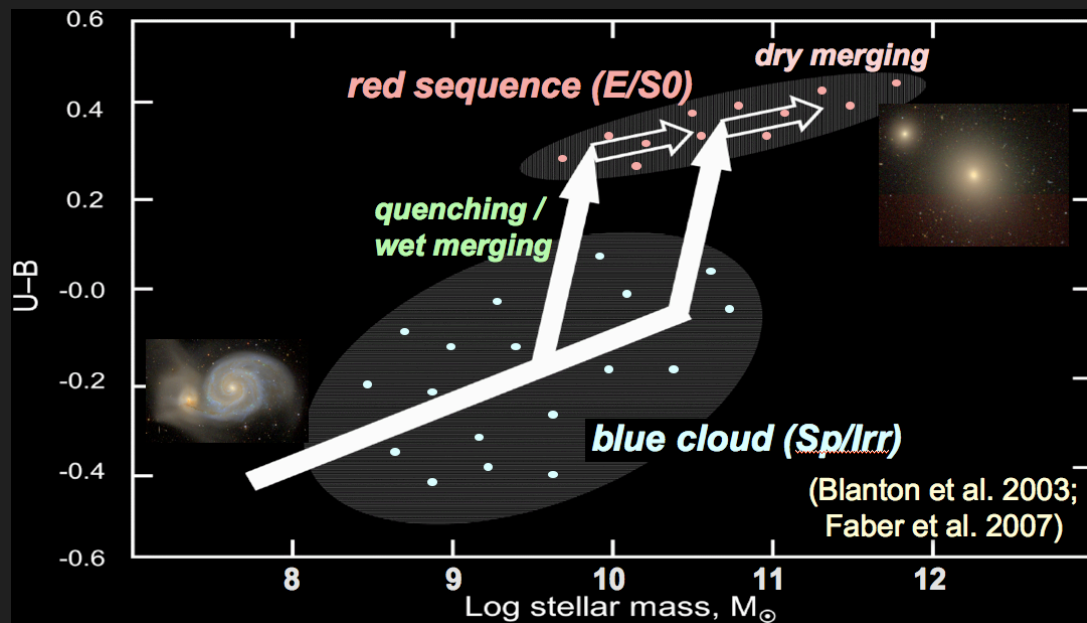


Observing the 2nd Phase of Early-type Galaxy Assembly

Jacob A. Arnold
UC, Santa Cruz

Jean Brodie
Aaron Romanowsky
Avishai Dekel
Daniel Ceverino
Loren Hoffman

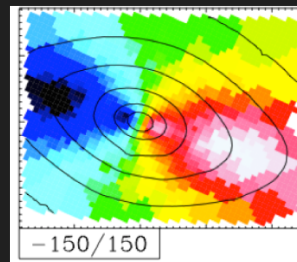


How are early-type galaxies assembled?

Lessons from SAURON / Atlas 3D

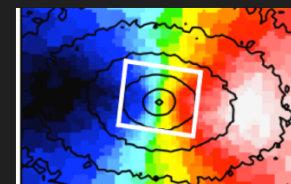
- 86 % of sampled ETGs are “fast rotators” with well-aligned photometric/kinematic axes
- Consistent with oblate axisymmetric major merger remnants

NGC 4660



Emsellem et al. 2004

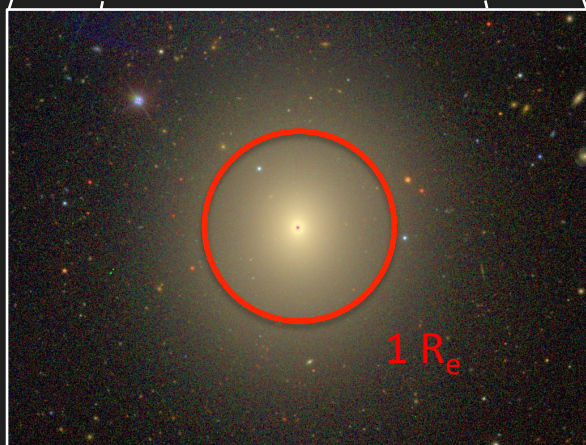
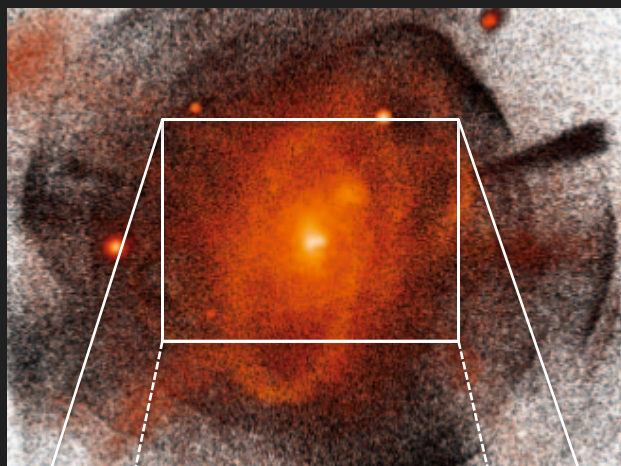
3:1 merger remnant



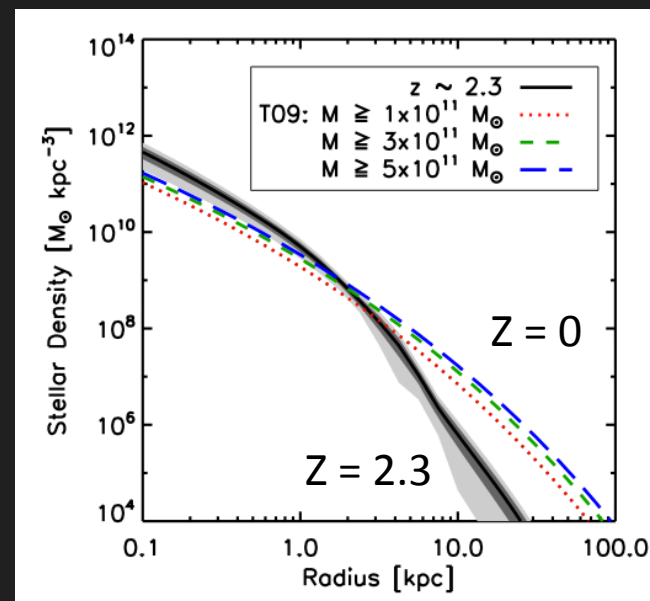
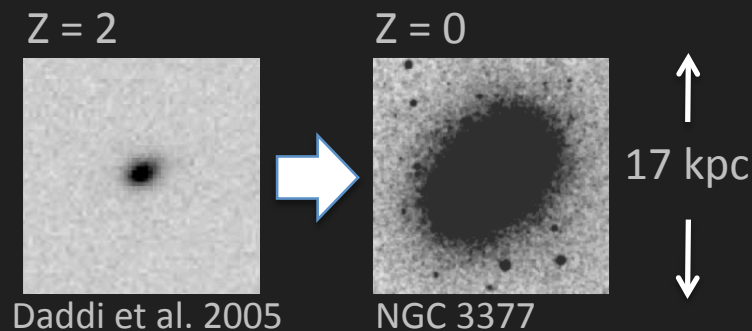
Bois et al. 2011

