Outer Halos of Nearby Elliptical Galaxies

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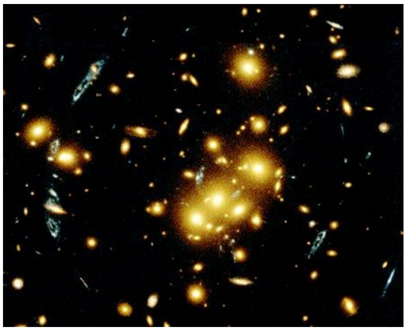
How did Elliptical Galaxies (ETGs) form?
- **The most massive galaxies, containing the oldest stellar populations, found in dense environments**
- **Early dissipative merger collapse vs late merger, multiple/binary, major/minor, dry/wet mergers**

Elliptical Galaxy Halos: Origin and Relation to Environment? Accretion vs. Merging?
- **Orbit distribution and dynamics, angular momentum of the halo stars?**
- **Density of dark matter halos?**
- **Stellar populations, age, metallicity?**
- **How do they blend into the environment, the Intracluster Light? Evolution in clusters?**



Bright ellipticals in rich cluster CL0024

Some recent results:
- **Kinematics and λ at large R**
- **Dark matter and vc(R)**
- **Evidence for accretion from kinematics and stellar populations**

Thanks to P. Das, F.de Lorenzi, L. Morganti, G.Ventimiglia, X. Wu (MPE), M. Arnaboldi, L.Coccato (ESO), E. Churazov, T. Naab (MPA), E. McNeil-Moylan (MSSO), PN.S team (AUS,D,IT,NL,UK)

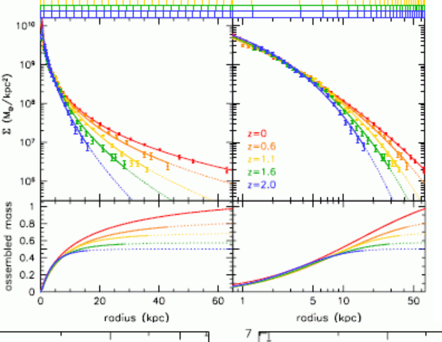
Size Evolution of Massive Galaxies from z=2 to now

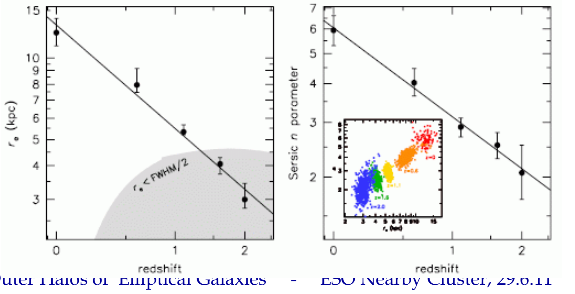
Recent evidence that z=1 and z=2 bright ellipticals were smaller and more compact than ellipticals of similar mass today: Daddi+'05, Trujillo+'07, van Dokkum+'08, van der Wel+'09

van Dokkum+'10 construct samples of massive galaxies at constant number density to show that profiles of stacked images become more extended (larger n, Re) with decreasing redshift. M(<5kpc)~const.: build-up of outer halos.

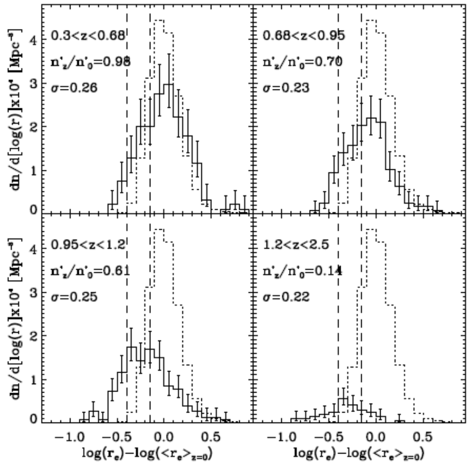
Interpretation from analysis of their SFR since z=2: accretion - merger process.

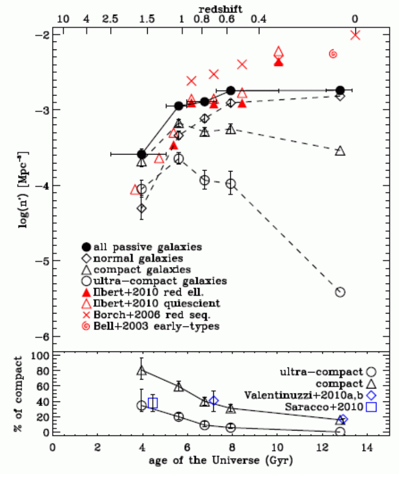
Consistent with minor merger driven accretion Abadi+'06, Naab+'09, Hopkins+'09





