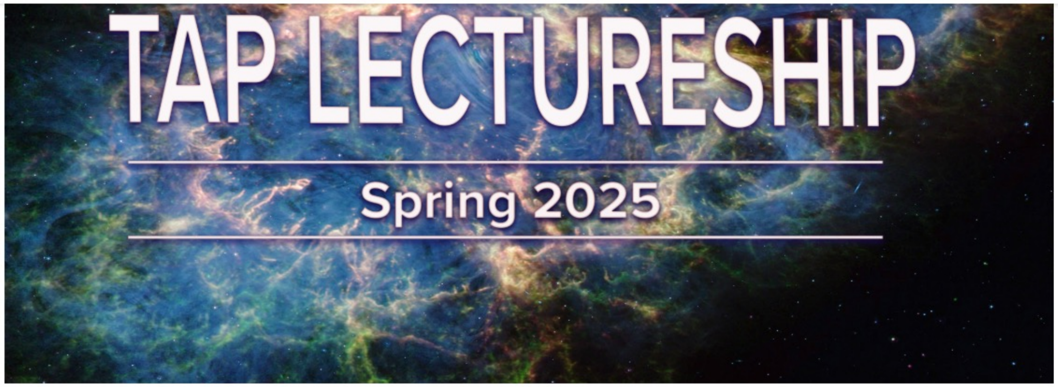


Dynamics Initiative Computational Workshop

<u>Daniel Tamayo</u>

Harvey Mudd College

Tuesday, March 18, 2025

10:30 am - 12:00 pm

Steward Observatory, Room 550

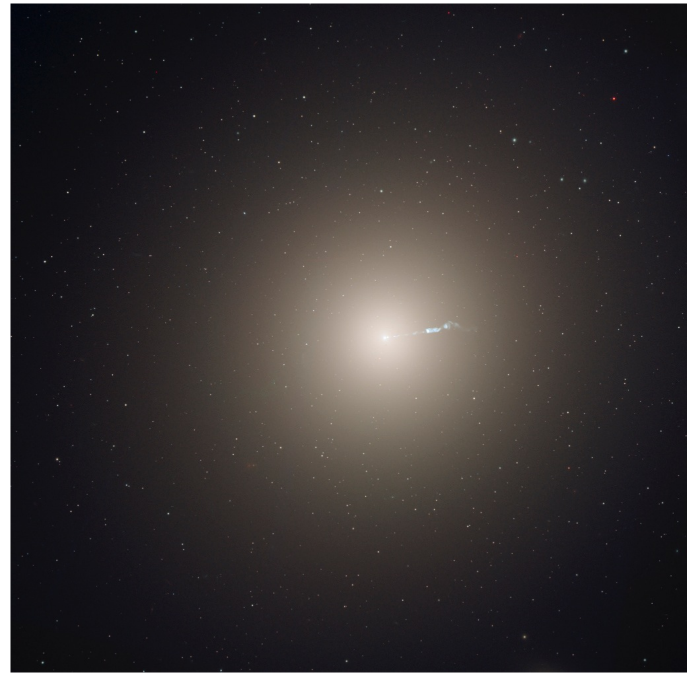
Orbital Dynamics in Python

Overview:

This computational workshop will provide a hands-on introduction to the REBOUND N-body integration package. We will introduce some of the basics, discuss its new visualization tools, as well as go through how to customize the code for your own scientific goals. We will then show how various common astrophysical effects (tides, oblateness, radiation pressure etc.) can be easily incorporated using the REBOUNDx library, and how you can add your own custom effects. Finally, we will introduce celmech, a new Python package for facilitating theoretical orbital mechanics calculations, and isolating the effects of resonances, secular dynamics, and much more!

Elliptical Galaxies

Photometry

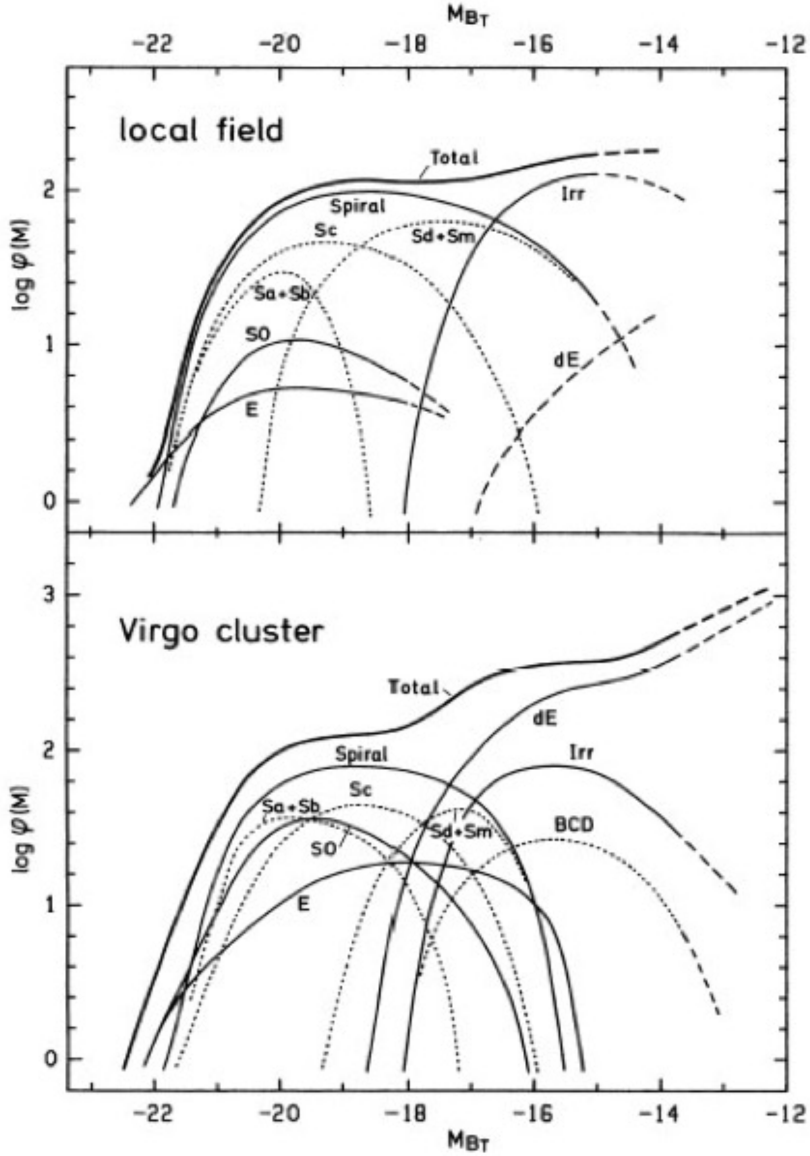


- E's span a huge range of luminosity from the brightest to some of the dimmest galaxies in the Universe!

- Useful to divide into 3 classes
  - **Giant ellipticals:** $L > 2 \times 10^{10}\ M_{\odot}$, $M_B < -20$
  - **Mid-sized ellipticals:** $L = 3 \times 10^{9} - 2 \times 10^{10}\ M_{\odot}$, $M_B = -18$ to -20
  - **Dwarf ellipticals** ($L < 3 \times 10^{9}\ M_{\odot}$, $M_B > -18$)

- For E's there is a strong correlation between radius and luminosity

The galaxy luminosity function varies with galaxy type and environment



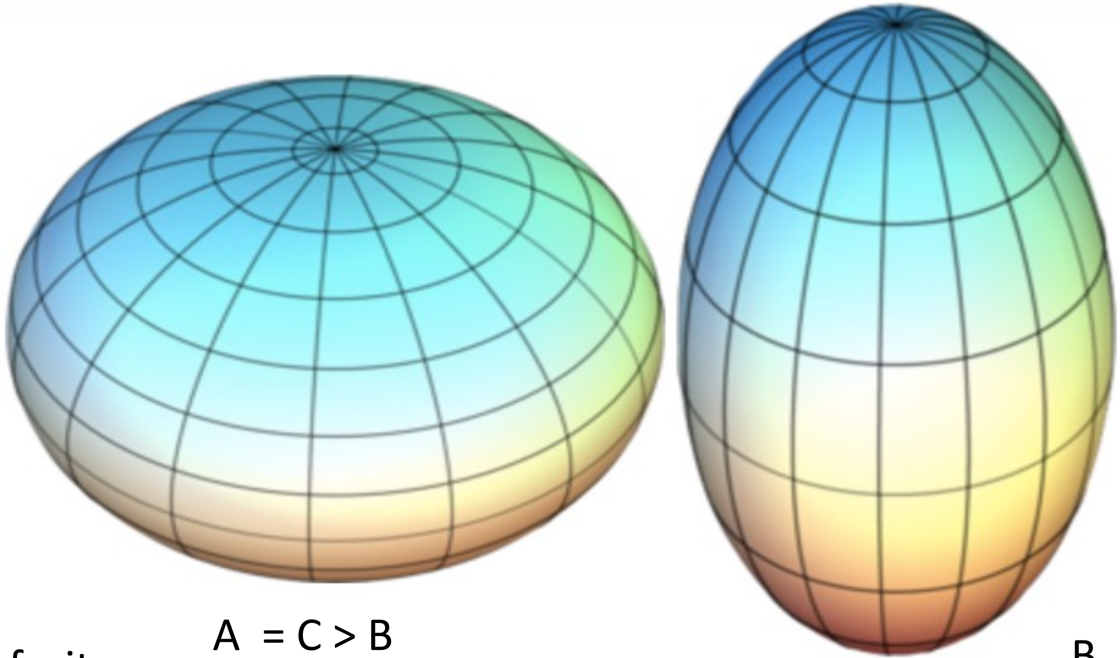
Bingelli (1988)

