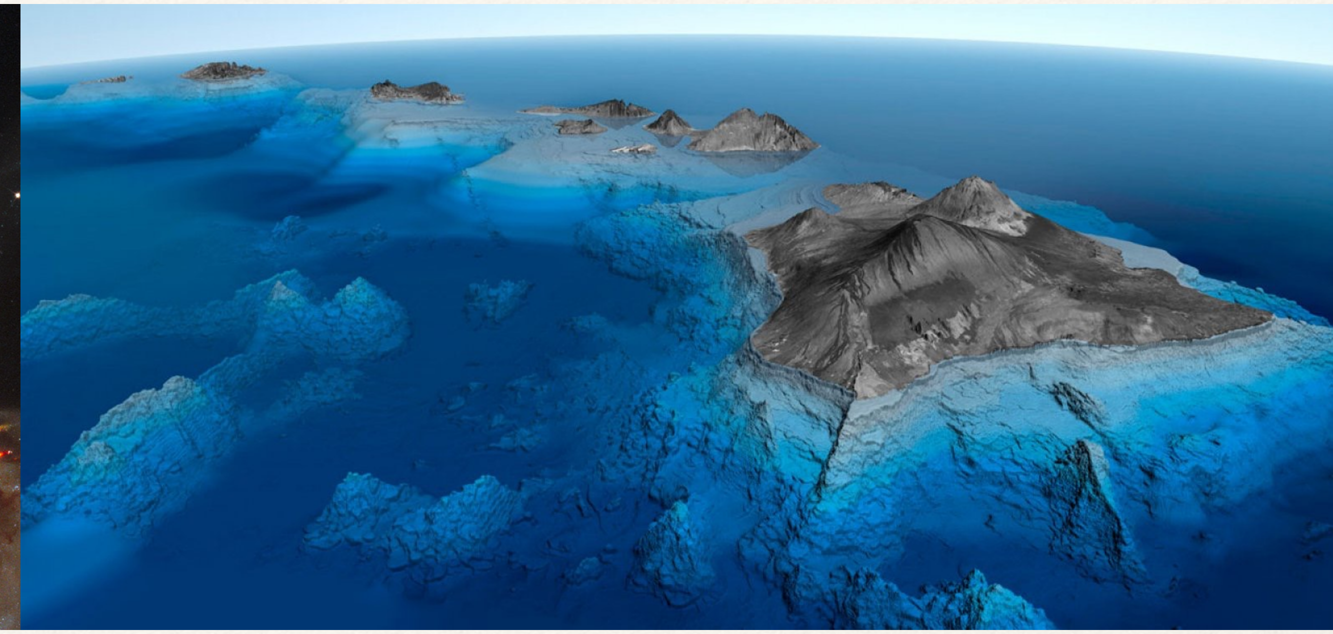


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Questions

- How are we able to differentiate the emission/absorption lines coming from dust/gas and those from our target that we're observing? Is it just from knowing which emission/absorption lines are more common in dust/gas clouds or is there a more refined method?
- Jason mentioned (in astrophysics class) a debate about dust attenuation; the astronomical community is not in an agreed upon method, what is the issue?

- How does doppler broadening change estimates of column density and vice versa?
- How would I start to consider the velocity dispersion I could measure with a given instrument in nominal conditions?

- How do we actually calibrate the distance ladder? We said that we use objects we know the intrinsic brightness of, but how do we actually know for sure what their intrinsic brightness is?
- How did we initially calibrate the distance modulus for type 1A supernova brightness?

- What fraction of our solar system is dark matter, and why is this not taken into account when calculating the gravitational interactions of the planets and sun?
- Is there a Hill Sphere equivalent to galaxies and or clusters? What does that look like since they can't really be approximated by point masses?
- At what mass regime can we no longer ignore general relativity corrections (or special relativity for that matter)? How would this affect the spectra aside from the Doppler Effect? Gravitational lensing?

Warm-up

- Consider a galaxy with:
    - a redshift of z~0.04
    - an old, mostly kinematically "hot" stellar population in the center
    - a recent burst of star formation at large radii in a disky ring
- What do you think the spectra, mean velocity, and velocity dispersion look like as a function of position?

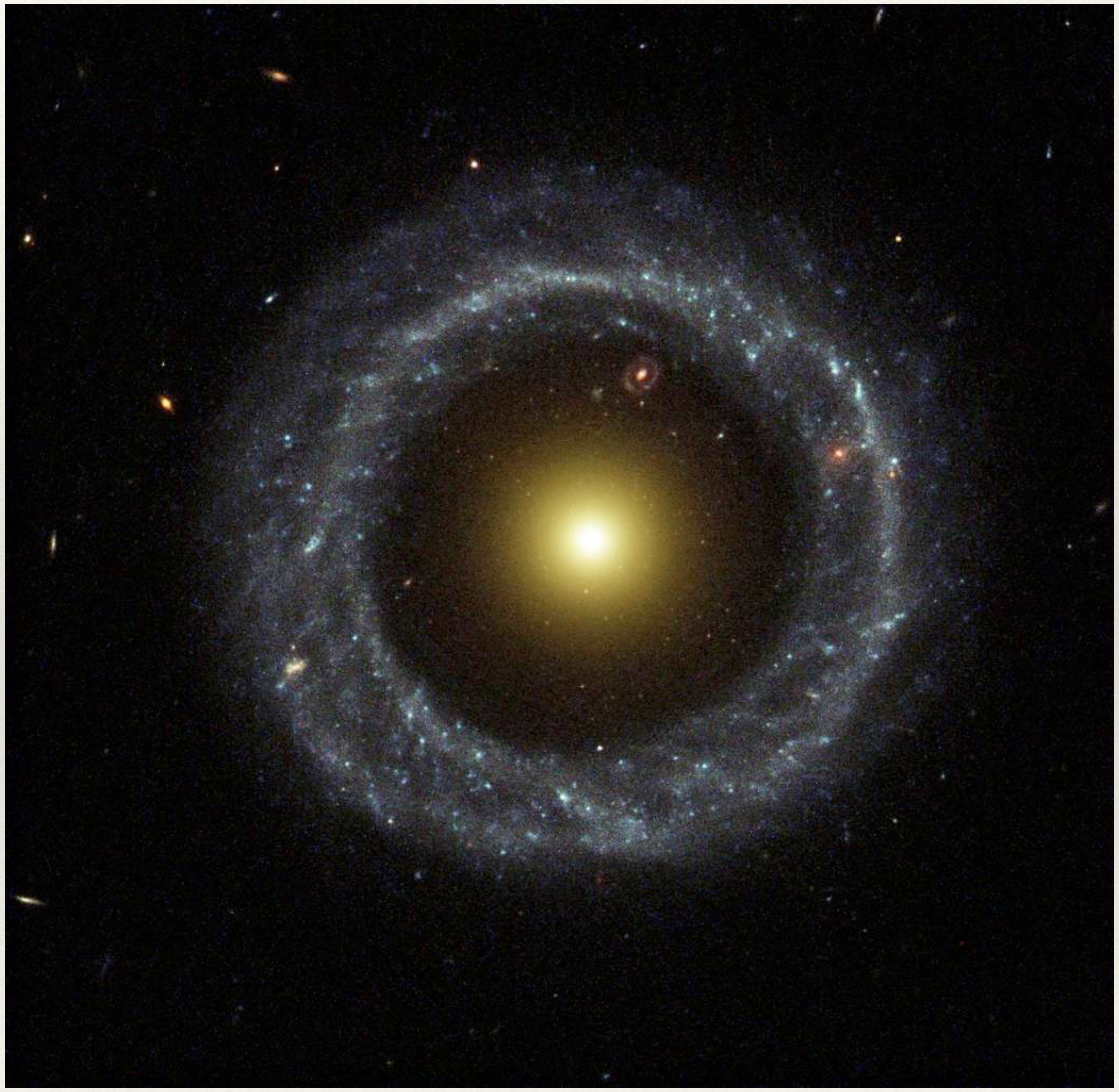
Warm-up

- Consider a galaxy with:
  - a redshift of z~0.04
  - an old, mostly kinematically "hot" stellar population in the center
  - a recent burst of star formation at large radii in a disky ring
- What do you think the spectra, mean velocity, and velocity dispersion look like as a function of position?

Does this object exist?

Warm-up

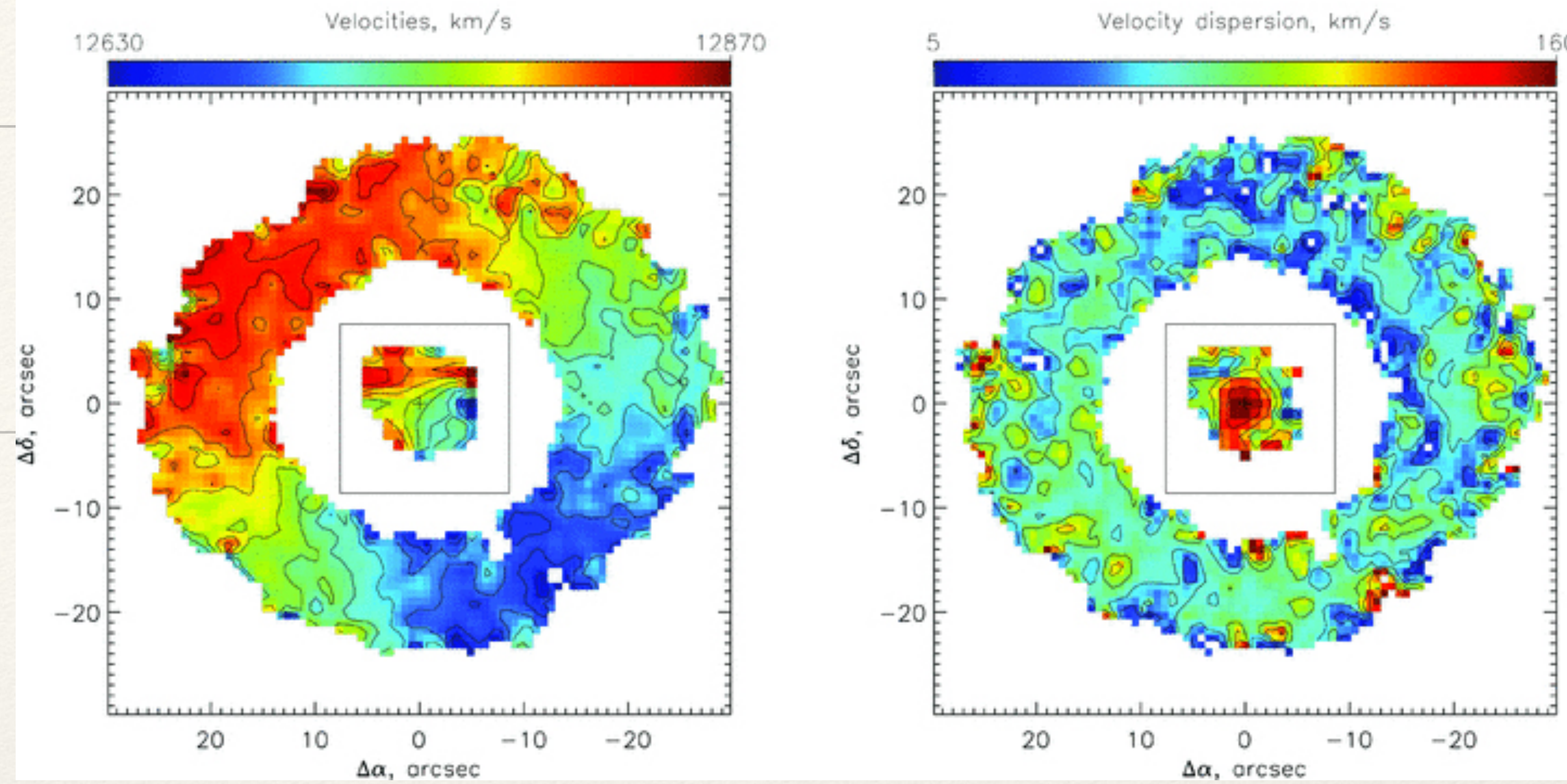
- Consider a galaxy with:
  - a redshift of z~0.04
  - an old, mostly kinematically "hot" stellar population in the center
  - a recent burst of star formation at large radii in a disky ring
- What do you think the spectra, mean velocity, and velocity dispersion look like as a function of position?

