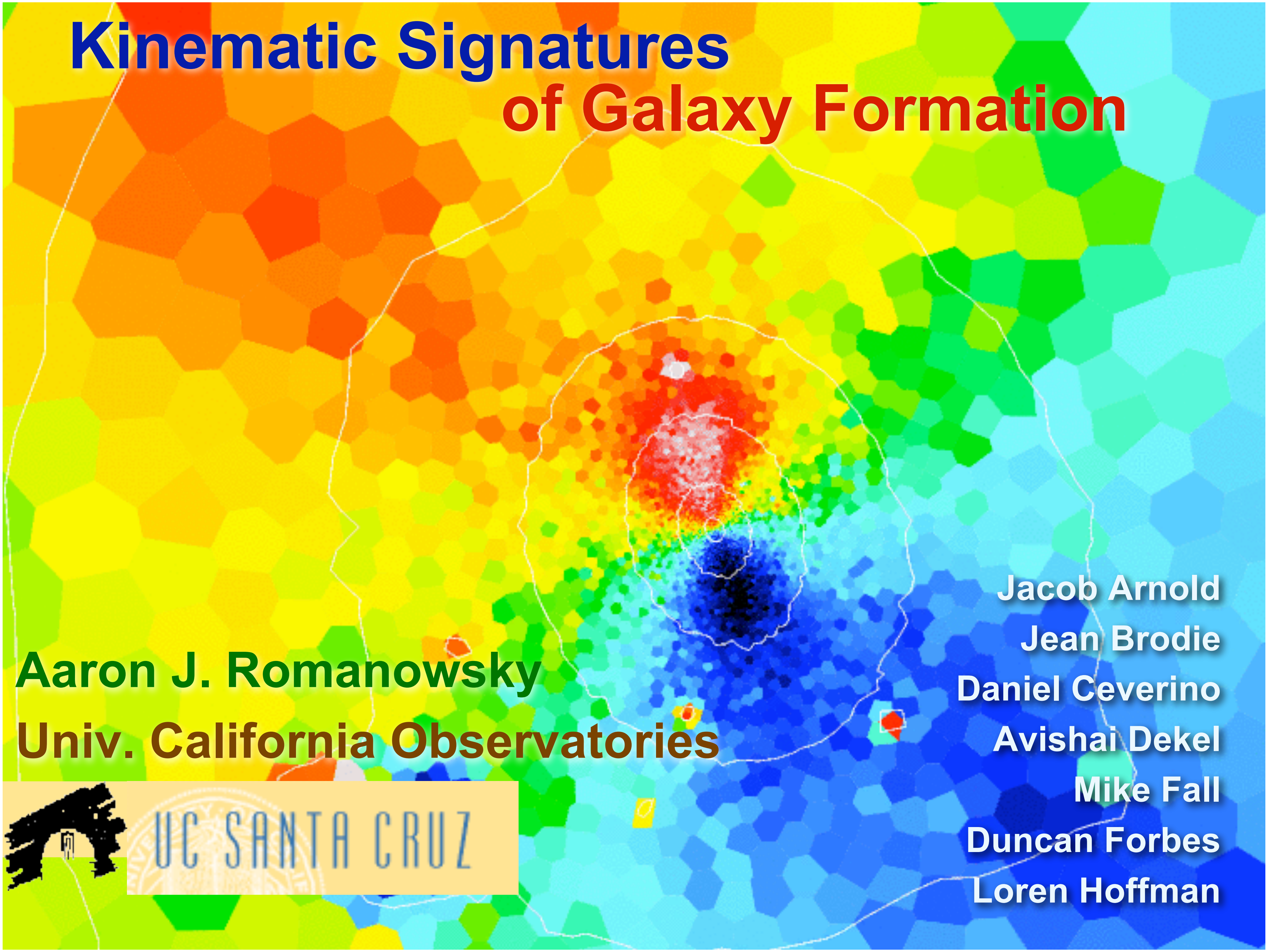
Kinematic Signatures of Galaxy Formation



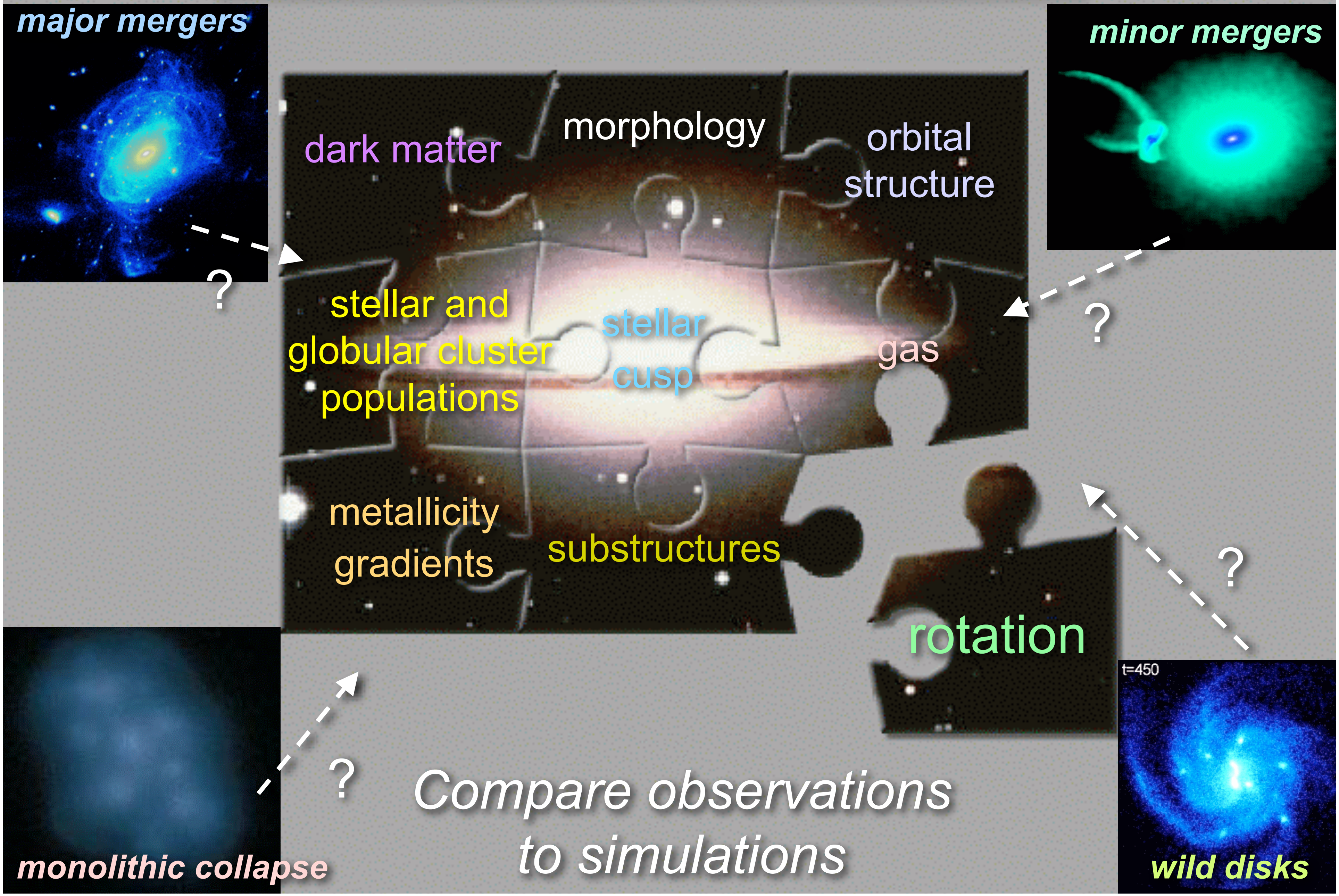
Aaron J. Romanowsky

Univ. California Observatories

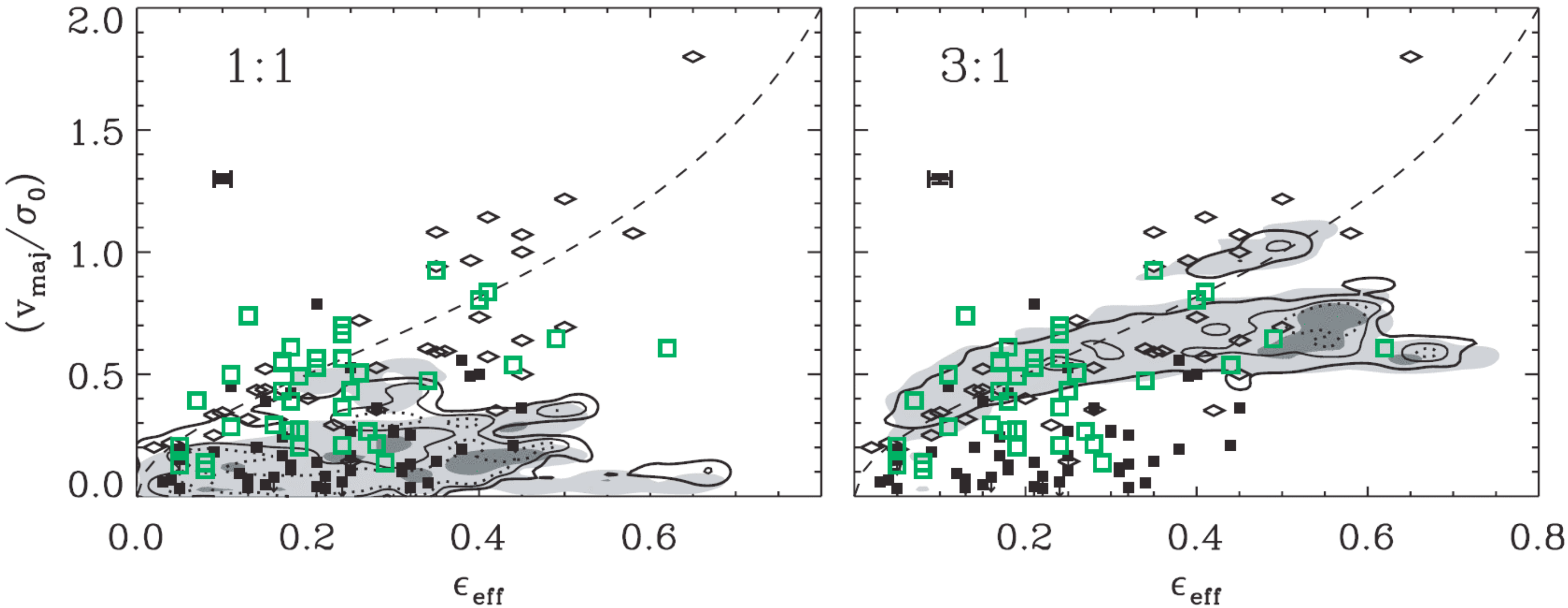
UC SANTA CRUZ

Jacob Arnold
Jean Brodie
Daniel Ceverino
Avishai Dekel
Mike Fall
Duncan Forbes
Loren Hoffman

Formational diagnostics



Central stellar rotation in E/S0s



Classic observational correlations: *v/σ*, *ε*, *a4*, etc.

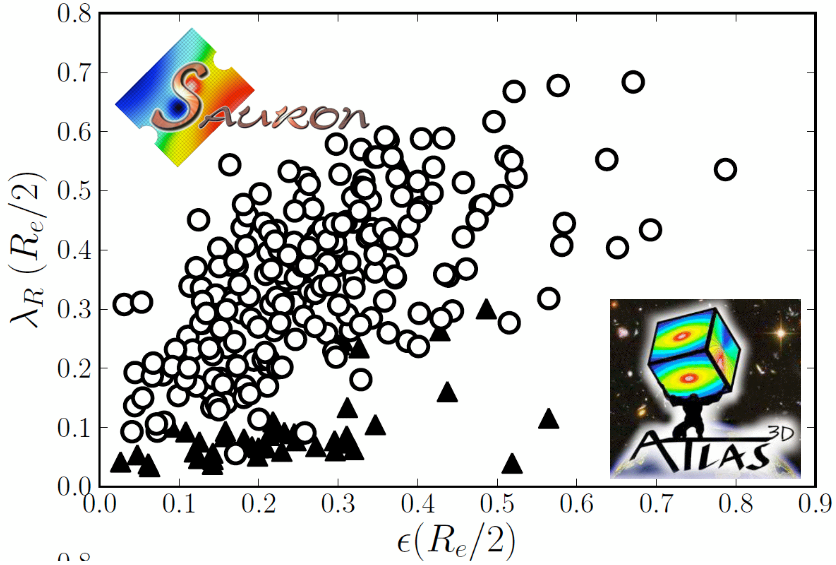
(Davies et al 1983; Bender et al. 1994; etc.)

By and large explainable by simulations of binary disk-galaxy mergers

(Naab et al. 2006; Cox et al. 2006; Burkert et al. 2008; etc.)

v/σ increases with gas fraction and mass ratio?

