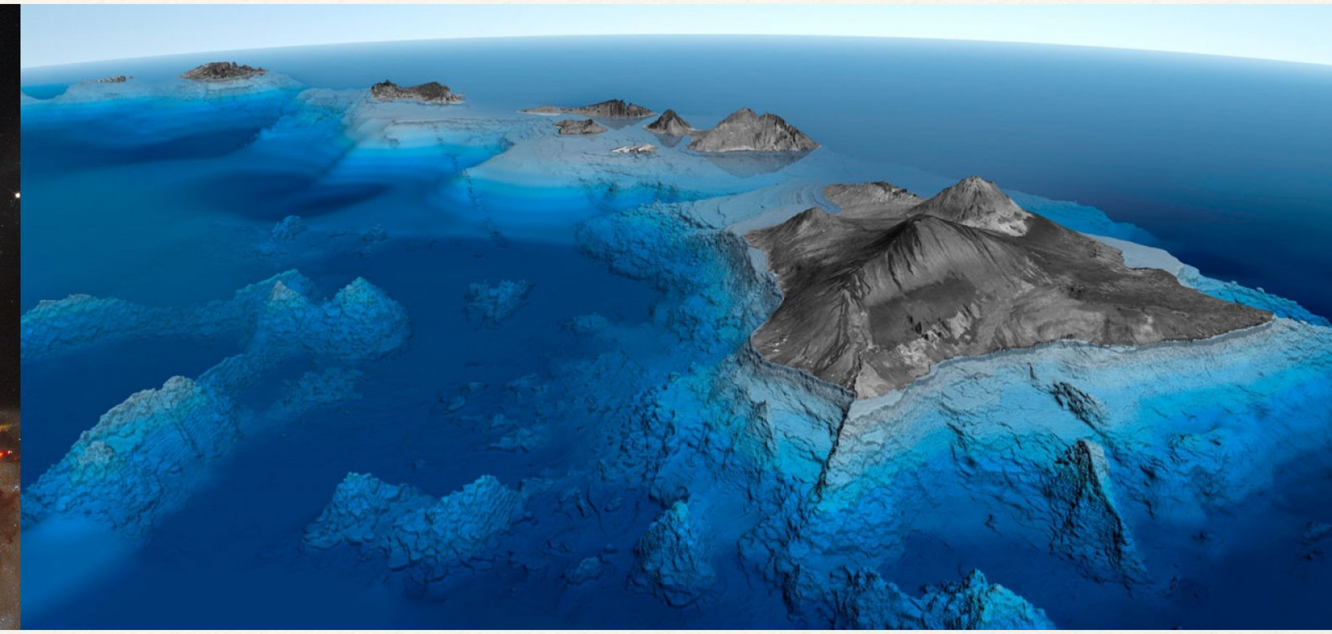


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

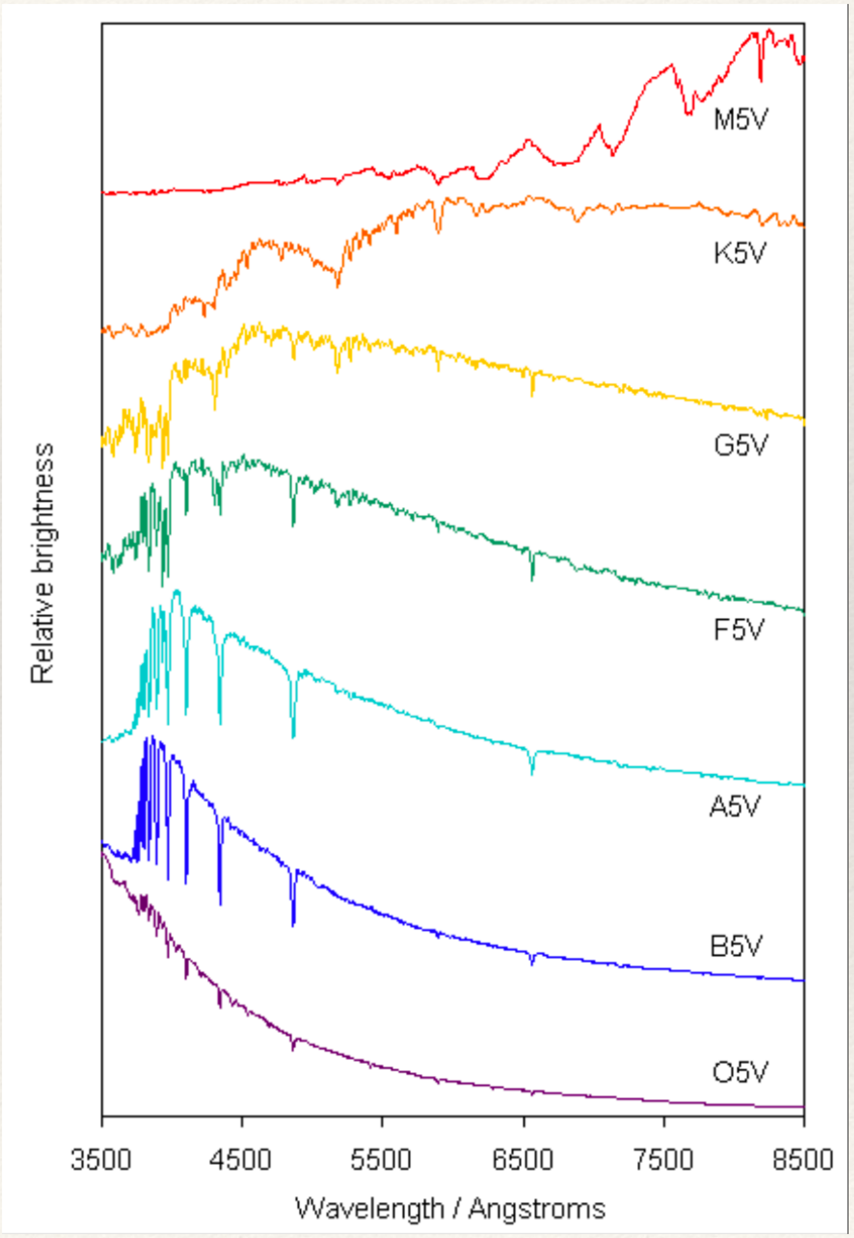
Outline for Today

- Observing Galaxies - Spectroscopy:
  - Composite Spectra
  - Internal Velocities

NGC1232 (ESO)

Spectroscopy: Composite Spectra (stars)

- Galaxy spectra include contributions from:
  - **stars (multiple types!)**
    - what properties of a stellar atmosphere determine what its spectrum will look like?



Main sequence:
Low Mass

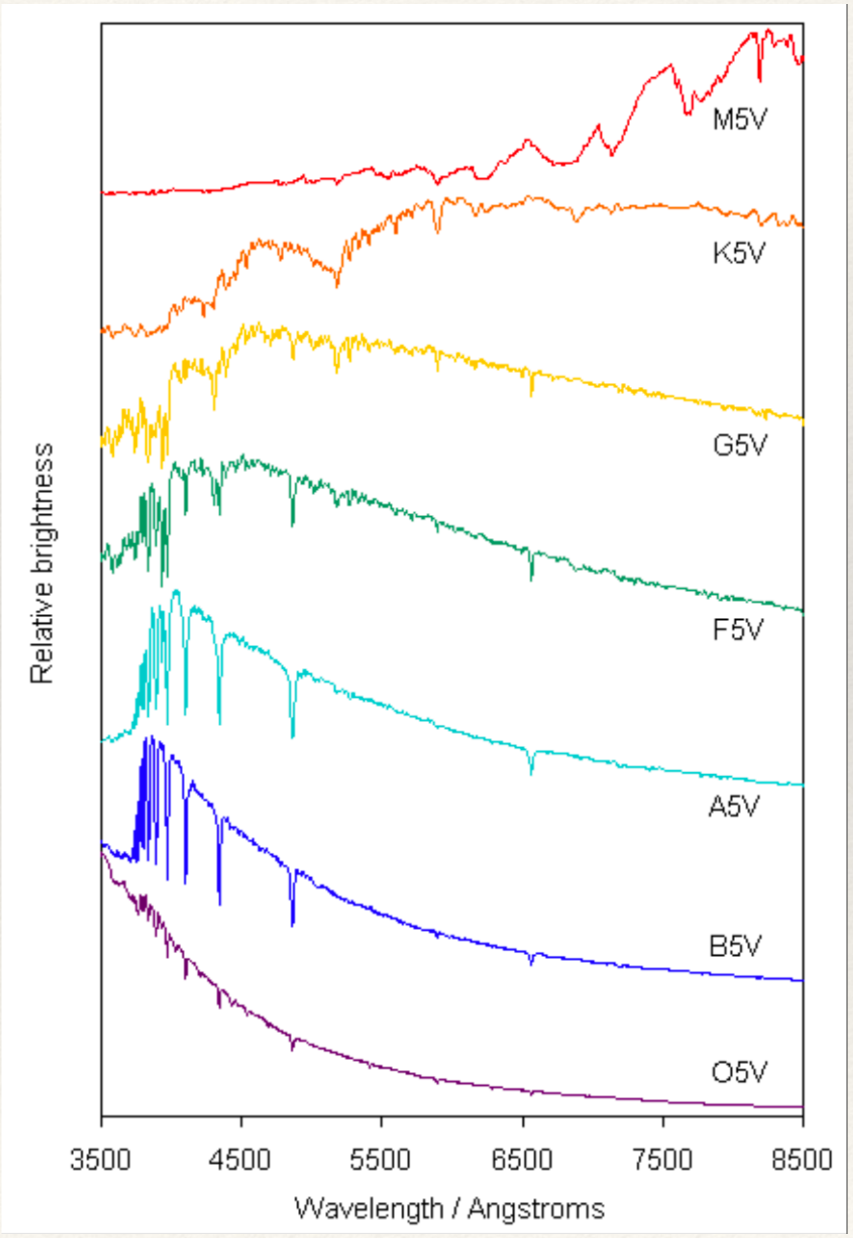
(~Solar Mass)

High Mass

https://www2.mpia-hd.mpg.de/homes/rix/sed.pdf

Spectroscopy: Composite Spectra (stars)

- Galaxy spectra include contributions from:
  - **stars**
    - what properties of a stellar atmosphere determine what its spectrum will look like?
      - Effective temperature
      - surface gravity
      - chemical composition
      - rotation, magnetic fields
    - remember evolved stars (giants!)



