Towards a new paradigm for early-type galaxies

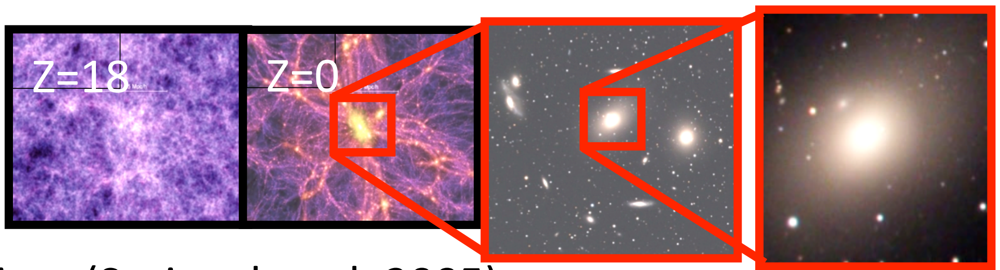
Harald Kuntschner

Heidelberg, 24 May 2011

Galaxy Formation and Evolution

- Galaxies form by hierarchical accretion/merging
  - Matter clumps through gravitation
  - Primordial gas starts forming first stars
  - Stars produce heavier elements ('metals')
  - Subsequent generations of stars contain more metals
  - Massive galaxies form from an assembly of smaller units

- Galaxy encounters still occur
  - Deformation, stripping, merging
  - Galaxies continue to evolve
- Central black hole also influences evolution



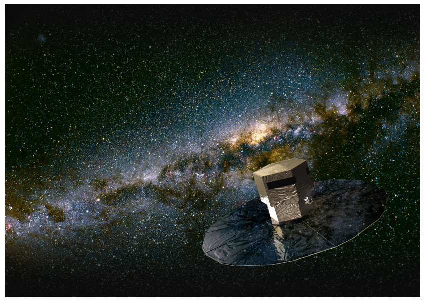
Millennium (Springel et al. 2005)

Observational Approaches

- Study (very) distant galaxies
  - Observe evolution (far away = long ago)
  - Objects faint and small: **little spatial information**

- Study nearby galaxies
  - Light not resolved in individual stars
  - Objects large and bright: **internal structure accessible**
  - Infer evolution through "**archaeology**"
  - **Fossil record** is cleanest in **early-type galaxies**

- Study resolved stellar populations
  - Ages, metallicities and motions of stars
  - Archaeology of Milky Way and its neighbours

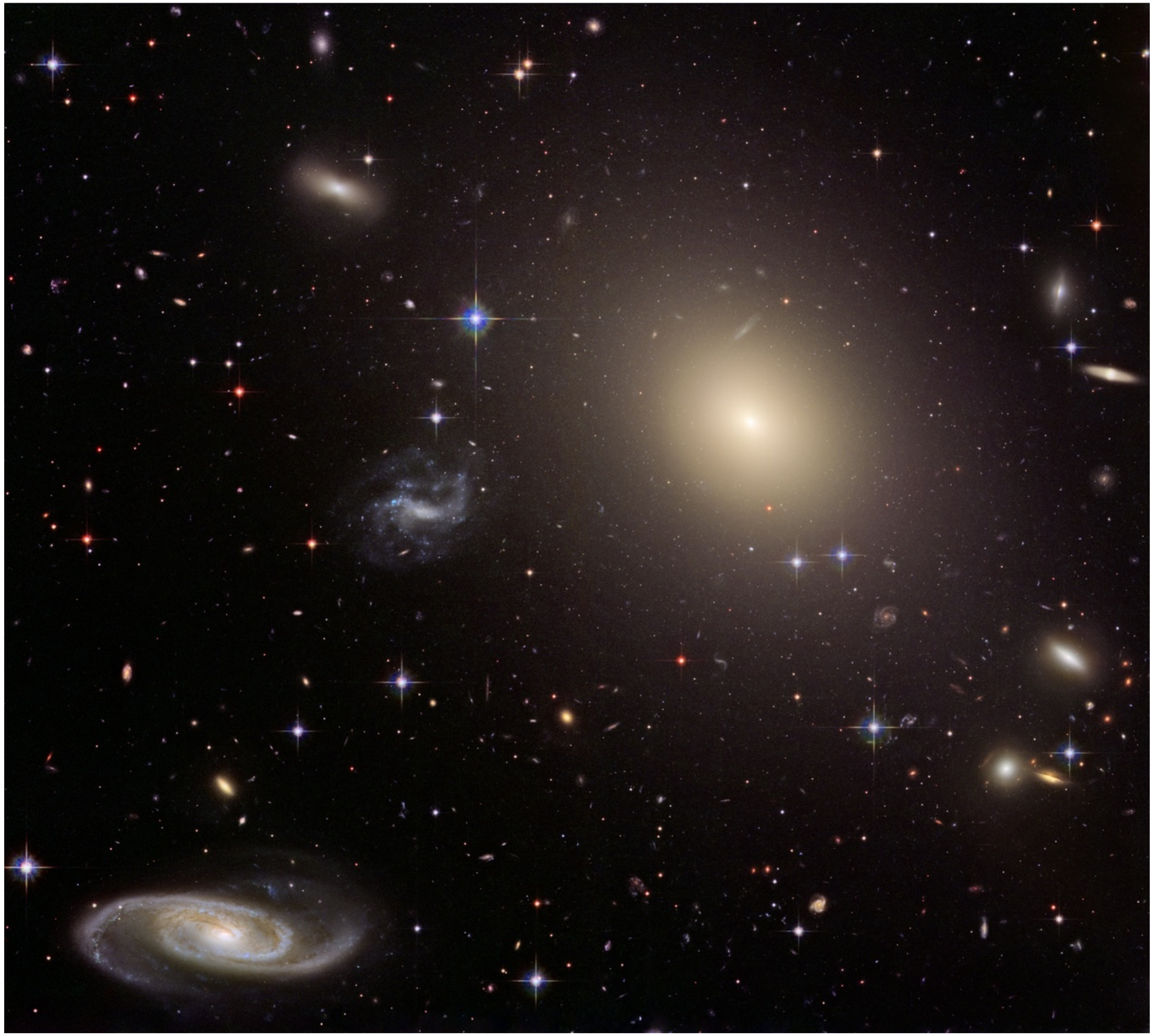


What are the early-type galaxies?

- **S0 galaxies**: contain stellar disks, no gas or star formation.
- **Ellipticals**: do not contain stellar disks, no gas or star formation.

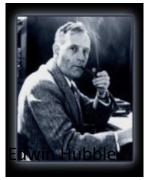
- $M_B < -17$
- Mass > a few 10^9 M_{sun}

Galaxy classification?

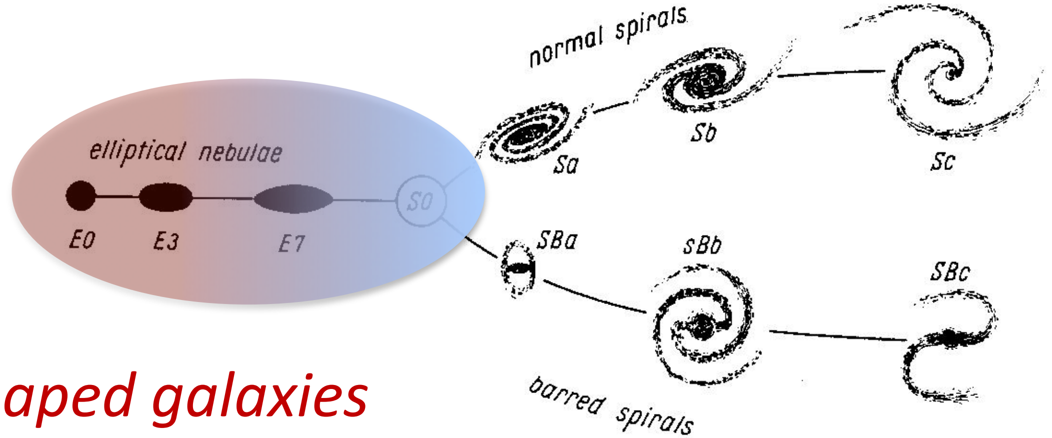


credit: HST

The paradigm



Early-type galaxies ≡



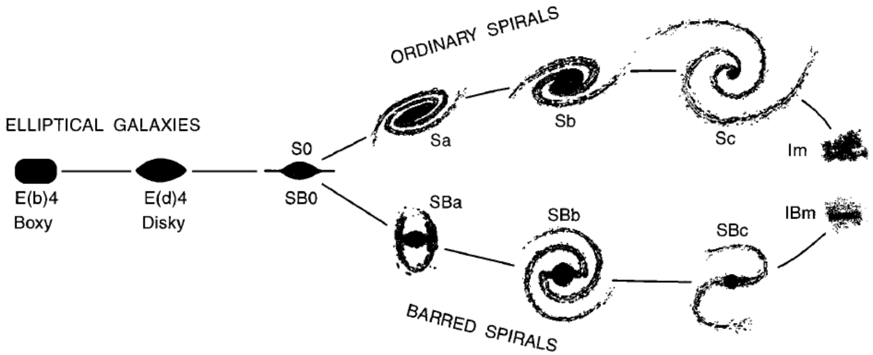
Hubble 1936

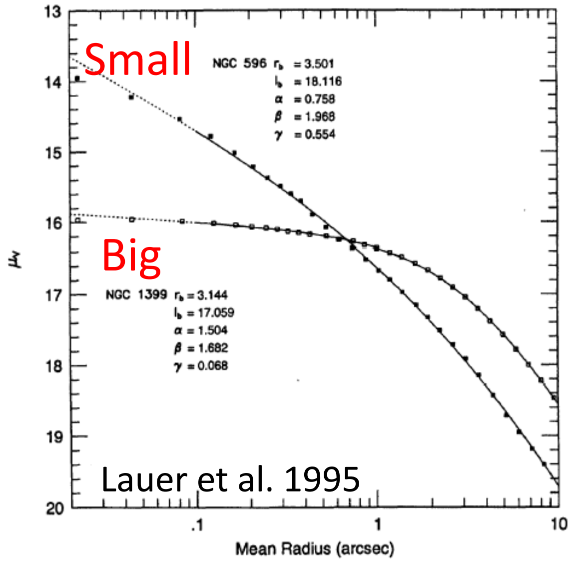
~50% of E's ≡ spheroid-shaped galaxies

~50% of S0s ≡ bulge dominated disk galaxies

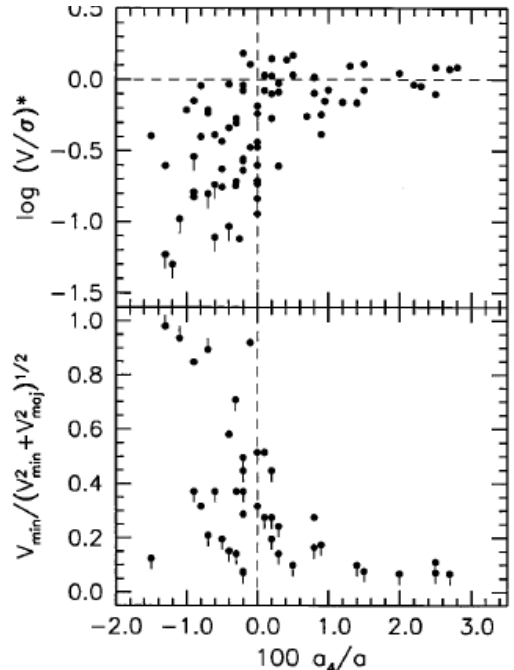
- E + S0s **~40%** of (SDSS) stellar mass (Bernardi et al. 2010)
- E/S0s are overall red (old), S0s can have younger stars
- ***Mergers*** ➔ important to build E's
- Two flavours of E's ? (Davies/Nieto/Kormendy/Bender/Lauer...)
  - Boxy with flat cores or light deficit, anisotropic, triaxial
  - Disky with cusps or light excess, nearly isotropic, oblate-spheroidal

Two flavours of ellipticals from photometry





- Disky ellipticals are intermediate between big ellipticals and lenticulars (Kormendy & Bender 1996)
- Almost all `radio-weak' ellipticals could have disks containing ~ 20% of the light (Rix & White 1990)
- Big and small ellipticals also distinct in their luminosity profile (Faber et al. 1997; Trujillo et al. 2004)
- Light Excess/Deficit also defines a "E-E dichotomy" (Kormendy et al. 2009)

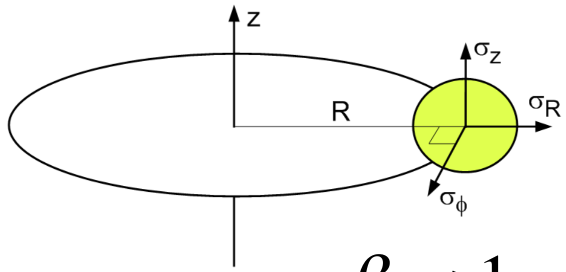


Kormendy & Bender (1996)

Two flavours of ellipticals from kinematics

« Low » luminosity ellipticals

Disky, light excess, rotate faster, isotropic, axisymmetric

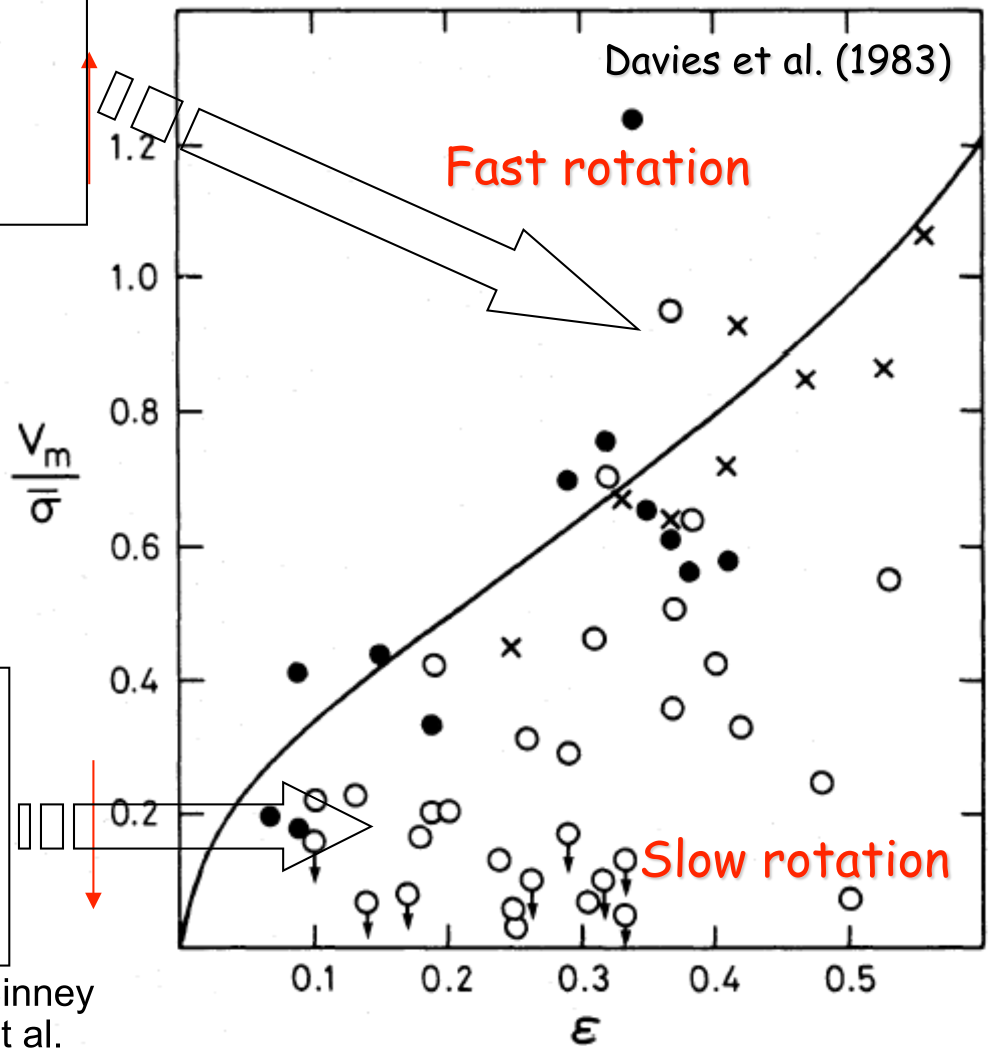


$$\beta \rightarrow 1 - \frac{\sigma_z^2}{\sigma_R^2}$$

Giant ellipticals

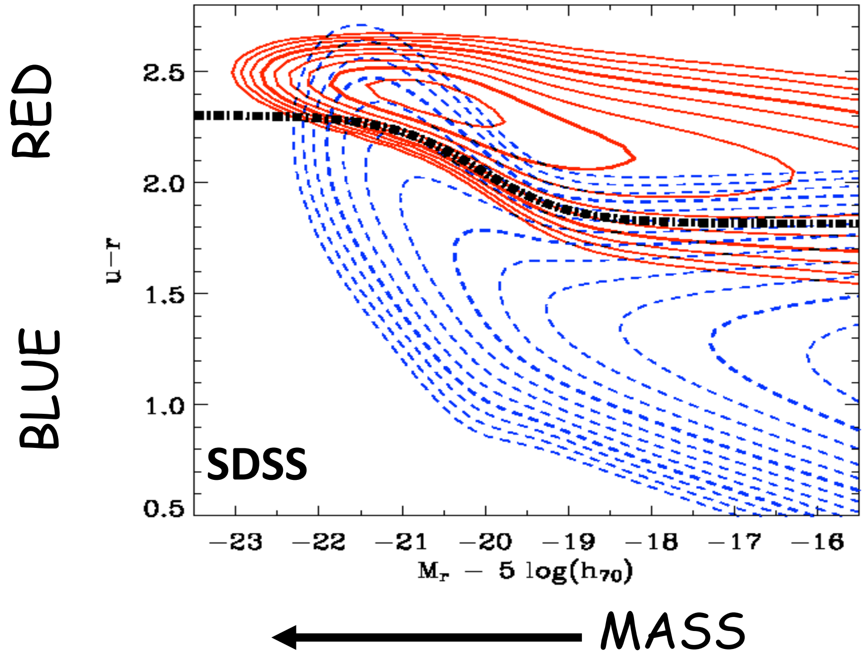
Boxy, light deficit, Rotate slowly, likely anisotropic, misaligned, triaxial

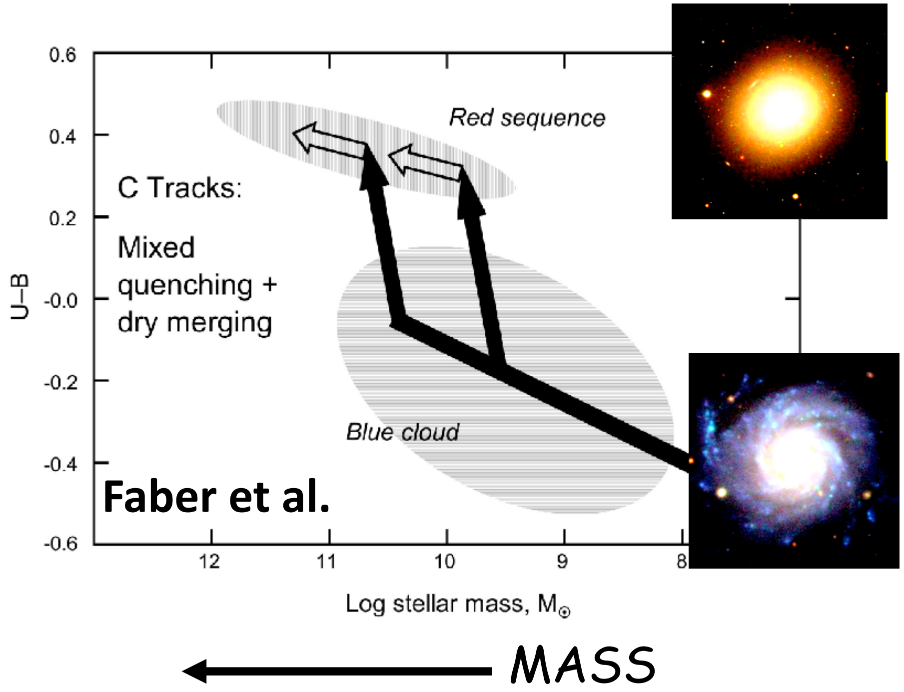
Bertola & Cappaccioli (1975), Illingworth (1977), Binney (1978), Kormendy & Illingworth (1982), Davies et al. (1983), Franx et al. (1989), Bender et al. (1994)….



