



AIP

# Dynamics of massive (local) galaxies

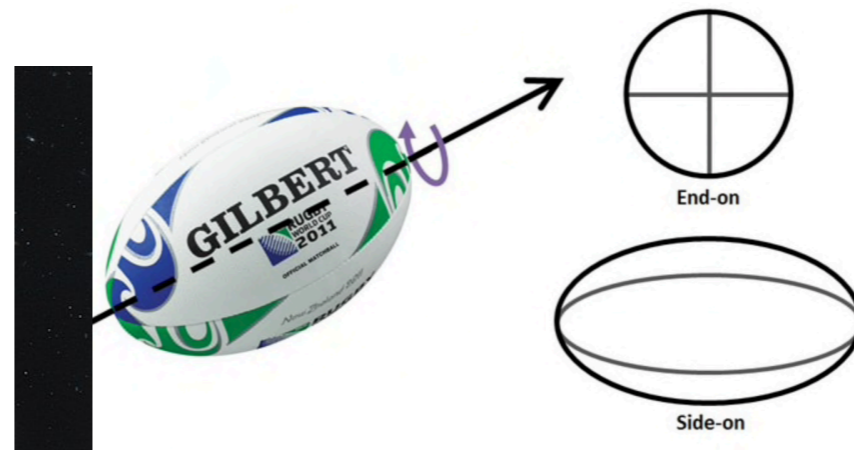
Davor Krajnović  
Favignana, 04 Sept 2018

3-7 September 2018, Favignana Island, Italy

Birth, life and fate of  
massive galaxies and their  
central beating heart

# Age old astro questions?

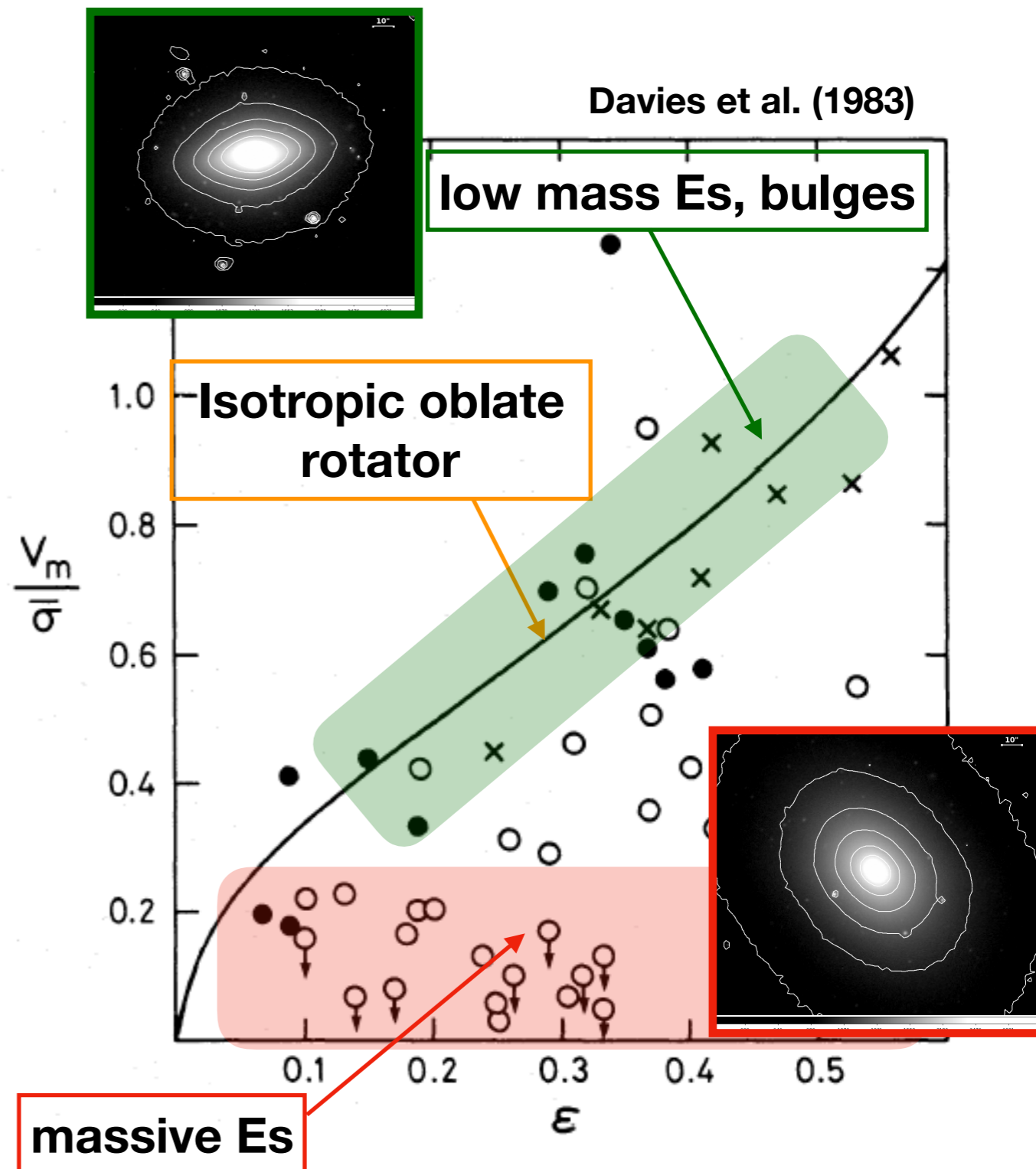
- what is the **mass** (or **mass density**) of the galaxy?
- what is the (intrinsic) **shape** of the galaxy?
- stellar **dynamical modelling** as an **extension** of observations
- key observable - **stellar motions**
- what can we learn about the **mass assembly** and the **formation** of (massive) galaxies?



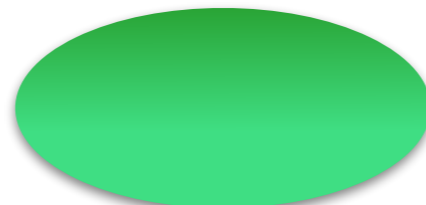
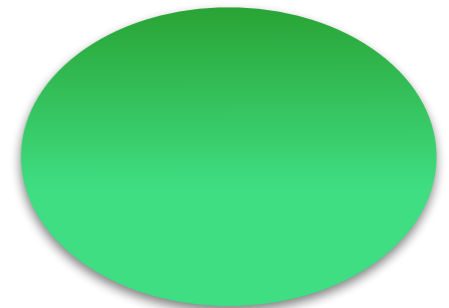
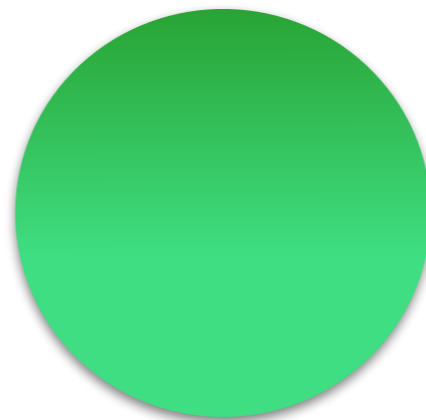
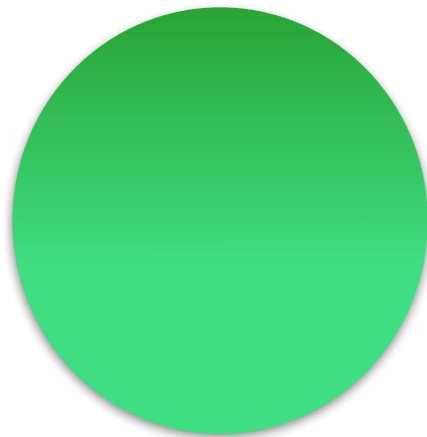
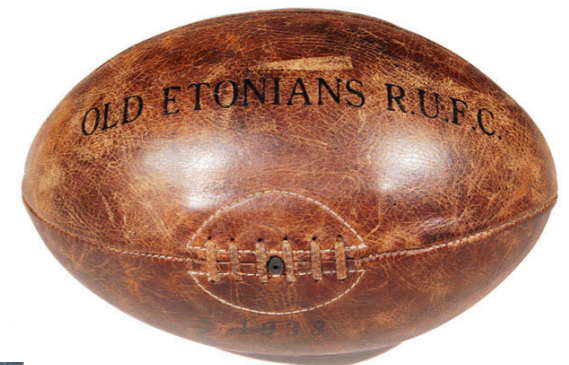
- Crucial ingredients:
  - high quality imaging
  - kinematical mapping
  - sophisticated models

# There are two types of ETGs

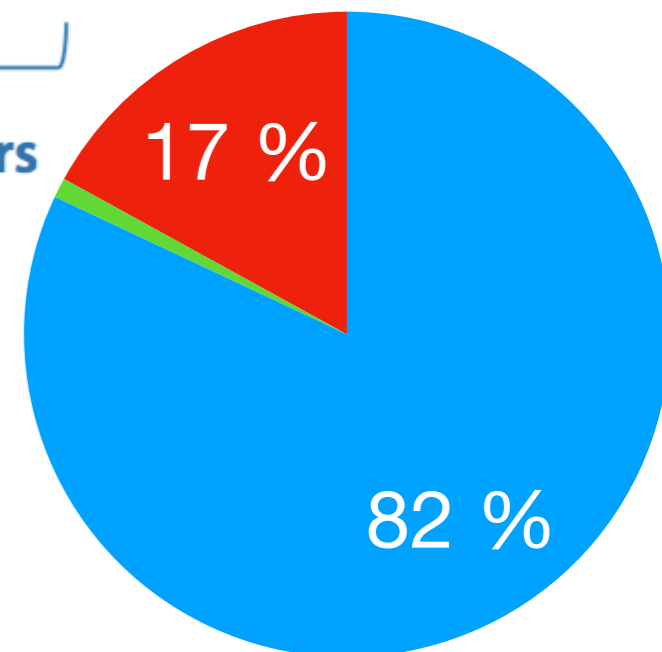
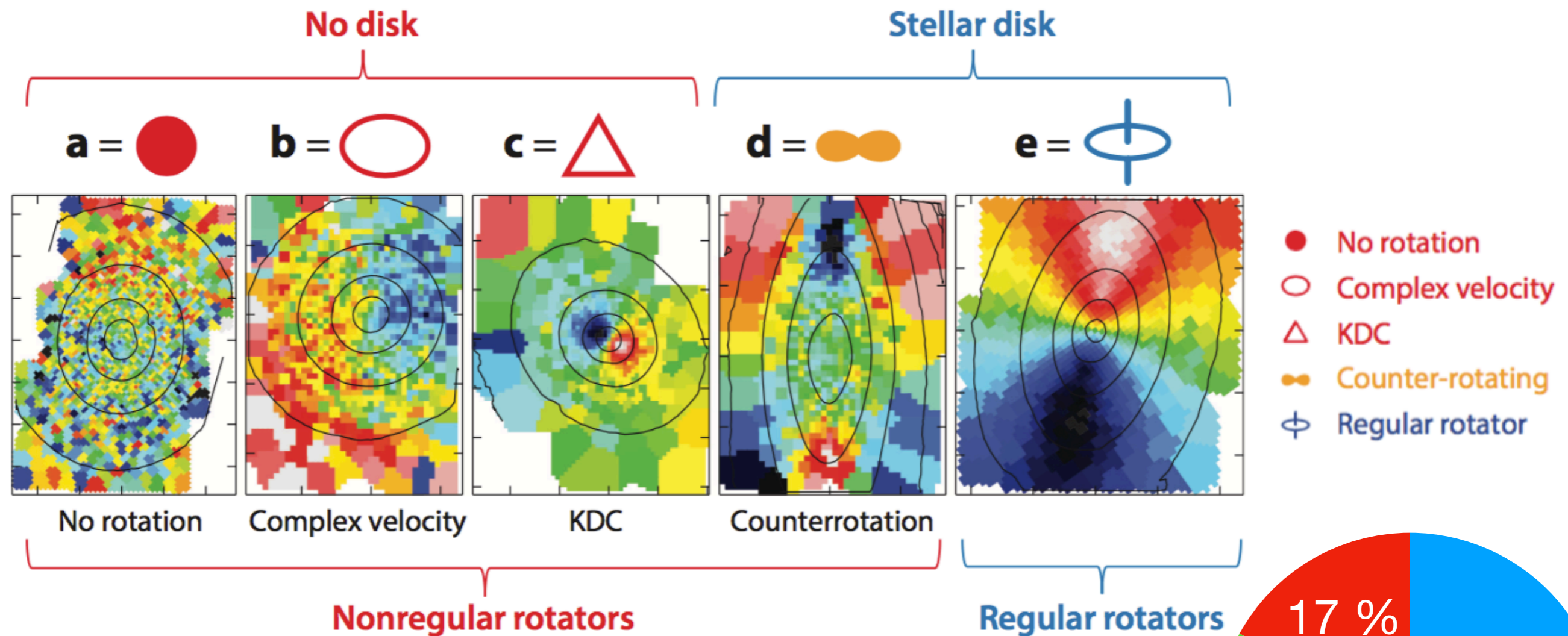
- dynamical studies of **massive galaxies** start with **stellar rotation curves**
  - from mid 70s (e.g. Bertola & Cappaccioli 1975, Illingworth 1977, Davies et al. 1983.....)
- **shapes** of massive galaxies are **not related to their rotation**
- **ellipticals** (as a class) are **not oblate** systems with **isotropic** velocity ellipsoids
  - **high  $V/\sigma$**  : fainter, diskly ellipticals --> isotropic (?)
  - **low  $V/\sigma$**  : bright, boxy elliptical --> anisotropic (?)
- Two problems:
  - limited data (**no IFU**)
  - **projection** effects



