

Title: PSI 2018/2019 - Cosmology Review - Lecture 7

Date: Jan 15, 2019 09:00 AM

URL: <http://pirsa.org/19010008>

Abstract:

lecture 6 appendix:

$$\left\langle \left(\frac{\delta m}{m} \right)^2 \right\rangle \sim P(k) k^3 \Big|_{k \sim \frac{1}{\lambda}}$$

history

tools

language

units conversion

③

① $E = k_B T$ kelvin $\rightarrow$ eV
 $1 \text{ K} \sim 10^{-4} \text{ eV}$

② $z+1 = \frac{1}{a(t)}$ early universe
 $z \gg 1$
 $z \sim \frac{1}{a(t)}$

$$\textcircled{3} \quad T \propto \frac{1}{a} \propto z$$

$$\Omega_k=0 \quad \Omega_\Lambda=0 \quad t_0=12 \times 10^9 \text{ yr}$$

$$\text{matter era: } a \propto t^{2/3}$$

$\textcircled{4}$ age in secs.

$$\text{rad. } a \propto t^{1/2}$$

$$\text{matter } a \propto t^{2/3}$$

$$\Omega_k=0 \quad \Omega_\Lambda=0 \quad t_0=12 \times 10^9 \text{ yr}$$

matter era: $a \propto t^{2/3}$

$$\left(\frac{T}{T_0} \right) = \left(\frac{t_0}{t} \right)^{2/3}$$

$$T_0 = 2.725 \text{ K}$$

$$\Omega_k = 0 \quad \Omega_\Lambda = 0 \quad t_0 = 12 \times 10^9 \text{ yr}$$

matter era: $a \propto t^{2/3}$

$$\left(\frac{T}{T_0} \right) = \left(\frac{t_0}{t} \right)^{2/3}$$

$$T_0 = 2.725 \text{ K}$$

up until
radiation take
over.

$$\frac{\Omega_r}{a^4} = \frac{\Omega_m}{a^3} \quad z \approx 3400$$

$$T_{rm} \approx 10^4 \text{ K} \quad \sim 1 \text{ eV} \quad t_{rm} \approx 60 \times 10^3 \text{ yr}$$

radiation era

$$\left(\frac{T}{T_{rm}} \right) = \left(\frac{t_{rm}}{t} \right)^{1/2}$$

$$\Gamma \sim H$$

interaction rate

start with $\Gamma \gg H$

$T \gg 10^3 \text{ GeV}$ all massless limit

$\sim T$ only energy scale

$$\Gamma \sim T$$

$$\Gamma = 16 \checkmark$$

$$= \frac{N}{V} \cdot A$$

$$= \frac{1}{L}$$

$$\left[\frac{1}{T} \right] = \left[\frac{1}{L} \right] = [E] = [m] = [T]$$

$$\underline{P \sim T}$$

$$P = \rho g V \quad \nearrow$$

$$= \frac{N}{V} \cdot A$$

$$= \frac{1}{L}$$

$$\left[\frac{1}{T}\right] = \left[\frac{L}{L}\right] = [E] = [m] = [T]$$

$$H^2 = \frac{8\pi G \rho}{3}$$

$$\frac{1}{\sqrt{8\pi G}} = M_{pl}$$

$$H^2 = \frac{\rho}{3M_{pl}^2} \sim \frac{T^4}{M_{pl}^2} \sim \frac{T}{V}$$

$$H \sim \frac{T^2}{M_{pl}}$$

$$\frac{P}{H} = \frac{T}{\frac{T^2}{M_{pl}}} = \frac{M_{pl}}{T}$$

year	redshift	energy	notes
146 yr.	0	0.24 meV	present
96 yr	0.4	0.33 meV	$\rho_n = \rho_m$

<u>~ 100-400 Myr</u>	11-30	2.6-7.0 meV	Galaxy formed.
380 kyr	1000	0.25 eV	photon decouple. CMB
26-78 kyr	1200	0.26-0.33 eV	Recombination

tomorrow

$\sim 100 - 400 \text{ kyr}$

380 kyr

$\sim 26 - 38 \text{ kyr}$

1000

1200

0.25 eV

0.26 - 0.33 eV

photon decouple. CMB

Recombination

60 kyr

3400

0.75 eV

$\rho_r = \rho_m$

3 minutes

4×10^8

100 keV

BBN

$\sim 6s$

$\sim 1s$

?

$10^{-5}s$

$10^{-10}s$

$10^{-16}s$

500keV

$\sim 1MeV$

200MeV

10TeV

$10^{19}GeV$

$e^+ + e^- \rightarrow \gamma\gamma$

neutrino decouple

HW2 $T \sim 1.9K$

Dark matter

QCD n.p. } SM
EW 200GeV GUT

Inflation SUSY GUT

QG

380 kyr	1000	0.25 eV	photon decouple. CMB
20-30 kyr	1200	0.26-0.33 eV	Recombination
60 kyr	3400	0.75 eV	$\rho_r = \rho_m$
3 minutes	4×10^8	100 keV	BBN $\rightarrow$ $\begin{matrix} \text{He} \\ \text{D} \end{matrix}$
$\sim 6s$		500 keV	$e^+ + e^- \rightarrow \gamma$
	$\sim 1 \text{ MeV}$		neutrino decouple $\rightarrow$ HWT $T_\nu \sim 1.9 \text{ K}$

Tools.

non equilibrium.

$$n \propto \frac{1}{a^3}$$

$$n \cdot a^3 = \text{const.}$$

$$\therefore \frac{d(na^3)}{dt} = 0 \Rightarrow \frac{dn_i}{dt} + 3Hn_i = 0 \quad \text{no interaction limit}$$

$$\frac{dn_i}{dt} + 3Hn_i = \mathcal{O}[\{\eta_i\}]$$

$$\frac{dn_i}{dt} + 3H n_i = C_i [\{n_j\}]$$

2 to 2 scattering

$1+2 \longleftrightarrow 3+4$ not in equilibrium

$$\frac{dn_1}{dt} + 3 H n_1 = -\alpha n_1 n_2 + \beta n_3 n_4$$

$$\alpha = \langle \sigma v \rangle$$

$$(-\alpha n_1 n_2 + \beta n_3 n_4) = 0|_{eq}$$

$$\beta = \alpha \left(\frac{n_1 n_2}{n_3 n_4} \right)_{eq}$$

equilibrium

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

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

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

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

← Fermi
← Boson

relativistic $T \gg m, \mu$

non-relativistic $m \gg T, \mu$

m.p.

$$n \approx \frac{5(3)}{\pi^2} g T^3 \begin{cases} 1 & \text{boson} \\ \frac{3}{4} & \text{fermion} \end{cases} \rightarrow T \propto \frac{1}{a}$$

$$p \approx \frac{\pi^2}{30} g T^4 \begin{cases} 1 & \text{boson} \\ \frac{7}{8} & \text{fermion} \end{cases}$$

T.p.

$$n \approx g \left(\frac{mT}{2\pi} \right)^{3/2} e^{\frac{\mu-m}{T}} \quad \begin{array}{l} \text{equilibrium hates} \\ \text{massive particles} \end{array}$$

