



AIP



Angular momentum and nuclear surface brightness profiles

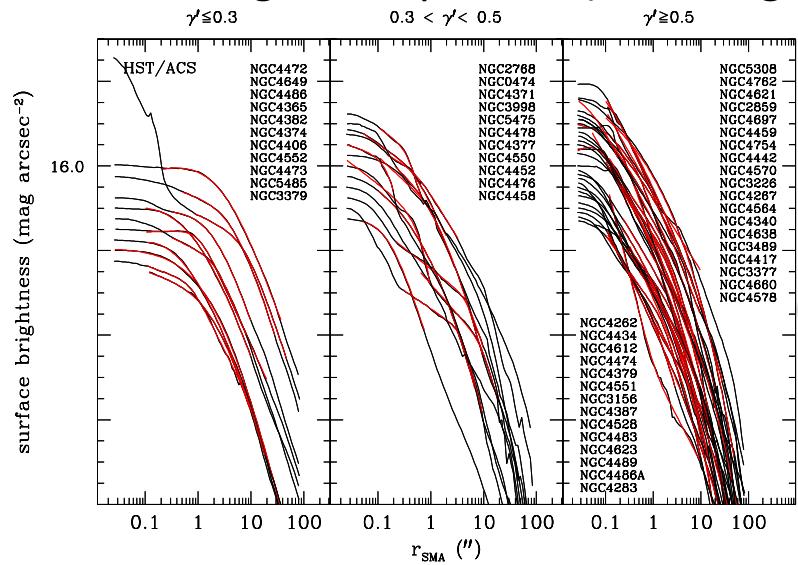
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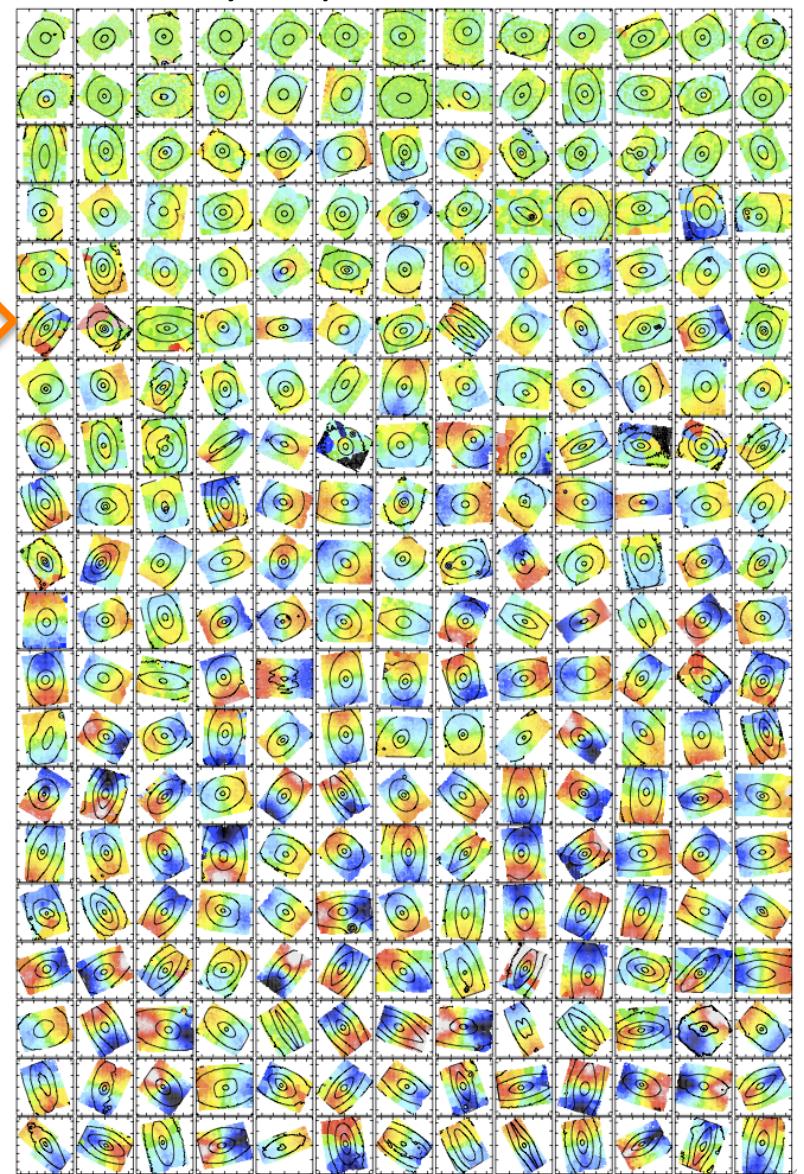


Complex formation paths make complex systems

Surface brightness profiles (HST imaging)



Velocity maps, SAURON IFU



- Is there are link between kinematics and nuclear structure?
(e.g. Faber et al. 1997)
 - Core = low V/σ
 - Core-less = high V/σ
- A new view of kinematics with integral-field spectrographs

