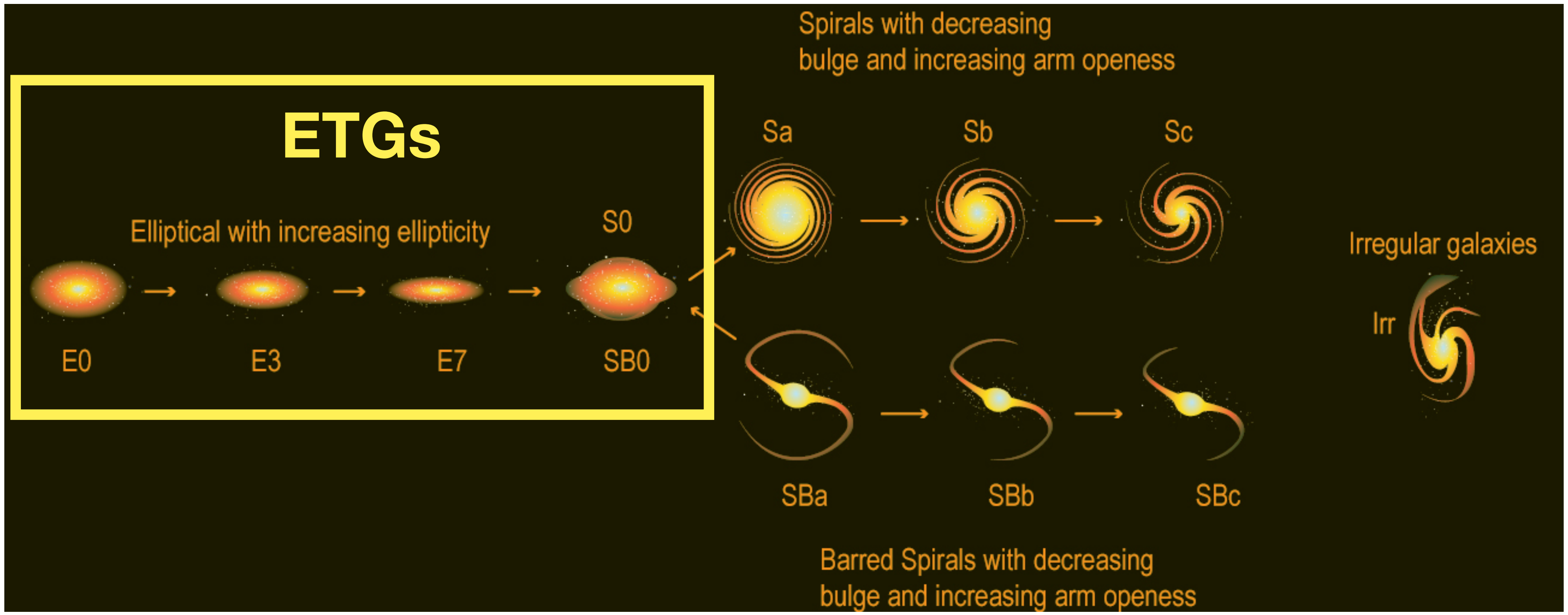
The specific angular momentum of ETGs

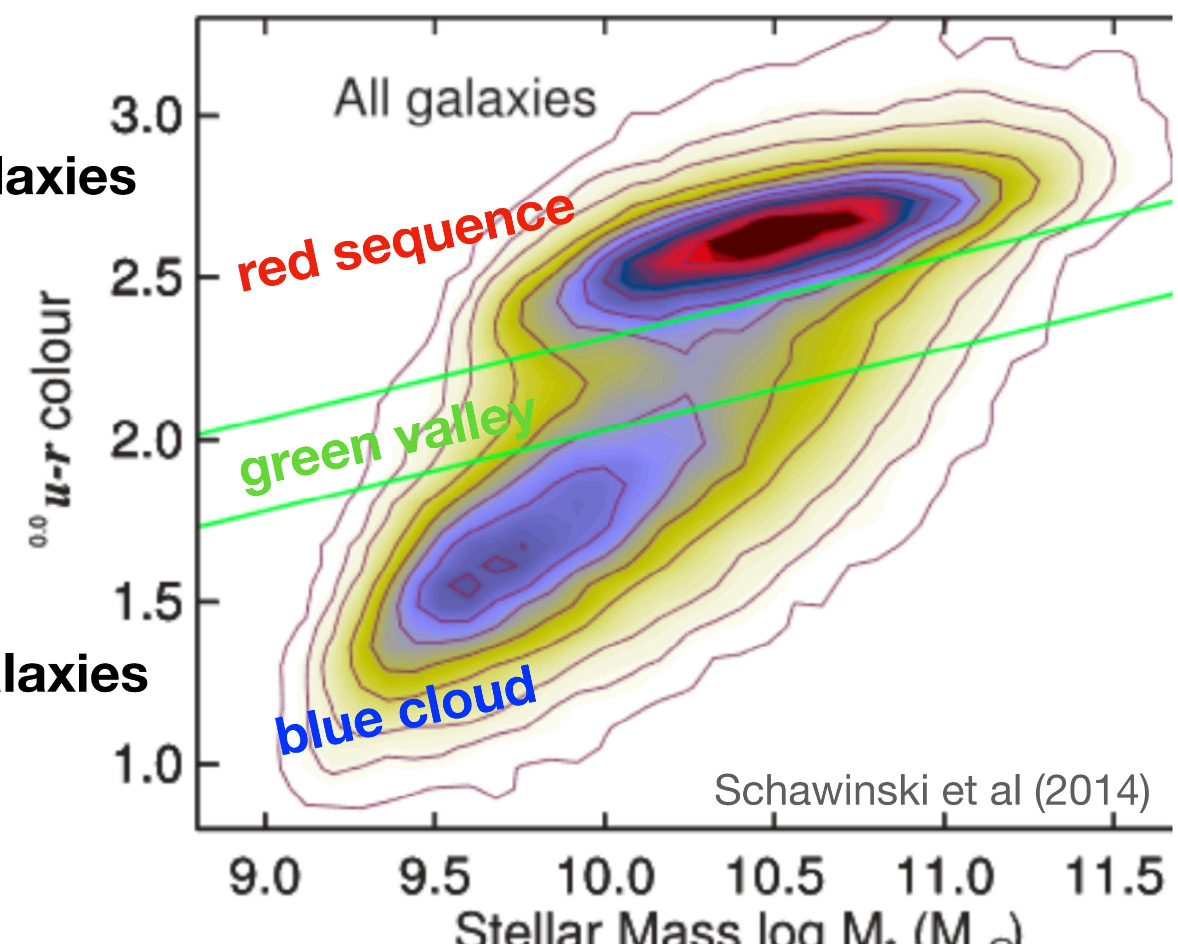
Claudia Pulsoni, Ortwin Gerhard, Michael Fall, Magda Arnaboldi, A. Ennis, J. Hartke, L. Coccato, N. Napolitano

Early Type Galaxies (ETGs)



Red galaxies

Blue galaxies



- Spheroidal with $n \gtrsim 4$ (+ disks)
- Dominate the population of massive galaxies at z=0
- Quiescent

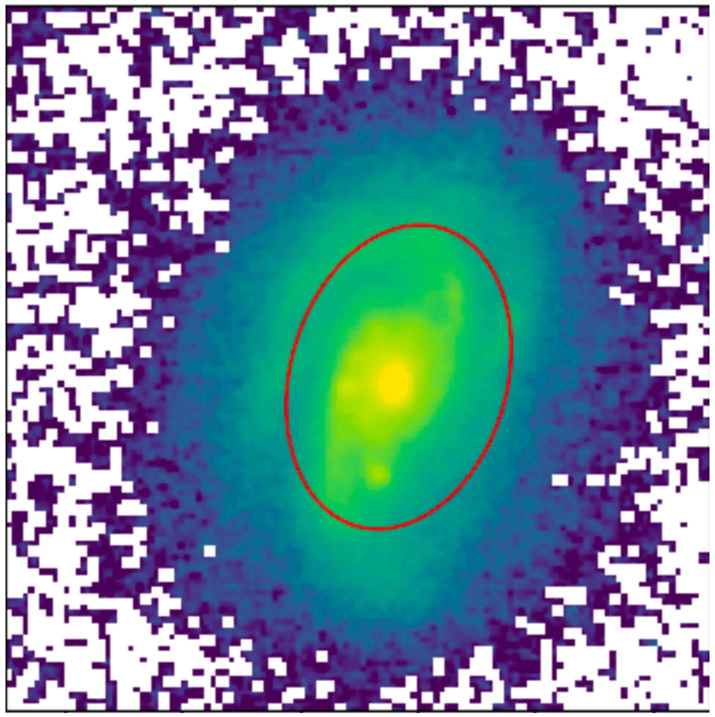
Galaxy angular momentum

$$\vec{J} = M\,\vec{r} \times \vec{v}$$

specific AM $$j_\star = \frac{|\overrightarrow{J_\star}|}{M_\star}\ [\mathrm{kpc\ km\ s^{-1}}]$$

$$= \frac{\int \overrightarrow{r} \times \overrightarrow{v_\star}(x,y,z)\ \rho_\star(x,y,z)\ dx\ dy\ dz}{\int \rho_\star(x,y,z)\ dx\ dy\ dz}$$

Effective radius, Re = encloses 1/2 of the total light



How do galaxies acquire AM?

- **Tidal torques induce dm halo angular momentum**

Halo specific angular momentum

$$j_h \equiv \frac{J_h}{M_h} \propto \left(\frac{M_h}{M_\odot} \quad \right)^{2/3} \mathrm{kpc\ km\ s^{-1}}$$

Peebles 1969

How do galaxies acquire AM?

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Halo specific angular momentum

$$\frac{j_*}{j_*} \; j_h \equiv \frac{J_h}{M_h} \propto \left(\frac{M_h}{M_\odot}\,\frac{M_*}{M_*}\right)^{2/3} \text{kpc km s}^{-1}$$

Peebles 1969

- **Galaxies “inherit” a fraction of the halo angular momentum**

retained fraction of AM

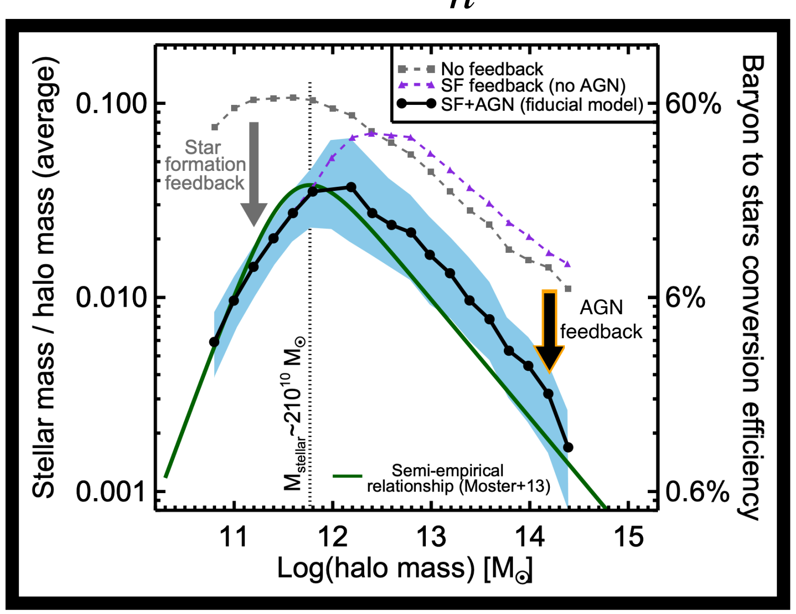
$$f_j \equiv \frac{j_*}{j_h}$$

star formation efficiency

$$f_* \equiv \frac{M_*}{M_h}$$

$$j_* \propto f_j \, f_*^{-2/3} \left(\frac{M_*}{M_\odot}\right)^{2/3} \text{kpc km s}^{-1}$$

Romanowsky & Fall 2012
Posti et al. 2018



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$$\frac{j_*}{j_*}\, j_h \equiv \frac{J_h}{M_h} \propto \left(\frac{M_h}{M_\odot}\frac{M_*}{M_*}\right)^{2/3} \text{kpc km s}^{-1}$$

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$$f_j \equiv \frac{j_*}{j_h}$$

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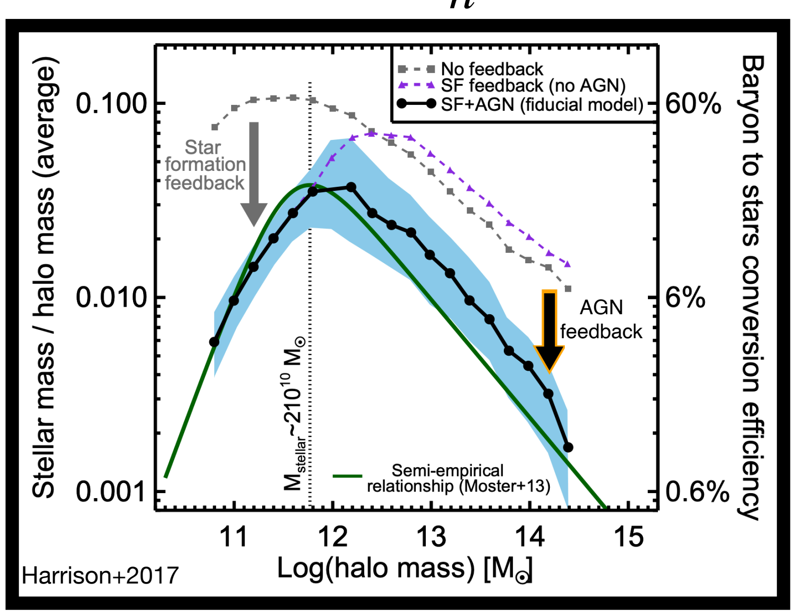
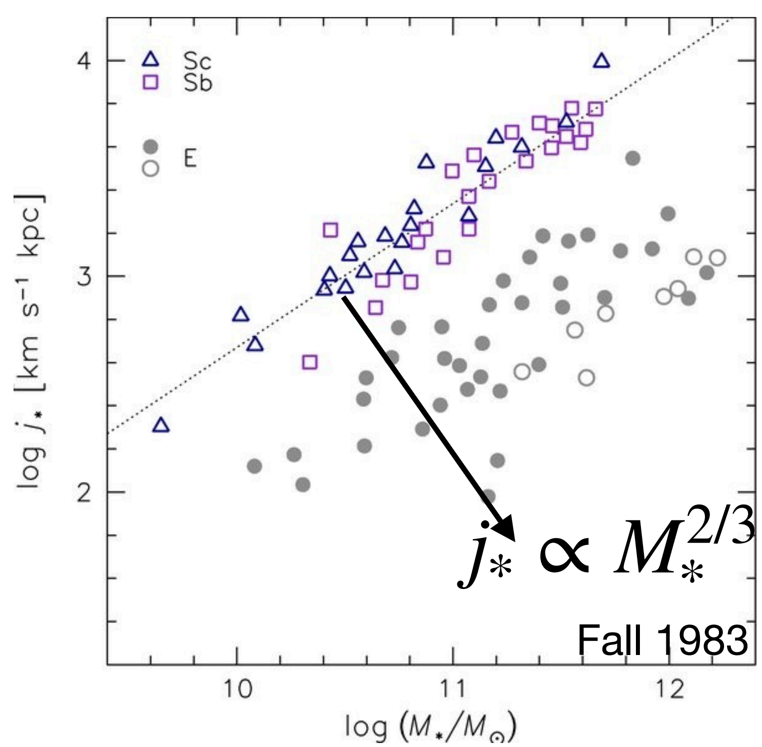
~const with M_*!!!

