

Getting to know the “island universes” out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Questions

- How did we determine the contribution of dark energy, dark matter, and baryonic matter within our Universe?

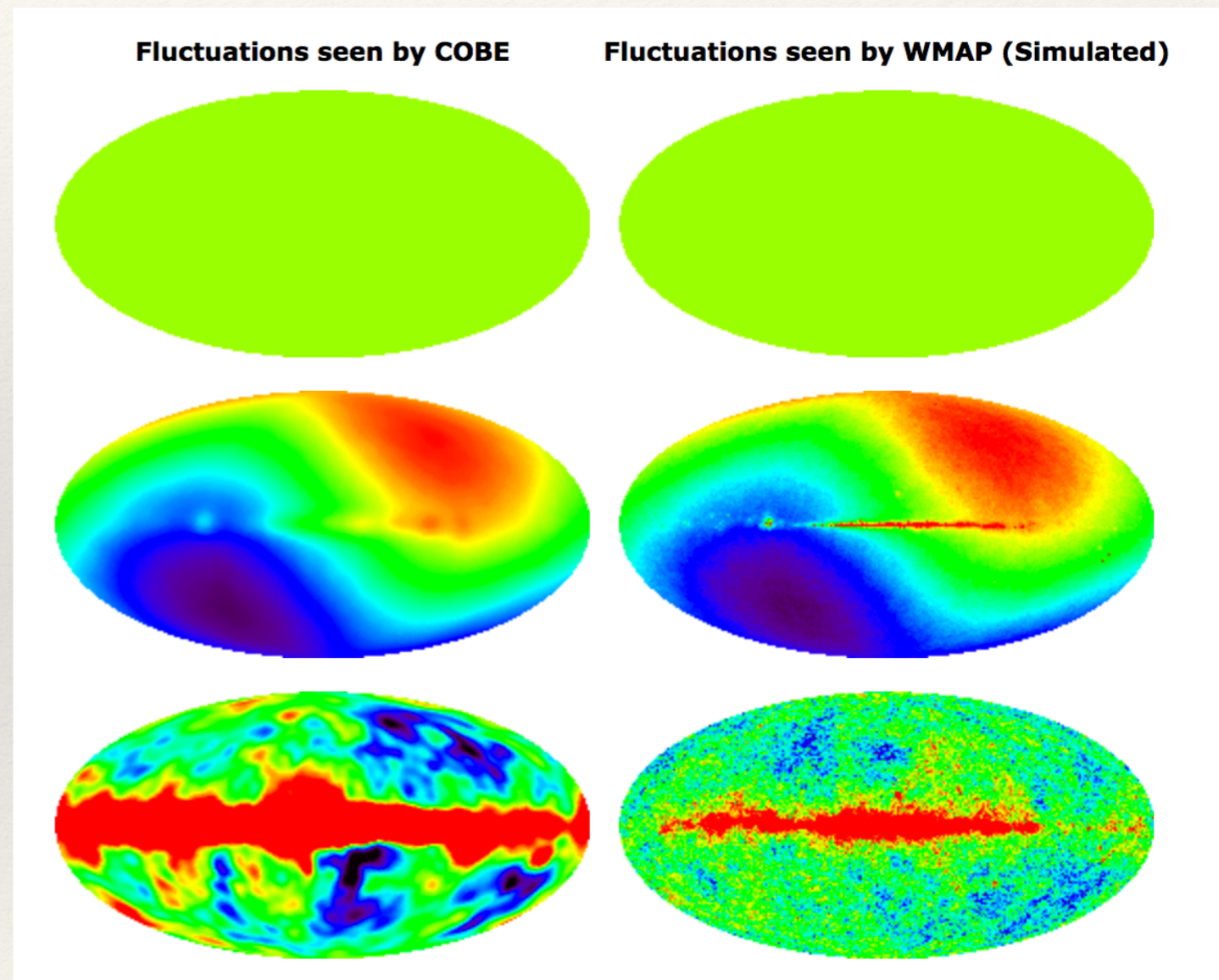
- What was the source of van Manner's (van Maanen) error, was it a physical observation plate error or calculations, how do you detect galactic rotation?
- Vera Rubin used a spectrometer as a way to measure galaxy rotation curves, but how exactly did she do this? Did you look at individual stars? Whole clusters?
- Did early Astronomers apply Kepler's Laws to stellar motion?
 - Kepler was from the late 1500s through the early 1600s...Were there attempts to apply these laws to nebulae before it was realized many of them were made up of stars?

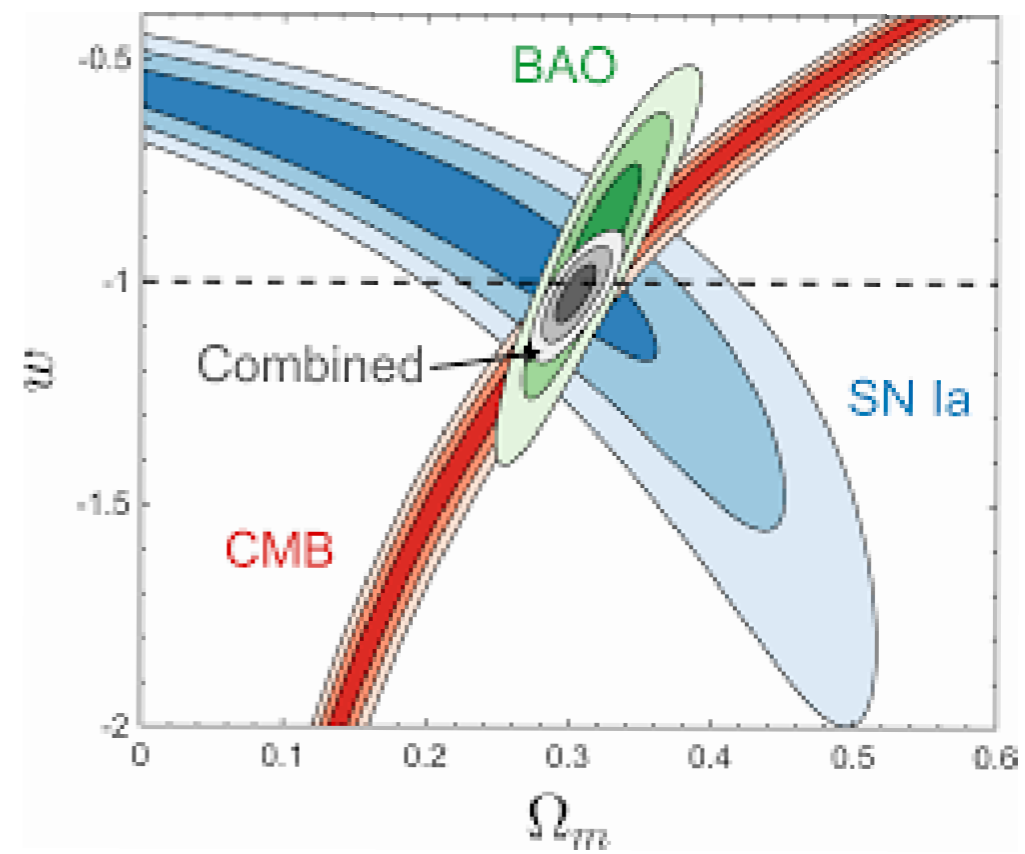
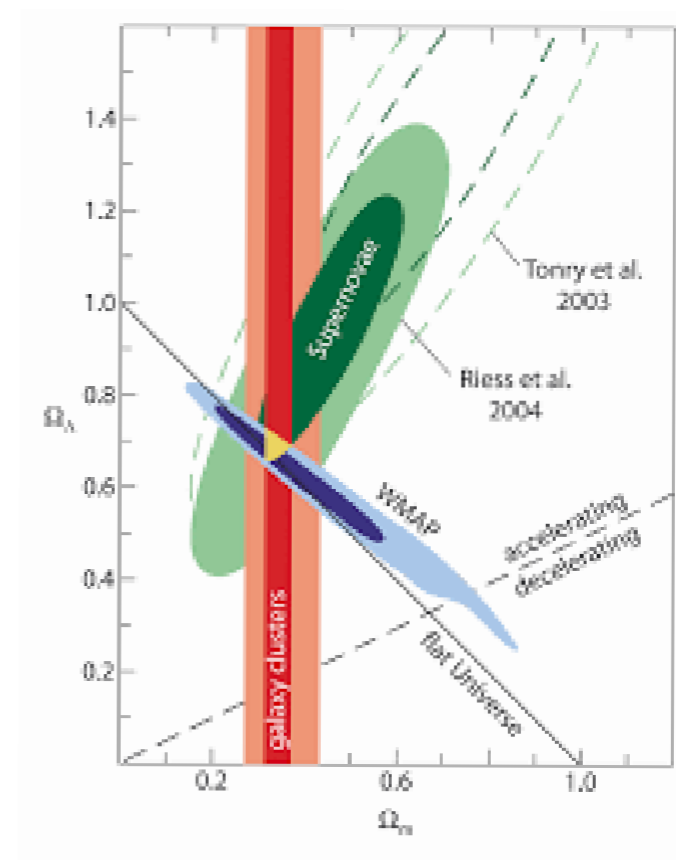
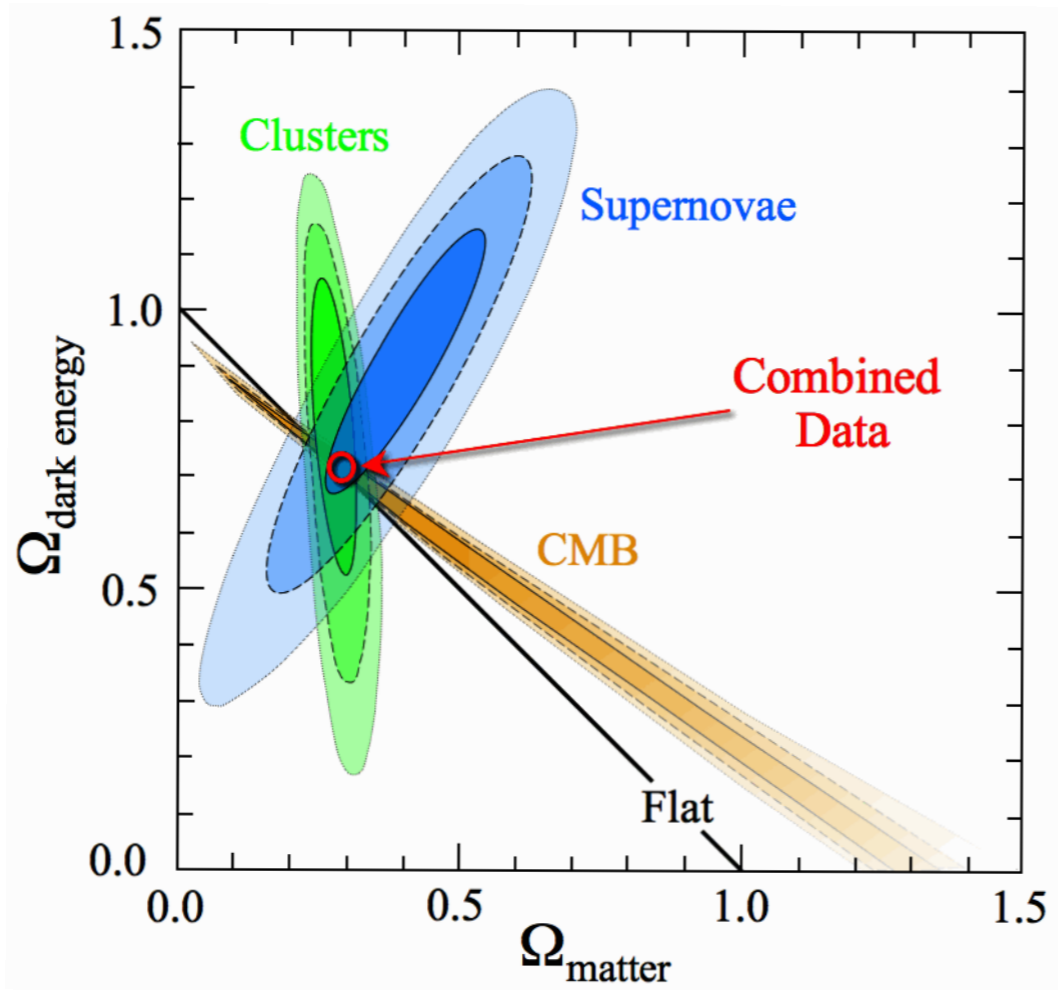
- How much do globular clusters vary by size, is this a flawed assumption?
- What portion of the Messier and NGC catalogs were not galaxies?
- Star counting is difficult. How accurate was the Herschels' method?

