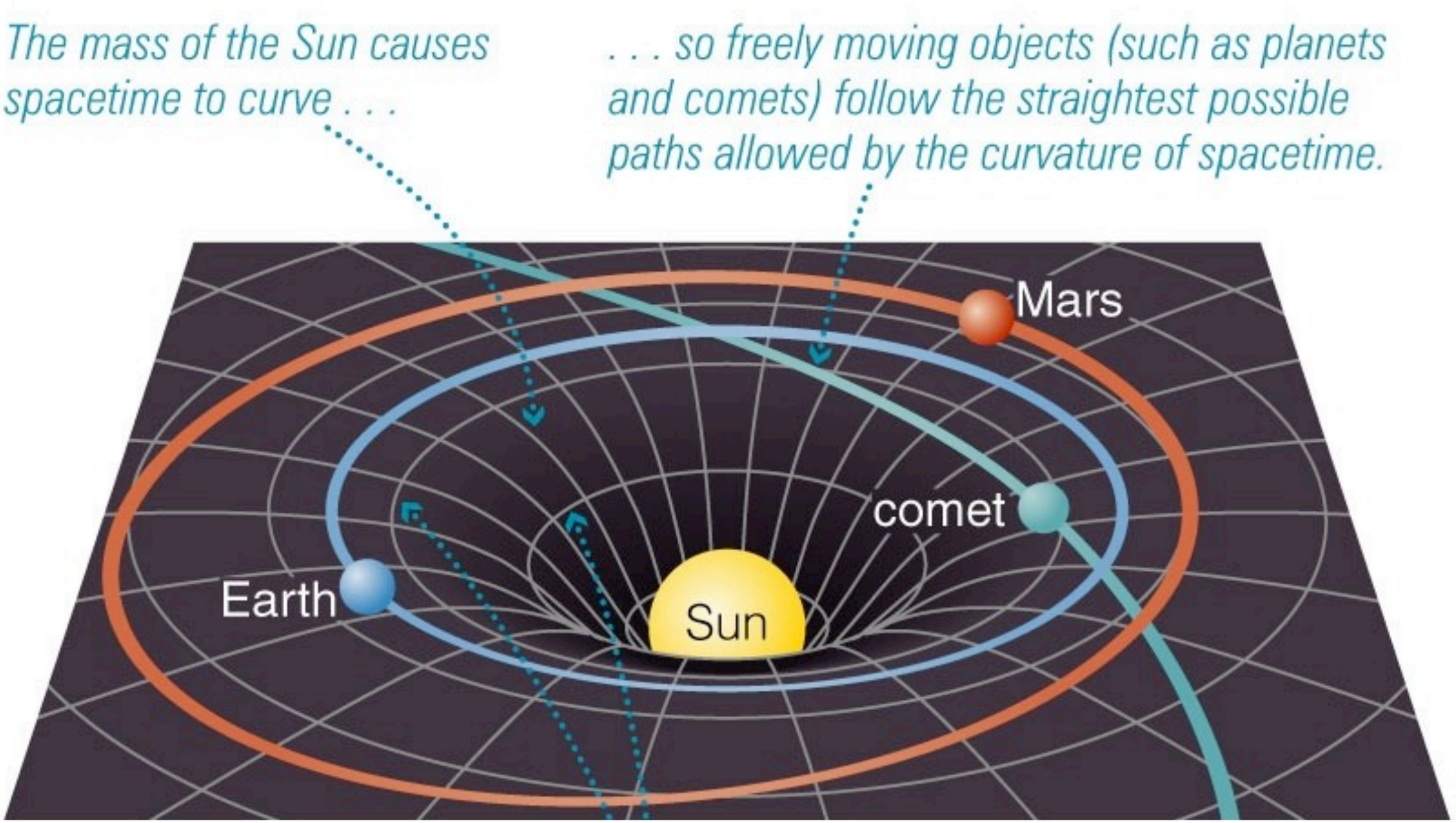
straight is the path to follow:

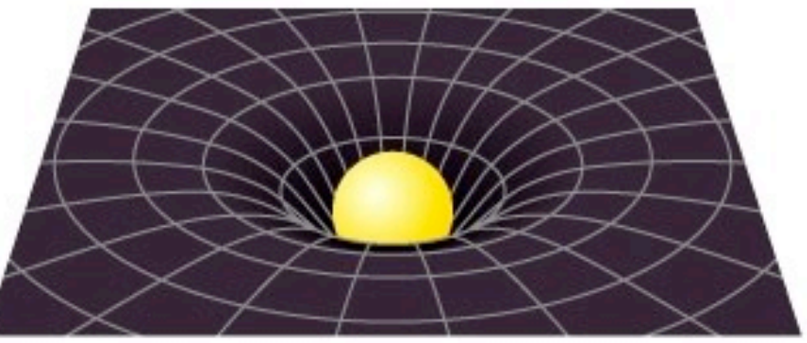
a freely moving flatland inhabitant follow geodesics

(think a bullet out of a barrel....)

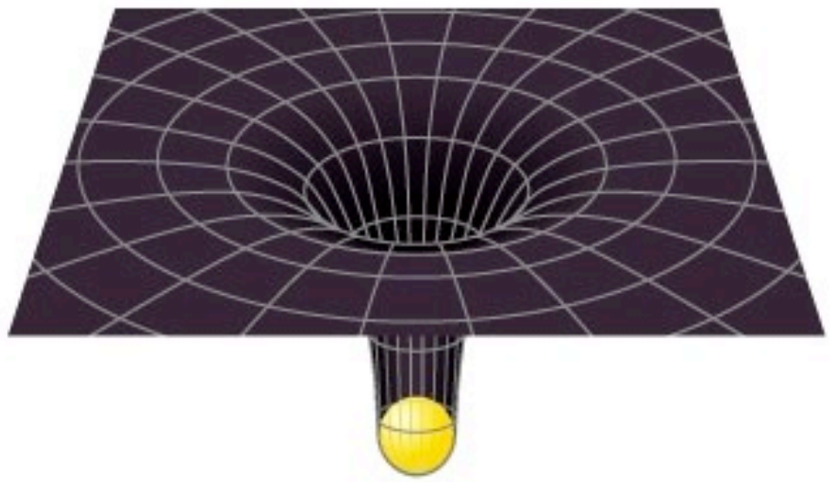


Extreme Geodesics: a blackhole

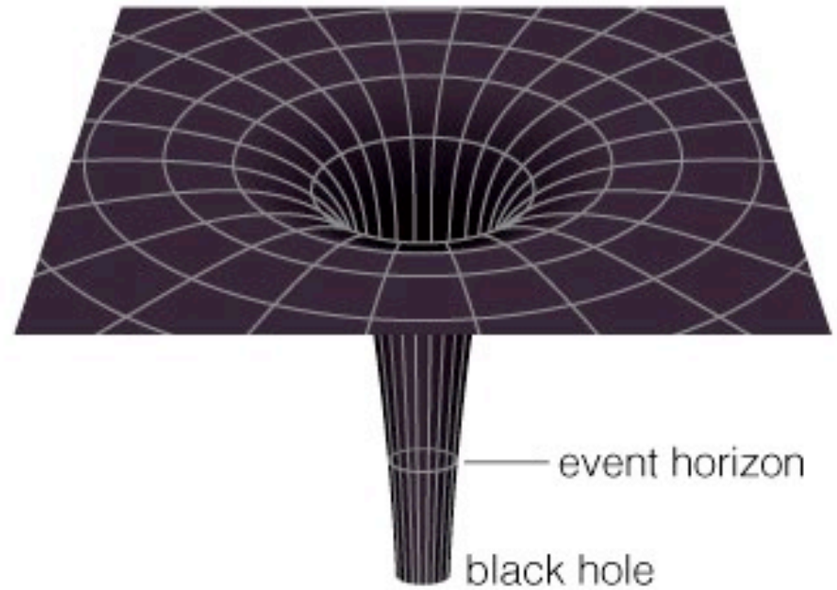
This rubber sheet represents spacetime curvature around the Sun today.