Field – dominated by Spirals, faint end dIrr

Clusters – many more E/S0 galaxies, faint end dE, more dwarfs than in field

Ellipticals vs. spirals

- Very different than spirals.
- Disk is rarely present.
- No cold gas.
- No ongoing star formation.
- Old stellar populations.
- Little or no internal substructure.
- Span a wide range of masses and dominate the most massive galaxy population.
- Can be oblate (like grapefruit) or triaxial (like football).



football

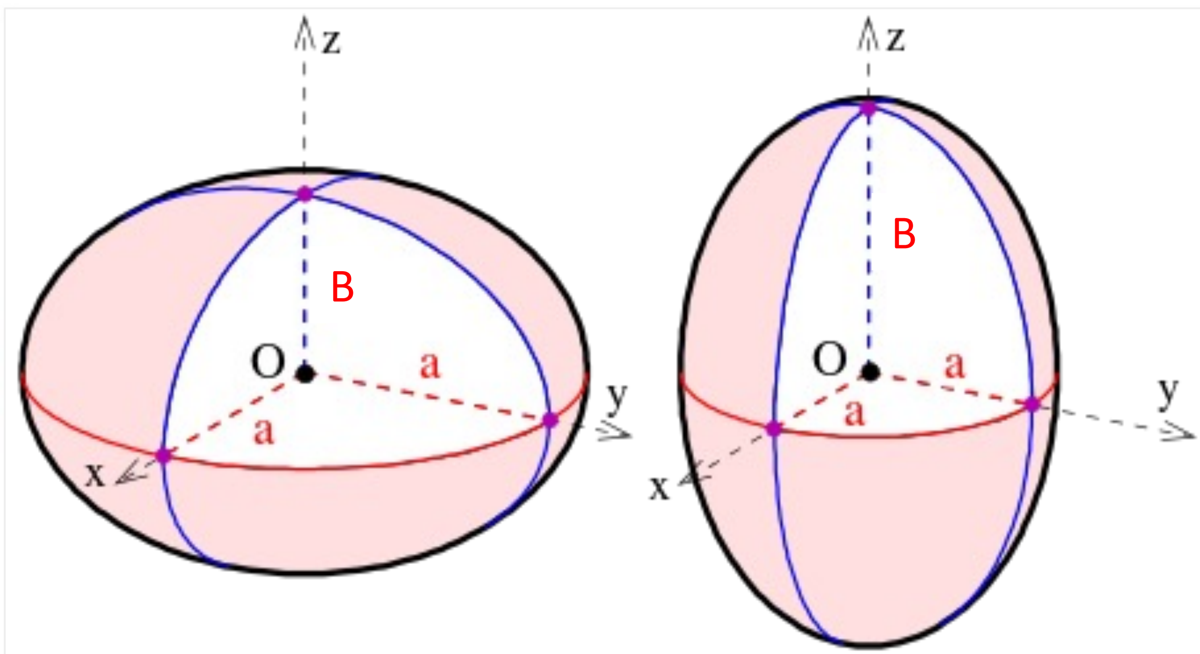
grapefruit

A = C > B

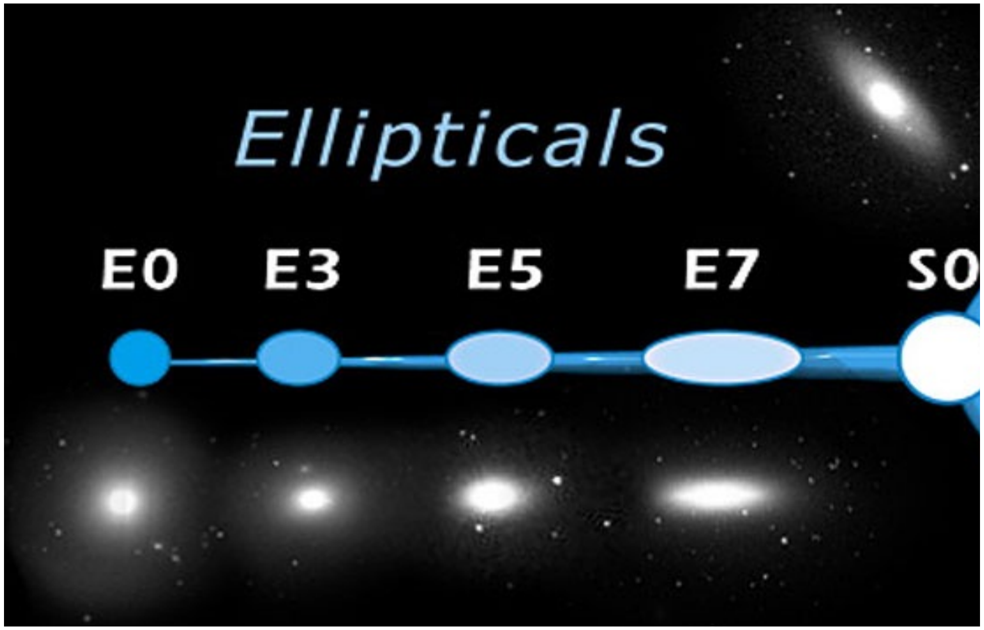
oblate spheroid

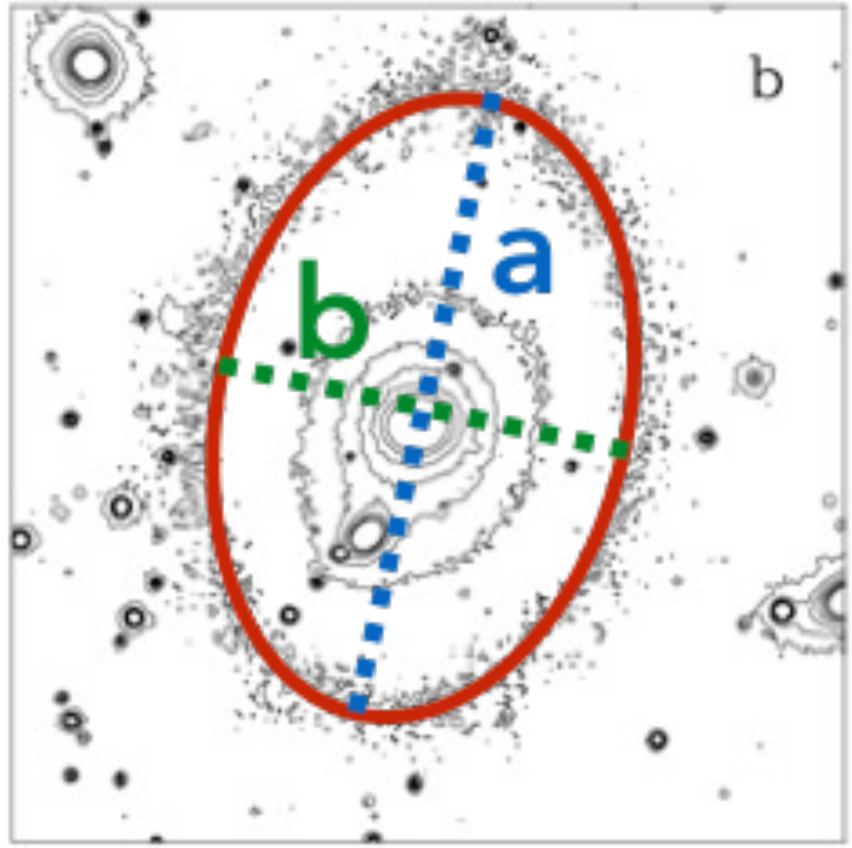
prolate spheroid

B > A = C



Triaxial : Three axes are different , in this case: C > B > A



