Beyond the Standard Model

Koichi Hamaguchi (University of Tokyo)

@22nd Vietnam School of Physics (VSOP 22)
September 2016.

The purpose of this lecture is:

to introduce some of

Motivations for BSM physics

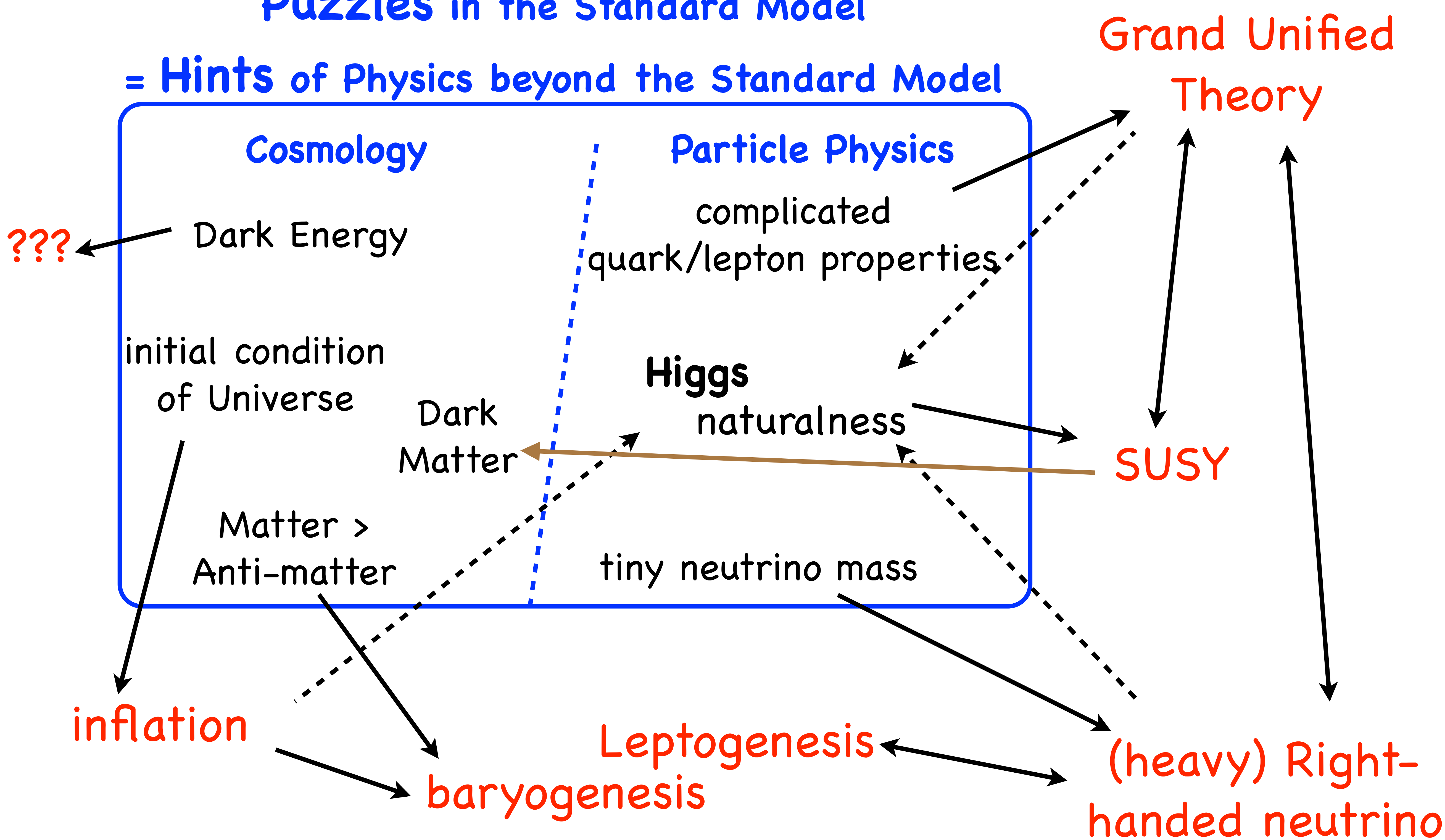
and

Candidates for BSM physics.

(NOTE: biased!)

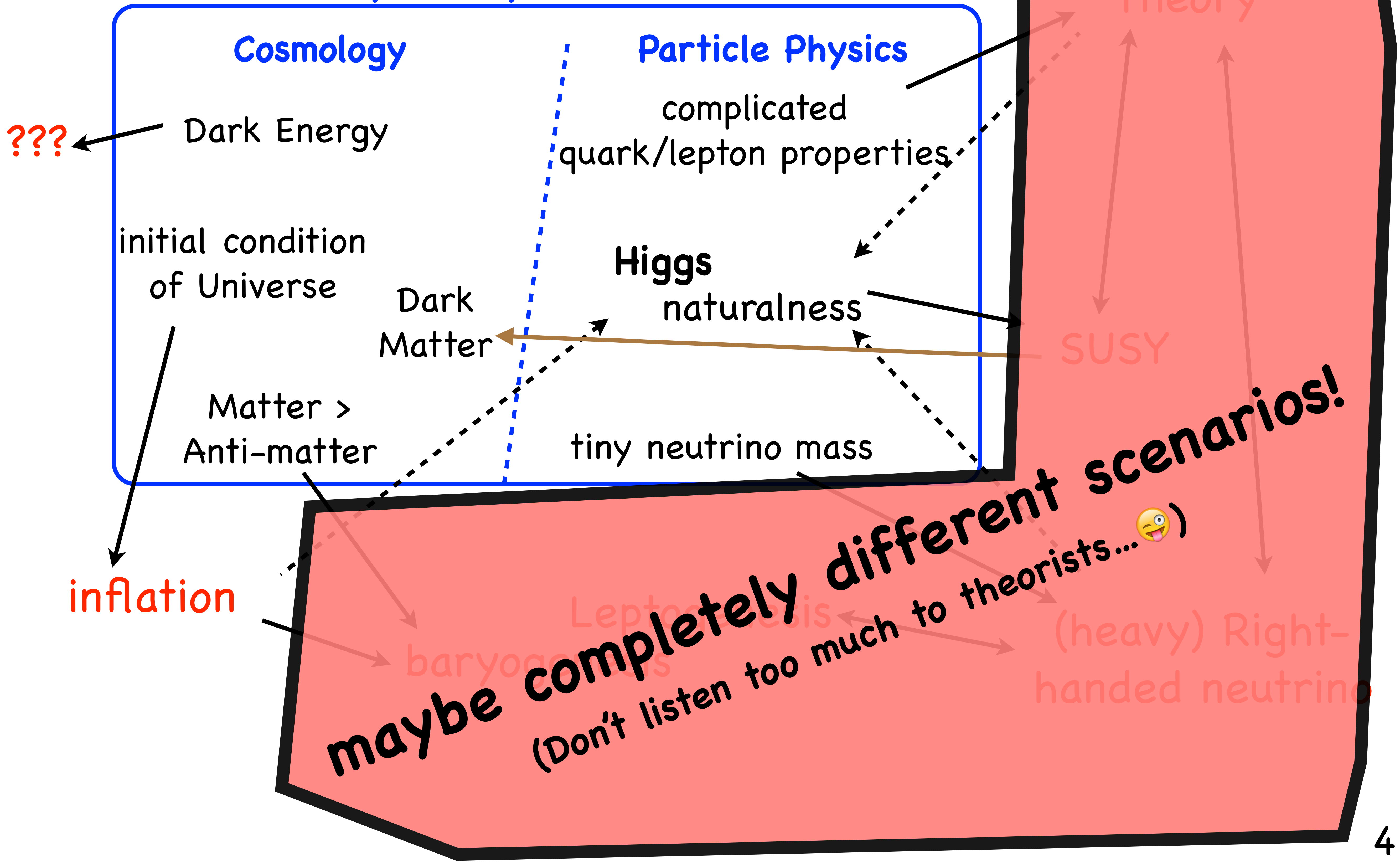
Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



comment:

perturbative 4d QFT up to high scale?

YES

▷ compatible with

- perturbative GUT,
- seesaw and leptogenesis with heavy right-handed neutrino.

▷ cosmology can be discussed within perturbative QFT.
(inflation, baryogenesis,...)

this lecture

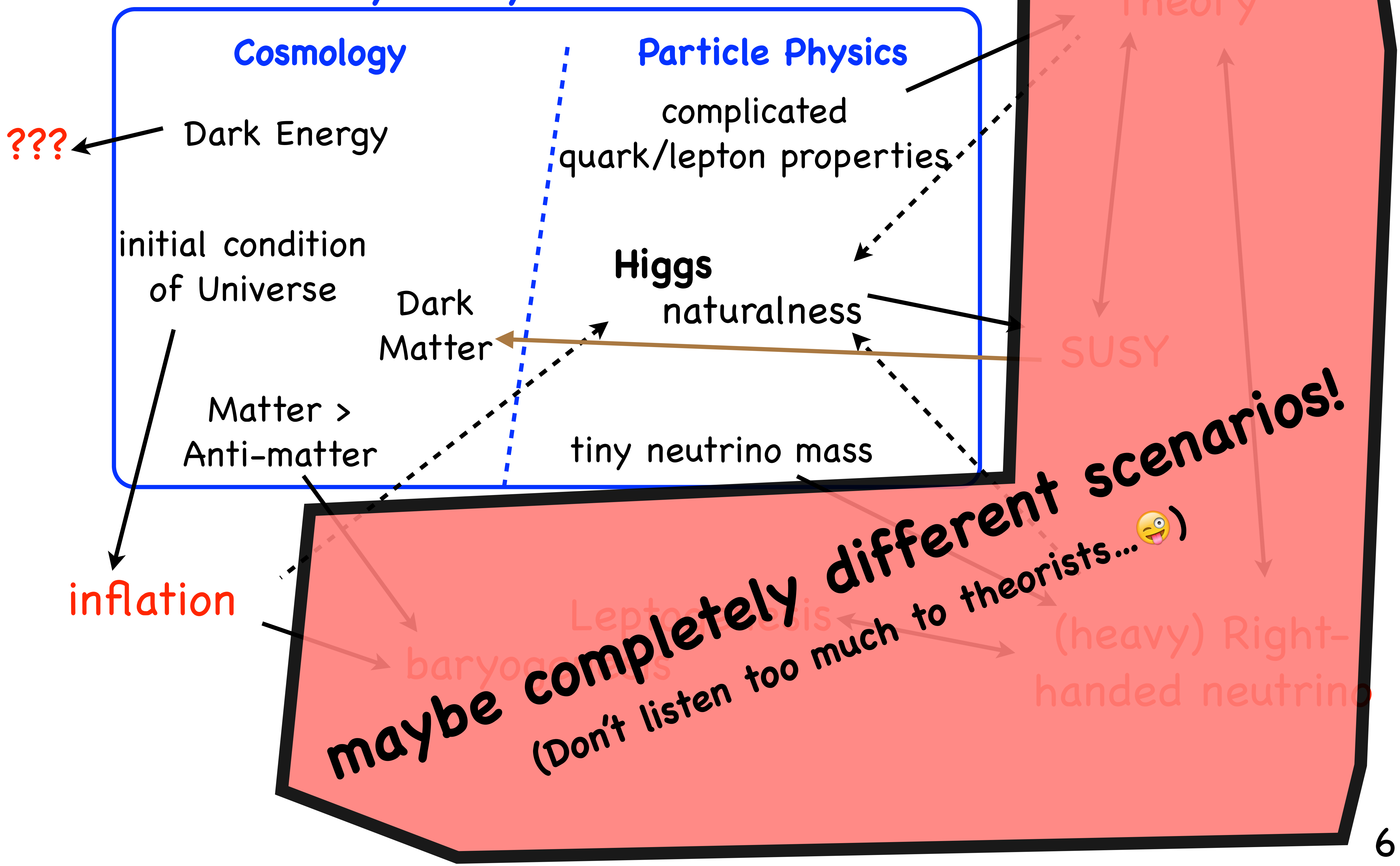
NO

example

- extra-dimension (large, warped,...)
- composite Higgs
- ......

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



CONTENTS

Part 1: [projector]

Overview of BSM physics

Part 3: [projector]

Supersymmetry

Part 2: **[blackboard]**

Mini-reviews on each topic,

2-A: GUT

2-B: Neutrino mass and seesaw

2-C: Standard Cosmology

2-D: Inflation

2-E: Leptogenesis

CONTENTS

Part 1: [projector]

Overview of BSM physics

(1～2 lectures)

Part 2: [blackboard]

Mini-reviews on each topic,

2-A: GUT

2-B: Neutrino mass and seesaw

2-C: Standard Cosmology

2-D: Inflation

2-E: Leptogenesis

(> 3 lectures)

Part 3: [projector]

Supersymmetry

(> 2 lectures)

Probably too much for 6 lectures.

-> Let's take a vote after Part 1.

CONTENTS

Part 1: [projector]

Overview of BSM physics

Part 2: [blackboard]

Mini-reviews on each topic,

2-A: GUT

2-B: Neutrino mass and seesaw

2-C: Standard Cosmology

2-D: Inflation

2-E: Leptogenesis

Part 3: [projector]

Supersymmetry

Please interrupt and ask questions at any time!

Any questions so far?

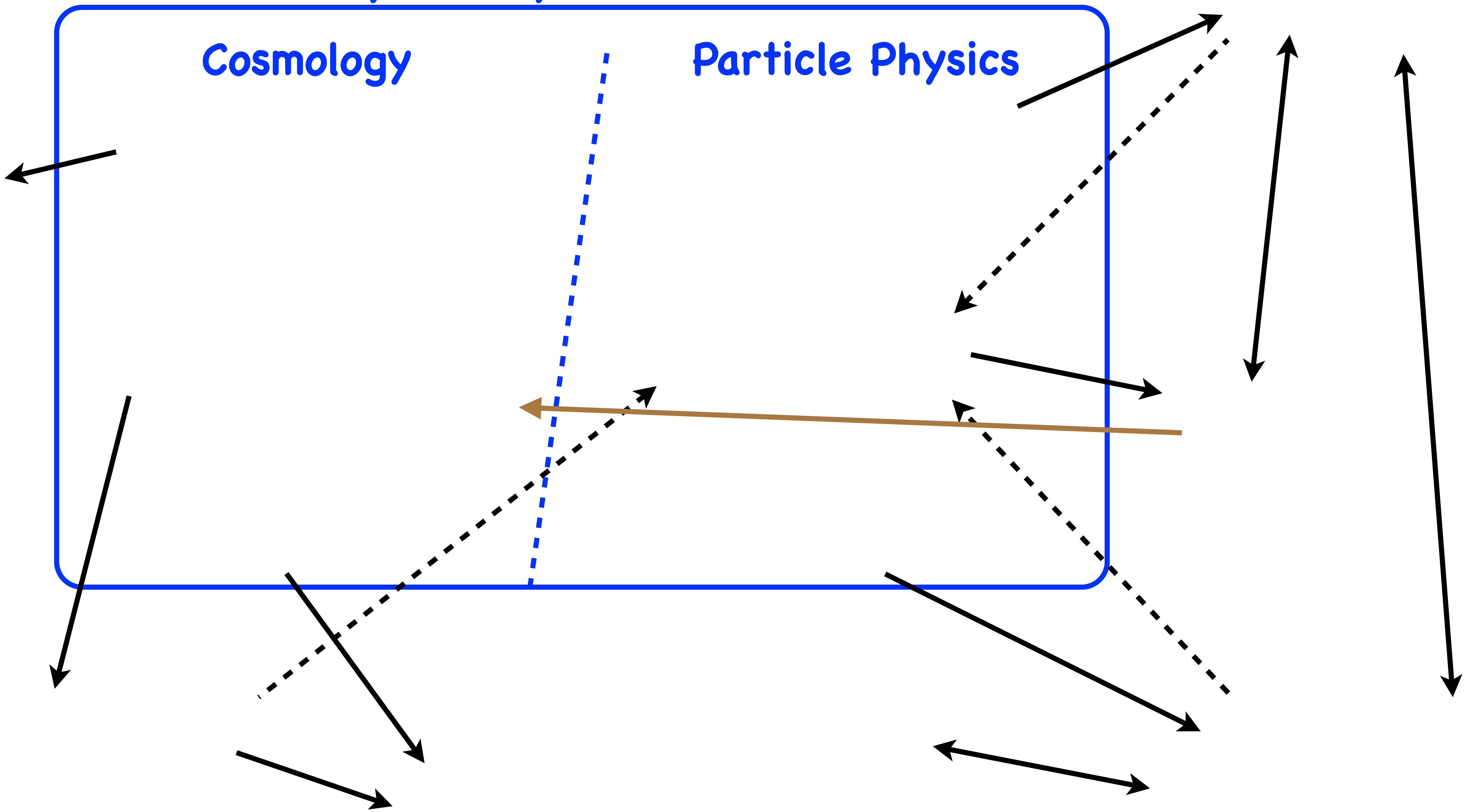
Part 1:

Overview of BSM physics

(NOTE: biased!)

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



Where shall we start...?

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model

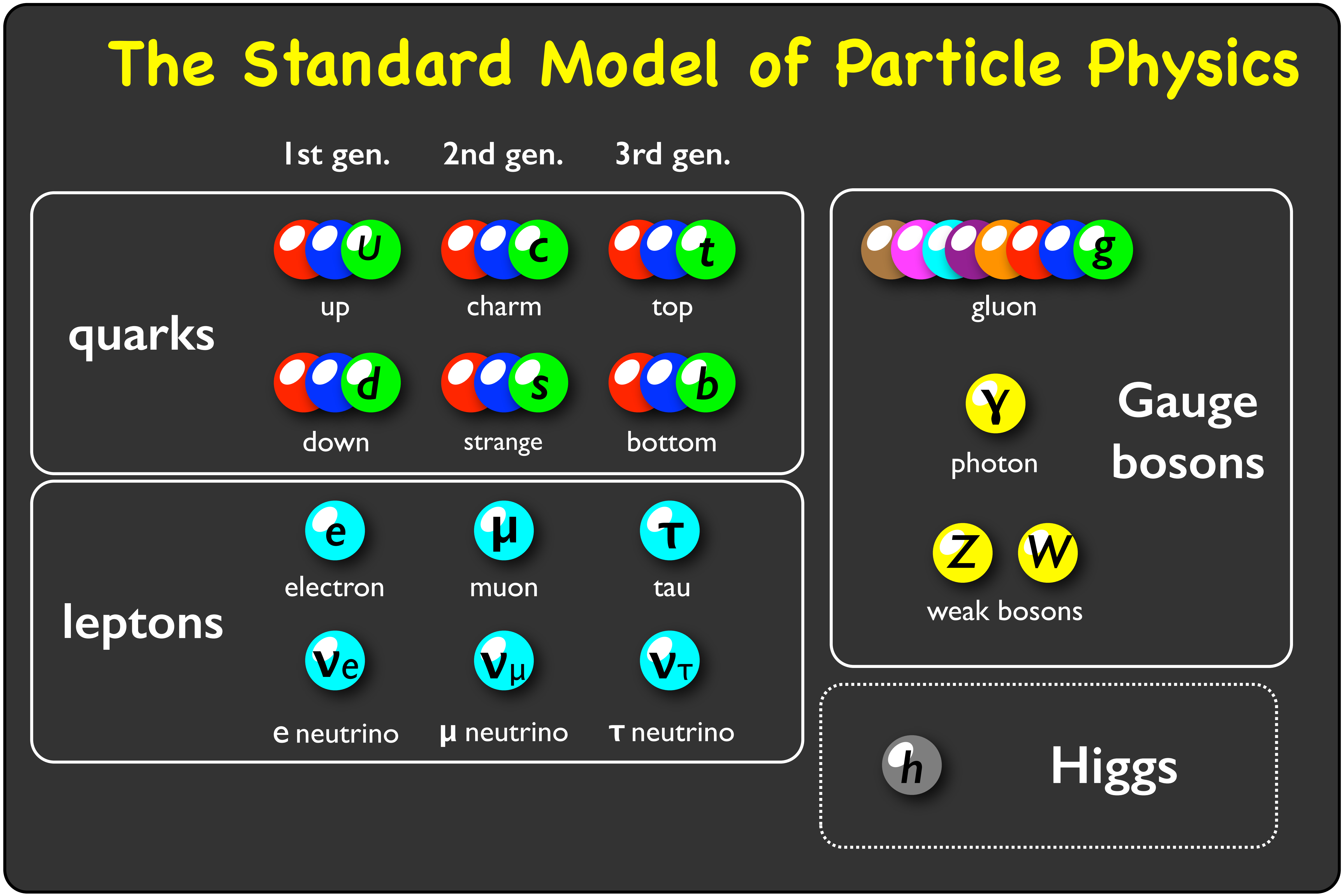
Cosmology

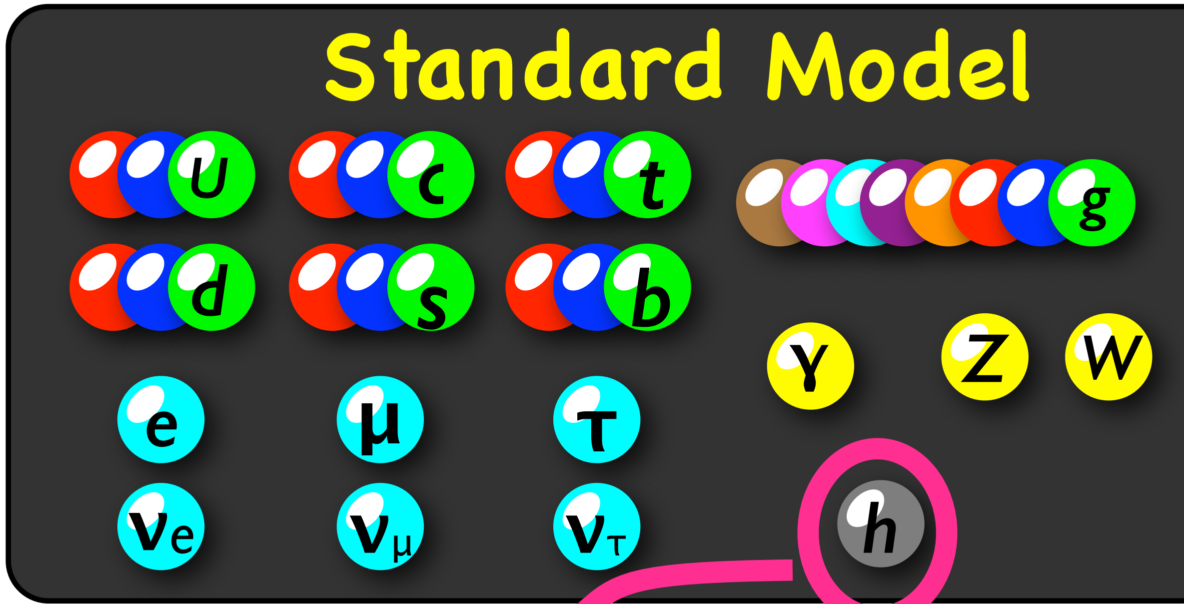
Particle Physics

complicated
quark/lepton properties

Let's start from here.

Where shall we start...?


