

2) REVIEW OF Λ CDM

•) 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 : $a(t)$ $d(t) = a(t) d_0$

•) Today $a(t_0) = 1$

↑
proper
distance

↑
comoving
distance

•) 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

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

• 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.

$$\int \rho \dots \frac{\text{energy}}{\text{volume}} \dots \text{energy density}$$

• ρ_r or ρ_{r} ... radiation : everything which is non-relativistic is radiation

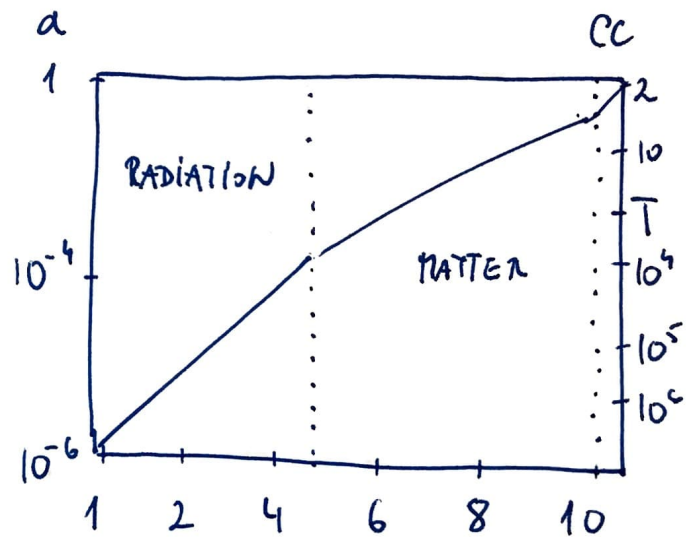
• ρ_m ... matter : when $p \ll \rho$ we have a non-zero matter component

• $\rho_\Lambda = \text{const.}$... cosmological constant

$$\rho_r \propto t^{-4}$$

$$\rho_m \propto t^{-3}$$

$$\rho_\Lambda \propto e^{-3t}$$



•) The type of content defines the Hubble rate $\log_{10} t$

$$\ln a_r = \frac{1}{2} \ln t \quad \left| \frac{d}{dt} \Rightarrow \frac{\dot{a}}{a} = H = \frac{1}{2t} \right.; \quad \text{matter} \quad \frac{\dot{a}}{a} = \frac{2}{3} \frac{1}{t}$$

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

CMB with Planck

- Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.53
- Pogosian et al. (2020), eBOSS+Planck $\Omega_m H^2$: 69.6 ± 1.8
- Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60
- Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54
- Ade et al. (2016), Planck 2015, $H_0 = 67.27 \pm 0.66$

CMB without Planck

- Dutcher et al. (2021), SPT: 68.8 ± 1.5
- Aiola et al. (2020), ACT: 67.9 ± 1.5
- Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1
- Zhang, Huang (2019), WMAP9+BAO: $68.36^{+3.33}_{-3.33}$
- Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2

No CMB, with BBN

- D'Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2
- Philcox et al. (2020), P_f +BAO+BBN: 68.6 ± 1.1
- Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1
- Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97

$P_f(k)$ + CMB lensing

- Philcox et al. (2020), $P_f(k)$ +CMB lensing: $70.6^{+3.7}_{-3.7}$

Cepheids - SNIa

- Riess et al. (2020), R20: 73.2 ± 1.3
- Breuval et al. (2020): 72.8 ± 2.7
- Riess et al. (2019), R19: 74.0 ± 1.4
- Camarena, Marra (2019): 75.4 ± 1.7
- Burns et al. (2018): 73.2 ± 2.3
- Dhawan, Jha, Leibundgut (2017), NIR: 72.8 ± 3.1
- Follin, Knox (2017): 73.3 ± 1.7
- Feeney, Mortlock, Dalmasso (2017): 73.2 ± 1.8
- Riess et al. (2016), R16: 73.2 ± 1.7
- Cardona, Kunz, Pettorino (2016), HPs: 73.8 ± 2.1
- Freedman et al. (2012): 74.3 ± 2.1

