Towards A New Paradigm for Early Type Galaxies

Roger Davies

This talk reports the work of two two large teams:

The SAURON Team

PIs: Roland Bacon (Lyon), RLD, Tim de Zeeuw (ESO)

~ 30 papers published

and

The ATLAS^{3D} team

PIs: Michele Cappellari (Oxford) ,

Eric Emsellem, Davor Krajnović (ESO)

Richard McDermid (Gemini)

8 ATLAS^{3D} papers submitted

5 now accepted & on ADS

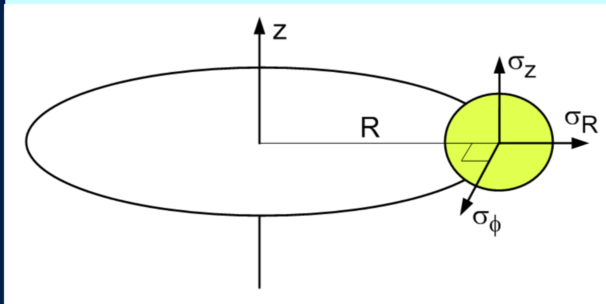
Outline

- Overview of early type galaxies (ETGs)
- Summary of SAURON survey
- Towards a new paradigm
- First results from ATLAS-3D

V/σ diagram

Low luminosity ellipticals

Disky, Rotate faster, isotropic

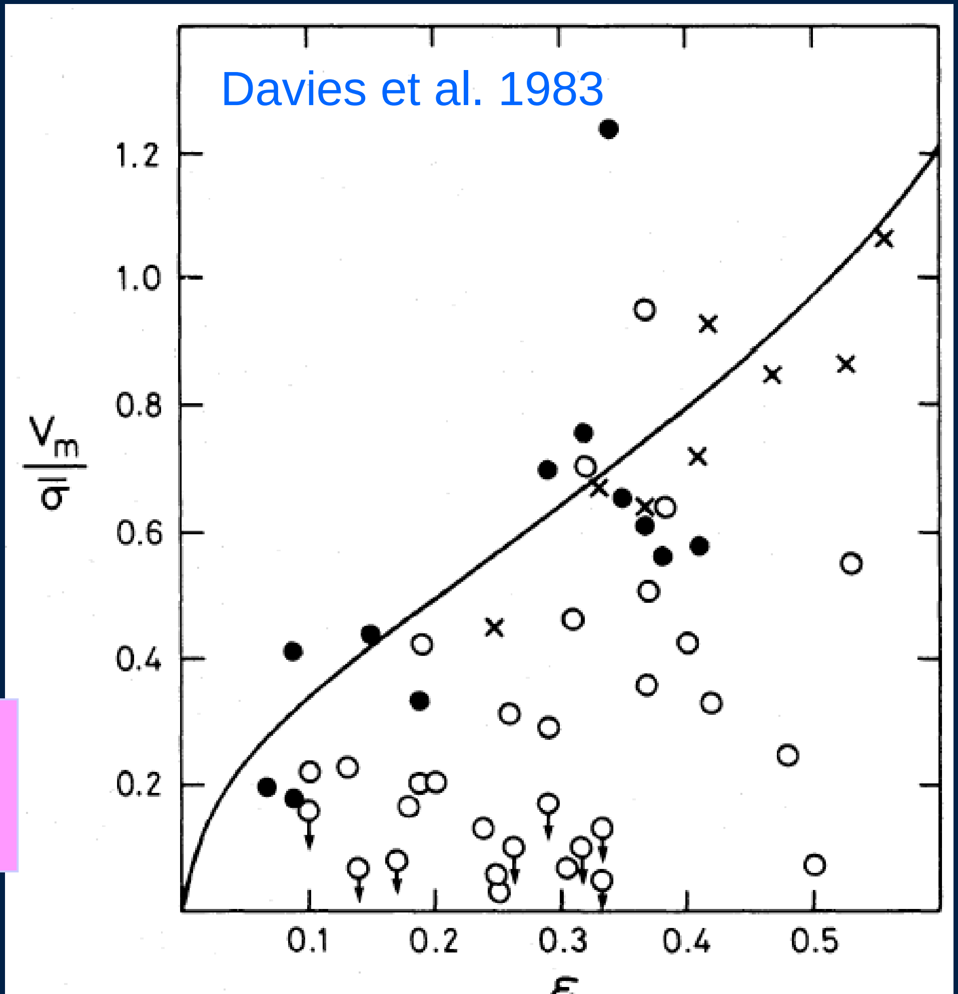


$$\beta \rightarrow 1 - \frac{\sigma_z^2}{\sigma_R^2}$$

Giant ellipticals

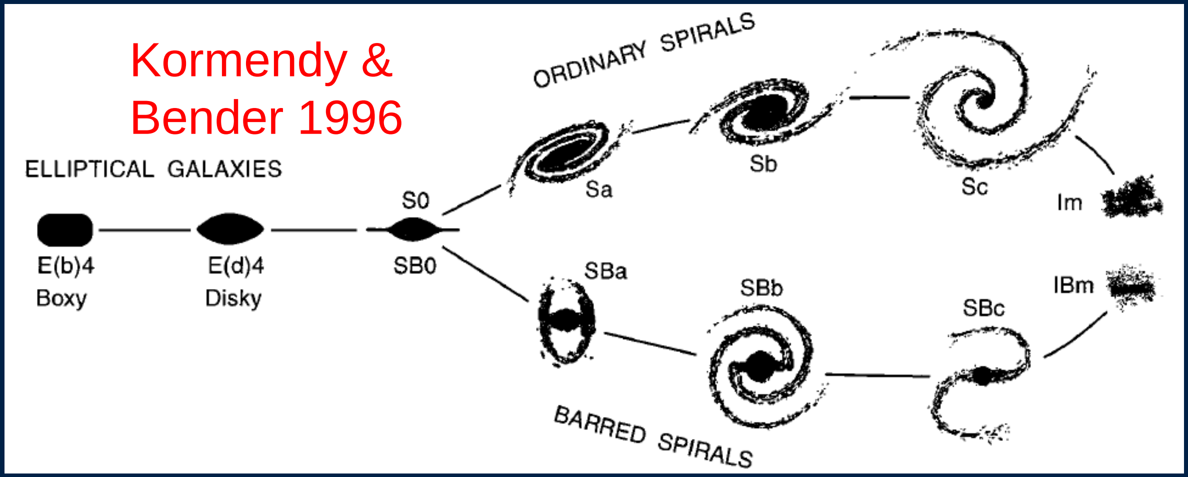
Boxy, Rotate slowly, likely anisotropic

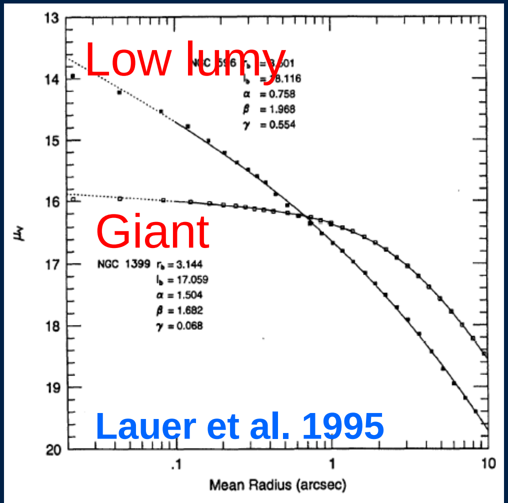
Illingworth (1977), Binney (1978)
Kormendy & Illingworth (1982),
Davies et al. (1983)



O = giant ellipticals
● = low lumy ellipticals
x = bulges

`Dichotomy' of ellipticals





Bender et al 1989: boxy galaxies are radio loud, have X-ray halos, and higher M/L

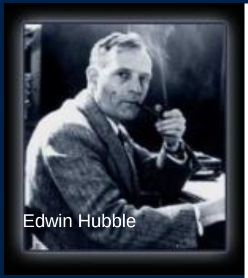
Rix & White 1990 : almost all `radio-weak' ellipticals could have disks containing ~ 20% of the light

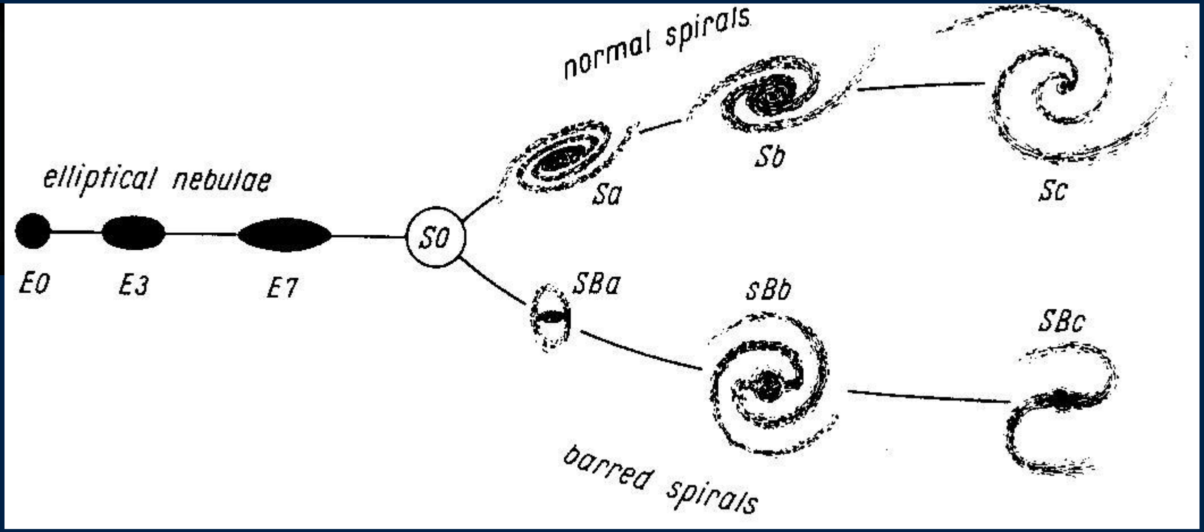
Kormendy & Bender 1996 : disky ellipticals are intermediate between big ellipticals and lenticulars

Lauer et al 1995 + Faber et al. 1997 : giant & low lum'y ellipticals also distinct in their luminosity profile

Kormendy et al. 2009 Light Excess/Deficit also defines a dichotomy

The paradigm





- E + S0s **~ 50%** of (SDSS) mass   Bernardi et al. 2009
- E/S0s are overall red; S0s have bluer colours
- Two flavours of E's..
  - Boxy with flat cores or light deficit, anisotropic, triaxial
  - Disky with cusps or light excess, isotropic, oblate

What is needed is a physical classification!

The SAURON survey

The SAURON Team

Roland Bacon, Lyons,

Michele Cappellari & Roger Davies, Oxford,

Tim de Zeeuw, ESO, Jesus Falcon-Barroso, IAC

Eric Emsellem, Davor Krajnović, Harald Kuntschner, ESO

Richard McDermid, Gemini, Marc Sarzi, UHerts,

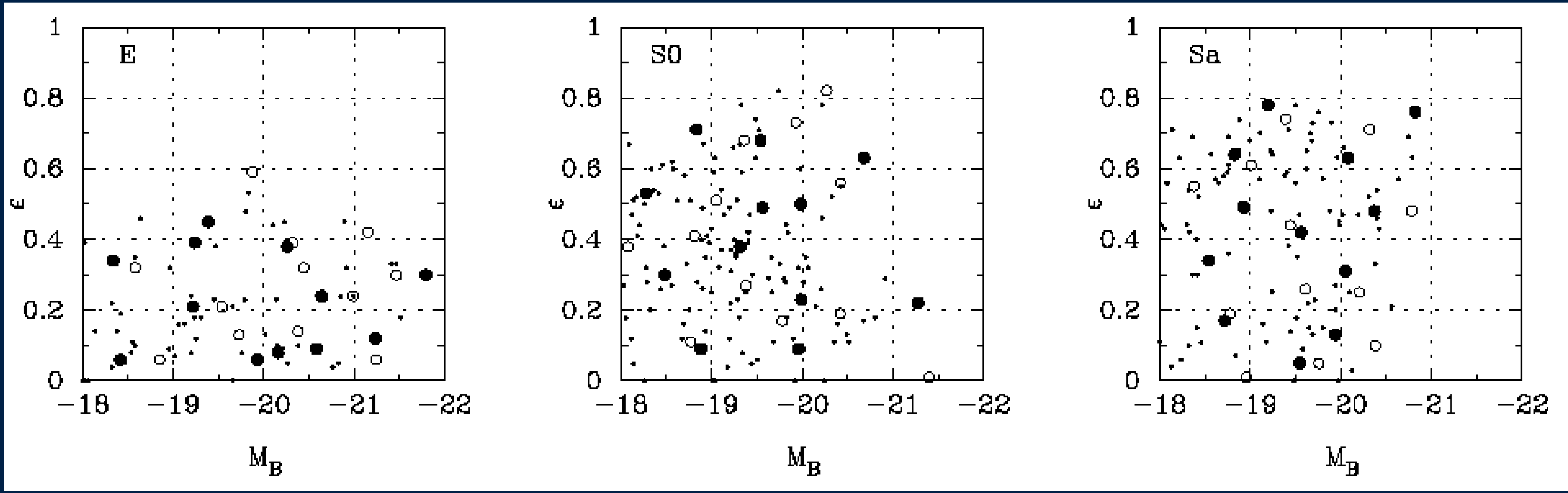
Glen van de Ven & Remco van den Bosch, MPIA Heidelberg,

& Reynier Peletier, Groningen.

Associates: Bureau, Fahti, Ganda, Maier, Miller, Monnet, Scott, Shapiro, Statler, Weijmans

SAURON survey: selection

Elliptical S0 Sa



- cz < 3000 km/s
- -6° < d < +64°
- |b| ≥ 15°

$M_B \leq$ -18 mag

24 E, 24 S0, 24Sa

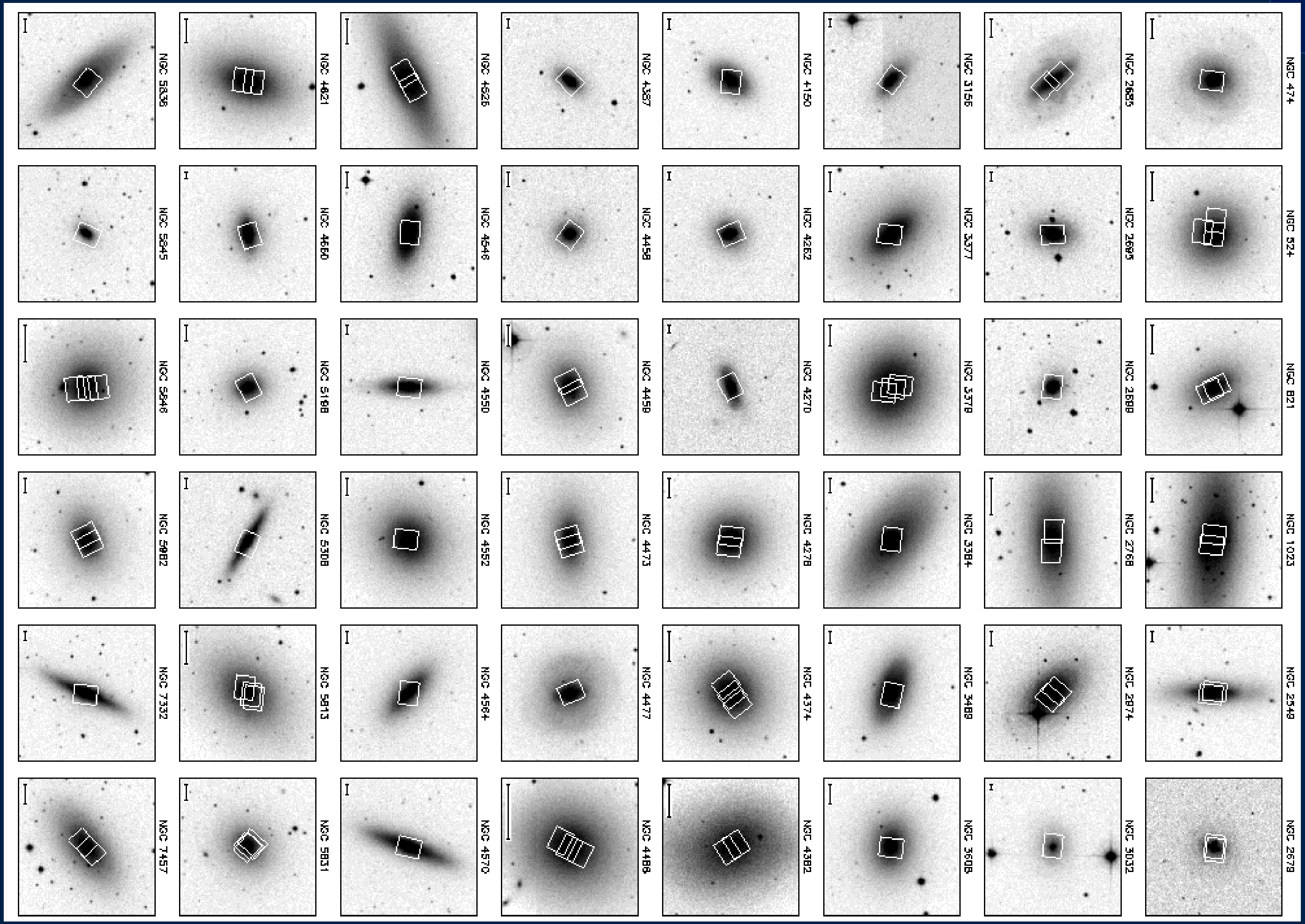
12 ‘cluster’, 12 ‘field’

56 nights on WHT; 36 clear.