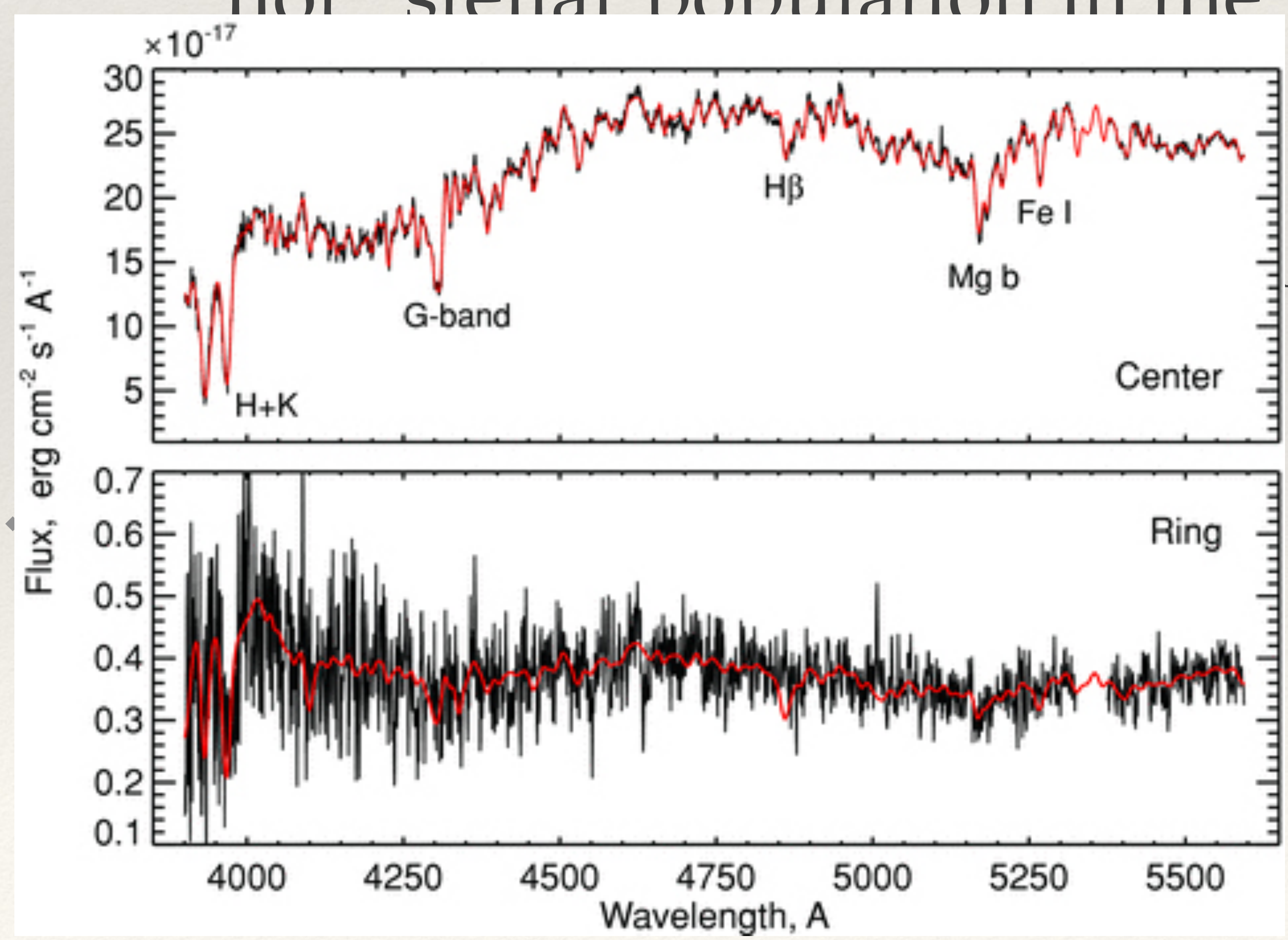


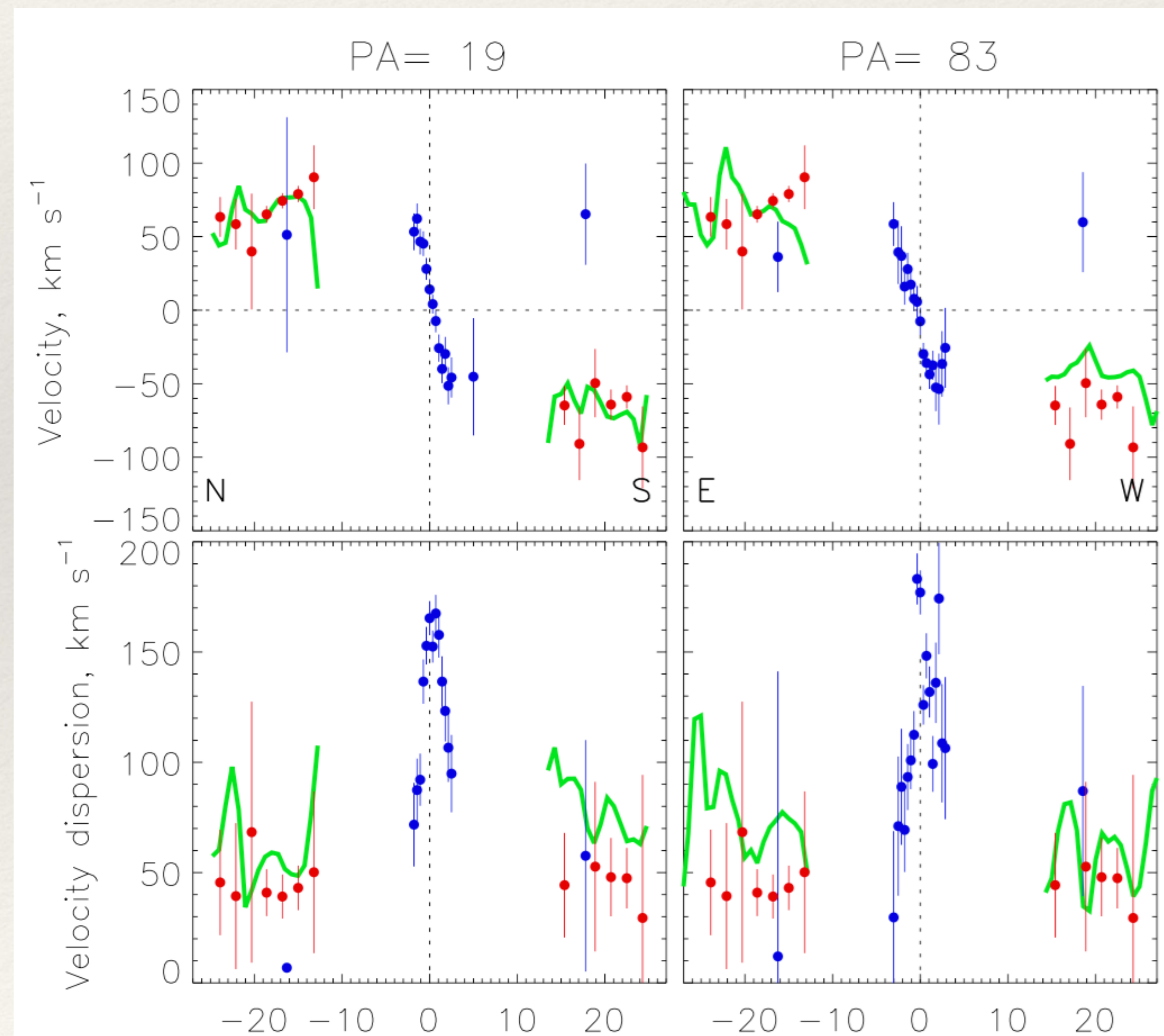
Hoag's Object (NASA)

Warm-up

- Consider a galaxy with:
  - a redshift of $z \sim 0.04$
  - an old, mostly kinematically “hot” stellar population in the





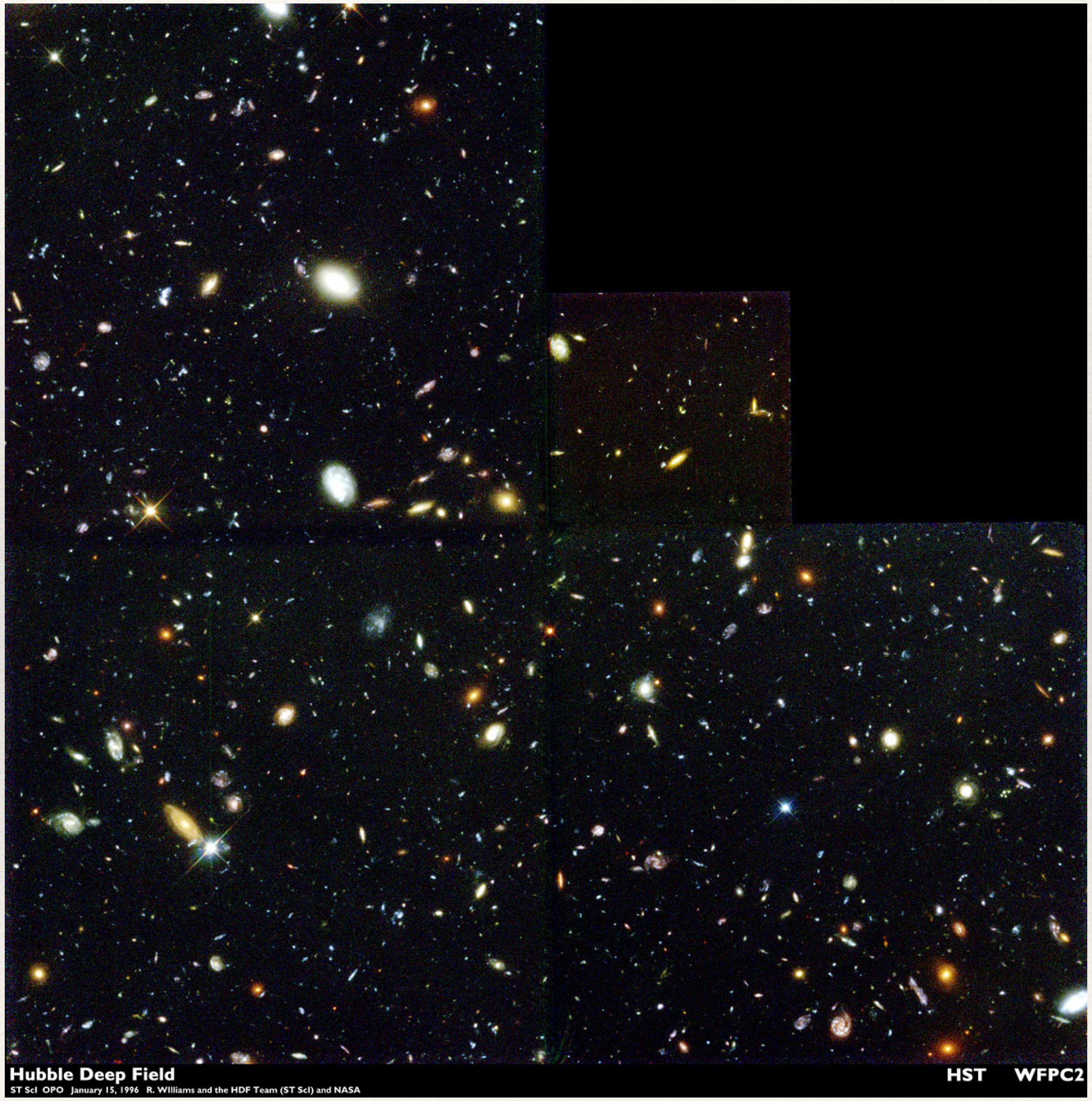


Finkelman et al. 2011

Hoag’s Object (NASA)

Warm-up

- Suppose you were observing a diverse sample of galaxies using images in several filters. What issues would you have to think about in order to figure out which galaxy was intrinsically the brightest of the bunch?



R. Williams (STScI), the Hubble Deep Field Team and NASA/ESA

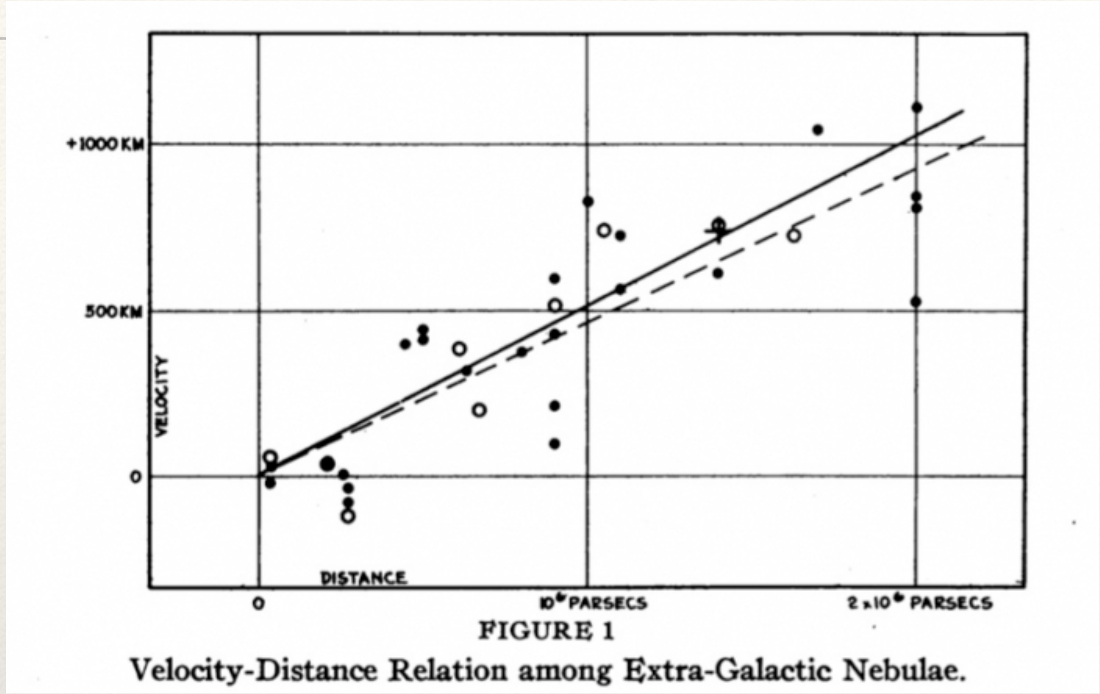
Outline for Today

- Observing Galaxies
  - Hubble flow
  - Distances
    - Rungs of the Distance Ladder
    - Getting Redshifts

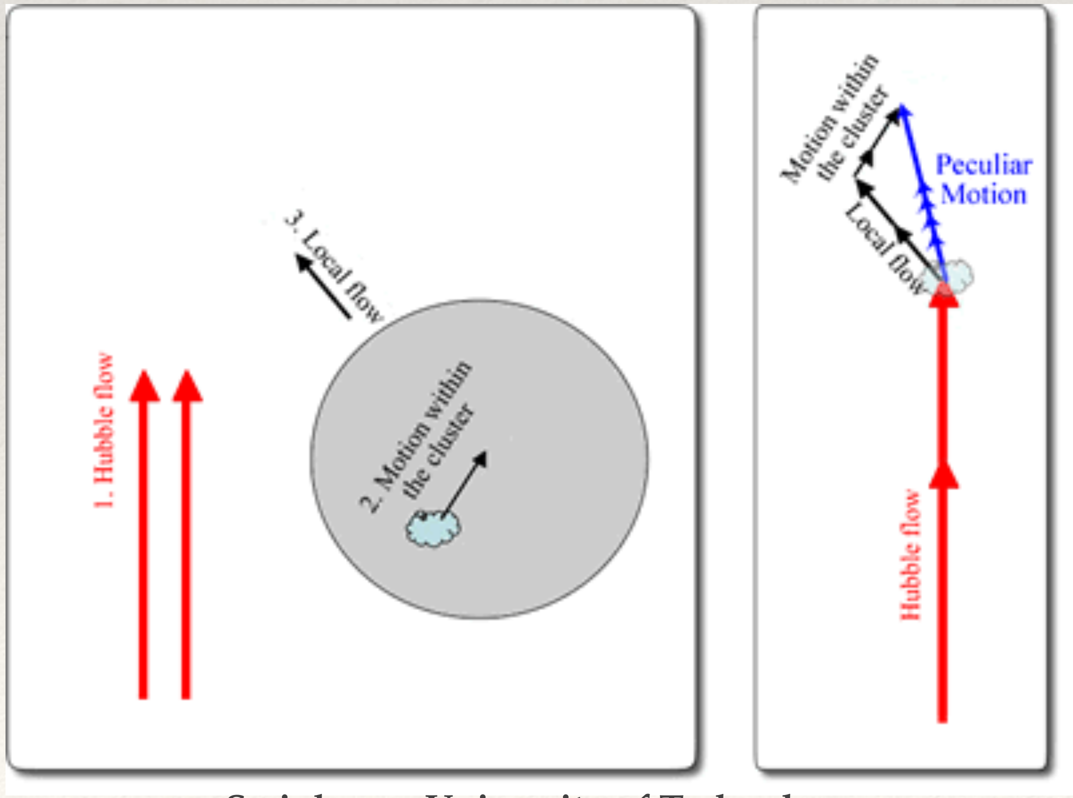
NGC1232 (ESO)

Spectroscopy: Hubble Flow

- Mean velocities of galaxies called the **Hubble Flow**:
  - galaxies are receding with velocity proportional to distance -> **expansion of the universe!**
- Dispersion of galaxy velocities around the mean relation called **peculiar velocity**:
  - $V_{total} = H_0 D + V_{pec}$
  - V_{pec} ~ a few 100s km/s in the field
  - ~1000 km/s in galaxy clusters



Hubble 1929



Swinburne University of Technology

Galaxies - Distances

- We can observe properties like flux F and angular size θ
- Some key properties of galaxies require knowledge of **distance** r:
  - Luminosity L or absolute magnitude M *(apparent magnitude if moved to 10pc)*
  - Linear size s

$$F = \frac{L}{4\pi r^2}$$

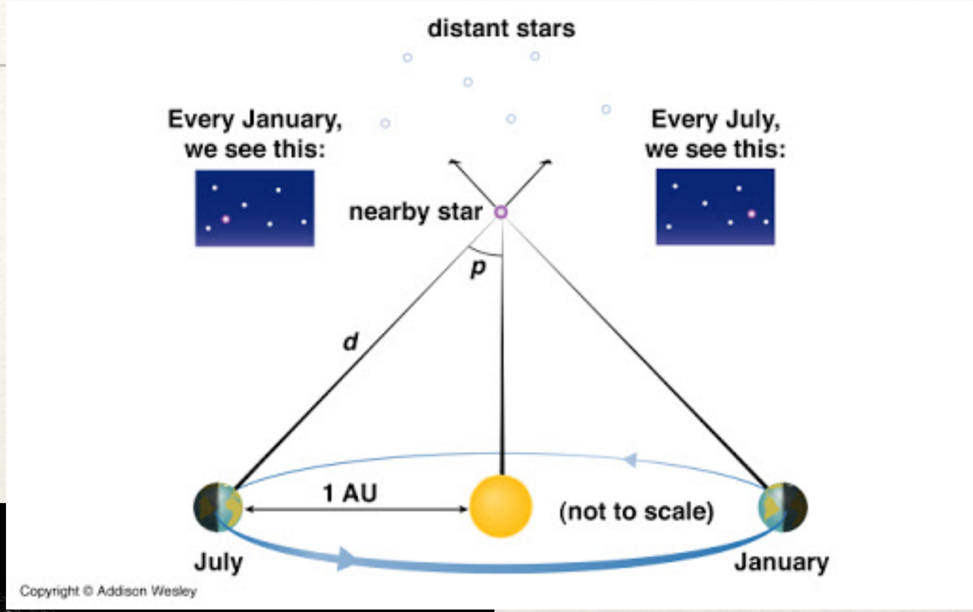
$$\underbrace{m - M}_{\text{Distance Modulus (DM)}} = 5\log(\boldsymbol{r}) - 5$$

in parcsecs

$$s = r\theta$$

Galaxies - Distances

- Cleanest distance method is **trigonometric parallax** — but galaxies are too far away!



