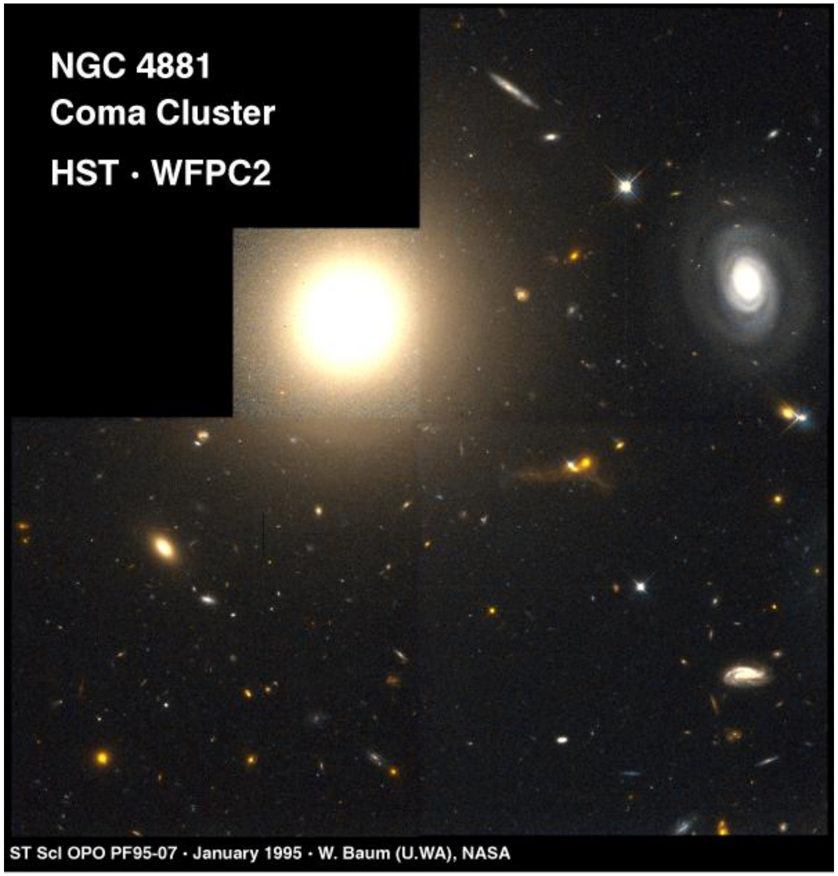
# ASTR 303
# Elliptical Galaxies

1. Introduction
2. Photometry
3. Stellar Motions
4. The Faber-Jackson relation and the Fundamental Plane
5. Stellar Populations
6. Central black holes




# Elliptical Galaxies

- Smooth stellar objects
- Prevalent in galaxy clusters and other regions of high density
- Deceptively simple shapes (dynamical equilibrium?)
- Little cold gas or star formation
- Much more centrally concentrated than spirals

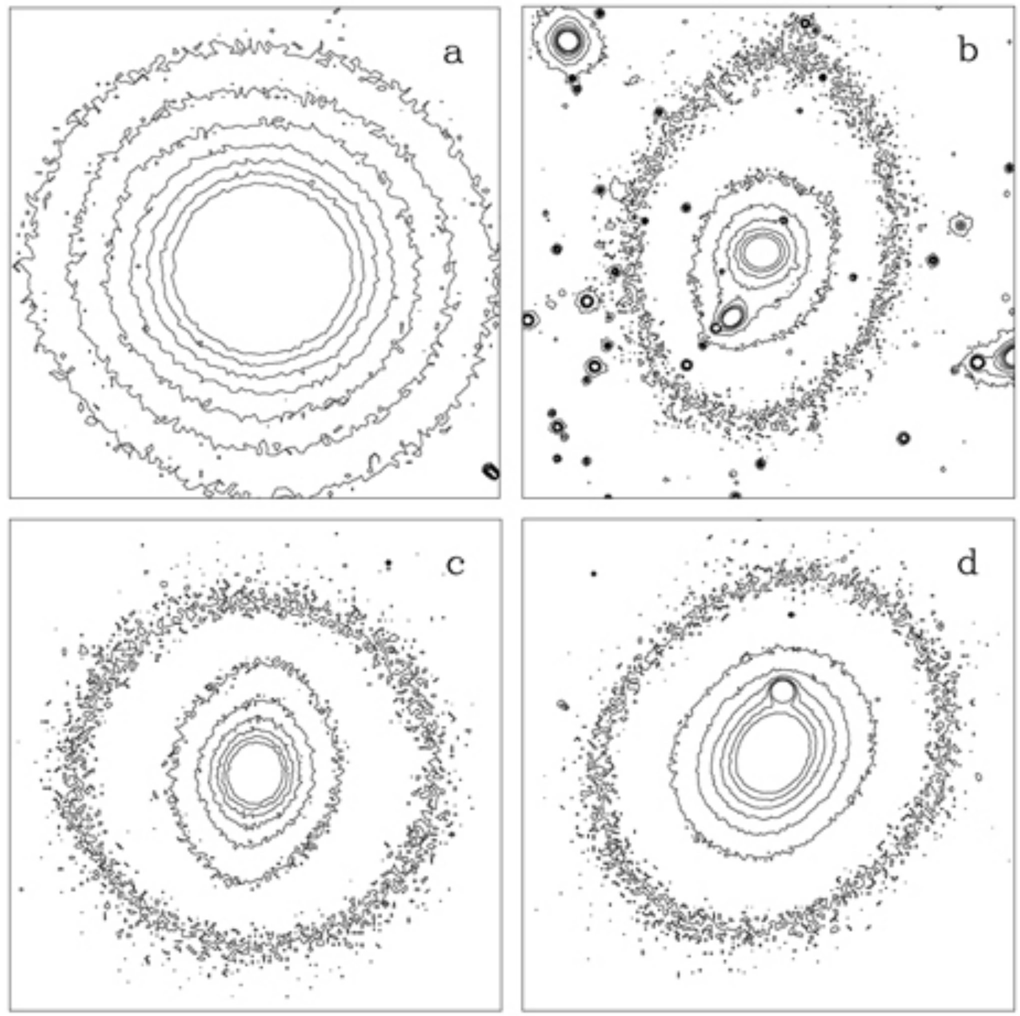


# Elliptical Galaxies

- Structure (triaxiality, rotation, etc) correlates with luminosity
- Slow rotators, even when flattened
- Span a very wide range in luminosity:
  - both the brightest and faintest galaxies known are ellipticals!
- Bright ellipticals surrounded by tenuous halos of hot gas (visible in the X-rays)
- Little evidence for dark matter within the "optical radius"


# Photometry of Elliptical Galaxies

- Isophotes of elliptical galaxies are usually quite regular
  - Well approximated by ellipses of axes *a* and *b*
  - Typically classified by its apparent ellipticity; E*n* with *n=10*(1-b/a)*
  - Depends on viewing direction!



# Photometry of Elliptical Galaxies

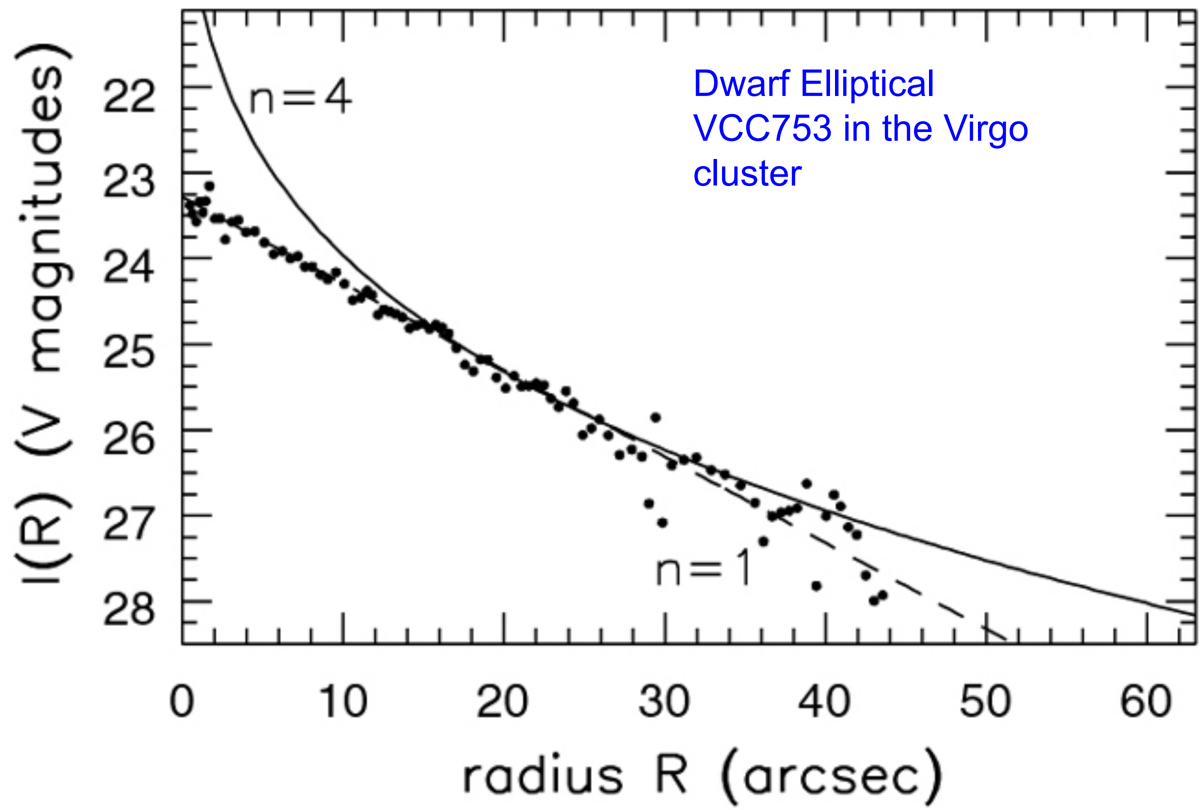
- Radial dependence well approximated by "Sérsic's law:

$$I(R) = I(0)\exp[-(R/R_0)^{1/n}].$$

José Luis Sérsic

- The exponent n depends on the galaxy's luminosity:
  - n~1 for L<L*
  - n~4 for L>L*

  ($L^* \sim 2e10\ L_{sun}$)



