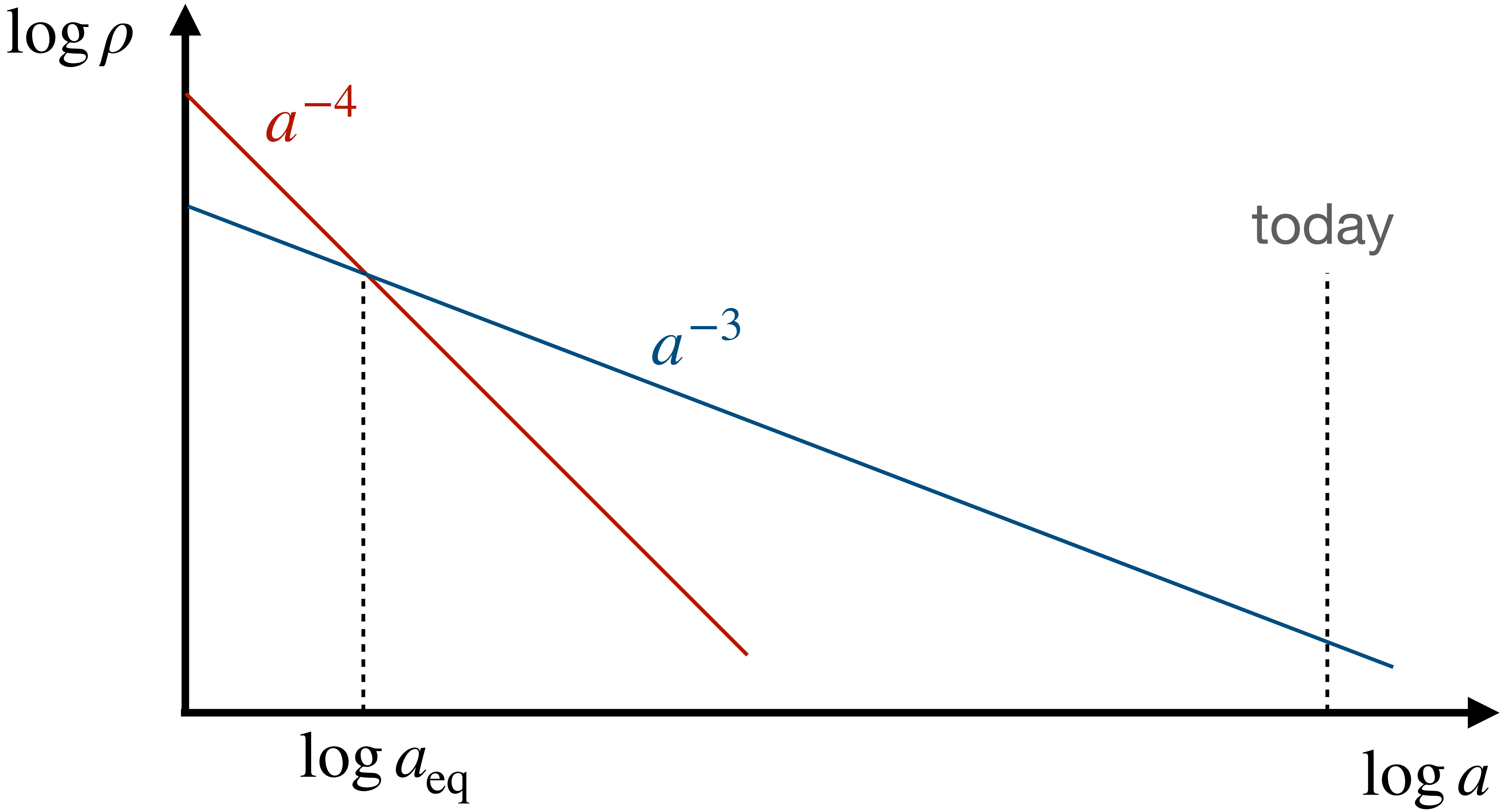
Cosmology

Lecture 2

Hot Big Bang



Luminosity distance and deceleration

Luminosity distance

$$F \equiv \frac{L}{4\pi d_L^2} = \frac{L}{4\pi(1+z)^2 r^2} \qquad \longrightarrow \qquad d_L = (1+z)\int_0^z \frac{dz'}{H(z')}$$

Expanding around $z = 0$ we find

$$d_L = \frac{z}{H_0}\left(1 + \frac{1}{2}(1-q_0)z + \cdots\right) \qquad q(t) \equiv -\frac{\ddot{a}a}{\dot{a}^2}$$