Central stellar rotation in early-types

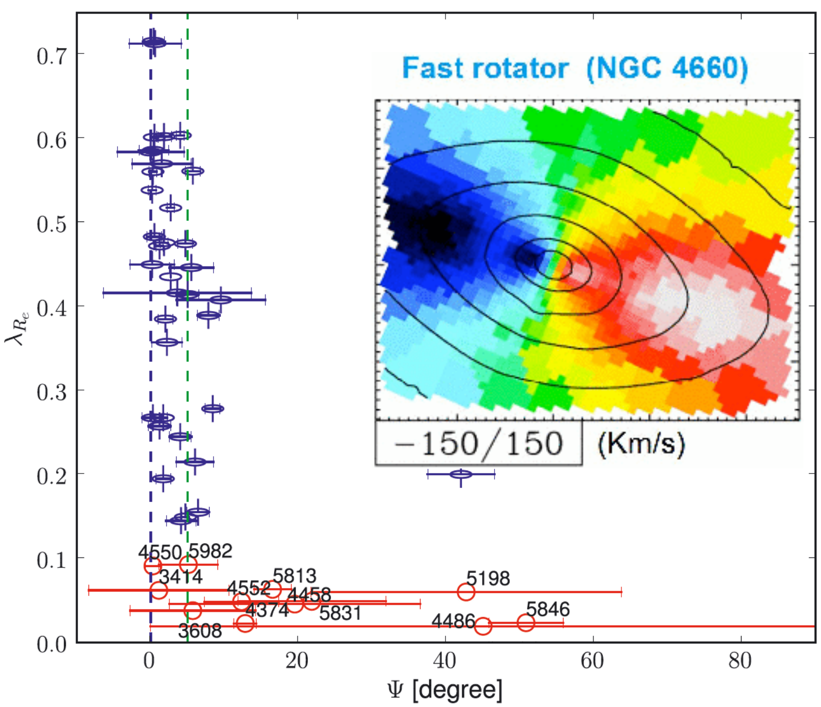


λ_R: specific angular momentum proxy

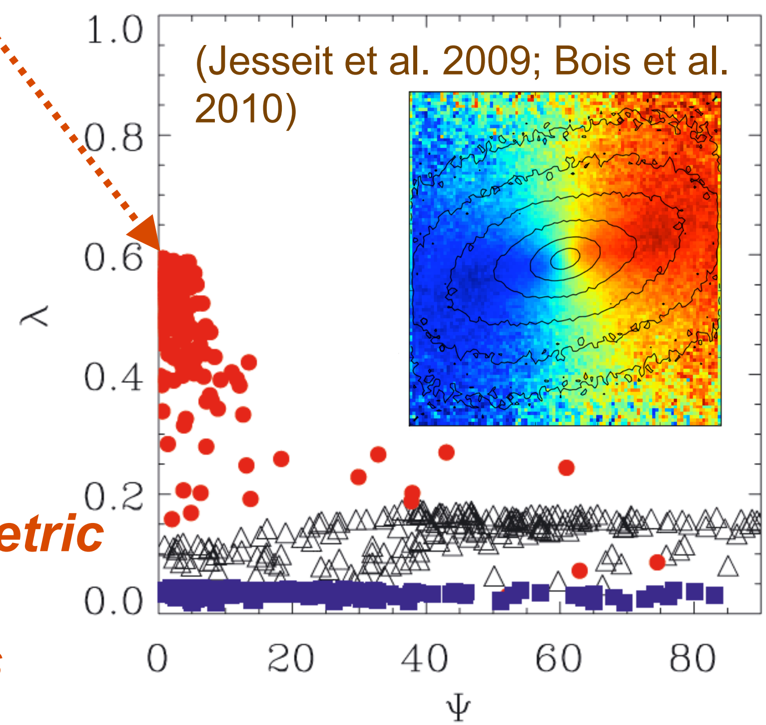
$$\lambda_R = \frac{\langle R \times |V| \rangle}{\left\langle R \times \sqrt{V^2 + \sigma^2} \right\rangle}$$

(Emsellem et al. 2007, 2010)

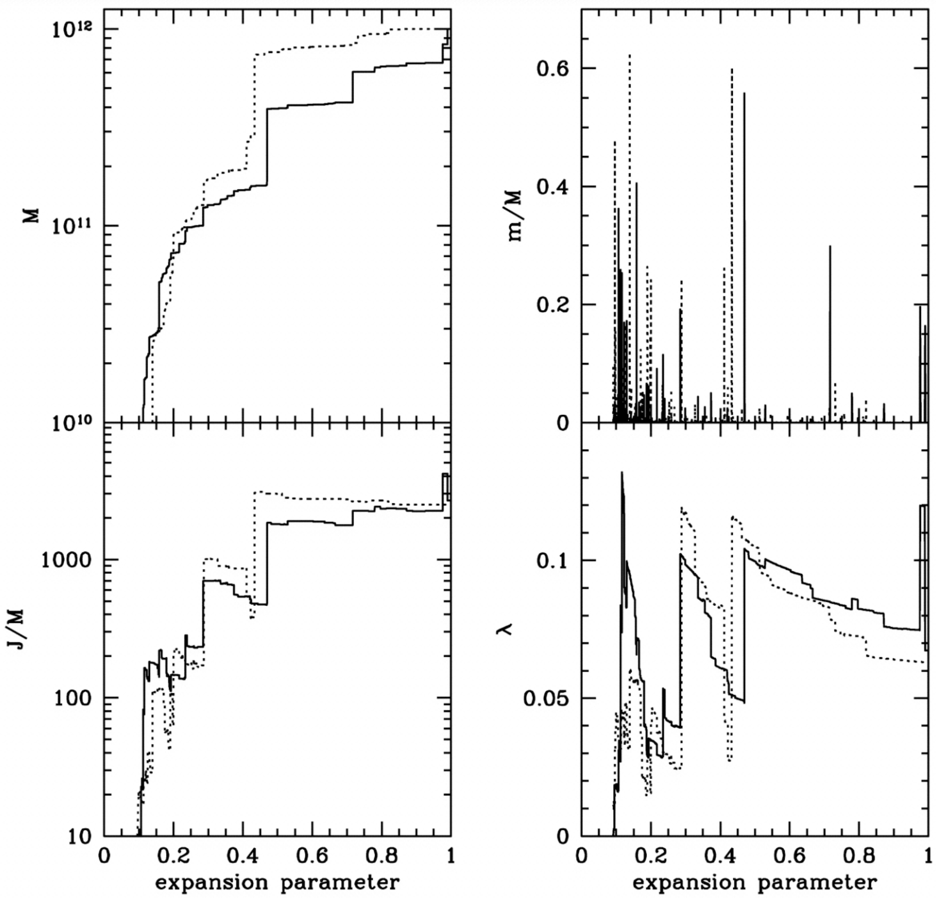
SAURON/Atlas[3D]: *abundant class of "fast rotators" with small kinematic misalignments*



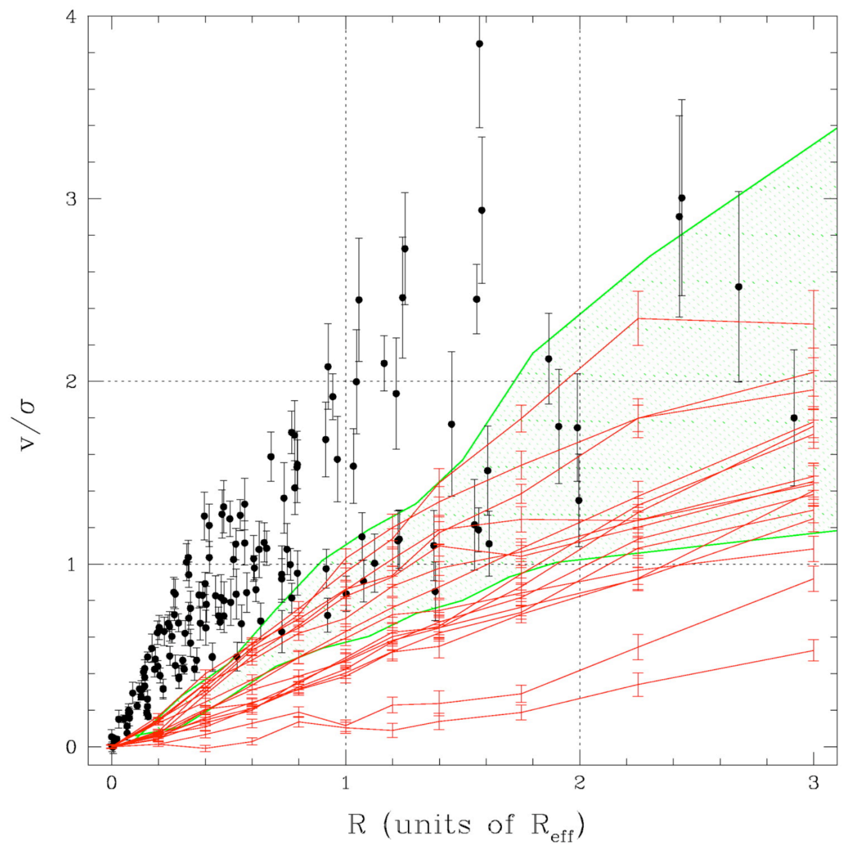
oblate axisymmetric merger remnants



Outer regions: *angular momentum transfer*



(Vitvitska et al. 2002)

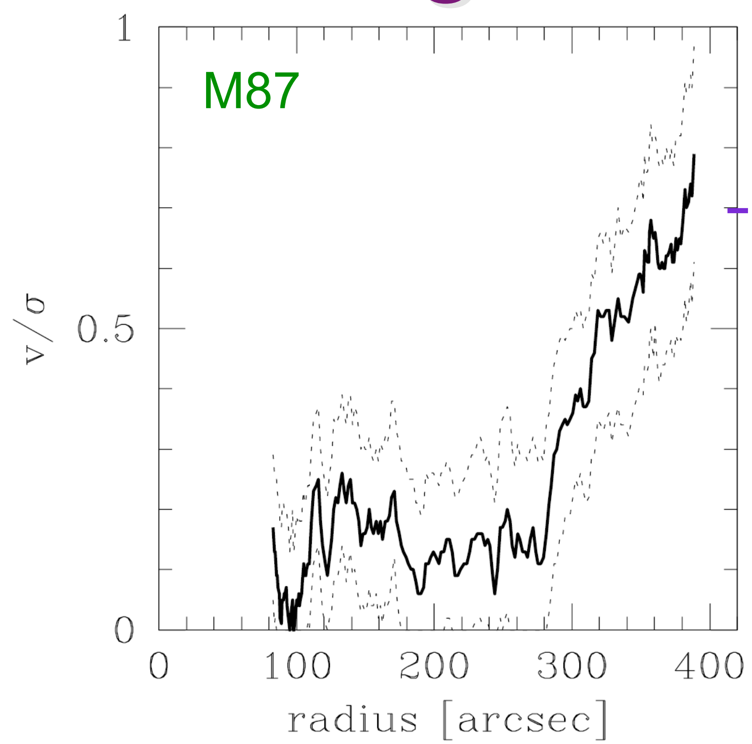


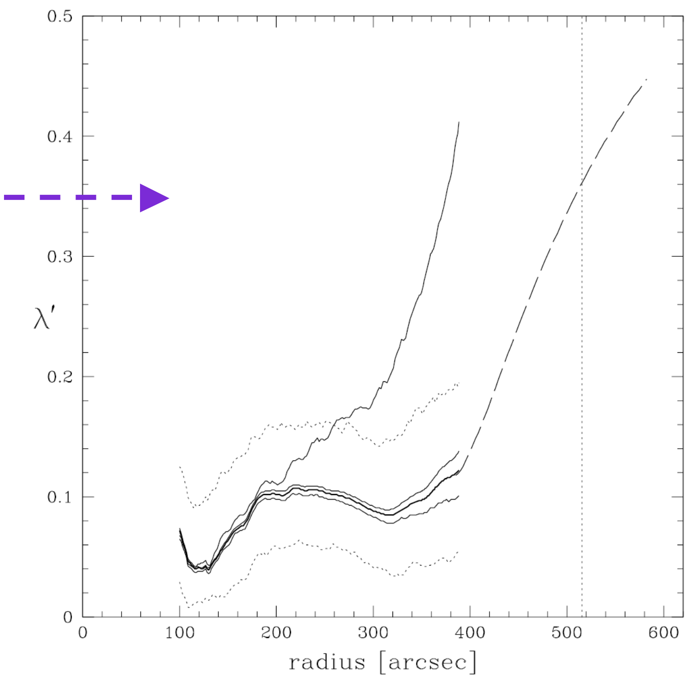
(Hernquist 1992; Bendo & Barnes 2000; Cretton et al. 2001; etc.)

