BSM in the Early Universe

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Precision Cosmology

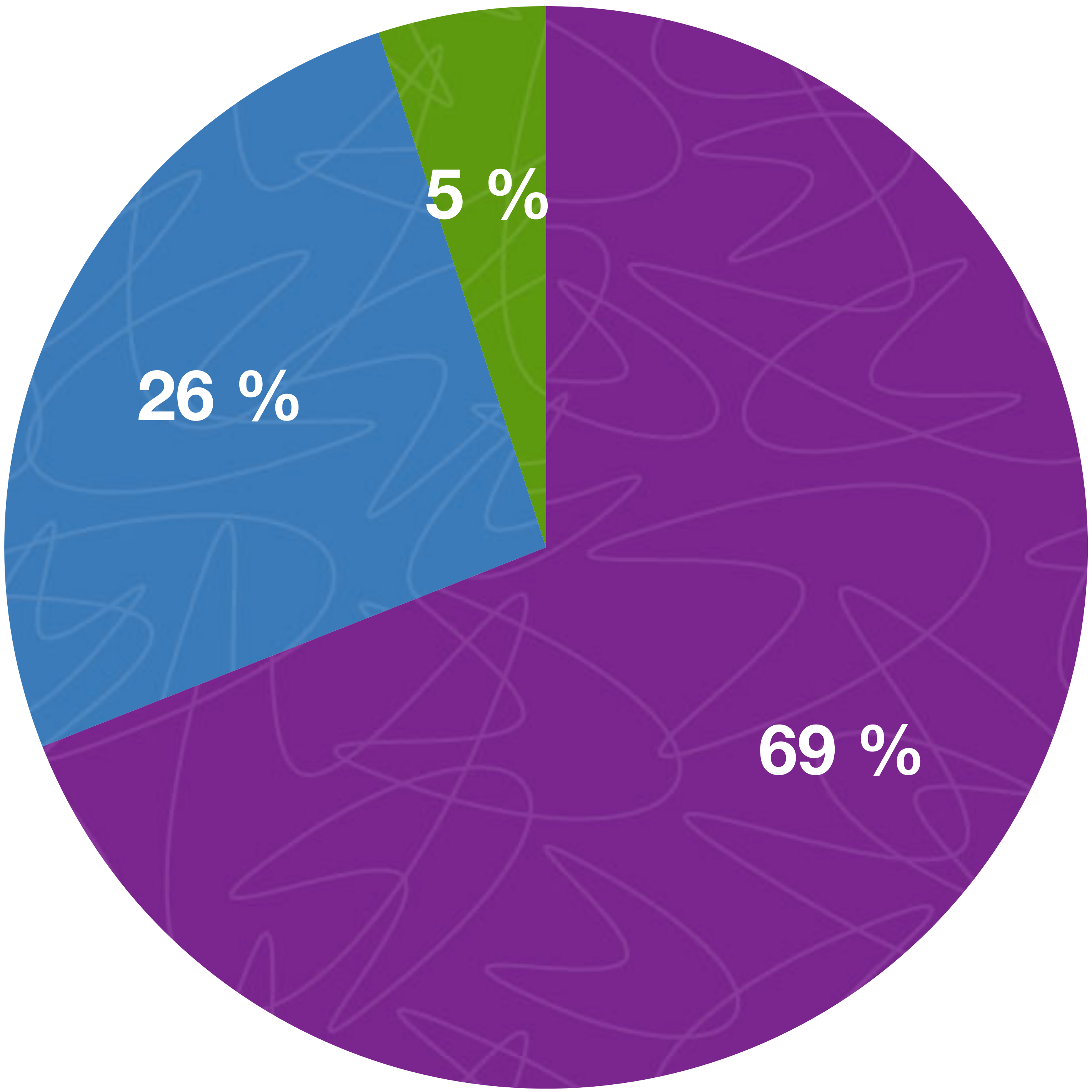
Planck 2018 1807.06209

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

Baryonic Matter

Dark Matter

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



Dark Energy

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

Theoretical Understanding?

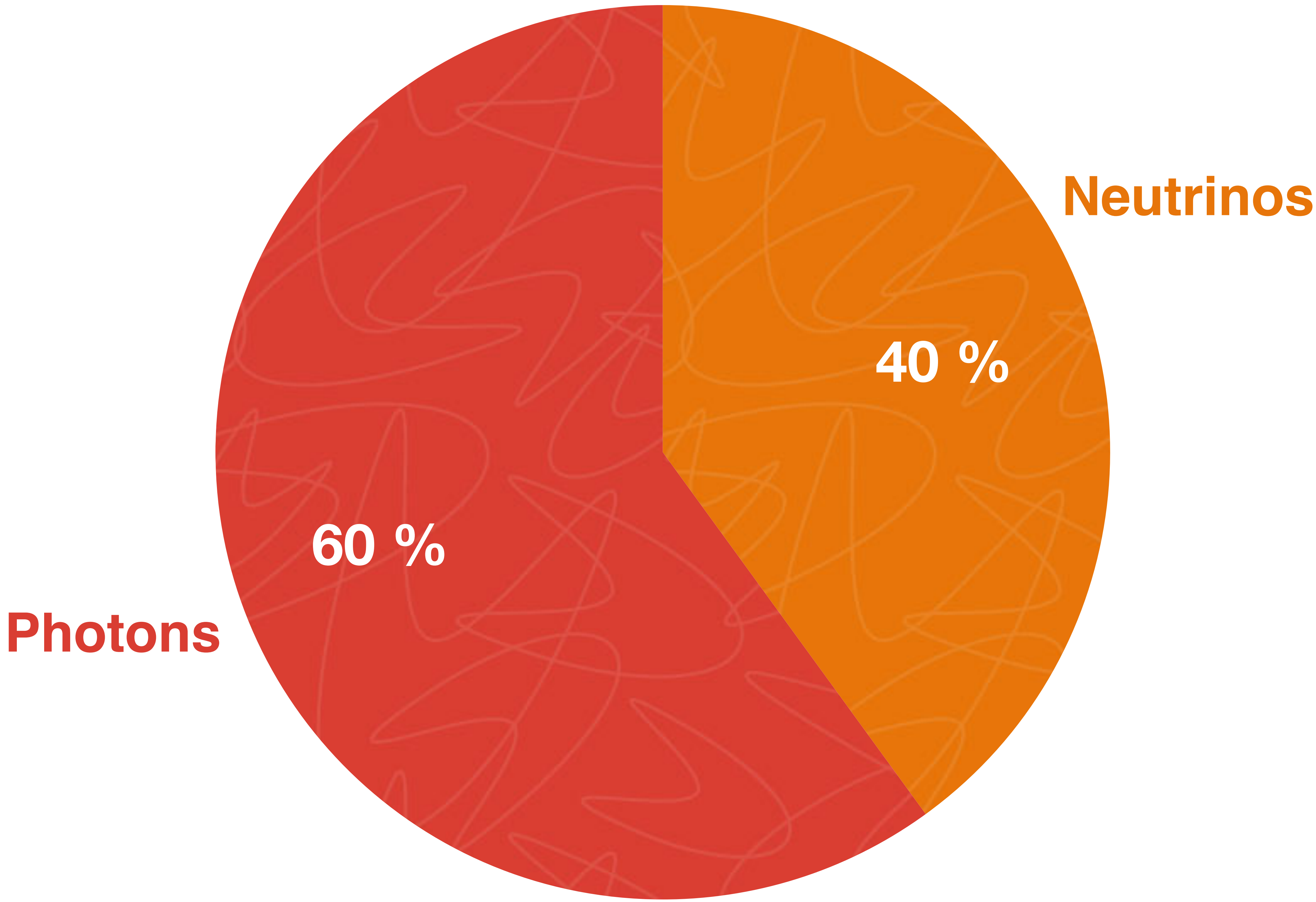
Motivating Question:

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:

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

Main goal of these Lectures

Have an understanding of the physical state of the Early Universe

Early Universe Thermodynamics

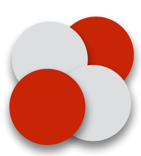
Explore key potential BSM cosmological events:

The formation of the hot Cosmological Axion Background

Thermal Dark Matter freeze-out

Baryogenesis via out-of-equilibrium decays

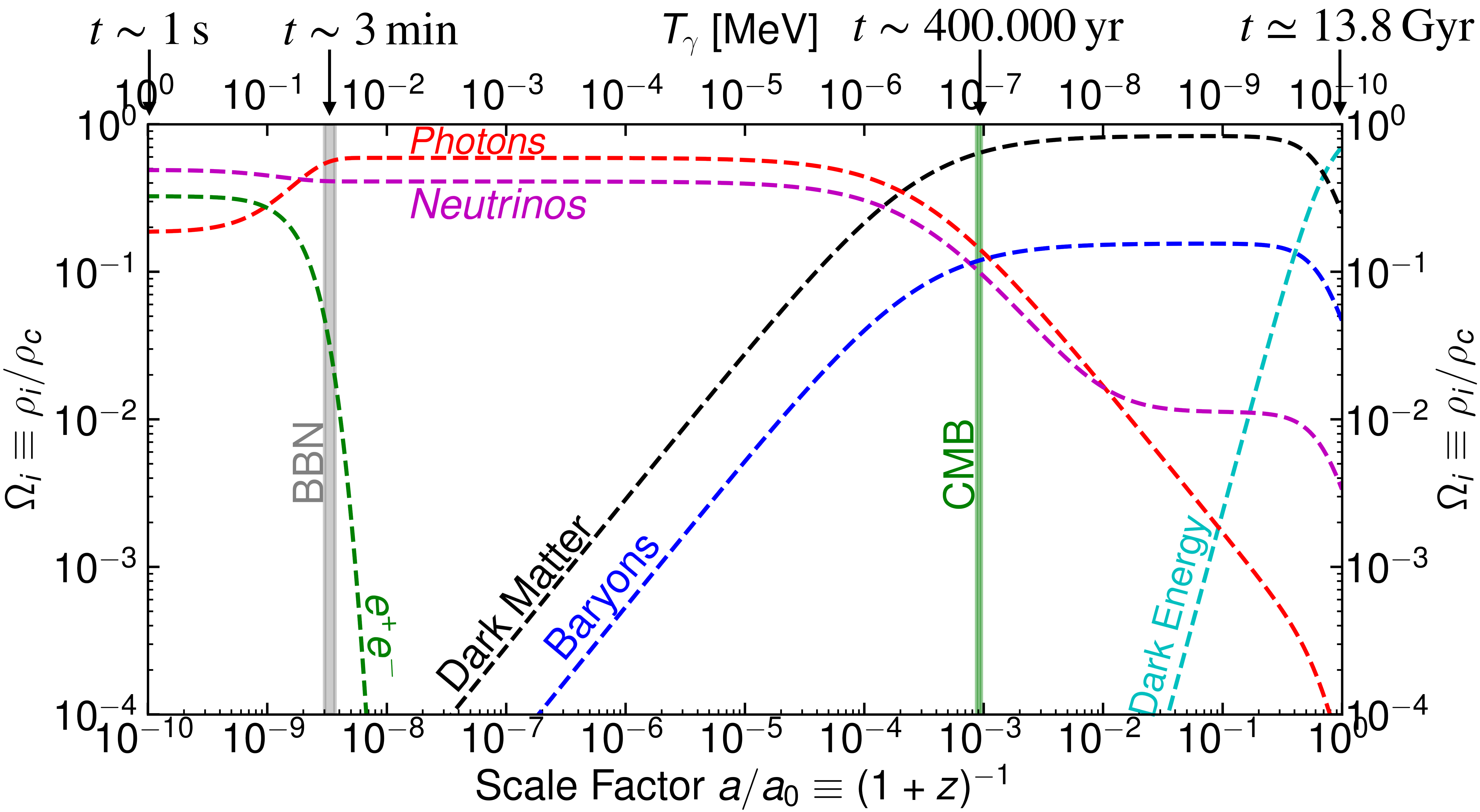
Exercise:



