

Kinematics and Dark Matter in Galaxy Halos

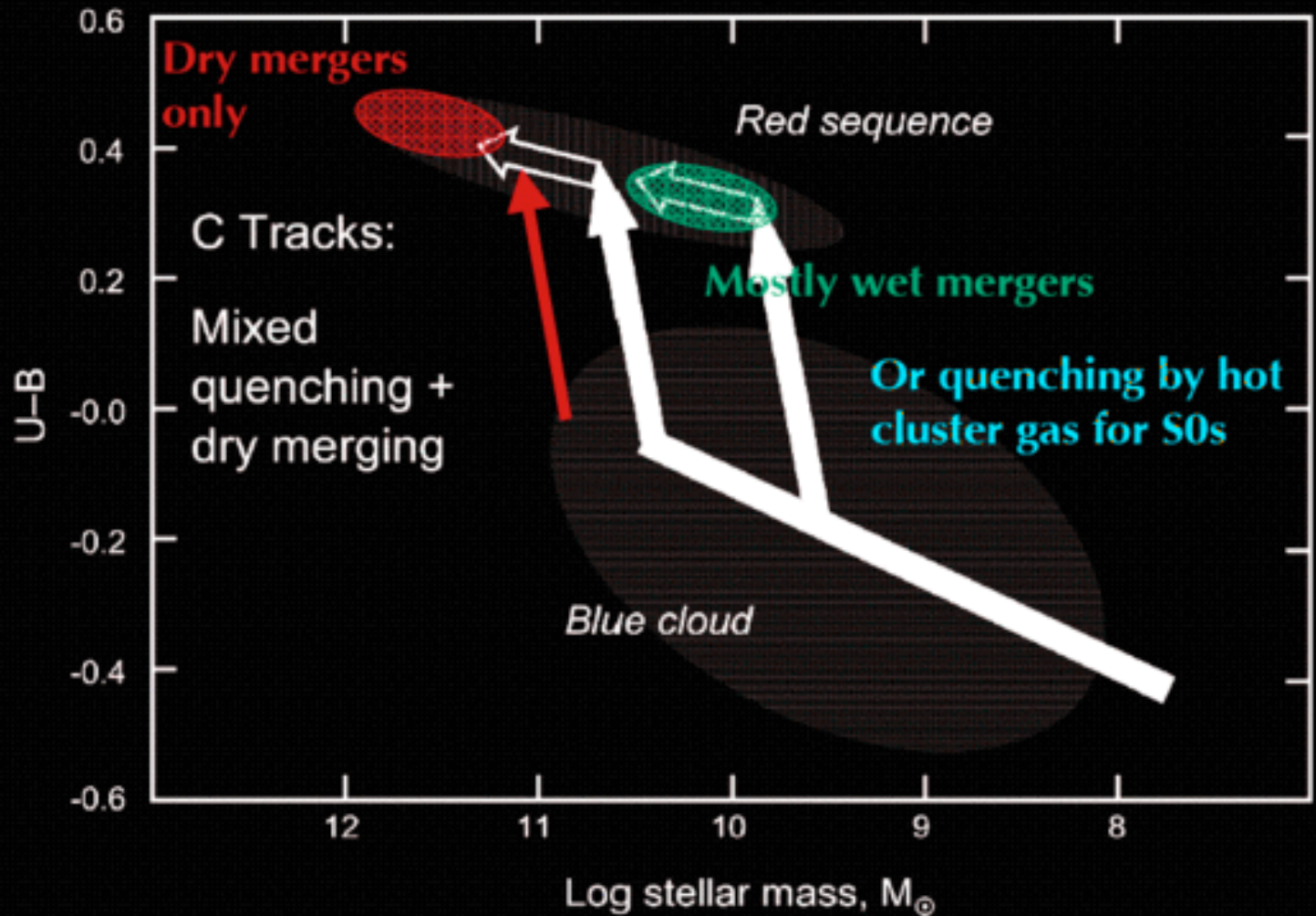
*M. Arnaboldi, J. Arnold, S. Bamford,
G. Bergond, J. Brodie, M. Capaccioli,
M. Cappellari, L. Coccato, A. Cortesi,
P. Das, F. De Lorenzi, N. Douglas, F. Faifer,
D. Forbes, C. Foster, K. Freeman, D. Geisler,
O. Gerhard, R. Johnson, A. Jordán,
C. Kochanek, K. Kuijken, B. Kumar, M. Lee,
M. Merrifield, N. Napolitano, E. Noordermeer,
E. O'Sullivan, T. Ponman, R. Proctor,
S. Raychaudhury, K. Rhode, T. Richtler,
P. Sánchez-Blázquez, Y. Schuberth,
R. Sharples, L. Spitler, J. Strader, S. Zepf*

Aaron J. Romanowsky
Univ. California Observatories



How to make an early-type galaxy

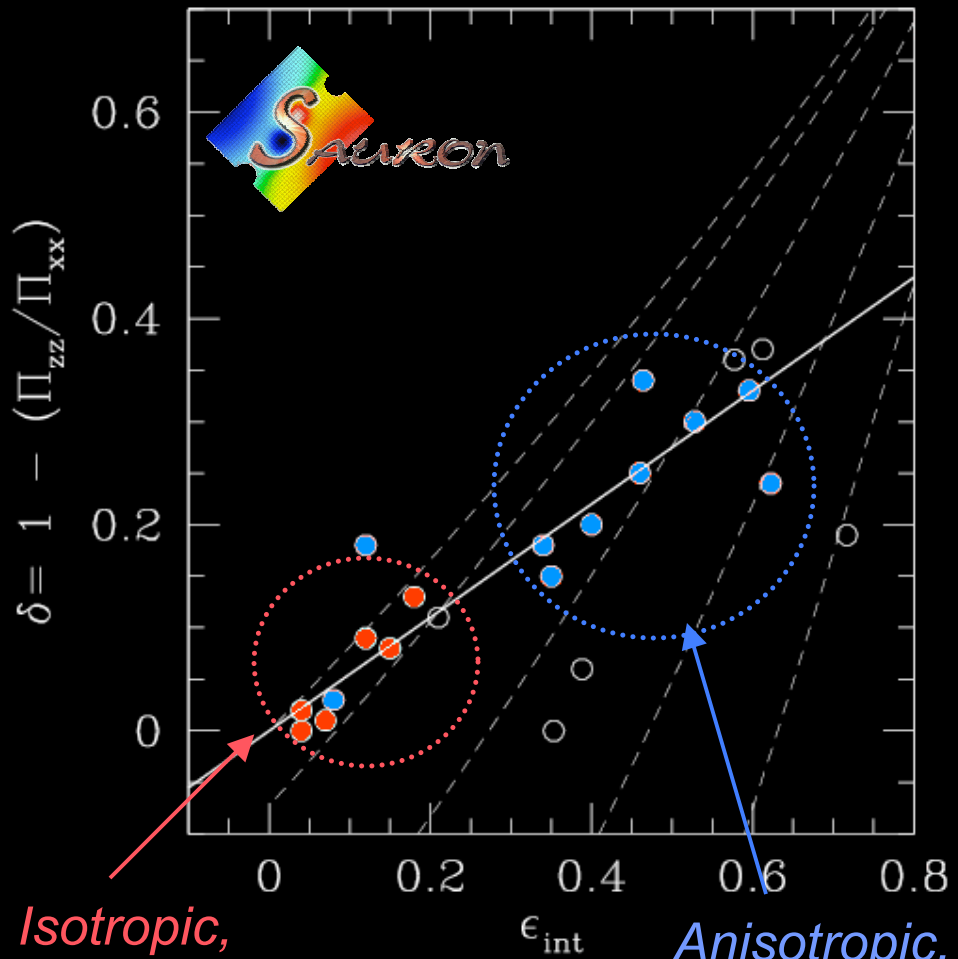
$\sim L^*$ red sequence built up since $z \sim 1$, by multiple pathways (Faber et al. 2007)



Is there a pathway missing (esp. at $\gg L^$) ?*

Do more detailed galaxy properties tell us about their formational pathways?

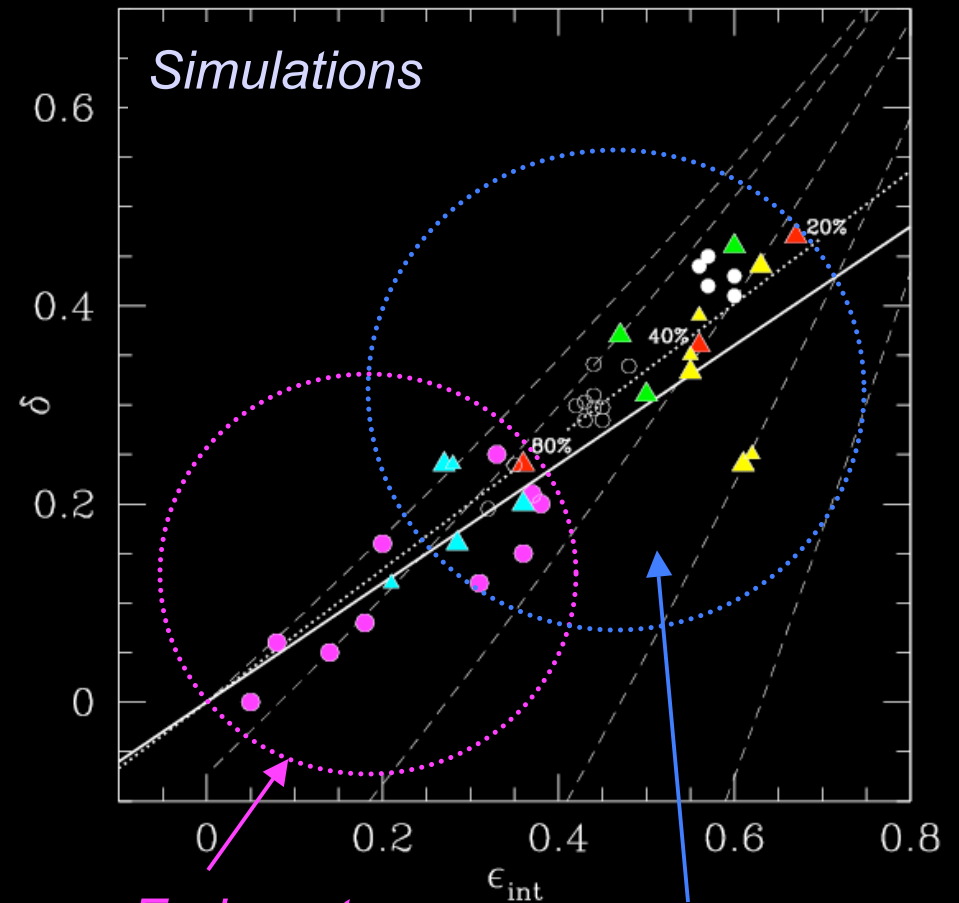
Dynamical bimodality of ellipticals



*Isotropic,
round,
slow rotators*

*Anisotropic,
flattened,
fast rotators*

(Cappellari et al. 2007)