If the Sun became compressed, spacetime would become more curved near its surface (but unchanged farther away).



If compression of the Sun continued, the curvature would eventually become great enough to create a **black hole** *in the universe.*



R=700,000 km R = 100 km R=1.4km

Notice: as the Sun is compressed into a blackhole,
1) curvature at large distances unchanged;
2) interior curvature steepens so that within event horizon, even light's straight paths are bent down;
3) if you are falling inward, tidally stretched...

TA sessions:

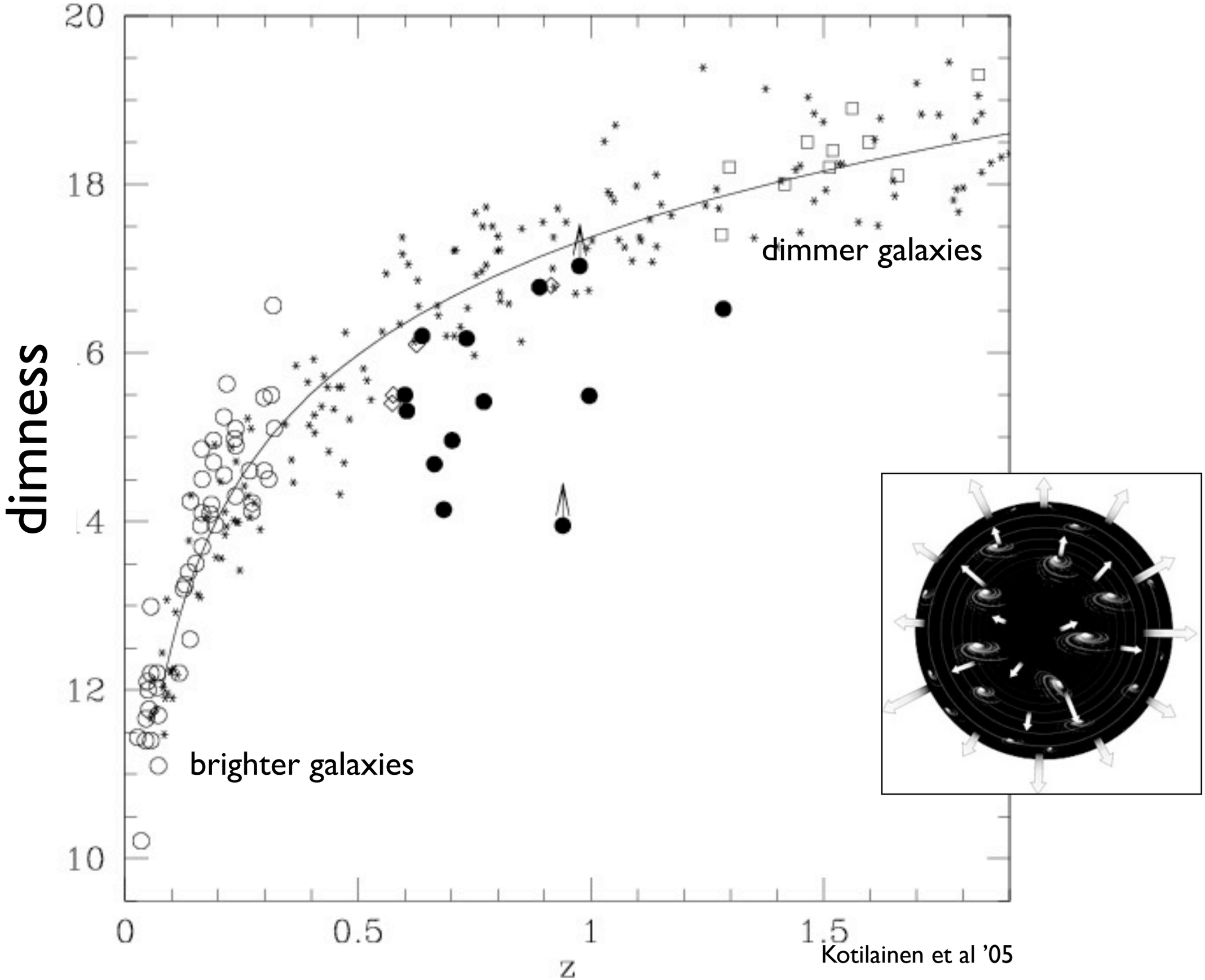
Monday 5-6PM Charles MP1203A

Tuesday 4-5PM Serguei MP1318A

Thursday 12-1PM tutorial MP202

Exam: Friday Feb. 15th, MP102, 12-1PM

Lecture 5: Expansion of the Universe



Kotilainen et al '05

Most are redshifted. They satisfy the 'Hubble's Law'

this was first pointed out by Edwin Hubble in the 1920s. It is one of the greatest scientific discoveries of the 20th century.

What did Hubble discover in 1920s?

Slipher (1912) reported velocities for 15 spiral nebulae all over the sky, all but three having recessional velocities.