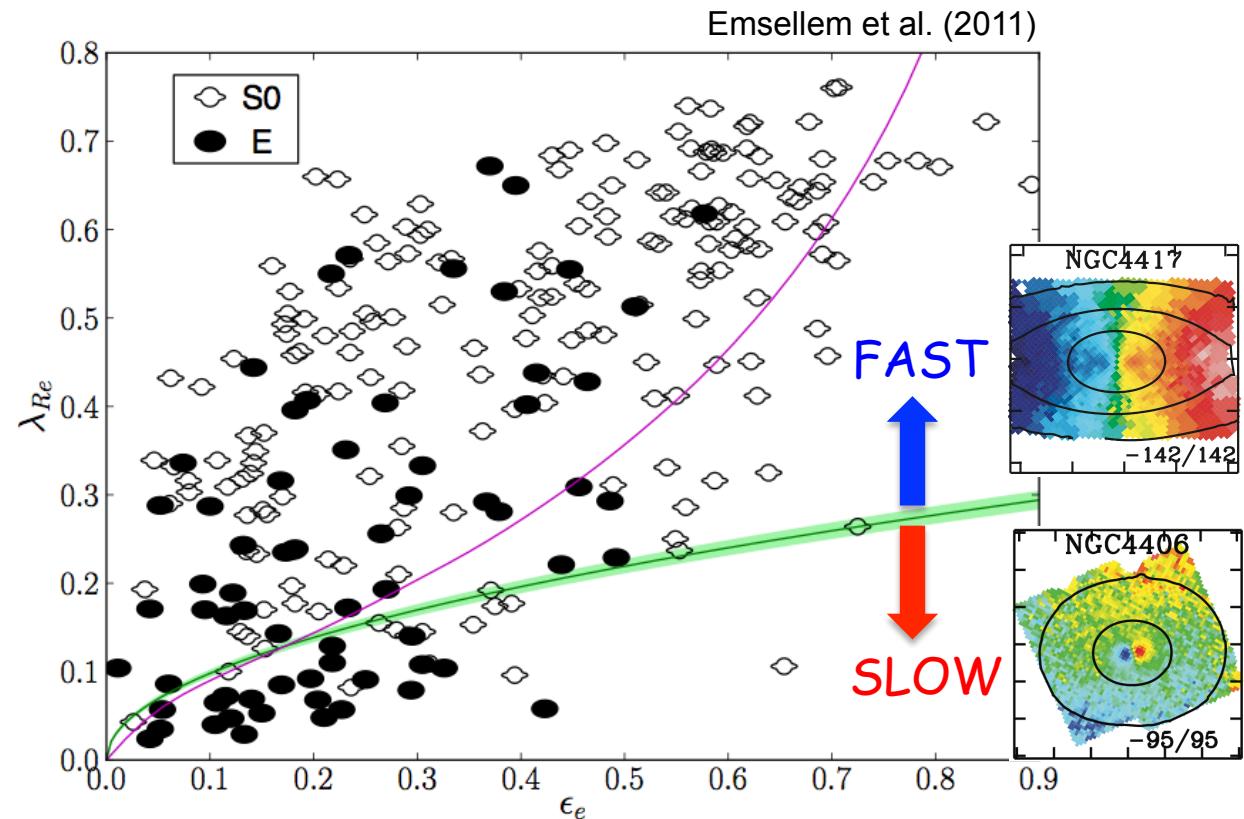
Specific angular momentum - λ_R

- Kinematic classification using ***specific angular momentum*, λ_R**

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

- Fast rotators
 - Regular, disk-like velocity maps
 - Axisymmetric, with (embedded) disks
- Slow rotators
 - Non-regular velocity maps, KDCs, no net rotation
 - Weakly triaxial, spherical

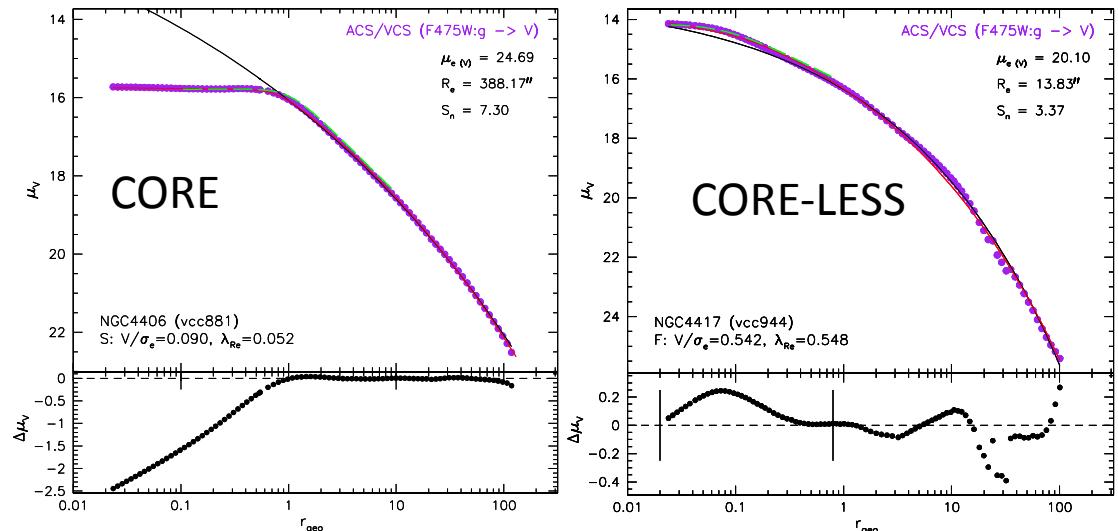
Emsellem et al. (2004, 2011), Cappellari et al. (2011b, 2012b), Krajnović et al. (2011, 2012), Weijmans et al. (2013)



