Models for Baryogenesis

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Lecture I

Color meets Flavor
Bad Honnef Physics School
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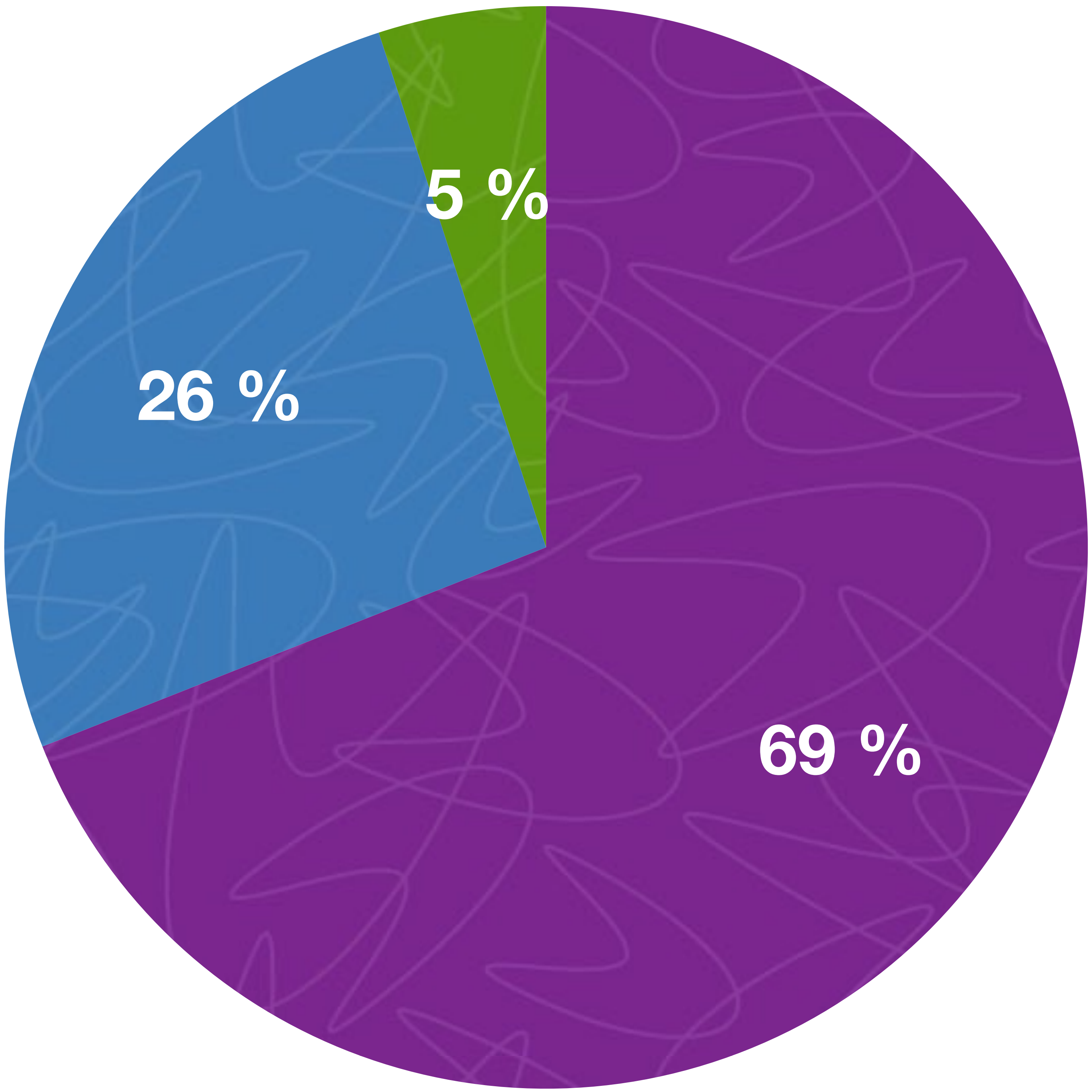
Precision Cosmology

Planck 2018 1807.06209

$$\Omega_b h^2 = 0.02237(15)$$

Baryonic Matter



Dark Matter

$$\Omega_{\rm cdm} h^2 = 0.1200(12)$$

Dark Energy

$$\Omega_\Lambda = 0.6847(73)$$

Theoretical Understanding?

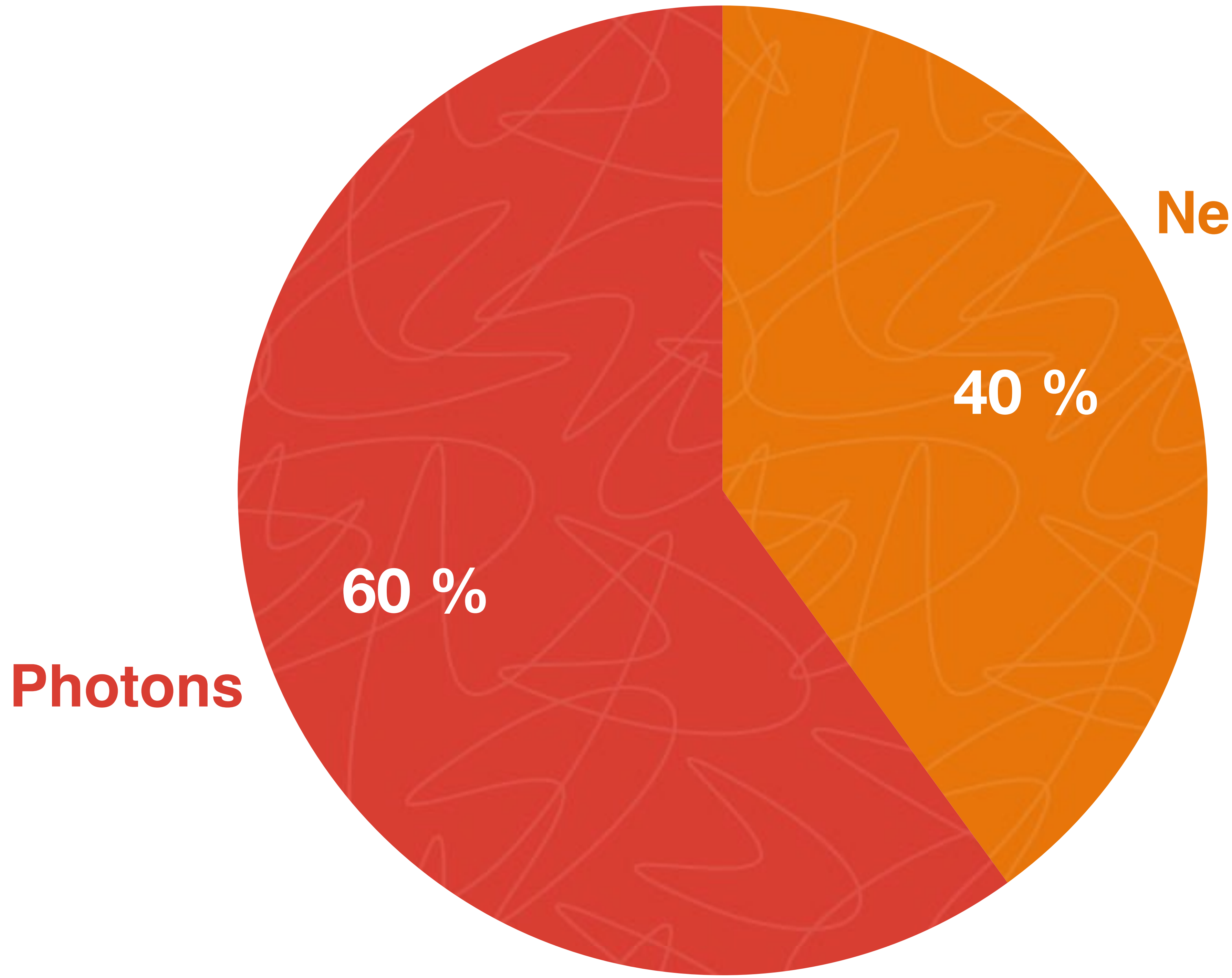
Motivating Question:

What fraction of the Energy Density of the Universe comes from Physics Beyond the Standard Model?

99.85%!

Standard Model Prediction:

We should be living in a Radiation Dominated Universe!



Theoretical Understanding?

Dark Energy — **Little to nothing**

Dark Matter

The CMB anisotropies clearly motivate a particle description
Many candidates: WIMPS, Axions, Sterile Neutrinos ...
Existing experimental constraints on the various possibilities

Baryons

Small number of Baryons per photon point towards a primordial asymmetry:

$$\left.\frac{n_B}{n_\gamma}\right|_{\text{today}} = \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\text{today}} = 6.1 \times 10^{-10}$$ **CMB & BBN**

Baryogenesis

Extrapolation of the Standard Model to the early Universe predicts a Universe with

$$\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\rm SM} \ll 10^{-20}$$

Baryogenesis: dynamical generation of the baryon asymmetry of the Universe

Three key requirements: The Sakharov conditions (1967)

1) C and CP violation

2) Departure from Thermal Equilibrium

3) Baryon number violation

Outline

Lecture 1:

- **What is the Universe made of? Is there any antimatter?**
- **Introduction to key elements of Cosmology**
  - **Isotropic and Homogeneous Universe**
  - **Extrapolation to the very early Universe:**
    - **Equilibrium Thermodynamics**
    - **Out of equilibrium conditions**
- **The Sakharov Conditions in the Standard Model**
- **Key ingredients of the Standard Model thermal history**

Outline

Lecture 2:

- **Most popular mechanisms for baryogenesis**

  Baryogenesis via out-of equilibrium decays

- **Baryogenesis through Leptogenesis**

  Cosmology meets flavor

- **B-Mesogenesis: Baryogenesis from B-Mesons**

  Cosmology meets color and flavor

Three main aims:

1) Understand what is the problem we are trying to solve

why? $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$

2) Have a global view on the thermal history of the early Universe

3) Have a broad idea of how the most popular mechanisms work

References

Books:

The Early Universe, Kolb & Turner, Addison-Wesley, 1990

Introduction to the Theory of the Early Universe, Rubakov & Gorbunov, World Scientific, 2011

Modern Cosmology, Dodelson & Schmidt, Academic Press, 2020

Reviews/Lectures:

Baryogenesis, TASI lectures, James Cline, hep-ph/0609145

Leptogenesis for pedestrians, Buchmüller, Di Bari & Plümacher, hep-ph/0401240

Leptogenesis, Davidson, Nardi & Nir hep-ph/0802.2962

Non-GUT baryogenesis, Dolgov, *Phys.Rept.* 222 (1992) 309-386

The Origin of the matter - antimatter asymmetry, Dine & Kusenko, hep-ph/0303065

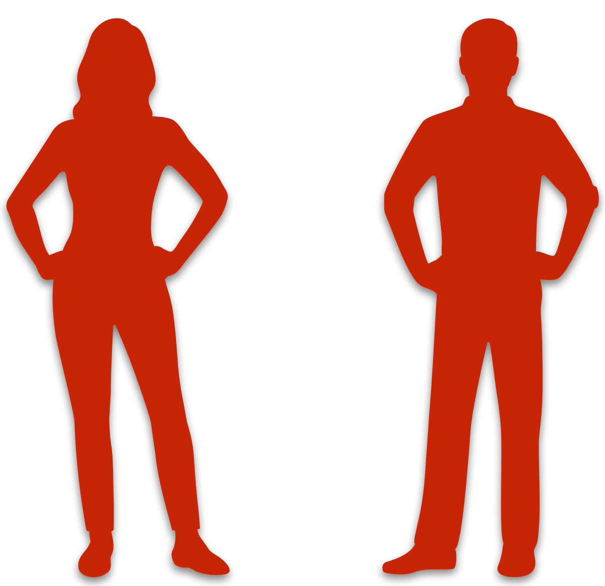
Recent developments:

New ideas on Baryogenesis, Snowmass: 2203.05010

Set Up

The plan is to discuss and learn as much as possible. Therefore:

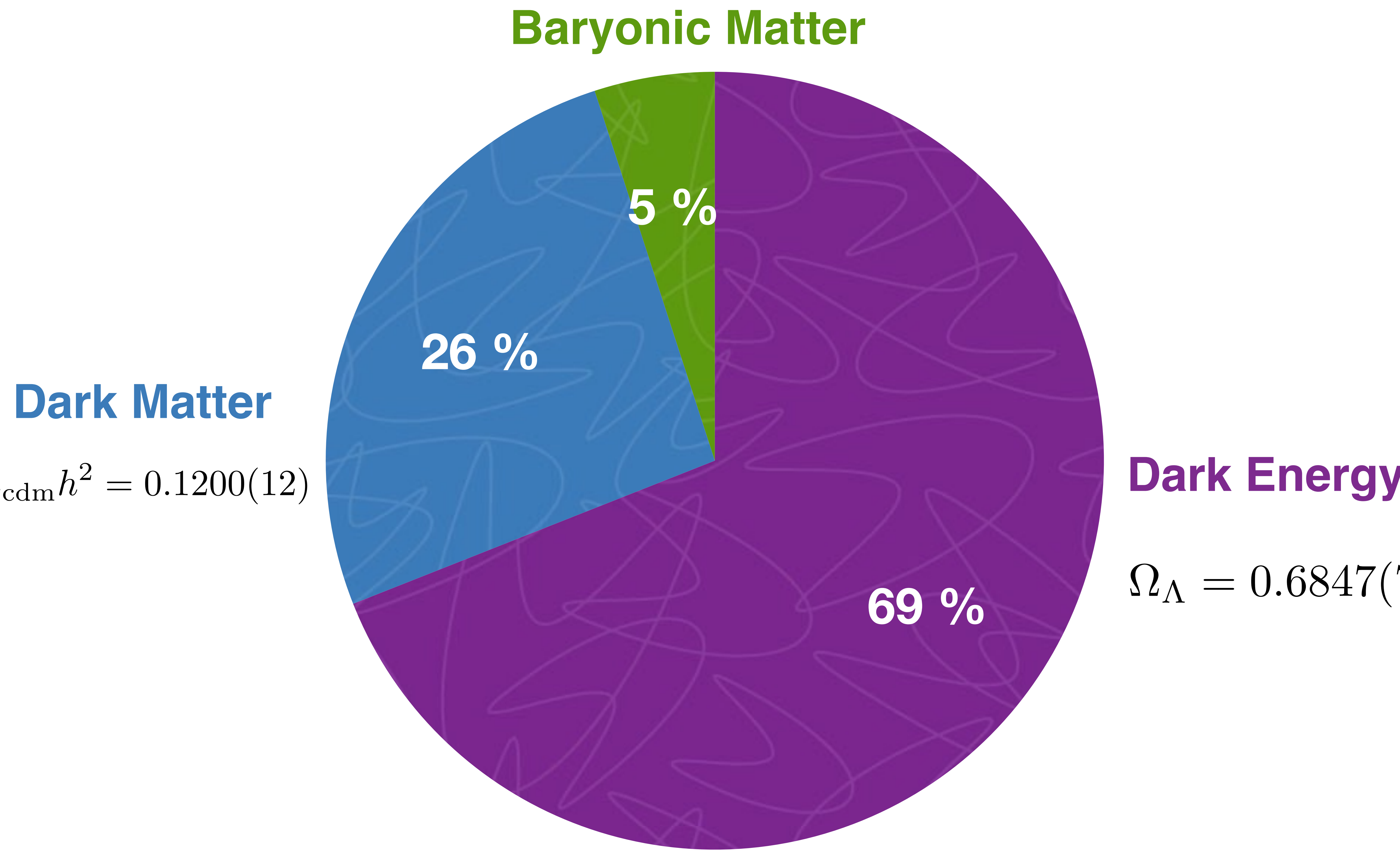
Questions and Comments are most welcome, at any time!!!!



