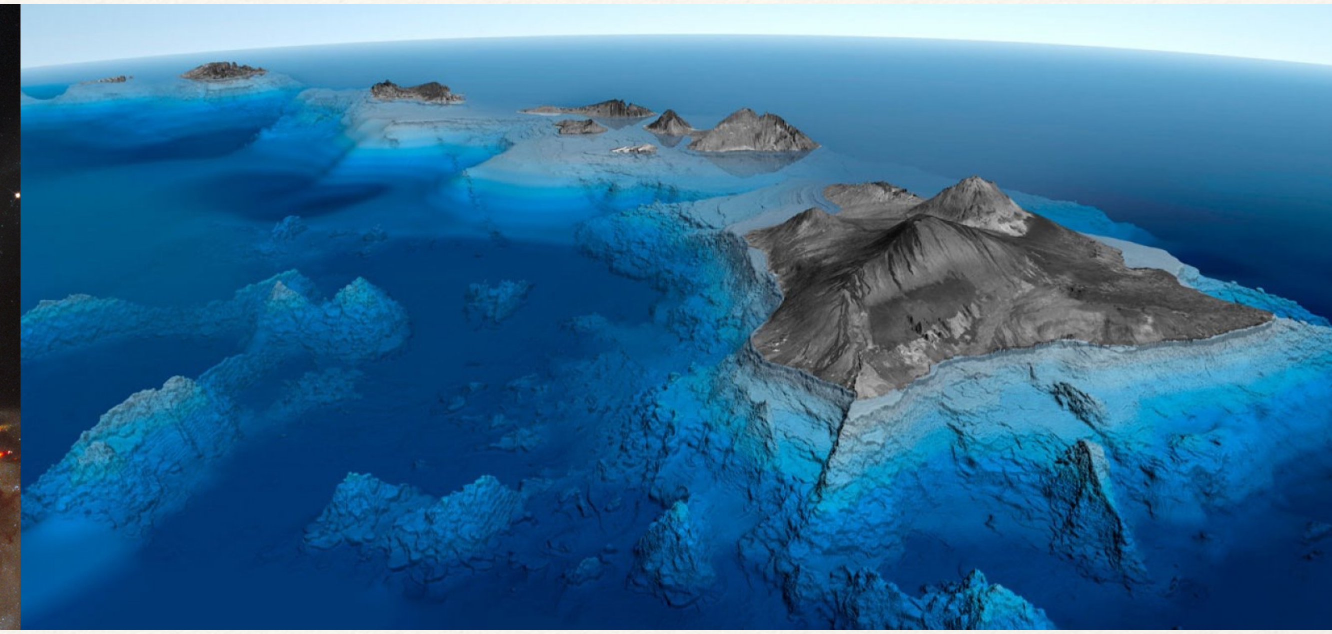
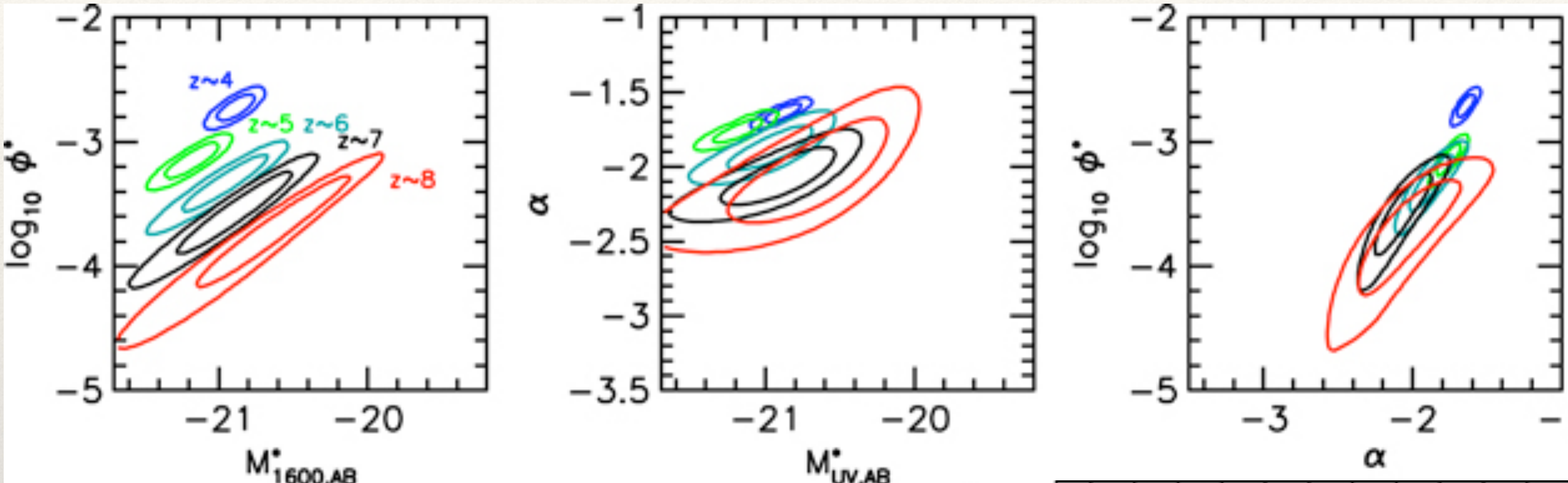


Getting to know the "island universes" out there.

Galaxies I

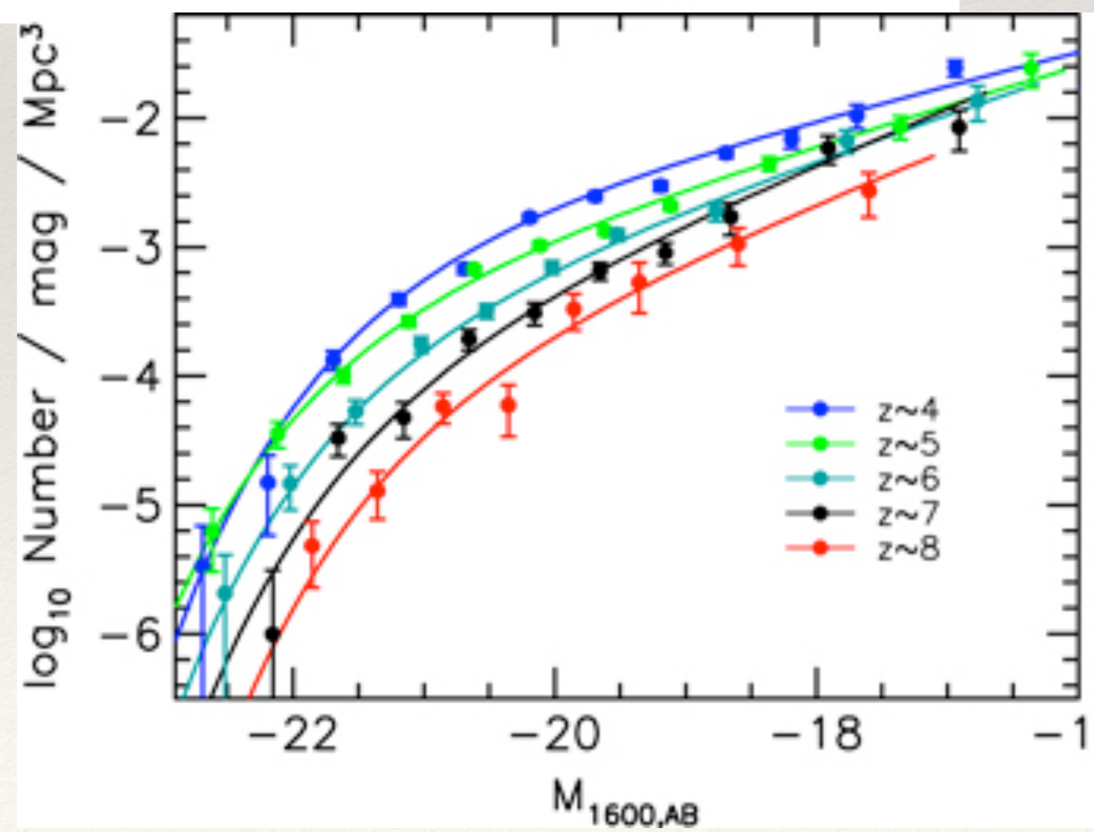
ASTR 555
Dr. Jon Holtzman

Warm-up



Bouwens+2015

- Consider the evolution in Schechter parameters for galaxies at z~4-8.
- What might these changes mean physically?



Outline for Today

- Galaxy Population - Ellipticals/Spheroids:
  - Structure
    - Surface Brightness Profiles
    - 3D Shapes

NGC4636

Galaxy Population - Ellipticals/Spheroids

- 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

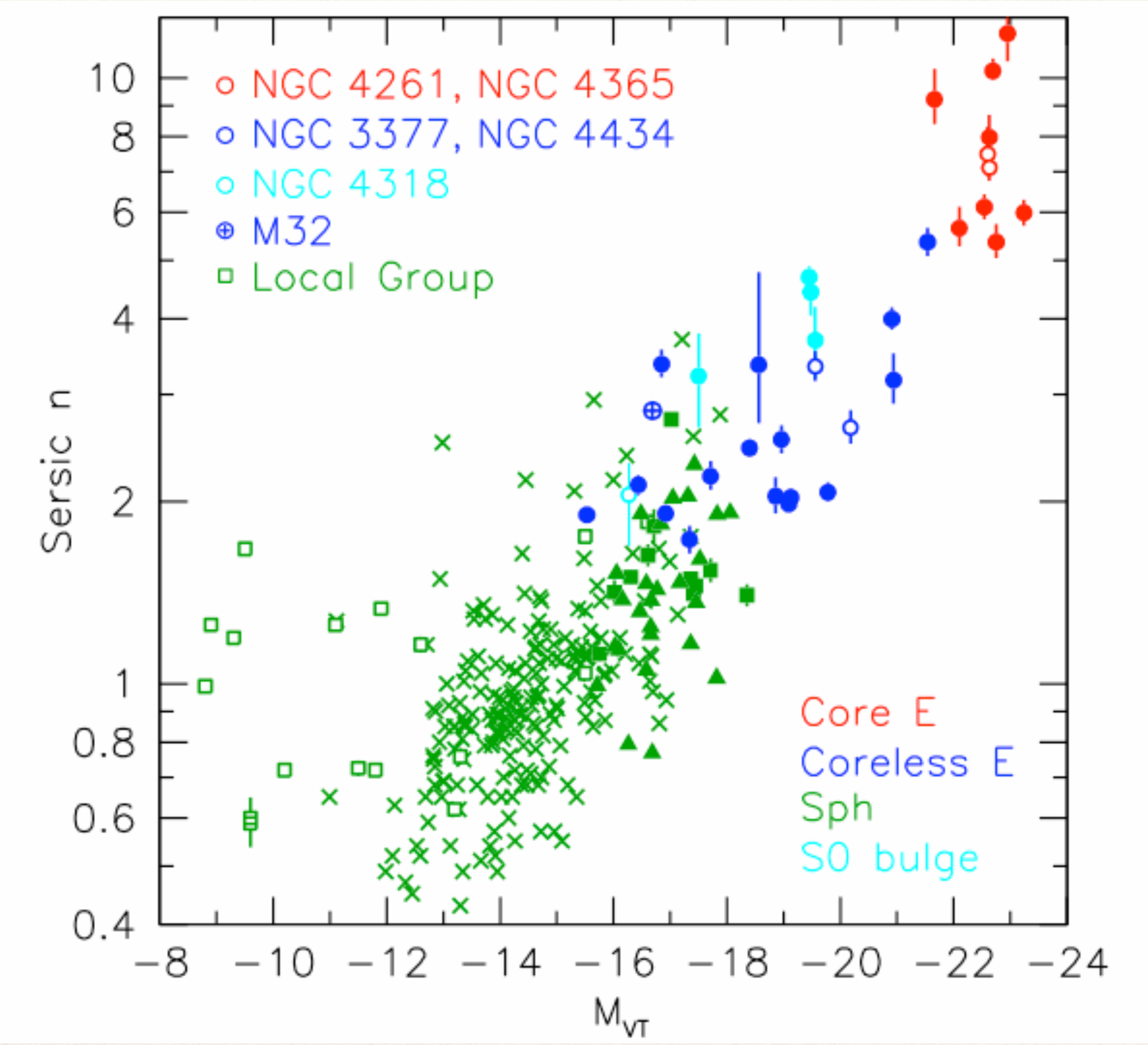
All of the above are now thought to be (at least partly) wrong!