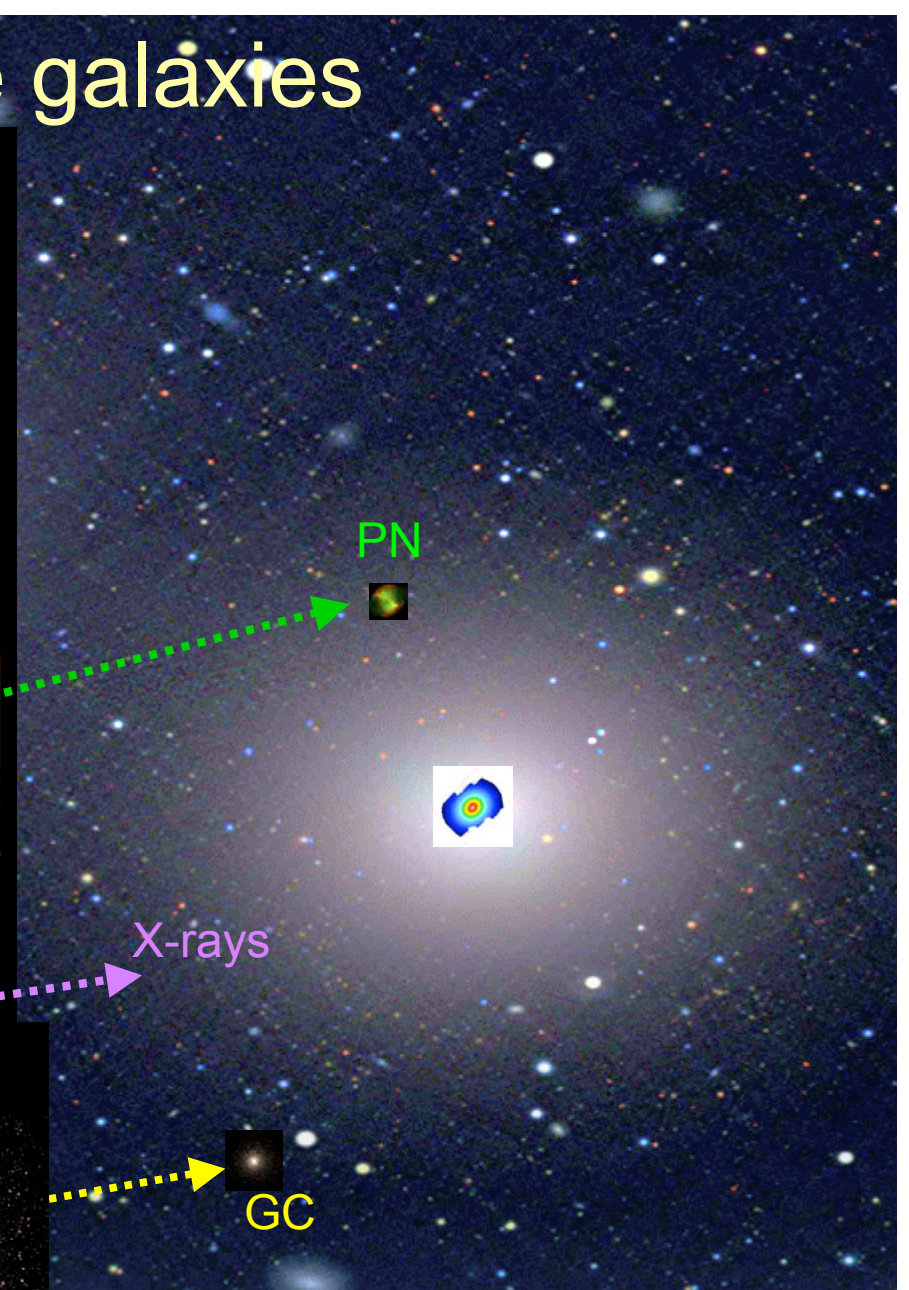
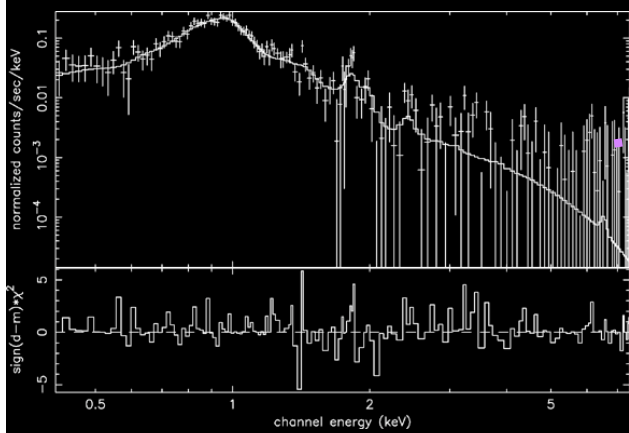
*Early wet
multiple
mergers*

*Wet/dry pair
major mergers*

(Burkert et al. 2008)

Halo tracers in early-type galaxies

- Field stars
- Planetary nebulae
- Globular clusters
- X-ray gas



Halo surveys of nearby galaxies



Planetary Nebula Spectrograph
Elliptical Galaxy Survey (PI: N. Douglas)

Stellar kinematics to $\sim 5 R_{\text{eff}}$:

Primary: 12 representative ellipticals

Extended: 40 volume/magnitude-limited early-types



SAGES Legacy Unifying Globulars and Galaxies Survey
(PI: J. Brodie)

~ 20 representative galaxies, mostly early-type
Stellar, globular cluster photometry & kinematics