For $\rho + 3p > 0$ we have $\ddot{a} < 0$ and $q_0 > 0$

Luminosity distance and deceleration

Observations give $q_0 < 0$

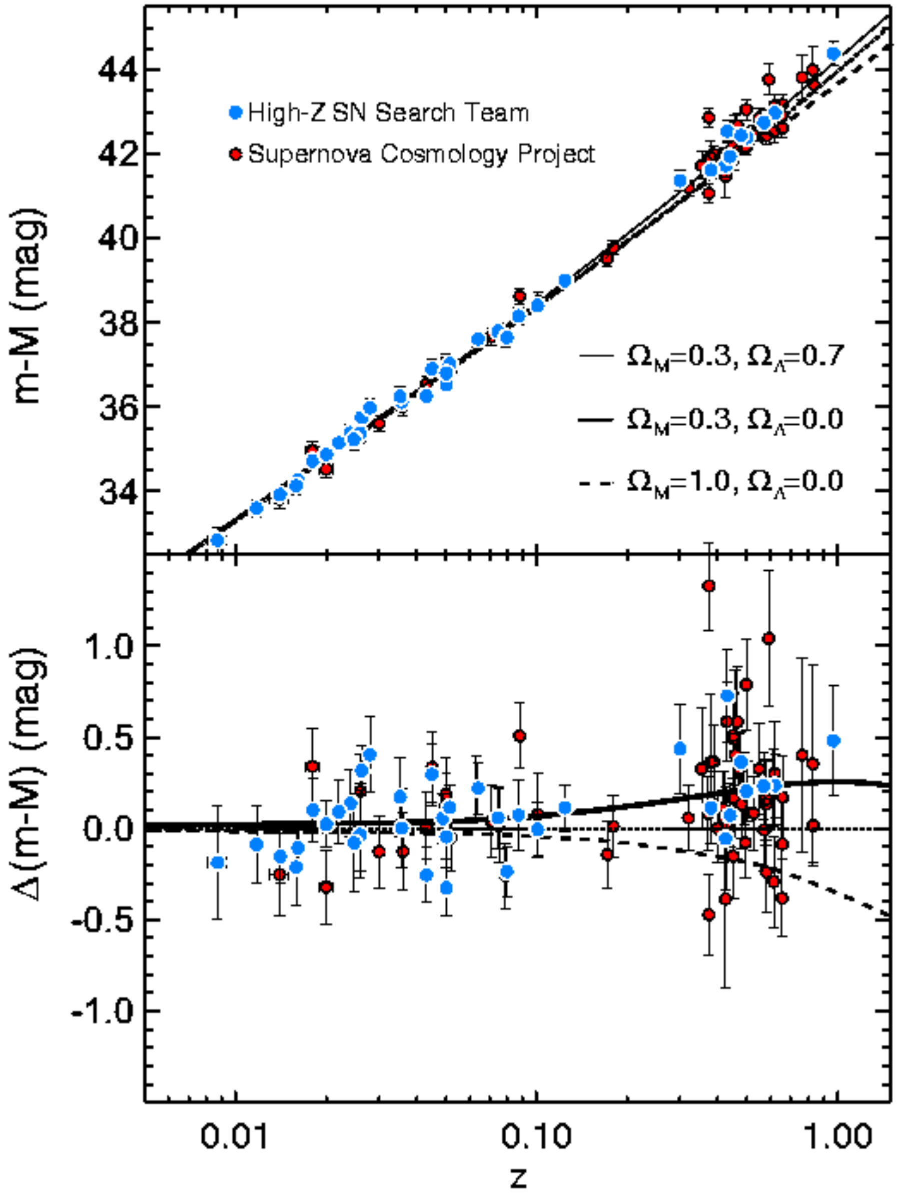
Only possible for $\rho + 3p < 0$

Natural candidate is vacuum energy

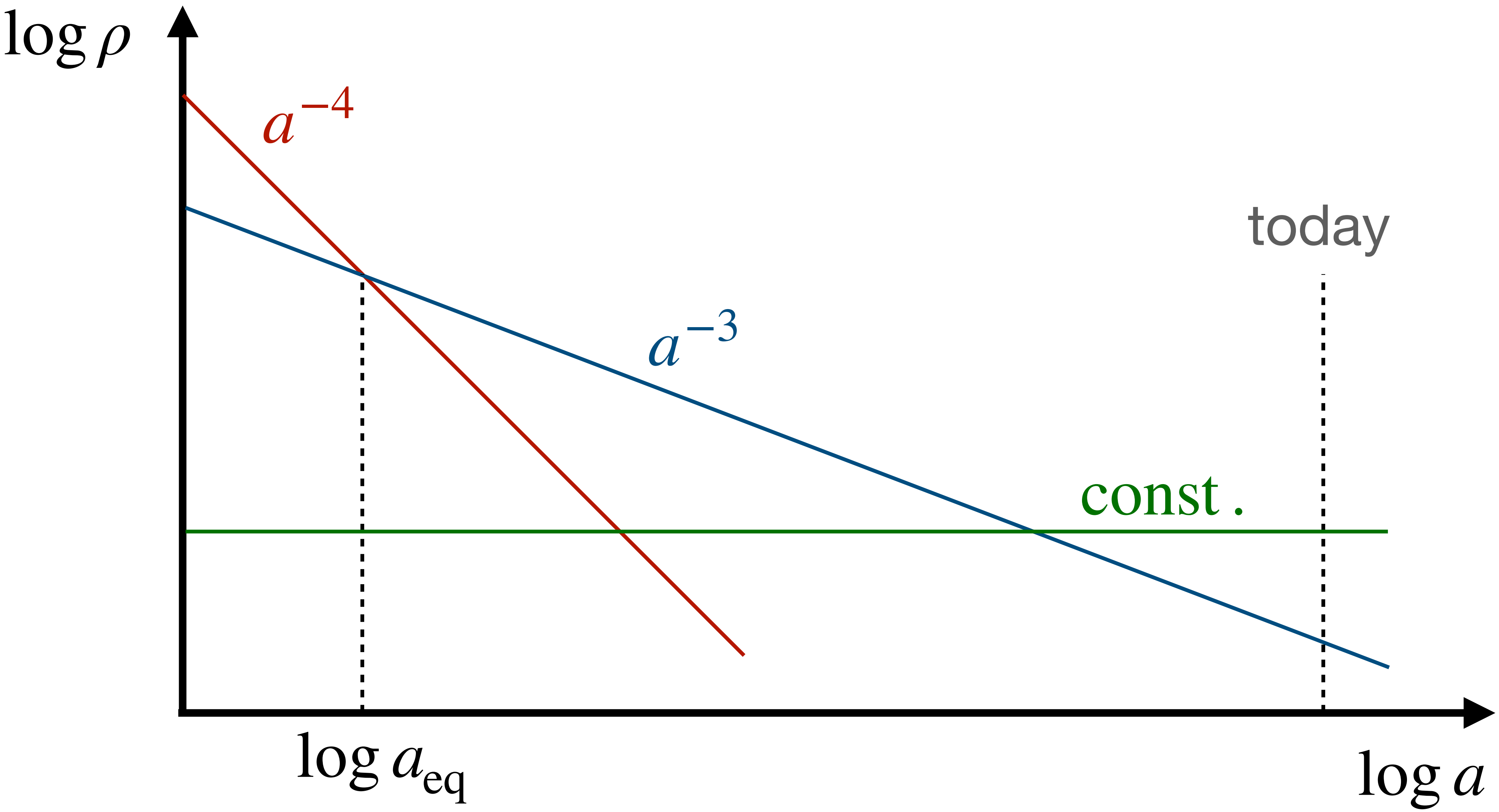
$$\rho = \text{const.} \qquad p = -\rho$$

$$\Omega_{\mathrm{m},0} \approx 0.3 \qquad \Omega_\Lambda \approx 0.7$$

This is Λ in ΛCDM cosmological model



Vacuum energy and its puzzles



Vacuum energy dominates the energy budget today!

Vacuum energy and its puzzles

Observed energy density of the vacuum is $\rho_\Lambda \approx (10^{-3}\ \mathrm{eV})^4$

We could never do it in a laboratory

O(100) orders of magnitude smaller than the naive expectations

Similar to the hierarchy problem, but much worse…

Resolution may have dramatic consequences:

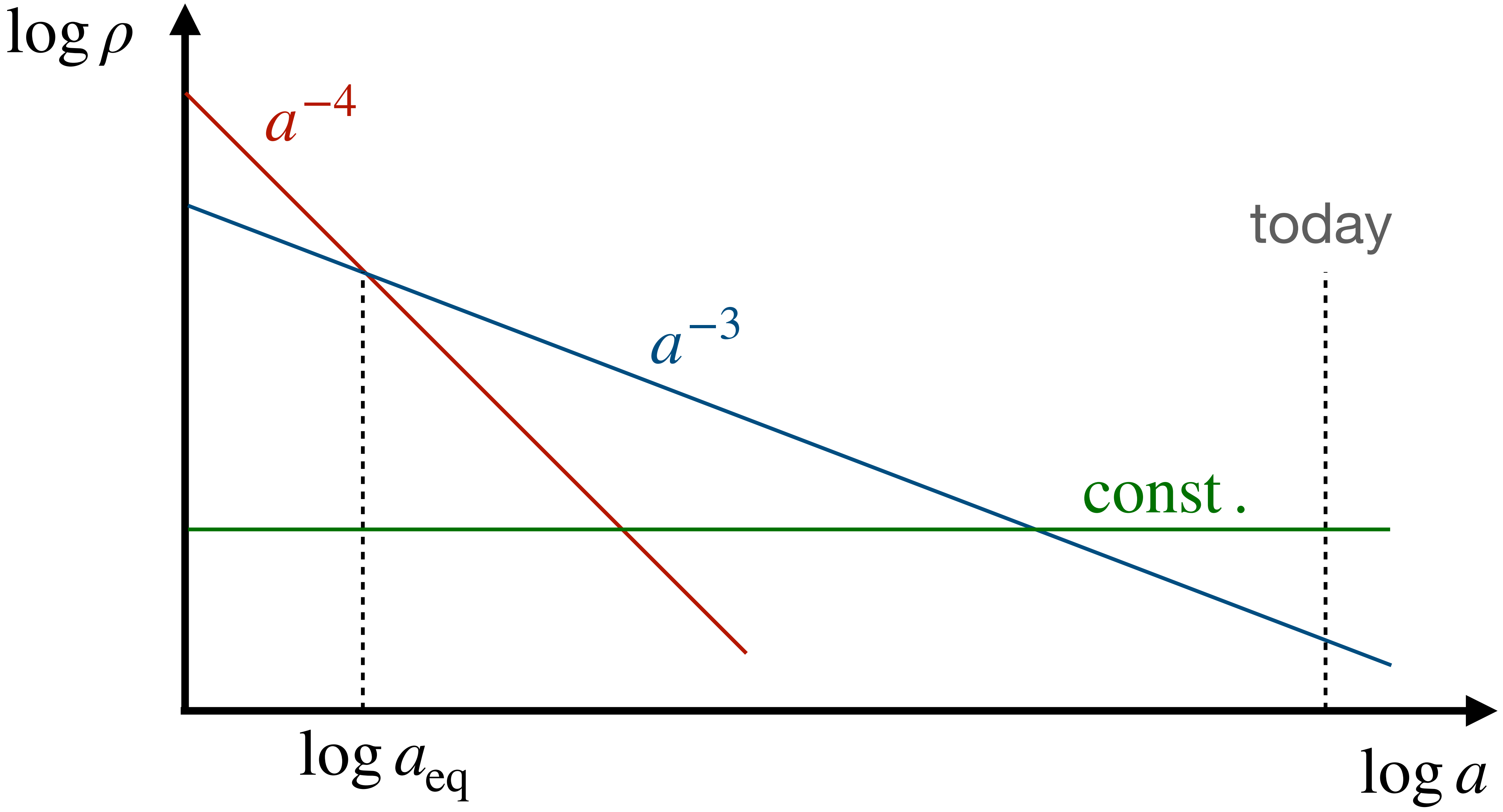
Multiverse and anthropic principle

Giving up EFT paradigm

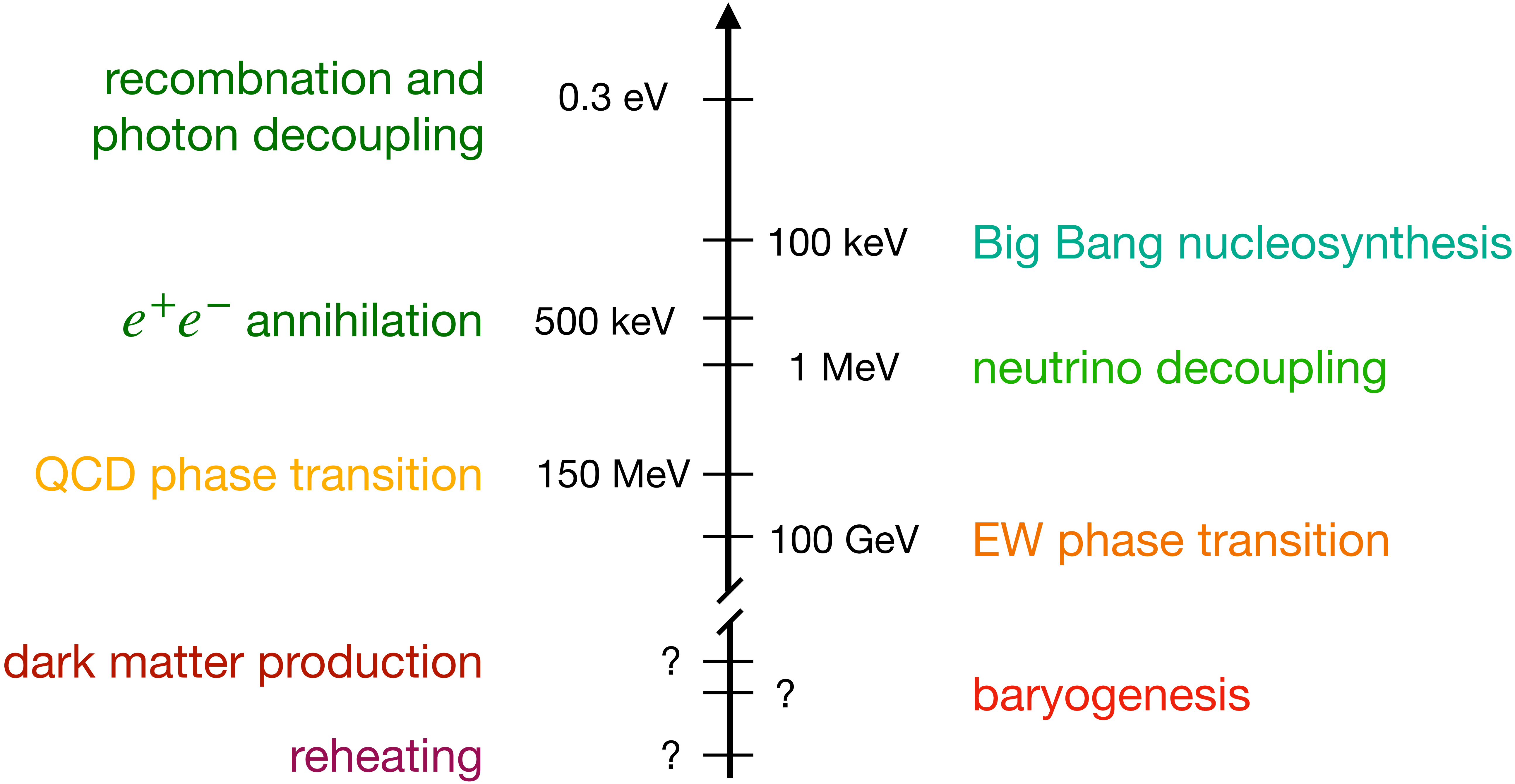
Landscape vs. swampland

…

All energy components



Thermal history of the universe



recombnation and
photon decoupling

0.3 eV

100 keV

Big Bang nucleosynthesis

e^+e^- annihilation

500 keV

1 MeV

neutrino decoupling

QCD phase transition

150 MeV

100 GeV

EW phase transition

dark matter production

?

?

baryogenesis

reheating

?

Part 2

Equilibrium thermodynamics in the early universe

Neutrino decoupling and cosmic neutrino background

Boltzmann equation and freeze-out

Big Bang nucleosynthesis

Cosmic Microwave Background

Implications for dark matter and matter-antimatter asymmetry

Equilibrium quantities

Homogeneous plasma in termal equilibrium

$$n = \frac{g}{(2\pi)^3}\int d^3p f(p)$$

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

$$P = \frac{g}{(2\pi)^3}\int d^3p \frac{p^2}{3E(p)} f(p)$$

Distribution function

$$f(p) = \frac{1}{e^{(E-\mu)/T} \pm 1} \xrightarrow{T \ll E-\mu} f(p) = e^{-(E-\mu)/T}$$

+ fermions, - bosons

Equilibrium quantities

Relativistic particles

$$n = \frac{\zeta(3)}{\pi^2} g T^3 \qquad \rho = \frac{\pi^2}{30} g T^4 \qquad P = \frac{1}{3}\rho$$

x 3/4 for fermions

x 7/8 for fermions

$$H^2 \sim \frac{T^4}{M_{\text{pl}}^2} \quad \longrightarrow \quad \frac{T}{1\ \text{MeV}} \approx \left(\frac{1\ \text{sec}}{t}\right)^{1/2}$$

Non-relativistic particles

$$n = g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-\frac{m-\mu}{T}} \qquad \rho = nm$$

Equilibrium quantities

Entropy density $$s \equiv \frac{S}{V} = \frac{\rho + P}{T} = \frac{2\pi^2}{45} g T^3$$

Entropy S is conserved in equilibrium → $s \sim a^{-3}$

Useful to trace temperature throughout thermal history

What can particles do?