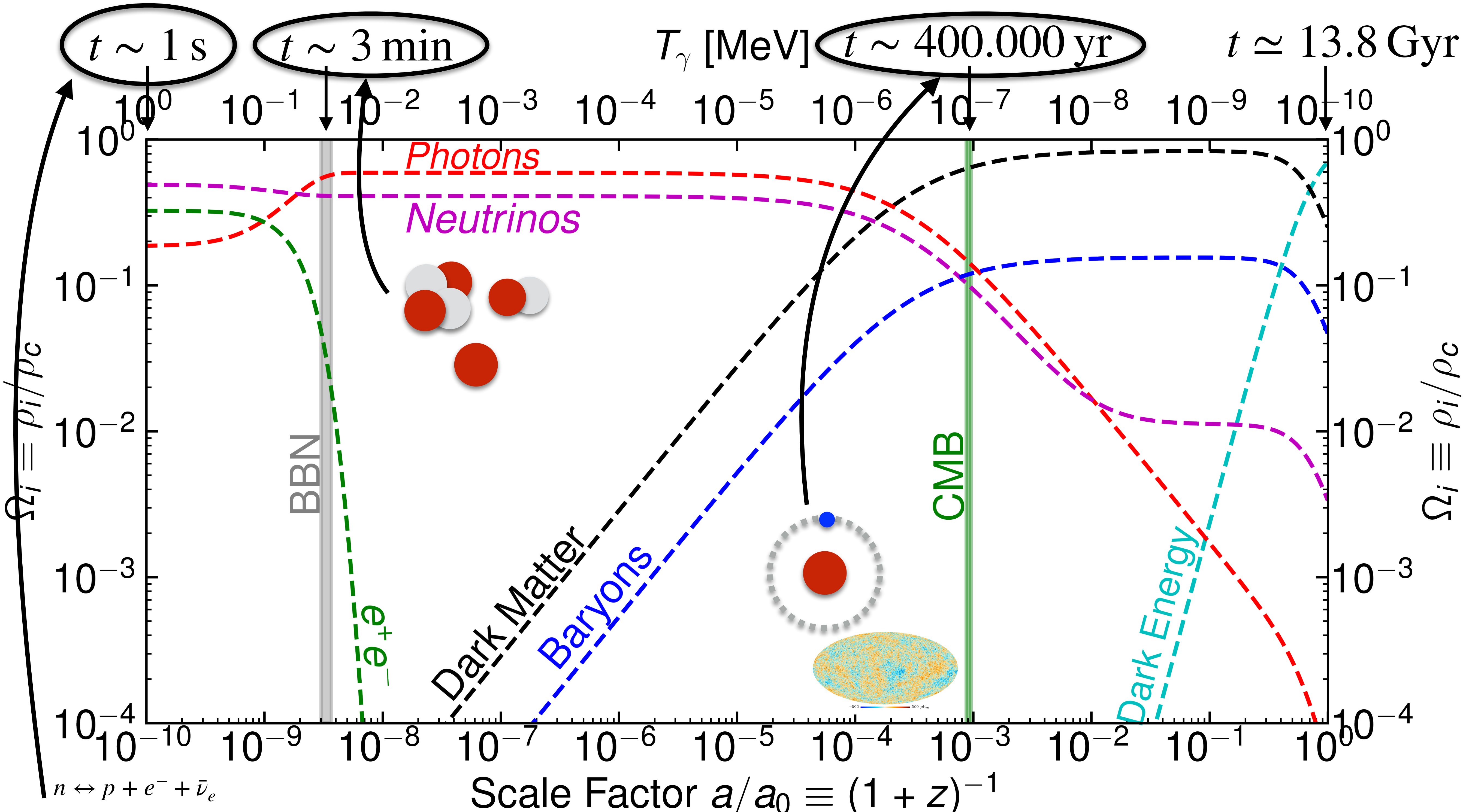
Primordial Helium abundance in the presence of dark radiation

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

The Known Thermal History



The Known Thermal History



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

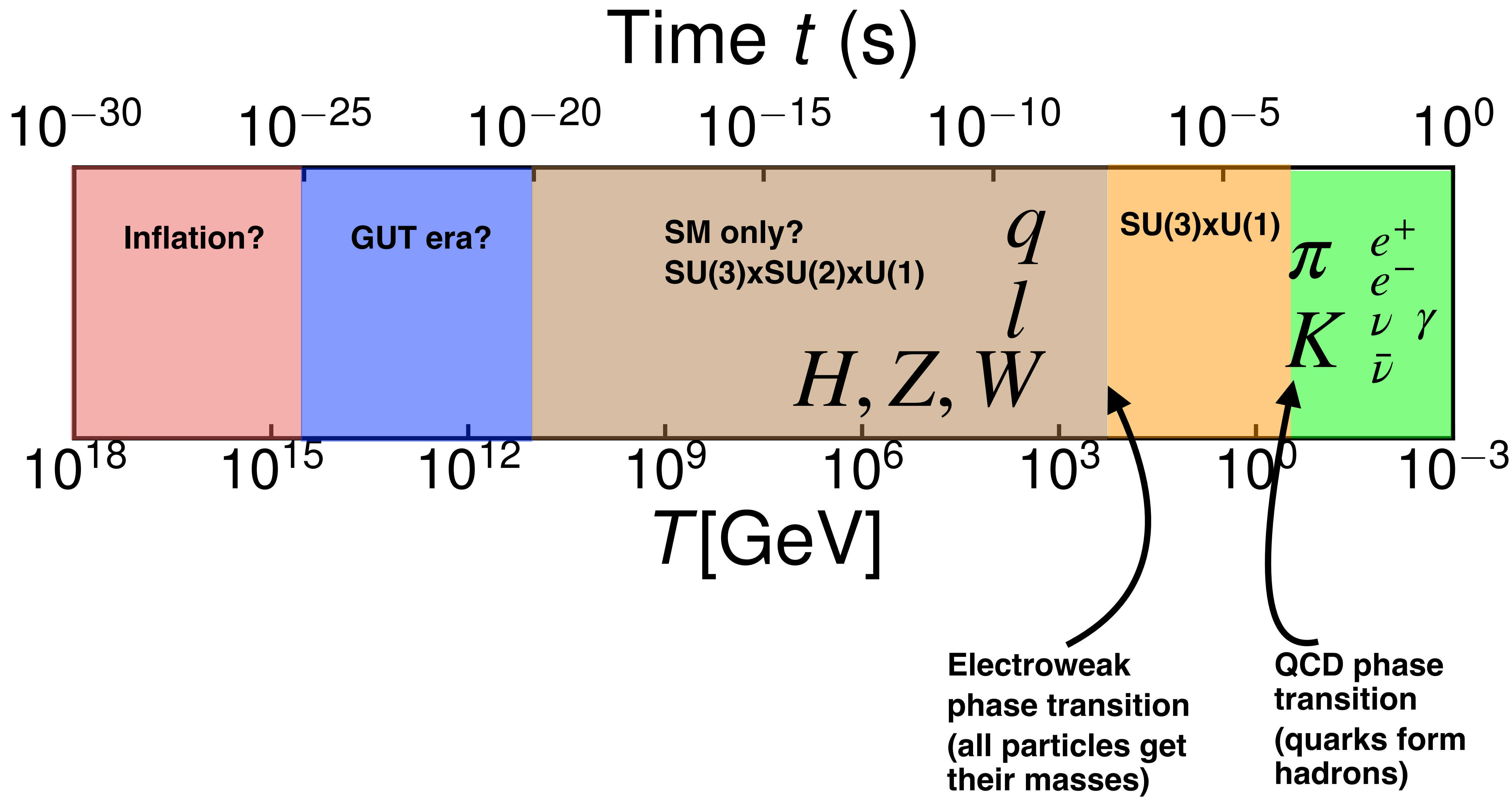
$n + e^+ \leftrightarrow p + \bar{\nu}_e$

$n + \nu_e \leftrightarrow p + e^-$

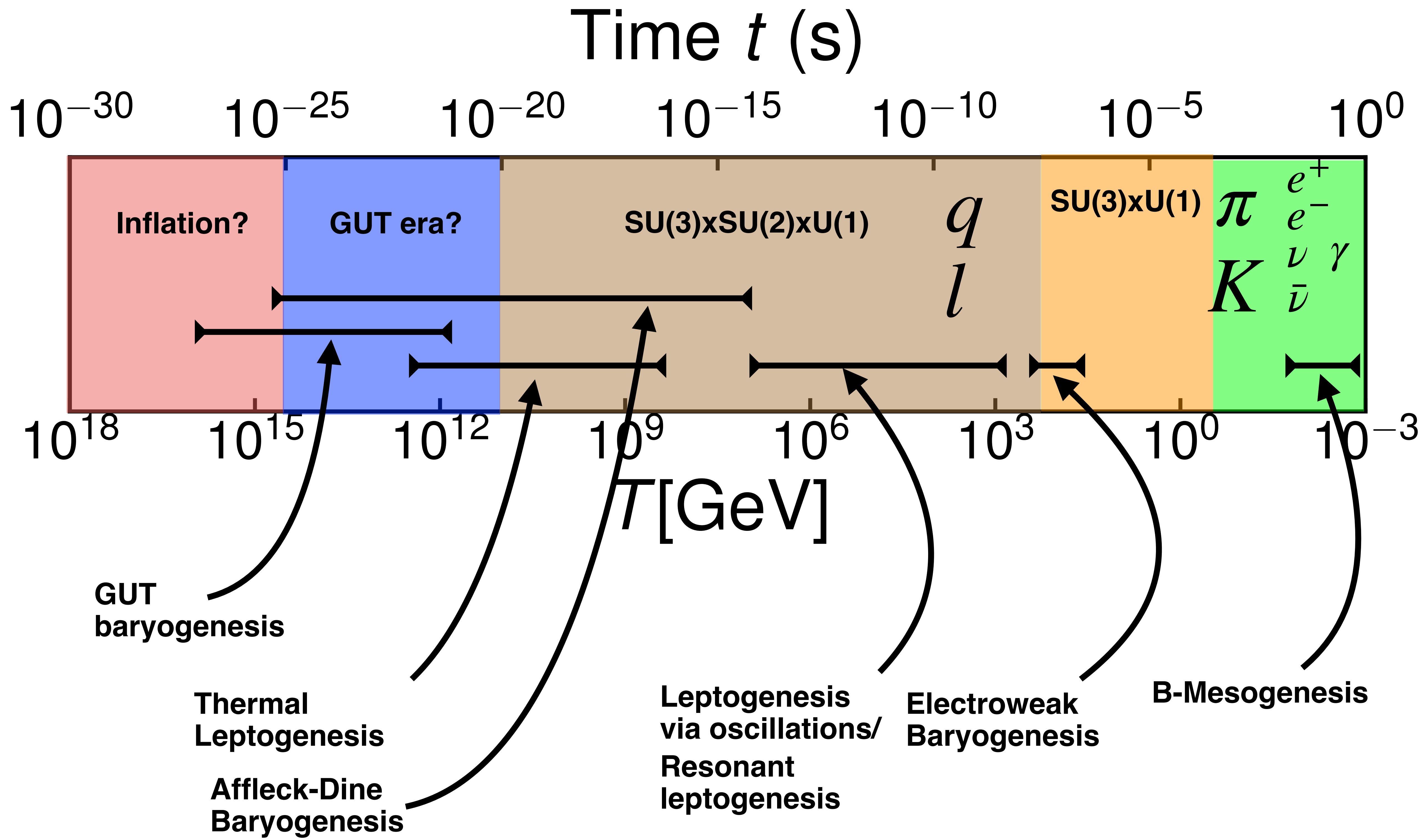
$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu e^\pm \leftrightarrow \nu e^\pm$