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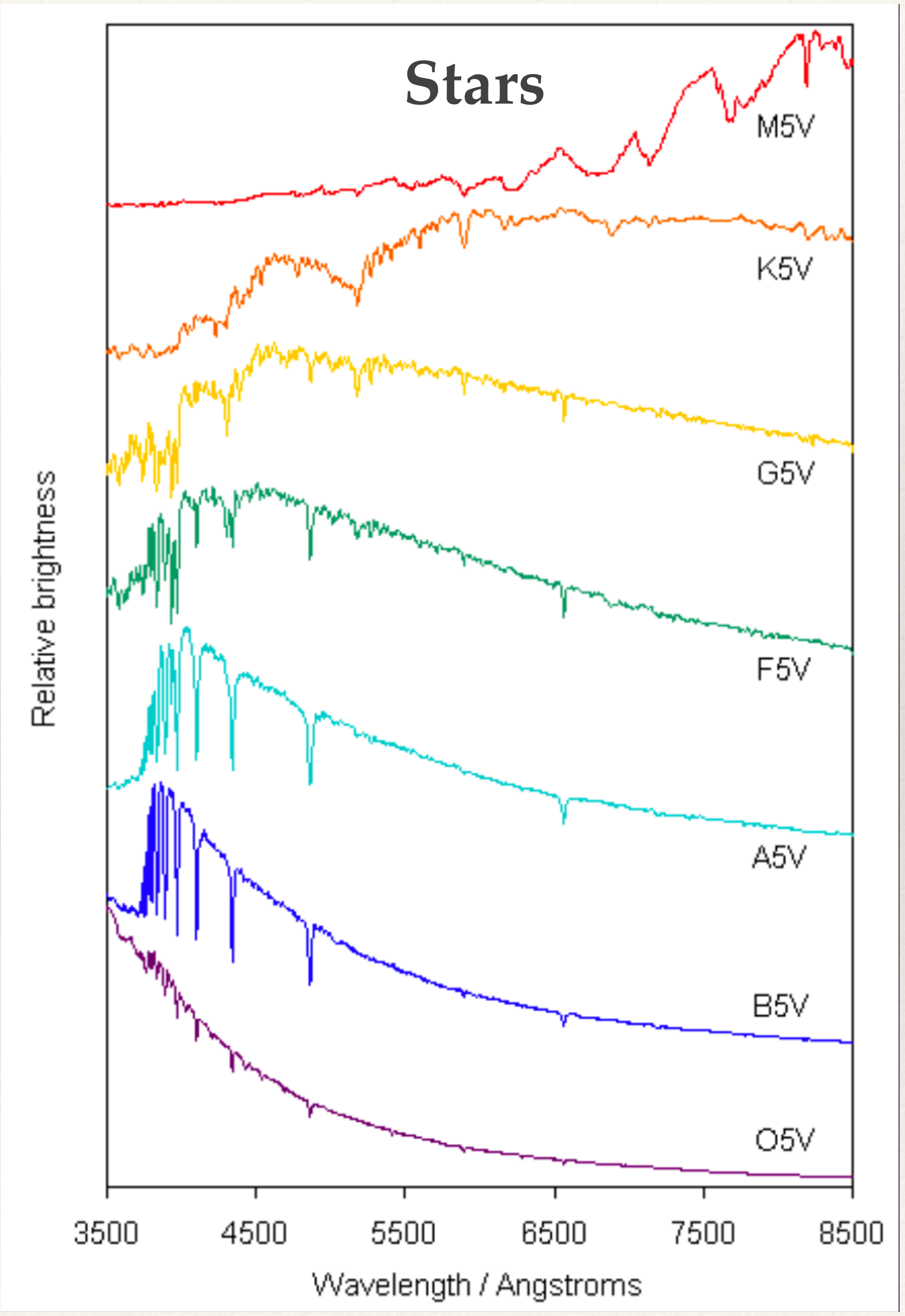
Thought Question

- Consider a galaxy composed of many such stars.
  - Which type of star will be more numerous?
  - Which type of star will be more luminous?
- Will your answers above depend on when the stars in the galaxy were formed?
  - Sketch the optical spectrum for a galaxy with recent star formation vs a galaxy with only older stars



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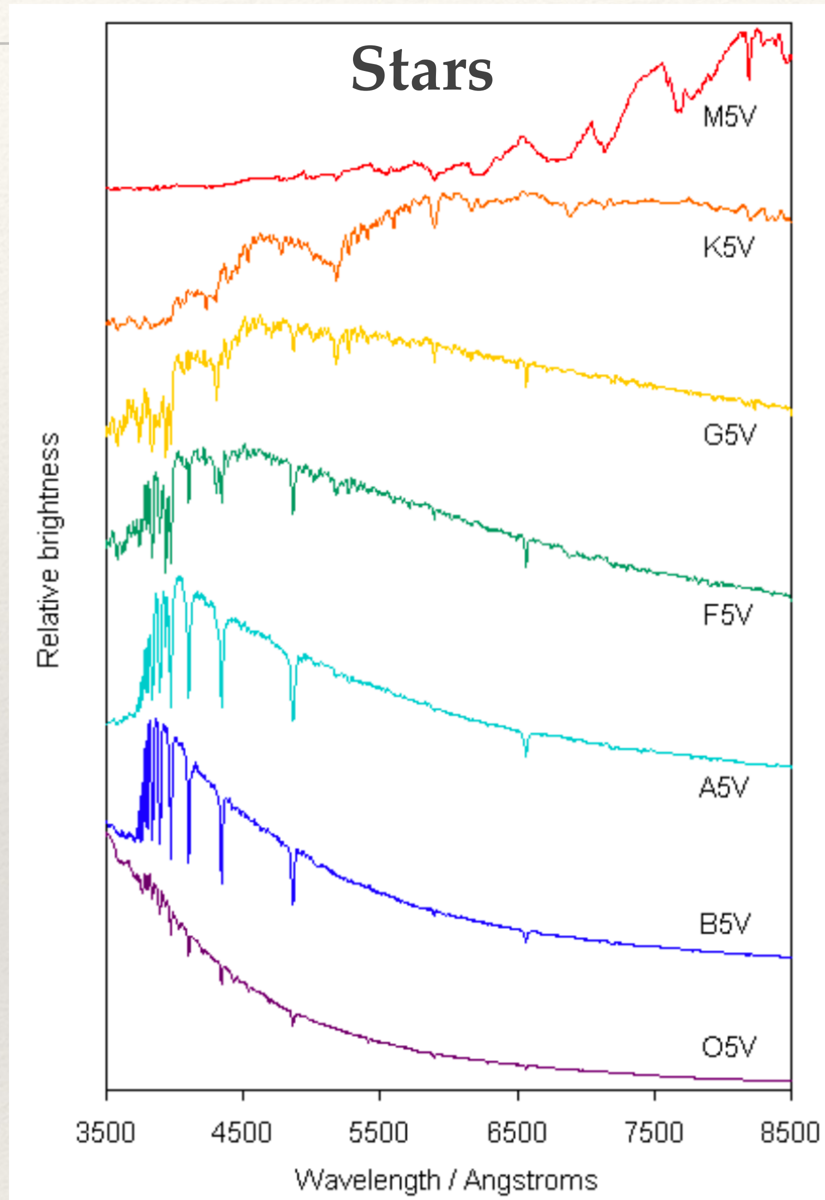