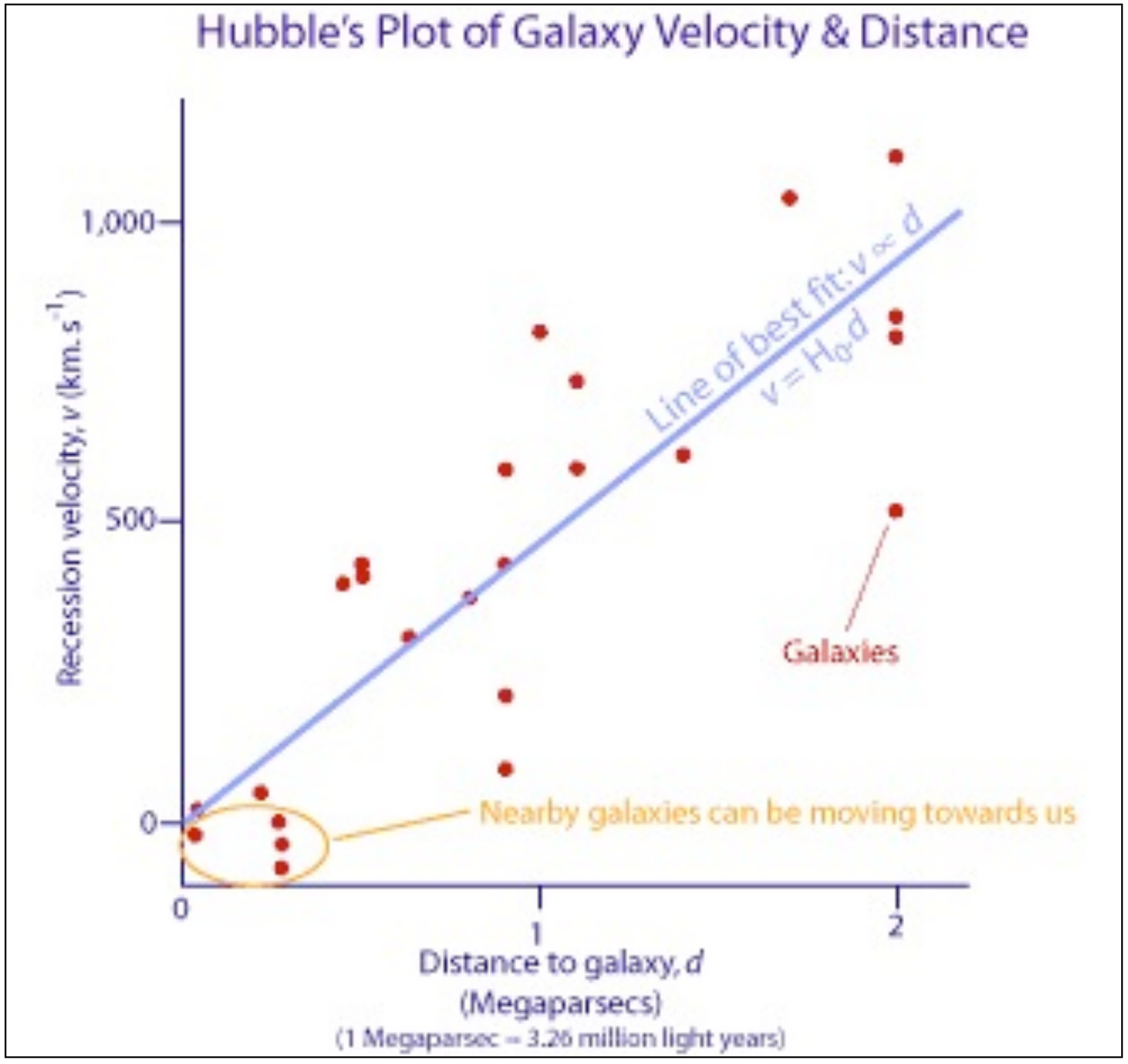
Henrietta Leavitt (1912) established that Cepheid stars (a kind of variable stars that are very luminous) can be used to measure distances to these “nebulae”.

1920s, Edwin Hubble discovered a striking correlation between the redshifts of such "nebulae" (now known to be galaxies) and their distances -- Hubble’s Law.

This led to widespread acceptance of an expanding universe and the Big Bang.

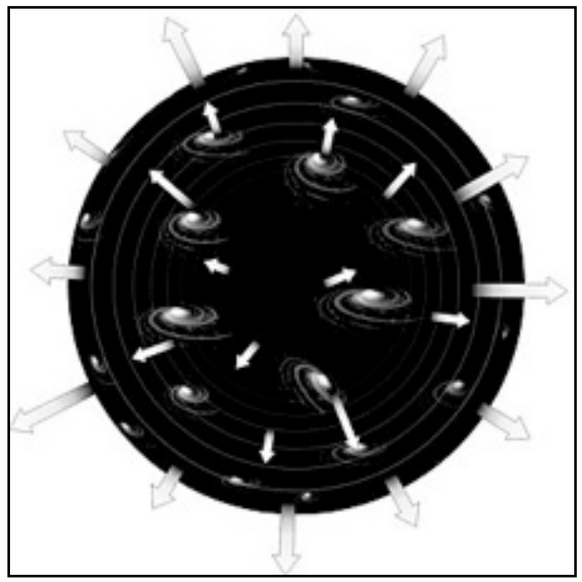
Hubble's Law: v (or, c * z) = H_0 * d

H_0: Hubble constant,



What could this correlation mean?

The Universe is expanding.
Galaxies are in for a ride.

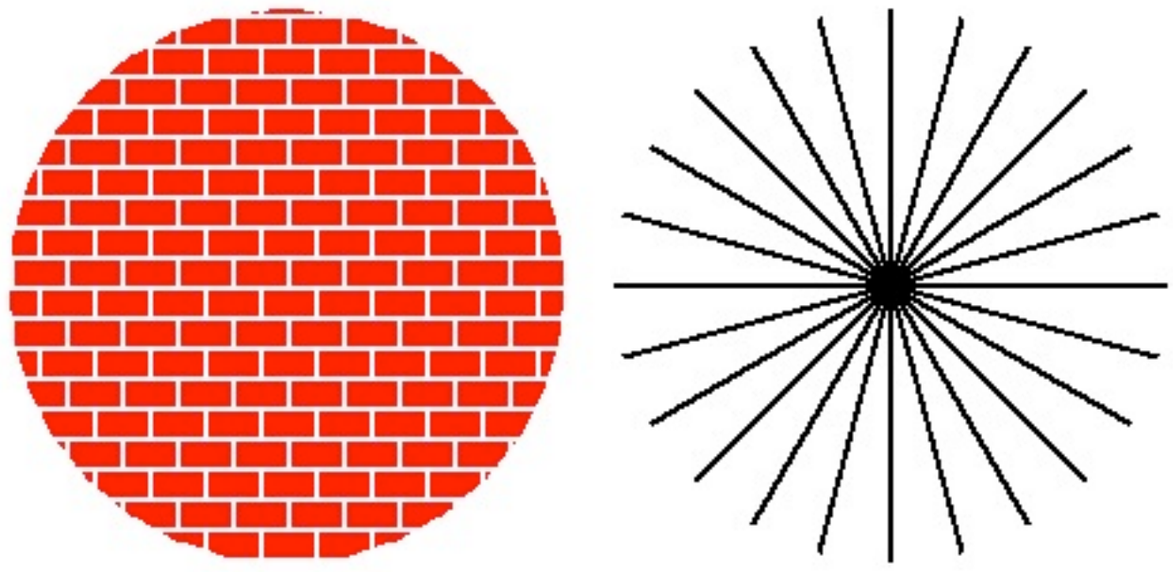


The Universe has a beginning,
when a giant kick was imparted to
space itself.

Let's adopt the Socratic approach....

- why is everyone leaving us? does it mean we are the centre of the universe?
- if universe is expanding, does it mean I am getting bigger?
- why is supercluster the largest structure in the universe?
- is space expanding, or just galaxies moving apart in space?
- can recession velocity be greater than the speed of light?
- if universe is expanding, what is it expanding into? does it have an edge? and where is the edge?
- where in space did the big bang happen?

The universe looks isotropic, homogeneous.



The cosmological principle:

viewed on a sufficiently large scale,
the universe looks the same for all observers.

