AST 1420

Galactic Structure and Dynamics

Q&A

Presentations next week! Schedule

Wednesday	**noon to 1 pm**
Sam Berek	The Magellanic clouds and their interaction with the MW
Emaad Paracha	Milkomeda
Yuyang Chen	The M-sigma relation
Dang Pham	The M-sigma relation in dwarf galaxies
Wednesday	**3 to 4 pm**
BoLin Fan	Ultra-diffuse galaxies
Seery Chen	Dark matter in ultra-diffuse galaxies
Amanda Cook	Galaxies without dark matter
Oliver Cardinal	Cluster dark matter profiles
Thursday	**noon to 1:30 pm**
Steffani Grondin	Dark matter in globular clusters
Jibran Haider	Simulations of the large-scale structure of the Universe
Henry Leung	Cosmological simulations of galaxy formation
Bethany Ludwig	Reionization and binary systems
Ayush Pandhi	Action-angle coordinates for stars in the solar neighborh’d
Jacob Taylor	The mass of the Milky Way

Reminders

- Assignment 3 due now!

The shape of elliptical galaxies

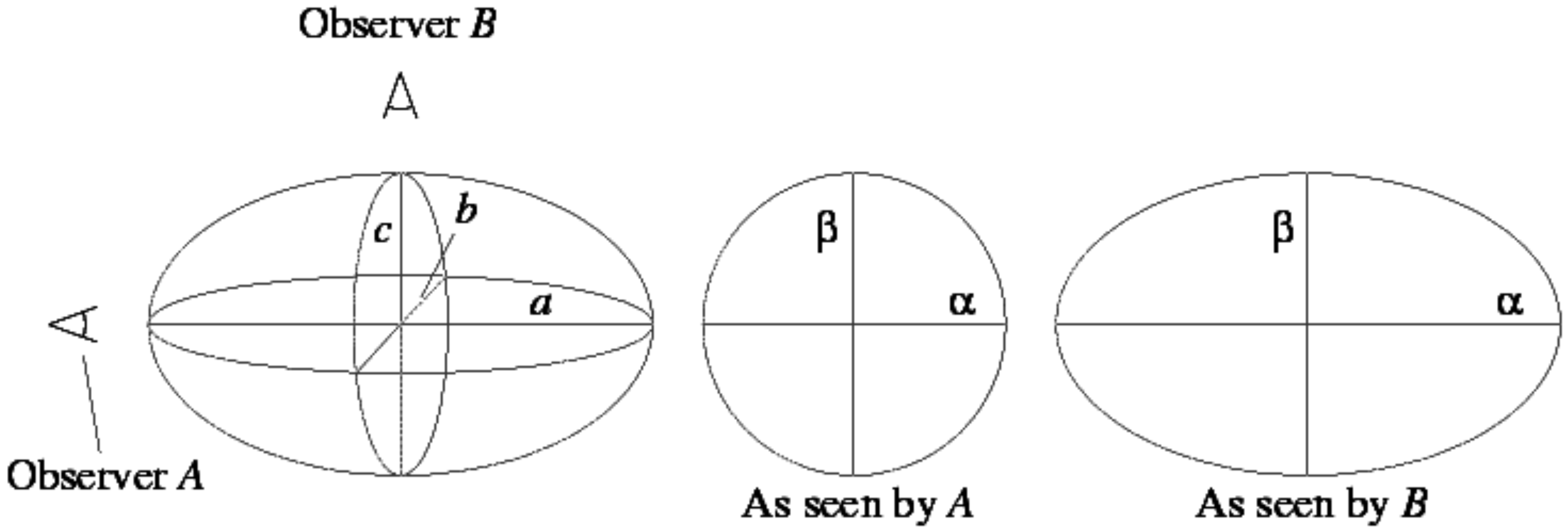
The tensor virial theorem

$$2\,\mathbf{K}_{\alpha\beta} + \mathbf{W}_{\alpha\beta} = 0$$

- Regular virial theorem says that total kinetic and potential energy have to be balanced
- Tensor virial theorem generalizes this to saying that the kinetic and potential energies in different directions have to be balanced separately
- Don’t get hung up on the ‘tensor’ part, for our purposes these are simply matrices.

