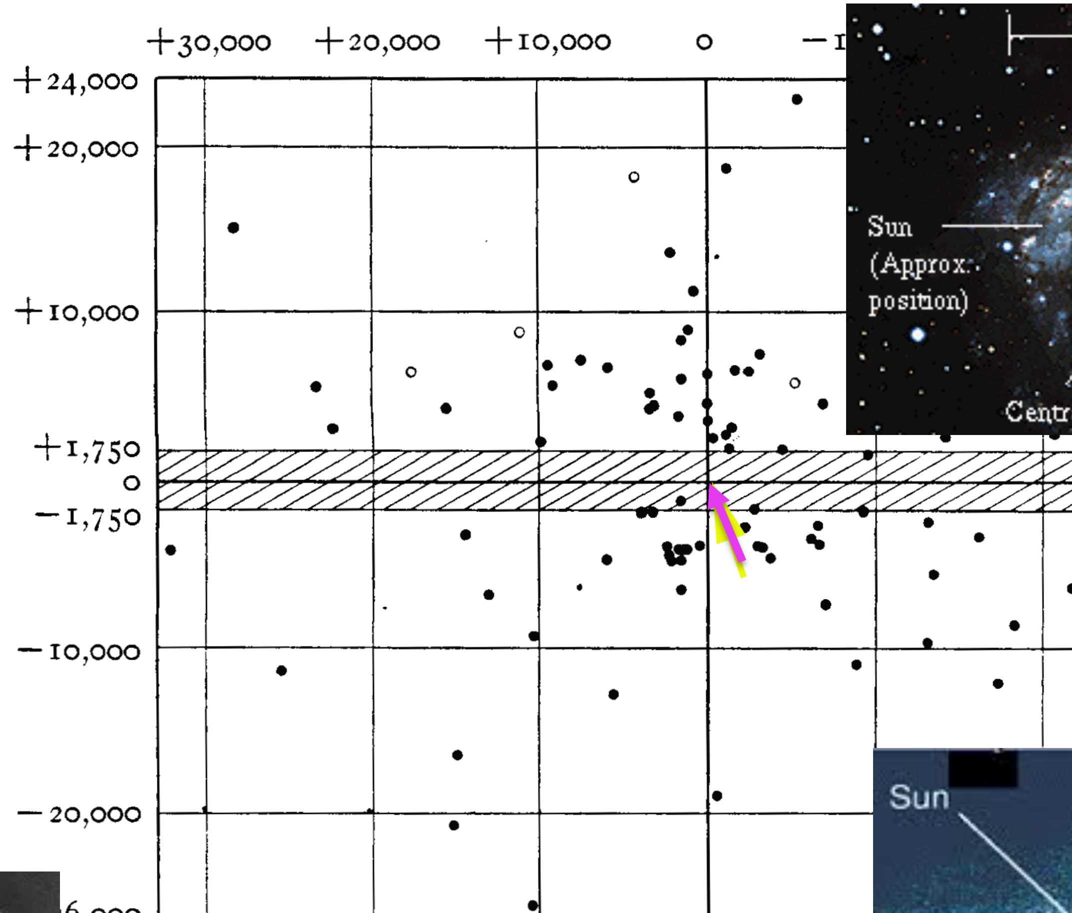

1900-20: Are we at the Center of the Cosmos?

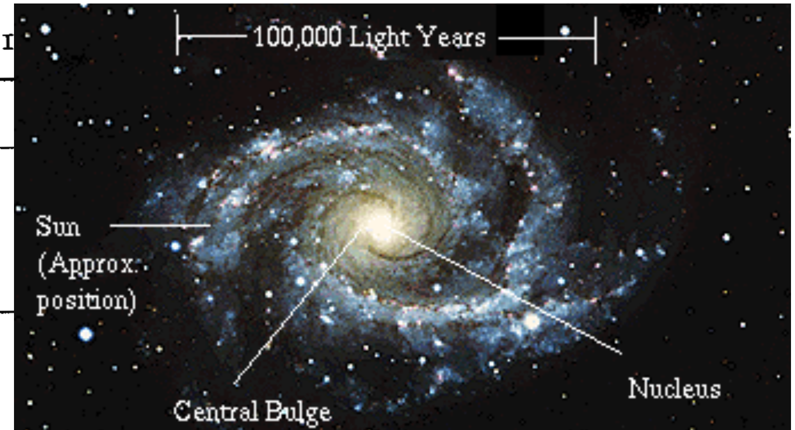
Where's the Center?

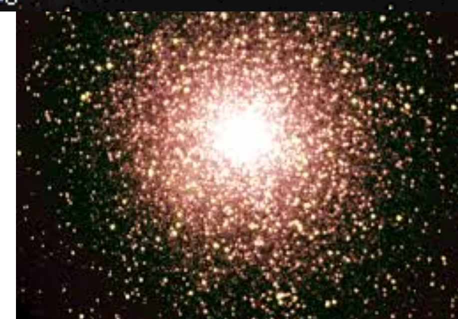
The power of symmetry

Where’s the Center?

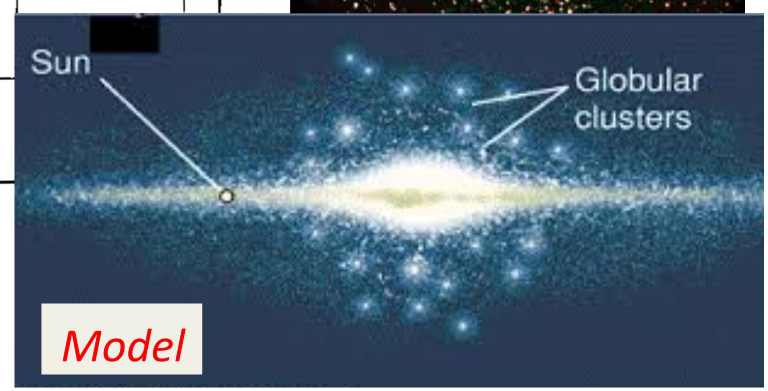
1920s: Shapley and “Globular Clusters”