# Misleading shapes



# Stellar kinematics with IFUs

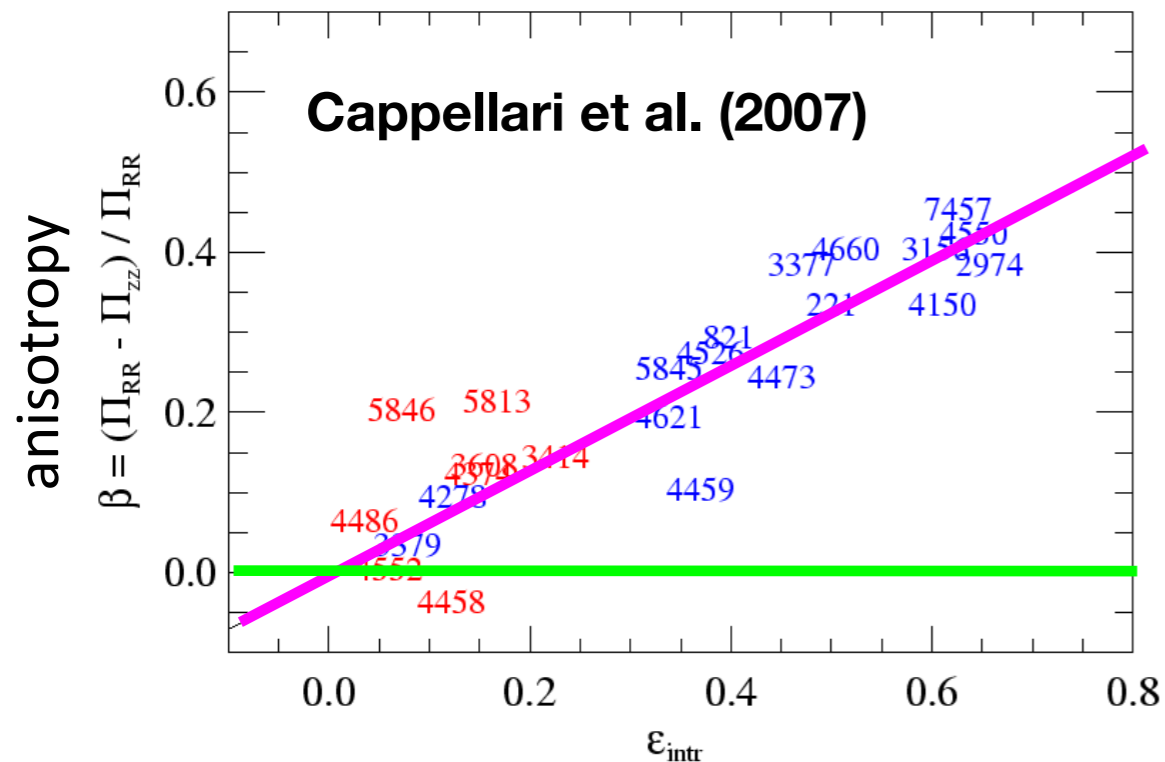


- a magnitude limited sample of ETG
- majority of ETGs show **regular rotation** -- boring (like disks)
- others have **non-regular rotation** -- exciting (KDC, counter rotation, no rotation)

Krajnović et al. 2008, 2011 (top image from Cappellari 2016, ARAA)

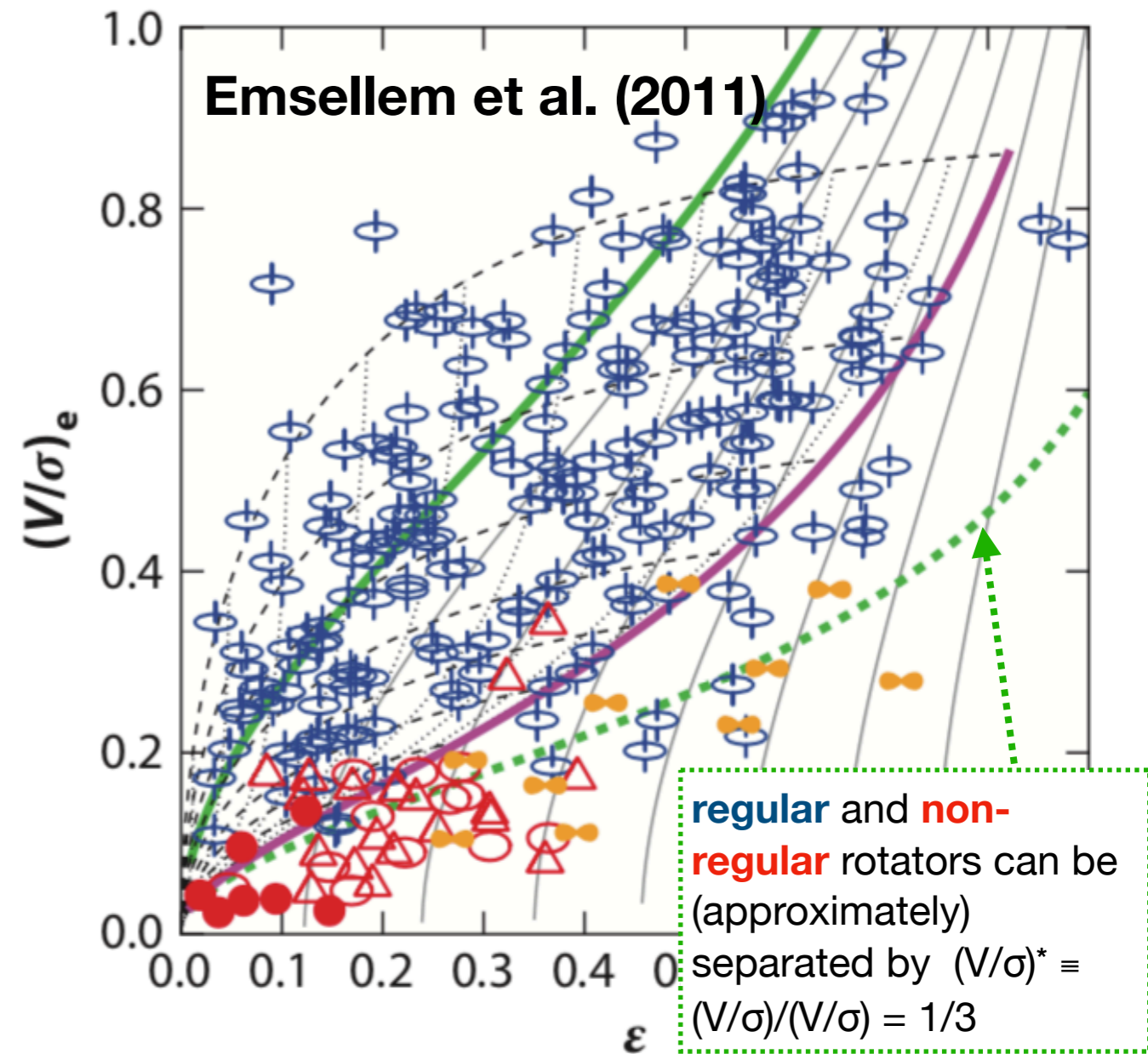
# Dynamical modelling to the rescue!

$$(V/\sigma)_e^2 \equiv \frac{\langle V^2 \rangle}{\langle \sigma^2 \rangle} \quad \text{Use new formalism for IFU kinematics (Binney 2005)}$$



**Anisotropy trend based on dynamical models and IFU kinematics.**

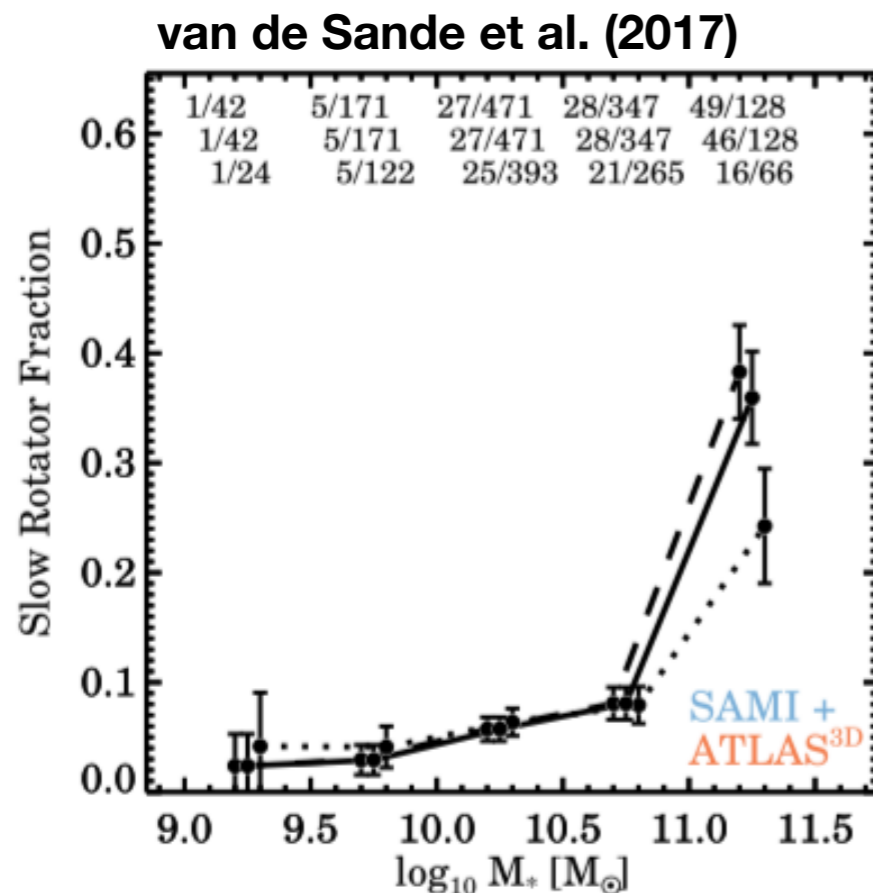
**The power of  $(V/\sigma, \epsilon)$  diagram**



- **regular** and **non-regular** rotation is the crucial distinction between galaxies
- **regular rotators** span a large range of anisotropies
  - they are **not isotropic**, but fall close to the isotropic line due to **projections**!

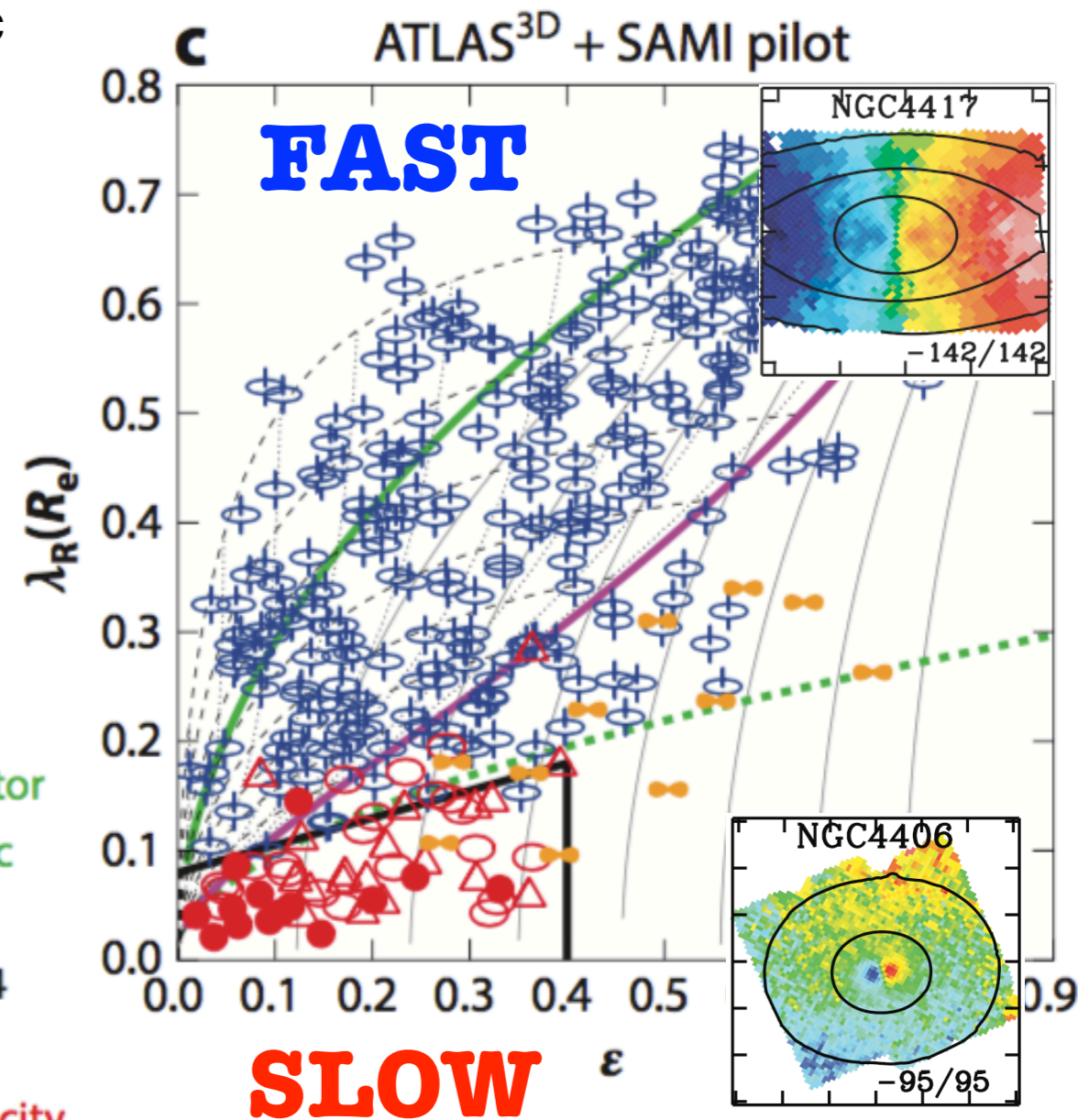
# A physical way of classifying galaxies