The Standard Model of Particle Physics
1st gen.
2nd gen.
3rd gen.
quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
leptons
e
electron
μ
muon
τ
tau
νe
e neutrino
νμ
μ neutrino
ντ
τ neutrino
g
gluon
γ
photon
Gauge bosons
Z
W
weak bosons
h
Higgs

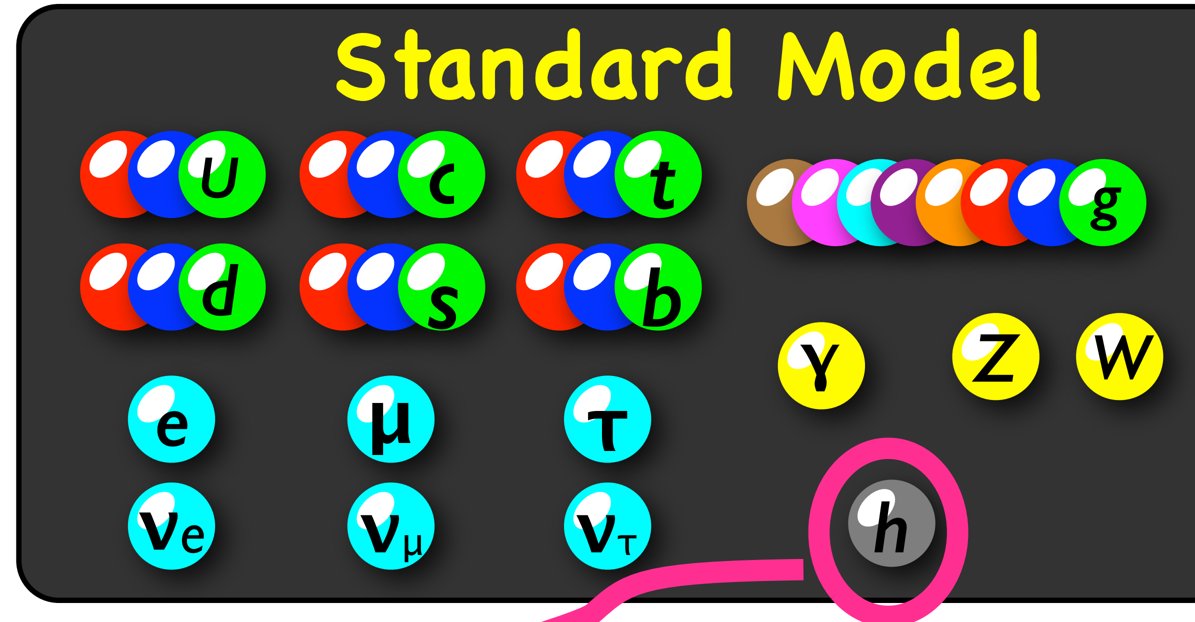


First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lectures on Standard Model and Higgs.

e.g. electron:

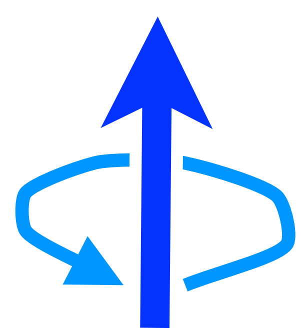


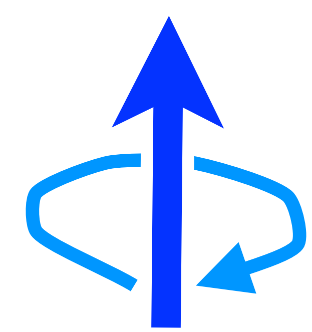
First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lectures on Standard Model and Higgs.

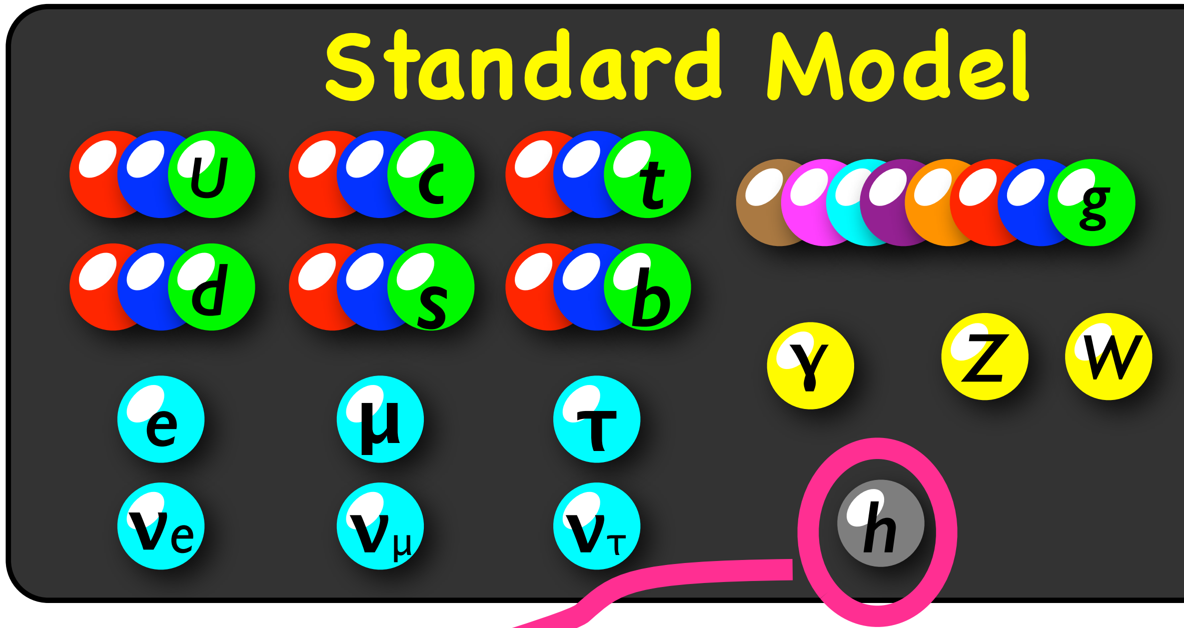
e.g. electron:





e = right-handed e_R + left-handed e_L

(not weakly interacting) (weakly interacting)



First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lectures on Standard Model and Higgs.

e.g. electron: **without Higgs,.....**

(not weakly interacting)

right-handed e_R

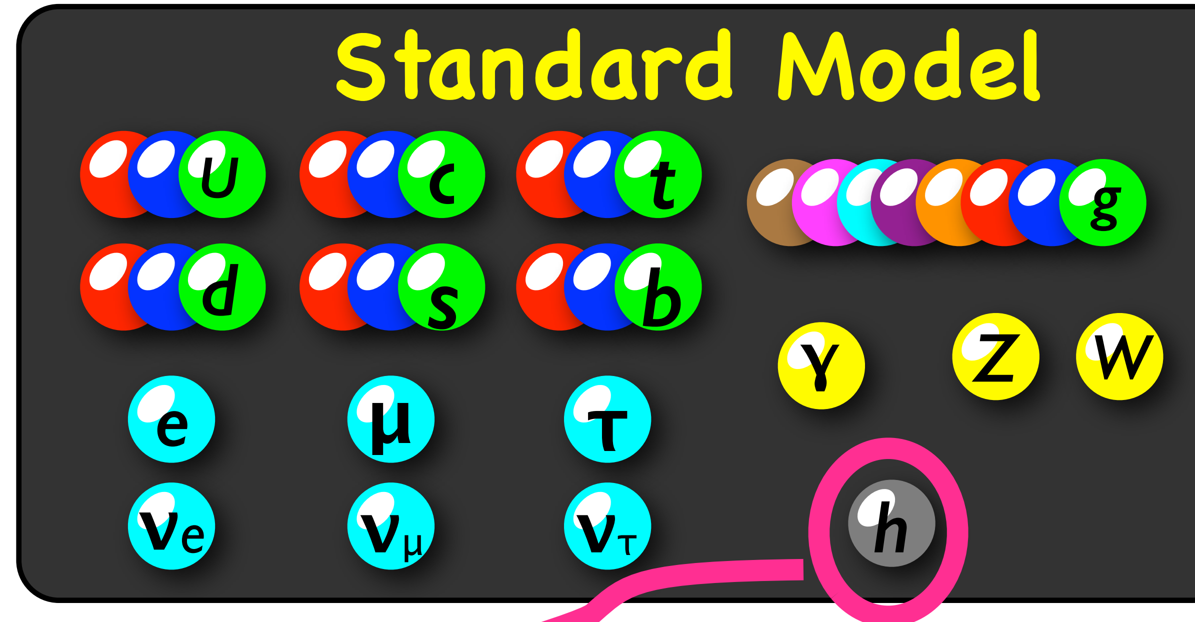
left-handed e_L

(weakly interacting)

different particles !!

zero masses !

(moving with a speed of light)



First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lectures on Standard Model and Higgs.

e.g. electron: the **Higgs** connects the two components.

(not weakly interacting)

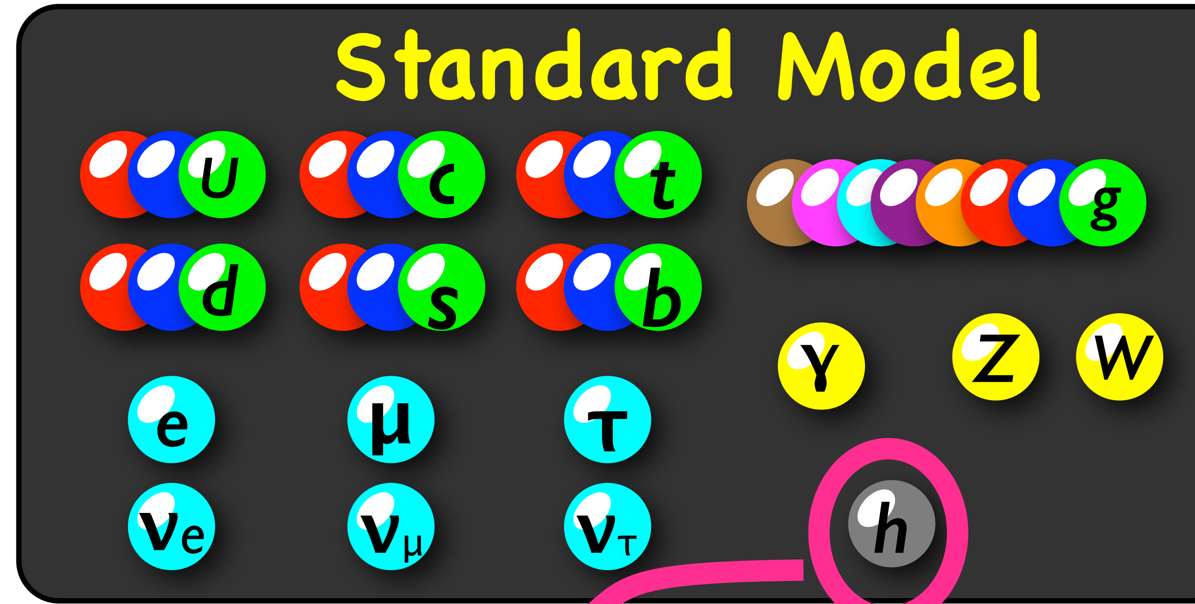
right-handed e_R

left-handed e_L

(weakly interacting)

Higgs

Yukawa interaction



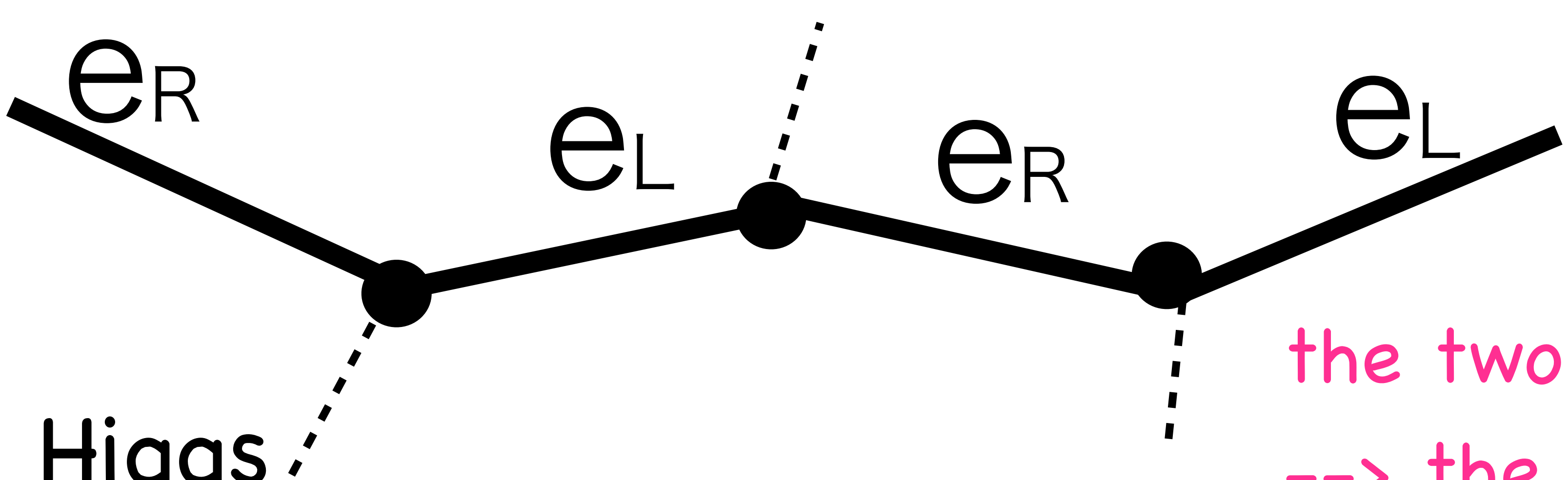
First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lectures on Standard Model and Higgs.

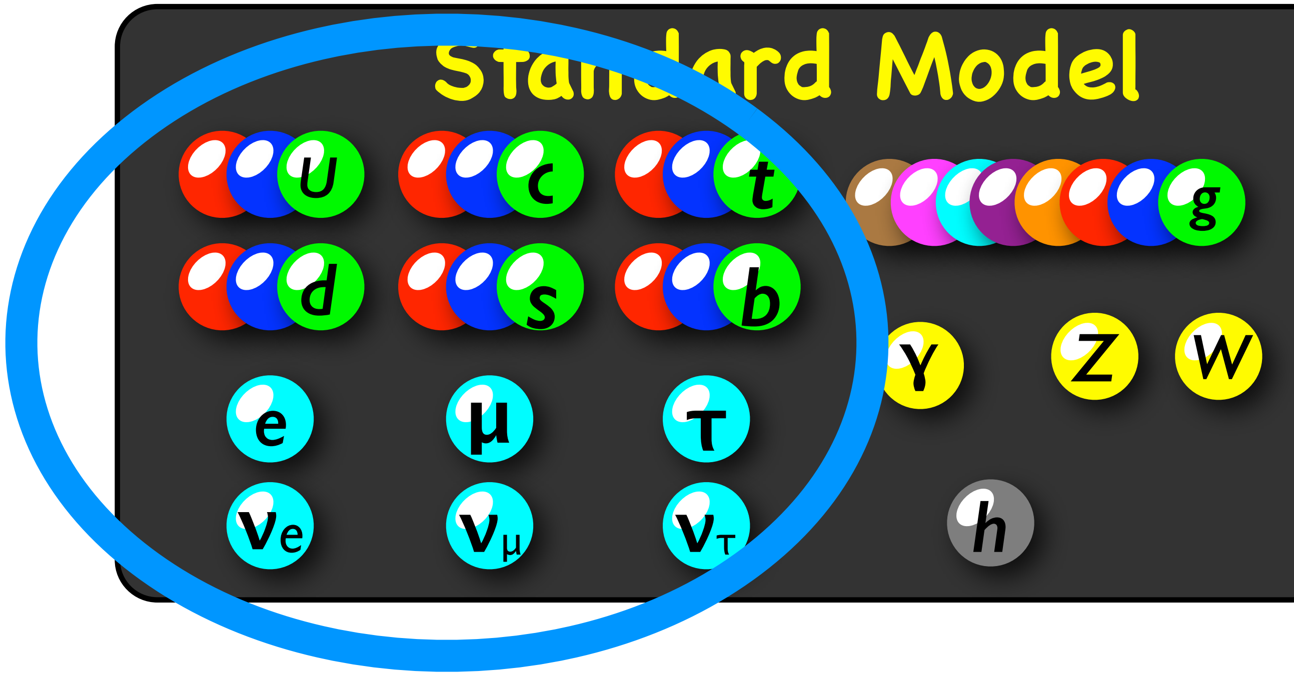
e.g. electron:

thanks to the "Higgs condensation" in vacuum....

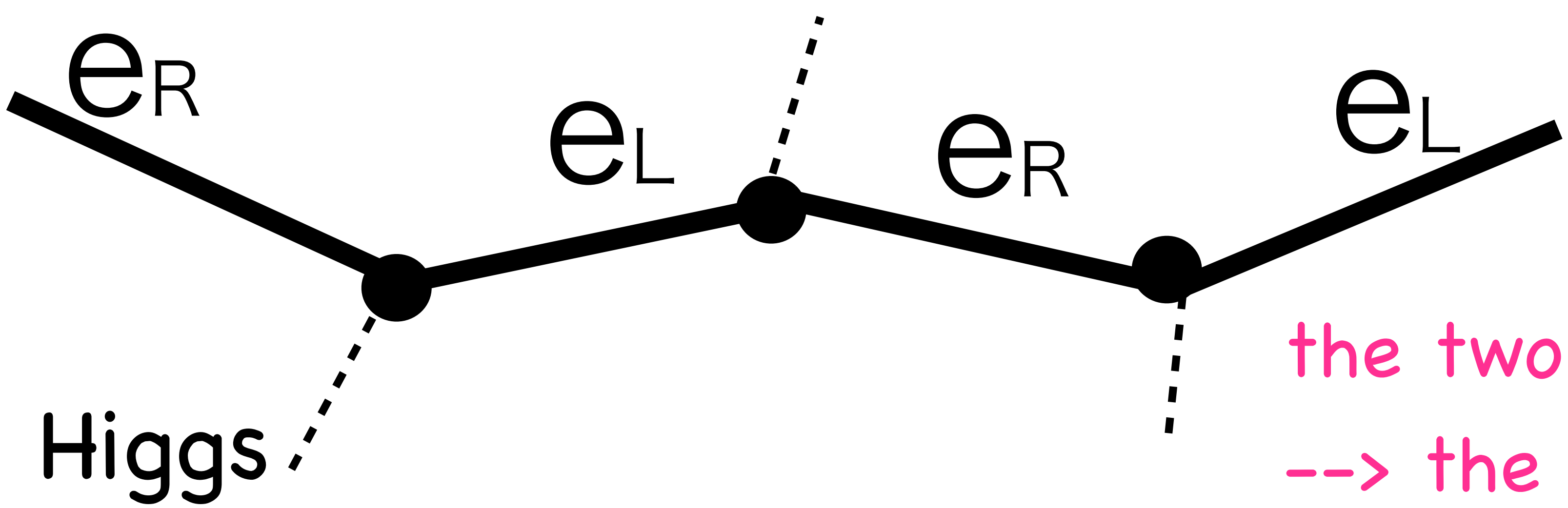


the two components are exchanged

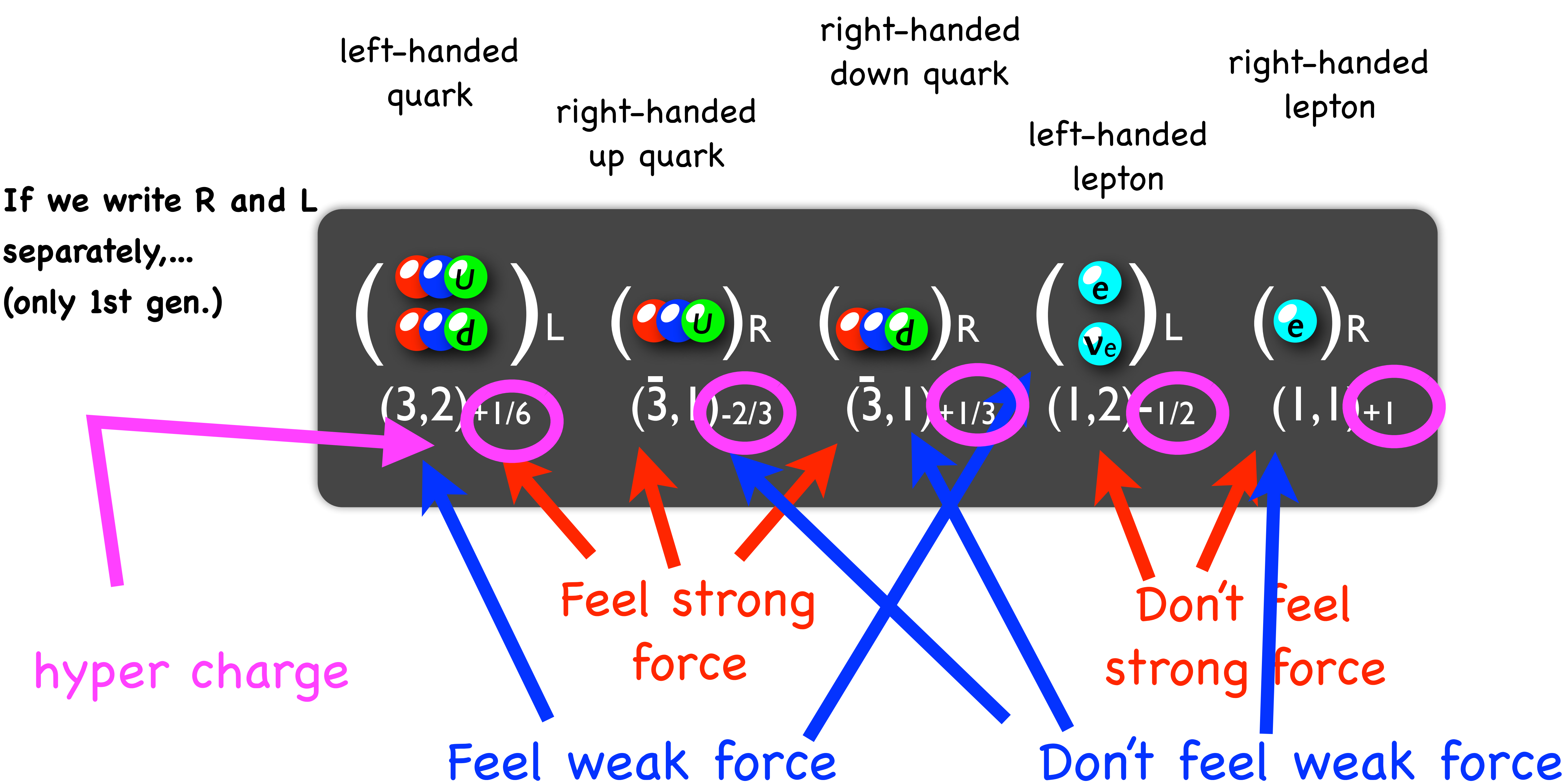
--> the electron gets a **mass** !!



Other quarks and leptons get masses in similar ways.
"Left + Right"

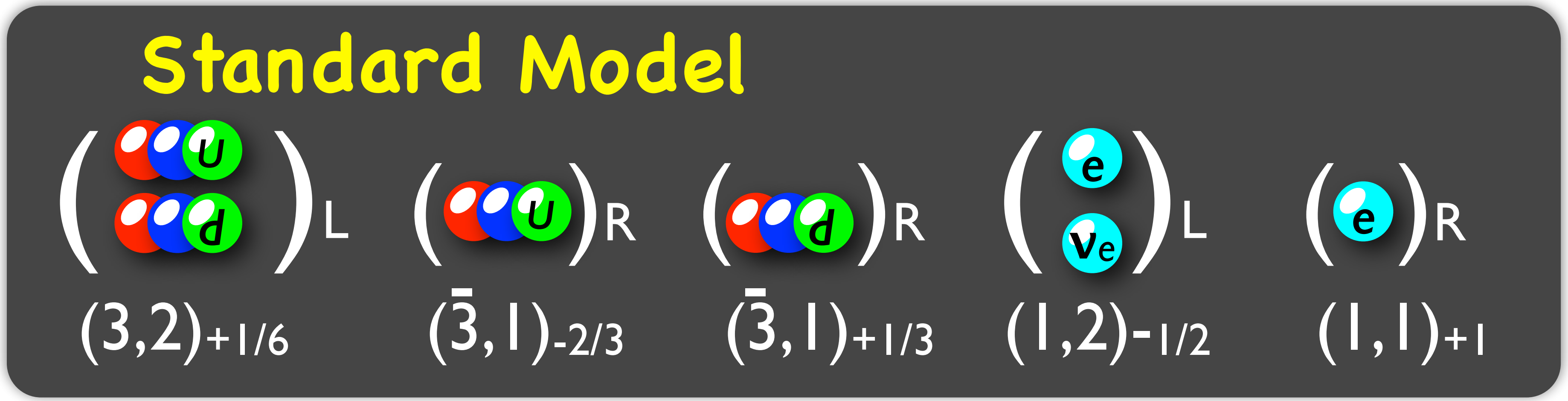


the two components are exchanged
--> the electron gets a **mass** !!