~200,000 independent galaxy spectra.

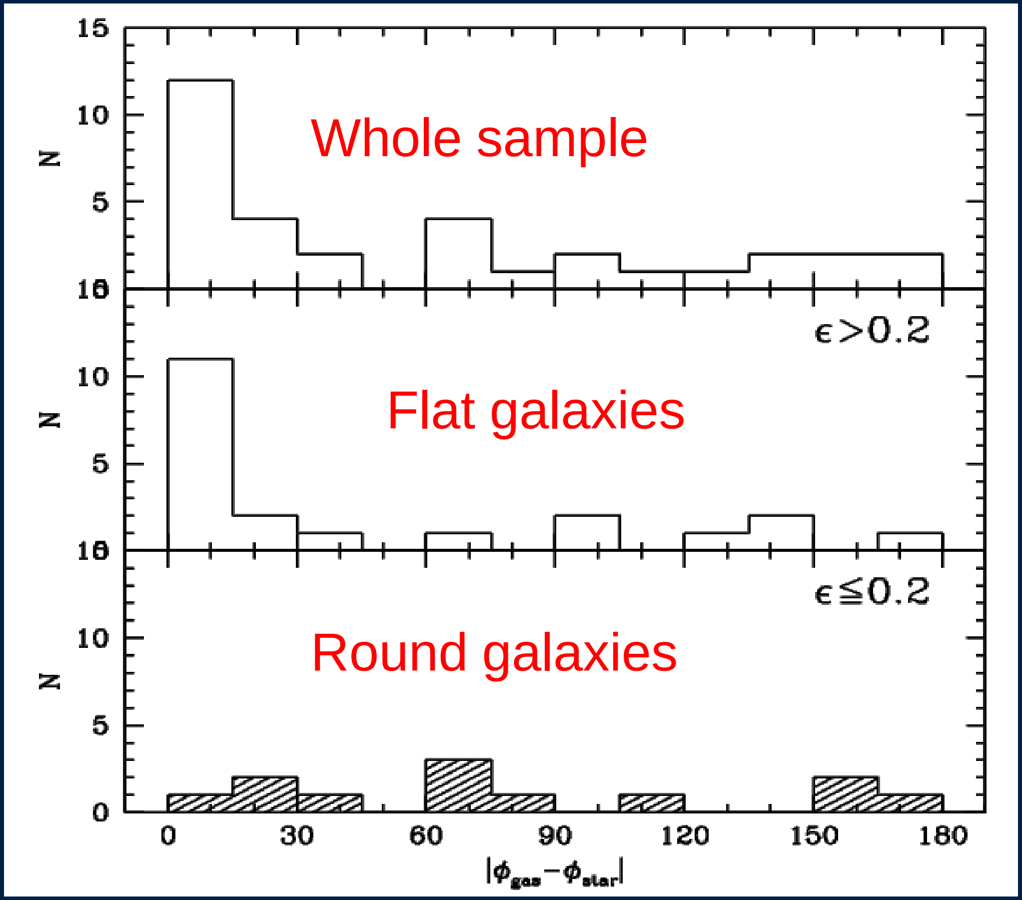
de Zeeuw et al 2002

48 E/S0 Galaxies



Ionised Gas

Mis-alignment of the gas & stars



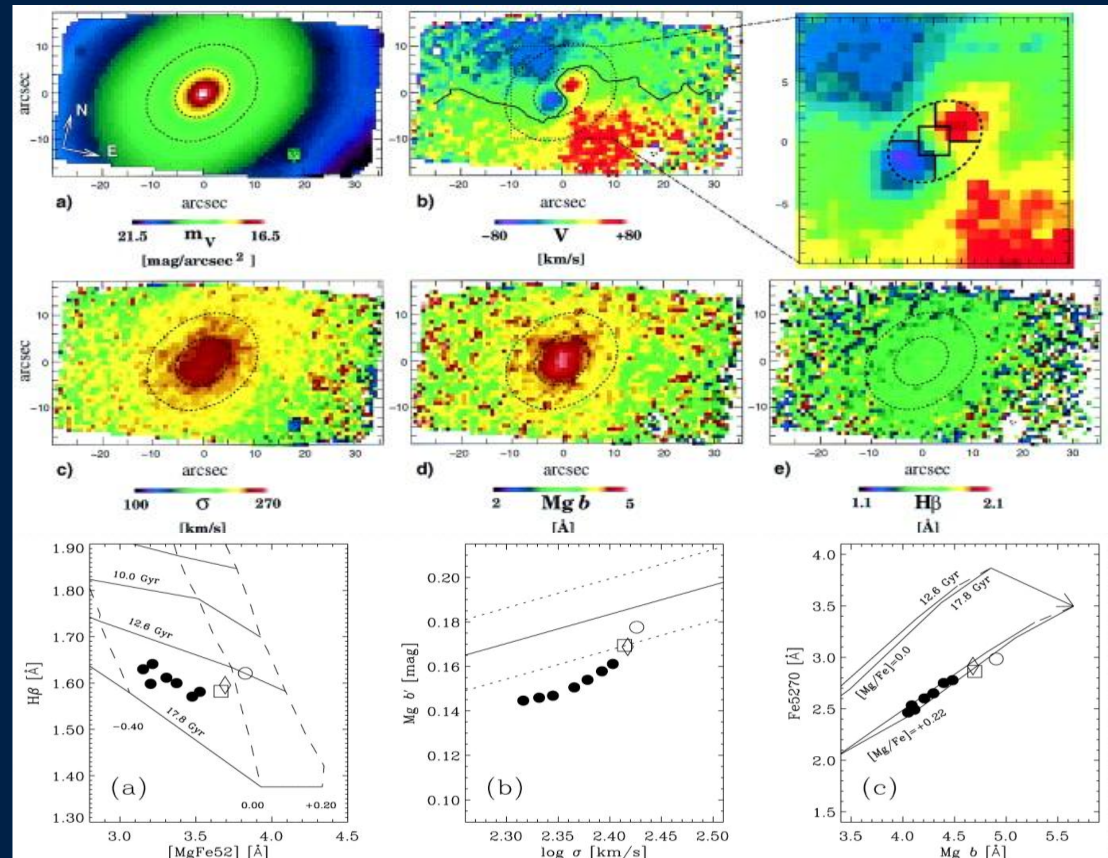
Sarzi et al 2005

- Suggests that some galaxies accrete their ISM & others retain stellar mass loss.
- Clear distinction between round & flat galaxies.

The decoupled core in NGC4365

The population of the core has *the same* high metallicity, Mg enhancement and 14 Gyr age as the underlying galaxy.

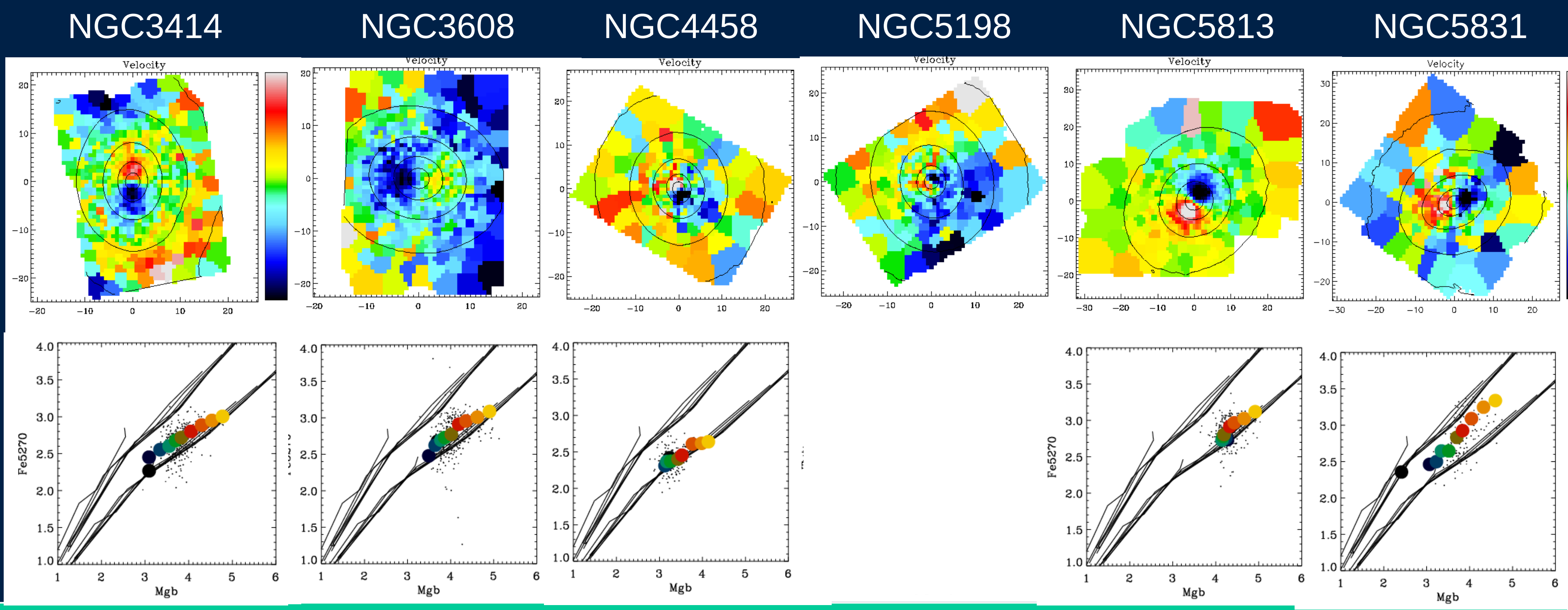
When did such a decoupled core form? …………at the time of the initial assembly.



Davies et al 2001

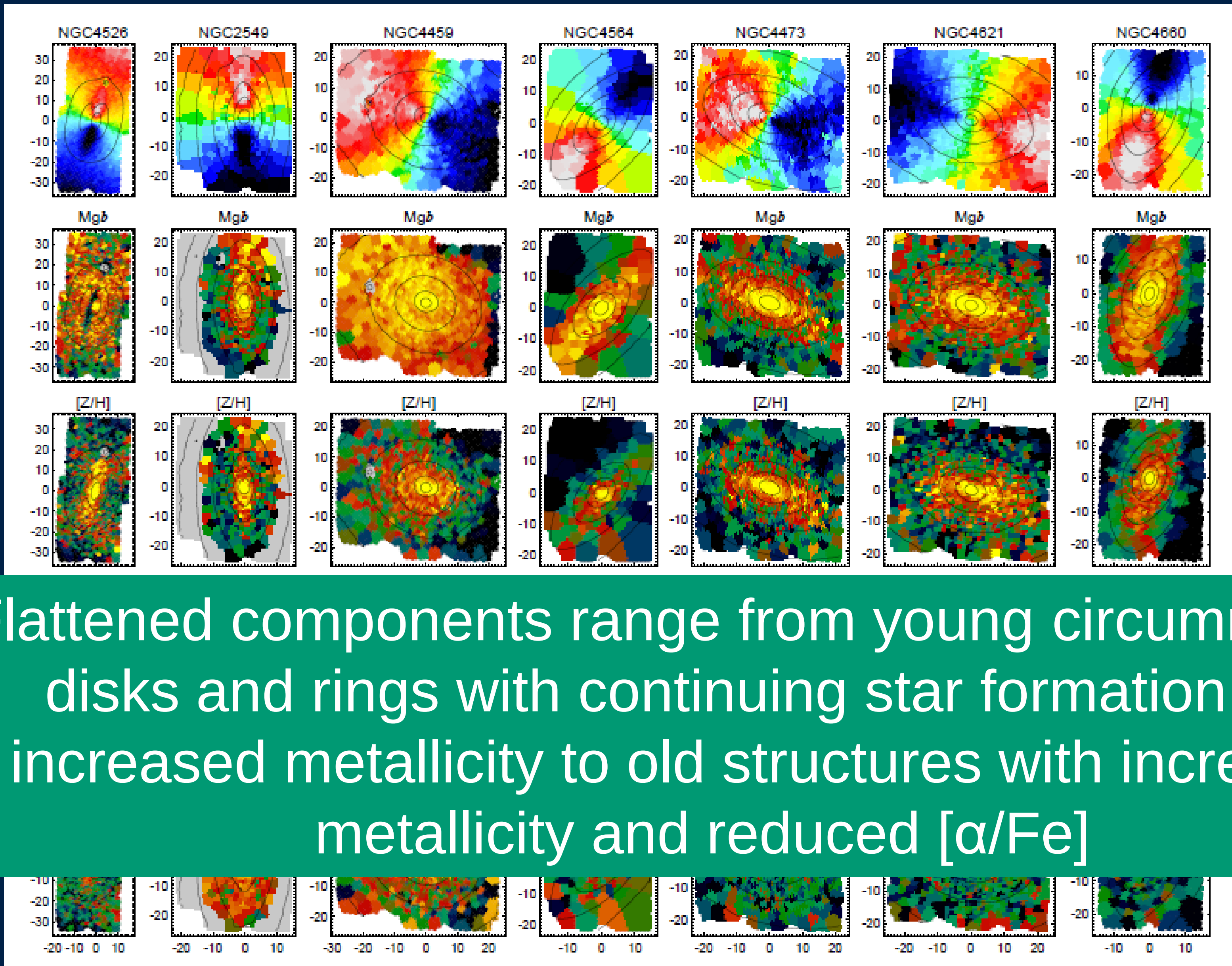
This galaxy is old and the decoupled core is stable

KDCs in slow rotators



Galaxies hosting kpc-scale KDCs are slow rotators. The KDCs are old and do not differ significantly from the surrounding stars (Kuntschner et al 2010)

Metallicity enhanced disks



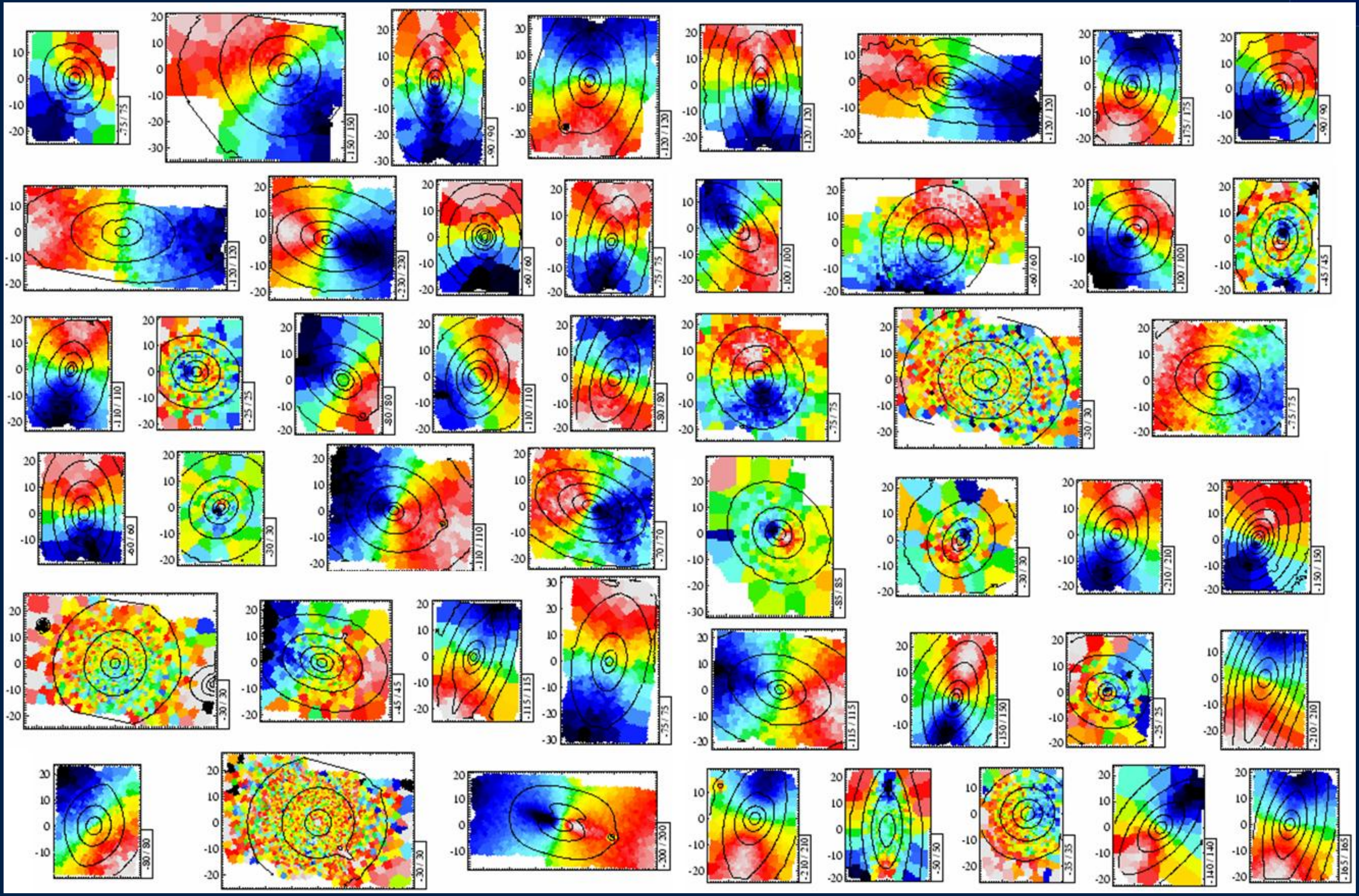
Flattened components range from young circumnuclear disks and rings with continuing star formation and increased metallicity to old structures with increased metallicity and reduced [α/Fe]

