AST 1420

Galactic Structure and Dynamics

Q&A

Questions submitted

- Disk scale length and scale height
- More on gas
- Classical mechanics
- Spherical potentials
- Orbits in spherical potentials
- Miscellaneous

Scale length and scale height

Surface brightness

- Extended objects like galaxies have flux (apparent brightness) and an extent (how large they appear)

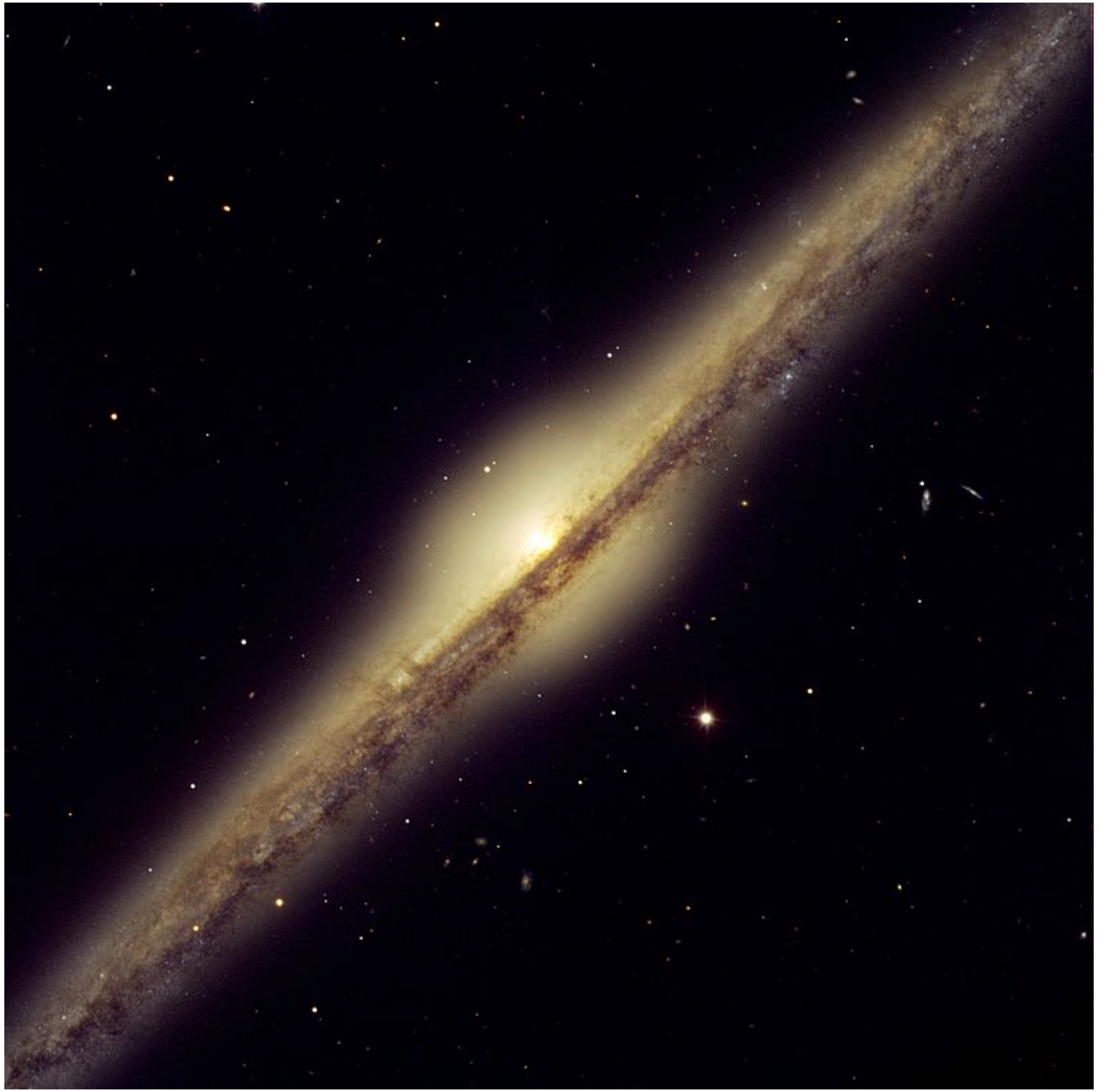
- Surface brightness = flux density per unit area

- Typically very confusingly expressed as a logarithmic quantity in units of *magnitudes per square arcsecond*