Key Stages in the Thermal History

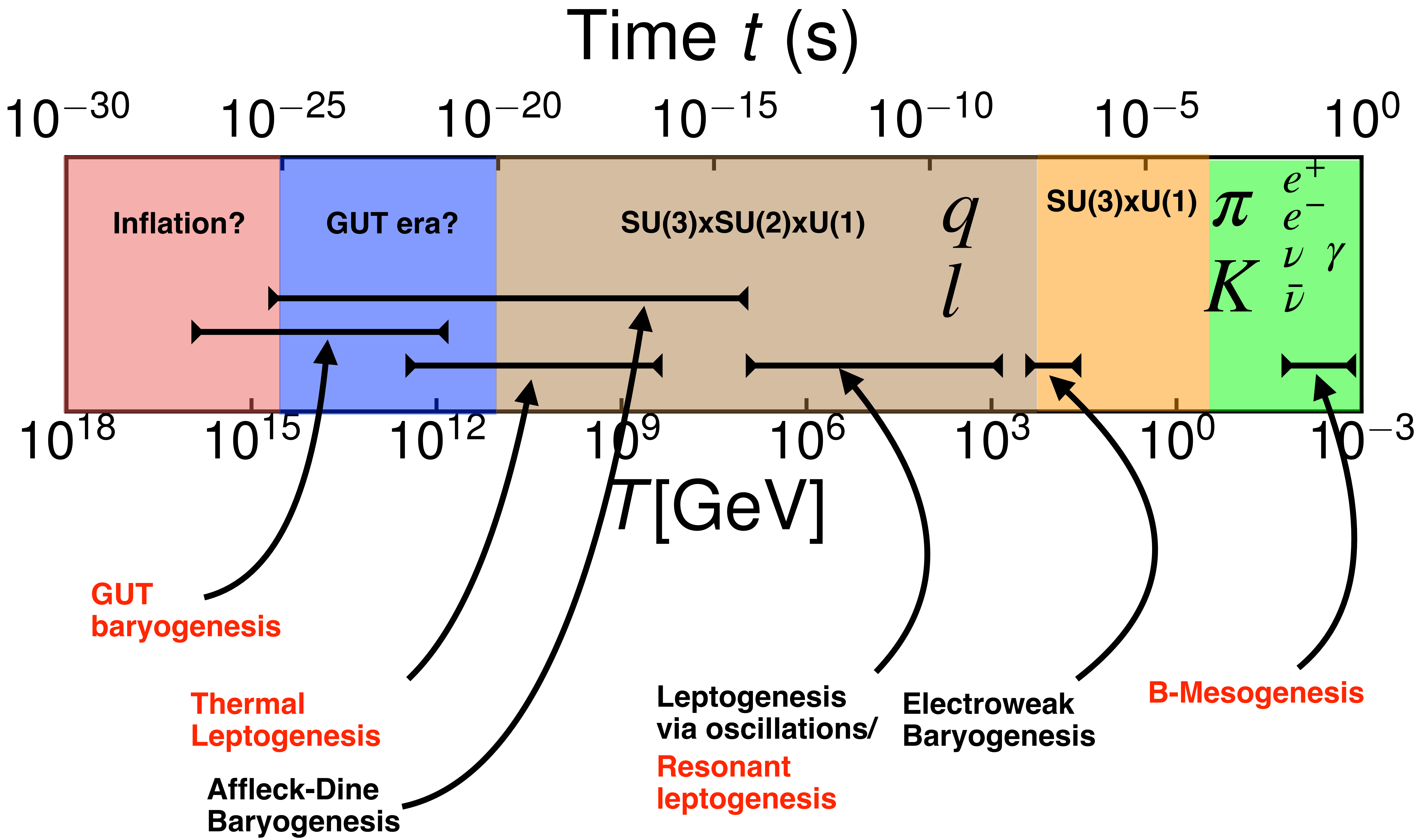


Baryogenesis Models



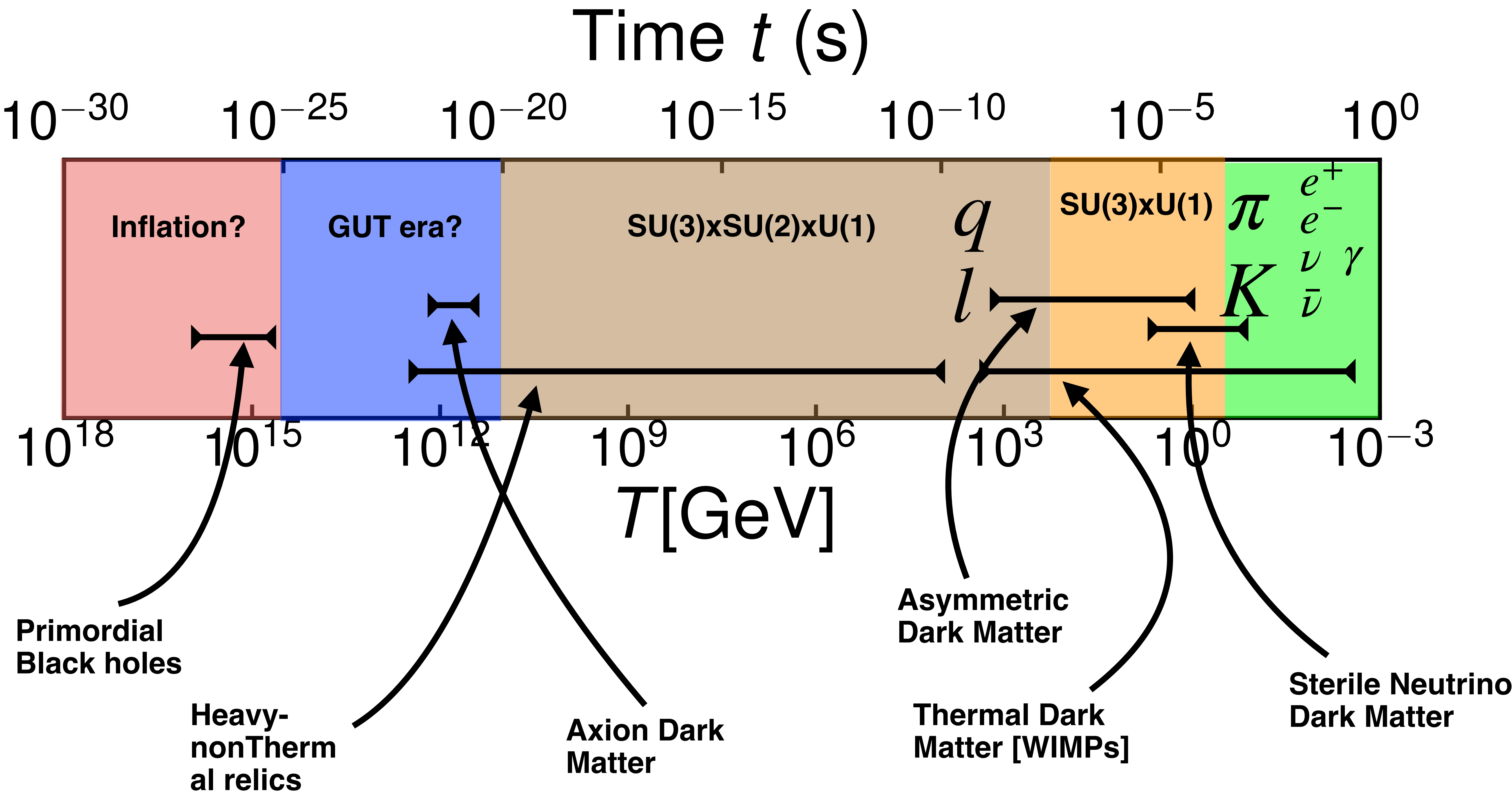
*not an exhaustive list, but it does include some of the most popular models

Baryogenesis Models



*Baryogenesis via out-of-equilibrium decays

Dark Matter Models



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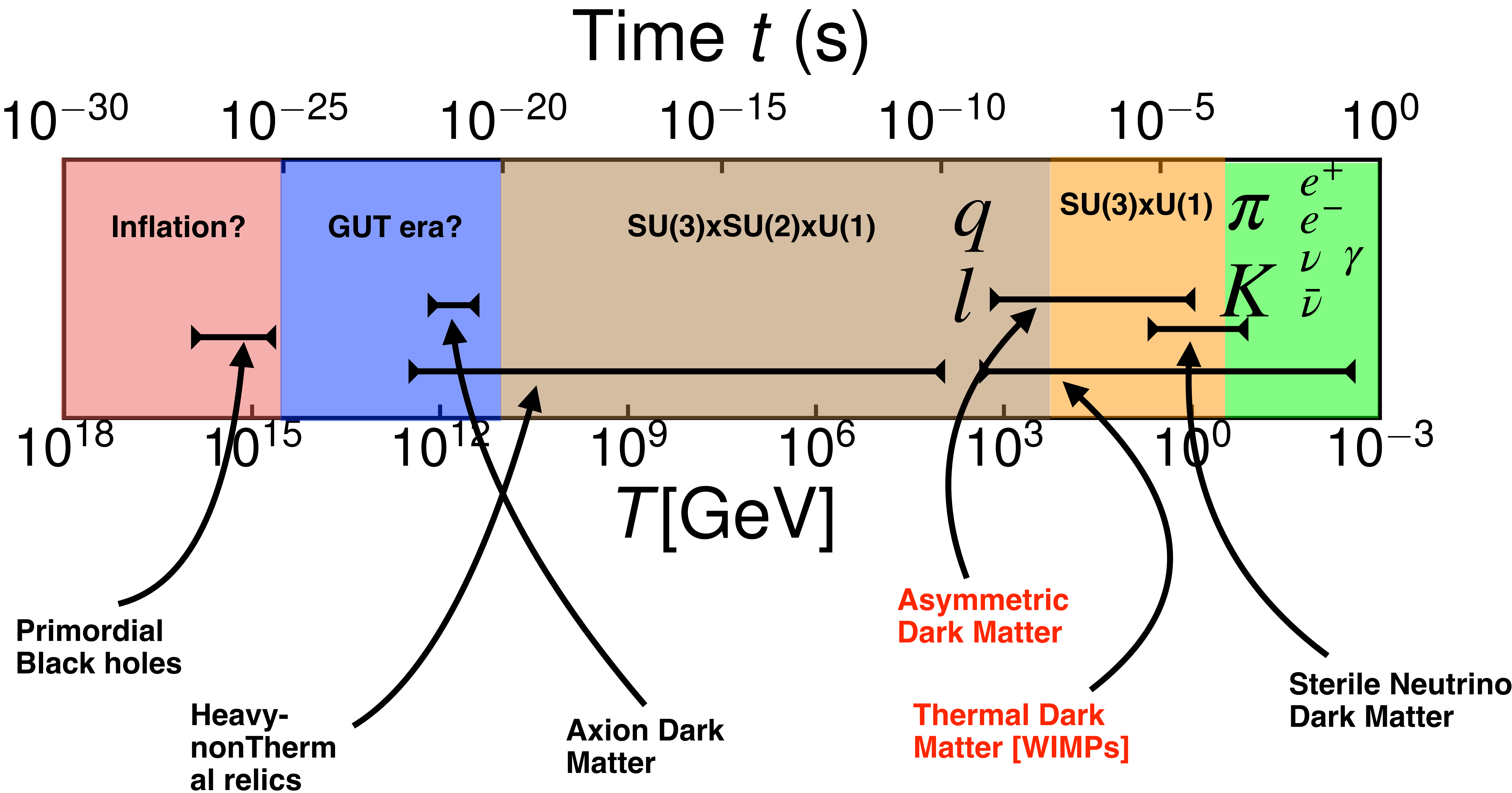
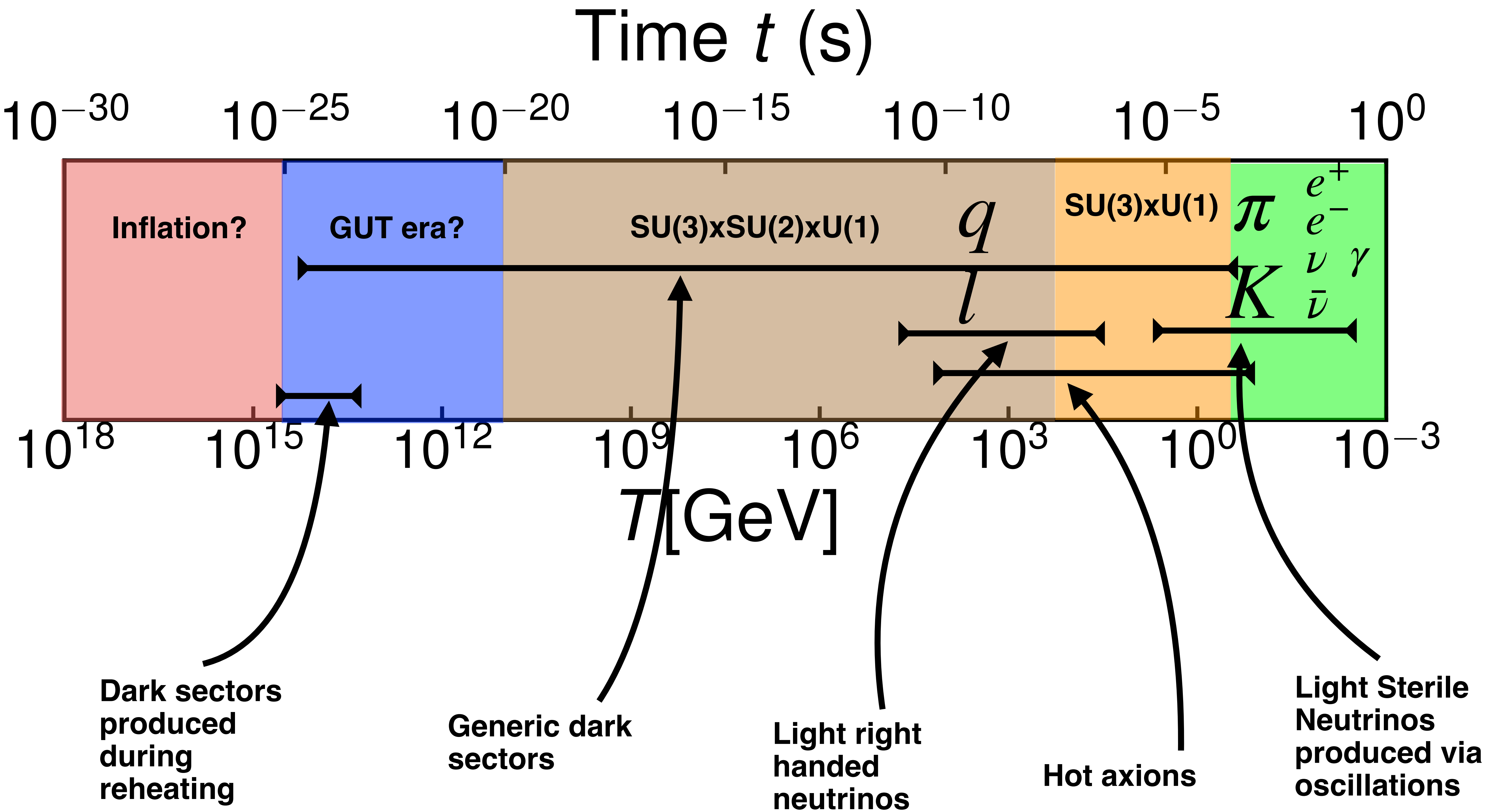
Dark Matter Models



