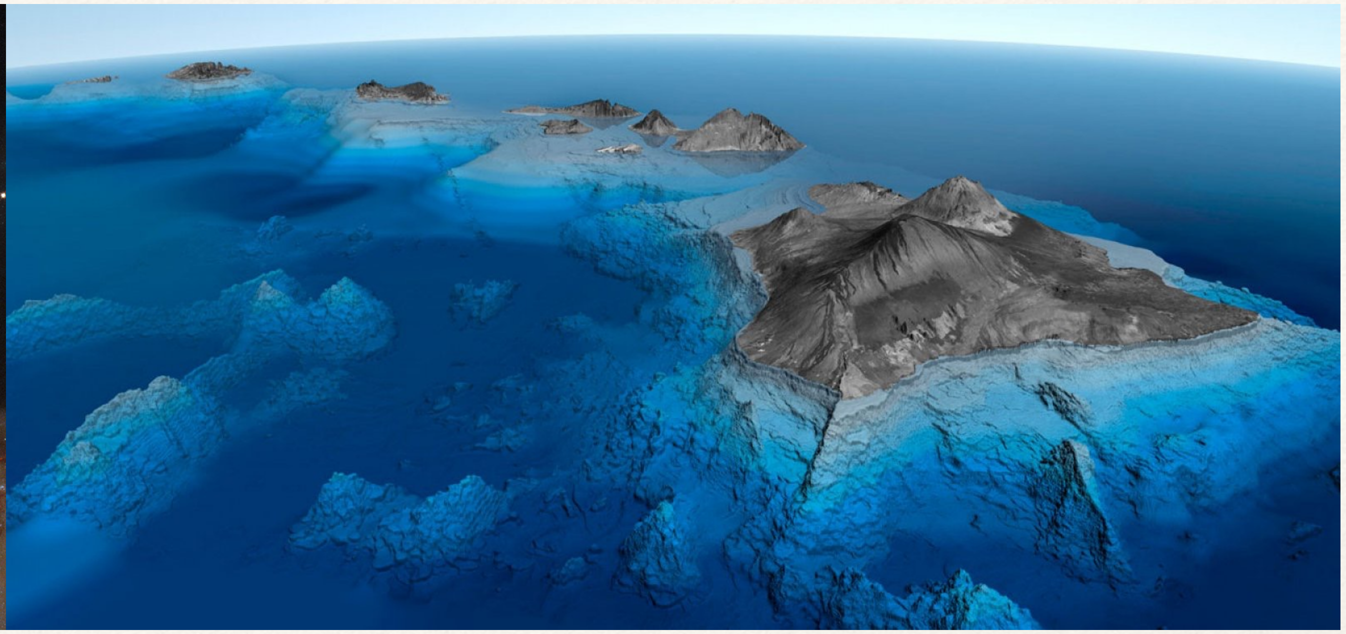


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Review

- Why would we expect elliptical galaxies to sit on a "fundamental plane"?
- Derive the rough scaling of luminosity with velocity dispersion using the same line of reasoning
    - does this scaling correspond to any observed relation?

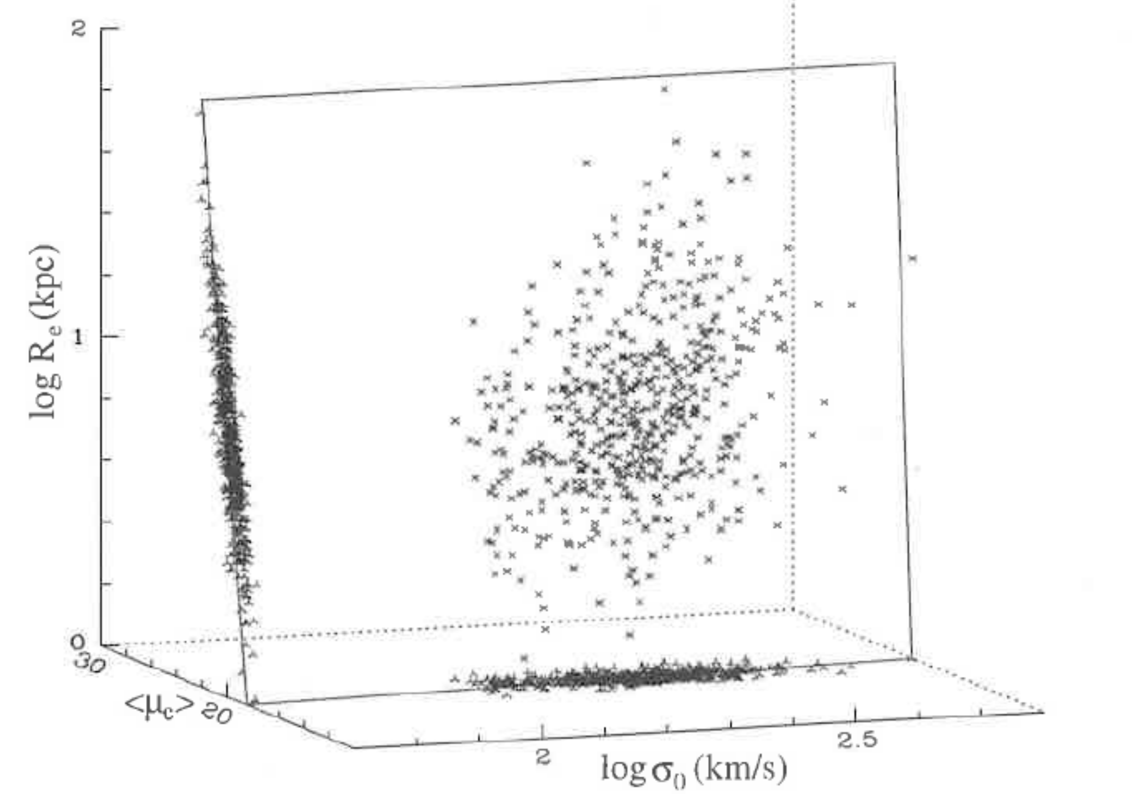


Fig. 2.18. The fundamental plane of elliptical galaxies in the $\log R_e$-$\log \sigma_0$-$\langle\mu\rangle_e$ space (σ_0 is the central velocity dispersion, and $\langle\mu\rangle_e$ is the mean surface brightness within R_e expressed in magnitudes per square arcsecond). [Plot kindly provided by R. Saglia, based on data published in Saglia et al. (1997) and Wegner et al. (1999)]

Mo, van den Bosch, & White; Fig 2.18

$$R_e = G k_R k_V k_L (\frac{M}{L})^{-1} \sigma_0^2 I_e^{-1}$$

$$L = k_L I_e R_e^2$$

$$L \propto (\frac{M}{L})^{-1} \sigma_0^4 I_e^{-1}$$

ick (

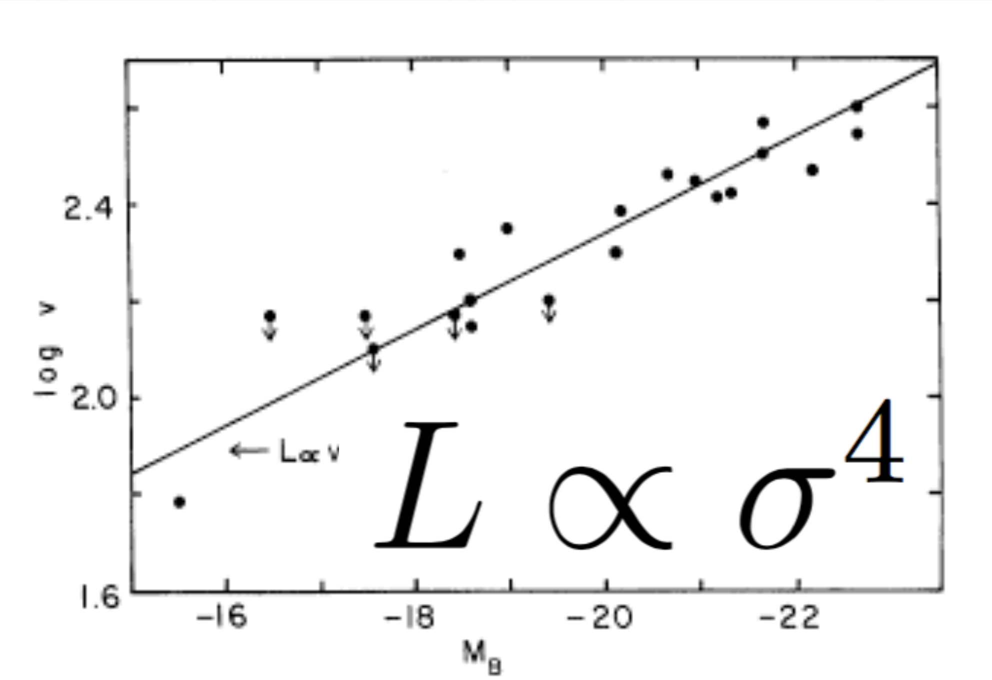
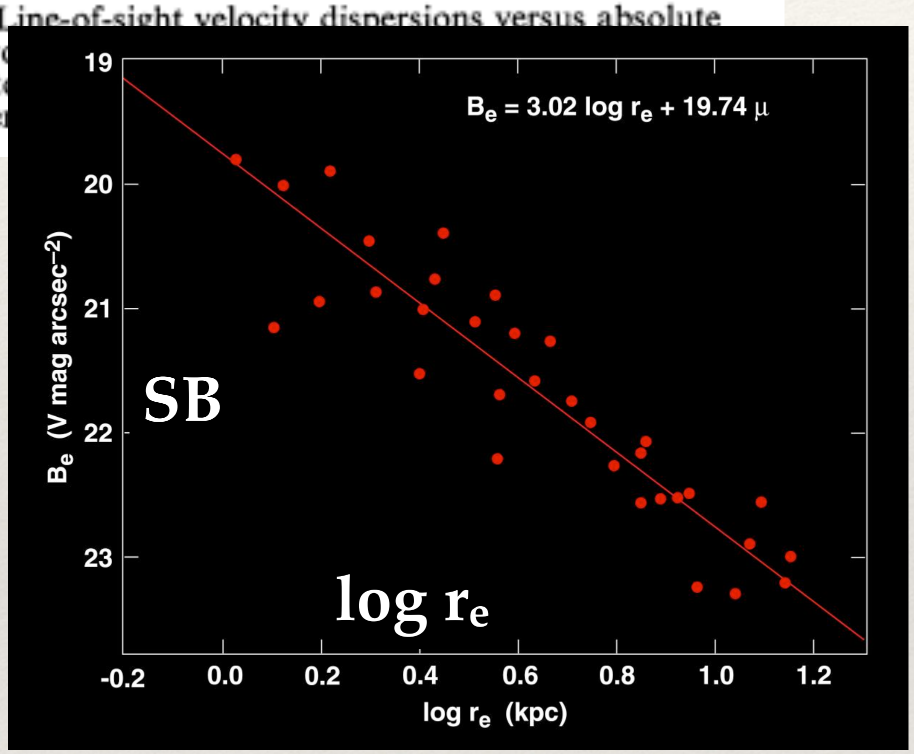
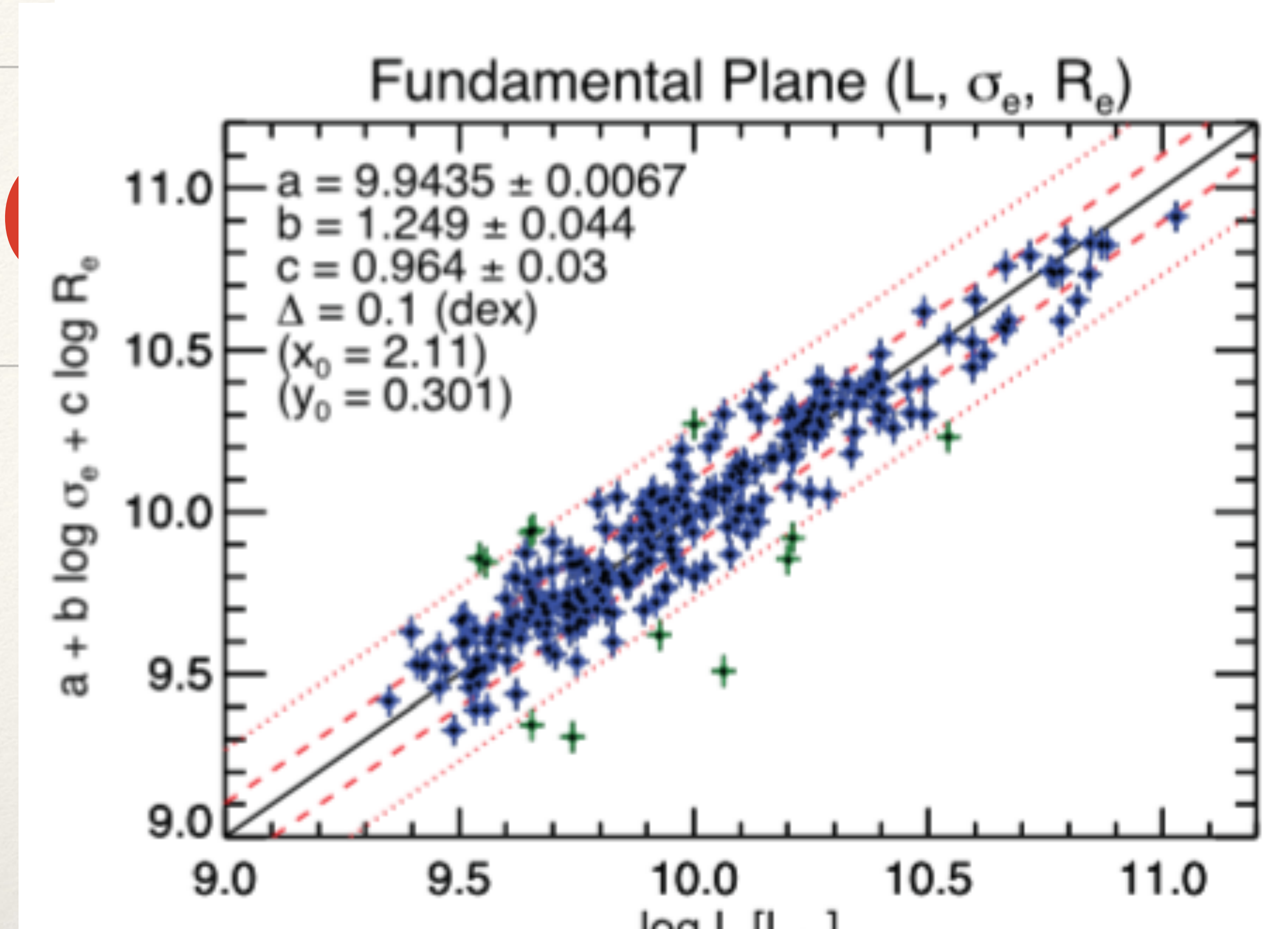


FIG. 16.—Line-of-sight velocity dispersions versus absolute magnitude fr
corresponds t
s⁻¹) was take