- **difference** in kinematics is quantifiable by the specific **stellar angular momentum**
- **Fast rotators** - high angular momentum and **regular** rotation
- **Slow rotators** - low angular momentum and **non-regular** rotation
- strong **dependance on mass** (and environment?)



$$\lambda_R \equiv \frac{\langle R|V| \rangle}{\langle R\sqrt{V^2 + \sigma^2} \rangle}$$

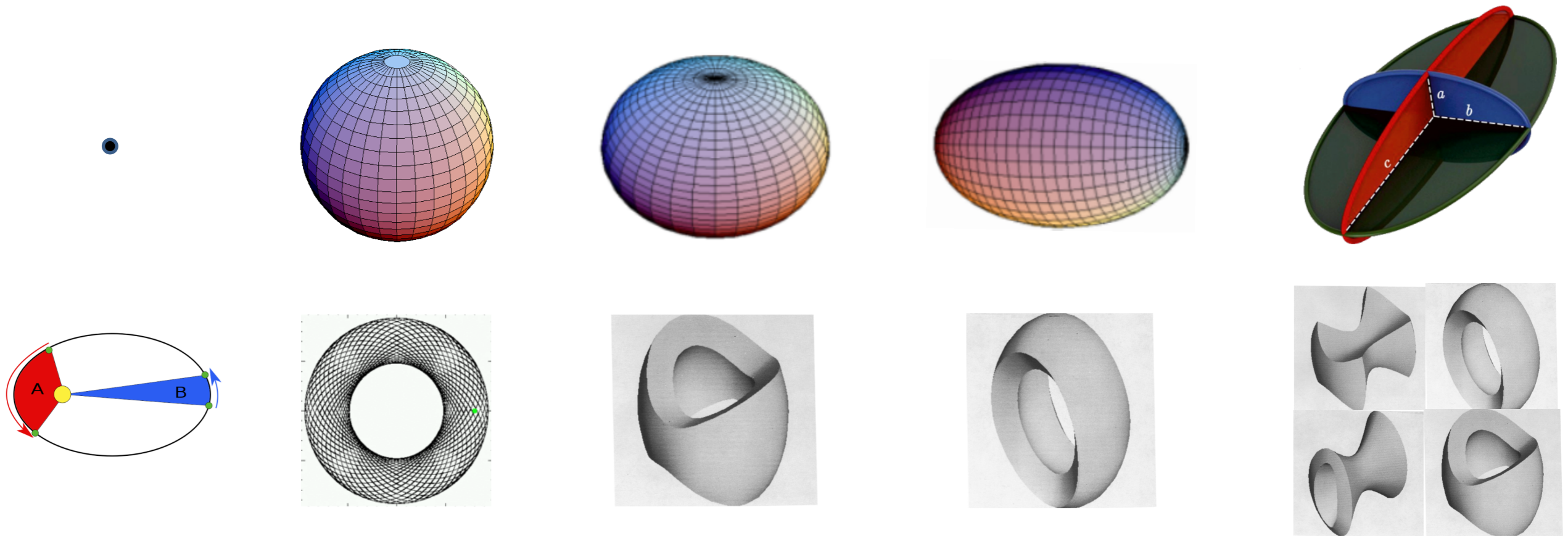
- Isotropic rotator
- - - 1/3 × isotropic
- $\delta = 0.7 \times \varepsilon_{\text{intr}}$
- $\lambda_R = 0.08 + \varepsilon/4$
- No rotation
- Complex velocity
- △ KDC
- ⊞ Counter-rotating
- ⊕ Regular rotator



Emsellem et al. 2007, 2011 (image from Cappellari 2016, ARAA)

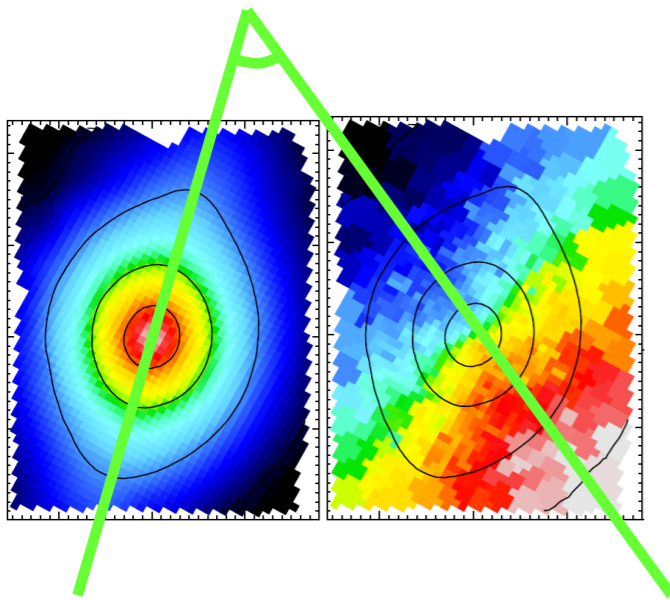
See also Graham et al. (2018) for MANGA version with >2500 galaxies

# The importance of shape - orbital structure

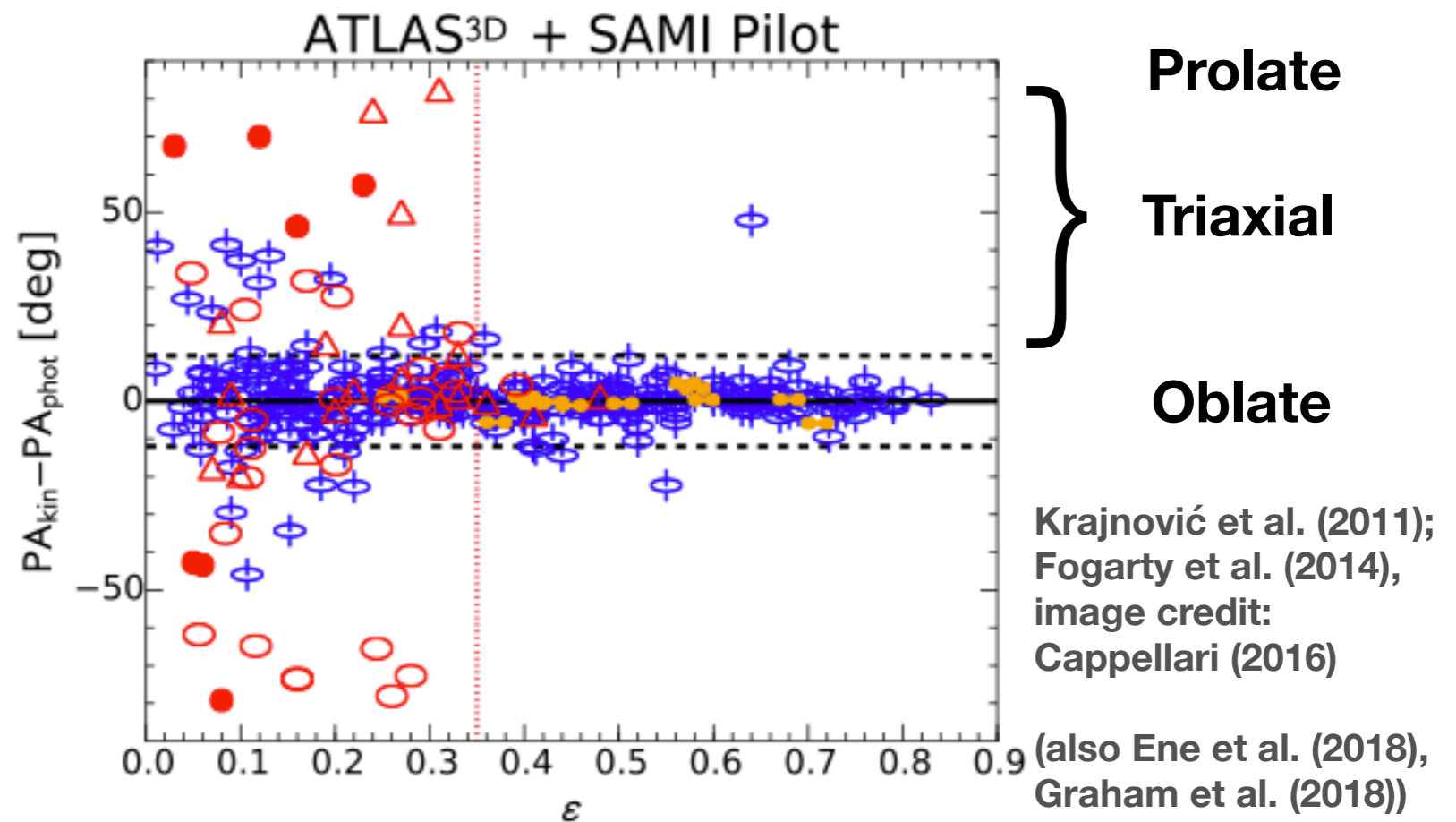


- **simple potentials** have **simple orbits**, e.g. point mass: ellipses
- **axisymmetric**: 1 major orbital family: **short axis tubes** (SAT)
- **prolate**: 1 major orbital family: **long axis tubes** (LAT)
- **triaxial**: **3 major orbital families**: short (SAT) and long axis tubes (ILAT, OLAT) and box orbits (no angular momentum) (e.g. de Zeeuw 1984)

# Kinematic misalignment

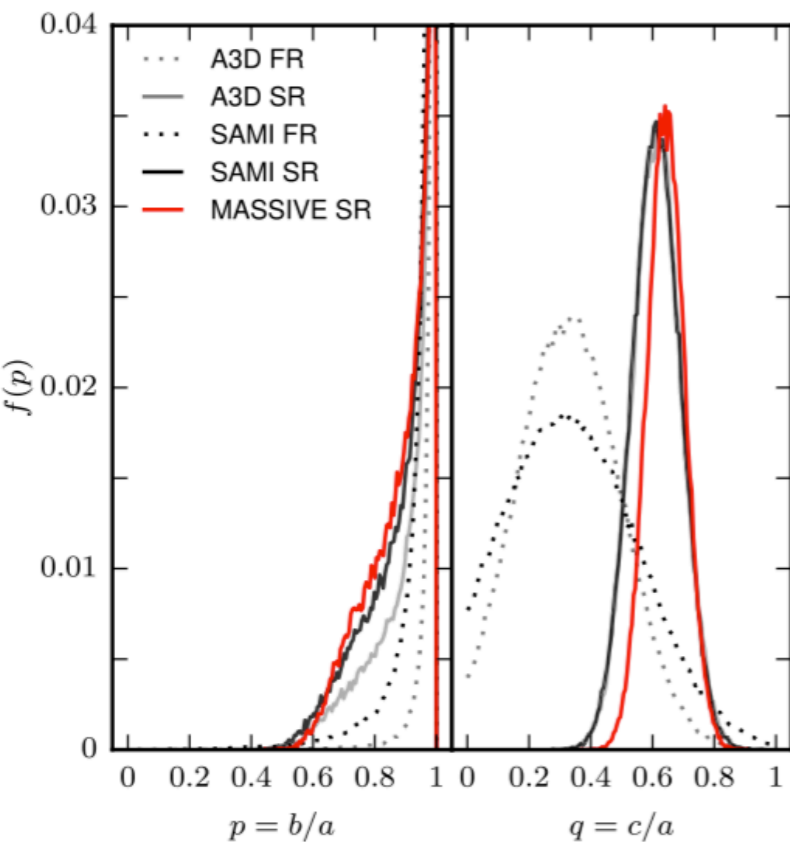


- **regular rotation:** aligned  $\rightarrow$  nearly axisymmetric systems (+ bars or interacting)
- **non-regular rotation:** (also) misaligned  $\rightarrow$  triaxial systems