o = big ellipticals
● = small ellipticals

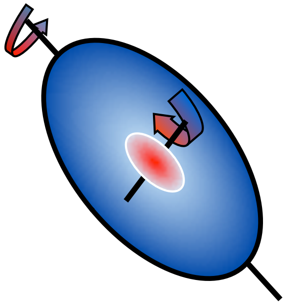
Hierarchical Galaxy Formation



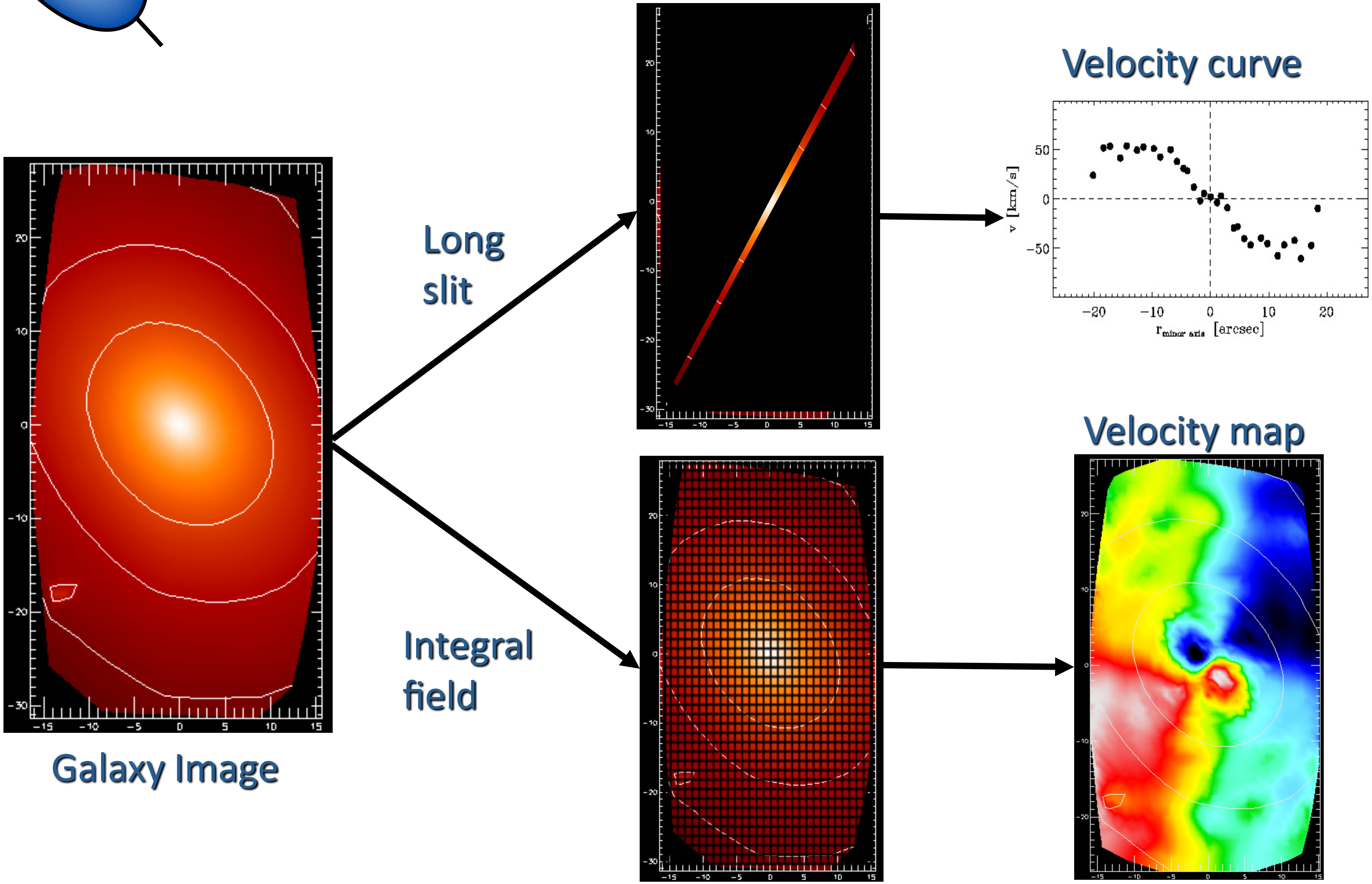


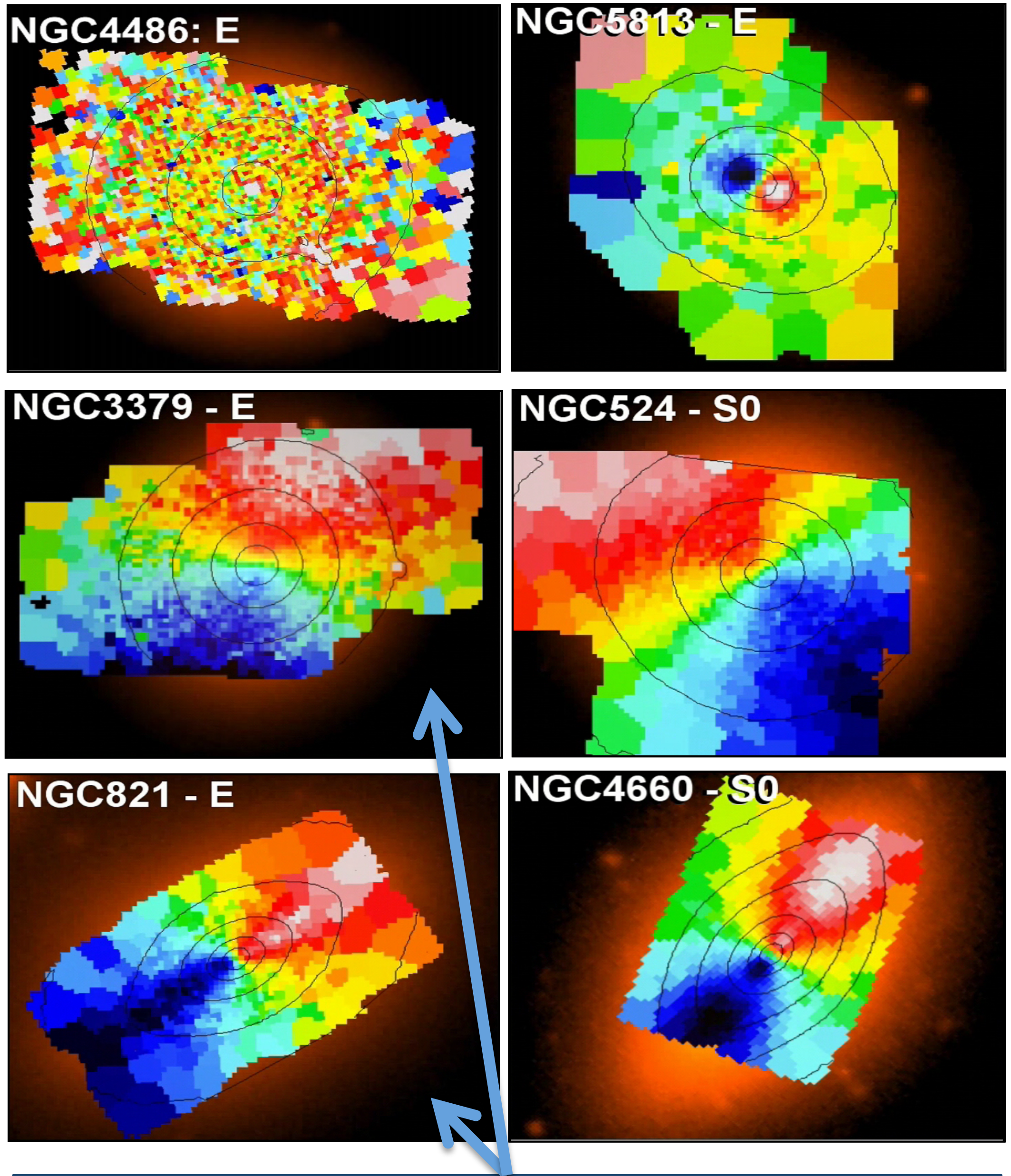
- Bimodal galaxy colour distribution needs merging + feedback to jump from blue to red (Baldry et al. 2004, Bell et al. 2004)
- For most-massive objects, need merging ***within*** red sequence
- Red sequence is a mixture of remnants from gas-rich (blue cloud) and gas-poor (red sequence) mergers (e.g. Cattaneo et al. 2006)

A "dichotomy" on the red sequence?



The power of Integral-field Spectroscopy





Some E's have "S0-like kinematics"

Photometric Classification

- E's are spheroidal
  - ➔ look similar from all directions
- S0's contain disks
  - ➔ look like E's if near face-on

Need for a more physical classification

The SAURON Project

- Systematic study of ***representative*** sample of 48 nearby early-type galaxies and 24 spiral bulges (Sa)
- Ground-based **integral-field spectroscopy** + imaging
  - Kinematics of stars/gas and line-strengths
  - Large-scale surface-brightness distribution
- Hubble, SPITZER (IR) & GALEX (UV)
- Construction of models to determine:
  - M/L, intrinsic shape and stellar motions
  - Mass of central black hole, and relation to galaxy structure
  - Origin and properties of ionised gas
  - History of metal enrichment of the stars

PIs: Bacon, Davies, de Zeeuw

de Zeeuw et al. 2002

Sorting by angular momentum

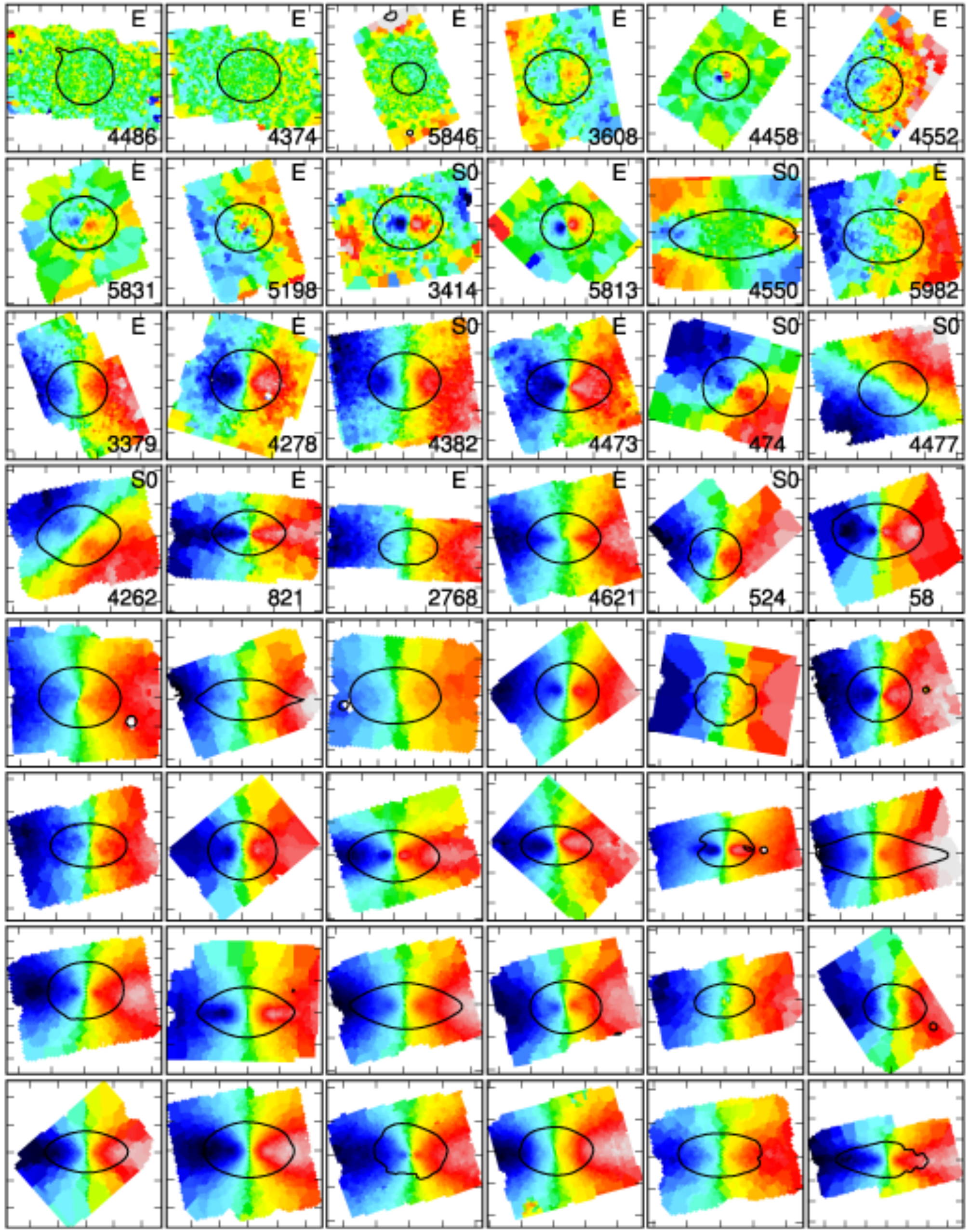
Angular momentum

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

Spatial average

➔ needs IFU

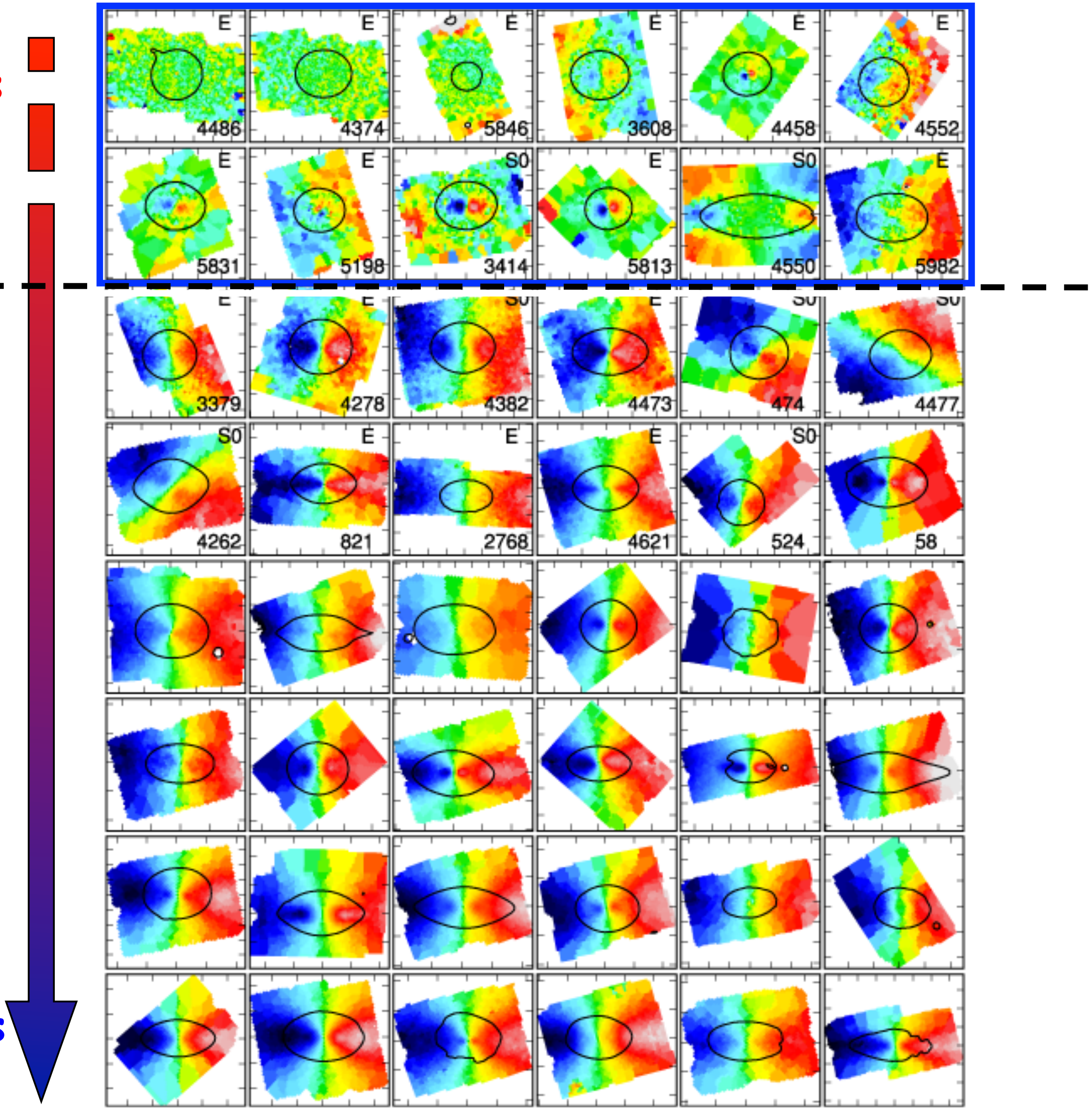
Normalised by Mass



SAURON ***velocity maps*** Emsellem et al. (2007)

Slow rotators

λ_R=0.1



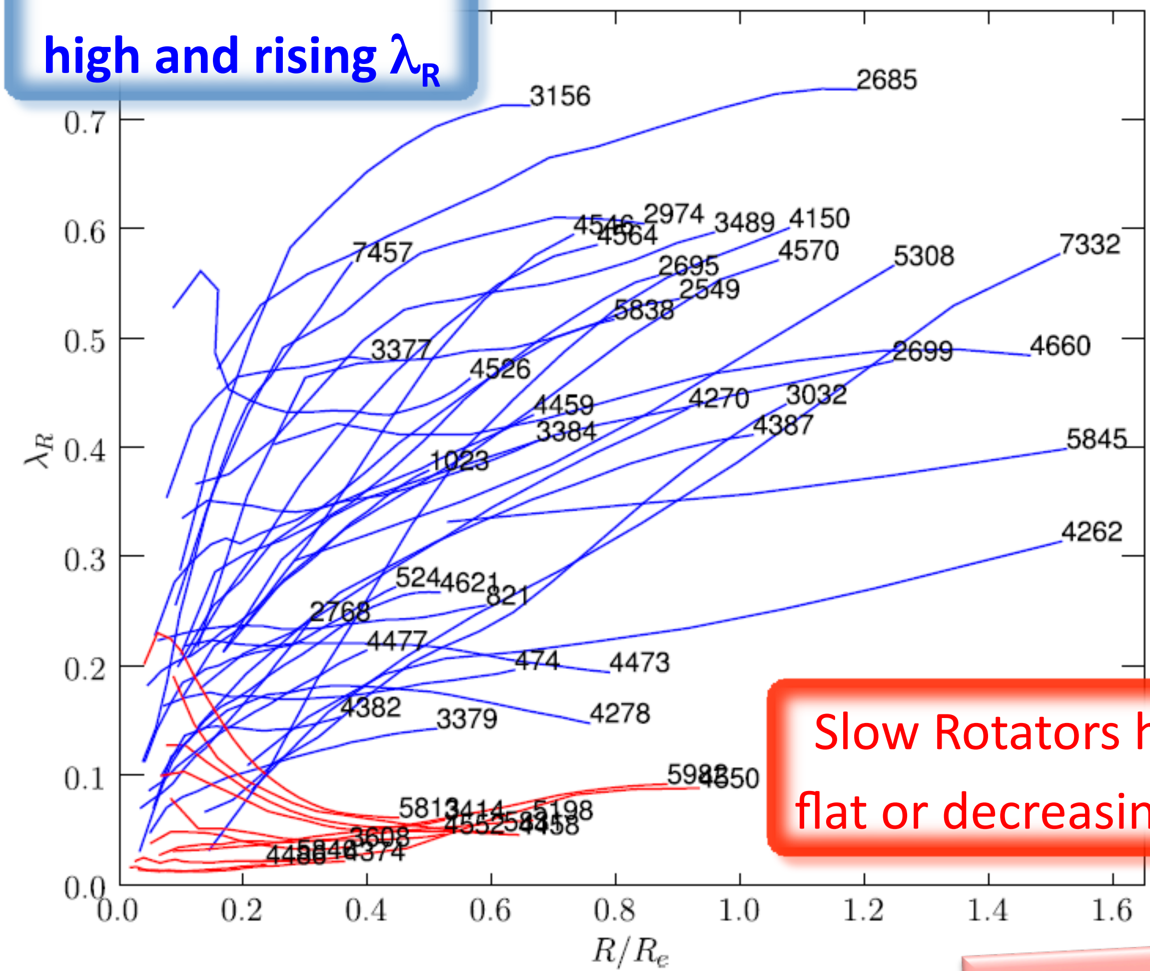
$$\lambda_R \equiv \frac{\langle R \cdot |V| \rangle}{\left\langle R\sqrt{V^2 + \sigma^2} \right\rangle}$$

Fast rotators

Emsellem et al. (2007)

The SAURON hypothesis

Fast Rotators have high and rising λ_R



Slow Rotators have flat or decreasing λ_R

Emsellem et al. (2007)

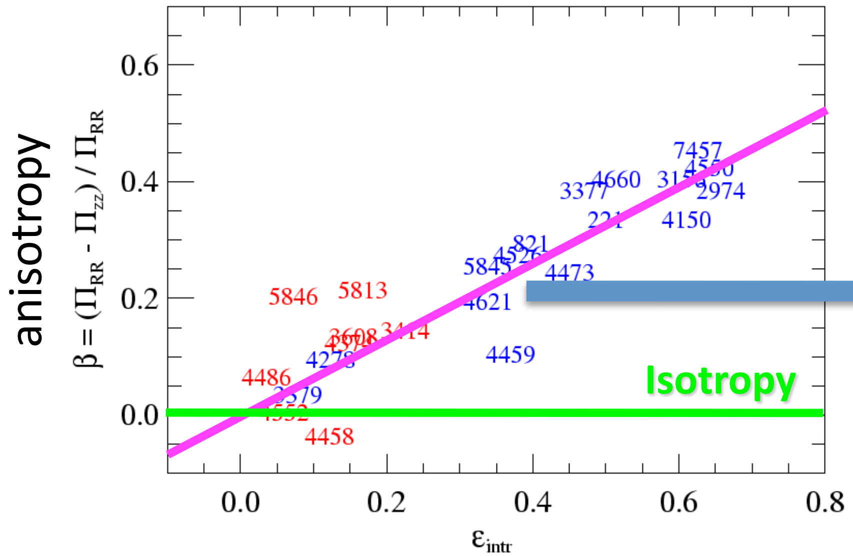
- SAURON Survey (de Zeeuw et al. 2001 + 18 papers)
- **Hypothesis**
  - FR & SR ETGs are physically distinct
  - FR & SR are the end products of different evolutionary paths
  - λ_R is a *physical* parameter for galaxy classification

Not a complete sample! only representative

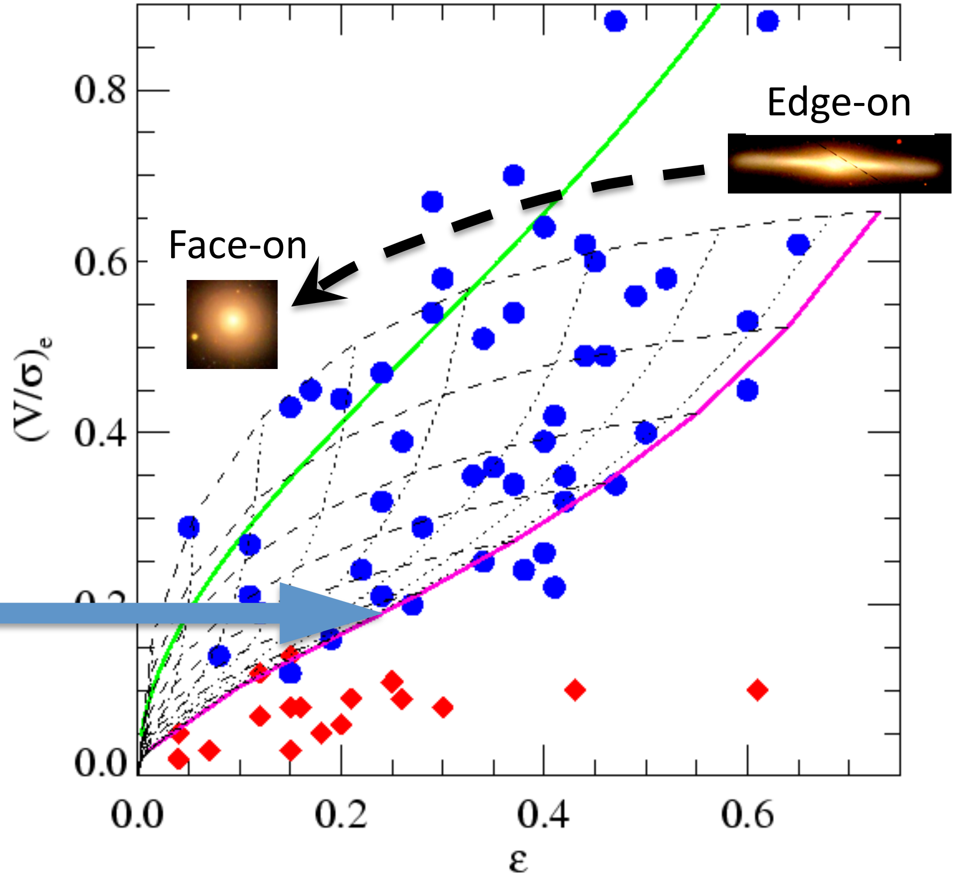
FR/SR: Revisiting the V/σ diagram

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

Use new formalism for integral-field kinematics (Binney 2005)