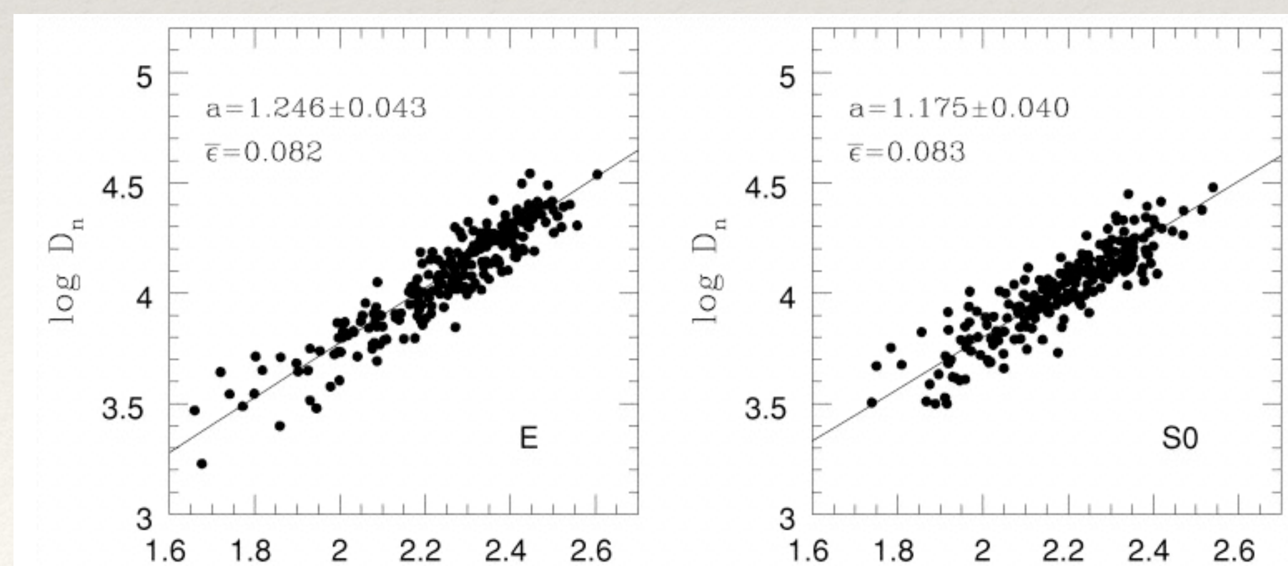


Kormendy 1977 (PhD Thesis)



Cappellari et al. 2013

- Can plot 3D plane in 2D with appropriate coefficients



Bernardi et al. 2002

- Faber-Jackson, Kormendy, and D_n- σ relations are all projections of the Fundamental Plane onto two dimensions

Outline for Today

- Galaxy Population - Ellipticals/Spheroids:
  - Spectral Energy Distributions (SEDs)
  - Interstellar Medium (ISM)
  - Recap

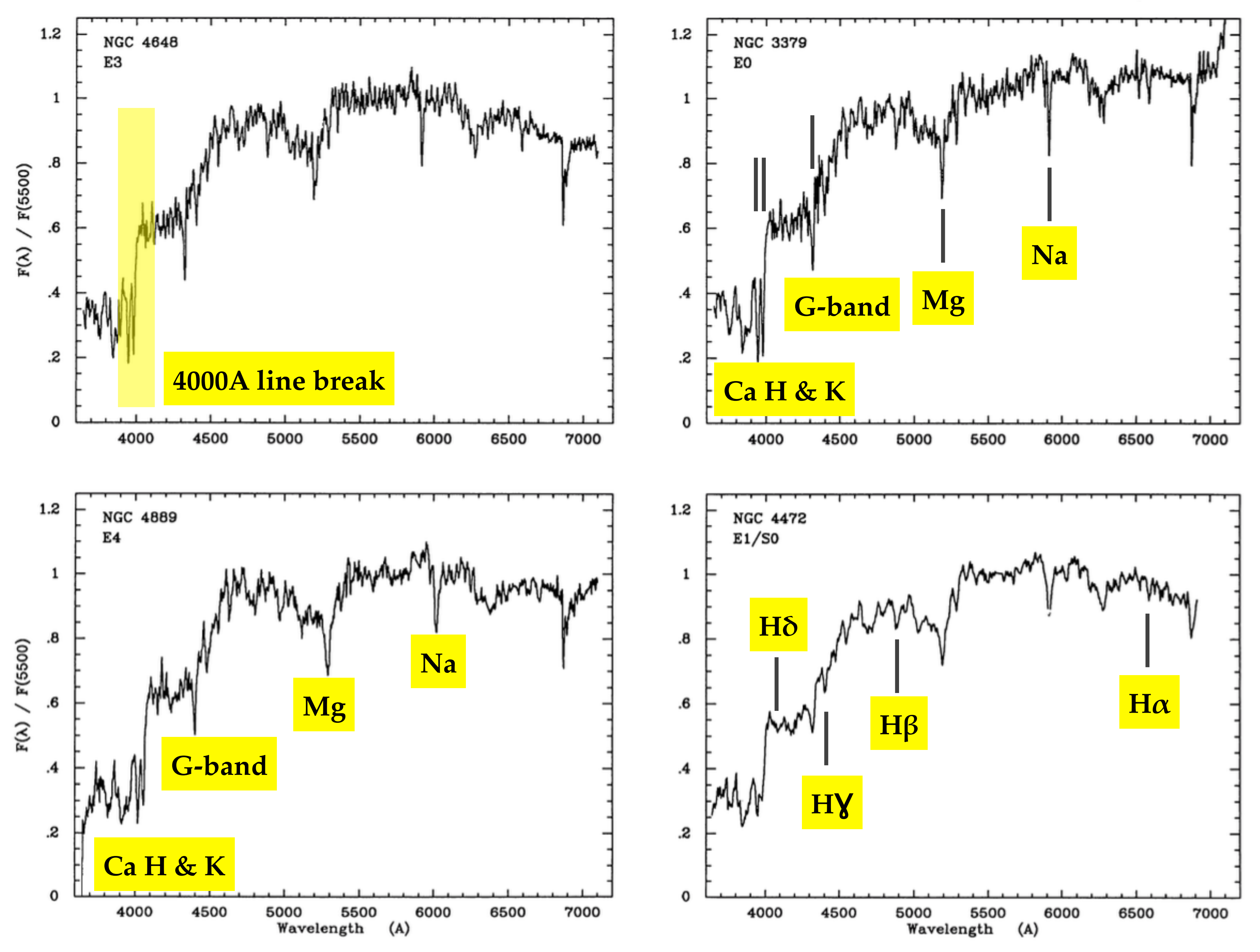
NGC4636

Thought Question

- Sketch the spectrum of an elliptical galaxy.
  - What sort of spectral features do you expect and what do they come from?
- How will the strength of these features change as the galaxy ages or becomes more metal-enriched?

Galaxy Population - Ellipticals/Spheroids: SEDs

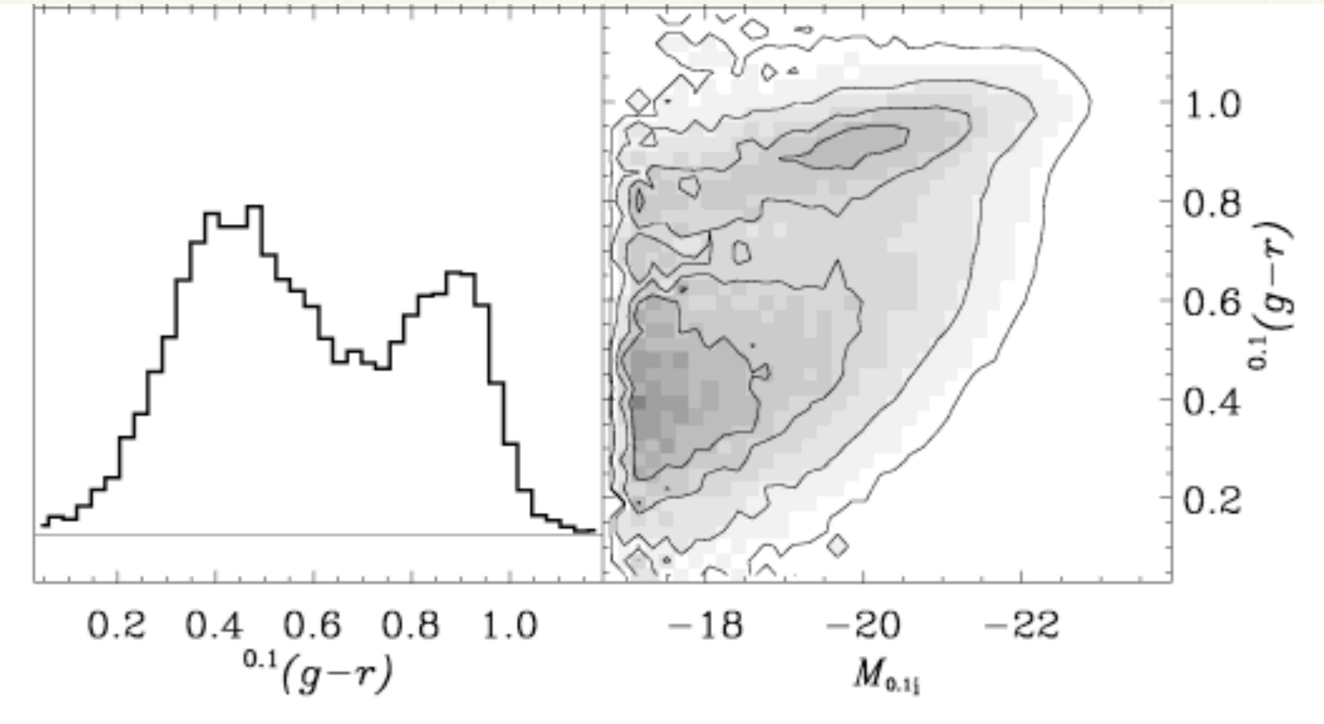
- Elliptical spectra energy distributions (SEDs):
  - Typical features are from stellar continuum (Balmer/4000A break, lines of Ca, Mg, Fe, etc.)



Kennicutt 1992

Galaxy Population - Ellipticals/Spheroids: SEDs

- Ellipticals are generally red compared to spirals — predominantly old stellar population



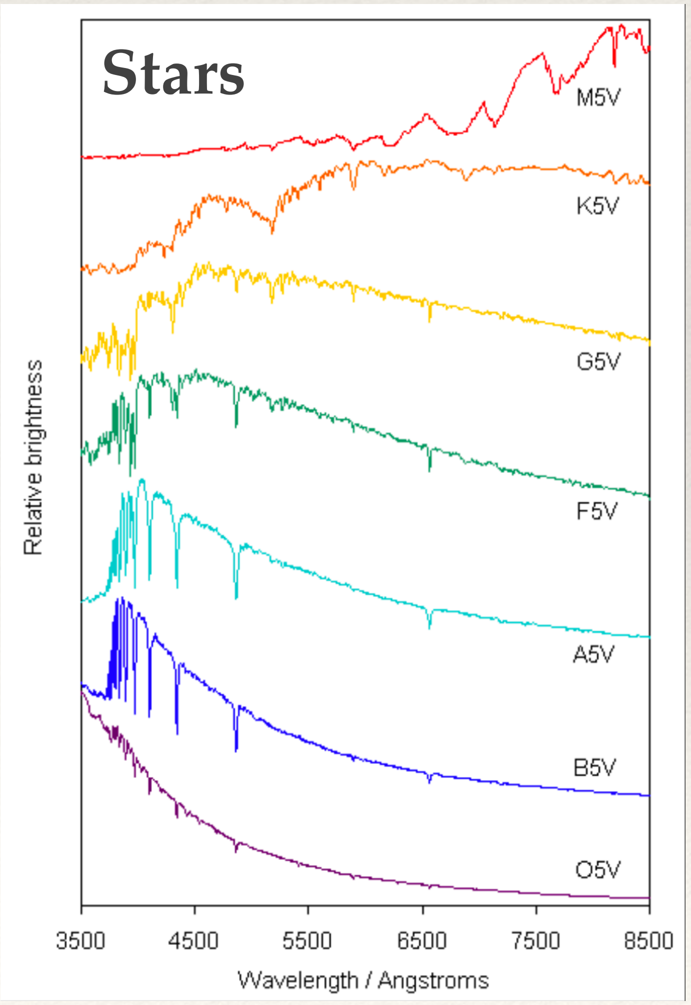
http://people.virginia.edu/~dmw8f/astr5630/Topic01/t1_SDSS_montage.html

See Mo, van den Bosch, & White; Figure 2.27

Low Mass

(~Solar Mass)

High Mass

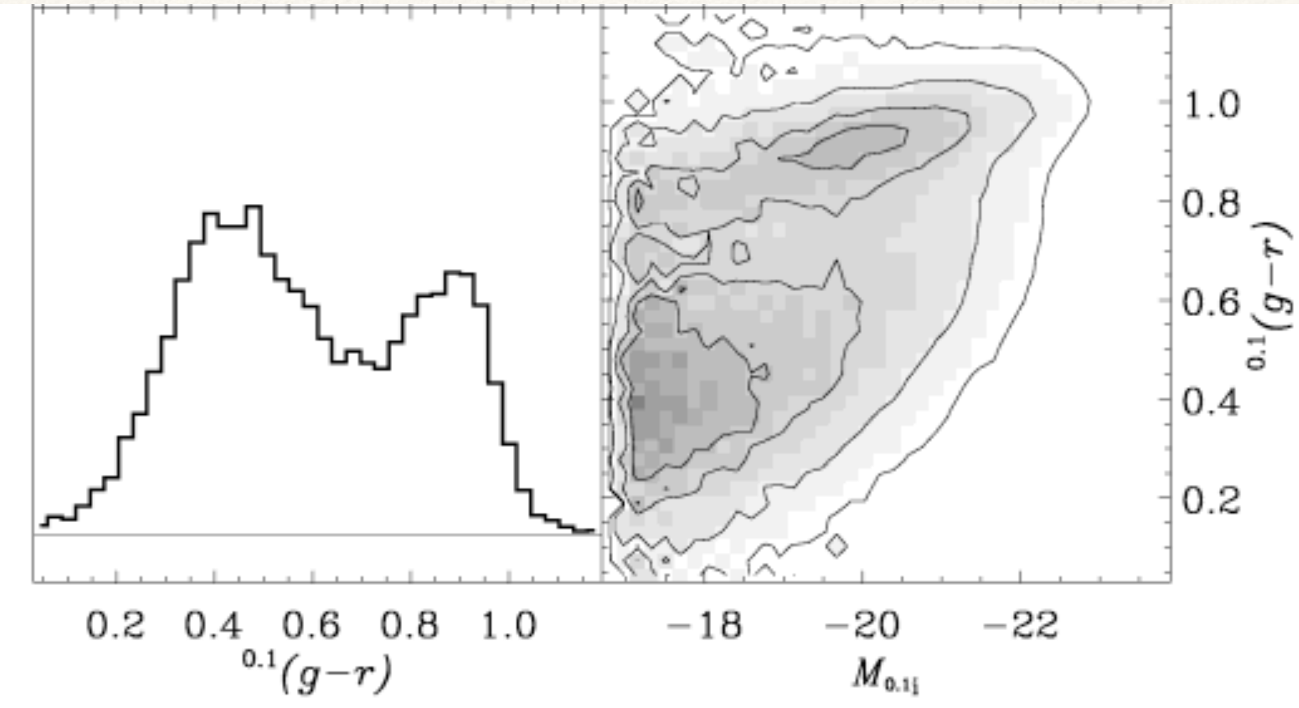


https://www2.mpia-hd.mpg.de/homes/rix/sed.pdf

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

Galaxy Population - Ellipticals/Spheroids: SEDs

- Ellipticals are generally red compared to spirals — predominantly old stellar population



