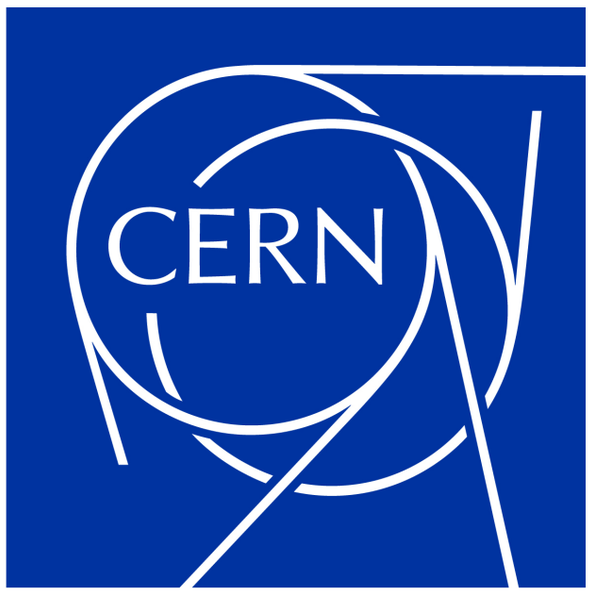
BSM in the Early Universe

Miguel Escudero Abenza

miguel.escudero@cern.ch

1st UNDARK School
Benasque
March 2025



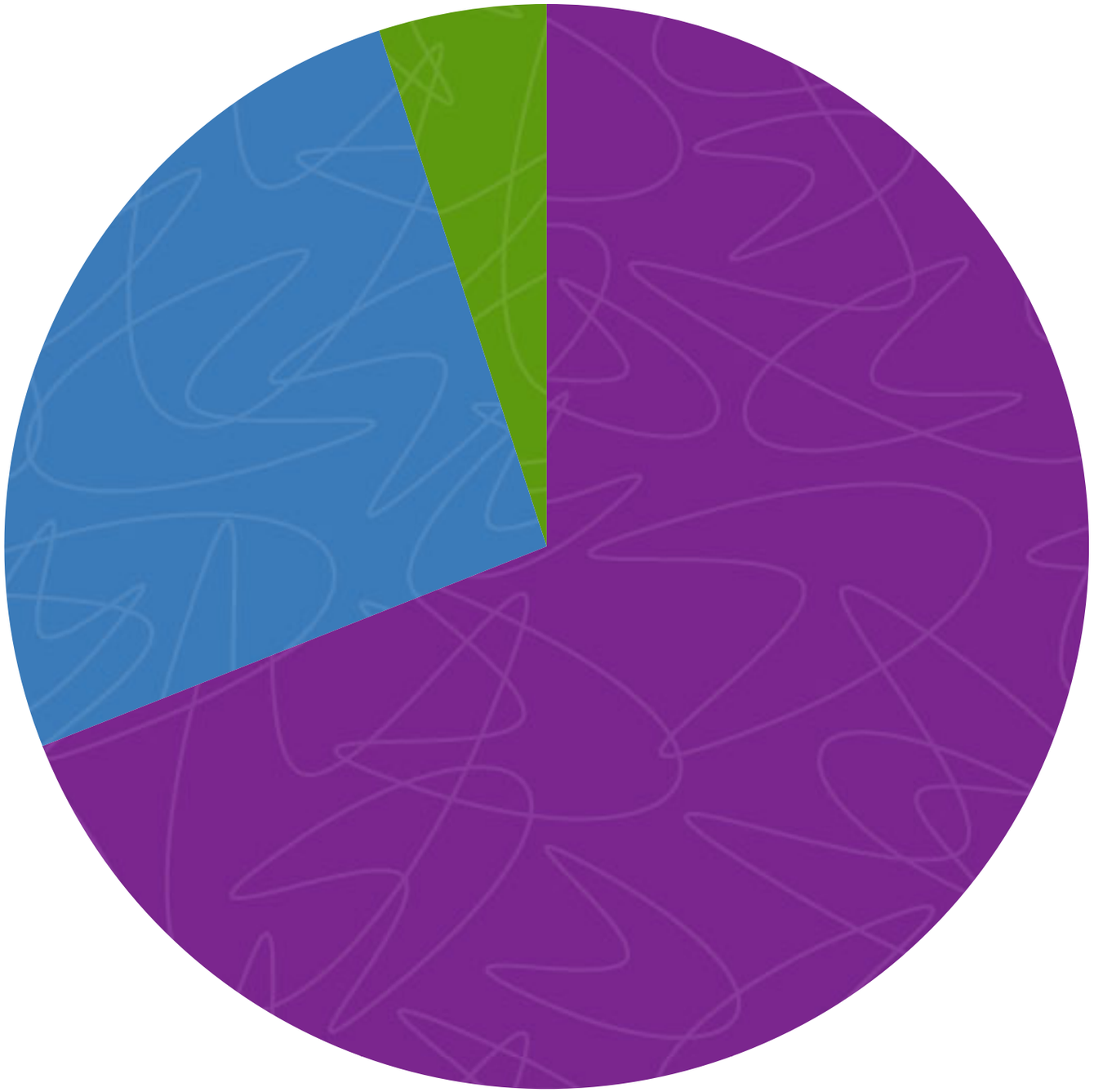
Funded by the European Union

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?

