2) REVIEW OF ΛCDM

•) The SM is well tested at small distances.

At large distances, astrophysical scales > few Mpc we need a joint description of space-time and matter/radiation = energy content.

•) Here we will (quickly) review the concepts to establish the notation and phenomenologically relevant parameters.

SCALE FACTOR : $a(t)$ $\qquad$ $d(t) = a(t)\, d_0$

proper distance $\qquad$ comoving distance

Today $a(t_0) = 1$

•) In an expanding universe $\dot{a} = \frac{da}{dt} > 0$

We define the Hubble rate $H(t) = \frac{\dot{a}}{a}$

Then $\dot{d} = \frac{\dot{a}}{a} a d_0 = H d \Rightarrow$ the observed recession is growing linearly with d.

•) Physically we measure the spectra of stars that shift in frequency because of the expansion. The redshift parameter z is defined as

$$z+1 = \frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_{obs}}{a_{em}} = \frac{1}{a(t)}$$

REDSHIFT : $z+1 = \frac{1}{a}$ today : $a_0 = 1$

$$z_0 + 1 = 1$$

$$z_0 = 0$$

•) Redshift 0 is today. Galaxy surveys go to redshifts ≤ 1, the farthest quasars go to redshift $z \sim 6$, before that the universe is dark and photons decouple at $z \sim 1100$. At that time the universe was smaller by $\frac{1}{z} \sim 10^{-3}$.

•) The evolution of the scale factor $a(t)$ is dictated by the Friedmann equation, which relates the expansion to the content.

$$\rho_i \ldots \frac{\text{energy}}{\text{volume}} \ldots \text{energy density}$$

× ρ_γ or ρ_r ... radiation : everything which is non-relativistic is radiation

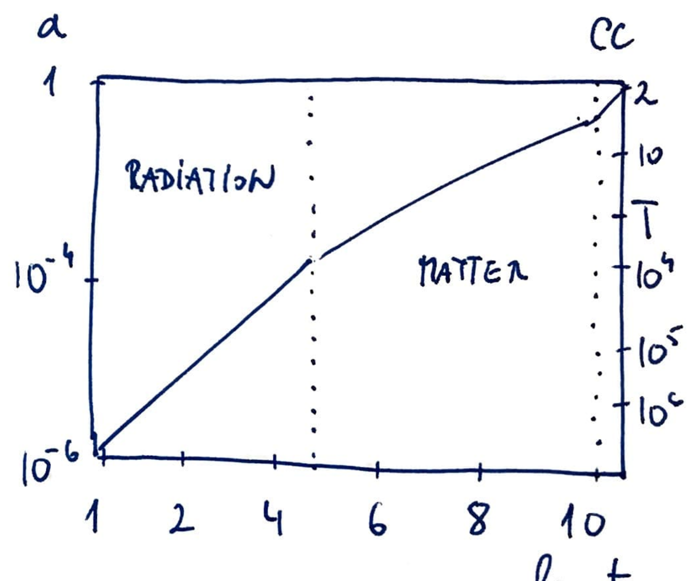
× ρ_m ... matter : when $p \leq m$ we have a non-zero matter component

× ρ_Λ = const. ... cosmological constant

$$a_\gamma \propto \sqrt{t}$$

$$a_m \propto t^{2/3}$$

$$a_\Lambda \propto e^t$$



•) The type of content defines the Hubble rate

$$\ln a_\gamma = \frac{1}{2} \ln t \,\Big/ \frac{d}{dt} \Rightarrow \frac{\dot{a}}{a} = H = \frac{1}{2} t^{-1}; \text{ matter } \frac{\dot{a}}{a} = \frac{2}{3}\frac{1}{t}$$