http://people.virginia.edu/~dmw8f/astr5630/Topic01/t1_SDSS_montage.html

See Mo, van den Bosch, & White; Figure 2.27

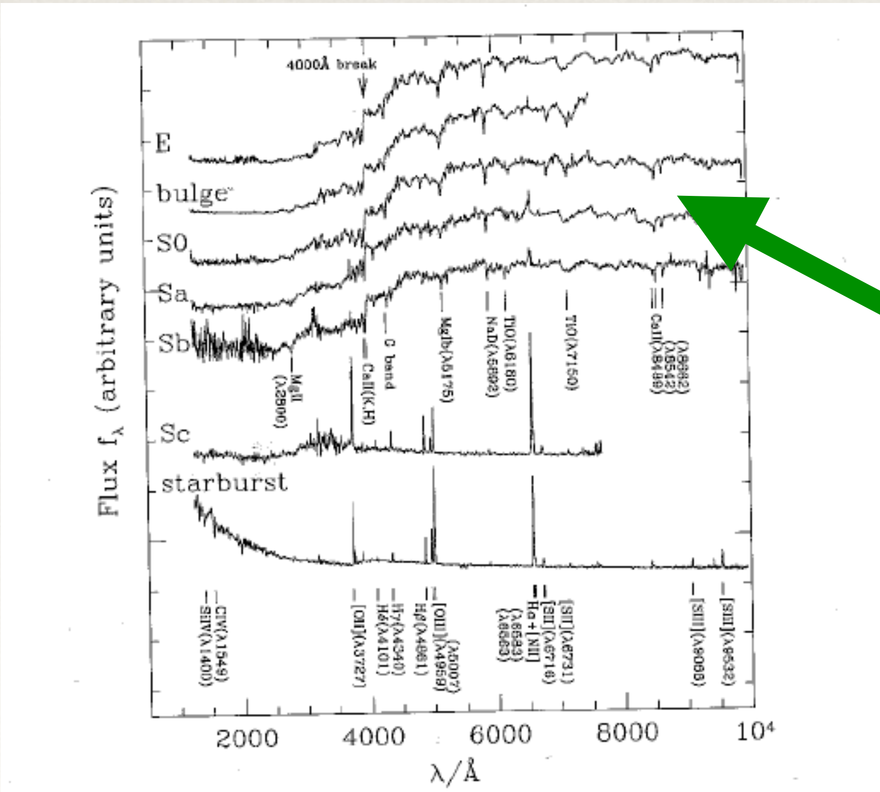
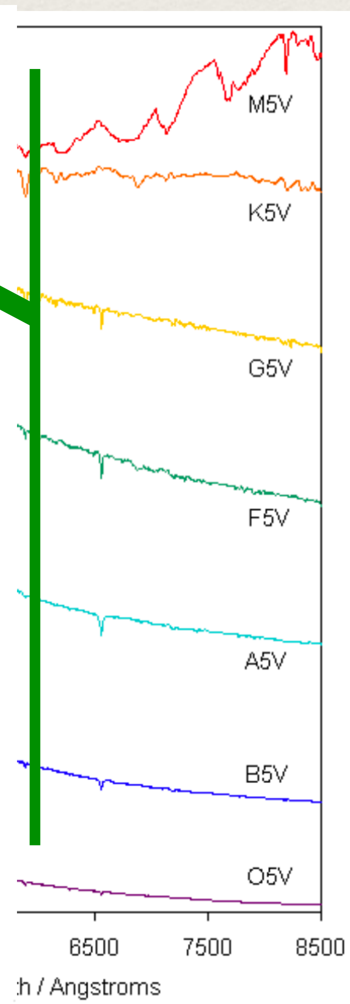


Fig. 2.12. Spectra of different types of galaxies from the ultraviolet to the near-infrared. From ellipticals to late-type spirals, the blue continuum and emission lines become systematically stronger. For early-type galaxies, which lack hot, young stars, most of the light emerges at the longest wavelengths, 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]



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

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

Galaxy Population - Ellipticals/Spheroids: SEDs

- **Color-Magnitude Relation**:
  - More luminous ellipticals are slightly redder — older?
  - However, color variations could come from age or metallicity:
    - Older — dominated by redder stars
    - More metal-rich — stronger metal lines around 4000A break, so redder colors

Age-Metallicity Degeneracy

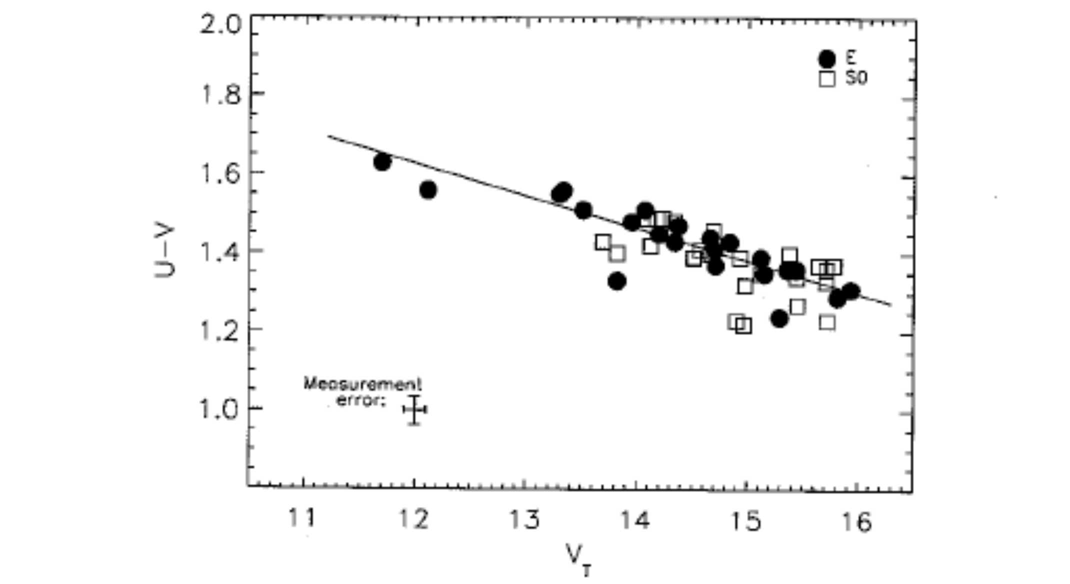
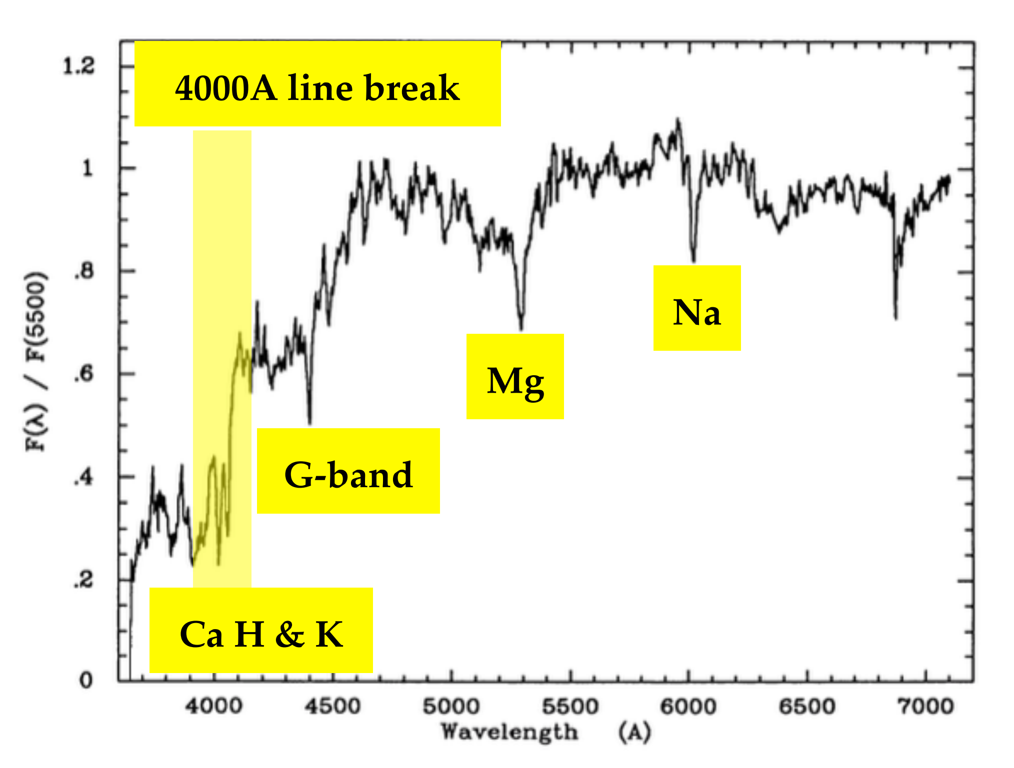


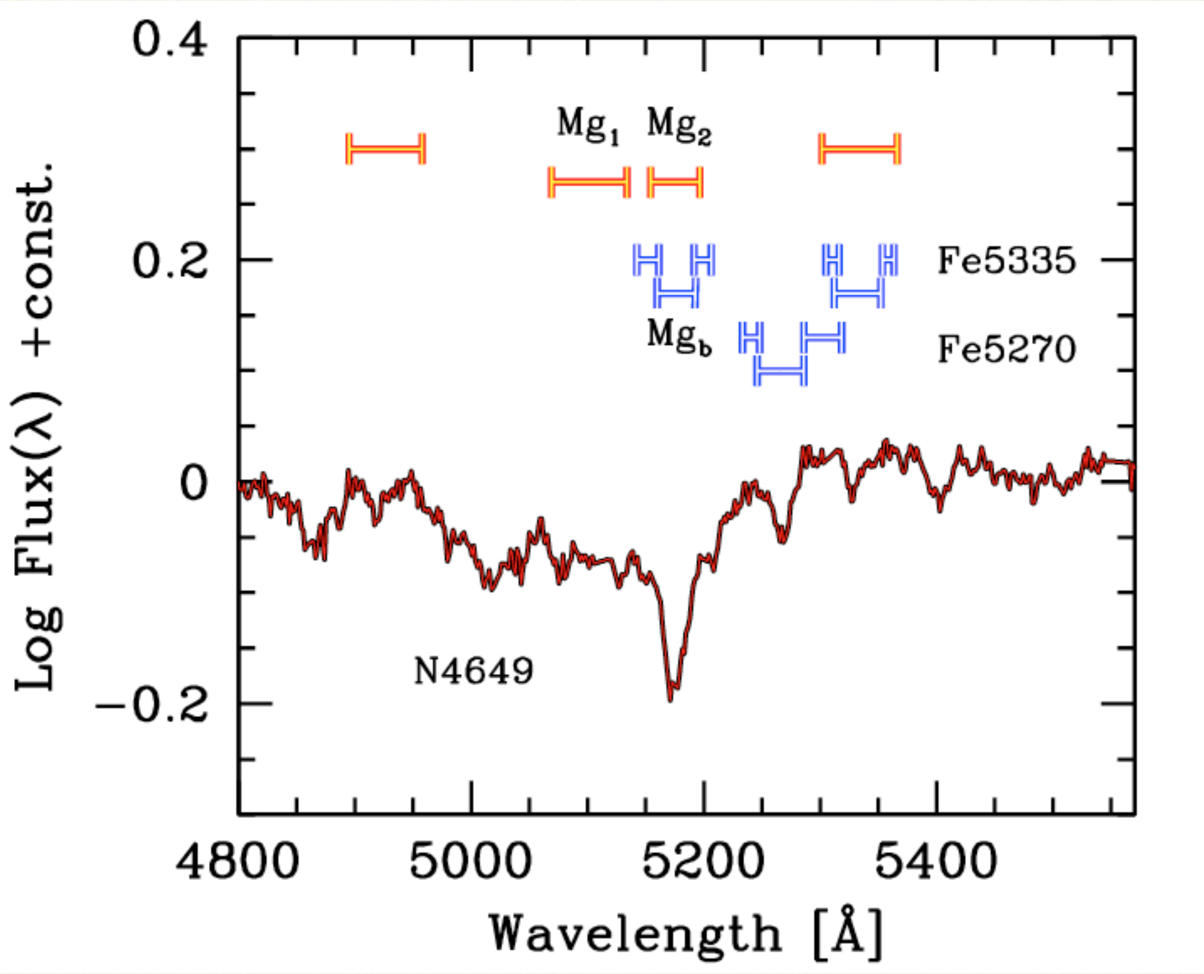
Fig. 13.7. The color–magnitude relation for early-type galaxies in the Coma Cluster. [Adapted from Bower et al. (1992)]



Kennicutt 1992

Galaxy Population - Ellipticals/Spheroids: SEDs

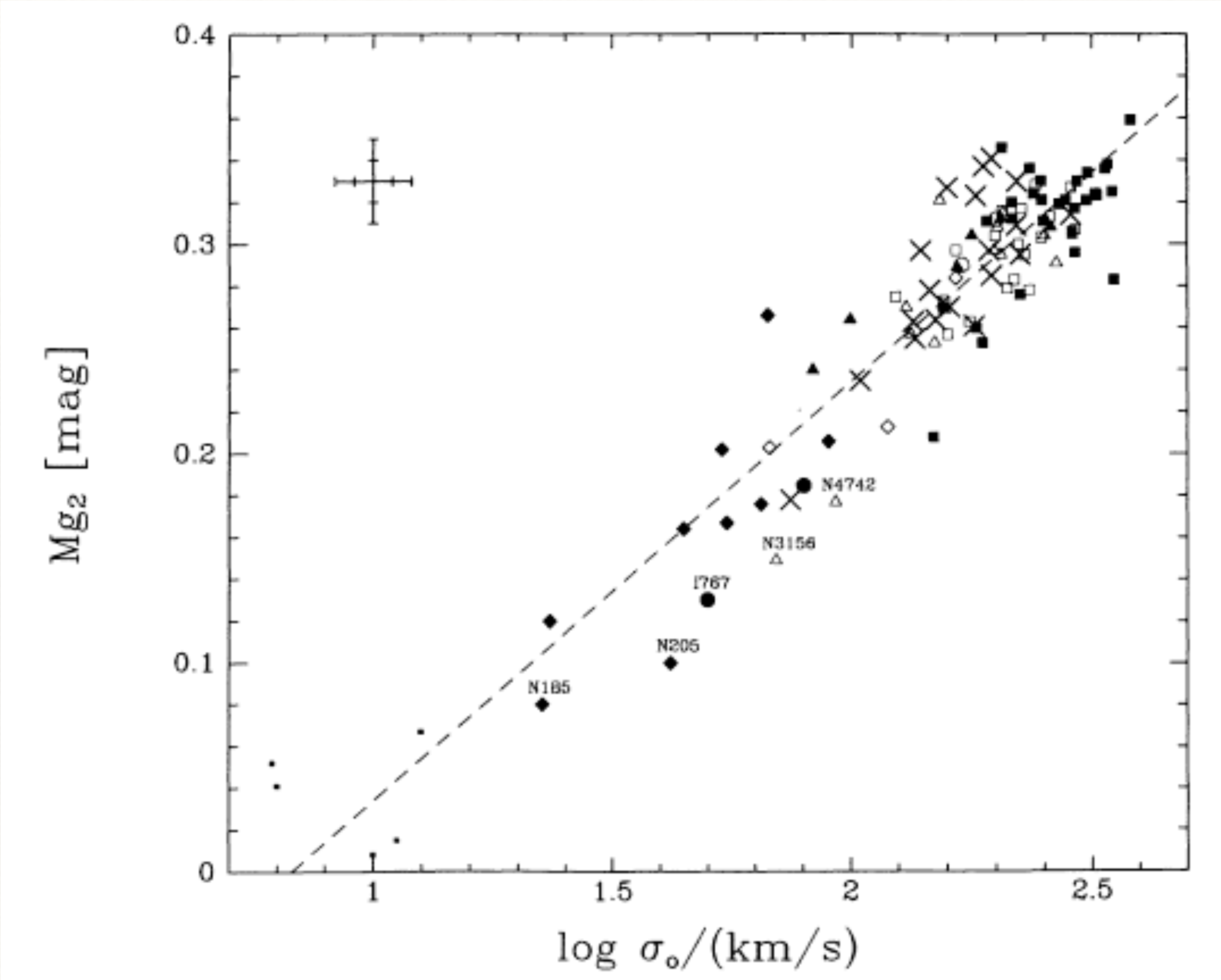
- Measure metal line strength using line indices, e.g., Lick indices, Mg_2 index (Faber et al. 1977)
- Some lines are more sensitive to age (e.g., Hbeta, Hgamma), some more sensitive to metallicity (Mgb, Fe5270)