Bullock & Johnston 2005;
Font et al. 2008

Two-phase / Inside-out Galaxy Formation



Accreted material dominates at larger radius (Naab et al. 09, Oser et al. 2010), but detailed IFU kinematics are typically within $0.7 R_{\text{eff}}$



Bezanson et al. 2009

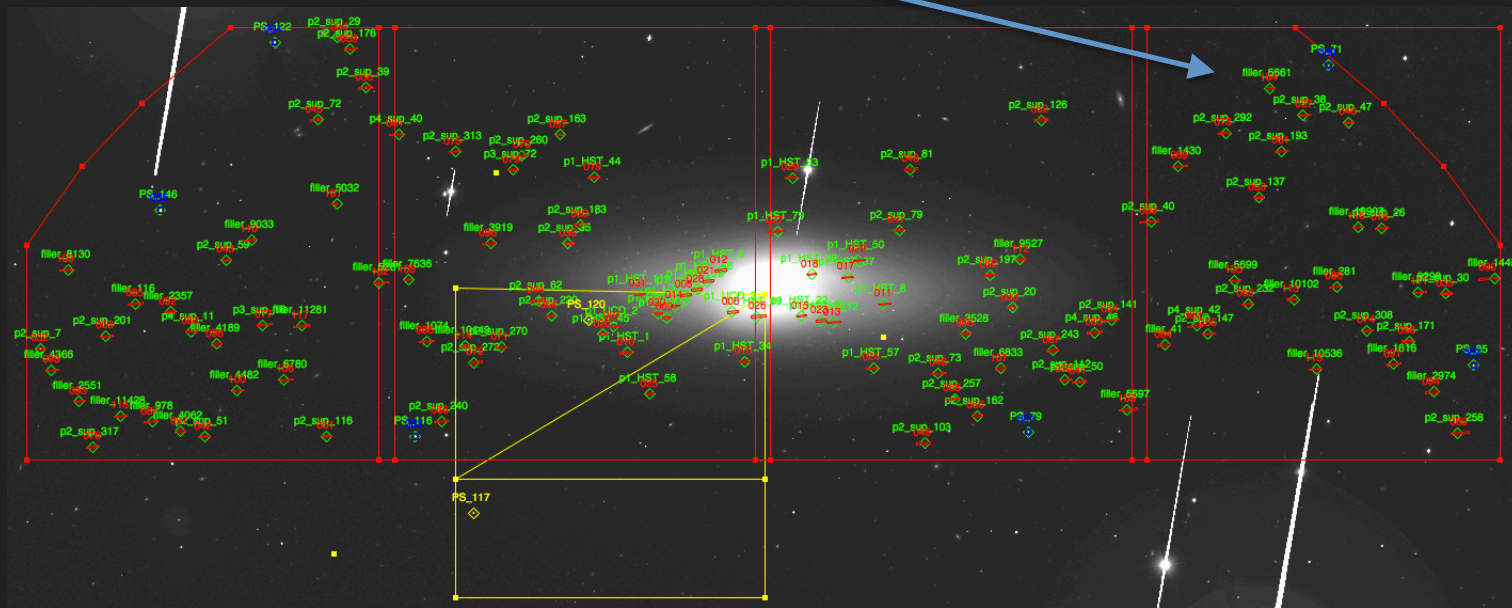
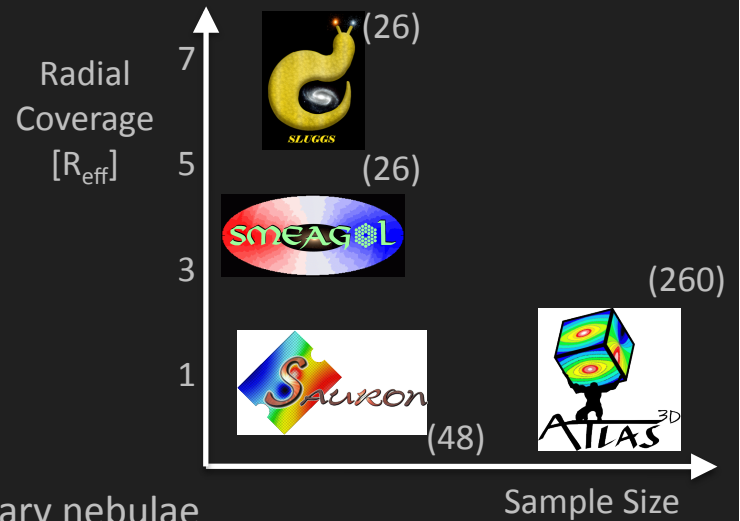
Wide-field Kinematics

Integrated stellar light measurements at 1-3 R_{eff}

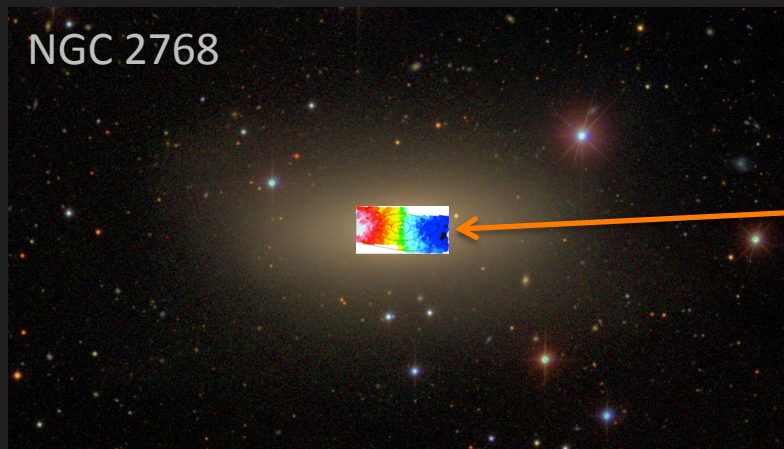
- Wide-field IFUs in light-bucket mode
- Longslits at multiple position angles
- Multislit masks used with, e.g., DEIMOS on Keck II (SMEAGOL)

