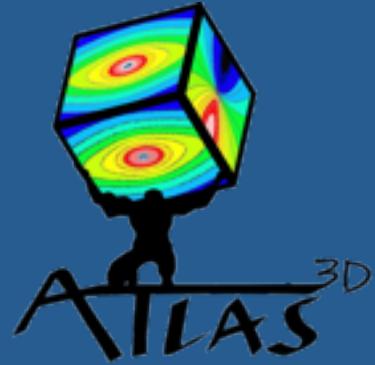




Leibniz-Institut für
Astrophysik Potsdam



ATLAS^{3D} Project: connecting early-type galaxies to spirals

Davor Krajnović

So different...



NGC4203



NGC4051

So different...



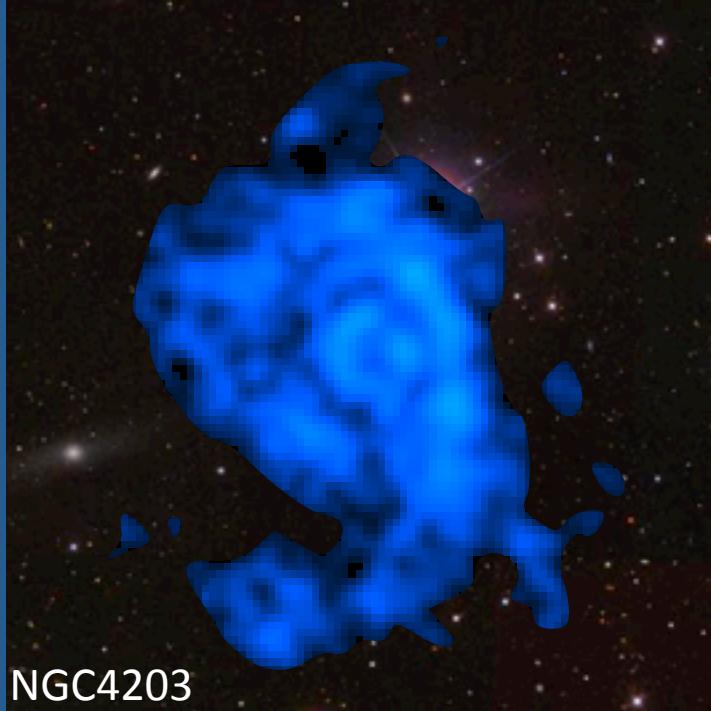
NGC4203



NGC4051

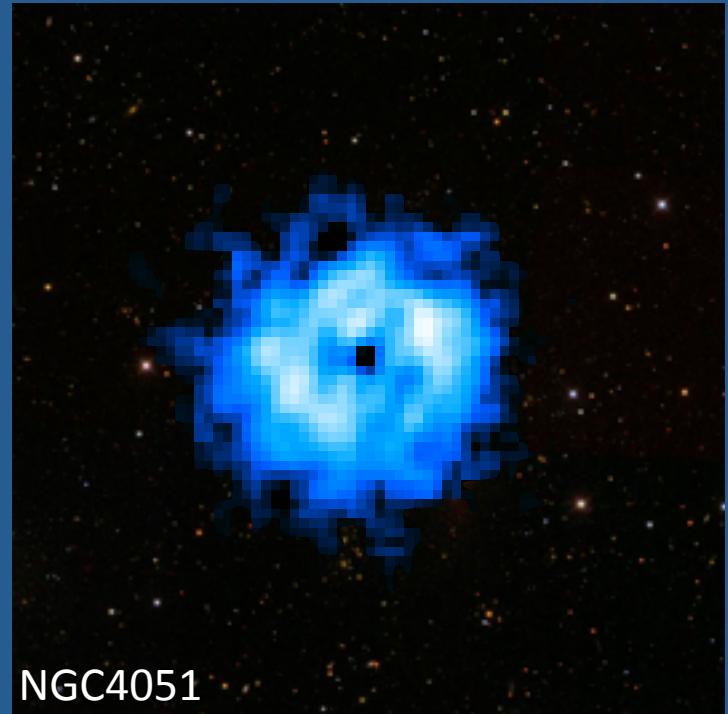
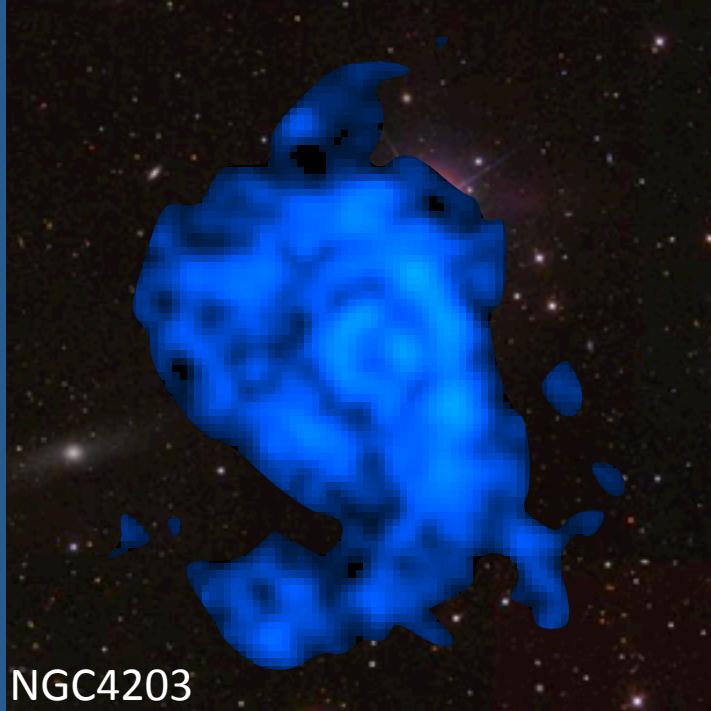
Same stellar mass, same environment, same HI mass, yet so different

So different...



Same stellar mass, same environment, same HI mass, yet so different

So different...



Same stellar mass, same environment, same HI mass, yet so different

Key questions of galaxy formation

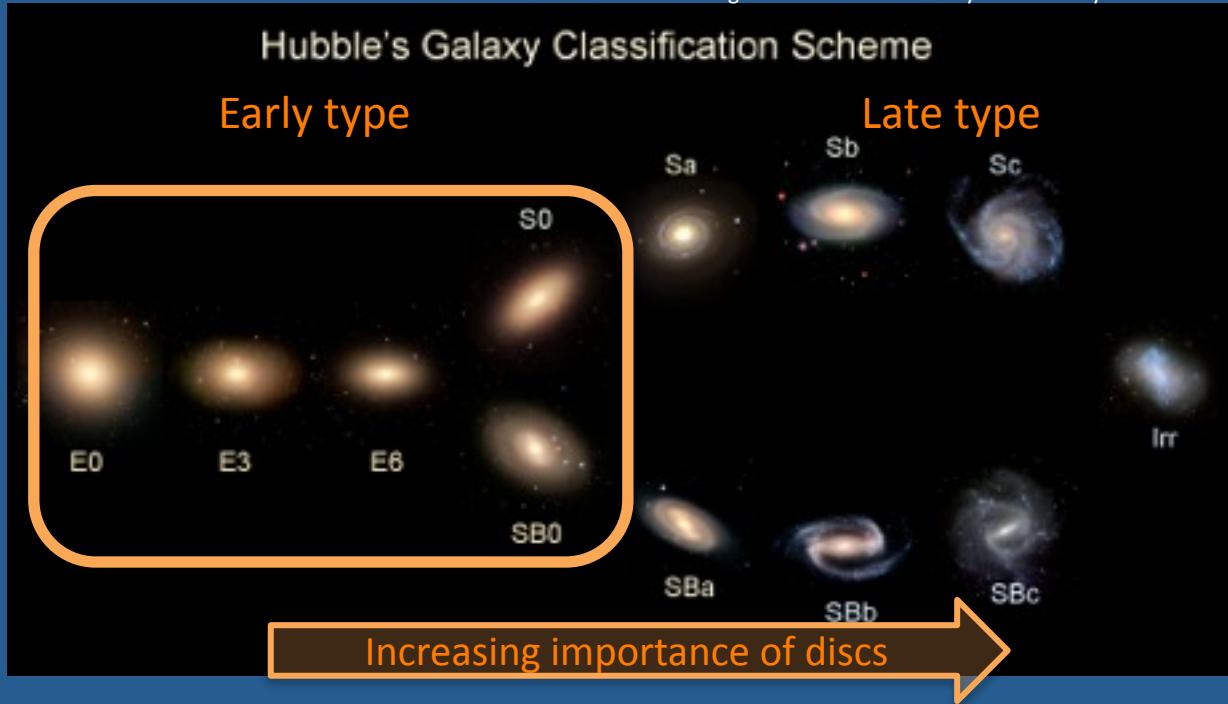
- What processes control star formation?
- What processes control mass assembly?
- What is the relation between these?

Goal: determine the key evolutionary processes and understand them in the cosmological context



Galaxy classification

Image credit: John Kormendy's Astronomy 301 web site



- Textbook picture based on Hubble Tuning fork, updated by Kormendy & Bender (1996)
- Early-type galaxies (Ellipticals and S0s) $\leftarrow \rightarrow$ late-type galaxies (spirals)
- Morphology is a transient phenomenon (e.g. Steinmetz & Navarro 2002)
- Sequence of increasing (from left to right) importance of disks

Galaxy classification



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Hubble diagram - SDSS-like observations



surface brightness cut at ~ 27 mag/arcsec 2



Blue star forming spirals

Red and dead ellipticals



Hubble diagram - deep MegaCam images



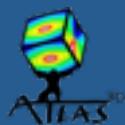
surface brightness cut at ~ 29 mag/arcsec 2



Spirals with red halos

Ellipticals with star forming discs

P-A. Duc @ MegaCam +



Misleading shapes

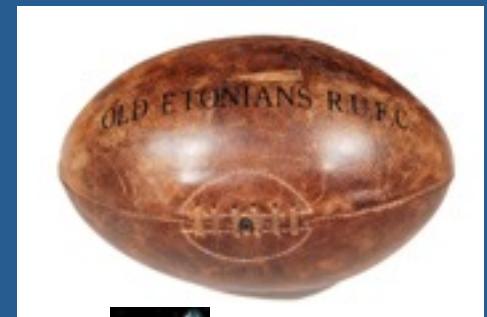
Sphere

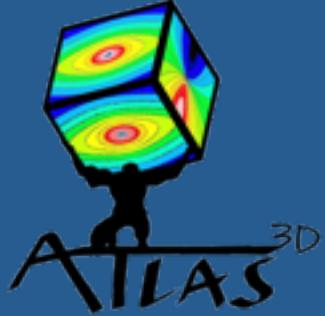


Disk



Ellipsoid





Project

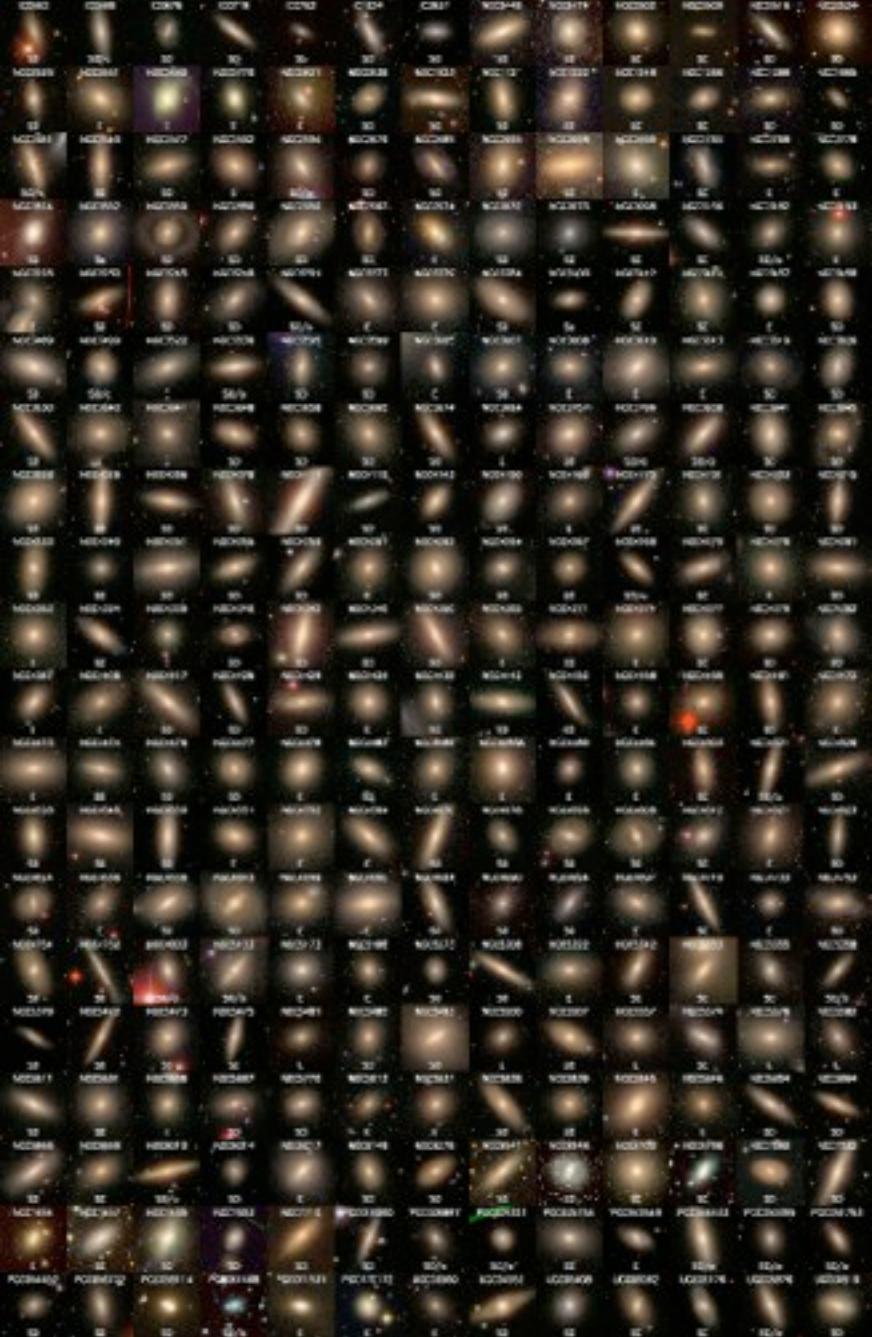
$M_K < -21.5$

$D < 42 \text{ Mpc}$

$|\delta - 29| < 35^\circ$

$|b| > 15^\circ$

- Parent sample: 871 nearby galaxies
- Morphological selection: No spiral arms (DSS/SDSS)
- No colour cut
- Observe a complete volume limited sample of ETGs: 260
- Mass range: $\sim 7 \times 10^9 - 5 \times 10^{11} M_{\text{sun}}$





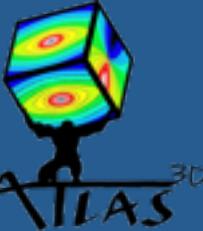
Comprehensive approach

OBSERVATIONS

Optical Spectra	Optical imaging	Radio	mm	NIR spectra	Archive
SAURON IFU	MegaCam, INT	WRST, EVLA	IRAM 30m, Carma	NIFS, SINFONI	2MASS, SDSS, HST, Spitzer, Chandra, Galex, Herschel

MODELLING AND SIMULATIONS

Dynamics	Stellar populations	High-res sim. binary mergers	High-res sim. of gas in ETGs	Cosmological simulations	Semi-Analytic Models
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The ATLAS^{3D} team

