The Morphological Structure of Early Type Galaxies

Outline

I. *Theoretical Prospective*: Processes at Play in the Formation of Massive ETGs

II. *A changing population*: the cosmic evolution of ETG number densities, sizes and stellar populations

III. *Evolutionary end-point*: the (mostly) large scale morphology of local ETGs

What I will NOT discuss:

Dynamics and kinematic constraints (See talks by Cappellari, Fogarty)

Stellar populations

Dwarf galaxies (see afternoon talks, Lisker, Janz, Sanchez-Janssen, etc.)

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Victoria BC, Canada

Important Processes in the Formation of Massive ETGs

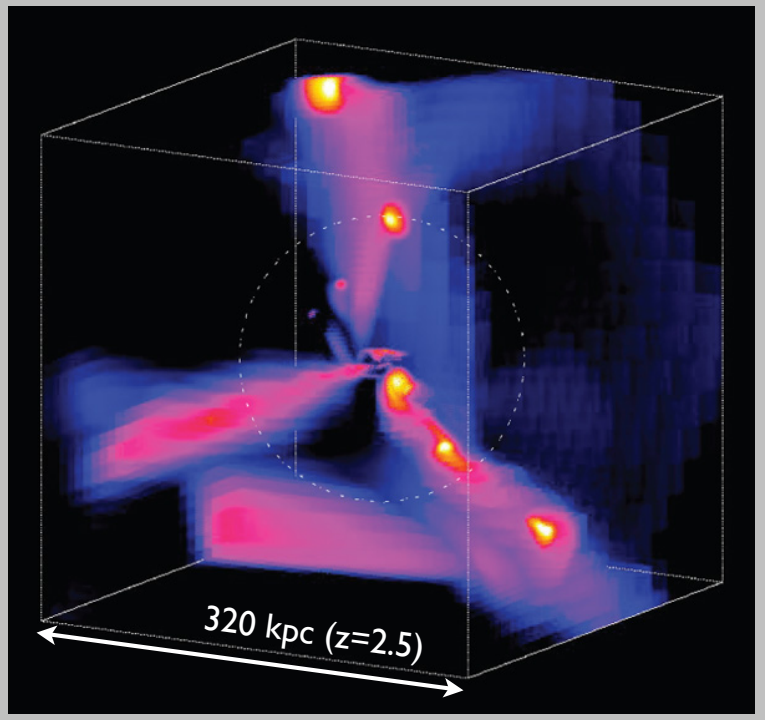
In-situ star formation, cold accretion disk instabilities and clumps
➔ Contributing most of the mass at high-z

Minor mergers
➔ *Very frequent, contributing most of the mass at low-z; deposit stars at large radii*

Major mergers, interactions black hole feedback shock-driven star formation radiative cooling SNe feedback
➔ Rare, but strongly affecting morphology/dynamics and mass growth

Secular evolution, bars
➔ *Strong morphological/dynamical signature; less marked effects on stellar populations.*

Initial growth dominated by compact in-situ star formation; accretion of cold gas along filaments capable of fueling the high star formation rates in the early Universe (e.g. Birnboim & Dekel 2003; Brooks et al. 2009; Hopkins et al. 2009; Keres & Ma 2001; Kacprzak et al. 2012; Crighton et al. 2013)



Dekel et al., 2008

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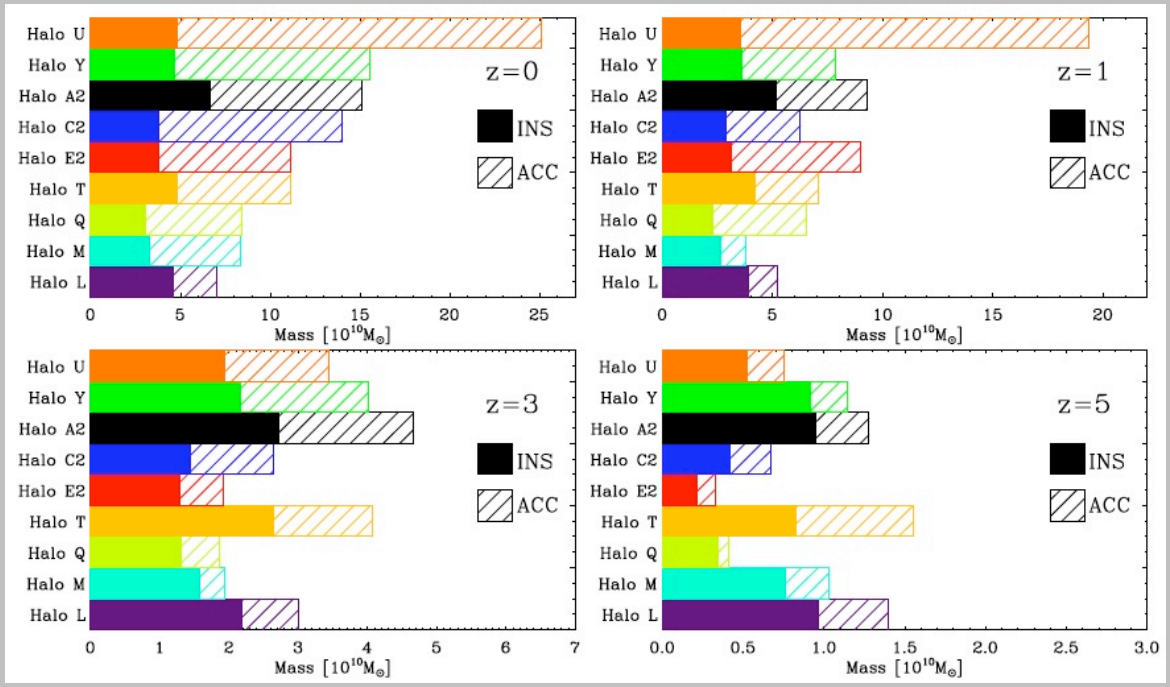

Johansson, Naab & Ostriker, 2012

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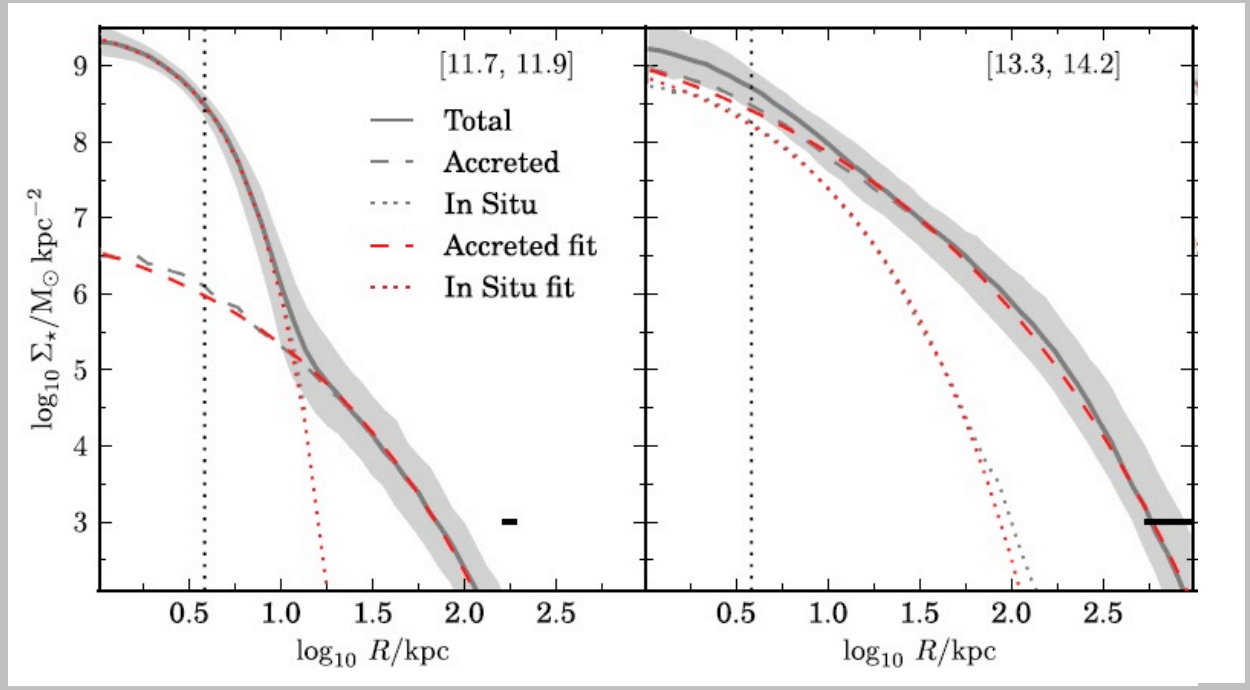

