[18] Hubble's Law (4/5/18)

Upcoming Items

1. Midterm #2 on Tuesday
2. Read Ch. 21.1–21.2 for next class (one week from today) and do the self-study quizzes.

M51 (Whirlpool) & NGC 5195

Credit: Caleb Harada, UMD Obs.

LEARNING GOALS

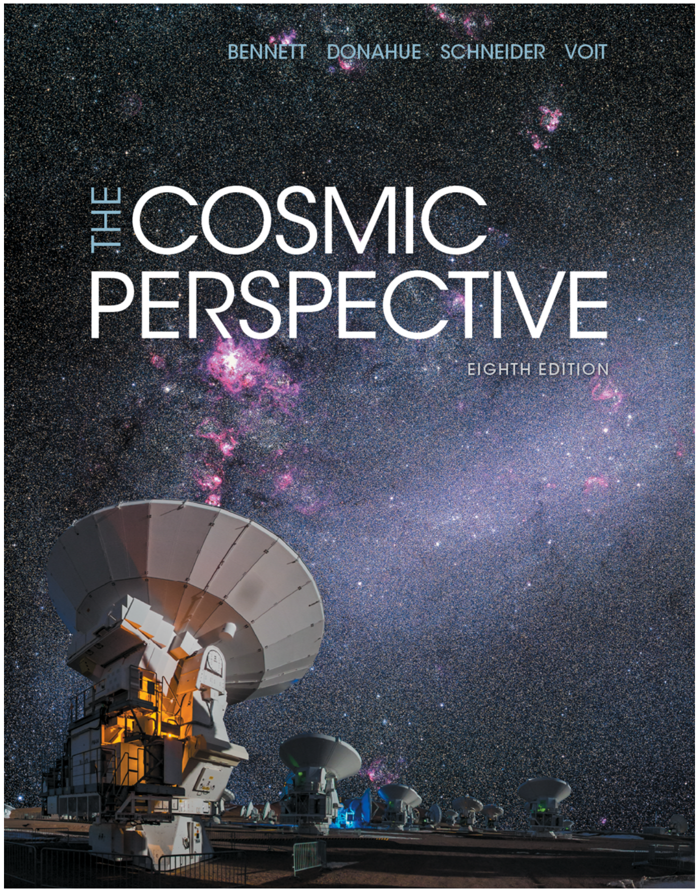
Ch. 20.3

For this class, you should be able to…

… *estimate the distance of a galaxy based on its cosmological redshift using Hubble's law, and know the limitations of this calculation;*

… *predict how the estimated age of the universe changes if Hubble's constant H_0 is smaller or larger in value;*

… *determine the change in average relative distances between galaxies as a function of cosmological redshift.*



Any astro questions?

Hubble's Law

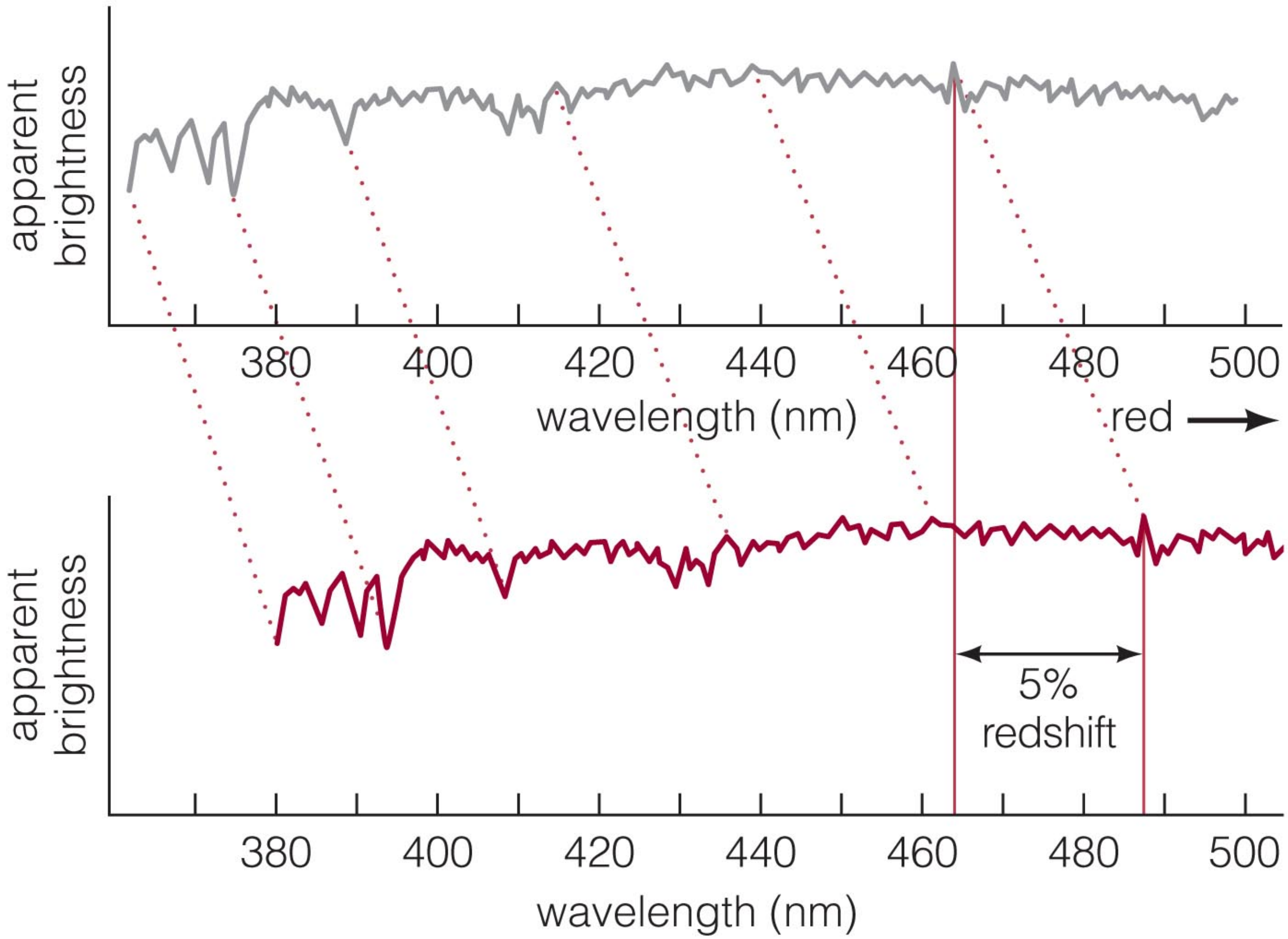
- The recession speed and distance of a galaxy are related by Hubble's law, $v_r = H_0 d$, where H_0 is Hubble's constant.
  - Note: galaxies also have *peculiar motion*, relative to the overall flow of motion (called the *Hubble flow*)
  - It is *space itself* that is expanding, according to General Relativity.
  - The recession speed can be related to observed redshift according to $v_r = cz$, **only for $z << 1$** (otherwise need a cosmological model).
  - The redshift is caused by the stretching of the photon's wavelength as it travels through the expanding universe, *not* physical motion.
- For simple expansion, the age of the universe is $1/H_0$.
- Use "lookback time" to quantify large distances.
- The average separation of galaxies is related directly to the cosmological redshift: $z = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{emit}} - 1 = R_{\mathrm{now}}/R_{\mathrm{then}} - 1$.

