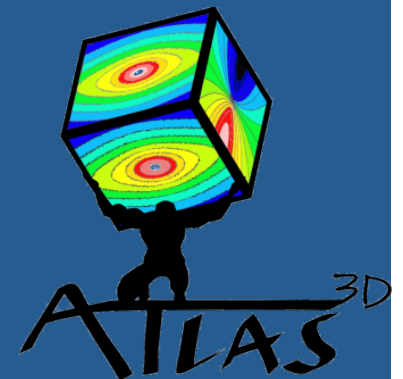
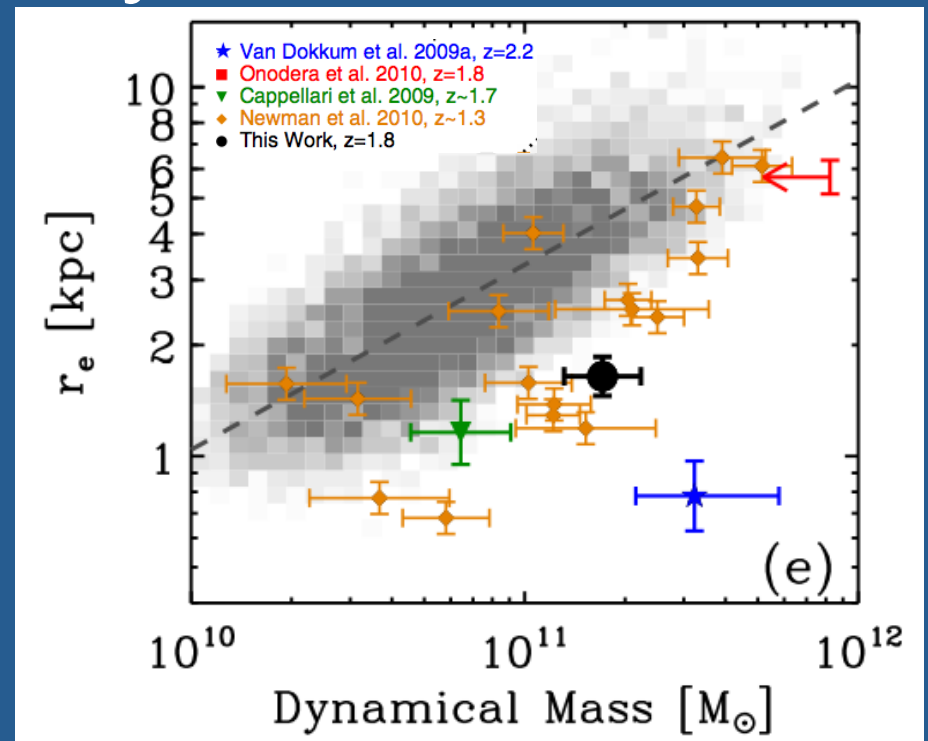
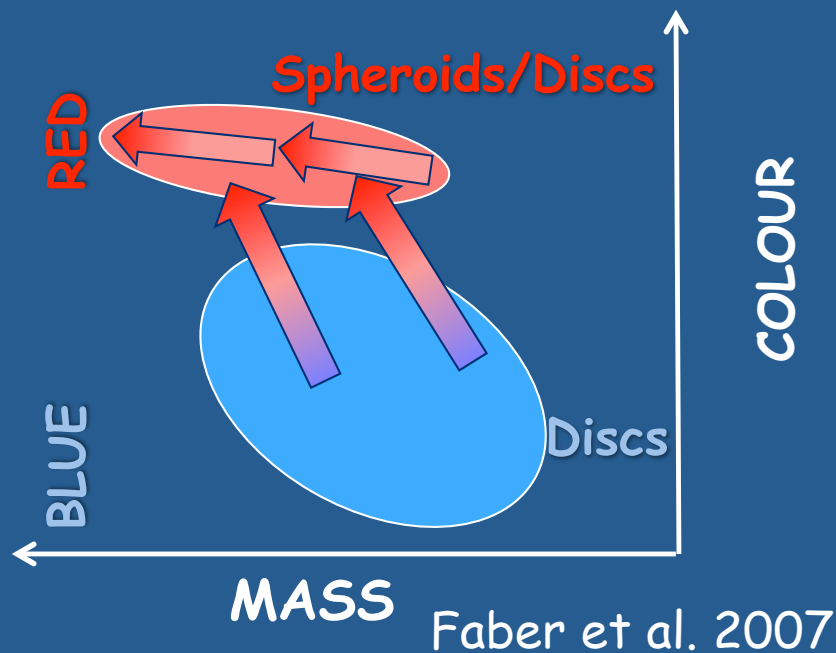


ATLAS^{3D}: IFU driven synergy of multi-wavelength observations

Davor Krajnović



Hierarchical Galaxy Formation



van de Sande et al. 2011

- Bimodal galaxy colour distribution needs merging + feedback to jump from blue to red (Baldry et al. 2004, Bell et al. 2004)
- Red sequence is a mixture of remnants from gas-rich (blue cloud) and gas-poor (red sequence) mergers (e.g. Cattaneo et al. 2006)
- Stellar densities (or sizes) have evolved (decreased) with time

Two phase formation scenario

Oser et al. (2010)

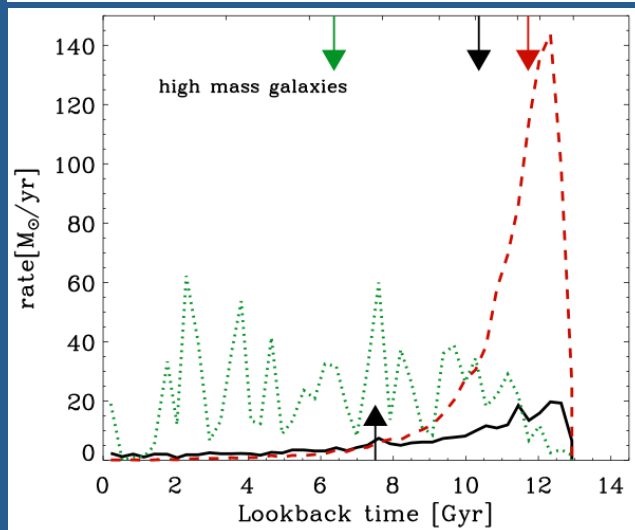
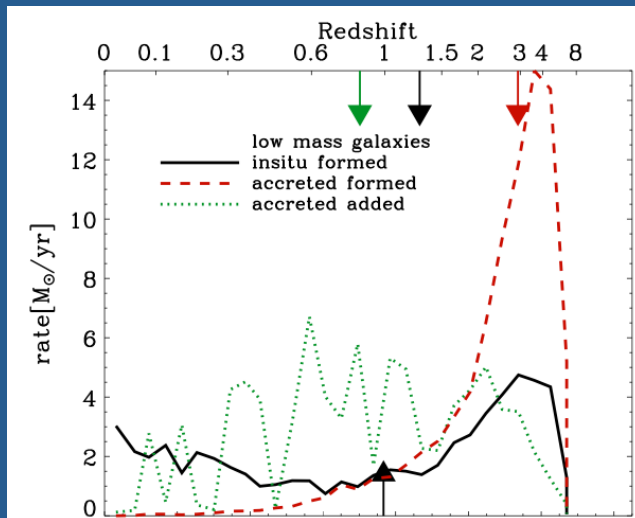


TABLE 2
THE ASSEMBLY OF STARS IN MASSIVE GALAXIES

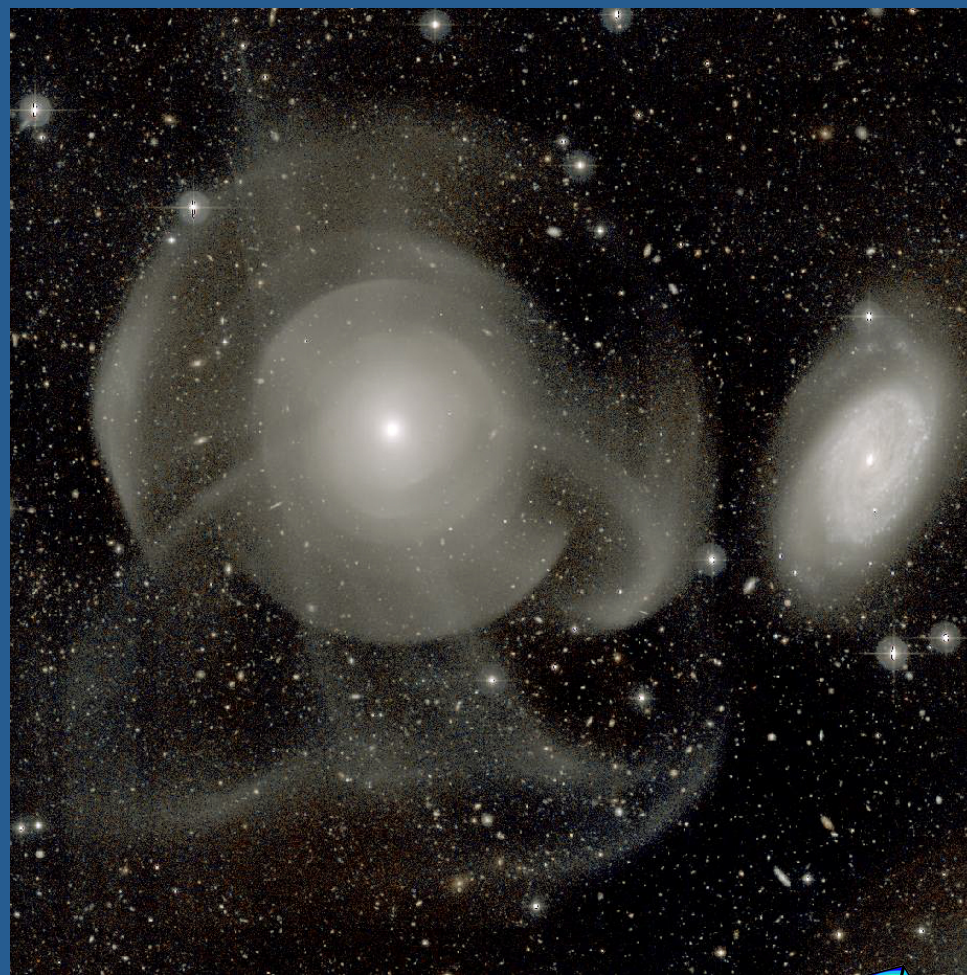
	In-situ	Accreted
Epoch	$6 \gtrsim z \gtrsim 2$	$3 \gtrsim z > 0$
Baryonic mass source	cold gas flows	minor & major mergers
Size of region	$r_{1/2} \approx 2\text{kpc}$	$r_{1/2} \approx 7\text{kpc}$
Energetics	Dissipational	Conservative

