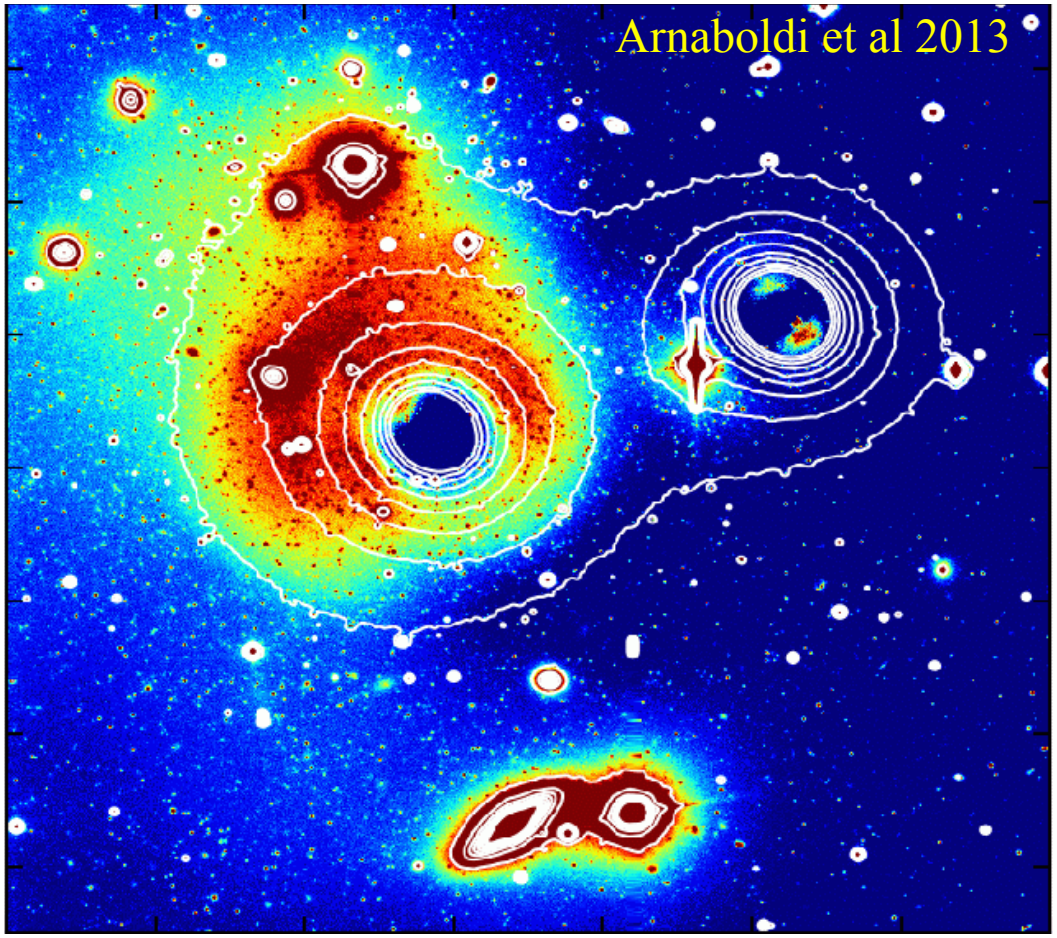
Stellar Orbits and Angular Momentum in Early-Type Galaxy Halos

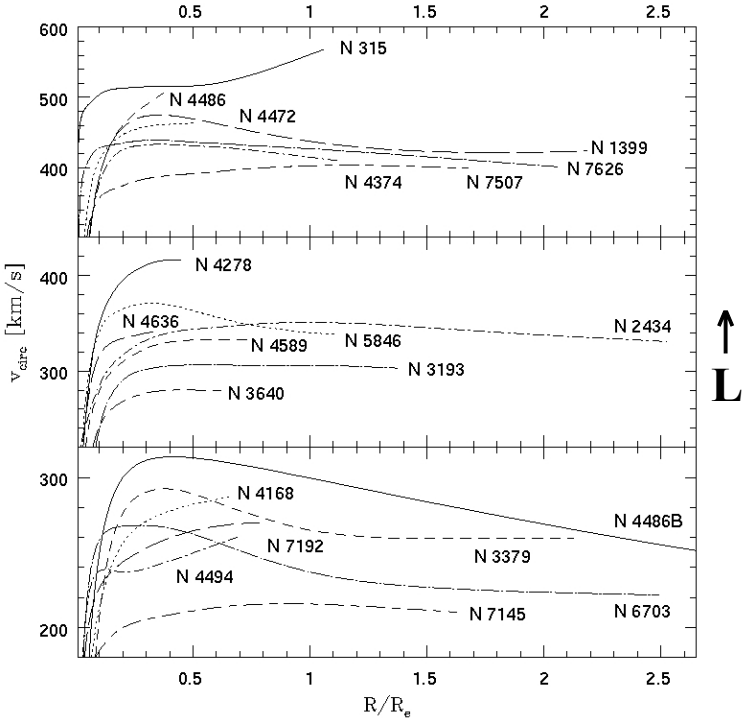
Ortwin Gerhard, MPE, Garching gerhard@mpe.mpg.de

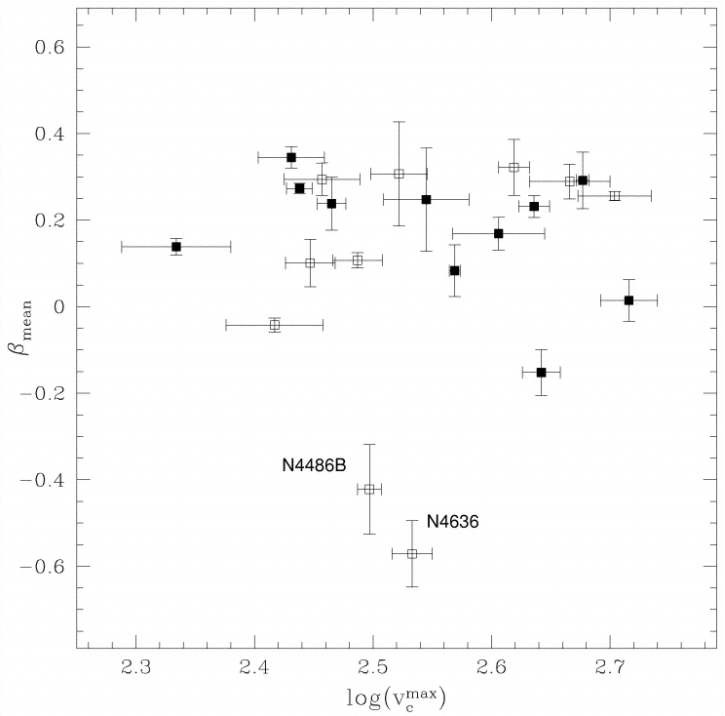
1. **Preamble**
2. **Predictions: ETG halos in cosmological simulations**
3. **Kinematics and angular momentum in ETG halos: New results from the PN.S key project**
4. **Orbits and mass distribution: see also talk by Nicola Napolitano**



Galaxy Disruption in the Outer Halo of the Hydra I Cluster Central Galaxy NGC 3311

ETG Halos -- from Stellar Kinematics





Gerhard+'01

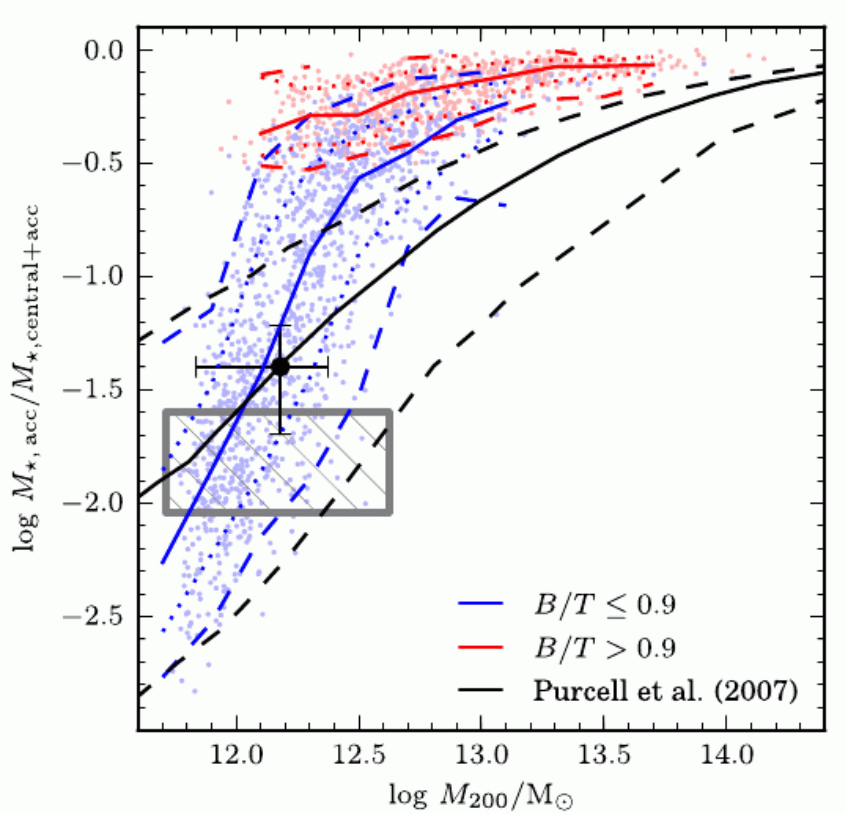
Modelling early slit stellar kinematics to 1-2 Re showed that

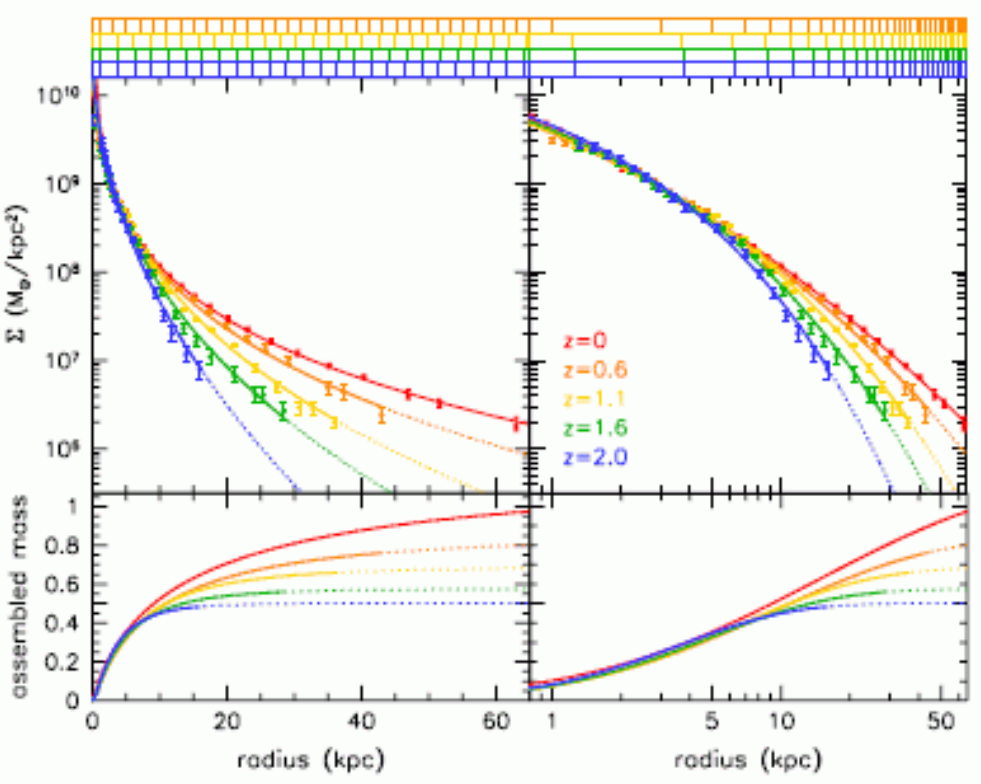
- Circular velocity curves of ETGs approximately flat; ETG Tully-Fisher
- Moderately radially anisotropic stellar velocity ellipsoids
- Dark matter fraction small within Re (10%-40%) , dominates outside 2-3 Re

Working definition for stellar halo = where dark matter dominant - R > 2-3 Re

See also Cappellari+'06, '13; Thomas+'07,'09 -- Treu & Koopmans '04, Auger+'10.