Galaxy Population - Ellipticals/Spheroids

- Ellipticals:
  - are **not** simple collections of stars that are all similar to one another
  - have a wide range in luminosities, sizes, and surface brightnesses.
- Three main "classes":
  - **Low Luminosity** (dwarfs): $L < 0.1\ L^*$; M_B fainter than -18.
  - **Medium Luminosity** (including massive spiral bulges): $L \sim 0.1 - 1\ L^*$; M_B in the range -18 to -20
  - **High Luminosity**: $L > 1$-few L^*; M_B brighter than about -20
  - There is OVERLAP in luminosity between these groups

Galaxy Population - Ellipticals/Spheroids: SB Profiles

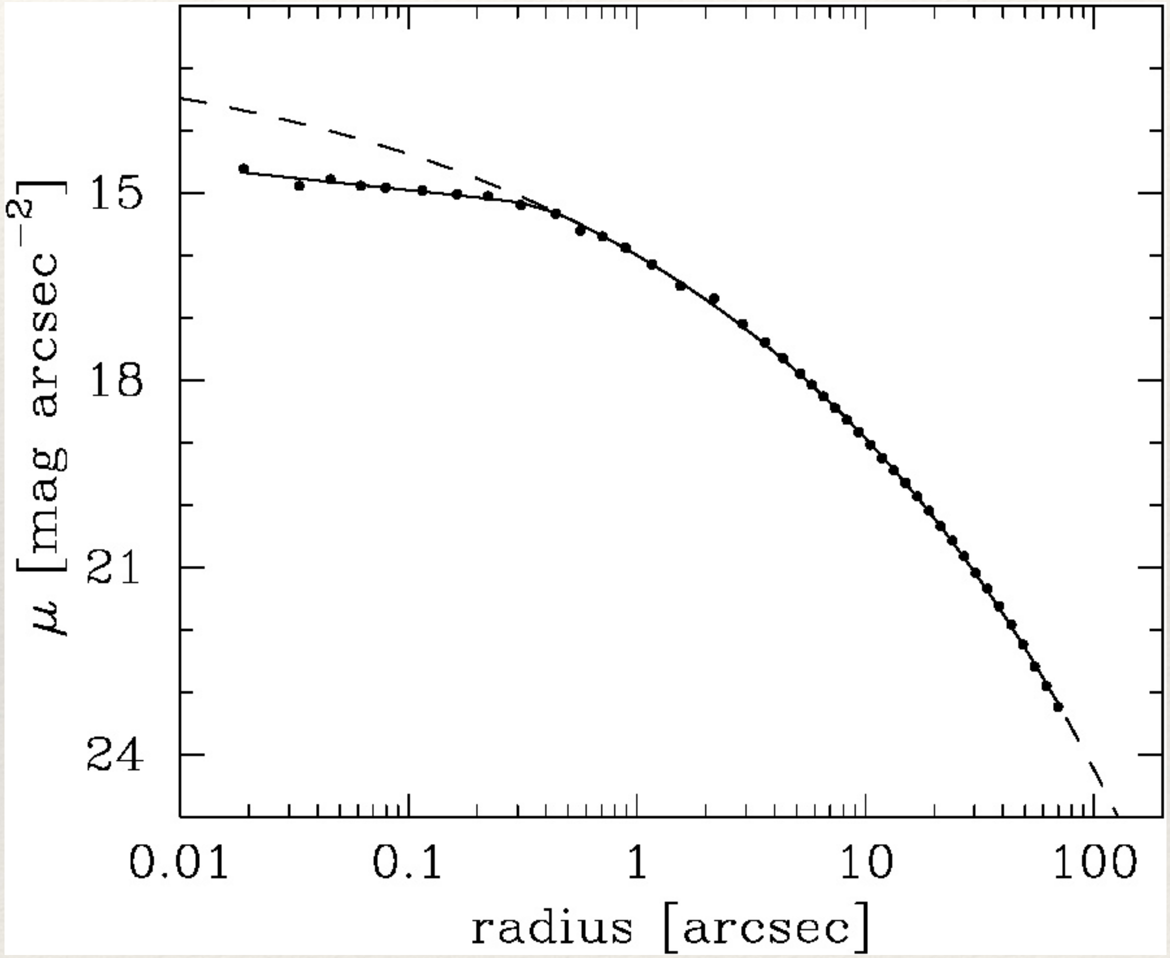
- In general, Ellipticals are well fit by Sersic profiles
- Sersic ***n*** correlates with luminosity:
  - Low luminosity Es are less concentrated (***n*** < 4)
  - $R^{1/4}$ law (***n*** ~ 4) fits best near M_B~ -21.
  - High luminosity Es are more concentrated (***n*** > 4)



Kormendy 2006

Galaxy Population - Ellipticals/Spheroids: Inner SB Profiles

- Inner regions often deviate from overall Sersic profile fit:
    - **Core** = flatter center, “missing light”
    - **Cusp** = steep inner profile, “extra light”
- Inner regions are important!
    - give insight into the galaxy's formation history
    - reflect dissipational collapse of low angular momentum material
    - can be influenced significantly by a central black hole



NGC 3348; Graham & Driver 2005

Galaxy Population - Ellipticals/Spheroids: Inner SB Profiles

- Early (pre-1975) work suggested that profiles all turned over in a **flat core** of constant density.
- Tried to understand assuming simple profiles (e.g., isothermal profile or modified forms "King profile", "Hubble profile")

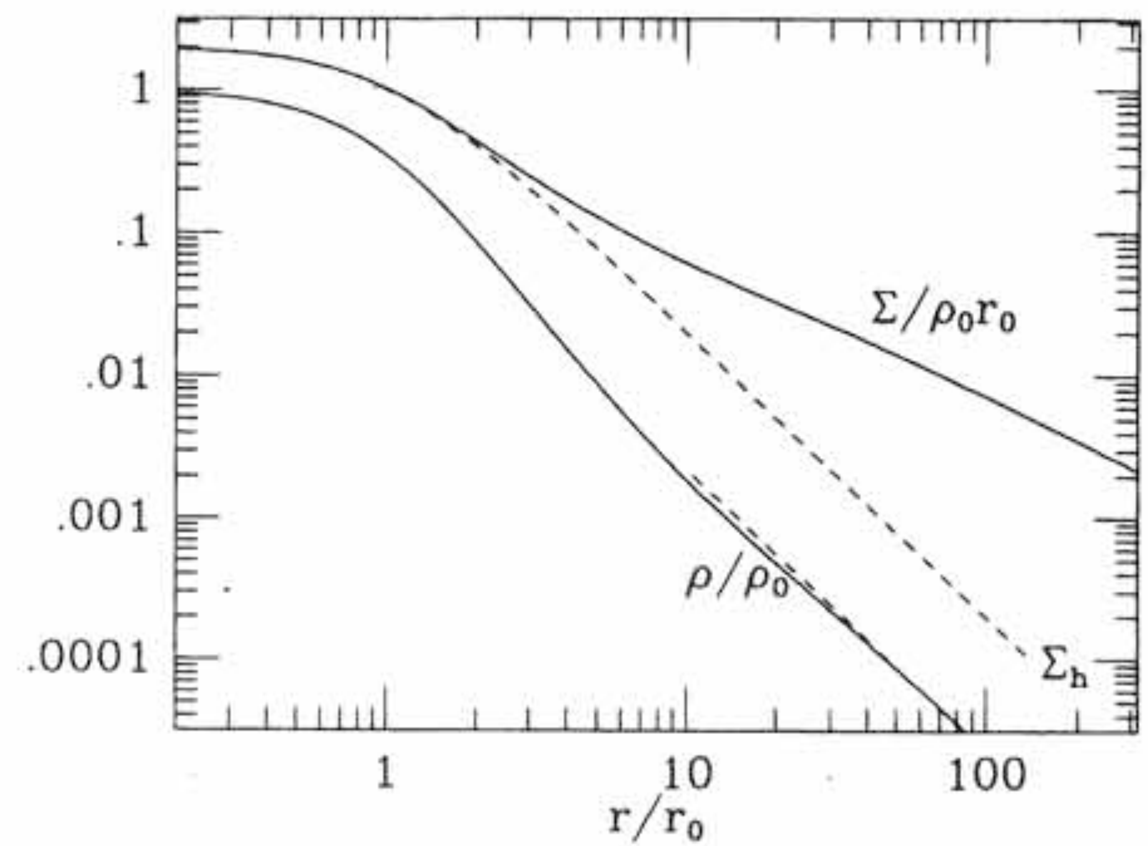
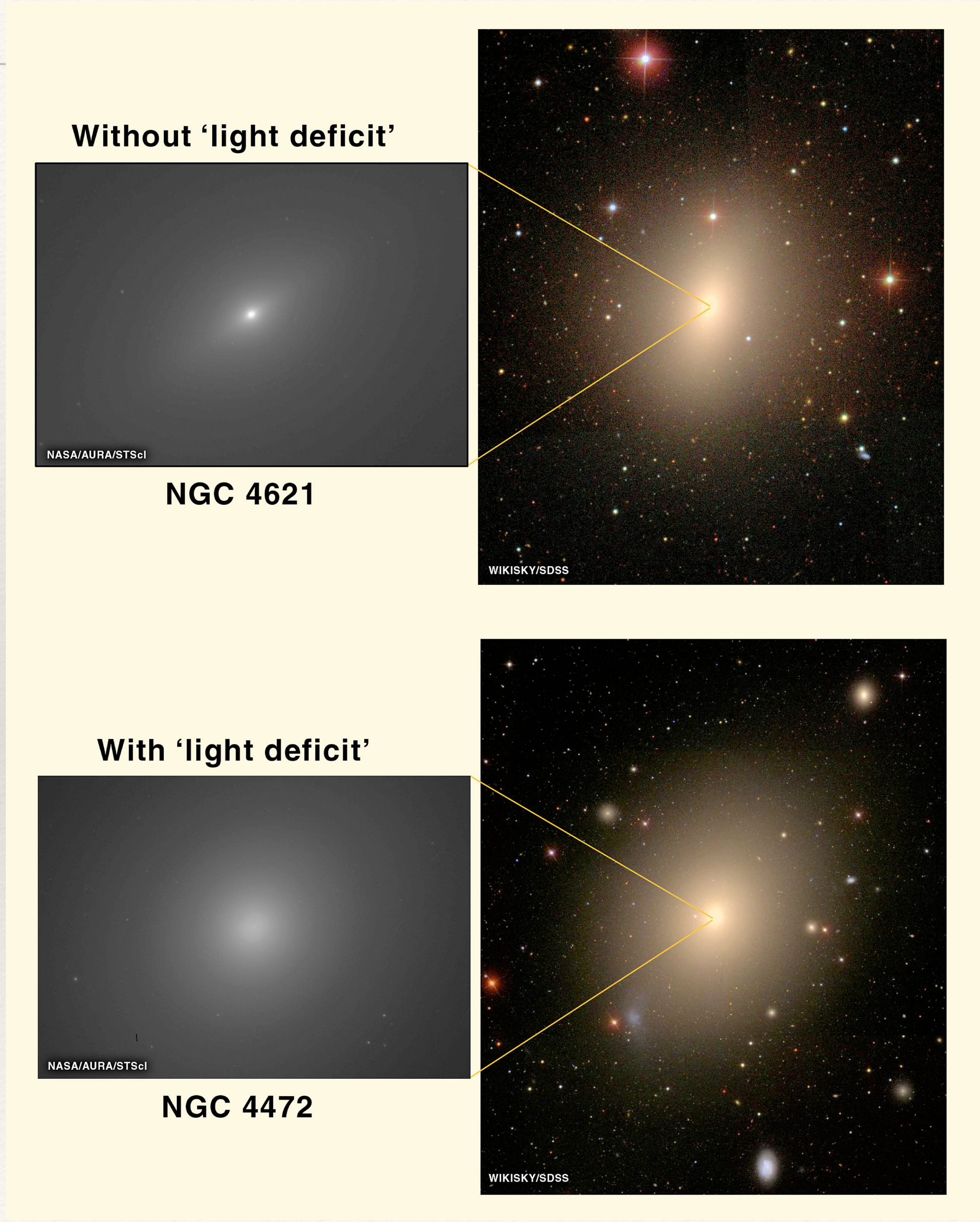