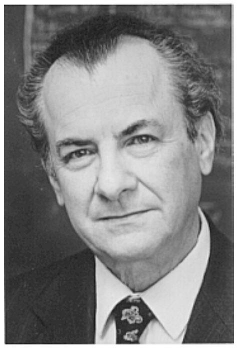
# Photometry of Elliptical Galaxies

José Luis Sérsic

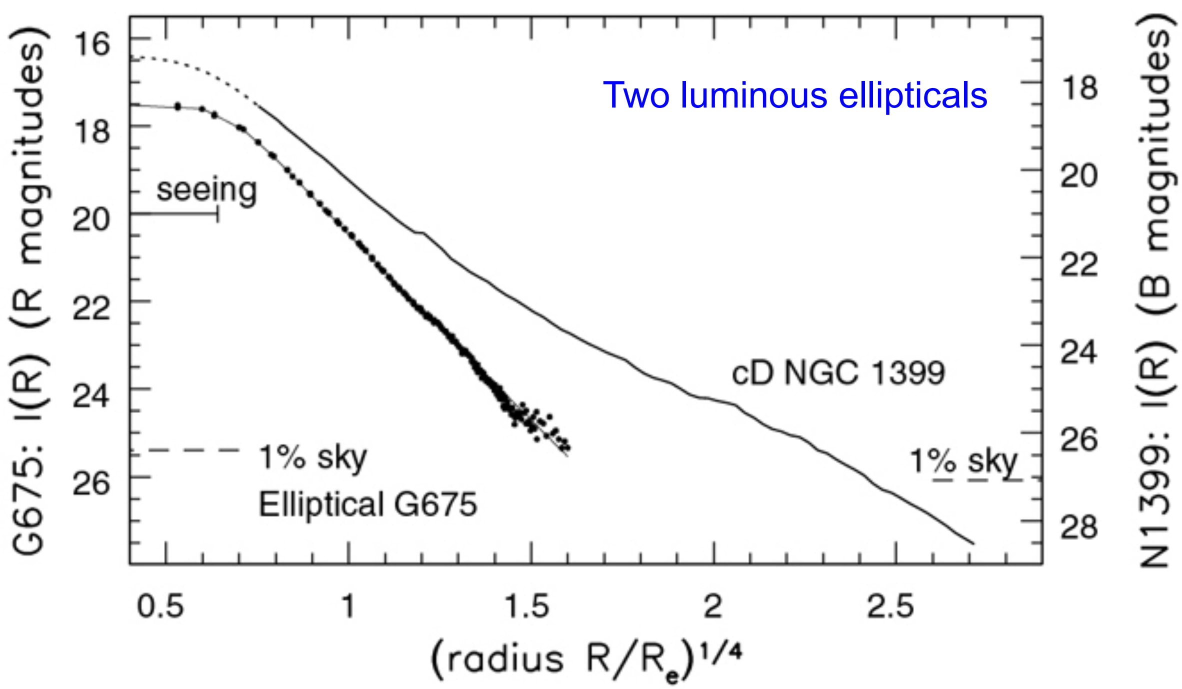
- Sérsic's law may also be written as

$$I(R)=I(R_{eff})*\exp\{-b*[(R/R_{eff})^{1/n} - 1]\}$$

- Where $R_{eff}$ is the "effective radius" enclosing half of the total light of the galaxy and b=2*n-0.327
- *n=4* fits well bright ellipticals. This is *de Vaucouleurs' law*.