Accreted Mass Fraction Increases Steeply with Mass

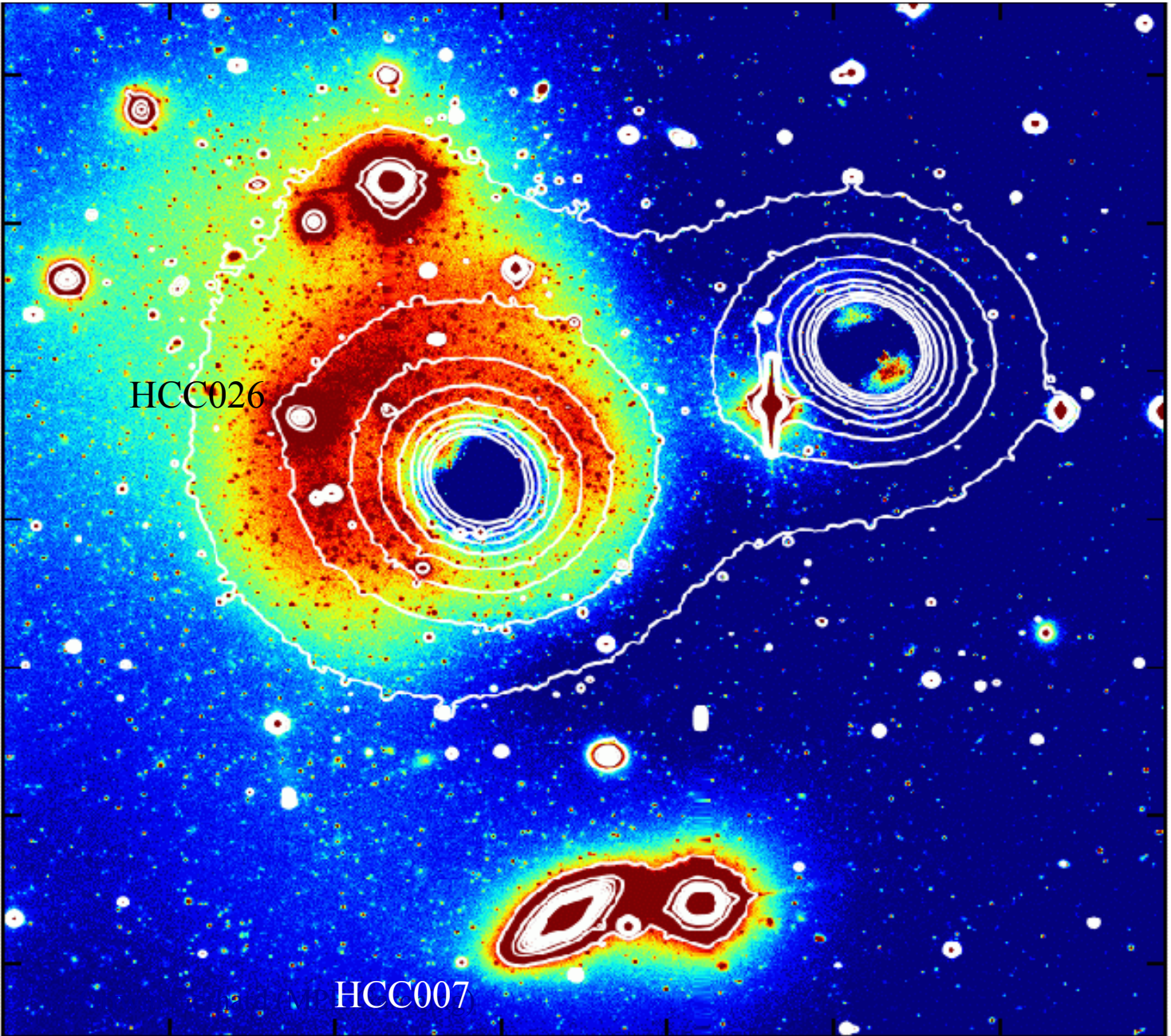




Prediction: stellar halos in ETGs largely accreted
Oser+'10, Cooper+13

Observed size evolution of compact ETGs over redshift
Daddi+'05, Trujillo+'07, van Dokkum+'10

On-going Build-Up of Halo/ICL around NGC 3311



RESIDUAL IMAGE after subtracting N3311, N3309

Down to μ_V~26, see

- Extended, off-centered envelope, ~10^{10} $L_\odot$ ~1/3 halo ~15% L_{tot}
- ~10^9 $L_\odot$ tidal stream of HCC 26
- 100 kpc, few ~10^9 $L_\odot$ tidal stream of HCC 007, ~50%

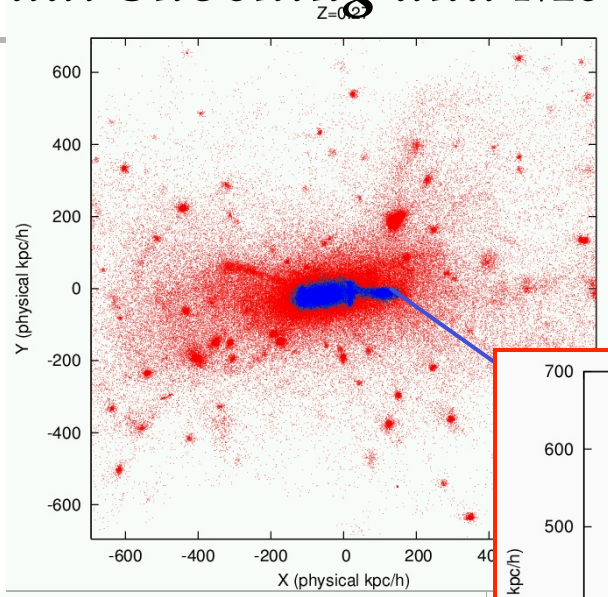
No galaxies within 100 kpc around syst. velocity (destroyed)

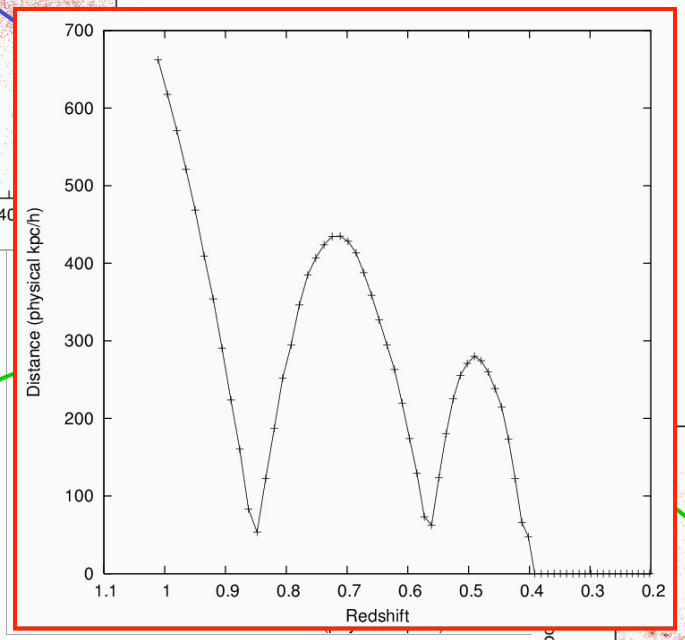
Infalling galaxies (Δ=1000 km/s) being disrupted

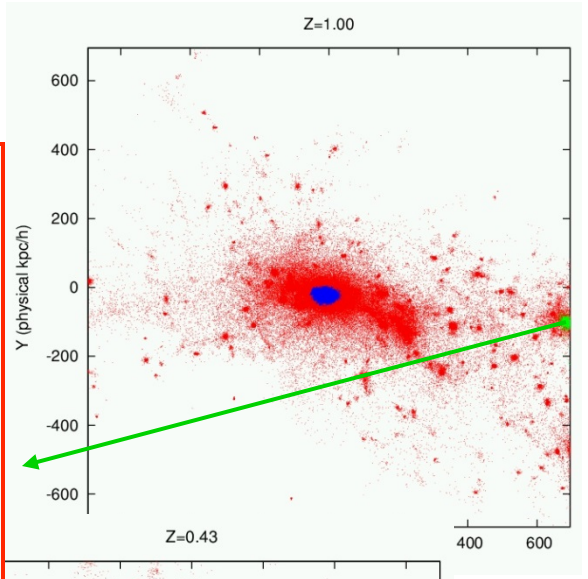
Arnaboldi+'13

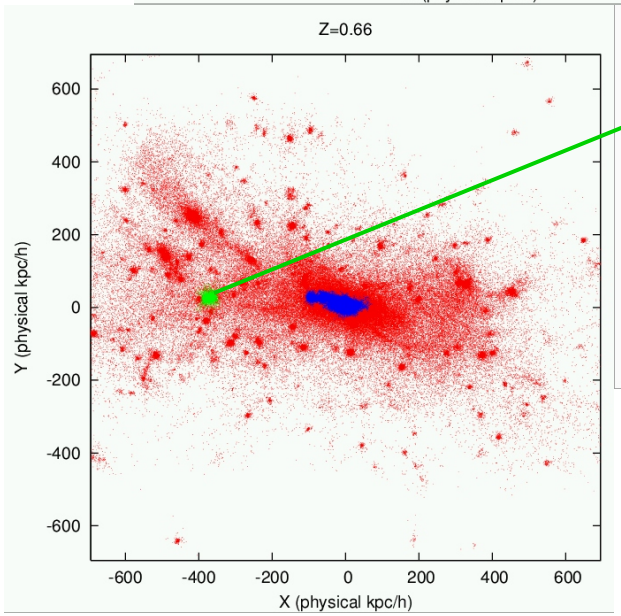
Tidal Shocking and Merging with Brightest Cluster Galaxy

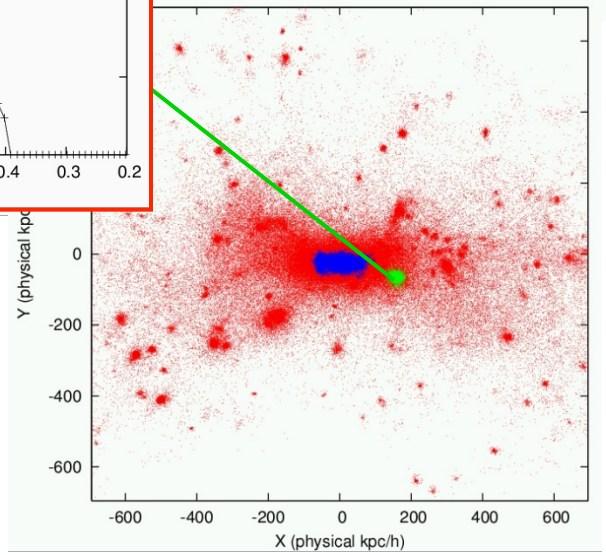
Murante et al. 2007, based on simulation by K. Dolag