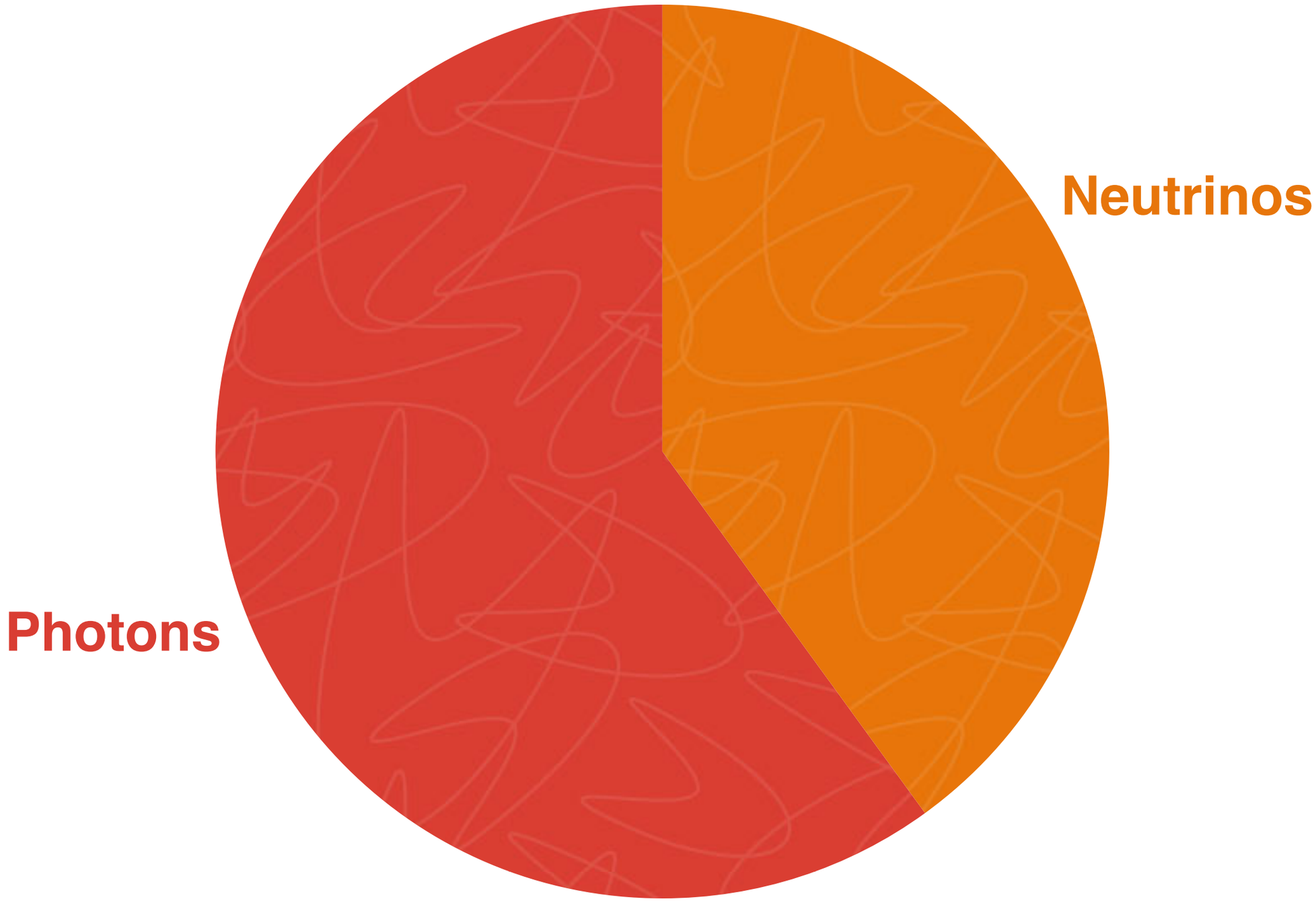
Motivating Question:

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**

Main goal of these Lectures

Have an understanding of the physical state of the Early Universe

Early Universe Thermodynamics

Explore key potential BSM cosmological events:

The formation of the hot Cosmological Axion Background

Thermal Dark Matter freeze-out

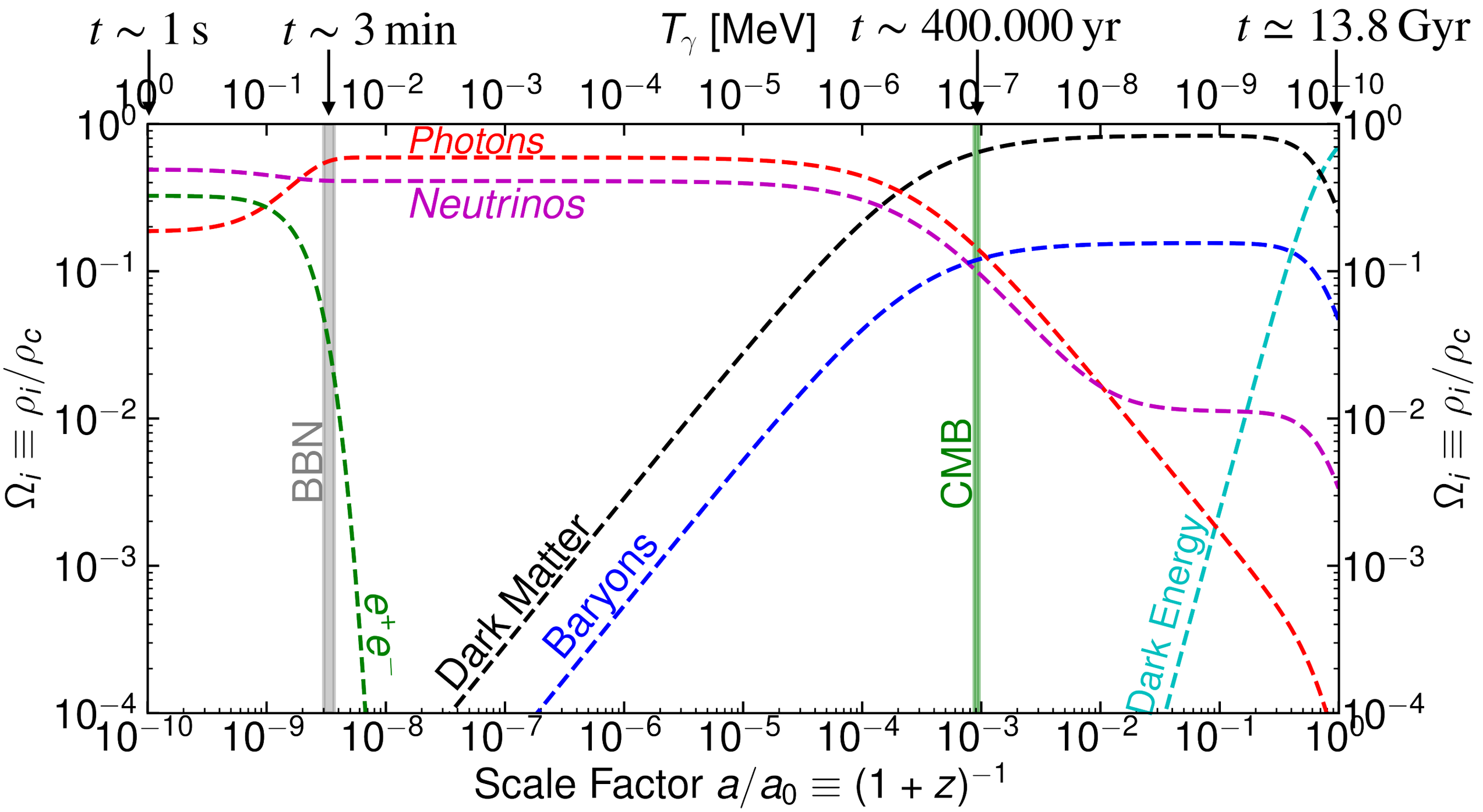
Baryogenesis via out-of-equilibrium decays

Exercise: 

