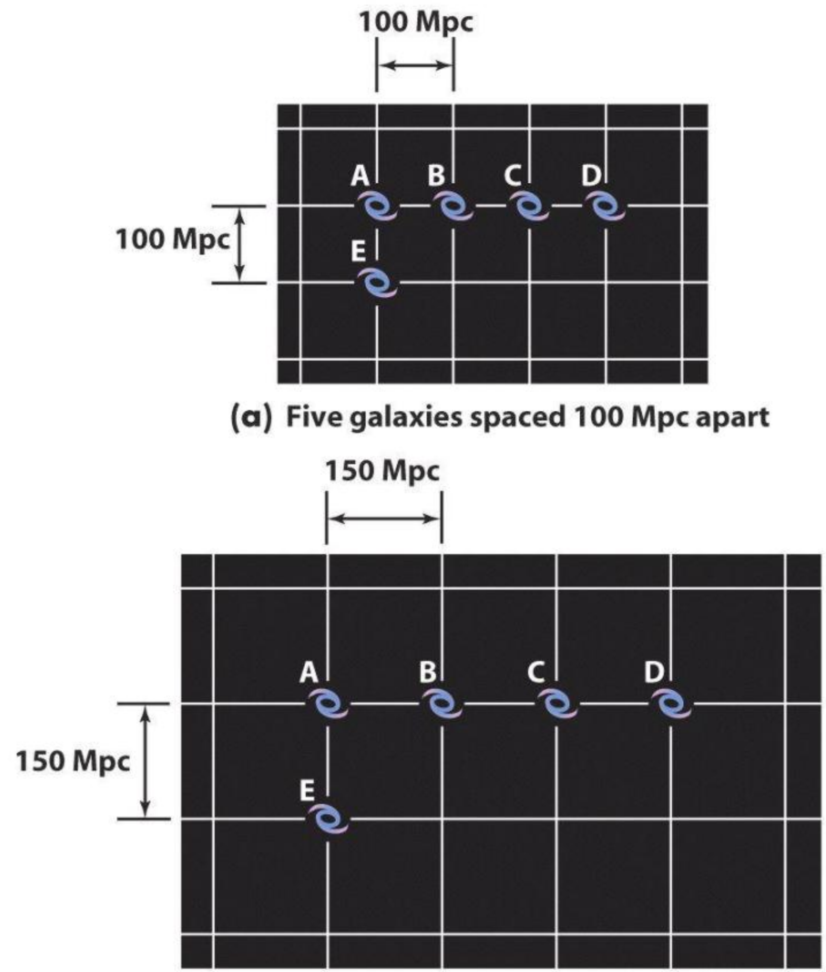
Astronomy 120

The Expanding Universe



(a) Five galaxies spaced 100 Mpc apart

(b) The expansion of the universe spreads the galaxies apart

Class 19

Prof J. Kenney

June 21, 2018

Astronomy 120 Overview

Lec 1-5: intro, physics review

Lec 6-8: stars

Lec 9-14: galaxies, clusters & dark matter

Lec 15-18: active galaxies & black holes

Lec 19-24: cosmology & the universe

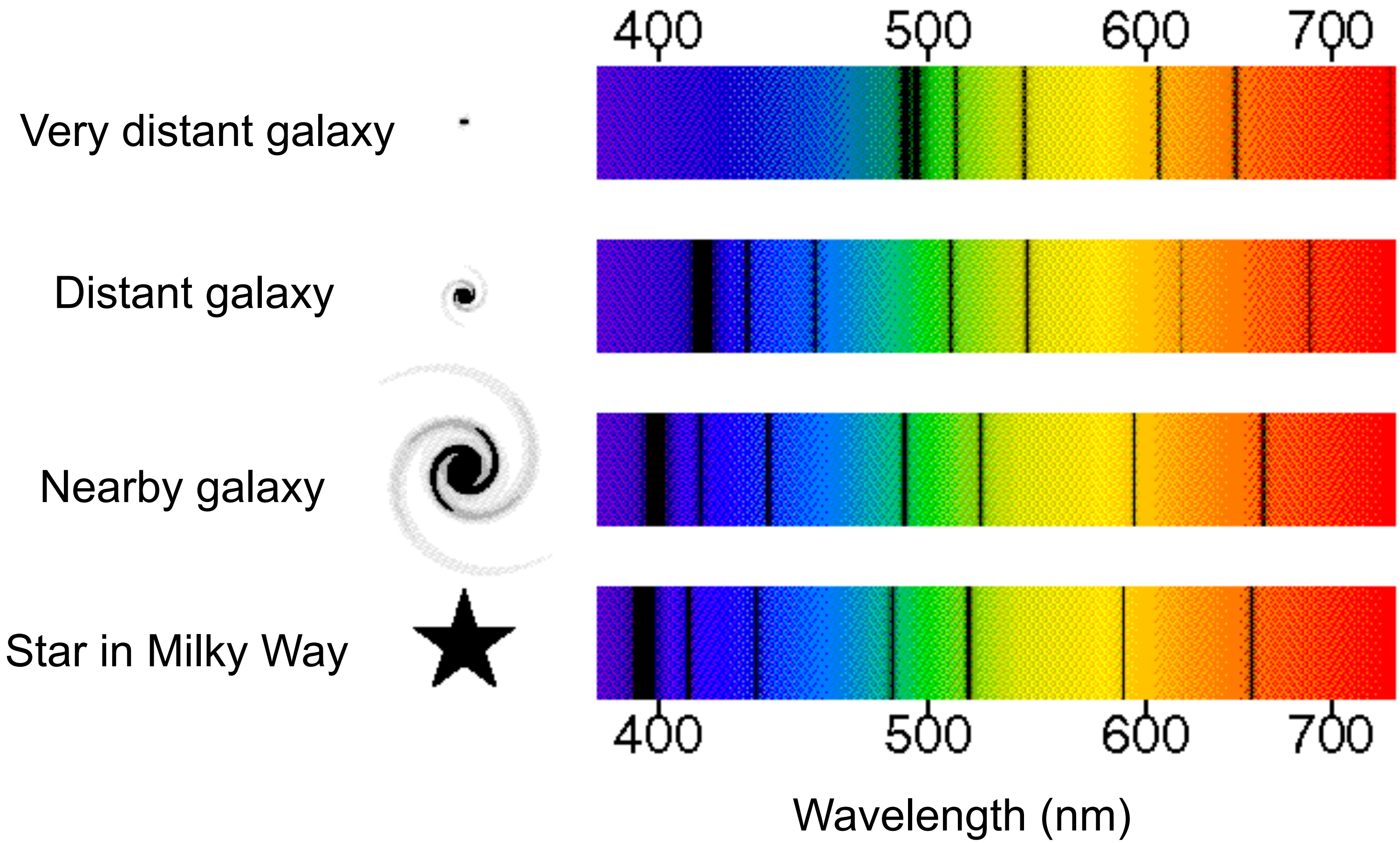
Redshifted & blueshifted spectra

wavelength λ $\longrightarrow$

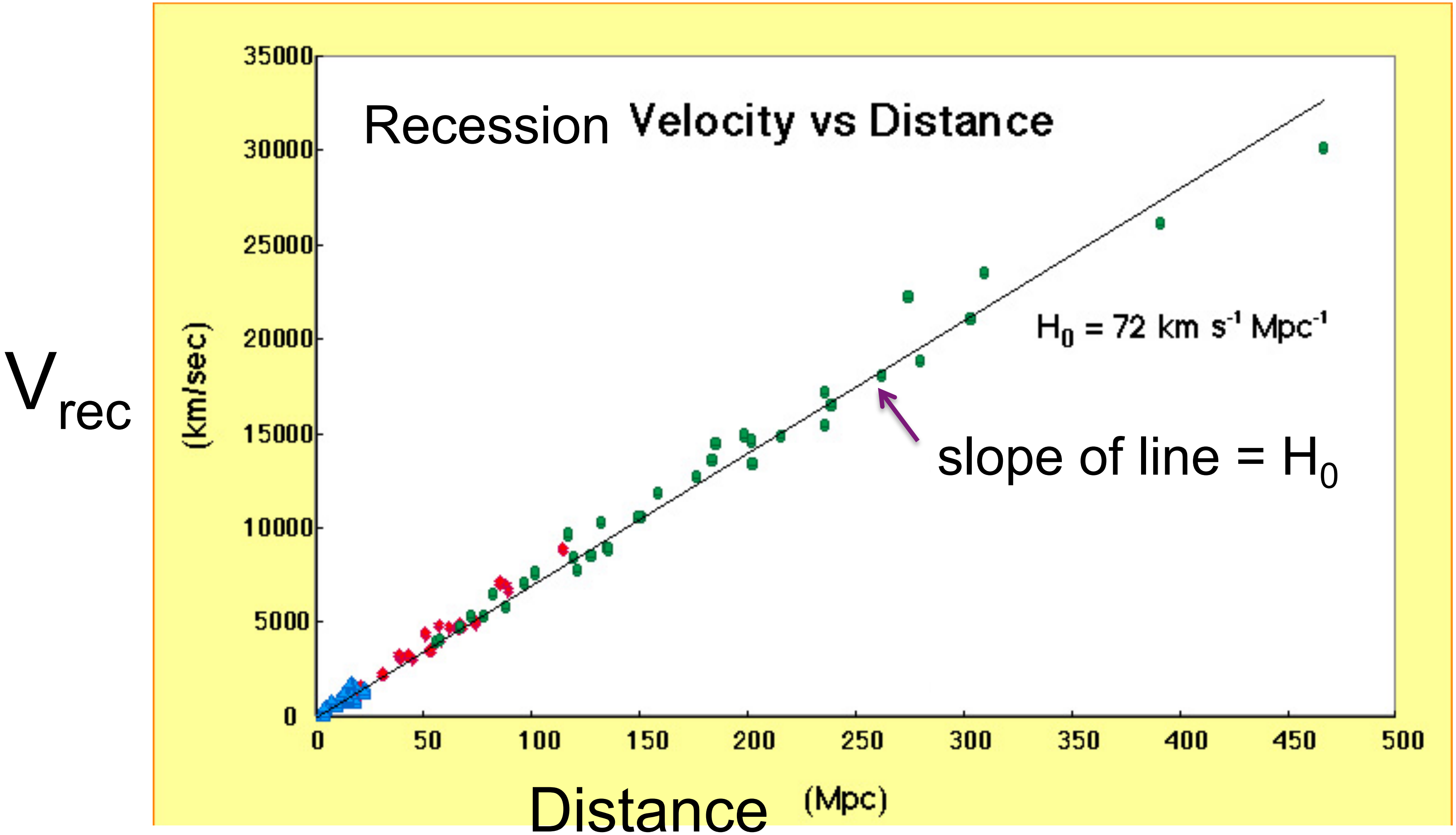
Hubble Law

Galaxies of increasing distance …

… have increasingly large redshifts (recession velocities)



Hubble Law



Recession Velocity vs Distance
V_{rec}
(km/sec)
35000
30000
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
500
Distance (Mpc)
H_0 = 72 km s^{-1} Mpc^{-1}