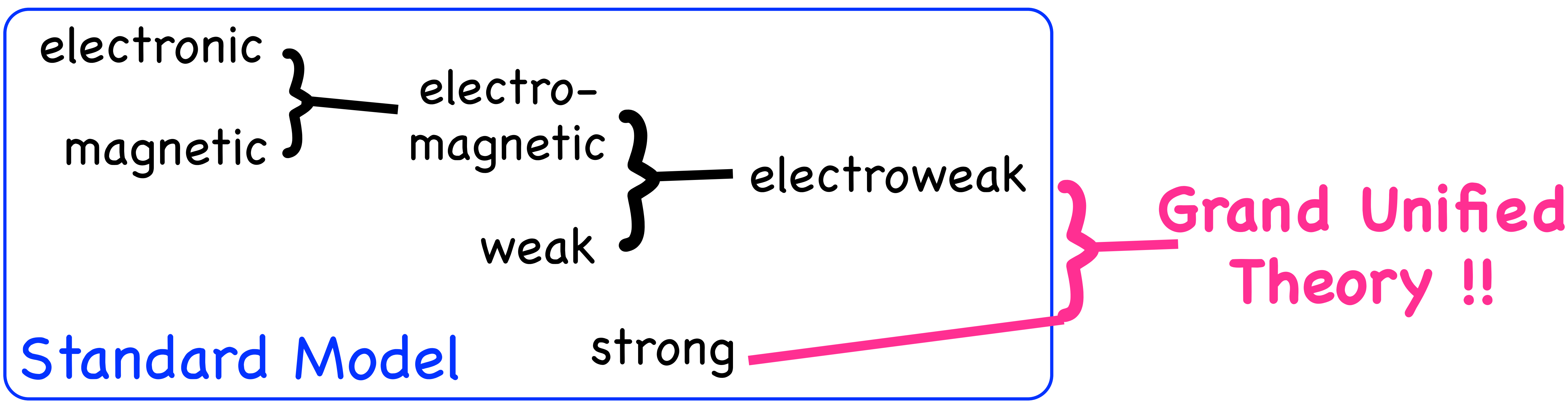


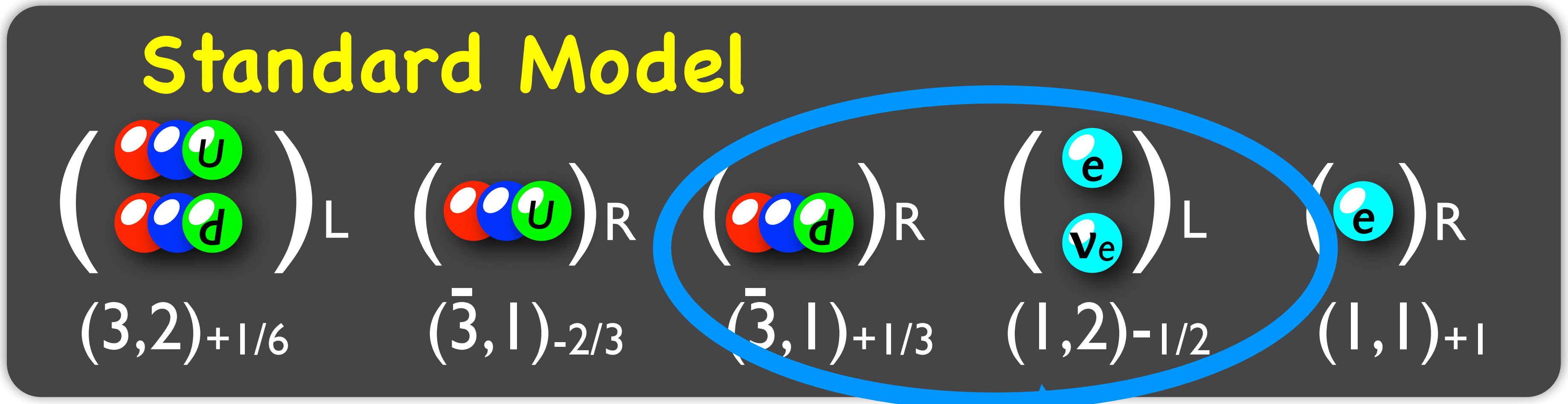
... very complicated !!

Q: any simple, unified theory to explain it?



Q: any simple, unified theory to explain it?

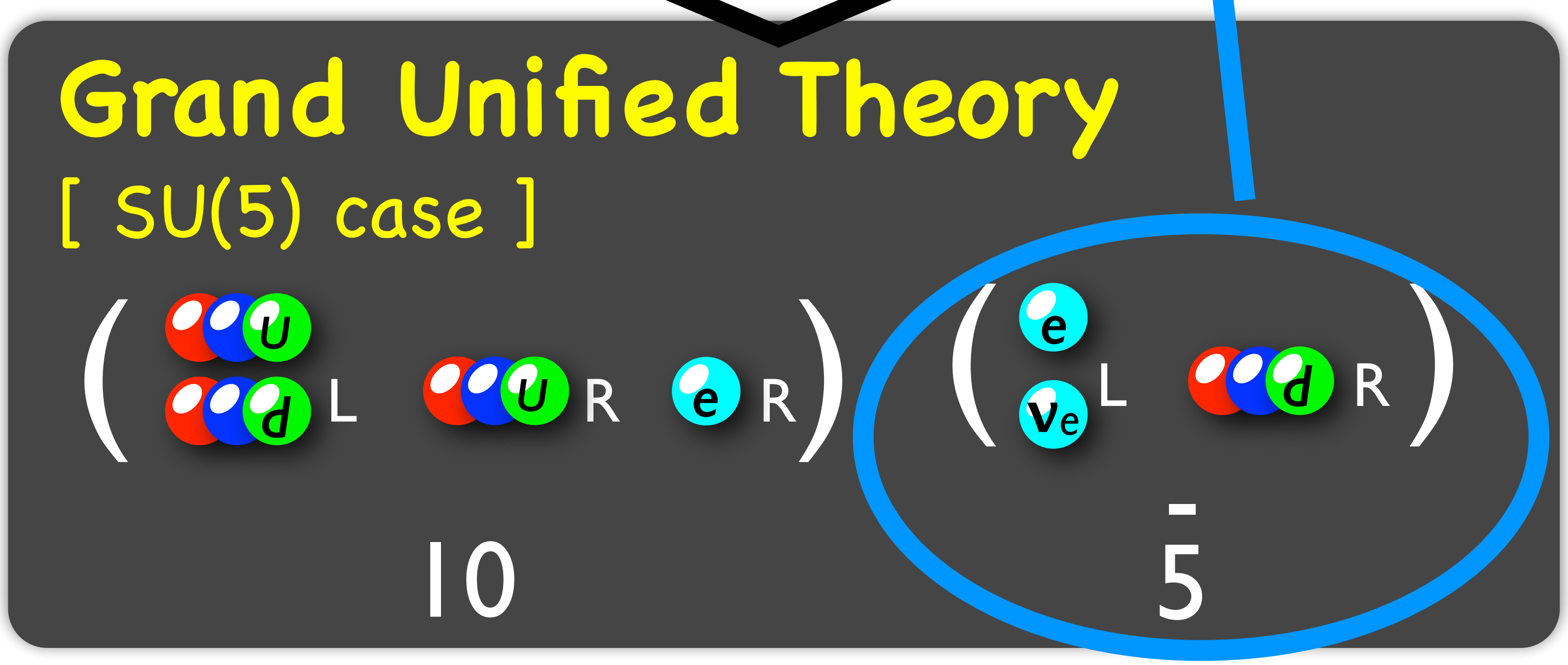




Q: any simple, unified theory to explain it?

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

Complicated numbers are naturally explained !



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

[Georgi, Glashow 1974]

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model

Cosmology

Particle Physics

complicated
quark/lepton properties

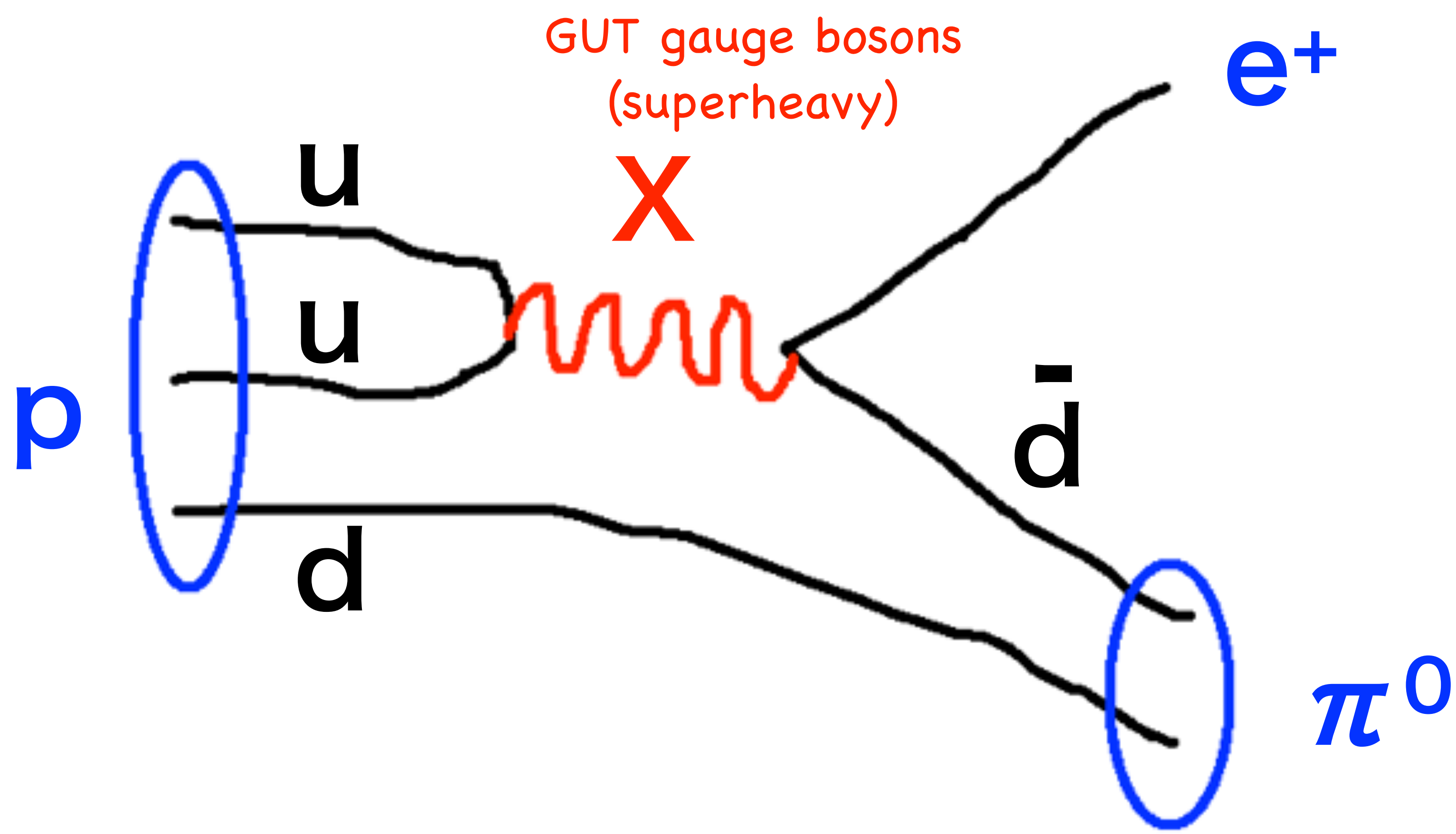
Grand Unified Theory

Any prediction by Grand Unified Theorie (GUT) ?

Any prediction by Grand Unified Theorie (GUT) ?

prediction 1. If GUT is correct,.....

protons decay!



But the proton lifetime strongly depends on the GUT model.

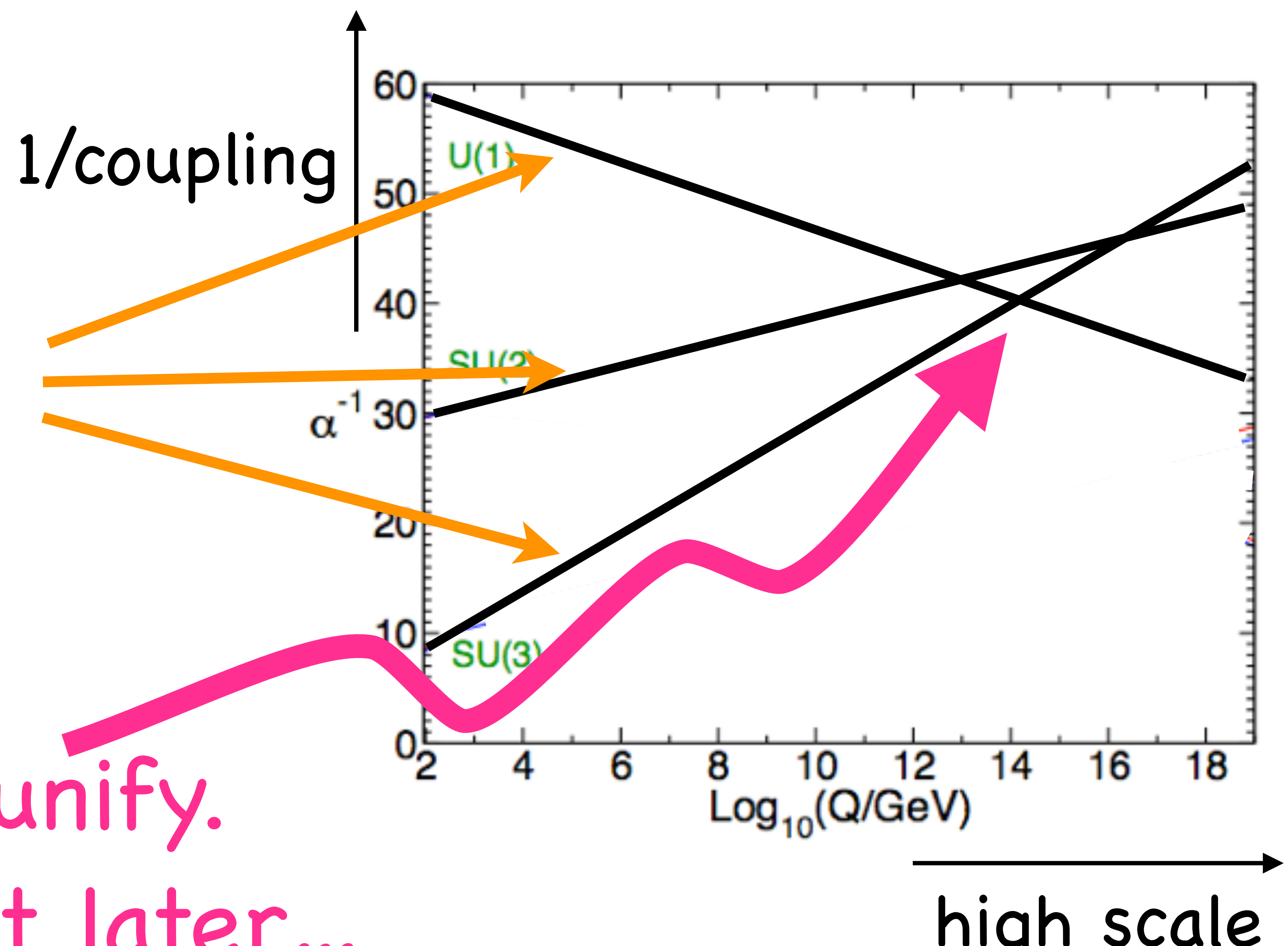
(Don't listen too much to theorists...😜)

Any prediction by Grand Unified Theorie (GUT) ?

prediction 2. If GUT is correct,.....

the three gauge couplings unify at high scale.

3 couplings



They don't really unify.

More on this point later...

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model

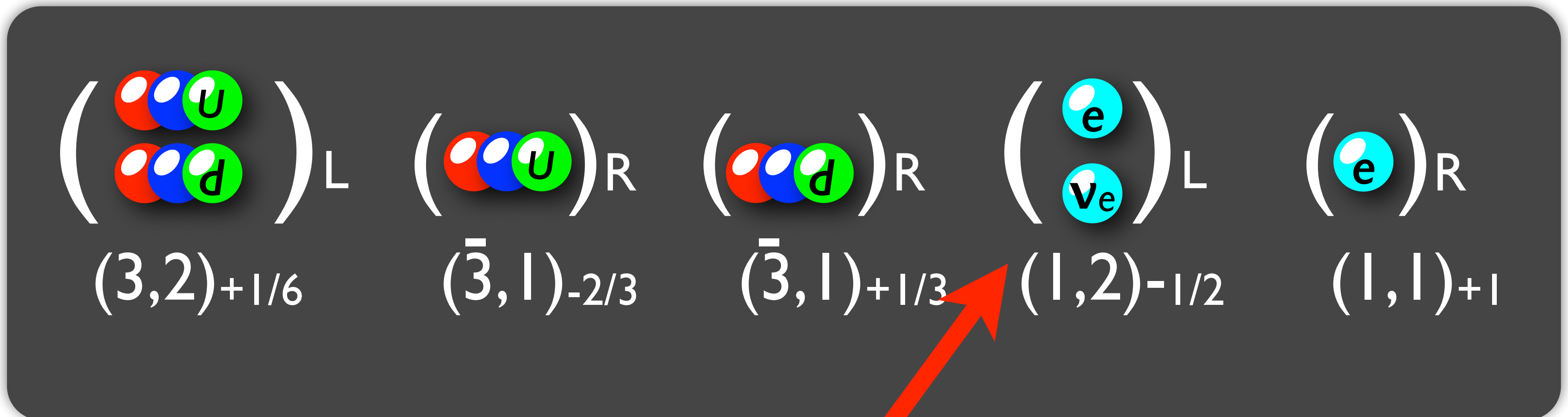
Cosmology	Particle Physics
	complicated quark/lepton properties
	tiny neutrino mass

Grand Unified Theory

proton decay?!

Next,...

puzzle: neutrino masses



left-handed quark

right-handed up quark

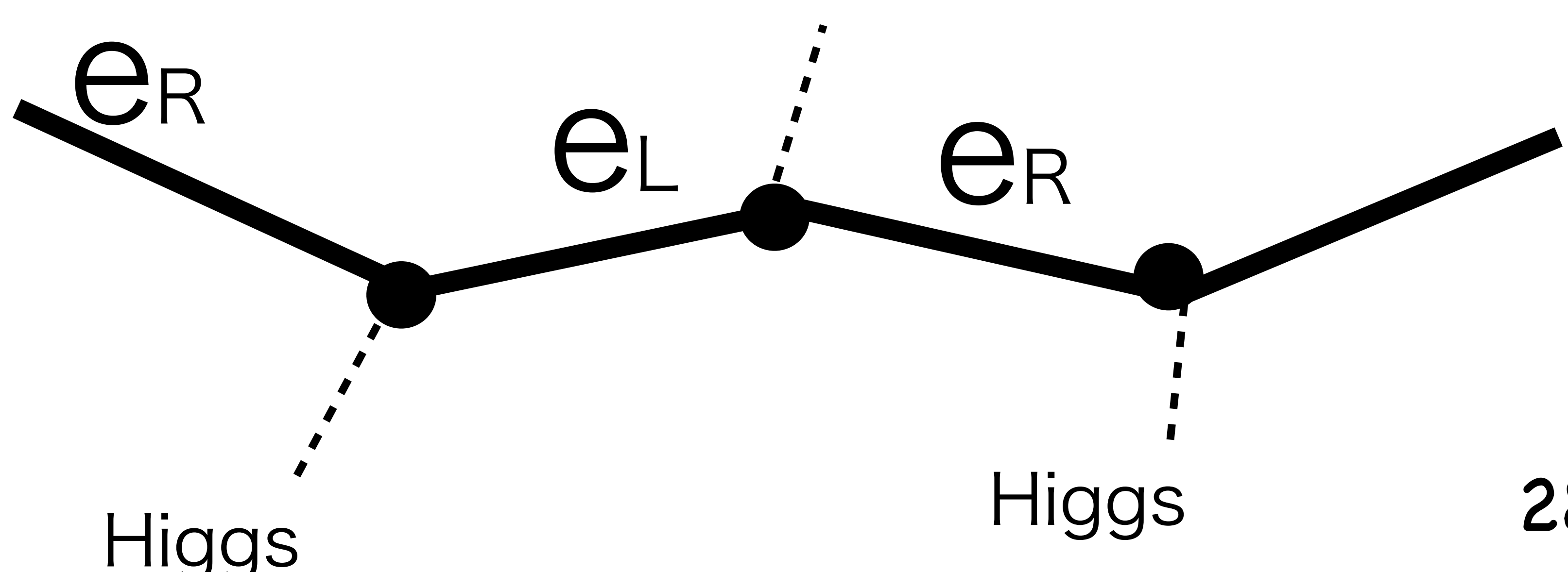
right-handed down quark

left-handed lepton

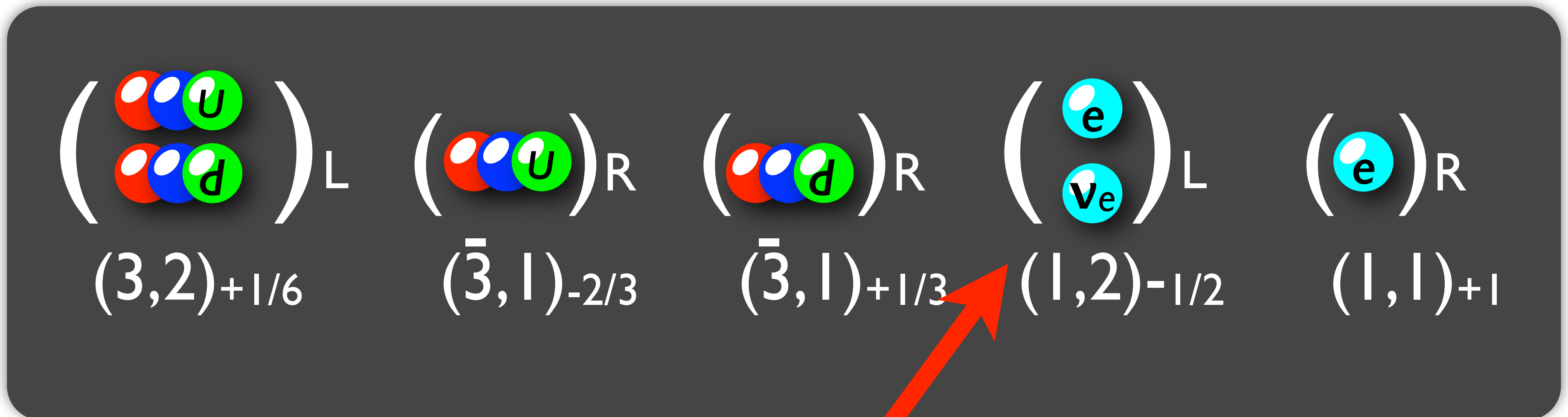
right-handed lepton

The neutrino has only left-handed component.

recall the case of electron...



puzzle: neutrino masses



left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

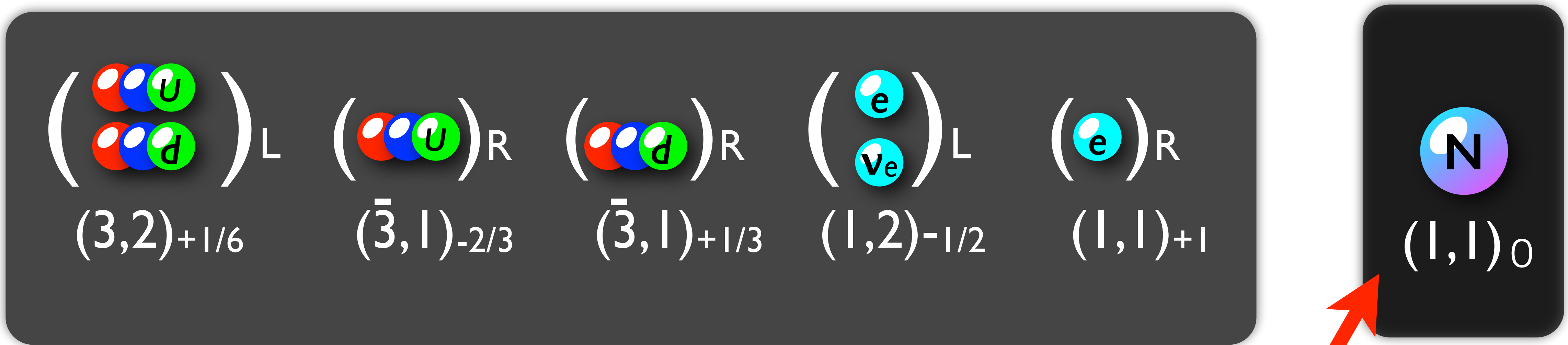
right-handed lepton

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

right-handed down quark

left-handed lepton

right-handed lepton

right-handed neutrino

a solution is ...