Conclusions: 1

- 75% show clear and extended ionised gas.
- External and internal origin for ionised gas.
- ½S0s & ¼ of field Es have `young' populations.
- Stars in KDCs are indistinguishable from the of the rest of the non-rotating galaxies in which they reside.
- Disks of enhanced metallicity identified.
- M/L $\propto \sigma^{0.82}$ accounts for Fundamental Plane tilt.
- Trend of M/L with σ_e is due to age.
- M/L from dynamics and populations broadly agree
- `Burstein relation' recovered
- Tight relationship between Mgb & V_{esc}
- GALEX colours used to identify RSF : UV FP measured

Towards a new paradigm: 1

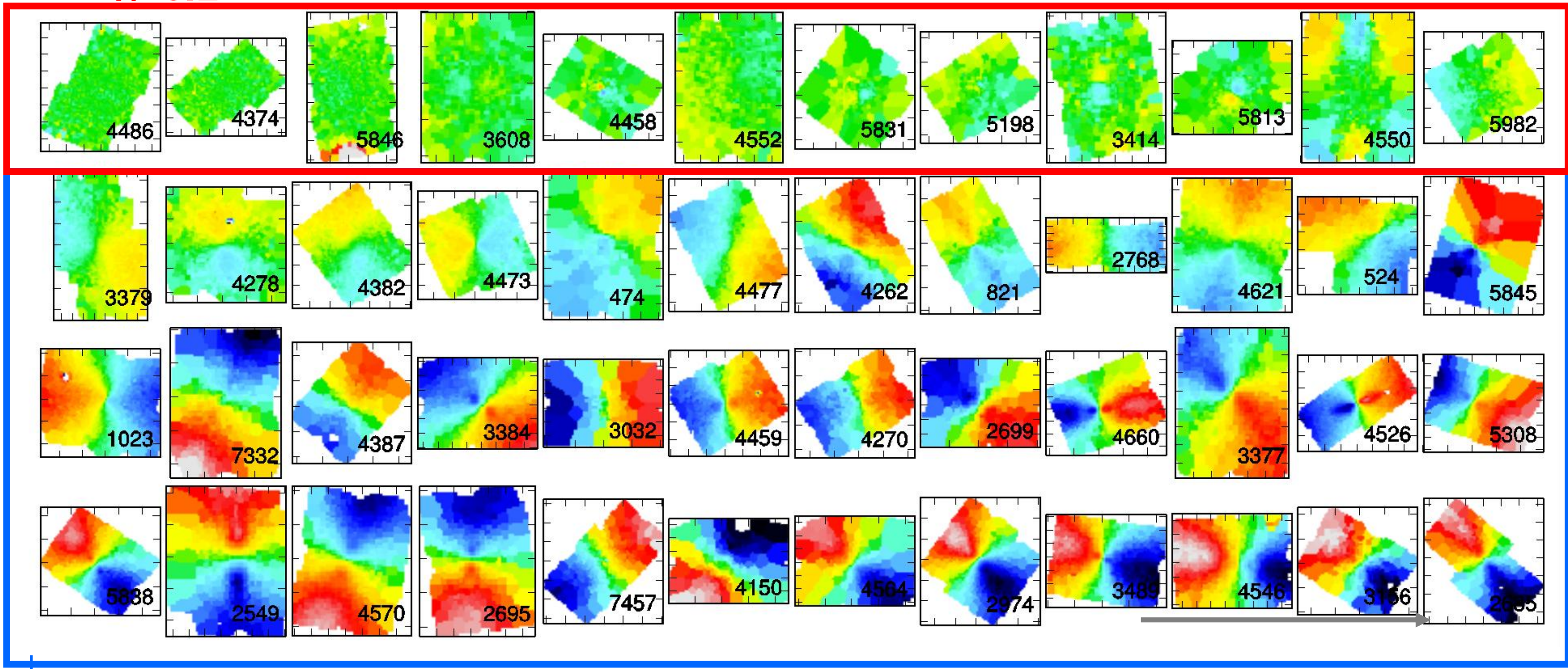
48 E & S0 velocity fields



Fast & Slow Rotators

Slow rotators $\lambda<0.1$

$$\lambda_R = \langle RV \rangle / R\sqrt{\langle (V^2 + \sigma^2) \rangle}$$

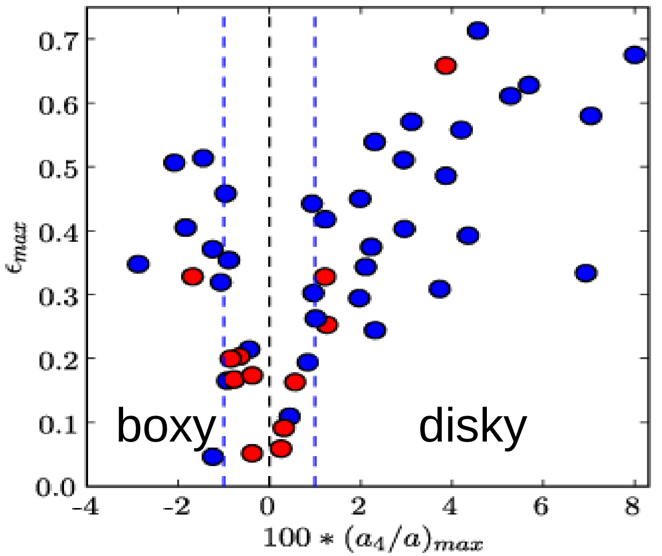


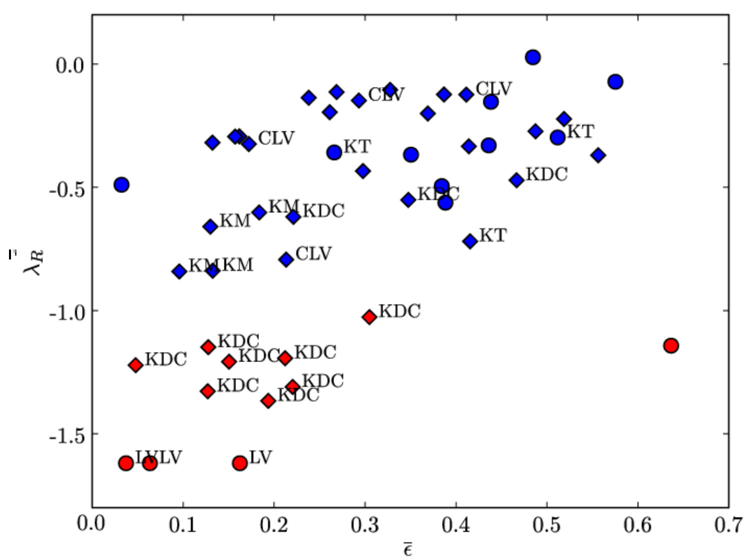
Fast rotators $\lambda>0.1$

Emsellem et al., 2007 – MNRAS 379, 401

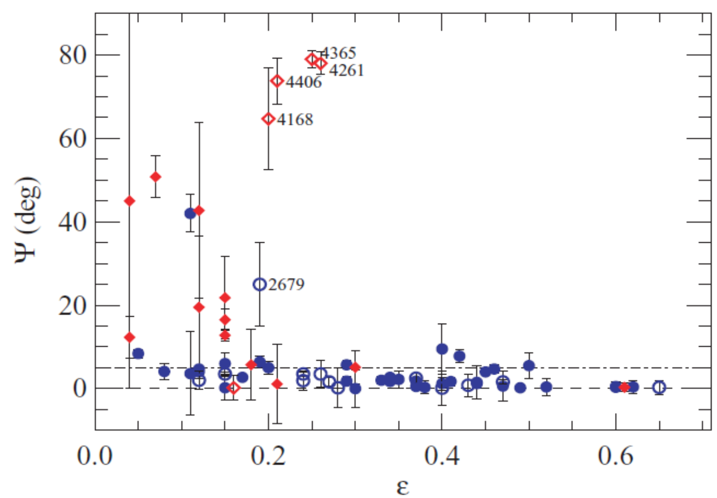
Two varieties of ETGs

$$\lambda_R = \langle RV \rangle / \langle R\sqrt{(V^2 + \sigma^2)} \rangle$$



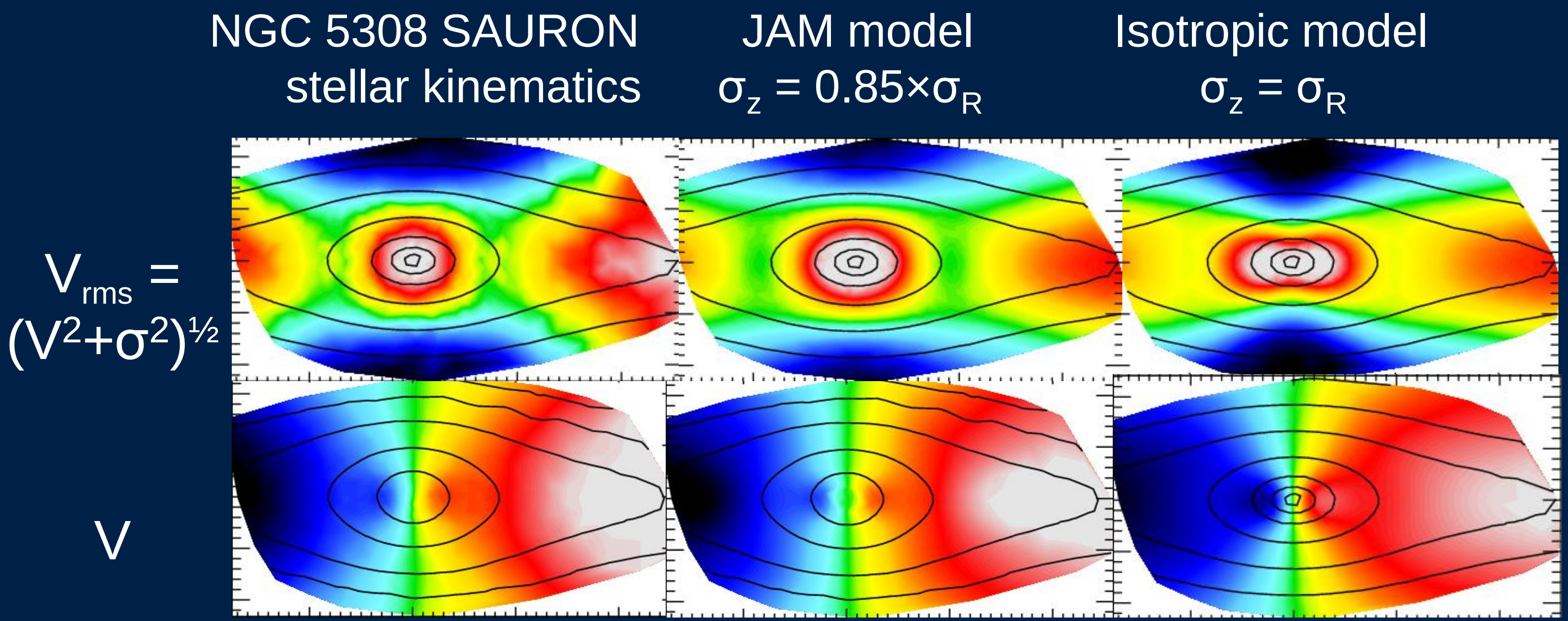


Slow rotators
Fast rotators



Slow rotators are closer to spherical, have elliptical isophotes, mis-aligned photometry and kinematics and frequently possess KDCs.
Faster rotators are flatter, have aligned kinematics & usually disky.

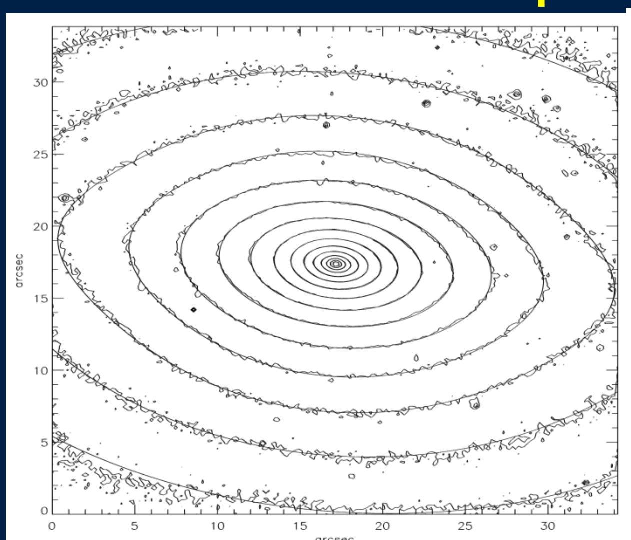
Jeans Anisotropic Models

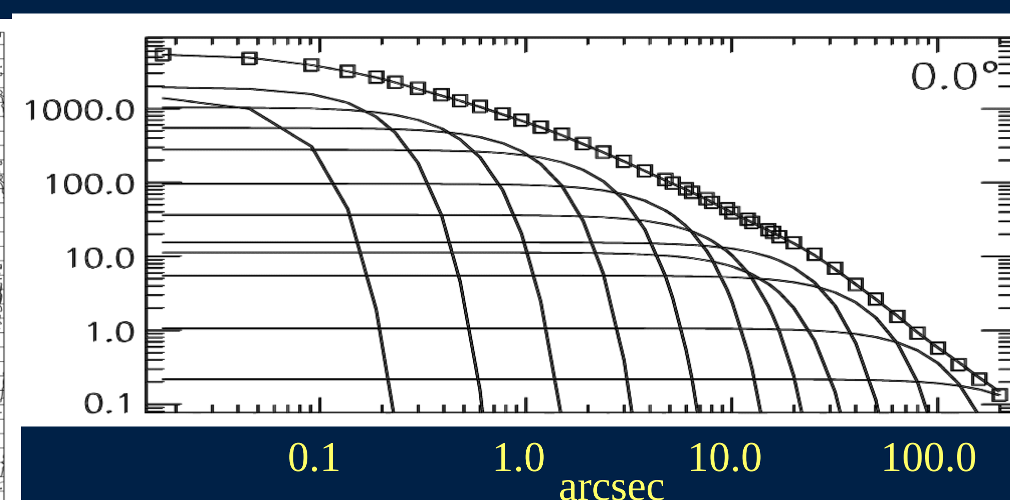


- 2-integral Jeans models have DF = f(E,L_z) → $\sigma_z = \sigma_R$
- But real axisymmetric ETGs galaxies have $\sigma_z < \sigma_R$
  (Cappellari et al 2007, Thomas et al 2009)
- We now allow for $\sigma_z \neq \sigma_R$ → DF = f(E,L_z,I_3) (Cappellari 2008)
- Just two parameters (i, σ_z/σ_R) fit shape of both V_{rms} and V
  (http://purl.org/cappellari/idl)

Jeans anisotropic models : M/L, i & anisotropy

- Multi-Gaussian representation of the projected 2-D light distribution (HST+ground).
- Assume light traces mass + BH (Ferrerese & Ford 2005) ⇒ total potential.
- Best fit model gives: M/L, inclination & anisotropy from SAURON maps