Rotation and velocity dispersion measurements out to 8-10 R_{eff}

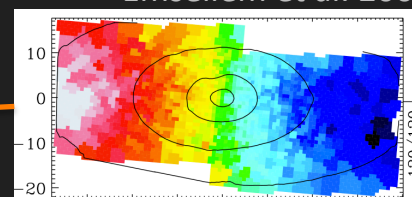
- Discrete velocity tracers: globular clusters (SLUGGS) and planetary nebulae



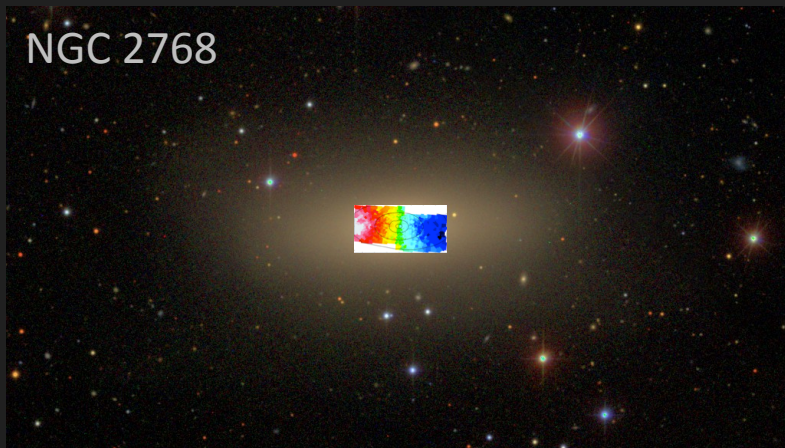
NGC 2768



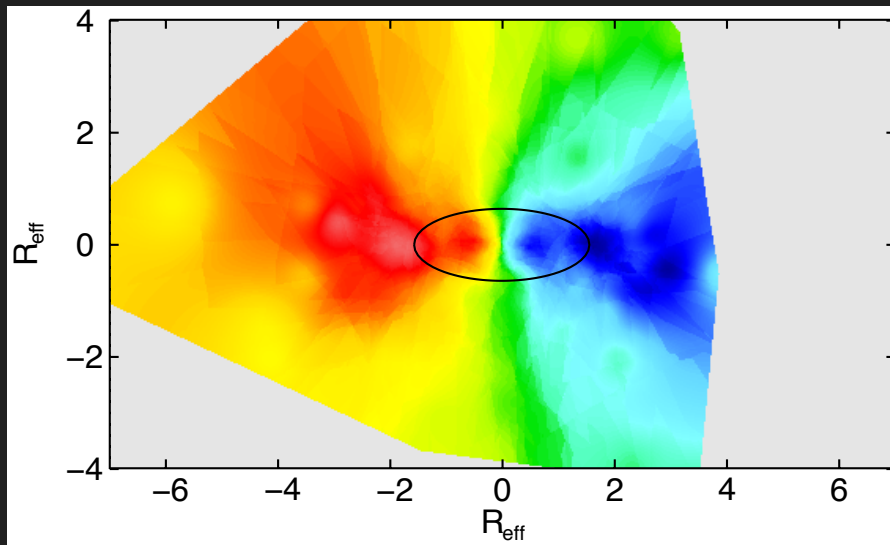
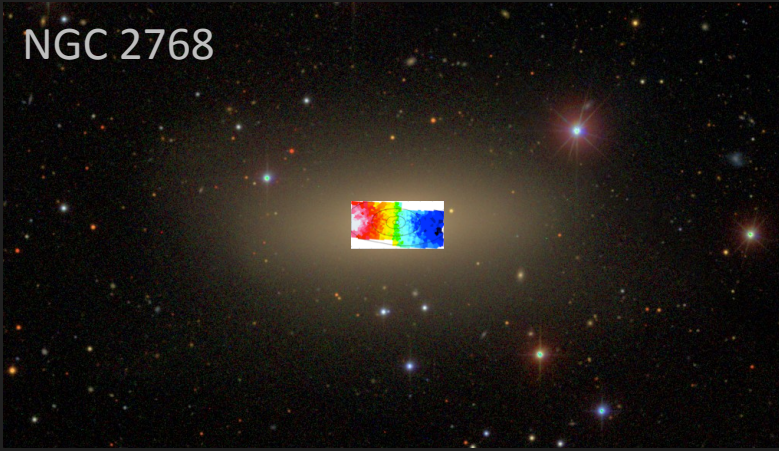
SAURON Velocity Map
Emsellem et al. 2004