Observations: Shapley’s diagram of GC directions

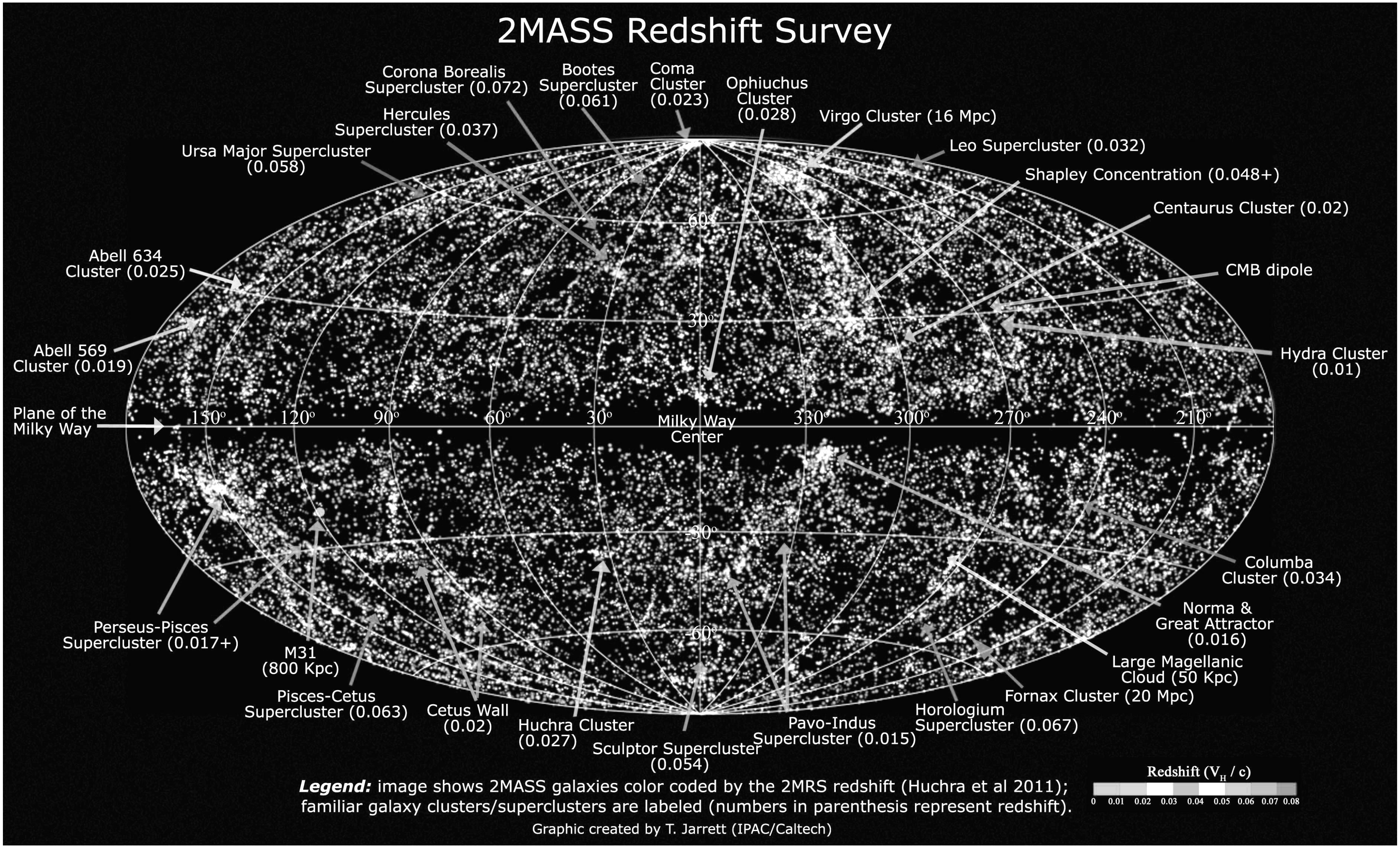


Model

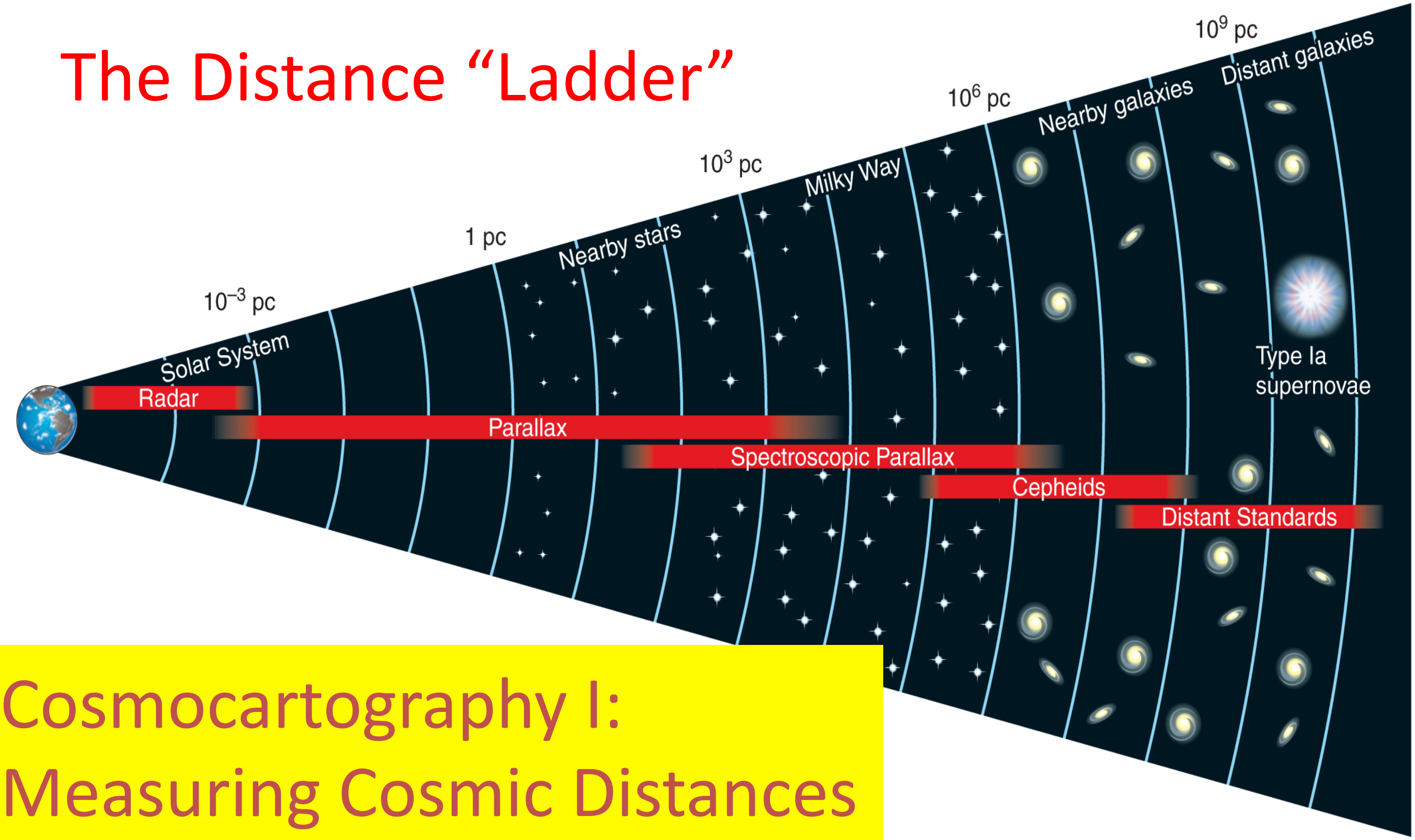
Our Observational Toolkit

- Our toolkit of Vital Measurement Methodologies
- Cosmocartography I: How we measure cosmic distances
- "standard candles"
- Cosmocartography II: How we measure cosmic speeds
- "Doppler shifts, $\Delta\lambda$" (aka redhifts $z = \Delta\lambda/\lambda_o$)
- How z relates to the speed of recession when $z < 0.7$
- How this relation changes when $z > 0.7$
-

Cosmocartography I: Measuring distances



The Distance "Ladder"



Cosmocartography I: Measuring Cosmic Distances

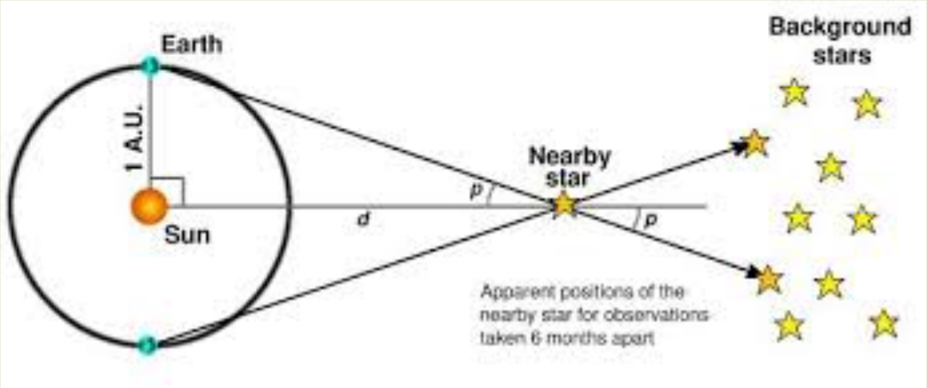
Radiation, Luminosity, Brightness, and the Inverse Square Law

- ***Luminosity: the total rate of light emission (energy per seond)***
  Radiant energy per second, Intrinsic property
  Watts, Solar luminosit
- ***Brightness: Energy reaching the surface of a detector***
- ***(energy per second per area)***
  Radiant energy per second per aperture area
  your pupil, front end of a telescope)
  Not intrinsic; depends on distance between emitter (source) and aperture
- ***Inverse Square Law***
  Brightness prop.. to Luminosity / $(\text{distance})^2$

$$\boldsymbol{L} = 4\pi(\text{dist})^2 \times \boldsymbol{B}$$

How distances are measured?