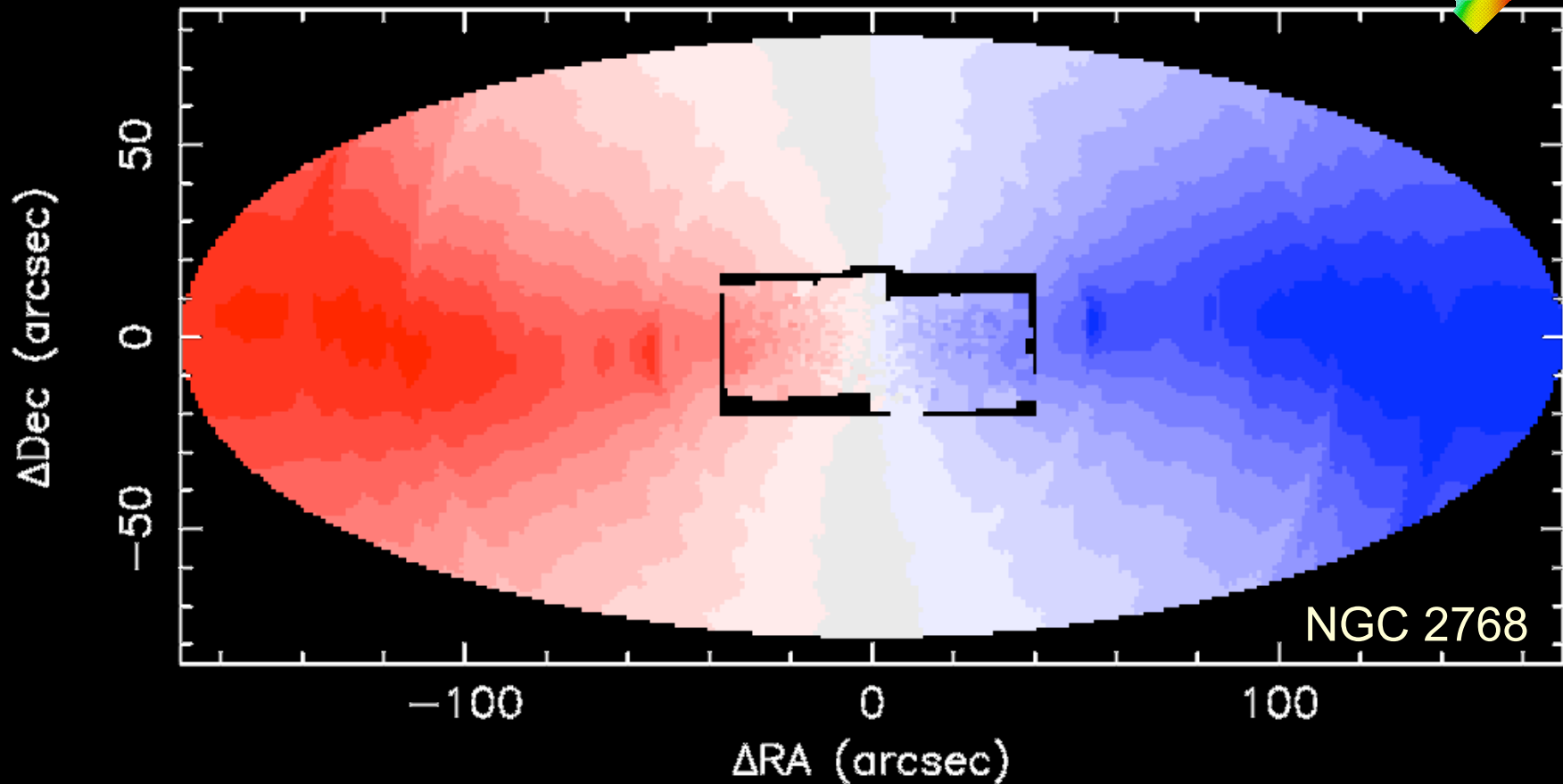




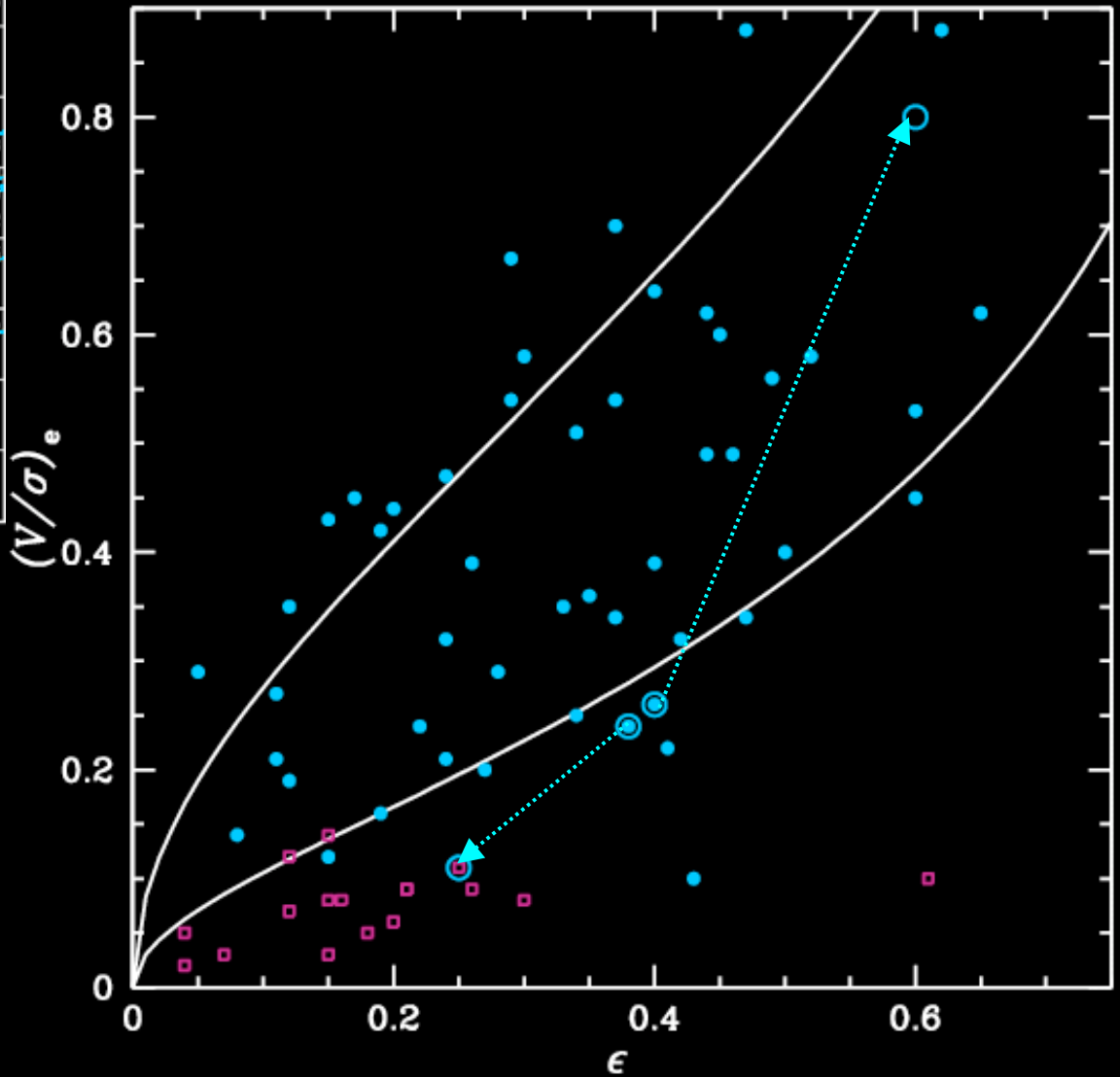
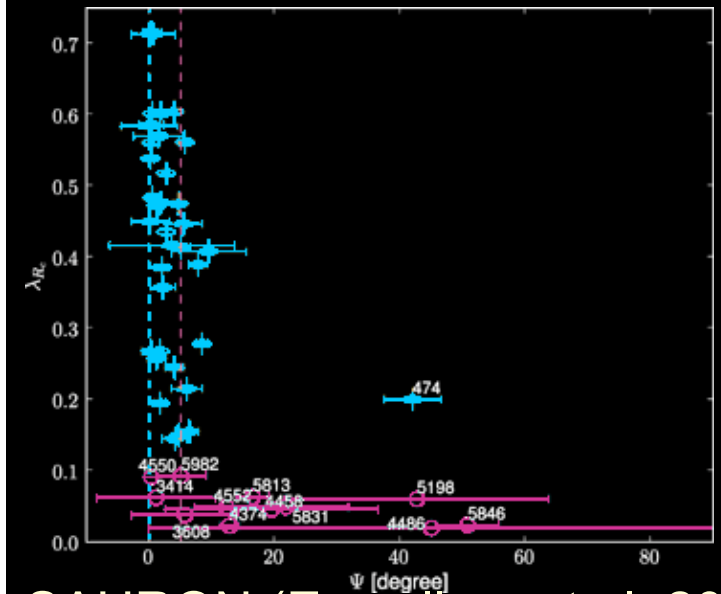
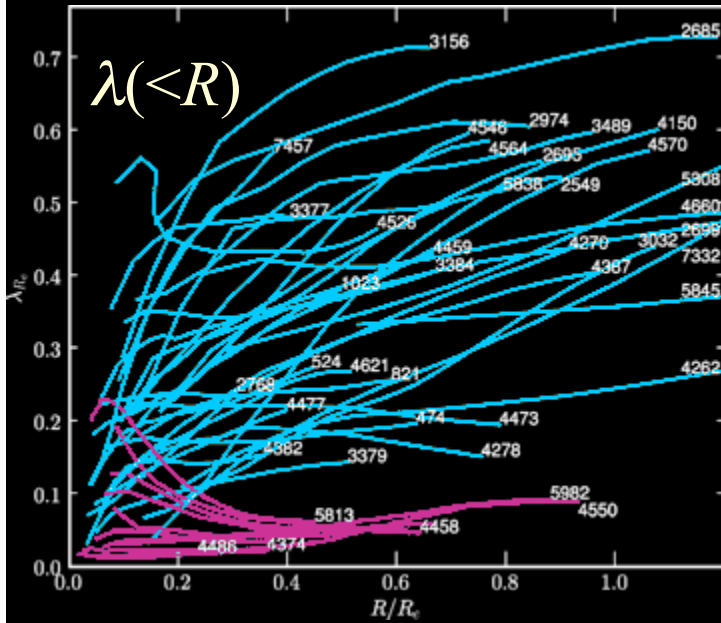
3-D stellar kinematics with Keck

Use leftover slit light from DEIMOS GC spectra to probe galaxy kinematics to $\sim 3 R_{\text{eff}}$ (*poor man's IFU*)