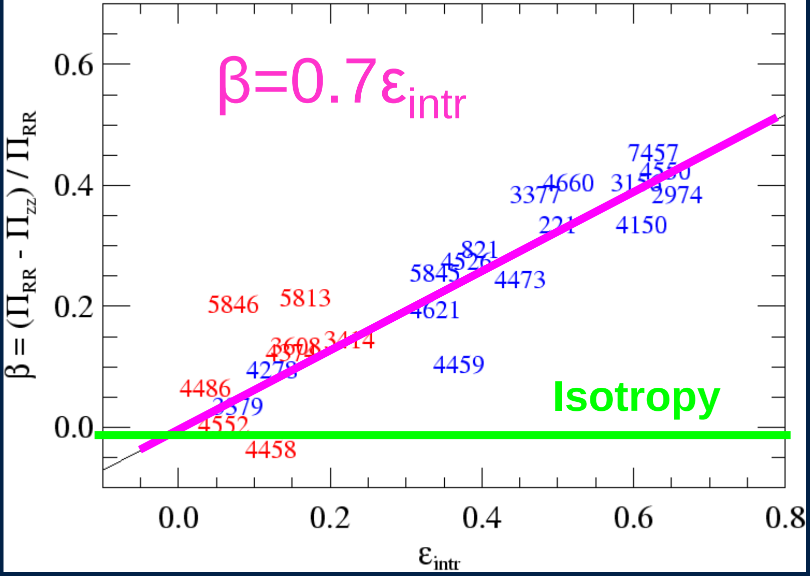


Revisiting the V/σ diagram

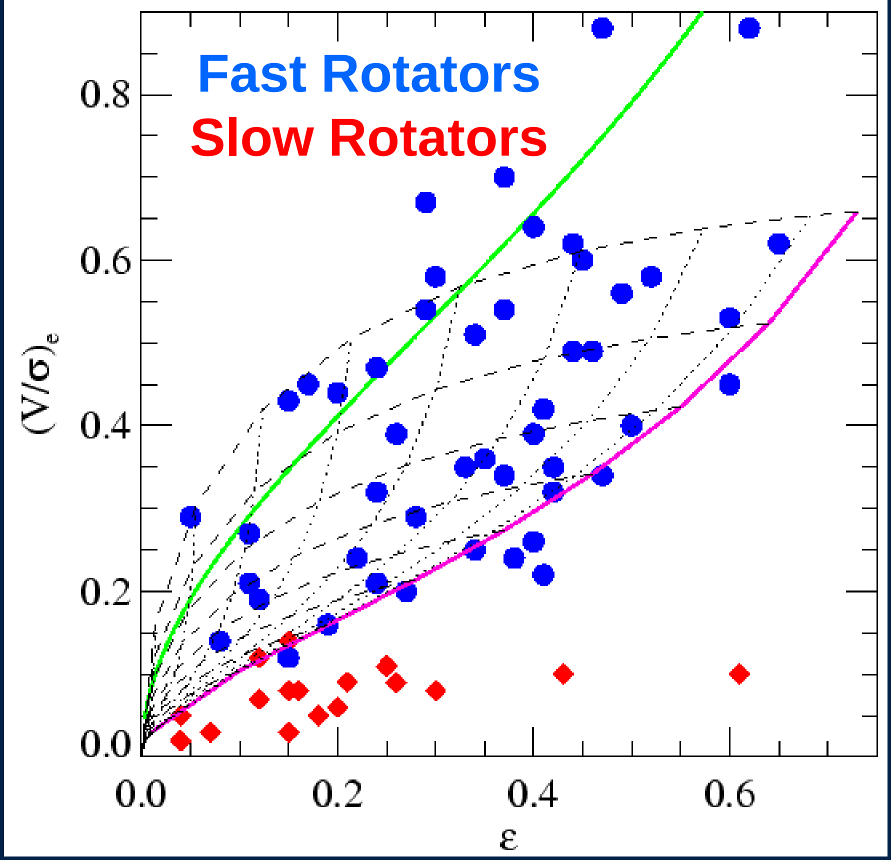
$$(V/\sigma)_e^2 \equiv \frac{\langle V^2 \rangle}{\langle \sigma^2 \rangle}$$

Use new formalism for integral-field kinematics
Binney 2005

anisotropy



Anisotropy trend from 25 Models
Cappellari et al., 2007



Fast-rotators: family of oblate systems

Slow-rotators: distinct - likely triaxial

Conclusions: 2

Fast rotators (36) : flattened, light & kinematics aligned ⇒ probably oblate, radially anisotropic, young central disks or rings, flattened high metallicity component.

Slow rotators (12) : close to spherical (isophotes almost perfect ellipses), often have large misalignments between light & kinematics ⇒ signature of triaxiality,
close to isotropic, host large, old, KDCs.

Hypothesis: Fast & slow rotating ETGs are physically distinct, they are the end products of different evolutionary paths

Towards a new paradigm: 2

The Team

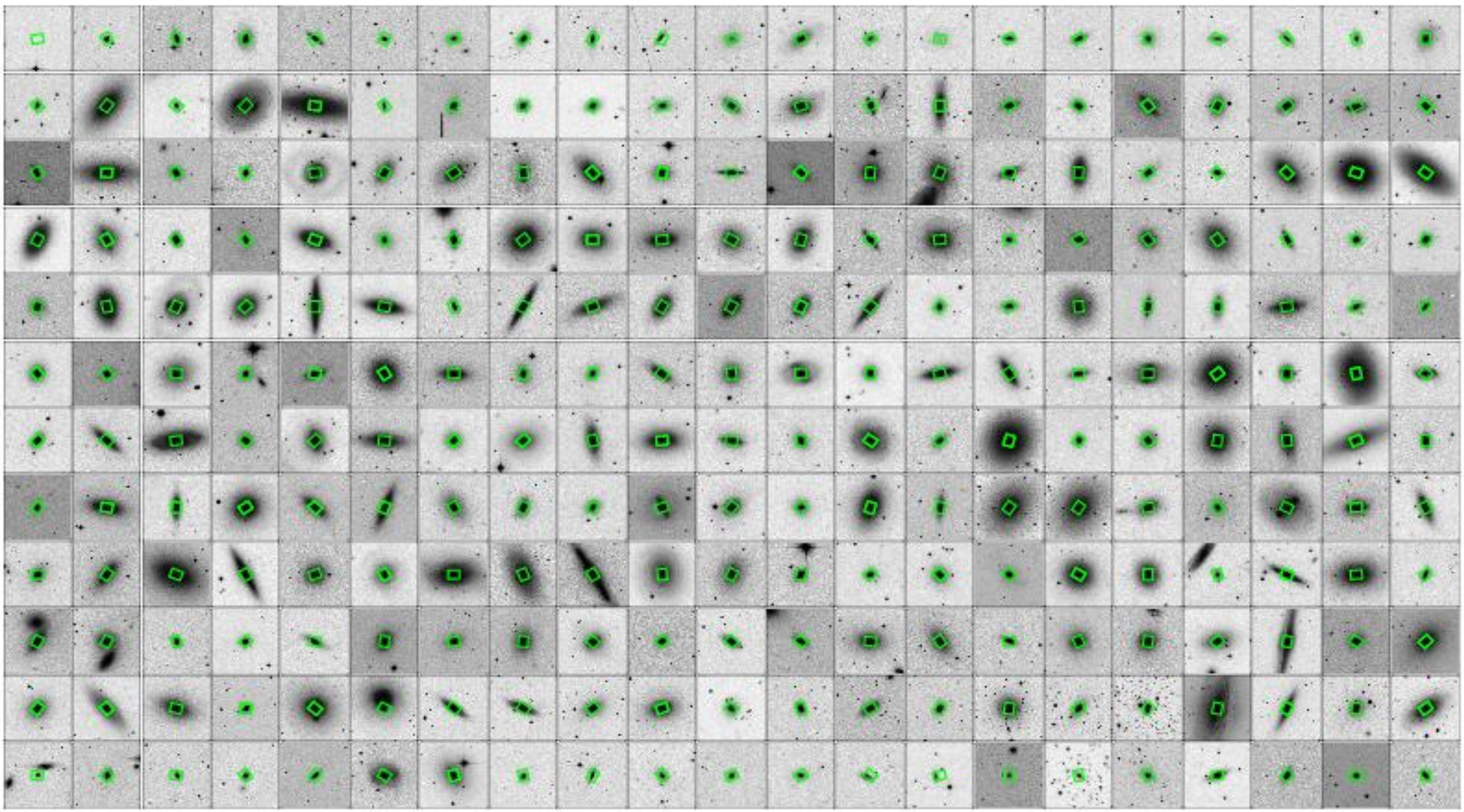
PIs: Michele Cappellari (Oxford), Eric Emsellem (ESO), Davor Krajnović (ESO), Richard McDermid (Gemini)

CoIs / Students:

(France, Germany, Spain, The Netherlands, UK, USA)

Kathey Alatalo, Roland Bacon, Leo Blitz, Maxime Bois, Frederic Bournaud, Martin Bureau, Roger Davies, Tim de Zeeuw, Jesus Falcon-Barroso, Sadegh Khochfar, Harald Kuntschner, Raffaella Morganti, Thorsten Naab, Tom Oosterloo, Marc Sarzi, Nicholas Scott, Paolo Serra, Remco van den Bosch, Glenn van de Ven, Gijs Verdoes-Kleijn, Lisa Young, Anne-Marie Weijmans

The ATLAS^{3D} Team



Multi-wavelength approach

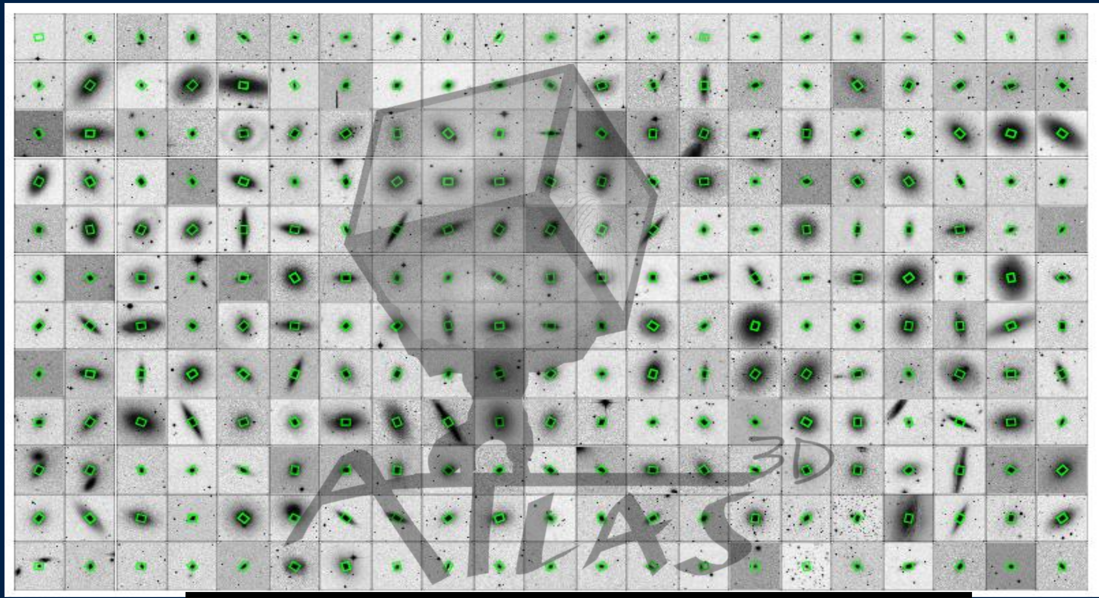
- ***Optical integral-field:*** Large Program with SAURON@WHT
  - 38 nights over 3 semesters (4 runs)
- ***Single-dish CO:*** survey of full sample (IRAM 30m)
  - 209 new galaxies (+ literature)
- ***CO interferometry*** of detections with CARMA
- ***HI survey:*** 171 galaxies ($\delta>10^{\circ}$) with WSRT (excl. Virgo)
  - 12h per galaxy (+44 galaxies from ALFALFA survey)
- ***Photometry:*** multi-bands (INT, 2MASS, SDSS)
- ***Archival*** data (Chandra, XMM, GALEX, HST, Spitzer)

ATLAS^{3D}

➔ **a complete volume-limited sample of ETGs**

2MASS extended source catalog Jarrett et al 2000:

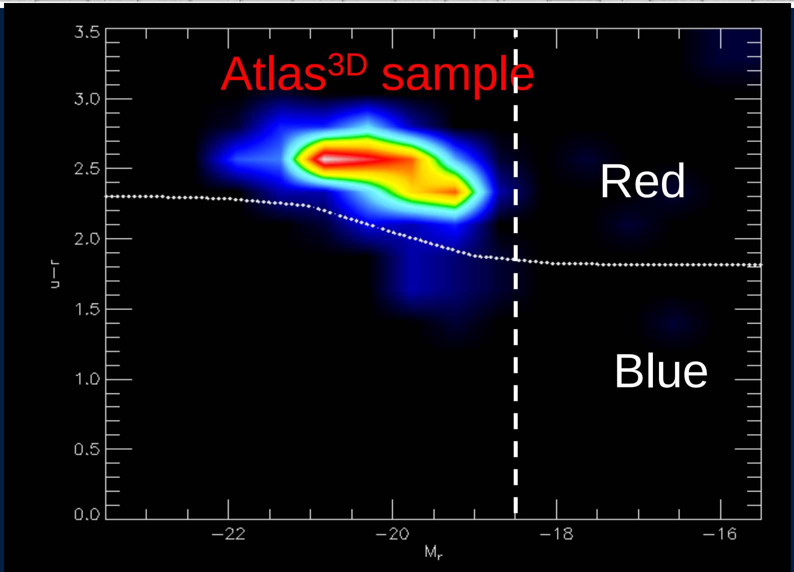
- $M_K < -21.5$
- $D < 41$ Mpc
- $|\delta - 29| < 35^o$
- $|b| > 15^o$
- 871 galaxies



Subset of E / S0s

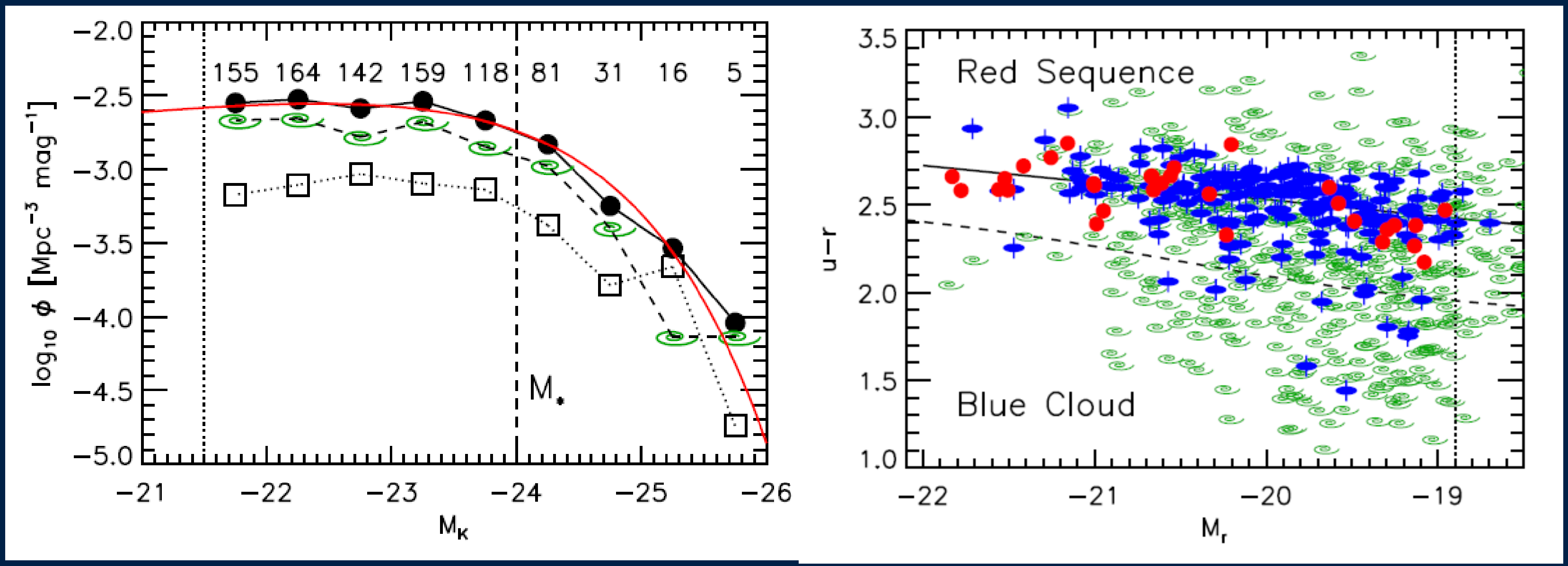
"No spiral structure" (SDSS/DSS2)