The Hubble's Law must be observed by
everyone in the universe ("homogeneity")

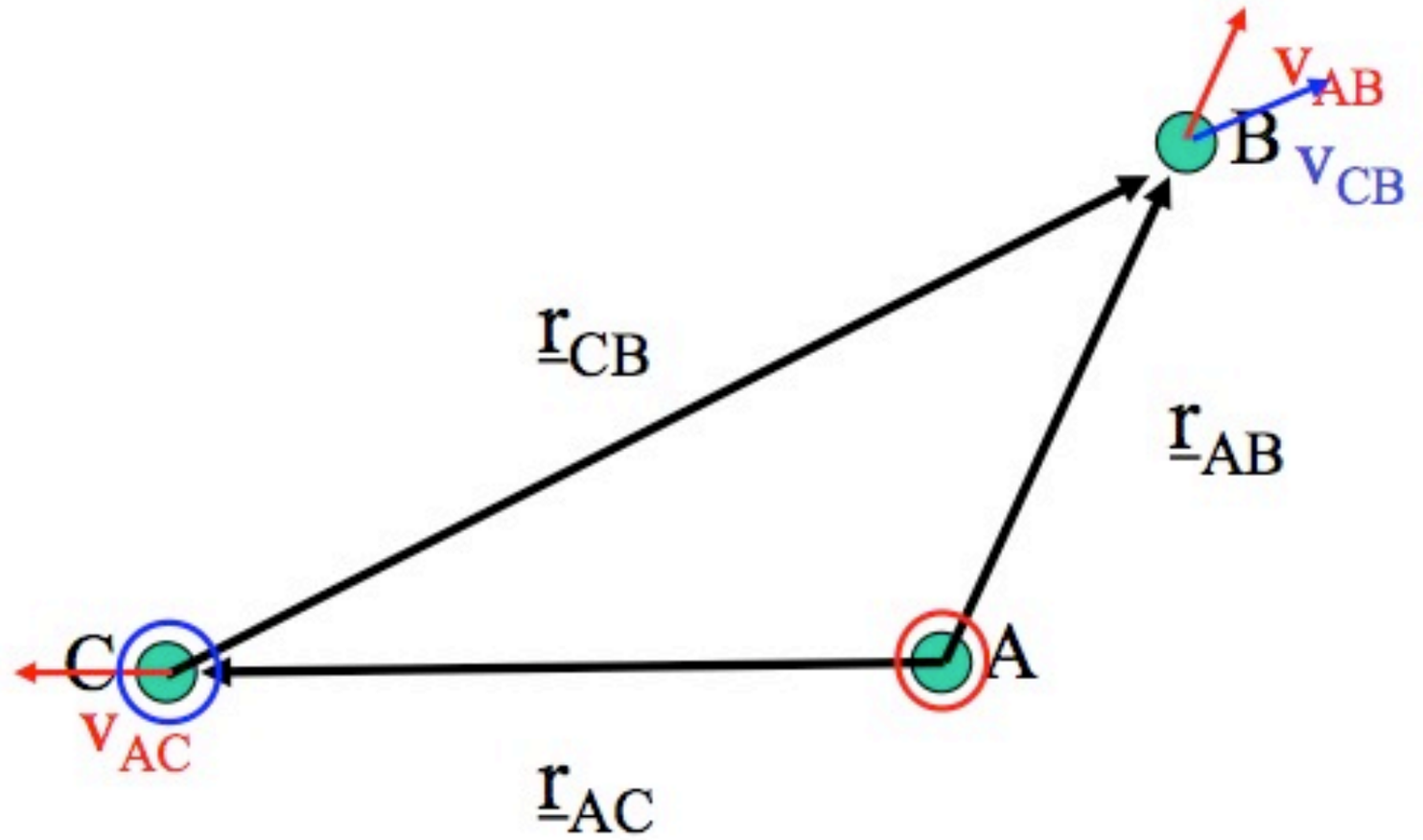
Hubble's Law

$V = H_0 \times r$

satisfies

1) isotropy

2) homogeneity



If Hubble's law is seen to apply for galaxy A, then

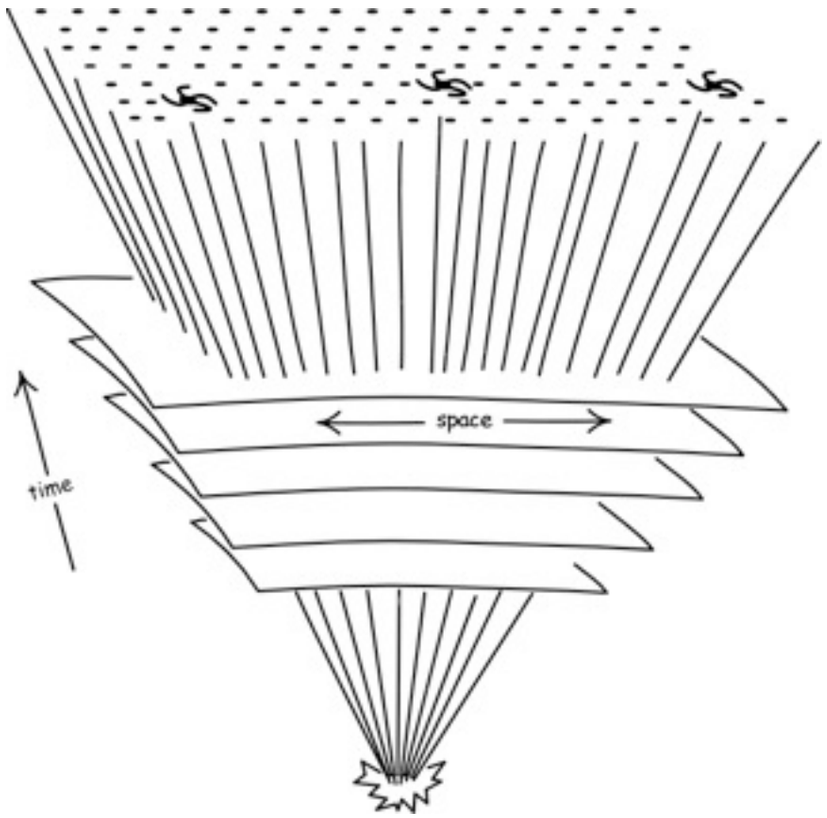
$$v_{AB}=H_0 r_{AB} \qquad v_{AC}=H_0 r_{AC}$$

By vector addition: $v_{CB}= v_{AB} - v_{AC} = H_0 r_{AB} - H_0 r_{AC} = H_0 (r_{AB} - r_{AC})$

But $r_{AB} - r_{AC} = r_{CB}$ so $v_{CB}=H_0 r_{CB}$.

So galaxy C follows Hubble's law too!