NGC 2768



NGC 2768

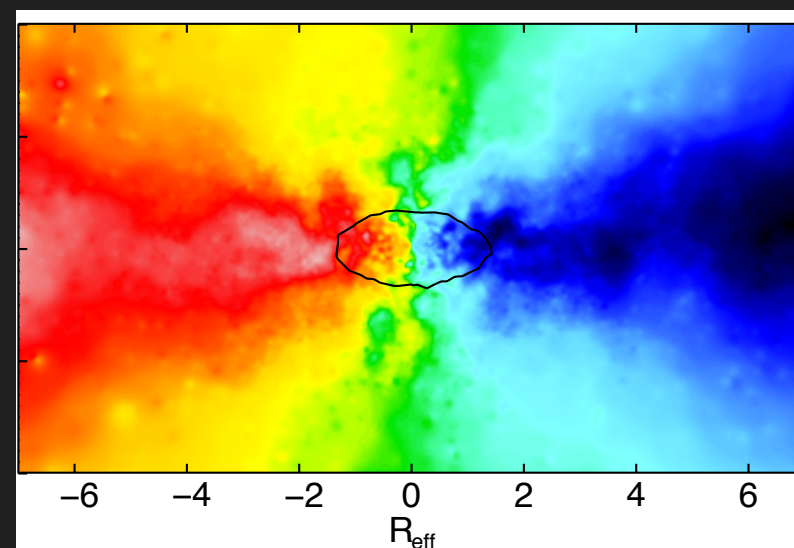
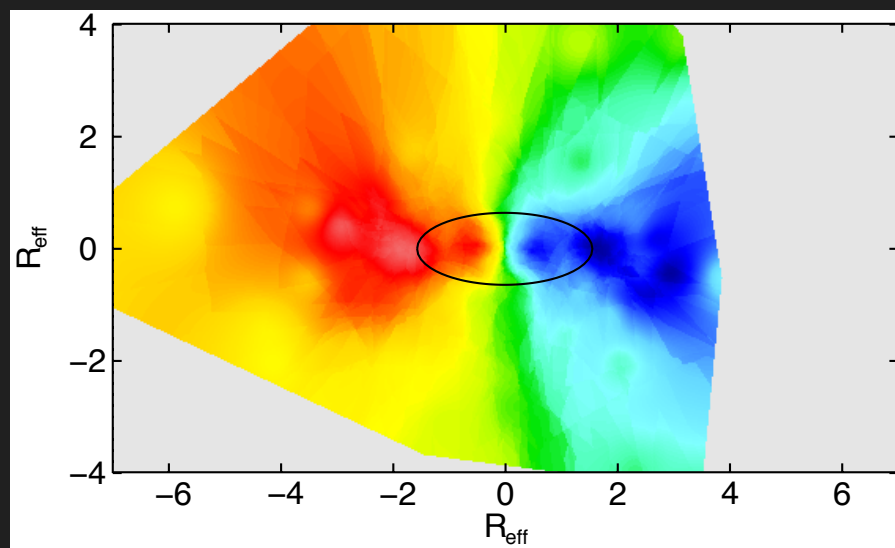
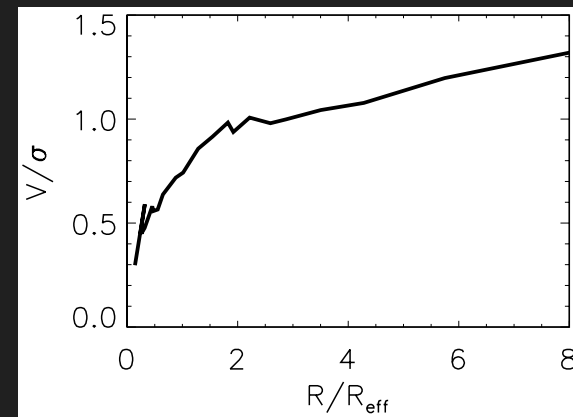
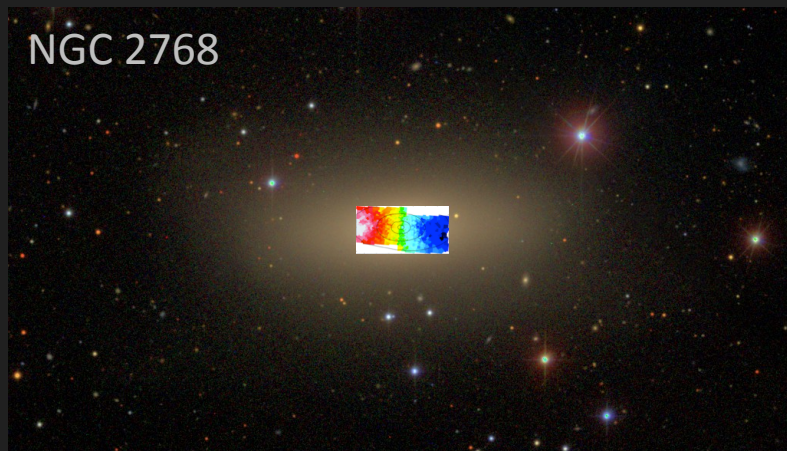


Wide-field velocity structure of NGC 2768

SAURON

- + DEIMOS multi-slit (Proctor et al. 2009, Caroline Foster)
- + metal-rich globular cluster velocities

- Aligned, rapid-rotation out to $\sim 3 R_{\text{eff}}$
- Farther out, rotation begins to decline



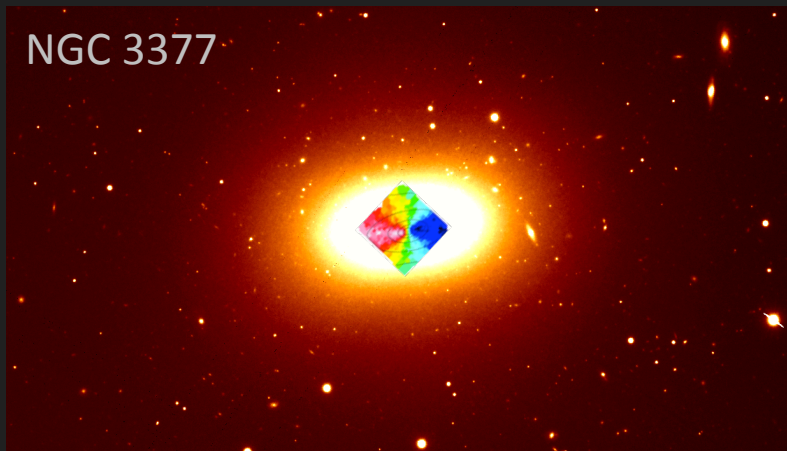
Wide-field velocity structure of NGC 2768

3:1 merger remnant (Loren Hoffman)

