§1 Introduction

1.1 Units and conventions

Will use <u>natural units:</u> $c = \hbar = k_B = 1$

$\Rightarrow$ $[\text{mass}] = [\text{momentum}] = [\text{temperature}]$

$$= [\text{energy}] = \text{GeV}$$

Conversion: $1\ \text{GeV} = 1.8 \cdot 10^{-24}\ \text{g} = 1.2 \cdot 10^{13}\ \text{K}$

$$[\text{time}] = [\text{distance}] = [\text{energy}^{-1}] = \text{GeV}^{-1}$$

Conversion: $1\ \text{GeV}^{-1} = 2.0 \cdot 10^{-14}\ \text{cm} = 6.6 \cdot 10^{-25}\ \text{s}$

$\Rightarrow$ Newton's constant of gravity:

$$G = 6.67 \cdot 10^{-11}\ \frac{\text{m}^3}{\text{kg} \cdot \text{s}^2} = 6.71 \cdot 10^{-39}\ \text{GeV}^{-2}$$

Convenient to write $G = M_{pl}^{-2}$ with

$$\boxed{M_{pl} = 1.22 \cdot 10^{19}\ \text{GeV} \qquad (\text{Planck mass})}$$

Will sometimes need astrophysical units

$1\ \text{pc} = 3.1 \cdot 10^{18}\ \text{cm}$ $\qquad$ $1\ M_\odot = 1.99 \cdot 10^{30}\ \text{kg}$

1.2 The present universe

Observations:

- At sufficiently large scales, universe is homogeneous & isotropic

  homogeneous: same everywhere

  isotropic: same in every direction

- The universe expands

  ↳ galaxies "move away" from us

  $\Rightarrow$ Doppler effect: $\lambda_{ab} > \lambda_{em}$

  (λ_{ab}: absorption, λ_{em}: emission)

  Define redshift $z = \dfrac{\lambda_{ab}}{\lambda_{em}} - 1$

  ↳ Hubble's law: $z \overset{z \ll 1}{=} H_0 \cdot r$

  with $H_0 \approx 67 \pm 1 \ \dfrac{km}{s \cdot Mpc}$

  H_0: Hubble constant

Convenient to define $h = \dfrac{H_0}{100 \ km/s \cdot Mpc} = 0.67 \pm 0.01$

$\Rightarrow h^2 \approx 0.5$

Note: $[H_0] = [\text{rate}] = [\text{time}^{-1}]$

$\Rightarrow H_0^{-1} \approx 1.4 \cdot 10^{10}$ yrs

defines typical time scale

(age of the universe)

1.3 Content of the universe

Universe filled with photons following (almost perfect) black body spectrum of temperature $T_0 = 2.7255 \pm 0.0006$ K

↳ Cosmic Microwave Background (CMB)

$\Rightarrow$ Confirms isotropy of universe at the level $< 10^{-4}$

$\Rightarrow$ Contains huge wealth of information about early universe

Expect also Cosmic Neutrino Background (not yet detected)

Dominant contributions to total energy budget:

- Visible matter: 5%
  - Baryons (i.e. nuclei) but no anti-baryons
  - Electrons ensure charge neutrality
  - Dominant form: Diffuse gas of H and He
  - Heavier elements very rare
- Dark matter: 25%
  - Accounts for "missing mass" needed to stabilise galaxies and galaxy clusters
  - Must be non-baryonic, non-relativistic and very weakly interacting
  - Unknown elementary particle?
- Dark energy: 70%
  - Uniformly fills space ("vacuum energy")
  - Accounts for (accelerated) expansion
  - Fundamental theory completely unknown

1.4 Universe in the past

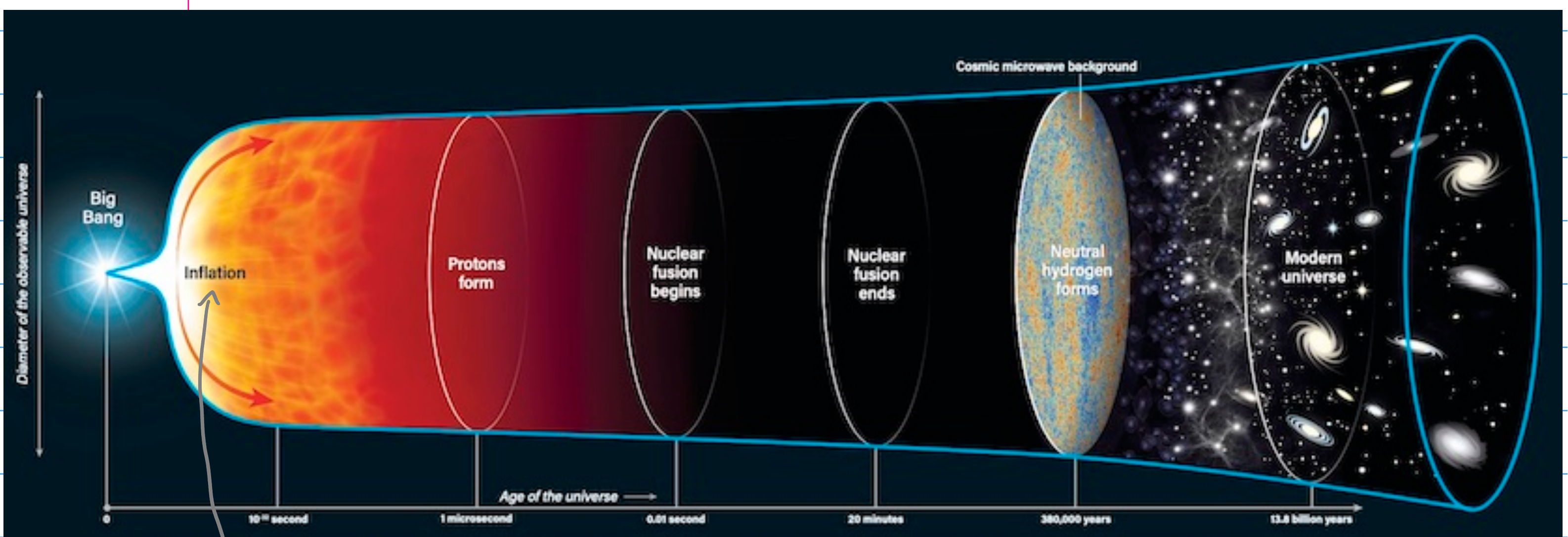
Early universe was denser and hotter

For $T \gtrsim 1\,eV$: No bound atoms
→ free electrons & nuclei

$T \gtrsim 100\,keV$: No bound nuclei
→ free protons & neutrons

$T \gtrsim 100\,MeV$: No bound baryons
→ free quarks & gluons

Even higher temperatures: Speculative
↳ Electroweak phase transition ?
↳ Dark matter production ?
↳ Generation of baryon - antibaryon asymmetry ?



Inflation: Sets initial conditions for evolution