http://ircamera.as.arizona.edu/NatSci102/NatSci102/text/parallax.htm

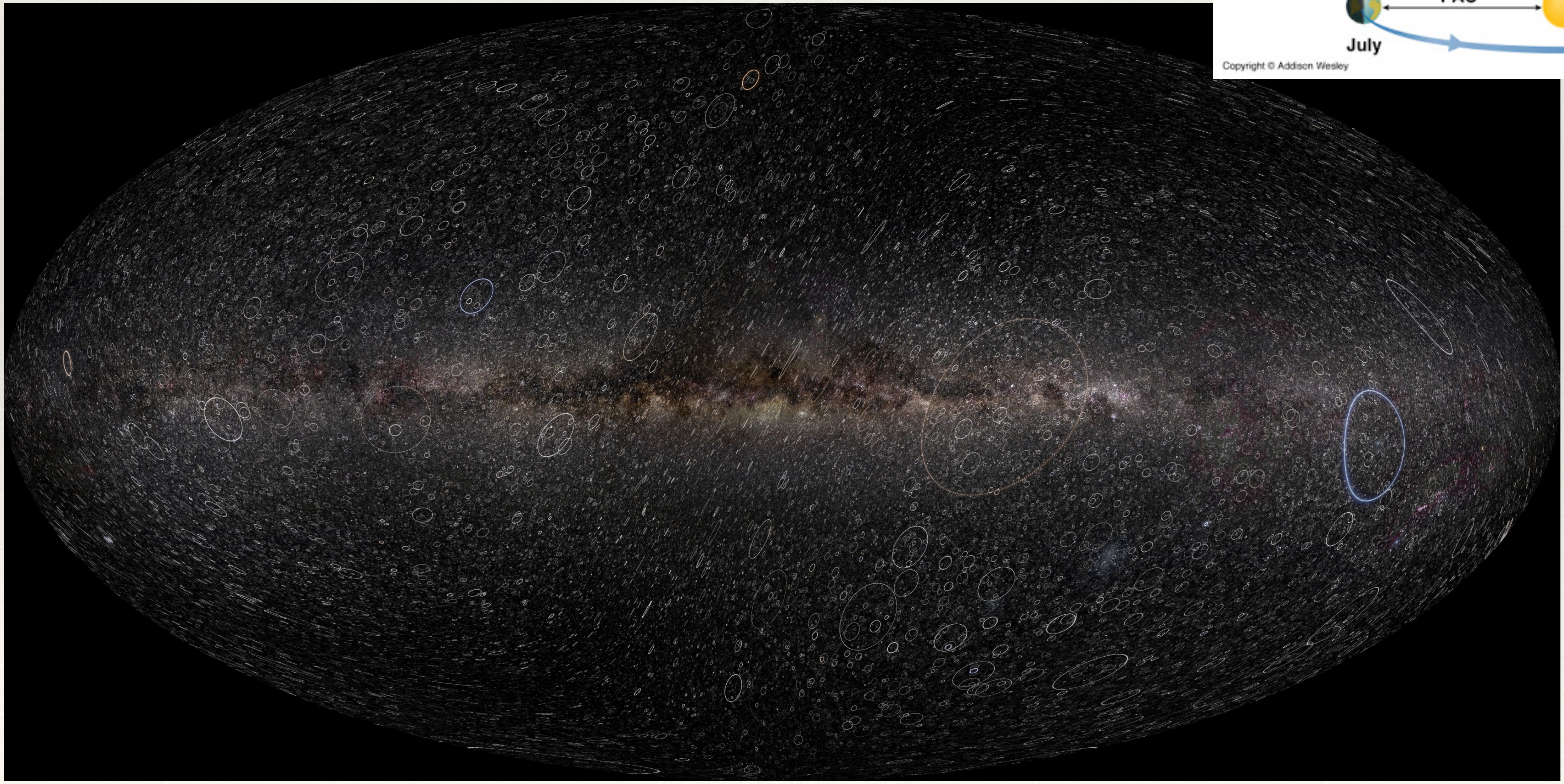


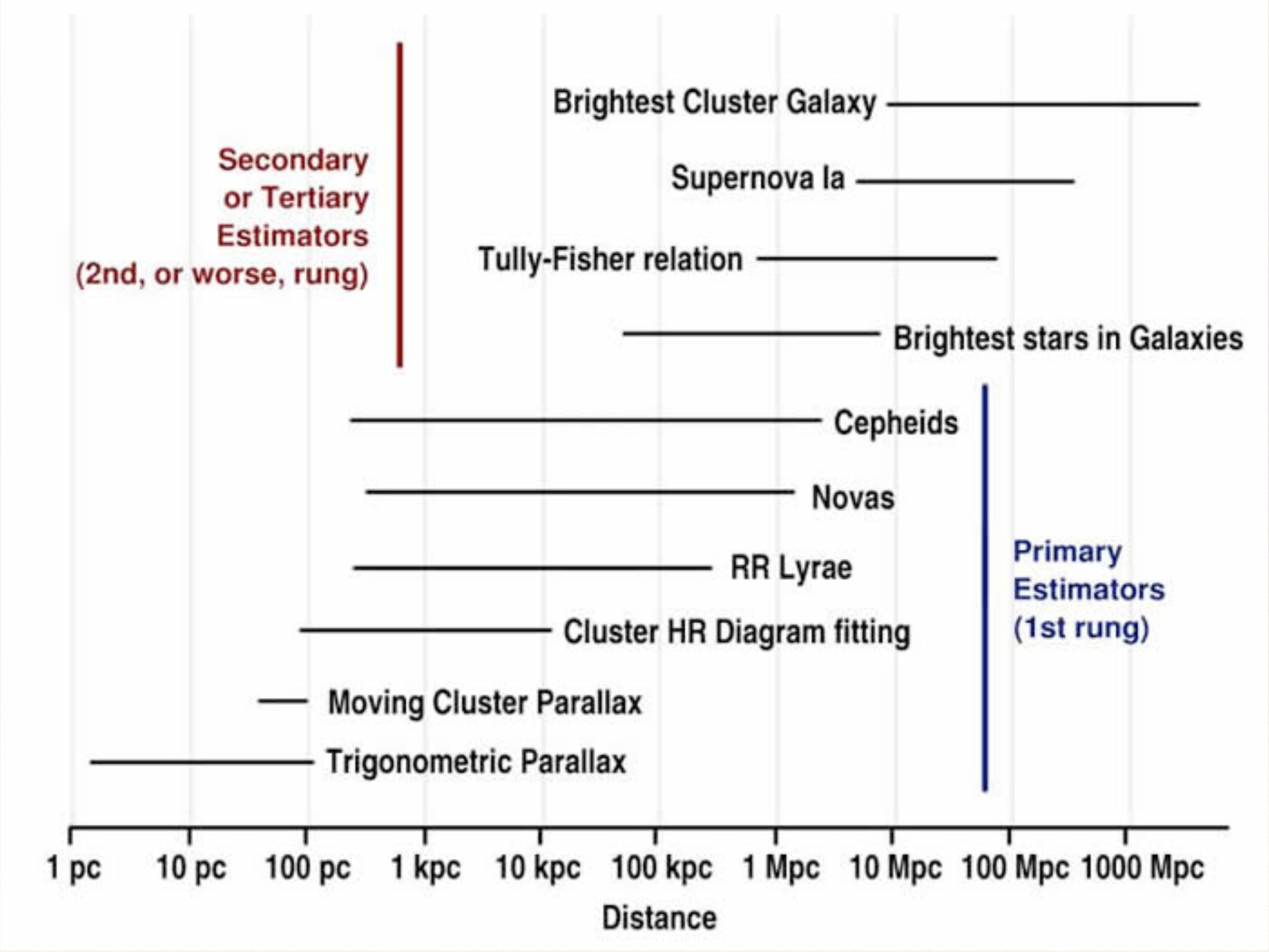
Image Credit: ESA/Gaia/DPAC

Galaxies - Distances

- Instead, use **standard "things"** (e.g., candles, rulers):
  - compare how bright or big something *should* be to what is actually observed
  - use nearby methods to calibrate more distance methods — **Distance Ladder**

$$F = \frac{L}{4\pi r^2}$$

$$s = r\theta$$

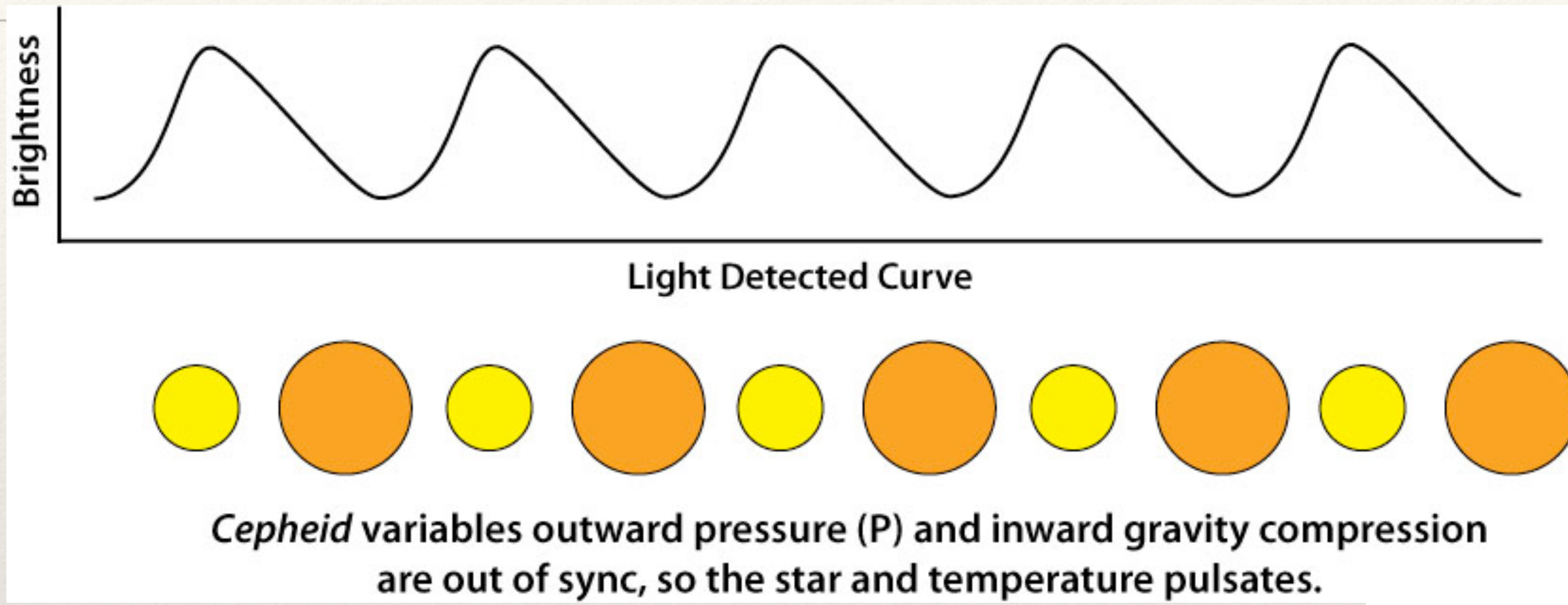


https://briankoberlein.com/2015/08/28/climbing-the-ladder/

Big Picture Question

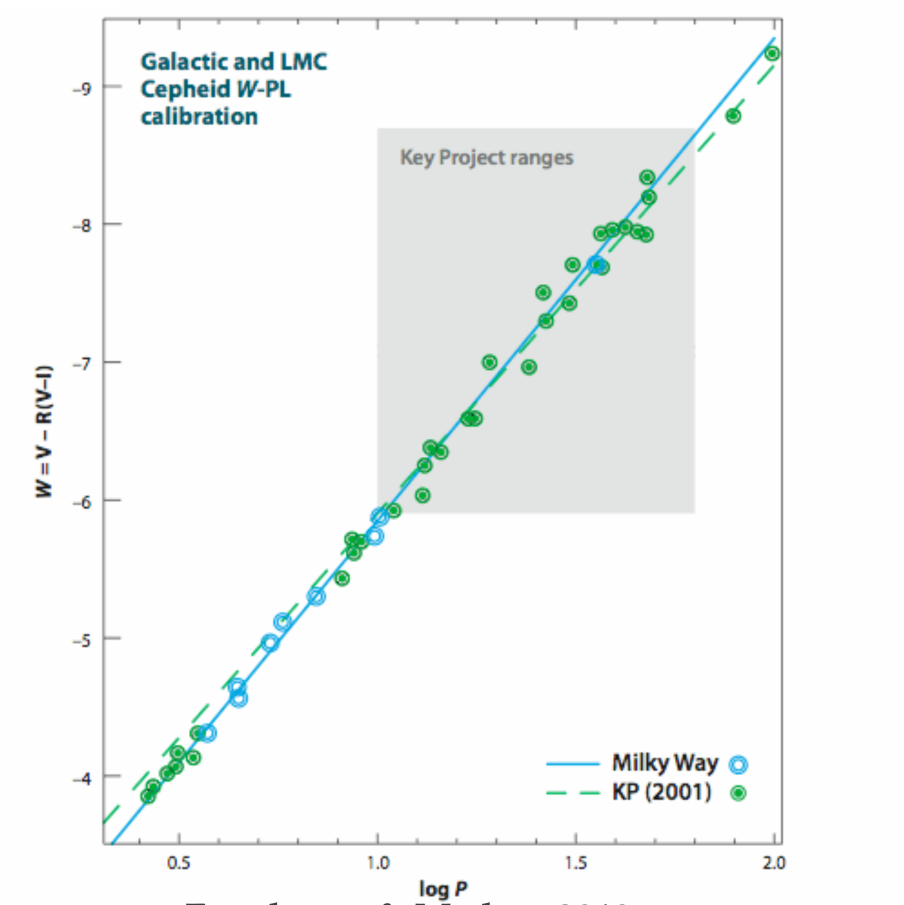
- Suppose you were trying to find a completely new method for getting distances — what would you be looking for?
  - That is, what general characteristics make something a good **standard "thing"** (e.g., candle, ruler)?
  - What types of objects or situations in the universe could give rise to a **standard "thing"**?

