Astro 406
Lecture 41
Dec. 9, 2013

Announcements:

- no PS this week!
- **Final Exam Dec 20** `www: info online` here, 8:00 to 11:00 am ...sorry!
- pay it forward: do your **ICES**

ASTR 401:
Comments this week
Paper in final form due **no later than Dec 20**
No extensions are possible!

Last time: cosmic inflation

- more than just expansion *Q: how so?*
- solves horizon and flatness *Q: how?*

Inflation Status

Inflation Scorecard: Fall Semester 2013

Prediction	Score
flatness	⋆
isotropy	⋆
fluctuations	⋆⋆⋆⋆⋆
gravity waves	DF*

*Grade deferred till *Planck Surveyor* results

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?

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
  ruled out by the data–and inflation wasn't

Who's right?

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

Stay tuned!

Structure Formation

The Cosmological Principle Revisited

the cosmological principle is not exact

Q: wait–what was the cosmological principle?

Q: why isn't it exact?

Q: range of validity today?

Cosmological Principle: Simplistic Version

the Universe is (and always was)

- *homogeneous*
- *isotropic*

`www: galaxy survey slices of the Universe`

Today at t_0: not exact

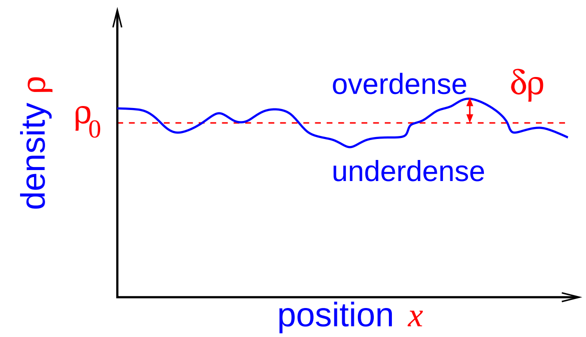
- *totally wrong on small scales* $\lesssim 30$ Mpc
  i.e., if average over spheres of $r \lesssim 30$ Mpc
  density, composition, temperature are very lumpy

- *good approximation* on larger scales
  i.e., averaging over $r \gtrsim 30$ Mpc

Cosmic Density Fluctuations

more quantitatively: at every point $\vec{x}$, write

$$\rho(\vec{x}) = \rho_0 + \delta\rho(\vec{x})$$



- ρ_0 is the cosmic *average density*
- $\delta\rho$ is the local *density fluctuation*

  a region with $\delta\rho > 0$: *overdensity*

  with $\delta\rho < 0$: *underdensity*

if we average over all points in space:

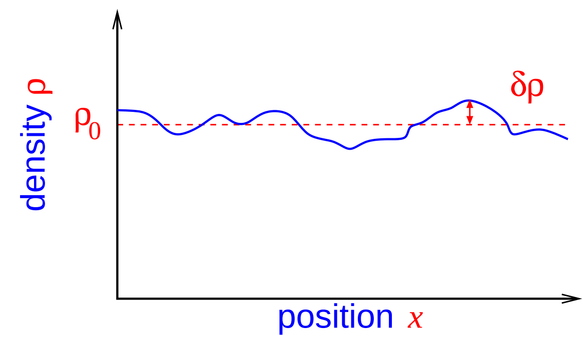
Q: what is $\langle\rho\rangle$*?*

Q: what is $\langle\delta\rho\rangle$*?*

Q: what's a good definition of large vs small fluctuations?

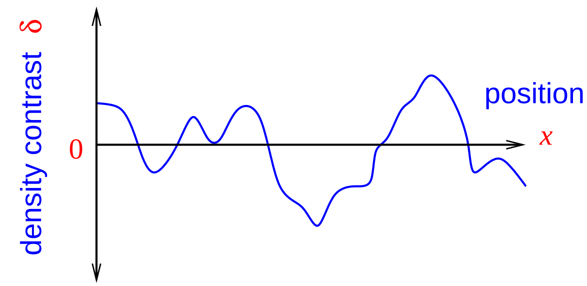
averaging over space:

- $\langle\rho\rangle = \rho_0$ and $\langle\delta\rho\rangle = 0$ by definition
- today: galaxy observation show smoothed over $r \lesssim 30$ Mpc: $|\delta\rho| \gtrsim \rho$ but $|\delta\rho| \ll \rho$ for large r



useful to also define **density contrast**

$$\delta(\vec{x}) \equiv \frac{\delta\rho(\vec{x})}{\rho_0} = \frac{\rho(\vec{x}) - \rho_0}{\rho_0}$$



i.e., the density field is

$$\rho(\vec{x}) = [1 + \delta(\vec{x})] \ \rho_0$$

iClicker Poll: The Cosmological Principle in Time

today, the cosmological principle is only approximate

Is the situation different at early times?

