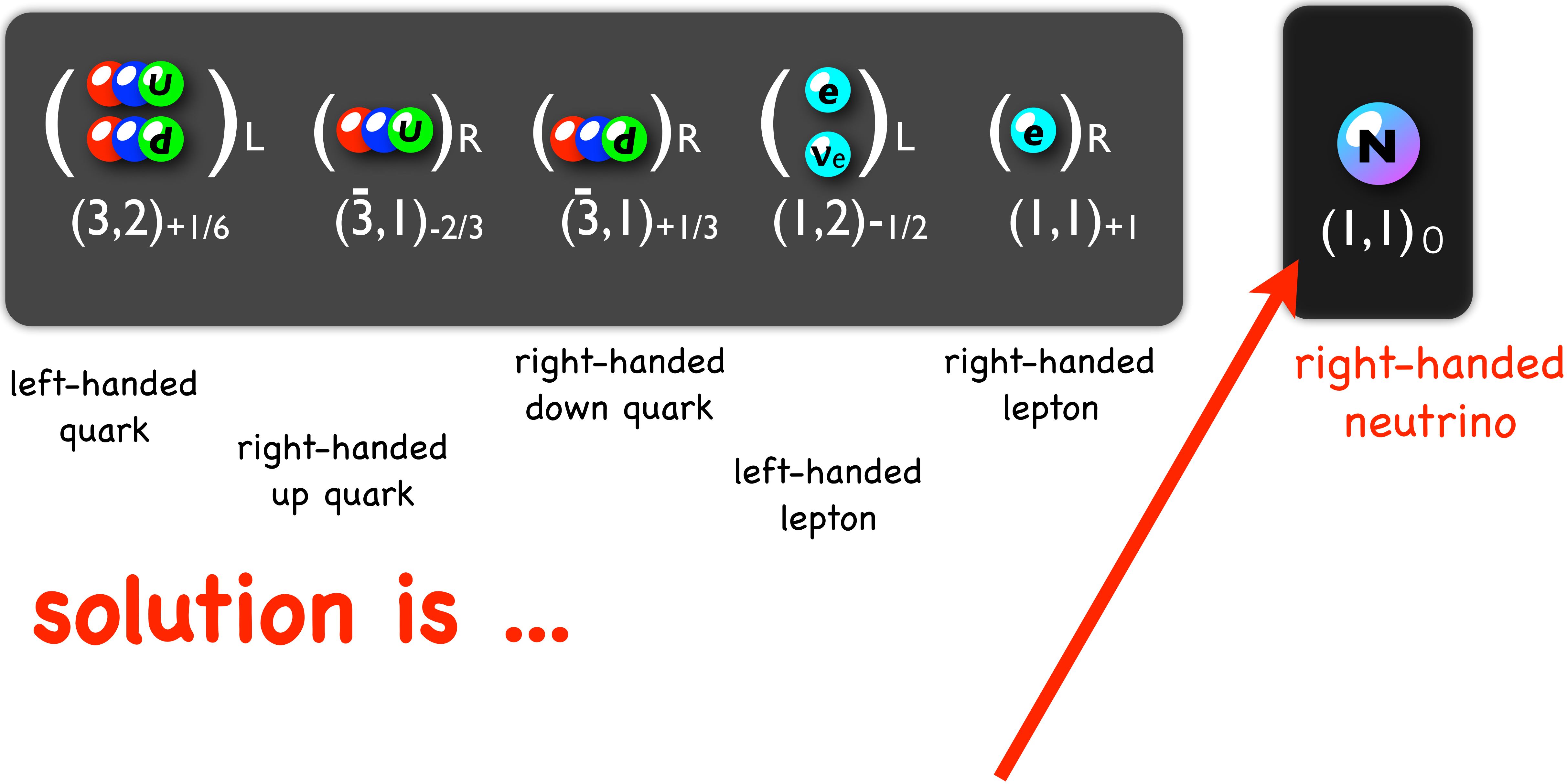


The neutrino has only left-handed component.

===> Massless !!

But the neutrino masses are confirmed
by neutrino oscillations!

puzzle: neutrino masses



a solution is ...

To add a right-handed neutrino !!

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

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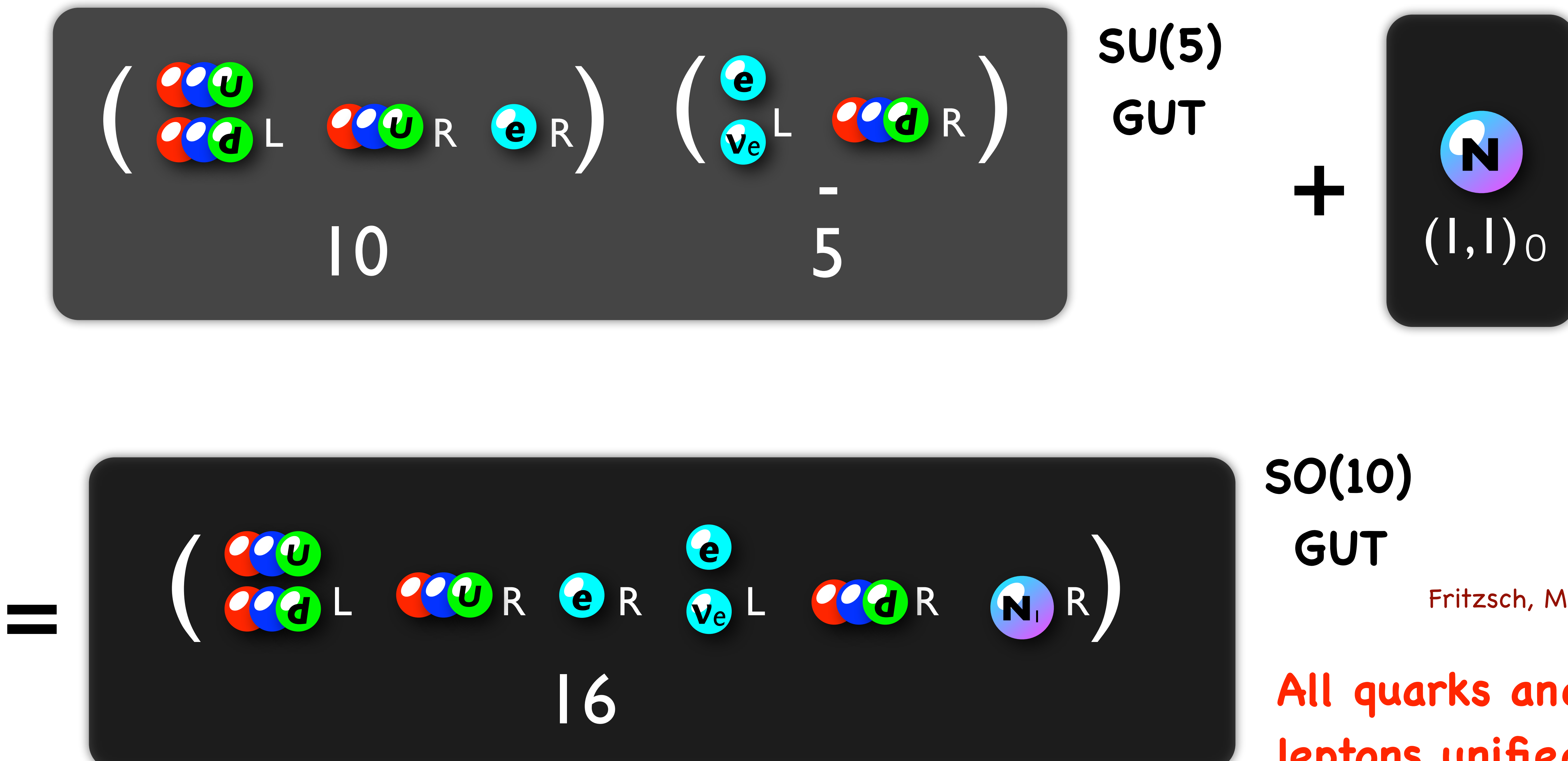
① quarks and leptons completely unified



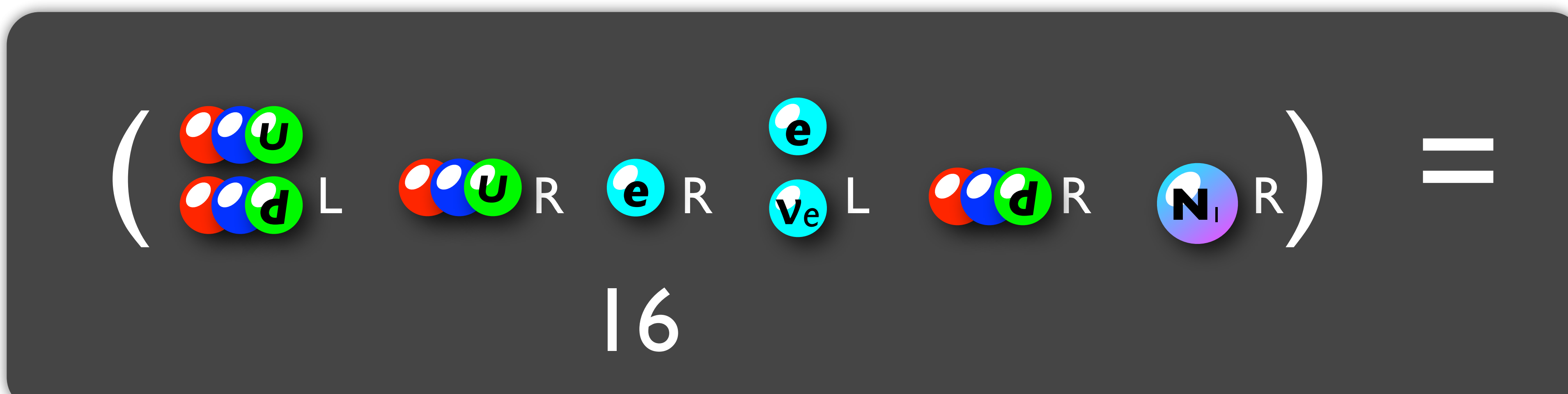
[Georgi,74
Fritzsch, Minkowski,75]

All quarks and leptons unified !

The right-handed neutrino plays a triple role.

[Review of Particle Physics]

① quarks and leptons completely unified

=


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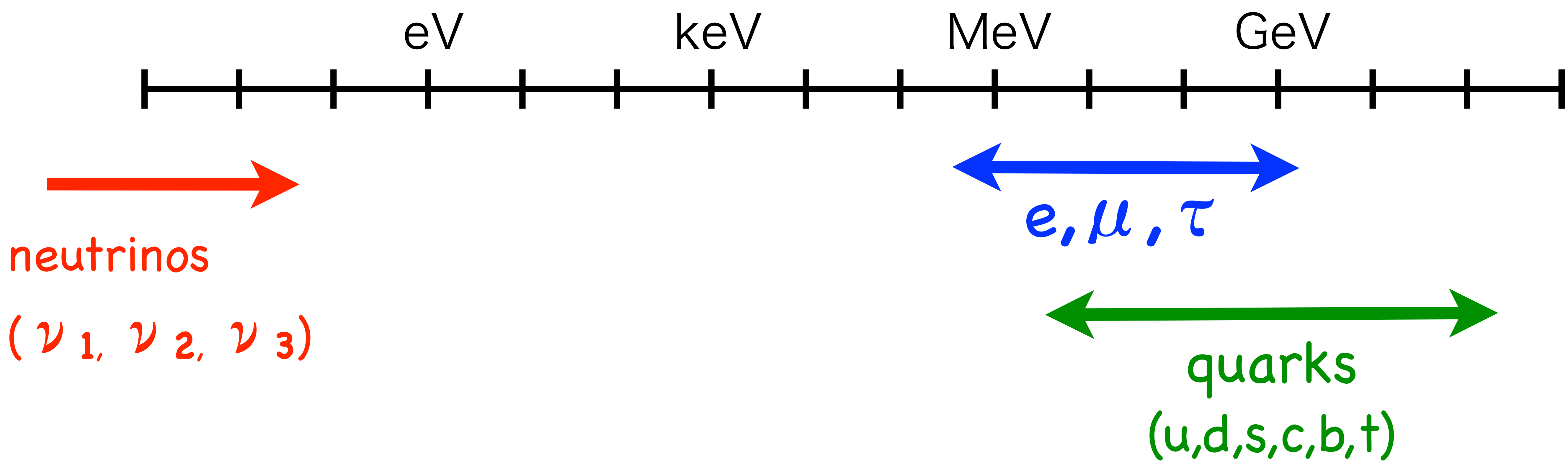
The right-handed neutrino plays a **triple role.**

