Astro 350
Lecture 25
Oct. 21, 2011

Announcements:
- HW7 due now
- Good news: no HW for next week
- Bad news: Hour Exam 2 next week

`www: info online`

Last time:
large-scale structure, Hubble's Law
Q: What's the cosmological principle? What does it mean?
What is it's range of applicability?
Why is cosmo principle very restrictive?
Why is it the "cosmologist's friend?
Q: What's Hubble's law? What does it say in simple terms?
What's the pattern of galaxy motions relative to us?
What are possible interpretations of this motion?

Structure + Dynamics: Evolution

observe:

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

i.e., galaxies smoothly spread in space, yet moving too
and motions are all directed away from us!
i.e., galaxy 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

The Magic of Hubble

Slightly technical derivation:

consider three arbitrary cosmic points:

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

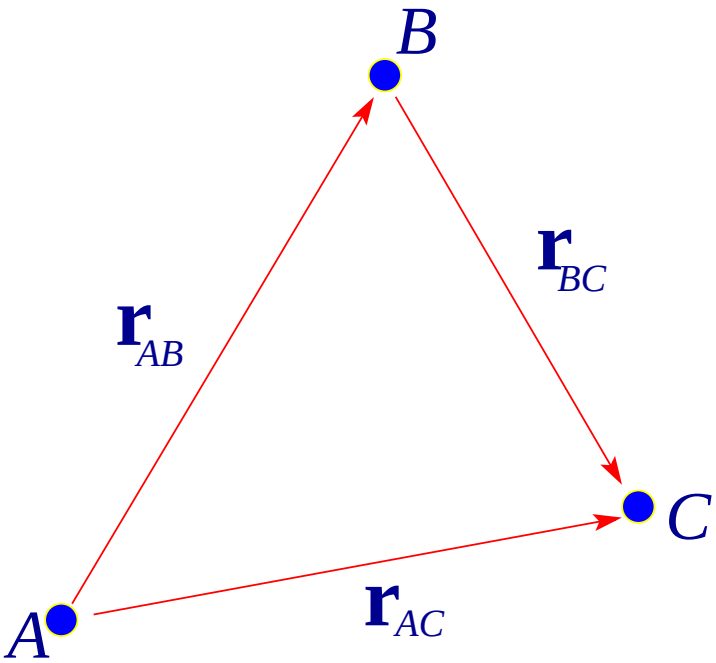
Assume A sees Hubble's law:

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

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!

Coincidence? I think not! $\rightarrow$ trying to tell us something!

Leads to the other interpretation of Hubble's Law...

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!

transparency demo: photocopy universe

Q: implications?

Expansion and Cosmology

All of cosmology is nothing more or less
than the evolution of a system that is

- homogeneous
- isotropic
- expanding

⋆ much of cosmology amounts to imagining a box
  - filled homogeneously with galaxies (today)
    or atoms/particles (in the early Universe)
  - with other identical expanding boxes on all sides

and asking: *how do the contents respond as the box expands?*

⋆ to do this don't need to know if U. has finite or infinite volume!
question is interesting but can distract and confuse

Describing Expansion

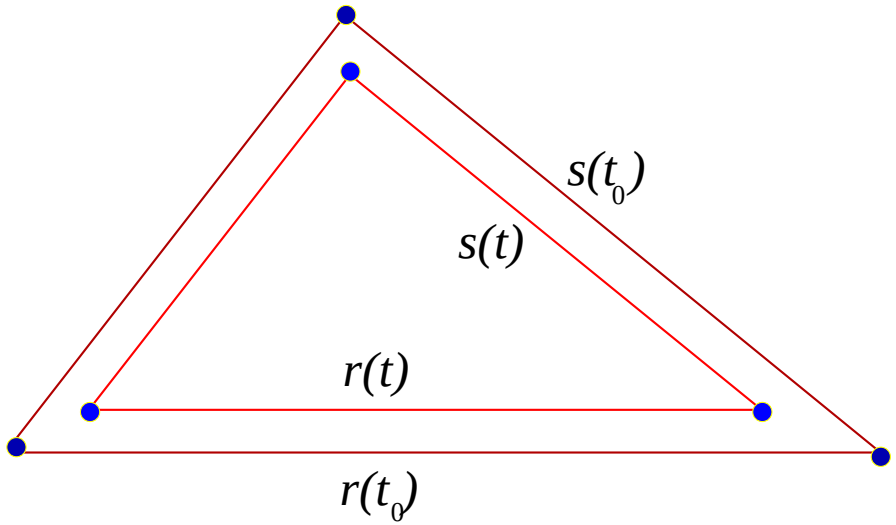
consider triangle defined by 3 observers at t_1

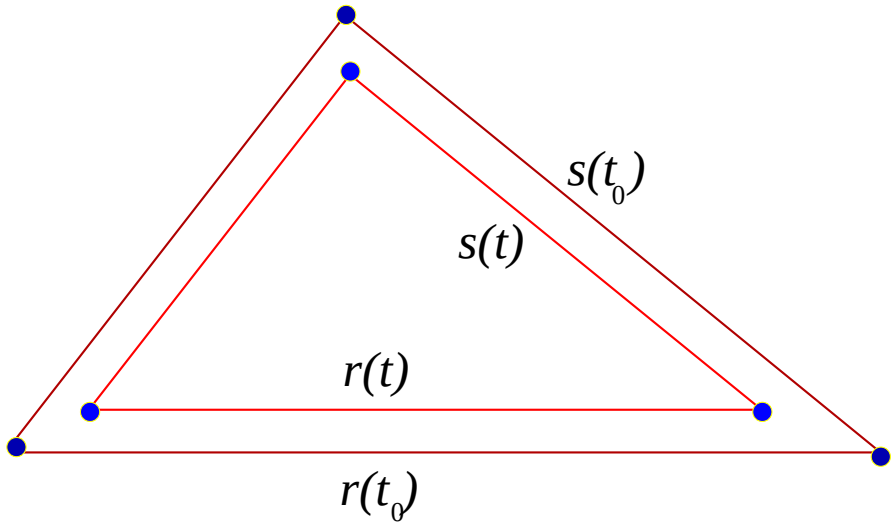
if homogeneous and isotropic expansion

at any later time t_2, new triangle *must always be*

"similar to" original triangle

i.e., have same "shape" – same angles, ratios of sides *Q: why?*





similar $\rightarrow$ ratio C/B always the same so

$$\frac{r(t_1)}{s(t_1)} = \frac{r(t_2)}{s(t_2)} \tag{1}$$

rearrange:

$$\frac{r(t_2)}{r(t_1)} = \frac{s(t_2)}{s(t_1)} \tag{2}$$

Q: what does this imply? Hint: must work for any *triangle!*

cosmo principle $\rightarrow$ triangle *must be* similar:
if stretched more in one direction $\rightarrow$ expansion not isotropic
there would be a preferred direction

since for *any* triangle at *any* two times t_1, t_2

$$\frac{r(t_2)}{r(t_1)} = \frac{s(t_2)}{s(t_1)} \tag{3}$$

then these ratios must have a universal (triangle-indep) value!
and *any* length ℓ changes with time so that

$$\frac{\ell(t_2)}{\ell(t_1)} = \frac{a(t_2)}{a(t_1)} \tag{4}$$

where $a(t)$ must be universal **scale factor**
measures stretching of space due to expansion