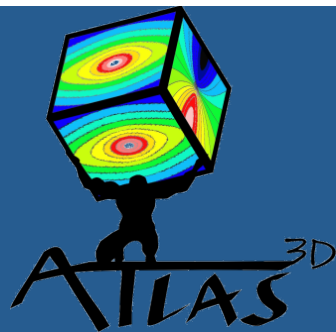
- Distinction between *in-situ* and *ex-situ* star-formation (SF)
- SF in small galaxies continues today

Key questions of galaxy formation

- What controls star formation?
- What controls mass assembly?
- What is the relation between these?
- How do we tackle these questions?!?

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

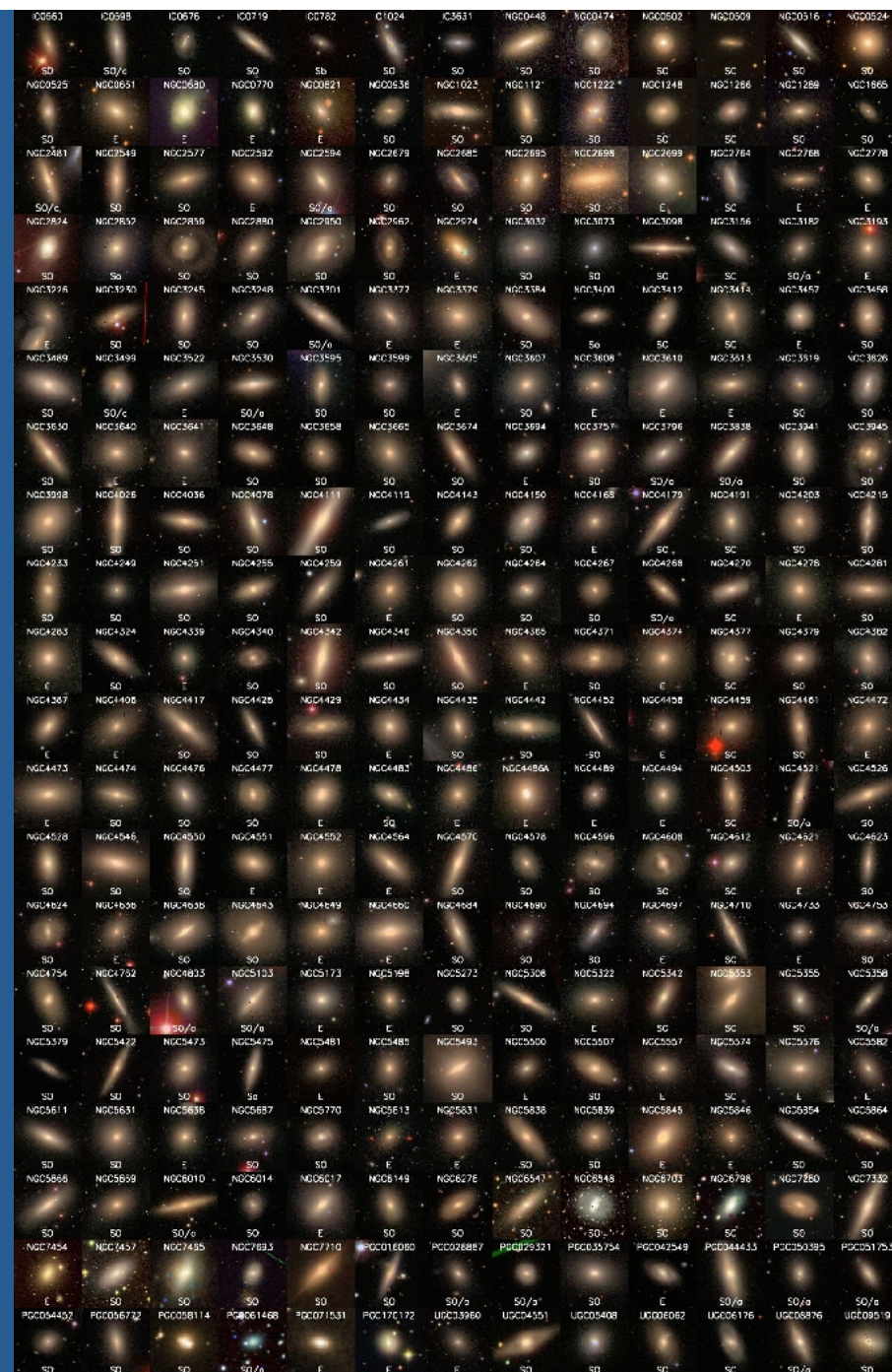




Project

$$\begin{aligned}
 M_K &< -21.5 \\
 D &< 42 \text{ Mpc} \\
 |\delta - 29| &< 35^\circ \\
 |b| &> 15^\circ
 \end{aligned}$$

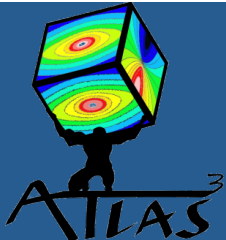
- Parent sample: 871 nearby galaxies
- Morphological selection: No spiral arms (DSS/SDSS)
- No colour cut
- Observe a complete volume limited sample of ETGs: 260
- Mass range: $\sim 7 \times 10^9 - 5 \times 10^{11} M_{\text{sun}}$



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



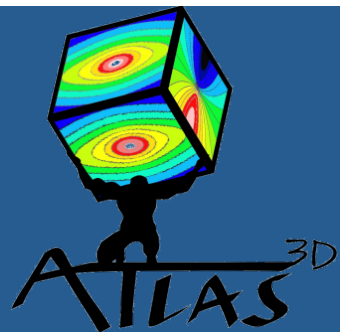
The ATLAS^{3D} team

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

Researchers:

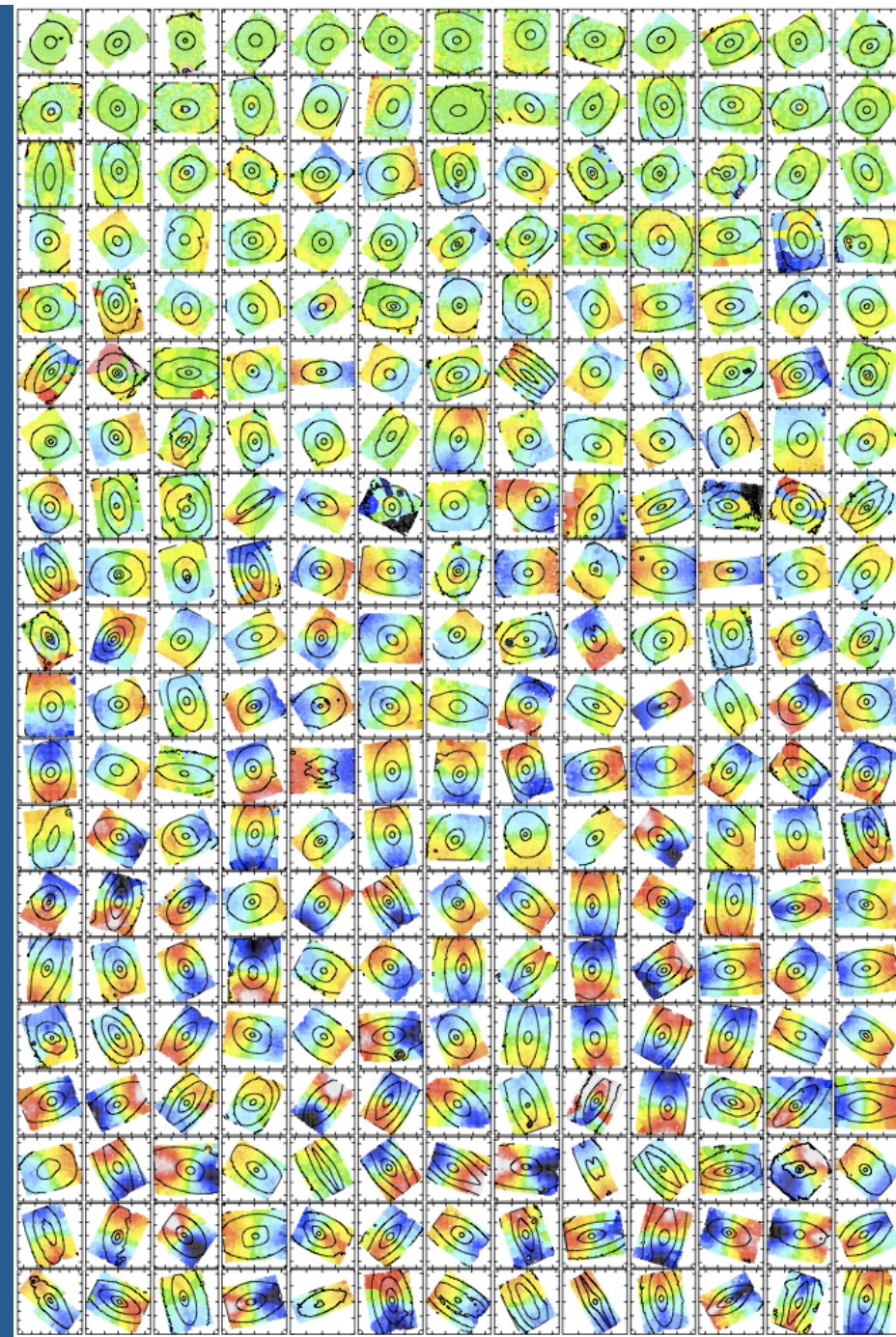
Katey Alatalo, Estelle Bayet, Leo Blitz, Maxime Bois,
Frederic Bournaud, Martin Bureau, Alison Crocker, Jean-
Charles Cuillandre, Roger Davies, Tim Davies, Tim de
Zeeuw, Pierre-Alain Duc, Etienne Ferriere, Jesus Falcon-
Barroso, Sadegh Khochfar, Harald Kuntschner, Pierre-
Yves Leblanche, Leo Michel-Dansac, Raffaella Morganti,
Thorsten Naab, Kristina Nyland, Ludwig Oser, Tom
Oosterloo, Marc Sarzi, Nicholas Scott, Paolo Serra,
Kristen Shapiro, Remco van den Bosch, Glenn van de Ven,
Gijs Verdoes-Kleijn, Anne-Marie Weijmans, Lisa Young

(36 researchers in ~16 institutes)

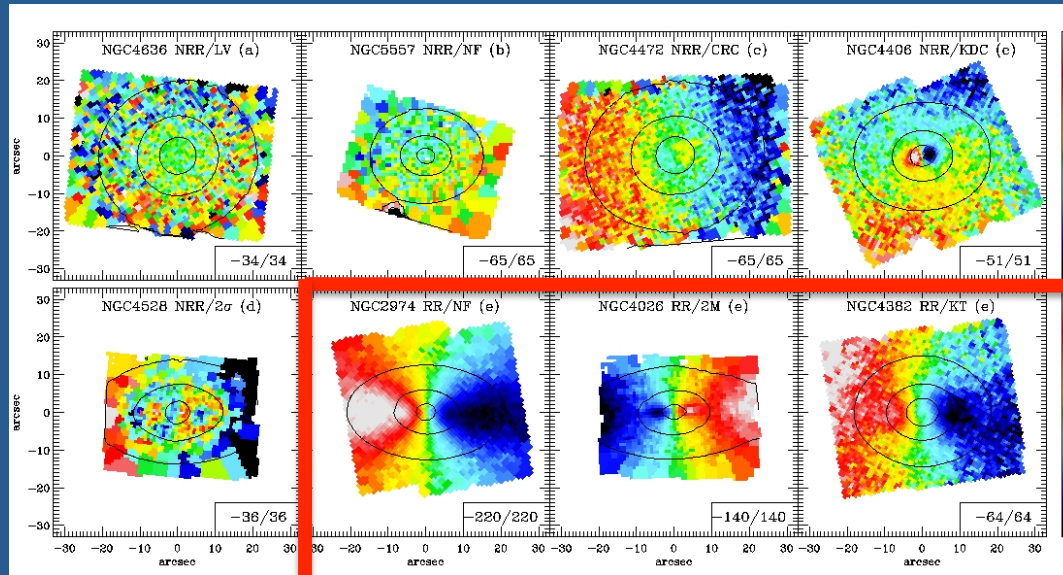
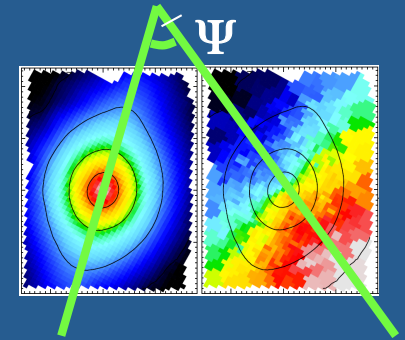


Kinematics

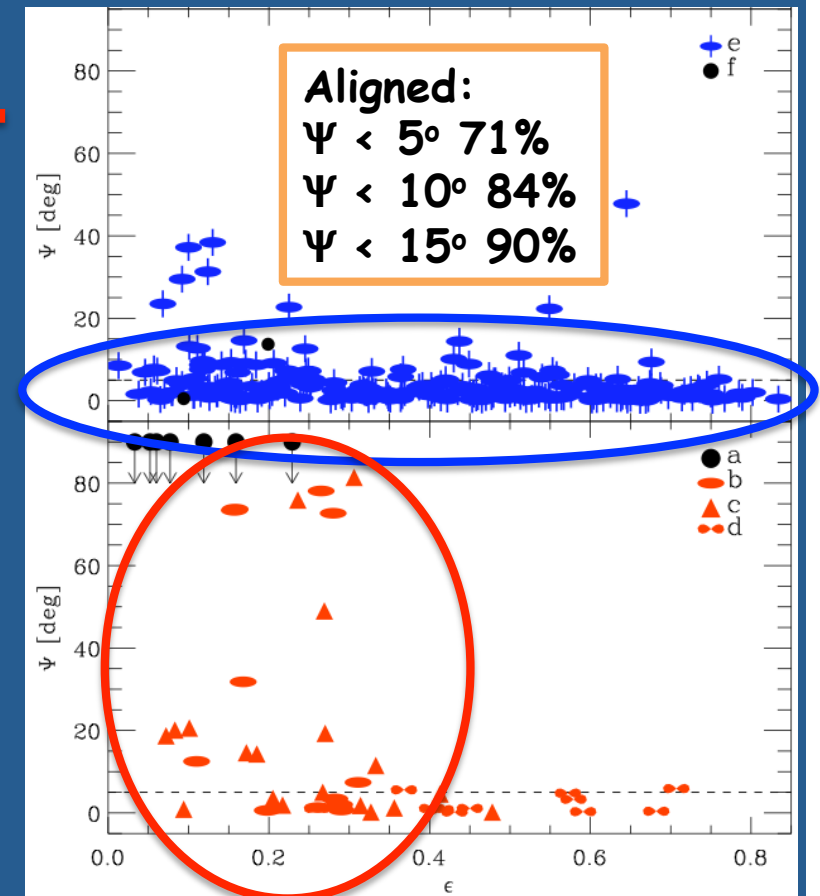
- Large variety of kinematic features
- Classification of velocity structures
- Measurement of stellar angular momentum