TRGB - SNIa

- Soltis, Casertano, Riess (2020): 72.1 ± 2.0
- Freedman et al. (2020): 69.6 ± 1.9
- Reid, Pesce, Riess (2019), SH0ES: 71.1 ± 1.9
- Freedman et al. (2019): 69.8 ± 1.9
- Yuan et al. (2019): 72.4 ± 2.0
- Jang, Lee (2017): 71.2 ± 2.5

Miras - SNIa

- Huang et al. (2019): 73.3 ± 4.0

Masers

- Pesce et al. (2020): 73.9 ± 3.0

Tully - Fisher Relation (TFR)

- Kourkchi et al. (2020): 76.0 ± 2.6
- Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8

Surface Brightness Fluctuations

- Blakeslee et al. (2021) IR-SBF w/ HST: 73.3 ± 2.5
- Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1

SNII

- de Jaeger et al. (2020): $75.8^{+3.2}_{-4.9}$

HII galaxies

- Fernández Arenas et al. (2018): 71.0 ± 3.5

Lensing related, mass model - dependent

- Denzel et al. (2021): $71.8^{+3.9}_{-3.3}$
- Birrer et al. (2020), TDCOSMO+SLACS: $67.4^{+4.3}_{-3.3}$, TDCOSMO: $74.5^{+6.1}_{-6.1}$
- Millon et al. (2020), TDCOSMO: 74.2 ± 1.6
- Baxter et al. (2020): 73.5 ± 5.3
- Qi et al. (2020): $73.6^{+1.8}_{-1.8}$
- Liao et al. (2020): $72.8^{+1.8}_{-1.7}$
- Liao et al. (2019): 72.2 ± 2.1
- Shajib et al. (2019), STRIDES: $74.2^{+2.7}_{-2.7}$
- Wong et al. (2019), HOLICOW 2019: $73.3^{+1.9}_{-1.9}$
- Birrer et al. (2018), HOLICOW 2018: $72.5^{+2.1}_{-2.1}$
- Bonvin et al. (2016), HOLICOW 2016: $71.9^{+2.3}_{-3.0}$