Composition of the Universe

Planck 2018 1807.06209

$\Omega_b h^2 = 0.02237(15)$

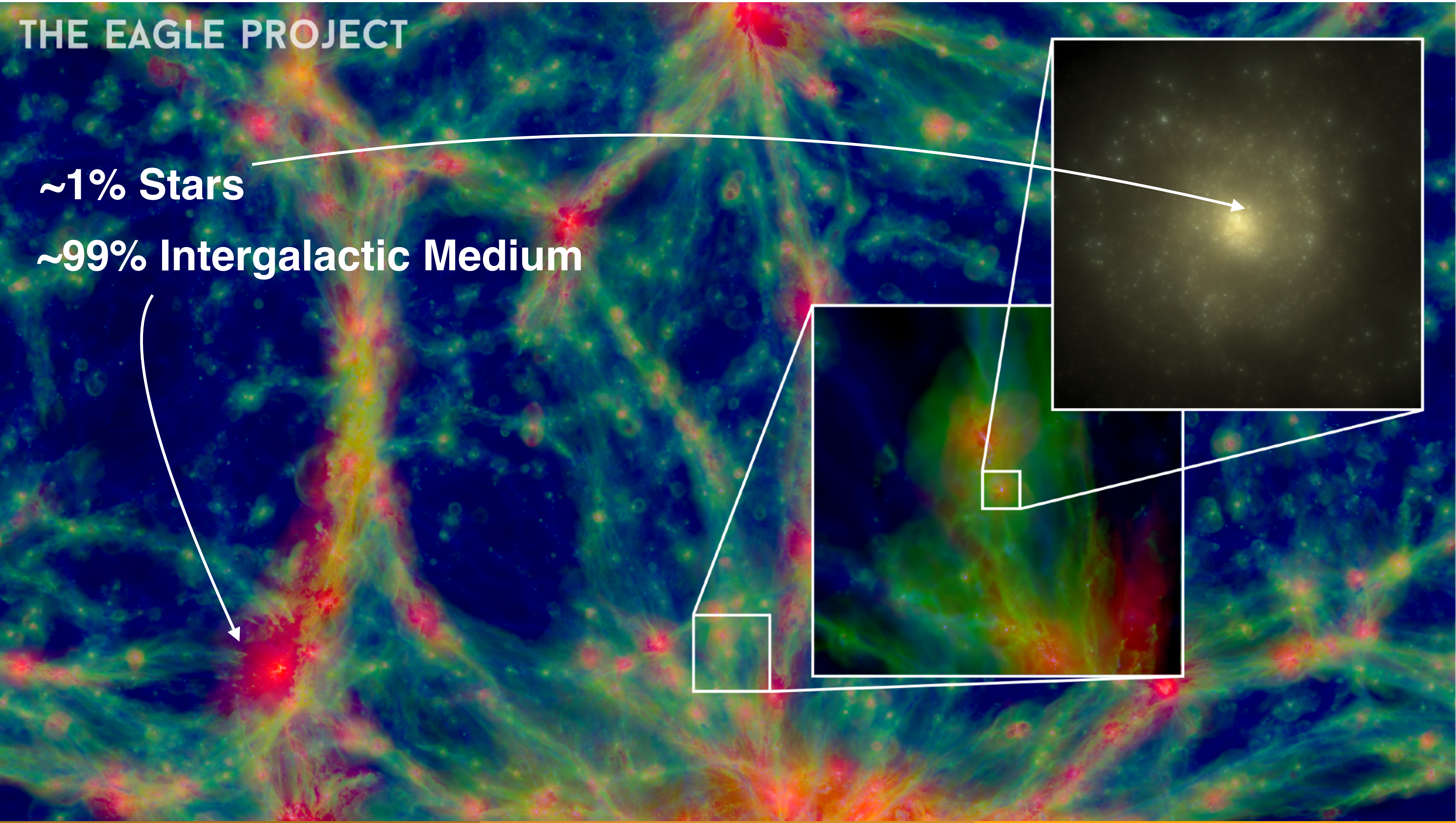


$\Omega_{\rm cdm} h^2 = 0.1200(12)$

$\Omega_\Lambda = 0.6847(73)$

Where are the baryons?

Baryonic inventory: Fukugita, Hogan & Peebles '98



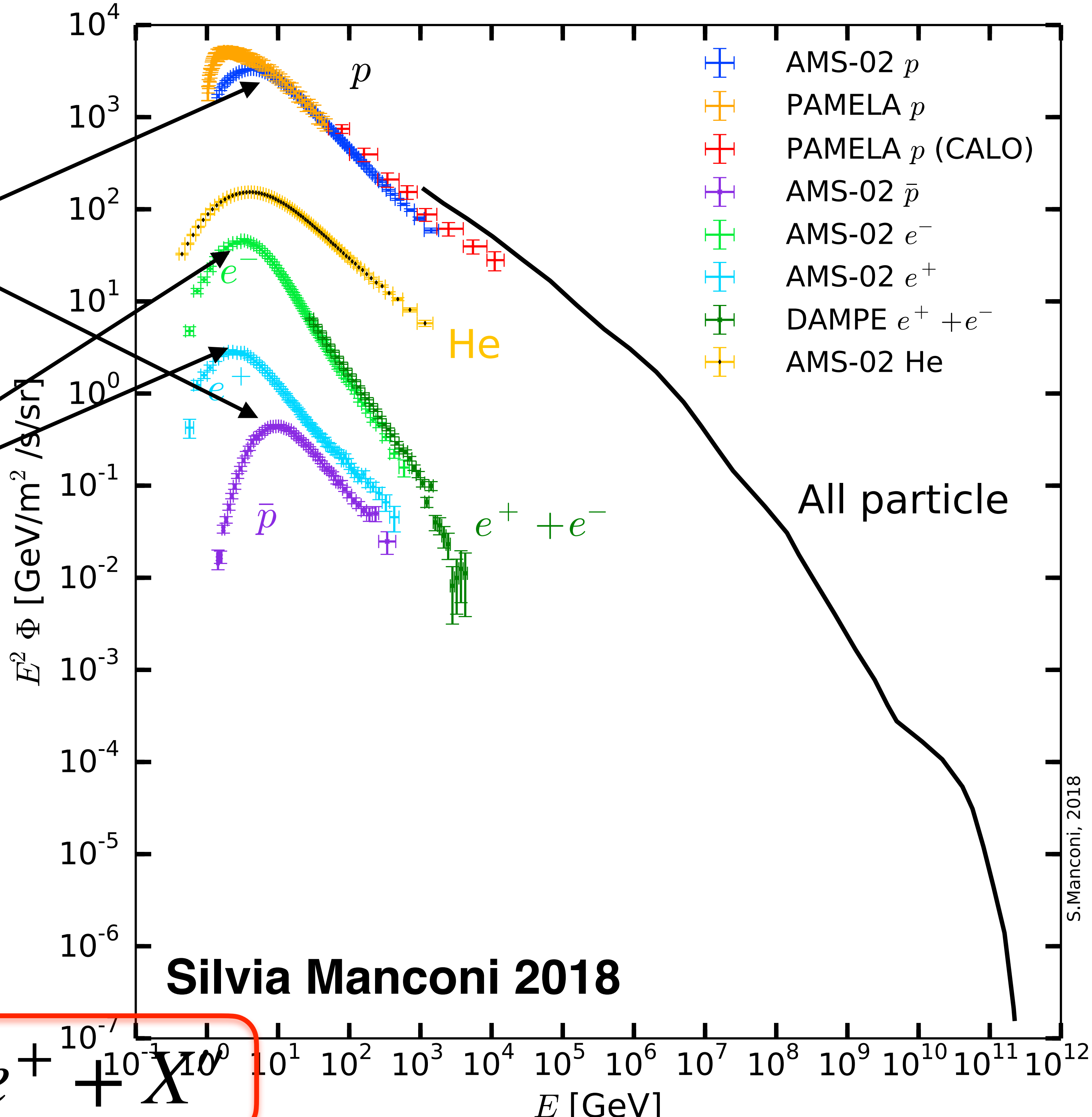
Is there any cosmic antimatter?

Yes! We have observed cosmic antiprotons and positrons on Earth

Typical fluxes are

$$\frac{\text{antiprotons}}{\text{protons}} \simeq 10^{-4}$$

$$\frac{\text{positrons}}{\text{electrons}} \simeq 10\,\%$$



Importantly, no confirmed detection of antinuclei!

source?:

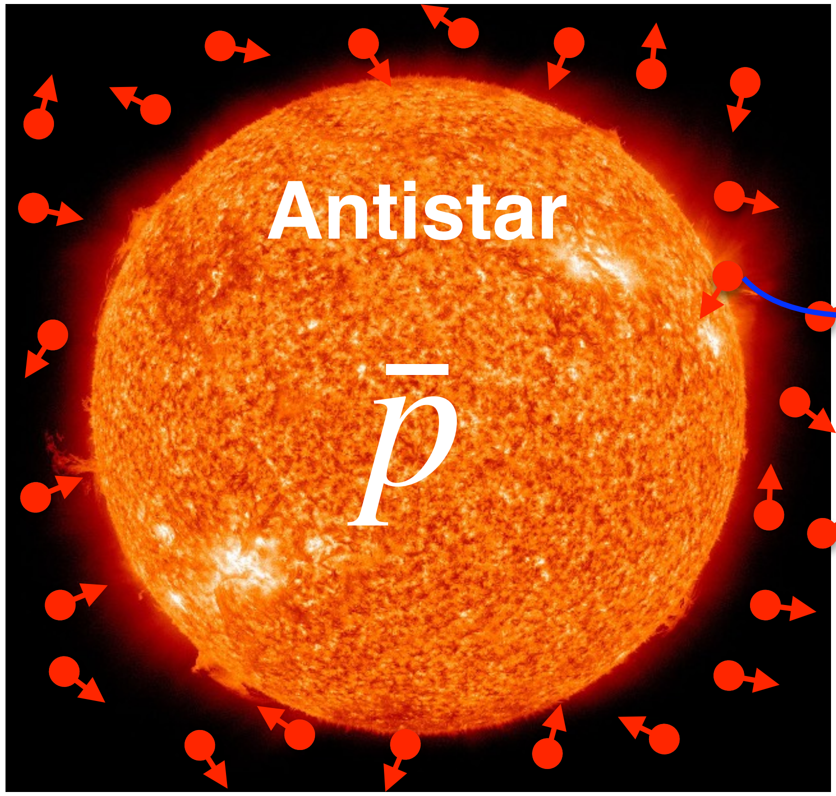
$$p + X \to \bar{p} + X'$$

$$p + X \to \pi^+ + X' \to e^+ + X''$$

Any evidence for antimatter stars?

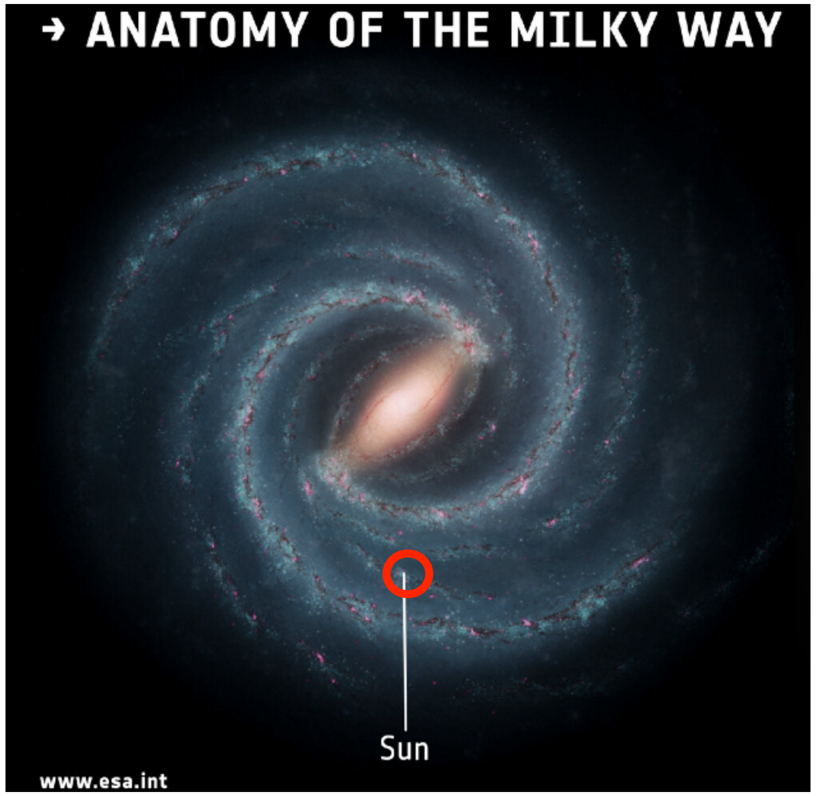
No!

Antistars will lead to a high flux of gamma-rays which are not found by experiments such as FermiLAT, see Steigman review '76



$$\bar{p}p \to \bar{\pi}\pi \to \gamma\gamma$$

$$E_\gamma \sim m_{\pi^0}/2$$



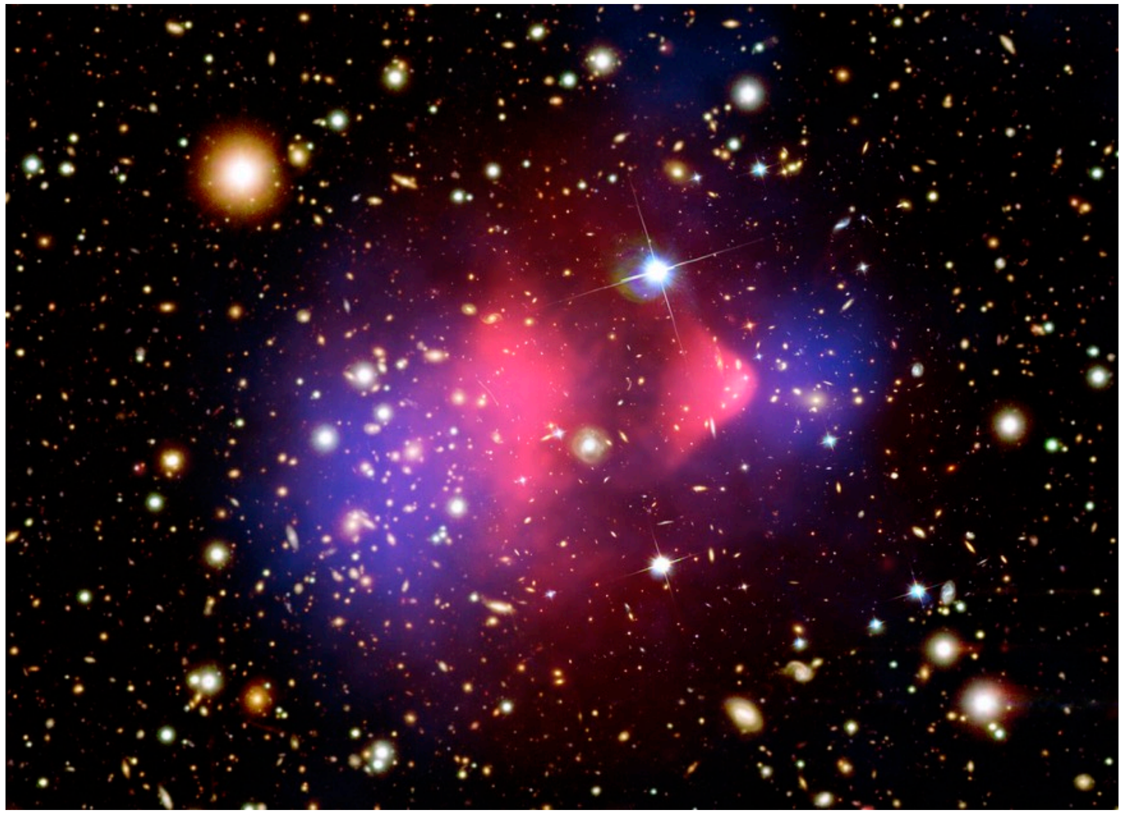
Dupourque, Tibaldo, von Ballmoos [2103.10073]

No antistars within $R < 1\,\mathrm{pc} \simeq 10^{16}\,\mathrm{m}$**,**
probably up to $R \simeq 100\,\mathrm{pc}$

Any evidence for antigalaxies?

No!

