Astro 507
Lecture 3
Jan 26, 2020

Announcements:

- Preflight 1 due Fri. Jan 31, noon **www: assignment**
  Note: answer in *two parts*
  1. reading response: private, only I see
  2. open-ended discussion question: public, everyone sees

Last time: cosmologist's toolbox of observables
www: Galactic coordinates
Q: we're doing cosmo–why even use Galactic coords?
Q: zone of avoidance? why are galaxies scarce here?

Today: Observational/Conceptual Foundations of Cosmology
★ Cosmological Principle
★ Observed Cosmic Kinematics: Hubble's Law
★ Implications of Cosmo Principle + Hubble Law

Galaxy Maps and Cosmic Structure

observable cosmo "building blocks" – galaxies
$\approx$ all stars in galaxies

`www: Galaxy Survey: 2dFGRS`
map galaxies in "slices" of sky 2° thick
Q: qualitative trends–small scales? large scales?

Q: how could we make this more quantitative?

Q: how to test these conclusions?

Large Scale Structure–First Look

galaxy distribution: qualitative trends
zoom in to **small scales:** **lumpy**
step back to **largest scales:** **smooth**

tests, e.g., with Sloan Digital Sky Survey `www: SDSS`
- is pattern same in "slices" from other directions? yes!
- if we focus select very luminous sources
  does pattern extend to large distances? yes!

quantitatively: smooth/"coarse-grain" U at different scales
find rms *mass or density fluctuation in sphere of radius* R
- clearly, $\delta M/M \gg 1$ over typical gal separation $R \sim 1$ Mpc
- but $\delta M/M \sim 1$ at $R \sim 10$ Mpc
- $\delta M/M < 10^{-4}$ at $R \sim 1000$ Mpc

Q: lesson?

The Homogeneous Universe

mass fluctuations on large scales:
$\delta M/M \rightarrow 0$ for $R \gg 10$ Mpc

we will revisit this in much more detail later
but for now we already see:

on large scales ($\gg 10$ Mpc)

- cosmic properties the same everywhere
- the Universe is homogeneous on large scales

Q: how does the distribution compare in different directions?

Isotropy

Now scan around the sky

directional dependence:
on large scales, galaxy distribution looks
(statistically) *same in all directions*

on large angular scales:
the Universe is isotropic

The Universe to Zeroth Order: Cosmological Principle

Observations teach us that
• at any instant of cosmic time ("epoch")
• to "*zeroth order*":
the Universe is both

1. **homogeneous** *average properties same at all points*
e.g., mass density anywhere is same as mass density everywhere!
i.e., $\rho(\vec{r}) = \rho$ indep of $\vec{r}$!

2 **isotropic** *looks same in all directions*

"Cosmological Principle"
the universe is homogeneous & isotropic
first guessed(!) by A. Einstein (1917)
• no special points! no center, no edge!
• "principle of mediocrity"? "ultimate democracy?"

The Far Reach of the Cosmological Principle

Do you need both homogeneity and isotropy?

Q: e.g., can a Universe be isotropic but not homogeneous?