Figure 4-7. Volume (ρ/ρ_0) and projected ($\Sigma/\rho_0 r_0$) mass densities of the isothermal sphere. The dashed line at bottom right shows the density profile of the singular isothermal sphere. The dashed curve labeled Σ_h shows the surface density of the modified Hubble law (4-128).

Galaxy Population - Ellipticals/Spheroids: Inner SB Profiles

- However, central regions were heavily influenced by seeing in early photographic plate data
- Completely flat cores shown to be incorrect using higher resolution CCD data
- HST imaging showed galaxies with both flatter (**core**) and steeper (**cusp**) inner profiles



Credit: NASA/AURA/STScI and WikiSky/SDSS

Galaxy Population - Ellipticals/Spheroids: Inner SB Profiles

- Lauer et al. (1995) introduced the "Nuker" profile:

$$I(r) = I_b 2^{(\beta-\gamma)/\alpha} \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

  - β: outer power law ($r \gg r_b$): $I(r) \sim r^{-\beta}$
  - γ: inner power law ($r \ll r_b$): $I(r) \sim r^{-\gamma}$
  - r_b: "break" radius between the two regions
  - α: sharpness of transition near r_b.

2648 LAUER *ET AL.*:EARLY TYPE GALAXIES

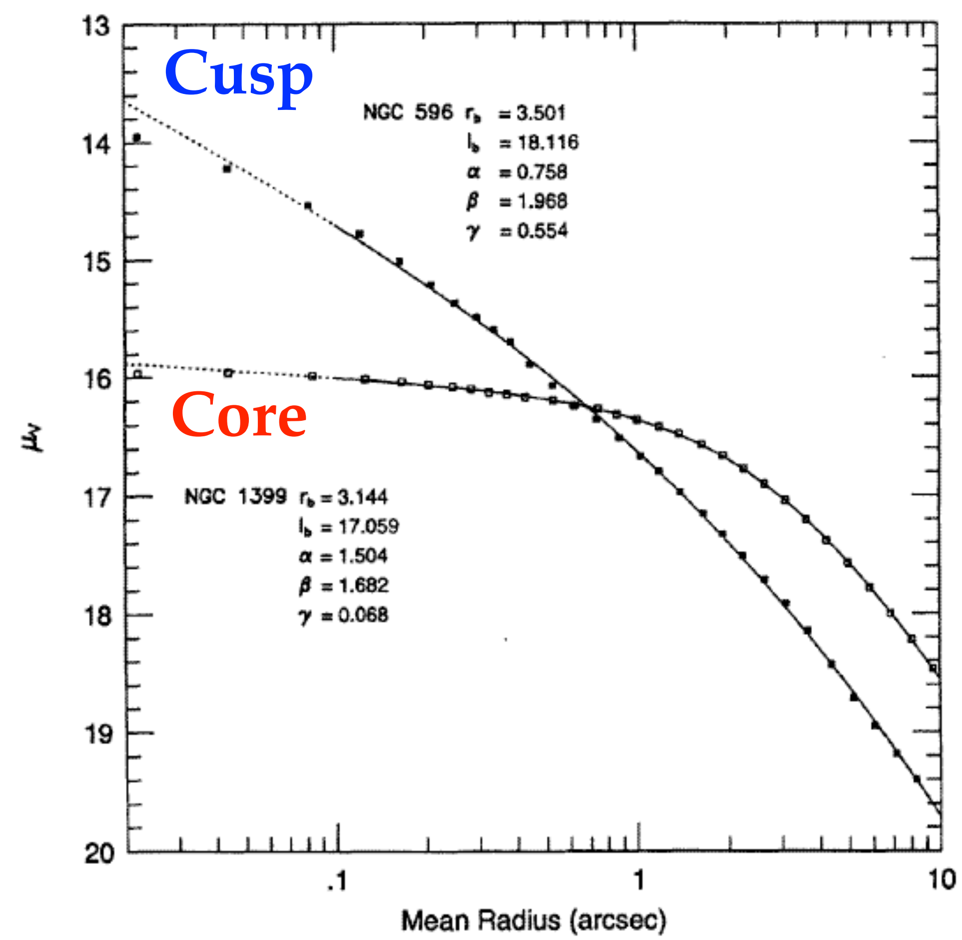


FIG. 9. Nuker law fits (smooth lines) to NGC 1399, a core galaxy (open symbols), and NGC 596, a power-law galaxy (solid symbols). The dotted line indicates the inner region limited by *HST* resolution. The observed brightness profile over this region is most likely a lower limit to the intrinsic profile.

Galaxy Population - Ellipticals/Spheroids: Inner SB Profiles

- "Nuker" profile fits to large samples showed:
  - No completely flat cores
  - Inner profiles divide into:
    - **Non-flat (cuspy) Cores**: profile breaks to shallower power-law — **High Luminosity**
    - **Coreless/Power Laws**: profile keeps rising steeply — **Medium Luminosity (+spiral bulges)**
  - Profile type is correlated with luminosity

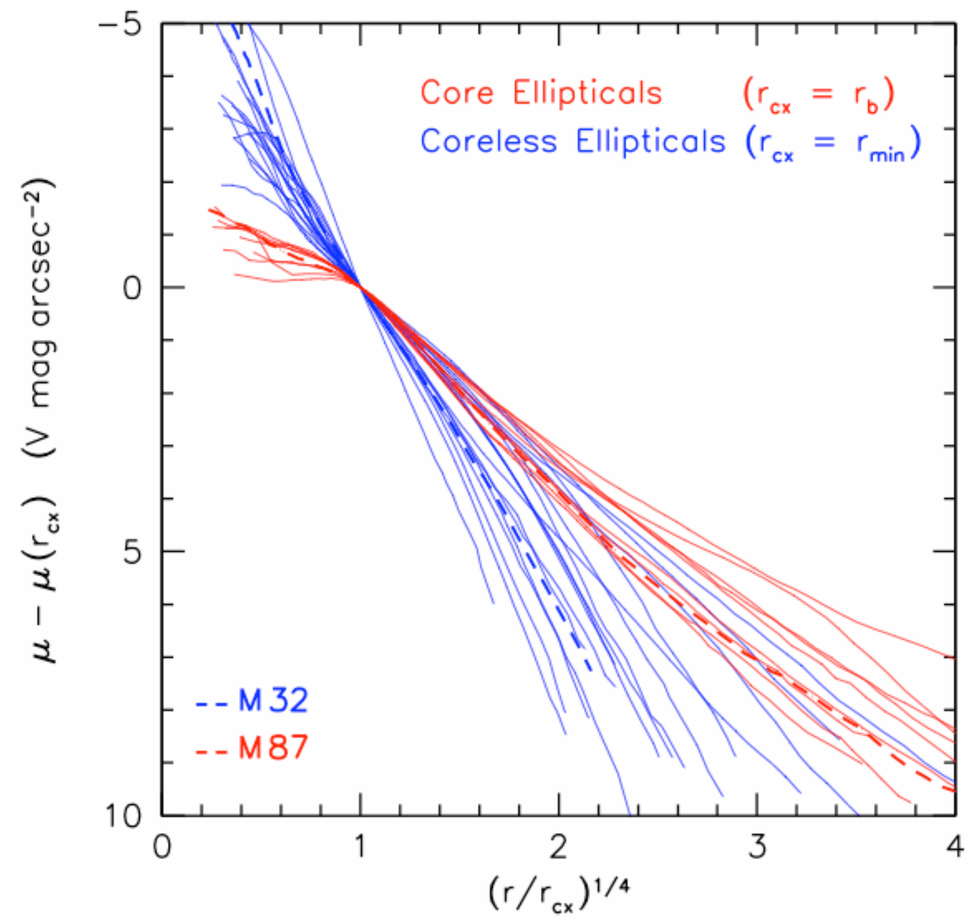
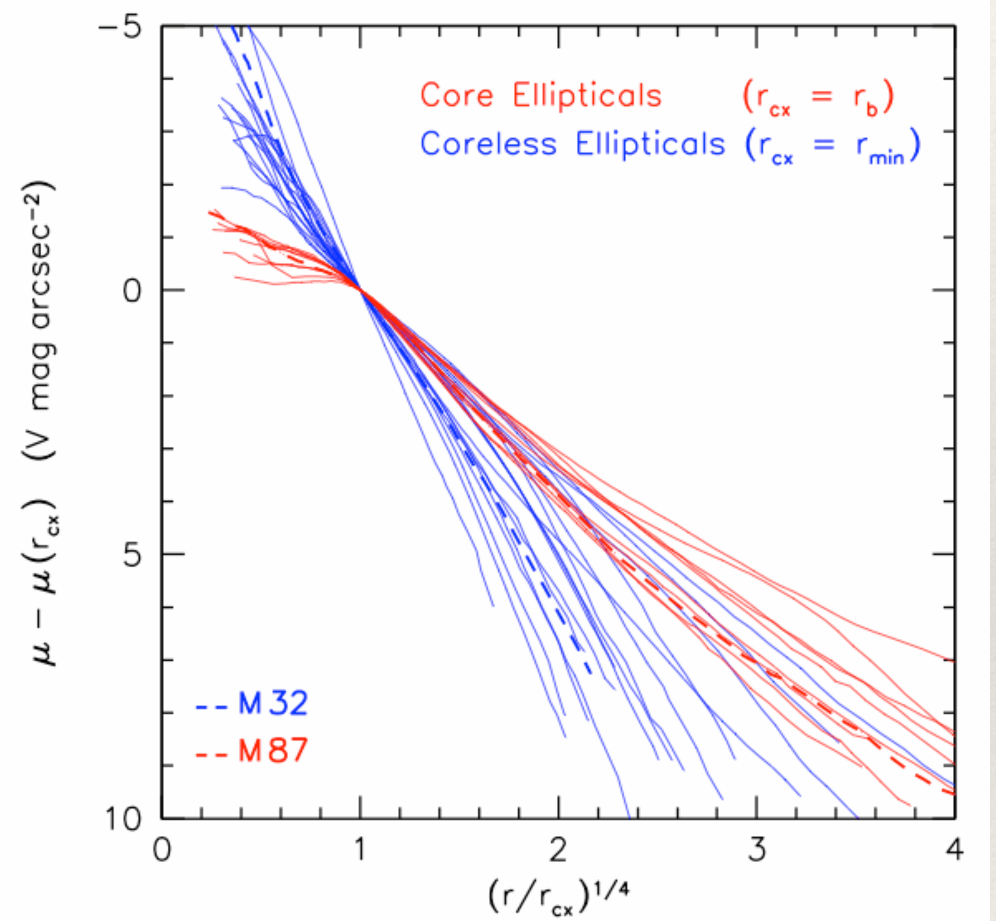


FIG. 40.— Major-axis profiles of all of our ellipticals scaled together to illustrate the dichotomy between core and coreless ellipticals. Core ellipticals are scaled together at $r_{cx} = r_b$, the break radius given by the Nuker function fit in Lauer et al. (2007b). Coreless ellipticals are scaled 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.