The intrinsic and projected ellipticity

- We only observe the 2D shape of elliptical galaxies: this is an ellipse with an ellipticity eps_obs = 1-beta/alpha
- Axisymmetric ellipsoid has an intrinsic ellipticity eps_int = 1-c/a (fig. below with b=a)



Credit: Chris Mihos

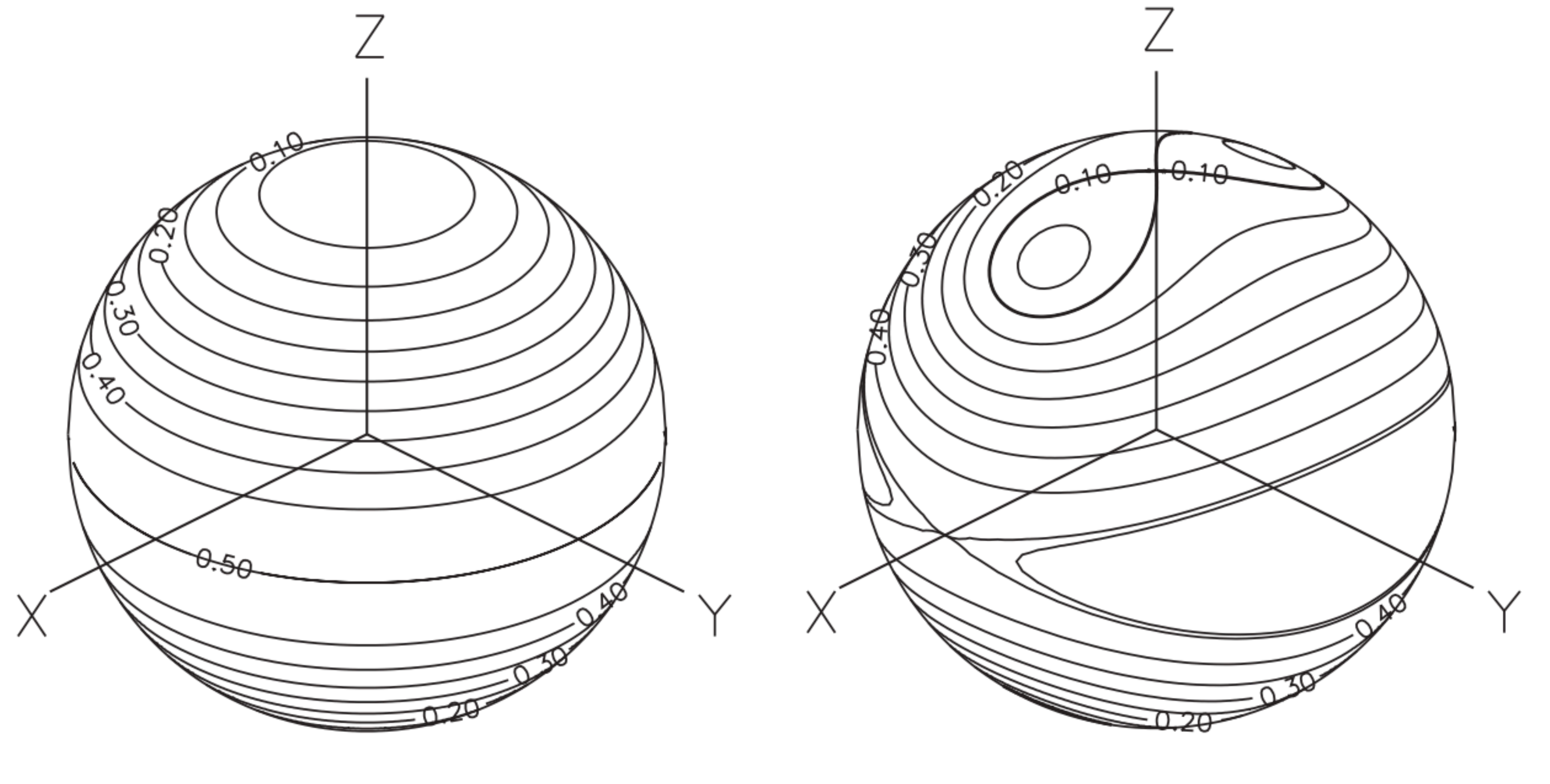


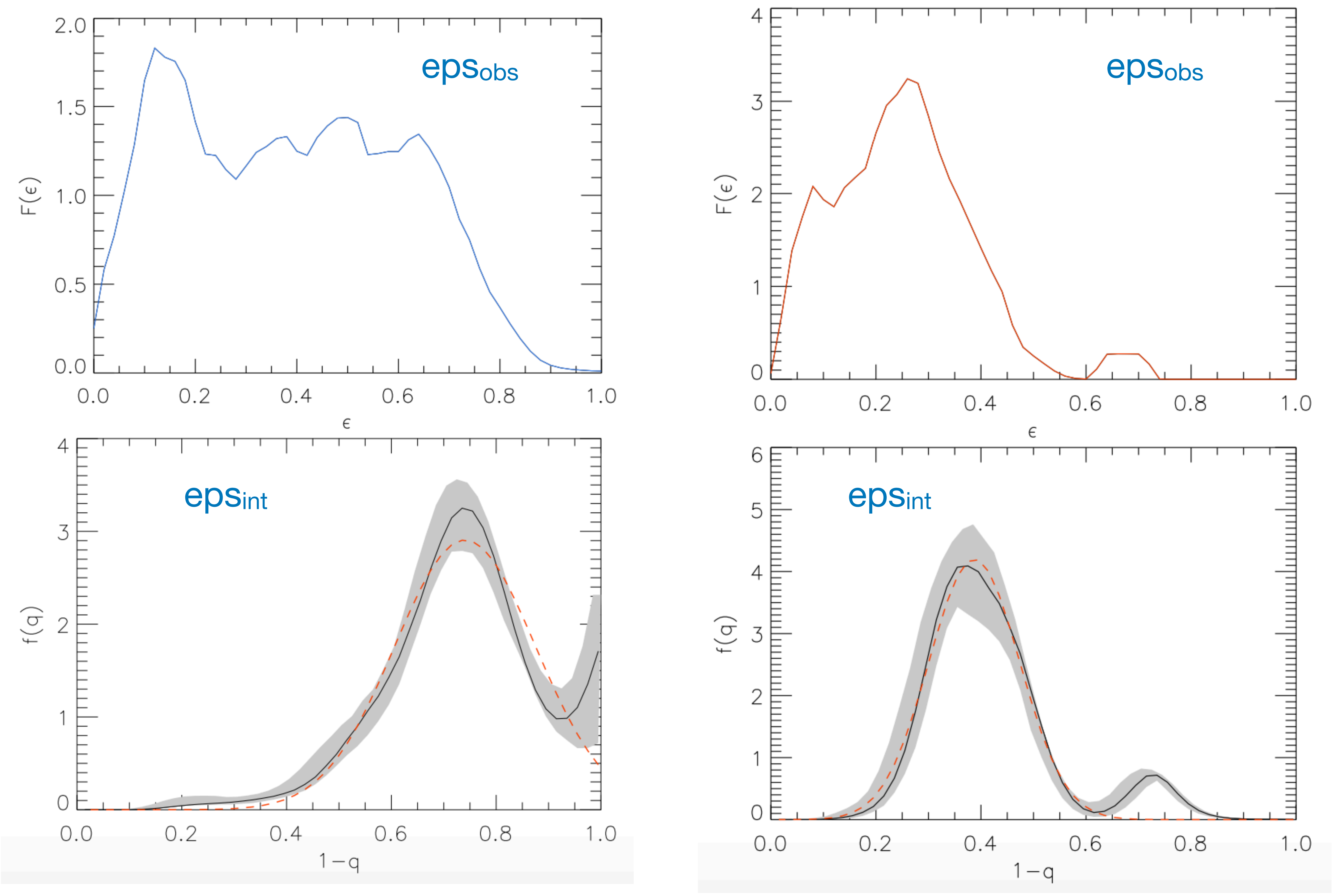
Figure 3. Contours of constant ellipticity on the sphere of viewing angles, for an oblate galaxy ($p = 1$ and $q = 0.5$, left) and a triaxial galaxy ($p = 0.9$ and $q = 0.5$, right). The ellipticity varies between 0 and $1 - q$.