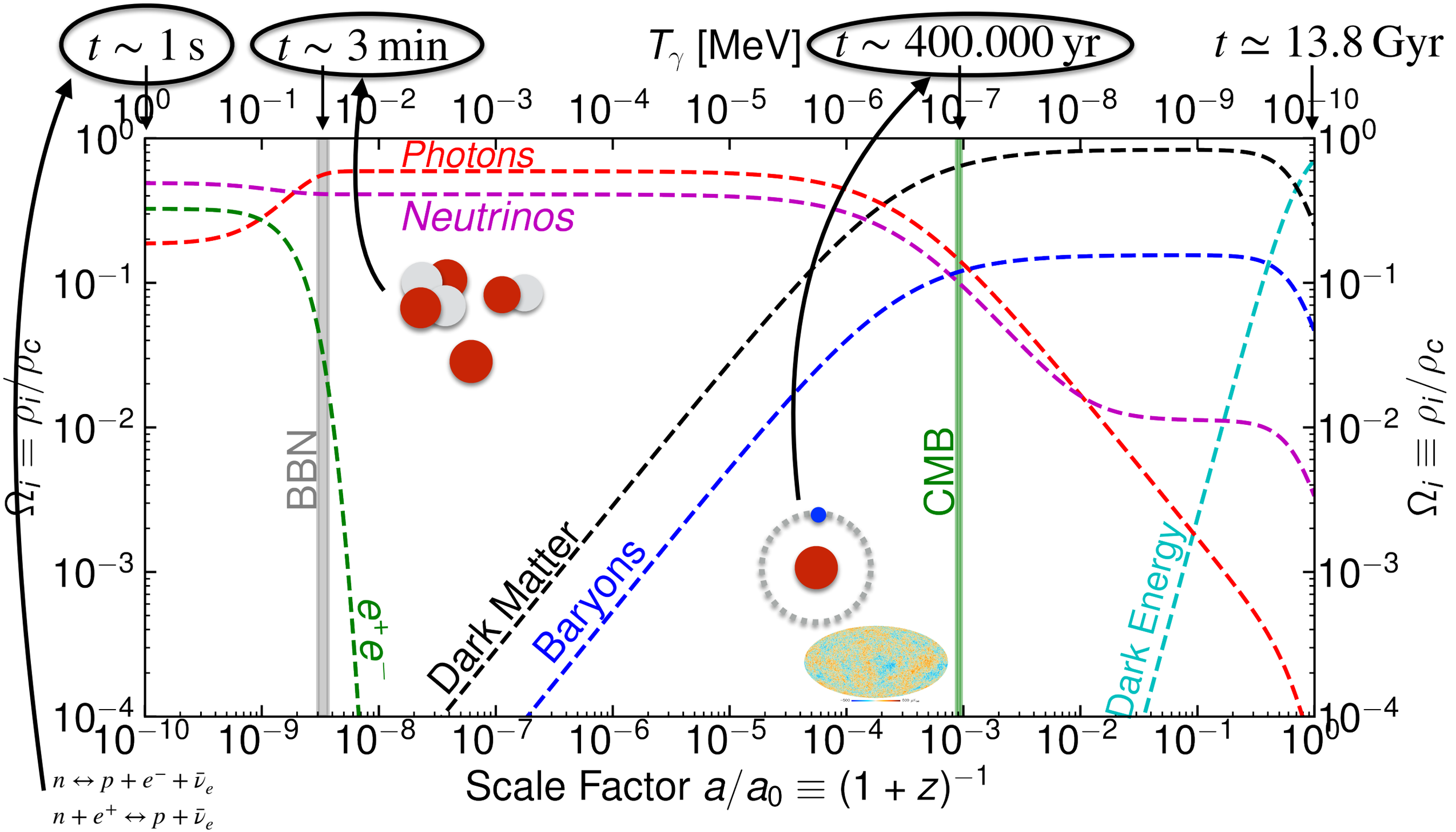
Primordial Helium abundance in the presence of dark radiation

Other cool BSM topics I cannot cover: phase transitions, GWs, topological defects, inflation …