Expansion of the universe changes temperature

Decoupling

Departure from thermal equilibrium

expansion rate H vs $\Gamma = \frac{dN_{\mathrm{int}}}{dt} = n\sigma v$

interaction cross section

Neutrino decoupling

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

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

Estimate of the cross section $\sigma \sim G_F^2 T^2 \rightarrow \Gamma \sim G_F^2 T^5$

$$\frac{\Gamma}{H} \sim \left(\frac{T}{1\ \mathrm{MeV}}\right)^3$$

Below 1MeV interactions stop and neutrinos decouple

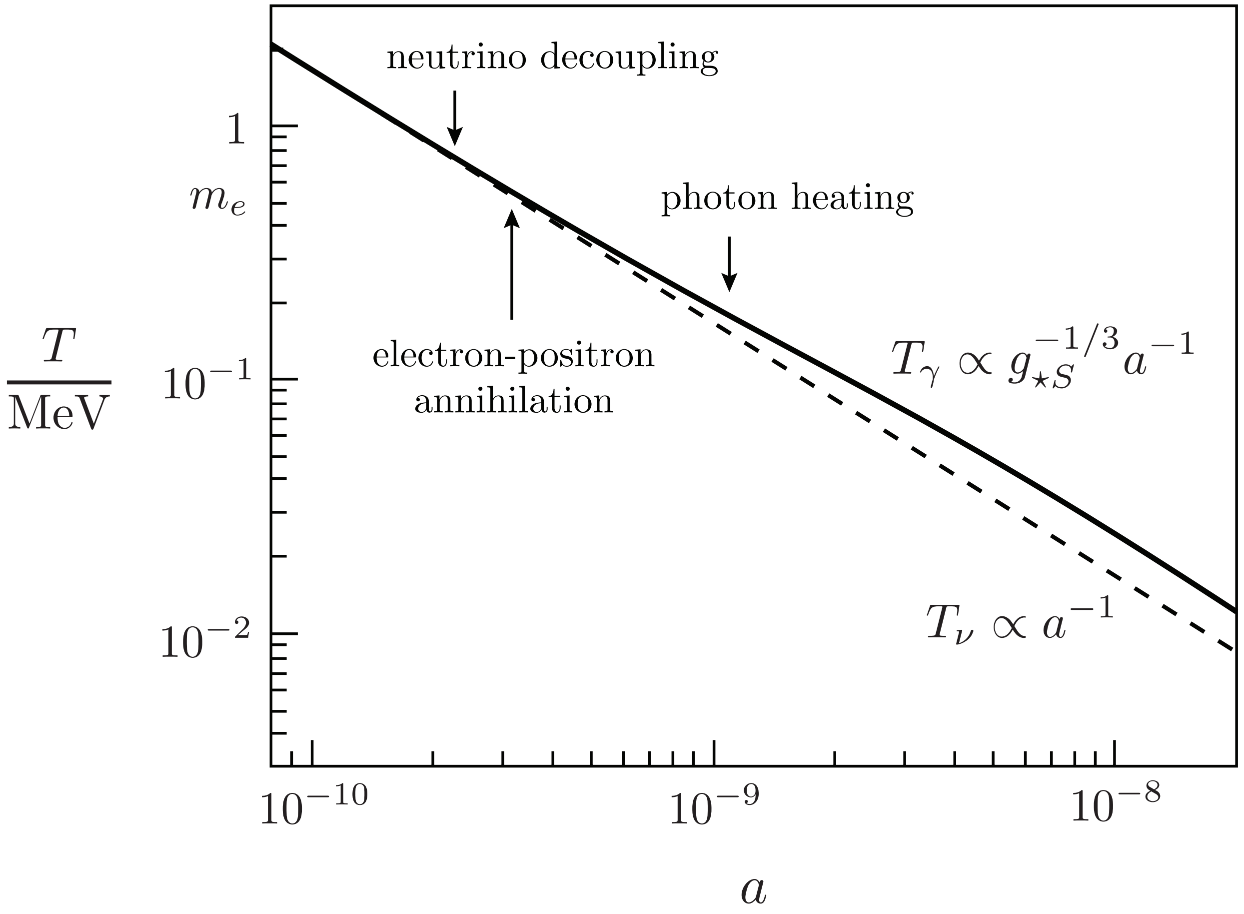
e^+e^- annihilation

Entropy conservation

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

credit D. Baumann

$$e^- + e^+ \leftrightarrow \gamma + \gamma$$

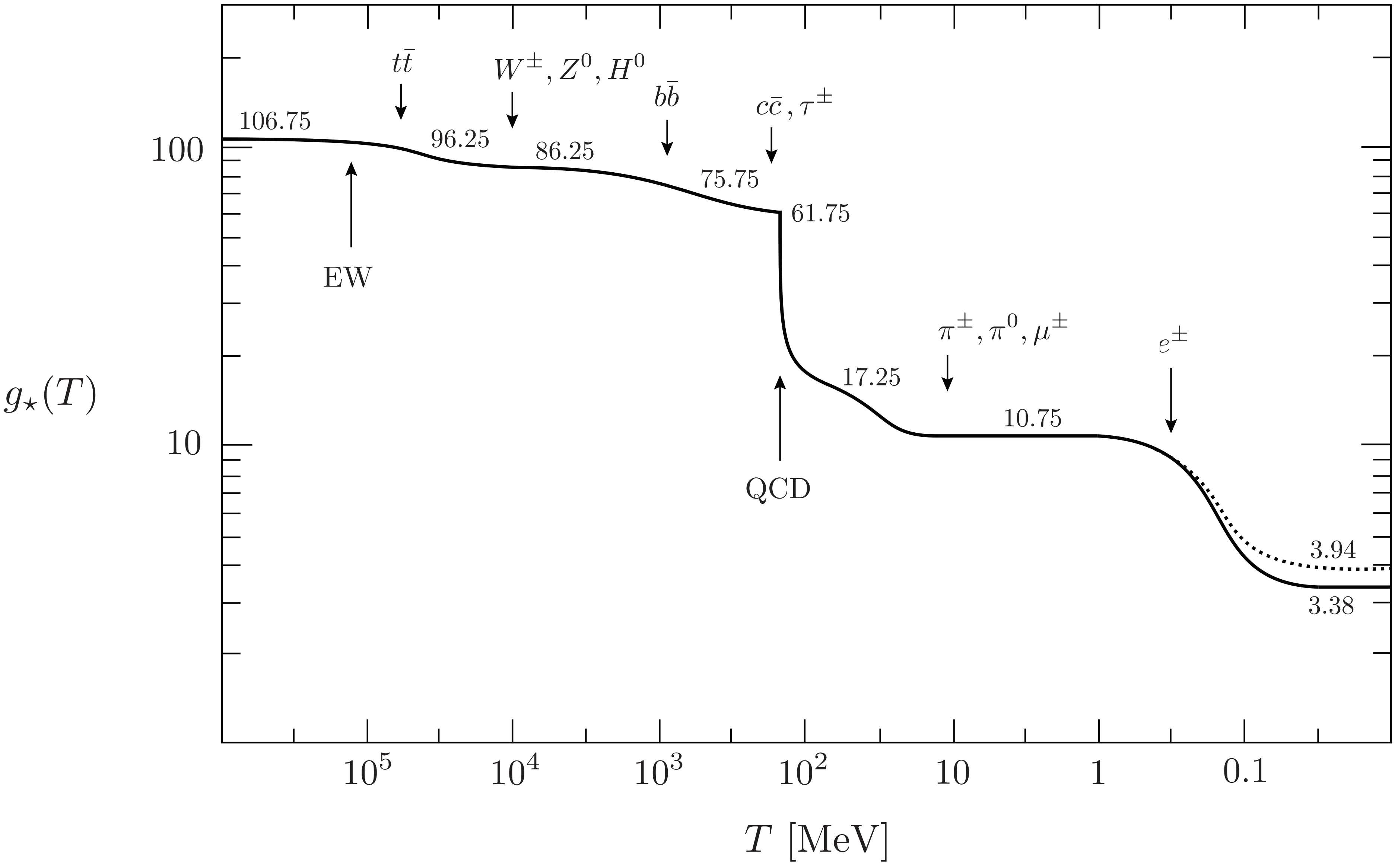


Cosmic neutrino background ~300 neutrinos per cm³

Neutrinos are massive $\Omega_\nu > 0.001$

Effective number of dof

credit D. Baumann



$$g_\star^{th}(T) = \sum_{i=b} g_i + \frac{7}{8} \sum_{i=f} g_i$$

$$g_\star^{dec}(T) = \sum_{i=b} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=f} g_i \left(\frac{T_i}{T}\right)^4$$