② explains **tiny** neutrino mass

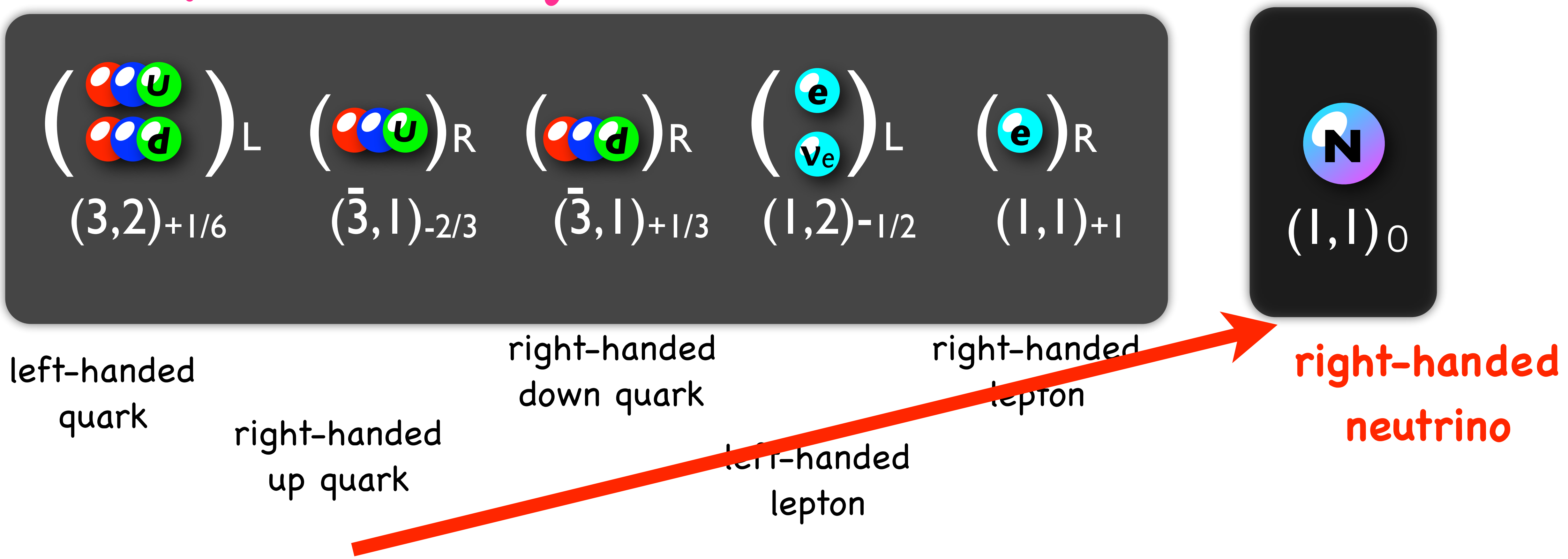
masses of quarks and leptons



・・・why neutrino masses are so small??

The right-handed neutrino plays a triple role.

② explains tiny neutrino mass



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

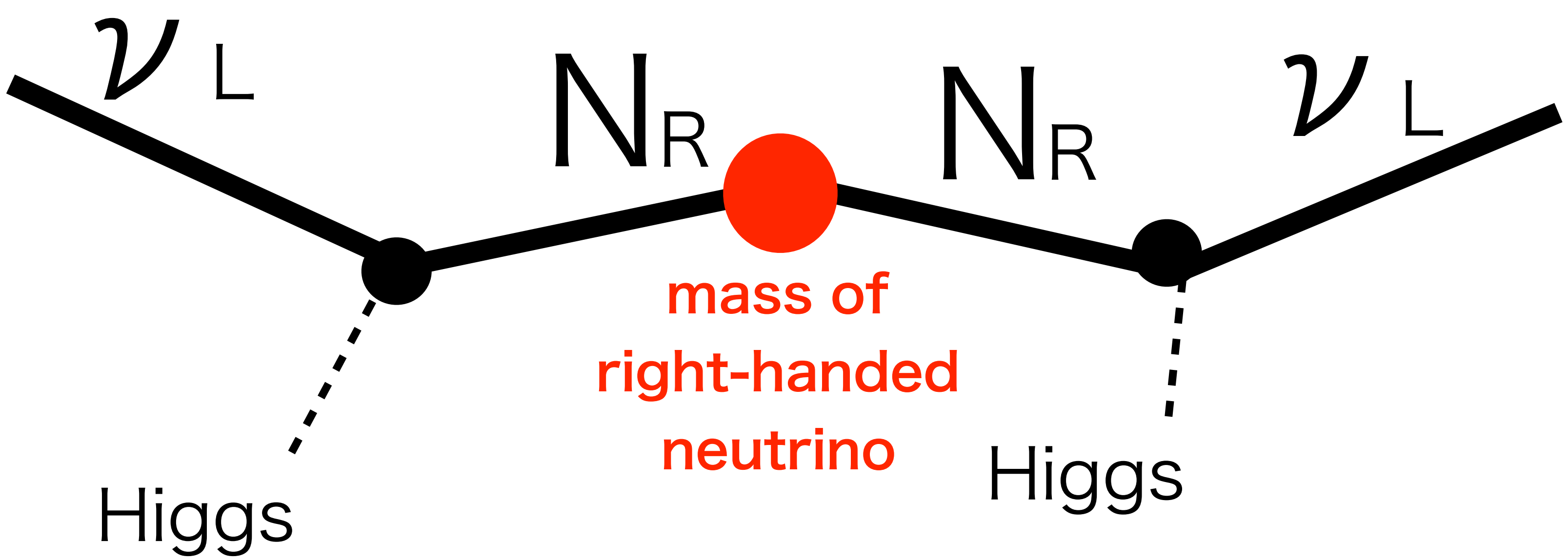
→ it has no charge.

→ it can be its own anti-particle.

→ it can have a mass without Higgs.

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

② explains **tiny** neutrino mass



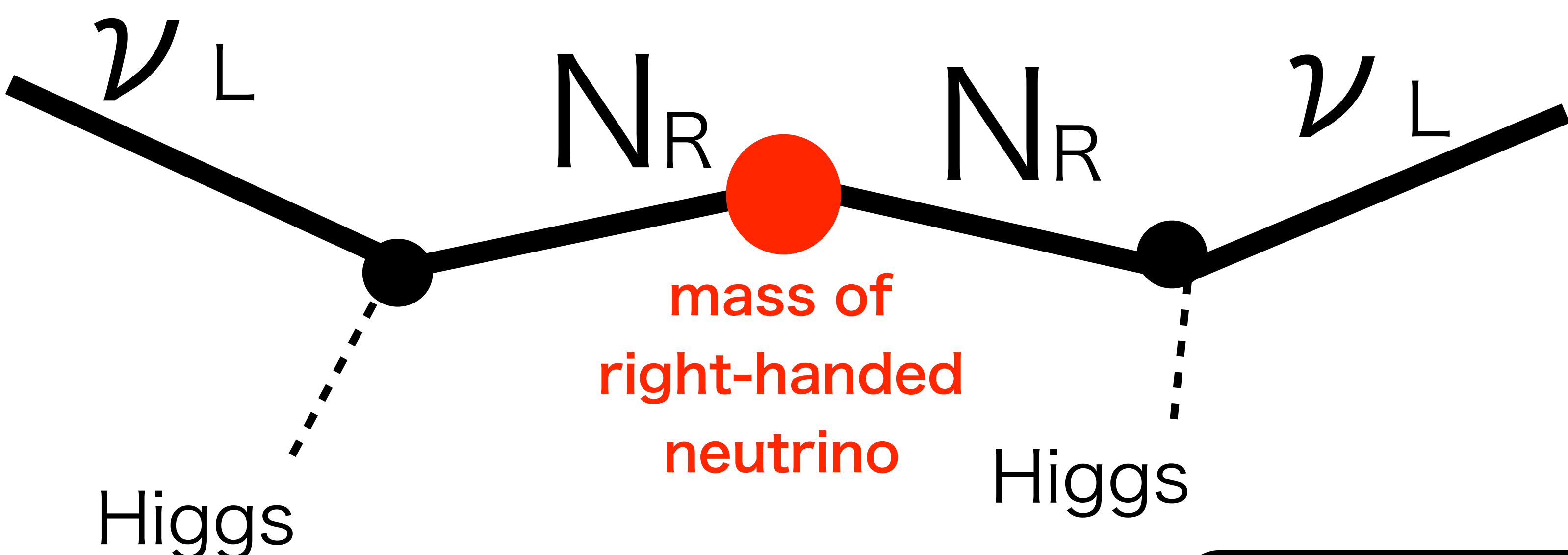
$$\text{Neutrino mass} = \frac{(\sim \text{other quark/lepton mass})\text{^}2}{\text{mass of right-handed neutrino}}$$

(seen e.g., by oscillation exp.)

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

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

② explains **tiny** neutrino mass



e.g. (100 GeV)^2

$$\text{Neutrino mass} = \frac{(\sim \text{other quark/lepton mass})\hat{}2}{\text{mass of right-handed neutrino}}$$

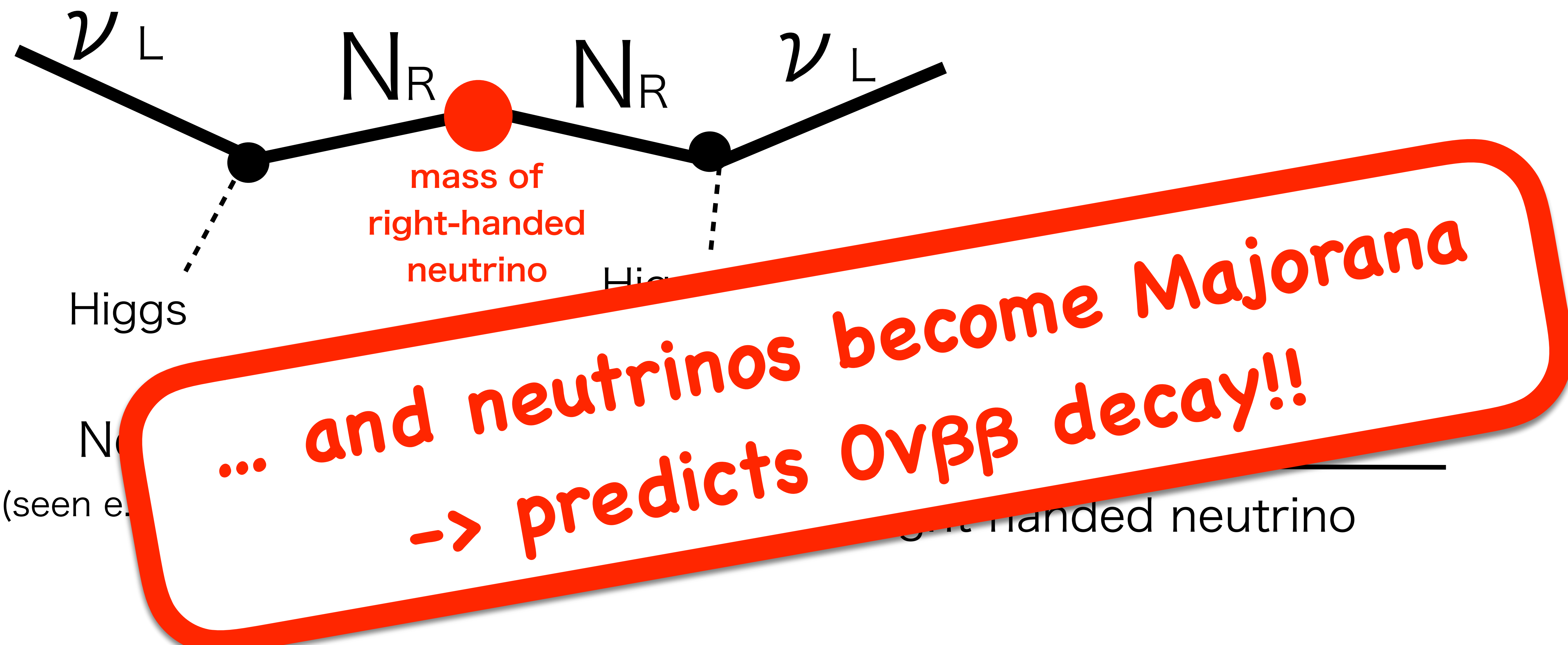
0.01 eV

e.g. 10^{15} GeV

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

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

② explains **tiny** neutrino mass



heavy R.H. $\nu \rightarrow$ small neutrino masses ("see-saw mechanism")