Buzzoni et al. 2015

Galaxy Population - Ellipticals/Spheroids: SEDs

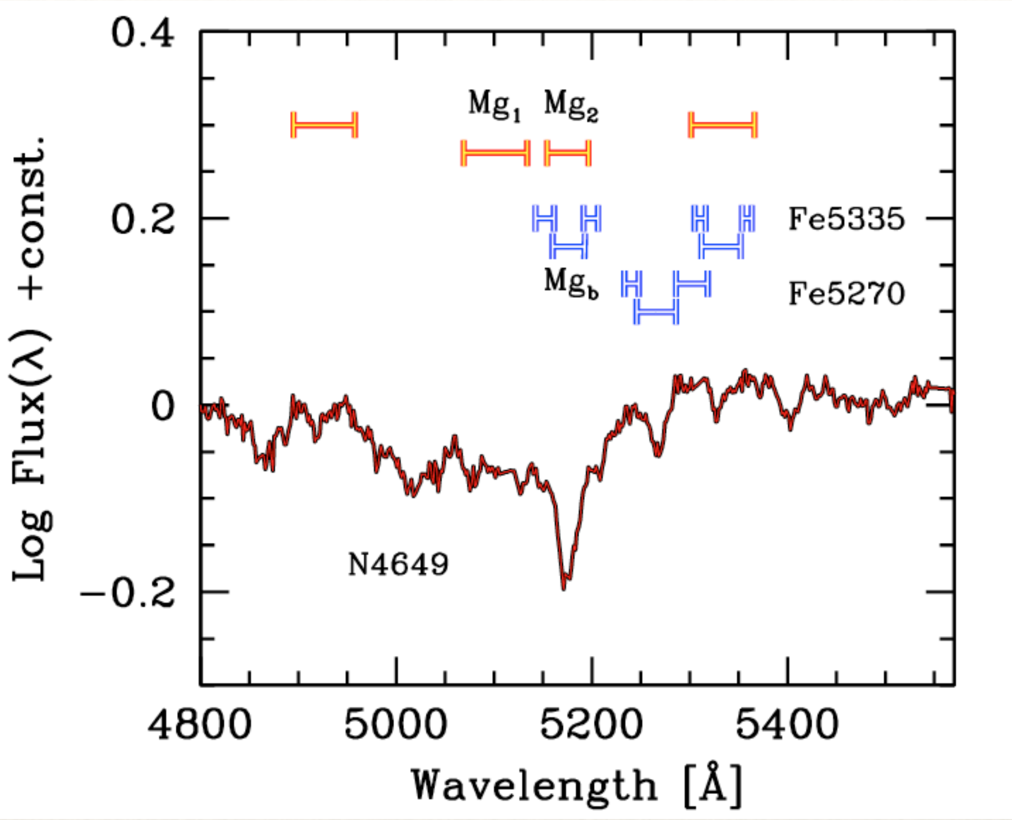
- **Mg_2-Luminosity and Mg_2-σ_0 Relations:**
  - More luminous Es have stronger lines
  - Tighter correlation between line strength and central velocity dispersion σ_0
  - More massive galaxies = more metal-rich, or older
- See similar correlations/gradients within individual galaxies:
  - Inner regions more metal-enriched (and slightly younger)



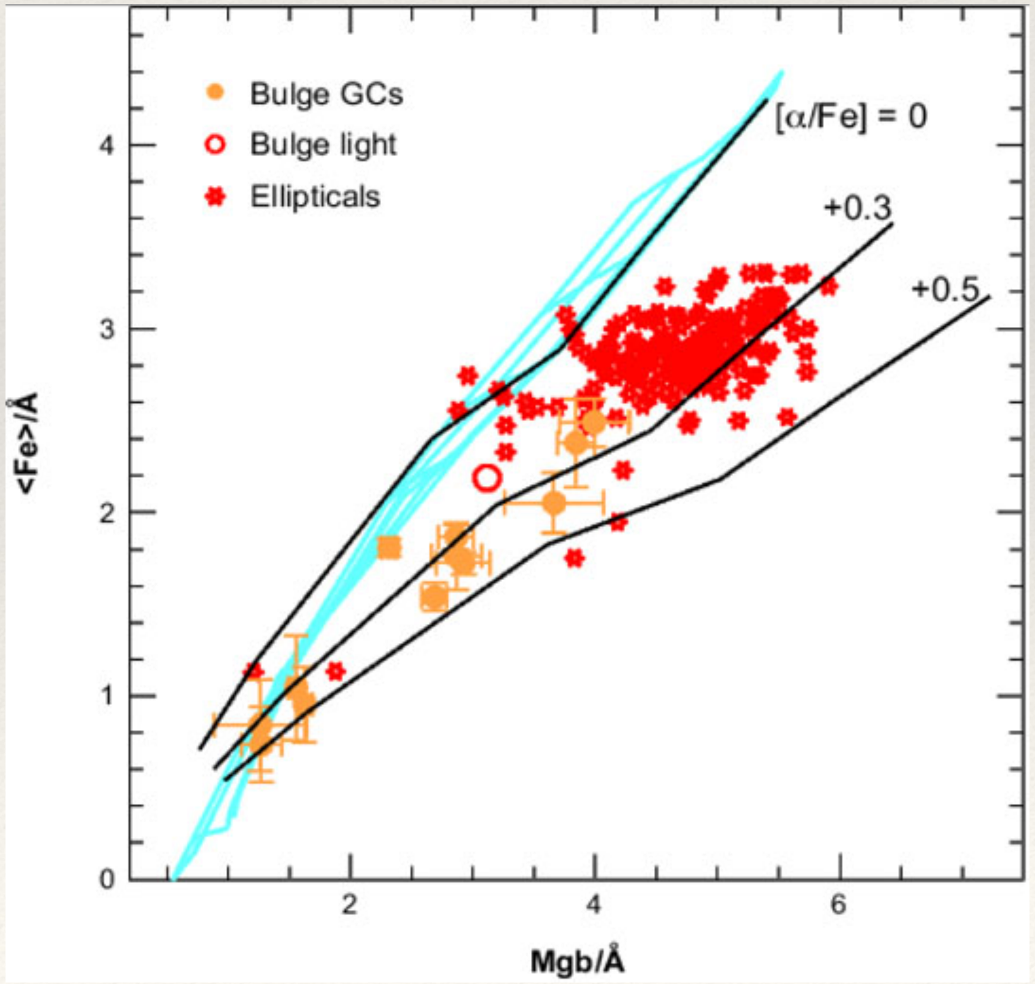
Bender, IAU Symposium 149

Galaxy Population - Ellipticals/

- Metal line indices can also reveal abundance variations (relative to solar) — alpha/Fe ratio
  - alpha elements (even proton number, e.g., O, Mg, Si, S, Ca, Ti) — from Type II supernovae (shorter timescale)
  - Fe — from Type II but also Type 1a supernovae (longer timescale)
- See enhanced Mg vs. Fe in more massive galaxies



Buzzoni et al. 2015



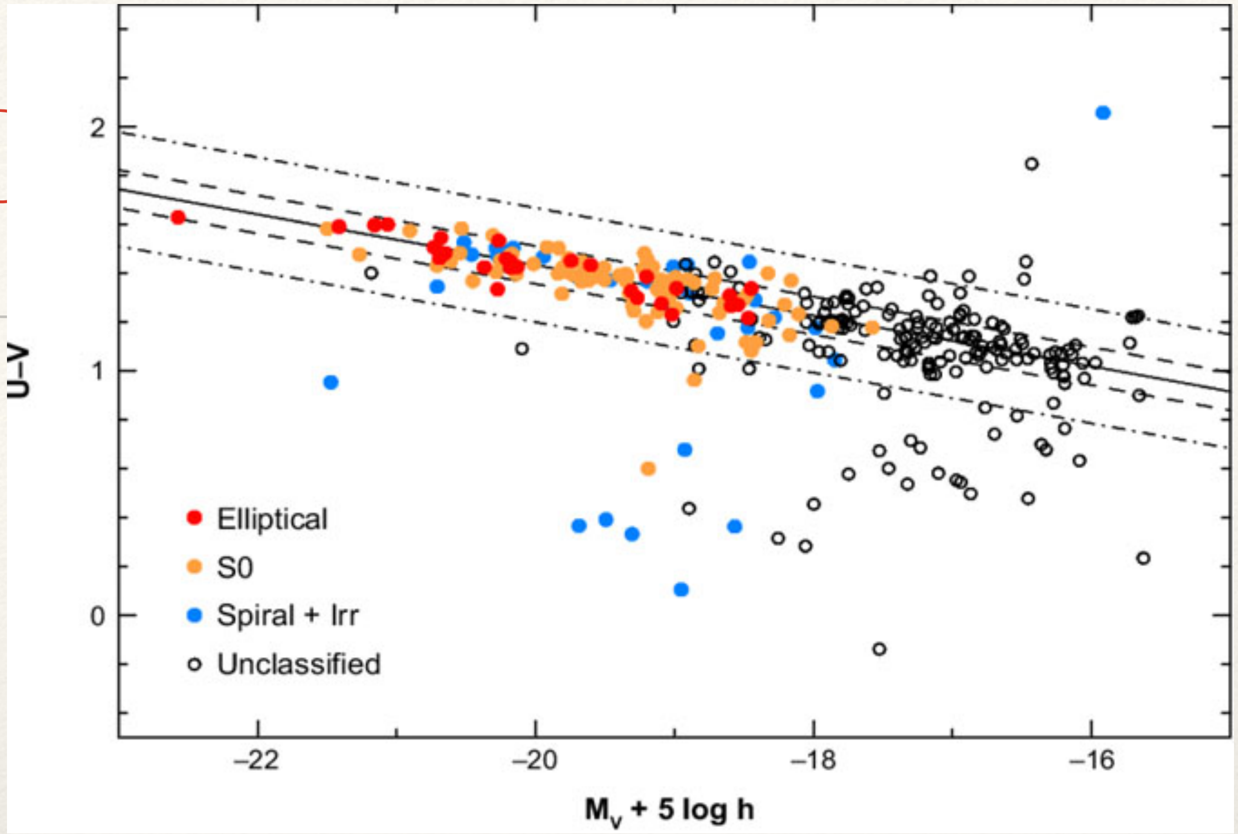
https://ned.ipac.caltech.edu/level5/March06/Renzini/Renzini3.html#Figure%206

Thought Question

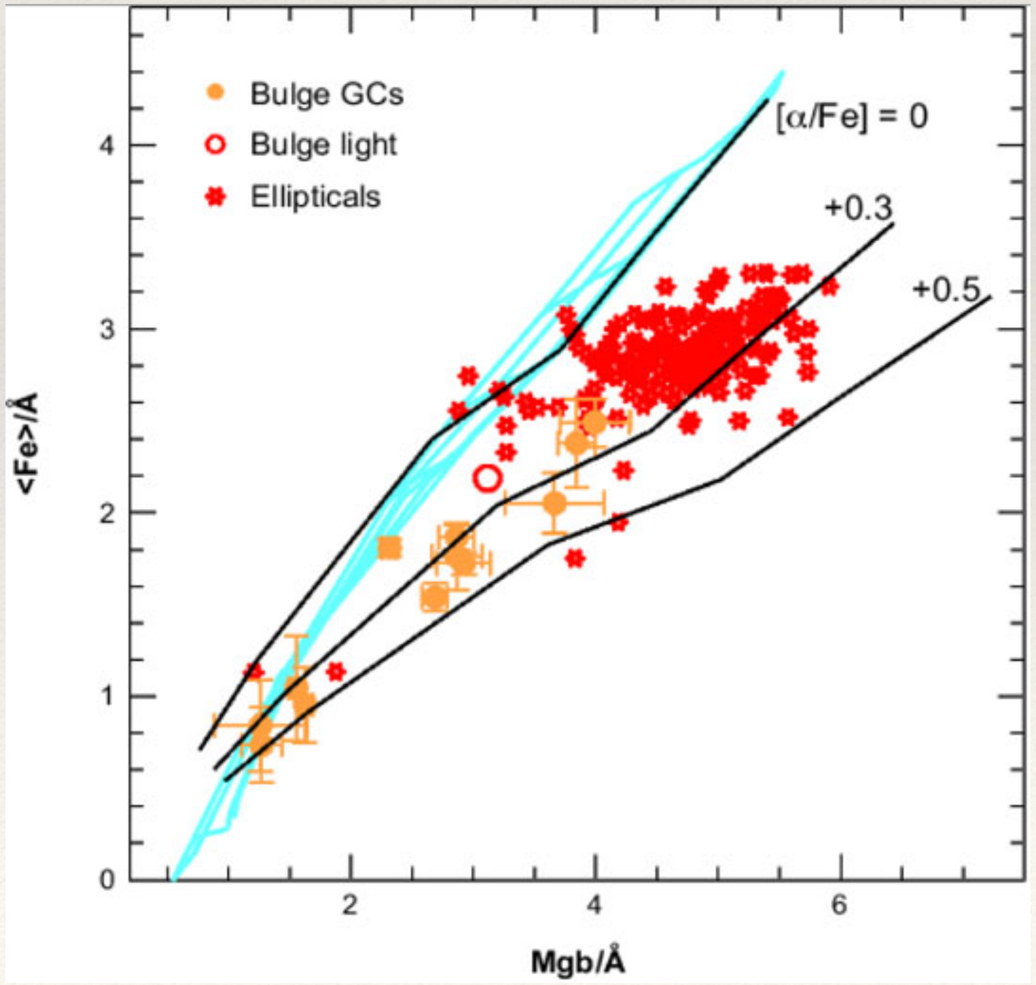
- Imagine a galaxy with a first generation of stars that evolve until Type II supernovae start to go off. The supernova ejecta enriches a second generation of stars. Once enough time has passed, Type 1a supernovae start to occur as well. Finally a third generation of stars forms.
- What will the stellar metallicity look like for the second vs. third generation?
- What will the alpha/Fe ratio look like for the second vs. third generation?

