

Outline

Lecture 1: cosmology overview, general constraints on DM

Lecture 2: thermal dark matter scenarios & some implications (WIMPs)

Lecture 3: non-thermal ultralight dark matter, axion cosmology (WISPs)

Lecture 4: (if time permits) non-minimal dark sectors

Goals for Lecture 1:

- Overview ~~of~~ of cosmic history, FLRW metric, cosmic expansion in matter/radiation/dark energy-dominated epochs
- Outline what we (think we) know about dark matter
- Derive/show generic constraints on dark matter

Lecturer info:

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$$ds^2 = -dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right]$$

$$k=0,\pm 1$$

$$\left(\frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G}{3} \rho - \frac{k}{a(t)^2}$$

Friedmann
equation

Describing our universe

- Framework: general relativity
 - Metric of spacetime governs how light & particles propagate
 - Matter/energy content determines metric & how it evolves, via Einstein equations
- We are interested in large scales - approximate universe to be spatially isotropic & homogeneous, evolving in time
 - approximate matter content as a perfect fluid, characterized fully by pressure^(P) & energy density ρ

\Rightarrow These approximations allow exact solution of Einstein equations:

$$ds^2 = -dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right] \quad k=\pm 1, 0 \quad \begin{array}{l} \text{Friedmann-Lemaître} \\ \text{- Robertson-Walker} \\ \text{metric} \end{array}$$

$$\left(\frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G}{3} \rho - \frac{k}{a(t)^2} \quad \text{Friedmann equation} \quad \left\{ \begin{array}{l} \text{often write} \\ H \equiv \frac{\dot{a}}{a} \end{array} \right.$$

- "Comoving observers/particles" - at fixed r, θ, ϕ coords
 - Since FLRW metric has no preferred spatial direction, particles initially at rest in $r\theta\phi$ coords will remain there. Physical distance between such particles will change with $a(t)$.
- Similarly, "comoving volume" = fixed region of $r-\theta-\phi$ space - physical volume changes w/ $a(t)$

- Can show that light gains energy as it propagates:

$$\frac{\text{Emission}}{\text{Ereception}} = \frac{a(t_{\text{reception}})}{a(t_{\text{emission}})}$$

If universe is expanding, $a(t_{\text{reception}}) > a(t_{\text{emission}})$
 $\Rightarrow \text{Emission} > \text{Ereception}$ - light is "redshifted"
 loses energy w/ time

Types of perfect fluid: characterized by parameter w , $P = \rho w$

Matter: zero pressure, $w=0$

Radiation: $w=\frac{1}{3}$, $P=\frac{1}{3}\rho$

From stress-energy conservation can
 show that $\rho \propto a^{-3(1+w)}$

Define
 "redshift"
 $1+z = \frac{a(t_0)}{a(t)}$

Check: Matter: $\rho \propto a^{-3} \rightarrow$ matter density dilutes as volume increases
 " " " " "

Radiation: $\rho \propto a^{-4} \rightarrow$ radiation "
 + energy per particle scales as $1/a$, due
 to redshift

It turns out we need one more (exotic) ingredient to describe
 observed cosmos.

Dark energy: $w=-1$ (-1.01 ± 0.04 , Alam et al, MNRAS 470, 2617 (2017))
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 $\Rightarrow \rho \propto a^0$ - energy density stays the same as space expands

Overall, we can write

$$\rho = \rho_{m,0} \left(\frac{a(t)}{a_0}\right)^{-3} + \rho_{rad,0} \left(\frac{a(t)}{a_0}\right)^{-4} + \rho_{\Lambda,0} \quad \text{Define } H \equiv \frac{1}{a} \frac{da}{dt}, \text{ & F.E becomes:}$$

$$H^2 = \frac{8\pi G}{3} \left[\rho_{m,0} \left(\frac{a(t)}{a_0}\right)^{-3} + \rho_{rad,0} \left(\frac{a(t)}{a_0}\right)^{-4} + \rho_{\Lambda,0} - \frac{3k}{8\pi Ga_0^2} \left(\frac{a(t)}{a_0}\right)^{-2} \right]$$

"critical density" $\rho_c = 3H^2/8\pi G$

Define $\Omega_x = \frac{p_{x,0}}{p_{c,0}}$, $\Omega_k = -\frac{k}{a_0^2 H_0^2}$. Then we can write:

$$\frac{H^2}{H_0^2} = \Omega_r \left(\frac{a}{a_0}\right)^{-4} + \Omega_m \left(\frac{a}{a_0}\right)^{-3} + \Omega_k \left(\frac{a}{a_0}\right)^{-2} + \Omega_\Lambda \xrightarrow{\text{"dark energy"}}$$

Current values: $\Omega_r = 9 \times 10^{-5}$, $\Omega_m = 0.308 \pm 0.012$, $\Omega_\Lambda = 0.692 \pm 0.0012$,

$$\begin{aligned} \Omega_k &= -0.005^{+0.016}_{-0.017} (25\%) \\ &\text{mostly "dark matter"} \\ &\text{from early-universe probes, ordinary matter} \\ &\text{has } \Omega_b \approx 0.0484 \end{aligned}$$

The universe's history: at early times, $a \ll a_0$, Ω_r term dominates
(at very early times we believe there may have been another epoch of
accelerating expansion, inflation, but set that aside for now)

- When did radiation energy density = matter?