Distances: Rungs of the Ladder



Henrietta Swan Leavitt
1868-1921

- **Variable stars:**
  - Cepheids/RR Lyrae stars obey the Leavitt Law, or period-luminosity(-color/metallicity) relation

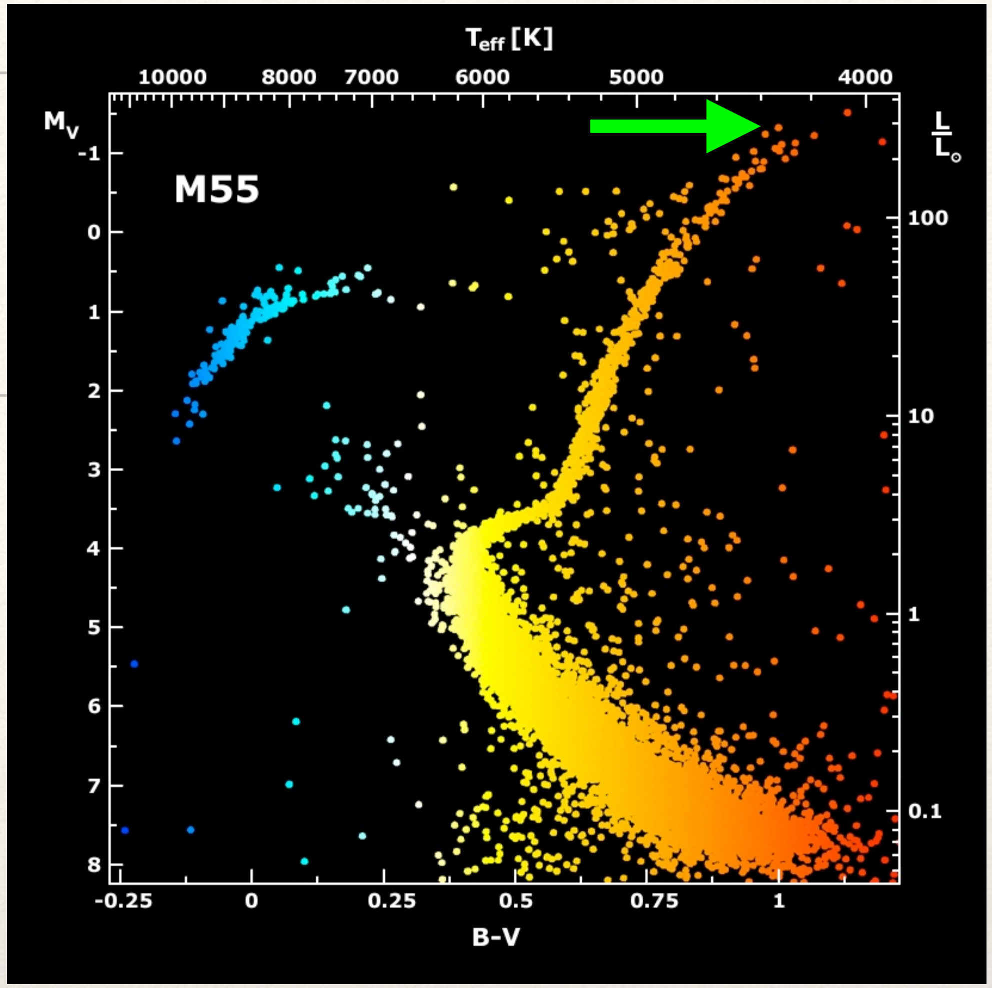


Freedman & Madore 2010

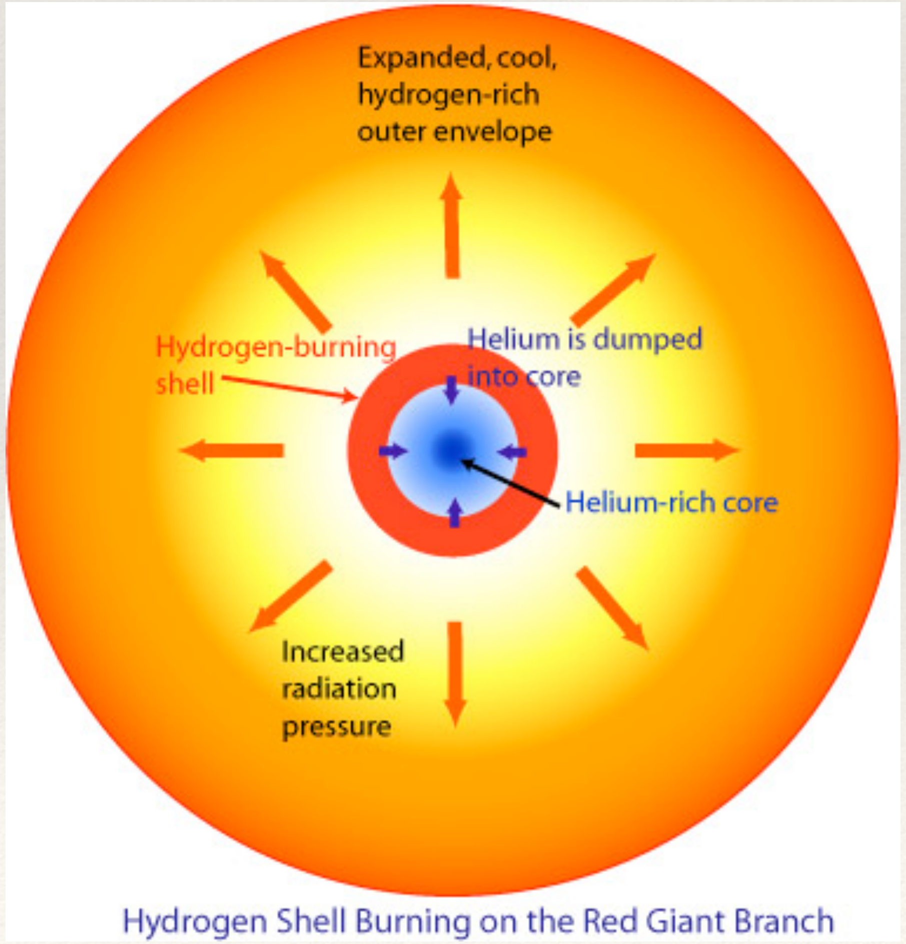
Figure 5

Distances: Rungs of the Ladder

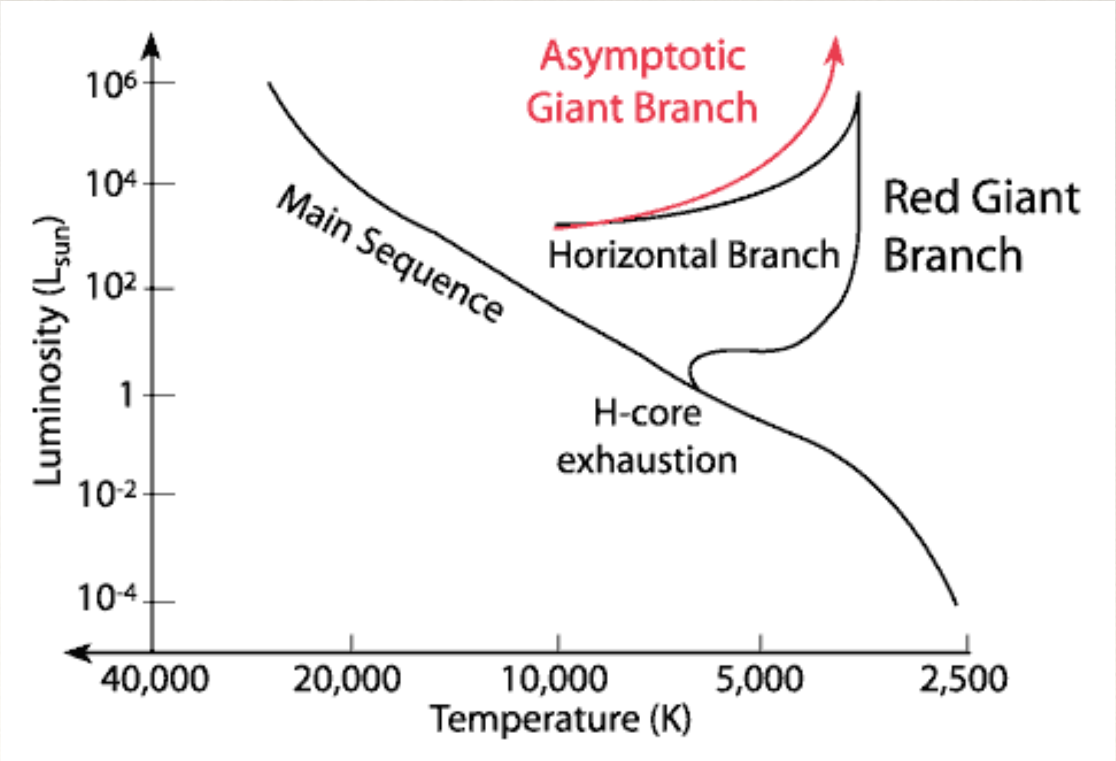
- **Tip of the red giant branch (TRGB):**
  - Physics of stellar evolution sets a characteristic maximum brightness
  - Does depend somewhat on the stellar population : more constant for old population



B.J. Mochejska, J. Kaluzny (CAMK), 1m Swope Telescope



Australia Telescope National Facility



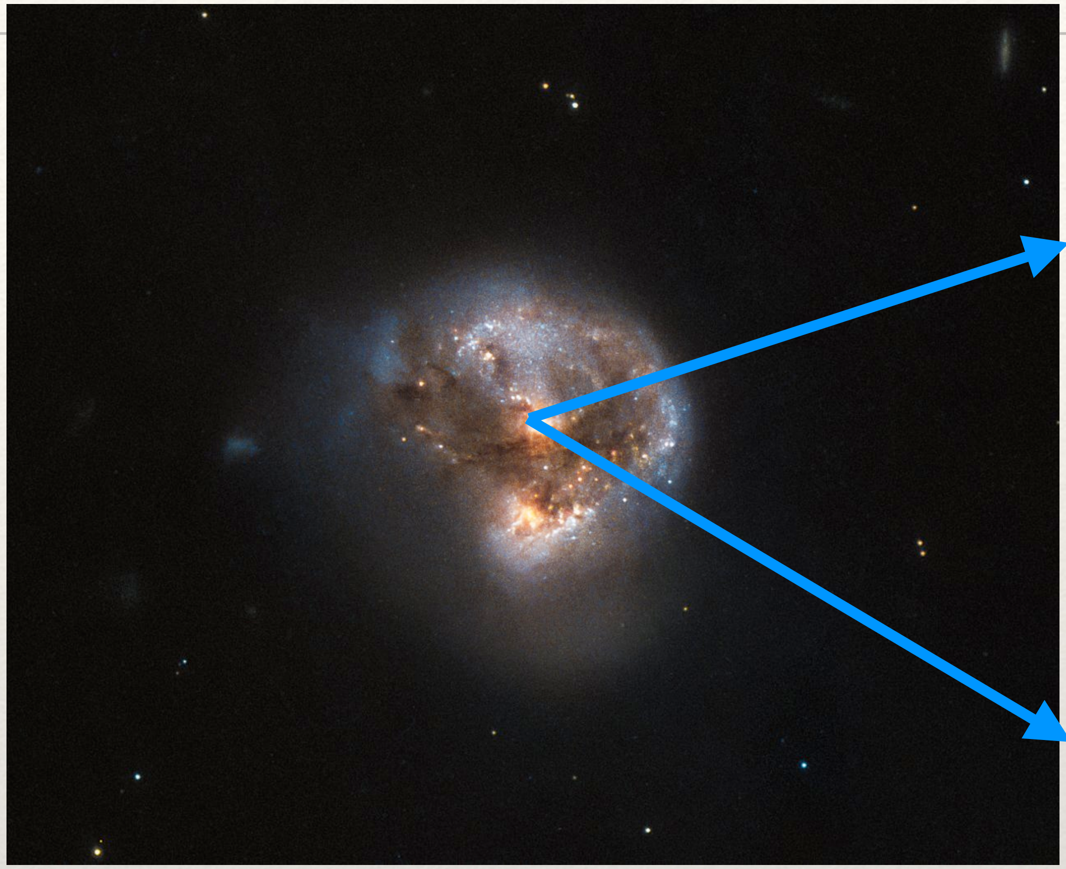
www.noao.edu

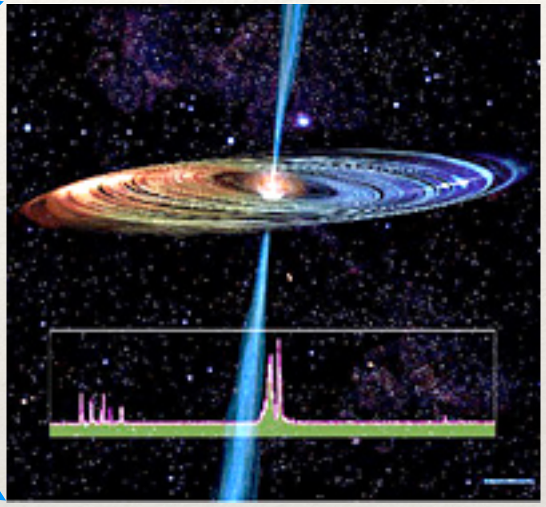
Distances: Rungs of the Ladder

- **Masers:**
  - Using interferometry, proper motion (arcsec/year) can be compared with radial velocity in black hole accretion disk

$$v = 4.74\mu d$$

    for v (km/s) mu ("/yr),d(pc)

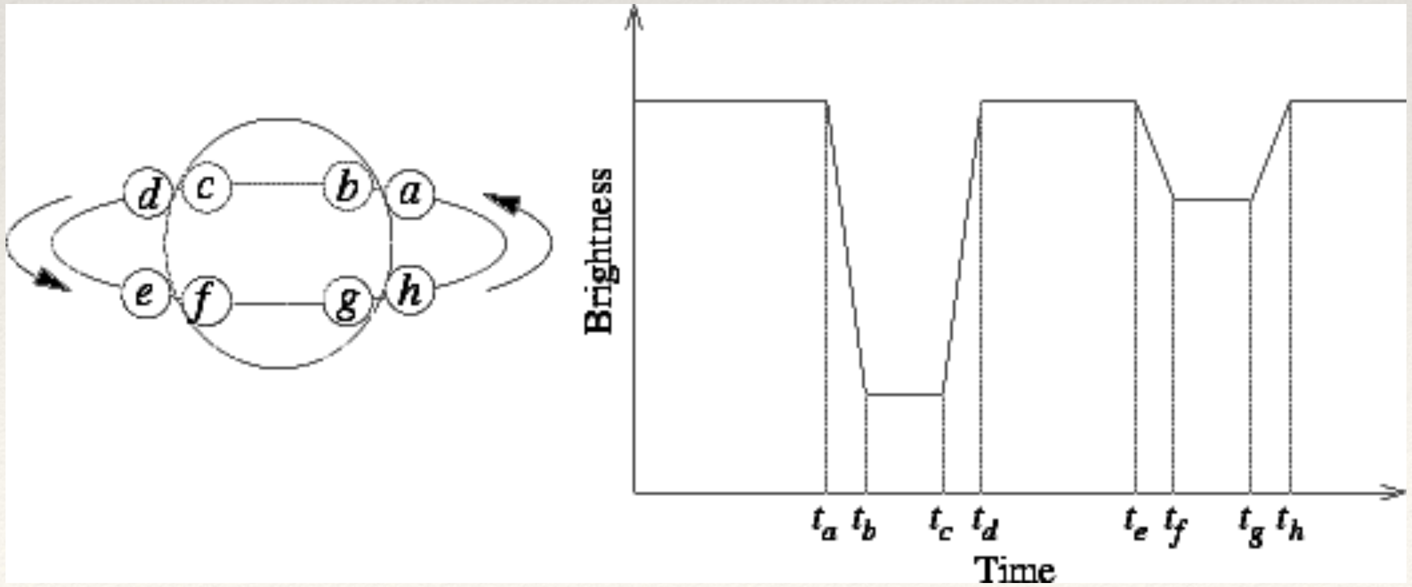




J. Kagaya (Hoshi No Techou), M. Inoue (NAO).

IRAS 16399-0937, a water megamaser — ESA/Hubble & NASA (Judy Schmidt)