Ellipticals/Spheroids: SED

- Tightness of relations implies stellar content must be fairly uniform — a similar (old) age
  - Suggests stars formed early
- Evidence for abundance variations (enhanced Mg vs. Fe in more massive galaxies)
  - Suggests that star formation may have ended quickly in more massive galaxies



https://ned.ipac.caltech.edu/level5/March06/Renzini/Renzini3.html#Figure%206



Thought Question

- Consider the SED of an old galaxy with a more recent burst of star formation that has now turned off:
  - what sort of continuum/absorption features do you expect?
  - what about emission lines?

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- Consider the SED of an old galaxy with a more recent burst of star formation that has now turned off:
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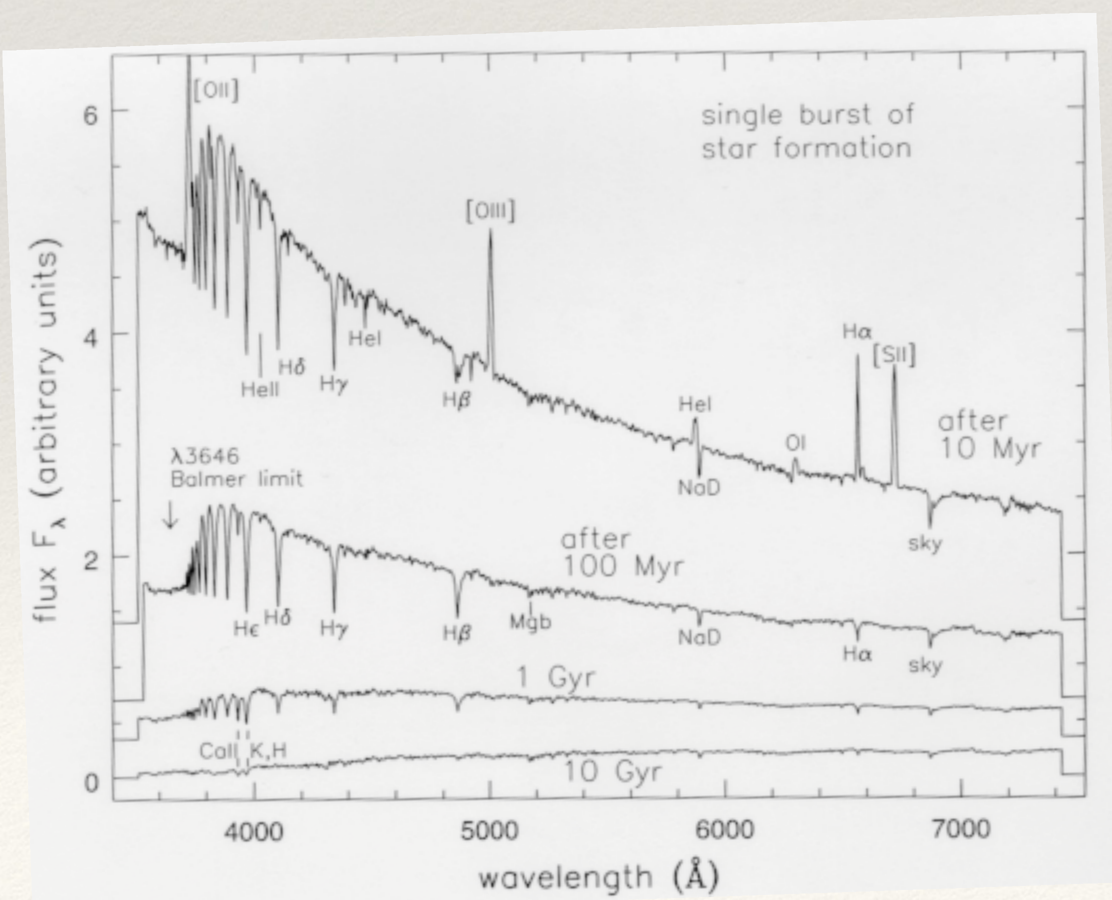
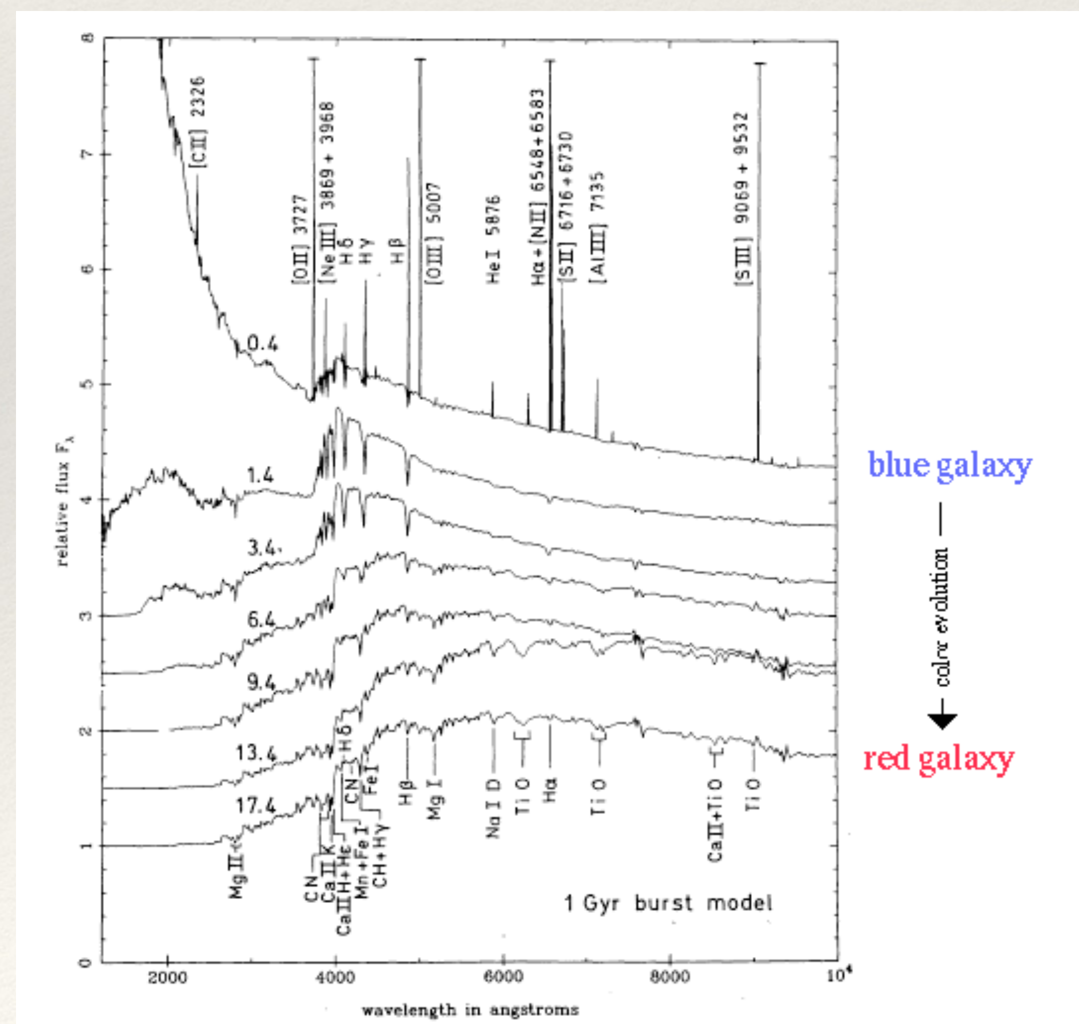
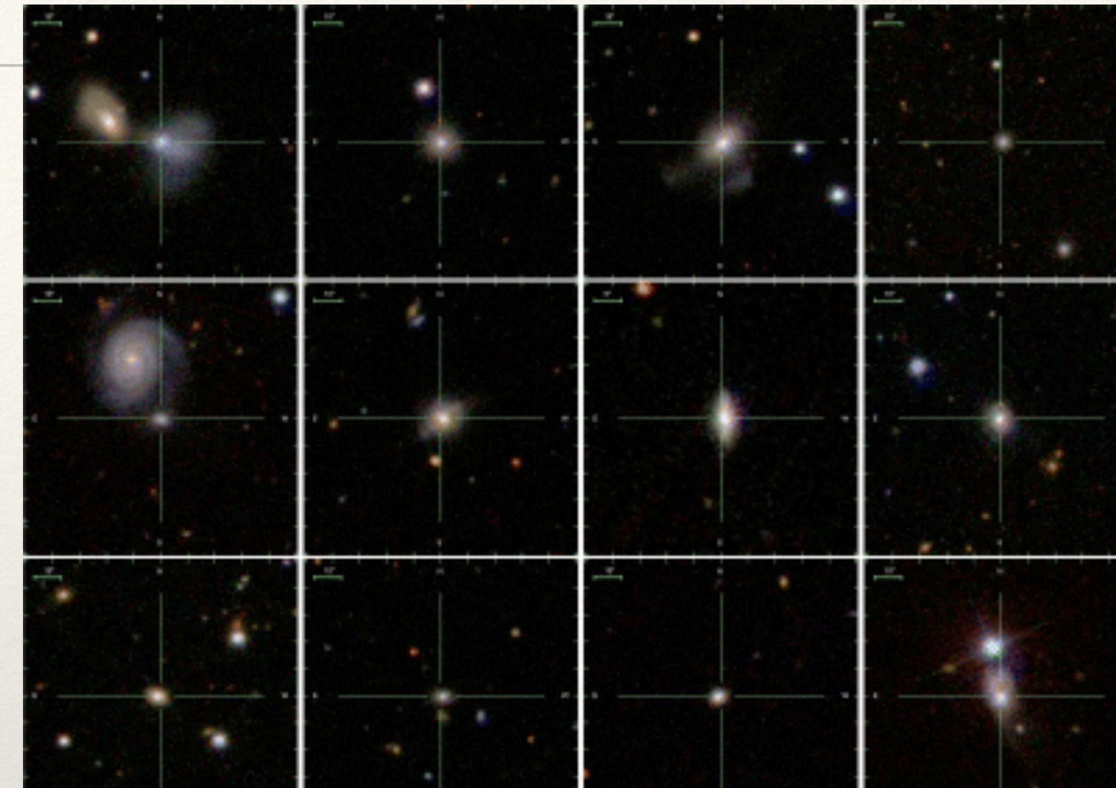
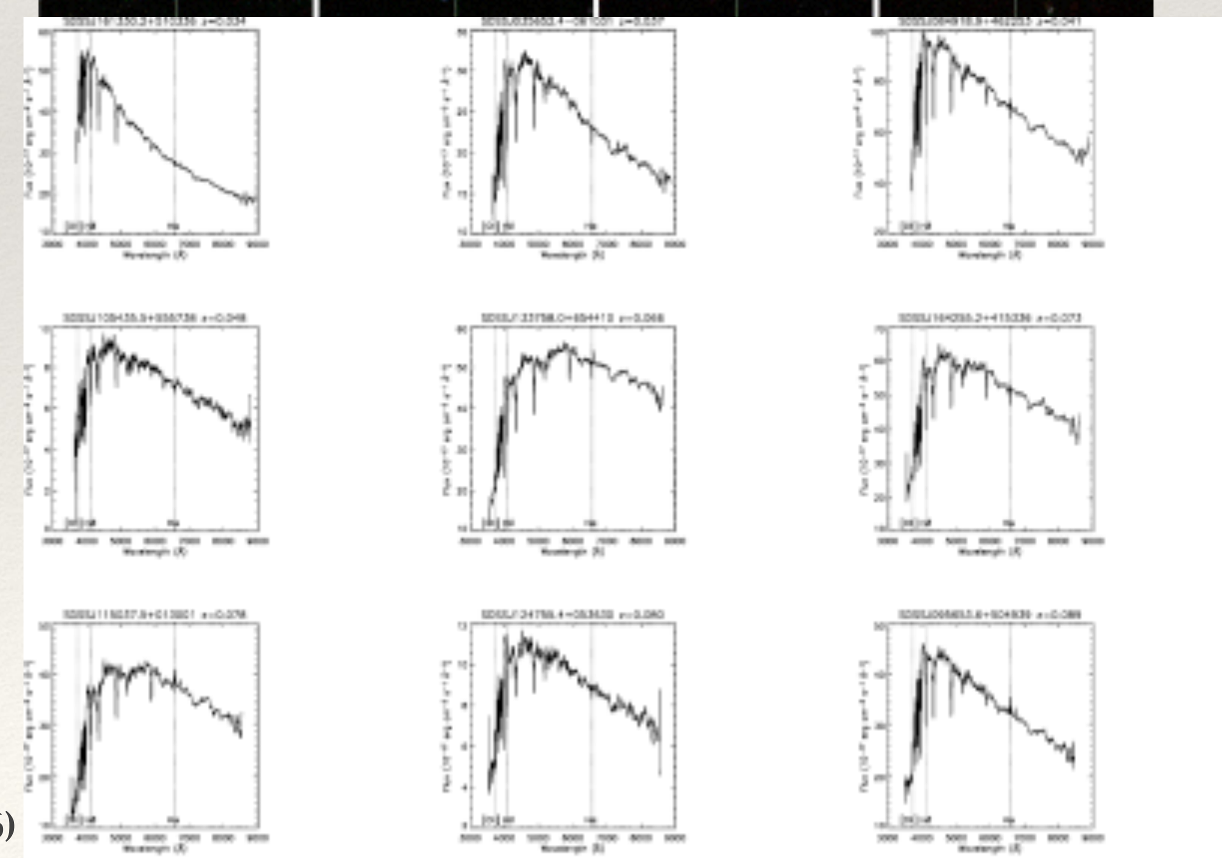
  - what about emission lines?