- Our knowledge of galaxies is founded on the basis of the cosmological principle, is there any evidence against it?
- With the heat death of the universe theory, where space itself has expanded so much that individual galaxies are so far apart that they can't interact with each other anymore.... will the "Island Universe" hypothesis be technically correct for galaxies
 - What would extraterrestrial life experience in one of these old, red galaxies?
 - Would their astronomers see the universe as only their own galaxy?

Questions

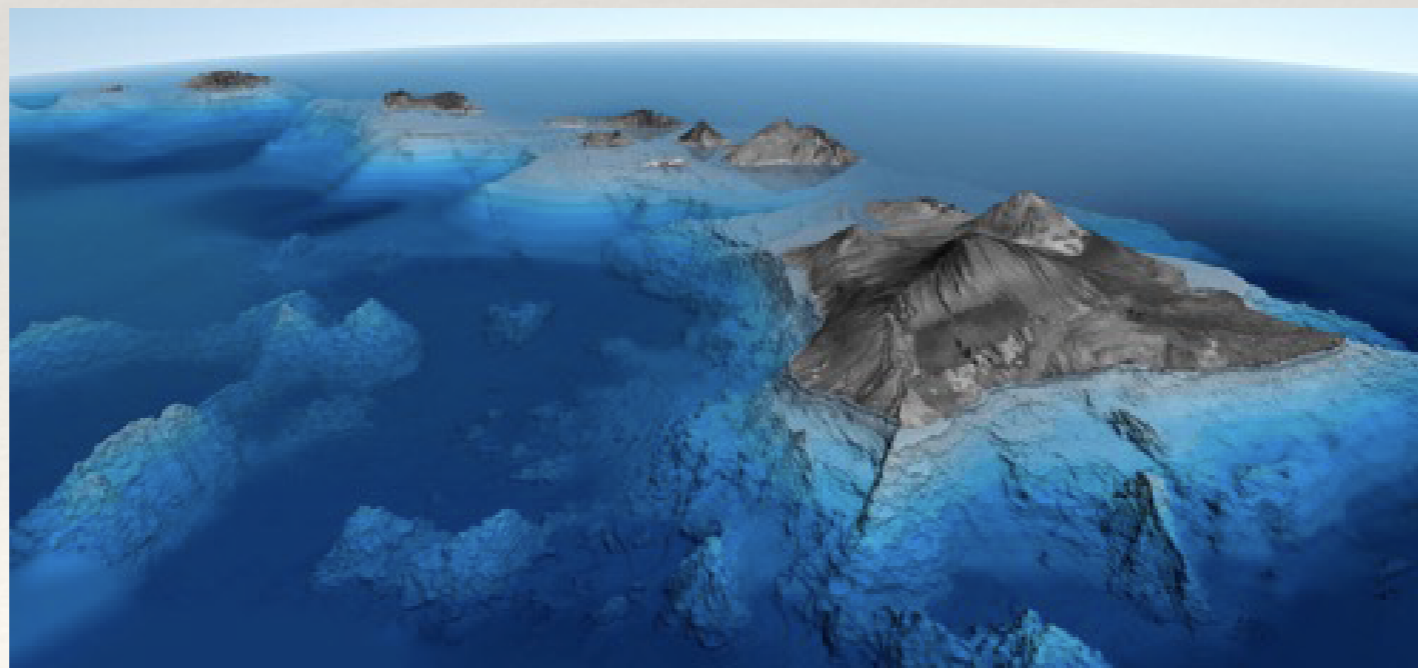
- ❖ COBE map of the Cosmic Microwave Background:
 - ❖ Tiny temperature fluctuations believed to trace fluctuations in the density of matter in the early universe, related to the origin of galaxies.
 - ❖ What leads to the middle panel?
 - ❖ What about the bottom panel?





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



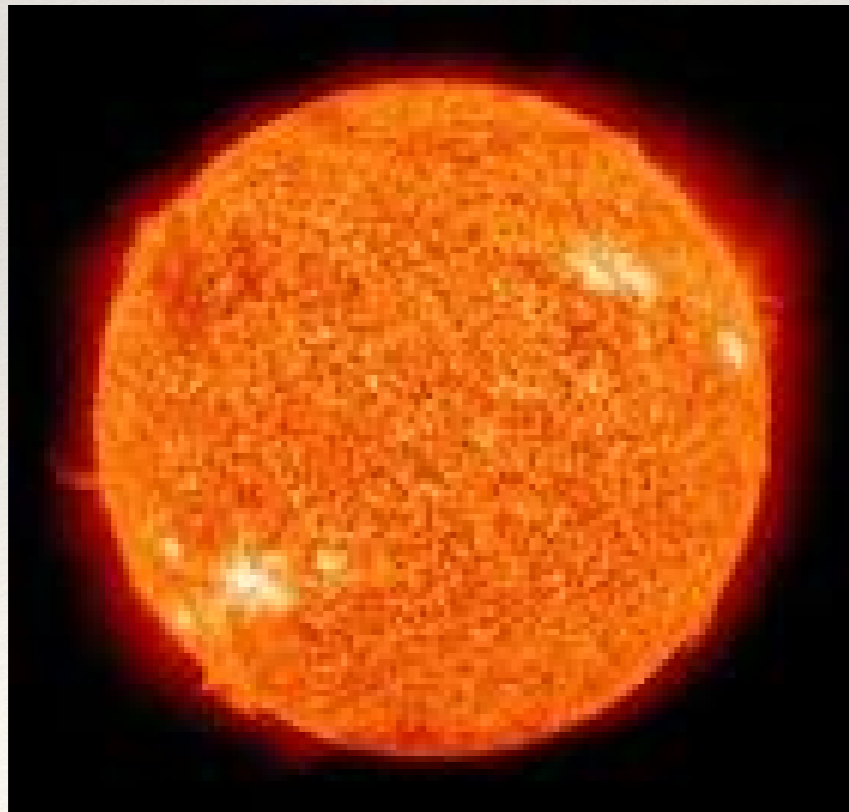
NGC1232 (ESO)

