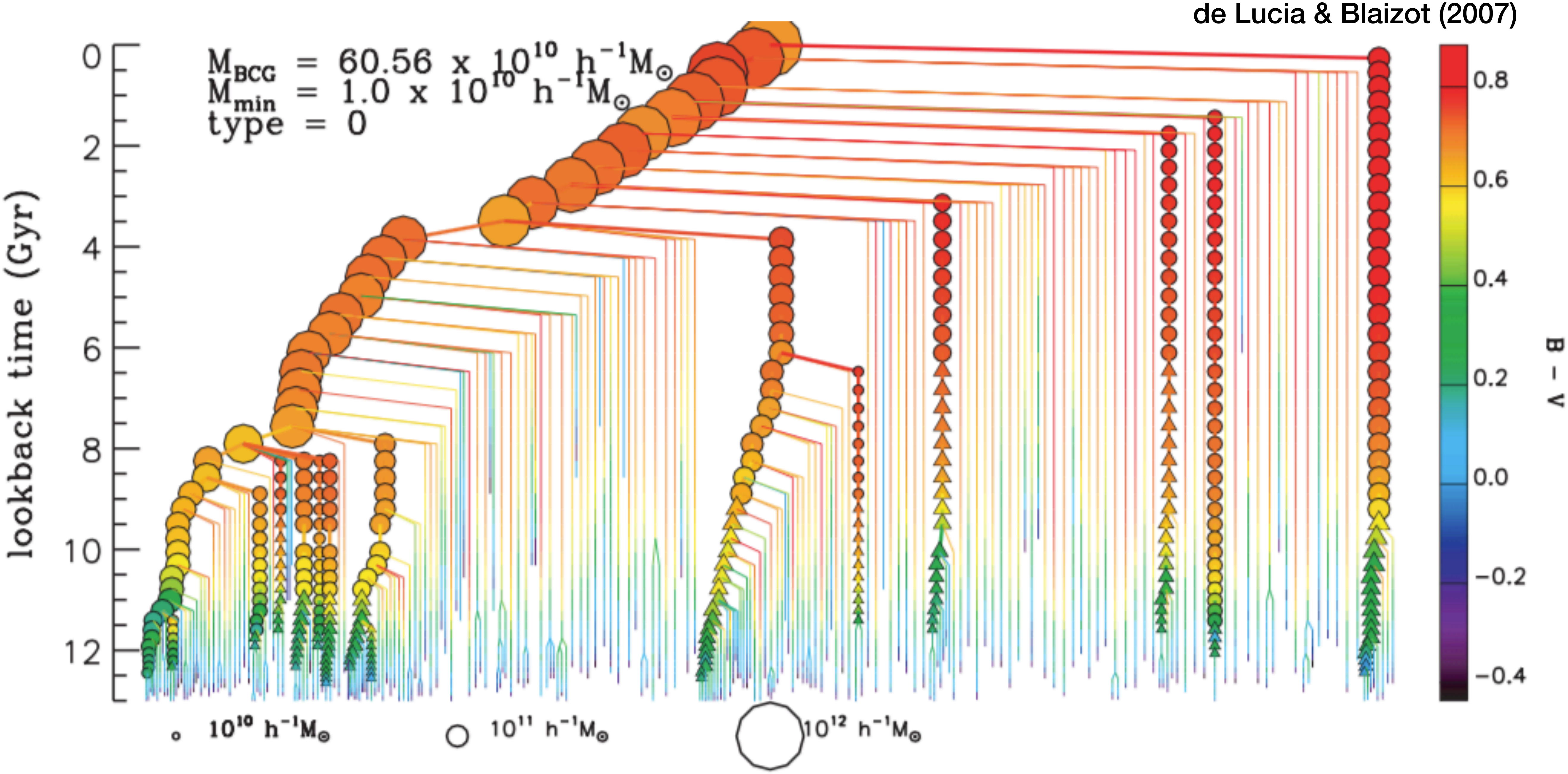
Formation processes of massive galaxies

AIP

Davor Krajnović
Vienna, 16.04.2018

How do massive galaxies assemble their mass?

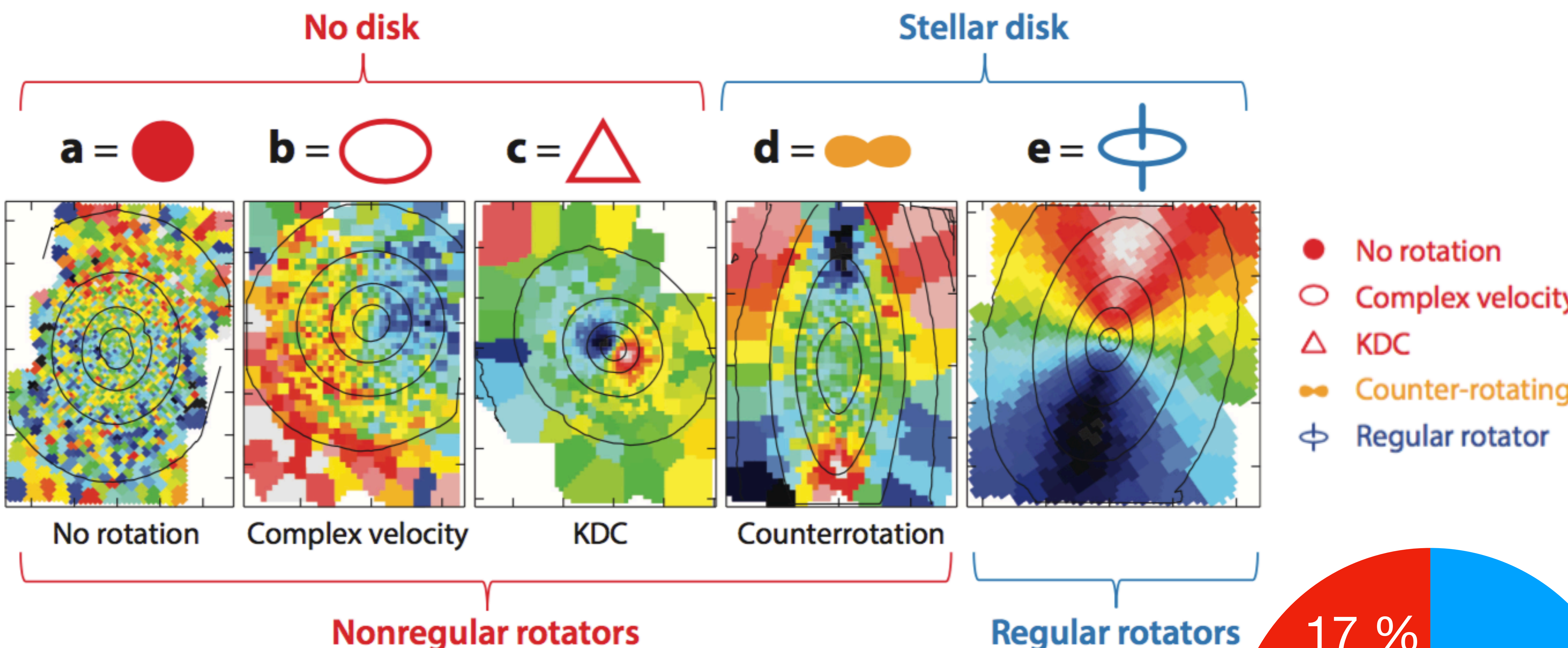
de Lucia & Blaizot (2007)

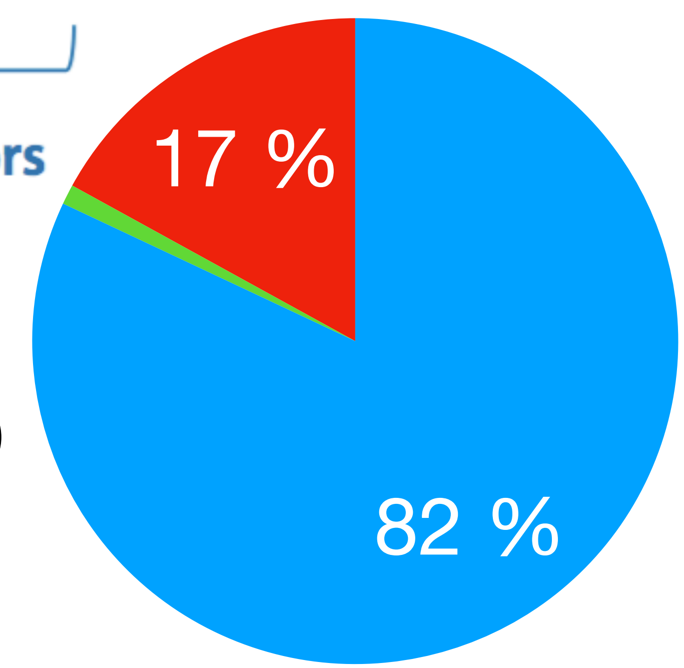


What are the constraints that distinguish between formations paths ?

What do we know (from nearby Universe)?

Stellar kinematics





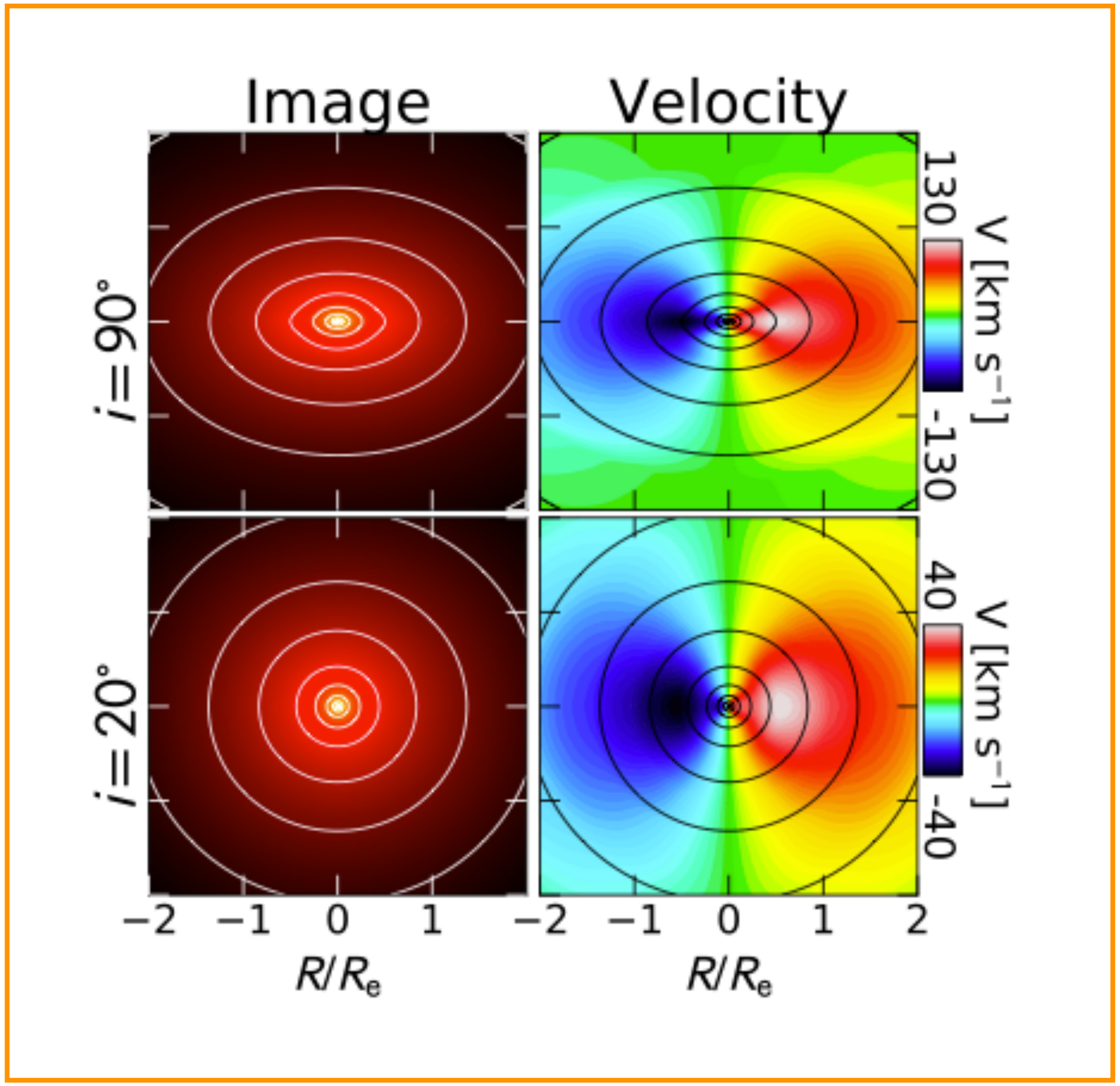
- a magnitude limited sample of ETG
- majority of ETGs show **regular rotation --** boring (like disks)
- others have **non-regular rotation --** exciting (KDC, counter rotation, no rotation)

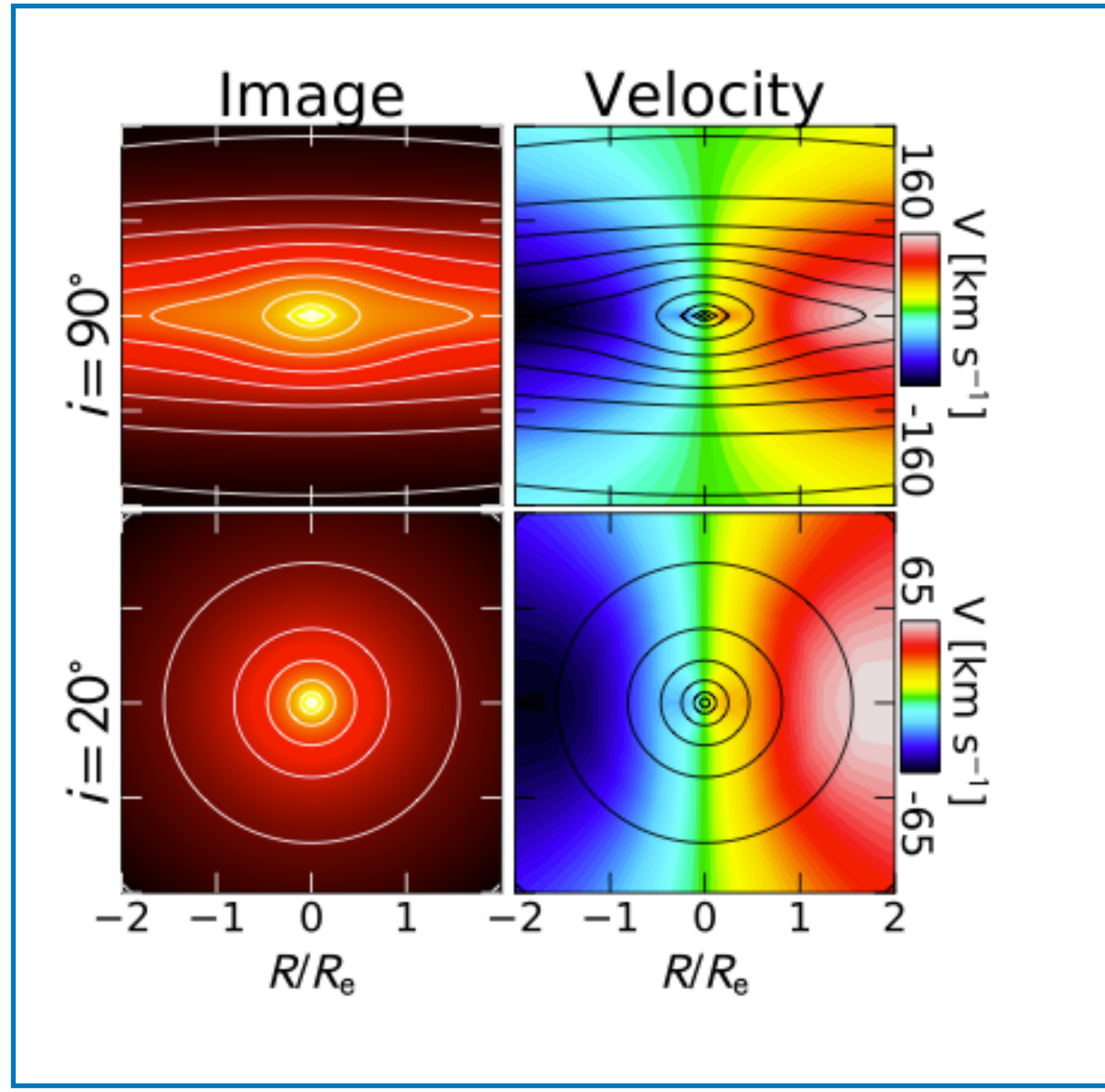
Krajnović et al. 2008, 2011 (top image from Cappellari 2016, ARAA)

Misleading shapes

Stellar kinematics to the rescue

Cappellari (2016)



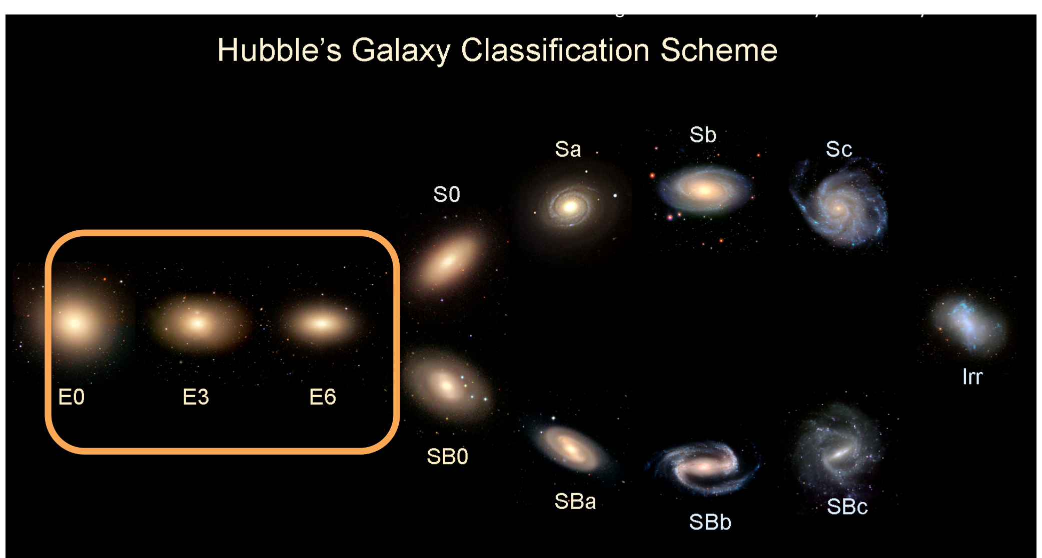


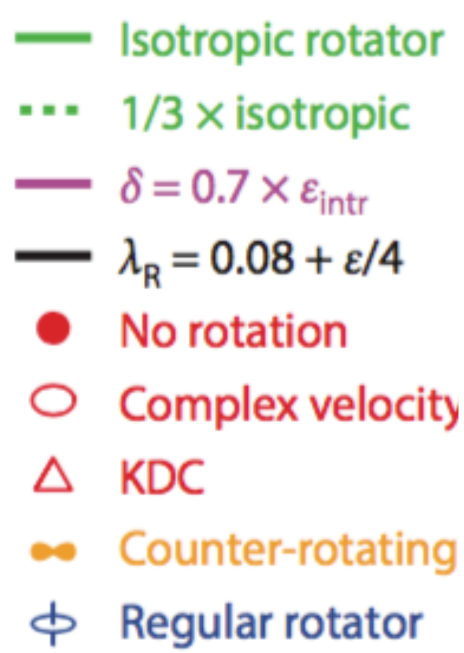
- two different galaxies seen at different inclinations - **kinematics always tells the truth**
  - **discy elliptical** - an ellipsoid with an embedded disc
  - **S0** - disc dominated galaxy with a spherical bulge

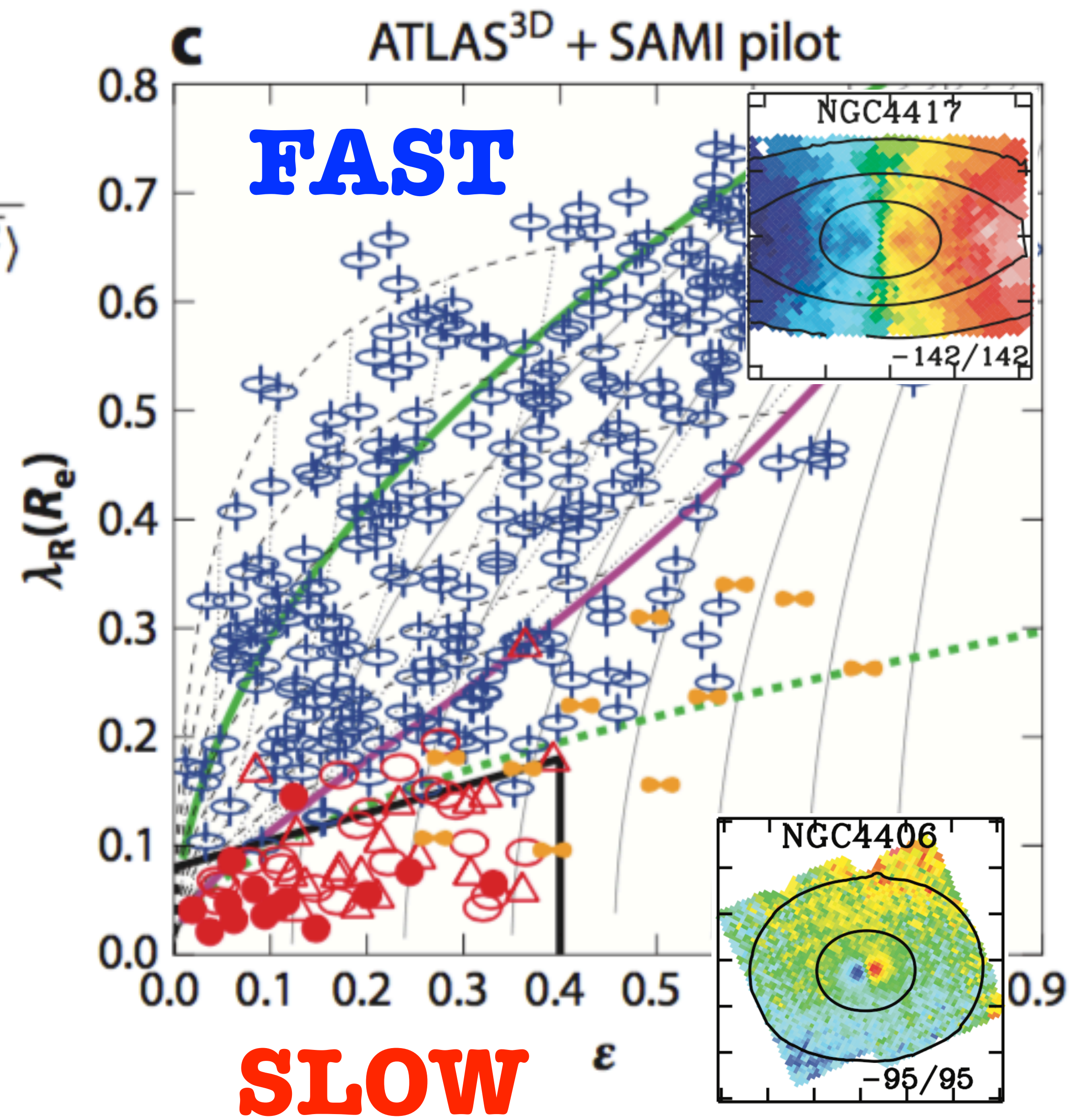
Classifying galaxies

- **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
- a **physical way** to classify early-type galaxies