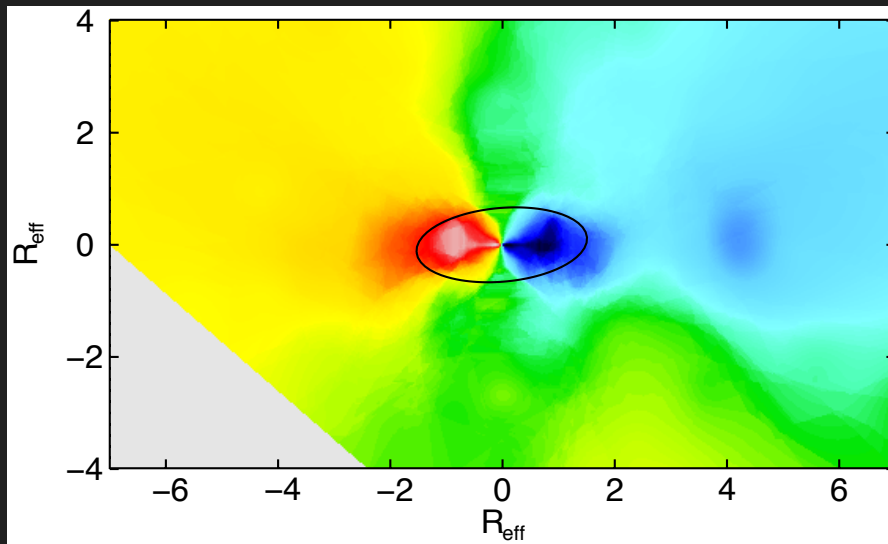
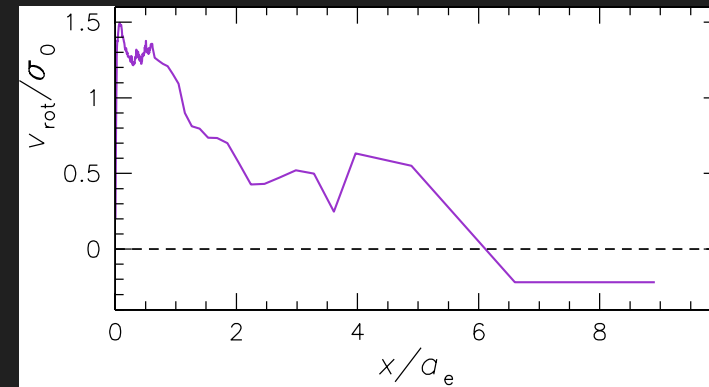
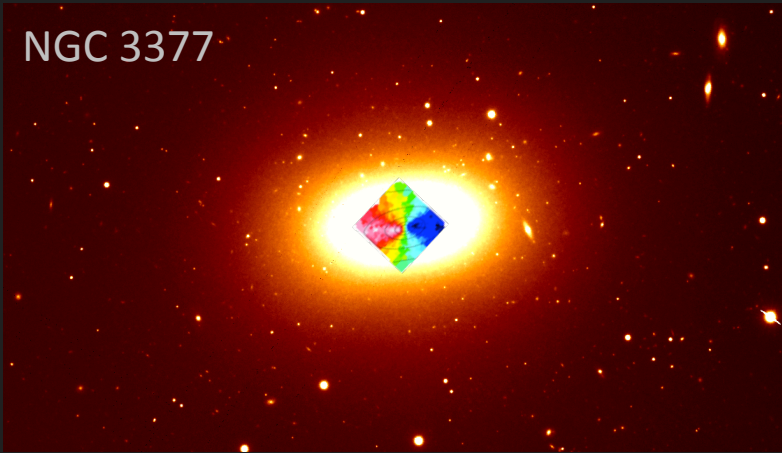
- SAURON
- + DEIMOS multi-slit (Proctor et al. 2009, Caroline Foster)
- + metal-rich globular cluster velocities

- Residual progenitor disk spin and the conversion of orbital into internal angular momentum produce radially increasing V/σ

NGC 3377



NGC 3377



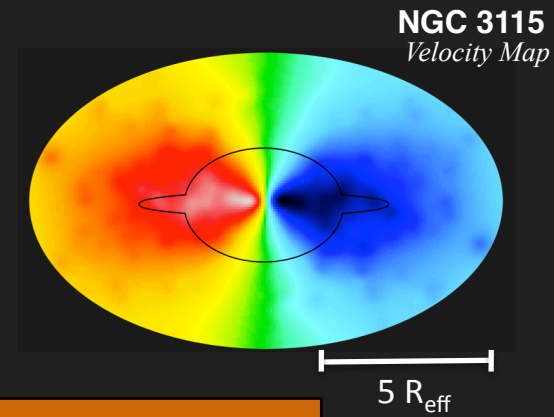
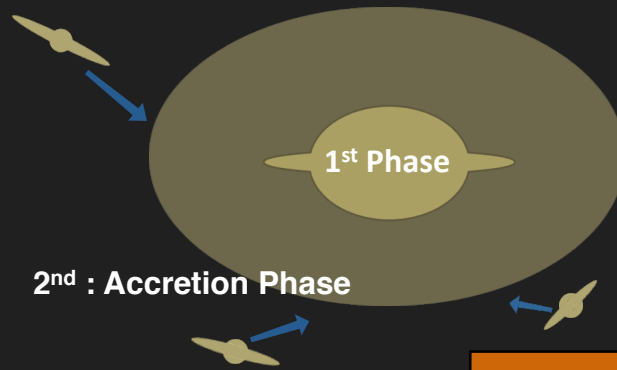
- Rapid, inner rotation begins to decline near $\sim 1 R_{\text{eff}}$
- Potential kinematic twist at several R_{eff}

Wide-field velocity structure of NGC 3377

SAURON

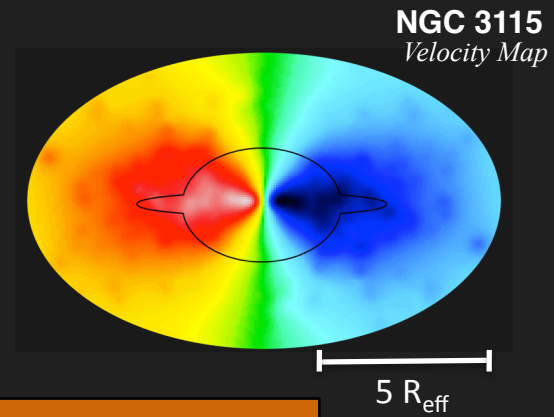
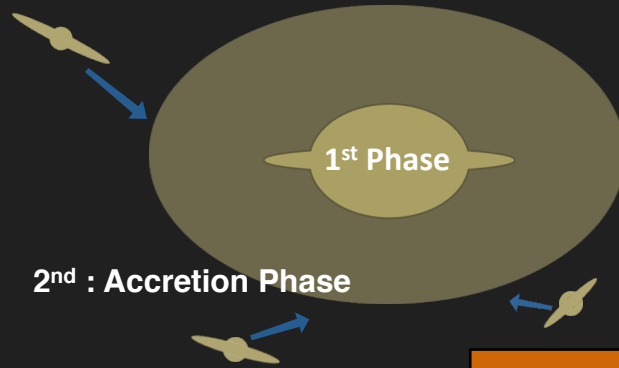
- + long-slit (Cocato et al. 09)
- + planetary nebulae velocities (Cocato et al. 09)