Proctor et al. in prep



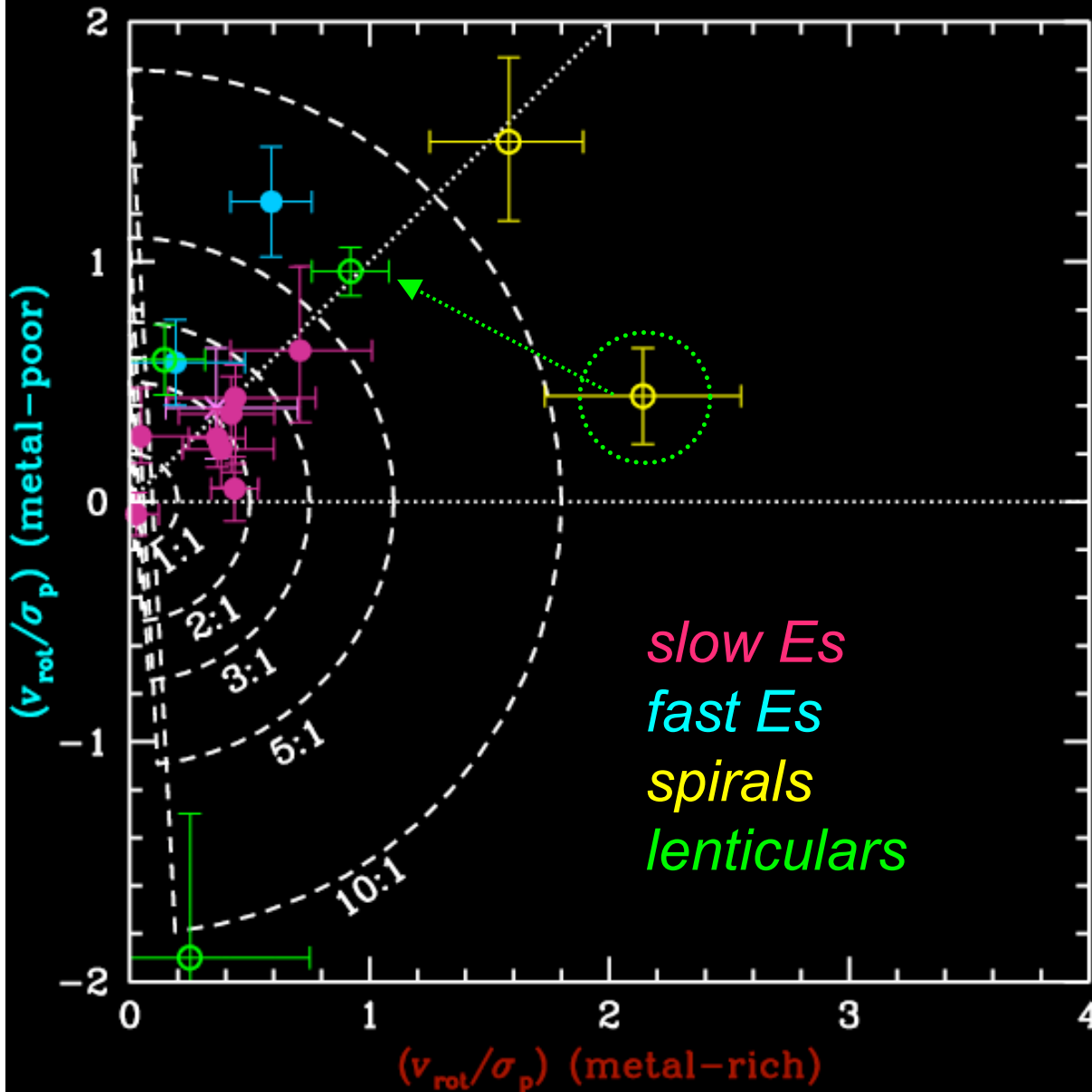
Stellar halo rotation in early-types



SAURON (Emsellem et al. 2007)

Noordermeer et al. (2008); Proctor et al. in prep; Arnold et al. in prep.

Halo rotation _ galaxy formation

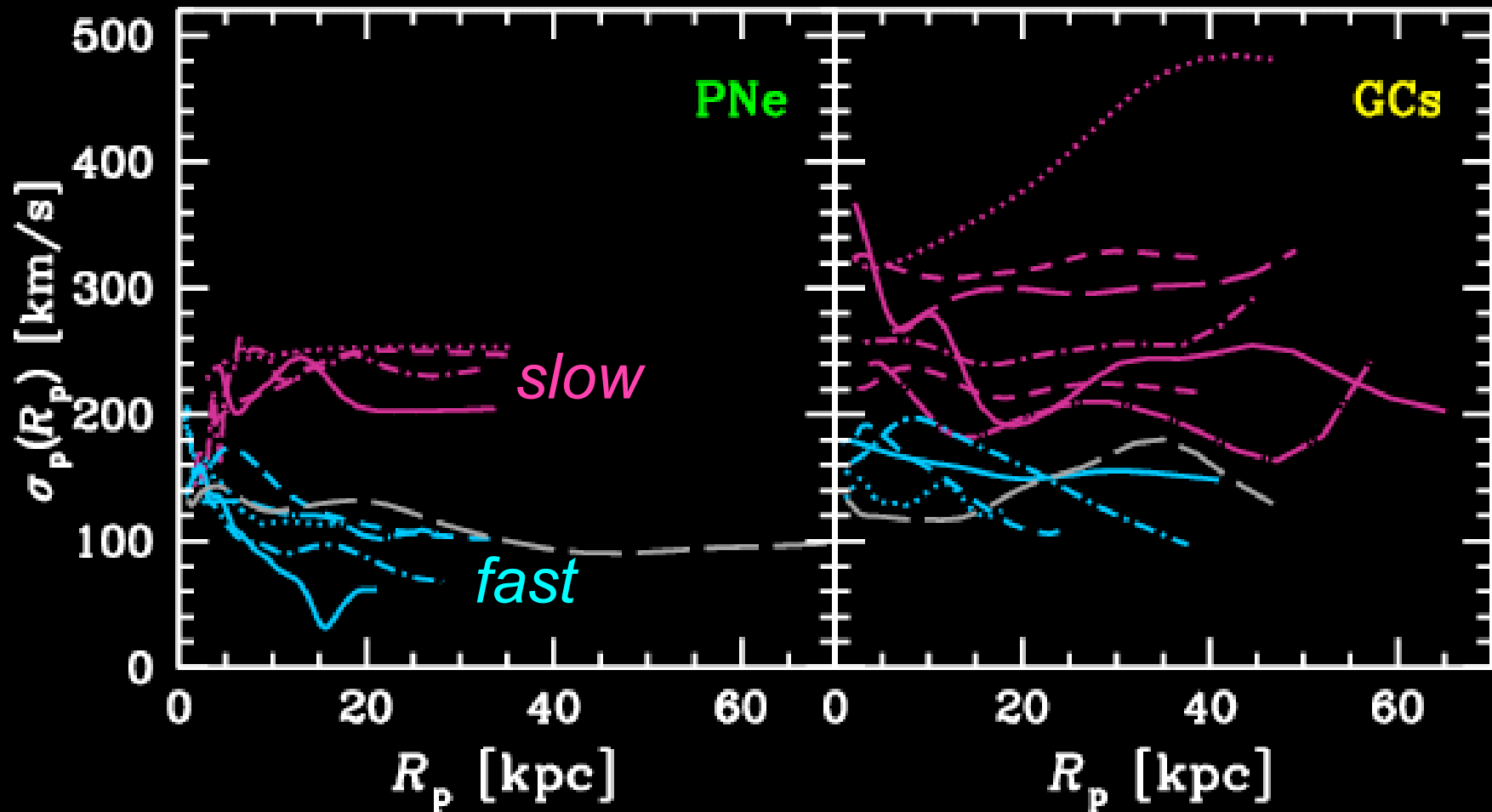


GCs as proxies for old disk/bulge and halo

*Merger sims:
lower mass ratio
= higher rotation
(Bournaud et al. 2005)*

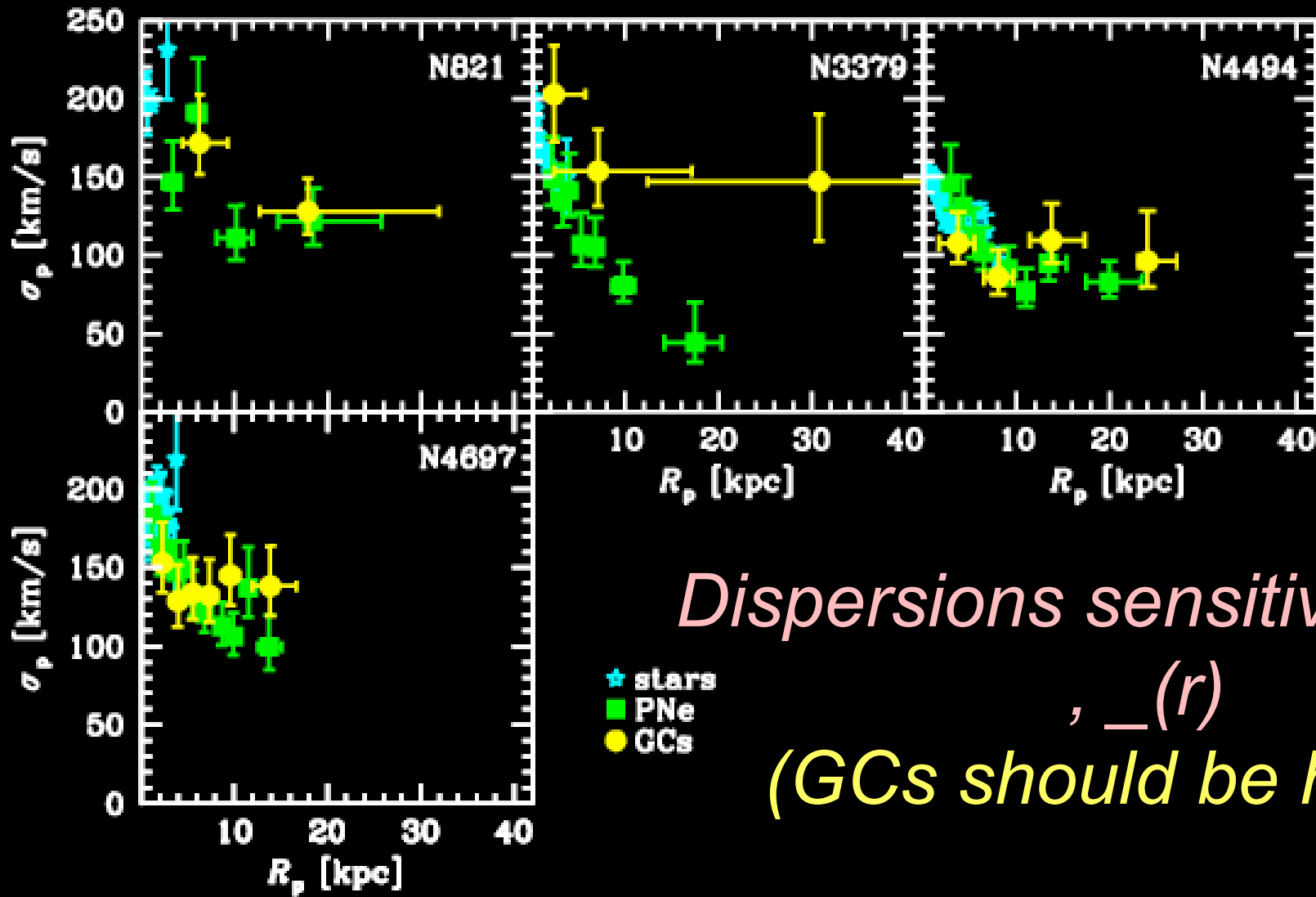
Lenticulars from faded spirals or merger?

