Brightest cluster galaxies and intracluster light - Observations

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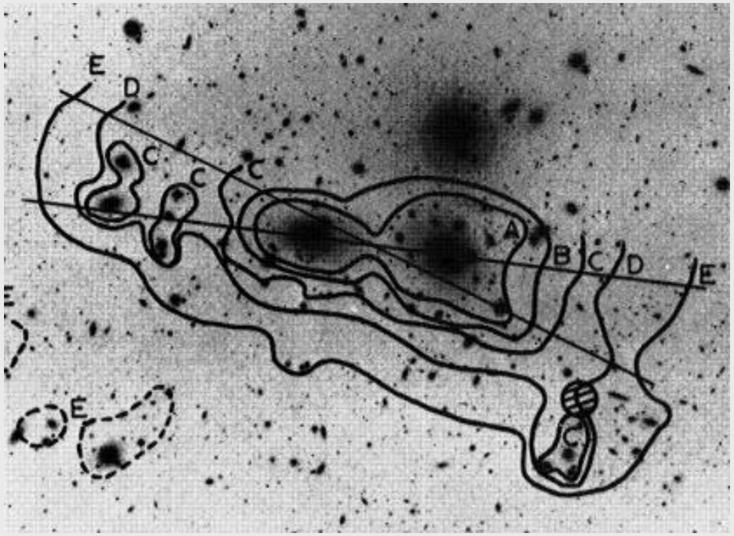
Outline

1. Brightest Cluster Galaxies and Intracluster light in clusters
2. Planetary nebulae as kinematical tracers
3. The Virgo cluster & M87
   - The PNs' V_{LOS} and the projected phase space distribution
   - Dynamical status of the Virgo core
   - Large scale distribution of the ICL
4. The Hydra cluster & NGC 3311
   - Observations : long-slit spectroscopy, MSIS, surface photometry
   - Debris from disrupted galaxies by the cluster potential
5. The Coma cluster core & the NGC 4874/NGC 4889 binary merger
6. Conclusions

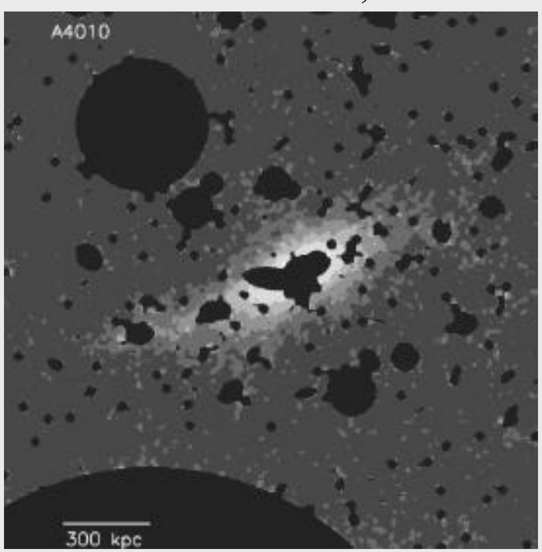
1. ICL from deep photometry

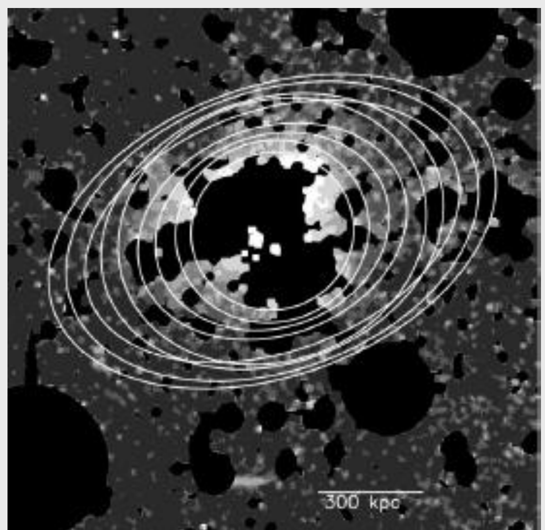


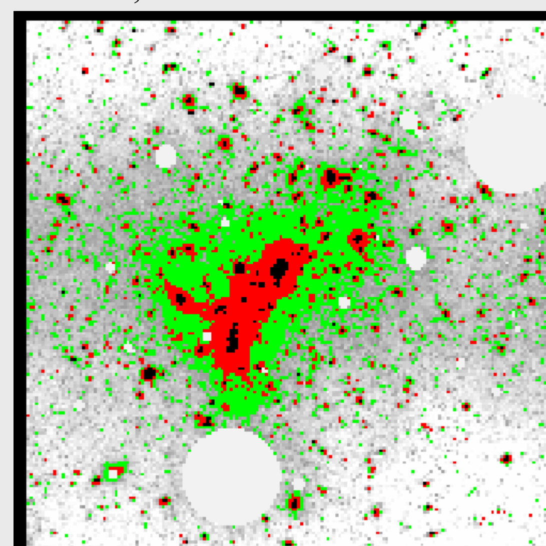
- **Core of the Coma cluster:**
  Photographic photometry
  Thuan & Kormendy 1977

- **Abell 4010 (left, z=0.096)**
  Abell 3888 (center, z=0.151)
  Deep CCD photometry
  Krick & Bernstein 2007
  Abell 1914 (right)
  Feldmeier+2004

See also Melnick+'77, Bernstein '95, Feldmeier+'04, Gonzalez+'05, Mihos+'05, Krick+'06

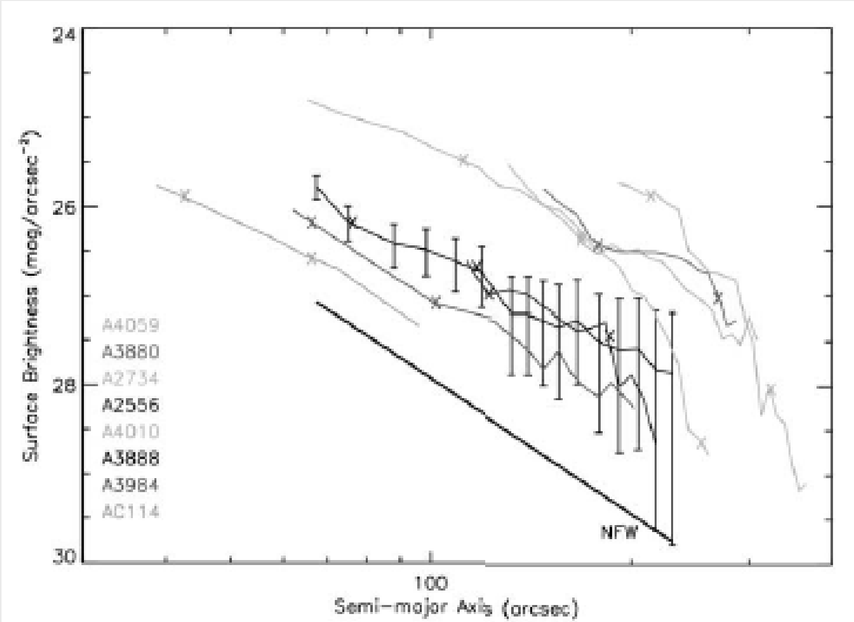




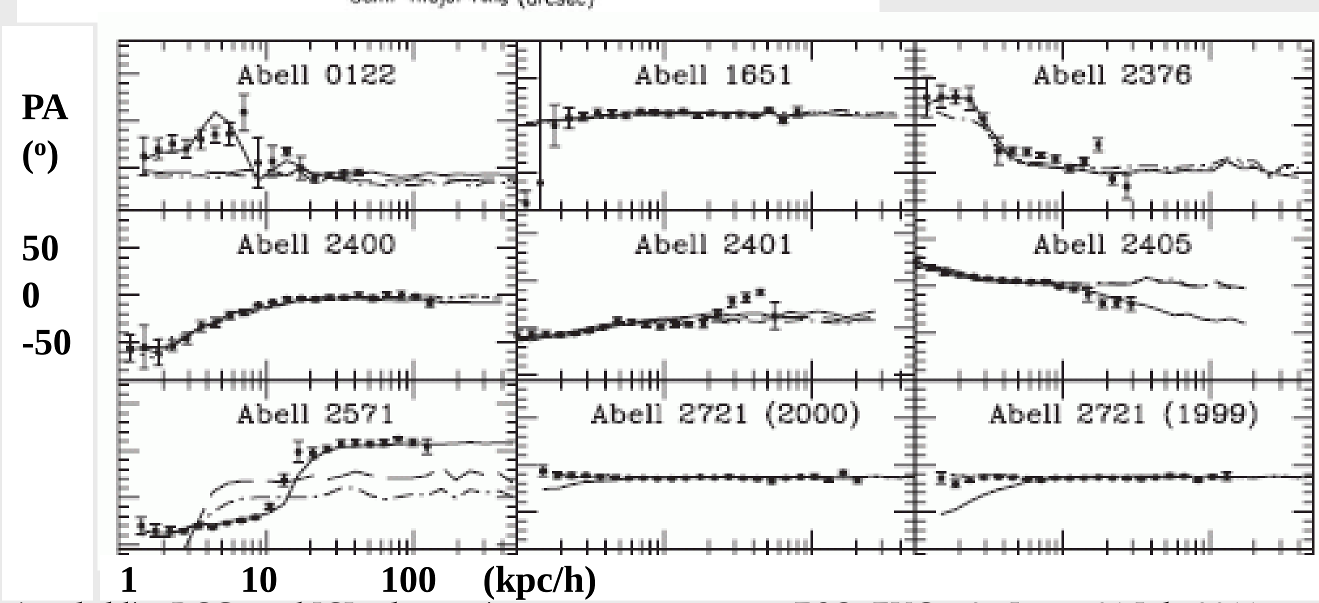


See contributions from J. Krick, J. Melnick, C. Rudick, S. Okamura

ICL properties in individual clusters



- ICL surface brightness profile shape varies between clusters - Krick & Bernstein 2007
- Ellipticity generally increases with radius, position angle sometimes has sharp variations - Gonzalez + 2005
- **Suggests ICL is dynamically young and separate from BCG**