Hubble's Second Discovery

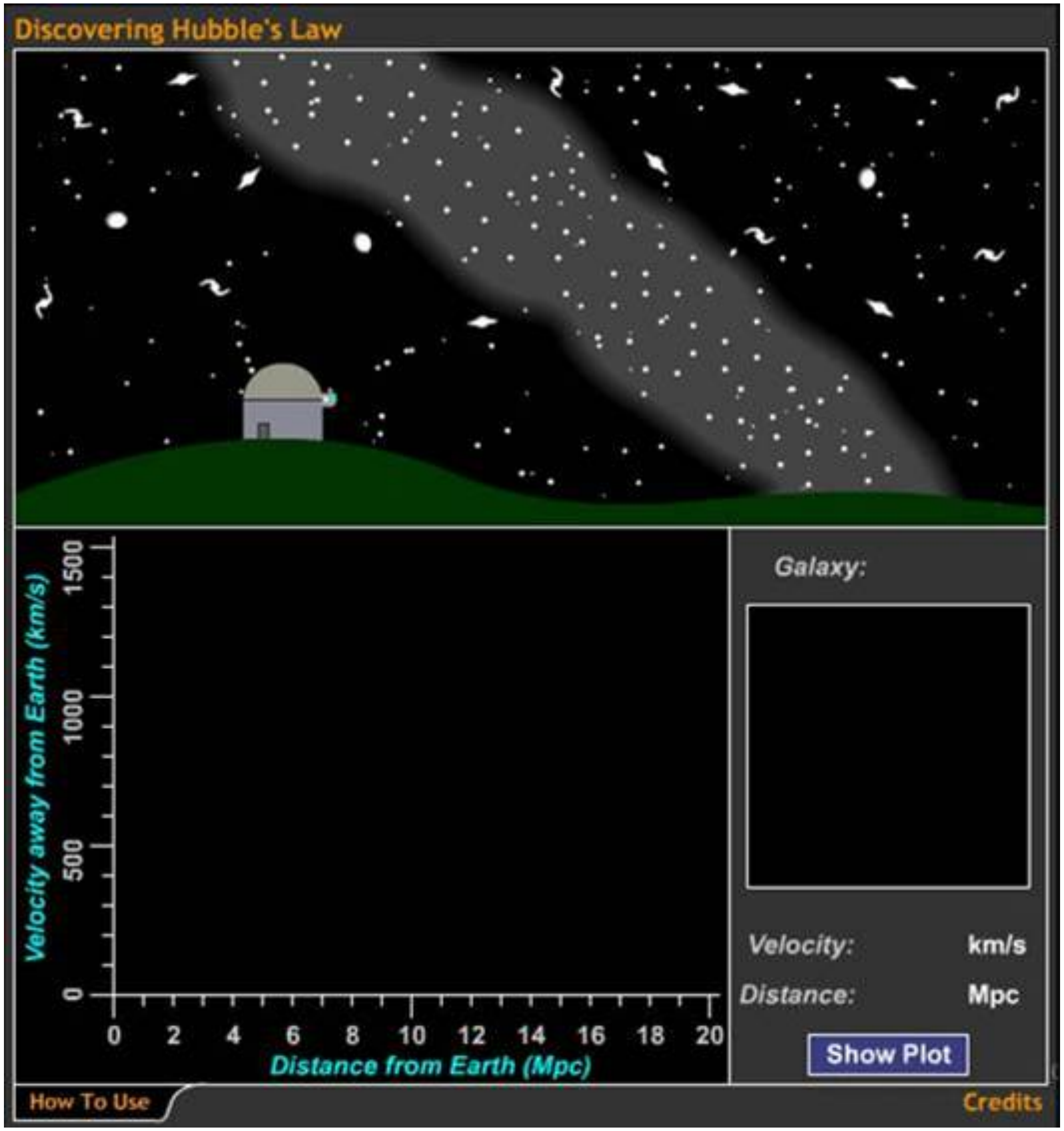
- Soon after Hubble proved that the "spiral nebulae" are external galaxies, he started to look at their spectra in order to determine their line-of-sight speeds.
- He found some surprising results…
  - The vast majority of galaxies (all but a few of the closest ones) are moving away from us! That is, they are all redshifted.
  - The further the galaxy, the faster it is moving away. The relation found between recession speed v_r and distance d is very simple:

$$v_r = H_0 d.$$

  - This is now known as ***Hubble's law***.
- The rate of expansion of the universe is given by the constant of proportionality in Hubble's law, H_0. This is ***Hubble's constant***.

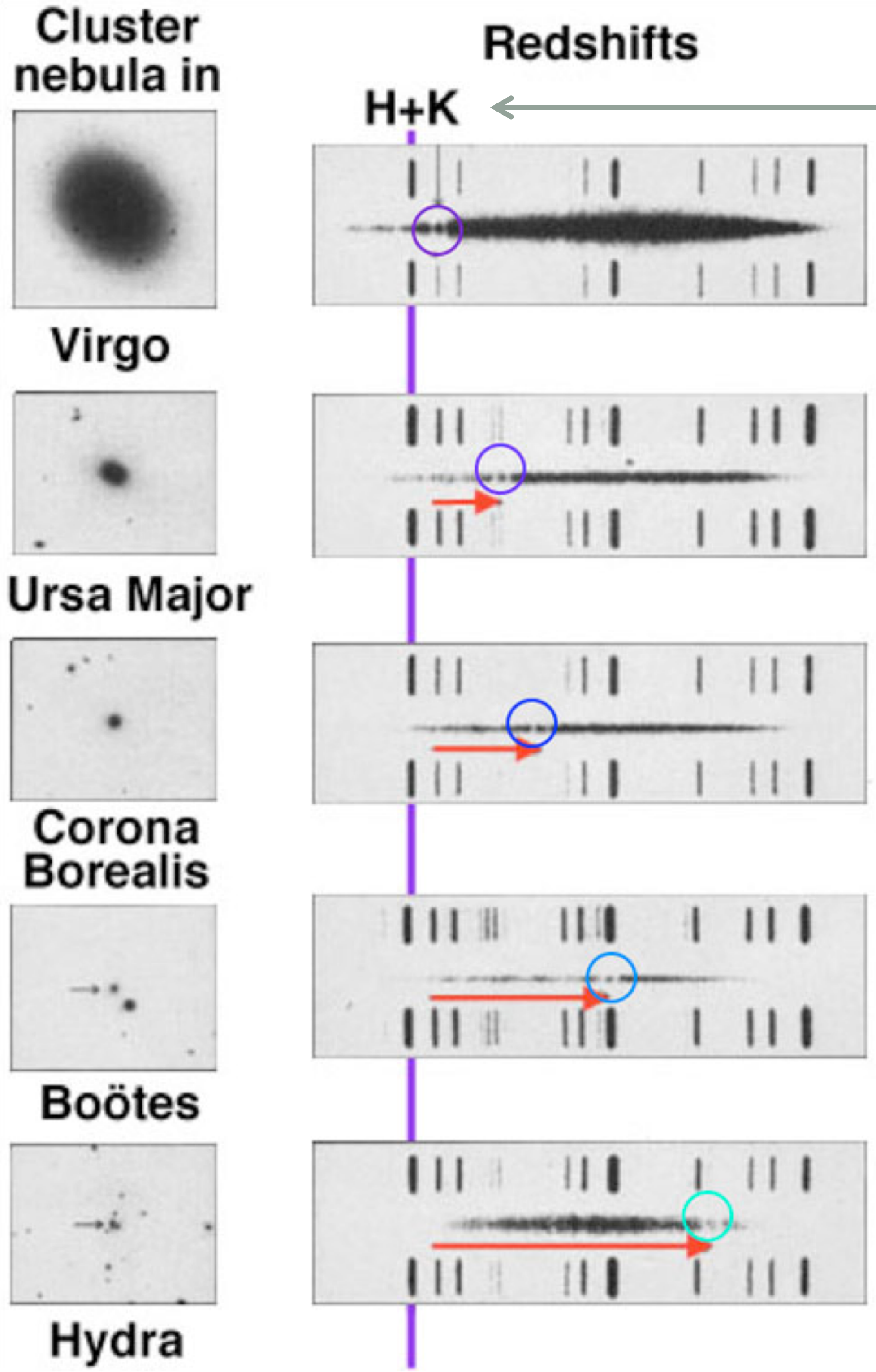


The spectral features of virtually all galaxies are redshifted, which means that they're almost all moving away from us.



- By measuring distances to galaxies, Hubble found that redshift and distance are related in a simple way.

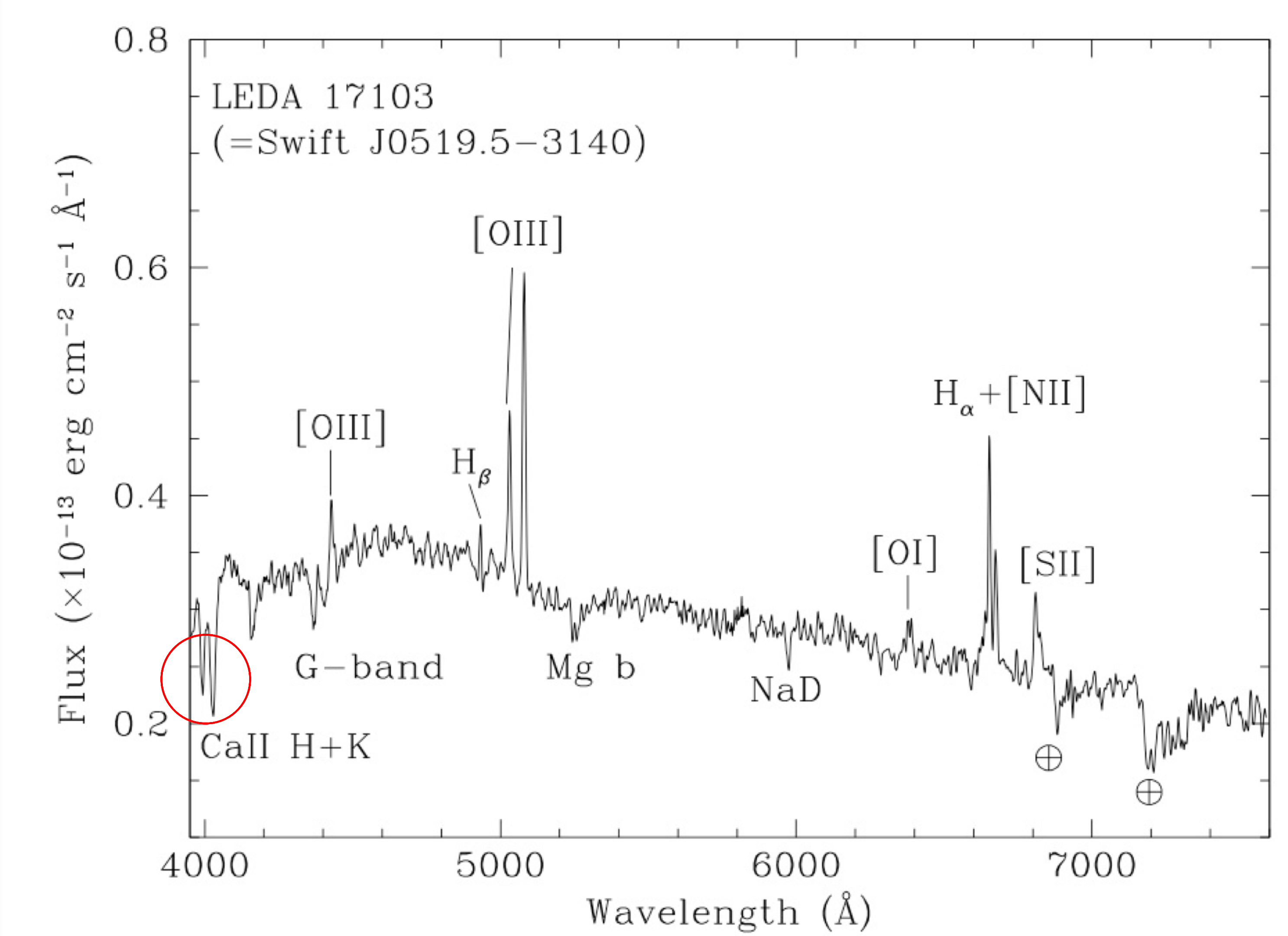
- The more distant the galaxy, the greater its redshift, thus the faster it appears to be moving away from us.