slope of line = H_0

Hubble Law

$$\mathbf{v = H_0\, d}$$

v = recession velocity of galaxy

d = distance to galaxy

H_0 = Hubble "constant"

= slope of line

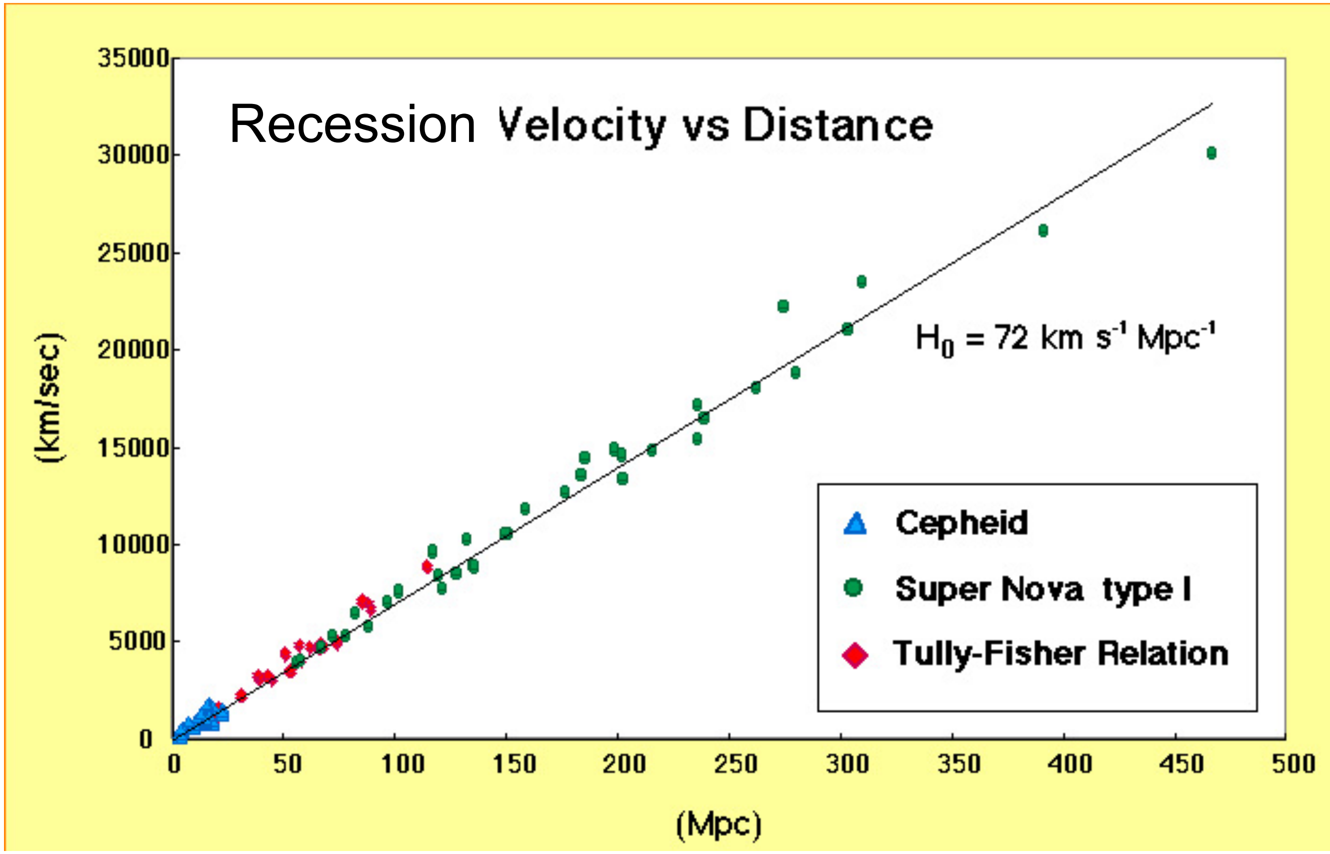
= constant of proportionality

= (current) expansion rate of the universe

= 73 ± 2 km s^{-1} Mpc^{-1}

Hubble Law: what is actually measured?

Redshift – observed from spectrum & interpreted as recession velocity V_{rec}

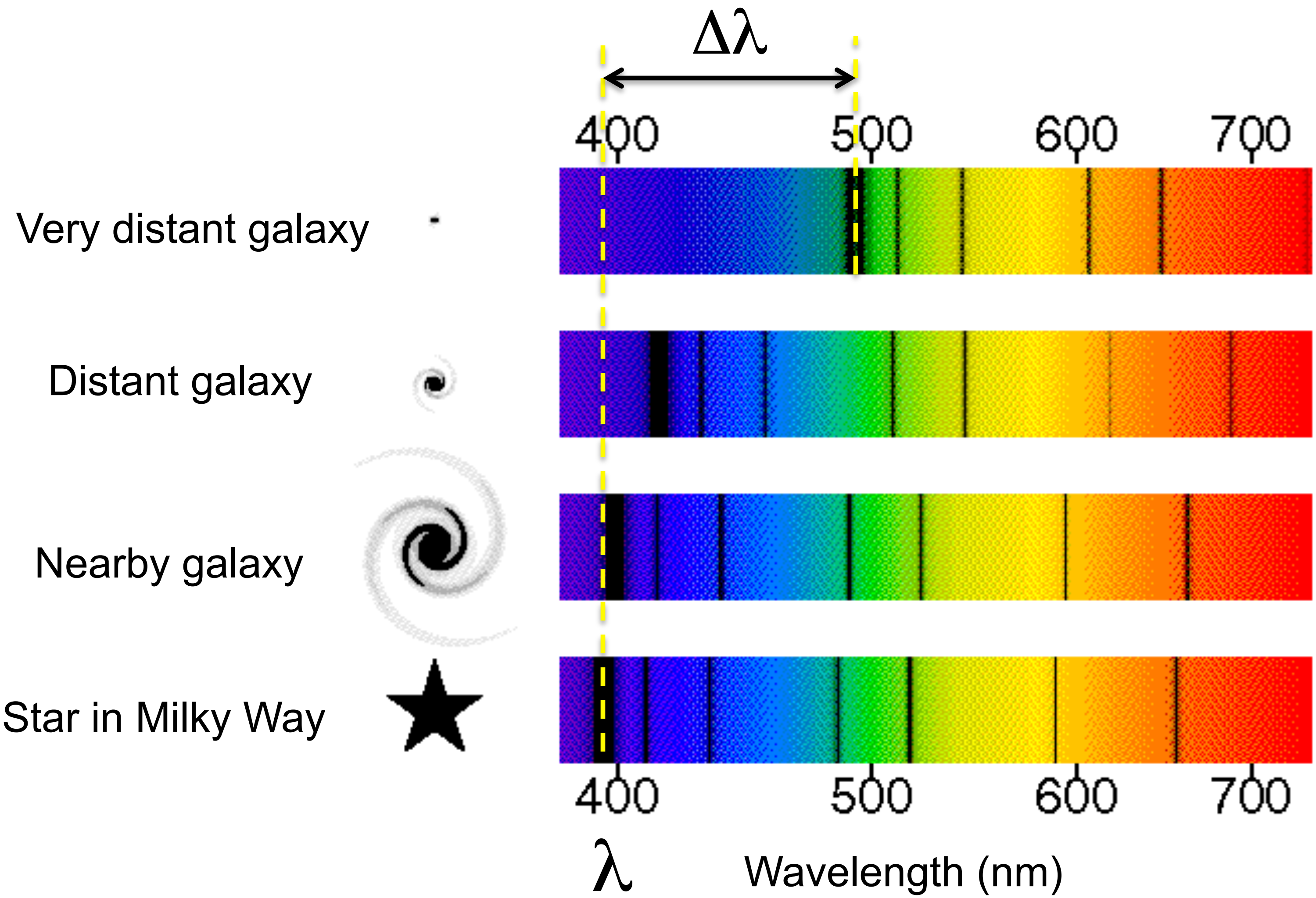


Distance – measured somehow e.g. by “standard candle”

we observe redshift $\Delta\lambda$ or $z = \Delta\lambda/\lambda$

we convert this to velocity using Doppler formula $v = c\,(\Delta\lambda/\lambda)$

even though this is not strictly a Doppler shift!



cosmological redshift $z_{cos} = \Delta\lambda/\lambda$

interpreted as a recession speed using the Doppler formula..