Cooper et al., 2013

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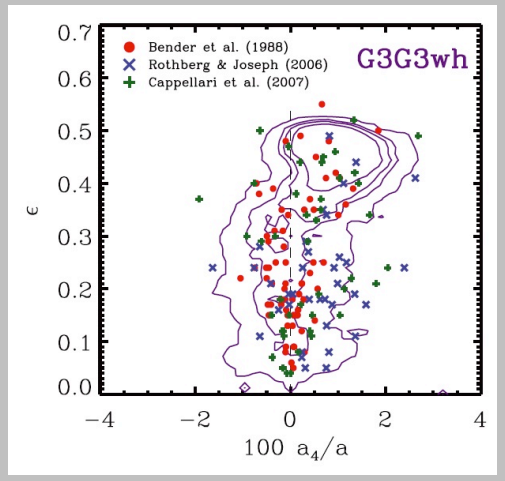
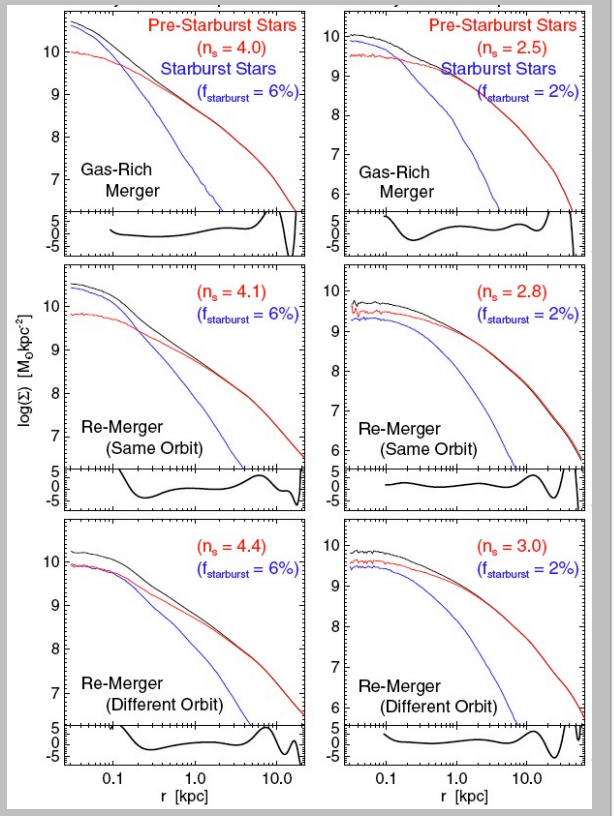
Major mergers of spirals produce hot spheroid with elliptical like properties (e.g. Toomre 1977, Gerhard 1981; Barnes 1992; Heyl Hernquist & Spergel 1994).

Morphology, dynamics and stellar population driven by the morphology, mass-ratio and gas content of the mergers (e.g. Mihos & Hernquist 1994; Khochfar & Burkert 2005)



Moster et al., 2011



Hopkins et al., 2009

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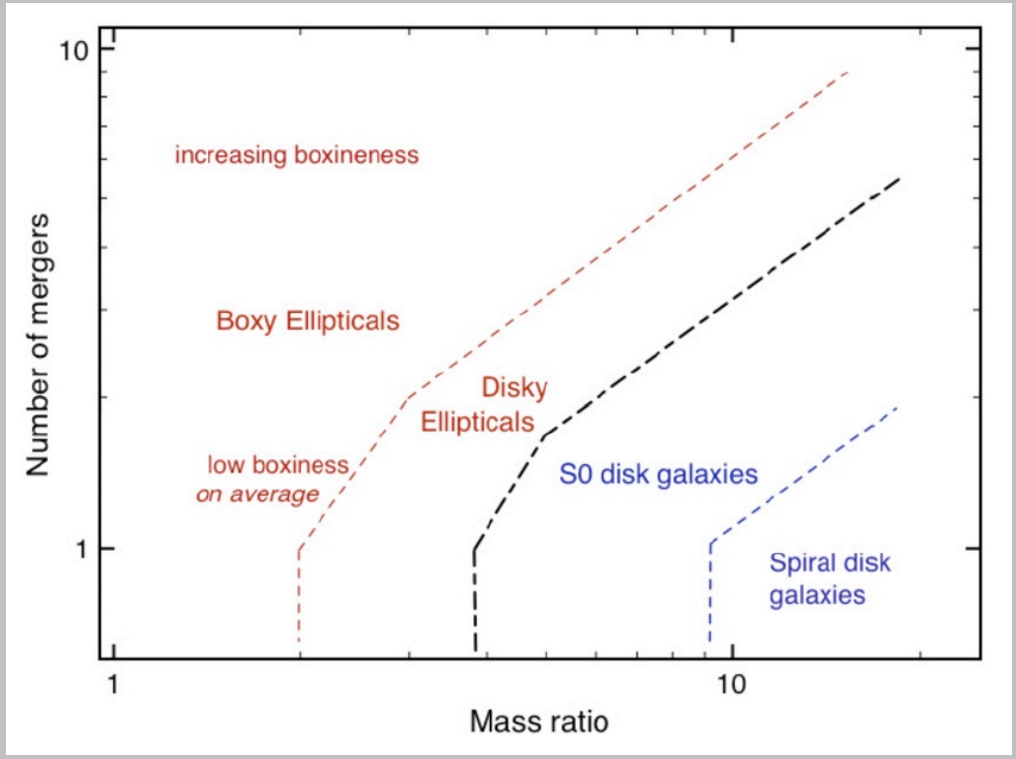