There is no observation of mergers of galaxies + antigalaxies which means that if there are domains of antimatter they should be separated in domains of at least $d > 20\,\mathrm{Mpc}$ see Steigman ‘76



But, the size of the Universe is $L \sim 10^4\,\mathrm{Mpc}$

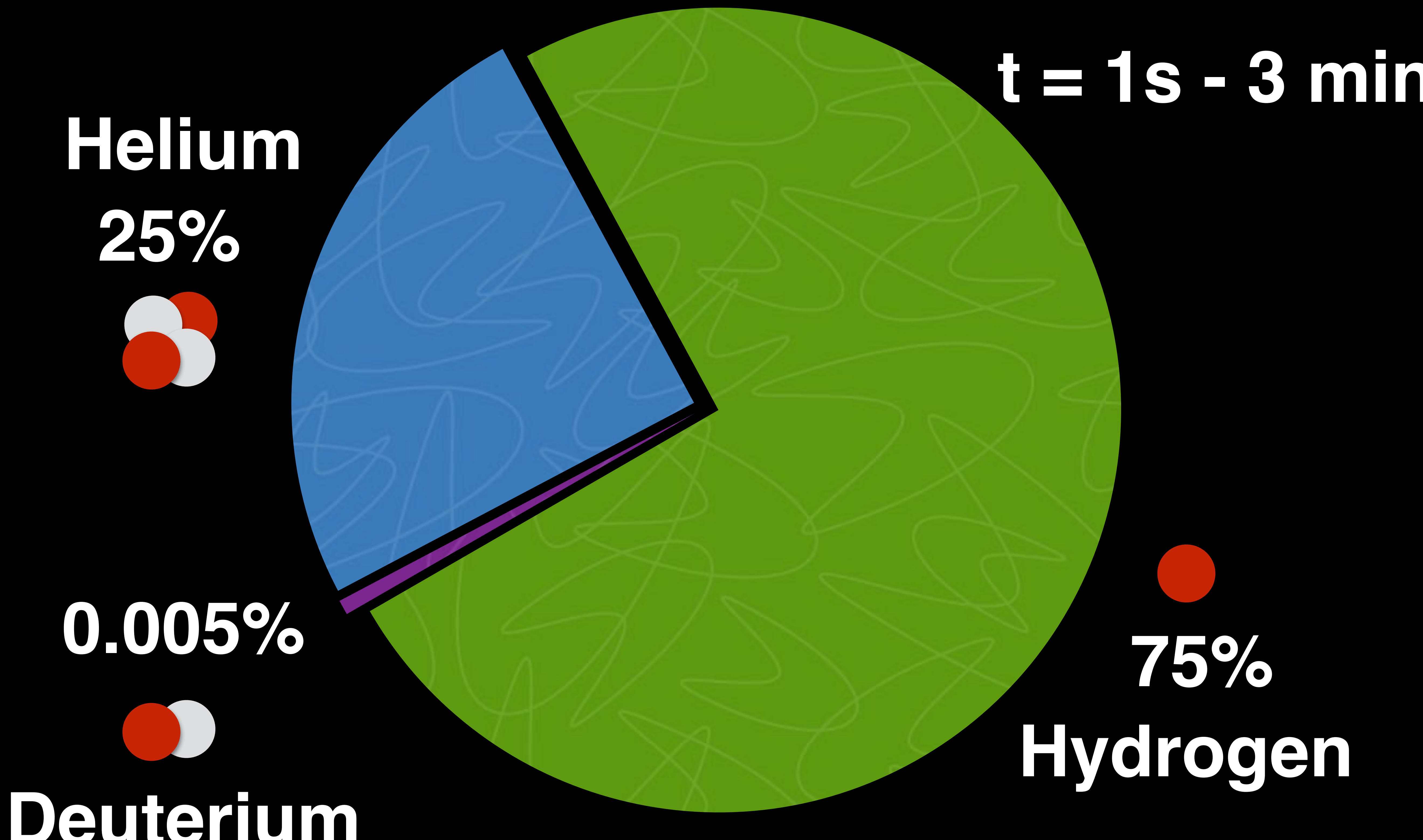
However, matter antimatter annihilation in the boundaries of these regimes is not allowed by the CMB unless $d > 10^3\,\mathrm{Mpc}$, see Cohen, De Rujula & Glashow [astro-ph/9707087]

Conclusion: **Our observable Universe appears to be made out of only matter**

The Universe

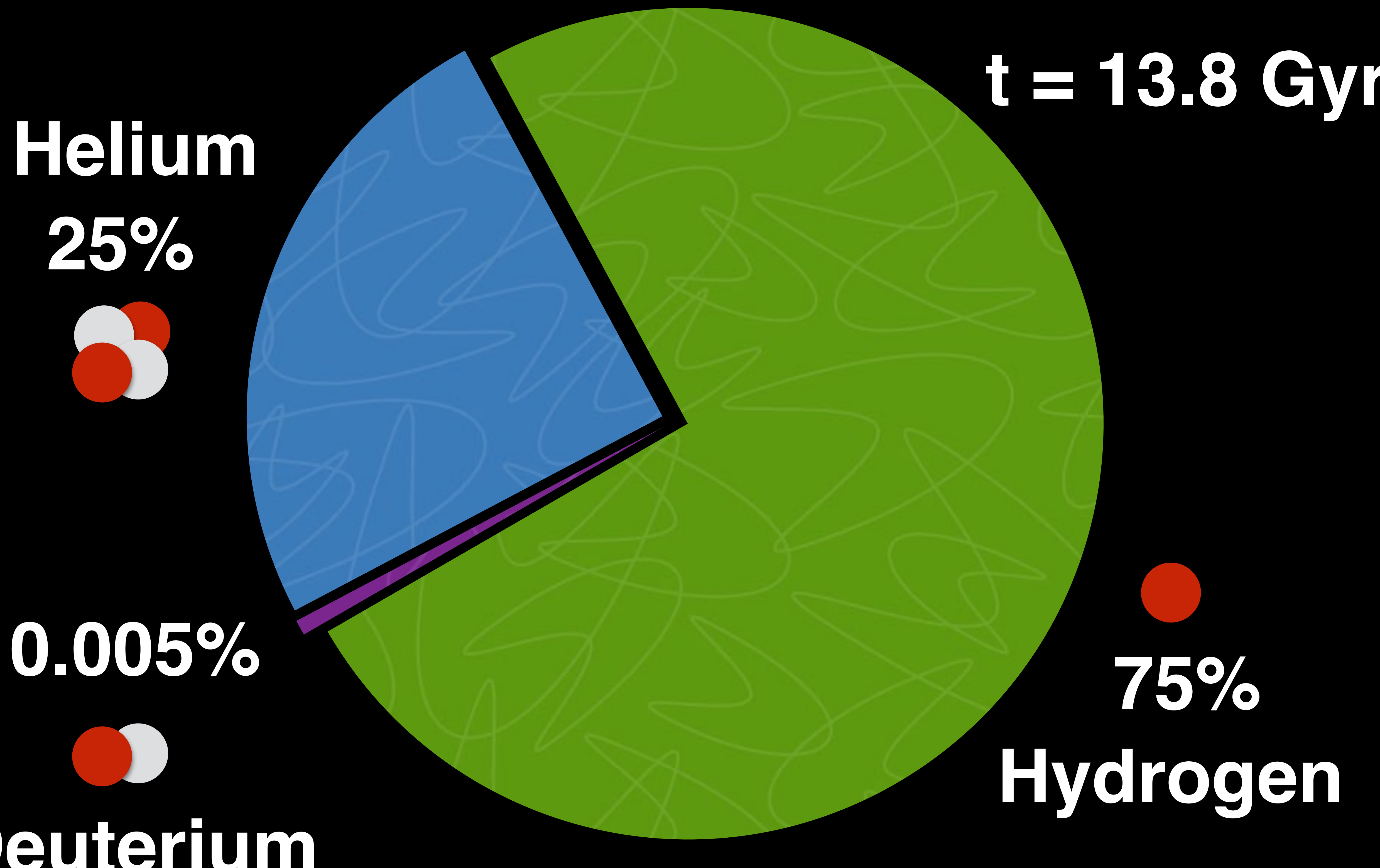
Prediction of a baryon asymmetric Universe:

Homogeneous and Isotropic Universe + Einstein + Nuclear =



The Universe

Observation:



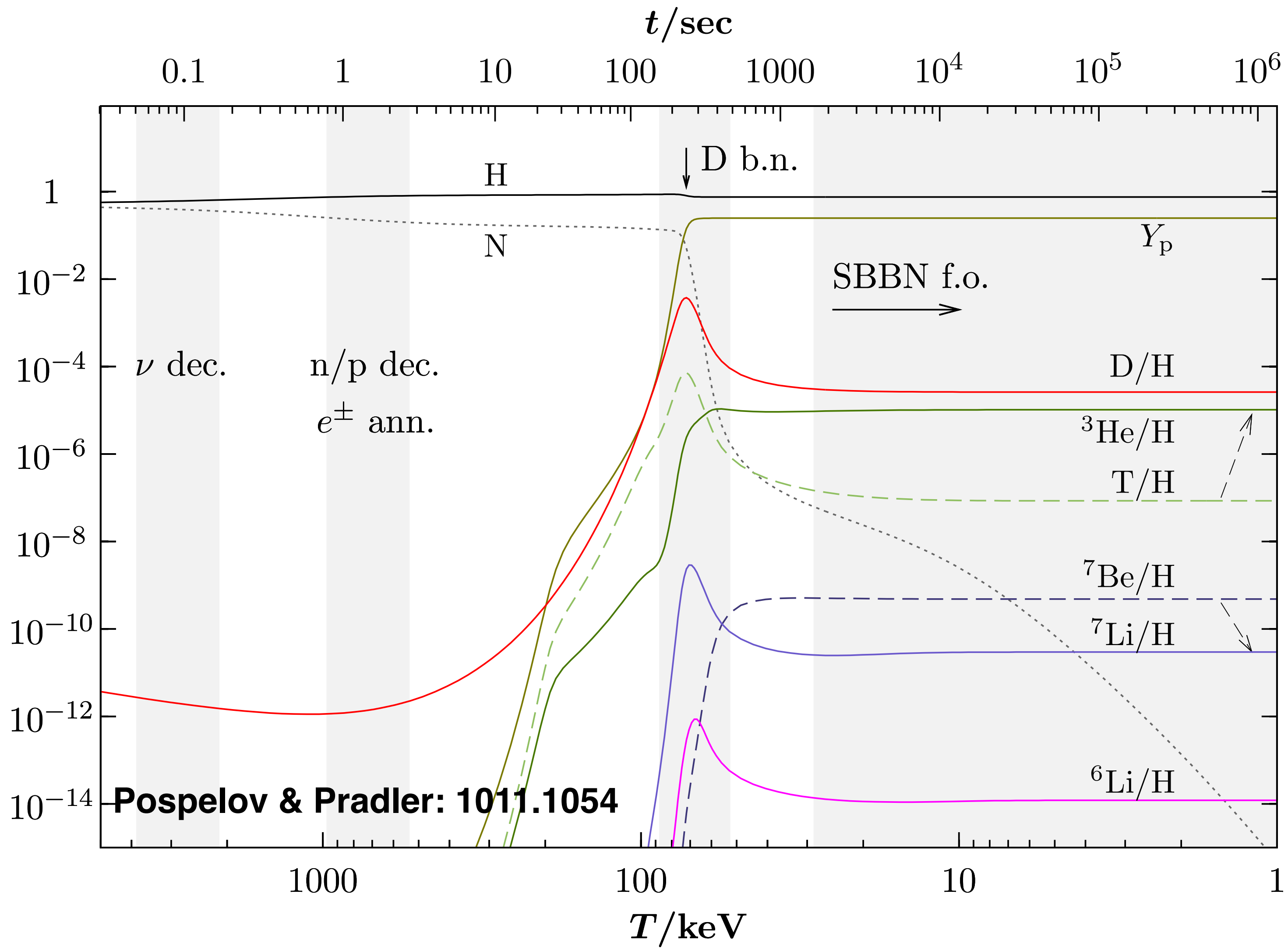
How much matter and when?

Big Bang Nucleosynthesis

Current measurements are consistent with the SM picture

H ~ 75% **^{4}He ~ 25%** **D ~ 0.005%**

To explain this we really need $\eta_B \sim 6 \times 10^{-10}$ at $t_U \lesssim 1\,\mathrm{s}$

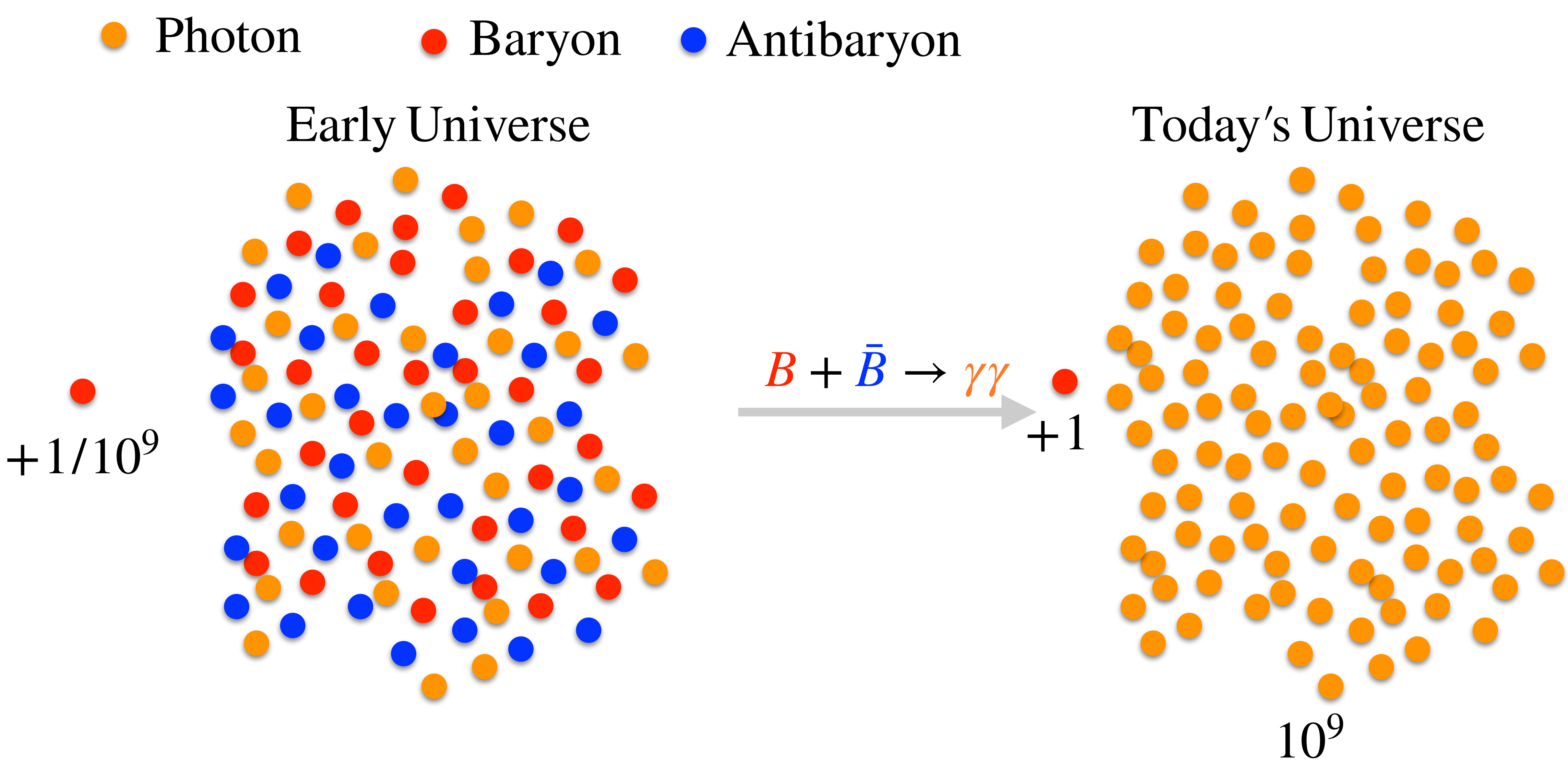


Binding energies are in the MeV range. To explain BBN, the baryon asymmetry of the Universe should have been there at $T \gtrsim \mathrm{MeV}$ or at $t \lesssim 1\,\mathrm{s}$

The Baryogenesis aim

1) What is the problem we are trying to solve?