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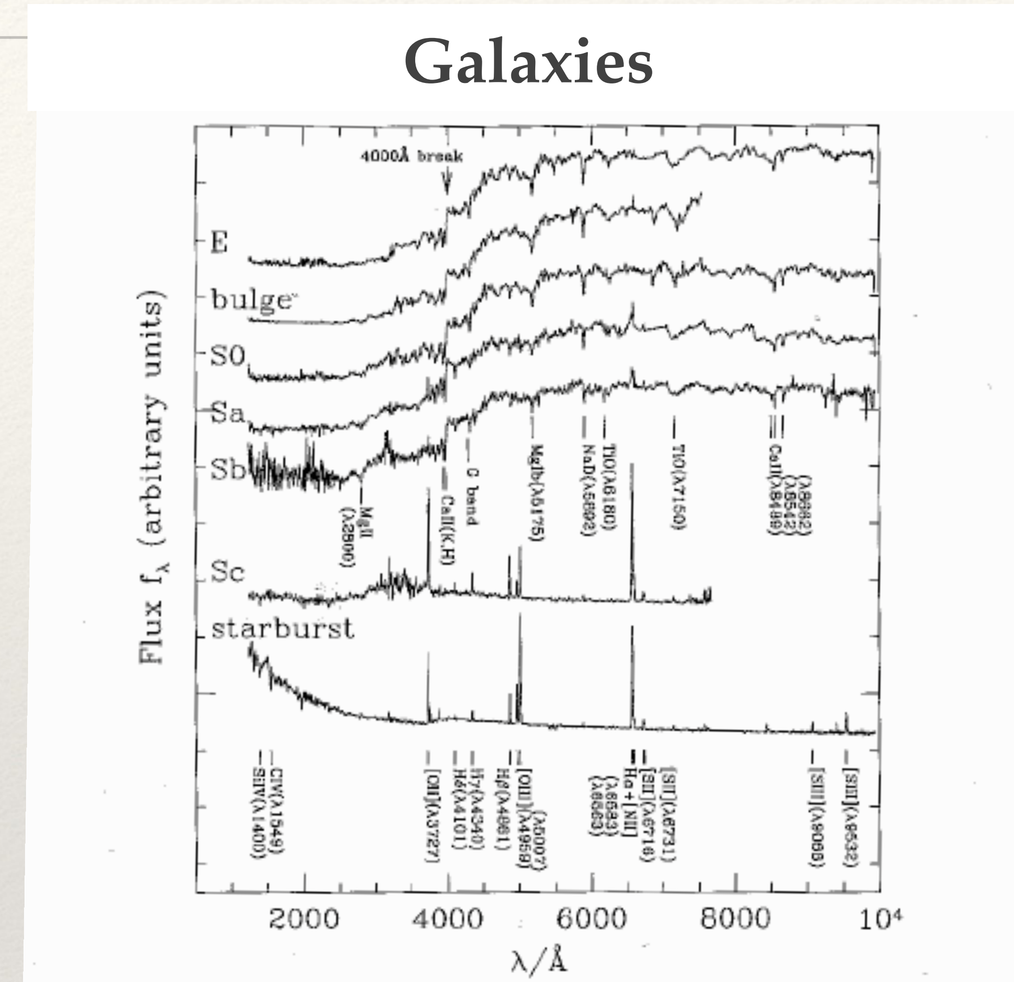
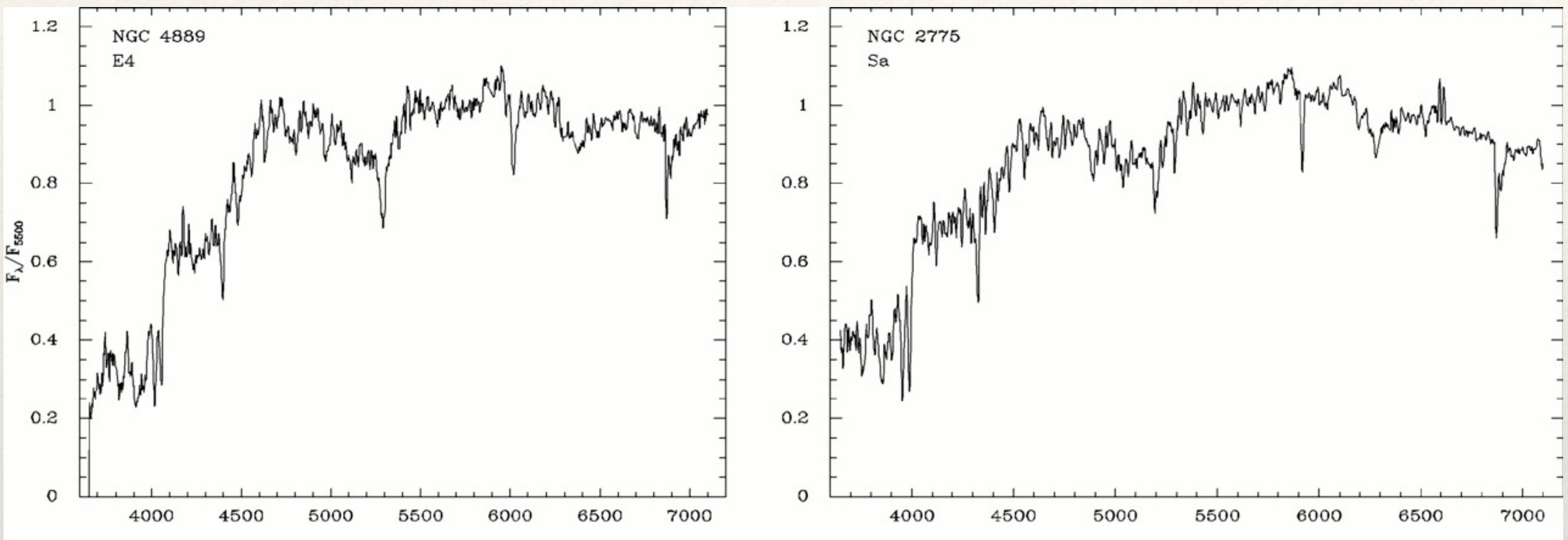


Fig. 2.12. Spectra of different types of galaxies from the ultraviolet to the near-infrared. From ellipticals to late-type spirals, the blue continuum and emission lines become systematically stronger. For early-type galaxies, which lack hot, young stars, most of the light emerges at the longest wavelengths, where one sees absorption lines characteristic of cool K stars. In the blue, the spectrum of early-type galaxies show strong H and K absorption lines of calcium and the G band, characteristic of solar type stars. Such galaxies emit little light at wavelengths shorter than 4000 Å and have no emission lines. In contrast, late-type galaxies and starbursts emit most of their light in the blue and near-ultraviolet. This light is produced by hot young stars, which also heat and ionize the interstellar medium giving rise to strong emission lines. [Based on data kindly provided by S. Charlot]

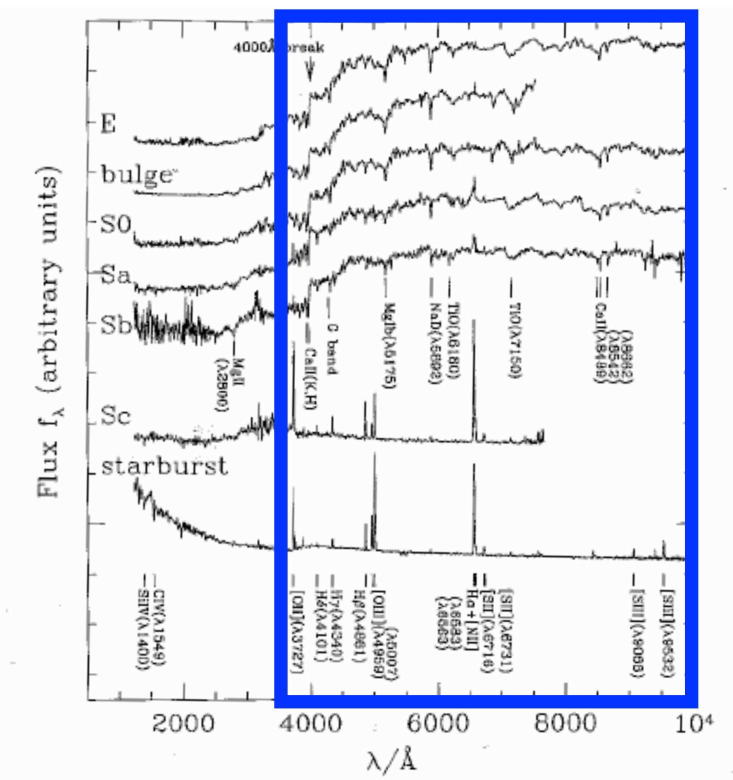
- Galaxy spectra contain a luminosity-weighted combination of stellar spectra

Spectroscopy: Composite Spectra (stars)



Kennicutt 1992

Galaxies



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- Galaxy spectra contain a luminosity-weighted combination of stellar spectra

Spectroscopy: Composite Spectra (gas)

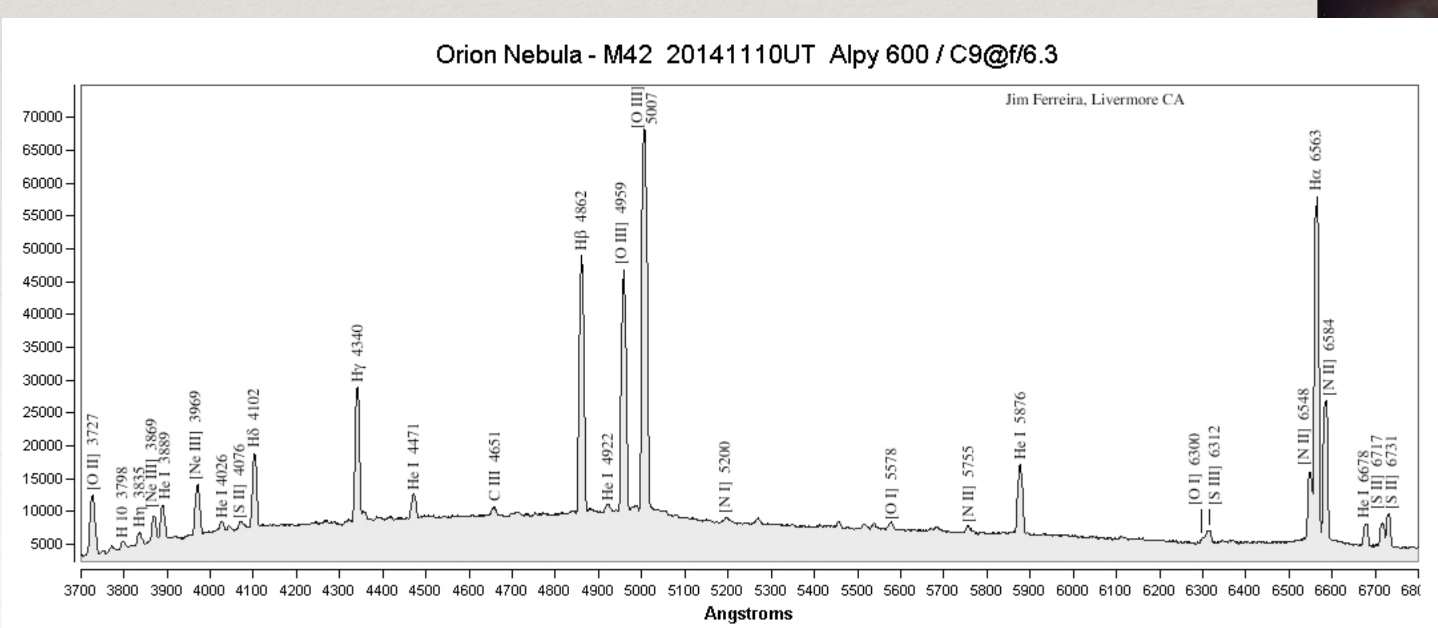
- Galaxy spectra include contributions from:
  - stars
    - luminosity weighted (for each type of star, number of stars times luminosity per star), absorption lines
  - **gas**

Thought Question

- What happens when energetic photons from stars hit a nearby cloud of gas?
- What effect will this have on the spectrum of a galaxy?
    - Add to your sketch.
- What sort of stars (and what sort of galaxy) will produce more energetic photons?