Weijmans et al. (2014)

The intrinsic and projected ellipticity

Determining the ratio

- Under the assumption of axisymmetry and random viewing orientations, we can uniquely determine the distribution of intrinsic ellipticities from a distribution of observed ellipticities
- Wide distribution of both and of the ratio, but typically ~2
- Uses galaxies widely separated in the cosmic web, so intrinsic alignments are small
- Without assumption of axisymmetry, there is no unique solution

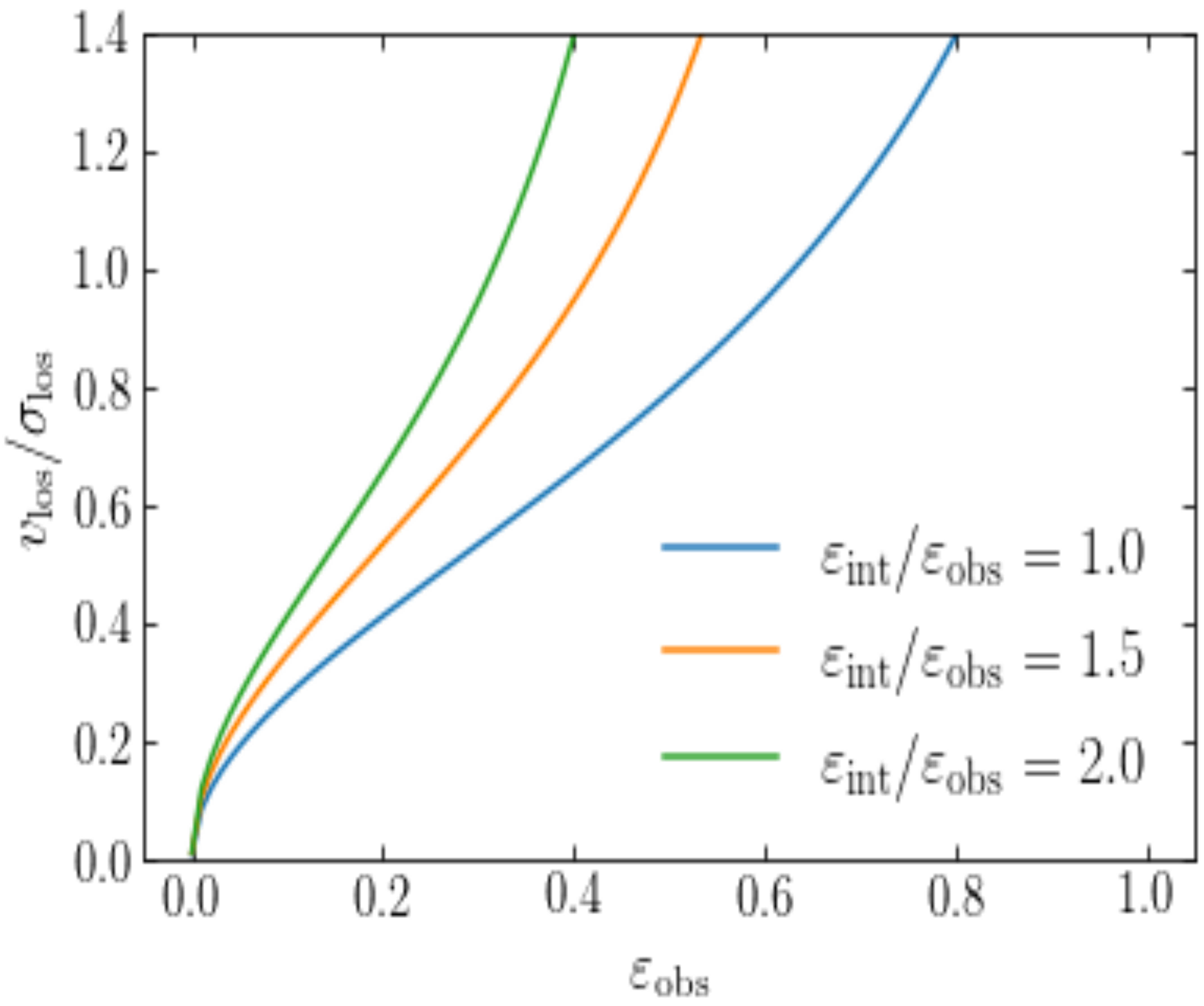


Are elliptical galaxies flattened by rotation?