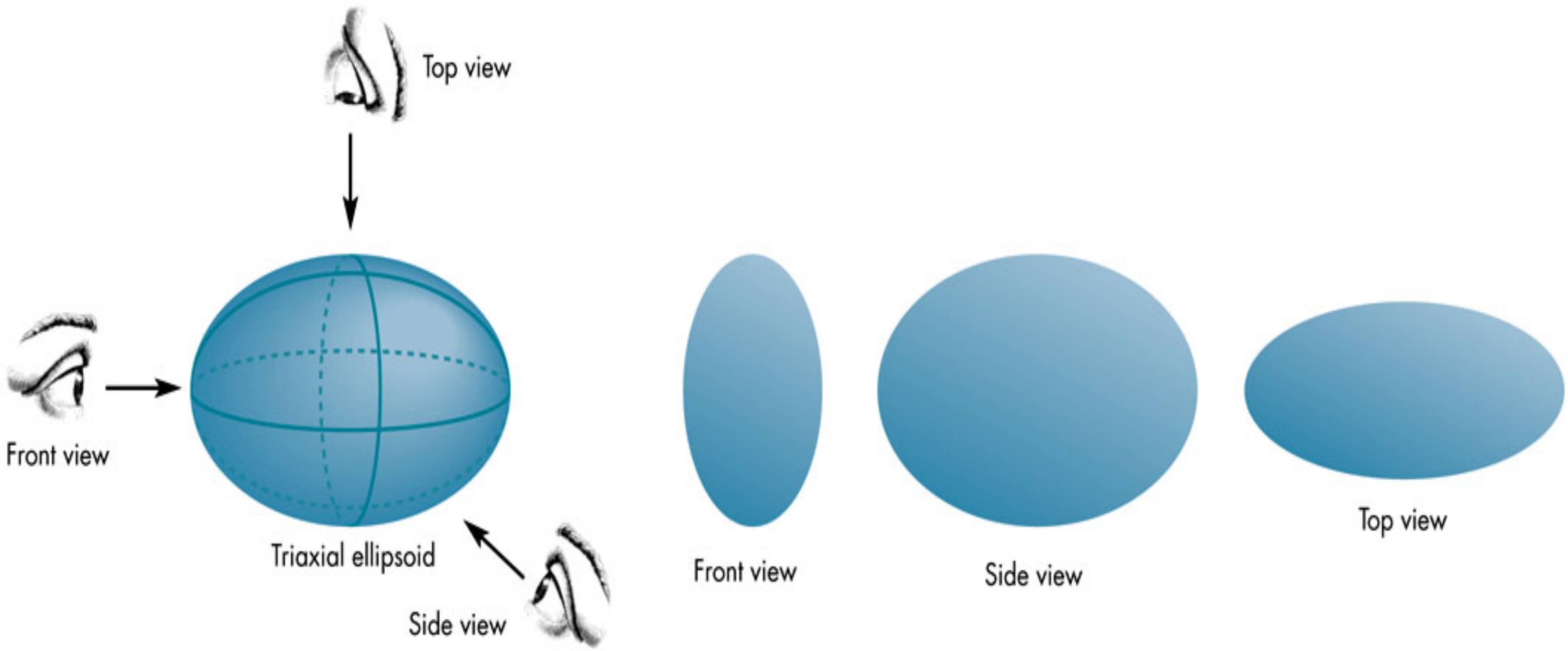


Ellipticity $\varepsilon = 1\text{-}b/a$

Ellipticals often labeled by “En” where n=10*ε

E0: circular appearance
E5: $\varepsilon = (1\text{-}b/a) = 0.5$

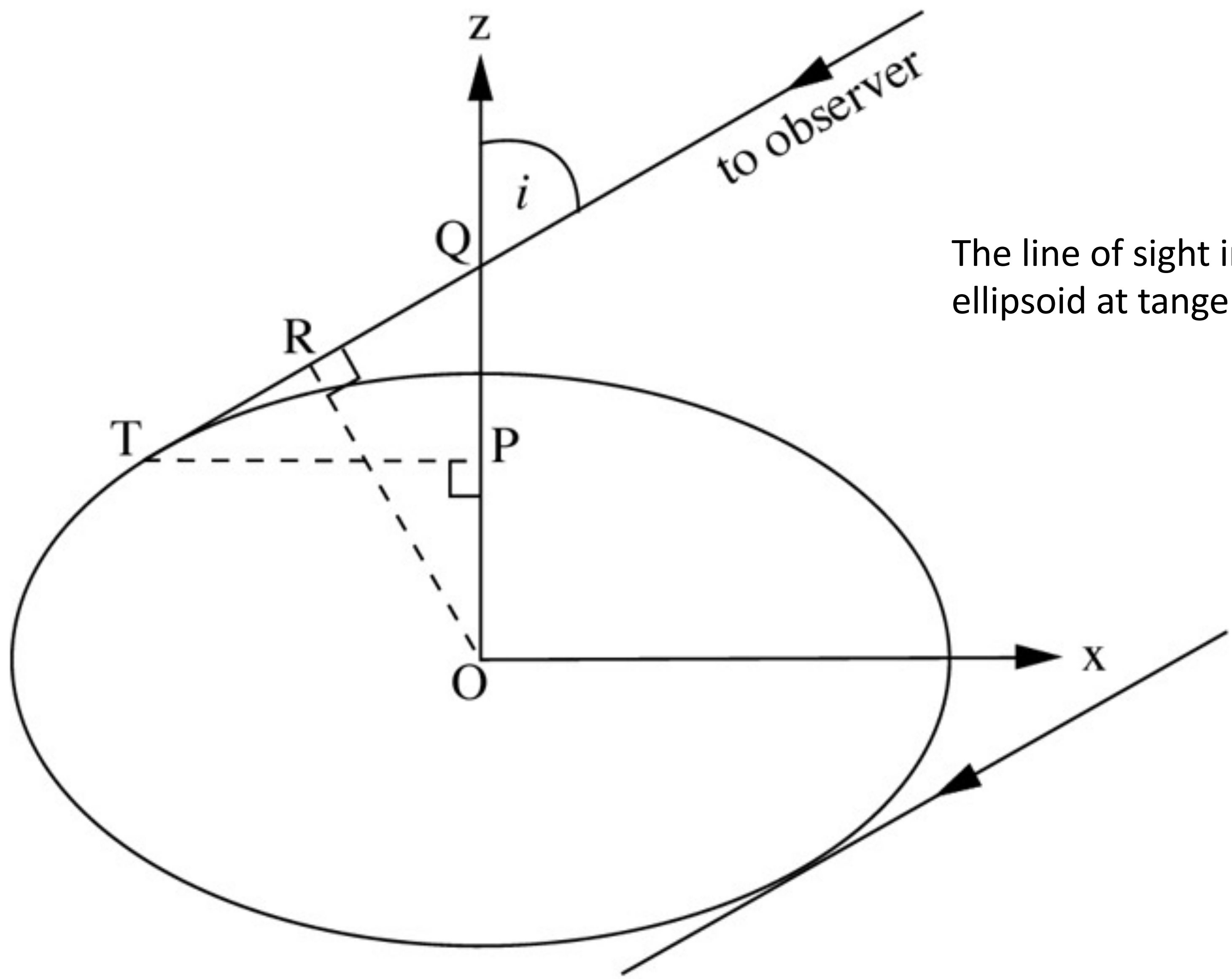
3D Shapes of Elliptical Galaxies



3D shape of any given elliptical is not possible to determine from projection on the sky.

Instead, examine the statistics of the full population..

Viewing geometry for an oblate galaxy



The line of sight intersects the ellipsoid at tangent point T

Fig 6.8 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

$(b/a)^2 = (B/A)^2 sin^2 i + cos^2 i$

the **observed axis ratio (b/a) is always greater than the intrinsic axis ratio (B/A)**, i.e.