➔ 260 galaxies



Luminosity Function & CMD

Cappellari et al 2011

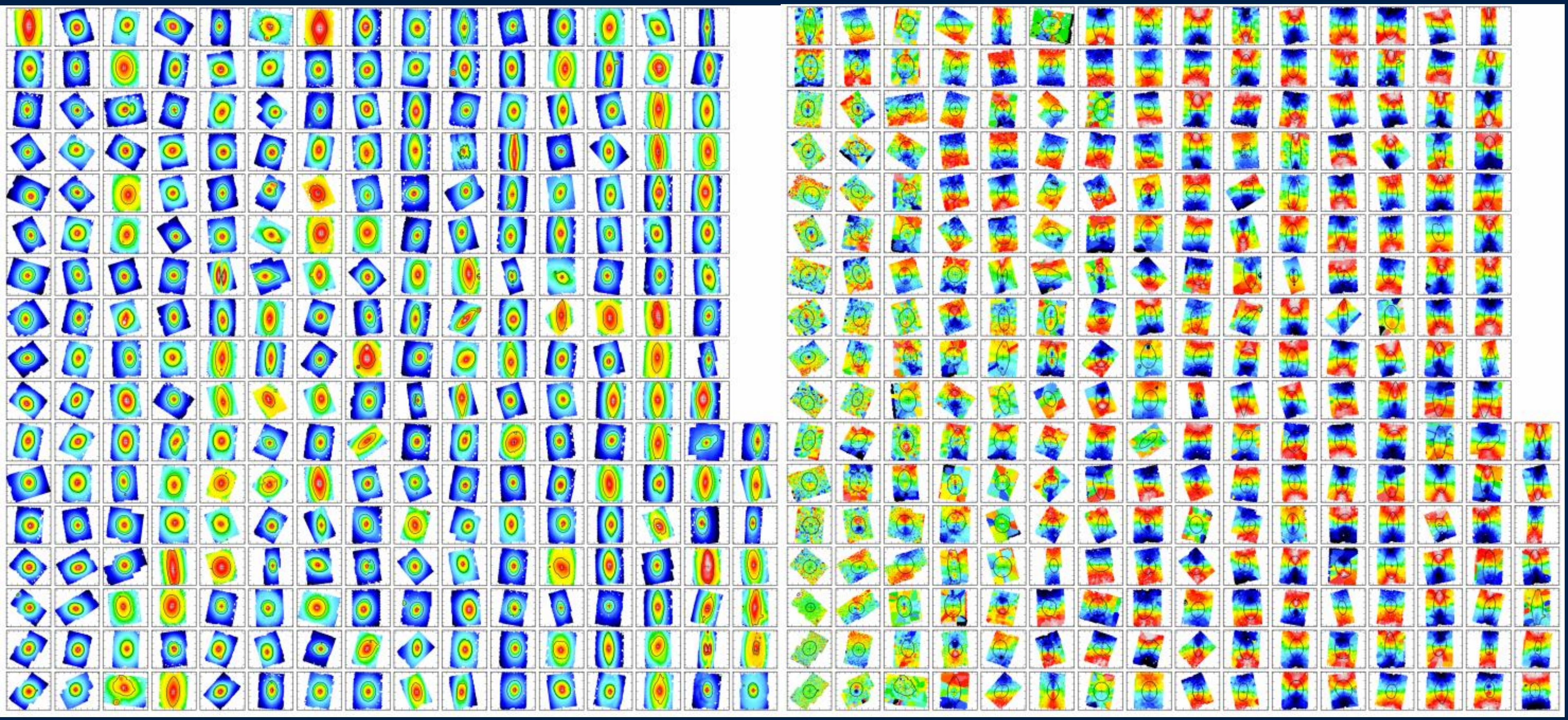


Compare with LF Bell et al. (2003); On red sequence of Baldry et al. (2004)

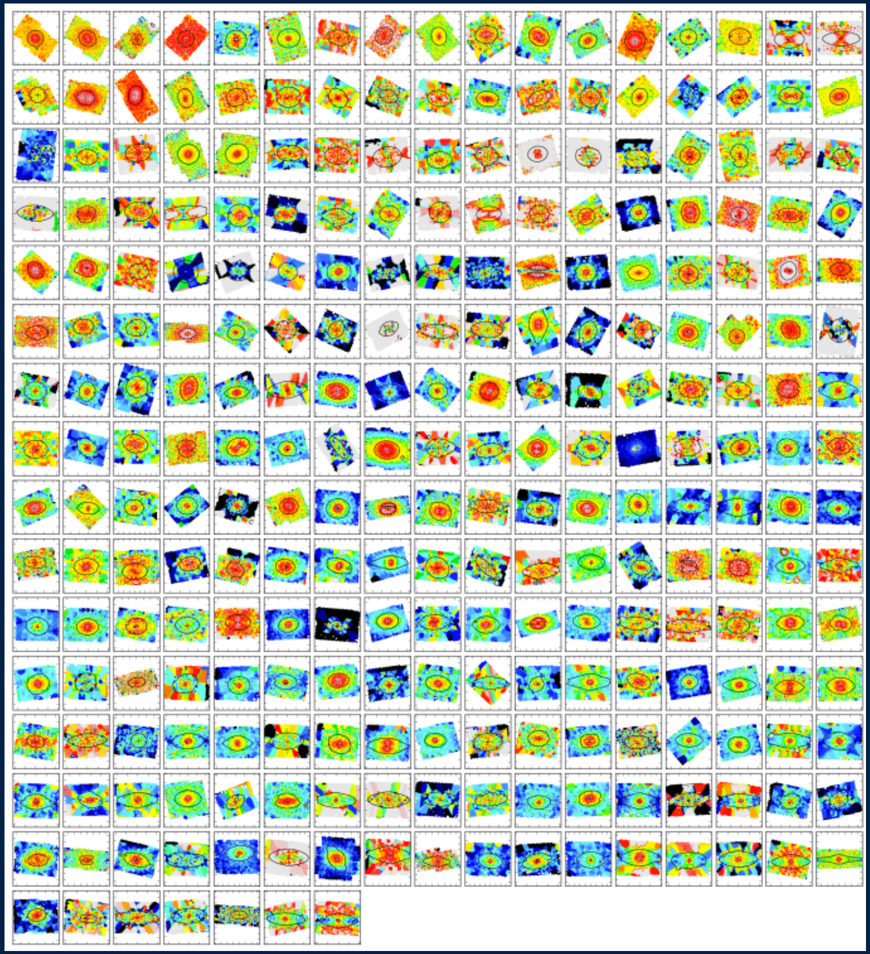
- LF representative of local universe
- Atlas^{3D} ETGs galaxies mostly on red sequence

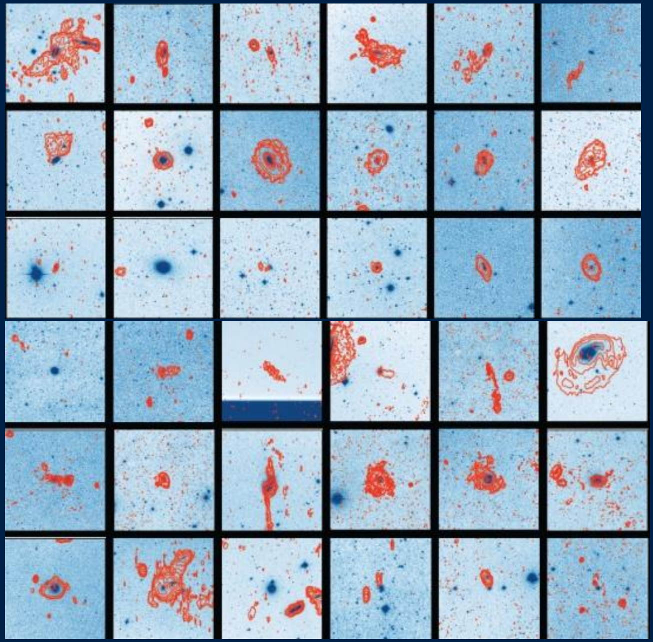
(as in Strateva et al. 2001; Conselice 2006; van den Bergh 2007)

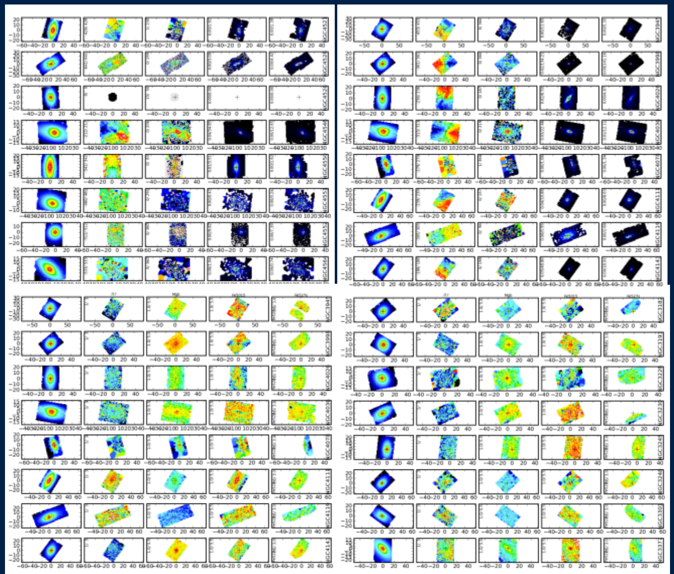
A few spectra and maps…



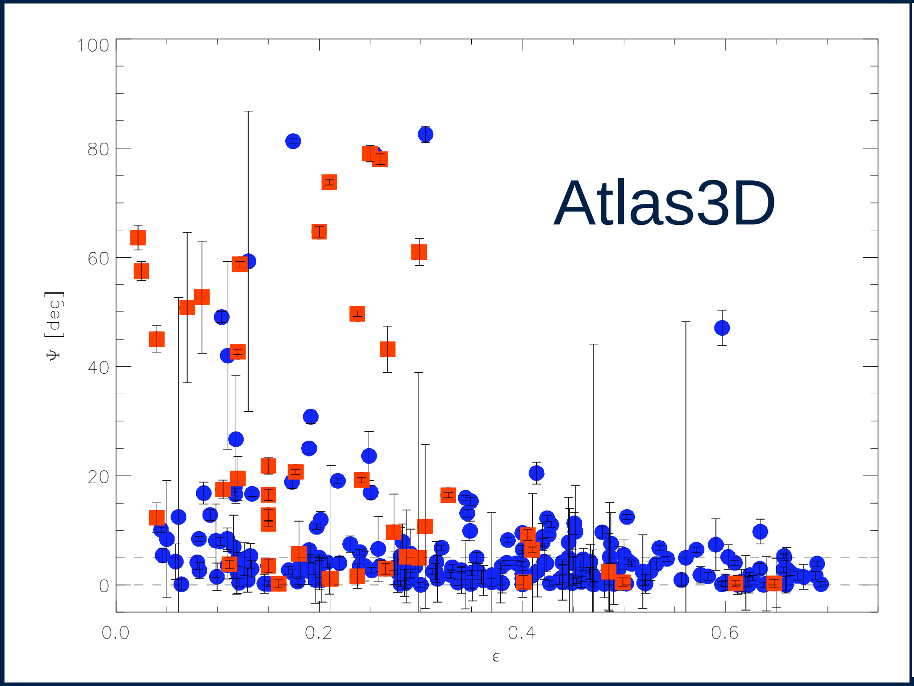
A few spectra and maps…

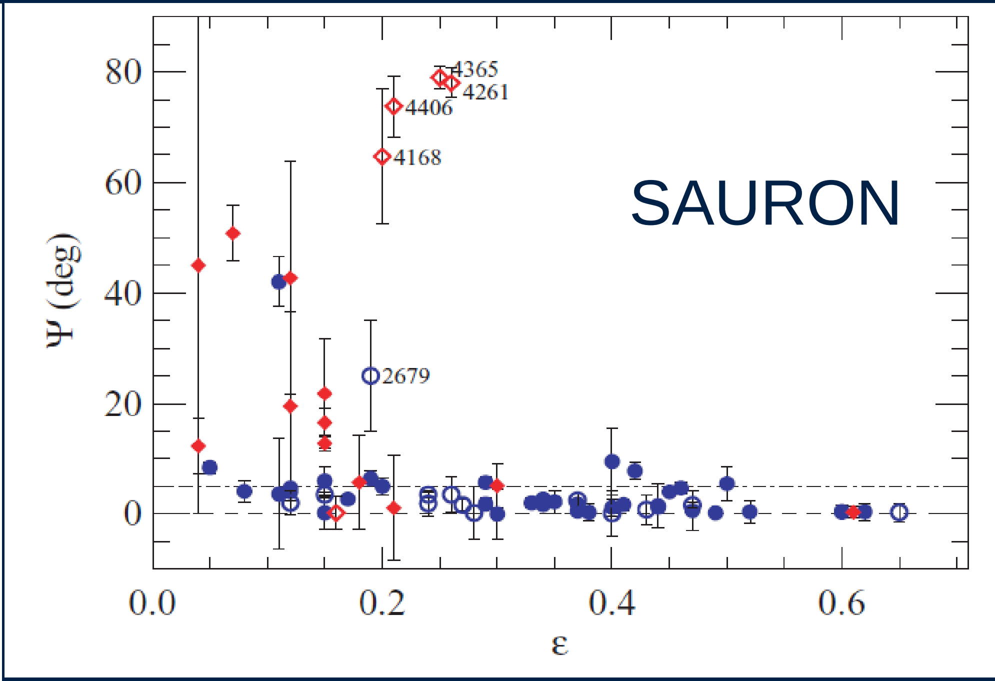






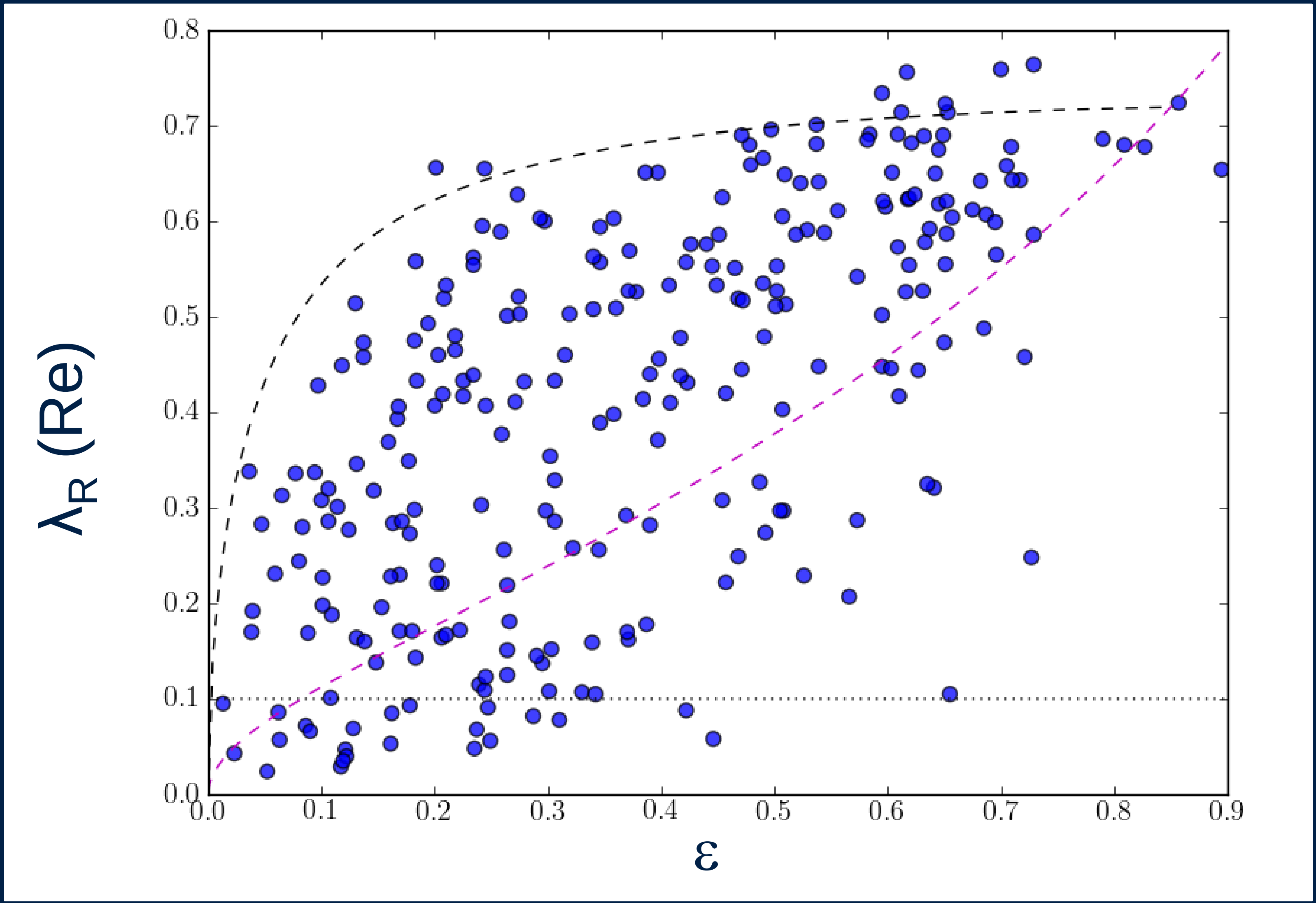
Mis-alignment





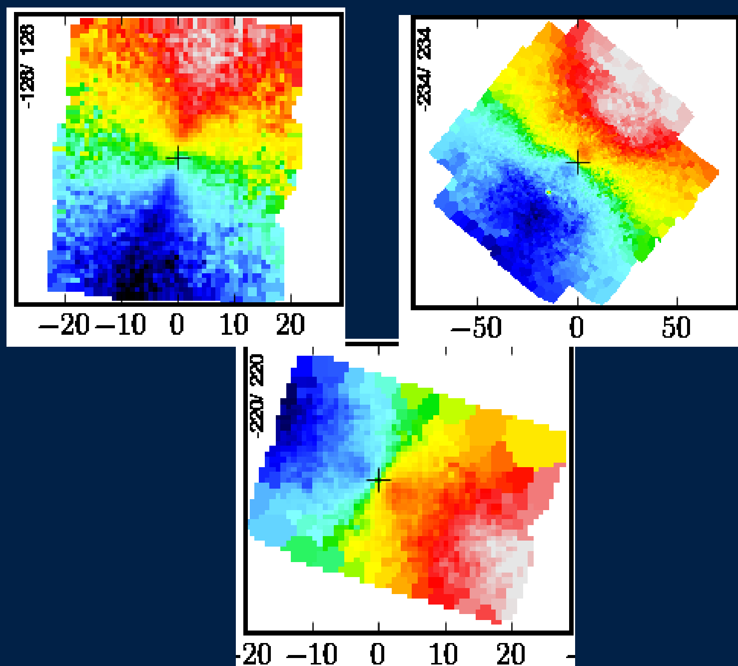
- In fast rotators the light and kinematics are generally aligned. but beware bars.
- Slow rotators are intrinsically rounder and extend to larger mis-alignments. Some aligned flattened slow rotators are co-extensive counter-rotating disks.