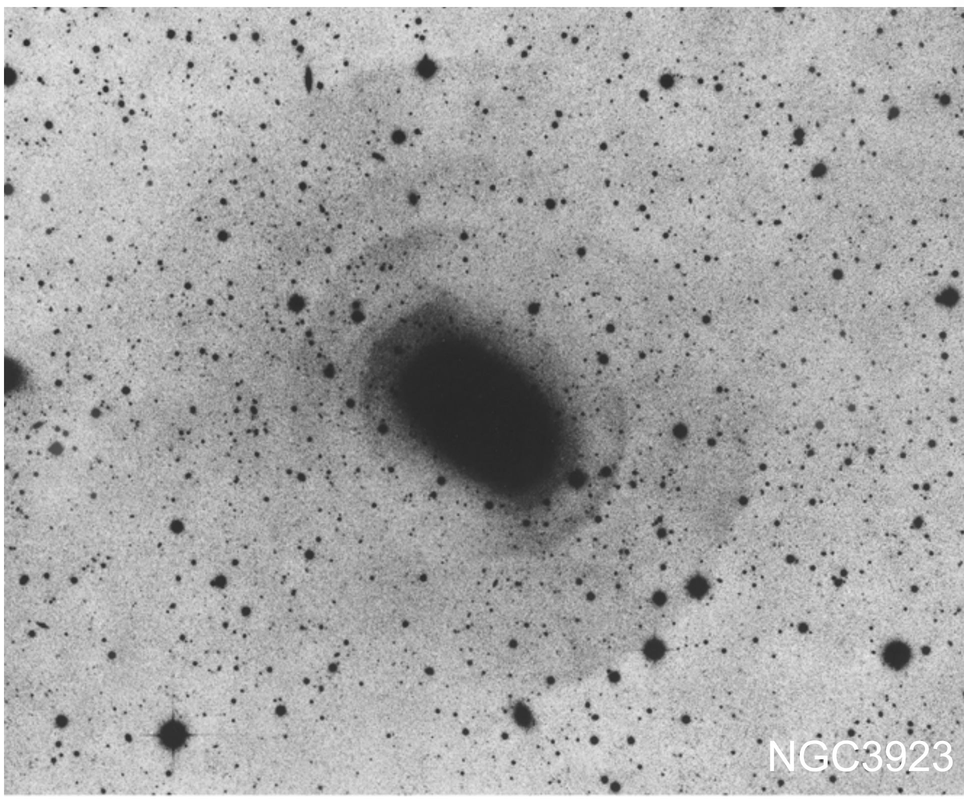


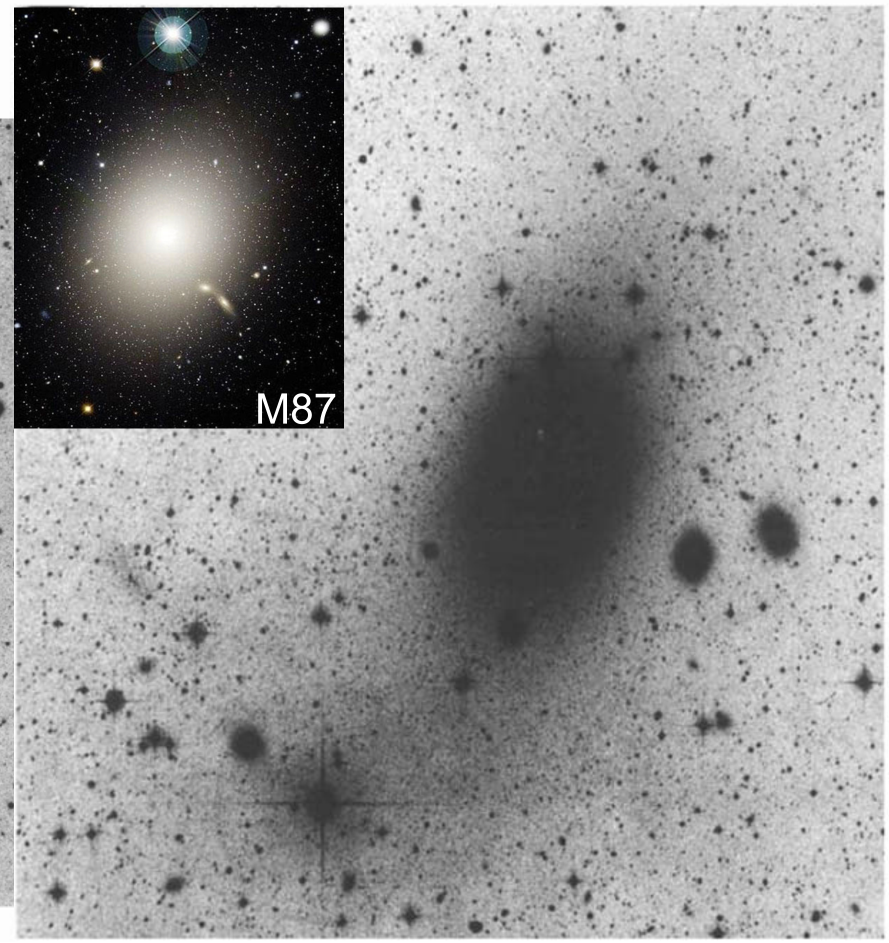
Gérard de Vaucouleurs



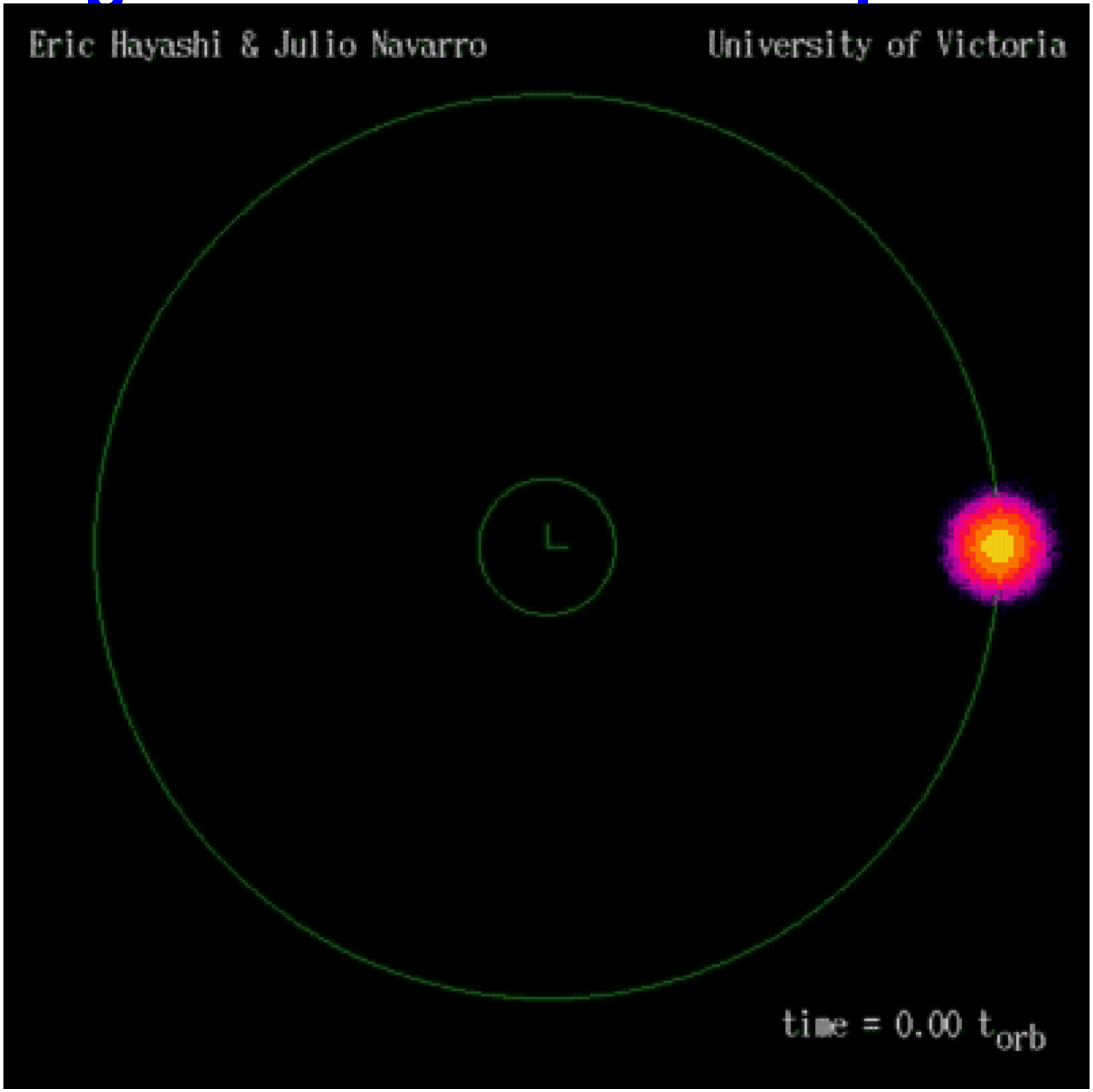
# Outskirts of Elliptical Galaxies

- Shells, ripples, and other non-axisymmetric features reveal the turbulent dynamical past of elliptical galaxies---many of them are thought to be *the remnants of ancient mergers*



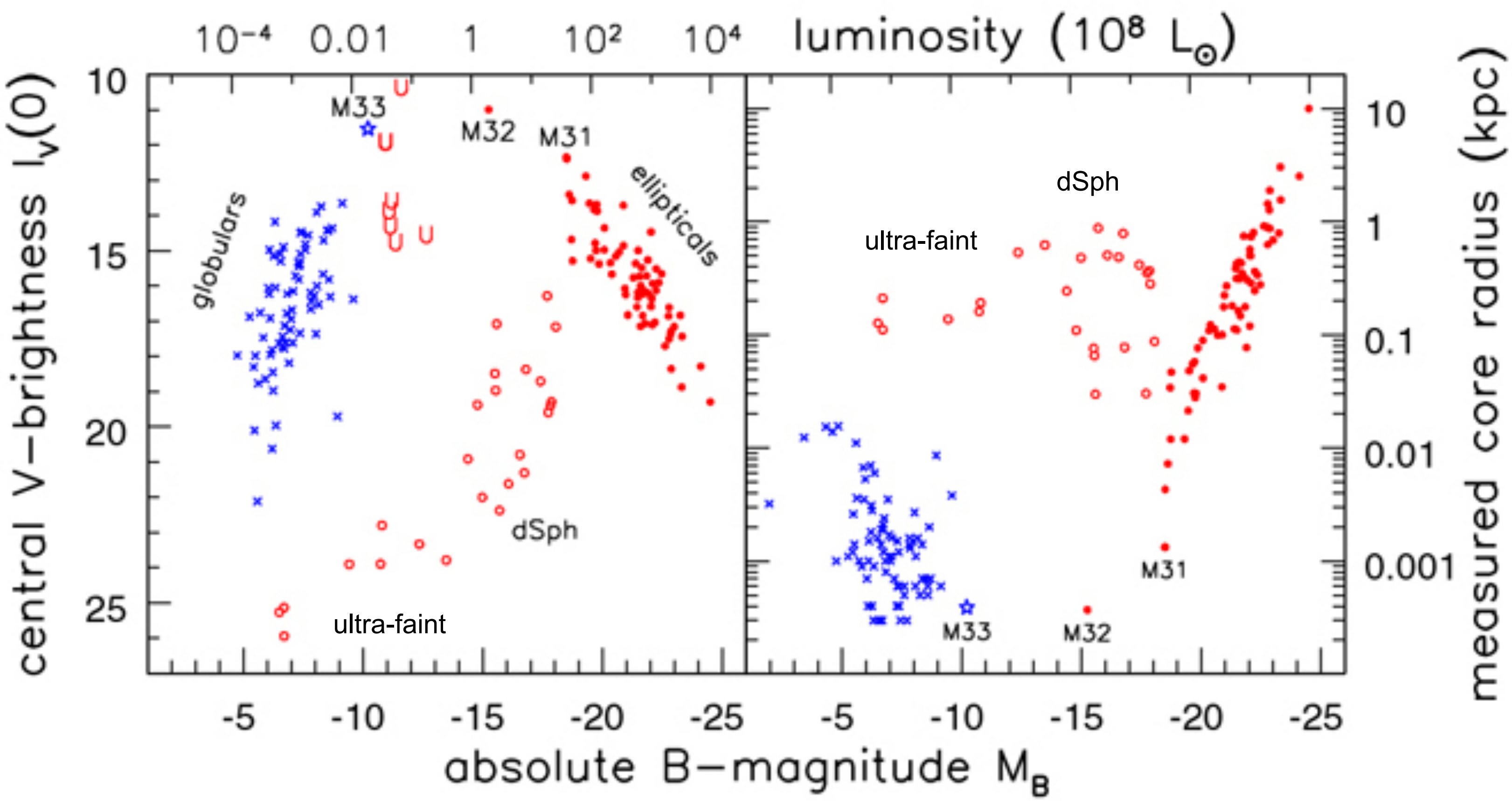
# Signatures of tidal disruption



# Signatures of merger events

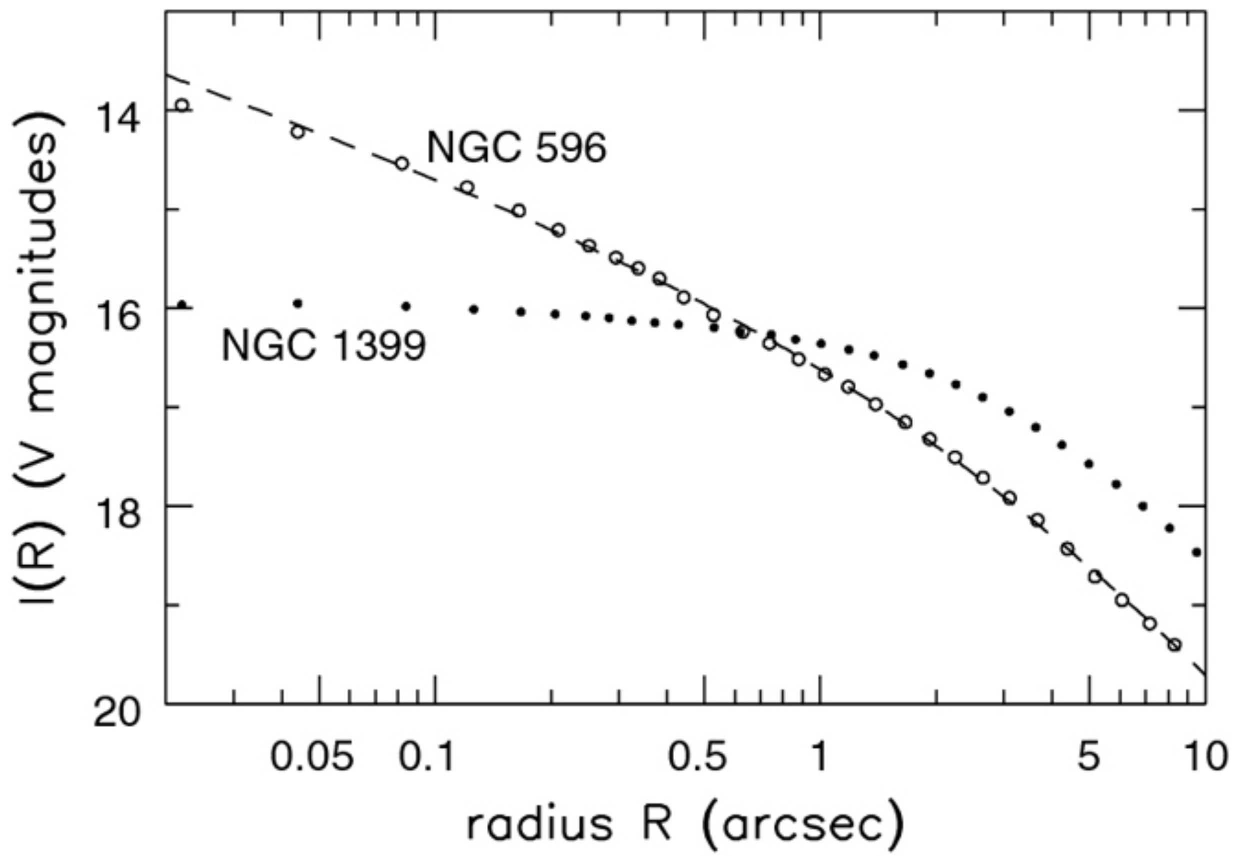
# Luminosity and Structure

- Luminosity and structure are highly correlated in elliptical galaxies:
  - The two branches in the size-luminosity plane distinguish "spheroidals" from "ellipticals"