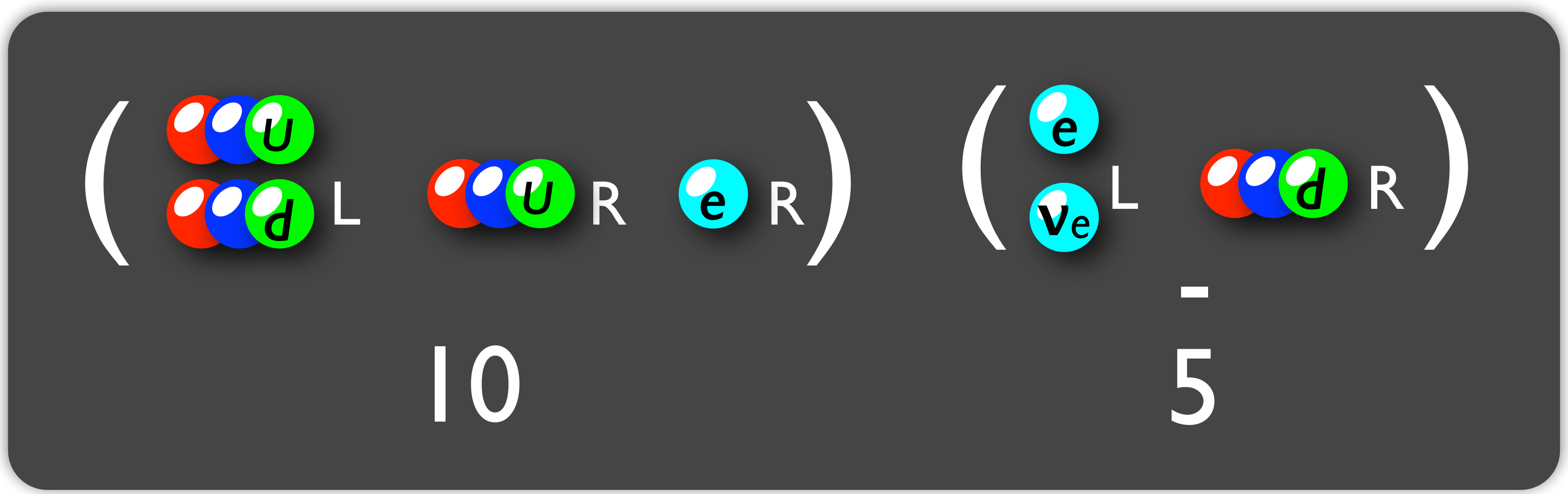
To add a right-handed neutrino !!

The right-handed neutrino N

plays a **triple role.**

The right-handed neutrino N plays a triple role.

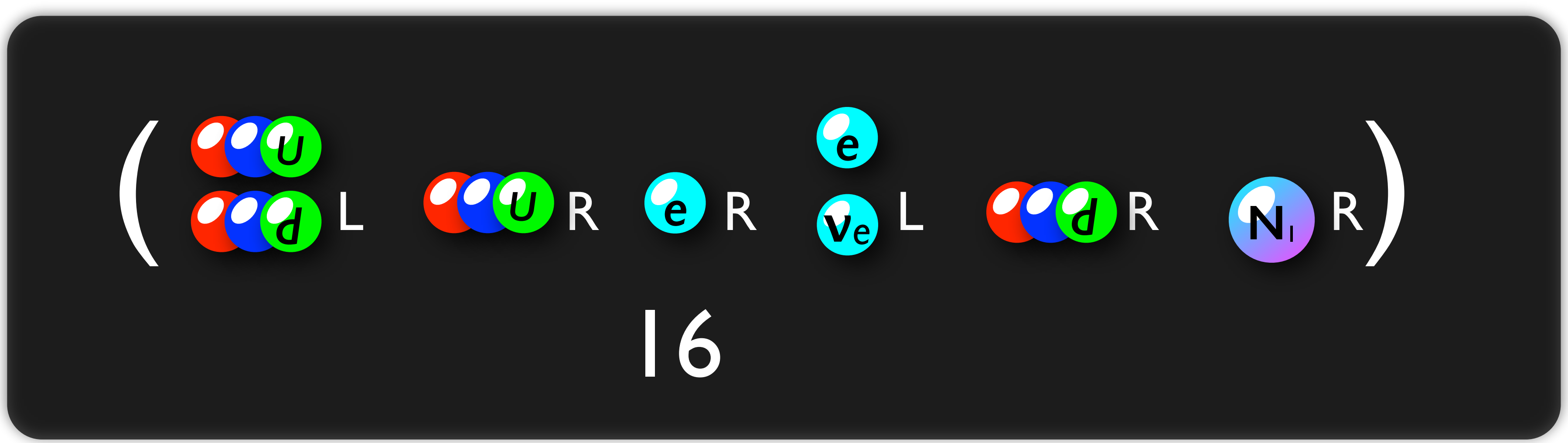
① quarks and leptons completely unified



SU(5)
GUT

+

=



SO(10)
GUT

All quarks and leptons unified !

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

① quarks and leptons completely unified

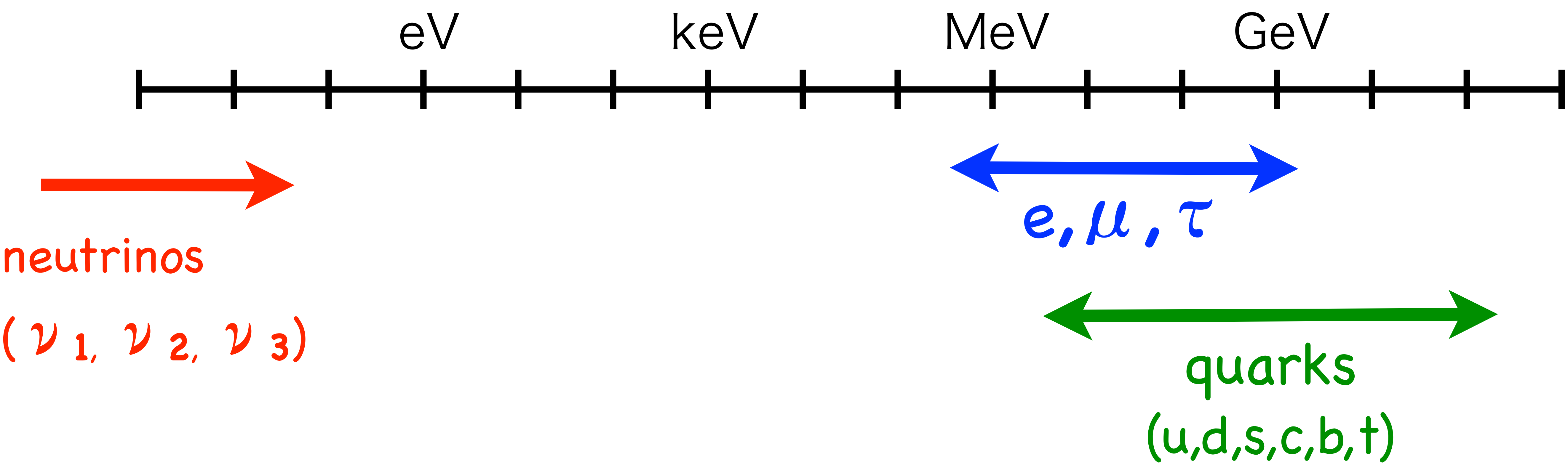
$$= \underbrace{\left(\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_R \; e_R \; \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \; d_R \; N_{1R} \right)}_{16} =$$

(↑↓ ↓↓↑)
(↑↓ ↓↑↓)
(↑↓ ↑↓↓)
(↓↑ ↓↓↑)
(↓↑ ↓↑↓)
(↓↑ ↑↓↓)
(↑↑ ↑↑↓)
(↑↑ ↑↓↑)
(↑↑ ↓↑↑)
(↓↓ ↑↑↓)
(↓↓ ↑↓↑)
(↓↓ ↓↑↑)
(↑↓ ↑↑↑)
(↓↑ ↑↑↑)
(↑↑ ↓↓↓)
(↓↓ ↓↓↓)

The right-handed neutrino N plays a triple role.

② explains **tiny** neutrino mass

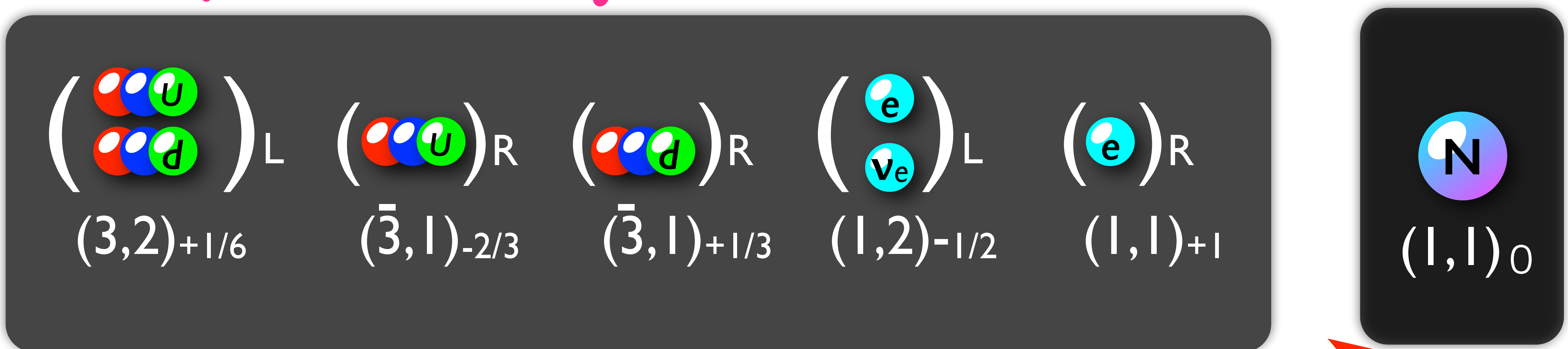
masses of quarks and leptons



・・・why neutrino masses are so small??

The right-handed neutrino N plays a triple role.

② explains tiny neutrino mass



left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

right-handed lepton

right-handed neutrino

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

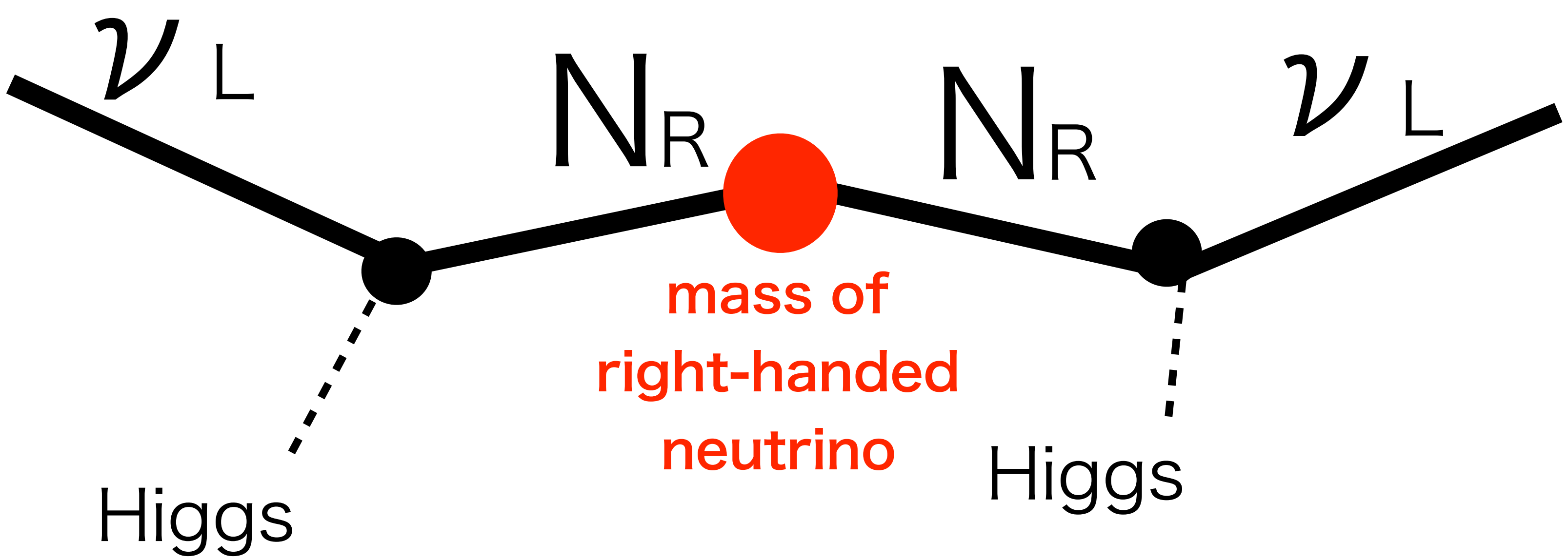
→ **it has no charge.**

→ **it can be its own anti-particle.**

→ **it can have a mass without Higgs.**

The right-handed neutrino N plays a triple role.

② explains tiny neutrino mass



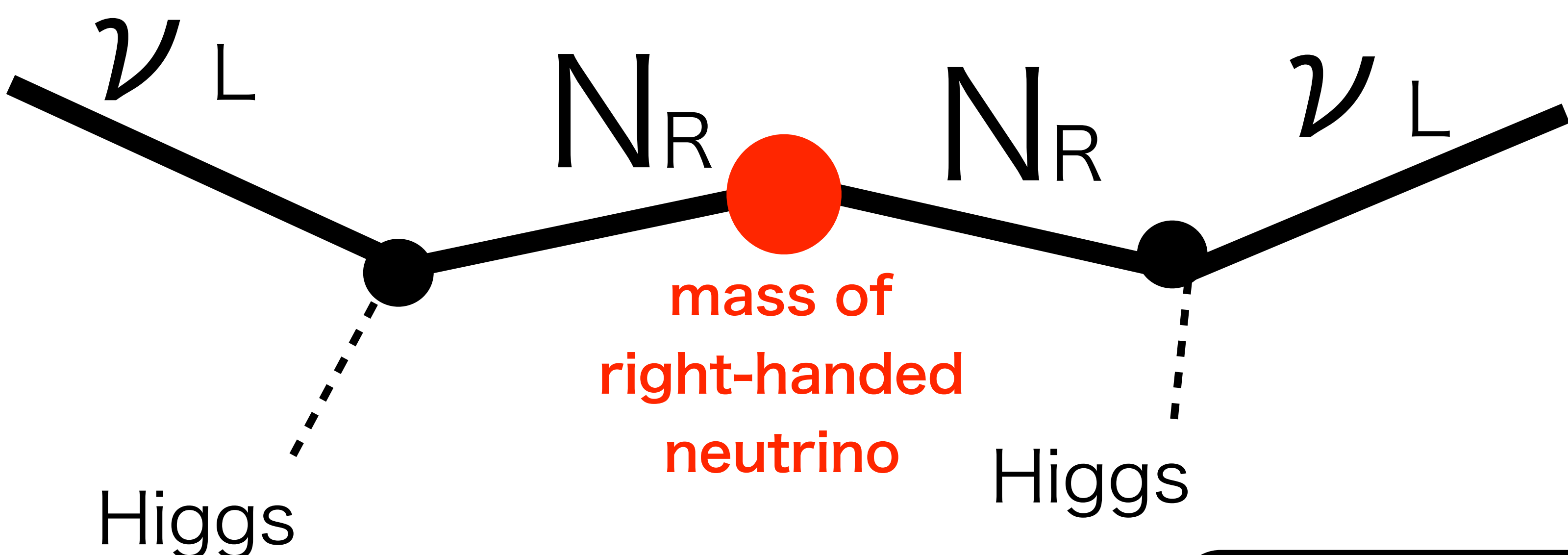
$$\text{Neutrino mass} = \frac{(\sim \text{other quark/lepton mass})^2}{\text{mass of right-handed neutrino}}$$

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

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

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

② explains **tiny** neutrino mass



e.g. (100 GeV)^2

Neutrino mass = (~ other quark/lepton mass)^2 / 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 N

plays a **triple role.**

③ explains **matter > anti-matter**

asymmetry of the universe.

-----> Leptogenesis !!

more on this later ...

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model

Cosmology

Particle Physics

complicated quark/lepton properties

tiny neutrino mass

Grand Unified Theory

proton decay?!

(heavy) Right-handed neutrino

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model

Cosmology ; Particle Physics

...d

...perties

...ss

Part 2: [blackboard]

Mini-reviews on each topic,

2-A: GUT

2-B: Neutrino mass and seesaw

2-C: Standard Cosmology

2-D: Inflation

2-E: Leptogenesis

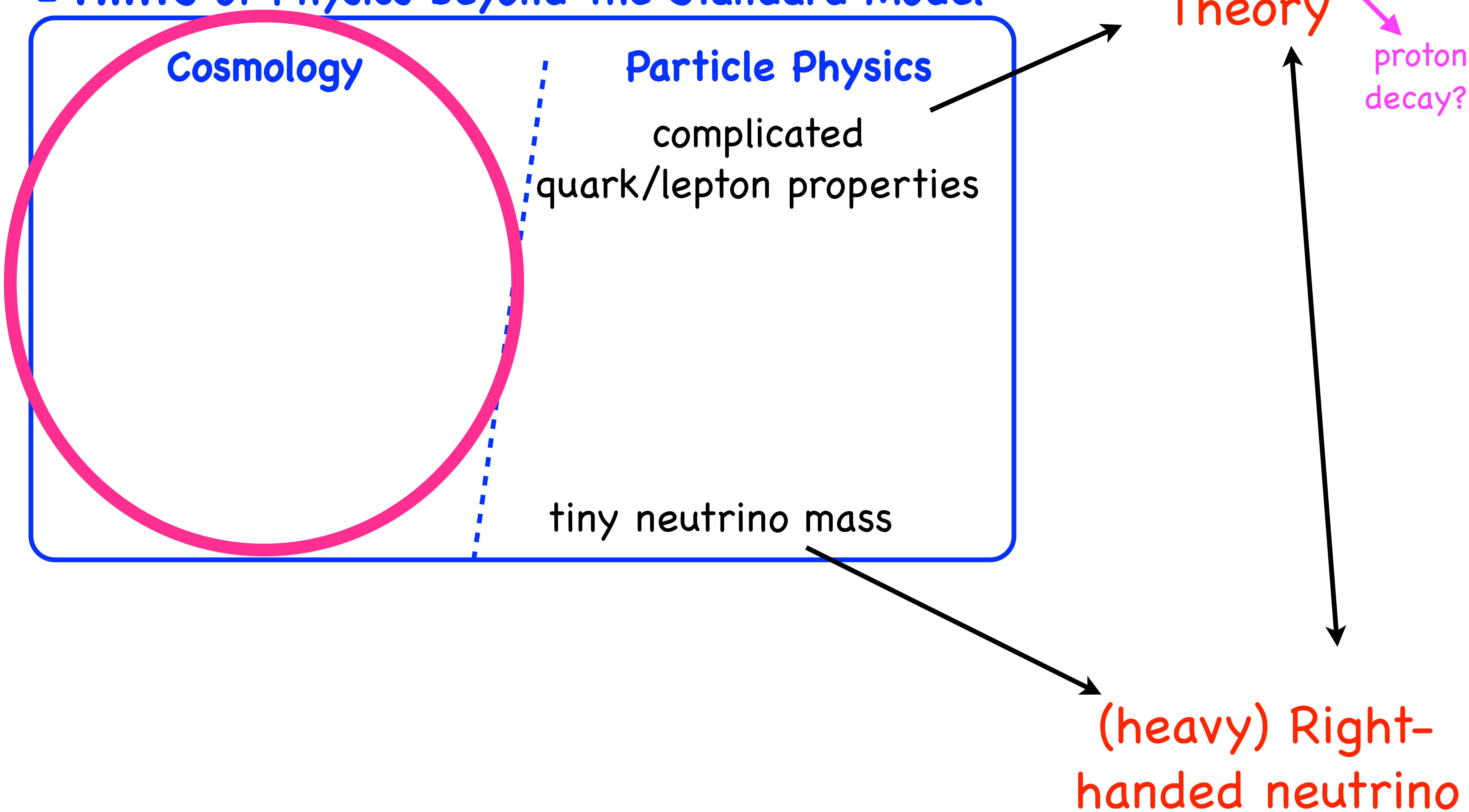
Grand Unified Theory

proton decay?!

(heavy) Right-handed neutrino

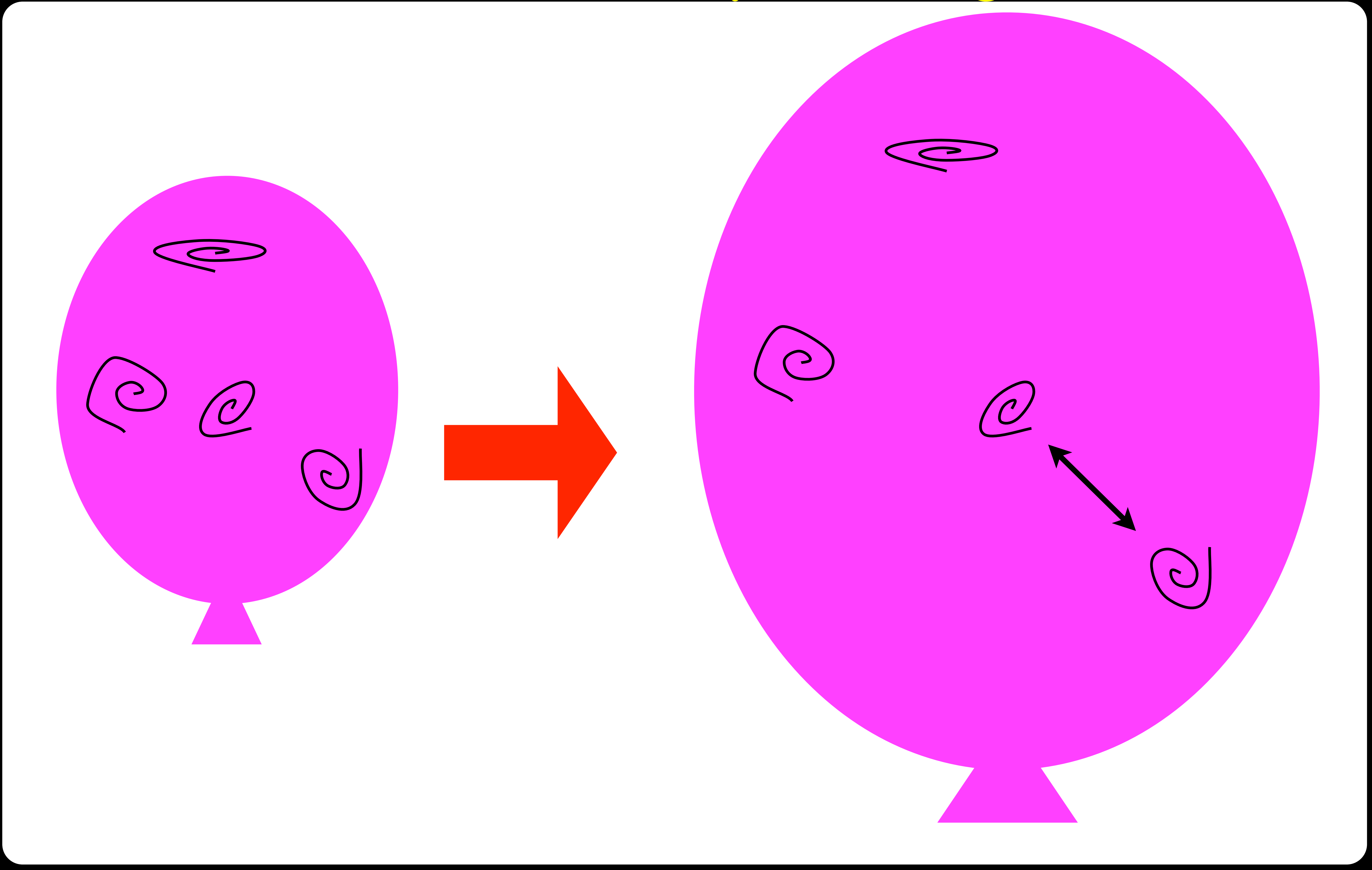
Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Next,... [cf. Lectures by Prof. Tait.]

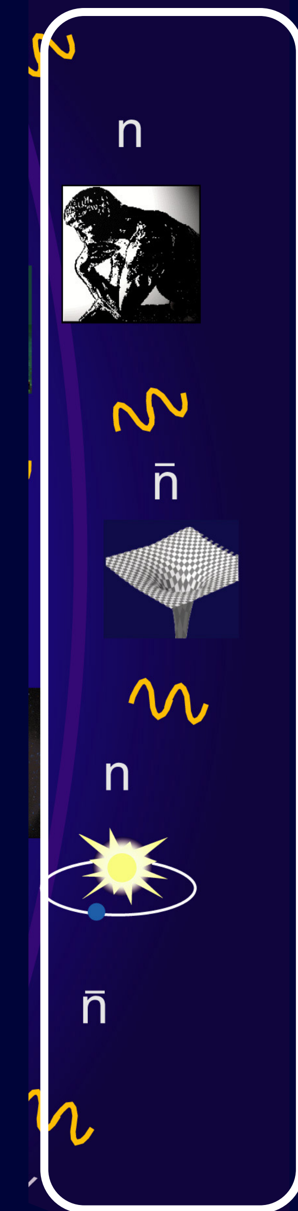
Our universe is expanding



Our universe is expanding

now

going back...