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



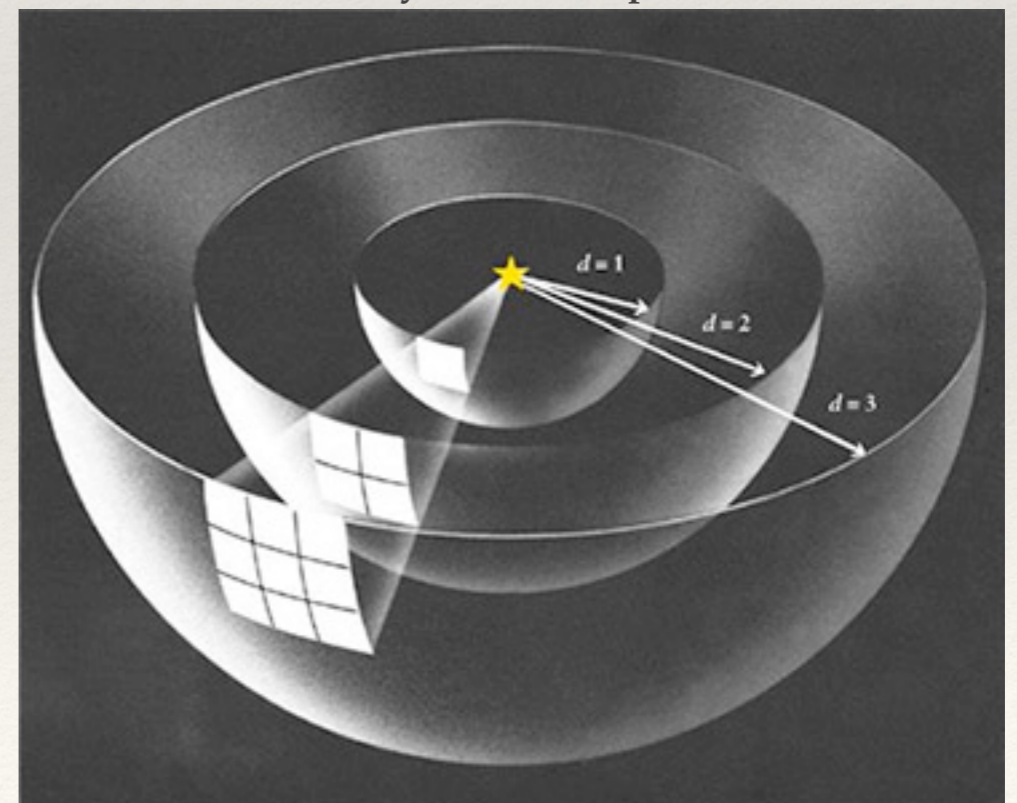
Observing Galaxies - Imaging: Surface Brightness

- ❖ 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

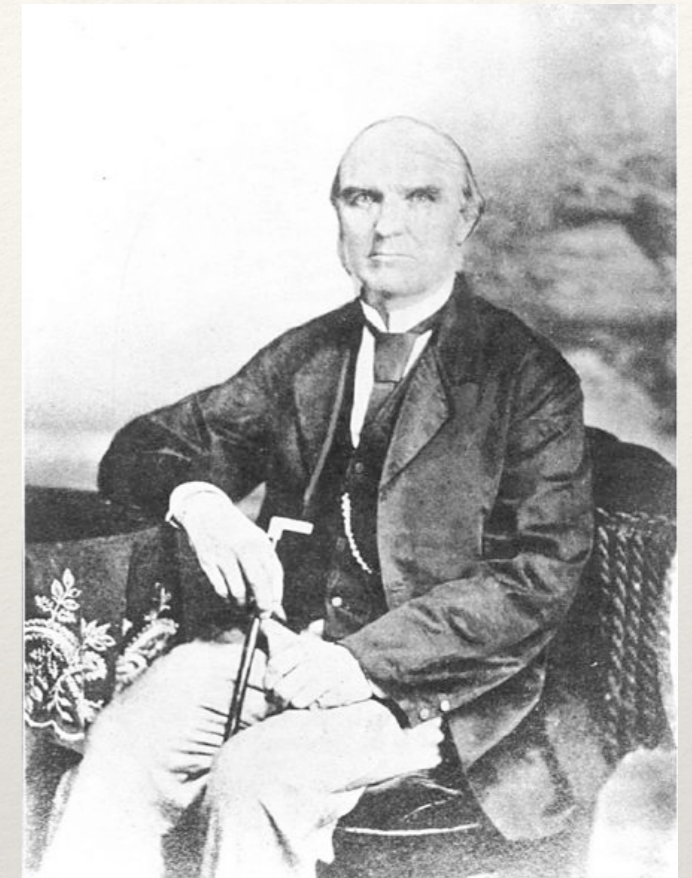


Observing Galaxies - Imaging: Surface Brightness

- ❖ 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)

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

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

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

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., IB or μV



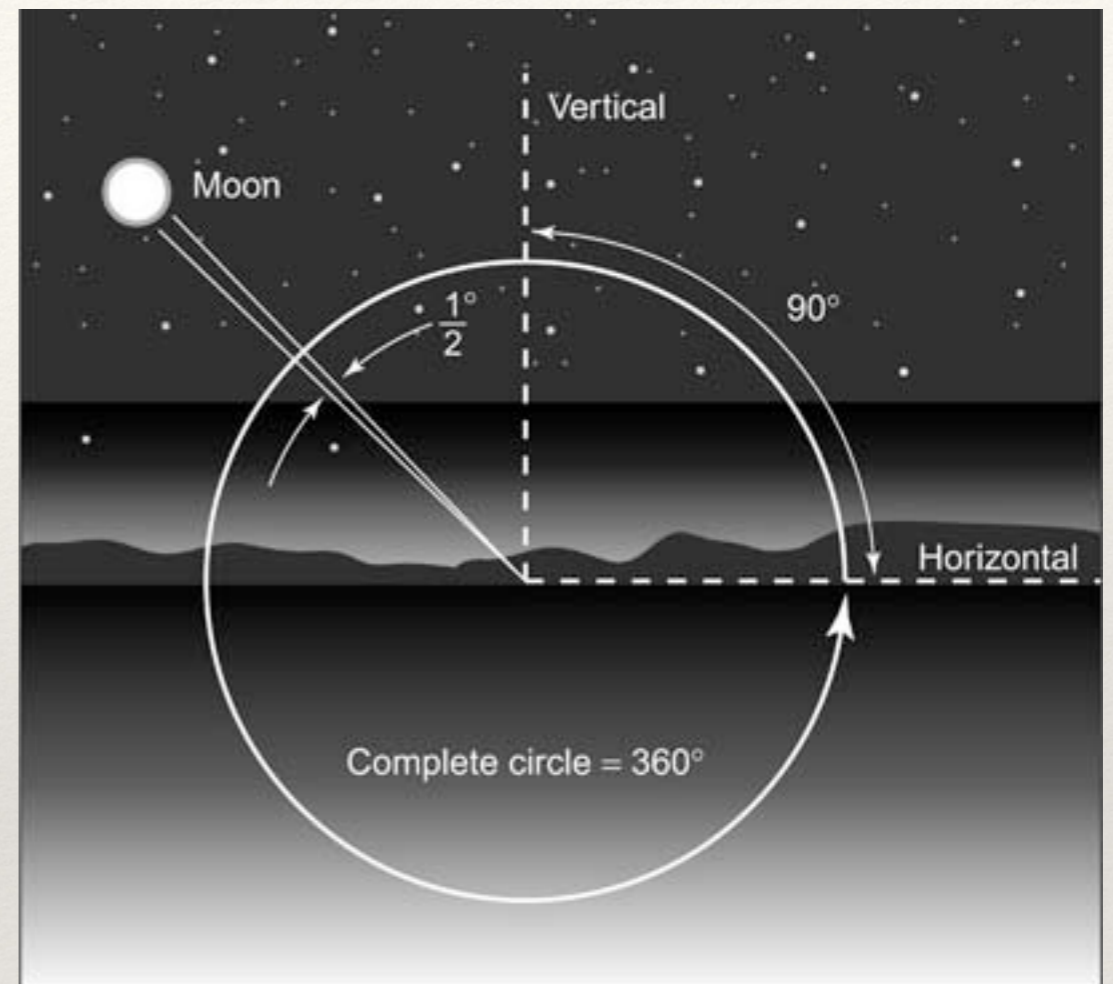
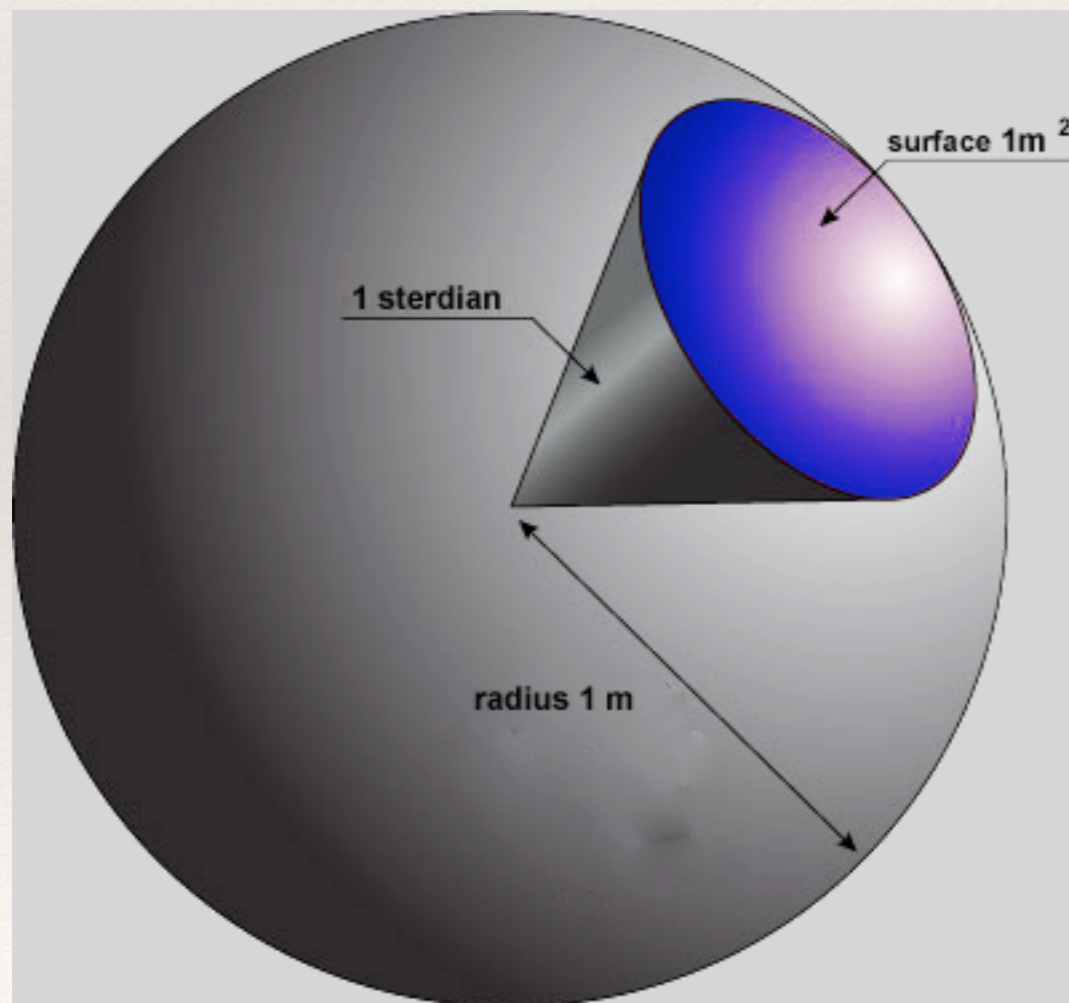
HST image of Helix Nebula (NASA/ESA)

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

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

Observing Galaxies - Imaging: Surface Brightness

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



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- ❖ 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 in magnitudes?
- ❖ M87 has a central surface brightness in the V band of $\mu_V = 17 \text{ mag/arcsec}^2$. 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?