The Known Thermal History

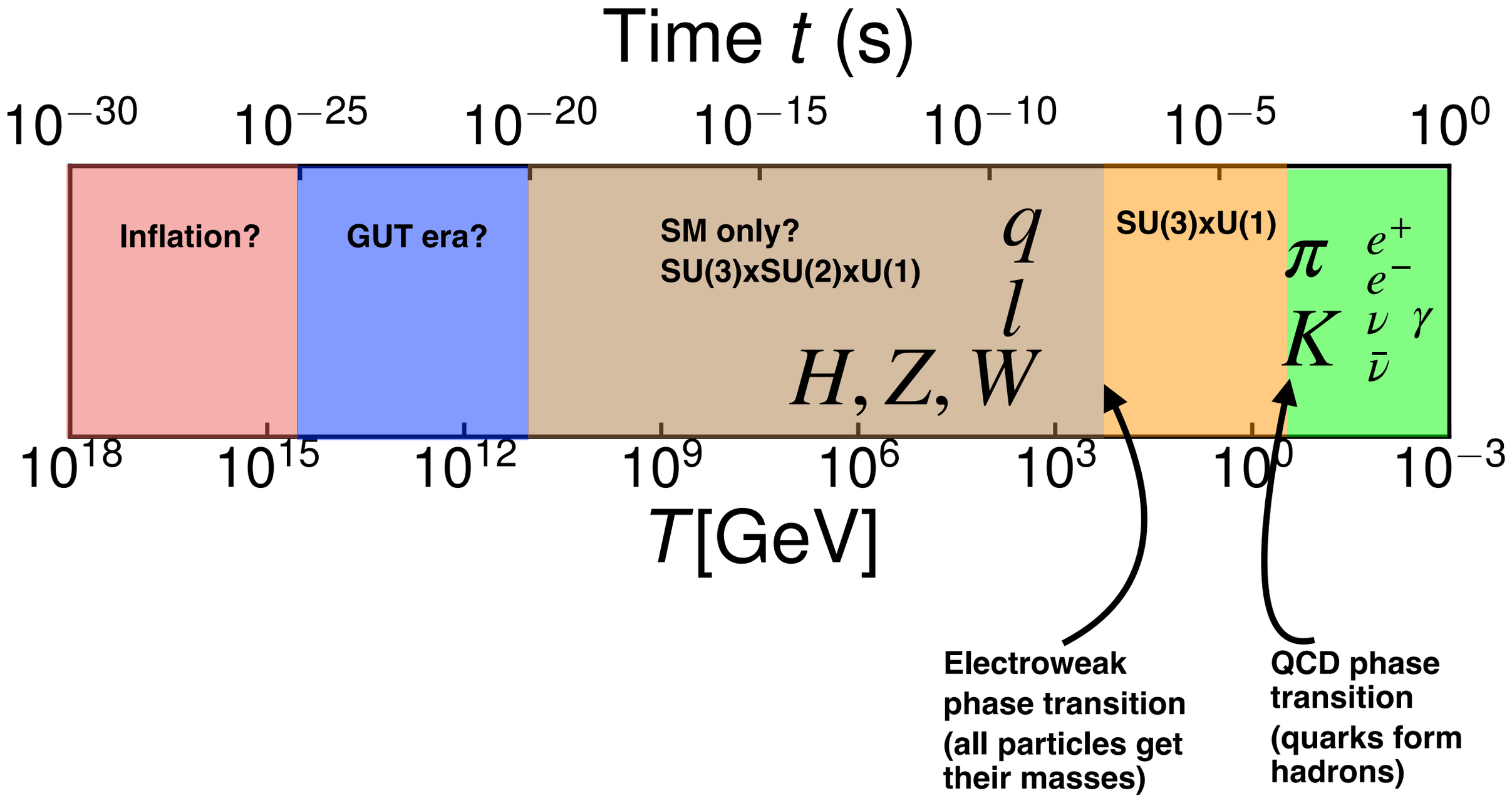


The Known Thermal History

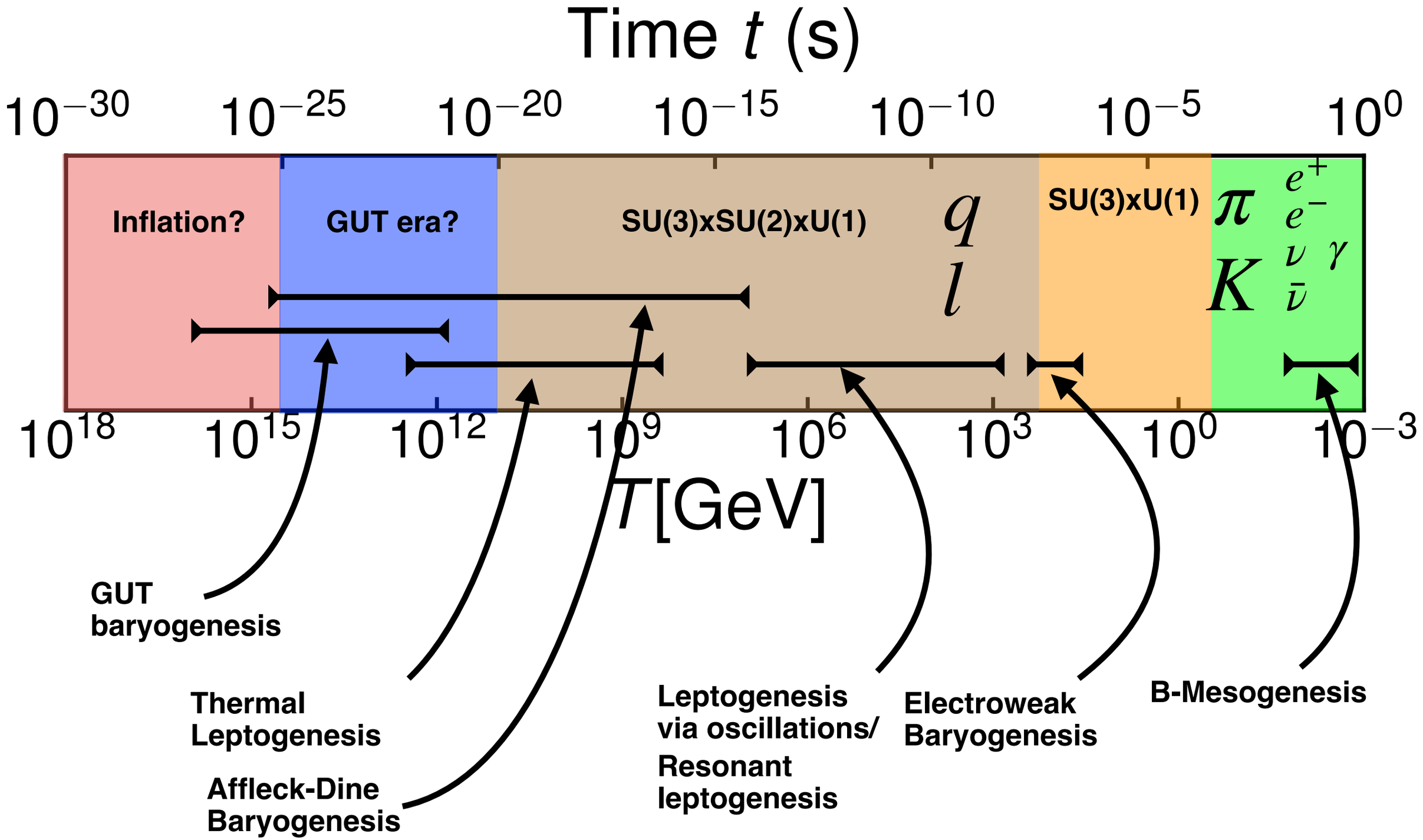


$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$e^+e^- \leftrightarrow \nu\bar{\nu}$$
$$\nu e^\pm \leftrightarrow \nu e^\pm$$