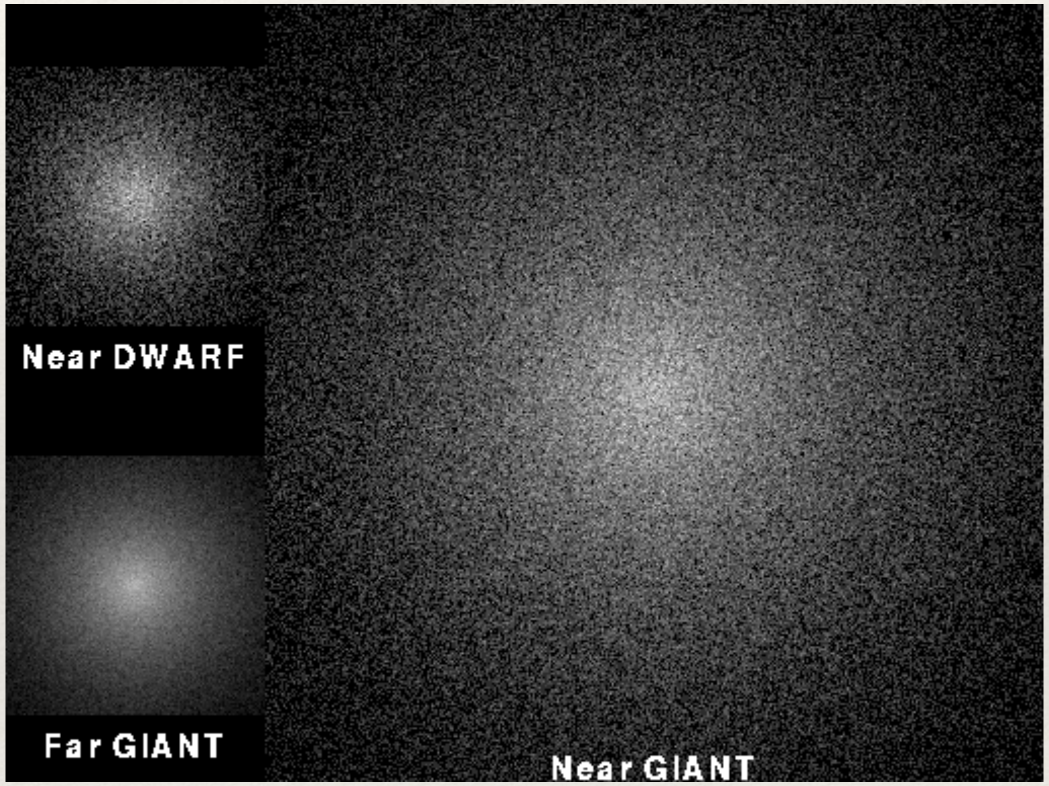
- **Eclipsing binaries:**
  - Properties of the binary components from light curve and radial velocity data compared with angular size/apparent magnitude : radius and flux give luminostiy



burro.case.edu

Distances: Rungs of the Ladder

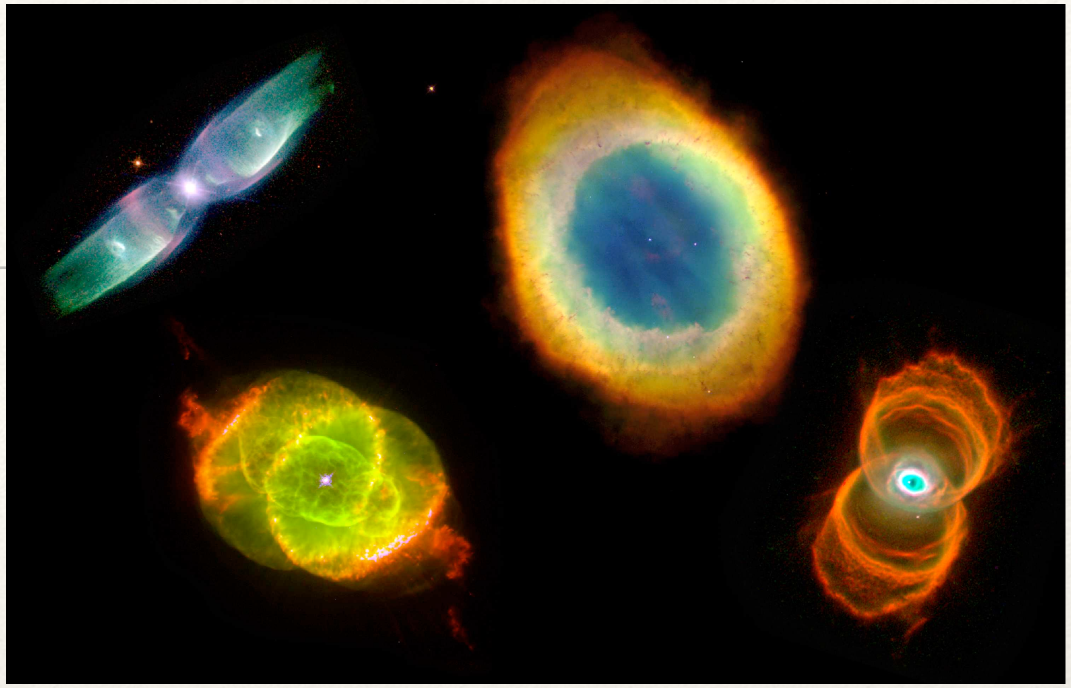
- **Surface brightness fluctuations:**
  - Measure imprint of Poisson statistics
    - A nearby galaxy with N=100 stars per pixel would show statistical fluctuations of $\sqrt{(N)}/N \sim 10\%$
    - A distant galaxy with 1000 stars per pixel would show statistical fluctuations of $\sqrt{(N)}/N \sim 3\%$
  - Requires objects with a "standard" population (i.e. red giant branch stellar population comparable in different galaxies)



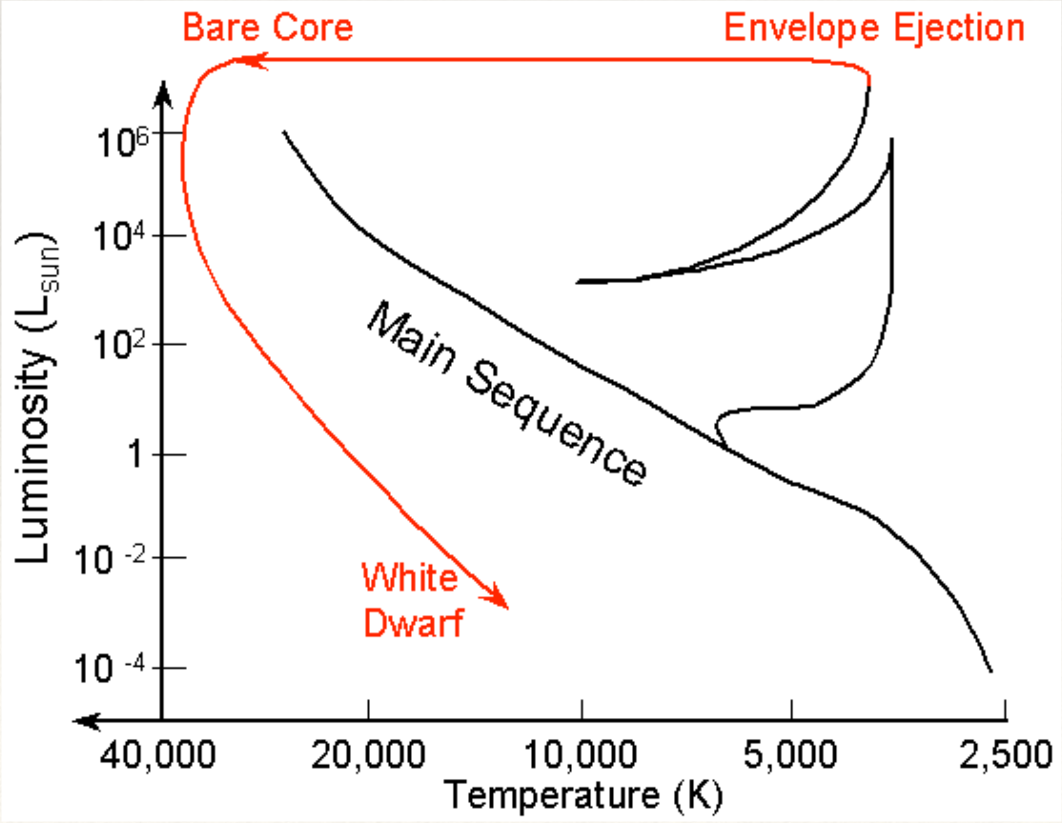
http://www.astro.ucla.edu/~wright/distance.htm

Distances: Rungs of the Ladder

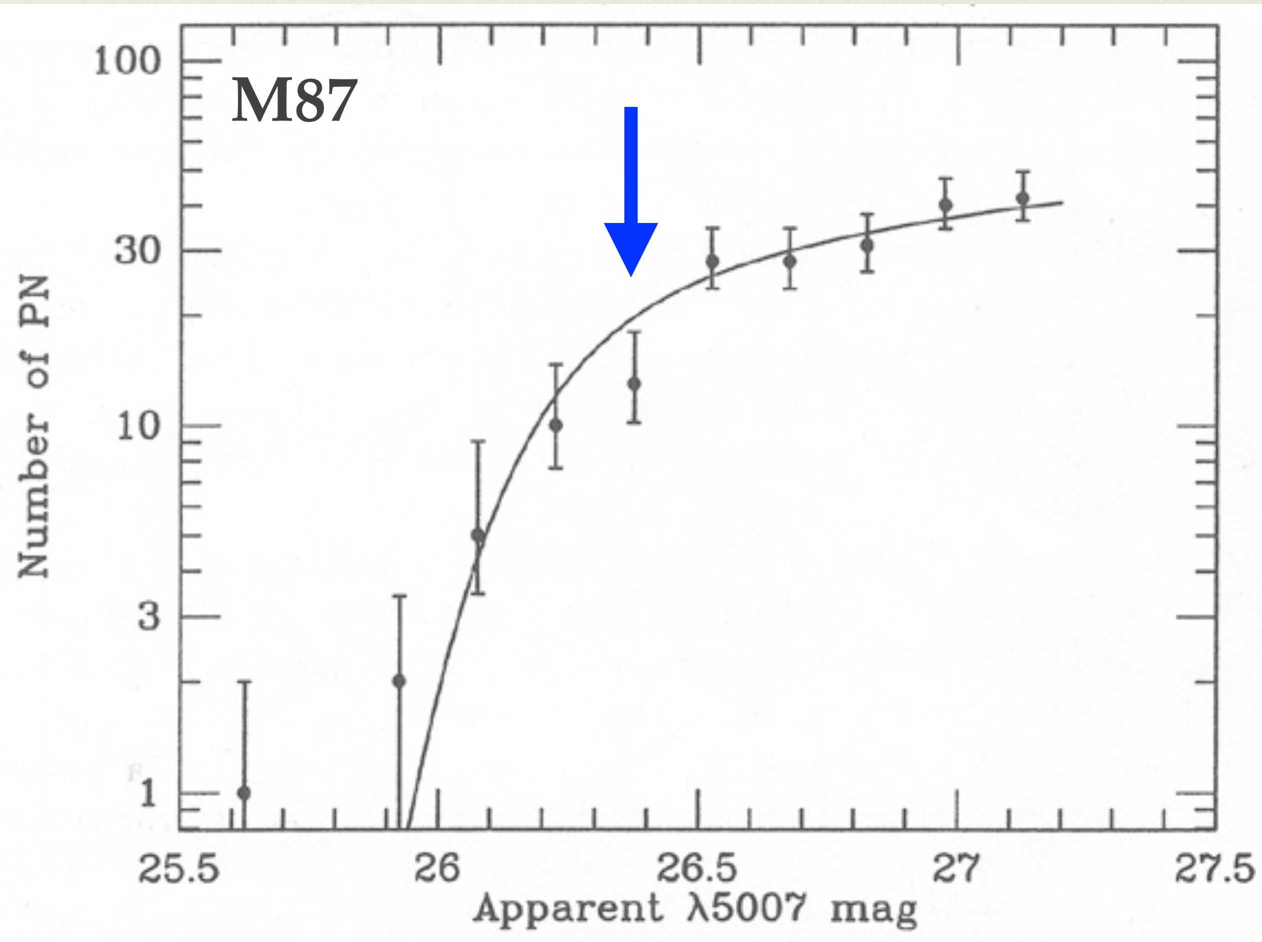
- **Planetary nebulae luminosity function:**
  - End stage of low mass star's life
  - Characteristic brightness where luminosity function turns over