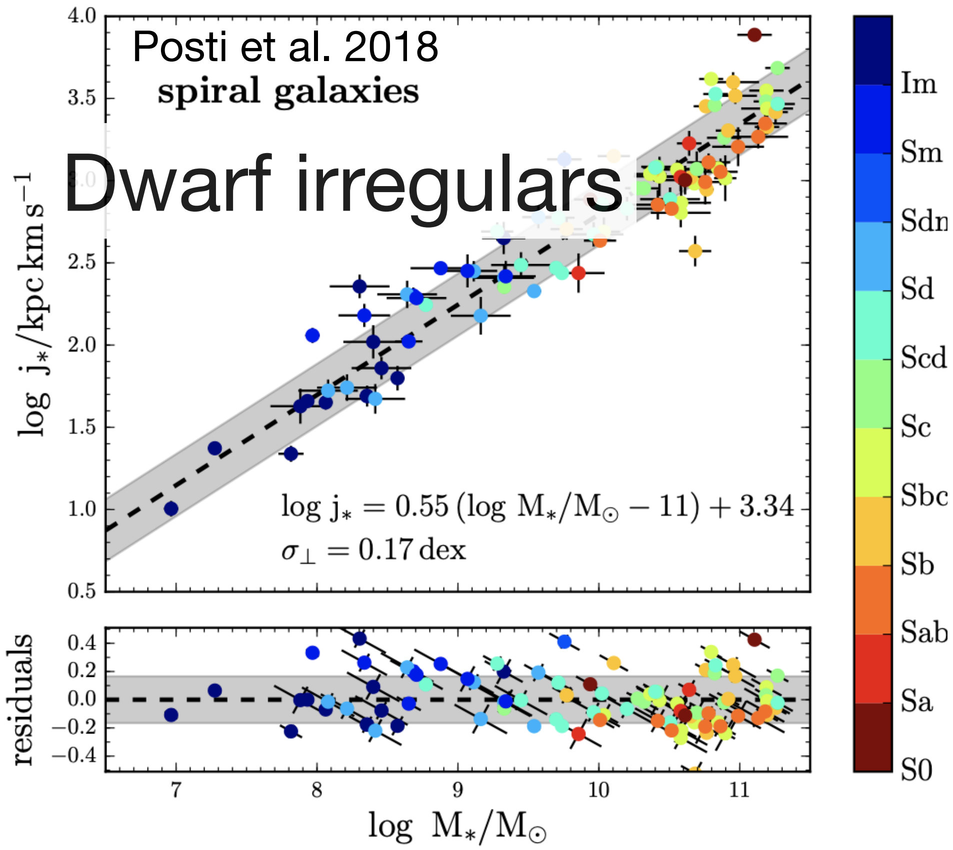
$$j_* \propto f_j f_*^{-2/3} \left(\frac{M_*}{M_\odot}\right)^{2/3} \text{kpc km s}^{-1}$$

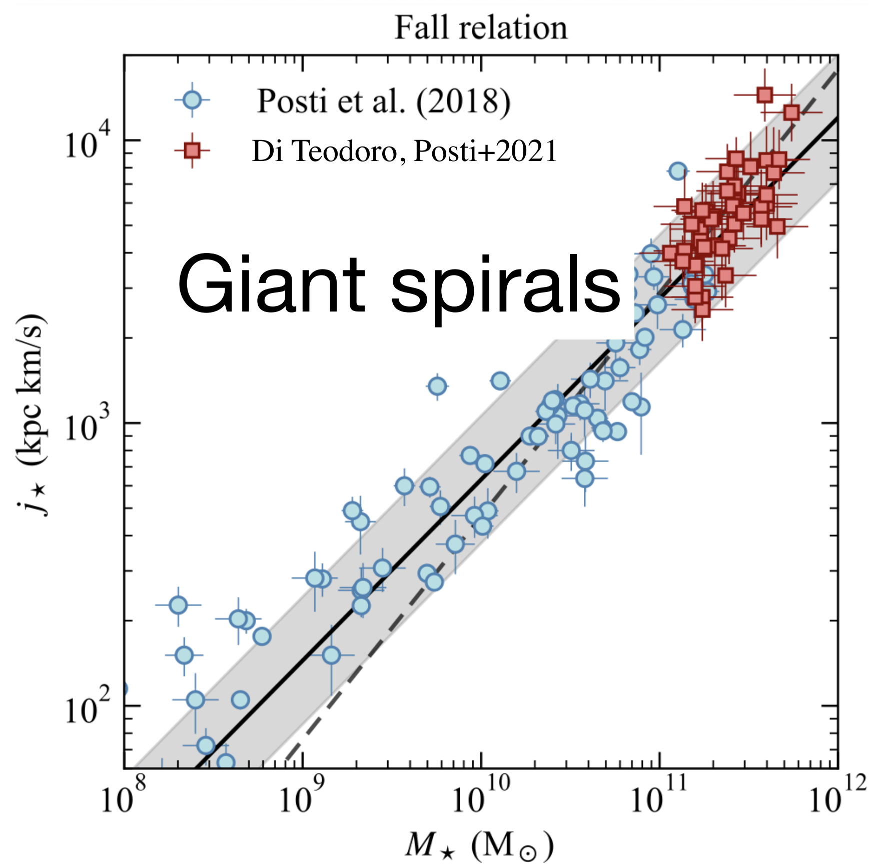




Romanowsky & Fall 2012
Posti et al. 2018

The Fall relation

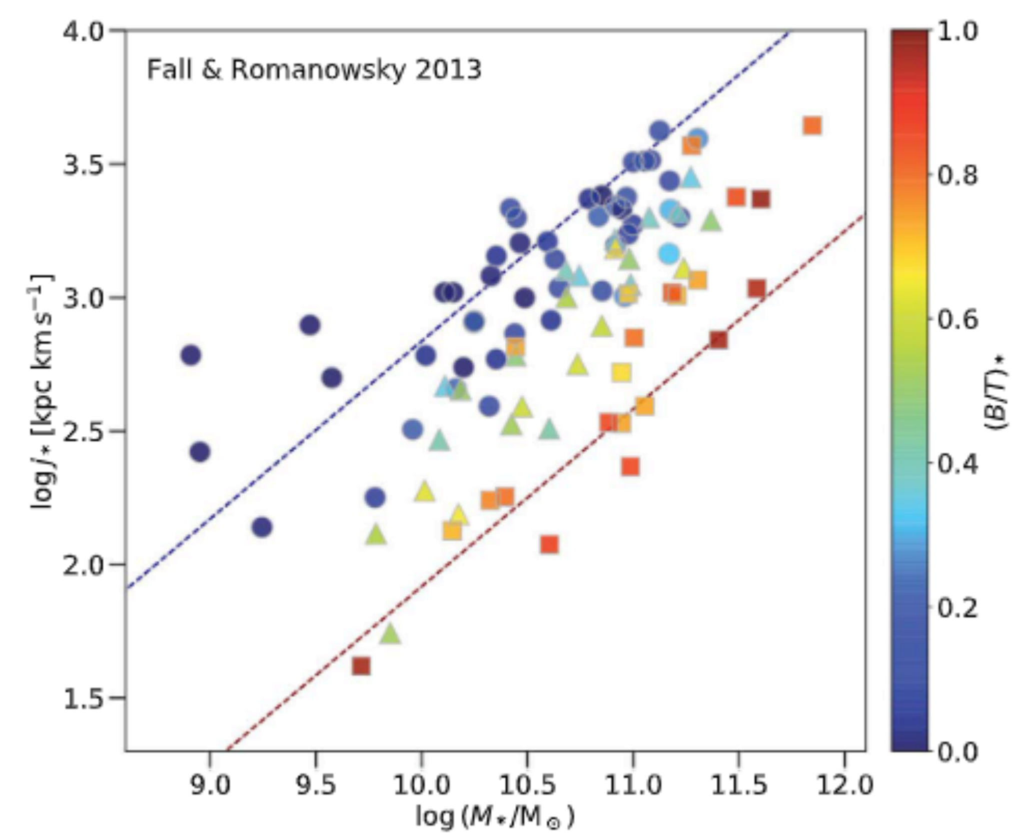




VS morphology

- The scatter in the $j_* - M_*$ plane is strongly correlated with morphology: an alternative to Hubble sequence! (Obreschkow and Glazebrook 2014, Cortese 2016, Fall & Romanowsky 2018)

- j_* **measured "in detail" for only 8 ETGs** (from major axis kinematics, assuming axisymmetry and cylindrical velocity fields; Romanowsky&Fall 2012) + 32 galaxies where $j_* = k_n\, V_{rot,2R_e}\, R_e$ (calibrated on models and verified on the 8 galaxies above)



Why are ETGs problematic?

- Kinematics
- Stellar mass distribution
- Geometry

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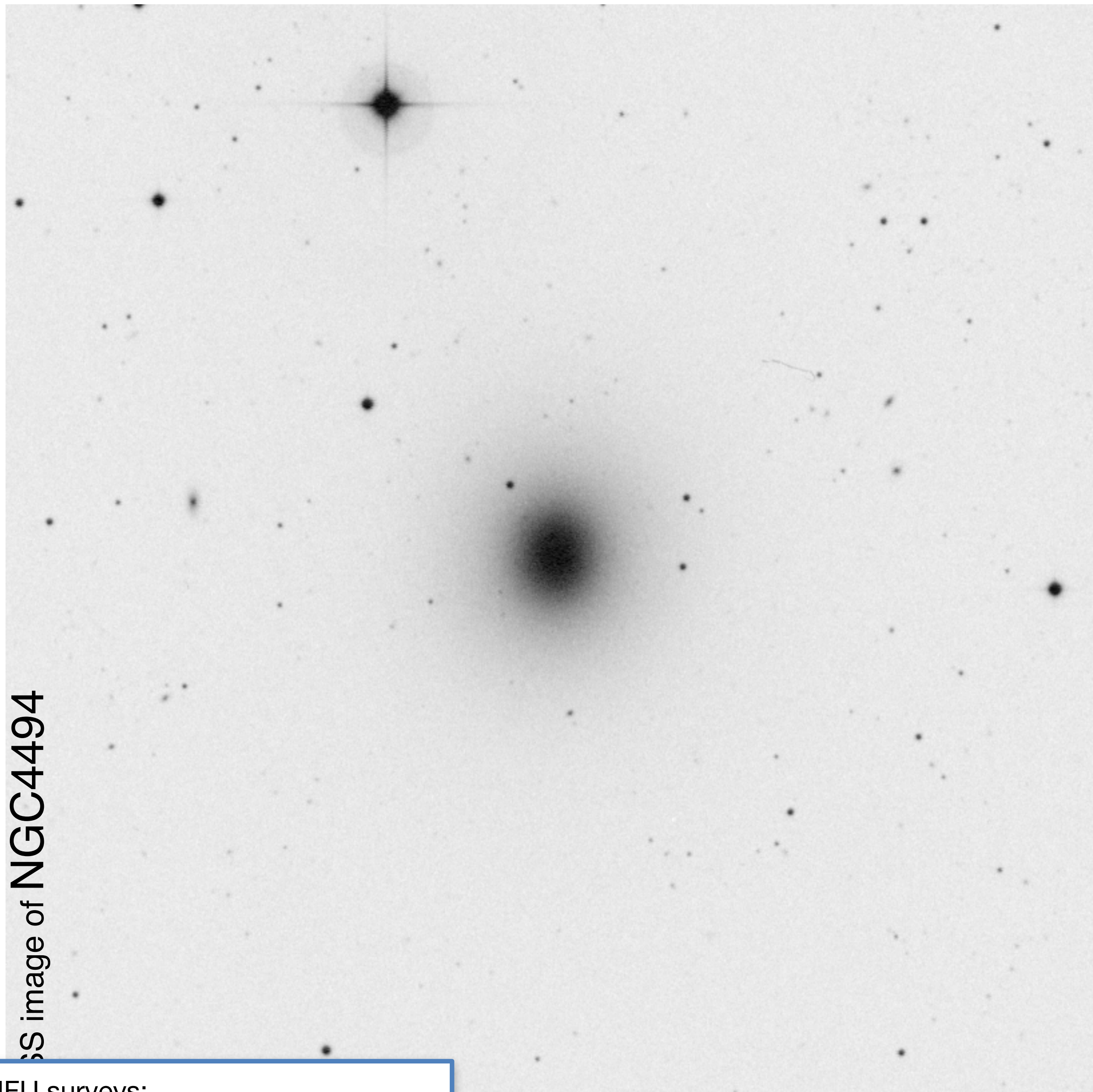
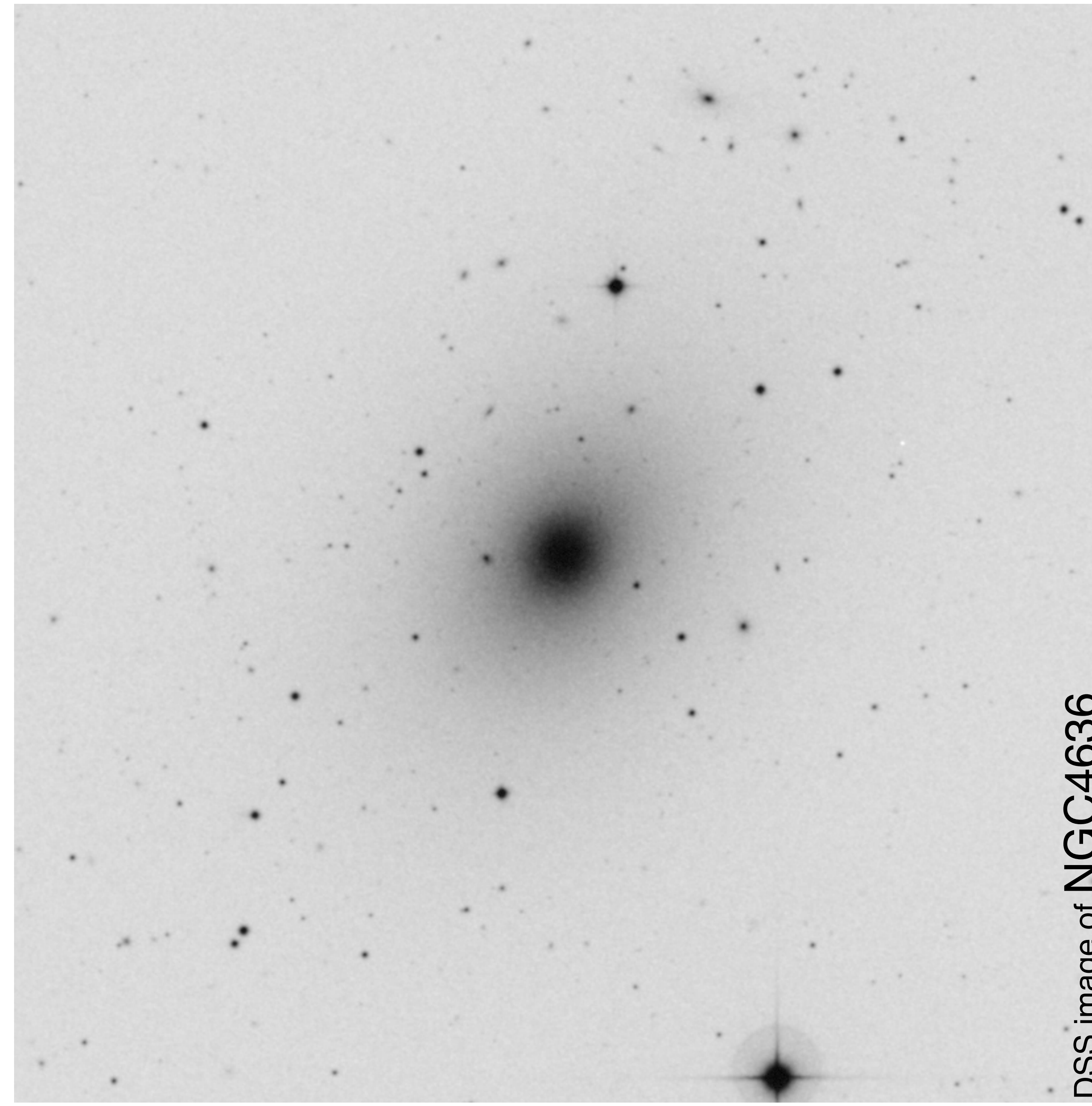
ETG kinematics