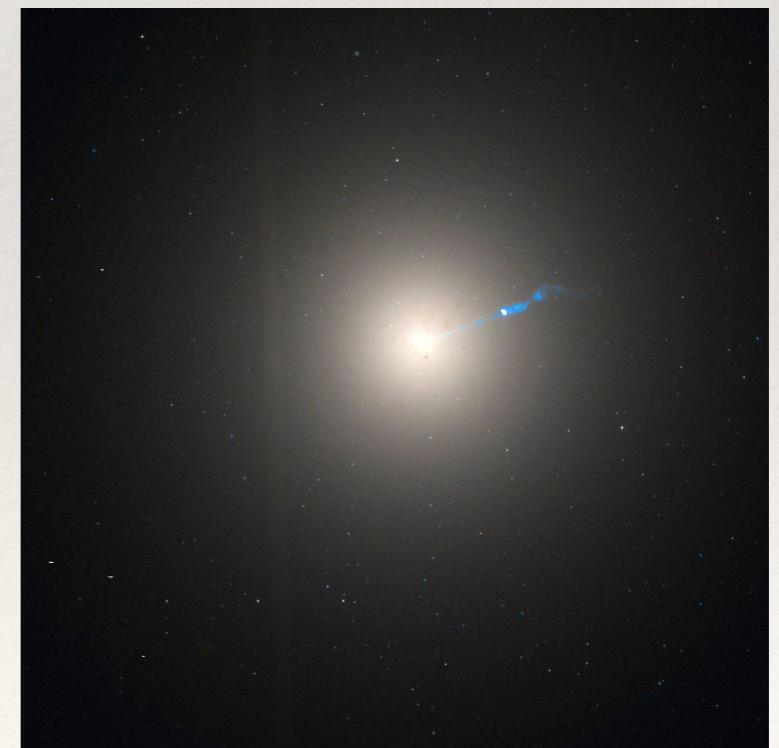
$$\frac{f_2}{f_1} = 100^{(m_1 - m_2)/5}$$

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

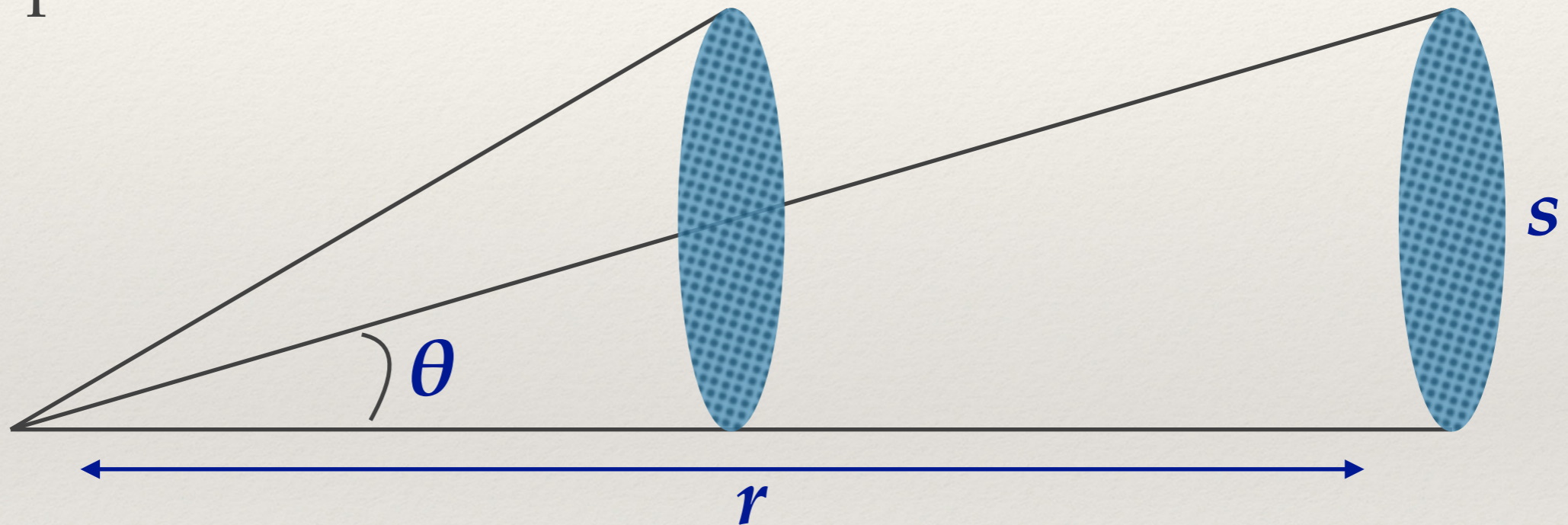
$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{f_1}{f_2}\right)$$

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.



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

$$S \approx r\theta$$

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

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 shrink as much 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 $SB < SB_{\text{sky}}$
 - ❖ need deep images — (long integration time, big telescopes, dark sky)
- ❖ Challenging to observe fainter than $\sim 24\text{-}25$ mag/sq.arcsec in unresolved light
- ❖ seeing — affects central SB
- ❖ sky determination — affects outer SB distribution

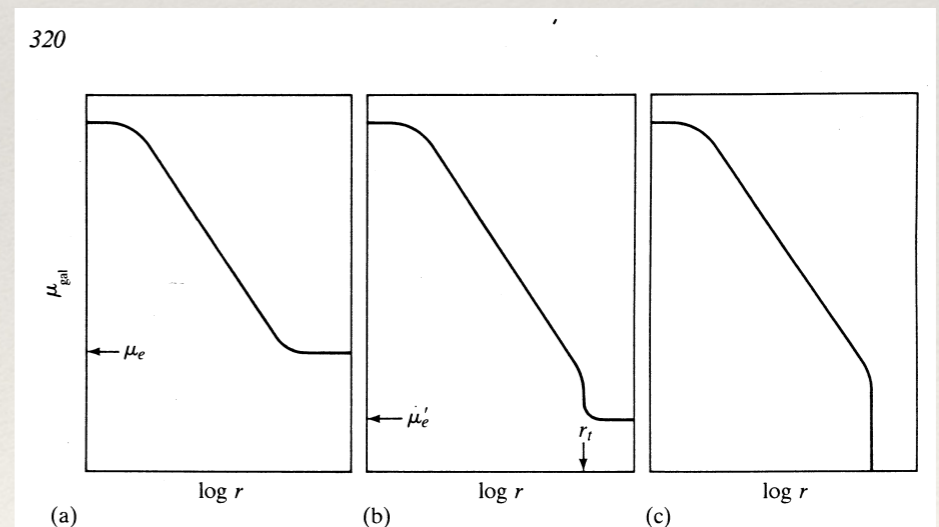
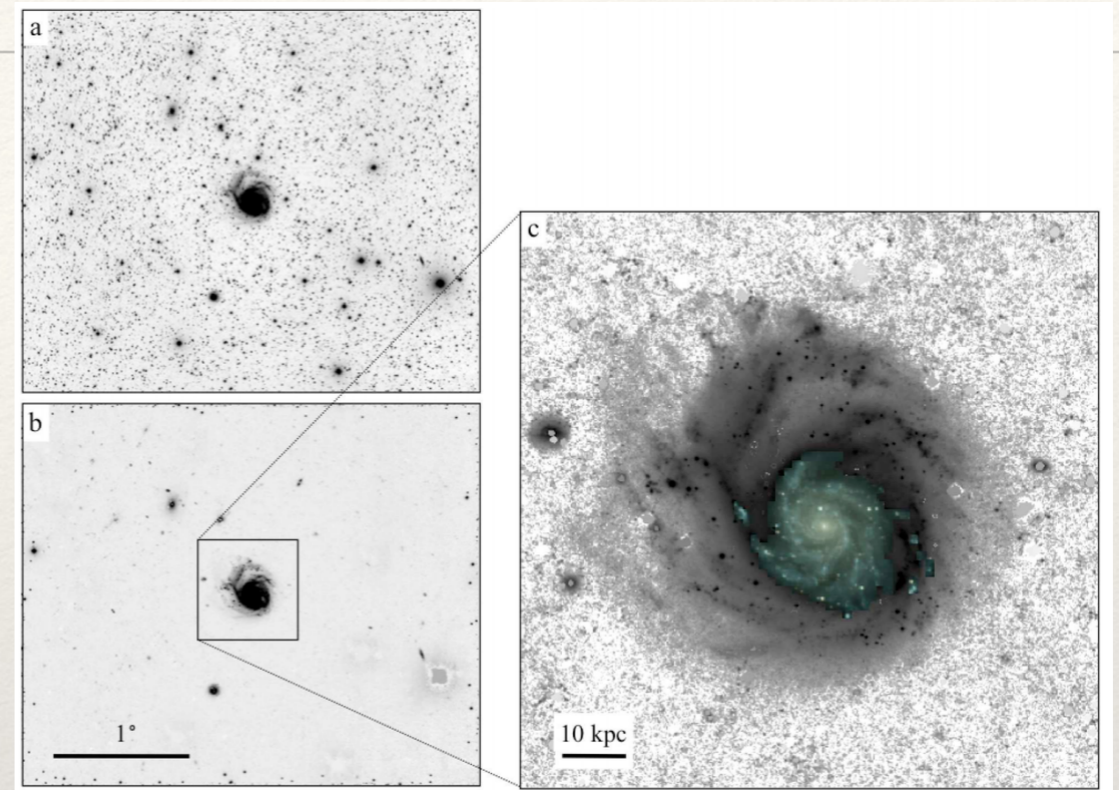
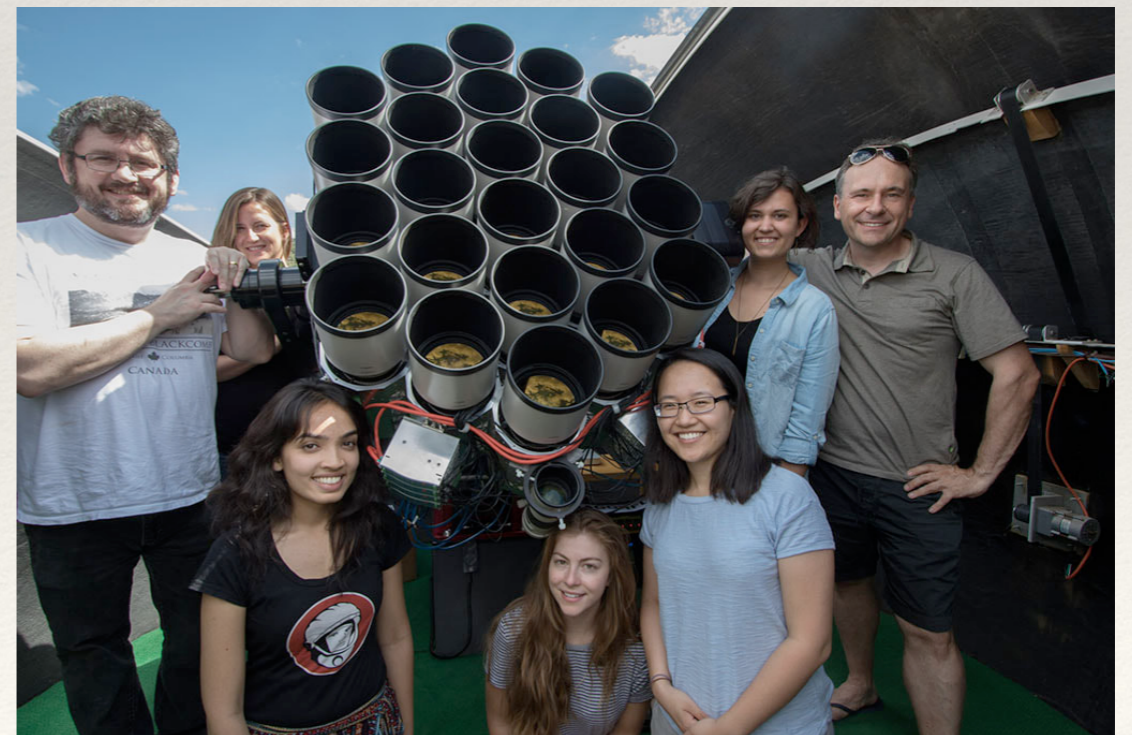


