Astro 350

Lecture 26

March 26, 2022

Announcements:

- **Discussion 7 due Wednesday**
- **Homework 7 due Friday**
- Paper abstracts graded–nice job!
  more grades coming soon!

Last time: mapping the Universe

survey galaxies, map locations in space

Q: behavior on small scales, at different locations, distances?

Q: behavior on large scales, at different locations, distances?

Q: lessons?

The Large-Scale Structure of the Universe: I

Observations teach us that, to a "first approximation":
the Universe *today* is

1. homogeneous: average properties same at all points
e.g., mass density anywhere is same as mass density everywhere!

and

2 isotropic: looks same in all directions

universe is homogeneous & isotropic:
the **"cosmological principle"**
first guessed(!) by A. Einstein (1917)

Q: as exact (not approximate) statement,
cosmo principle obviously false! Why?
In what sense could it be true?

Example: Cosmo principle and galaxy properties

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

Q: how could you test this?

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

Cosmo principle and galaxy properties:

at any given time:

- **average** density of galaxies same everywhere
- distribution of galaxy properties same everywhere

e.g., types, colors, L, M, ...

- time evolution: must maintain large-scale homogeneity and isotropy

but otherwise, **by itself** principle allows any changes!

Real Galaxies in the Real Universe

Beyond the First Approximation

cosmo principle a very good approximation

on large scales ($\gtrsim 50$ Mpc) `www: 2dF`

recall 1 Mpc $= 10^6$ pc $\sim$ typical distance between galaxies

but do observe fluctuations around average galaxy density

`www: 2dF maps`

on small to medium scales ($\lesssim 50$ Mpc),

galaxies **clustered** in space:

- loners: "field" galaxy
- few ($\lesssim 50$) galaxies: group
- 100's-1000's of galaxies: cluster
- assemblies of groups and clusters: supercluster

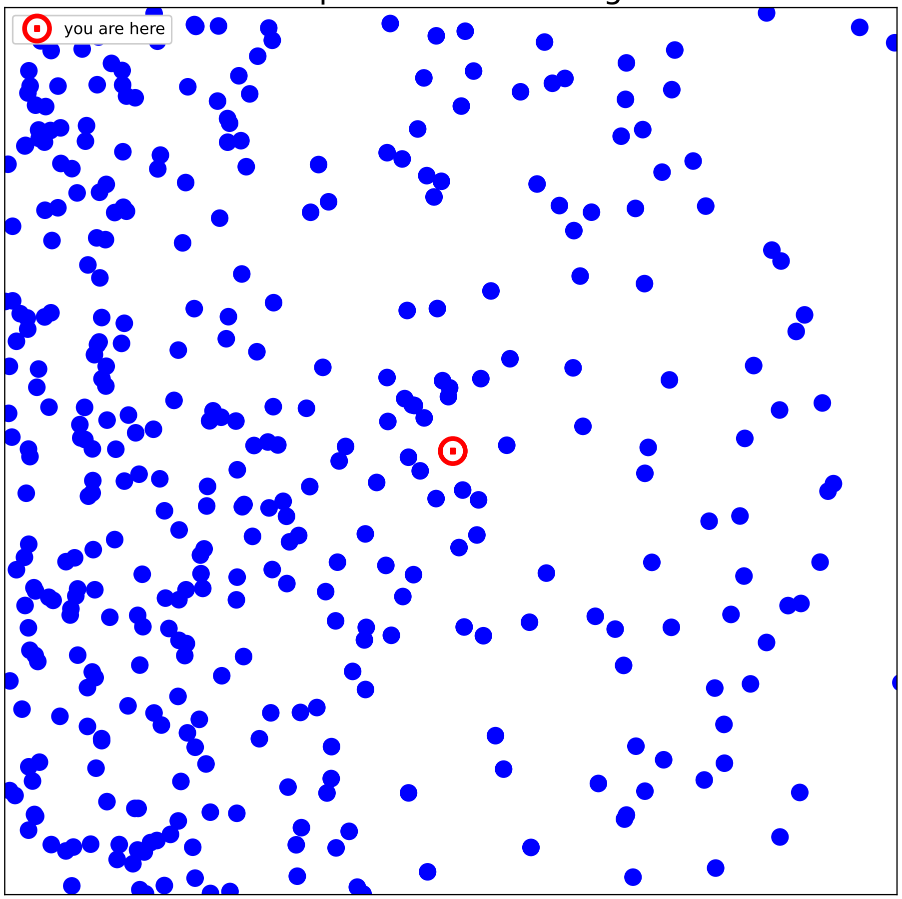
The Logic of the Cosmo Principle

Cosmo Principle:
On large scales ($\gtrsim 50$ Mpc), universe is
- homogeneous $\rightarrow$ smooth
- isotropic