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

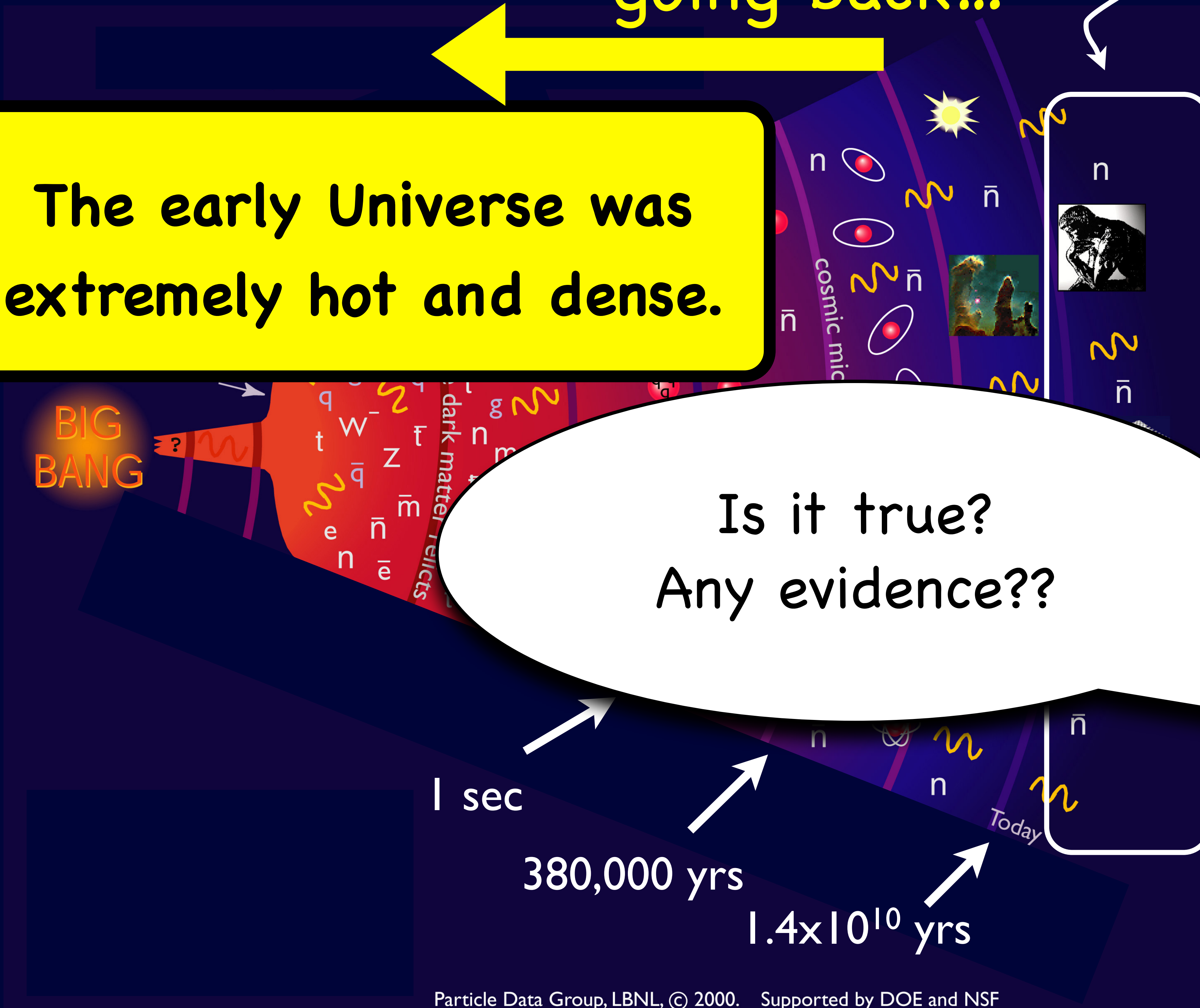
http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

Our universe is expanding

now

going back...

The early Universe was extremely hot and dense.



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

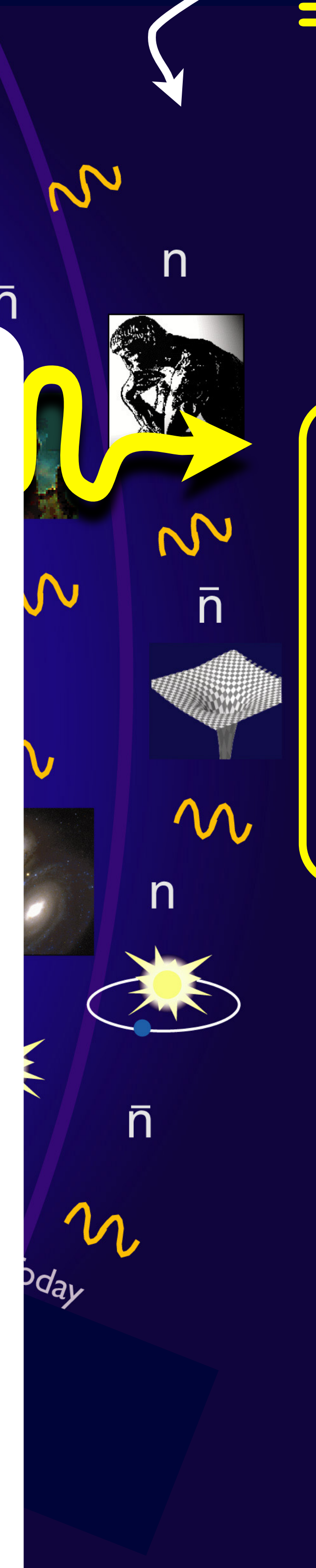
http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/

Is it true?
Any evidence??

Photons emitted when the universe was 380,000 yrs old

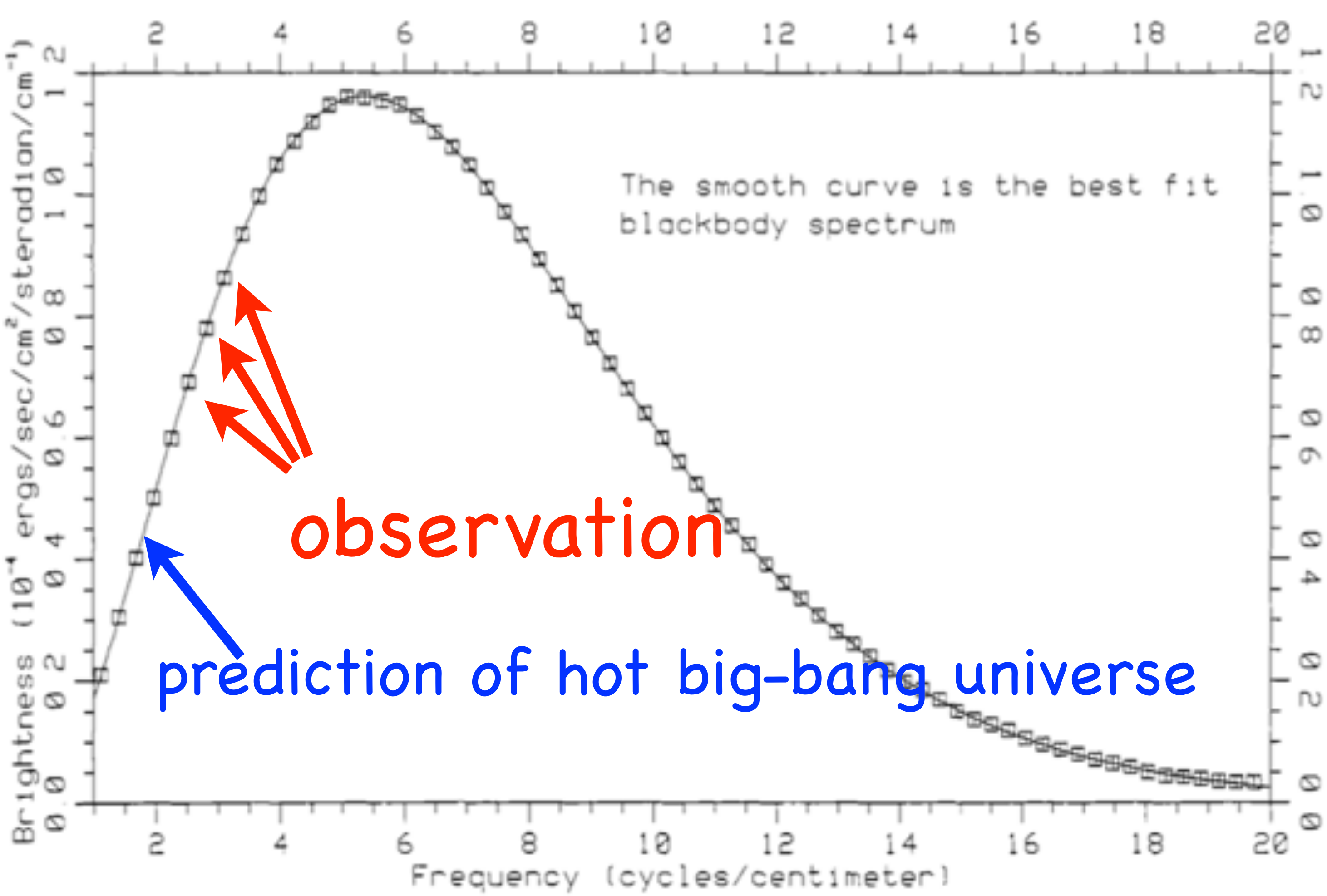
now

= 1.4×10^{10} yrs old



... are seen now, after 1.4×10^{10} yrs

Cosmic Microwave Background



J.C.Mather et al. Astrophys. J. 354: L37-L40, 1990

ss/chart_cutouts/universe_original.pdf

Photons emitted when the universe was 380,000 yrs old

now

= 1.4×10^{10} yrs old

... are seen now, after 1.4×10^{10} yrs

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

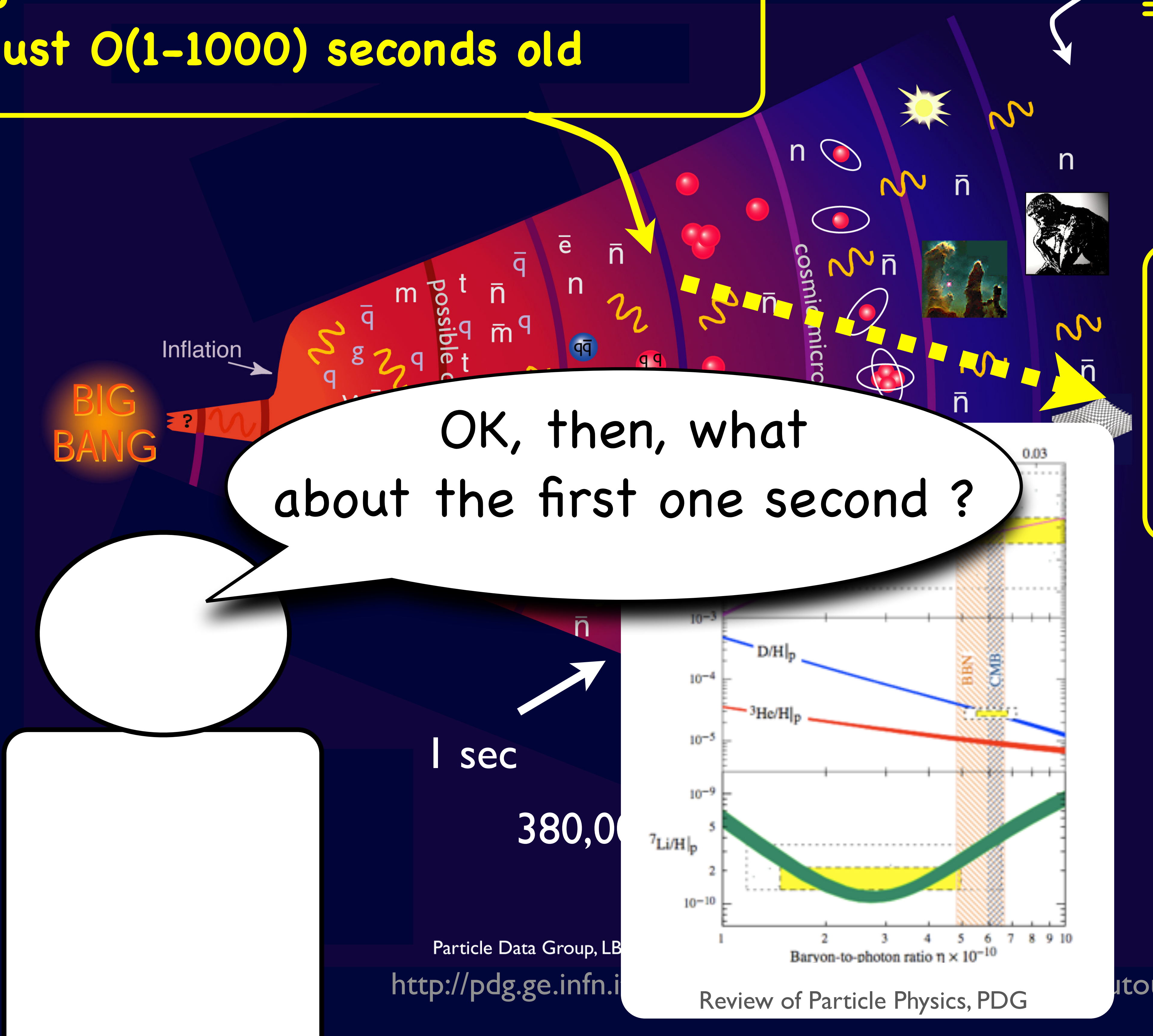
http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

Light elements (e.g., Helium-4) generated when the Universe was just O(1-1000) seconds old

now = 1.4×10^{10} yrs old

... are seen now, after 1.4×10^{10} yrs

OK, then, what about the first one second ?



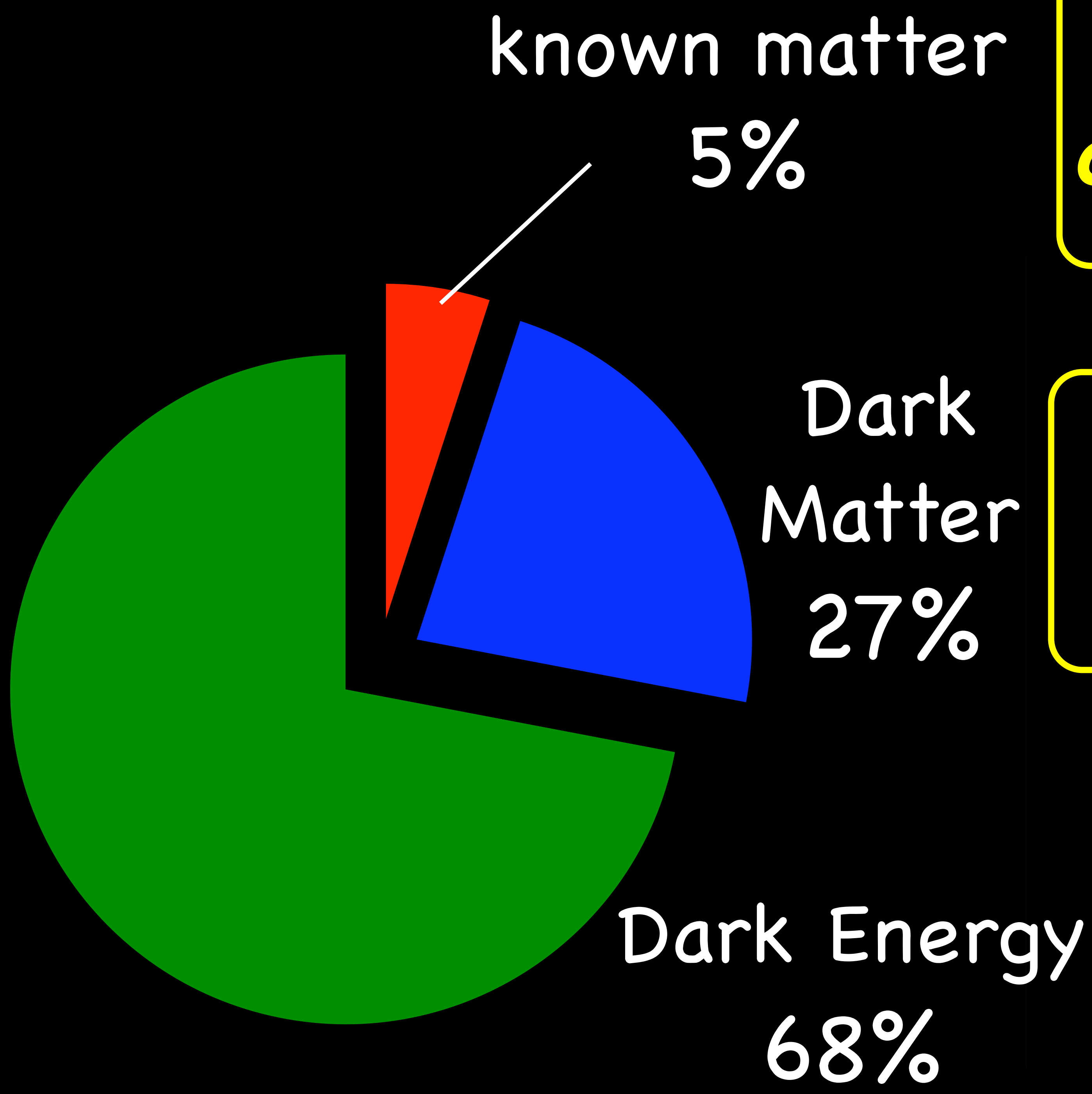
Review of Particle Physics, PDG

http://pdg.ge.infn.i … utouts/universe_original.pdf

There is no direct evidence
what happened
in the first one second.

But there are puzzles that
cannot be solved unless one
understands this first one second.

Puzzles in our Universe



Why no anti-matter?

What is DM?

What is DE?

Furthermore...

problems of initial conditions

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

tiny neutrino mass

Grand Unified Theory

(heavy) Right-handed neutrino

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model

Cosmology

Dark Energy

initial condition of Universe

Dark Matter

Matter > Anti-matter

- Flatness problem
- Horizon problem
- density fluctuation

Particle Physics

complicated quark/lepton properties

tiny neutrino mass

Grand Unified Theory

(heavy) Right-handed neutrino

Our Universe is very flat.

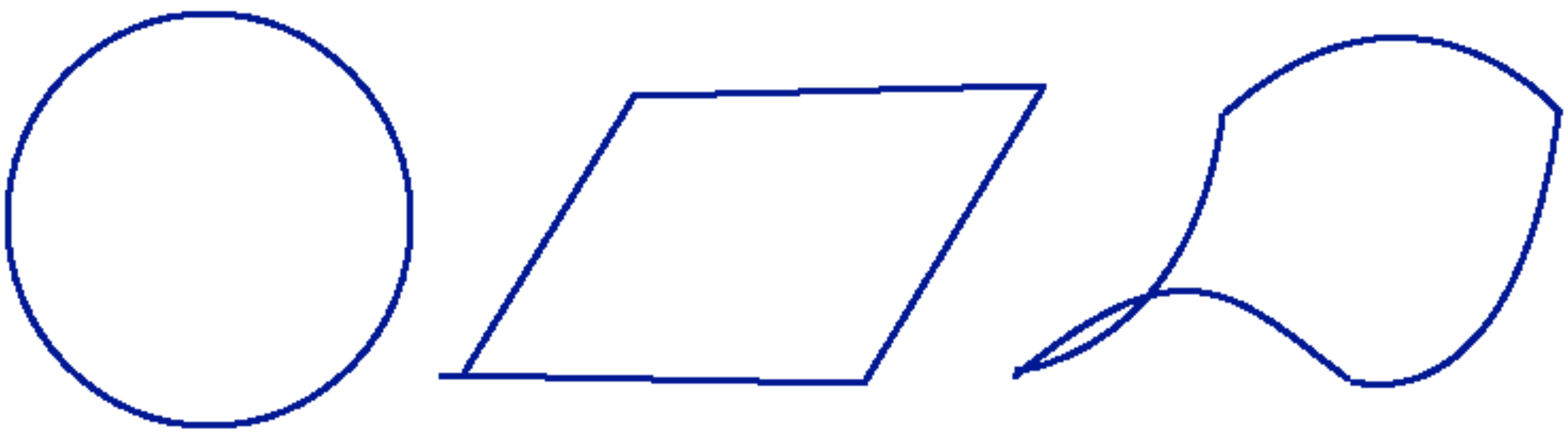
Newton const.

energy density of the Univrse

"flatness" of the Universe

$$\Omega = \frac{8\pi G}{3} \frac{\rho}{H^2}$$

Hubble parameter (expansion rate)



$\Omega > 1$ closed

$\Omega = 1$ flat

$\Omega < 1$ open

observation: $\Omega = 1.001 \pm 0.006$ (very flat)

This is very, very strange!

According to Einstein eqs.

$$\left|\frac{\Omega - 1}{\Omega}\right| \propto \frac{1}{\rho \cdot a^2}$$

"scale factor" of the Universe

energy density of the Universe

But according to Standard Cosmology

(Einstein eqs. + hot Big-bang Universe)

$$\frac{1}{\rho \cdot a^2} \propto \begin{cases} t & (\text{for } t < 10000 \text{ yrs}) \\ t^{2/3} & (\text{for } t > 10000 \text{ yrs}) \end{cases}$$

According to Einstein eqs. $$\left|\frac{\Omega - 1}{\Omega}\right| \propto \frac{1}{\rho \cdot a^2}$$

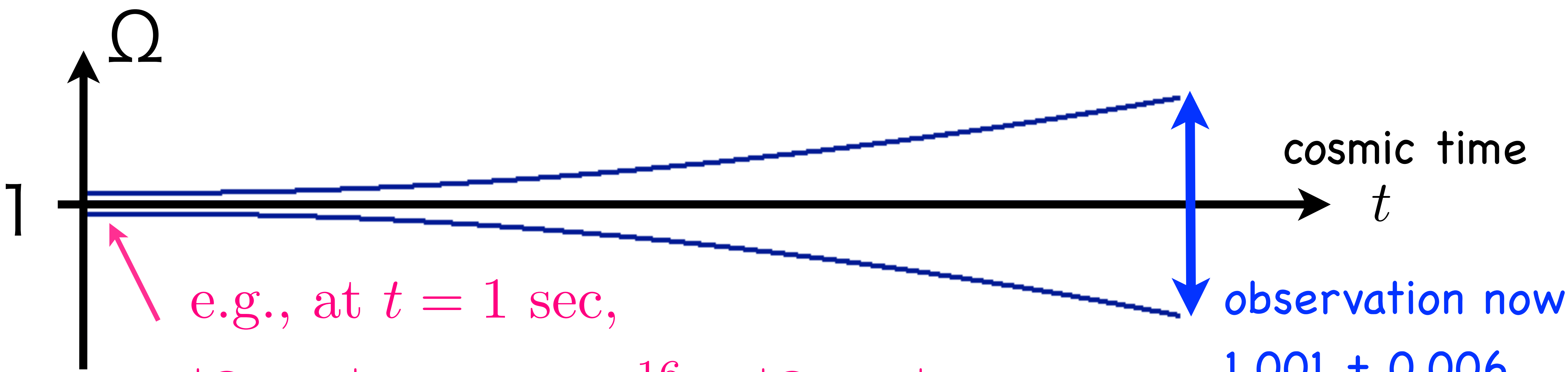
"scale factor" of the Universe

energy density of the Universe

But according to Standard Cosmology

(Einstein eqs. + hot Big-bang Universe)

$$\frac{1}{\rho \cdot a^2} \propto \begin{cases} t & (\text{for } t < 10000 \text{ yrs}) \\ t^{2/3} & (\text{for } t > 10000 \text{ yrs}) \end{cases}$$



e.g., at $t = 1$ sec,

$$|\Omega - 1|_{1\text{ sec}} \sim 10^{-16} \times |\Omega - 1|_{\text{now}}$$

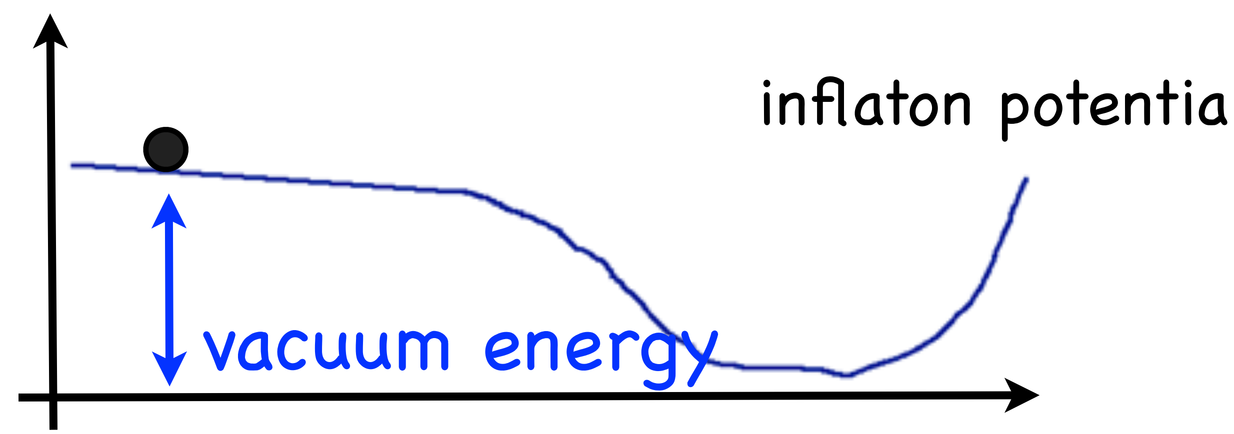
The Universe was extreeeeeeeemly flat.