Figure 5-19. The effects of errors in the subtracted sky background on the profile of a galaxy with a truncated brightness distribution. (a) The background has been underestimated so that the night sky contributes to the “galaxy” brightness at large radii. (b) The background is higher than in (a) but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

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



Observing Galaxies

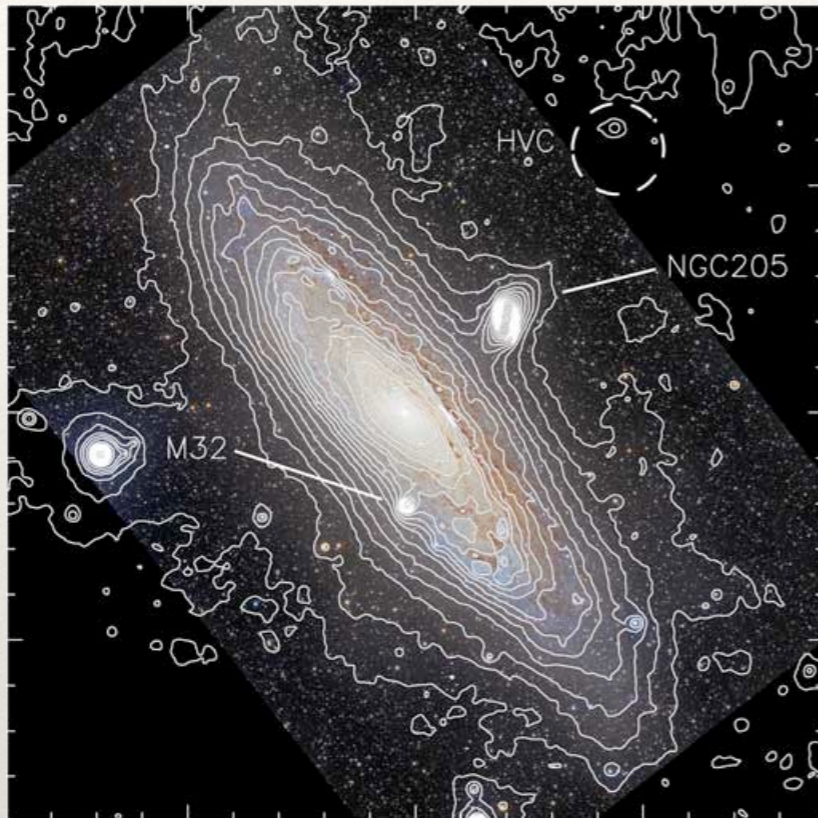
- ❖ Strong selection effects against low surface brightness objects
- ❖ Apparent “size” and “total magnitude” of a galaxy will depend on its surface brightness.
- ❖ Example: NGC 4526 vs. NGC 4535 (the “Lost Galaxy”). Both $m_V=10.7$ mag but have very different surface brightnesses!



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

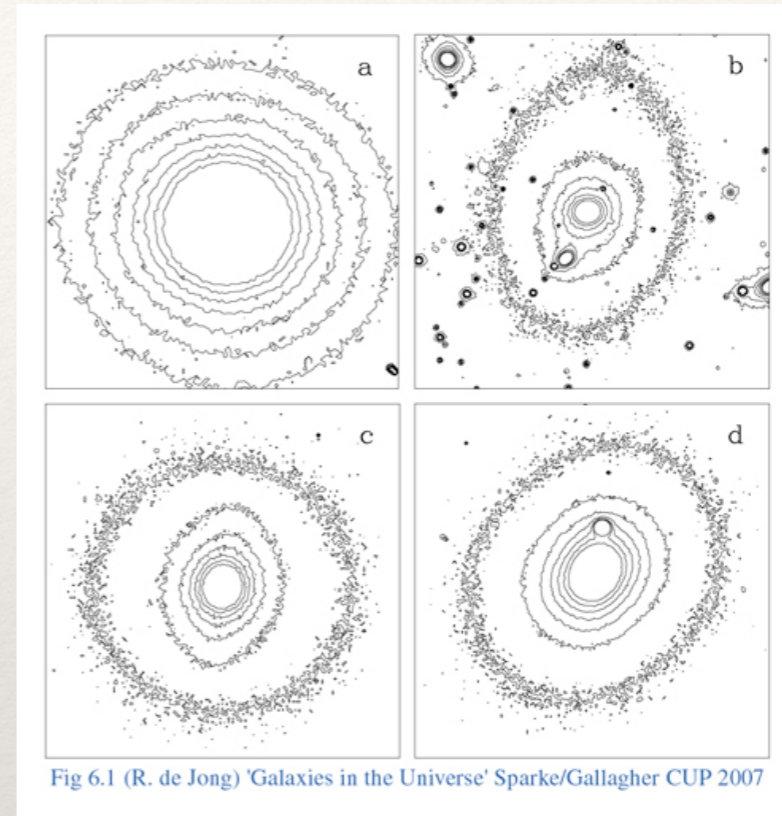


Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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, $e^2 = (1-(b/a)^2)$

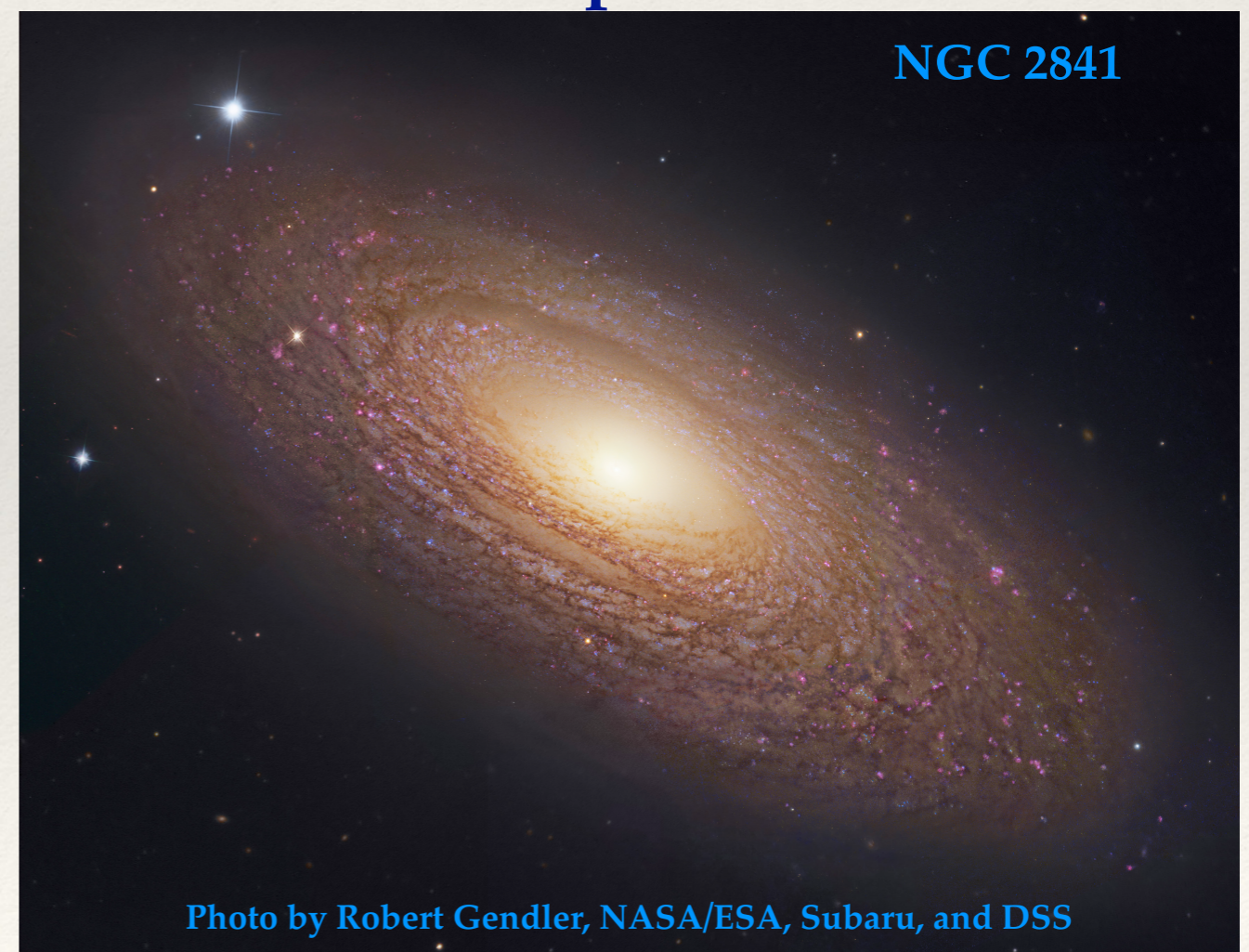
Observing Galaxies - Imaging: Surface Brightness Profiles