ICL is ubiquitous – statistical properties

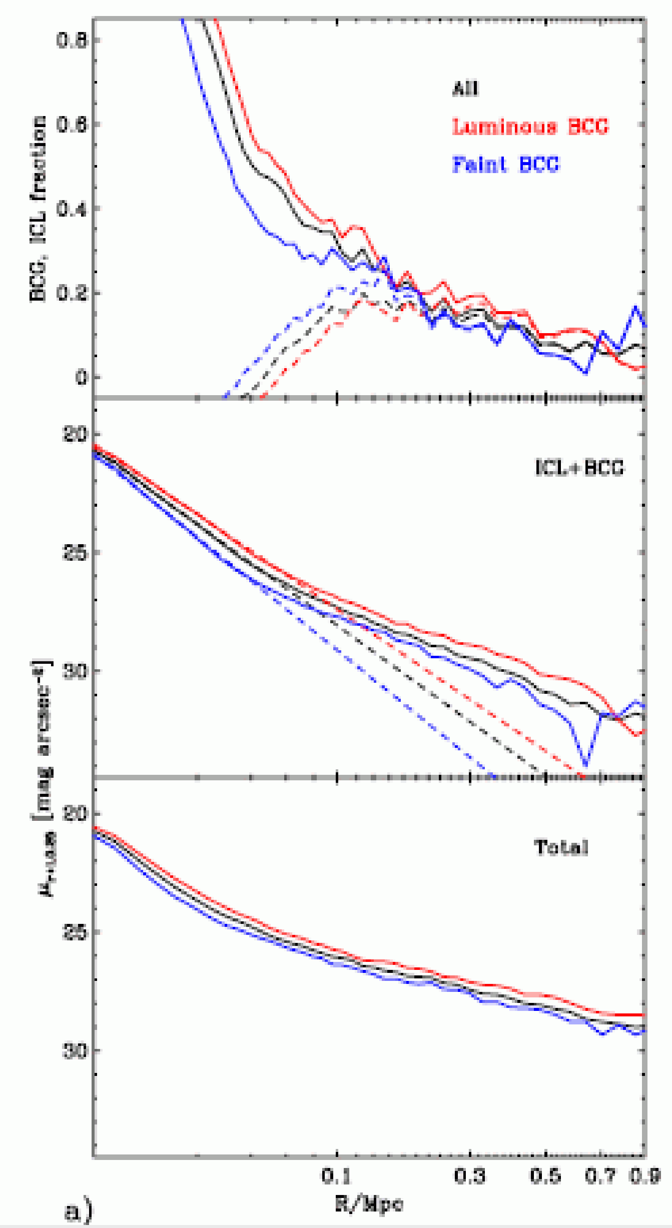
- ICL has been found in
  - BCG dominated clusters (e.g., Gonzalez+'05)
  - in clusters without BCG (e.g., Feldmeier+'04, Struble88)

- Average ICL+BCG and *total* (incl. galaxies) cluster surface brightness profiles, from stacking 683 (scaled) clusters from SDSS (Zibetti+'05):
  - ICL <u>(=SB excess w.r.t. $R^{1/4}$ profile of central BCG)</u> is more centrally concentrated than cluster galaxies
  - <*ICL fraction within 500 kpc*> ~11%; BCG ~22% (**)
  - ICL SB correlated with BCG luminosity and cluster richness, but ICL fraction almost independent

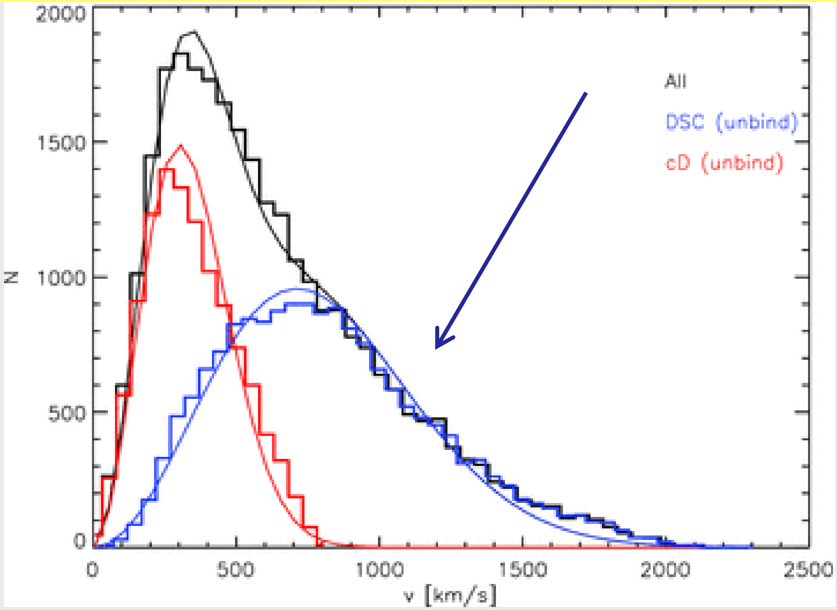
- ICL fraction in individual clusters varies:
  - ~4-21% (in B, Krick&Bernstein 2007)
  - ~10-30% (Feldmeier+'04)
  - ~5% in Virgo, isolated regions
  - ~50% in Bernstein+'95 field in Coma cluster core

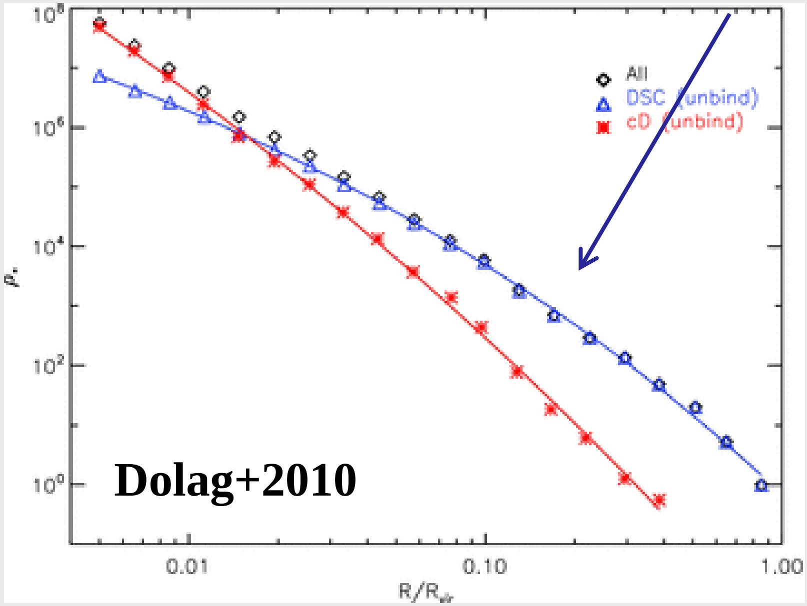
Depends on radial range and evolutionary stage of the cluster

(**) robust values, measured from profiles



BCGs & ICL





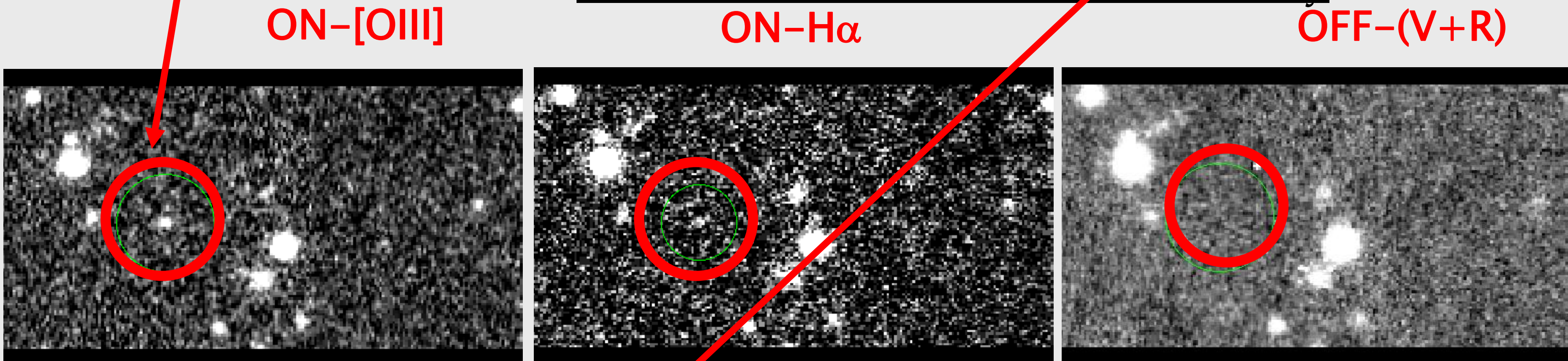
- Disentagle cD from ICL in clusters - use the velocity distribution of stars.
- Simulations of clusters - VD is bimodal. Fit by two Maxwelliansdistribution, one narrower (colder) for the central galaxy and a broader one (hotter) for the ICL.
- Hotter component is responsible for the "light excess" at large radii.
- Stellar particles in hydrodynamical cosmological simulations thus selected turn out to have different spatial distribution & star formation history.