Anisotropy trend from 25 Models

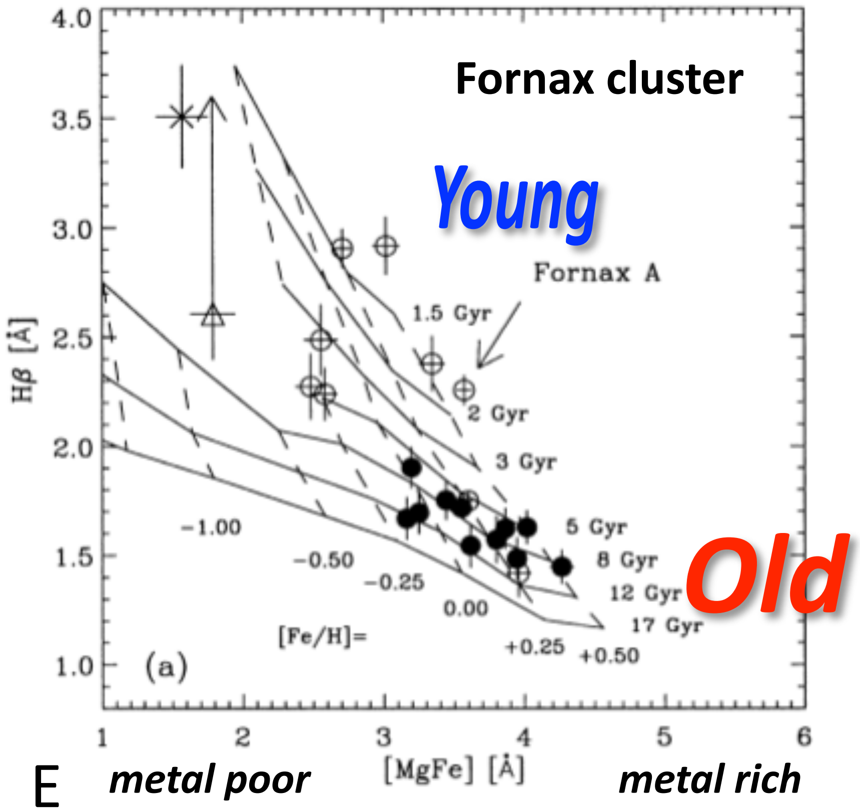


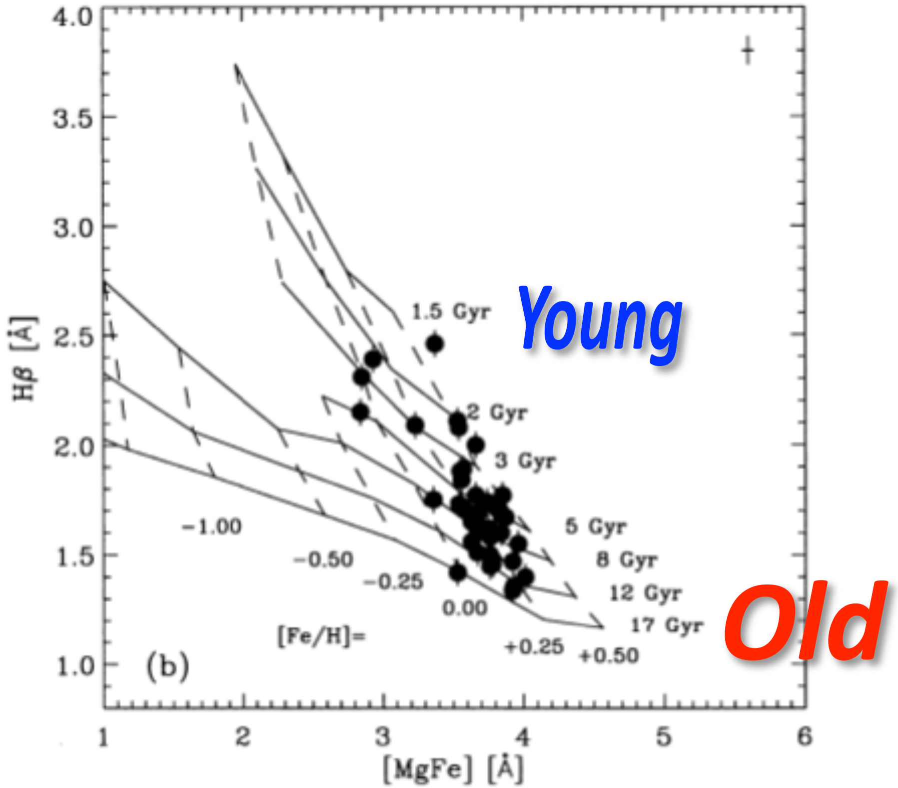
- Fast-rotators: family of oblate systems
- Slow-rotators: distinct - likely triaxial

Cappellari et al. (2007)

Stellar populations

Are all ellipticals red and dead?





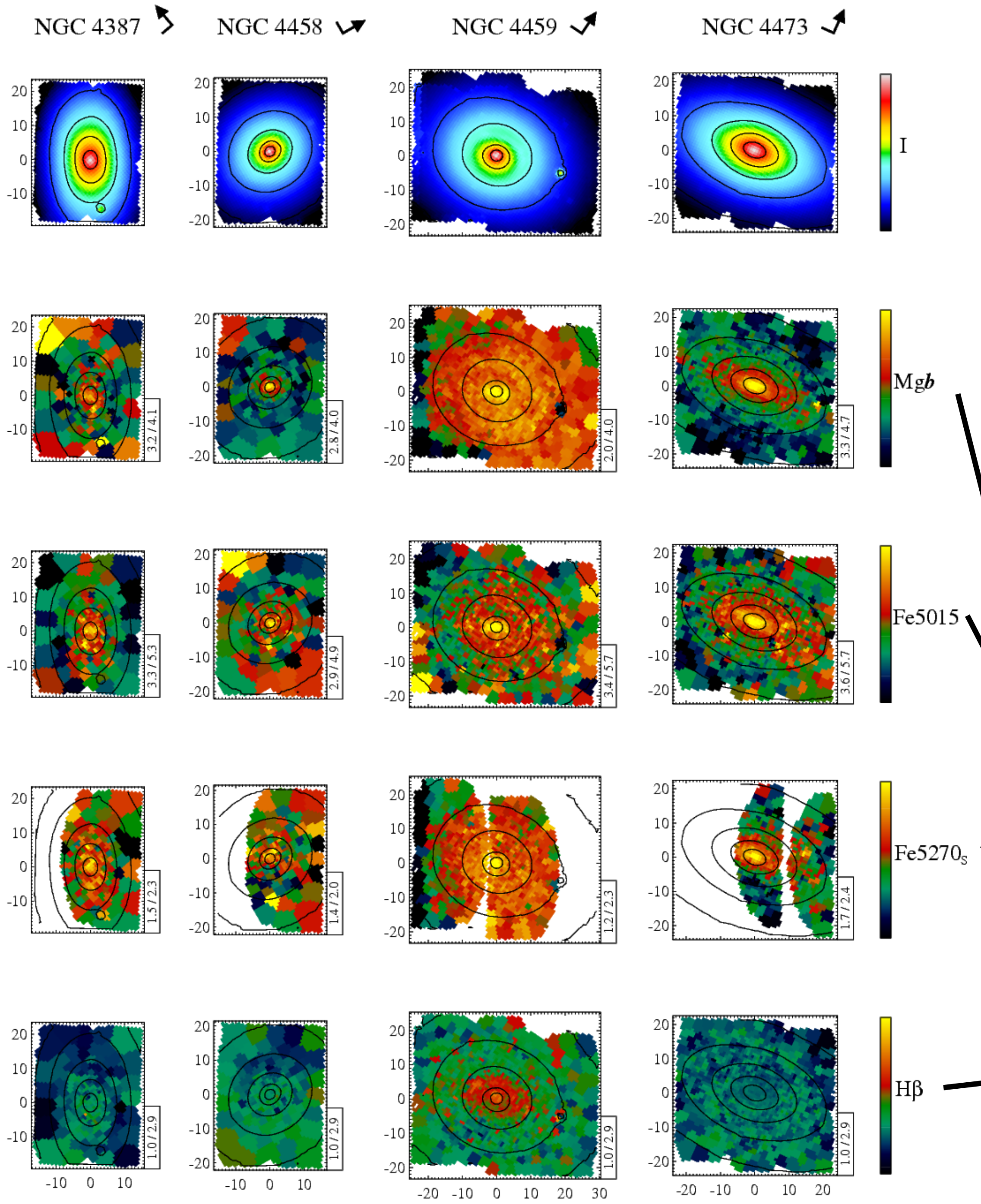
E

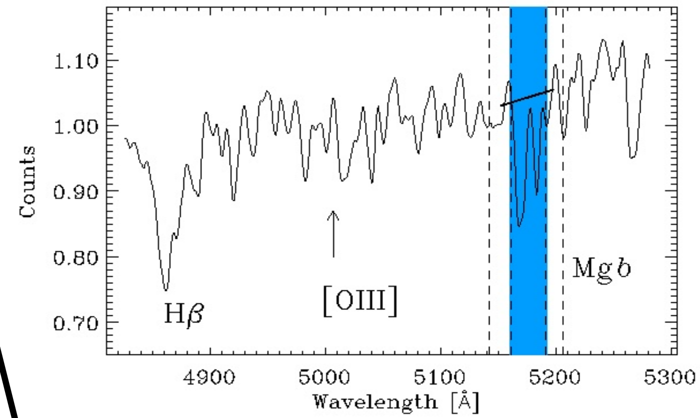
S0

Kuntschner & Davies 1998

González 1993

Line-strength maps



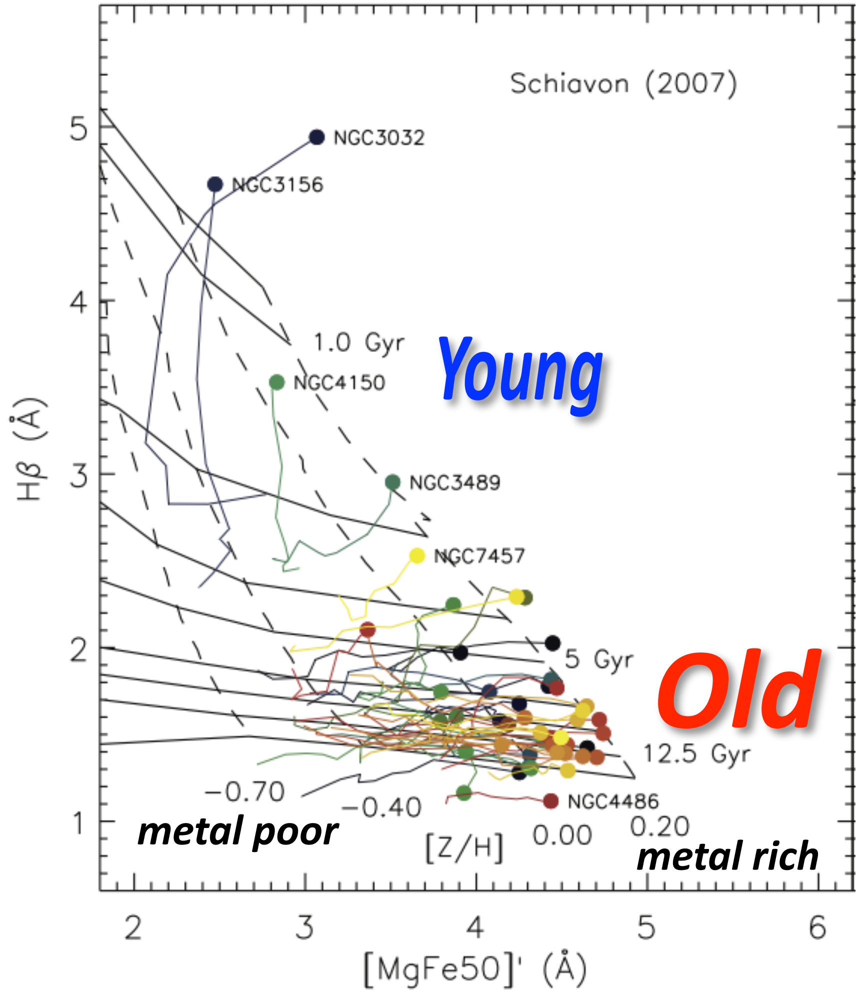


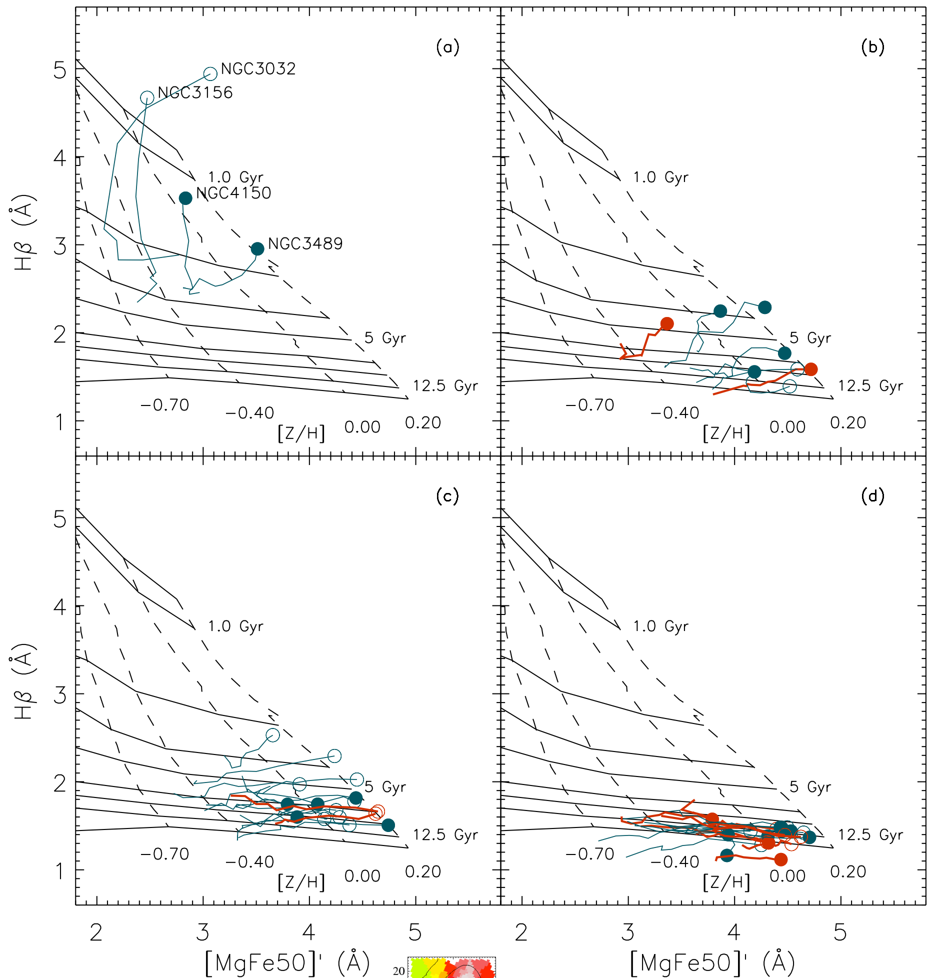
Metallicity and [α/Fe] sensitive indices

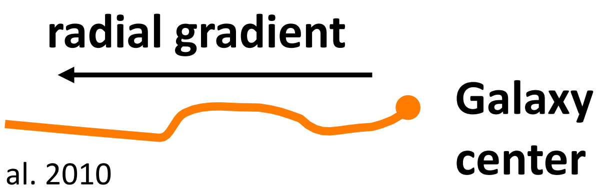
Hβ is primary age indicator (emission corrected)