In fact, an isotropic, homogeneous universe has to satisfy Hubble's law (H_0 can be +/-)


space
time


LIFE

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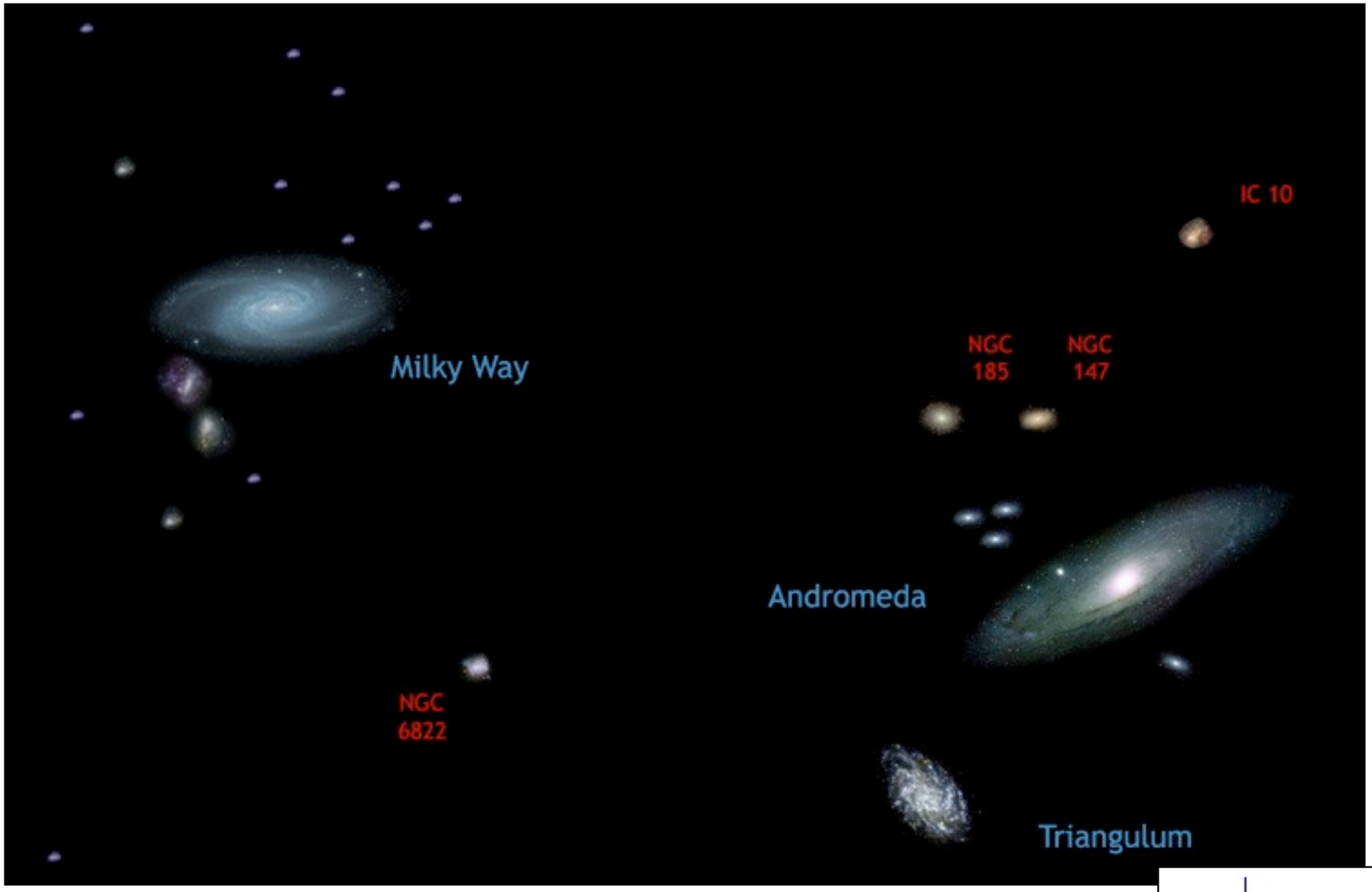
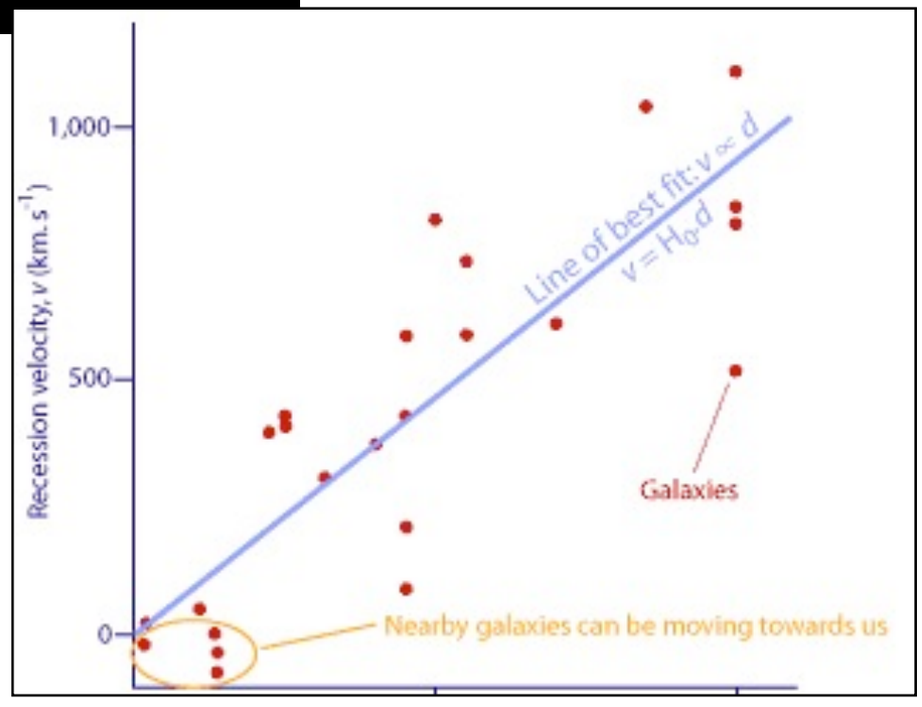


local group:
a few million lyrs.,
not receding
(similarly, your body, solar system, Milky Way galaxy)

within a group of close-by galaxies,
mutual gravity strong enough to resist expansion of the space