Spectroscopy: Composite Spectra

- Ionizing photons from young, hot stars are absorbed by surrounding gas
    - what energy photon is required to ionize hydrogen, and what wavelength does that correspond to?
- Recombination cascade leads to H emission lines
- Collisions lead to other emission lines (many forbidden lines)
- More prominent in galaxies with recent star formation



https:

https://apod.nasa.gov/apod/ap101023.html

Spectroscopy: Composite Spectra (gas)

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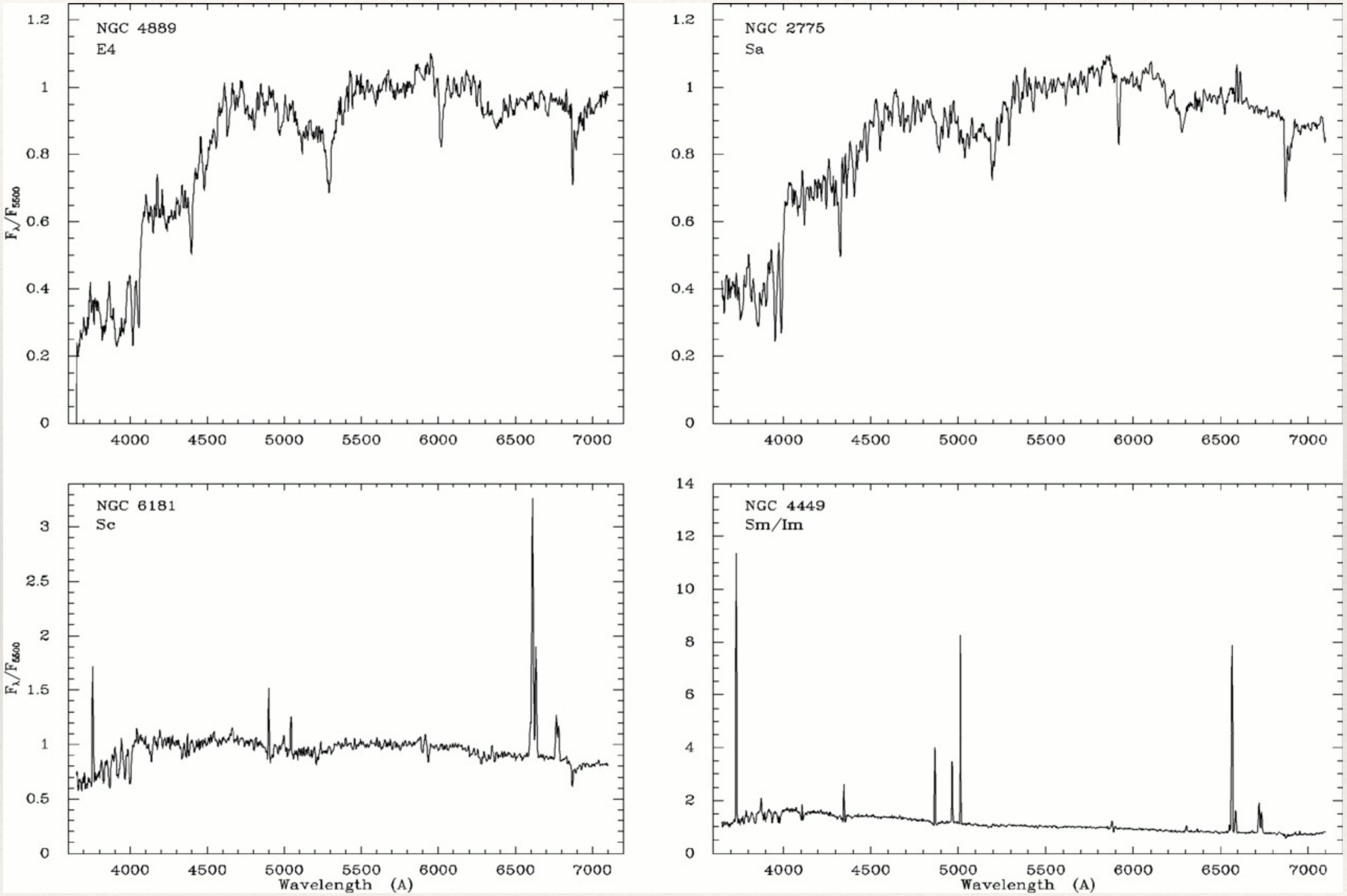


Kennicutt 1992

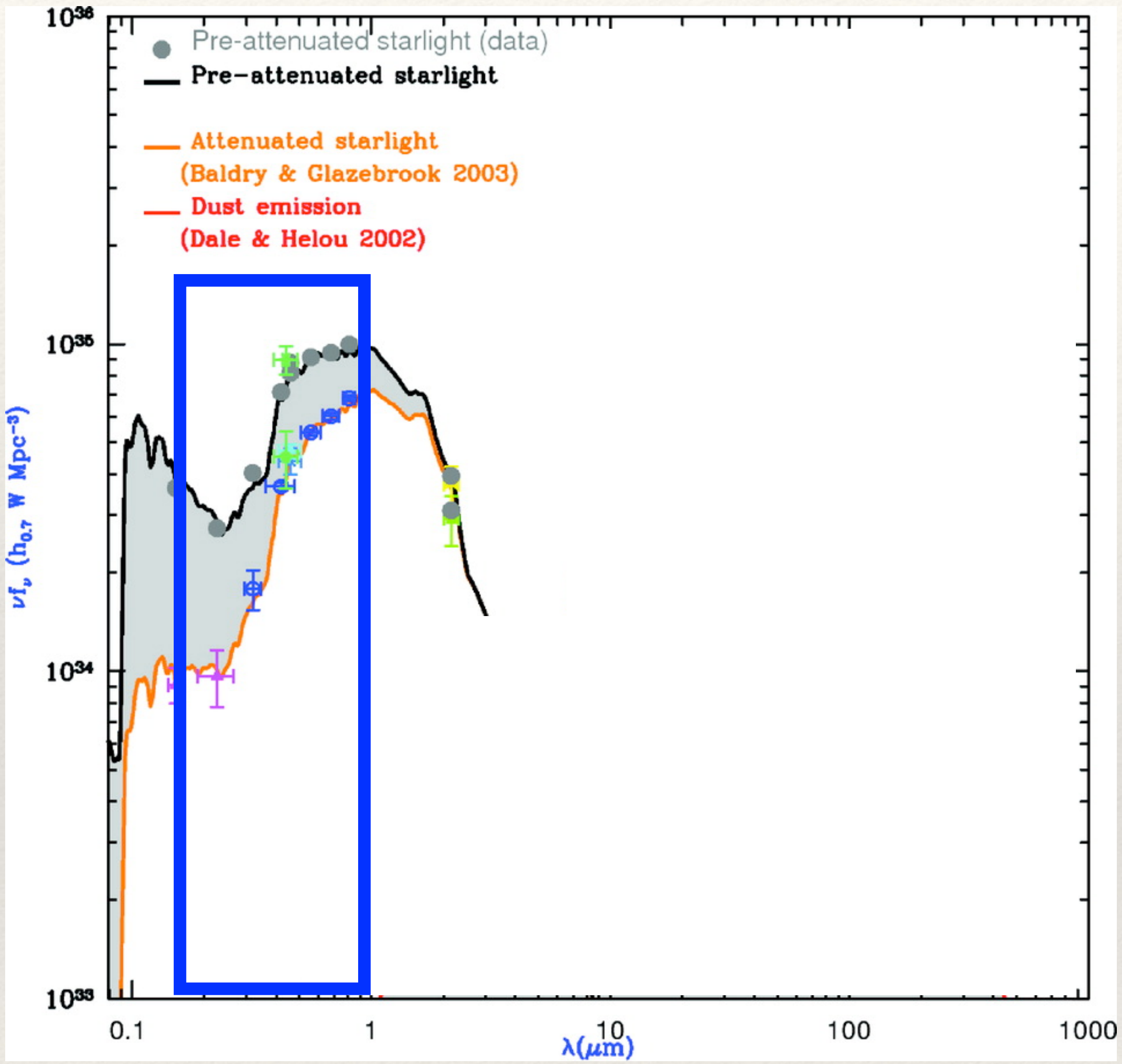
Spectroscopy: Composite Spectra (dust)

- Galaxy spectra include contributions from:
  - stars
    - luminosity weighted (for each type of star, number of stars times luminosity per star), absorption lines
  - gas
    - emission lines of H, O, N, S, He, C, Ne,…
  - **dust**

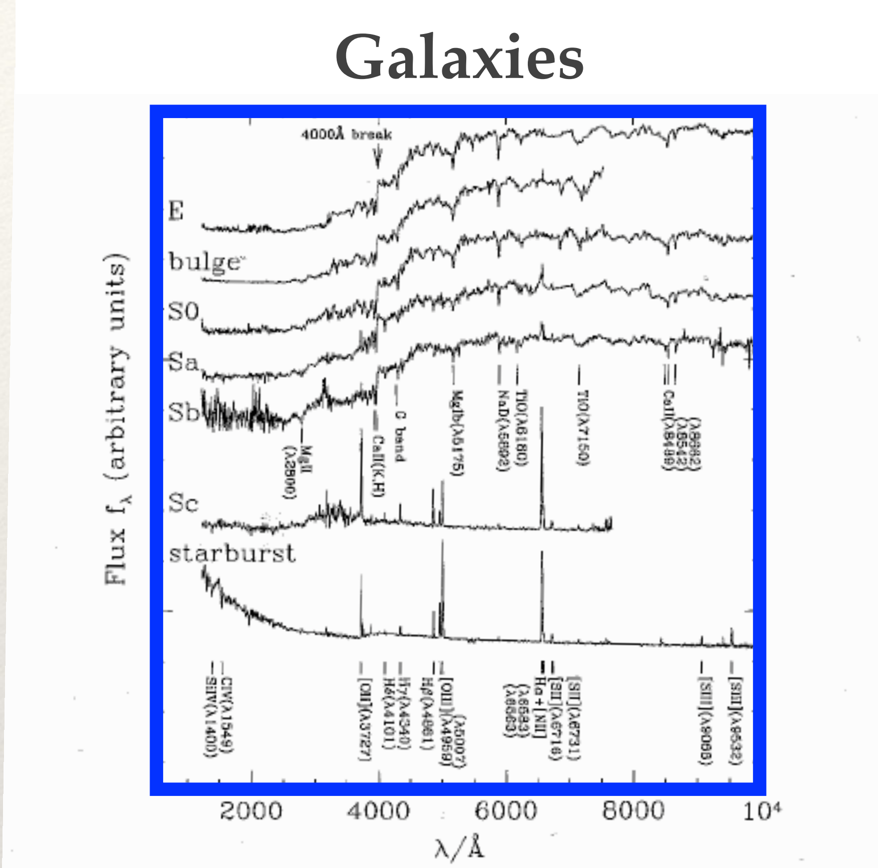
Thought Question

- What happens to photons when they hit dust grains?
- What happens to dust grains when they get hit by photons?
- What effect will this have on the spectrum of a galaxy?
    - Add to your sketch.