NASA

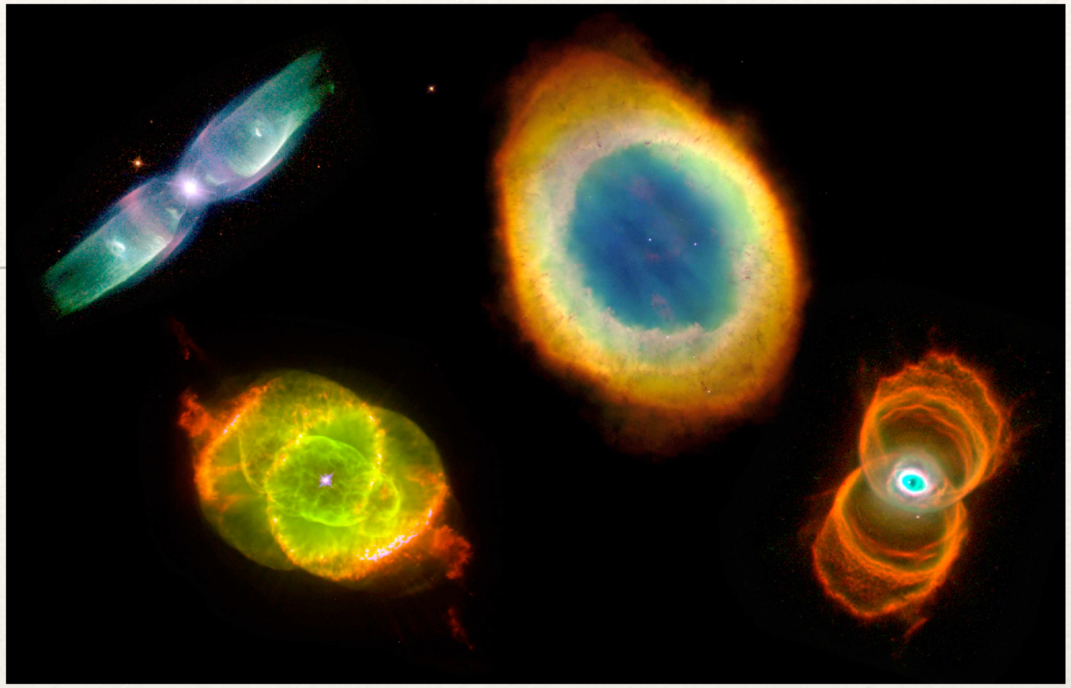


jillkamil.com



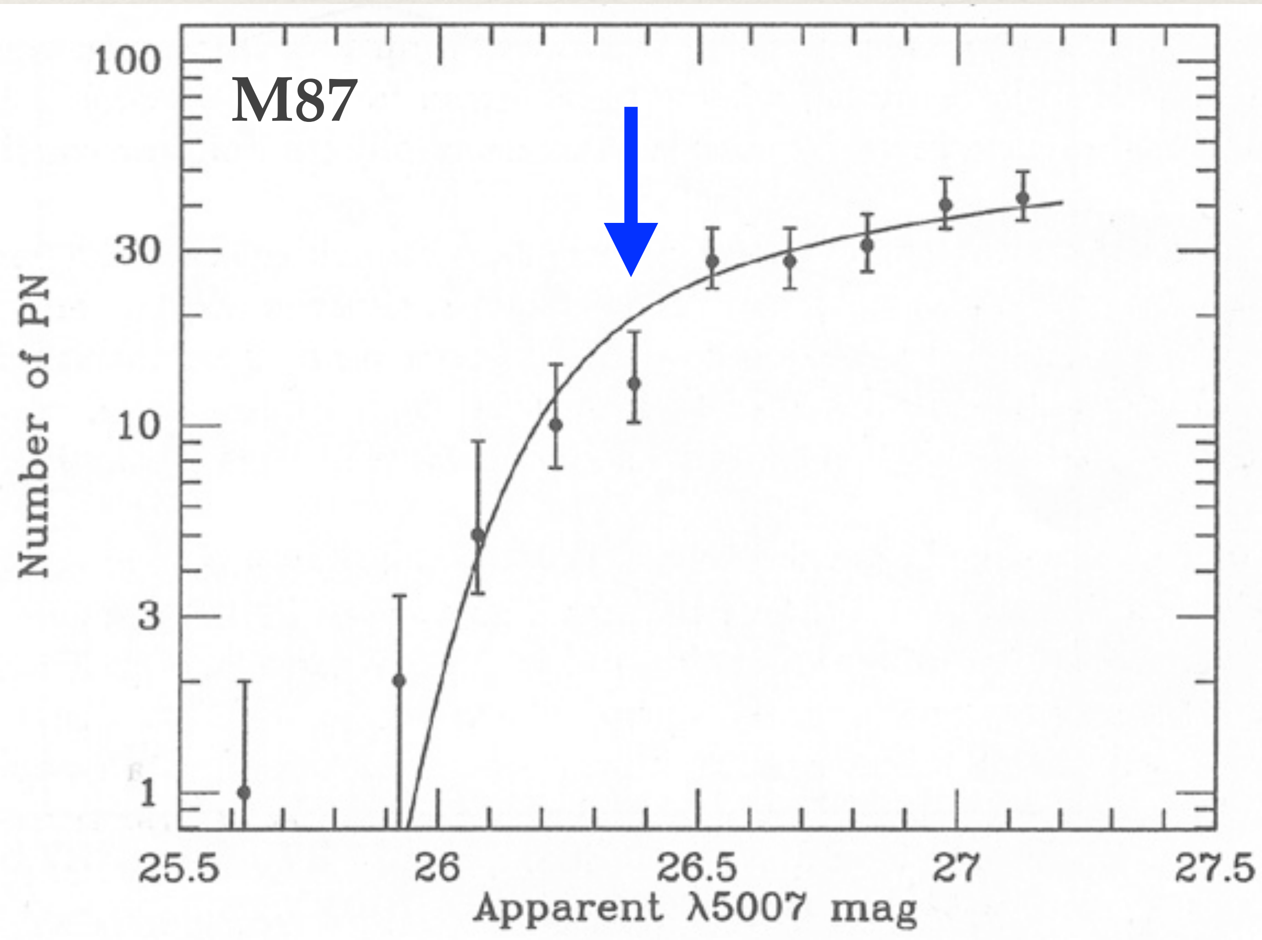
https://ned.ipac.caltech.edu/level5/March01/Jacoby/Jacoby7.html

Quick Question



NASA

- Suppose the characteristic brightness of the planetary nebulae luminosity function is M* = -4.54 (an absolute magnitude)
- Estimate the distance modulus and the distance to M87.



https://ned.ipac.caltech.edu/level5/March01/Jacoby/Jacoby7.html

$M^* = -4.54$ (absolute mag)

$m = \sim 26.4$ (apparent mag) for M87

$$m - M^* = 5 \log(r_{pc}) - 5$$

$$\left(\frac{m - M^*}{5}\right) + 1 = \log(r_{pc})$$

$$r_{pc} = 10^{\frac{26.4 + 4.54}{5} + 1} = 1.54 \times 10^7 \text{ pc}$$

$$\boxed{r = 15.4 \text{ Mpc}}$$

Distance modulus $DM = m - M^*$

$= 26.4 + 4.54$

$$\boxed{DM = 30.94}$$

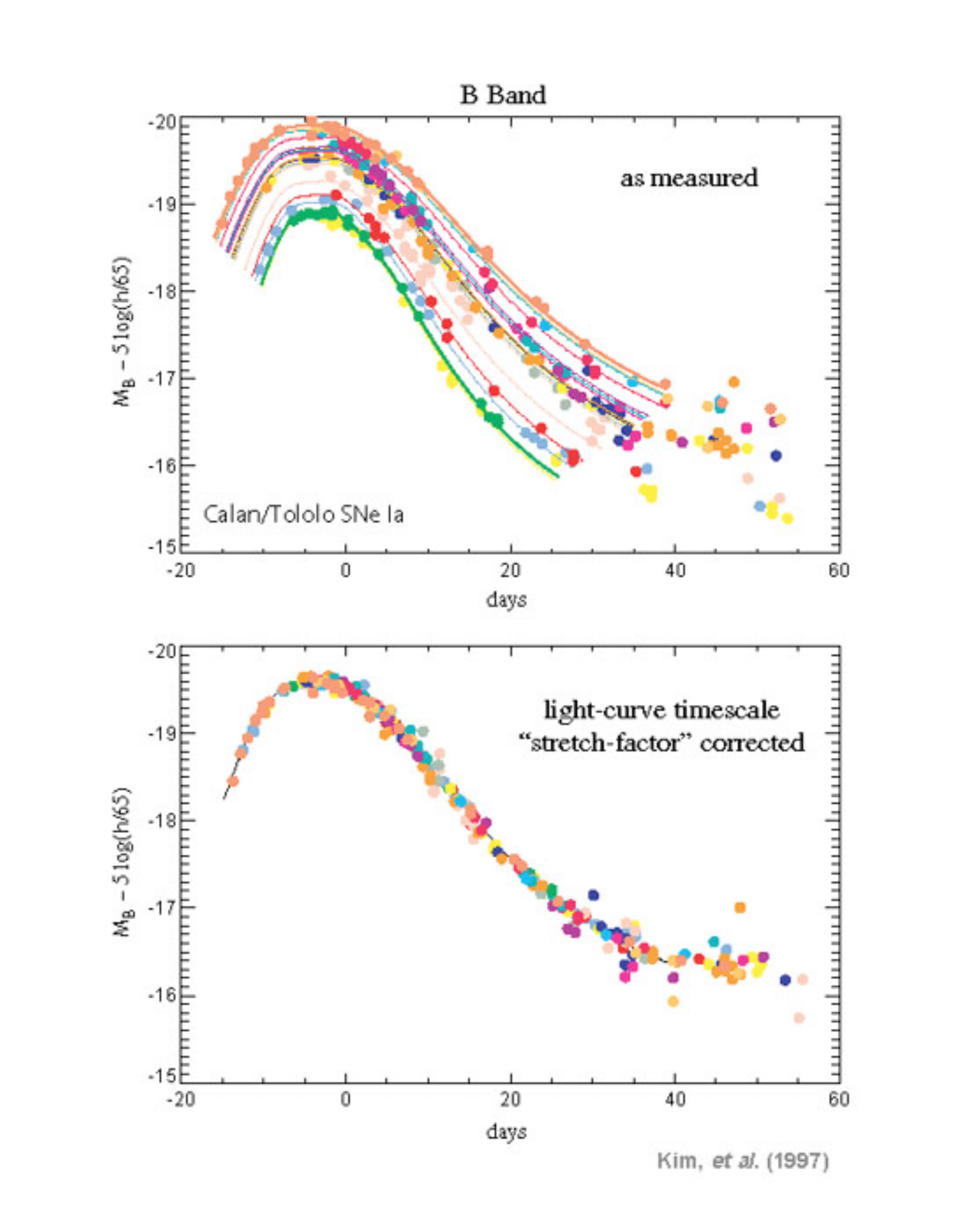
Note: actual $DM = 31.09$ for M87

$r = 16.8$ Mpc

Distances: Rungs of the Ladder

- **Type-Ia supernova peak luminosity:**
  - Explosion of white dwarf with the Chandrasekhar mass (1.4 solar masses)
  - "Standardizable" by light curve shape (longer delay time -> higher luminosity)

SN1994D in NGC 4526 (HST, NASA/ESA)

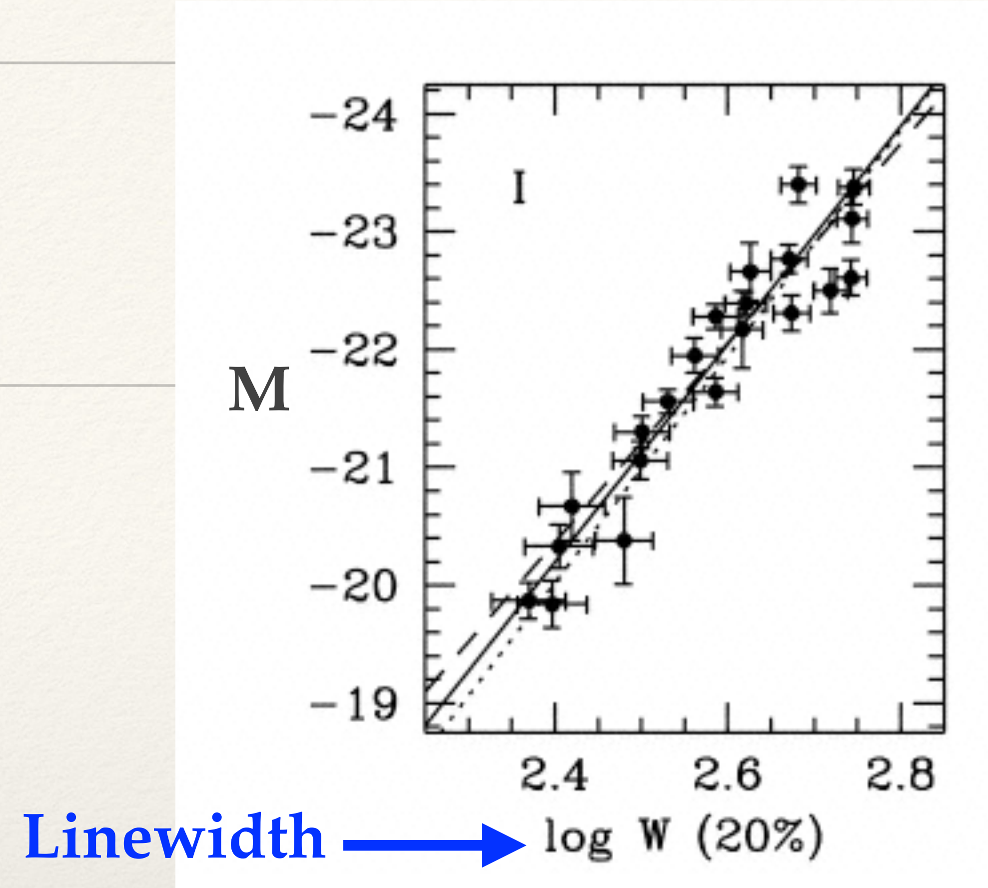


Top panel: SN Ia B-band light curves (Hamuy et al. 1996). Bottom panel: After a one-parameter correction for the brightness-decline correlation (Kim 2004).

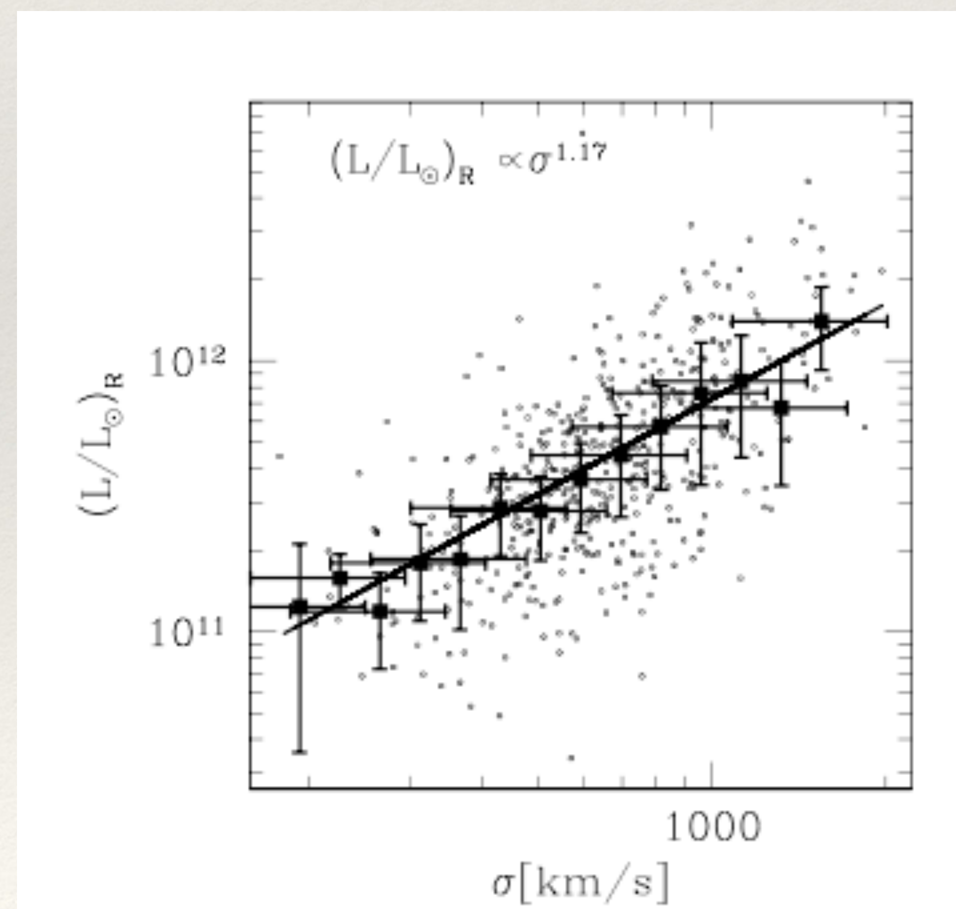
Distances: Rungs of the Ladder

- **Galaxy scaling relations**:
  - Spiral galaxies: **Tully-Fisher relation** between maximum rotational velocity and luminosity
  - Elliptical galaxies: **fundamental plane relation** between central velocity dispersion, physical size, and surface brightness/ luminosity
  - Higher velocities - higher mass -> bigger size - larger luminosity

(more later!)