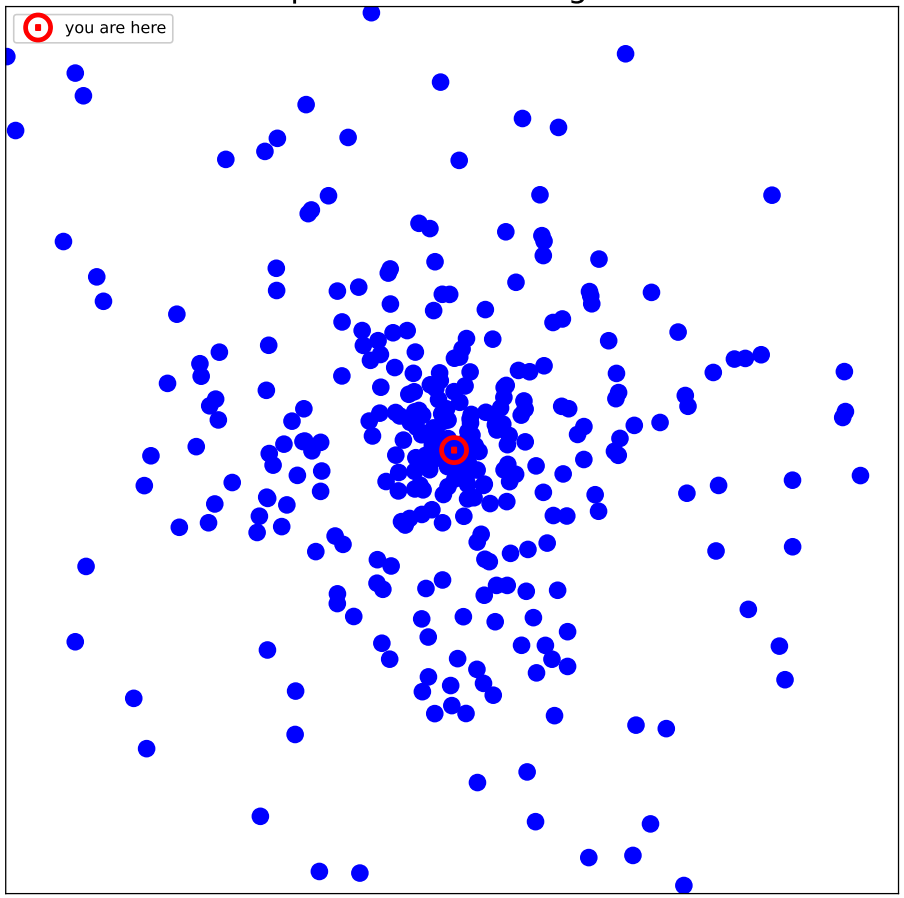
Q: do you need both?
Q: e.g., how can you be isotropic but not homogeneous?
Q: e.g., how can you be homogeneous but not isotropic?

Cosmo principle as cosmic democracy:
Universe has no center, no edge
no special places, directions!

Not Isotropic and not Homogeneous



Isotropic but not Homogeneous



The cosmo principle, in song

I'm just average, common too
I'm just like him, the same as you
I'm everybody's brother and son
I ain't different from anyone
It ain't no use a-talking to me
It's just the same as talking to you.

Cosmologist and Nobel Prizewinner Bob Dylan (1964)

Cosmological Principle: Implications

- demands enormous regularity

"maximal symmetry" $\rightarrow$ simplifies analysis!

- places stringent constraints on
  (i.e., simplifies!) the possible nature and behavior
  of the Universe and its contents
  i.e., is "the cosmologist's friend"

- "trying to tell us something"
  about how universe formed?
  (e.g., cosmic inflation in early universe?)

iClicker Poll: Cosmodynamics

galaxies have mass $\rightarrow$ gravitate
in general, expect galaxies to be in motion

What pattern of motions (relative to us) will we find?

A most galaxies move towards us

B roughly half move away, half towards us

C most galaxies move away from us

iClicker Poll: Cosmodynamics Twofer

in fact: the *majority* of galaxies move away from us

What percentage of galaxies are observed to move away?