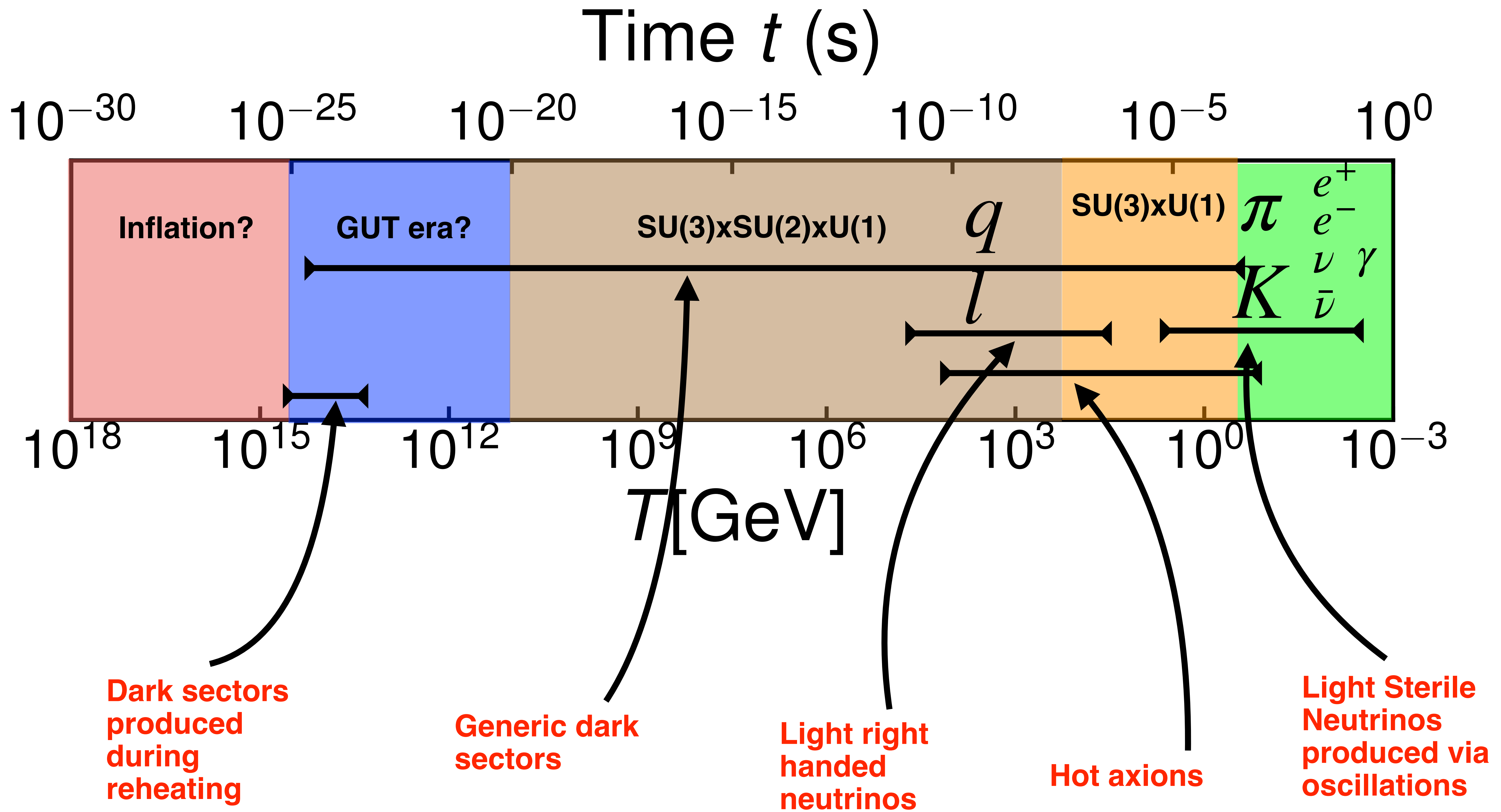
*models where particles were in thermal equilibrium