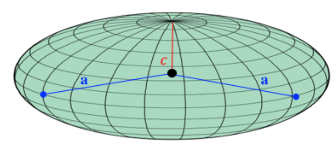
IFU surveys:
ATLAS3D (Cappellari+2011)
MANGA (Bundy+2015)
CALIFA (Sanchez+2012)
SAMI (Croom+2012 - Bryant+2015)
MASSIVE (Ma+2014)

Emsellem et al. 2007, 2011
Cappellari et al. 2007, 2011
Naab et al. 2014; Penoyre et al. 2017

ETG kinematics

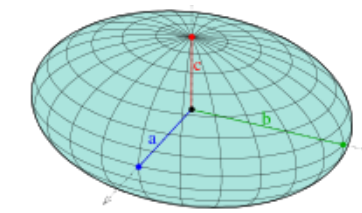
FAST ROTATORS

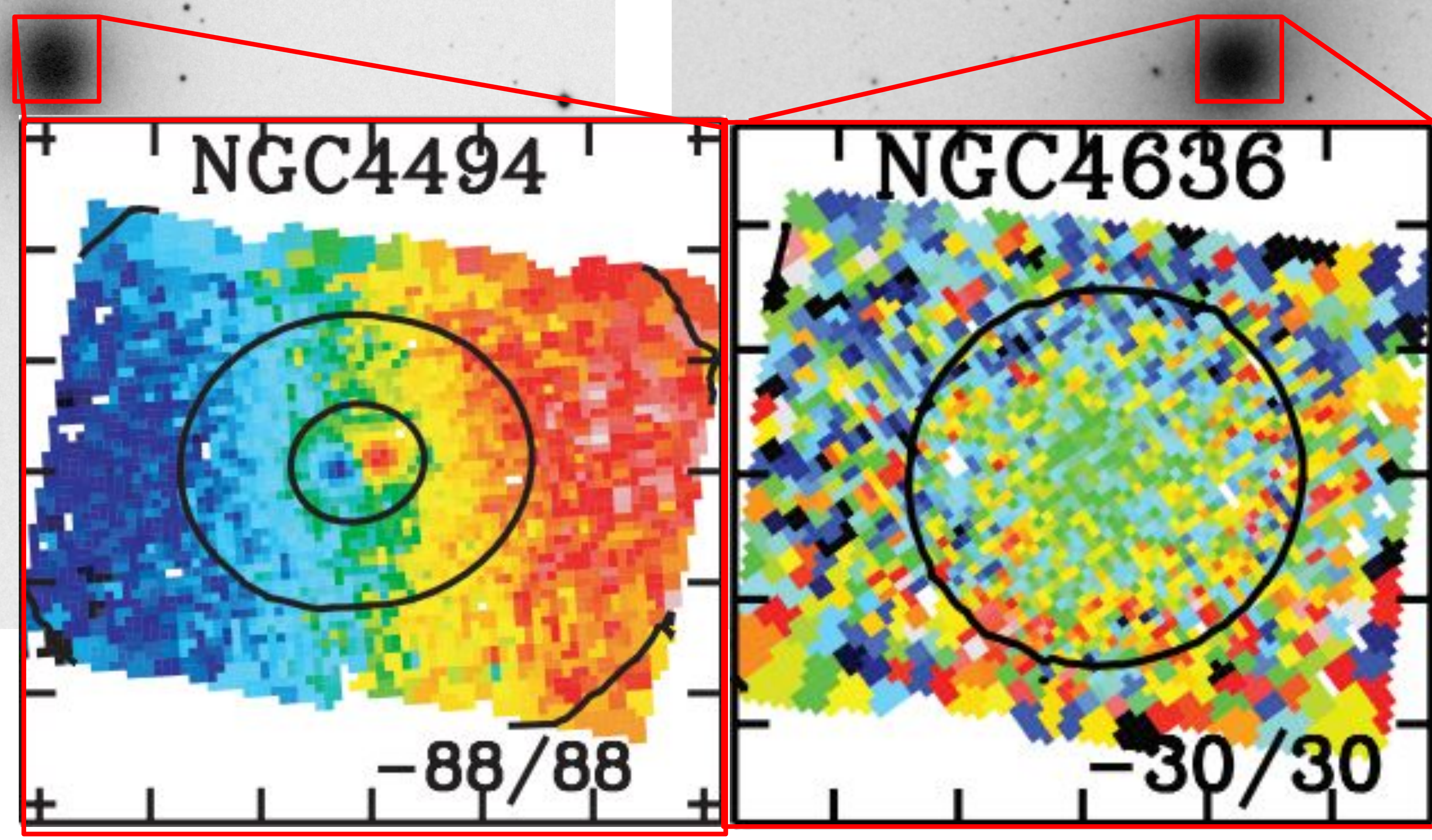
- >80% of the ETGs
- regular, disk-like rotators
- flattened, oblate, axisymmetric shapes
- formation history dominated by gas-rich processes



SLOW ROTATORS

- <20% of the ETGs
- irregular or no rotation
- triaxial
- massive
- formation history dominated by dry mergers





Krajnovic+2011

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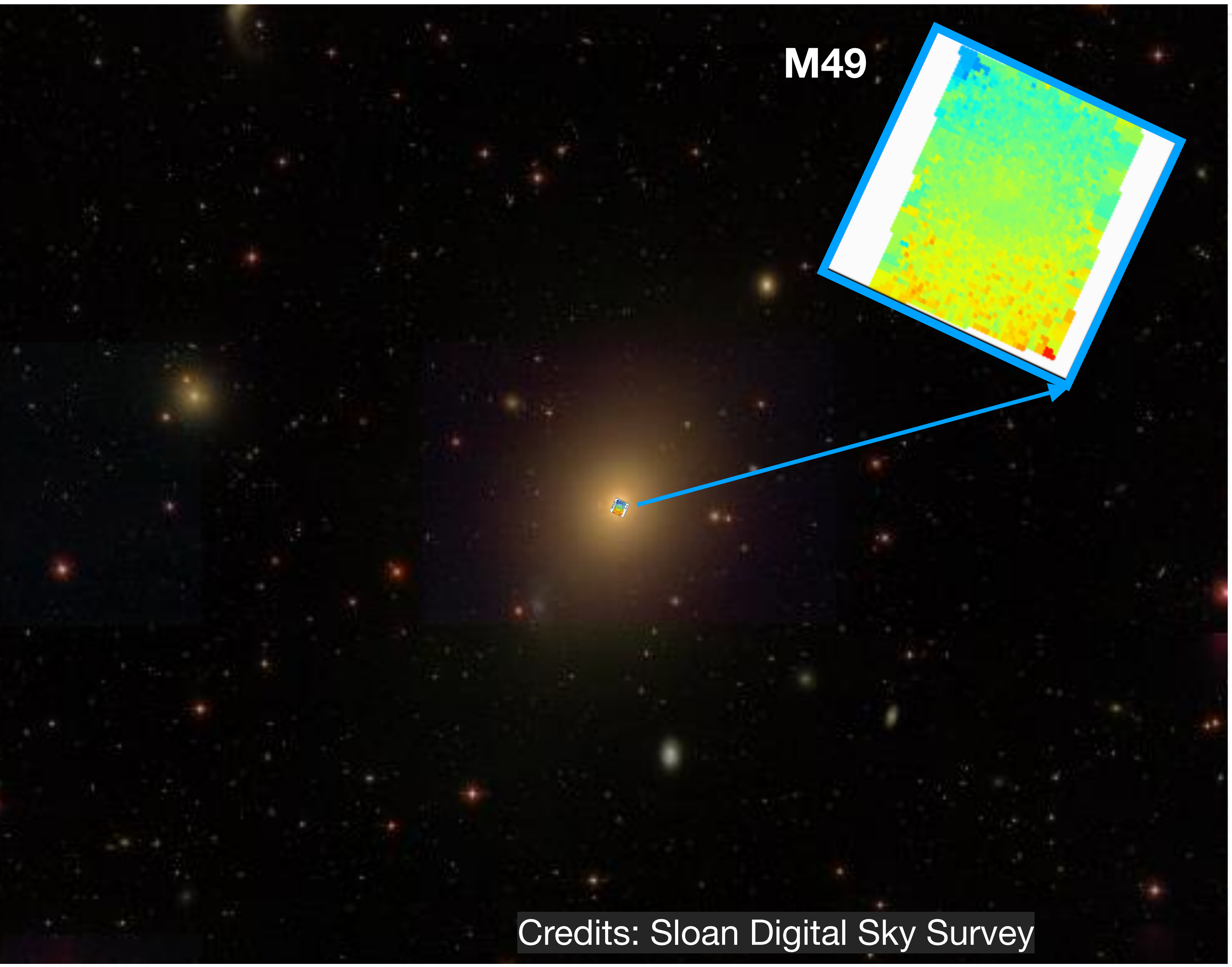
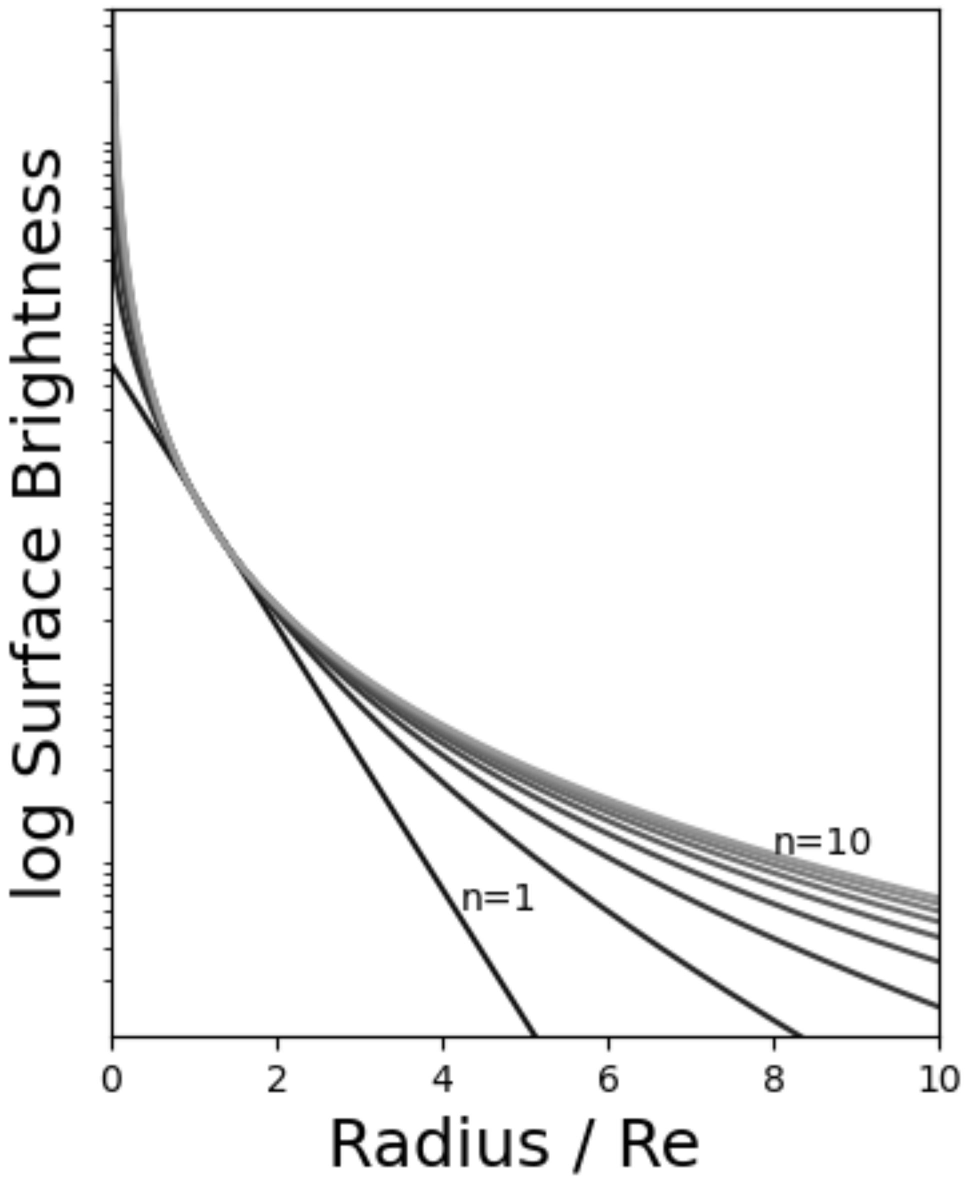
Extending the kinematics to large radii

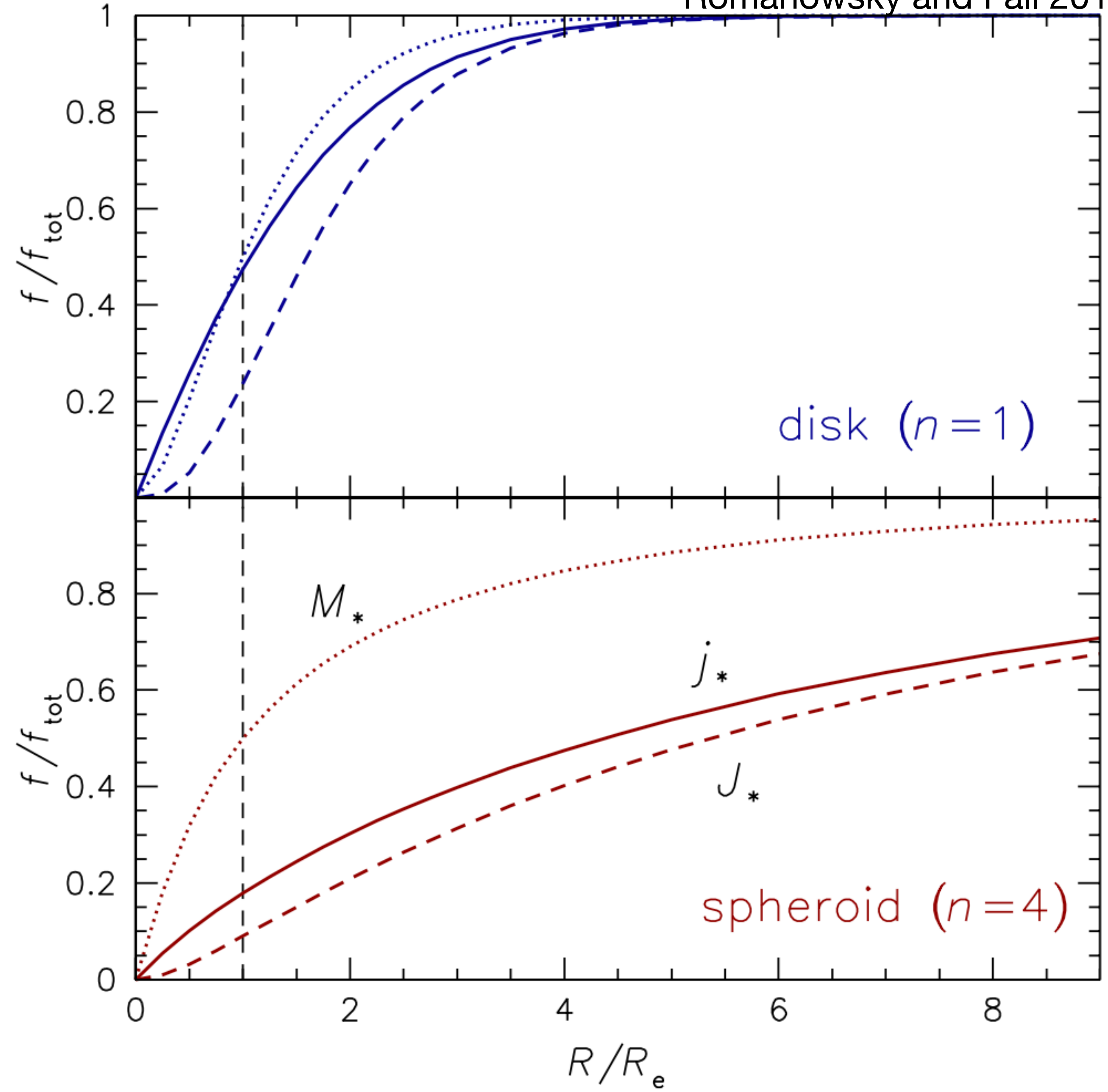


- **95% of the total mass**
- **dark matter** dominates
- halo **mostly accreted** (ex-situ) star material
- long settling time scales (~1 Gyr): signatures of the formation processes preserved
- **>50% of the stellar angular momentum**