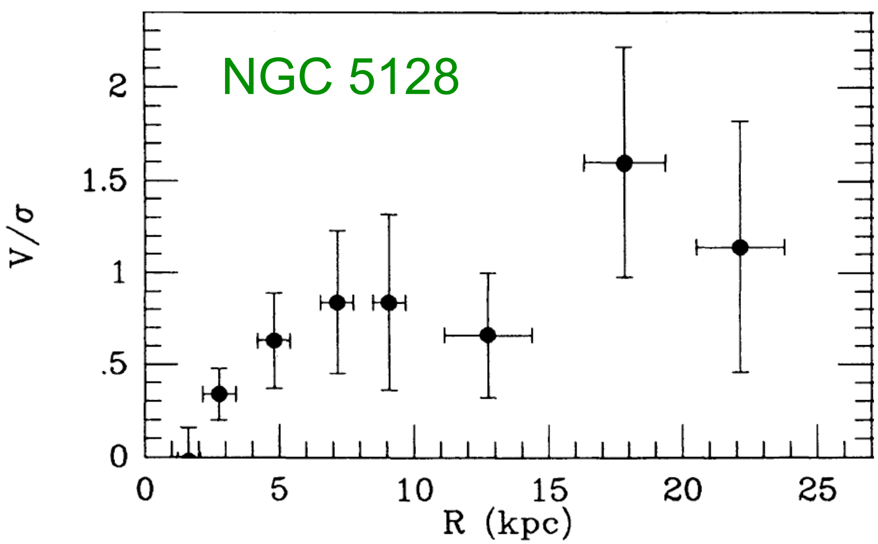
Dark halo assembly in cosmological context:
merger-spikes in spin parameter modulated by steady accretion

Binary merger simulations:
spin + orbital angular momentum transfer to halo

Outer regions: *angular momentum transfer*



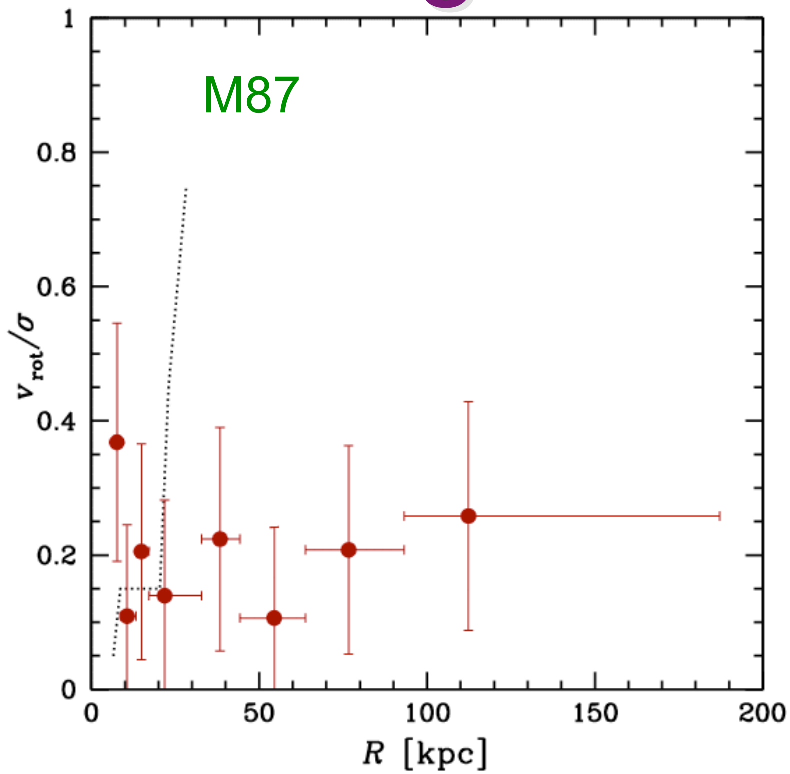


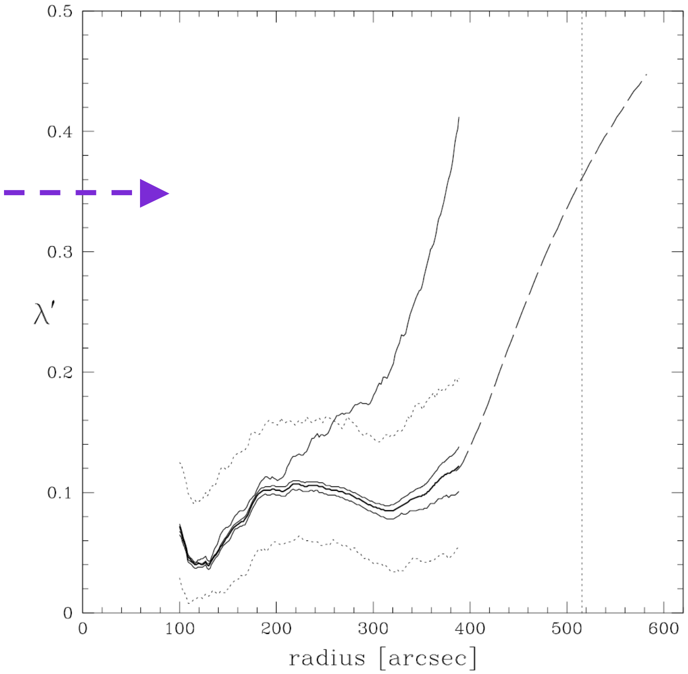


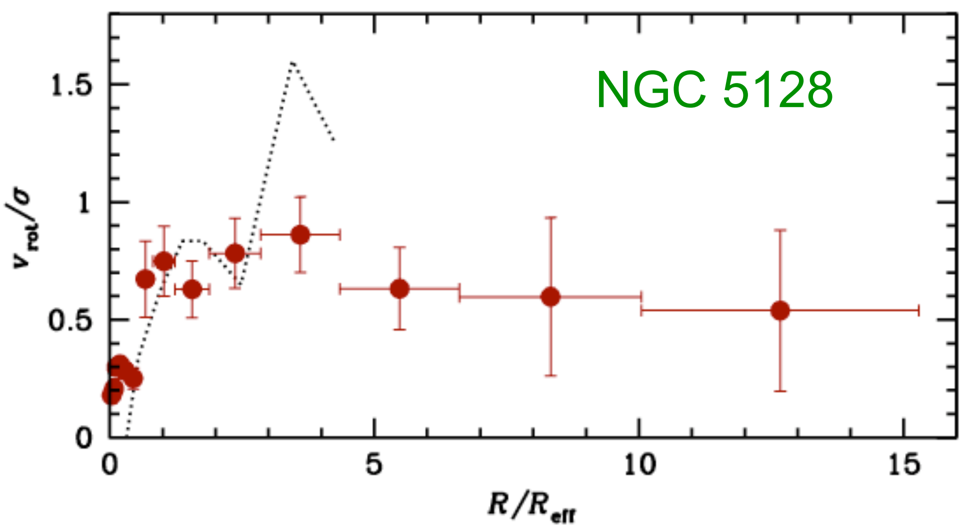
Observations of PNe and GCs confirmed high halo rotation

(Hui et al. 1995; Arnaboldi et al. 1998; Kissler-Patig & Gebhardt 1999)

Outer regions: *angular momentum transfer*







Observations of PNe and GCs confirmed high halo rotation

(Hui et al. 1995; Arnaboldi et al. 1998; Kissler-Patig & Gebhardt 1999)

… or did they?

(Woodley et al. 2010; Strader et al. 2010)

Halo surveys of nearby galaxies

PN.S

Planetary Nebula Spectrograph
Elliptical Galaxy Survey (PI: M. Arnaboldi)

- stellar/PN kinematics to ~ 7 R_{eff}:
- *primary:* 12 representative ellipticals
- *extended:* 40 volume/magnitude-limited early-types

S. Bamford, M. Capaccioli, L. Coccato, A. Cortese, P. Das, K. Freeman,
O. Gerhard, K. Kuijken, M. Merrifield, N. Napolitano, V. Pota, A. Romanowsky

SLUGGS

SMEAGOL

SAGES

NSF

SAGES Legacy Unifying Globulars and Galaxies Survey

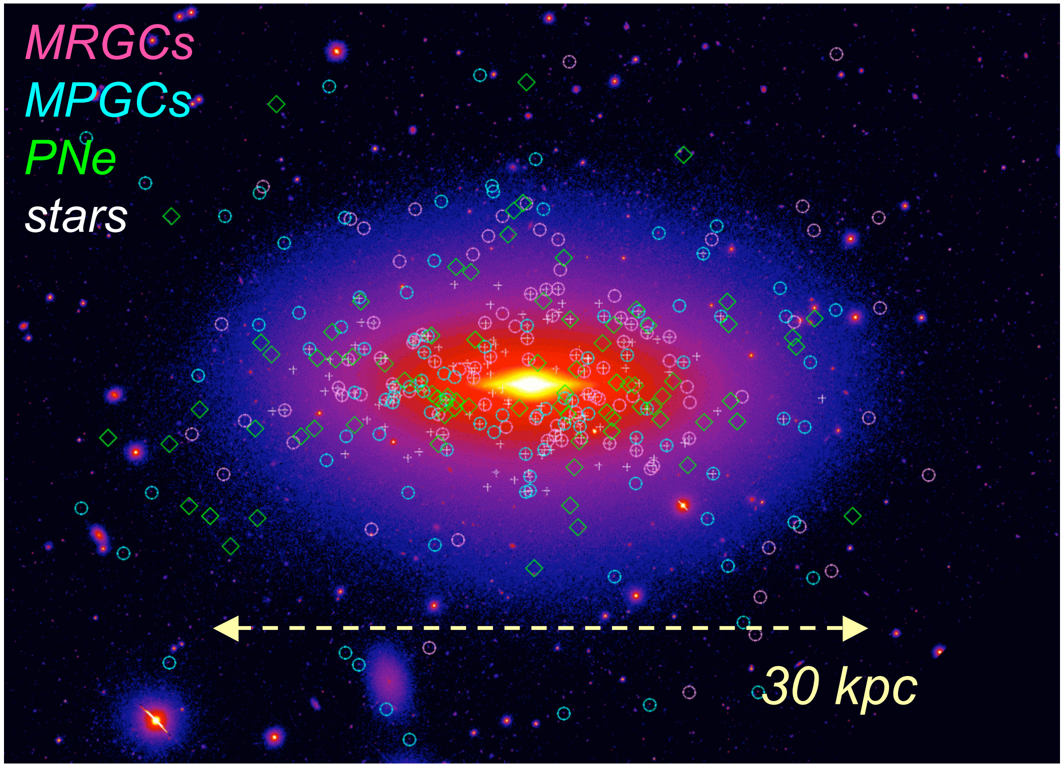
Spectroscopic Mapping of Early-type Galaxies to their Outer Limits

(PIs: J. Brodie, A. Romanowsky)

- 25 representative galaxies, mostly early-type
- field stars, globular clusters to ~ 3-10 R_{eff} : photometry, kinematics, metallicities