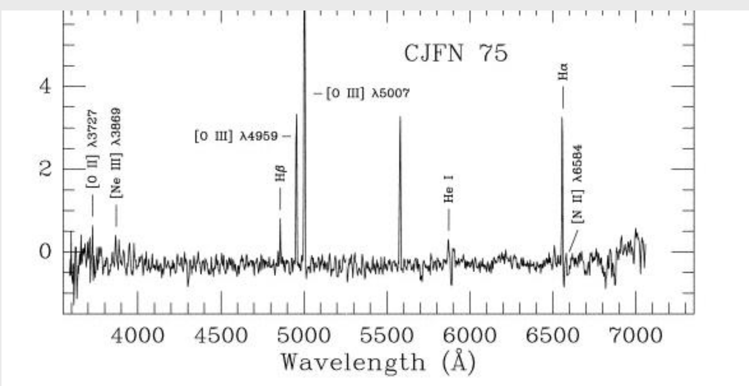
See also Kapferer et al., 2010, MNRAS, 516, 41.

Kinematics measurement can tag galaxy and ICL stars from their LOSVD at the same spatial location !

2. *Planetary nebulae as kinematical tracers*

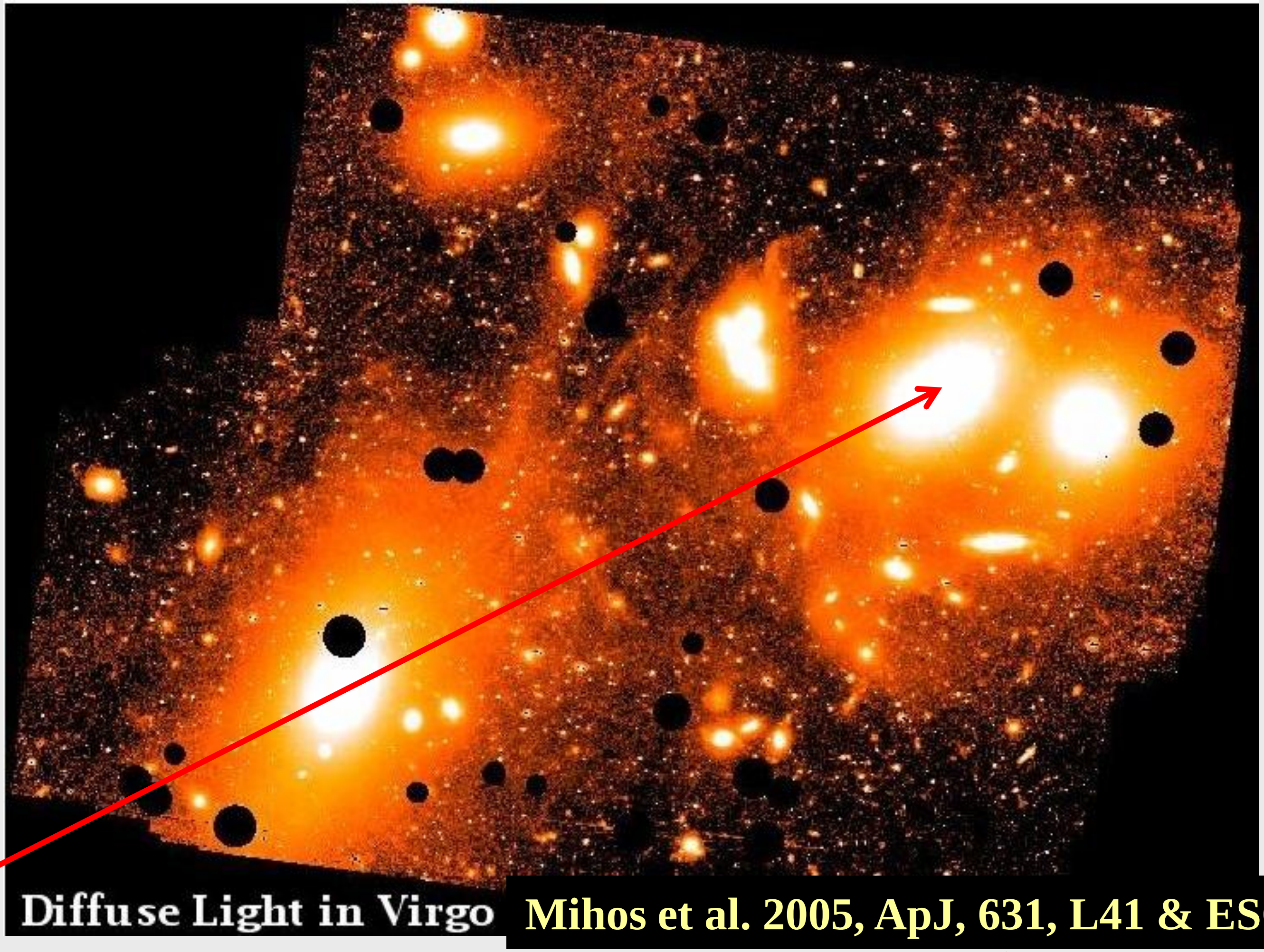
- PNs trace light because the luminosity-specific stellar death rate should be independent of the precise state of the underlying stellar population (Renzini & Buzzoni 1986), see also PN.S results from Coccato+09.
- PNs are distance indicators.
- The [OIII] line emission at 5007Å is the strongest emission from a PN; it allows the identification & the measurement of its radial velocity





- ***We obtain PN number density distribution and 2D radial velocity fields in regions where the stellar surface brightness is too faint with respect to the night sky!***

3. The core of the Virgo cluster



Mihos et al. 2005, ApJ, 631, L41 & ESO PR 2009/19a

And this is where it all started: 3 PNs at v_{mean} ~ 1400 kms^{-1} along the LOS to NGC 4406 (v_{sys} = - 240 kms^{-1}) → Arnaboldi, Freeman, et al. 1996, ApJ, 472, 145

