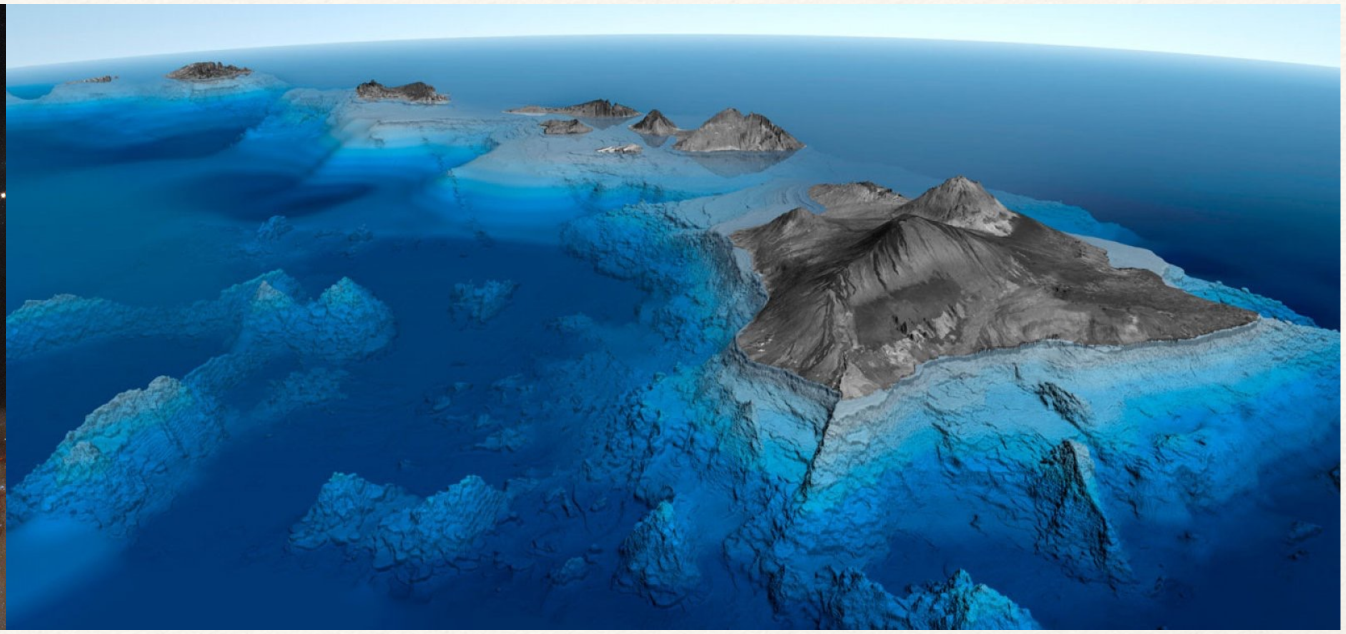


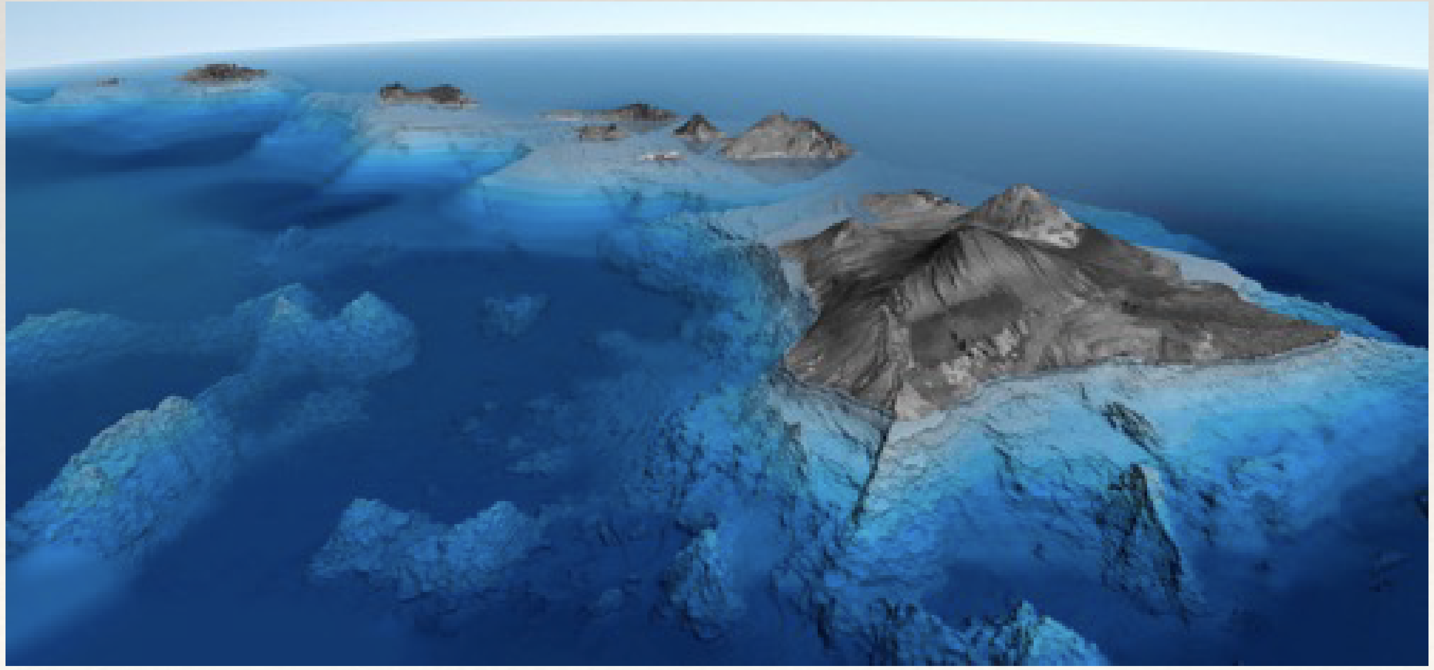
Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Be ready to discuss

- Of all the revelations in extragalactic astronomy that we discuss, which do you think was the most shocking and revolutionary to the people of the time?
- In what respect(s) is this image appropriate and/or inappropriate to a course on galaxies?



Course Overview

- We will aim to cover:
  - **Observing Galaxies — the main techniques used for observing galaxies**
  - Galaxy Population — the observed properties of galaxies
  - Building Blocks — the basic building blocks that make up individual galaxies
  - Milky Way — our own Galaxy

Outline for Today

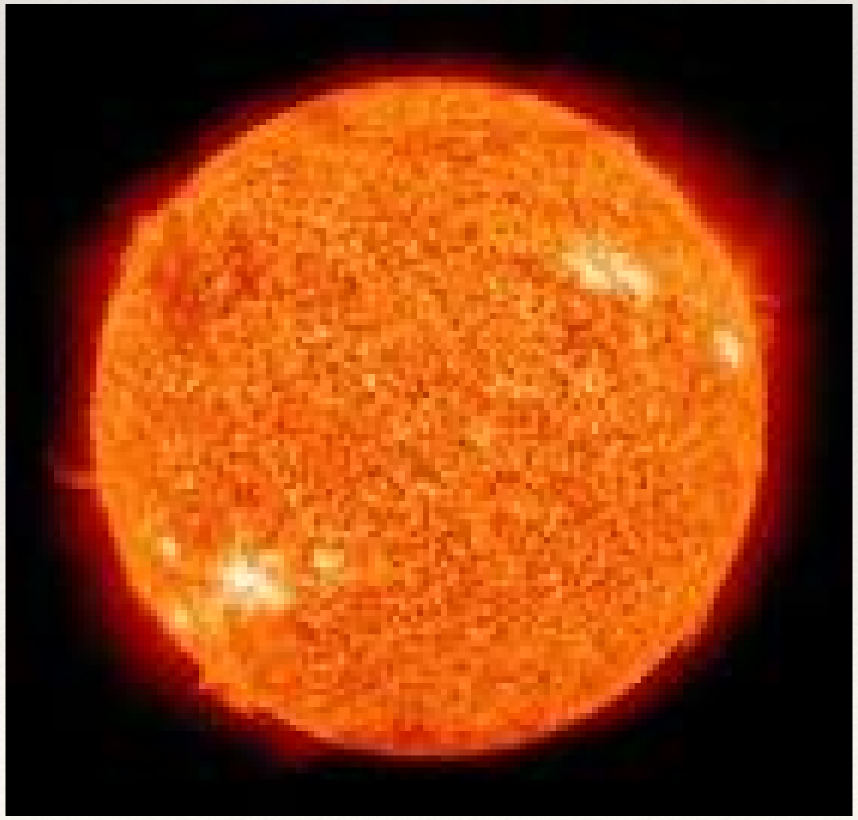
- Observing Galaxies - Imaging:
  - Surface Brightness
  - Elliptical Isophotes
  - Surface Brightness Profiles
  - Bulge/Disk Decomposition

NGC1232 (ESO)

Observing Galaxies - Imaging

What is the basic observable quantity for astronomical objects, i.e. it's name and units? Is it the same for all three types of objects shown here?