Size and Number Density Evolution of Passive ETGs

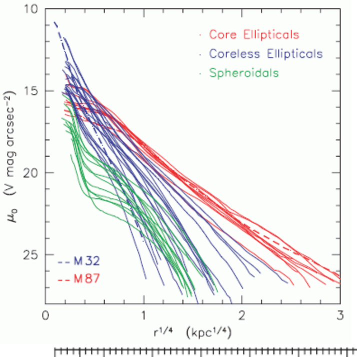


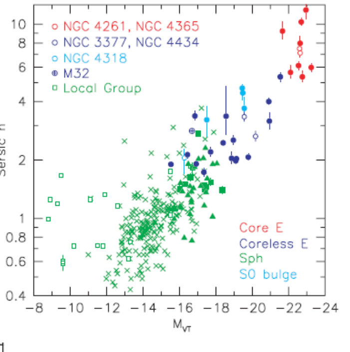


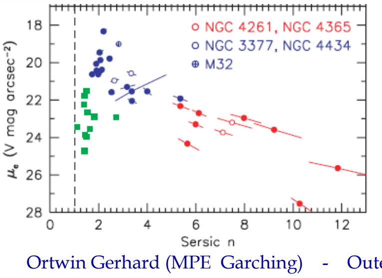
Size distribution, relative to local SDSS, and number density for ~complete GOODS sample of 563 passively evolving galaxies with $M>10^{10}M_\odot$ in different redshift bins ($SSFR<10^{-2}$/Gyr).

Interpretation: old compact ellipticals grow in size, but also many larger, lower-mass new ETGs appear [n(z=2)/n(z=1)~5; n(z=0)/n(z=1)~1.5]. **Cassata+1106.4308**

Core Ellipticals Have the Most Extended Stellar Halos





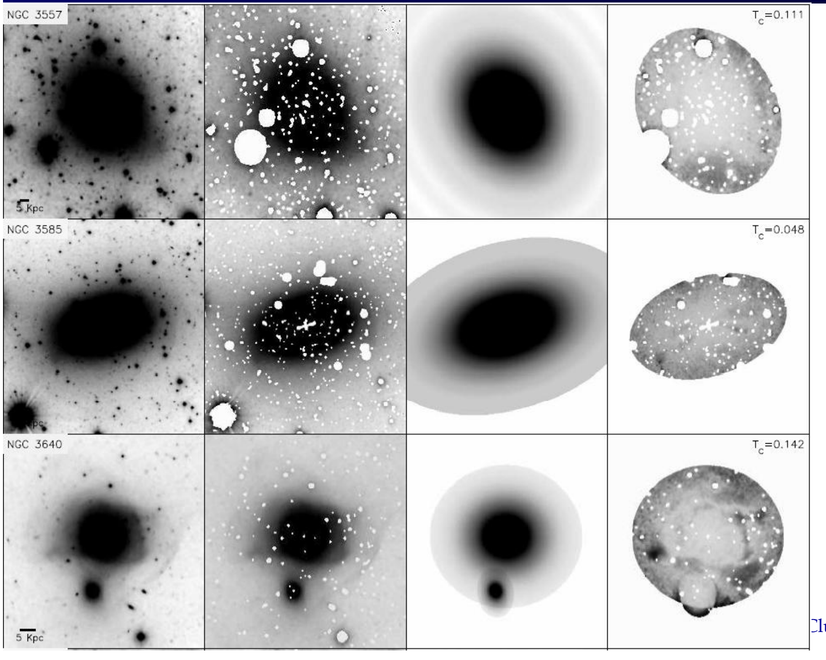


Brighter 'core' ellipticals have more extended brightness profiles (larger Sersic n, larger Re, fainter μe), but are brighter at all radii outside their cores than 'cuspy' ellipticals.

Within each group, n not correlated with Mv.

Kormendy et al. (2009), Virgo sample

Tidal Features at Large Radii



From broadband imaging study of luminous elliptical galaxies to V=27.7

Tal et al 2009 AJ

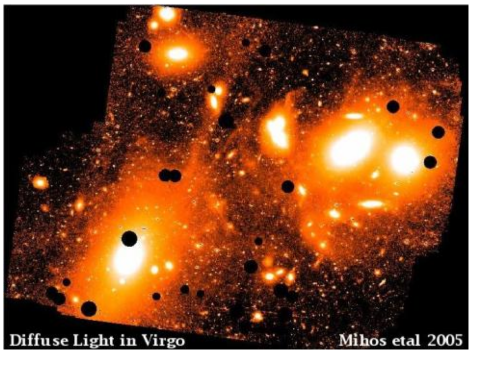
~70% of sample show shells, tails, fans, min.merger with residual “tidal” par. T>0.07

I. Stellar-kinematics in the Faint Surface Brightness Outer Halos of Elliptical Galaxies

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 ways to obtain data at larger radii and fainter surface brightness:

- **Planetary nebulae**, e.g., Hui+’95, Arnaboldi+’96, Peng+’04; trace stellar light and kinematics to ~ 8 Re, Coccato+’09, up to beyond 100 kpc, Doherty+’09 (to $\mu_V \sim 27.5$)
- **Slitlets** placed around halo globular clusters, Proctor+’09, Forster+’11 (to $\mu_V \sim 25$)
- **IFUs** placed at large radii, Sauron, Weijmans+’09, VIRUS-P, Gebhardt+’11 (to $\mu_V \sim 25.5$)
- **Globular clusters** (complicated; not direct light tracers); e.g., Hwang+’08. Schuberth+’09, Woodley+’10