- ***Radar***
  solar system
- ***Parallax***
  10,000 light years
  (not very far)

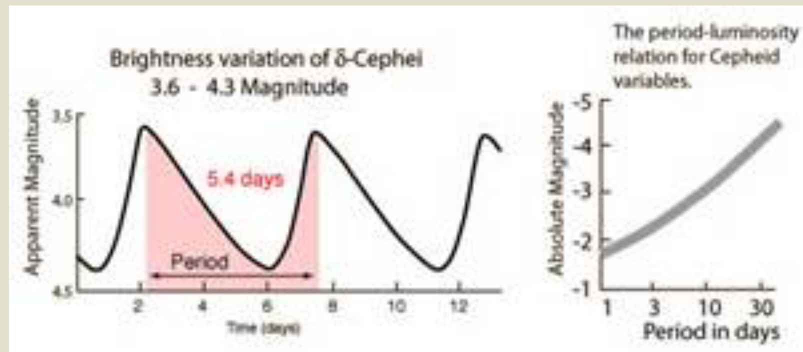


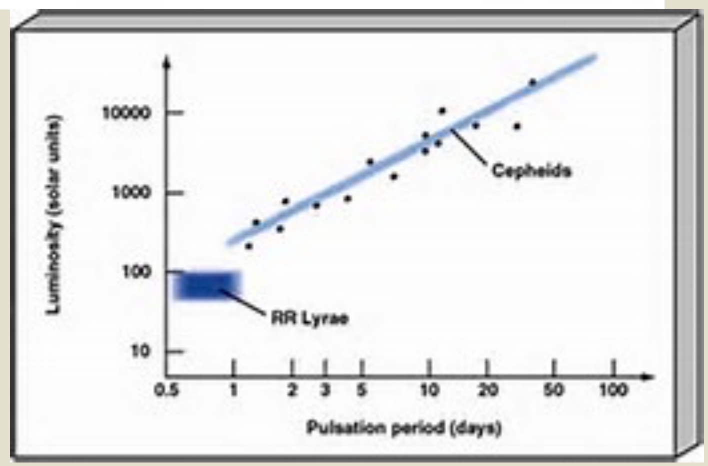
Standard Candles

- Bright stars of known luminosity
  nearest dozen galaxies
- Bright variable stars whose period and luminosity are calibrated ("Cepheids")
  nearest hundred galaxies
- Supernovae type Ia
  - Several billion light years

Cosmic Standard Candles

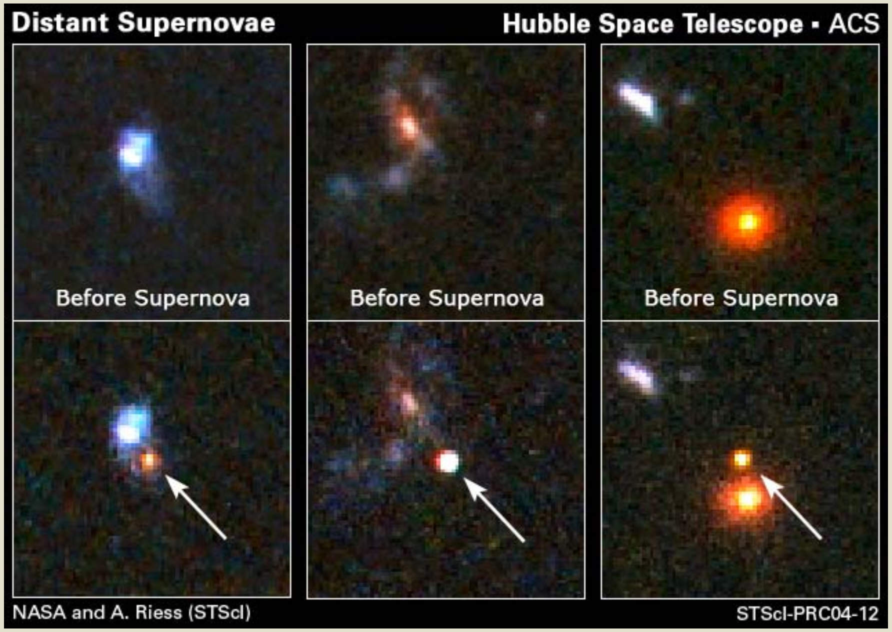
- ”Cepheid variables” are very luminous (> 1000 $L_{\odot}$) pulsating stars with large and highly characteristic brightness patterns. They are easily recognized.
- Their periods are correlated with their luminosities





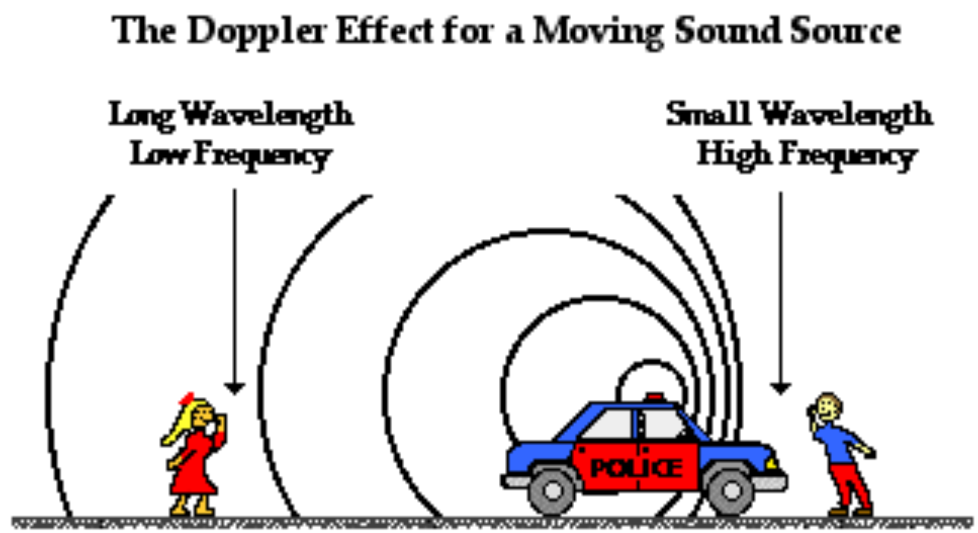
Cosmic Standard Candles

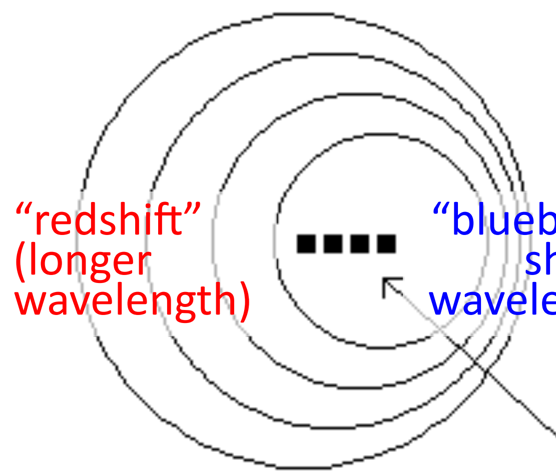
- "**SN Ia**" are examples of extremely rare and luminous standard candles
- can see them out to many billions of light years
- trace largest cosmic distances



Cosmocartography II: Measuring radial speeds

The "Doppler Shift"



