Higgs Physics
and
Beyond the Standard Model

(mainly SUSY)

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@AEPSHEP2014, Puri,
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Part 2

Plan

0. Introduction
1. Higgs
2. Beyond the Standard Model

We are still here...

2.1. puzzles in SM = hints of BSM.

2.2. renormalization and naturalness

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

Appendix:
mini review of Grand Unified Theory

necessary preliminary knowledge

- non-Abelian gauge theory
- group theory (a little)
- Standard Model

Appendix:
mini review of Grand Unified Theory

A.1 Standard Model

$$\mathcal{L} = \sum_{\text{matters}} \bar{\psi} i \gamma^{\mu} D_{\mu} \psi - \frac{1}{4} \sum_{\text{gauge bosons}} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

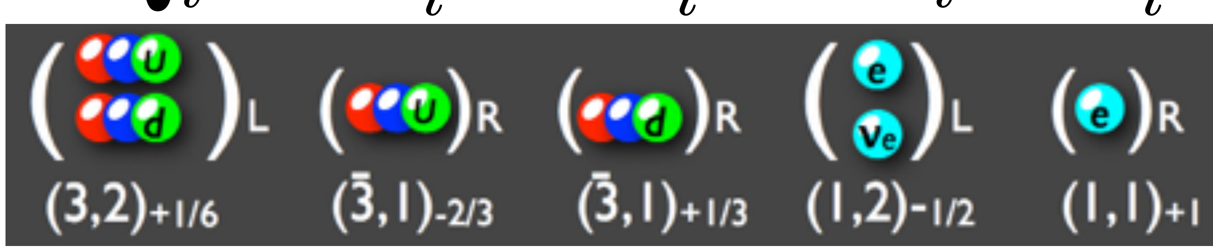
$$D_{\mu}\psi = (\partial_{\mu} + i g A^{(a)}_{\mu} T^{(a)})\psi$$

- gauge bosons

$$\begin{array}{ll} \text{SU}(3) & G^{1\sim 8}_{\mu} \\ \text{SU}(2) & W^{1\sim 3}_{\mu} \\ \text{U}(1) & B_{\mu} \end{array} \Bigg\} \overset{\text{Higgs mechanism}}{\Longrightarrow} \begin{cases} W^{\pm}_{\mu}, Z_{\mu} \\ A_{\mu} \text{ (photon)} \end{cases}$$

- matters

$\mathbf{Q}_i$ $\mathbf{u}^c_i$ $\mathbf{d}^c_i$ $\mathbf{L}_i$ $\mathbf{e}^c_i$



$\times$ 3 families

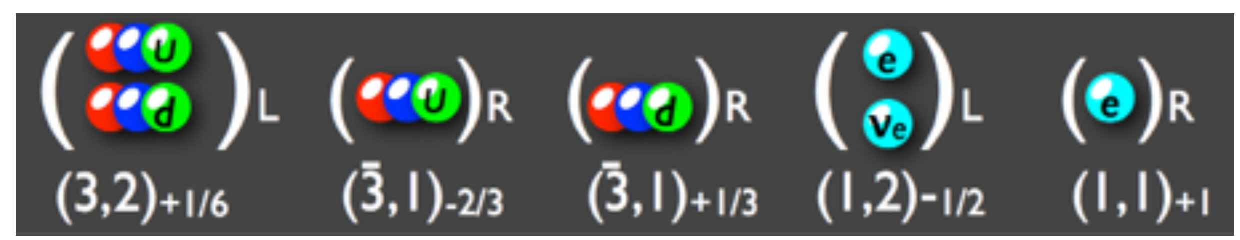
Appendix:
mini review of Grand Unified Theory

A.2 GUT

- conditions

A. includes SU(3) x SU(2) x U(1) as subgroups

B. has a representation including $\mathbf{Q}_i$ $\mathbf{u}_i^c$ $\mathbf{d}_i^c$ $\mathbf{L}_i$ $\mathbf{e}_i^c$



- from **A**, the rank ≧ 4.

(must include at least 4 commutative generators, $\underbrace{T_3, T_8}_{SU(3)}, \underbrace{\sigma_3}_{SU(2)}, U(1)$.)

- simplest possibility: rank = 4.

then, only 5 groups
(within compact simple Lie groups)

$$\left\{ \begin{array}{l} SU(5) \\ SO(8) \\ SO(9) \\ SP(8) \\ F_4 \end{array} \right.$$

Let's consider SU(5). ($SU(5)$)

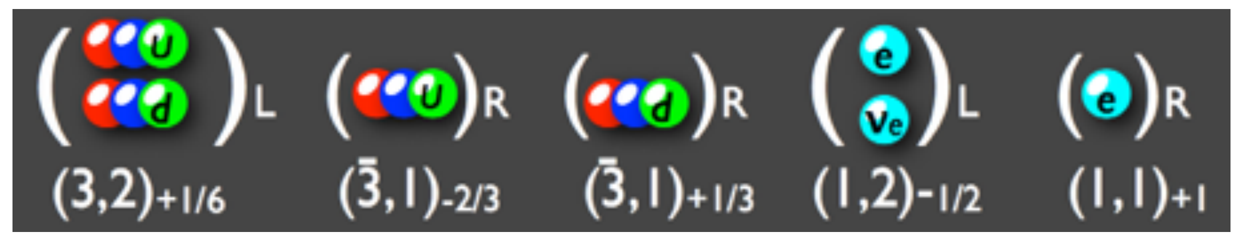
$SO(8)$, $SO(9)$, $SP(8)$, F_4: don't have complex reps.
—> don't satisfy **B.**

Appendix:
mini review of Grand Unified Theory

A.3 GUT representations

- Let' start from the fundamental representation of SU(5) = 5 rep.

From the matter content —> $\mathbf{Q}_i$ $\mathbf{u}_i^c$ $\mathbf{d}_i^c$ $\mathbf{L}_i$ $\mathbf{e}_i^c$



... there are two possibilities to add up to five:

$$\mathbf{u}^c + \mathbf{L} \qquad \text{or} \qquad \mathbf{d}^c + \mathbf{L}$$

- let's first try

$$\mathbf{u}^c + \mathbf{L}$$

$$(\bar{3},1)_{-2/3} + (1,2)_{-1/2}$$

$$Y \begin{pmatrix} \mathbf{u}^c \\ \mathbf{L} \end{pmatrix} = \underbrace{\begin{pmatrix} -2/3 & & & & \\ & -2/3 & & & \\ & & -2/3 & & \\ & & & -1/2 & \\ & & & & -1/2 \end{pmatrix}}_{\text{not traceless}} \begin{pmatrix} \mathbf{u}^c \\ \mathbf{L} \end{pmatrix}$$

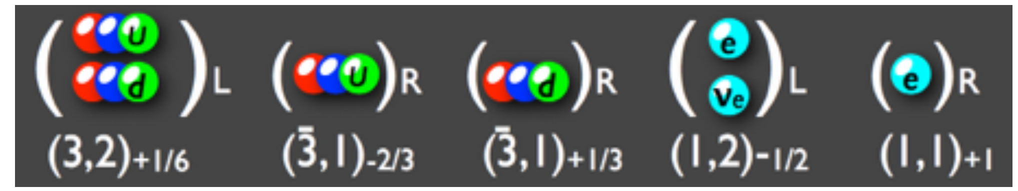
hypercharge

not traceless
-> not in SU(5) generator

Appendix:
mini review of Grand Unified Theory

A.3 GUT representations

$\mathbf{Q}_i$ $\mathbf{u}_i^c$ $\mathbf{d}_i^c$ $\mathbf{L}_i$ $\mathbf{e}_i^c$



- the other possibility of 5 rep. is...

$$\mathbf{d}^c + \mathbf{L}$$

$$(\bar{3}, 1)_{1/3} + (1, 2)_{-1/2} \quad = \bar{\mathbf{5}} \text{ representation!}$$

$$\text{gauge trf.} \quad \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix} \longrightarrow \exp\left[-i \sum_{a=1}^{24} \lambda^a(x) \left(T^a_{\mathrm{SU}(5)}\right)^*\right] \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix}$$

$$\text{covariant derivative} \quad D_\mu \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix} = \left[\partial_\mu + i g_5 \sum_{a=1}^{24} A_\mu^{(a)} \left(T^a_{\mathrm{SU}(5)}\right)^*\right] \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix}$$

SU(5) generators

SU(5) gauge coupling

gauge bosons

Appendix:
mini review of Grand Unified Theory

A.3 GUT representations

covariant derivative $$D_\mu \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix} = \left[\partial_\mu + i g_5 \sum_{a=1}^{24} A_\mu^{(a)} \left(T^a_{\mathrm{SU(5)}} \right)^* \right] \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix}$$

SU(5) generators

$$\mathbf{5}\left\{ \underbrace{\left(T^a_{\mathrm{SU(5)}} \right)}_{\mathbf{5}} \right. = \left(\begin{array}{c|c} T^{1\sim 8}_{\mathrm{SU(3)}} & \\ \hline & 0 \end{array} \right) + \left(\begin{array}{c|c} 0 & \\ \hline & \frac{1}{2}\sigma^{1\sim 3}_{\mathrm{SU(2)}} \end{array} \right) + \sqrt{\frac{3}{5}} \left(\begin{array}{ccc|cc} 1/3 & & & & \\ & 1/3 & & & \\ & & 1/3 & & \\ \hline & & & -1/2 & \\ & & & & -1/2 \end{array} \right) + \left(\begin{array}{ccc|cc} & & & * & * \\ & & & * & * \\ & & & * & * \\ \hline * & * & * & & \\ * & * & * & & \end{array} \right)$$

SU(3) <-> gluon

SU(2) <-> weak bosons

U(1)Y <-> B_μ

remaining 12 <-> X, Y gauge bosons

Note: normalization

$$\mathrm{tr}(T^a T^a) = \frac{1}{2}\delta^{ab}$$

Appendix:
mini review of Grand Unified Theory

A.3 GUT representations

- And the remaining matter particle also unify as...

$$\underset{(3,2)_{1/6}}{\mathbf{Q}} + \underset{(\bar{3},1)_{-2/3}}{\mathbf{u}^c} + \underset{(1,1)_1}{\mathbf{e}^c} = \mathbf{10} \text{ representation!}$$

- Therefore,....

$$\boxed{\mathbf{Q} + \mathbf{u}^c + \mathbf{d}^c + \mathbf{L} + \mathbf{e}^c = \bar{\mathbf{5}} + \mathbf{10} \quad \text{in SU(5) !!}}$$

All quantum numbers are just correct.

Appendix:
mini review of Grand Unified Theory

A.3 GUT representations

- what about gauge bosons ?

$$\text{adjoint } \mathbf{24} \text{ reps.} = \underbrace{(8,1)_0}_{G_\mu^{1\sim 8}} + \underbrace{(1,3)_0}_{W_\mu^{1\sim 3}} + \underbrace{(1,1)_0}_{B_\mu} + \underbrace{(3,2)_{-5/6} + (\bar{3},2)_{5/6}}_{X,Y\text{-bosons (become heavy by SU(5) breaking)}}$$

for instance, for **5** reps.,

$$\text{covariant derivative} \quad D_\mu \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix} = \left[\partial_\mu + i g_5 \sum_{a=1}^{24} A_\mu^{(a)} \left(T^a_{\mathrm{SU}(5)} \right)^* \right] \begin{pmatrix} \mathbf{d}^c \\ \mathbf{L} \end{pmatrix}$$

$$\left(\begin{array}{ccc|cc} & & & * & * \\ & & & * & * \\ & & & * & * \\ \hline * & * & * & & \\ * & * & * & & \end{array}\right)$$

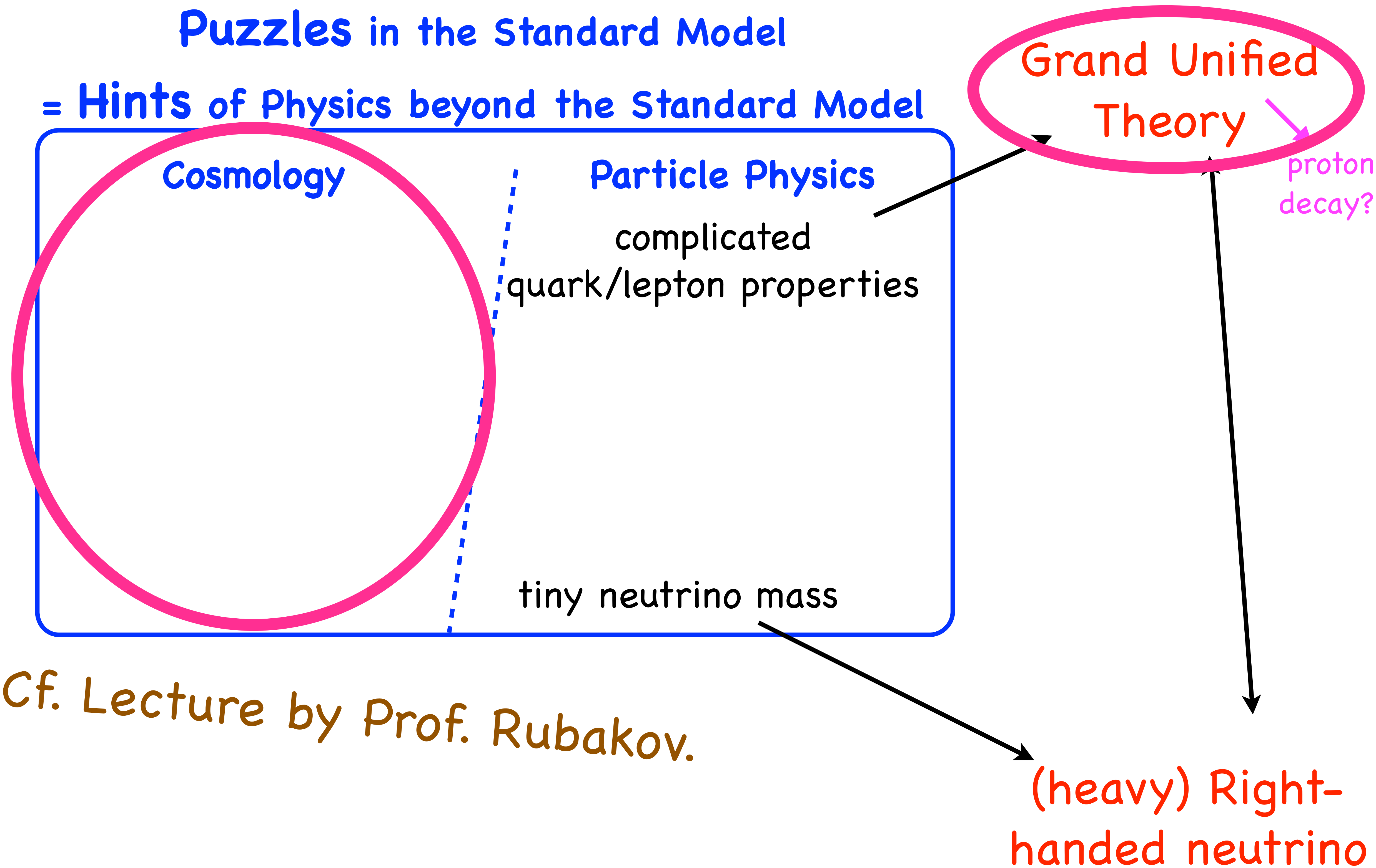
exchange
quarks <-> leptons
- - -> proton decay

Appendix:
mini review of Grand Unified Theory

A.4 coupling unification

👉 We'll discuss it later, in § 3.1.