Sky and Telescope



Observing Galaxies - Imaging: Surface Brightness

- Basic measured property for imaging of an unresolved or point-like object is **flux**

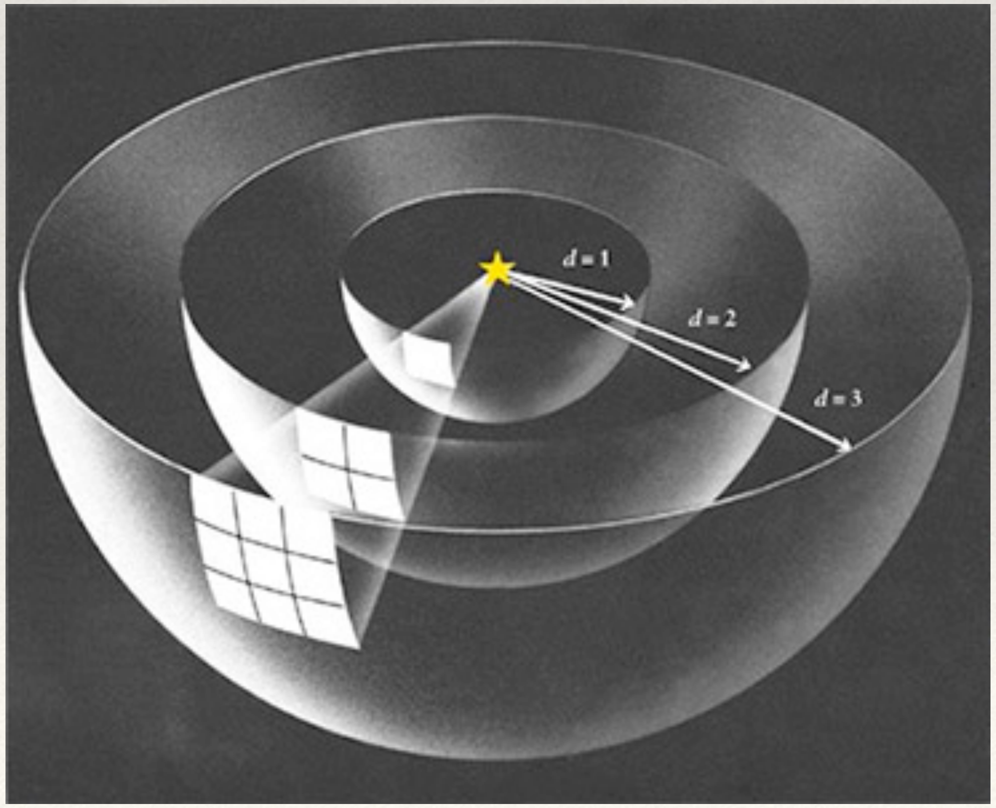
- Units: ergs/s /cm^2, W/m^2, or magnitudes

- Often given in terms of flux in a certain bandpass

- Obeys an inverse square law (for isotropically emitting source):

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

Sky and Telescope

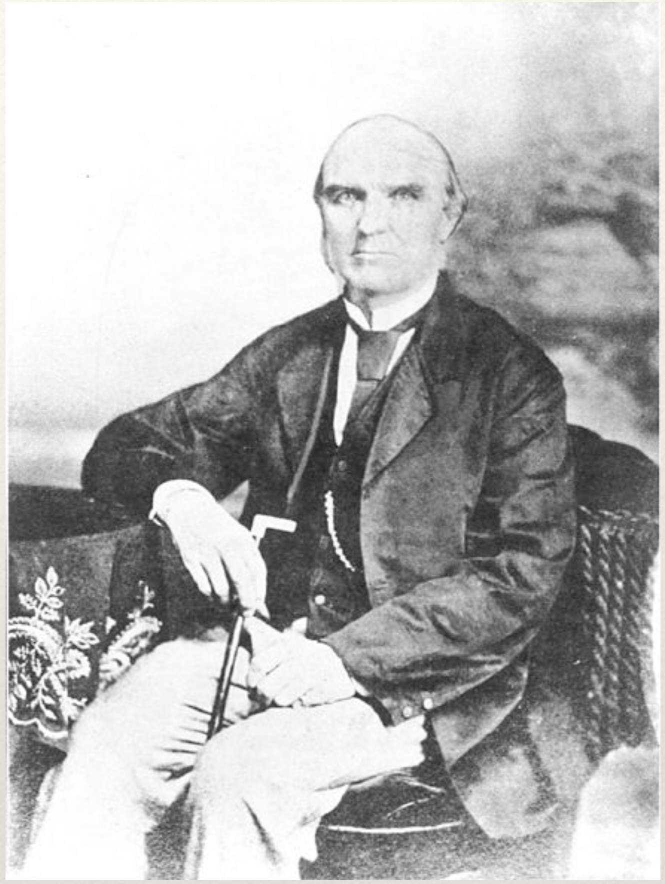


Michigan Astronomy - University of Michigan

Observing Galaxies - Imaging: Surface Brightness

- Magnitudes:
  - Greek Astronomer Hipparchus - devises magnitude system (1 - 6)
  - Norman Pogson - puts magnitudes on a rigorous mathematical scale
  - Often quoted in terms of a certain filter (UBVRI or SDSS ugriz), e.g., m_B or m_V

Hipparchus (190-120 BCE)


Norman Robert Pogson (1829 – 1891)

$$\Delta m = 5 \quad \rightarrow \quad 100 : 1$$

$$\Delta m = 1 \quad \rightarrow \quad (100)^{\frac{1}{5}} : 1$$
$$\sim 2.512 : 1$$

$$\frac{f_2}{f_1} = 100^{(m_1 - m_2)/5}$$

or

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{f_1}{f_2}\right)$$

Observing Galaxies - Imaging: Surface Brightness

- Basic measured property for imaging of a resolved or extended object is **surface brightness**, the flux per unit solid angle

- Units: ergs/s/cm2/arcsec2, ergs/s/cm2/sterradian, W/m2/arcsec2, or mag/arcsec2

$$\mu \propto -2.5 \log(I)$$

- Often given in terms of light in a certain bandpass, e.g., I_B or μ_V

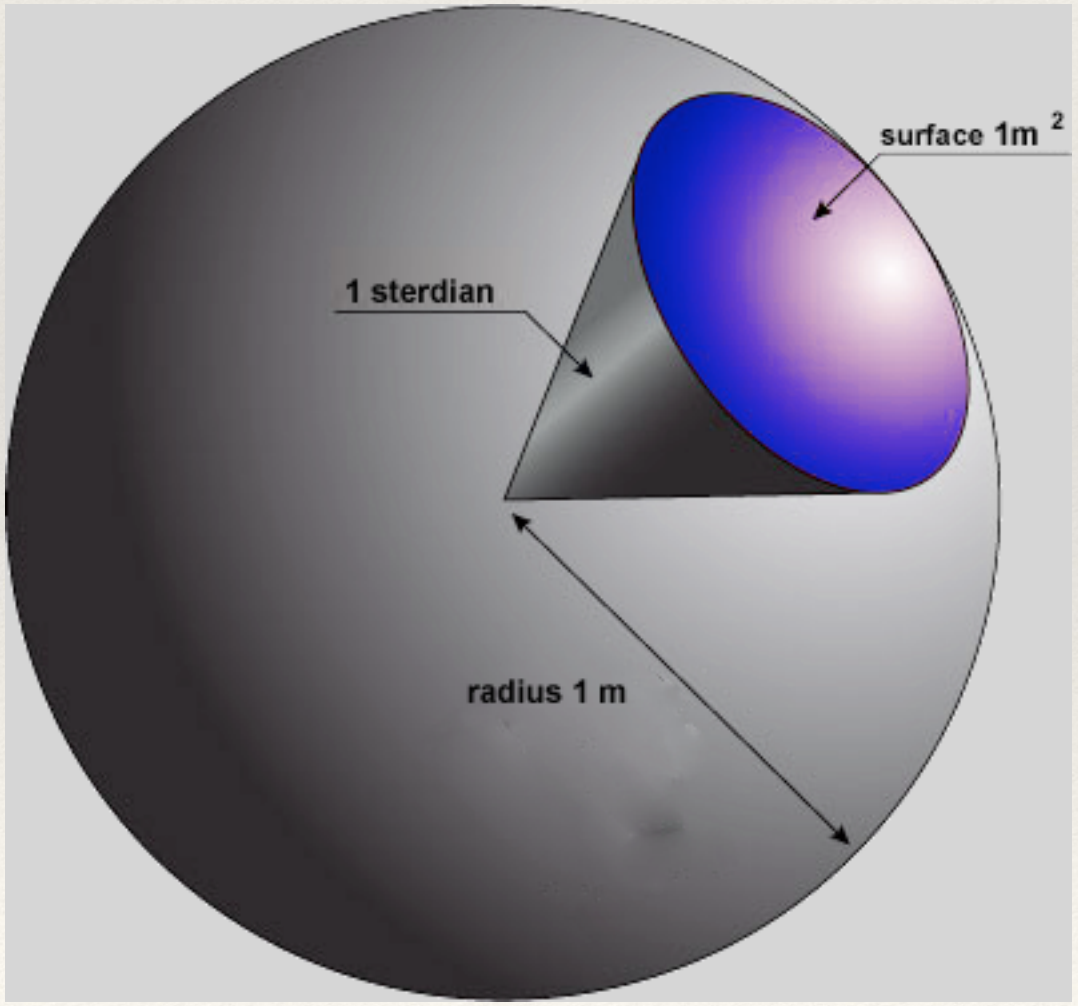
HST image of Helix Nebula (NASA/ESA)

