Astro 596/496 NPA
Lecture 13
February 15, 2019

Announcements:

- **Problem Set 2** due today
- **Preflight 3** due next Friday

Last time: *Al Friedmann's amazing equation*
Q: Friedmann (energy) eq is...?
Q: what factors are constant? what are variable?

Looking ahead: nuke/particle tour of cosmology

- known microphysics: cosmic microwave background
- known microphysics: big bang nucleosynthesis
- new physics: the dark universe
  particle dark matter, dark energy

Friedmann (Energy) Equation

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

variables change with time

a: cosmic scale factor

ρ: total cosmic mass-energy density

constants fixed for all time

$\kappa = \pm 1$ or 0: sign of "energy" (curvature) term

R: characteristic lengthscale, GR $\rightarrow$ curvature scale

The Cosmic Microwave Background

CMB: Discovery

Penzias & Wilson (1965)
"A Measurement of Excess Antenna Temperature at 4080 Mc/s"

- Bell Labs (Holmdel, NJ) radio telescope
- careful checks of systematics! this is most of their paper!
  ...obligatory pigeon story

`www: Penzias & Wilson paper`

note: *antenna temperature* $T_{\mathrm{ant},\nu}$ measures radio (bolometer) specific *intensity* I_ν at a given frequency ν

$$I_\nu = B_\nu(T_{\mathrm{ant},\nu}) \qquad (2)$$

to be same a blackbody with Planck spectrum B_ν at T_{ann}
Penzias & Wilson: $\nu = 4.080$ GHz

Excess Antenna Temperature at 4080 Mc/s

Penzias & Wilson (1965)

- $T_{\text{ant},\nu} = 3.5 \pm 1.0$ K at $\nu = 4.080$ GHz
- other properties:

> This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 - April, 1965).

Q: what does this imply about thermal/nonthermal components?

Q: why seasonal variations important?

Q: how did P&W know the spectrum is thermal?

Note: the strict empiricism in 2-page P&W writeup:

- *none* of the words "cosmology," "universe," or "background" appear in any form
- not even any direct claim that the signal is extraterrestrial!

Entire P&W interpretive discussion follows:

> A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter...

...which is entitled

"Cosmic Black-body Radiation"

The Isotropic CMB: Present Data

Spectrum

best data: FIRAS instrument on
Cosmic Background Explorer (COBE)
Fixsen et al (1996):

- `www:` $T_{\rm antenna}$ `plot` – consistent with purely thermal
- present all-sky temperature

$$\boxed{T_0 = 2.7255 \pm 0.0006 \text{ K}}$$

- from Wien's law: spectral peaks are

$$\lambda_{\rm max} = \frac{0.290 \text{ cm K}}{T_0} = 1.06 \text{ mm} \tag{3}$$

$$\nu_{\rm max} = 58.5 \text{ GHz K}^{-1} \, T_0 = 159 \text{ GHz} \tag{4}$$

Note: $\nu_{\rm max} \lambda_{\rm max} \neq c$!

Derived CMB Properties

the CMB is a blackbody, and thus:
the temperature completely determines its properties!

energy density

$$\varepsilon_{\gamma,0} = \frac{\pi^2}{15} \frac{(kT_0)^4}{(\hbar c)^3} = 0.26057 \text{ eV/cm}^3 \quad (5)$$

evolving as $\varepsilon_\gamma = \varepsilon_{\gamma,0}/a^4 = (1+z)^4 \ \varepsilon_{\gamma,0}$
Q: c.f. starlight? `www: cosmic radiation backgrounds`

equivalent mass density

$$\rho_{\gamma,0} = \frac{\varepsilon_{\gamma,0}}{c^2} = 4.6451 \times 10^{-34} \text{ g/cm}^3 \quad (6)$$

much less than matter density today! $\rho_{\gamma,0} \ll \rho_{\text{m},0}$

Q: Implications of Planck shape to spectrum?

Planck Form: Implications

The observed CMB is consistent, at high precision, with
a purely Planckian form
that is: to high precision, **the CMB is a perfect blackbody**

but a blackbody spectrum:
- characterizes a system in thermodynamic equilibrium at T
- is independent of the size, shape, or composition of the system in equilibrium
- see extras below for more on this

thus the CMB implies that
the Universe once attained thermodyanmic equilibrium
i.e., the Universe was once "*in good thermal contact*"
...we'll make this notion more precise

Note also that the *present* universe
must be *transparent* to the CMB

Q: why is this? what's the evidence?

Q: what does this imply about epoch probed by CMB?