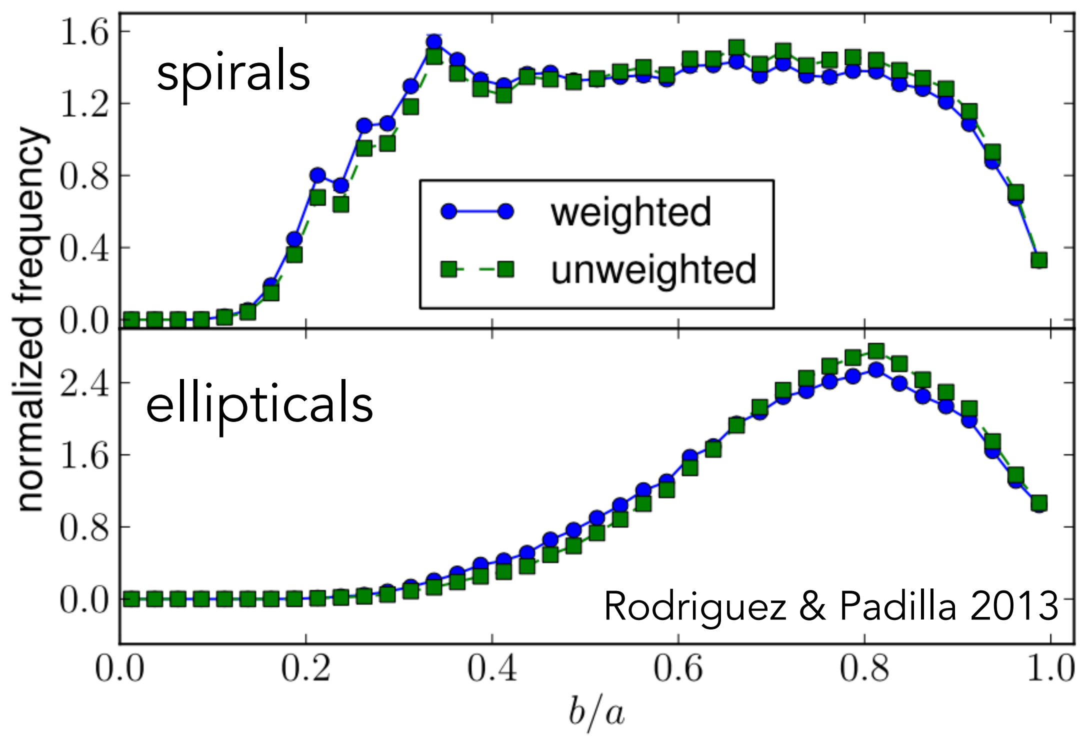
b/a > B/A
where (a, A major axes, b, B-minor axes)

A galaxy never appears more flattened than it actually is.

3D Shapes of Elliptical Galaxies

Assume that galaxies are on average randomly oriented.

How often you see that axis ratio.



Observed Axis ratio

For ellipticals:

Mean Ellipticity
ε = 1-b/a ~ 0.26

So b/a ~ 0.74
not very flattened

b/a

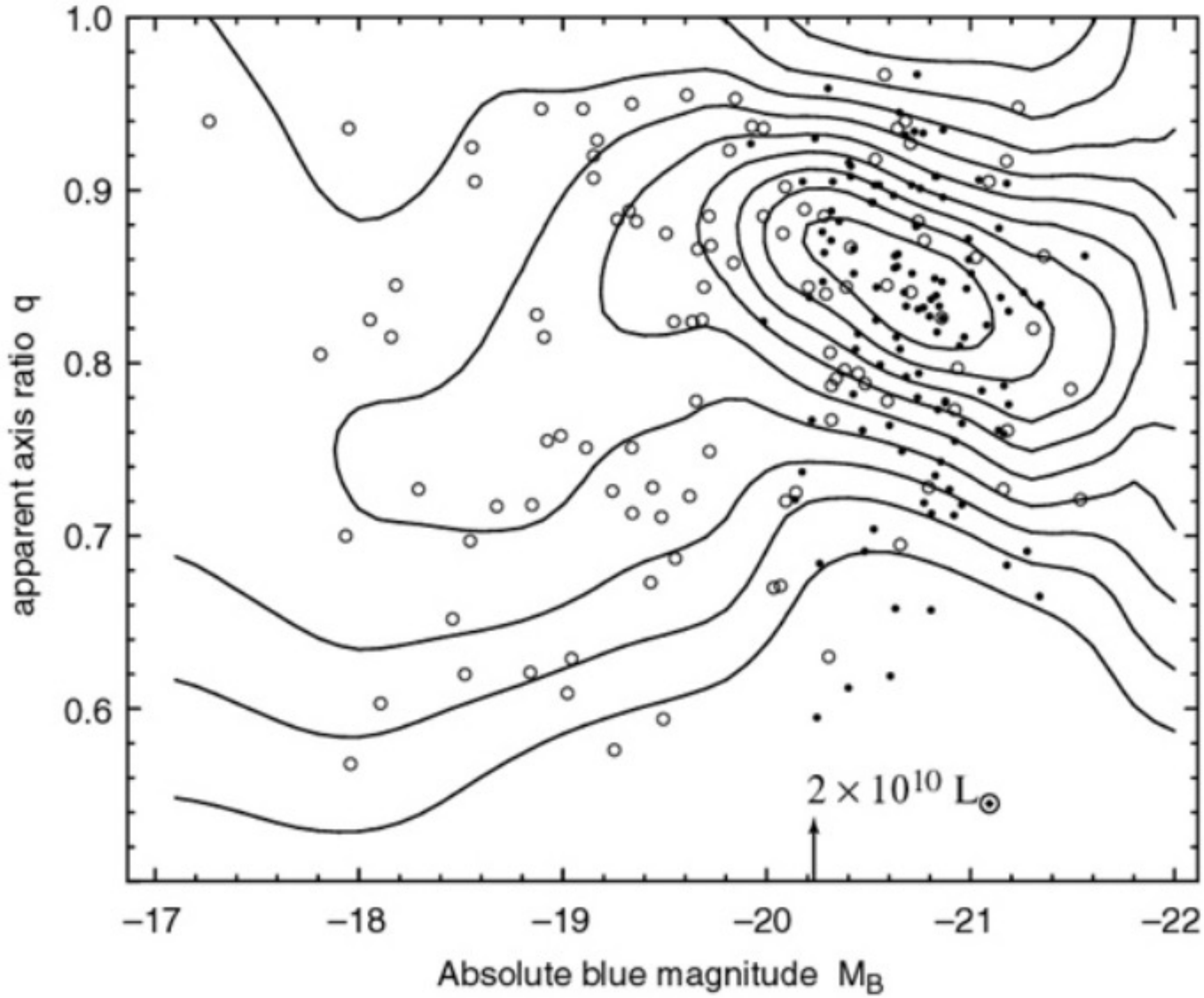


Fig 6.9 (Tremblay & Merritt) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Observed axis ratio b/a and blue absolute magnitude for elliptical galaxies. Bright galaxies (right) on average appear rounder. Contours show probability density: the top contour level is for probability density 4.5 times higher that at the lowest. Tremblay & Merritt 1996