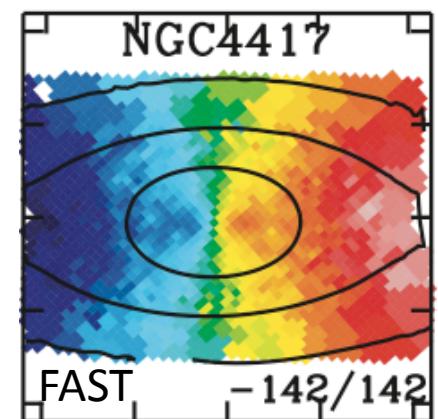
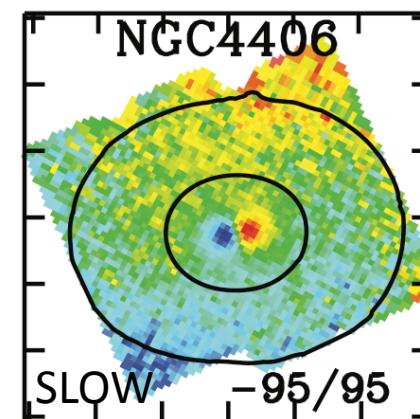
- **66% of E are FR**
- **20% of FR are E**
- $FR \approx S0 + E(d)$
- SR = “true” ellipticals

Two flavours of ETGs?

- Cores created by shrinking SMBH binary removing stars on intersecting orbits (e.g. Begelman et al. 1980; Milosavljević & Merritt 2001 ...)
- Angular momentum depends on the merger history (Jasbeit et al. 2009; Naab et al. 2006; Cox et al. 2006; Robertson et al. 2006; Bois et al. 2011)
- Processes on different scales, but linked
- Is core = slow and core-less = fast?
- What if not?

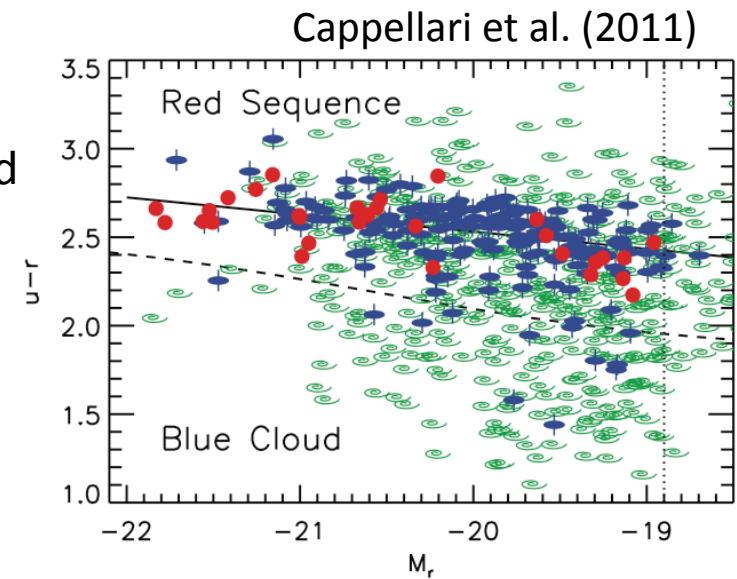


Emsellem et al. 2004, Krajnović et al. (2011, 2013)



HST imaging of ATLAS^{3D} Sample

- ATLAS^{3D} sample:
 - 260 ETGs from a complete sample of all galaxies with $M_K > -21.5$ and $D < 42$ Mpc
 - morphologically selected (no colour cut)
- HST overlap:
 - 135 galaxies observed with WFPC2 and ACS (and NICMOS, WFC3)
 - Heterogeneous analysis: 86 profiles published (Lauer et al. 2005, 2007, Ferrarese et al. 2006)
 - **Re-analysed 104 objects**
- Explored variety of light profiles
 - Core-Sersic (Graham et al. 2003), single Sersic (1968), Nuker (Lauer et al. 1995)
 - Data inhomogeneity: diverse instruments/filters, spatial extent
 - Only interested in the core/no-core classification
 - Decided on Nuker law
 - **Core:** $\gamma' (0.1'') \leq 0.3$
 - **Core-less:** $\gamma' (0.1'') > 0.3$