Extending the kinematics to large radii



Romanowsky and Fall 2012



- j_* measured "in detail" for only 8 bulge-dominated galaxies with strong assumptions on the geometry: 5FRs, 2 SRs and 1 Merger

$$\vec{J} = M\,\vec{r} \times \vec{v}$$

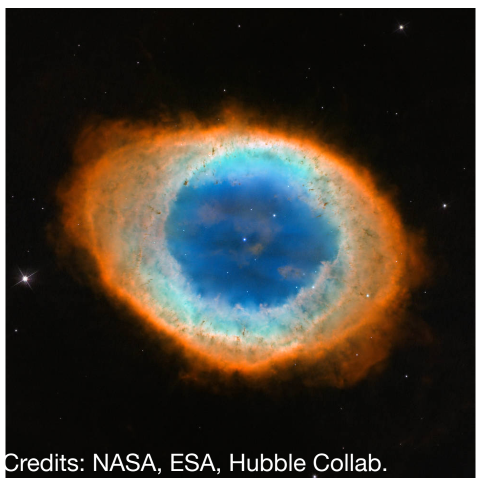
➡ **Need extremely extended kinematics out to** $R > 10R_e$

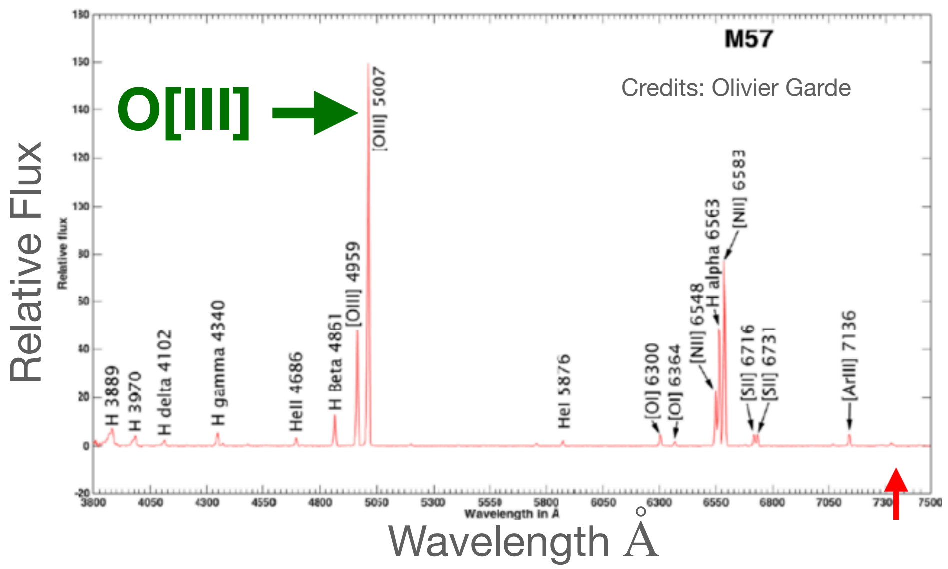
➡ **Use alternative tracers of the stellar kinematics beyond** $\sim 2R_e$

Planetary Nebulae as kinematic tracers

* The ePN.S survey *

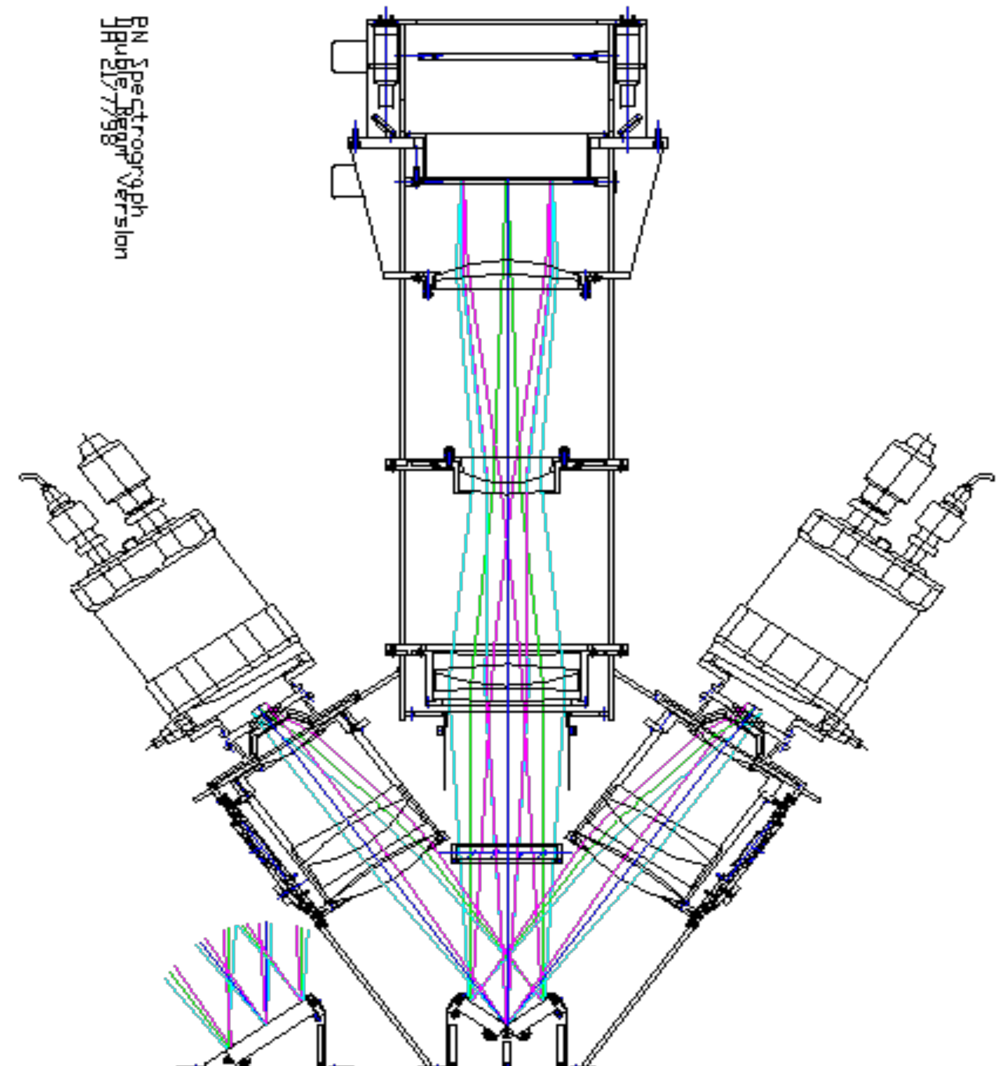
P.I. M. Arnaboldi
M. Capaccioli - A. Chies-Santos - L. Coccato - A. Cortesi - K. Freeman - O. Gerhard - J. Hartke - K. Kuijken - A. Longobardi - M. Merrifield - N. R. Napolitano - C. Pulsoni - A. Romanowsky - C. Tortora - E. Moylan - C. Narayan





The Planetary Nebula Spectrograph

W. Herschel Telescope, La Palma



Douglas+2002

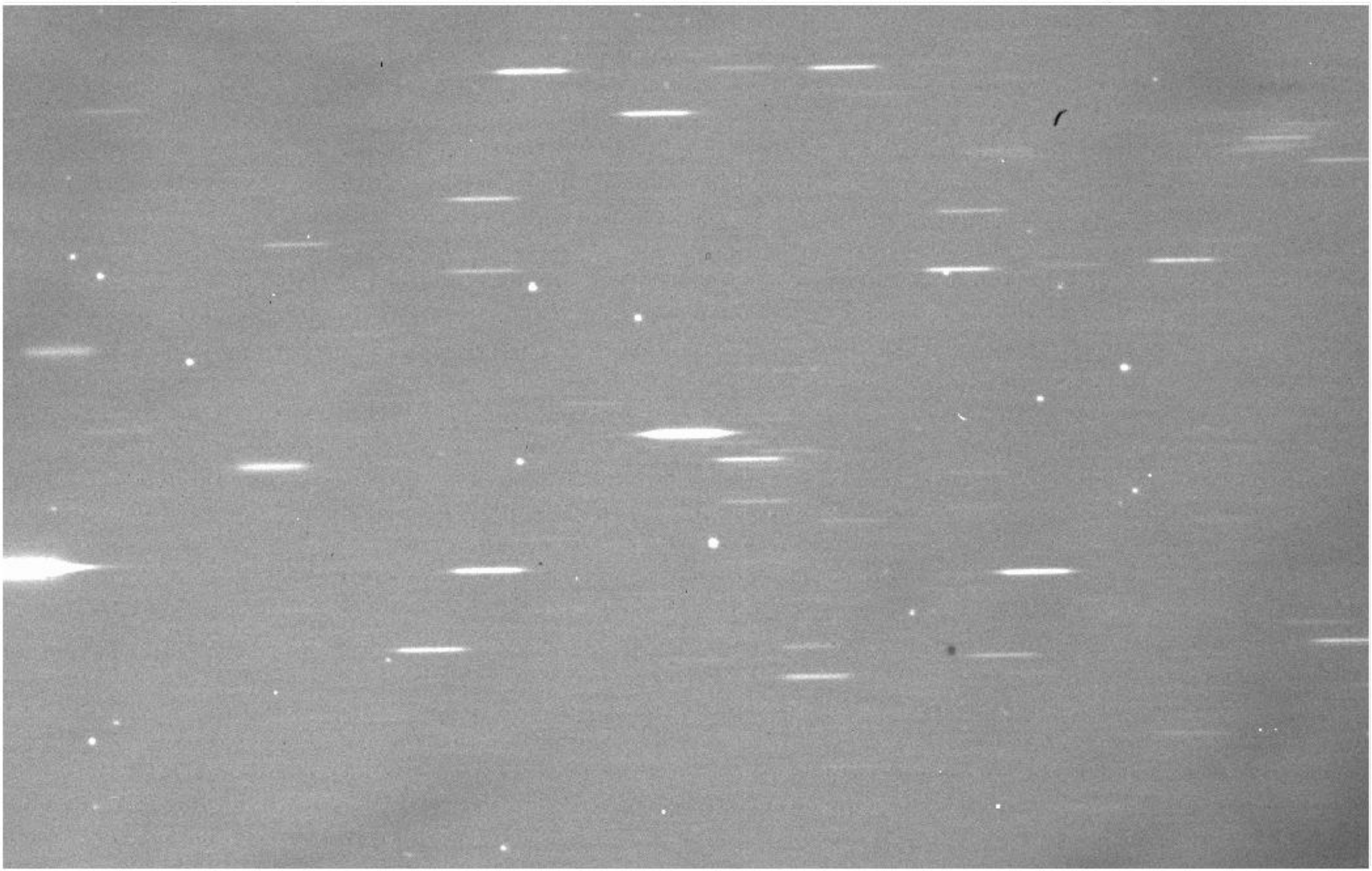
- Bright [OIII] emitters: **easily detectable**
- **PNe follow stars**:
  - Number density ∝ surface brightness
  - Kinematics agree in the overlap regions

➡ Good tracers of the stellar halo!

PN.S

Arnaboldi et al. 2017

Counter-dispersed imaging (Douglas+2002)



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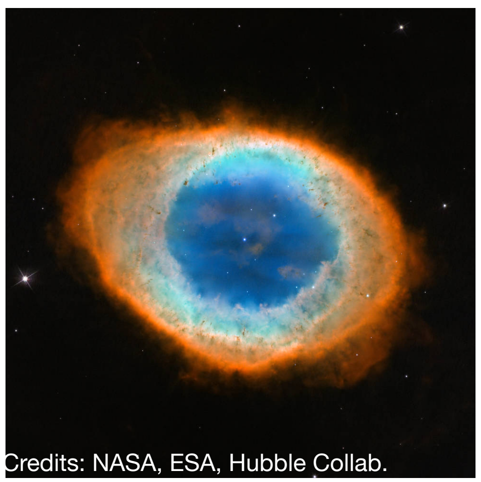