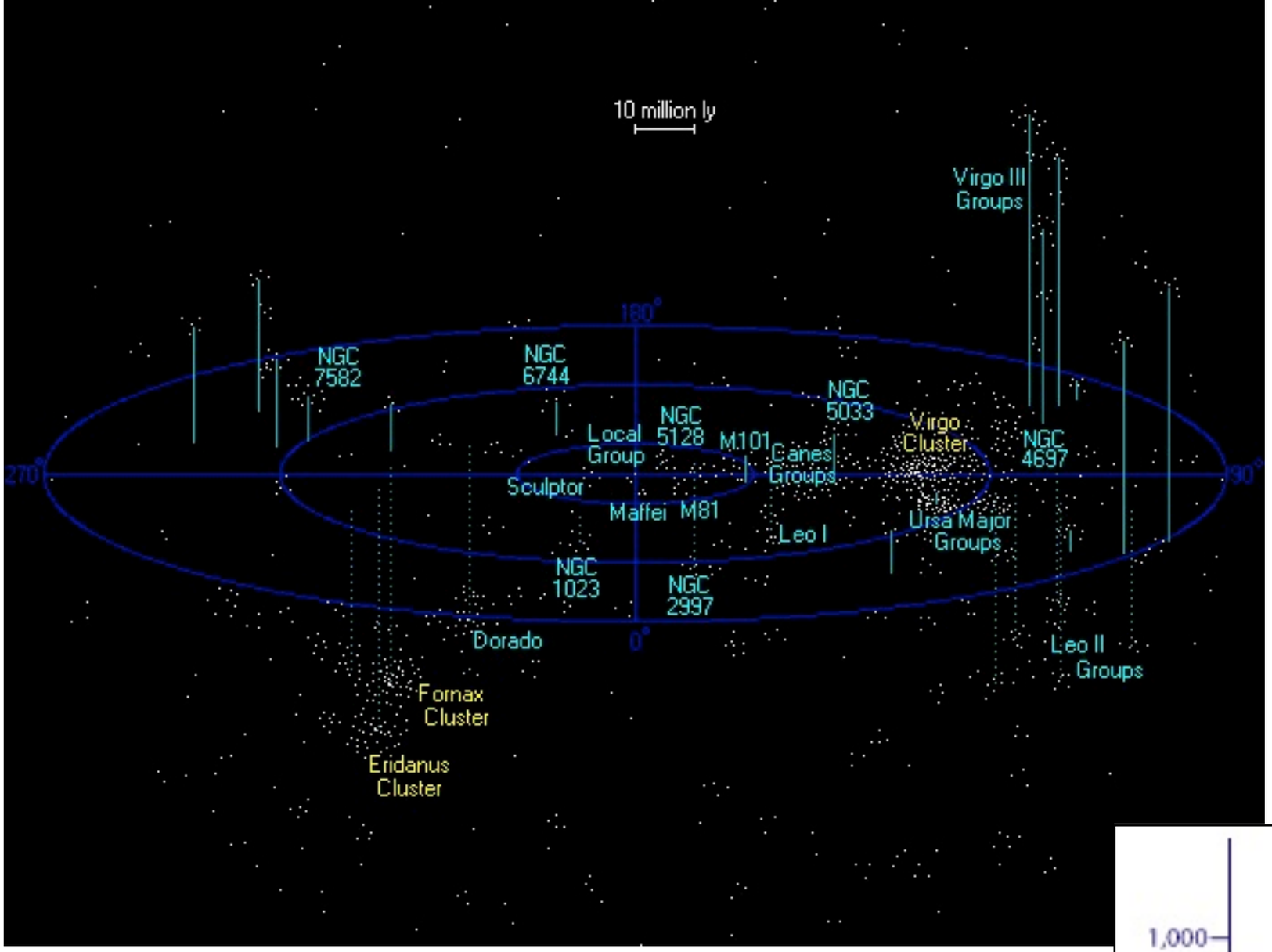


(From “Annie Hall” by Woody Allen)

Mrs. Felix: Why don't you do your homework?

Allen Felix: The Universe is expanding.
Everything will fall apart, and we'll all die.
What's the point?

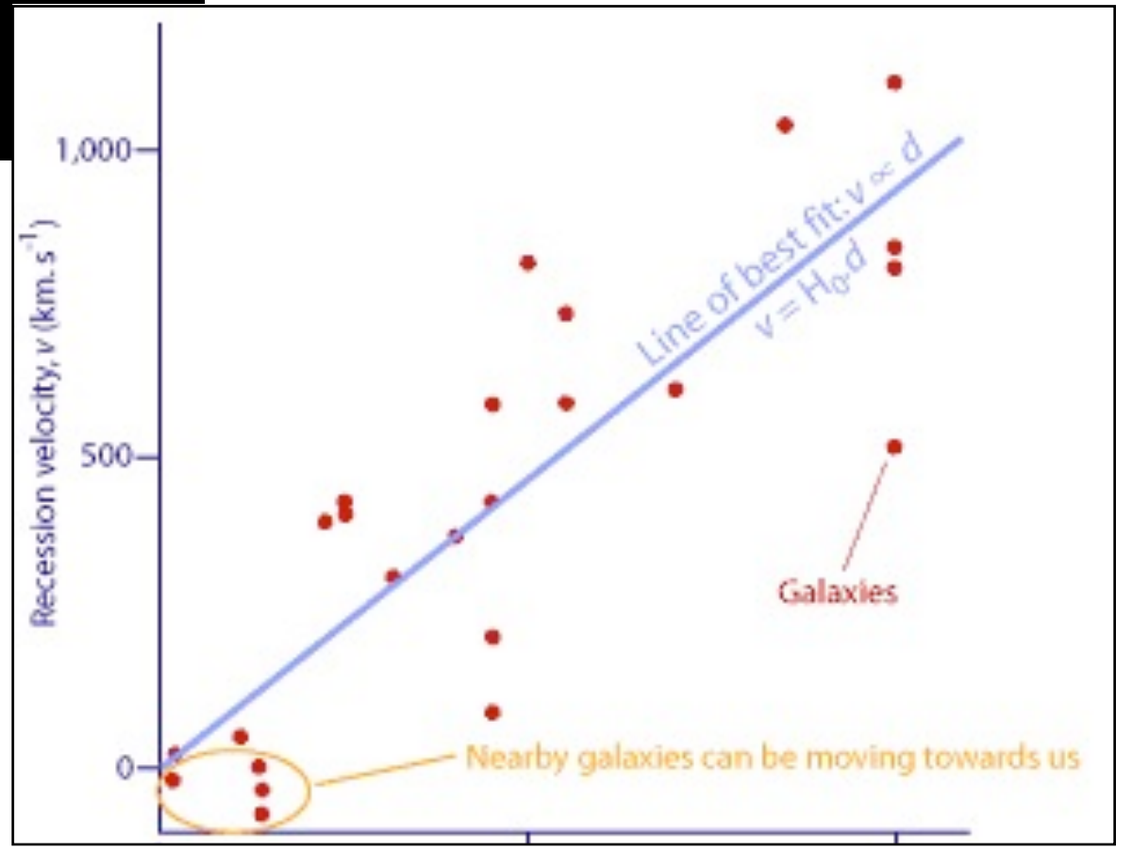
Mrs. Felix: We live in Brooklyn. Brooklyn is not expanding! Go do your homework.

