Astro 350
Lecture 39
Dec. 7, 2012

Announcements:

- **Homework 11** due now
- Good news: now more homework!
- Bad news: Final Exam next Friday Dec 14, 8-11am here
  `www: Final Exam Info online`
- **ICES** available online – please do it!
  I do read and use comments!

Last time: cosmic inflation

Q: what is it? How it is different from (more than) the usual expansion of the universe?

Q: how does inflation make the universe flat?

Q: how does inflation fix the horizon problem? lumpiness?

Inflation

idea: Early U had period of rapid *accelerated* expansion

- during inflation, scale factor grew by $e^{60} \simeq 10^{26}$!
- expansion accelerated–like dark energy now

flatness

curvature inflated away `www: balloon analogy`

horizon

▷ tiny initial causal region ($\ll$ atom size: microscopic!)

▷ expanded to huge scales ($\gg 1$ Mpc: macroscopic!)

diagram: cosmic spacetime with, without inflation

density fluctuations

pre-inflation: microscopic horizon

$\rightarrow$ quantum effects important

quantum fluctuations present & *inevitable*

if no expansion, or decelerating expansion

$\rightarrow$ fluctuations undone soon after created

but if *accelerated* expansion

"nearby" fluctuations soon far apart, carried at speed $> c$

can't be undone $\rightarrow$ inflated to macroscopic scales

Inflation Status

Inflation Scorecard: Fall Semester 2012

Prediction	Score
flatness	$\star$
isotropy	$\star$
fluctuations	$\star\star\star\star\star$
gravity waves	DF*

*Grade deferred till *Planck Explorer: Results public Jan 2013*

Pessimist's view

- most of these are really post-dictions
  $\rightarrow$ inflation *invented* to solve these problems
- no fundamental (i.e., particle physics) understanding of inflaton ϕ
- no competing theory as an alternative
  a lack of imagination? a cosmic epicycle?

Q: optimist's response?

Optimist's view

- fluctuations impressive, and a *pre*diction
- turn problem around:
  CMB probes inflation ϕ
  $\Rightarrow$ the U. as the "poor man's accelerator"
- there *were* competing theories
  for density fluctuation origins, but they're ruled out now

Who's right?

- the data will show (esp. gravity waves)
- but still a good idea to
  try to develop competing ideas...

Stay tuned!

Epilogue: Living With Inflation

Inflation arises from a marriage of
- ideas about unification of forces (inner space)
- ideas about cosmology (outer space)

something like inflation almost unavoidable if combine these

but much remains to be understood
- how did the universe *start* inflating?
  what made vacuum energy dominant?
- how did the universe *stop* inflating?
  what made vacuum energy revert to matter & radiation?

- what if some regions of the universe are still inflating? if so, continuously becoming exponentially larger

$\rightarrow$ and our observable universe is a tiny part of the mostly inflating cosmic volume

- how are we so lucky to live in a non-inflating region sounds very anthropic...

lesson: if true inflation, profoundly changes our view of what "the universe" means

Structure Formation

Formation of Cosmic Structures

Starting point:

CMB gives a picture of the Universe at $t = 400,000$ years

- nearly homogeneous

  Q: how would density evolve if $\delta\rho = 0$ everywhere?
- but not perfectly: tiny temperature fluctuations present

  $\Rightarrow$ density *inhomogeneities* present

$$\delta\rho = \rho - \rho_{\text{average}} \neq 0 \quad \text{typically} \tag{1}$$

- CMB: typical density fluctuation size at 400,000 years:

$$(\delta\rho)_{\text{typical,CMB}} \approx \pm 10^{-4} \rho_{\text{average}} \tag{2}$$

Q: what does $\delta\rho < 0$ mean? how often does this occur?

Q: what is $\delta\rho$ in this room?

Density Fluctuations Over Time

at each point in Universe, density fluctuations $\delta\rho = \rho - \rho_{\rm average}$ measures *difference* from all-Universe *average density*

- $\delta\rho < 0$: $\rho < \rho_{\rm average}$, underdense ("void")
- $\delta\rho > 0$: $\rho > \rho_{\rm average}$, overdense ("clump")

at early times:
$|\delta\rho|_{\rm CMB} \approx 10^{-4}\rho_{\rm average}$ – fluctuations *tiny*

today:
average cosmic density $\rho_{\rm average} = \rho_{\rm crit} \approx 10^{-26}$ kg/m^3
in this room: $\rho_{\rm room} \approx \rho_{\rm air} - \rho_{\rm water} \approx 1 - 1000$ kg/m^3
so $|\delta\rho|_{\rm room} \approx (10^{26} - 10^{29})\rho_{\rm average}$ – fluctuations *enormous*

Q: what does this tell us?

Cosmic Structure Formation: The Big Picture

The CMB tell us: at $t = 400,000$ years the Universe was

- nearly homogeneous on all length scales
- with tiny density fluctuations present

Present-day observations tell us: at $t = 13.6$ billion yrs, U is

- homogeneous on large scales $\gg 30$ Mpc
- but with huge density fluctuations on smaller scales

Lesson:

- a lot happened between then and now!
- somehow the fluctuations on small scales
  grew to become large fluctuations = galaxies, stars, people

Q: so what happened?

iClicker Poll: An Overdense Region Over Time

Consider an *overdensity* with $\rho > \rho_{\text{average}}$
and thus $\delta\rho > 0$

Over time, density in the initially overdense region will

A become an increasingly higher multiple of the average

B become increasingly closer to the average

C remain the same fraction of the average

Q: what about an underdensity?
Q: what do we conclude about structure formation?

overdense region:

- more matter → more gravity
- expands slower → less diluted than average
- becomes even more dense than average

→ runaway process: **gravitational instability**

underdense region: same story but opposite sign
→ runaway process of becoming ever less dense than average

basic outcome:
"the rich get richer and the poor get poorer"

Seeds of Cosmic Structure

gravity amplifies density fluctuation "seeds"
(e.g., from inflation)
grow to structures we see (and are!) today

Challenge:
given $\delta\rho$ + known cosmic ingredients
can we understand how we got
from recombination ("CMB era") to today?

A Simplified Inhomogeneous Universe

Consider a stupidly simplistic–but illustrative!–Universe:

- everywhere in space (the average "background") homogeneous: uniform matter density $\rho_{\text{bg}} = \rho_{\text{crit}}$
- *except* in a sphere which has uniform matter density $\rho > \rho_{\text{crit}}$ but at first just barely larger, say $\rho_{\text{init}} = 1l.00001\rho_{\text{bg,init}}$

"spherical overdensity"

Cool property of gravity:
behavior of the uniform sphere is *the same*
as an entire universe with same density
i.e., a Universe with $\rho/\rho_{\text{crit}} = \Omega > 1$

Initially, both the background U and sphere are expanding
Q: what will happen to the background U? to the sphere?
Q: lesson for what happens in an inhomogeneous U?

background Universe:
has $\rho = \rho_{\text{crit}} \rightarrow$ evolves like $\Omega = 1$ Universe
$\rightarrow$ expands forever, density keeps going down

overdense sphere
has $\rho > \rho_{\text{crit}} \rightarrow$ evolves like $\Omega > 1$ Universe

- initially expands
- but gravity of sphere slows expansion
- eventually expansion stops, sphere reaches maximum size
- but gravity still attractive: sphere begins to collapse
- continues until reaching high density

lesson: overdense regions initially expand, reach maximum size
then "pulls away" from cosmic expansion, and "turn around"
collapse to form dense object: (proto) galaxy !?
$\rightarrow$ galaxies formed from overdense "seeds"
$\rightarrow$ also, Brooklyn is not expanding!