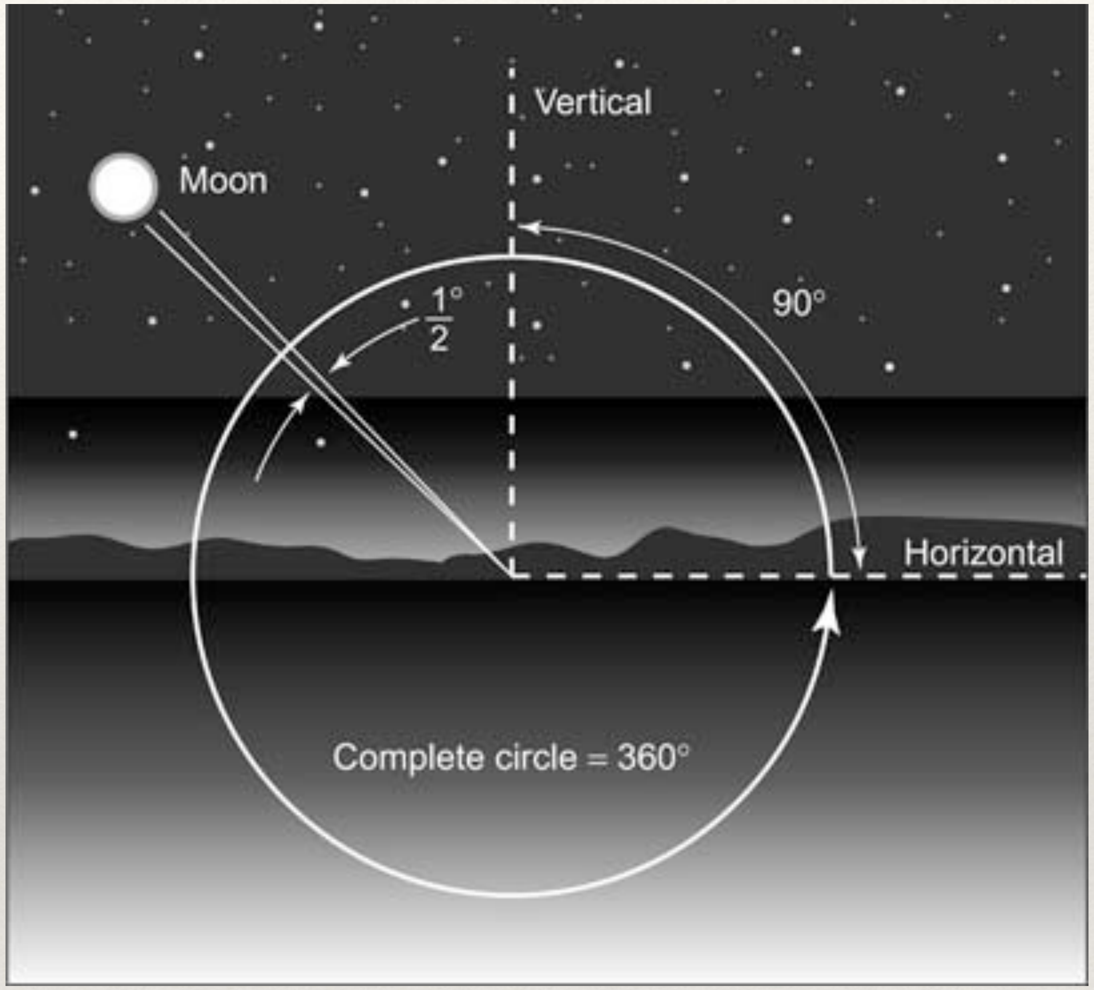
$$\mu = m + 2.5 \cdot \log_{10} A$$

(for uniform SB, A = in square angle!)

Observing Galaxies - Imaging: Surface Brightness

- angular sizes: degrees, arcminutes, arcseconds, or radians





www.cliffnotes.com

- Angular areas (solid angles) measured, e.g., in square degrees, square arcseconds, or steradians (square radians)

Exercises

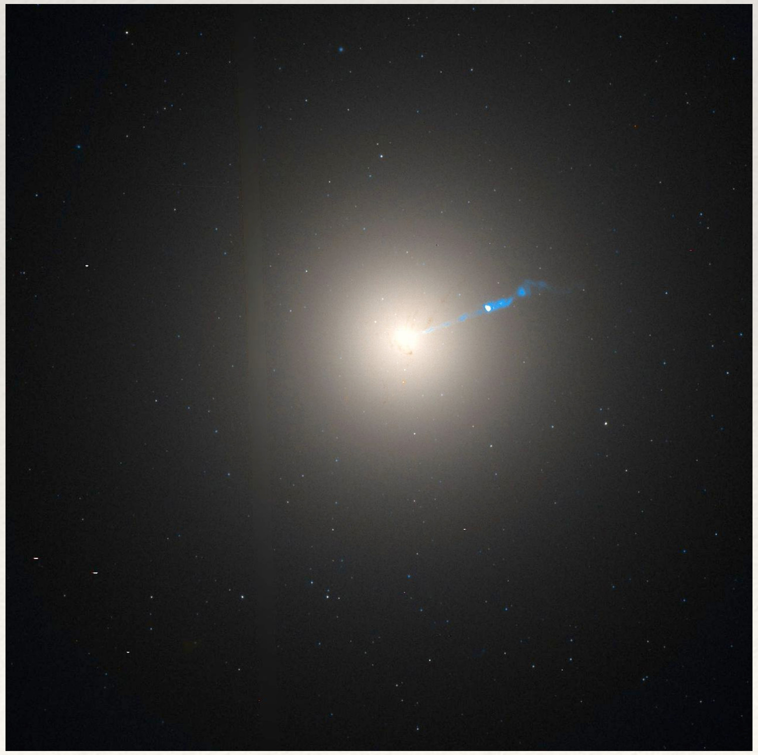
- The total flux of a certain galaxy is 10 times higher in the V band than that of another galaxy. What is the difference inmagnitudes?
- M87 has a central surface brightness in the V band of $\mu V = 17$ mag/arcsec^2. If the core radius is 10 arcsec and you make the (bad!) assumption that the surface brightness is constant, what's the core's apparent magnitude?

$$\frac{f_2}{f_1} = 100^{(m_1 - m_2)/5}$$

or

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{f_1}{f_2}\right)$$

NGC 4414 (NASA)



M87 (NASA/STScI/WikiSky)

Exercises

$$\frac{f_2}{f_1} = 100^{(m_1 - m_2)/5}$$

or

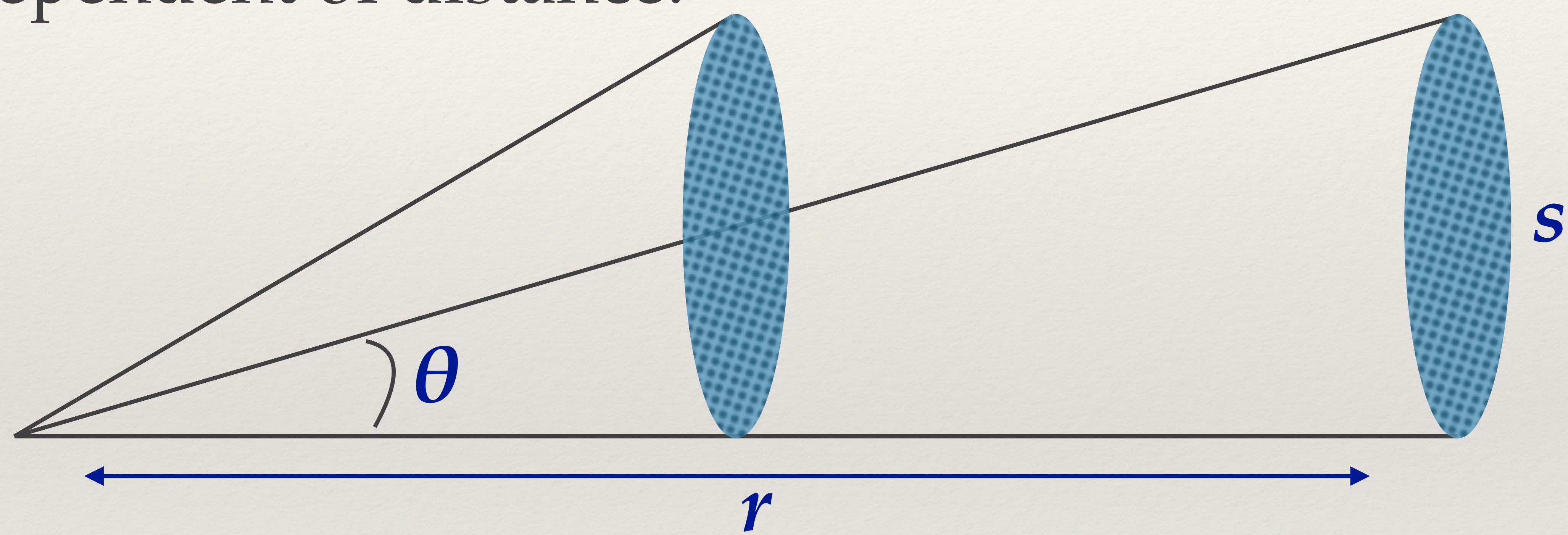
$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{f_1}{f_2}\right)$$

Observing Galaxies - Imaging: Surface Brightness

- How does surface brightness change with the distance of an object?