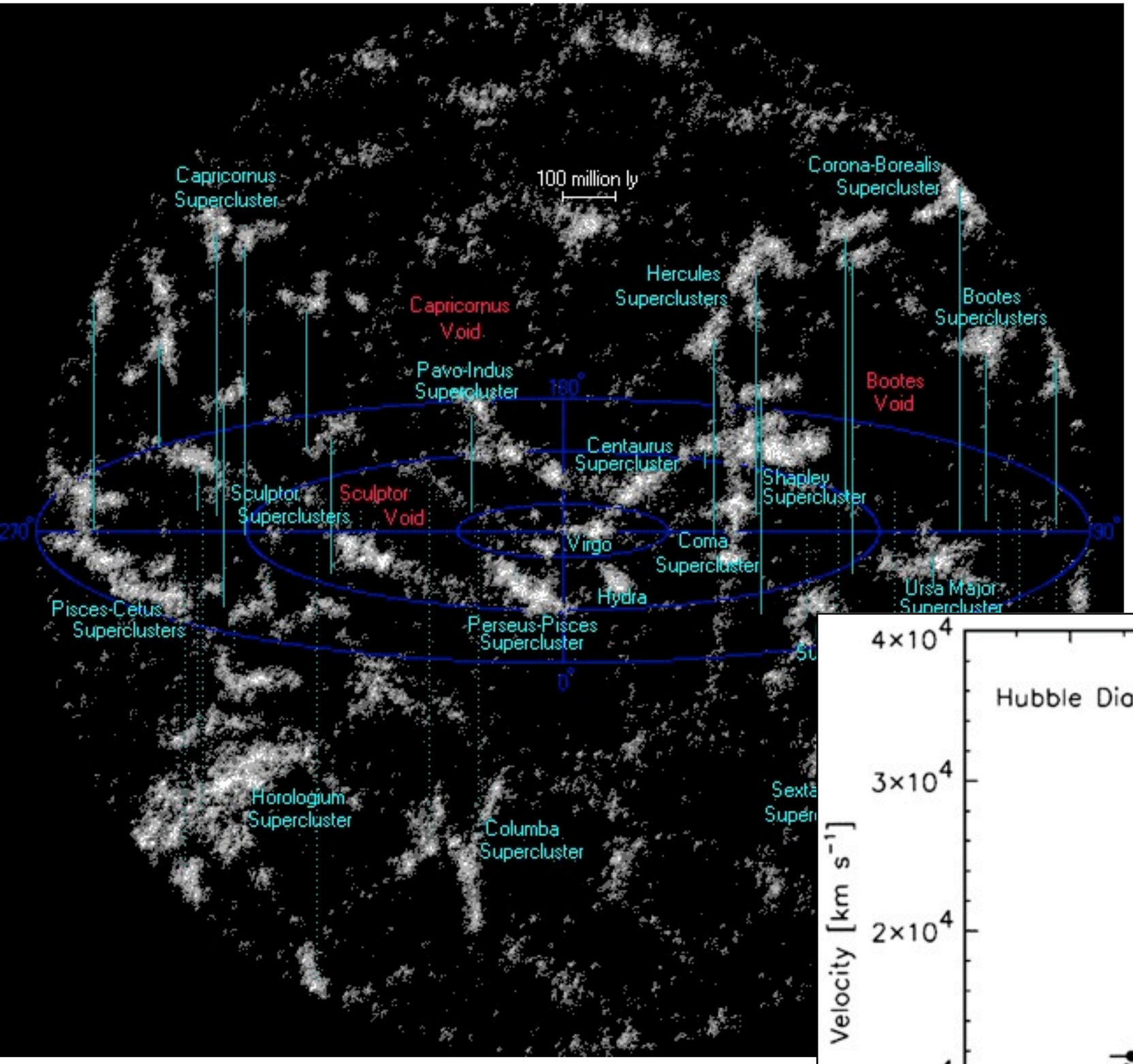


attractive force within supercluster counter-acted against the cosmic expansion, by ~ 20%

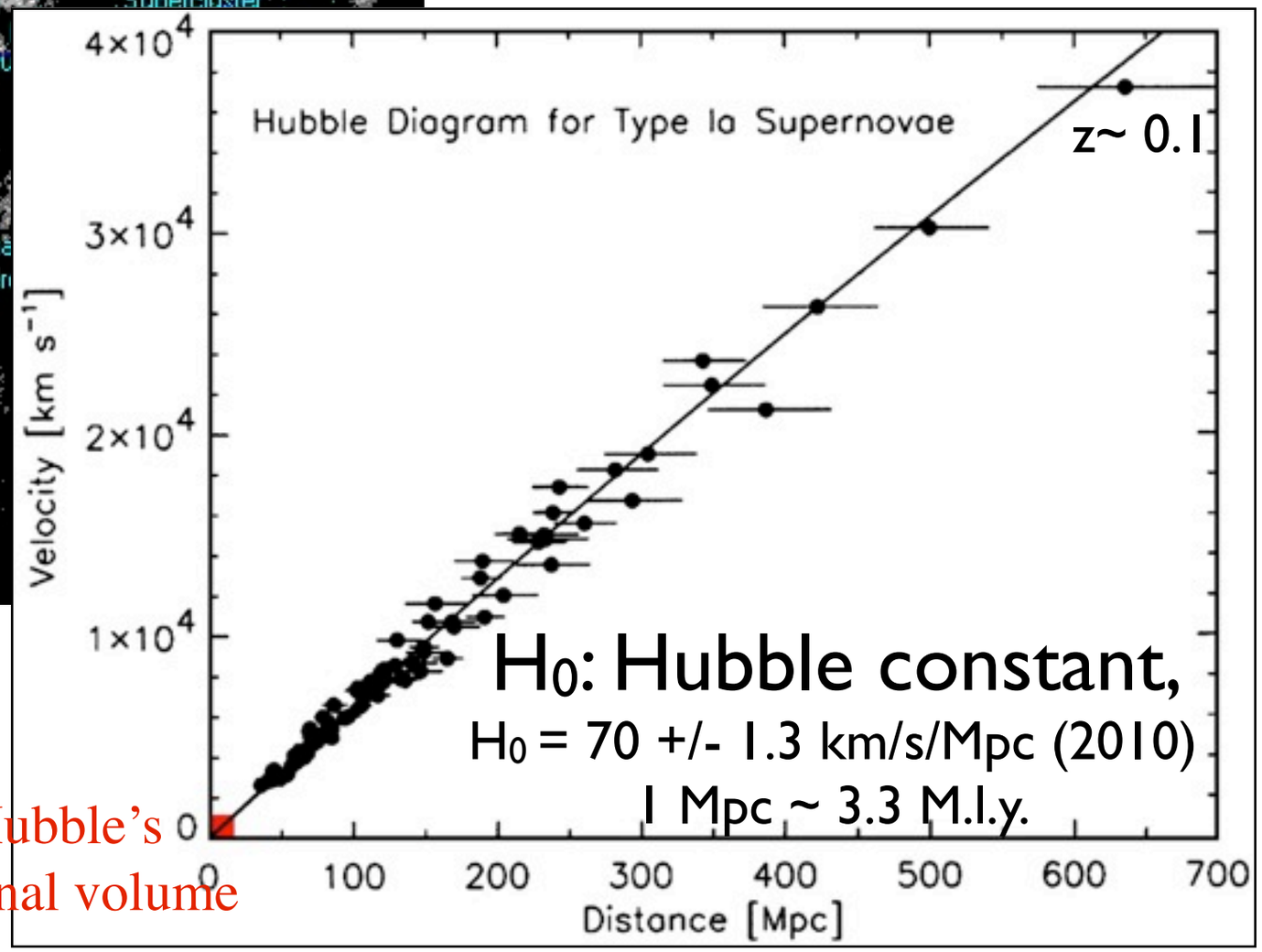
Virgo supercluster:
~ 100 million lyrs.
marginally bound