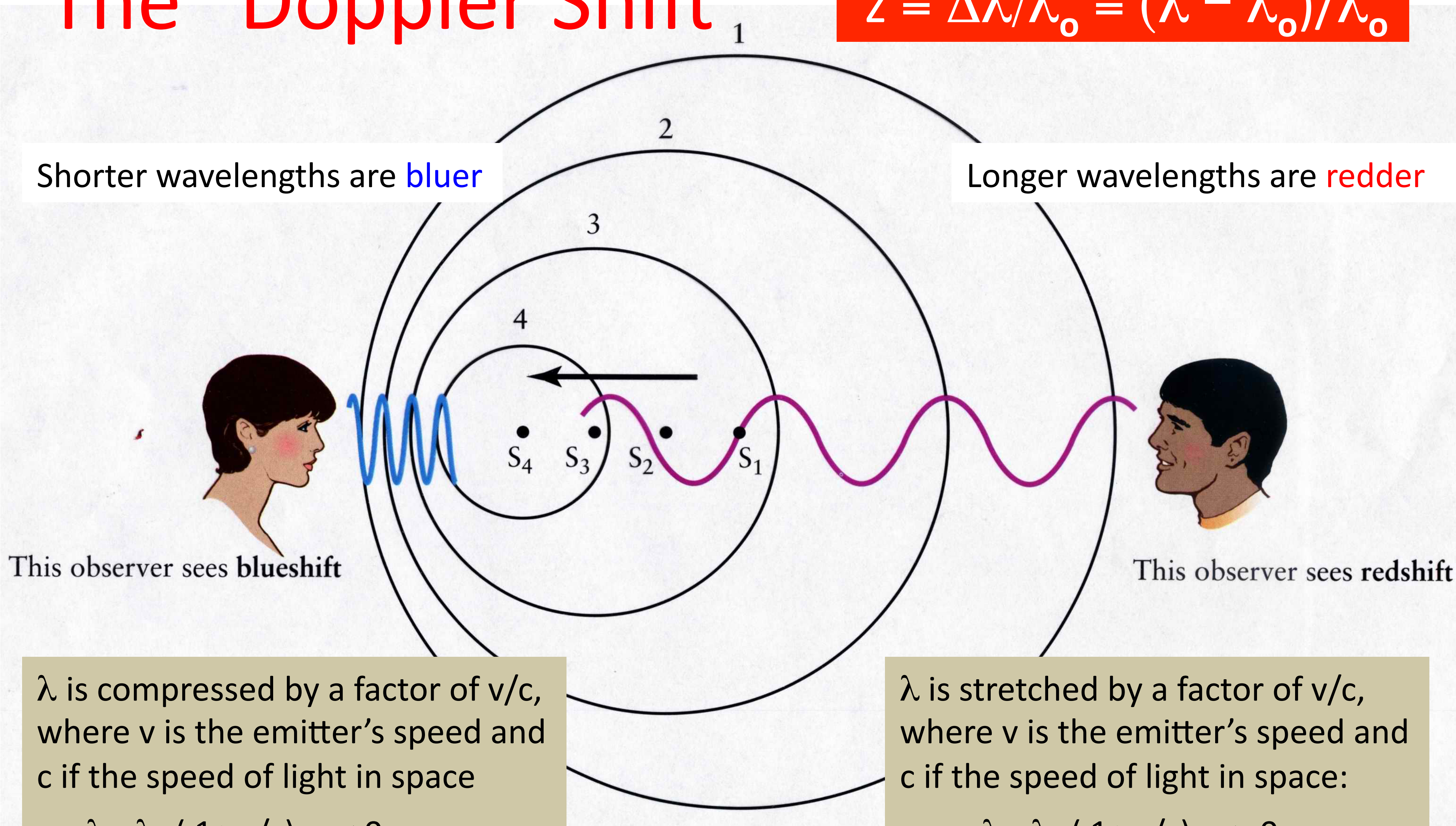


The “Doppler Shift”

$z = \Delta\lambda/\lambda_o = (\lambda - \lambda_o)/\lambda_o$

Shorter wavelengths are bluer

Longer wavelengths are redder



λ is compressed by a factor of v/c, where v is the emitter’s speed and c if the speed of light in space

$\lambda = \lambda o(1 + v/c),\ v < 0$

$v/c = z =$ “blueshift”

λ is stretched by a factor of v/c, where v is the emitter’s speed and c if the speed of light in space:

$\lambda = \lambda o(1 + v/c),\ v > 0$

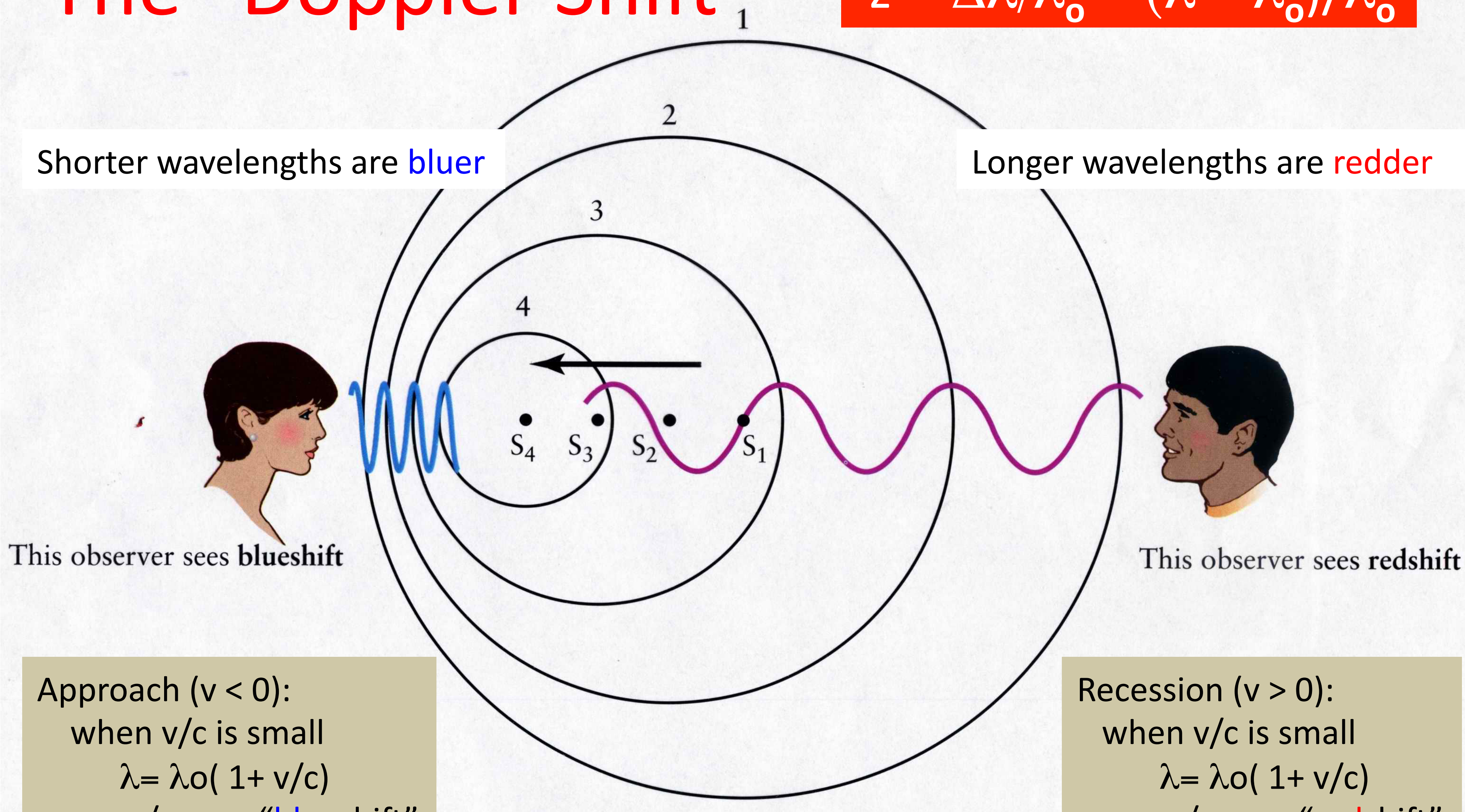
$v/c = z =$ “redshift”

The “Doppler Shift”