Thought Question

- Sketch the following profiles:
    - Flat core
    - Non-flat (cuspy) core
    - Coreless/Power-law
- What might cause a galaxy to be "missing light" or have "extra light" in the center?



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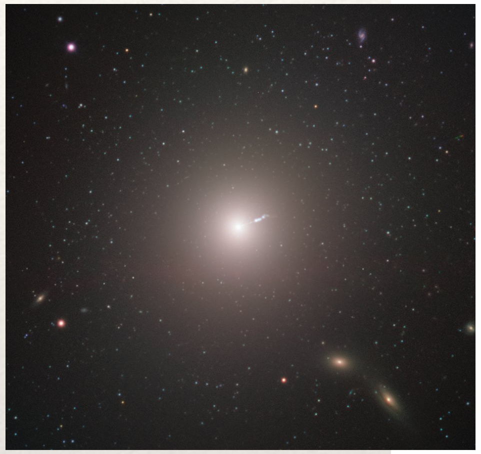
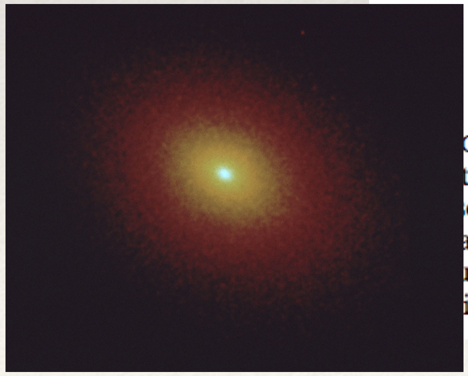
Galaxy Population - Ellipticals/Spheroids: Inner SB Profiles

- **Core** galaxies may have had a previous merging event:
    - merging central black holes “scour“ out the core?

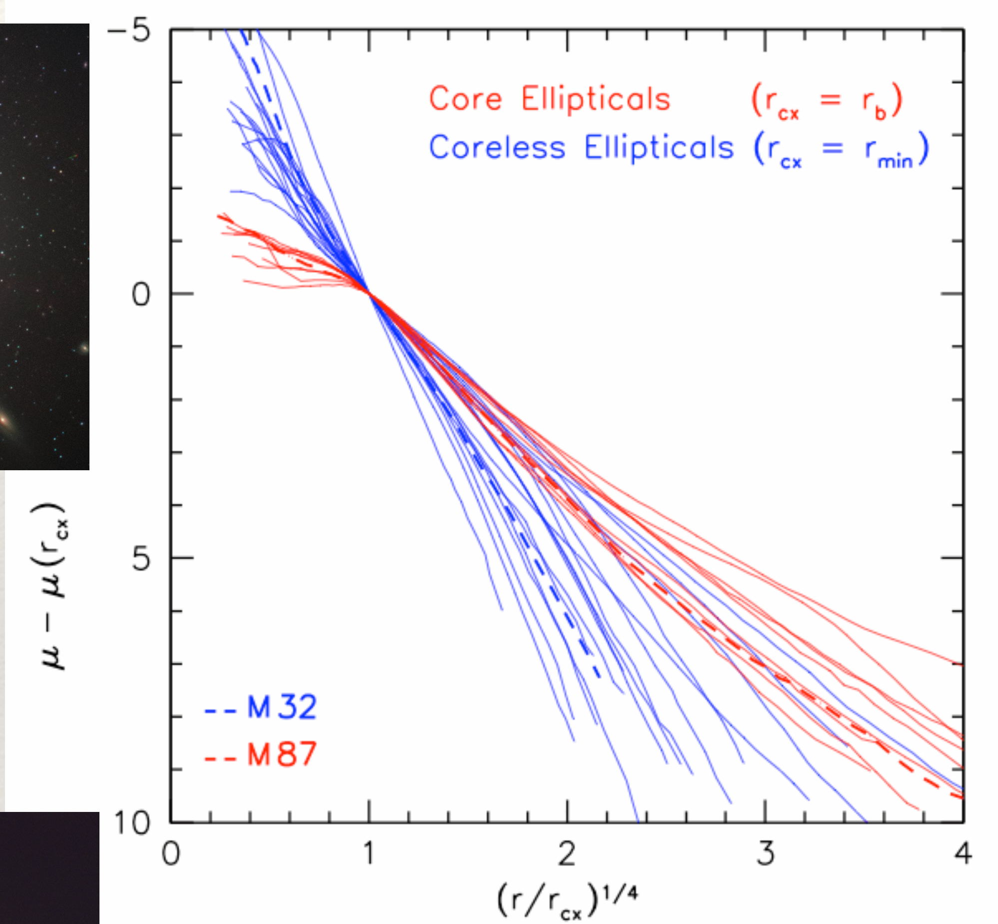


M87

- **Coreless/Power Law** galaxies have “extra light”:
    - an accretion event that triggered a burst of star formation in the center?



M32



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Galaxy Population - Ellipticals/Spheroids: Outer SB Profiles

- Outer profiles can deviate from Sersic fit, often due to environment:
  - Profiles of Ellipticals in dense clusters cut off at large radii
  - Ellipticals with near neighbor have raised outer profile
  - Profiles of central cluster galaxies (cD) lie above n~4 Sersic fit at R > 20 R_e
    - Extended halo likely from stars in the cluster

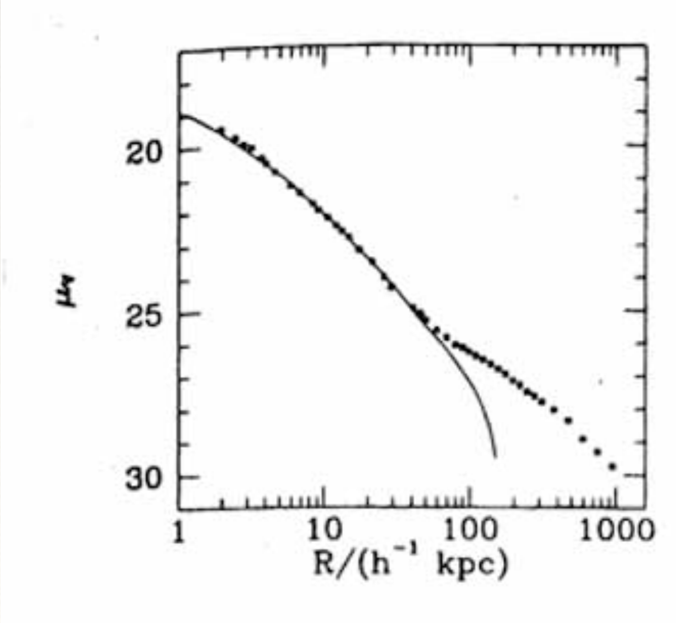
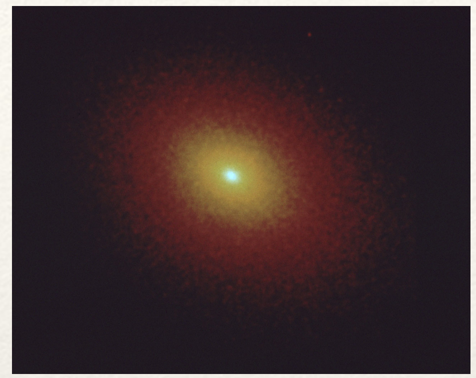


Figure 4.28 The surface-brightness profile of the cD galaxy that lies at the center of the cluster Abell 1413 (points). The line shows the $R^{1/4}$-law that best fits the inner points. [From data kindly provided by J. Schombert based on the work of Oemler (1976).]

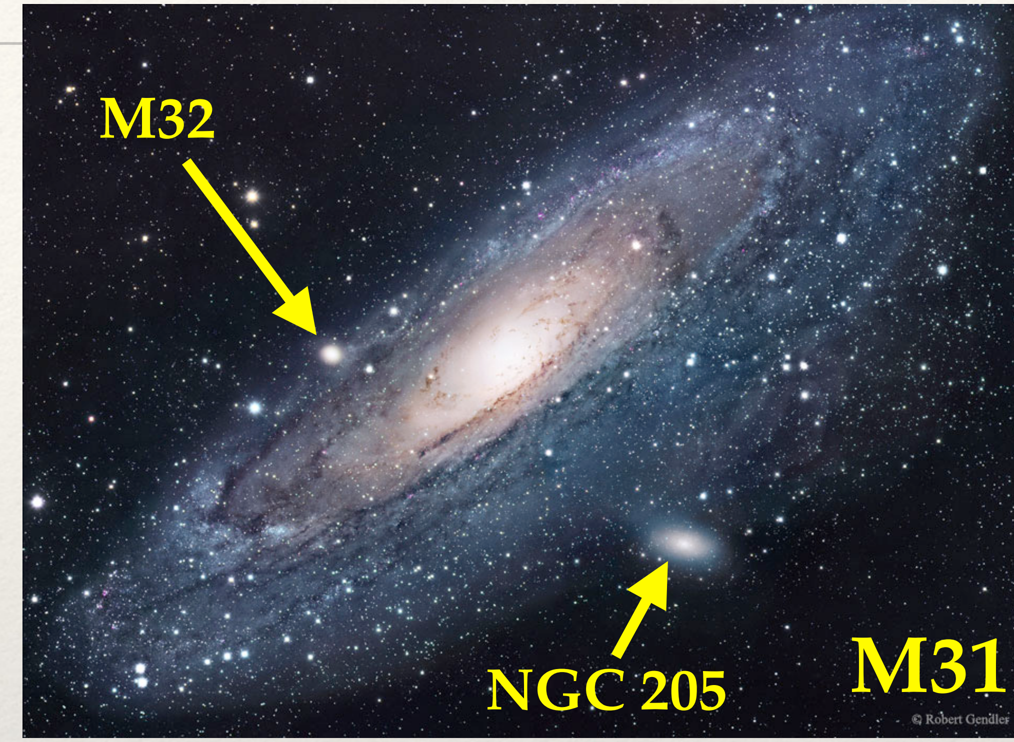
http://people.virginia.edu/~dmw8f/astr5630/Topic07/t7_cD_profiles.html