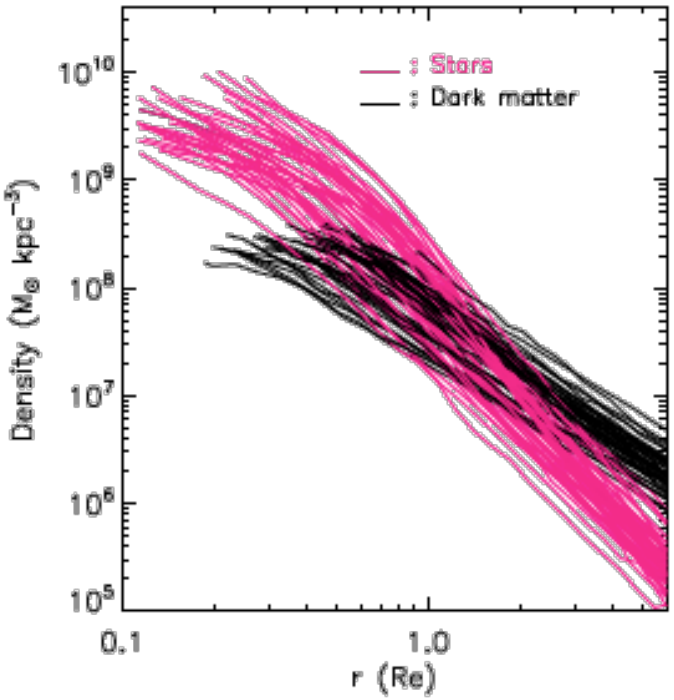




Near-radial accretion orbit generates radially biassed stellar orbits

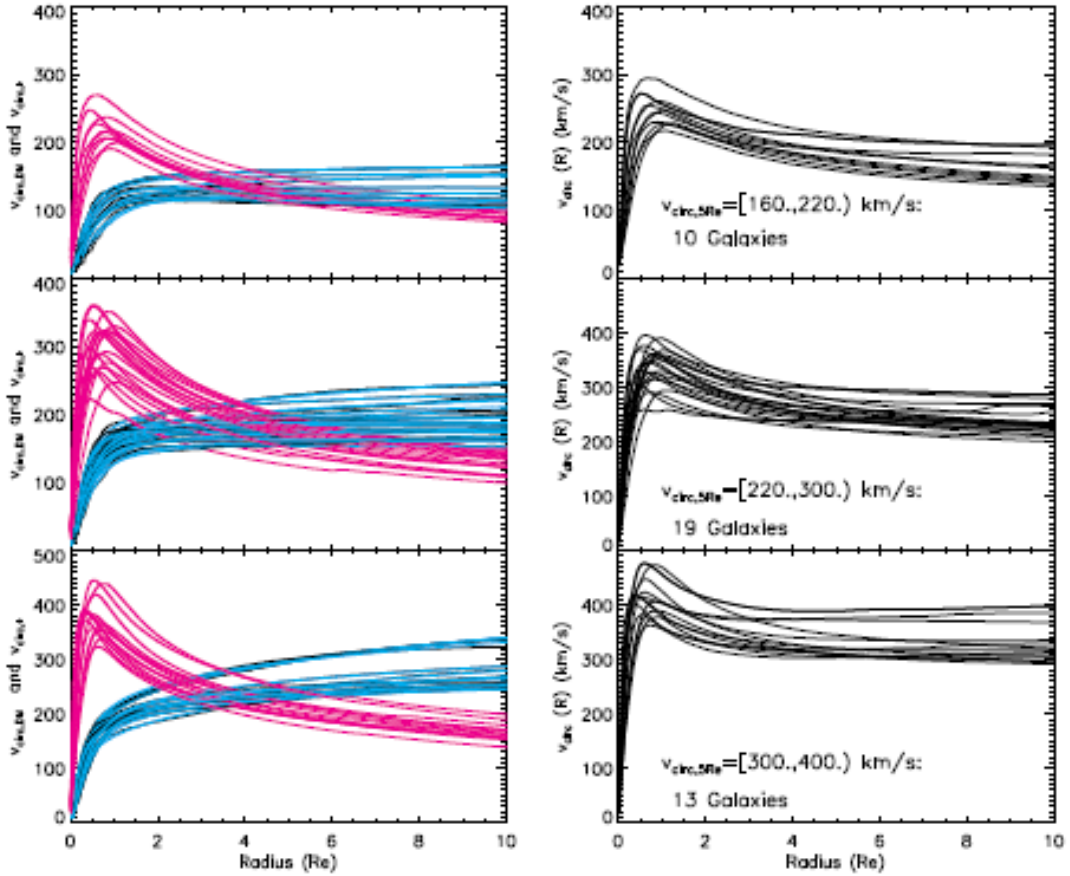
Early-Type Galaxy Halos in CosmoHydro Simulations

DM vs stellar densities



Wu, OG, Naab, et al. 2014

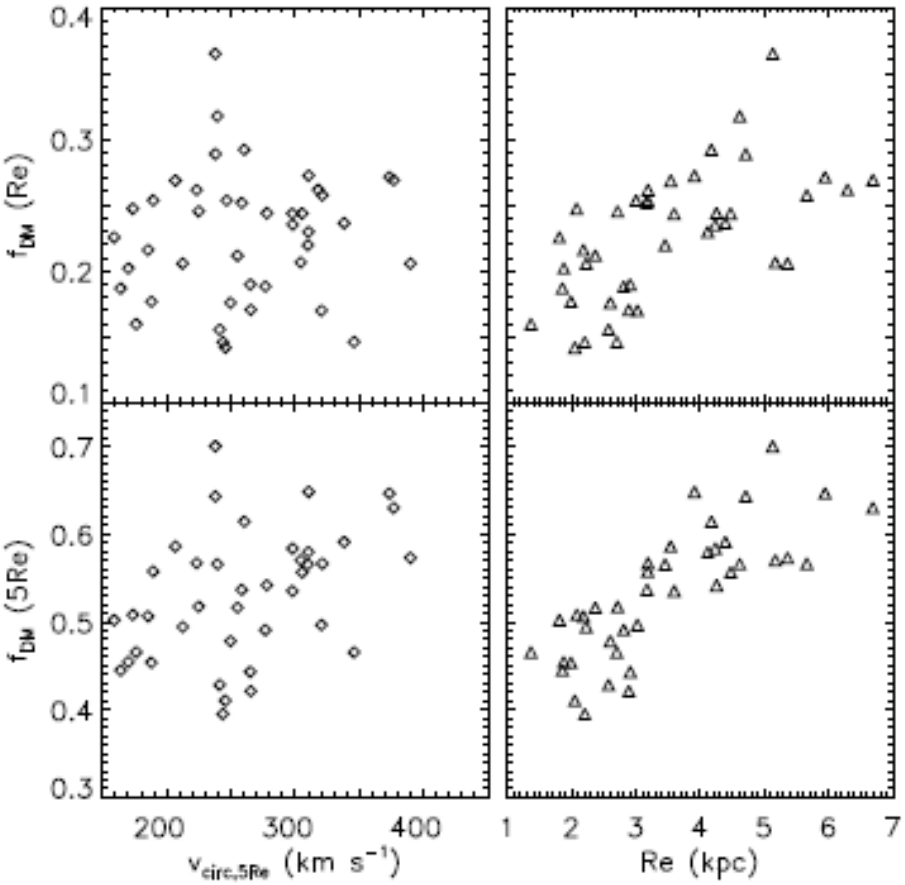
Circular velocity: stars, halo, total



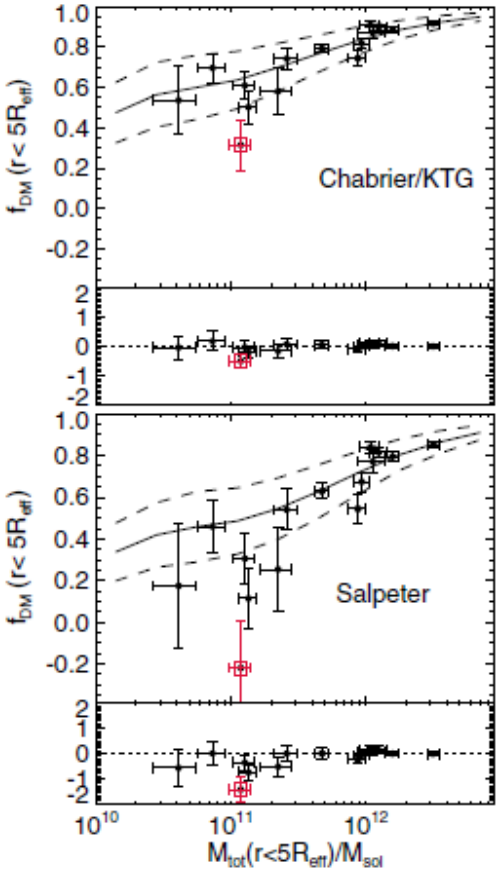
Power law halo density [-2, -1.4]
Slope of circular velocity curve increases with vc or mass

42 galaxies with stellar masses 2.0 $\times 10^{10}$ – 3.4 $\times 10^{11}$ M_{sun} from cosmo-hydro resimulations with cooling, feedback, star formation, **Oser+'10, +'11**. These systems have an early in situ component and have later grown by accretion of smaller satellite systems.

DM Fractions in Simulated Early-Type Galaxies



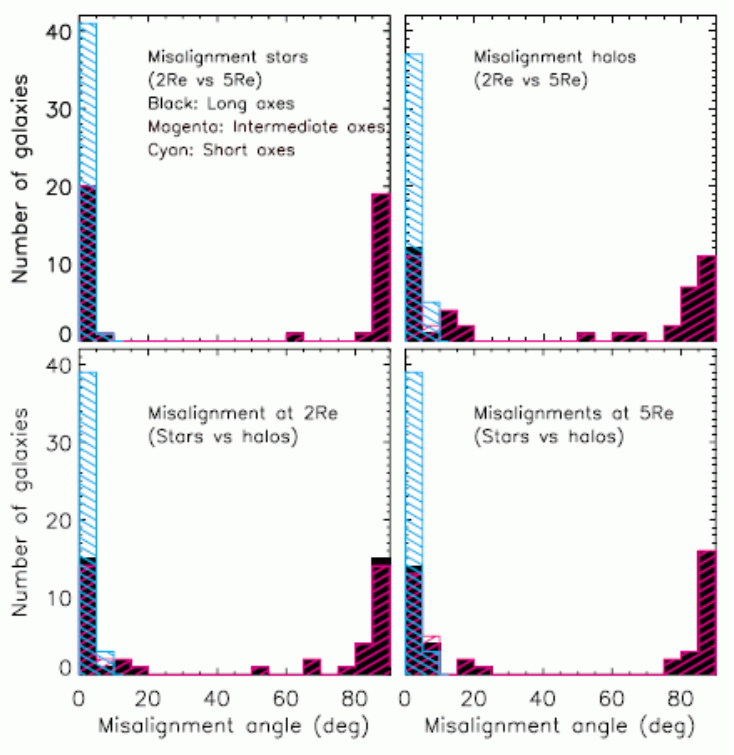
Wu et al 2014

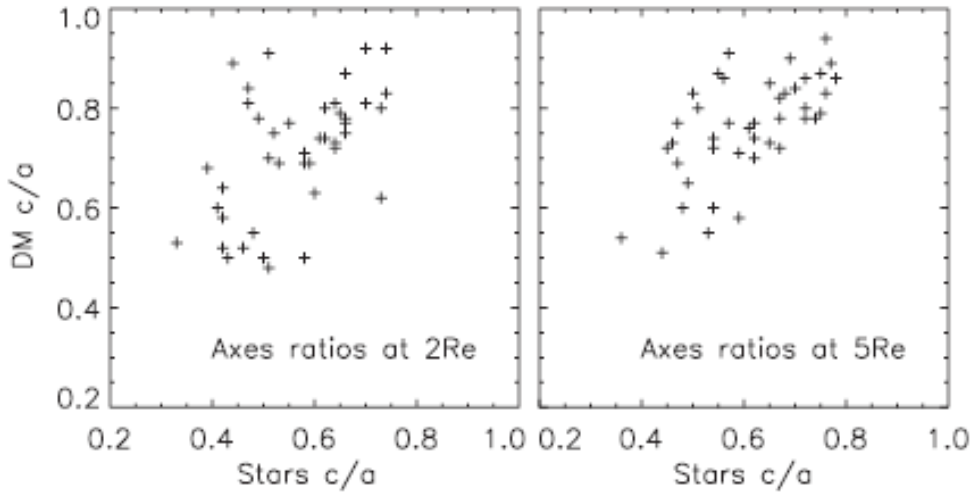


Deason et al 2012

- DM fractions in sETGs ~25% at 1 Re, ~50% at 5 Re, similar to obsvl results
- Increasing with Re in kpc or mass within Re