Optimistic average

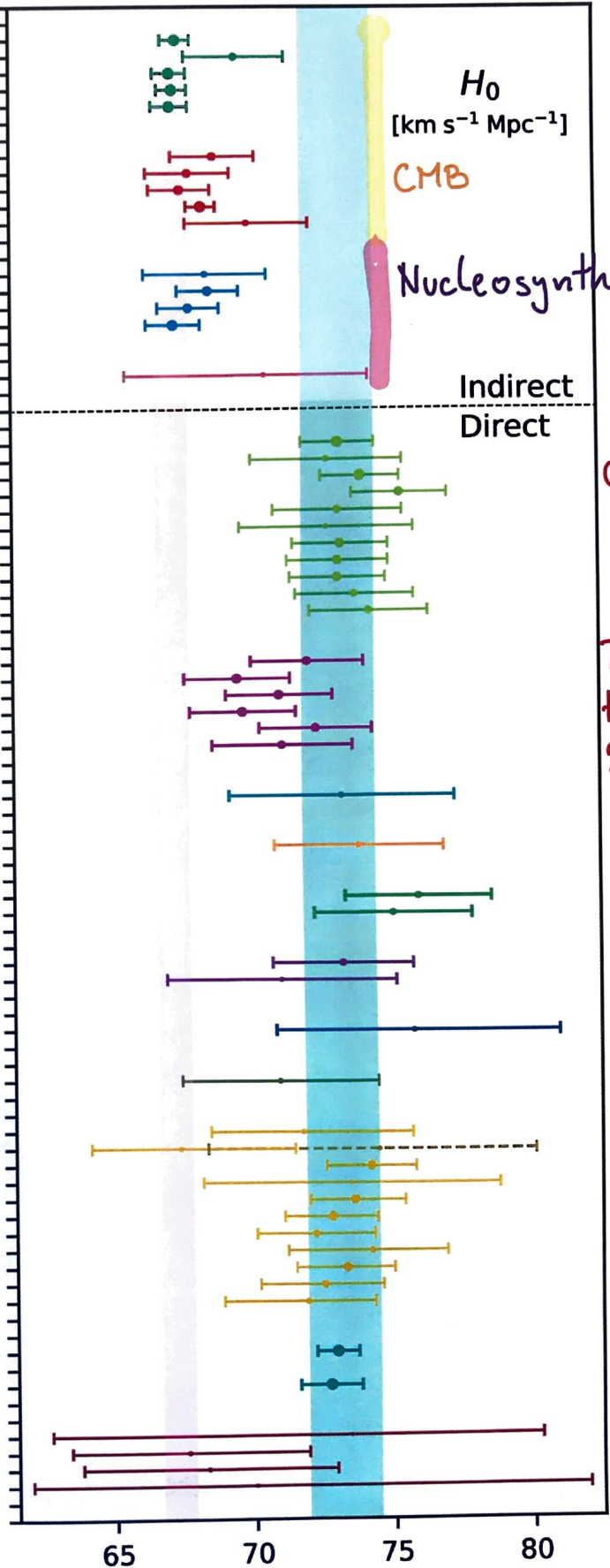
- Di Valentino (2021): 72.94 ± 0.75

Ultra - conservative, no Cepheids, no lensing

- Di Valentino (2021): 72.7 ± 1.1

GW related

- Gayathri et al. (2020), GW190521+GW170817: $73.4^{+5.9}_{-4.3}$
- Mukherjee et al. (2020), GW170817+ZTF: $67.6^{+4.3}_{-4.6}$
- Mukherjee et al. (2019), GW170817+VLBI: $68.3^{+4.6}_{-4.6}$
- Abbott et al. (2017), GW170817: $70.0^{+12.0}_{-8.0}$



$H_0 \Rightarrow t_{\text{matter}} \approx \frac{2}{3} \frac{1}{H_0} \sim 13.8 \text{ Gyr}$
- E - 2 - 4 -

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

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

(see the plot for determinations / discrepancies)

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

$$H^2 = \frac{8\pi G}{3} (\rho_r + \rho_m + \dots)$$

G ... Newton's constant

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

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

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

$$\Omega_i = \frac{\rho_i}{\rho_{\text{cr}}} \quad \dots \text{energy density parameter}$$

$$\sum \Omega_i \cong 1 \quad \dots \text{consistent with observations}$$

•) 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 $\Rightarrow n, f, P, S, \dots$

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

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

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

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

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

• Intuitively this is consistent with redshifting.

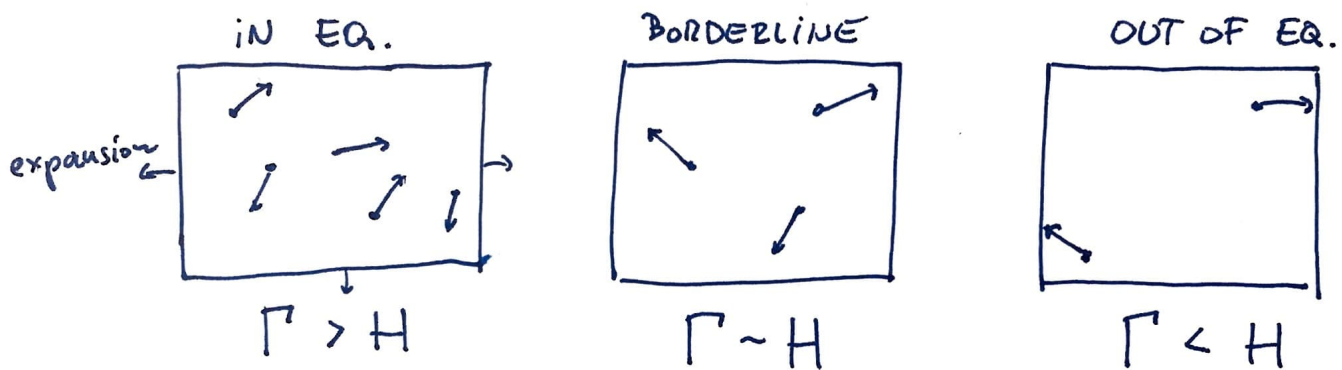
The expansion of the universe stretches the wavelengths $\lambda \propto a$ and $p \propto 1/\lambda$ so

the energy of the photon decreases with a , while the number density goes as a^{-3} ,

together $f_r \propto a^{-4}$.