Galaxy Population - Ellipticals/Spheroids: Classes

- Two classes of Dwarfs:
  - Compact dEs (Dwarf Ellipticals, dEs):
    - rare, resemble more luminous Ellipticals, e.g., M32 (n ~ 4)



M32



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

  - Diffuse dEs (Dwarf Spheroidals, dSphs):
    - common, differ from more luminous Ellipticals
    - exponential light profiles (n ~ 1), e.g., NGC 205

NGC 205

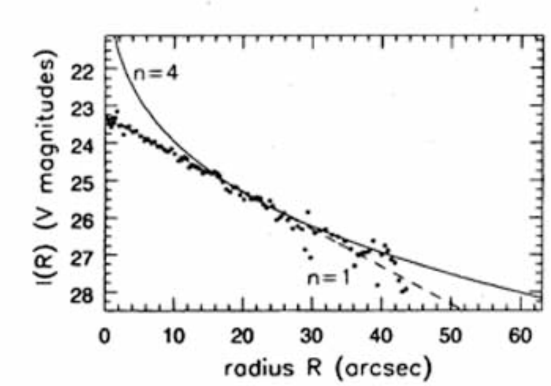


Figure 6.2 From Equation 6.1, $R^{1/4}$ ($n = 4$: solid) and exponential ($n = 1$: dashed) curves. Points show V-band surface brightness for dE galaxy VCC753 in the Virgo cluster. This elliptical has $R_e = 15.8''$ in the B band and $I_B(R_e) = 24.4$ mag arcsec^{-2}. Extrapolating the profile outward gives total apparent magnitude $B_T^0 = 16.4$; taking $d = 16$ Mpc, we find $L \approx 1.1 \times 10^8 L_\odot$ – H. Jerjen.

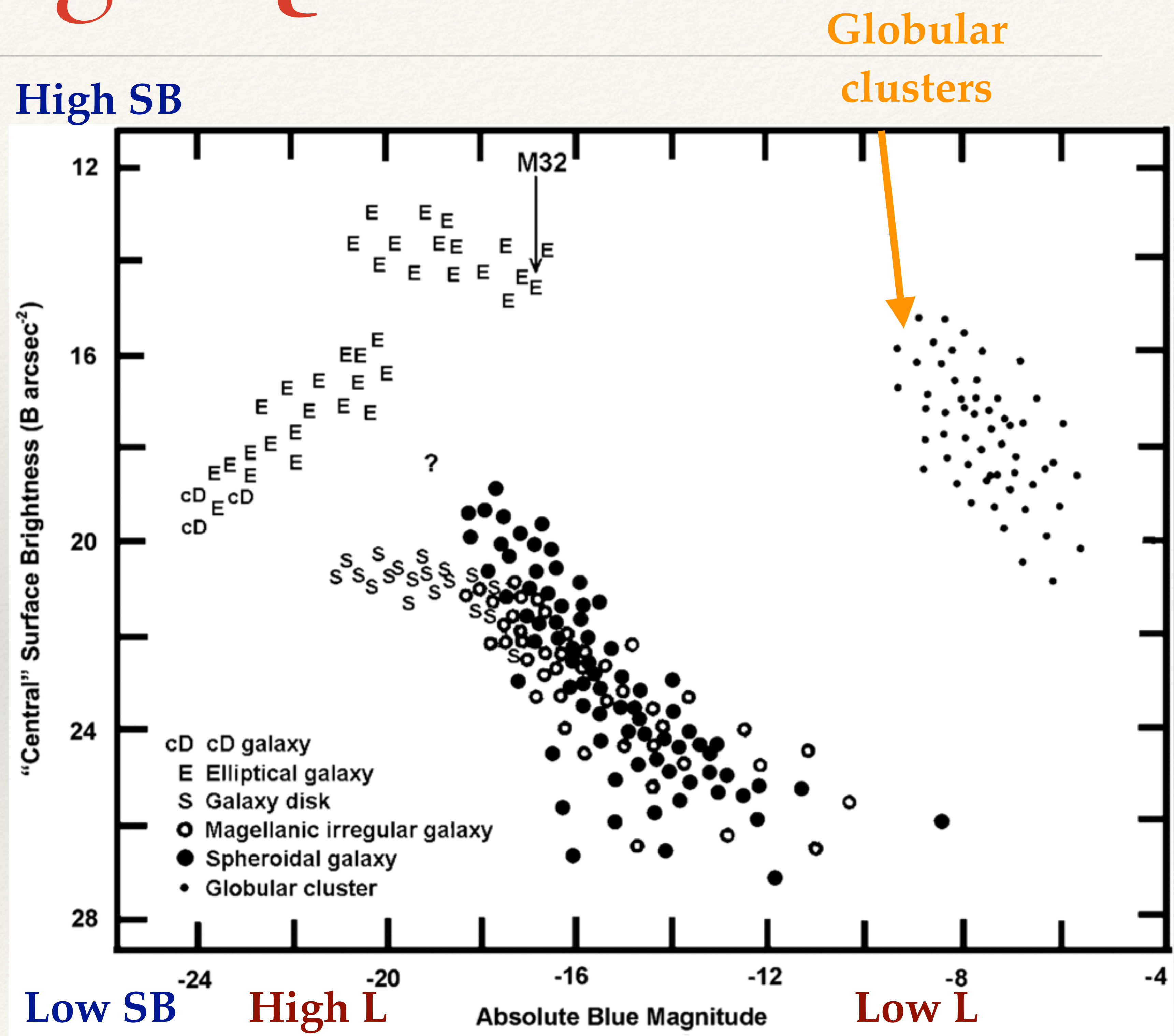
http://people.virginia.edu/~dmw8f/astr5630/Topic07/t7_spheroidal_profiles.html

Ellipticals/Spheroids: Classes

- **Low Luminosity — Spheroidals**: (diffuse dEs and dSph)
  - more like disks in profiles (n ~ 1), size, brightness, surface brightness, multiple age stellar populations
  - Likely gas stripped dwarf irregular (dIrr) and dwarf spiral (dS) galaxies
- **Medium Luminosity — Coreless Ellipticals**:
  - central profiles show steep power law to the smallest radii, medium luminosity, high central brightness
  - May have formed from "wet" mergers of other ellipticals, gas moves to center to form new stars
- **High Luminosity — Core Ellipticals:**
  - central profiles break to shallower slope, luminous, but lower central brightness
  - May have formed from dry mergers of other ellipticals (no gas dissipation), with binary black holes "scouring out" central regions, leaving a flatter core
- There is overlap in luminosity between these groups!

Thought Question

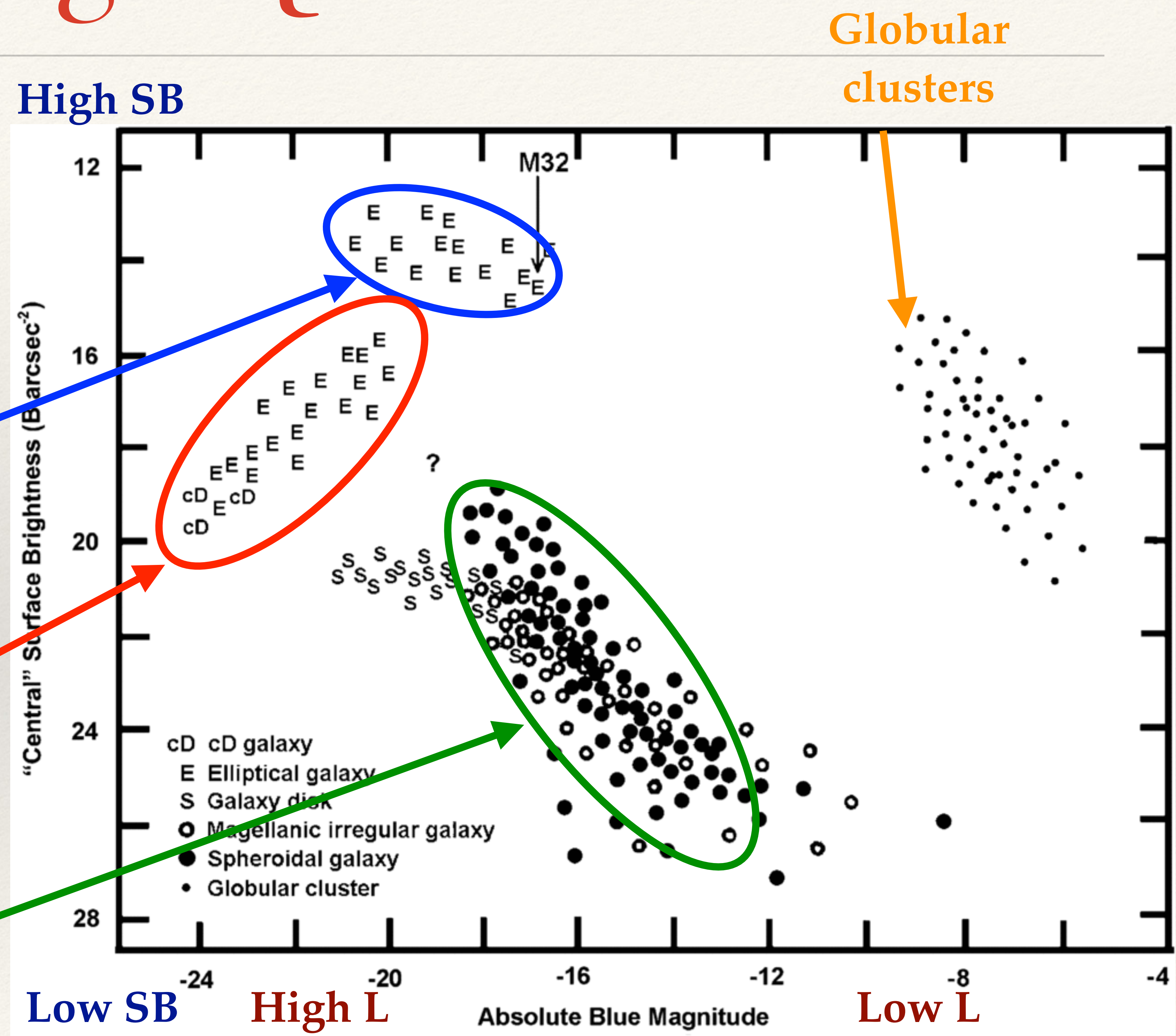
- Ellipticals split up into three classes in magnitude vs. surface brightness:
  - identify the three groups in the plots
  - Which are the **Coreless / Power Law** ellipticals?
  - Which are the **Non-flat (cuspy) Core** ellipticals?
  - Where are the **dwarfs**?
  - Is there overlap in luminosity between the groups?



Kormendy 2009

Thought Question

- Ellipticals split up into three classes in magnitude vs. surface brightness:
  - Which are the **Coreless / Power Law** ellipticals?
  - Which are the **Non-flat (cuspy) Core** ellipticals?
  - Where are the **dwarfs**?