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



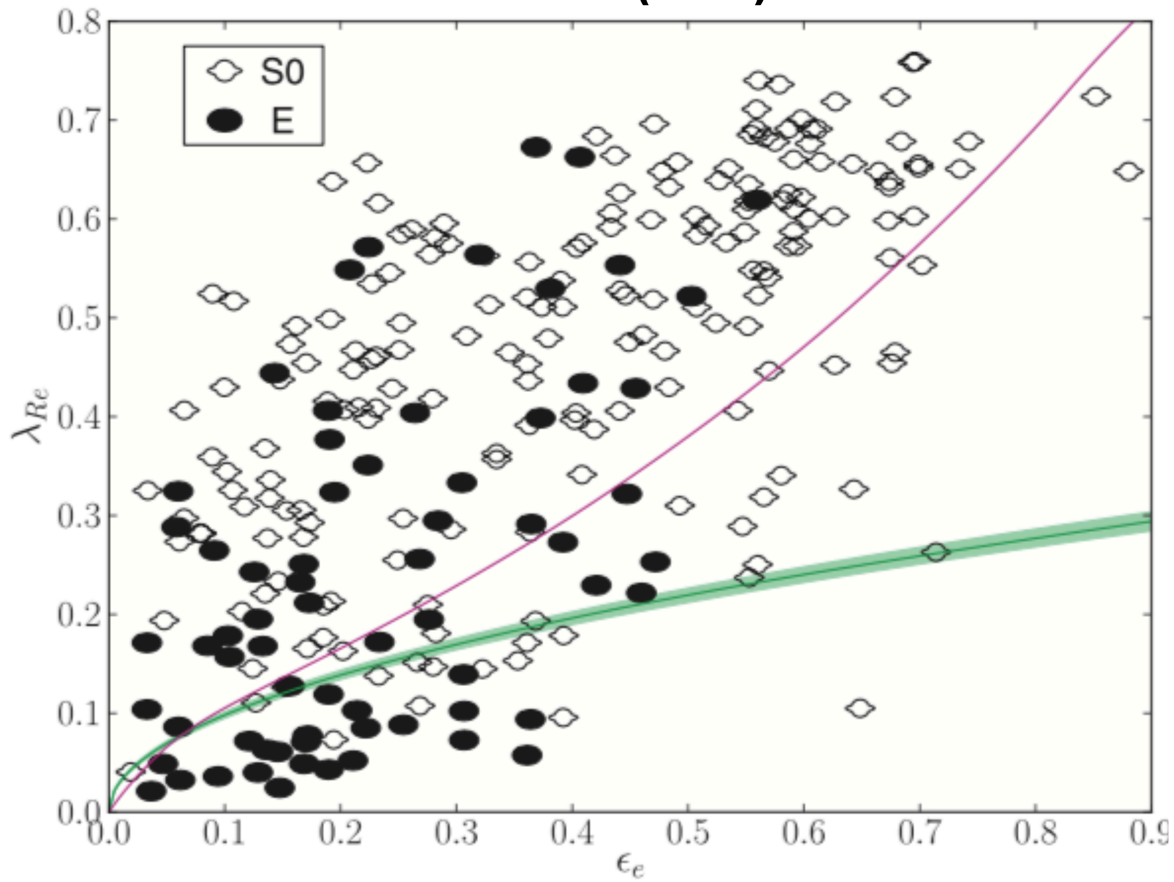




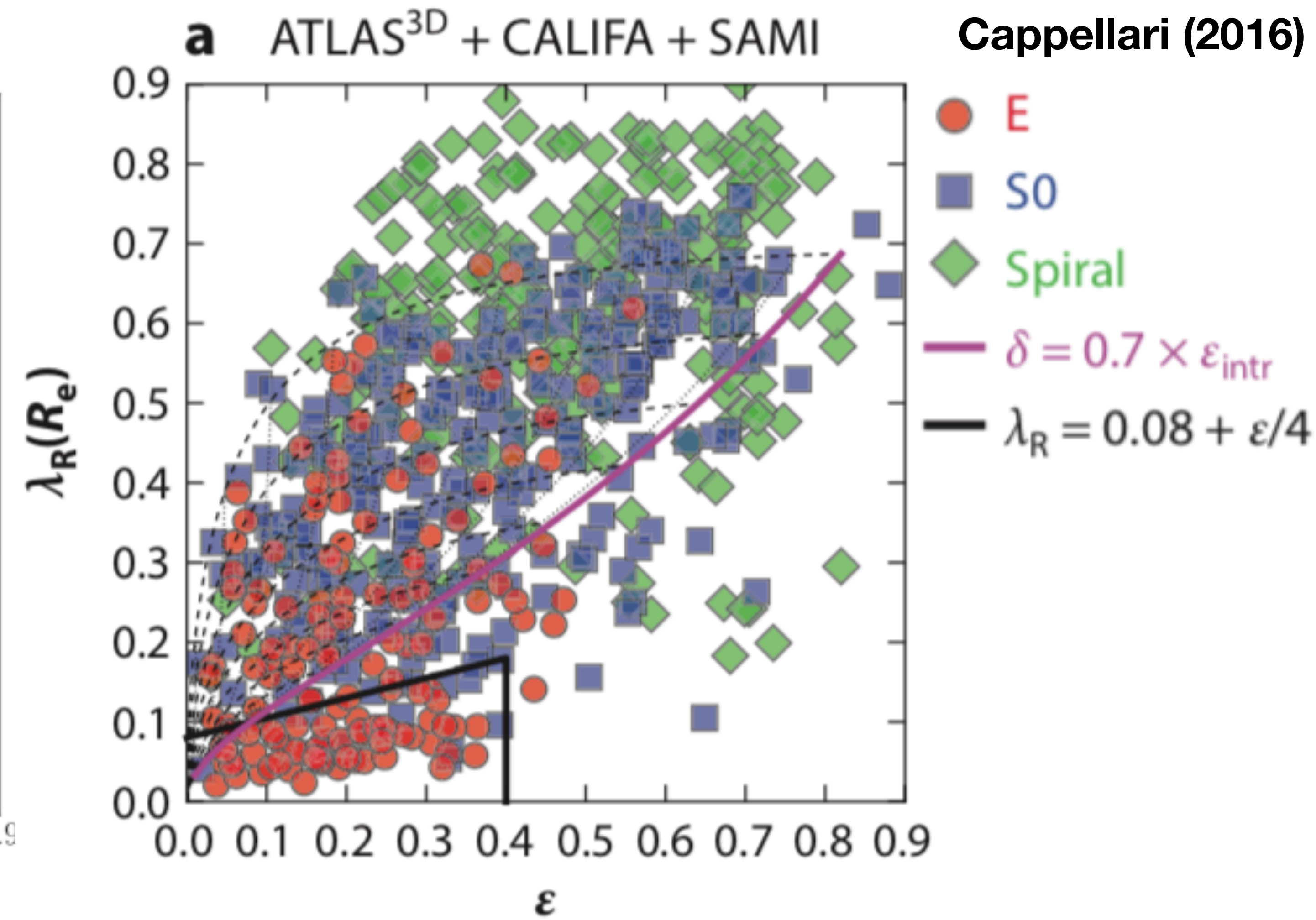
Emsellem et al. 2007, 2011 (image from Cappellari 2016, ARAA)

Hidden disks

Emsellem et al. (2011)

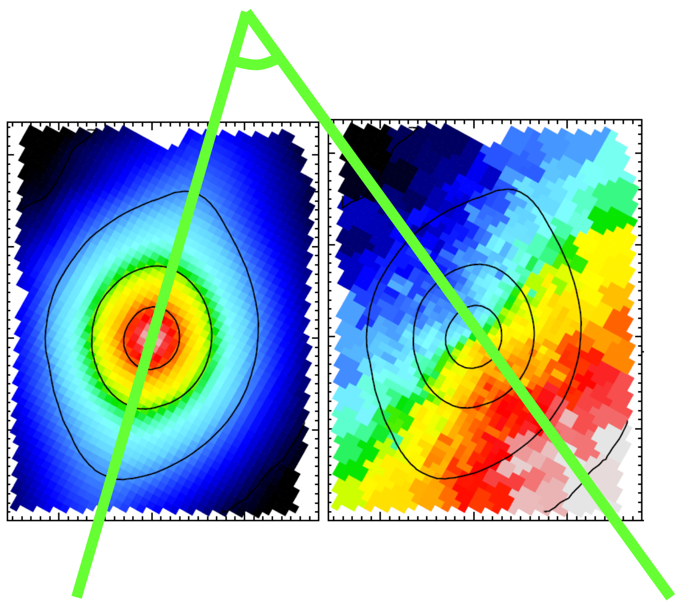


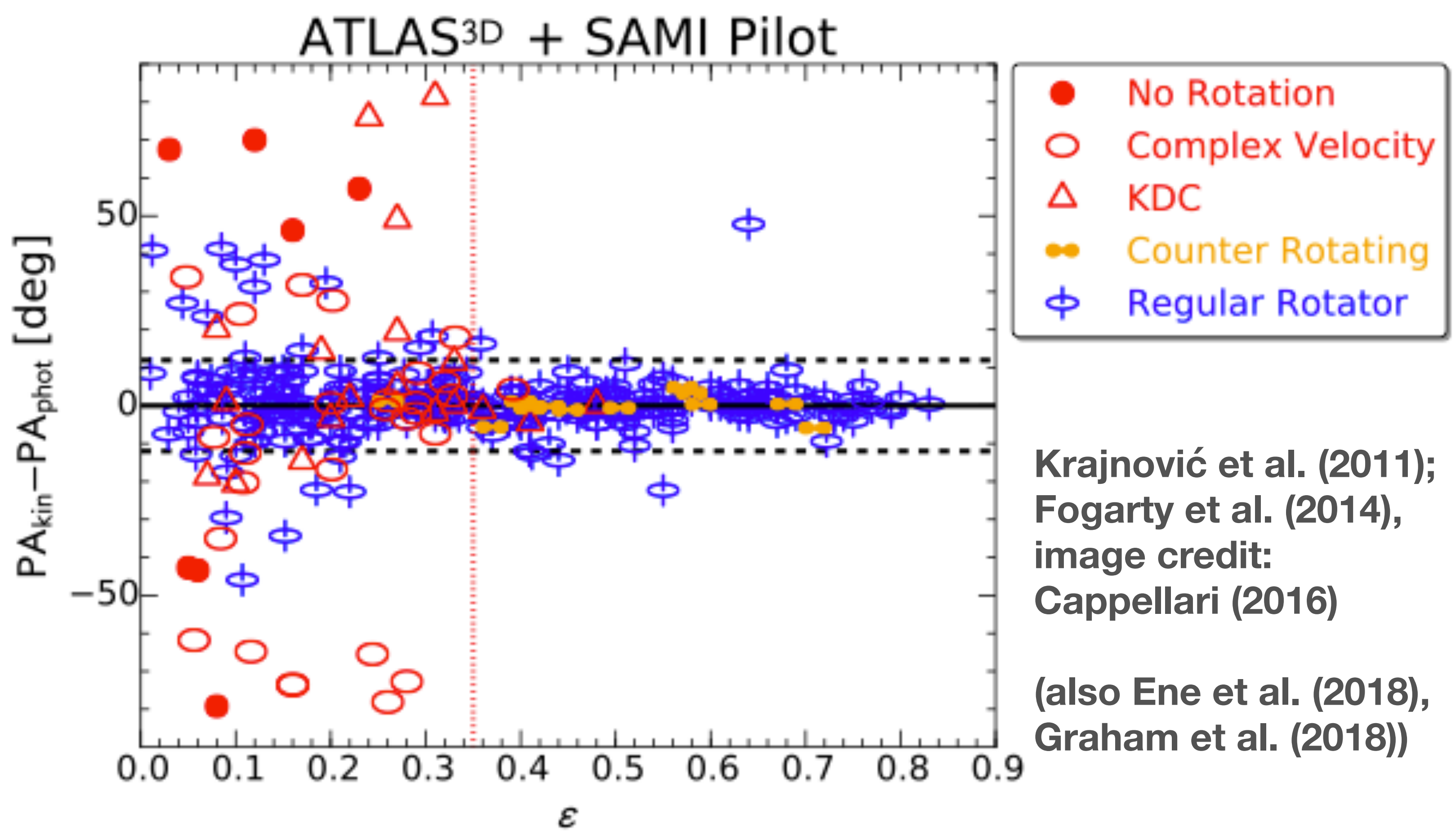
Cappellari (2016)



- **2/3** of ellipticals are **fast rotators** --> they **have** discs
- **1/3** of ellipticals are **slow rotators** --> they **do not have** discs
- **stellar kinematics offers the best means of finding disks in (passive) galaxies** (also at z>0)

Kinematic misalignment





Krajnović et al. (2011); Fogarty et al. (2014), image credit: Cappellari (2016)

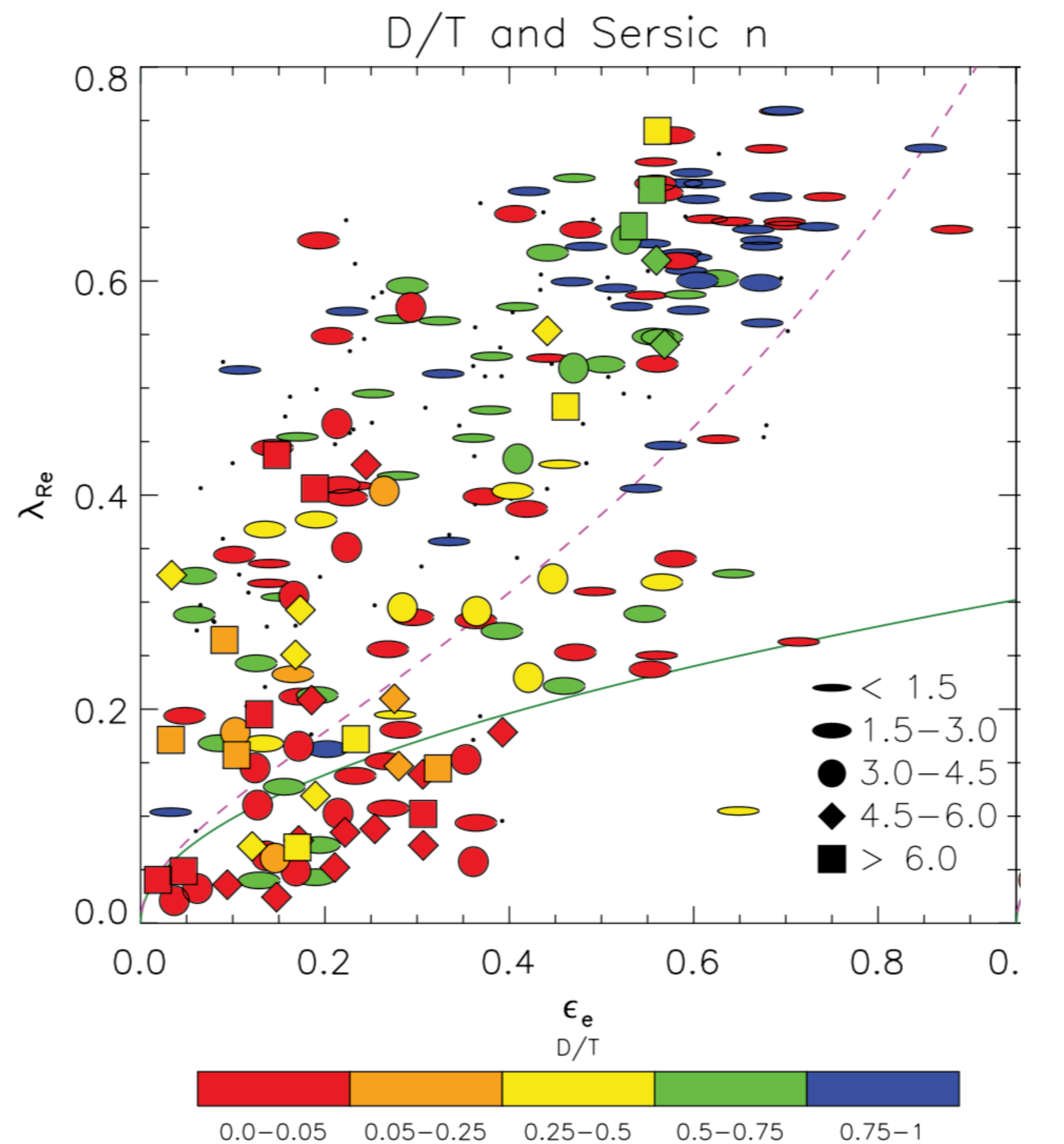
(also Ene et al. (2018), Graham et al. (2018))

- **regular rotation**: aligned —> nearly axisymmetric systems (+ bars or interacting)
- **non-regular rotation**: (also) misaligned —> triaxial systems

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

Disks in early-type galaxies

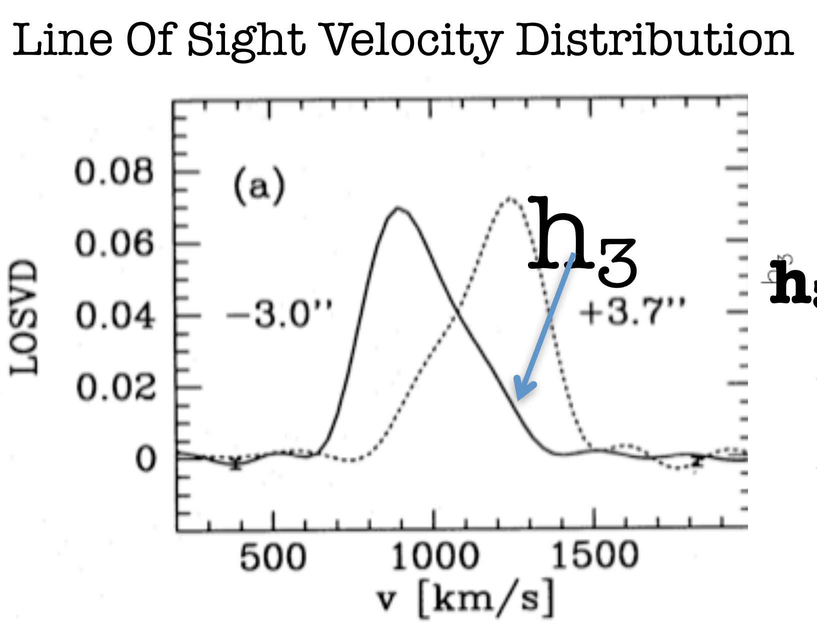
Krajnović et al. (2013a)



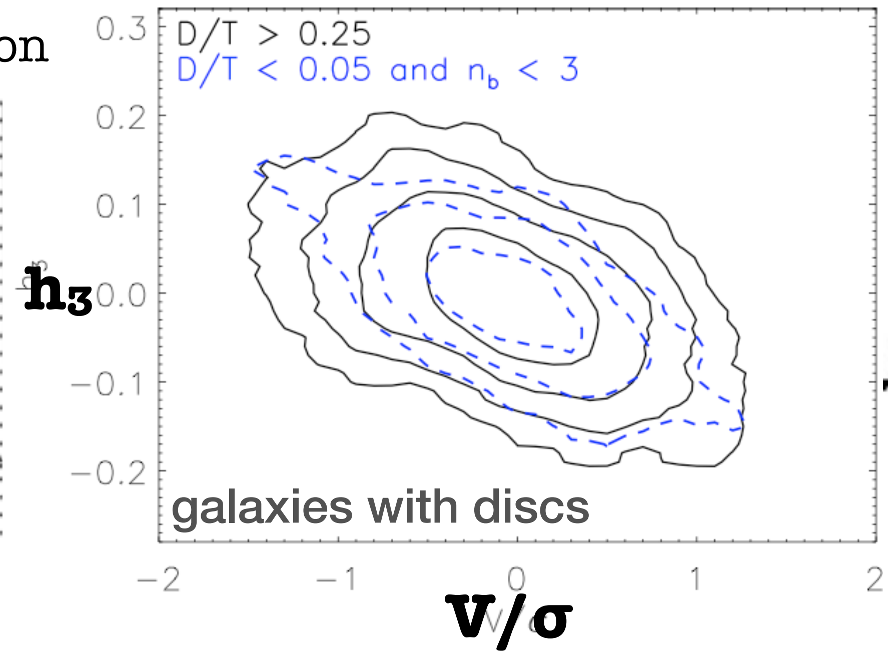
- **fast rotators** are oblate and axisymmetric, but **do they have disks**?
- photometric decomposition of non-barred ETGs
  - **light fraction** of disks **increases** with **angular momentum**
  - **Sersic index increases** with **decreasing angular momentum**
- clear correlation with photometric decomposition
- best tracer of stellar disks is kinematics

Kinematic evidence for discs

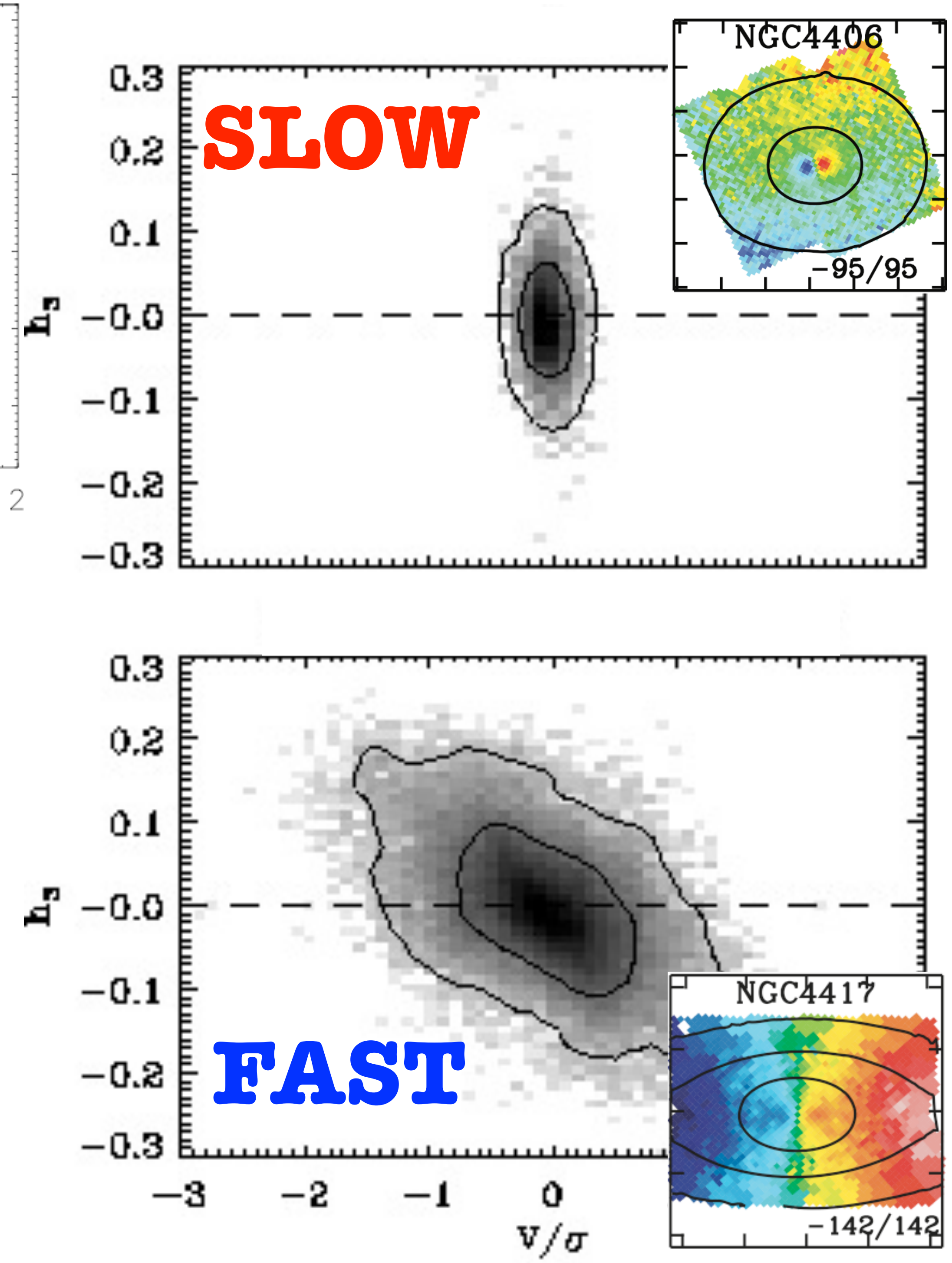
Bender et al. (1994)



Krajnović et al. (2013a)

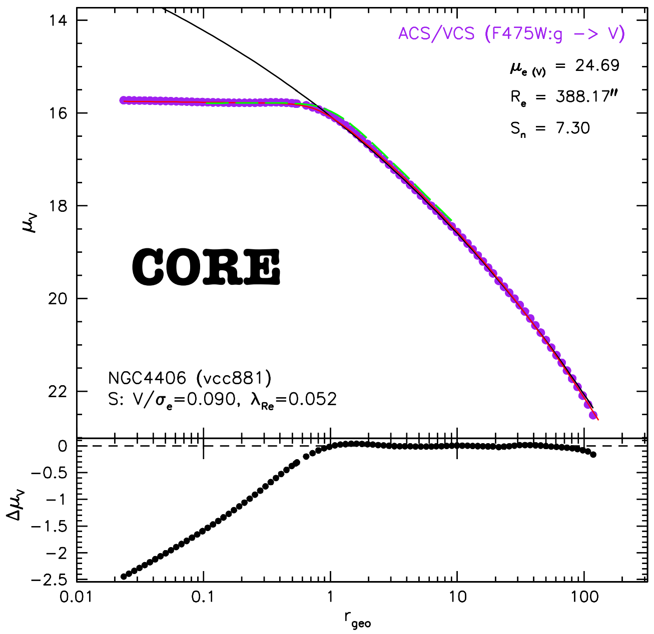


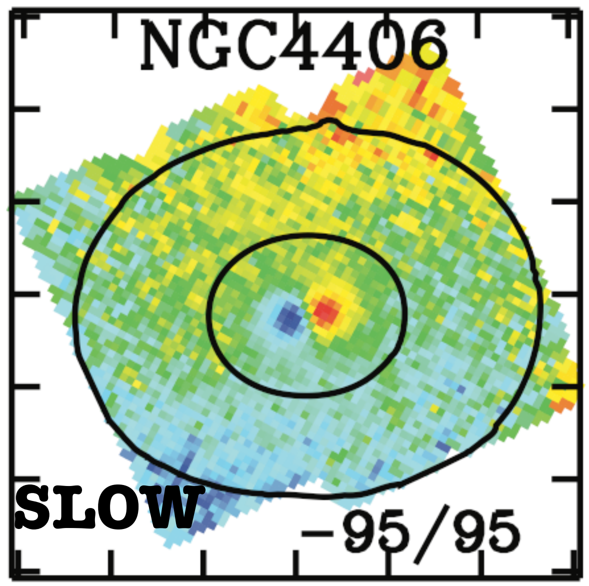
Krajnović et al. (2011)