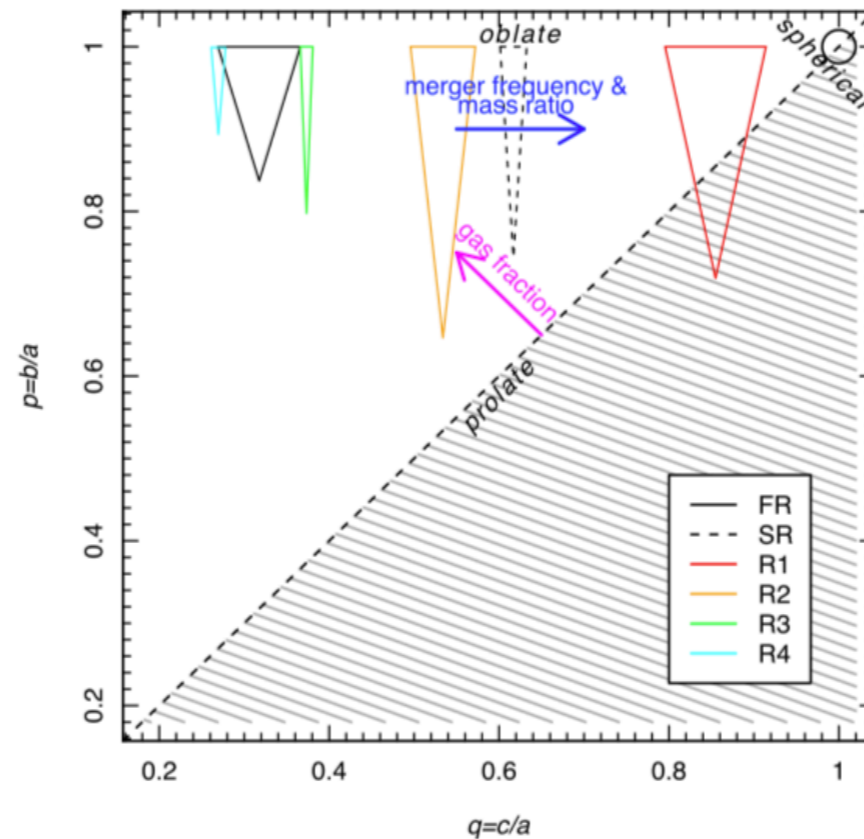


- misalignment between photometry and kinematics is only possible in **triaxial systems**
- majority of galaxies are consistent with being **oblate and axisymmetric**

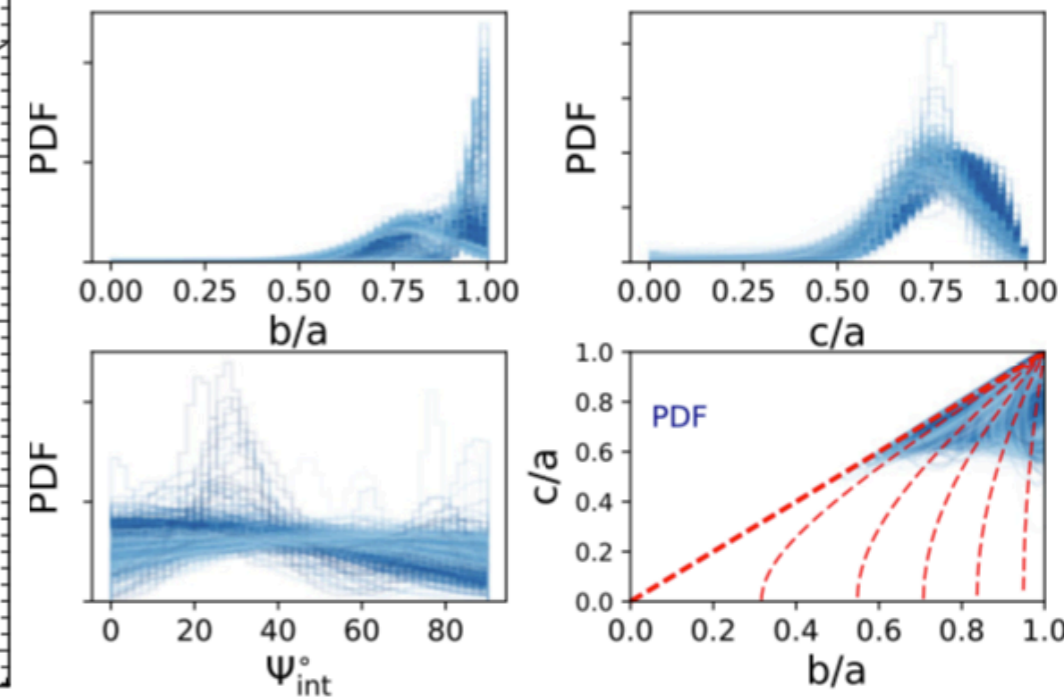
# Intrinsic shape



Ene et al. (2018) - MASSIVE  
Weijmans et al. (2014) - ATLAS<sup>3D</sup>



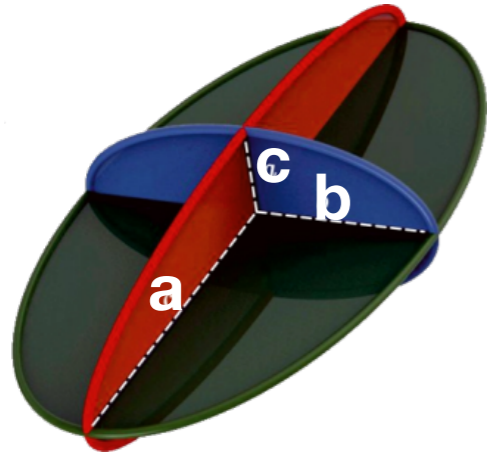
Foster et al. (2017) - SAMI



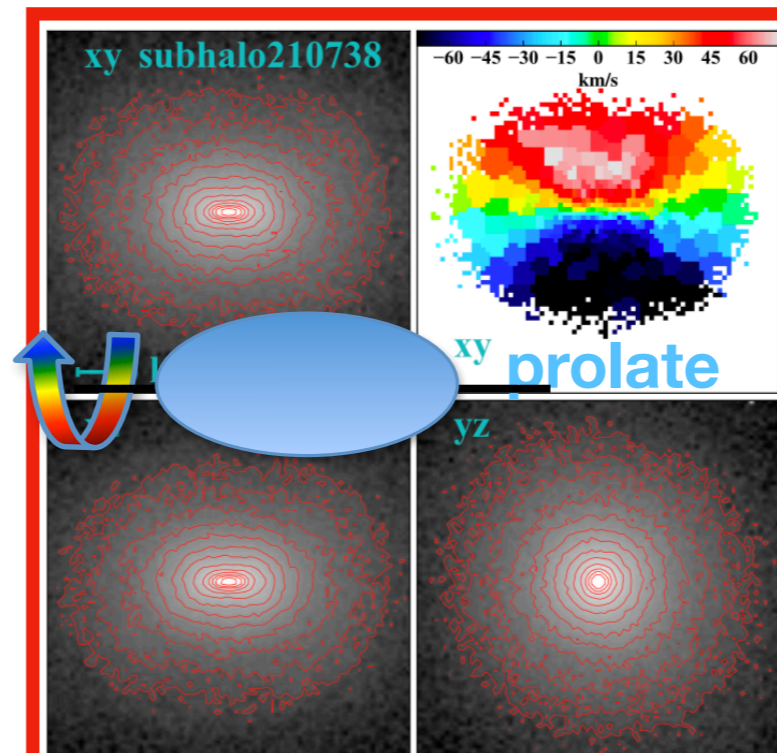
Li et al. (2018)- MaNGA

- **fast rotators** are **oblate axisymmetric** systems
- **slow rotators** are mostly **triaxial**, but can also be **oblate**, and relatively **round**, and there is evidence for a **prolate population**
- more **massive galaxies** are more likely to be **triaxial**?
- are massive galaxies **prolate**?

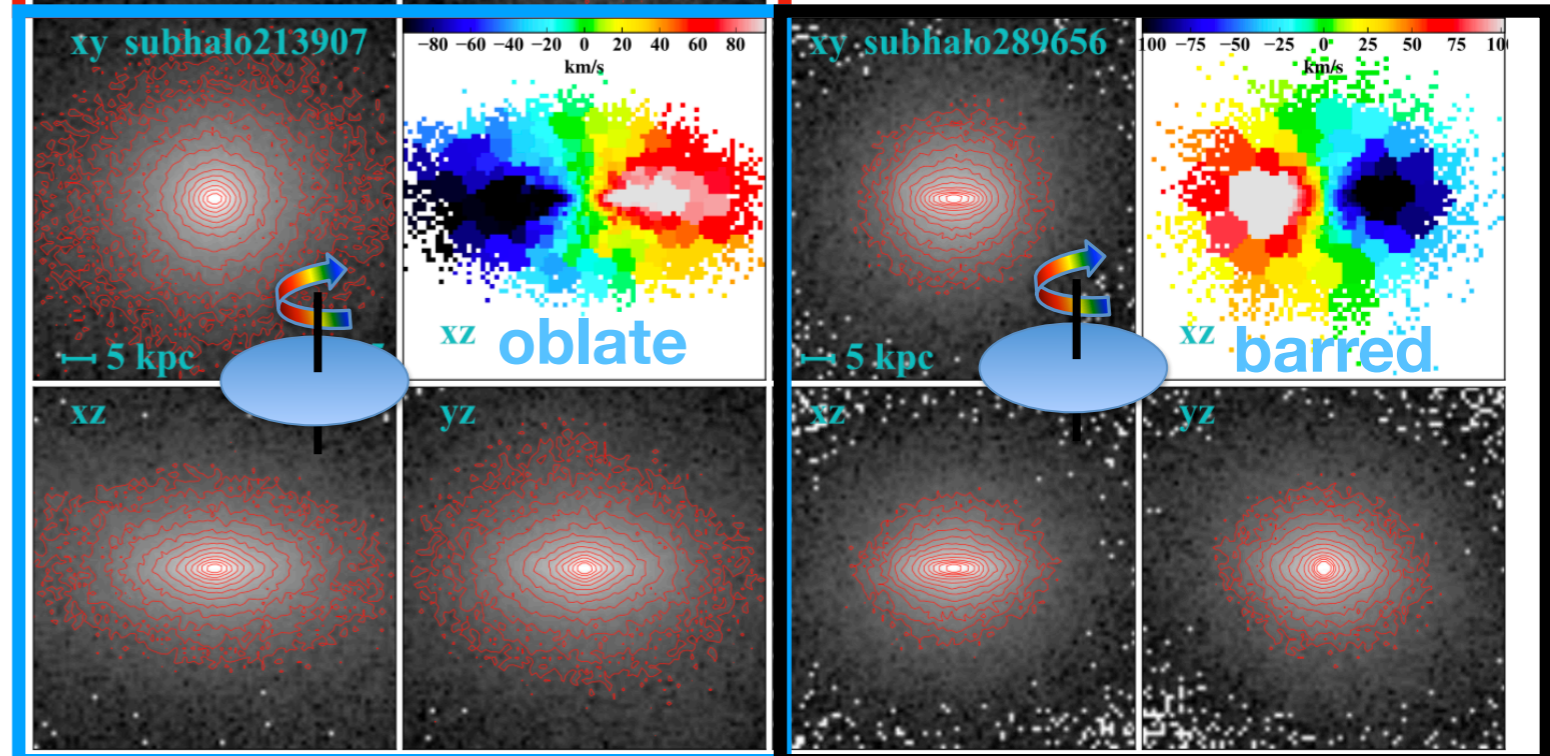
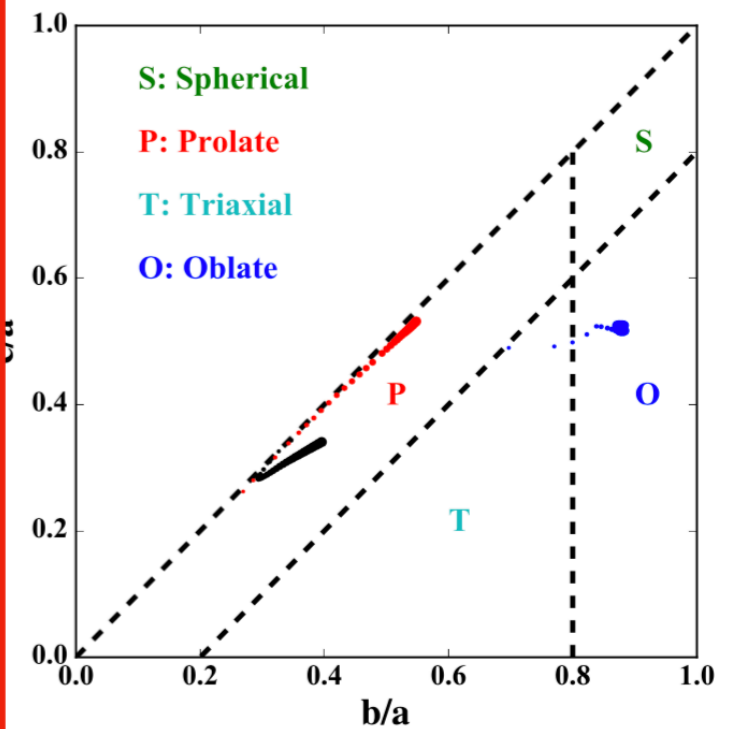
# What is a prolate galaxy?



- prolate and oblate galaxies can be mistaken in projection
- prolate is defined as  $c=b < a$
- bars are  $\sim$  prolate
- combination of kinematics and shape can help
  - only for those galaxies that show rotation!