A the cosmo principle is *more accurate* at $t \ll t_0$

B the cosmo principle is *less accurate* at $t \ll t_0$

C the cosmo principle at $t \ll t_0$ has *the same accuracy* as today

Formation of Cosmic Structures

today at t_0: galaxy surveys

- $\delta = \delta\rho/\rho \gg 1$ $r \lesssim 30$ Mpc
  i.e., large fluctuations at small scales
- $\delta < 1$ for larger scales

at *recombination* $t = 3 \times 10^{-5} t_0$: CMB tell us

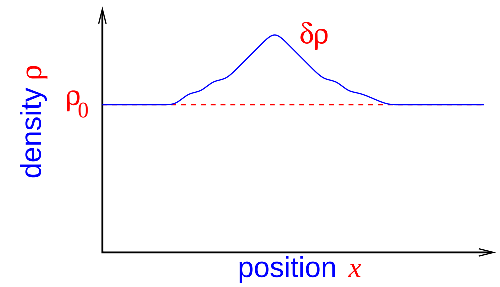
- typical $\delta_{\rm rec} = \delta\rho/\rho \sim 10^{-4}$
- *tiny (but nonzero!) fluctuations* at all scales
  somehow the *“seeds”* of structures today

Challenge:

given $\delta\rho_{\rm rec}$ + known cosmic ingredients
how did density fluctuation seeds
grow from recombination to structures seen today?

iClicker Twofer: Gravity and Cosmic Structures

Consider an *overdense* region
filled with *cold* matter (dark and baryons)



If no cosmic expansion, how will $\delta\rho$ change with time?

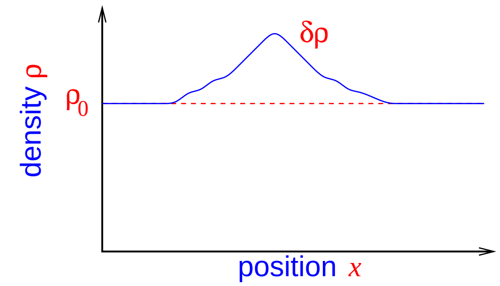
A it will increase

B it will decrease

C it will stay the same

With cosmic expansion, how will $\delta = \delta\rho/\rho$ change with time?

Jeans (Gravitational) Instability



Sir James Jeans:

if region overdense: what does it do?

if matter is *cold*, i.e., no pressure forces:
an overdense region $\delta\rho > 0$

- has more mass than neighbors
- has more gravity than neighbors
- draws in surrounding material
- becomes yet more overdense
- and draws in yet more matter...

system is unstable: **gravitational instability**
a.k.a. Jeans instability

"the rich get richer and the poor get poorer"

Gravitational Instability in Cosmology

In a *non-expanding system*
Jeans instability leads to *exponential growth*
i.e., $\delta_{\text{non-expand}}(t) = \delta_0 \ e^{+t/\tau}$, with grav. timescale $\tau \sim 1/\sqrt{G\rho_0}$

But in an *expanding universe*
expansion draws surrounding matter away from overdensity
competes with gravity
overdense region still gravitationally unstable and still grows
but growth not as fast:
for *cold matter* in a matter-dominated universe
with perturbations δ_{init} at time t_{init}

$$\delta(t) = \delta_{\text{init}} \ \left(\frac{t}{t_{\text{init}}}\right)^{2/3} \quad (1)$$

Q: what does this mean for how perturbations grow?

cold matter fluctuations in a matter-dominated universe grow as

$$\delta(t) = \delta_{\mathrm{init}} \left(\frac{t}{t_{\mathrm{init}}} \right)^{2/3} \tag{2}$$

so the initial density fluctuation pattern δ_{init}
is *amplified* over time

- initial overdensities become more overdense
- initial underdensities become more underdense
- and the *relative* contrast pattern remains the same

this continues until $|\delta\rho| \sim \rho_0$
i.e., $\delta \sim 1$

then: bound structures form–galaxy halos
and the halos interact and merge – nonlinear effects