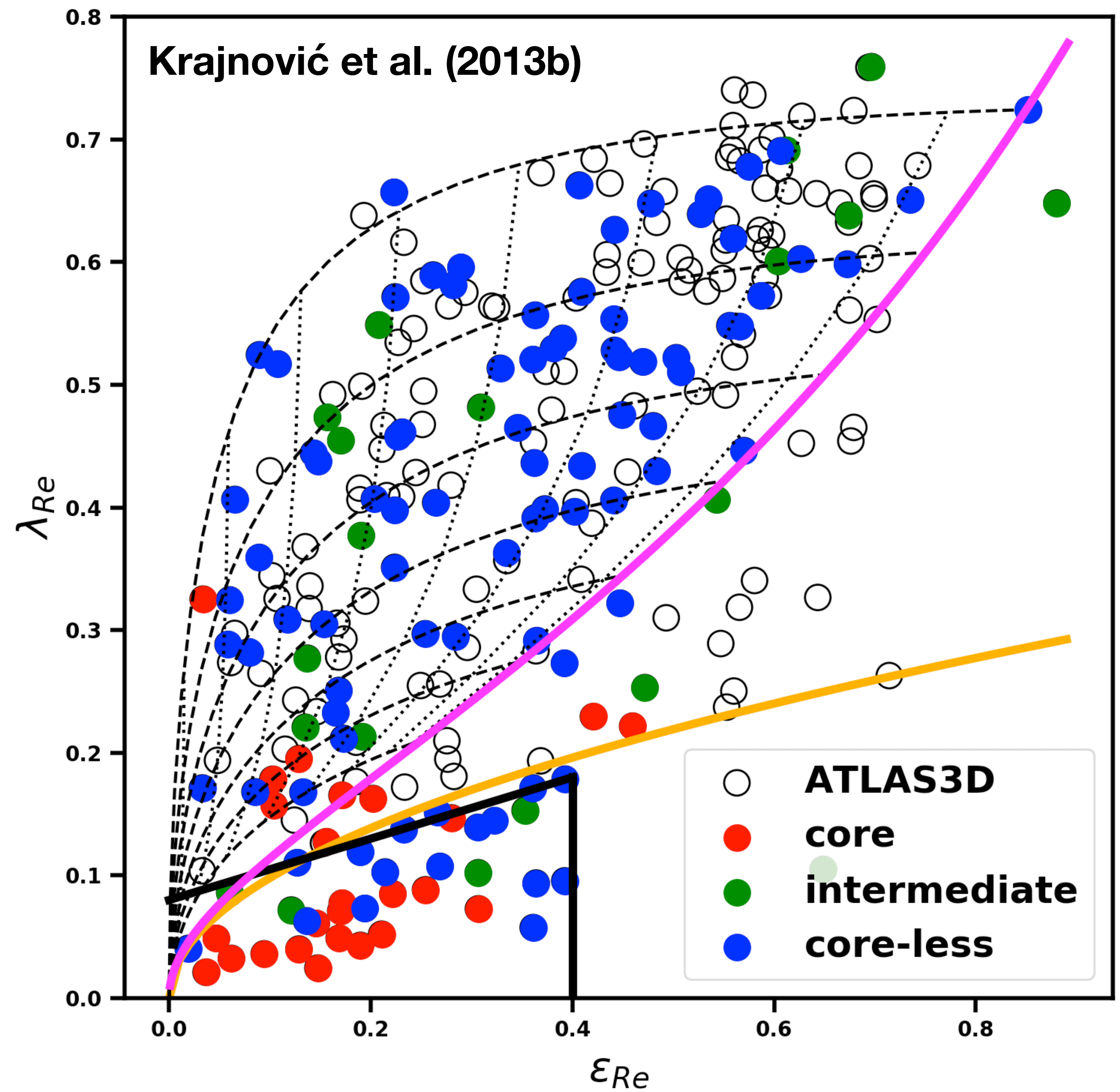


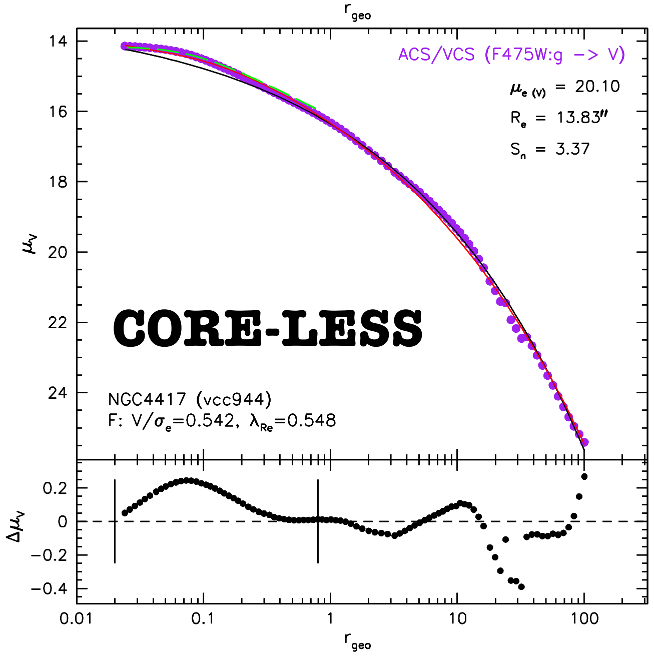
- Asymmetric deviation measured in LOSVD by h_3 Gauss-Hermite coefficient
    - Typical of embedded discs
- **Fast rotators** – have discs
- **Slow rotators** – no discs
- **Discs are present in the vast majority of galaxies**

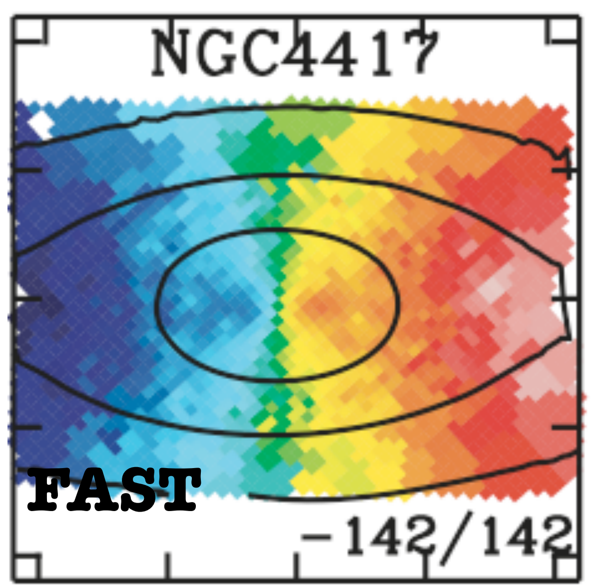
Nuclear surface brightness profiles









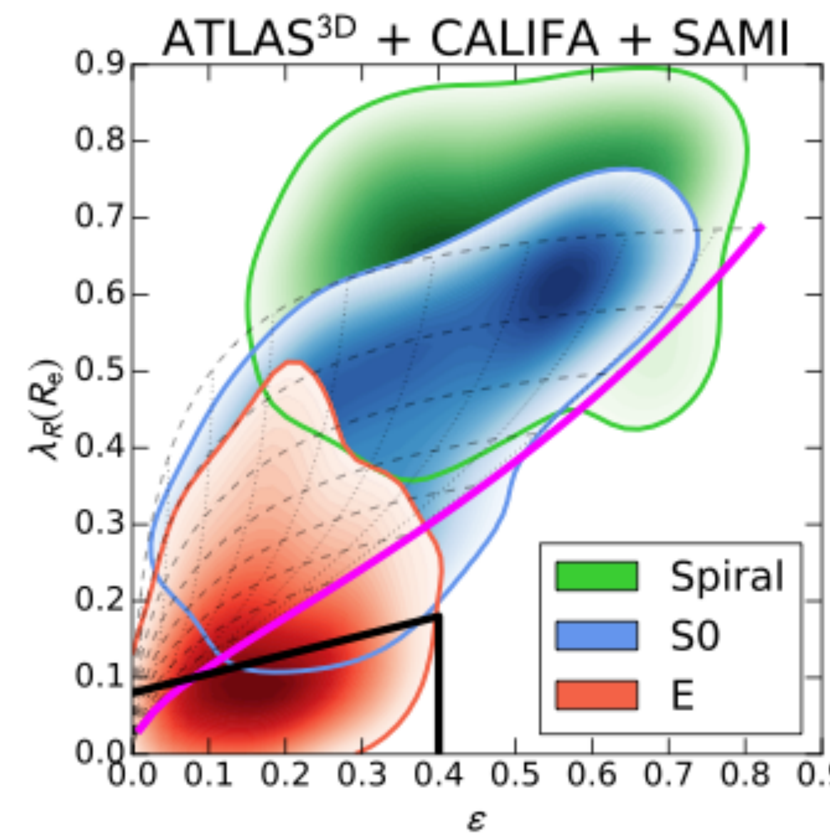


- **most massive** Slow Rotators **have cores,** but exceptions exist
- **cores** are thought of being formed in **mergers of SMBH**

Angular momentum across the Hubble sequence

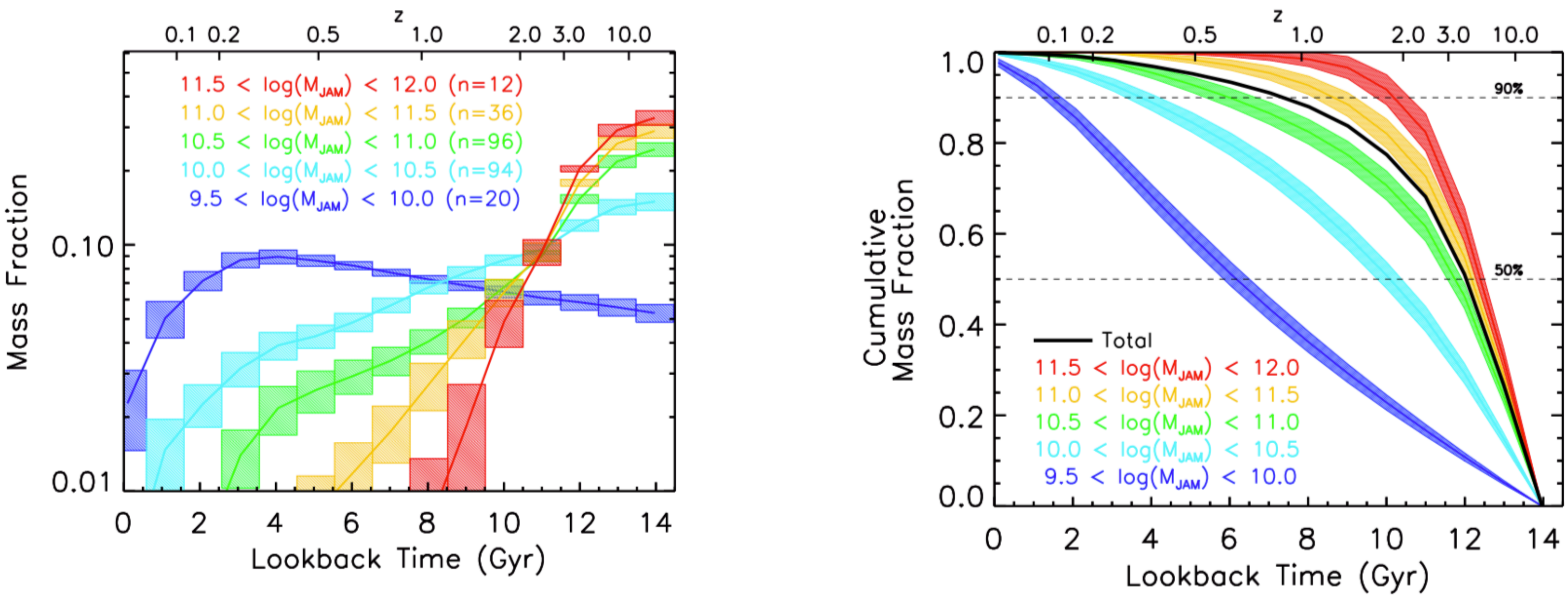
- Distinction between ellipticals and S0s has little physical meaning
- **Spiral galaxies** have highest angular momenta
- **Fast rotators**: galaxies with discs or flattened
    - rotation supported structure, low velocity dispersion, low Sersic index, core-less profiles, oblate axisymmetric
- **Slow rotators** (true ellipticals)
    - low rotation, high velocity dispersion, high Sersic index, core light profiles, spherical or triaxial (or prolate) shape

Cappellari et al. (2016)



Stellar populations in ETGs

McDermid et al. (2015)

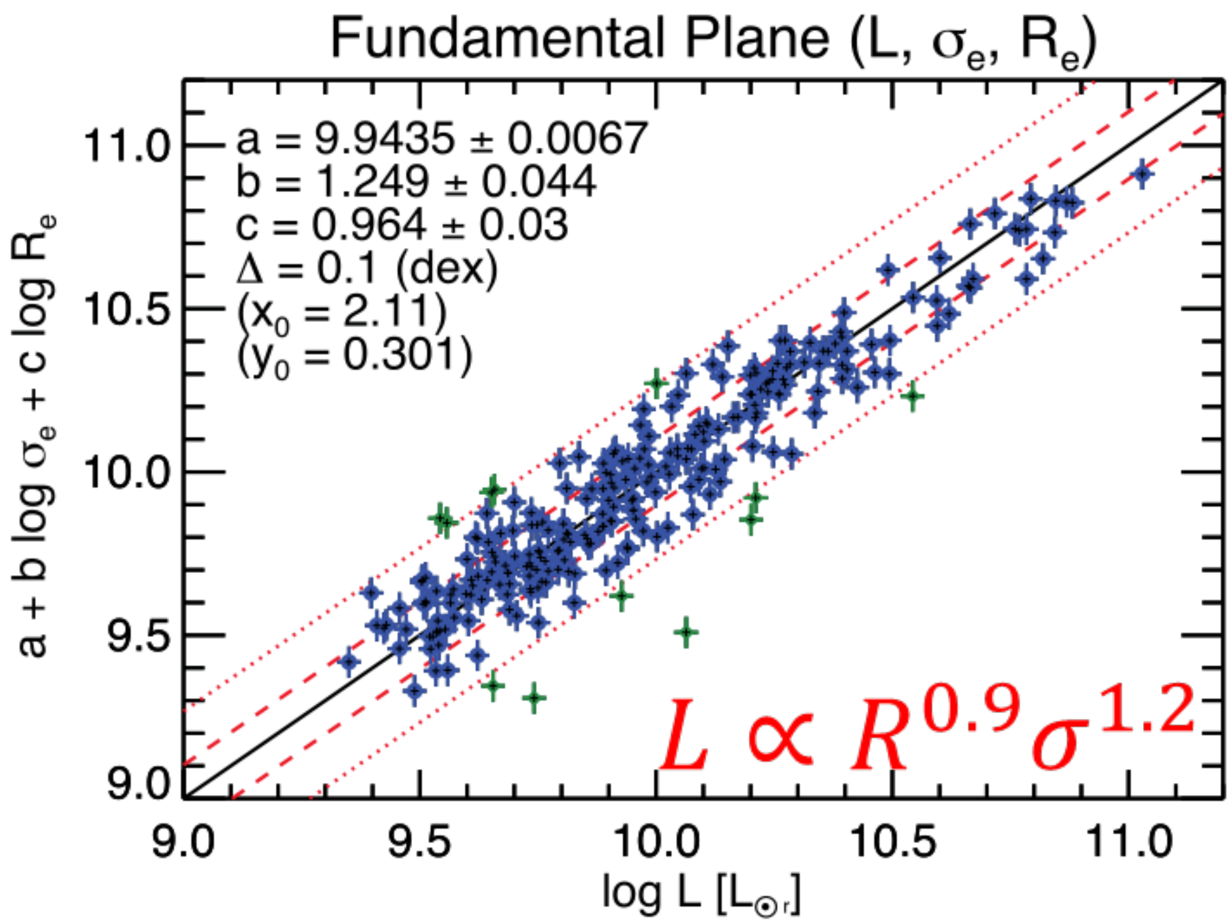


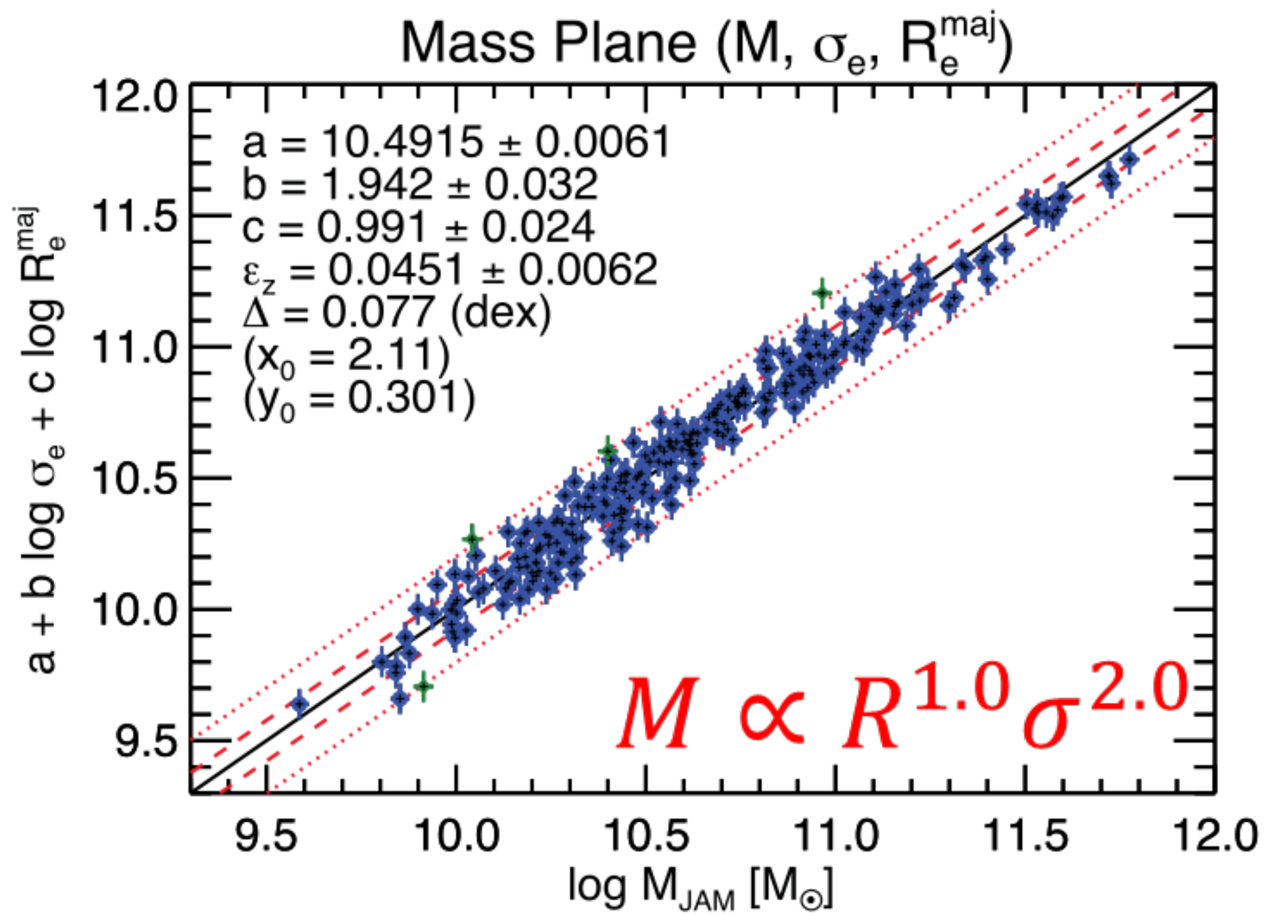
- star-formation is more **extended** in **lower mass** objects
- **massive galaxies** formed **90%** of their stars **by z~2** (only 50% for lower mass galaxies)
- for z<2 SF intense in all types of galaxies; for z>2 mass and environment influence
- the most massive ETGs have experienced fast quenching, most galaxies have extended stellar pop. build up at larger radii

Burstein et al. 1984; Peletier 1989; Faber et al. 1992; Davies et al. 1993; Worthey 1994, Jørgensen 1997, Trager et al. 2001; Maraston et al. 2003; Thomas et al. 1999, 2005; Kaviraj et al. 2007; Kuntschner et al. 2010; Vazdekis et al. 2012; Conroy & van Dokkum 2012; Greene et al. 2015; Wilkinson et al. 2015; Gonzalez-Delgado et al. 2017

Fundamental plane —> Mass plane

Cappellari et al. (2013)



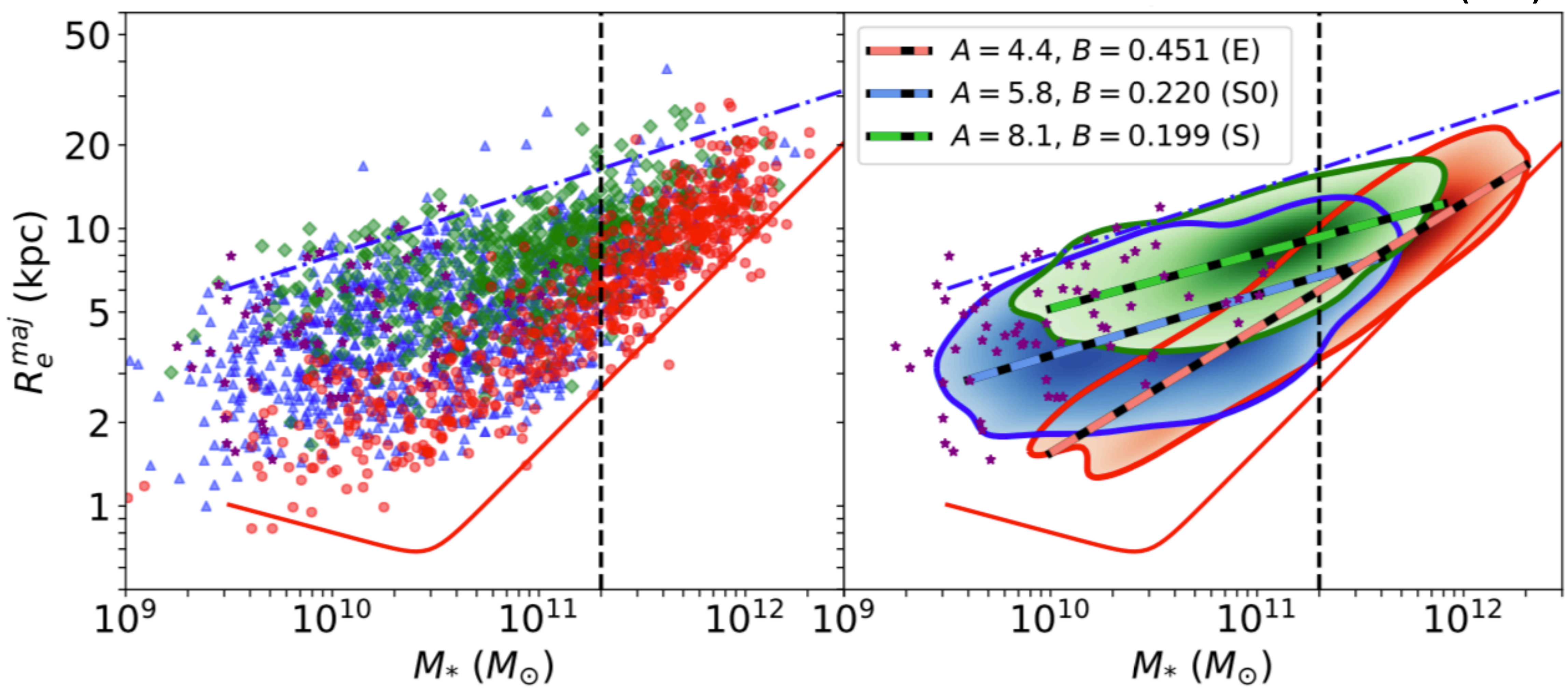


Luminosity → Mass (JAM models)

- MP has no intrinsic scatter: FP scatter due to population
- Follows virial prediction (Cappellari+06, Bolton+08, Auger+10)
- Technique used for R_e matters!

Mass-Size diagram

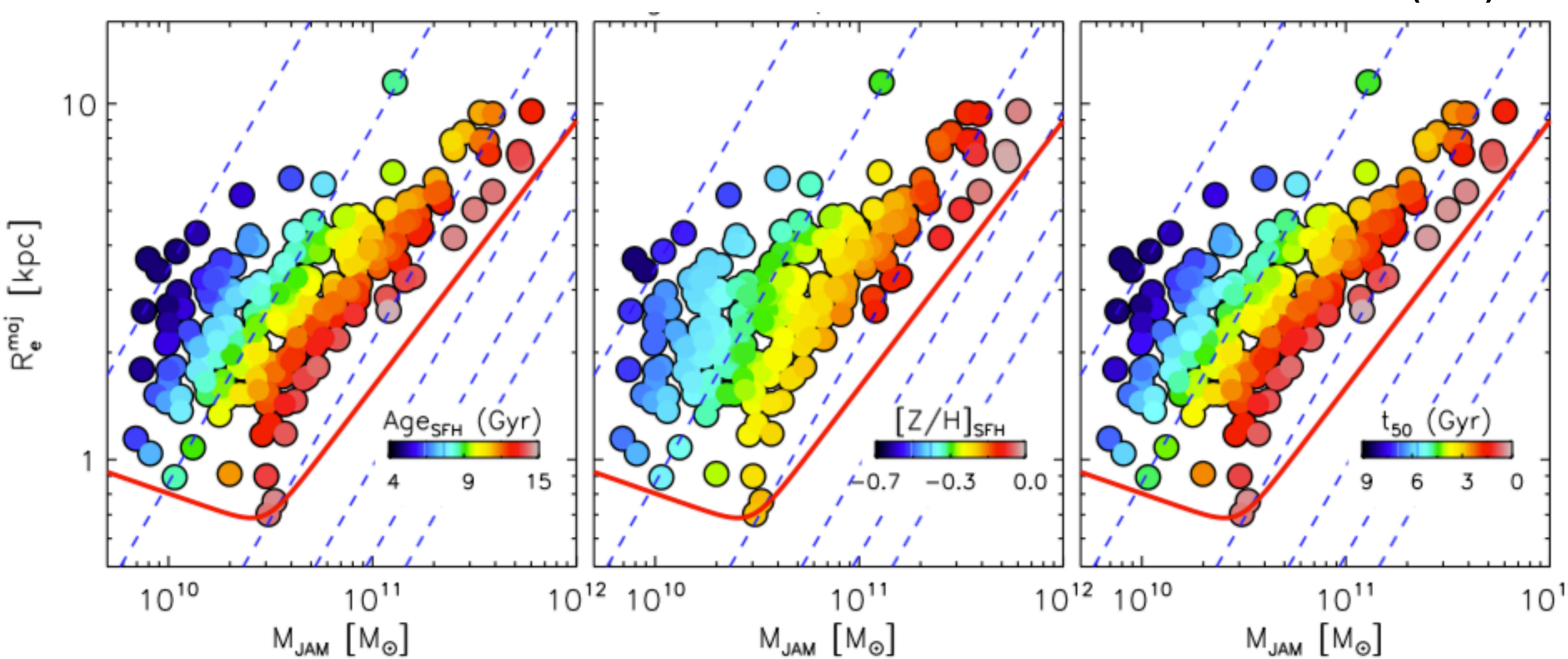
Graham et al. (2018)



- a projection of the mass plane
- how do properties of galaxies change on the mass - size?