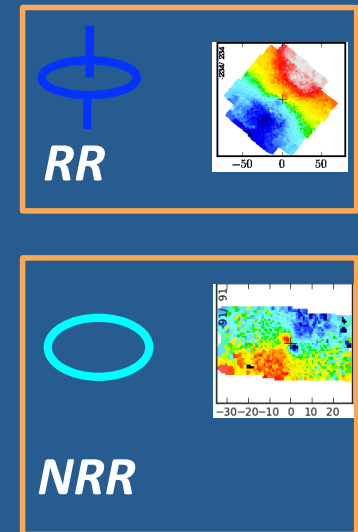
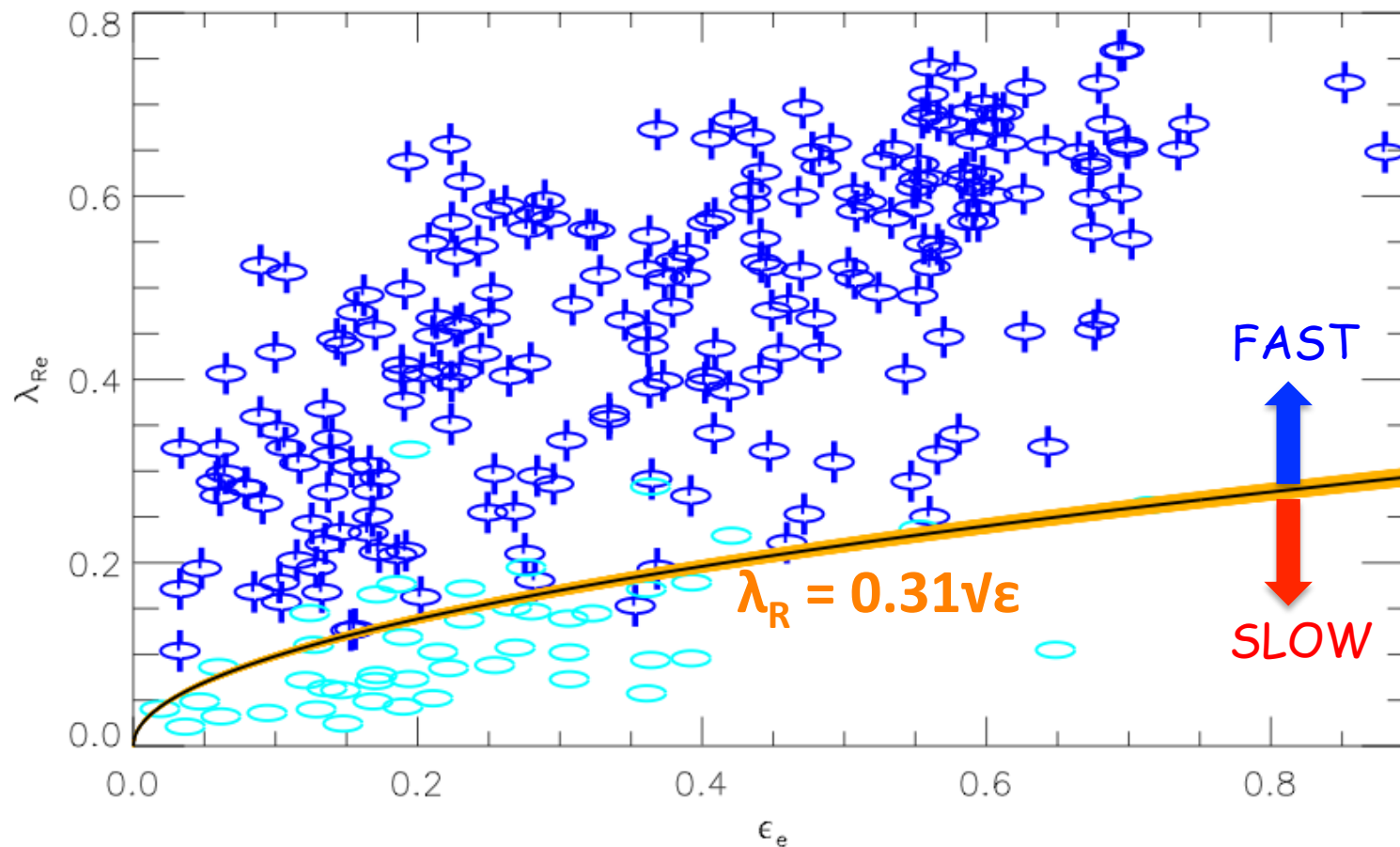
Kinematics



- Two general types of velocity fields: with regular and non-regular rotations (**RR/NRR**)
- **RR**: aligned \rightarrow nearly axisymmetric systems (+ bars!)
- **NRR**: (also) misaligned \rightarrow triaxial systems



Proxy for angular momentum

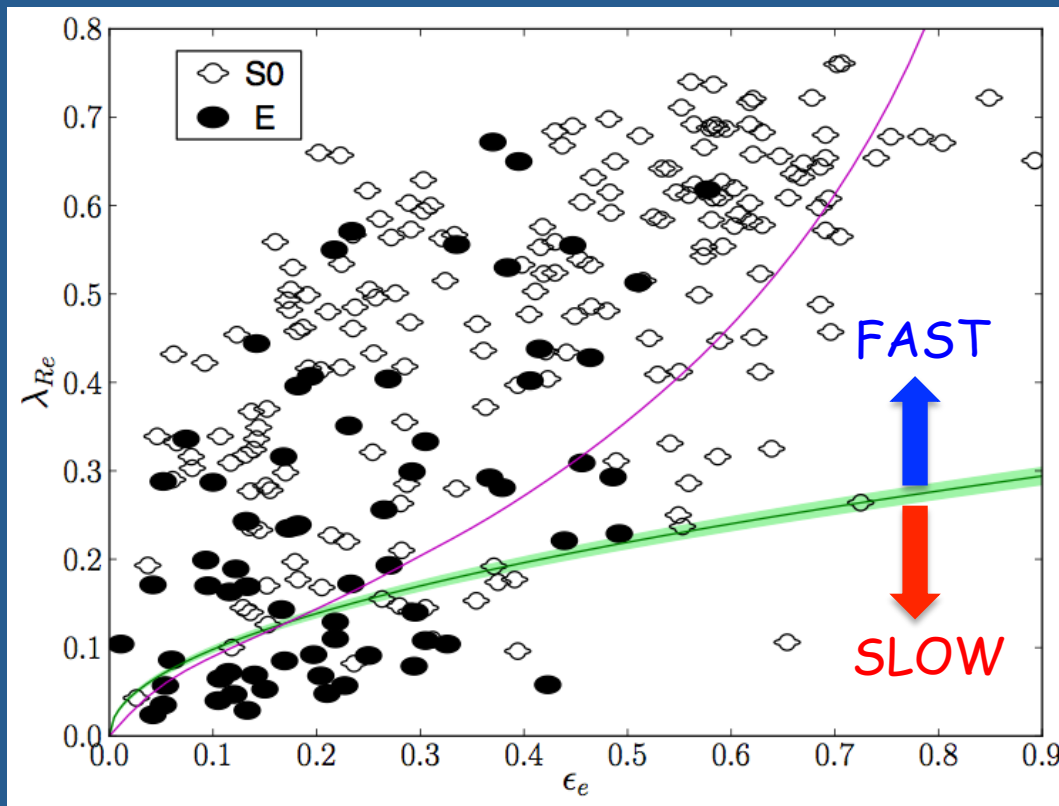


- λ_R depends on the flattening (ϵ)
- **85%** of all nearby ETGs are fast rotators

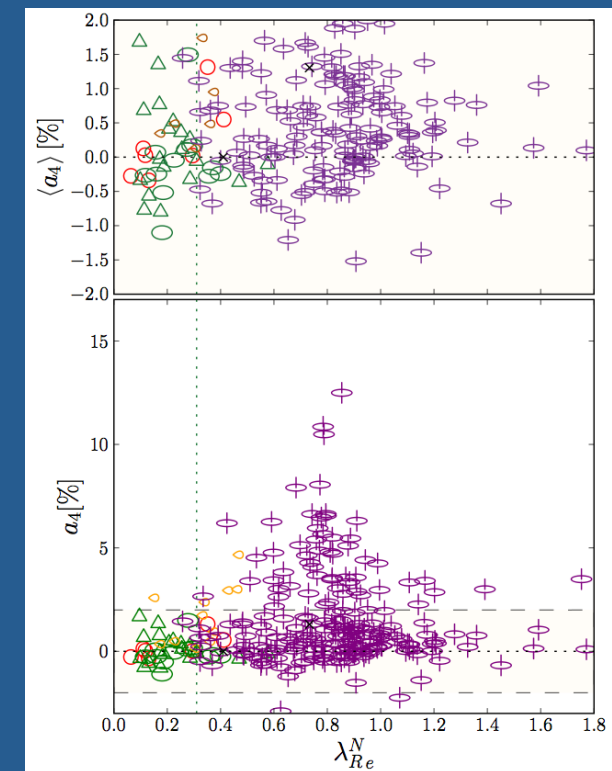
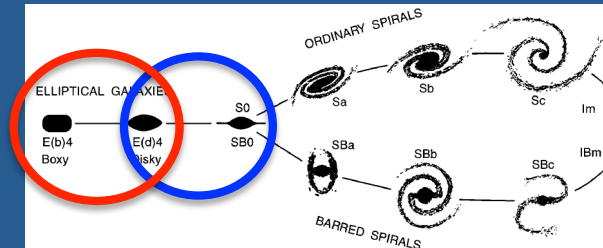
Emsellem, et al. 2011, Paper III