H_0 ... present-day value of $H(t_0)$

Di Valentino et al. '21: Review of H_0 tension solutions

$z \sim 1100$

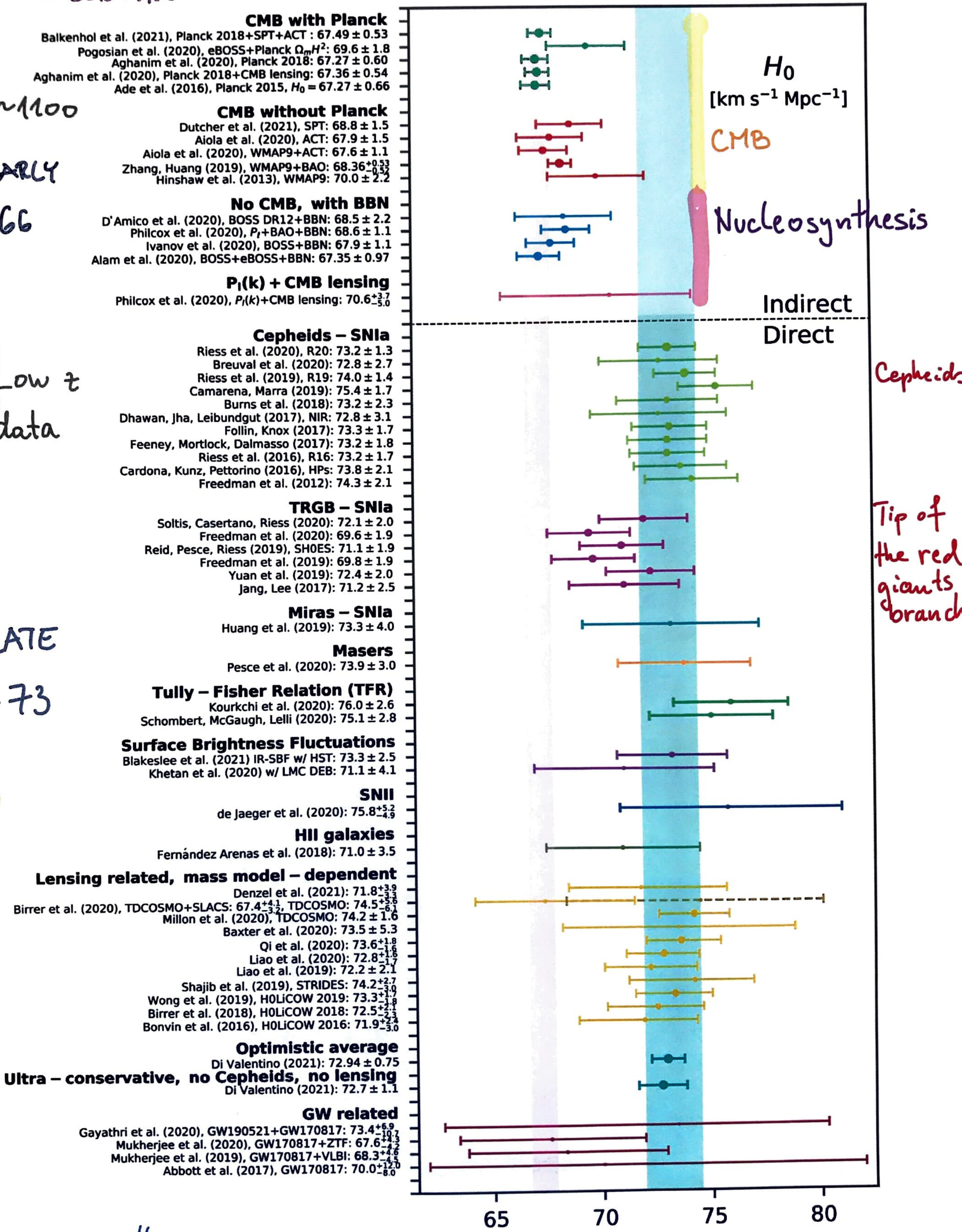
EARLY

~ 66

Low z data

LATE

~ 73



$$H_0 \Rightarrow t_u^{\text{matter}} \simeq \frac{2}{3}\frac{1}{H_0} \sim 13.8\,\text{Gyr}$$

•) The present-day value of $H(t) \equiv H_0$

$$H_0 \in (67-75)\ \frac{km}{s\,Mpc} = h \cdot 100\ \frac{km}{s\,Mpc}$$

(see the plot for determinations / discrepancies)

•) FRIEDMANN EQUATION determines the evolution of the Hubble parameter (or the scale factor)

$$H^2 = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_m + \dots\right)$$

G ... Newton's constant

$$G \sim \frac{1}{M_{Pl}^2}\ , \quad M_{Pl} \sim 10^{19}\ GeV$$

$$H_0^2 = \frac{8\pi G}{3}\rho_{cr}\ , \quad \rho_{cr} = \frac{3H_0^2}{8\pi G} = h^2 \cdot 10^{-29}\ \frac{g}{cm^3}$$