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 CMD that has a perfect black body spectrum:

$$\text{spectrum : } I_\nu = \frac{4\pi \nu^3}{e^{h\nu/kT} - 1}$$

$$T_0 = 2.75 \text{ K} \approx 2.4 \cdot 10^{-4} \text{ eV}$$

-) 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

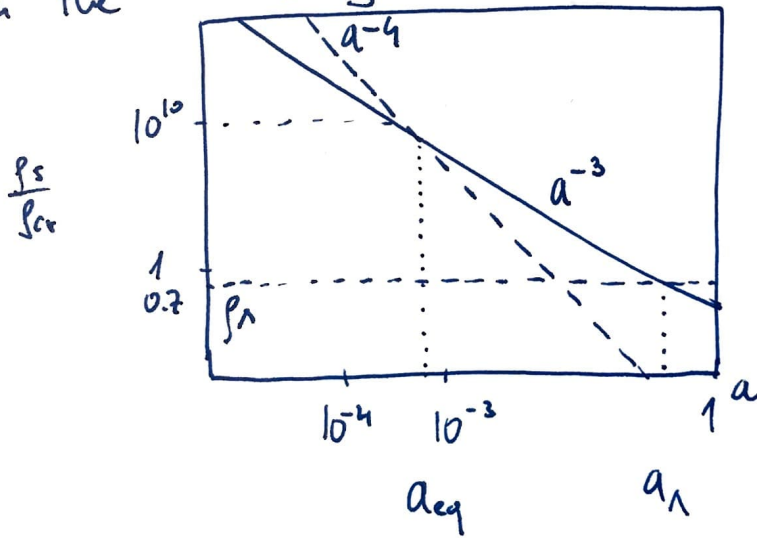
$$T \propto a^{-1}$$

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

This means that at early times

$$H \propto \sqrt{\rho_r} \propto T^2 \dots \text{radiation dominated universe (early times)}$$

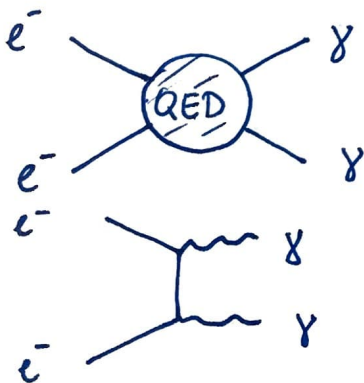
radiation will dominate in the \rightarrow early universe



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

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

•) Rates of equilibration : Γ vs. H

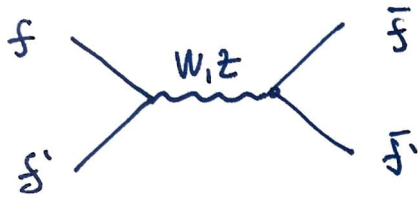


• scatterings and annihilations are $\propto \langle \sigma v \rangle n$ (we will derive in detail)