# Cusps vs Cores

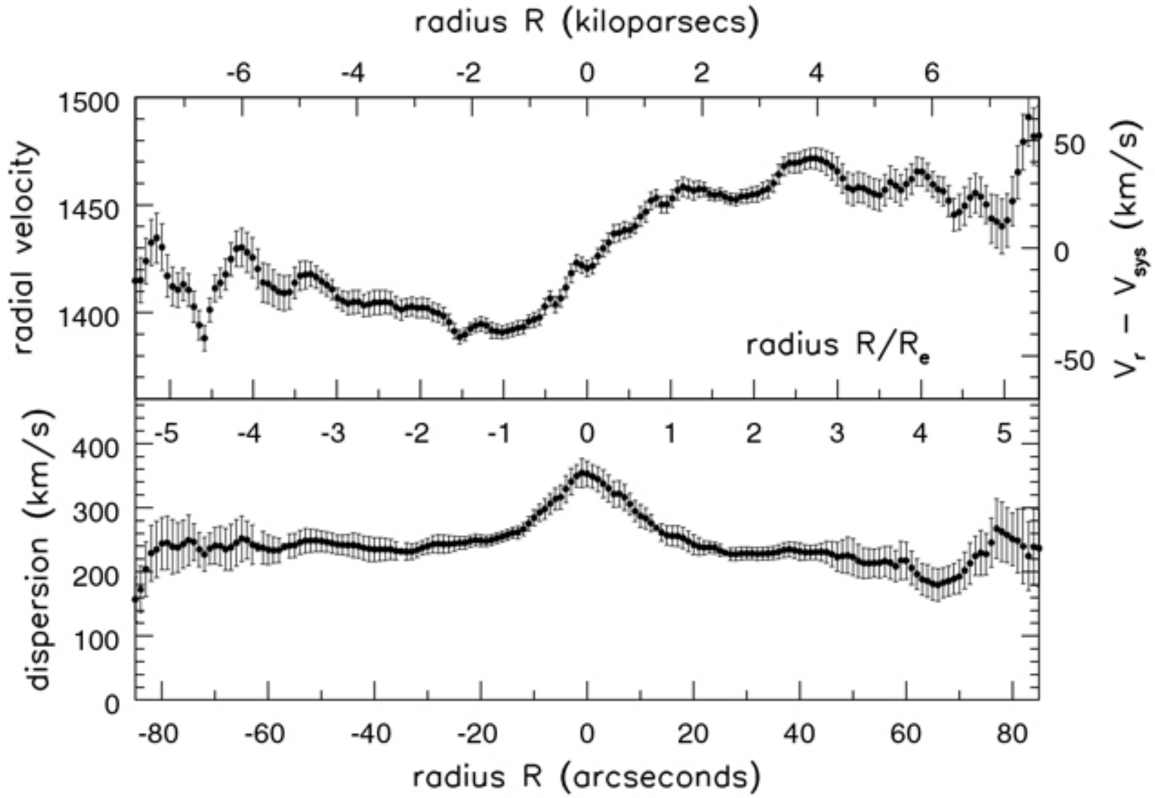
- The brightest ellipticals differ from the faintest in their very inner structure: a constant surface brightness “core” or an ever rising “cusp”




Data from the Hubble Space Telescope:
- Origin of this dichotomy?
- SMBHs?

# Stellar Kinematics

- The mean velocity and velocity dispersion may be measured as a function of distance from the center using a long slit (typically placed along the major axis.
  - Note the slow rotation characteristic of ellipticals ($V_{rot}/\sigma<1$)



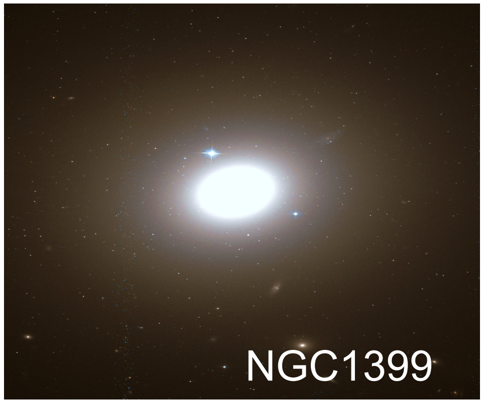

# The “Fundamental Plane” of Ellipticals

- According to the Virial Theorem, mass, velocity dispersion and size are governed by the relation $M \sim \sigma^2 * R$.
  - This defines a “plane” in the mass-size-velocity 3D space when expressed in logarithmic units

    $\log(M)-2*\log(\sigma)-\log(R)=0$ (eq. of a plane in 3D)
  - If the mass was proportional to the total luminosity, then we would have, in terms of the surface brightness, $\Sigma \sim L/R^2$, or

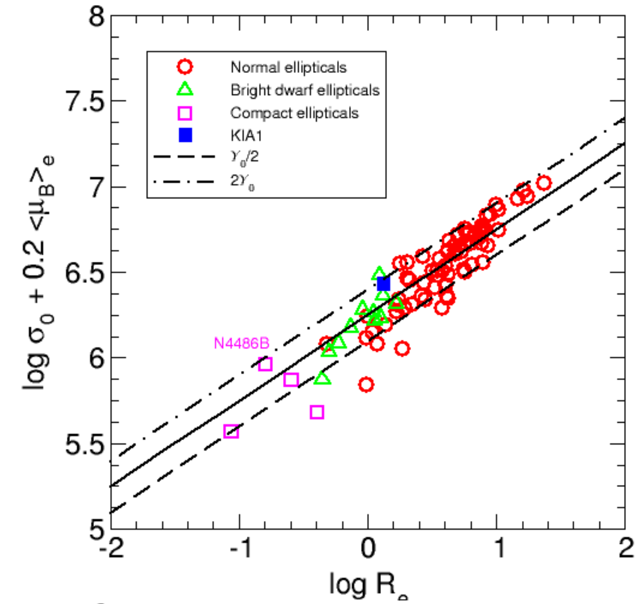
    $\log(\sigma)+0.2*\mu=const*\log(R)$

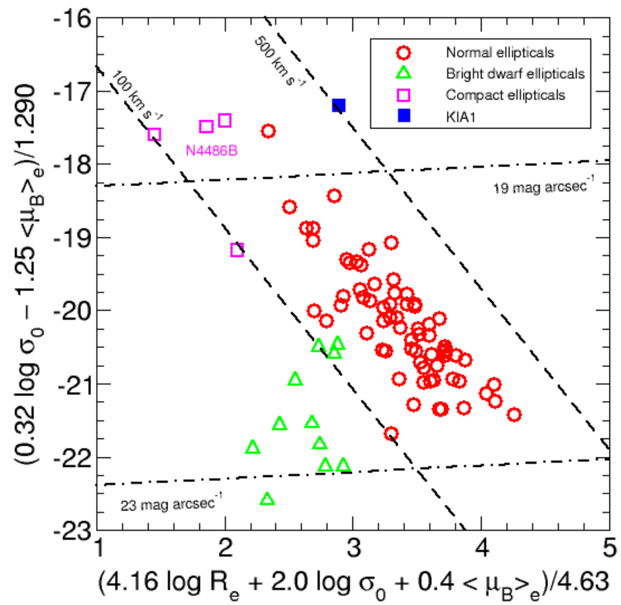
    when expressing the surface brightness in magnitude units: $\mu \sim -2.5\log(\Sigma)$

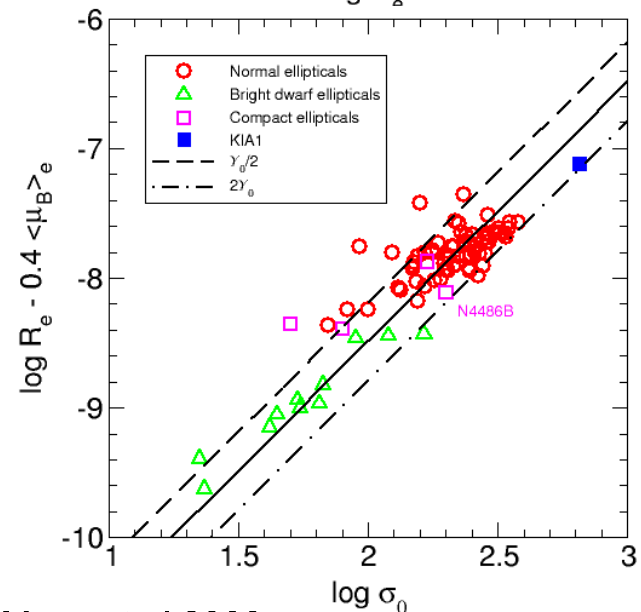


# The “Fundamental Plane” of Ellipticals

- Ellipticals follow such relations pretty accurately. These are two “edge-on” views and one “face-on” view of the Fundamental Plane of ellipticals in the Coma cluster.




Meza et al 2003

# Notes on the “Fundamental Plane” of Ellipticals

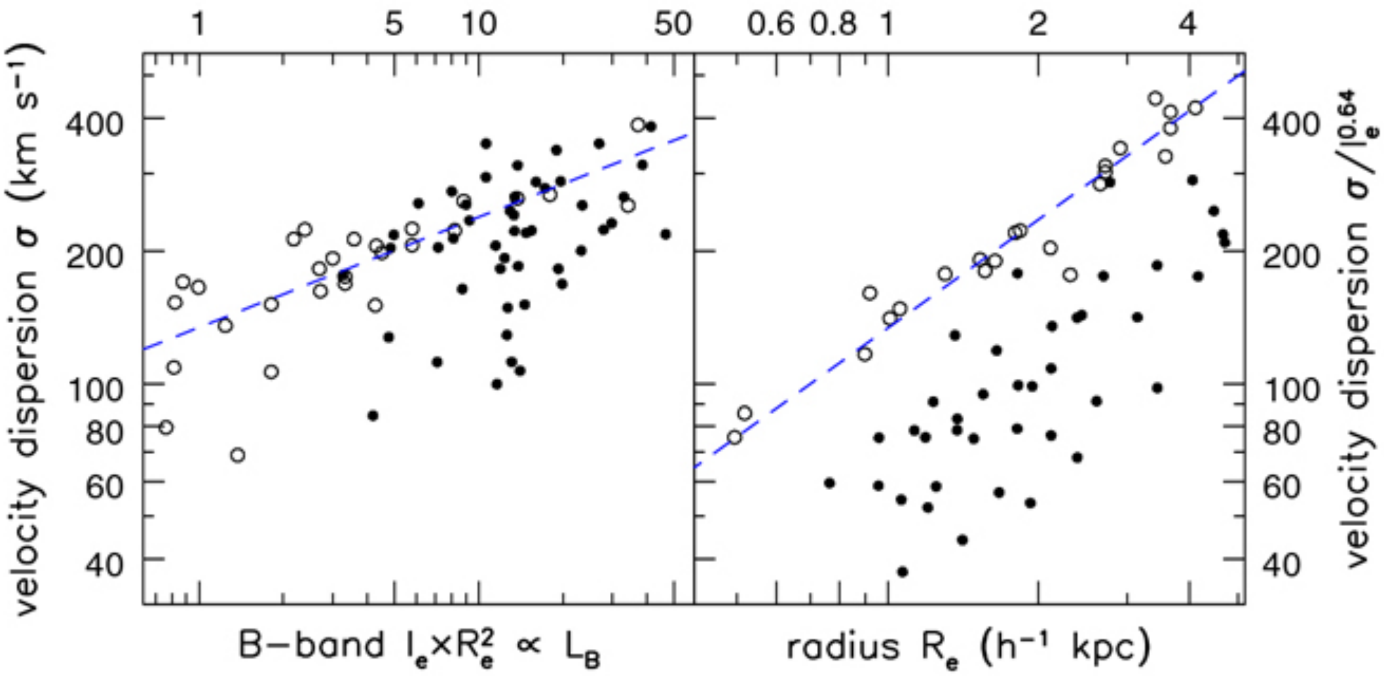
- The “best-fitting” plane in Coma has coefficients