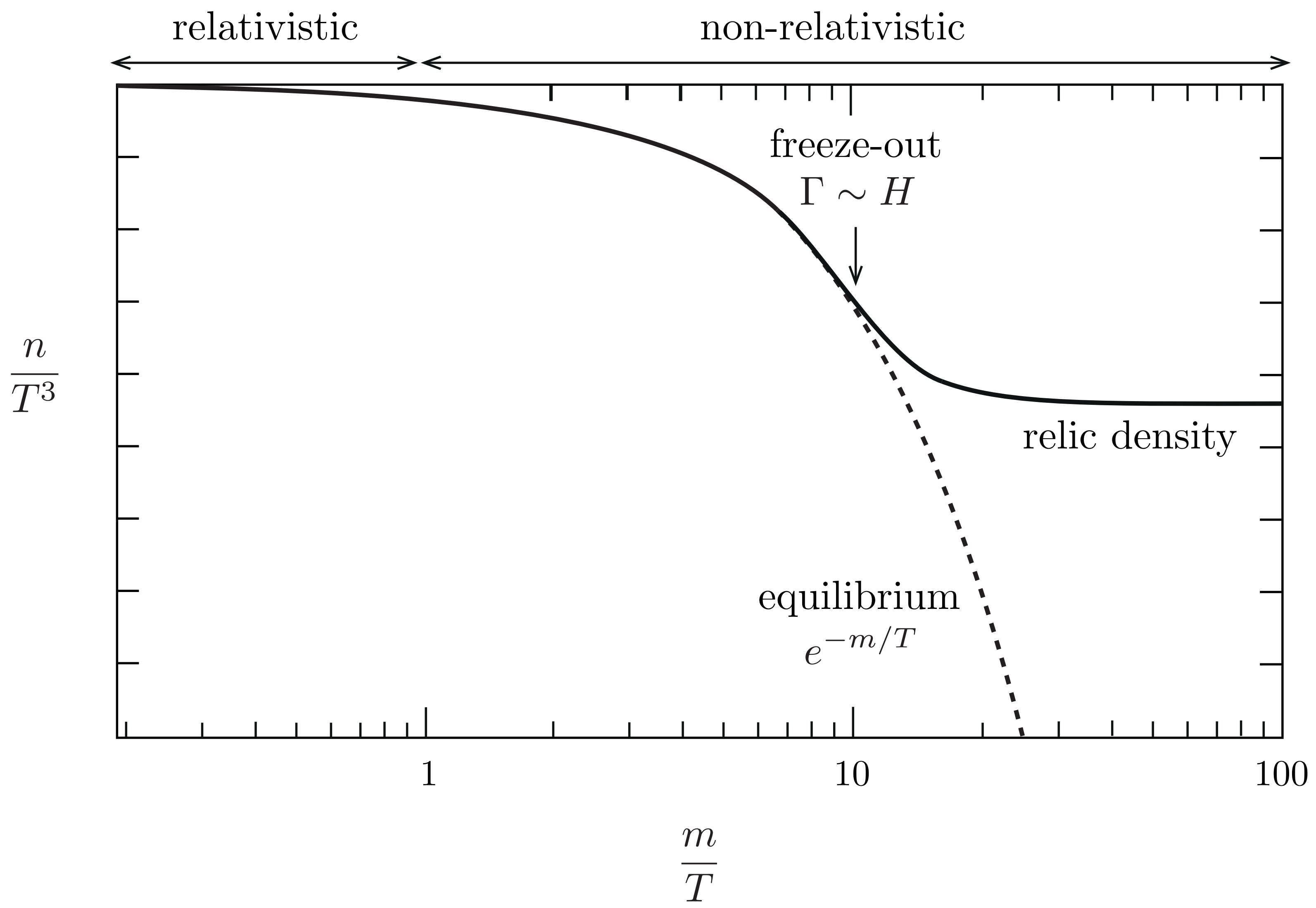
Beyond equilibrium

Boltzmann equation

$$\frac{d\ln N_1}{d\ln a} = -\frac{\Gamma_1}{H}\left[1 - \left(\frac{N_1 N_2}{N_3 N_4}\right)_{\rm eq} \frac{N_3 N_4}{N_1 N_2}\right]$$

$$N_i \equiv \frac{n_i}{s}$$

credit D. Baumann



Relics from
high energies!

Two major predictions of Hot Big Bang

Primordial nucleosynthesis

- Origin and primordial abundance of chemical elements

Cosmic Microwave Background

- Relic leftover radiation after the universe becomes transparent

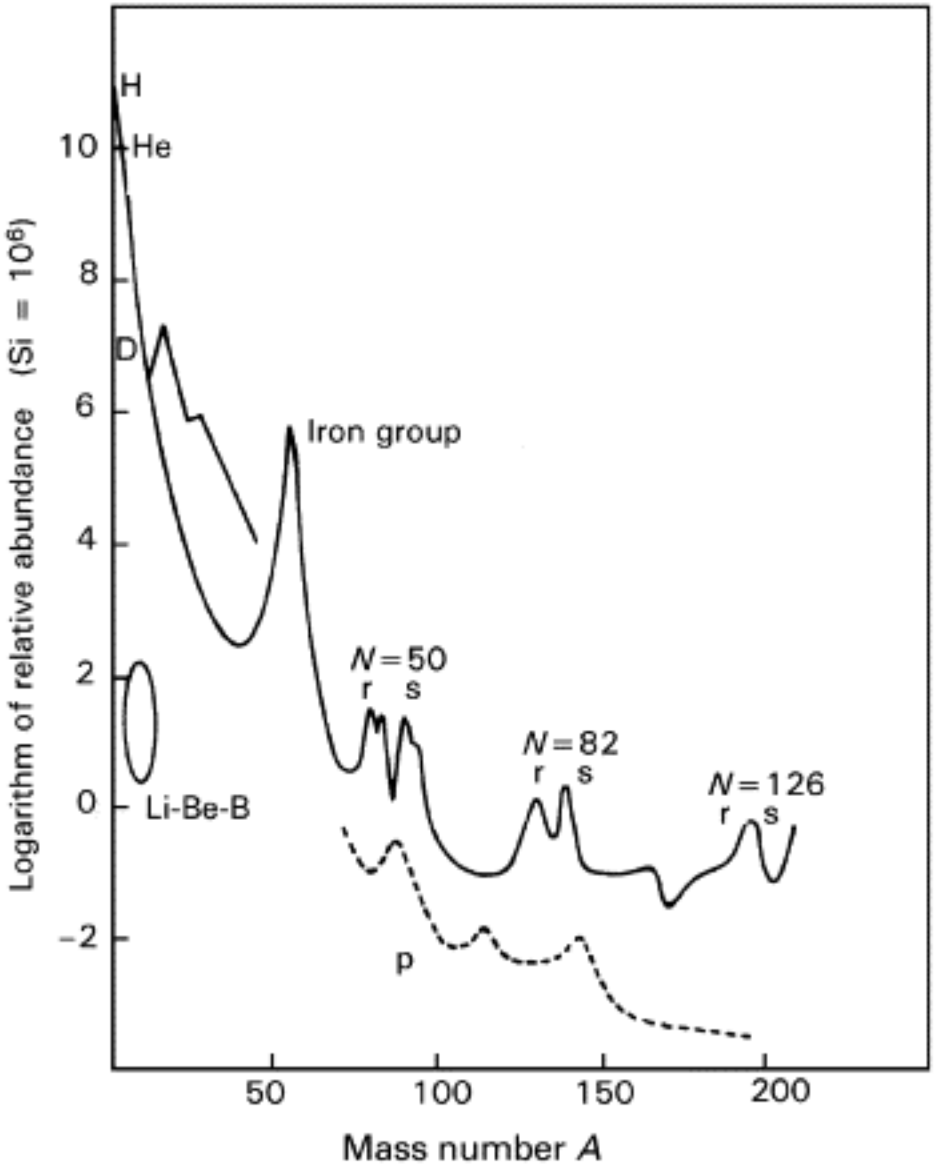
Primordial nucleosynthesis

Astronomical observations:

$$\frac{n_{\mathrm{He}}}{n_{\mathrm{H}}} \sim \frac{1}{16}$$

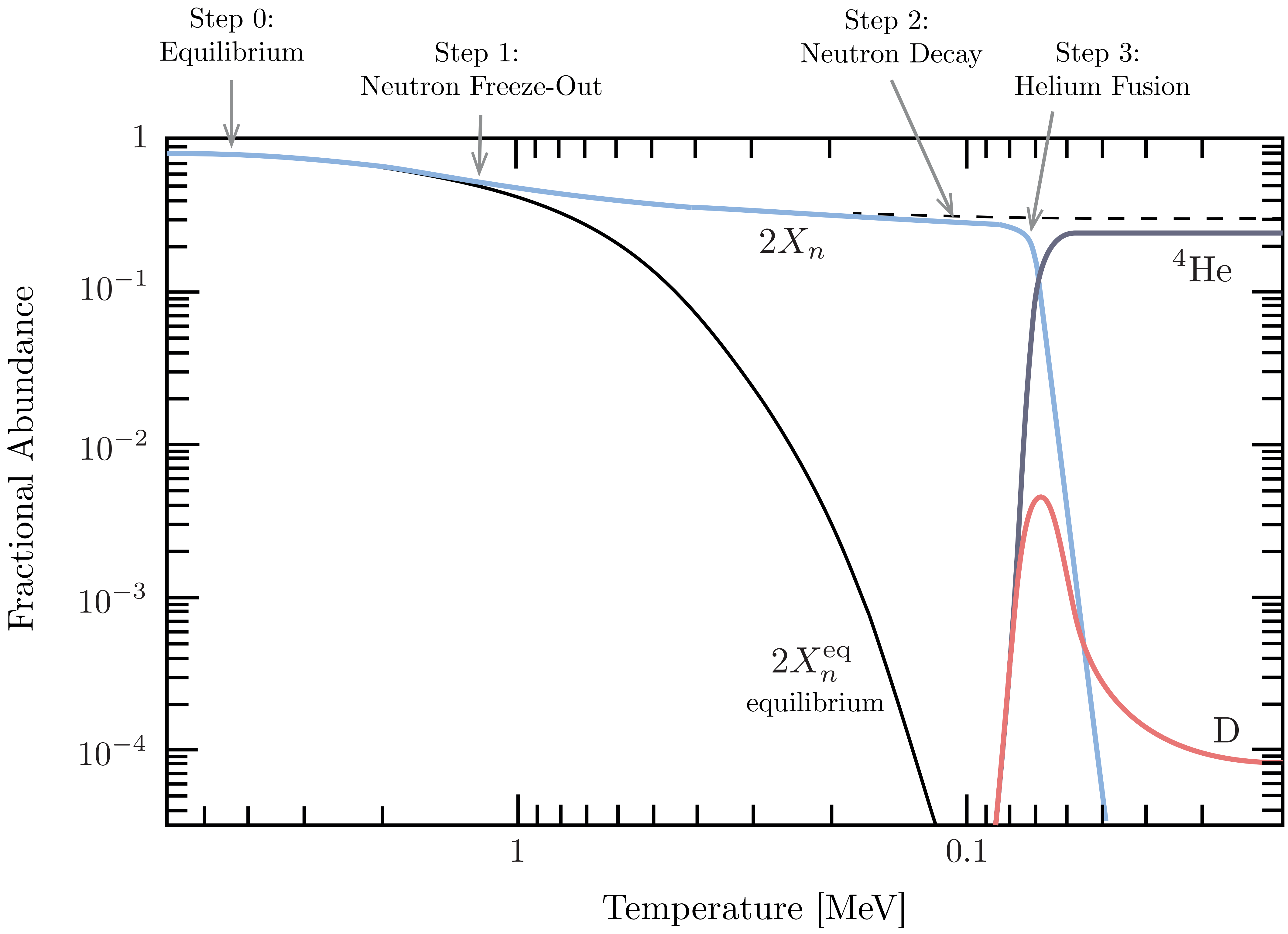
(all other elements in traces)

Why no heavier elements?



Primordial nucleosynthesis

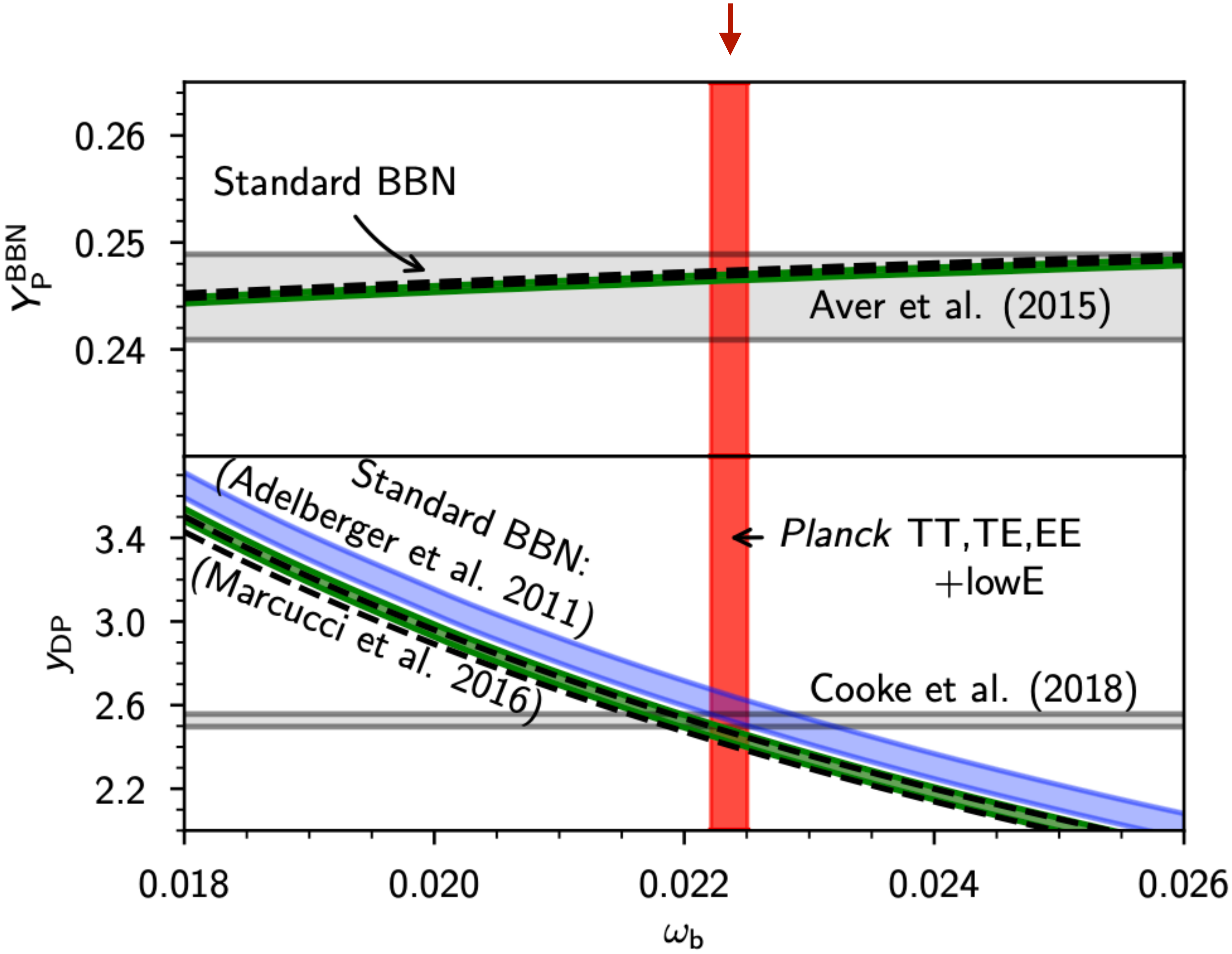
credit D. Baumann



Primordial nucleosynthesis

$$\eta_b \approx 5 \cdot 10^{-10}$$

Planck (2018)