Dark Radiation Relics



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

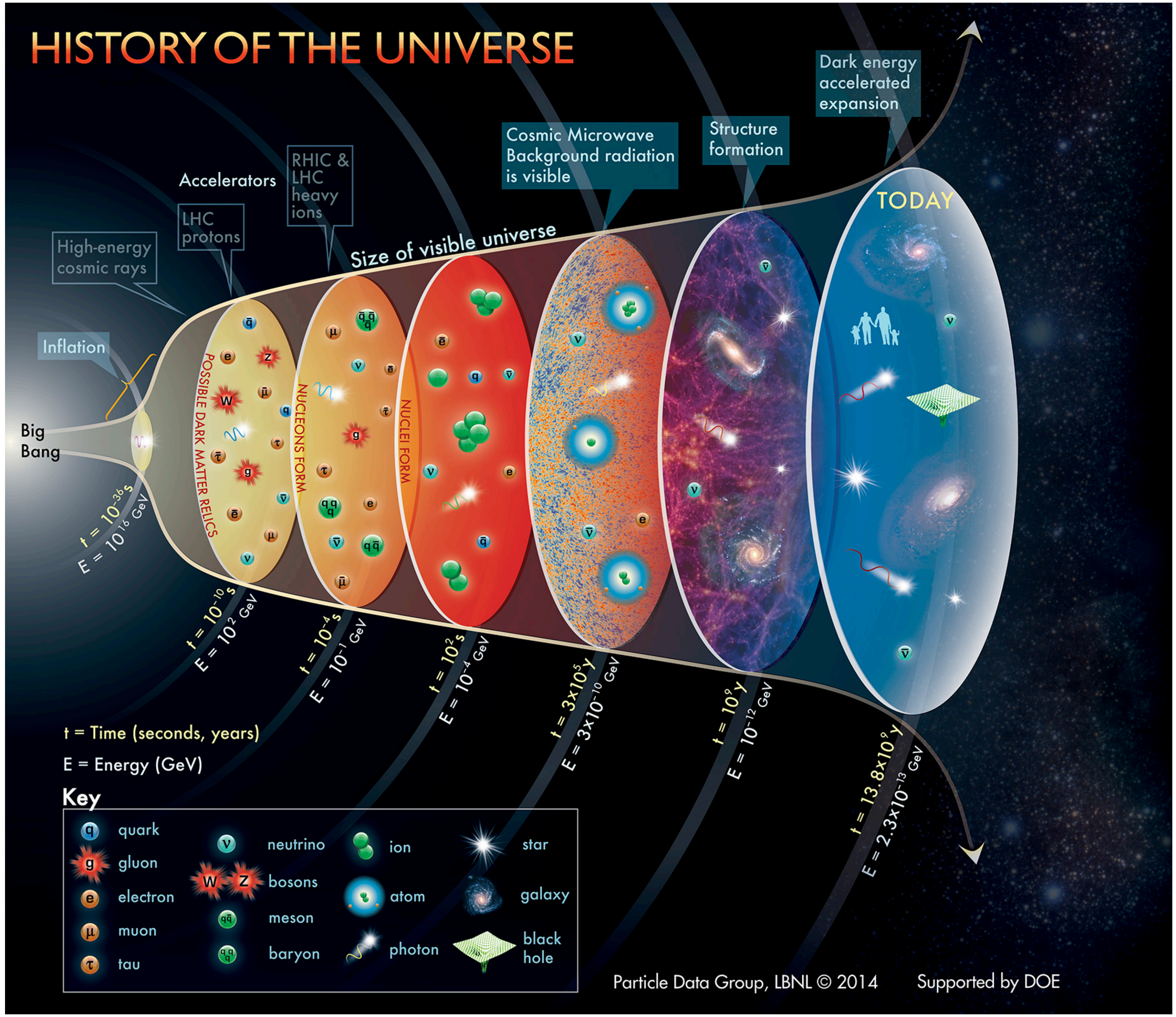
Dark Radiation Relics



*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

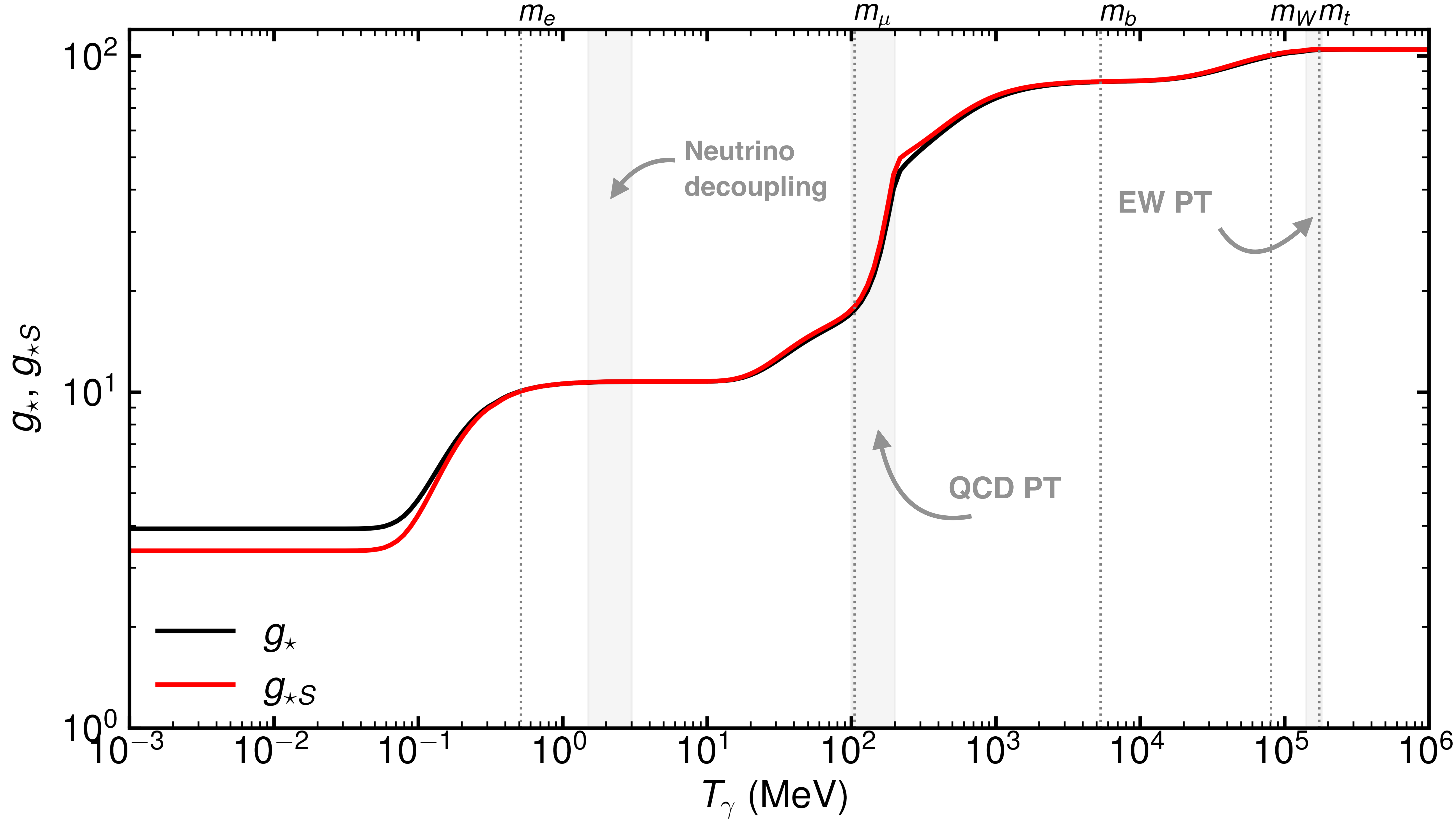
Hot Axion Background

WIMP freeze-out

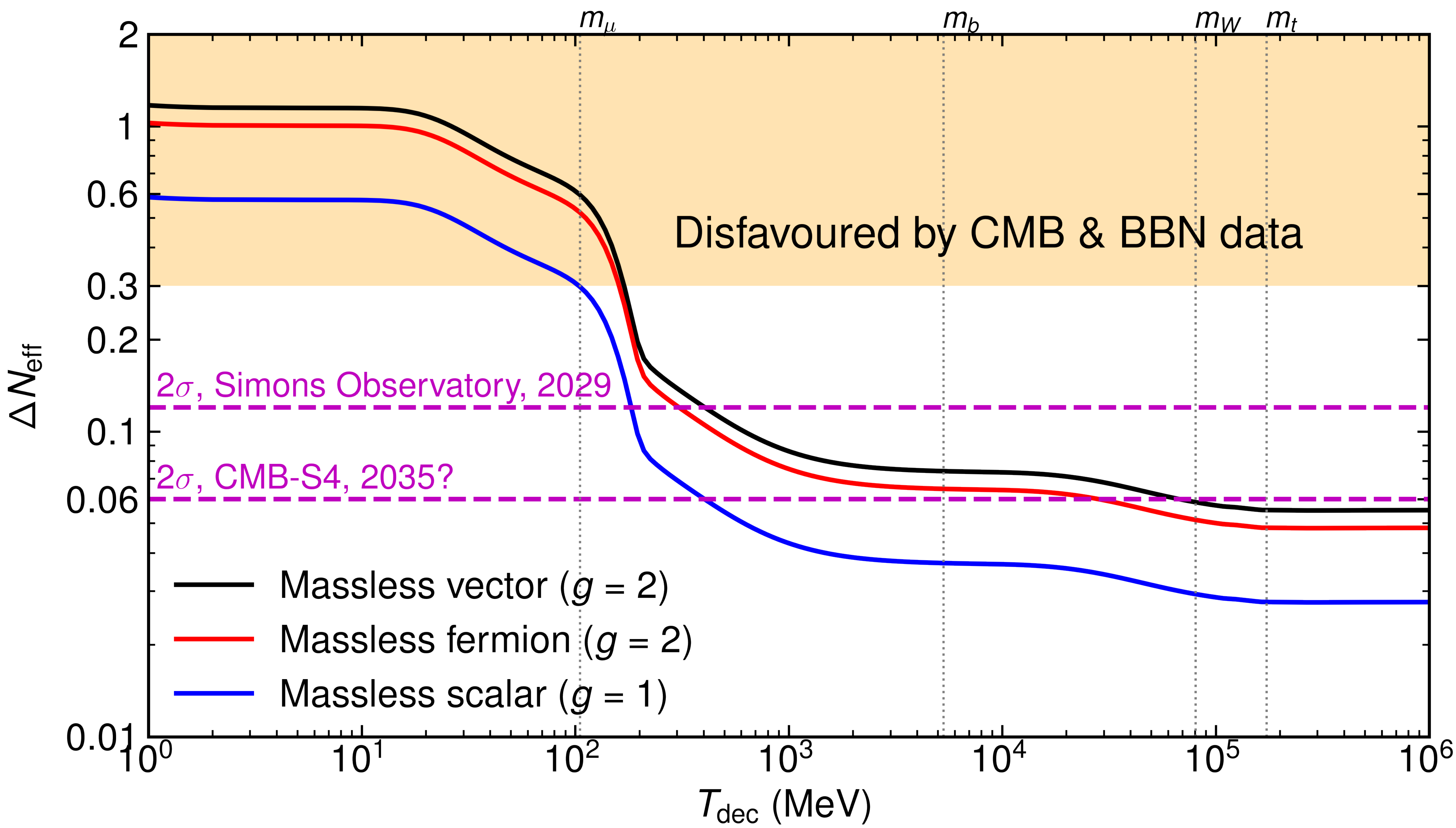
Baryogenesis via out-of-equilibrium decays

Degrees of Freedom

Data from Laine & Meyer [1503.04935]



Contribution to DNeff



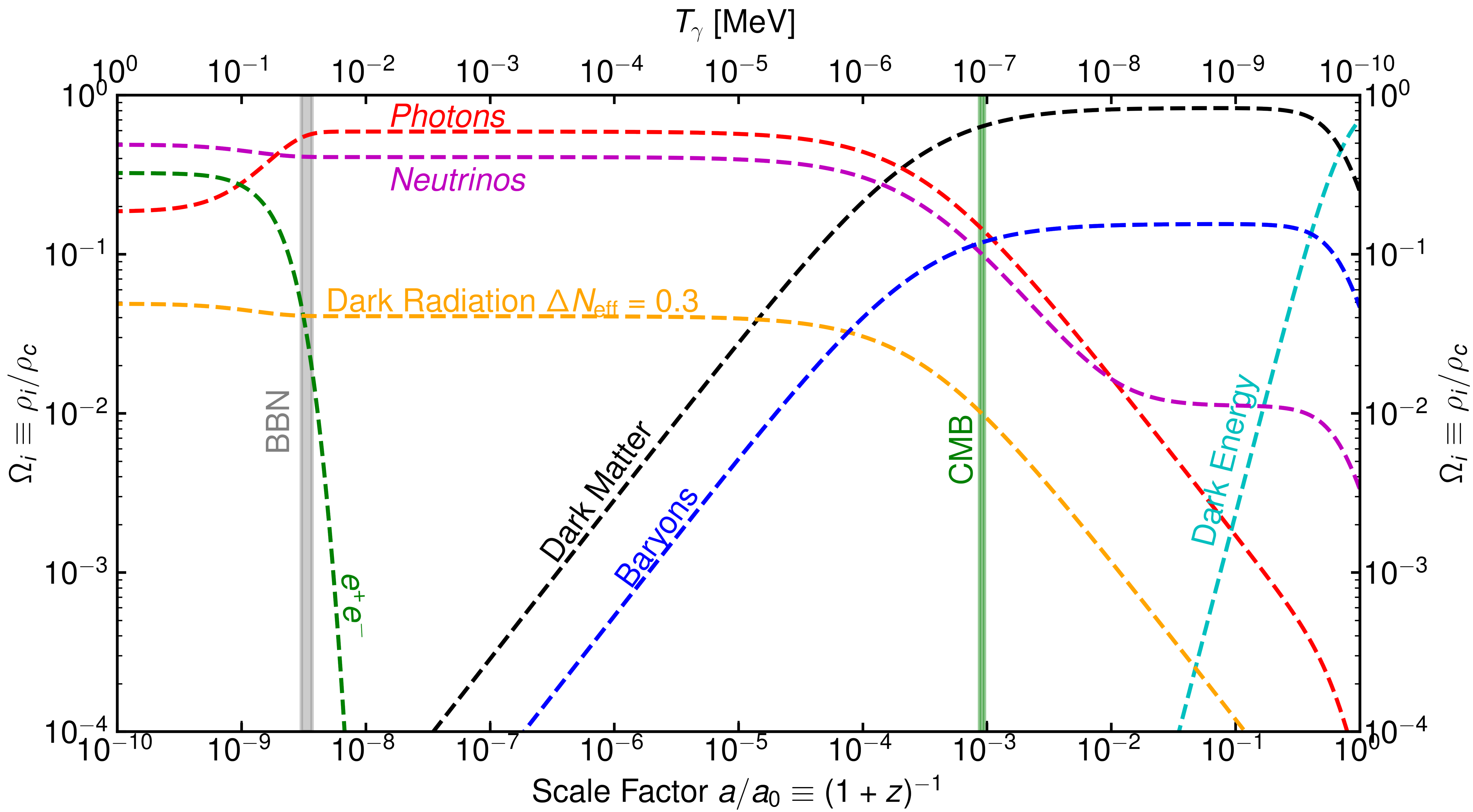
Implications:

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



Lecture III

Recap from Lectures I and II:

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

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

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

Equilibrium Thermodynamics

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

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

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

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

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

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

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

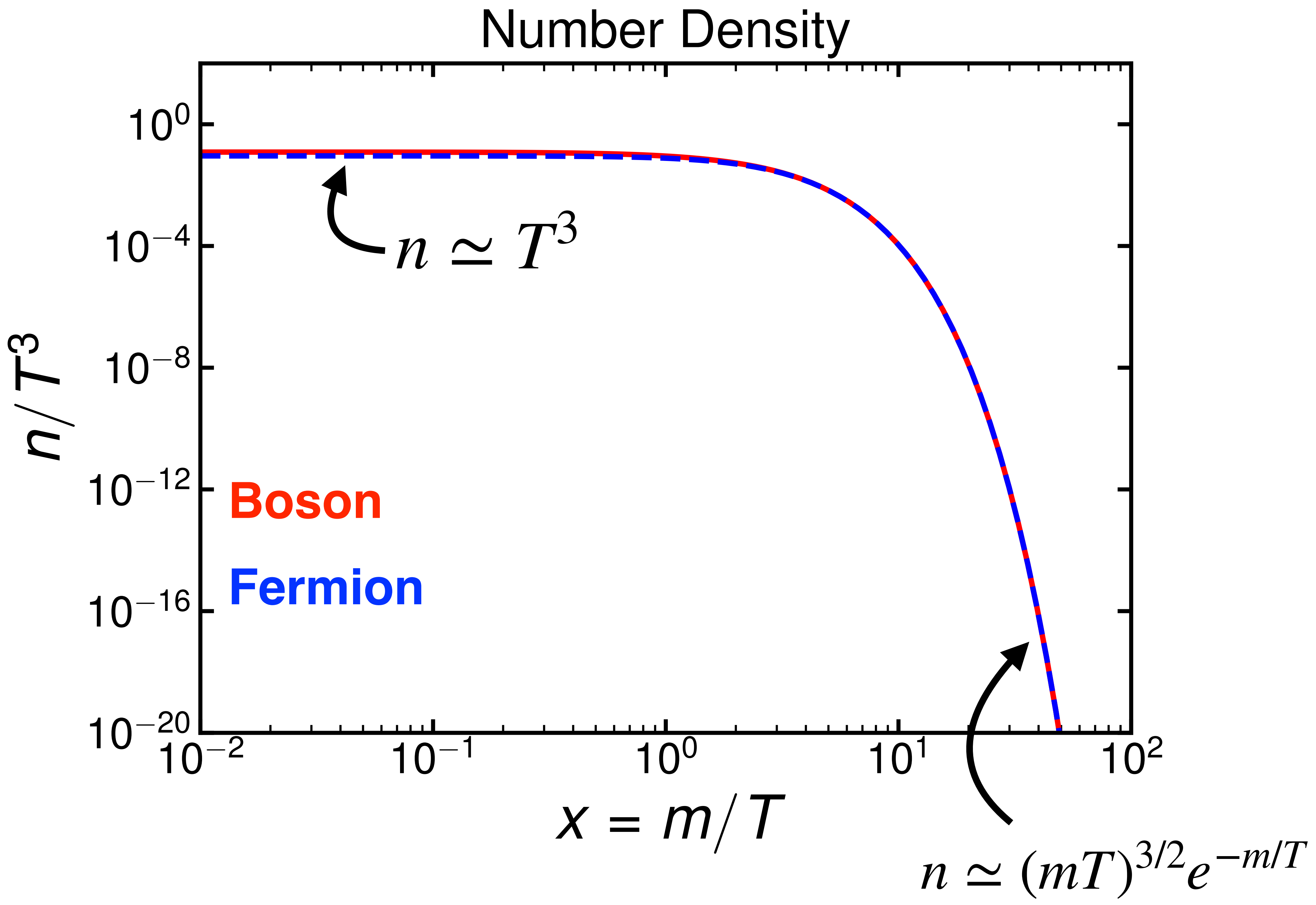
$$p = 1/3\rho$$

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

$$\rho = m \times n$$

$g =$ **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**

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

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

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

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:

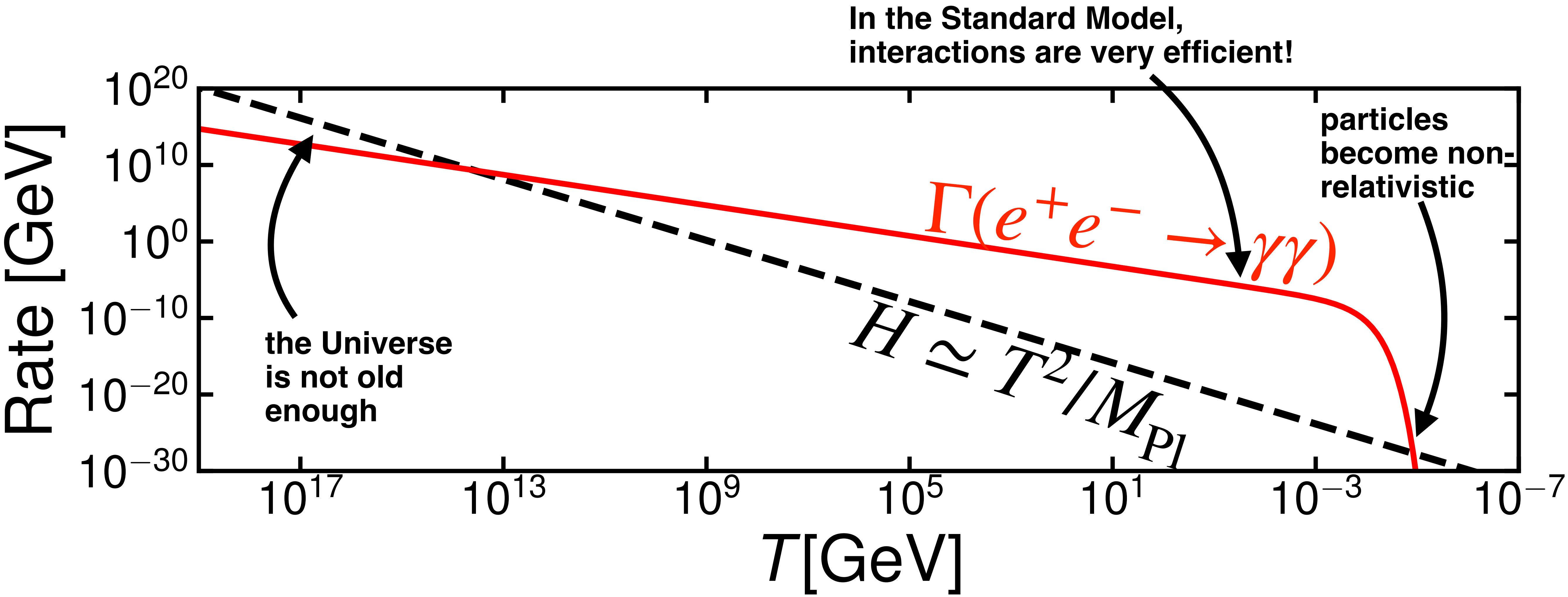
$$N \simeq t_U/\tau \simeq \Gamma/H$$

Particle Interaction Rates

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

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

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



2 Key Corollaries

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

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

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

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

The Boltzmann Equation

The Collision term:

$$C[f_1] = -\frac{1}{2E_1}\frac{1}{g_1}\int d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \delta^4(p_1+p_2-p_3-p_4) \times S \times$$
$$\Big[|\mathscr{M}|^2_{1+2\to3+4} f_1 f_2 [1\pm f_3][1\pm f_4] - |\mathscr{M}|^2_{3+4\to1+2} f_3 f_4 [1\pm f_1][1\pm f_2]\Big]$$

$$d\Pi_i \equiv \frac{d^3 p_i}{2E_i (2\pi)^3}$$

$S = 1/2$ **only if 3 and 4 are identical, otherwise** $S = 1$

$$g_1 \int \frac{d^3 p_1}{(2\pi)^3} C[f_1] = -\int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \delta^4(p_1+p_2-p_3-p_4) \times S \times$$
$$\Big[|\mathscr{M}|^2_{1+2\to3+4} f_1 f_2 [1\pm f_3][1\pm f_4] - |\mathscr{M}|^2_{3+4\to1+2} f_3 f_4 [1\pm f_1][1\pm f_2]\Big]$$

The Boltzmann Equation

The Collision term:

$$g_1 \int \frac{d^3 p_1}{(2\pi)^3} C[f_1] = - \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \times S \times$$

$$\left[|\mathscr{M}|^2_{1+2\to 3+4} f_1 f_2 [1 \pm f_3][1 \pm f_4] - |\mathscr{M}|^2_{3+4\to 1+2} f_3 f_4 [1 \pm f_1][1 \pm f_2] \right]$$

Assuming T invariance, neglecting statistical factors one gets:

$$|\mathscr{M}|^2_{1+2\to 3+4} \left[f_1 f_2 - f_3 f_4 \right]$$

Taking these distributions to be of Maxwell-Boltzmann type with the same temperature one finds:

$$|\mathscr{M}|^2_{1+2\to 3+4} e^{-(E_1+E_2)/T} \left[\frac{n_1}{n_1^{(0)}} \frac{n_2}{n_2^{(0)}} - \frac{n_3}{n_3^{(0)}} \frac{n_4}{n_4^{(0)}} \right]$$

The Boltzmann Equation

The Collision term:

$$g_1 \int \frac{d^3p_1}{(2\pi)^3} C[f_1] = -\int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \times S \times$$
$$|\mathcal{M}|^2_{1+2\to 3+4}\, e^{-(E_1+E_2)/T} \left[\frac{n_1}{n_1^{(0)}} \frac{n_2}{n_2^{(0)}} - \frac{n_3}{n_3^{(0)}} \frac{n_4}{n_4^{(0)}} \right]$$

Now it is very easy to map this to the cross section which is defined as:

$$d\sigma_{1+2\to 3+4} \equiv \frac{1}{2E_1 2E_2} \frac{1}{|v_1 - v_2|} d\Pi_3 d\Pi_4 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) S |\mathcal{M}|^2_{1+2\to 3+4}$$

And one literally arrives to:

$$\frac{dn_1}{dt} + 3Hn_1 = -\langle \sigma v \rangle\, n_1^{(0)} n_2^{(0)} \left[\frac{n_1}{n_1^{(0)}} \frac{n_2}{n_2^{(0)}} - \frac{n_3}{n_3^{(0)}} \frac{n_4}{n_4^{(0)}} \right]$$

with $$\langle \sigma v \rangle \equiv \frac{1}{n_1^0 n_2^0} \int \frac{d^3p_1}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} |\vec{v}_1 - \vec{v}_2| \times \sigma_{1+2\to 3+4}\, e^{-\frac{E_1+E_2}{T}}$$

which can be simplified to:
[Gondolo & Gelmini '90]

$$\langle \sigma v \rangle = \frac{1}{g_1 g_2 8 T m_1^2 m_2^2 K_2[m_1/T] K_2[m_2/T]} \int_{s_0^{\min}}^{\infty} ds\, s^{3/2} K_1\left[\frac{\sqrt{s}}{T}\right] \lambda[1, m_1^2/s, m_2^2/s]$$

The Boltzmann Equation

In most cases, 3 and 4 are in thermal equilibrium and then one simply gets

$$\frac{dn_1}{dt} + 3Hn_1 = -\langle \sigma v \rangle \left[n_1 n_2 - n_1^{\mathrm{eq}} n_2^{\mathrm{eq}} \right]$$

Write as a function of the yield: $Y_1 = n_1/s$ **to remove the expansion**

$$\frac{dY_1}{dt} = -s \langle \sigma v \rangle \left[Y_1 Y_2 - Y_1^{\mathrm{eq}} Y_2^{\mathrm{eq}} \right]$$

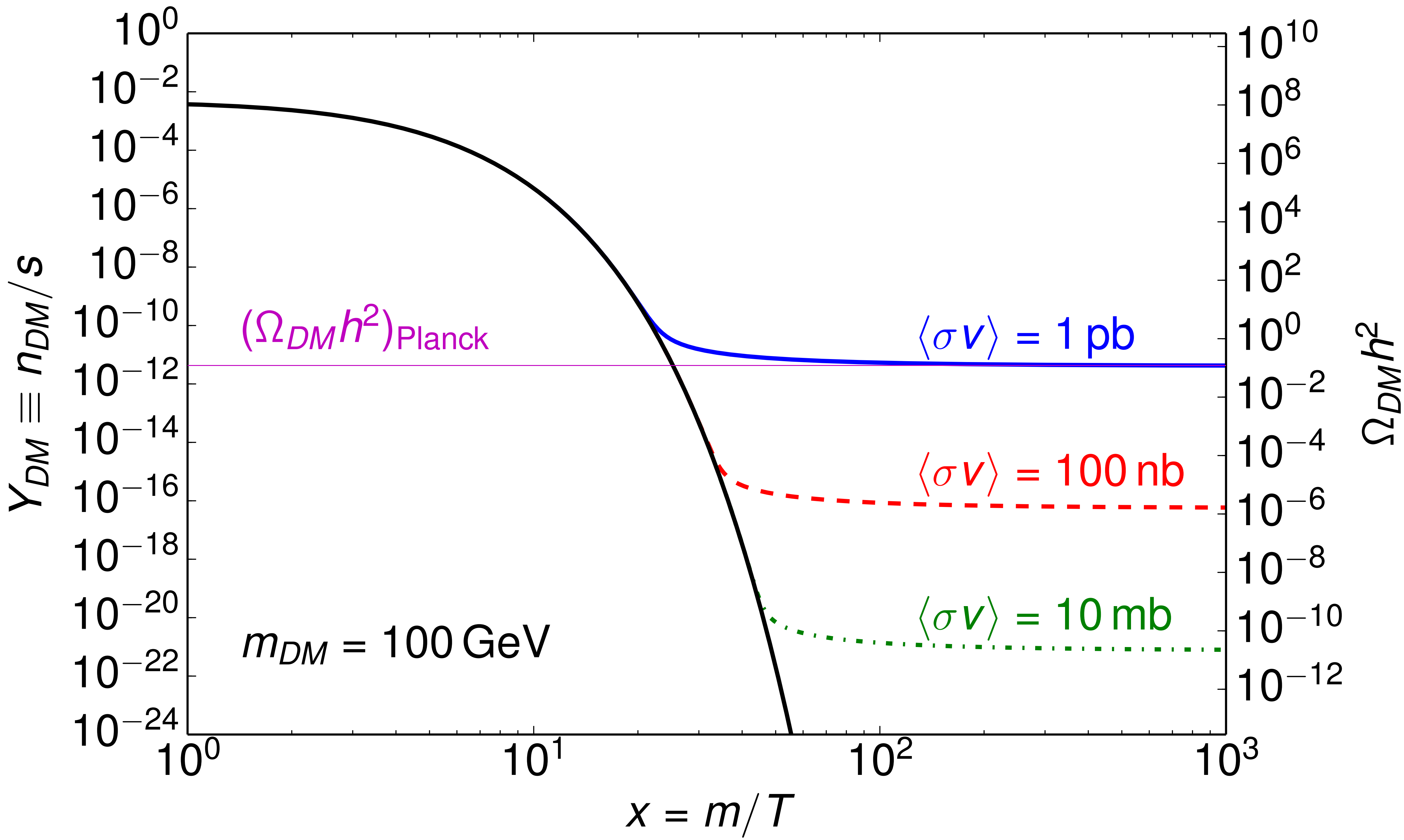
And since everything depends upon temperature:

$$\frac{dY_1}{dT} = \frac{s \langle \sigma v \rangle}{HT} \left[Y_1 Y_2 - Y_1^{\mathrm{eq}} Y_2^{\mathrm{eq}} \right]$$