Kuntschner et al. 2006

Estimating Ages and Metallicities



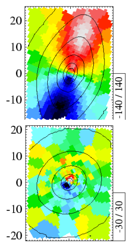




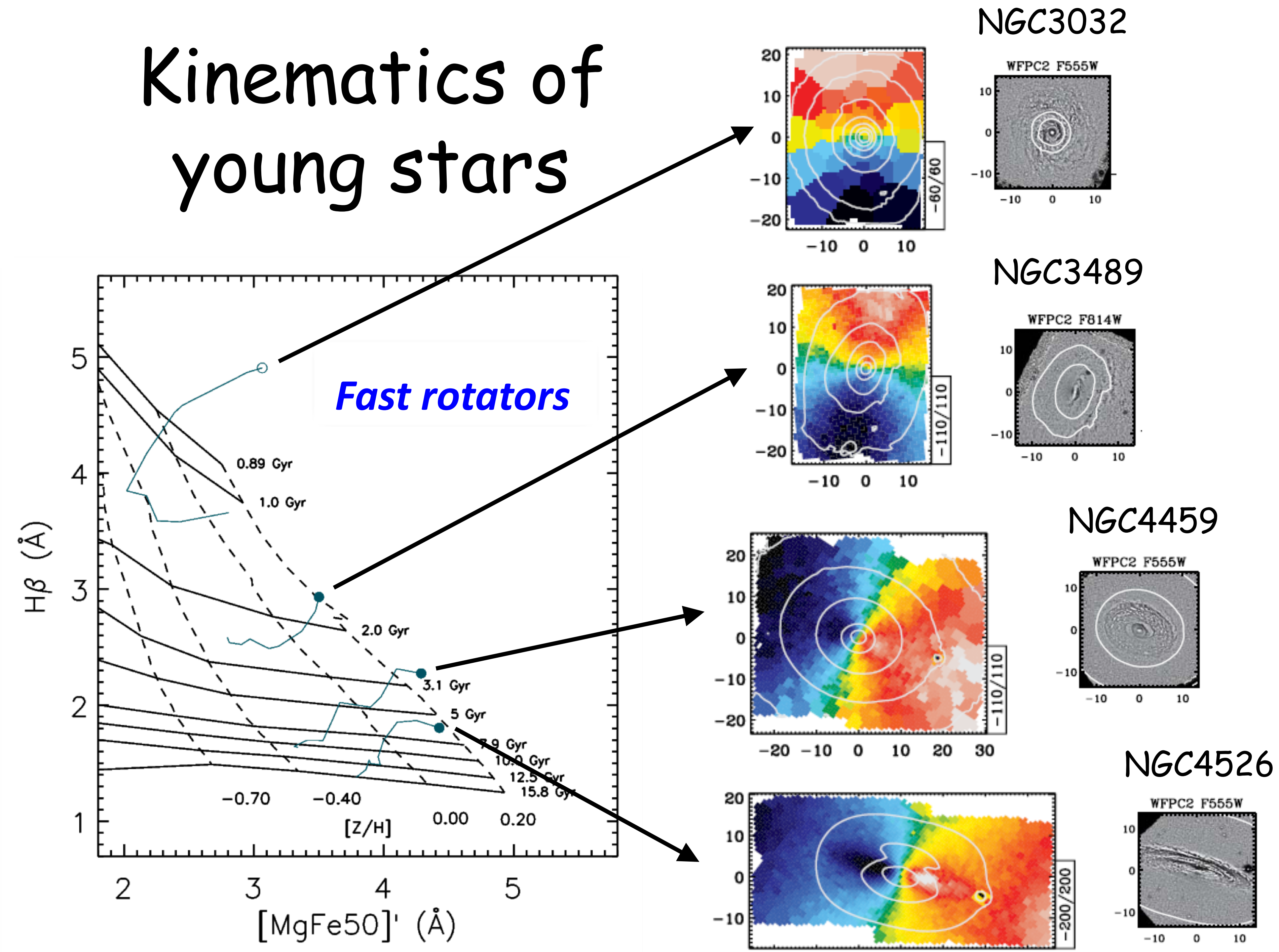
Kuntschner et al. 2010

Fast rotator   *Large range in ages*

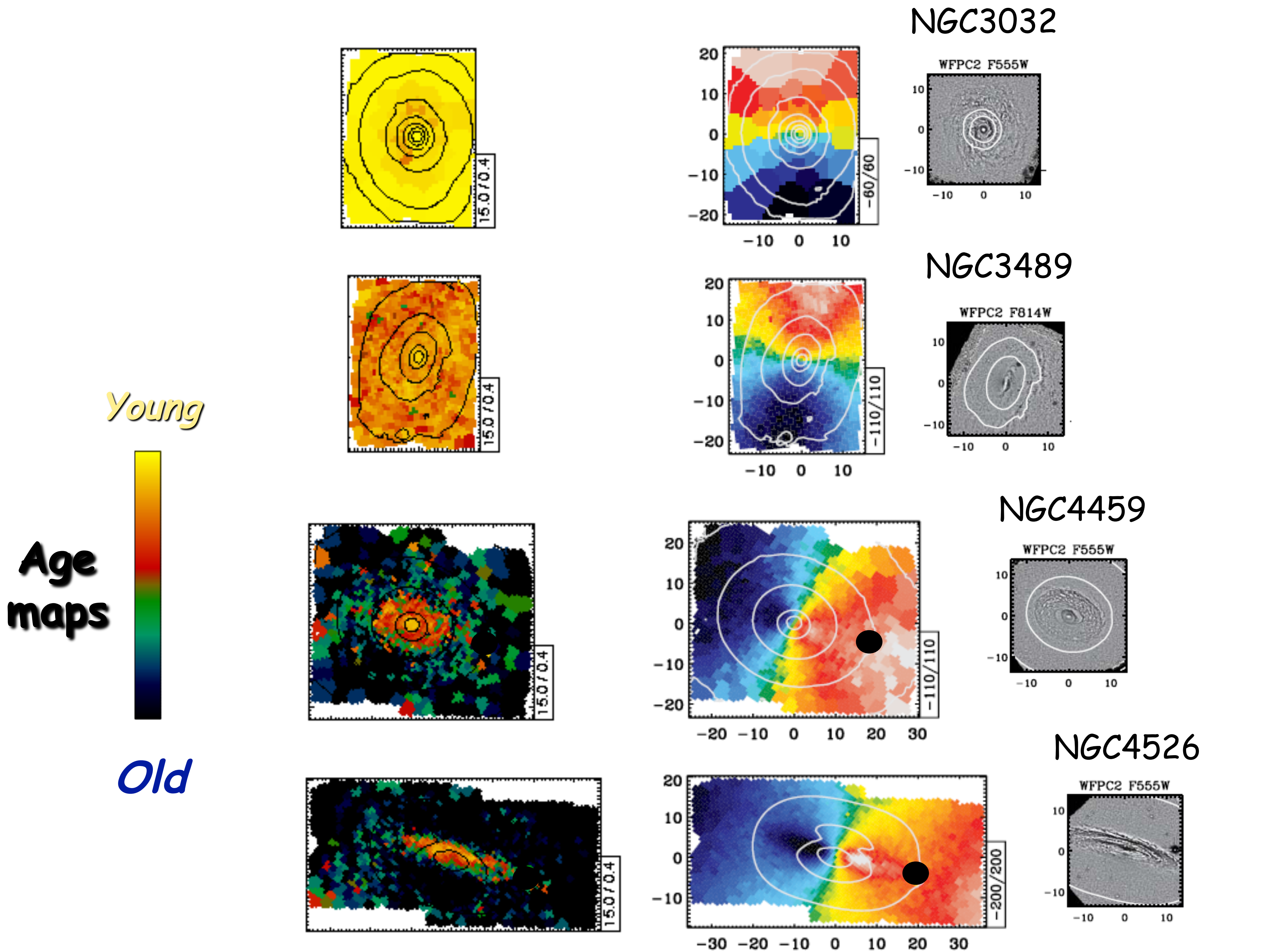
Slow rotator   *Predominantly old*



Kinematics of young stars



Kuntschner et al. 2010



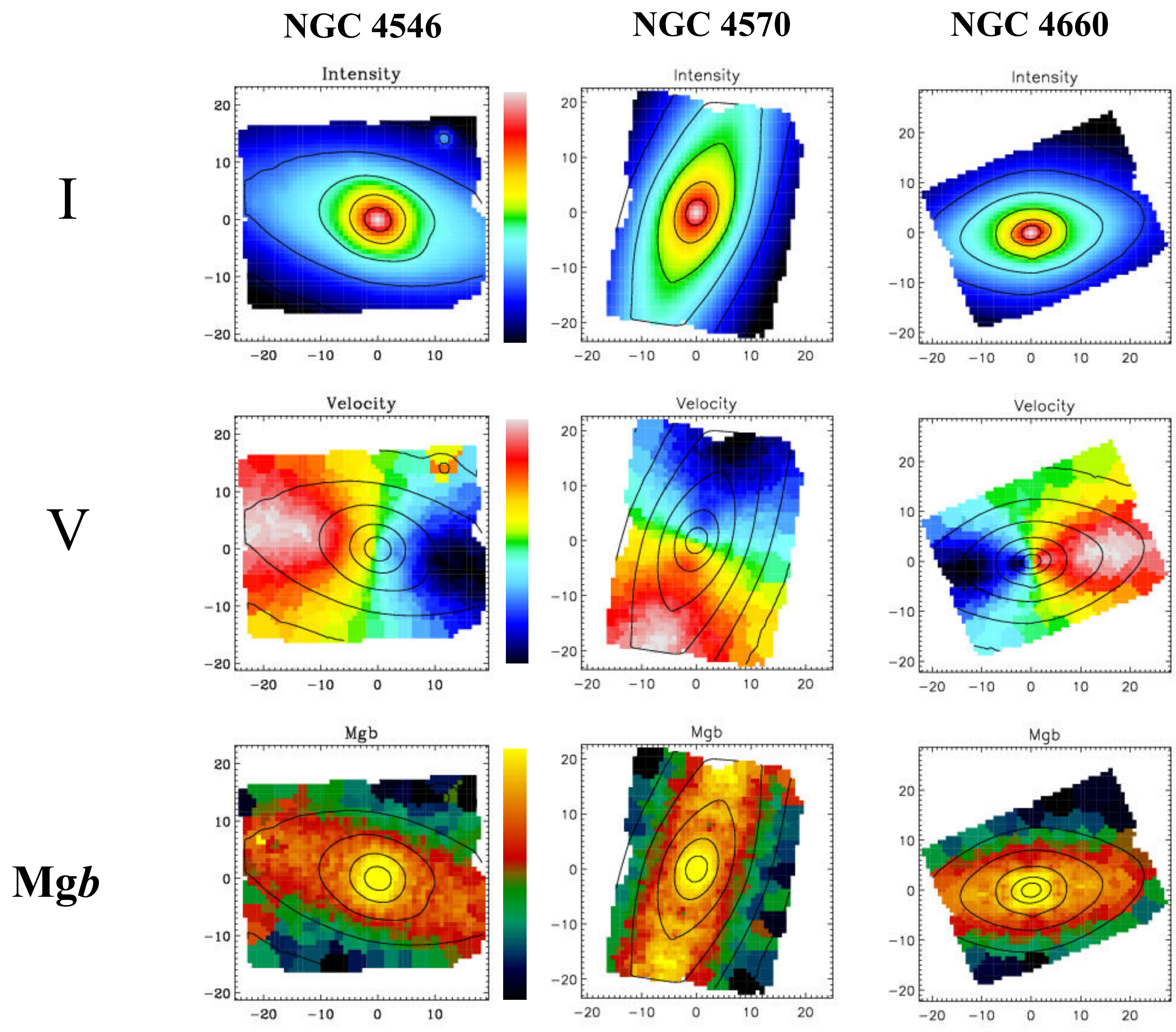
Young
Age maps
Old
NGC3032
WFPC2 F555W
15.0/0.4
−60/60
NGC3489
WFPC2 F814W
15.0/0.4
−110/110
NGC4459
WFPC2 F555W
15.0/0.4
−110/110
NGC4526
WFPC2 F555W
15.0/0.4
−200/200

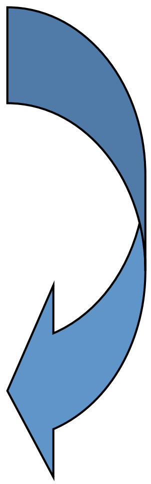
Star-formation in disks

- Young stars in early-type galaxies are connected to disk-like structures and kinematics -> fast rotators
  - Low mass galaxies show young stars over large radial extent - produced in gas rich mergers?
  - Intermediate mass galaxies show some examples of localized, central young disks within older rotating structures (internal/external gas origin?)

Can we find less prominent, “aged” examples of secondary star-formation in disks?

Morphology - Kinematics - *Mgb* connection





Fast Rotators

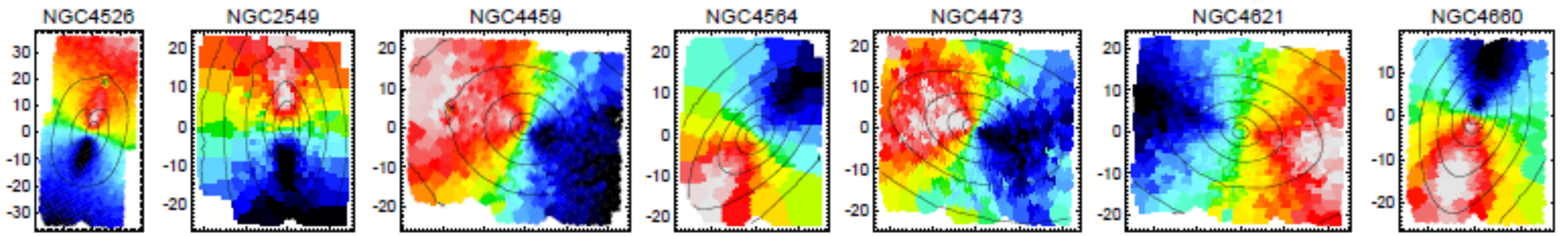
Enhanced *Mgb*

See also e.g. Fisher et al. 1996

Kuntschner et al. 2006

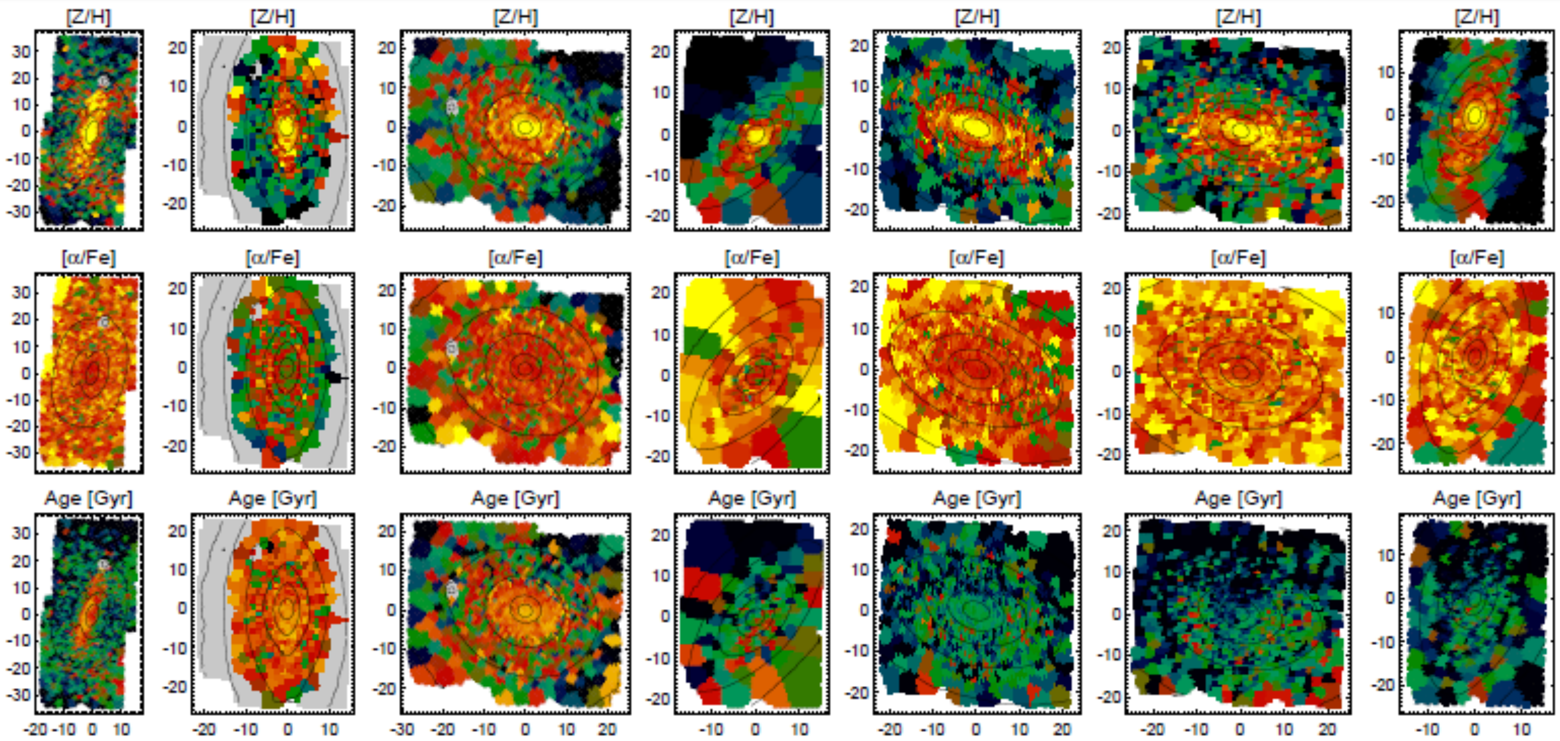
Metallicity enhanced disks

Young → Old



velocity

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]

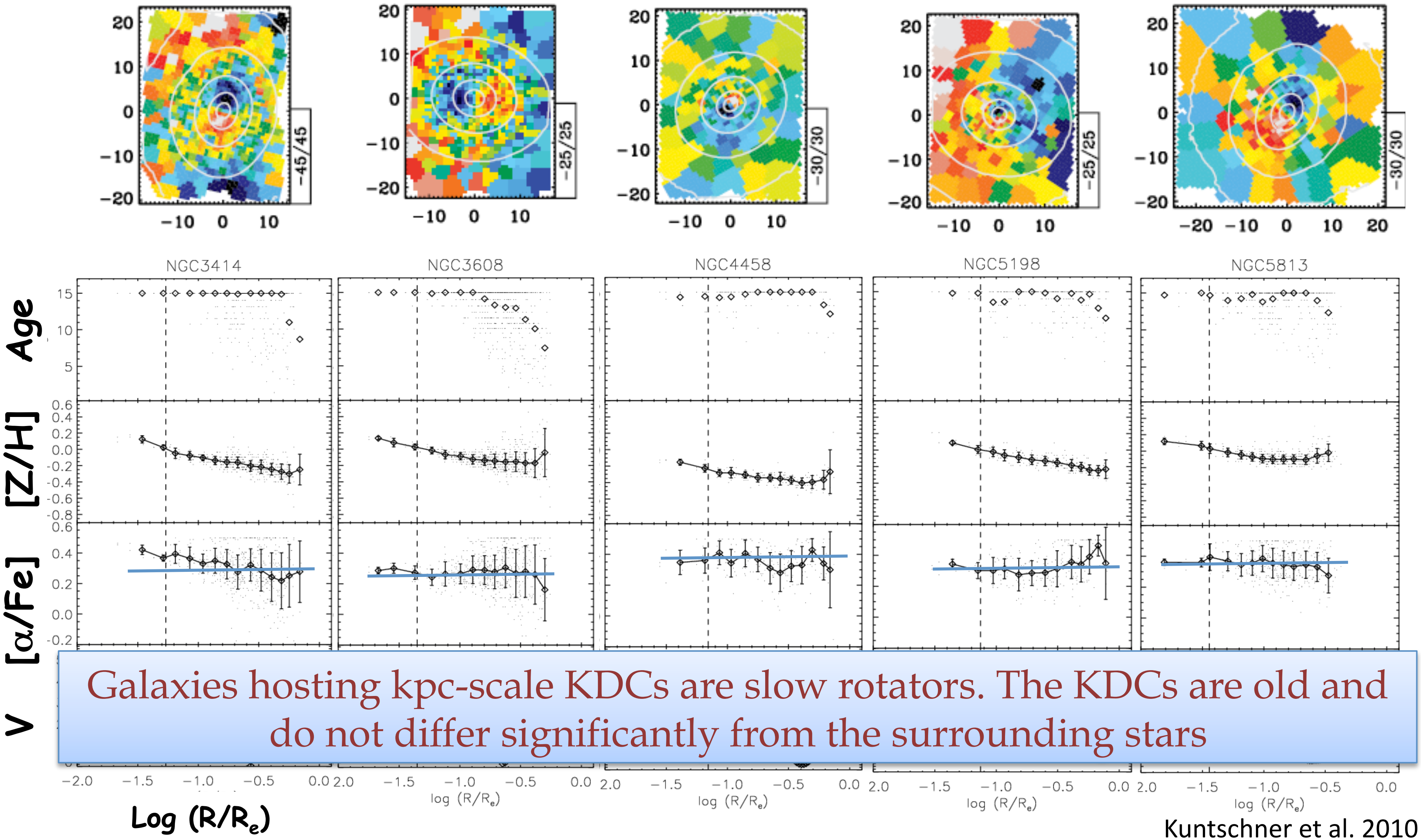


[Z/H]

age

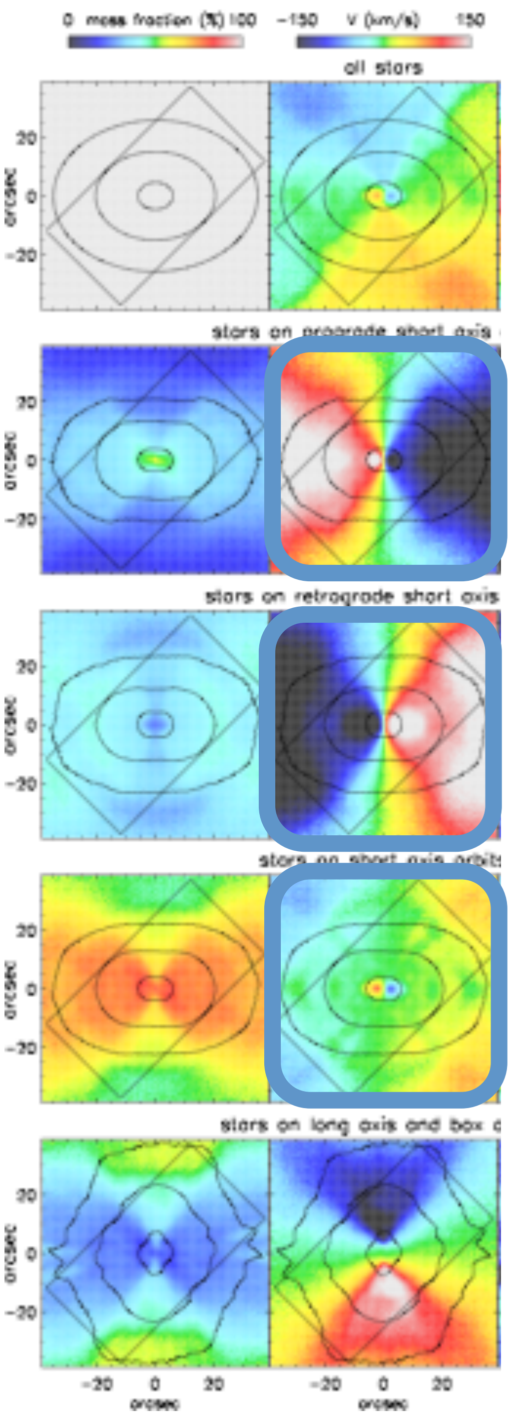
Kuntschner et al. 2010

What about KDCs ?

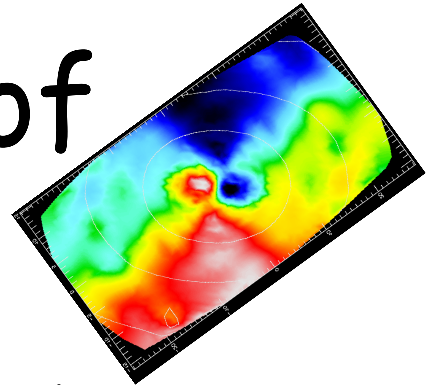


Galaxies hosting kpc-scale KDCs are slow rotators. The KDCs are old and do not differ significantly from the surrounding stars

Kuntschner et al. 2010



The showcase of NGC4365



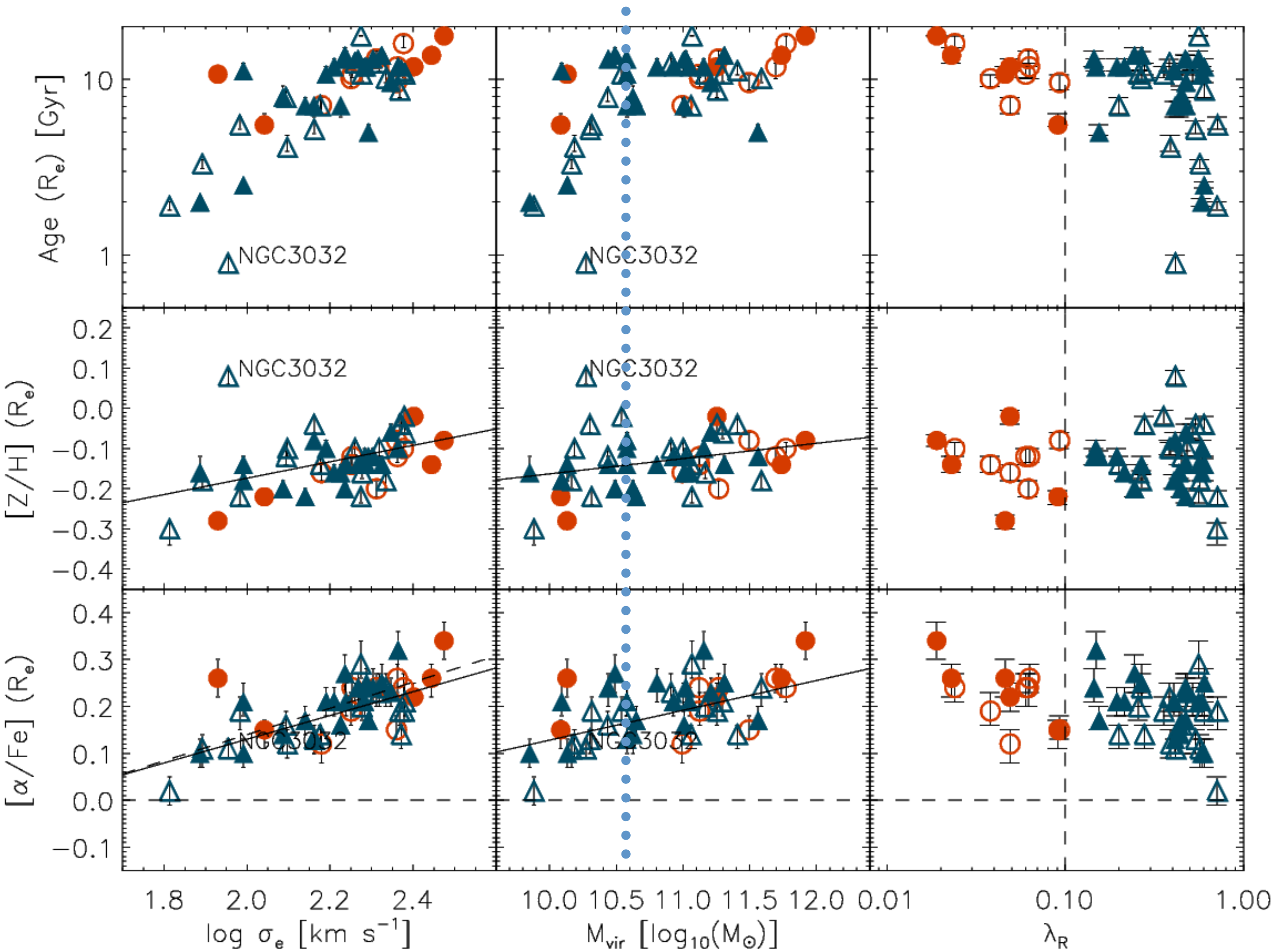
- Schwarzschild modeling shows KDC to be the result of ***prograde*** and ***retrograde*** short axis orbits ***superposition***

- KDC is "tip of the iceberg" rather than a well localized structure

van den Bosch et al. 2008

Global 1 R_e age, Z, [Mg/Fe] - trends

Consistent with e.g., Thomas et al. 2005; Bernardi et al. 2005, 2006; Kuntschner et al. 2002; …



Kuntschner et al. 2010

~40% of ETGs show signs of young stars

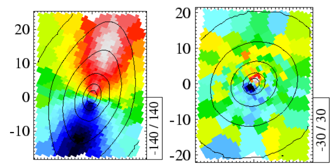
Low mass systems show strong scatter to young ages
-> growth of red sequence