Explain $\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$ **at** $T \gtrsim 1\,\mathrm{MeV}$



Outline

Lecture 1:

- What is the Universe made of? Where is the antimatter?
- Introduction to key elements of Cosmology
    - Isotropic and Homogeneous Universe
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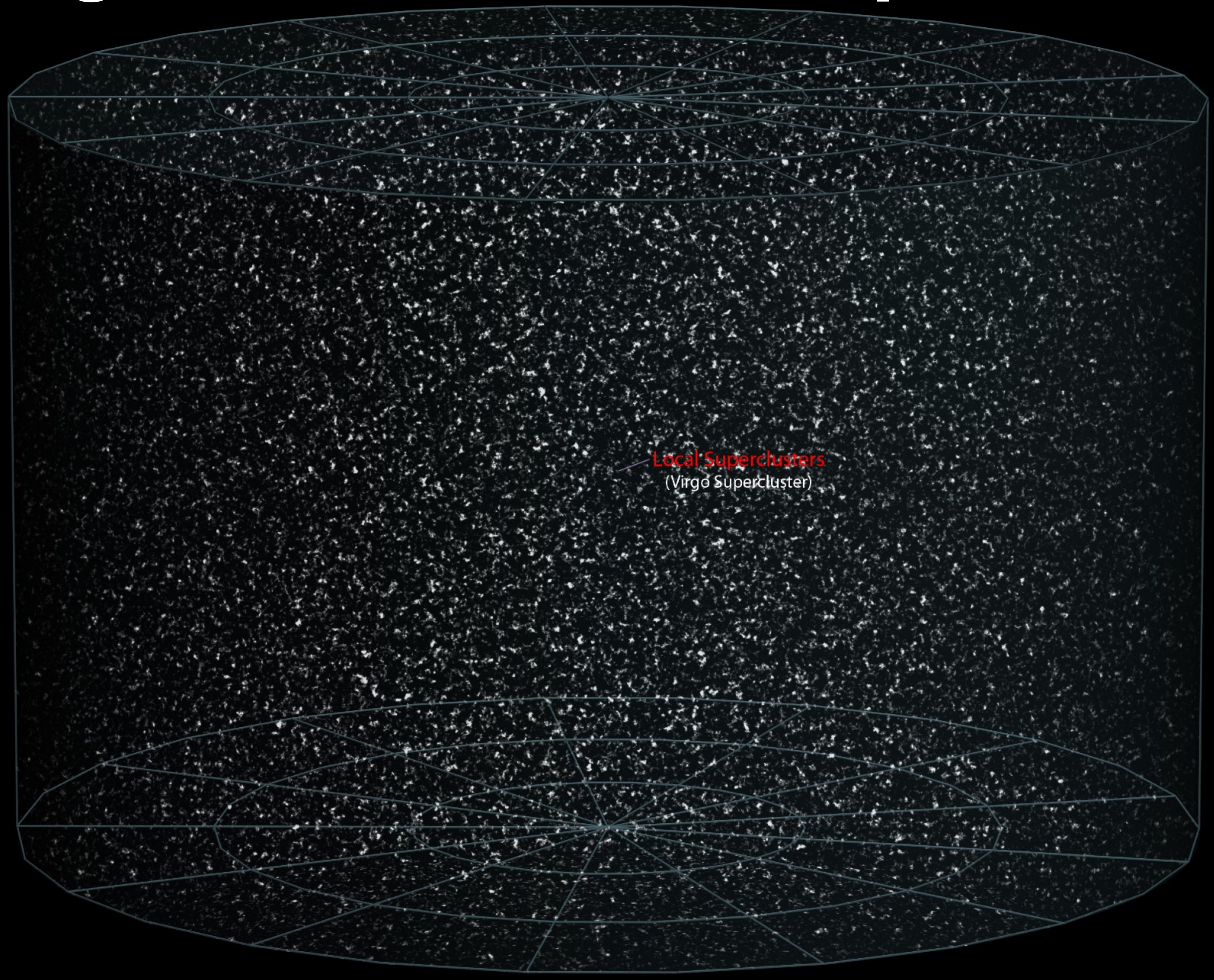
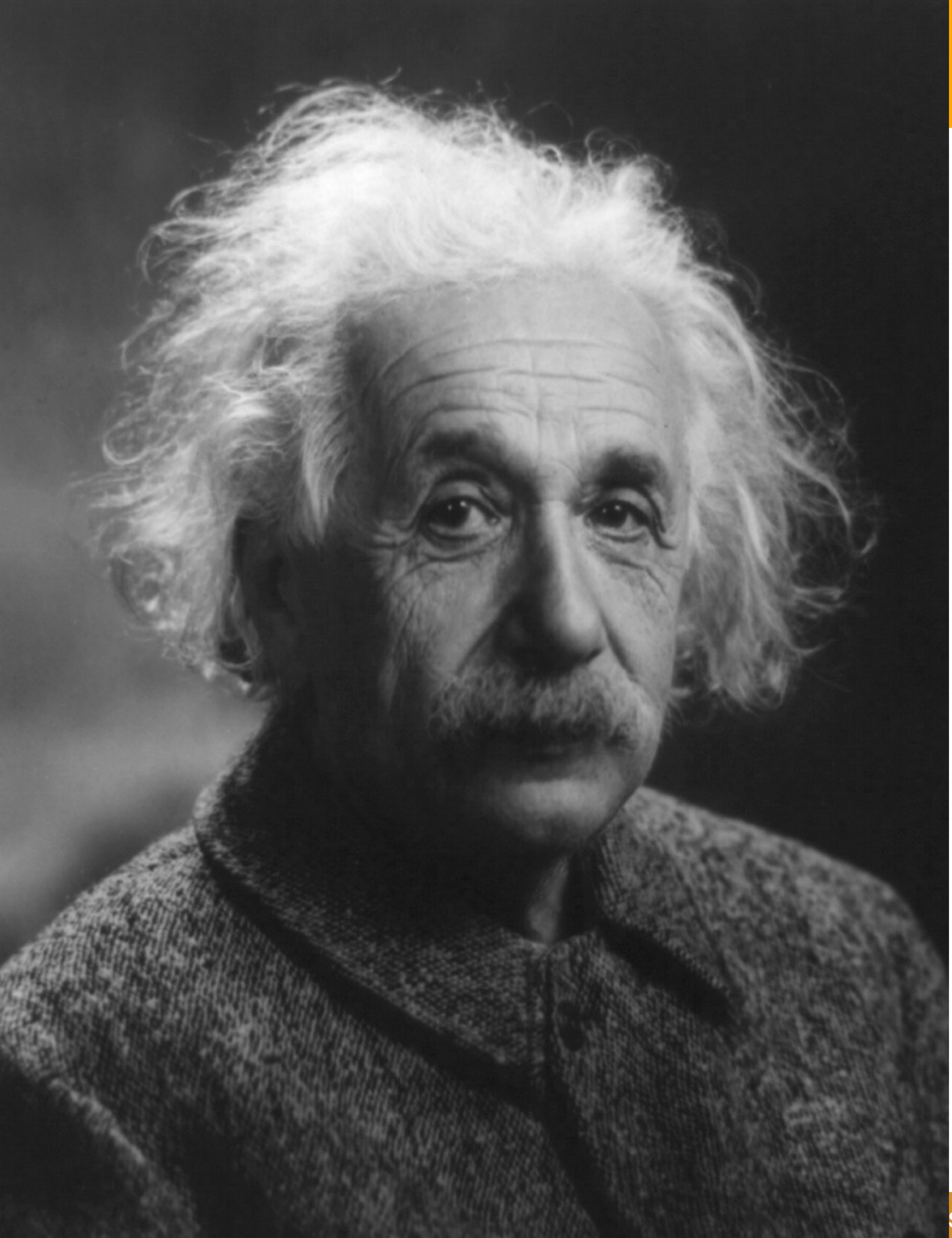
The Universe

Cosmological Principle: Homogeneous and Isotropic Universe



Credit: Wikipedia



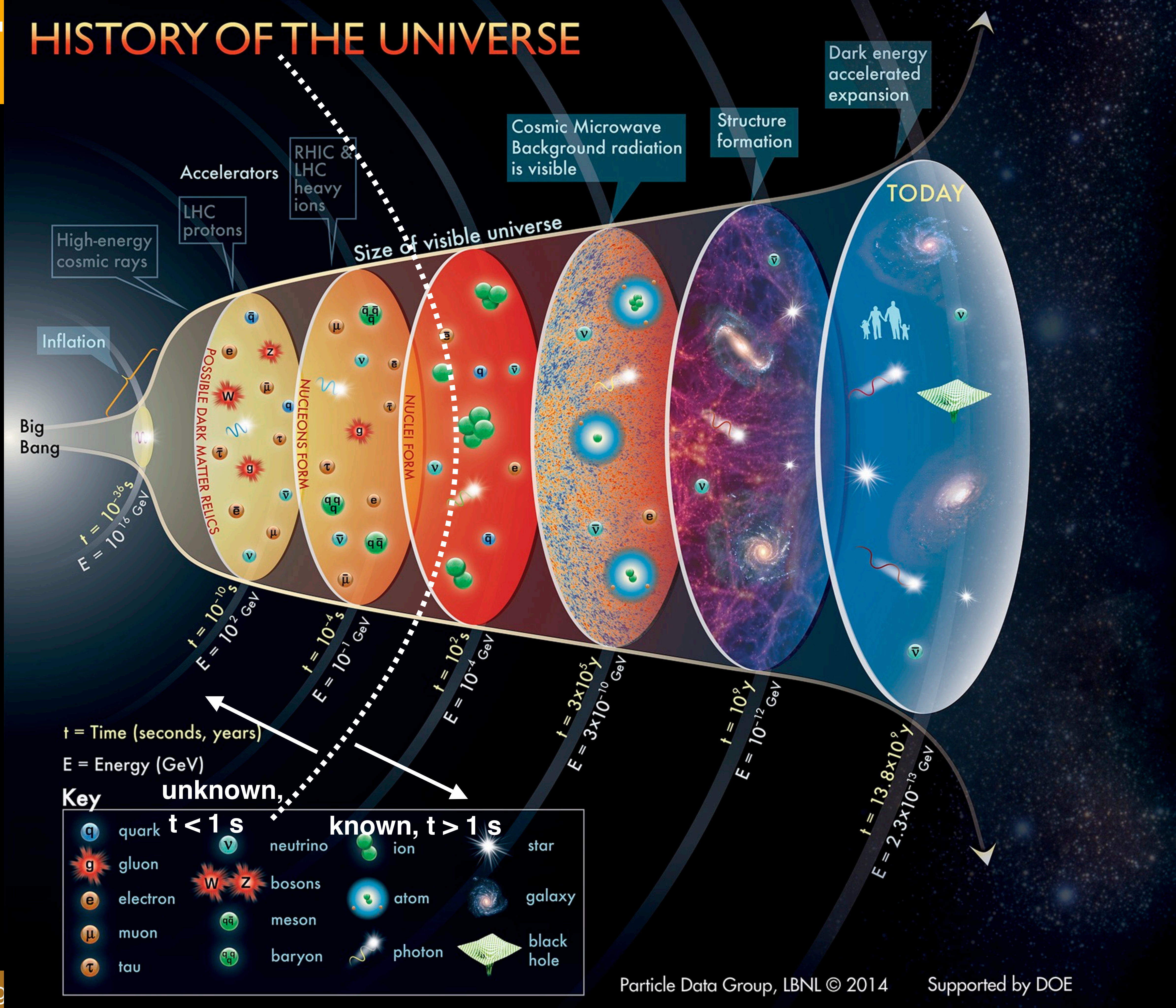
Einstein's Equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