Why? How? fine-tuning of initial condition.

Inflation:

Assume that the Universe was initially dominated by vacuum energy (inflaton potential energy).

Then,.....



energy density $\rho \sim \text{constant}$

scale factor $a \propto e^{H_i t}$ (exponential expansion: Inflation)

$$\left|\frac{\Omega - 1}{\Omega}\right| \propto \frac{1}{\rho \cdot a^2} \propto e^{-2H_i t}$$

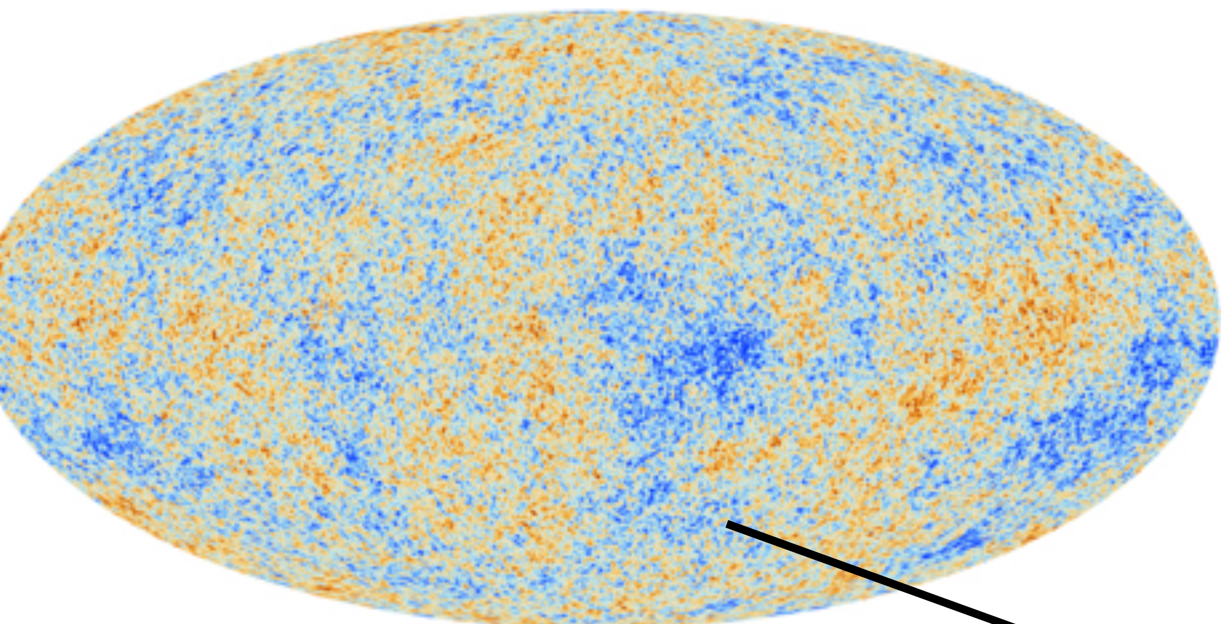
Automatically tuned to be Ω = 1 (flat Universe) !

furthermore...

Inflation also solves the ``Horizon problem.''

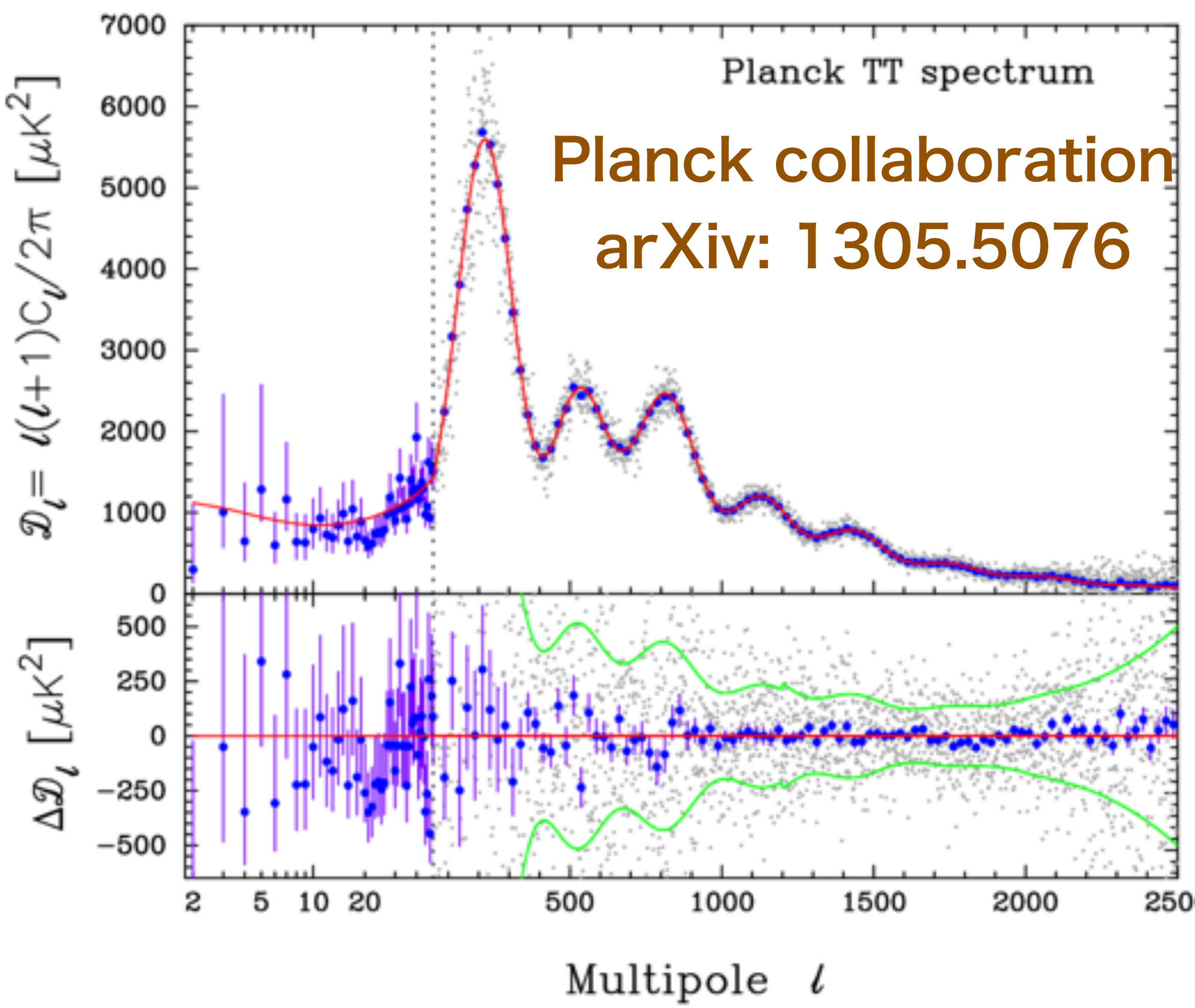
furthermore...

temperature fluctuation



spherical-harmonic-function expansion

very, very well-explained by inflation !



http://sci.esa.int/planck/

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

tiny neutrino mass

Grand Unified Theory

inflation

(heavy) Right-handed neutrino

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

tiny neutrino mass

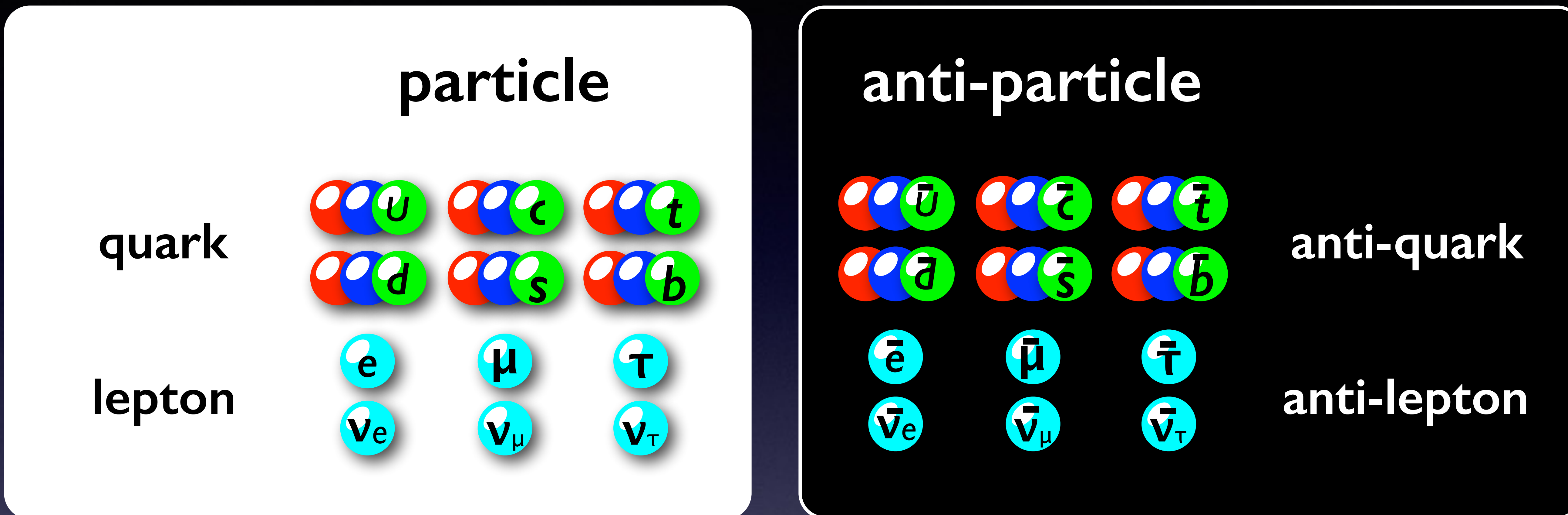
Grand Unified Theory

inflation

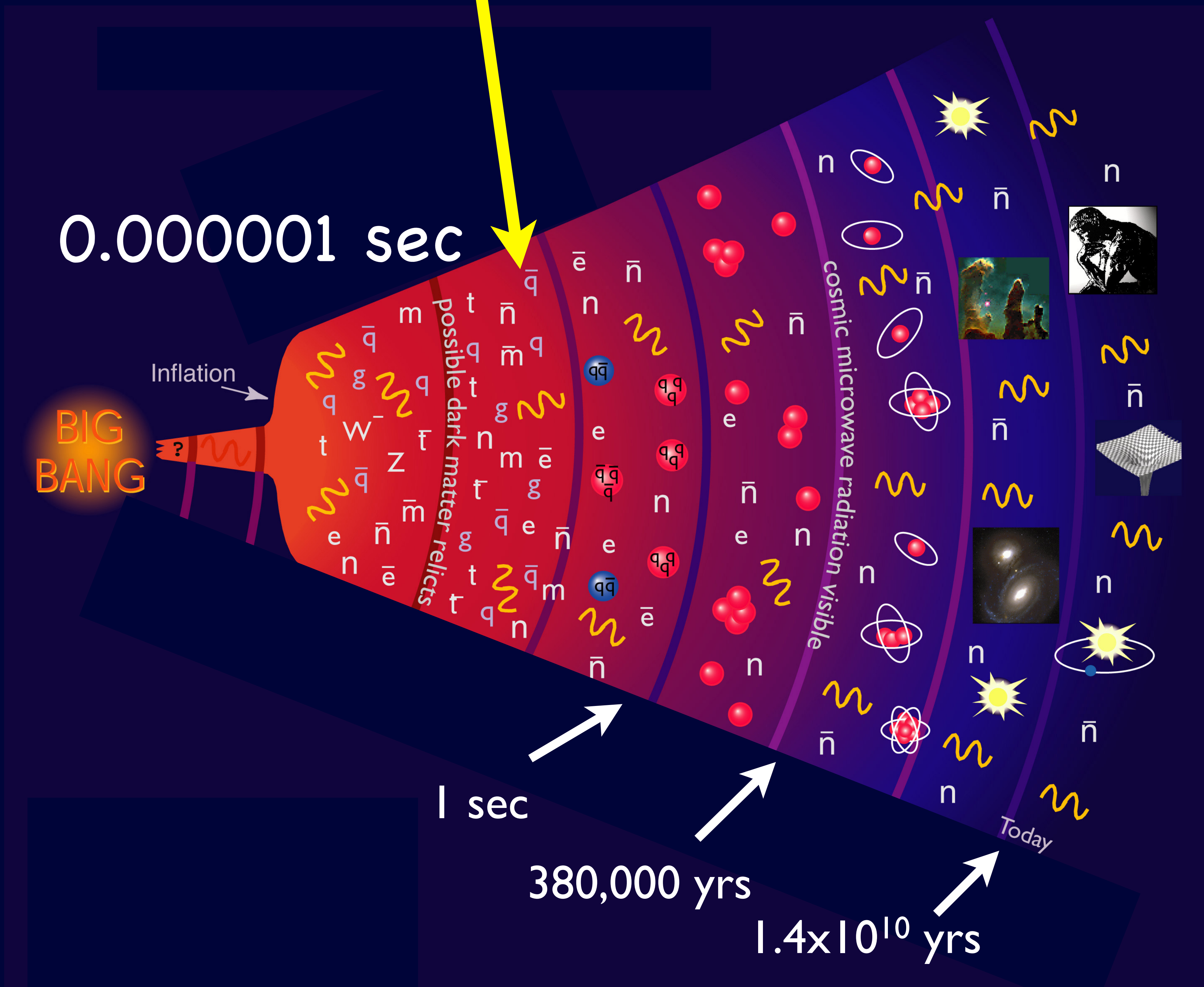
(heavy) Right-handed neutrino

Next,...

Each particle has its own **anti-particle.**



In the very early Universe,....



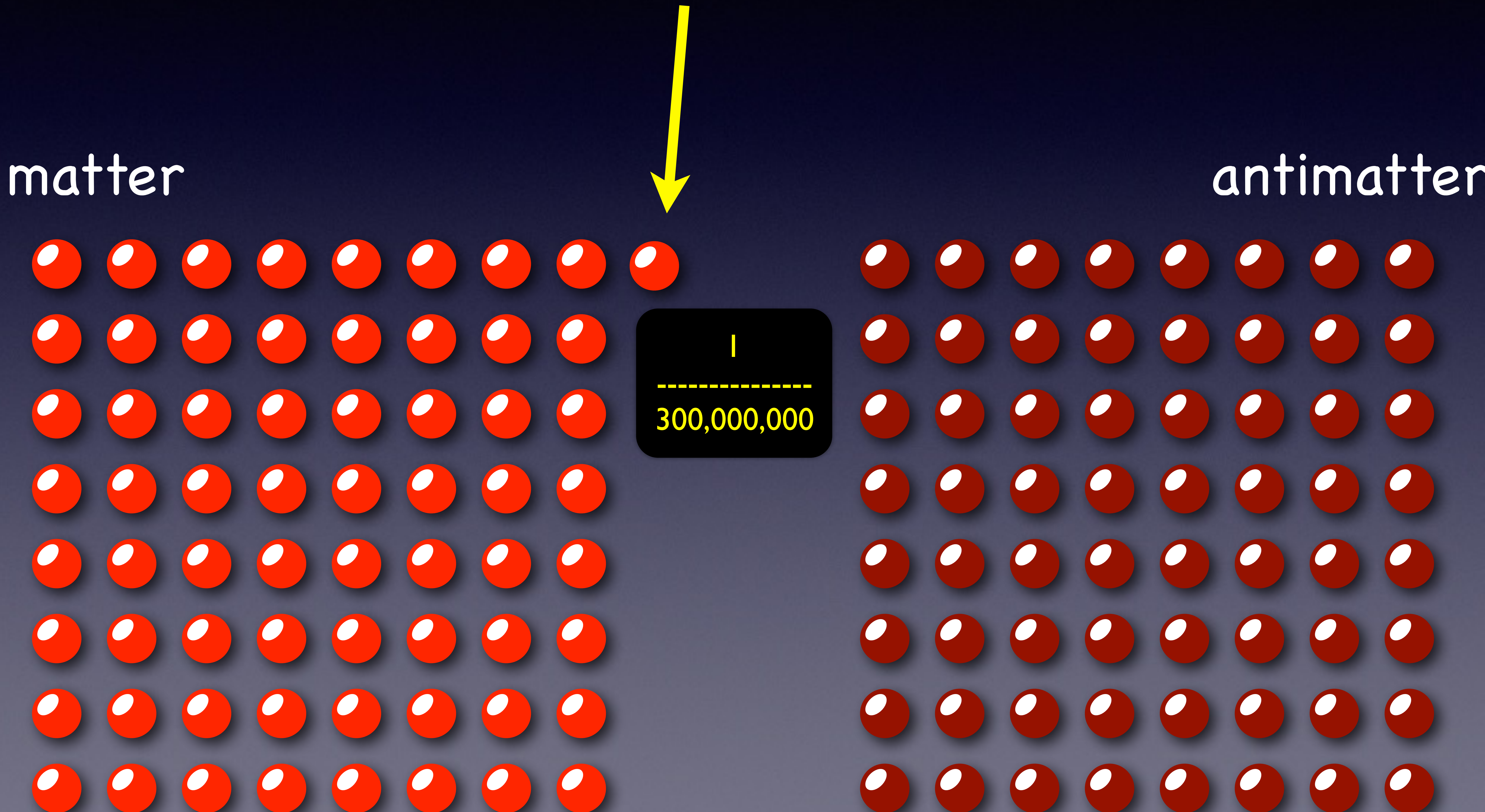
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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.

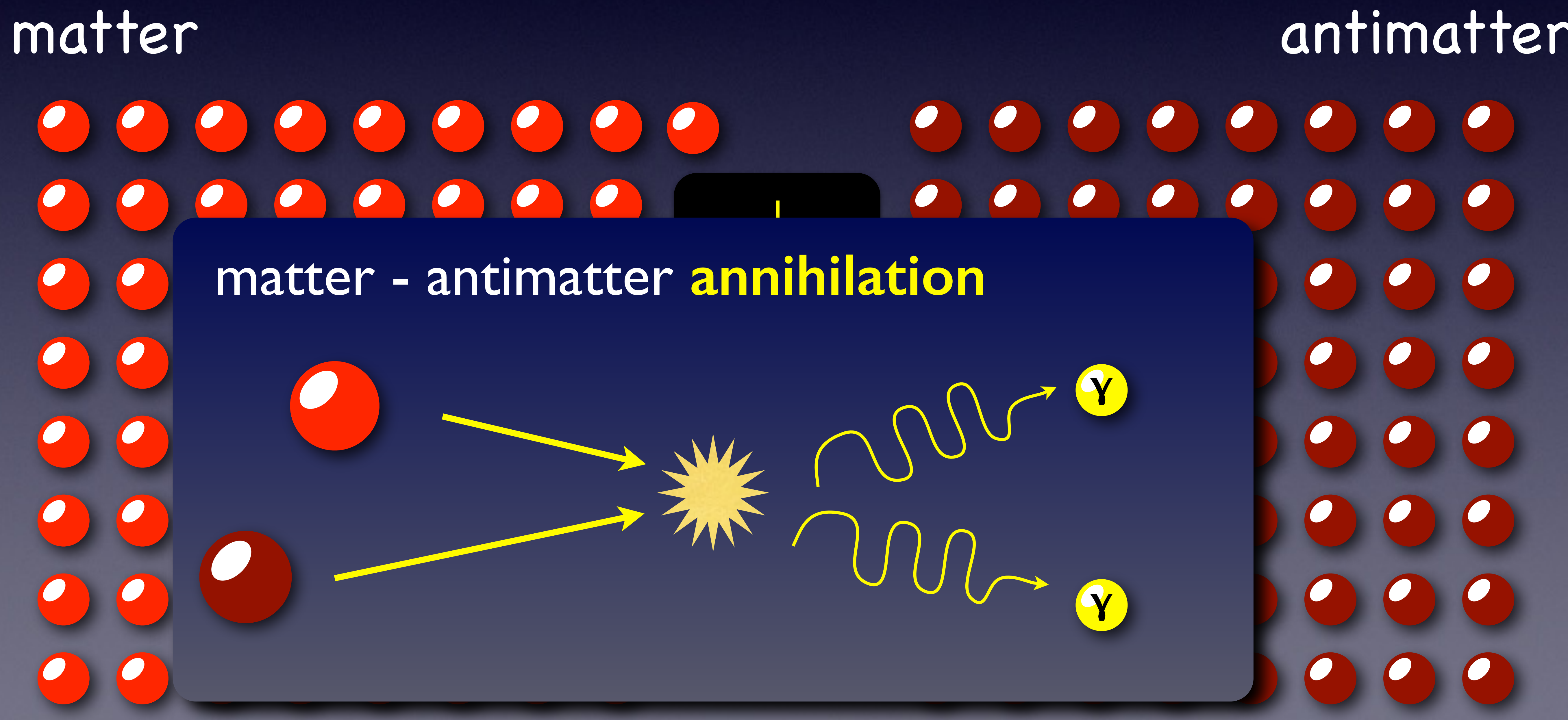
But there was tiny excess of matter over anti-matter.



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

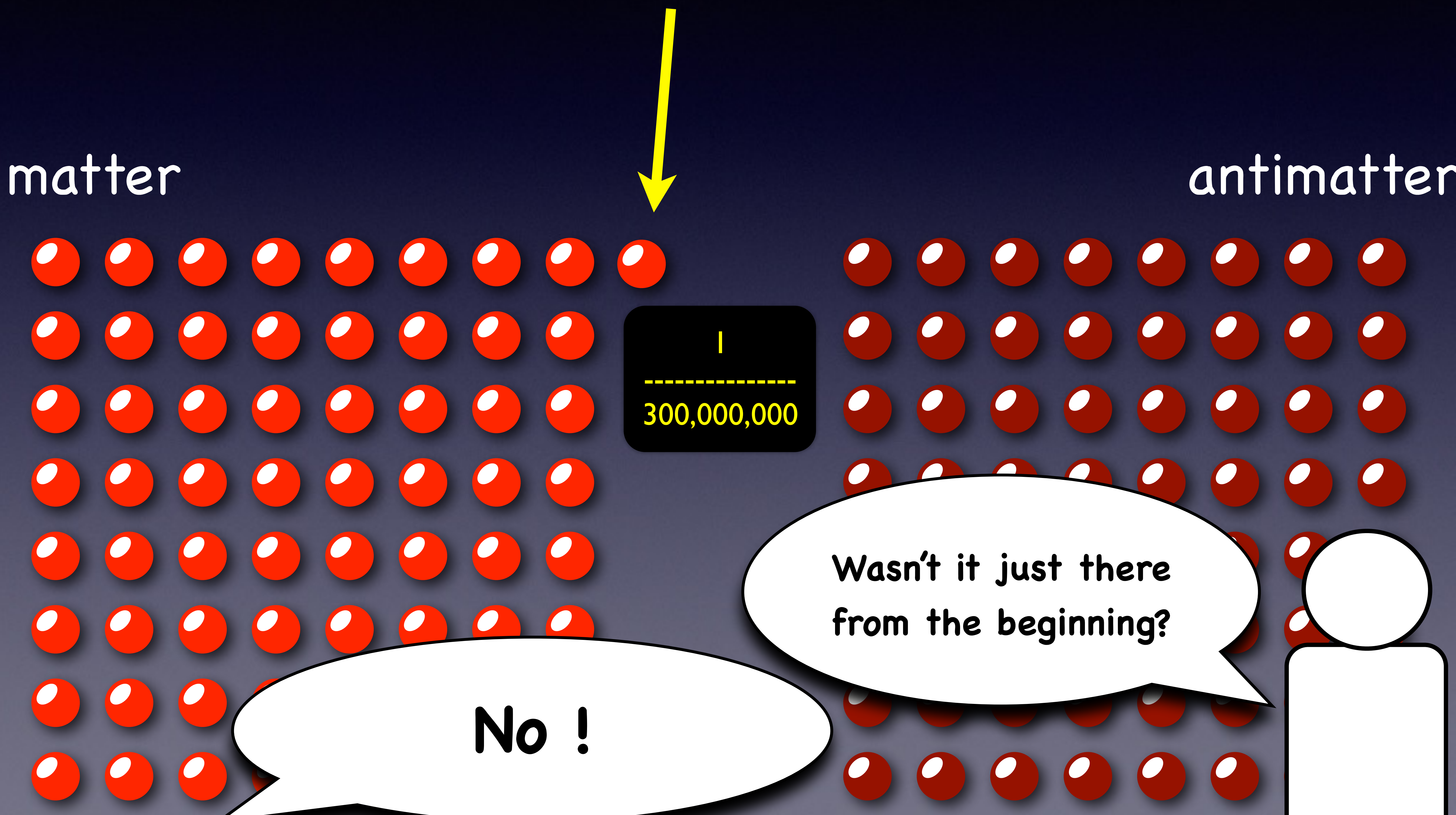
(no antimatter)

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

are made from this leftover matter.