Assembling the Outer Bulge



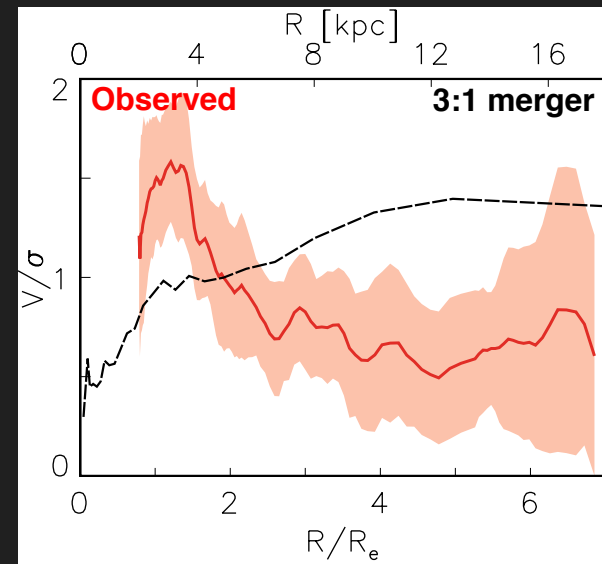
Rotation decreases in the outer, accretion dominated regions

Assembling the Outer Bulge



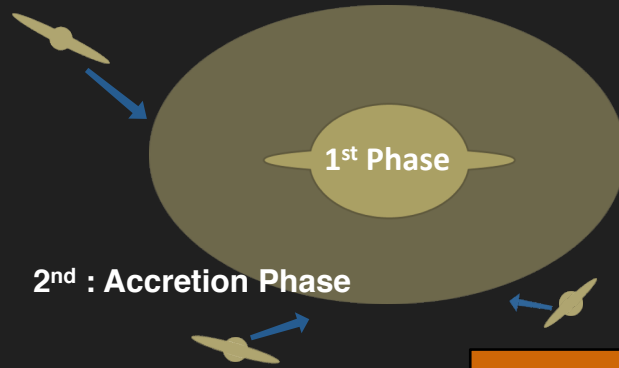
Rotation decreases in the outer, accretion dominated regions

Apparent discrepancy between observed and expected major-merger v/σ profiles

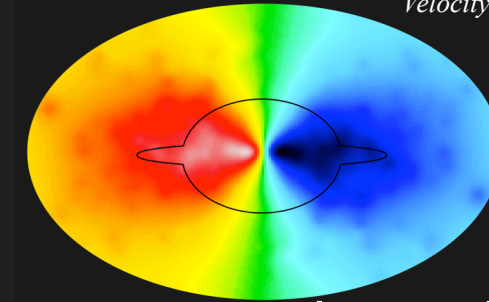


Arnold et al. 2011

Assembling the Outer Bulge



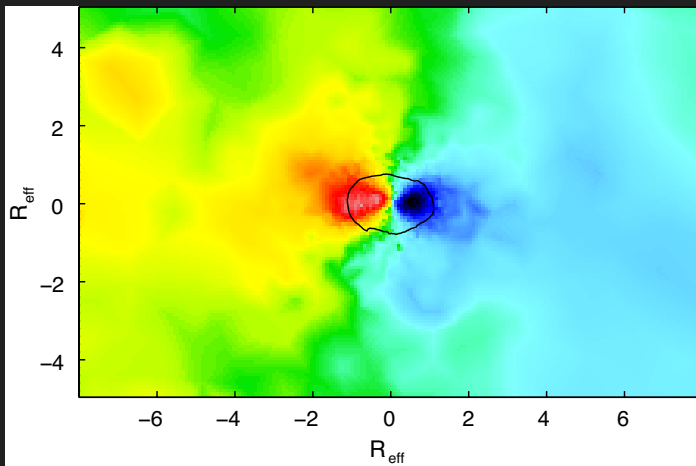
NGC 3115
Velocity Map



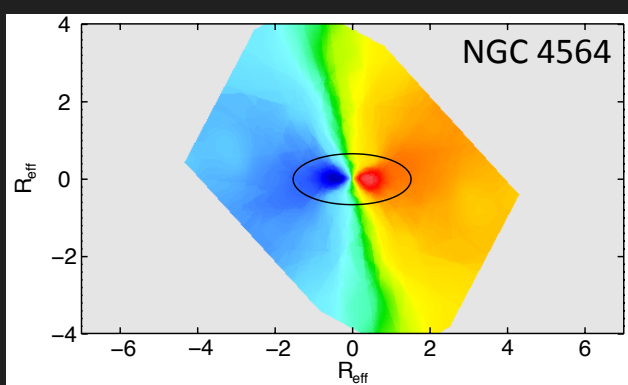
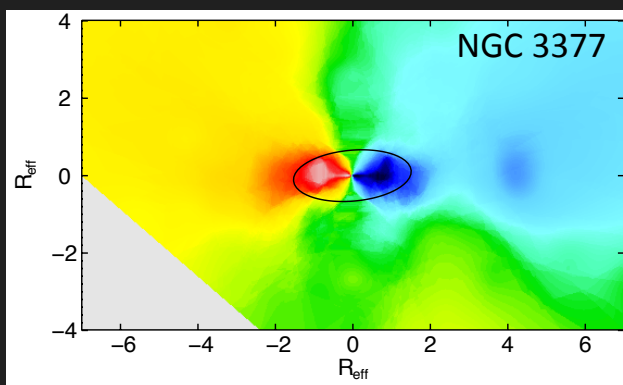
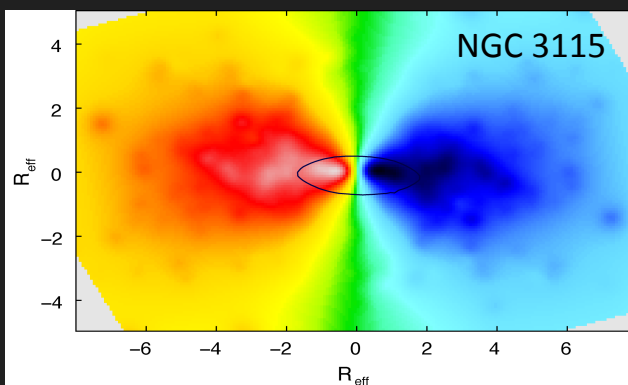
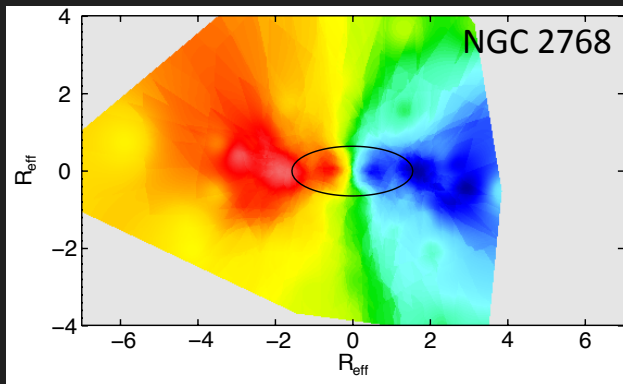
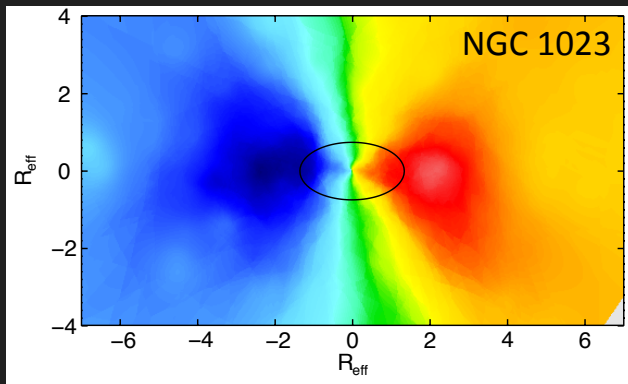
Rotation decreases in the outer, accretion dominated regions