Bournaud et al., 2007

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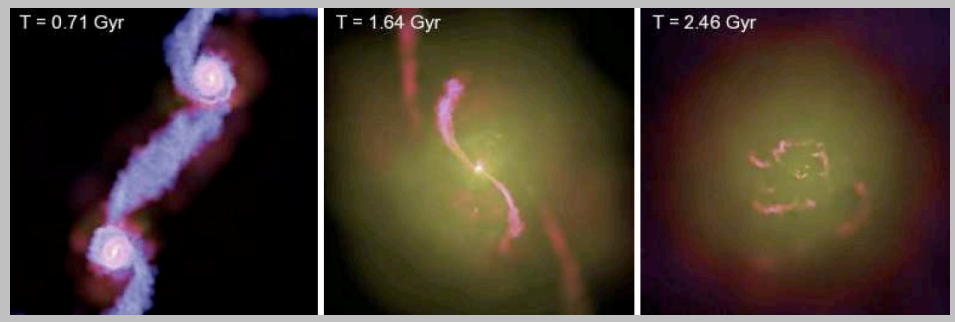
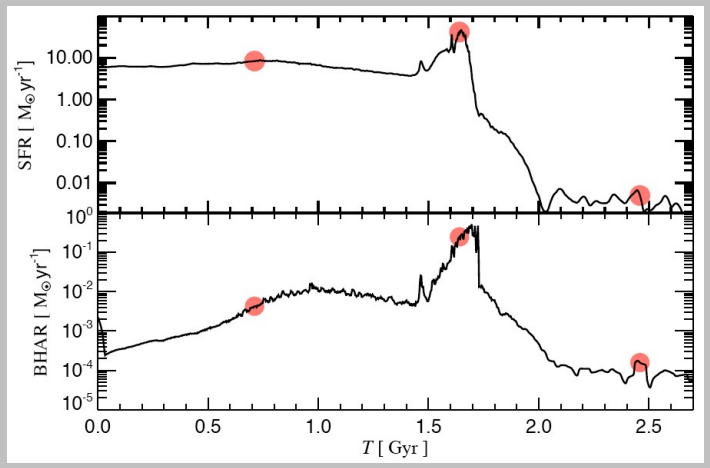
Black hole feedback controls the amount of in-situ star formation in massive galaxies (Di Matteo et al. 2005; Sijacki et al. 2006; Hopkins et al. 2006, Booth & Schaye 2009; Dubois et al. 2012; Martizzi et al. 2012; Liu et al. 2013, Choi et al. 2013).



Di Matteo et al. 2005



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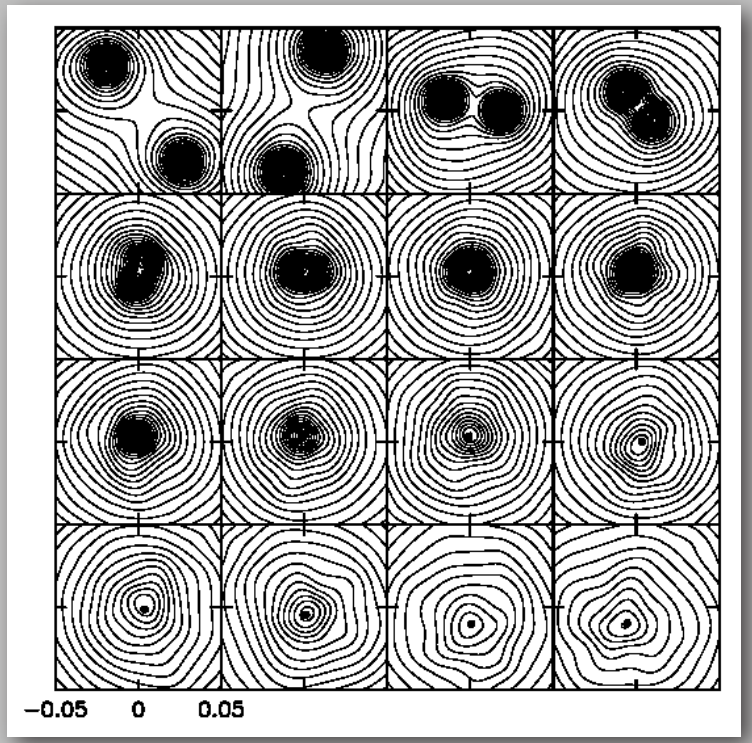


Milosavljevic & Merrit 2001

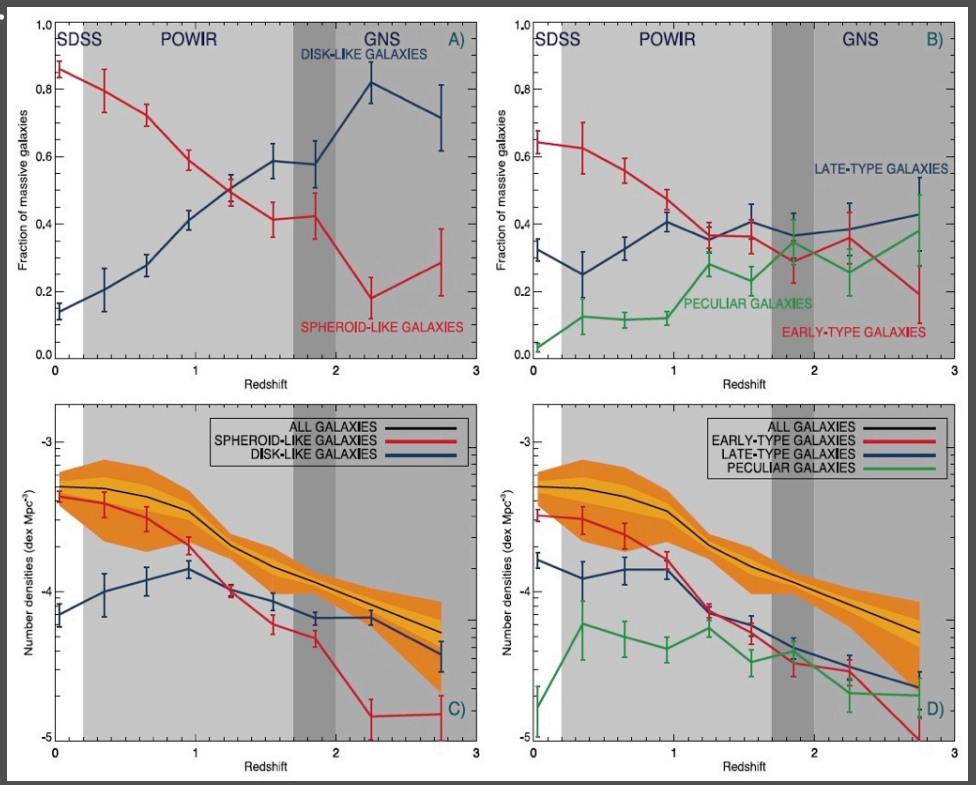
Cosmic Boundary Conditions

Fractional evolution by type

Size evolution

Evolution of stellar populations

Rapid cosmic evolution in the relative fraction of morphological types of massive galaxies. ETGs dominant morphological class since z~1. (e.g. Oesch et al. 2010; Cameron et al. 2011; van der Wel et al. 2011; Weinzirl et al. 2011; Law et al. 2012; Buitrago et al. 2012; Mortlock et al. 2013).



Buitrago et al. 2012

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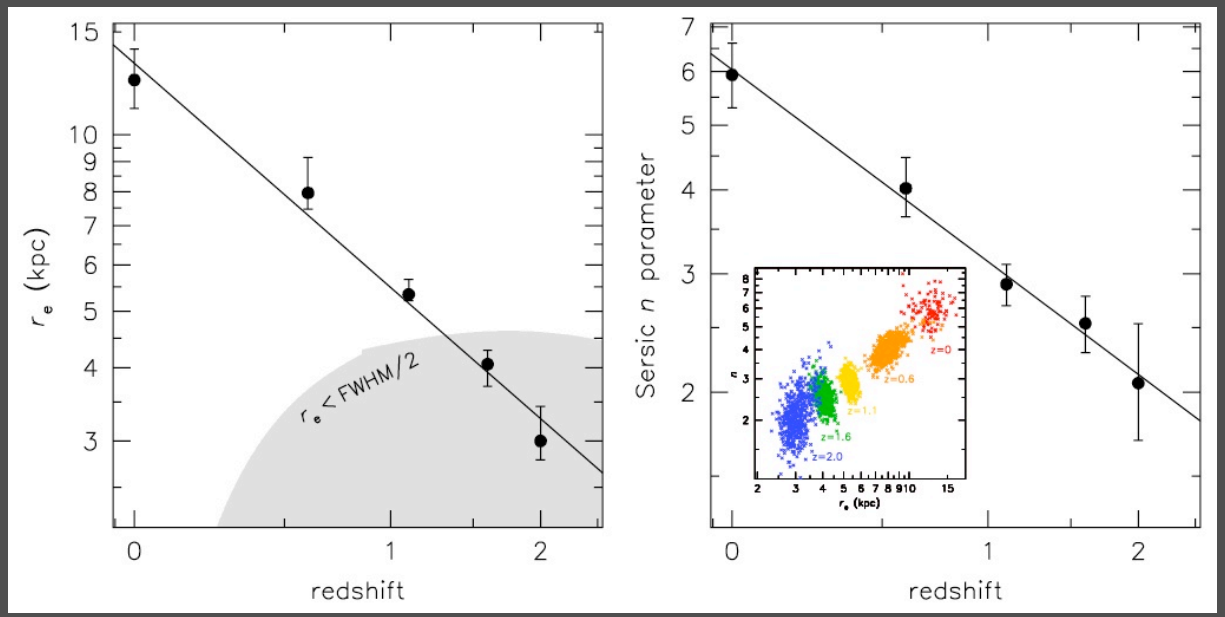
Evolution of stellar populations