λ_R vs ε

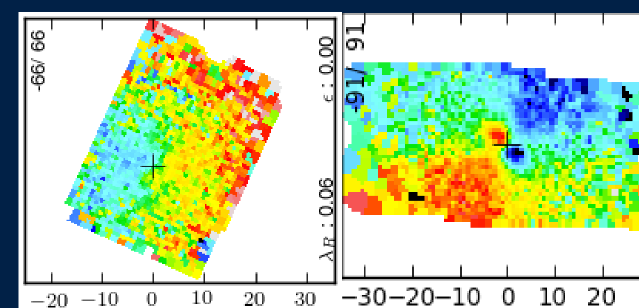


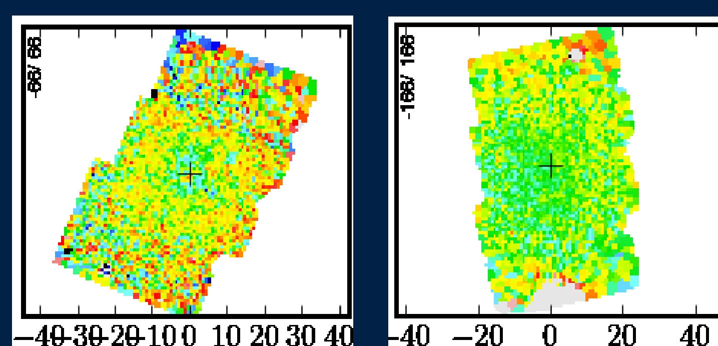
Rotation fields: Krajnović et al., 2011

Regular Rotators

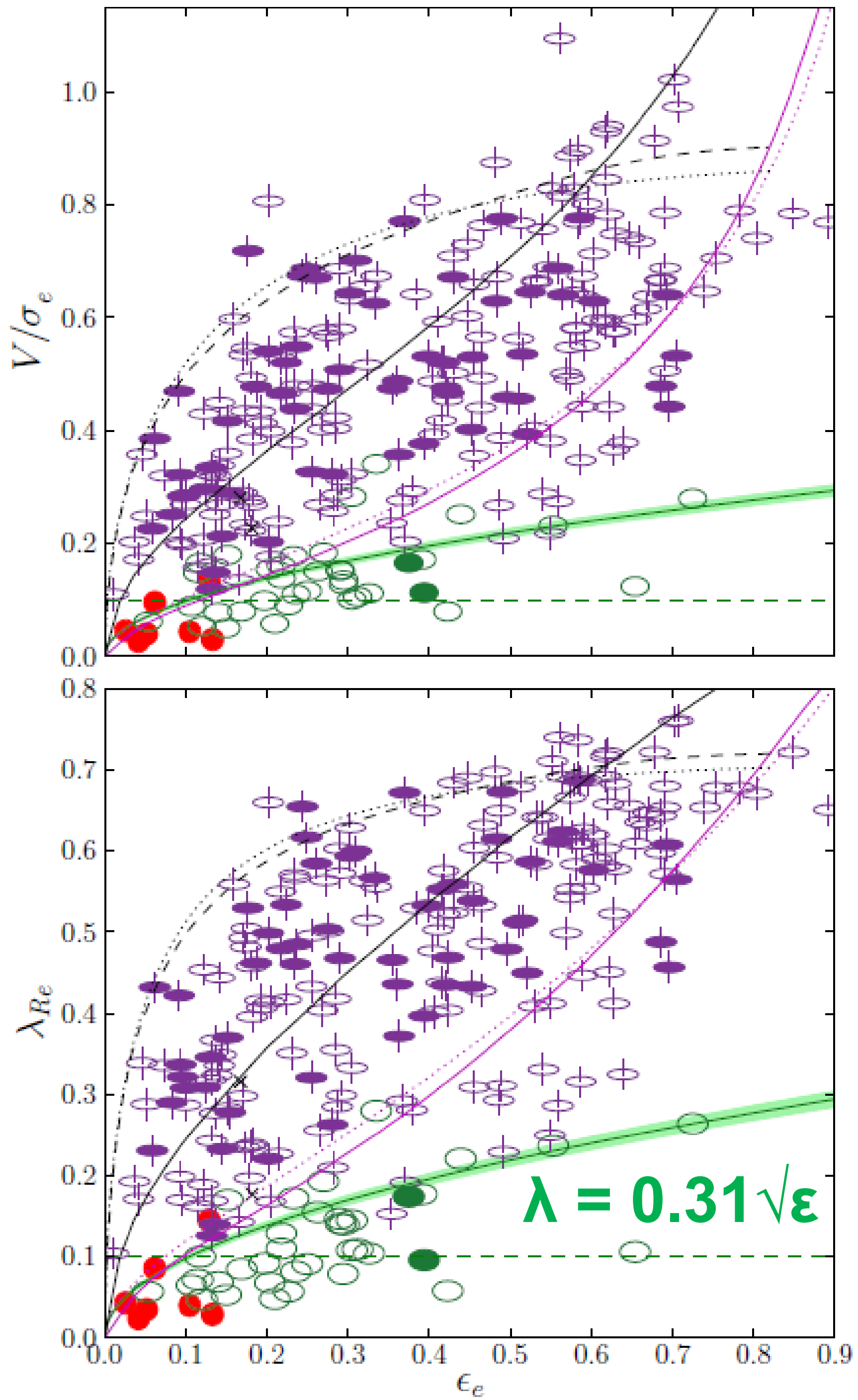


Non regular rotators





Non-rotators



Re-visit v/σ vs ε & λ vs ε

Non rotators

Non regular rotators

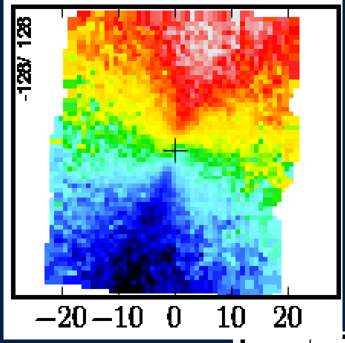
Regular Rotators

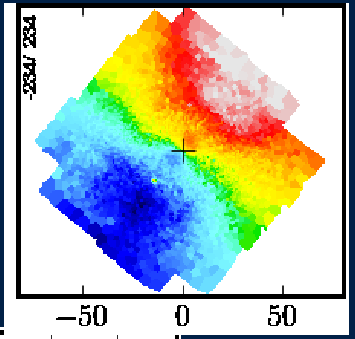
Filled symbols have bars

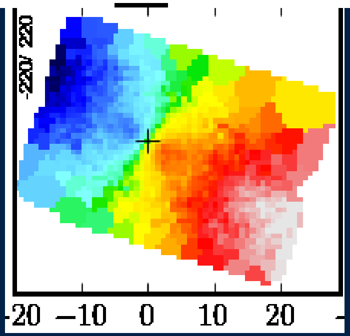
Emsellem et al., 2011

Rotation fields

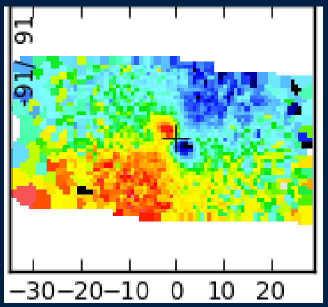
Disk-like Rotators



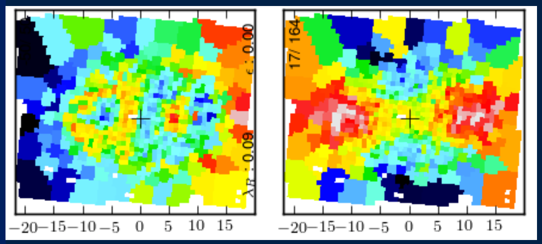


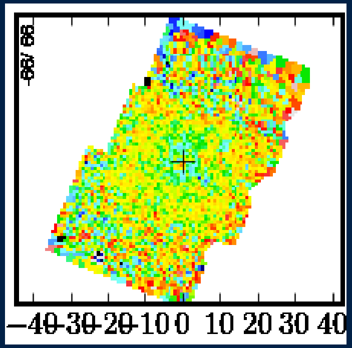


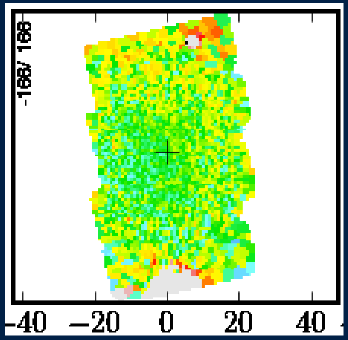
KDCs



2-σ



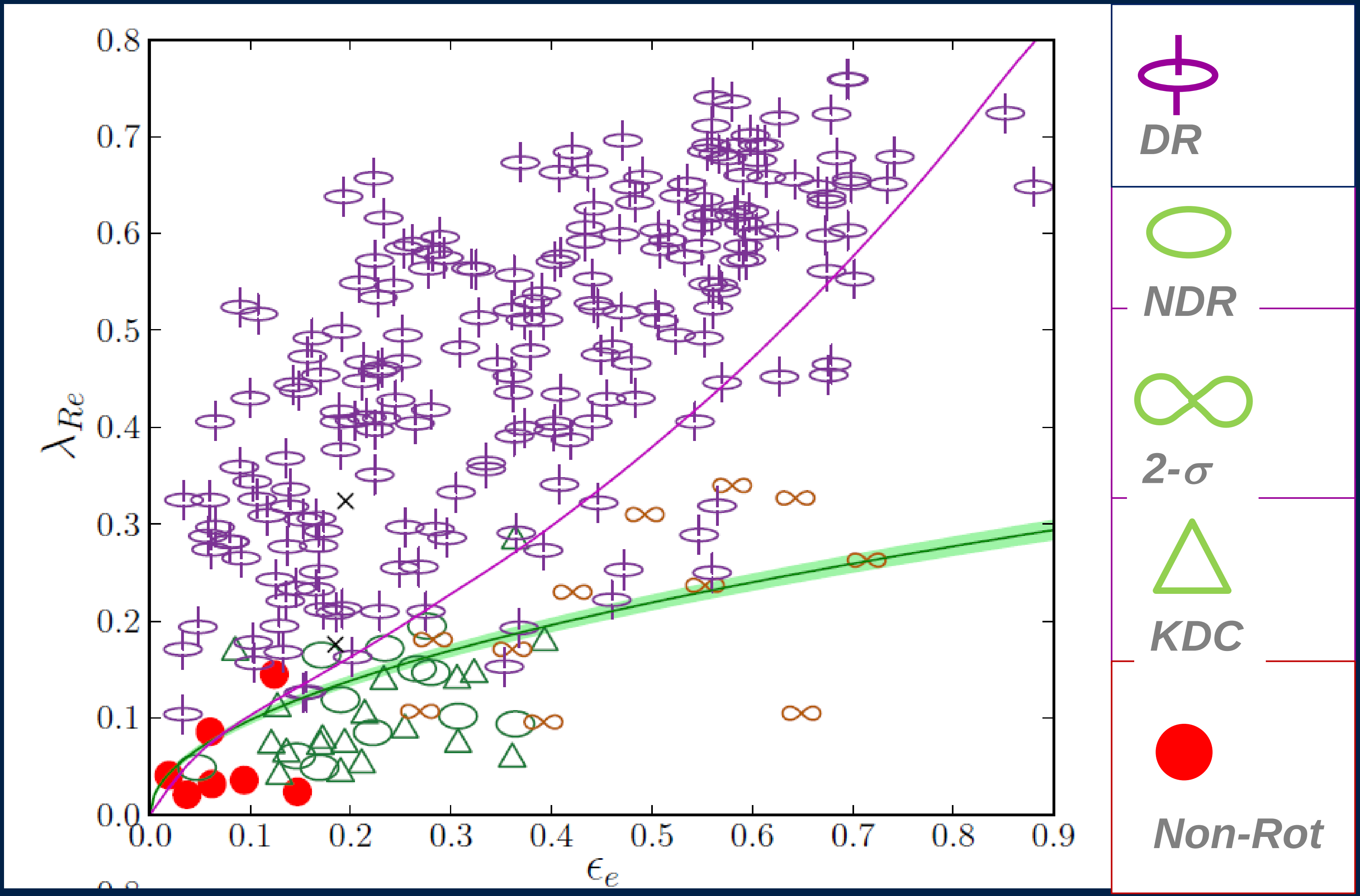




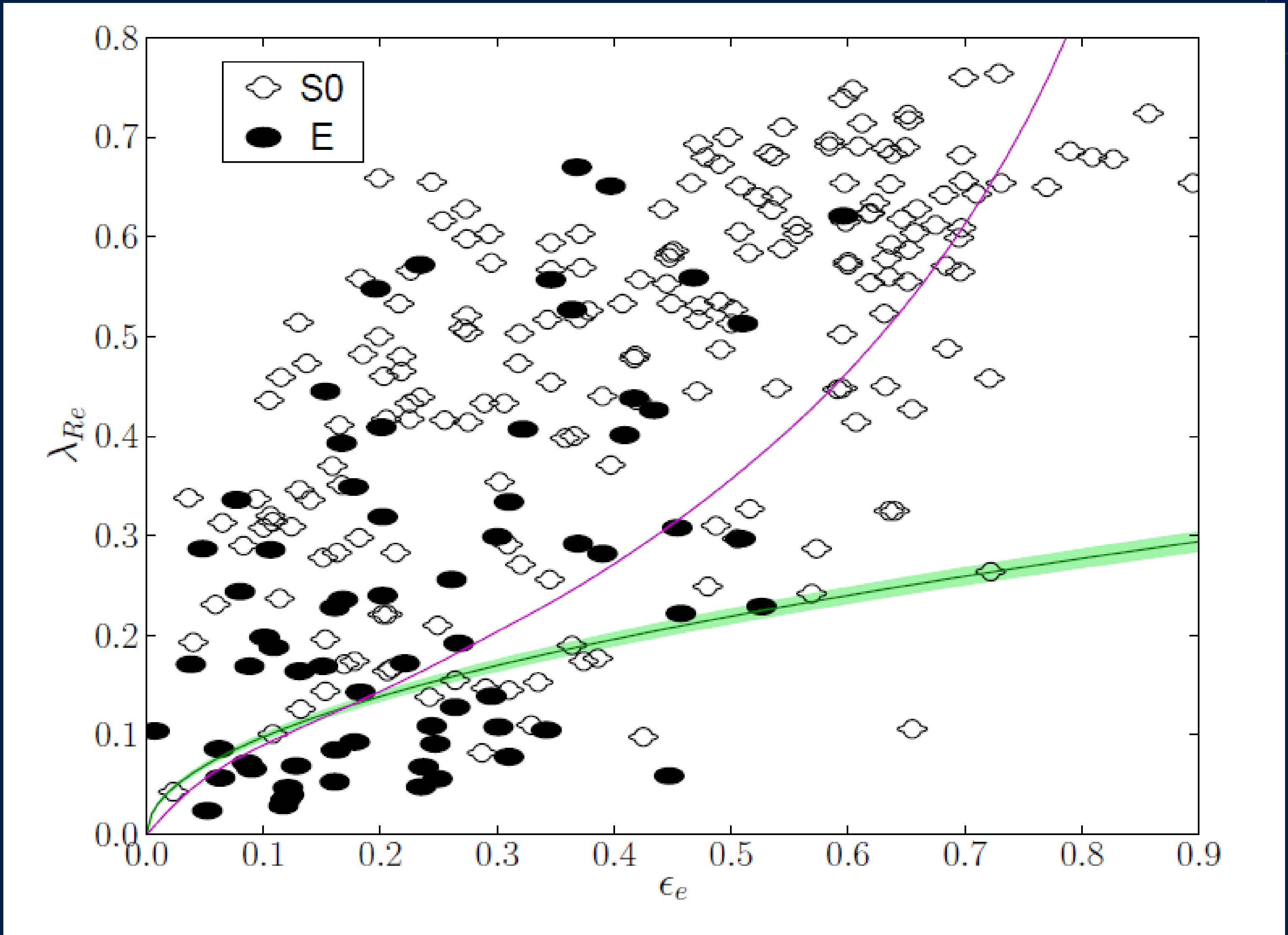
Non-rotators

Krajnović et al., 2011
Emsellem et al., 2011

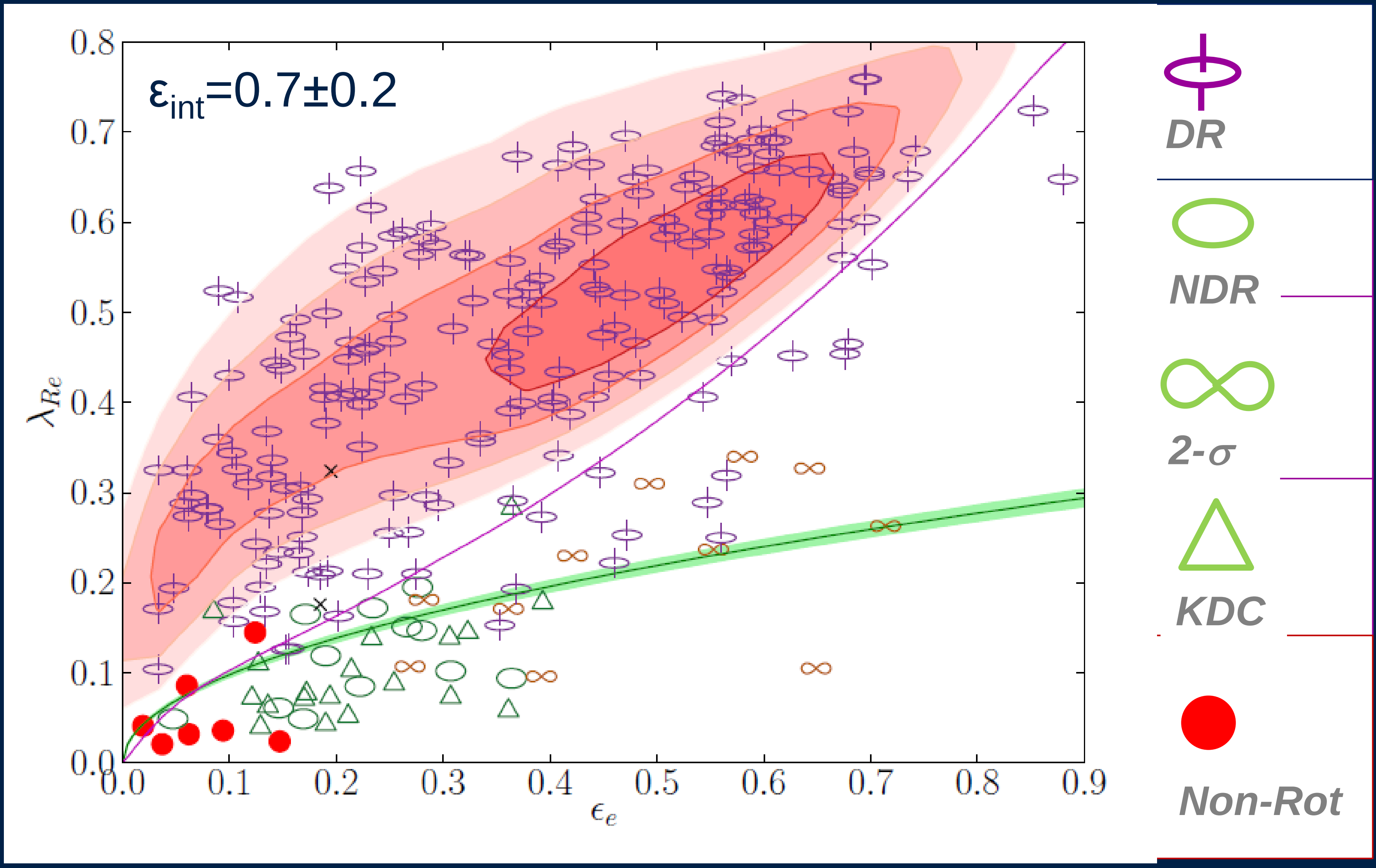
