Astro 596/496 PC
Lecture 27
March 29, 2010

Announcements:
• PF5 due Friday at noon

Up till now: worked up in z, back in t
studied homogeneous universe = cosmology to zeroth order
= unperturbed / background spacetime

Today: begin inflation
⋆ highest z, earliest t we will visit
⋆ transition from homogeneous → inhomogeneous Universe
⋆ afterward, we will go forward in t
study how inflationary (?) density perturbations
are written onto CMB and grow to structures today

Cosmological Inflation

The Standard Cosmology: Successes and Discontents

"Standard Cosmology" – FLRW

- General Relativity with
- cosmological principle, and
- perfect fluid, endowed with
- laboratory physics: atomic, nuclear, particle

How's it going?

Q: what are qualitative, quantitative successes?

Q: what questions, loose ends, untested assumptions remain?

Cosmology Scorecard: Triumphs

Standard Cosmology successfully accounts for observed

⋆ Hubble expansion

also cosmic time dilation

⋆ dark night sky (Olber's paradox)

Q: why is this is a problem? how does FLRW resolve it?

⋆ existence of a highly isotropic CMB

with a thermal spectrum

also its temperature redshifting

⋆ primordial light element abundances

^{4}He to $\sim$ 10%

D to $\sim$ 30%

^{7}Li to $\sim$ factor 2-3

A good list! Enough to inspire some confidence

...but pressing questions remain

Cosmic Loose Ends

Unexplained observations & unanswered puzzles

? what is the dark matter? why is $\rho_{\rm m}/\rho_{\rm B} \sim 7$ today?

? what is the dark energy? why is $\rho_{\Lambda}/\rho_{\rm m} \sim 2$ today?

? why is $\Omega_0 \approx 1$? **"flatness problem"**

? why is the CMB so isotropic
especially for angular scales $> \theta_{\rm horizon,recomb} \sim 1^\circ$
"horizon problem"

? why is the U so homogeneous on large scales?
"smoothness problem"

? what is the origin of *in*homogeneities on small scales?
"lumpiness problem"

Note:

- important questions but not *inconsistencies* per se
- suggests Standard Cosmology incomplete but not wrong
  points to new physics

From Outer Space to Inner Space: Other Triumphs and Questions

Elementary particle physics also has Standard Model

⋆ Incorporates (via quantum electrodynamics) non-rel QM
inherits successes of atomic physics ($\sim$ eV scales)

⋆ Incorporates (via quantum chromodynamics) nuke physics
inherits successes at $\sim$ MeV scales

⋆ all lab experiments understandable in terms of
3 families of quarks & leptons
4 fundamental interactions (strong, weak, E&M, gravity)

⋆ E&M and weak forces can be *unified*: "electroweak"
understood as low-energy asymmetric manifestation
of one high-energy symmetric interaction
i.e., at $E \gtrsim 100$ GeV, EM & weak have same coupling, strength
cost: invent new scalar field/spin-0 particle: Higgs
without Higgs: massive photon, massless electron!
with Higgs: unification, precision: agree w/ expts to $< 1\%$!

Beyond the Standard Model of Particle Physics

Spectacular successes raise questions:

- does the Higgs exist? is it a fundamental particle or composite?
- why 3 families?
- why particles masses, interactions?
- why is matter fermionic, force carriers bosonic?
- are other unifications possible?

$\Rightarrow$ Standard Model not wrong but incomplete!

Note similarity to Standard Cosmology: more than coincidence?
solutions might indeed be related
e.g., new interactions, particles $\rightarrow$ dark matter candidates

Particle Standard Model points beyond itself

motivates theories to explain observed patterns

- Supersymmetry (SUSY): boson-fermion symmetry
- unite strong + electroweak: "grand unification theory" (GUT)
  - ⋆ interaction strengths change with energy
  - ⋆ same at $E_{\rm GUT} \sim 10^{15}$ GeV
- unite gravity too: quantum gravity/string theory

  scale: Compton wavelength (QM) $\sim$ Schwarzchild radius (GR)

  when $E \sim M_{\rm Planck} = \sqrt{\hbar c/G} \sim 10^{19}$ GeV

  $r \sim 10^{-33}$ cm, $t \sim 10^{-43}$ s: Planck scale

All have major cosmological consequences

▷ e.g., SUSY: essentially *demands* WIMPs!

a problem if not discovered soon!