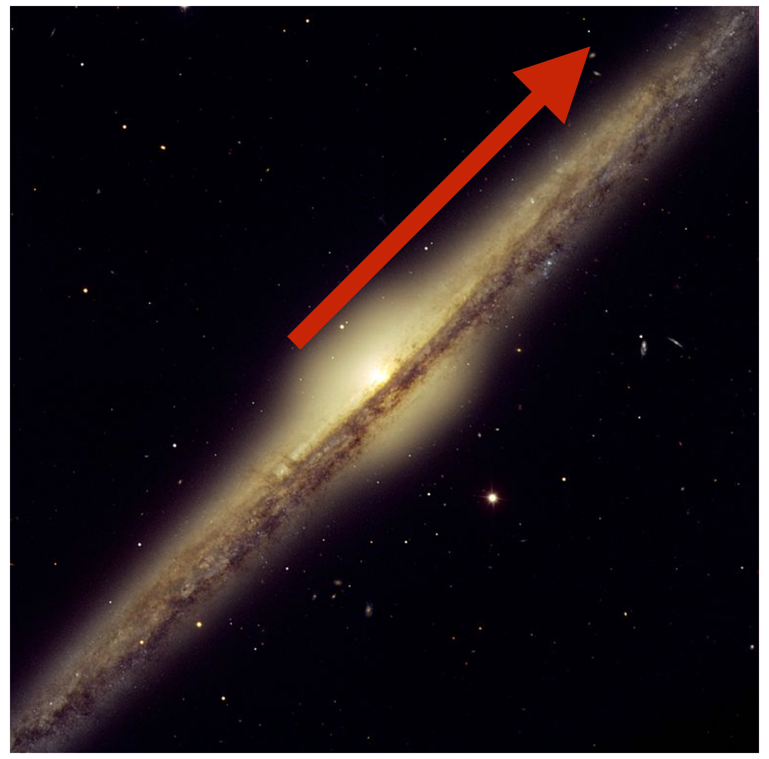
$$S = m + 2.5 \cdot \log_{10} A$$

- Useful because independent of distance:
  Object twice as far away —> flux 4 times smaller, but area also 4 times smaller (only works on scales << size of the Universe)