$v_{rec} = cz_{cos} = c\,\Delta\lambda/\lambda$ (OK for $z<0.1$)

for low z ($z<0.1$) $z = v/c$

for high z ($z>0.1$) $z = \sqrt{\frac{c+v}{c-v}} - 1$ effects of special relativity important!

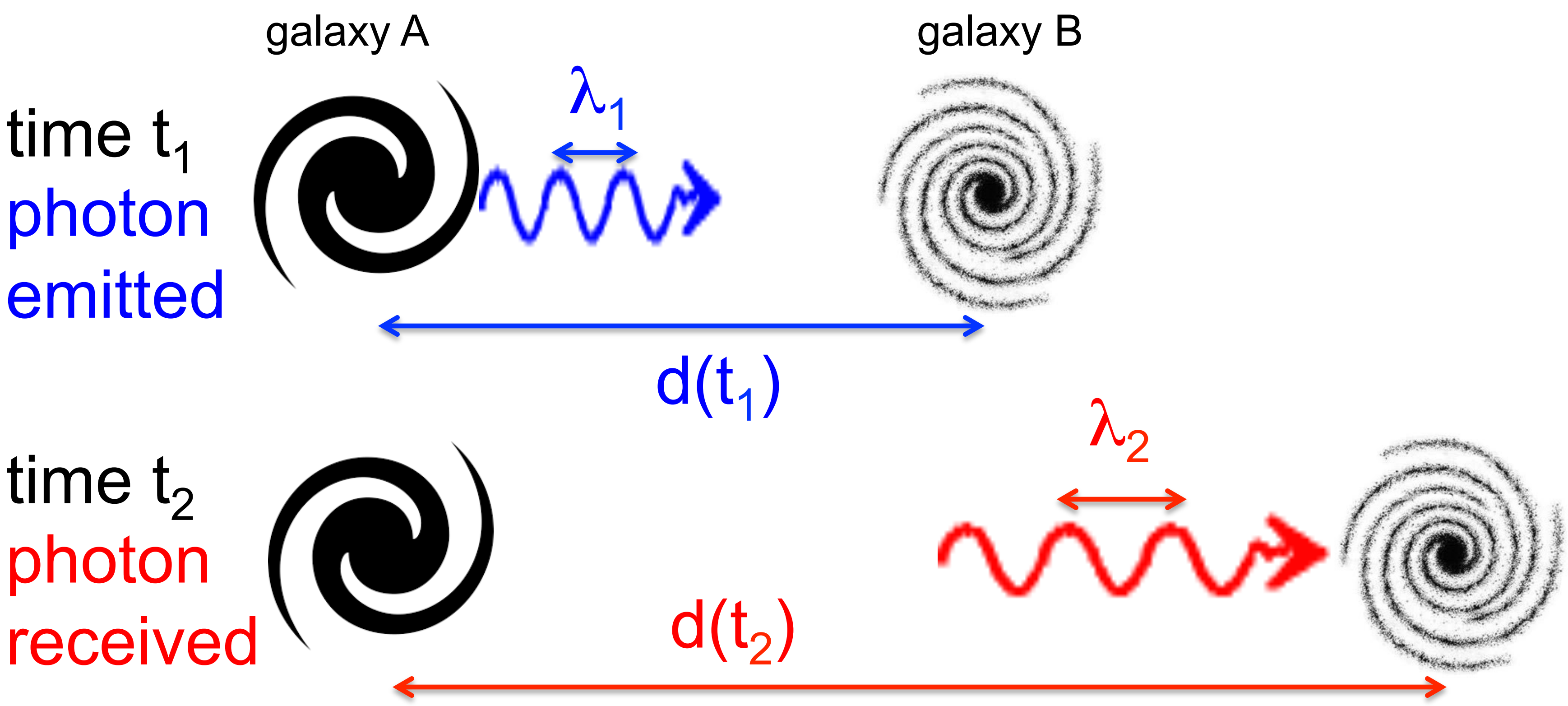
…although this is different from Doppler shift in subtle but important way!!

Doppler shift – caused by object's motion THROUGH space

Cosmological redshift – caused by expansion OF space

(not due to galaxies moving THROUGH space, but expansion of space that carries galaxies with it)

photons are "stretched out" to longer wavelengths as space in universe expands



for a photon emitted at time t_1 and detected at time t_2

$$\lambda_2/\lambda_1 = 1 + z_{cos} = d(t_2)/d(t_1)$$

recall:

$$z_{cos} = \Delta\lambda/\lambda = (\lambda_2 - \lambda_1)/\lambda_1 = \lambda_2/\lambda_1 - 1$$

d is the separation of any 2 points in space
e.g., distance between galaxy A and galaxy B

the distance d between galaxies changes over time due to expansion so good to think of distance as a function of time d(t)

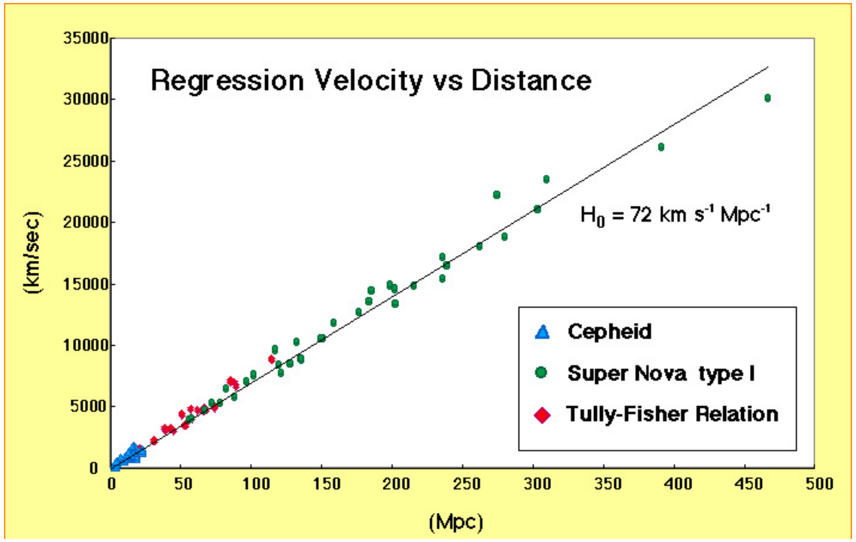
Hubble "constant"

$H_0 = 73 \pm 2$ km s^{-1} Mpc^{-1} expansion rate

units of length in both numerator & denominator
length units cancel, so H_0 has units of 1/time

the inverse of the Hubble constant gives a rough estimate for ***how long the universe has been expanding,***
or that is… ***the Age of the Universe!***

Significance of Hubble Law



1. linear relation between v_{rec} and d is *evidence that universe is expanding*

2. can be used to estimate galaxy distances (once the Hubble "constant" has been measured), using $d = v_{rec}/H_o$

For which galaxies would the regular (linear) Hubble law give a good distance estimate?

A. All galaxies
B. Only the nearest galaxies
C. Only the most distant galaxies
D. Only galaxies at intermediate distances
E. Only non-zombie galaxies
F. No galaxies

Linear Hubble law and $d=v/H_o$ don't work well for nearest and furthest galaxies

a. Nearest galaxies (D<20 Mpc)

b. Distant galaxies (D>400 Mpc, z>0.1)

Linear Hubble law and $d=v/H_o$ don't work well for nearest and furthest galaxies