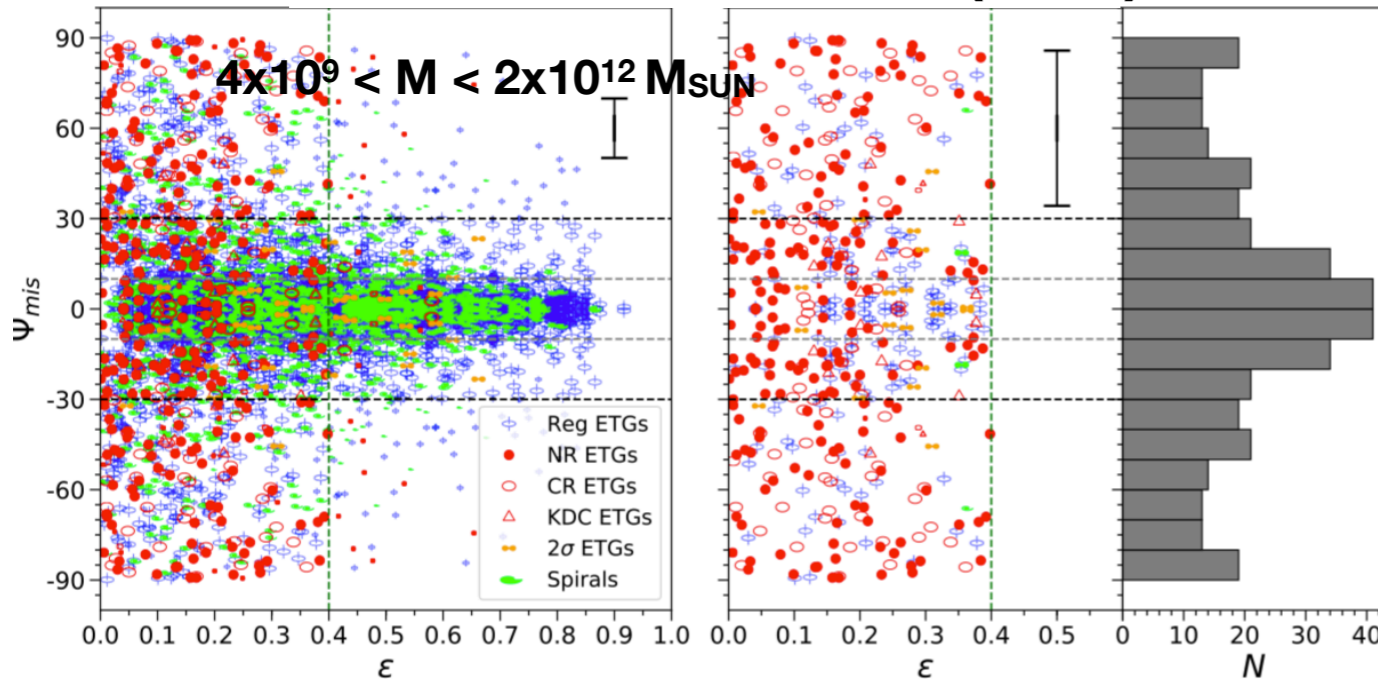


Honguy Li et al. (2017)

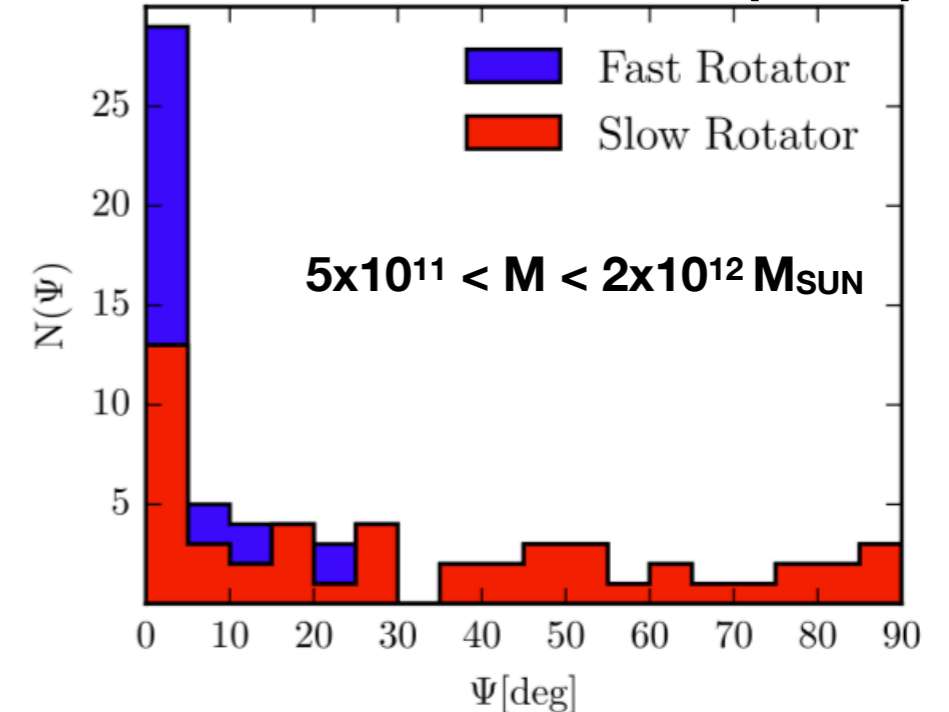


# Are there prolate galaxies?

MaNGA: Graham et al. (2018)

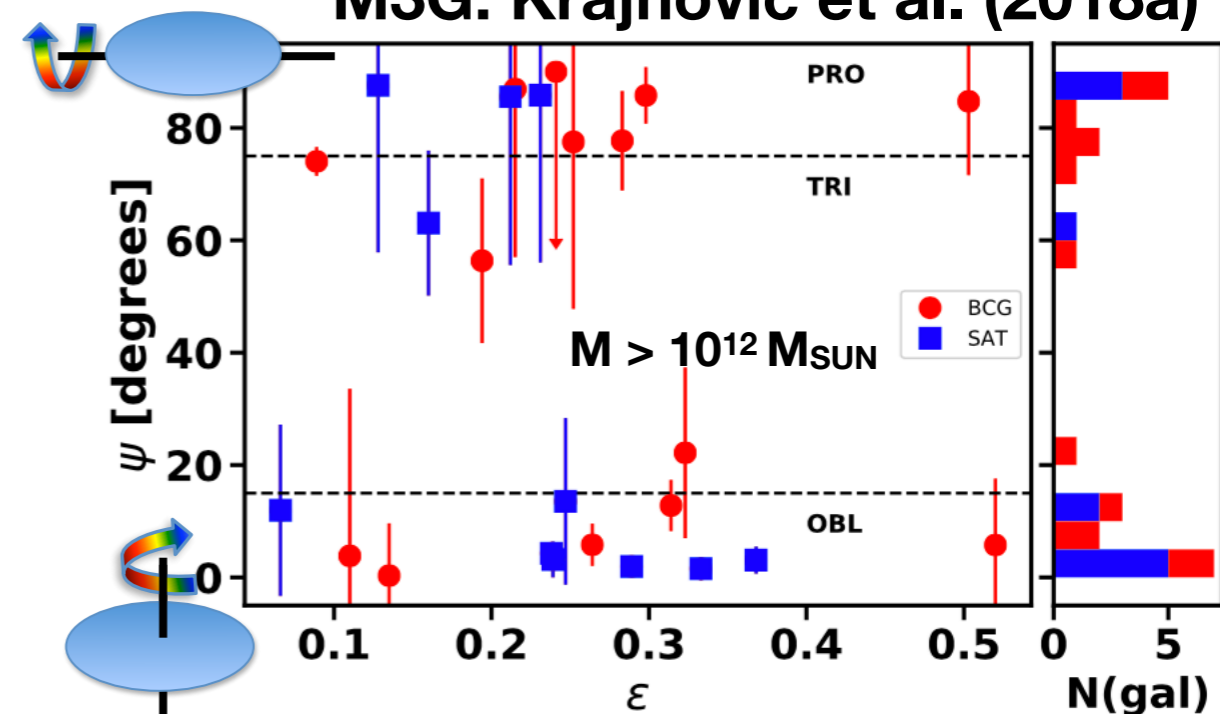


Massive: Ene et al. (2018)



- galaxies consistent with being prolate (or exhibiting prolate-like rotation) exist (e.g. Schechter & Gunn 1979; Wagner et al. 1988; Krajnović et al. 2011; Falcon-Barroso et al. 2017, Tsatsi et al. 2017...)
- more massive - more likely to be prolate**
- strong effect for  $> 10^{12} M_{\text{SUN}}$

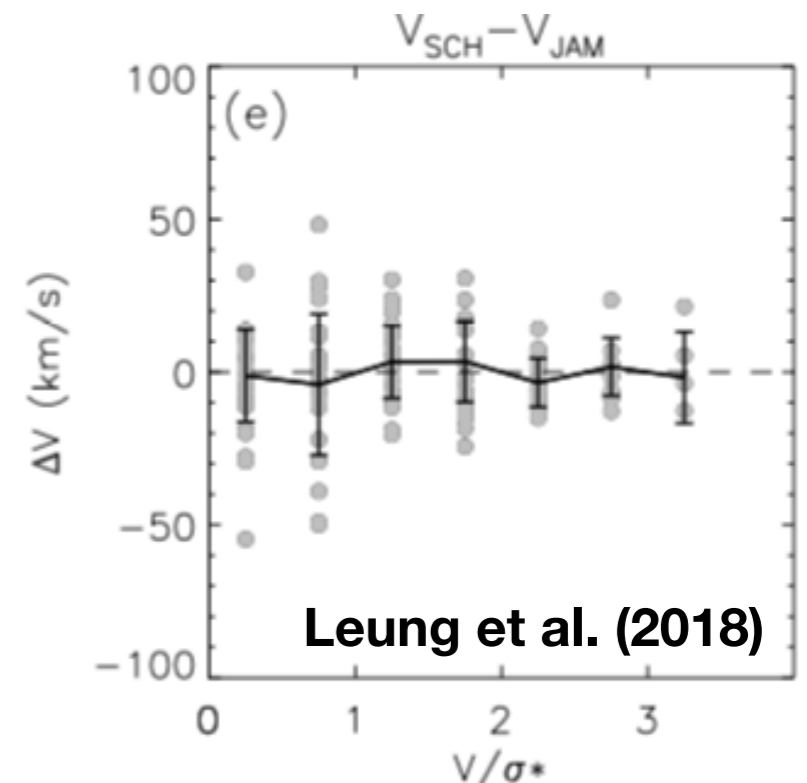
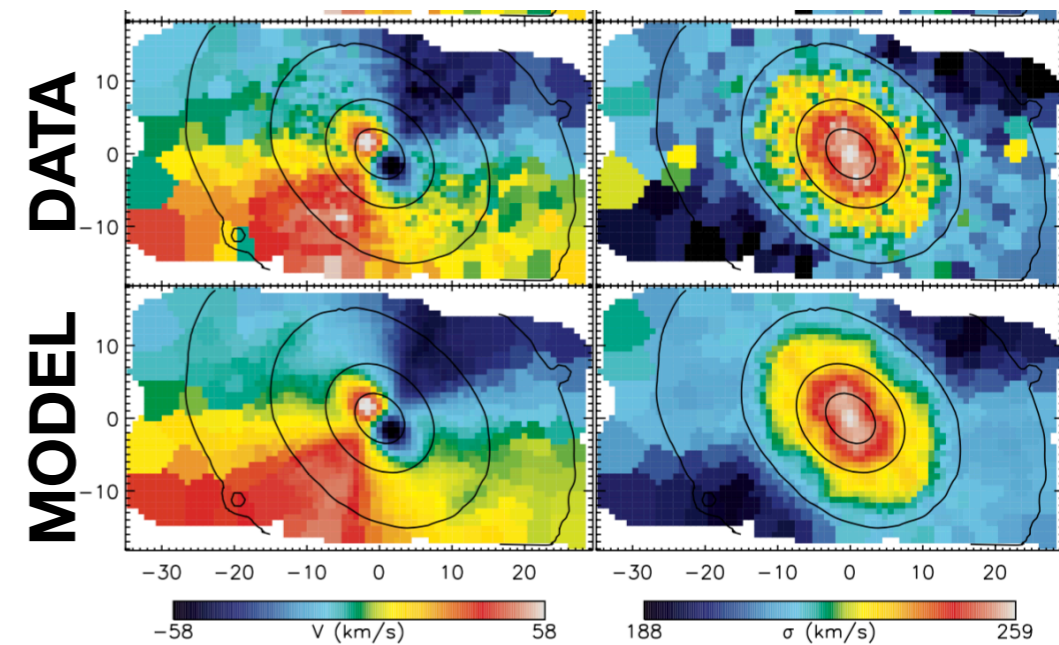
M3G: Krajnović et al. (2018a)



# Dynamics of galaxies

- **mass** of a galaxy **can not be measured**, only **estimated** using **dynamical models**
- actually, we get a handle on **mass - to - light ratio (M/L)** only!
- simple estimate: **Virial theorem**
- complex models
  - integrating **distribution functions** (e.g. Dejonghe & Merritt 1992)
  - based on **Jeans equations** (e.g. van der Marel et al. 1994; Cappellari 2008)
  - based on **integration of orbits**
    - averaging observables over an orbit - Schwarzschild (1979) method (e.g. Rix et al. 1997, Cappellari et al. 2006, Thomas et al. 2007...)
    - continuously updating the observables - made-to-measure (Syer & Tremaine 1996, de Lorenzi et al. 2007...)
  - good agreements between most common methods(!)
    - JAM (Cappellari et al. 2008) & Schwarzschild models

van den Bosch et al. (2008)



Leung et al. (2018)