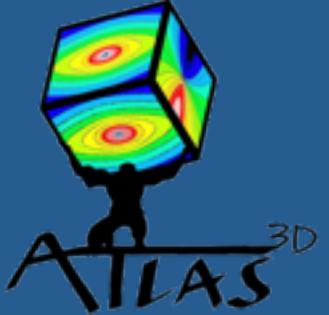
PIs: Michele Cappellari (Oxford), Eric Emsellem (ESO),
Davor Krajnović (Potsdam), Richard McDermid (Sydney)

Researchers:

Katey Alatalo, Leo Blitz, Maxime Bois, Frederic Bournaud,
Martin Bureau, Alison Crocker, Estelle Bayet, Jean-Charles
Cuillandre, Roger Davies, Tim Davies, Tim de Zeeuw, Pierre-
Alain Duc, Sadegh Khochfar, Harald Kuntschner, Raffaella
Morganti, Thorsten Naab, Tom Oosterloo, Marc Sarzi,
Nicholas Scott, Paolo Serra, Anne-Marie Weijmans, Lisa
Young

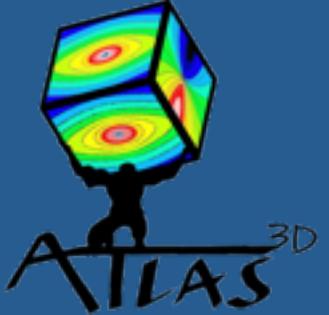
(25 researchers in ~15 institutes ~7 countries)

Data and tables available at: <http://www-astro.physics.ox.ac.uk/atlas3d/>

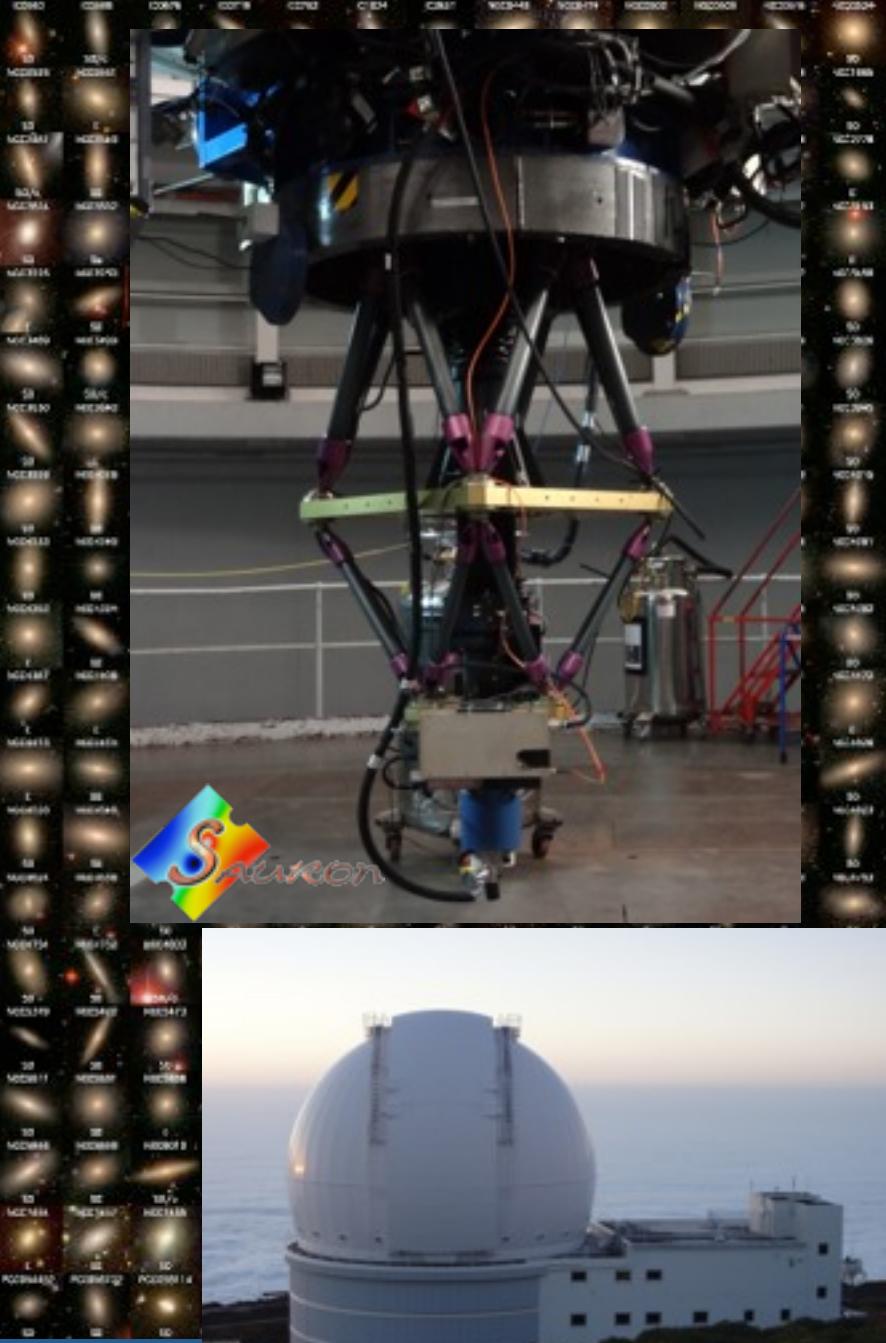


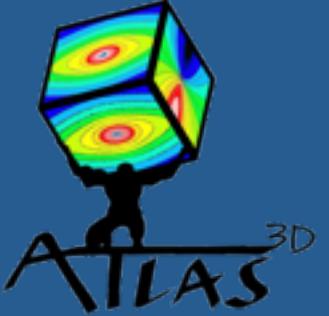
Outline





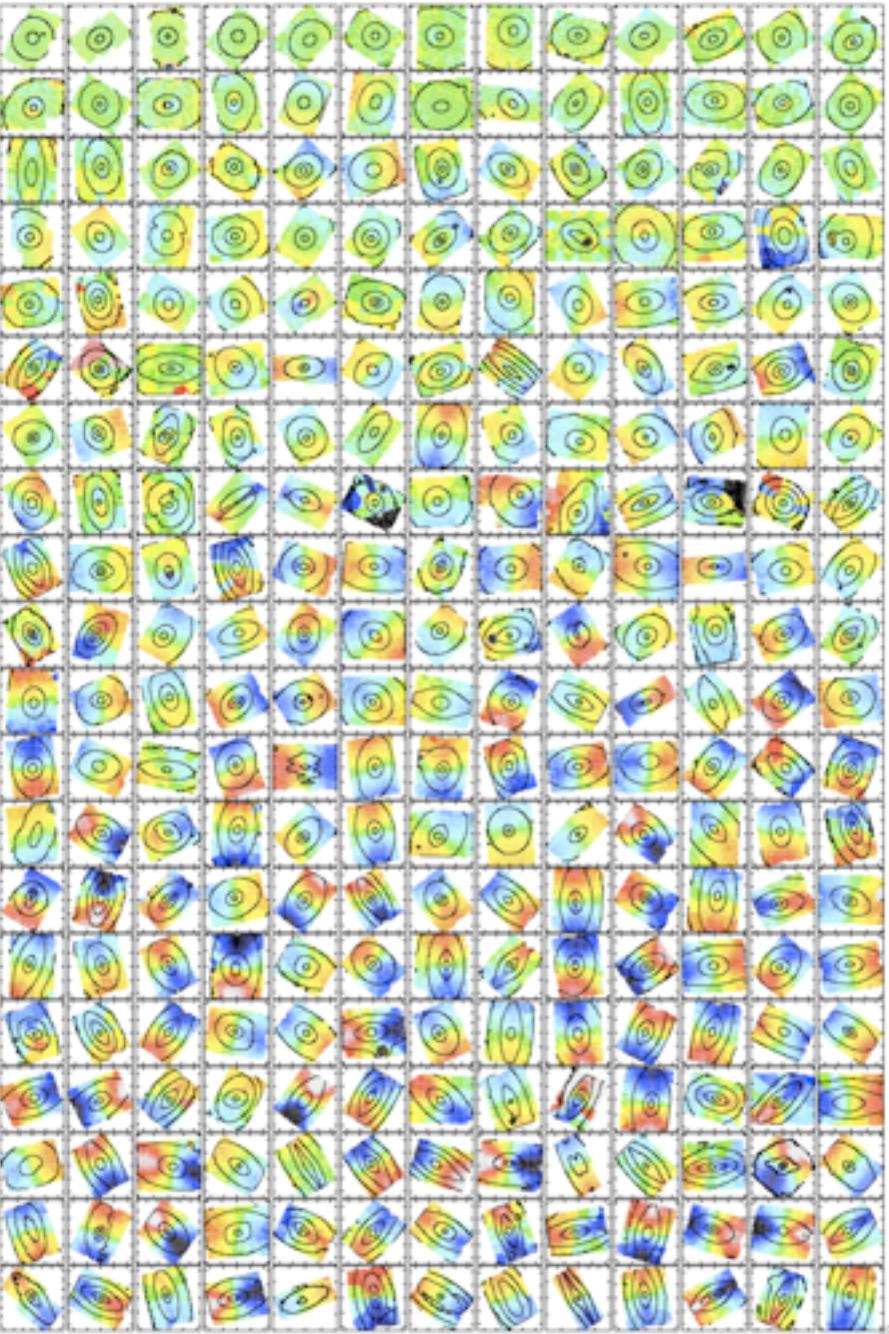
Outline





Outline

- Structure of ETGs
- Gas content of ETGs
- Formation paths
- Xmas holidays



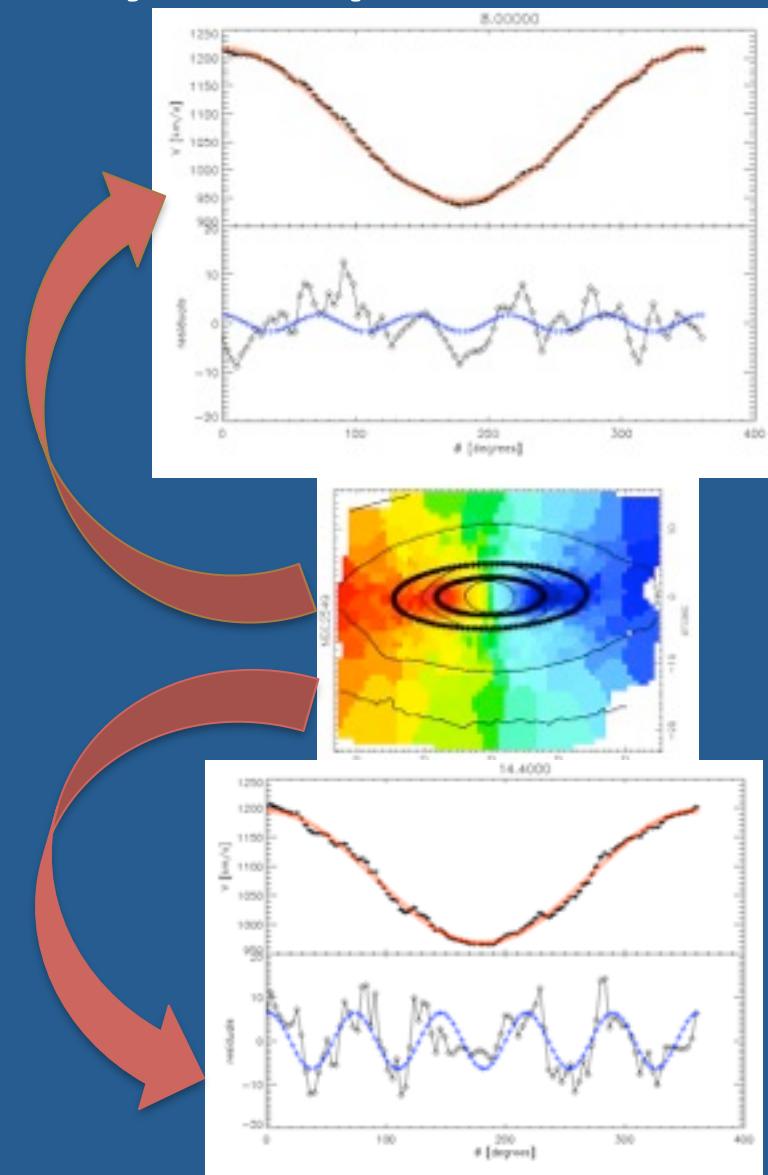
Structure of ETGs

Regularity of velocity maps

- Thin discs have regular velocity maps
- Along an ellipse (inclined circle) velocity is

$$V = V_0 + V_R \cos(\theta)$$

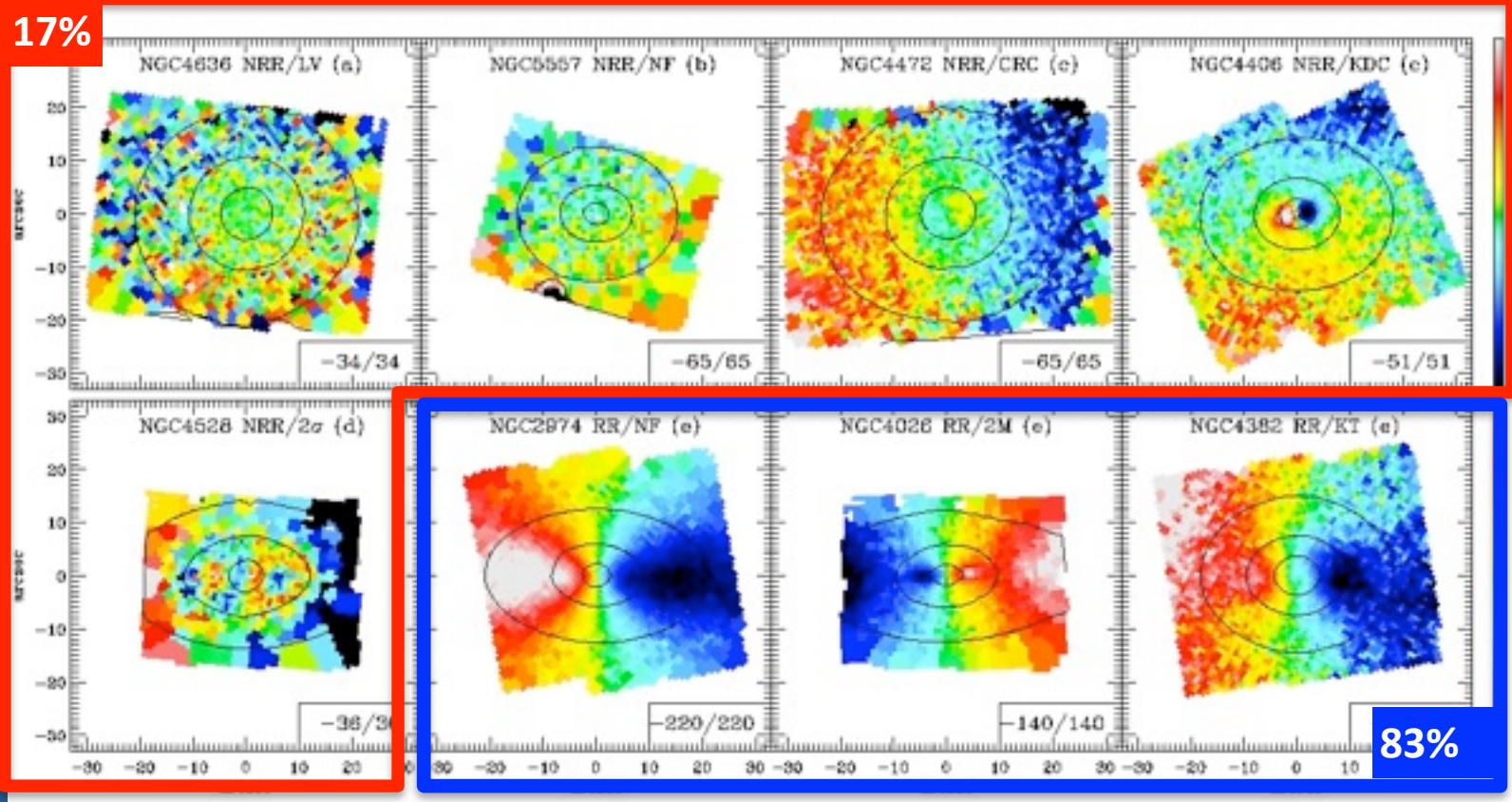
- as for stars on circular orbits in disks
- ***Kinometry***: a surface photometry (e.g. Jedrezejewski 1987) to higher-order moments of the LOSVD
- **~80% of ETGs have disk-like velocity maps at 4%**