$$R \sim \sigma^{1.2} * \Sigma^{-0.8} \sim \sigma^{6/5} * \Sigma^{-4/5}$$

  This is different than expected from the virial theorem

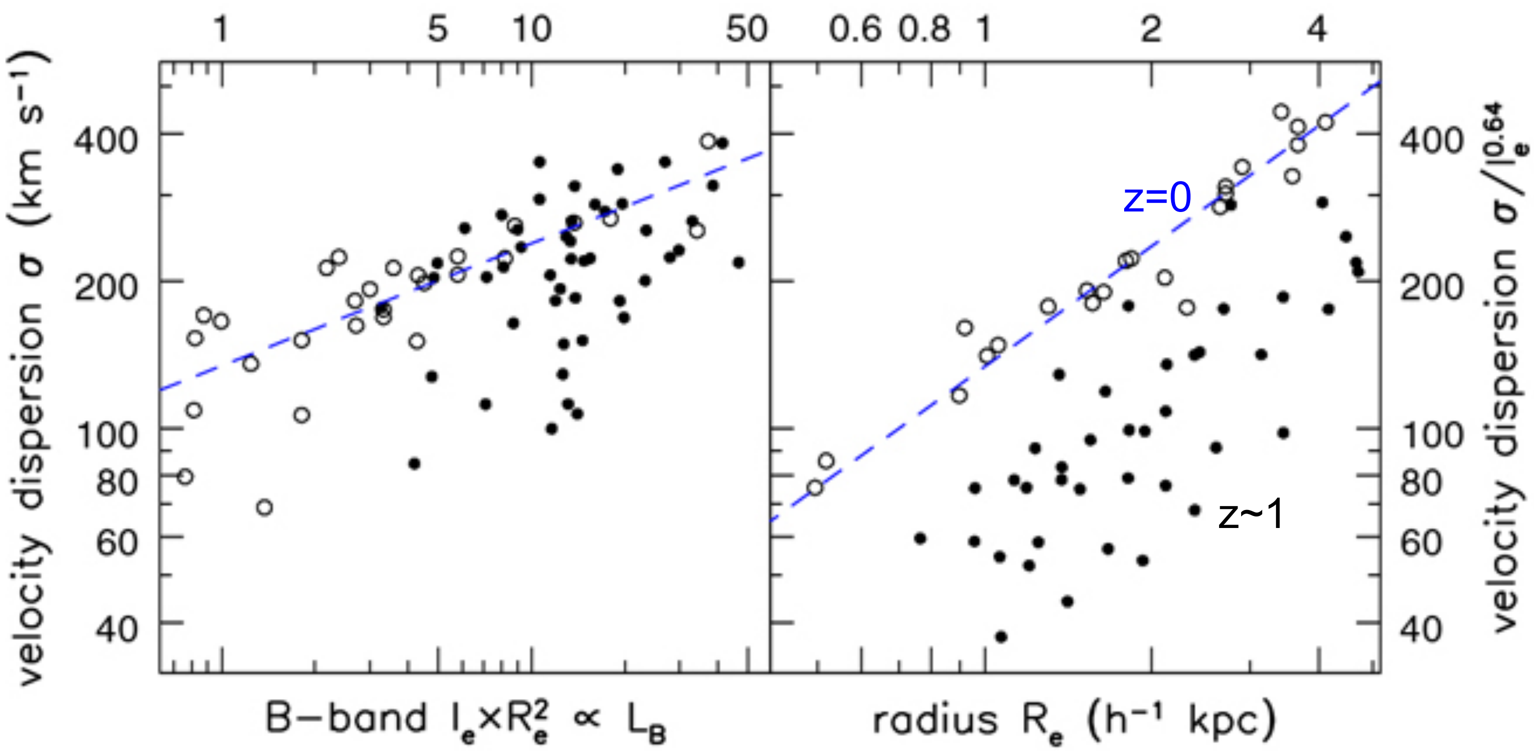
$$R \sim \sigma^{2} * \Sigma^{-1}$$

- This “tilt” of the Fundamental Plane suggests that the mass-to-light ratio in ellipticals increases with luminosity.



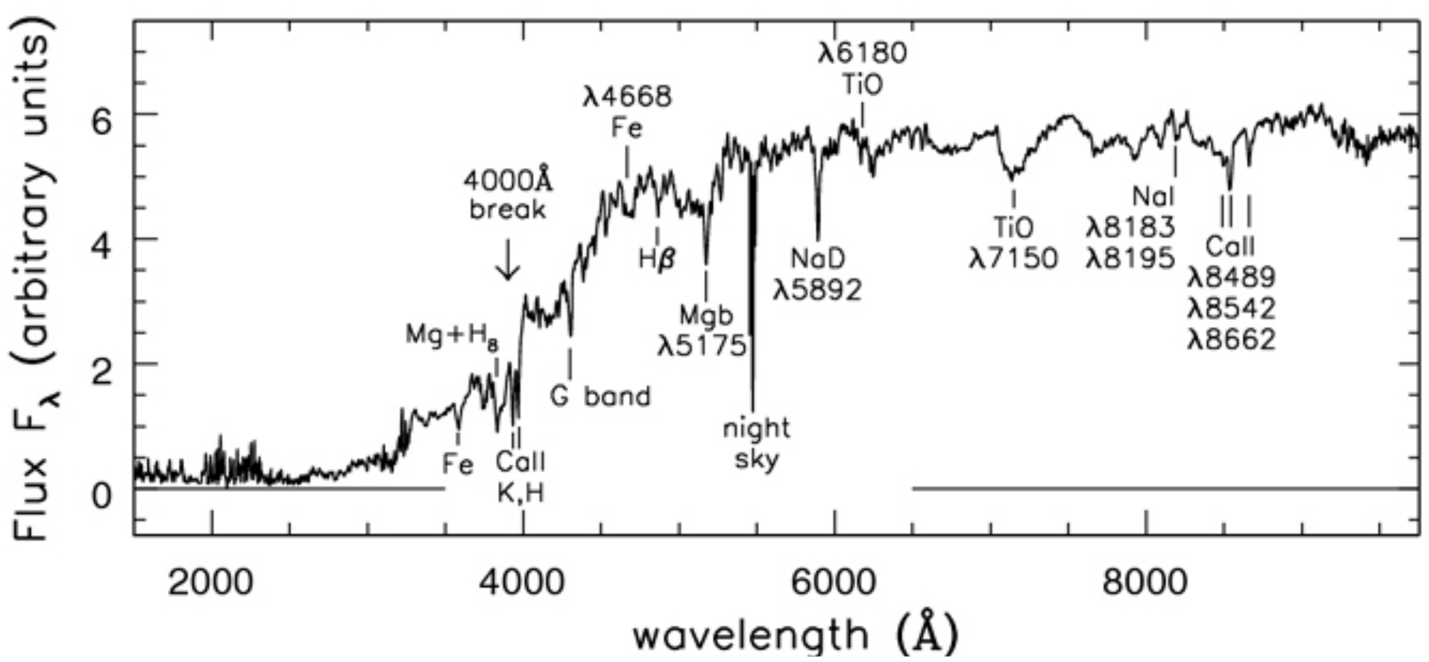
# Notes on the "Fundamental Plane" of Ellipticals

- The "tilt" of the Fundamental Plane depends on wavelength (what band has been used for the photometry?) and also on redshift (younger stellar populations are brighter on average than older ones)



# Stellar Populations in Ellipticals

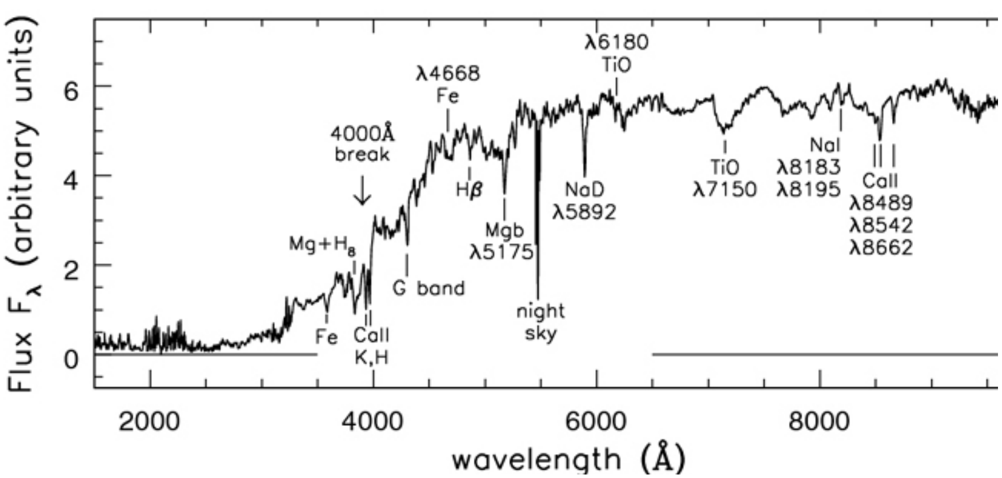
- Ellipticals lack luminous bright stars; the brightest stars are red giants and AGB stars.
- The integrated spectrum of an elliptical shows mostly absorption lines with little flux at short wavelengths
  - no stars have formed in the most recent ~2Gyr or more.
- The sudden “break” in the spectrum at ~4000 Angstroms and the deep absorption lines of Fe, Mg, etc, are indicative of the presence of heavy elements in stars