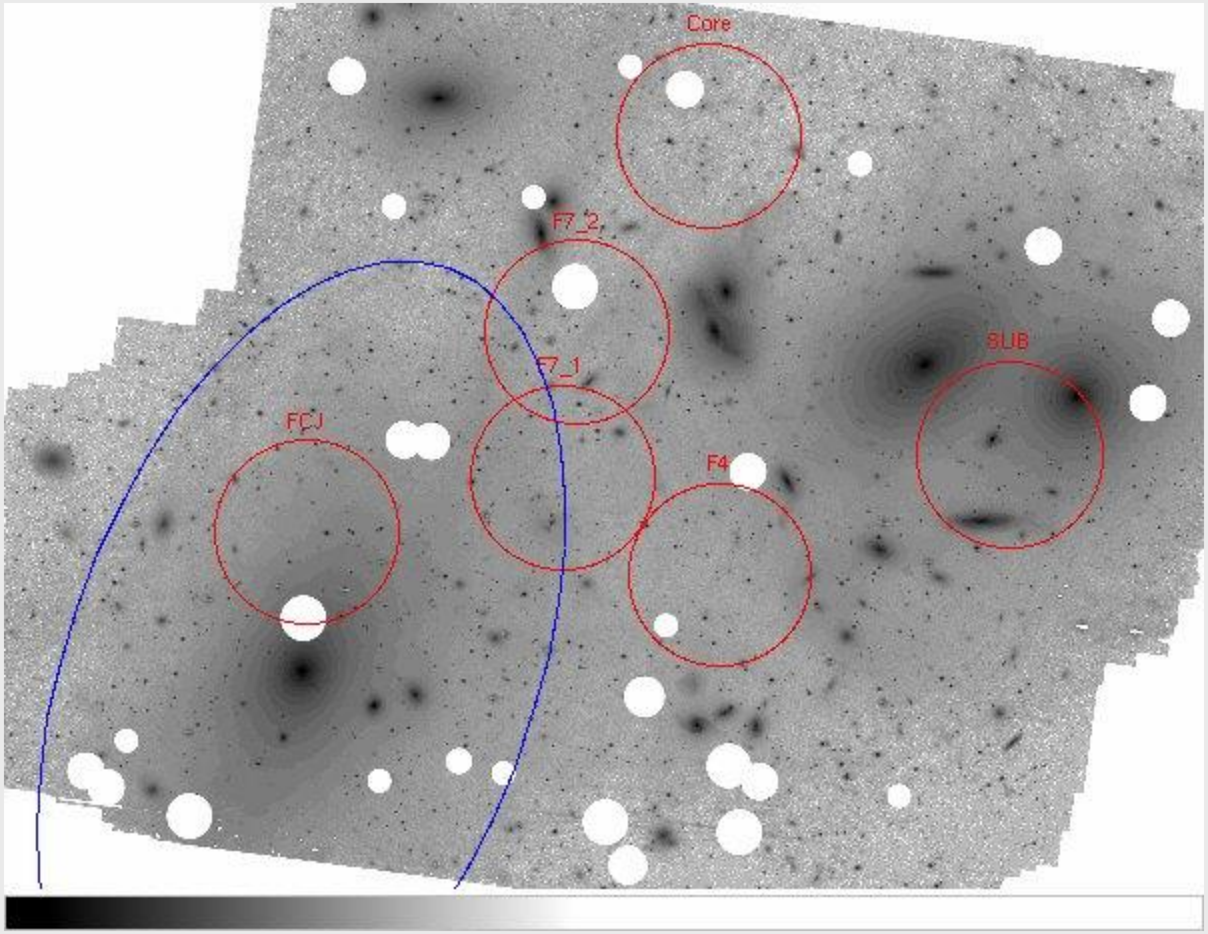
3. The core of the Virgo cluster

Narrow band imaging plus spectroscopy

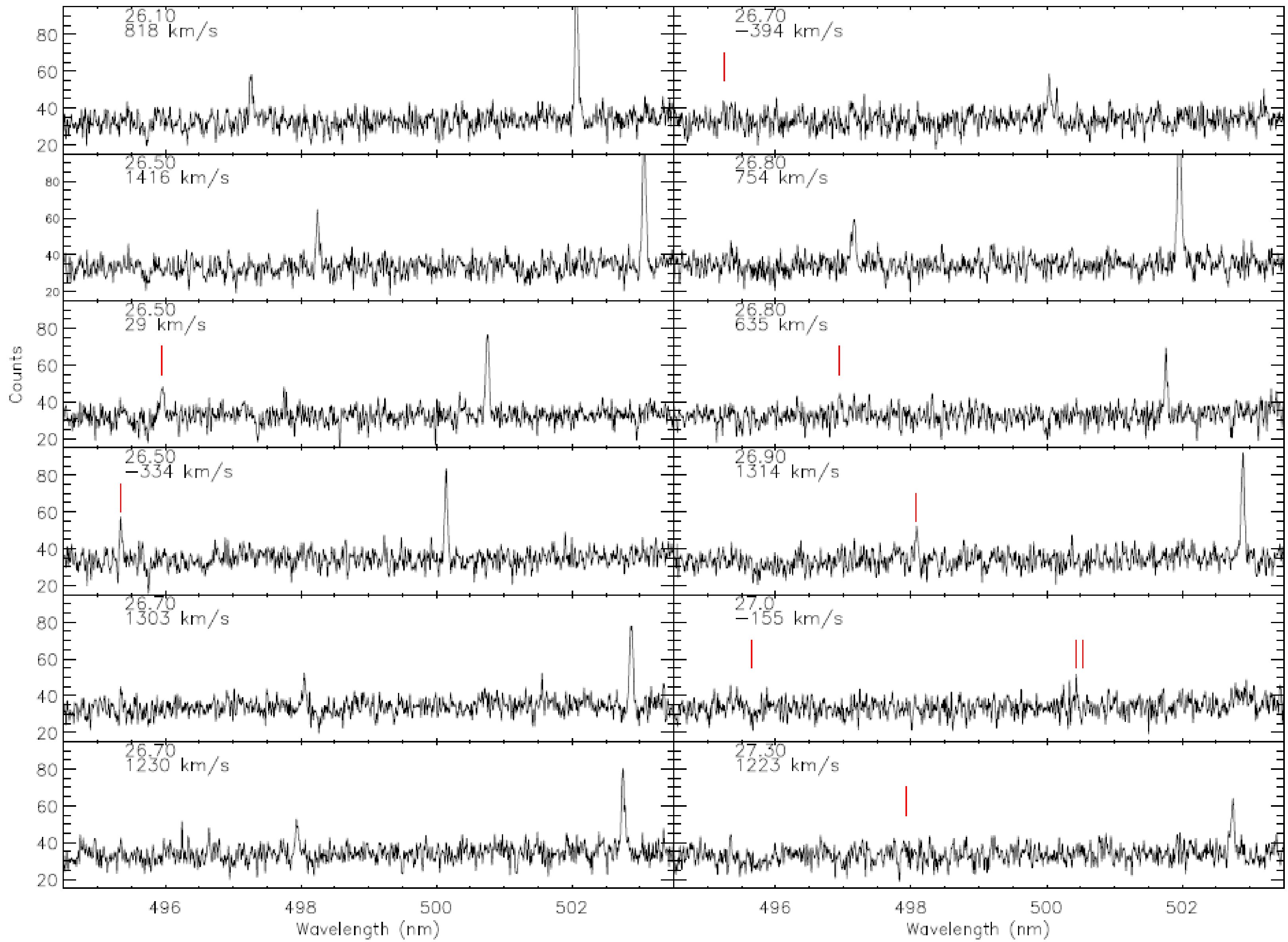
ICPN catalogs from Arnaboldi+02&03, Feldmeier+03&04

6 VLT-Flames fields
Core, FCJ, SUB from Arnaboldi+04
F7_1,F7_2, F4 from
Doherty et al. 2009, A&A, 502, 771
52 PNs v_{los} total

M87 halo according to Kormendy+09 photometry



****For optical and Spitzer IRAC surface photometry in Virgo see also oral presentations of C. Rudick and J. Krick .**



See also Freeman et al. 2000, ASP 197, 389, and Arnaboldi et al. 2003, AJ, 125, 514 for spectroscopic confirmation of ICPNs.

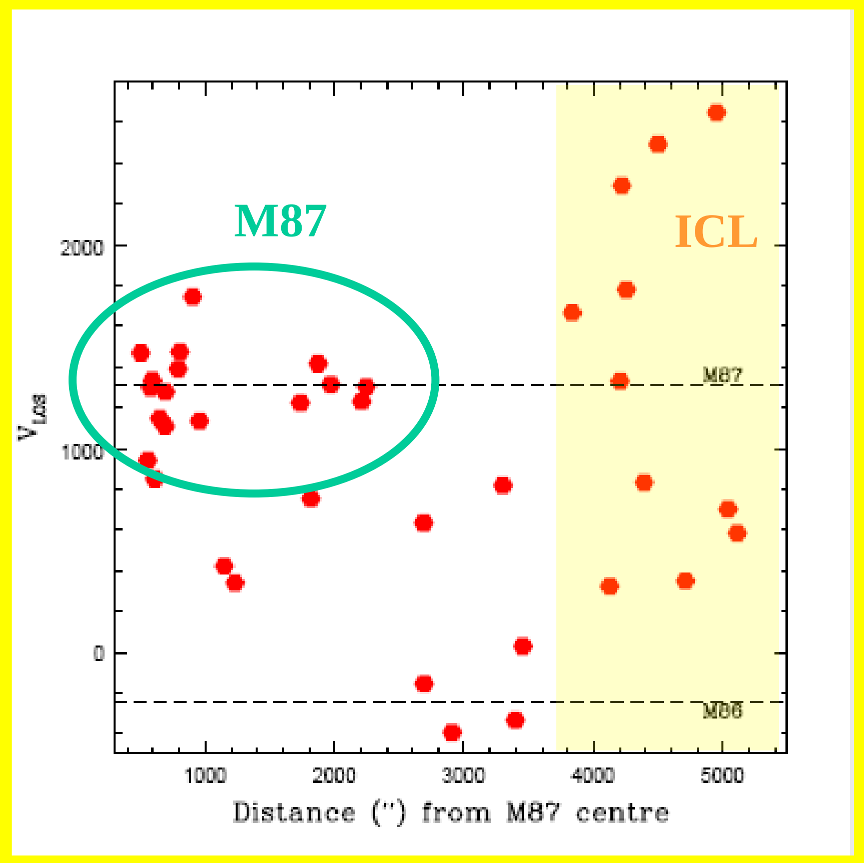
PNs' LOSVD and projected phase space

M87 halo

- does not rotate. From GCs' v_{rot} expects v_{ave} = 1150 kms^{-1} for M87 halo PNs.
- σ(r) decreases. From Montecarlo simulations of a Gaussian with σ=247 kms^{-1}, the combined probability for 2 measurements at > -2σ and 5 within +/- 0.3 σ is less than 1%.