D. Forbes, R. Proctor, J. Huchra, J. Strader, J. Arnold, C. Foster, L. Spitler, C. Blom, V. Pota, C. Usher

NGC 3115 : *an S0 in all it glory*

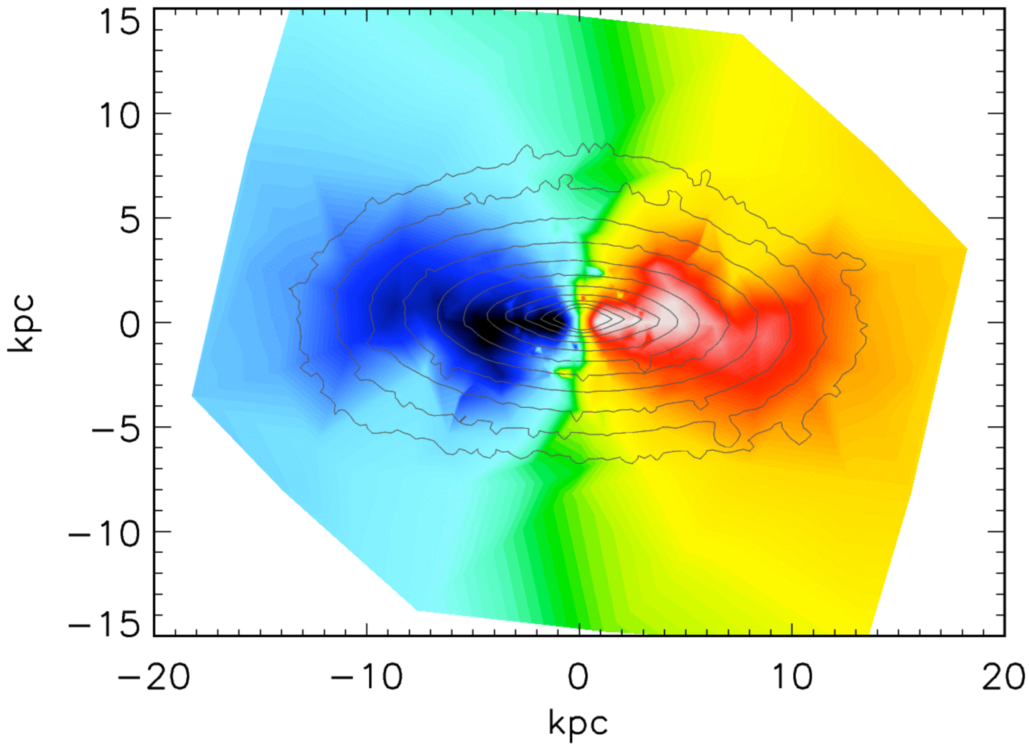


Jacob Arnold / UCSC

Unique data-set of stellar, PN, GC kinematics in ***nearest normal S0:***

Keck/DEIMOS,LRIS,
Magellan/IMACS,
Subaru/Suprime-Cam

NGC 3115 : *an S0 in all it glory*



Jacob Arnold / UCSC

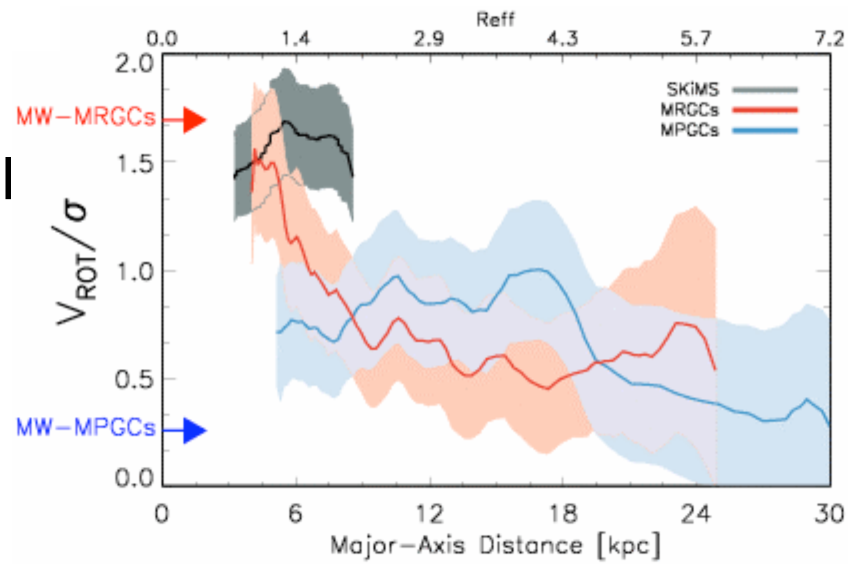
Unique data-set of stellar, PN, GC kinematics in ***nearest normal S0:***

Keck/DEIMOS,LRIS, Magellan/IMACS, Subaru/Suprime-Cam

Stars(?), metal-rich GCs: high central rotation declines outside ~ 1–2 R_{eff}

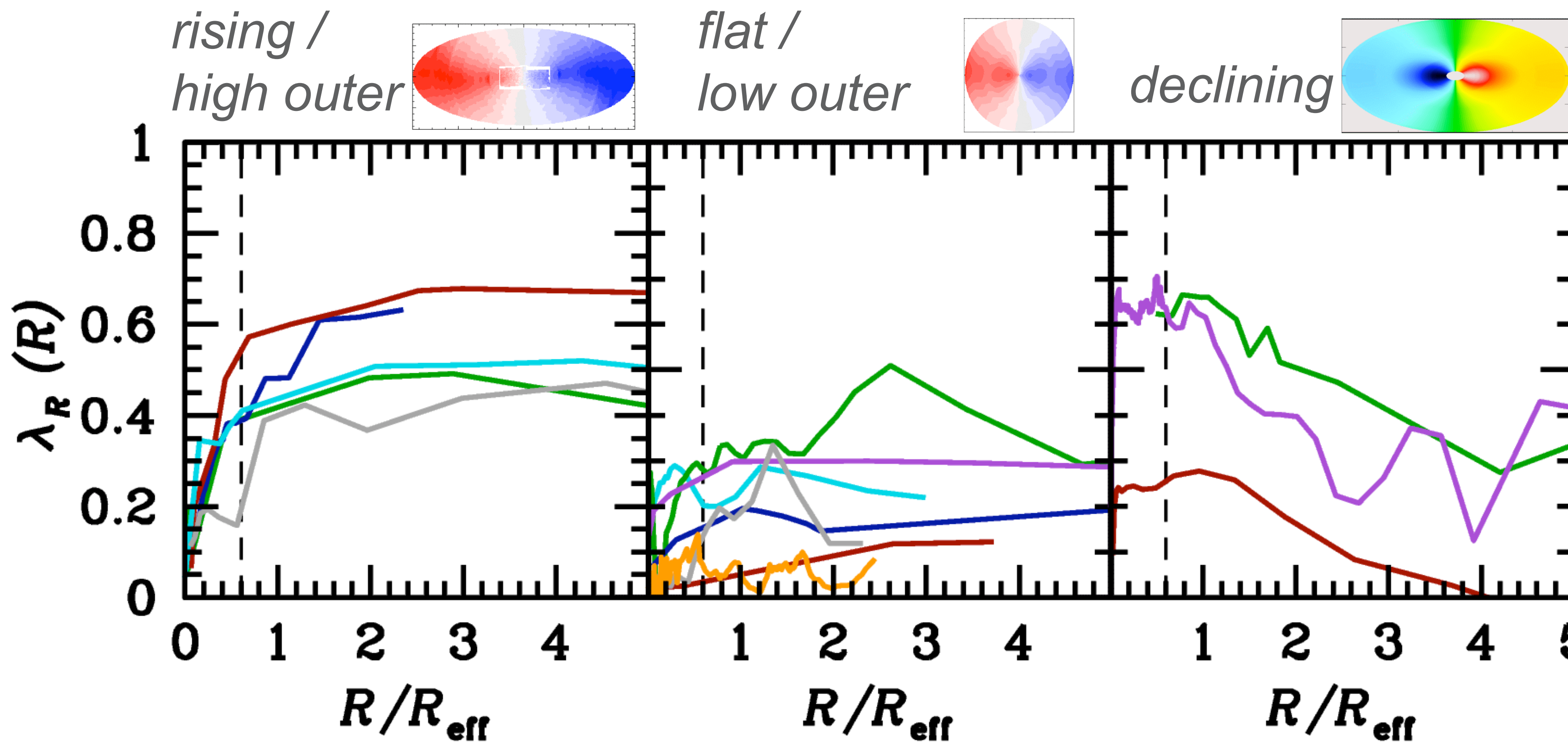
Metal-poor GCs: low rotation,

PNe : complex, non-equilibrium?



Extended rotation profiles of early-type galaxies

(Proctor et al. 2009; Coccato et al. 2009; Arnold et al. 2010; Romanowsky & Fall 2010)

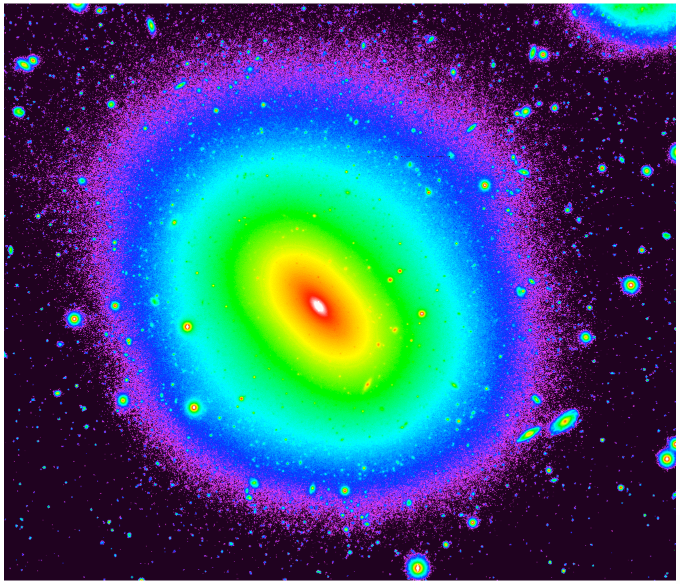


$$\lambda_R = \frac{\langle R \times |V| \rangle}{\langle R \times \sqrt{V^2 + \sigma^2} \rangle}$$

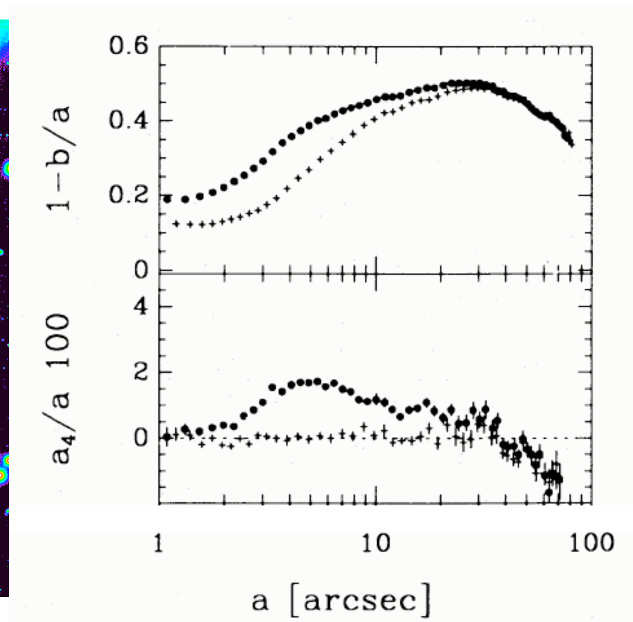
→ ***diverse outer rotation profiles***

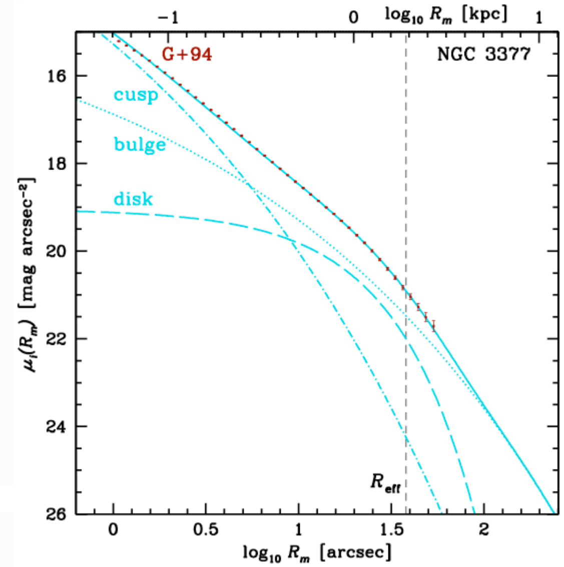
→ ***central homology not reflected in halos***

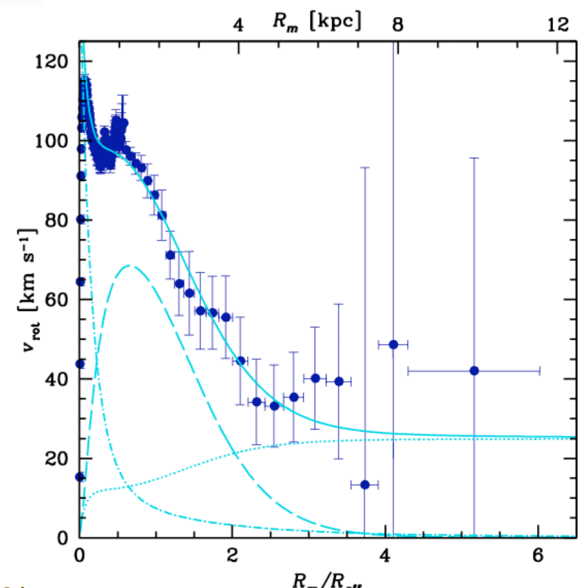
Curious cases of falling rotation profiles



NGC 3377: E4, M_B = -19.1







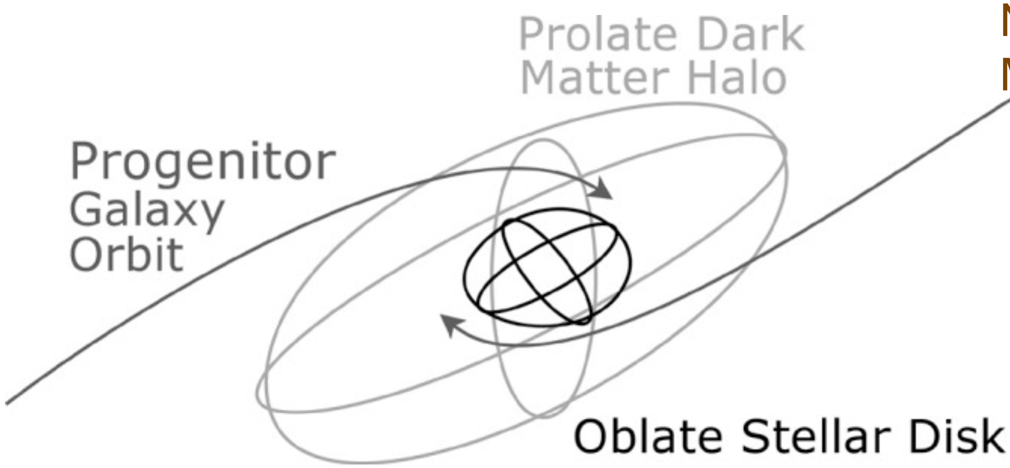
Fast-rotating disky component embedded in slow-rotating boxy bulge

Flurry of earlier papers on hidden disks, now traced with extended kinematics

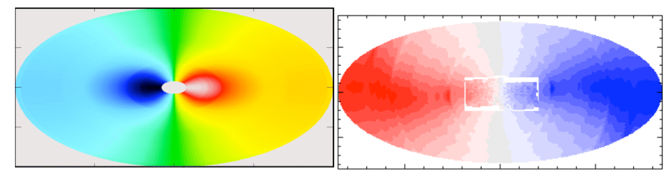
(Rybicki 1987; Rix & White 1990; Cinzano & van der Marel 1994;
Scorza & Bender 1995; Kochanek & Rybicki 1996;
Gerhard & Binney 1996; Romanowsky & Kochanek 1997; Magorrian 1999)

Major merger origin of core-halo decoupling?