Stellar populations & Mass - Size

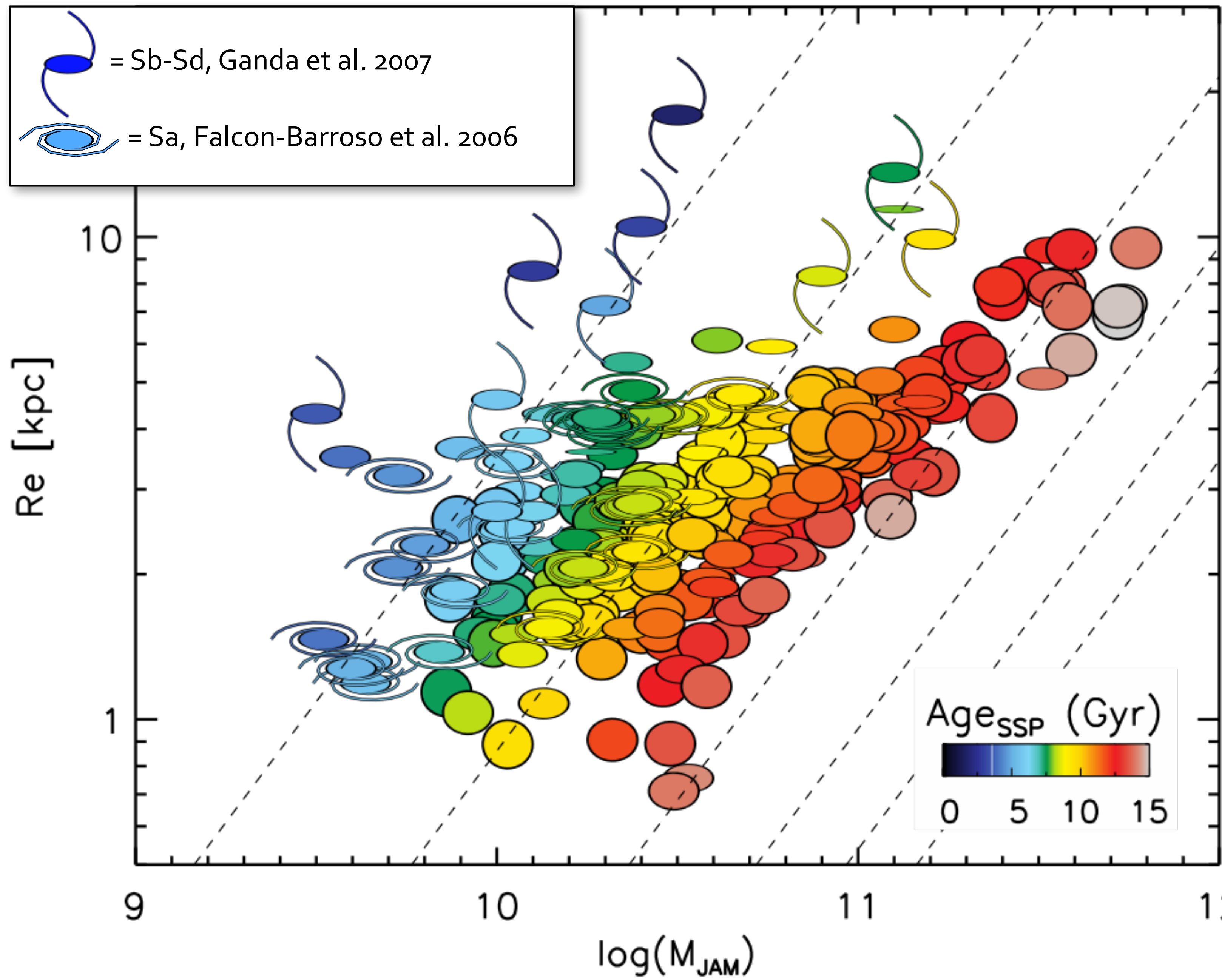
McDermid et al. (2015)



- **Early-type galaxies:**
    - **age** and **metallicity** change parallel to lines of constant σ (across galaxy types)
    - sequence of **increasing dominance of bulges**

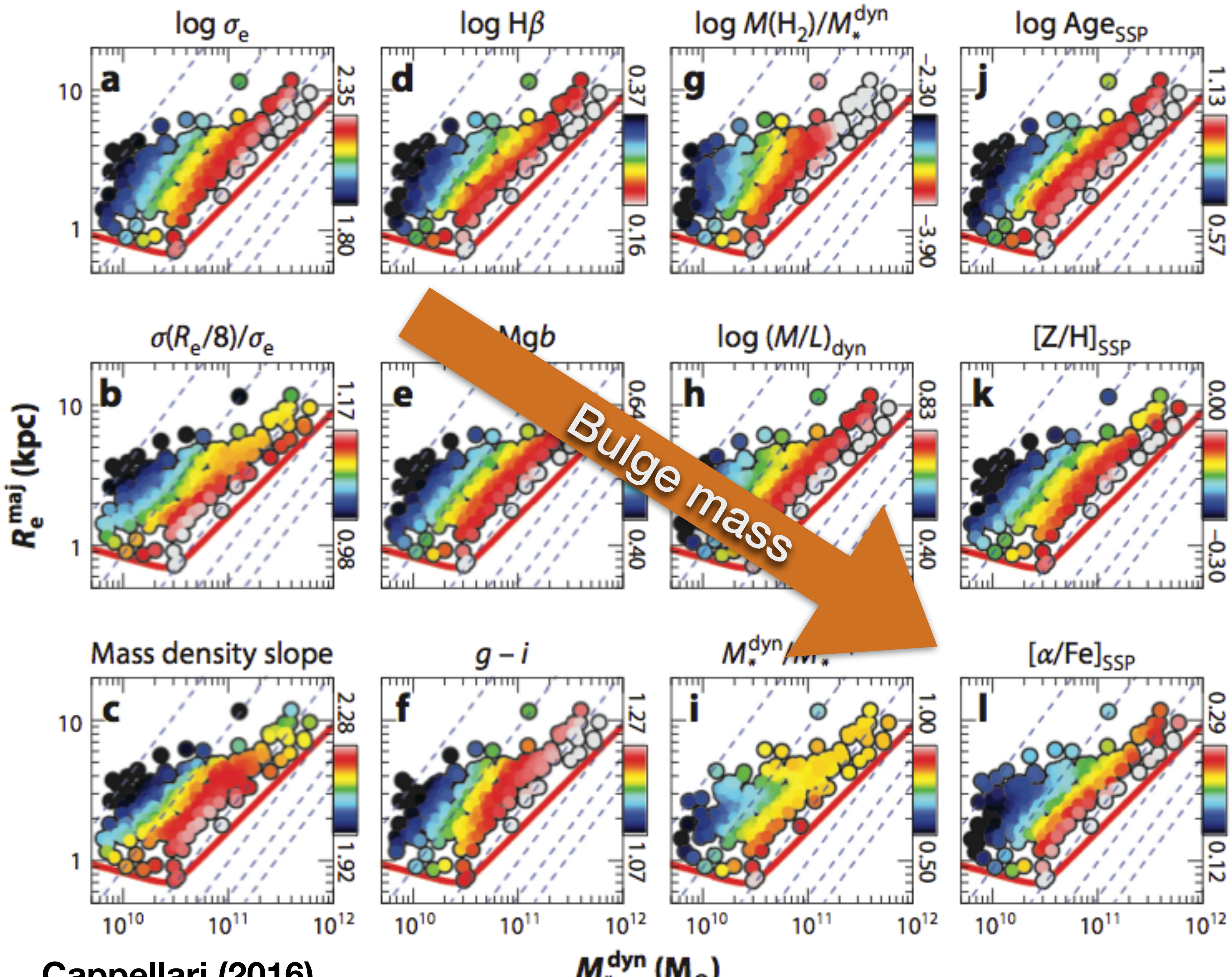
Adding spirals to Mass-Size Plane

- adding spirals
- colour = age
- **age changes parallel to lines of constant σ** (across galaxy types)
- sequence of increasing dominance of bulges



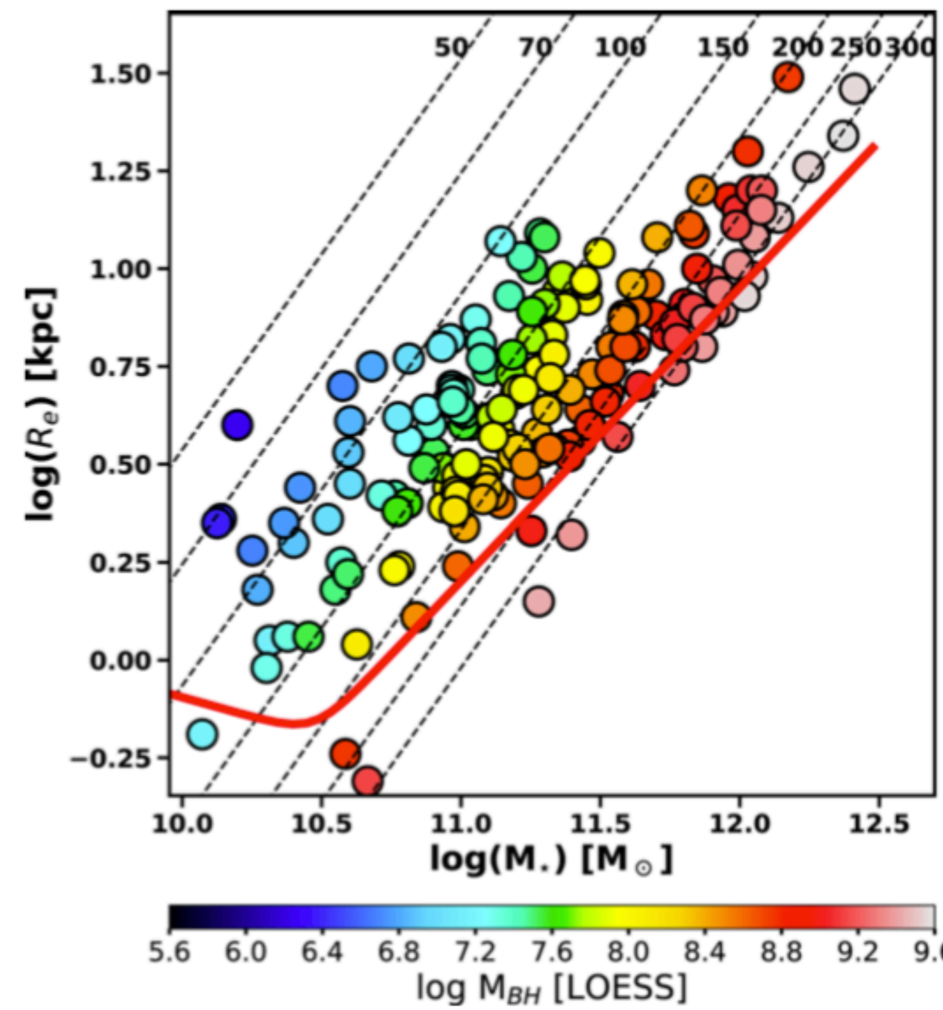
From R. McDermid's talk at "Most Massive Galaxies and their Precursors", Sydney Feb 2015

Galaxies on mass - size



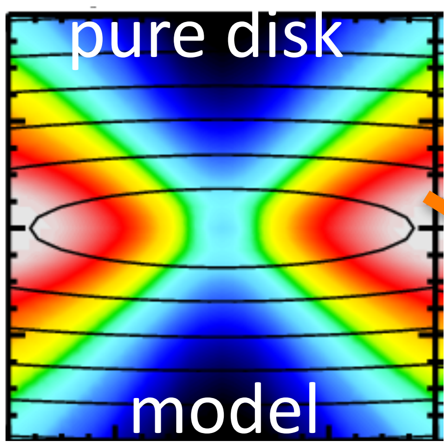
Cappellari (2016)

Krajnović et al. (2018a)



- galaxy properties closely follow lines of constant velocity dispersion

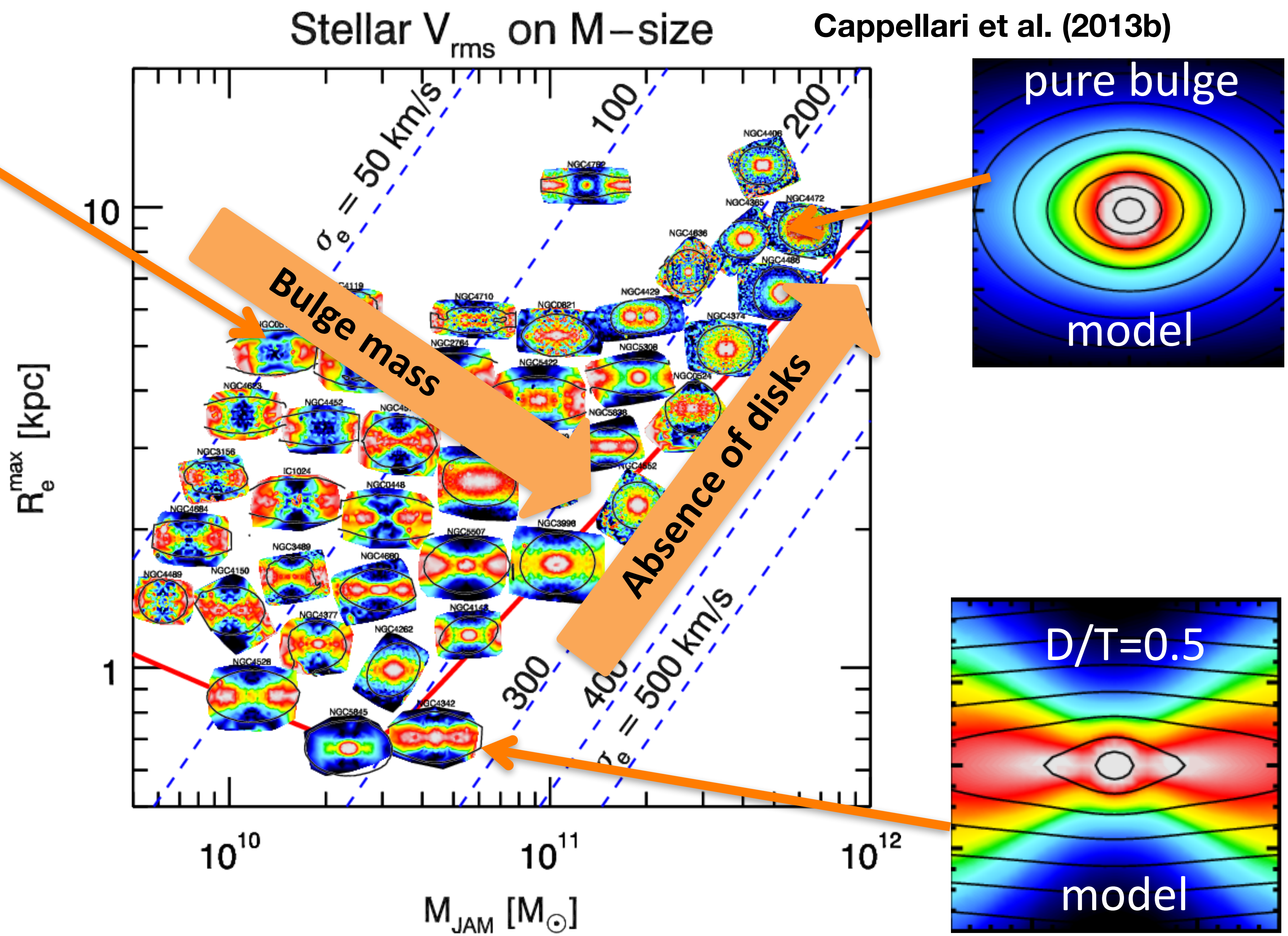
Lesson from Mass - Size plane



- second velocity moment

$$V_{RMS} = \sqrt{V^2 + \sigma^2}$$

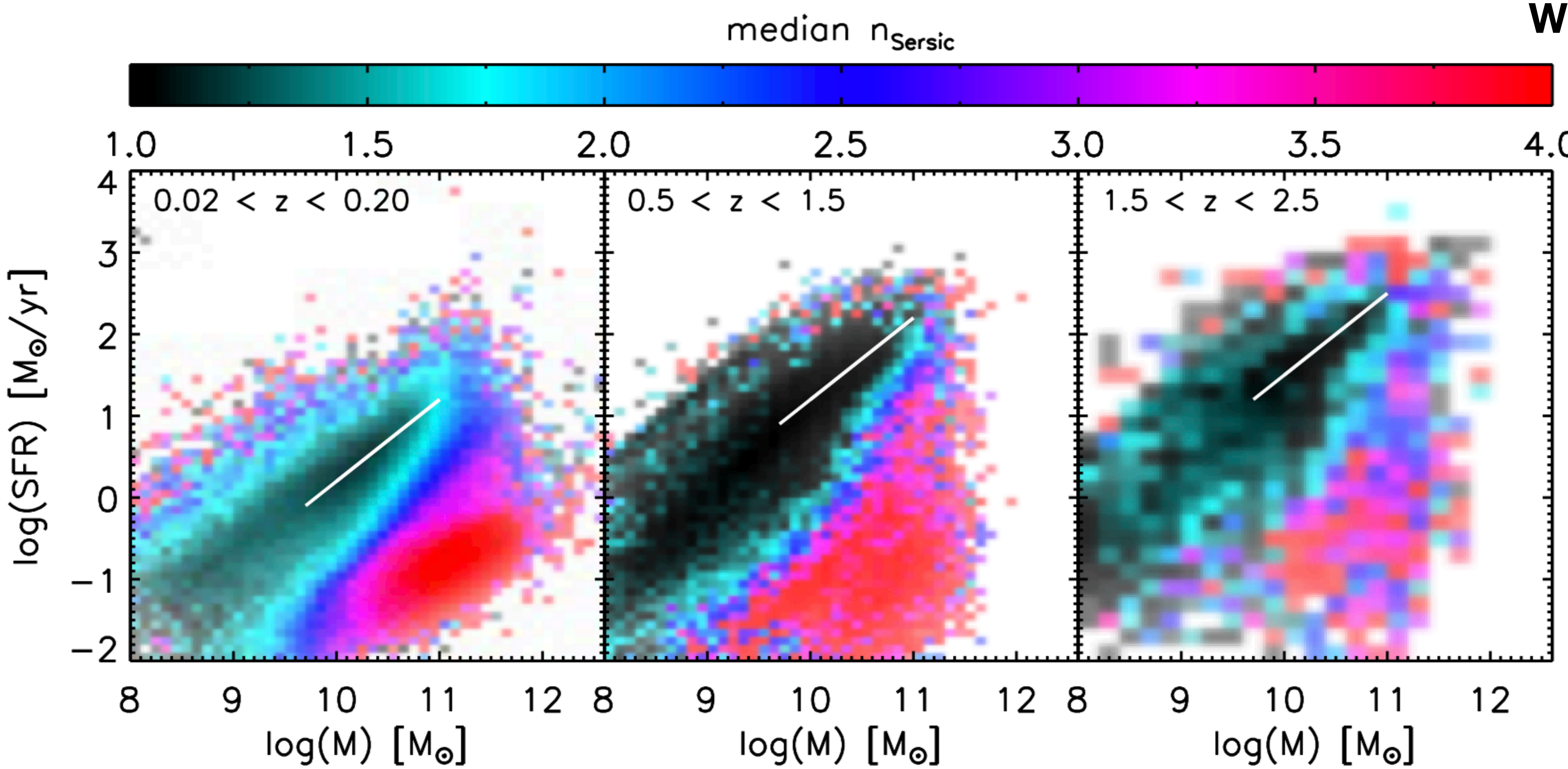
- Fraction of disks decreases with increasing σ
- Relation with mass and size more complex



What do we know (from distant Universe)?

Evolution of stellar properties

Wuyts et al. (2011)

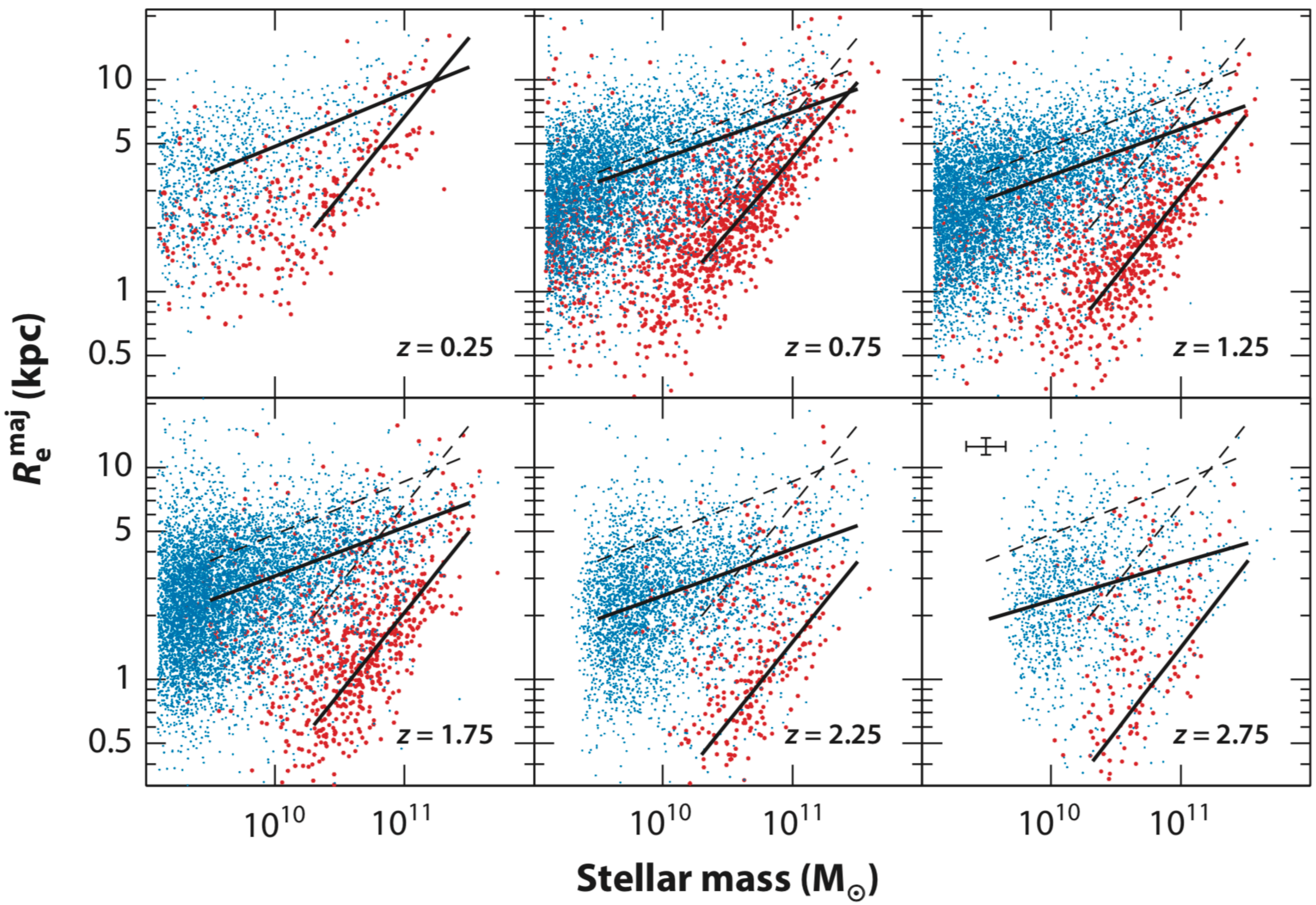


- looking only at stellar properties
- **main sequence of star formation**:
    - at all redshifts **stars are born in disk-like** systems
    - **passive galaxies have large Sersic index**, and might not be disks

Evolution of the mass-size distribution

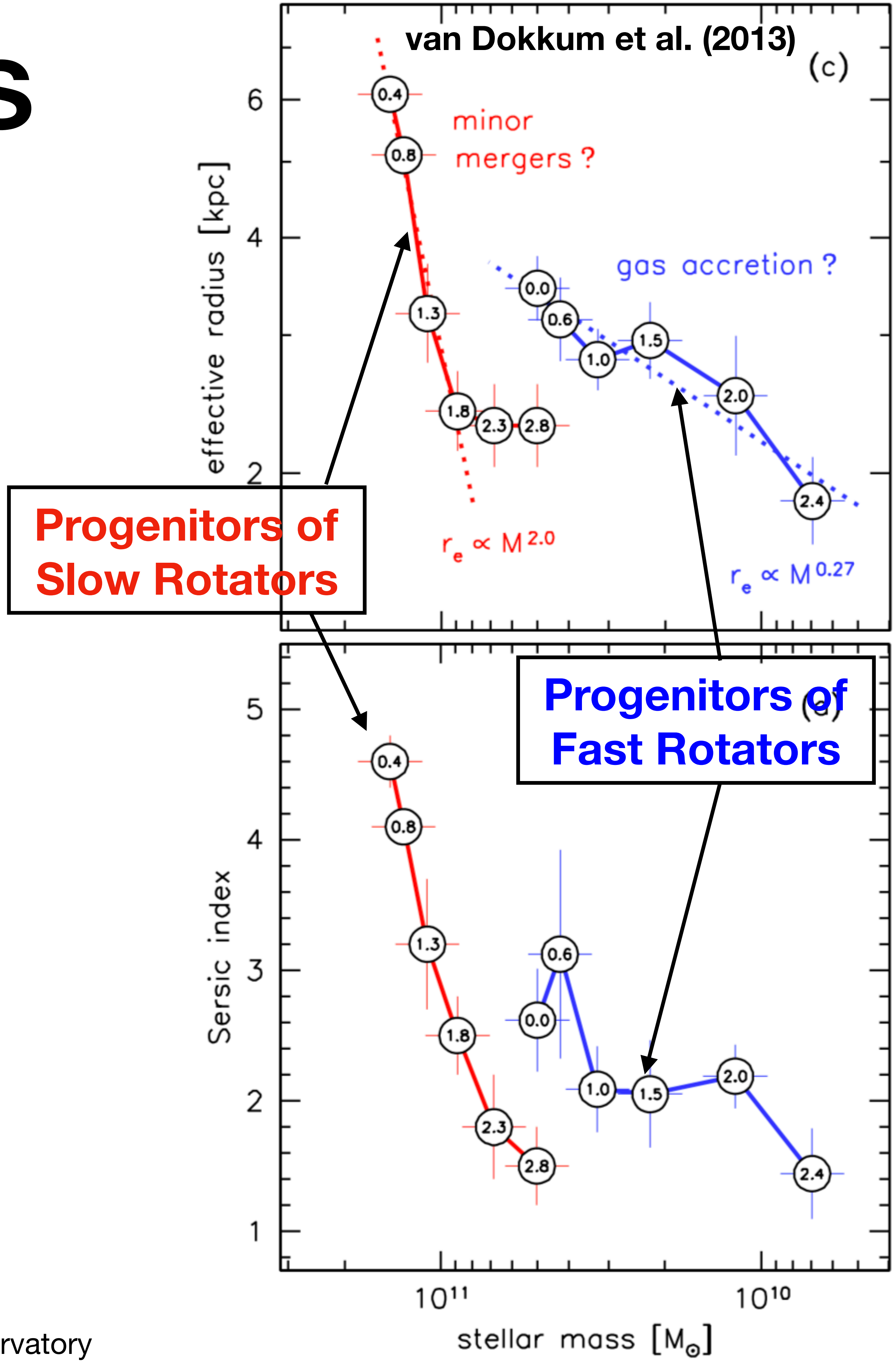
van der Wel et al. (2014)

- sizes of all galaxies evolve
- **passive galaxies** show **strongest** evolution



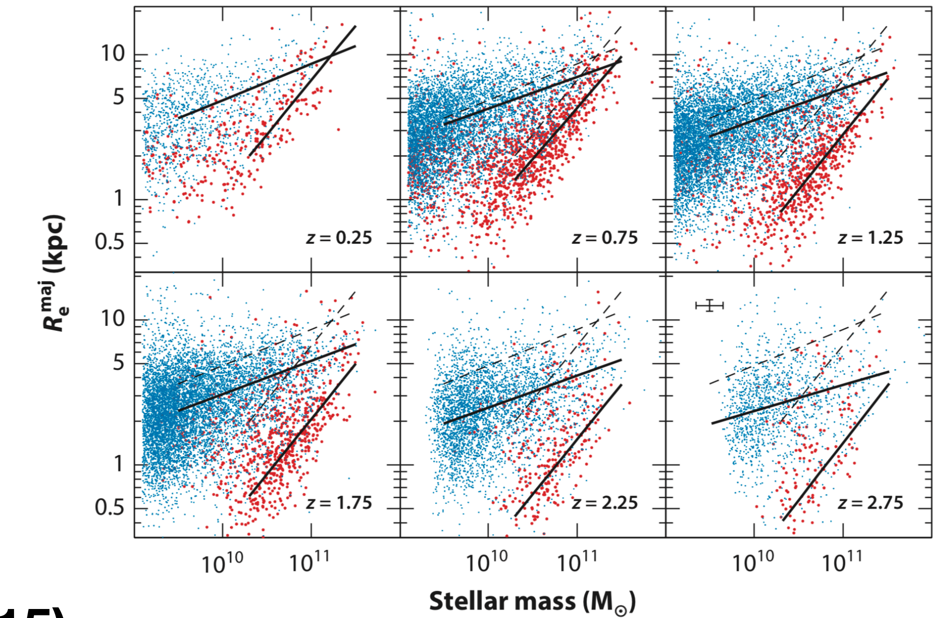
How galaxies evolve?