Observing Galaxies - Imaging: Surface Brightness

- In a simple, static universe, the surface brightness is independent of distance.



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

$$s \approx r\theta$$

$$I \propto \frac{L}{4\pi \cancel{r^2}\ \frac{s^2}{\cancel{r^2}}}$$

Our universe is not simple…

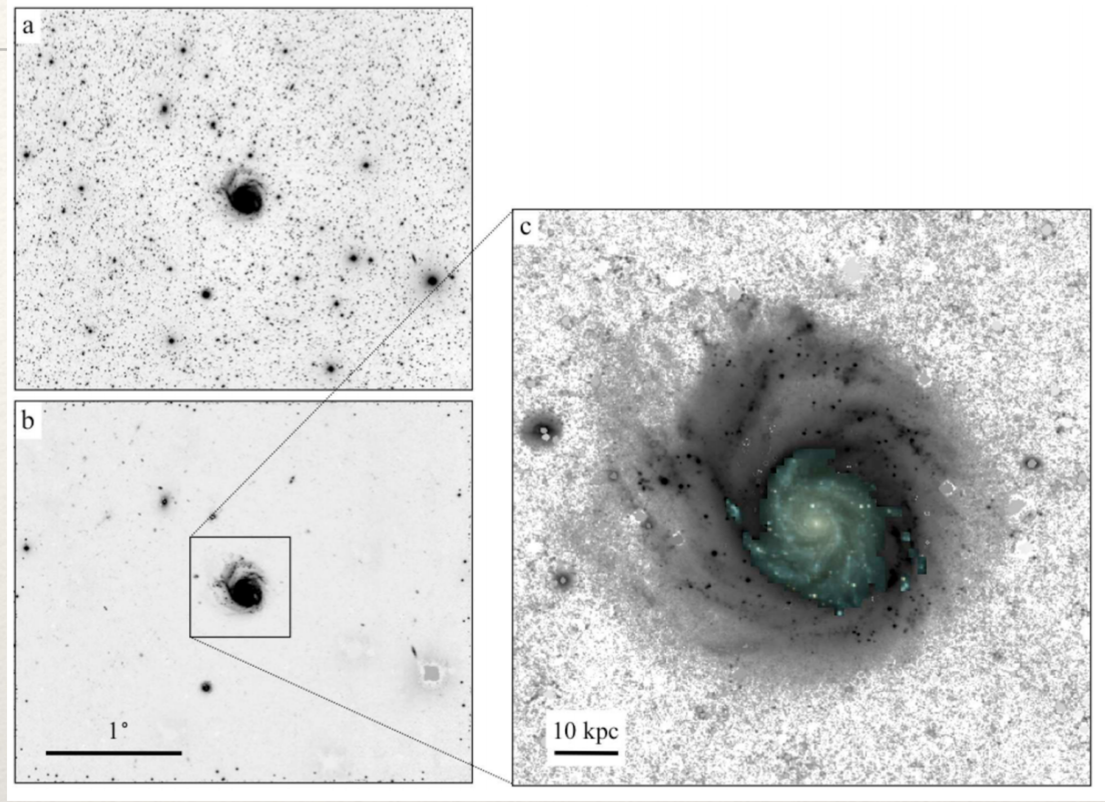
Observing Galaxies - Imaging: Surface Brightness

- In an expanding universe, there are several additional effects:
  - the rate at which photons are received is reduced — a factor of (1+z).
  - the energy of each photon is reduced — a factor of (1+z).
  - distant objects don t shrin as uch as in static universe — a factor of $(1+z)^2$.
- **Combining these effects together, in an expanding universe surface brightness decreases as $(1+z)^4$!**

(See Galaxies II for more details!)

Observing Galaxies - Imaging: Surface Brightness

- In principle, surface brightness measured directly from 2D image.
- Observational challenges:
  - galaxies are faint! — more than half of the light comes from regions with SB < SBsky
  - need deep images — (long integration time, big telescopes, dark sky)
- Challenging to observe fainter than ~24-25 mag/sq.arcsec in unresolved light
- seeing — affects central SB
- sky determination — affects outer SB distribution



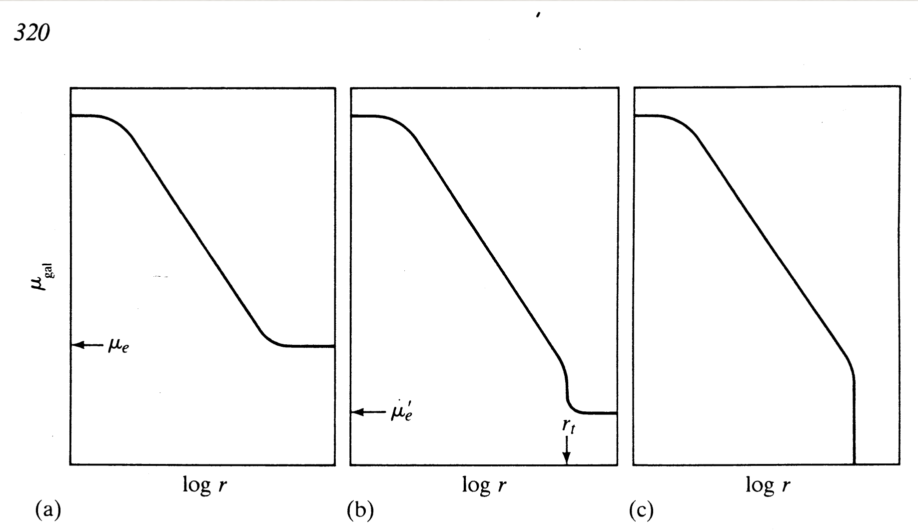


Figure 5-19. The effects of errors in the subtracted sky background on the profile of a galaxy with a truncated brightness distribution. (a) The background has been underestimated so that the night sky contributes to the "galaxy" brightness at large radii. (b) The background is higher than in (a) but still too low. (c) The correct background level.

Mihalas & Binney

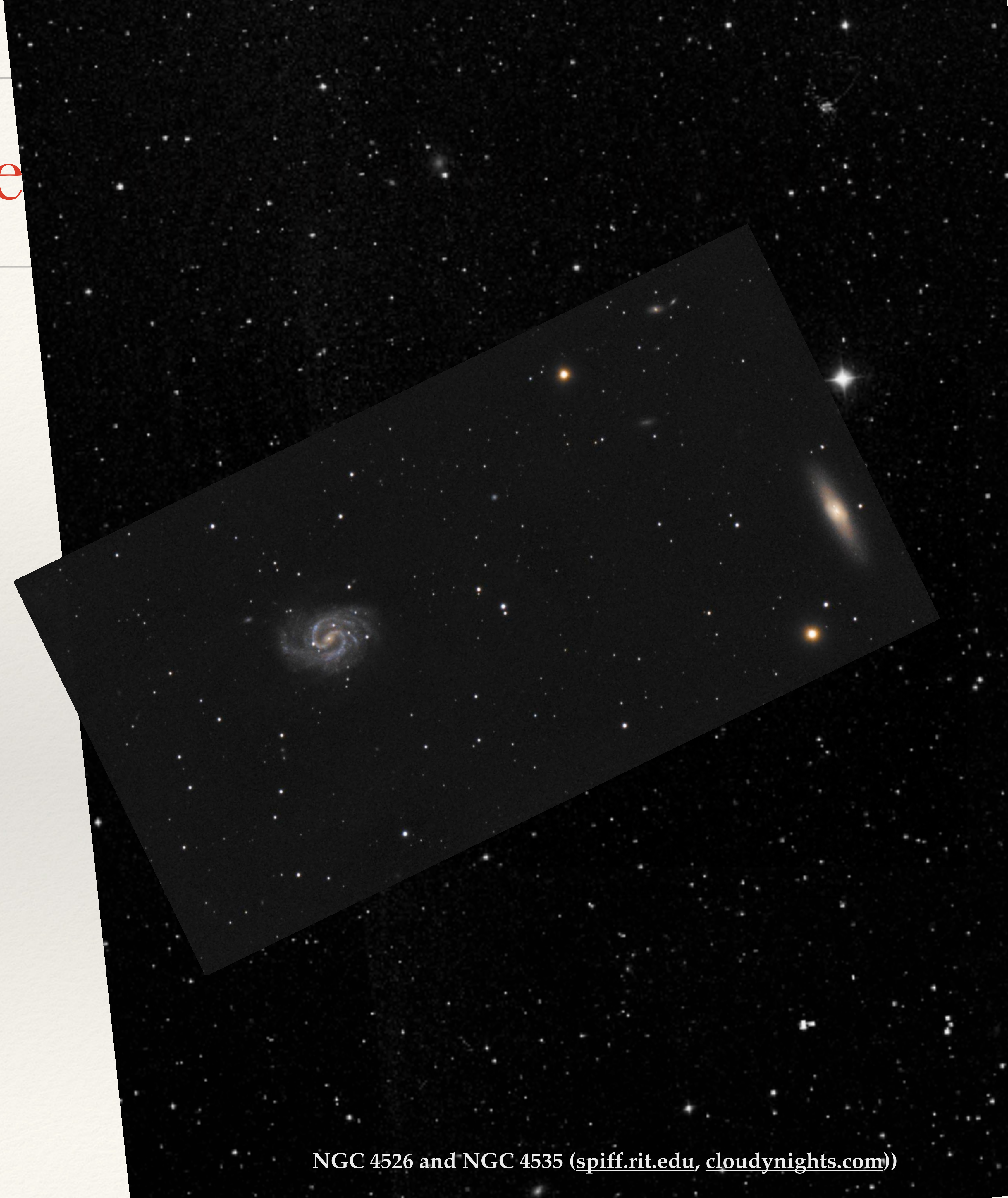
Observing Galaxies - Imaging: Surface Brightness

- Can observe to lower surface brightness (~30 mag/sq.arcsec) for nearby objects in which you can resolve stars, i.e. add up their individual brightnesses
- scattered light : if carefully controlled, can observe unresolved light significantly fainter, e.g. Dragonfly array

https://www.dragonflytelescope.org/gallery.html

Observing Galaxie

- Strong selection effects against low surface brightness objects
- Apparent "size" and "total magnitude" of a galaxy will depend on its surface brightness.
- Example: NGC 4526 vs. NGC 4535 (the "Lost Galaxy"). Both m_V=10.7 mag but have very different surface brightnesses!