# The need for integral-field coverage

V

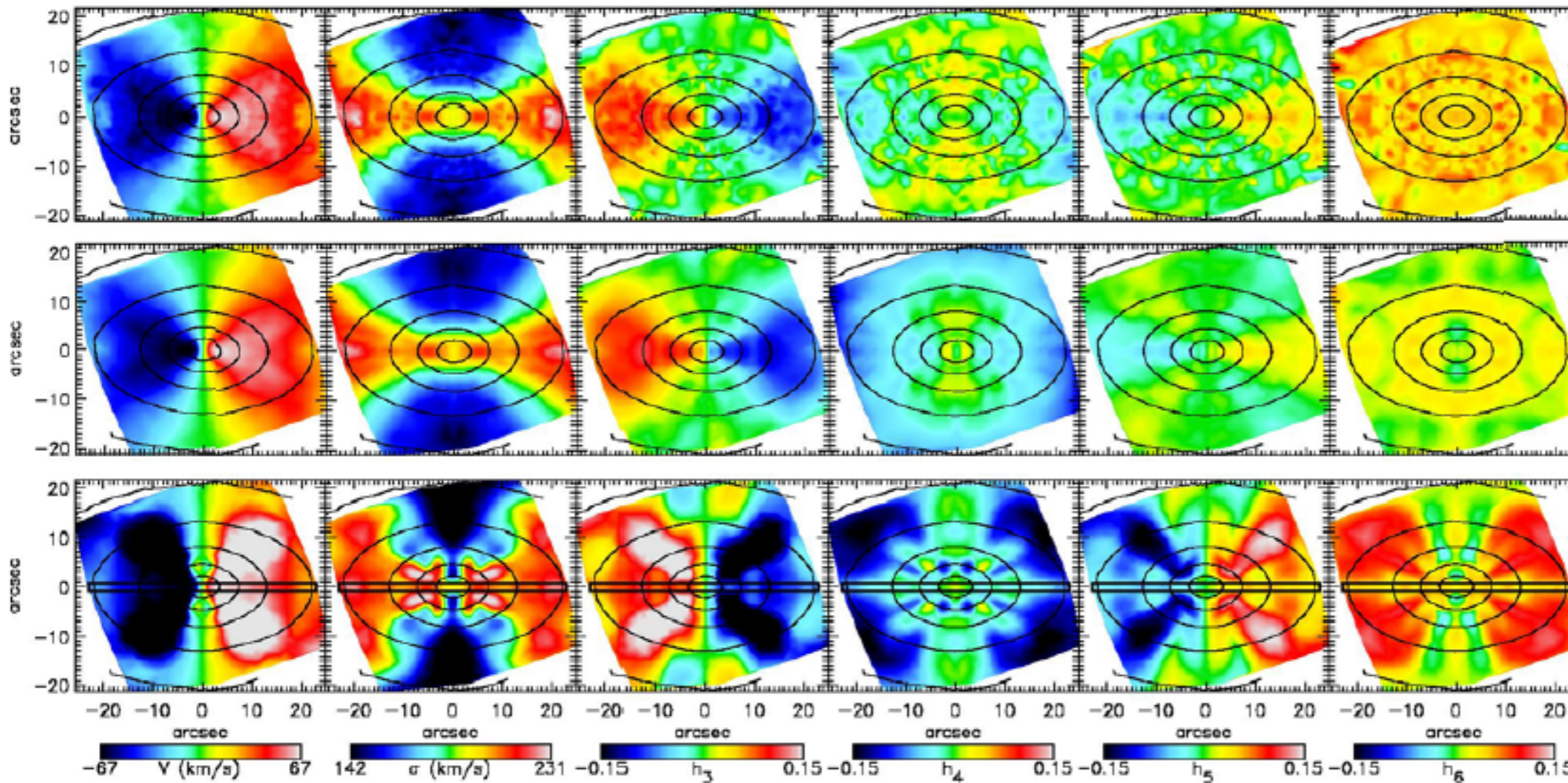
$\sigma$

$h_3$

$h_4$

$h_5$

$h_6$



Symmetrized  
SAURON data of  
NGC 4473

Best-fitting  
axisymmetric  
(Schwarzschild)  
model

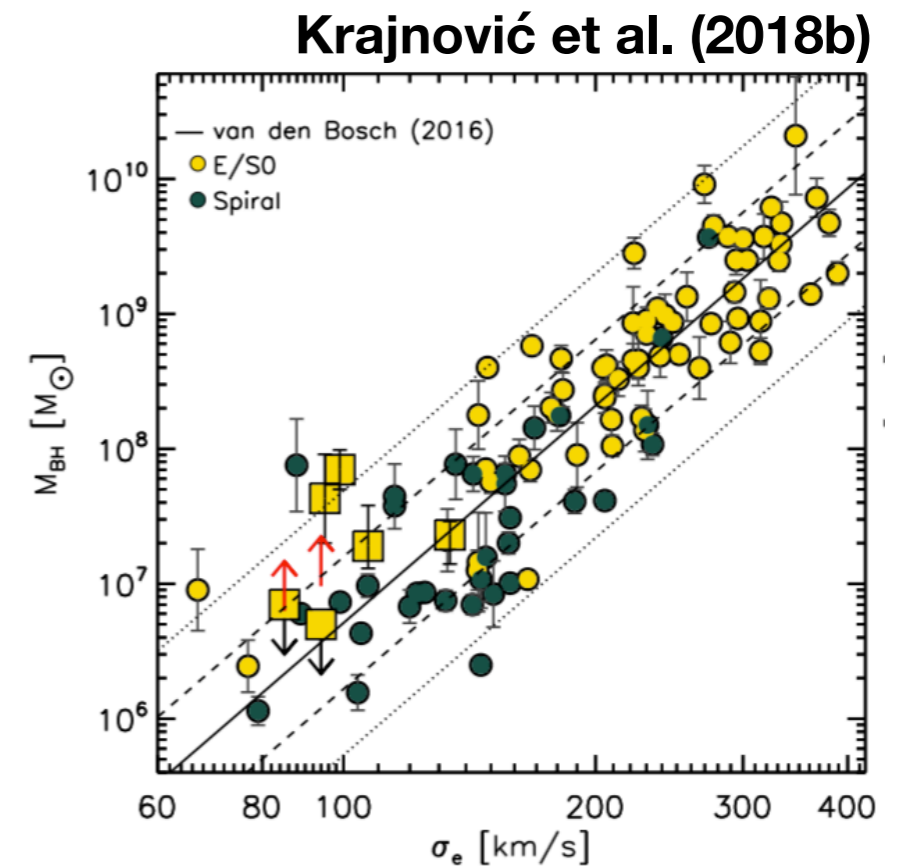
Model fit to long-  
slit only

McDermid & Cappellari (2005)

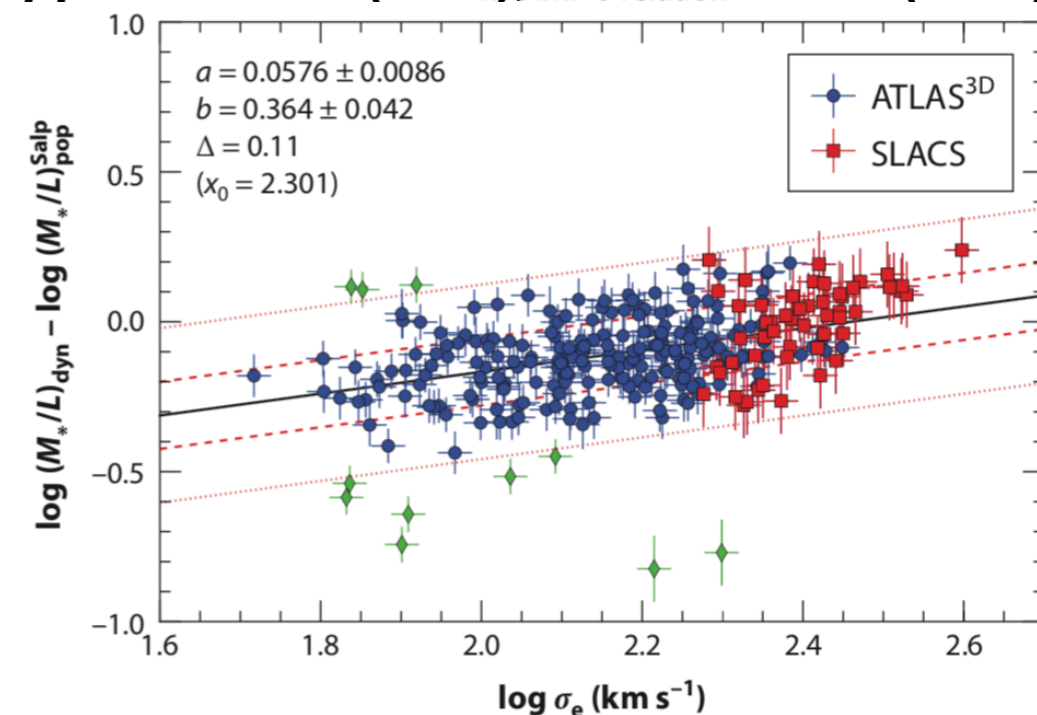
- Dimensional argument: the **distribution function is 3D**  $\rightarrow$  need **3D data**
- Little can be recovered of the true galaxy dynamics from single long-slit data

# Application of dynamical modelling

- Understanding the **internal structure** of galaxies (Binney 1975; Binney & Mamon 1982; de Zeeuw et al. 1985; Thomas et al. 2004; Krajnović et al. 2005, van de Ven et al. 2008, Yildirim et al. 2017)
- measuring **masses of SMBH** (i.e  $M_{\text{BH}}$  -  $\sigma$  relation; (e.g. Gebhardt et al. 2003, Gültekin et al. 2009, Rusli et al. 2013; Krajnović et al. 2018b; Kormendy & Ho 2013)
- **IMF** and/or **DM** fraction (e.g. Cappellari et al. 2013, Posacki et al. 2015; Poci et al. 2017)
- moving from **light** to **mass**, improvement on the **scaling relations**
- **total density profiles** of spirals and ETGs (using kinematics of globular clusters or HI)



Cappellari et al. (2013); Posacki et al. (2015)