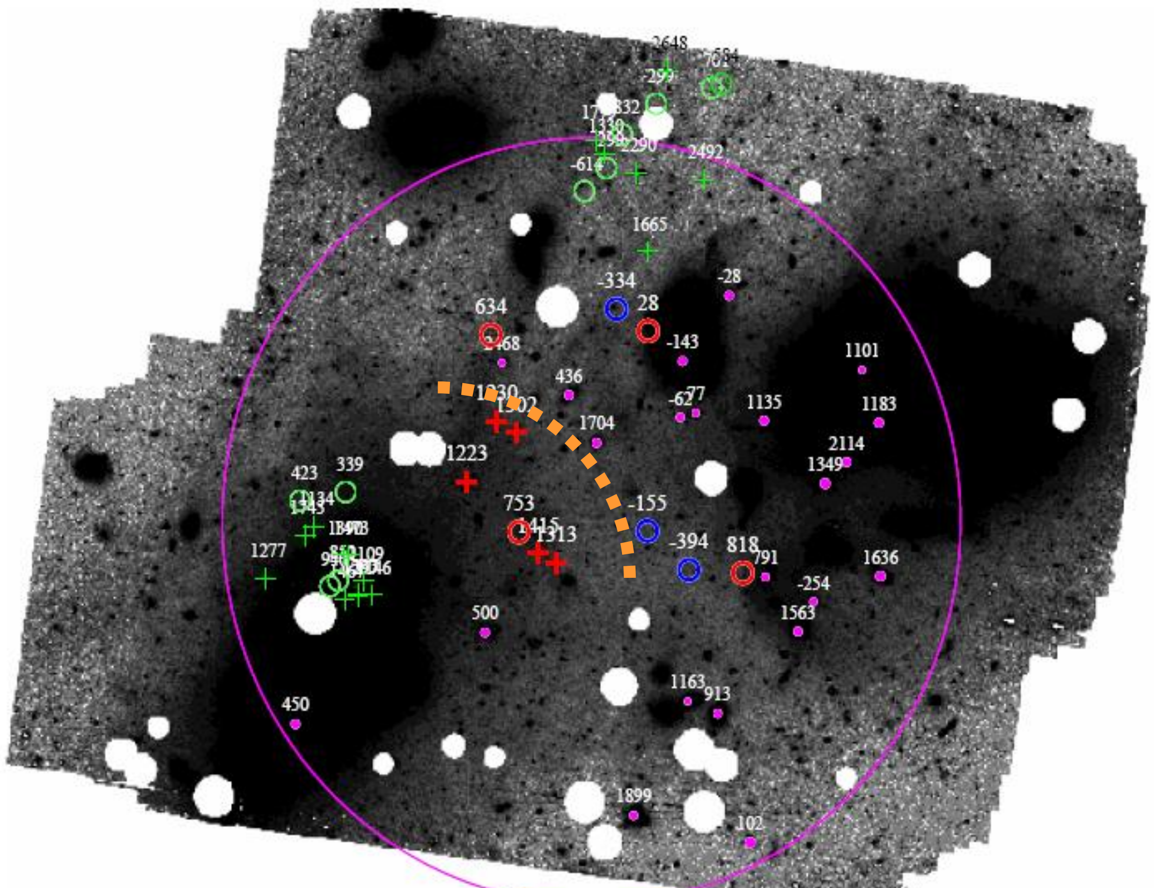
ICL

- No ICPN v_{LOS} redder than 1800 kms^{-1} at R<3600", while bluer velocities present at all radii.
- Broad velocity component at R>3600".



σ_{PN} = 247±52 kms^{-1} @ 60 kpc
σ_{PN} = 78±25 kms^{-1} @ 144 kpc

PNs' LOSVD and projected phase space



A04 ICPN detections
Dwarfs spheroidals
Red and blue symbols indicate the Doherty+09 PN detections.

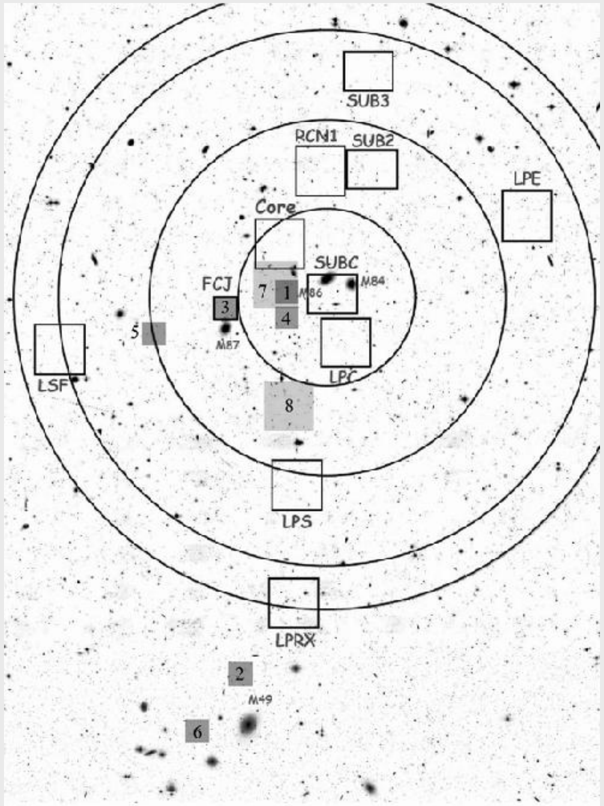
PNs with velocities higher than the mean velocity of the Virgo cluster (1100 km s^{-1}) are shown as +; those with lower velocities are shown as ○.

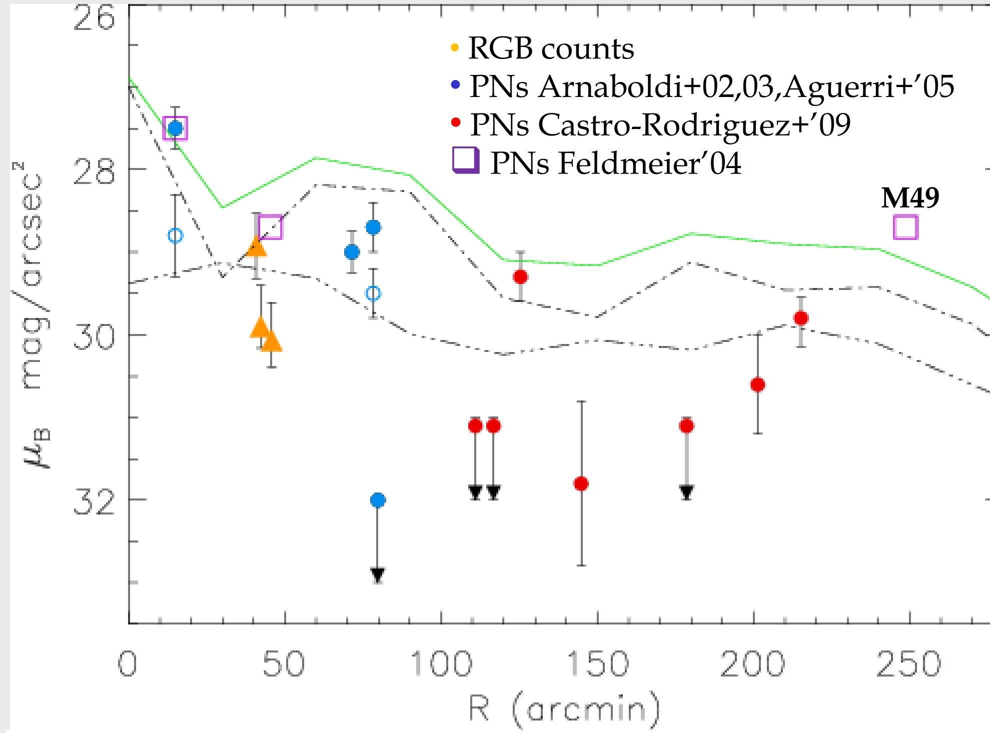
The PNs associated with the peak at the M87 v_{sys} are spatially segregated . There are no PNs at the M87 velocity at R > 150 kpc, while ICL PNs are scattered across the whole region!

Dynamical status of the Virgo core

- The LOSVD of dEs+dS0s is flat and broad with a peak at M87 (1300 kms^{-1}) with tails at $v_{LOS}<0$ (Binggeli+87); asymmetry in the ICPN LOSVD in the Virgo core center.
- Observed properties of the ICPN LOSVD are predicted in merging simulations of two sub-clusters with unequal mass along the LOS shortly before ~ 10^9 yrs the sub-clusters merge (Schindler & Böhringer 1999) .
- Recent and on-going assembly of Virgo core: M87 falling backwards from the front and M86 forwards from the back (Binggeli+93).
- The light in the M86 sub-group is tidally stripped by the more massive M87 component, while these two merge along the LOS -
- We do not see a diffuse light with a broad velocity component redwards of M87 v_{sys} because it has not yet been formed.

