Astro 596/496 NPA
Lecture 14
February 18, 2019

Announcements:

- **Preflight 3** due Friday
  Part (a) is individual
  Part (b) is group discussion of alternate universe

Last Time: the CMB
Q: What's the acronym?
Q: What is the CMB observationally? physically?
Q: cosmological significance of the CMB?
cosmic equation of state
Q: what's that? why is it important?
Q: what's the equation of state parameter w?
Q: physical significance of w?
Q: what counts as matter vs radiation in cosmology?
Q: w values for radiation? matter? cosmo constant?

Recap: Cosmic Equation of State

Friedmann: equations of motion for cosmic scale factor

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa c^2}{R^2 a^2} \quad (1)$$

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G}{3}\left(\rho + 3\frac{P}{c^2}\right) \quad (2)$$

to solve need $\rho(a)$ or $P(\rho)$

both are gotten from a cosmic equation of state $P(\rho)$ and

$$\boxed{d(\rho c^2 a^3) = -p\ d(a^3)} \quad (3)$$

useful to parameterize via "*state parameter*" w

$$\boxed{p = w\rho c^2} \quad (4)$$

can solve 1st Law eq for matter with **constant** w:

$$\rho_w \propto a^{-3(1+w)} \quad (5)$$

Q: what if $w = 0, +1/3, -1$*?*

Cosmic Constituents

In general:

$P = w\varepsilon = w\rho c^2 \Rightarrow$ $\boxed{\varepsilon = \rho c^2 \propto a^{-3(1+w)}}$

Matter (non-relativistic, a.k.a. "dust"):

$P_\mathrm{m} \ll \varepsilon_\mathrm{m} \approx \rho_\mathrm{m} c^2 \Rightarrow P_\mathrm{m} \simeq 0$ $(w_\mathrm{m} \simeq 0)$

$\Rightarrow \rho_\mathrm{m} \propto a^{-3}$

Radiation (relativistic species): today, photons and neutrinos

$P_\mathrm{rad} = \varepsilon_\mathrm{rad}/3 = 1/3\ \rho_\mathrm{rad} c^2 \Rightarrow w_\mathrm{rad} = 1/3$

$\rightarrow \rho_\mathrm{rad} \propto a^{-4}$

Cosmo constant Λ $w_\Lambda = -1$:

$P_\Lambda = -\varepsilon_\Lambda = -\rho_\Lambda c^2$ negative pressure ?!

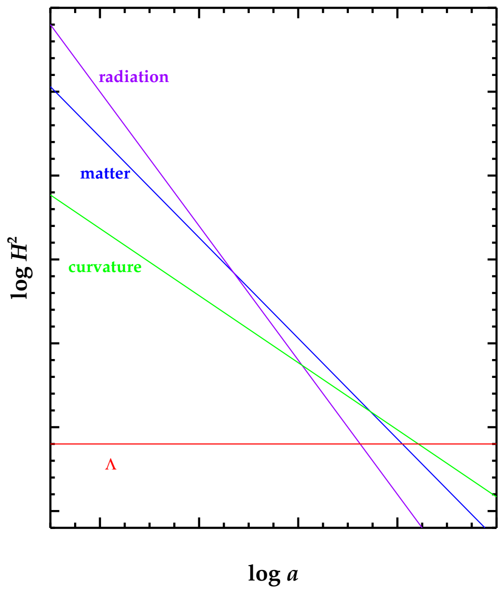
$\rho_\Lambda = const$ (indep of a!) *Q: why is this bizarre?*

Q: if all these components exist, which dominates at late times? early times?

The Cosmic Past

expansion rate: Friedmann says

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_{\rm r} + \rho_{\rm m} + \rho_\Lambda) - \frac{\kappa c^2}{R^2} a^{-2}$$