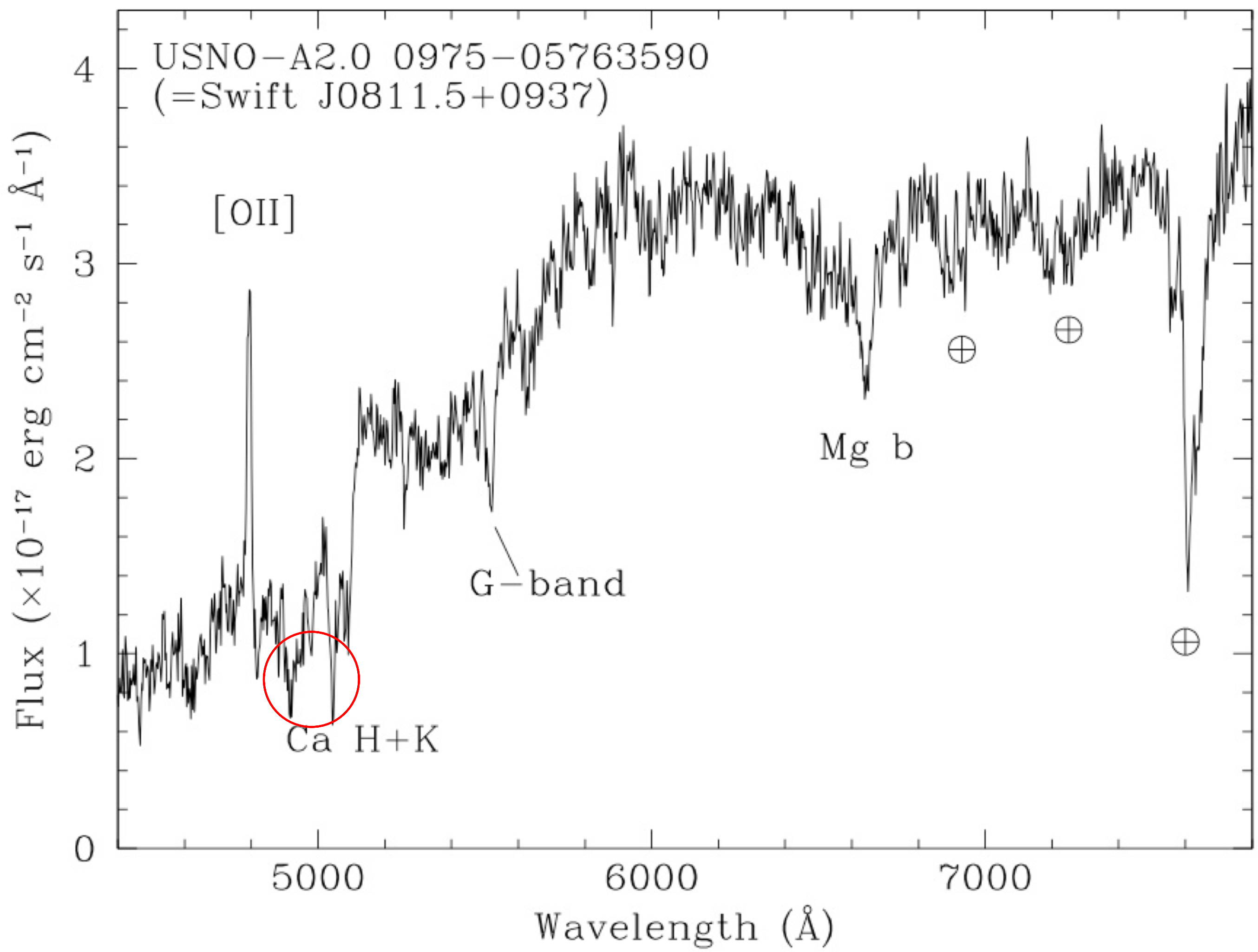
H & K absorption lines of singly ionized calcium: *lab wavelength*.

Colored circles show *observed wavelength* for different galaxies.