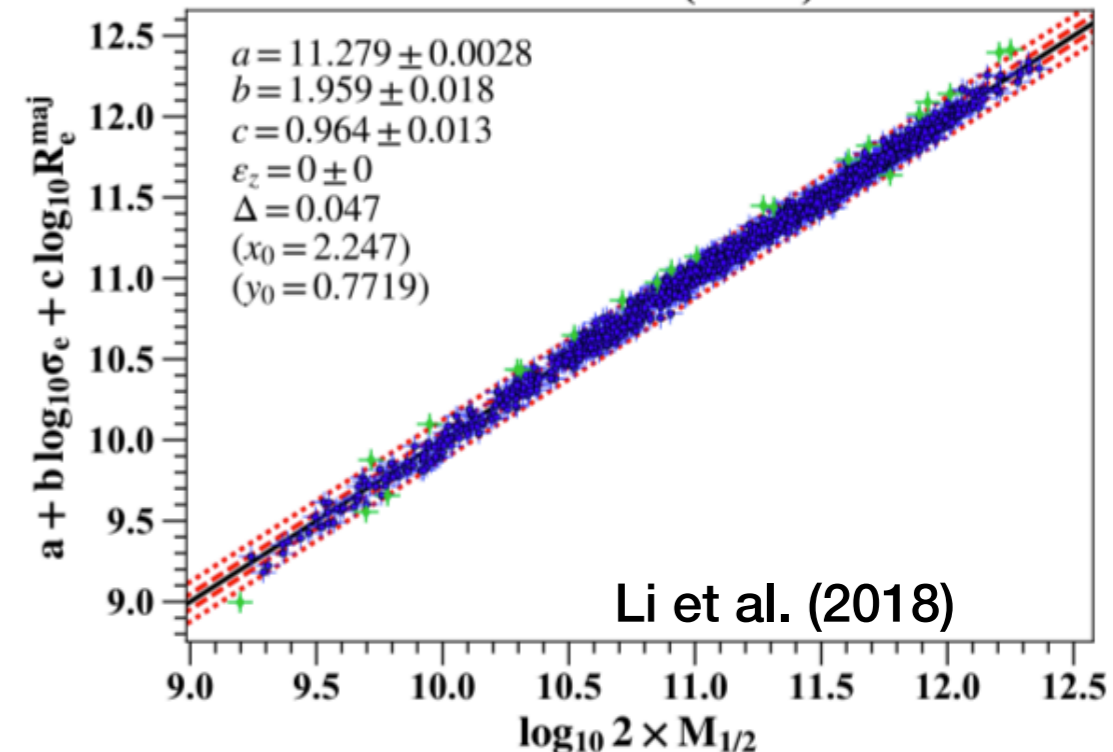
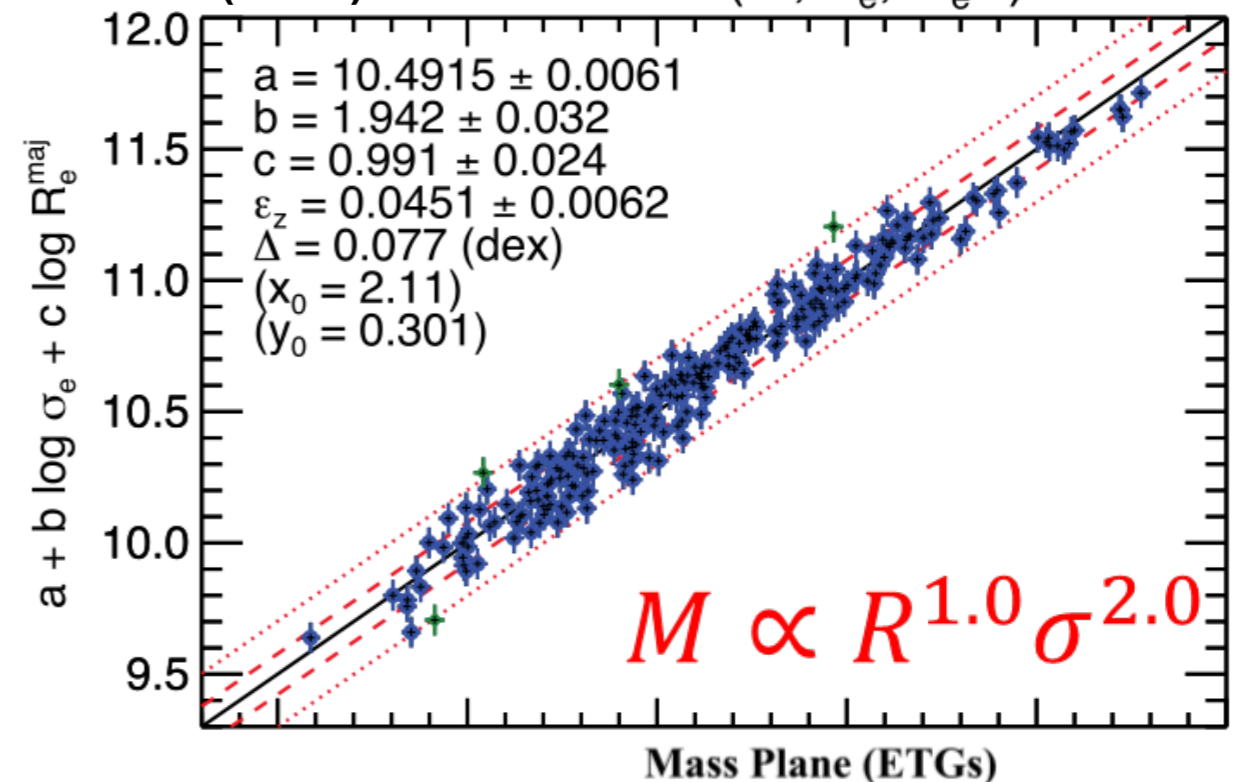
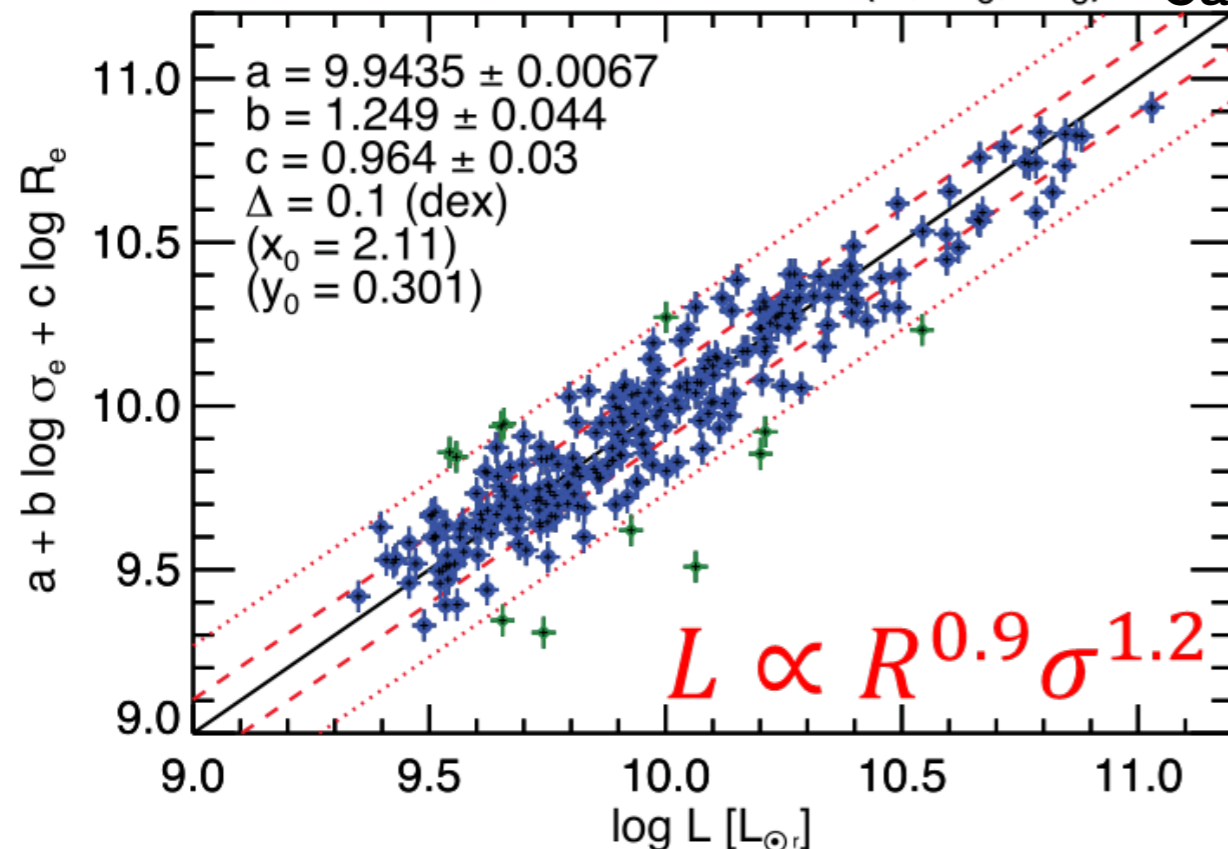
# Galaxies are virialized systems

Luminosity

Mass (dynamical models)

Fundamental Plane ( $L, \sigma_e, R_e$ )

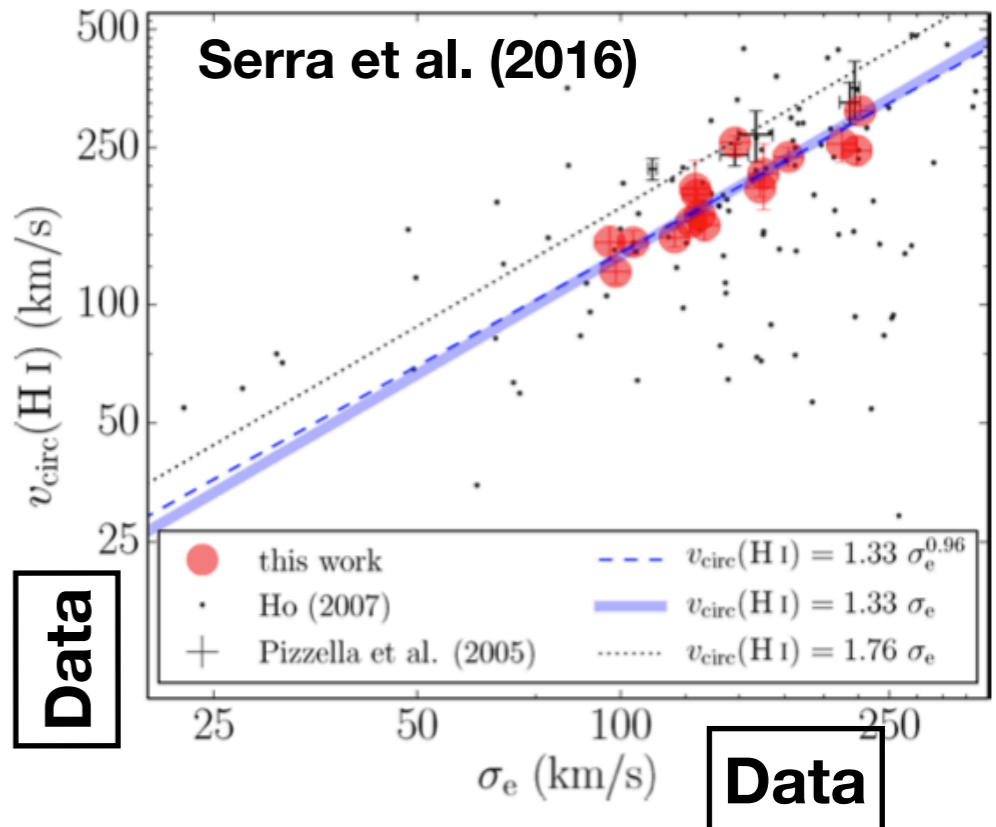
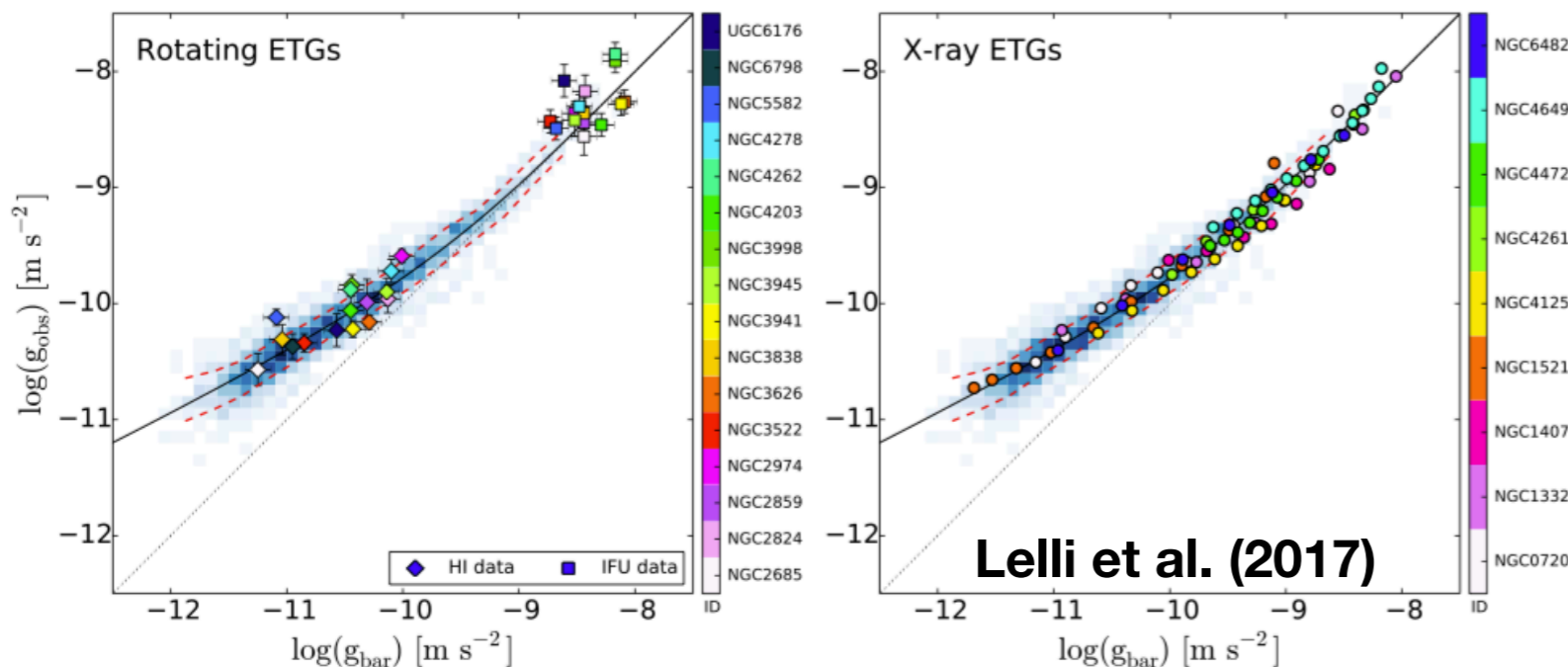
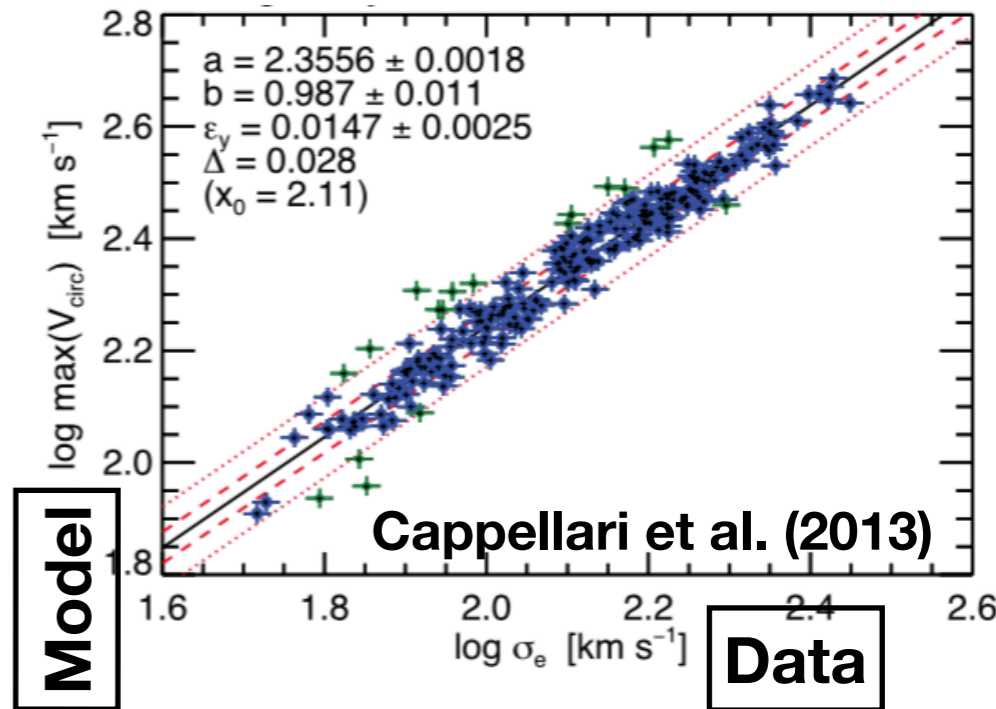
Cappellari et al. (2013) Mass Plane ( $M, \sigma_e, R_e^{\text{maj}}$ )