Cosmological Simulation (MW2)

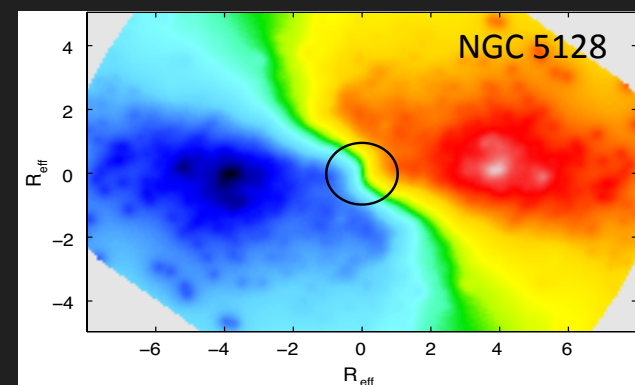
Daniel Ceverino, Avishai Dekel



These remnants with cosmological accretion histories reproduce the observed behavior

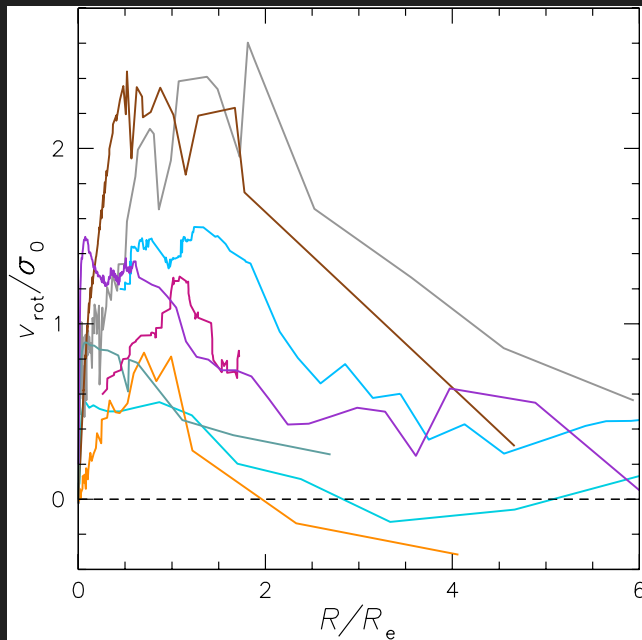


Declining "halo" rotation in a number of galaxies



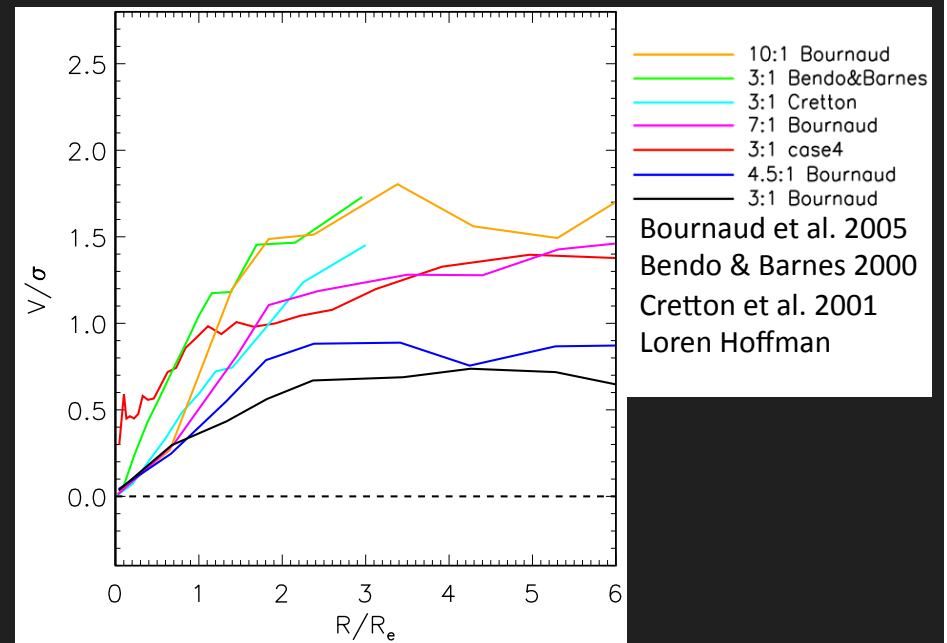
Sample of 8 near to edge-on galaxies

- All show an outer decline in v/σ



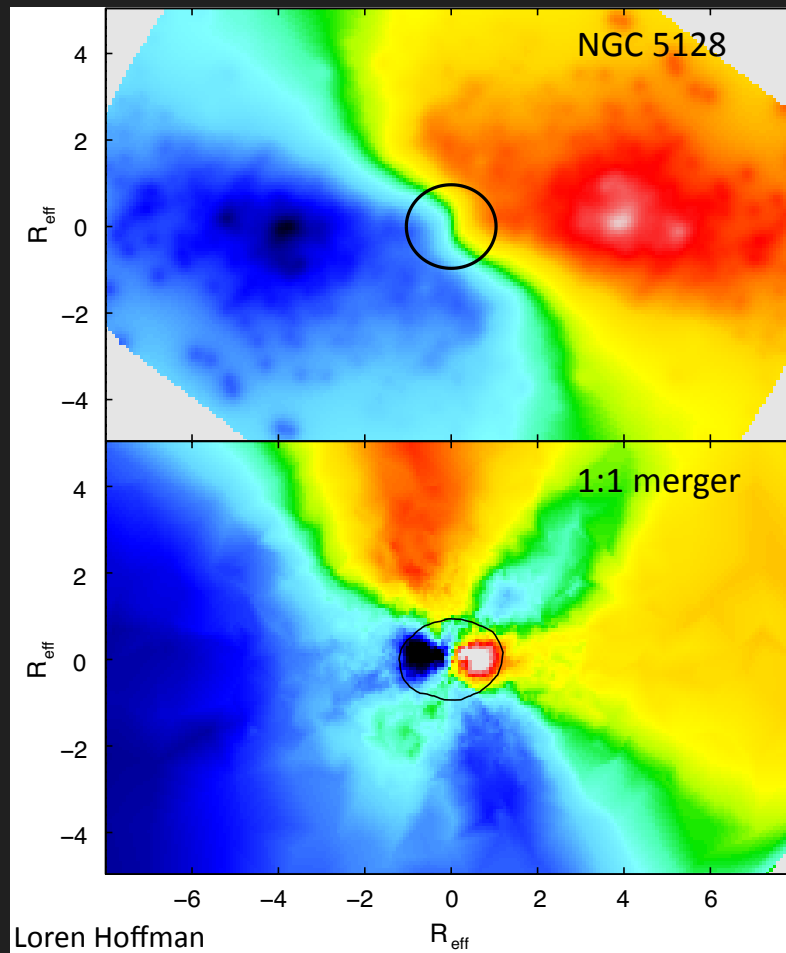
Representative major-merger remnants

- All show rising to flat v/σ profiles



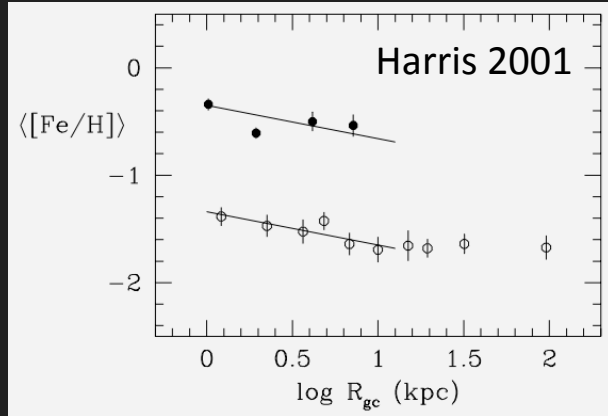
- The generic major-merger prediction is for flat or rising v/σ profiles resulting from residual progenitor disk spin and the conversion of orbital into internal angular momentum
(Hernquist 1992, Bendo & Barnes 2000, Cretton et al. 2001, etc.)

An Example of a Recent Major-Merger



Prominent kinematic twist and outer rising rotational profile indicative of a recent major-merger

Milky Way - Harris 2001

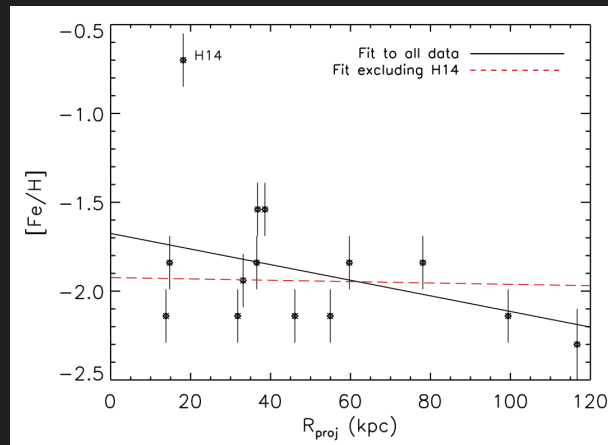


Searle & Zinn (1978)