Cosmic Microwave Background

Above energies of ~0.3 eV the universe is filled with plasma

$$e^- + p^+ \quad \leftrightarrow \quad \mathrm{H} + \gamma$$

$$e^- + \gamma \quad \leftrightarrow \quad e^- + \gamma$$

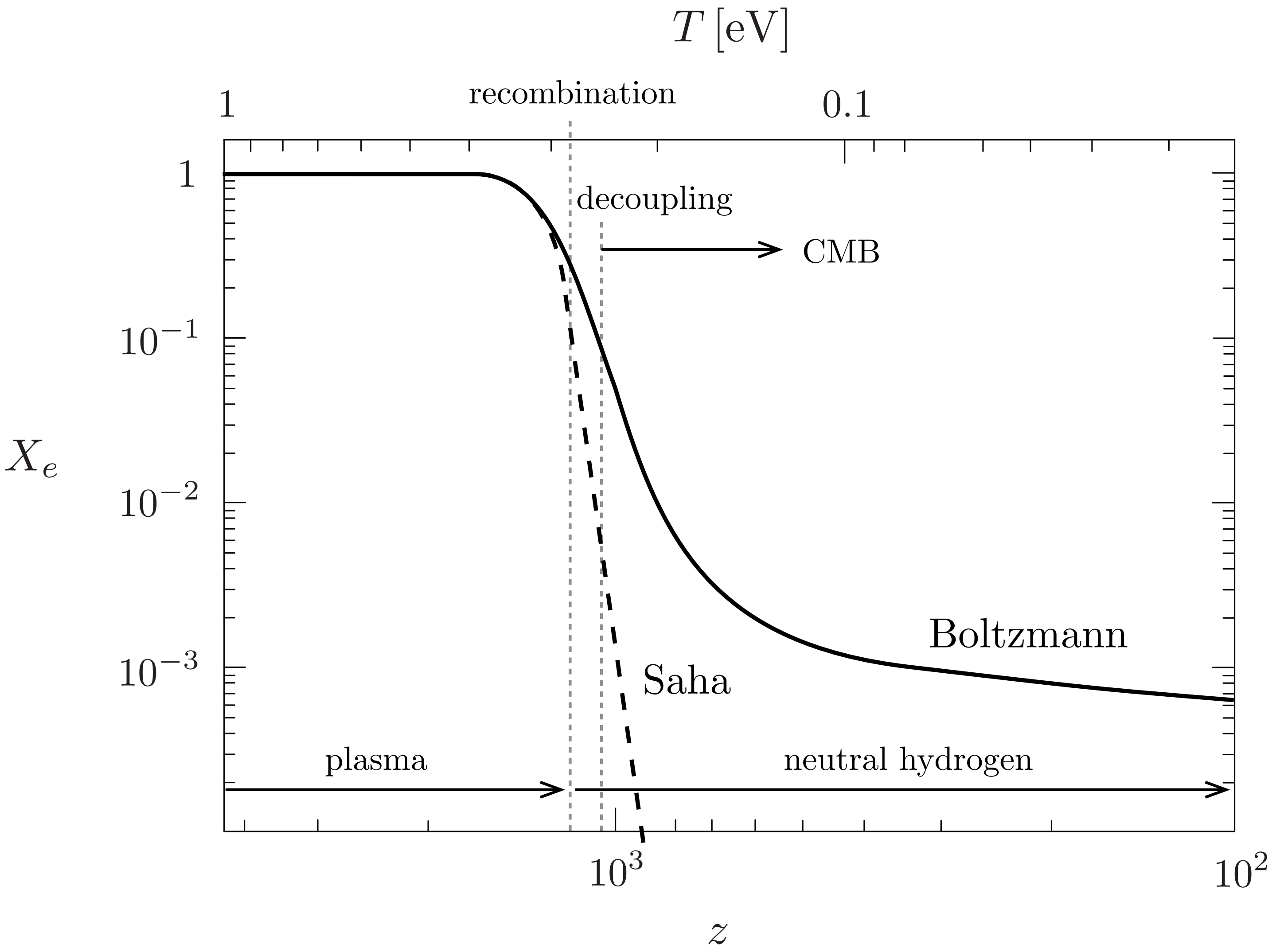
Eventually H atoms form

recombination

Soon after photons decouple

photon decoupling

credit D. Baumann



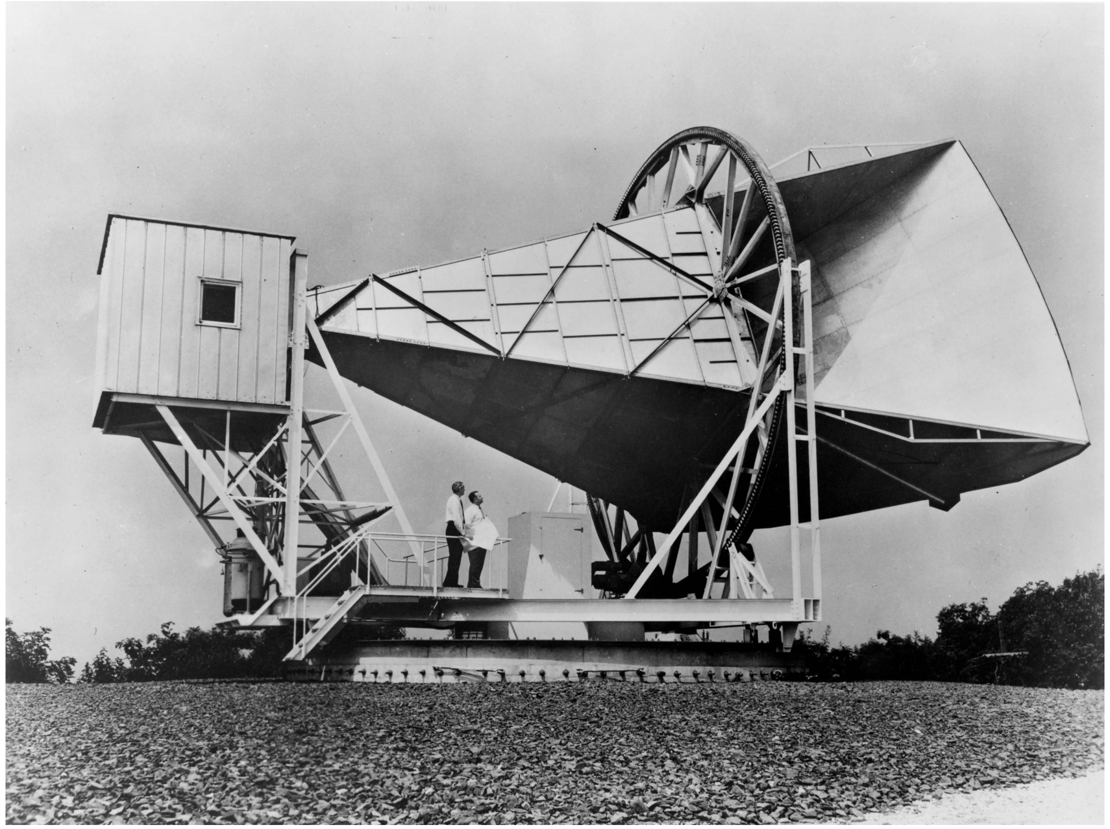
Cosmic Microwave Background

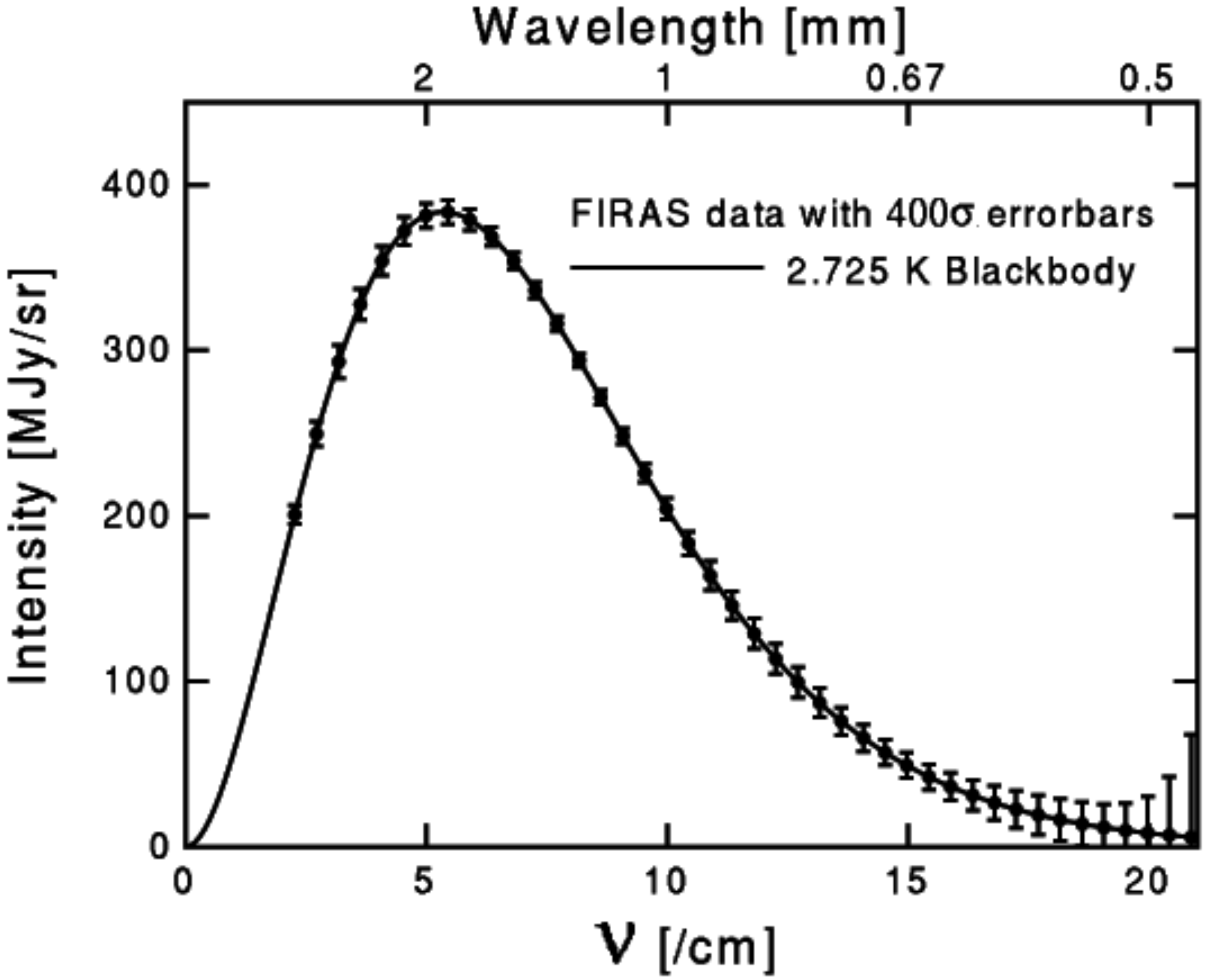
CMB forms at redshift z~1100

Temperature of the photons today ~2.7 K

COBE (1992)

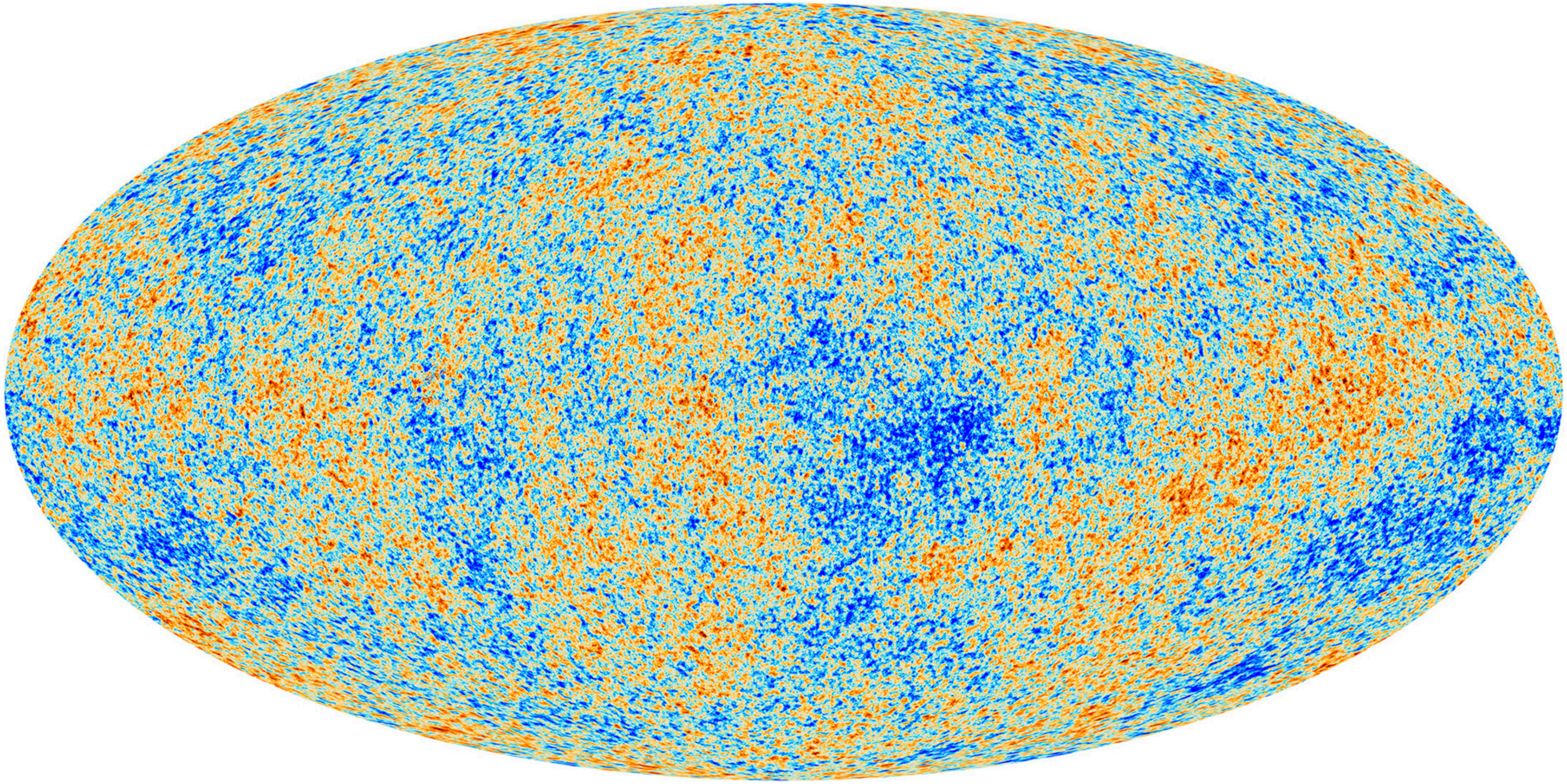
Penzias and Wilson (~1965)





Cosmic Microwave Background

Planck satellite, 2018



Implications of large η_b

Sakharov conditions for baryogenesis

$\cancel{B}$

$\cancel{C}$

$\cancel{CP}$

~~equilibrium~~

In SM possible in principle, but η_b is way too small

New physics must operate in the early universe to create this large matter-antimatter asymmetry!

Implications of large η_b

CMB temperature gives number density of photons

Given η_b we can compute number density of baryons

Not enough baryons for structure formation!

$$\Omega_{\mathrm{b},0} \approx 0.05$$

The rest of matter must be non-baryonic. Can it be neutrinos? No

We need non-baryonic cold dark matter (CDM in $\Lambda\mathrm{CDM}$)