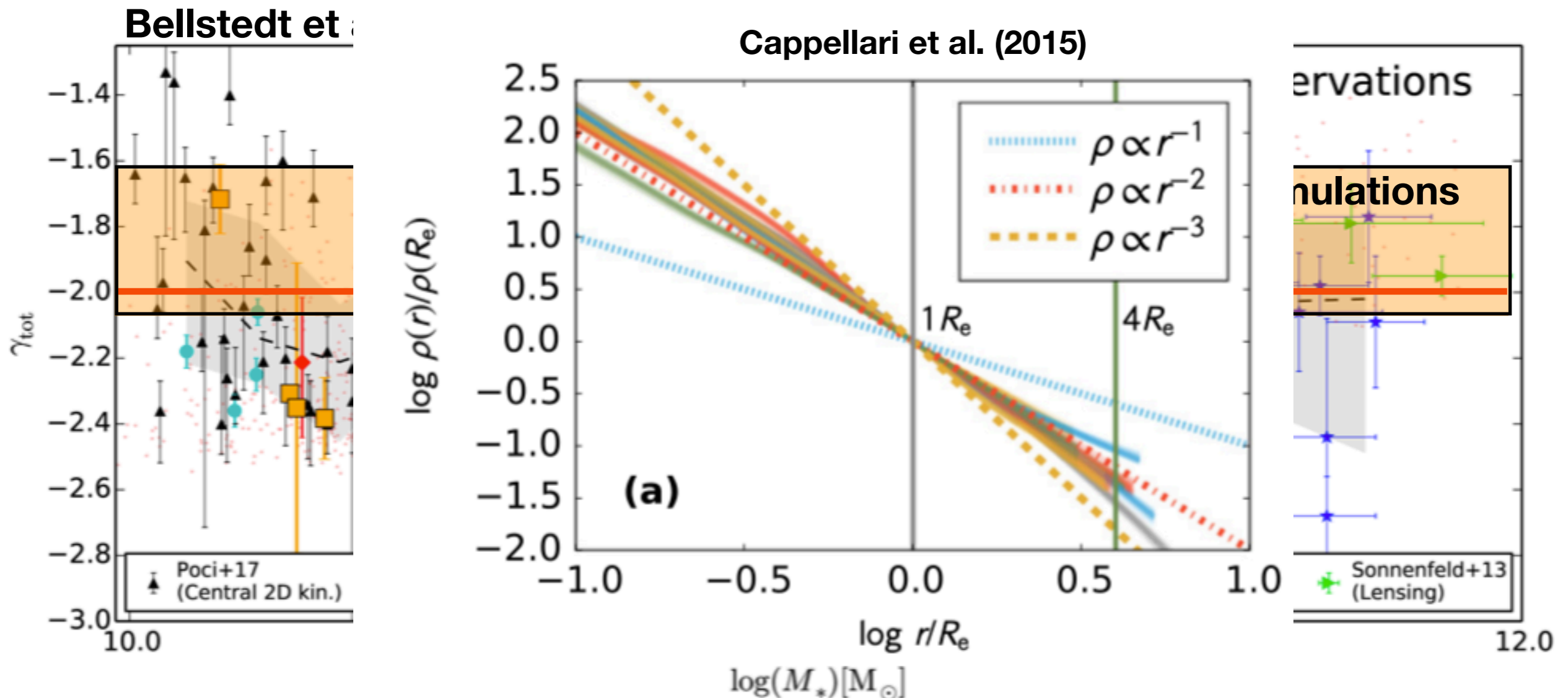
- once we have **good mass** estimates....
- **MP** has **no intrinsic scatter**: **FP tilt & scatter** due to stellar population variations
- galaxies follow **virial prediction** (Cappellari et al. 2006, 2013; Bolton et al. 2008; Auger et al. 2010)
- confirmed on large samples (MaNGA, Li et al. 2018)

# Linking spirals with ETGs

- **extending TFR to ETGs:** linking  $V_c$  vs  $\sigma_e$ 
  - $V_c$  as in spirals: asymptotic velocity
  - $V_c$  in ETGs measured at  $4 R_e$  (SLUGGS, ATLAS<sup>3D</sup>)
  - $\sigma_e$  - ETGs:  $\sigma_e = \sqrt{V^2 + \sigma^2}$
  - $V_c \sim 1.33 \times \sigma_e$  (Serra et al. 2016)
  - **linear relations:**  $L \sim V_c$ ,  $L \sim \sigma_e$
- **ETGs fall on the radial acceleration relation** (e.g. Lelli et al. 2017)



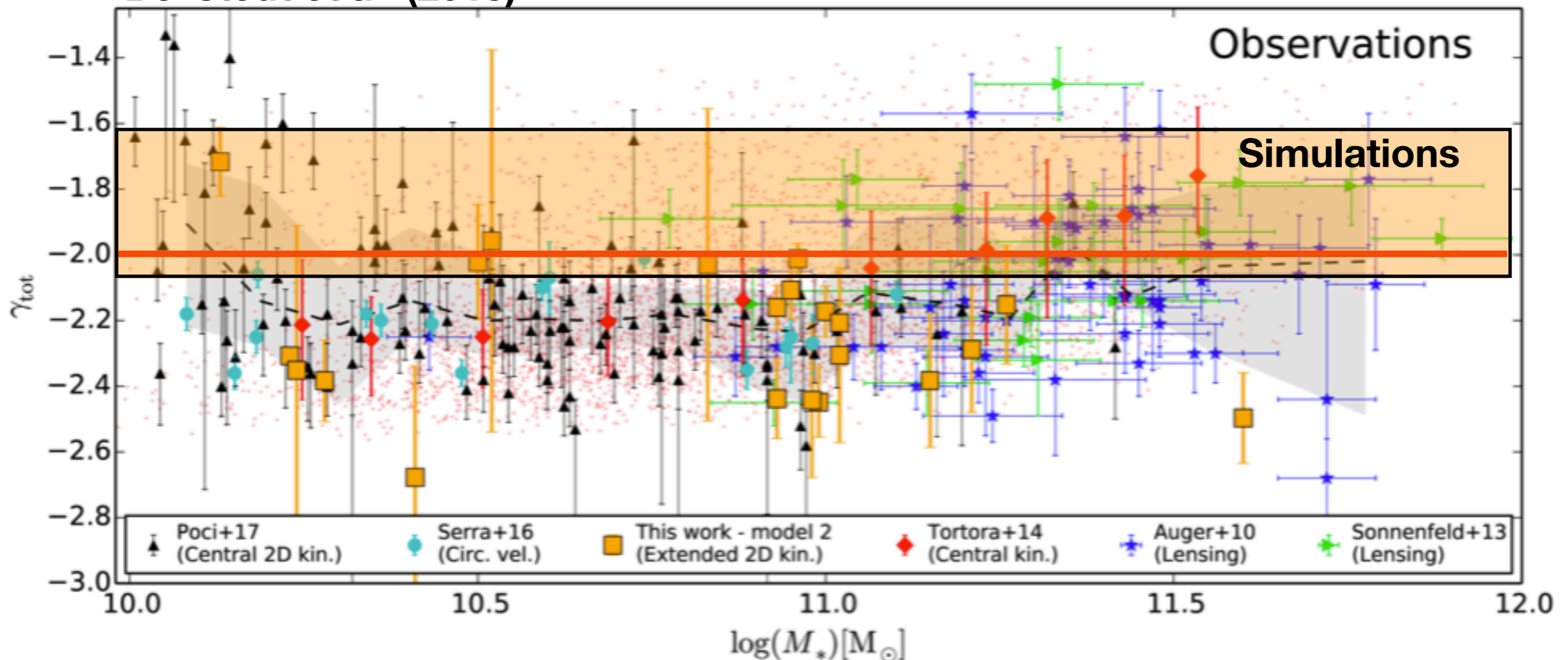
# Universal density slope?



- it is now possible to trace (some) ETGs to several effective radii (HI, globular clusters, PNe)
- dynamical models imply  $\gamma_{\text{tot}} \sim \mathbf{2.2}$  (e.g. Cappellari et al. 2015, Bellstedt et al. 2018), **steeper** than **isothermal** and **simulations**
- **no dependance** on **mass** (Serra et al. 2016, Bellstedt et al. 2018)

# Universal density slope?

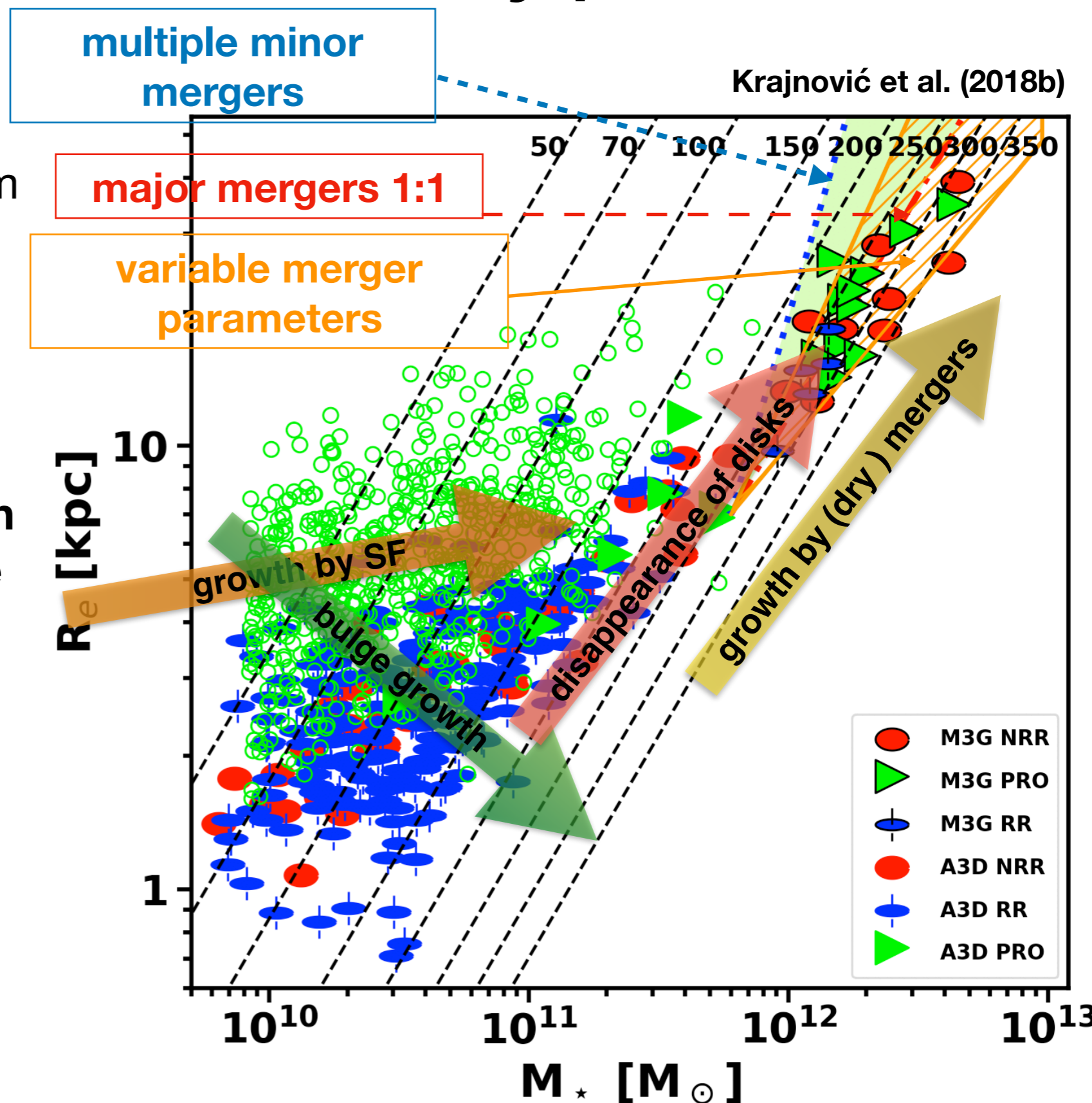
Bellstedt et al. (2018)



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# Constraining mass assembly processes

- massive galaxies **extend** from the bulk of galaxy population (ATLAS<sup>3D</sup> and M3G surveys)
- **occupy area** predicted for **dry major mergers**
- galaxies **grow** by **SF**, **quench** through the process of **bulge growth** (e.g. van Dokkum et al. 2015; Cappellari 2016)
- massive galaxies **lack disks**
- most massive galaxies ( $>10^{12}M_{\text{SUN}}$ ) **require dry major mergers**



# Dynamics of (local) massive galaxies

- **complex kinematics**
  - non-regular
- **complex shapes**
  - oblate-triaxial and prolate
- **do not have disks**
- old stellar pops, no (or little) star formation
- have cores in central light profiles
- located in dense environments
- **show multiple evidence for major dissipation-less merging**