Large scale distribution of ICL in the Virgo cluster

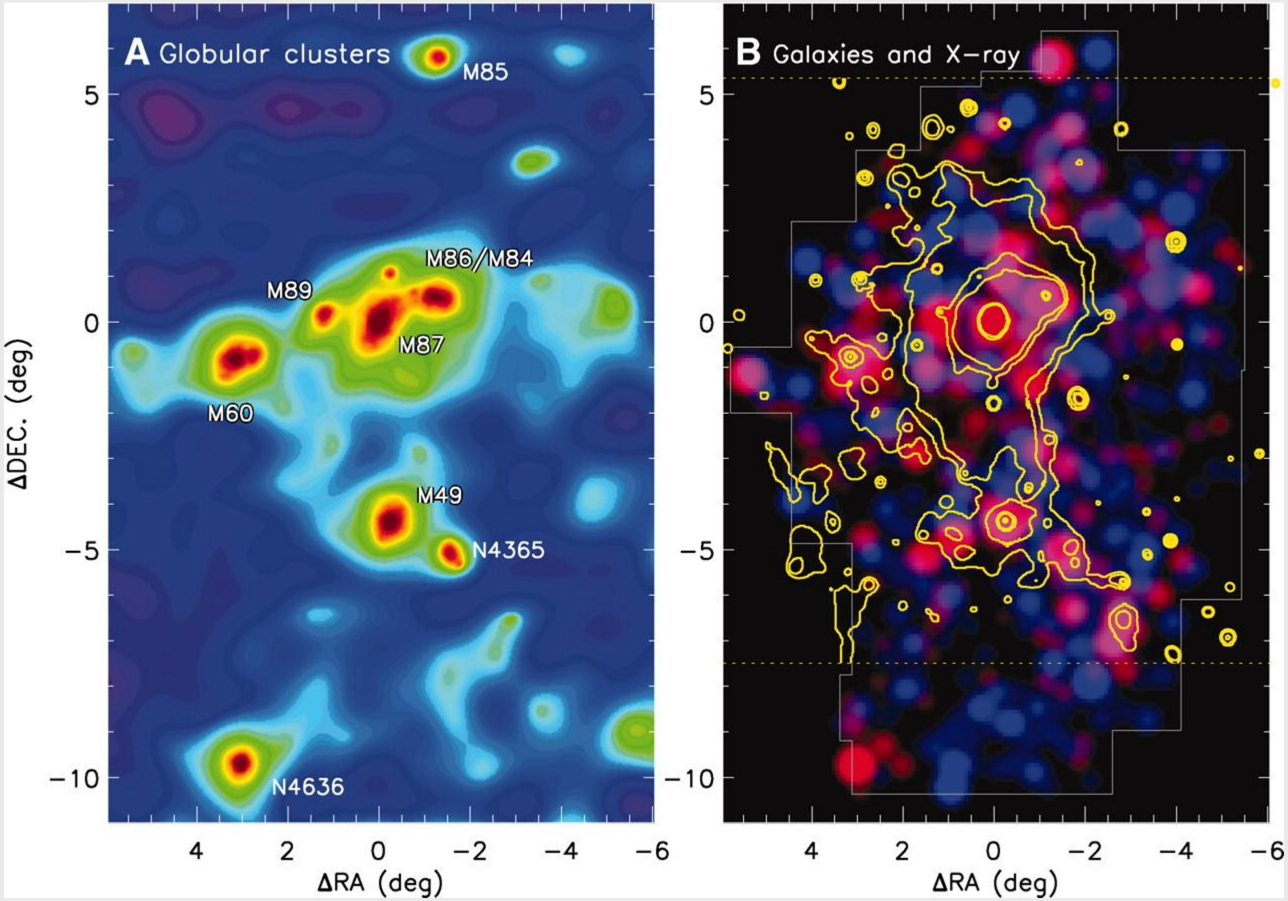




Radial Surface brightness from Virgo galaxies
Bingelli+'87 (- total, -.- giants, -…- dwarfs)

PN surveyed fields in the Virgo cluster (Castro-Rodriguez+09): PN number density is translated in B band. Surface Brightness (SB) and the large scale SB profile is plotted as function of the distance from M87 out to 4 degree = 1Mpc.

Large scale distribution of ICL in the Virgo cluster



Surface number density maps for the globular clusters in comparison with the spatial distribution of galaxies and x-ray emission in the Virgo cluster region. DDEC and DRA are distances from M87 along declination and right ascension, respectively (Lee et al. 2010, Science 328, 334).

Large scale distribution of ICL in the Virgo cluster

ICL distribution is clumpy & associated with the high density peaks in the Virgo cluster. There is not a smooth large scale light distribution out to the Virial radius of the Virgo cluster detected so far.

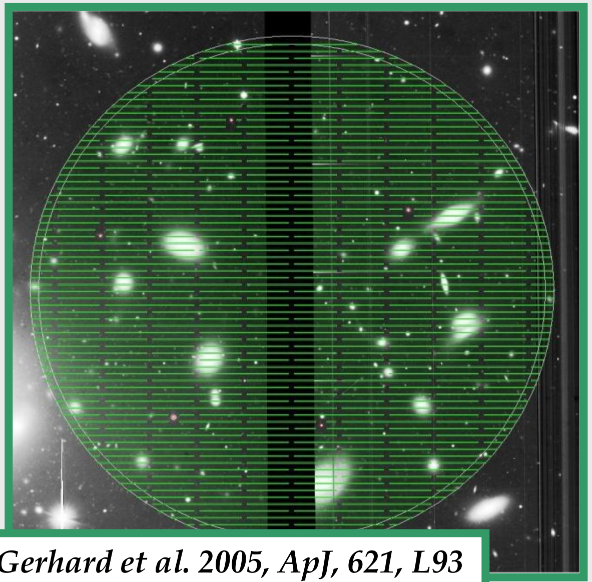
..A cautionary note for extrapolation of core ICL profile out to Virial radius for estimates of the baryonic fractions...

The next step beyond Virgo and Fornax ….

❖*The brightest PNe in the Coma cluster at ~100 Mpc distance have fluxes of* $\underline{2.2 \times 10^{-18}\ erg/s/cm^2}$ *(~2 photons/min on 8m tel.).*

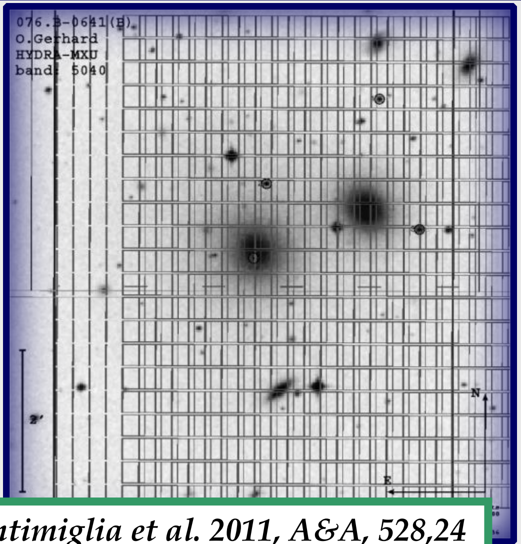
❖*They cannot be detected using a narrow band filter because the noise in the 30 – 40 Å sky is of the same order of the signal we want to detect.*

Subaru + FOCAS



Gerhard et al. 2005, ApJ, 621, L93

VLT + FORS2



Ventimiglia et al. 2011, A&A, 528,24

Multi Slit Imaging Spectroscopy Technique (MSIS)

❖*Blind search: it combines a mask of parallel multiple slits with a narrow band filter, centred on redshifted [OIII] 5007 Å line at Coma mean systemic velocity, to obtain spectra of all PNe that lie behind the slits.*

❖*The sky noise at the emission line of the PN come from few Å only, depending on slit width and spectral resolution…*

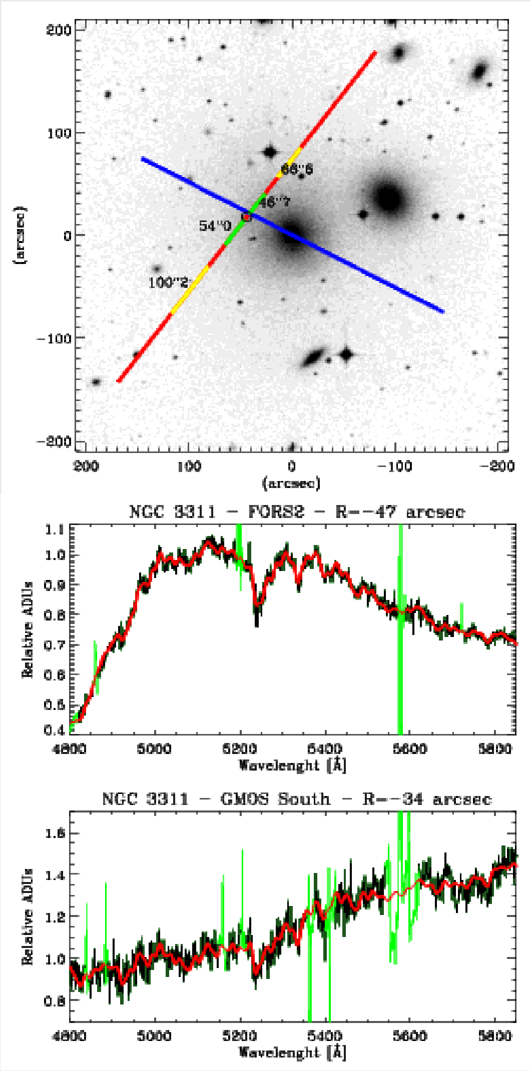
5. The Hydra I cluster & NGC 3311

Observations of the Hydra I core

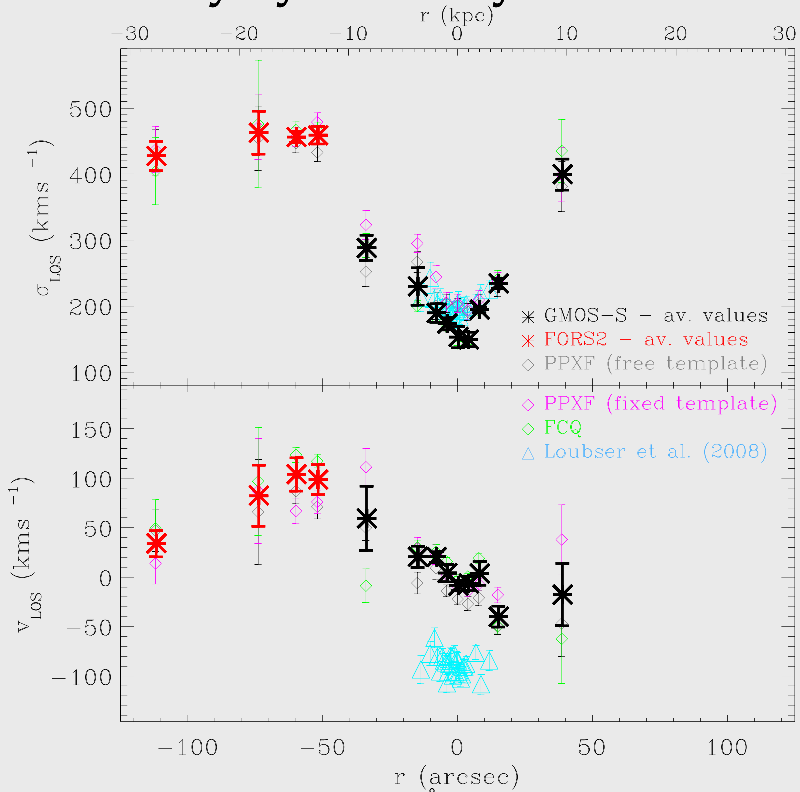
- Hydra I : example of a relaxed cluster
- LSS - Long slit data acquired with FORS2 at VLT
  - GRISM-1400V+18 (~0.75Å/pixel) (*)
- MSIS - Data acquired with FORS2 at VLT (*)
  - GRISM-600B (~ 1.5 Å $pixel^{-1}$) plus two narrow band filters centered at λ = 5045 Å and λ = 5095 Å, with a FWHM of 60 Å
  - One field centered on NGC 3311 – FoV of 6.8 x 6.8 $arcmin^2$, equivalent to 100 x 100 kpc^2 .
  - **56 PNs detected & 26 background galaxies**
- Surface photometry - V band imaging at the ESO/MPI 2.2m telescope and FORS1 archive data.