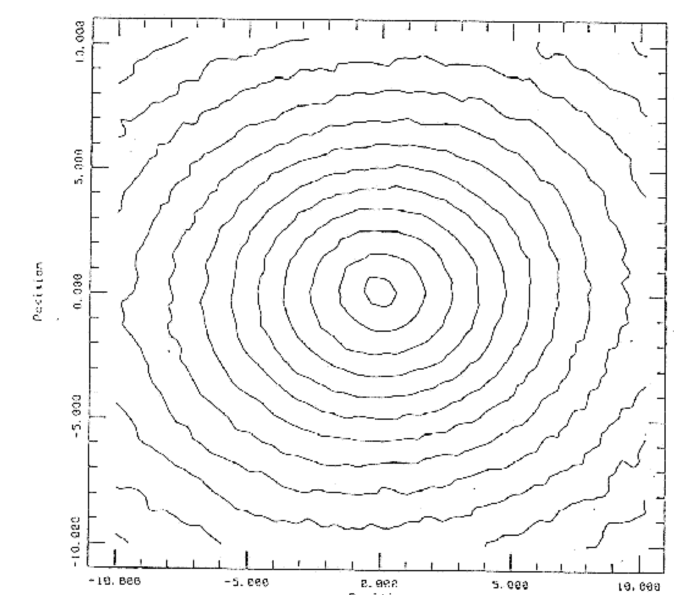


Kormendy 2009

Galaxy Population - Ellipticals/Spheroids: 3D Shapes

- To first order, isophotes are concentric, aligned, ellipses:
  - **b/a** = semi-minor / semi-major axis, i.e., apparent flattening
  - **Ellipticity ϵ = 1 - b/a**
- Ellipticals are classified by **En**, where **n = 10 (1 - b/a)**
- Apparent ellipticity combines the true shape and projection effects

E0 E2 E3



Central regions of the galaxy NGC 4649 out to radii of 10 arcsec.
The distance between the isophotes is 0.2 mag.
see: P. Surma (1988) *Diploma Thesis*

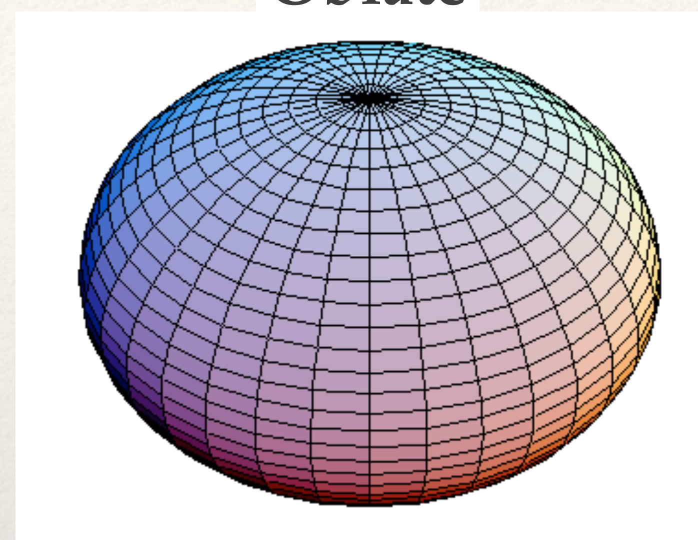
Galaxy Population - Ellipticals/Spheroids: 3D Shapes

- Assuming surfaces of constant density are ellipsoidal:

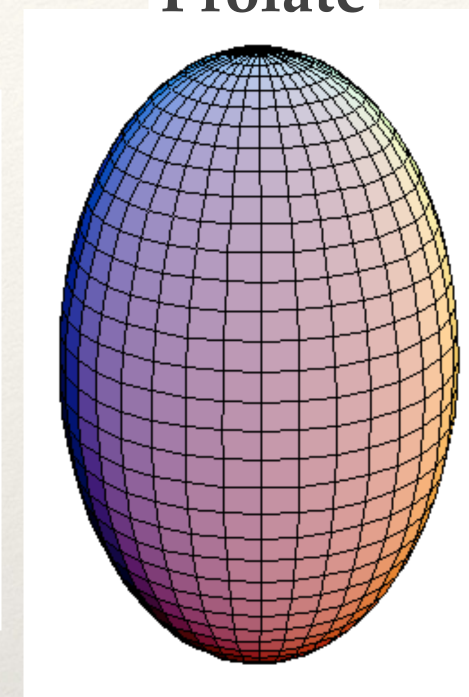
$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

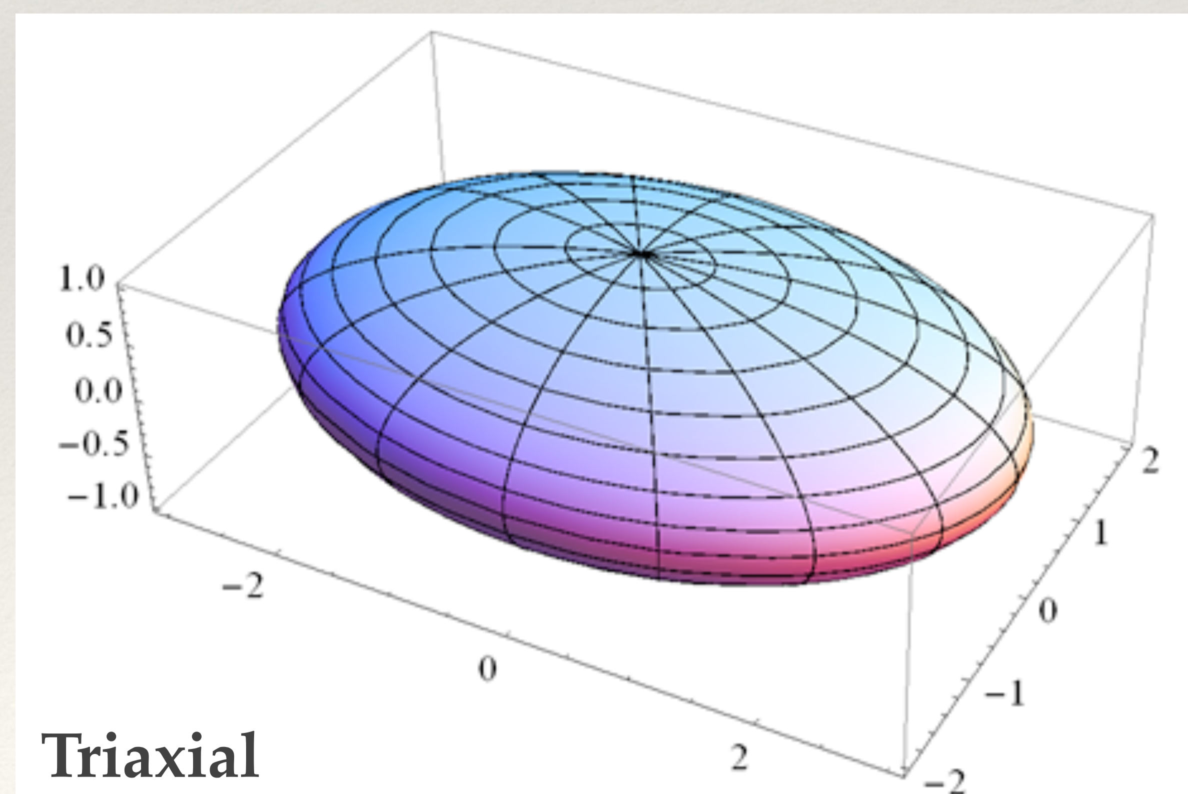
- **What 3D shape are ellipticals?:**
  - oblate, i.e., a = b > c (flying saucer)
  - prolate, i.e., a = b < c (cigar)
  - triaxial, i.e., a > b > c

Oblate



Prolate





Thought Question

- Suppose ellipticals were all thin prolate ellipsoids (thin cigars):
  - Roughly what sort of axis ratio distribution would we expect if galaxies are randomly oriented to our line-of-sight?

Thought Question

- Suppose ellipticals were all thin prolate ellipsoids (thin cigars):
  - Roughly what sort of axis ratio distribution would we expect if galaxies are randomly oriented to our line-of-sight?

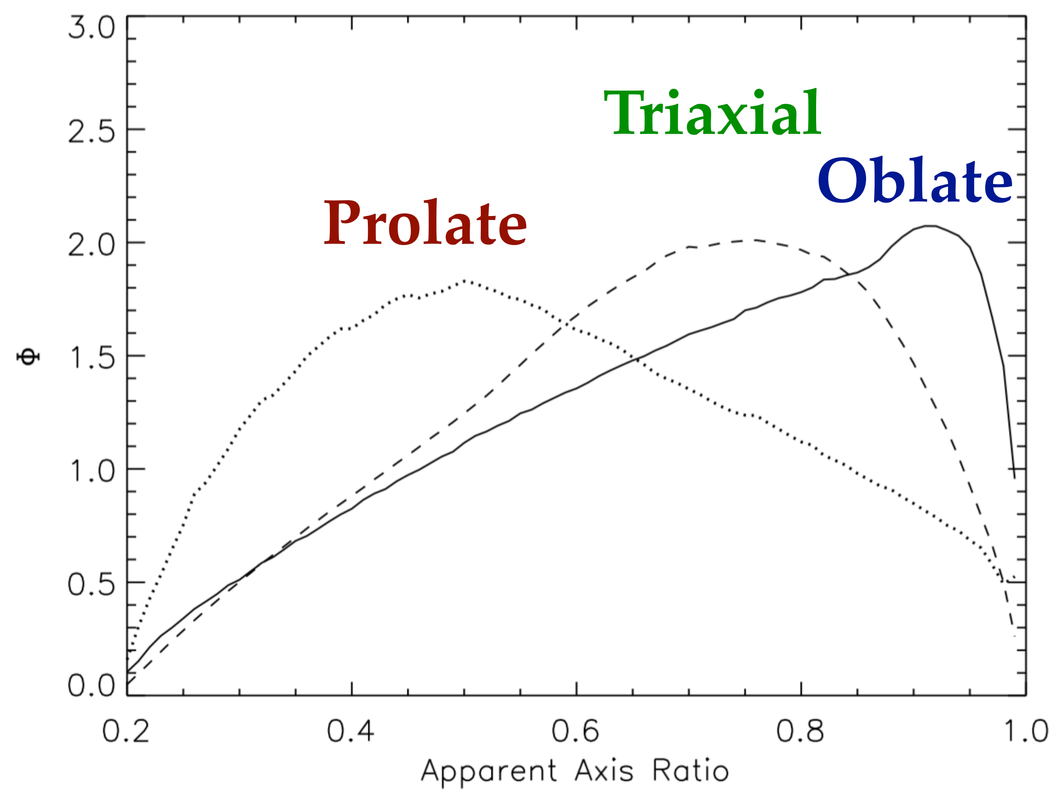
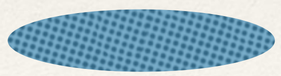
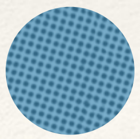


FIG. 2.— Apparent axis ratio distribution, Φ (i.e., the probability density of the projected shapes of a group of galaxies) for each type assuming a uniform intrinsic ARD. Solid, dotted, and dashed lines correspond to oblate, prolate, and triaxial, respectively.