$z = \Delta\lambda/\lambda_o = (\lambda - \lambda_o)/\lambda_o$

Shorter wavelengths are bluer

Longer wavelengths are redder

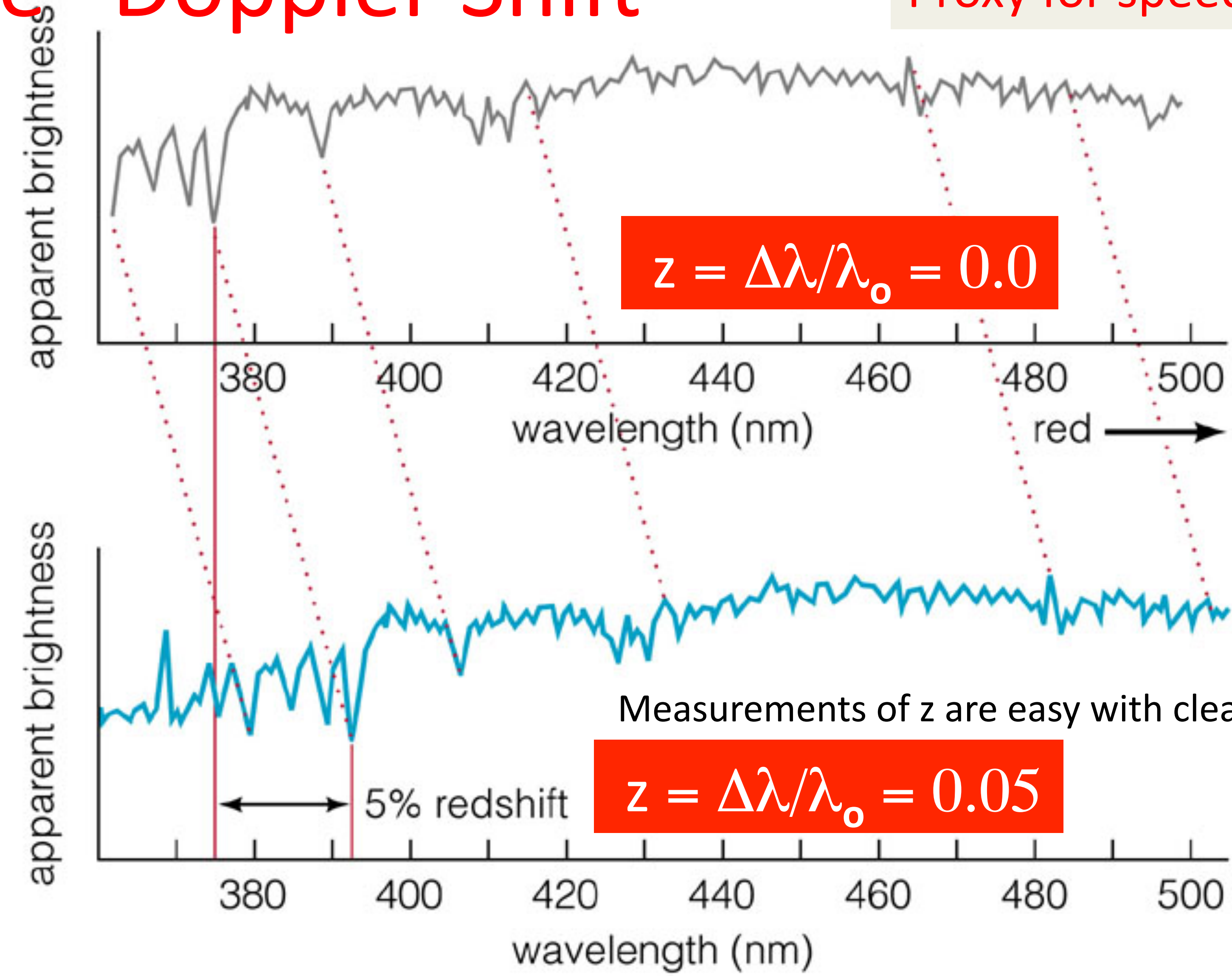


Approach (v < 0):
when v/c is small
$\lambda = \lambda o(1 + v/c)$
v/c = z = “blueshift”

Recession (v > 0):
when v/c is small
$\lambda = \lambda o(1 + v/c)$
v/c = z = “redshift”

The "Doppler Shift"