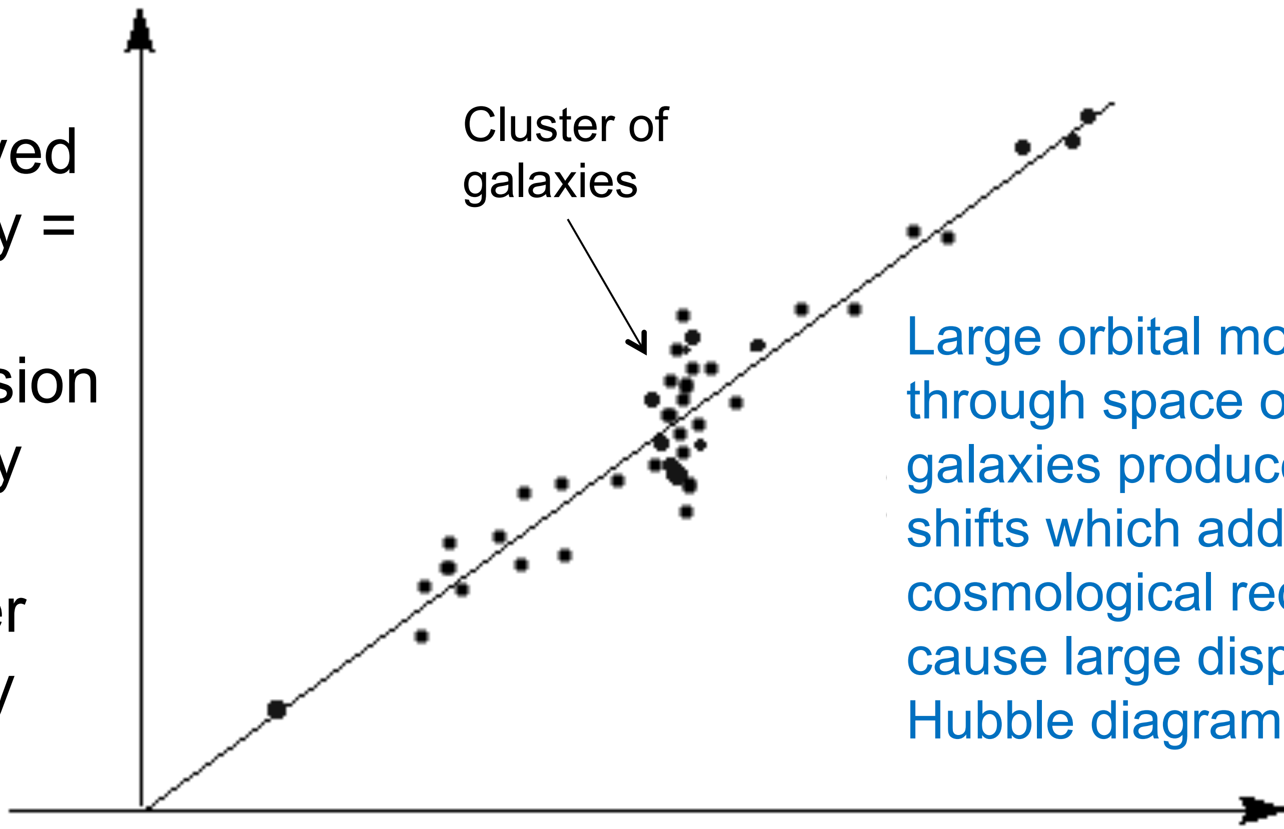
a. Nearest galaxies (D<20 Mpc)

Galaxies can have *motion through space* (causing Doppler shift) in addition to *recession due to expansion of space* (causing cosmological redshift)

Motion through space adds scatter to Hubble diagram

Observed Velocity =

Recession Velocity + Doppler velocity



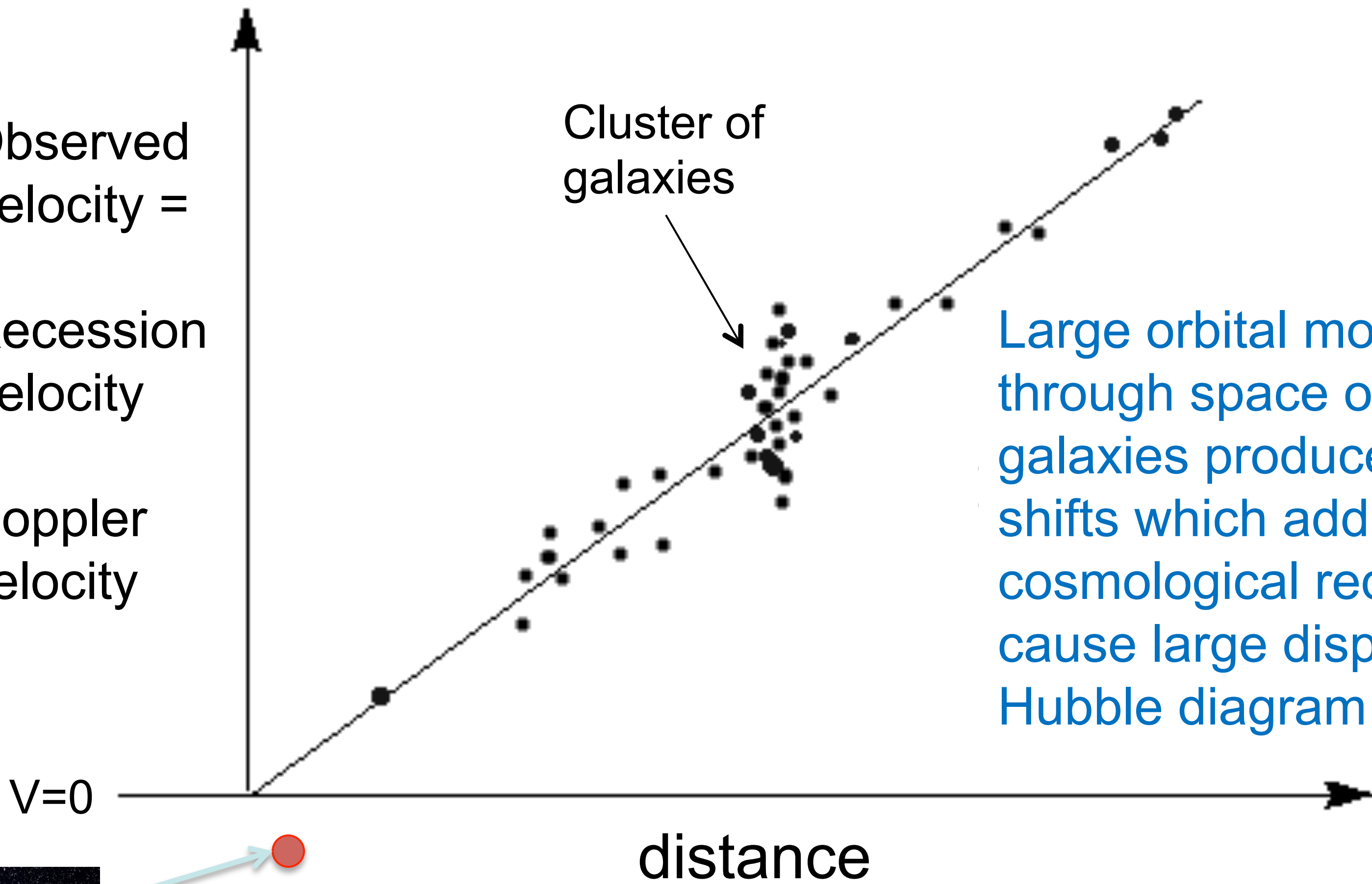
distance

Large orbital motions through space of cluster galaxies produces Doppler shifts which add to cosmological redshift to cause large dispersion in Hubble diagram

Motion through space adds scatter to Hubble diagram

Observed Velocity =

Recession Velocity + Doppler velocity



Large orbital motions through space of cluster galaxies produces Doppler shifts which add to cosmological redshift to cause large dispersion in Hubble diagram

M31 at v = -200 km/s

It is blueshifted since it has motion through space toward us

Linear Hubble law and $d=v/H_o$ don't work well for nearest and furthest galaxies

a. Nearest galaxies (D<20 Mpc)

Galaxies can have *motion through space* (causing Doppler shift) in addition to *recession due to expansion of space* (causing cosmological redshift)

Typical motion through space (due to gravity of other galaxies) is V_{dopp} ~100-1000 km/sec

For distant galaxies $V_{rec} > V_{dopp}$ but for some nearby galaxies $V_{rec} < V_{dopp}$

Linear Hubble law and $d=v/H_o$ don't work well for nearest and furthest galaxies

b. Distant galaxies (D>400 Mpc, z>0.1)

i. Hubble "constant" (expansion rate) varies with time. When we view distant galaxies, we are also looking back in time.

(H_o is *present value* of expansion rate).

Linear Hubble law and $d=v/H_o$ don't work well for nearest and furthest galaxies