(*) see Coccato and Ventimiglia's posters

5.1 Long slit spectroscopy



- NGC 3311 - Central galaxy velocity dispersion ~150 kms^{-1}
- In 15″-45″ (4-12 kpc) transition to σ~450 kms^{-1}~60% of dispersion of cluster galaxies (*)
- **Outer halo unusually dynamically hot for ETGs**



LS-spectra from FORS2 (082.A-0255(A) ,4655 – 5965 Å) and GMOS archive (3675-6266Å)
(*) see independent measurements from Richtler+11 (arXiv1103.2053)

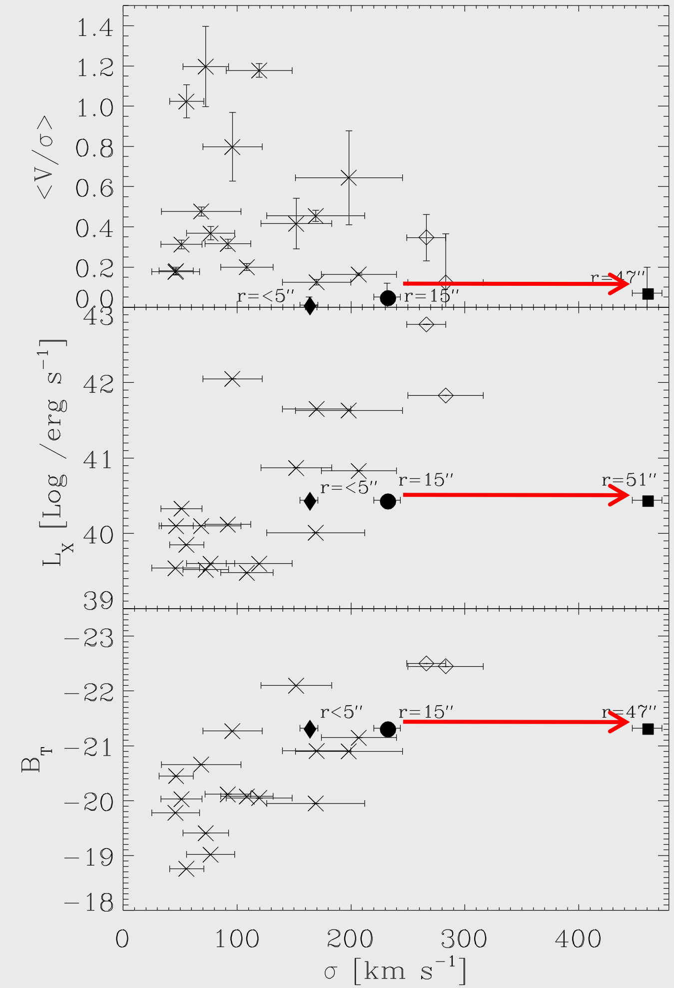
(Ventimiglia et al., 2010, A&A, 520, L9)

5.1 Long slit spectroscopy

The dynamically hot stellar halo around NGC 3311: a cluster dominated small galaxy

Properties of the early-type halos:

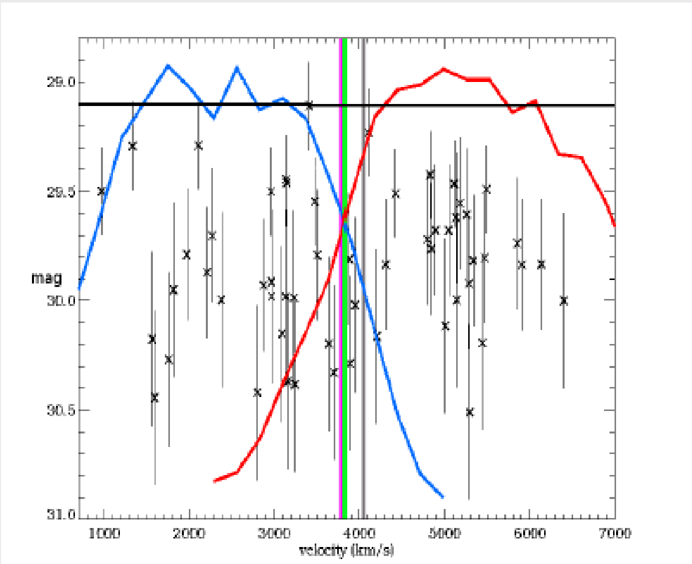
- * Halos mapped using PNs (Coccato+09)
- ◊ Coma BCG galaxies NGC 4889 & NGC 4874 (LS spectra Coccato+10)
- ♦●■ measurements of σ for NGC 3311 at the galaxy center, 15″ (3.7 kpc) and 47″ (12 kpc).

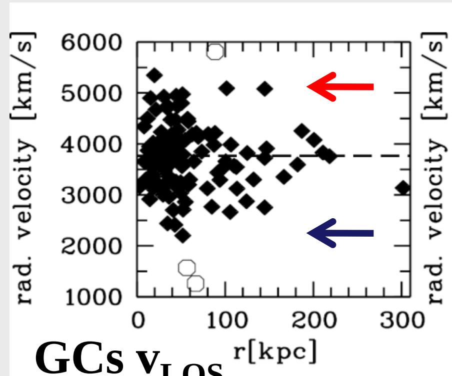


Intracluster stellar halo dominates completely for R>12 kpc

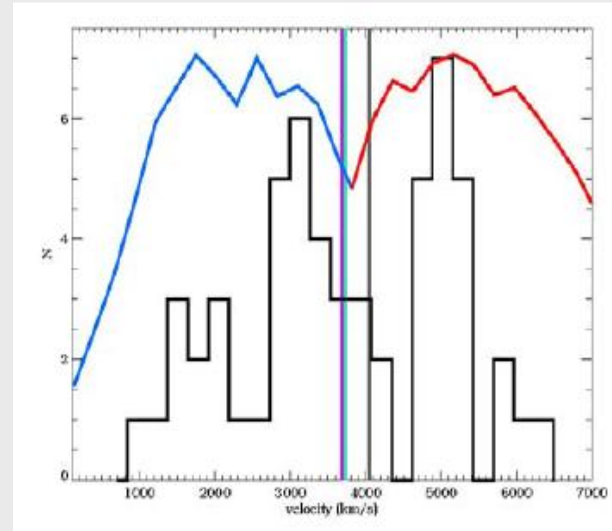
- **Halo was accreted – origin not co-eval with inner (R< 3.7 kpc) regions**