Galaxy Population - Ellipticals/Spheroids: SEDs



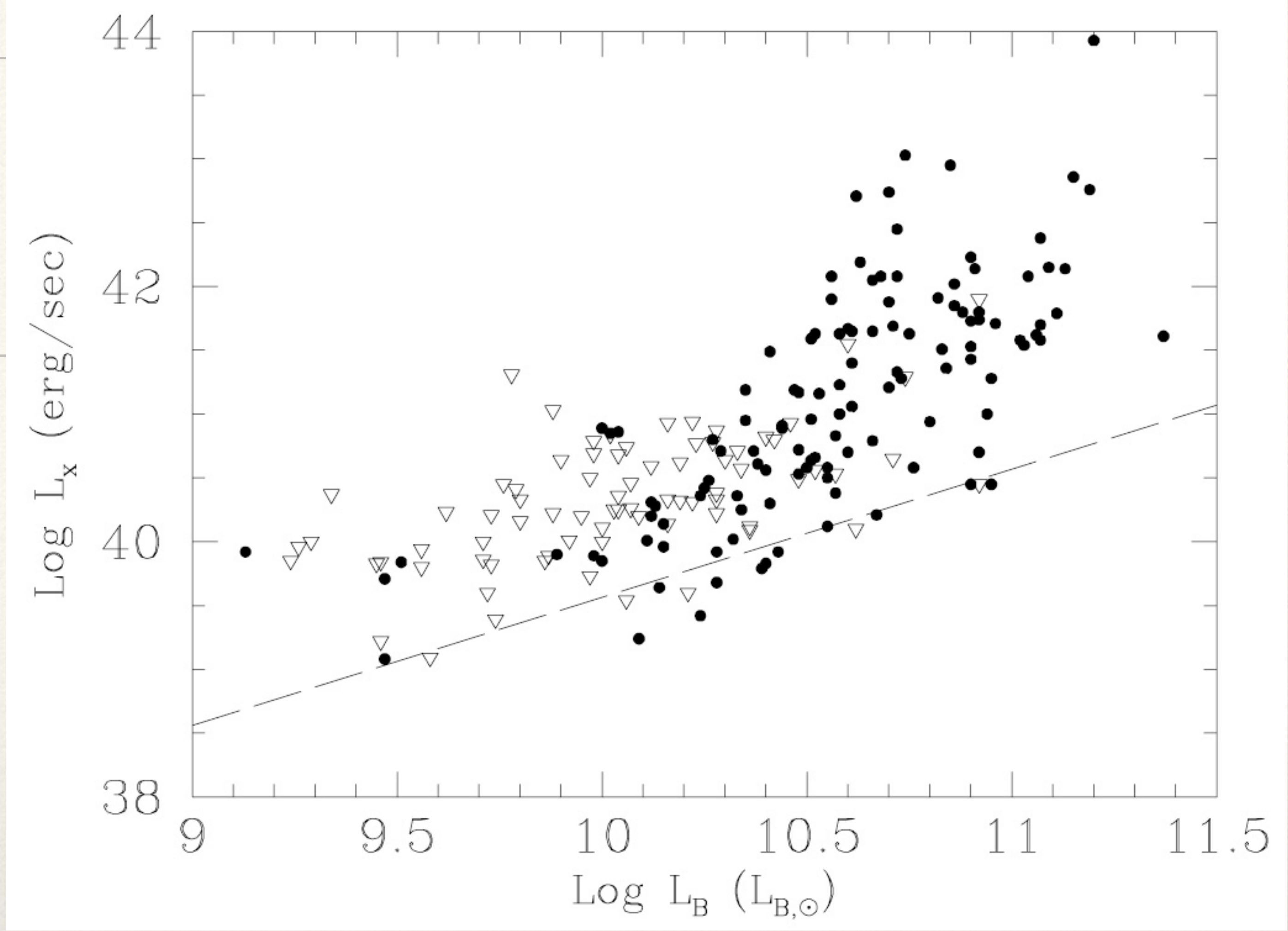


- Some Es have signatures of a younger stellar population:
  - **E+A (or K+A) galaxies** — no emission lines (E) yet strong Balmer absorption lines (~A stars)
- Likely "post-starburst" galaxies with significant star formation 1 Gyr ago that abruptly shut off
  - Rare (<1% of local galaxies)
  - Not correlated with cluster environment
  - Some show power-law inner profiles, morphological signs of recent interactions

(Goto 2004, 2006)

Ellipticals/Spheroids:

- **Interstellar matter in ellipticals:**
  - Hot gas seen in X-rays:
    - from stellar winds and supernovae
    - from new and previously expelled gas that is shock-heated as it falls in
  - Warm gas filaments with weak Halpha emission

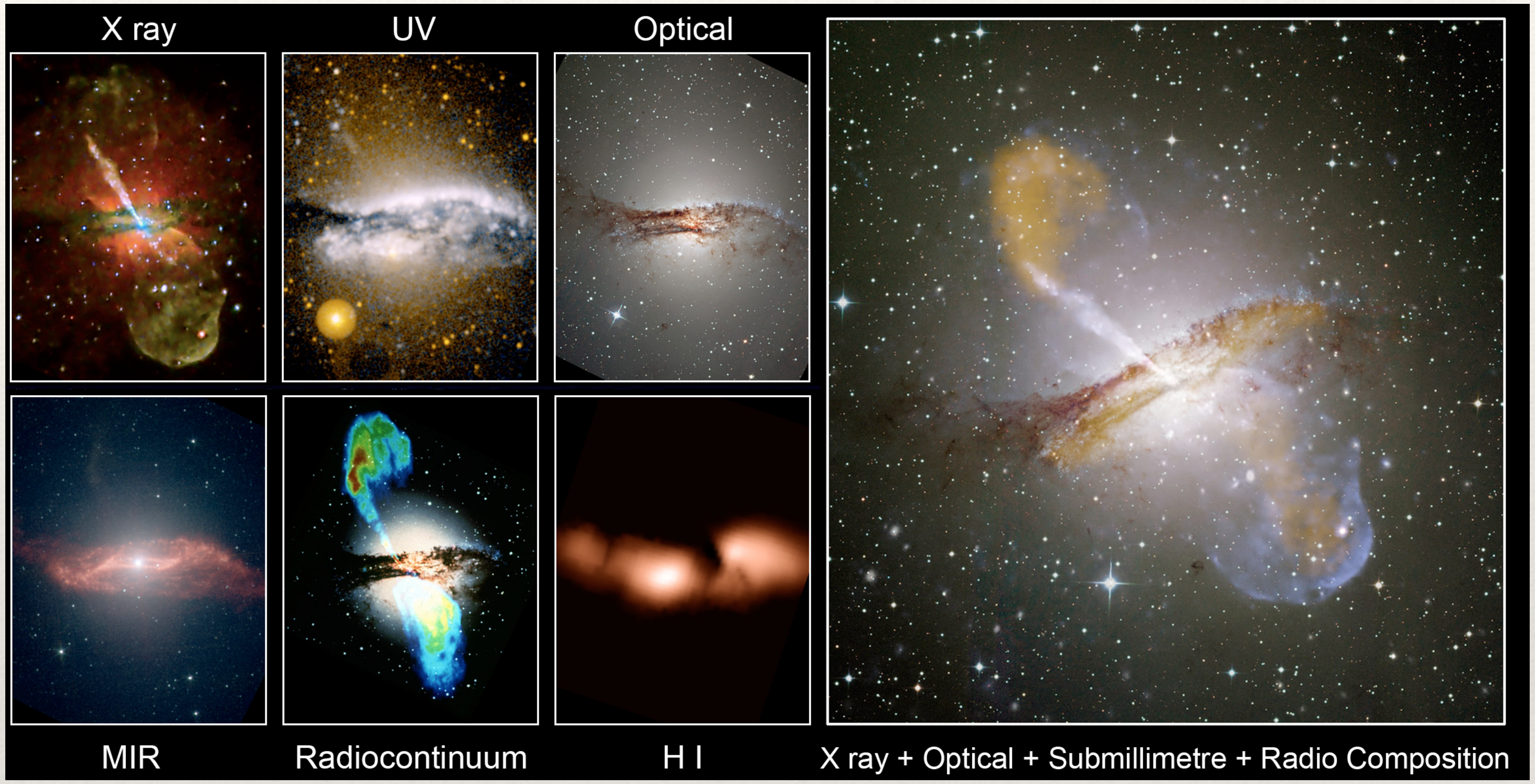


O'Sullivan et al. (2001)

Kenney+2008

Galaxy Population - Ellipticals/Spheroids: ISM

- **Interstellar matter in ellipticals:**
  - Cold gas and dust:
    - atomic and/or molecular gas in ~10-20% of ellipticals (van Gorkom 1992)
    - dust in ~50% of elliptical cores (Lauer et al. 2005)



Ángel R. López-Sánchez (2008)

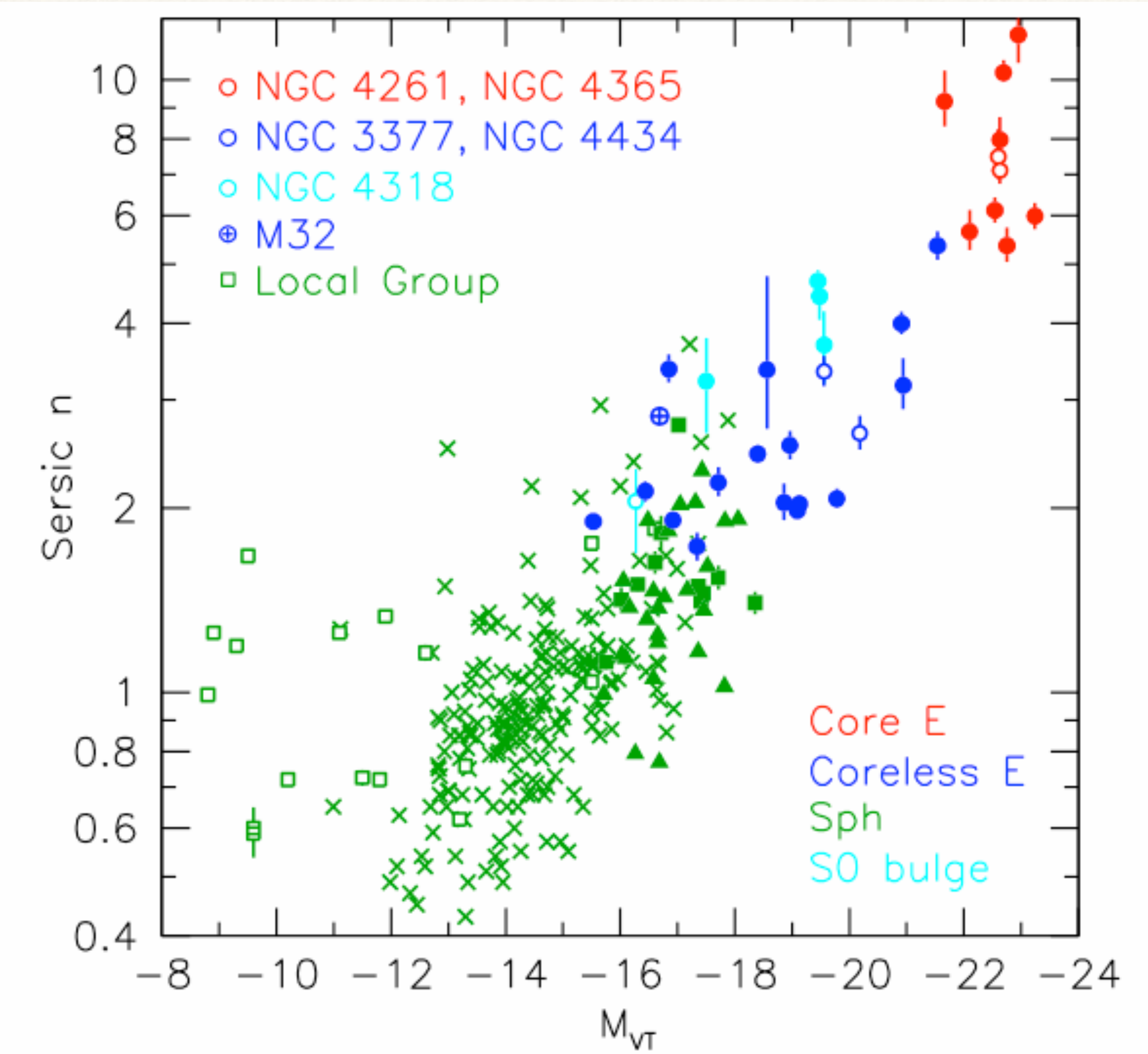
- dramatic merger examples (e.g., Cen A

Recap

- In the 1970s, we thought Ellipticals were:
  - diskless bulges with de Vaucouleurs ($R^{1/4}$) profiles and constant density cores
  - oblate spheroids flattened by rotation
  - relaxed, dynamically quiescent systems
  - void of gas and dust
  - dominated by a single ancient population of stars

How was our 1970s view correct vs. incorrect?
(Cite specific observational evidence.)

Galaxy Population - Ellipticals/Spheroids: Recap



Kormendy 2006

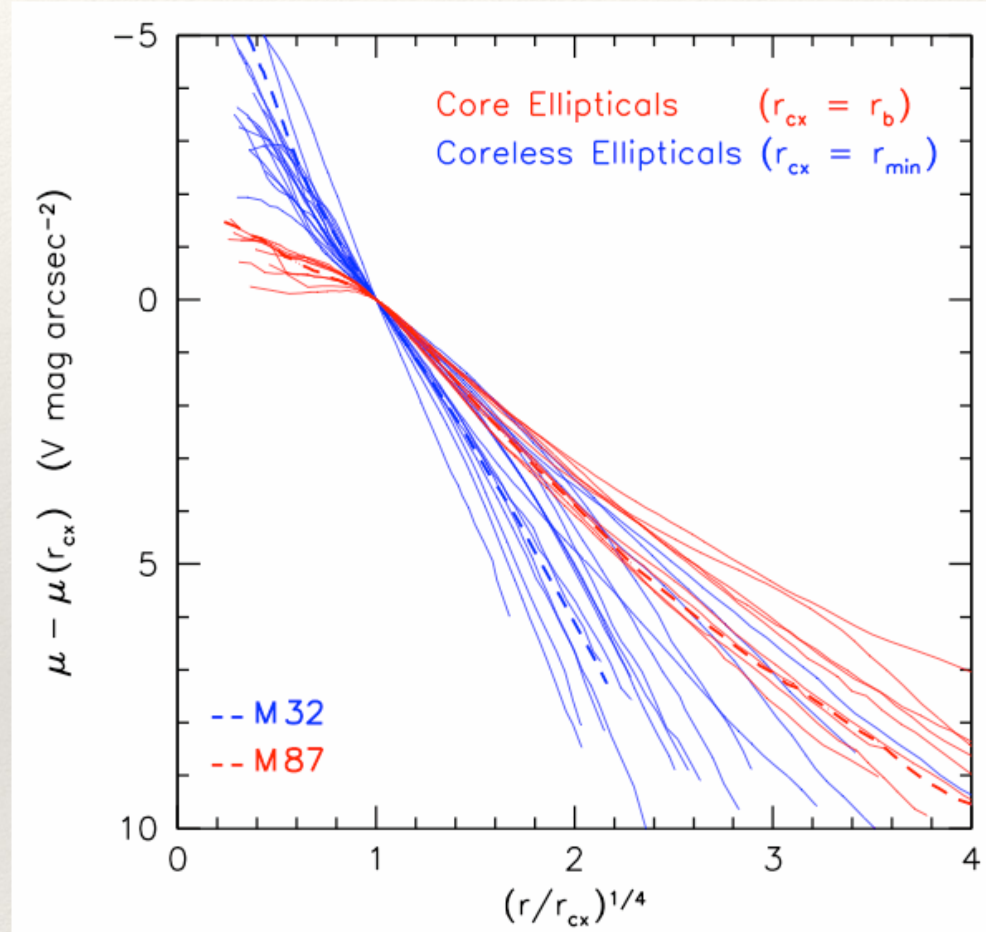
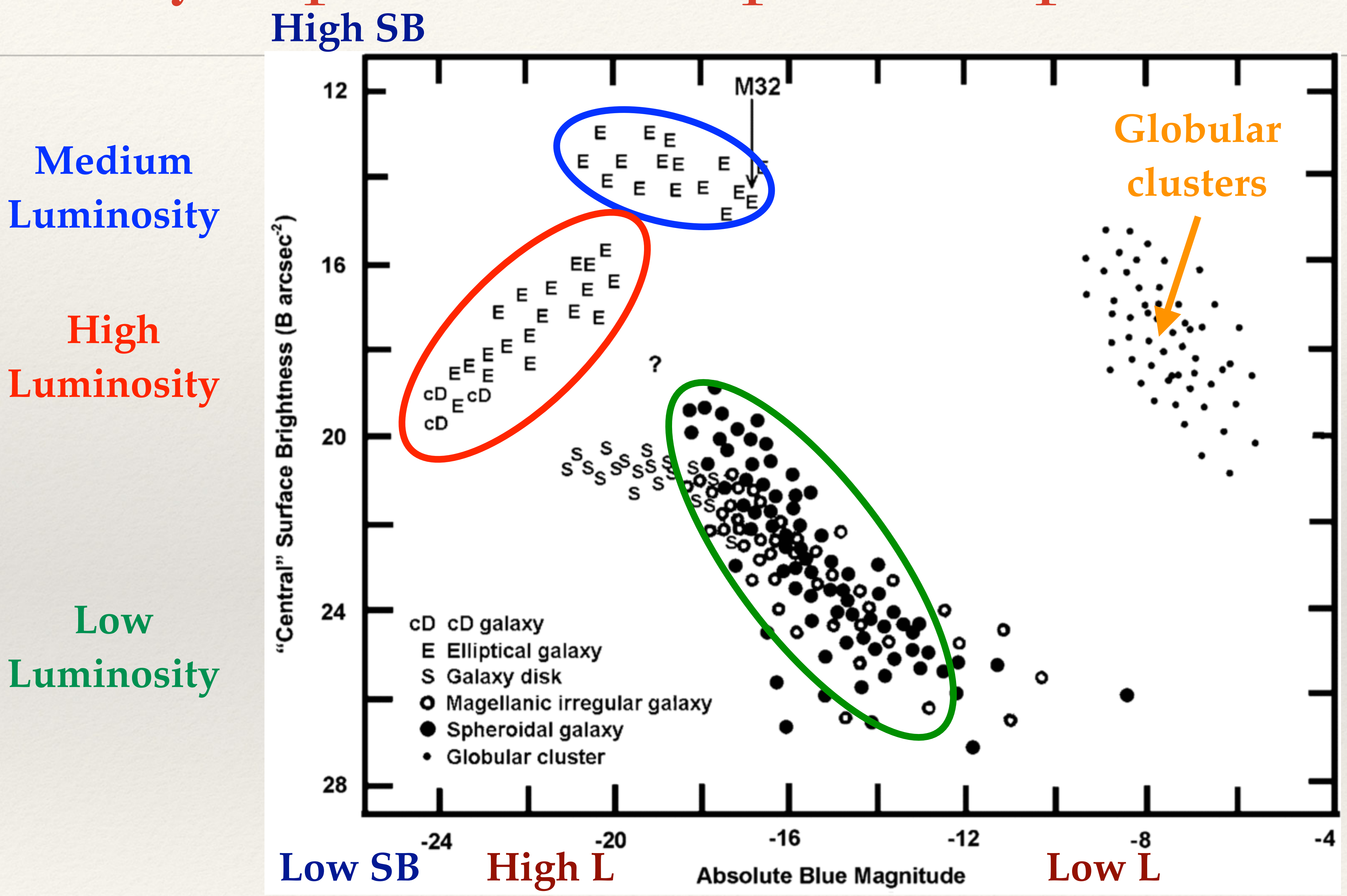