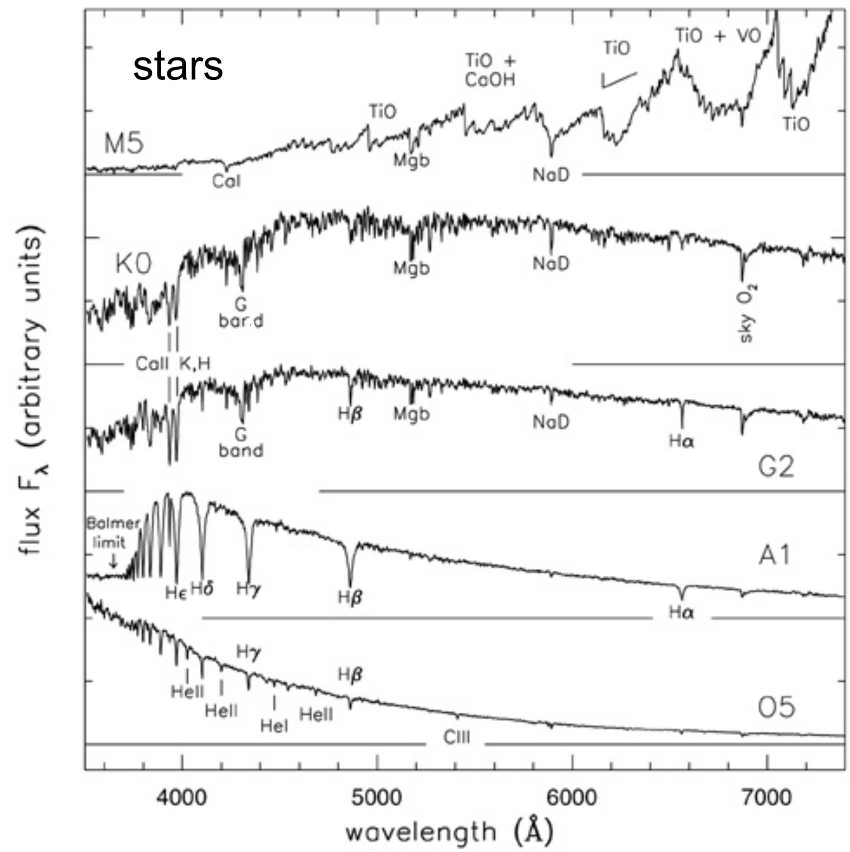
# Spectra of stars and galaxies

- Note resemblance between the spectra of elliptical galaxies and those of late-type stars, mostly K giants.
- No emission lines, which are prevalent in galaxies with ongoing star formation.

Elliptical galaxy



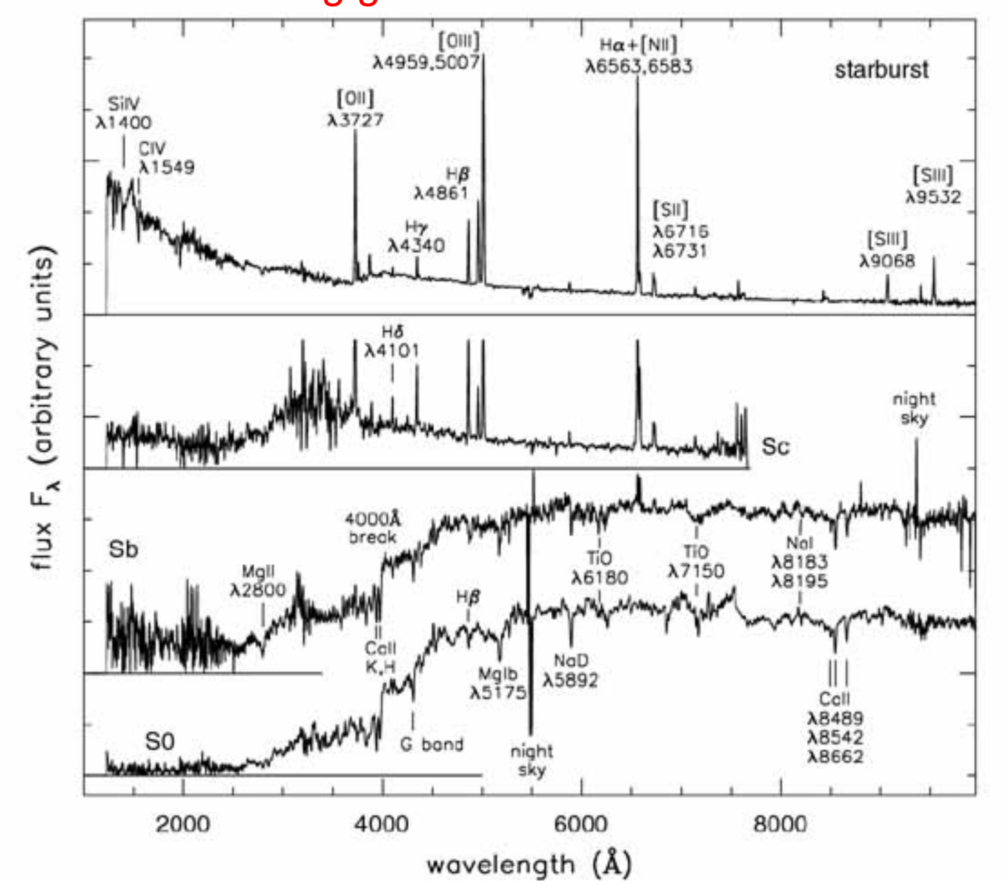

stars

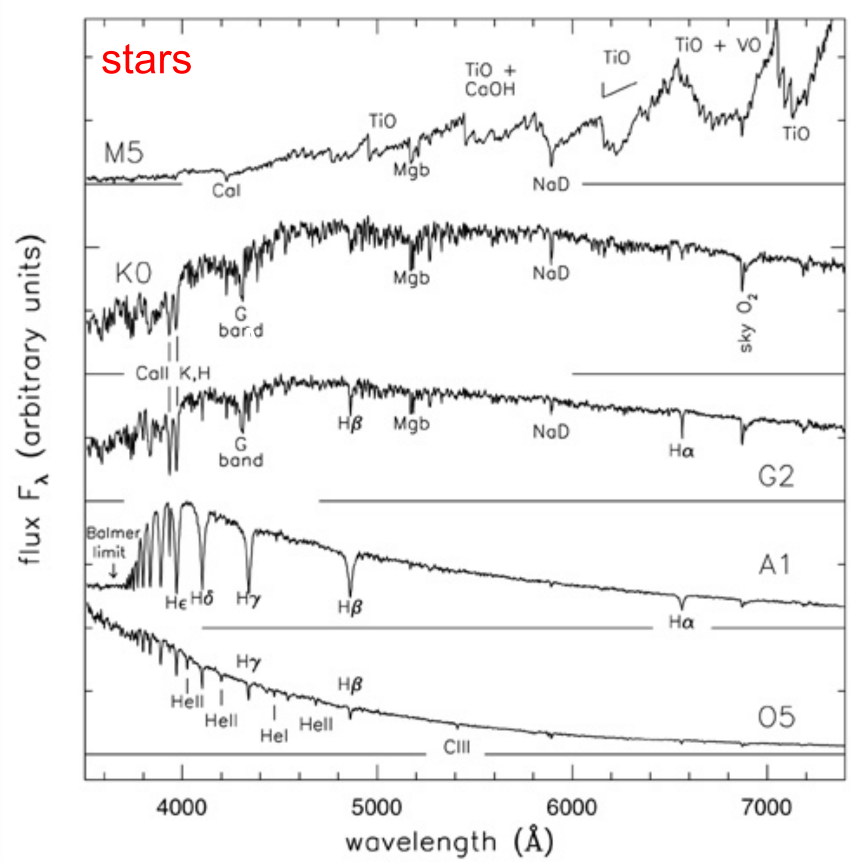


# Spectra of stars and galaxies

- Spiral galaxies, on the other hand, show evidence for the presence of hot, massive stars and young stellar populations
- Except for S0s, which look like ellipticals in their spectrum