λ_R vs Hubble classes

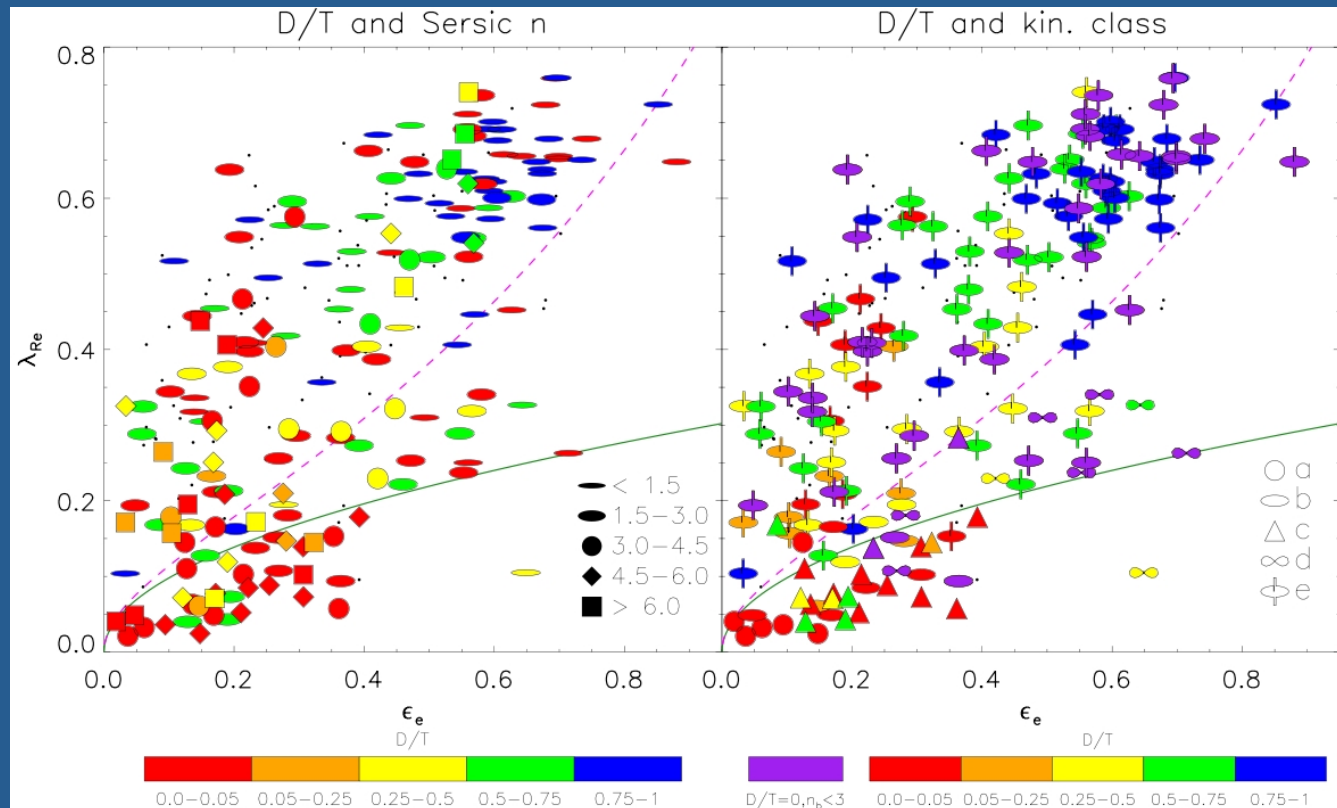
Emsellem et al. 2011, Paper III



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



Are there discs in ETGs?



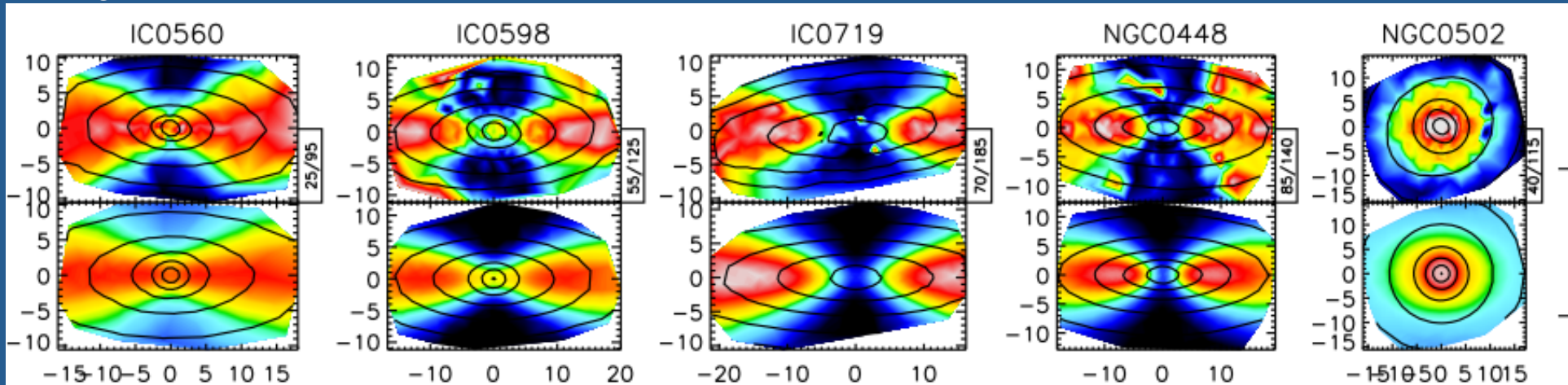
Sérsic +
exponential
fits to 180
non-barred
ATLAS^{3D}
objects (r
band SDSS
+INT
imaging)

Krajnović et al. 2012, Paper XVII

- Exponential components in ETGs can be associated with regular rotation
- FR: two comp. systems or 1 comp. of low Sérsic n
- SR: 1 comp. systems with large Sérsic n

Dynamics

$$V_{\text{rms}} = \sqrt{v^2 + \sigma^2}$$

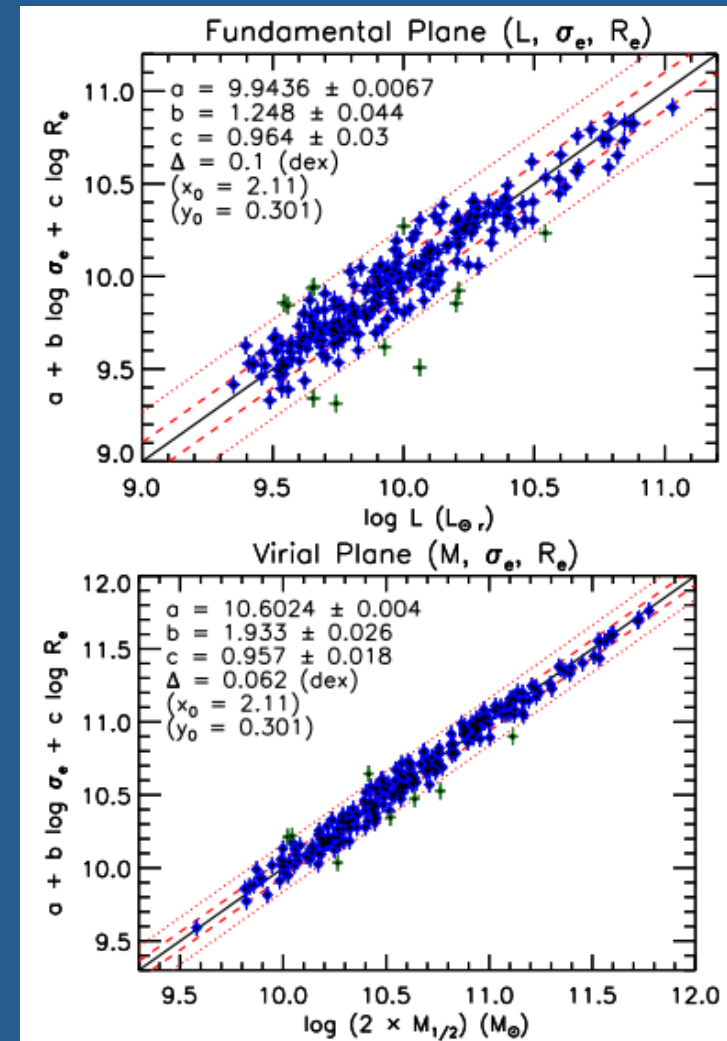


Cappellari et al. 2012, Paper XIX

- Dynamical models for all sample galaxies – accurate dynamical masses
- MGE (Emsellem et al. 1994)+ JAM (Cappellari et al. 2008) models: two parameters: (β_z , i)
- Mass follows light models: kinematics well reproduced:
 - DM is not important or traces light precisely

Role of DM and the Virial Plane

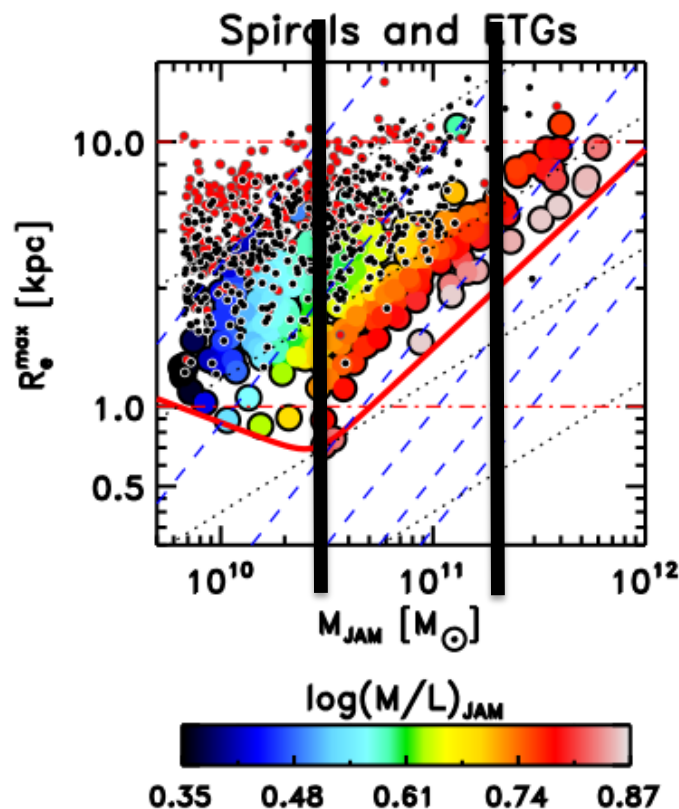
- 12 – 16% of DM within R_e on average (depending on the DM parameterisation and model quality)
- $f_{\text{DM}} < 39\%$ for 90% of models
- From FP to VP
 - $L \rightarrow M$
 - Reduction in observed scatter: 32 \rightarrow 19 %
 - Scatter in FP due to variations in M/L
 - $b \sim 2$, close to virial prediction
 - Tilt of FP due to M/L variations
- Galaxies are virialized stellar systems