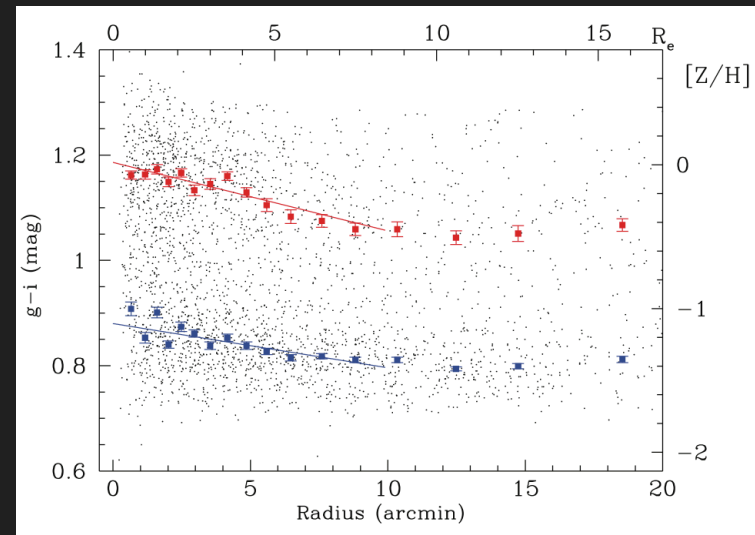
A stellar halo formed by the accretion of “transient protogalactic fragments” will exhibit a flat outer metallicity gradient

- Additional evidence for the hierarchical assembly of outer bulges & stellar-haloes from the metallicity structure of globular cluster systems

M31 - Huxor et al. 2011



NGC 1407 - Forbes et al. 2011



Summary

- Our sample of 8 close to edge-on early-type galaxies all show declining v/σ profiles at large radius
- This is in contrast to the general expectation from binary major-merger simulations that v/σ should increase with radius
- This behavior may be a natural consequence of inside-out assembly where material accreted from disrupted satellites builds an extended stellar halo with little net angular momentum

SMEAGOL : Spectroscopic Mapping of Early-type Galaxies to their Outer Limits

SLUGGS : SAGES Legacy Unifying Globulars and Galaxies Survey



- wide field chemo-dynamical surveys of stars and GCs in 25 *representative* early-type galaxies within 25 Mpc