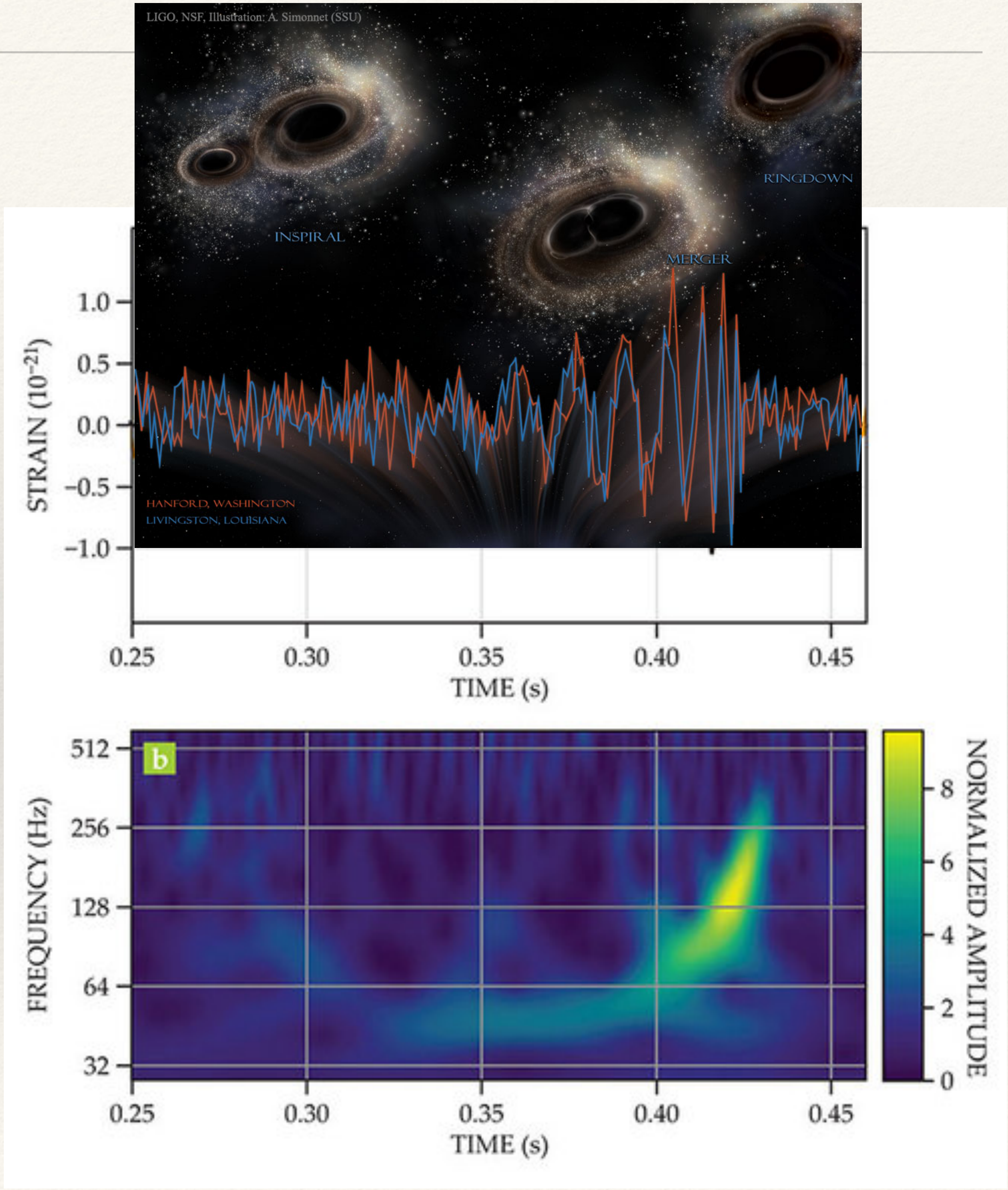
Sakai et al., ApJ 529, 698 (2000)



Diaz and Muriel, MNRAS 364, 1299 (2005)

Distances: Rungs of the Ladder

- Gravitational waves from black hole or neutron star binary mergers (independent of the ladder!):
    - Rate of change of frequency during inspiral depends upon the mass of binary, and binary mass determines energy of merger.
    - Comparing energy of the event with amplitude of observed gravitational waves, we get distance — **Standard Siren!**



https://physicstoday.scitation.org/doi/10.1063/PT.3.4090

Distances: Getting Redshifts

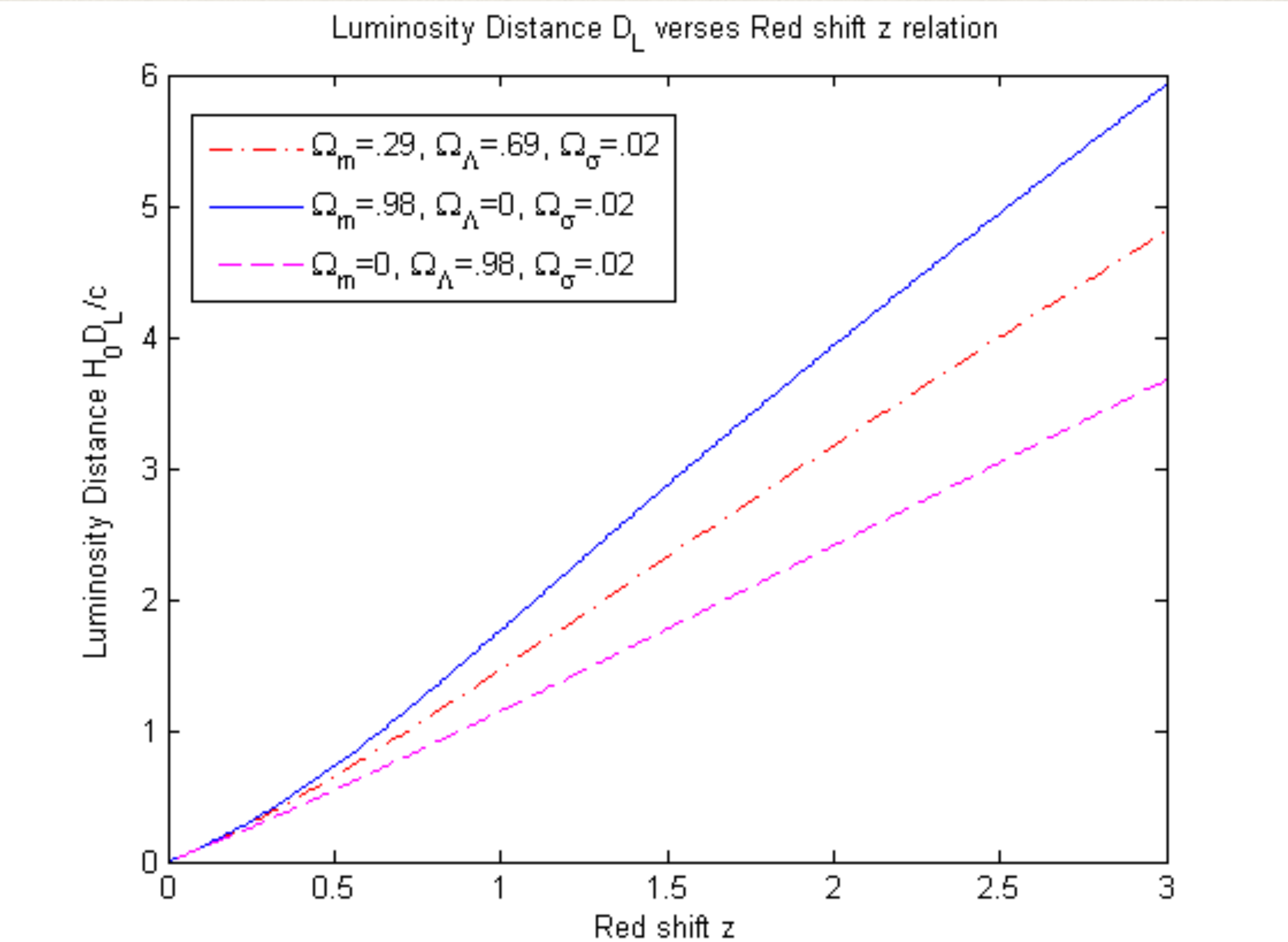
- In principle the observed *geocentric* velocities need to be corrected for:
  - Earth's motion (to heliocentric or barycentric) ~30 km/s
  - Sun's motion (to Local Standard of Rest, LSR) ~10 km/s
  - Milky Way rotation (to Galactic Standard of Rest, GSR) ~220 km/s
  - motion of Milky Way within Local Group ~178 km/s
- Corrections matter locally, but note that not a big correction for higher redshift galaxies, e.g., z=0.01 corresponds to ~3000 km/s

Distances: Redshifts

- Galaxies expand with the cosmic flow, so can **use redshift to get distance** (assuming a cosmology!), modulo the peculiar velocity!
- At low redshift (z ≲ 0.1):
    - Hubble-Lemaître Law—current best estimate H0 = ~70 km/s/Mpc
- At high redshift (z ≳ 0.1):
    - Need cosmological parameters to get distance from redshift

$$\frac{\Delta\lambda}{\lambda} = z,\ 1 + z = \lambda_{obs}/\lambda_{emit}$$

$$z \approx v/c,\ v = H_0 d$$



https://www.researchgate.net/publication/259804149_LCDM-type_cosmological_model_and_observational_constraints

Distances: Getting Redshifts

- Galaxies move relative to the overall expansion (Hubble Flow) due to local gravitational attraction —> **peculiar velocity**
  - $\mathbf{V_{total} = H_0\, d + V_{pec}}$
- Typical peculiar velocities:
  - a few 100s km/s in the field
  - ~1000 km/s in galaxy clusters

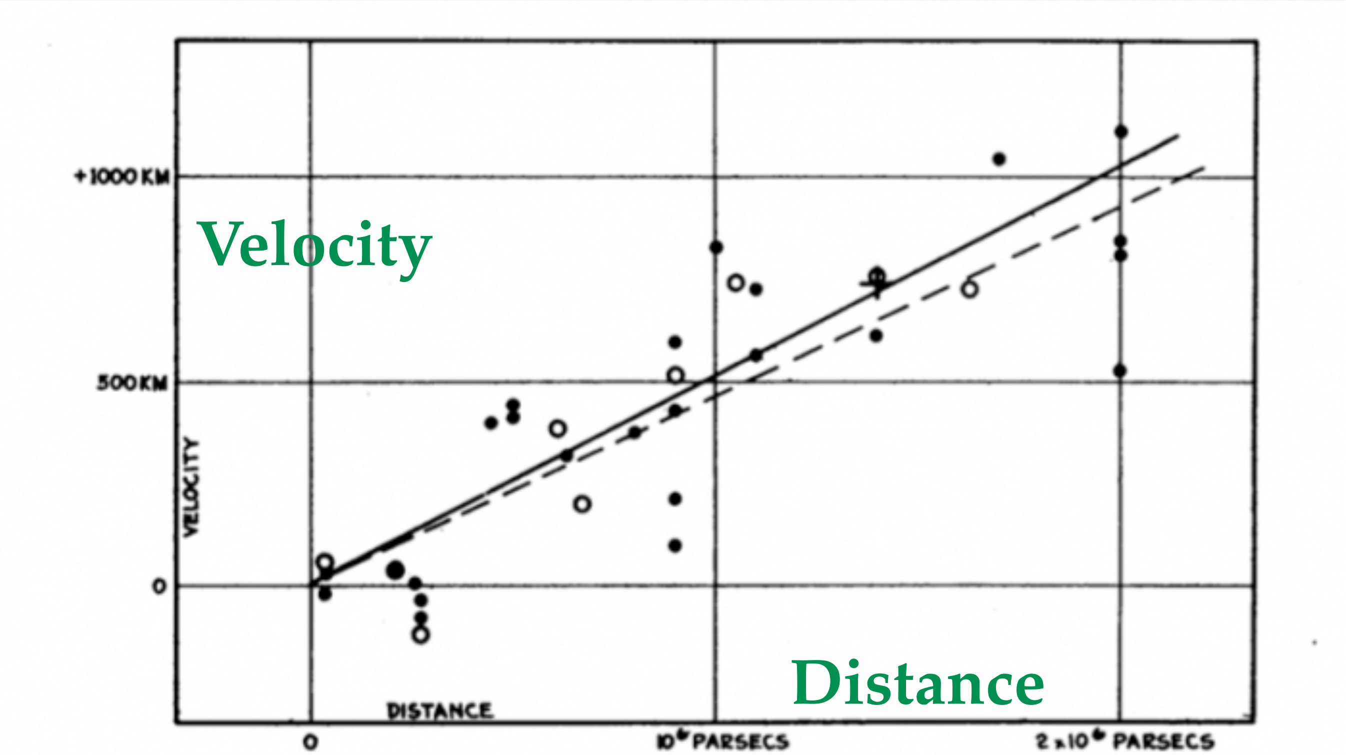


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

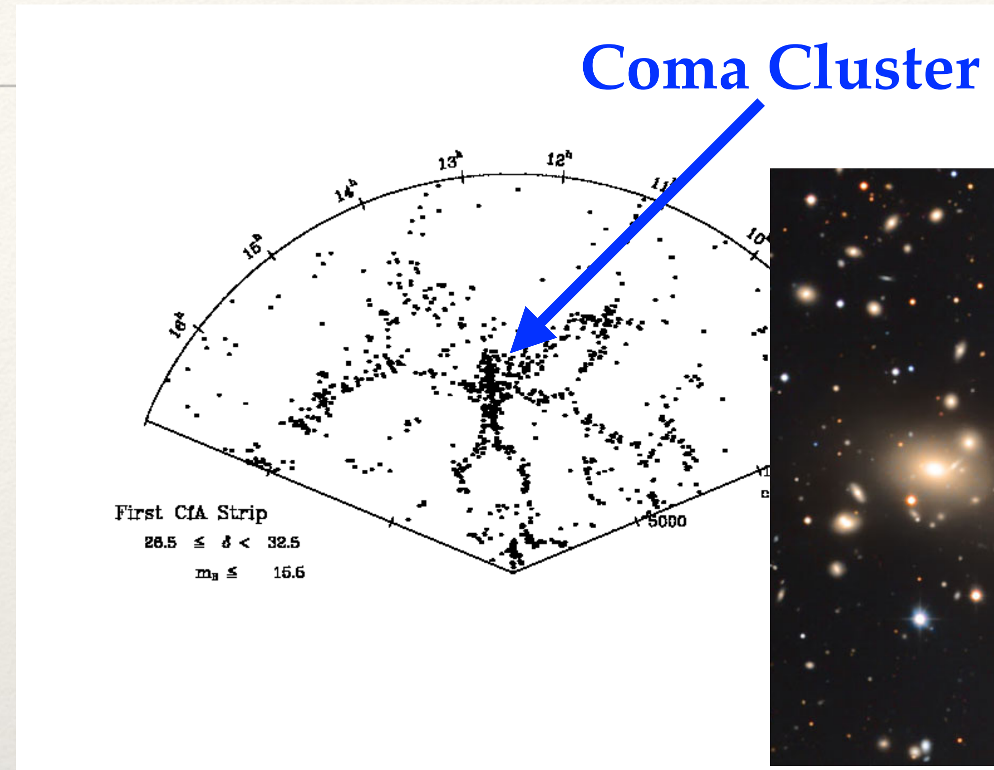
Hubble 1929

Why are peculiar velocities so high in galaxy clusters?