Dark Matter and Stellar Halo Shapes Correlated



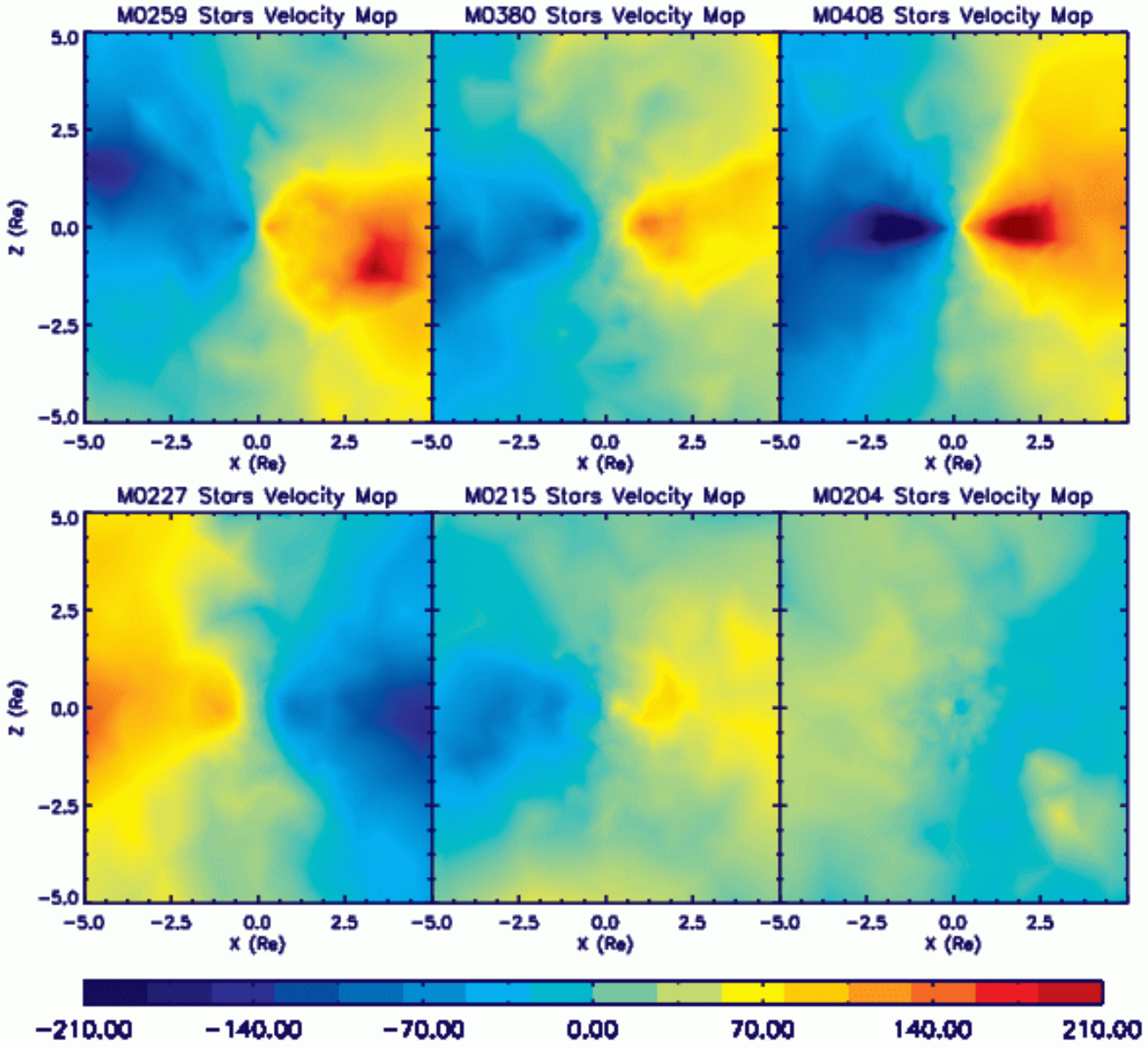


- Stellar and halo principal axes aligned
- Inner and outer shapes aligned
- Long and intermediate axes can inter-change for near-axisymmetric systems

- Rounder/flatter sETGs have rounder/flatter DM halos
- Stellar halos flatter than DM

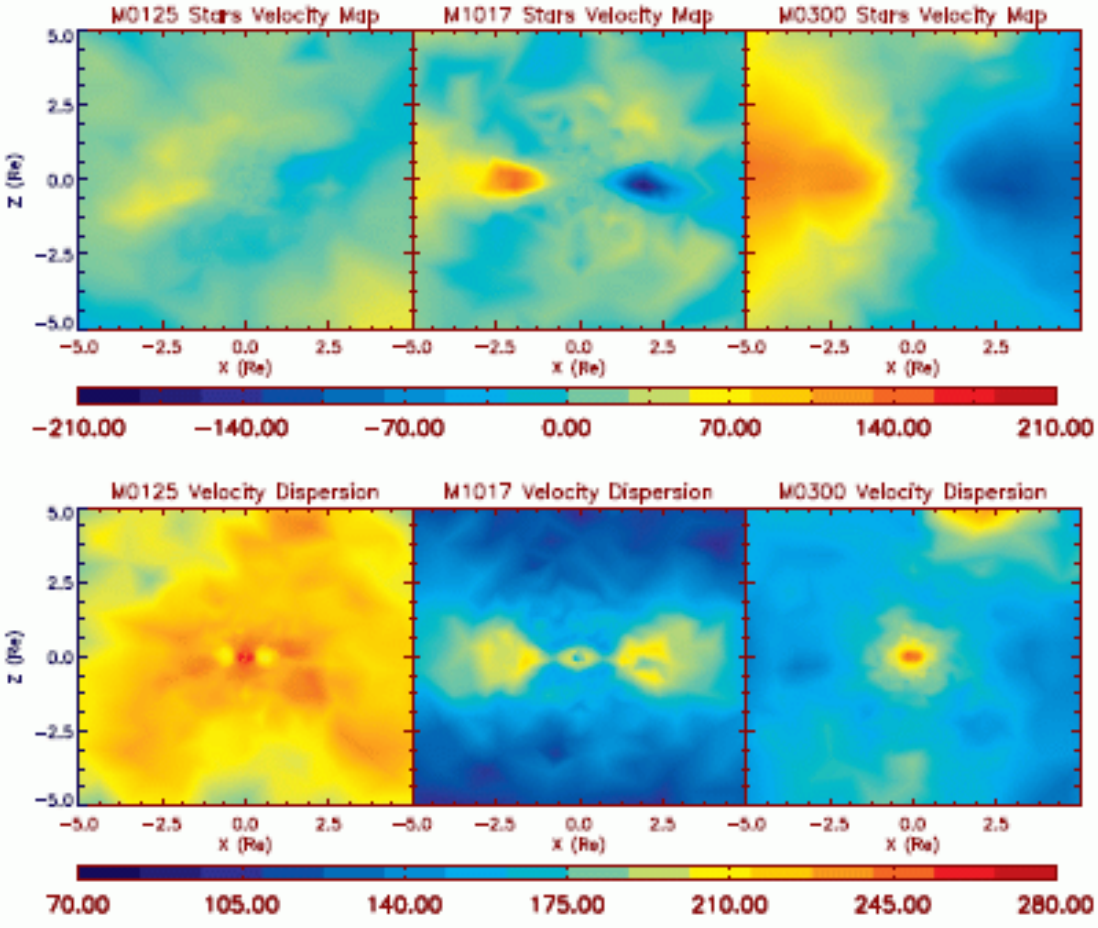
Wu et al 2014

Fast and Slow Rotators Among Simulated ETGs

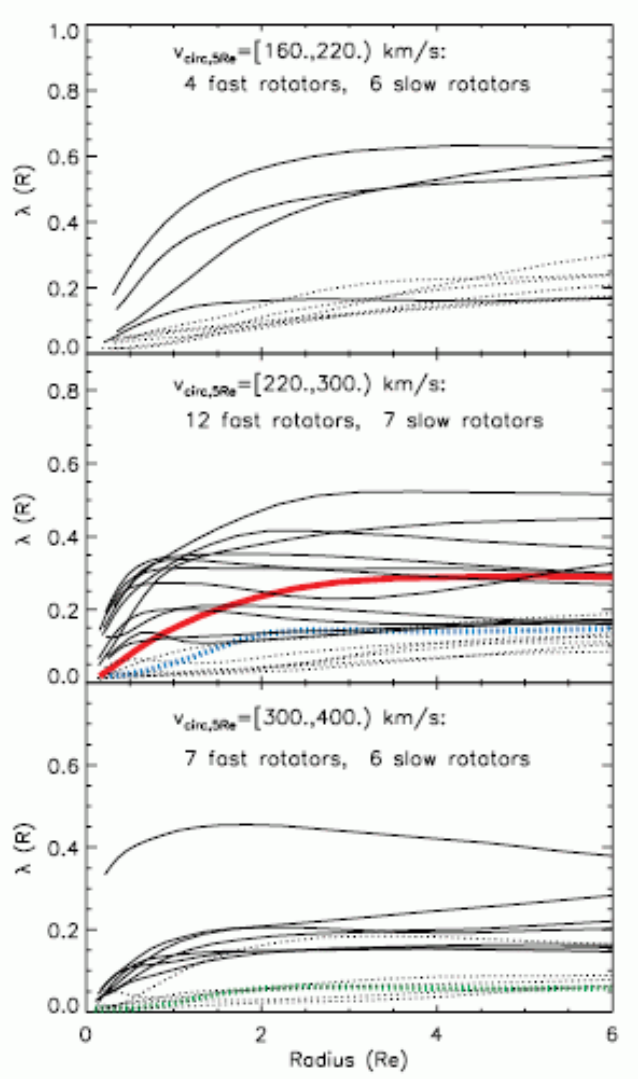


Fast rotators → slow rotators
Different major/ minor/mixed merger formation histories; see Naab, Oser +14

Rotation and Angular Momentum



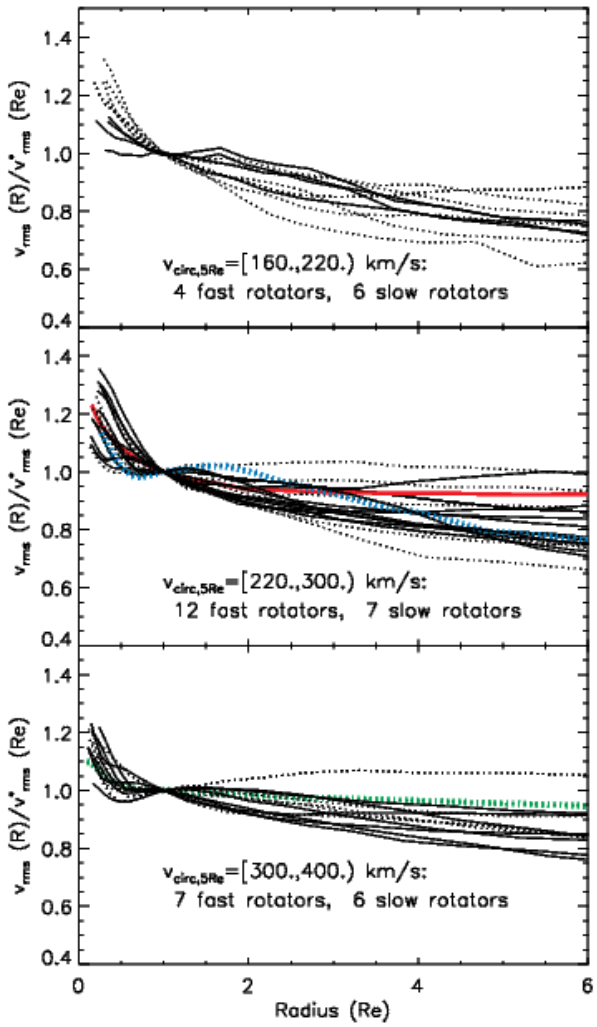
Edge-on maps of v and σ for star particles in three sETGs out to 5 Re, temporally smoothed