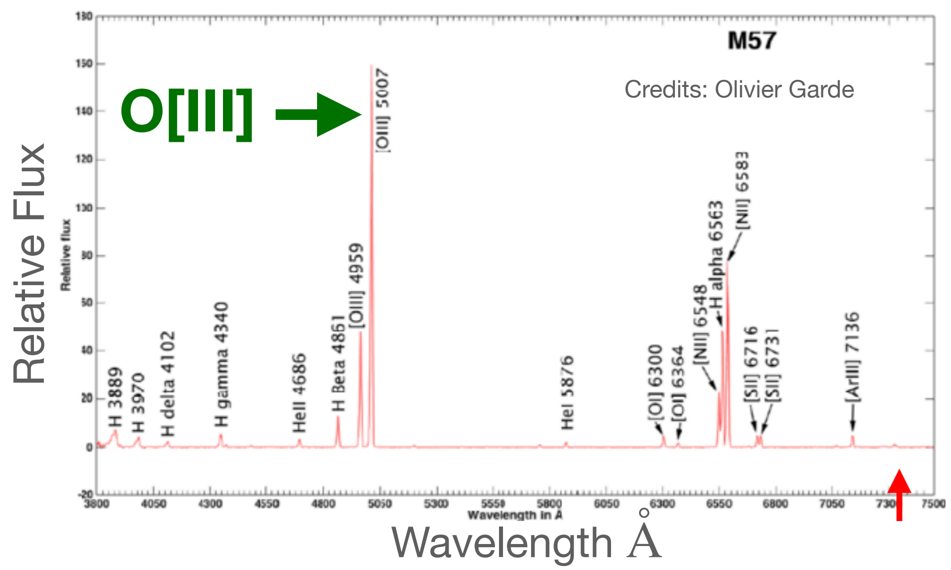

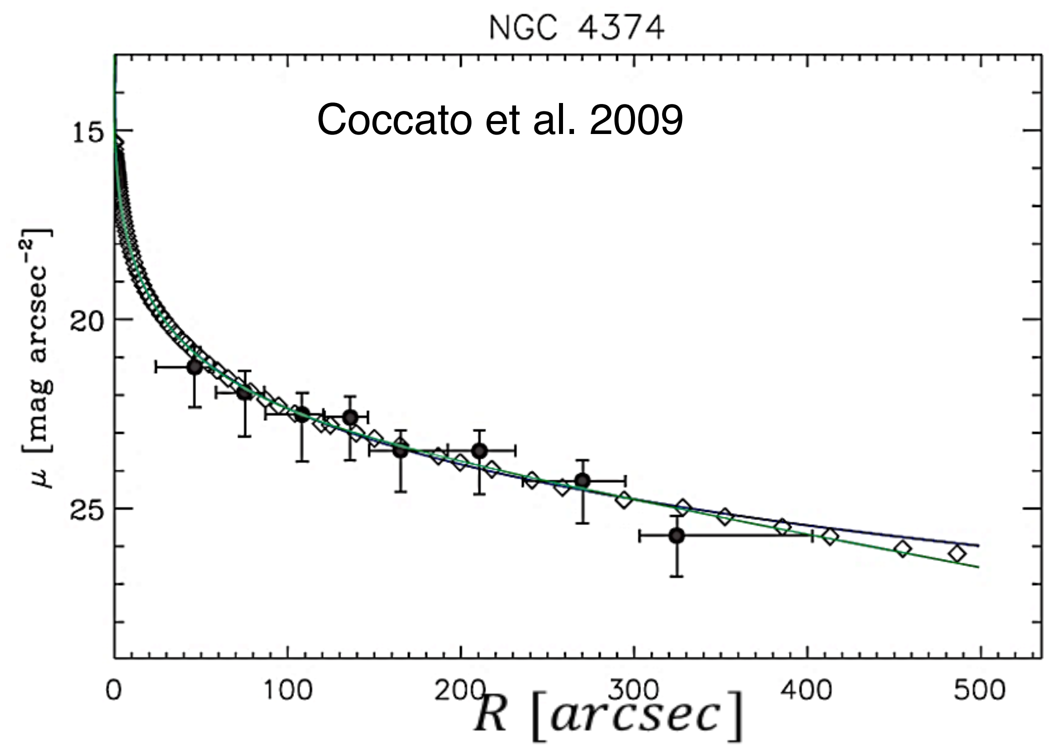

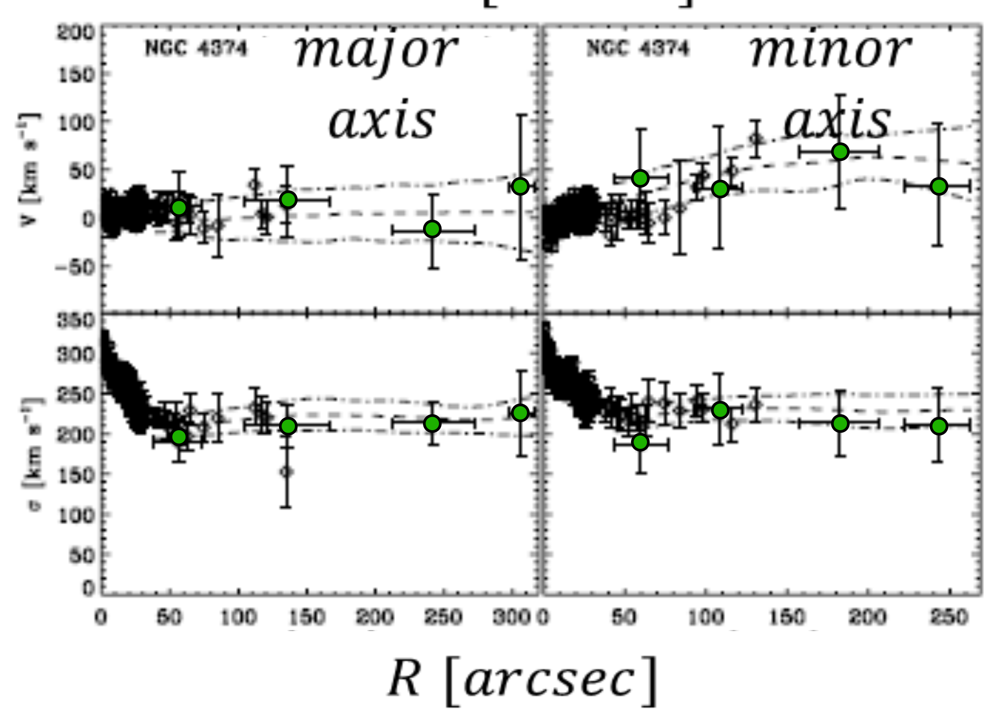

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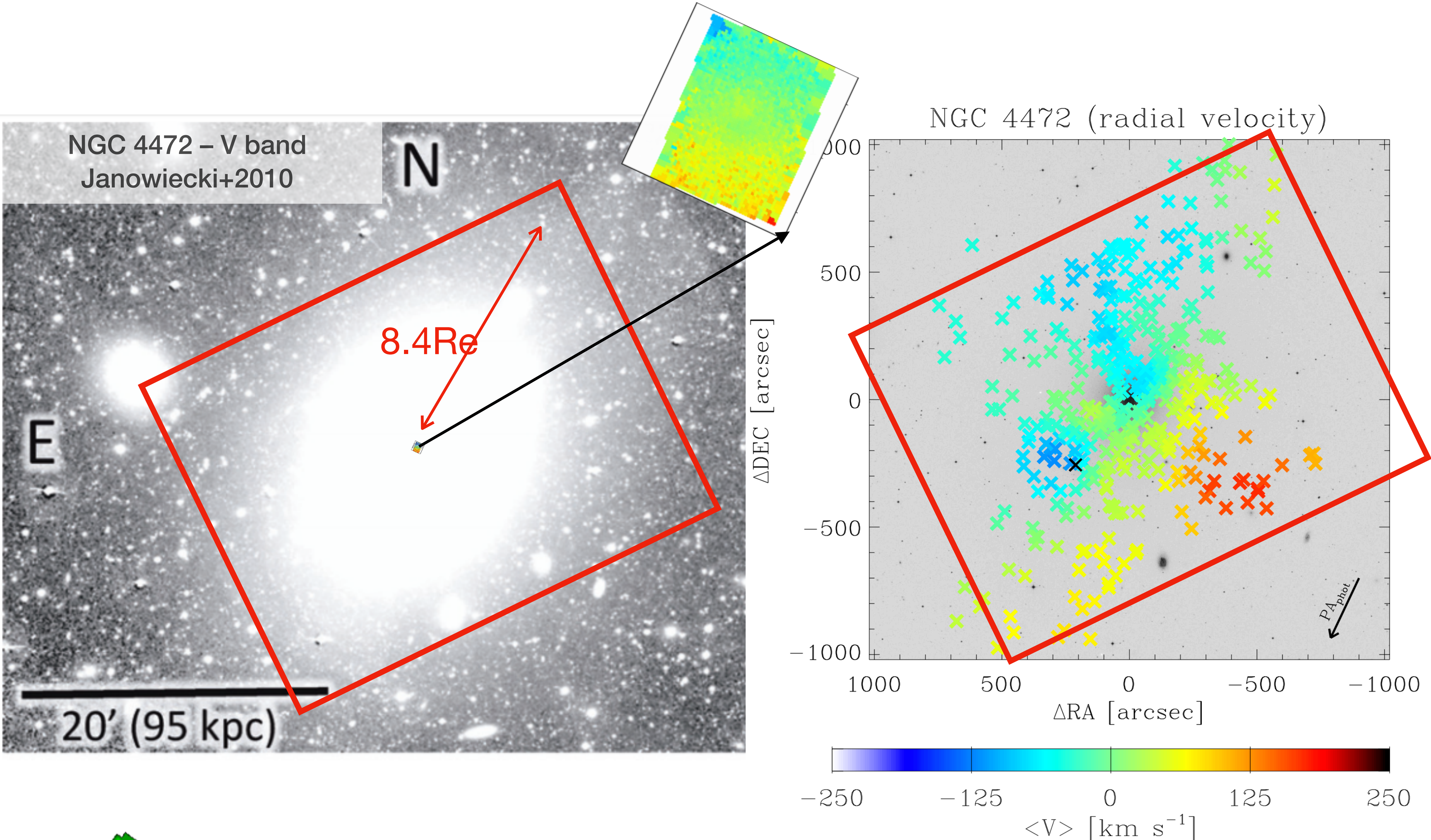
PN.S

Arnaboldi et al. 2017

An example: M49

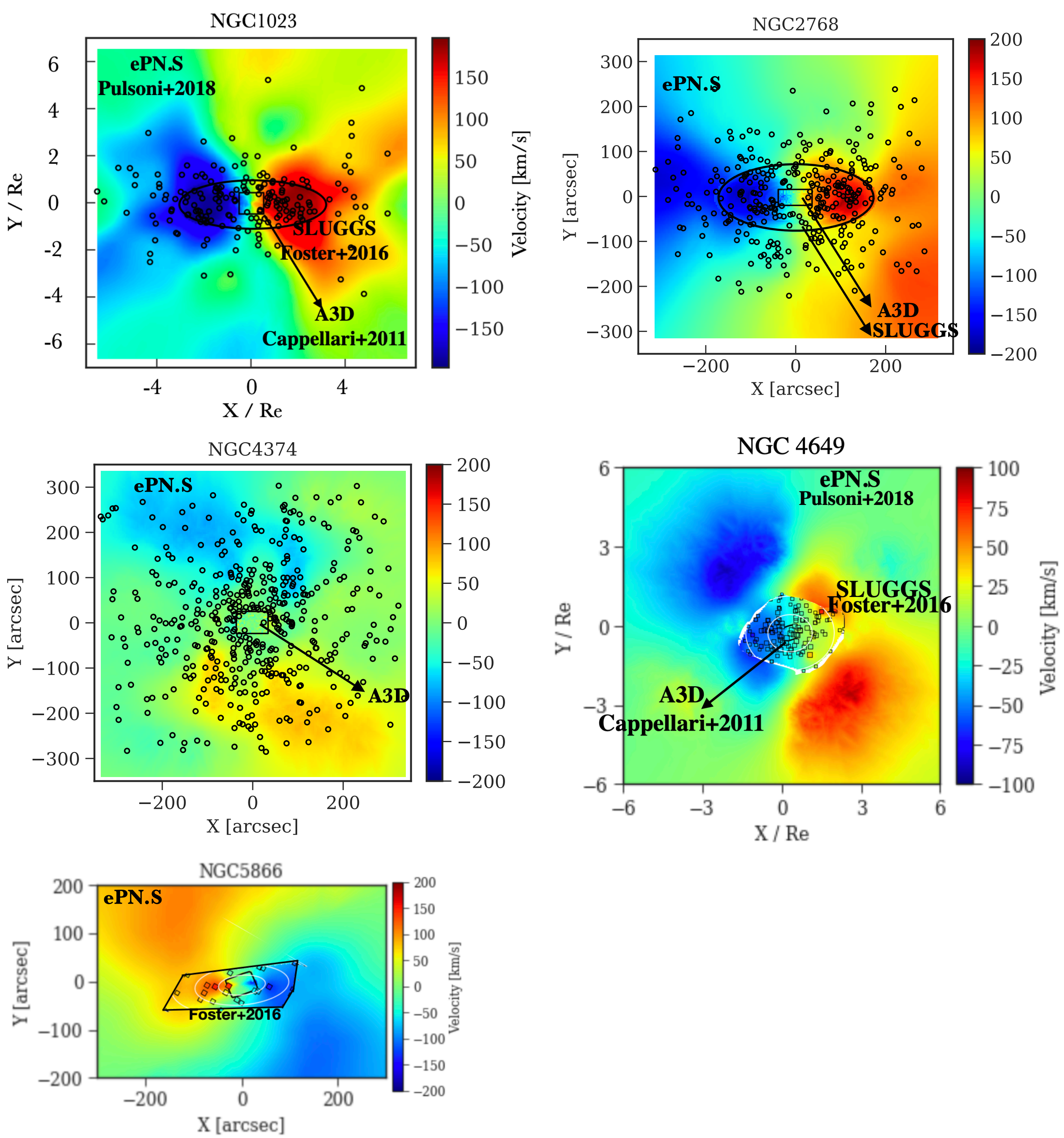


PN.S

Pulsoni+2018

* The ePN.S survey *

P.I. M. Arnaboldi



- **33 ETGs** with a wide range of parameters (luminosity, central velocity dispersion, ellipticity, boxy/diskyness)
- nearby, distance < 25 Mpc
- Magnitude limited sample, $10^{10.3} < M_*/M_\odot < 10^{11.7}$
- 24 fast and 9 slow rotators
- **2D Kinematics out to [3 - 13 Re], mean 6 Re** IFS (Atlas3D, SLUGGS, MUSE) + PNe
- **Increase statistics of ETGs with AM measured by x4**

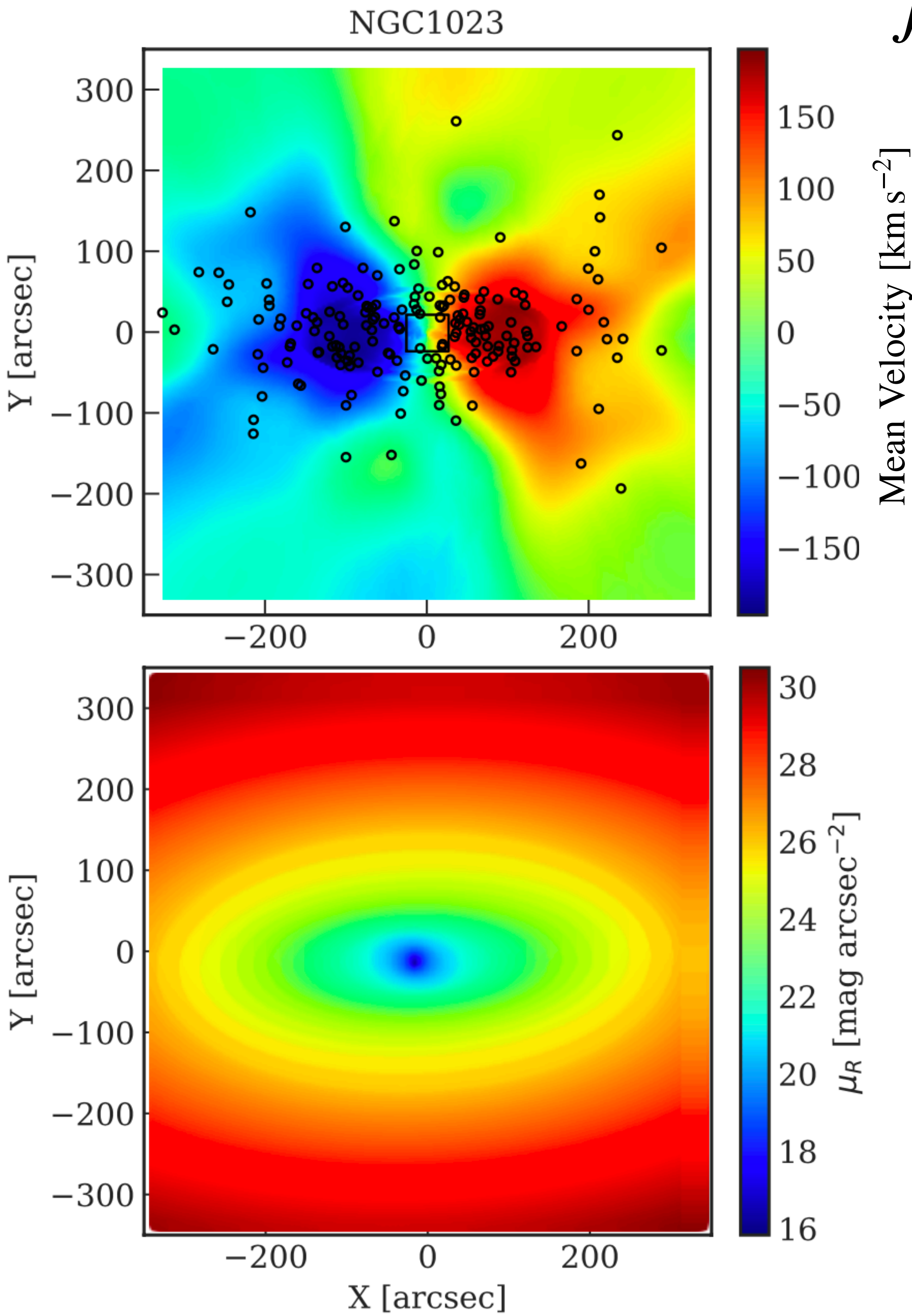
Pulsoni+2018
Pulsoni+2023

Why are ETGs problematic?