- ❖ 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



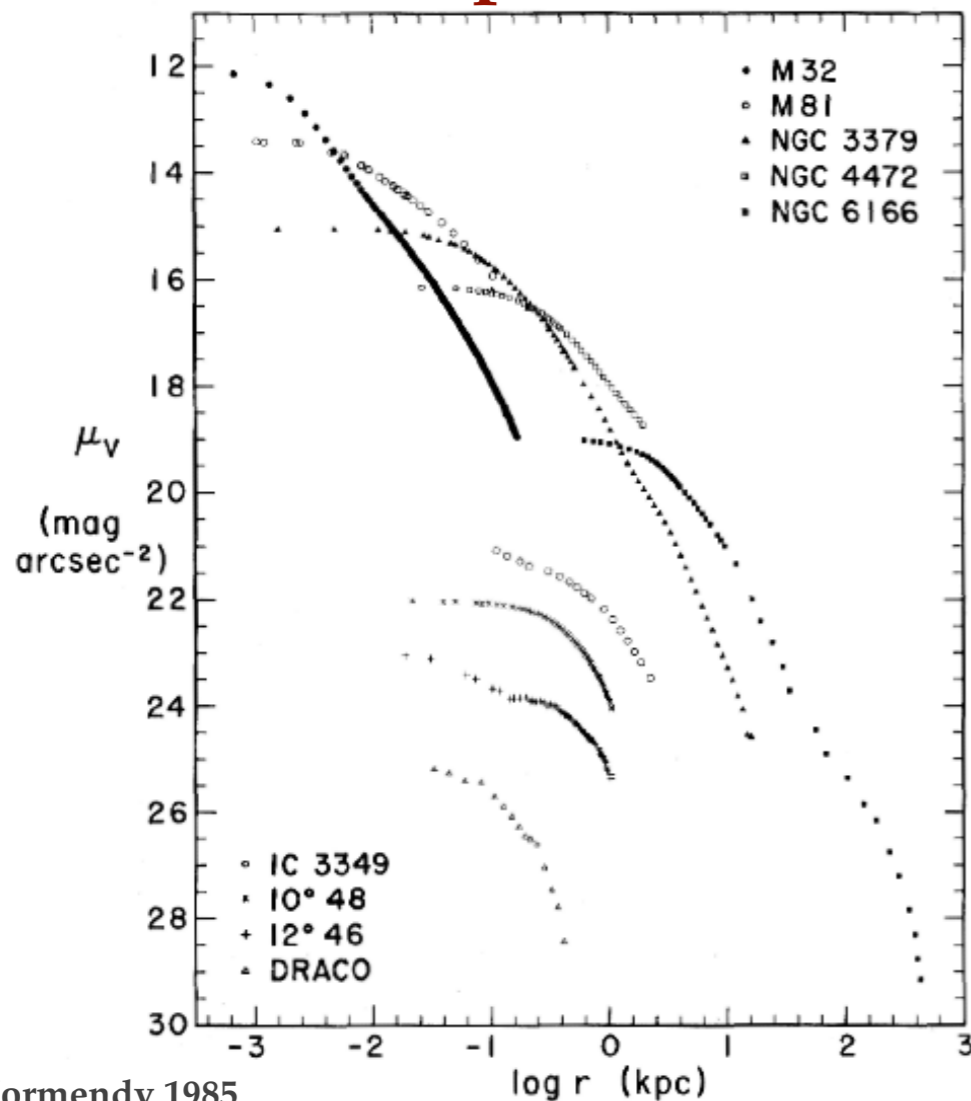
Spirals



Observing Galaxies - Imaging: Surface Brightness Profiles

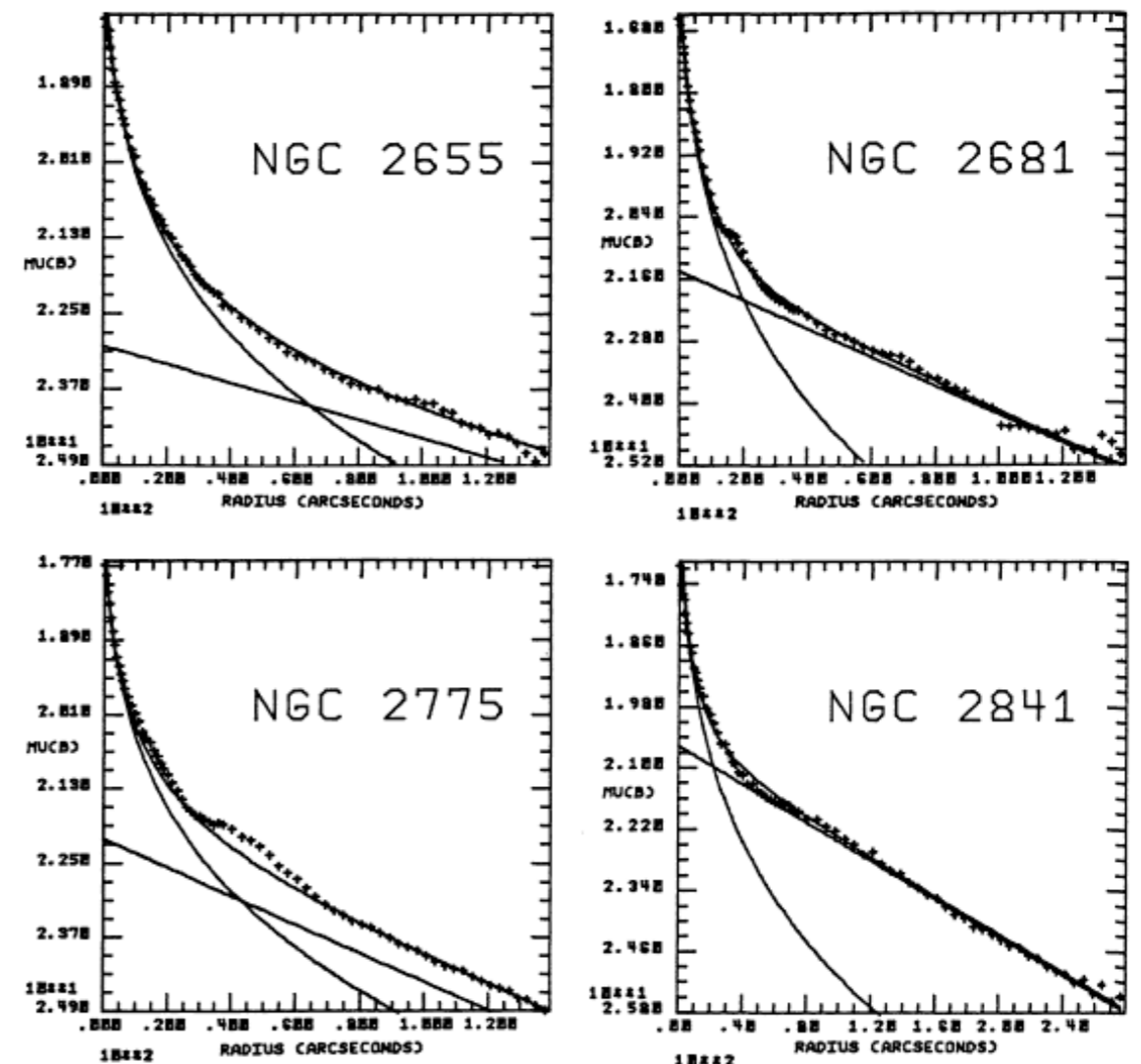
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Ellipticals