"Inside-out" growth: massive ETGs build up their outer regions over the past 10 Gyr, with the mass beyond 5kpc having increased by a factor ~4 since z=2 (e.g. Franx et al. 2008; Buitrago et al. 2008; van Dokkum et al. 2008,2010; Szomoru et al. 2012; Patel et al. 2013; Trujillo 2012).



van Dokkum et al. 2010

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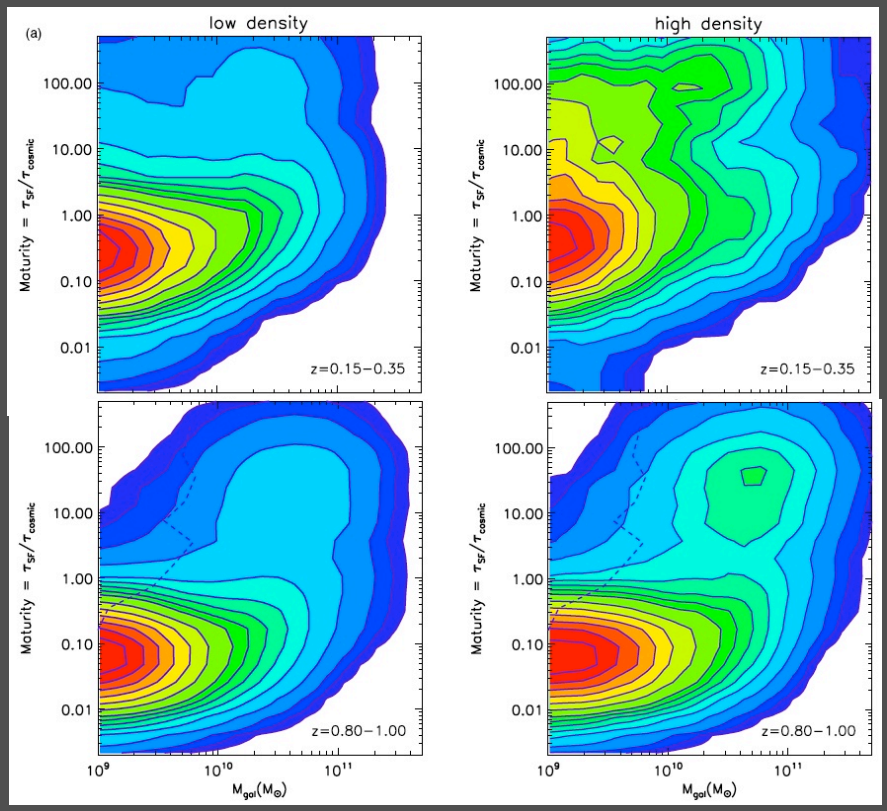
SFR depends on environment, cosmic time and mass (e.g. Balogh et al. 2004; Cooper et al. 2008; Patel et al. 2009; Ilbert et al. 2009). Appearance of lower mass red galaxies at z~0.2 in dense environment suggests environmental quenching (ram pressure stripping/starvation/ etc)



Scoville et al 2013

The Structure of Local Massive ETGs

Underlying regularities in the morphological structure
➔ to first order, implies continuity in formation/ evolutionary history

Large (R >> Re) scale structure
➔ consistent with minor mergers and low mass accretion events as main supplier of stars in the outskirts of massive galaxies

Tidal disturbances
➔ potentially direct tracers of both minor and major mergers

Discrete tracers

Danger: can't see the forest for the trees.

Virgo ETGs from the ACSVCS

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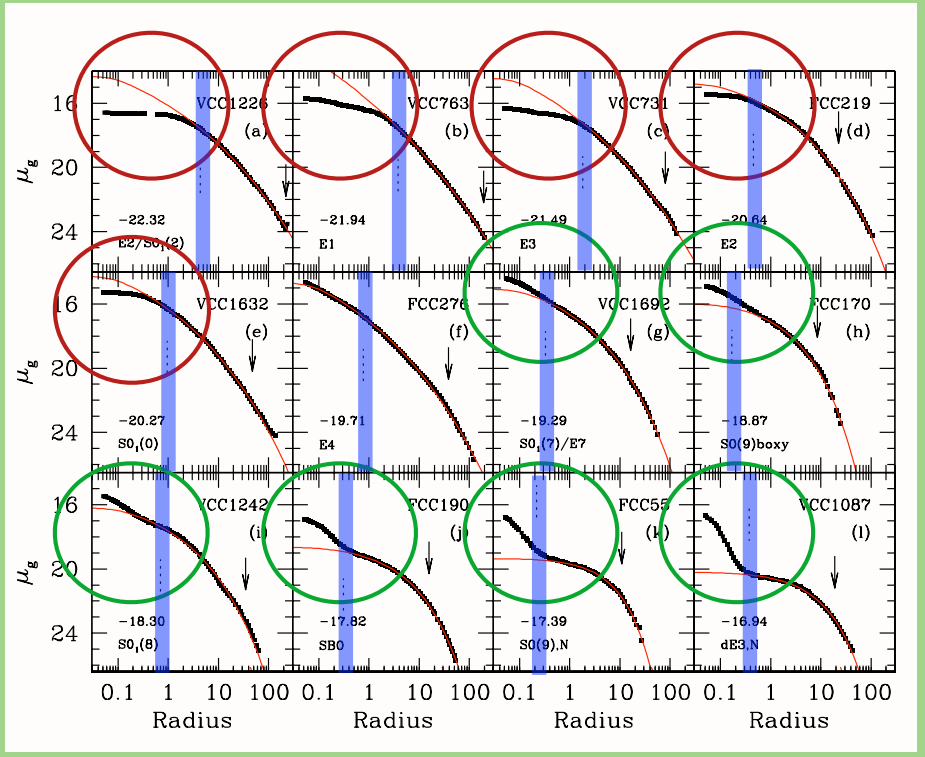
- Large Scales ($R > 2\%R_e$): surface brightness profiles well described by a Sersic law (e.g. Jerjen et al. 1997,2000; Graham et al. 2003ab; Gavazzi et al. 2005).
- Nuclear Scales ($R < 2\%R_e$): transition from central luminosity deficit to excess at M(B) ~ -20 mag