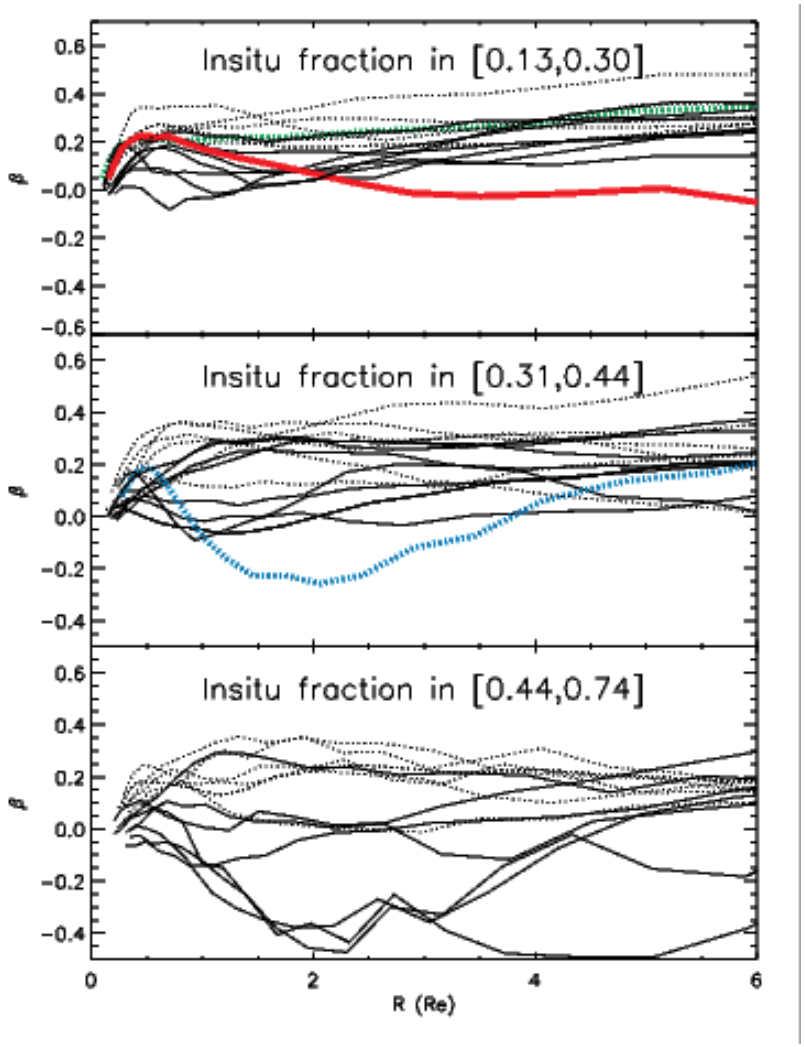


λ_R profiles generally smooth;
halos and inner regions correlated

Radial profiles of cumulative λ_R
Wu et al 2014

Velocity Dispersion - Anisotropy





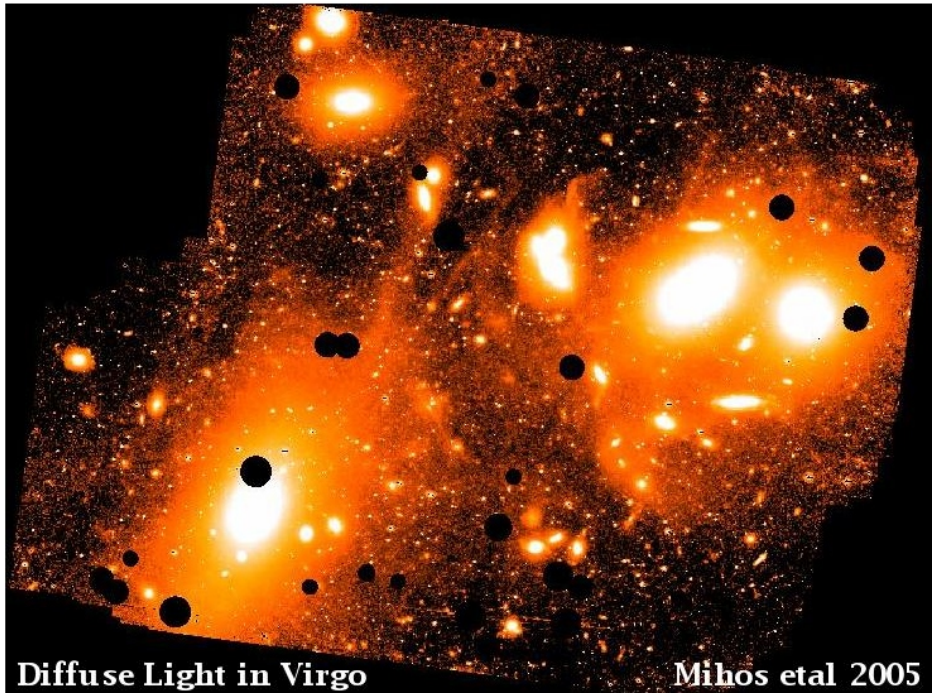
Moderate radial anisotropy especially in accretion-dominated systems

Kinematic Tracers for ETG Halos

Traditional long-slit kinematics reaches ~2 Re down to surface brightness of $\mu_V \sim 23.5$

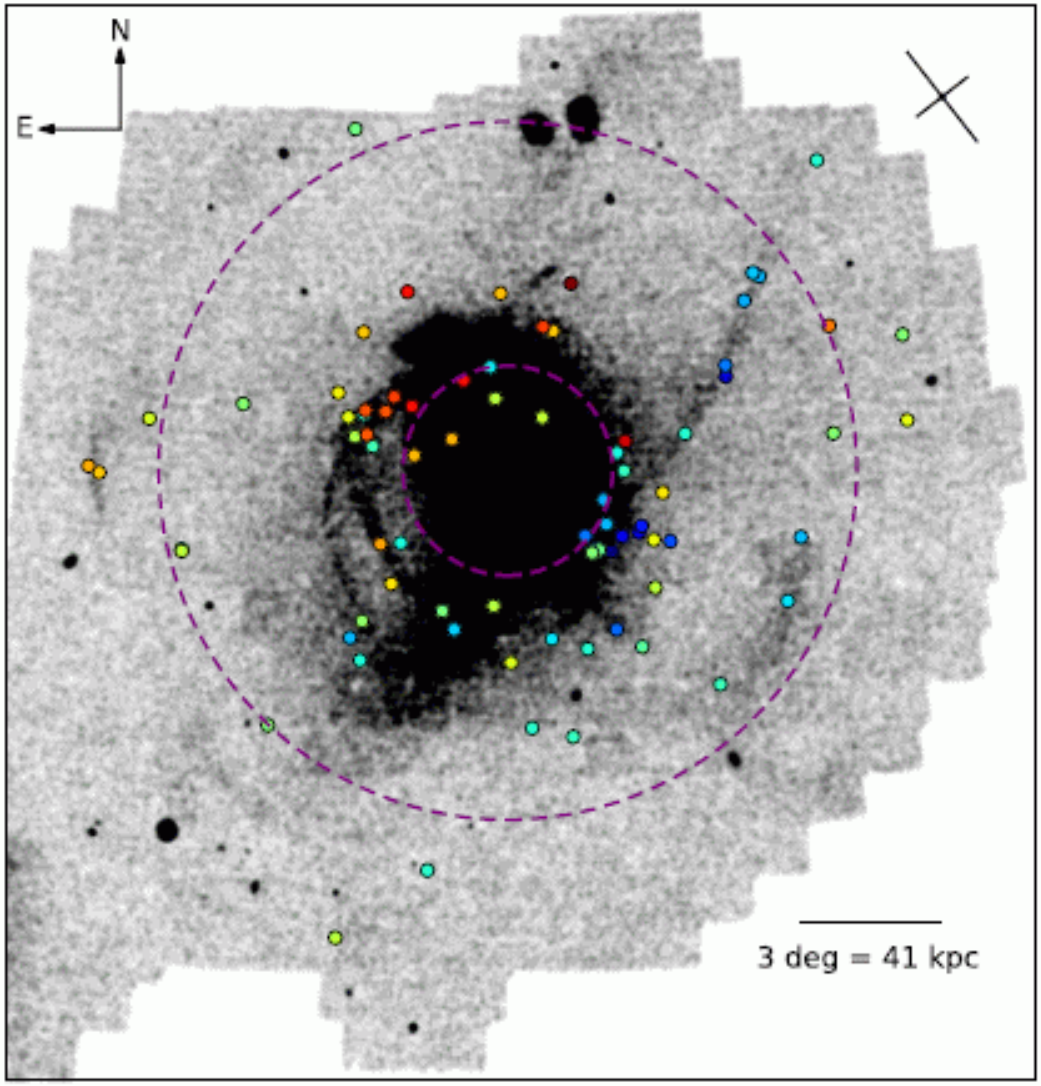
To determine dark matter and halo orbit distribution, need alternative data reaching to larger radii and fainter surface brightness:

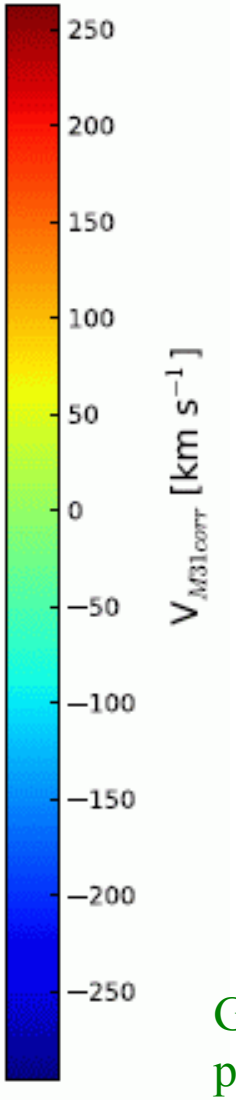
- **Planetary nebulae**, e.g., **Hui+'95, Arnaboldi+'96, Peng+'04;** trace stellar light and kinematics, mostly, to ~ 8 Re, **Coccato+'09**, up to beyond 100 kpc, **Longobardi+'13** (to $\mu_V \sim 27.5$)
- **Slitlets** placed around halo globular clusters, **Proctor+'09, Forster+'11, Arnold+'14** (to $\mu_V \sim 25$)
- **IFUs** placed at large radii, Sauron, **Weijmans+'09**, VIRUS-P, **Murphy+'11** (to $\mu_V \sim 25.5$)
- **Globular clusters** (complicated as light tracers); e.g., **Hwang+'08, Schuberth+'09, Woodley+'10, Pota+'13**



Core of the nearby Virgo cluster with luminous galaxies M87, M86, M84 and others

Halo Tracers: Globular Clusters vs Stars





Pandas Survey

Map from Veljanoski+14 shows distribution of GCs on surface density map of metal-poor stars in M31 halo

Globular clusters prominent on streams, but do not trace all the light

Halo Tracers: Planetary Nebulae and Globular Clusters

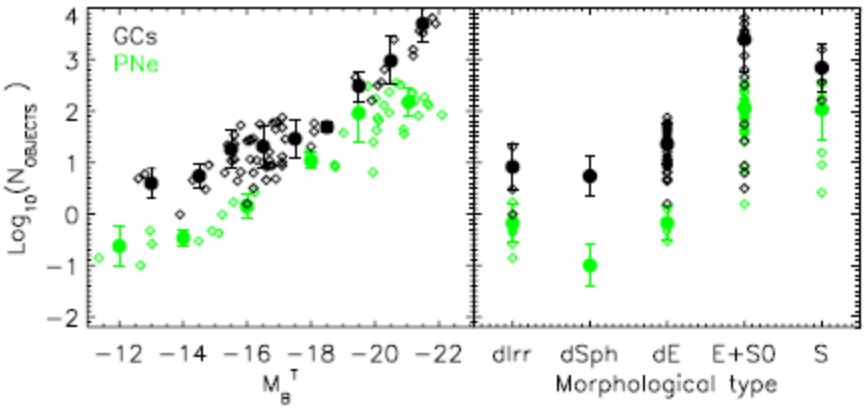
Mean velocities different for halo PNe, red and blue GCs in NGC 4649