Spectroscopy: Composite Spectra (dust)



Driver et al. 2008



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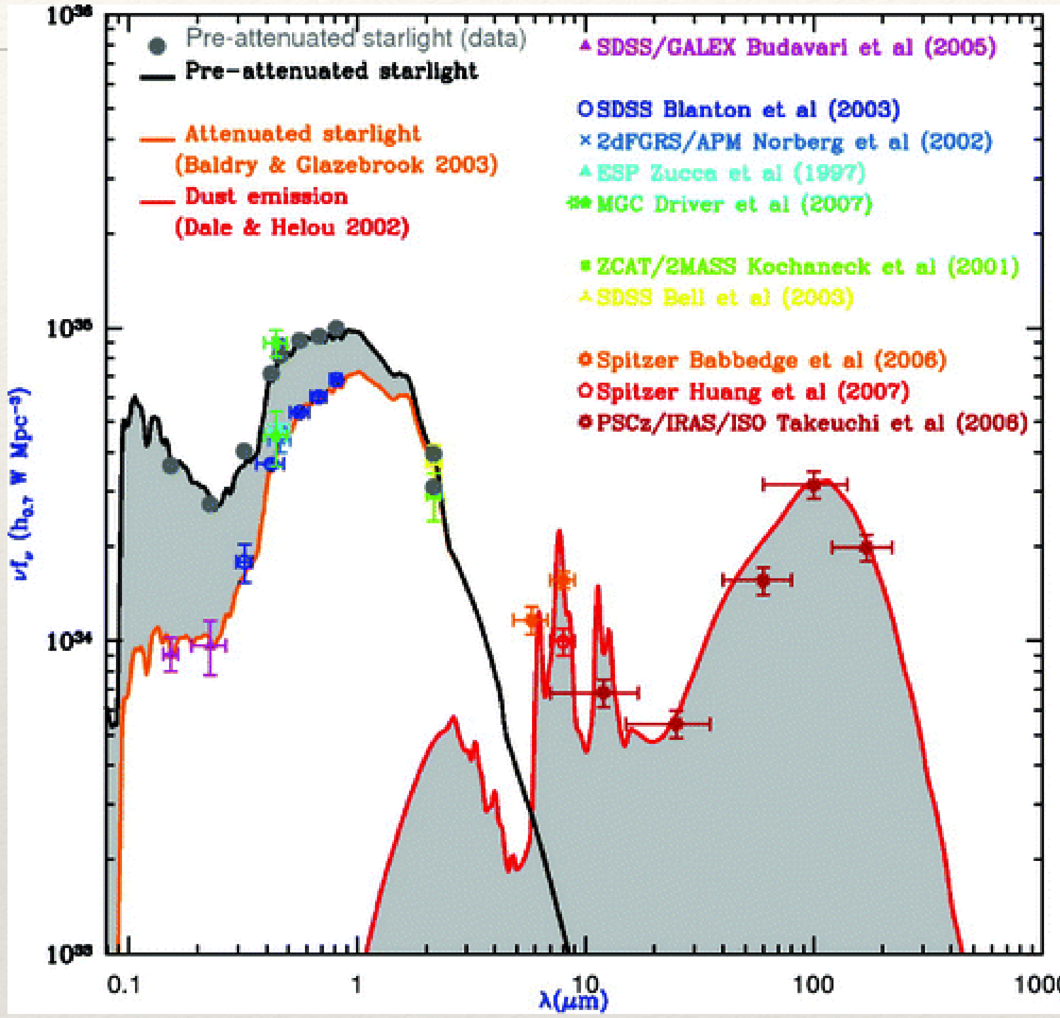
- Ultraviolet and optical photons are absorbed and scattered by dust grains
  - leads to dust attenuation, which is not the same as extinction/reddening, since light can be scattered into beam as well as out

Spectroscopy: Composite Spectra (dust)



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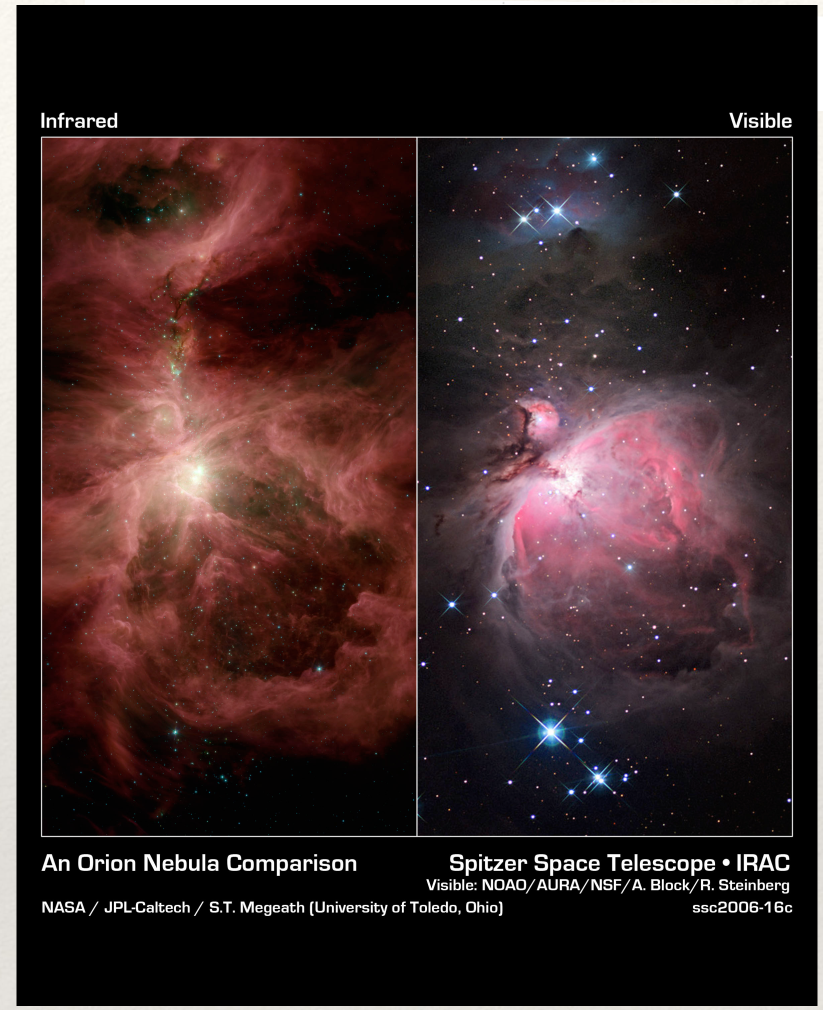


- Ultraviolet and optical photons are absorbed and scattered by dust grains
  - leads to dust *attenuation,* which is not the same as extinction/reddening, since light can be scattered into beam as well as out
- Absorbed energy reradiated in the infrared

Spectroscopy: Composite Spectra (dust)

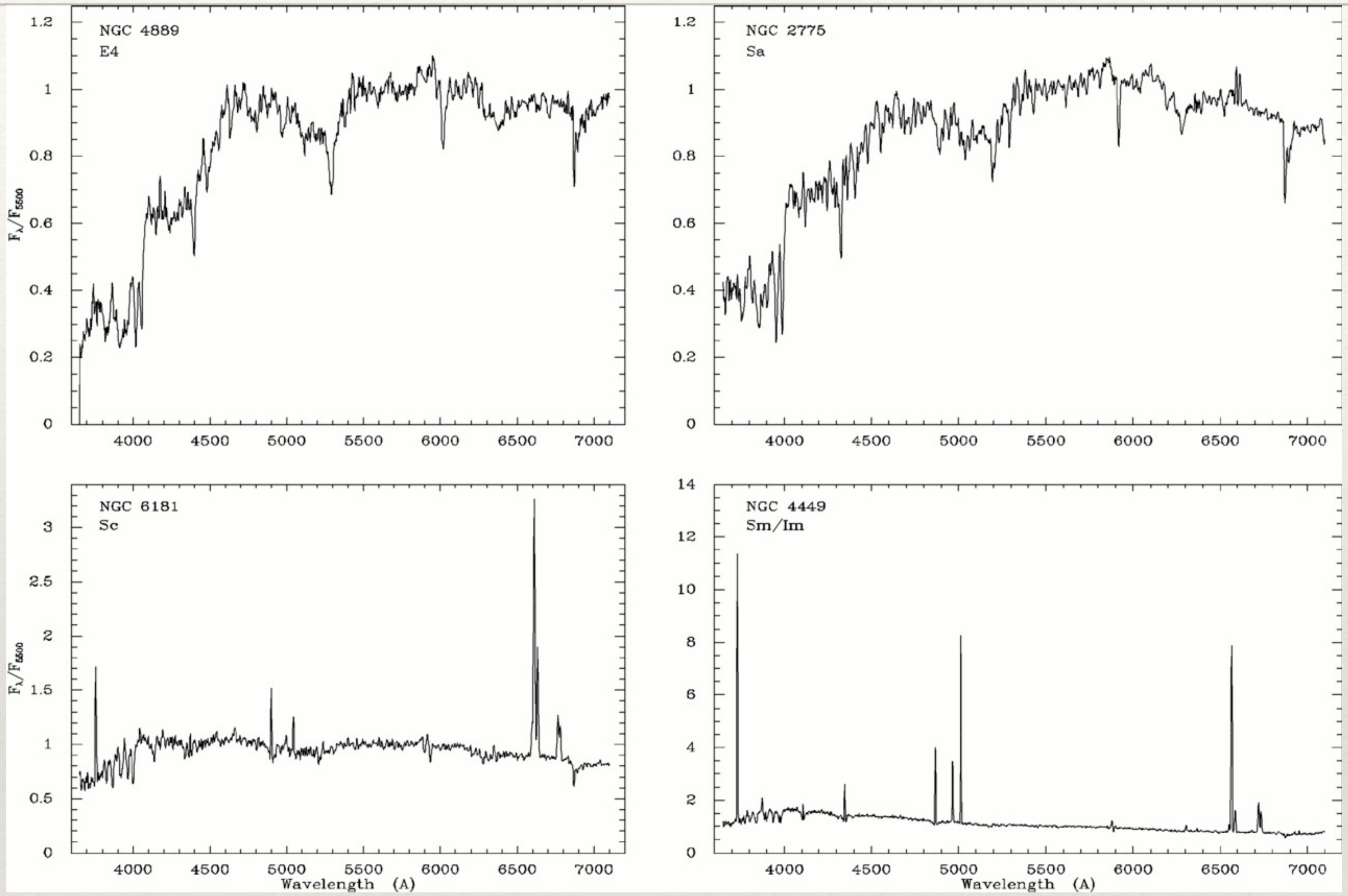
- Galaxy spectra include contributions from:
  - stars
    - luminosity weighted (for each type of star, number of stars times luminosity per star), absorption lines
  - gas
    - emission lines of H, O, N, S, He, C, Ne,…
  - dust
    - attenuation of UV/optical, emission of IR photons
- Star forming galaxies have typical spectra with a peak in optical and peak in mid/far-IR
- Quiescent galaxies don't have the mid/far-IR peak
- Remember that the contributions of different components may vary with location in the galaxy!
  - so can't really talk about "the spectrum" of a galaxy, often this is obtained in some aperture, and is weighted by surface brightness
  - Note integral field spectroscopy!