Ferrarese et al. 2006; Côté et al. 2006

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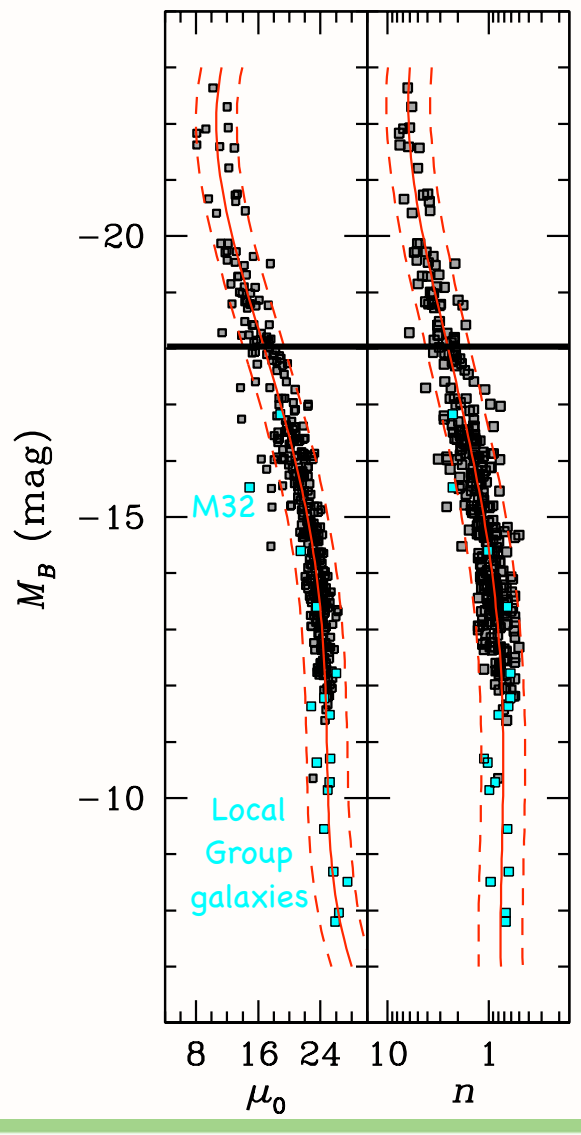

Curvature in relations not indicative of disjoint populations but natural consequence of the Sersic nature of the profiles (Graham et al. 2003).

➔ The processes involved in the assembly of progressively more massive systems (mergers, harassment, accretion, ram pressure stripping, etc) act continuously, but with different weights, across the ETG sequence

- No separation between dwarfs and giants.
- No distinction between Es and SOs

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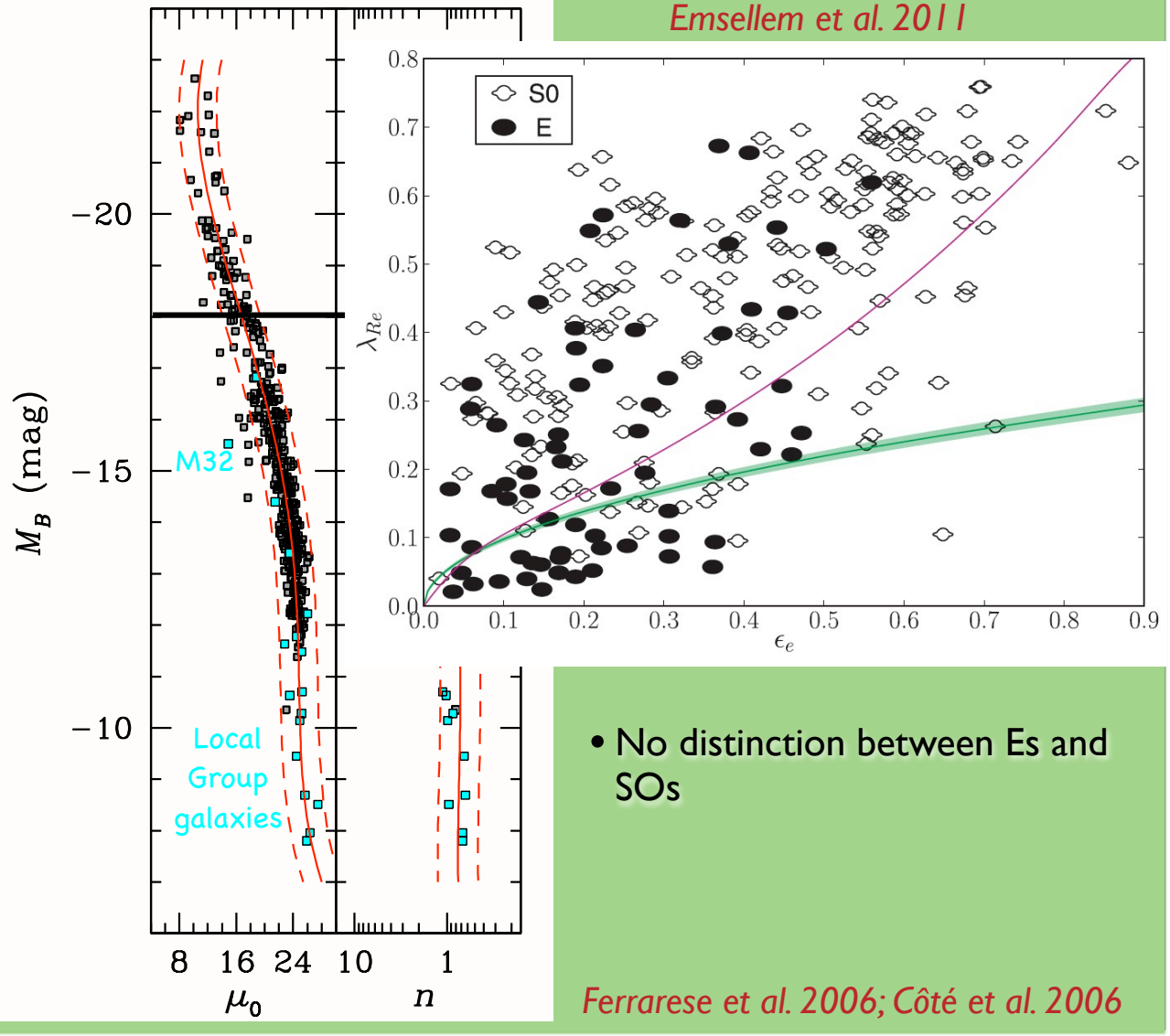
Emsellem et al. 2011



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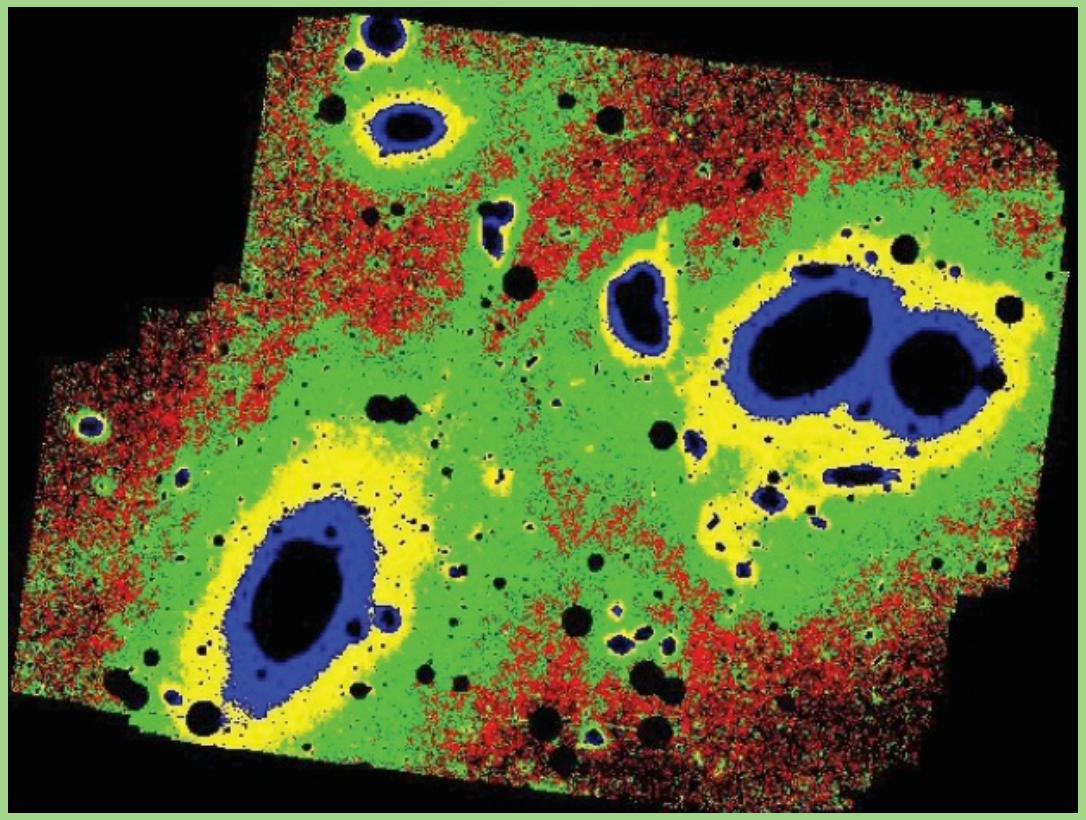
Large scale structure of massive ($M > 10^{10.2} M_\odot$) ETGs reveals extended halo dominating beyond several R_e, accompanied by a flattening of the isophotes and bluer colors (e.g. Mihos et al. 2005; Zibetti et al. 2005; Tal & van Dokkum 2011; Huang et al. 2013; Rudick et al. 2010) arising from low metallicities and high α abundances (e.g. Greene et al. 2012).