•) In a flat, Euclidean universe: $\sum_i \rho_i = \rho_{cr}$

$$\Omega_i = \frac{\rho_i}{\rho_{cr}}$$ ... energy density parameter

$$\sum \Omega_i \cong 1$$ ... consistent with observations

•) Number densities: $n(t) = \frac{N}{V} \propto \frac{1}{a^3}$

We will treat the early universe as a TD system where the microscopic physics (stat. mech.) defines the macroscopic state $\Rightarrow n, \rho, P, s, \ldots$

$$n \propto a^{-3}$$

•) For non-relativistic matter: $E^2 = p^2 + m^2 \sim m^2 + \ldots$

$$\rho_m \propto m n \propto a^{-3}$$

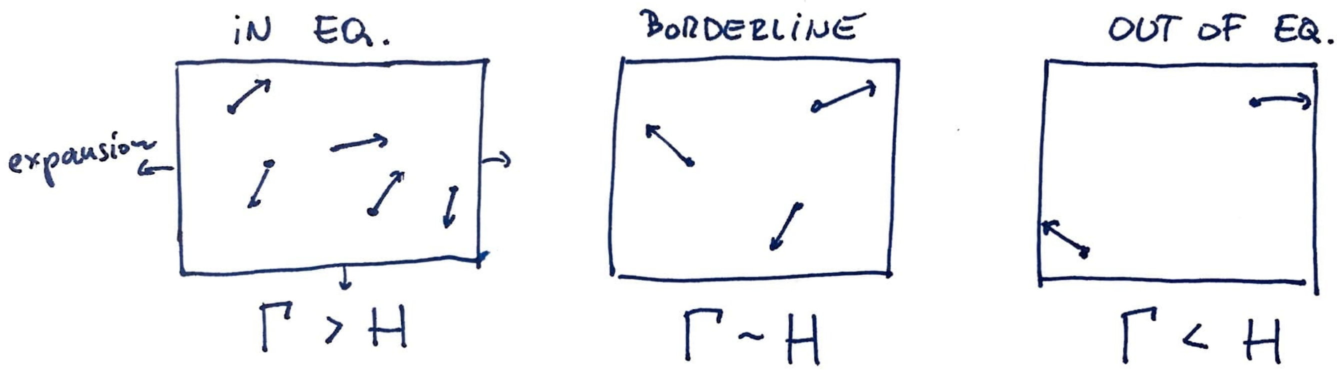
•) For relativistic (matter): $E \sim p \quad (m \to 0)$

$$\rho_m \propto p n \propto \frac{1}{a} a^{-3} \propto a^{-4}$$

Intuitively this is consistent with redshifting. The expansion of the universe stretches the wavelengths $\lambda \propto a$ and $p \propto 1/\lambda$ so the energy of the photon de-creases with a, while the number density goes as a^{-3}, together $\rho_\gamma \propto a^{-4}$.

EQUILIBRATION

•) In order to treat the universe as a TD system, the species have to interact often enough to exchange momenta (kinetic eq.) and their number densities (chemical eq.).



•) The most compelling proof of equilibration is the CMB that has a perfect black body spectrum :

$$I_\nu = \frac{4\pi\,\nu^3}{e^{p/T}-1} ,$$

$$T_0 = 2.75\ \mathrm{K} \simeq 2.4 \cdot 10^{-4}\ \mathrm{eV}$$

•) The spectrum is completely fixed by E_γ / T_γ which defines the T_γ. Since $E_\gamma \propto a^{-1}$, we have :