$$9 \times 10^{-5} \left(\frac{a}{a_0}\right)^{-4} = 0.31 \left(\frac{a}{a_0}\right)^{-3} \Rightarrow 1+z = \frac{0.31}{9 \times 10^{-5}} \approx 3000 \quad \begin{array}{l} \text{- epoch of} \\ \text{matter-radiation} \\ \text{equality} \end{array}$$

Temperature of universe today ≈ 2.7 K. Temperature at MRE $\sim 10,000$ K
 $\sim \text{few} \times 10^{-4}$ eV $T_0(1+z) \sim 1$ eV

For $T > 1$ eV, universe was radiation-dominated, FE becomes

$$\frac{1}{a^2} \left(\frac{da}{dt}\right)^2 = H^2 \approx \frac{8\pi G}{3} \rho = \frac{8\pi G}{3} p_0 \left(\frac{a}{a_0}\right)^{-4} \Rightarrow \frac{1}{2} \frac{d(a^2)}{dt} = \sqrt{\frac{8\pi G p_0}{3}} a_0^2 dt \Rightarrow \boxed{a \propto t^{1/2}}$$

Parametrically, writing $p \sim T^4$, $G \sim \frac{1}{m_{PL}^2}$, we have $\boxed{H \sim \frac{T^2}{m_{PL}}}$
(blackbody spectrum)

At later times/lower temperatures, the universe became matter-dominated,

$$H^2 = \frac{8\pi G}{3} p_0 \left(\frac{a}{a_0}\right)^{-3} \Rightarrow \sqrt{a} da = \sqrt{\frac{8\pi G p_0}{3}} dt \Rightarrow [a \propto t^{2/3}]$$

Then becomes dark-energy-dominated when:

$$\underline{0.3 \left(\frac{a}{a_0}\right)^{-3} \approx 0.7} \Rightarrow (1+z) = \sqrt[3]{0.7/0.3} \approx 1.3 - \text{just a moment ago}$$

in expansion history!

Questions: why these abundances? what is dark energy? why the mismatch between Ω_m & Ω_b ? how do we find out?

Next few days will focus on these last two questions.

Dark matter properties: has gravity, $\rho \propto a^{-3}$, but doesn't feel (much)
radiation pressure

(see upcoming lectures

by Prof. Crocker)

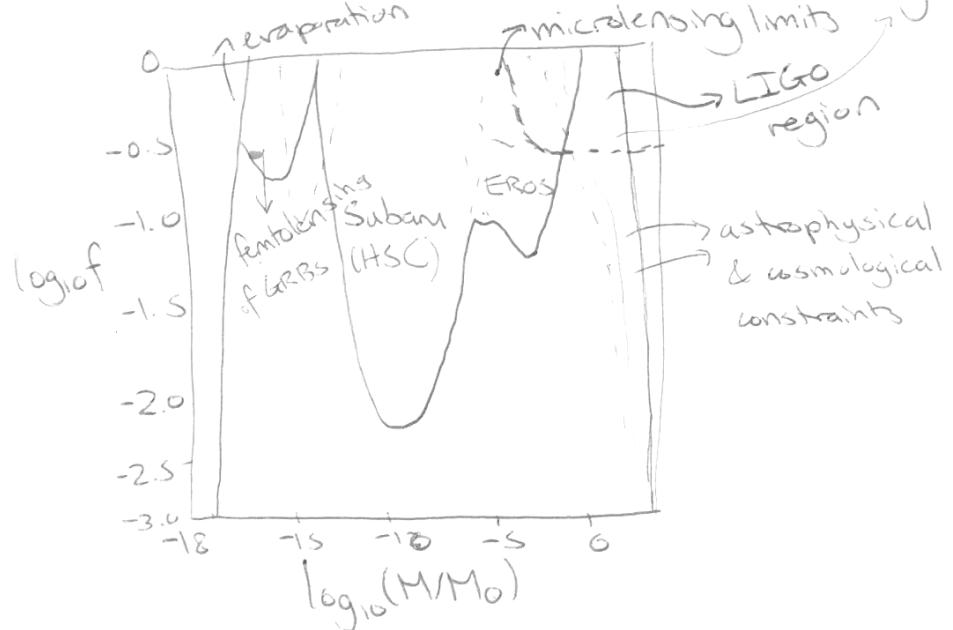
must have already been around by $T \sim 1 \text{ eV}$
assembles into large halos ~~that seed~~ galaxies
cannot be too "warm" (fast-moving), or this \rightarrow not
"galactic scaffolding" would fail to form neutrinos!
must be stable (lifetime \gg age of universe)

No good candidates in SM except maybe primordial black holes.

Primordial black holes as DM:

- Dark matter could be made of macroscopic objects - no radiation pressure, nearly non-interacting because they are charge-neutral & rare (we know ρ , so high mass = low # density)
- But need to form very early in the universe, as we have a measurement of Ω_m from $T \sim 0.3\text{eV}$ ($1+z \sim 1000$)
- Most-discussed candidate: black holes formed in the v/ early universe, seeded by inflation - production mechanism still an open q

References: Carr et al '17, Zumalacarregui & Seljak '18 (supernova lensing)
1705.05567
1712.02240



Currently seems challenging to reconcile observations with cosmos where PBH's are 100% of DM
Only a few ^{narrow mass} windows where they can be O(1) fraction