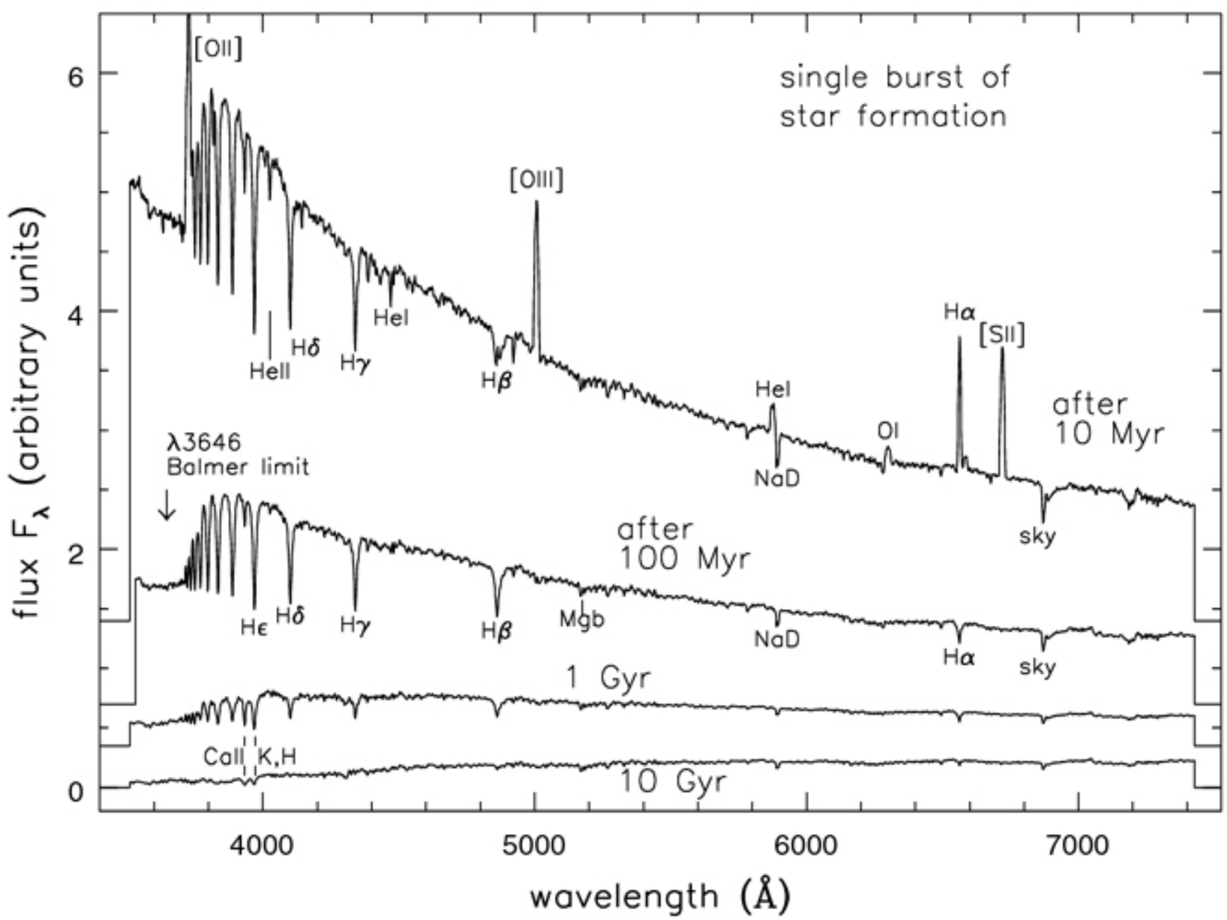
Star forming galaxies



# Stellar population synthesis models

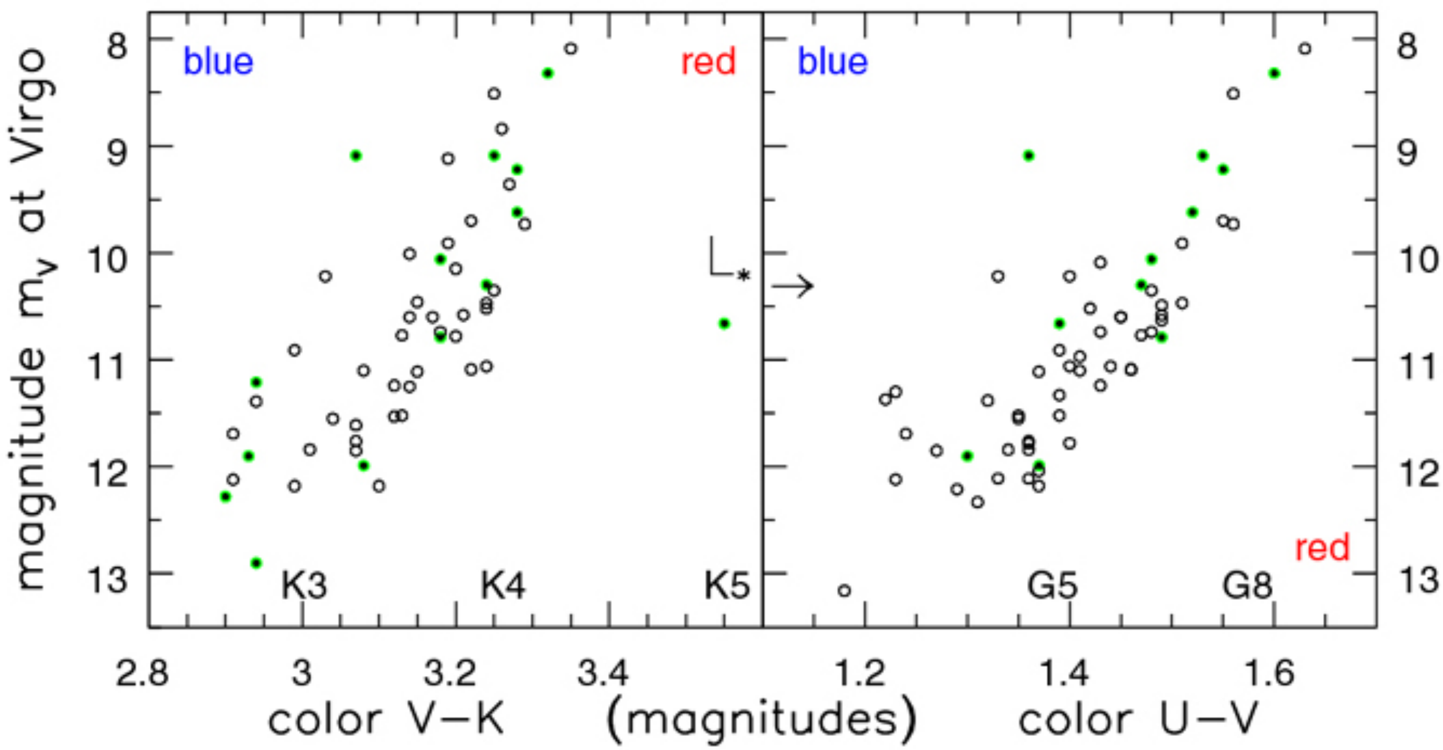
- These models predict the integrated spectrum of light emitted by stellar populations created at different times by integrating the spectrum of a single burst and convolved over time.



# Age-metallicity degeneracy

- Brighter ellipticals are redder than fainter ones.
- Not clear from colors whether this is a result of the fact that
  - (i) more luminous ellipticals are older

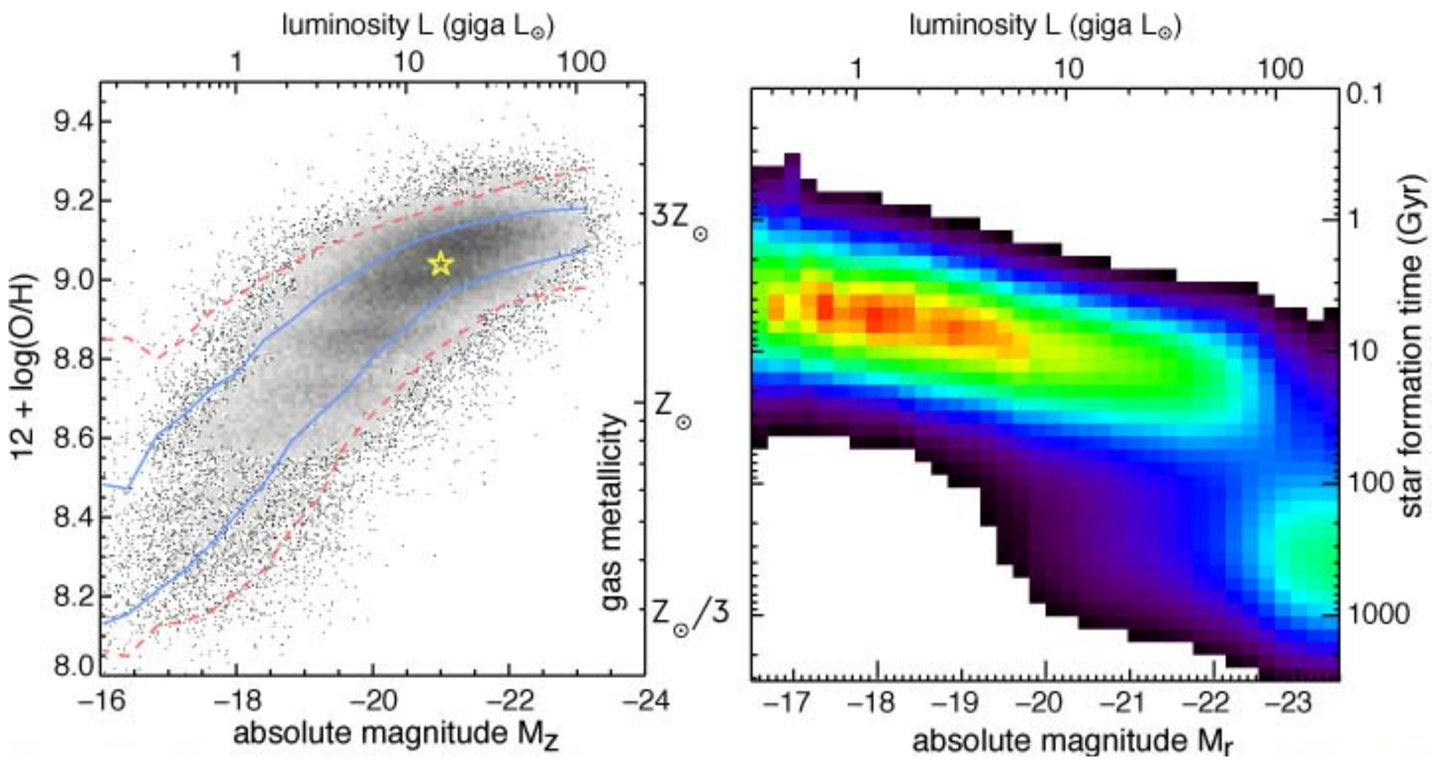
  or
  - (ii) more luminous ellipticals are richer in heavy elements (Fe, Mg, O, etc)