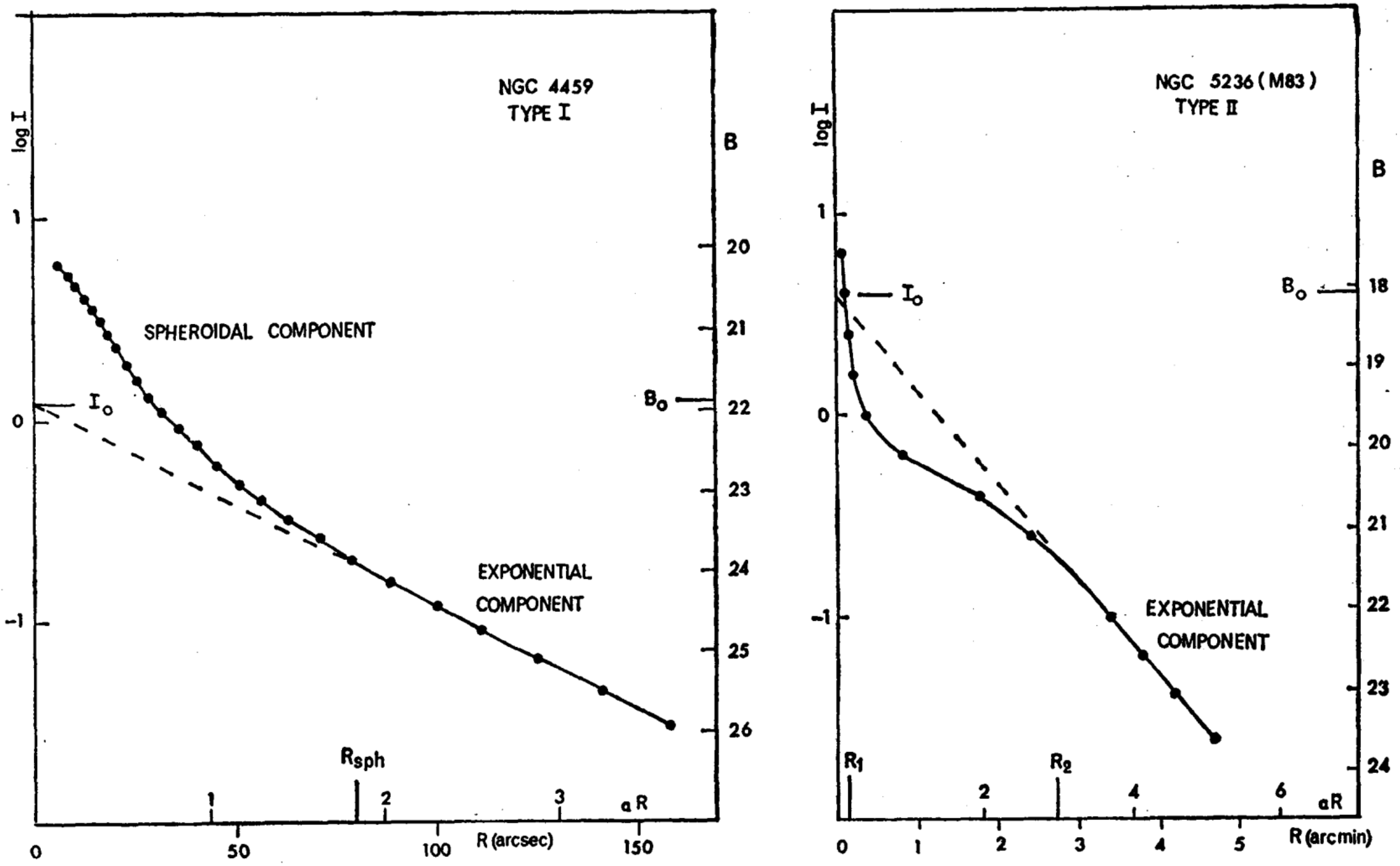
NGC 4565
~ MW



Radial distribution of stars in disks: exponential light distribution