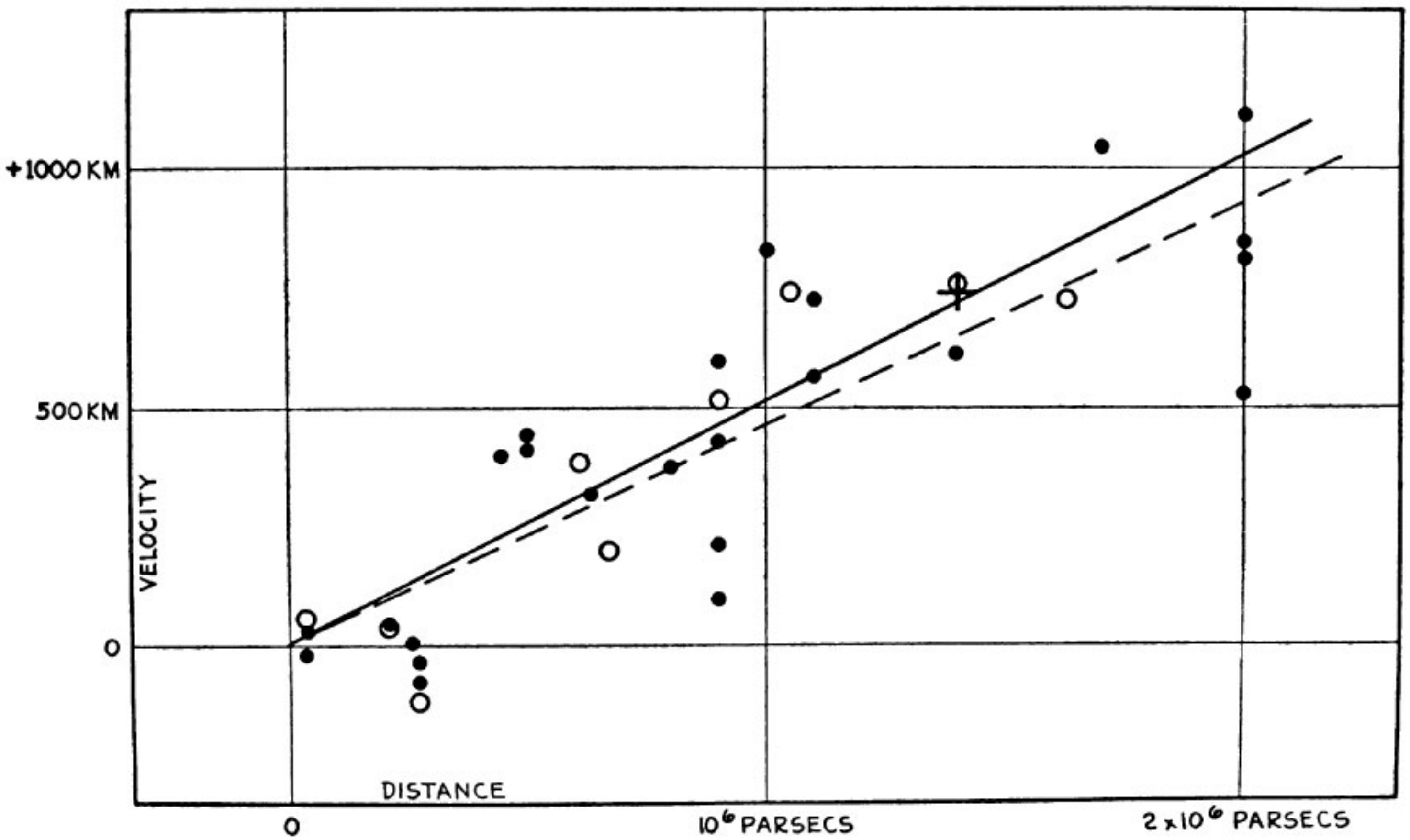
Spiral Galaxy Spectrum



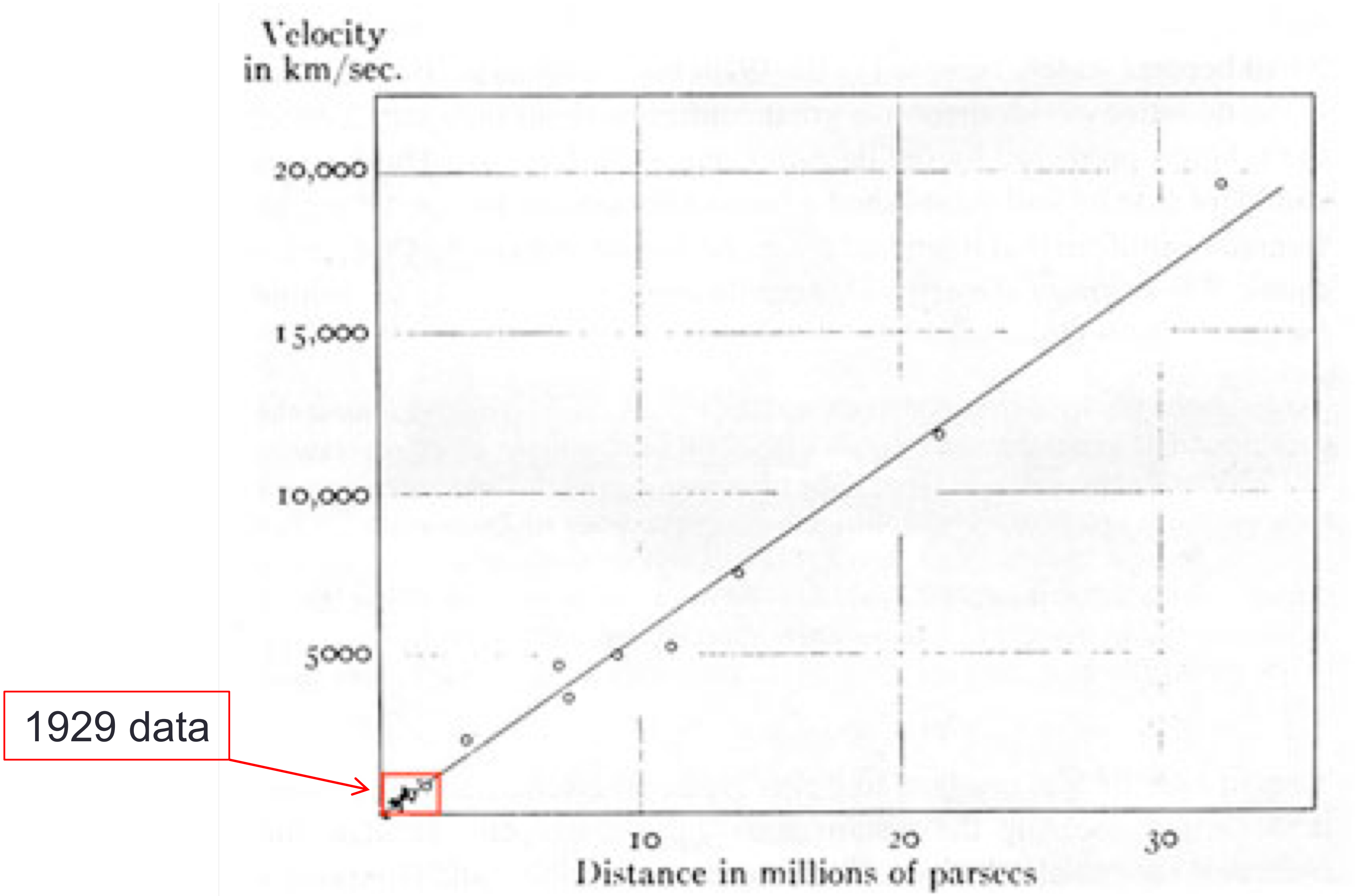
Elliptical Galaxy Spectrum

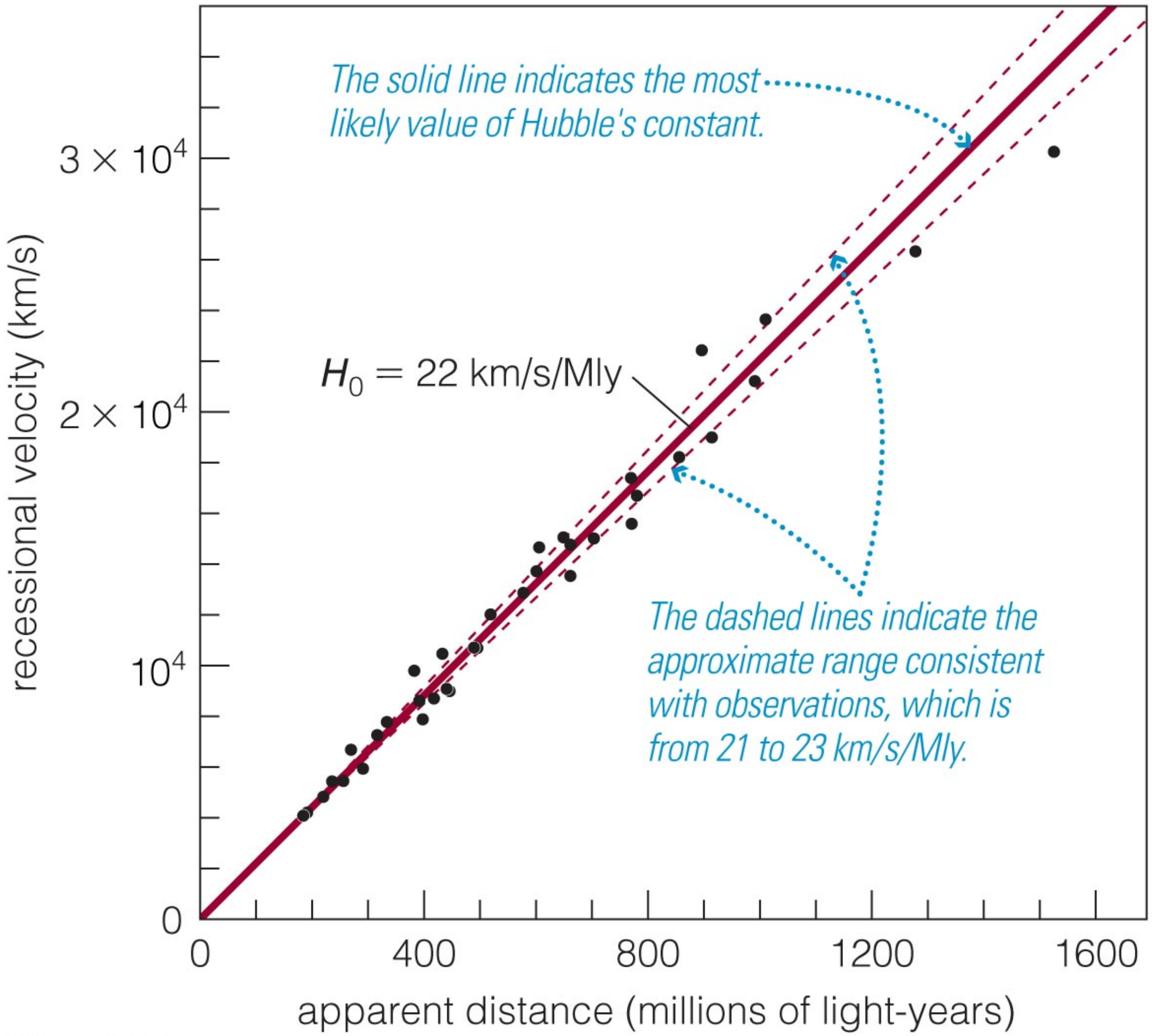


Hubble's Data (1929)



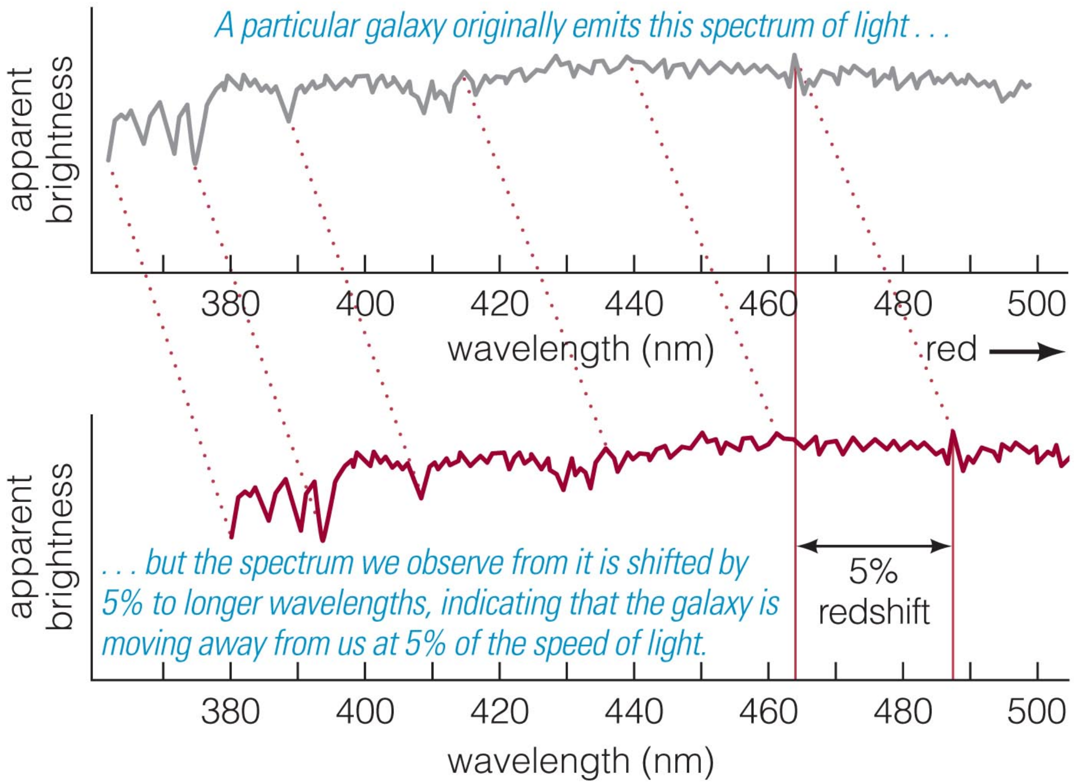
Hubble & Humason (1931)





Hubble's law: recession speed = $H_0 \times$ distance.