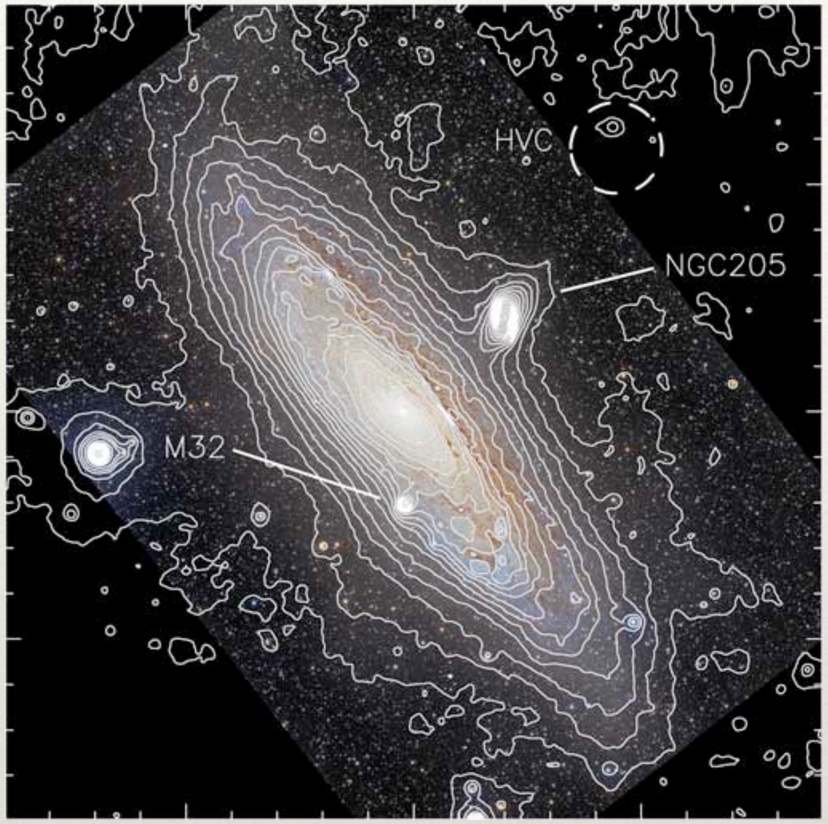


NGC 4526 and NGC 4535 (spiff.rit.edu, cloudynights.com))

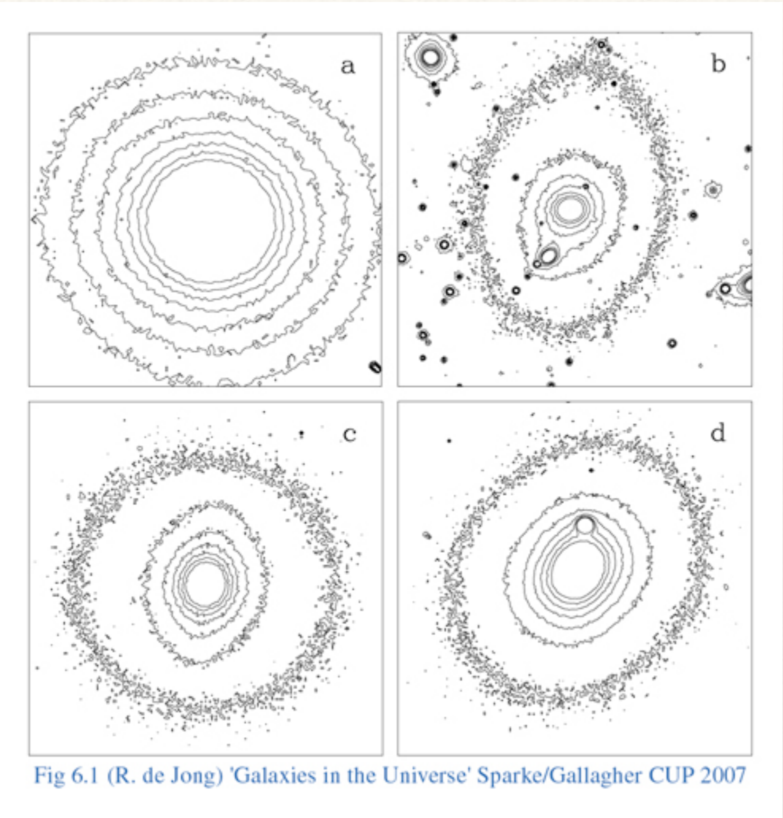
Thought Question

- What is the surface brightness actually telling us about the galaxy? (That is, why do we care?)
- What should we **do** with the surface brightness information once we measure it?

Observing Galaxies - Imaging: Elliptical Isophotes



M31 isophotes — Image Credit: Vahid K. Alilou, MathWorks.com



Isophotes of four giant elliptical galaxies — Sparke & Gallagher 2000

- Most galaxies are symmetric at a significant level
- Galaxy **isophotes** (contours of equal surface brightness) are typically well represented by **ellipses** (but not perfectly!).
- Elliptical contours fit spirals and ellipticals for slightly different reasons (i.e., viewing angle/ disk thickness vs. intrinsic ellipticity).
- Ellipse flattening characterized by ellipticity=(1-b/a) or eccentricity, $e^2 = (1-(b/a)^2)$

Observing Galaxies - Imaging: Surface Brightness Profiles

- For a purely axisymmetric object, surface brightness distribution reduces to a 1D (major axis) surface brightness profile.
- Goal: to find a "good fit" to the surface brightness profile