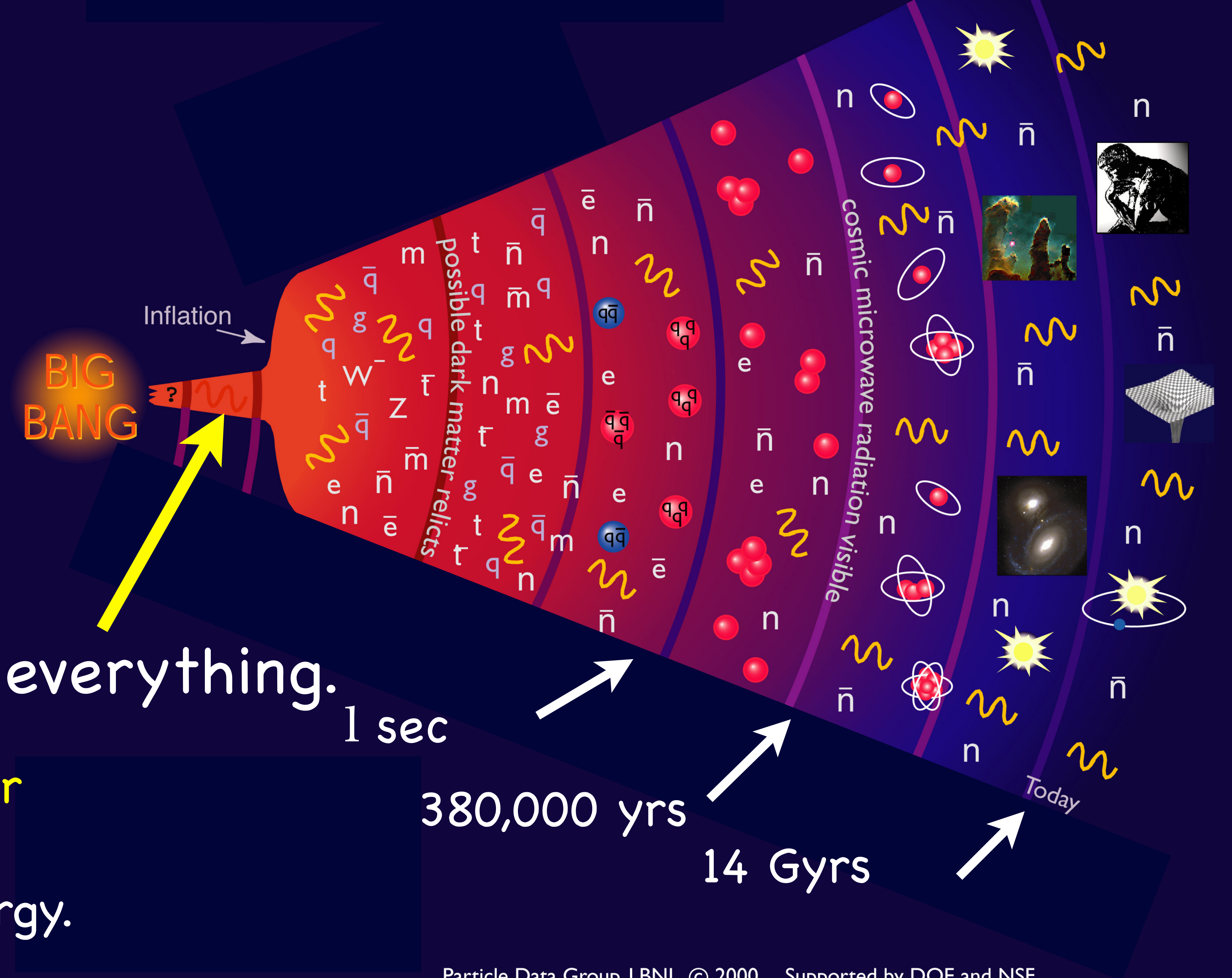
Puzzle

How was the initial excess of matter created ?



Puzzle

How was the initial excess of matter created ?



Inflation dilutes everything.

1 sec

380,000 yrs

14 Gyrs

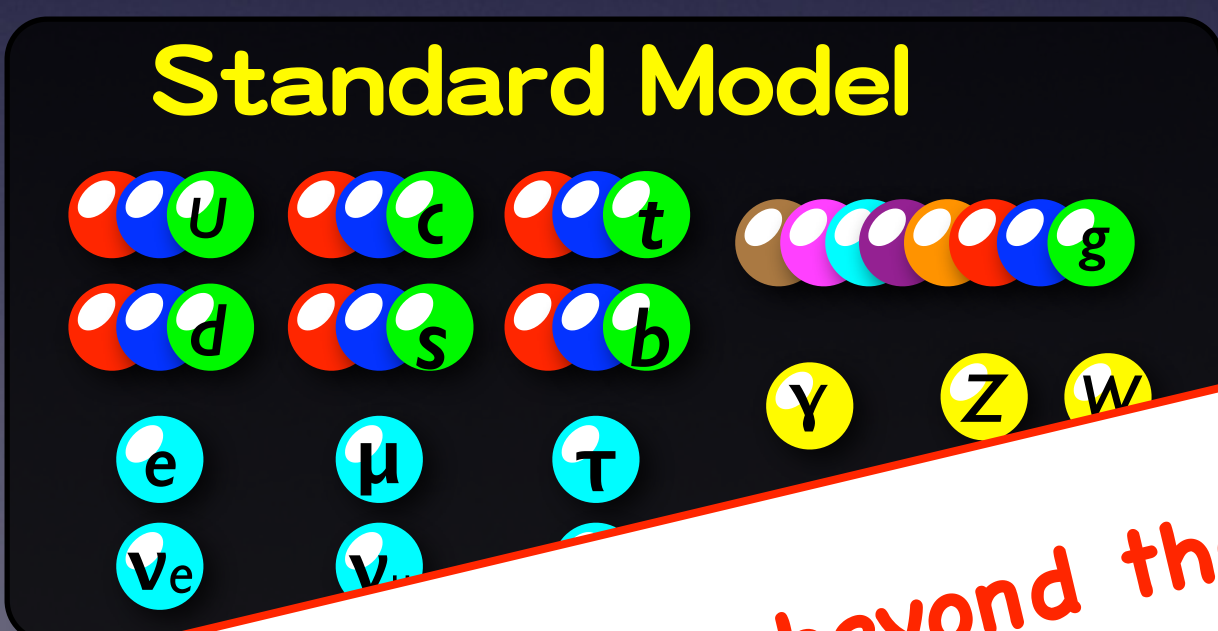
Matter and antimatter
had to be generated
from the vacuum energy.

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

Puzzle

How was the initial excess of matter created ?

Some mechanism ("Baryogenesis")
is necessary to create
matter - antimatter asymmetry.



... does not work.

Three necessary c
for Ba

olation
olation ... (but too small)
out-of-equilibium

Something beyond the Standard Model is necessary.

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

tiny neutrino mass

Grand Unified Theory

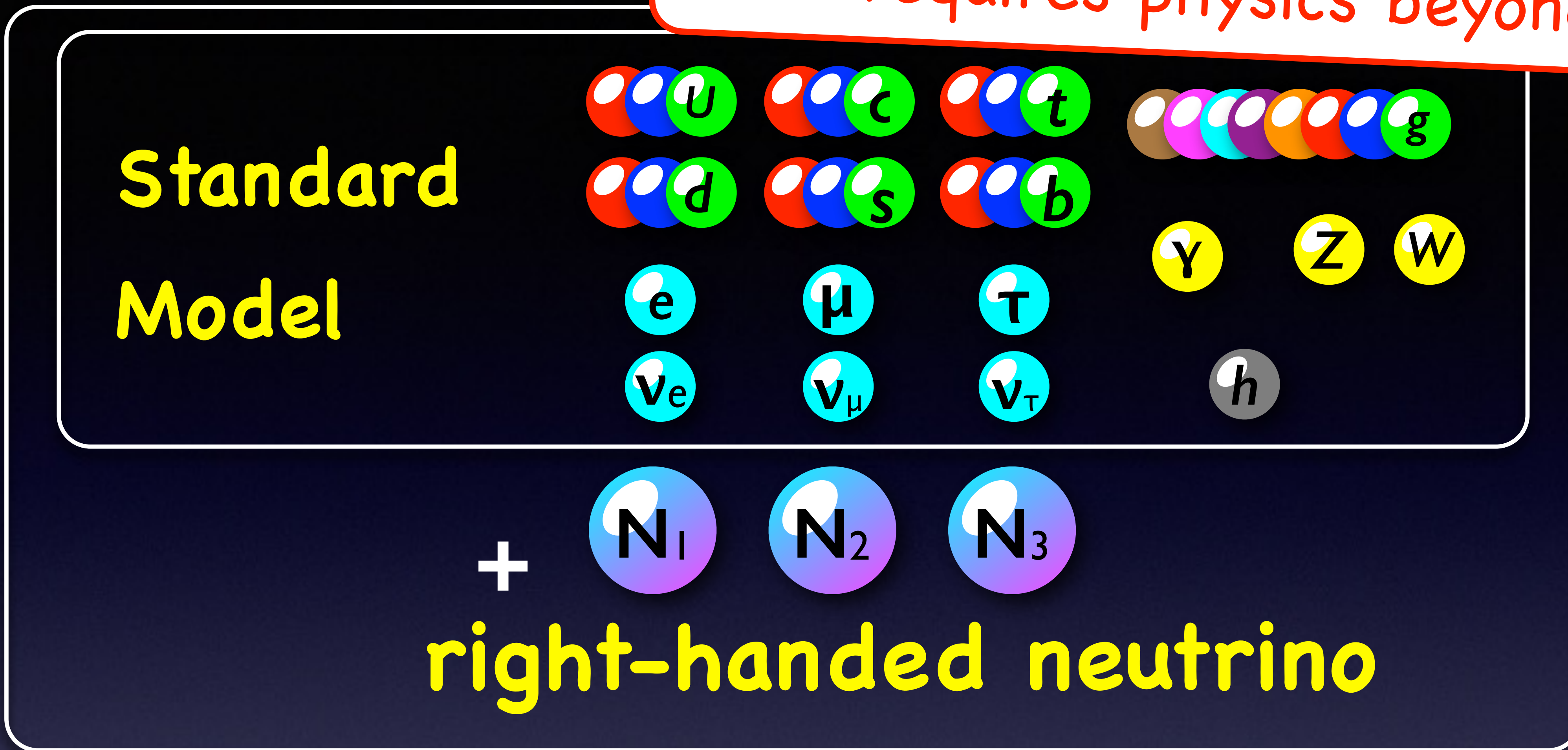
inflation

baryogenesis

(heavy) Right-handed neutrino

matter > antimatter

requires physics beyond SM.



- an attractive candidate : **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_I are in thermal bath.

Leptogenesis

[Fukugita, Yanagida,1986]

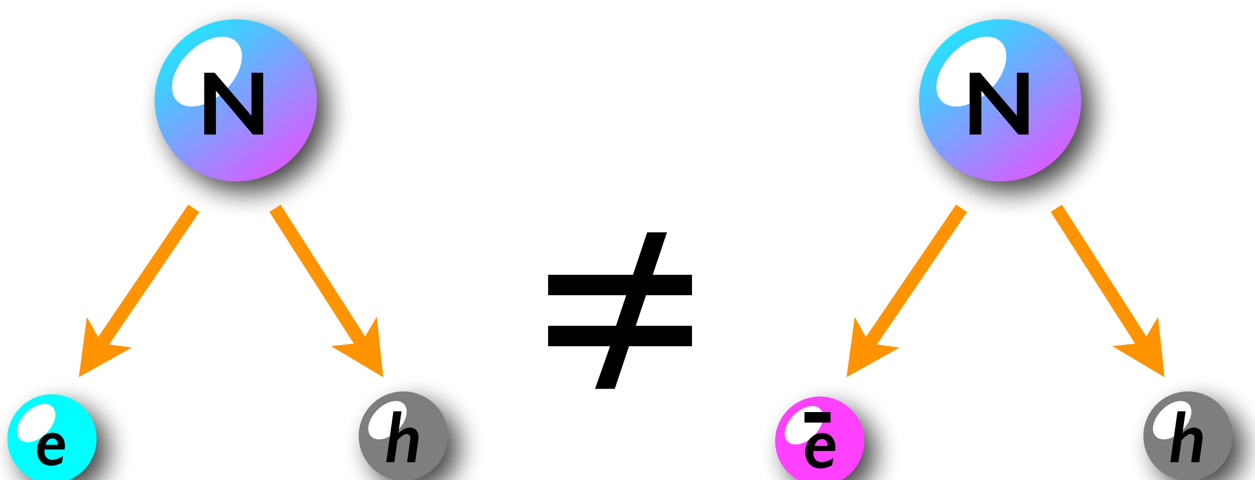
scenario

temperature RH ν'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, $\Delta L \neq 0$.



CP violation
is essential.

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, $\Delta L \neq 0$.

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)

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

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

effective CP violating phase

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

Yukawa

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

Leptogenesis

[Fukugita, Yanagida,1986]

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)

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

wash-out factor (< 1)

(calculable: by Boltzmann eq.)

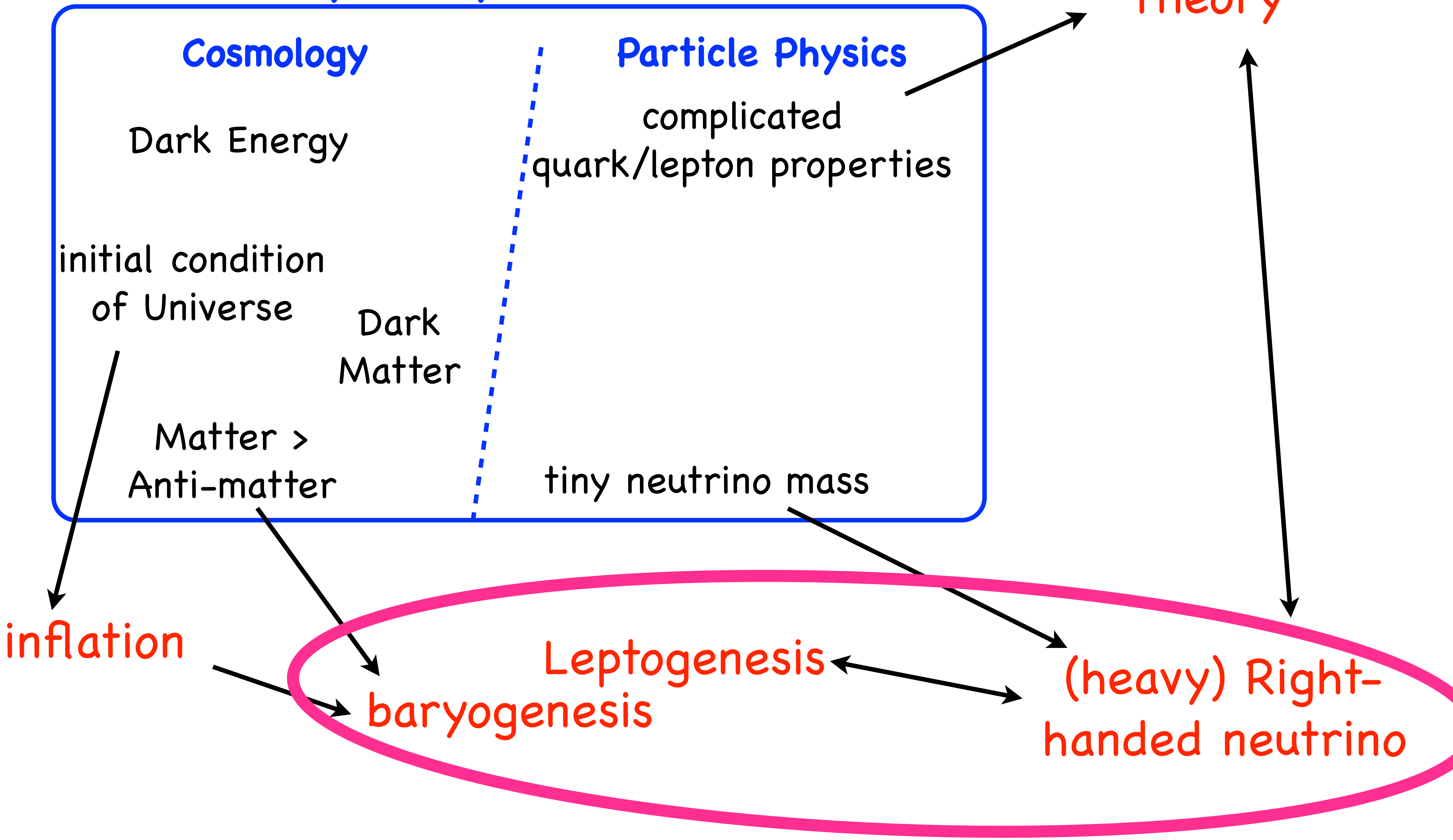
effective CP violating phase

$$\frac{n_B}{s}\text{(observed)} \simeq 0.8 \times 10^{-10}$$

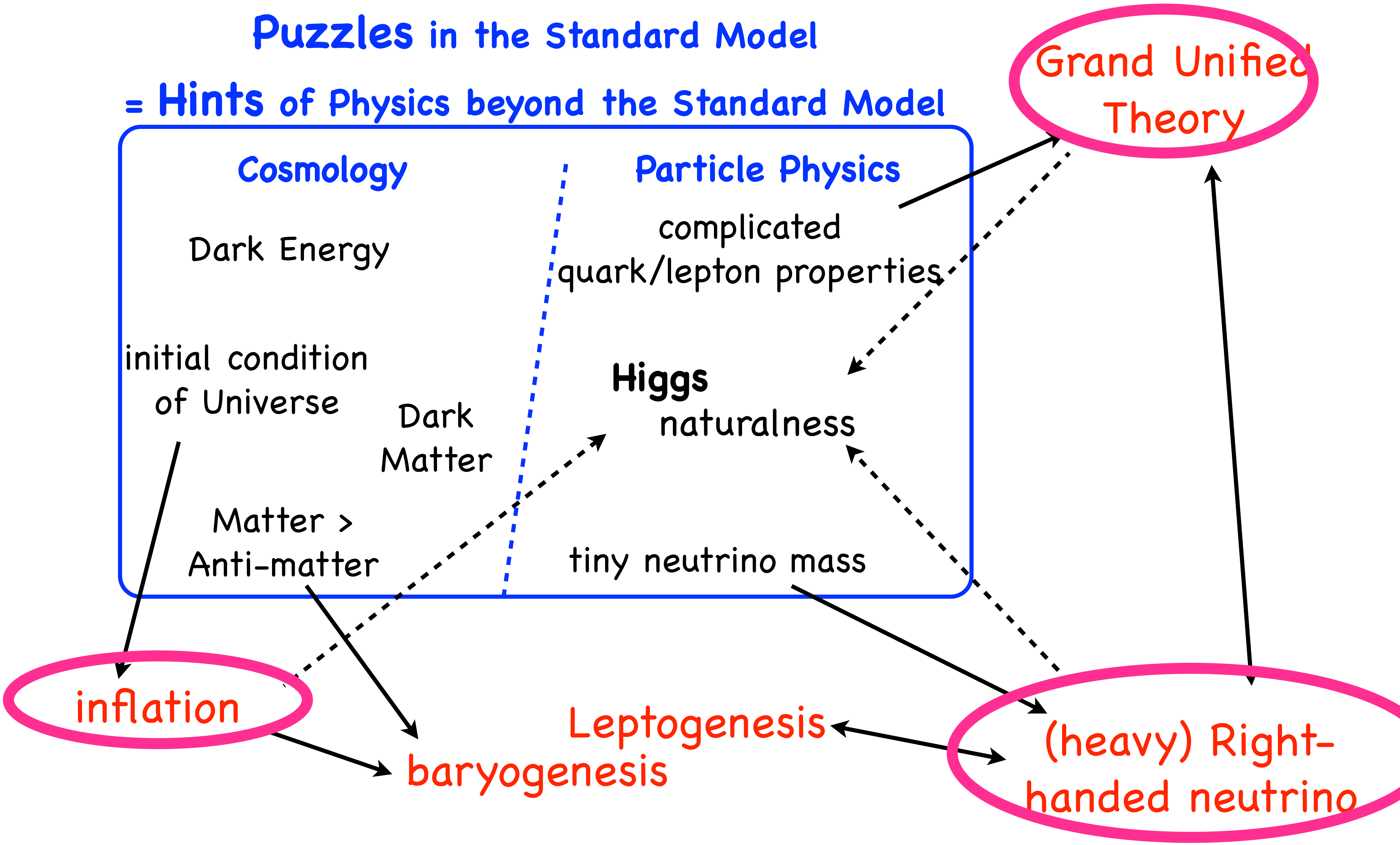
It works !! (for M_R > 10^9–10^{10} GeV).

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



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



Next,...

Higgs mass = 125 GeV, on the other hand…..

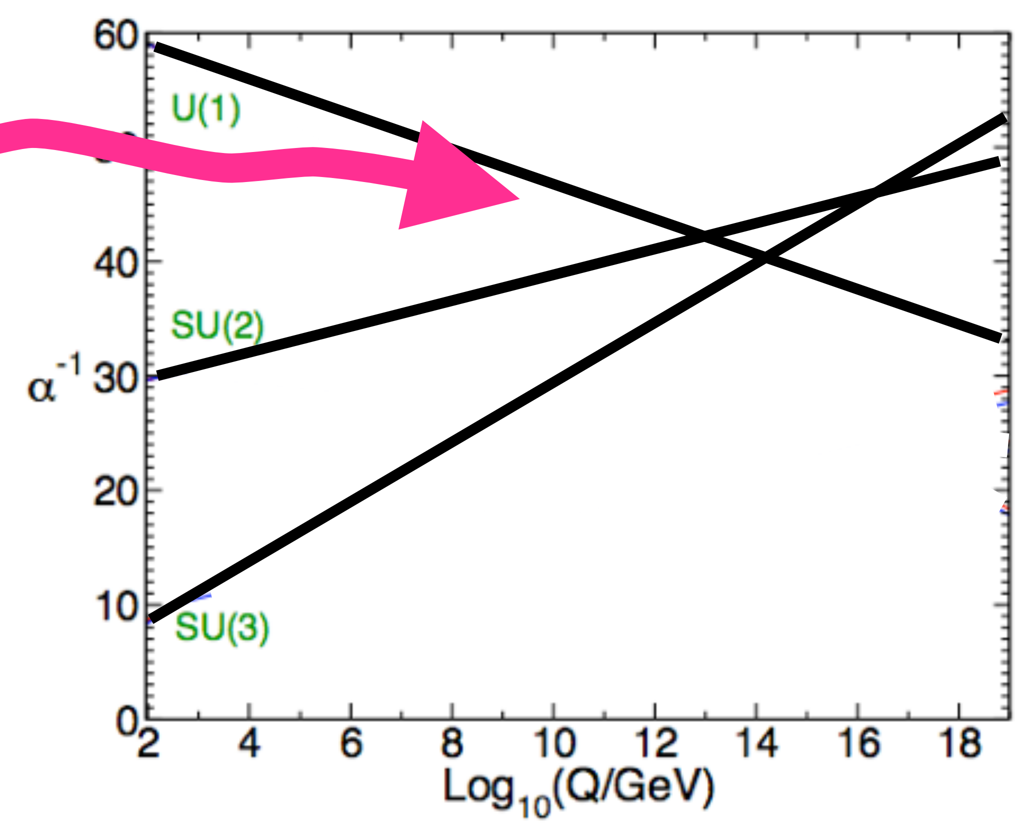
1. heavy right-handed neutrino

To explain the matter asymmetry, N_1 **mass > 10^9 GeV** is necessary.

(Davidson, Ibarra,'02: in the simplest scenario. See also KH, Murayama, Yanagida'01.)

2. Grand Unified Theory

GUT scale = 10^{14}– 10^{16} GeV



3. Inflation

……also requires a high scale.

For instance, in chaotic inflation,

$$\text{inflaton mass} \sim \underbrace{\text{Planck scale}}_{(\sim 10^{18}\,\text{GeV})} \times \underbrace{\frac{\delta T}{T}}_{(\sim 10^{-5})} \sim \mathbf{10^{13}\ GeV}$$

Higgs mass = 125 GeV, on the other hand.....