Current "best" estimate: $H_0 \approx 70$ km/s/Mpc.



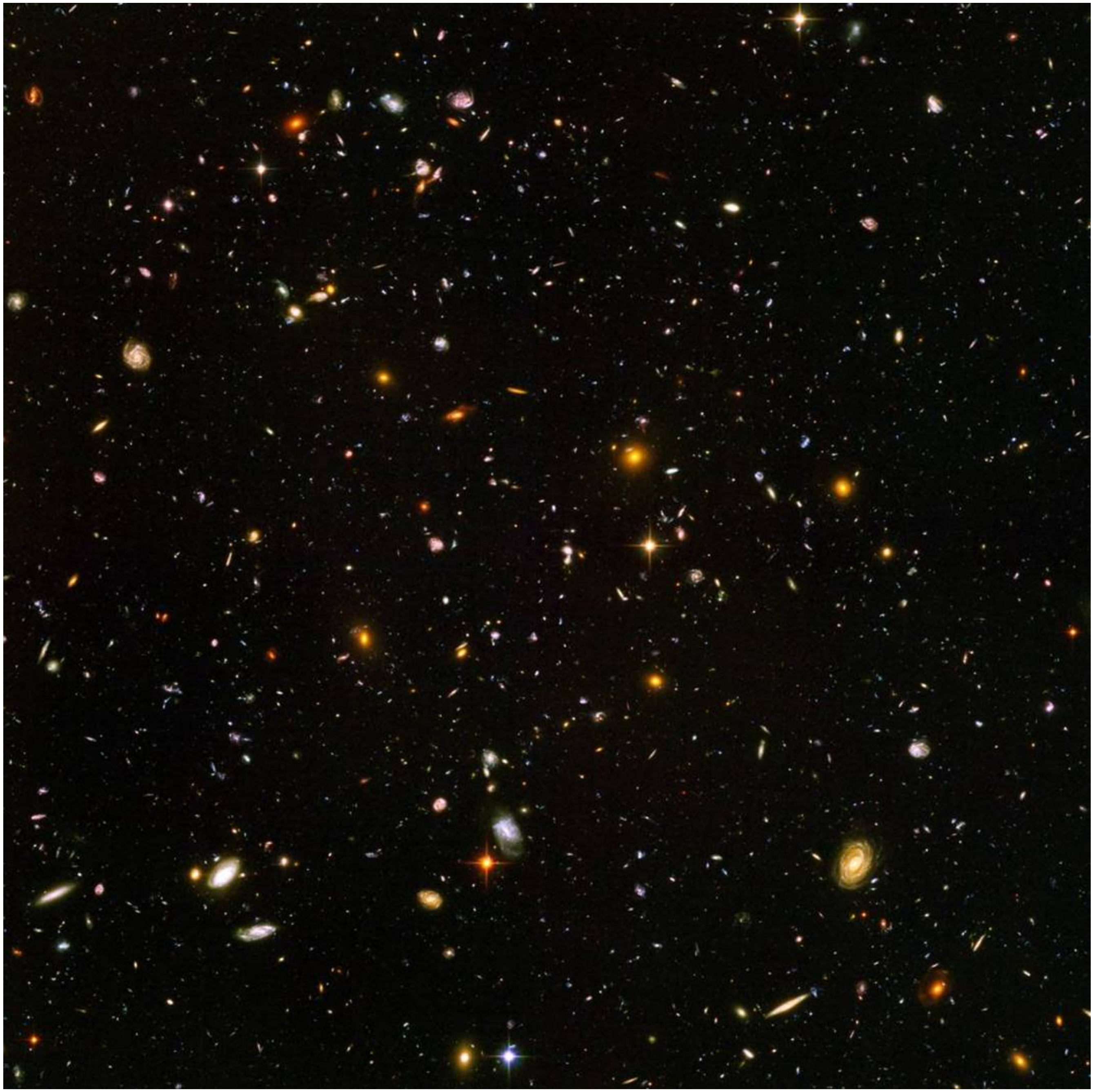
Step 5

Redshift of a galaxy tells us its distance through **Hubble's Law**:

$$\text{distance} = \frac{v_r}{H_0}$$

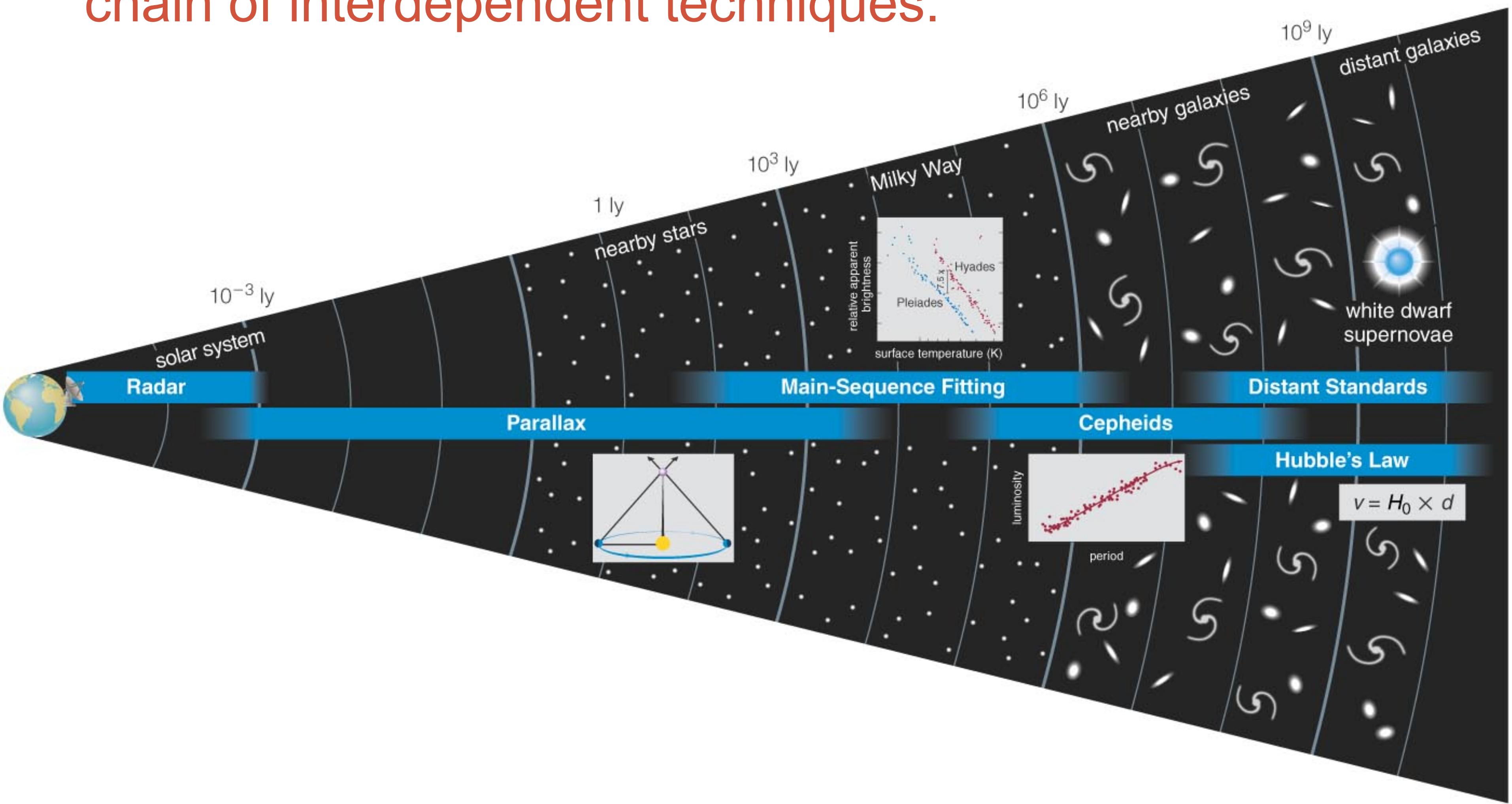
$$\approx \frac{cz}{H_0} (z << 1).$$

See Lab 6!