Kinematics

Krajnović et al. (2011)

17%



83%

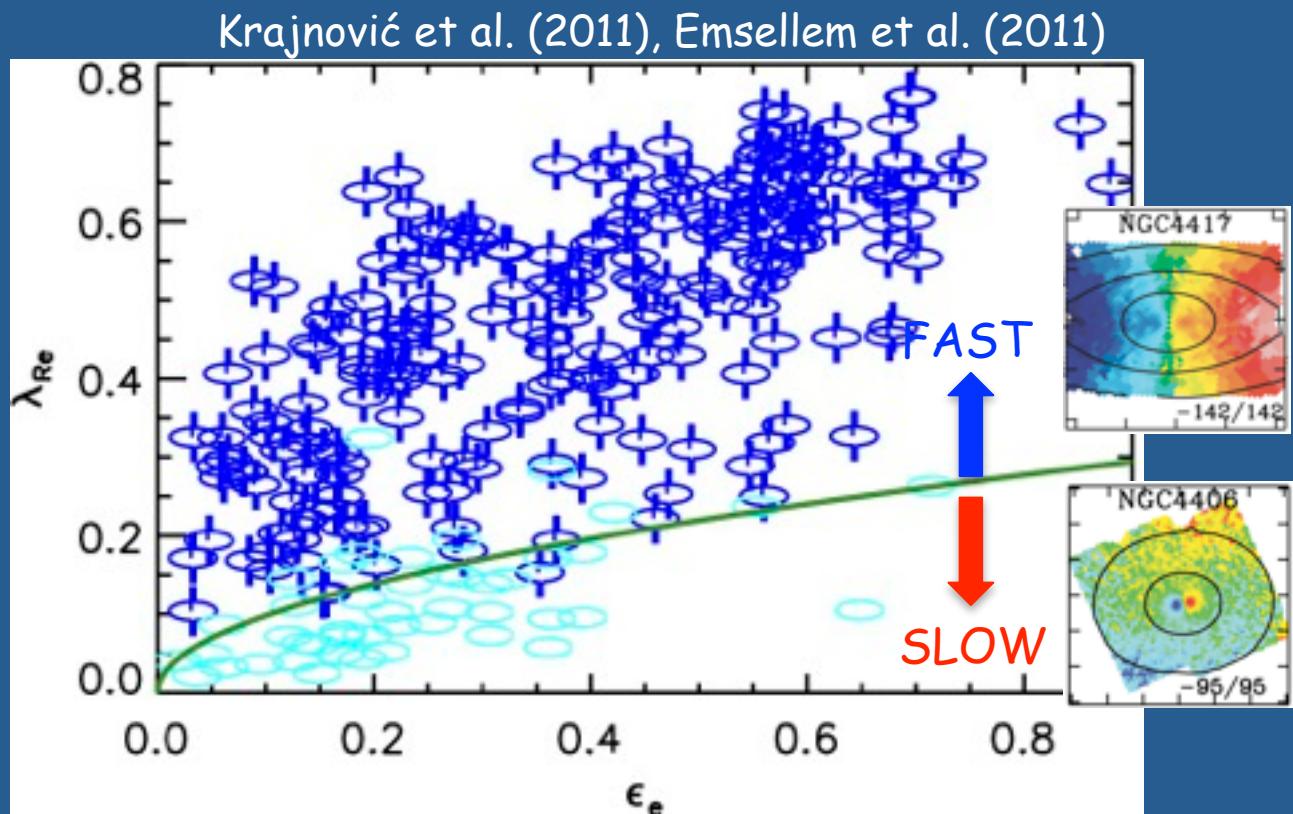
- Two general types of velocity fields: with regular (**disk-like**) and non-regular rotations

Specific angular momentum - λ_R

- Kinematic classification using *specific angular momentum*, λ_R
(Emsellem et al. 2007)

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

- Fast rotators
 - Regular, disk-like velocity maps
- Slow rotators
 - Non-regular velocity maps, KDCs, no net rotation

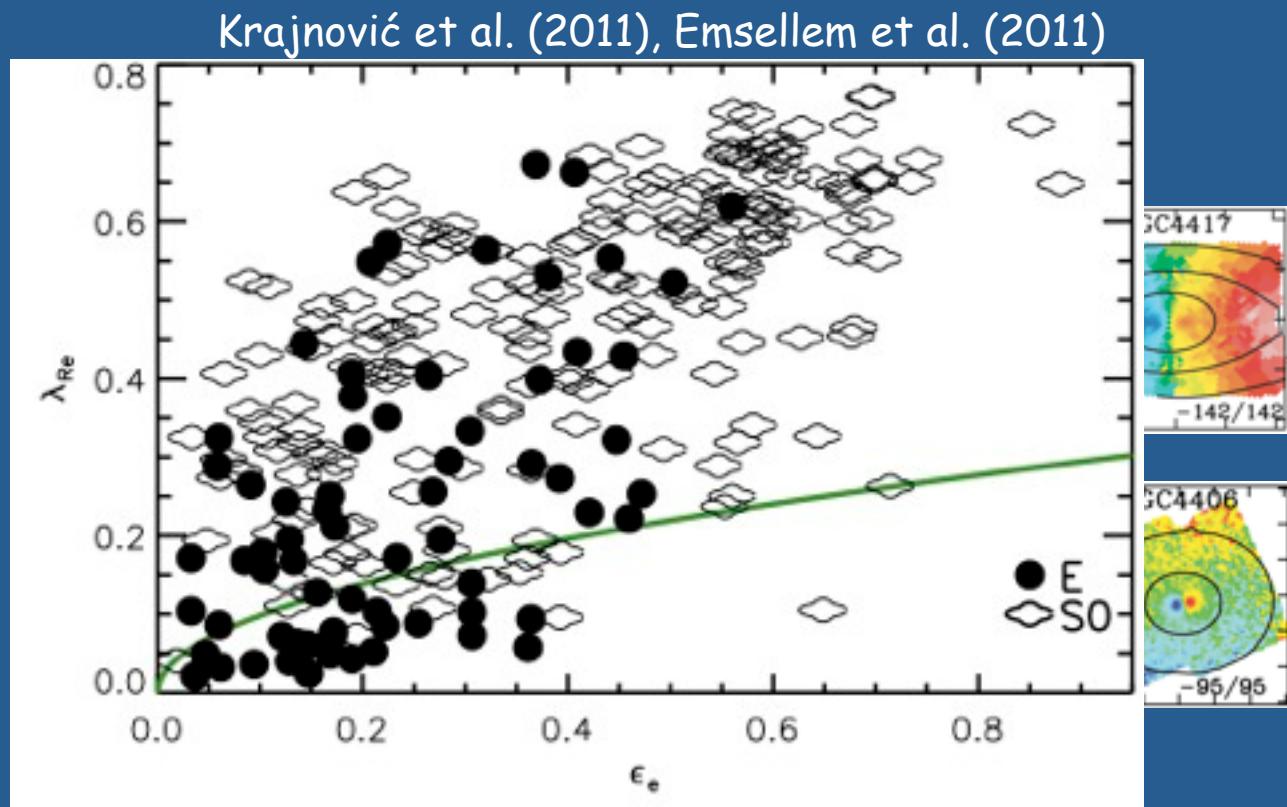


Specific angular momentum - λ_R

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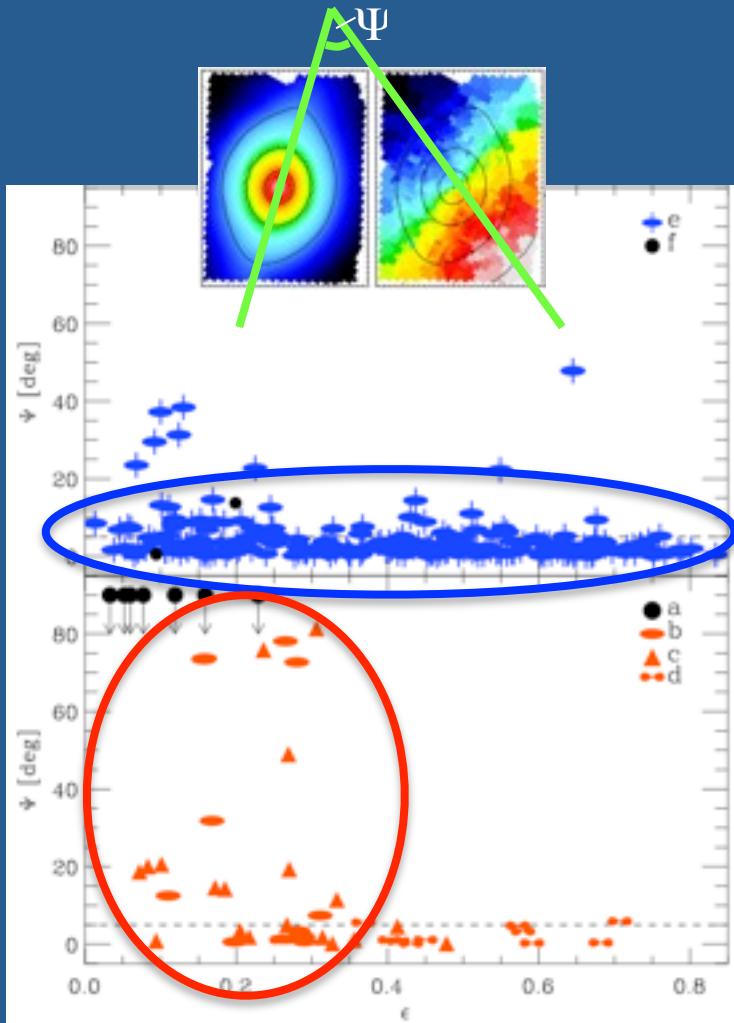
$$\lambda_R = \frac{\langle R \cdot |V| \rangle}{\langle R \sqrt{V^2 + \sigma^2} \rangle}$$

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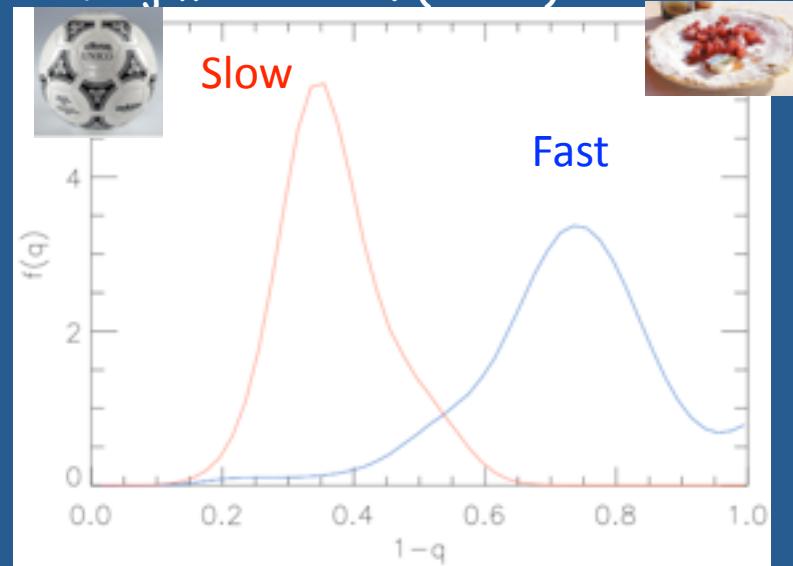
- **66% of E are FR**
- $FR \approx S0 + E(d)$
- 20% of FR are E
- SR = “true” ellipticals

Shapes of fast and slow rotators differ



Krajnović et al. (2011)

Weijmans et al. (2013)

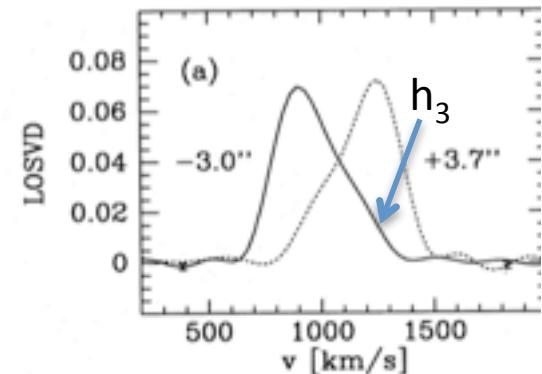


- **FR:** aligned \rightarrow nearly axisymmetric systems (+ bars!)
- **SR:** (also) misaligned \rightarrow triaxial systems
- **FR shape:** $q=0.25\pm0.14$ - similar to spirals (Lambas+1992, Padilla & Strauss2008)
- **SR shape:** $q=0.63\pm0.09$ - rounder than previous studies of Es

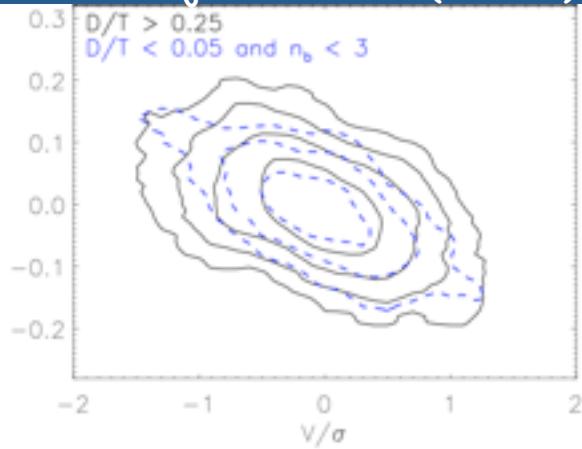
Kinematic evidence for disks

Bender et al. (1994)

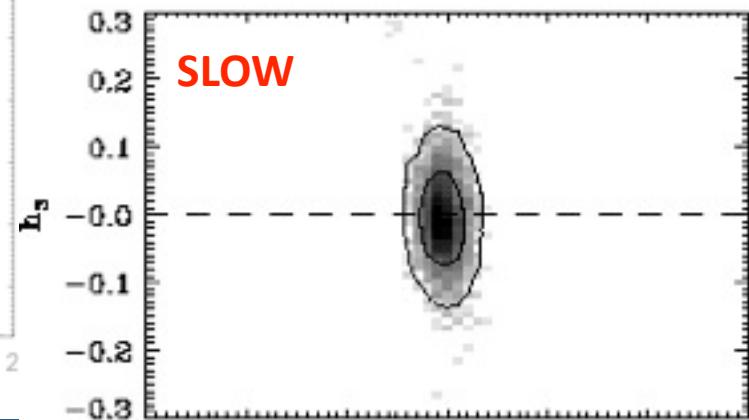
Line Of Sight Velocity Distribution



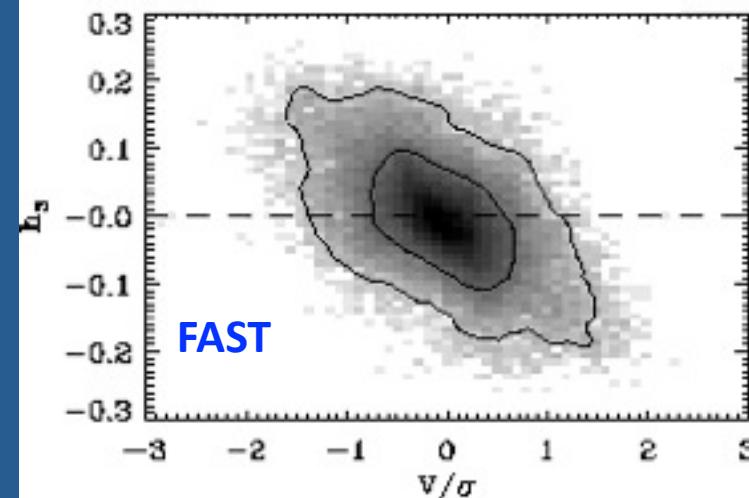
Krajnović et al. (2013a)



Krajnović et al. (2011)



- Asymmetric deviation measured in LOSVD by h_3 Gauss-Hermite coefficient (van der Marel & Franx 1993, Gerhard et al. 1993)
- Typical of embedded disks
- **Fast rotators – disks**
- **Slow rotators – no disks**



Decomposing galaxies

- Assume that an ETG is made of a bulge and a disk (and a bar....)