- progenitor of massive galaxies $M>10^{11}M_{SUN}$ (slow rotators)
    - **rapid** growth in **size**, and **Sersic** index, **little** in **mass**
- progenitors of spirals and fast rotators ($M\sim3x10^{11}M_{SUN}$)
    - **minor** changes in **size, mass** and **Sersic** index

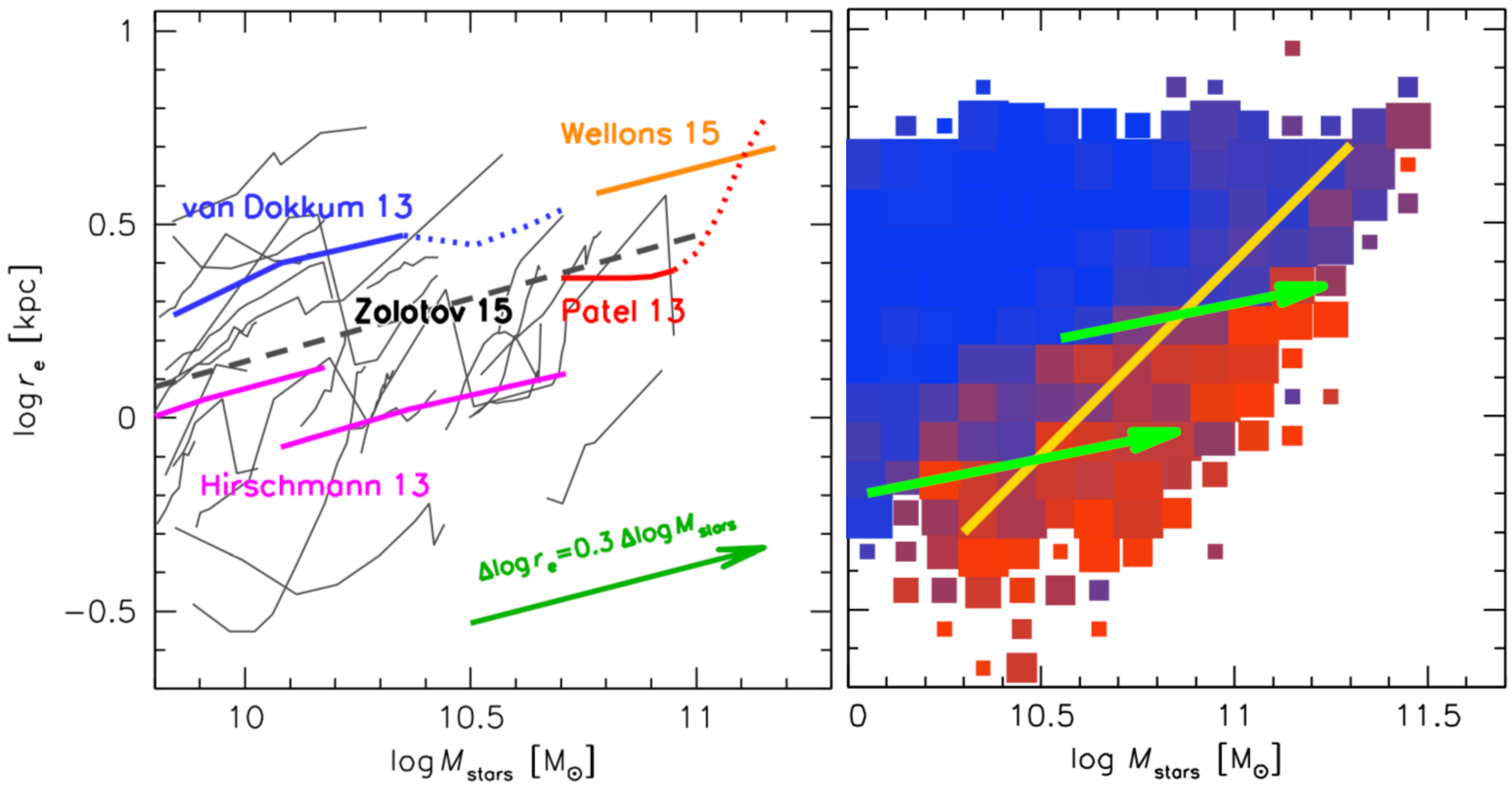


Growth of galaxies on the mass - size distribution

- growth of galaxies in M - size plane can be described by a simple statistical model (on a population)
- galaxies (seem to) grow along a shallow line ΔlogR~0.3Δ logM due to gas accretion
- galaxies become **denser, increasing velocity dispersion**, until a threshold when SF is quenched



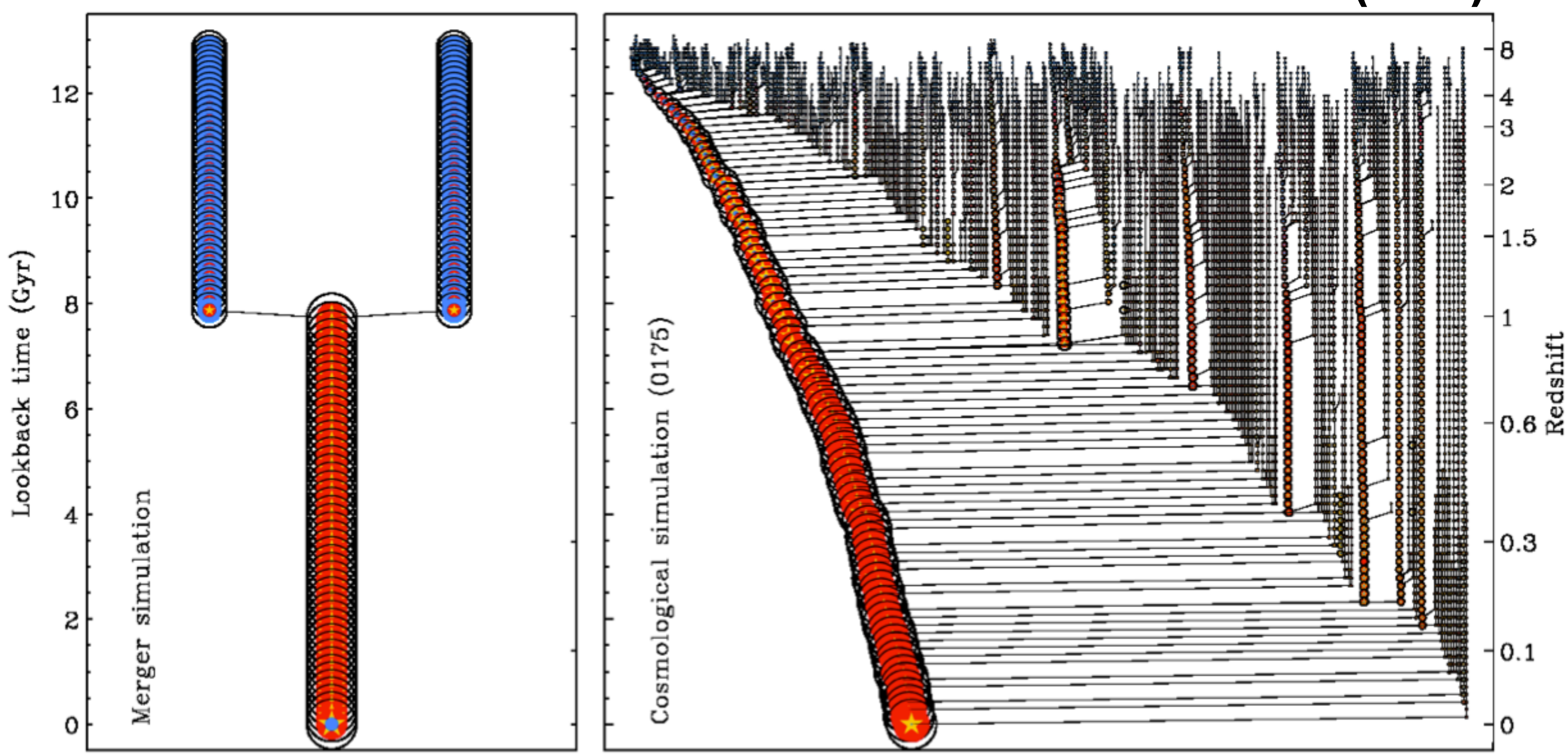
van Dokkum et al. (2015)



What do we know (from virtual Universe)?

Simulations of mass assembly

Naab et al. (2014)

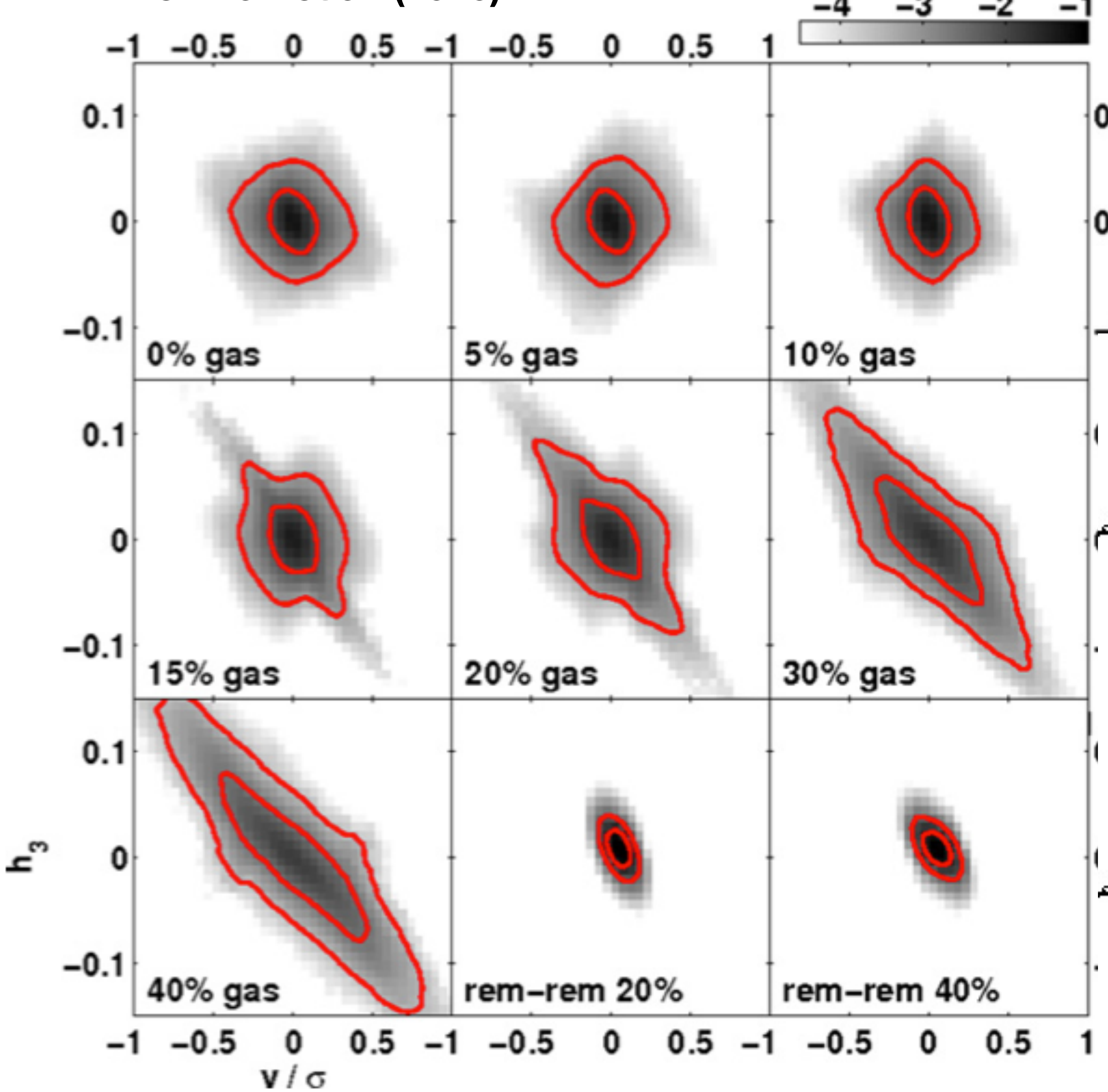


- binary mergers, cosmological simulations, zoom in simulation
- detailed view into galaxy (internal structure)

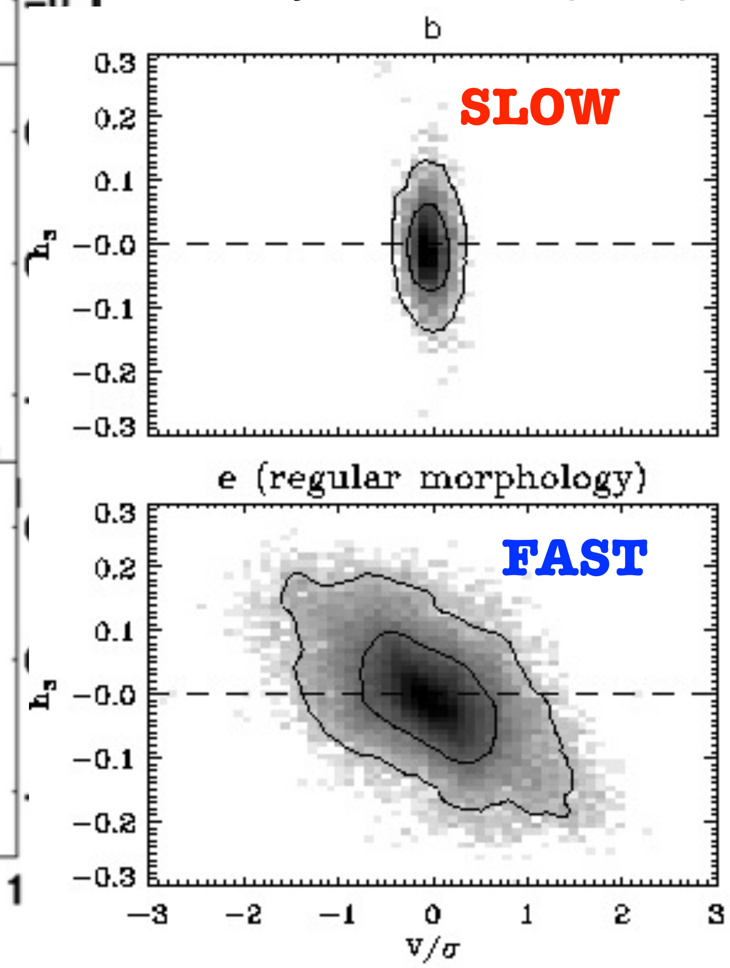
Importance of gas

- from binary mergers
- **gas builds discs** - oblate axisymmetric systems
- shape of the LOSVD depends on the amount of gas

Hoffman et al. (2010)

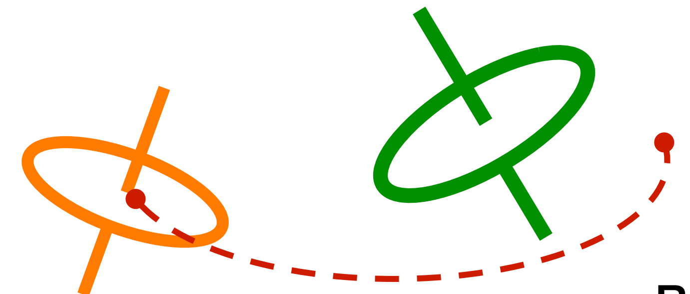


Krajnović et al. (2011)

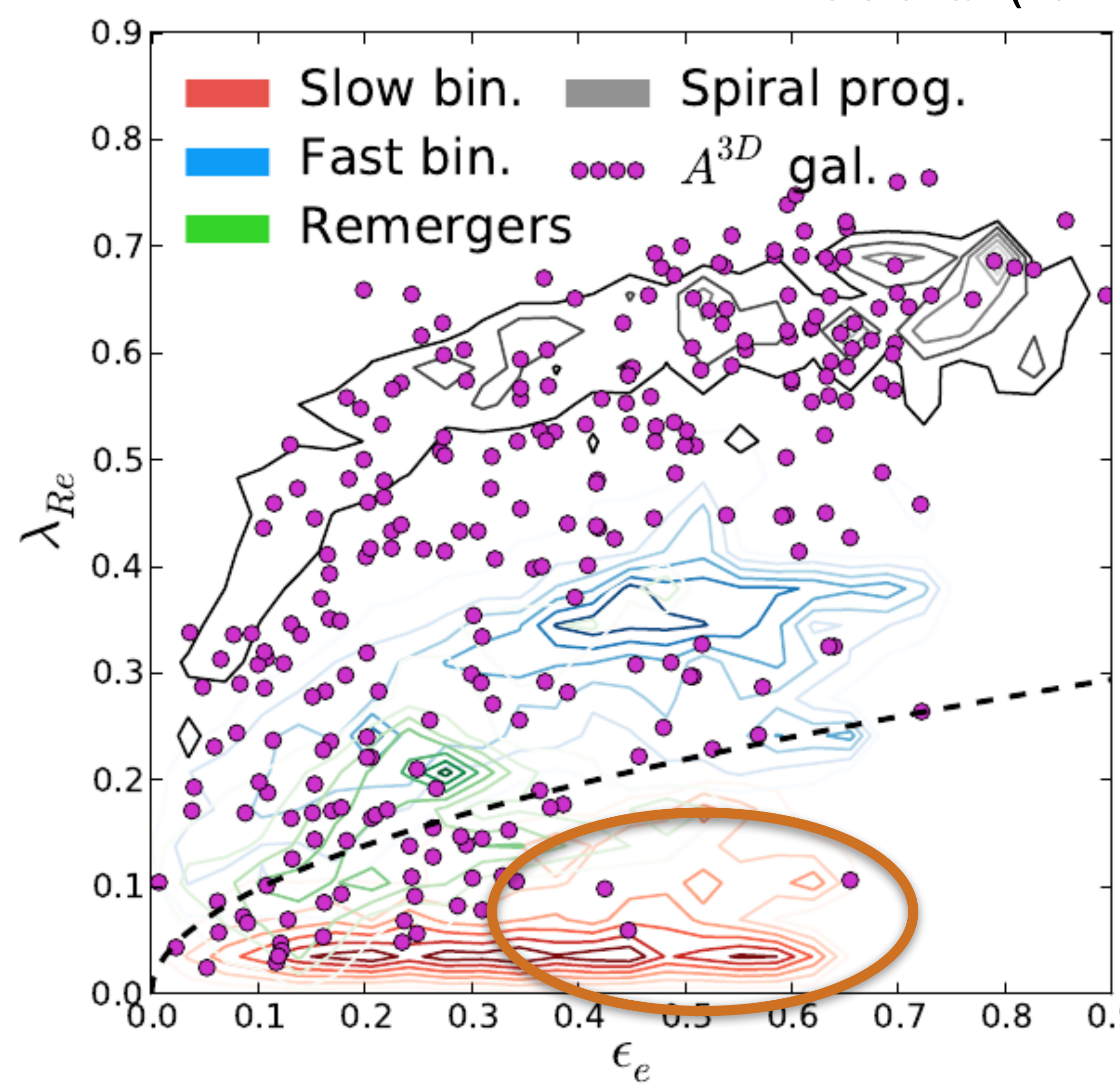


Reproducing λR - ε diagram

- mass fractions of 1:3 - 1:6 —> **fast rotators**
- mass fractions of 1:1,1:2 disc mergers—> **fast & slow**! (depending on orbit)
- slow rotators: mostly with KDCs + too flat

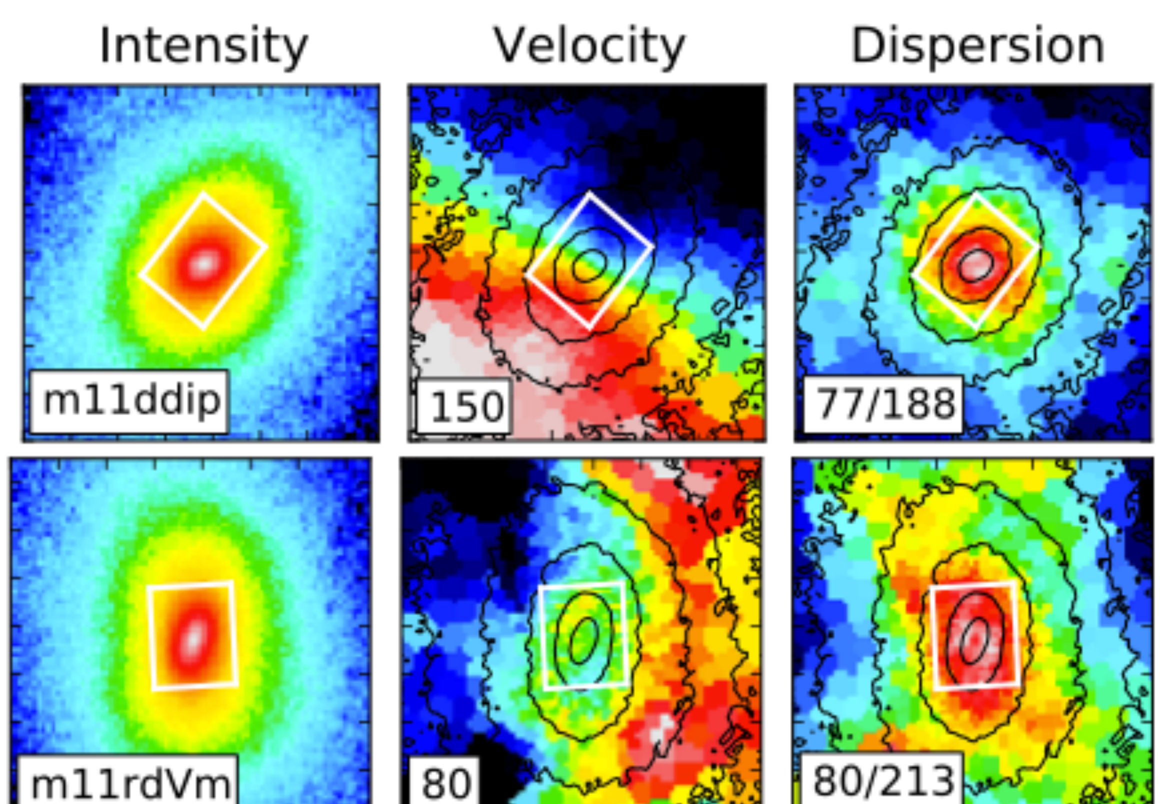


Bois et al. (2011)