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

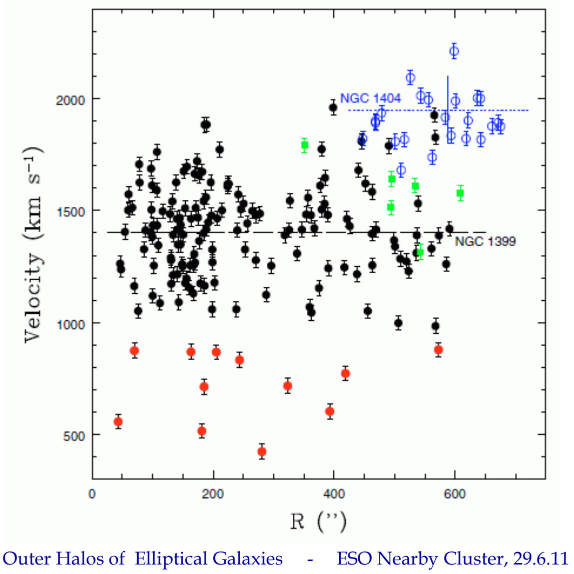
PNe around NGC 1399

Phase-space plot R-v_{los} shows three components:

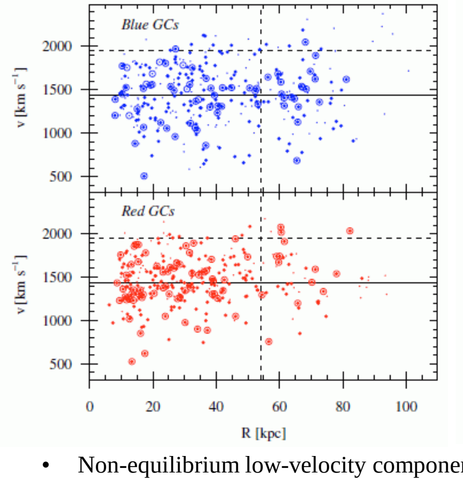
- **NGC 1399**
- **NGC 1404**
- **Low-velocity outliers, at ~750±250 km/s**

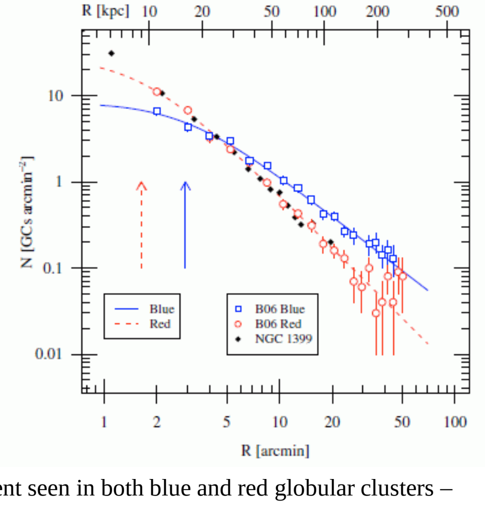
McNeil et al. 2010

Many large ellipticals have a second galaxy within a 10-20' field.



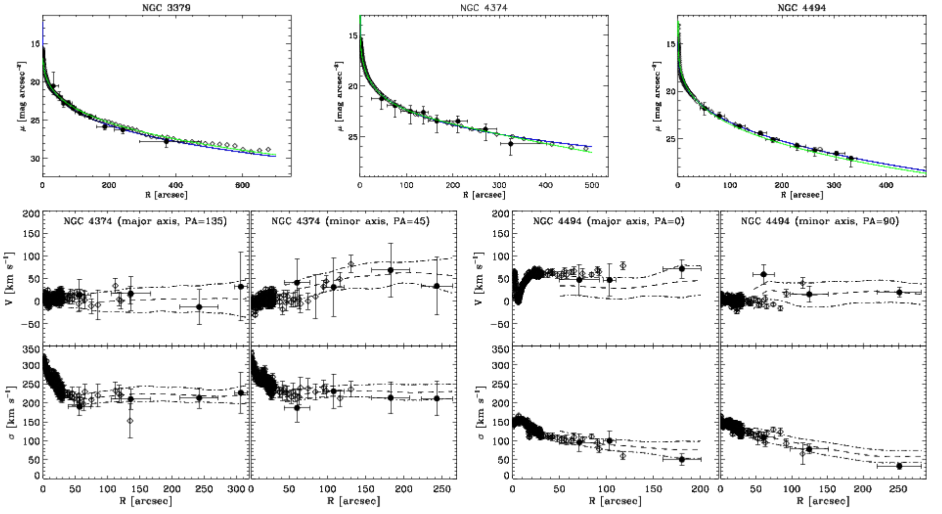
Globular Clusters around NGC 1399





- Non-equilibrium low-velocity component seen in both blue and red globular clusters – no component is galaxy only. Opportunity to see infalling components.
- In NGC 1399, number density profile of red GCs ~ follows stellar light; that of blue GCs doesn't. Decontaminated red GCs seem in ~ equilibrium, but the blue ones not. Counterexamples – need to check case by case. **Schuberth et al. 2009**

PNe trace stars in ETGs

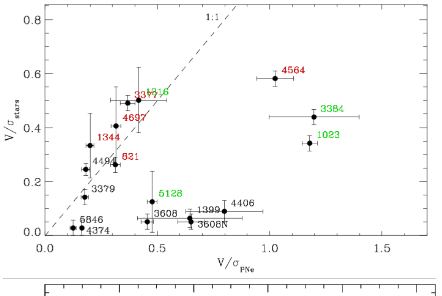


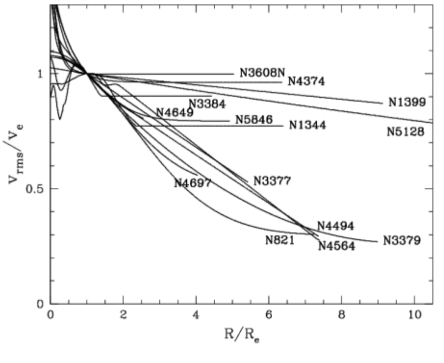
PN density and kinematics consistent with integrated light within errors; one possible exception NGC 4697. **Coccato, OG, Arnaboldi, et PN.S. 2009**