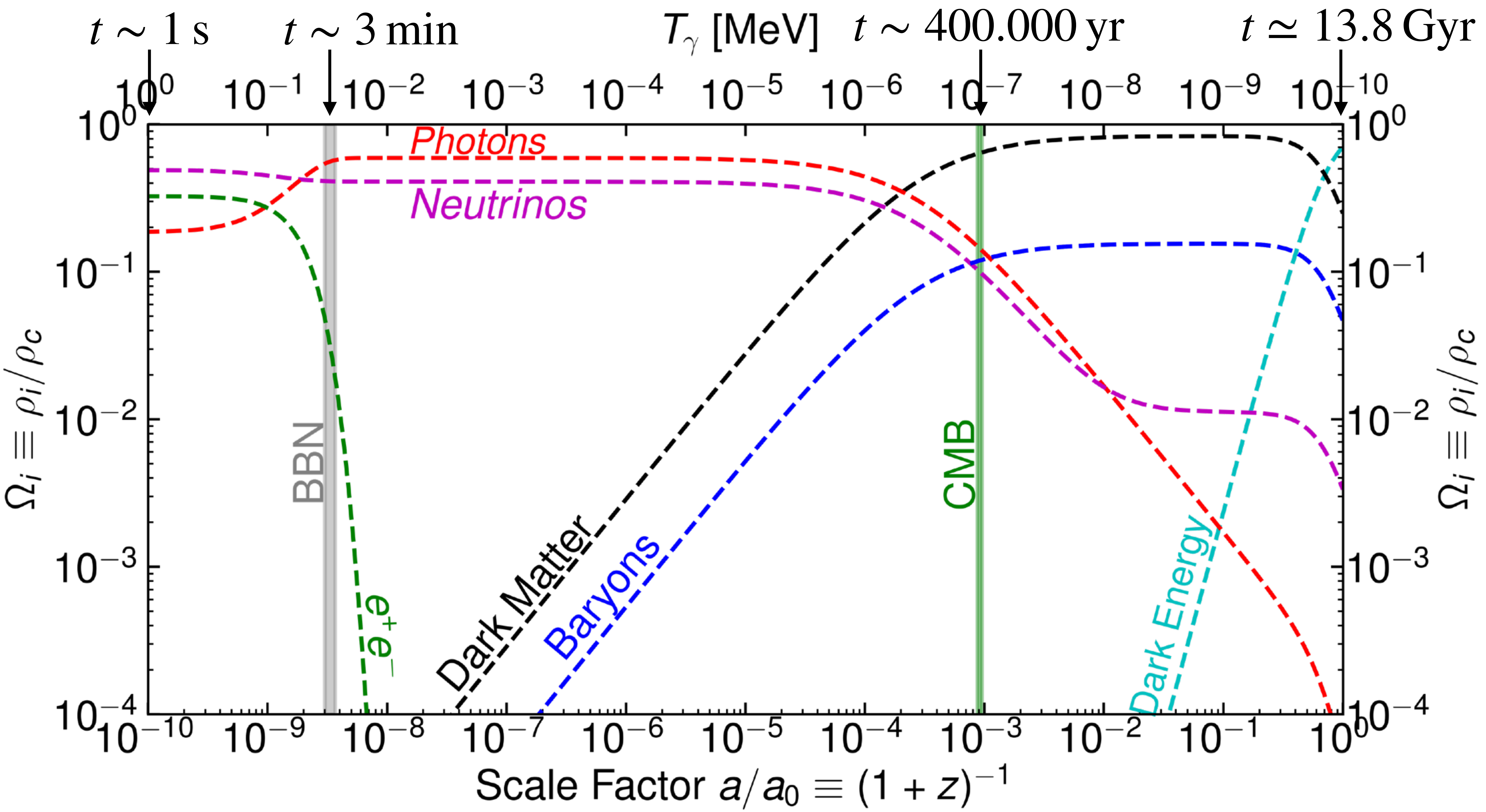
Matter: $T_{\mu\nu}$

Space-Time Geometry: $G_{\mu\nu}$

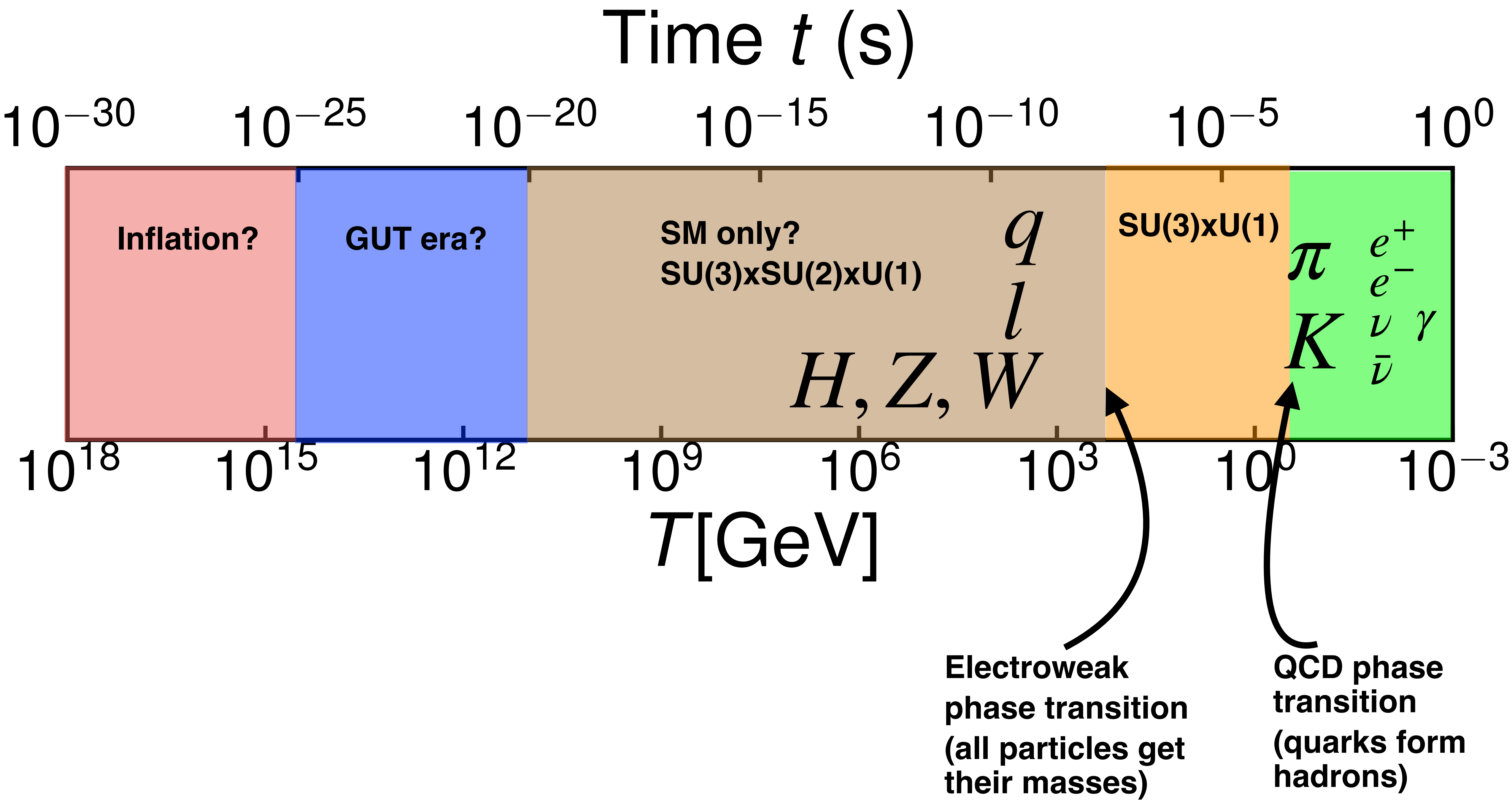
Expansion!


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
unknown,
t < 1 s
known, t > 1 s
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

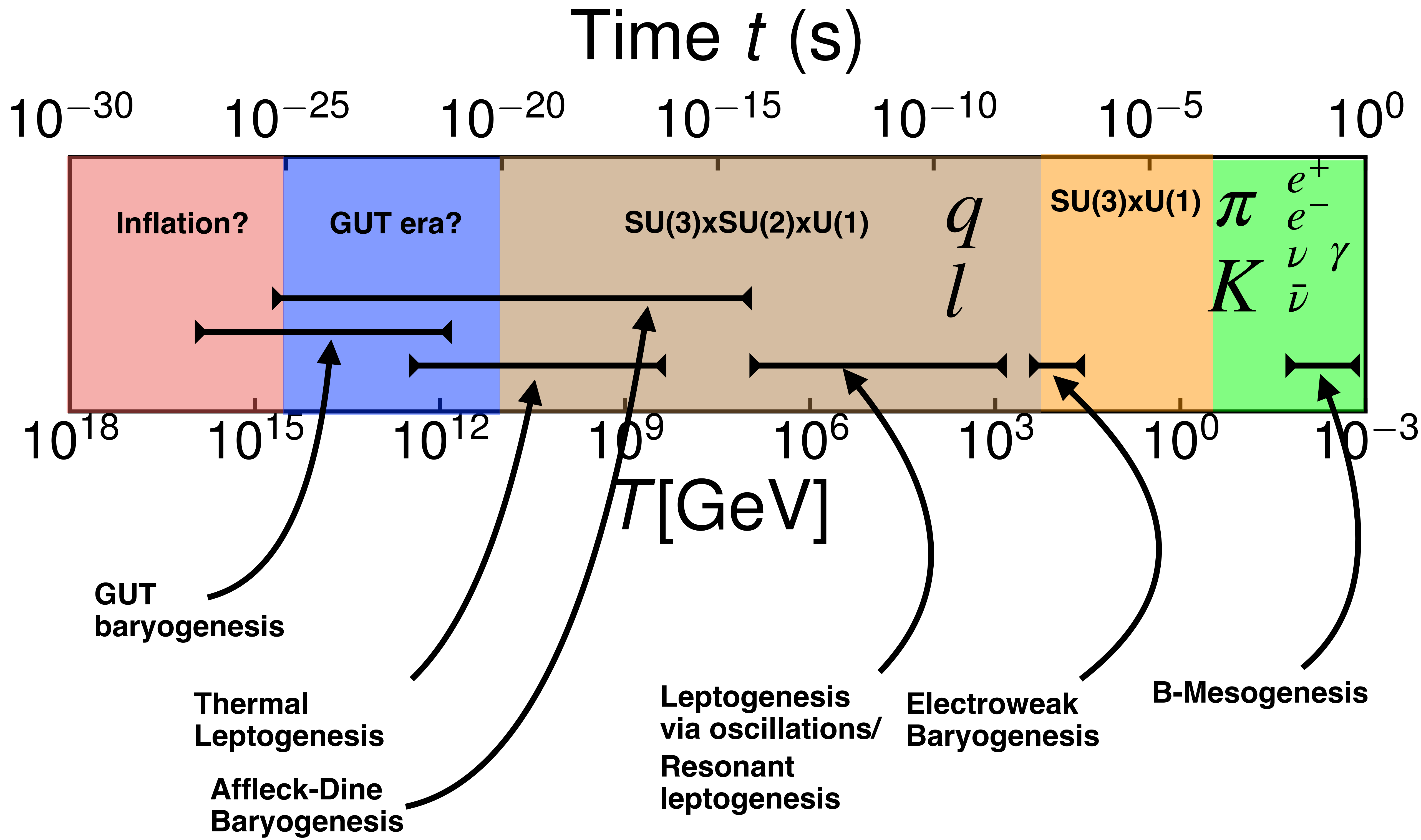
The Known Thermal History



Key Stages in the Thermal History

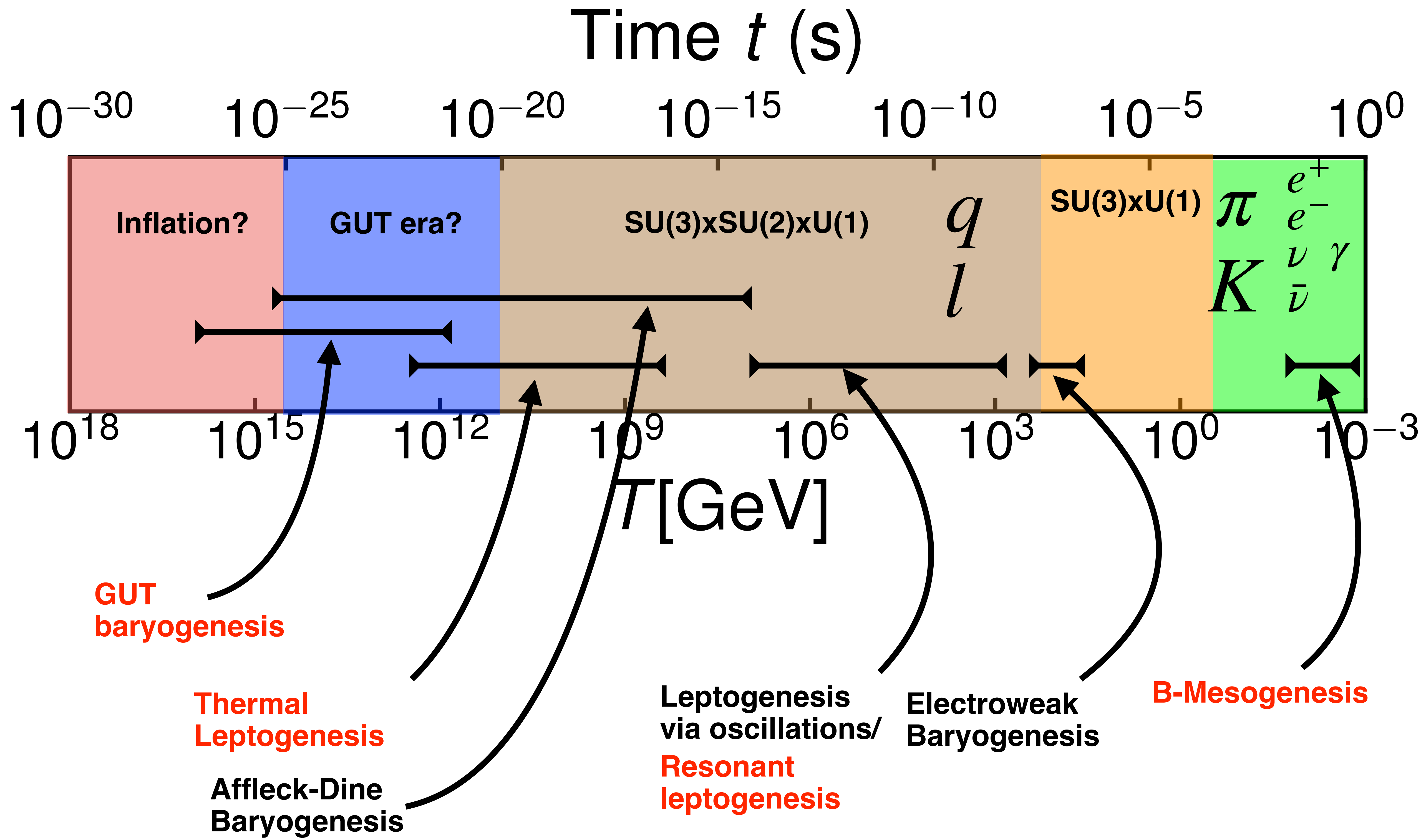


Baryogenesis Models



***not an exhaustive list, but it does include some of the most popular models**

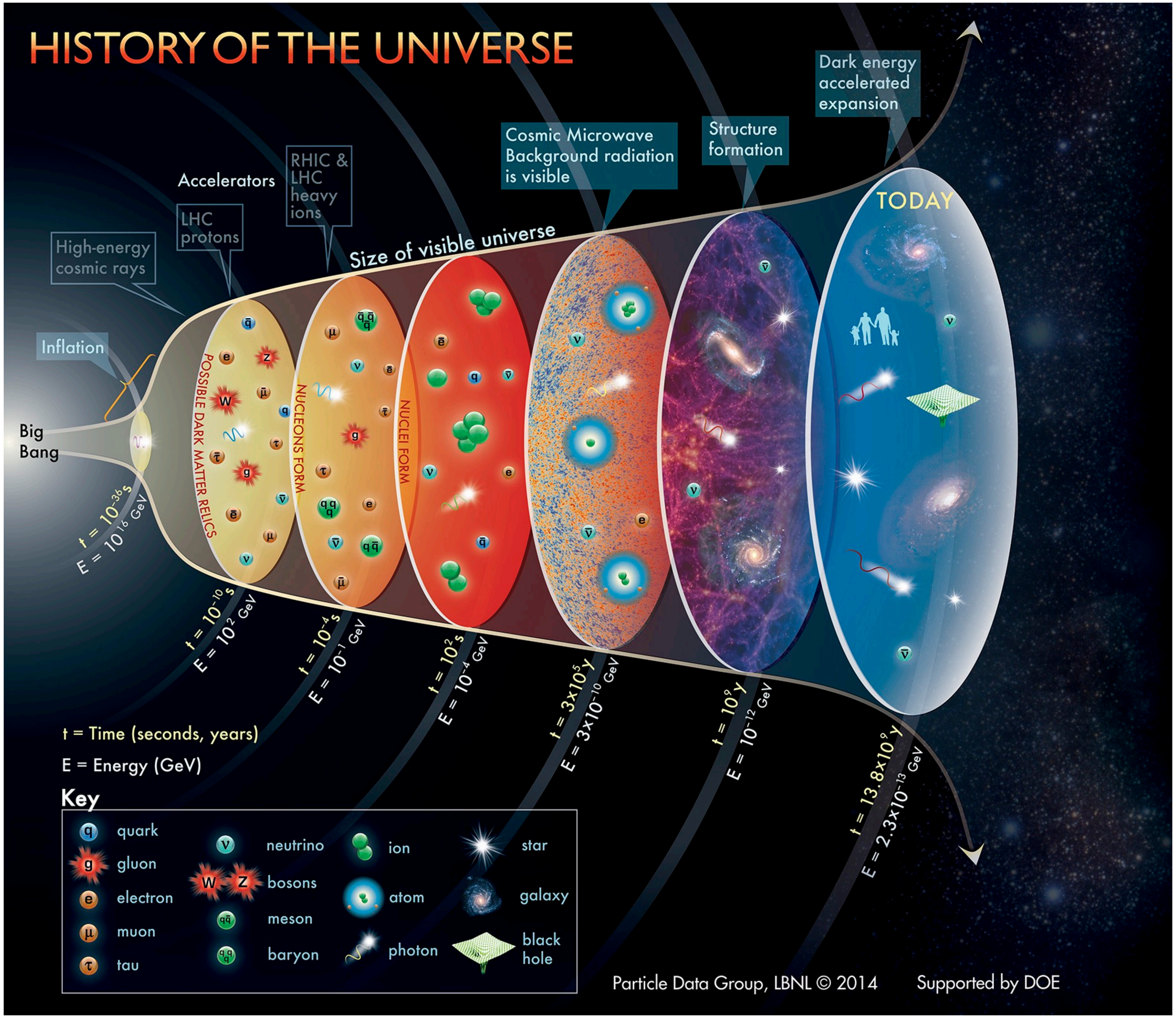
Baryogenesis Models



Baryogenesis via out of equilibrium decays

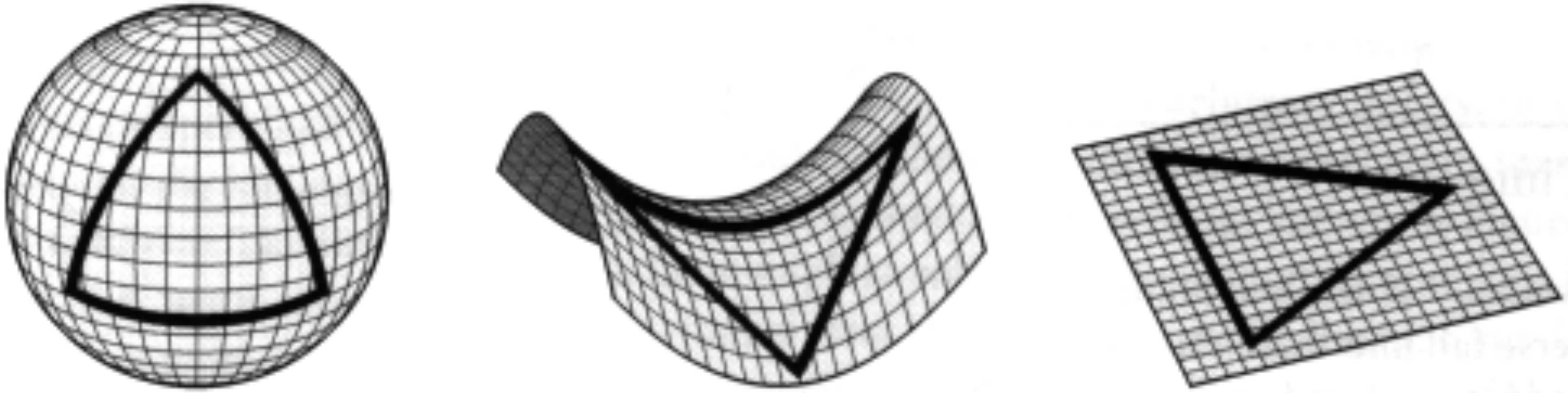
A Crash Course on Cosmology

In 6 slides! 💪



Isotropic and Homogeneous Universes

Three possibilities:



Positive Curvature	Negative Curvature	Flat Curvature
$k = 1$	$k = -1$	$k = 0$

From cosmological data we know that even if the Universe is not flat its curvature radius is very large. Which means it will not have an effect on the early Universe! From now on, consider $k = 0$ (as also expected from Inflationary models).