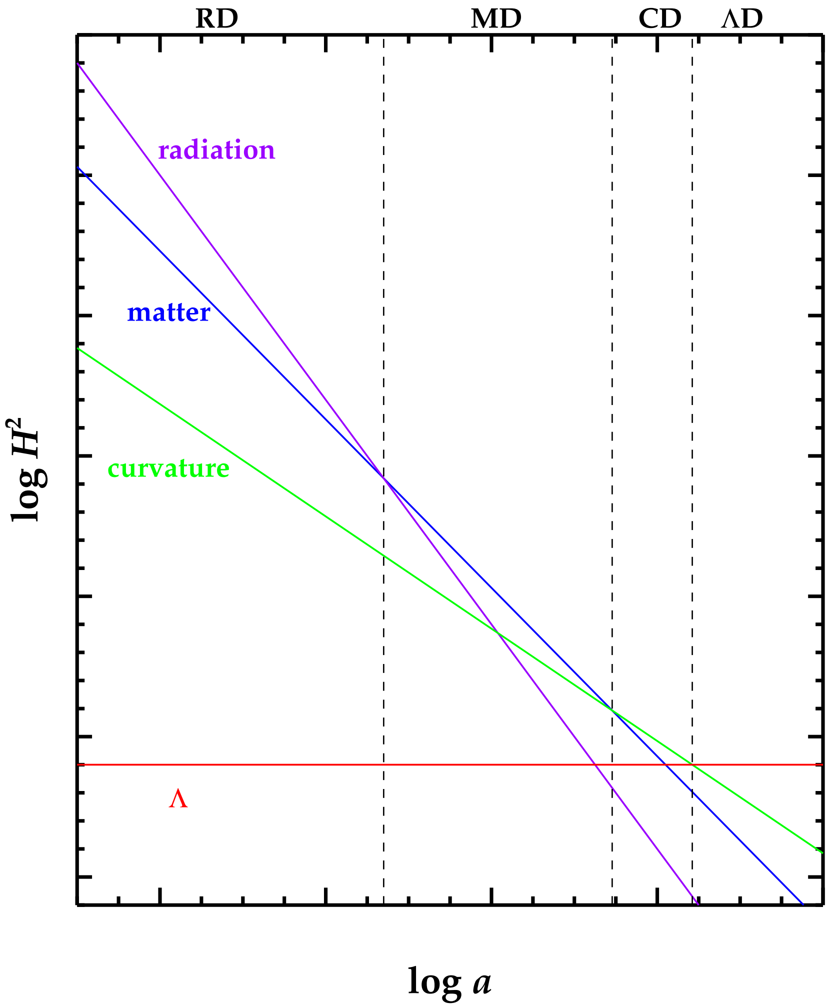
Mix-n-match:

Q: evolution if only matter & rad?

Q: ... if matter, rad, and curv(±)?

Q: ... if matter, rad, and Λ?

Q: ... if matter, rad, curv, and Λ?



In order of appearance:

RD = radiation dominated

MD = matter dominated

CD = curvature dominated

ΛD = Λ dominated

Radiation and the Early Universe

note: radiation *always wins out* at early times *Q: why?*
and so:

the early Universe is radiation-dominated

$$\rho = \rho_{\rm m} + \rho_{\rm rad} + \rho_{\Lambda} \approx \rho_{\rm rad} \quad (6)$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho - \frac{\kappa c^2}{R^2 a^2} \approx \frac{8\pi}{3}G\rho_{\rm rad} \quad (7)$$

later evolution (which components dominate)
depends on cosmic ingredients
and their relative amounts

The Early Universe and Particle Physics

The Early Universe: Particle Content

radiation density scaling $\rho_{\rm rad} \propto T^4 \propto a^{-4}$
guarantees that the Early Universe is radiation dominated

in Early Universe:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 \approx \frac{8\pi G}{3}\rho_{\rm rad} \tag{8}$$

Q: what determines when this approximation is good?
Q: Hint–when does this approximation break down?

imagine: "run the movie backwards" to ever earlier times
Q: what particles become relativistic? When?
Q: will new varieties of particles appear? When?
Q: what particles will be around at $T \gtrsim 1$ TeV?
Q: how can we learn about the microphysics of such epochs?
Q: how can we learn about earlier times?

Radiation Domination requires $\rho_{\rm rad} \gg \rho_{\rm matter}$

breaks down at *matter-radiation equality* $\rho_{\rm rad} = \rho_{\rm matter}$

$$\rho_{\rm rad,0}\ a_{\rm eq}^{-4} \ = \ \rho_{\rm matter,0}\ a_{\rm eq}^{-3} \tag{9}$$

- equality scale factor $a_{\rm eq} = \rho_{\rm r,0}/\rho_{\rm m,0} \sim 10^{-4}$
- redshift $z_{\rm eq} \sim 10000$
- temperature $T_{\rm eq} \sim 3 \times 10^4$ K ~ 2.5 eV

relativistic particles have $mc^2 \ll kT$ or in energy units $m \ll T$

- today: γ, possibly some ν are relativisitic
- at matter-rad equality: all (standard) ν definitely relativitistic
- earlier still: always attain T above any known mass m and then *the cosmic thermal bath creates new particles*
- all known (accelerator) particles today have $m < 1$ TeV so all known particles abundant and relativistic at $T > 1$ TeV
- earlier still: *unknown* particles created if they exist!

The Universe is

the poor [wo]man's accelerator

–Yakov Zel'dovich

Particle Physics

Antimatter

Fundamental result of Relativistic QM:

every particle has an antiparticle

- $\overline{e^-} = e^+$ positron
- $\bar{p} =$ antiproton

Fermilab: $p\bar{p}$ collisions

antimatter is **not** second class citizen!

e.g.: e^+ totally *stable* when left alone

So why so volatile in the lab?

`www:` e^+ `annihilation in Galactic center`

Antiparticle Properties

mass $m(\bar{x}) = m(x)$
decay lifetime $\tau(\bar{x}) = \tau(x)$
spin $S(\bar{x}) = S(x)$
electric charge $Q(\bar{x}) = -Q(x)$

sometimes particle = own antiparticle
Q: if so, what must be true?
e.g., $\bar{\gamma} = \gamma$
but: $\bar{n} \neq n$