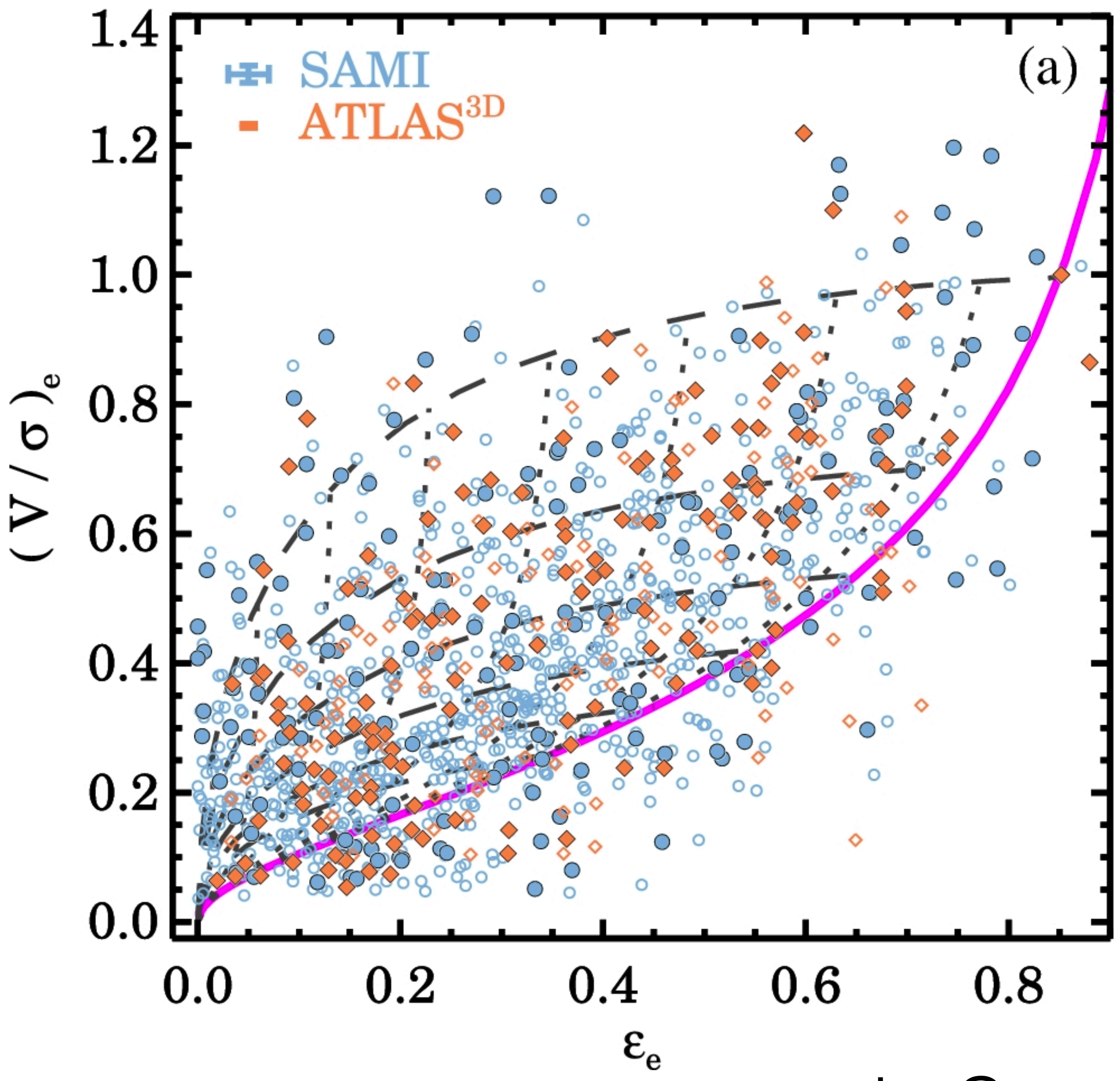
- Let's assume elliptical galaxies are flattened by rotation:
  - Rotation around z-axis: $\mathbf{T}_{\alpha\beta} = \frac{M\,v^2}{2}\,\delta^{\alpha\beta}\,(1 - \delta^{\alpha z})$
  - Isotropic dispersion tensor: $\mathbf{\Pi}_{\alpha\beta} = M\,\sigma^2\,\delta^{\alpha\beta}$.
- TV theorem: $M\,v^2\,\delta^{\alpha\beta}\,(1 - \delta^{\alpha z}) + M\,\sigma^2\,\delta^{\alpha\beta} = -\mathbf{W}_{\alpha\beta}$.
- Ratio of xx and zz:

$$\frac{v}{\sigma} = \sqrt{\frac{W_{xx}}{W_{zz}} - 1}\,.$$

Are elliptical galaxies flattened by rotation?

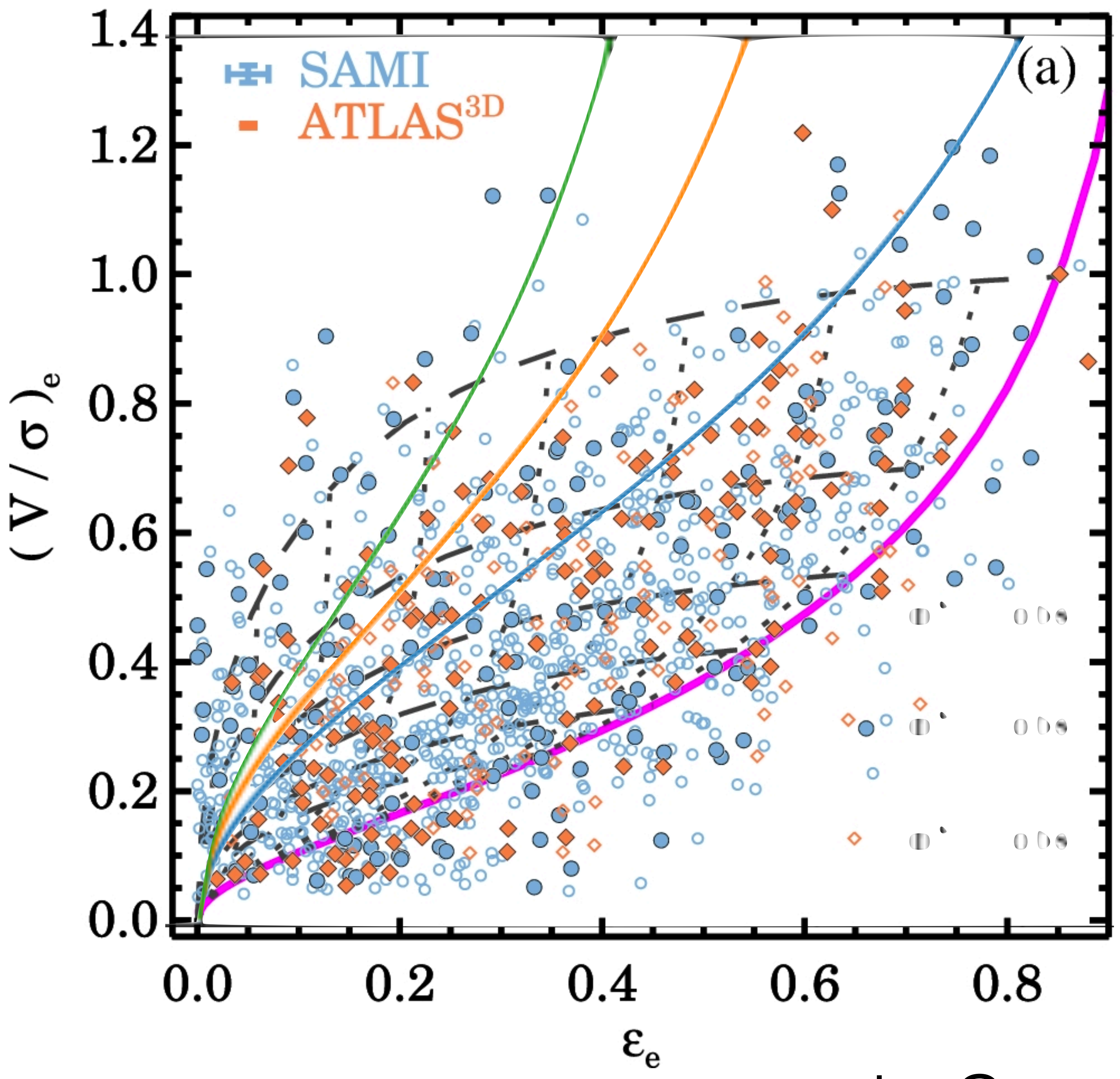


Are elliptical galaxies flattened by rotation?



van de Sande et al. (2017)

Are elliptical galaxies flattened by rotation?



van de Sande et al. (2017)

Are elliptical galaxies flattened by rotation?