- Kinematics
- Stellar mass distribution
- Geometry

The angular momentum content of ETGs

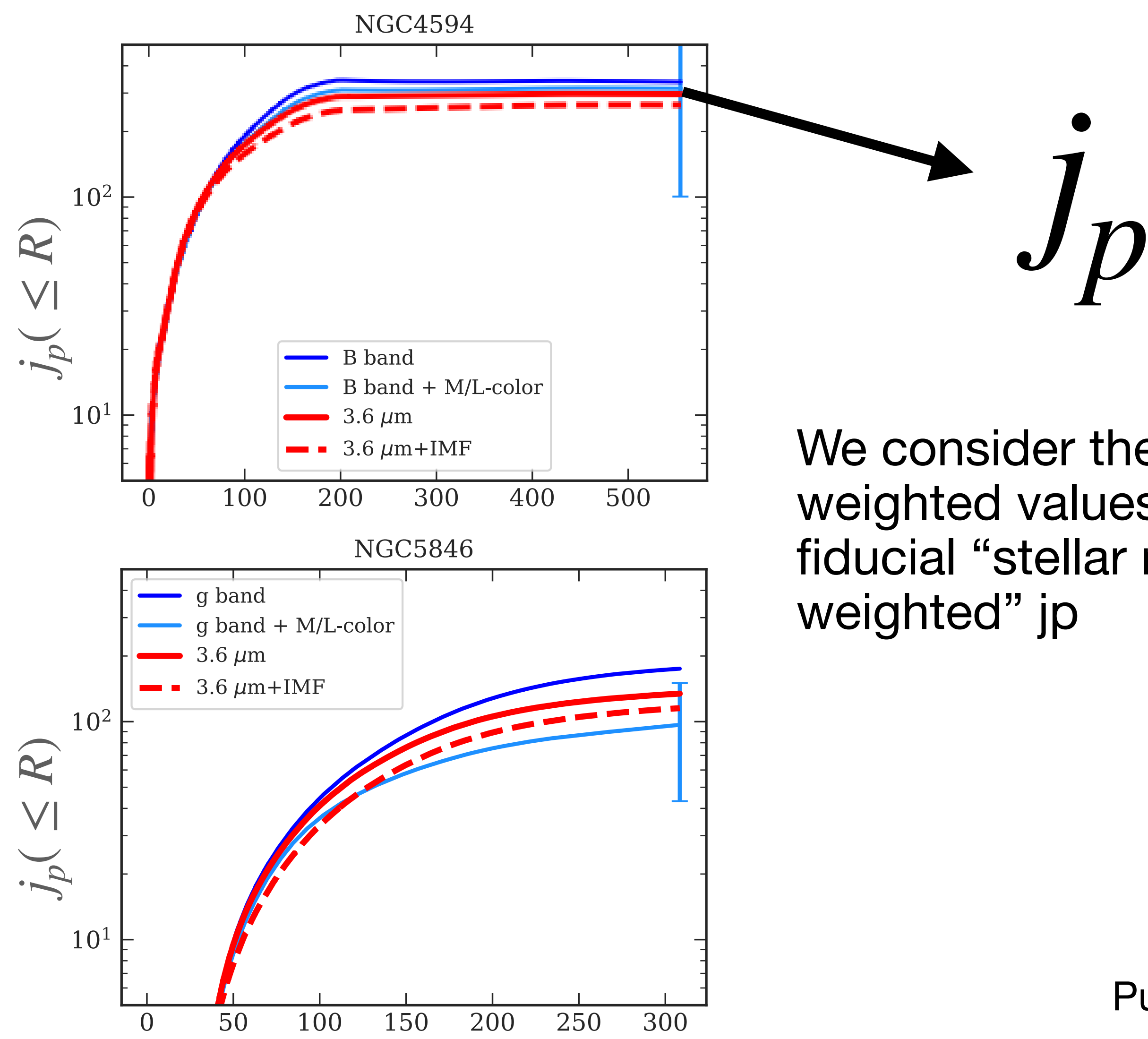
$j_p(R)$ profiles



surface mass density

$$\vec{j_p} \equiv \frac{\vec{J_p}}{M_*} = \frac{\int \vec{R} \times \hat{z} V(x,y)\, M/L(x,y)\, \Sigma(x,y) dx\, dy}{\int M/L(x,y)\, \Sigma(x,y) dx\, dy}$$

$$j_p = \sqrt{j_{p,x}^2 + j_{p,y}^2}$$



We consider the IR-weighted values as our fiducial "stellar mass-weighted" jp

Pulsoni+2023

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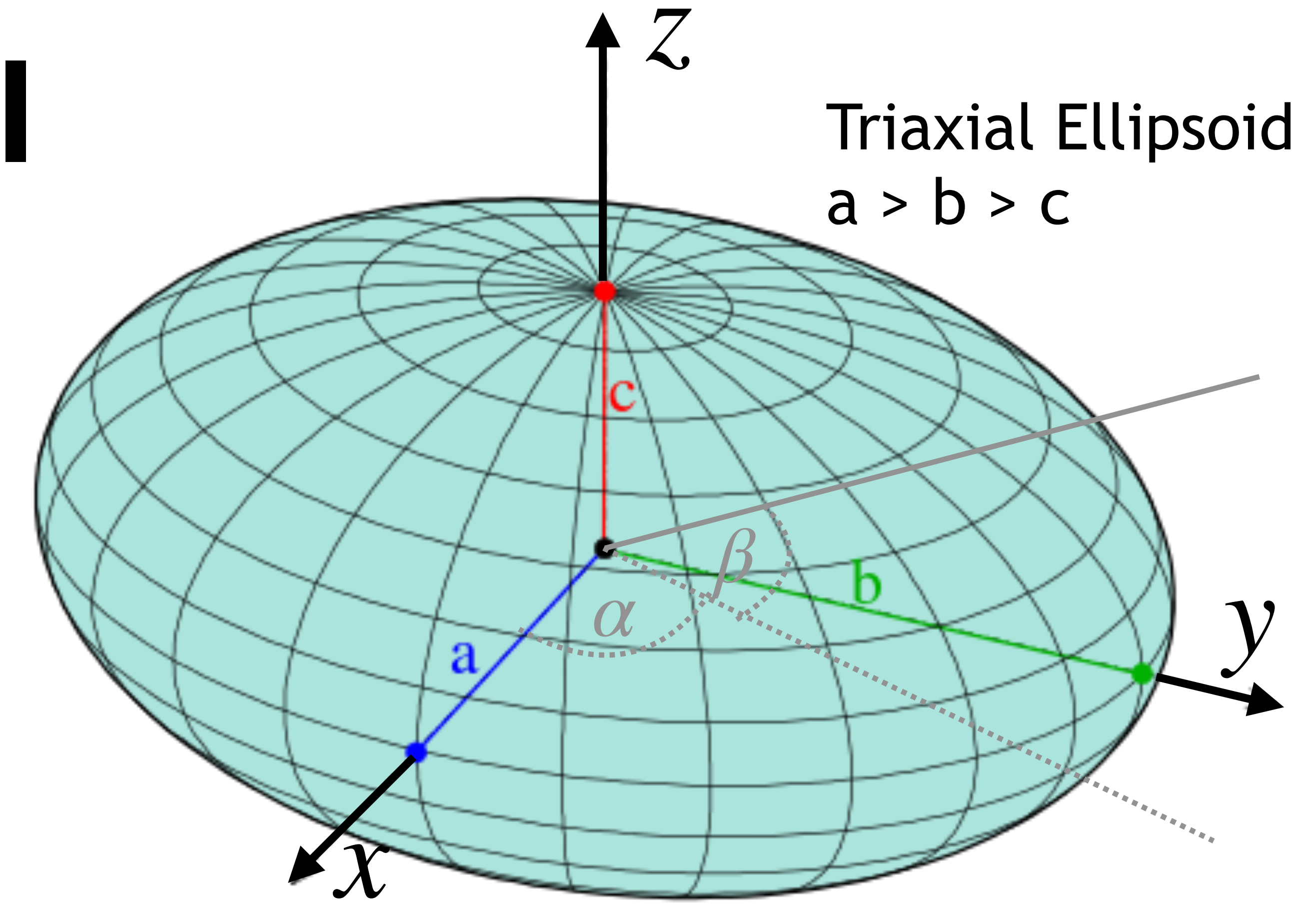
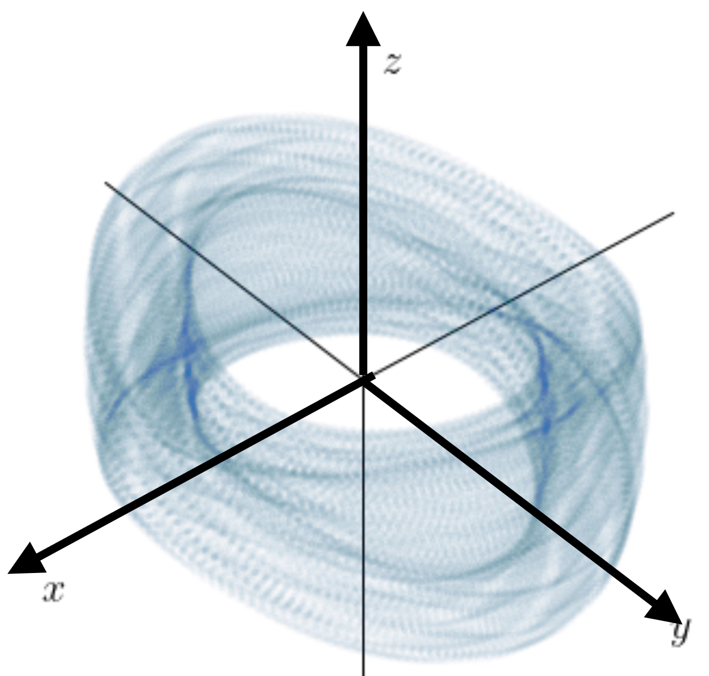
$$j_p \longrightarrow j_t$$

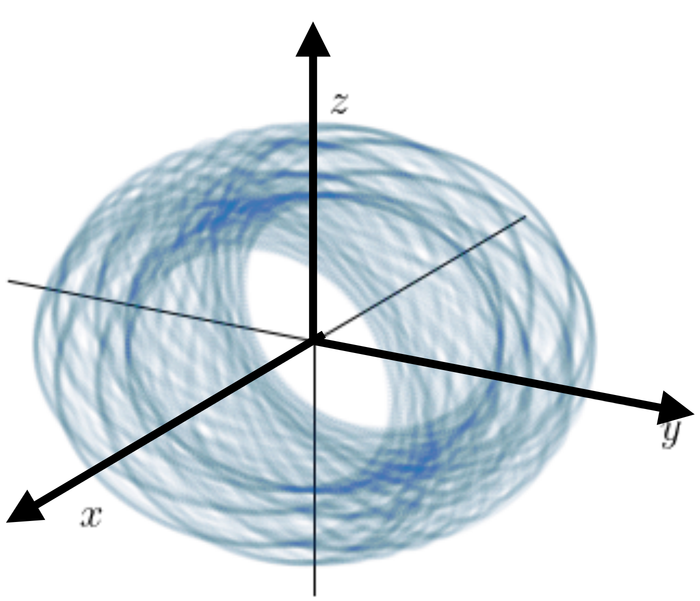
"projected" j from line-of-sight kinematics