Spectroscopy

One can learn about the nature of the components (stars, gas, dust) by studying the spectra

What other information can one get from spectra?

Spectroscopy: Velocities



Kennicutt 1992

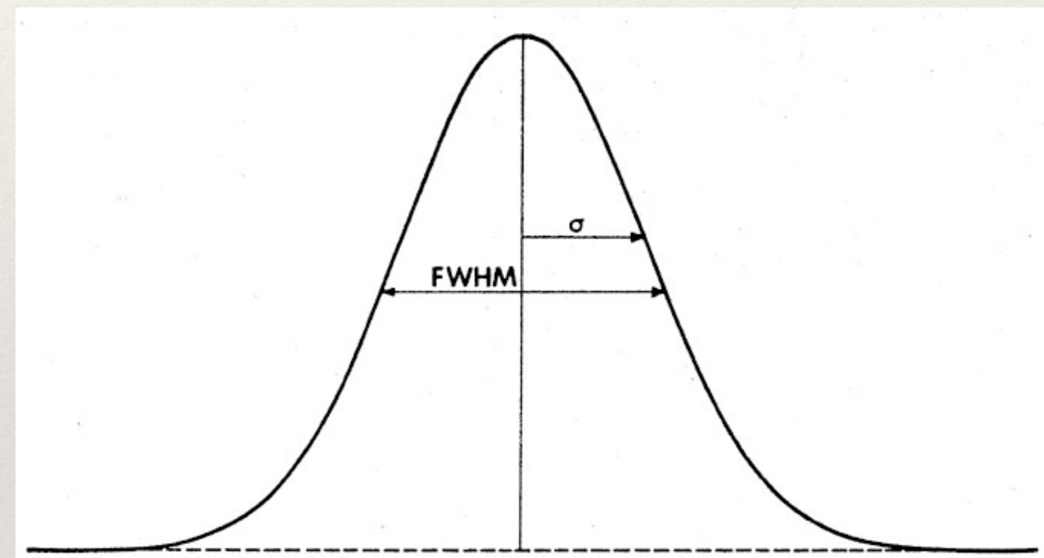
- Spectra allow study of velocities via the Doppler shift ($\Delta\lambda/\lambda = v/c$)
  - distribution of velocities of stars within a galaxy (internal velocities)
  - bulk velocity of galaxy through space (mean galactic velocities)

Spectroscopy: Velocities (internal)

- Galaxy spectral lines contain contributions from multiple stars at multiple velocities:

$$I(\lambda) \propto \int dv_{los} F(v_{los}) S(\lambda - \frac{v_{los}\lambda}{c})$$

  - $F(v_{los})$ = line-of-sight velocity distribution (LOSVD) of stars
  - v_{los} = velocity along the line of sight
  - S = spectrum of an individual star



ned.ipac.caltech.edu

- Galaxy LOSVD and spectral lines usually *fairly* well represented by a Gaussian with:
  - the **mean velocity** v and
  - the **velocity dispersion** $\underline{\sigma}$ (or FWHM)
    FWHM = 2.354 σ

$$\bar{v} = \int dv_{los} v_{los} F(v_{los})$$

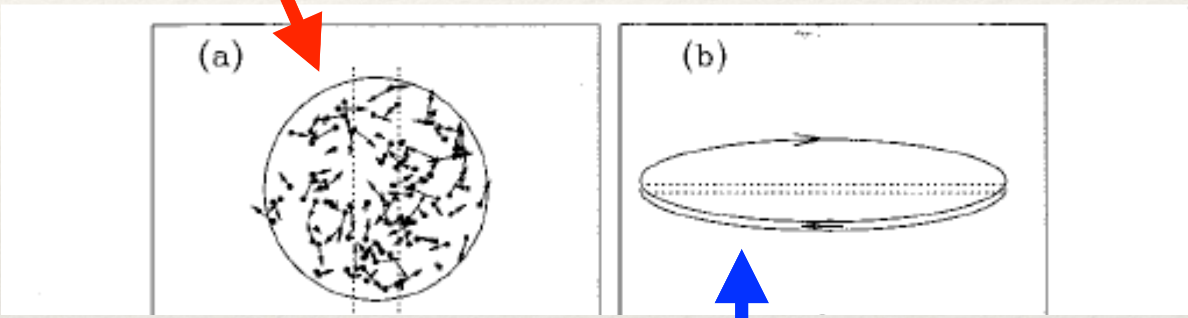
$$\sigma^2 = \int dv_{los} (v_{los} - \bar{v}_{los})^2 F(v_{los})$$

- higher order term can and do exist!

Spectroscopy: Internal Velocities

- **Internal velocities:**
  - can be "random"
  - can be "ordered", e.g. rotation
  - Caveats:
    - inclination needed to derive intrinsic rotation velocity using $v_{los} = v \sin(i)$.
    - real galaxies have some of both "ordered" and "random" motion

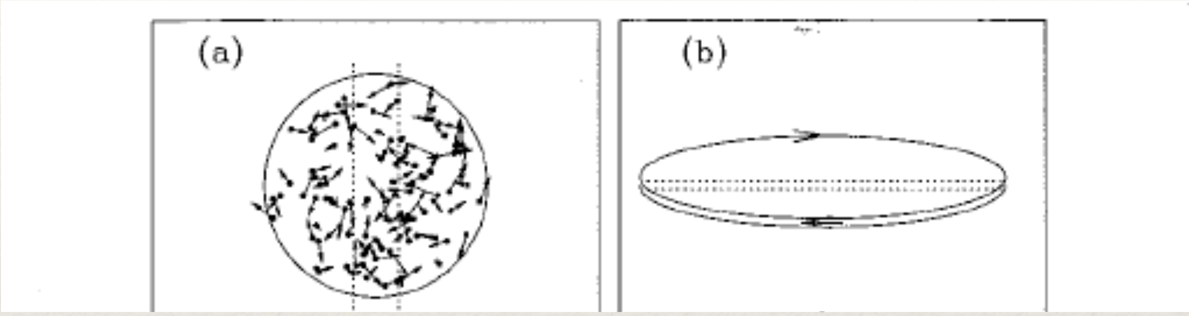
("kinematically hot" or "dispersion supported")



("kinematically cold" or "rotation supported")

Thought Question

- Suppose the internal velocities in one galaxy are dominated by rotation and in another they are characterized by random motions:
  - What effects will this have on the spectra?
  - How would you tell the difference observationally?



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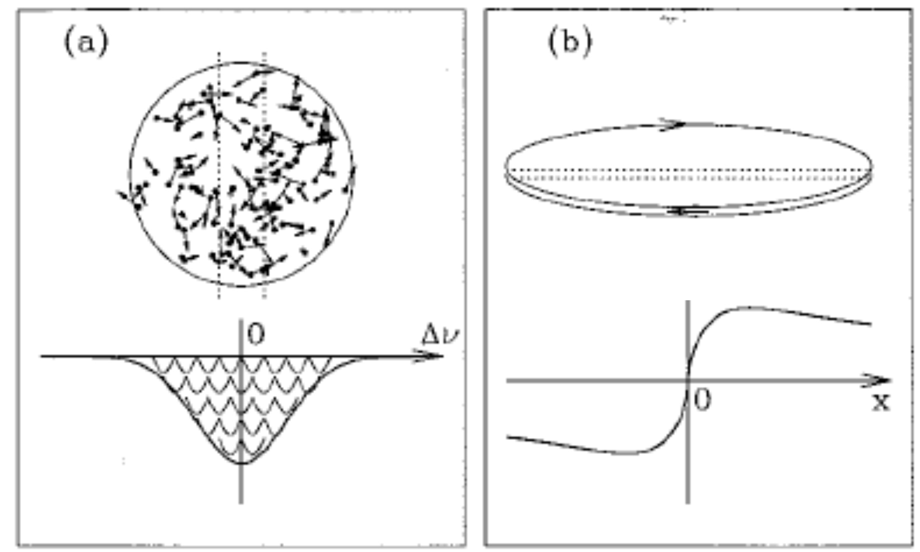
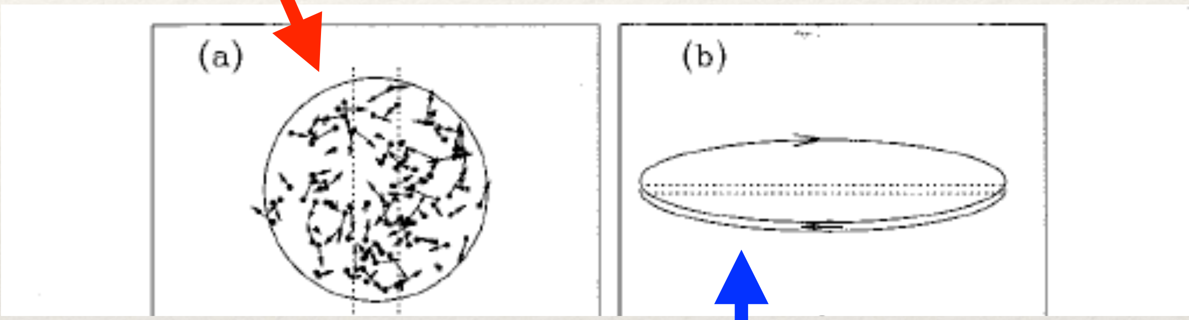


Fig. 2.4. (a) An illustration of the broadening of a spectral line by the velocity dispersion of stars in a stellar system. A telescope collects light from all stars within a cylinder through the stellar system. Each star contributes a narrow spectral line with rest frequency ν_{12}, which is Doppler shifted to a different frequency $\nu = \nu_{12} + \Delta\nu$ due to its motion along the line-of-sight. The superposition of many such line profiles produces a broadened line, with the profile given by the convolution of the original stellar spectral line and the velocity distribution of the stars in the cylinder. (b) An illustration of long-slit spectroscopy of a thin rotating disk along the major axis of the image. In the plot, the rotation speed is assumed to depend on the distance from the center as $V_{\rm rot}(x) \propto \sqrt{x/(1+x^2)}$.