Discussion

- Physically, without rotation, you need to oscillate less in the flattened direction, because otherwise the orbits would fill in a spherical region
- With rotation that's not necessary, part of the shape is due to the rotational part of the orbits
- Comparison to observed v/sigma shows that elliptical galaxies must have an anisotropic velocity dispersion tensor —> triaxial?
  - No mathematical need for triaxiality, but axisymmetric anisotropic tensor leads to the question why two axes would be the same? No obvious physical reason a priori that dispersion should be axisymmetric

Schwarzschild modeling

Schwarzschild modeling

Basic idea

- Basic idea is to represent a galaxy as a set of discrete orbits
- Because we use many fewer orbits than there are actual stars, don't think of these orbits as representing the orbit of individual stars
  - Each orbit represents a set of stars
  - Quite possible that data would show that the weight is zero —> no stars on this orbit
- Each orbit has a weight that represents the fraction of the mass that is in stars on this orbit
- General hierarchy is that Norbits >> Nconstraints
  - Fit is therefore underdetermined —> infinitely many combinations of weights give the same density
  - Choose 'best' one using some smoothness criterion: e.g., maximize entropy

Schwarzschild modeling

Orbit library

- How many orbits?
  - Schwarzschild (1979): 1500 orbits
  - More modern implementations (e.g., van den Bosch 2008): 3528 orbits
  - Use dithering: integrate a bundle of orbits for each ‘base’ orbit to smooth out predictions: add factor of ~100 (e.g., vdB uses 3528 x 125 = ~450k orbits)
- One of the main issues in building the orbit library is how to make sure you are sampling all orbits:
  - Remember: axisymmetric systems typically have 3 integrals, but we can’t determine the third
  - One way to do it for axisymmetric systems: start orbits at (E,Lz) along the zero-velocity curve
    - Going from z=0 to z = z_thin-tube samples all orbits (except for some resonant ones)
  - Triaxial case is much harder, but people similarly use the surface of section