The right-handed neutrino 

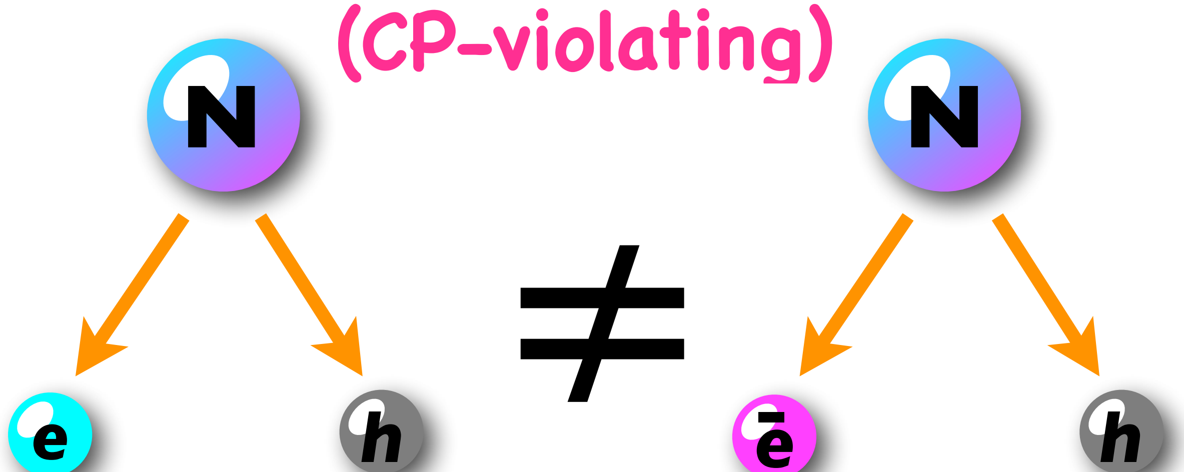
plays a **triple role.**

③ explains matter > anti-matter

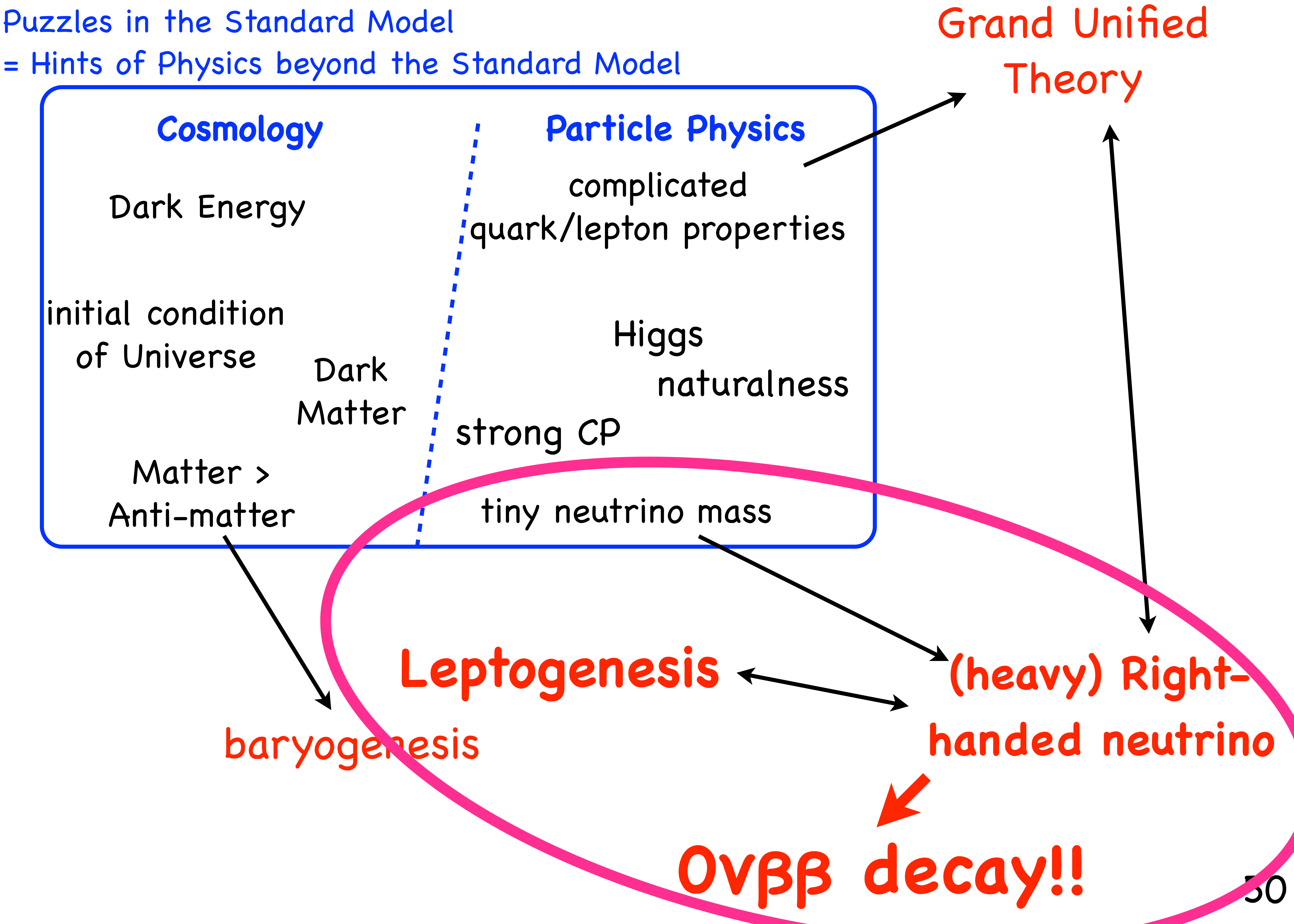
asymmetry of the universe.

-----> Leptogenesis !!

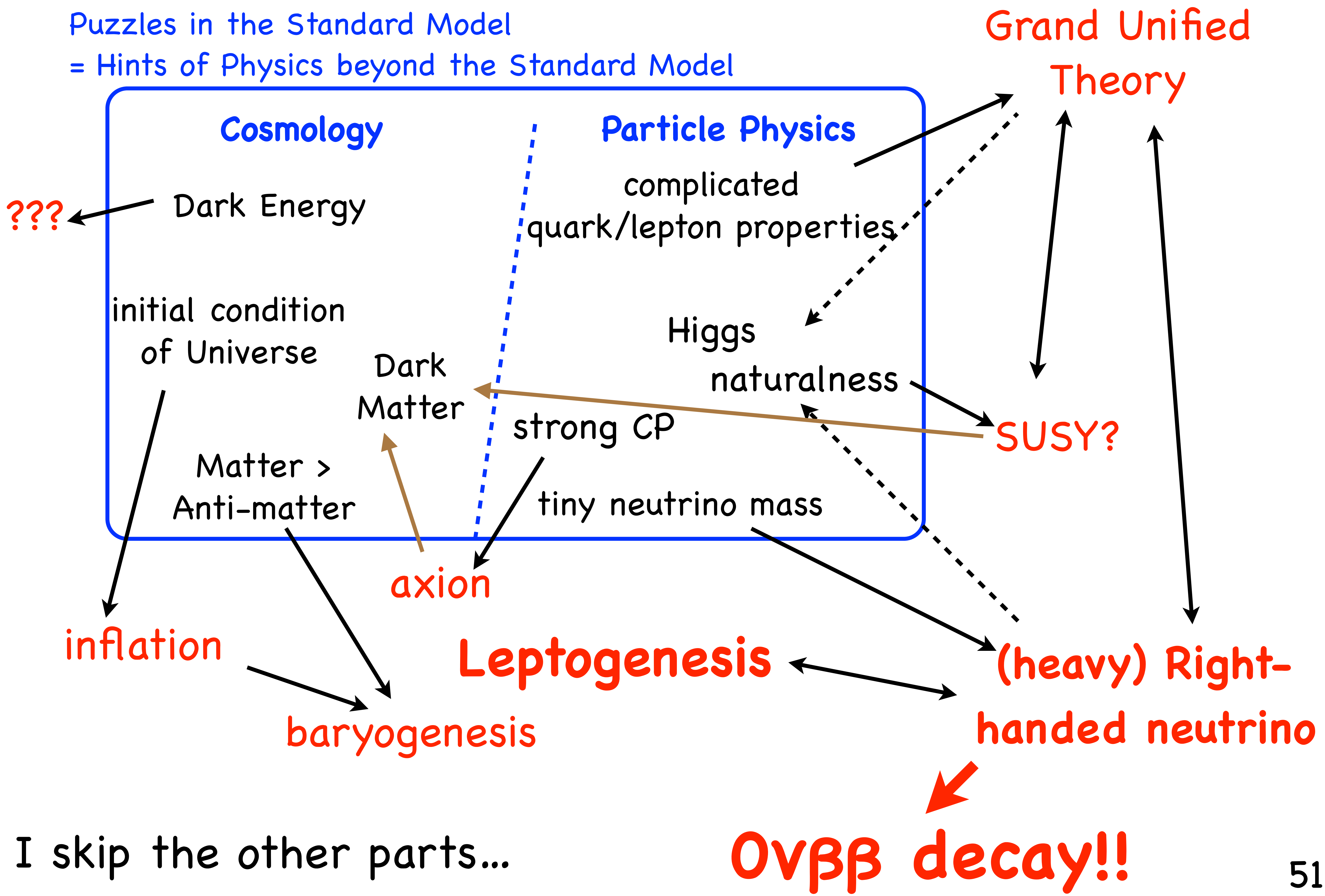
right-handed neutrino decay
(CP-violating)



Seesaw and Leptogenesis in a ``big picture"



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"
- Leptogenesis and 0νββ decay
- gauged U(1) $\mu - \tau$
- Summary

What if $0\nu\beta\beta$ decay is discovered ??

What if $0\nu\beta\beta$ decay is discovered ??

→ • Majorana neutrino !!

• Lepton number violation !!

→ Strong support for

Seesaw and Leptogenesis !!

But,... any <u>quantitative</u> information about high energy theory ?

What if 0νββ decay is discovered ??

The same Lagrangian.