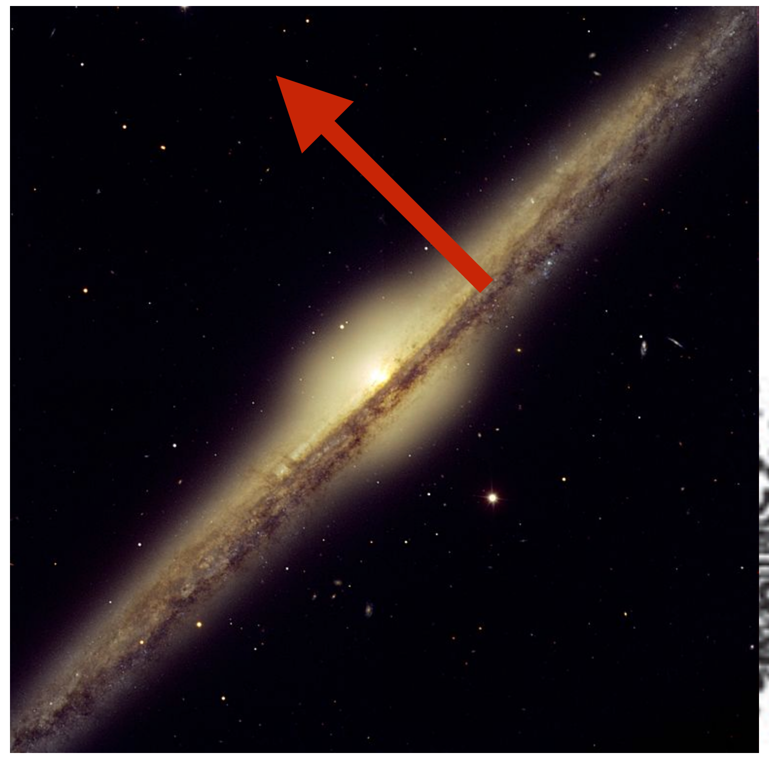


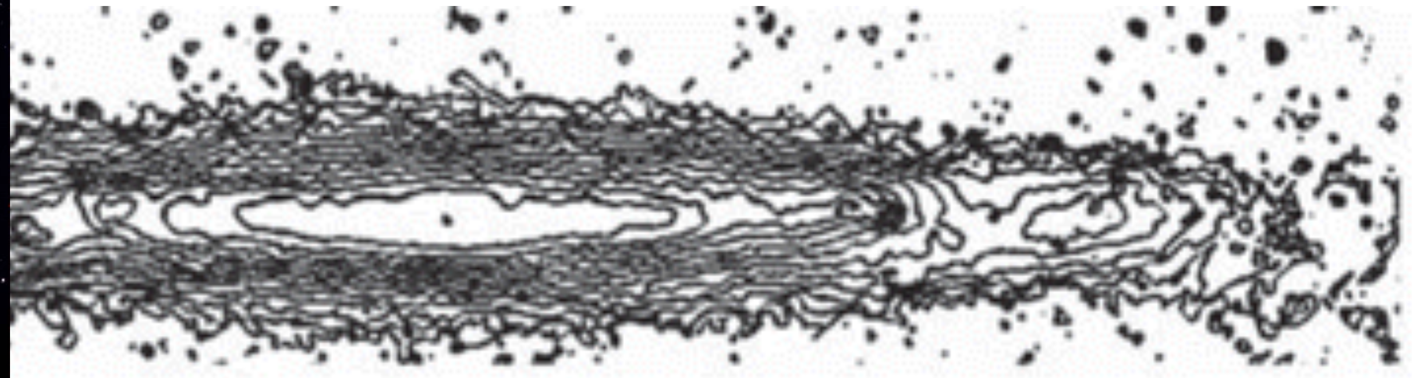
$$I(R) = I_0 \exp(-R/h_R)$$

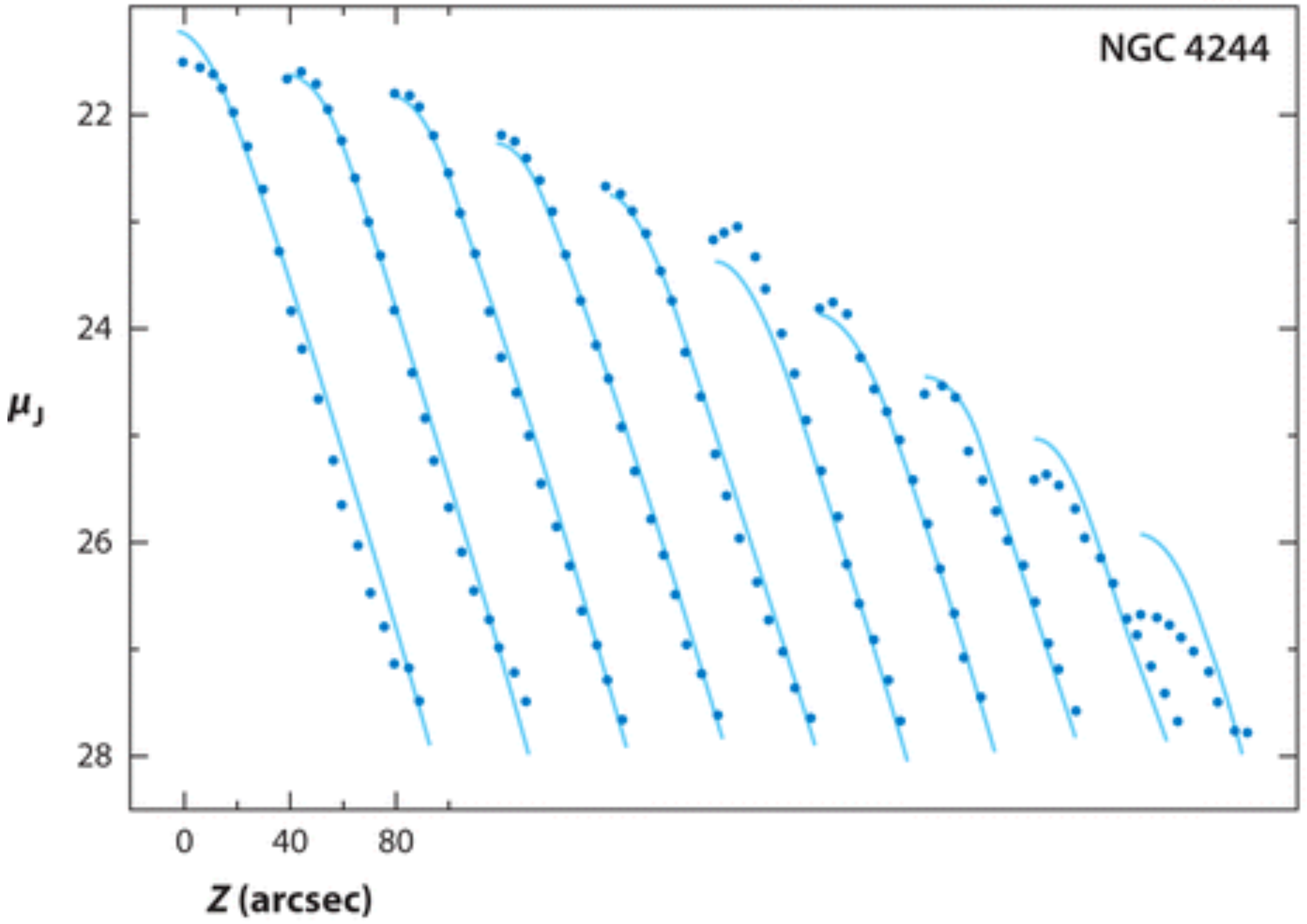


Freeman (1970)