FLRW: Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu = dt^2 - a(t)^2 \left[dx^2 + dy^2 + dz^2 \right]$$

Only dependent upon a single dynamical variable: The scale factor: $a(t)$

Cosmological Dynamics

— **General Relativity relates the expansion rate of the Universe with the energy density in all the species contained on it**

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Friedmann Equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

H **: Expansion rate (Hubble parameter)**

ρ **: Energy density**

$$\nabla^\mu T_{\mu\nu} = 0$$

Continuity equation:

$$\frac{d\rho}{dt} = -H(\rho + p)$$

p **: pressure**

ρ **: energy density**

Equilibrium Thermodynamics

We will be dealing with situations in the early Universe with very dense systems of interacting particles: plasmas. Need to study equilibrium thermodynamics

homogeneity and isotropy imply: $f(\vec{x}, \vec{p}) = f(\,|\vec{p}\,|\,)$

Bosons:

$$f(E) = \frac{1}{-1 + e^{(E-\mu)/T}}$$

Fermions:

$$f(E) = \frac{1}{+1 + e^{(E-\mu)/T}}$$

Thermodynamic quantities

number density $$n = \frac{1}{(2\pi)^3}\int d^3p\, f(p)$$

energy density $$\rho = \frac{1}{(2\pi)^3}\int d^3p\, E\, f(p)$$

pressure density $$p = \frac{1}{(2\pi)^3}\int d^3p\, \frac{p^2}{3E}\, f(p)$$

entropy density $$s = \frac{\rho + p}{T}$$

Equilibrium Thermodynamics

Bosons: $f(E) = \frac{1}{-1 + e^{(E-\mu)/T}}$

Fermions: $f(E) = \frac{1}{+1 + e^{(E-\mu)/T}}$

Ultrarelativistic regime: $T \gg m \;\; \mu \ll T$

non-relativistic regime: $m \ll T \;\; \mu \ll T$

$$n = \quad g\frac{\xi(3)}{\pi^2}T^3$$ **Bose-Einstein**

$$n = \frac{3}{4}g\frac{\xi(3)}{\pi^2}T^3$$ **Fermi-Dirac**

$$\rho = \quad g\frac{\pi^2}{30}T^4$$ **Bose-Einstein**

$$\rho = \frac{7}{8}g\frac{\pi^2}{30}T^4$$ **Fermi-Dirac**

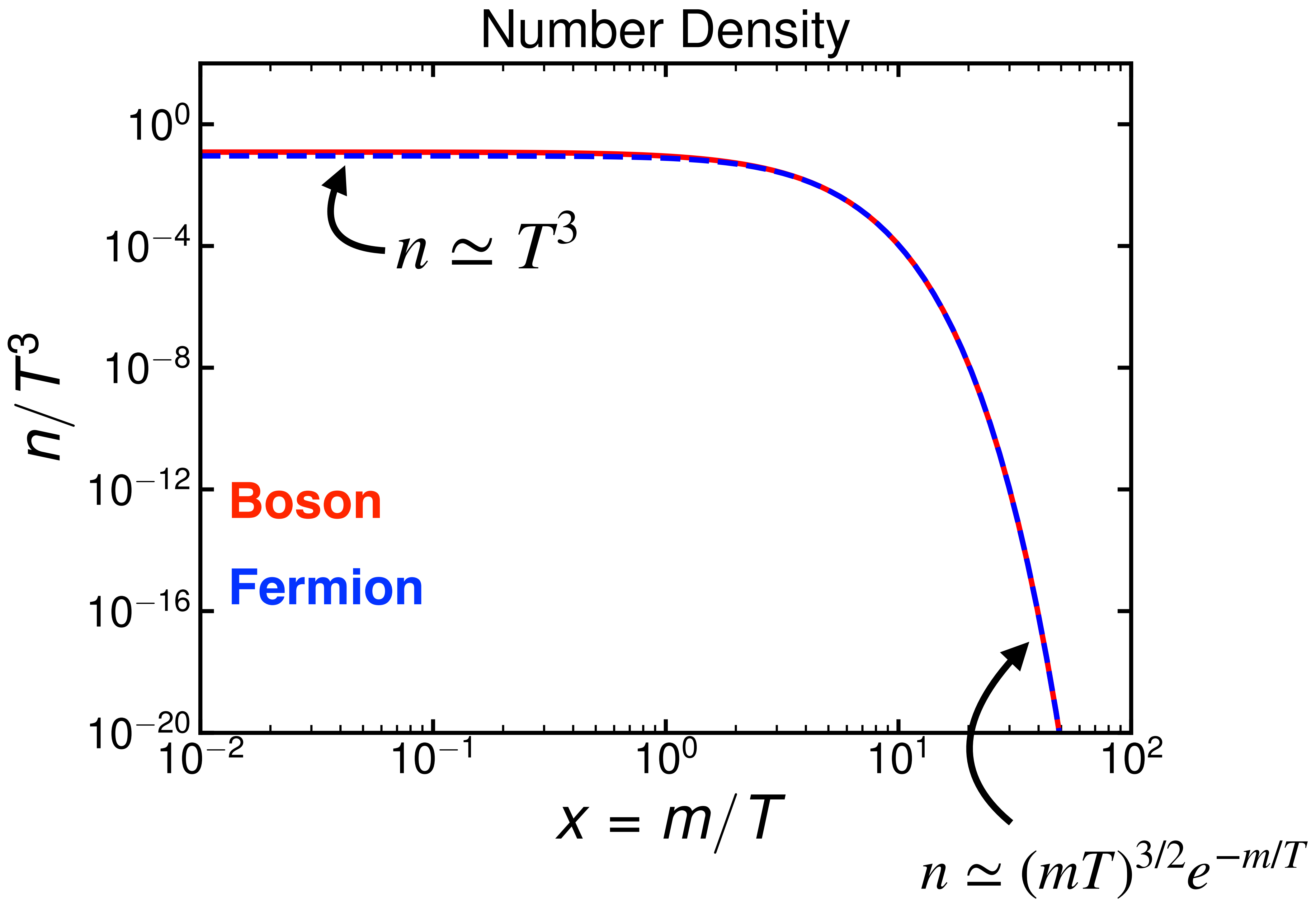
$$p = 1/3\rho$$

$$n = g(Tm/(2\pi))^{3/2}e^{-m/T}$$

$$\rho = m \times n$$

$g =$ **Internal degrees of freedom**

Equilibrium Thermodynamics



Equilibrium Thermodynamics

Key things to remember:

$T \gg m$	$T \ll m$
$n \simeq T^3 \quad \langle E \rangle \simeq 3T$	$n \simeq (Tm)^{3/2} e^{-m/T}$
$\rho \simeq T^4 \quad p = 1/3\rho$	$\rho \simeq mn$

Main consequence: **Ultra relativistic particles dominates the energy density of the Universe**

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \qquad s = \frac{\rho + p}{T}$$

$$H = 1.66 g_\star^{1/2} \frac{T^2}{M_{\rm Pl}} \qquad t = \frac{1}{2H}$$

$$s = \frac{\pi^2}{45} g_{\star S} T^3$$

Departures from Equilibrium

A process will be in equilibrium in the early Universe if:

$$\Gamma \gtrsim H$$ **(equilibrium)**

$$\Gamma \lesssim H$$ **(out-of-equilibrium)**

why?

number of interactions over the Universe lifetime will simply be:

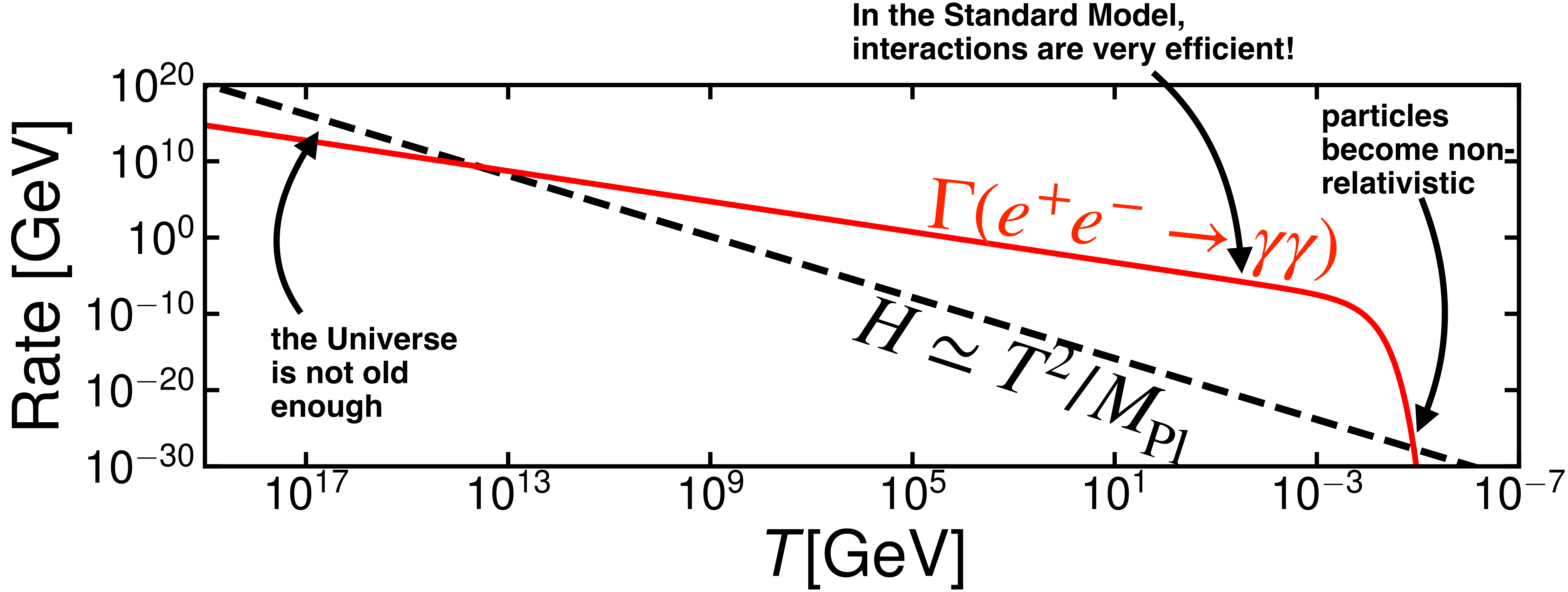
$$N \simeq t_U/\tau \simeq \Gamma/H$$

Particle Interaction Rates

Consider the following interaction: $e^+e^- \to \gamma\gamma \qquad \sigma \simeq \alpha^2/s$

interaction rate: $\Gamma = n_e \times \langle \sigma v \rangle$

regime:	number density:	cross section:	rate:
$T \gg m_e$	$n_e \simeq T^3$	$\langle \sigma v \rangle \simeq \alpha^2/T^2$	$\Gamma \simeq \alpha^2 T$
$T \ll m_e$	$n_e \simeq (m_e T)^{3/2} e^{-m_e/T}$	$\langle \sigma v \rangle \simeq \alpha^2/m_e^2$	$\Gamma \simeq \alpha^2 T e^{-m_e/T}$



3 Key Corollaries

1) Interaction rates in the Standard Model are typically fast compared to the expansion of the Universe

$$\Gamma \gtrsim H \qquad \text{e.g.:} \qquad e^+e^- \to \gamma\gamma$$

🙁 **bad news for baryogenesis because departures from thermal equilibrium will be small.**

2) We would expect an array of BSM particles floating around in the early Universe since they can be produced by particle interactions!

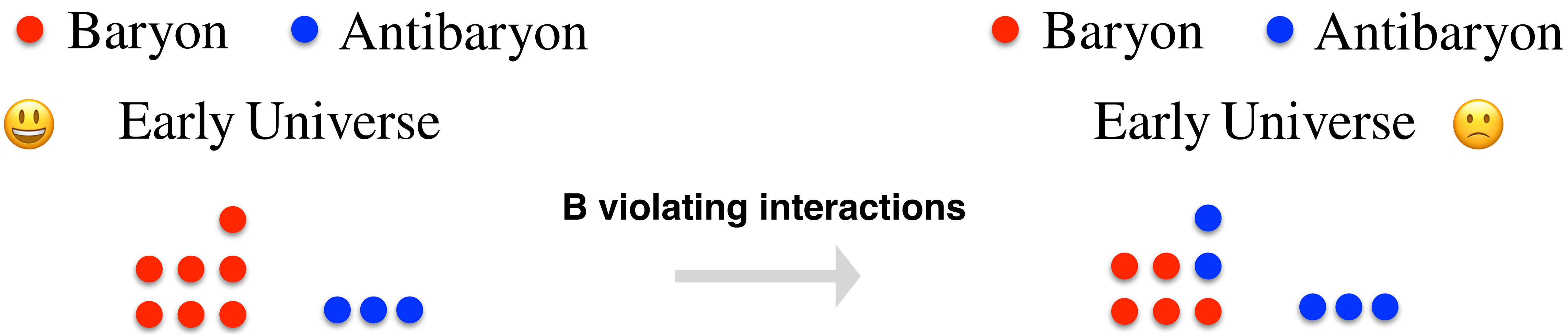
$$\Gamma \gtrsim H \qquad \text{e.g.:} \qquad e^+e^- \to XX$$

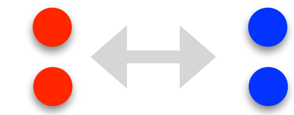
with X being a GUT gauge boson

😃 **good news for baryogenesis because we could use them to produce a baryon asymmetry in the Universe!**

3 Key Corollaries

3) If there are interactions that break baryon number and they are efficient they will erase any baryon asymmetry



If baryon number violating processes are active, then 

- **This means that, once successful baryogenesis happens then new baryon number violating interactions should not be active in the early Universe!**

The Sakharov Conditions

The Three Sakharov Conditions (1967):

1) C and CP violation

2) Out of equilibrium

3) Baryon number violation

The Sakharov Conditions in the SM

1) C and CP violation

Maximal C violation is built in the Standard Model

$$\pi^+ \to \mu^+ \nu_\mu|_L \qquad \Gamma(\pi^+ \to \mu^+ \nu_\mu|_R) = 0$$

CP violation has been established in the Standard Model in many ways

Best example may be the K_L

This particle has a well defined mass and lifetime and is its own antiparticle

$$\delta_L = \frac{\Gamma(K_L \to \ell^+ \nu_\ell \pi^-) - \Gamma(K_L \to \ell^- \bar{\nu}_\ell \pi^+)}{\Gamma(K_L \to \ell^+ \nu_\ell \pi^-) + \Gamma(K_L \to \ell^- \bar{\nu}_\ell \pi^+)} \qquad \delta_L = (3.32 \pm 0.06) \times 10^{-3}$$

This number is not small compared to $\eta_B \sim 10^{-9}$, but to date, there is no know baryogenesis mechanism that is able to proceed with only the CP violation in the Standard Model