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

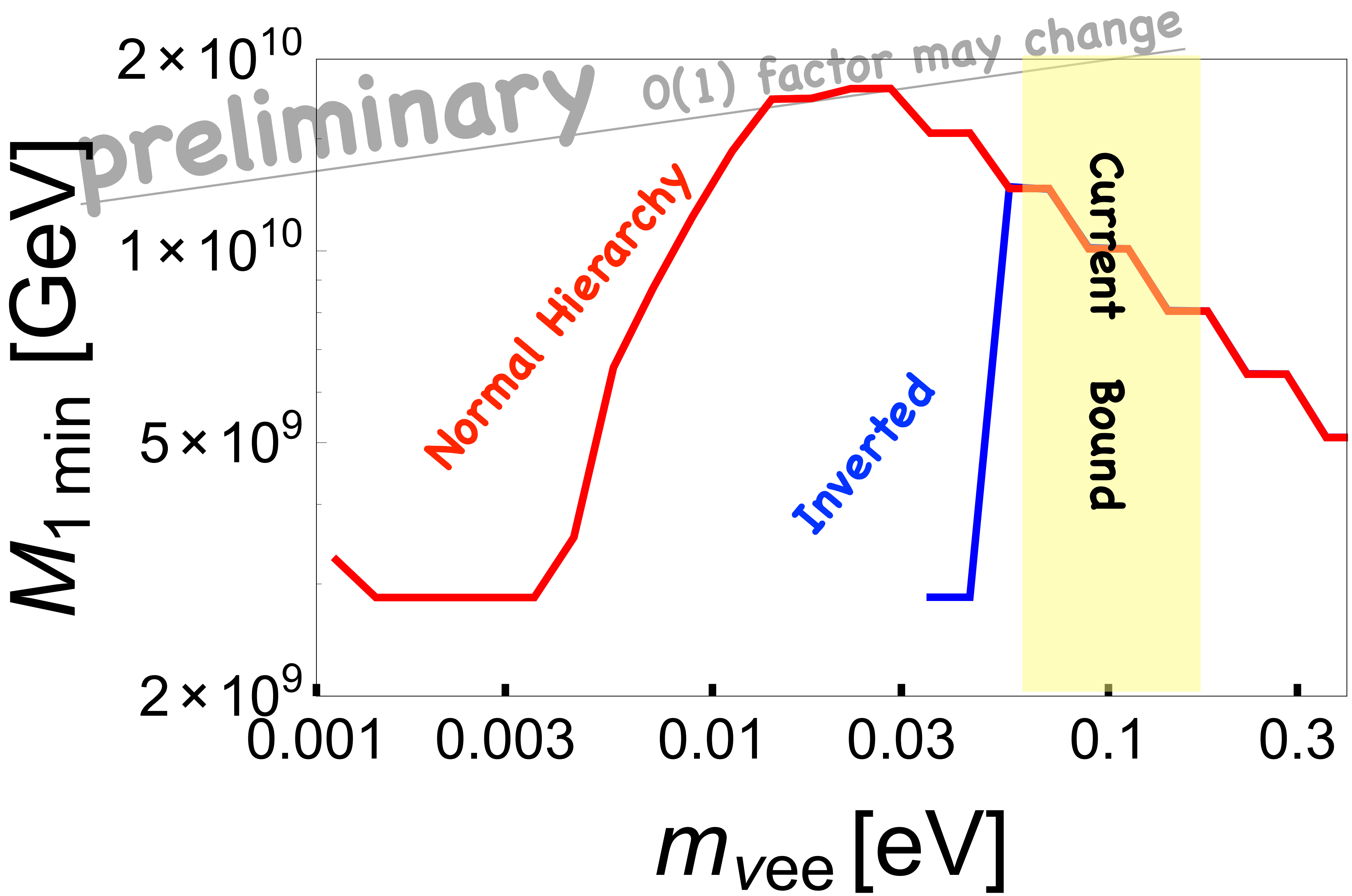
Leptogenesis

$m_{\nu ee}$

0νββ decay

Can one obtain any information ?

What if 0νββ decay is discovered ??



K.Hamaguchi, K.Shimada, in preparation.

(Assuming $M_1 \ll M_{2,3}$. With **flavor effect**. Neglecting scattering and spectator effects for simplicity.)

Depending on m_{vee}, stronger lower bound on M_1 (R.H.ν mass) can be obtained! than Davidson-Ibarra bound

Plan

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Predictions for the neutrino parameters

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

K. Asai, K. Hamaguchi, N. Nagata,

[arXiv:1705.00419] Eur.Phys.J. C77 (2017) 763

heavy RHν

$$\underbrace{U^\dagger_{\rm PMNS}\begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} U^*_{\rm PMNS}}_{\text{low energy}} = \underbrace{\begin{pmatrix} m_{\nu ee} & m_{\nu e\mu} & m_{\nu e\tau} \\ m_{\nu\mu e} & m_{\nu\mu\mu} & m_{\nu\mu\tau} \\ m_{\nu\tau e} & m_{\nu\tau\mu} & m_{\nu\tau\tau} \end{pmatrix}}_{m_\nu} = -\underbrace{\mathcal{M}_D^T \mathcal{M}_R^{-1} \mathcal{M}_D}_{\text{high energy}}$$

Take inverse

$$U_{\rm PMNS}\begin{pmatrix} m_1^{-1} & & \\ & m_2^{-1} & \\ & & m_3^{-1} \end{pmatrix} U^T_{\rm PMNS} = m_\nu^{-1} = -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1}$$

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heavy RHν ($\mathcal{M}_R$)

Take inverse

With gauged $U(1)_{\mu-\tau}$ ...

$$U_{\rm PMNS}\begin{pmatrix} m_1^{-1} & & \\ & m_2^{-1} & \\ & & m_3^{-1} \end{pmatrix} U^T_{\rm PMNS} = m_\nu^{-1} = -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1}$$

$$\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix} \quad \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix} \quad \begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}$$

diagonal — two zeros

$$\Rightarrow \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

→ <u>predictions for low-E neutrino parameters</u>

Predictions for the neutrino parameters in the minimal gauged $U(1)_{\mu-\tau}$ model.

K. Asai, K. Hamaguchi, N. Nagata,

$U_{\rm PMNS}^{\dagger} \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m \end{pmatrix}$

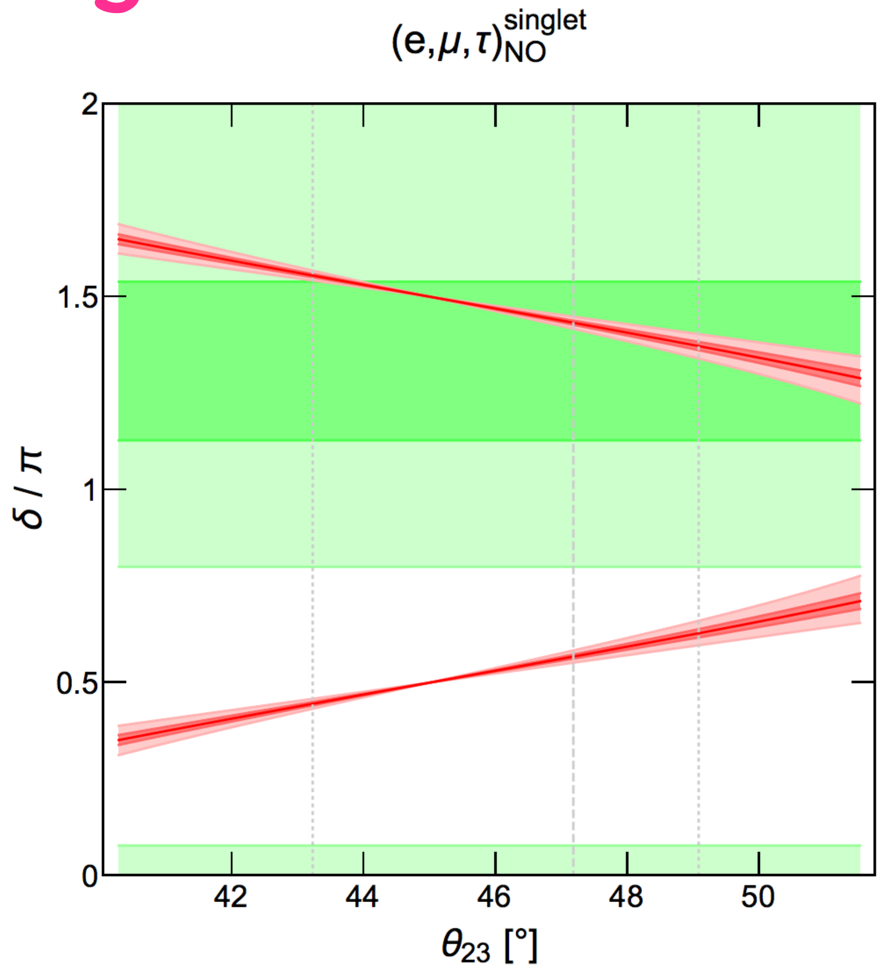
low energy

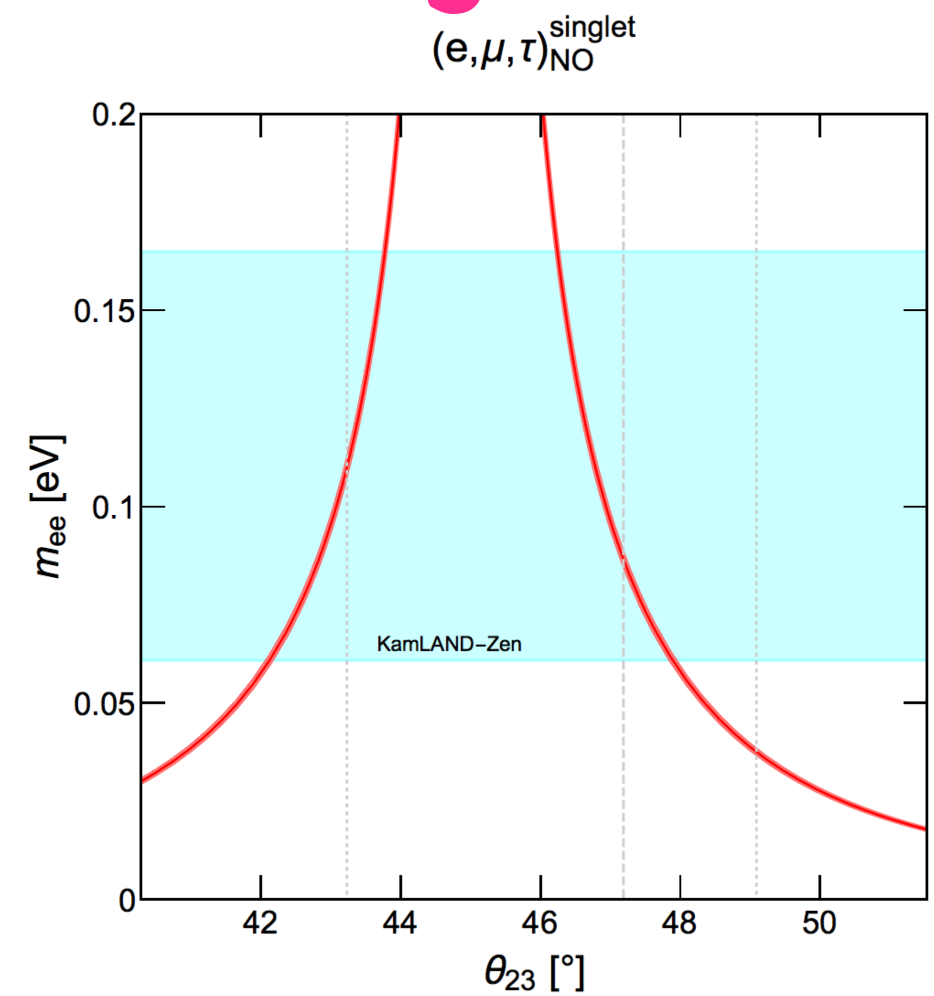
Take inverse

$U_{\rm PMNS} \begin{pmatrix} m_1^{-1} & & \\ & m_2^{-1} & \\ & & \end{pmatrix}$

$$\begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

e.g., Dirac CP … and large $m_{\nu ee}$!!





K. Asai, KH, N. Nagata, '17, revised with new data.

But,… it also predicts $\sum_i m_{\nu i} \gtrsim 0.12$ eV

in tension with the latest Planck data….

(We are working on other extensions.)