- Define:

- Disk as

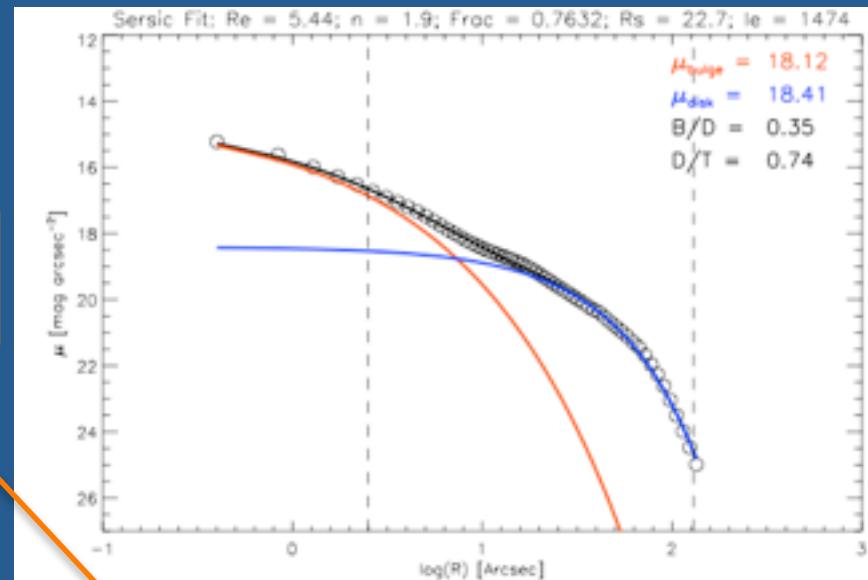
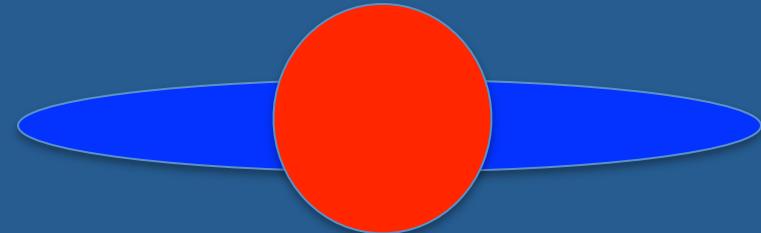
$$I_d(r) = I_0 \exp\left(-\frac{r}{R_d}\right)$$

- Bulge as

$$I(r) = I_e \exp\left\{-b_n \left[\left(\frac{r}{R_e}\right)^{1/n} - 1\right]\right\}$$

- Look for Disk-to-Total ratio (D/T)

- Bulge is not well defined
 - $n < 2$ or 2.5 or 3 is often consider “disk-like”



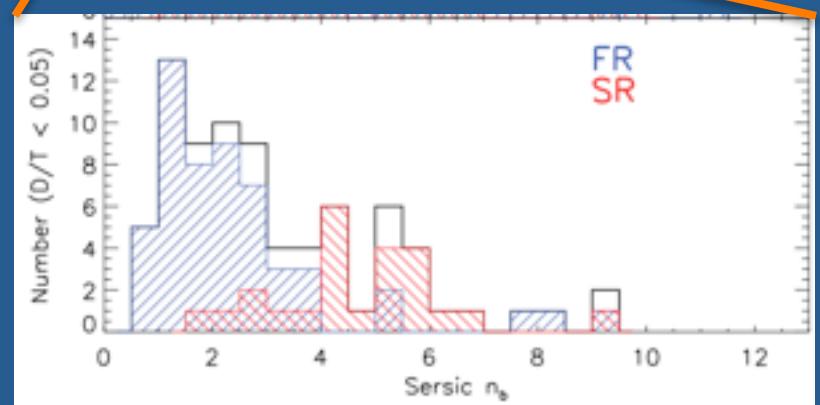
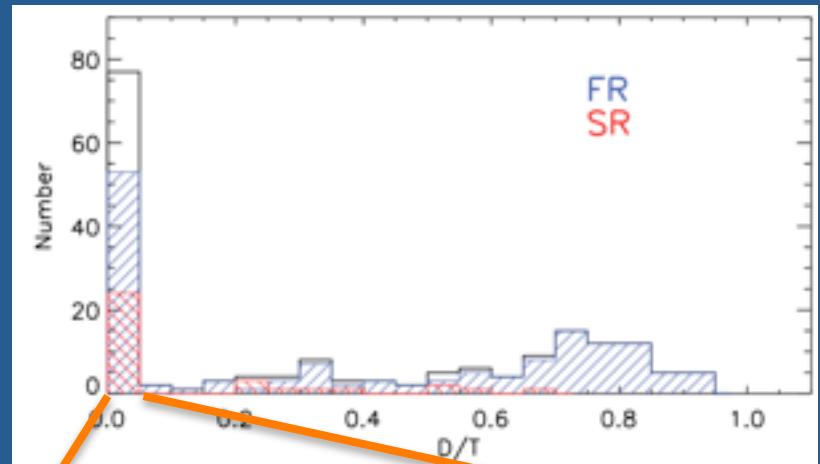
Sersic (1968)

Structure of fast rotators

- 85% of ETGs contain disks
- They represent 40% of the total mass of these objects
- Full range of D/T (or small n) in ETGs (FR)*, mimicking the spiral galaxy population
- **Fast rotators** cover the range of disky ellipticals to nearly bulge-less S0s
- **Slow rotators** (few exceptions!) do not contain significant disks

* Consequence: rotation in FR does not have to always increase with radius (it can decrease!)

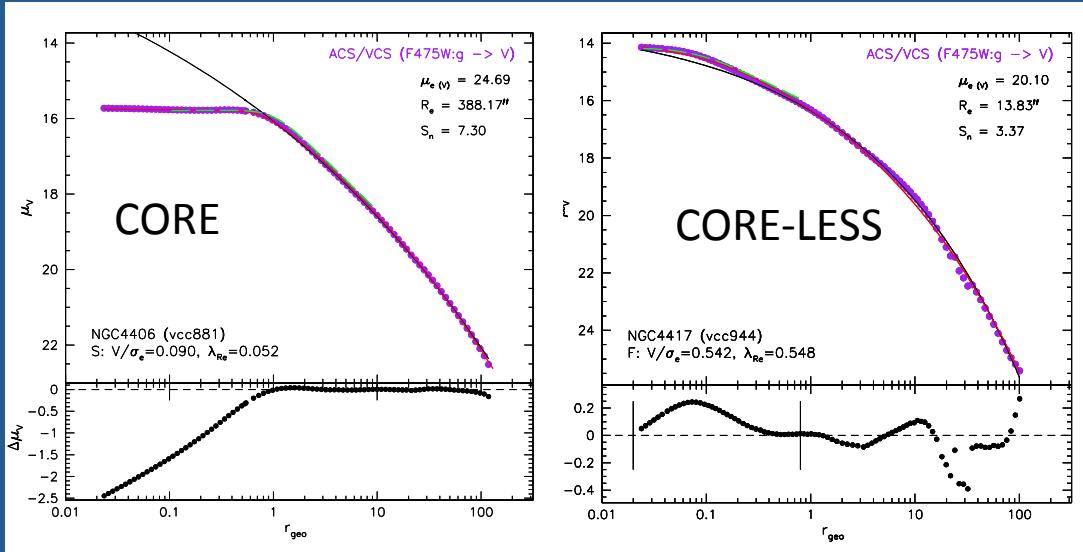
Decomposition: Total = “Disc” + “Bulge”



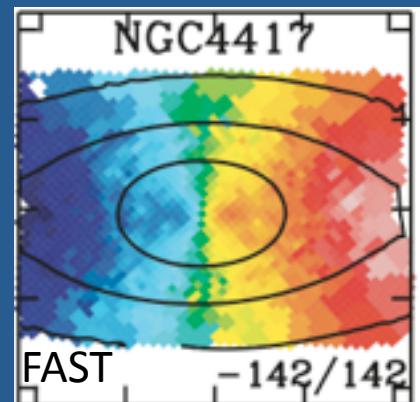
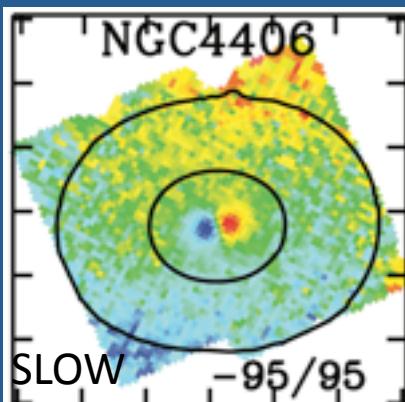
Krajnović et al. (2013a)

Clues in the nuclear structure

- Two types of profiles
 - Core
 - Core-less
- Two types of kinematics
 - “Slow rotator”
 - “Fast rotator”
- Different scales
- Link between kinematics and nuclear structure (e.g. Faber 1997)
 - Core = low V/σ
 - Core-less = high V/σ
- Is core = slow and core-less = fast?
- What if not?



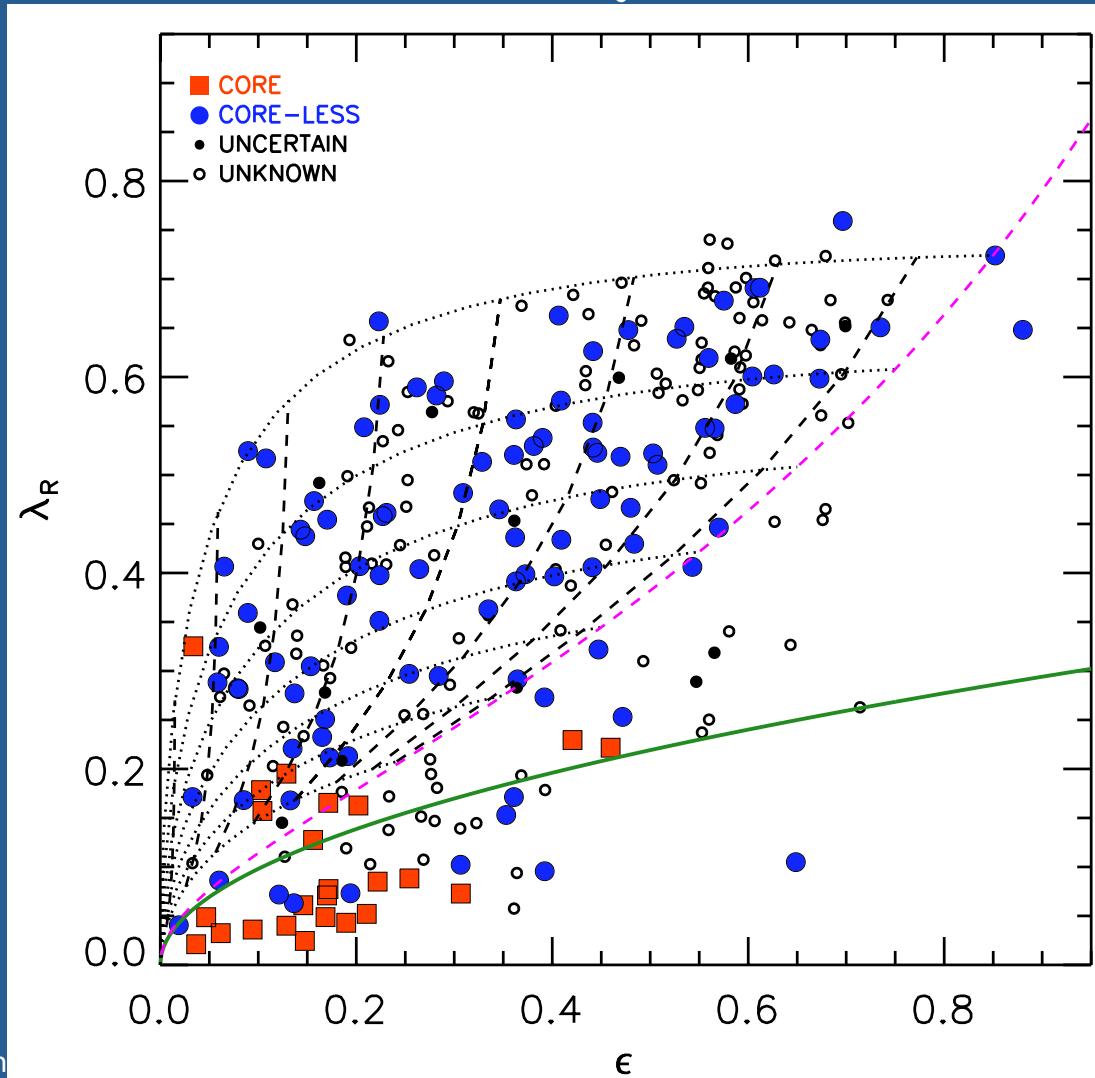
Krajnović et al. (2013b)



λ_R vs ϵ with nuclear profiles

Krajnović et al. (2013b)