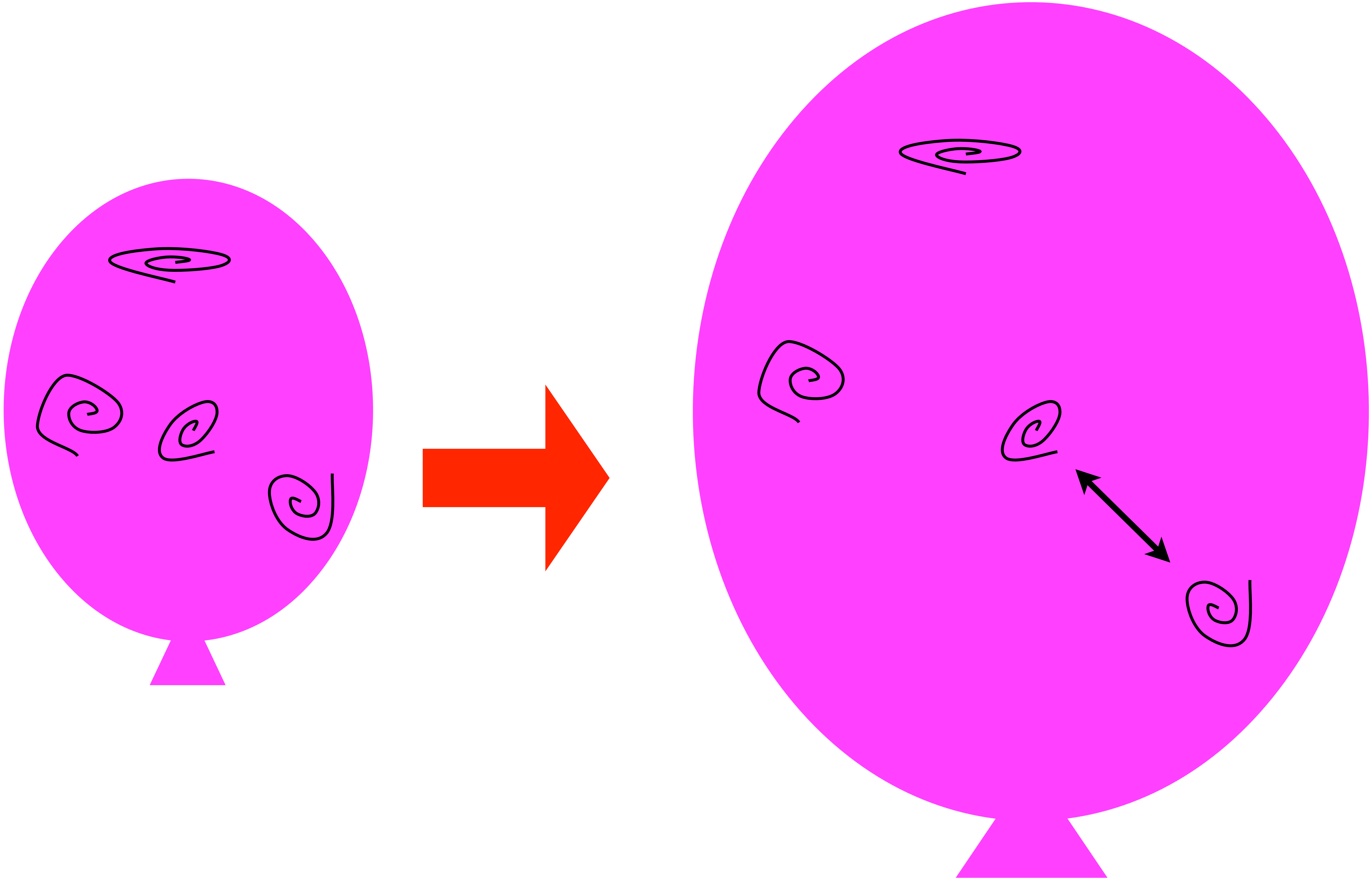
2.1. puzzles in SM = hints of BSM.



☞ Cf. Lecture by Prof. Rubakov.

Next,...

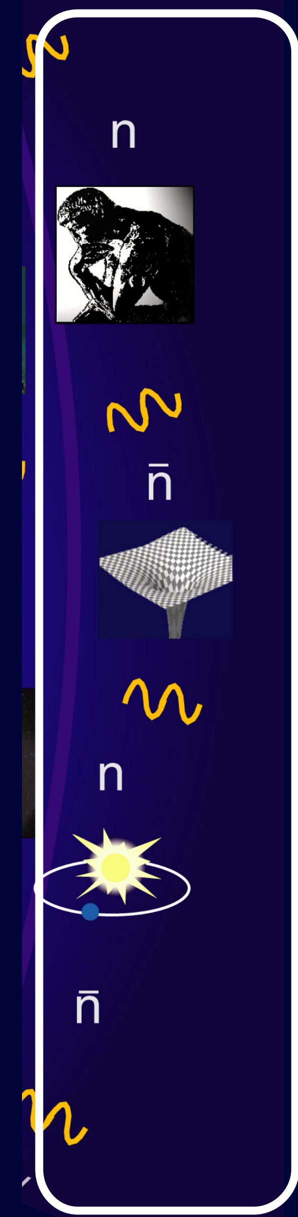
Our universe is expanding



Our universe is expanding

now

going back...



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

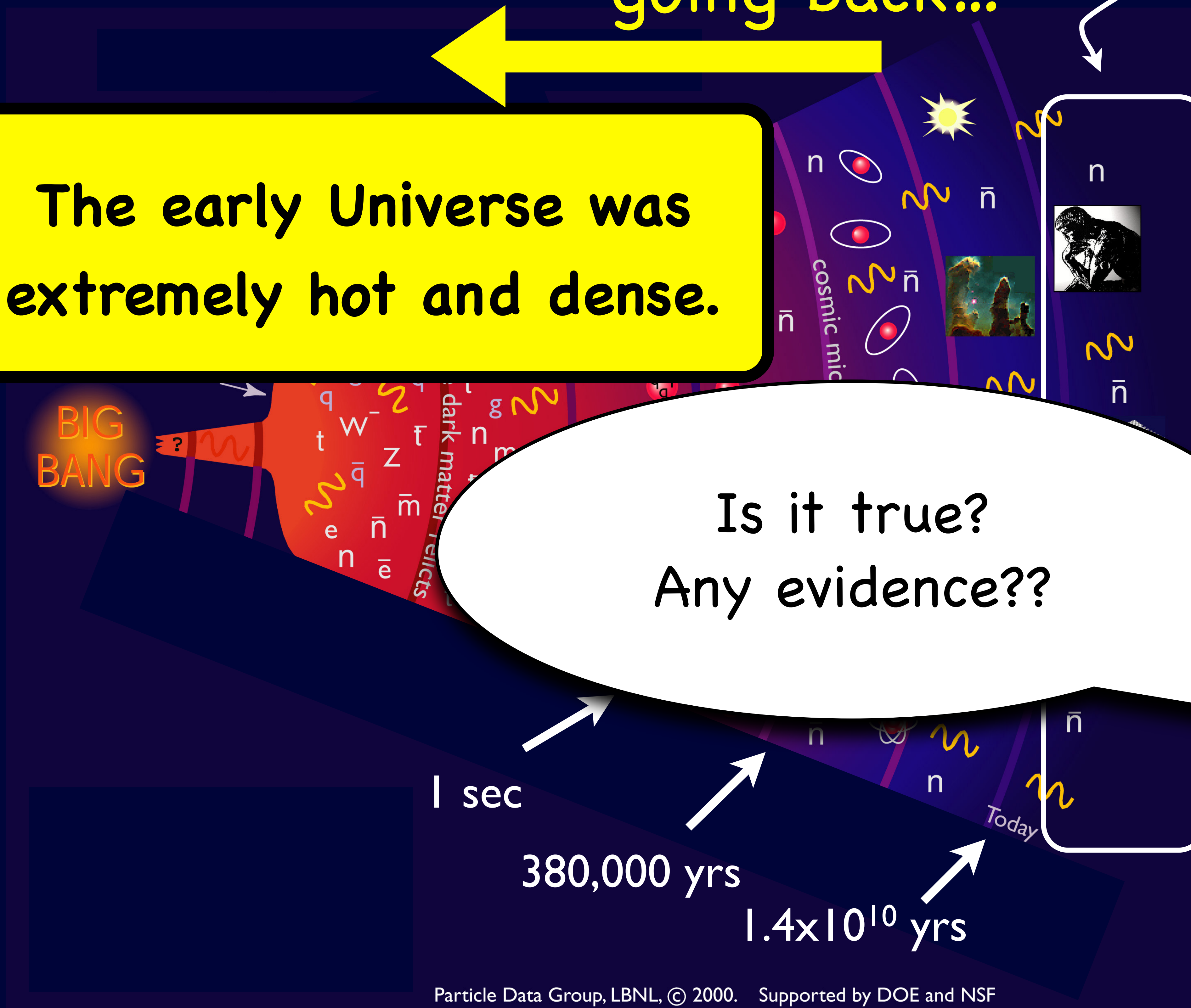
http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

Our universe is expanding

now

going back...

The early Universe was extremely hot and dense.



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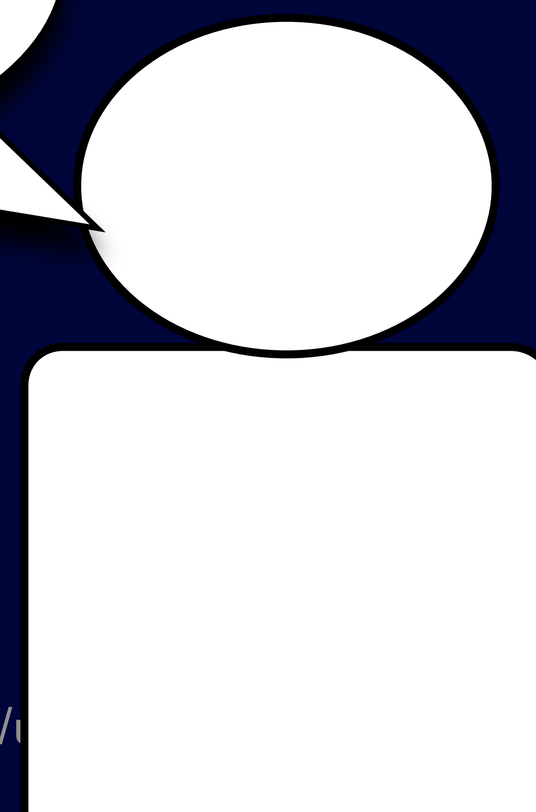
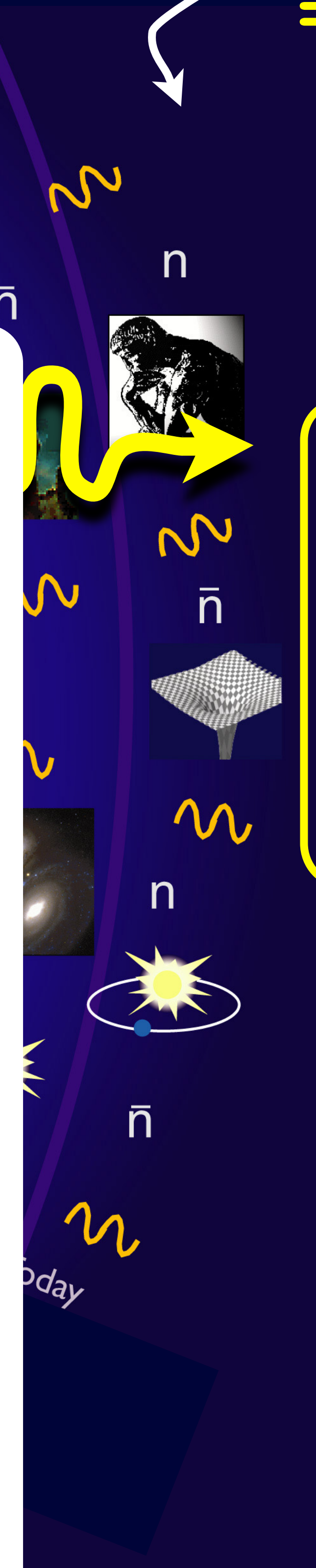
Is it true?
Any evidence??