Spirals

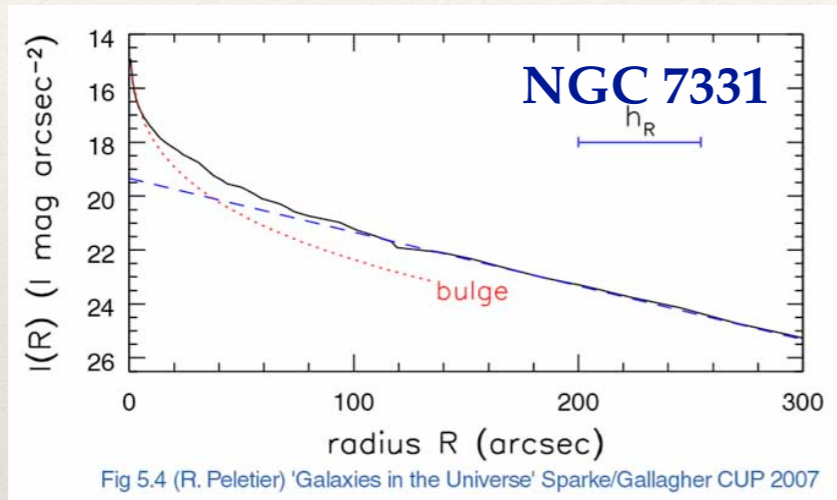
Boroson 1981



Observing Galaxies - Imaging: Surface Brightness Profiles

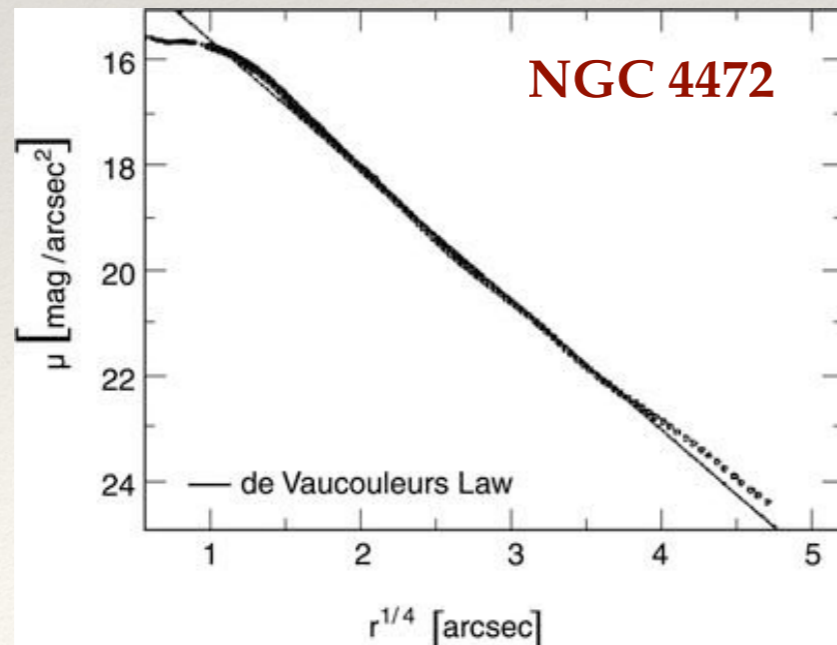
❖ Surface brightness profiles often parameterized:

❖ spirals/disks: **exponential profile**

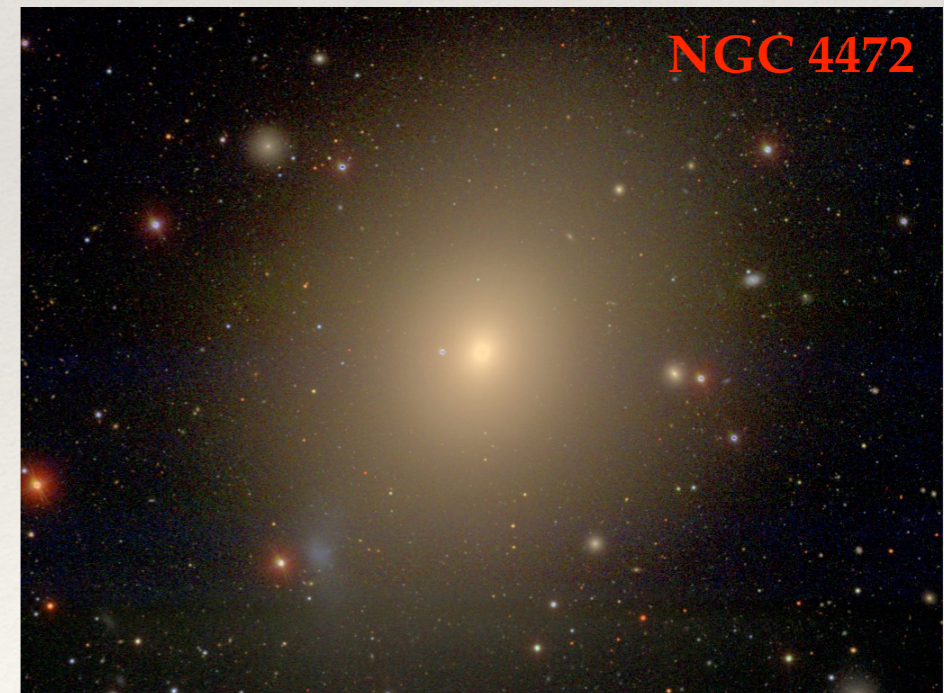


NGC 7331; Image Credit: Dietmar Hager, Torsten Grossmann, APOD

❖ ellipticals: **de Vaucouleurs ($r^{1/4}$) profile**



Schneider 2015, Fig. 3.9



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: $\Sigma_0 \sim 2000 \Sigma_e$)

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

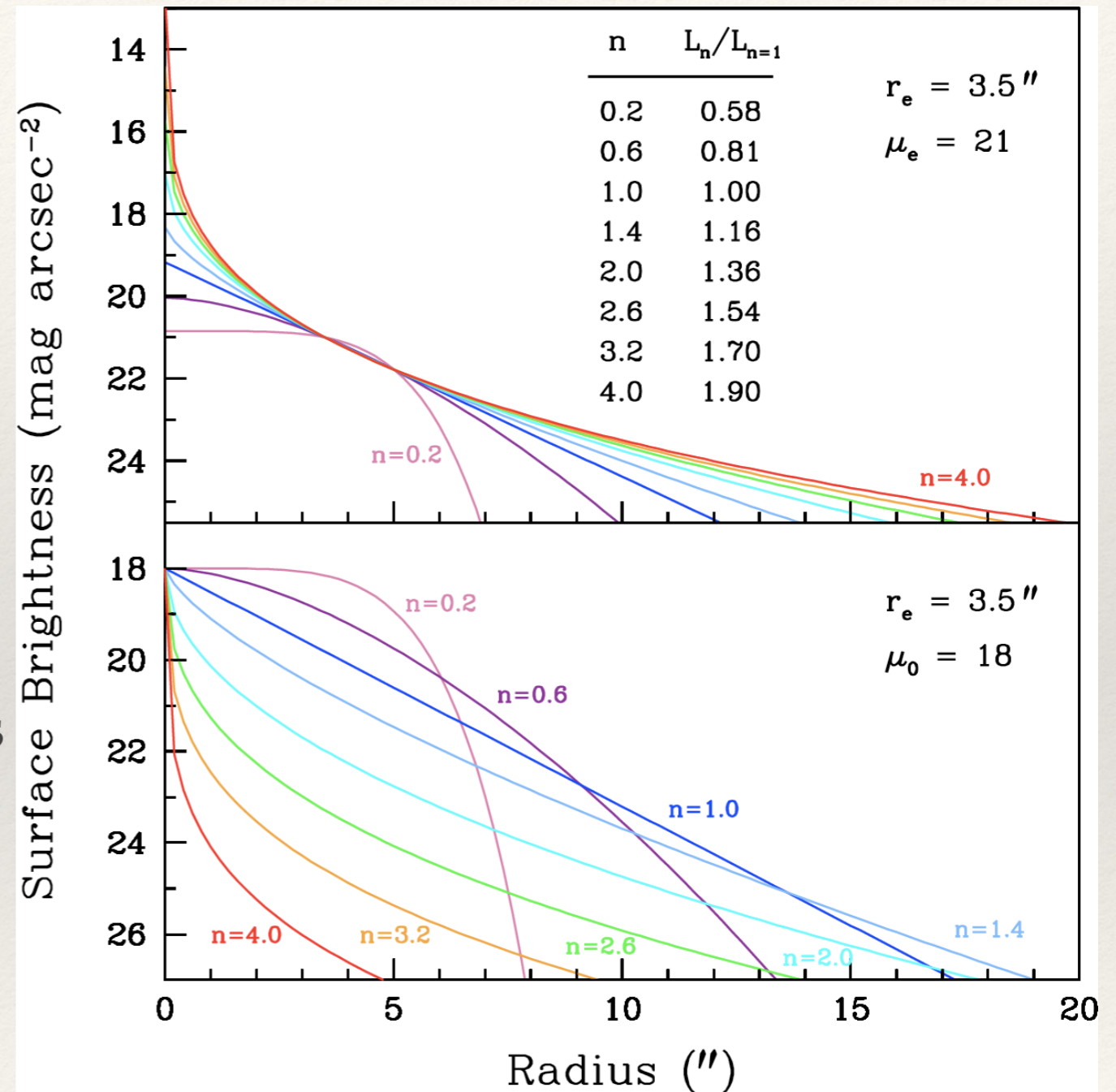
Observing Galaxies - Imaging: Surface Brightness Profiles