intrinsic "true" j

ETGs are triaxial ellipsoids*

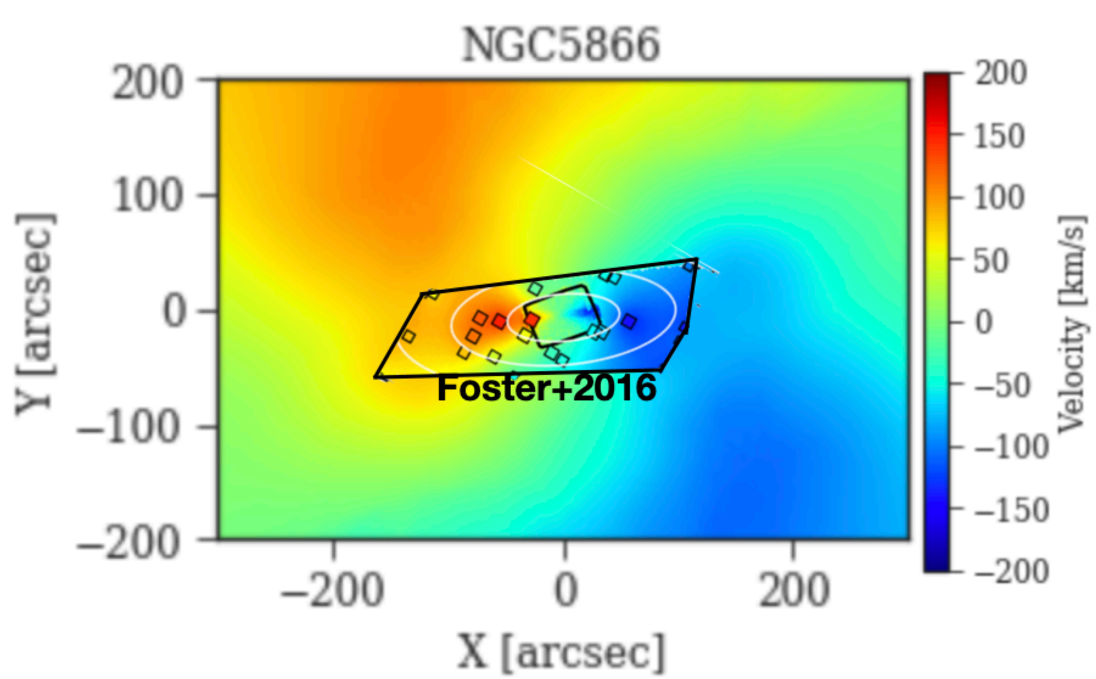


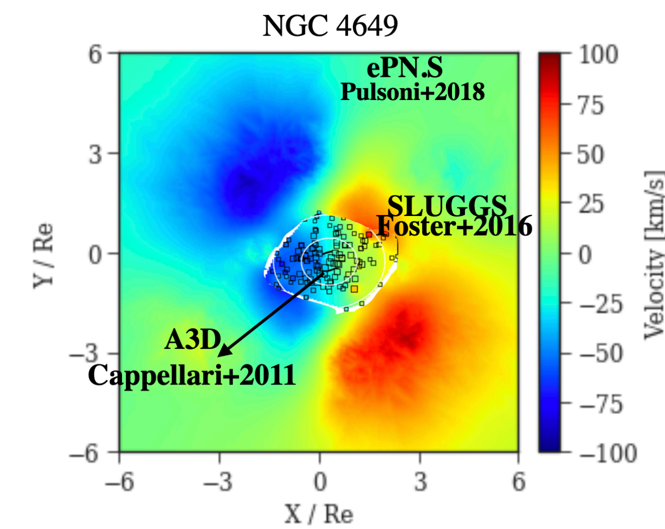


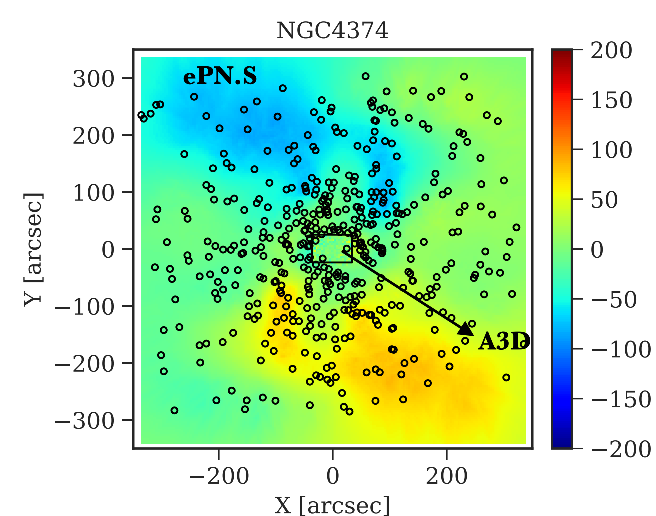


Credits: Jo Bovy

- ✳ and change shape with radius
- ✳ and have different distribution of orbits

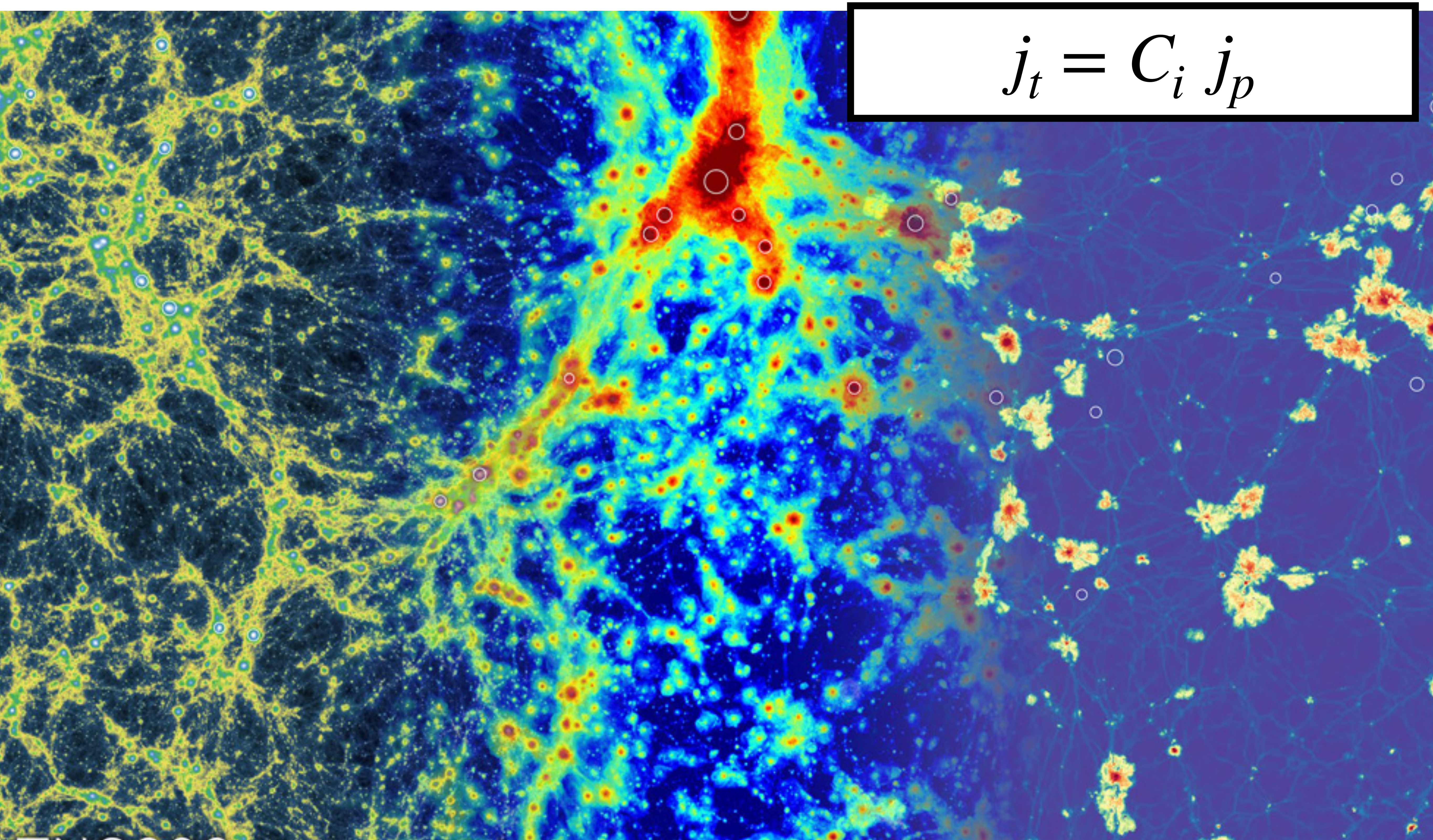






The angular momentum content of ETGs

Reconstructing j_t - use simulated galaxies from IllustrisTNG



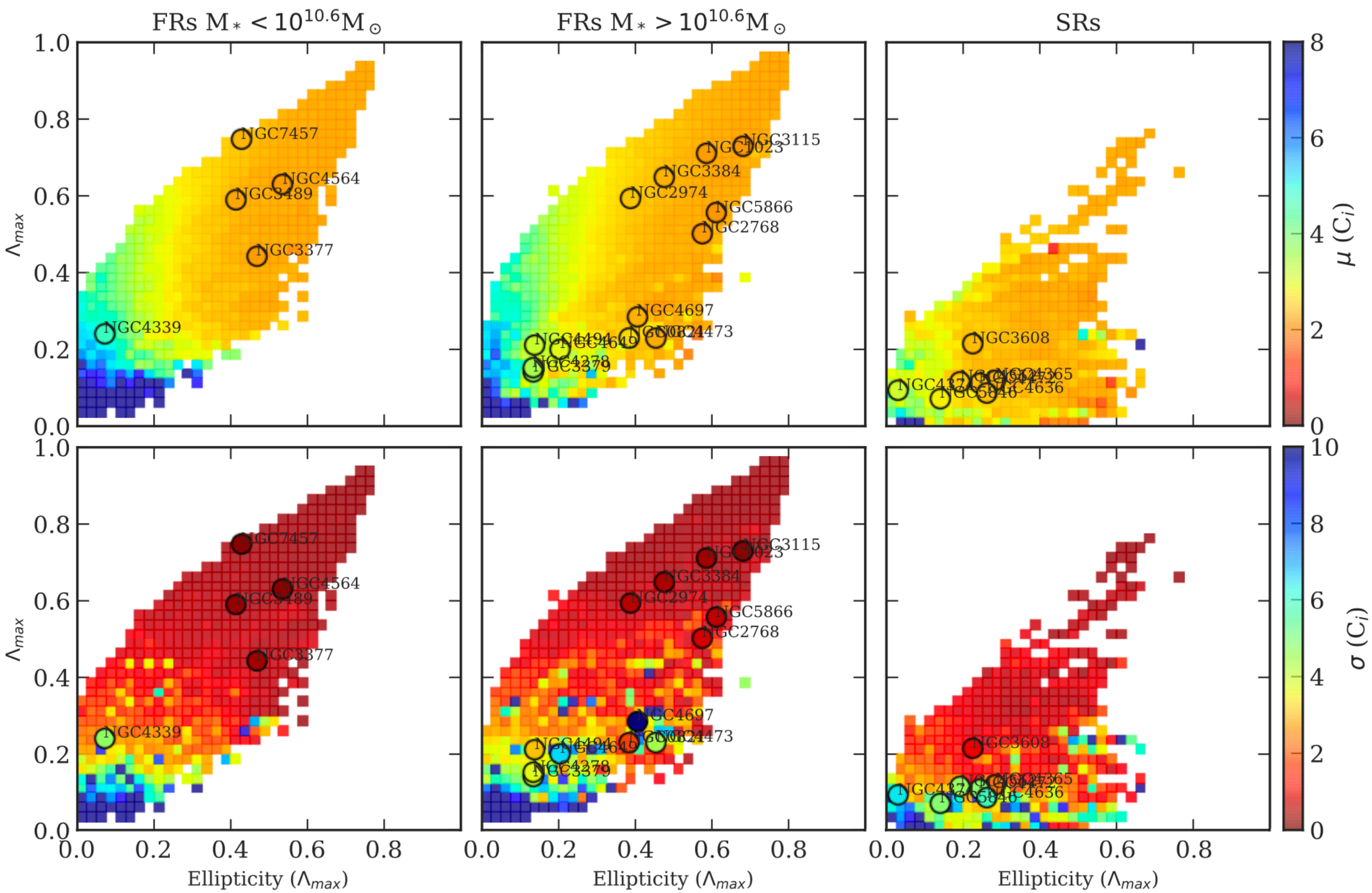
$$j_t = C_i \; j_p$$

The angular momentum content of ETGs

Reconstructing j_t - use simulated galaxies from IllustrisTNG

$$\Lambda = \frac{\sqrt{l_{p,x}^2 + l_{p,y}^2}}{\sqrt{K}} \qquad \vec{l}_p = \frac{\sum_n \vec{R}_{circ,n} \times \hat{z} v_{z,n} m_n}{\sum_n \vec{R}_{circ,n} m_n} \qquad K = \frac{\sum_n m_n v_{z,n}^2}{\sum_n m_n}$$

$$j_t = C_i \, j_p$$

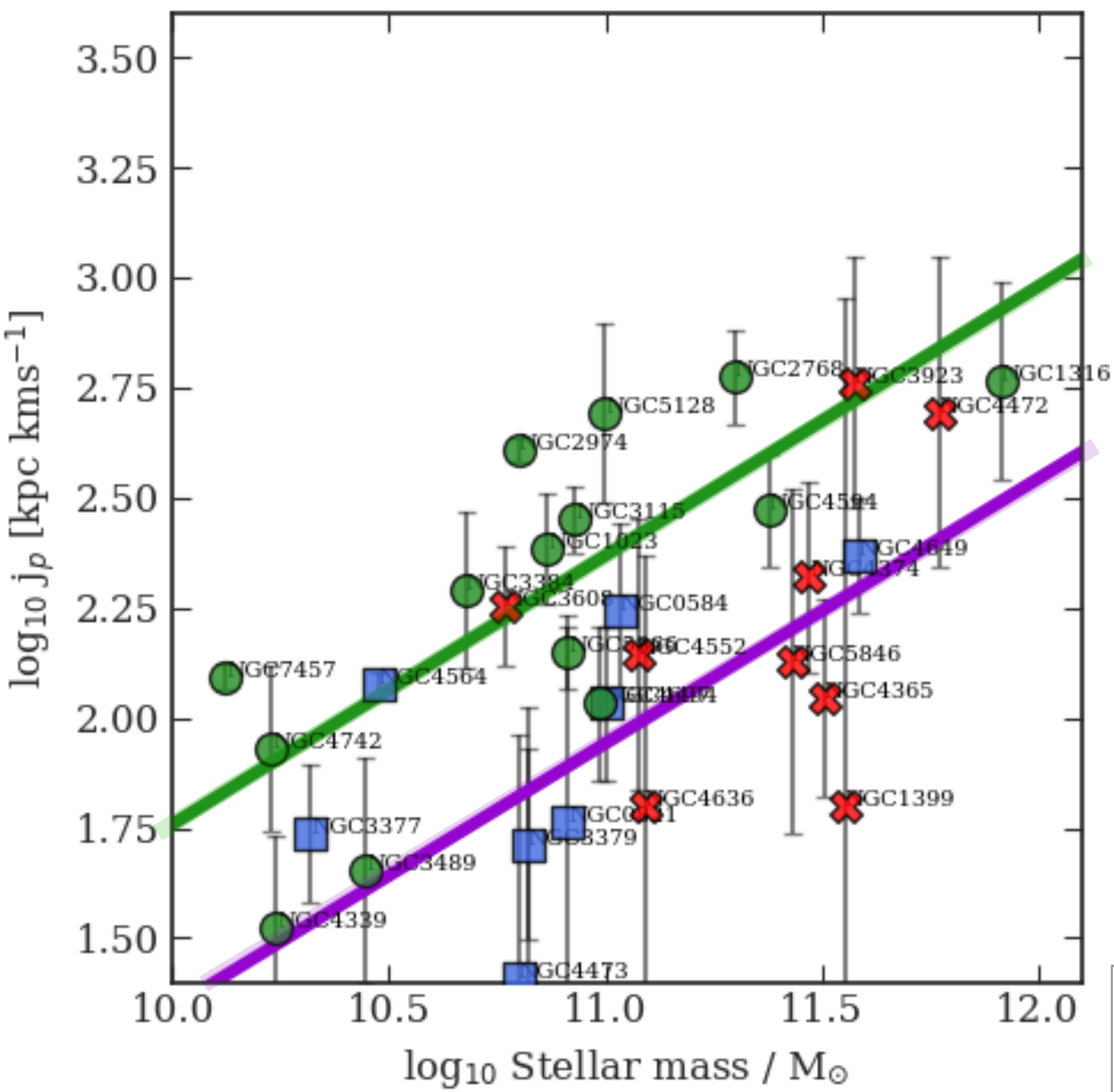


- In the (Λ-ε-rotator class) space the scatter in C_i is smaller than VS inclination
- j_t can be well predicted, given the projected ε and the velocity field of an ETG.

Pulsoni et al. 2020
Pulsoni et al. 2023

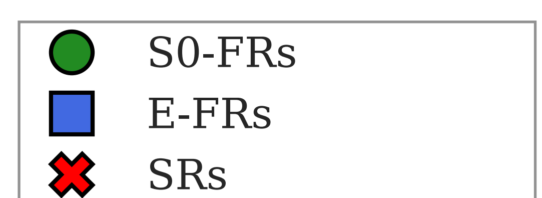
The angular momentum content of ETGs

The Fall relation for ETGs



$$j_t = C_i \; j_p$$

- dependence on mass and morphology, but no difference between FRs and SRs
- Slope close to 2/3
- mass-weighted j_* is 0.07dex lower than light-weighted
- accounting for IMF variations gives 0.2dex lower than light-weighted case



Pulsoni+2023

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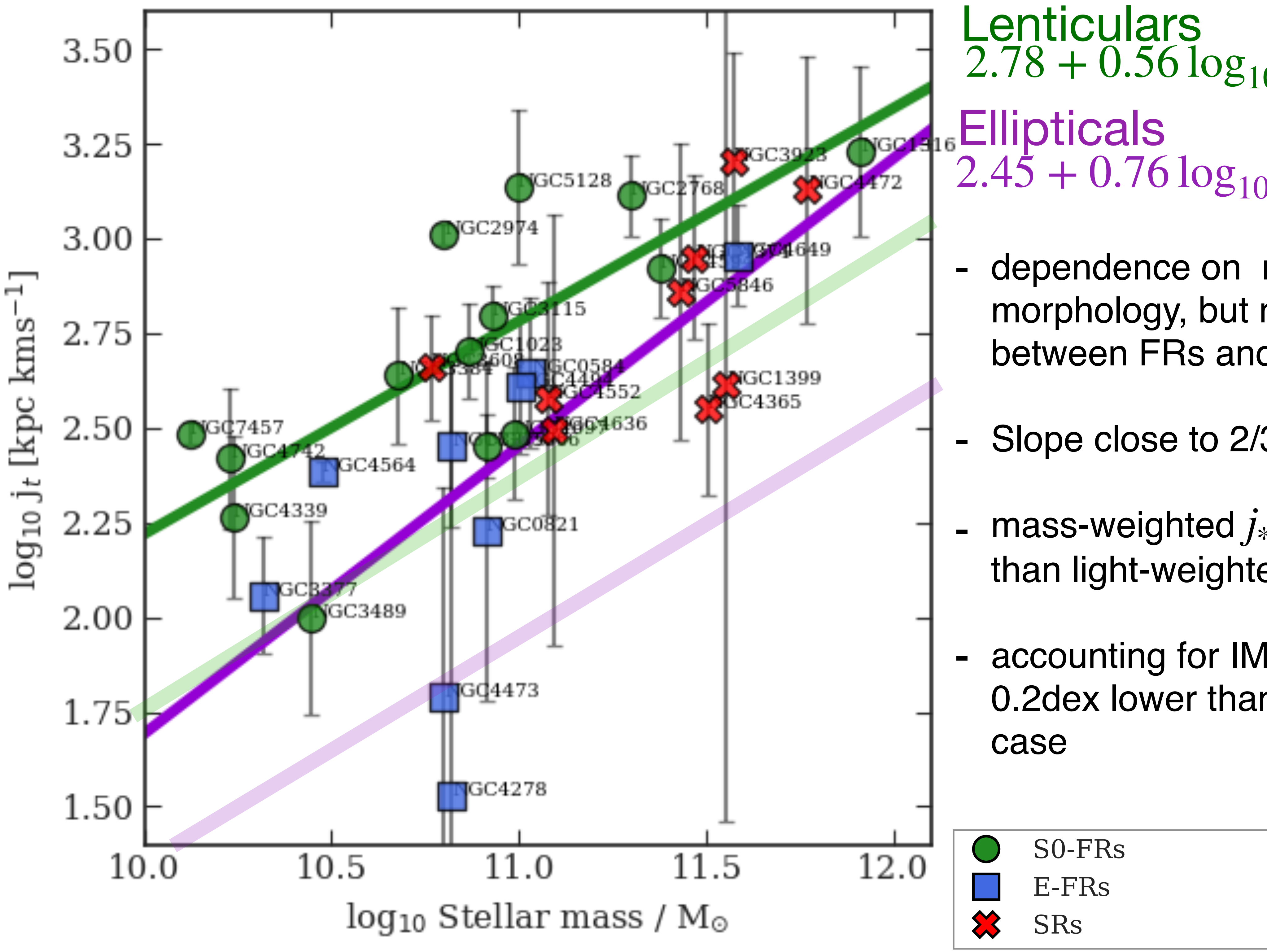