Doppler shift $\Delta\lambda/\lambda_o$:
Proxy for speed

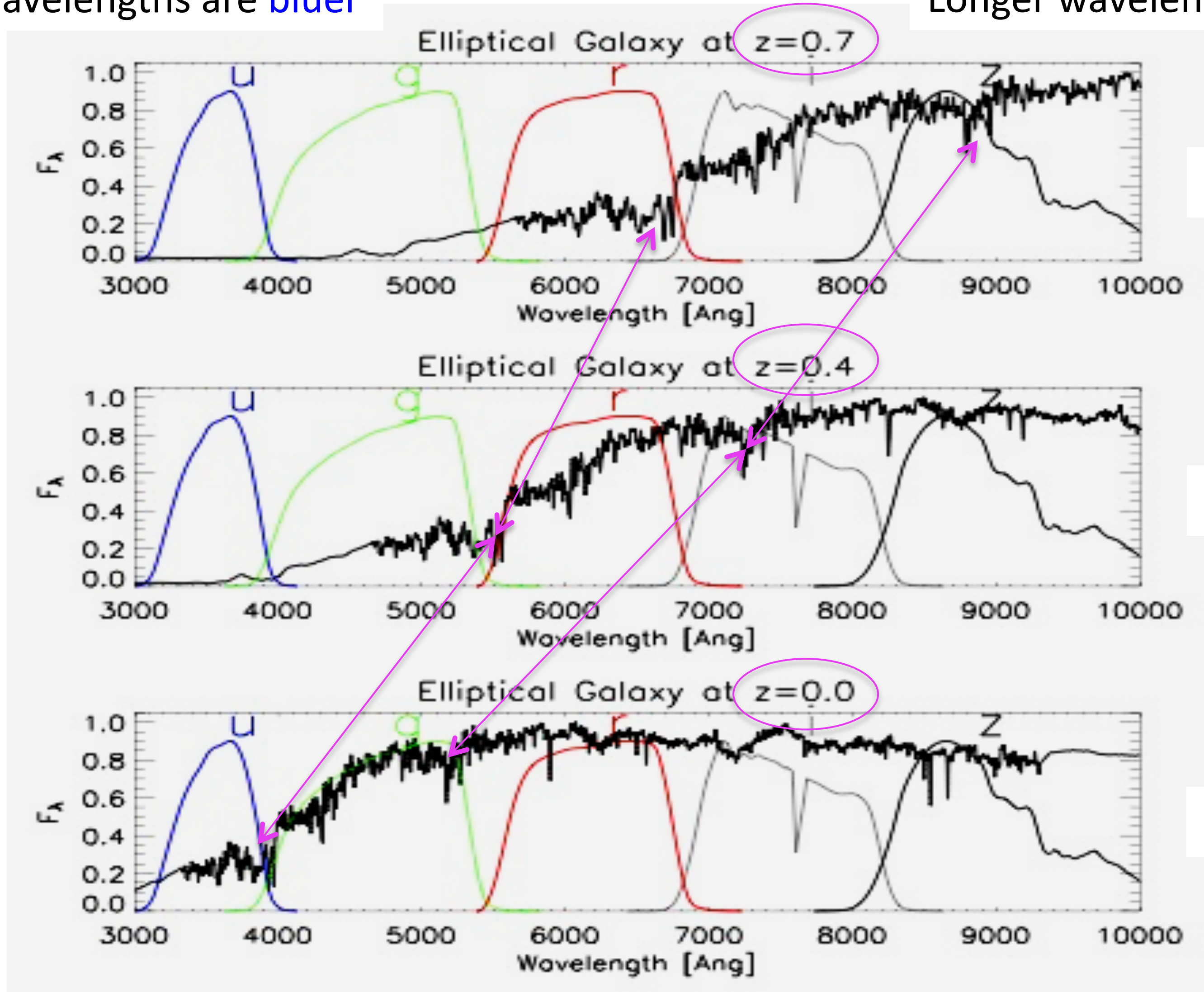


Shorter wavelengths are bluer

Longer wavelengths are redder

Shorter wavelengths are bluer

Longer wavelengths are redder



70% stretch

40% stretch

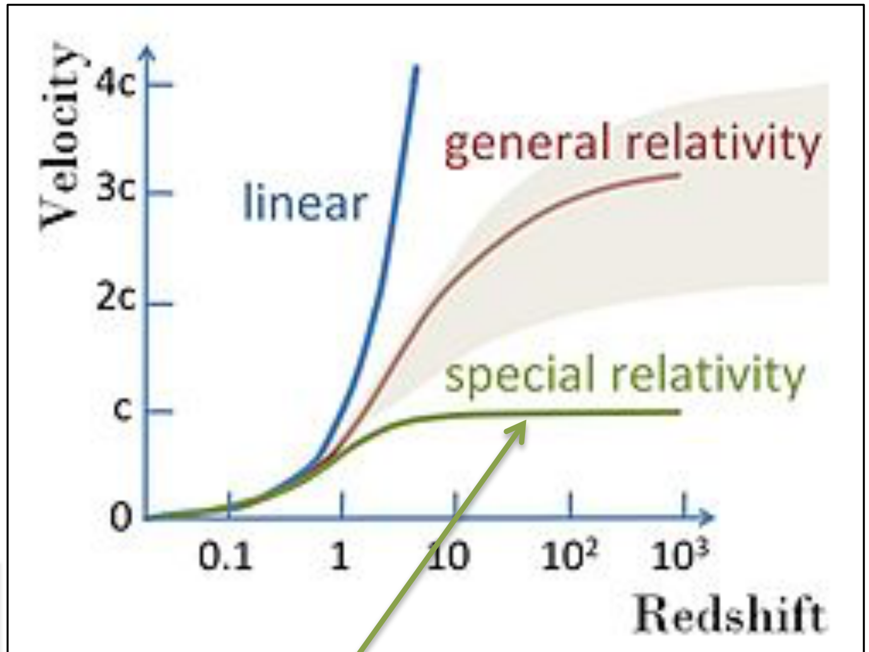
no stretch

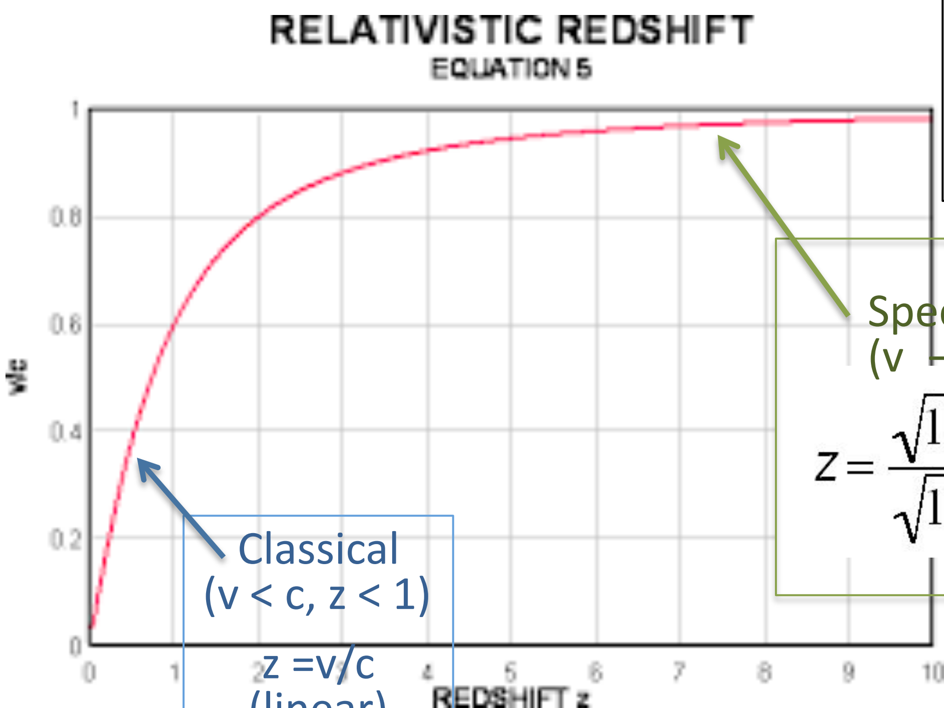
Although v/c cannot exceed 1, z is not limited by relativity. We have measured redshifts of 10 in very distant galaxies!

Redshift and Recession Speed when v approaches c

Classical: z = v/c < 1

Relativity: no upper limit to z





Special relativity
(v —> c, z > 1))

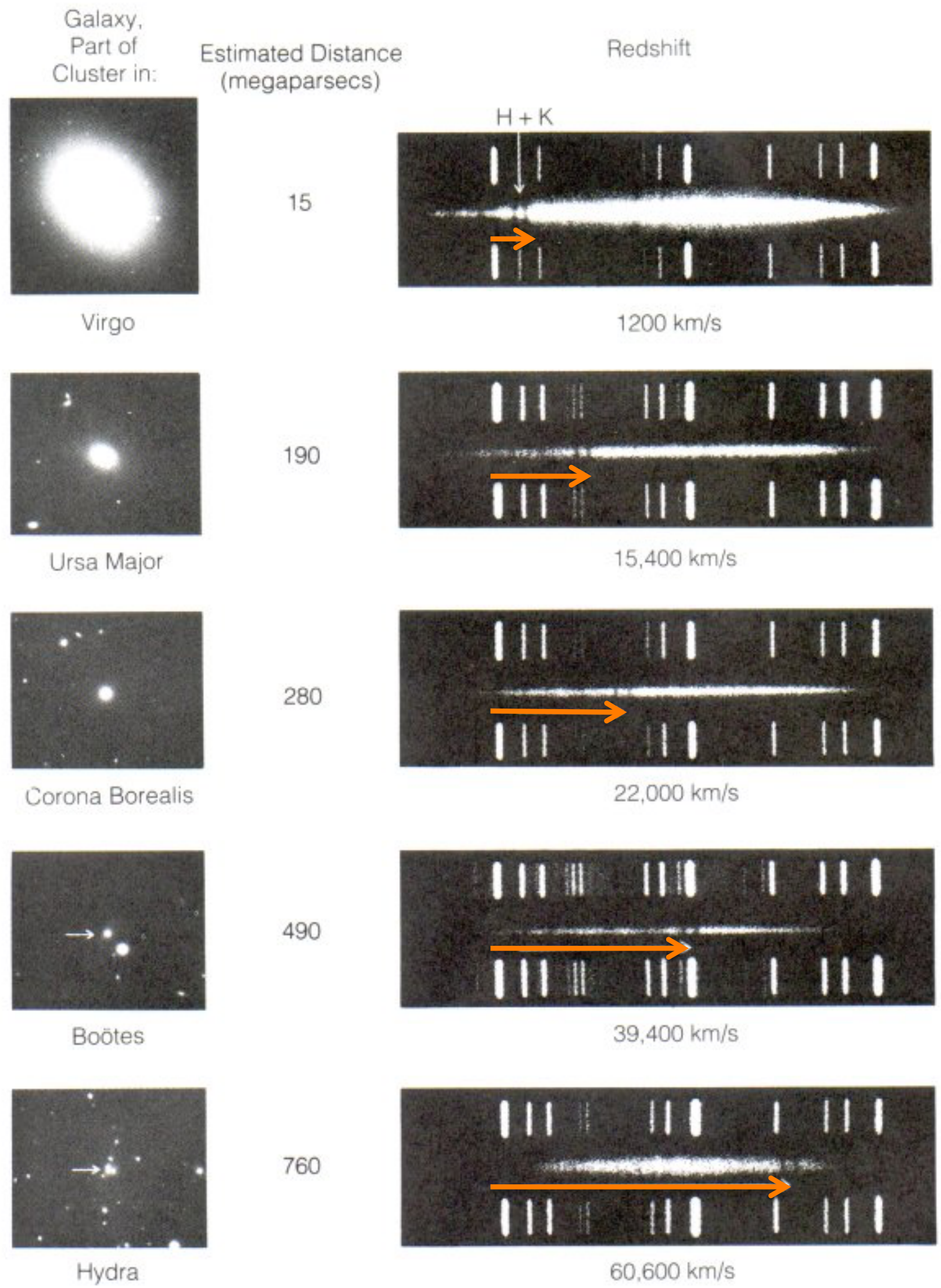
$$z = \frac{\sqrt{1 + v_r / c}}{\sqrt{1 - v_r / c}} - 1$$