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

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

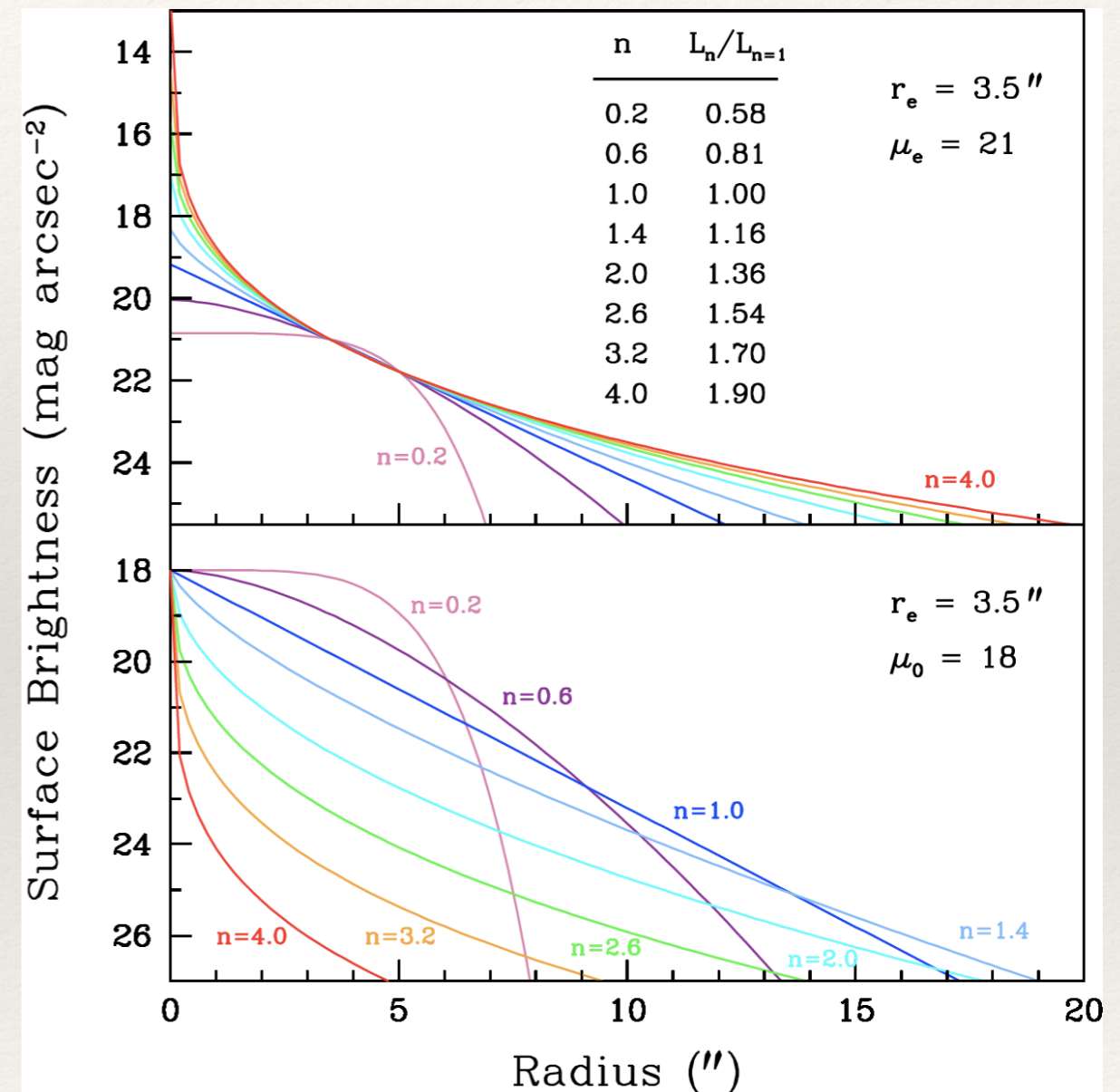
- Sérsic index n governs shape
- $n=4$ for ellipticals; $n=1$ for disks
- r_e = half-light radius
- b_n = determined from the definition of r_e as the half-light radius ($b_n \sim 2n - 0.324$).

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



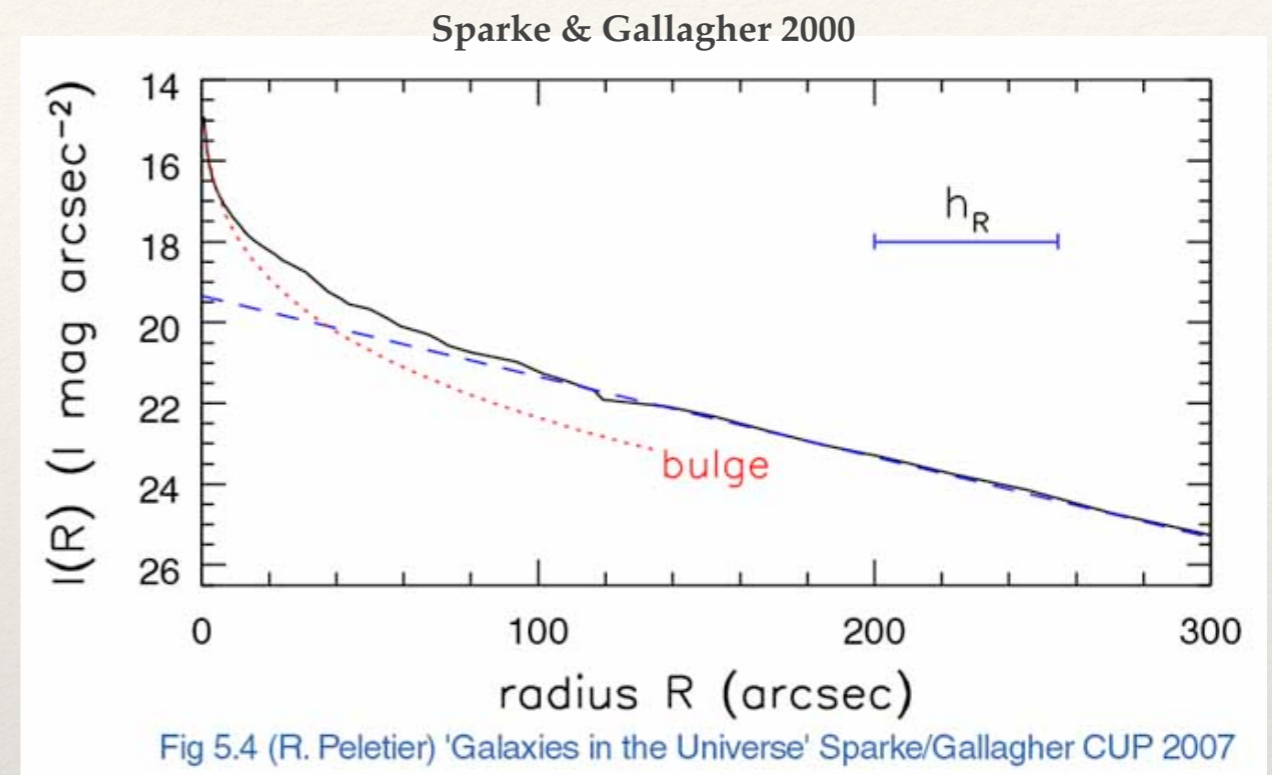
Discussion

- ❖ 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 ($n=1$)?



Observing Galaxies - Imaging: Bulge/Disk Decomposition

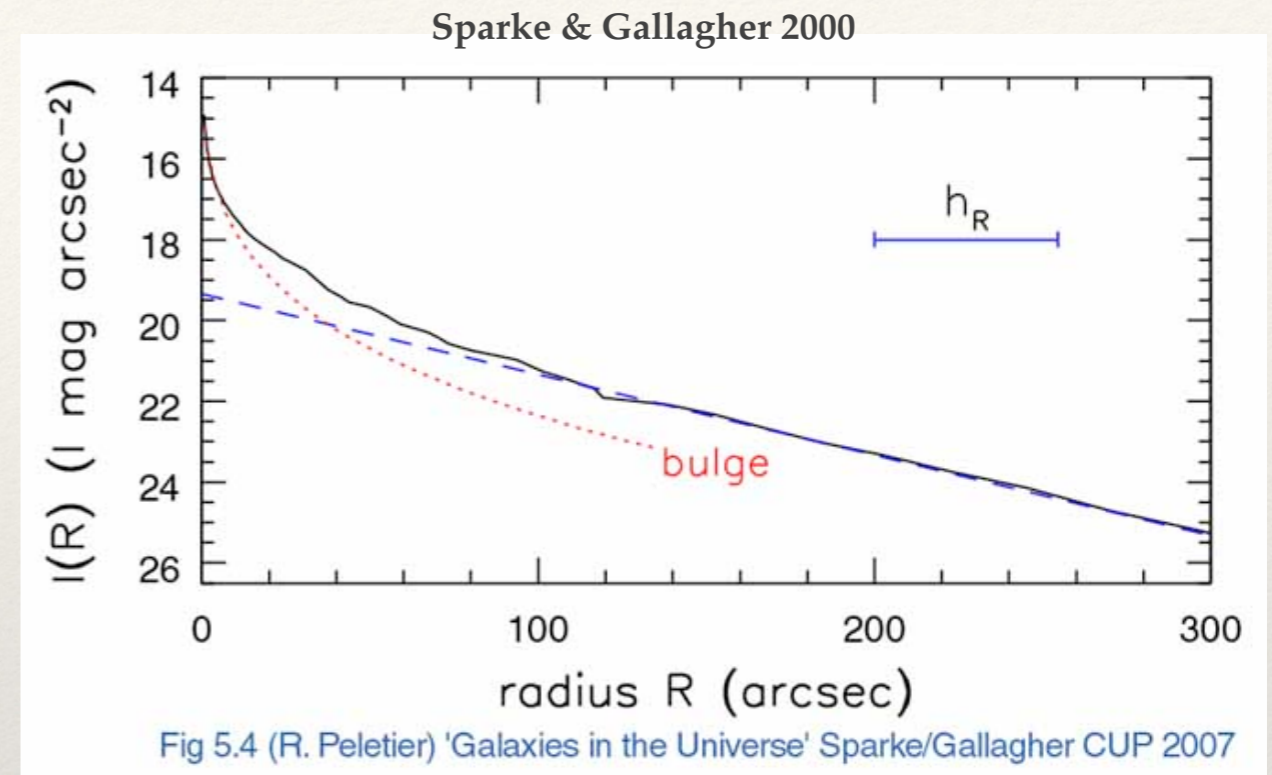
- ❖ Many galaxies are well fit by multiple components, e.g., a central bulge plus an extended disk
- ❖ Can split the different components via **bulge-disk decomposition** (e.g. MacArthur, Courteau, & Holtzman 2003).
 - ❖ Why would one want to do this?
 - ❖ 1D vs 2D decomposition
- ❖ Problems / assumptions?



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



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 $z\sim 4$ with ZFOURGE and CANDELS”*
- ❖ Problems 1 - quantitative/coding assignment related to the paper - due September 8



Dr. Caroline Straatman
Ghent University,
Belgium