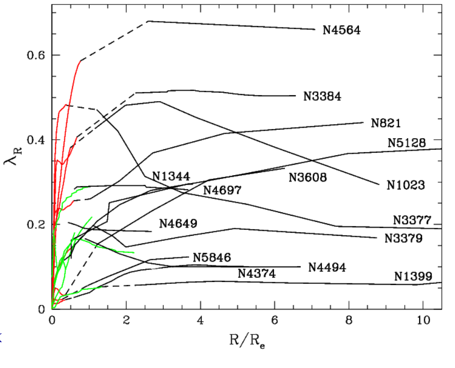
Outer Halo Kinematics from Planetary Nebulae

- **2 types of slowly falling and rapidly falling kinematic profiles**
- **v/σ in the halo correlates with that within Re for greater part of the sample**
- **Slow/fast rotator division in the outer halos similar as in cores (Emsellem et al 2007), some more complicated cases**

Coccato et al. 2009, + updates

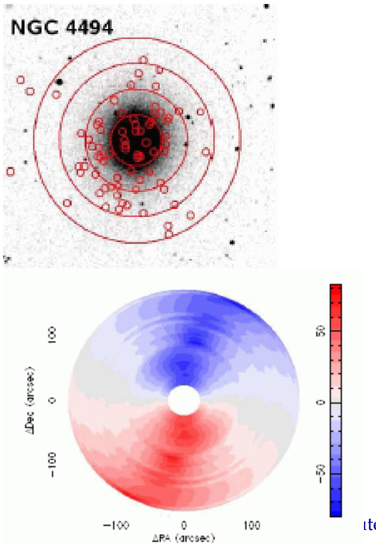




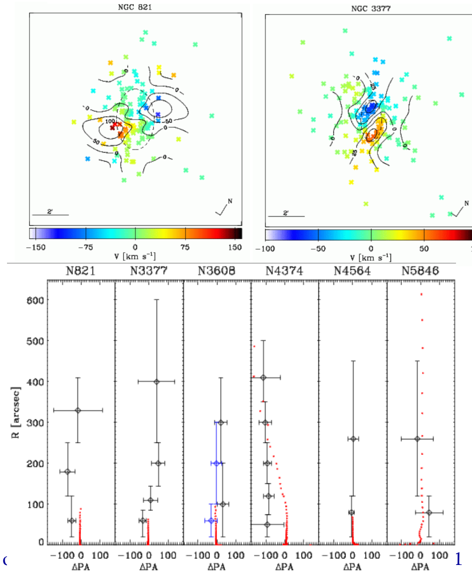


Kinematic Misalignments More Frequent at Large Radii

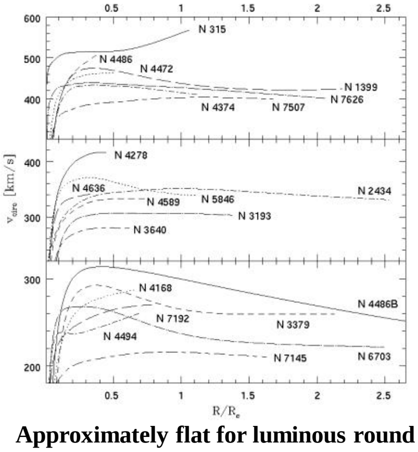
From slitlets:
Proctor et al. 2009, Foster et al. 2011



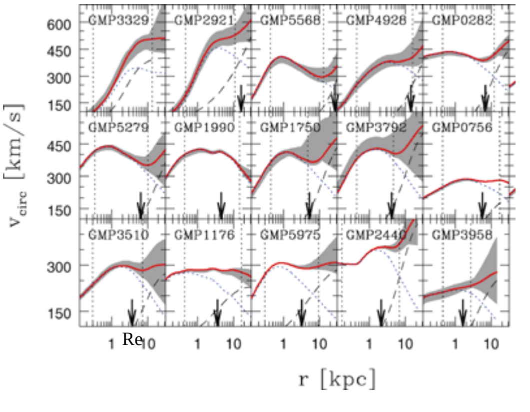
From PNe:
Coccato et al. 2009



II. Dark Halo Circular Velocity Curves from Stellar Kinematics



Approximately flat for luminous round galaxies, using data to 1-2 Re, nonpara-metric spherical DF models. Panels ~ by decreasing luminosity Gerhard+'01



More varied for flattened Coma ellipticals, M_B=[-18.8,-22.6], derived from data to 1-3Re, axisymmetric Schwarzschild models. Thomas+'07

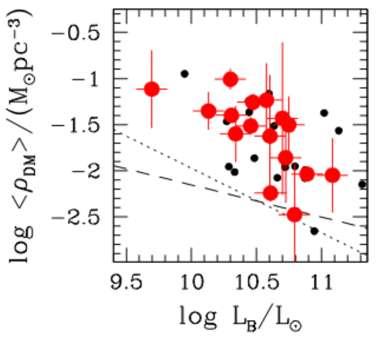
⇒ ~flat Vc(r) and dark matter fraction ~10-50% within Re.