$$T_\gamma(t) = \frac{T_0}{a(t)} .$$

•) Temperature vs. a vs. ρ

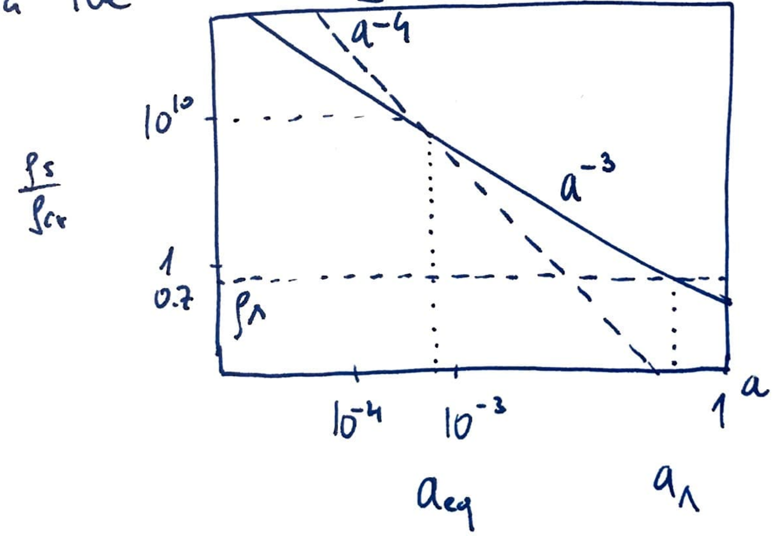
$$T \propto a^{-1}$$

and we had $\rho_\gamma \propto a^{-4} \Rightarrow \rho_\gamma \propto T^4$ Stefan-Boltzmann law

This means that at early times

$$H \propto \sqrt{\rho_\gamma} \propto T^2 \; \dots$$ radiation dominated universe (early times)

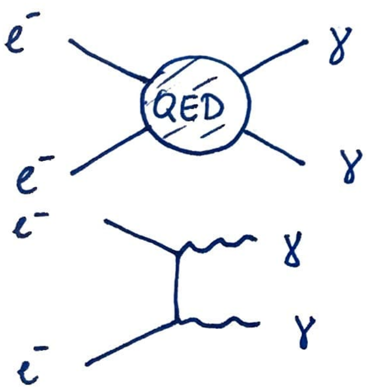
radiation will dominate in the → early universe



$a_{eq} \sim 10^{-4}$

$T_{eq} \sim 10^4 T_0 \sim eV$

•) Rates of equilibration : Γ vs. H

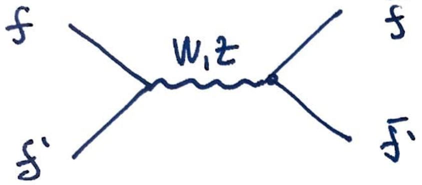


• scatterings and annihilations are $\propto \langle \sigma v \rangle n$ (we will derive in detail)

$\langle \sigma v \rangle$ ... thermally averaged cross-sections

$$[\langle \sigma v \rangle] = cm^2 \text{ or } GeV^{-2}$$

- e.g. at high $M_W > T > m_f$, $\sigma_{weak} \sim G_F^2 T^2$

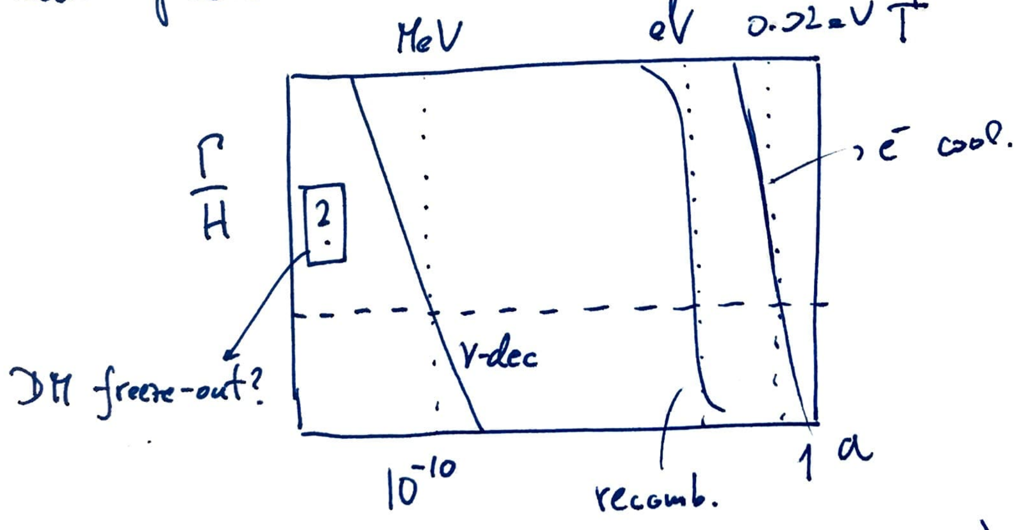


$m_f < T \qquad \mathcal{A} \propto \dfrac{g^2}{M_W^2}$

$$\sigma \propto \frac{\alpha_w}{M_W^4} \sim G_F^2$$

- for units to make sense $\langle \sigma v \rangle \sim G_F^2 T^2$
- in the NR limit $T \to m$.