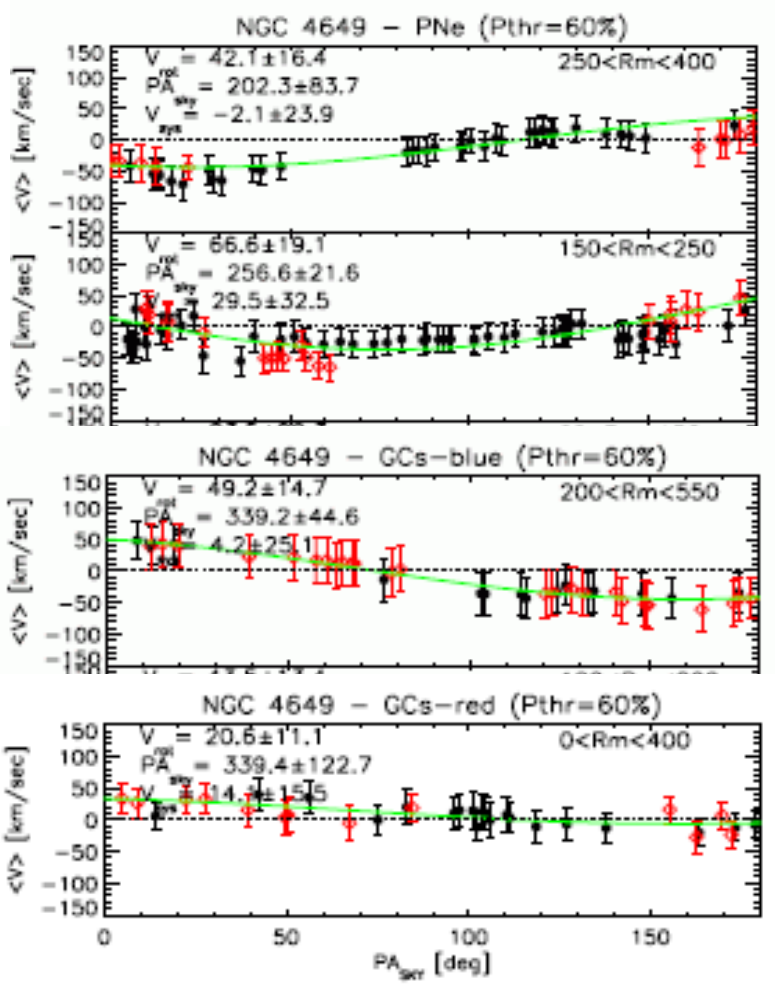
Coccato et al 2013

Points to

- Accretion origin
- Different progenitors

Specific frequencies of GCs and PNe depend differently on M_B and type





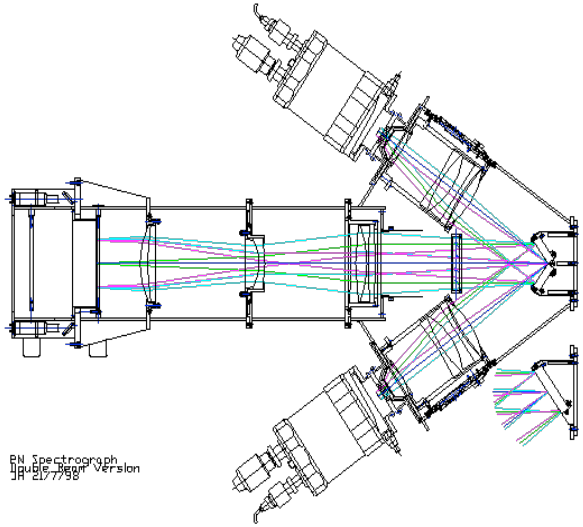
PNe as Dynamical Probes of Early-Type Galaxy Halos

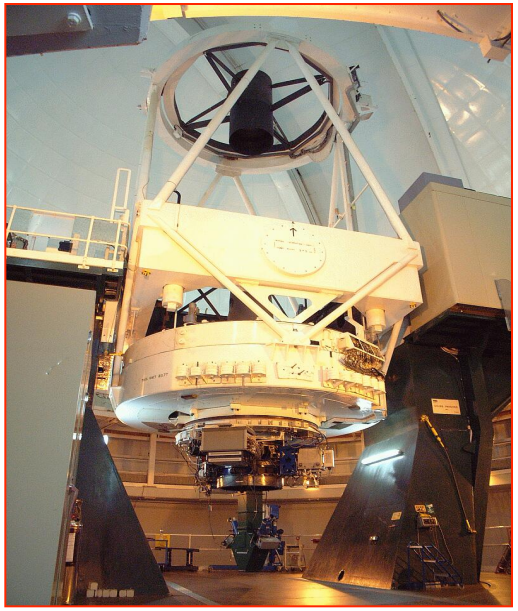
Planetary Nebula Spectrograph Galaxy Survey
P.I. Magda Arnaboldi

Kinematics, dynamics, angular momentum, mass in ETG halos

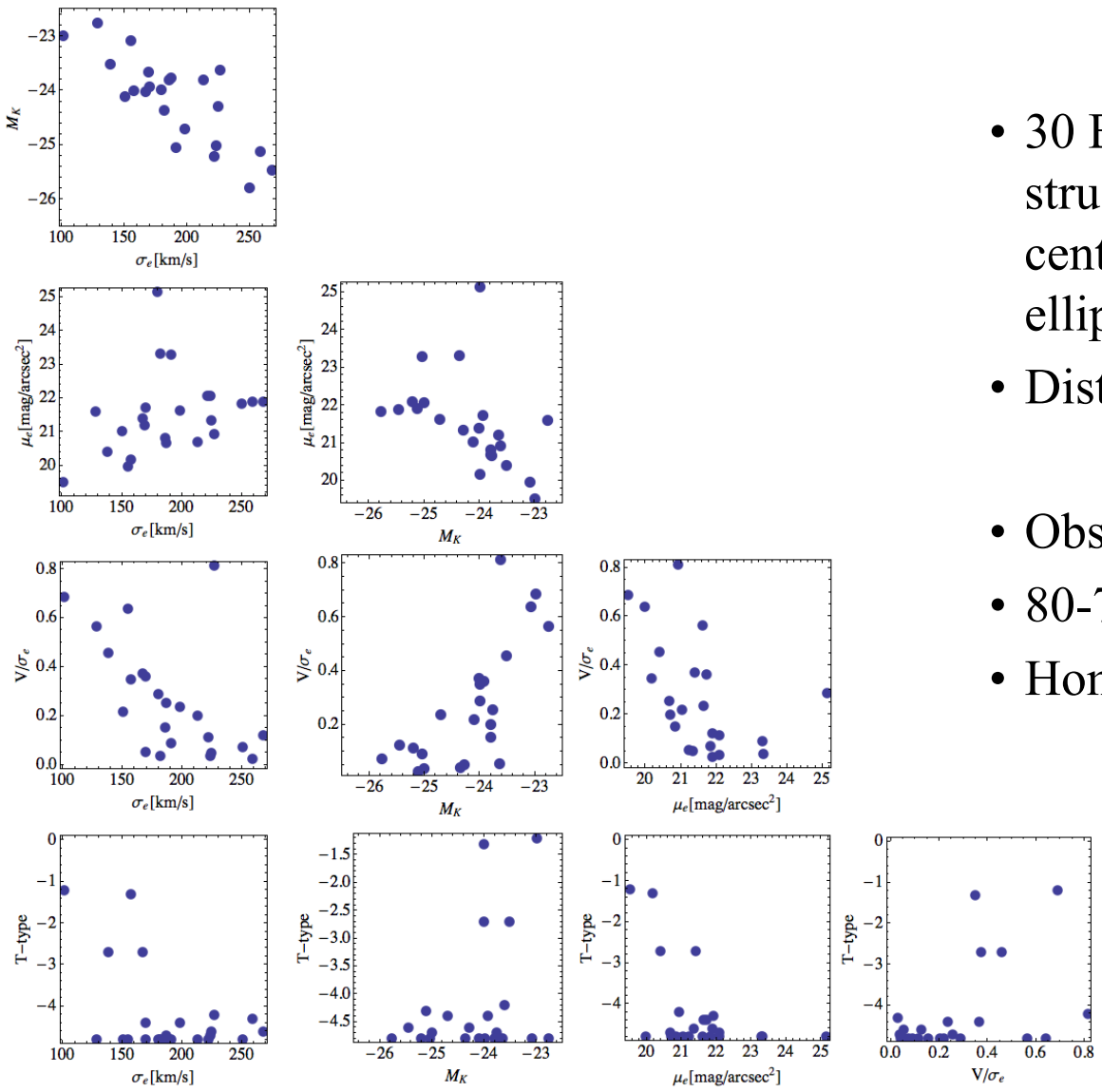
See also: talk by Nicola Napolitano

M. Arnaboldi
M. Capaccioli
A. Chies-Santos
L. Coccato
A. Cortesi
N. Douglas
K. Freeman
O. Gerhard
K. Kuijken
M. Merrifield
N. R. Napolitano
C. Pulsoni
A. Romanowsky
C. Tortora





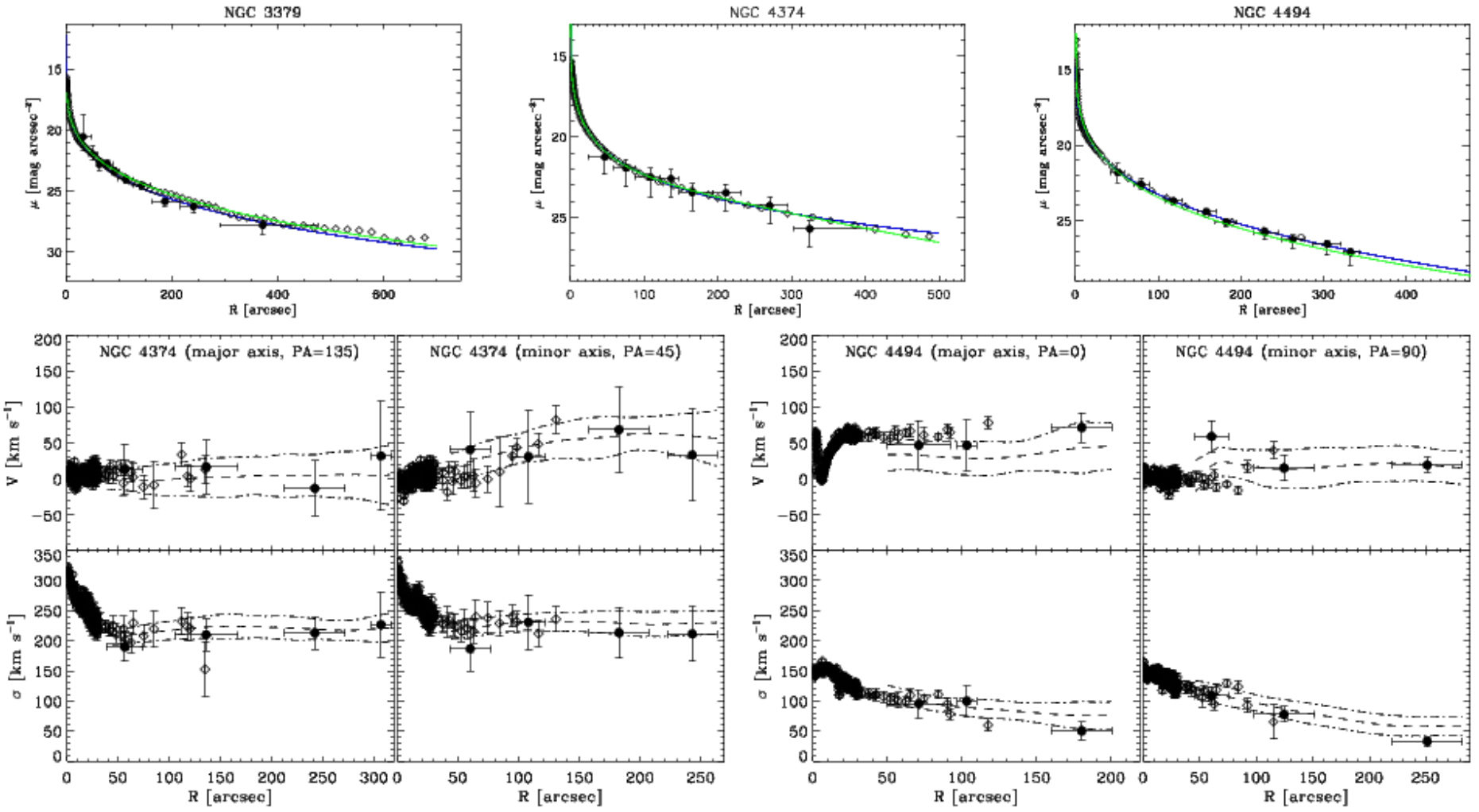
PNS ETG Sample



- 30 ETGs with wide range of structural parameters (luminosity, central velocity dispersion, ellipticity, boxy/diskyness
- Distance to ~25 Mpc