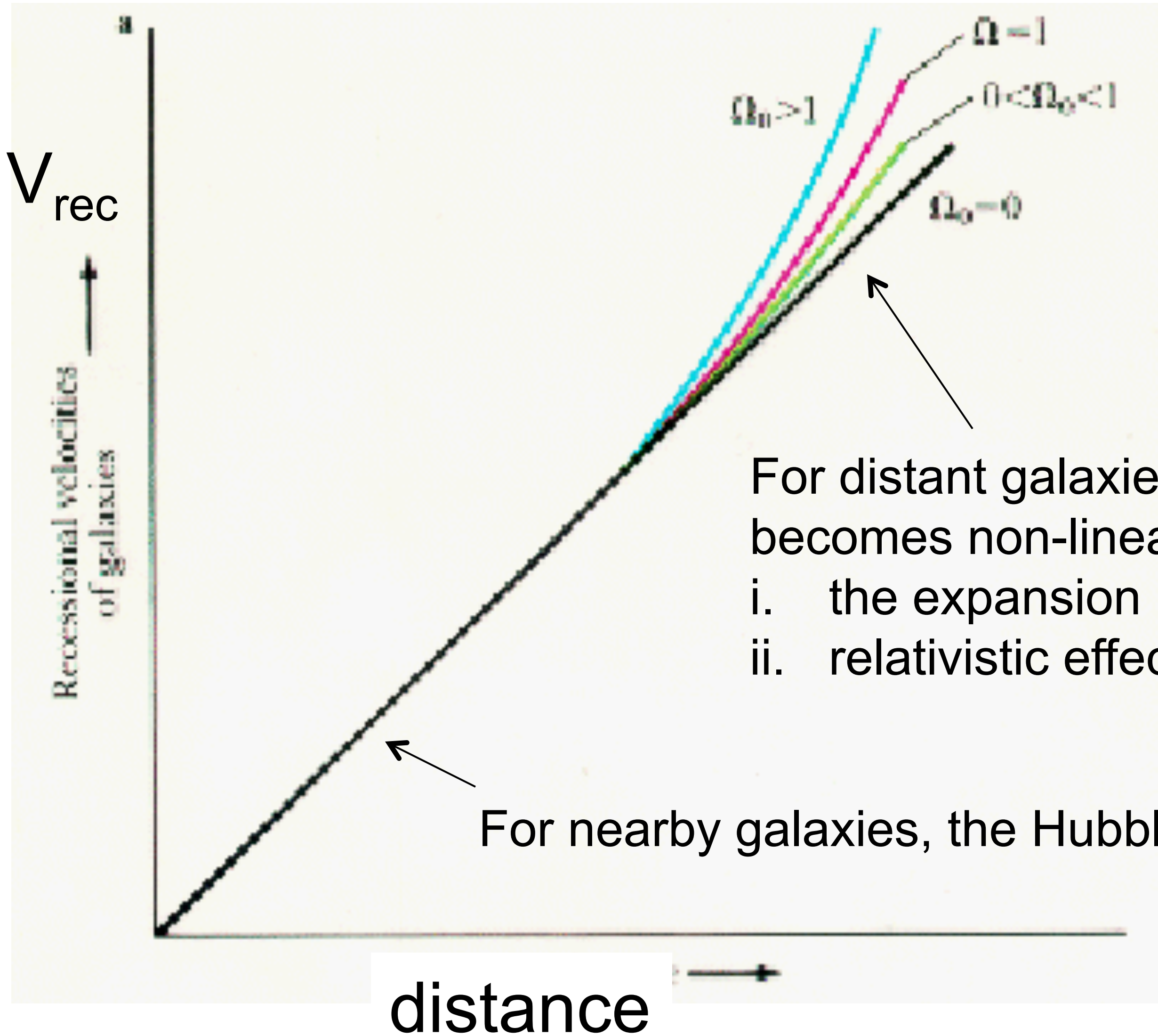
b. Distant galaxies (D>400 Mpc, z>0.1)

i. Hubble "constant" (expansion rate) varies with time. When we view distant galaxies, we are also looking back in time.

(H_o is *present value* of expansion rate).

ii. Relativistic effects make relation between observed redshift and velocity more complicated

Hubble law becomes non-linear at large distances



For distant galaxies, the Hubble law becomes non-linear because:

i. the expansion rate varies with time
ii. relativistic effects

For nearby galaxies, the Hubble law is linear

Linear Hubble law and $d=v/H_o$ don't work well for nearest and furthest galaxies

a. Nearest galaxies (D<20 Mpc)

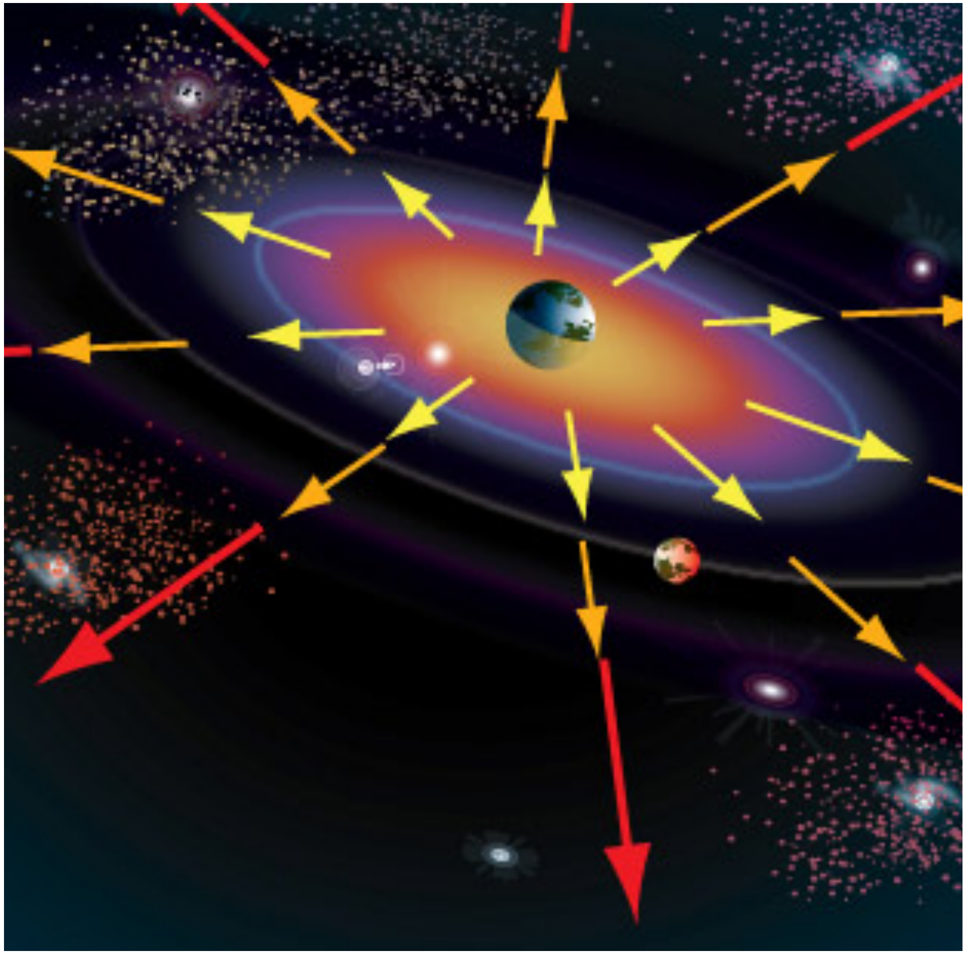
Galaxies can have *motion through space* in addition to *recession due to expansion of space*

b. Distant galaxies (D>400 Mpc, z>0.1)

i. Hubble "constant" (expansion rate) varies with time. When we view distant galaxies, we are also looking back in time.

ii. Relativistic effects make relation between observed redshift and velocity more complicated

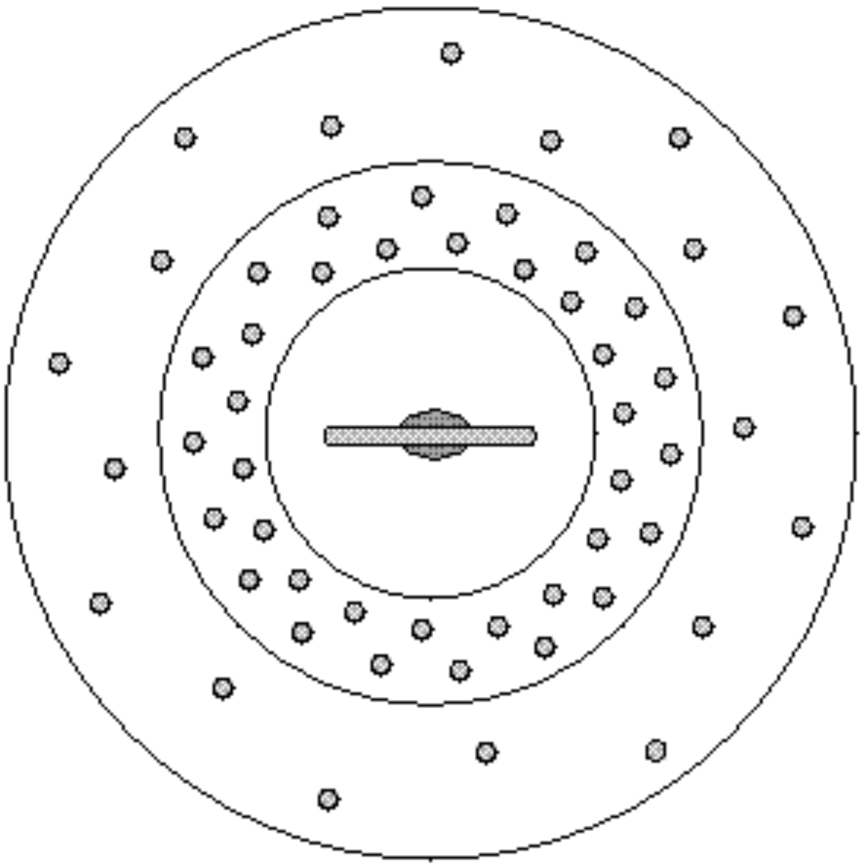
ARE WE AT THE CENTER OF THE EXPANSION?