•) The combination of T and coupling strength determines when (cosmologically speaking) a certain species will decouple, or freeze-out.



•) at very high T: $\langle \sigma v \rangle_w \cong \alpha^2 / T^2$

$\Rightarrow \langle \sigma v \rangle n \sim \alpha^2 T < \dfrac{T^2}{M_{Pl}} \Rightarrow T > \alpha^2 M_{Pl}$ out of equilibrium at very high T.

•) Going back in time to high temperatures different processes enter equilibrium.

@ $T \gtrsim E_{Ry}$ the photons destroy the atoms into nuclei and e^-, γ plasma

@ $T \gtrsim$ MeV at the typical scales of nuclear interactions, the light nuclei H, He, Li, ... disacociate as well.

$\Rightarrow$ <u>BBN</u> covered by Lorenzo

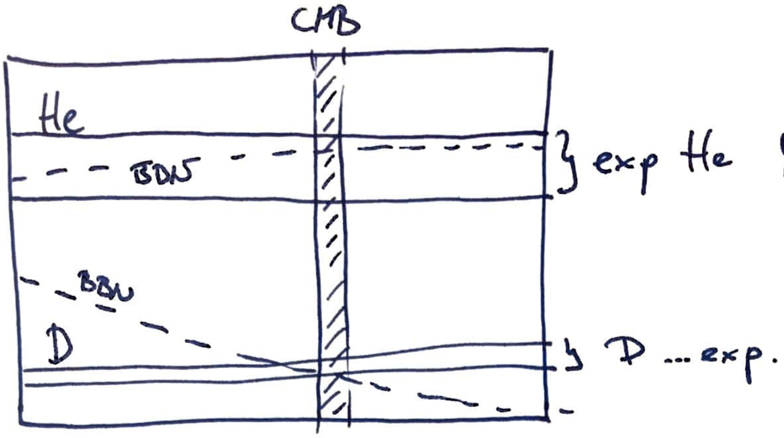
@ $T \gtrsim$ GeV $\sim \Lambda_{QCD}$ at this point even the protons, and mesons fall apart and we get a plasma of quarks, leptons

@ $T \gtrsim 100$ GeV the entire SM is essentially massless (apart from say m_t) and behaves as a equilibrated plasma

•) From the known nuclear physics σ-s and decay rate of the neutron we get precise predictions on the amount of light elements, depending on Ω_b.

BBN

@ $T \lesssim$ MeV



$Y_p^{BBN} = \frac{\rho^{He}}{\rho^p + \rho^n}$

$\omega_b \sim 0.022 \rightarrow \Omega_b \lesssim 0.05$

$\shortparallel$

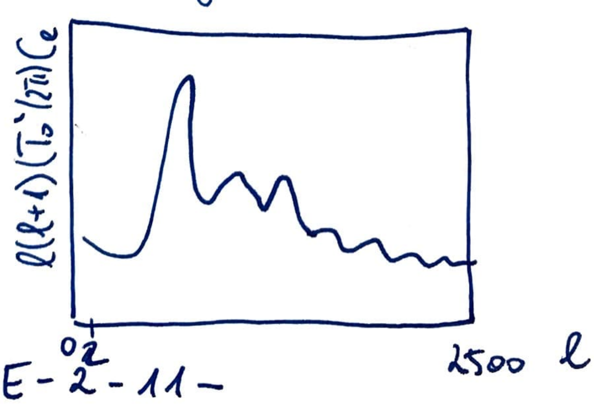
$\Omega_b h^2$

-) The bottom-line is $\Omega_B \sim 5\%$ from CMB & BBN.

-) After BBN the universe with p^+ and e^-, ... cools down and is still rather opaque, the photons scatter frequently on e^- & p^+.

At $T \sim 13.6\,eV$ or $z \sim 1100$ the ionization disappears and $e^- + p \rightarrow H$ neutral atoms form and light travels freely $\Rightarrow$ CMB.

It is a perfect black body with $T \sim 2.75\,K$ and very uniform:



·) The CMB is decomposed in (θ, φ) via $Y_{lm}(\theta, \varphi)$ and measured to very small angles $\simeq \frac{\pi}{\ell} \lesssim 0.1°$.

requires
This highly constrains the presence of extra matter (DM) and radiation (N_{eff}, ν's) at the time of recombination.