Schwarzschild modeling

Some other practical difficulties

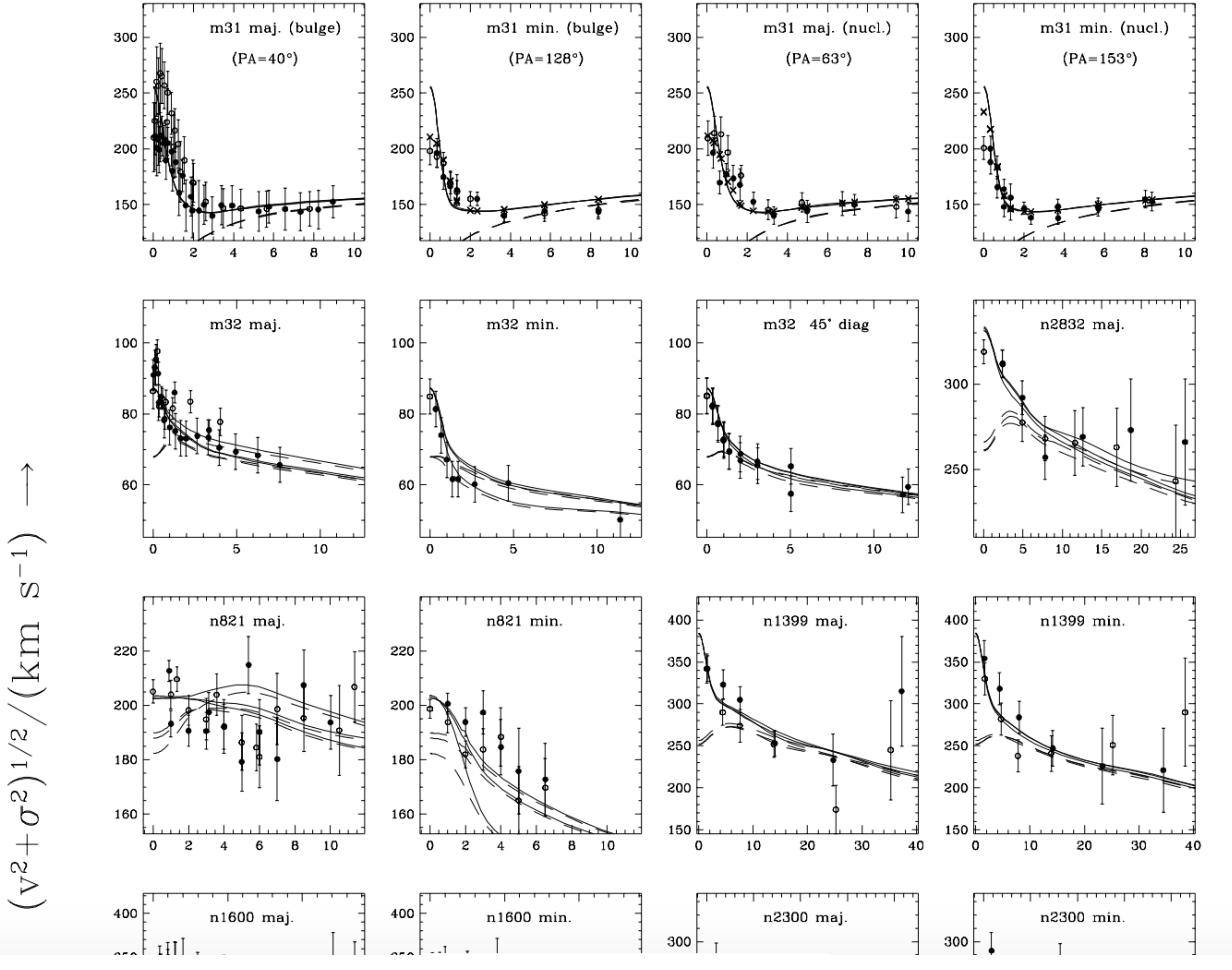
- Need to deproject an individual galaxy:
  - Can guess, but no unique answer even for axisymmetric elliptical galaxy
  - Deprojection becomes part of the model: which deprojection leads to the best agreement with the observed kinematics?
- Hard to model more complex systems, like bars in disk galaxies:
  - Sampling orbits is difficult, because rotating bars have complex orbits
  - One solution: made-to-measure modeling: rather than integrating all orbits ahead of time, integrate orbits with N-body forces while changing their weights —> N-body dynamics can automatically populated relevant orbits [but still tricky!]

Schwarzschild modeling: applications: black holes at the centers of galaxies

- Big discovery in late 1990s from HST observations combined with Schwarzschild modeling: all large galaxies have supermassive black holes at their centers

- Used axisymmetric Schwarzschild modeling, could rule out ‘no black hole’ solutions

- Further investigations led to M-sigma relation (Ferrarese & Merritt 2000, Gehbhardt et al. 2000)



Magorrian et al. (1998)

Black hole masses from Schwarzschild modeling

- Why is an increased velocity dispersion evidence for a black hole?
  - Gravitational potential sets the velocity at which stars orbit (very roughly, v ~ sqrt[phi])
  - Stellar surface brightness allows us to compute stellar potential and predict the velocities that should result from that
  - If velocities are bigger, then there has to be an additional source of gravity —> black hole

Disk stability

Toomre Q

- Q parameter:

$$Q \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma} > 1$$

- Similar criterion for fluid disks with sound speed c_s:

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma_0} > 1$$

- When Q < 1, disk unstable to some axisymmetric perturbations, more so the smaller Q gets

Toomre Q

Discussion

- Computed using axisymmetric perturbation, so that’s technically what it directly applies to
- Can determine this whenever you can determine the velocity dispersion, surface density, and epicycle frequency —> can be done in external systems
- As far as I can tell, only a few people have watched this lecture, so please watch it as it’s probably one of the most important things you will learn in this course!