Hubble observed out to ~ 50 million lyrs ($z < 0.003$)





no bound structure beyond super-cluster



~ 1 billion lyrs

Hubble's original volume

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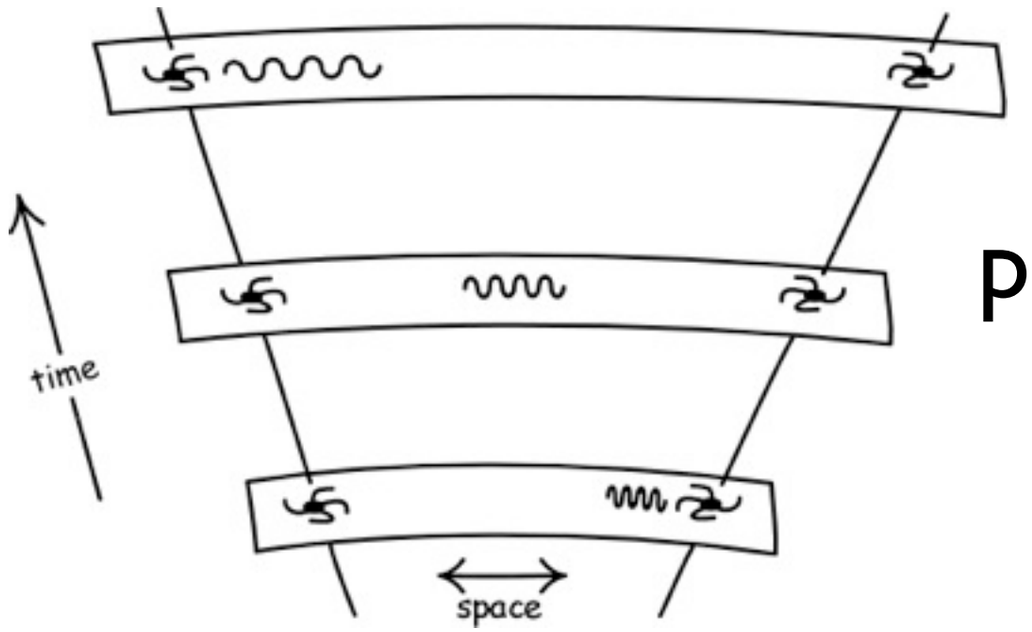
Cosmological Redshift:

light redshifted by **expansion**, **not** Doppler Effect

photon emitted with λ_0
when universe size a_0



a=a(t) is also called
the scale factor of
the universe.

photon stretched as it propagates
toward us with speed of light

at reception, $\lambda(t)$
universe size a(t)

$$1 + z = \lambda(t)/\lambda_0 = a(t)/a_0$$

(where z is redshift)

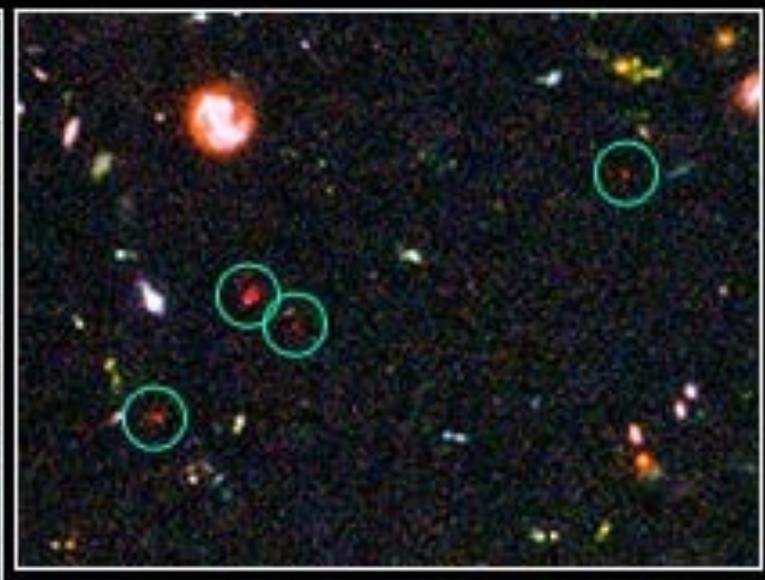
for $z=1$, $a(t) = 2\ a_0$

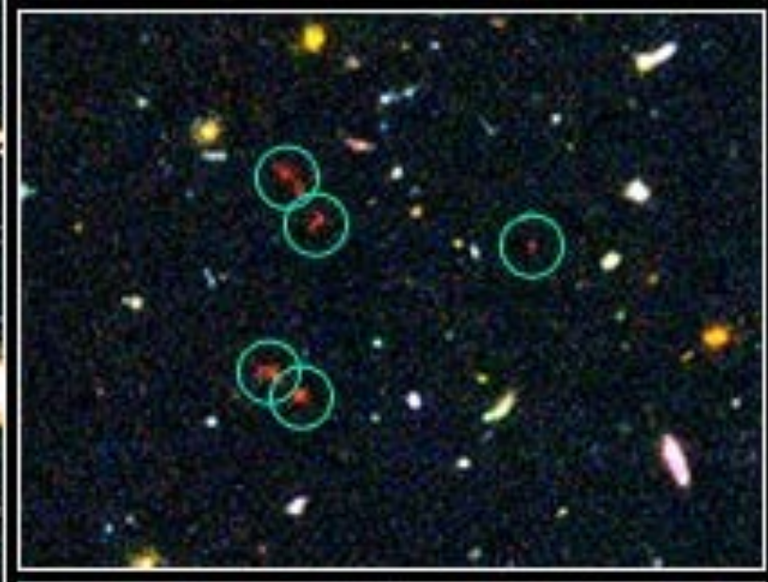
redshift tells about the size of the universe when the light was emitted. Or, the age of the universe.

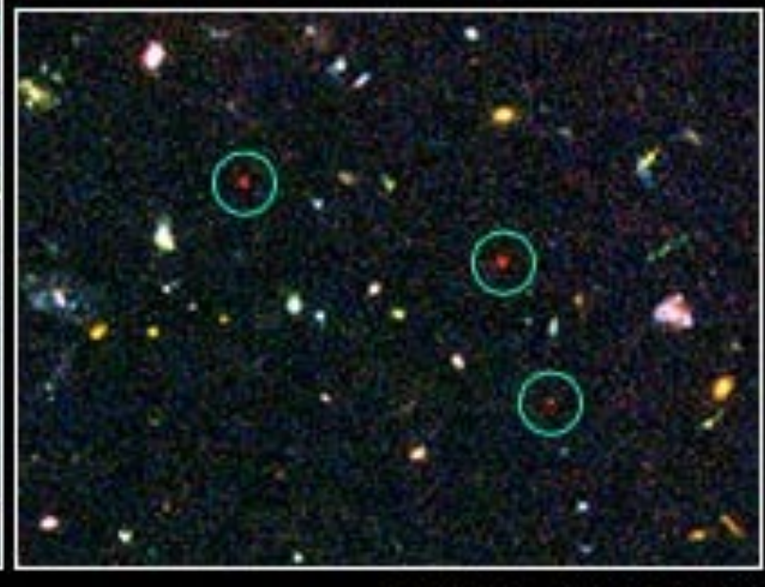
Distant Objects in the Hubble Ultra Deep Field

HST • ACS

space between us and far away galaxies CAN stretch faster than speed of light







NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

STScI-PRC04-28

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Now some magic:

$$v = c * z = H_0 * d$$

$$H_0 = 70.8 \text{ km/s/Mpc}$$

$$1/H_0 = 13.9 \text{ billion years}$$

Are we sure?

Depends critically on how distances are measured.

How do we measure distances to far-away galaxies?