Vertical distribution of stars in disks: ~exponential

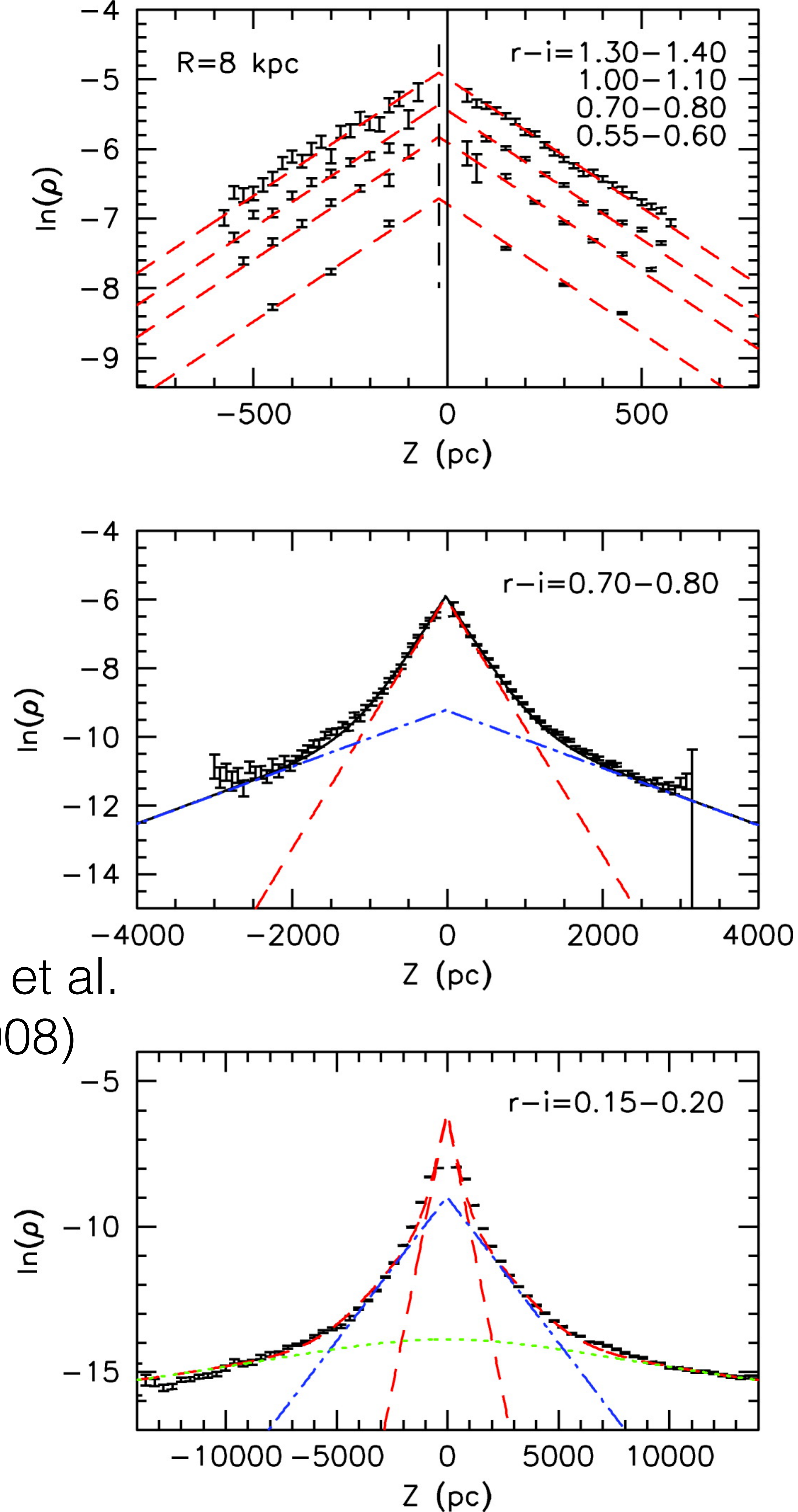






van der Kruit PC, Freeman KC. 2011.
Annu. Rev. Astron. Astrophys. 49:301–71

- To first approximation, light drops exponentially when going away from the mid-plane
  $$I(z) = I_0 \exp(-|z|/h_z)$$
- Slight turn-over at small heights —> sech^2(z)
- Profile ~ independent of R —> constant thickness
- Typical thickness: 300 pc (old stars)



Juric et al. (2008)