A between 50% and 75%

B between 75% and 90%

C between 90% and 95%

D between 95% and 99%

E $>$ 99%

Cosmodynamics I

of >1 million galaxies with redshift/blueshift measurements

<20 galaxies have blueshifts! (only nearest ones)

so: $>99.9999\%$ of galaxies have redshifts!

$\Rightarrow$ essentially all galaxies have **redshift**:

$$z \equiv \frac{\lambda_{\rm obs} - \lambda_{\rm rest}}{\lambda_{\rm rest}} > 0 \qquad (1)$$

$\rightarrow$ move away!

line-of-sight speed: Doppler law sez $v = cz$

first approximation:

Hubble (1929) v & distance r related:

`www: Hubble original data`

Q: how are v and r related mathematically?

Hubble: galaxy speed and distance *proportional*

$\Rightarrow v \propto r$

$\boxed{v = H_0 r}$ Hubble law

in fact: $\vec{v} = H_0 \vec{r}$

that is, speed and distance directions the same

$\rightarrow$ galaxies all move *radially* away from us!

Q: why did it have to be this way?

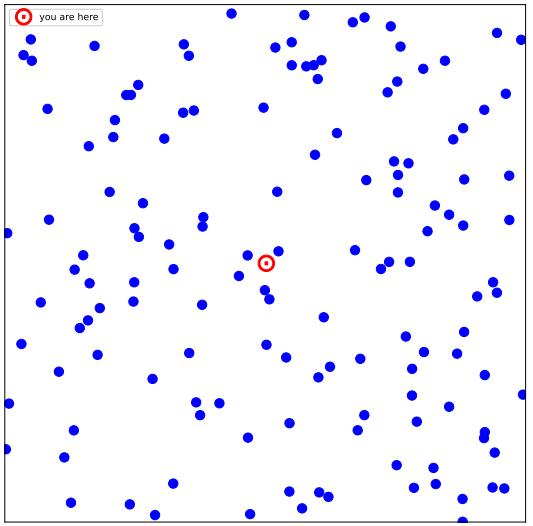
Hubble Law $v = H_0 r$

Hubble parameter (a.k.a. "Hubble constant")

$$H_0 \simeq 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{2}$$

e.g., galaxy at $r = 10$ Mpc moves away at 720 km/s

Try it!
draw $\vec{v}$ on galaxies
Comment on pattern

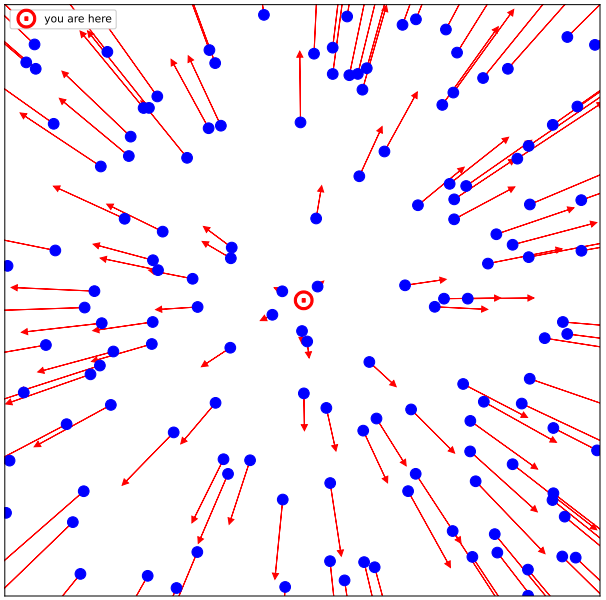


Structure + Dynamics: Evolution

observe:

- U. homogeneous, isotropic
- Hubble law $v = Hr$

i.e., galaxies smoothly spread in space
yet moving too
and motions all directed away from us!
so velocity pattern "points back to us"



Q: how reconcile?

at least 2 logical possibilities...

1. "Egoist" interpretation: we are at the center of U.

Imagine galaxies all launched from same point (here)
initially: each launched with different speed $v_{\rm gal}$
afterwards: each coasts, keeping its $v_{\rm gal} = const$

Then after time t, a galaxy seen at distance $r = v_{\rm gal} t$
so $r \propto v_{\rm gal} \Rightarrow$ farther = faster: Hubble!

In this picture: Hubble law means $r = v_{\rm gal} t = H_0 r t$
so "coasting time " is $t_{\rm H} = 1/H_0 = 14 \times 10^9$ yr = 14 billion yrs
"Hubble time"* – "egoist" age of Universe

and since max "launch" speed is $v_{\rm gal} < c$
expect "edge" of galaxy sphere
at radius $d_{\rm H} = c t_{\rm H} = c/H_0 = 4200$ Mpc
"Hubble Radius/Length"* – "egoist" size of Universe

*When egoism is discarded, we'll reinterpret the Hubble length & time,
but still find both useful & interesting numbers

So “egoist” picture gives Hubble’s law!