Lenticulars

$2.78 + 0.56\log_{10} M_*/(10^{11}M_\odot)$

Ellipticals

$2.45 + 0.76\log_{10} M_*/(10^{11}M_\odot)$

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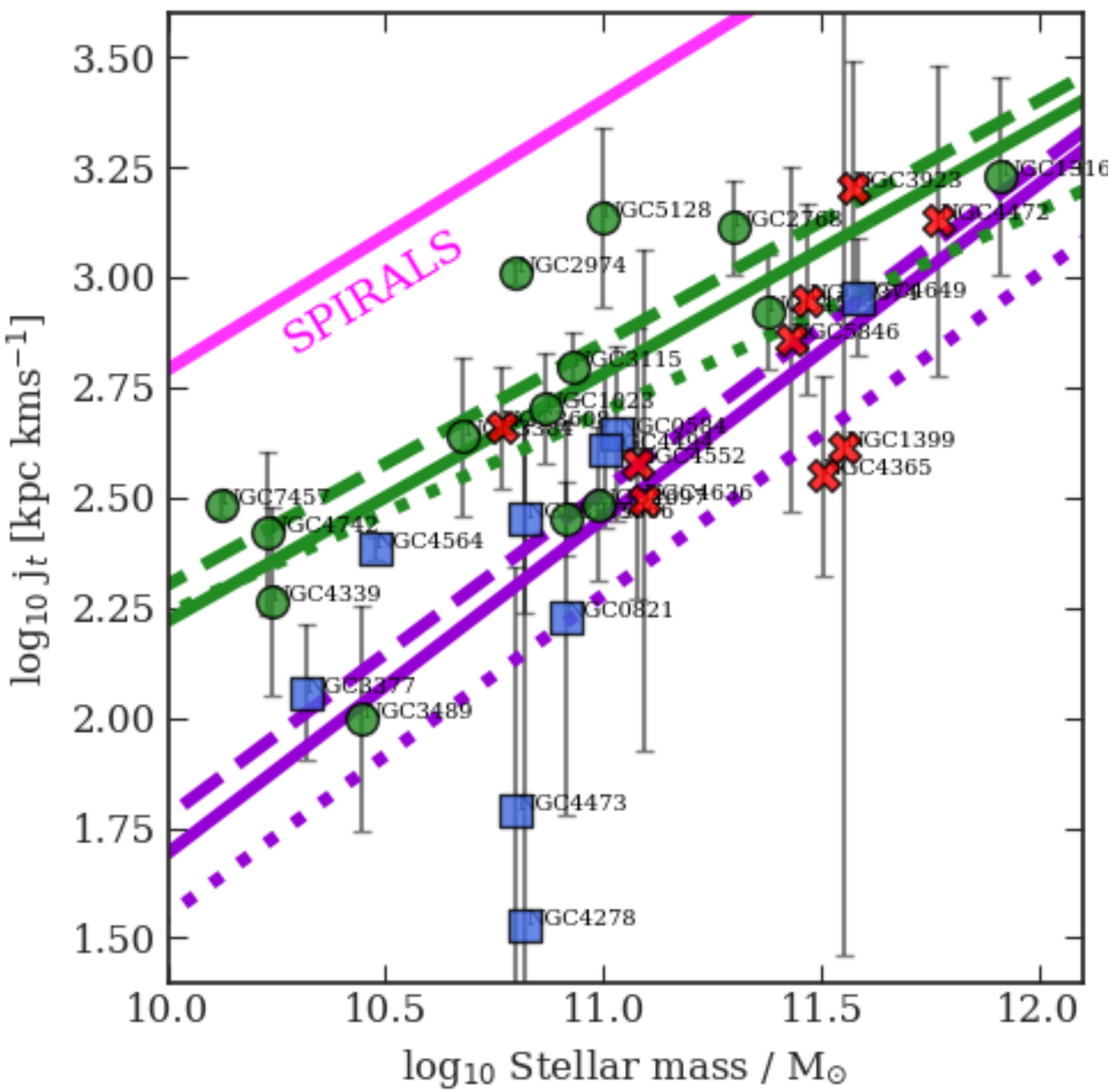

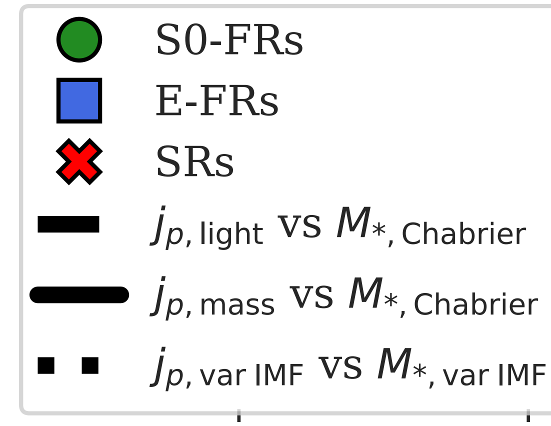

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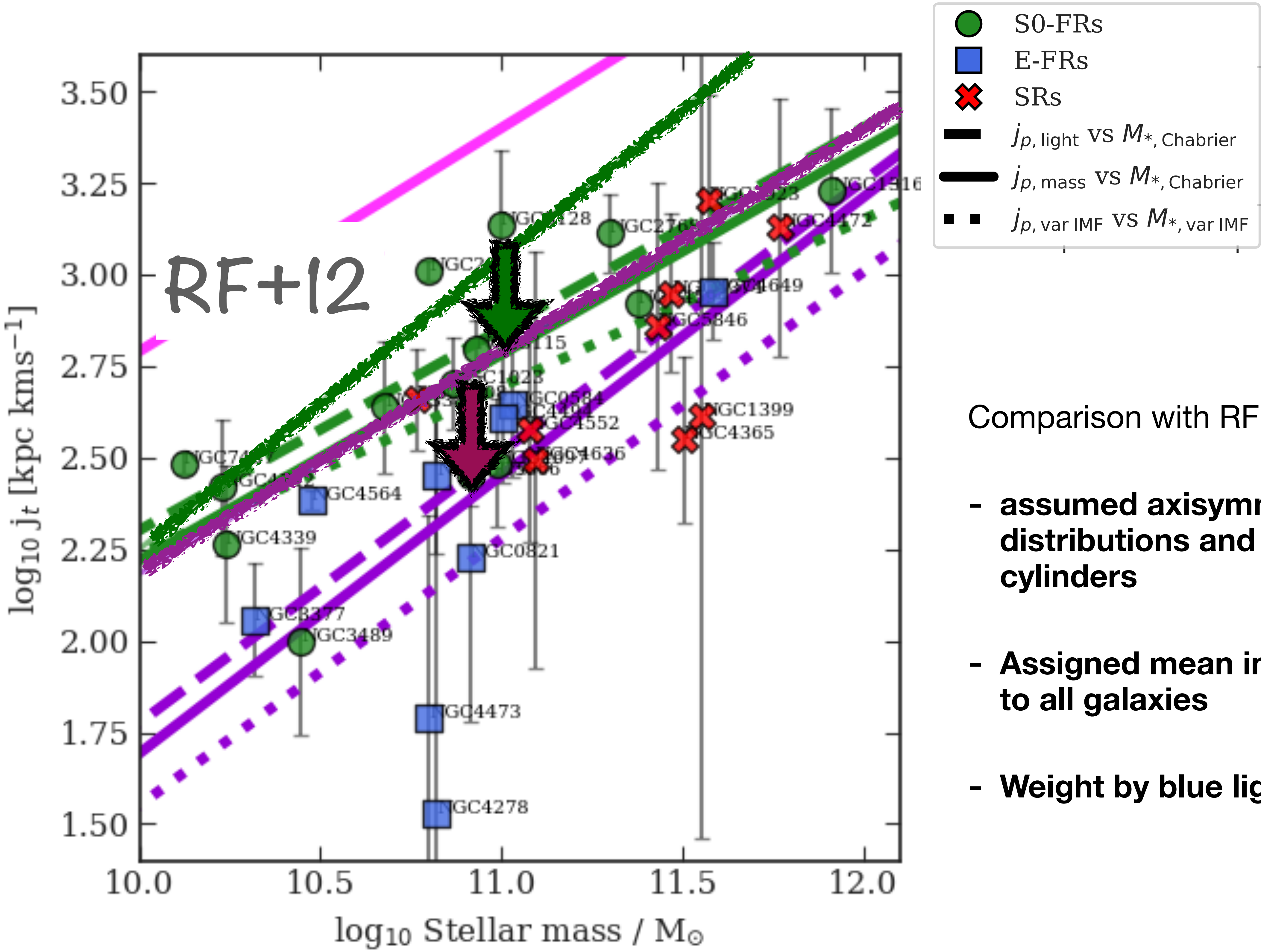
Es have a factor of 2-3 lower j_* than S0s and about 10-15 times lower than the spirals

Pulsoni+2023

The angular momentum content of ETGs

The Fall relation for ETGs

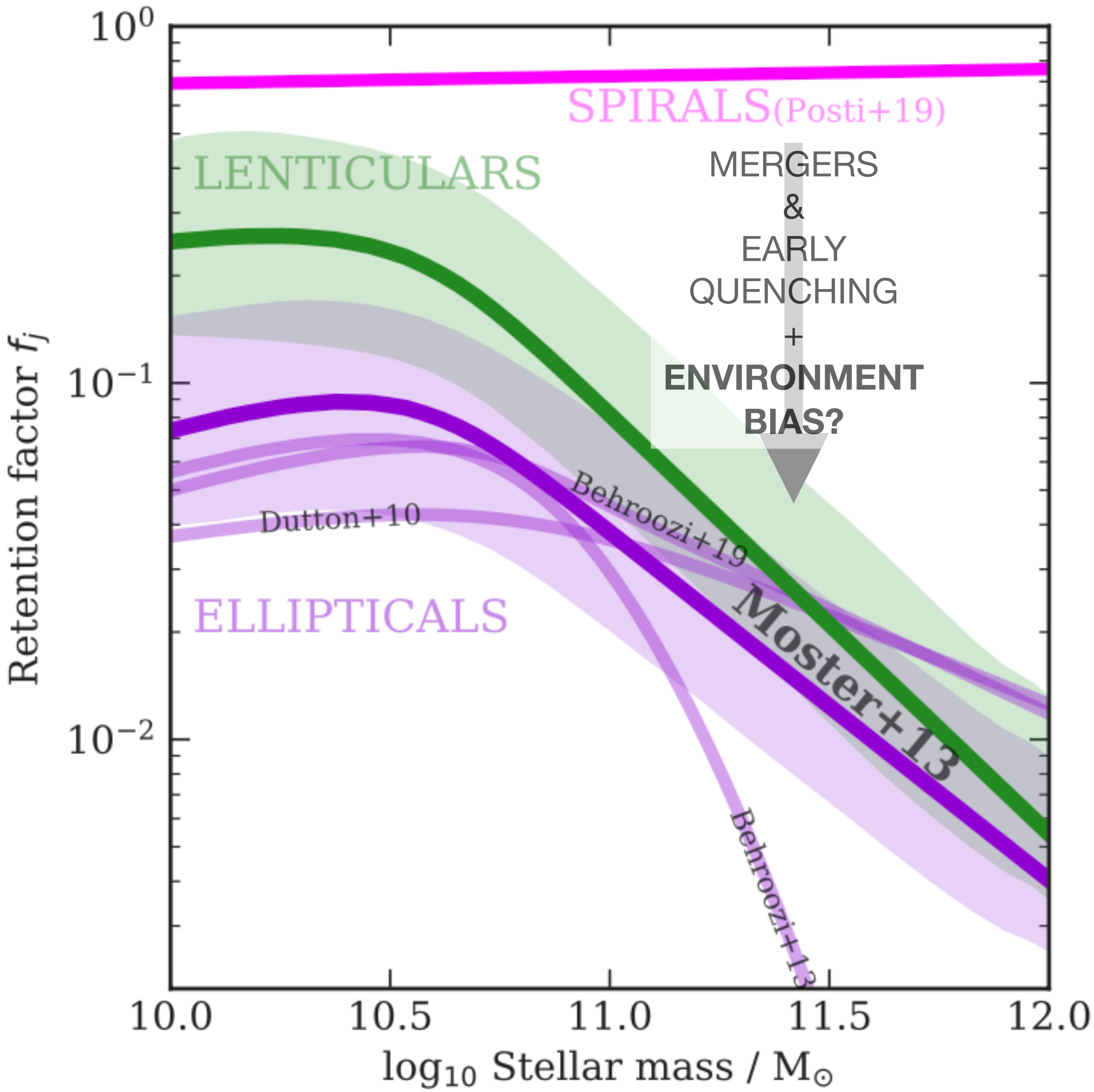


Comparison with RF+12

- **assumed axisymmetric density distributions and rotate on cylinders**
- **Assigned mean inclination of 40deg to all galaxies**
- **Weight by blue light**

Pulsoni+2023

The sAM retention factor



Pulsoni+2023

Tidal torque theory
Peebles 1969

$$j_h \equiv \frac{J_h}{M_h} \propto \left(\frac{M_h}{M_\odot}\right)^{2/3} \text{ kpc km s}^{-1}$$

retained fraction of sAM

$$f_j \equiv \frac{j_*}{j_h} = \frac{j_*}{\text{const } M_h^{2/3}}$$

- At $10^{10} - 10^{10.5} M_\odot$ S0s retain $\sim 30\,\%\, j_h$, while Es only $\sim 10\,\%$.
- At higher M_*, f_j strongly decreases with the star formation efficiency
- Difference with spirals from (dry) mergers, AGN feedback, and early SF quenching

(Genel et al. 2015; Zavala et al. 2016; Lagos+2017,2018; Rodriguez-Gomez et al. 2022)

Conclusions

- We measured j_* in a sample of 32 ETGs using 2D kinematic data out to a mean 6Re
- In the $j_* - M_*$ plane, S0s and Es follow power-laws similar to spirals but much lower normalisation: Es have factor of 2-3 lower j_*than S0s and 10-15 times lower than the spirals
- At $10^{10} - 10^{10.5} M_{\odot}$, the retention factor is of the order fj~30% for the S0s and fj<10% for the Es and strongly decreases with the star formation efficiency. Uncertainties due to the environment.
- Way forward: understand the evolution of $j_{\star}$ in ETGs by targeting their likely progenitors at high z.