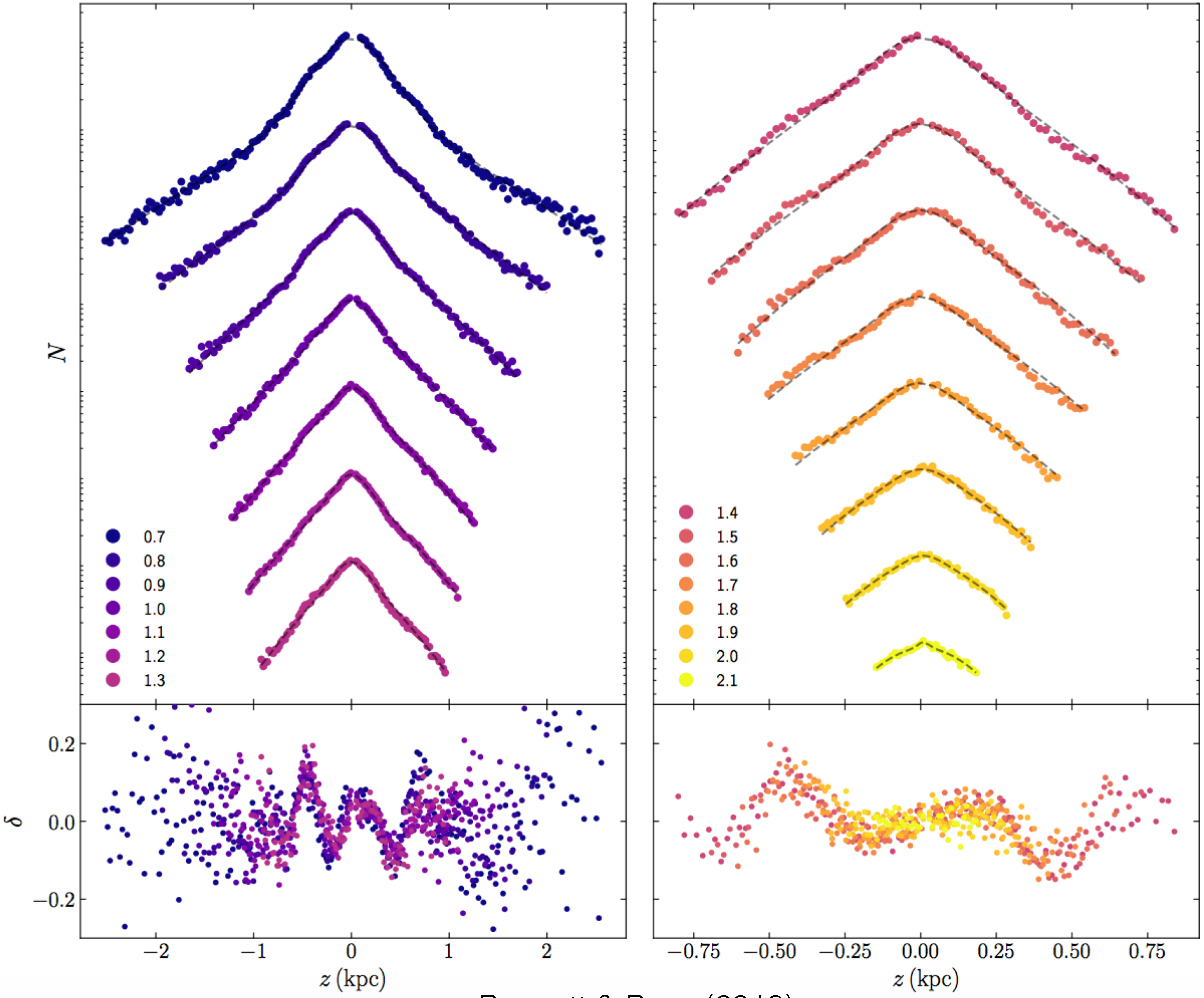
- Looking in more detail, vertical profile is much more complicated

- Thin disk, thick disk, …, eventually halo

- *Exact* structure does not matter greatly for orbits and dynamical modeling

Measuring the scale length and scale height in our own galaxy

- Difficult, because we can't see the entire galaxy
- Determine stellar density over a range of radii near the Sun, fit an exponential to them
- Similar for vertical direction
- Gas:
    - Look at intensity as a function of radius and height
    - Hard to get distances to gas, so typically need to fit a full model and fit it to the intensity (+velocity) measurements (see later)
    - Molecular gas: largely in clouds, so look at distribution of the clouds



Bennett & Bovy (2018)