Key Stages in the Thermal History

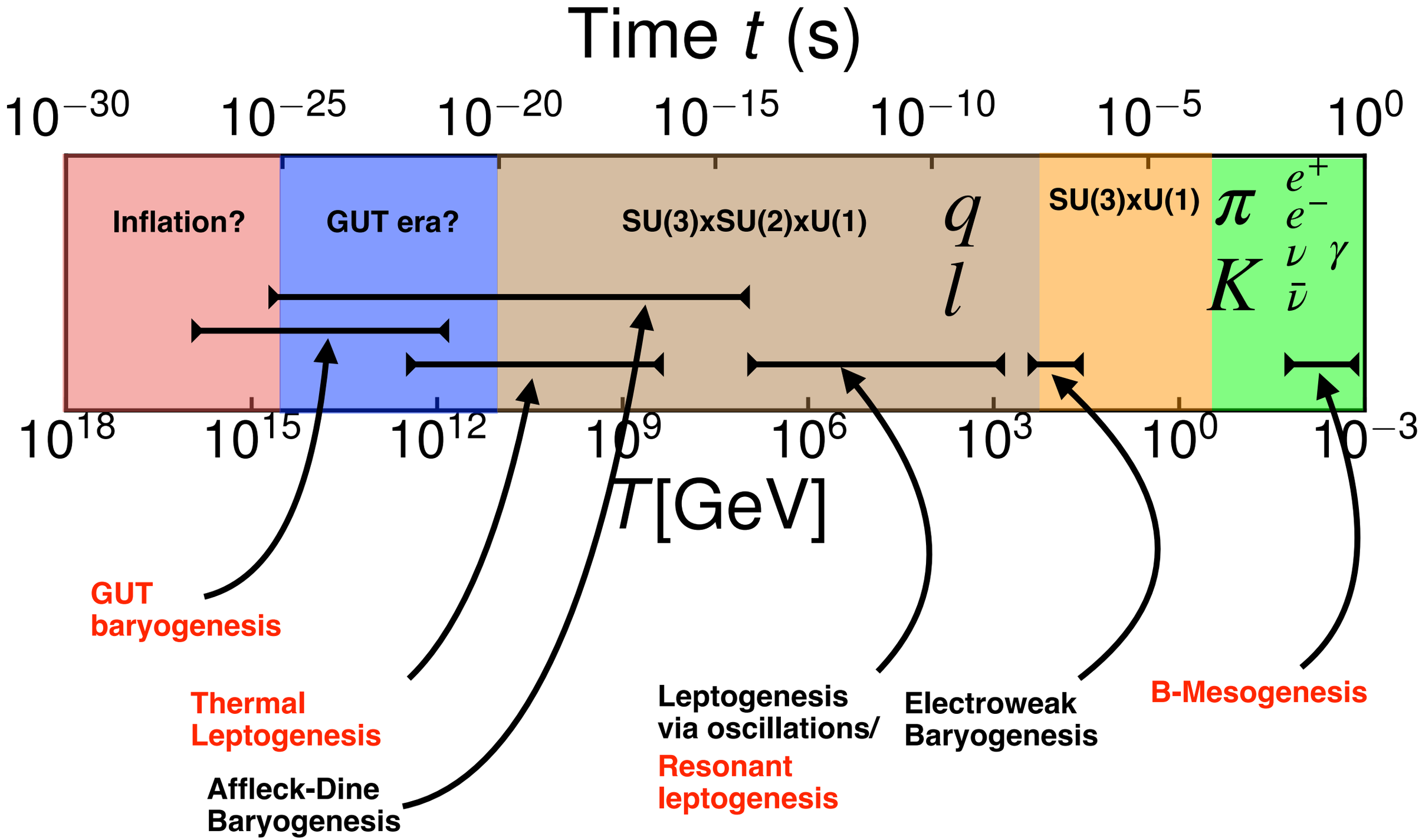


Baryogenesis Models



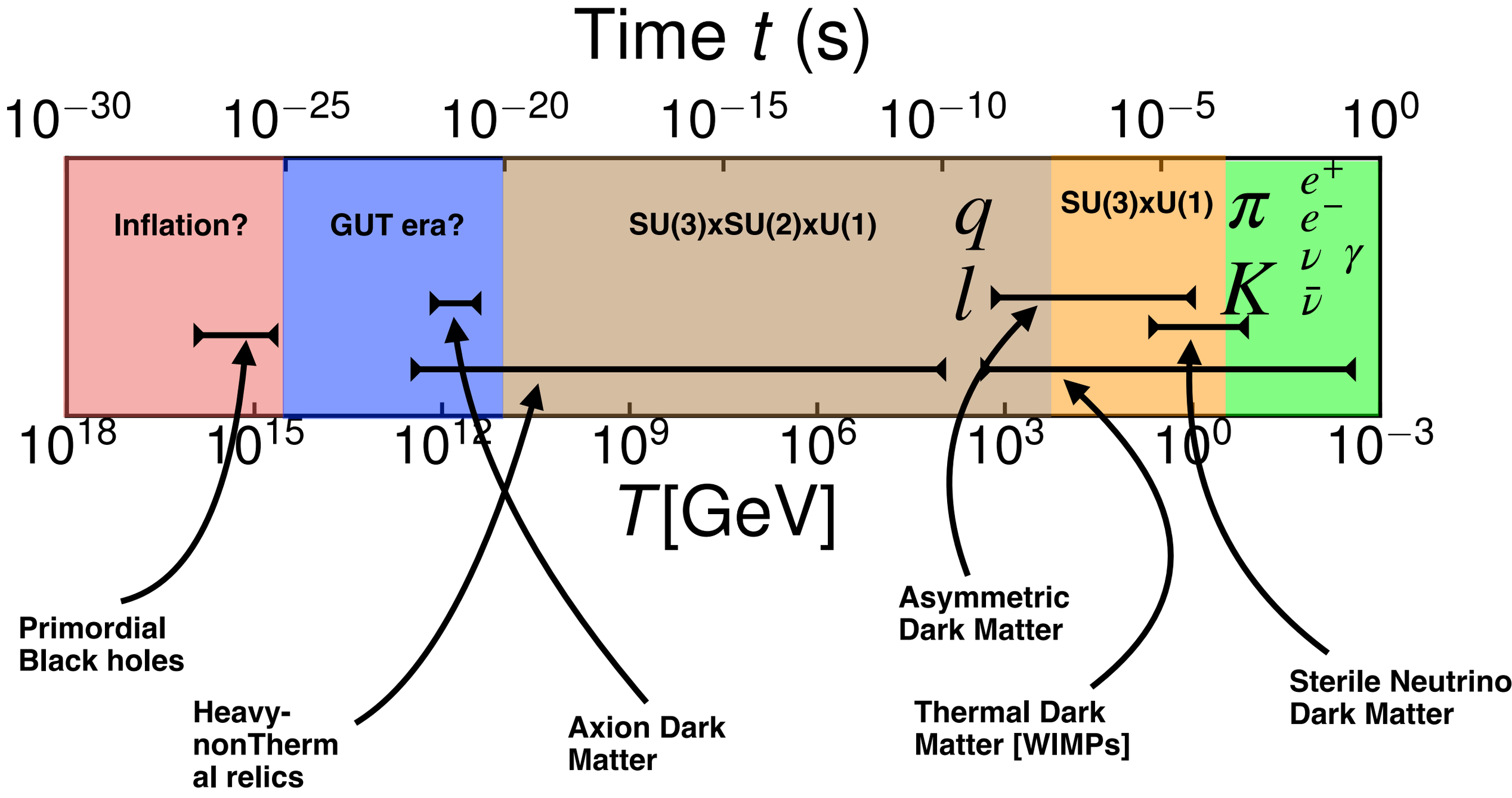
***not an exhaustive list, but it does include some of the most popular models**