Mass - metallicity correlation

Mass - [α/Fe] correlation

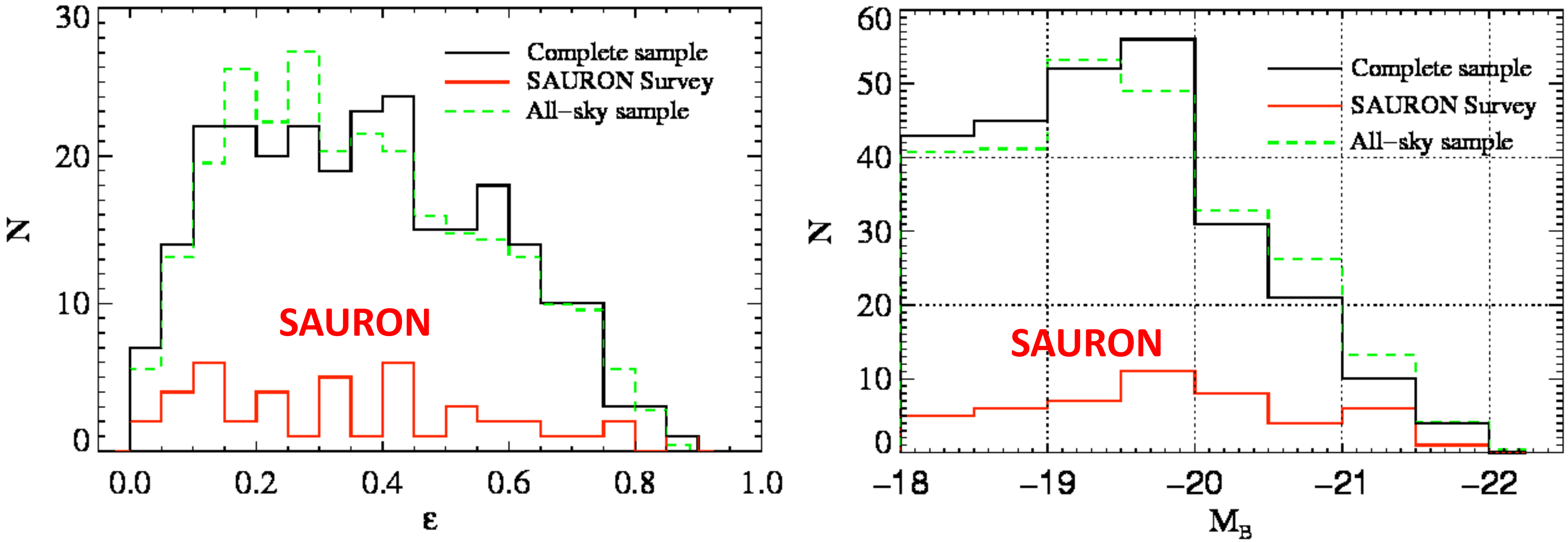
Fast rotator

Slow rotator



The Next Step
A Complete Survey

- Need volume-limited sample
  - To understand the distribution of Fast & Slow Rotators
  - To determine the importance of “wet” / “dry” mergers
  - To provide strong low-z constraints on simulations
  - To better understand the role of SF and feedback



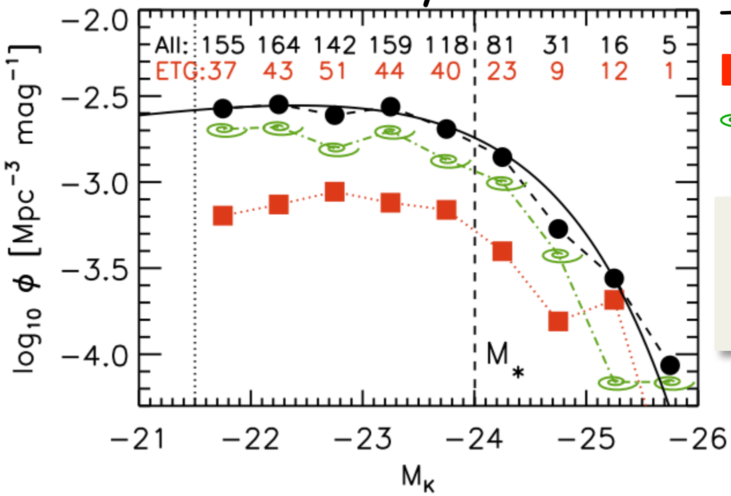
ATLAS^{3D}

$M_K < -21.5$
$D < 42$ Mpc
$|\delta - 29| < 35°$
$|b| > 15°$

- **Observe a complete volume limited sample of 260 ETGs**
- Parent sample:
  871 nearby galaxies
- Morphological selection:
  No spiral arms (DSS/SDSS)
- No colour cut

Atlas3D Sample Properties

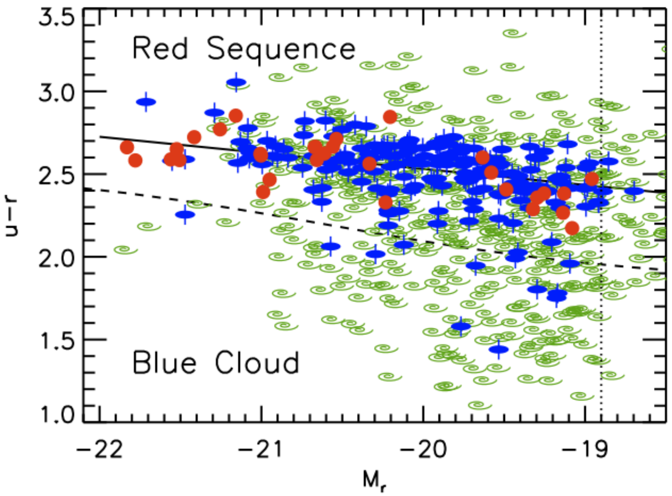
Luminosity function



- Bell et al. 2003
Atlas3D
spirals

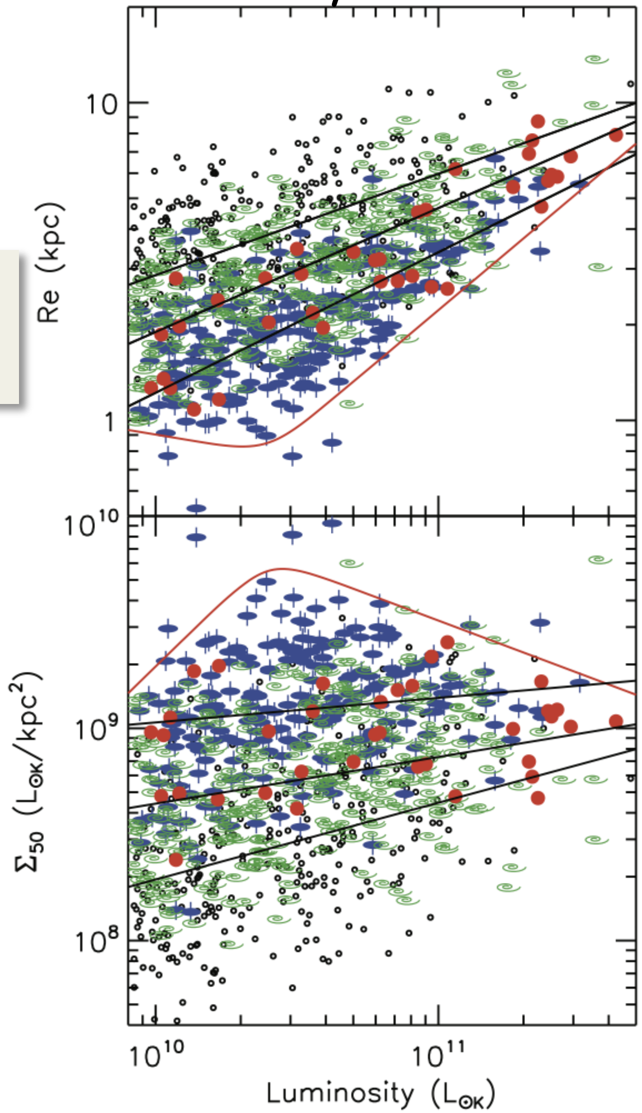
Parent sample: 871
ETGs: 260

Galaxies on the red sequence



Fast Rotator
Slow Rotator
Spiral

Luminosity-size relation



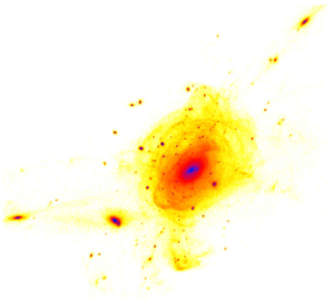
Cappellari et al. (2011)

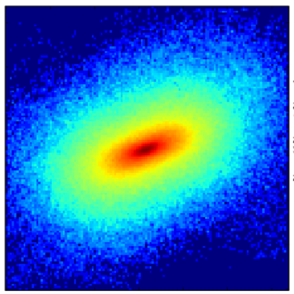
Multi-λ approach

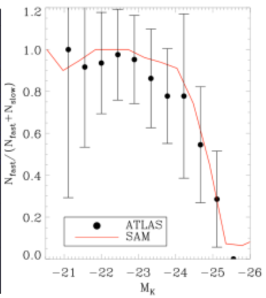
- *SAURON (IFU)* Large Program on WHT (38 nights in 4 runs)
- *HI survey* ~150 northern galaxies with WSRT (excl. Virgo)
- Radio continuum VLA
- *Single-dish CO* survey of full sample IRAM 30m
- *CO interferometry* of detections with CARMA
- *Photometry* multi-bands (INT, 2MASS, SDSS, MegaCam)
- *Archival* data (SDSS, Chandra, XMM, GALEX, HST, Spitzer)

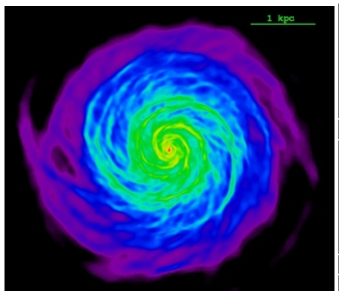
Modelling and Simulations

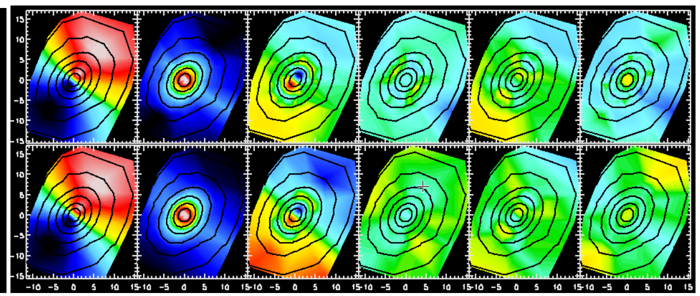
- New modelling for stellar populations
- Dynamical modeling, Mass-to-Light ratios
- Suite of high-res numerical simulations of mergers
- High resolution of gas in early-type galaxies
- Simulations of galaxy formation and evolution in a cosmological context
- Semi Analytic Models



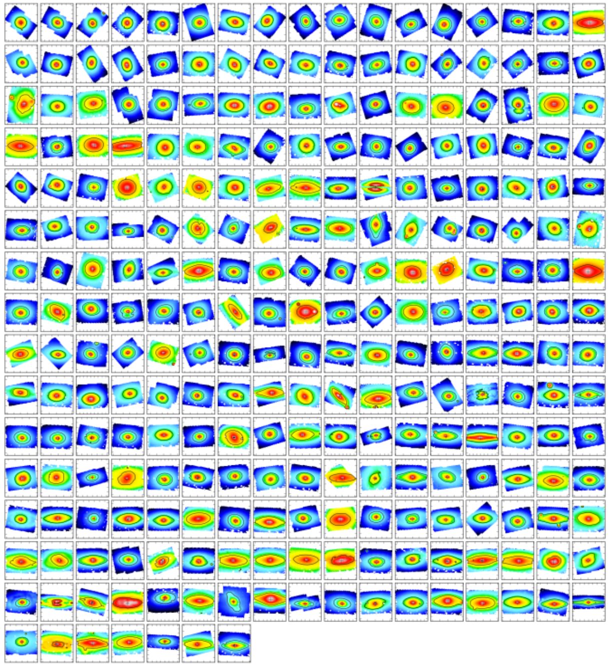


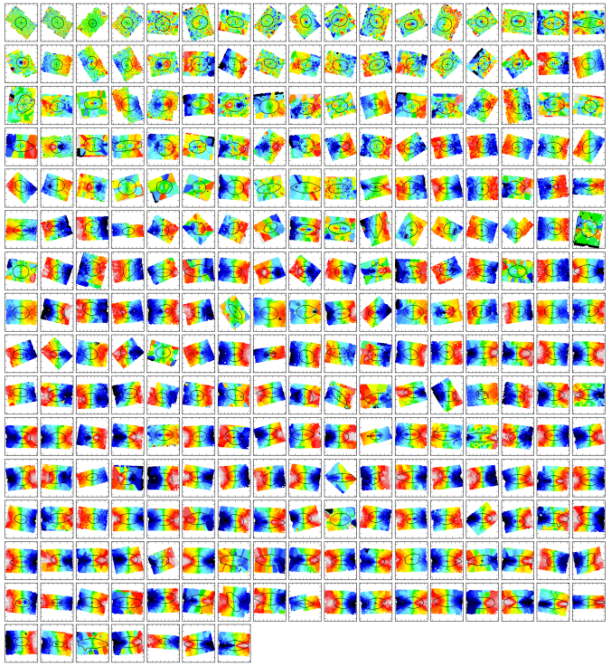


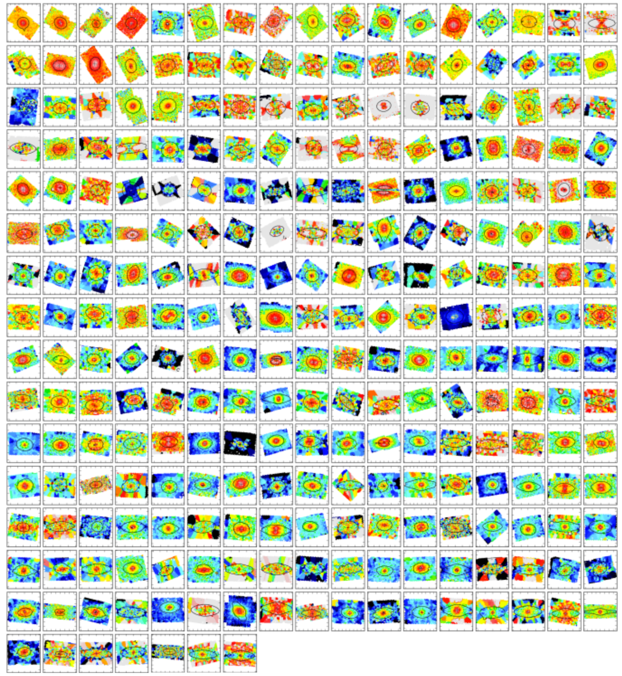


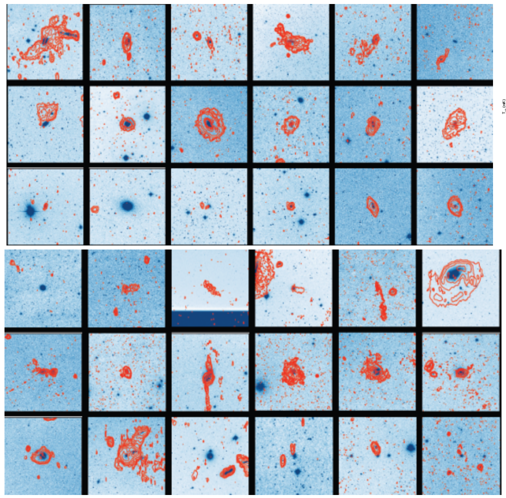


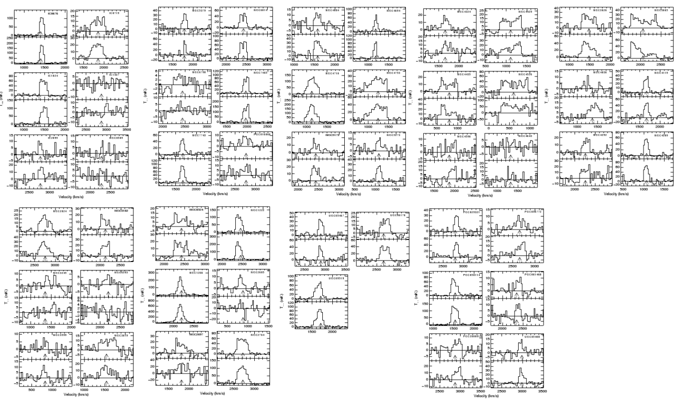
A few spectra and maps…

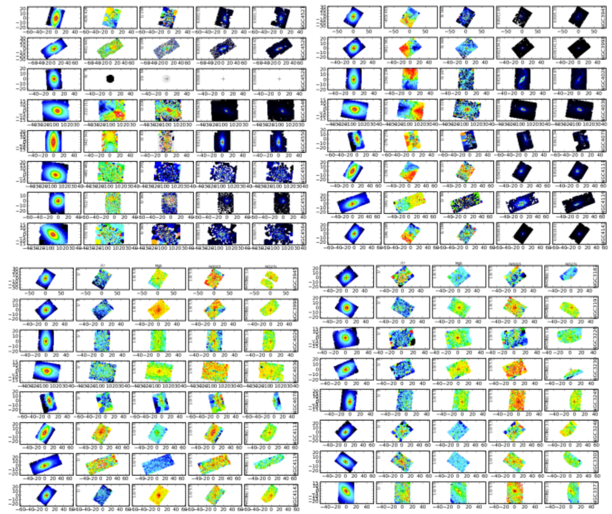












The $ATLAS^{3D}$ team

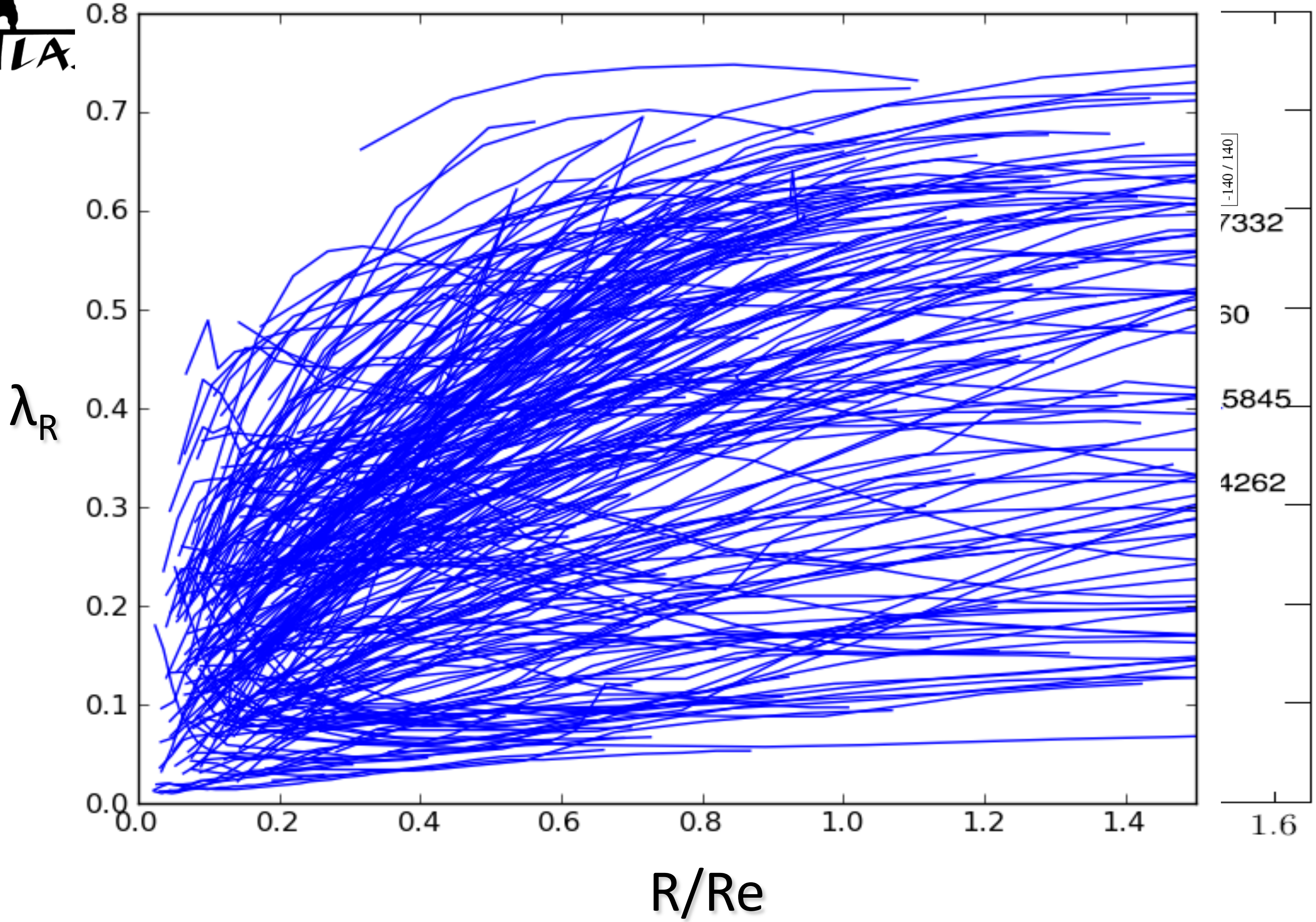
PIs: Michele Cappellari (Oxford), Eric Emsellem (ESO),
Davor Krajnović (ESO), Richard McDermid (Gemini)

Team members:

Katey Alatalo, Estelle Bayet, Leo Blitz, Maxime Bois, Frederic Bournaud, Martin Bureau, Alison Crocker, Roger Davies, Tim Davies, Tim de Zeeuw, Pierre-Alain Duc, Jesus Falcon-Barroso, Sadegh Khochfar, Harald Kuntschner, Pierre-Yves Leblanche, Leo Michel-Dansac, Raffaella Morganti, Thorsten Naab, Kristina Nyland, 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