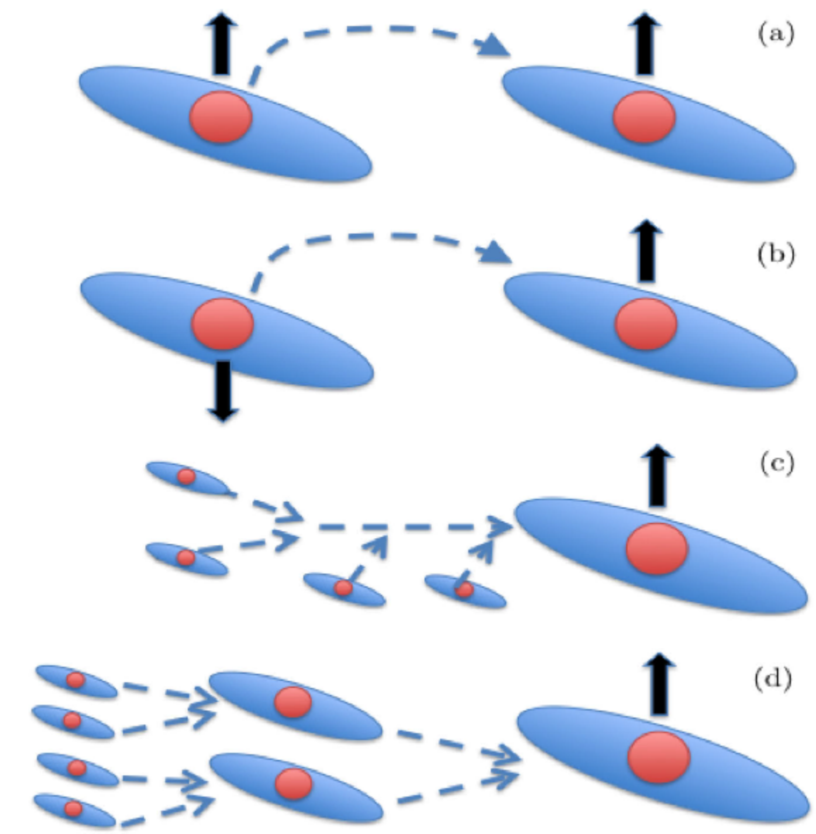
Fast

Slow

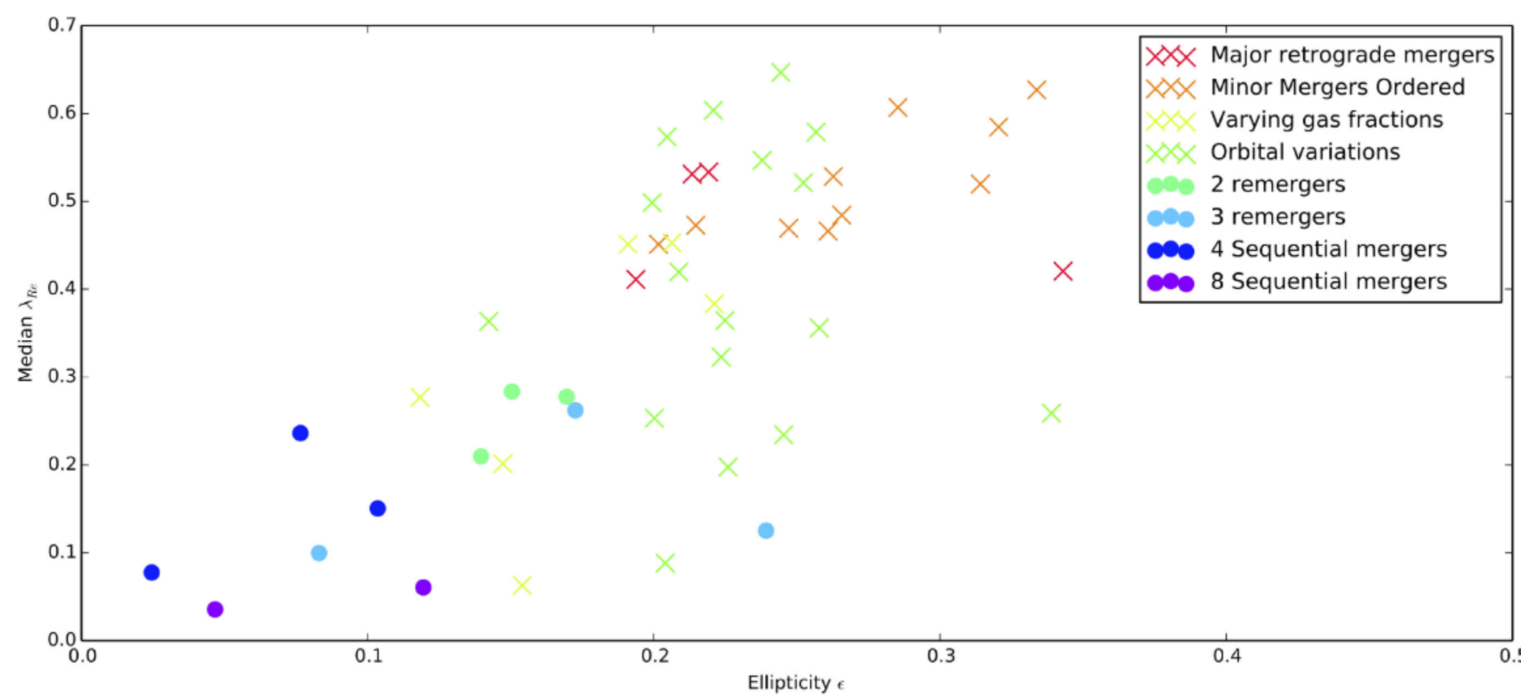


Reproducing λ_R - ε diagram

- minor and major binary mergers
- binary merger trees with multiple progenitors, and multiple sequential mergers
- **binary mergers** - Fast rotators
- **multiple sequential** mergers —> (round) Slow rotators



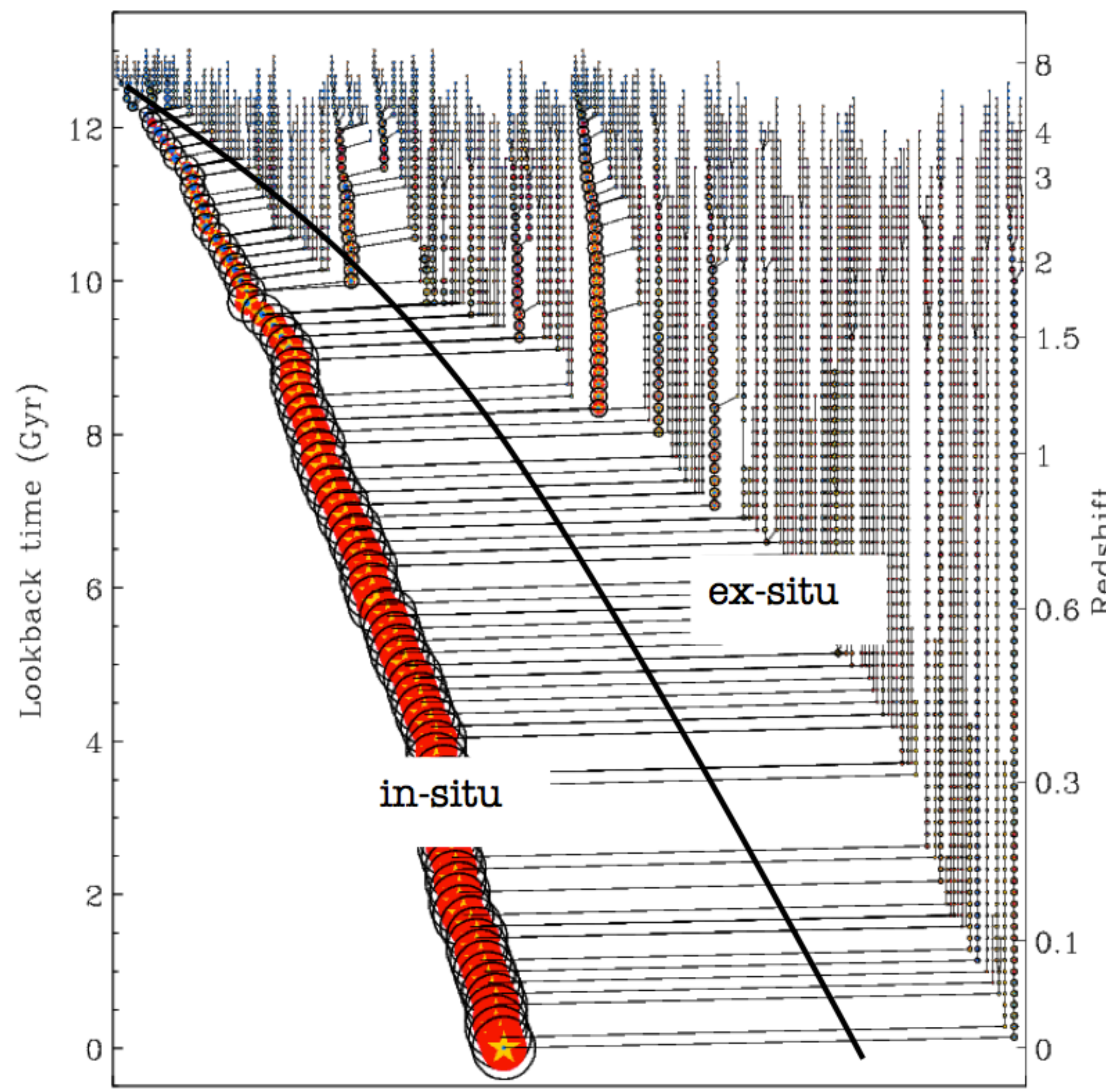
Moody et al. (2014)



Cosmological context

- binary mergers are useful tools for understanding processes, but not (necessarily) realistic
- complex assembly histories, frequent minor and occasional 'major' mergers (e.g. de Lucia & Blaizot 2007)
- contribution of mergers with >1:4 from z~2 is 30-40% (in massive galaxies)
- extract dark matter and merger histories for 'zoom-in' simulations
- cosmological hydro-dynamical simulations

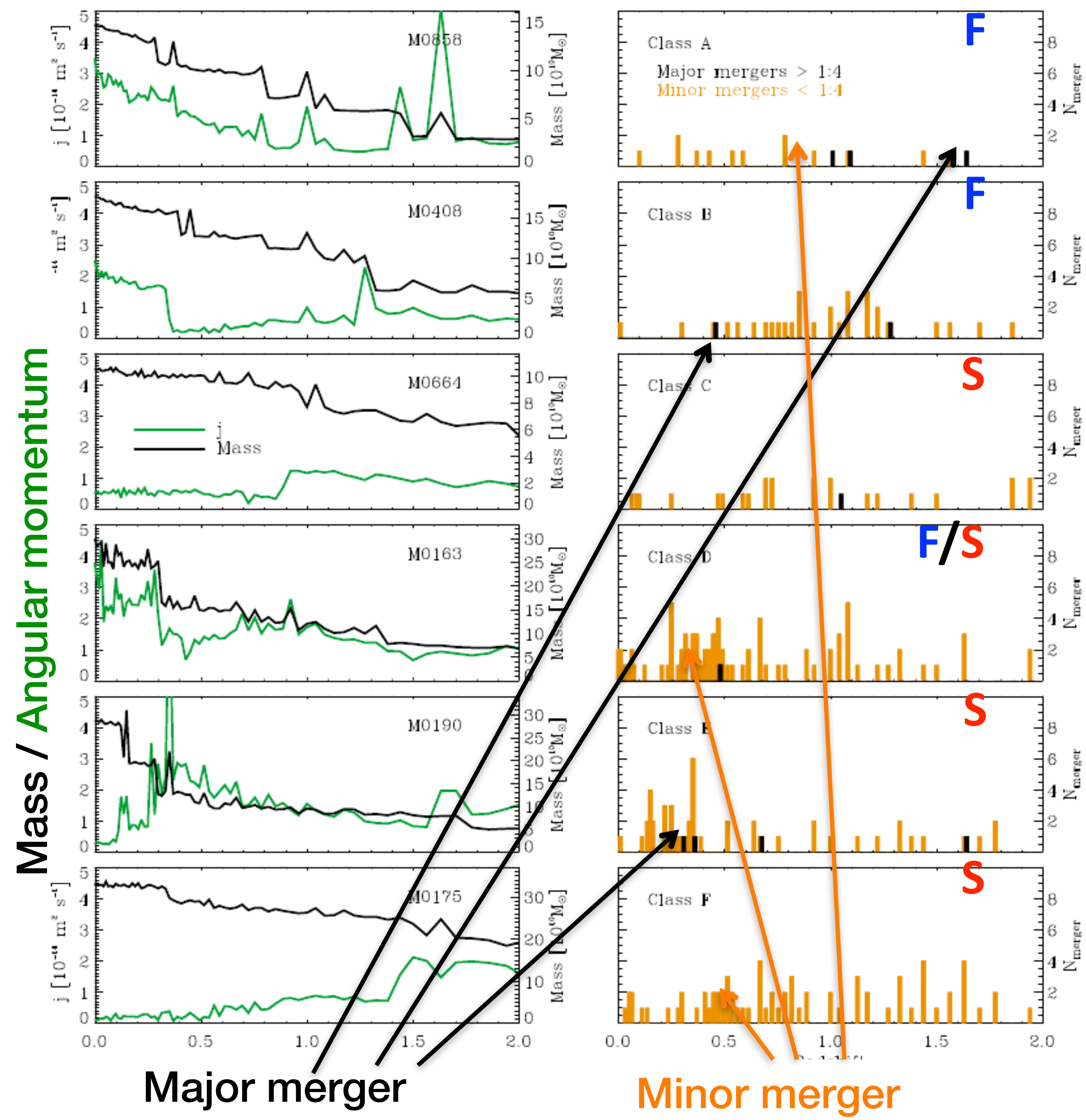
Hirschmann et al. (2013), Oser et al. (2012)



Galaxy assembly 'types'

- **Gas** dissipation and **star formation increase** rotation (A)
- **Major mergers** can **increase** (B,D) or **decrease** (C,E) rotation
- Many **minor mergers decrease** rotation (F)
- **Gas rich** (wet/dissipative)
  - **create** disks
  - excess of central light distribution (**core-less** light profiles)
  - **increase** angular momentum
- **Gas poor** (dry/dissipation-less)
  - **destroy** disks
  - create **cores** in central light distribution (through mergers of black holes)
  - **decrease** angular mometnum

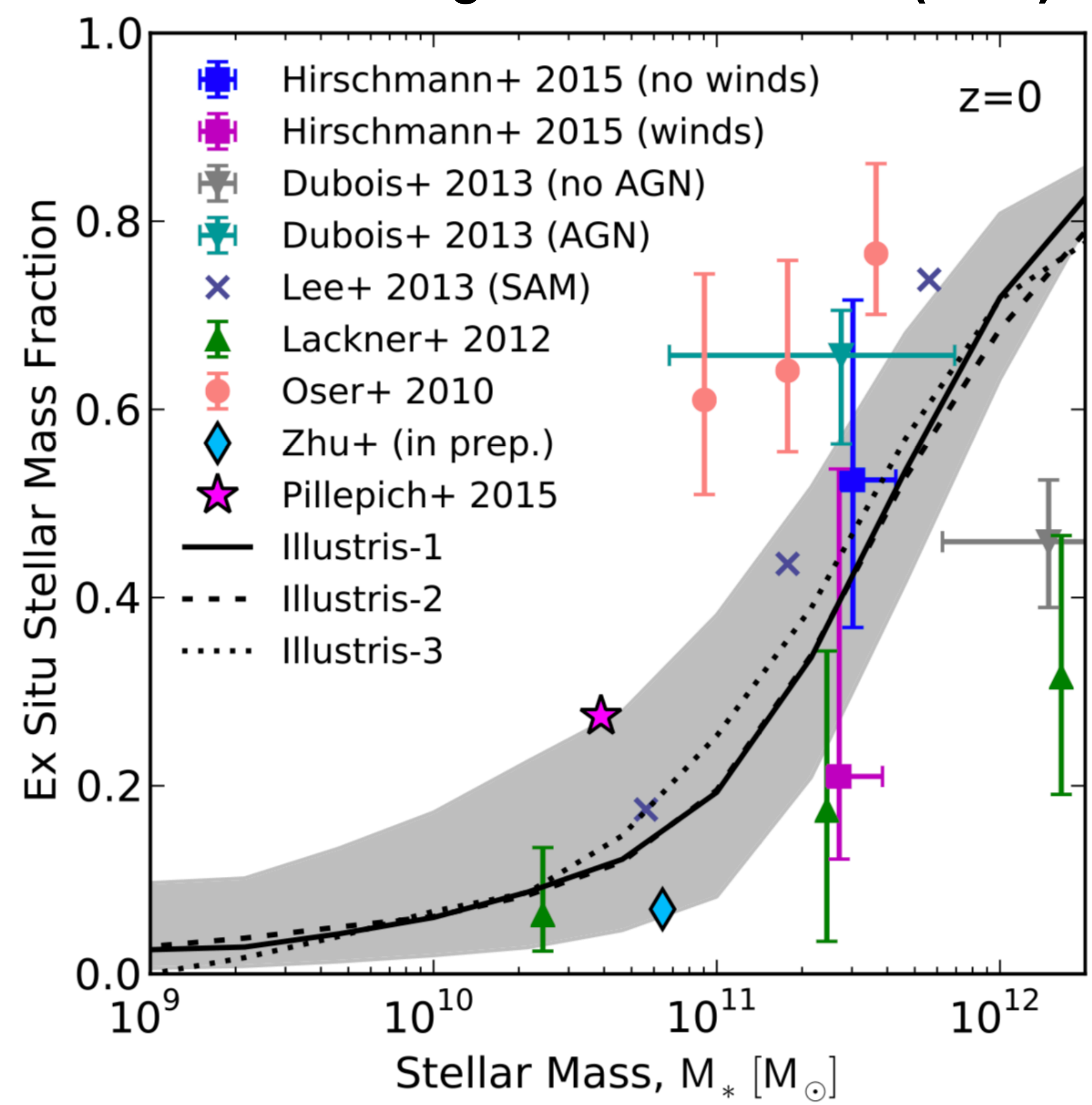
Naab et al. (2014)



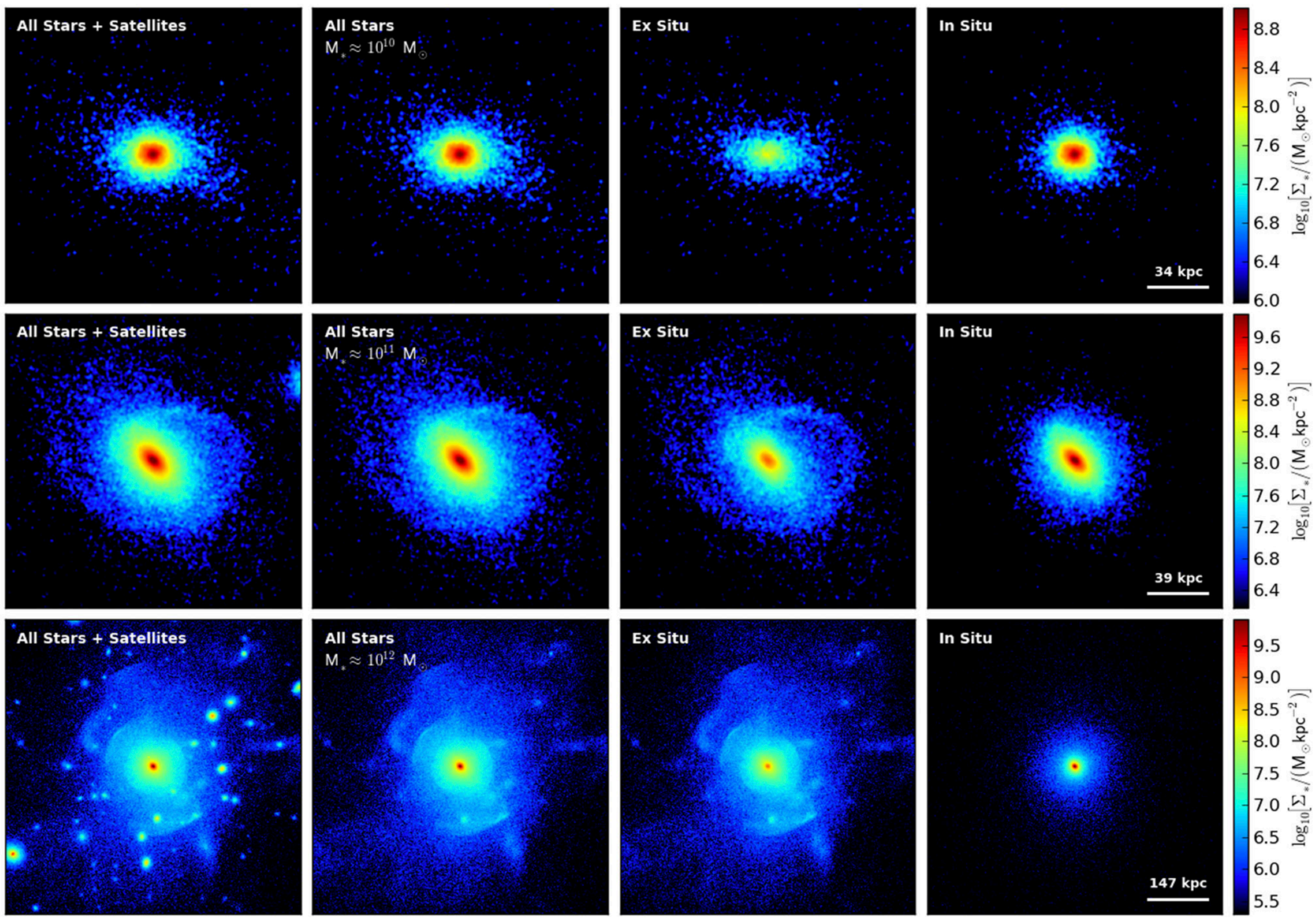
Two channels of galaxy assembly

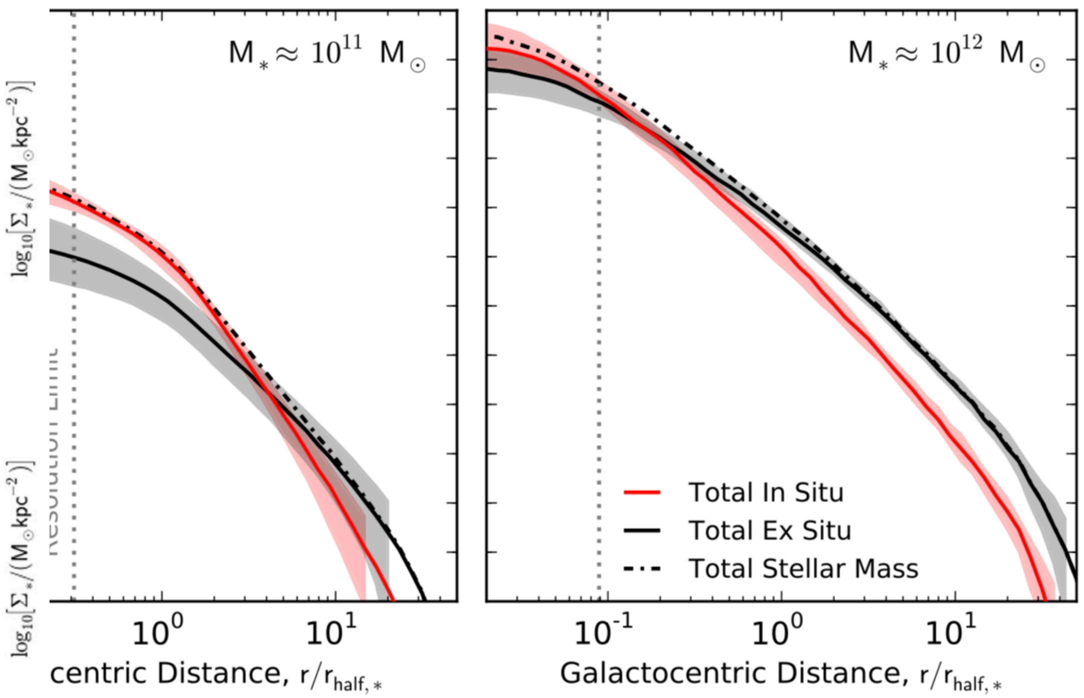
- 2 phases of mass assembly (Oser et al. 2010)
  - rapid early phase (z>2) of **in situ** star formation
  - prolong secondary phase (z>3) of accretion of stars formed **ex situ**
- **early-universe**:
  - violent and rapid SF fuelled by cold flows
  - mostly **in situ** stars for all galaxies
- **late universe**:
  - massive galaxies - **ex situ**
  - less massive galaxies - **in situ** (continuous SF)

Rodrigues-Gomez et al. (2016)



"Downsizing"





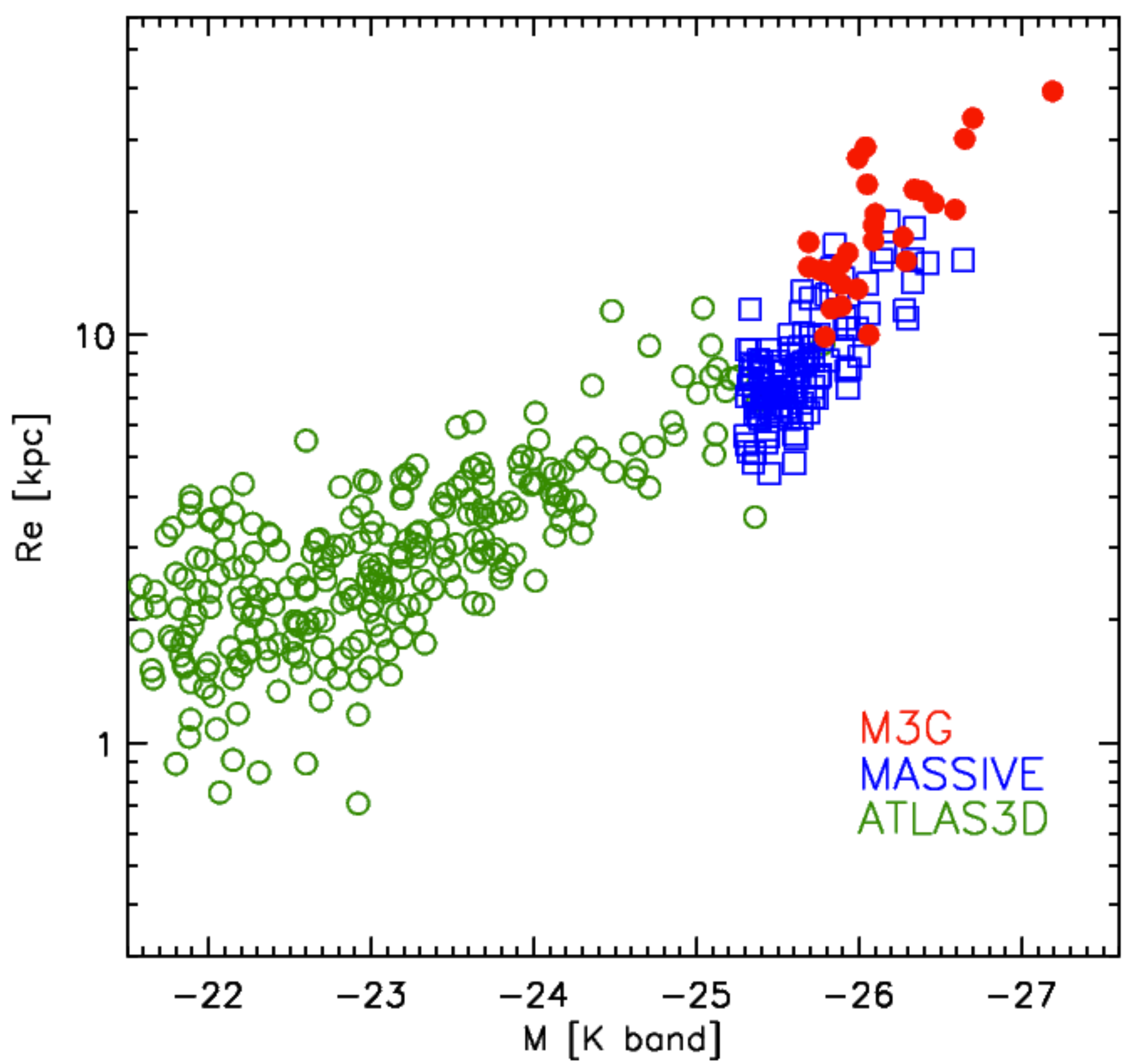
Rodrigues-Gomez et al. (2016)

- In situ / ex situ mass assembly is **not only a function of time**, but of mass
- **in situ** formation **dominates smaller systems**
- most **stars in massive galaxies are formed early** in small systems, but **galaxies are formed late**