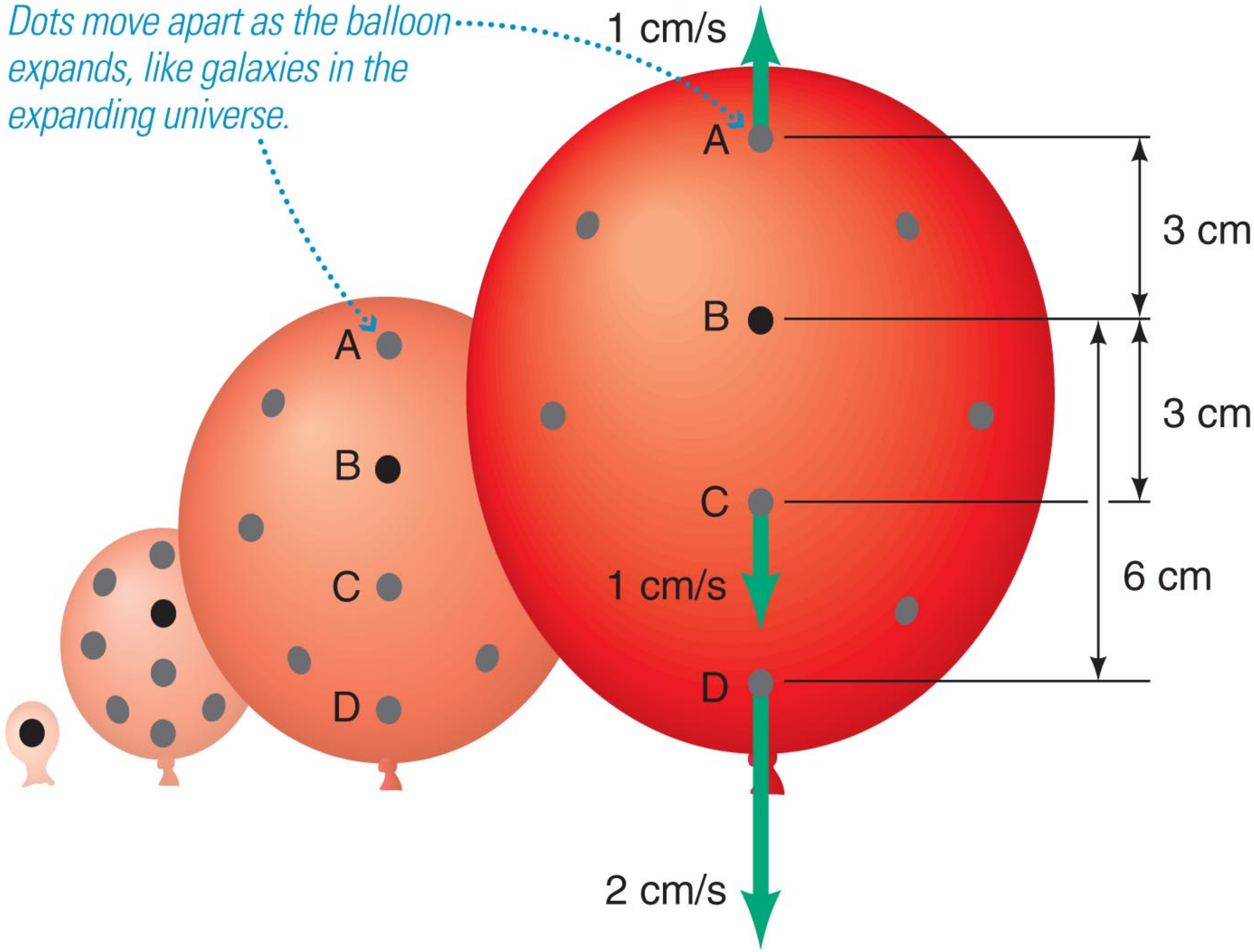


Distances of the farthest galaxies are measured from their redshifts.

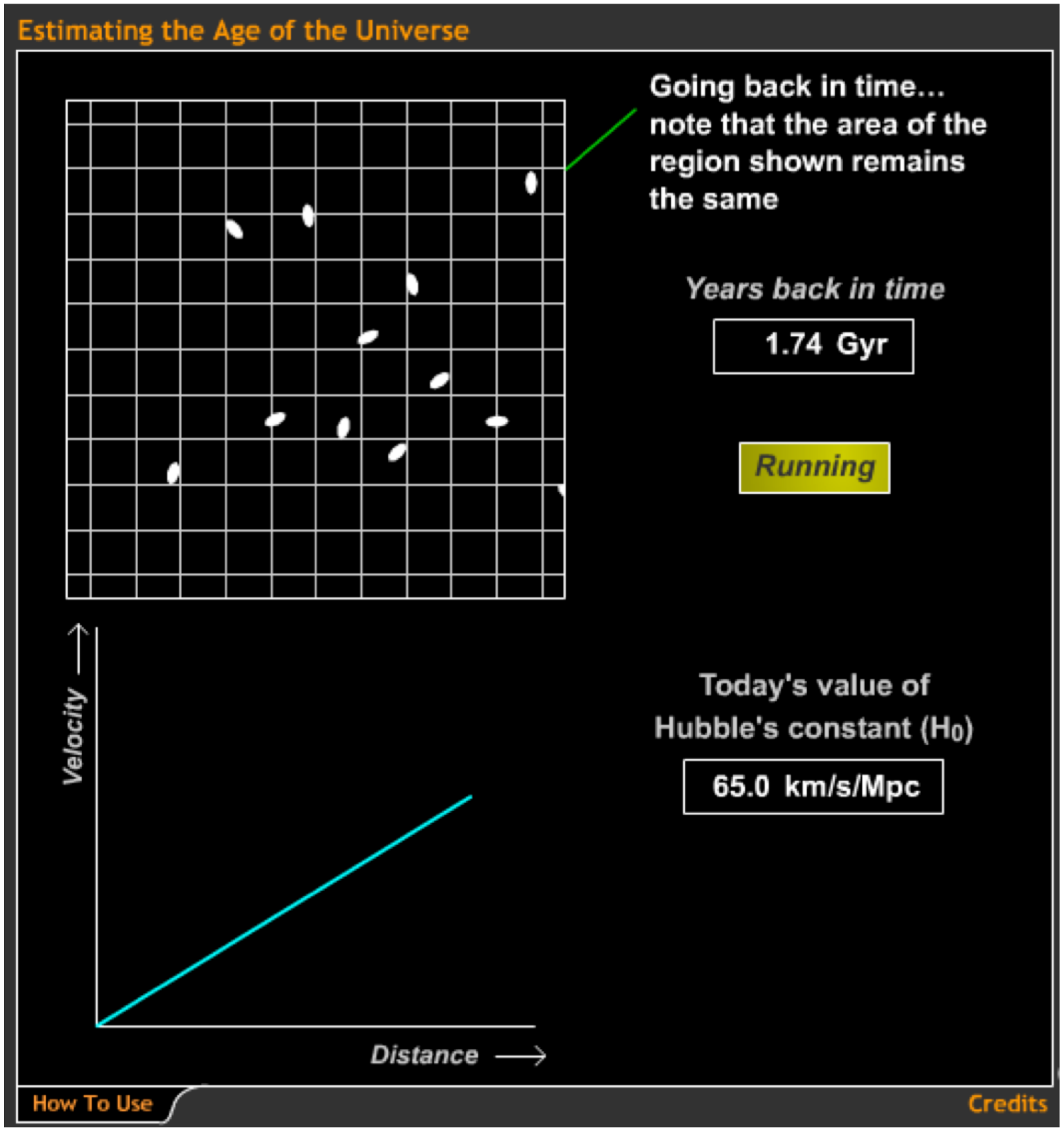
We measure galaxy distances using a chain of interdependent techniques.



- The expansion rate appears to be the same everywhere in space.
- The universe has no center and no edge (as far as we can tell).



One example of something that expands but has no center or edge is the surface of a balloon.