Lecture IV

WIMP freeze-out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - n_\chi^2 |^{\text{eq}} \right]$$



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

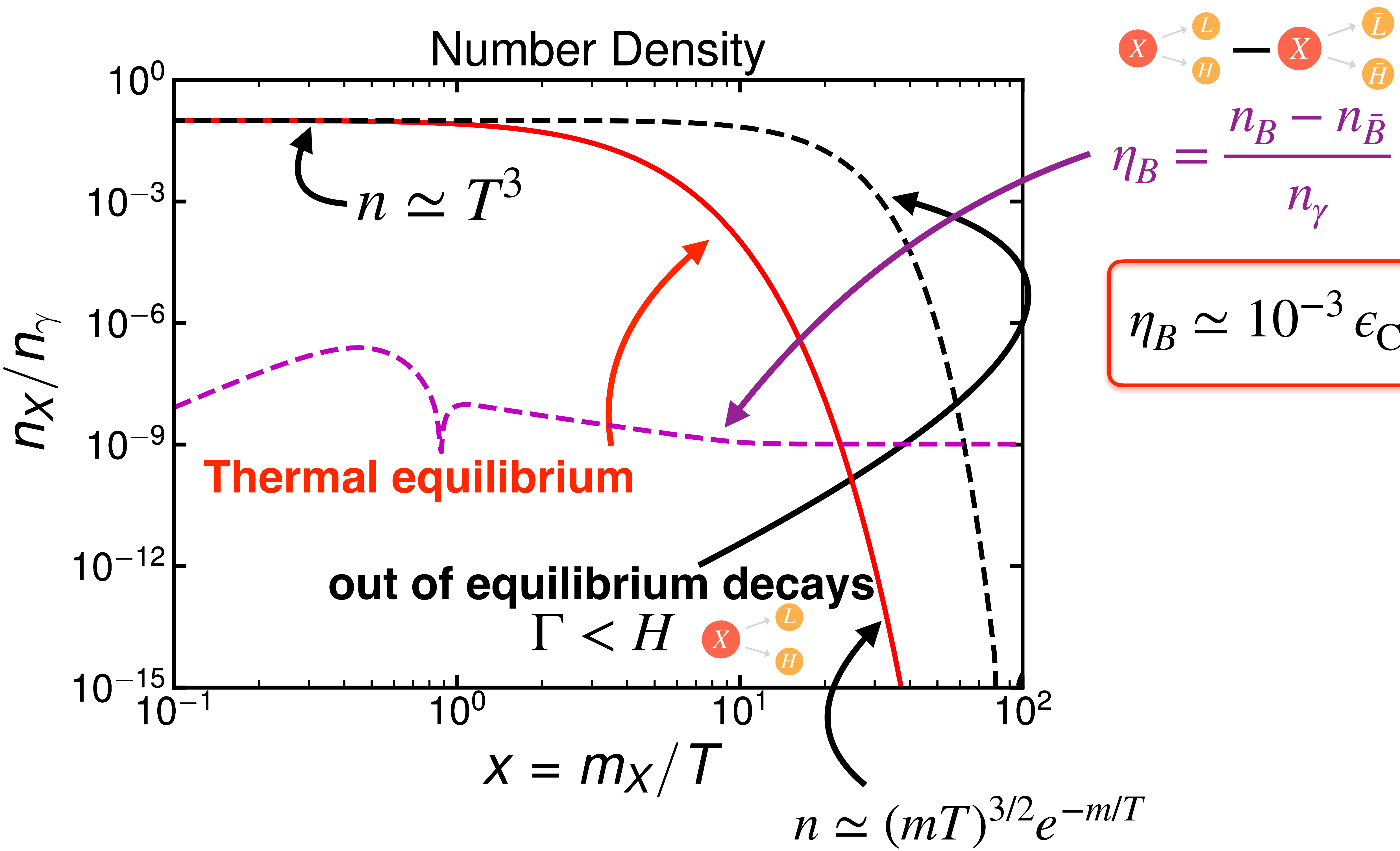
Three key requirements: The Sakharov conditions (1967)

1) C and CP violation

2) Departure from Thermal Equilibrium

3) Baryon number violation

Baryogenesis $\frac{dY_B}{dt} = + \langle \Gamma_X \rangle \epsilon (Y_X - Y_X^{\rm eq}) - 2Y_B \langle \Gamma_{\rm B-breaking} \rangle$



$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

$$\eta_B \simeq 10^{-3} \, \epsilon_{\rm CP} \, {\rm BR}$$

General BSM bounds

BSM from early Universe Cosmology

- **Any massless or light particles in your spectrum?**

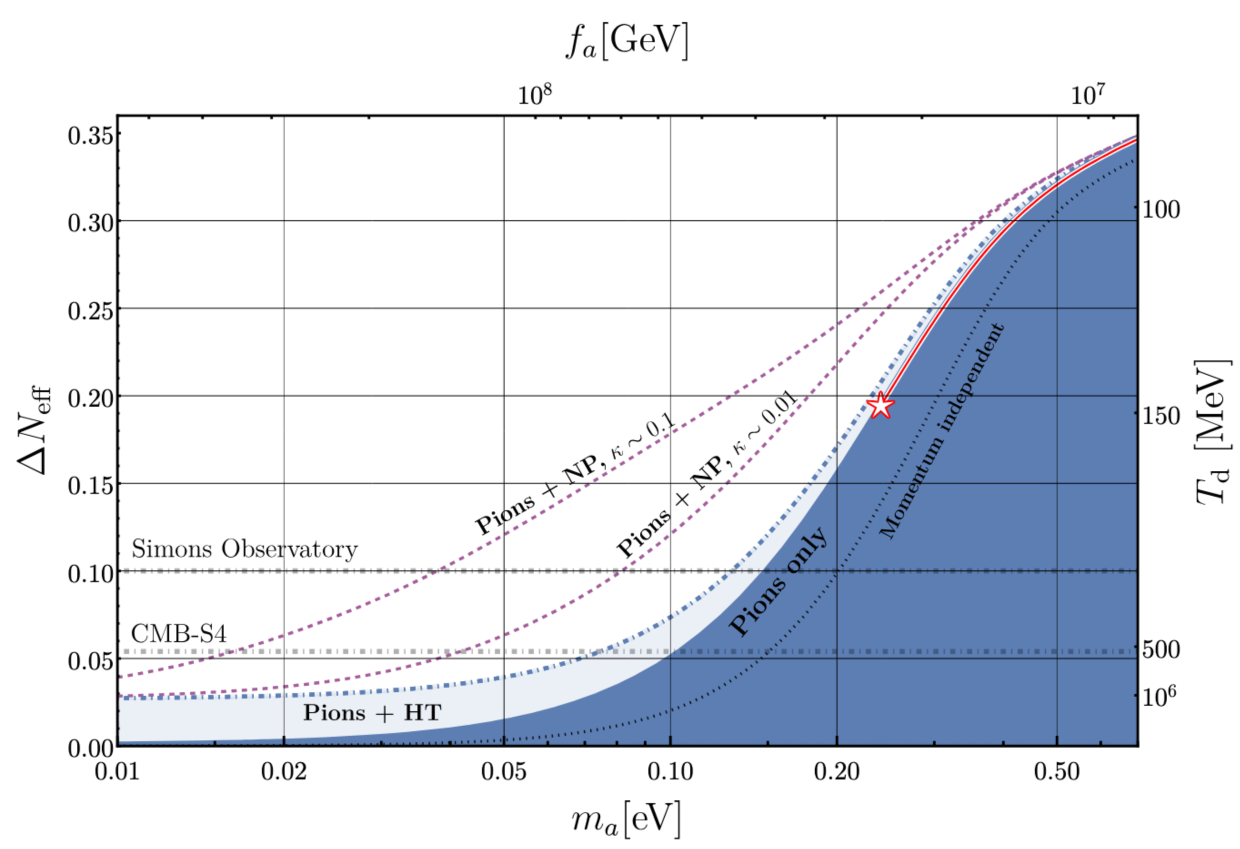
If yes, calculate their production rate

If $\mathrm{Max}[\frac{\Gamma}{H}] > 1$ **then they would have been produced abundantly**

$\Delta N_{\rm eff}$ **and hot dark matter bounds:** $\Omega_{\rm ncdm} h^2 < 0.0013$

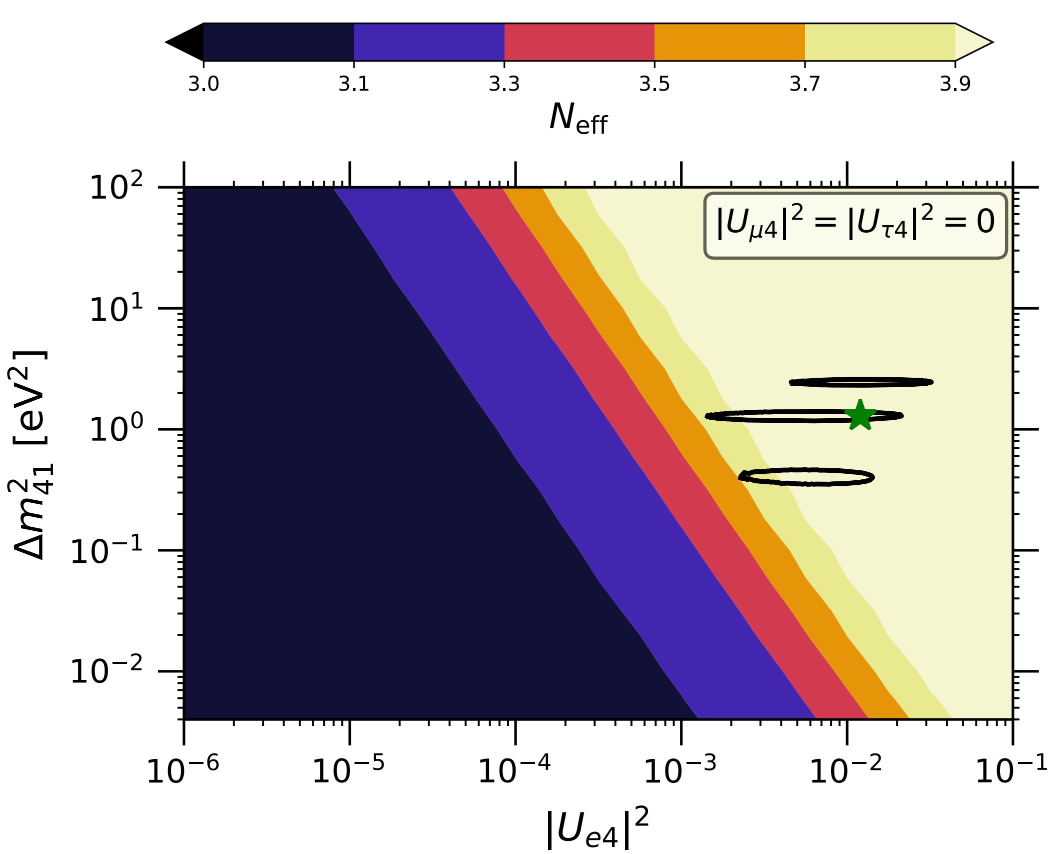
Hot Axions:

Notari, Rompineve, Villadoro [2211.03799]



eV-scale sterile neutrinos

Gariazzo, de Salas & Pastor 1905.11290



BSM from early Universe Cosmology

- **Any massive particles in the spectrum?**

Calculate their production rate and estimate their abundance.