See also Cappellari+'06; Treu & Koopmans '04, Auger+'10.

Dark Matter Densities of Early Type Galaxies

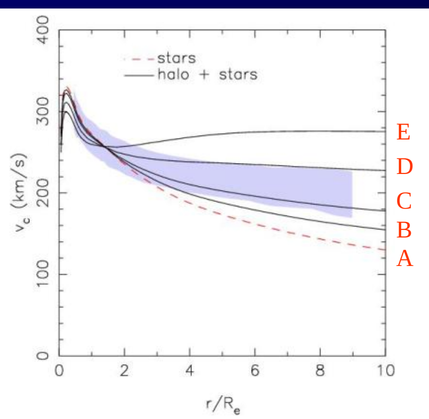
- **Sample of 17 early-type galaxies in the Coma cluster, kinematic data to ~ 2-3 Re, Schwarzschild orbit superposition models in luminous + halo potentials**
- **dark matter densities 7x higher than in spirals of same L (13x higher at same M) , less luminous Es have higher halo densities**
- **baryonic contraction not sufficient to explain the difference**
- **elliptical galaxies inferred to assemble earlier than spirals of same luminosity**

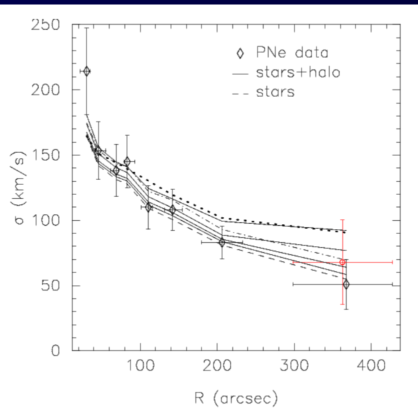
Thomas et al. 2009



● Coma early-types
● round galaxies (Gerhard et al. 2001)
– – spirals (Kormendy & Freeman 2004)
····· spirals (Persic, Salucci & Stel 1996)

Dynamical Masses: Intmd.-Luminosity Elliptical NGC 3379





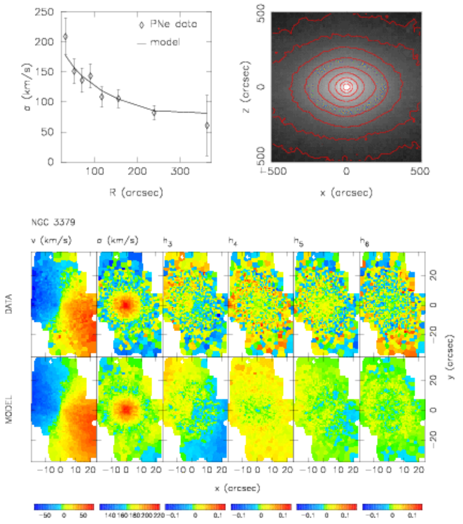
- **NGC 3379 model potentials: stars only (- -. bottom, Model A), to stars plus dark halo models (—, B-E, top). Models A, E (weakly) ruled out by likelihood analysis**
- **Shaded range is from Dekel et al. (2005) star-forming merger simulations on orbits from ΛCDM cosmology**

de Lorenzi et al. 2009, updates previous Douglas+'07, Romanowsky+'03; see also Weijmans et al. 2009

►Falling PN dispersion profile can be reproduced in A-D, PN likelihood favours B-D.

►Baryons centrally concentrated, but no contradiction to ΛCDM if β>>0 and vc ↘

NMAGIC – A New Way of Modeling Galaxies



(final model instead of film)

Developed @ Basel&MPE 2002-2007
De Lorenzi, Gerhard etal., MNRAS

N-particle model approaches target data for elliptical galaxy NGC 3379

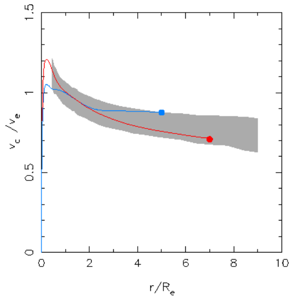
Top right: Light distribution (observer sees ~spherical image from top)
Top left: radial profile of stellar velocity dispersion

Left: Projected kinematics of NGC 3379 (SAURON data)
v=mean line-of-sight velocity
σ=velocity dispersion of the stars
hn= higher order moments

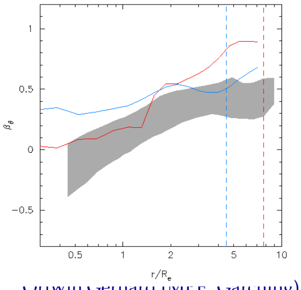
Lower left: Initial → Final model fit

Applications: black hole masses, dark matter halos, galactic nuclei, star clusters, also in Galactic Center

Halo Dynamics & Masses in NGC 3379 & NGC 4697

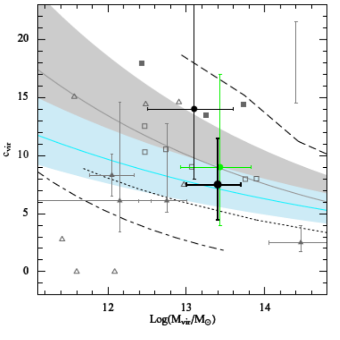


Best axisymmetric models for NGC 3379 (red) and N4697 (blue) have moderately falling circular velocity curves and radially anisotropic halos (de Lorenzi et al. 2008, 2009). Shaded range is for models from Dekel et al. 2005, *including* v_{rot} in β values.