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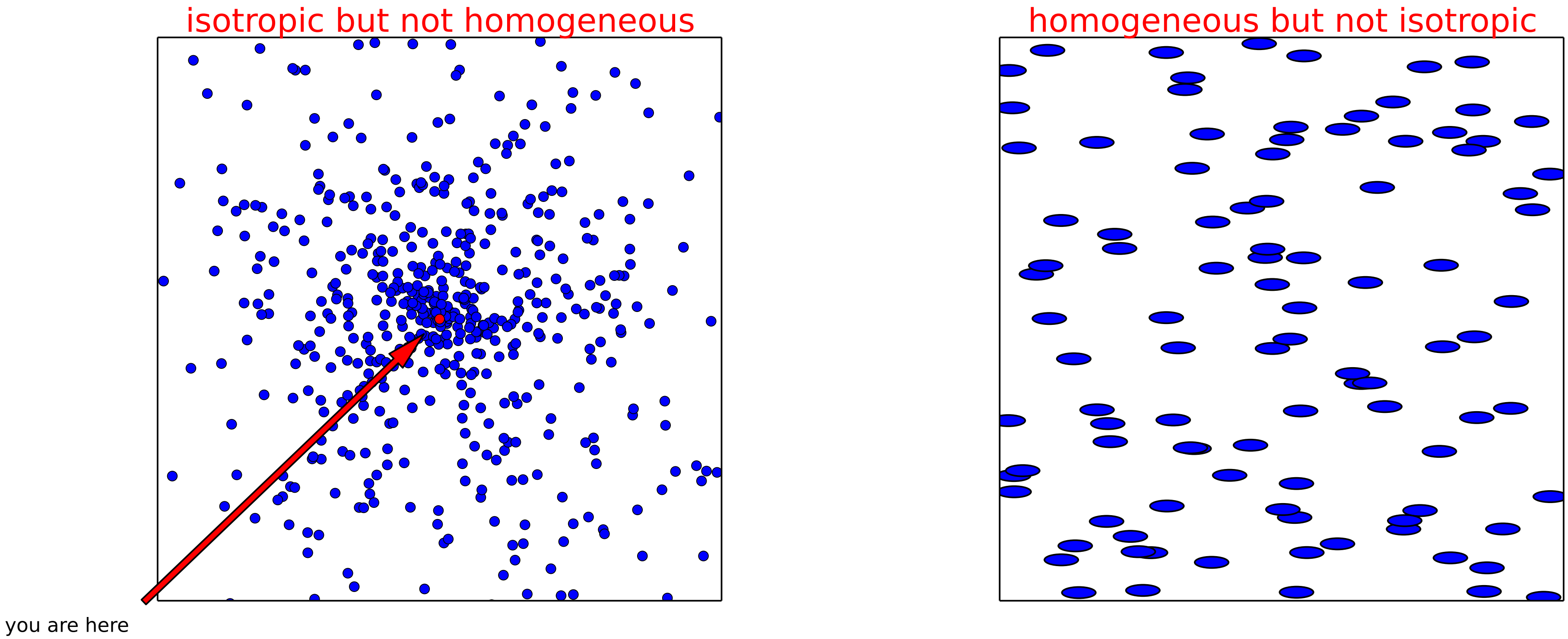
isotropic but not homogeneous
you are here
homogeneous but not isotropic

Example: Cosmological Principle and Galaxy Properties

Q: if cosmo principle true, how should it be reflected in observations of galaxies at any given time?

Q: what does cosmo principle say about how galaxy properties evolve with time?

Cosmo Principle and Galaxy Properties

at any instant of cosmic time:

- **average** density of galaxies same everywhere

- *distribution* of galaxy *properties* same everywhere
  range of types
  range of colors
  range of L, M, ...
  ratios of normal/dark matter

Note that these are very restrictive constraints!

time evolution of galaxies:

- must maintain large-scale homogeneity and isotropy
- but otherwise, *by itself cosmo principle allows any changes!*

Cosmo Principle hugely powerful & the "cosmologist's friend"
very strongly constrains possible cosmologies
$\rightarrow$ large-scale spatial behavior maximally simple

Cosmic Kinematics

Slipher, Hubble 1920's: galaxies' spectral lines shifted:

- galaxies move wrt us!
- all* galaxies show shift to red:

$\lambda_{\rm obs} > \lambda_{\rm lab} = \lambda_{\rm rest}$

Define: **redshift** z

$$z = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}} \quad (1)$$

if interpret as Doppler (for non-relativistic $v \ll c$)

$$v \approx cz$$

*Sloan Digital Sky Survey (SDSS: $\sim 10^6$ spectroscopic galaxy redshifts

16 galaxy blueshifts (many spurious), all $|z| \lesssim 0.001 \rightarrow$ Local Group (bound structure)

a big ASTR596PC thanx to data miner Adam Myers

Bizarre/Elegant Relativity/Particle Units I

chic relativity/particle physics parlance:
all v implicitly *in units of* c

amounts to

$$v_{\text{chic}} = \frac{v_{\text{ordinary}}}{c} \tag{2}$$

equivalent to putting $\boxed{c = 1}$
with rule: insert c factor anytime need v units

example: chic first-order Doppler relation
"$v \approx z$"

Distance–Speed Correlation

Edwin Hubble (1929)

`www: Hubble PNAS paper`

`www: original, old-school Hubble diagram`

groundbreaking despite challenges:
- data available only for nearby galaxies
- lots of scatter
- distance measures later found to be systematically wrong by huge factor

speed-distance correlation: linear

$$v_r \propto r \tag{3}$$

Hubble: $v_r = Kr$

but isotropy implies *Q: what?*

Hubble's Law

Hubble: $v_r = Kr$

isotropy $\Rightarrow$ same K in all directions

modern: Hubble's Law

$$\vec{v} = H\vec{r} \tag{4}$$

at present: time t_0 ("sub-0 = today")

measure: *Hubble* Key project (2001, based on Cepheids)

$$H_0 = 73 \pm 3_{\rm stat} \pm 7_{\rm sys}\ {\rm km\,s^{-1}\,Mpc^{-1}} \tag{5}$$

Hubble parameter or Hubble "constant" *Q: why scare quotes?*

Q: what are dimensions of H?

Q: why these crazy units?

The Plague of "Little h"

Back in the old days ($\gtrsim$ 10 yr ago): H_0 poorly measured
$H_0(\text{old data}) \sim 50 - 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$
Worse still: many cosmo results sensitive to H_0
$\rightarrow$ how to show effect of uncertainties?

Parameterized Uncertainty:
introduce "little h" via

$$H_0 \equiv 100 \; h \; \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{6}$$

i.e., $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$; (sometimes also called h_{100})

- back in the day, could only say: $h = 0.5 - 1$
- now–*HST* Cephieds: $h = 0.73 \pm 0.03 \pm 0.07$
  Planck CMB lensing $h = 0.673 \pm 0.012$

Q: little h is ugly–why invent it? why is it useful?

Why Little h?

can always write today's Hubble parameter as

$$H_0 \equiv 100 \; h \;\; \text{km s}^{-1} \; \text{Mpc}^{-1} \tag{7}$$

Why useful?

Historically: H_0 uncertain, major revisions since Hubble (1929)
1970s–1980s, debate: $H_0 = (50 \text{ or } 100) \text{ km s}^{-1} \text{ Mpc}^{-1}$
corresponds to $h = 0.5 - 1.0$

We will see: H_0 enters in most cosmological measurements

- uncertainty in H_0 propagates to many other quantities
- convenient to see how H_0 affects each quantity

example: distance to galaxy at $z = 0.1$? use Hubble law

$$d(z = 0.1) \approx \frac{cz}{H_0} = 300 \; h^{-1} \; \text{Mpc} \tag{8}$$

$\rightarrow$ in old days, all cosmo distances uncertain to factor 2!

Hubble Trouble Revived?

Today H_0 nightmare mostly over, thanks to HST and other measurements
...or is it?

In past ~ 4 years: discrepancy has emerged
• local astrophysical distance estimators give, e.g.,

$$H_0 = 73.24 \pm 1.74 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad \text{Riess+ 2016} \tag{9}$$

• we will see: high-redshift/large distance data imply

$$H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad \textit{Planck} \text{ 2018} \tag{10}$$

differences $\gg$ quoted uncertainties!
• a problem with either or both?
• or a hint of new physics?

so fossil h haunts us still! but note:
• H_0 and h precision is now $\sim 10\%$ or better
• for homework, roughly: $h \approx 0.7 \approx 1/\sqrt{2}$