Mihos et al. 2005

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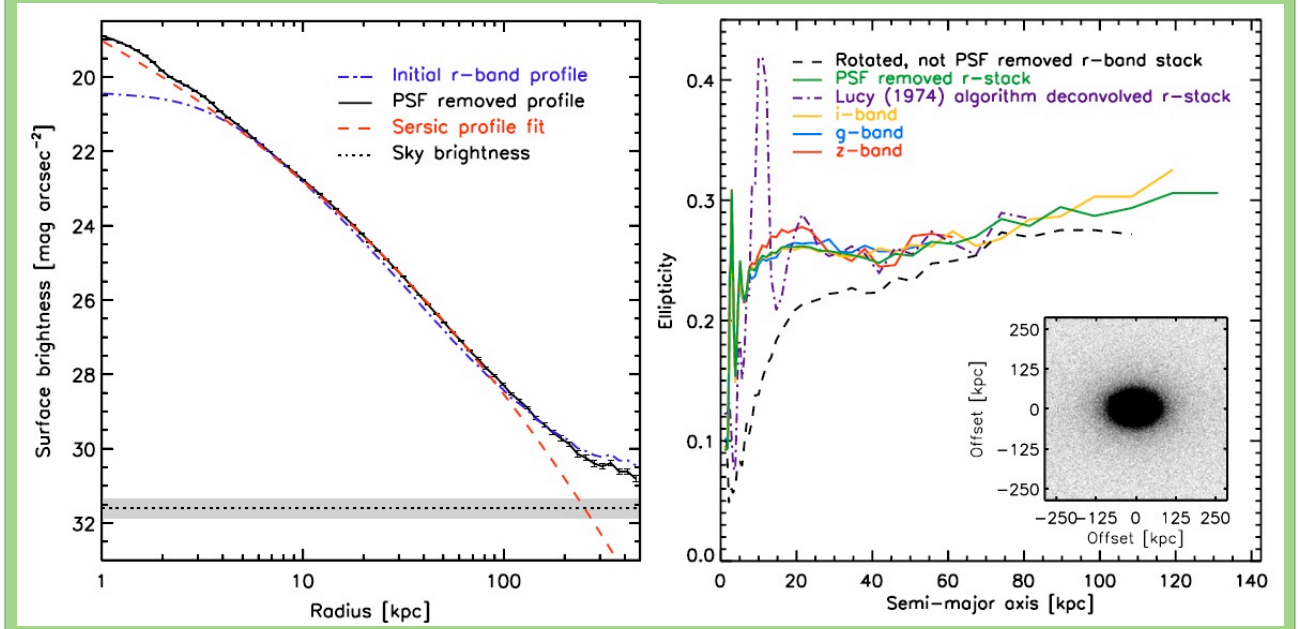

Tal & van Dokkum 2011

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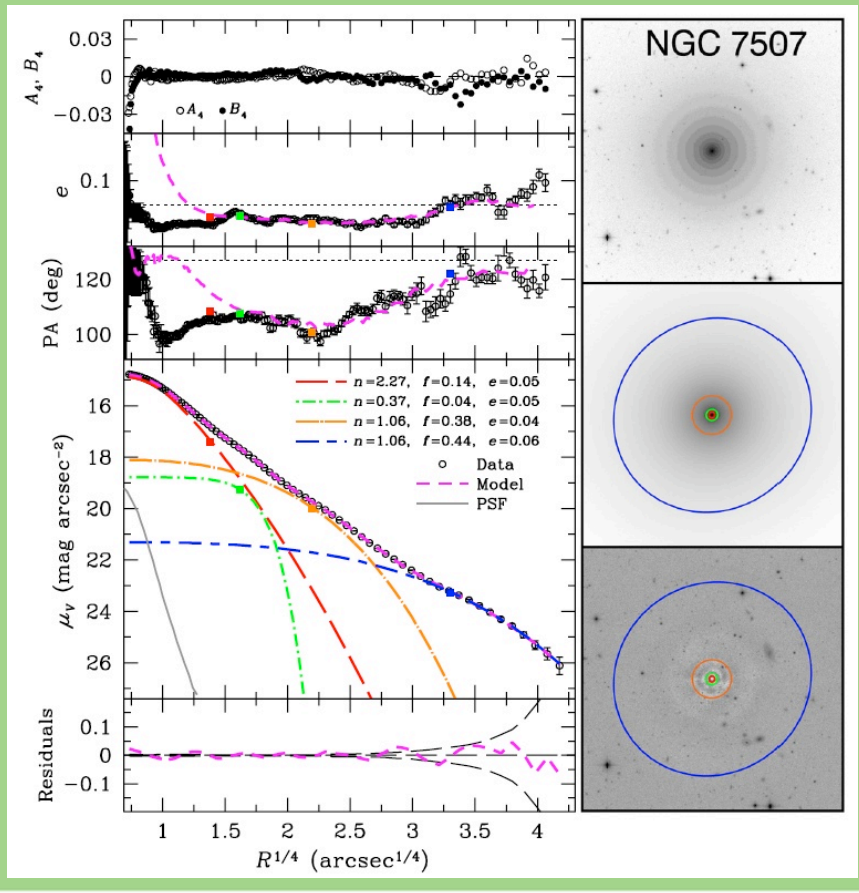