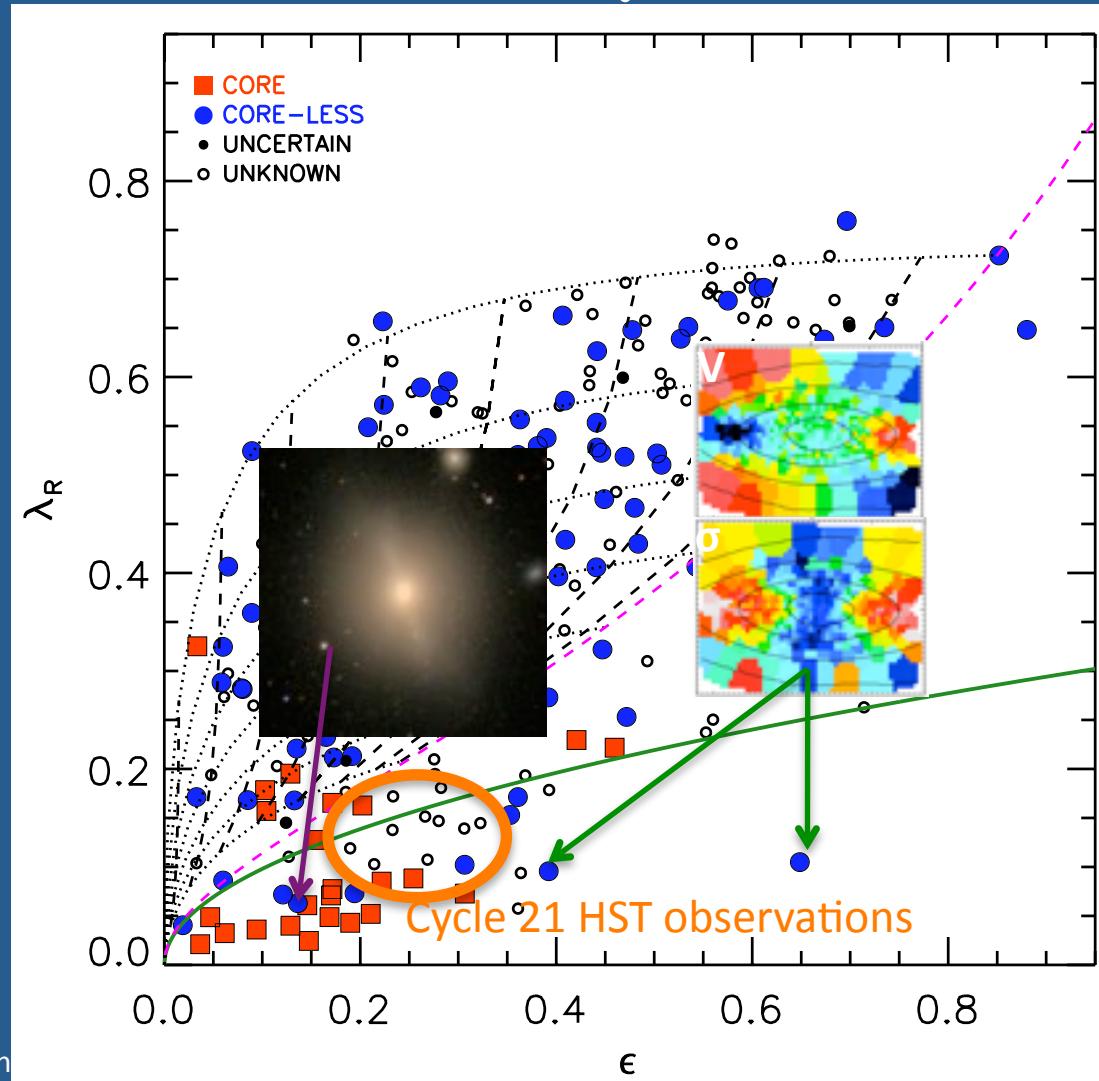
- **Fast rotators -> core-less**
 - **Slow rotators -> core**
- BUT
- 9 core FR
 - 9 core-less SR + as many more unknown
 - What are core FR?
 - how are the cores made/preserved?
 - What are core-less SR?



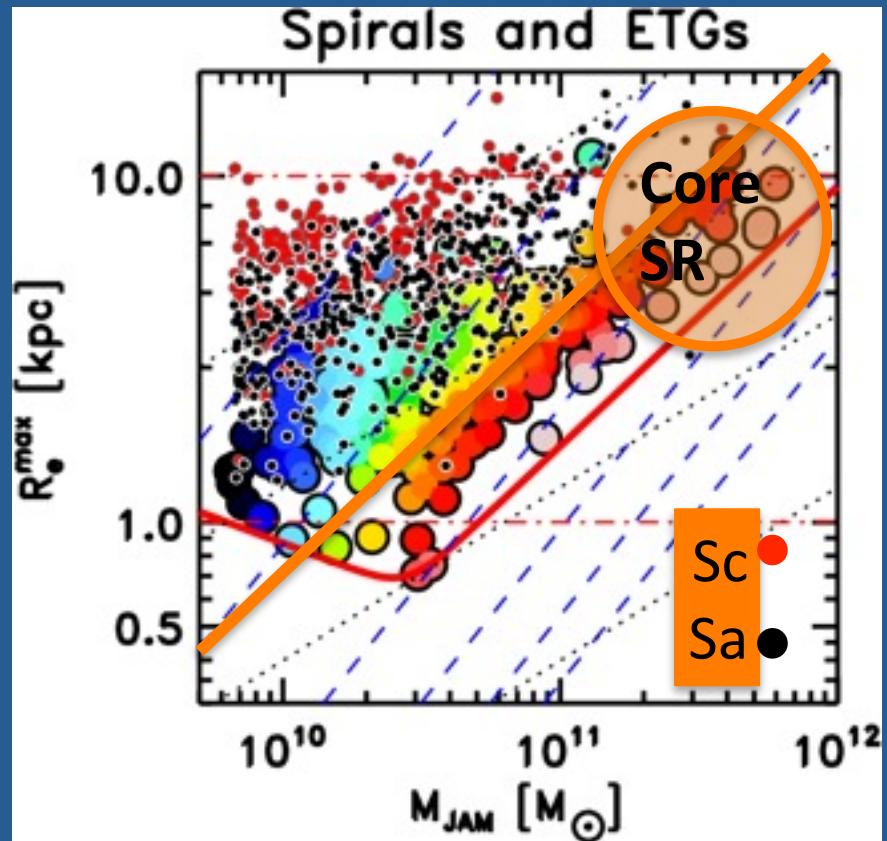
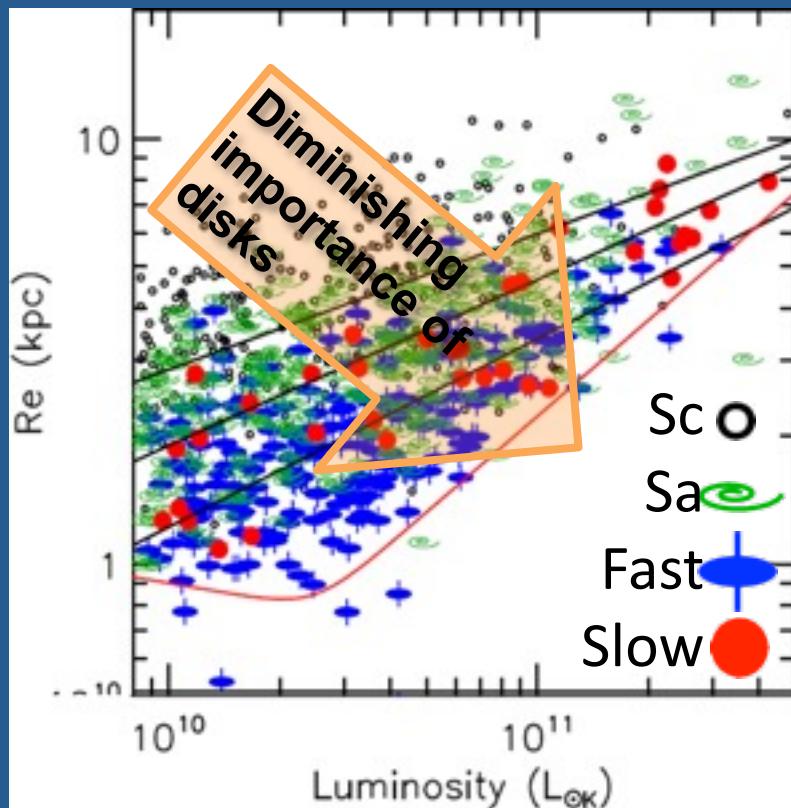
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Krajnović et al. (2013b)

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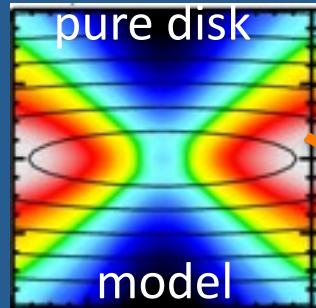
Linking spirals and ETGs



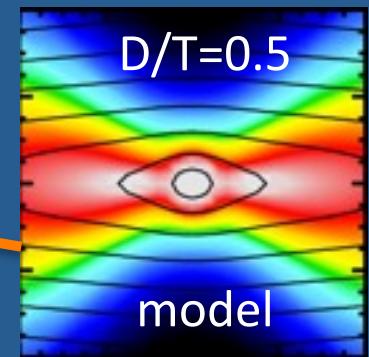
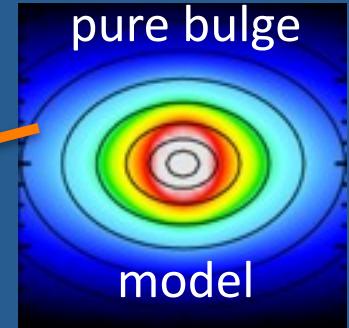
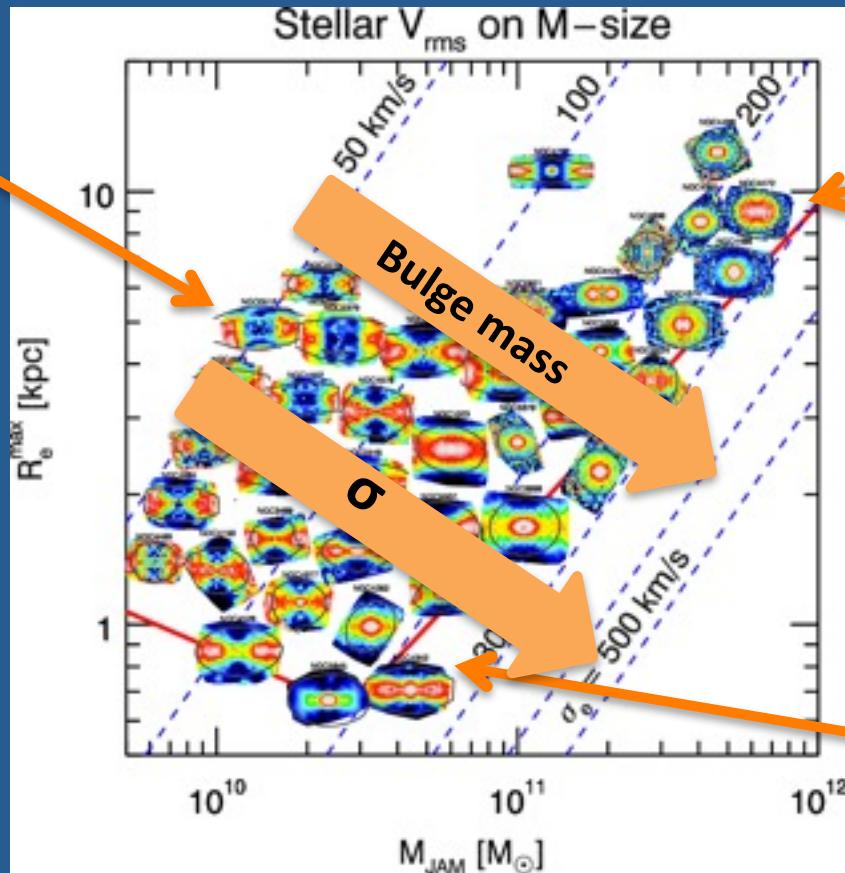
Cappellari et al. (2011, 2013)

- Spiral-ETG continuity on scaling relations
- Spirals essential to understand the big picture

Disks in Mass - Size plane



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



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

A parallel sequence of galaxies

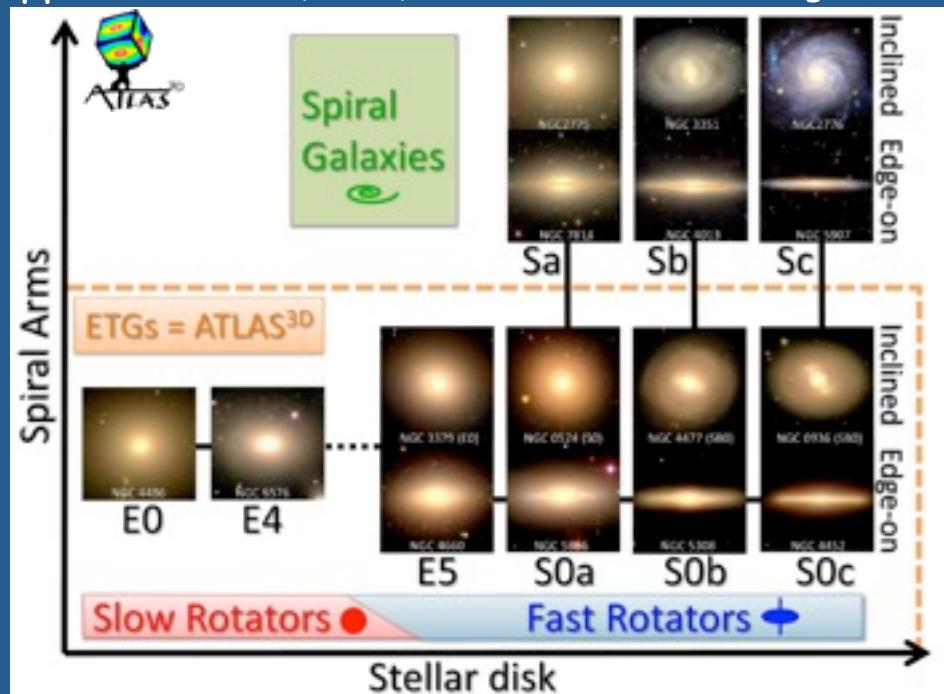
Cappellari et al. (2011); based on van den Bergh (1976)

SLOW ROTATORS

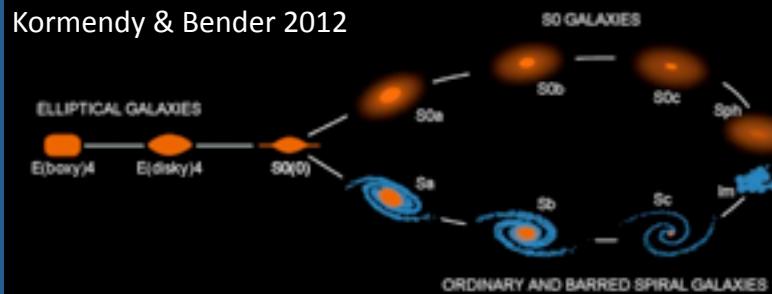
- complex (and varied) kinematics
- spherical or (weakly) triaxial
- nuclear cores (missing light)
- massive

FAST ROTATORS

- simple kinematics
- significant disk contribution (all ratios)
- axisymmetric, but anisotropic



- A strong link between spirals and the majority of ETGs (fast rotators), but **not** slow rotators (see also Kormendy & Bender 2012)
- Transition between slow and fast rotators murky → a variety of processes responsible for their creation