Isophote Shape

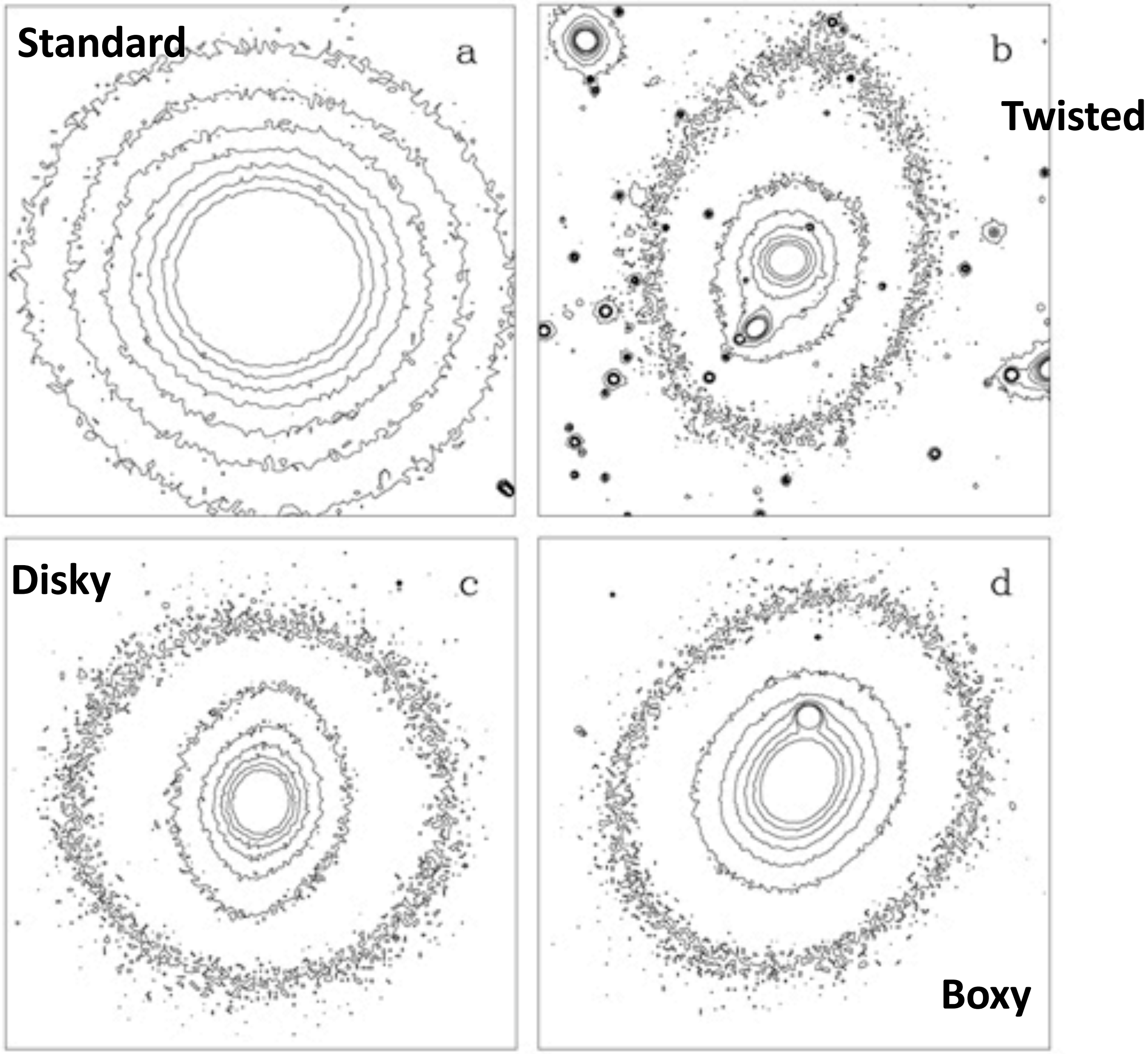


Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Isophotes in the R band of four giant elliptical galaxies. A) Isophotes are elliptical (NGC 5846) B) The long axis of the inner isophotes is roughly horizontal, twisting to near-vertical at the outer contour (EFARJ16WG); C) Diamond-shaped 'disky' isophotes (Zw 159-89 in Coma); D) Rectangular 'boxy' isophotes (NGC 4478). Compact objects are mainly foreground stars.

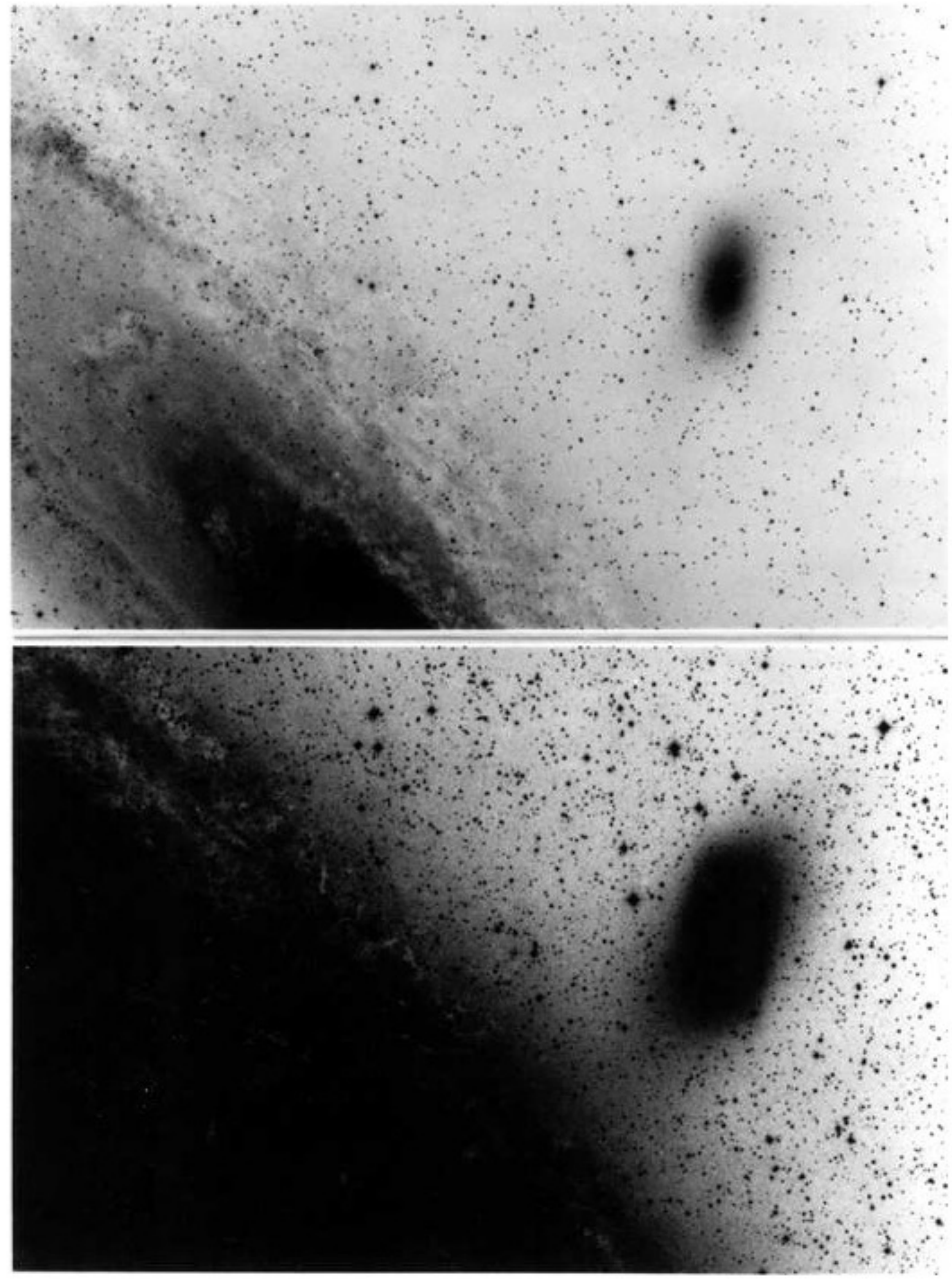
Isophote Twisting

Example: M31 Satellite NGC 205

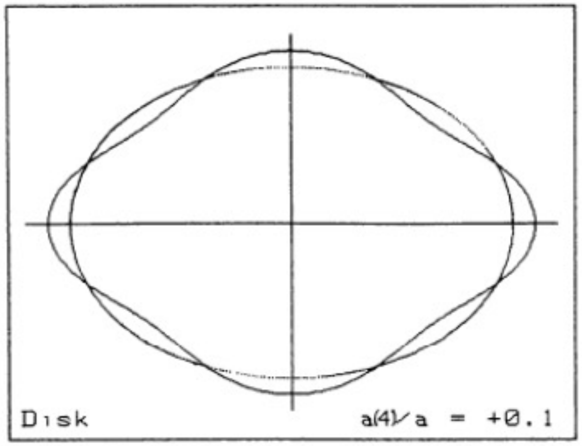
The first, shallower, exposure shows the brightest part of the galaxy.

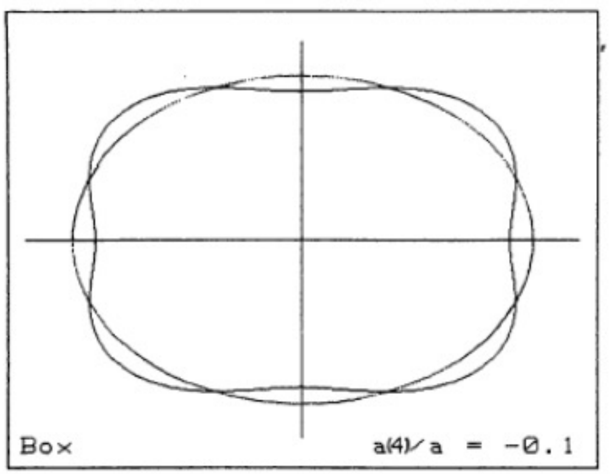
The second, deeper, exposure shows the weaker more extended emission.