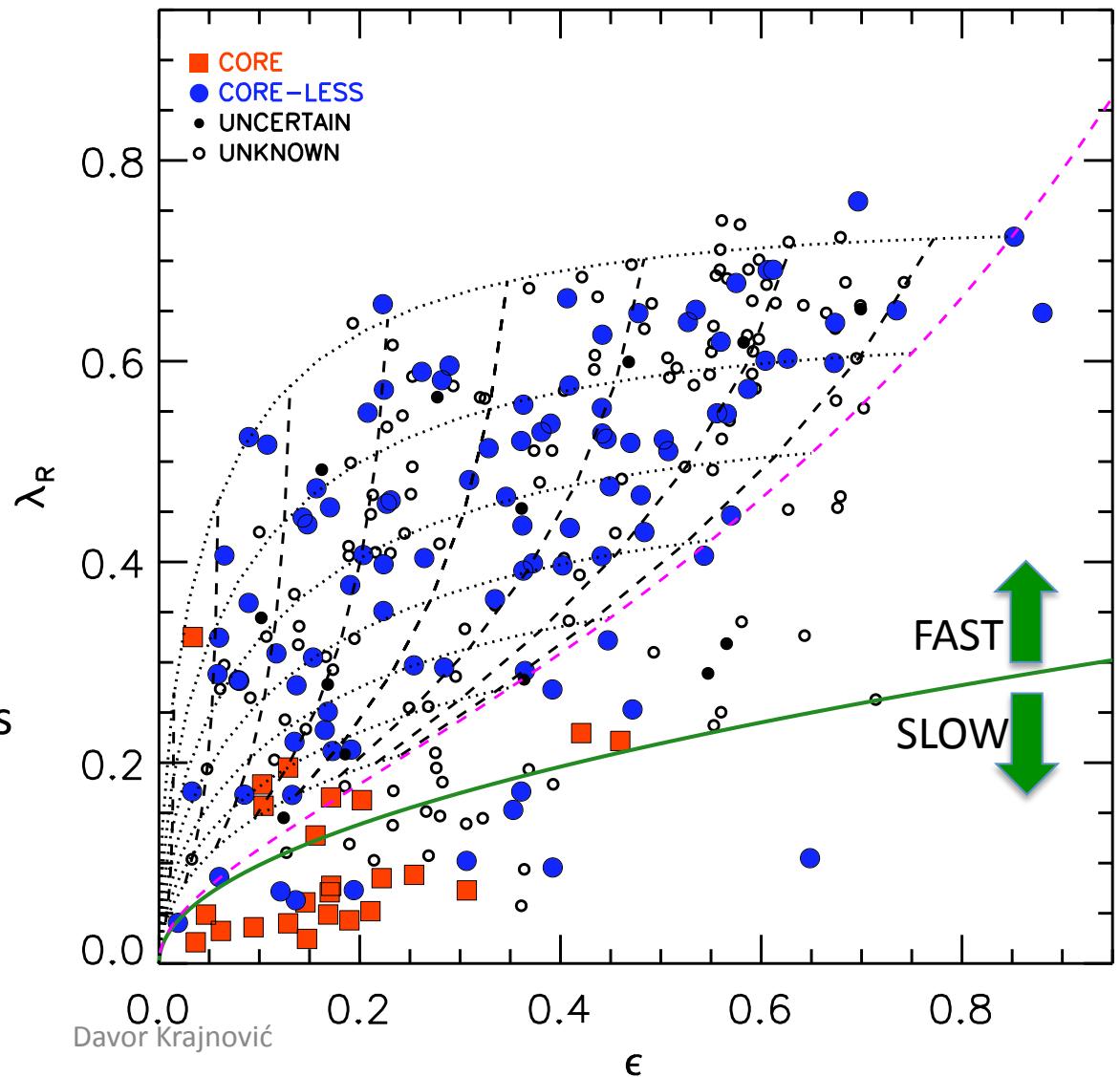


λ_R vs ϵ with nuclear profiles

- Fast rotators -> core-less
- Slow rotators -> core

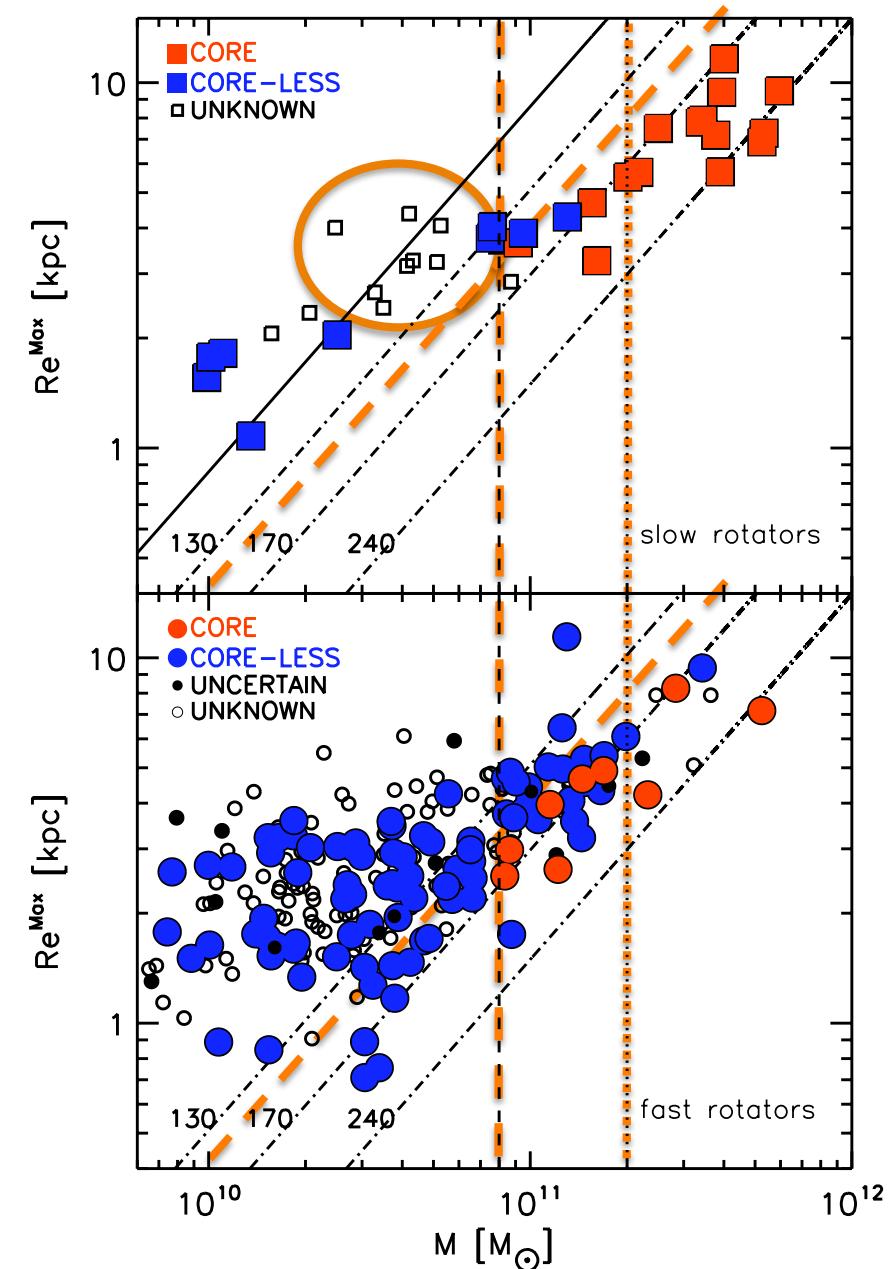
BUT

- 9 core FR
- 9 core-less SR + as many more unknown
- What are core FR?
 - SR (e.g. Lauer 2012)?
 - if not, how are the cores made/preserved?
- What are core-less SR?
 - how to make them?



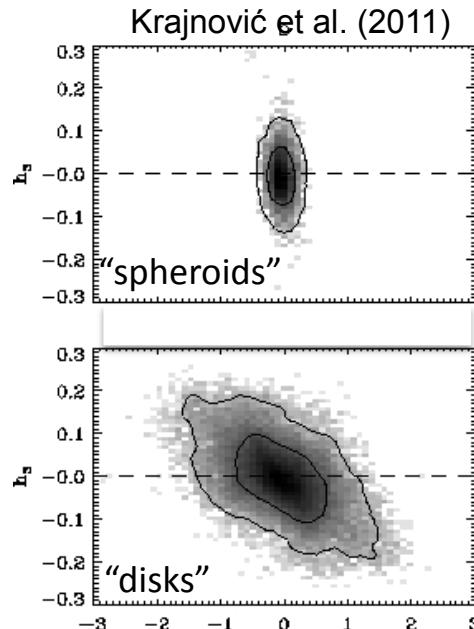
Mass - size

- Cores **only** for
 - $M > 8 \times 10^{10} M_{\text{sun}}$
 - $\sigma > 160 \text{ km/s}$
 - $\lambda_R < 0.25$
- Slow rotators
 - Only cores above $\sim 2 \times 10^{11} M_{\text{sun}}$
 - “mixed” region: $0.8-2 \times 10^{11} M_{\text{sun}}$
 - Low mass SR might not have cores, but no data!
- Fast rotators
 - Cores and core-less mix at all masses above $8 \times 10^{11} M_{\text{sun}}$