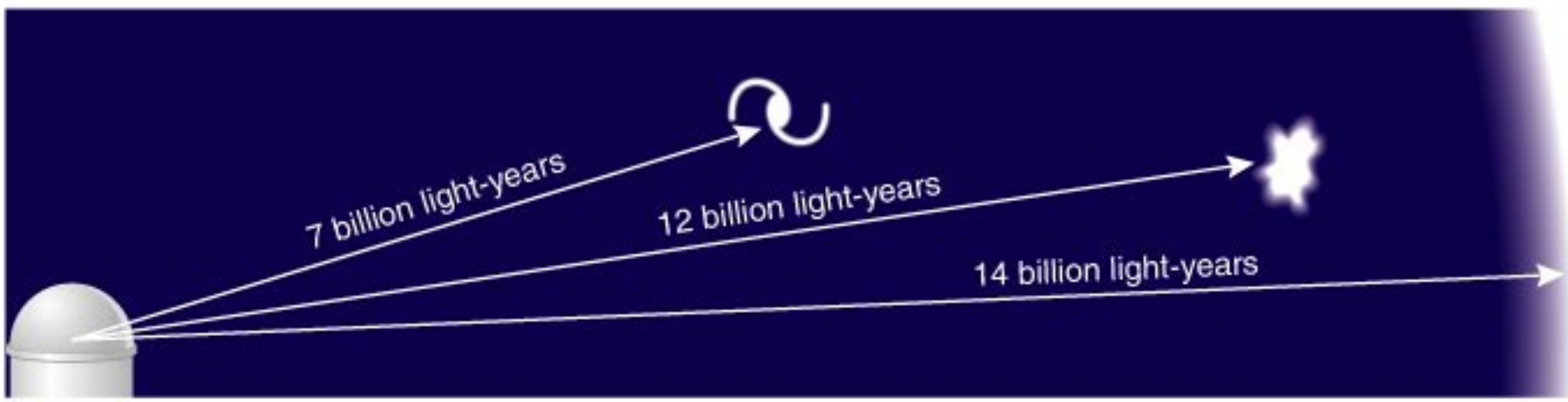


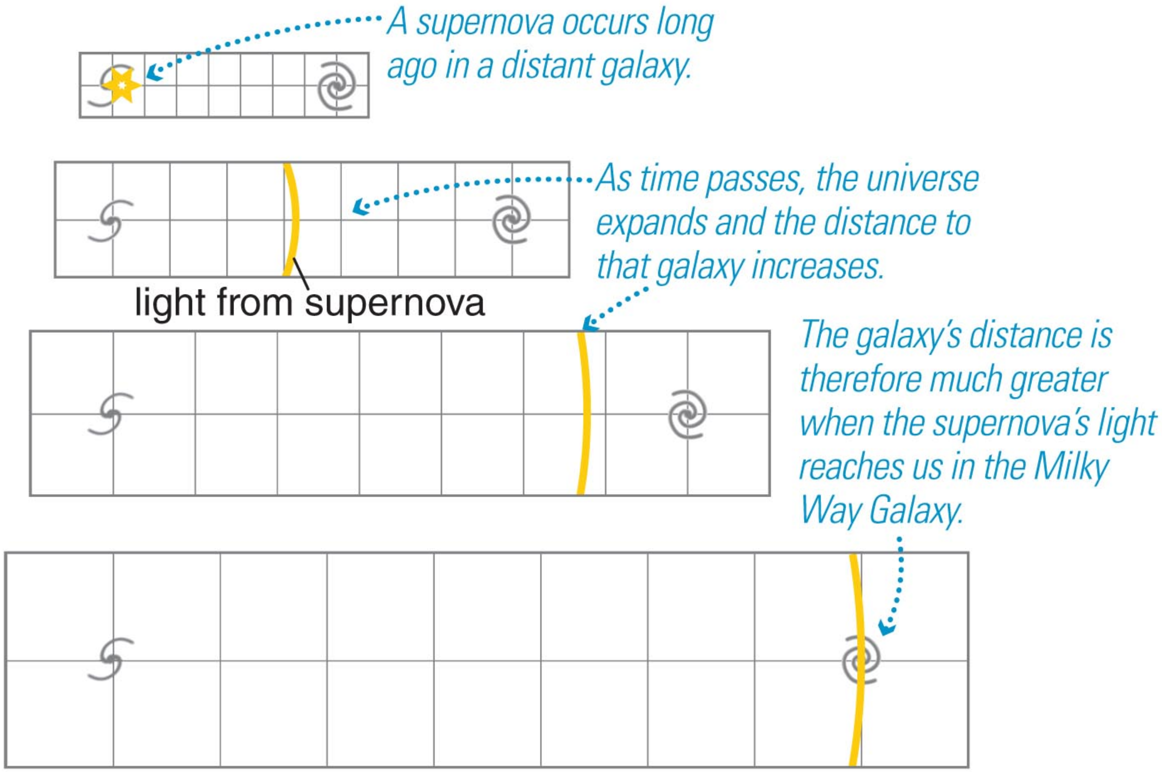
Hubble's constant tells us the age of universe because it relates the speeds and distances of all galaxies.

$$\text{Age} = \frac{\text{distance}}{\text{speed}} = \frac{d}{v_r} = 1/H_0.$$

What important assumption does this make?

- Recall, at great distances, we see objects as they were when the universe was much *younger*. Why?

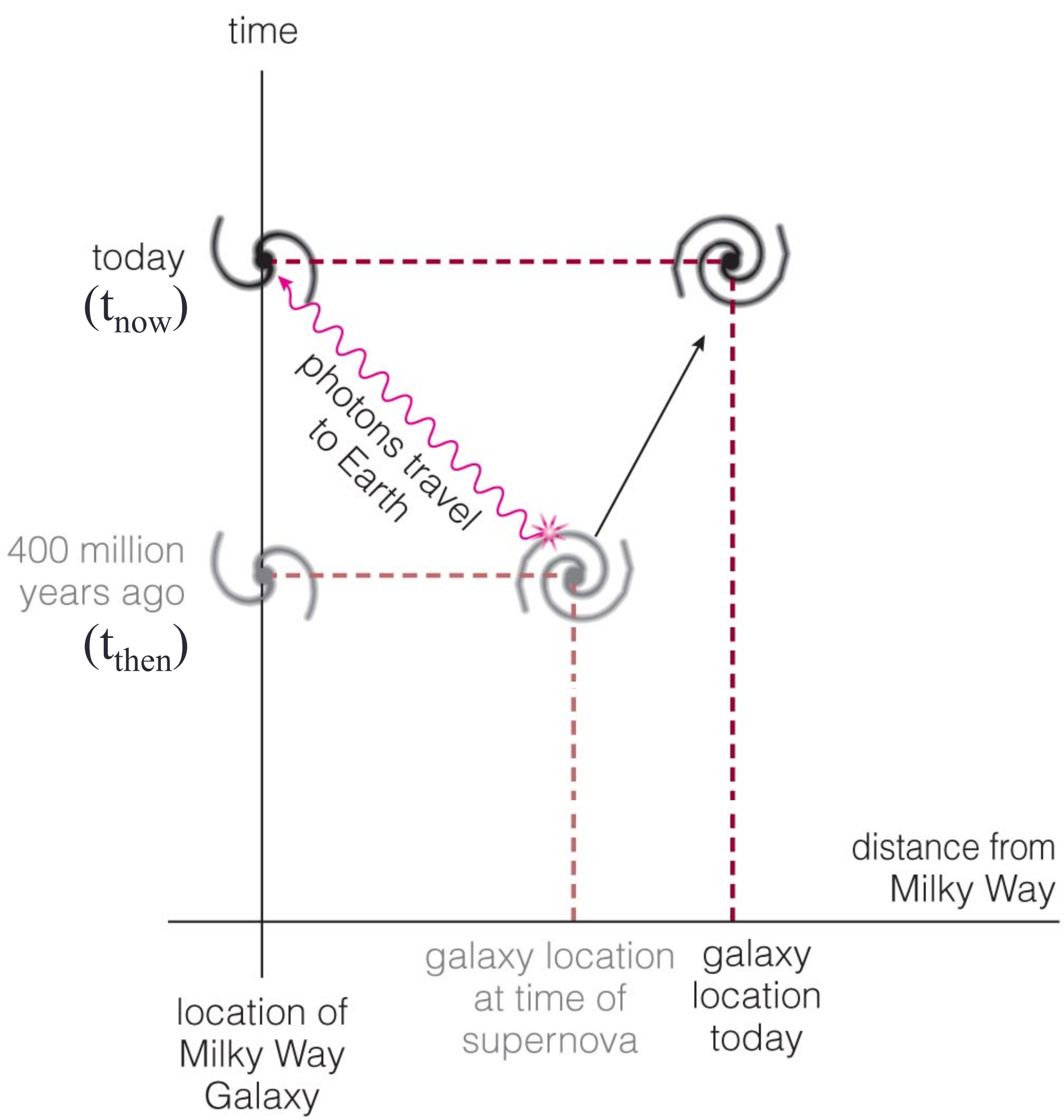




- Distances between faraway galaxies change while light travels.
- Astronomers think in terms of ***lookback time*** rather than distance:

$$\boxed{t_{\text{lookback}} = t_{\text{now}} - t_{\text{then}}\,.}$$

- This is the time it has taken for the light to reach us.