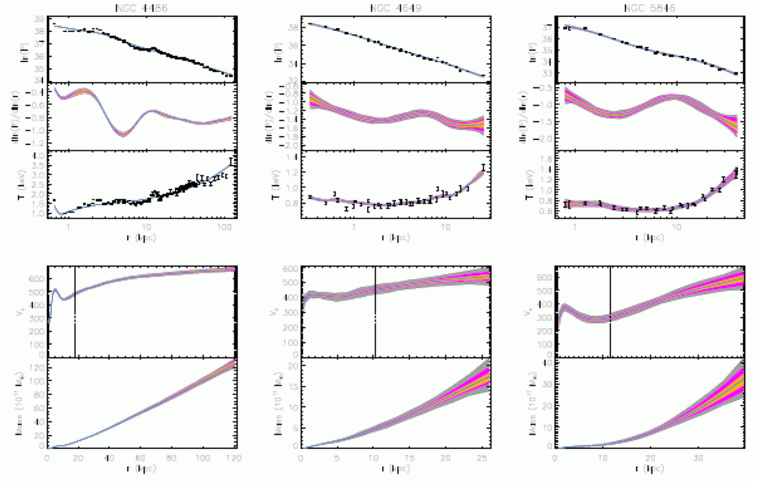
Strongly falling dispersion profiles in NGC 3379, NGC 4697 do not necessarily imply non-standard diffuse halos, but may be consistent with predicted scatter for radially anisotropic models.

Fig. from Napolitano+ '11 shows virial masses and concentrations from fitted NFW models & compares with LCDM 1sigma range from Bullock+'01, Maccio+'08



Modelling of further objects in progress.

Mass Distributions: X-ray Bright Ellipticals

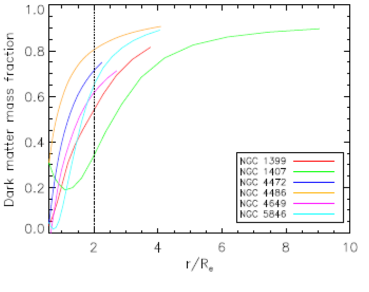


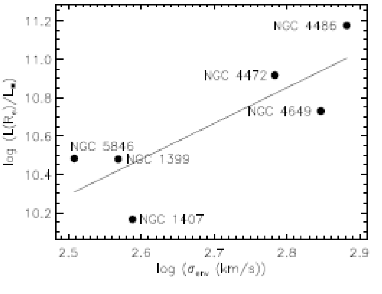
Bayesian reconstruction from deprojected temperature and density profiles, assuming hydrostatic pressure equilibrium. Data from Churazov et al 2010. ⇒ derived circular velocity curves rising. Due to group halo? Compare with dynamical masses.

Das, OG, Churazov, Zhuravleva 2010

Other recent X-ray mass determinations: Humphrey+'06, Nagino & Matsushita '09

Dark Matter Halos from Hydrostatic Equilibrium

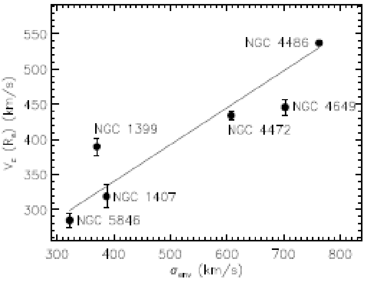




Top: dark matter mass fractions ~60-80% at 20-30 kpc

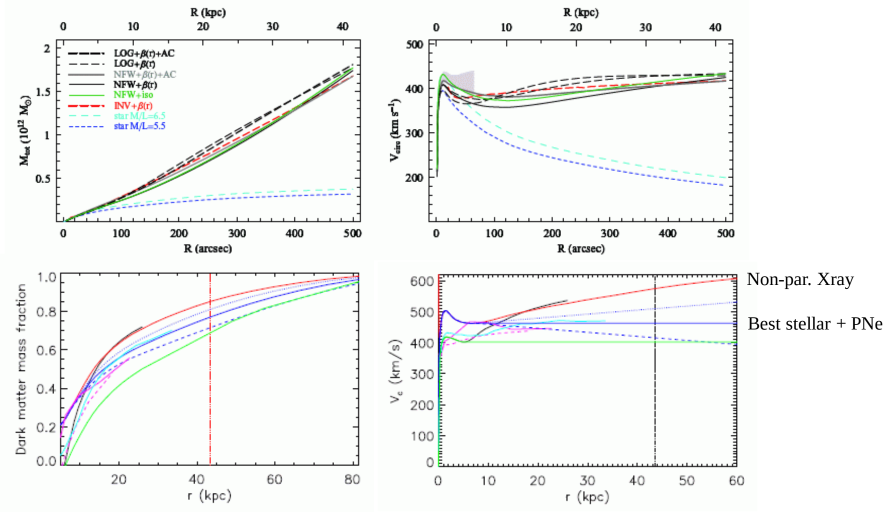
Right: Galaxy luminosity and circular velocity at Re correlate with velocity dispersion of environment on sub-Mpc scale.