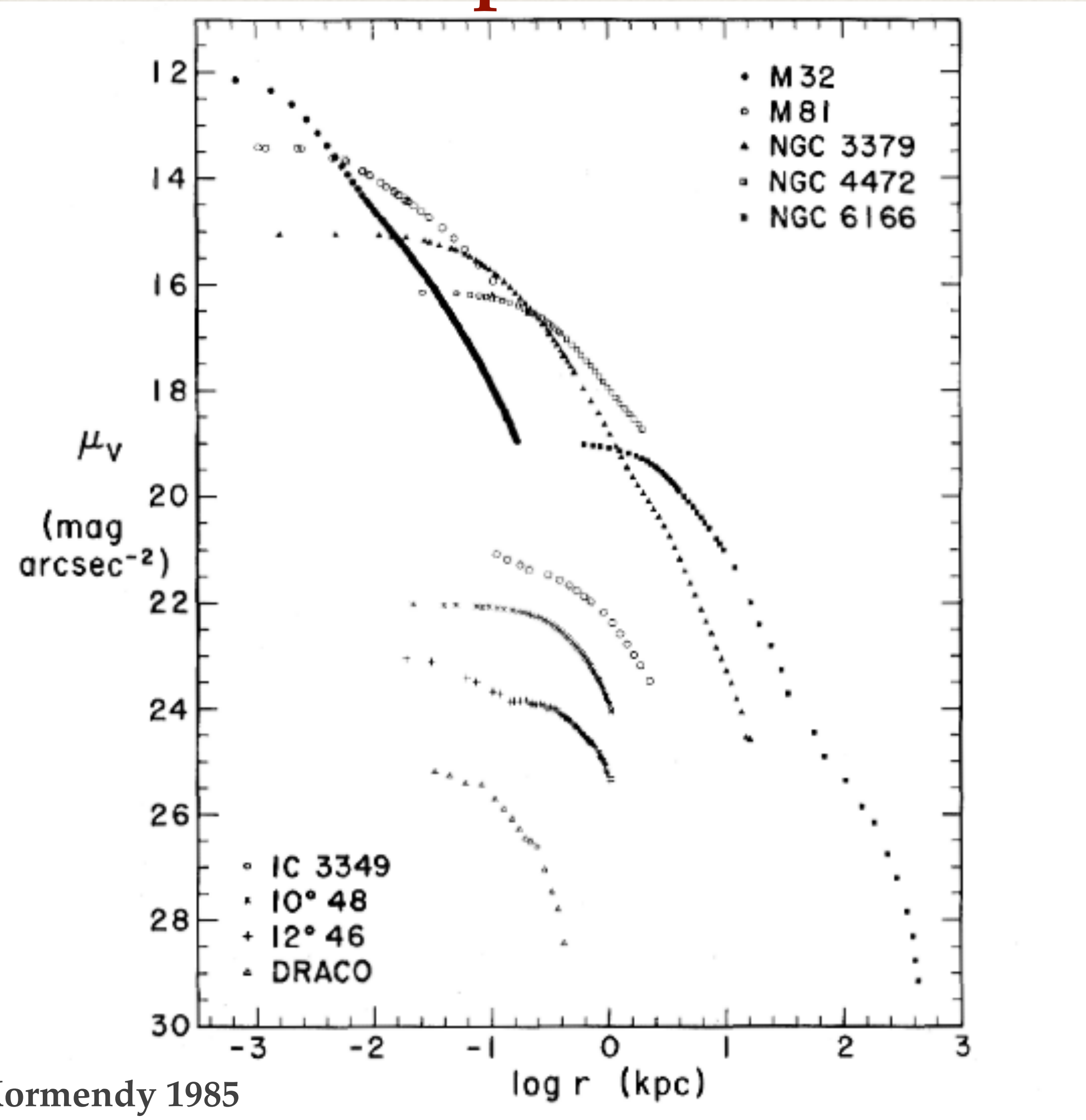
Ellipticals

Spirals

Observing Galaxies - Imaging: Surface Brightness Profiles

- For a purely axisymmetric object, surface brightness distribution reduces to a 1D (major axis) surface brightness profile.
- Goal: to find a “good fit” to the surface brightness profile

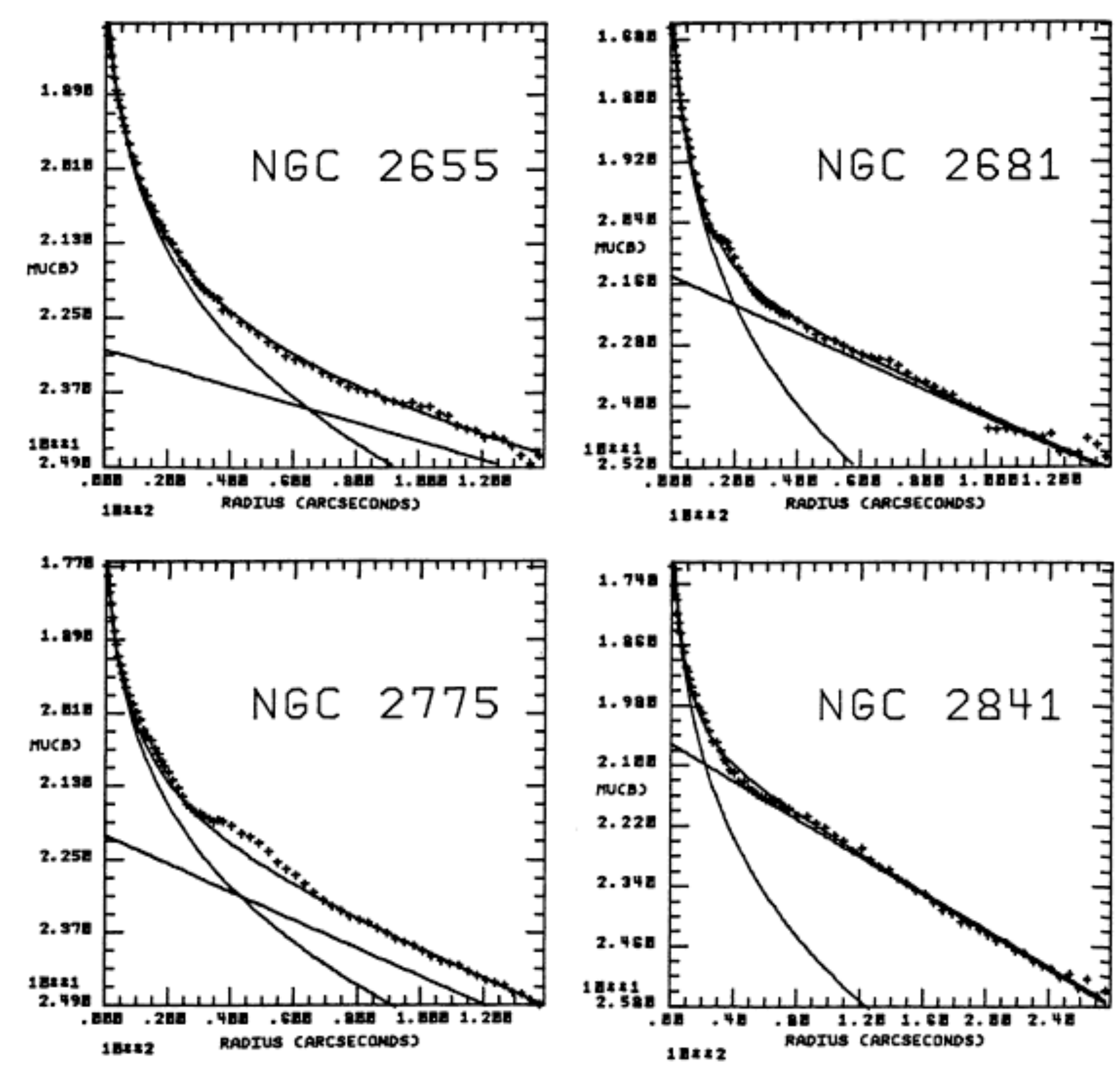
Ellipticals



Kormendy 1985

Spirals

Boroson 1981



Observing Galaxies - Imaging: Surface Brightness Profiles

- Surface brightness profiles often parameterized:
  - spirals/disks: **exponential profile**

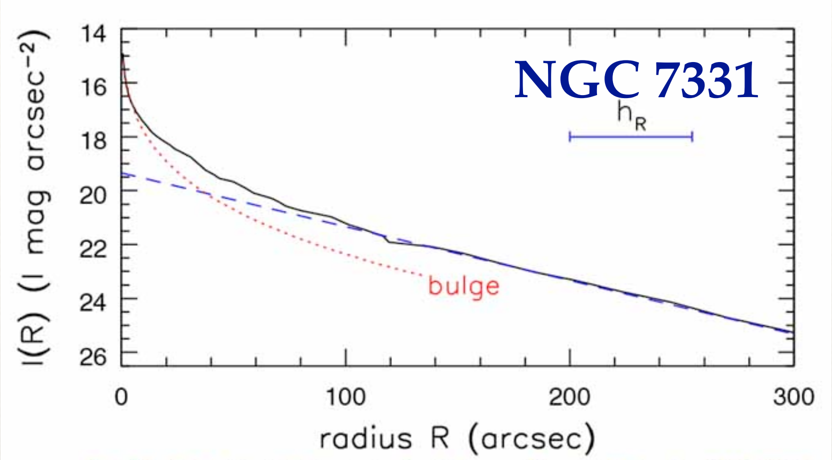
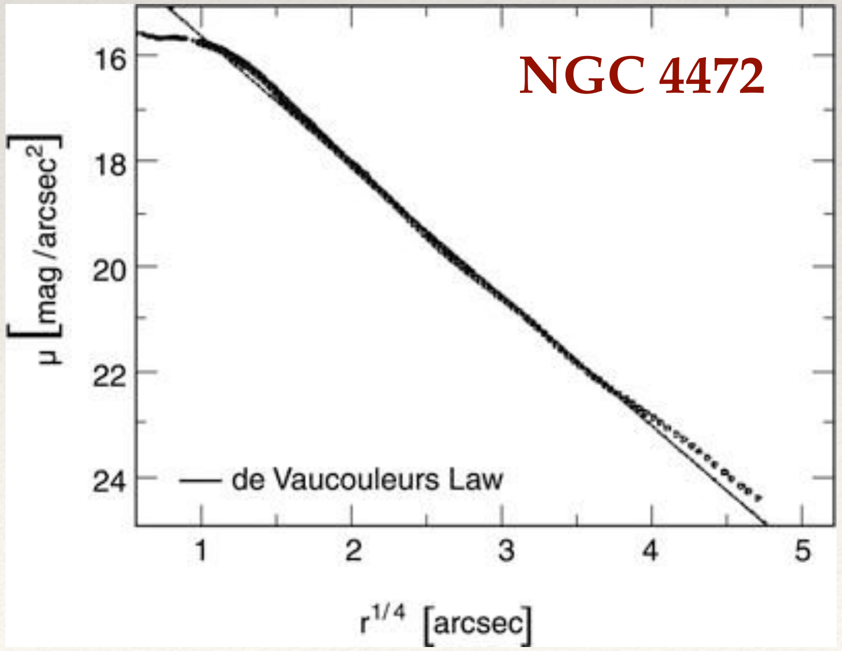