# Age-metallicity degeneracy

- Recent data (mostly from the Sloan Digital Sky Survey) show conclusively that brighter galaxies are more metal rich.
- They also show that galaxies are *bimodal*: most of them lie in two sequences
  - (i) the red sequence

  and
  - (ii) the blue cloud



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  - (i) the red sequence

  and
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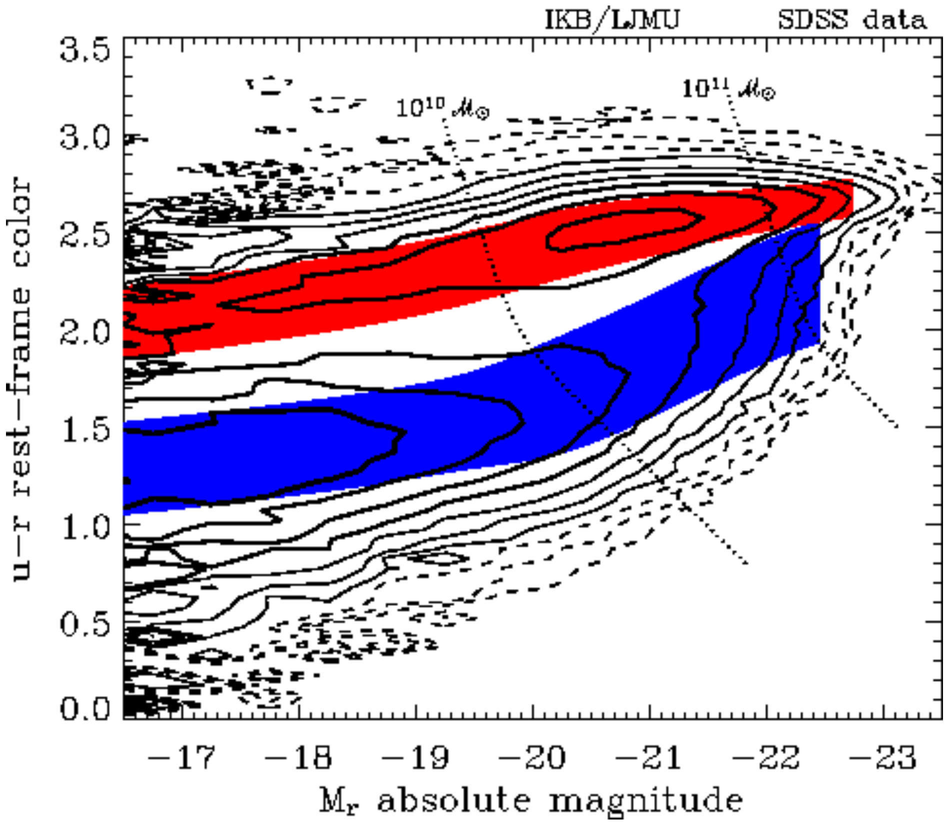
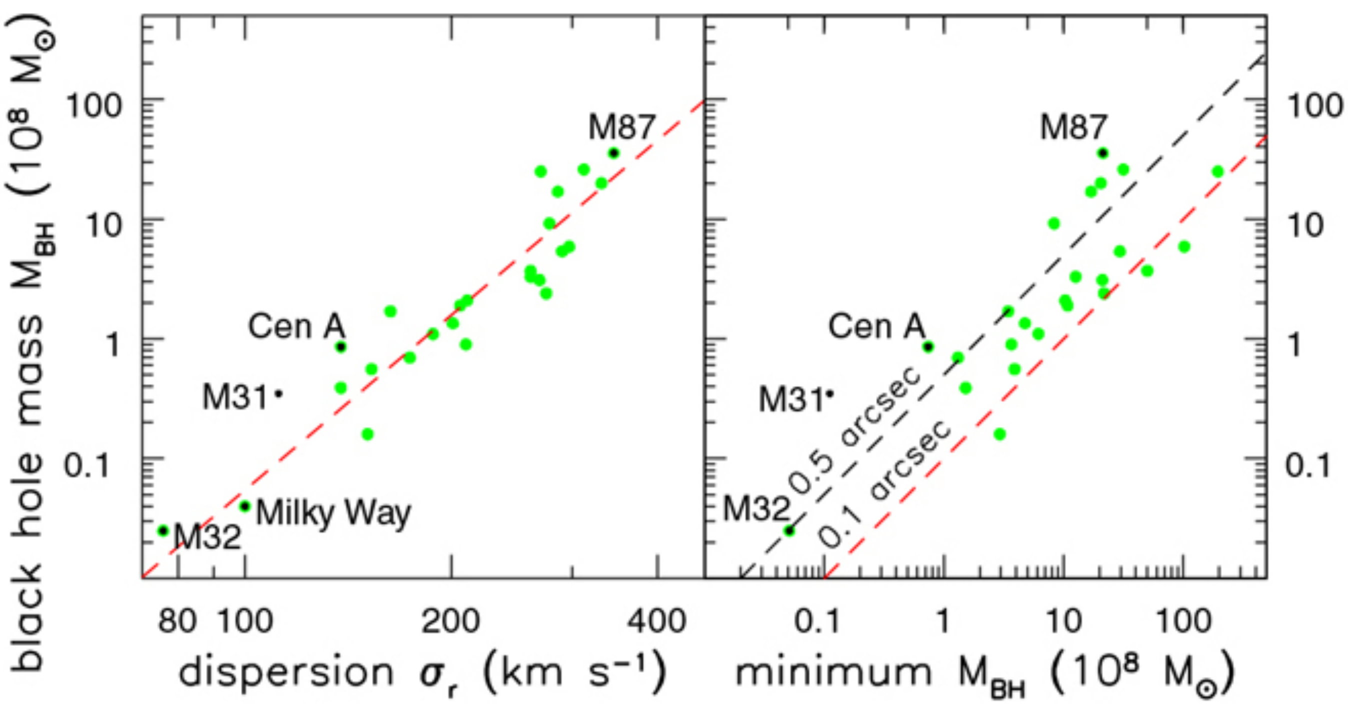
  What about
  - (iii) the green valley?



# Supermassive black holes

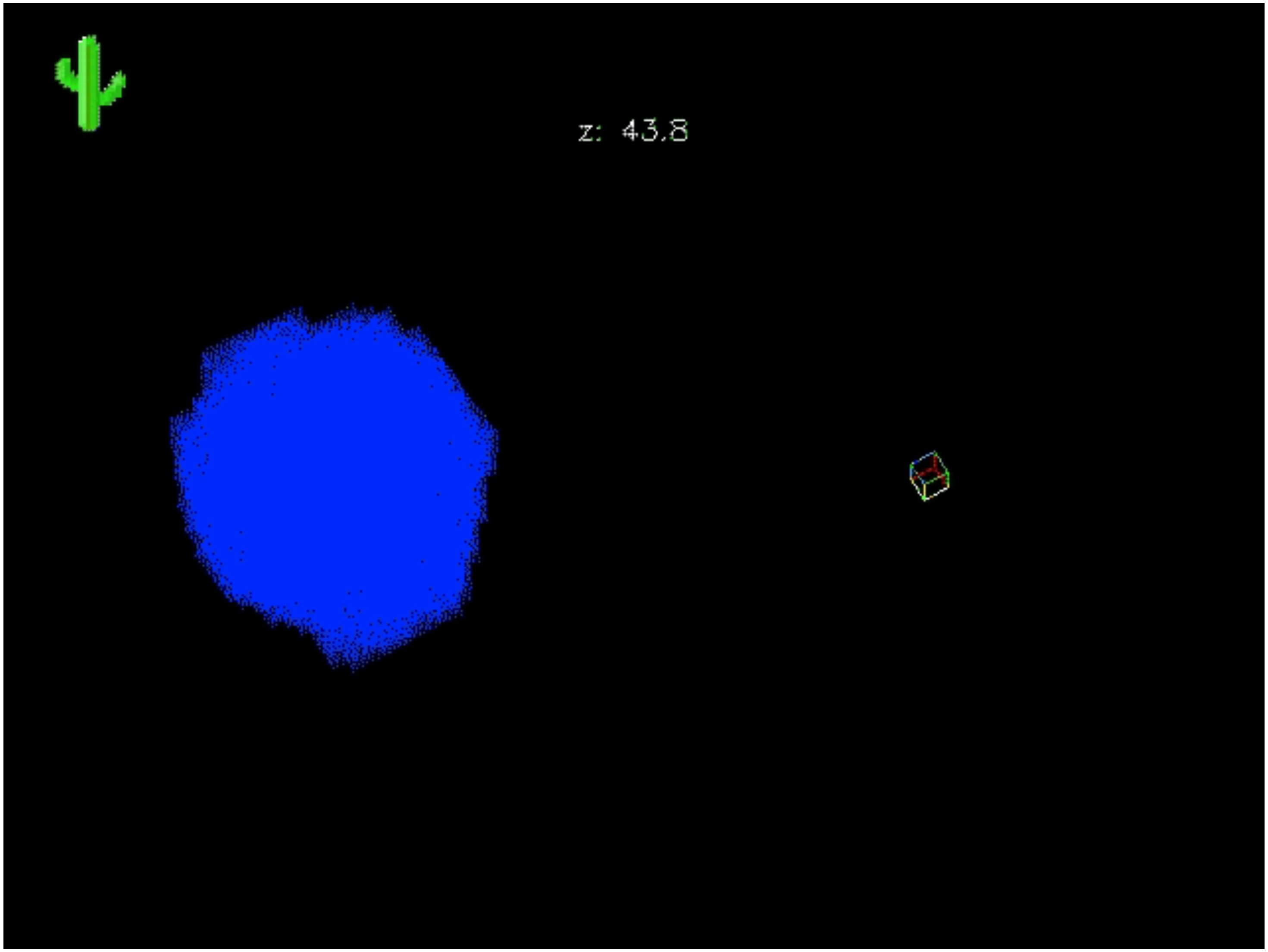
- The kinematics of stars and gas reveal the presence of very compact and large masses at the centers of galaxies: these are thought to be supermassive black holes (SMBHs)
- Their origin is unclear, but recent observations show striking correlations between the properties of the spheroidal component of a galaxy (such as a bulge) and the mass of the SMBH: not clear how these objects form!



# The formation of an elliptical galaxy in a CDM universe

- These simulations follow the hierarchical formation of a spheroidal galaxy with properties similar to those of luminous elliptical galaxies
- The first animation shows the gas and stars in the simulation.
  - The dark matter component is not shown, for clarity, although it is the dominant component gravitationally.
- The elliptical forms as a result of a late major merger between two disk-dominated galaxies.
  - The merger results in the prompt consumption (transformation into stars) of all the remaining gas, and the stirring of the stellar disks into a spheroidal remnant.
- Since no stars form after the merger, the final galaxy appears smooth and round, resembling in most properties a luminous elliptical.
- If you are interested in more details, check the following (technical!) references:
  - Steinmetz & Navarro (2002) New Astronomy, Volume 7, Issue 4, p. 155-160
  - Meza, Navarro, Steinmetz & Eke (2003), The Astrophysical Journal, Volume 590, Issue 2, pp. 619-635

# Elliptical Galaxy Formation: Gas and Stars



# Elliptical Galaxy Formation: Stars