Interstellar gas

The source and structure of the interstellar medium

- Depletion time < age of the Universe —> there has to be new gas accretion
  - Comes from flows from the intergalactic medium
- Why is the ISM disk much thinner than the stellar disk?
  - Gas cools, so can loose energy and collapse into a thin disk (until pressure keeps it puffy)
  - Stars cannot cool, because they only feel gravity and it takes too long for energy changes to occur
  - Stars are heated through random scattering with gas clouds and perturbations form spiral structure
  - Atomic, neutral gas typically extends out beyond the stellar disk, because star formation is not a linear function of gas density, instead star-formation scales as ~(gas density)$^{1.5}$ (Kennicutt-Schmidt law)

Classical mechanics

Mass in galactic dynamics

- Because **F**(**x**) = m **g**(**x**) and Newton's second law says that **F** = m **a**, we have that
  - **a** = **g**
- So as long as the time evolution of **g** is not affected by m, the mass m does not come into the trajectory of a body
- (counter-examples: binaries, collisional systems, dynamical friction)
- Because mass does not enter calculations of bodies' trajectories, we can ignore it:
  - Pretend that m=1
  - Or that all relevant quantities are per unit mass ('specific')
  - Thus, typically, 'energy' means 'specific energy' (kinetic, and potential), angular mom. means 'specific angular momentum'
  - But also the Lagrangian is written per unit mass, the Hamiltonian, …

Escape velocity

$$v_{\rm esc} = \sqrt{2[\Phi_\infty - \Phi(\mathbf{x})]}\,,$$

- Measures the difference between the potential at infinity and the potential at a location
- Spherical potential

$$\Phi(r) = -G\int_r^\infty \mathrm{d}r'\,\frac{M(< r')}{r'^2}\,,$$

Spherical potentials

Newton’s shell theorems

- Do they hold in GR?
- Yes! Known as Birkhoff's theorem in the GR context
- Birkhoff's theorem’s says that “any spherically symmetric solution of the vacuum field equations must be static and asymptotically flat. This means that the exterior solution (i.e. the spacetime outside of a spherical, nonrotating, gravitating body) must be given by the Schwarzschild metric.”
    - Because the Schwarzschild metric —> the point mass potential in the non-relativistic regime, this reduces to Newton’s 2nd shell theorem
    - Can also show that the interior solution to a shell needs to be Minkowski space time, so flat space —> Newton’s 1st shell theorem

Plummer and isochrone potentials

$$\Phi(r) = -\frac{GM}{\sqrt{r^2 + b^2}} .$$

$$\Phi(r) = -\frac{GM}{b + \sqrt{r^2 + b^2}} .$$

- Both approach a homogeneous sphere for r << b and a point-mass for r >> b
- b is thus the length scale at which the potential is between the two
- Because galaxies are neither close to a homogeneous sphere or a point mass, b ~ size of the galaxy (order of mag)
- Plummer is used in smoothing kernel for N-body simulations, isochrone is not (could be?); but better smoothing kernels exist
    - Smoothing is purely to remove the effect of unphysical close encounters
- These and other examples of spherical potentials are only really used for stellar systems that are very close to spherical:
    - Star clusters, the more spherical of elliptical galaxies, bulges, dwarf spheroidals

Orbits in spherical potentials

Motion in the orbital plane

$$\ddot{r} = \frac{L^2}{r^3} + g_r(r) = \frac{L^2}{r^3} - \frac{\mathrm{d}\Phi(r)}{\mathrm{d}r}$$