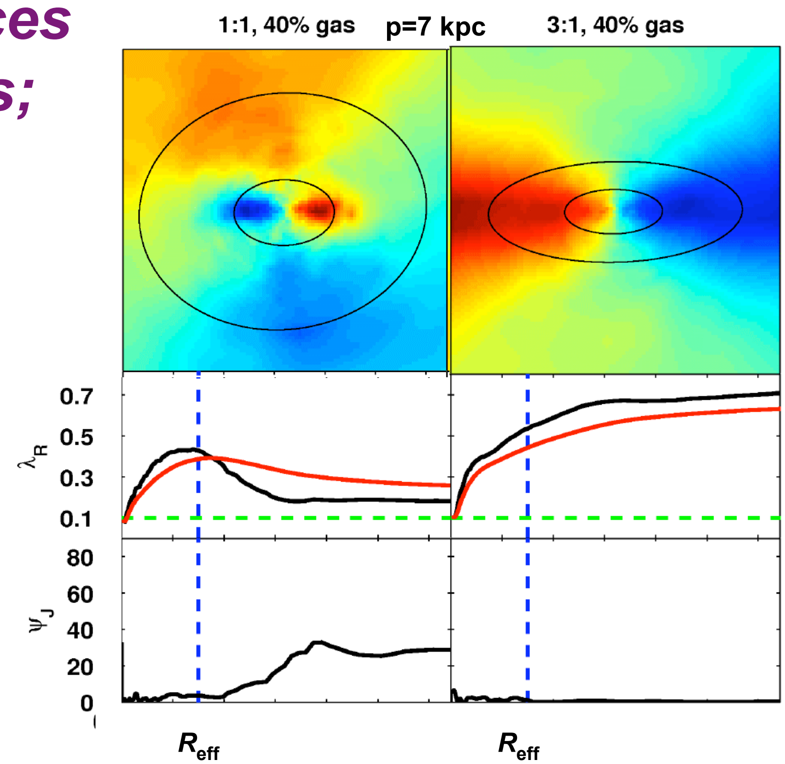
Novak et al. 2006; Hoffman et al. 2010a,b; Moody et al. in prep; Guedes et al. in prep.



observations



simulations



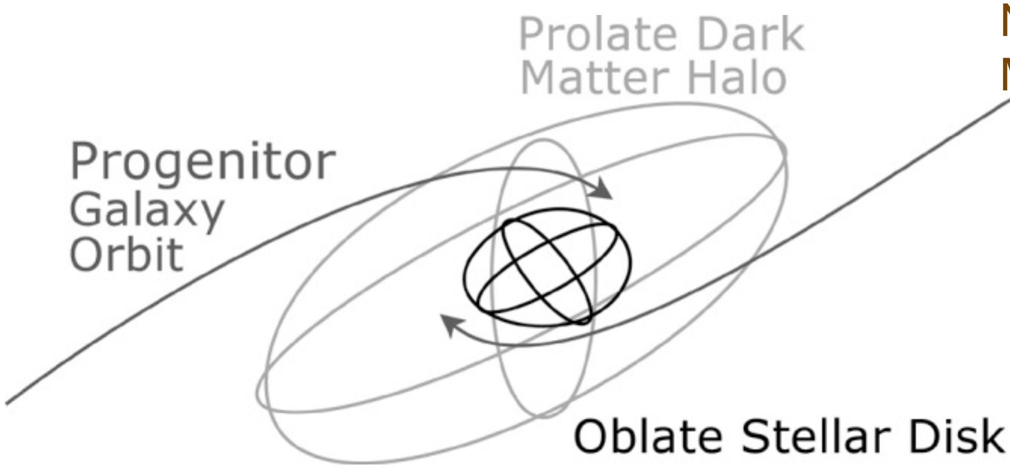
Wet major merger: ***dissipation produces fast-rotator homology in central regions; outer regions reflect triaxial dry merger***

Low-angular momentum 1:1 merger needed for low halo rotation
→ rare?, predicts kinematic twist

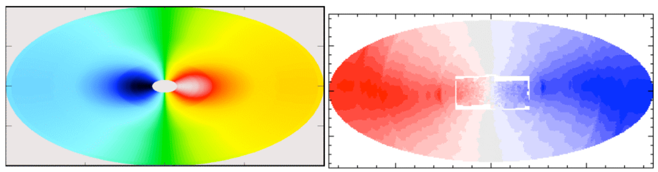
Halo *x*-tube streaming from progenitor disk spin

Major merger origin of core-halo decoupling?

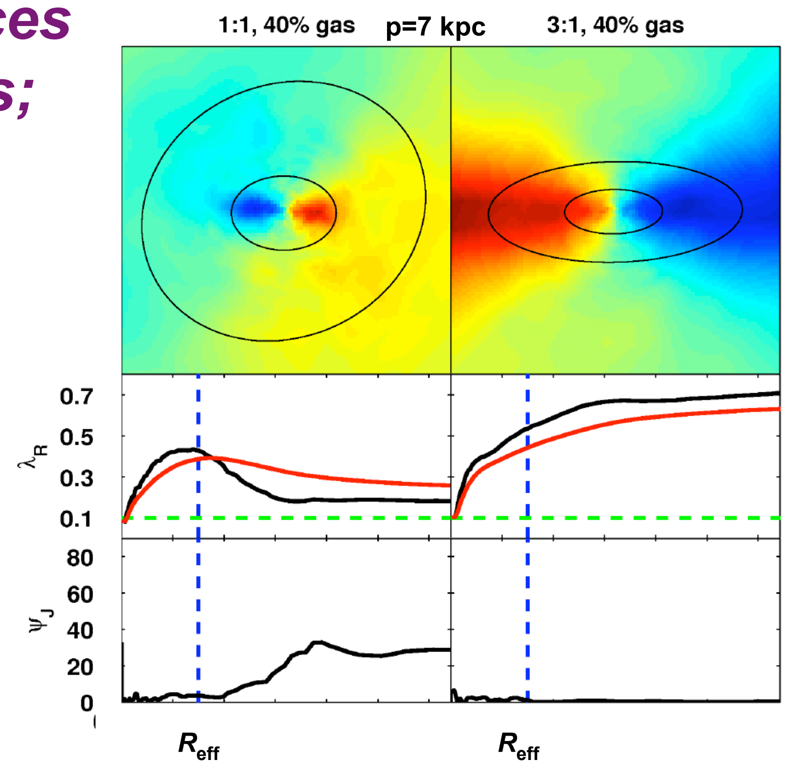
Novak et al. 2006; Hoffman et al. 2010a,b; Moody et al. in prep; Guedes et al. in prep.



observations



simulations

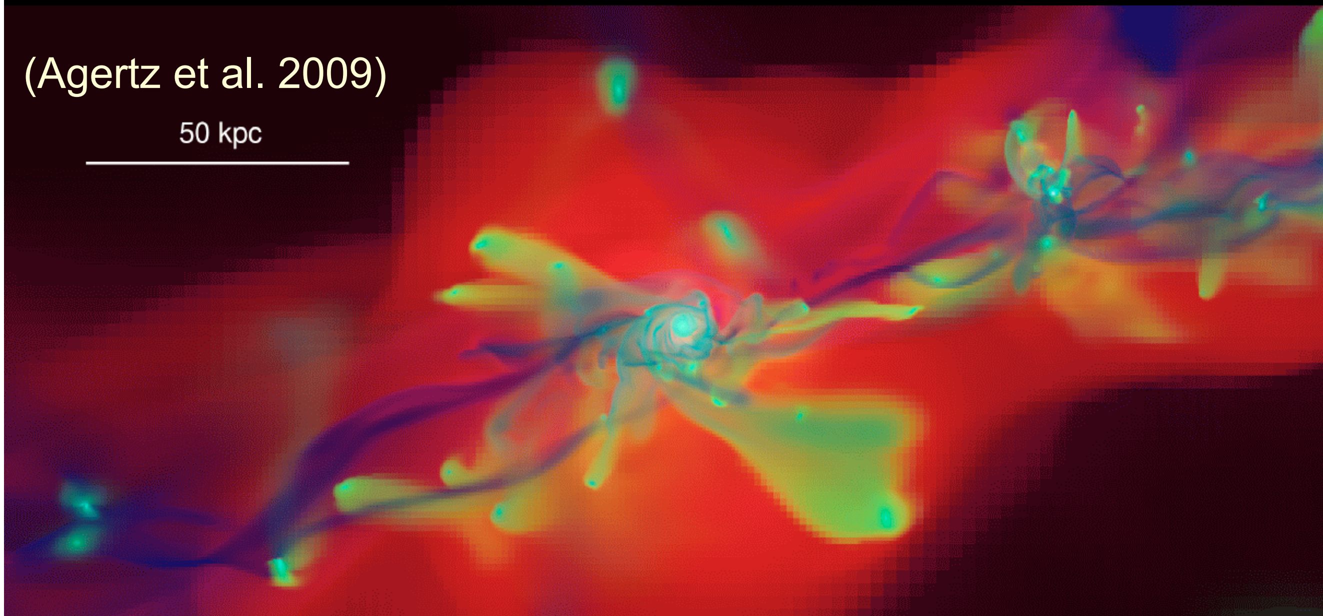


Wet major merger: ***dissipation produces fast-rotator homology in central regions; outer regions reflect triaxial dry merger***

Low-angular momentum 1:1 merger needed for low halo rotation
→ rare?, predicts kinematic twist