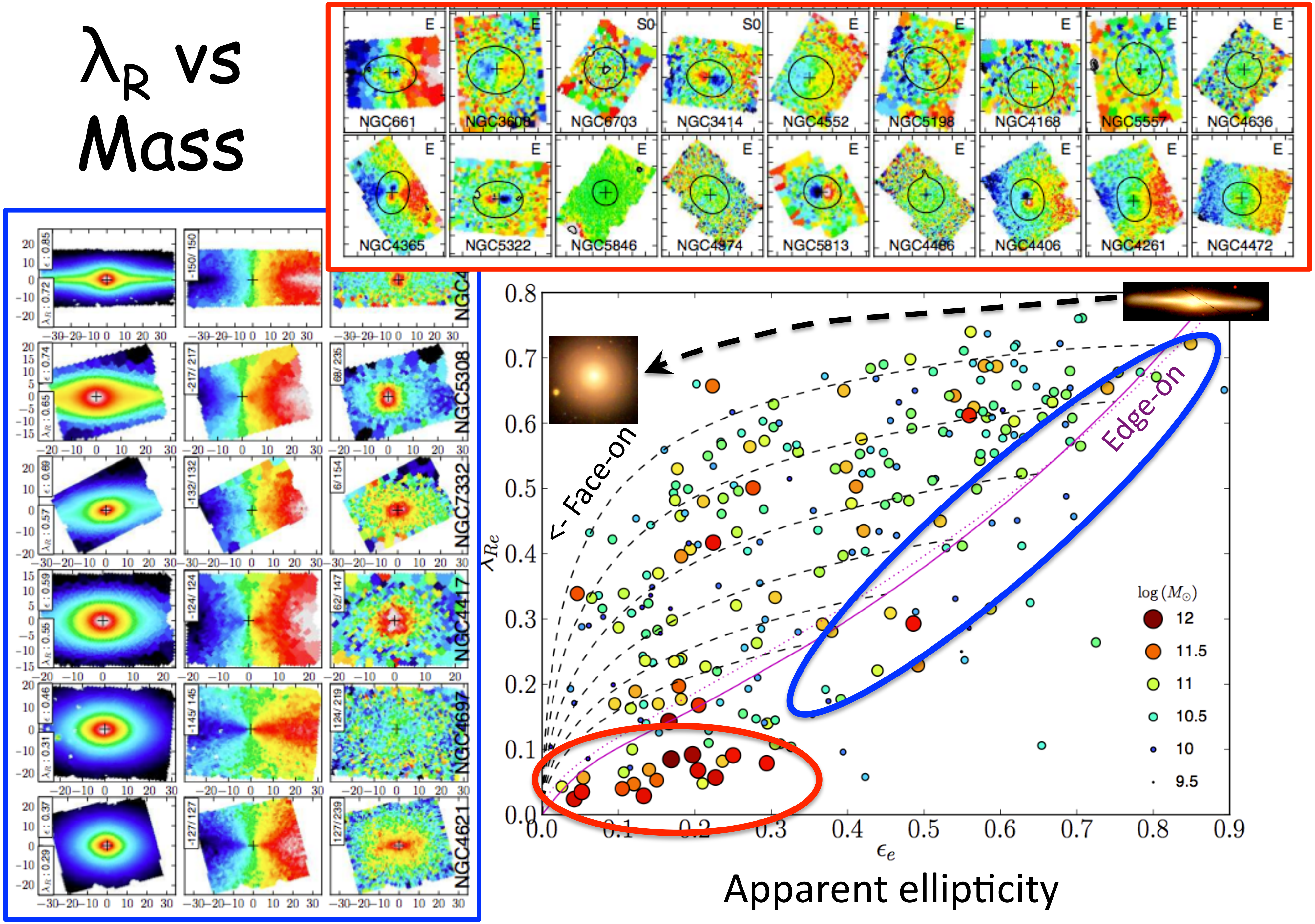
(33 researchers in ~16 institutes)

λ_R: radial profiles



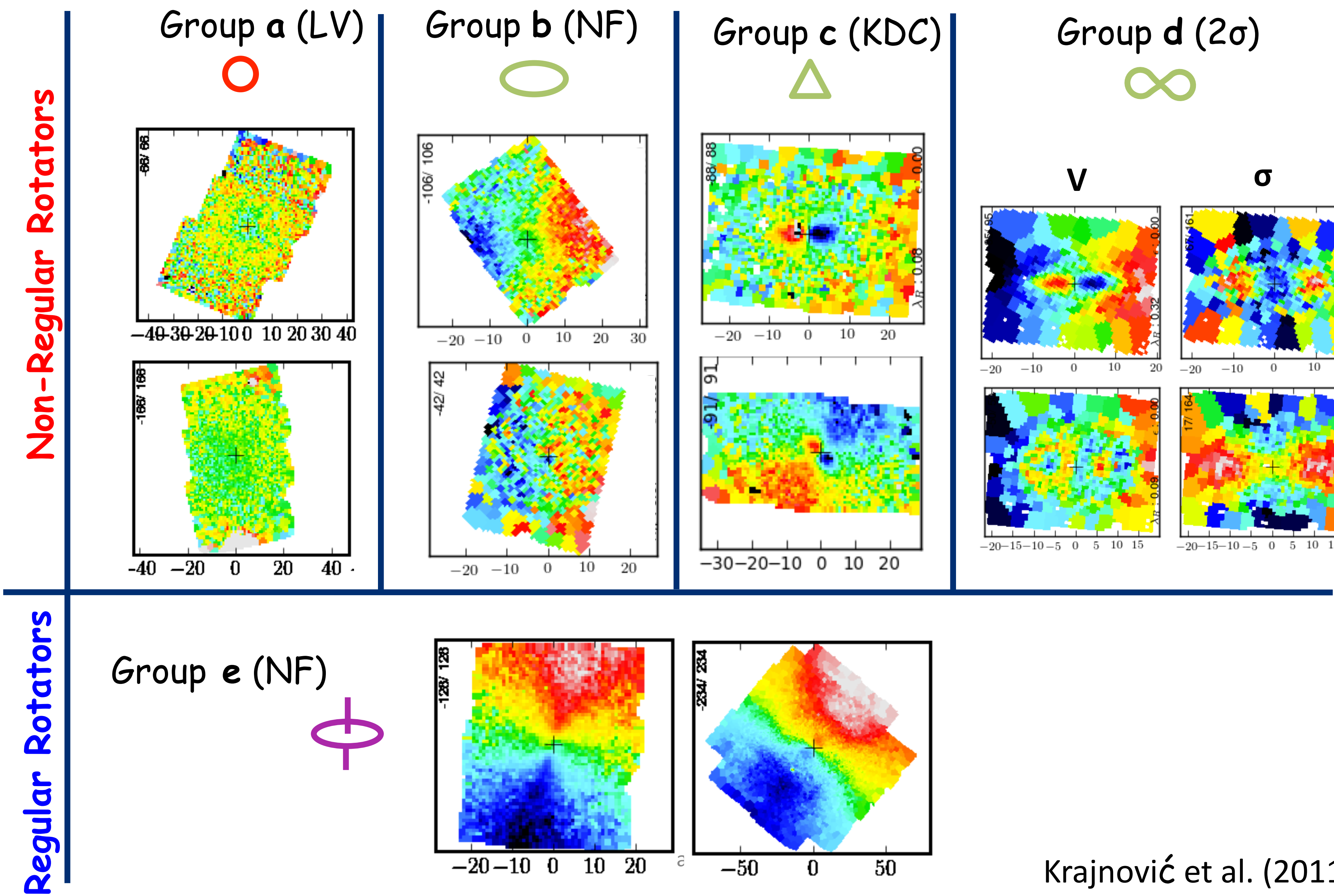
Emsellem et al. 2011

λ_R vs Mass



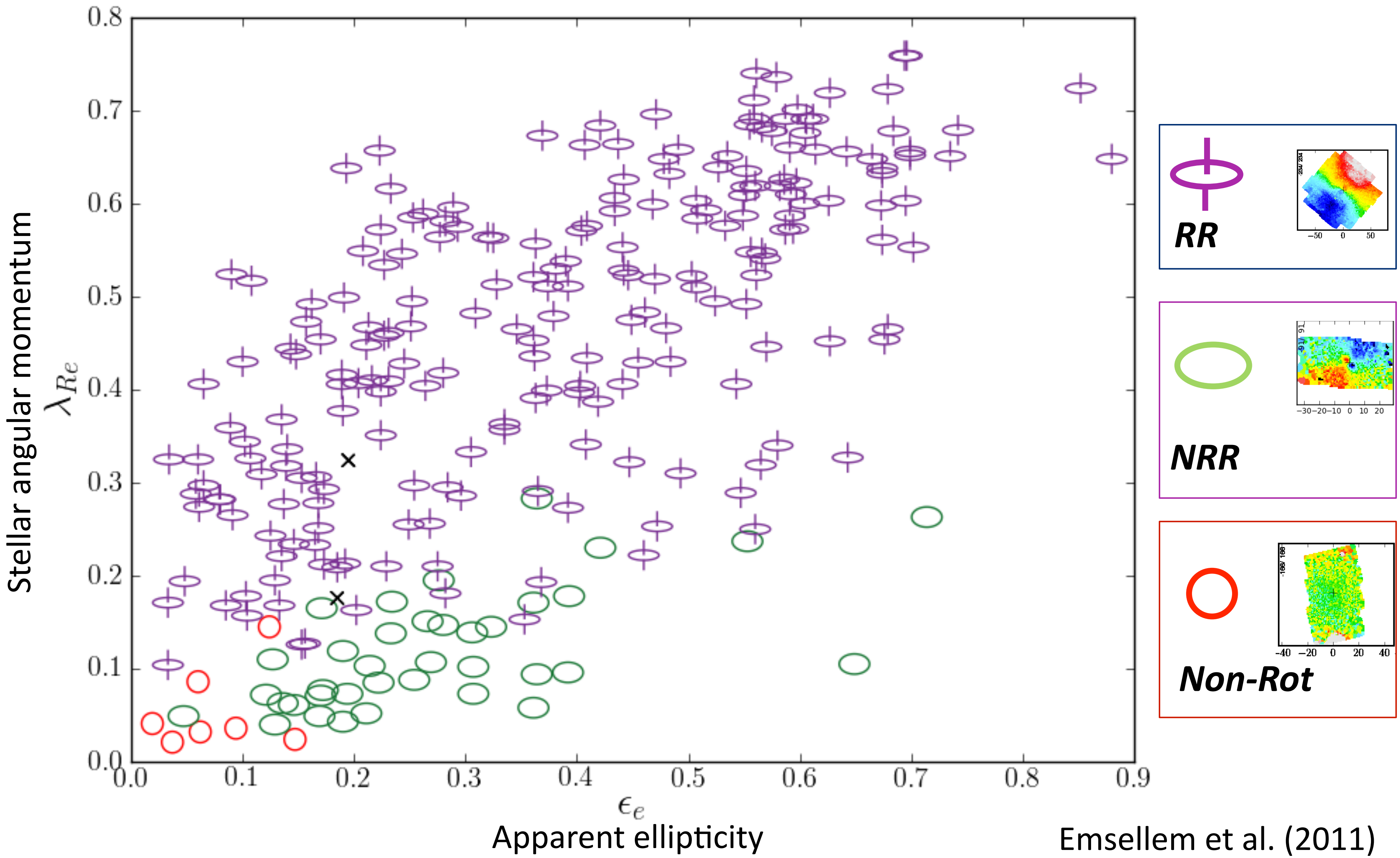
Emsellem et al. (2011)

Kinematic richness: classification



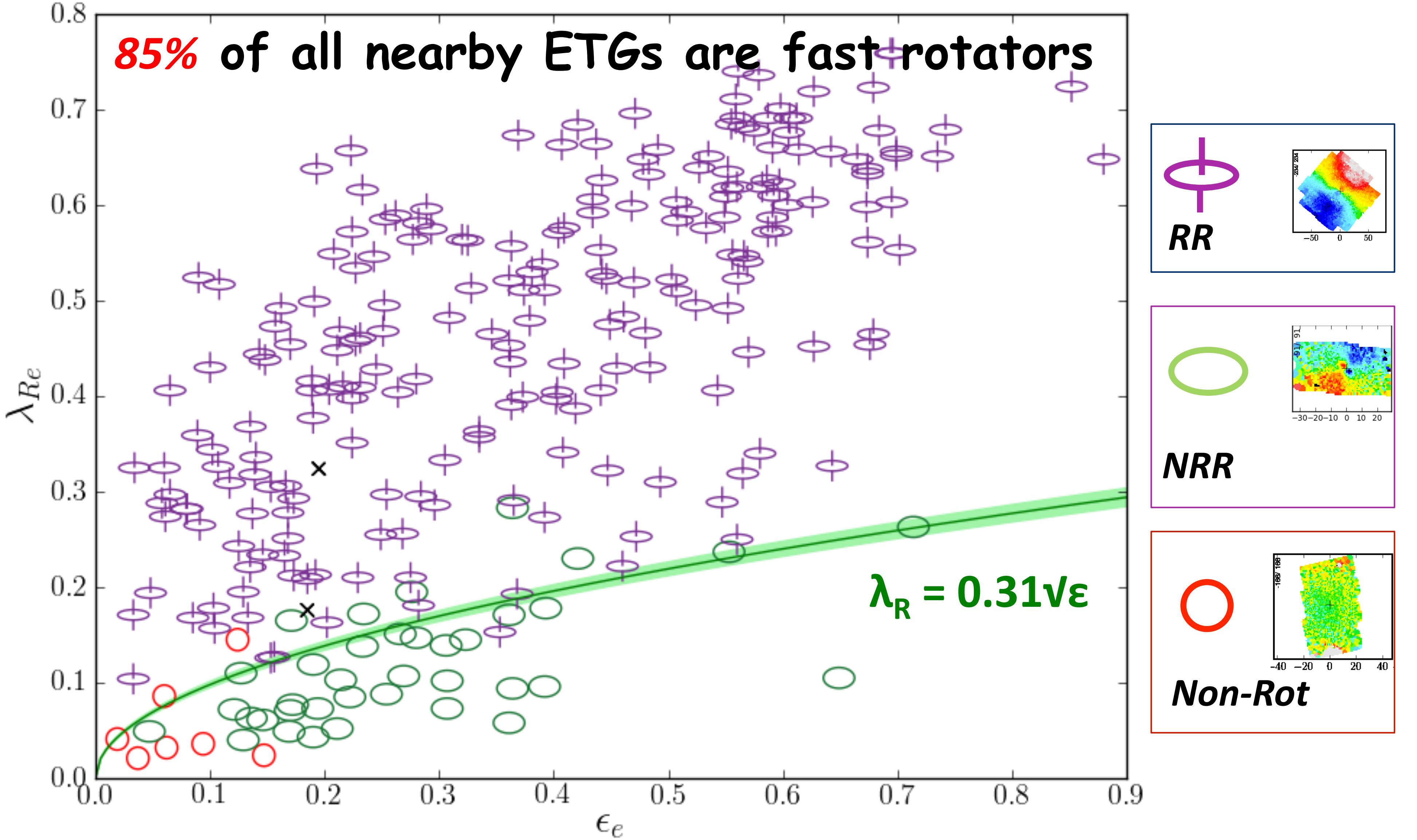
Krajnović et al. (2011)

λ_R: Stellar angular momentum ($1R_e$)



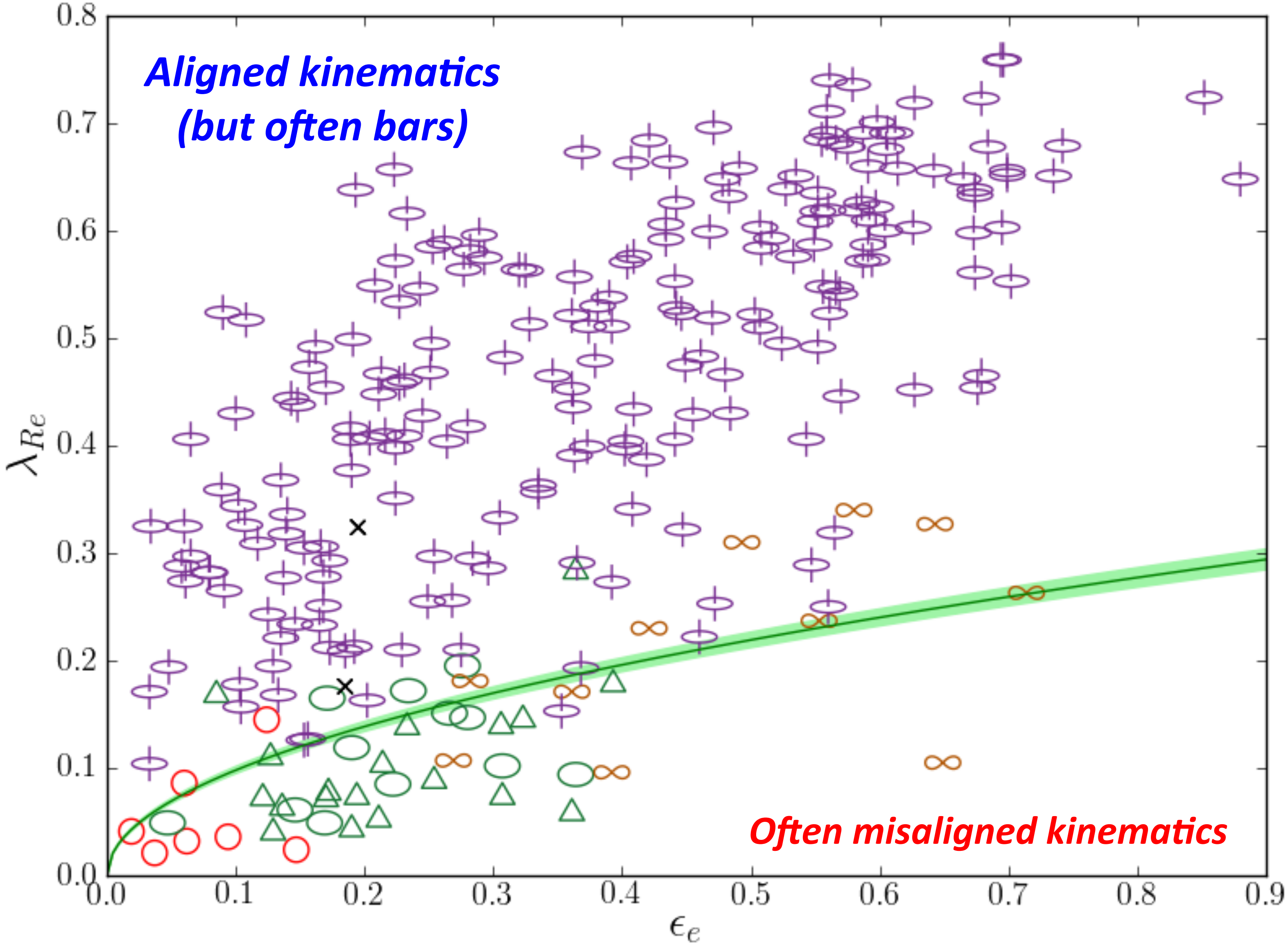
Emsellem et al. (2011)

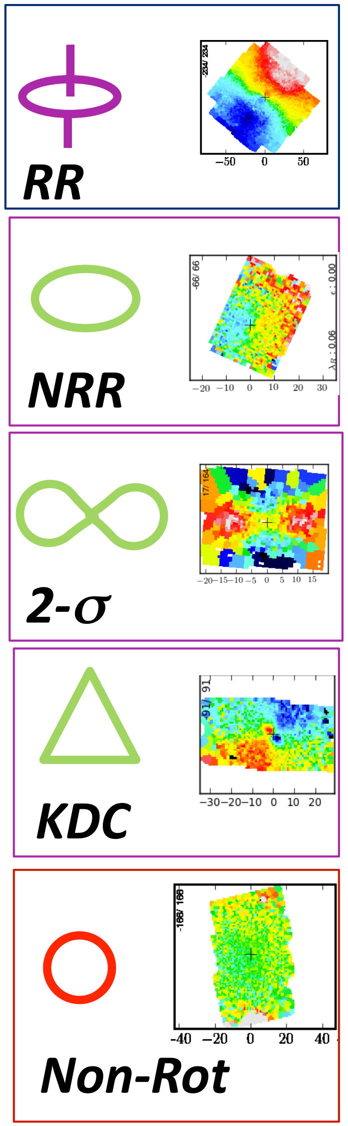
λ_R: Stellar angular momentum



Emsellem et al. (2011)

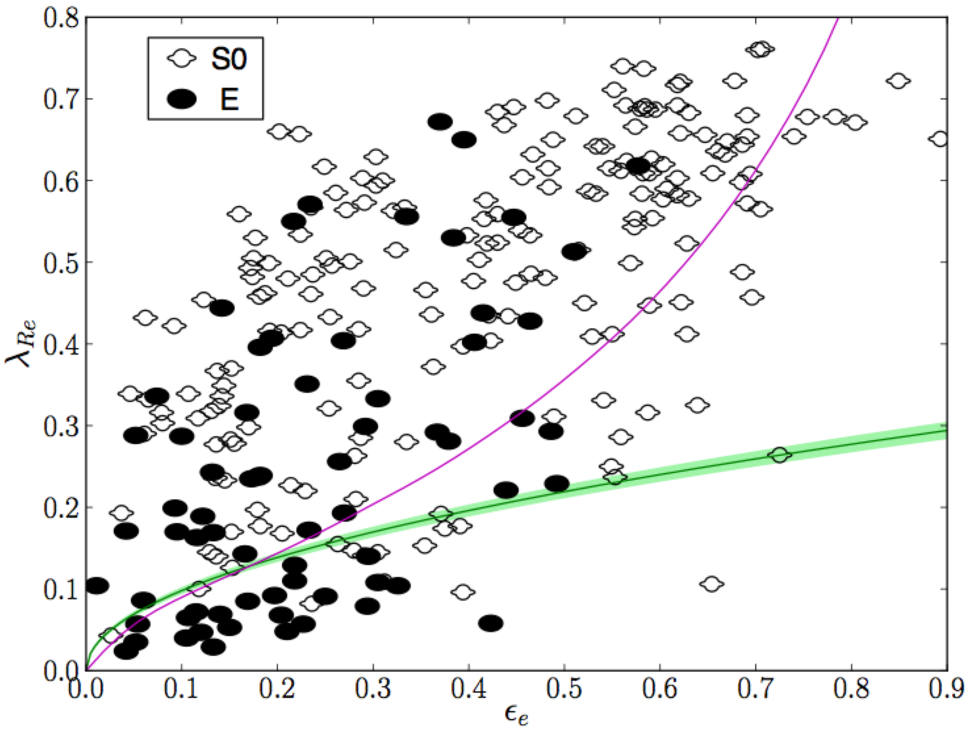
λ_R vs kinematic structure

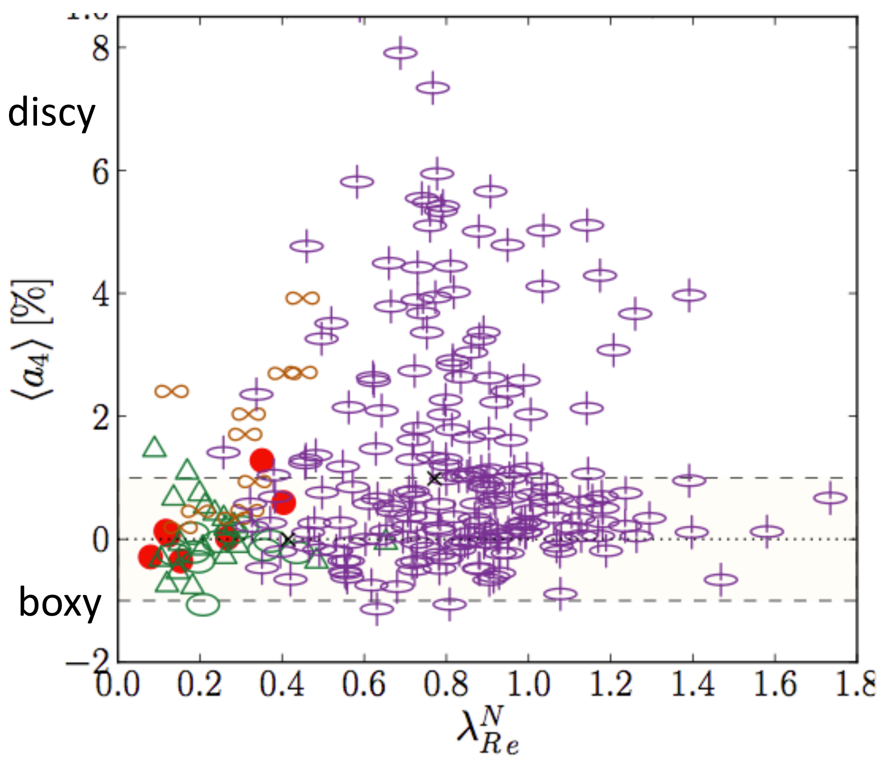




Emsellem et al. (2011)