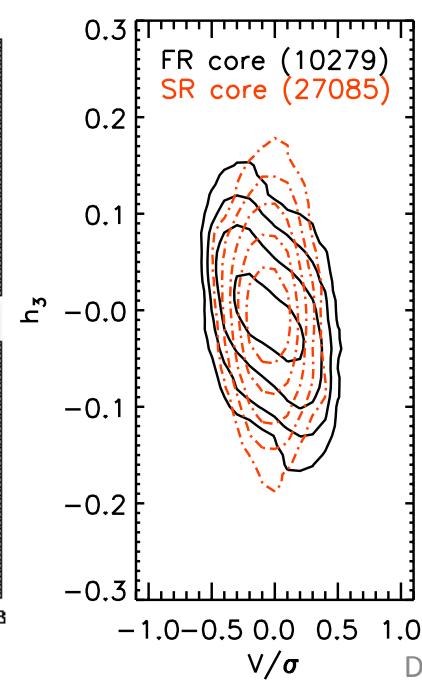


Dynamical state of core FR

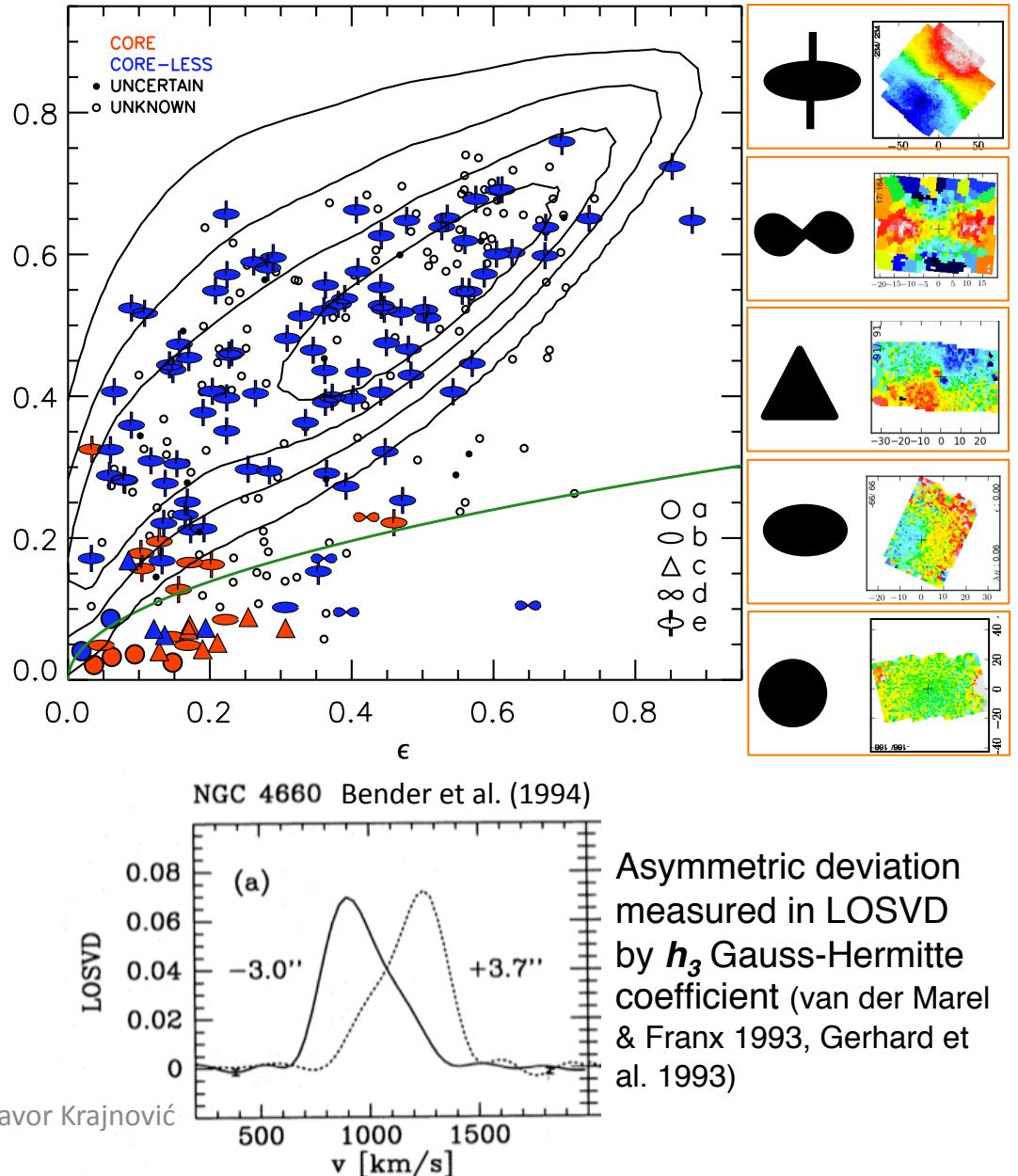
- Ordered disk-like rotation (like other FR)
- $V/\sigma - h_3$ anti-correlation
- A number (not all) contain embedded disks



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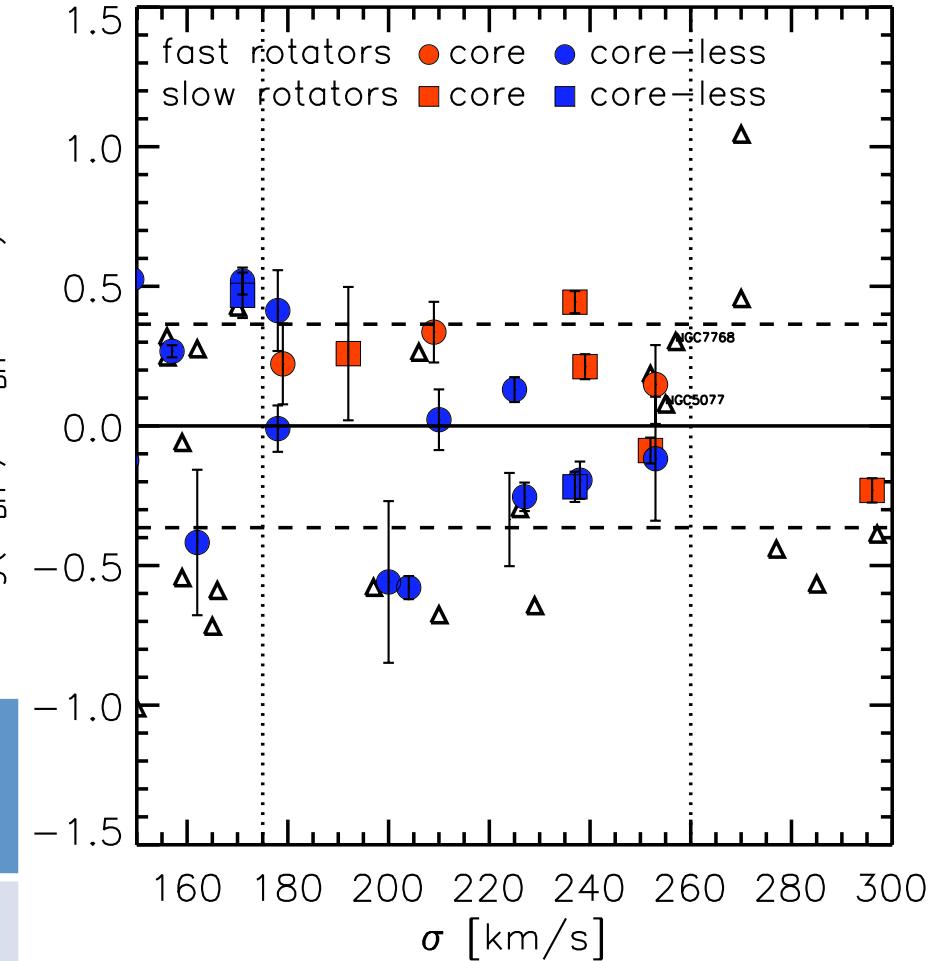