FIG. 40.— Major-axis profiles of all of our ellipticals scaled together to illustrate the dichotomy between core and coreless ellipticals. Core ellipticals are scaled together at $r_{cx} = r_b$, the break radius given by the Nuker function fit in Lauer et al. (2007b). Coreless ellipticals are scaled together at the minimum radius r_{min} that was used in our Sérsic fits; interior to this radius, the profile is dominated by extra light above the inward extrapolation of the outer Sérsic fit.

- Range of properties suggest differences in formation

Galaxy Population - Ellipticals/Spheroids: Recap



Kormendy 2009

- Range of properties suggest differences in formation

Galaxy Population - Ellipticals/Spheroids: Recap

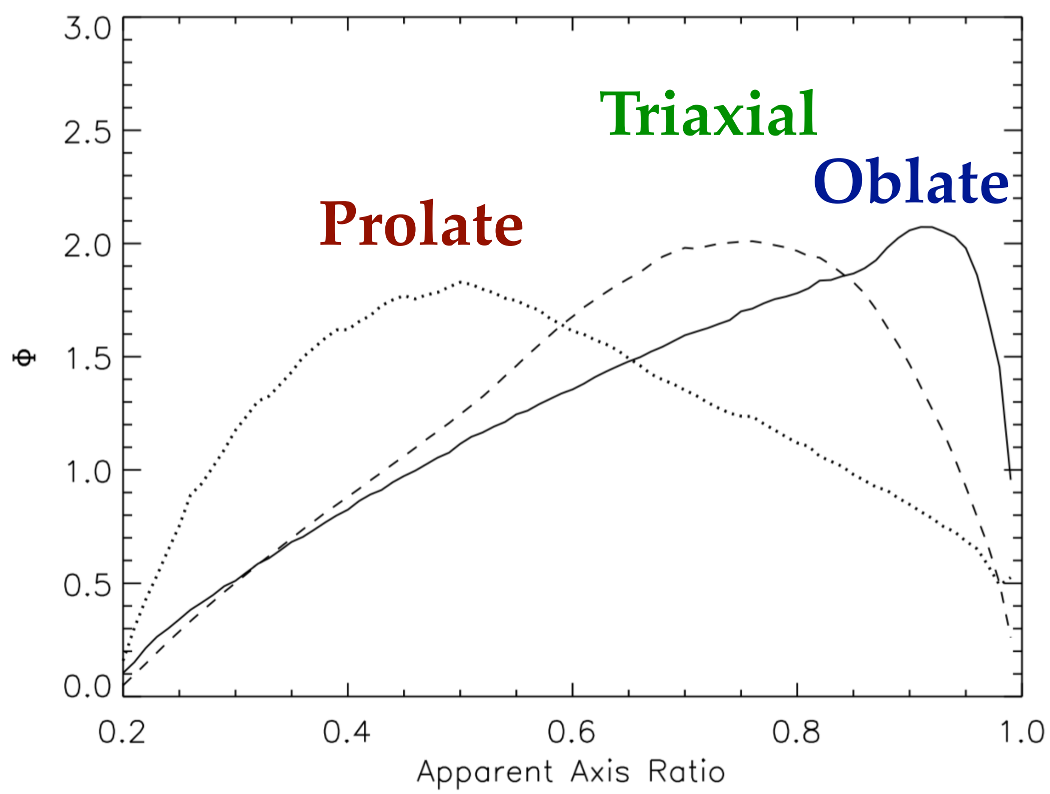


FIG. 2.— Apparent axis ratio distribution, Φ (i.e., the probability density of the projected shapes of a group of galaxies) for each type assuming a uniform intrinsic ARD. Solid, dotted, and dashed lines correspond to oblate, prolate, and triaxial, respectively.

Kimm et al. 2007

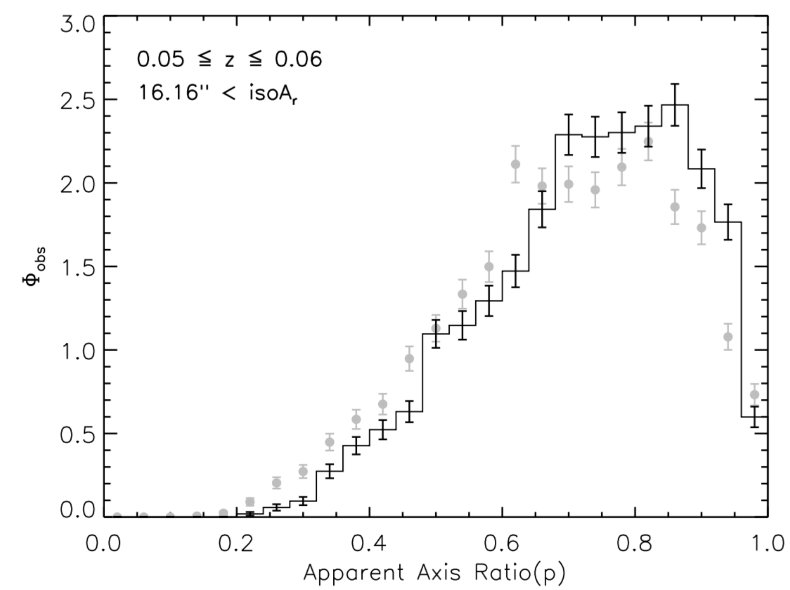


FIG. 4.— Our final SDSS sample compared to the previous APM sample of Loveday (1996) (Gray dots). We derive a relatively-complete sample concerning luminosity and major axis radius.

Kimm et al. 2007

- Distribution of axis ratios rules out purely prolate/oblate 3D shapes

Galaxy Population - Ellipticals/Spheroids: Recap

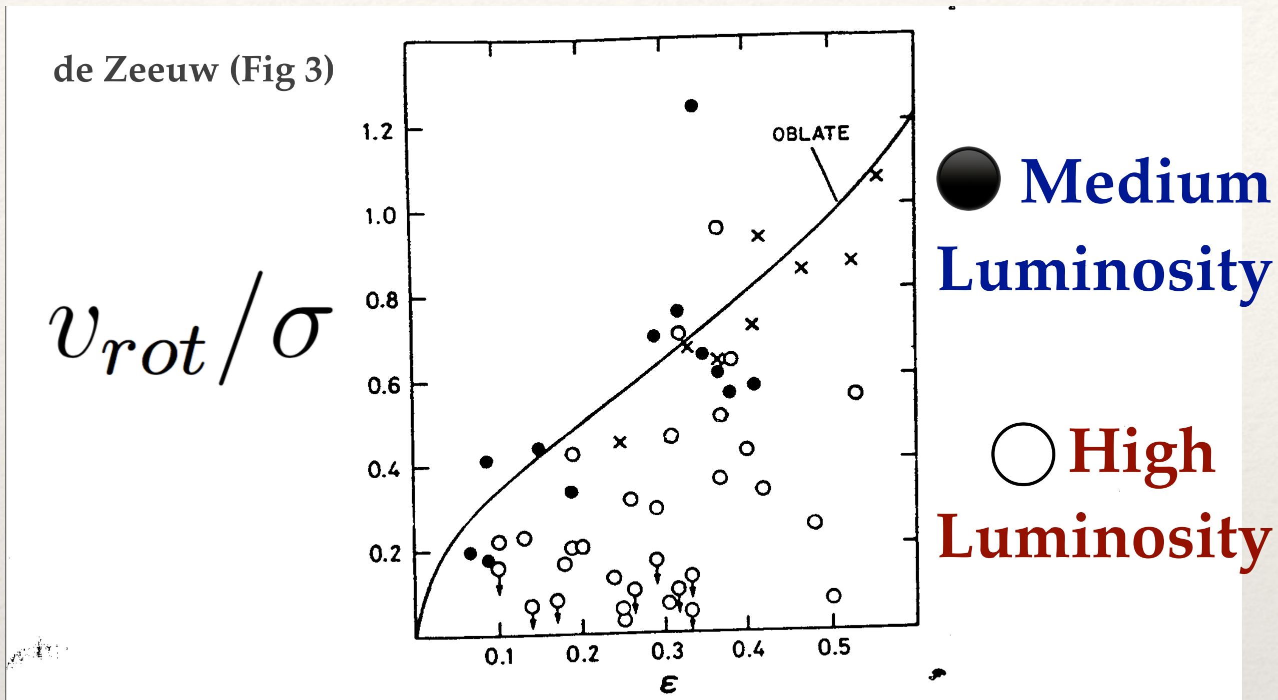
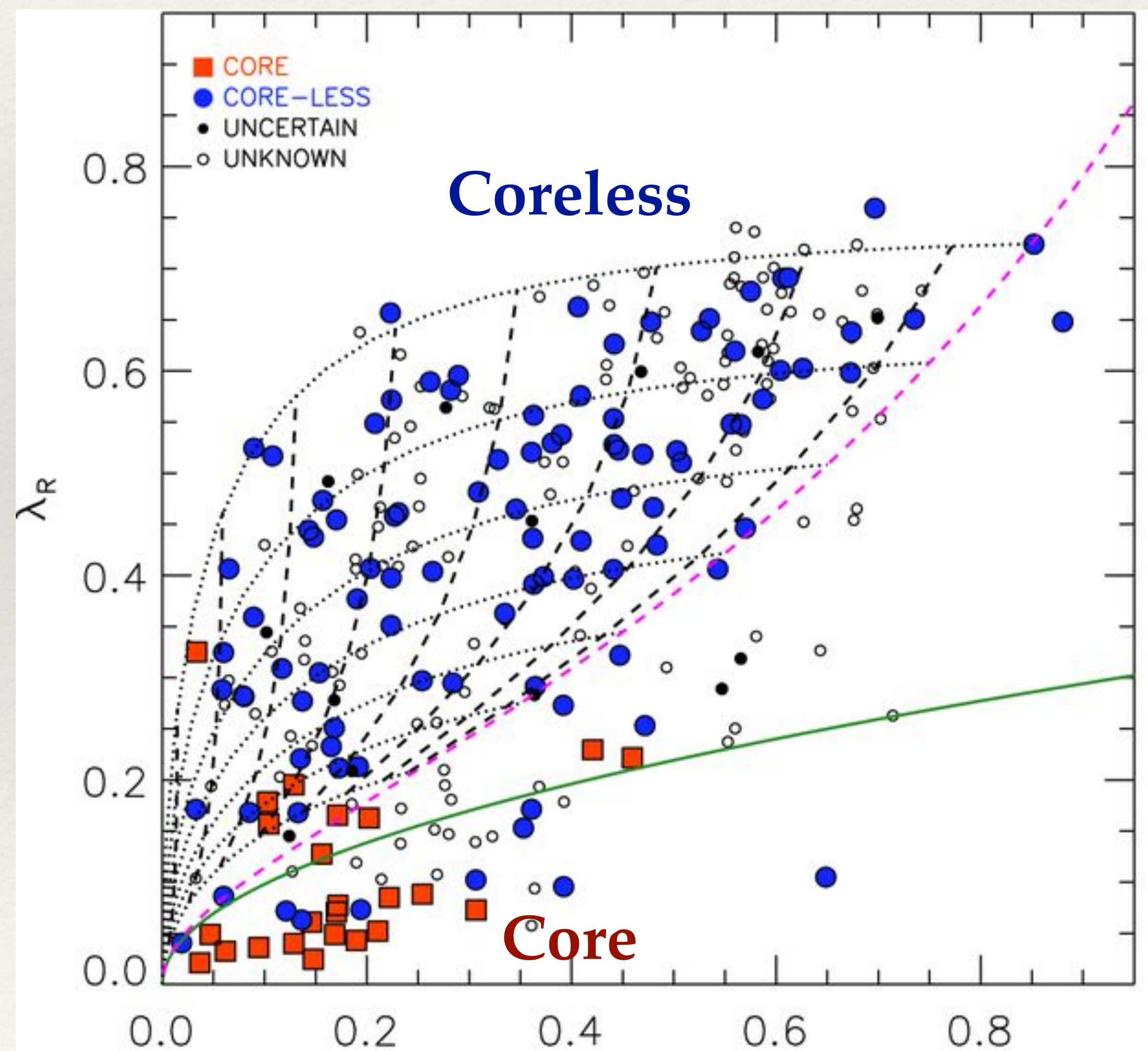