The present Universe is transparent to the CMB

e.g., high-redshift radio sources (quasars) are visible
thus the CMB is now *decoupled* from cosmic matter
and has been, at least to largest observed sources $z \gtrsim 10$

thus: for at least $z \lesssim 10$, matter and radiation
in the Universe were *not held in equilibrium*

the equilibrium and thermalization needed to come earlier

- higher density
- higher temperature

the Planckian CMB points to a hot, dense early Universe

To Be or Not to Be Relativistic

for a particle ("species") of mass m
relativistic status set by comparison: typical speed v vs c
equivalent to comparing: typical $E_{\rm kin}$ vs mc^2
but if thermal, $E_{\rm kin} \sim kT$
$\rightarrow$ relativistic: $kT \gg mc^2$ $\rightarrow$ non-relativistic: $kT \ll mc^2$

massless particles
if $m = 0$: always have $v = c$ $\rightarrow$ forever relativistic

massive particles
if $m > 0$: *always* a time in Early U when $kT \gg mc^2$
$\rightarrow$ massive particles born relativistic, become non-rel!
$\rightarrow$ relativistic status is time-dependent!

Q: are there species which are always *relativistic? non?*
Q: what is relativistic, non-rel today?

Today: $kT_{\text{CMB},0} \sim 10^{-4}$ eV
always: photons relativistic because $m_\gamma = 0$
gravitons also massless (if they exist)
clearly: $m_e c^2, m_p c^2 \gg kT_0 \to$ non-relativistic today!
but *were* relativistic in early U

but what about *neutrinos?*
looking ahead, we know: 3 massive species exist
do not (yet!) know mass of any species
but we *do* know their mass differences
for experts: oscillation experiments measure $\delta m_{ij}^2 = m_i^2 - m_j^2$
which set a laboratory-based *lower limit*:
heaviest neutrino must have $m_\nu > 0.04$ eV
$\to$ *at least one ν species non-relativistic today!*
$\to$ contributes to matter density ρ_{matter}

Radiation and Friedmann

definition: to cosmologist, **radiation** $\equiv$ *relativistic* matter
photons or *any* particle with $v \sim c$, $E \sim T \gg mc^2$
energy density $\varepsilon_{\rm rad} \propto a^{-4}$
equivalent gravitational mass density: $\varepsilon = \rho c^2 \rightarrow \rho_{\rm rad} \propto a^{-4}$

Add radiation to Friedmann:

$$\rho = \rho_{\rm total} = \rho_{\rm m} + \rho_{\rm rad}$$

note: today, $\rho_{\rm r,0} < 10^{-4} \rho_{\rm matter}$

Also: Maxwell says pressure $P_{\rm EM} = \varepsilon_{\rm EM}/3$
- include this in Friedmann acceleration
- put $V = a^3$, so $\varepsilon \propto V^{-4/3}$, and

$$d(\varepsilon_{\rm rad} V) = -1/3\, \varepsilon\, dV = -p_{\rm rad}\, dV$$

Q: physical interpretation?

Density Evolution

to solve Friedmann, need $\rho(a)$ for all cosmic components

Cosmological "**1st Law of Thermodynamics**"

$$\boxed{d(\rho c^2 a^3) = -p\ d(a^3)} \tag{7}$$

GR verifies this is correct!

$\Rightarrow$ reconciles Friedmann energy, accel eqs:

ensures that $\ddot{a} = d\dot{a}/dt$ (try it!)

to solve, need to relate p to ρc^2 $\rightarrow$ **equation of state**

- non-rel matter: $p_{\rm m} \ll \rho_{\rm m} c^2 \approx 0$ *Q: why? e.g., ideal gas?*
- radiation: $p_{\rm rad} = \rho_{\rm rad} = \rho_{\rm rad} c^2/3$

Equation of State: Constant Scaling with Density

generalize:

$$\boxed{p = w\rho c^2} \tag{8}$$

defines "*state parameter*" w

Q: what are w_{matter} *and* w_{rad}*?*

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

$$\rho_w \propto a^{-3(1+w)} \tag{9}$$

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"):
$P_{\rm m} \ll \varepsilon_{\rm m} \approx \rho_{\rm m} c^2 \Rightarrow P_{\rm m} \simeq 0$ ($w_{\rm m} \simeq 0$)
$\Rightarrow \rho_{\rm m} \propto a^{-3}$

Radiation (relativistic species): today, photons and neutrinos
$P_{\rm rad} = \varepsilon_{\rm rad}/3 = 1/3\ \rho_{\rm rad} c^2 \Rightarrow w_{\rm rad} = 1/3$
$\rightarrow \rho_{\rm rad} \propto a^{-4}$

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?