Photons emitted when the universe was 380,000 yrs old

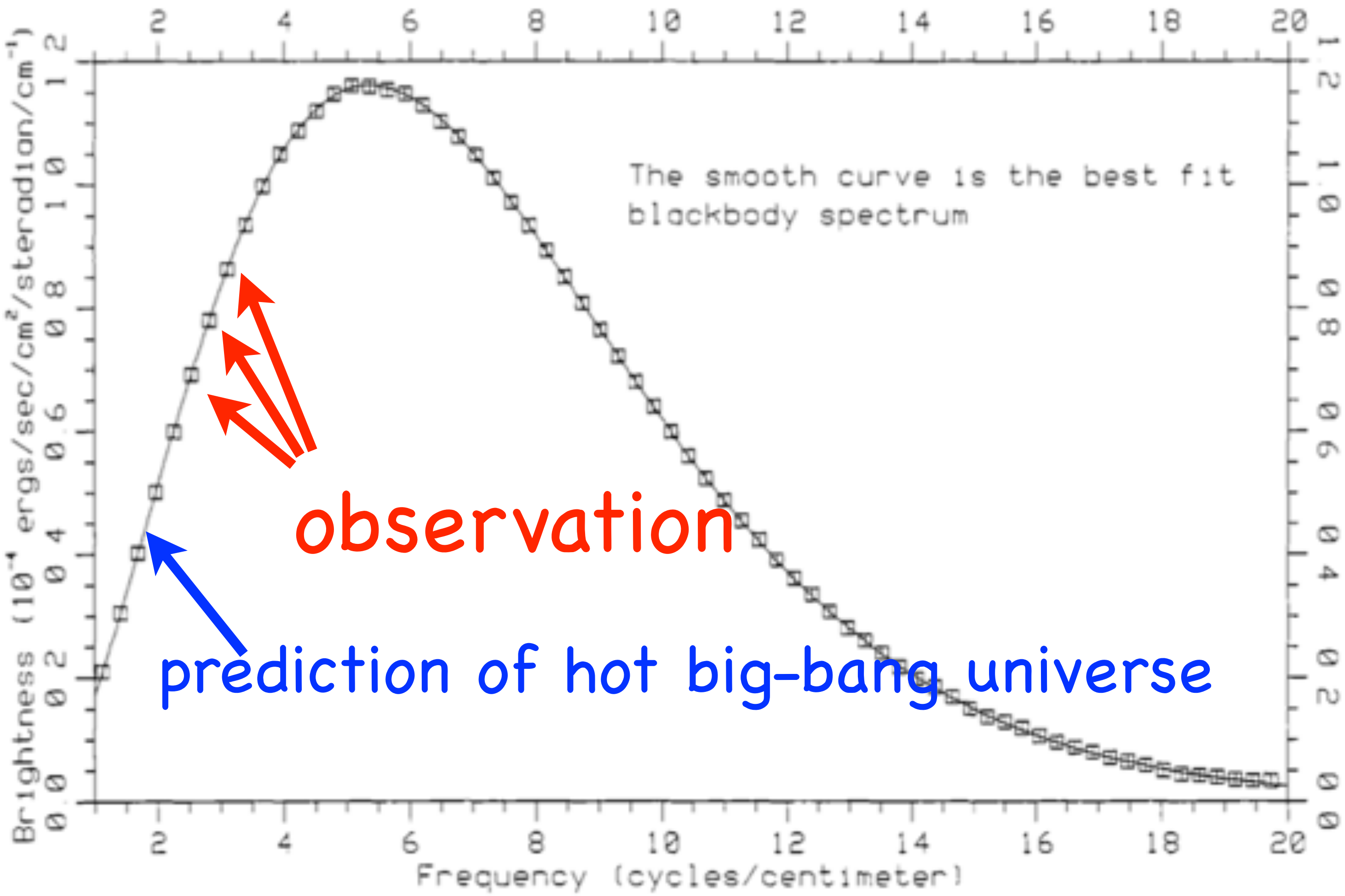
now

= 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

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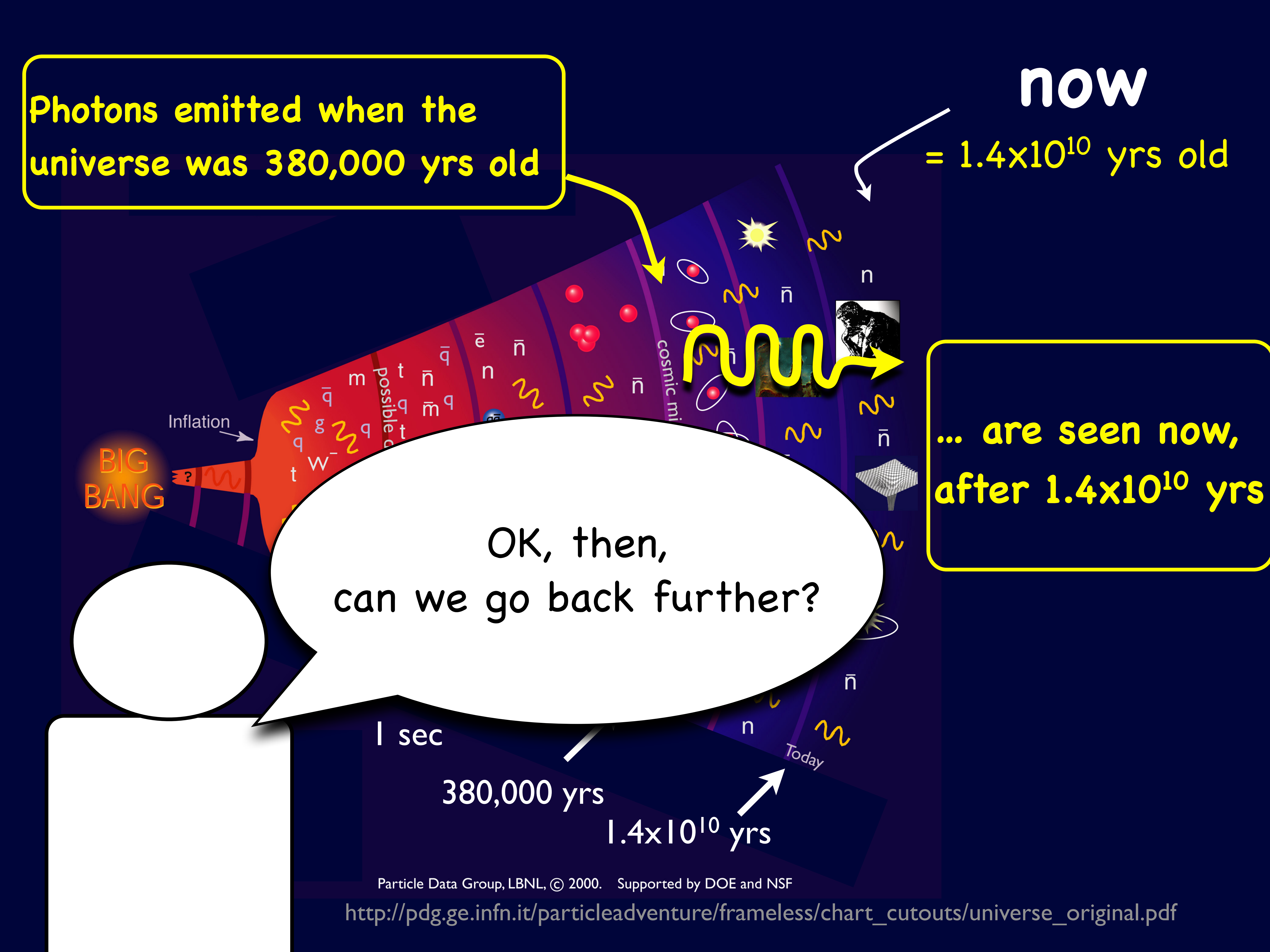
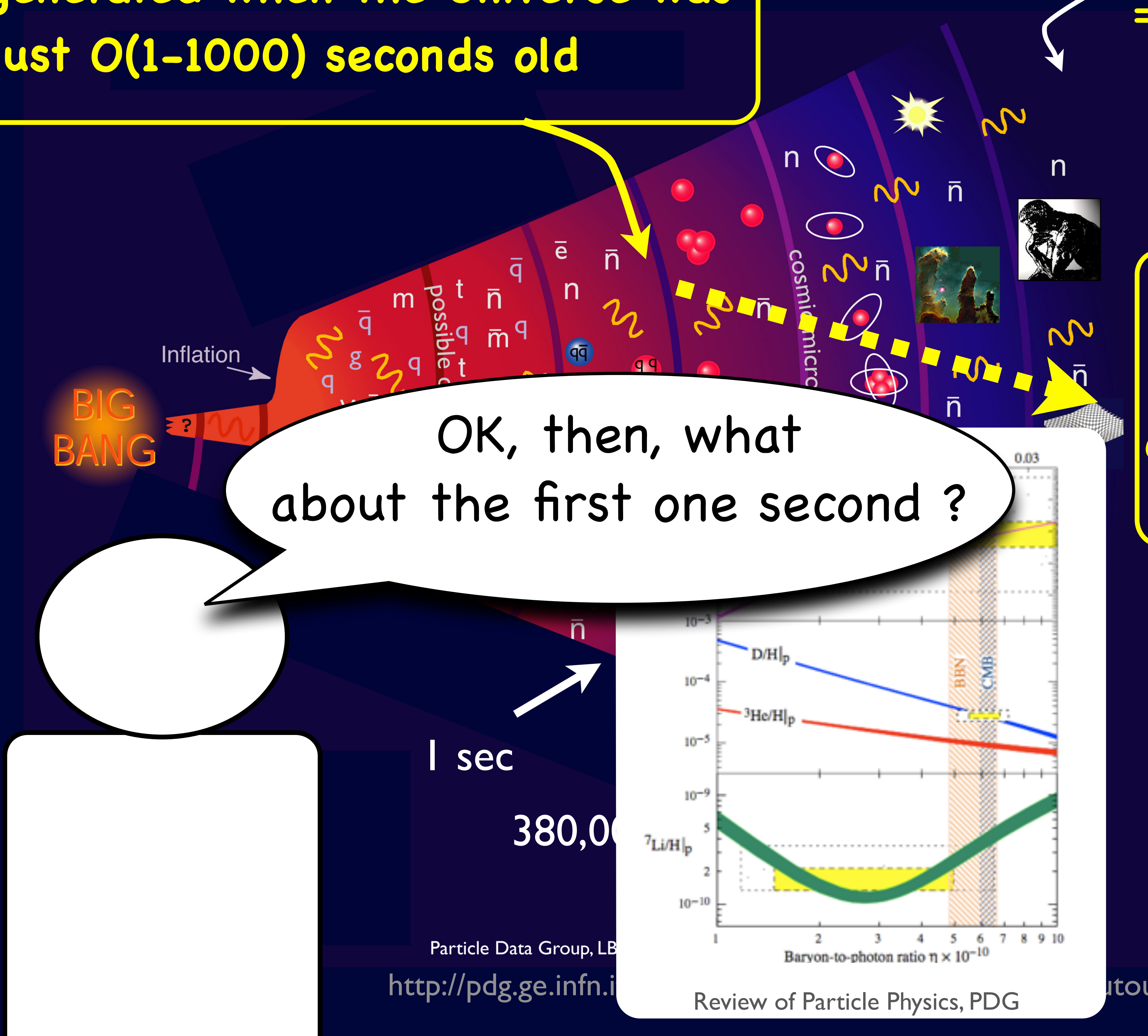

Photons emitted when the universe was 380,000 yrs old
now
= 1.4x10^10 yrs old
... are seen now, after 1.4x10^10 yrs
OK, then, can we go back further?
Inflation
BIG BANG
1 sec
380,000 yrs
1.4x10^10 yrs
Today
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

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

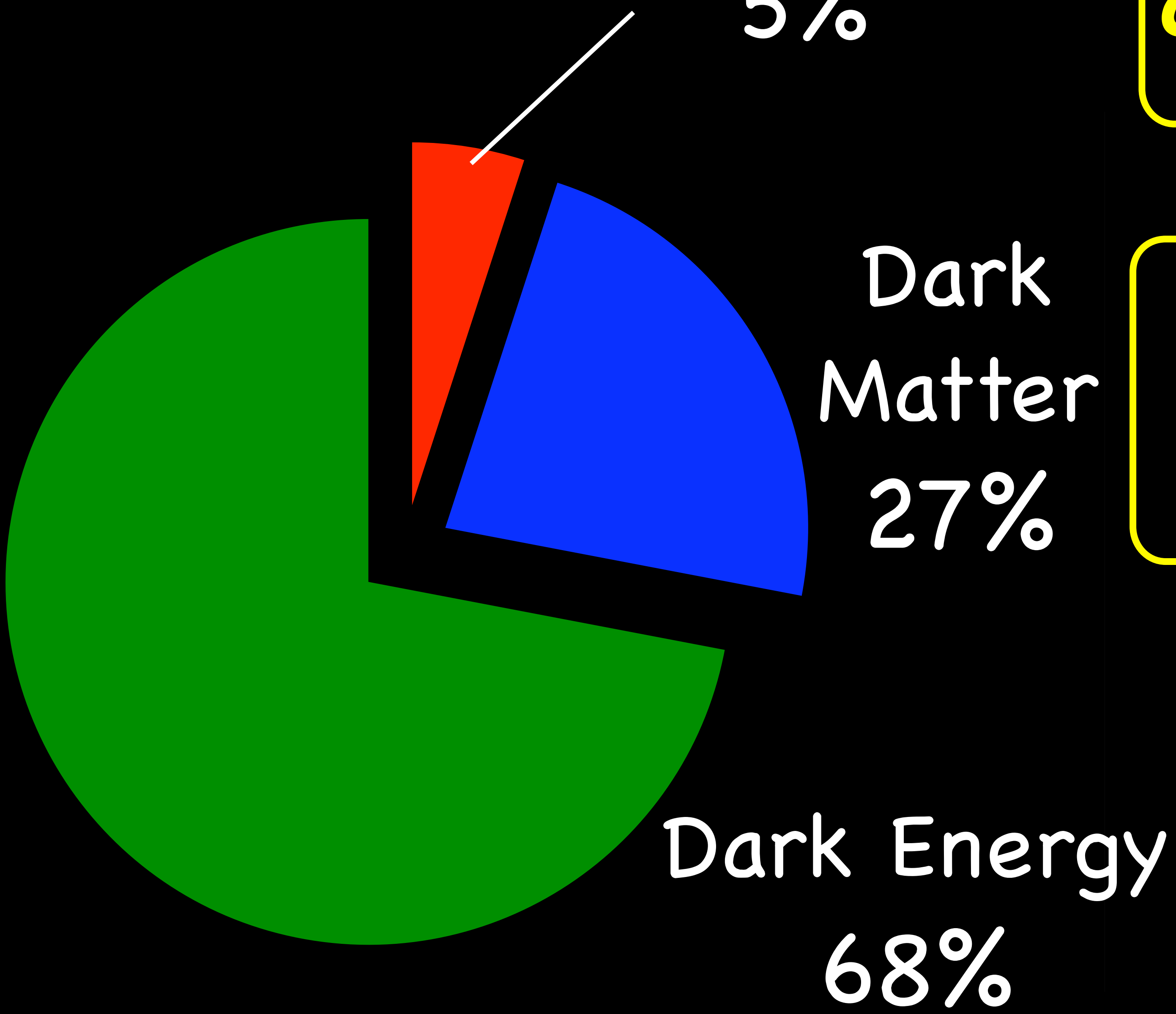


Review of Particle Physics, PDG

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?

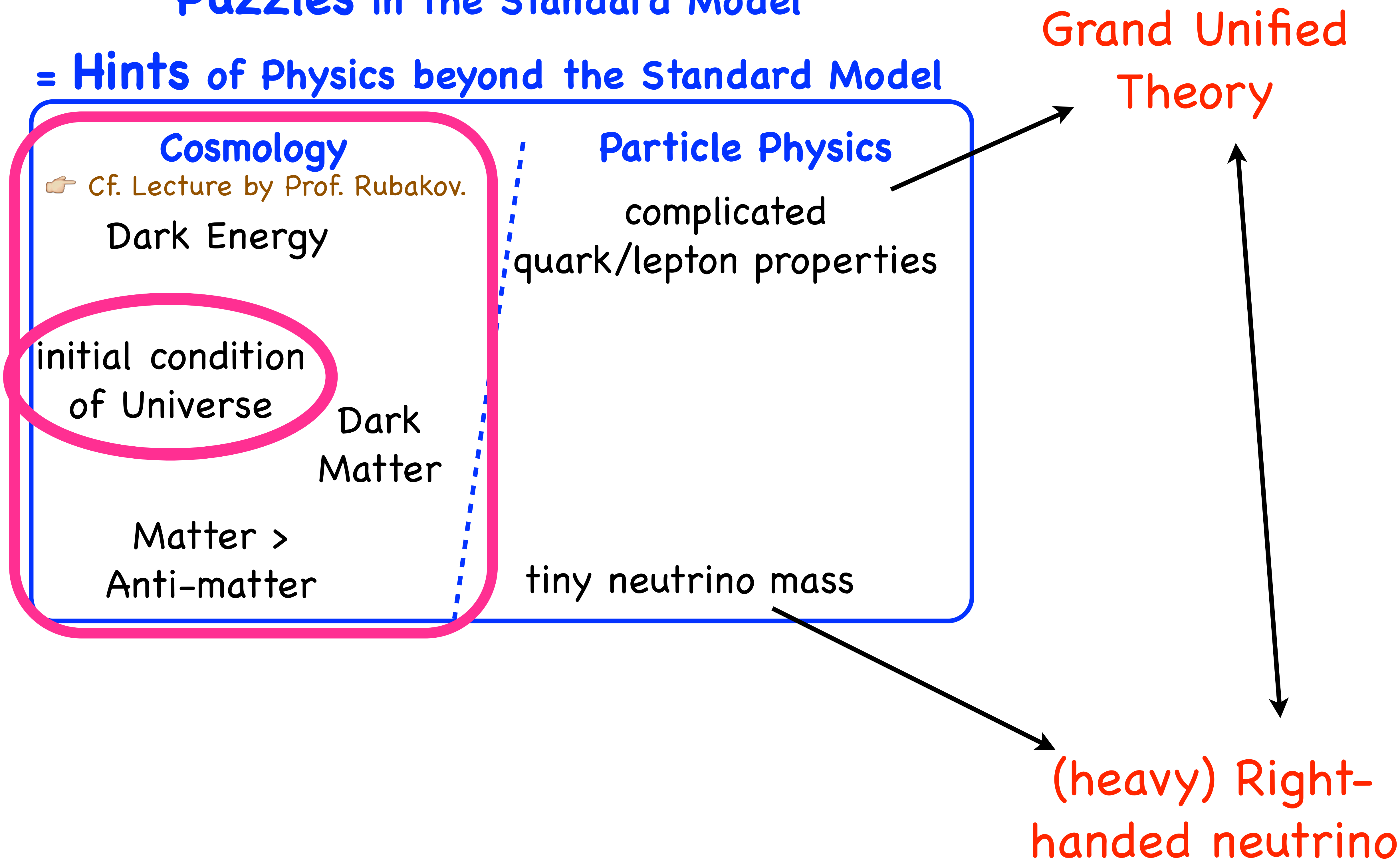
What is DE?

Furthermore...

problems of initial conditions

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



Our Universe is very flat.

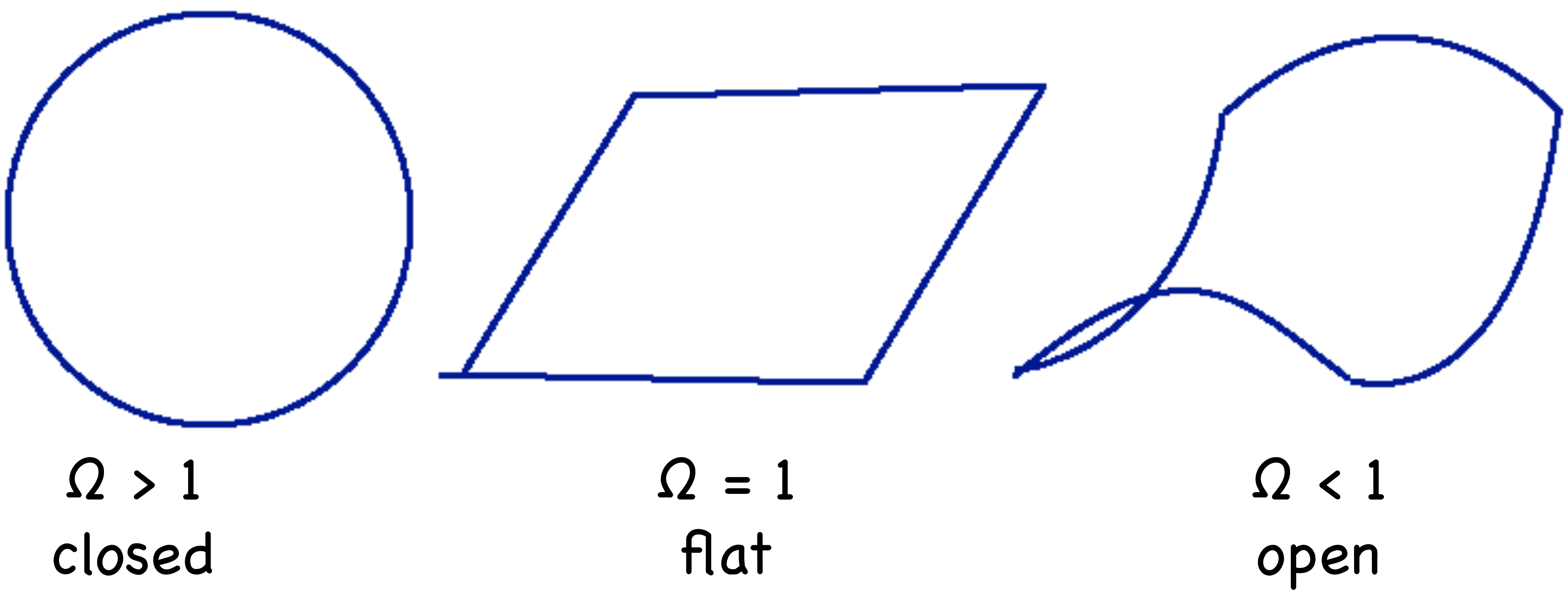
"flatness" of the Universe

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

Newton const. (G)

energy density of the Univrse (ρ)

Hubble parameter (expansion rate) (H)



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

This is very, very strange!

According to Einstein eqs.

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

"scalar factor" of the Universe (a)

energy density of the Universe (ρ)

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.