Huang et al. 2013

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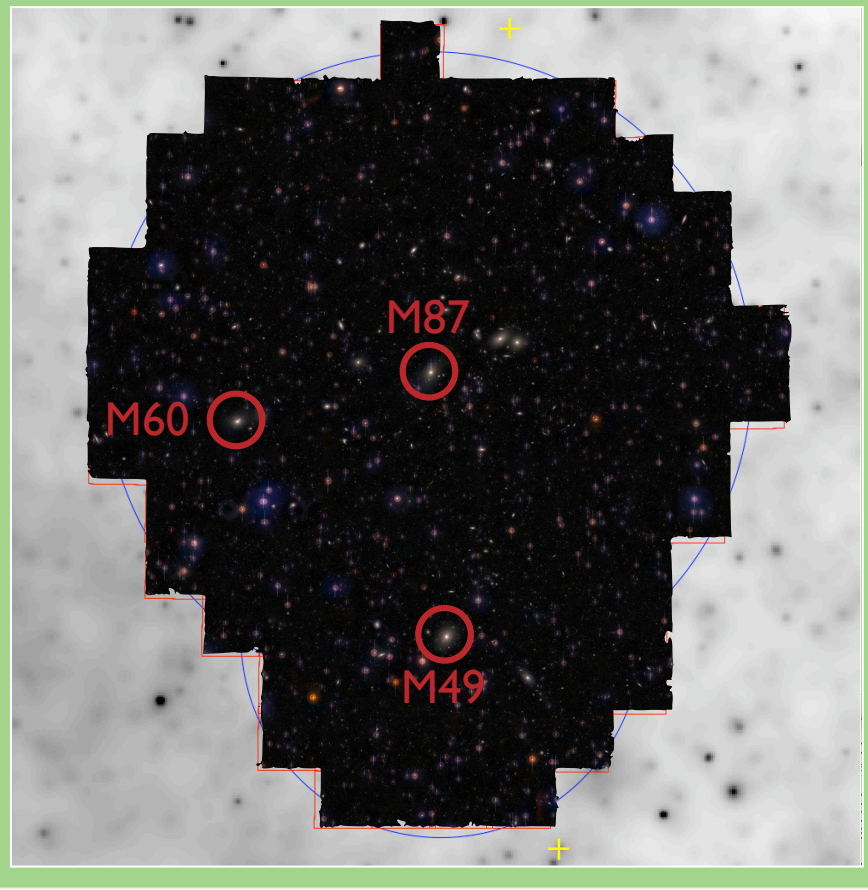

Ferrarese et al. 2014 (NGVS)

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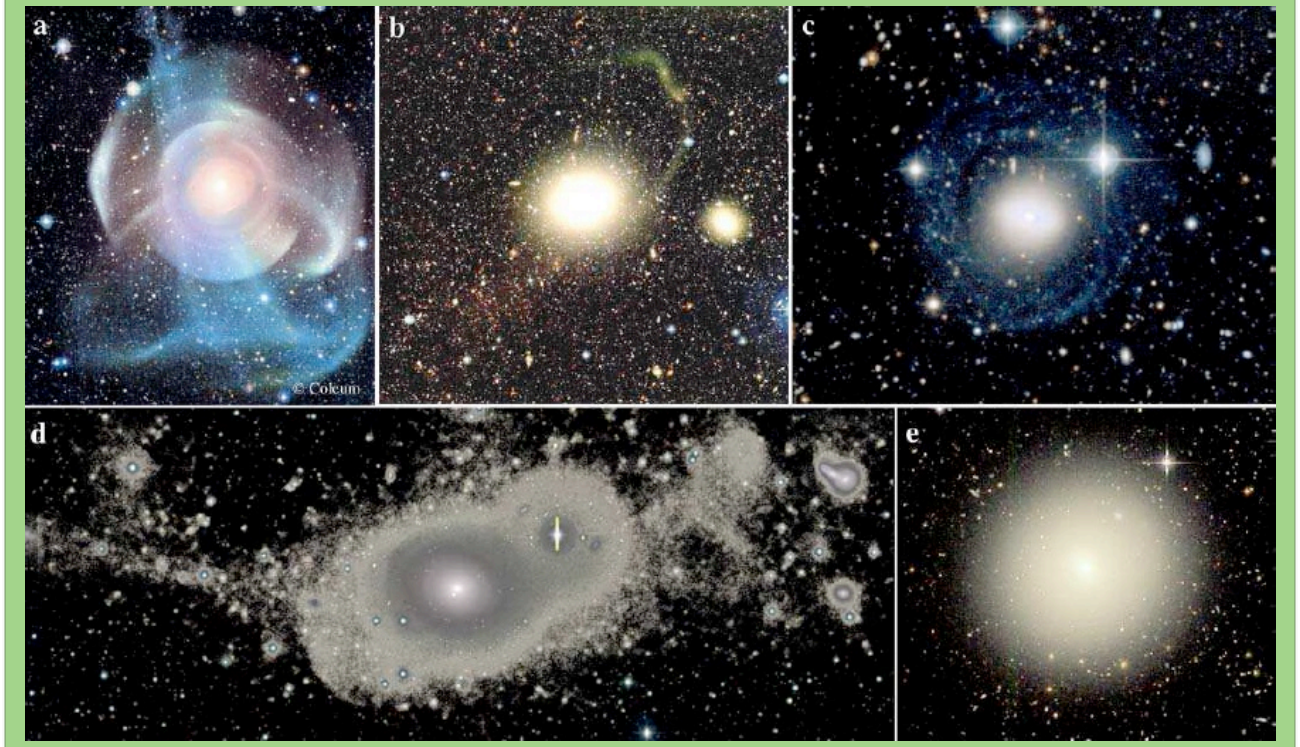

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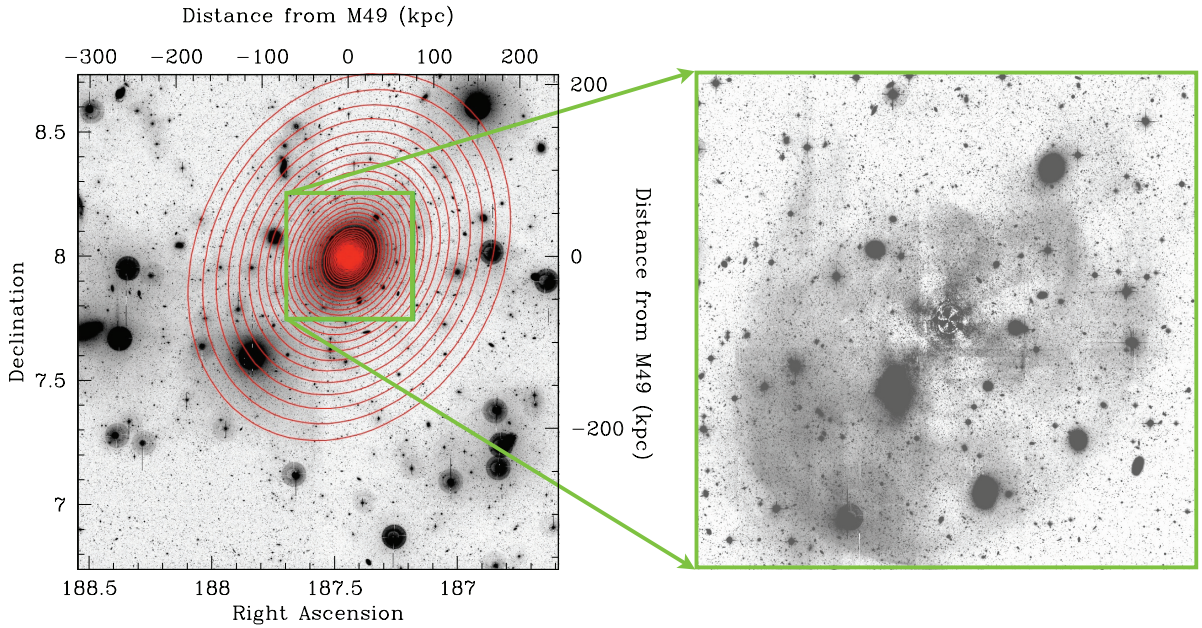