- Observations completed
- 80-700 PNs per galaxy
- Homogeneous analysis on-going

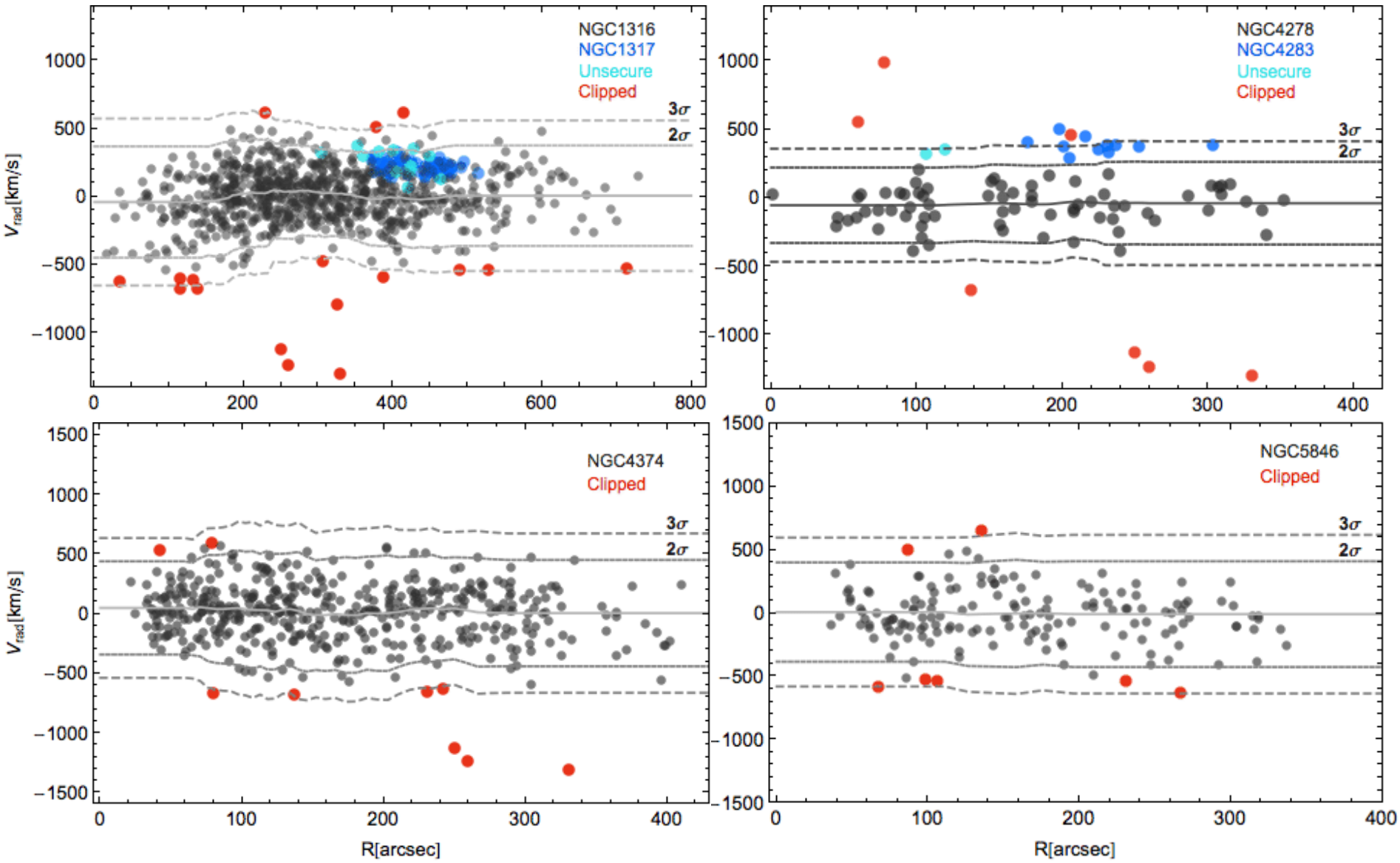
PNe trace stars in ETGs



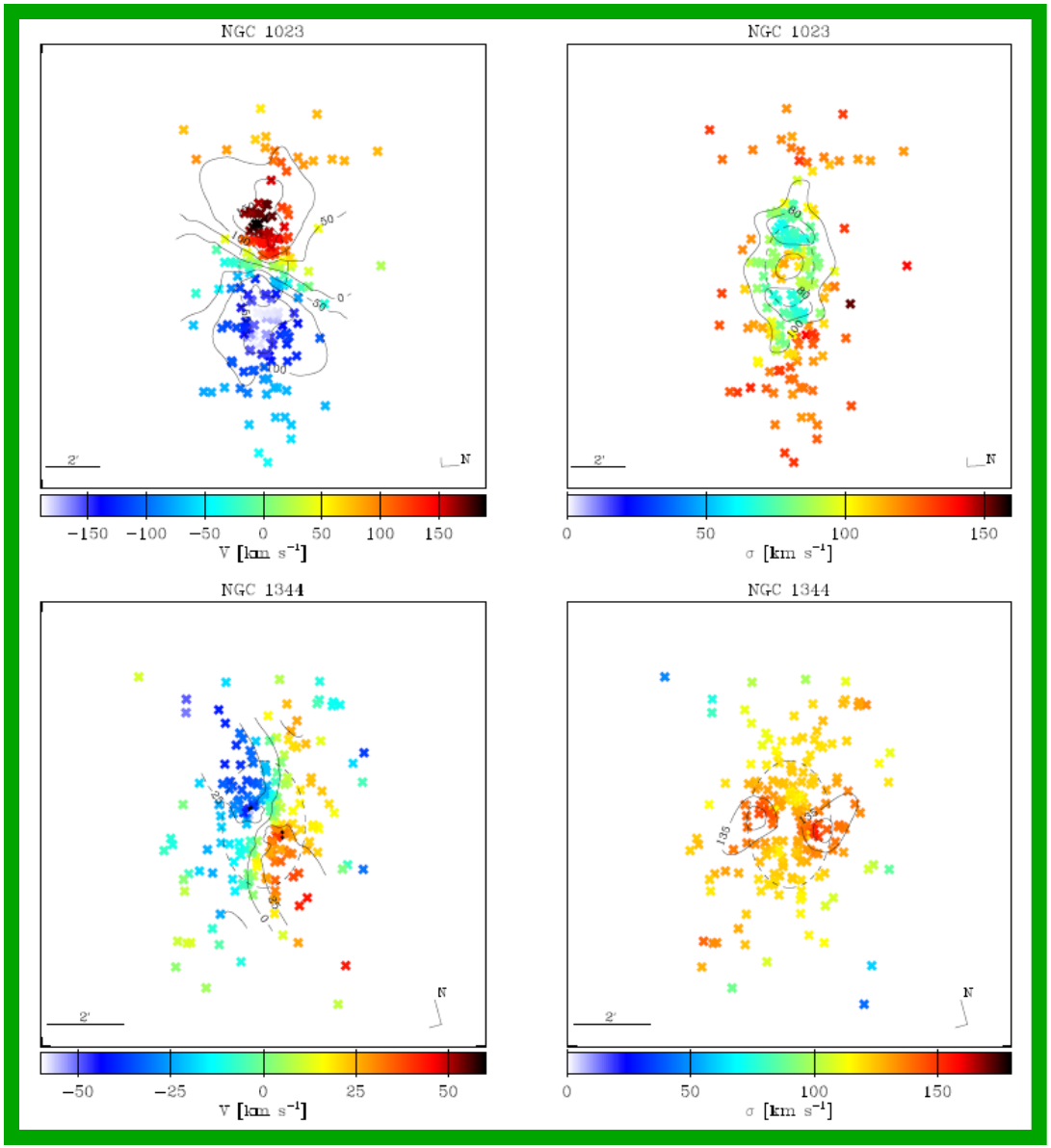
PN density and kinematics consistent with integrated light within errors. Very old populations may have low α; e.g. old gEs vs accreted satellites

Coccato, OG, et PN.S. 2009

Projected Phase-Spaces



Rotation and Velocity Dispersion Fields



With Kernel smoothing method, after removal of companions and outliers

Coccato+2009
McNeil+2012

Ortwin Gerhard (MPE Garching)

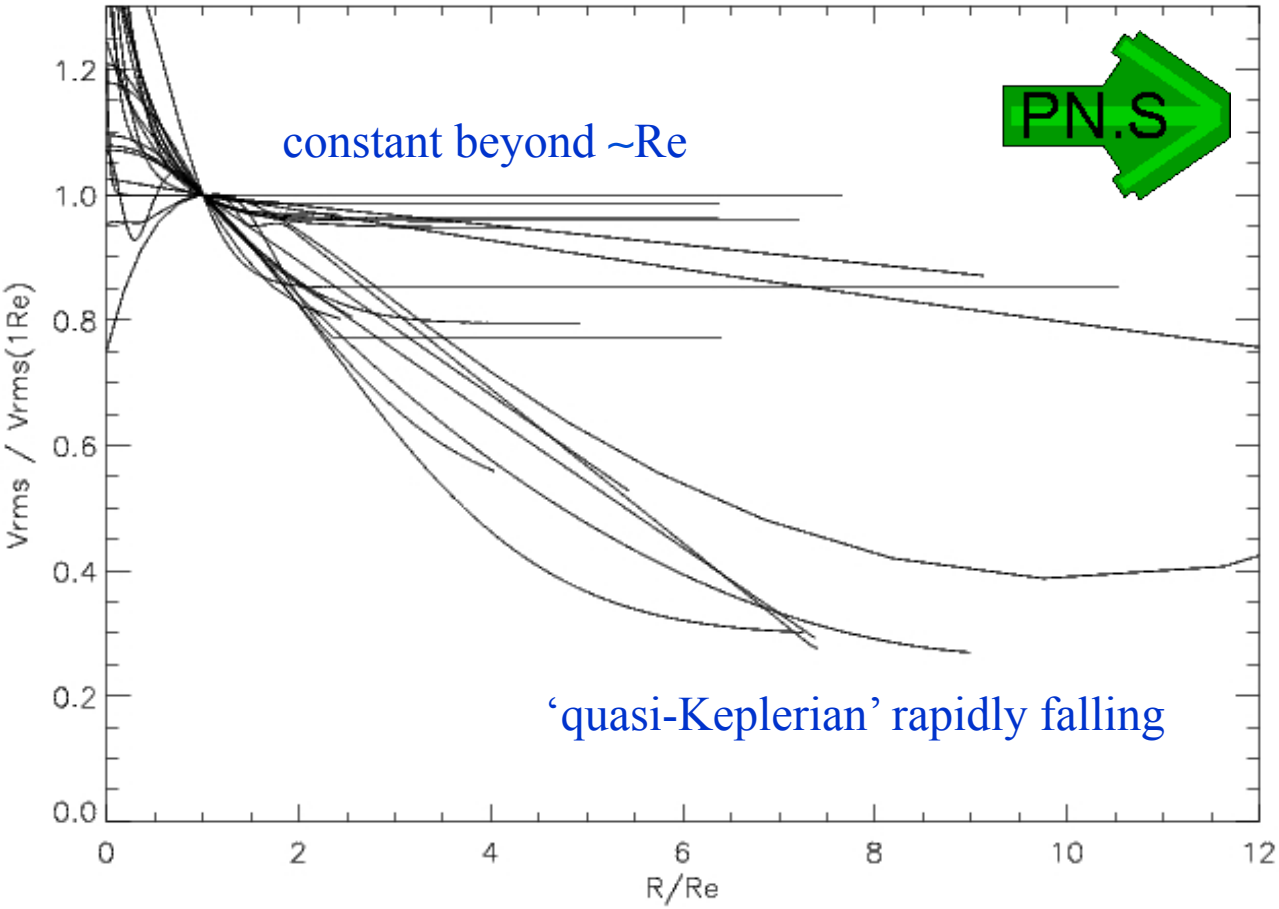
Velocity Dispersion Dichotomy !?

What is nature of quasi-Keplerian ETGs?