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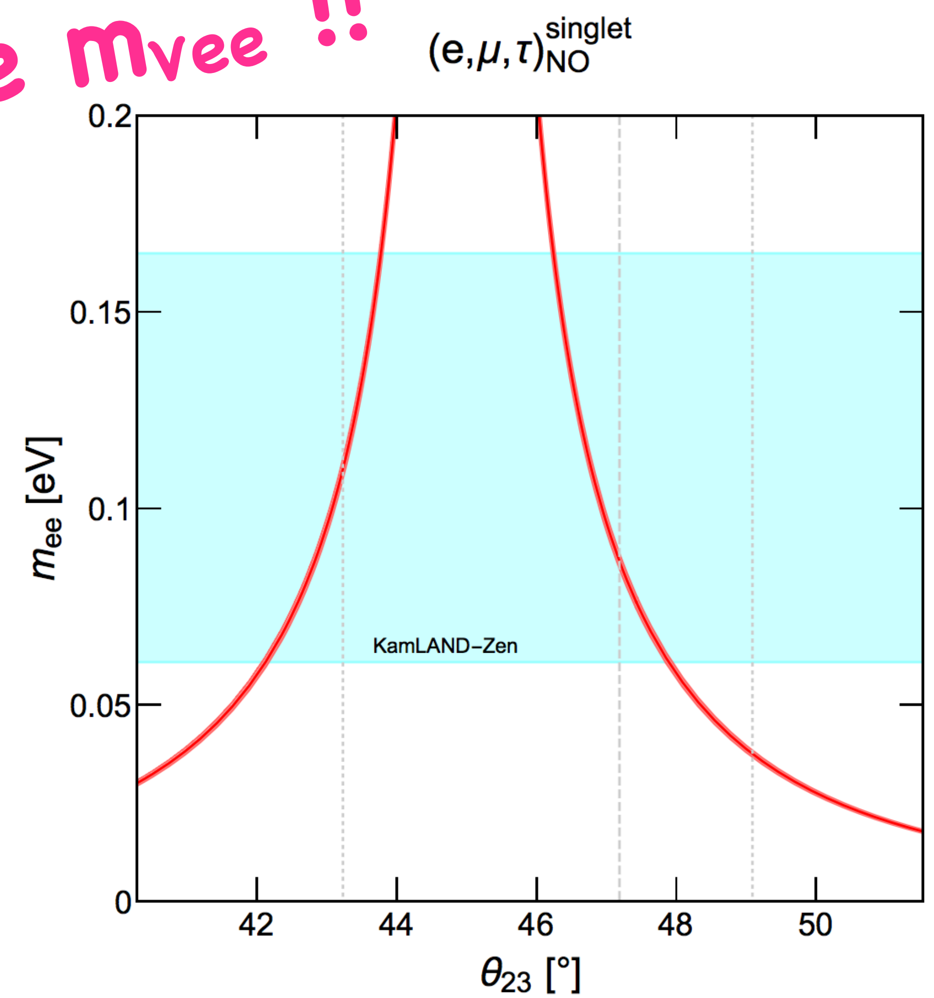
$$\begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

predictio

large mvee !!



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But,... it also predicts

$$\sum_i m_{\nu i} \gtrsim 0.12 \text{ eV}$$

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(We are working on other extensions.)

Summary

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

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

  (2). Small neutrino masses. (seesaw)

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

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

- Discovery of $0\nu\beta\beta$ decay will strongly support this ``big picture''.

- $0\nu\beta\beta$ decay may also give a quantitative implication for leptogenesis (e.g., RHν mass).

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

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

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

- C and CP violation

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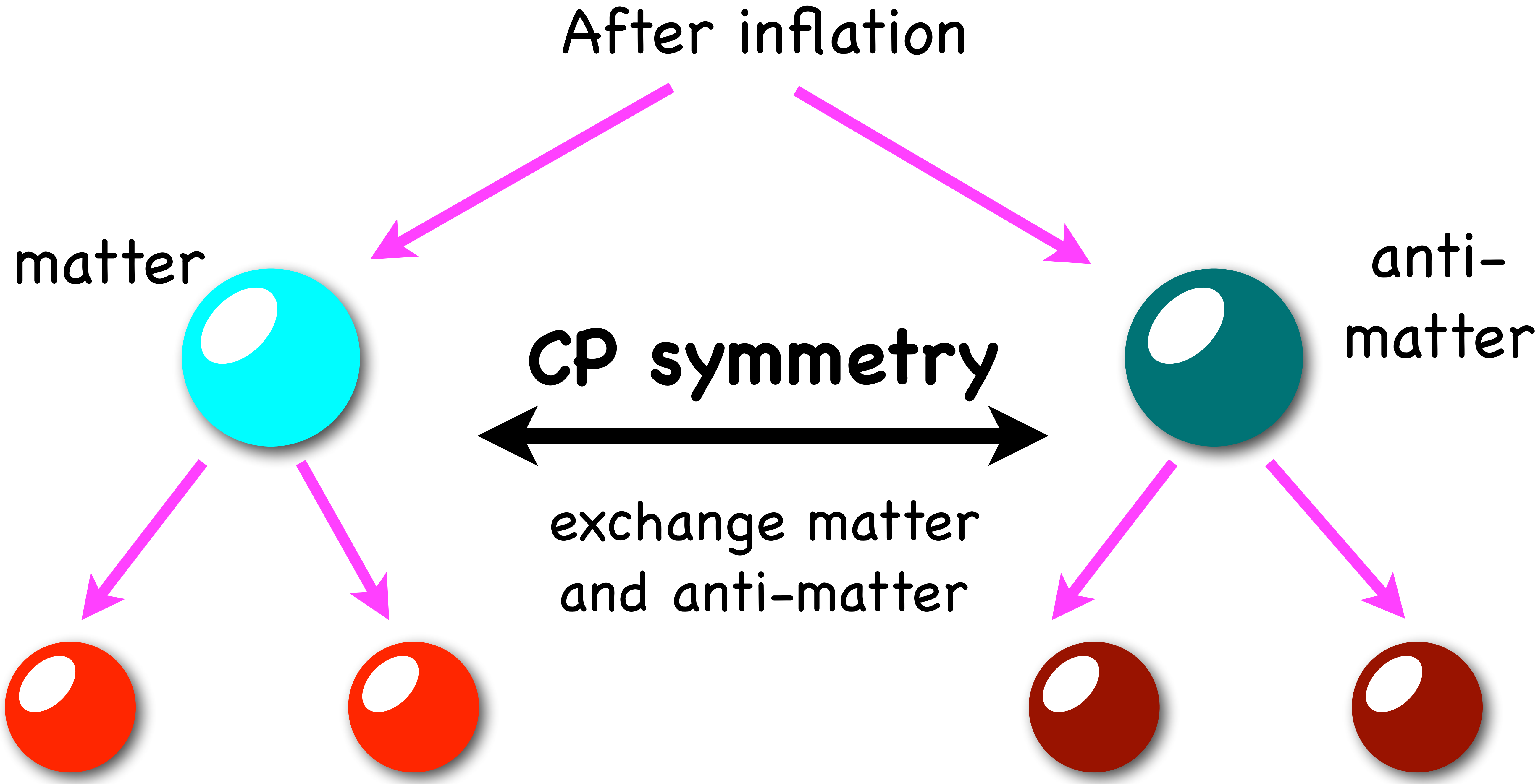
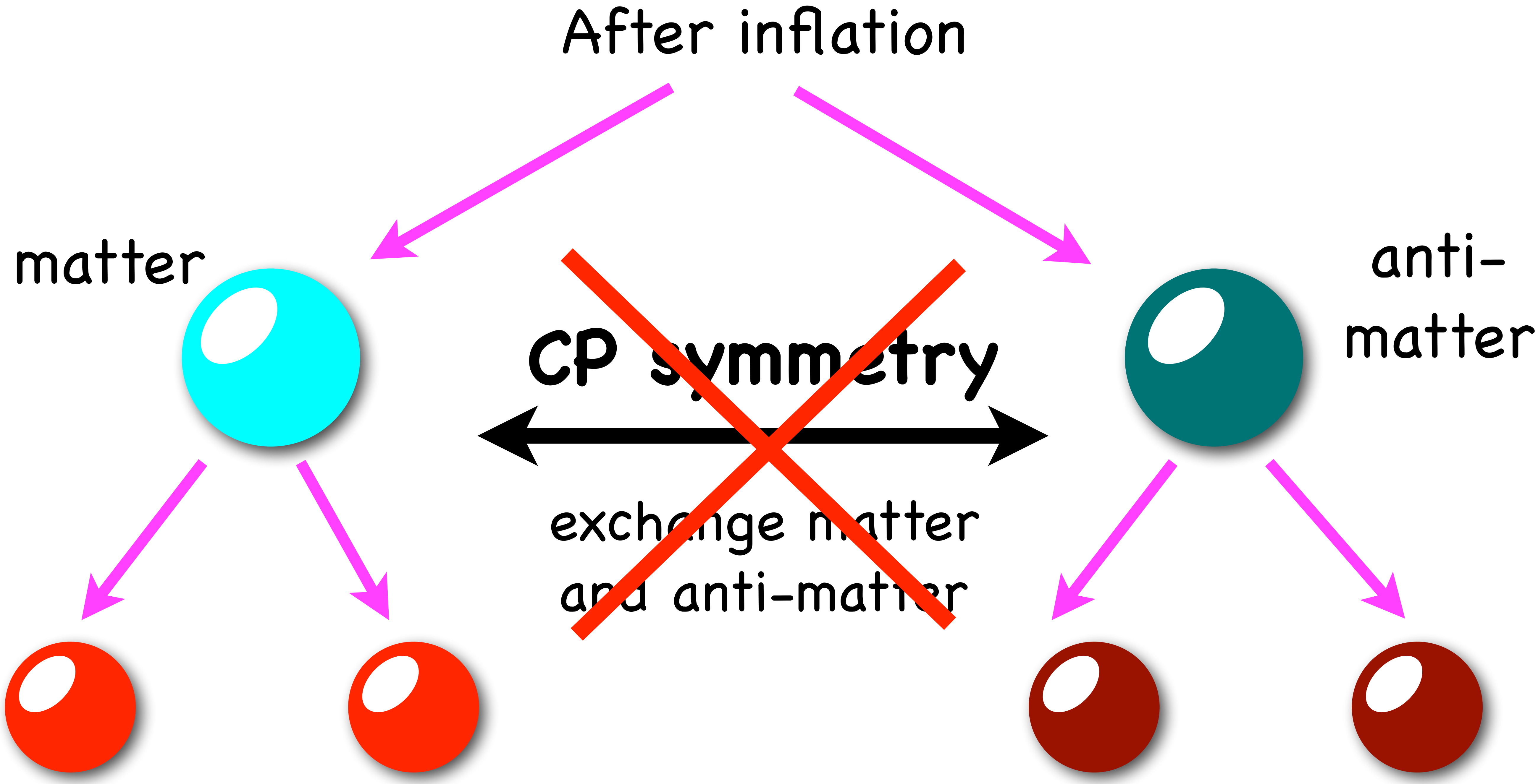
  If all processes conserve CP, then impossible to have $n_B = 0 \rightarrow n_B \neq 0$.

- Out-of-equilibrium



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.

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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 $n_B = 0 \underset{\longleftarrow}{\longrightarrow} n_B > 0$.