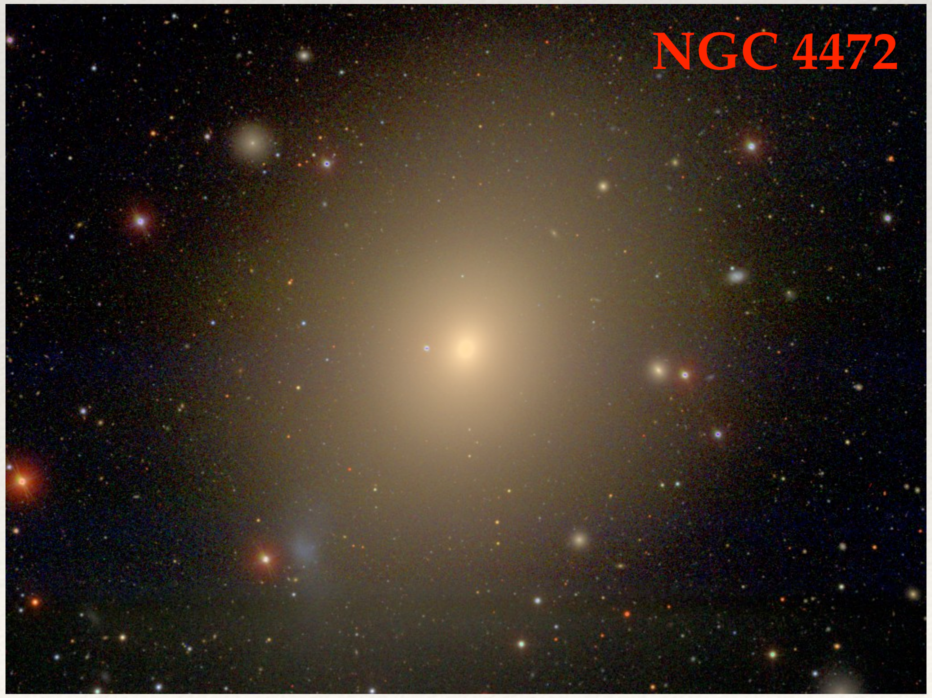
Fig 5.4 (R. Peletier) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

  - ellipticals: **de Vaucouleurs (*r*1/4) profile**



Schneider 2015, Fig. 3.9

NGC 7331; Image Credit: Dietmar Hager, Torsten Grossmann, APOD



NGC 4472 (M49), most luminous member of Virgo Cluster
Image Credit: David Hogg, Michael Blanton, SDSS

Observing Galaxies - Imaging: Surface Brightness Profiles

- Surface brightness profiles often parameterized:
  - spirals/disks: **exponential profile**
    - r_s = scale radius (where SB drops by 1/e)
    - Σ_s = surface brightness at scale radius

$$\Sigma(r) = \Sigma_s \exp\left(-\frac{r}{r_s}\right)$$

- ellipticals: **de Vaucouleurs ($r^{1/4}$) profile**
  - r_e = half-light radius, i.e. radius that encloses half total light if model is extrapolated to infinity
  - Σ_e = surface brightness at effective radius
  - Σ_0 = central surface brightness (note: $\Sigma_0 \sim 2000\ \Sigma_e$)

$$\Sigma(r) = \Sigma_e \exp\left(-7.67\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]\right)$$

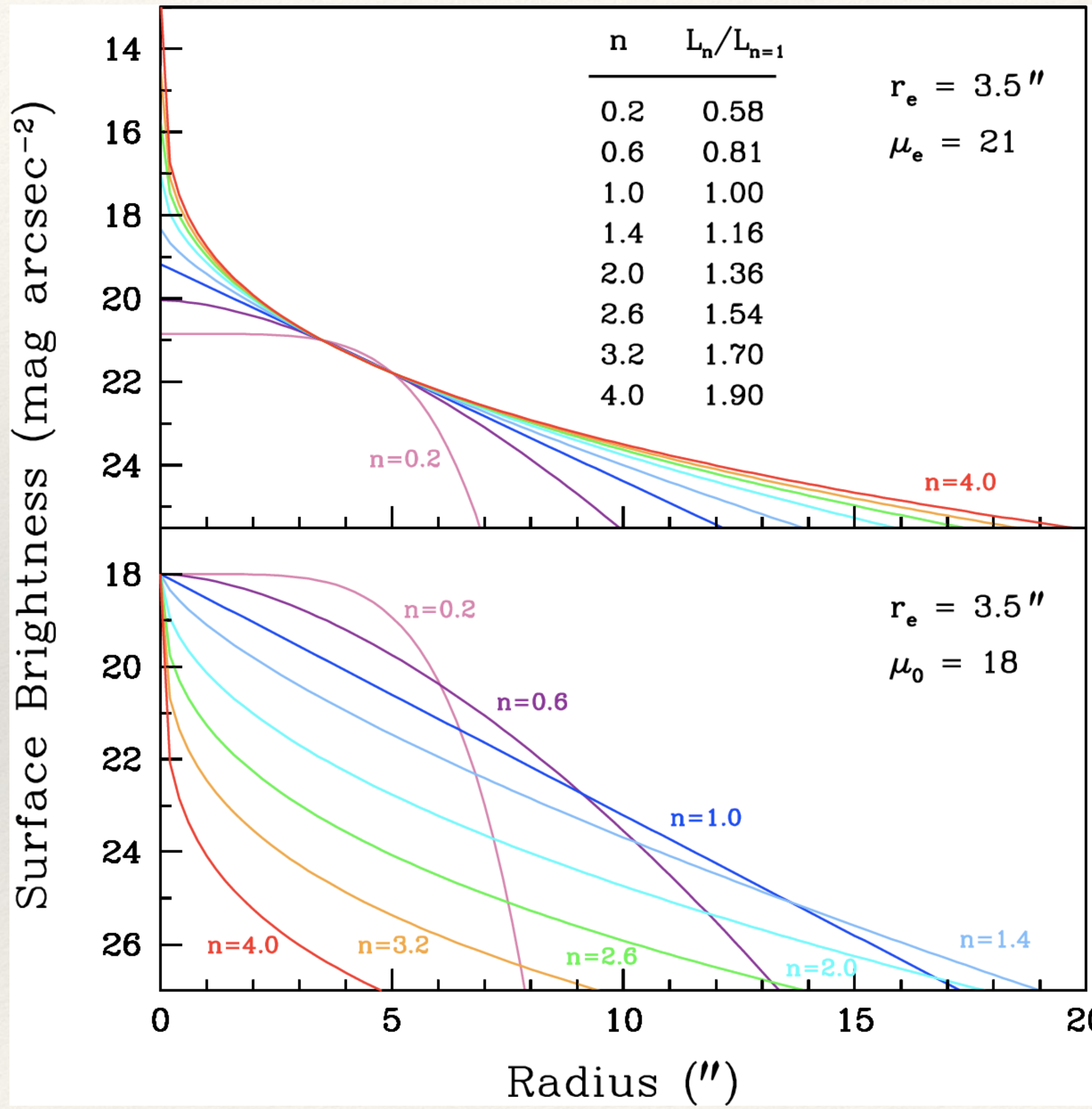
Observing Galaxies - Imaging: Surface Brightness Profiles

- Both profiles can be described using a more general form, the **Sérsic profile**:

$$\Sigma(r) = \Sigma_e \exp\left(-b_n\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]\right)$$

  - Sérsic index n governs shape
  - n=4 for ellipticals; n=1 for disks
  - r_e = half-light radius
  - b_n = determined from the definition of r_e as the half-light radius (b_n ~ 2n - 0.324).

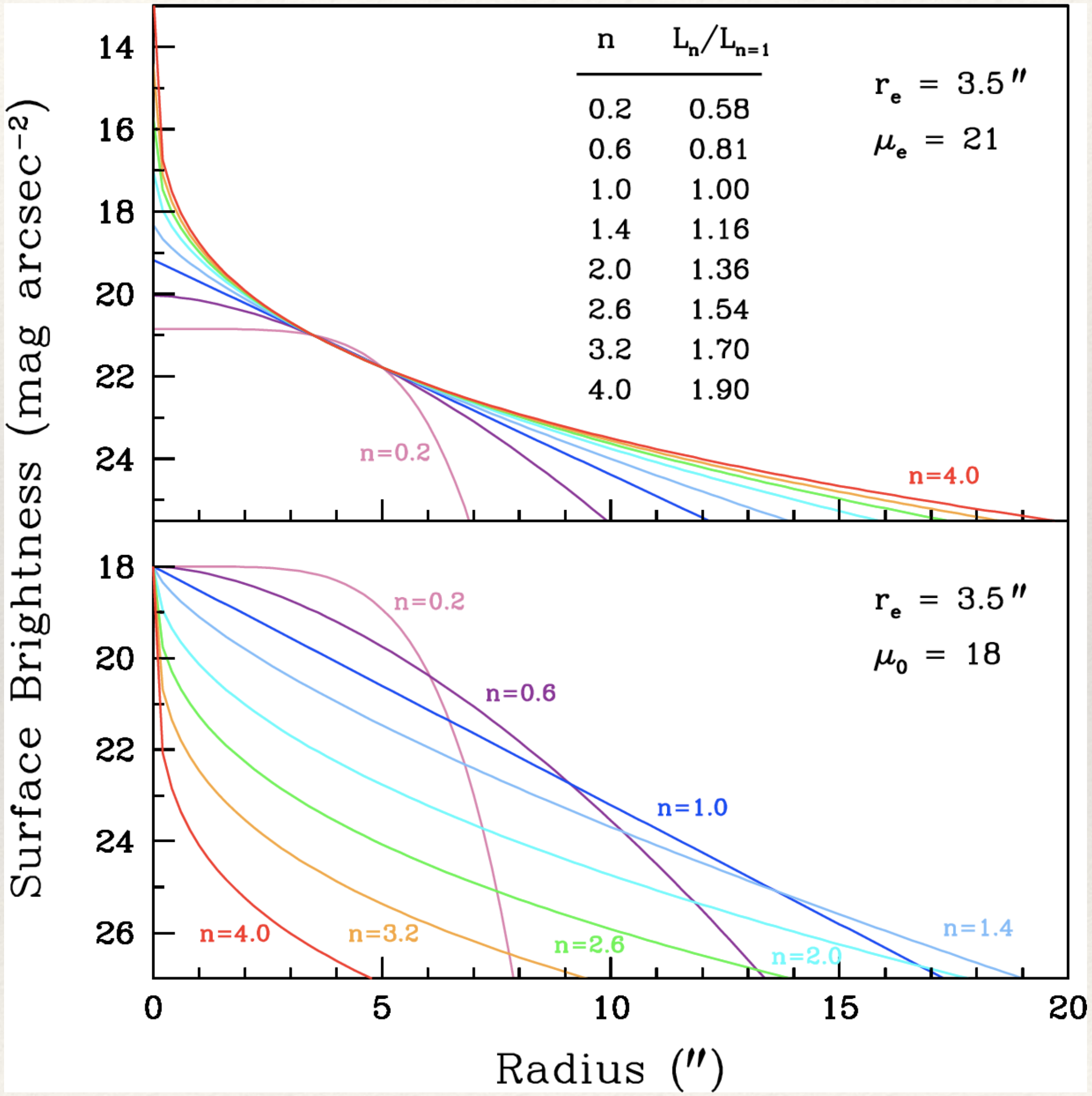
$$\int_0^\infty I_b(r) 2\pi r\, dr = 2\int_0^{r_e} I_b(r) 2\pi r\, dr \,. \qquad (9)$$