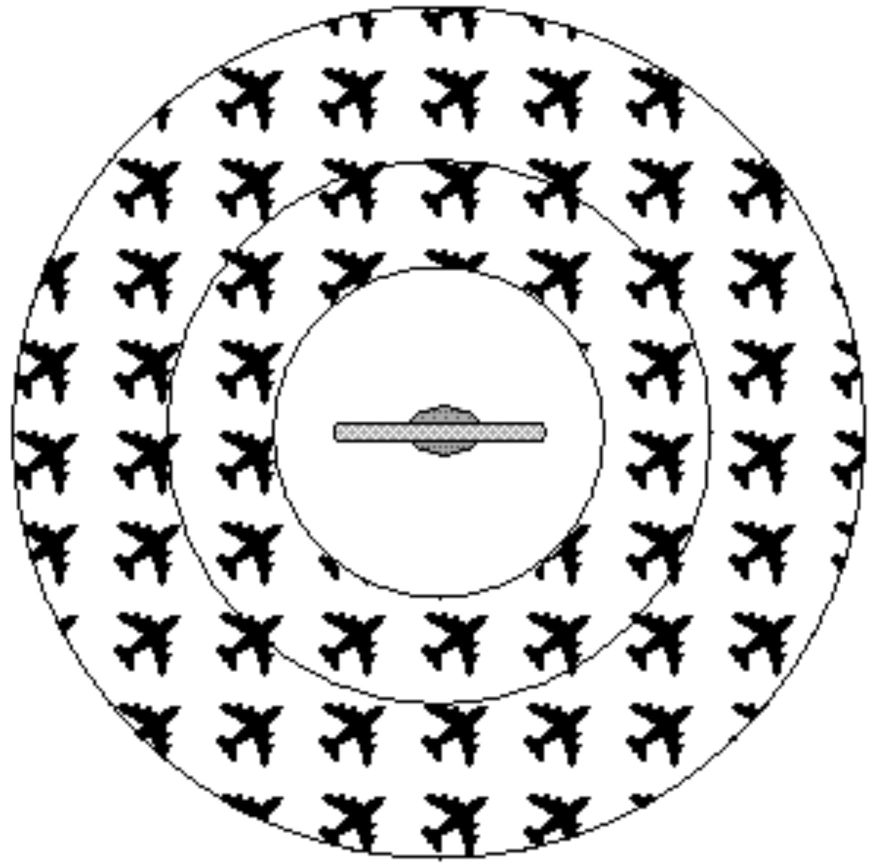
Cosmological principle

- At any instant of time, the universe on large scales is homogenous (same at every location) and isotropic (same in every direction)

Homogenous & isotropic?

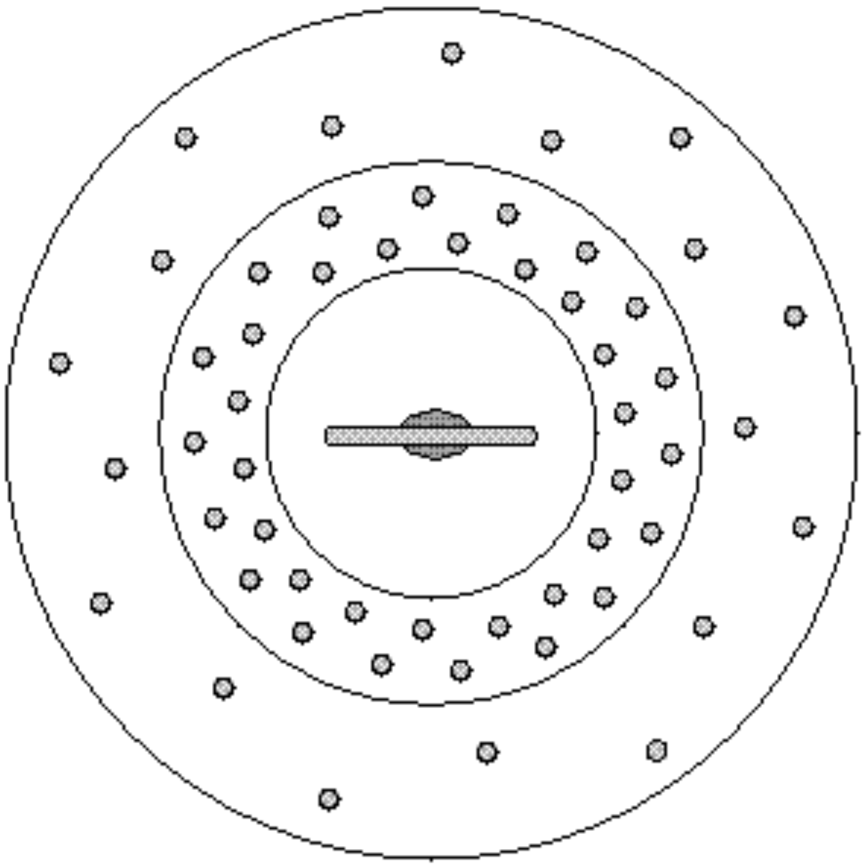


Is this *homogeneous* and *isotropic*? Which aspect is it not?

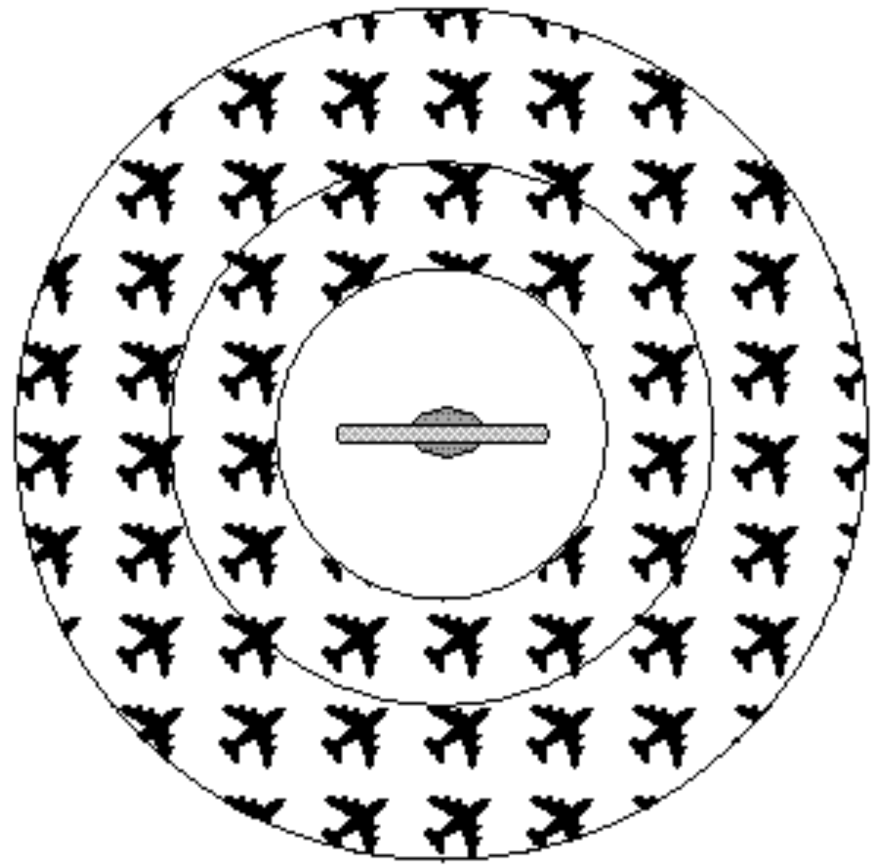


Outside the central sphere, is this universe *homogeneous* and *isotropic*? Which aspect is it not?

Homogenous & isotropic?