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 → T ; RH ν's mass → M_R

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

Leptogenesis

[Fukugita, Yanagida,1986]

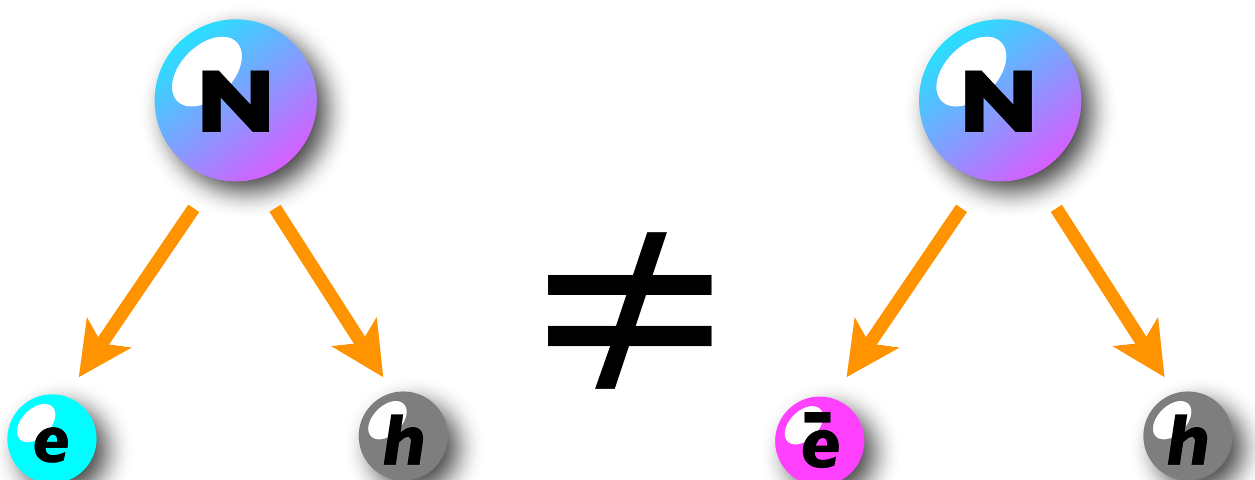
scenario

temperature → T, RH ν's mass → M_R

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, $\Delta L \neq 0$.



CP violation
is essential.

Leptogenesis

[Fukugita, Yanagida, 1986]

scenario

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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)

final baryon asymmetry

RH ν 's mass

heaviest neutrino mass ($\sim$ atmospheric)

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

wash-out factor (< 1)
(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

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

Leptogenesis

[Fukugita, Yanagida,1986]

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effective CP violating phase

↕

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

[PDG, 2012]

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

$m_{\nu ee} \rightarrow M_1$ bound

Why $m_{\nu ee} \rightarrow M_1$ bound ?

(For illustration, let's first consider normal hierarchy, unflavored case.)

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

In Leptogenesis (unflavored case),...

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final baryon asymmetry

RH ν 's mass

heaviest neutrino mass ($\gtrsim \sqrt{\Delta m^2_{\text{atm.}}}$)

effective CP violating phase

$\delta_{\text{eff}} < 1$

KH, Murayama, Yanagida, '01
Davidson, Ibarra, '02

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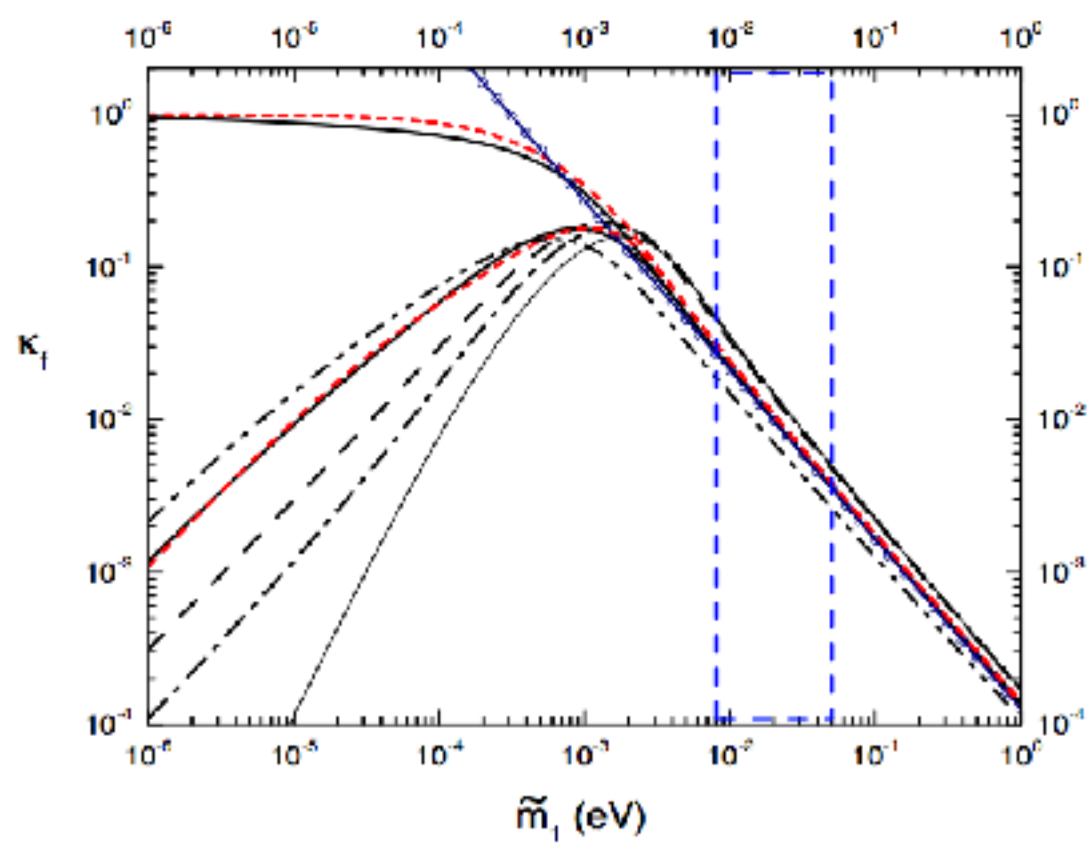
efficiency factor κ



[Buchmuller Di Bari Plumacher, '04]

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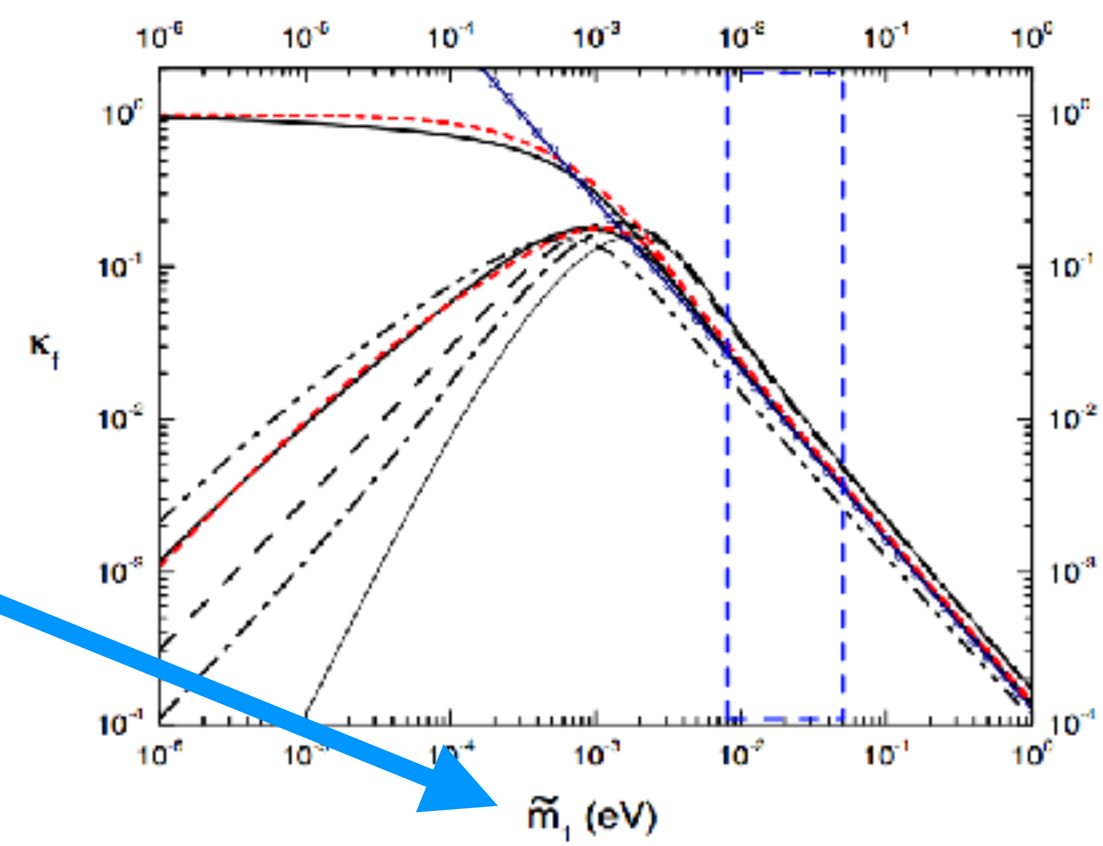

[Buchmuller Di Bari Plumacher, '04]

$$\widetilde{m_1} \equiv \sum_{\alpha=e,\mu,\tau} \frac{y_{1\alpha} y_{1\alpha}^{\dagger}}{M_1} \langle H \rangle^2$$

Determines the efficiency of Leptogenesis.

(corresponds to R.H.ν's interaction strength.)

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Roughly,...