Cappellari et al. 2012, Paper XIX

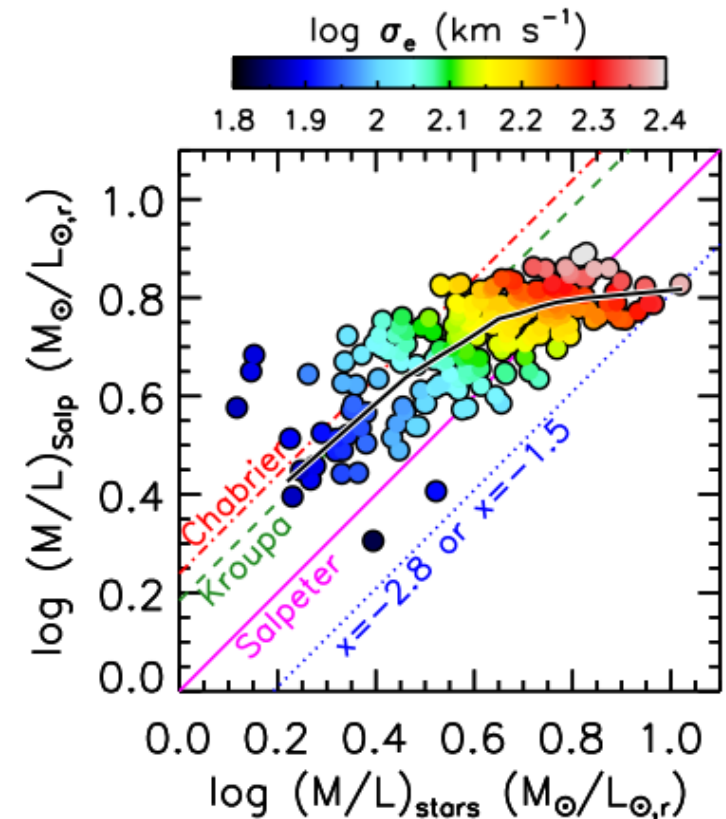
Connecting ETGs to spirals

- Two characteristic masses: 3×10^{10} and $2 \times 10^{11} M_{\text{sun}}$
- σ – best predictor of properties (M/L, $H\beta$, colour, concentration...)
- Parallel sequence to spiral galaxies
 - overlap for low M/L, break in similarities at large M/L (M or σ)
 - largest M/L ETGs have no counterpart in spirals
- Systematic variation of IMF from Kroupa to Salpeter as function of sigma (M/L)



Cappellari et al.
2012, Paper XX

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Gas observations

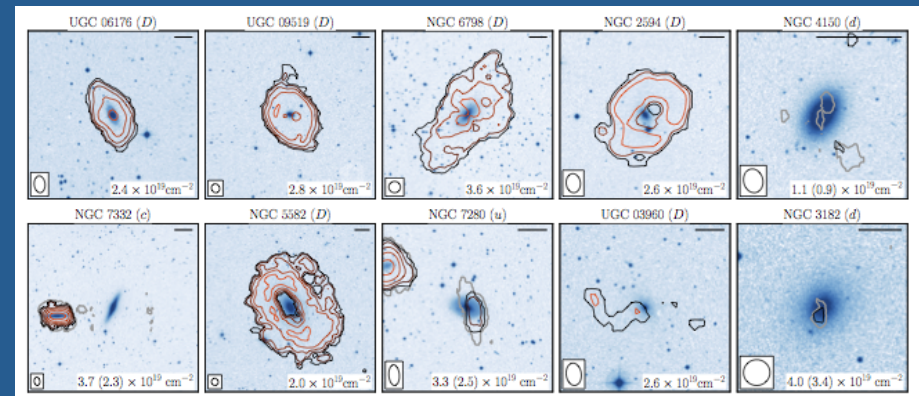
- WRST – HI interferometry
 - ~2500 hours (198 galaxies - 32 from literature)
 - All galaxies visible from WRST ($\delta > 10^\circ + 15'$ from Virgo)
- IRAM 30 m – single dish
 - Full sample
- Carma – CO interferometry
 - 500 hours
 - Flux limited sample of IRAM detections (40 galaxies – 10 from literature)