λ_R vs Hubble classes





E 20% of **FR** are E

S0 66% of E are **FR**

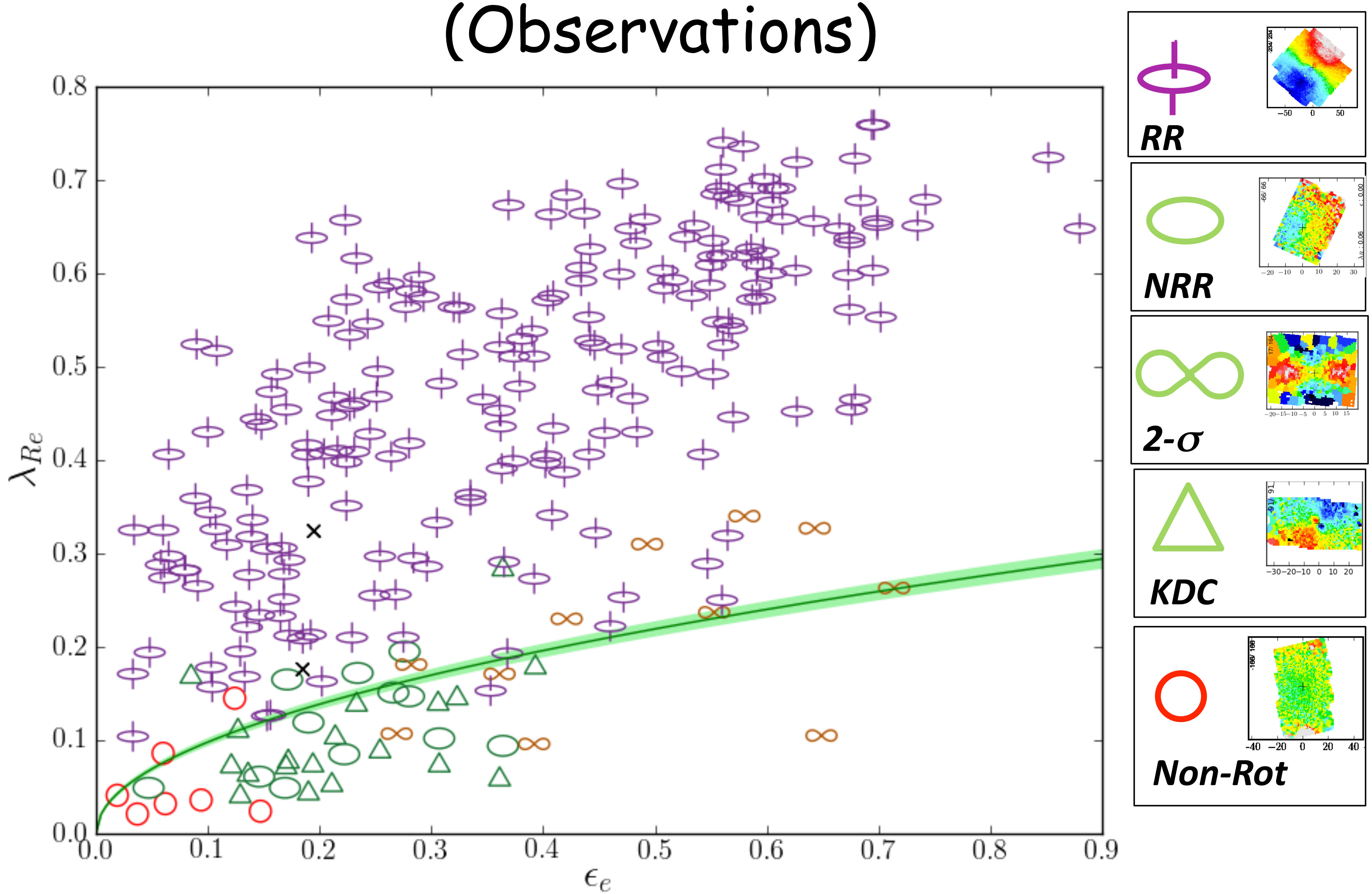
FR ≈ S0 + E(d)

SR = true ellipitcals

λ_R = physical parameter

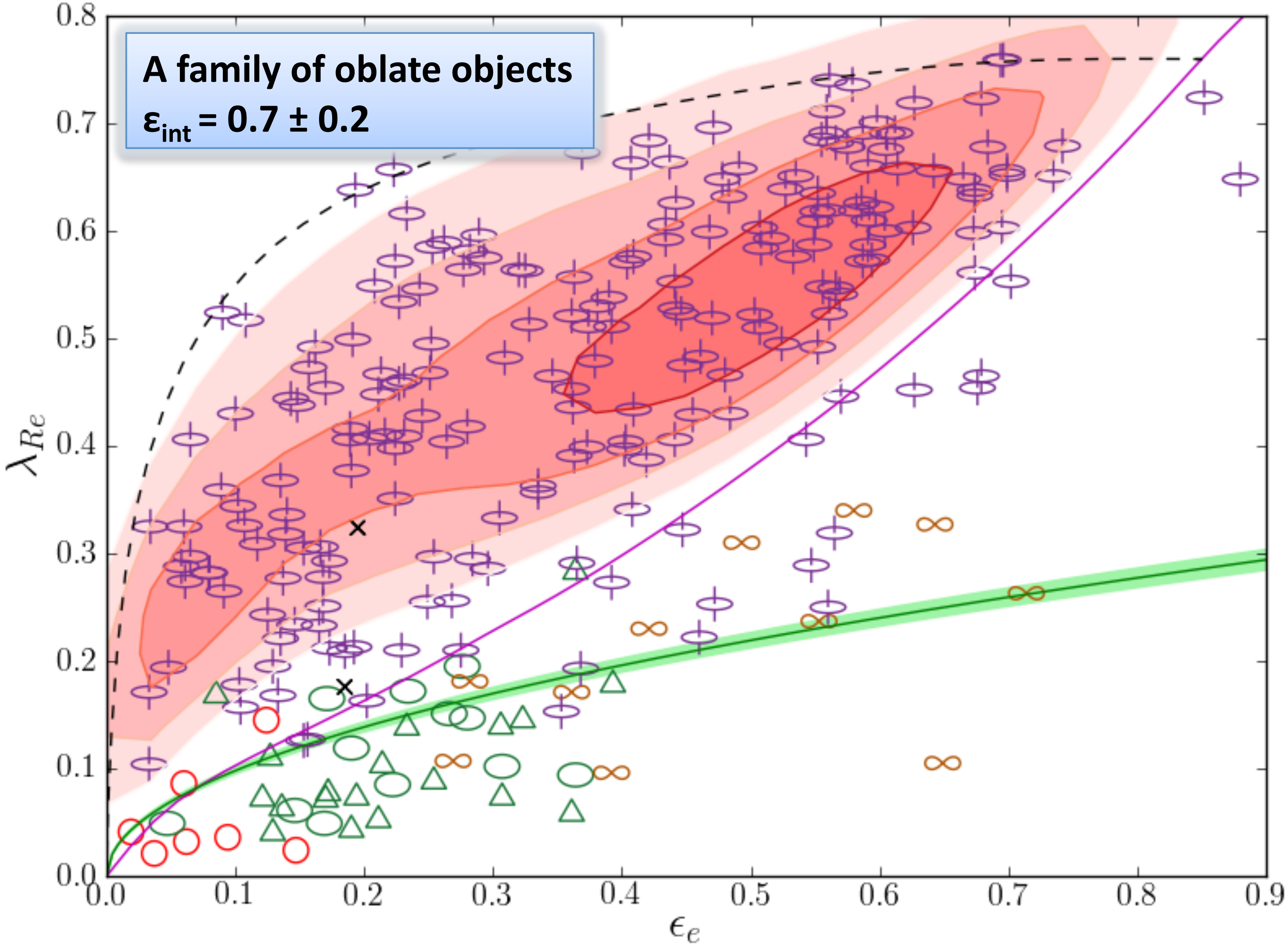
Emsellem et al. (2011)

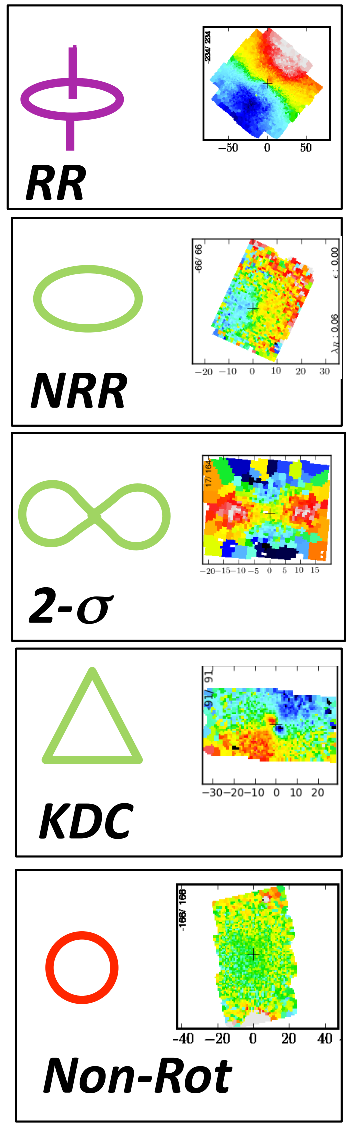
What are the nearby ETG?
(Observations)



Emsellem et al. (2011)

What are the nearby ETG?
(Observations)

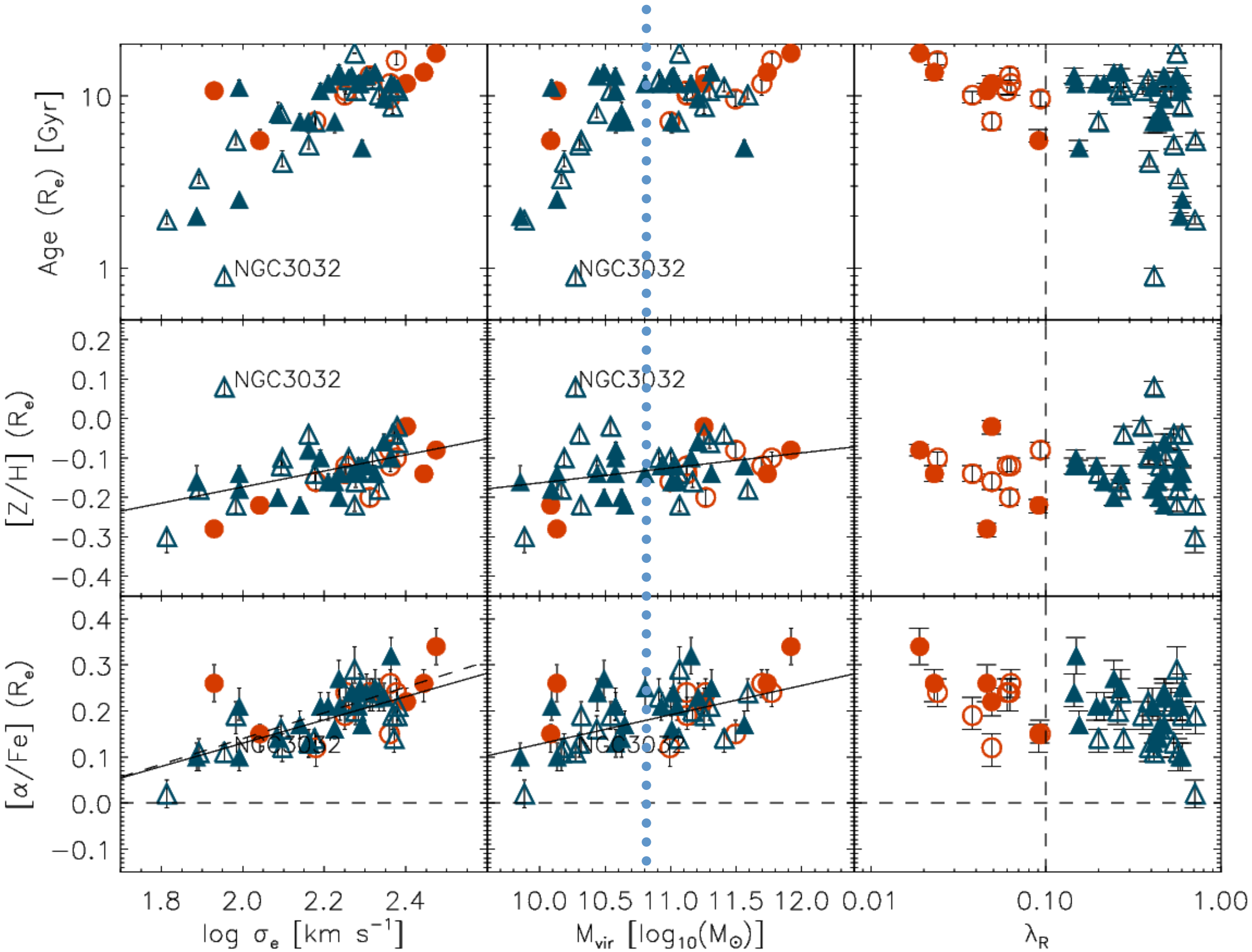




Emsellem et al. (2011)

Global 1Re age, Z, [Mg/Fe] - trends

Consistent with e.g. Thomas et al. 2005; Bernardi et al. 2005, 2006; Kuntschner et al. 2002; …



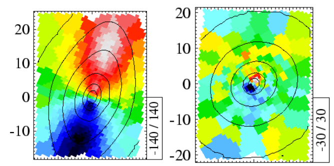
Low mass systems show scatter to young ages -> growth of red sequence

Mass - metallicity correlation

Mass - [α/Fe] correlation

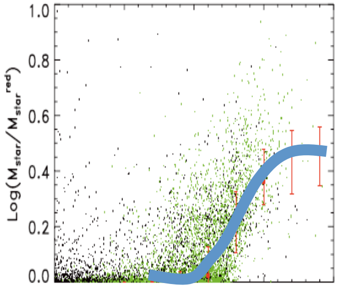
Fast rotator

Slow rotator



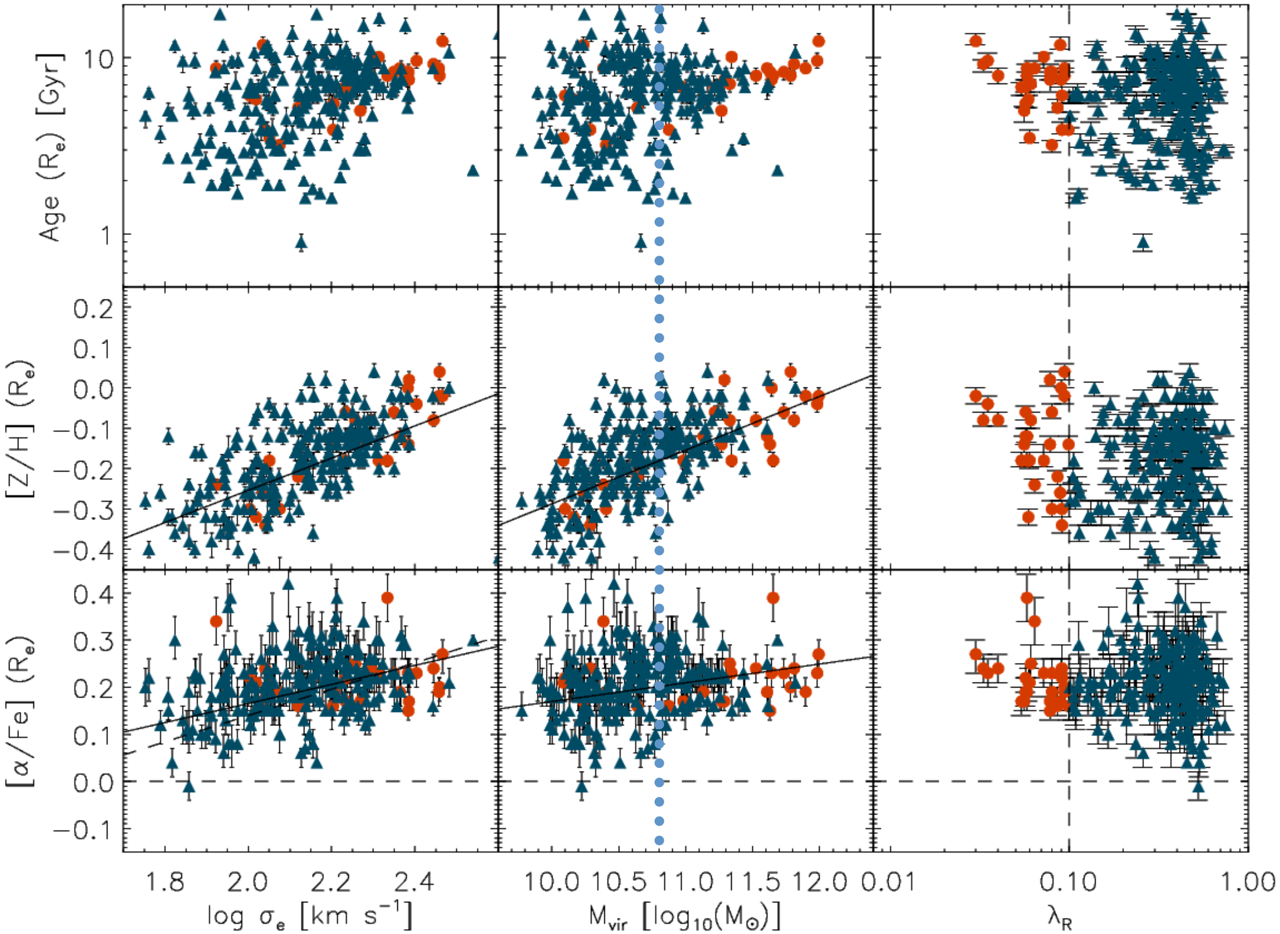
Kuntschner et al. 2010

- complete sample



Cattaneo et al. 2008

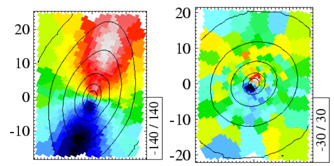
“dry”merging rate



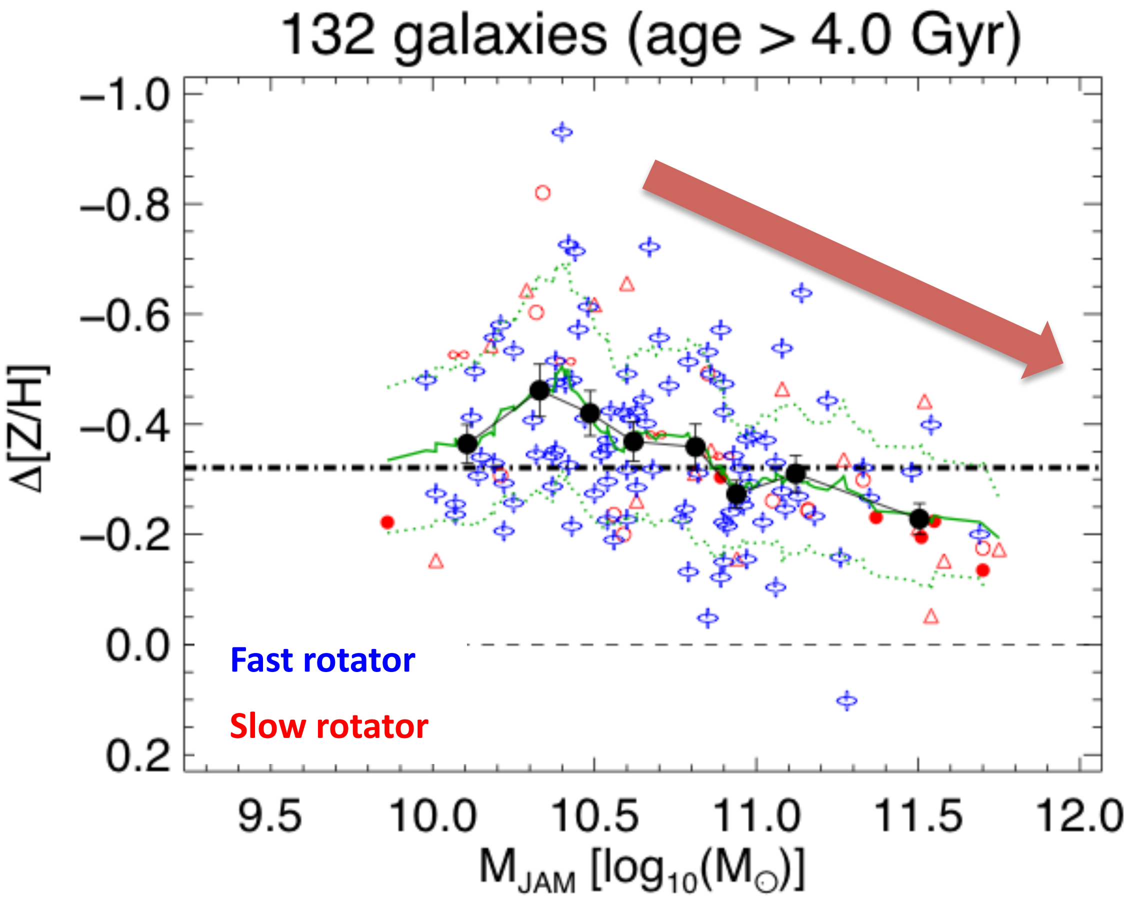
McDermid et al., 2011 in prep.

