Astro 507
Lecture 28
April 2, 2014

Announcements:

- **PF 5 was due today**
- **PS 5 out, due next Friday**
- **No class next Monday April 7;** see you Wednesday

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

Now: begin inflation
★ highest z, earliest t we will visit
★ transition from homogeneous $\rightarrow$ 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 $\sim$ 5%

^{7}Li to $\sim$ factor 3–4

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

July 5, 2012: Higgs discovery announced!
Nobels distributed 2013!
last particle of Standard Model accounted for
$\longrightarrow$ *if other particle every found: new physics*

Spectacular successes raise questions:

- is Higgs 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 $E_{\text{GUT}} \sim 10^{15}$ GeV
- unite gravity too: quantum gravity/string theory
  scale: Compton wavelength (QM) $\sim$ Schwarzchild radius (GR)
  when $E \sim M_{\text{Planck}} = \sqrt{\hbar c/G} \sim 10^{19}$ 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 quantifying more precisely
since maybe Early U also offers solution

Standard Cosmology: Quantitative Questions

Flatness Problem

Now: $\Omega_0 \sim 1$, i.e., $|\Omega_0 - 1| = 0.0005^{+0.00033}_{-0.00033} \ll 1$
(Planck 2013 + LSS!)
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 $z_{\rm rec} \sim 1000$, $\Omega_{\rm rec} = 1 \pm 10^{-6}$
at $z_{\rm BBN} \sim 10^{10}$, $\Omega_{\rm bbn} = 1 \pm 10^{-19}$
$\Rightarrow$ *what made the Universe this flat?*

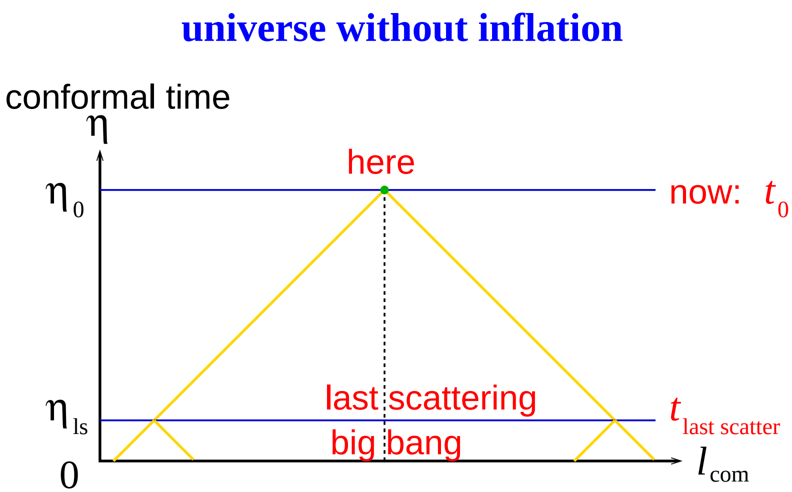
Horizon Problem

angular size of particle horizon at recombination (PS4):

$$\theta_{\rm hor,rec} \gtrsim 1^\circ \tag{2}$$

Q: implications for CMB regions $> 1^\circ$ apart?

CMB regions separated by angles $\theta_{\text{hor,rec}} \gtrsim 1^\circ$
lie outside each other's particle horizon
$\longrightarrow$ *causally disconnected*



so CMB sky surveys contains a number of regions

$$\frac{\Omega_{\text{sky}}}{\Omega_{\text{hor,rec}}} \sim \frac{4\pi}{\pi\theta^2_{\text{hor,rec}}} \sim 10^5 \qquad (3)$$

which are 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:

Imagine the early U. experienced a phase of

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

if so:

several cosmological birds killed with one stone

Q: which problems, how fixed?

Inflation: the Magic of Acceleration

Flatness Problem

qualitatively: inflate away the curvature

⋆ curvature scale $R(t) = a(t)\, R_0$ hugely enlarged
Friedmann curvature term $\kappa/R(t)^2 \rightarrow 0$

⋆ 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 $\Omega \rightarrow 1$!
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

$$\delta\ell_{\mathrm{phys}}(t) \leq c\delta t = \frac{c}{H} = d_{\mathrm{H}}(t) \tag{4}$$

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

$$\delta\ell_{\mathrm{com}} = \frac{\delta\ell_{\mathrm{phys}}}{a} = \frac{c}{aH} = d_{\mathrm{H,com}} \tag{5}$$

comoving Hubble length at t

★ compare with: comoving particle horizon

$$d_{\mathrm{hor,com}} = \int_0^t \frac{dt'}{a(t')} = \int_0^{a(t)} \frac{da}{a^2 H} = \int_0^{a(t)} \frac{da}{a} d_{\mathrm{H,com}} \tag{6}$$

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

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!

Inflating Away the Horizon Problem

quantitative solution to horizon problem:
comoving **particle horizon** $d_{\text{hor,com}}$
sets region *ever* causally connected, and
always increases

but: causally connected universe at time t
has size set by comoving **Hubble length** $d_{\text{H,com}} = 1/aH = 1/\dot{a}$

▷ if $\dot{a}$ increasing = cosmic acceleration, then $d_{\text{H,com}}$ decreasing
causal region of U *shrinks* during inflation

▷ also, shows that horizon, flatness linked
solving one solves the other!

Monopole Problem

qualitatively: solution via dilution: inflate them away!

quantitatively: relic number density $n_{\text{monopole}} \propto a^{-3}$

if a grows by e^{60}, number drops by e^{180}

"dilution is the solution to your pollution!"

some benefits of acceleration appreciated pre-inflation

e.g., Hoyle, Gold, Bondi, Starobinskii, Kazanas...

$\longrightarrow$ by 1980, it was "in the air" that

early U. acceleration is devoutly to be wished for

Yes, But..

but wishing doesn't make it so:

- what causes acceleration?
- how can it be tested?