Logically possible! But...

Q: give a philosophical reason why we don’t believe this

Q: give a physical reason why this treatment can’t be right?

Q: give an observational reason why we don’t believe this

Critiques of Cosmic Egoism

We are at the center of the universe?

Philosophically:

- not Copernican (violates "principle of mediocrity")

Physically:

- haven't included gravity!

Observationally:

- Milky Way, local galaxies don't look special

not what expect from center of explosion

compare supernova $\rightarrow$ distinctive neutron star/BH at center

- no evidence for "edge" to Universe at great distances

2. Einstein interpretation of Hubble's law:

using General Relativity:

Universe is expanding

that is, **space itself is expanding**!

recall: this is possible, since GR says spacetime is dynamic!

But this implies that

- all galaxies receding from all others
- and they do so because they are "riding" on points within an expanding grid!
  imagine rubber graph paper being stretched!

bold, strange idea!

demo: expanding universe

Q: implications?

The Magic of Hubble

Somewhat technical derivation:

consider three arbitrary cosmic points:

$\vec{r}_{BC} = \vec{r}_{AC} - \vec{r}_{AB}$

Assume A sees Hubble's law:

- $\vec{v}_{AB} = H\vec{r}_{AB}$
- $\vec{v}_{AC} = H\vec{r}_{AC}$

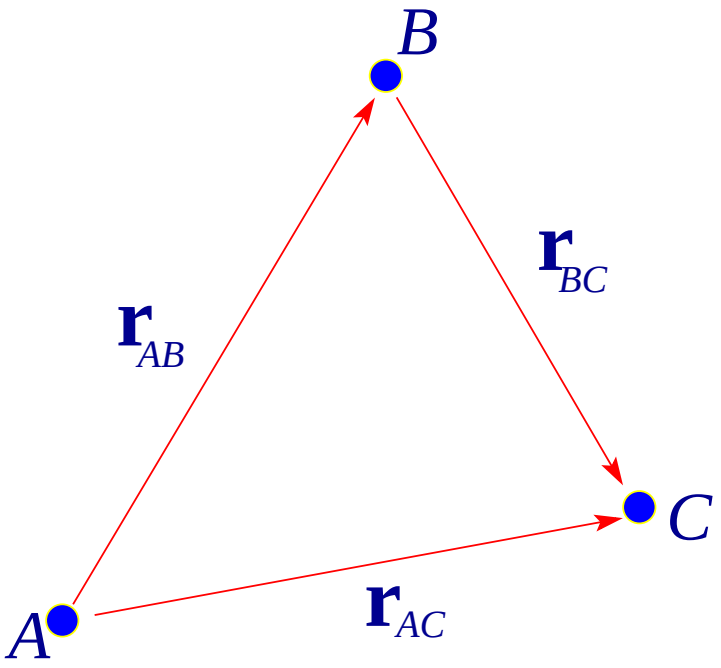
Then ask: *what does B see? C?*

find velocities relative to B:

$\vec{v}_{BC} = \vec{v}_{AC} - \vec{v}_{AB} = H(\vec{r}_{AC} - \vec{r}_{AB}) = H\vec{r}_{BC}$

This is huge!

Q: why? What have we proven?



we have shown:
if A sees Hubble's law, then so do (arbitrary) B and C
thus: if *any* observer measures Hubble's law
then *all* observers will measure Hubble's law!

so: Hubble law implies
$\rightarrow$ *all* galaxies recede according to same law
$\rightarrow$ no need for center, space has no special points

Moreover: Hubble law is *only* motion
which preserves homogeneity and isotropy
i.e., *any* other motion breaks cosmo principle
...but Hubble law is exactly what's observed!

Revolution Re-Re-Re-Visited

Copernican Revolution I (17th Century):
Earth is one typical planet among many
not center of solar system

Copernican Revolution II (earth 20th Century):
Sun is one typical star among many
not center of Milky Way Galaxy

Copernican Revolution III (1920's):
Milky Way is one typical galaxy among many
Universe much larger than previously thought

Copernican Revolution III (late 20th century):
most matter in the U is weakly interacting dark matter
we are not even made of the dominant stuff

Copernican Revolution IV (20th century):
Universe is homogeneous on large scales,
and has no center

... stay tuned for more...