The most massive galaxies in the Universe

The M3G Project

- A MUSE GTO programe (PI: Emsellem)
- Goals:
  1. explore the most massive galaxies
  2. explore the densest environments
  3. derive kinematics, dynamics
  4. dark matter, star formation histories pops & IMF
  5. test predictions of numerical simulations
- observations: 2014 - 2017
- a few papers in preparation

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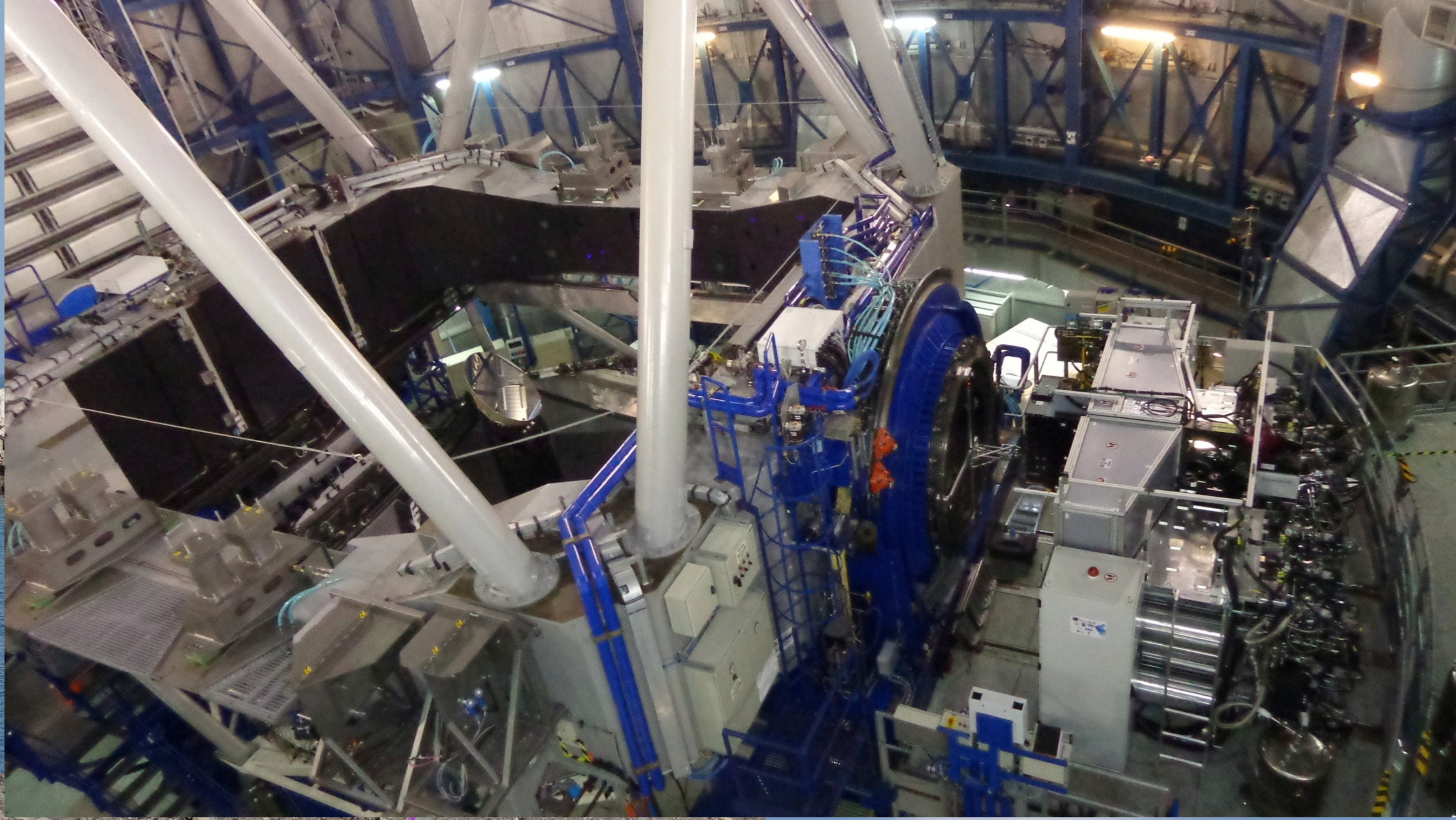
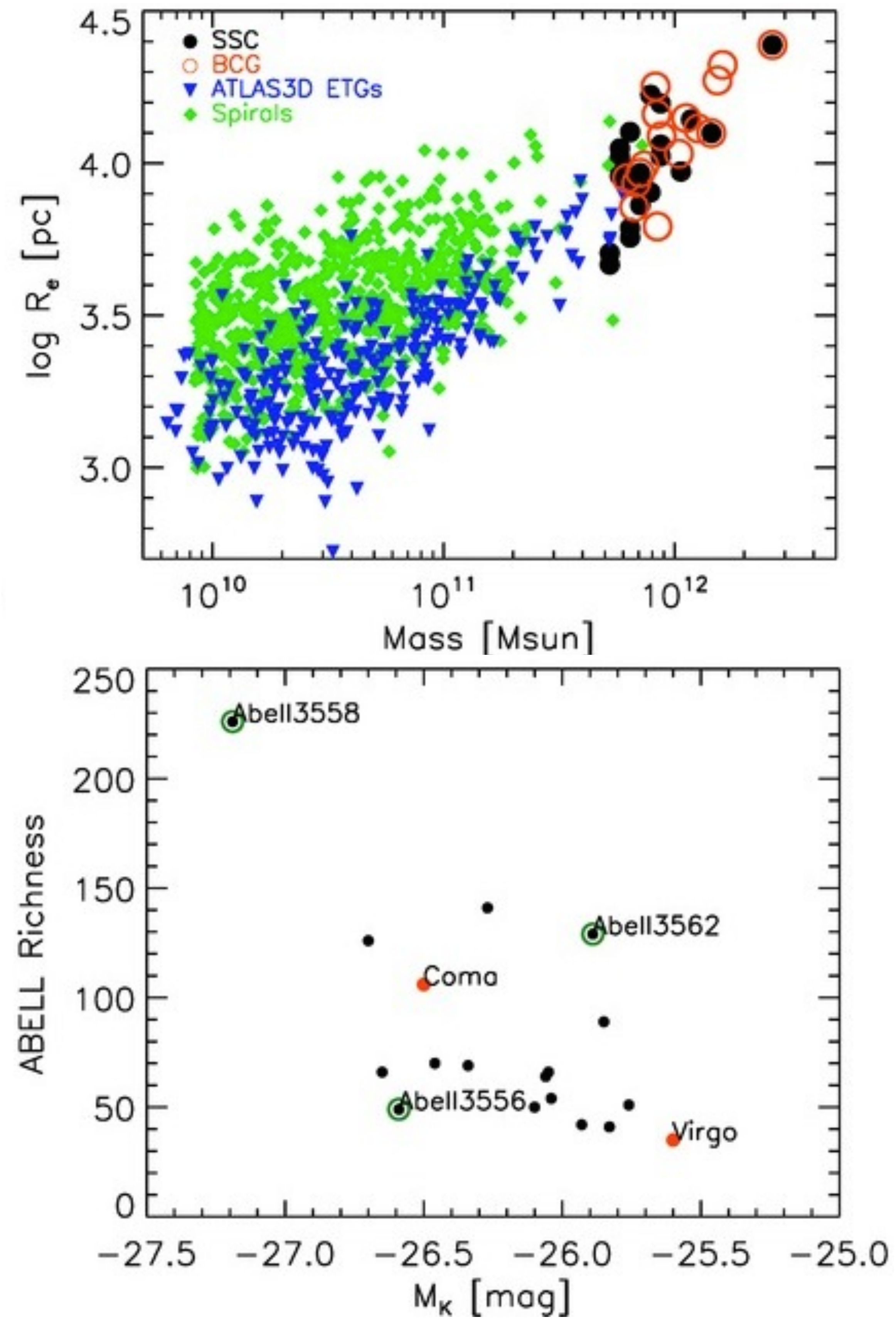


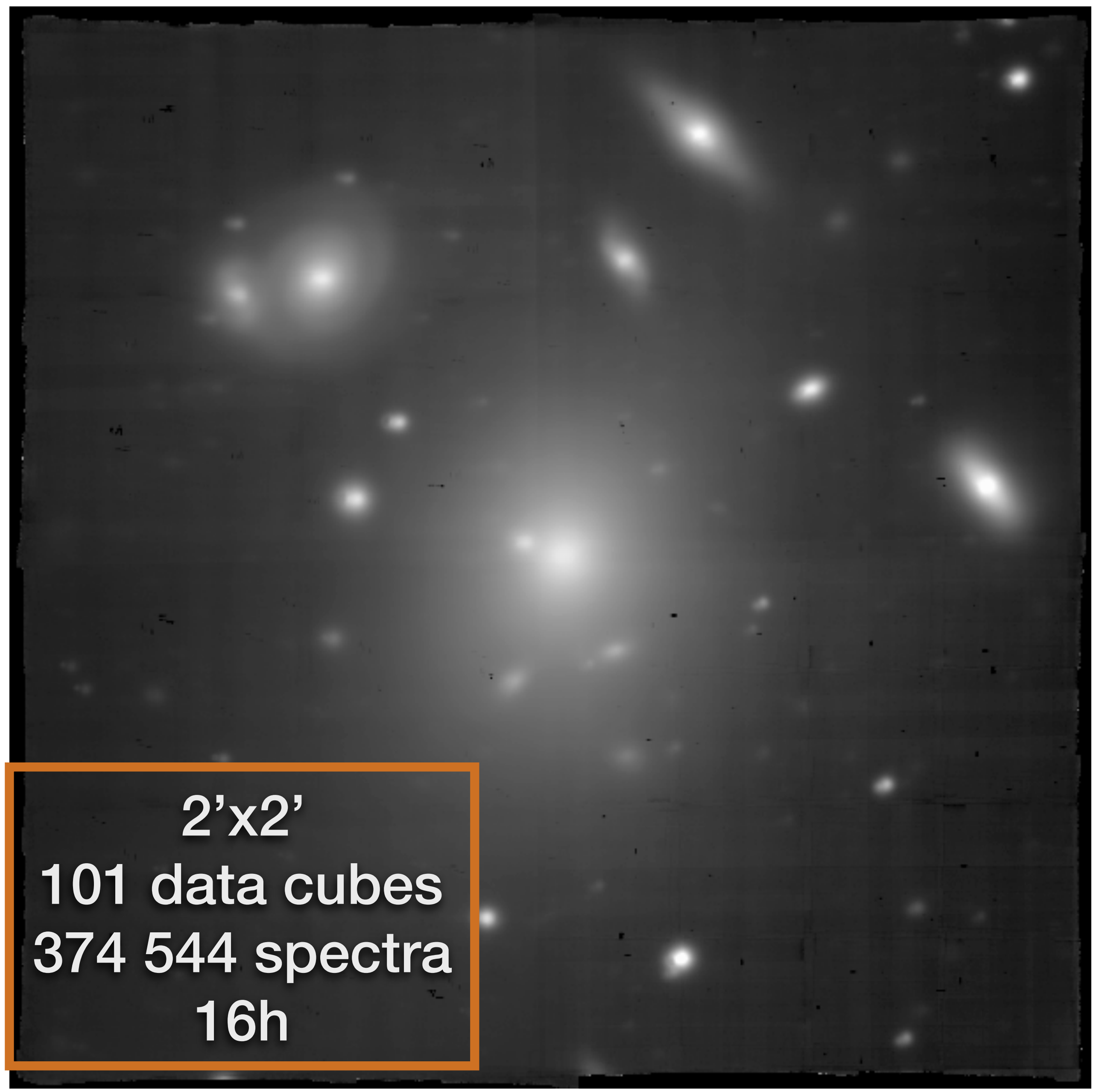
Most Massive Galaxies with MUSE

- **Sample selection**
  - **brighter** than ATLAS[3D] galaxies
  - **denser** environments
  - magnitude limited (brighter than -25.7 in K band)
  - at a distance such that 2 Re fit within 1 MUSE FoV
  - selection based on 2MASS
- **Observe two matching samples**
  - **brightest cluster galaxies** (BCGs) and
  - **massive galaxies** in the densest environment - Shapley Super Cluster (SSC) - Abell3556, Abell3558, Abell3562
  - **25 galaxies** in total

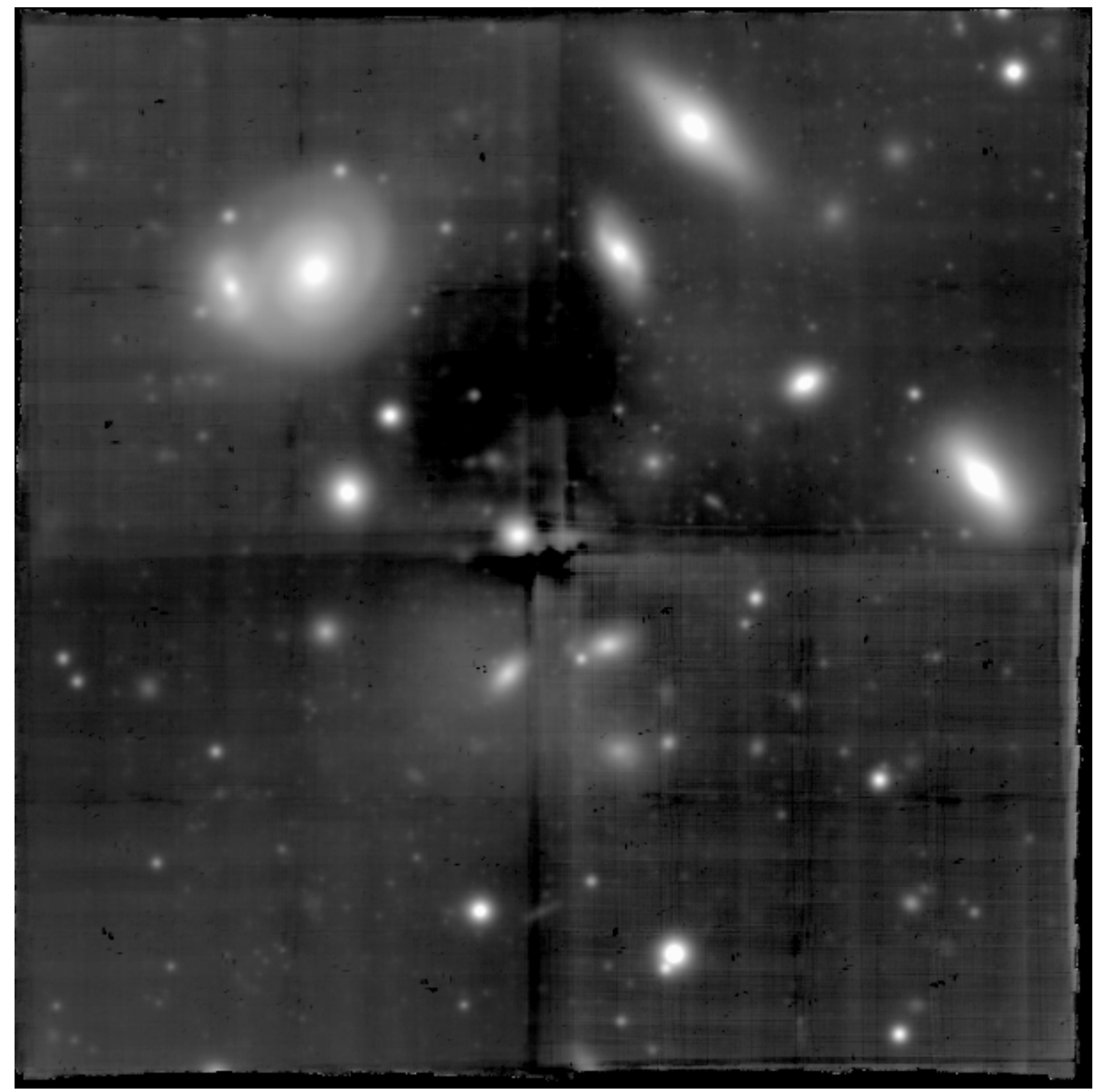


The central galaxy in Shapley

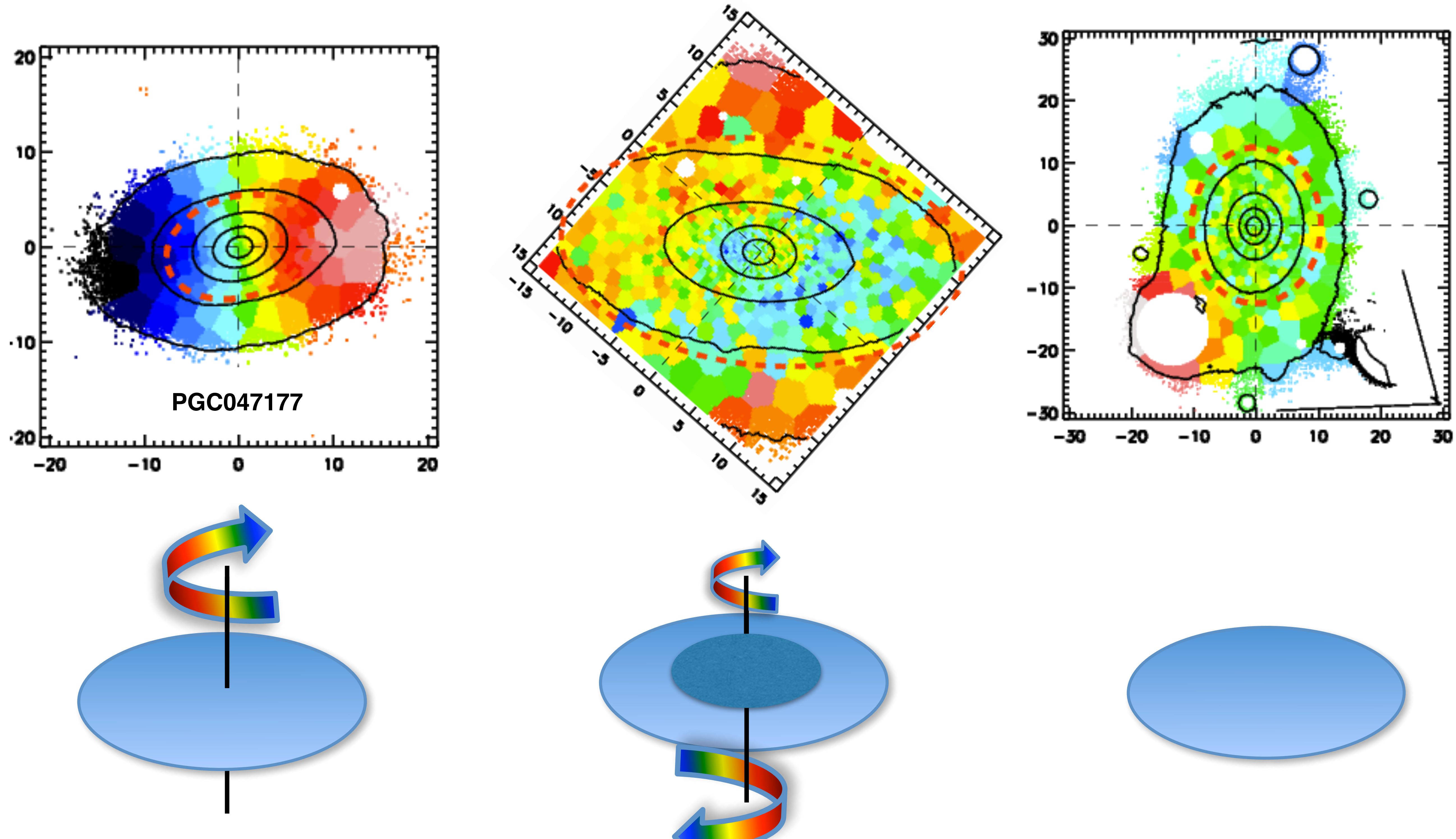
MUSE white light



MUSE white light residual



Stellar kinematics of massive galaxies



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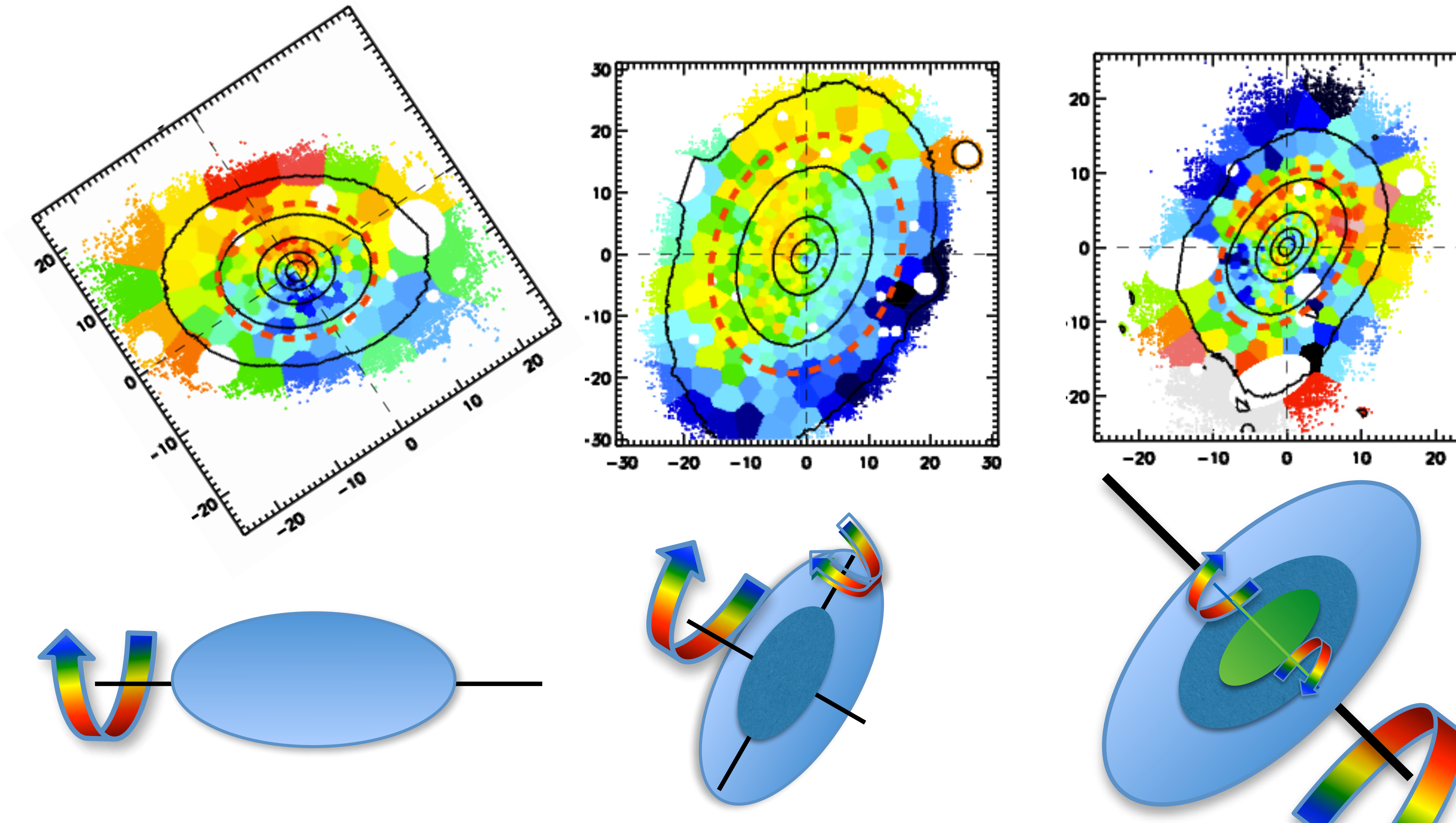
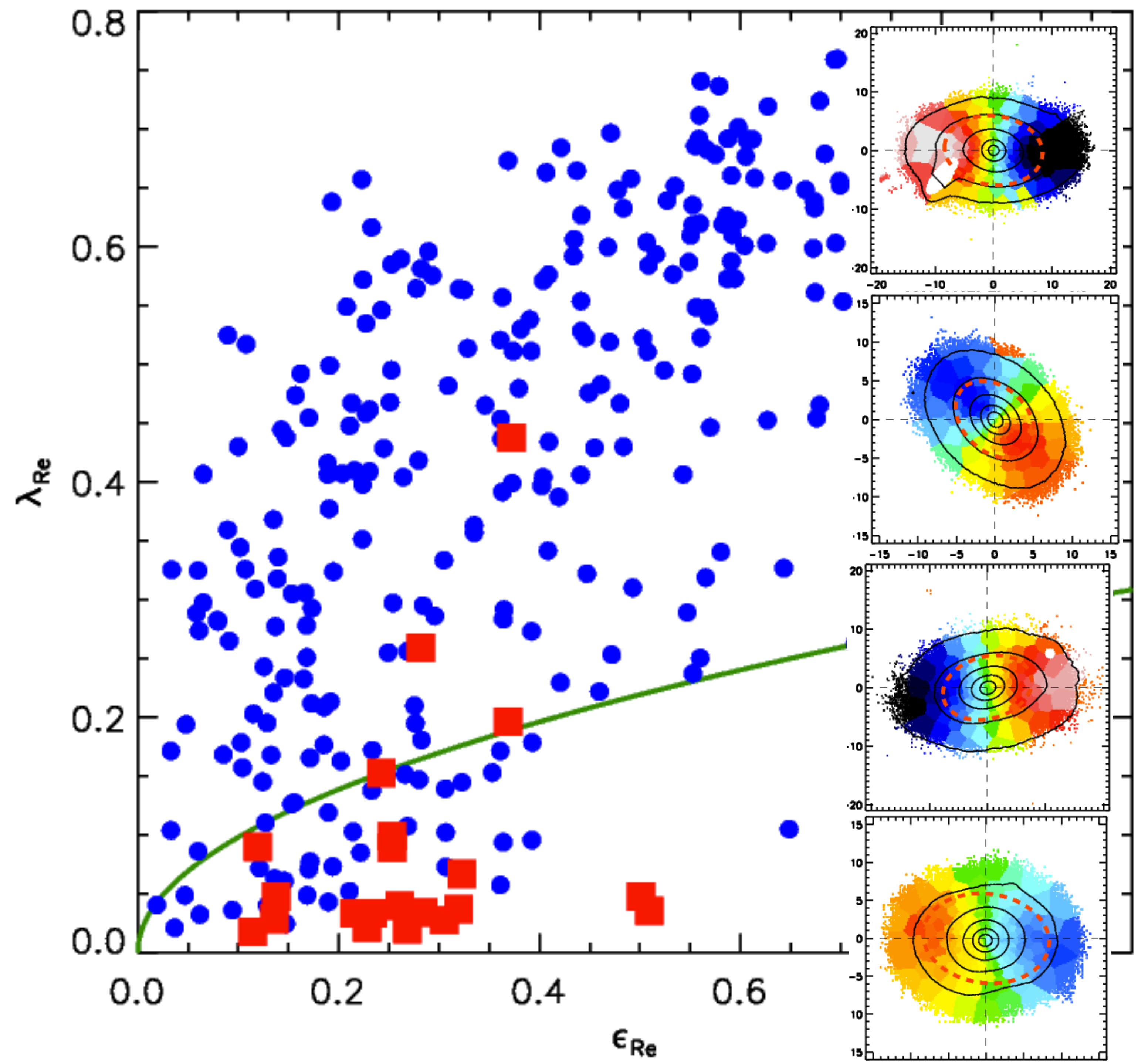
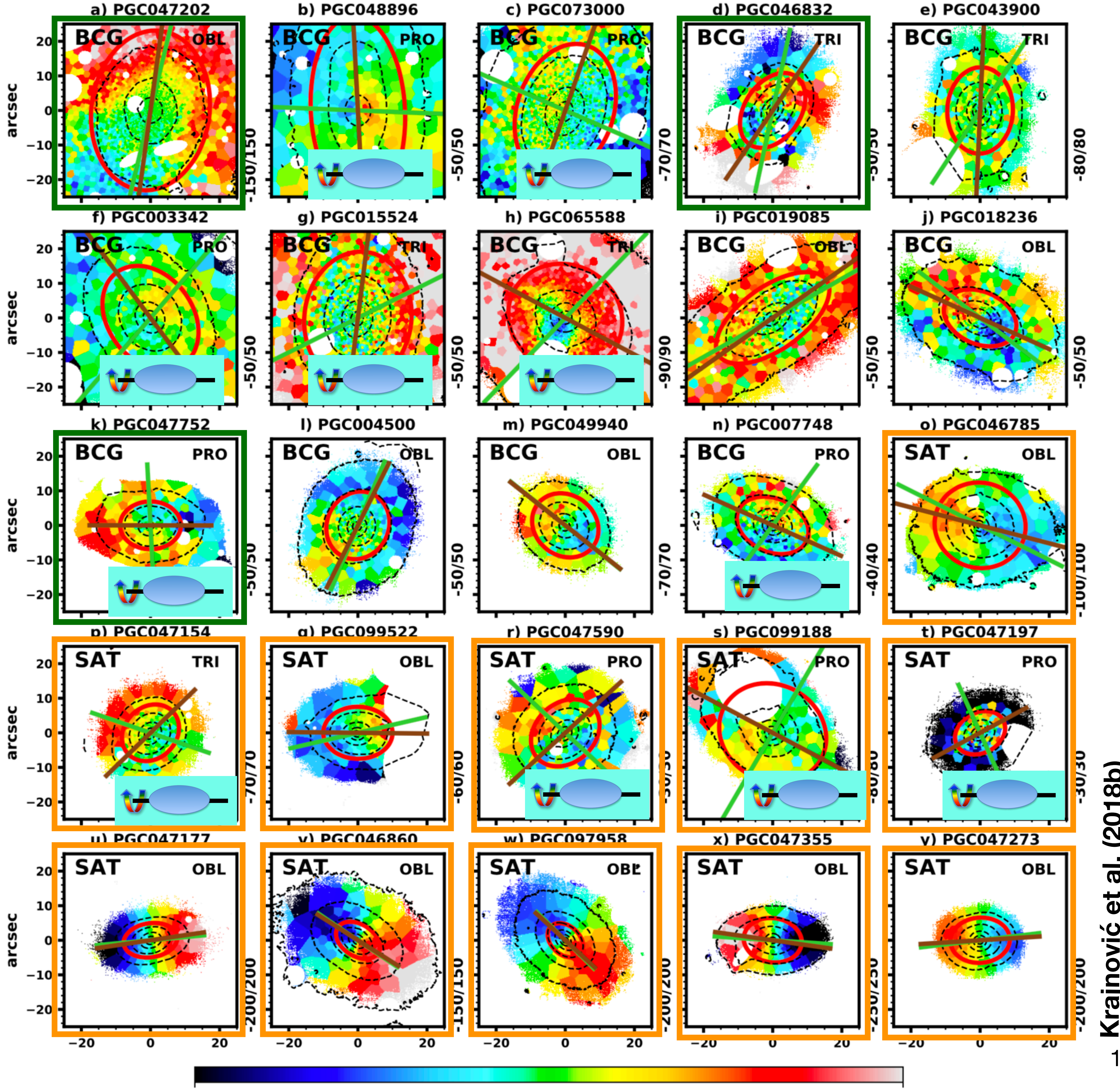


