Astro 350

Lecture 40

Dec. 5, 2011

Announcements:

- **Final Exam**: Tue Dec 13, 8-11am `www: info online`
- Discussion Question *second chance*
  can do up to 2 missed questions for half credit each
  must turn in by end of this Wed Dec 7
- **ICES** available online – please do it!
  I do read and use comments!

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 $\delta\rho = \rho - \rho_{\text{average}}$ measures difference from all-Universe average density

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

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

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

Q: what does this tell us?

iClicker Poll: An Overdense Region

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

Compared to a region with $\rho = \rho_{\text{average}}$ the overdense region will

A expand faster

B expand at the same rate

C expand slower

Q: what about an underdensity?

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?

basic outcome:

“the rich get richer and the poor get poorer”

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 to today?

Q: consider overdense region: what does it do?

Gravitational (Jeans) Instability

Sir James Jeans:

if region overdense: what does it do?

competition:

outward expansion, pressure

vs

inward gravity

$\rightarrow$ like hydrostatic equil

during *radiation domination* (early U):

expansion too fast

density fluctuations barely grow

structure formation stalled until...

during *matter domination* ($z \lesssim 3000$):

gravity wins! density fluctuations amplified over time

Cosmic ingredients behave differently

• **dark matter** most of mass

form potential wells for baryons

weakly interacting $\rightarrow$ pressureless, begins collapse

galaxy "dark halos" form first!

• **baryons**=atoms: stil ionized, pressure too high

...until recomb., then begin collapse

free fall until $v >$ sound speed

shock waves form, gas slowed, heated $\rightarrow$ comes to equilibrium

Hierarchical Structure Formation

`www: movies! structure growth over cosmic time`

a "bottom-up" scenario
small structure form first
then **merge** to form larger structures
...which merge to form larger structures
...etc
`www: cluster formation`

dense regions connected by linear "filaments"
form knots in "cosmic web"
`www: cosmic web`

Testing Structure Formation

Q: what observations are available?

Q: what complications are there in comparing with predictions?
Hint–think about us:
at the location of the Milky Way, there was a “seed”
i.e., the density was higher than the cosmic average:
ρ(here) $>$ ρ(average) *Q: why?*

Q: so what determines what the cosmic density excess here?
Q: how does this complicate comparing predictions vs observations?

Since matter is gathered into galaxies
galaxies themselves are much denser than the U on average
and thus galaxies mark regions where cosmic density was
initially higher than average
i.e., galaxies tell (roughly) where the “seeds” were

But: theories like inflation “sow the seeds” **randomly**
i.e., no way to predict whether a specific point (x, y, z)
will be an overdensity or underdensity

So: the mere presence of a galaxy neither verifies or
refutes our models
Q: how can we overcome this problem?