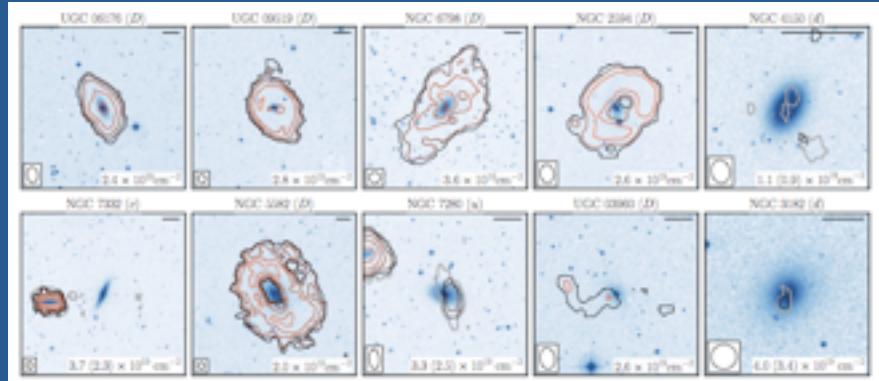


Gas content of ETGs

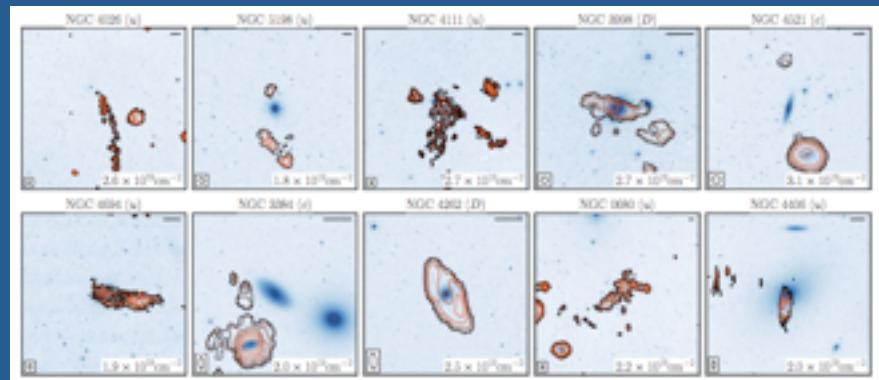
HI gas: large scale structures

- Detection: strong environmental dependence:
10% (virgo) vs **40%** (field)
- **Disc/ring: 64%**
- **Unsettled: 8%**
- **Clouds: 28%**
- A continuum of morphologies:
 - clouds – unsettled – discs
- Weak trend with luminosity
 - Less HI
 - mostly more perturbed

Serra et al. (2012)



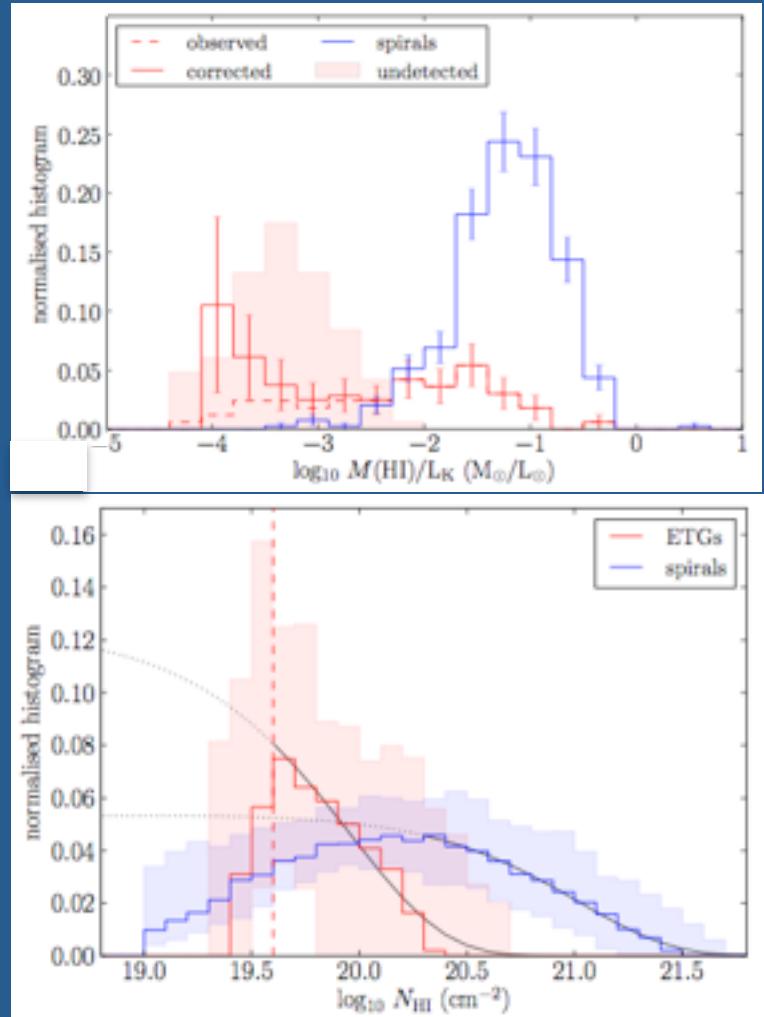
10 galaxies in least dense environment



10 galaxies in densest environment

HI: ETGs vs Spirals

- HI provides material for star formation in ETGs
- overlap with spirals in $M(\text{HI})$ and $M(\text{HI})/L_K$
 - $\log M(\text{HI}) = 7\text{-}10 M_{\text{sun}}$
- less HI than spirals, **but**
- many ETGs have similar amount of HI as spirals
- **but** smaller column densities in ETGs



Serra et al. (2012)

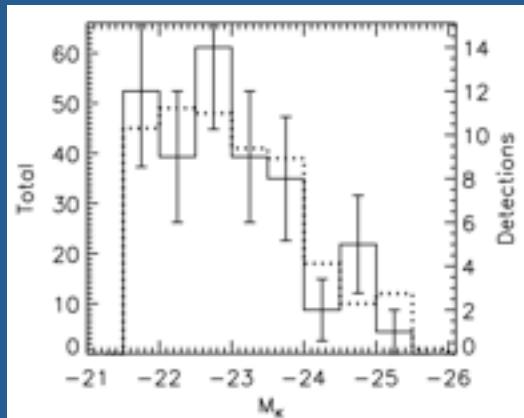
Molecular gas

Young et al. (2011)

IRAM 30m Single Dish Survey

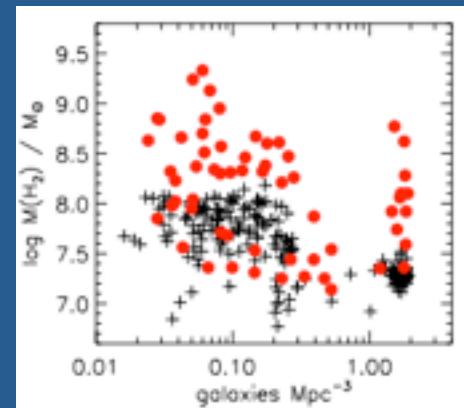
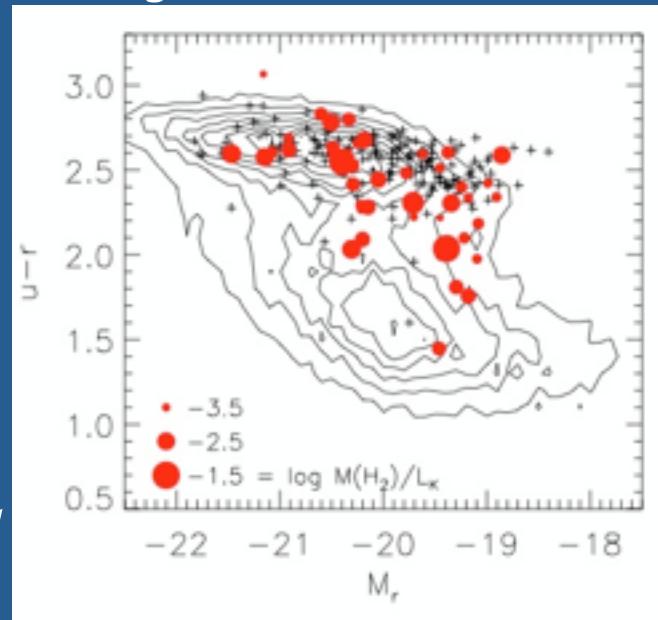
- **Detection rate: 22%**
- Molecular gas masses in range 10^7 to 10^9 Msun
- Upper limits down to 6.3×10^6 Msun
- Molecular gas fractions: 7% to 0.02% (Msun/L_K)
- No detections of molecular gas in slow rotators

Detection rate independent of luminosity!

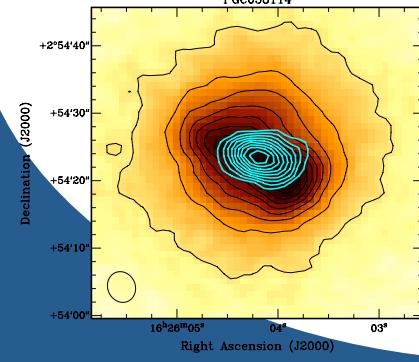
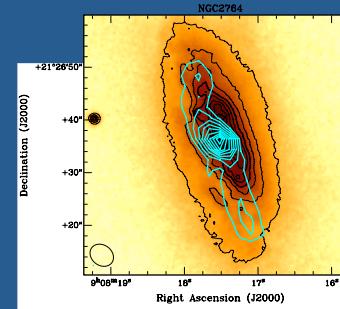
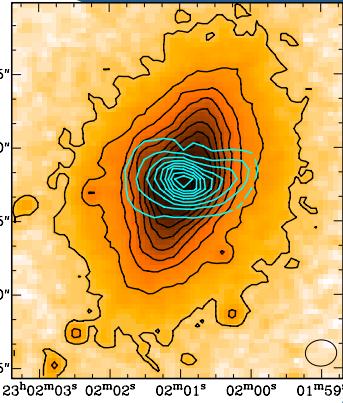
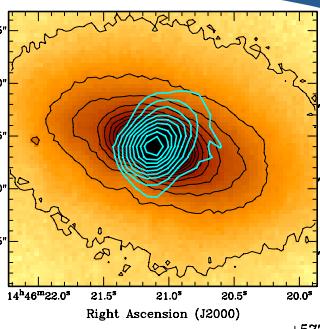
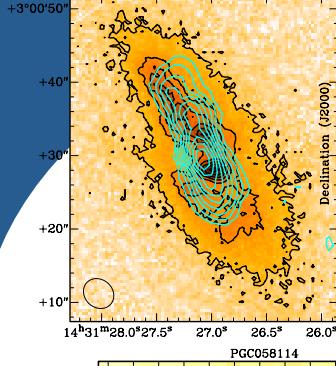


Red and dead? Not really

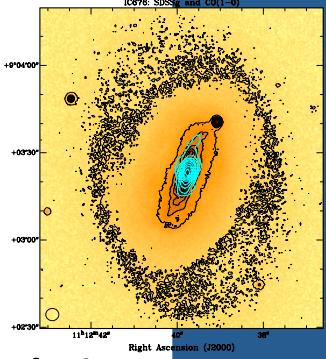
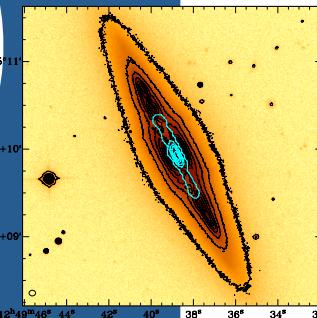
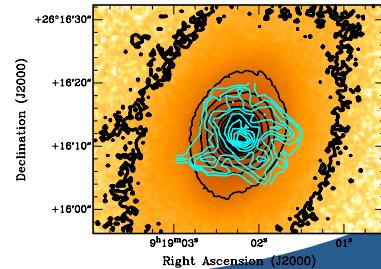
Detection rate also seems to be independent of environment!



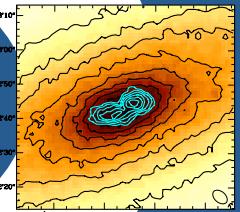
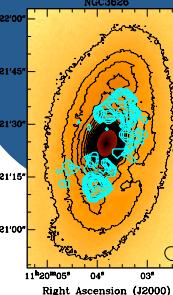
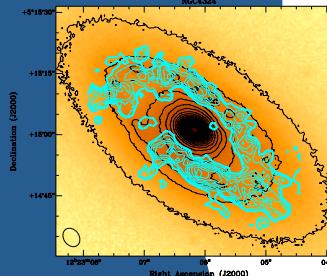
CO gas morphologies



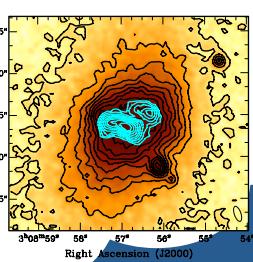
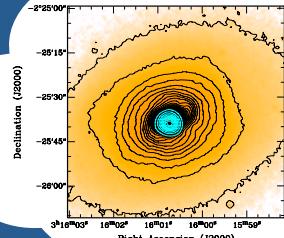
Discs



Bars and Rings (~35%)



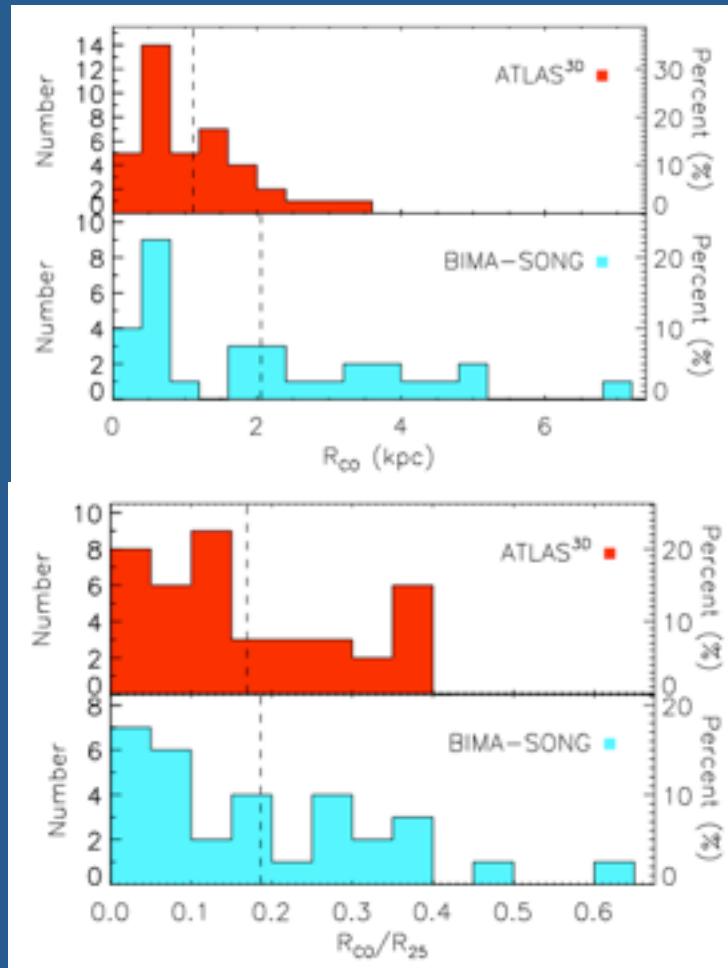
Disturbed Distributions (~10%)



Alatalo et al. (2013)