Angular momentum

- our galaxies are more massive than 10^{12} M_{sun}
- population is dominated by slow rotators
- a few of those are FR (non-BCGs from Shapley - with regular rotation)

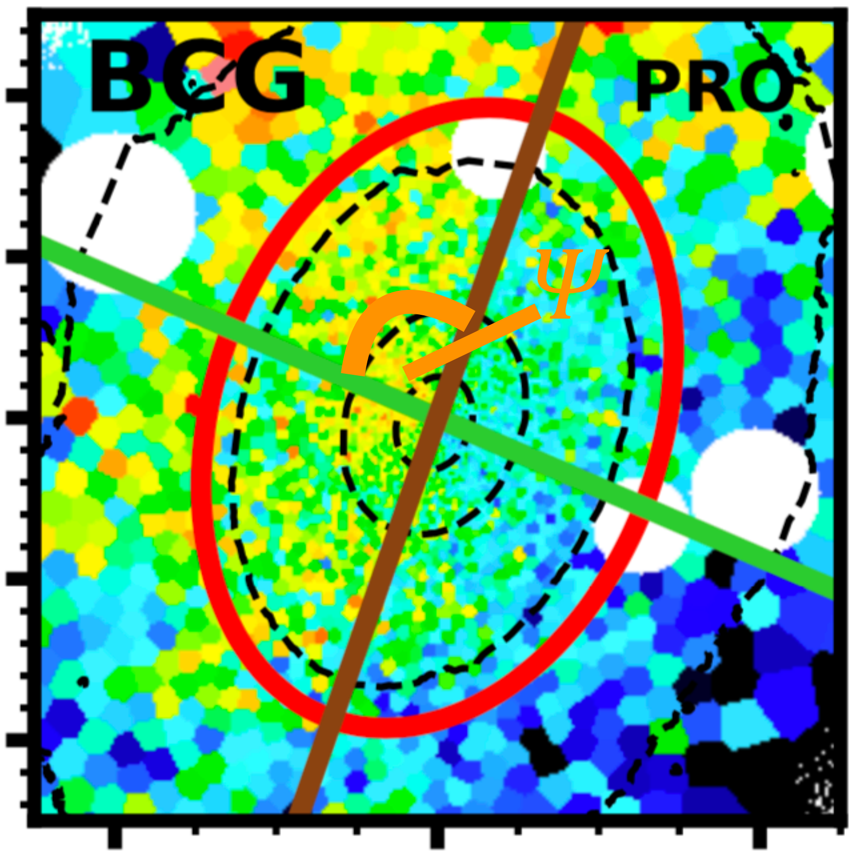
Krajnović et al. (in prep)



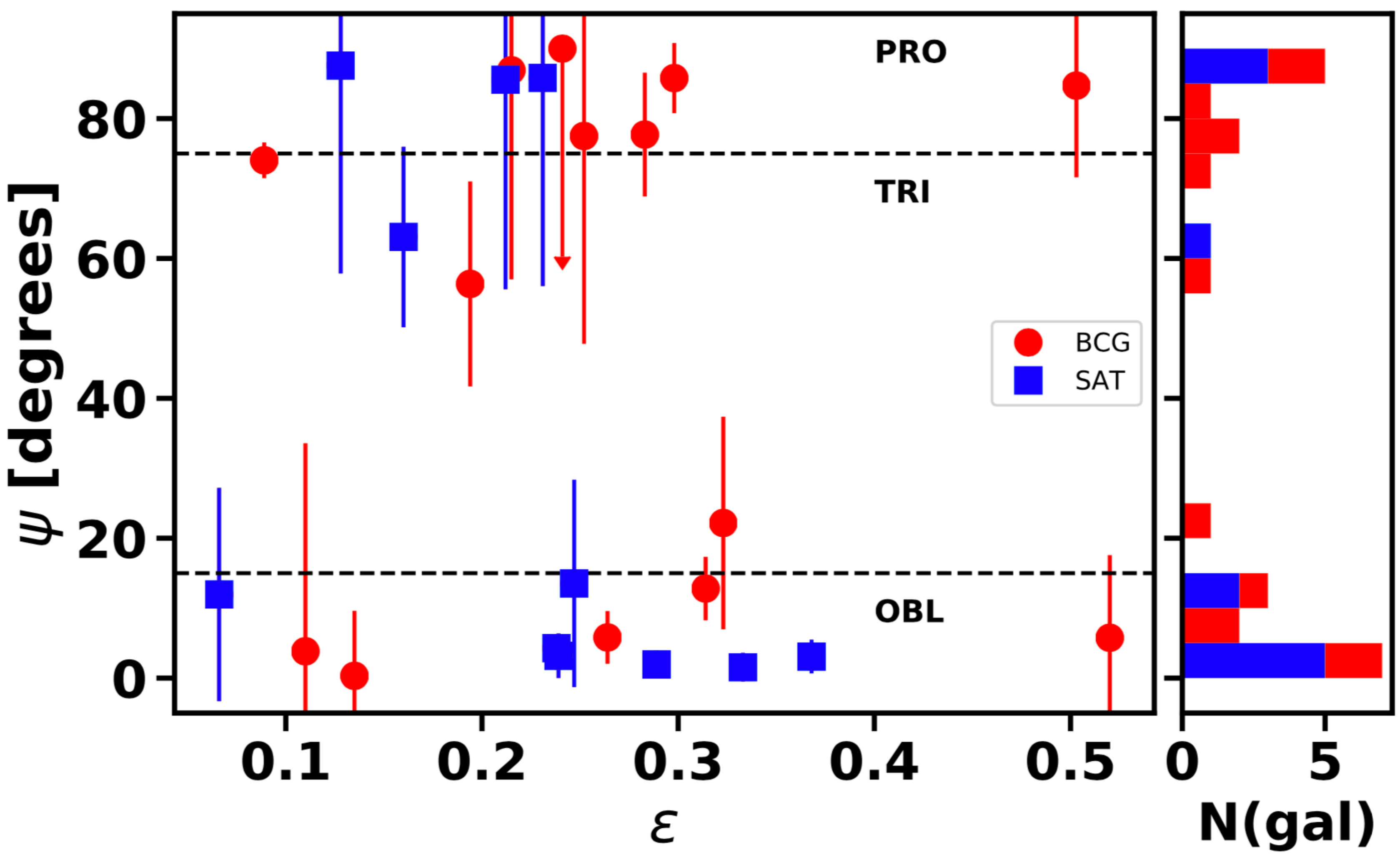

a) PGC047202
b) PGC048896
c) PGC073000
d) PGC046832
e) PGC043900
f) PGC003342
g) PGC015524
h) PGC065588
i) PGC019085
j) PGC018236
k) PGC047752
l) PGC004500
m) PGC049940
n) PGC007748
o) PGC046785
p) PGC047154
q) PGC099522
r) PGC047590
s) PGC099188
t) PGC047197
u) PGC047177
v) PGC046860
w) PGC097958
x) PGC047355
y) PGC047273
BCG
SAT
OBL
PRO
TRI
arcsec
-150/150
-50/50
-70/70
-80/80
-90/90
-40/40
-100/100
-60/60
-30/30
-200/200
Krajnović et al. (2018b)

Frequent prolate-like rotation

Krajnović et al. (2018b)



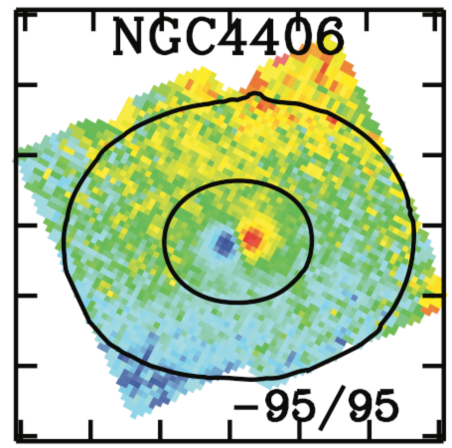
prolate-like rotation

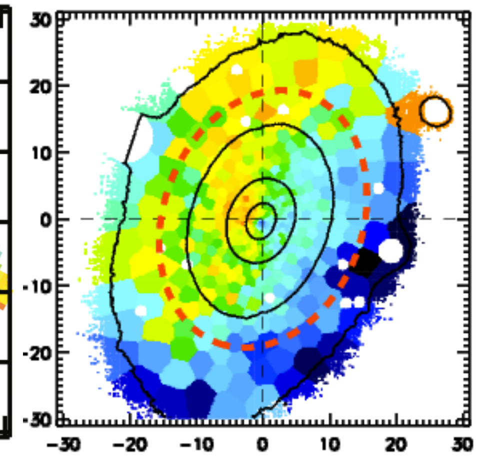


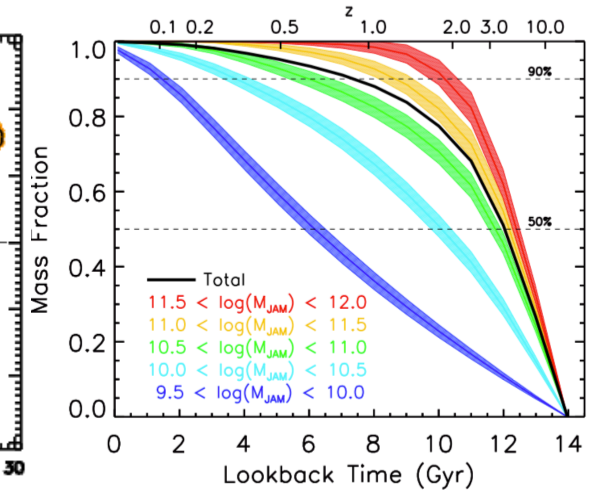
- galaxies with **prolate-like** rotation **exist at lower masses** (e.g. Franx et al. 1991; Krajnović et al. 2011; Tsatsi et al. 2017, Ene et al. 2018, Graham et al. 2018), but
- **bi-modality** distribution of kinematic misalignment, once **above a certain mass** (~10^{12} M_{sun})

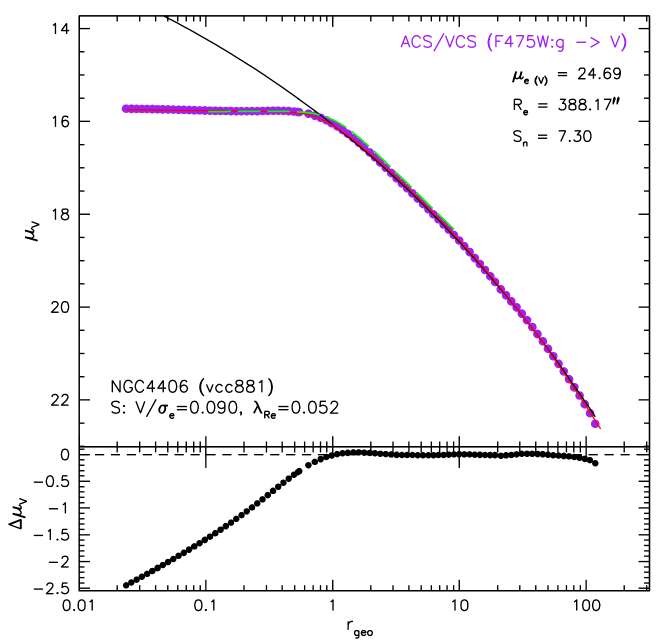
Massive galaxies - Slow rotators

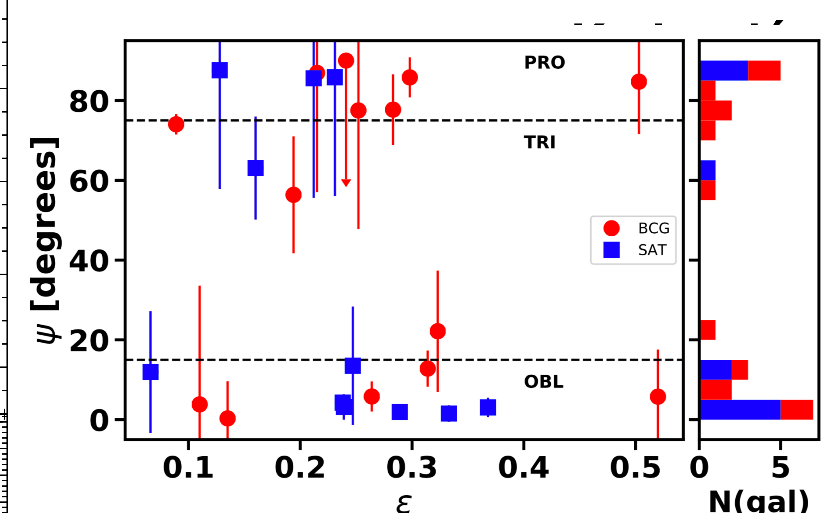
- **show multiple evidence for major dissipation-less merging**
  - complex kinematics
  - no disks
  - old stellar pops, no (or little) star formation
  - have cores in central light profiles
  - often triaxial or even prolate
  - located in dense environments



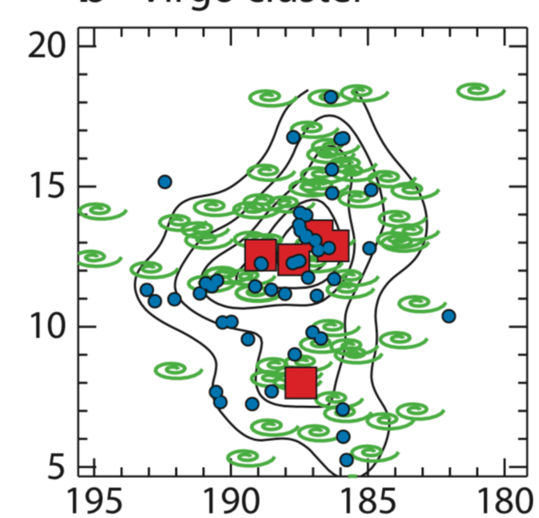








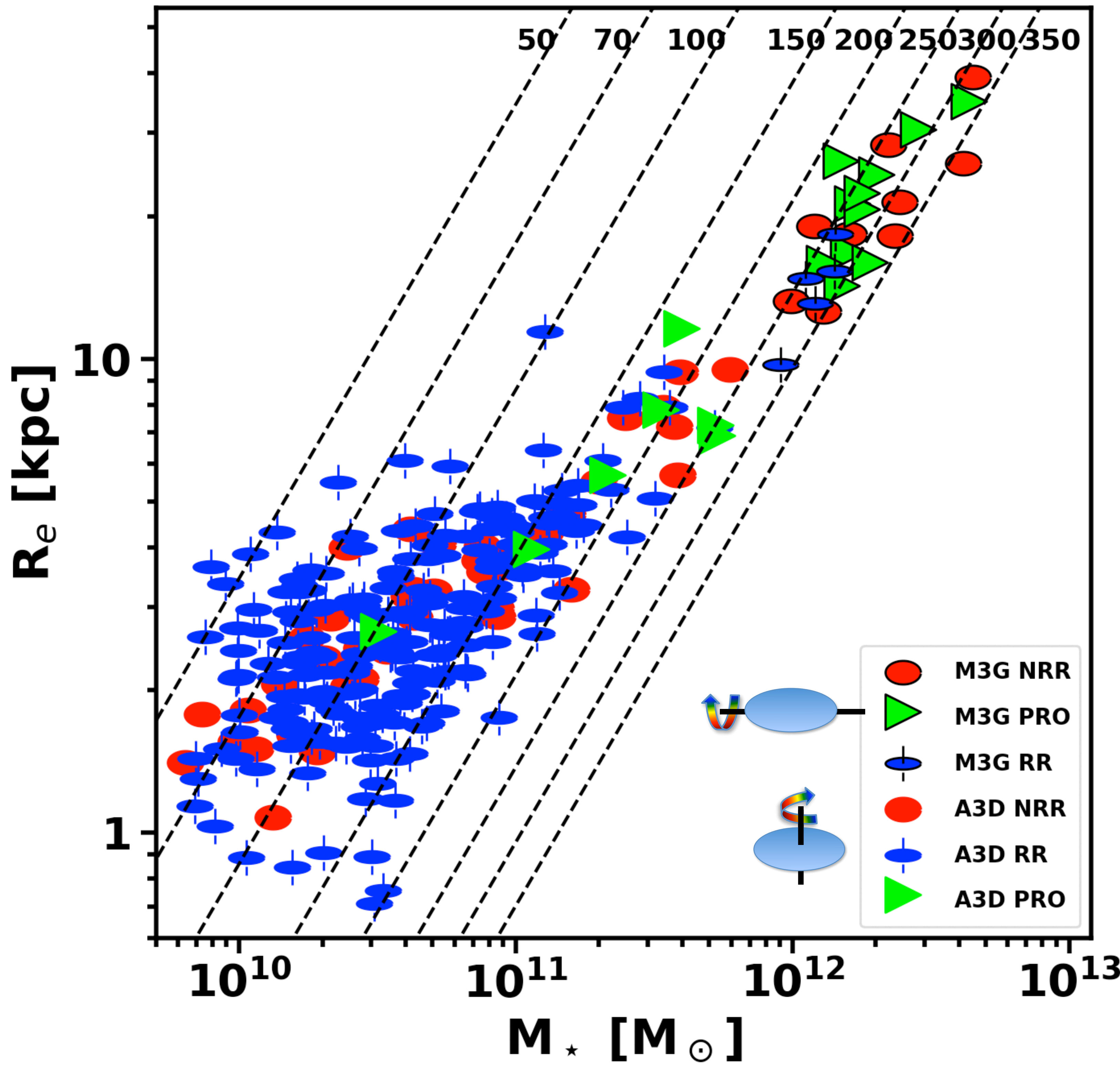
b Virgo cluster



Constraining mass assembly processes

- massive galaxies **extend** from the bulk of galaxy population
- **occupy area** predicted for **dry major mergers**
- galaxies **grow** by **SF**, **quench** through the process of **bulge growth**
- most massive galaxies ($>10^{12}M_{SUN}$) **require** dry major mergers

Krajnović et al. (2018b)



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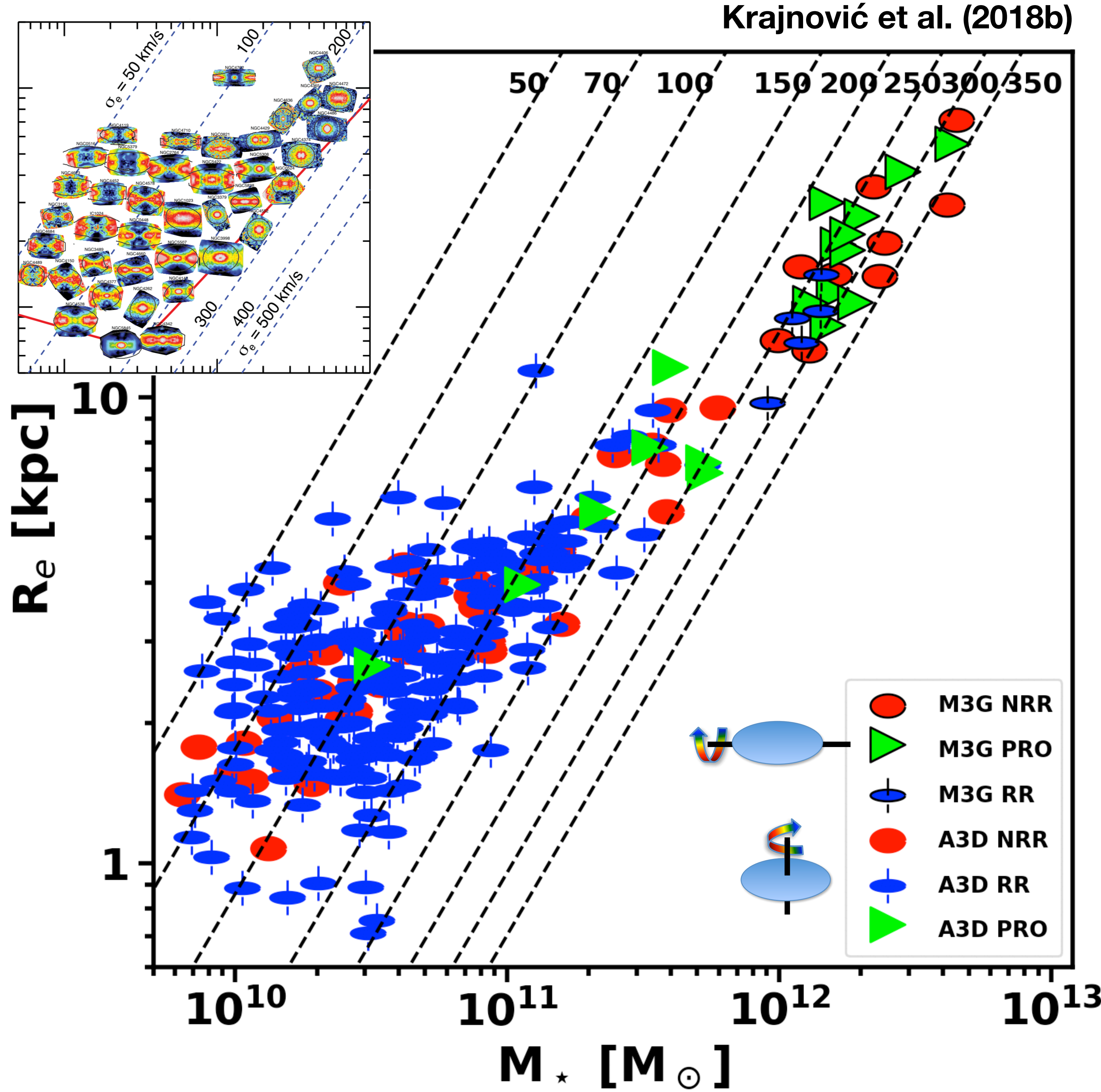

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