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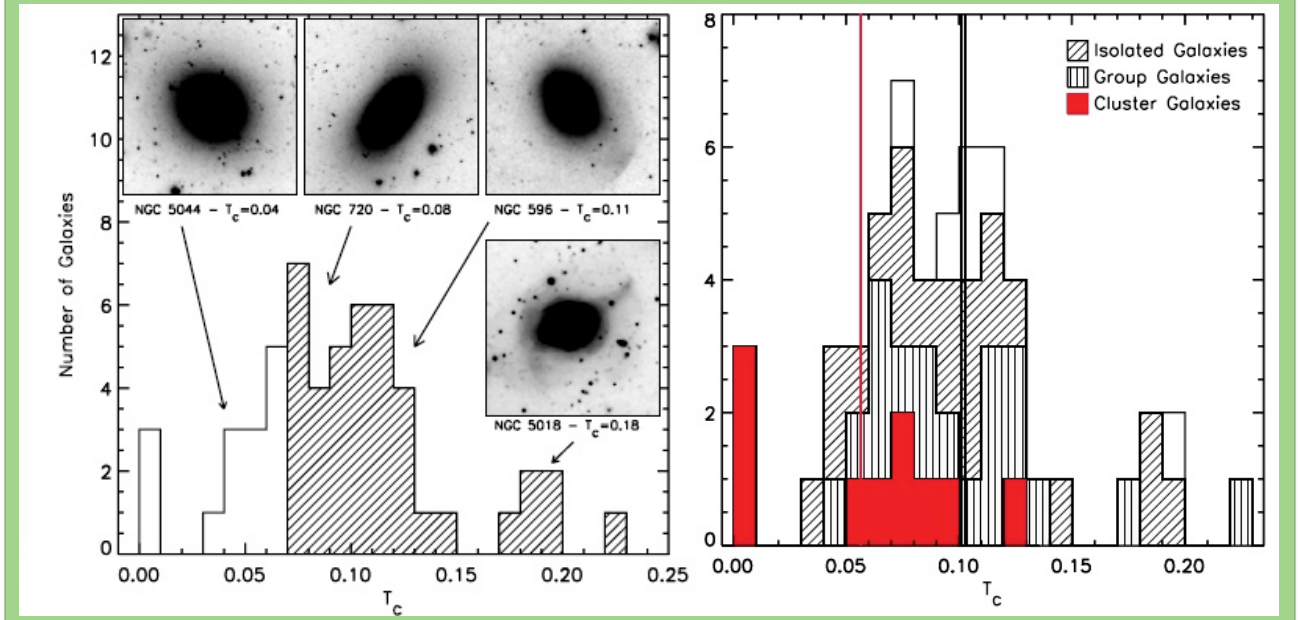

Tal et al. 2009

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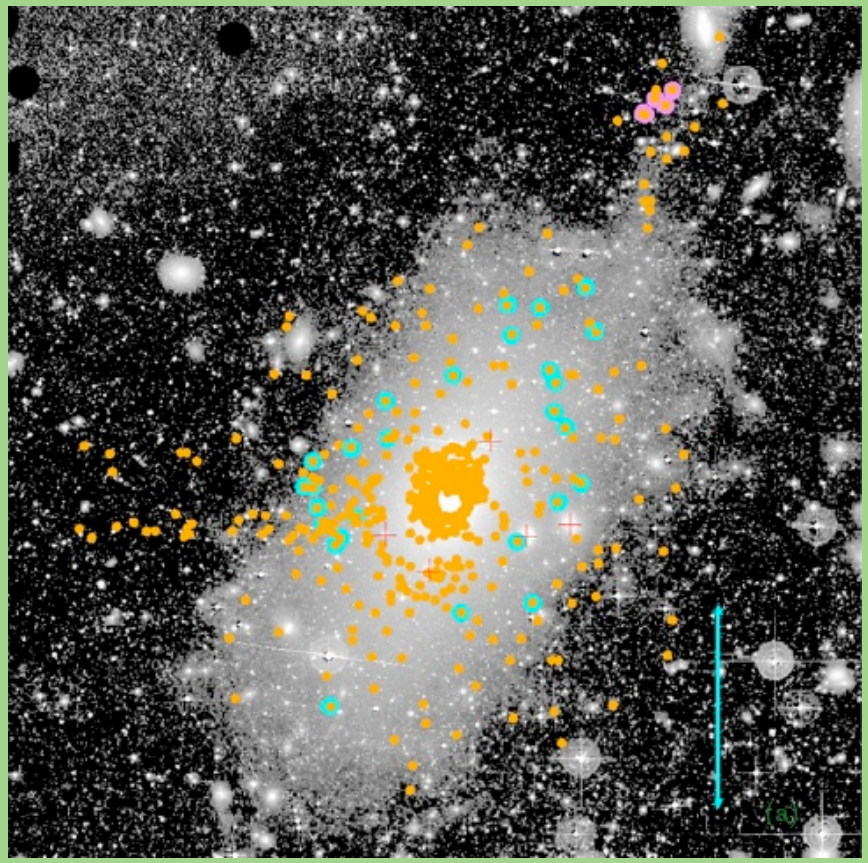
Discrete tracers as signatures of phase-space substructures (Côté et al. 2003; Romanowsky et al. 2009; Schuberth et al. 2010; McNeil et al. 2010;Woodley & Harris 2011; Romanowsky et al. 2012; Longobardi et al. 2013; Durrell et al. 2014)



Romanowsky et al. 2012

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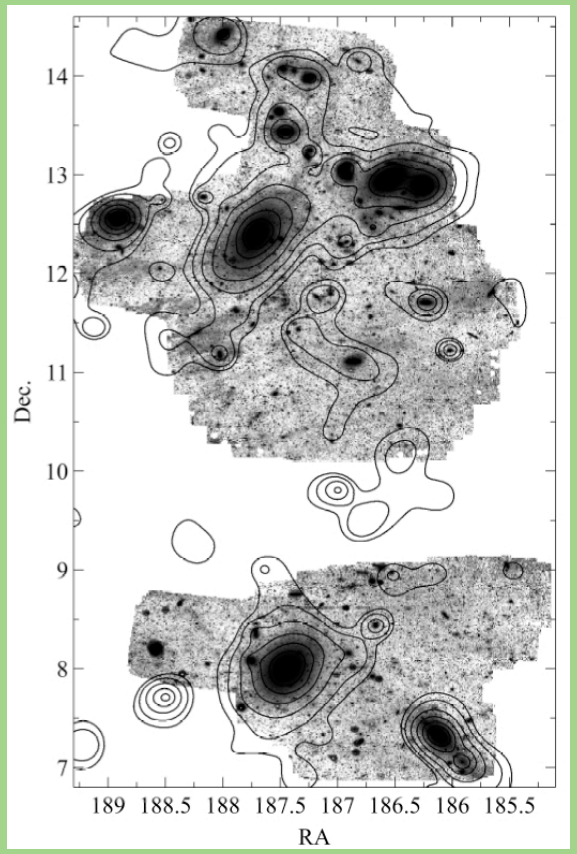

Durrell et al. 2014 (NGVS)

Conclusions

- Different evolutionary scenarios affect galaxy morphology of ETGs in (often) distinct ways:
  - Early, in-situ star formation build high phase-space density cores;
  - Minor mergers most effective in building the extended envelope;
  - Balance between the two processes likely mass and environment dependent.

  This scenario is in qualitative agreement with the observational data for local ETGs and with the observed cosmic evolution of ETGs' sizes.

- Major mergers can lead to core formation (due to dynamical feedback from the evolution of SBH binaries), dissipation, formation of extended tidal tails. Fine structure produced by minor mergers is qualitatively different. Discrete tracers (globular clusters, planetary nebulae) provide information that is complementary to that carried by the stellar fine structure.

- Observationally, there is little indication of discontinuities in the overall morphological (and dynamical) properties of ETGs. Transition between core and nucleated galaxies; transition between slow and fast rotators (?); changes in Sersic index, sizes, etc, all appear *continuous*.