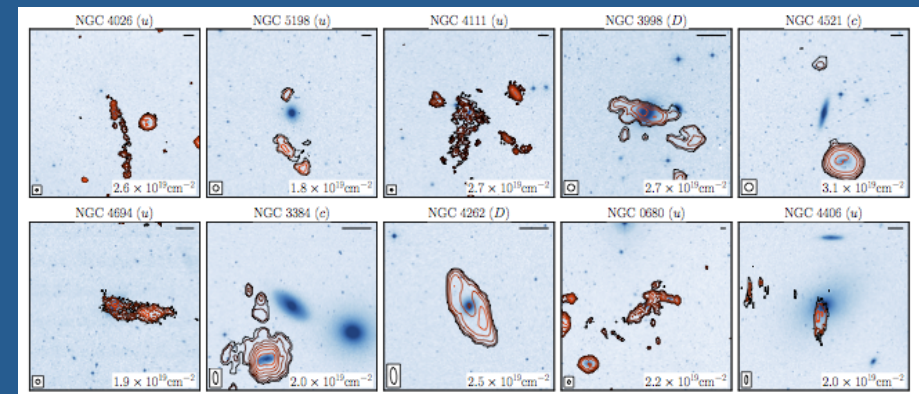
HI gas: large scale structures

- 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, Paper X



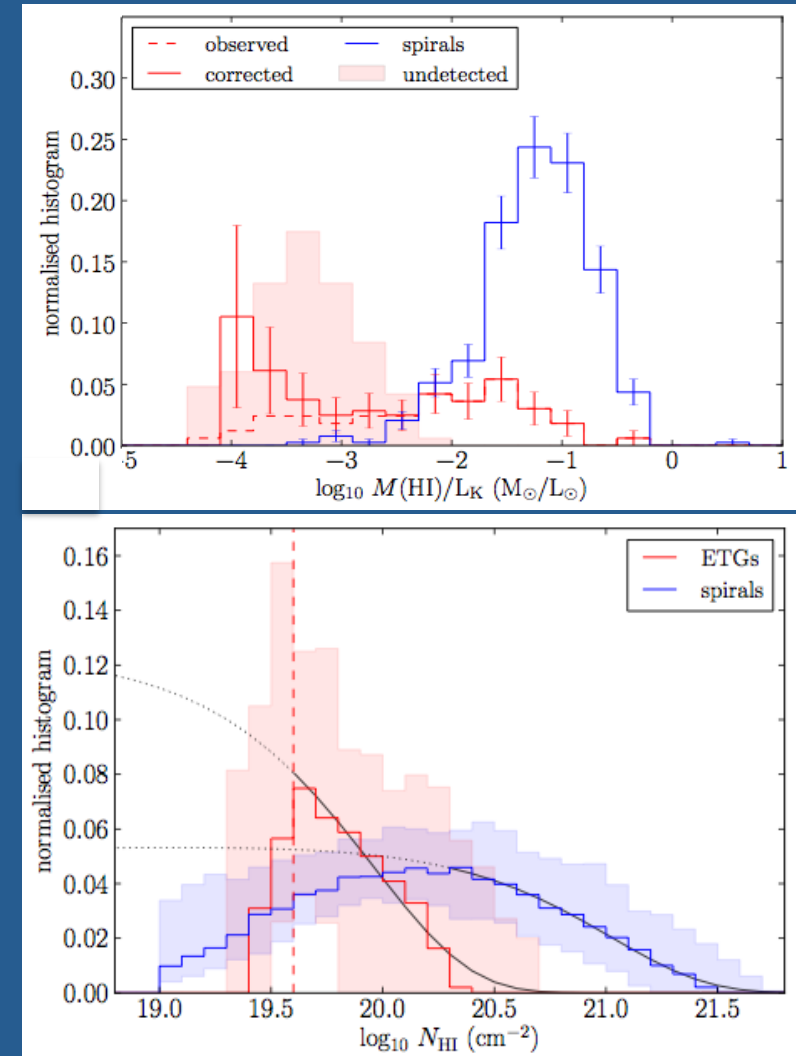
10 galaxies in least dense environment



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



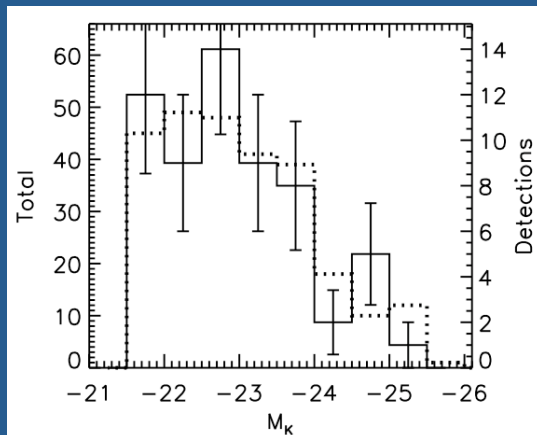
Molecular gas

Young et al, 2011, Paper IV

IRAM 30m Single Dish Survey

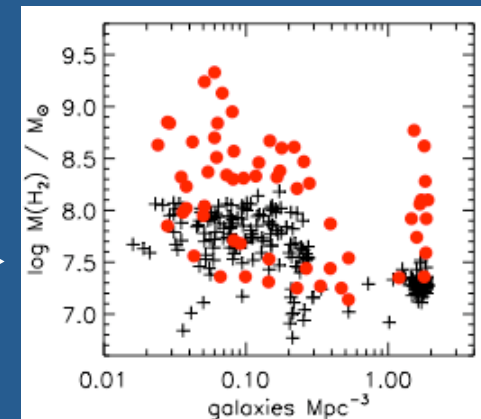
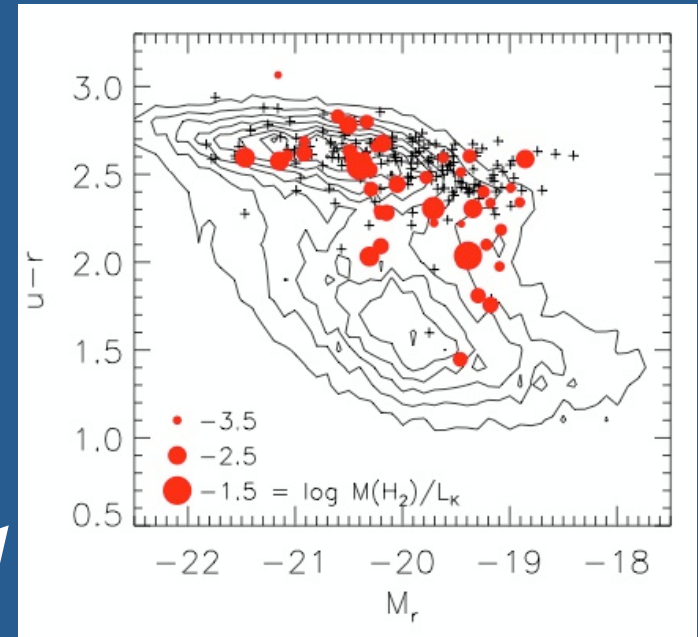
- Detection rate: **22%**
- Molecular gas masses in range 10^7 to 10^9 Msun
- Upper limits down to 6.3×10^6 Msun
- Molecular gas fractions: 7% to 0.02% (M_{H_2}/L_K)
- No detections of molecular gas in slow rotators

Detection rate independent of luminosity!



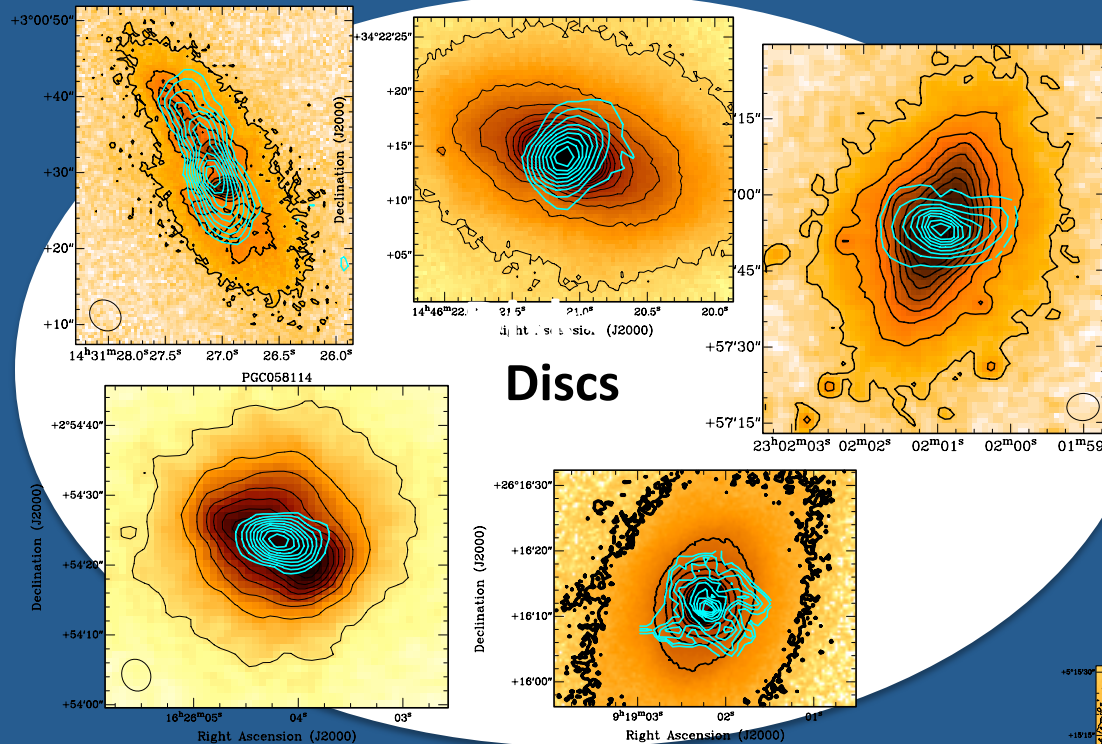
Red and dead? Not really

Detection rate also seems to be independent of environment!

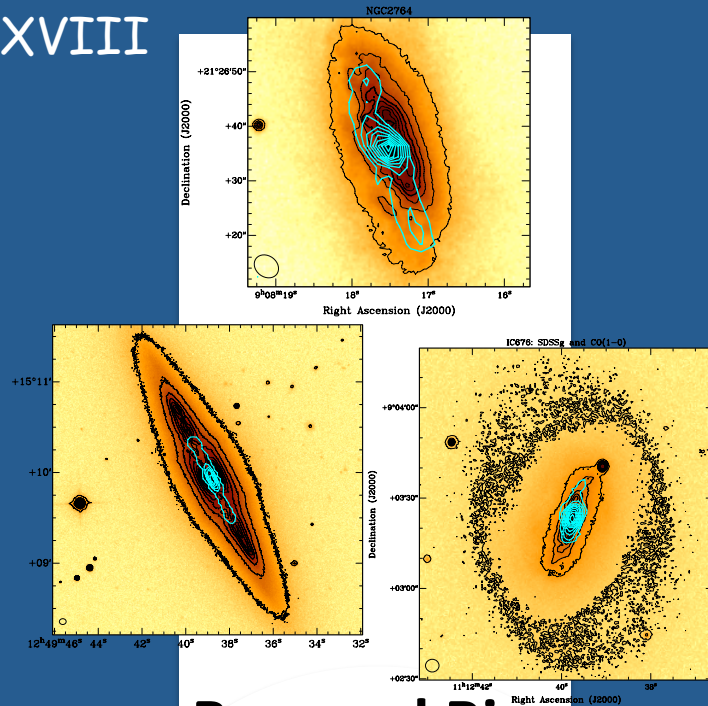
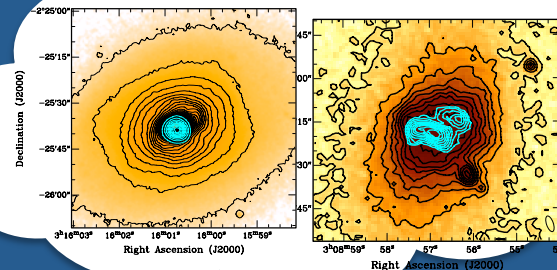


CO gas morphologies

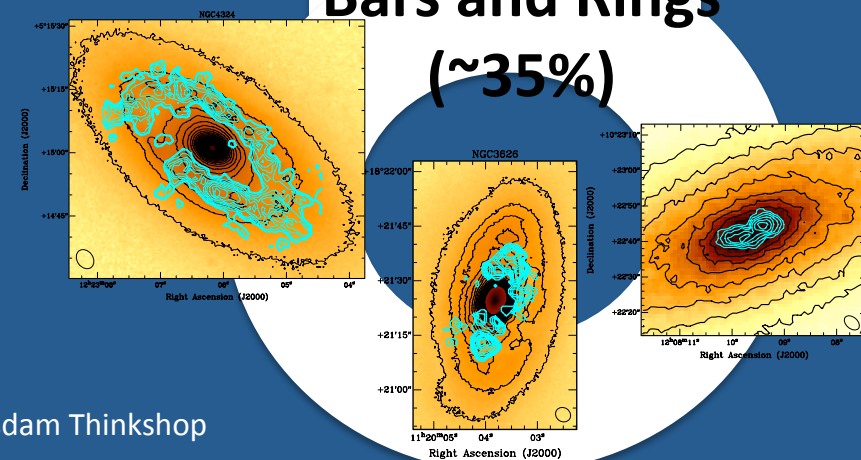
Alatalo et al., 2012, Paper XVIII



Disturbed Distributions (~10%)