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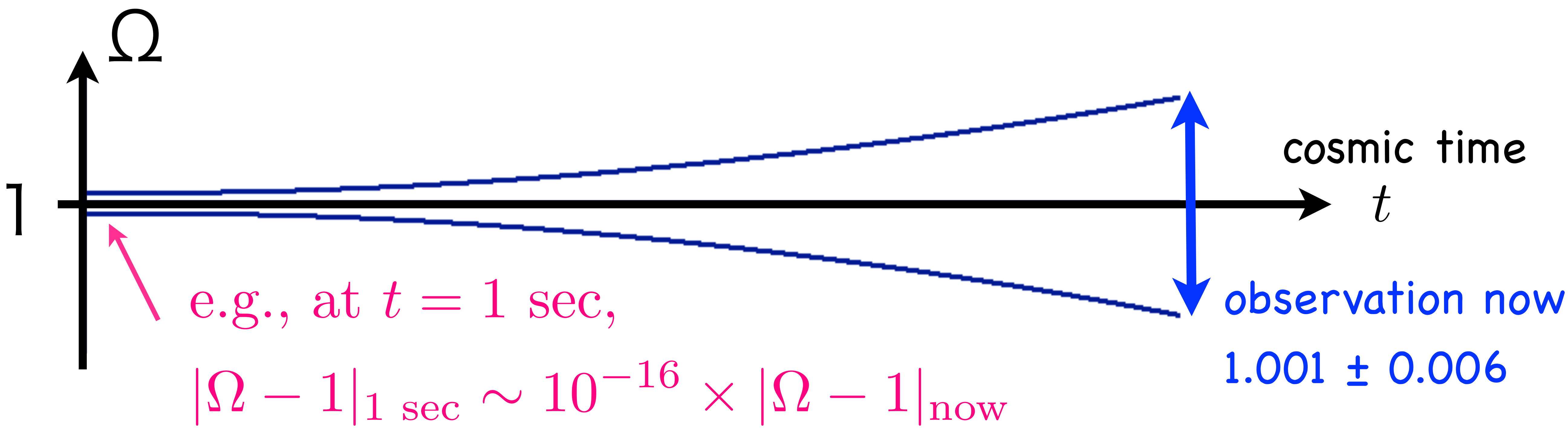


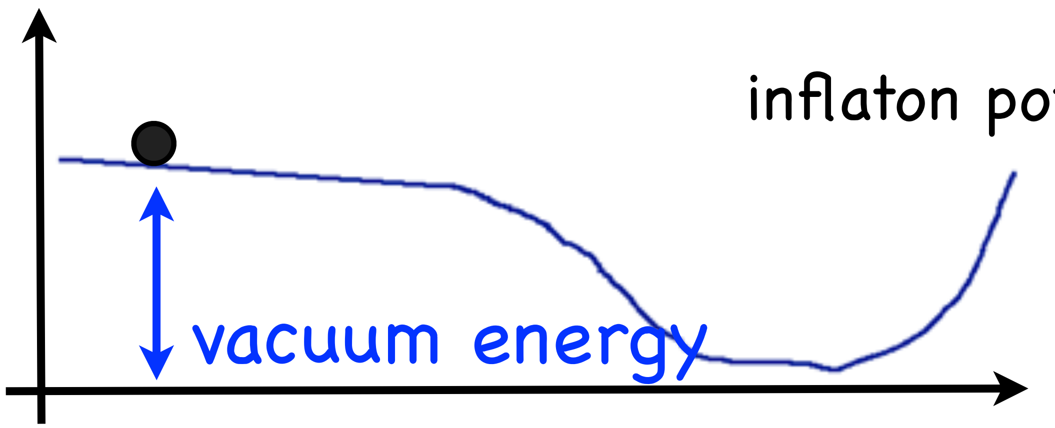
The Universe was extreeeeeeeemly flat.

Why? How? fine-tuning of initial condition.

Inflation:

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

Then,.....



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

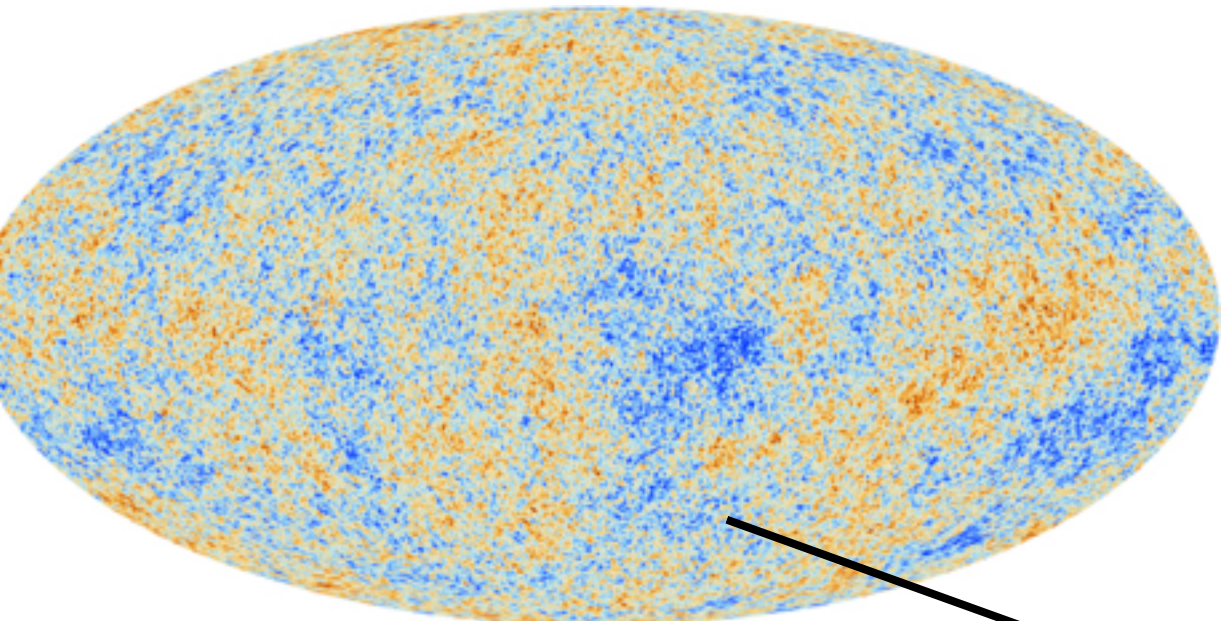
scalar factor $a \propto e^{H_i t}$ (exponential expansion: Inflation)

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

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

furthermore...

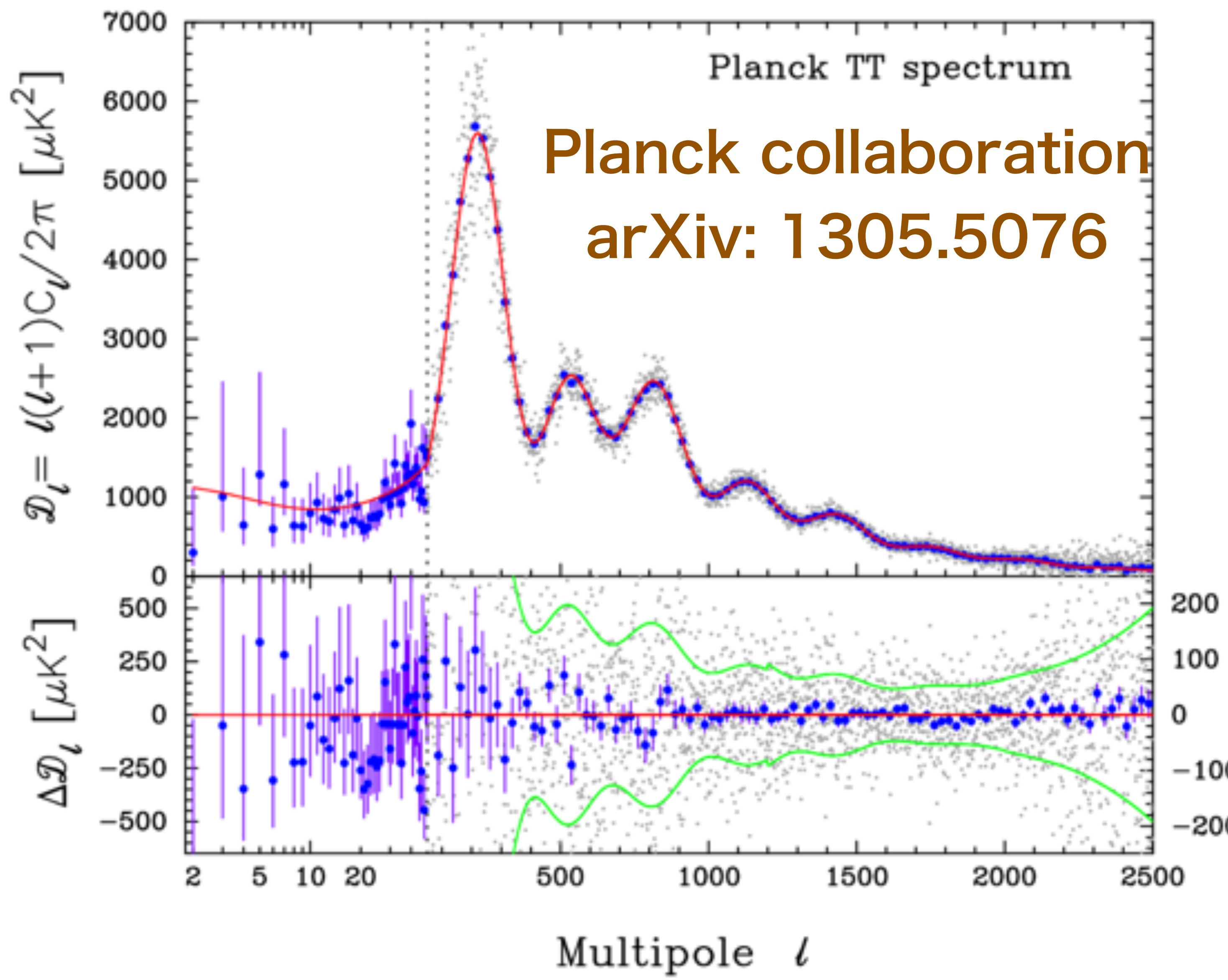
temperature fluctuation



spherical-harmonic-function expansion

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

very, very well-explained by inflation !



Planck collaboration arXiv: 1305.5076

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

Cosmology

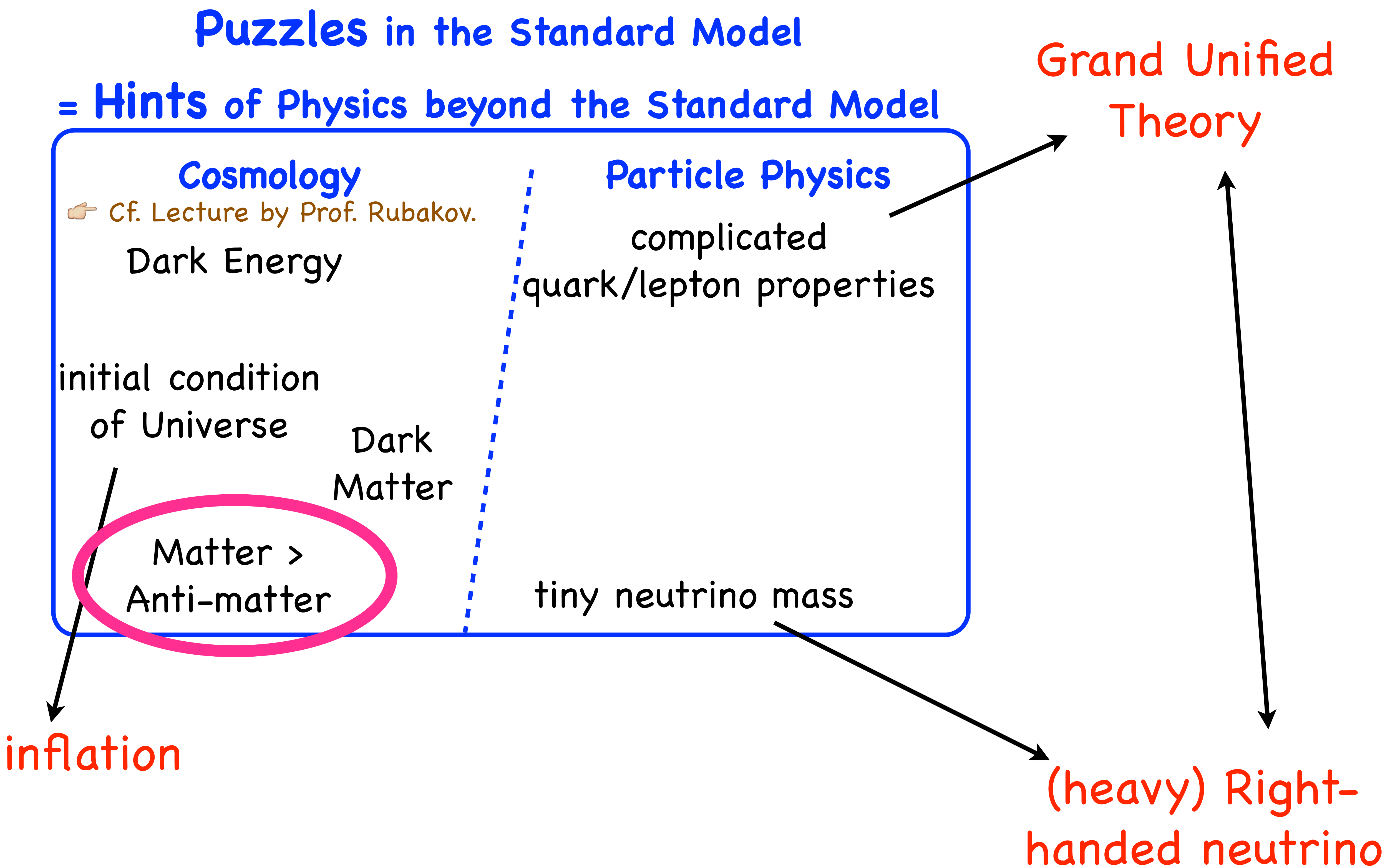
👉 Cf. Lecture by Prof. Rubakov.

- Dark Energy
- initial condition of Universe → inflation
- Dark Matter
- Matter > Anti-matter

Particle Physics

- complicated quark/lepton properties → Grand Unified Theory
- tiny neutrino mass → (heavy) Right-handed neutrino