$$\delta_{\text{eff}} < 1$$

$$\kappa \cdot M_1 > \text{const}$$

$$M_1 > (\text{const}) \cdot \frac{1}{\kappa}$$

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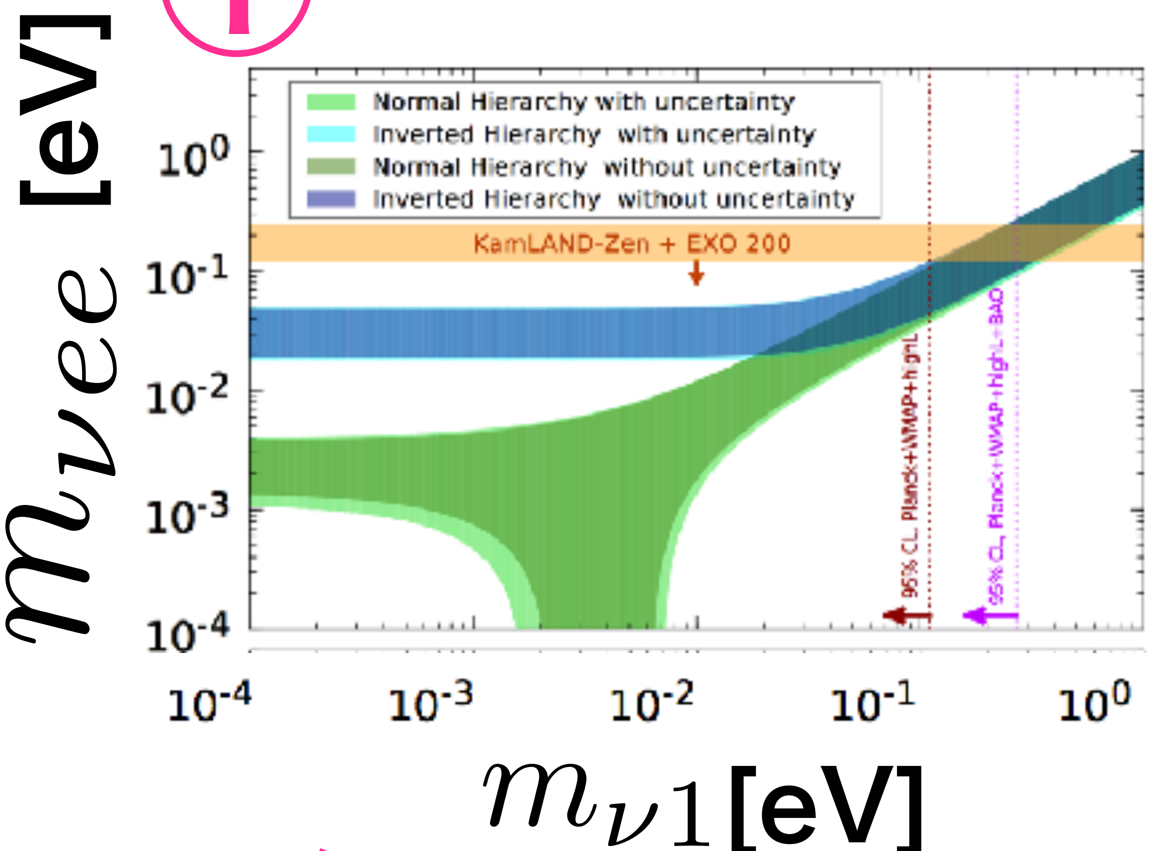
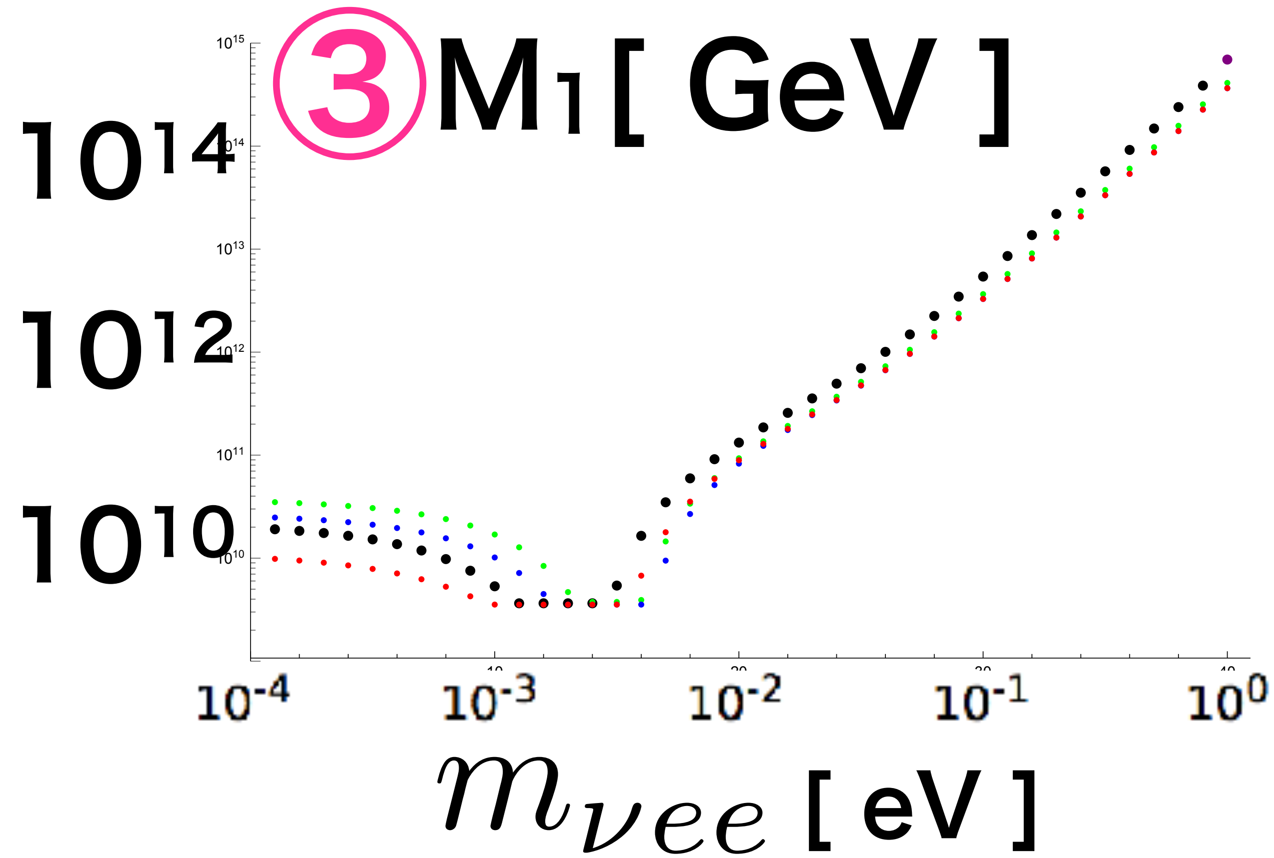
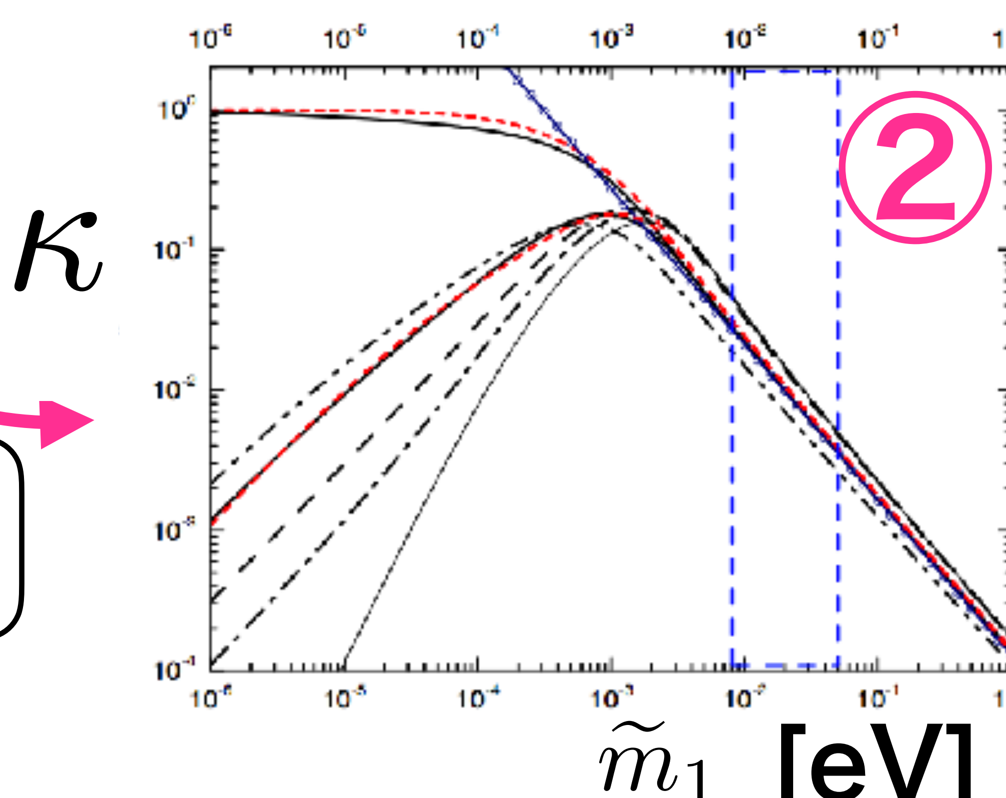
(For illustration, let's first consider normal hierarchy, unflavored case.)

①







$$\widetilde{m}_1 \geq m_{\nu 1}$$

Fujii, KH, Yanagida, '02

Roughly,...

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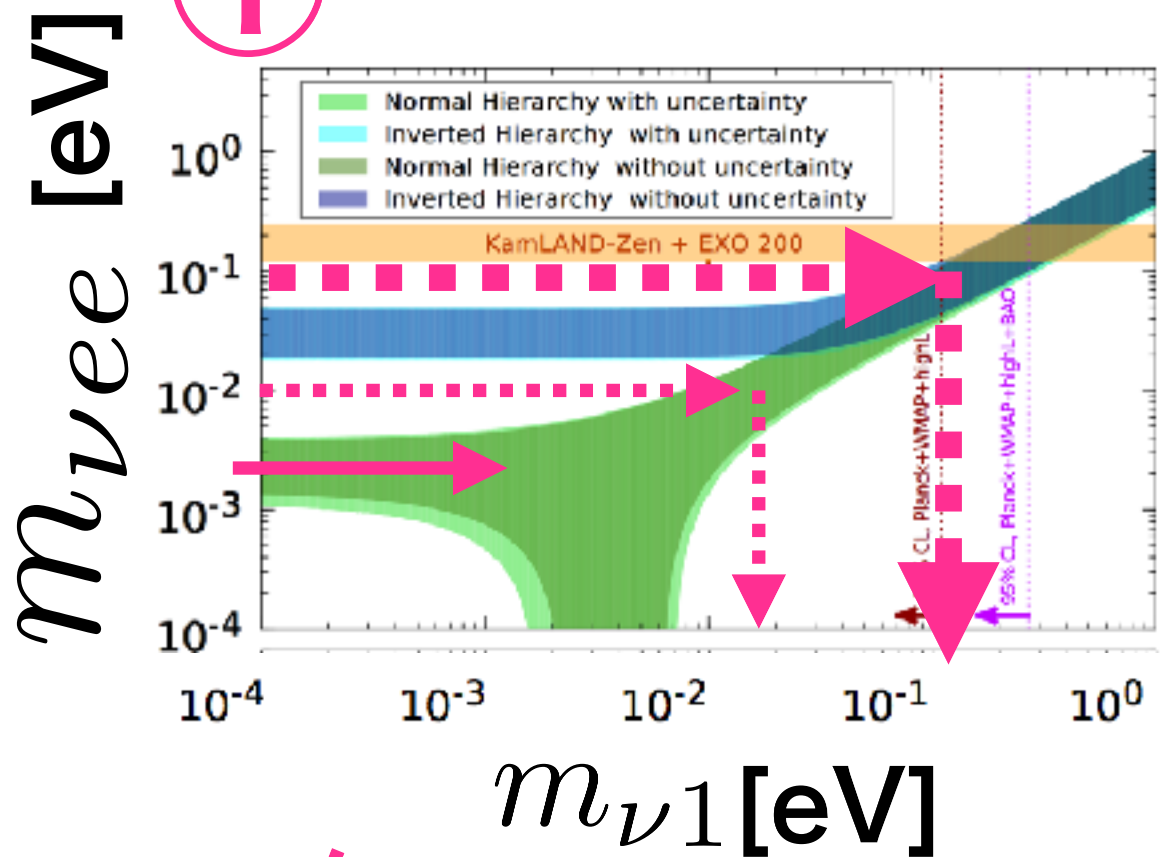
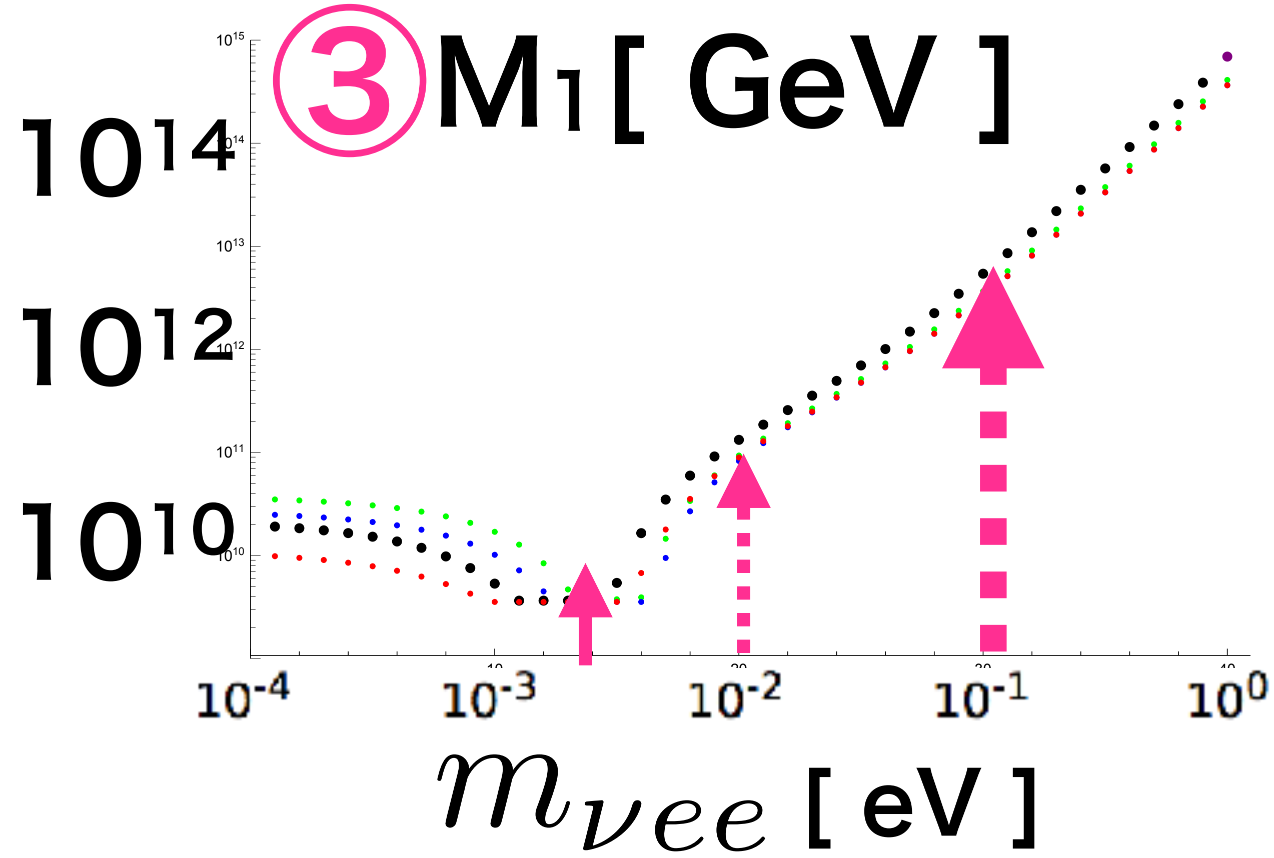