1. heavy right-handed neutrino

To explain the matter asymmetry, N_1 **mass > 10^9 GeV** is necessary.

(Davidson, Ibarra,'02: in the simplest scenario. See also KH, Murayama, Yanagida'01.)

If this simple scenario is correct, 4d perturbative QFT picture

seems valid at least up to 10^9 GeV.

then,...

naturalness problem (more on this in § 3)

$$m_H^2 \;=\; m_{H,0}^2 \;+\; \Lambda^2 \qquad\qquad (\Lambda \gg m_H)$$

(fine tuning like 1.0000000000000001 - 1)

This unnaturalness can be avoided by.....

Supersymmetry (SUSY)

		spin		
quarks q	$\frac{1}{2}$	$\longleftrightarrow$	0	squarks $\tilde{q}$
leptons ℓ	$\frac{1}{2}$	$\longleftrightarrow$	0	sleptons $\tilde{\ell}$
gauge bosons A_μ	1	$\longleftrightarrow$	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	$\longleftrightarrow$	$\frac{1}{2}$	higgsinos $\tilde{h}$

(more on this in § 3)

fine-tuning problem

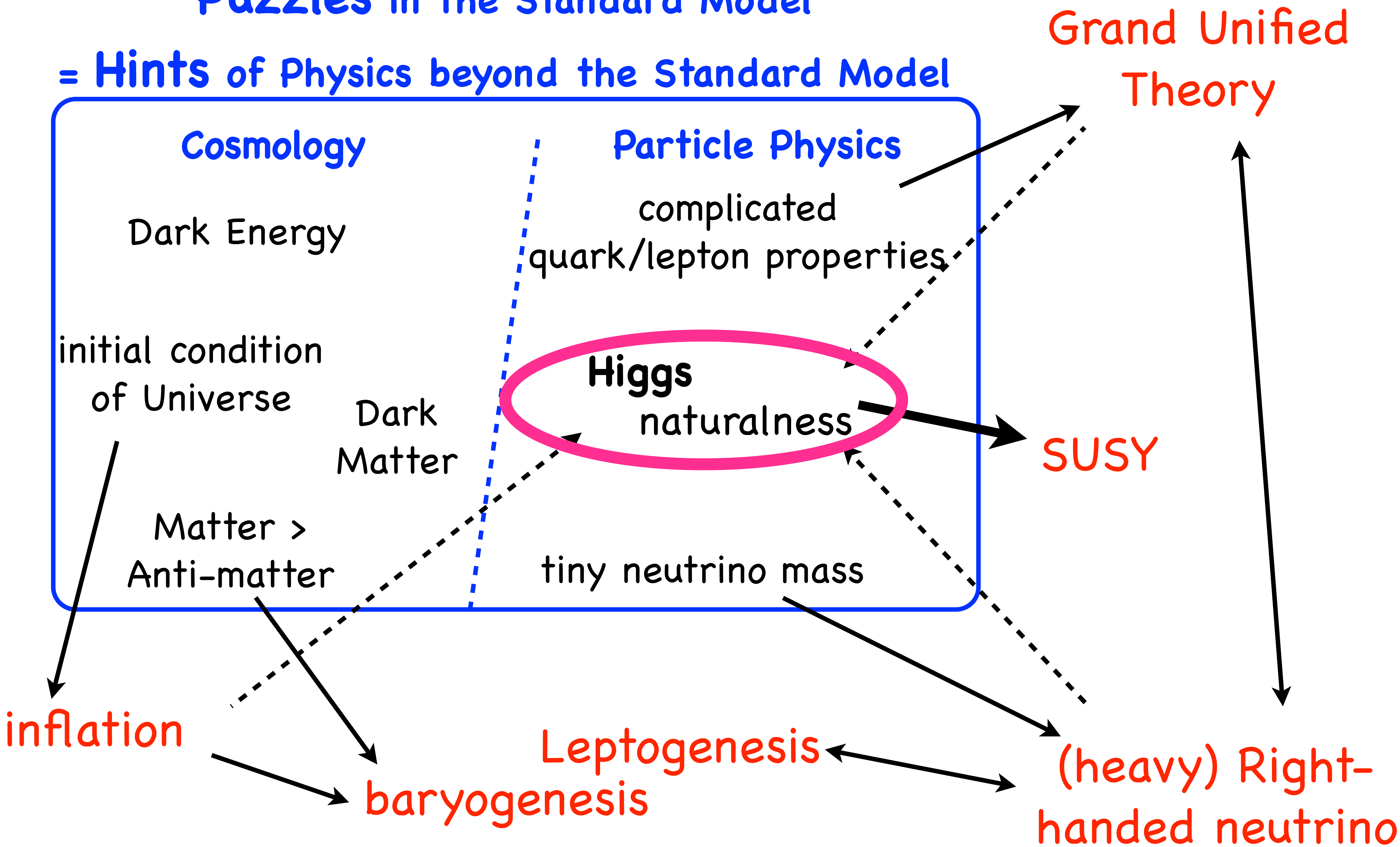
$$m_H^2 = m_{H,0}^2 + \Lambda^2 \qquad (\Lambda \gg m_H)$$

(fine tuning like 1.0000000000000001 - 1)

$\rightarrow$ solved by the supersymmetry !

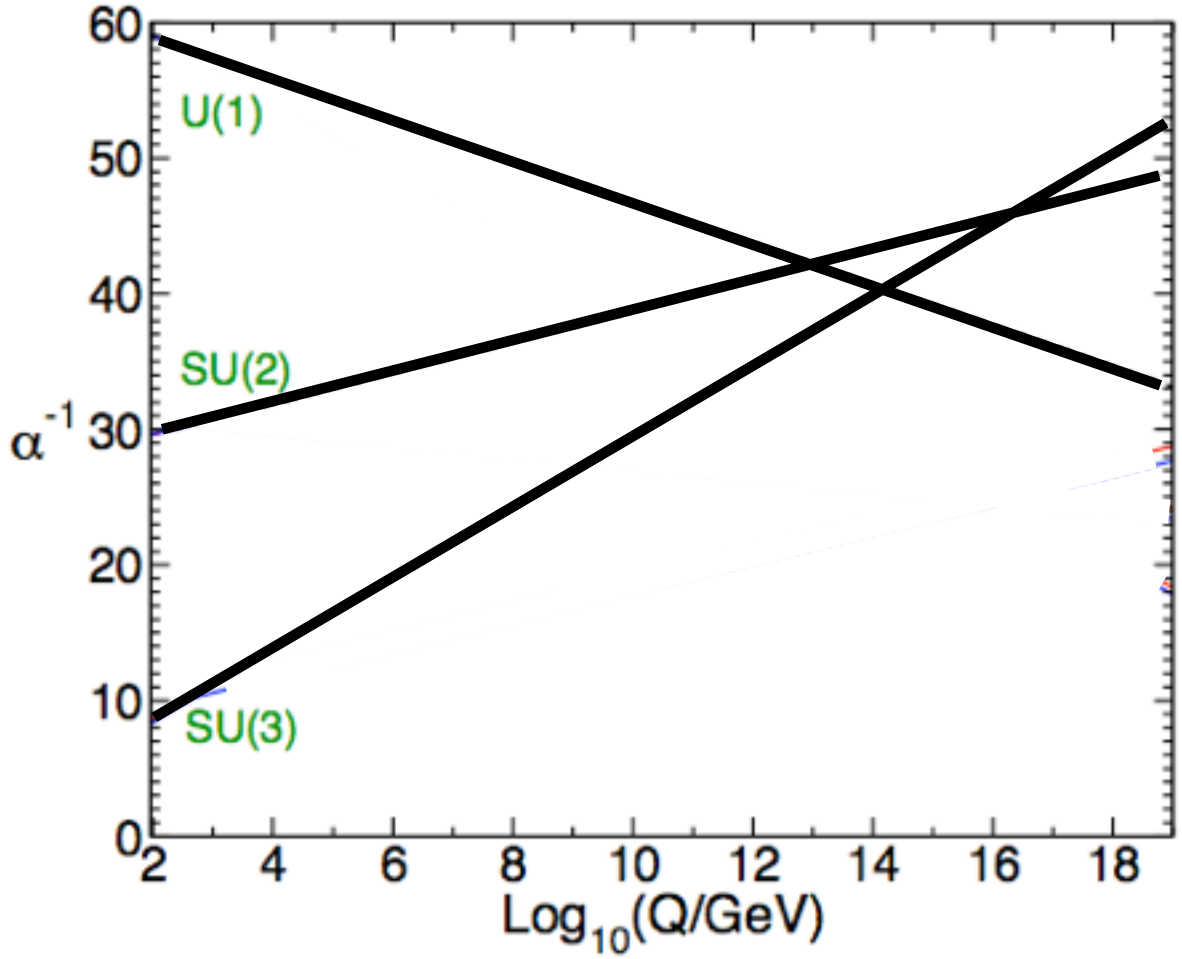
$$m_H^2 = m_{H,0}^2 + (\Lambda^2 - \Lambda^2)$$

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

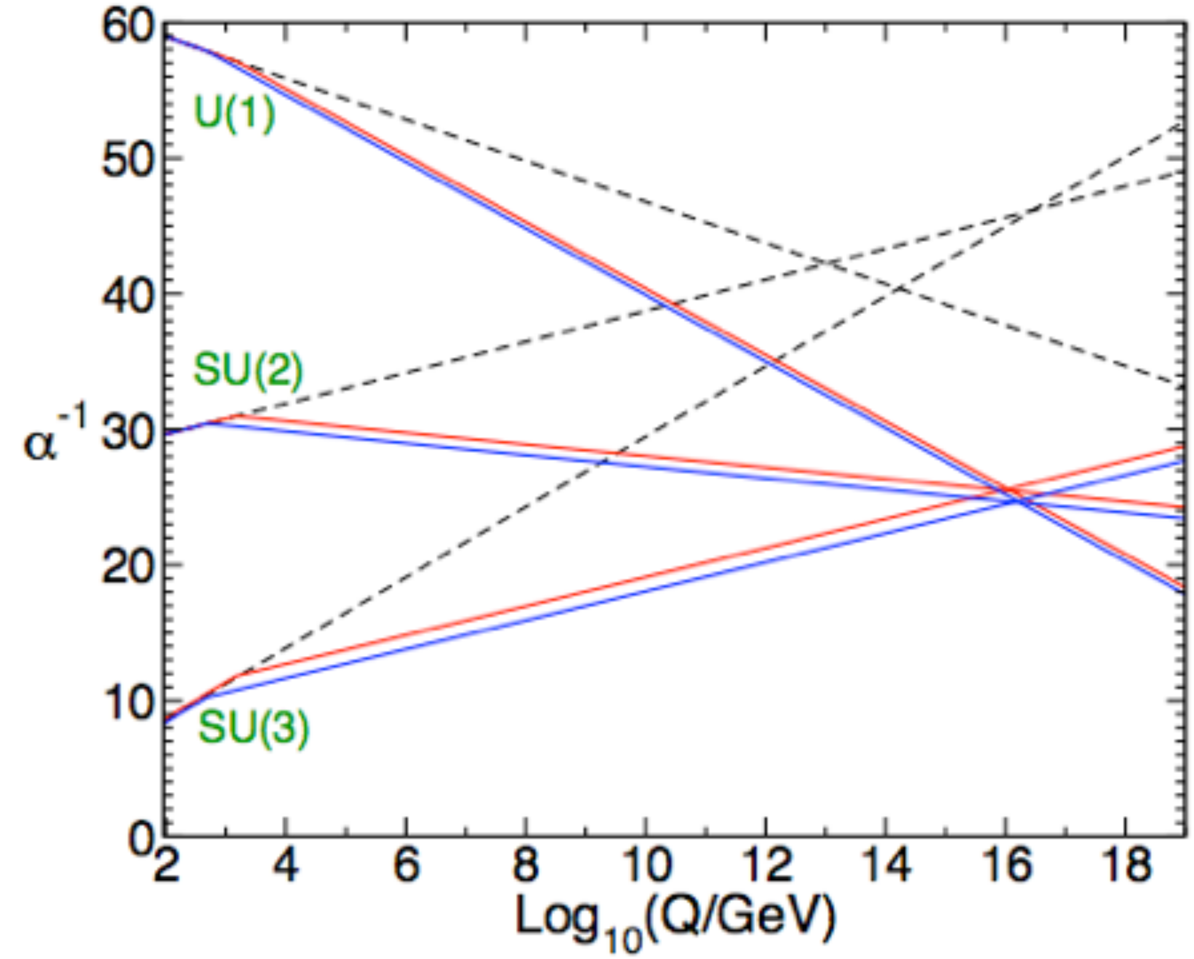


furthermore...

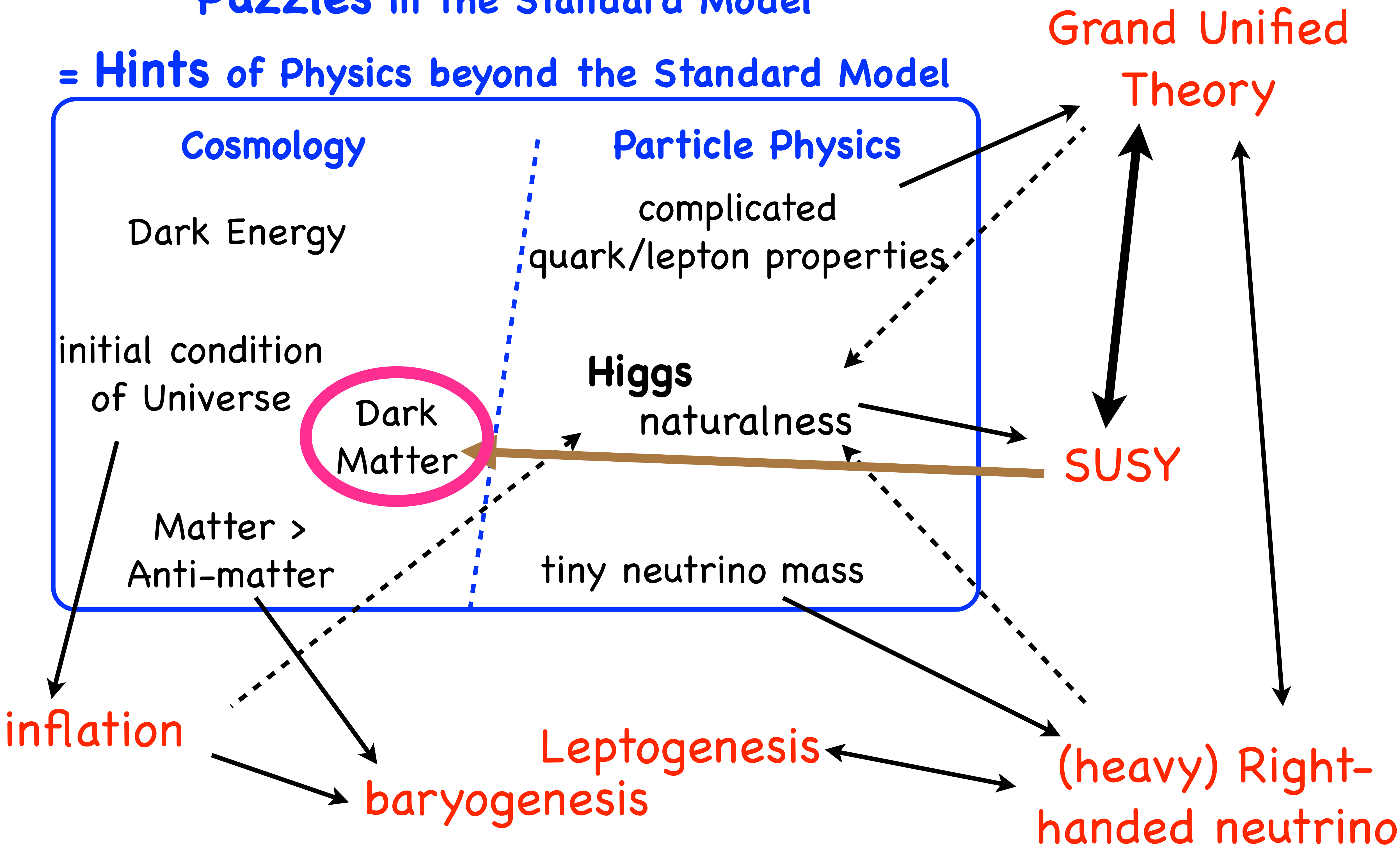
Standard Model



Standard Model + SUSY



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



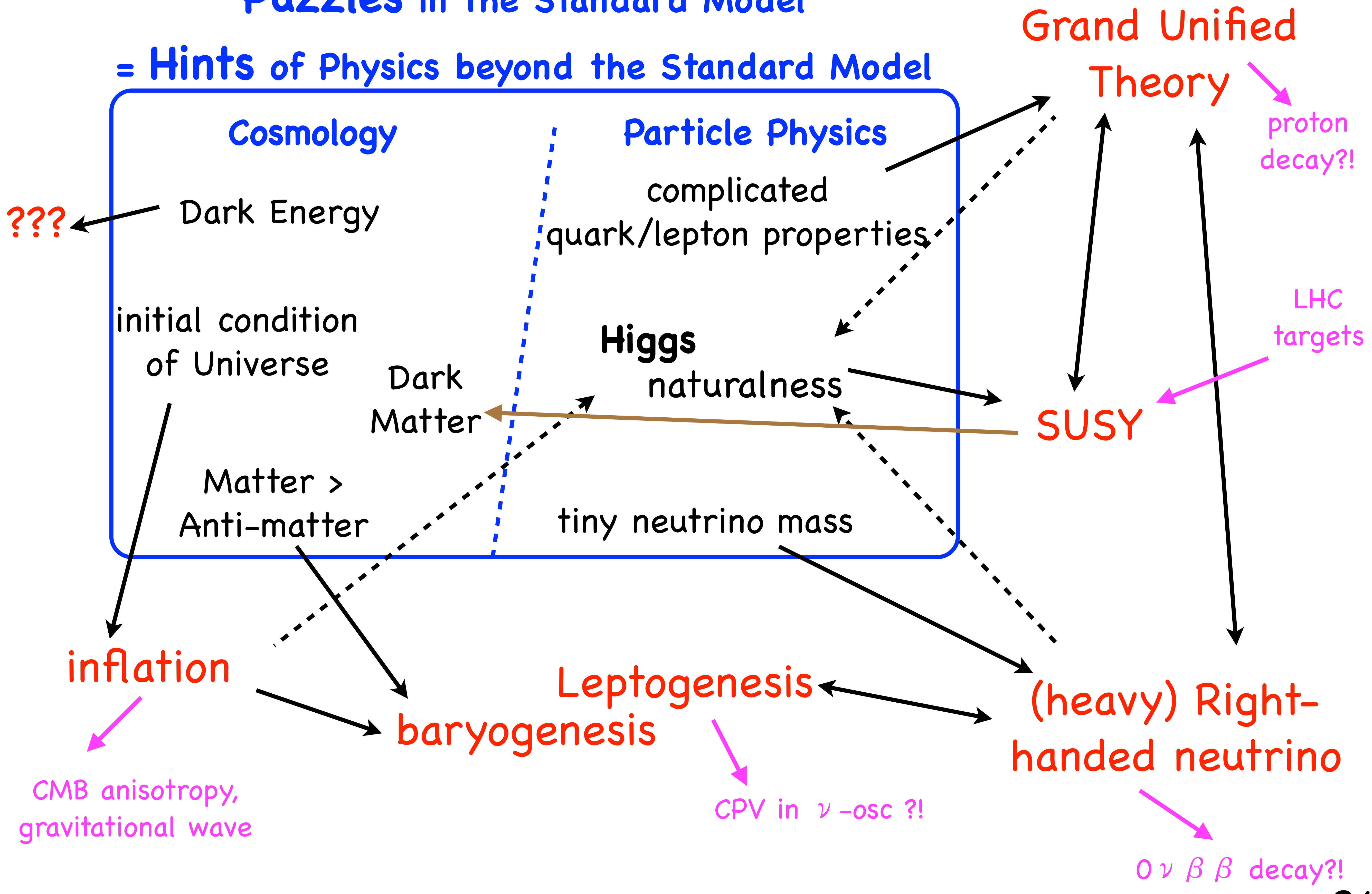
furthermore...

[cf. Lectures by Prof. Tait.]

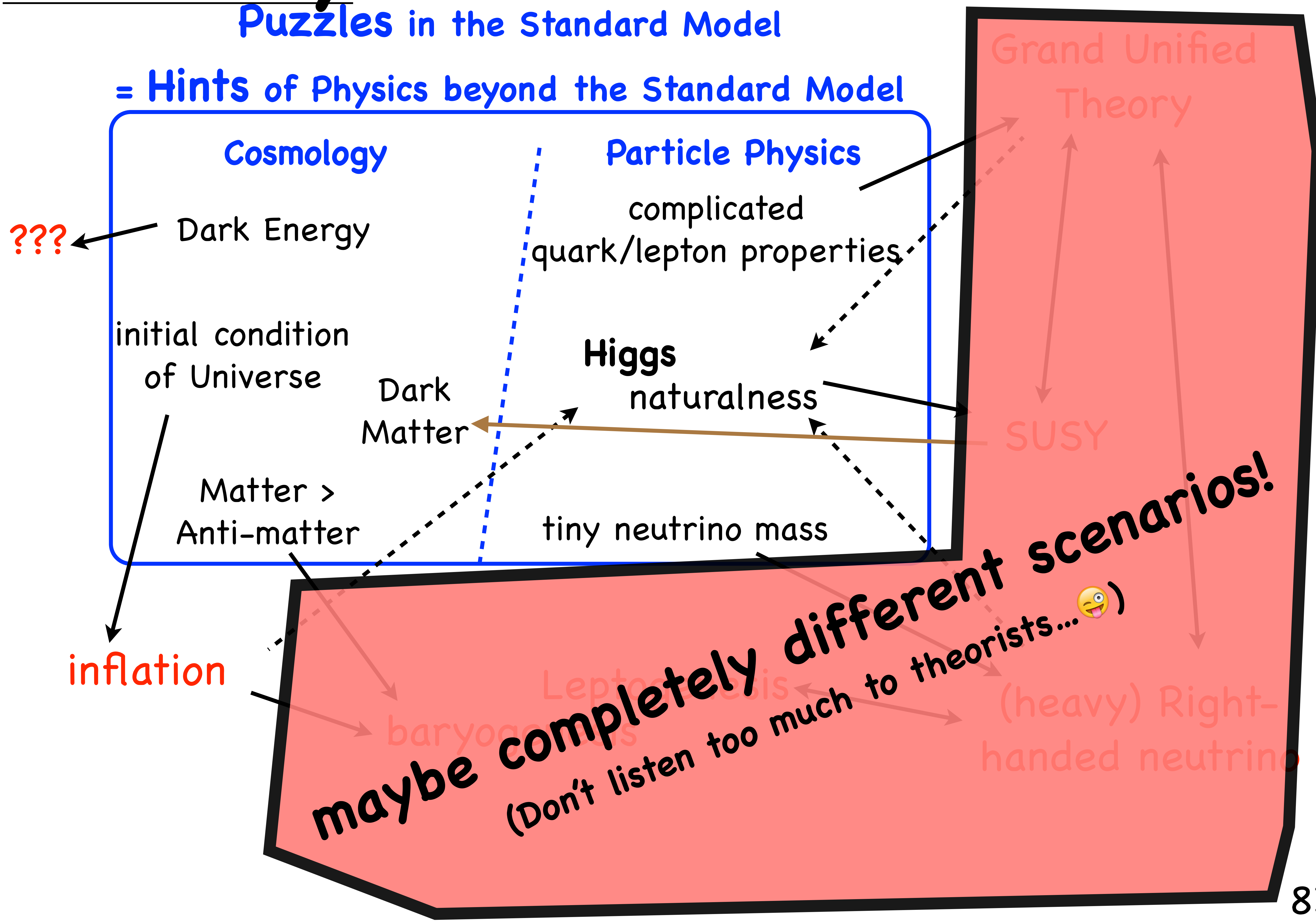
Summary

Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Summary



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
Dark
Matter
Higgs
naturalness
Matter >
Anti-matter
tiny neutrino mass
inflation
Grand Unified
Theory
SUSY
(heavy) Right-
handed neutrino
maybe completely different scenarios!
(Don't listen too much to theorists...😜)

CONTENTS

Part 1: [projector]

Overview of BSM physics

..... done!

Part 3: [projector]

Supersymmetry

(> 2 lectures)

Part 2: **[blackboard]**

Mini-reviews on each topic,

2-A: GUT

2-B: Neutrino mass and seesaw

2-C: Standard Cosmology

2-D: Inflation

2-E: Leptogenesis

(> 3 lectures)

Which part next?

-> Let's take a vote.