Classical
(v < c, z < 1)

z =v/c
(linear)

1920s: Slipher and his spectra

Observations: Hubble's distances and Slipher's Doppler shifts (TBD)



1920s: Hubble and his first diagram

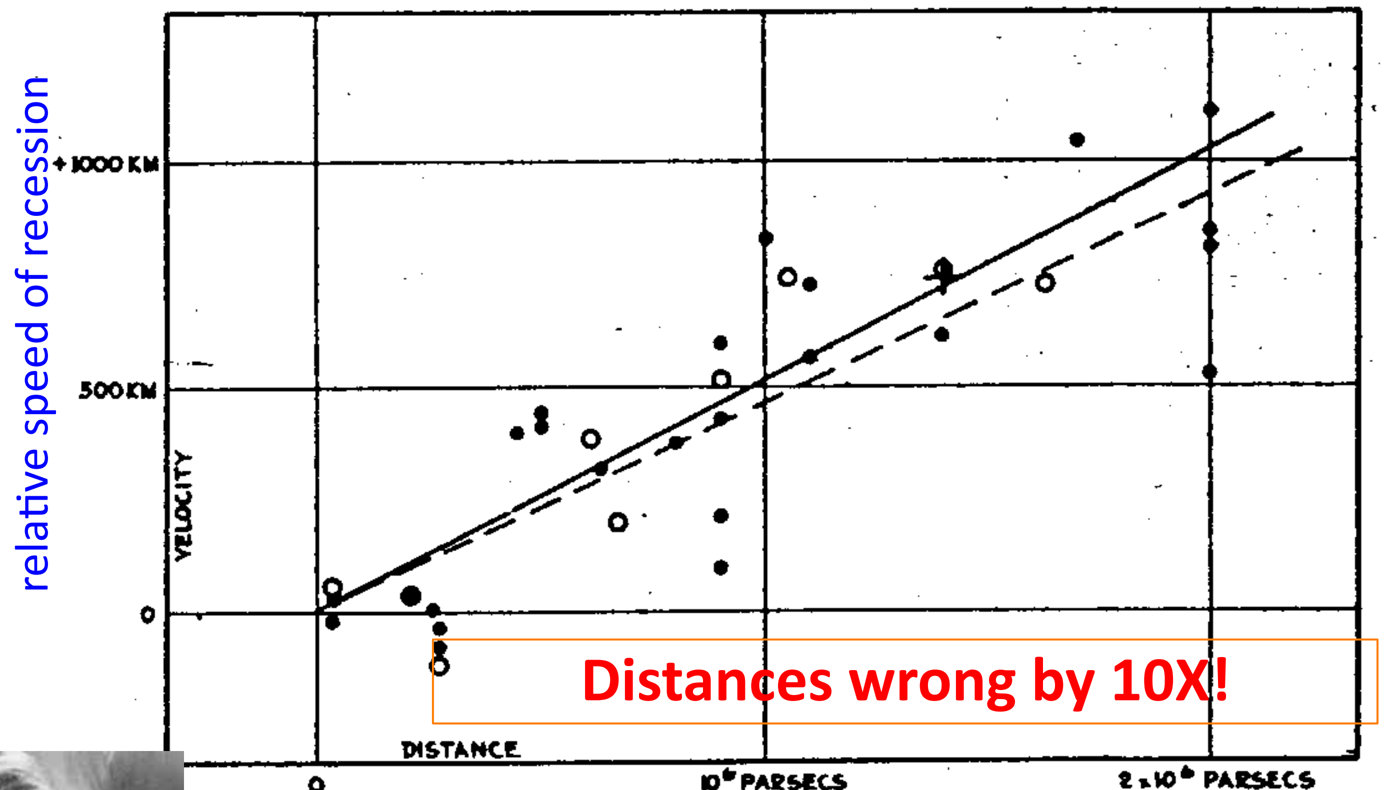


FIGURE 1

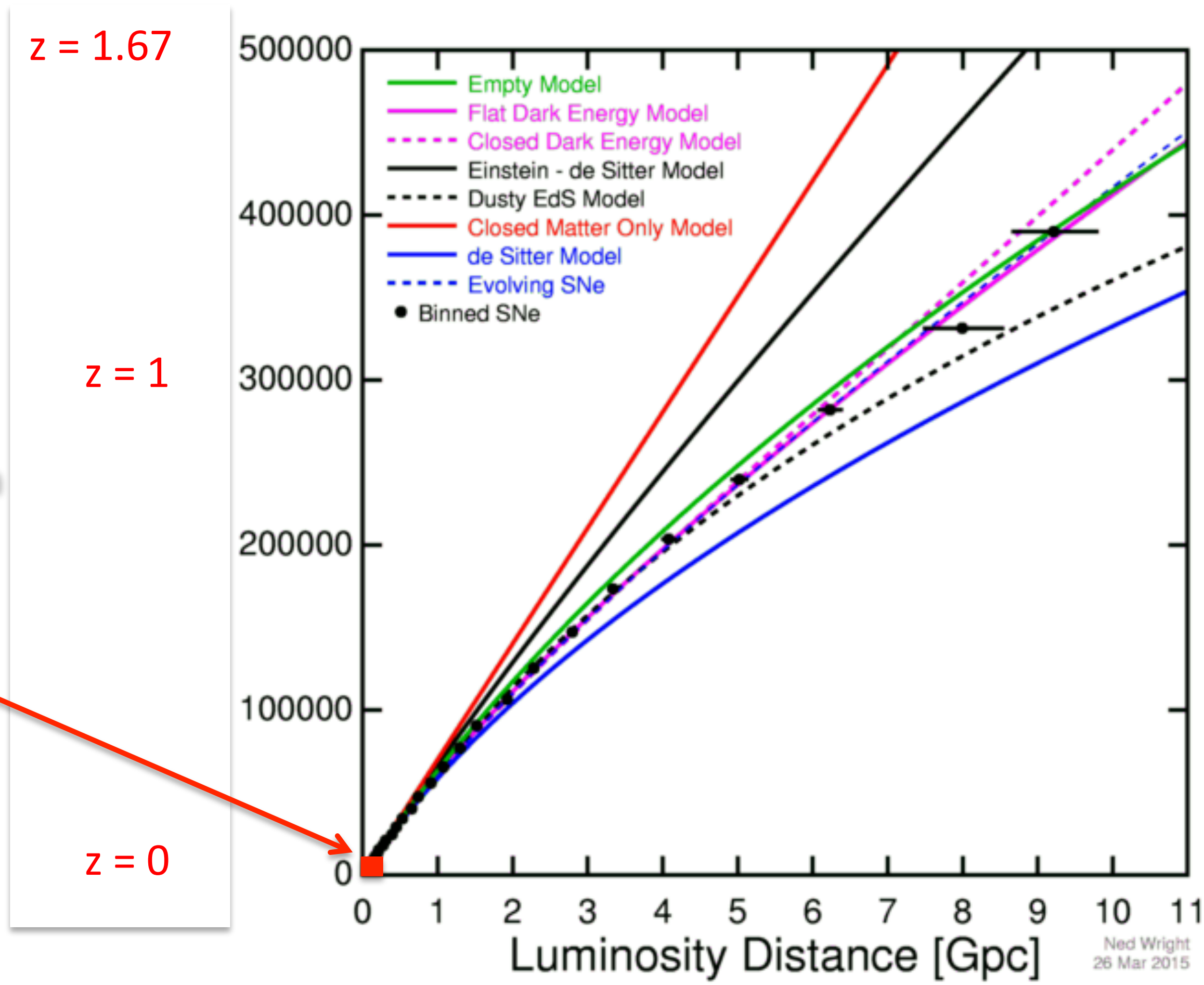
Distance from Milky Way

Hubble correlated the Doppler shifts and distances of galaxies

Hubble's distances,
Slipher's Doppler shifts,
Humason's observing skills
Hubble presents the "Hubble Diagram"