③



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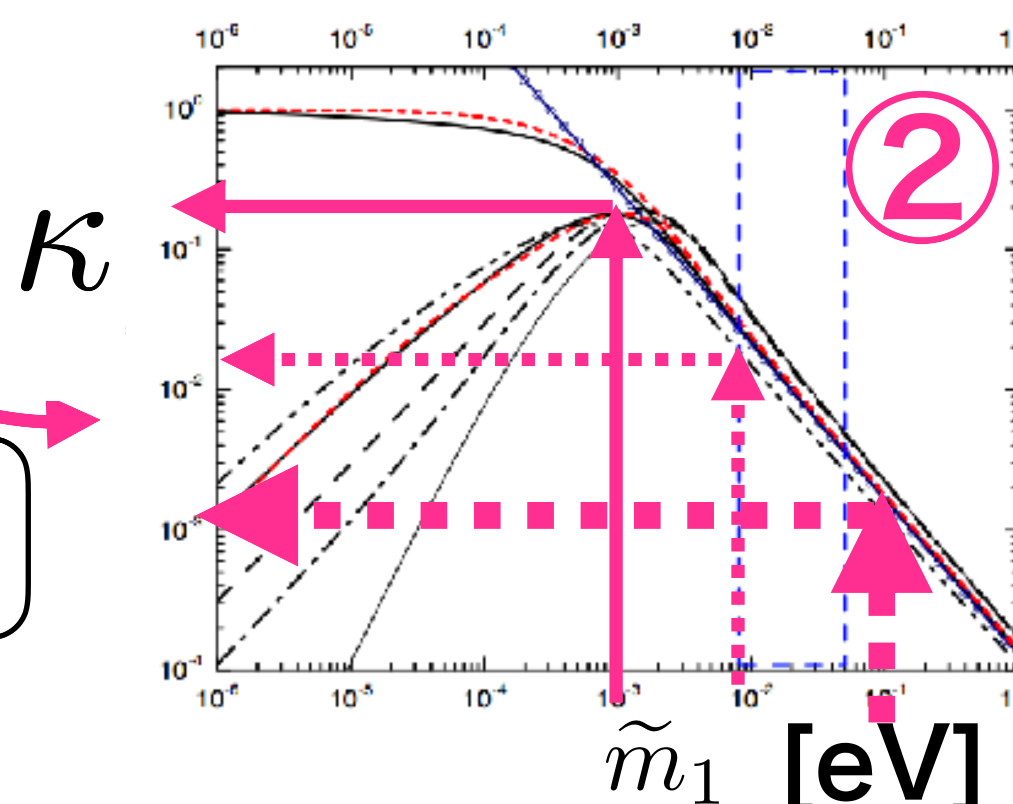

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Abada, Davidson, Josse-Michaux, Losada, Riotto, '06
Nardi, Nir, Roulet, Racker, '06
Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto, '06

With **Flavor effects**,
the analysis becomes much more complicated.

For T < 10^{12}GeV, τ-Yukawa is in eq. —> 2 distinguishable flavors
(μ-Yukawa is in eq. for T < 10^{9}GeV.)

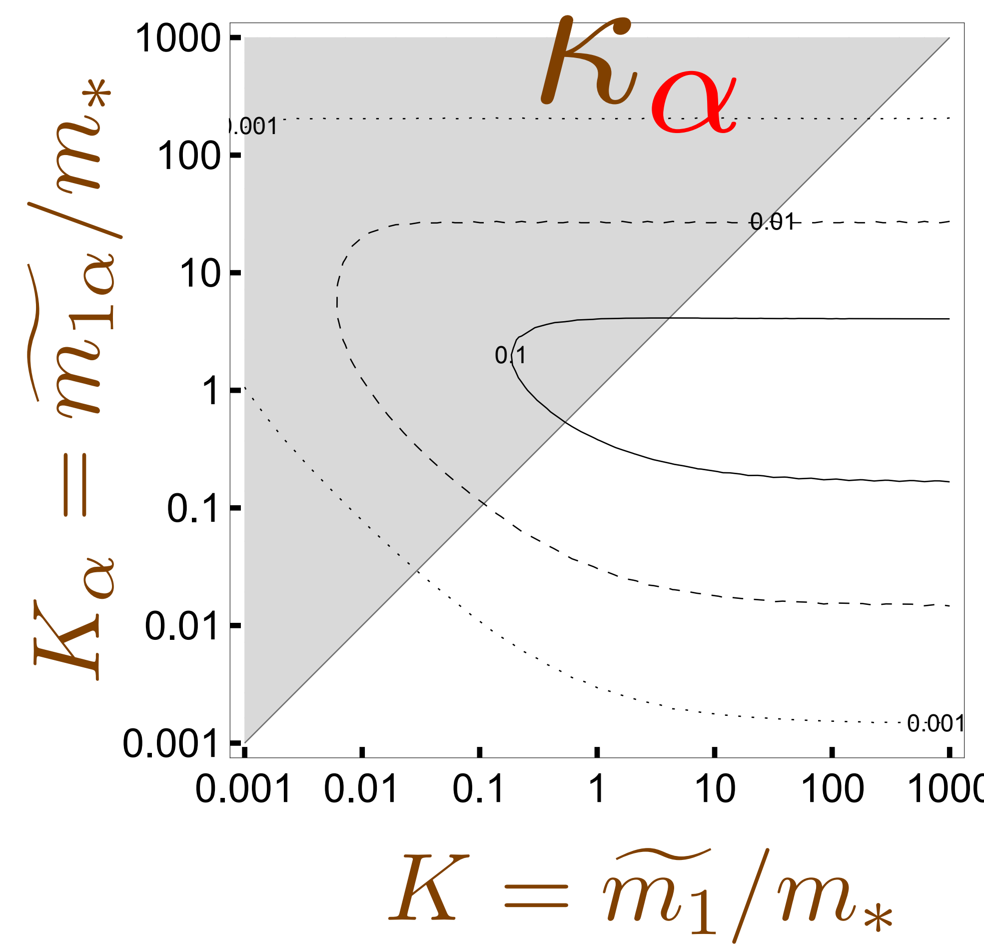
$$\frac{n_B}{s} = (\text{const.}) \cdot \kappa \cdot \epsilon \quad (\text{without flavor effect})$$

$$\Longrightarrow \frac{n_B}{s} \simeq (\text{const.}) \cdot \sum_{\alpha=\tau, e+\mu} \kappa_\alpha \cdot \epsilon_\alpha \quad (\text{with flavor effect})$$

(Here, the spectator effect neglected, for simplicity.)

$$\left(\sum_\alpha \kappa_\alpha = \kappa, \quad \sum_\alpha \epsilon_\alpha = \epsilon \right)$$

Technically, we have numerically maximized the nB/s with respect to the components in Casas-Ibarra orthogonal matrix R
(for each given Majorana and Dirac phases, which leads to fixed $m_{\nu ee}$.)



This figure is calculated by using the formula in Blanchet, Di Bari '06, neglecting the scattering, for simplicity.

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Abada, Davidson, Josse-Michaux, Losada, Riotto, '06
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K.Hamaguchi, K.Shimada, in preparation.
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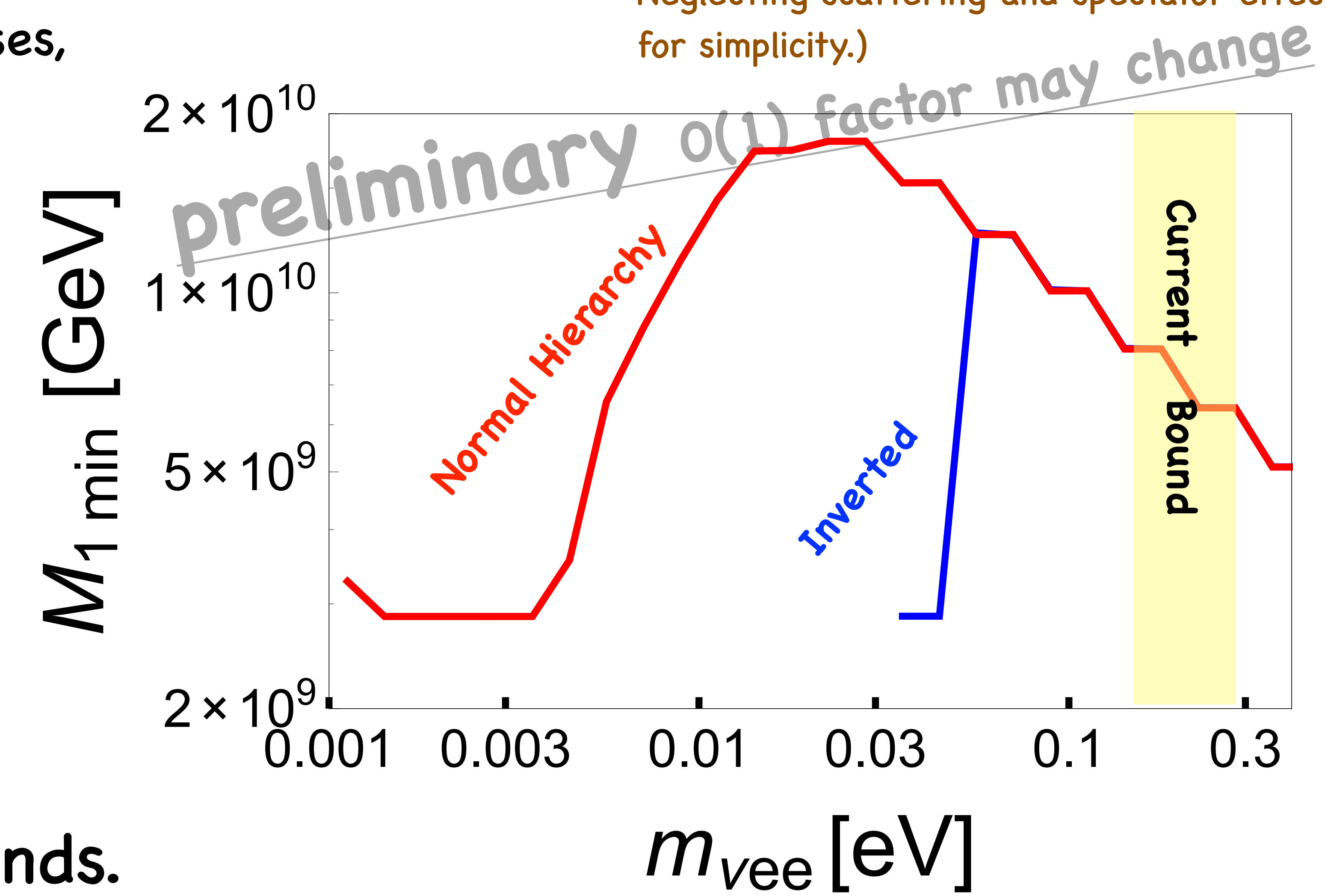

Weaker than the unflavored case, but still non-trivial bounds.