Halo *x*-tube streaming from progenitor disk spin

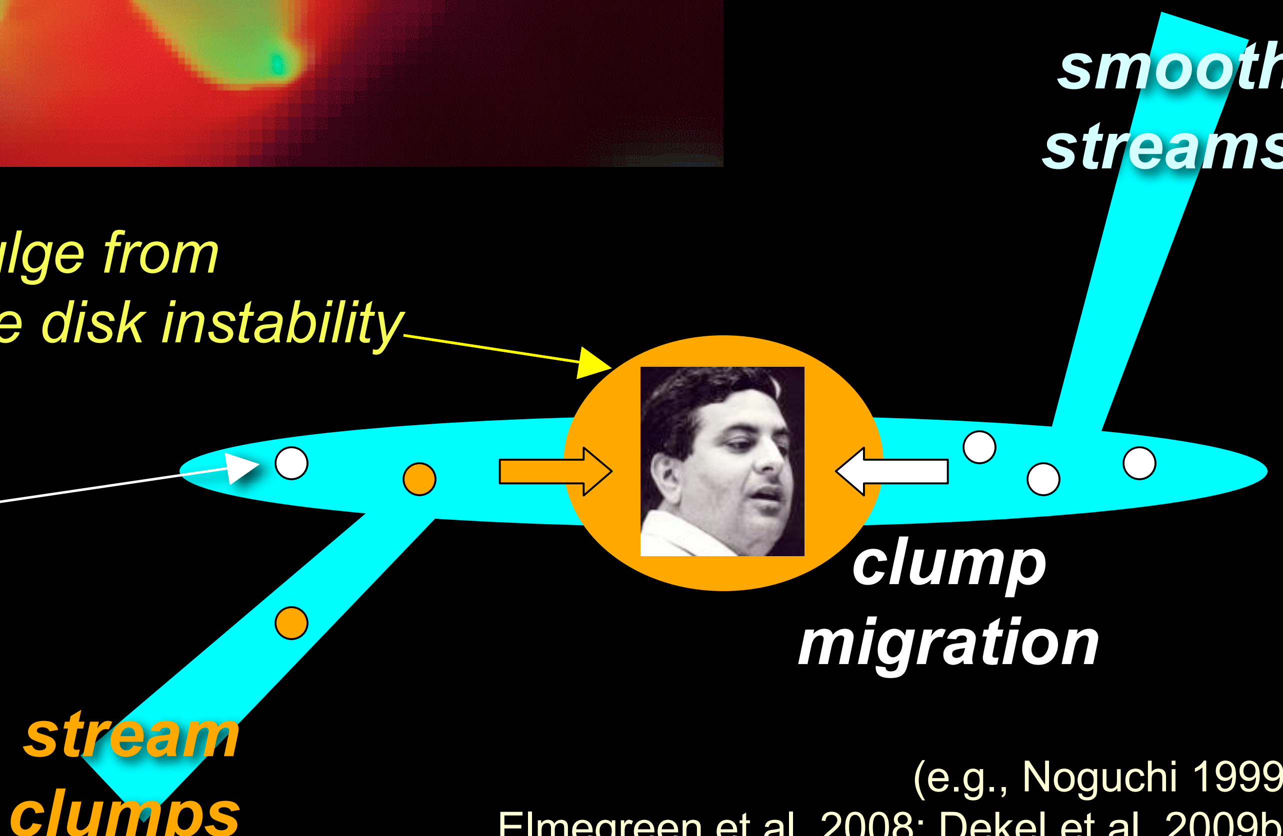
“Wild disk” mode of galaxy formation



cold gas streams penetrate to small radii at $z > \sim 2$

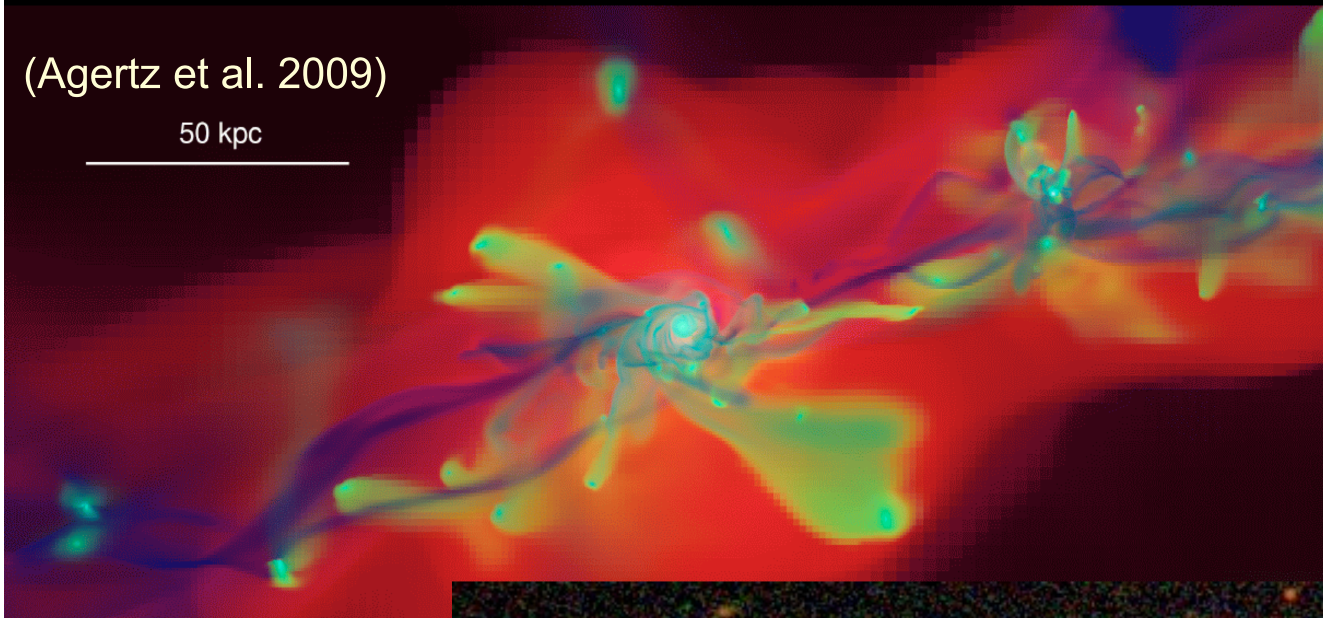
classical bulge from steady-state disk instability

YMCs → GCs?



(e.g., Noguchi 1999; Elmegreen et al. 2008; Dekel et al. 2009b)

“Wild disk” mode of galaxy formation



cold gas streams penetrate to small radii at $z > \sim 2$

smooth

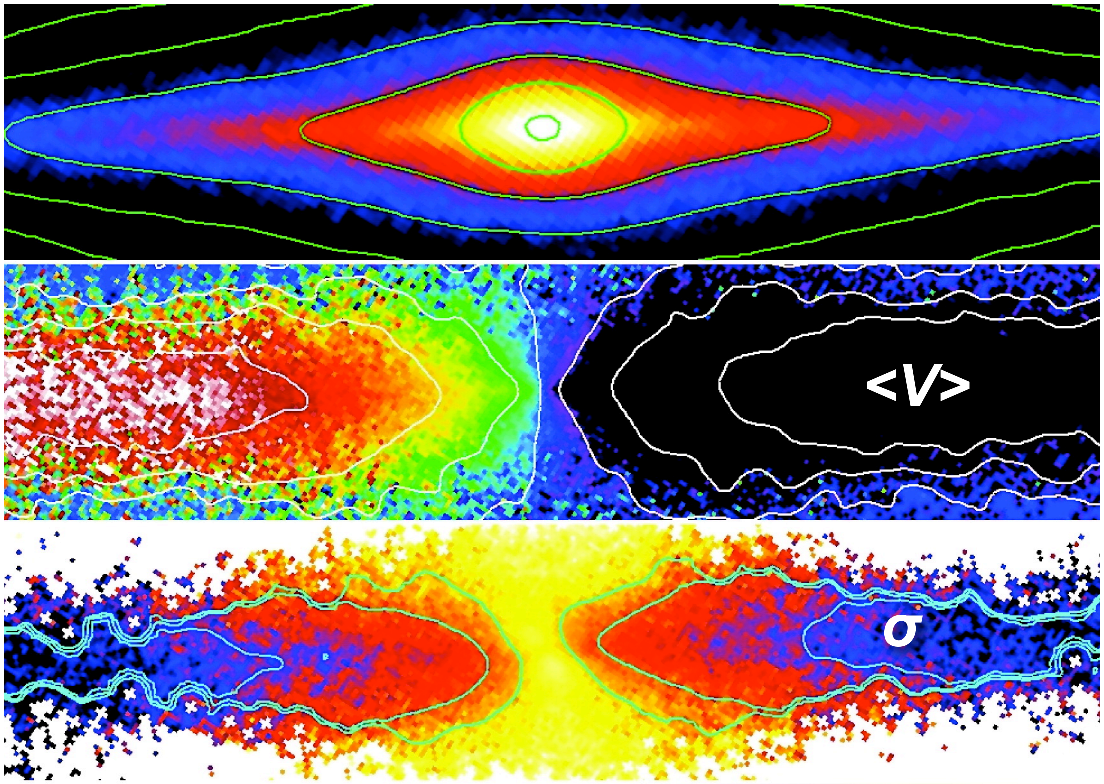
→ *Evolve into present-day Sa, S0, E by fading or mergers?*

(Conroy et al. 2008; Genel et al. 2008)

Elmegreen et al. 2008; Dekel et al. 2009b)

Multiple pathways for bulge formation?

What are the contributions to bulge assembly from major mergers and wild disks?



Isolated simulation of wild disk

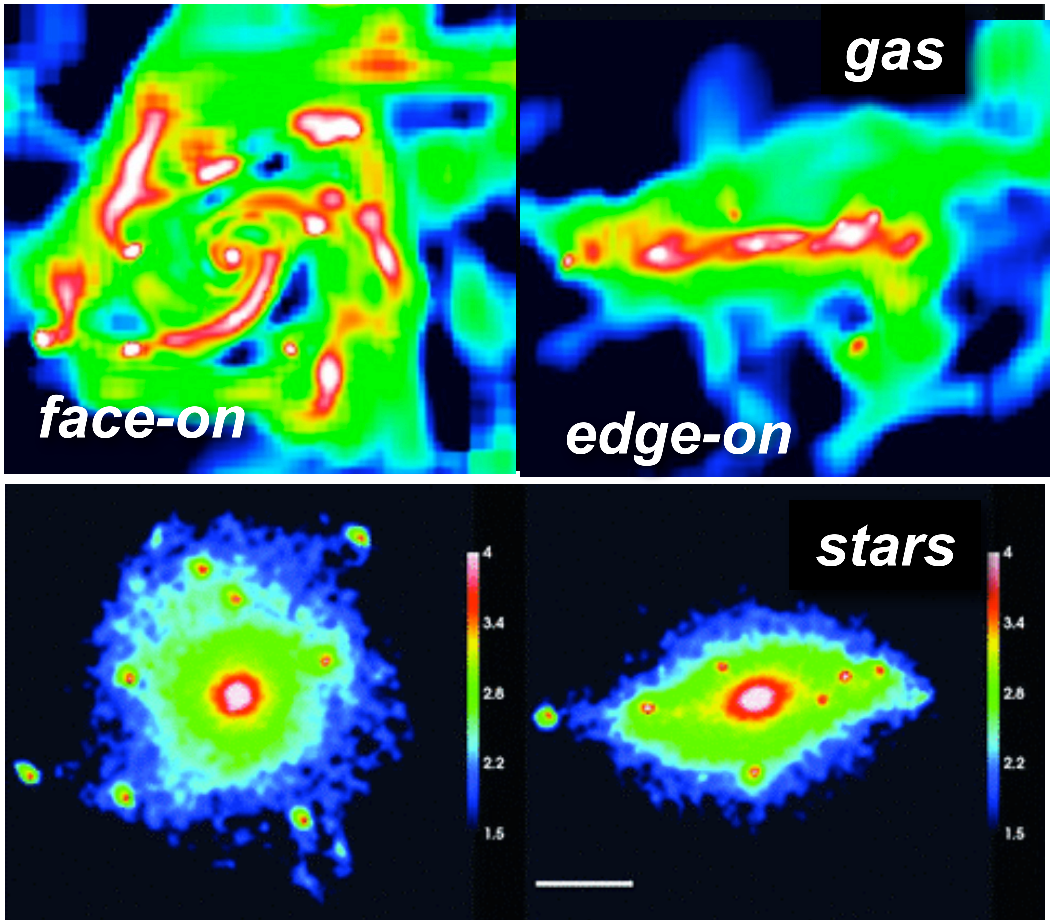
(Elmegreen, Bournaud & Elmegreen 2008)

$(V/\sigma)_{\text{bulge}} \sim 0.4\text{–}0.5$

Inner regions similar to wet major merger remnant:
oblate, axisymmetric fast rotator

→ ***Large-radius diagnostics?***

Cosmological simulations of galaxy formation



including wild disk mode

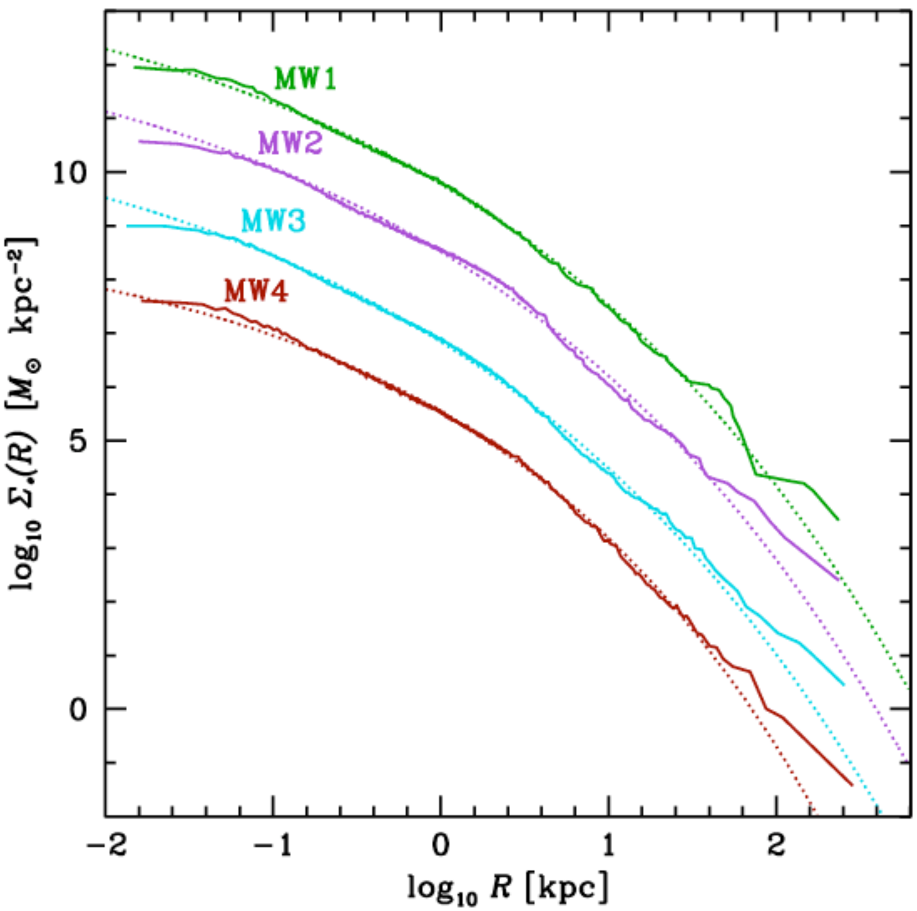
(Ceverino, Dekel & Bournaud 2010)