Velocity dispersion profiles



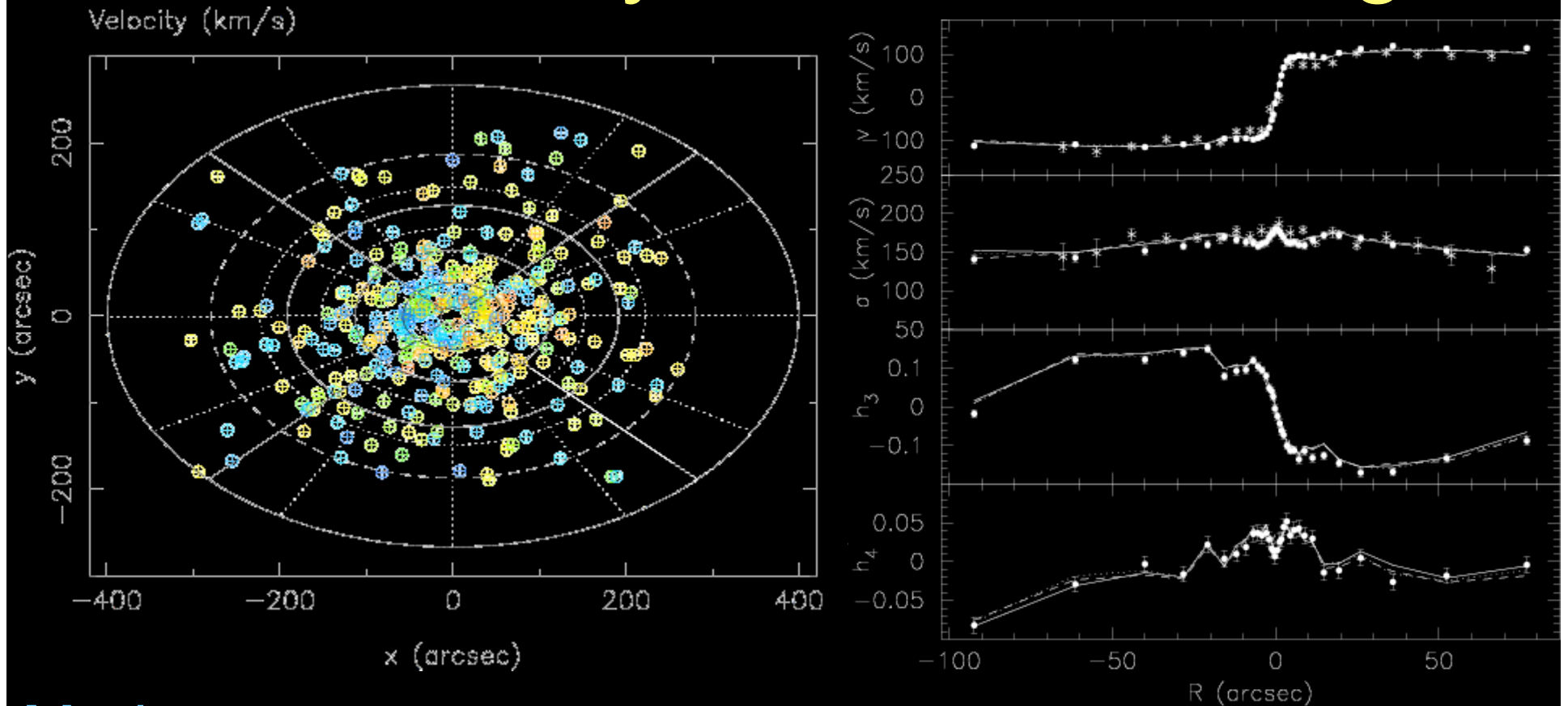
- **Bimodality in PN velocity dispersions**
(fast rotators in Romanowsky et al. 2003)
- GCs similar but less dramatic

Comparing PN & GC dispersions *in fast rotators*



Dispersions sensitive to $\sigma_p(r)$, $\sigma_p(r)$
(GCs should be higher)

NMAGIC dynamical modeling



Made-to-measure non-parametric
particle-based axisymmetric /
triaxial code

(De Lorenzi, Gerhard et al. 2007, 2008;
after Syer & Tremaine 1996.)

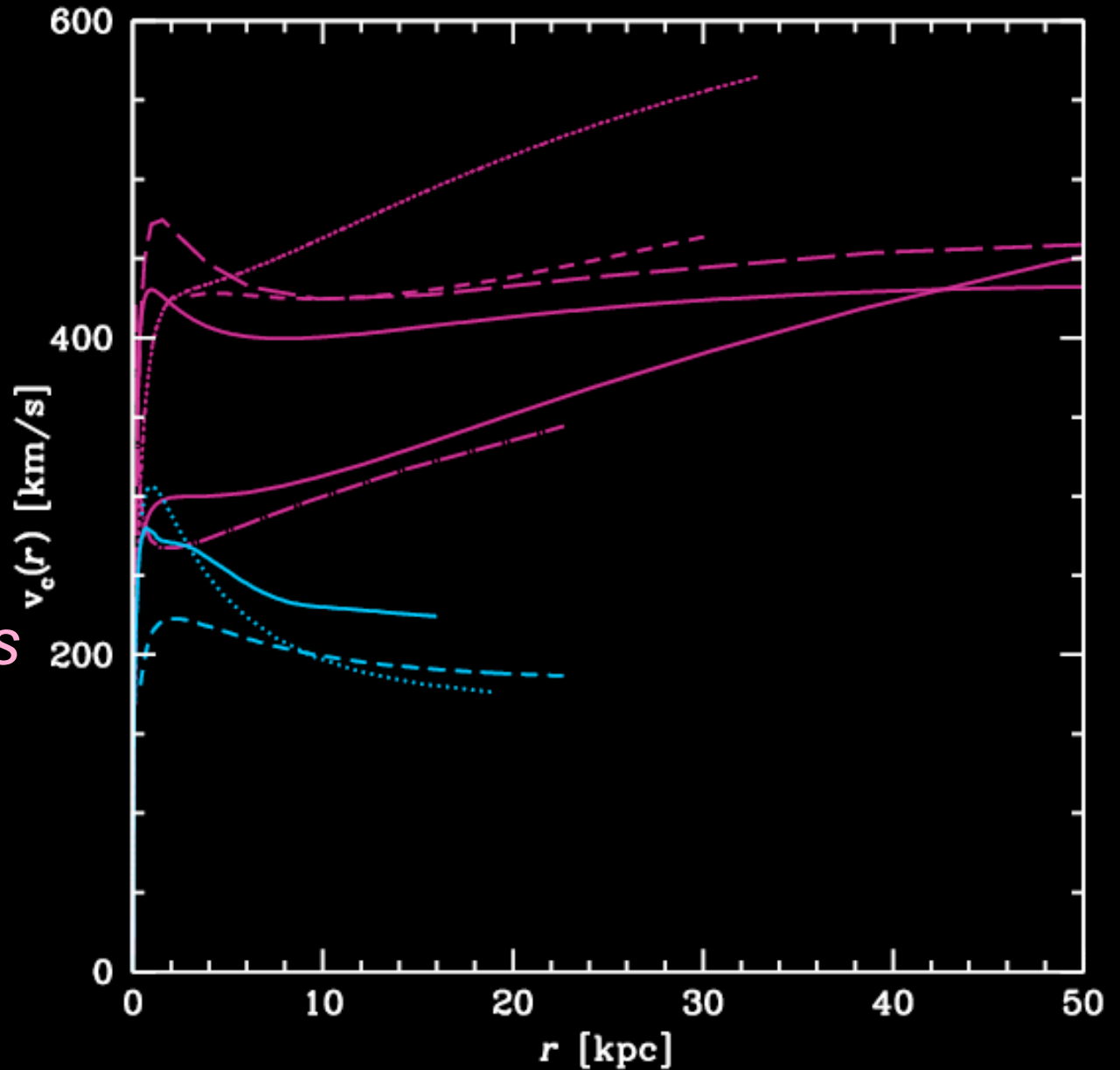
Applied to
NGC 4697:
381 PNe +
6 long-slits