Grand Unified Theory ↔ (heavy) Right-handed neutrino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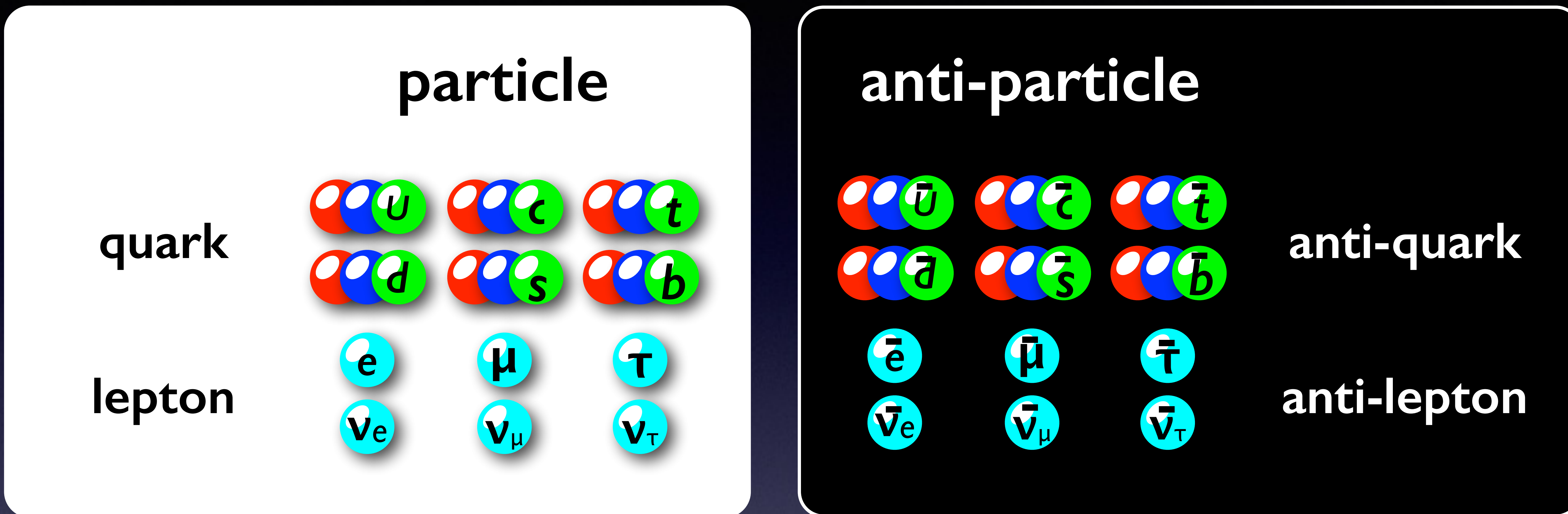
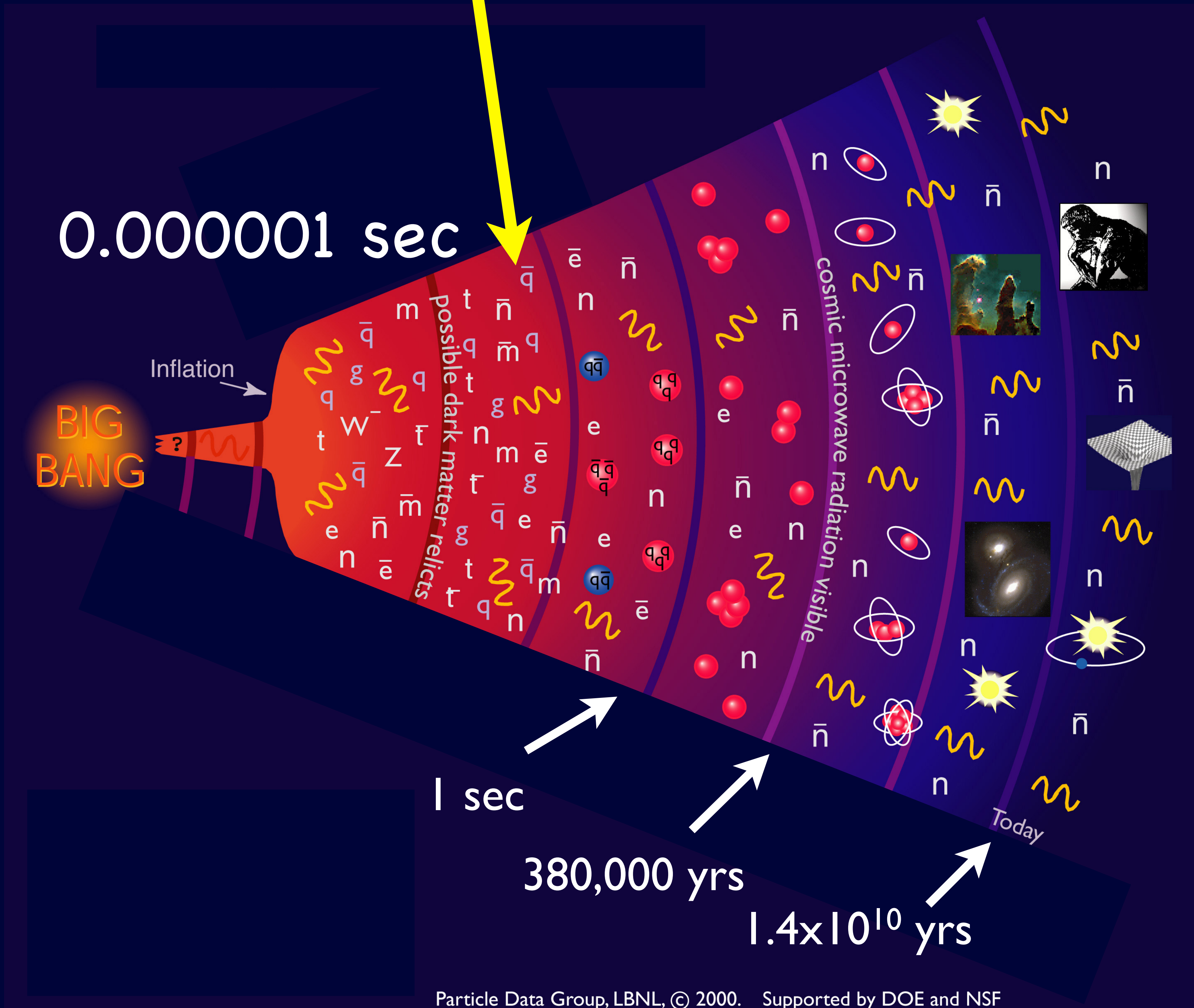
(heavy) Right-handed neutrino

Next,...

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



In the very early Universe,....

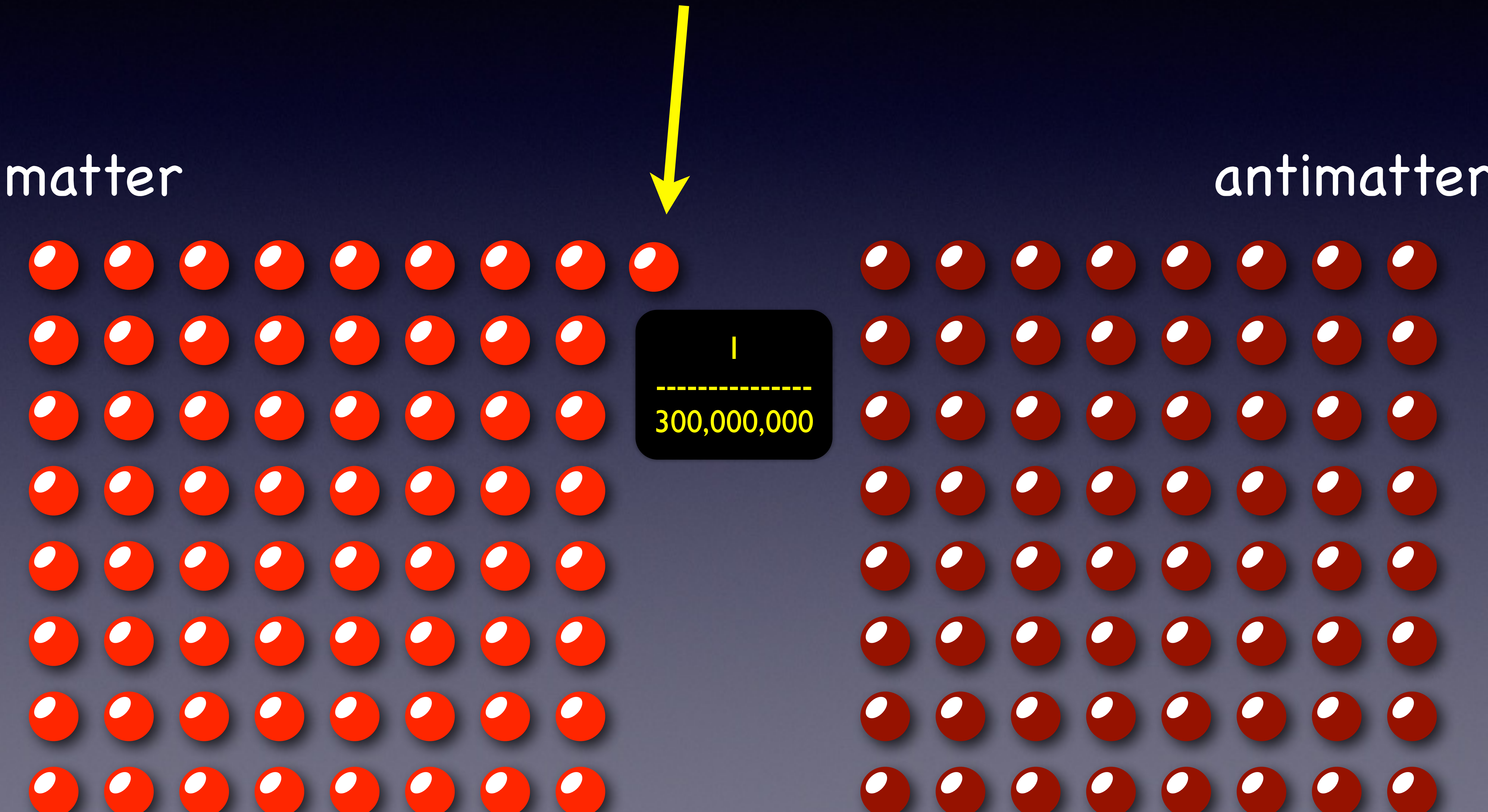


http://pdg.ge.infn.it/particleadventure/frameless/chart_cutouts/universe_original.pdf

In the very early Universe,....

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

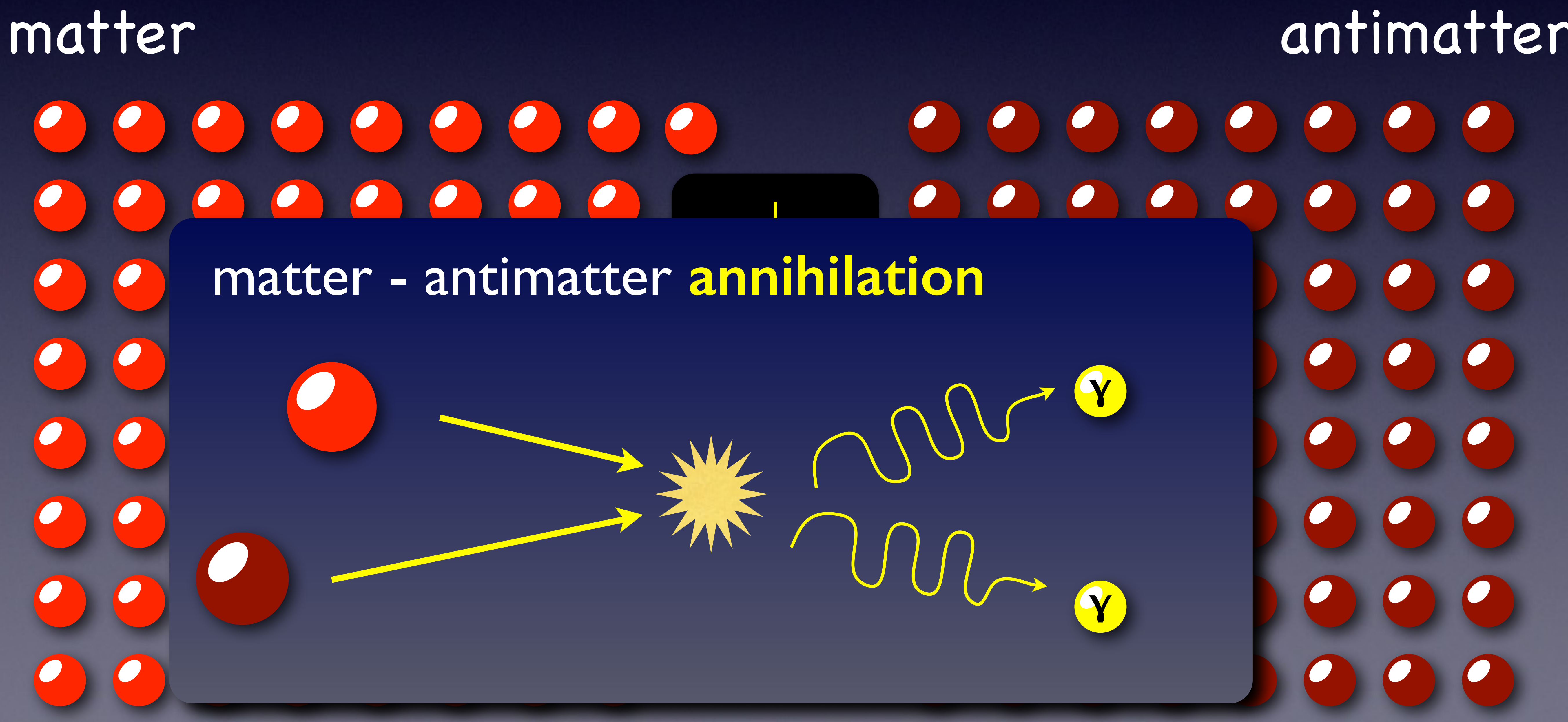
But there was tiny excess of matter over anti-matter.



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

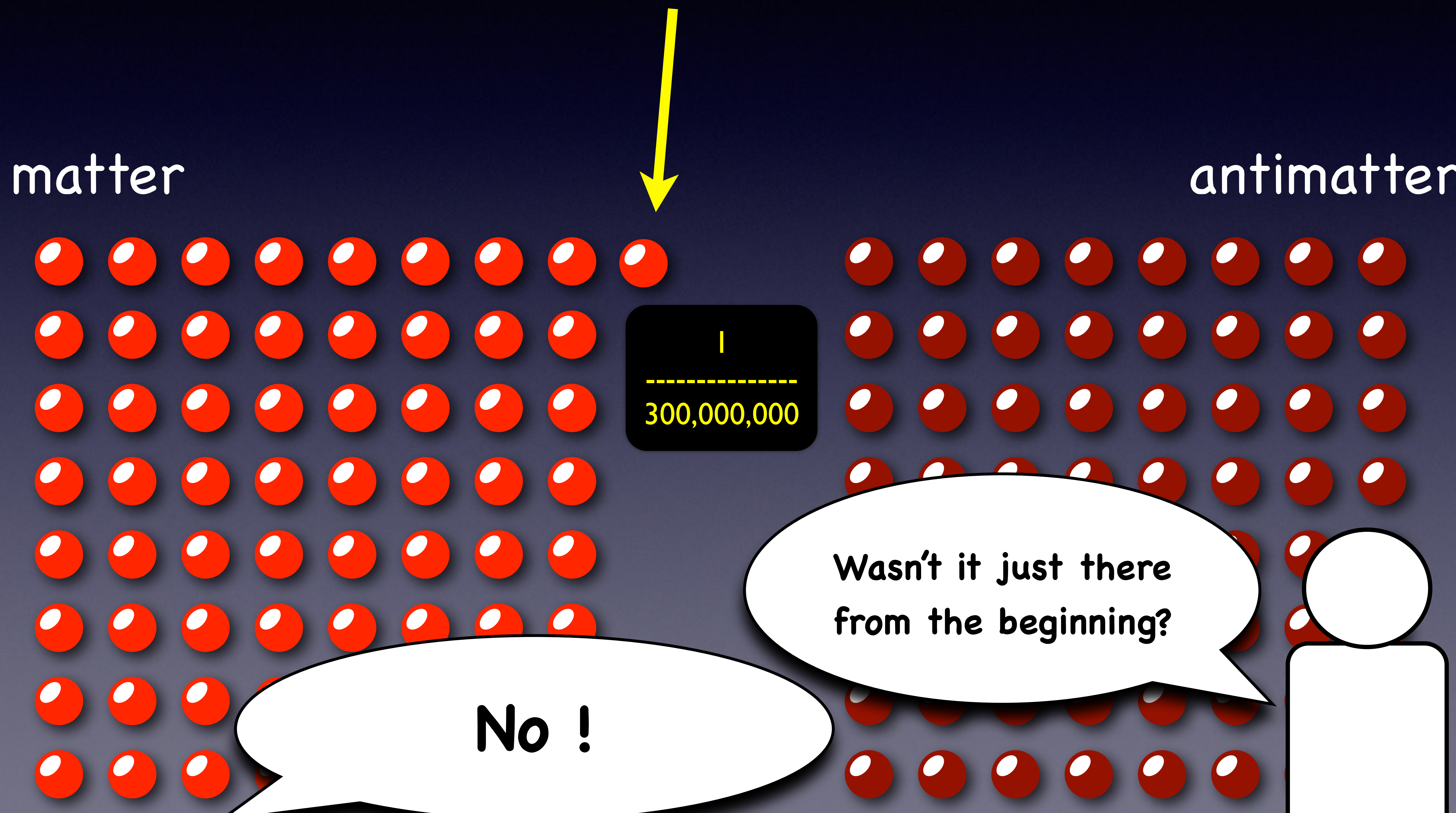
(no antimatter)

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

are made from this leftover matter.