Kimm et al. 2007



Ellipticals/Spheroids: 3D Shapes

- Distribution of observed axial ratios contains information on 3D shapes of ellipticals:
  - **High luminosity Es:**
    - difficult to explain with just randomly oriented oblate or prolate ellipsoids
    - require distribution dominated by triaxial ellipsoids
  - Lower luminosity Es:
    - can perhaps fit as oblate ellipsoids

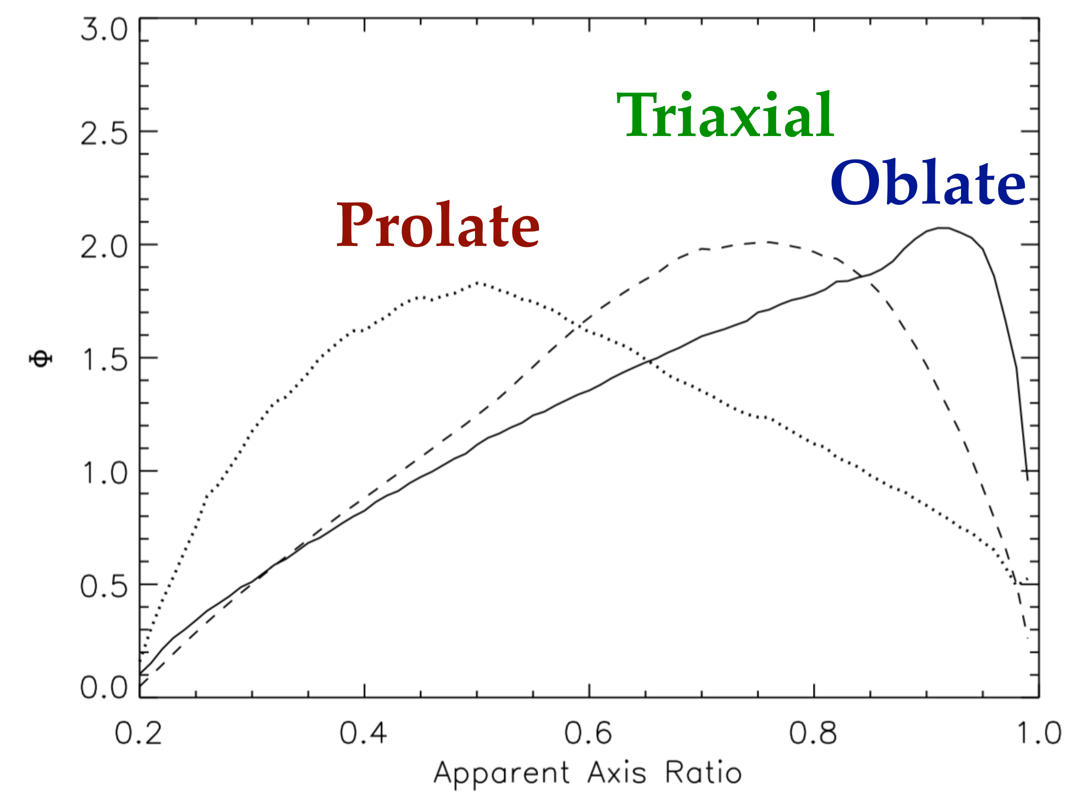


FIG. 2.— ... ty
density of th ... pe
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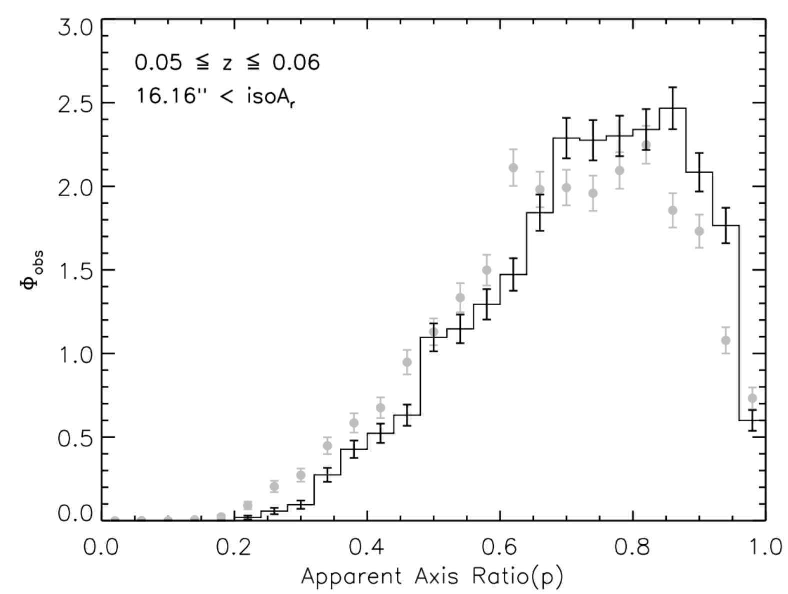
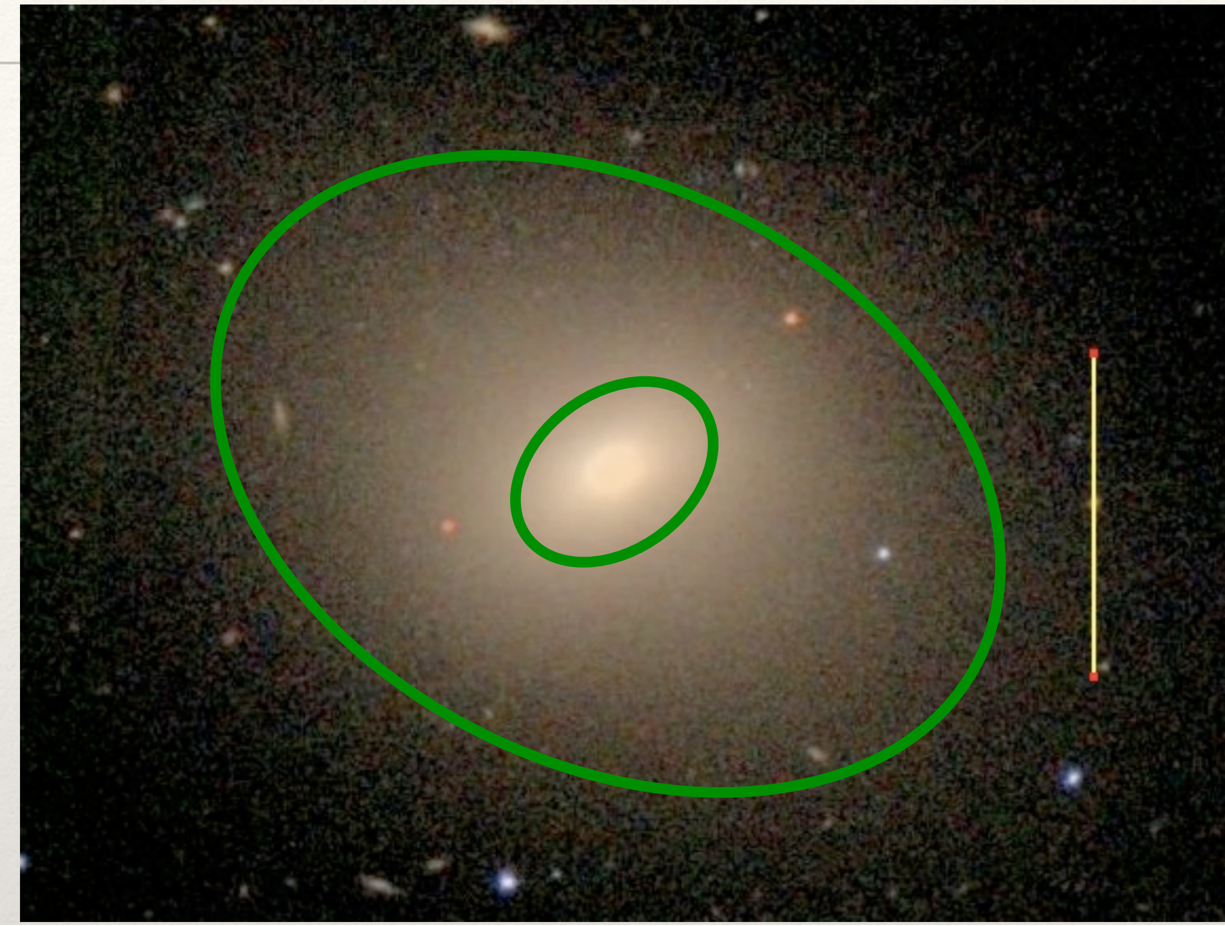


FIG. 4.— Our final SDSS sample compared to the previous APM sample of Loveday (1996) (Gray dots). We derive a relatively-complete sample concerning luminosity and major axis radius.

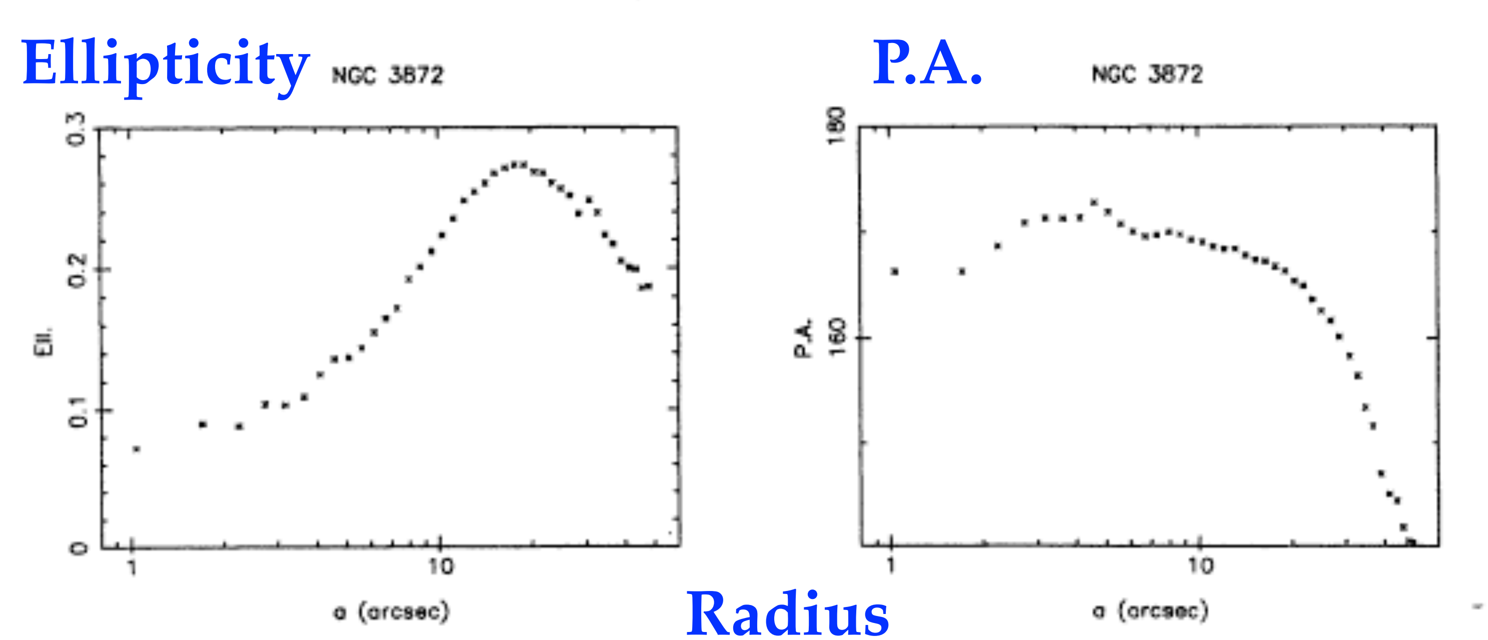
Kimm et al. 2007

Ellipticals/Spheroids: 3D Shapes

- Some giant ellipticals show isophotal twists:
  - Position angle of major axis (P.A.) or ellipticity change with radius
  - **Cannot** result from projection of purely oblate or prolate
  - **Can** occur if triaxial with axial ratios varying with radius.