Distances: Getting Redshifts

Distances: Getting Redshifts

- Ignoring peculiar velocities creates **redshift space distortions**:
    - “Fingers of God” effect
    - Kaiser effect (“pancakes of God”)
- At $z \lesssim 0.1$, need model of mass distribution and velocity field (not easy!)
- At $z \gtrsim 0.1$, peculiar velocities cause relatively small distance errors



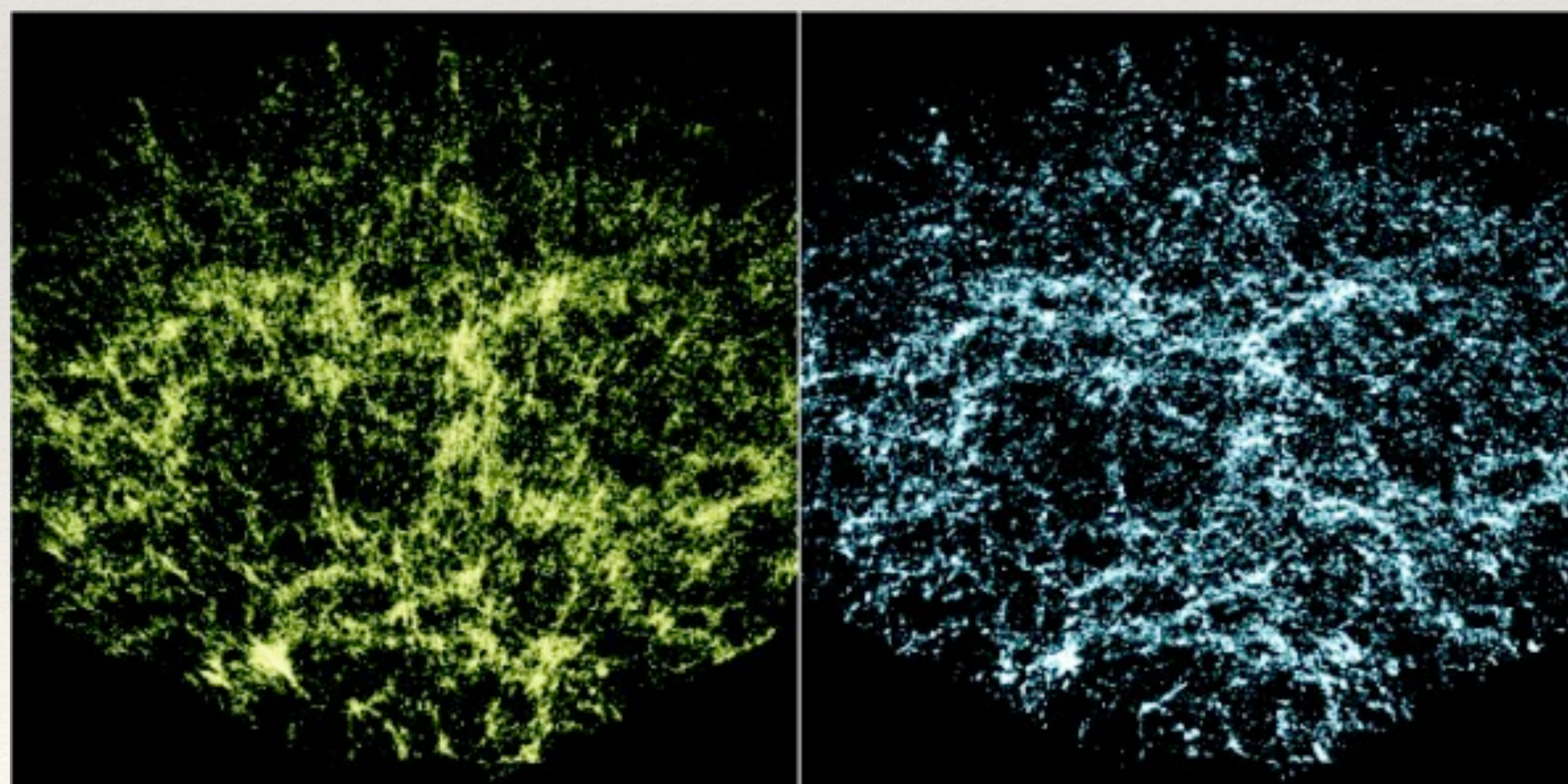
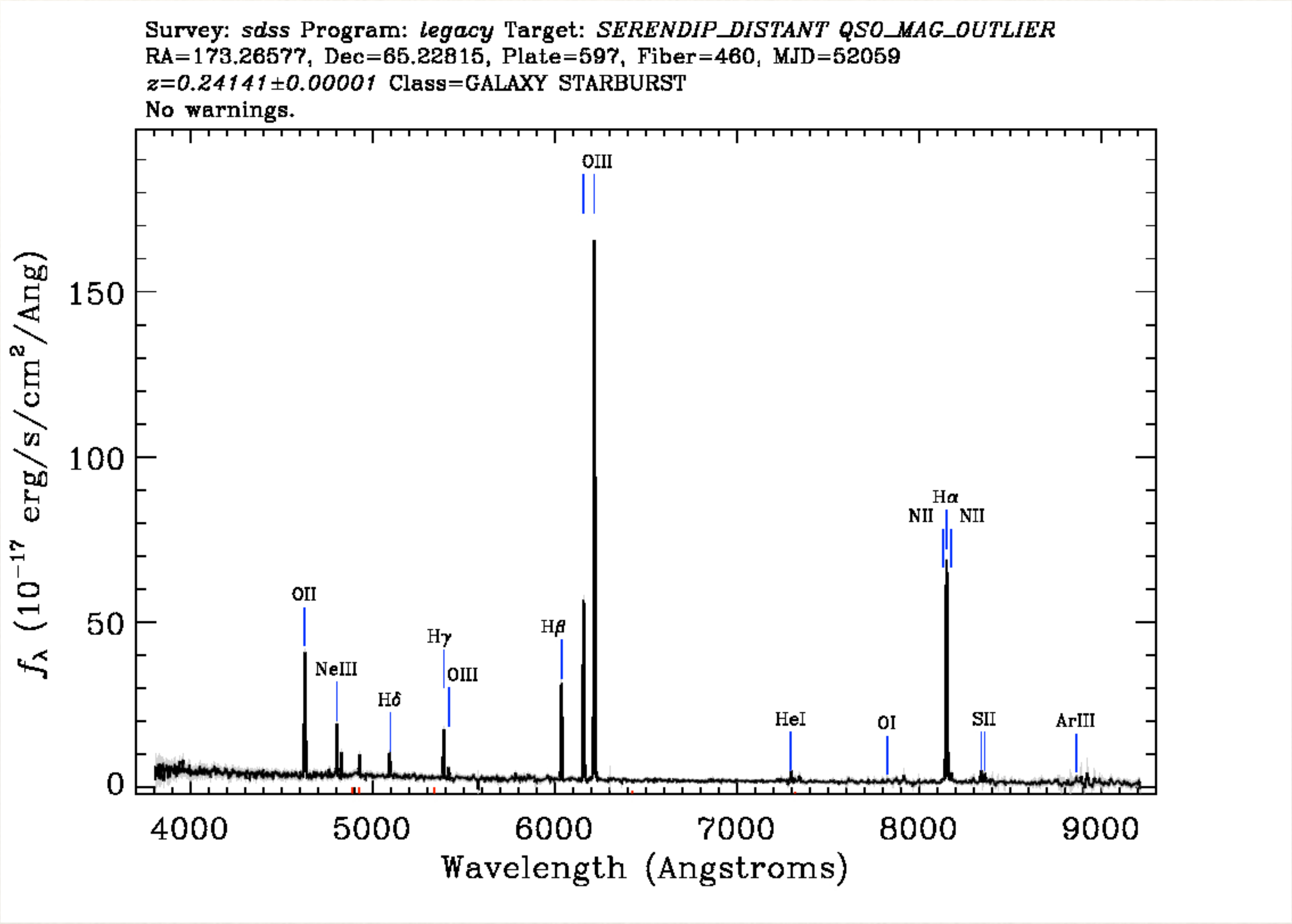


Image credit: M.U. SubbaRao et al., New J. Phys. 10 (2008) 125015, via IOPscience.

Distances: Getting Redshifts

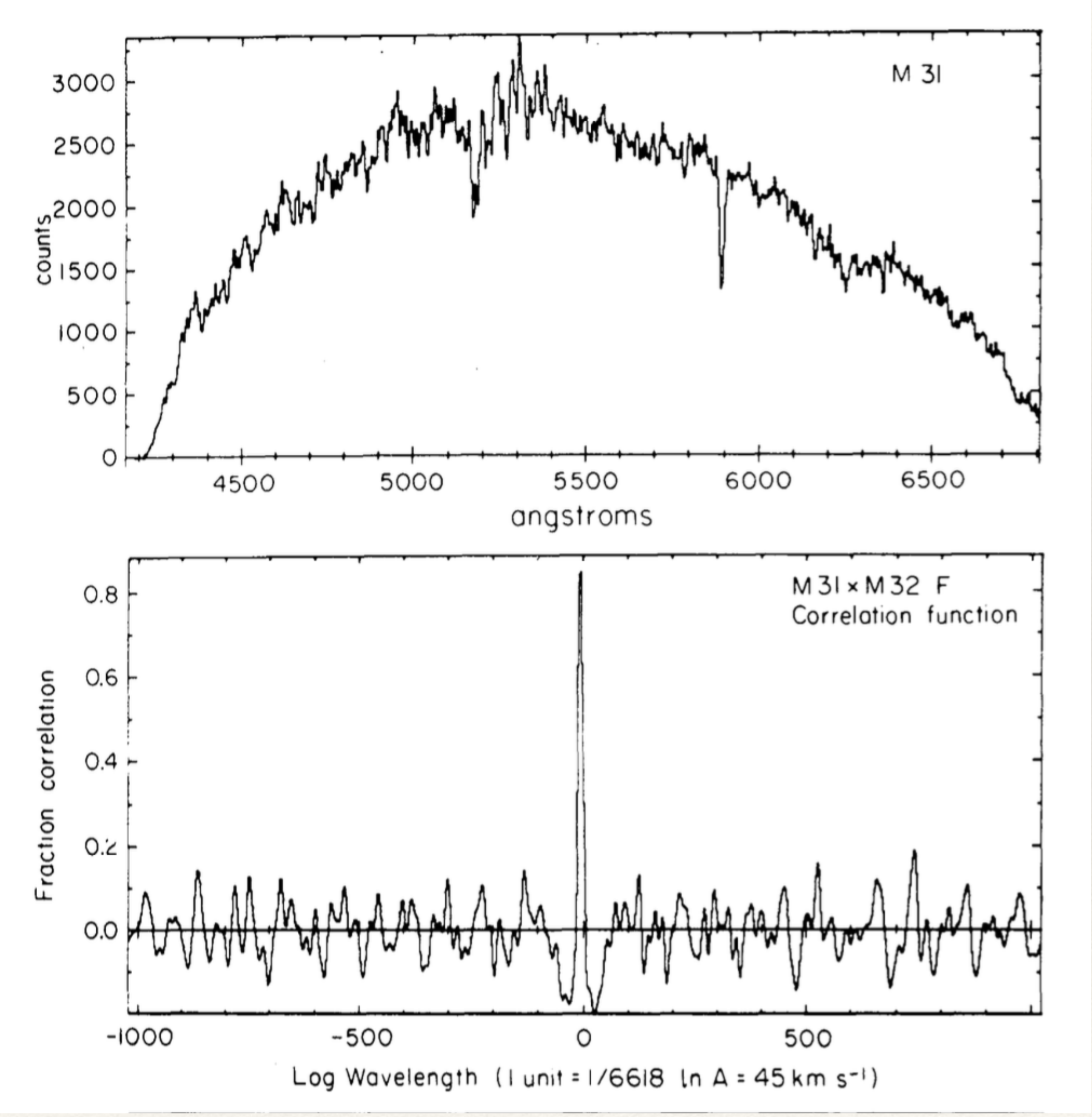
- Determining **spectroscopic redshifts** for distant (faint) galaxies:
  - Use measured wavelengths of individual lines
  - Requires good S/N, so observationally time consuming
  - Emission line galaxies are easier!



$$\frac{\Delta\lambda}{\lambda} = z,\ 1 + z = \lambda_{obs}/\lambda_{emit}$$

Distances: Getting Redshifts

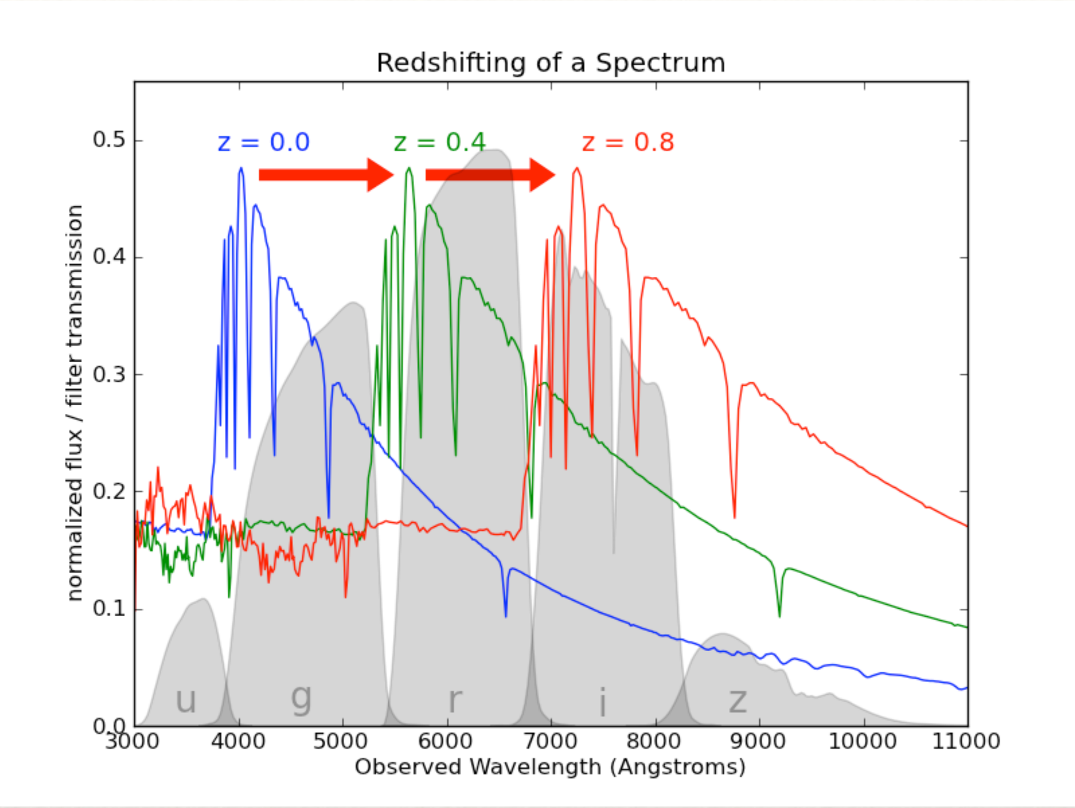
- Determining **spectroscopic redshifts** for distant (faint) galaxies:
  - Use combined effect of multiple (weaker) spectral features
  - Cross-correlate spectrum against a template spectrum in log λ space
  - Can get good redshifts from lower S/N observations



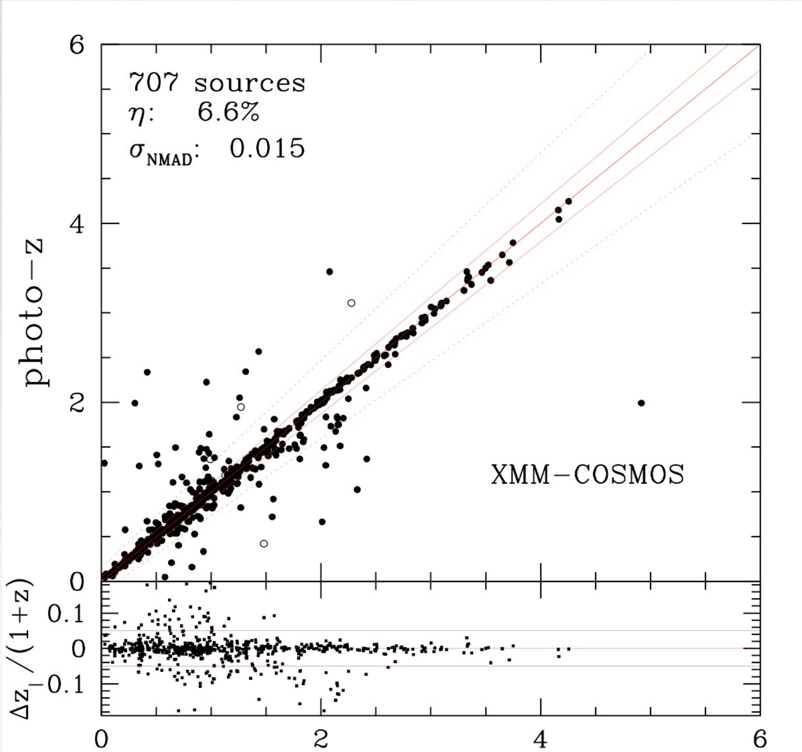
Tonry & Davis 1979

Distances: Getting Redshifts

- Lower accuracy distances are possible from **photometric redshifts:**
  - Use multiband photometry as low resolution spectra and fit with spectral templates
  - How good are photo-zs?:
    - $\Delta z/(1+z) \sim 0.1$
    - ~10% outlier fraction (depends on galaxy type)
    - it all depends on quality of photometry, number of bandpasses, and fidelity of templates



http://ogrisel.github.io/scikit-learn.org/sklearn-tutorial/tutorial/astronomy/



Salvato et al. 2011