MacArthur, Courteau, & Holtzman 2003

Discussion

- **Describe how the profiles of an elliptical and a spiral galaxy differ.**
  - How would you describe the comparison of the profiles of the two galaxies if they had the same total luminosity? Is this represented by one of the plots at the right?
  - Which profile is more concentrated, deVaucouleurs (n=4) or exponential (n=1)?

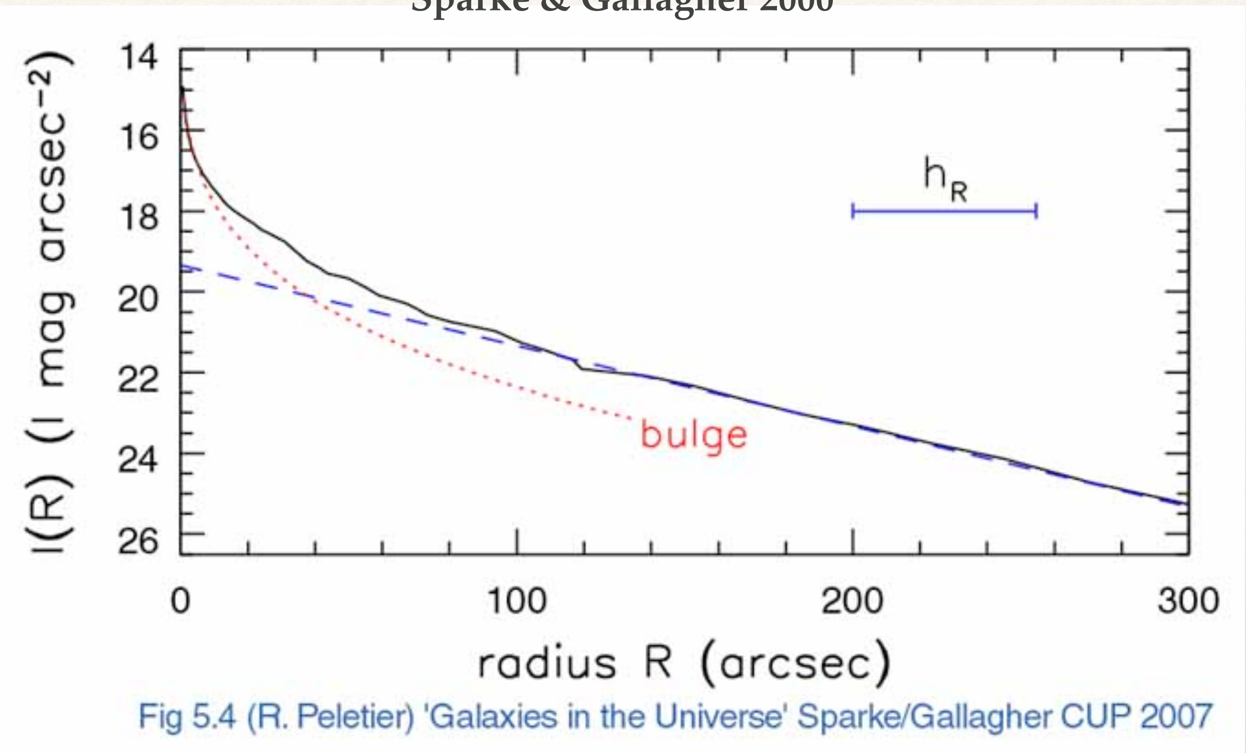


MacArthur, Courteau, & Holtzman 2003

Observing Galaxies - Imaging: Bulge/Disk Decomposition

- Many galaxies are well fit by multiple components,
  e.g., a central bulge plus an extended disk
- Can split the different components via **bulge-disk decomposition** (e.g. MacArthur, Courteau, & Holtzman 2003).
  - Why would one want to do this?
  - 1D vs 2D decomposition
- Problems / assumptions?

Sparke & Gallagher 2000

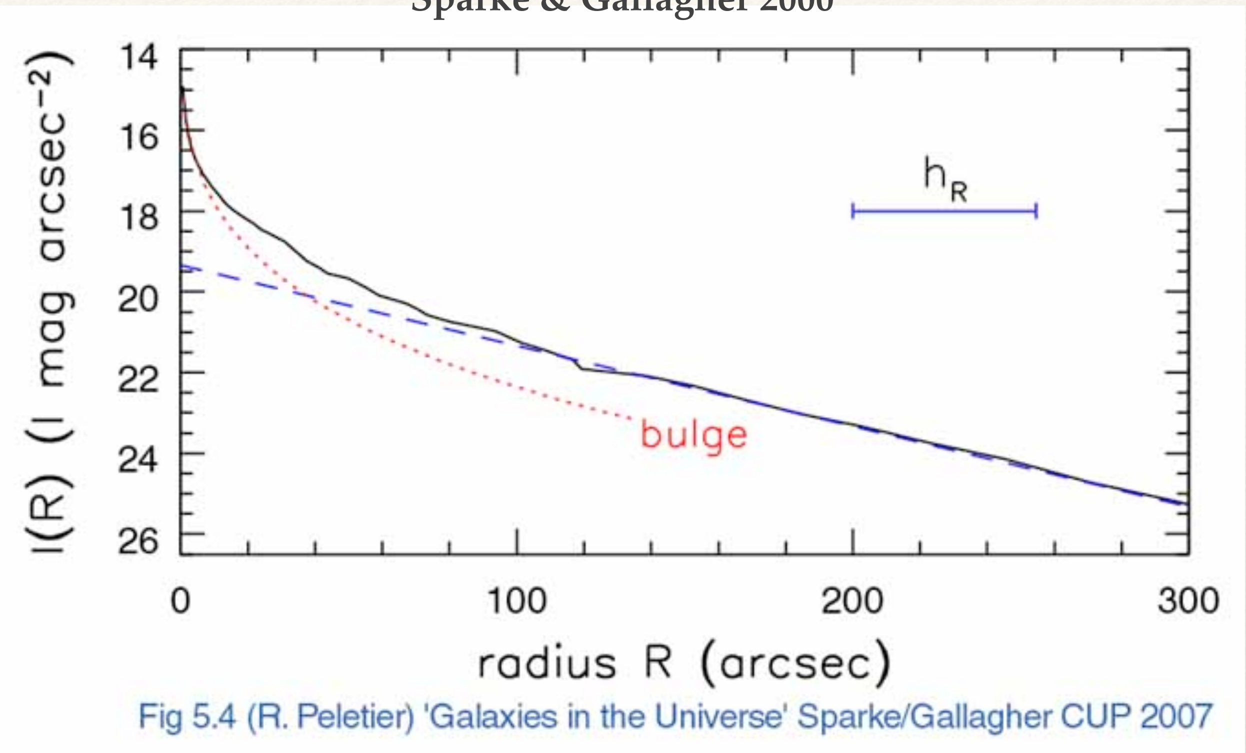


NGC 7331; Image Credit: Dietmar Hager, Torsten Grossmann, APOD

Observing Galaxies - Imaging: Bulge/Disk Decomposition

- Looking ahead:
  - are bulges like elliptical galaxies?
  - maybe not, at least for later type spirals: bulge Sersic profiles closer to n=1 than to n=4 in many cases
  - secular evolution

Sparke & Gallagher 2000



NGC 7331; Image Credit: Dietmar Hager, Torsten Grossmann, APOD

Paper summary 1 / Problems 1

- Surface brightness, magnitudes, flux, Sersic profiles
- Paper summary 1 - read / synthesize paper - **due September 1**
    - Straatman et al. 2015 — *"The Sizes of Massive Quiescent and Star-forming Galaxies at z~4 with ZFOURGE and CANDELS"*
- Problems 1 - quantitative / coding assignment related to the paper - due September 8

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