$$\dot{\psi} = \frac{L}{r^2} .$$

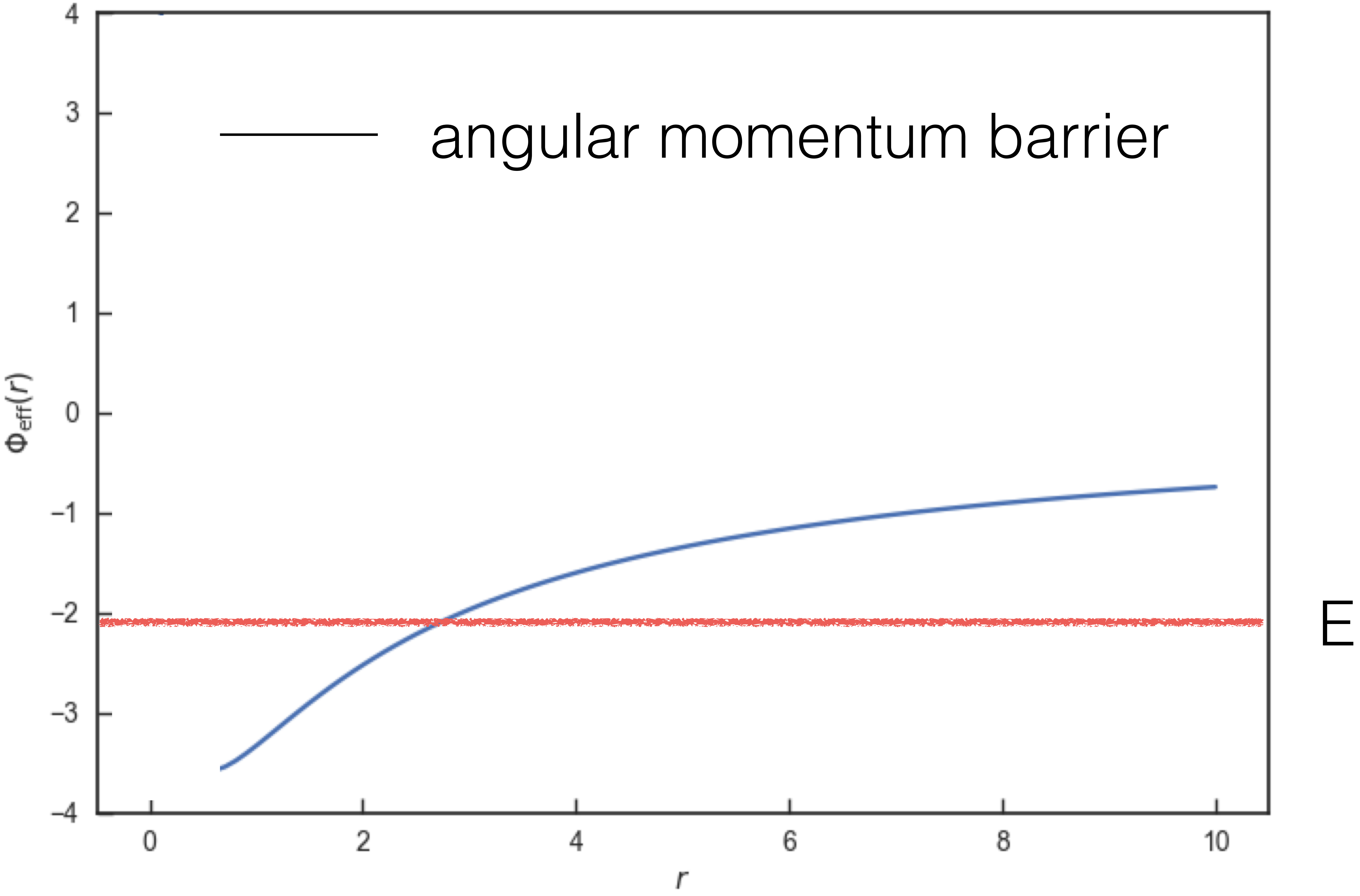
- The first equation can be written in terms of an *effective potential*

$$\Phi_{\mathrm{eff}}(r) = \Phi(r) + \frac{L^2}{2\,r^2} ,$$

- With energy

$$E = \frac{\dot{r}^2}{2} + \Phi_{\mathrm{eff}}(r)$$

Effective potential



Pericenter, apocenter, eccentricity

- Orbit with angular momentum L oscillates radially between r_p and r_a, *pericenter and apocenter*

$$\dot{r}^2 = 2[E - \Phi(r)] - \frac{L^2}{r^2} = 0\,,$$

- Can define measure of how circular an orbit is, the *orbital eccentricity*

$$e = \frac{r_a - r_p}{r_a + r_p}\,.$$

Miscellaneous

Miscellaneous questions

- Mass-to-light ratios: stars or dark matter?
  - Sometimes used to only mean mass in stars, sometimes mass in baryons, sometimes all mass
  - Typically say “stellar mass to light ratio” for the former
  - Mass and light can be total in a galaxy, integrated out to some radius, or integrated over an annulus, … if not total, it will vary within the galaxy
- Dynamical time for solar-type stars ~ dynamical time:
  - Means that they can, e.g., move significantly between when they are born and they die, thus complicating determining their effect on the chemical evolution of the galaxy

Miscellaneous questions

How do disks form?

- To form a disk, you need to lose energy; most cooling mechanisms lead to energy loss without angular momentum loss —> collapse to rotating disk (disk keeps the angular momentum)
- For collisionless systems, energy loss does not occur on galactic timescales, so pure collisionless systems do not form disks (no dark disks)
- Collisional stellar systems also do not form a disk or collapse significantly, because the system as a whole does not lose energy (energy just gets redistributed).