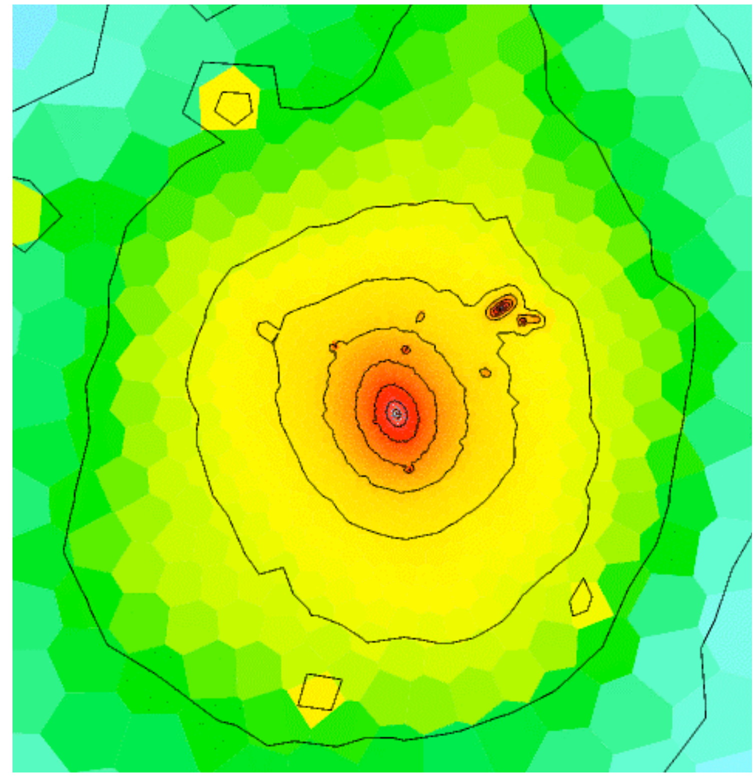
Adaptive mesh refinement code ART:
stellar feedback +
gas cooling below 10^4 K,
$\sim 10^7$ particles,
resolution down to 35 pc,
$\sim 10^{12}\ M_{Sun}$ virial mass,
to z ~ 1.4,
4 galaxies: “MW1,2,3,4”
typical merger histories

Giant star-forming disk clumps: $\sim 10^8\ M_{Sun}$, ~1 kpc
→ ***migrate to center, form bulge by violent relaxation***

Wild disk simulations: *stellar density*

analyzed at z~1.4: onset of passive mode





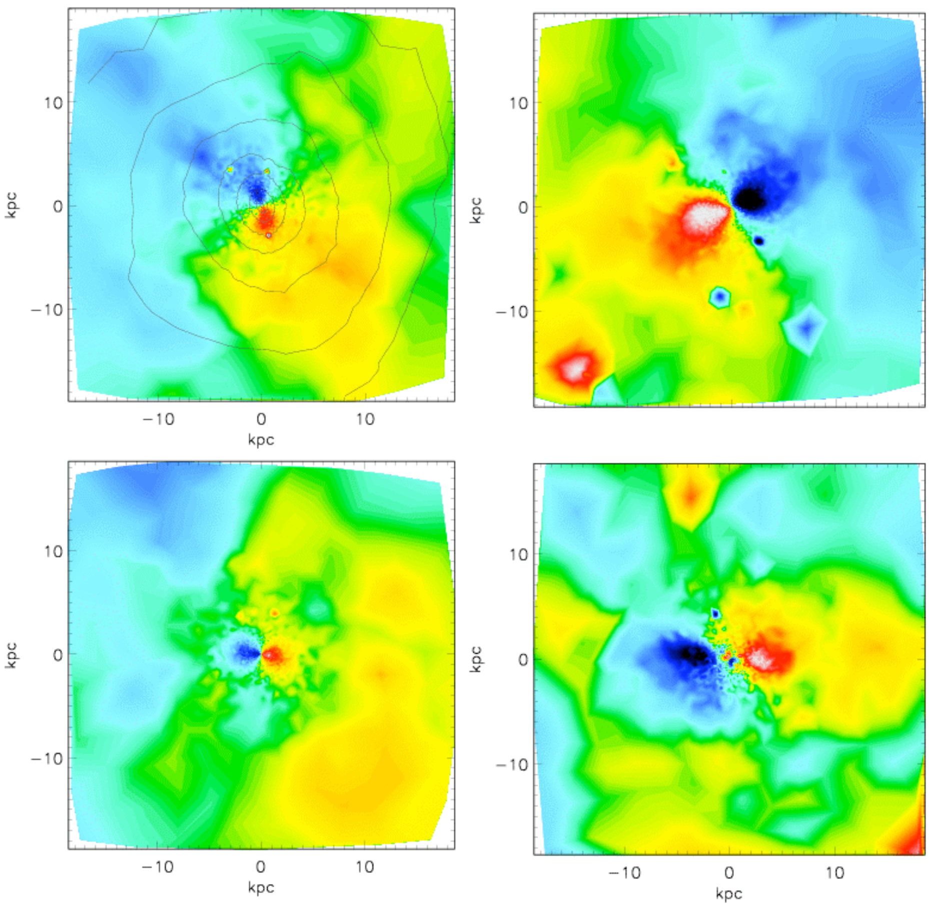
(Romanowsky et al., in prep.)

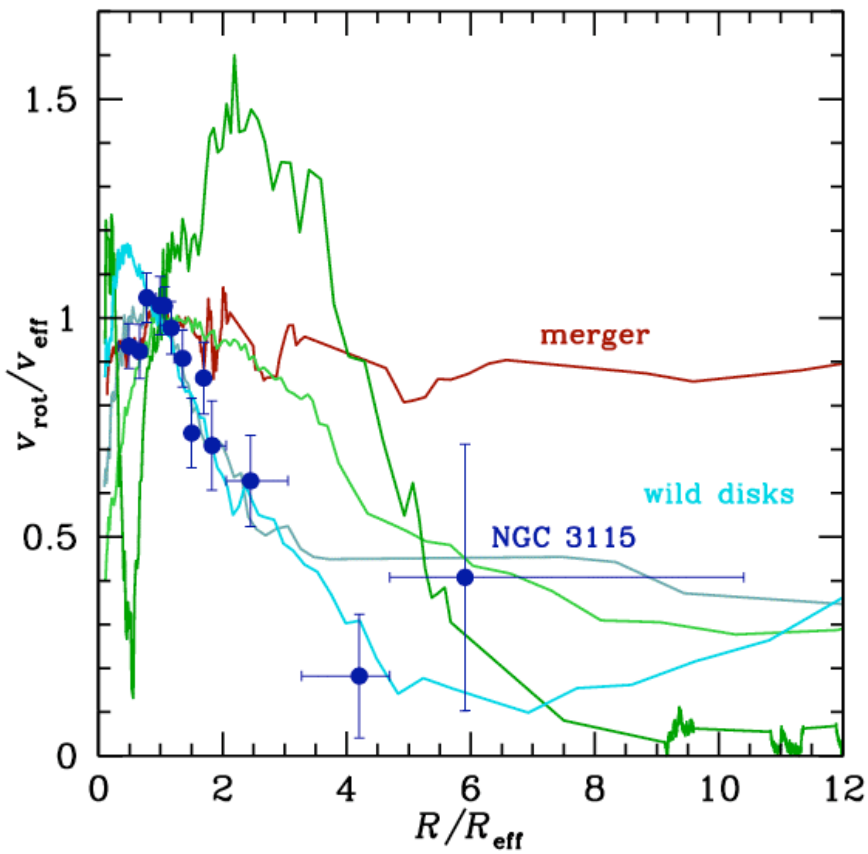
Sérsic profiles, *n* ~ 4.5 – 6, R_{eff} ~ 1.0 – 1.4 kpc

→ *classical bulges with embedded stellar disks*

→ *similar-mass early-types at z=0 have R_{eff} ~ 5 – 10 kpc*

Wild disk simulations: *stellar kinematics*





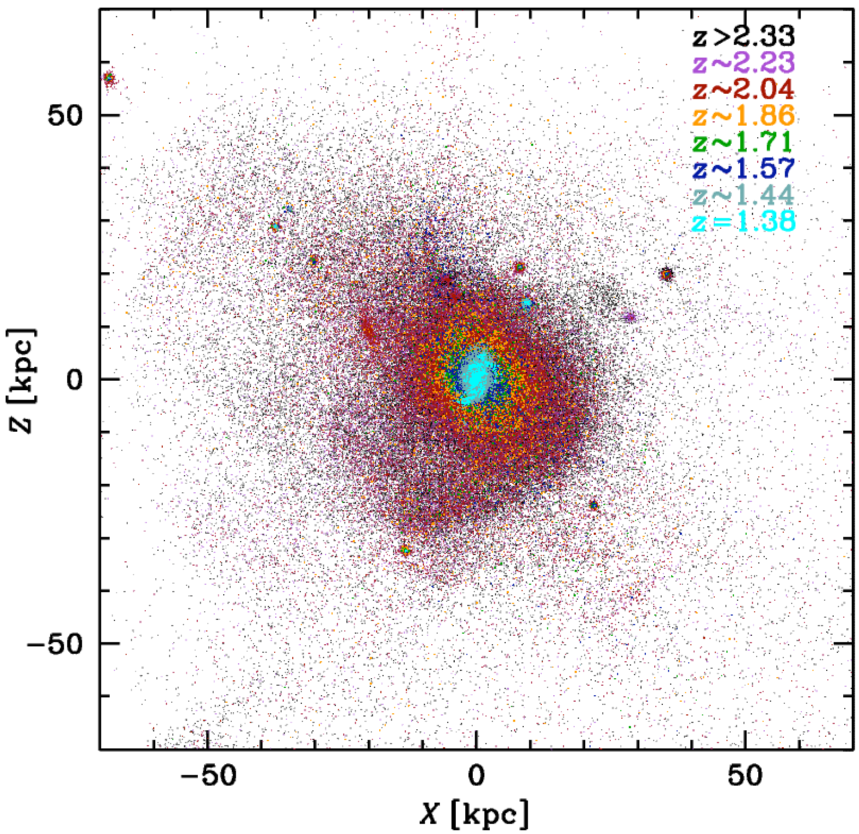
Rotating disky component inside slowly-rotating halo, with transition at ~ 1– 4 R_{eff}

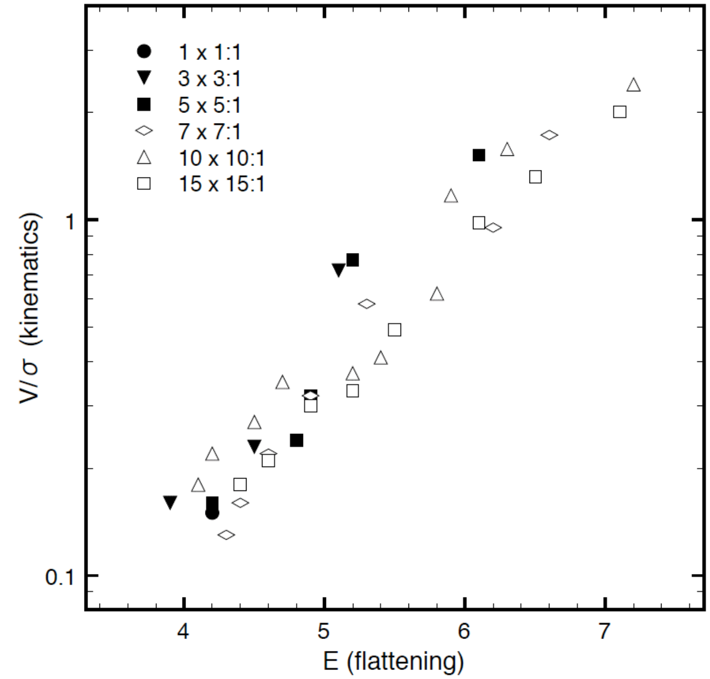
→ *resembles observations of declining rotators*