Redshift and Recession Speed when v approaches c

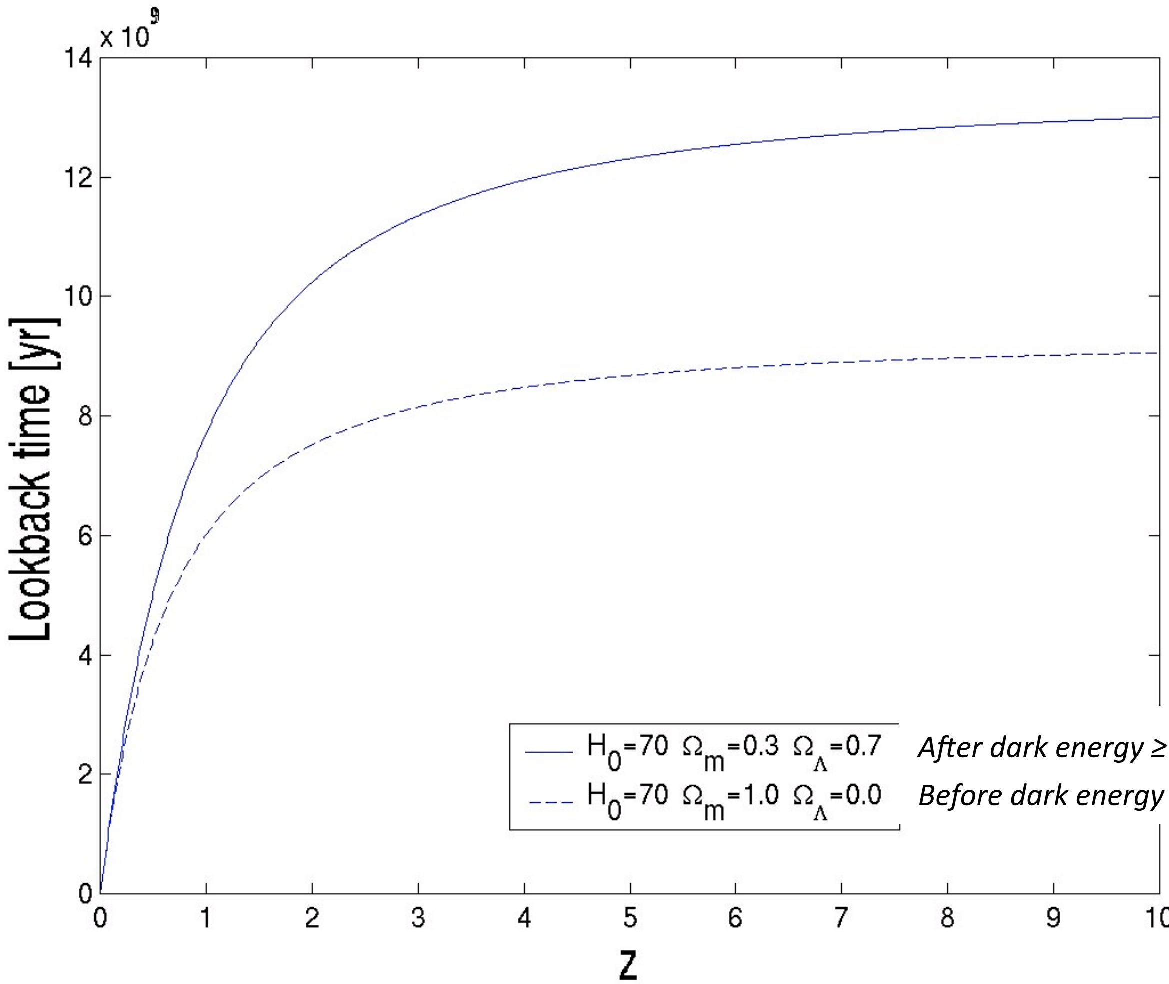
We routinely measure z > 1



Imagine if today's data had been available in the 1920s!

Redshift and Lookback time

We routinely measure z > 1



After dark energy ≥ 2000

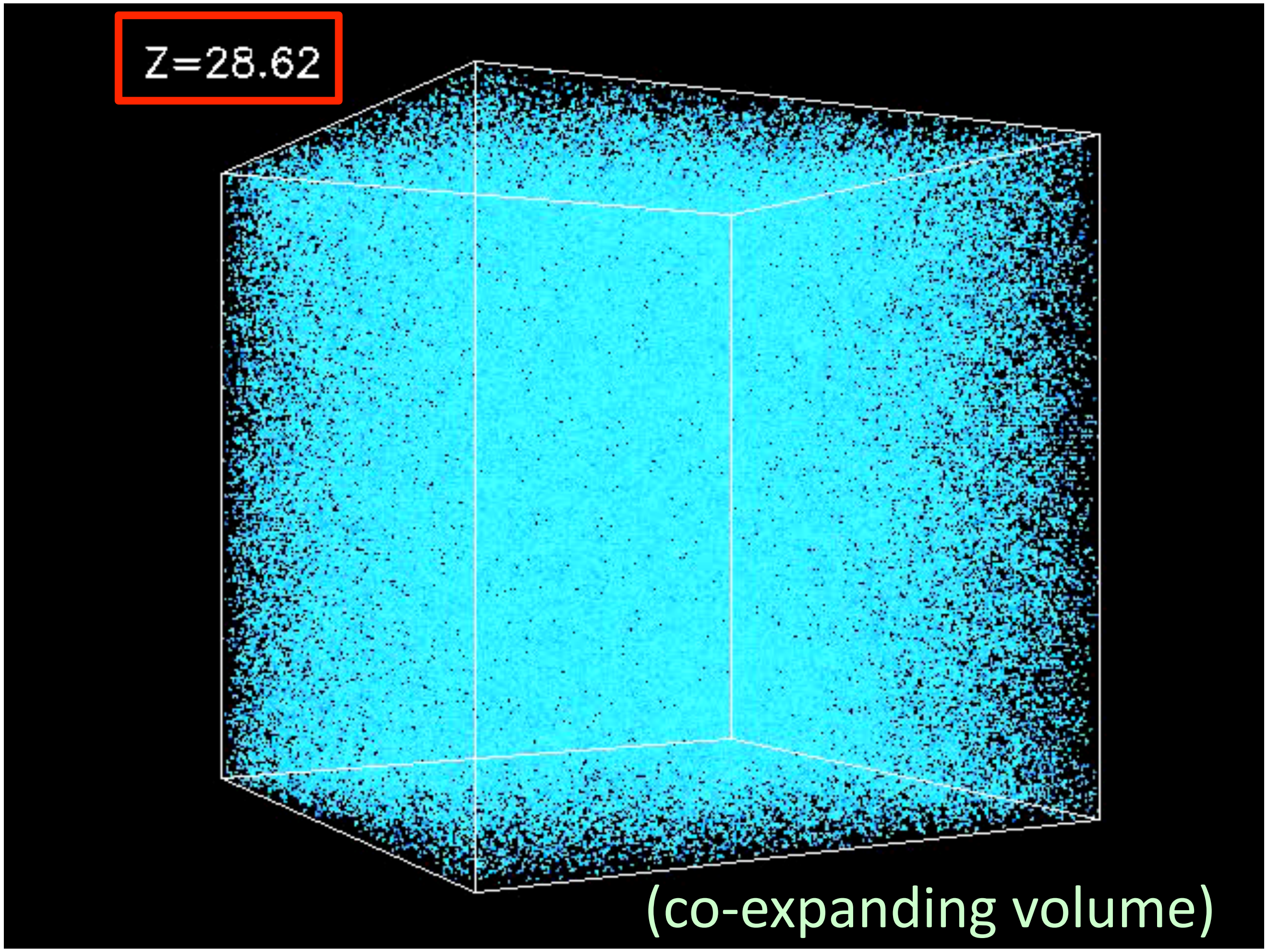
Before dark energy < 2000

"GN-z11"
(HW2)

Redshift
= 11.09 ± 0.08

Evolving structure (model)

Z = Redshift



Opaque surface (CMB) is at z ≈ 1000