Baryogenesis Models



*Baryogenesis via out-of-equilibrium decays

Dark Matter Models



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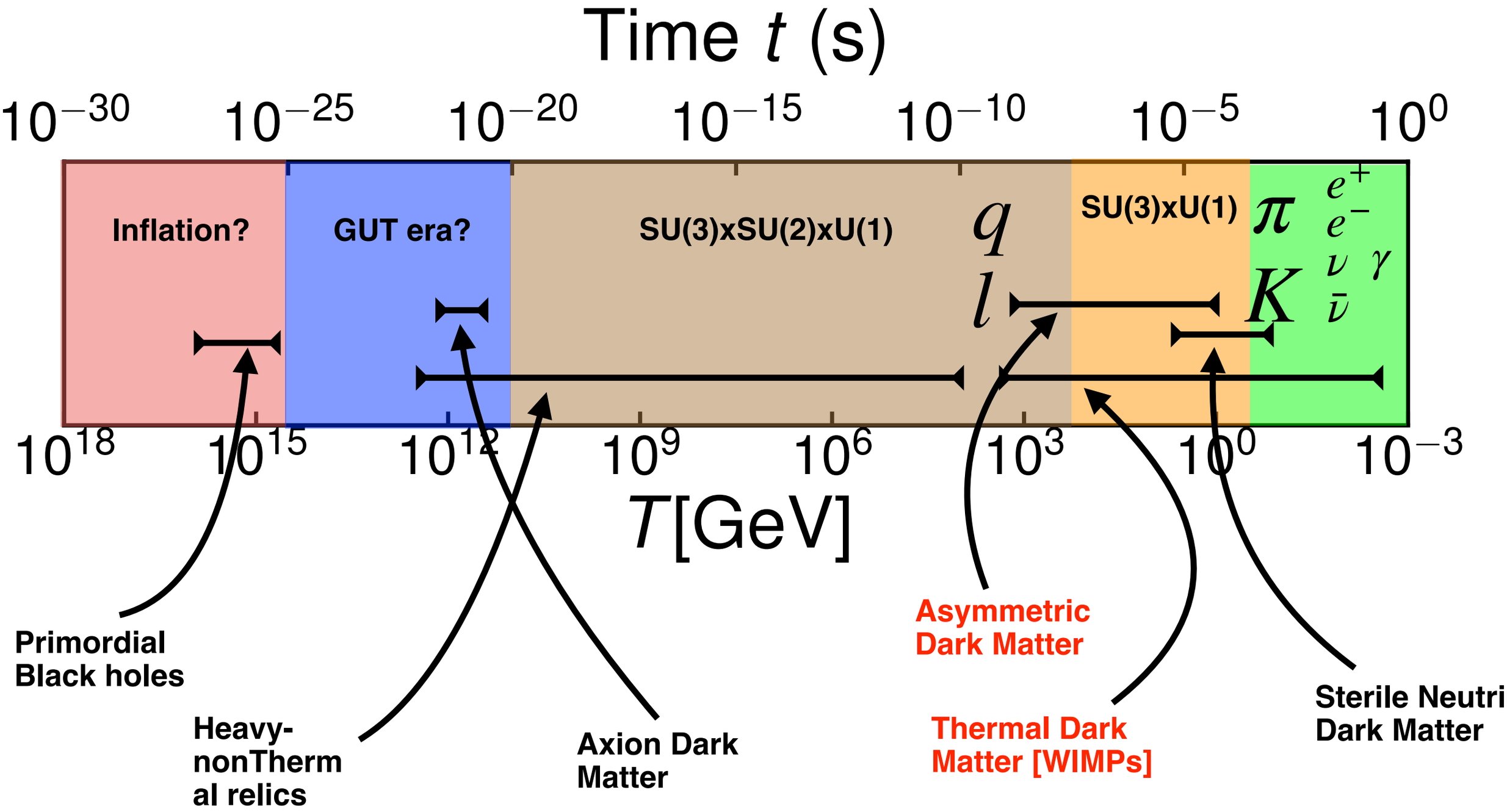
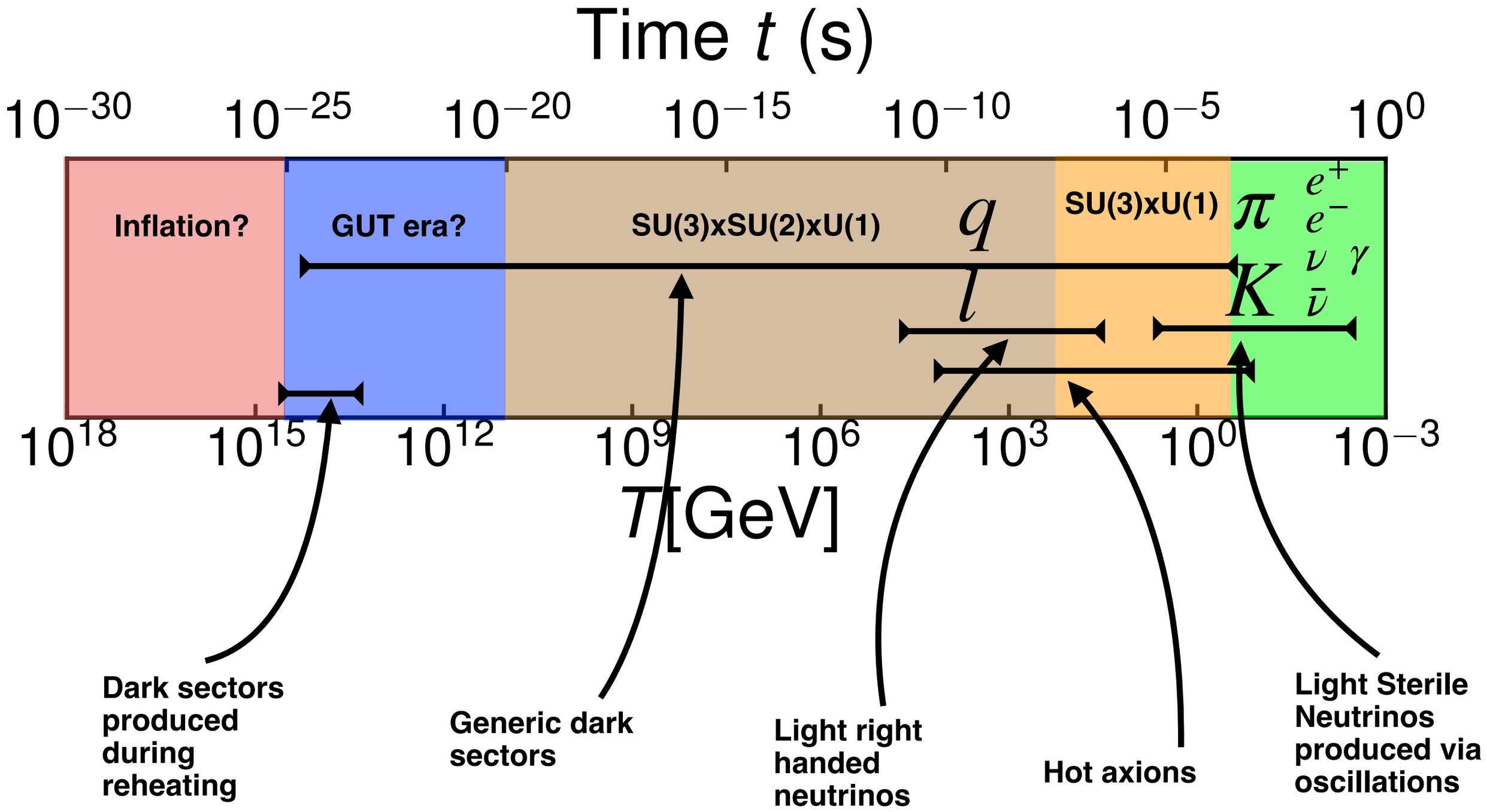
Dark Matter Models



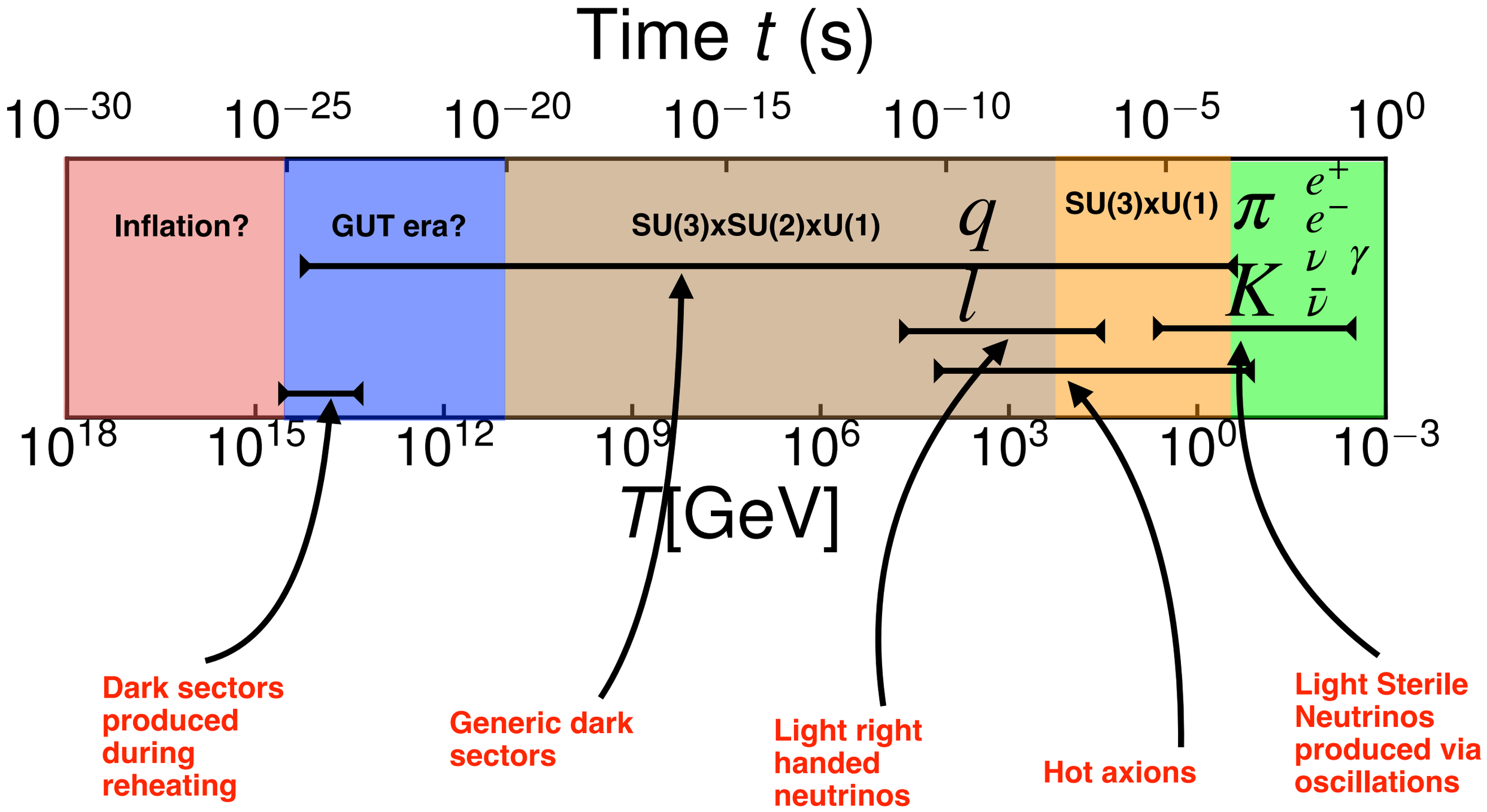
*models where particles were in thermal equilibrium