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

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

• e.g. at high $M_w \gg T > m_f$, $\sigma_{\text{weak}} \sim G_F^2 T^2$



$$m_f < T$$

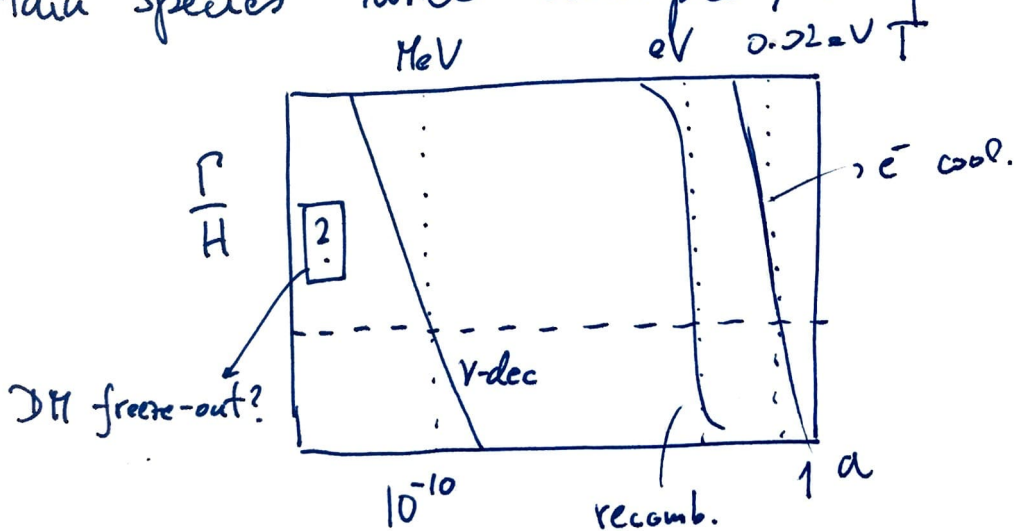
$$d \propto \frac{g^2}{M_w^2}$$

$$\sigma \propto \frac{d^2}{M_w^4} \sim G_F^2$$

• for units to make sense $\langle \sigma v \rangle \sim G_F^2 T^2$

• in the NR limit $T \rightarrow m$.

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



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

$\Rightarrow \langle \sigma v \rangle_w \sim d^2 T < \frac{T^2}{M_{\text{pe}}} \Rightarrow T > d^2 M_{\text{pe}}$ out of equilibrium at very high T .

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

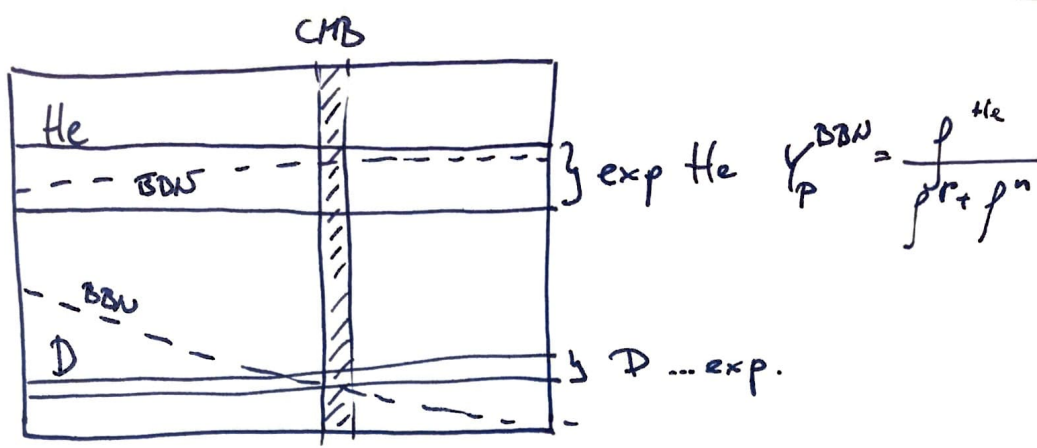
@ $T \gtrsim E_{\text{ry}}$ the photons destroy the atoms into nuclei and e^- , γ plasma

@ $T \gtrsim \text{MeV}$ at the typical scales of nuclear interactions, the light nuclei $\text{H}, \text{He}, \text{Li}, \dots$ disassociate as well.

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

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

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



BBN

@ $T \approx \text{MeV}$

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

$$\Omega_b h^2$$

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

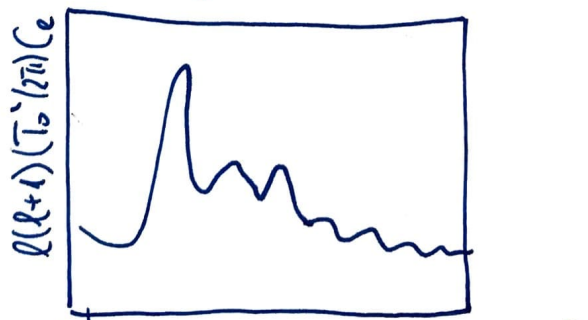
.) After BBN the universe with p^+ and e^- , ... cools down and is still rather opaque, the photons scatter frequently on e^- & p^+ .

At $T \sim 13.6 \text{ eV}$ or $z \sim 1100$ the ionization

disappears and $e^- + p \rightarrow \text{H}$ neutral atoms form and light travels freely \Rightarrow CMB.