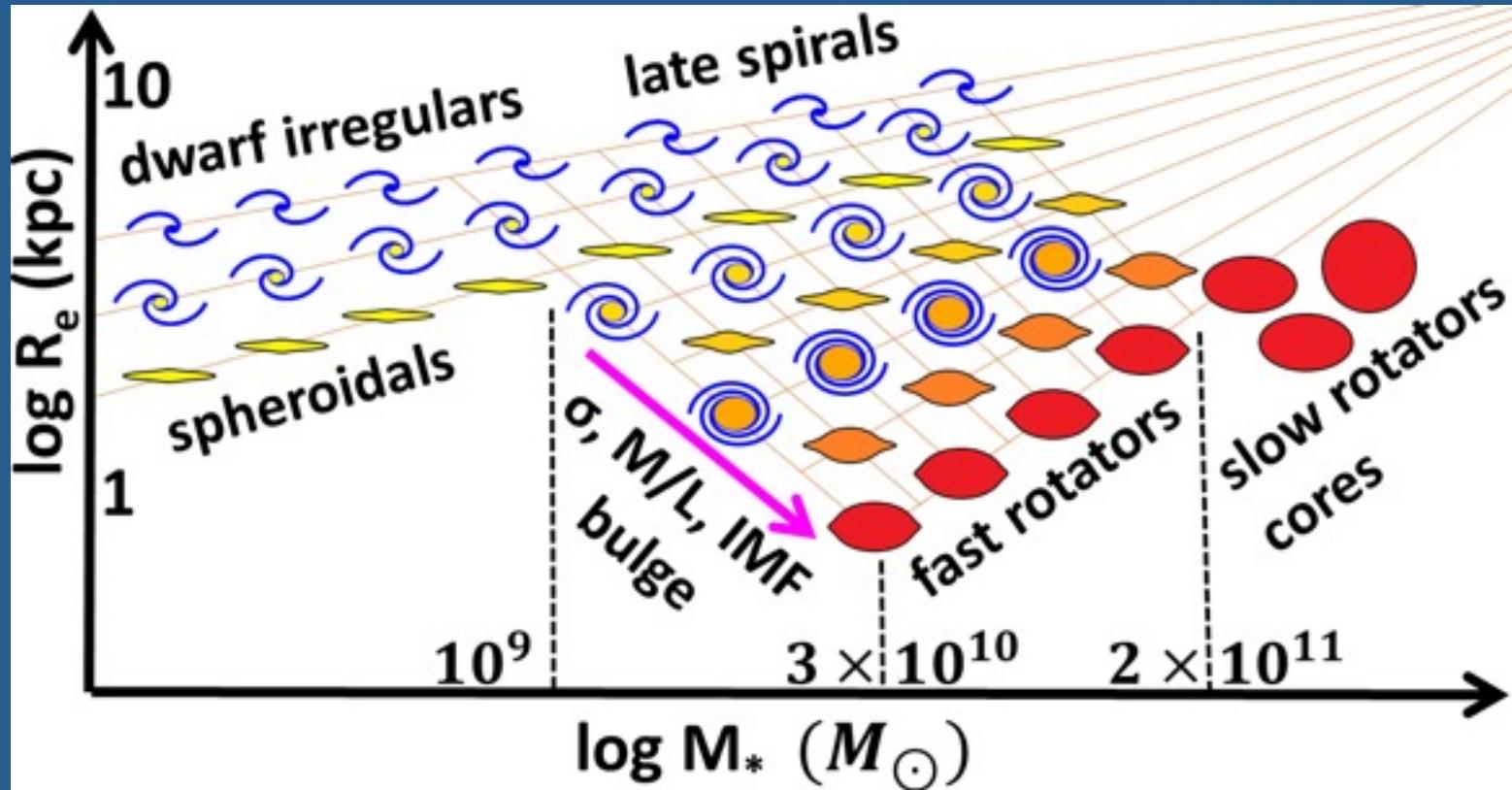
CO: ETGs vs Spirals

- less CO than spirals
- smaller **absolute** spatial extent, but **relative** spatial extent similar (scaled to stellar characteristic length/luminosity)



Davis et al. (2012)

A schematic summary



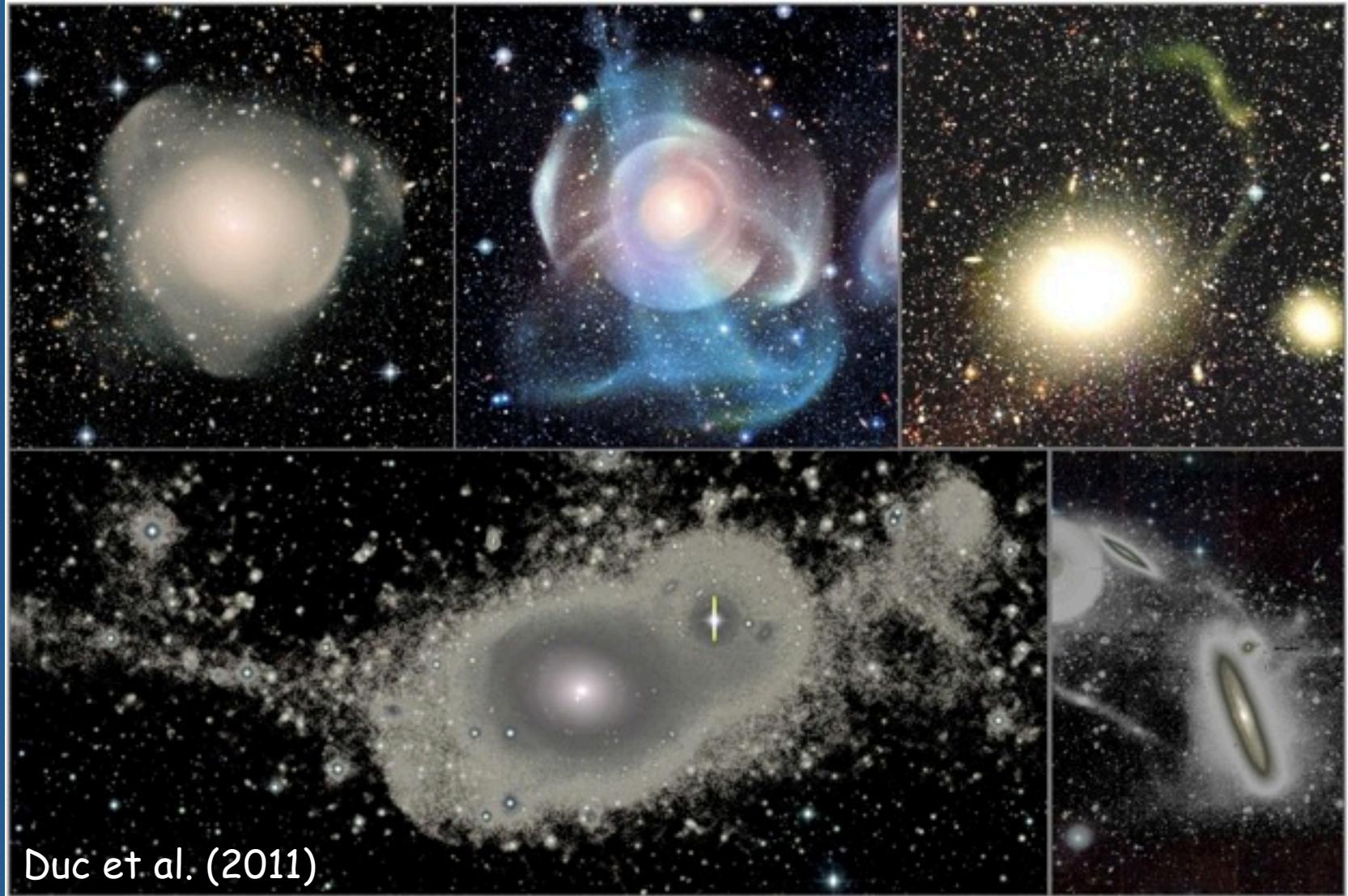
Cappellari et al. (2013)

- Bulge growth and SF quenching are related
- Growth of bulges drives SFR – size relations
- Three characteristic galaxy stellar masses

e.g. van der Wel+2009, Williams +2010, Faber+1997, Kauffmann +2001, van der Wel+2010, Bernardi+2011, Kormendy & Bender 2012...

FORMATION OF SR and FR

Shells, streams and tidal tails



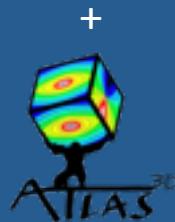
Duc et al. (2011)

Relaxed, unperturbed, boring...

down to 29 mag/arcsec²

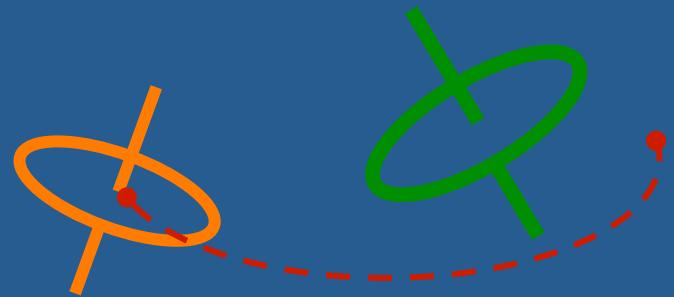
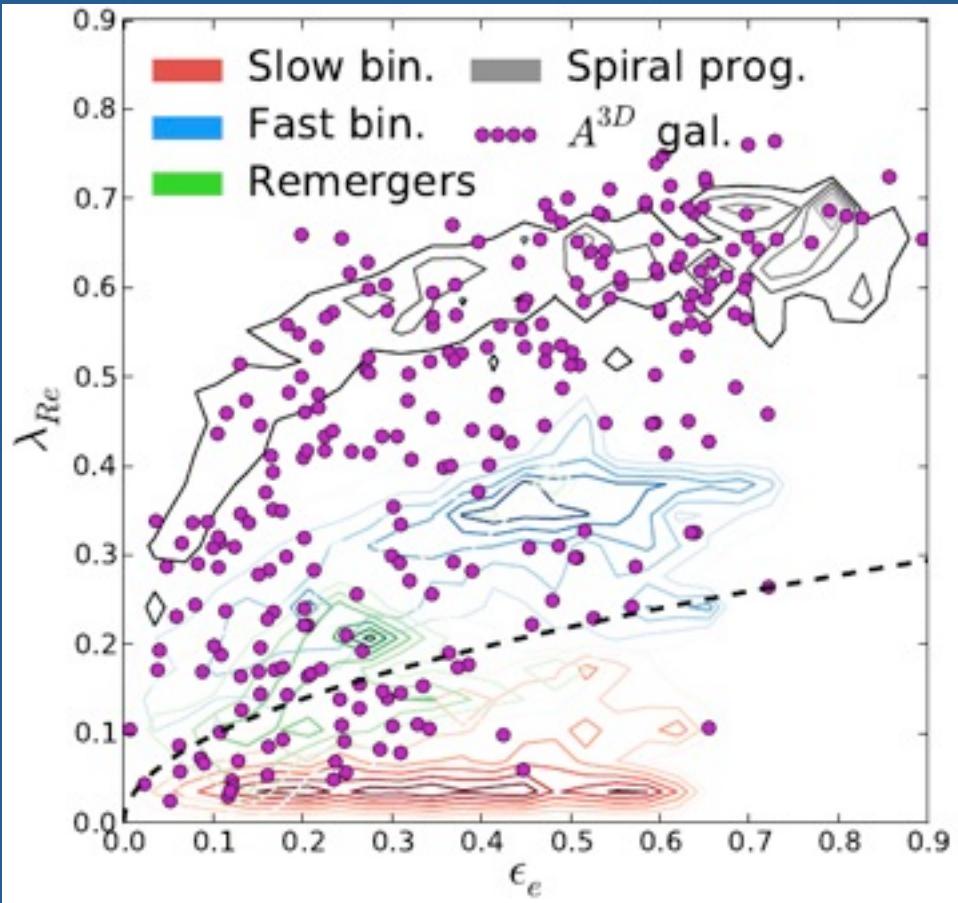


P-A. Duc @ MegaCam



Binary mergers

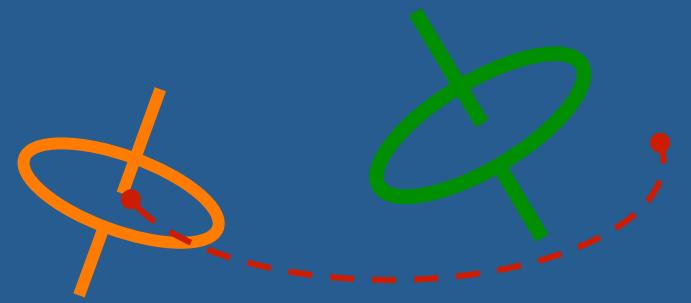
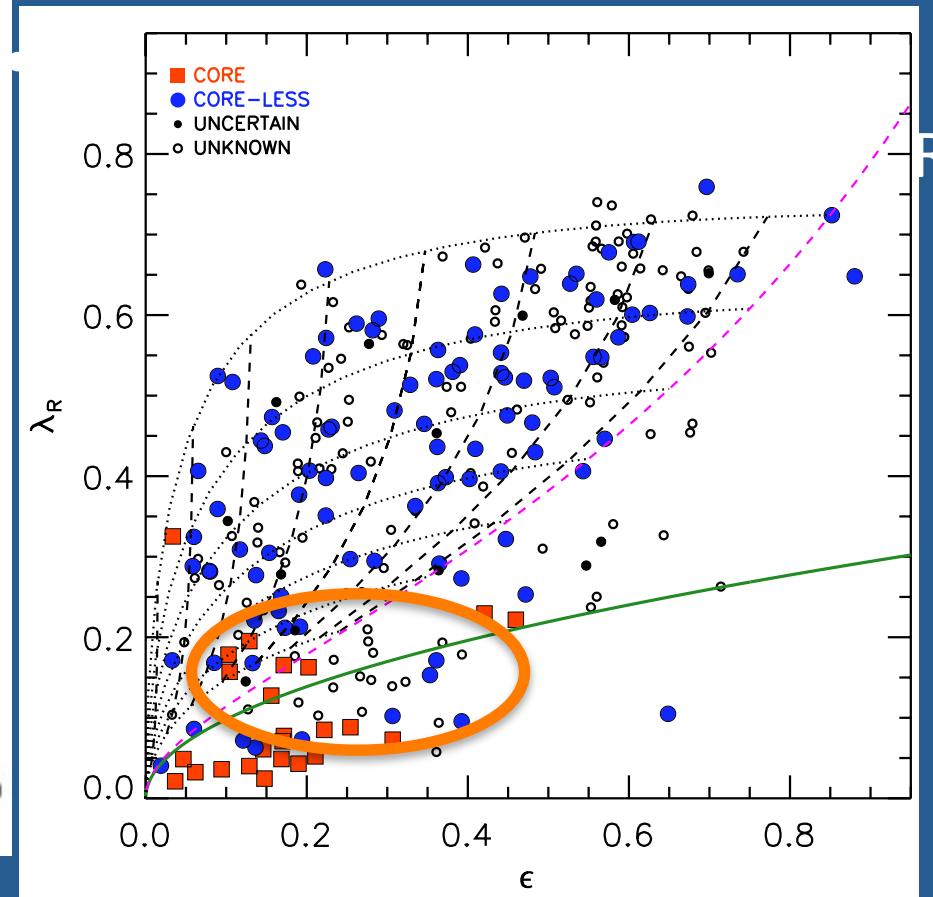
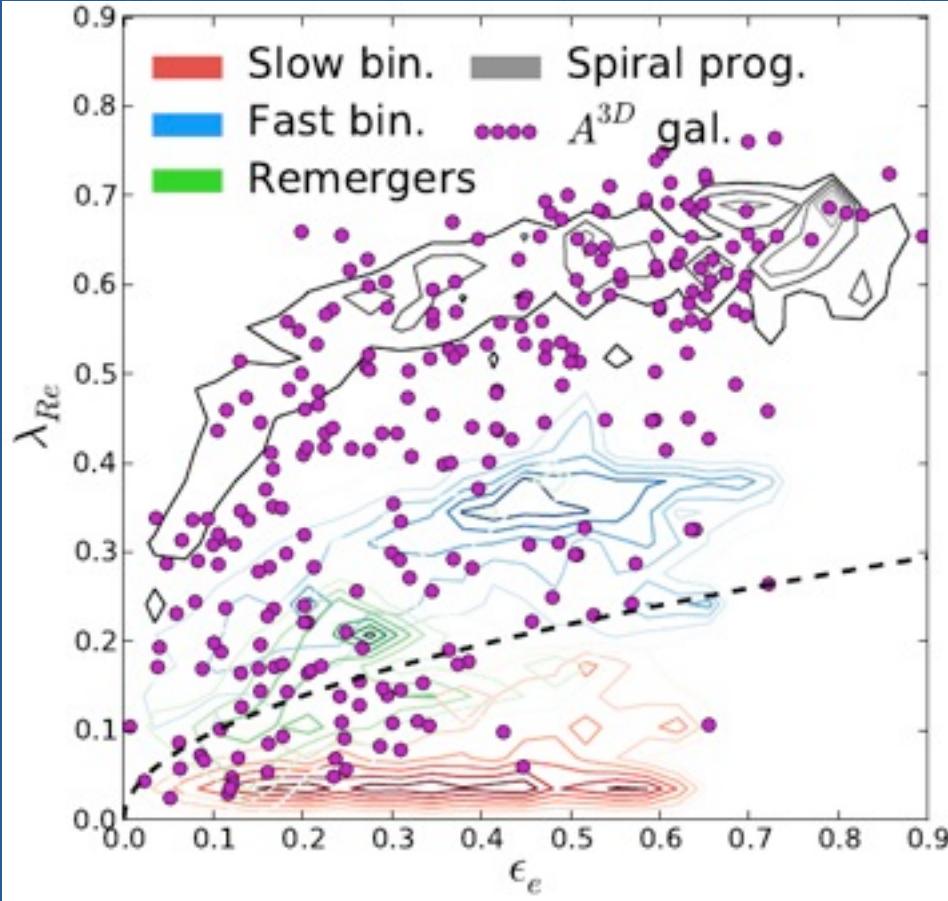
Bois et al. (2011)