Circular velocity profiles

Slow rotators:
flat/rising v_c

Fast rotators:
declining v_c

*GC cross-checks
support PN results
in 3/4 cases*

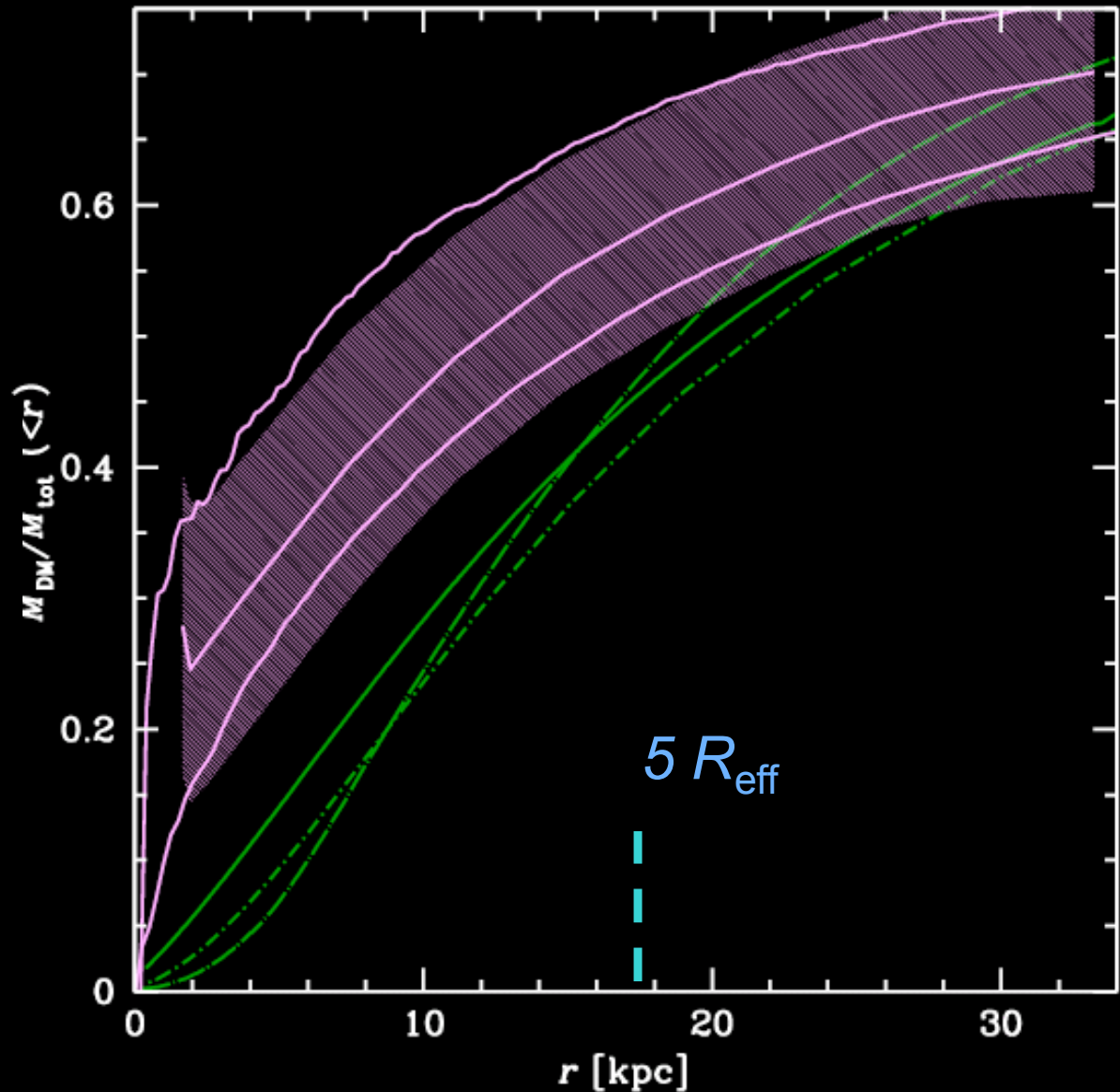


Simulations of elliptical formation

Sims including
baryon physics
(Dekel et al. 2005;
Naab et al. 2007;
Oñorbe et al. 2007)

- **Systematic central dark matter difference between simulations and observations**

- partial stellar M/L degeneracy as in spirals



DM trends of early-type galaxies

**Systematic
difference:
slow, fast rotators
(opposite
DM, stellar
concentrations)**

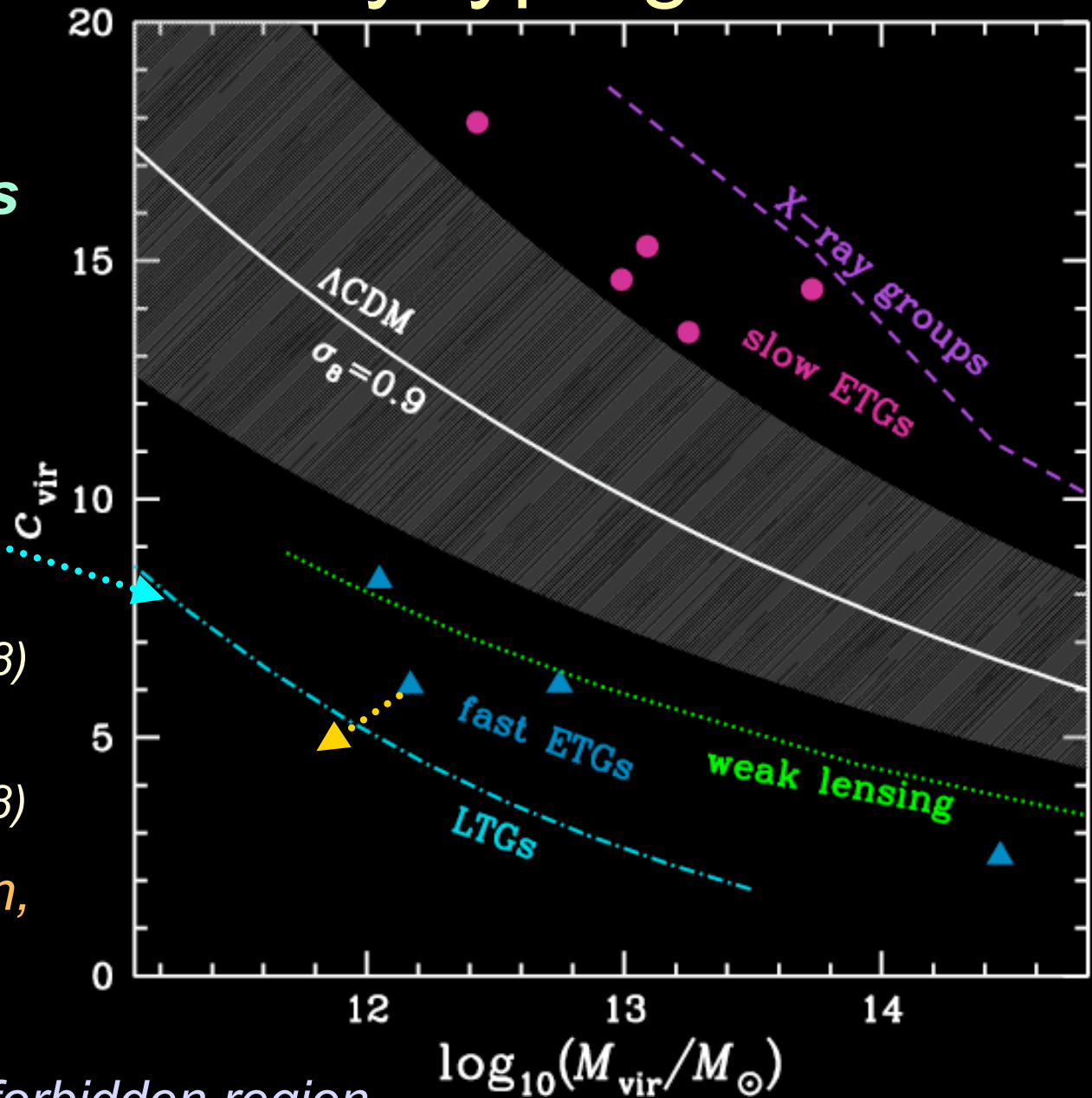
spirals
(McGaugh et al. 2007)

X-ray: Duffy et al. (2008)

weak lensing:
Mandelbaum et al. (2008)

**Adiabatic contraction,
 Υ_* free**
(Gnedin et al. 2006)

Bullock et al. (2001) forbidden region



Dark matter bimodality

Fast/slow rotator dichotomy not explainable via:

- smooth scalings with luminosity
- biasing with formation redshift
- biasing with angular momentum
- anti-hierarchical/downsizing DM (WDM, etc.?)
- dynamical modeling systematics (geometry/orbit structure)
- selection effects
- alternative gravitational dynamics (MOND, etc.)
- stellar populations modeling systematics

Could be due to:

- baryonic physics: cooling, feedback, merger dynamics, etc.
- environment: all slow rotators are (fossil) group central?

DM bimodality from coupled merger histories + baryonic physics?

Fast rotators from $z < 1$ quenching and wet mergers with substantial feedback to lower σ_{DM}

Slow rotators from $z > 1$ quasi-monolithic collapse in high-overdensity regions with dissipation to raise σ_{DM} (dry merging doesn't work):

Blumenthal et al. (1984); Burkert et al. (2008);
but see Kang et al. (2007)