Key with rotation field morphology



and by Hubble type



Compare rotators with expected distribution of disk galaxies



Census of ATLAS^{3D}

871 galaxies in the parent sample of which:
611 are spirals &
260 are ETGs (68 Es & 192 S0s) of which
224 are fast rotators – oblate

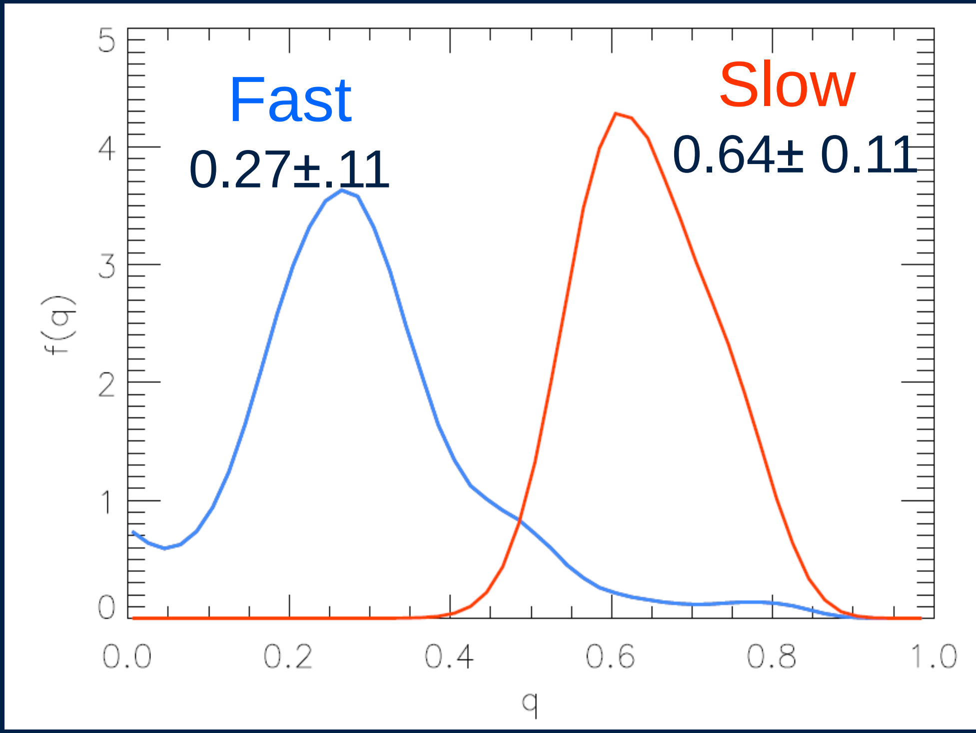
of the 36 slow rotators 4 have counter-rotating disks
leaving 32 true slowly rotating `ellipticals'
ie. <4% of the parent (volume limited) population

Intrinsic shapes

Selection:
All fast rotators with ε from large radius (~ 3Re) to avoid the influence of bars.
Slow rotators do not include co-extensive, counter-rotating disks. ε at 1Re.

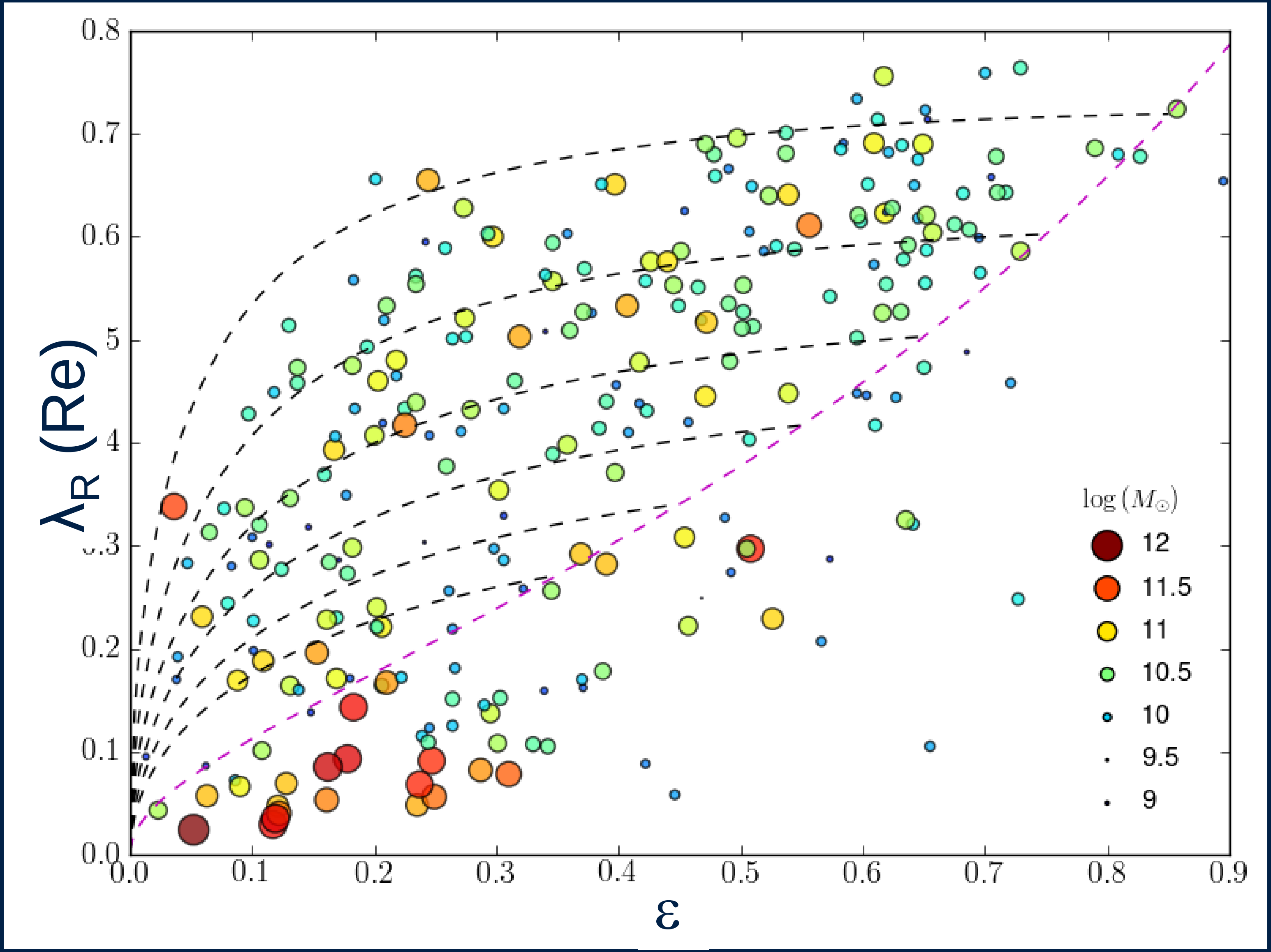
Method : Invert observed distribution assuming oblate figures & using Lucy iteration.

Weijmans et al 2011



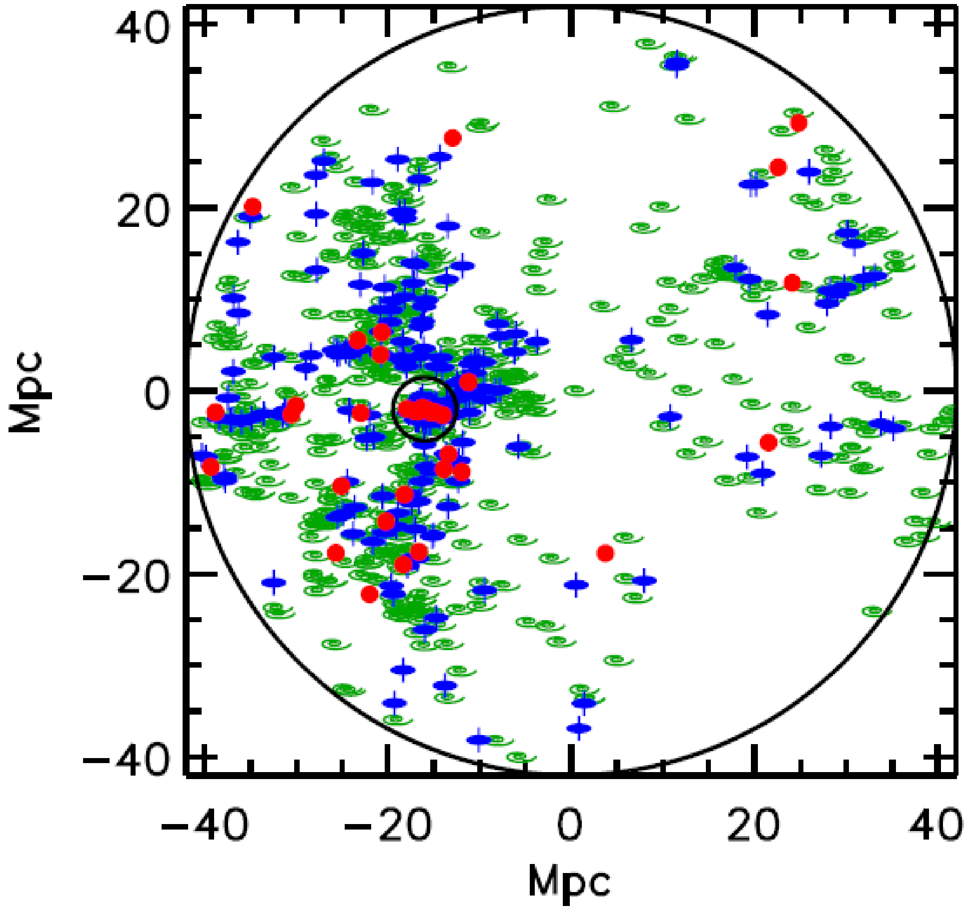
Fast & Slow rotators have distinct distributions of intrinsic shapes