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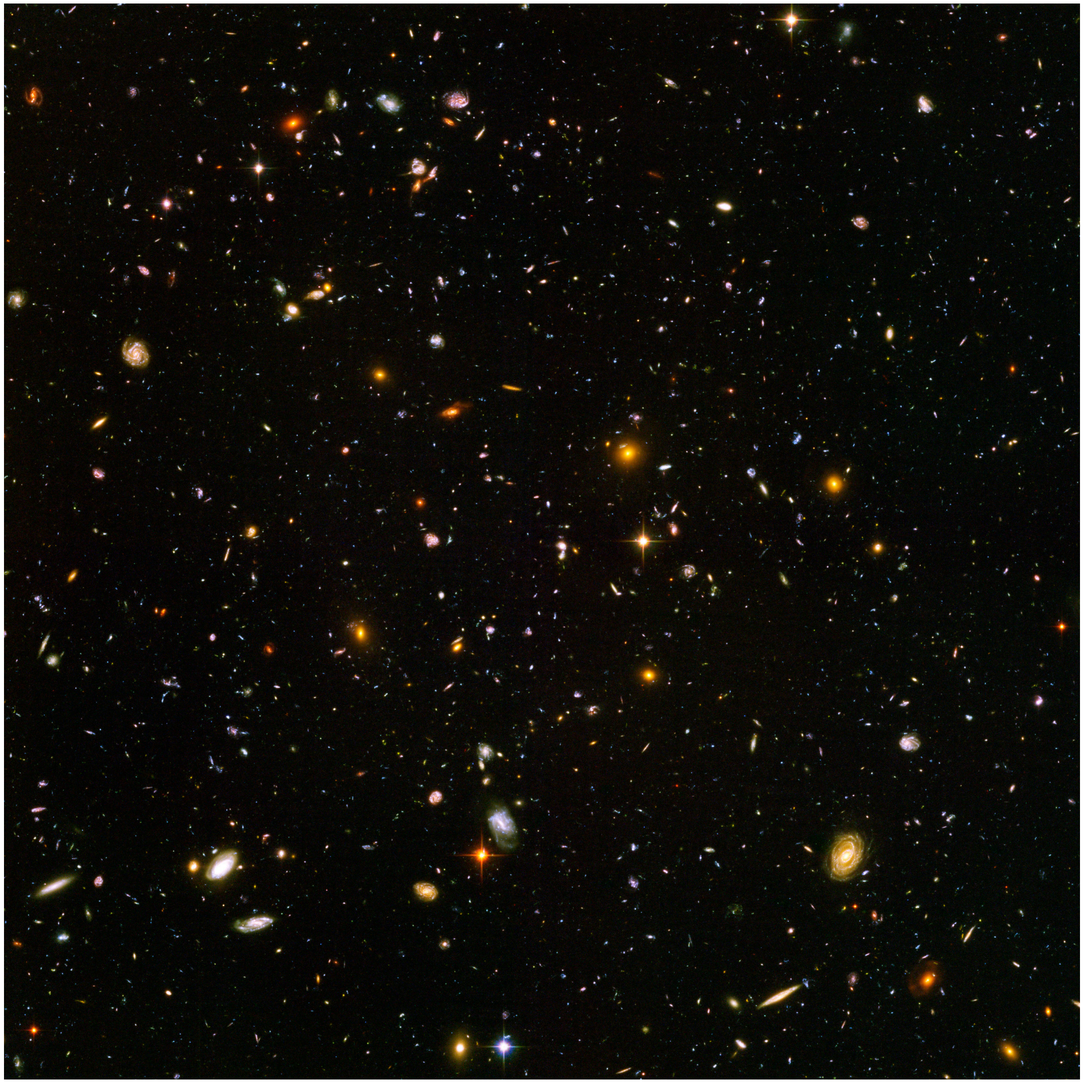
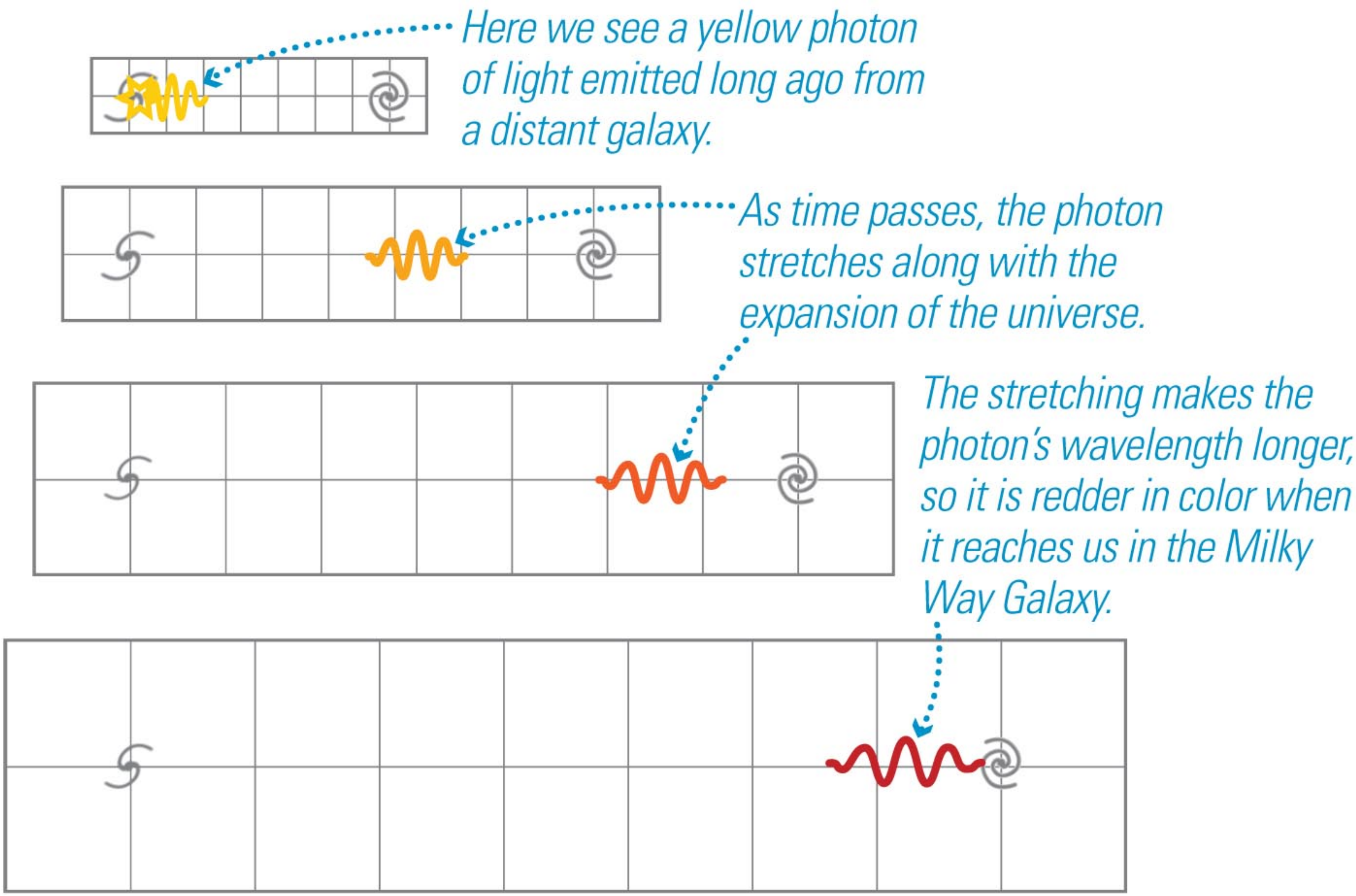


Cosmological Horizon

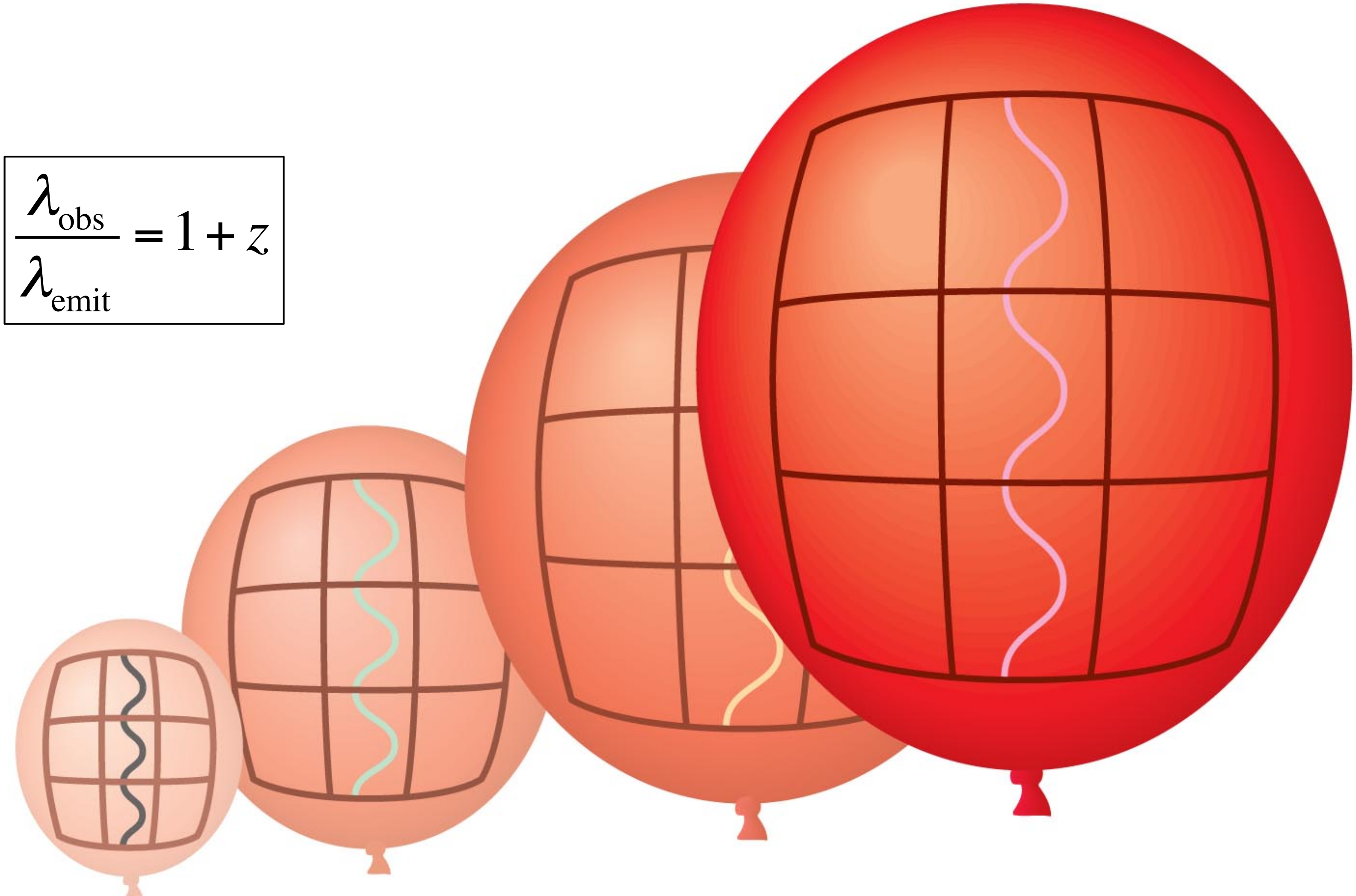
Maximum lookback time of 13.8 Gyr (the age of the universe) limits how far we can see (the size of the observable universe).

It is a horizon in *time* rather than *space*. Since looking far away means looking back in time, there must be a limit—the beginning of the universe!



Expansion stretches photon wavelengths, causing a ***cosmological redshift*** directly related to lookback time.

$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = 1 + z$$



Expansion stretches photon wavelengths, causing a ***cosmological redshift*** directly related to lookback time.

- The space between galaxies stretches by the same amount due to cosmological expansion:

$$\boxed{\frac{R_{\mathrm{now}}}{R_{\mathrm{then}}} = 1 + z}$$

- Here R is the "scale factor" of the universe—more in class 25!

Also: Class16 Supplement!