J.L. Nieto *et al.*



http://people.virginia.edu/~dmw8f/astr5630/Topic07/t7_twists.html

Ellipticals/Spheroids: Isophotal Shapes

- **Non-axisymmetric features:**
  - Isophotes are not exact ellipses: typical deviations ~few %
  - Can express as a Fourier series:

$$R(\phi) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\phi) + \sum_{n=1}^{\infty} b_n \sin(n\phi)$$

  - a4 = the boxiness or diskiness:
    - a4 < 0 : boxy
    - a4 > 0 : disky
- Disky vs. boxy dichotomy not completely understood, but correlated with kinematics and other galaxy properties:
  - most luminous Es tend to be boxy
  - lower luminosity Es tend to be disky

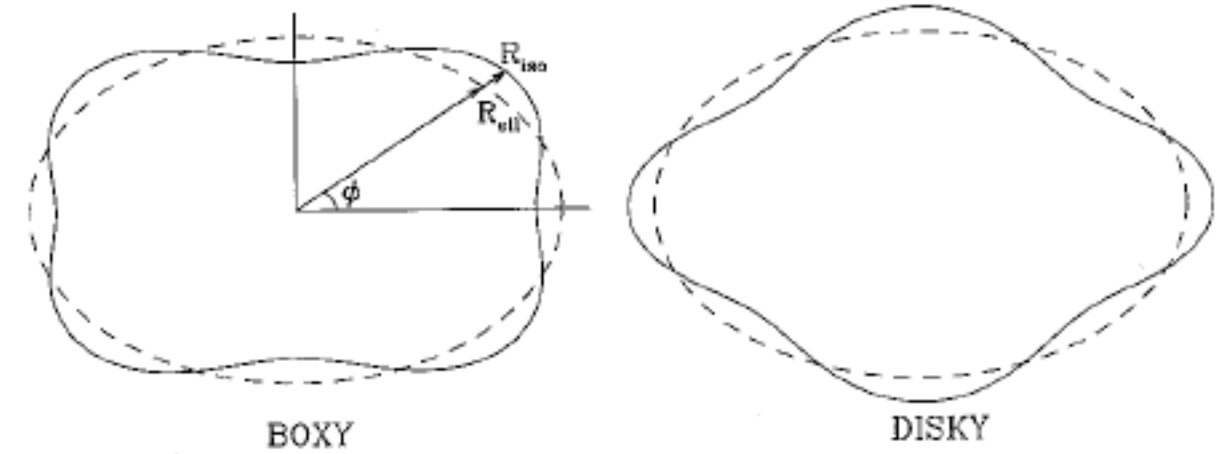


Fig. 2.15. An illustration of boxy and disky isophotes (solid curves). The dashed curves are the corresponding best-fit ellipses.

FIGURE 3. — Distribution of the ellipticity classes for all observed elliptical galaxies.

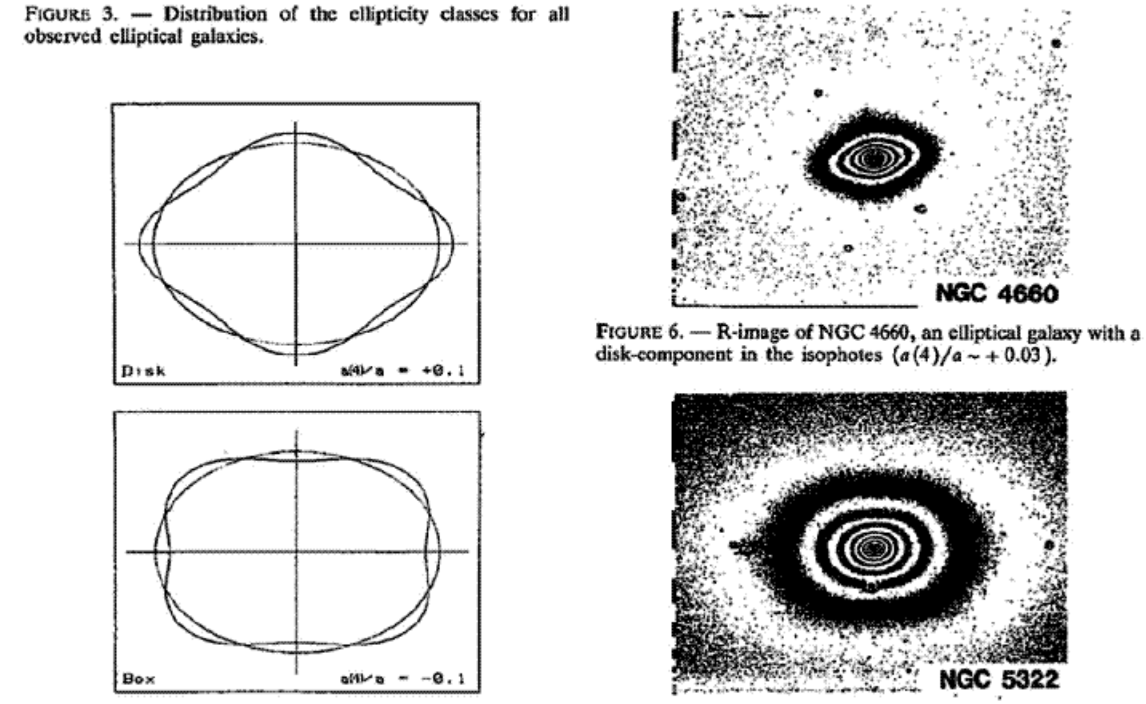


FIGURE 5. — Schematic drawing illustrating isophotes with $a(4)/a = +0.1$ and $a(4)/a = -0.1$.

FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes $(a(4)/a \sim +0.03)$.

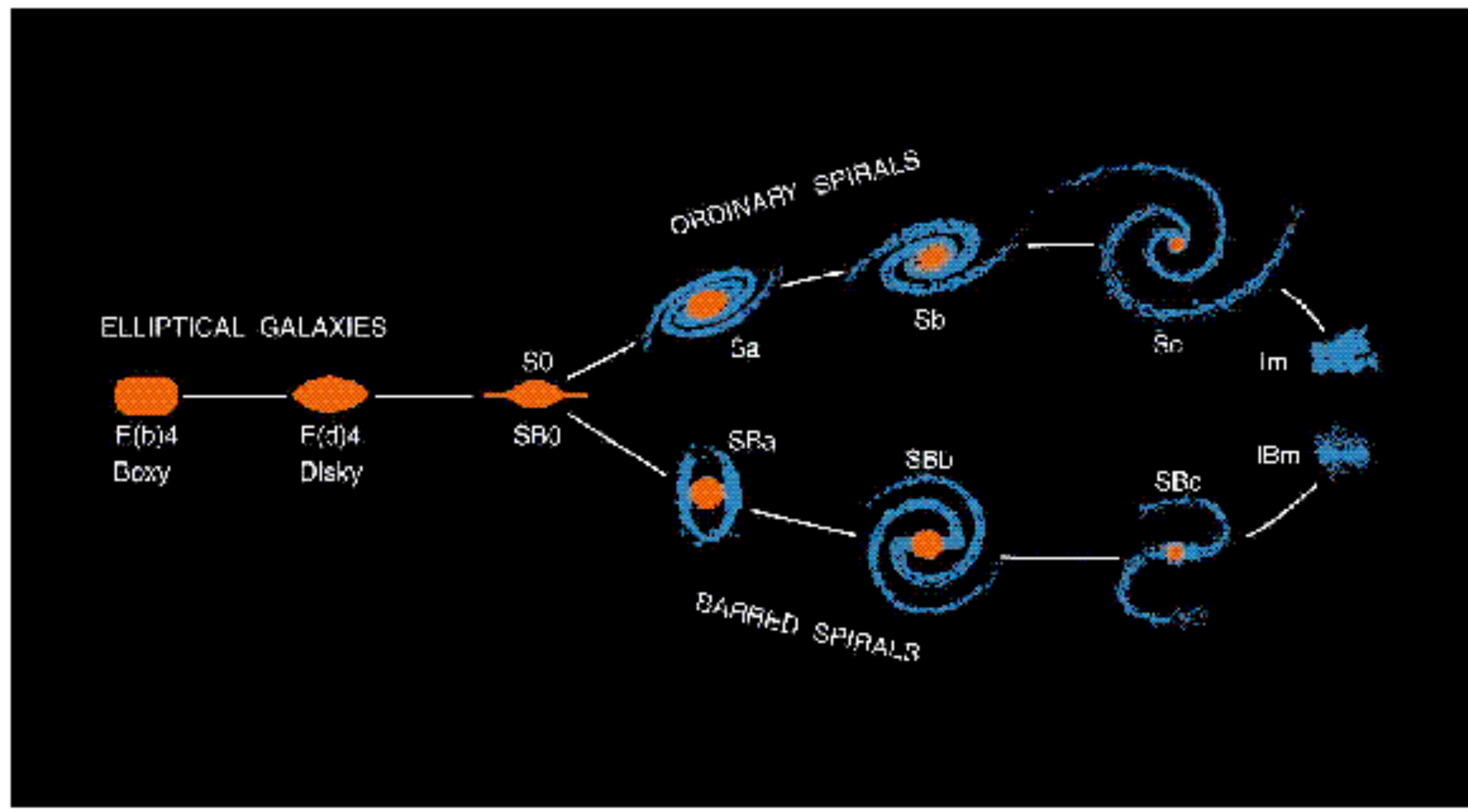
FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes $(a(4)/a \sim -0.01)$.

Examples for boxy and disky isophotes from Bender et al. (1988)

Ellipticals/Spheroids: Isophotal Shapes

- Possible that isophotal deviations form a continuous sequence or that there are two distinct classes
- Empirical adjustment to Hubble Tuning Fork proposed (Kormendy & Bender 1996)

Hubble Sequence (Revised for Ellipticals):



see: Kormendy J., Bender R. (1996) *ApJ*, **464**, L119

Ellipticals/Spheroids: Shapes

- **Non-axisymmetric features:**
  - Many ellipticals show ripples, shells, and streams, especially in outer regions
  - Probably remnants of mergers/interactions, recent accretion of disk galaxies
- Mergers play a role in the formation of at least some ellipticals.

Image: P.-A. Duc 2011; CEA/CFHT

Ellipticals/Spheroids

- **Low Luminosity — Spheroidals**: (diffuse dEs and dSph)
  - more like disks in profiles (n ~ 1), size, brightness, surface brightness, multiple age stellar populations
  - Possibly gas stripped/tidally shaken dwarf irregular (dIrr) and dwarf spiral (dS) galaxies
- **Medium Luminosity — Coreless Ellipticals**:
  - central profiles show steep power law to the smallest radii, medium luminosity, high central surface brightness; outer Sersic profiles intermediate n
  - disky isophotes
  - possibly oblate spheroids
  - may have formed from "wet" mergers, gas moves to center to form new stars
- **High Luminosity — Core Ellipticals:**
  - central profiles break to shallower slope, luminous, but lower central brightness; outer profiles n~4
  - boxy isophotes
  - triaxial
  - May have formed from dry mergers of other ellipticals (no gas dissipation), with binary black holes "scouring out" central regions, leaving a flatter core
- There is overlap in luminosity between these groups, and some question about whether they are distinct groups or form a continuous sequence