Black holes in core FR

- Different relations for core /core-less galaxies (e.g. McConnell & Ma 2013, Graham & Scott et al. 2013)
- $\log M_{\text{BH}} - \log M_{\text{BH}}^{\text{predicted}}$ (using best fit to all data from Graham & Scott et al. 2013)
- What about core and core-less FR?
 - $175 < \sigma < 260 \text{ km/s}$
 - Similar M_{BH} in *core FR* and *core SR* (for same σ range)
 - Tentative result dependent on low number statistics

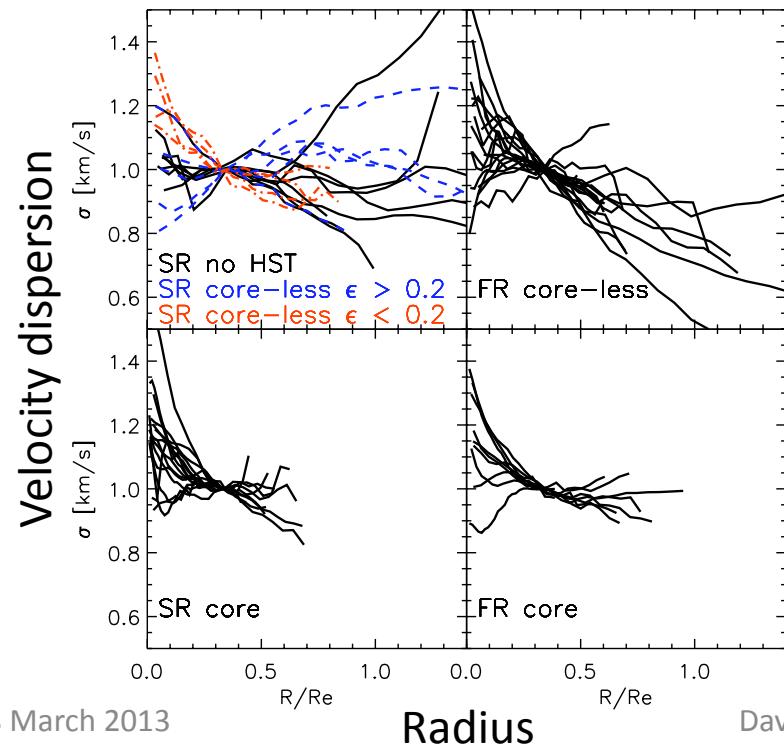
Weighted mean and error for $\log(M_{\text{BH}}/M_{\text{BH}}^{\text{pred}})$

ΔM_{BH} core SR	ΔM_{BH} core FR	ΔM_{BH} core-less FR
0.22 ± 0.02	0.24 ± 0.07	-0.19 ± 0.02