Dark Radiation Relics



***not an exhaustive list, but it does include some of the most studied scenarios**

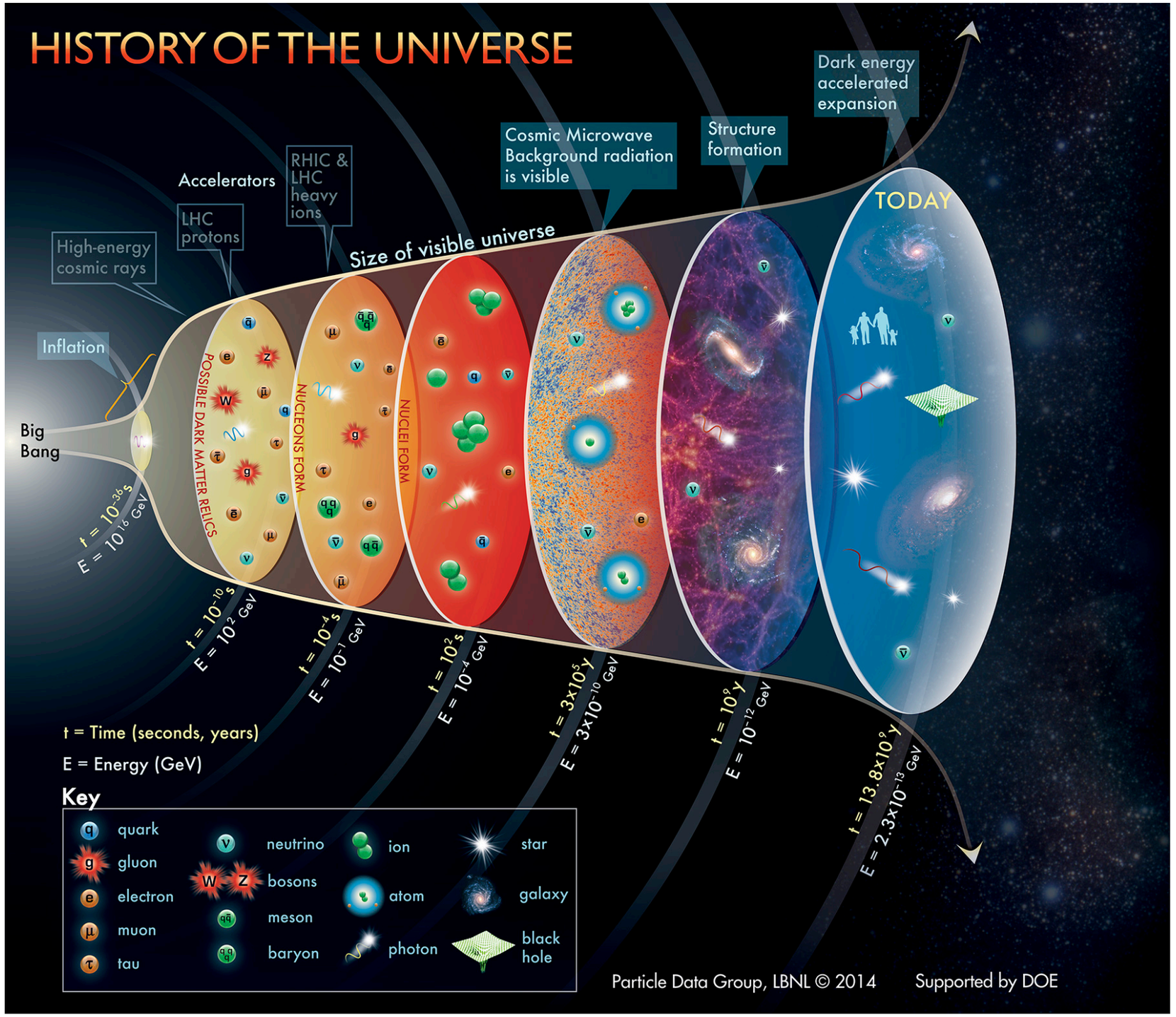
Dark Radiation Relics



*scenarios that we will generically understand how much they contribute to Neff

A Crash Course on Early Universe Cosmology

In 3.5 hours! 💪



The Outline

Lectures I and II:

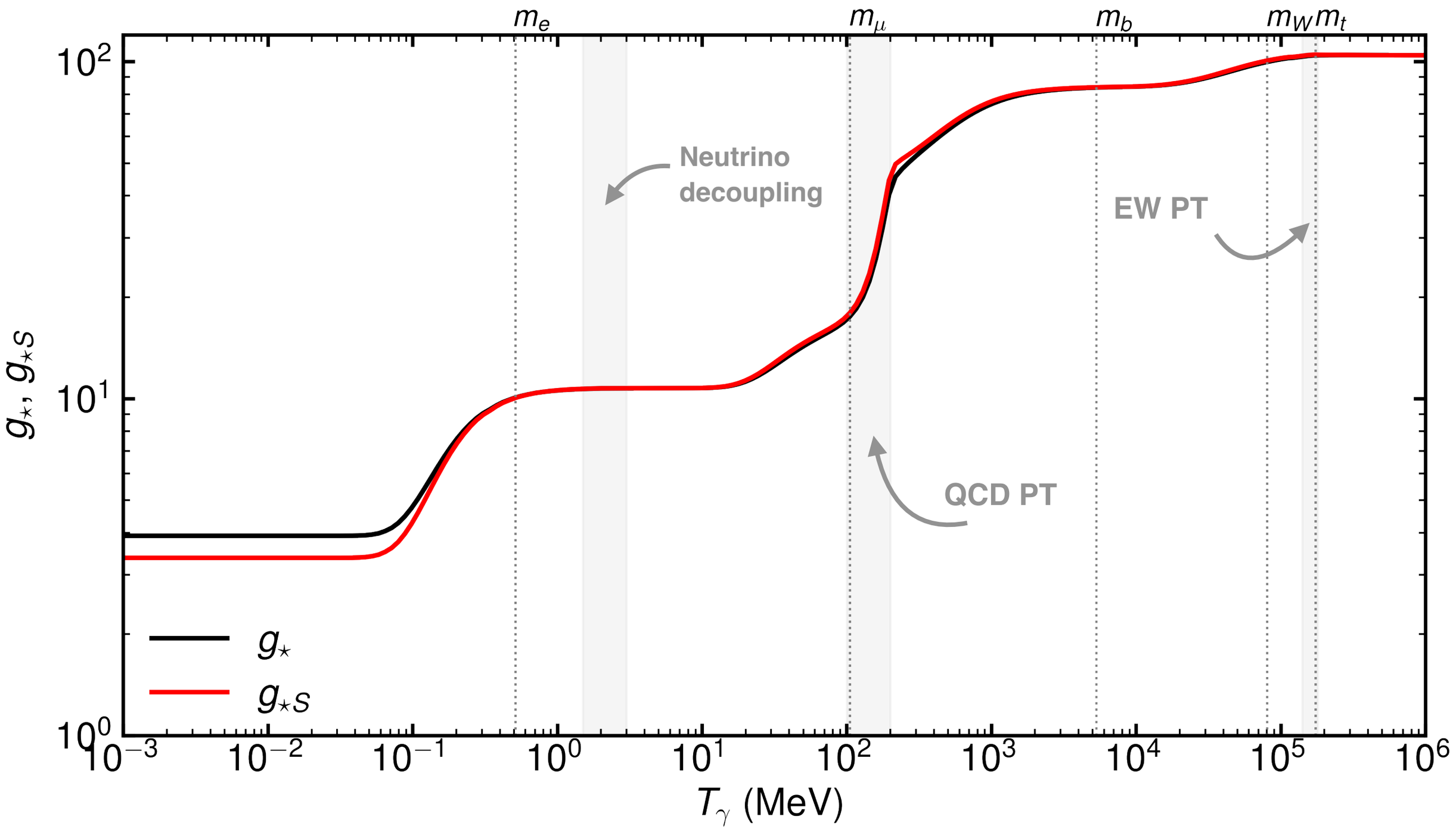
- **Thermal History overview [done]**
- **Cosmological Dynamics**
- **Early Universe Thermodynamics:**
  - **Distribution functions**
  - **Densities and entropy**
  - **Time-temperature relation**

Lectures III and IV:

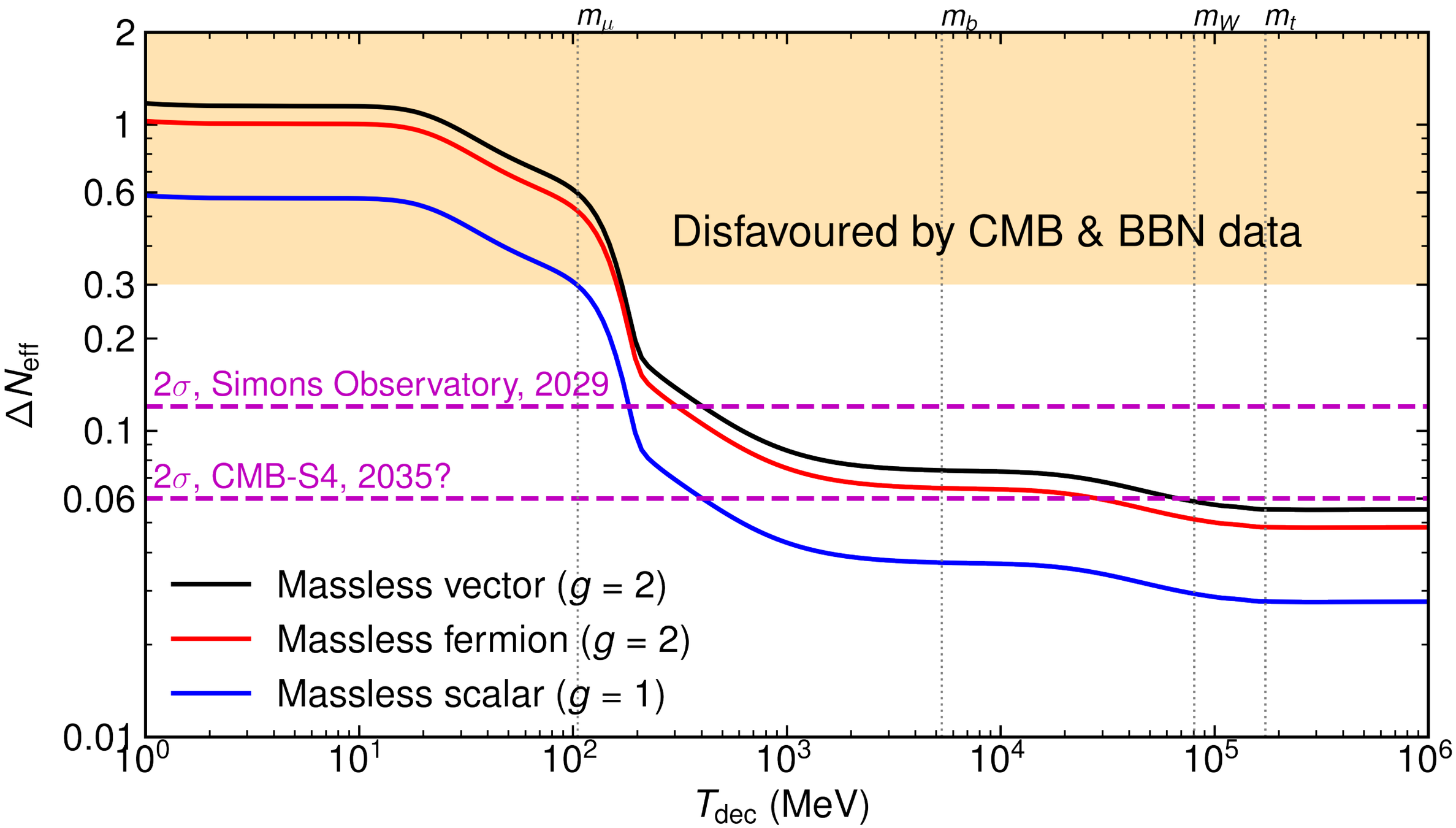
- **Interaction rates and thermal state of the SM plasma**
- **Production of relics**
- **Hot Axion Background**
- **WIMP freeze-out**
- **Baryogenesis via out-of-equilibrium decays**

Degrees of Freedom

Data from Laine & Meyer [1503.04935]



Contribution to DNeff



Implications:

No thermalized eV-scale sterile neutrinos

Bound on the axion decay constant/ mass of $m_a \lesssim 0.2\,\mathrm{eV}$

Key bound on Stochastic Gravitational Wave backgrounds

Implication of current DNeff bound