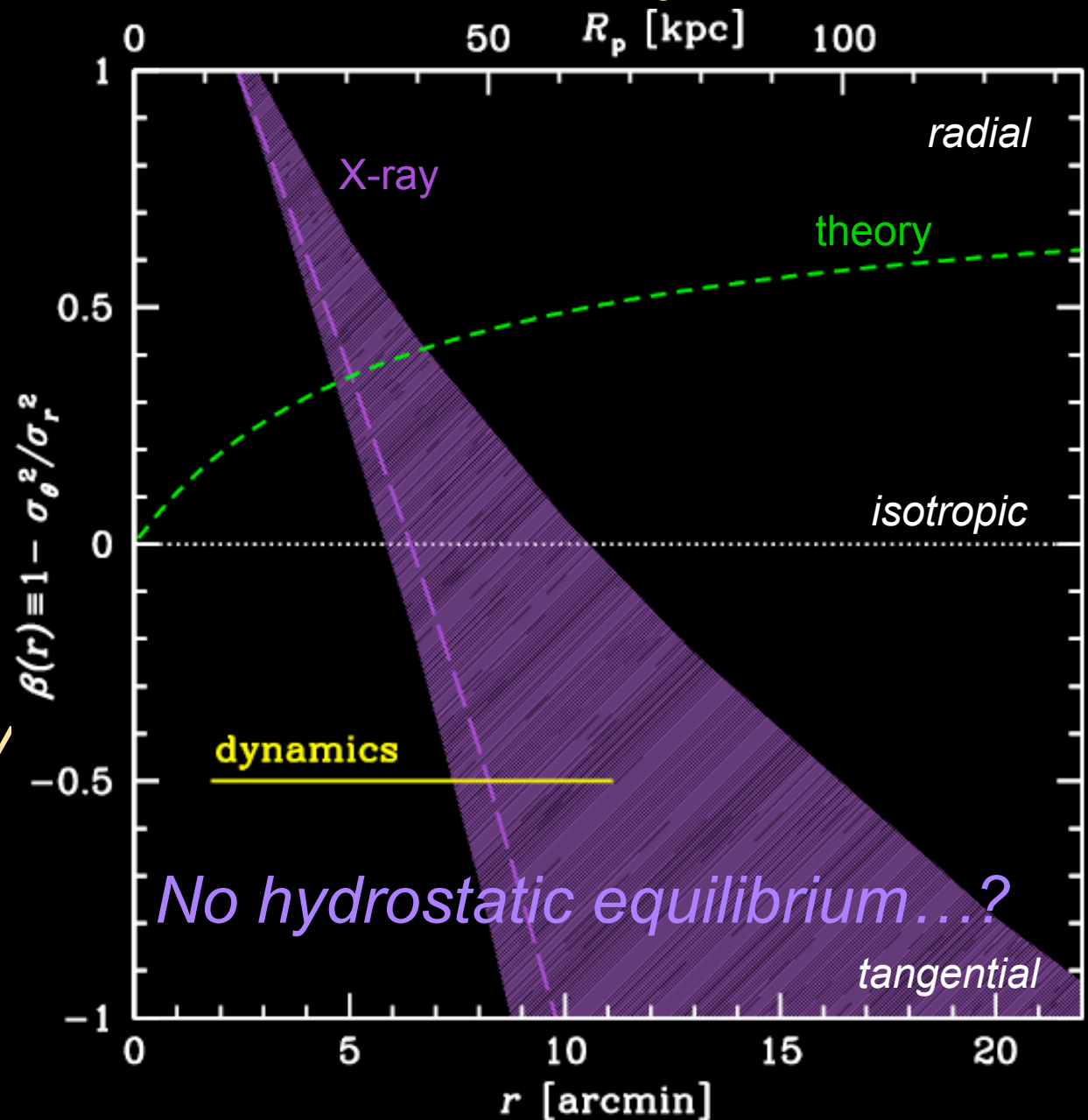
_ Why two distinct episodes for early-type galaxy formation?

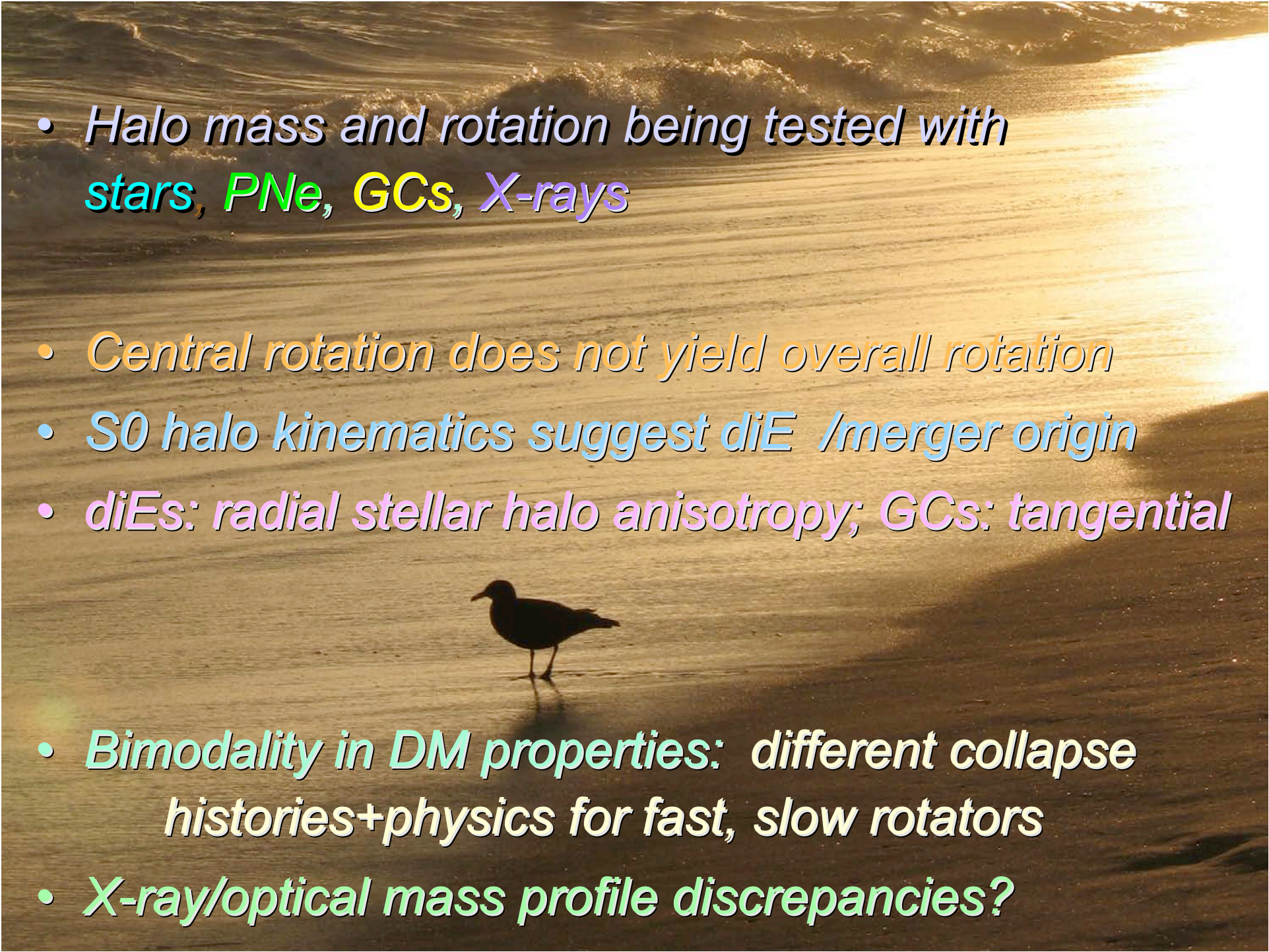
NGC 1407 mass profile: X-rays vs GCs

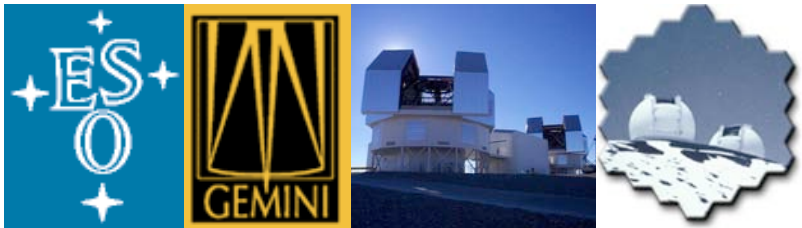
GC kinematics
from DEIMOS,
X-ray mass
from Chandra

NFW halos from
GCs and X-rays
discrepant at 2
(cf. high- c_{vir} , low Υ_*
found by Humphrey
et al. 2006)

What $\beta(r)$ for GCs
required for
consistency?

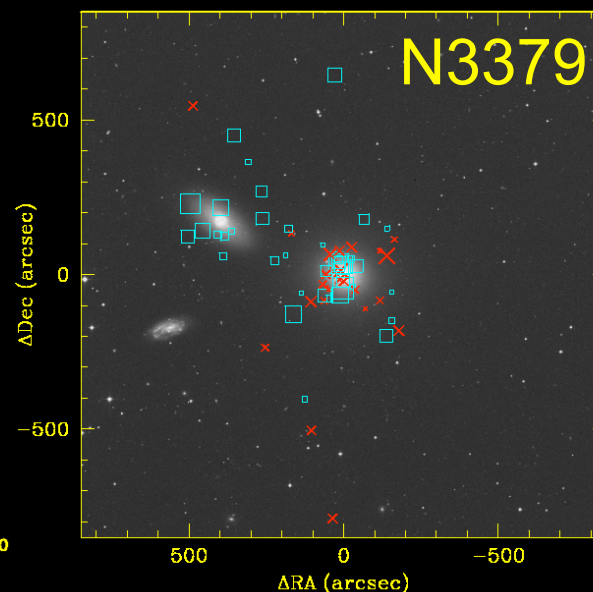
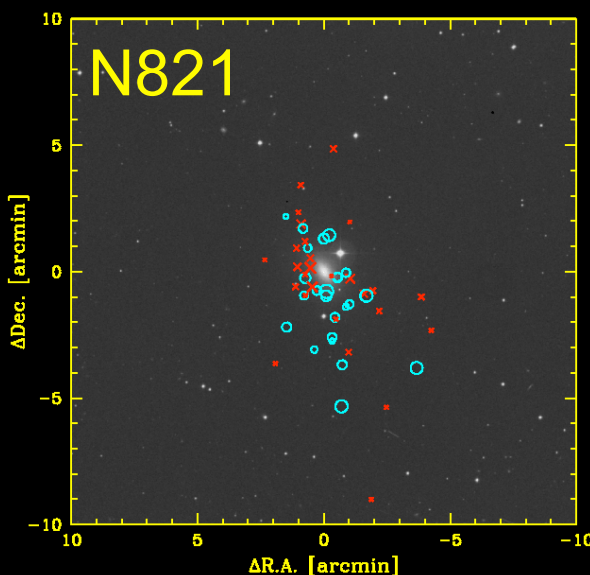


- 
- Halo mass and rotation being tested with stars, PNe, GCs, X-rays
 - Central rotation does not yield overall rotation
 - S0 halo kinematics suggest diE /merger origin
 - diEs: radial stellar halo anisotropy; GCs: tangential
 - Bimodality in DM properties: different collapse histories+physics for fast, slow rotators
 - X-ray/optical mass profile discrepancies?