If they are stable they contribute to dark matter, and then $\Omega_{\rm DM}h^2 \leq 0.12$

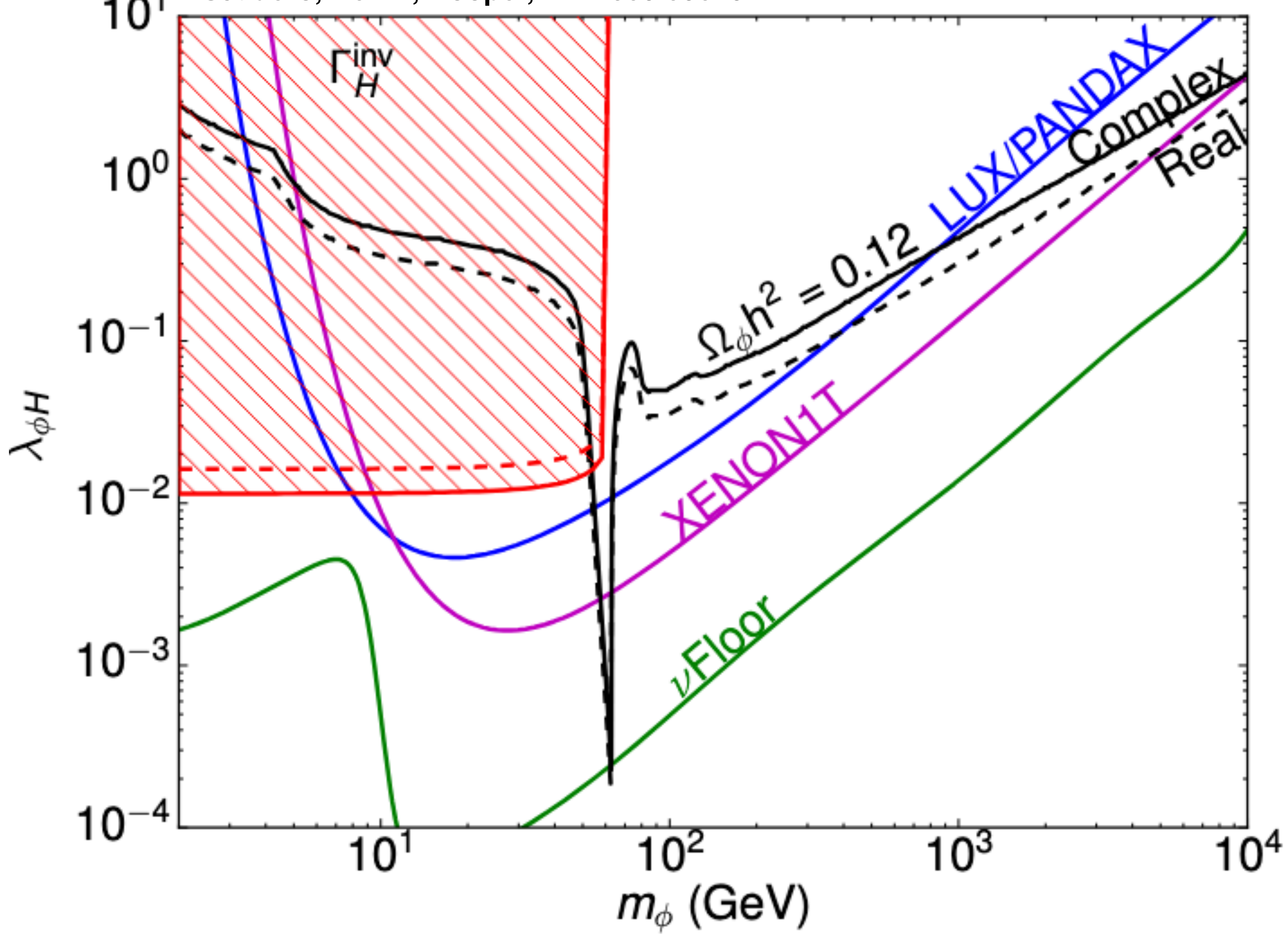
If they are not stable then they can lead to modifications of the early Universe. Either leading to theoretical inconsistencies or leading to actual bounds from BBN or the CMB

BSM from early Universe Cosmology

- **Thermal Dark Matter**

  scalar coupled to the Higgs:

Escudero, Berlin, Hooper, Lin 1609.09079

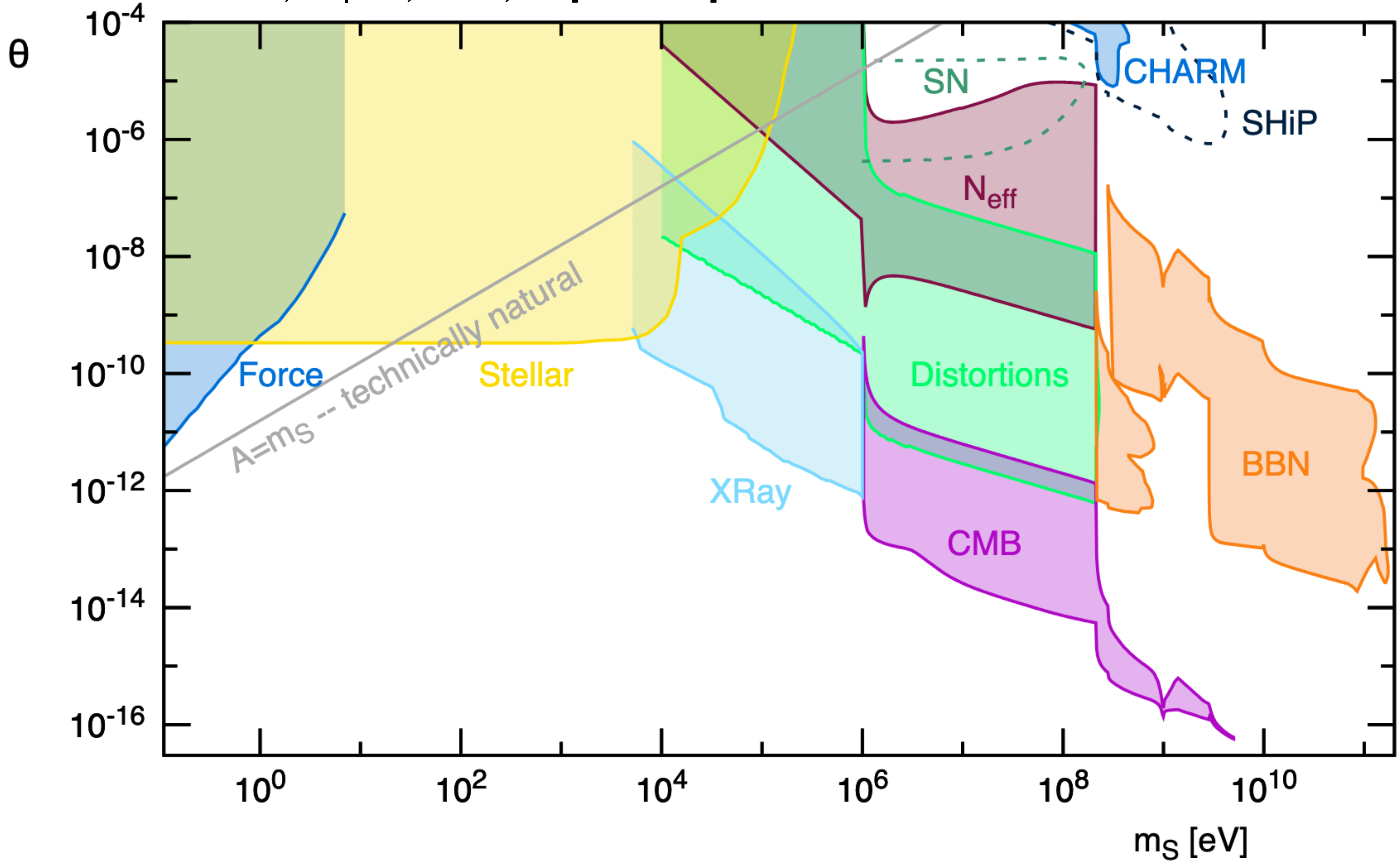


BSM from early Universe Cosmology

- **Long-lived particles**

  scalar mixed with the Higgs:

Fradette, Pospelov, Pradler, Ritz [1812.07585]

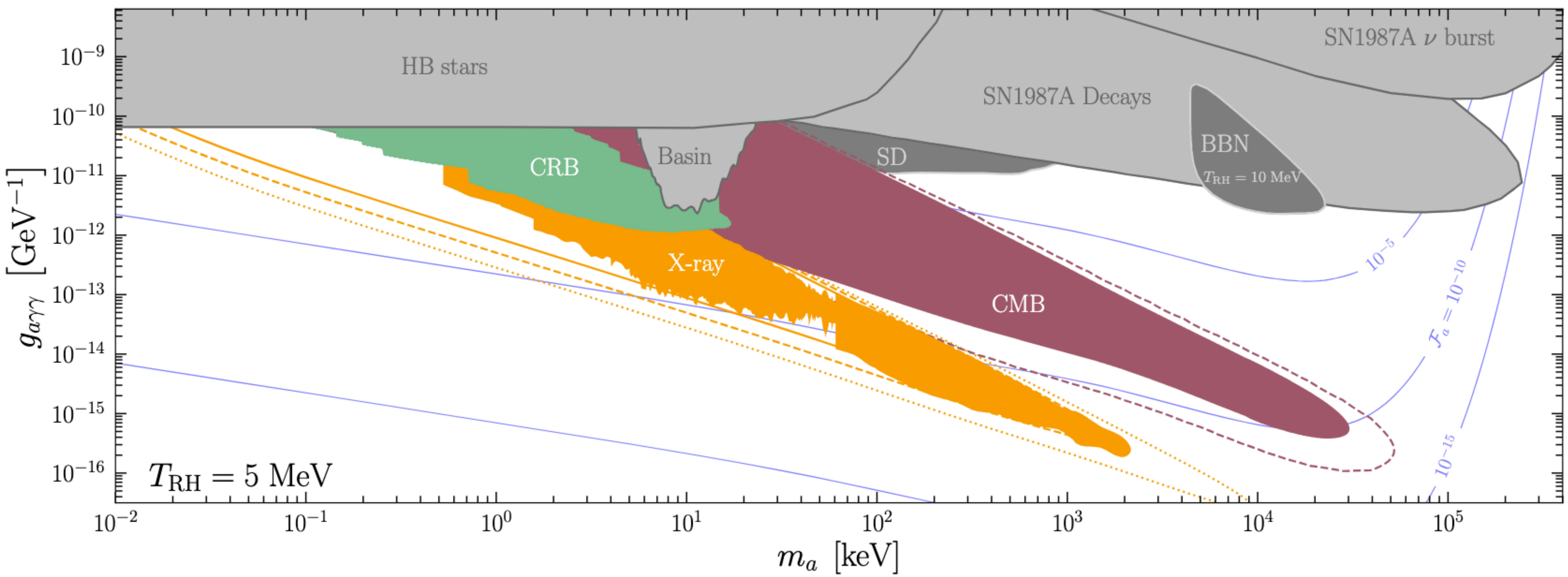


BSM from early Universe Cosmology

- **Long-lived particles**

  ALP

Langhoff, Outmezguine, Rodd [2209.06216]



BSM from early Universe Cosmology

- **Long-lived particles**

  Gravitinos

Kawasaki, Kohri, Moroi [astro-ph/0408426]