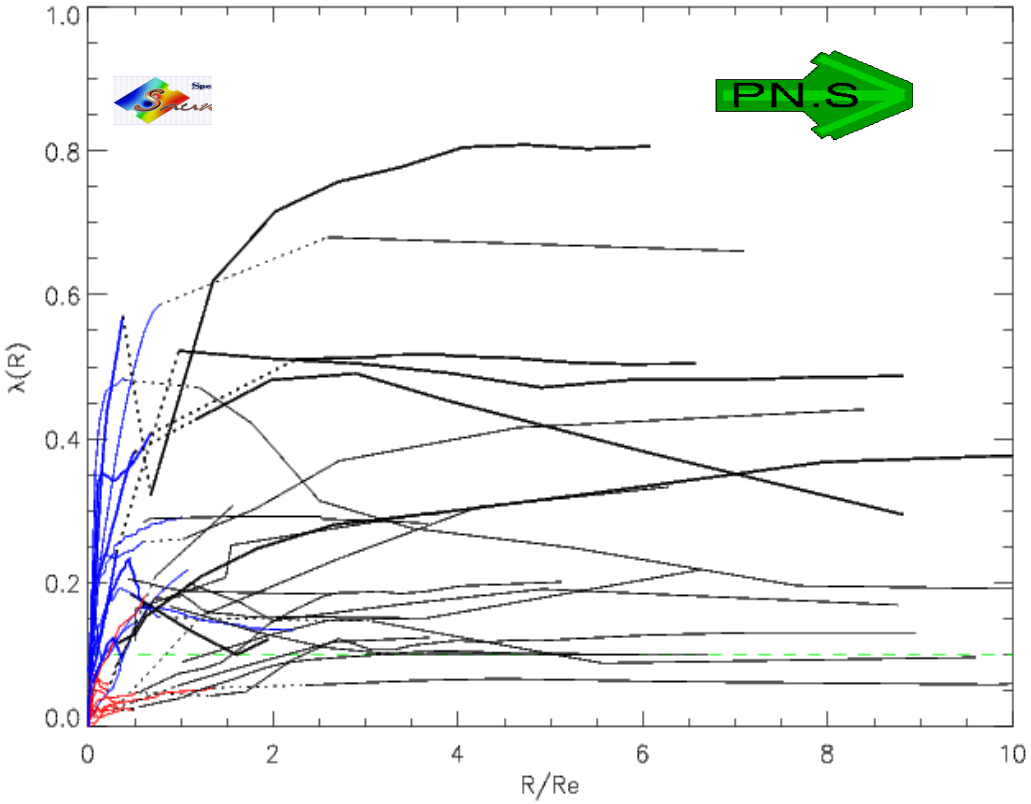
Face-on disks of fast rotators?
- >E2, then triaxial
- Major axis rotation !?

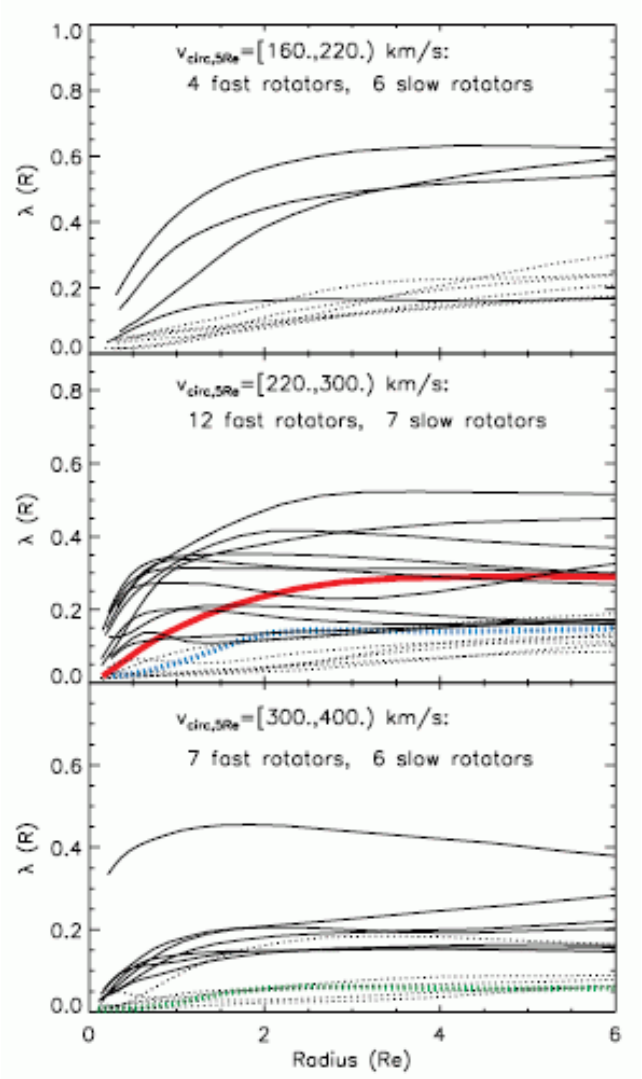
Low-mass halos or radial anisotropy?
- Strong degeneracy in dynamical models
- Perhaps in binary mergers (Dekel+'05)

Not in Wu+'14 sETG sample



Halo Rotation and Angular Momentum

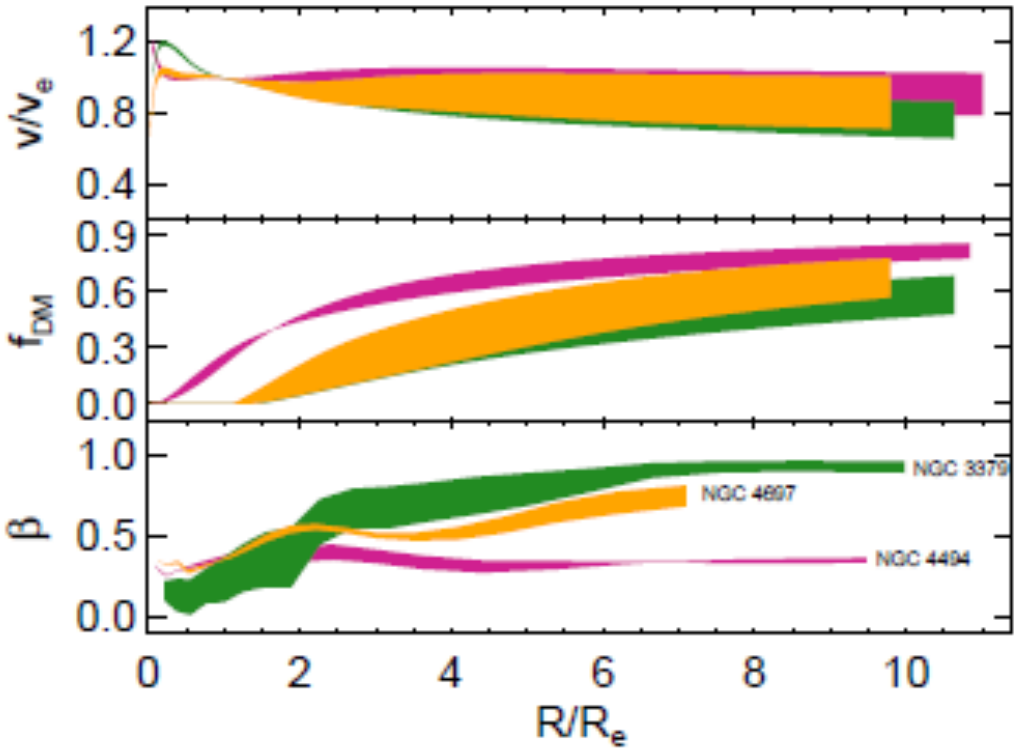




- Halo v/σ and λ correlates with that within Re for most of the ETGs
- Division slow/fast rotators similar in the outer halos similar as in cores; some more complicated cases
- Range of profiles as in sETGs

Wu et al 2014
simulated halos

Dynamics: Quasi-Keplerian Ellipticals

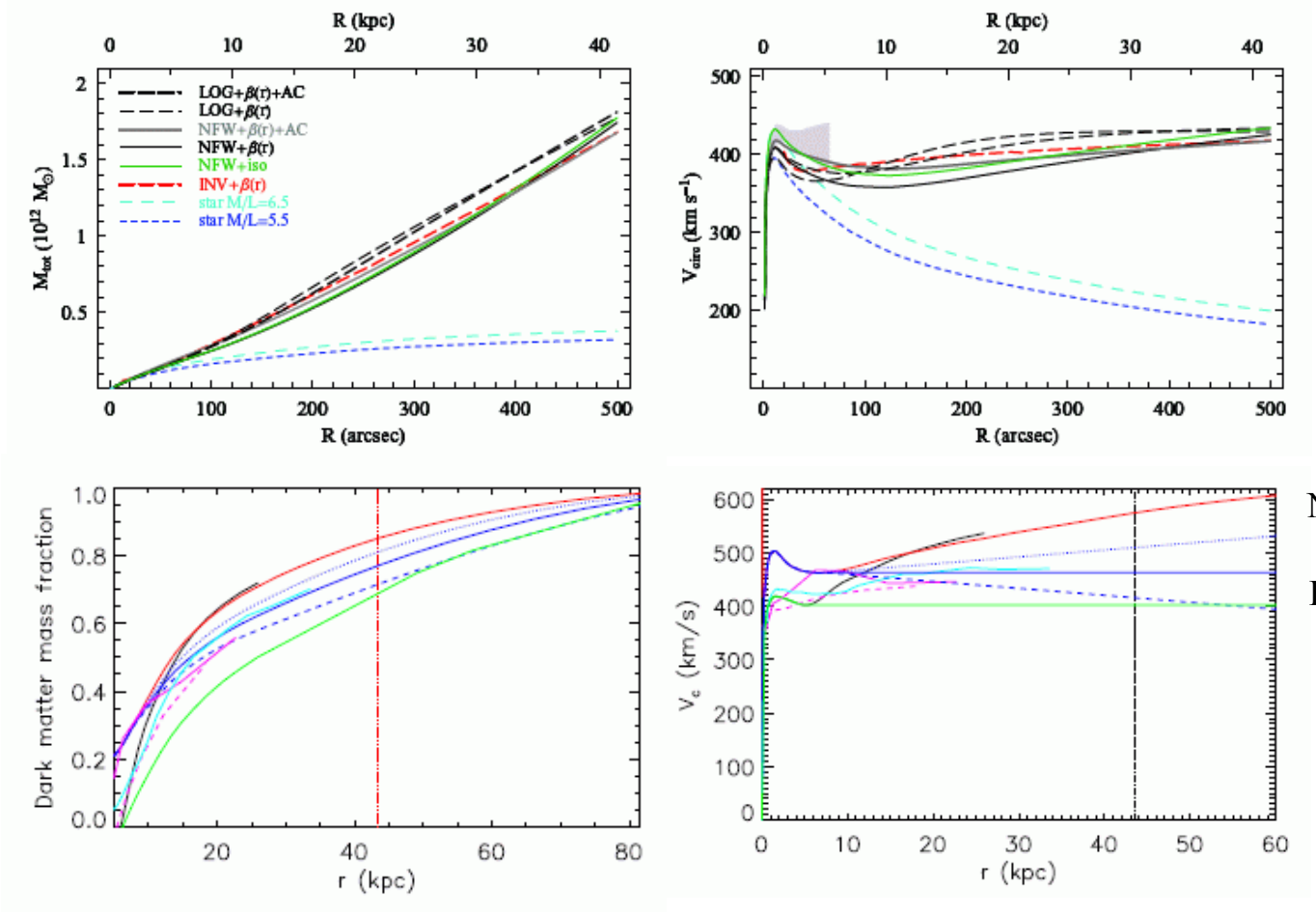


Range of valid NMAGIC axisymm.particle models for NGC 4494 (70% C.R.), NGC 3379, 4697 (PN Lhd,)

de Lorenzi+'08, '09
Morganti+'13

- Range of DM fraction, highest in NGC 4494
- Range of radial anisotropies
- Slightly falling CVCs
- Baryonic central concentrations as could be achieved in gas-rich mergers

Dynamical Masses: Luminous X-ray Bright Ellipticals



Non-par. Xray

Best stellar + PNe

Top: Mass and circular velocities for NGC 4374 from anisotropic Jeans models, Napolitano+'10

Bottom: For NGC 4649 from NMAGIC particle models of NGC 4649, Das+'11: Stars + PNe prefer lower-vc models over some (but not all) X-ray derived mass distribution (red) .

Generally ~flat circular velocity curves preferred in massive ETGs (Gerhard+'01, Koopmans+'06, Auger+'10, Churazov+'10), and mildly radially anisotropic orbits

Conclusions

- Simulated and real ETG halos consistent in angular momentum, mass distributions, dark matter fraction
- Angular momentum in halo and within Re correlated, with some transition cases and misalignments
- Halo orbits mildly to sometimes strongly radially biassed, record of radial infall orbits
- Velocity dispersion dichotomy? What is the nature of the quasi-Keplerian ETGs?
- Globular clusters and Planetary Nebulae trace complementary mix of progenitor systems

IAU Symposium 317

The General Assembly of Galaxy Halos: Structure, Origin and Evolution

Honolulu, August 2015, IAU General Assembly

http://www.iau.org/science/meetings/future/symposia/1124/

Co-Chairs: Angela Bragaglia, Magda Arnaboldi

Structure of galaxy halos, Milky Way, stellar tracers, halo clusters, substructure vs smooth components, first stars, age and metallicity, galactic archeology, halos at high z, formation and growth over time