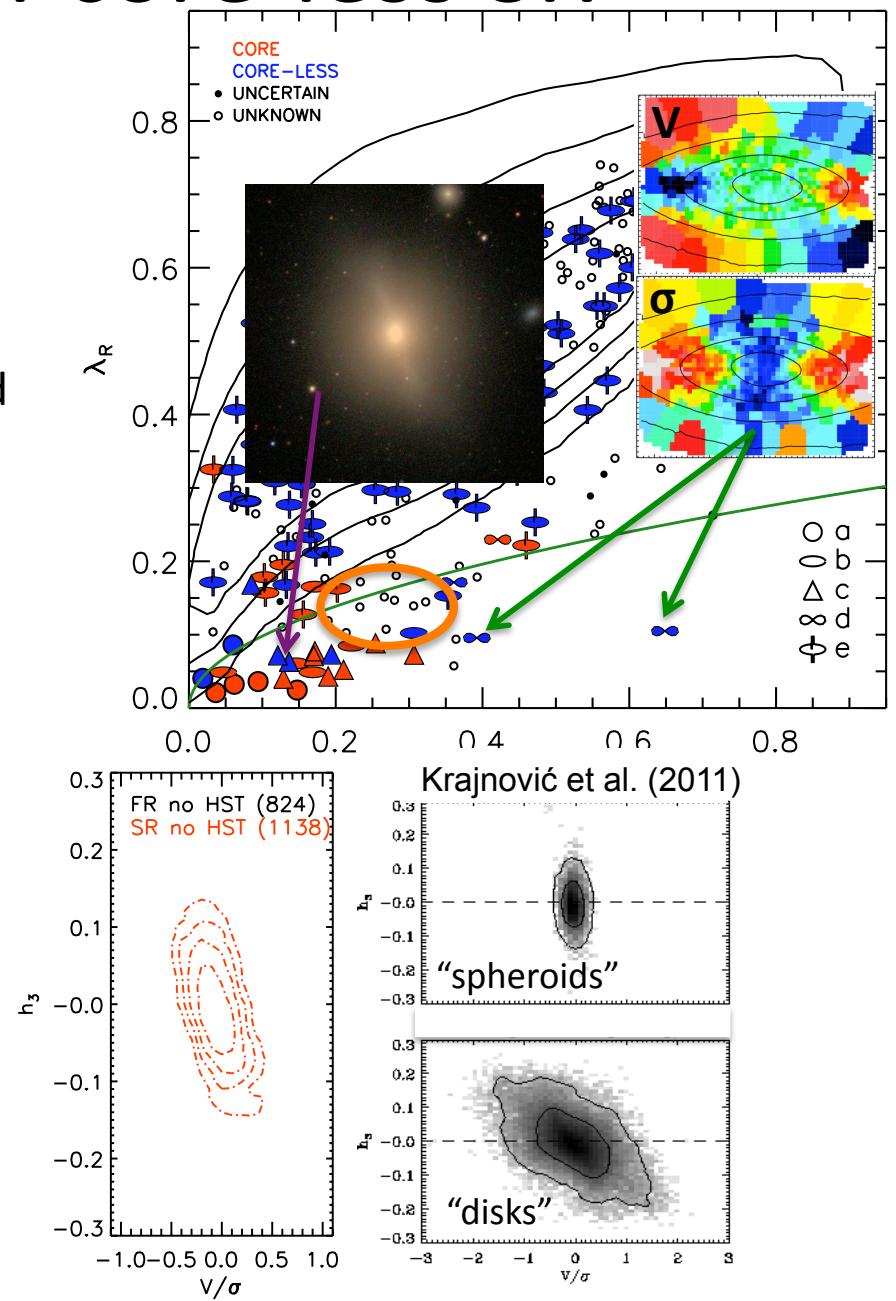
Dynamical state of core-less SR

- Core-less SR with $\epsilon > 0.35$ are counter-rotating disks
- Some special cases (?) for $\epsilon < 0.35$
 - NGC3414, NGC4258, NGC5831
 - KDCs
- SR with no HST imaging have embedded cold components (disks?)
- A sub-classes of SR ?



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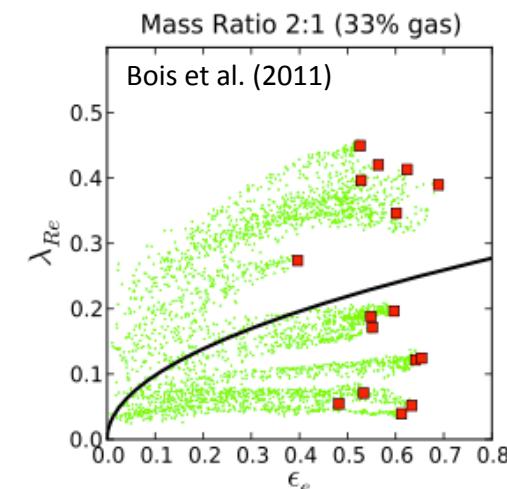
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Implications for galaxy formation

- Core FR are (mostly) disk-like systems at half light scales (see also Dullo & Graham 2013)
- Core-less SR might contain embedded discs
- Strong dependence on mass and σ
- **How to create/preserve a core in FR?**
 - Cores were made early, host evolved into a FR by accretion/minor mergers (e.g. Dullo&Graham 2013)
 - core preserved via
 - Morphological quenching
 - AGN feedback
 - Cores were made at the same time as the FR
 - Is there an argument for a new way of making cores?
 - Expansion of core due to a sudden mass loss (e.g. Hills 1980, Pontzen&Governato2012, Martizzi et al. 2012)
- **How to create a core-less SR?**
 - Dissipative event that lowers the angular momentum, but fills the core
 - What is the role of dissipation in galaxy formation?

	CORE	CORE-LESS
FAST	<p>MERGER TYPE:</p> <ul style="list-style-type: none"> • Dissipative major & minor • Dissipationless minor <p>CORE GROWTH/PRESERVATION:</p> <ul style="list-style-type: none"> • BH binaries (longer duration than nuclear starburst) • Regulation of nuclear star formation (AGN feedback, morphological quenching) 	<p>MERGER TYPE:</p> <ul style="list-style-type: none"> • Dissipative (range in mass fractions and amounts of gas) <p>CUSP GROWTH:</p> <ul style="list-style-type: none"> • Nuclear starburst • Subsequent interaction between BH and surrounding stars
SLOW	<p>MERGER TYPE:</p> <ul style="list-style-type: none"> • Dissipationless major & multiple minor <p>CORE GROWTH/PRESERVATION:</p> <ul style="list-style-type: none"> • BH binaries • AGN induced • Adiabatic expansion • Hot halo gas 	<p>MERGER TYPE:</p> <ul style="list-style-type: none"> • Dissipative major (retrograde orbits) • Accretion of gas <p>CUSP GROWTH:</p> <ul style="list-style-type: none"> • Nuclear starburst (refilling of existing core)



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