Supports embedding in group-size halo and link between central XRBEs and their environment.



Das, OG, Churazov, Zhuravleva 2010

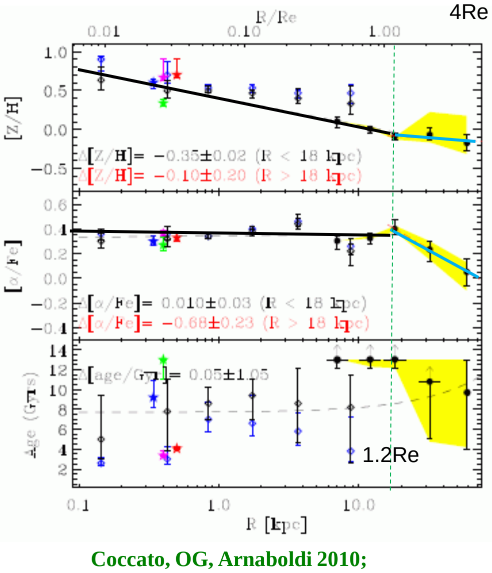
Dynamical Masses: Luminous X-ray Bright Ellipticals



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 clearly prefer lower-vc models over X-ray derived mass distribution (red).

III. Assembly History of Nearby BCGs
(a) Halo Stellar Population NGC 4889 in Coma Cluster



Coccato, OG, Arnaboldi 2010; see poster by L. Coccato

Line strength indices Hb, [MgFe]', Mgb, <Fe> measured with deep Subaru spectra to 65 kpc radius.

Fitting Single Stellar Population Models (Thomas et al. 2003) to indices gives for:

R<~1.2Re:

- **steep metallicity gradient (from ~5 solar to ~solar);**
- **constant abundance ratio (2.5 solar);**

R > 1.2Re

- **hardly any metallicity gradient**
- **strong [α/Fe] gradient (drops to ~solar)**

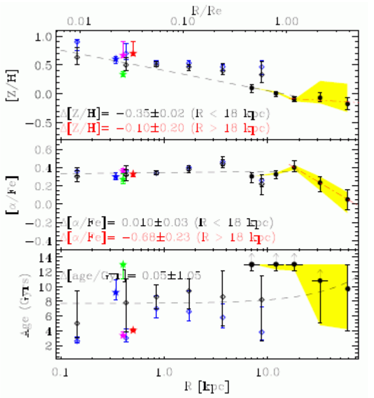
Stellar ages increase with radius

Δ : stellar population from literature data

● : stellar population from our Subaru data

: maximal sky systematic errors

Constraints on Formation History



Coccato et al. 2010

Inner half of NGC 4889 (R~<Re)

High central [Z/H] and steep gradients of -0.5 are produced in rapid "monolithic" collapses (Chiosi & Carraro '02; Kobayashi '04; Pipino+'06, '08, Oser+10). Then reduced by subsequent dry mergers (White '80, Kobayashi '04, di Matteo+'09)

Constant inner [α/Fe] (~2.5 solar) implies rapid star-forming collapse of entire inner half of the galaxy, ~10^8yr (Thomas et al formula) ~ tdyn to ~10^9yr, perhaps in dissipative multiple merger.

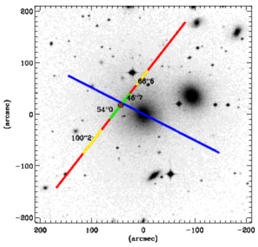
Younger central ages might be due to minor accretion event (e.g., 10% 1 Gyr ago).

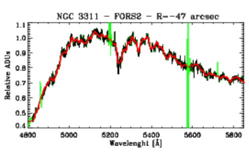
Brough+'07 find range of gradients in BCGs.

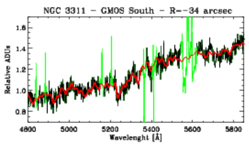
Halo (R~>Re)

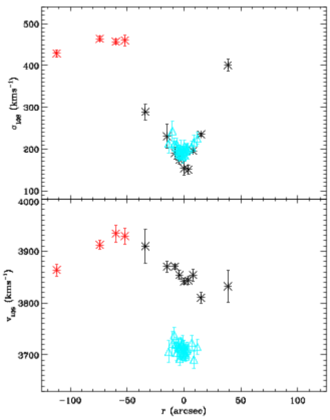
Near-solar [α/Fe] indicates longer SFH, >~1Gyr. Together with near-solar [Z/H] and lack of gradient ⇒ most likely origin is accretion of lower-mass galaxies with long SFH. Preventing central late SF would blow out entire halo gas. Note that the halo stars are old (~10 Gyr). Consistent with in situ vs accreted stars in simulations of galaxies (Abadi+06, Oser+10).