isotropic but not homogenous

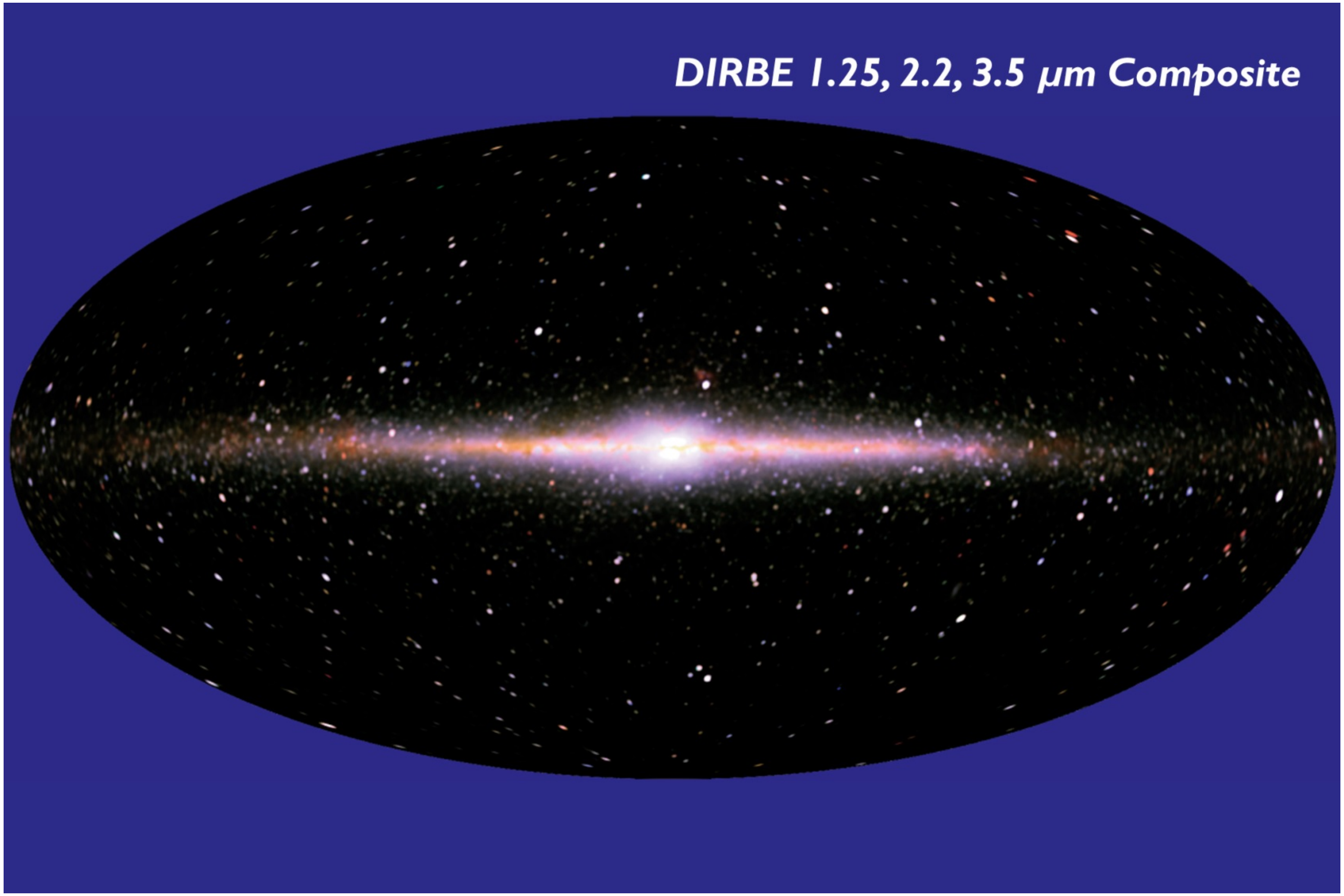


homogenous but not isotropic

Cosmological principle

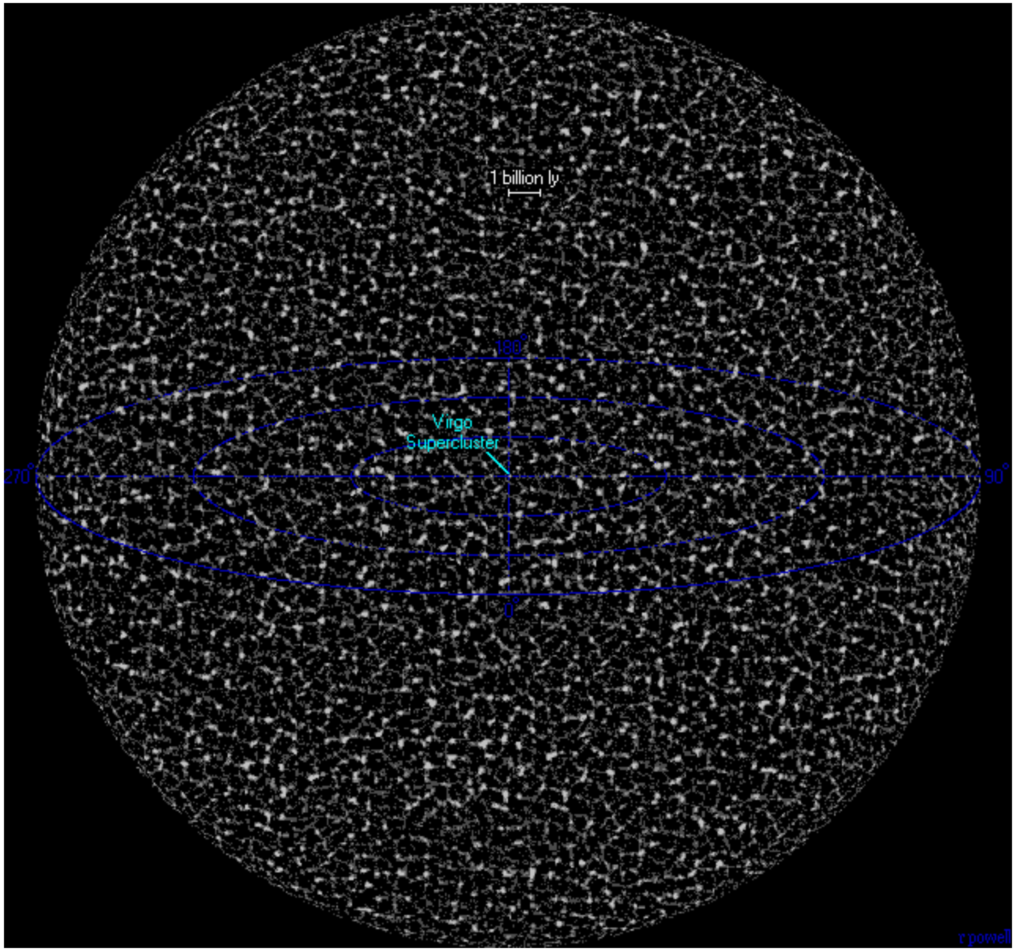
- At any instant of time, the universe on large scales is homogenous (same at every location) and isotropic (same in every direction)

- We have evidence that this is true on large scales – >10^8 light years -- larger than superclusters & voids



on small scales (100,000 LY), we see that there IS a special location in space (the center of the Milky Way Galaxy)

Universe out to 12 billion light years



On large scales, no special place! No obvious “center”.

This is evidence that space is expanding –

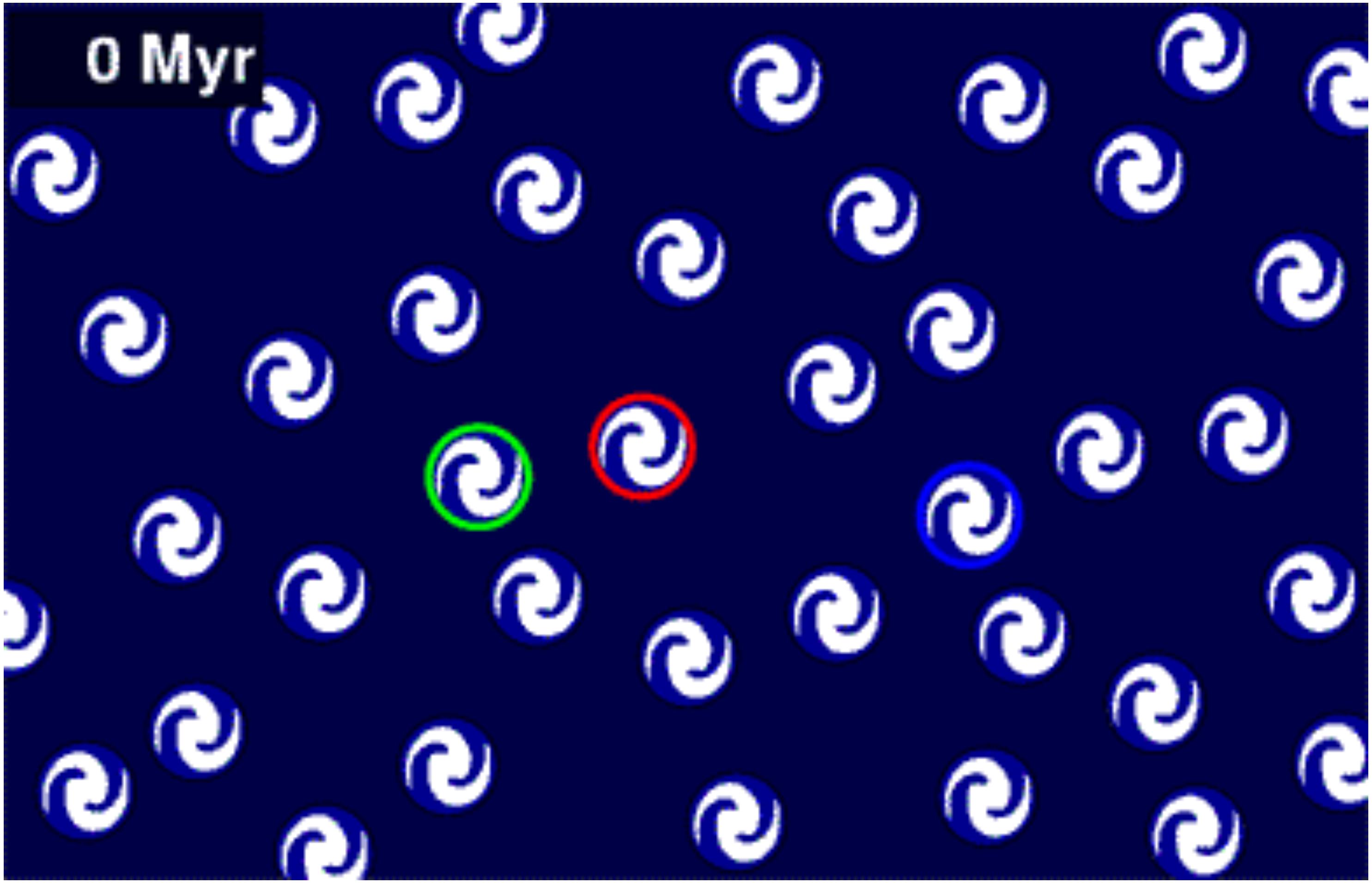
expansion not due to an explosion IN space.