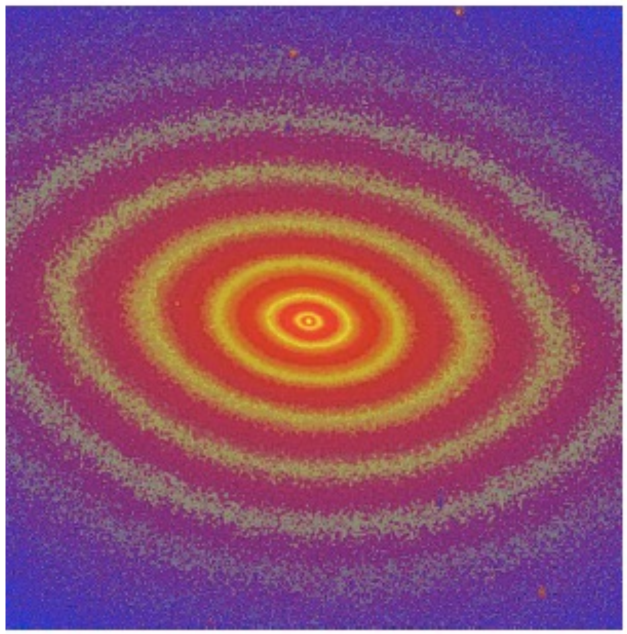
A twist between both images of the same galaxy are apparent (the orientation in the sky is the same in both figures).



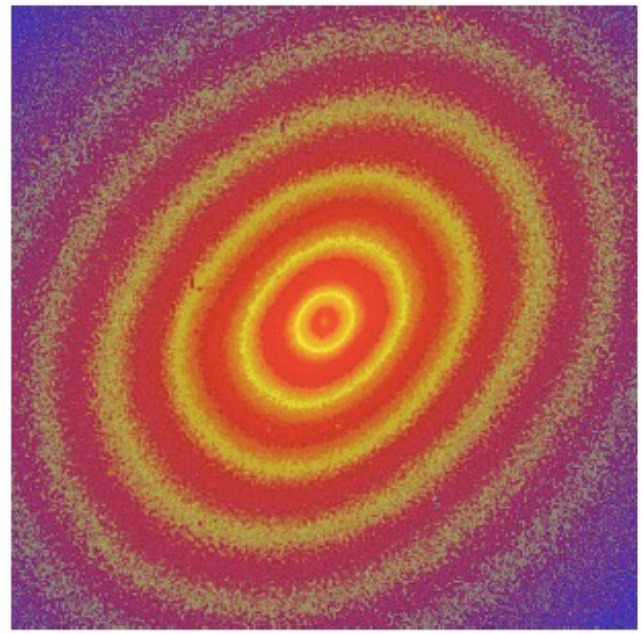
Boxy and Disky Isophotes







NGC 821: $a_4/a \sim +0.02$, disky



NGC 2300: $a_4/a \sim -0.02$, boxy

Boxy:
Tend to Brighter Ellipticals
Tend to have twisted Isophotes

Boxy or disky?

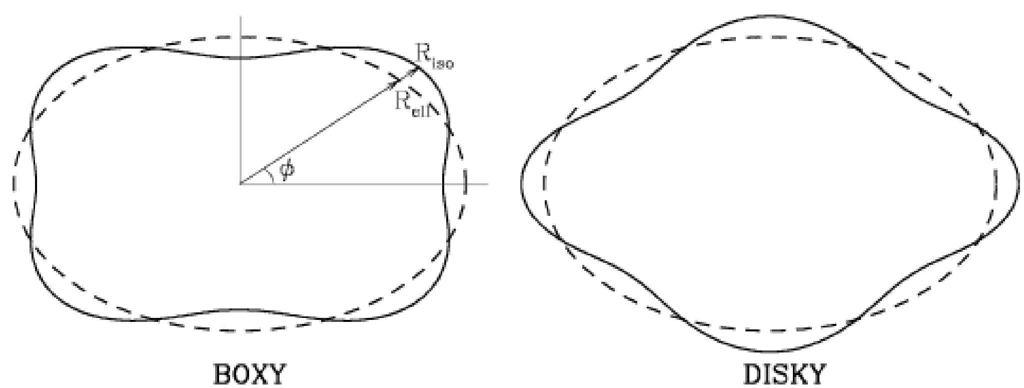
- We fit the isophote with an ellipse in parametric form:

$$x = a\cos t, \quad y = b\sin t$$

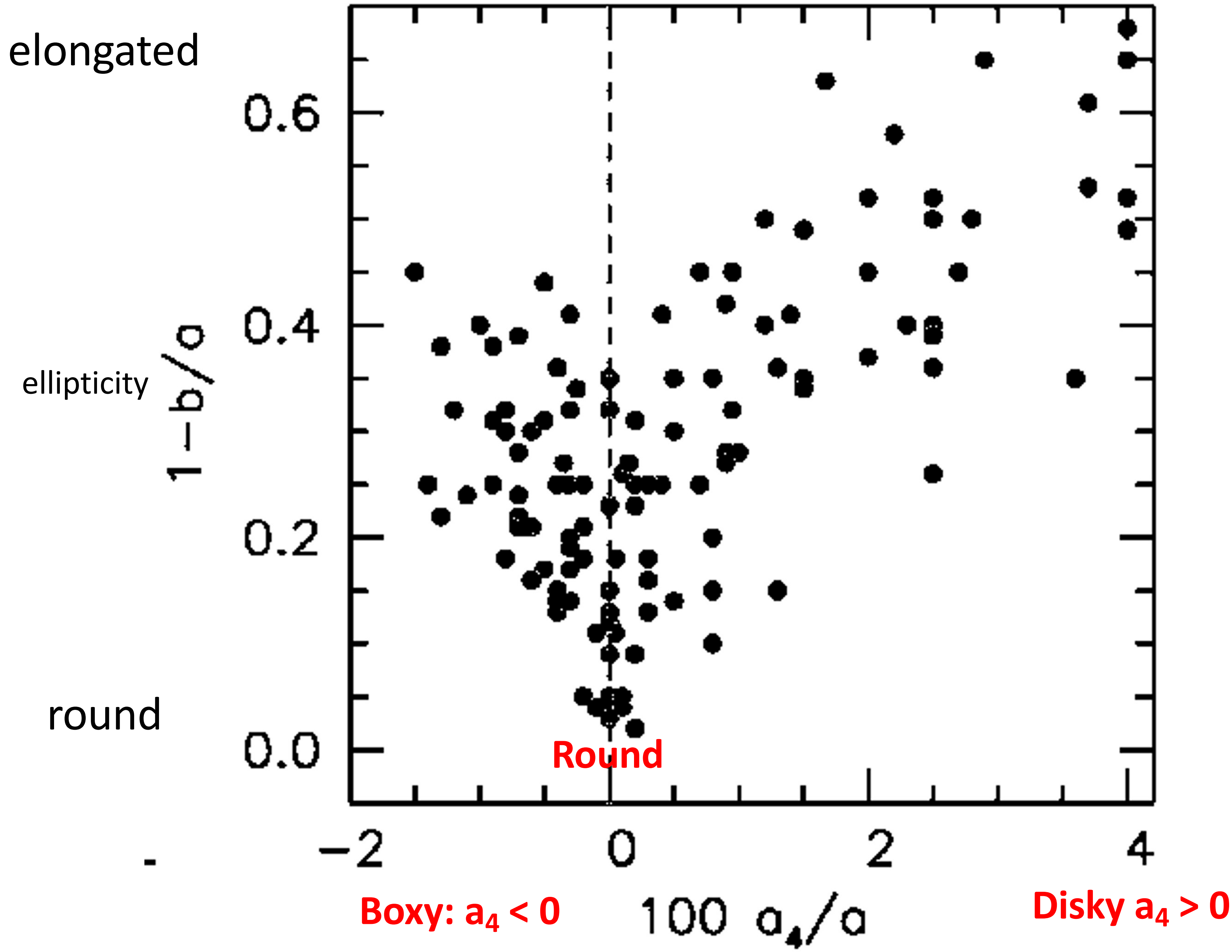
- And look for functional form of deviation (Fourier expansion in azimuth):

$$\Delta r(t) \approx \sum_{k\geq 3} a_k \cos(kt) + b_k \sin(kt)$$

- We fit the best matching ellipse, (for k=0,1,2 all terms are zero) k=3 terms are small but k=4 (a4) is not. a4 > 0 ellipse is "pushed out" on major and minor axes, while if a4 < 0 it bulges out at 45 deg from the axes.