Spectroscopy: Internal Velocities

- **Internal velocities:**
  - spiral galaxies are typically rotationally dominated, i.e., kinematically cold, but not entirely so!
    - e.g., Milky Way has rotation at the Solar radius about 220 km/s, with velocity dispersion tens of km/s, depending on the population
  - elliptical galaxies are kinematically hotter, but some also have some rotation

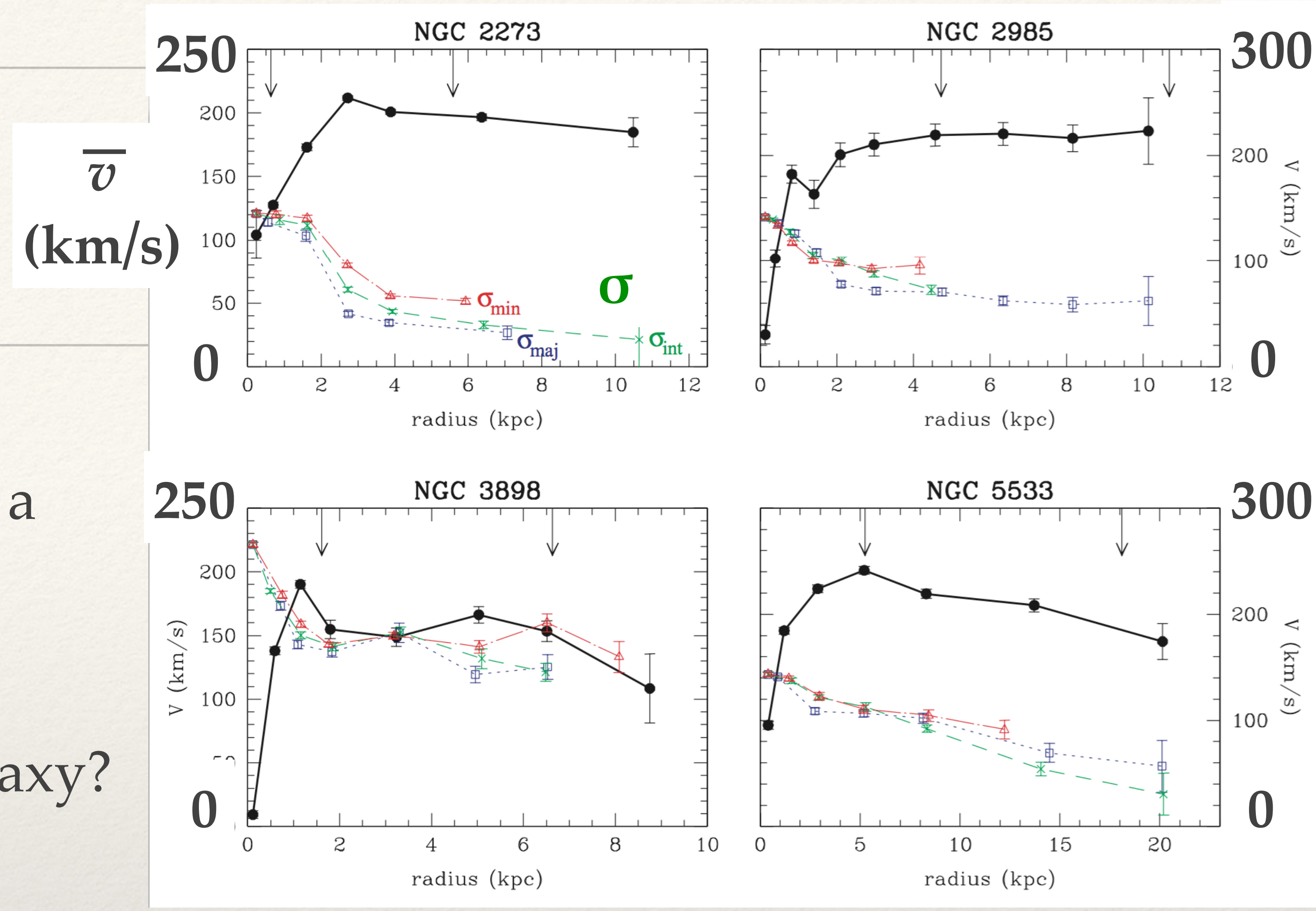
("kinematically hot" or "dispersion supported")



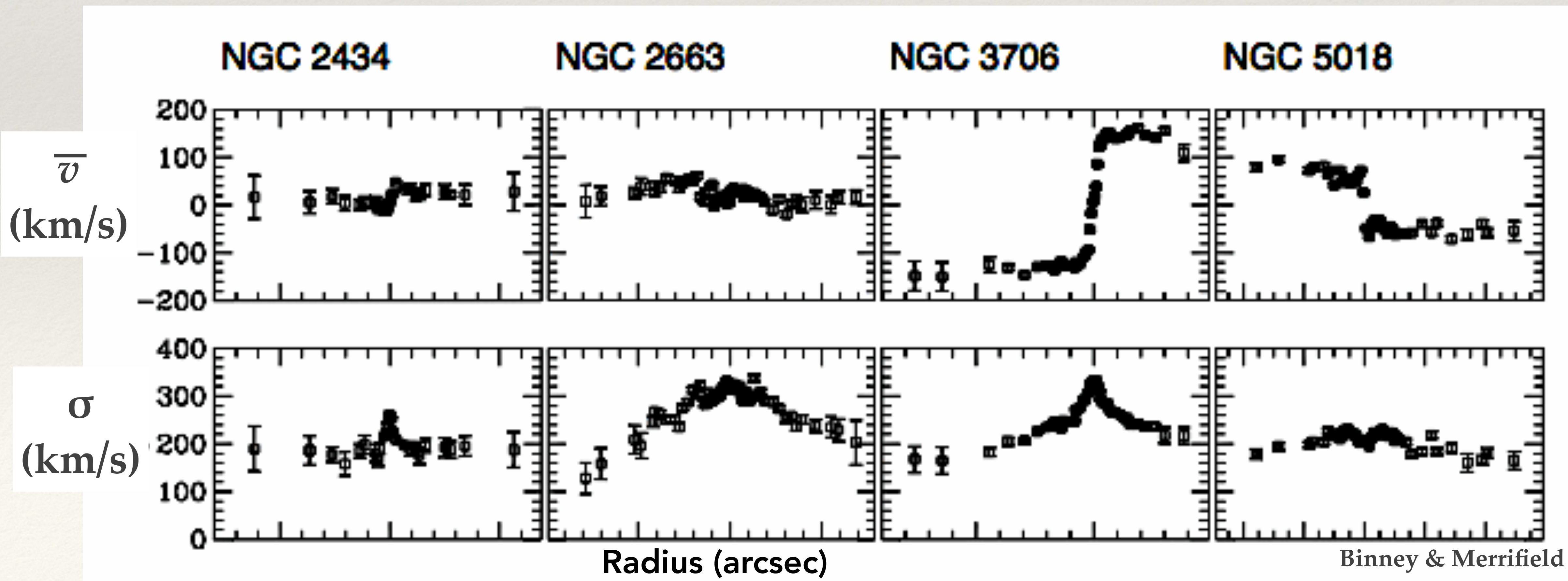
("kinematically cold" or "rotation supported")

Examples

- Here are the **mean velocity** $\overline{v}$ and **velocity dispersion σ** profiles for a bunch of galaxies.
- How do the maximum $\overline{v}$ and **σ** compare to each other in each galaxy?
- What kinds of galaxies are they?



Noordermeer et al. 2008



Binney & Merrifield

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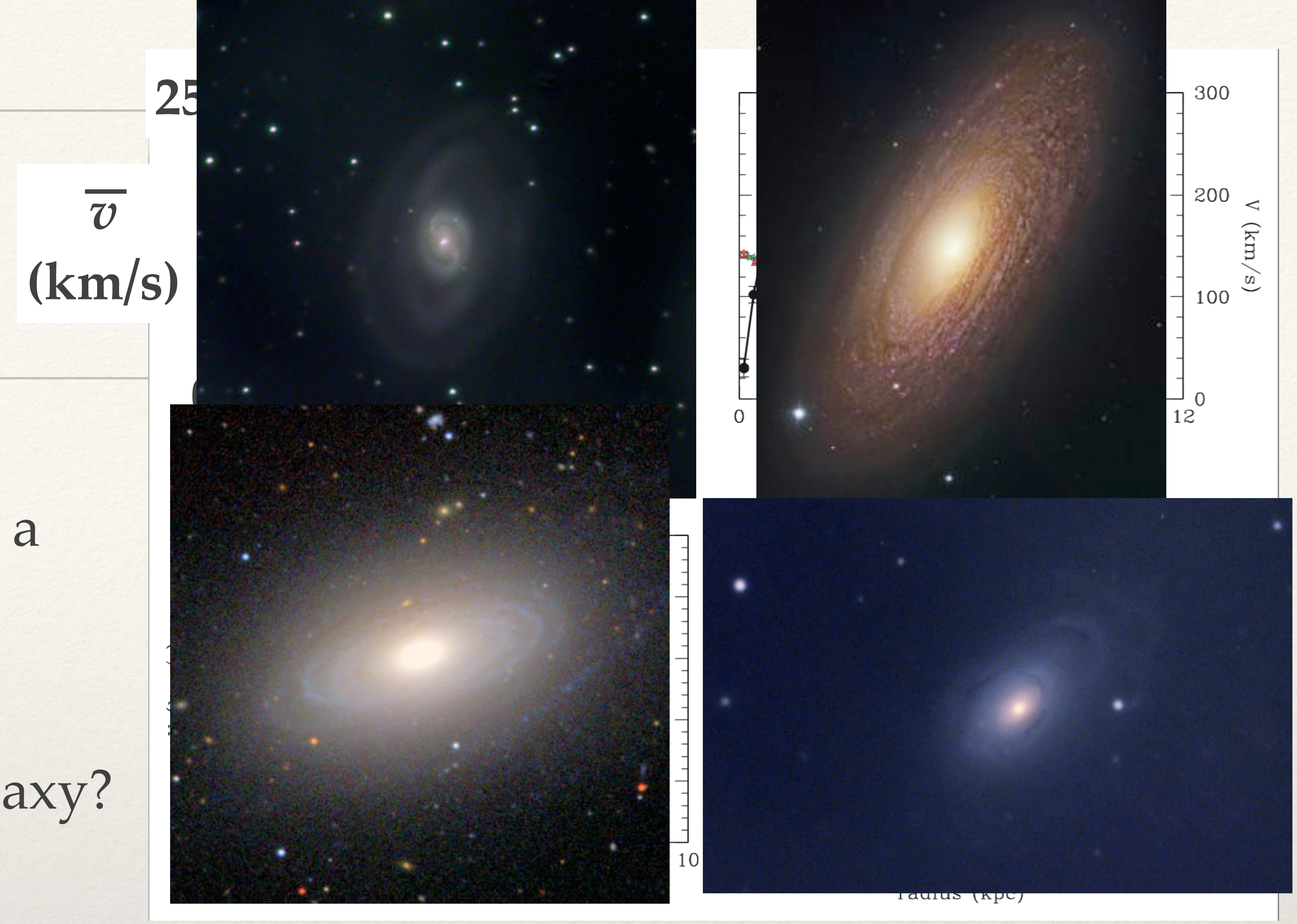