▷ but also, present cosmo puzzles more severe

in Early Universe: worth quantifiying more precisely

since maybe Early U also offers solution

Standard Cosmology: Quantitative Questions

Flatness Problem

Now: $\Omega_0 \sim 1$, i.e., $|\Omega_0 - 1| = 0.0023^{+0.0054}_{-0.0056} \ll 1$ (WMAP 2010!)
but Friedmann says

$$|\Omega - 1| \equiv |\Omega_\kappa| = \frac{c^2}{R^2}\left(\frac{1}{aH}\right)^2 = \frac{c^2}{R^2}\left(\frac{1}{\dot{a}}\right)^2 \tag{1}$$

expect $|\Omega - 1|$ smaller in rad-dom, matter-dom past *Q: why?*
at $z_{\text{rec}} \sim 1000$, $\Omega = 1 \pm 10^{-5}$
at $z_{\text{BBN}} \sim 10^{10}$, $\Omega = 1 \pm 10^{-18}$
$\Rightarrow$ *what made the Universe this flat?*

Horizon Problem

CMB almost at particle horizon
regions $\theta_{\text{hor,rec}} \gtrsim 1^\circ$ outside particle horzion at recomb
so CMB sky surveys $\Omega_{\text{sky}}/\Omega_{\text{hor,rec}} \sim 4\pi/\pi\theta^2_{\text{hor,rec}} \sim 10^5$
causally disconnected regions
$\Rightarrow$ *how did they become coordinated to $\Delta T/T \sim 10^{-5}$ level?*

Unwanted Relics

Particle theories beyond the standard model
bring trouble as well as benefits
$\longrightarrow$ often predict relic particles we *don't* want

canonical example: grand unification (GUTs)
good news: naturally violate baryon number
source of matter/antimatter asymmetry?
bad news: naturally predict magnetic monopoles
unobserved, strongly constrained (lead to topological defects)
$\Rightarrow$ no more than $\lesssim 1$ per horizon today

If GUTs correct, monopole production seems unavoidable
$\Rightarrow$ *how did the U. get rid of monopoles?*

Beyond Standard Cosmology: Inflation

Part I: Abstract Inflation

The basic idea:

If the early U. experienced a extended phase of

accelerated expansion, huge ($\sim e^{60}$) increase in scale factor a

...several cosmological birds killed with one stone

Q: which problems, how fixed?

Inflation: the Magic of Acceleration

Flatness Problem

qualitatively: inflate away the curvature

quantitatively:

★ curvature scale $R(t) = a(t)\, R_0$ hugely enlarged

Friedmann curvature term $\kappa/R(t)^2 \to 0$

★ departure from flatness $|\Omega - 1| \equiv |\Omega_\kappa| \sim 1/R^2\dot{a}^2$

changes as $d/dt\ |\Omega_\kappa|\ \propto \ddot{a}$

$\Rightarrow$ **acceleration** drives $\Omega \to 1$!

but note: then lumpiness problem worse! (for now)

Horizon Problem

qualitatively: small causal (sub-horizon) region
expanded to exponentially large scales
CMB really samples one causal region!

★ at time t, max physical distance any particle can travel in next Hubble time $\delta t = t_H = 1/H(t)$ is

$$\delta\ell_{\rm phys}(t) \leq c\delta t = \frac{c}{H} = d_{\rm H}(t) \tag{2}$$

i.e., the Hubble length at t, and max comoving distance is

$$\delta\ell_{\rm com} = \frac{\delta\ell_{\rm phys}}{a} = \frac{c}{aH} = d_{\rm H,com} \tag{3}$$

comoving Hubble length at t

★ compare with: comoving particle horizon

$$d_{\rm hor,com} = \int_0^t \frac{dt'}{a(t')} = \int_0^{a(t)} \frac{da}{a^2 H} = \int_0^{a(t)} \frac{da}{a} d_{\rm H,com} \tag{4}$$

Q: what is physical distinction between $d_{\rm hor,com}$ and $d_{\rm H,com}$?

The difference: *now* versus *ever*!

- comoving Hubble length $d_{\mathrm{H,com}}$ is
  max comov dist a particle can travel in next Hubble time
  $\Rightarrow$ size of U *presently* (i.e., at t) in causal contact
- comoving particle horizon $d_{\mathrm{hor,com}}$ is
  max comov dist a particle can ever have traveled
  $\Rightarrow$ size of U *ever* in causal contact

Can be comparable, but do not have to be!

Note different time evolution:

▷ $\dot{d}_{\mathrm{hor,com}} = c/a \geq 0$ never decreases *Q: why?*

▷ but $\dot{d}_{\mathrm{H,com}} = d(aH)^{-1}/dt = -\ddot{a}/\dot{a}^2 < 0$ in **accelerating** U!

$\Rightarrow$ acceleration shrinks causal region!