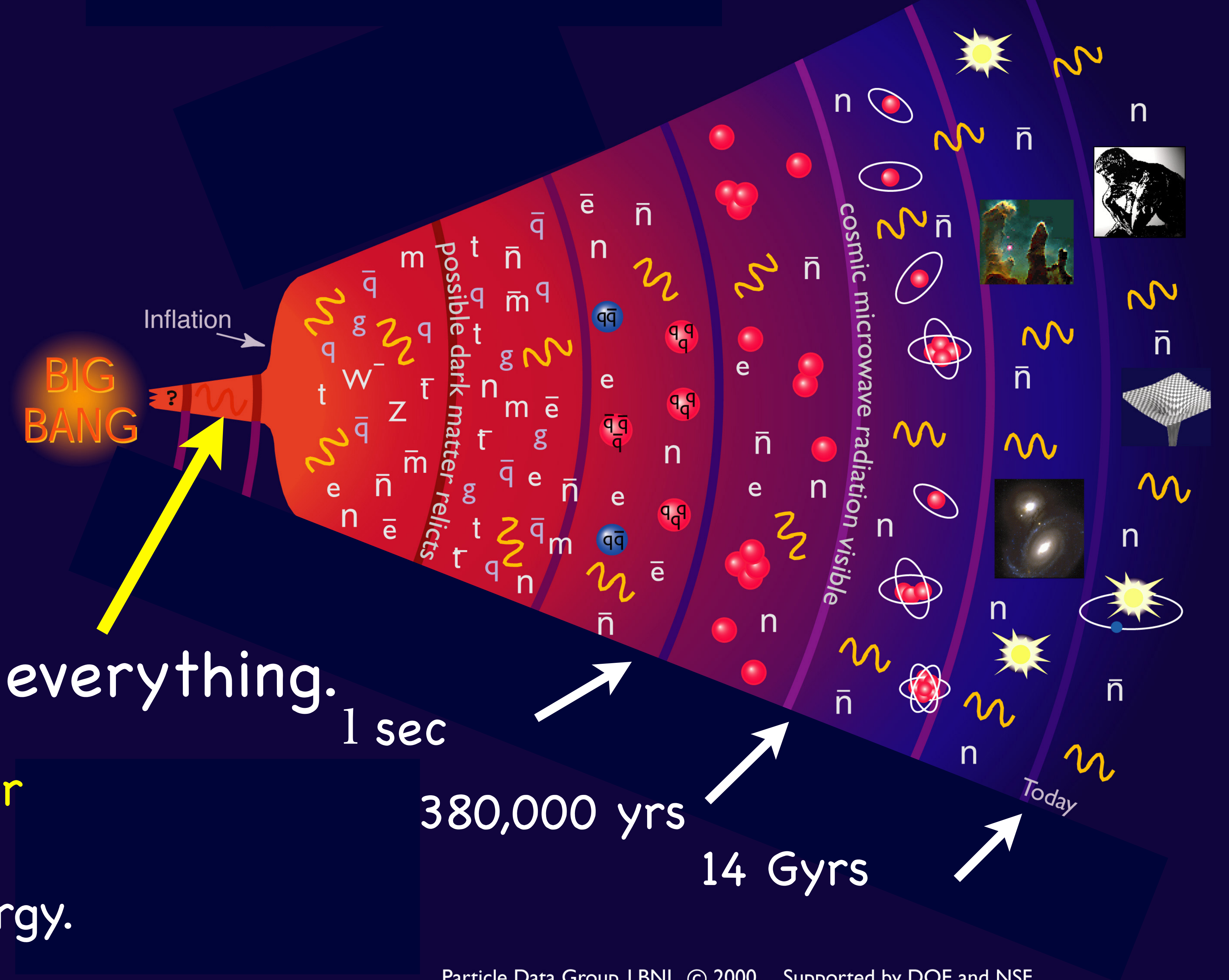
Puzzle

How was the initial excess of matter created ?



Puzzle

How was the initial excess of matter created ?



Inflation dilutes everything.

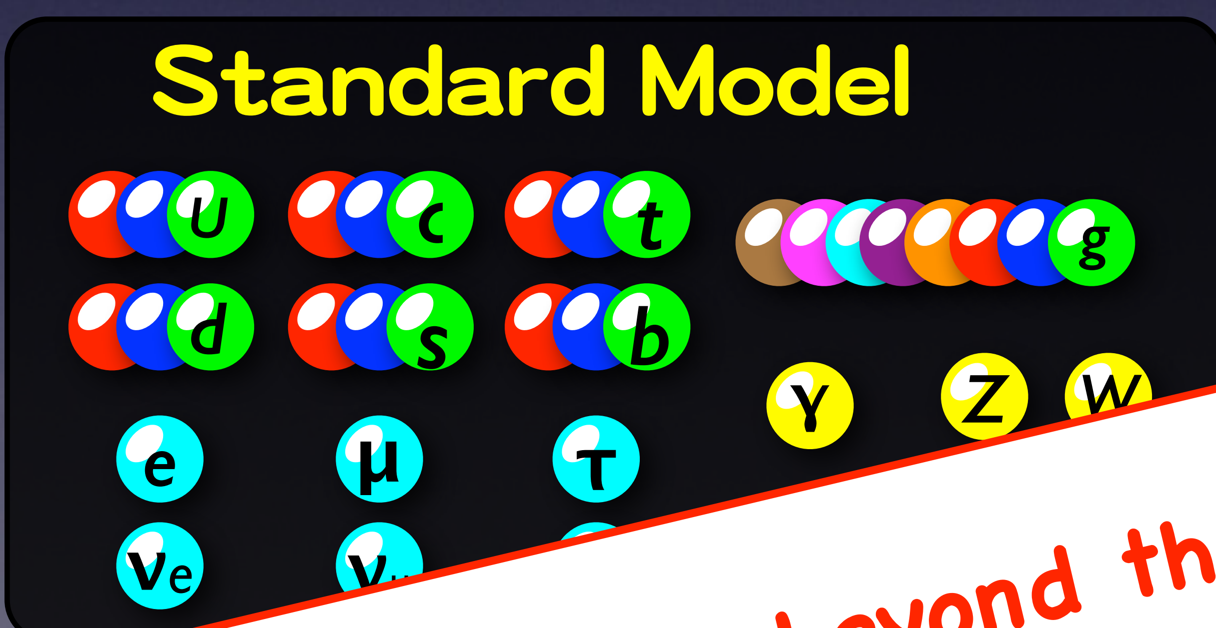
Matter and antimatter
had to be generated
from the vacuum energy.

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

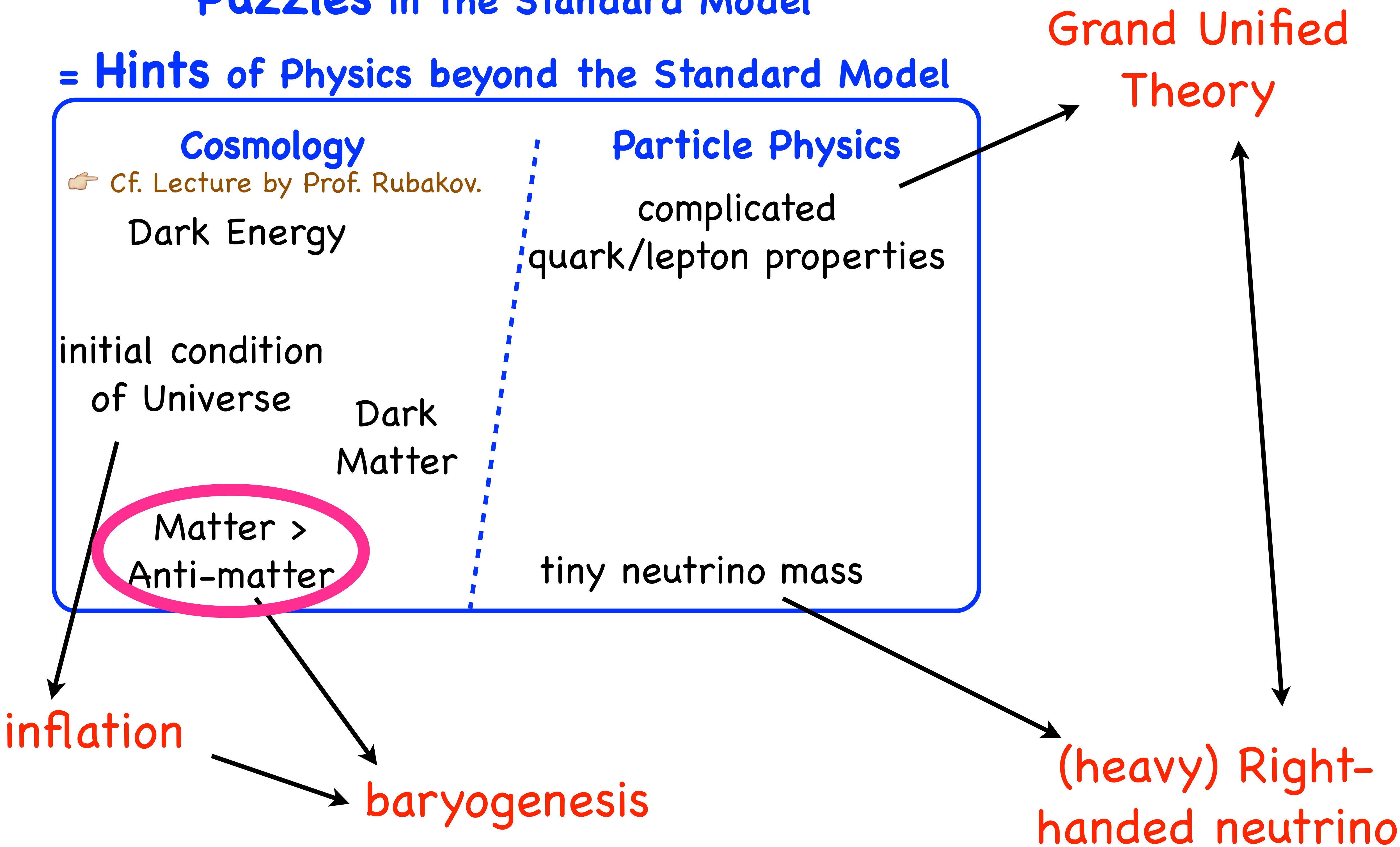
...olation ... (but too small)

out-of-equilibium

Something beyond the Standard Model is necessary.

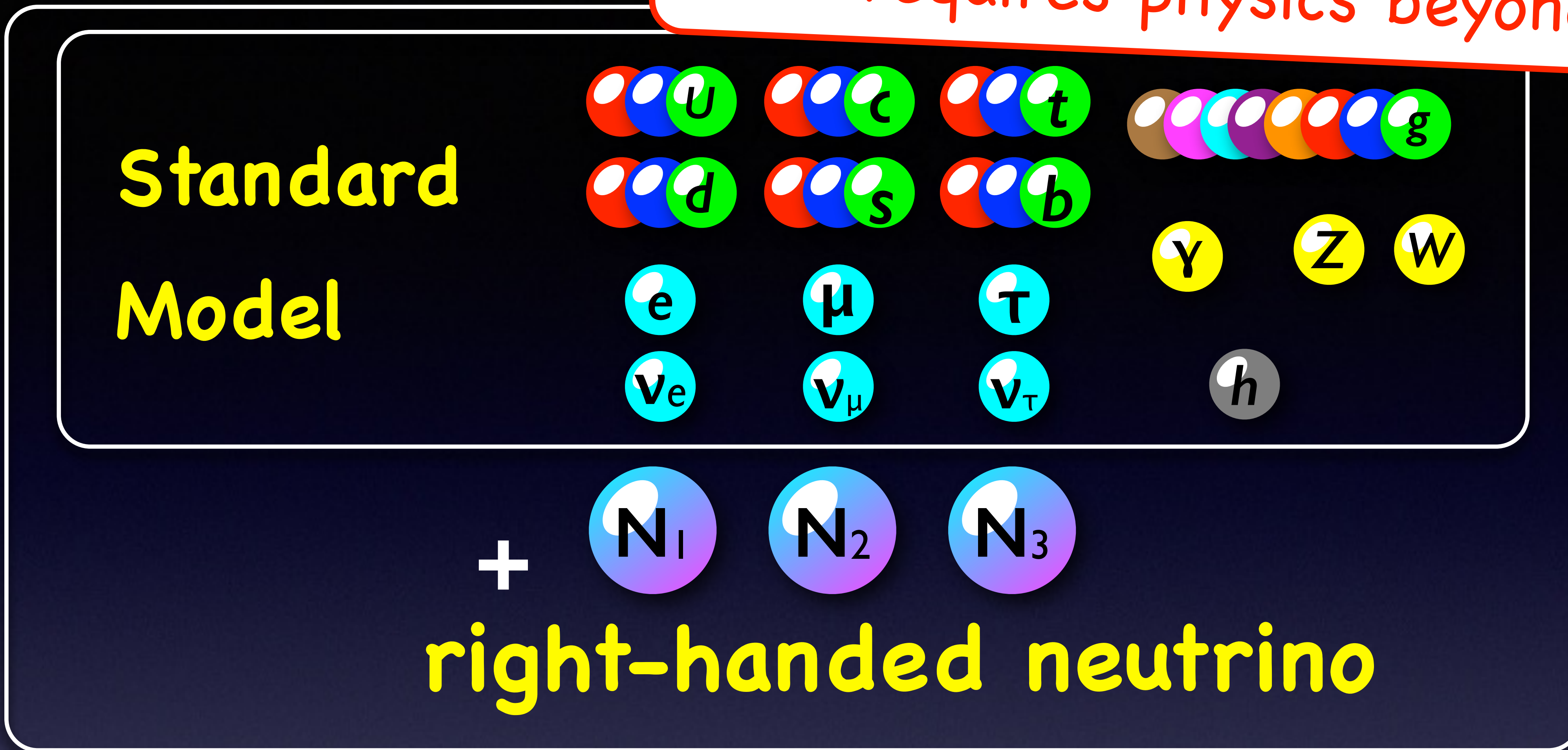
Puzzles in the Standard Model

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



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 → T; RH ν's mass → M_R

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

Leptogenesis

[Fukugita, Yanagida,1986]

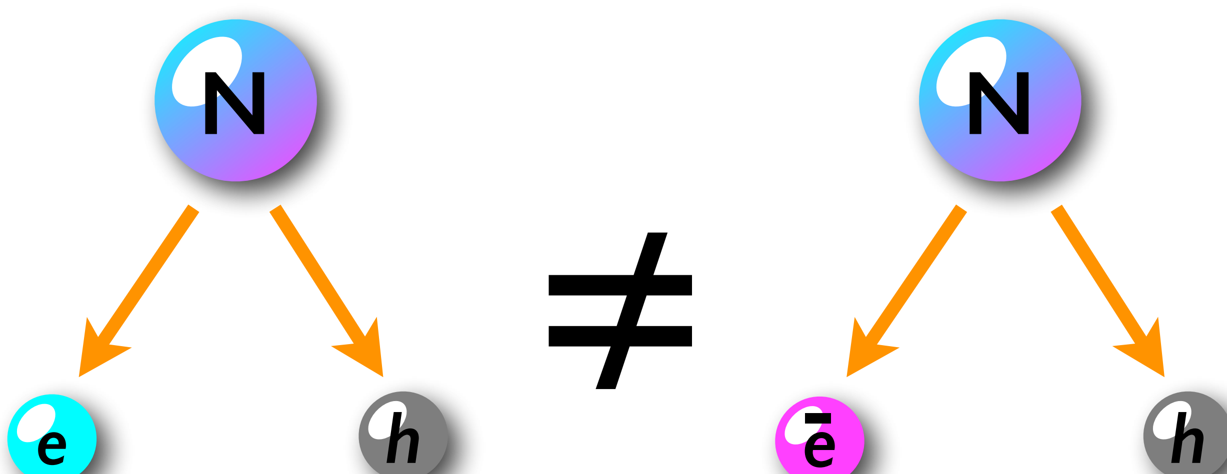
scenario

temperature → T, RH ν's mass → M_R

step 1: $T > M_R$: N_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 → T, RH ν's mass → M_R

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, $\Delta L \neq 0$.