Trend with Mass



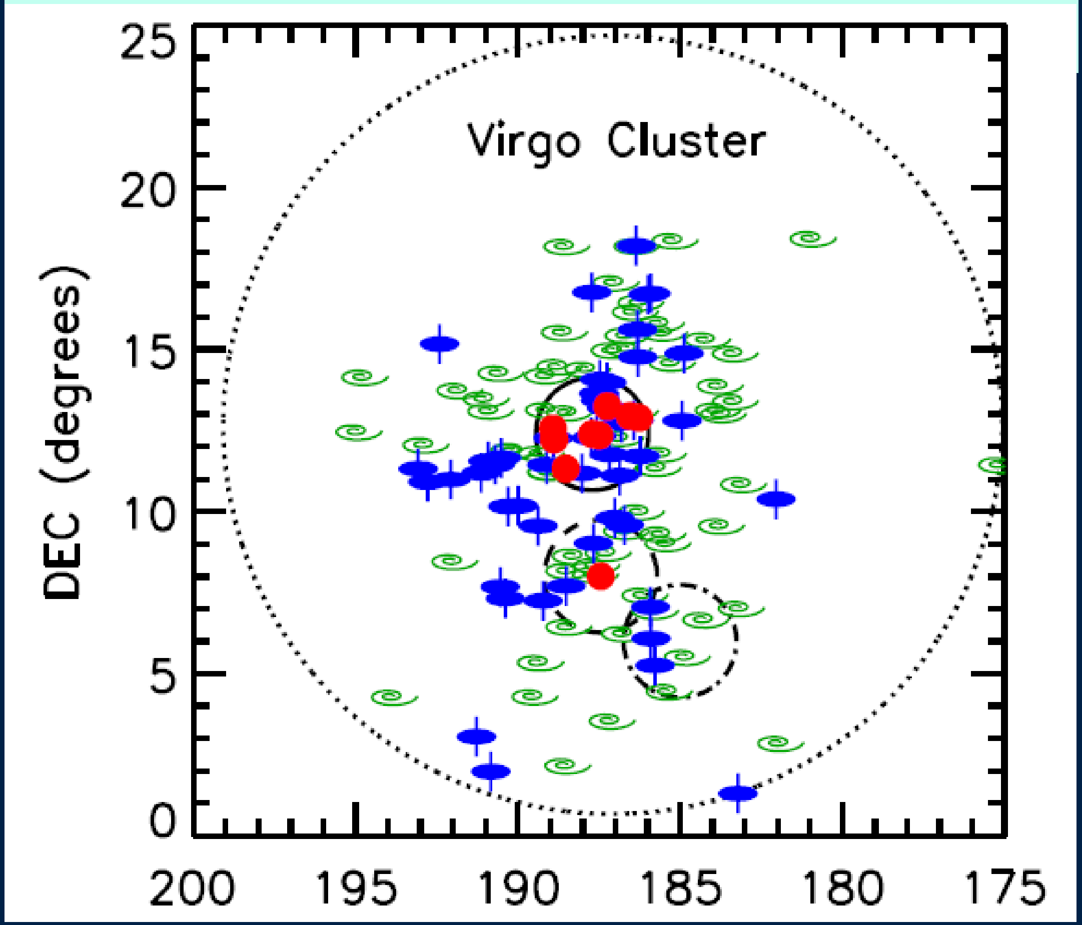
Morphology-density relation

Complete volume

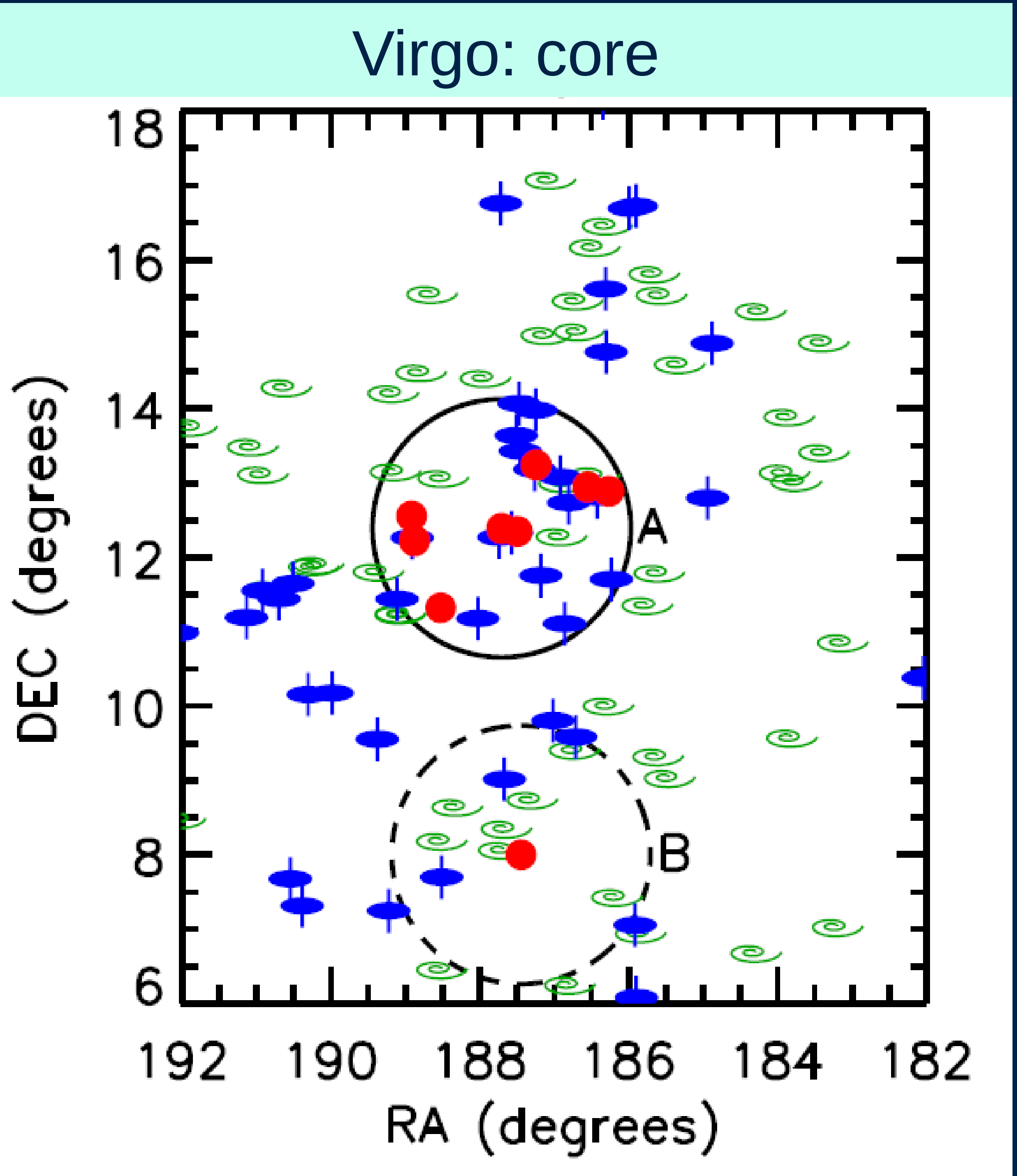


Morphology-density relation

Virgo: R < 12º



Morphology-density relation



Morphology-density relation

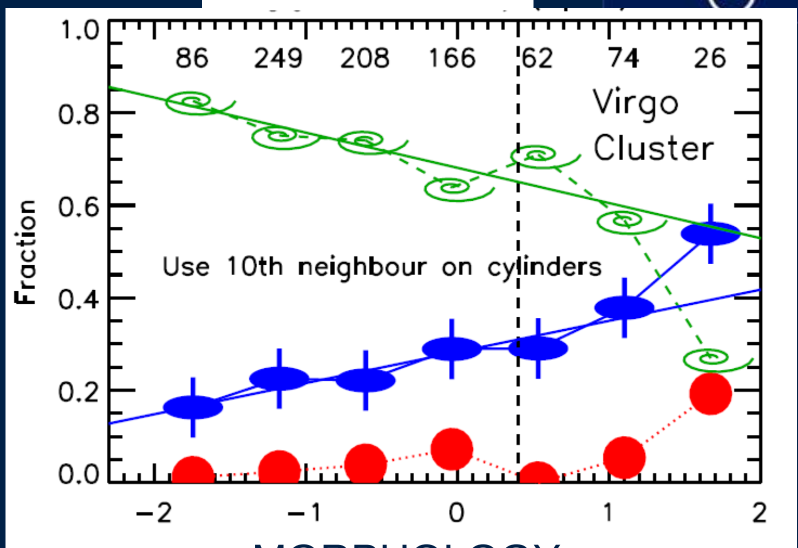
Slow rotators constitute 4% of the population overall.

Only in the core of Virgo does this raise to 20%.

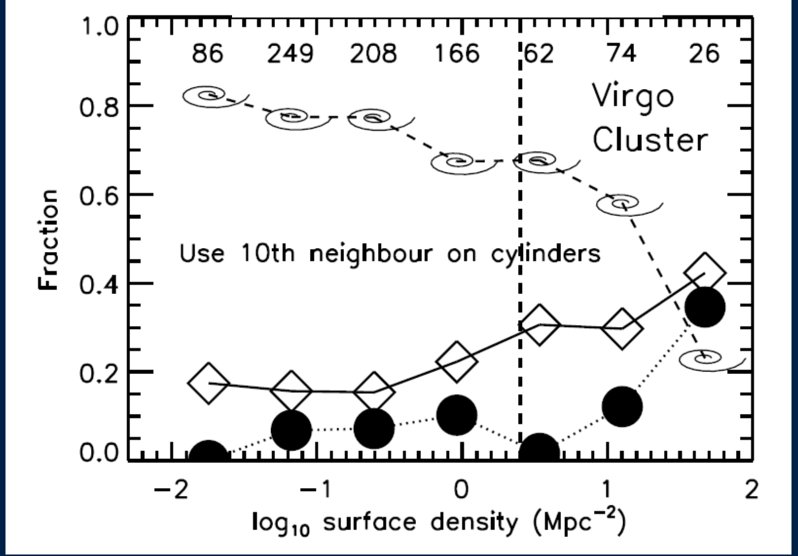
There is a mechanism converting Sp → S0's working at all densities.

A separate, efficient mechanism forms slow rotators in the core of the Virgo cluster.

KINEMATICS

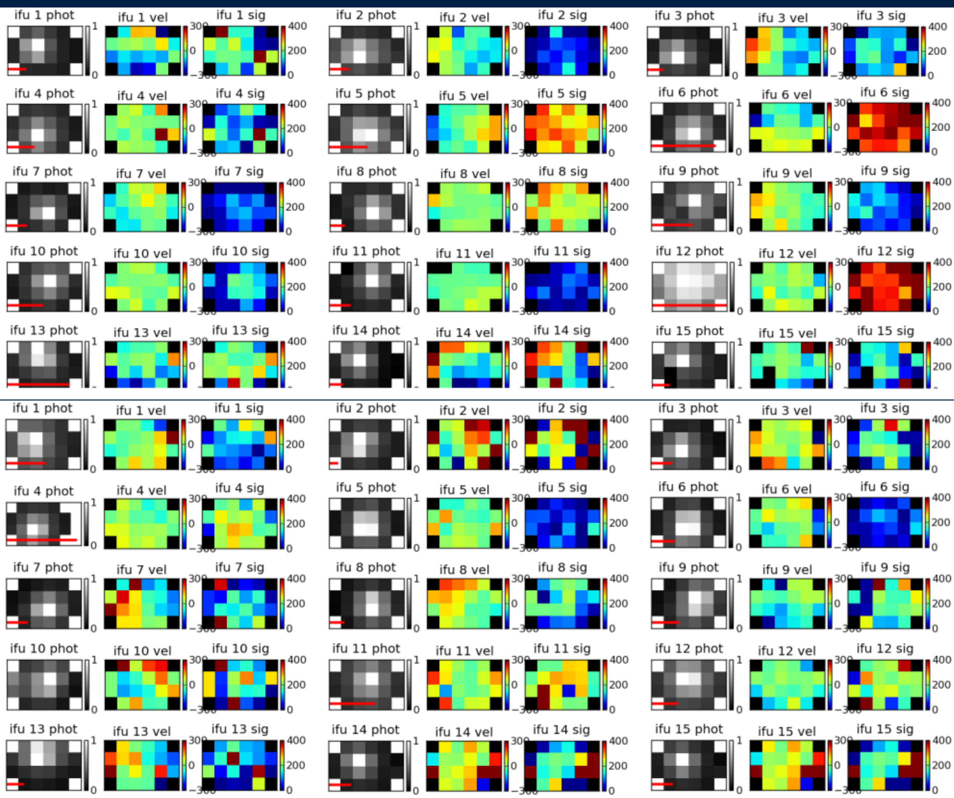


MORPHOLOGY



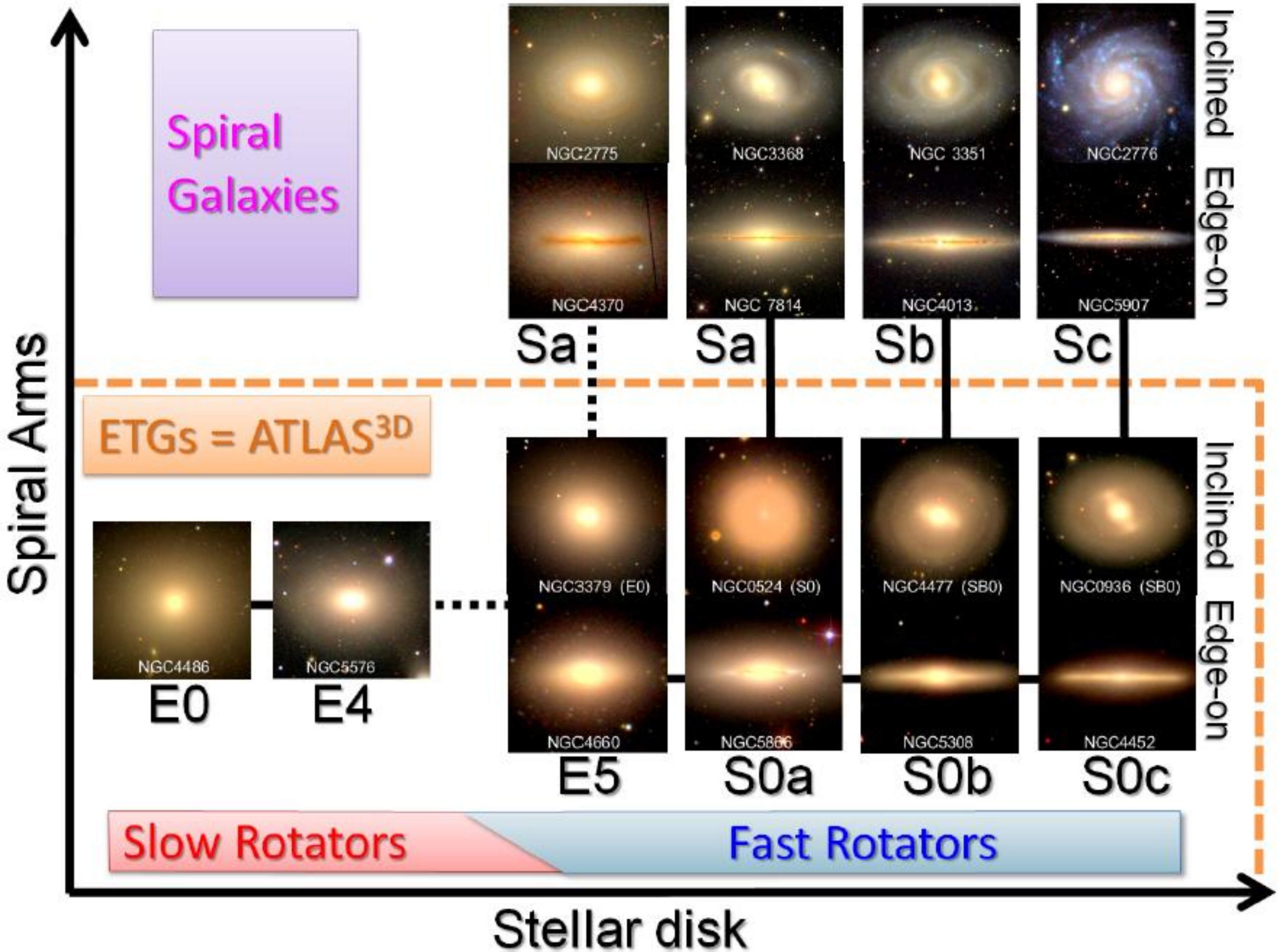
Dense environments

Do the same experiment in Coma & Abell 1689 using SWIFT & FLAMES.

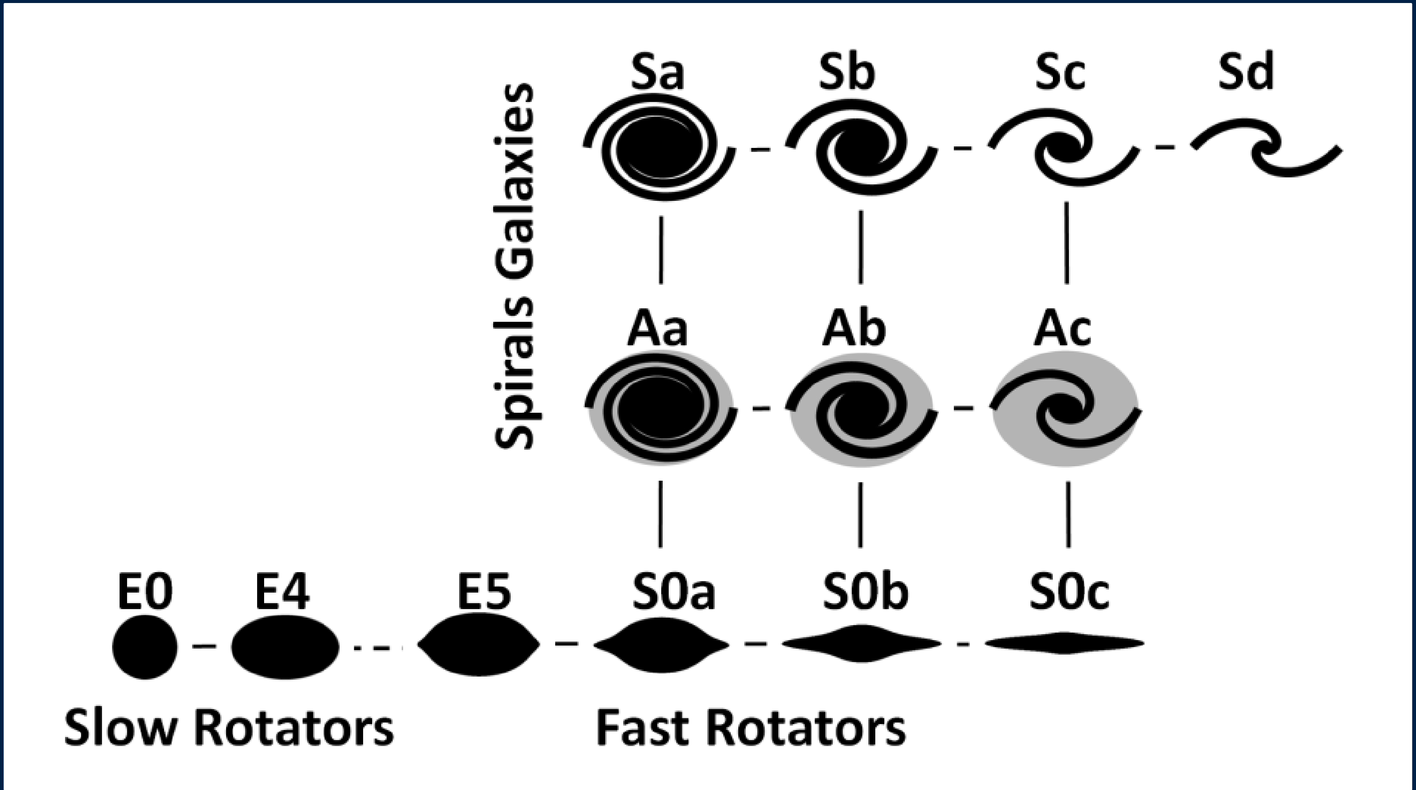


RLD + Francisco d'Eugenio, Nic Scott,
Ryan Houghton & Elena dalla Bonta

So what does this mean?


Spiral Galaxies
ETGs = ATLAS3D
Spiral Arms
Stellar disk
NGC2775
NGC3368
NGC 3351
NGC2776
NGC4370
NGC 7814
NGC4013
NGC5907
Sa
Sa
Sb
Sc
Inclined
Edge-on
NGC3379 (E0)
NGC0524 (S0)
NGC4477 (SB0)
NGC0936 (SB0)
NGC4486
NGC5576
NGC4660
NGC5866
NGC5308
NGC4452
E0
E4
E5
S0a
S0b
S0c
Inclined
Edge-on
Slow Rotators
Fast Rotators

A proposed new (partial) Hubble diagram



Recall : van den Bergh 1976, ApJ, 206, 883 and
van den Bergh 1990, ApJ, 348, 57

Conclusions: 3

- E/S0 separation does not capture the physical differences among ETGs and should be abandoned. Conclusions in papers that depend on making this distinction should be viewed sceptically.
- 86% of ETGs are disk-like with various amounts of star formation. These form parallel tracks in the Hubble diagram: S0, anaemic spiral & regular, each can be barred.
- 14% of ETGs have low angular momentum (predominantly, but not exclusively, the most massive). They are quiescent, triaxial & intrinsically rounder than E3.
- The rotators possibly evolved from z~2 hot disks, formed via cold streams + minor mergers (e.g. Förster-Schreiber)
- The slow rotators are likely formed though major mergers which we conclude are rare.

Thanks to the ING staff for their tremendous support