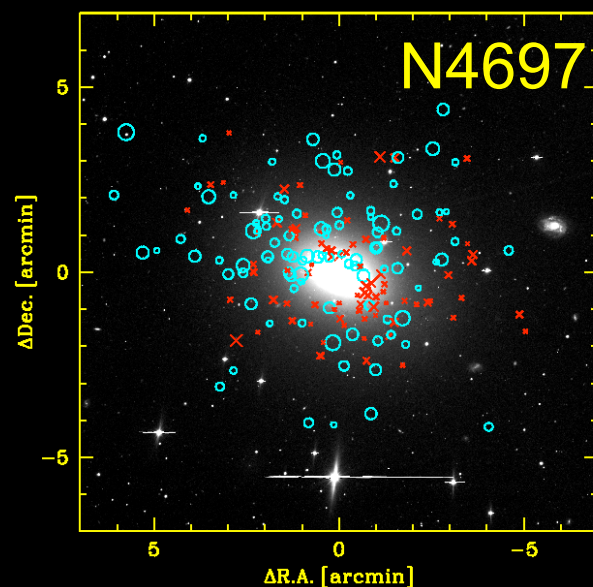
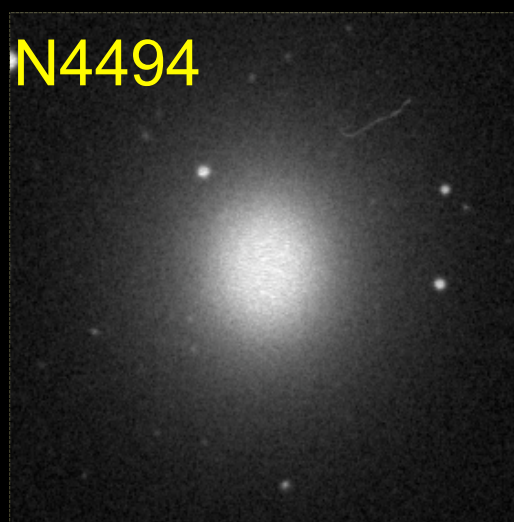
GC kinematics in "Science 4" fast rotators

DEIMOS
Proctor,
Romanowsky,
et al., in prep.:
53 velocities



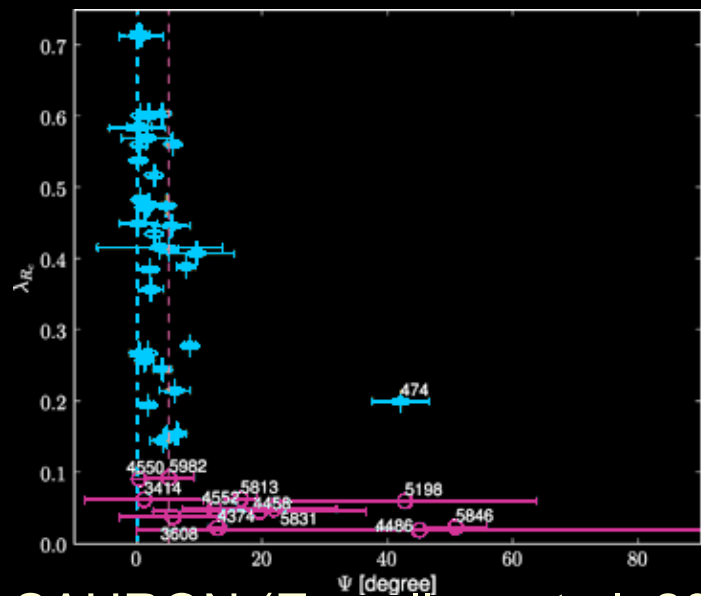
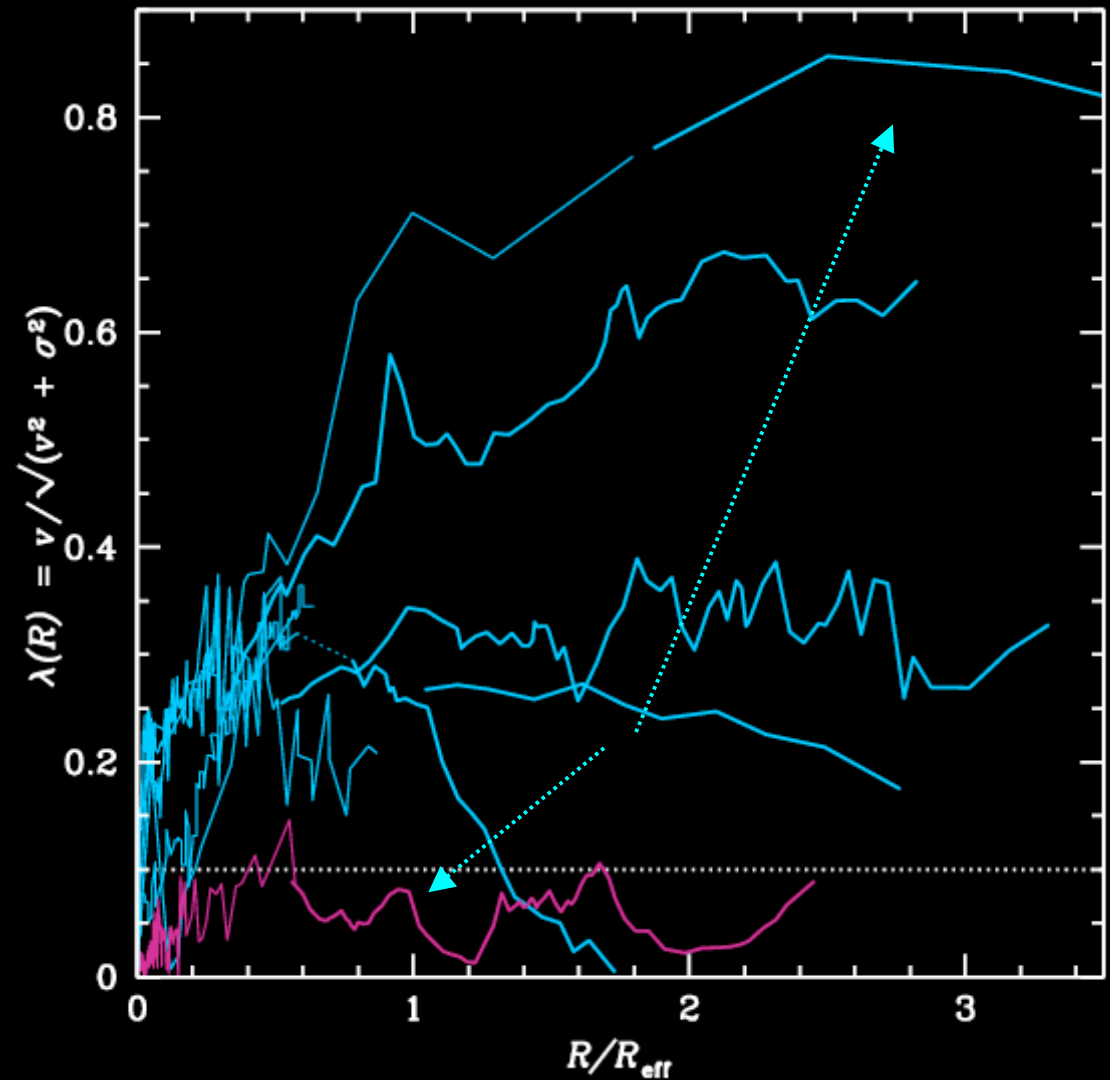
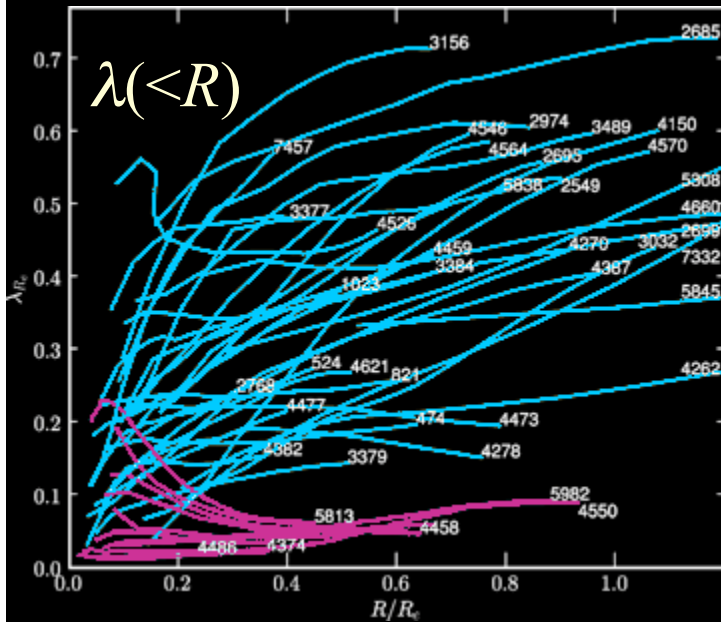
FORS2,
GMOS,
FLAMES
Puzia et al.
2004; Pierce
et al. 2006;
Bergond et al
2006, in prep.
~100 vels

DEIMOS
Brodie et al.,
Apr 2008



GMOS,
FORS2,
IMACS
Romanowsky,
Schuberth,
Faifer, et al.,
in prep.:
187 vels

Stellar halo rotation in early-types



SAURON (Emsellem et al. 2007)

Noordermeer et al. (2008); Proctor et al. in prep; Arnold et al. in prep.



3-D stellar kinematics with Keck

Use leftover slit light from DEIMOS GC spectra to probe galaxy kinematics to $\sim 3 R_{\text{eff}}$ (*poor man's IFU*)

Proctor et al. in prep