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)

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

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

effective CP violating phase

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

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)

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

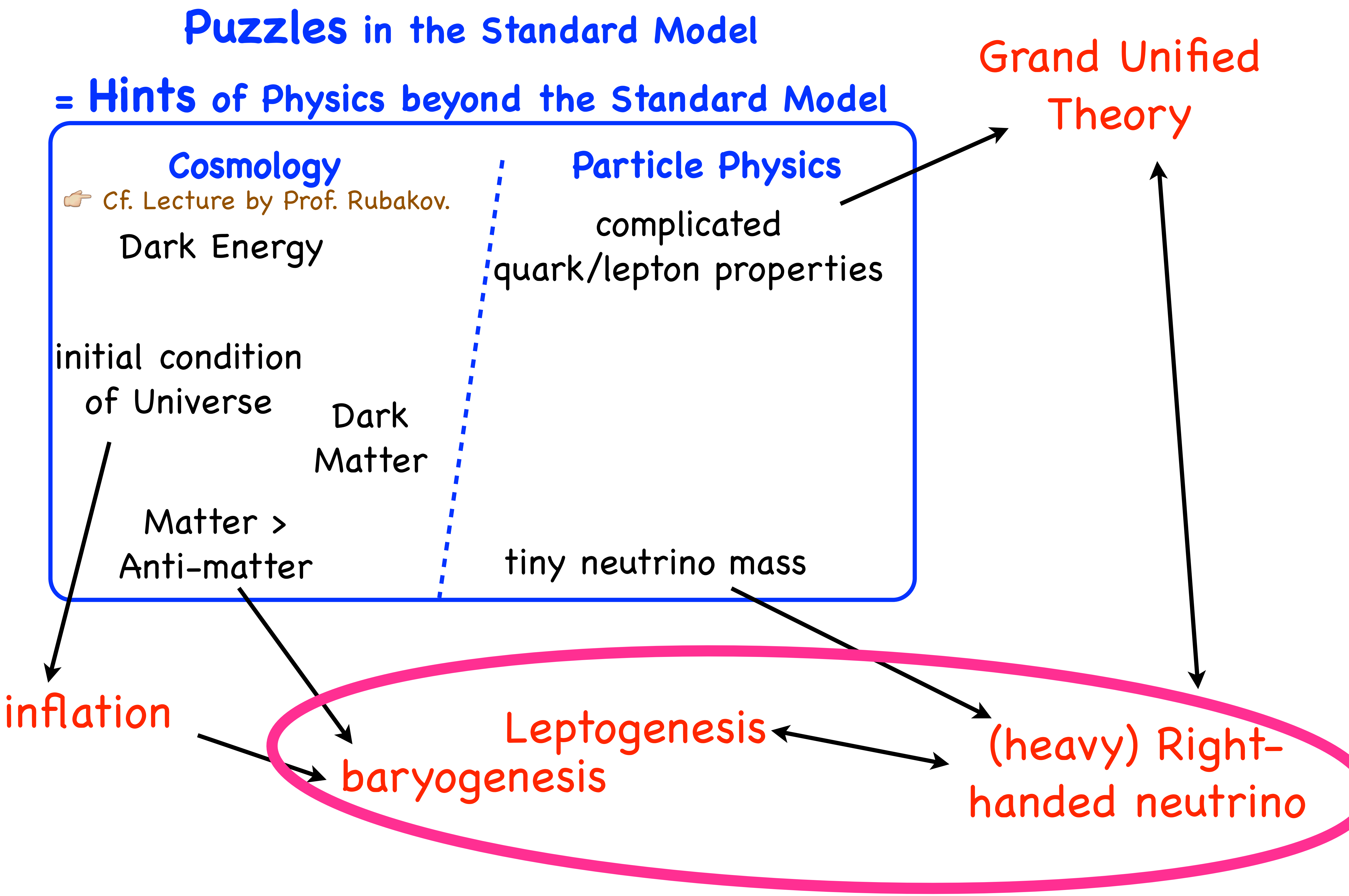
wash-out factor (< 1)
(calculable: by Boltzmann eq.)

effective CP violating phase

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

[PDG, 2012]

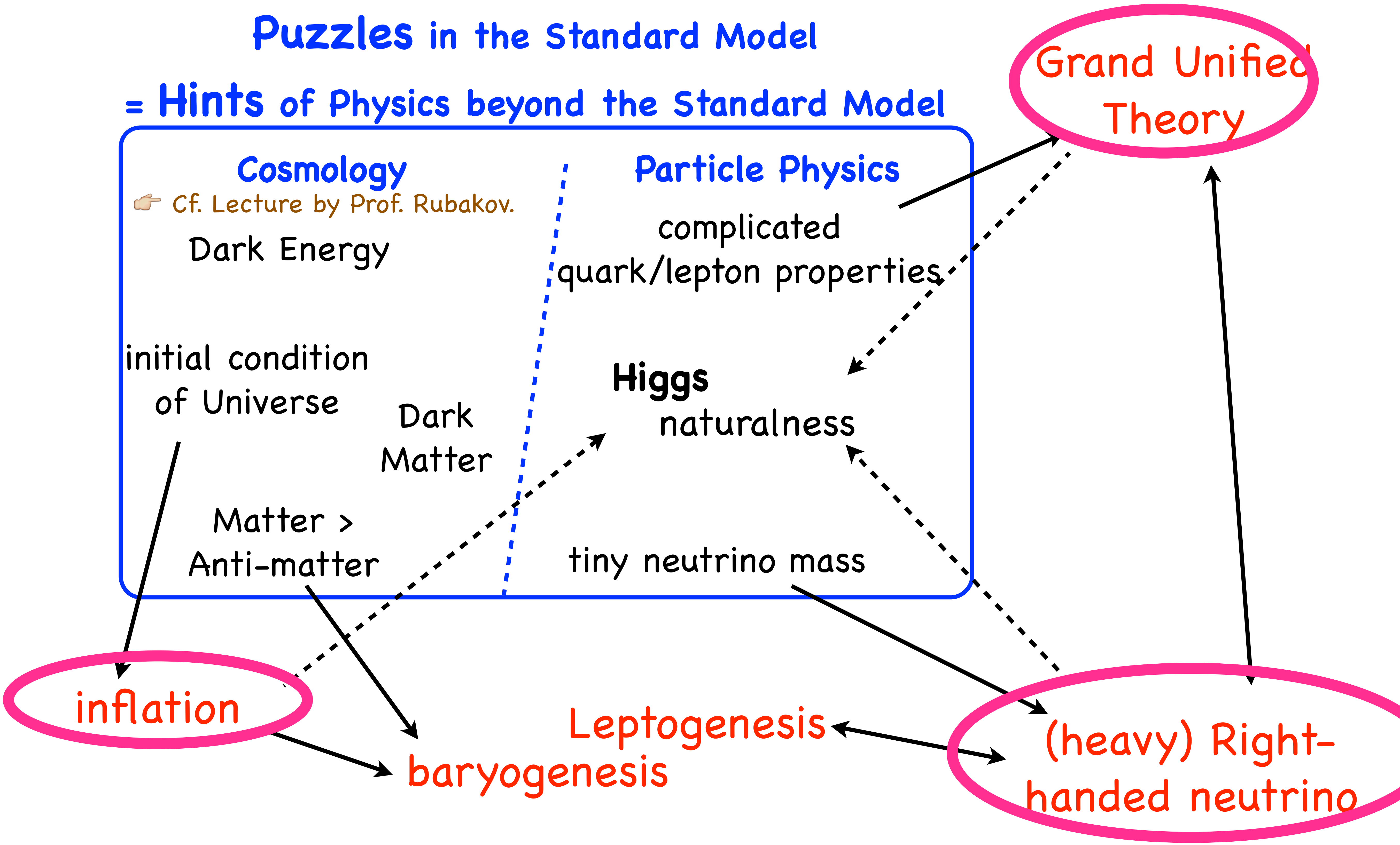
It works !! (for M_R > 10^9–10^{10} GeV).


Puzzles in the Standard Model
= Hints of Physics beyond the Standard Model
Cosmology
Cf. Lecture by Prof. Rubakov.
Dark Energy
initial condition of Universe
Dark Matter
Matter > Anti-matter
Particle Physics
complicated quark/lepton properties
tiny neutrino mass
Grand Unified Theory
inflation
Leptogenesis
baryogenesis
(heavy) Right-handed neutrino

2.1. puzzles in SM = hints of BSM.

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



Next,...

Higgs mass = 126 GeV, on the other hand.....

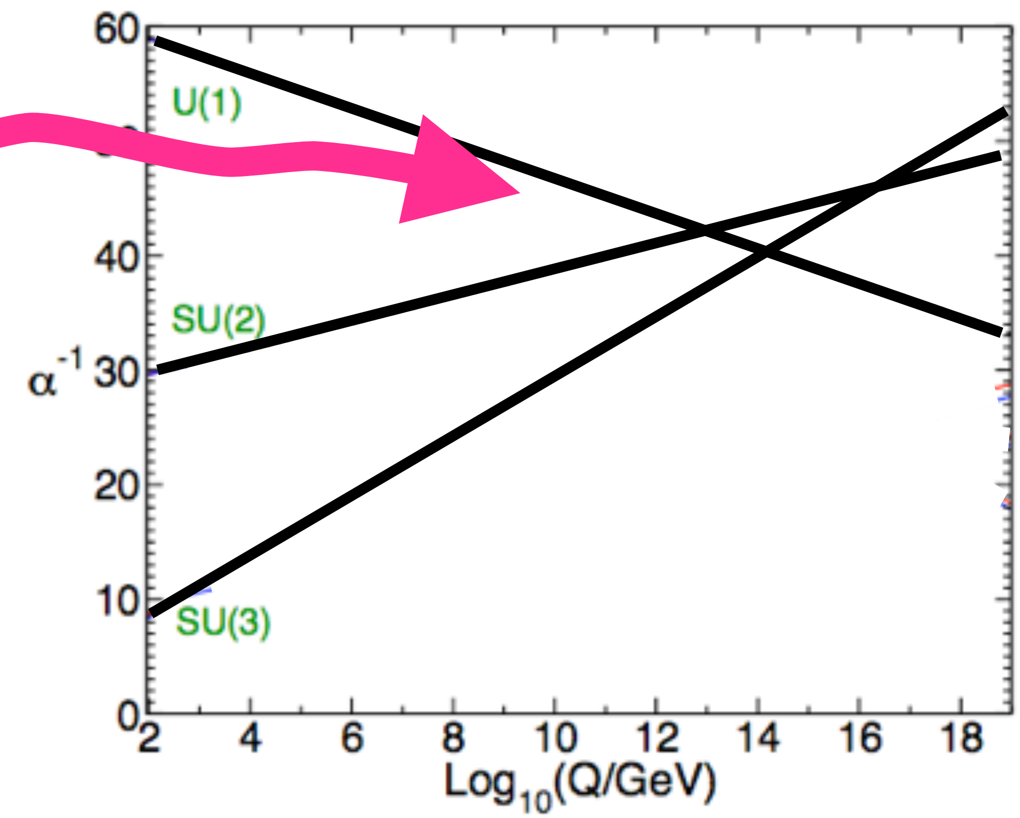
1. heavy right-handed neutrino

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

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

2. Grand Unified Theory

GUT scale = 10^{14}– 10^{16} GeV



3. Inflation

……also requires a high scale.

For instance, in chaotic inflation,

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

Higgs mass = 126 GeV, on the other hand.....

1. heavy right-handed neutrino

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

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

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 § 2.2)

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

(fine tuning like 1.0000000000000001 - 1)

This unnaturalness can be avoided by.....

Supersymmetry (SUSY)

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

(more on this in § 3)

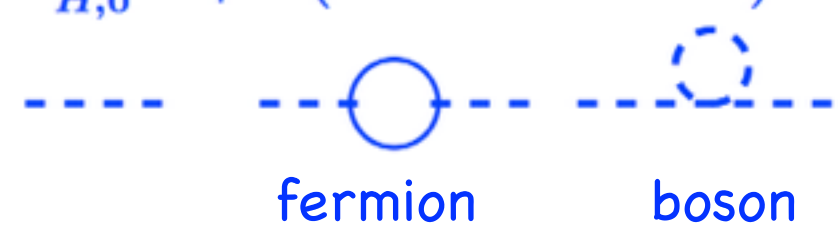
fine-tuning problem

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

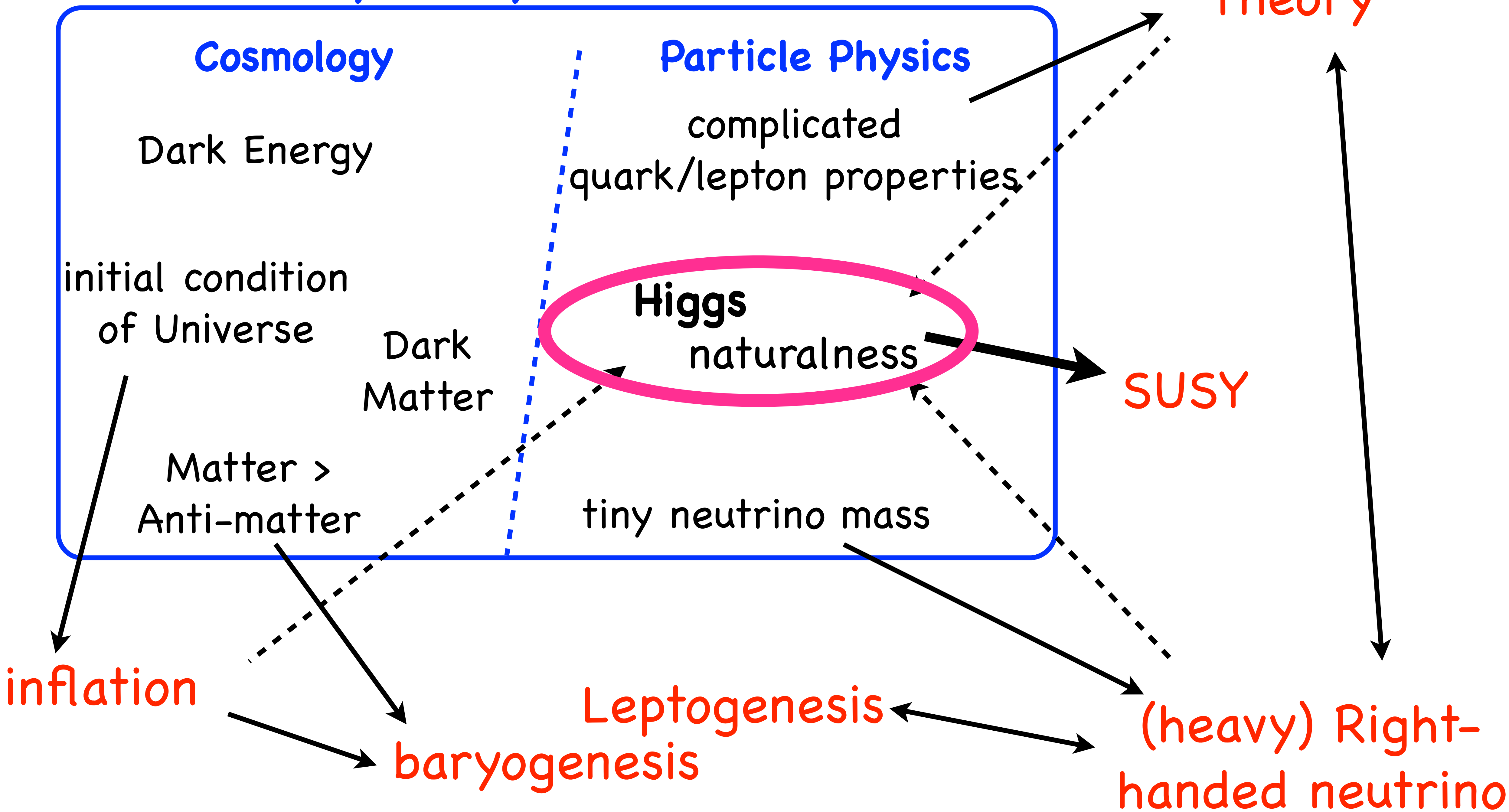
(fine tuning like 1.0000000000000001 - 1)

→ solved by the **supersymmetry** !