Cosmological principle

- At any instant of time, the universe on large scales is homogenous (same at every location) and isotropic (same in every direction)

- We have evidence that this is true on large scales – >10^8 light years -- larger than superclusters & voids

- If true, any observer in universe will observe same expansion that we do!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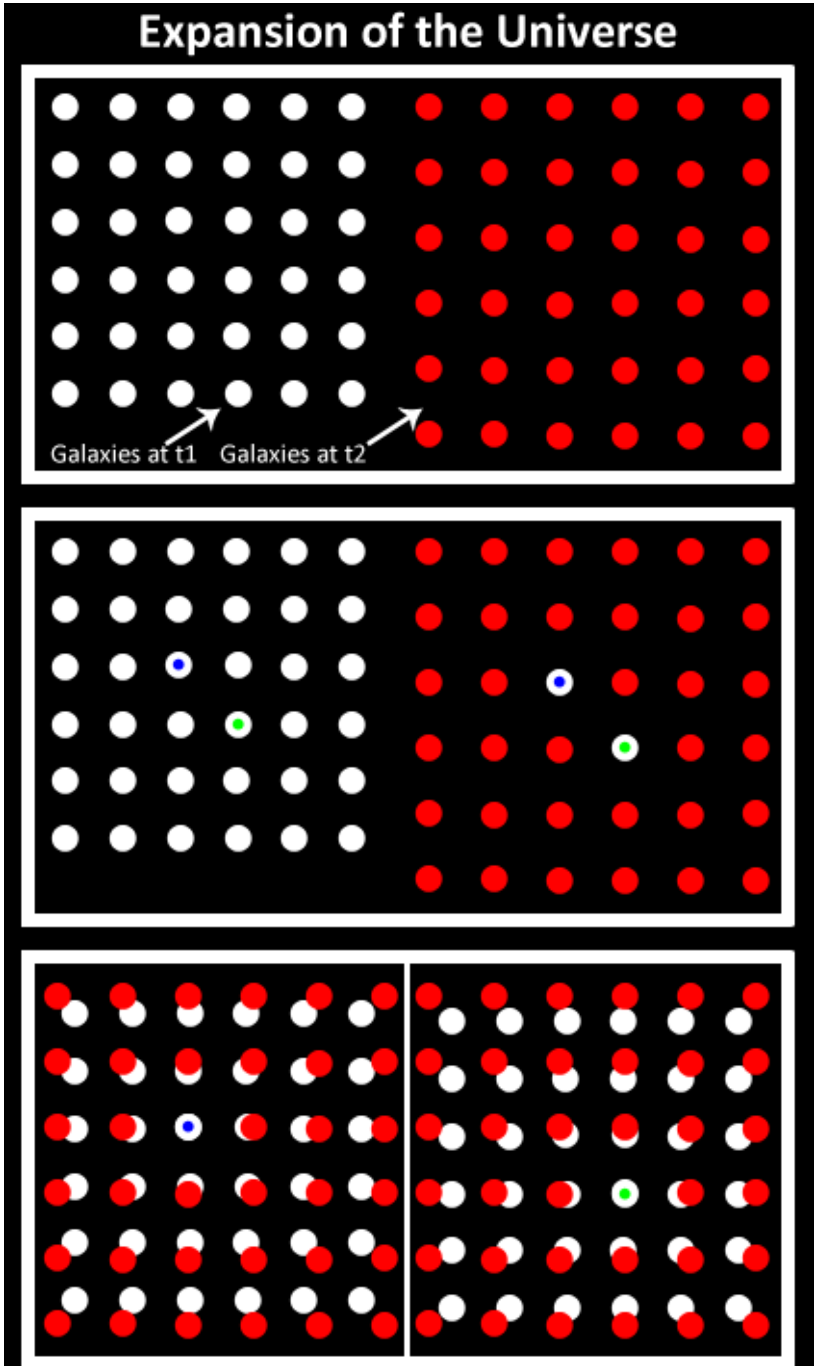
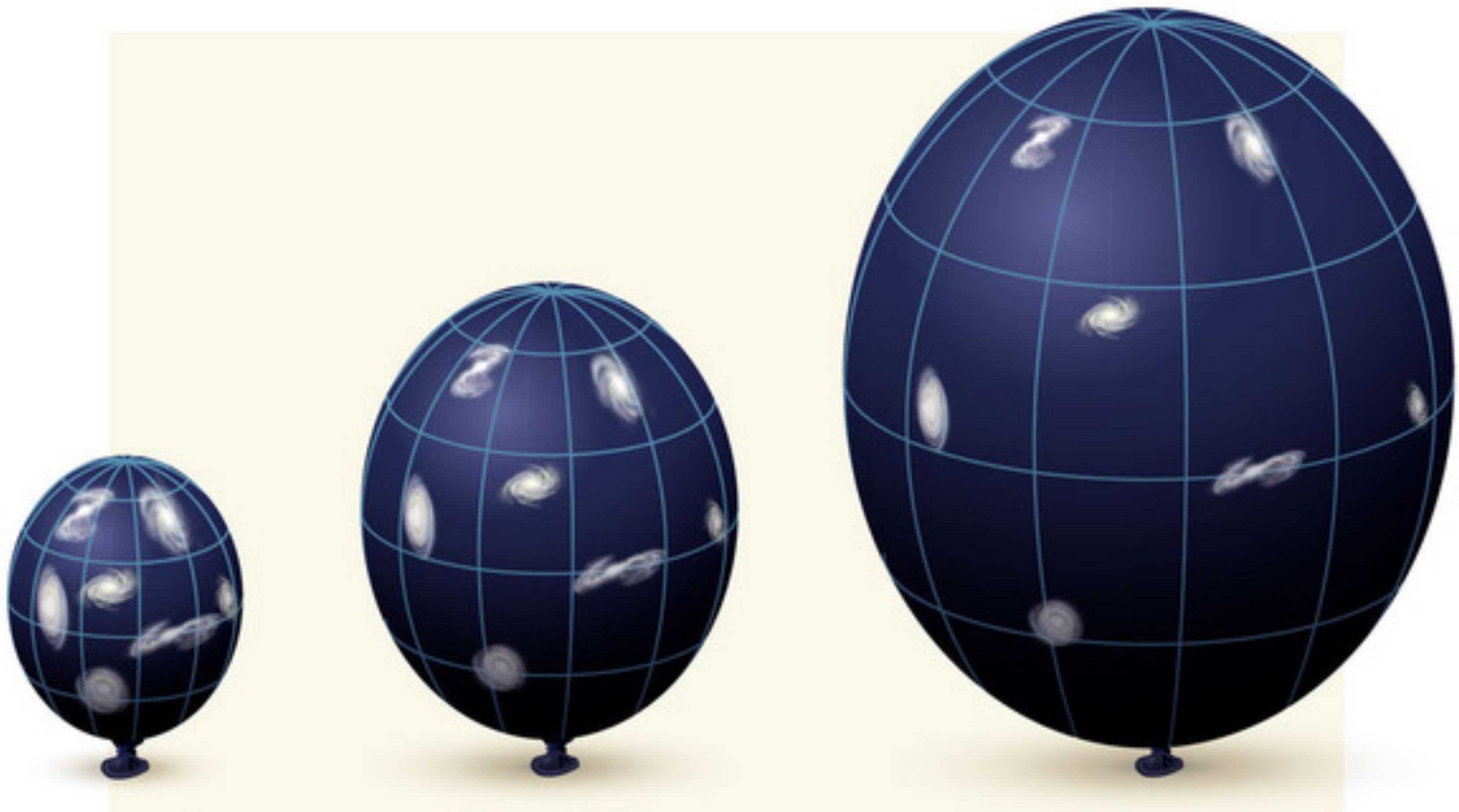


Expansion from different perspectives

Each observer observes expansion around them with same Hubble Law



The expansion of the universe takes place

A. between all objects, even between atoms in our bodies, although the expansion of a person is too small to be measured reliably.

B. only between objects separated by a near vacuum; as a result, our bodies do not expand but the Earth-Moon system does.

C. only over distances about the size of a galaxy or larger; consequently, our galaxy expands but the solar system does not.

D. primarily in the huge voids between clusters of galaxies: "small" objects like galaxies or the Earth do not expand.

What is it that keeps localized regions of space, such as planetary systems, star clusters, and whole galaxies, from participating in the general expansion of the universe?

A. pressure from dark energy
B. their mutual or self-gravity
C. gravity from the central object (e.g., Supermassive Black Holes)
D. centrifugal force produced by their motion around a massive central object (e.g., the Sun, SMBHs)
E. electromagnetic attraction of atoms (for people)
F. subatomic stubborness

If the Universe is expanding, what is it expanding into?

A. A higher dimensional space
B. The future
C. It is not expanding into anything: expanding means that the distances between objects (galaxies) in the Universe are increasing with time.
D. The Universe is not actually expanding: it's just a convenient way for describing Hubble's Law
E. We don't know
F. Run-down parts of New Haven

Grading

35% Weekly Homework (was 40%)
10% Reading quizzes
10% Attendance & Class Participation
10% Observing & Planetarium assignment
15% Midterm exam (was 0%)
20% Final exam (was 30%)

Final Exam

- Friday June 29 (last day of class)
- 2pm-5pm (?)

Homeworks

- HW 8 due *Fri June 22*
- HW 9 due *Tues June 26*
- HW 10 due *Thurs June 28*