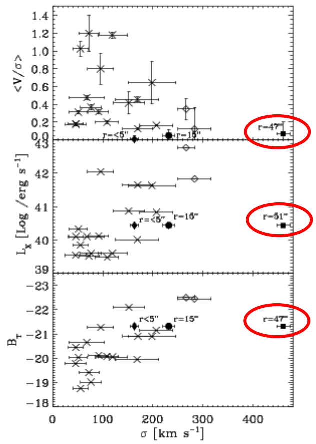
(b) The Dynamically Hot Stellar Halo around NGC 3311







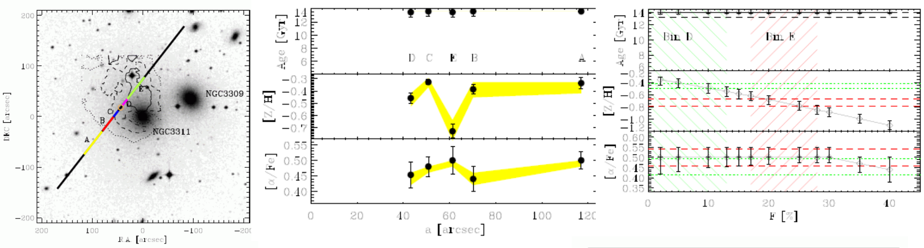


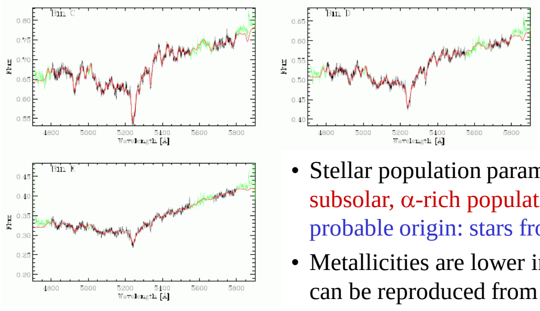


Ventimiglia et al. 2010, A&A
Richtler et al. 1103.2053

- **Central galaxy velocity dispersion ~150 km/s**
- **In 15"-45" (4-12 kpc) transition to σ~450 km/s ~60% of dispersion of cluster galaxies**
- **Outer halo unusually dynamically hot for ETGs -- accreted**
- **Intracluster stellar halo dominates completely for R>12 kpc**

Accretion Past and Present in the Hydra Cluster Core





ID	a	Age	[Z/H]	[α/Fe]
	["]	[Gyr]		
(1)	(2)	(3)	(4)	(5)
D	43.2	$13.5^{+0.0}_{-0.8}$	-0.46 ± 0.04	0.45 ± 0.04
C	50.8	$13.5^{+0.0}_{-0.8}$	-0.33 ± 0.02	0.48 ± 0.03
E	61.3	$13.5^{+0.0}_{-0.8}$	-0.73 ± 0.06	0.50 ± 0.06
B	70.2	$13.5^{+0.0}_{-0.8}$	-0.39 ± 0.04	0.44 ± 0.04
A	117.0	$13.5^{+0.0}_{-0.8}$	-0.34 ± 0.05	0.50 ± 0.03

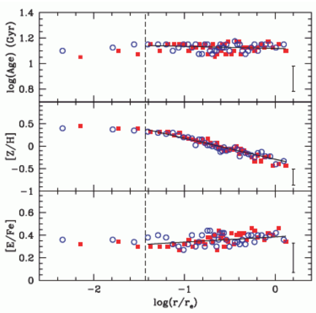
Coccato et al. (2011)

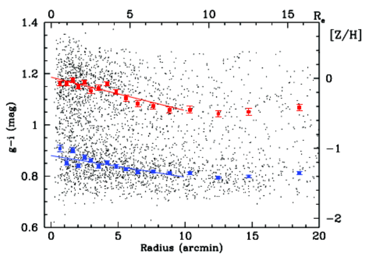
- Stellar population parameters for the ICL halo indicate old, subsolar, α-rich population; radially constant metallicity – probable origin: stars from ETG halos and dwarf galaxies
- Metallicities are lower in region of a photometric excess; this can be reproduced from halo spectra contaminated by 5% (D) to 20% (E) with the spectrum of the dwarf galaxy HCC 26 (center of slit, v_{rel}=1000 km/s)

(c) Recent Results on ETG Halo Stellar Populations

- **Brough+'07, Spolaor+'08, +'10 find a range of Z gradients and [α/Fe] but no breaks in the profiles out to < 2-3 R_e for small samples of ETGs and BGGs.**
- **Foster+'09, '11 use special slit extraction technique to measure [Fe/H] for 3 ETGs to 3 R_e consistent with single power law gradients.**
- **Forbes+'11, Jacob+'11 see break in globular cluster colour profile at very large R in ETGs NGC 1407 and NGC 3115.**

No wide-spread population change seen at ~2 Re





IV. Summary and Conclusions

- **Extended, low surface brightness halos** in bright ellipticals (M87: ~150 kpc). PN kinematics (to μ_V=27.5, up to ~8 Re) start showing kinematic substructure.
- **Outer halo kinematics:**
  - Basic slow/fast rotator dichotomy of elliptical galaxies also in the halos but some more diversity in halo λ- or v/σ profiles.
  - Vrms dispersion profiles either slightly, or strongly falling.
  - Broadly in agreement with model galaxies from hydro-cosmo-simulations; one issue still is the strongly falling Vrms profiles.
- **Dark matter halos in ellipticals:**
  - ~flat vc curves in high-mass ellipticals, high DM density, ~60-80% dark matter within 20-30 kpc, X-ray optical comparison needs some more work.
  - In some intermediate-luminosity systems Baryonic central concentration + either low density halo or strong radial anisotropy or both.
  - Dark matter densities higher than in spirals of same baryonic mass.
- **First stellar population signatures of accretion in nearby bright ellipticals (BCGs) but not ubiquitous at 2 Re and further work needed.**