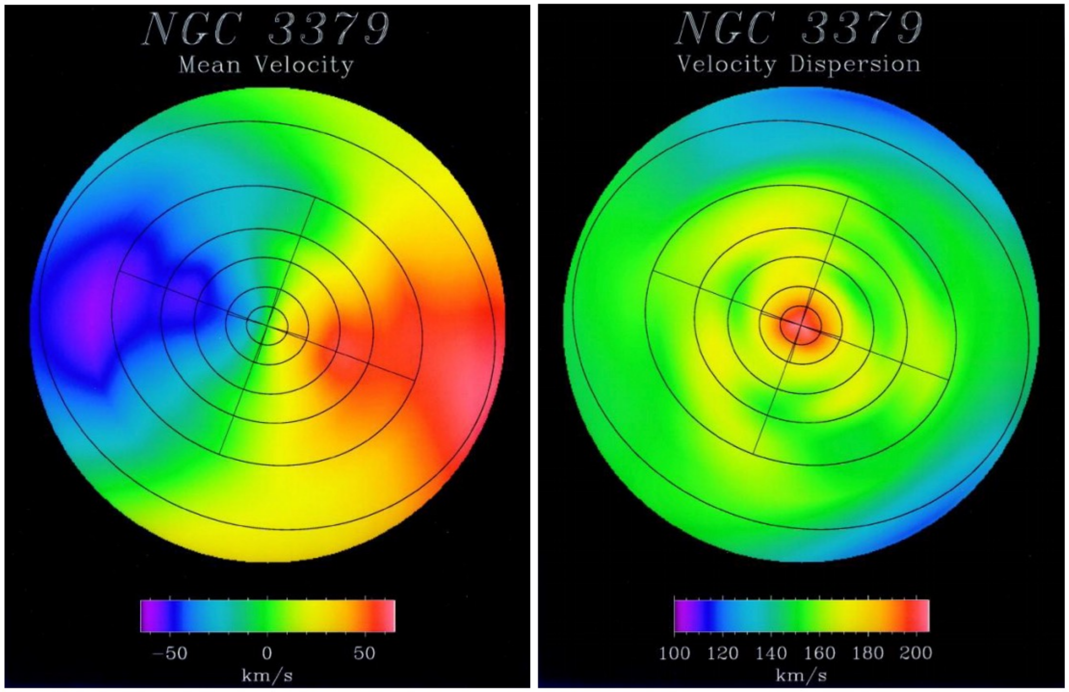
a4 < 0 a4 > 0

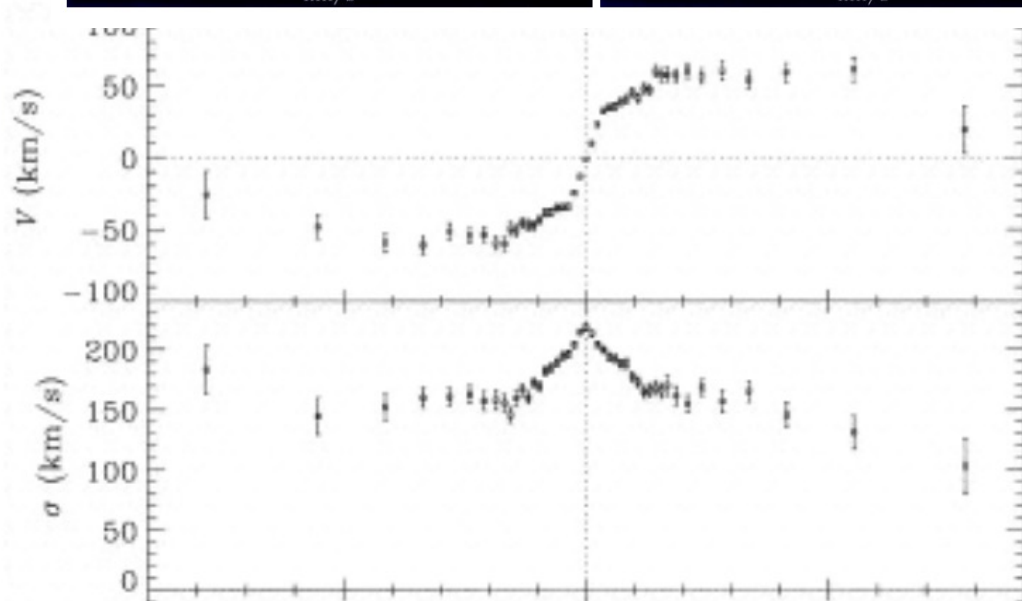


elongated
ellipticity
round
1−b/a
0.6
0.4
0.2
0.0
Round
−2
0
2
4
100 a_4/a
Boxy: $a_4 < 0$
Disky $a_4 > 0$

Some Elliptical Galaxies do Rotate

So are they rotationally elongated?





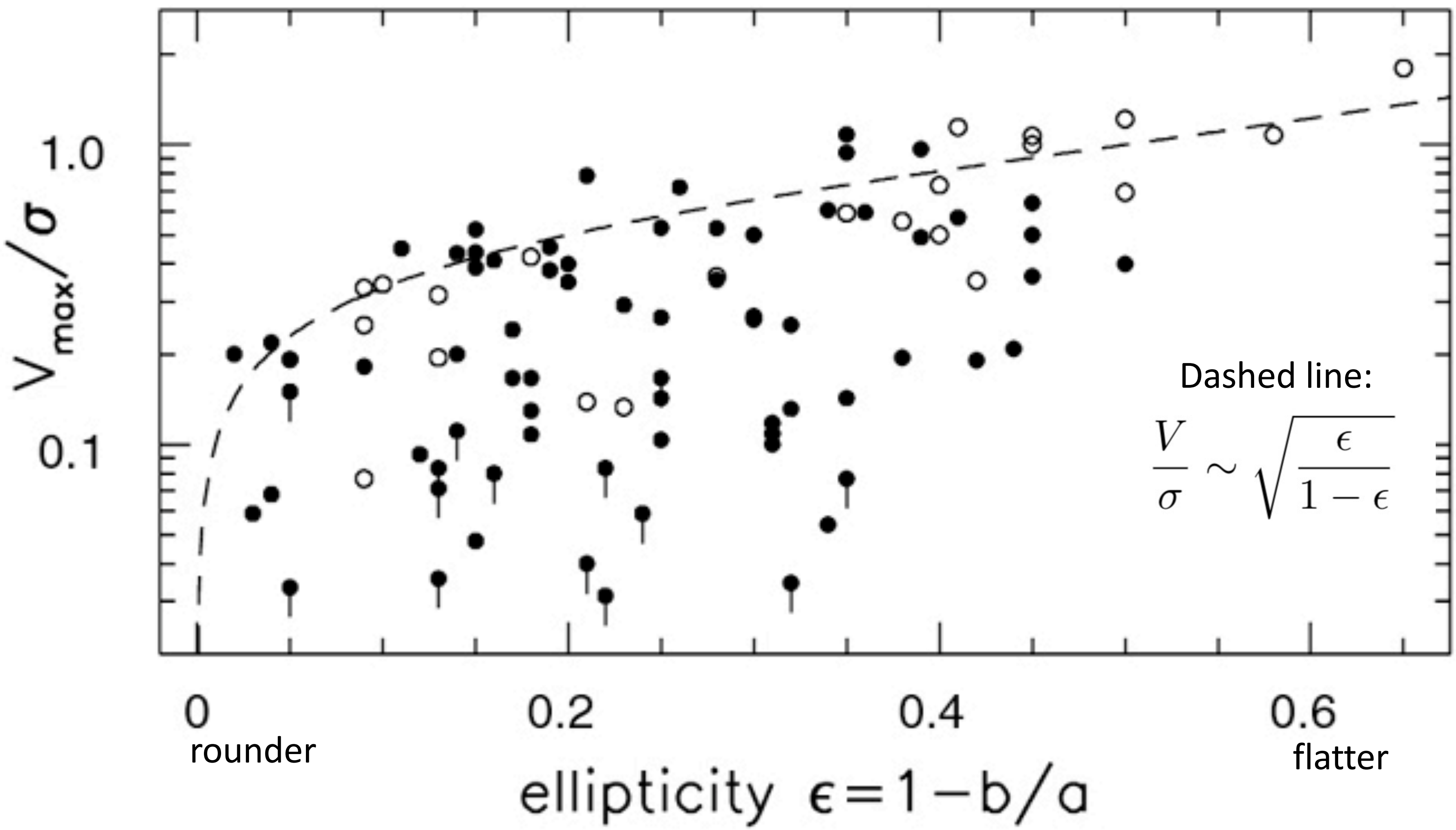


Fig 6.14 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The ratio of measured peak rotation speed to central velocity dispersion for elliptical galaxies, plotted against apparent ellipticity: filled circles show bright galaxies (Mv< -19.5); open circles are dimmer galaxies. Points with downward extending bars indicate upper limits on Vmax. The dashed line gives the theoretical **(V/ σ)iso**, assuming **isotropy** and the virial theorem (the fastest rotation expected for a given flattening.)