Figure 3: *Peak line-of-sight rotation velocity v_m divided by the mean velocity dispersion $\bar{\sigma}$ in the central region, as a function of apparent ellipticity ϵ. Open circles are luminous ellipticals with $M_B < -20^m.5$, filled circles are lower luminosity ellipticals and crosses are the bulges of spiral galaxies (Davies 1987). The solid curve is the mean line for oblate isotropic galaxies flattened by rotation.*

$$v_{rot}/\sigma = \sqrt{\epsilon/(1-\epsilon)}$$

- Others are clearly not rotationally flattened, and have flatter inner profiles

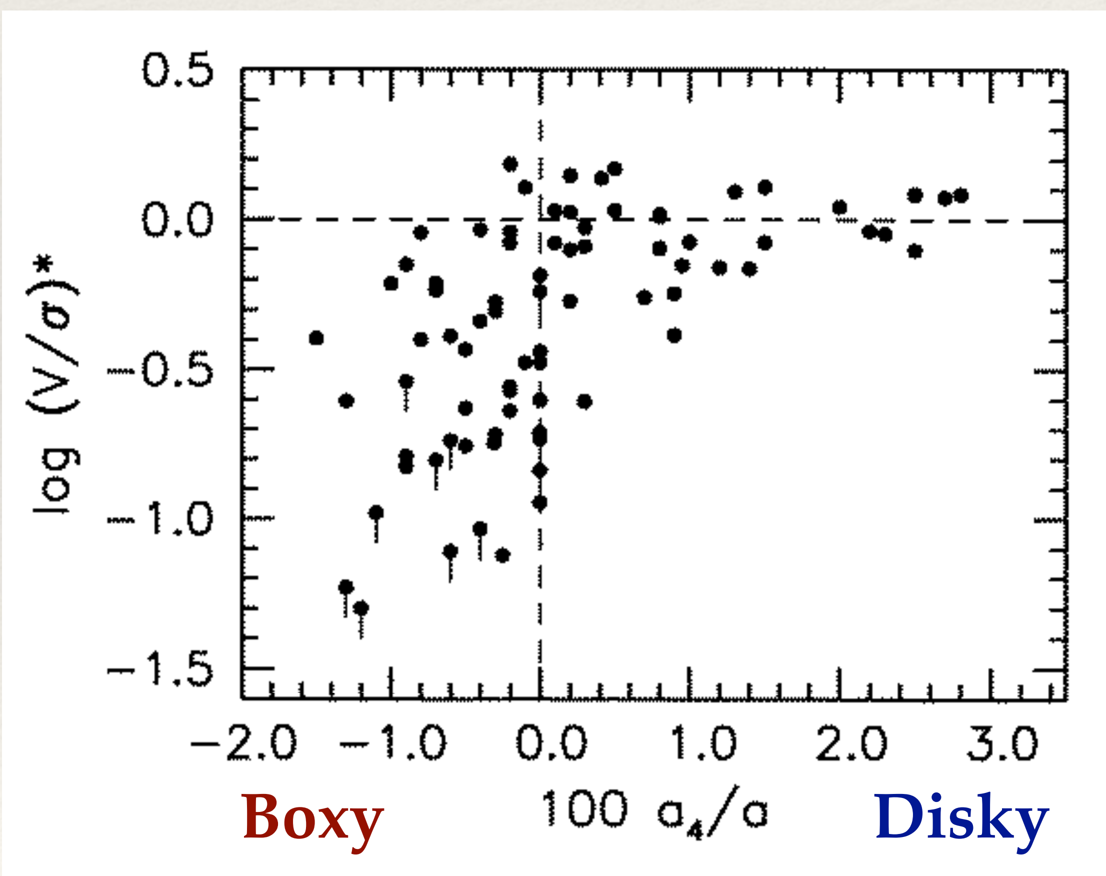
- Some are likely oblate, rotationally flattened, with steeper inner profiles



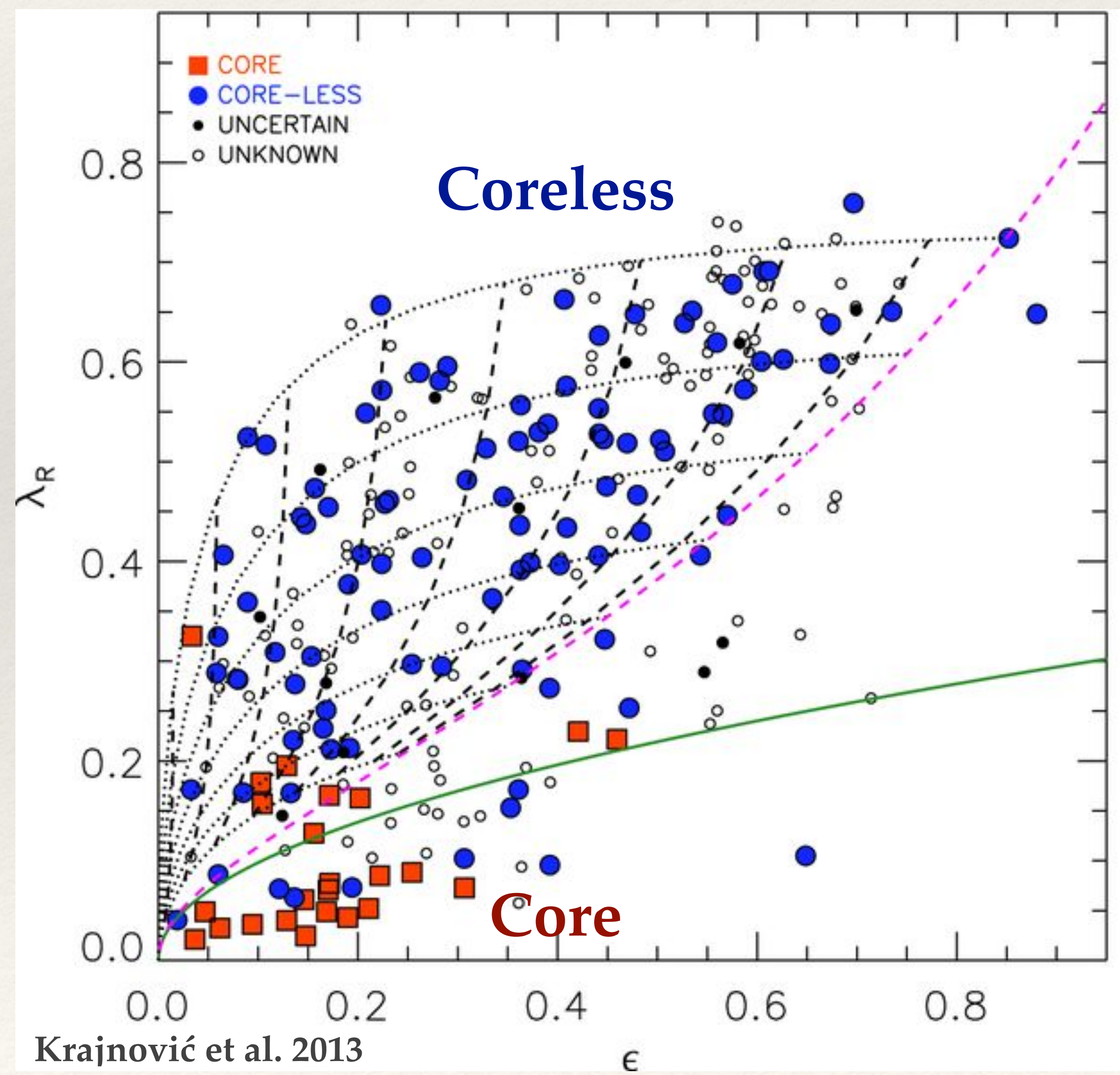
Krajnović et al. 2013

Galaxy Population - Ellipticals/Spheroids: Recap

- Differences in isophotal shape correlate with differences in kinematics and inner profiles, all hinting at different formation scenarios



Kormendy & Bender (Fig 2)



Krajnović et al. 2013

Galaxy Population - Ellipticals/Spheroids: Recap

- Fundamental Plane and other scaling relations imply Elliptical galaxies:
    - are relatively well described as virialized, self-similar (homologous) structures
    - have stellar populations that fulfill tight age and metallicity constraints, forming early and quickly
- Substantial evidence that mergers and interactions are important:
    - Inner profiles, non-axisymmetric features, diffuse ellipticals

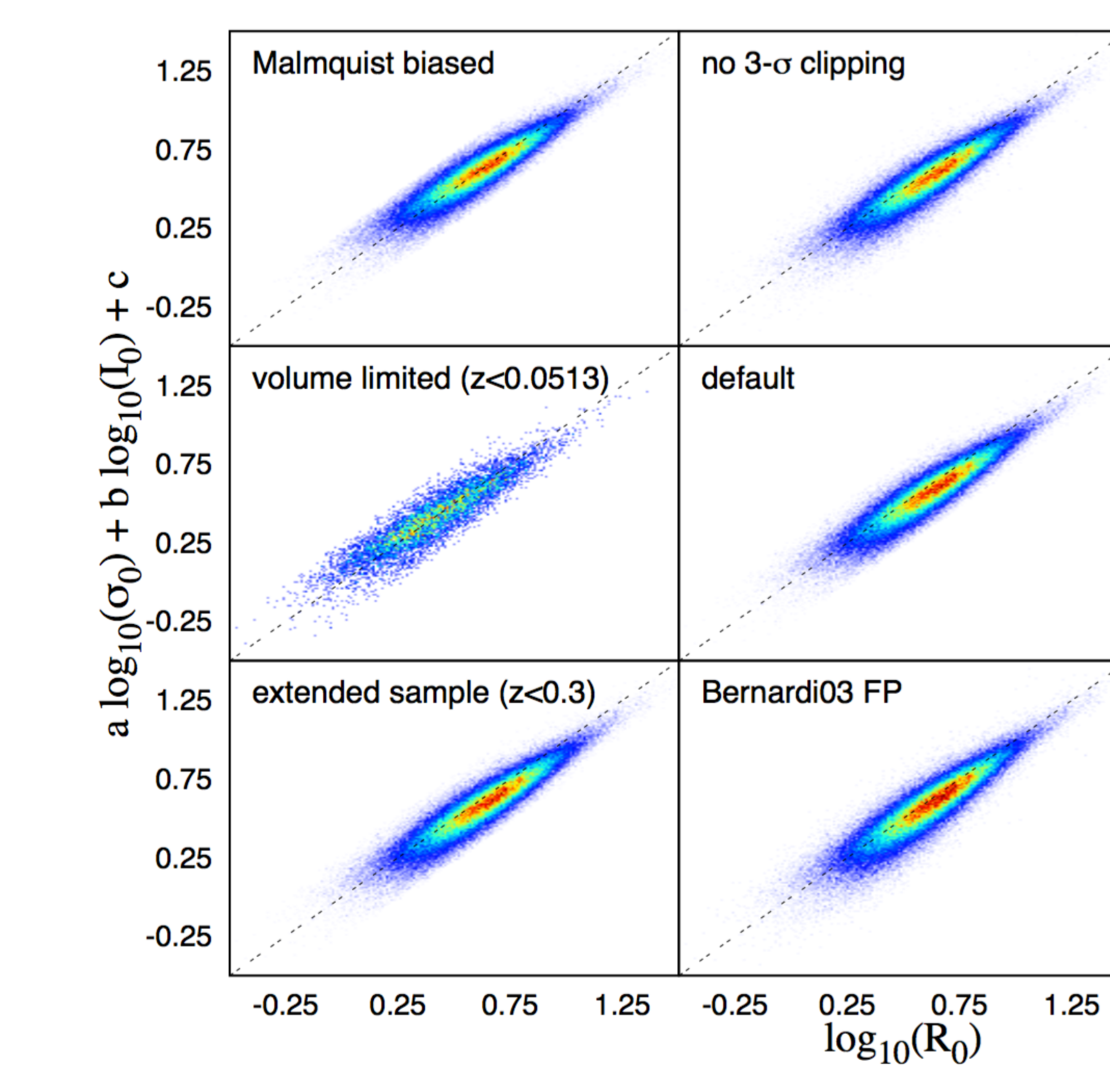


Figure 17. Results for the fundamental plane in the i band for the dV model using our alternatives
the Malmquist bias. We did not perform a 3-σ clipping for the plot in the top-middle panel. Th
evolution. The results of the volume-limited sample (z < 0.0513) can be found in the central-left
the default i band fit for the dV model for comparison. We are considering the surface brightness
form galaxy number densities in the central-right panel. In the bottom-left panel, the results are
fundamental plane plotted using the coefficients of Bernardi et al. (2003c), but with our sample
similar plot using the coefficients of Hyde & Bernardi (2009) can be found in the bottom-right p

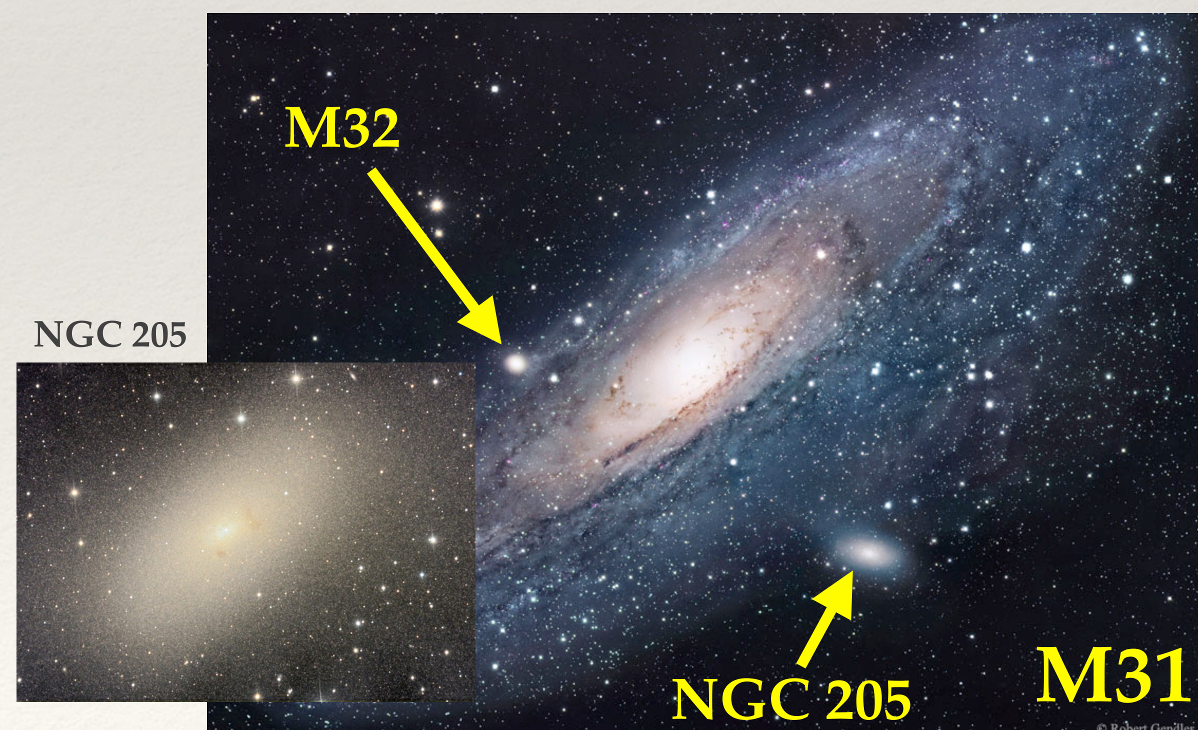
Saulder+2013, A&A

Galaxy Population - Ellipticals/Spheroids: Recap

- How do Elliptical galaxies form?:
  - Medium/high luminosity "normal" ellipticals —
    - early formation of stellar population
    - dissipational ("wet") mergers — disky, oblate, fast rotators with steep inner profile (induced star formation)
    - dissipationless ("dry") mergers — boxy, slow rotators, with flatter inner profile (binary central black holes)
  - Low luminosity "diffuse" ellipticals/dSph —
    - irregular/disk galaxies transformed via gas stripping and harassment?

NGC4636

NGC 205



https://apod.nasa.gov/apod/ap150830.html