Fast rotator

Slow rotator



metallicity gradients



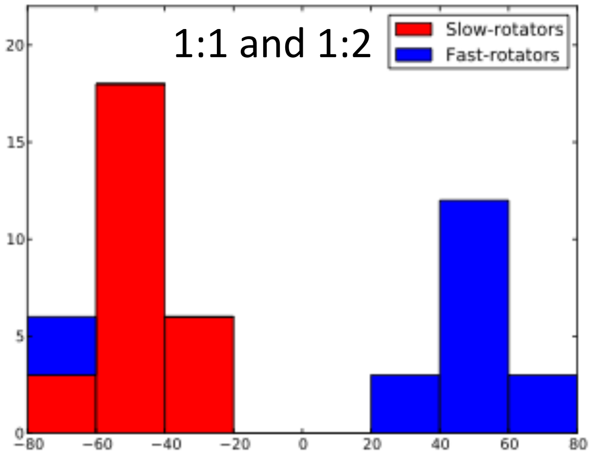
Change from gas-rich to increasingly gas-poor merging and accretion

Median Δ[Z/H] = - 0.32

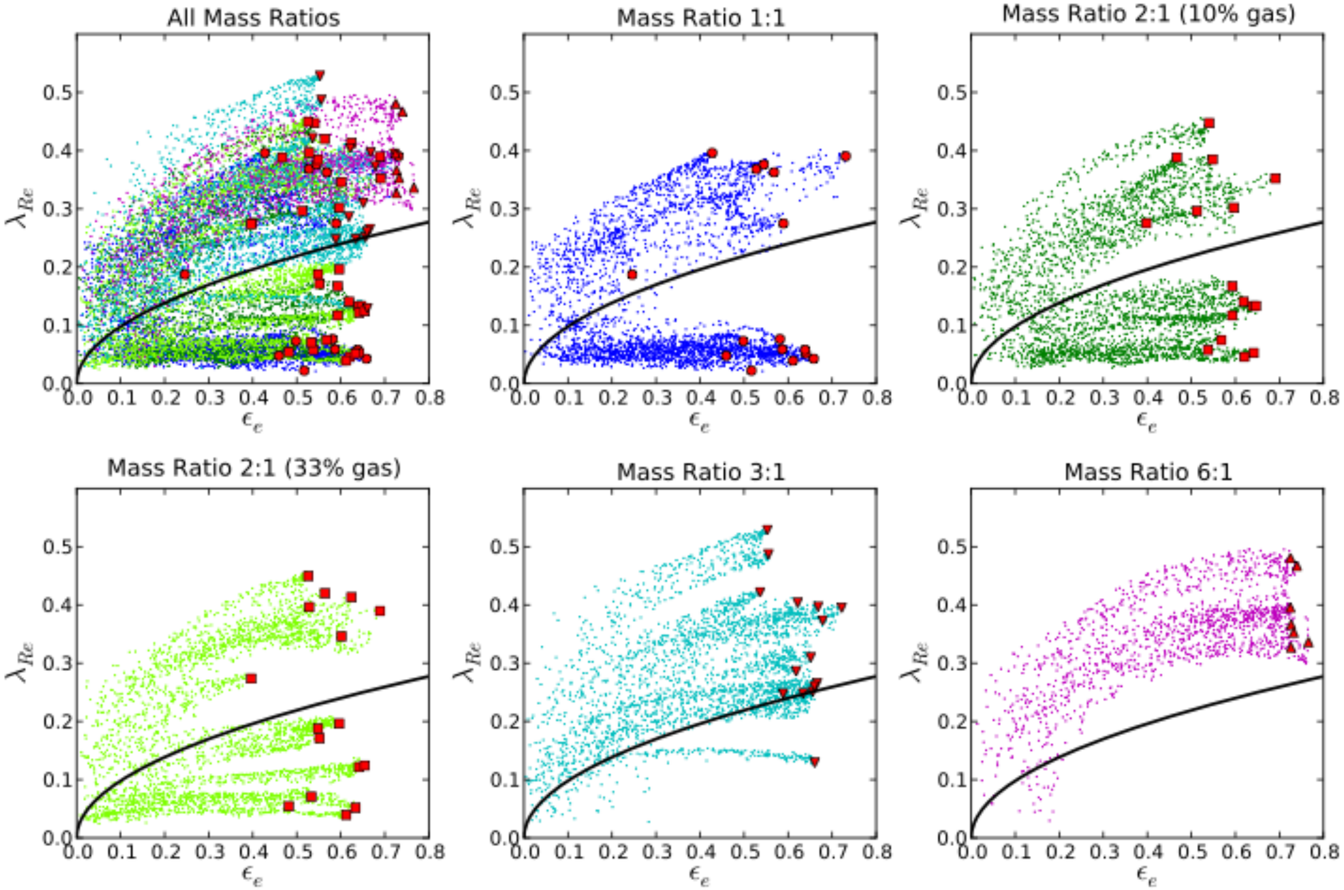
ETGs show on average negative [Z/H] gradients but trend with mass

Kuntschner et al. in prep

Idealized binary mergers



Inclination relative to the orbit



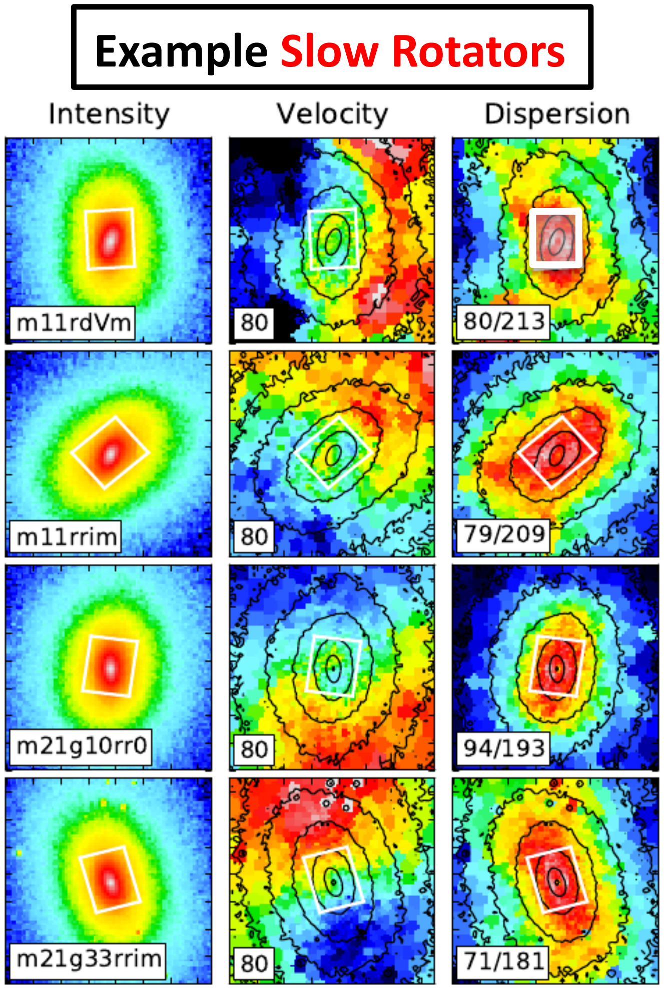
Sb - Sc disc mergers

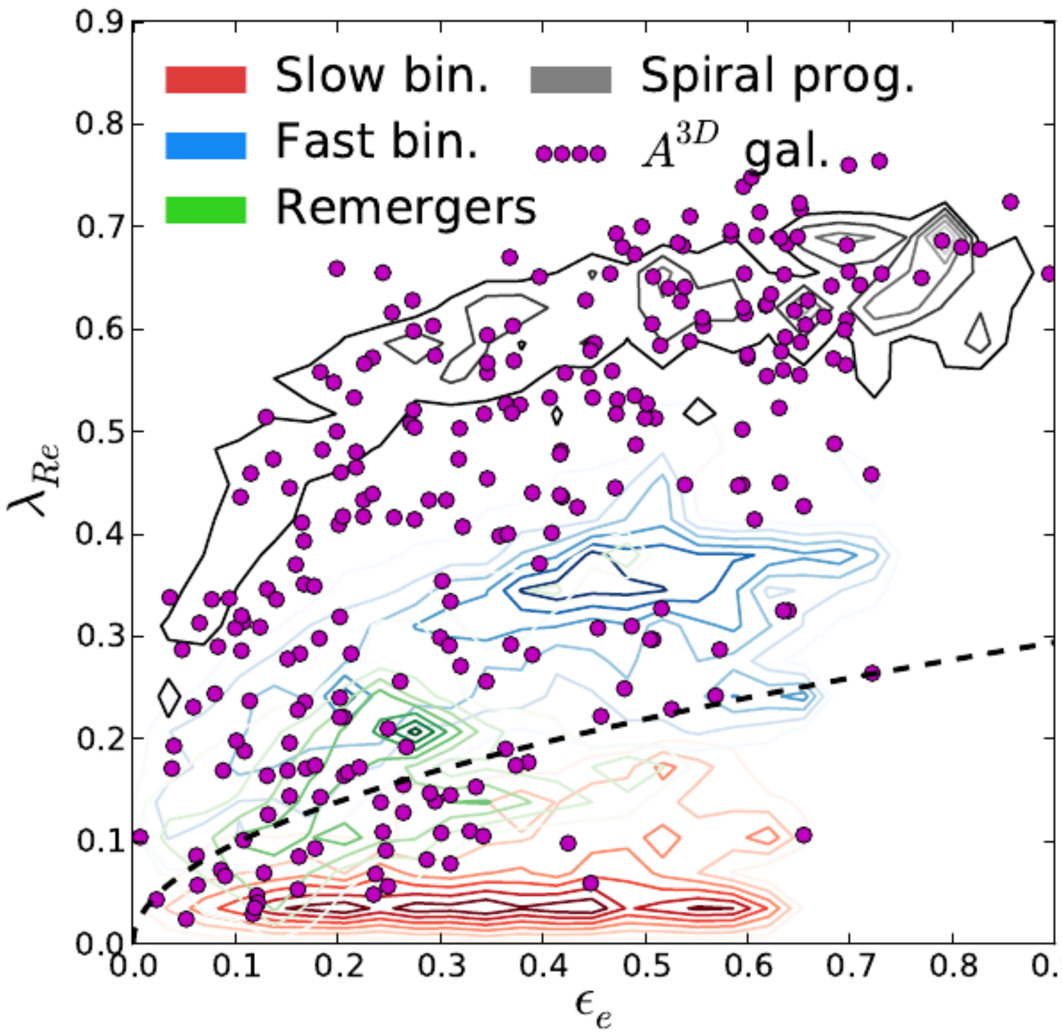
10% gas

- 1:1 and 2:1: form both FR and SR (retrograde spin wrt orbit)
- 3:1 and smaller: FR
- SR can be made in specific and violent major mergers

Bois et al. (2011)

Idealized binary mergers



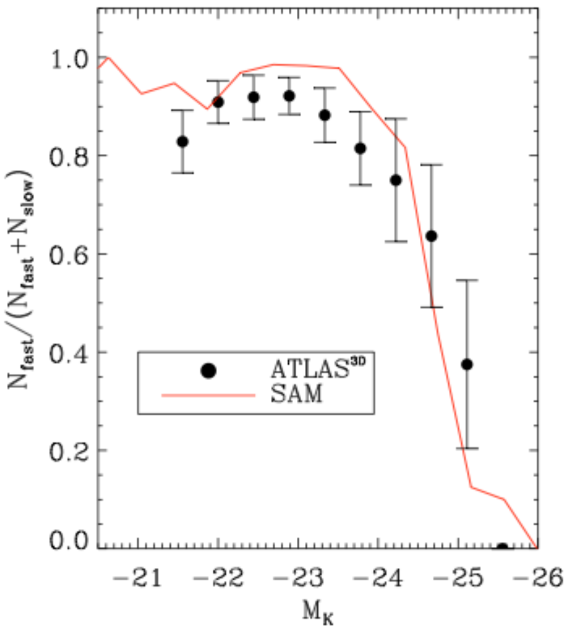


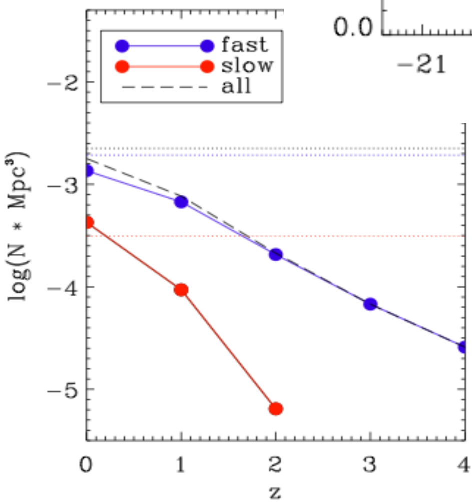
- Fastest ETGs are like spirals
- Slow rotators have KDCs, but are too flat
- Slow rotators are not velocity scaled FR

Bois et al. 2011

Semi-analytic modelling

Fraction of Fast Rotators





Prediction for redshift evolution

- Growth of **SR** and **FR** different
- **Slow Rotator**:
  - 50-90% of mass accreted from satellites
  - Up to 3 major mergers for most massive (z > 1.5)
- **Fast Rotator**:
  - Less then 50 % of mass accreted from satellites
  - Less then 1 major mergers
- Reason:
  - Slow-down and shut-down of gas cooling in massive galaxies
  - Star-formation stops in disks
  - Manifold satellite accretion causes destruction of disks and lowering of λ_R

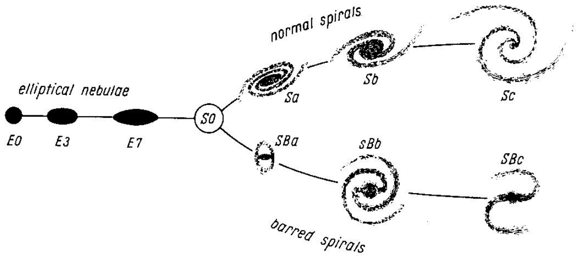
Khochfar et al. (2011)

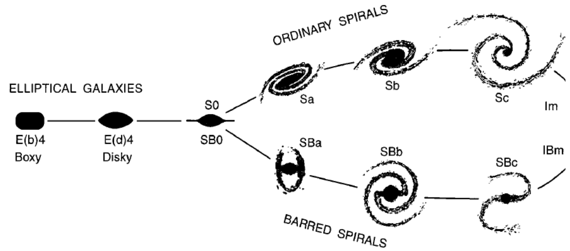
Census of ATLAS3D

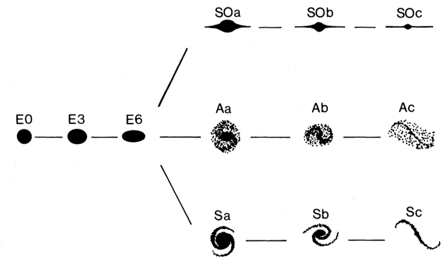
- **871 galaxies in the parent sample** of which
- 611 are spirals &
- **260 are ETGs** (70 Es & 190 S0s) of which
- 224 are fast rotators – oblate, disk-related objects

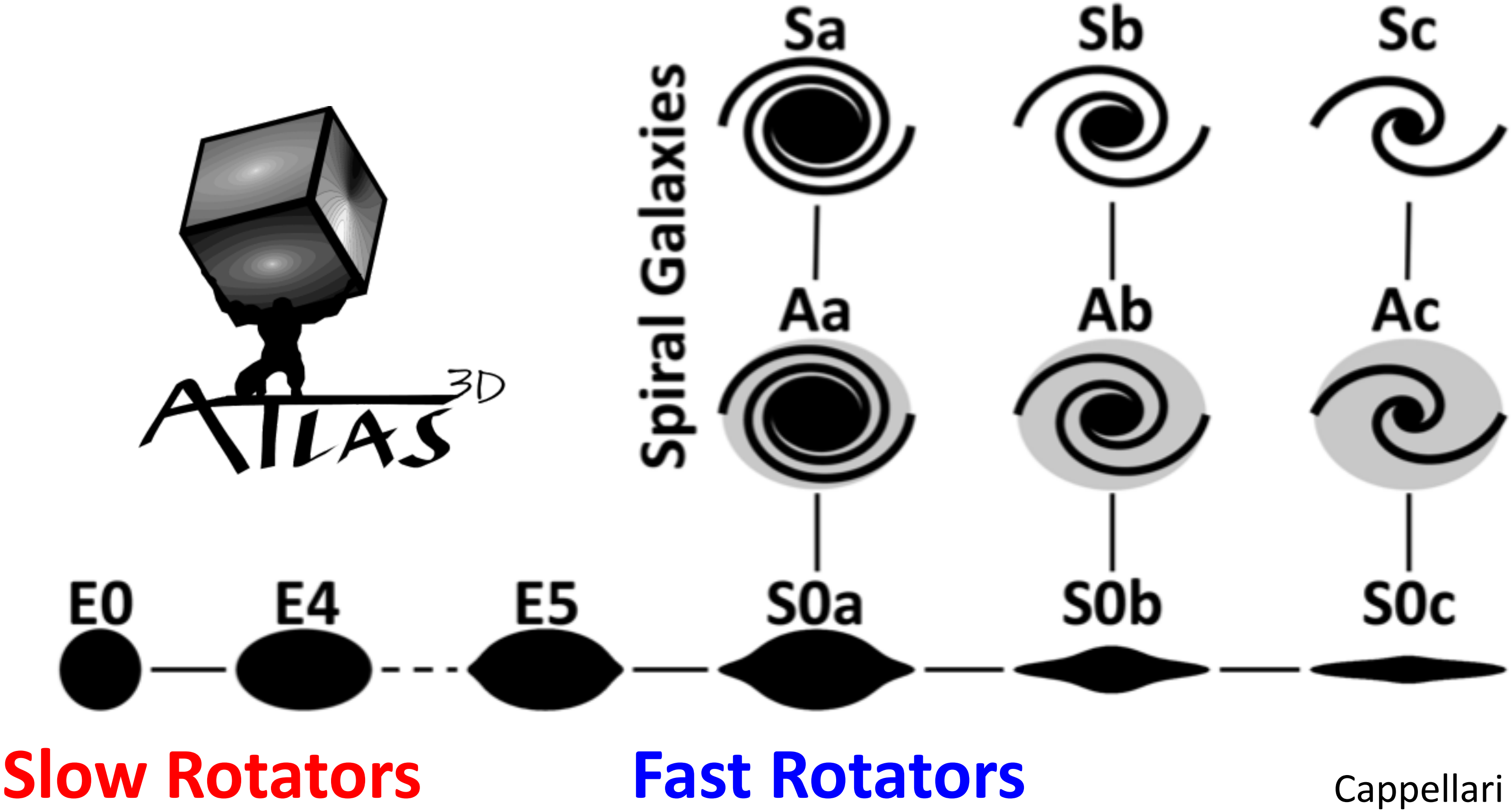
- Of the 36 slow rotators 4 have counter-rot disks
- Leaving 32 true, slowly rotating, "ellipticals"
- < 4% of the parent (volume limited) population
- < 6% in mass

A change of view









Cappellari et al. (2011)

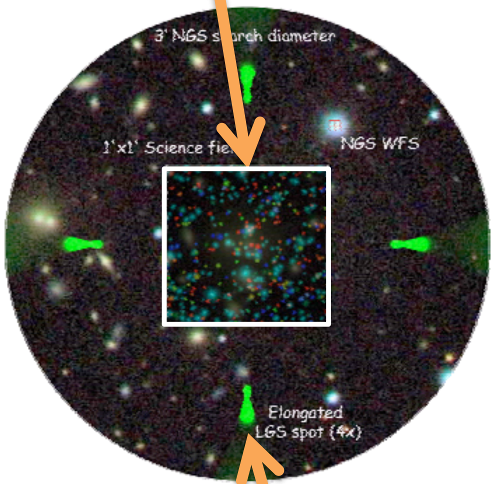
Conclusions

- Morphological E/S0 separation does not capture the physical differences among ETGs and should be abandoned.
- 86% of ETGs are "disk-like" with various amounts of star formation. These form parallel tracks in the Hubble diagram: "S0", anaemic & regular spirals, each can be barred.
  - 14% of ETGs have low angular momentum (predominantly, but not exclusively, the most massive). They are the "handle" in the Hubble diagram.
- **Fast Rotators:**
  - flattened, light & kinematically aligned ⇒ oblate, radially anisotropic, (young central disks or rings, flattened high metallicity component).
  - possibly evolved from z~2 hot disks, formed via cold streams + minor mergers/occasional major merger (e.g. disks of Förster-Schreiber et al.?)
- **Slow rotators:**
  - close to spherical (isophotes almost perfect ellipses), roundish $\varepsilon < 0.4$, often have large misalignments between light & kinematics ⇒ mildly triaxial, close to isotropic, can host large and old KDCs.
  - likely formed though (a few) major mergers ($z > 1.5$) and accrete most of mass from satellites.

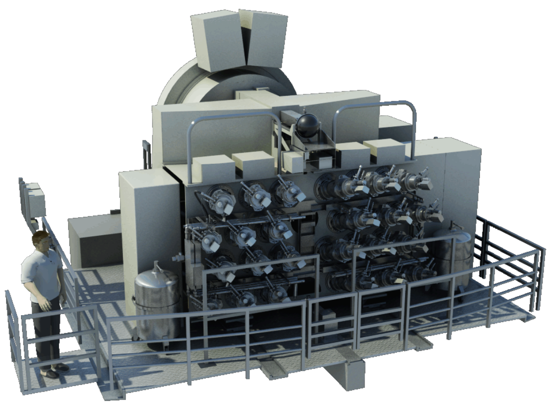
MUSE at ESO VLT

(Multi Unit Spectroscopic Explorer)

1’x1’ FoV (Q4 2013)



AO with Lasers (~2015)



90,000 spectra in one shot (Q4 2013)

Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 $arcmin^2$
Spatial sampling	0.2x0.2 $arcsec^2$
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I_{AB} = 25.0 (R=3500)
	I_{AB} = 26.7 (R=180)
Limiting Flux in 80h	3.9 10^{-19} $erg.s^{-1}.cm^{-2}$

PI: Roland Bacon (CRAL, Lyon, France)

CRAL Lyon · ESO · Sterrewacht Leiden · Observatoire Midi-Pyrénées OMP · Institut für Astrophysik Göttingen · ETH · AIP