- Major binary mergers
 - 1:1 and 2:1: **both** FR and SR (retrograde spin wrt orbit)
 - 3:1 and smaller: FR
 - SR are not velocity scaled FR
 - SR can be made in specific and violent major mergers
 - Re-mergers occupy a transitional region

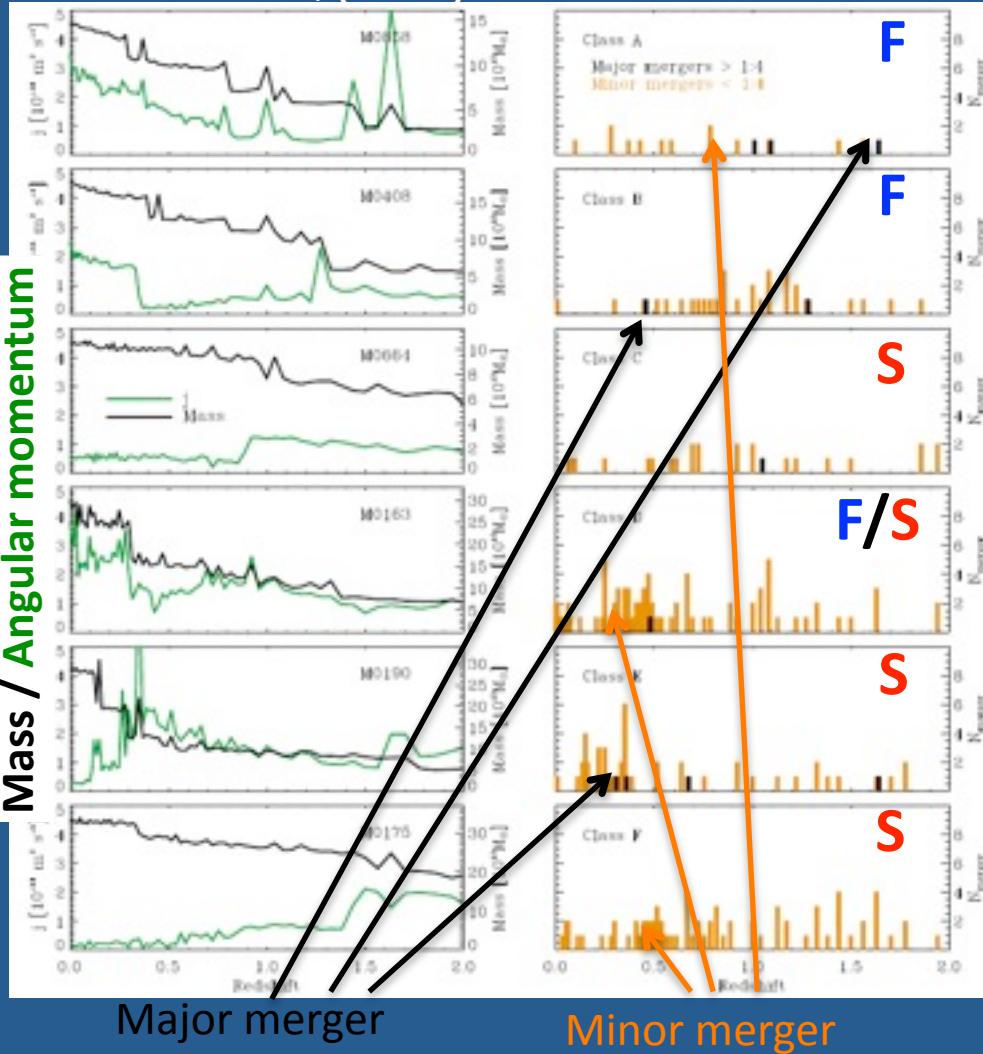
Binary mergers

Bois et al. (2011)



Formation of ETGs in a cosmological context

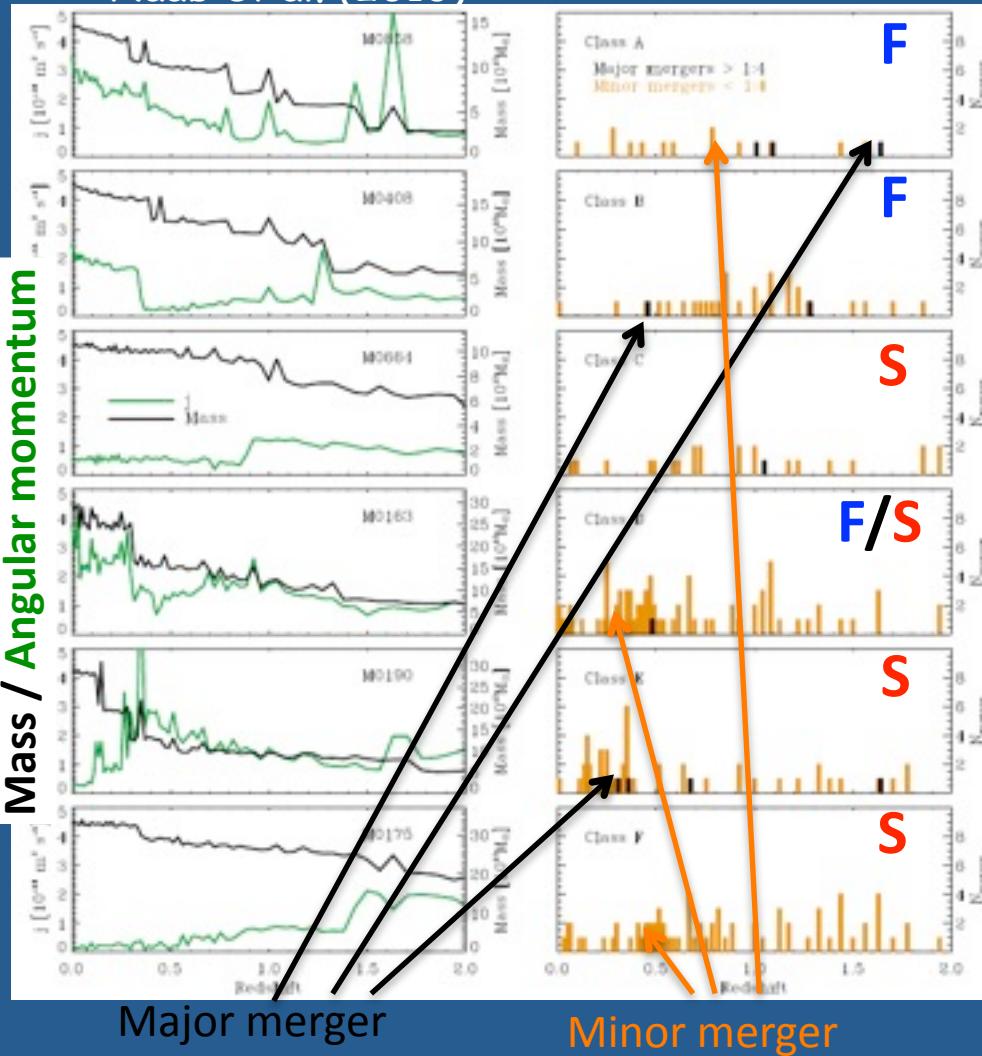
Naab et al. (2013)



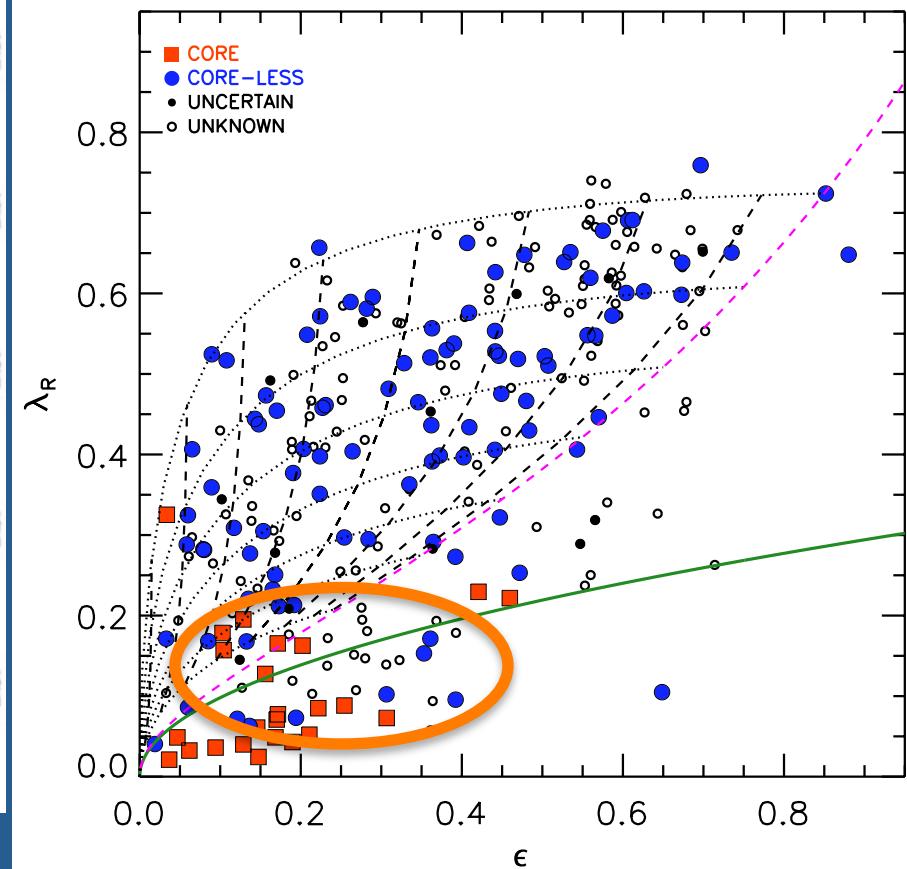
- Linking kinematic properties to individual cosmological formation histories
- Major mergers important for both spin up and spin down
- FR in:
 - Gas-rich minor and major mergers (Groups A,B)
 - Gas-poor (late) major mergers (Group D)
- SR in:
 - Gas-poor (late) **major** mergers (Group E)
 - Gas-poor **minor** mergers (Group F)

Formation of ETGs in a cosmological context

Naab et al. (2013)



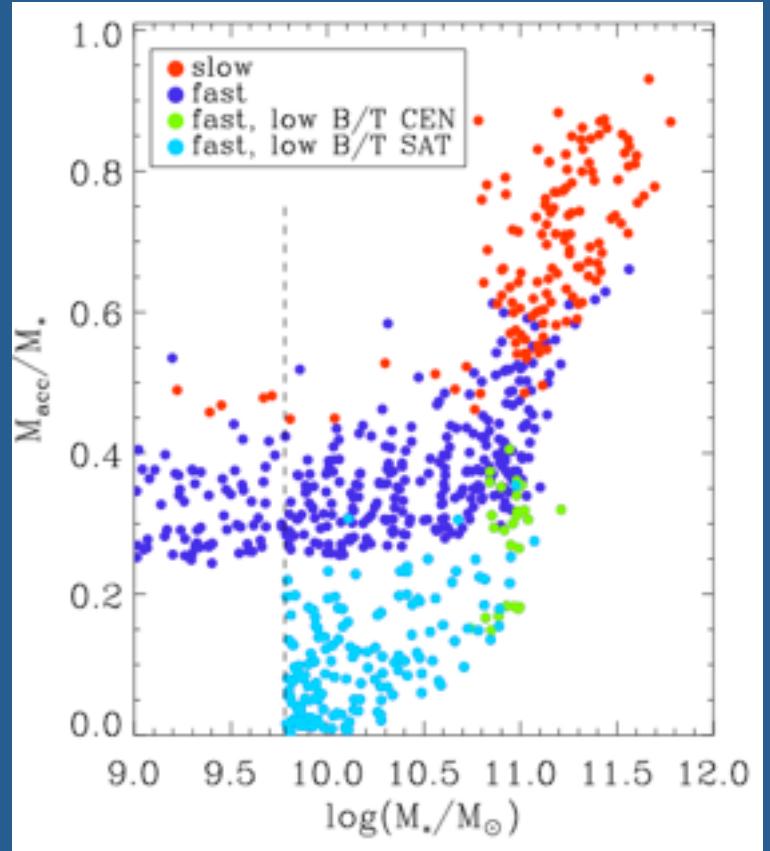
- Linking kinematic properties to individual cosmological formation histories



Discs as proxy for λ_R

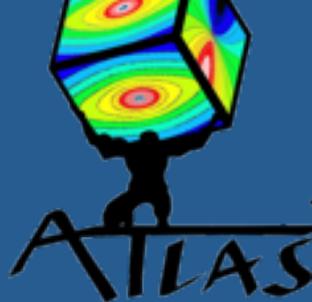
Slow Rotators Fast Rotators

- mass fraction of stellar discs in ETGs is a proxy for the specific angular momentum
- 50-90% of mass accreted from satellites
- Up to 3 major mergers for most massive
- Very few slow rotators at high z (progenitors are fast)
- Less than 50 % of mass accreted from satellites
- Less than 1 major mergers
- Two types: high and low B/T ratios
 - High B/T: access to gas, rebuilding of discs, but frequent minor mergers build Bulges
 - Low B/T: satellites in dense environments (devoid of gas): red disc dominated galaxies



Khochfar et al. (2011)

An ATLAS^{3D} view



- E/SO separation should be abandoned
- Most ETGs (>85) are **fast rotators** with significant disk components
- Parallelism and continuity in physical parameters between early-type and spiral galaxies
- Various formation paths: in-situ, environmental processing, ex-situ,