It is a perfect black body with $T \sim 2.75 \text{ K}$

and very uniform:



1) The CMB is decomposed in (θ, ℓ) via $Y_{\ell m}(\theta, \varphi)$
 and measured to very small angles $\sim \frac{\pi}{\ell} \in 0.1^\circ$.
 This highly constrains ^{requires} 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.

$$\begin{aligned}
 n_{\text{ca}} \rightarrow \delta_g(x) = \frac{n_g - \bar{n}_g}{\bar{n}_g} \stackrel{\text{F.T.}}{\Rightarrow} \tilde{\delta}_g(k) \Rightarrow \langle \delta_g, \delta_g^* \rangle \\
 = 8\pi^3 \delta(k-k') P_g(k)
 \end{aligned}$$

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

•) 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, phers) separately.

⇓

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

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

•) At late times $z < 1/3$ the universe seems

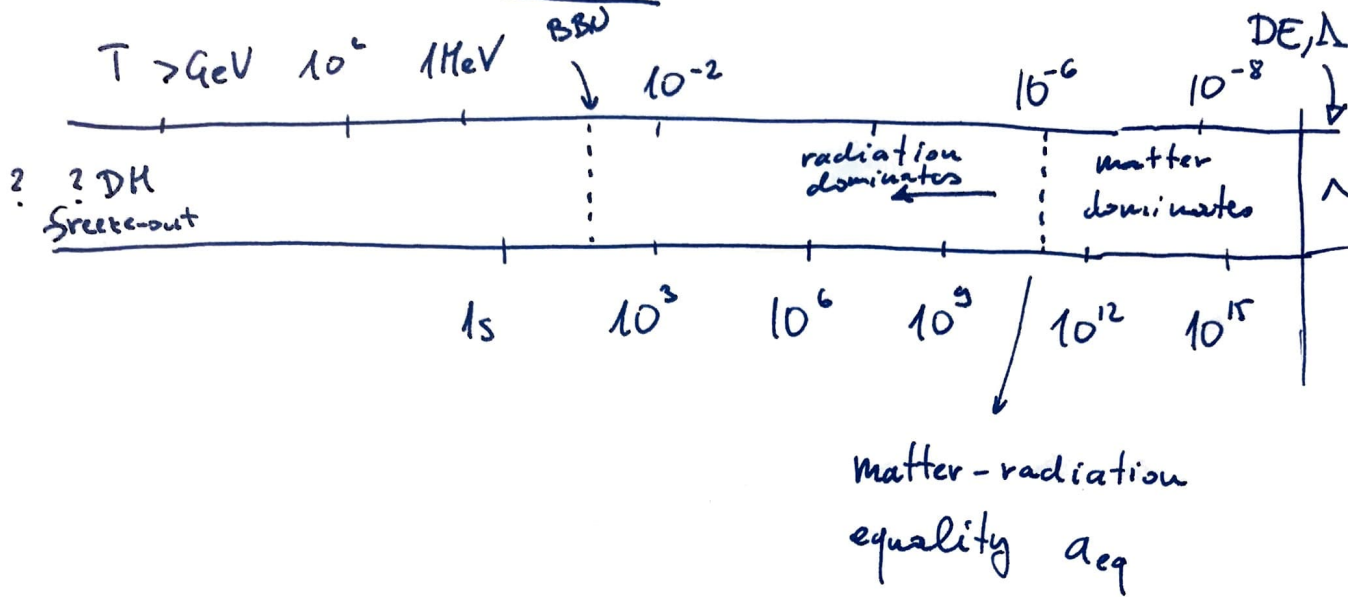
to be expanding acceleratingly, which requires something different from $f_m \propto a^{-3}$, $f_r \propto a^{-4}$.

The simplest option is $f_\Lambda \sim \text{const.}$ Measurements of SN in '98-'99 give

$$\Omega_\Lambda \sim 0.7 \quad \Rightarrow \quad \text{flat universe w}$$

$$\Omega_m + \Omega_\Lambda = 1$$

TIMELINE SUMMARY



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

$\Omega_b \sim 5\%$

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

$\Omega_\Lambda \sim 70\%$