The Sakharov Conditions in the SM

2) Out of equilibrium

Interaction rates are always very efficient in the early Universe 🙁

Possibility could arise from a strong first order phase transition 😃

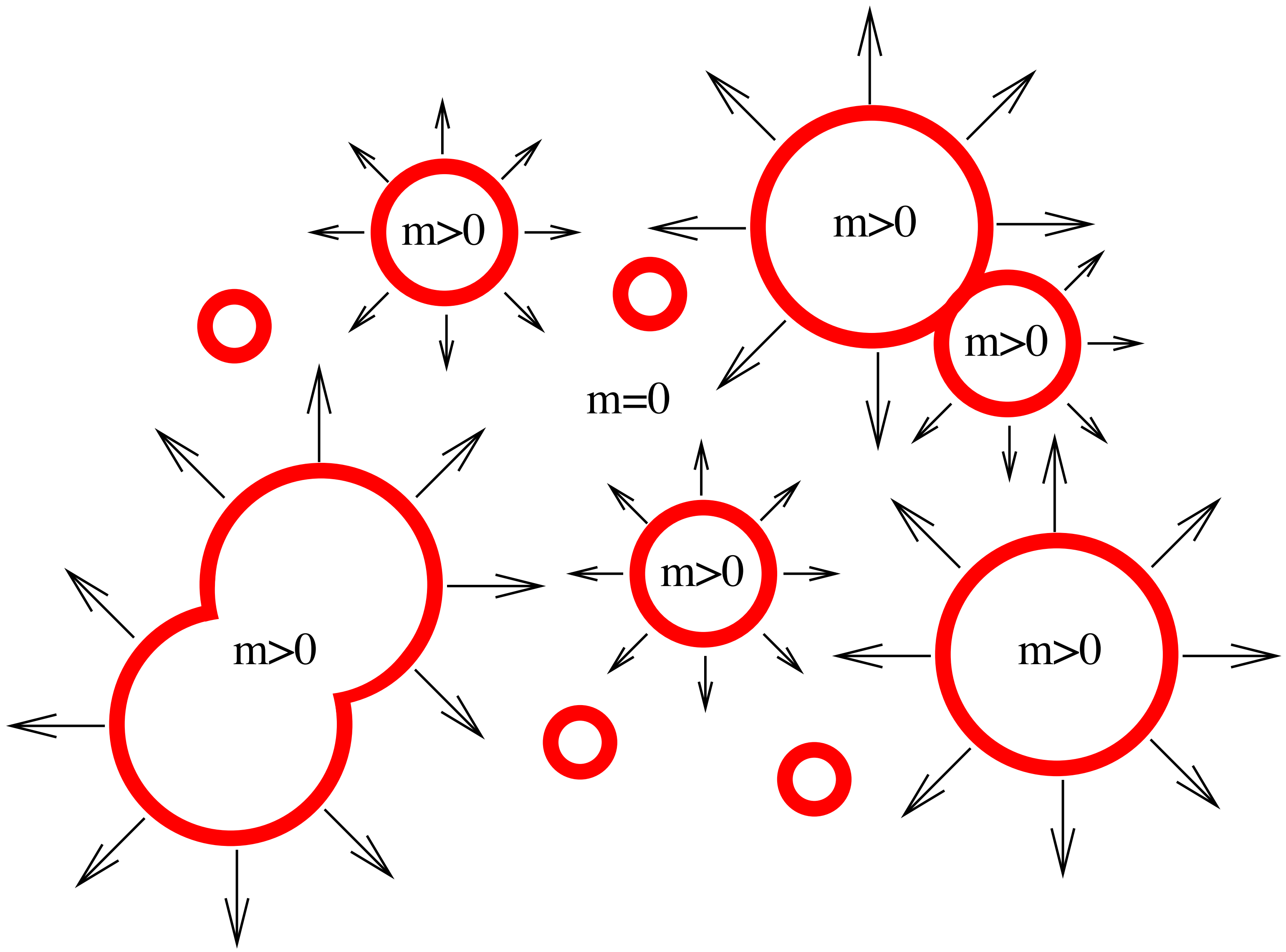


Fig. 11. Bubble nucleation during a first-order EWPT.

Cline hep-ph/0609145

The Sakharov Conditions in the SM

2) Out of equilibrium

What is a phase transition? E.g.: $SU(2)_L \times U_Y(1) \to U(1)_{\rm EM}$ at $T_c \sim v$

In the early Universe, the Higgs potential is not the same as in vacuum

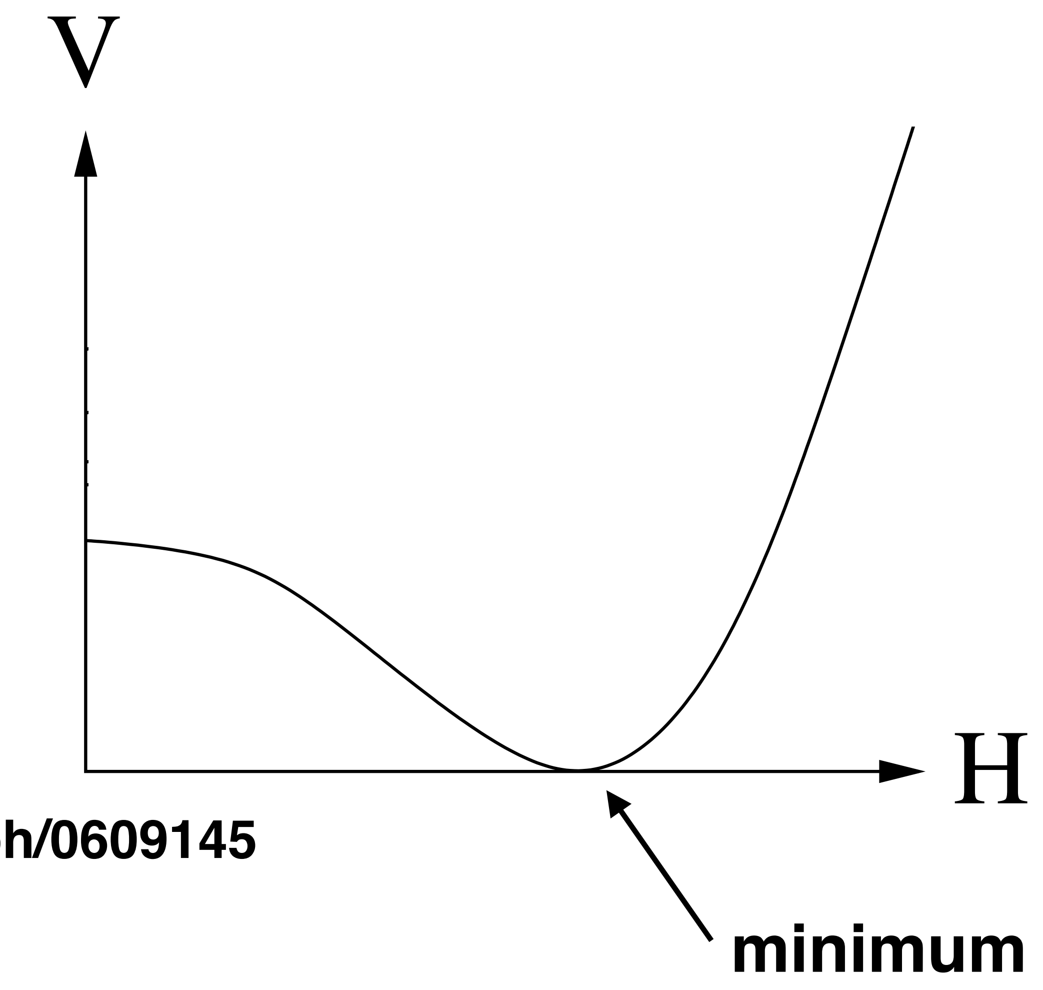
vacuum:

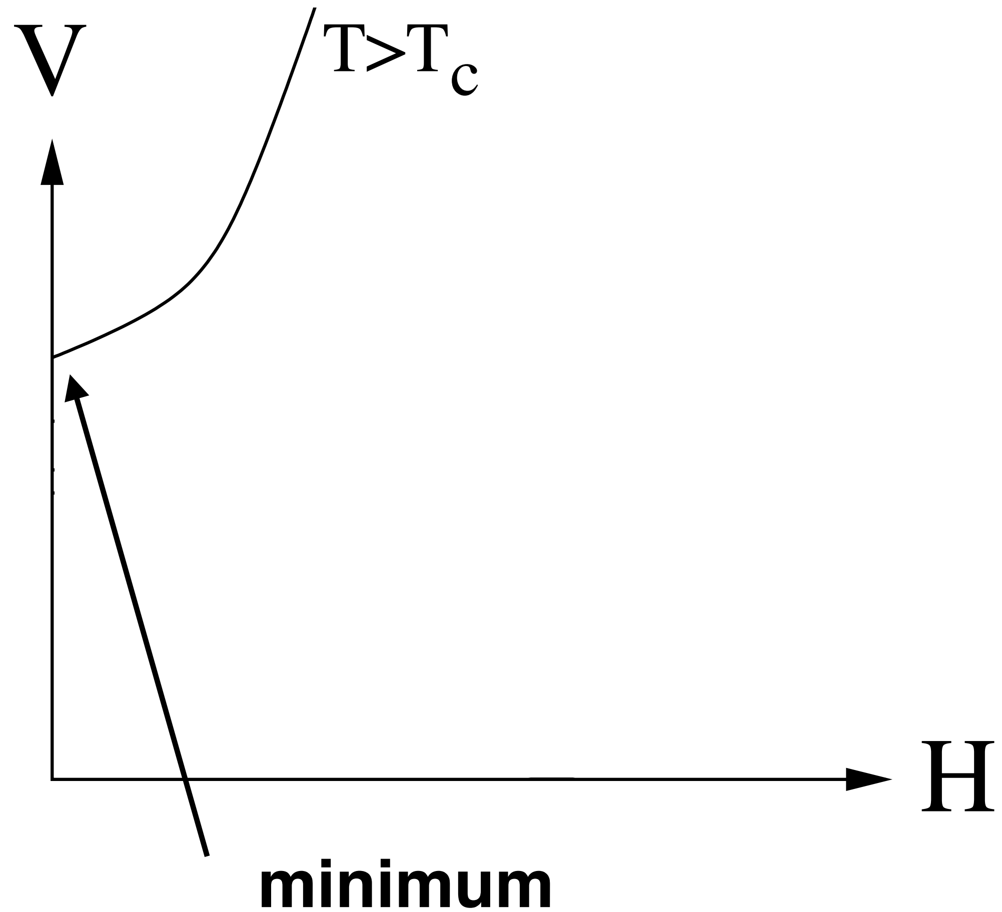
$$V_{\rm eff} = -\lambda v^2 \phi^2 + \lambda \phi^4$$

finite temperature:

pressure from particles with $m(\phi) = g\phi$

$$V_{\rm eff} = (-\lambda v^2 + \frac{\alpha}{24} T^2)\phi^2 + \lambda \phi^4$$





Cline hep-ph/0609145

2) Out of equilibrium

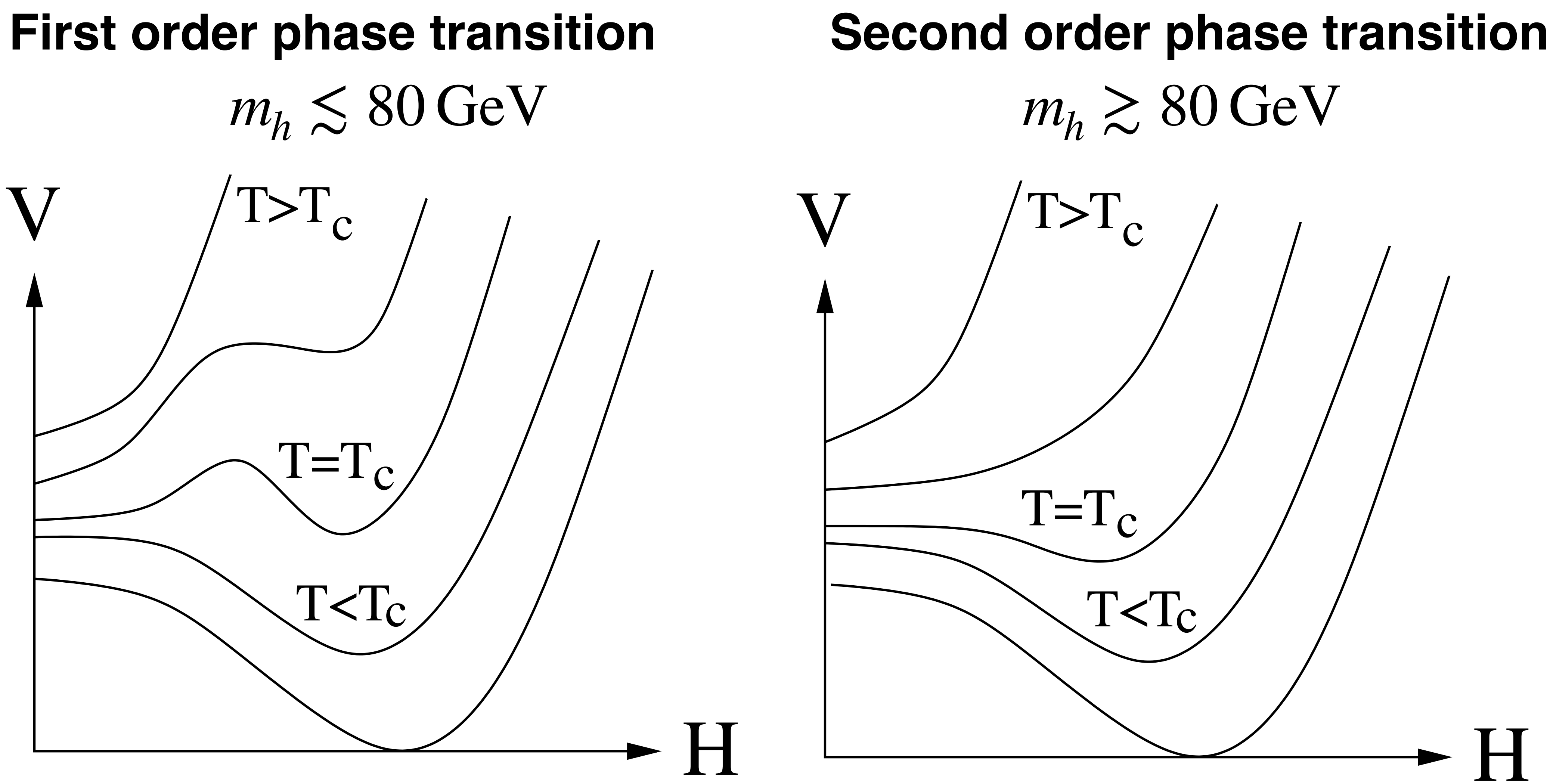


Fig. 10. Schematic illustration of Higgs potential evolution with temperature for first (left) and second (right) order phase transition. **Cline hep-ph/0609145**

In the Standard Model:

$T_{\mathrm{EW}} \simeq 160\,\mathrm{GeV}$ **D'Onofrio & Rummukainen [1508.07161]**

and departures from thermal equilibrium are negligibly small

The Sakharov Conditions in the SM

3) Baryon Number Violation

B+L is an anomalous symmetry in the Standard Model, while B-L is a good symmetry even under quantum corrections

$$\partial_\mu J^\mu_{B_L+L_L} = \frac{3g^2}{32\pi^2}\epsilon_{\alpha\beta\gamma\delta}W_a^{\alpha\beta}W_a^{\gamma\delta}$$

t'Hooft '76

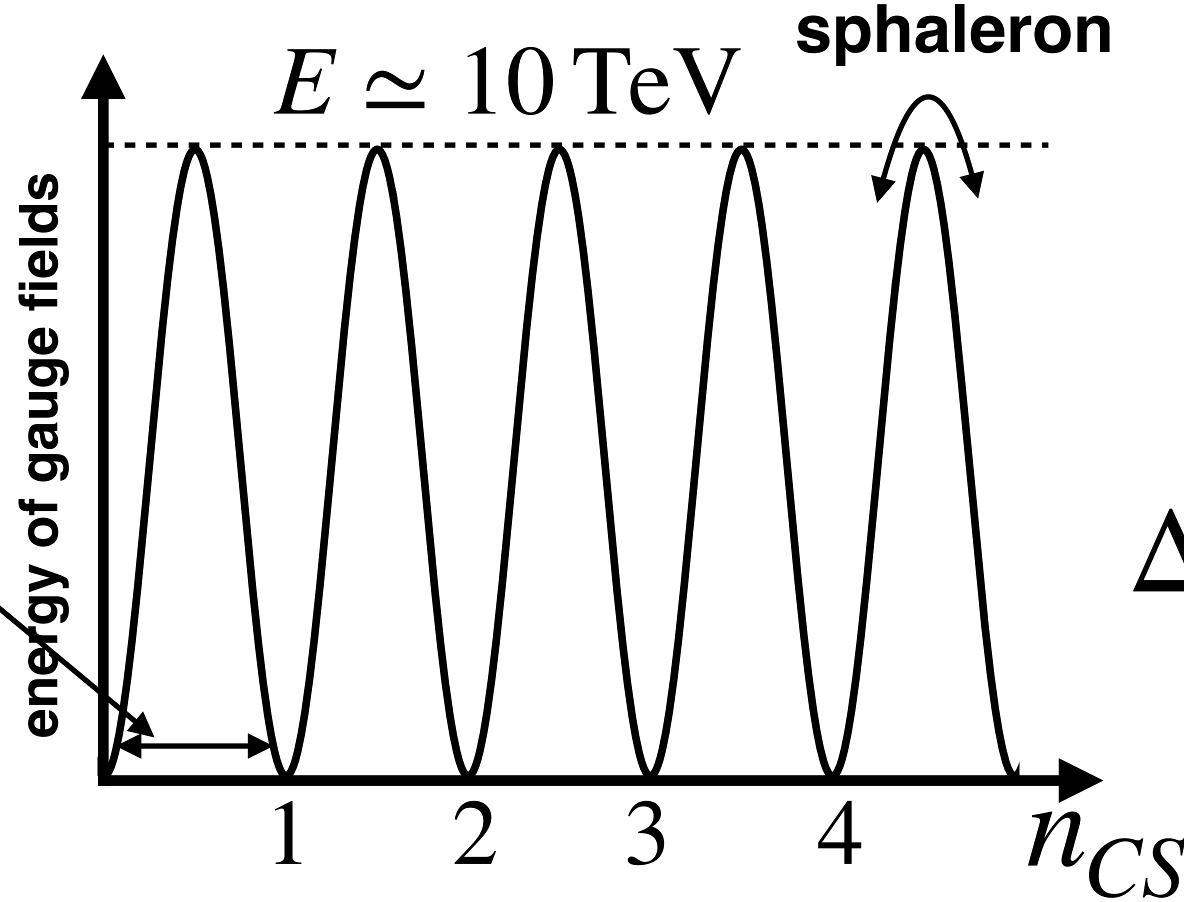
Kuzmin, Rubakov & Shaposhnikov '85

$\Gamma \simeq T\alpha_W^5$

instanton
[t'Hooft '76]

$\Gamma \sim e^{-8\pi^2/g^2}$

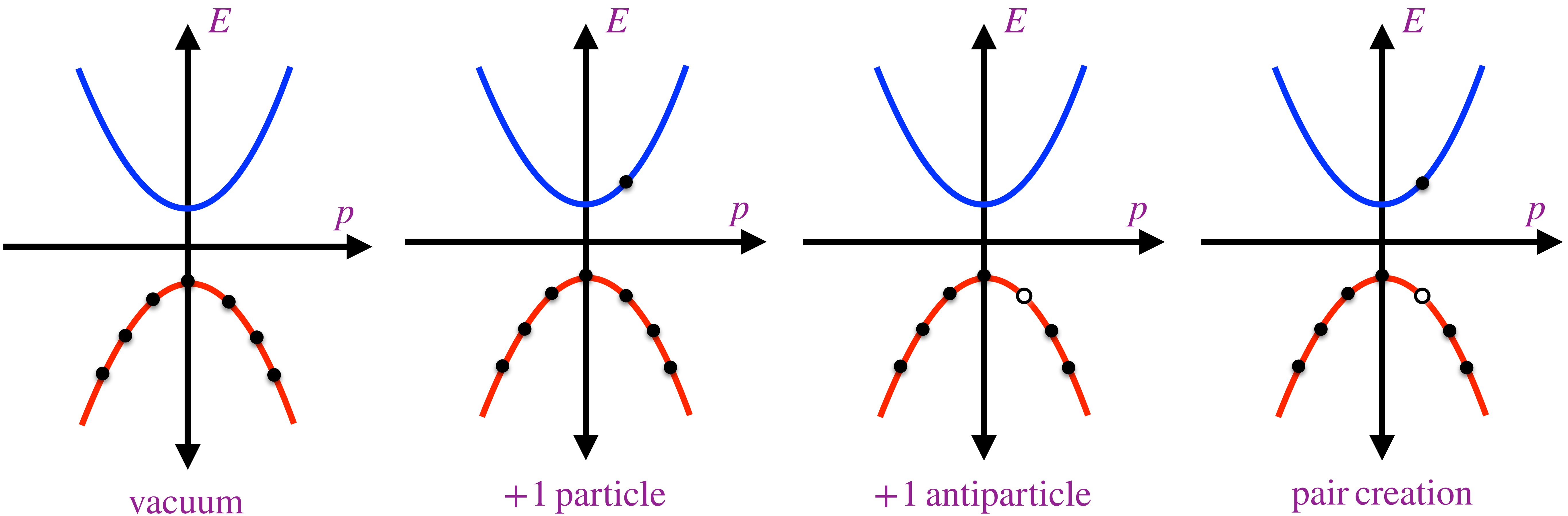
$\Gamma \simeq 10^{-90}$



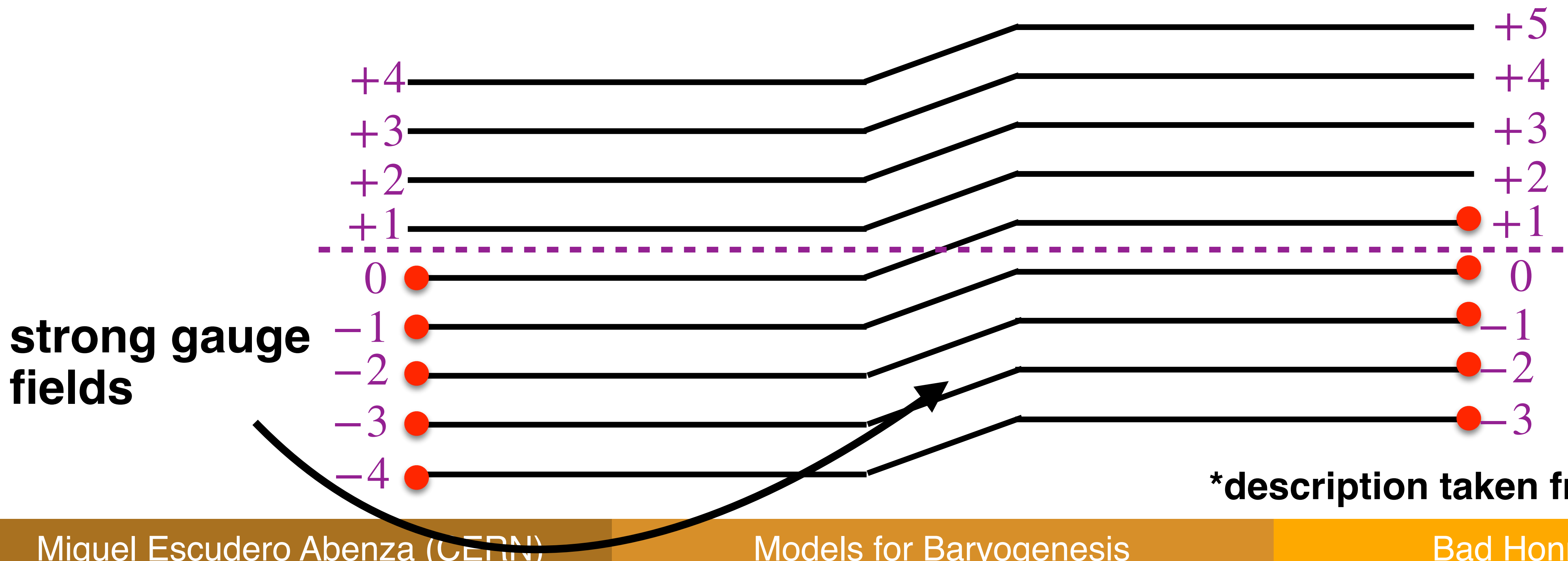
$\Delta B = \Delta L = 3n_{CS}$

Topologically distinct vacua

The Electroweak Vacuum



vacuum to vacuum transitions:



***description taken from Shaposhnikov**

The Sakharov Conditions in the SM

3) Baryon Number Violation

Cosmological Implications:

1) Sphaleron processes break B+L number at

$$130\,\mathrm{GeV} \lesssim T \lesssim 10^{12}\,\mathrm{GeV}$$

D'Onofrio, Rummukainen & Tranberg [1404.3565]

2) There is a direct relation between the Baryon number in the Universe and a primordial B-L asymmetry

$$B \simeq \frac{1}{2} \times (B - L)$$

$$B = \frac{28}{79} \times (B - L)$$

Harvey & Turner '90

Cosmological Implication: If baryogenesis takes place at $T > T_{\rm EW}$, there is need to generate a $B - L$ asymmetry!

The Sakharov Conditions in the SM

The Three Sakharov Conditions (1967):

1) C and CP violation

Present and potentially siezable

2) Out of equilibrium

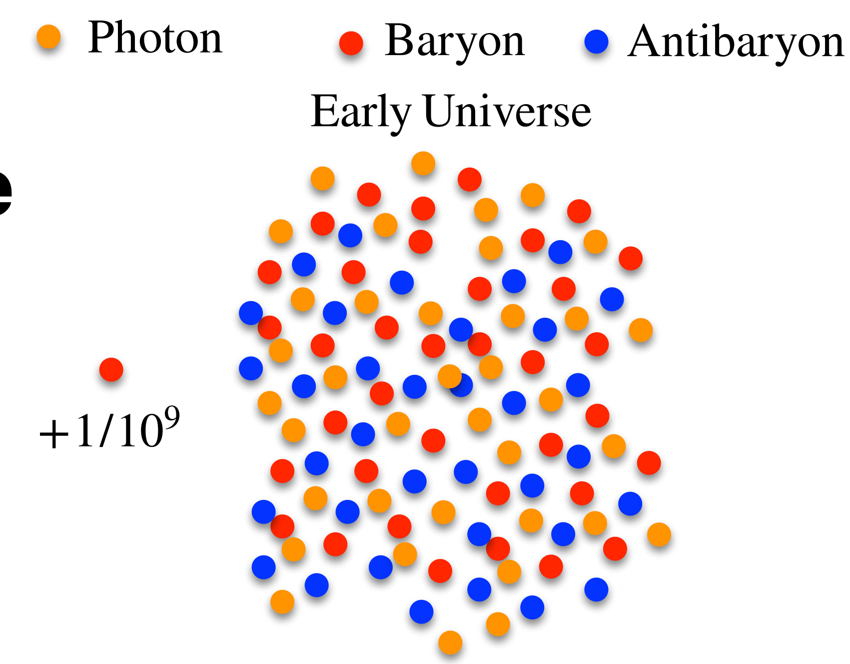
Not present

3) Baryon number violation

Present and active at $T \gtrsim 130\,\mathrm{GeV}$

Summary & Takeaways of Lecture 1

- **Our observable Universe appears to be made out of only matter**



- **We can explain this if in the early Universe there were $+1$ baryon out of every 10^9 particle antiparticle pairs**

- **Ultra relativistic particles are expected to dominate the energy density of the early Universe**

expansion rate: $H \simeq \sqrt{\rho}/M_{\rm Pl}$

$$\rho \simeq T^4 \quad (T \gg m)$$
$$n \simeq T^3$$

- **SM particles were efficiently interacting in the early Universe** $\Gamma > H$
  - 🙁 **bad news for baryogenesis because departures from thermal equilibrium will be small**
  - 😃 **good news for baryogenesis because an array of BSM particles could have been produced!**
  - 😃 **once baryogenesis happens, B violating processes should not be active!**

Summary & Takeaways of Lecture 1

Three key conditions need to be met for successful Baryogenesis:

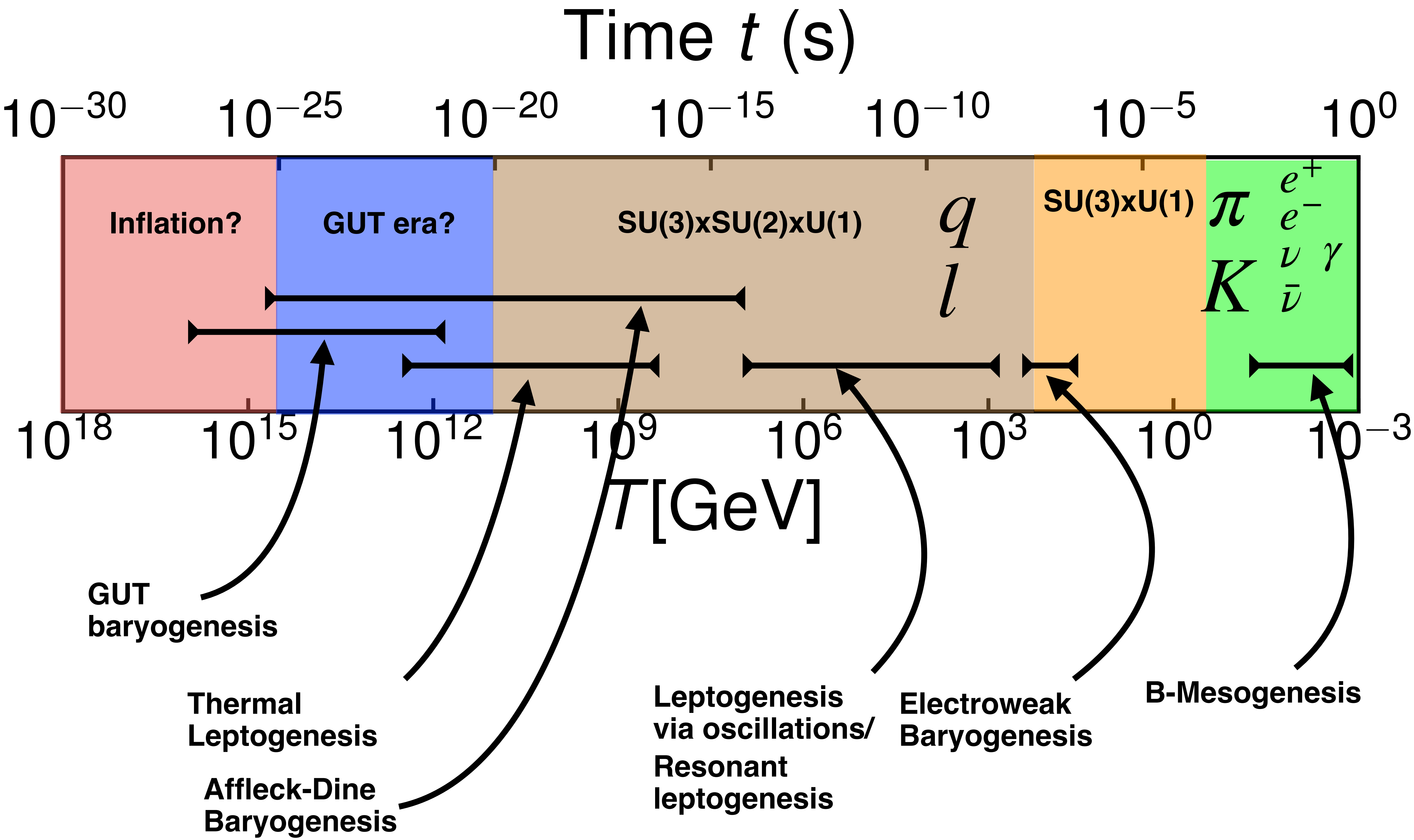
in the Standard Model

1) C and CP violation — **present and not-small** 😃

2) Out of equilibrium $\Gamma < H$ — **not present** 🙁
SM particles interact very efficiently
no 1st order phase transition

3) Baryon number violation — **present and effective** 😃
at $T \gtrsim 130\,\mathrm{GeV}$

Tomorrow



Time t (s)
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
Inflation?
GUT era?
SU(3)xSU(2)xU(1)
q
l
SU(3)xU(1)
π
K
e^+
e^-
ν γ
$\bar{\nu}$
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
T[GeV]
GUT baryogenesis
Thermal Leptogenesis
Affleck-Dine Baryogenesis
Leptogenesis via oscillations/ Resonant leptogenesis
Electroweak Baryogenesis
B-Mesogenesis