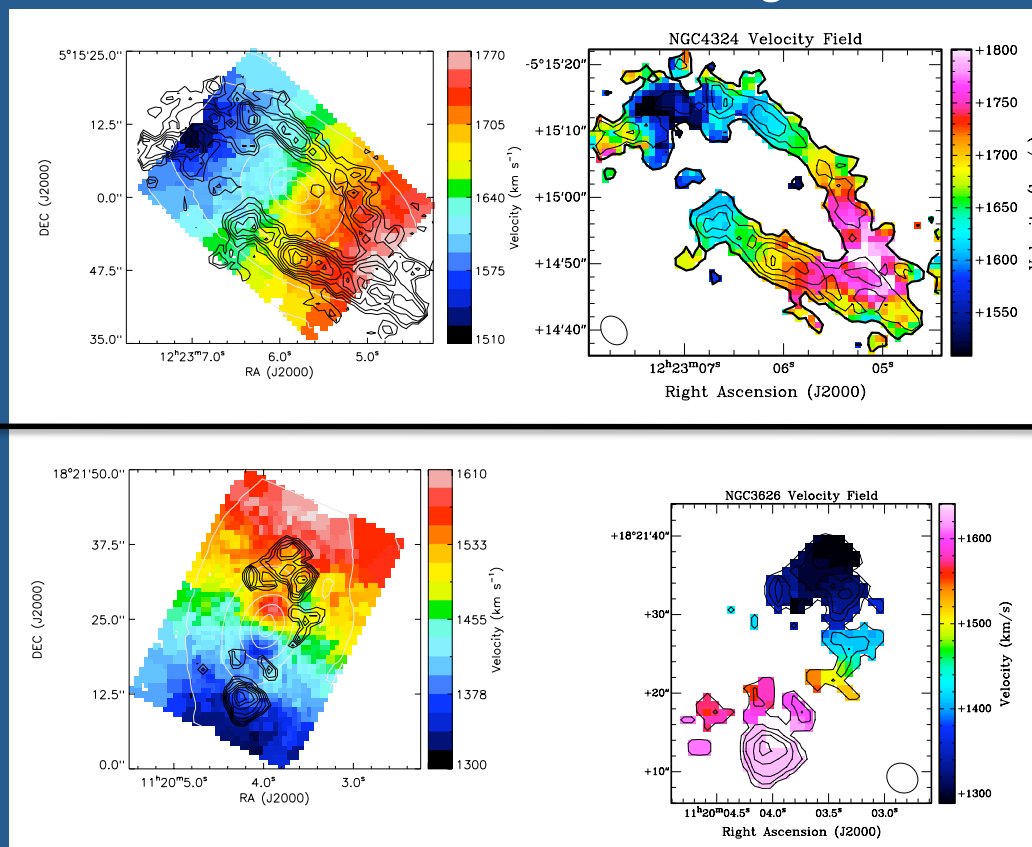
Bars and Rings (~35%)



What is the origin of gas?

- Internal (e.g. stellar mass loss)
 - gas rotates like stars
- External (e.g. cold accretion)
 - all possible orientation (in axisymmetric system co- and counter-rotation)
- Molecular, atomic and ionised gas often seen to make one single structure (e.g. Morganti et al. 2006, Oosterloo et al. 2010)
- Use large sample in a statistical sense

Stars vs molecular gas



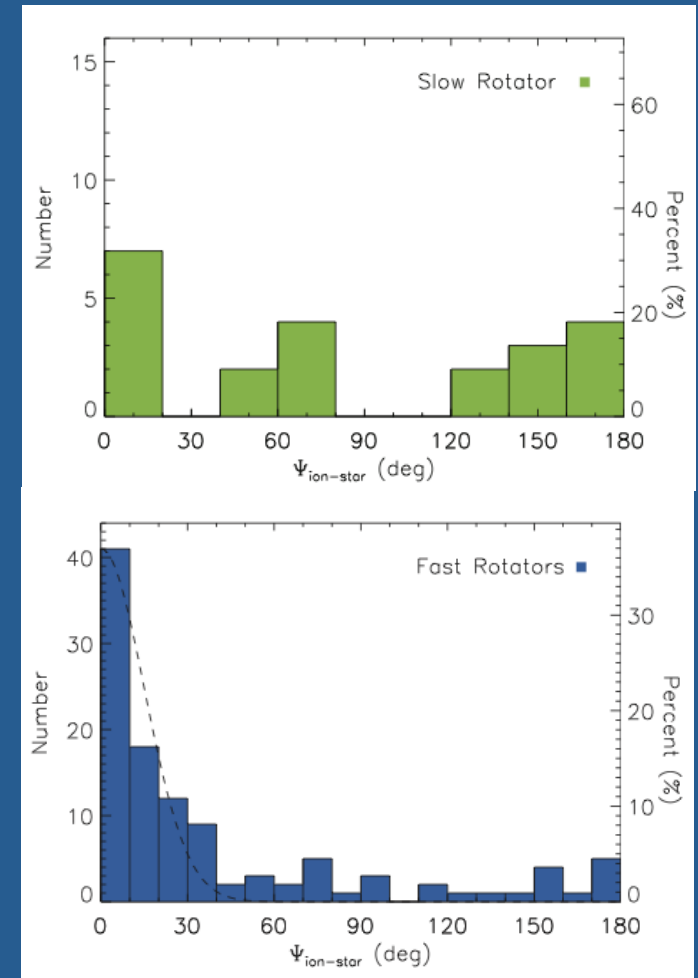
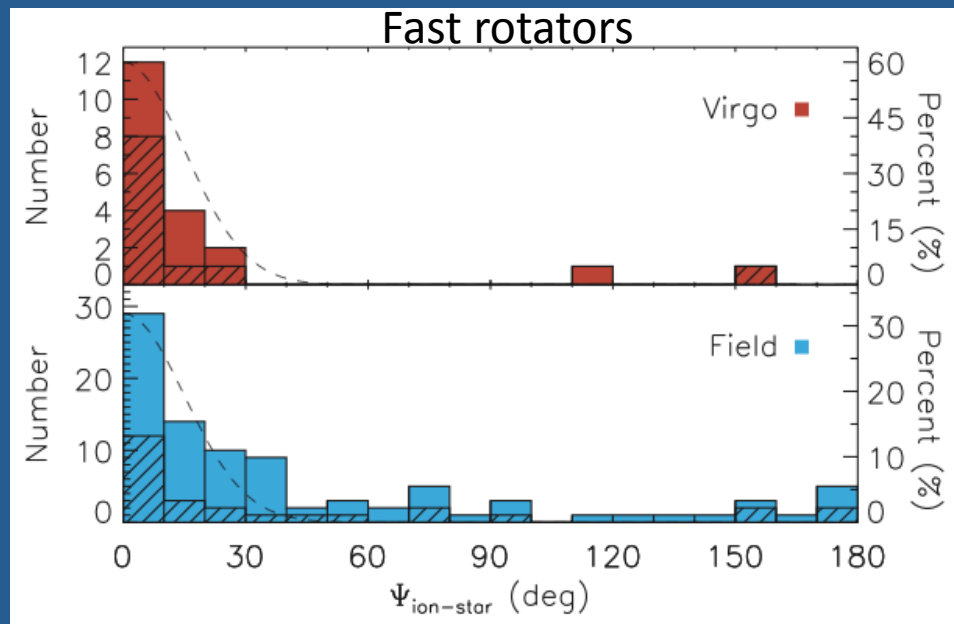
ALIGNED

MISALIGNED

Davis et al. 2011, Paper X

Alignment with stars

- FR – gas mostly aligned, but not all...
- SR – aligned and misaligned (similar numbers)
- For FR – strong environmental dependence (Virgo/non-Virgo)
- Evidence for at least **46%** of objects to have external gas origin

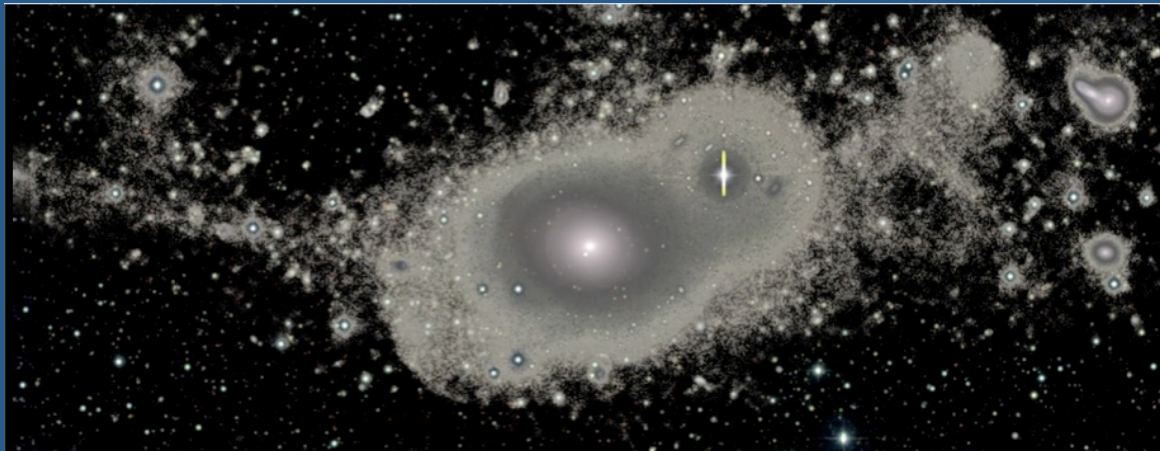


Deep imaging

- Multi-band imaging with MegaCam
- Depth: up to 28.5 - 29 mag/"² in g band
- ~400 hours of CFHT time (LP starting now)

Dating the merger: major wet, not younger than 1 Gyr, but merger happened after $z < 0.5$

Duc et al. 2011, Paper IX



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- Multiple
- Deep
- ~40
- now
- Dating
- than



IX



Boring ETG

Major merger

Minor merger

Outlook

- Synergy of multi-wavelength observations is not a new concept, and it really works!
- Parallelism and continuity in physical parameters between early-type and spiral galaxies (Paper VII)