Velocity Dispersion

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(v - \langle v \rangle)^2$$

np.mean(v)

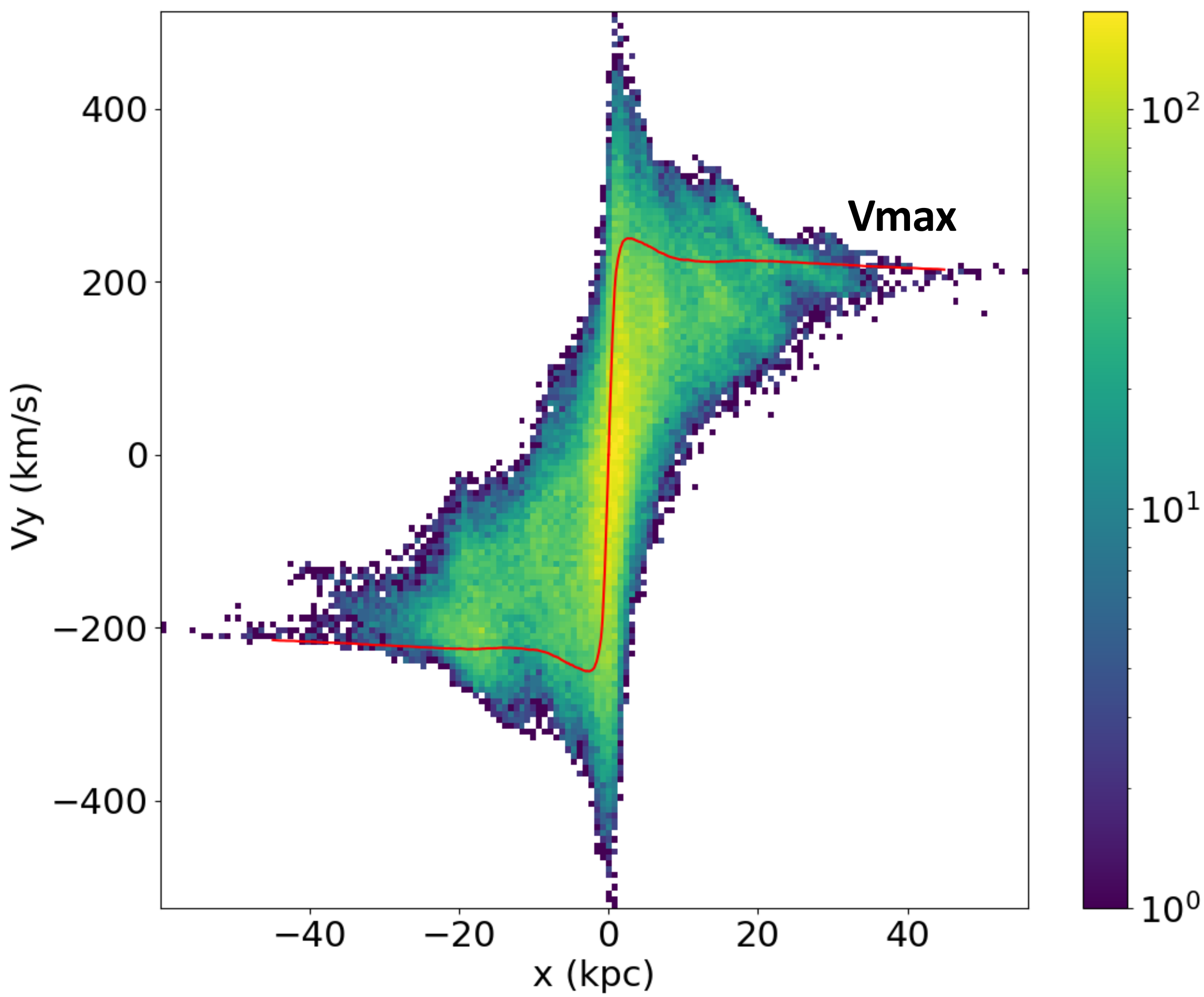
$$\langle v \rangle = \frac{1}{N}\sum_{j=1}^{N} v_j$$

np.std(v)

the spread or dispersion of data points around the mean

You can do this per velocity component

Recall Lab 7…



Rapid Rotators

Slow Rotators

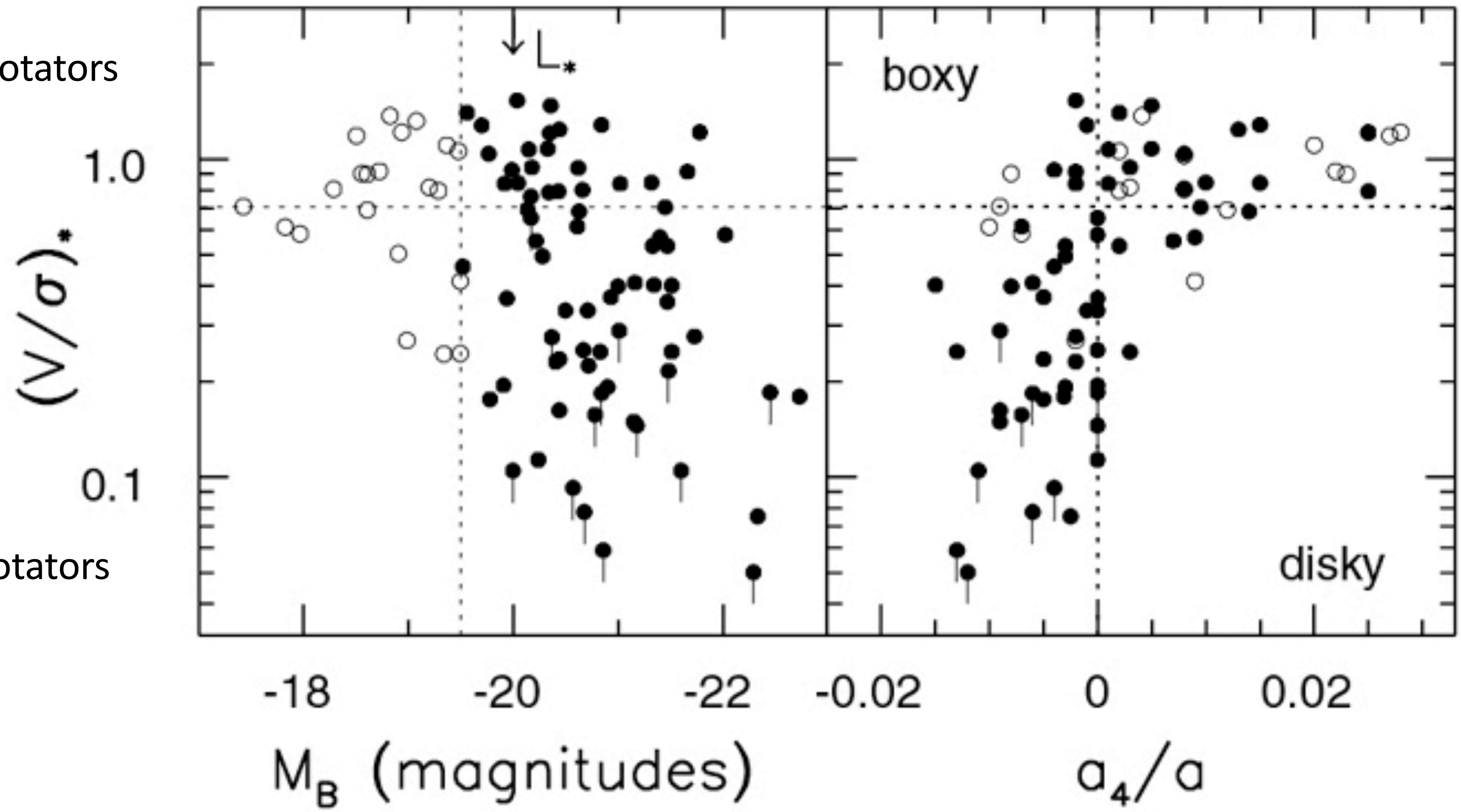


Fig 6.15 (R. Bender) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Y-axis: The ratio of the measured Vmax/σ to (V/σ)iso (theoretical). Down-ward pointing bars show upper limits on Vmax; filled circles are bright galaxies. Left, luminous galaxies often rotate slowly, falling below the dotted horizontal line at (V/σ)* = 0.6. Right, boxy galaxies with a4<0 are almost all slow rotators; many of these are luminous.

Q – is the MW+M31 Merger Remnant a rapid or slow rotator?