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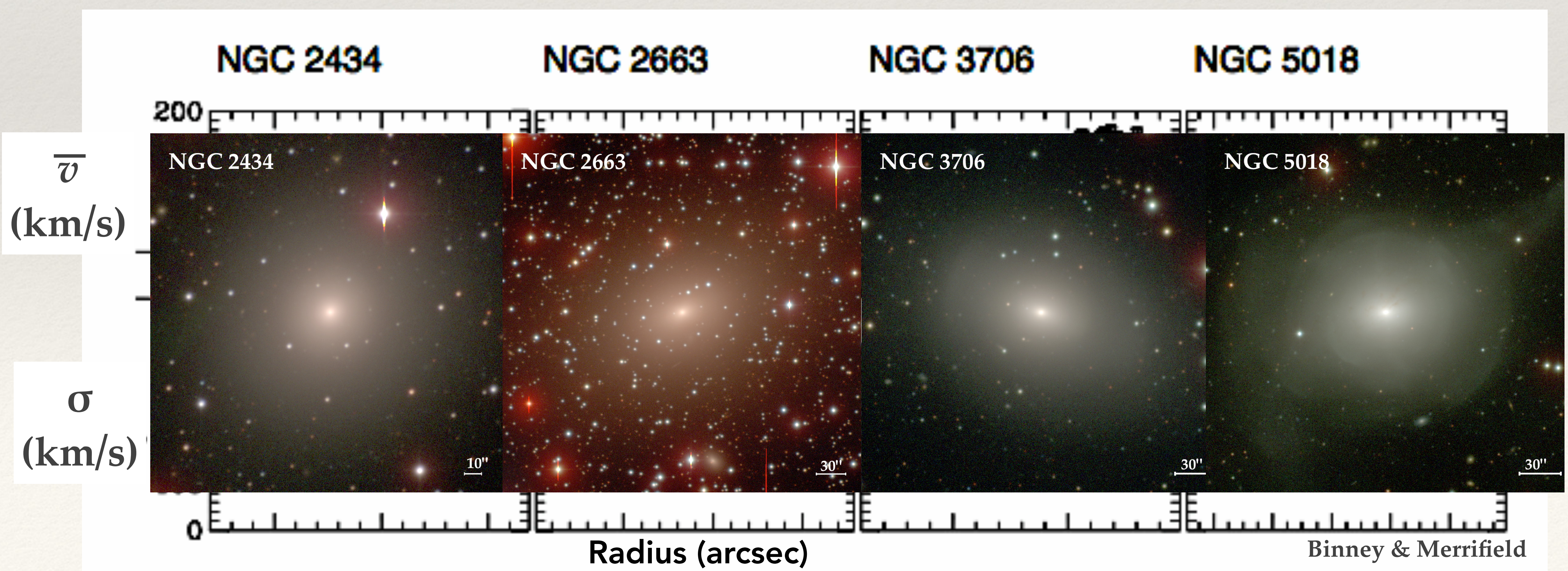
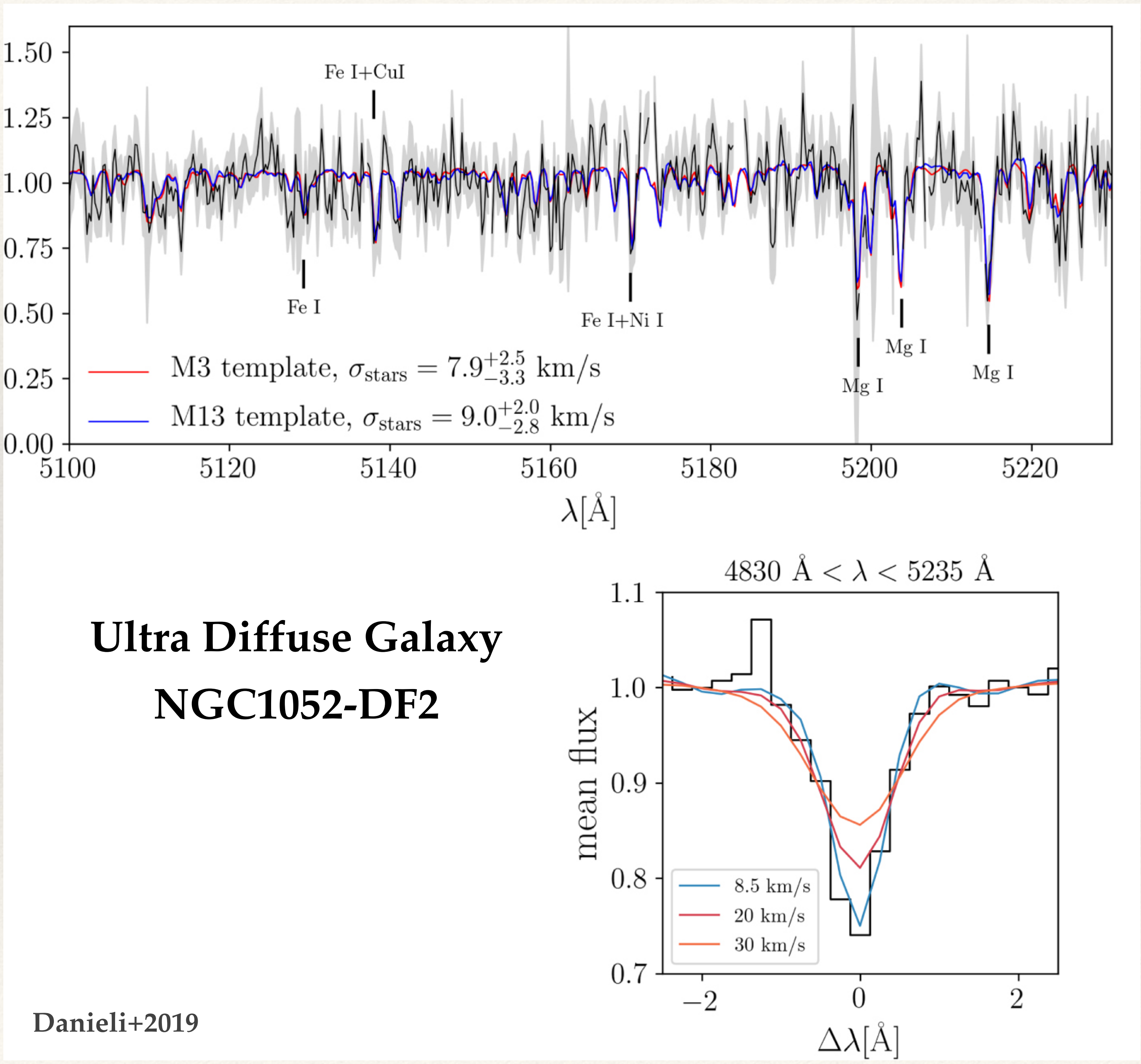


Binney & Merrifield

Spectroscopy: Internal Velocities

- To extract information about velocity distribution need:
  - Template for the underlying spectrum
  - Instrumental broadening, i.e., the line spread function (LSF)
  - Determine velocity dispersion needed to match template to observed data, subtracting instrumental width in quadrature (assuming Gaussians), or, better, by forward modeling
- More sophisticated techniques exist, e.g. penalized pixel fitting (pPXF - Cappellari 2017)



Ultra Diffuse Galaxy NGC1052-DF2

Danieli+2019

Spectroscopy

What are the observational requirements for measuring velocities in galaxies?

For measuring a mean velocity, it's generally not too hard to measure the position of a line to 1/10th of a pixel, so desired accuracy leads to a requirement on the dispersion

- the accuracy also depends on the S/N and resolution
- if you have many lines, that can substitute for lower S/N

For measuring a velocity dispersion, note that the total line width will be a quadrature sum of the velocity dispersion and the instrumental broadening profile (the LSF)

- LSF often characterized as a Gaussian and width can depend on slit width and/or seeing
- generally, might measure a line width to 10% accuracy, so might be able to measure the velocity dispersion of a galaxy to 50% of the instrumental resolution

$$FWHM = \Delta\lambda$$

$$R = \frac{\lambda}{\Delta\lambda}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Observing Galaxies - Spectroscopy

What are the observational requirements for measuring velocities in galaxies?

At APO, the KOSMOS spectrograph has a maximum resolution around R=2600. What is the smallest velocity dispersion you might expect to measure?

The dispersion is about 1 Angstrom/pixel. How accurate of a velocity might you measure around the H alpha line?

$$FWHM = \Delta\lambda$$

$$R = \frac{\Delta\lambda}{\lambda}$$

$$\frac{\lambda}{\Delta\lambda} = \frac{v}{c}$$

Spectroscopy: Internal Velocities --> Masses!

- Assuming gravity is driving the motion, internal velocities tell us about the mass distribution within galaxies!
  - For of kinematically "cold" (rotationally supported) system:

$$\frac{v(r)^2}{r} = \frac{G\,M(<r)}{r^2}$$

so

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

  - For kinematically "hot" systems:
    - Mass modeling requires using the **Jeans equation** and knowing the **velocity ellipsoid** — the velocity dispersion in radial, azimuthal, and vertical directions (often unknown!)
      - β = the velocity anisotropy:

$$\beta(r) \equiv \left(1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}\right)$$