Title: Cosmology Lecture (230411)

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Collection: Cosmology (2022/2023)

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URL: https://pirsa.org/23040056

Last time: Friedmann eqns

Solns: evolution determined by Ω's

determined by: distances, CMB, LSS ...

ΛCDM

matter: $\Omega_{m0} \sim 0.3$

vacuum: $\Omega_{\Lambda 0} \sim 0.7$

radiation: $\Omega_{r0} \sim 10^{-4}$

curvature: $\Omega_{k0} \simeq 0 \pm 1\%$

Hubble: $H_0 \simeq 70 \frac{\text{km/s}}{\text{Mpc}}$

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Hubble: $H_0 \simeq 70 \frac{km/s}{Mpc} \equiv h \cdot 100 \frac{km/s}{Mpc}$

⇒ dark matter

evidence in: CMB, galaxies, clusters, grav. lensing...

DM: what is known?

1. gravitates
2. responds to gravity
3. no detected interactions besides gravity

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if $M \simeq 100\,GeV \Rightarrow n \simeq 10^{-8}\ cm^{-3}$

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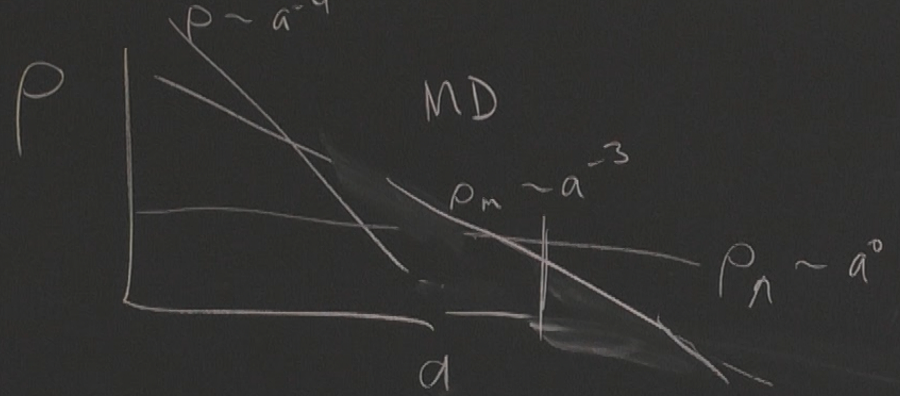
if $M \simeq 100\,GeV \Rightarrow n \simeq 10^{-8}\ cm^{-3}$

baryons: $n \sim 2 \cdot 10^{-7}\ cm^{-3}$

$n_\gamma \simeq 400\ cm^{-3}$

theory: expect $\dfrac{\rho_{vac}}{\rho_{crit}} \simeq 10^{120}$, not $\sim O(1)$



$\Omega_\Lambda \sim 1$

$\Omega_m, \Omega_r, << 1$

$\Omega_k \sim \dfrac{1}{a^2}$

$\rho_{rad}/\rho_m \sim \frac{1}{3000}$

$z \simeq 3000 \quad \rho_r \simeq \rho_m$

$> \quad \rho_r > \rho_m$

$\simeq 10^{-8}\ cm^{-3}$

cm^{-3}

cm^{-3}

$T_{CMB} \simeq 2.73K$ today

$z \simeq 10^3$

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

no atoms, mostly ions

electrons

th

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$T_\gamma > MeV$

$> 100 MeV$

theor

Thermal history of universe

distribution function $f(x,p,t)\,\dfrac{d^3x\, d^3p}{(2\pi\hbar)^3} \sim$ # particles within d^3x of x, d^3p of p

set $c = \hbar = 1$

$$[\text{length}] = [\text{time}] = [\text{mass}]^{-1}$$

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

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$$E^2 = m^2 + p^2$$

$$T^{\mu}{}_{\nu} = g \int \frac{p^{\mu} p_{\nu}}{E} f(x,p) \frac{d^3p}{(2\pi)^3}$$

$$\rho = -T^{0}{}_{0} \qquad P = \frac{1}{3} \mathrm{Tr}(T^{i}{}_{j}) = \frac{T^{i}{}_{i}}{3} = g \int \frac{p^2}{3E} f(x,p) \frac{d^3p}{(2\pi)^3}$$

$f_{\gamma}, f_{e},$

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$f_\gamma, f_e,$

evolution: Boltzmann eqn $\displaystyle \frac{df_i}{dt} = C_i[\vec{f}]$

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \underbrace{\cancel{\frac{\partial f}{\partial x^i}}}_{0} \frac{dx^i}{dt} - H \frac{\partial f}{\partial p^i}\, p^i$$

$$\frac{d^3p}{(2\pi)^3}$$

$$f(p,t)$$

$$C[\vec{f}]$$

$$\frac{d\vec{p}}{dt} + H\vec{p} = 0$$

Suppose $C[f] = 0$

$$\int \frac{d^3p}{(2\pi)^3} \left[E \frac{\partial f}{\partial t} - H \frac{\partial f}{\partial p^i} p^i E \right] = 0$$

$$\frac{\partial \rho}{\partial t} + H \int f \frac{\partial}{\partial p^i}\left(E p^i\right) \frac{d^3p}{(2\pi)^3}$$

suppose $C[f] = 0$

$$\int \frac{d^3p}{(2\pi)^3}\left[E\frac{\partial f}{\partial t} - H\frac{\partial f}{\partial p^i}\, p^i E\right] = 0$$

$$\frac{\partial \rho}{\partial t} + H\int f\,\frac{\partial}{\partial p^i}\left(E\,p^i\right)\frac{d^3p}{(2\pi)^3}$$

$$\int f\cdot\left(3E + \frac{p^2}{E}\right)\frac{d^3p}{(2\pi)^3}$$

3ρ

$$\frac{\partial \rho}{\partial t} + 3H \int f \frac{\partial}{\partial p^i}\left(E\, p^i\right) \frac{d^3p}{(2\pi)^3}$$

$$\int f \cdot \left(3E + \frac{p^2}{E}\right) \frac{d^3p}{(2\pi)^3}$$

$$\frac{\partial \rho}{\partial t} + 3(\rho + P)H = 0$$