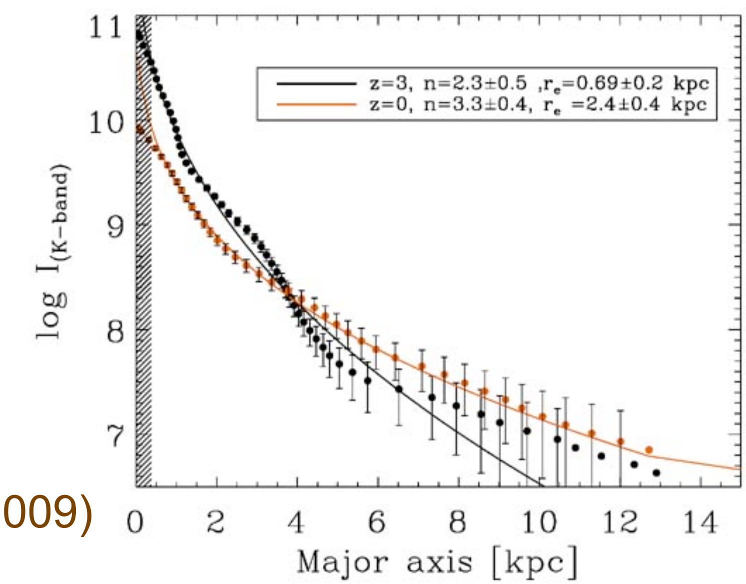
NB: NGC 3115 has thin stellar disk out to ~1 R_{eff}, ~6.5 Gyr age

→ structure "frozen in" at z ~ 0.7, w/little energy input from later mergers

Origin of low outer rotation







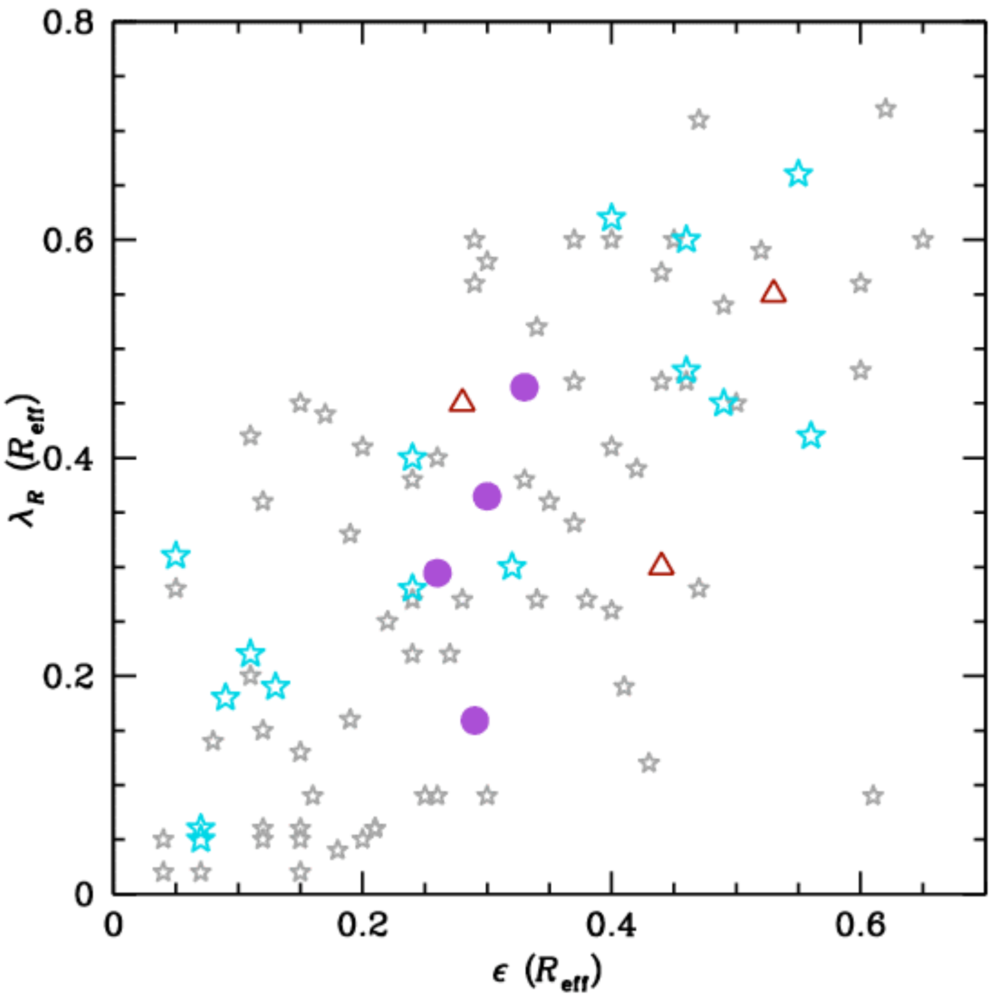
Outer envelope build-up by multiple minor mergers(?):

→ ***may explain observed E size growth***

→ ***predicted to dilute outer rotation***

(Bournaud et al. 2007; Naab et al 2009; Hopkins et al. 2009)

Mergers vs wild disks: *inner properties*



SAURON data

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

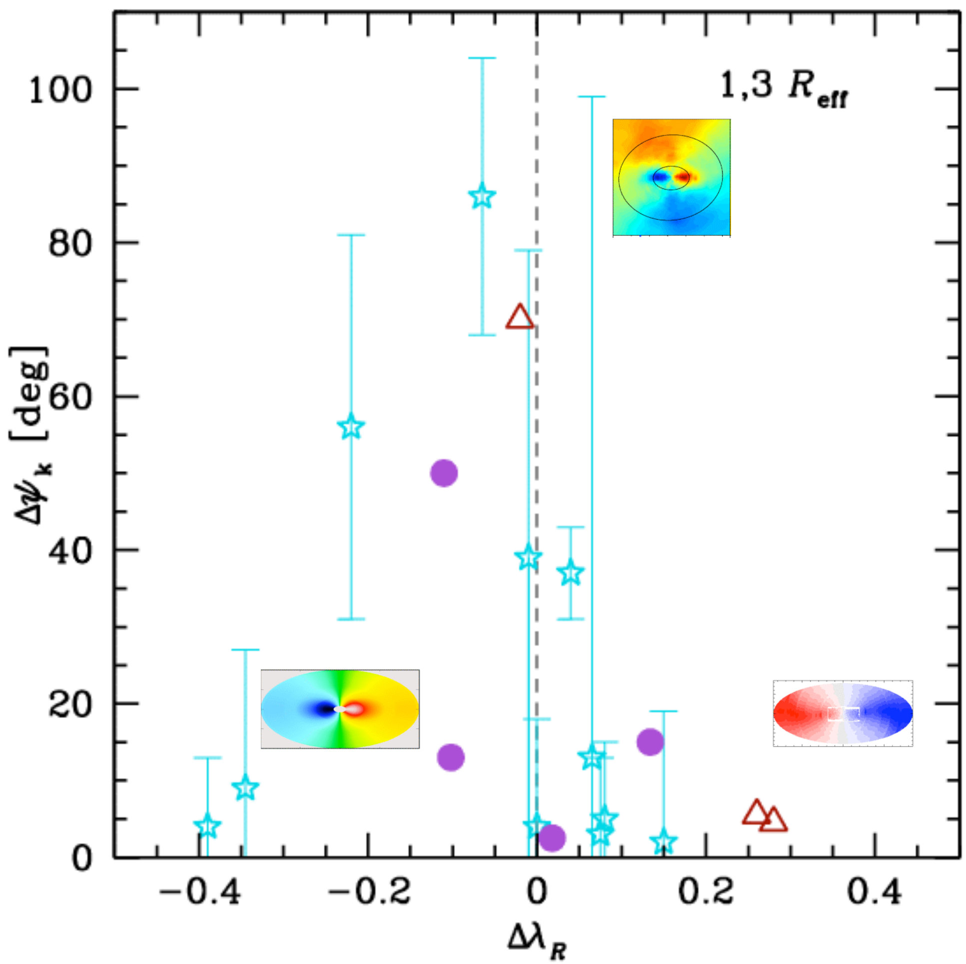
Galaxies with large-radius observations

Cosmological simulations
(near edge-on)

Major mergers
(averages of multiple orbit and viewing directions)

***Cosmological* and *major merger* simulations both consistent with *observations* on ~R_{eff} scales**

Mergers vs wild disks: *outer rotation*



Angular momentum change vs. kinematic twist

Large-radius observations

Cosmological simulations
(near edge-on)

Major mergers
(averages of multiple orbit and viewing directions)

Observations: most have weak twists + constant/declining rotation
→ *better match to cosmological sims than to major mergers*

NB: major merger remnants may **later** build up halo by minor mergers

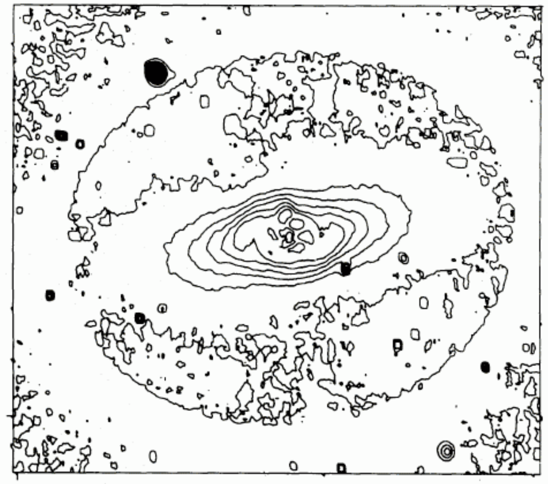
The internal structure of disky elliptical galaxies

Cecilia Scorza[1,⋆] and Ralf Bender[1,2,⋆]

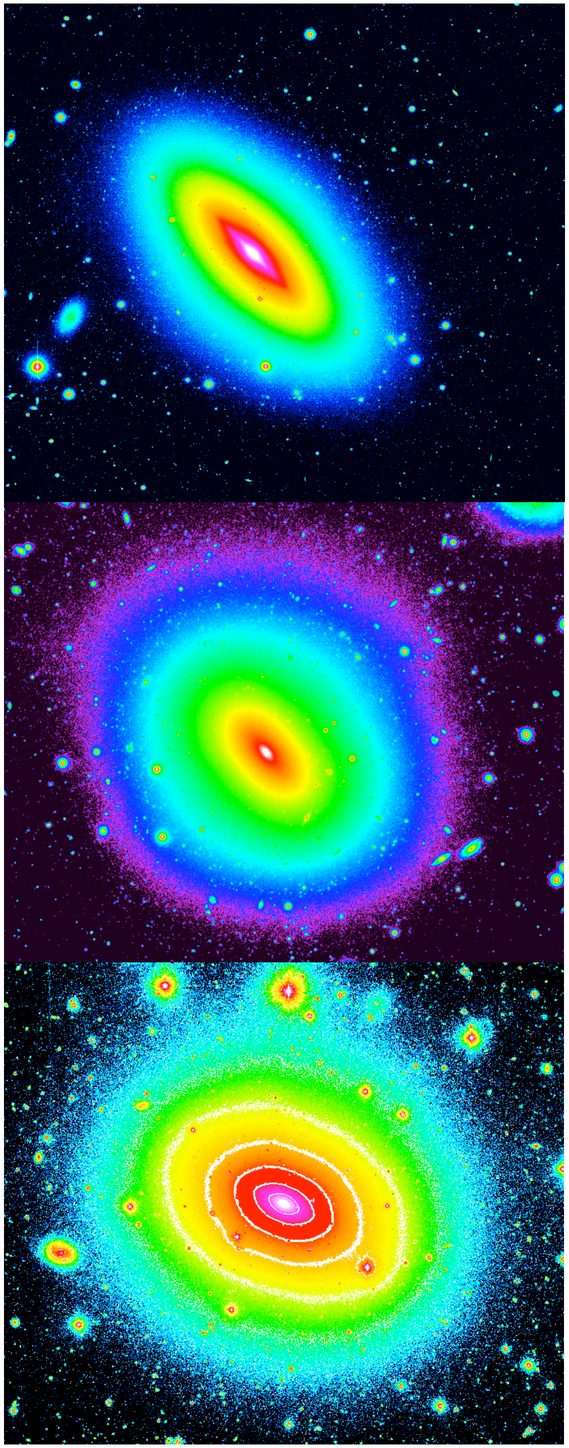
Astron. Astrophys. 293, 20–43 (1995)

Abstract. The structure of seven disky ellipticals, one bulge-dominated S0 (NGC 3115) and one boxy elliptical with a disky core (NGC 5322) has been investigated on the basis of two-component decomposition techniques applied to photometric and kinematic data. We find that both disky isophotes and the observed asymmetric velocity line profiles of these objects can consistently be interpreted within simple disk + bulge mod-

between exponential and $r^{1/4}$ profiles. In all disky ellipticals bulges and disks have parallel angular momenta. This demonstrates that stellar disks in disky ellipticals are not the result of late accretion or merger events but are likely to be primordial (in the same sense as are disks in S0's). The anisotropy parameter



Forgotten clues to galaxy formation!



Observations of E/S0 outer rotation:

- *3 classes of λ_R : rising, flat, falling*
- *outer rotation usually well aligned*

Major mergers:

*naturally produce rising rotation,
or "decoupled" core/halo rotation
with twisting*

Cosmological wild disk mode:

*provides fast-rotating "seed" galaxy;
slow-rotating envelope builds up by
minor mergers*

*→ predictions for DM profiles,
orbit structure, ∇Z, etc.?*