•) On top of CMB which is fixed at $z = 1100$, we can measure the luminous matter = galaxies in 3D maps (θ, φ, z) up to $z \sim 0.15$, (SDSS, 2dF) on scales below 100 Mpc where the universe is not homogeneous anymore.

$$n_g \rightarrow \delta_g(x) = \frac{n_g - \bar{n}_g}{n_{\bar{g}}} \xRightarrow{F.T.} \tilde{\delta}_g(k) \Rightarrow \langle \delta_g, \delta_g^* \rangle$$

$$= (2\pi)^3 \delta(k - k') P_g(k)$$

the resulting power spectrum $P_g(k)$ gives complementary late-time constraints on N_{eff}, m_ν, DM properties.

·) From the matter power spectrum (Large Scale Structures) we see that DM has to be cold (non-relativistic) in order to clump on galactic scales. We'll discuss also other evidence for the existence of DM (and candidates, pheno) separately.

$$\Downarrow$$

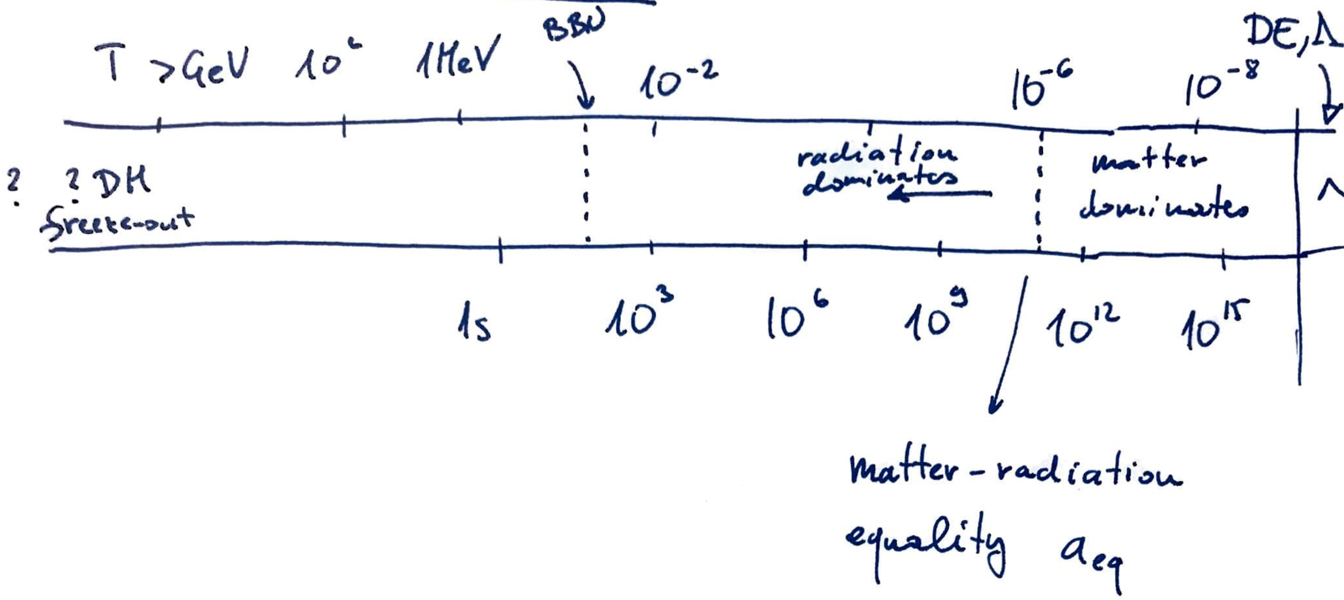
$$\Omega_b \sim 5\% \quad , \quad \Omega_{DM} \sim 25\%$$

$$\text{total matter} \quad \Omega_m \sim 30\%$$

·) At late times $z < 1/3$ the universe seems to be expanding acceleratingly, which requires something different from $\rho_m \propto a^{-3}$, $\rho_\gamma \propto a^{-4}$. The simplest option is $\rho_\Lambda \sim$ const. Measurements of SN in '98-'99 give

$$\Omega_\Lambda \sim 0.7 \quad \Rightarrow \text{flat universe w/} \quad \Omega_m + \Omega_\Lambda = 1$$

TIMELINE SUMMARY



TODAY: $\Omega_\gamma \sim 10^{-5}$ $\qquad \Omega_\nu \sim \Omega_\gamma$

$\Omega_b \sim 5\%$

$\Omega_{DM} \sim 25\%$

$\Omega_\Lambda \sim 70\%$