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

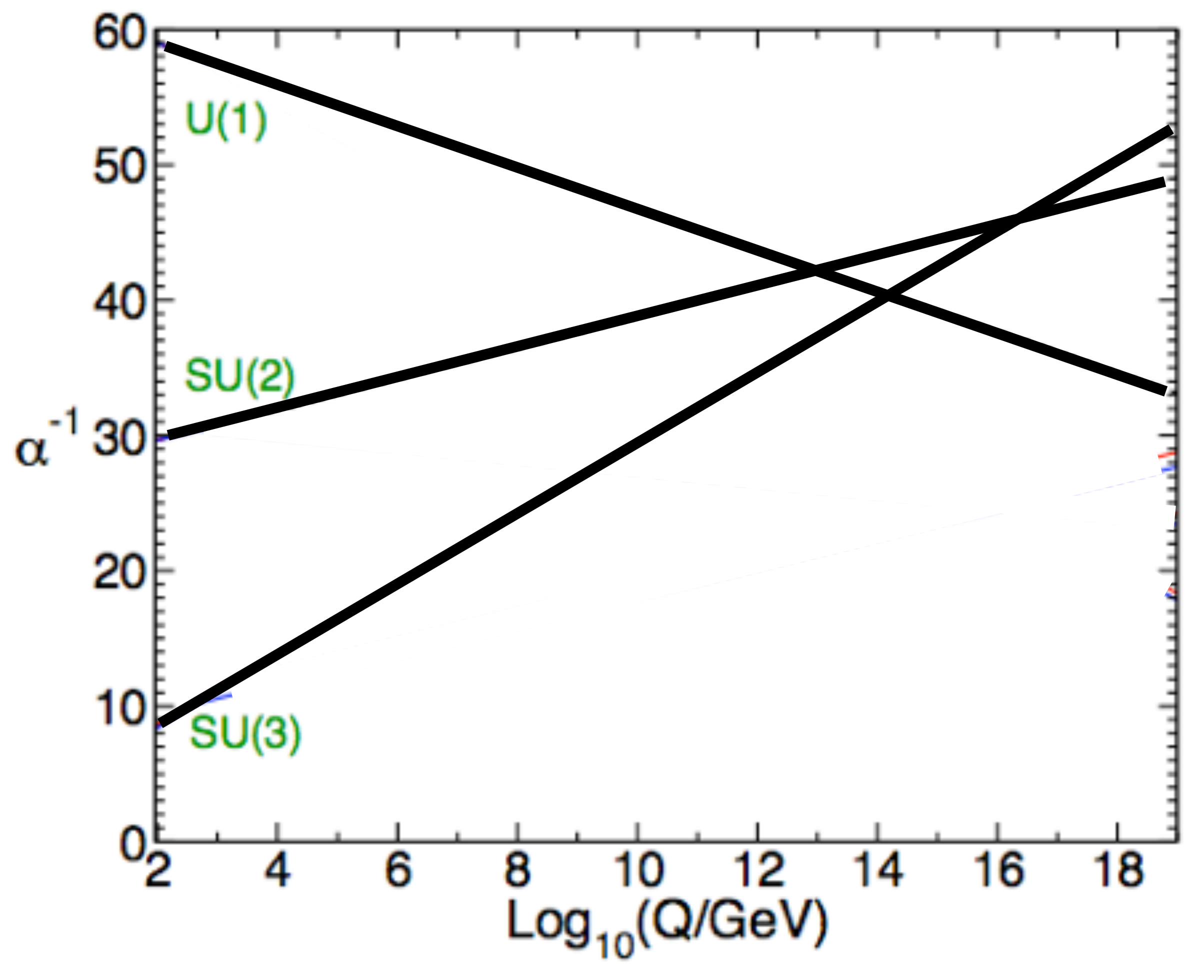


Puzzles in the Standard Model
= Hints of Physics beyond the Standard Model

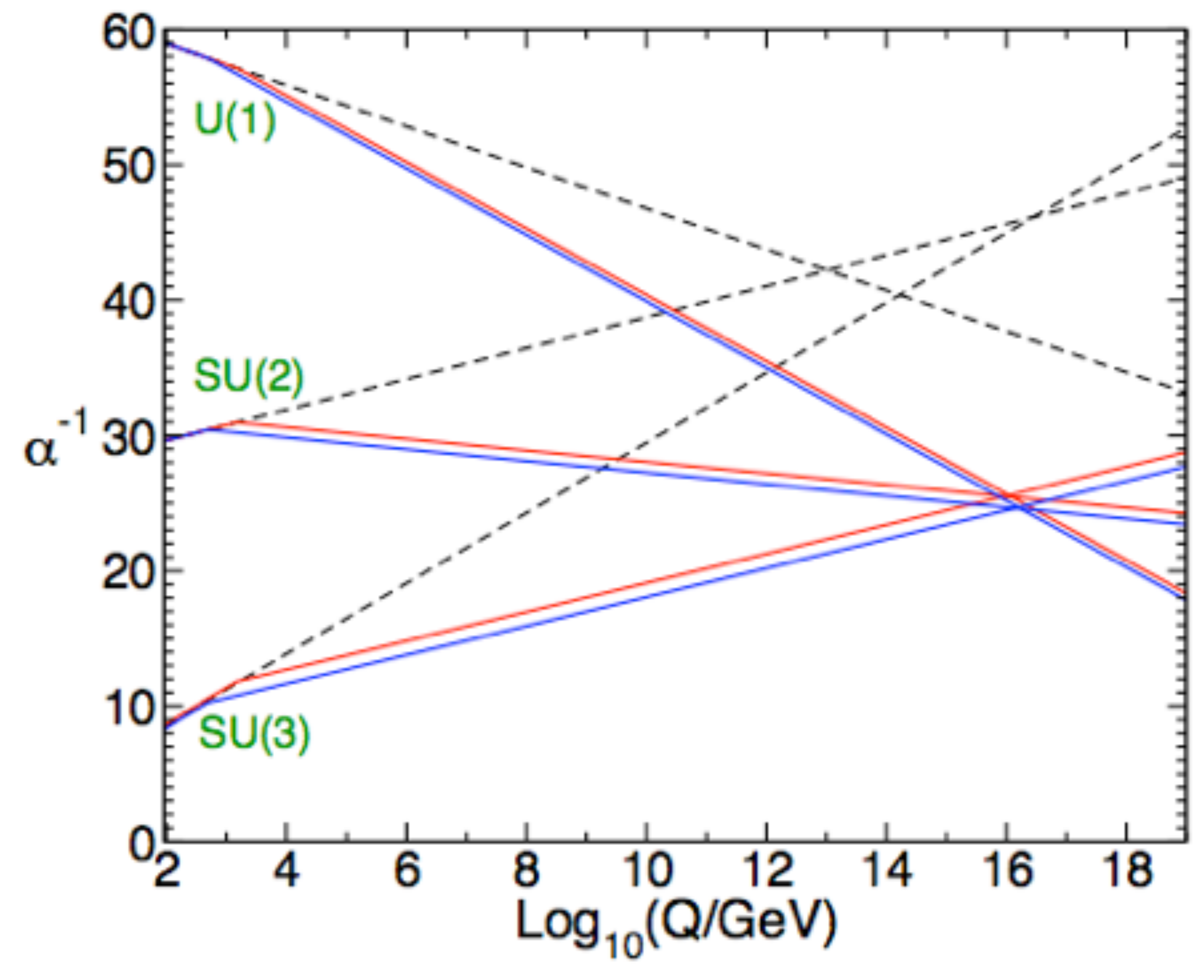


furthermore...

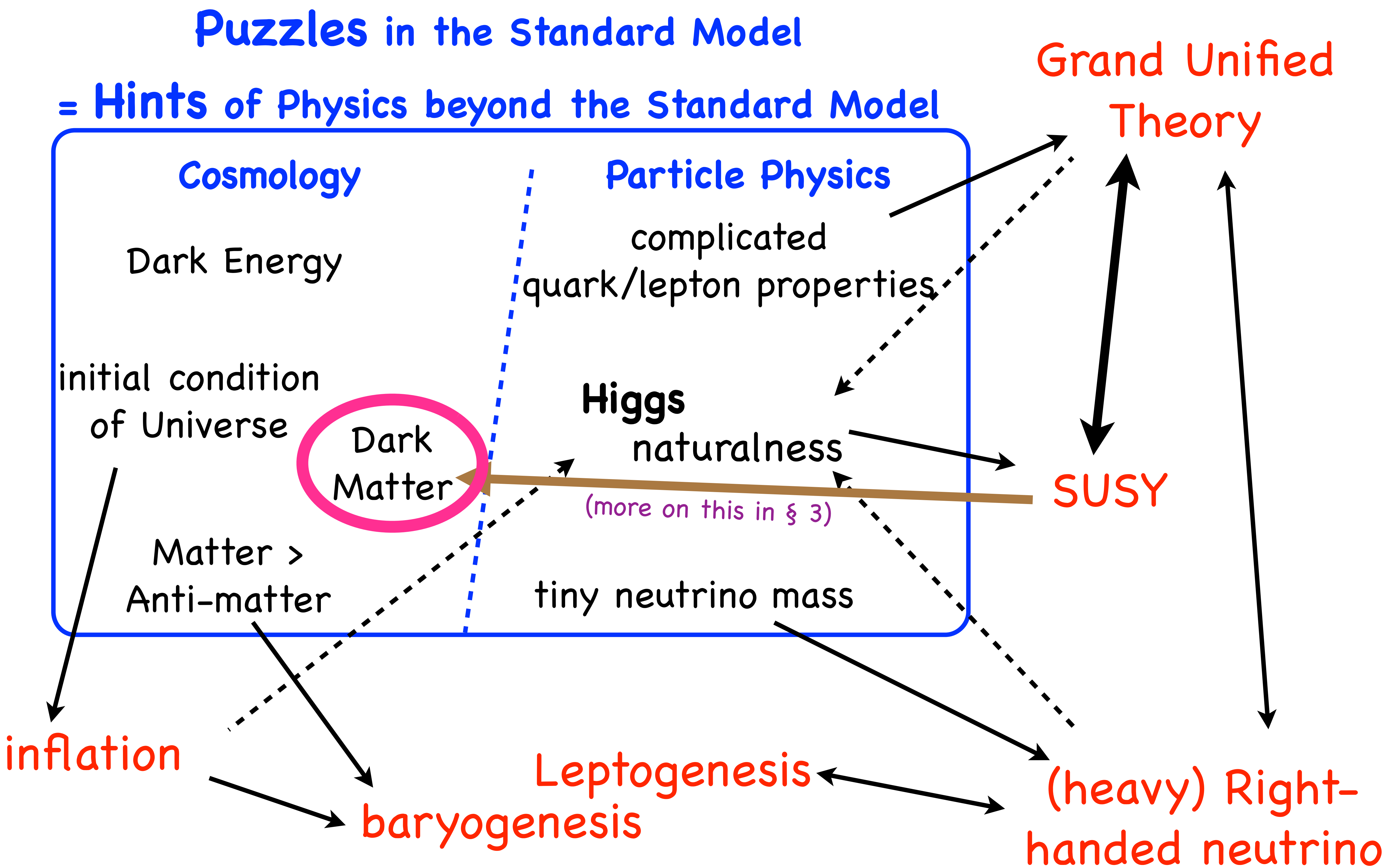
Standard Model



Standard Model + SUSY

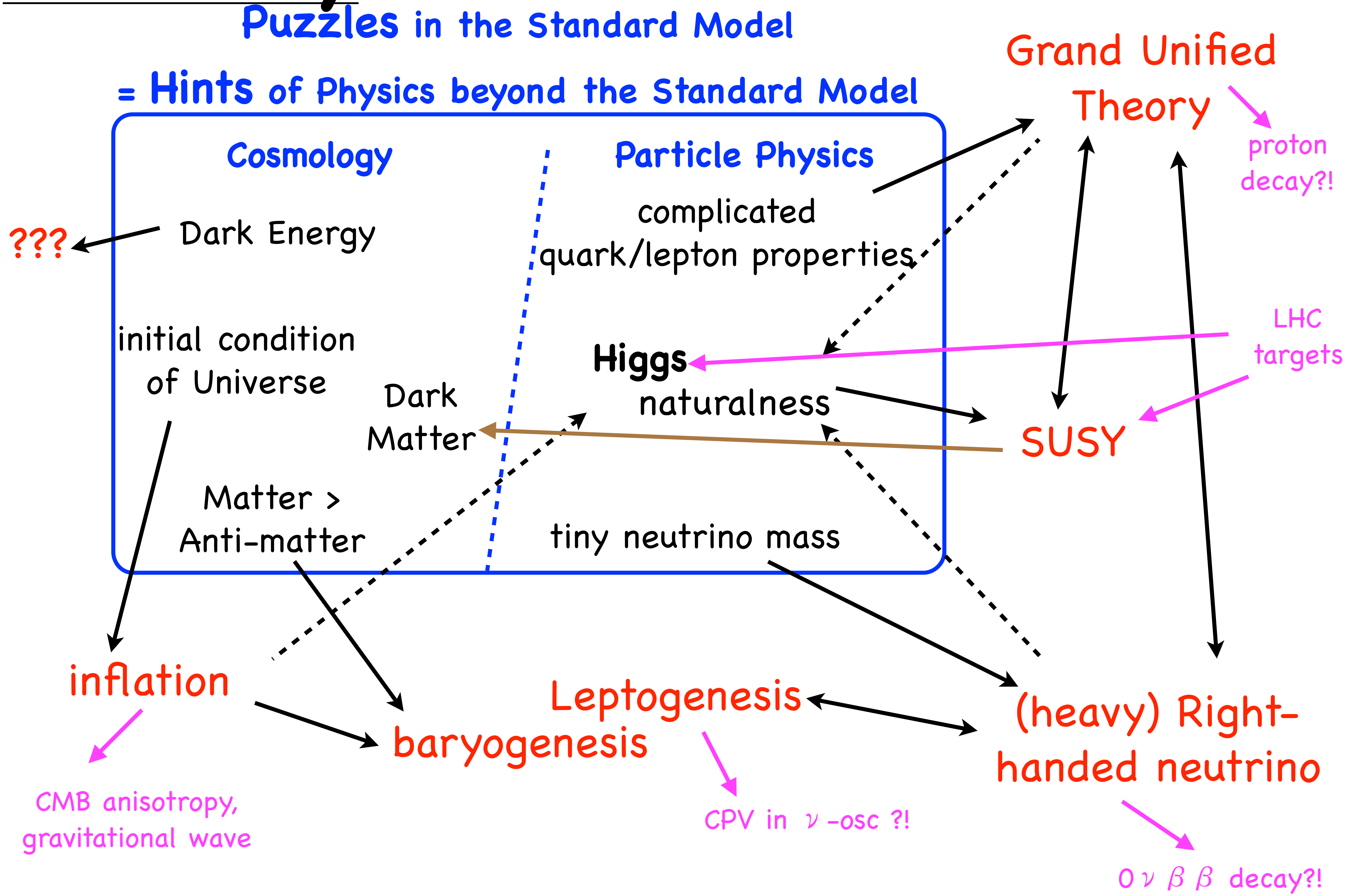


(more on this in § 3)



furthermore...

Summary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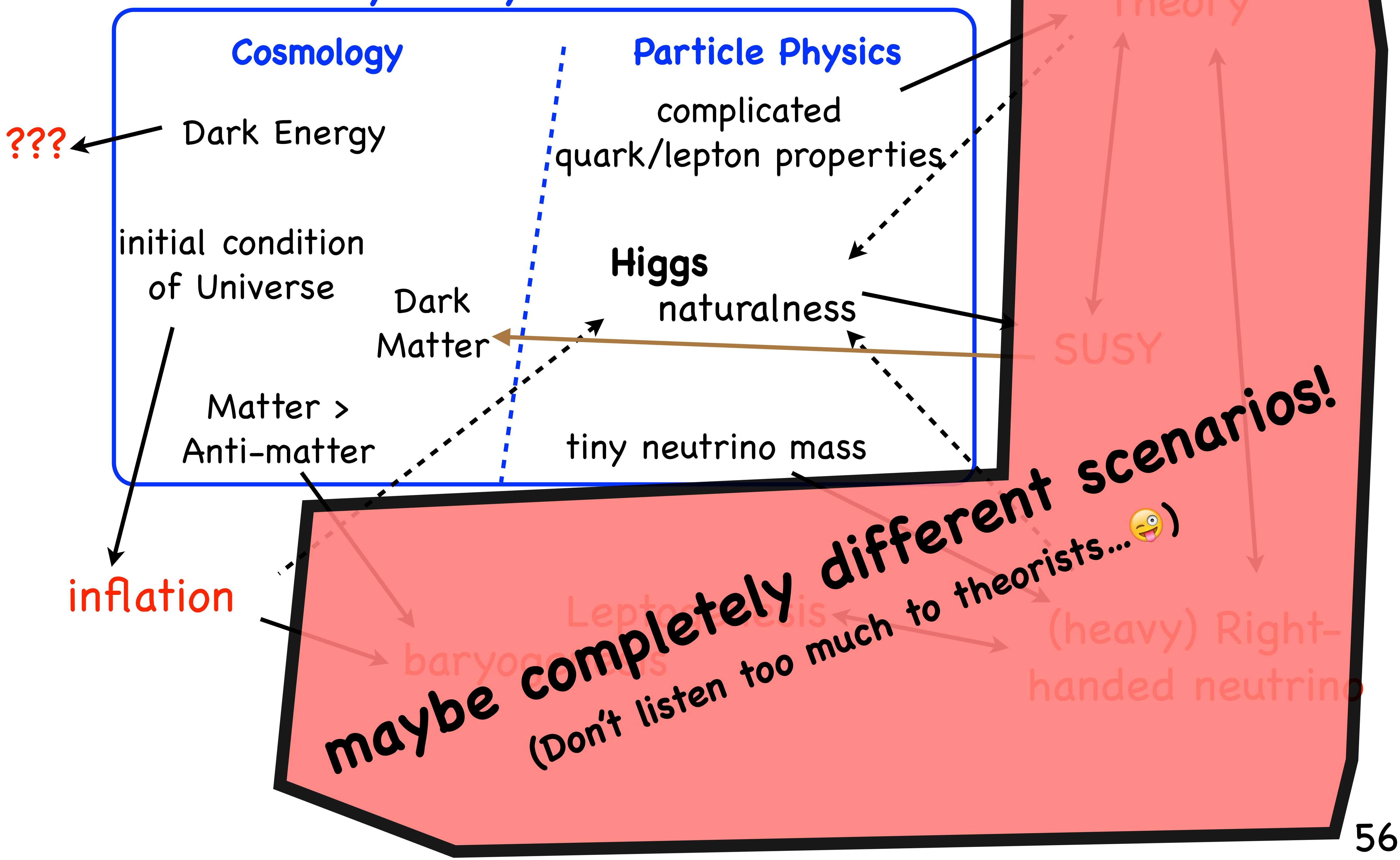
(heavy) Right-
handed neutrino
0 ν β β decay?!

Summary

Puzzles in the Standard Model

= Hints of Physics beyond the Standard Model



Plan

0. **Introduction**
1. **Higgs**
2. **Beyond the Standard Model**
   2.1. puzzles in SM = hints of BSM.
   done
   2.2. renormalization and naturalness