5.2 MSIS observations of the Hydra I core

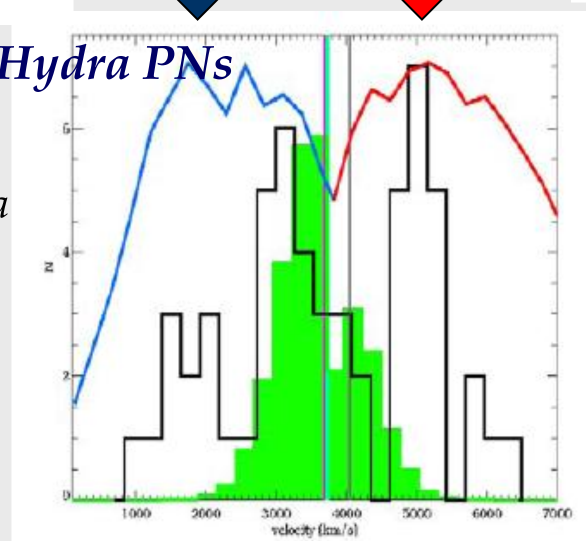




GCs v_{LOS}



m_{5007} vs v_{los} diagram for the Hydra PNs



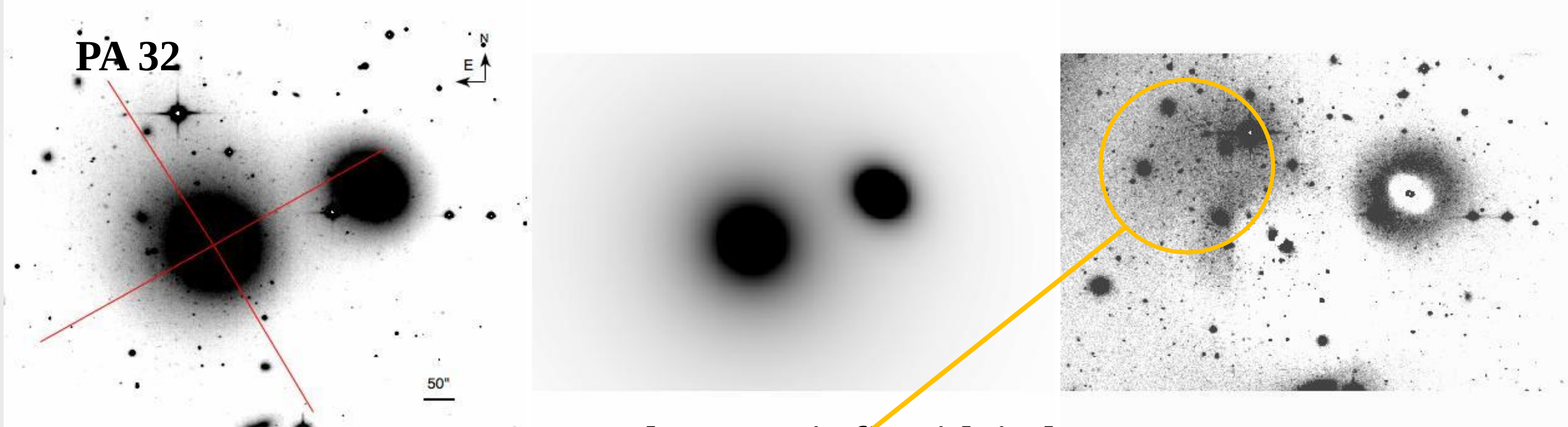
Comparison of the observed PNS LOSVD with the simulated Hydra cluster PN LOSVD (a Gaussian VD centered at 3709 kms^{-1}, with $\sigma = 500$ kms^{-1}).
PNLF @ D=50 Mpc convolved with slit losses and filter transmission.

Hydra PNs LOSVD

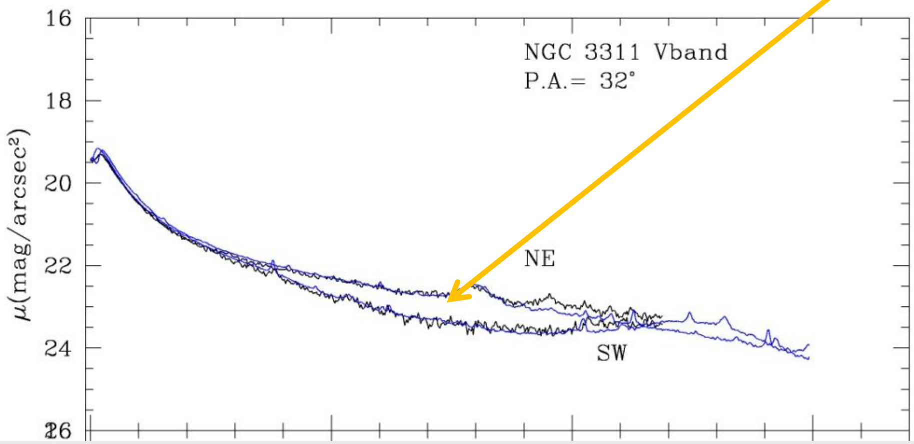
There are two additional velocity subcomponents in the observed PN LOSVD:
a blue (1800 kms^{-1}) and a red (5000 kms^{-1}) secondary peaks.
GCs LOSVD not Gaussian (Richtler+11) with similar secondary peaks!

(Ventimiglia et al., 2011, A&A, 528, 24)

Red PNs distribution peaks in the NE quadrant of the NGC 3311 halo….



2D GALFIT best Sersic fit with index n=6.3



Excess of light in the NE quadrant

Total luminosity

L_{excess} = 3.2 ·10^9 $L_\odot$(±5.2 ·10^8)$L_\odot$

***2D surface brightness profile for NGC 3311 : R_e = 11 kpc** (from light-growth curve)*

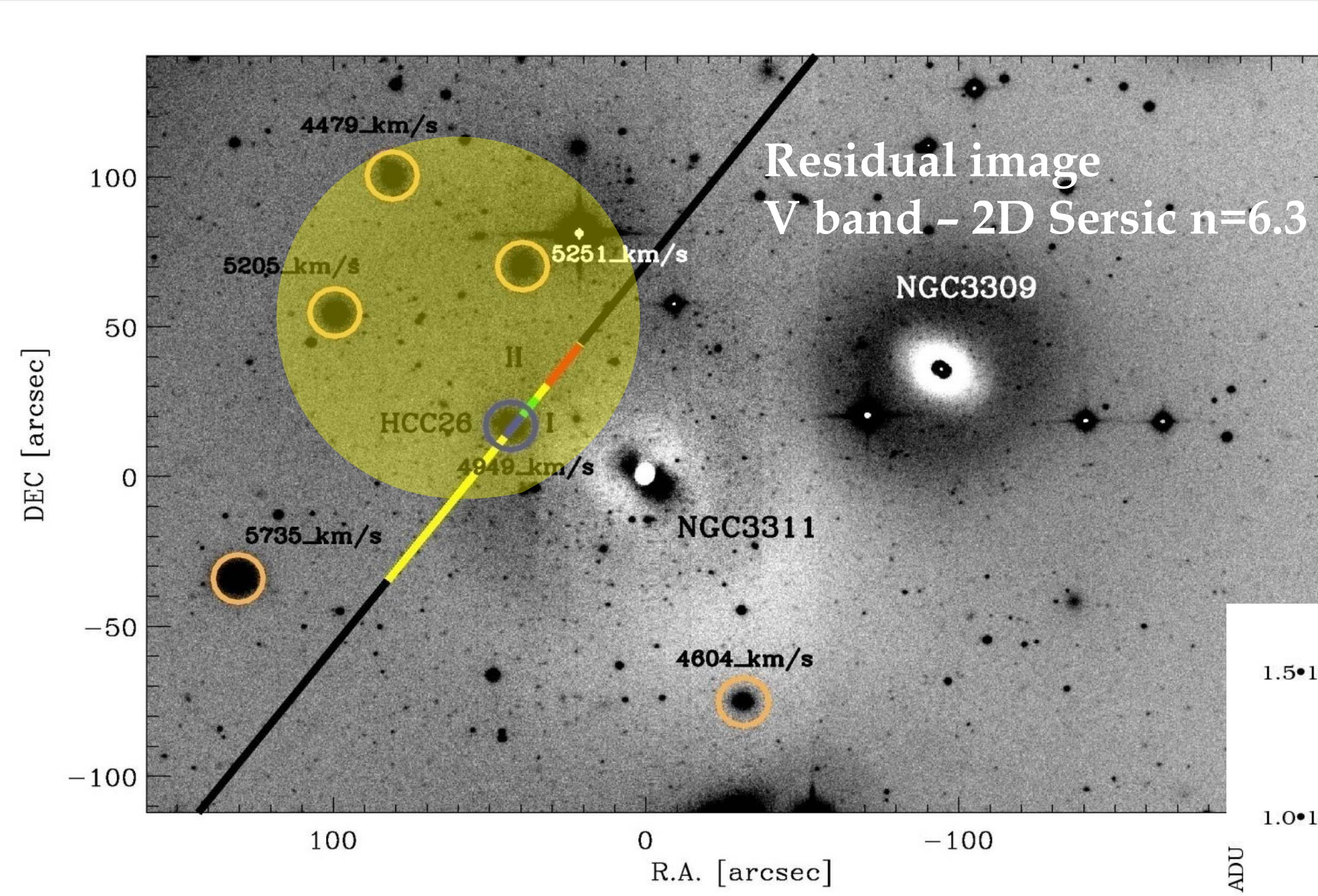
Total luminosity in the dwarfs

L_{DWs}= 1.1 ·10^9 $L_\odot$

-ESO/MPI 2.2 m telescope WFI data – FORS1 V band imaging (ESO archive)

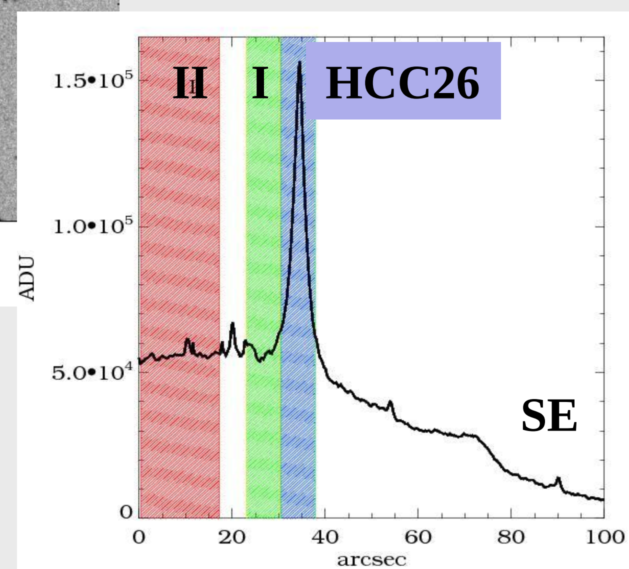
- (Arnaboldi+2011 A&A submitted.)

5.4 Light Excess in the Halo of NGC 3311



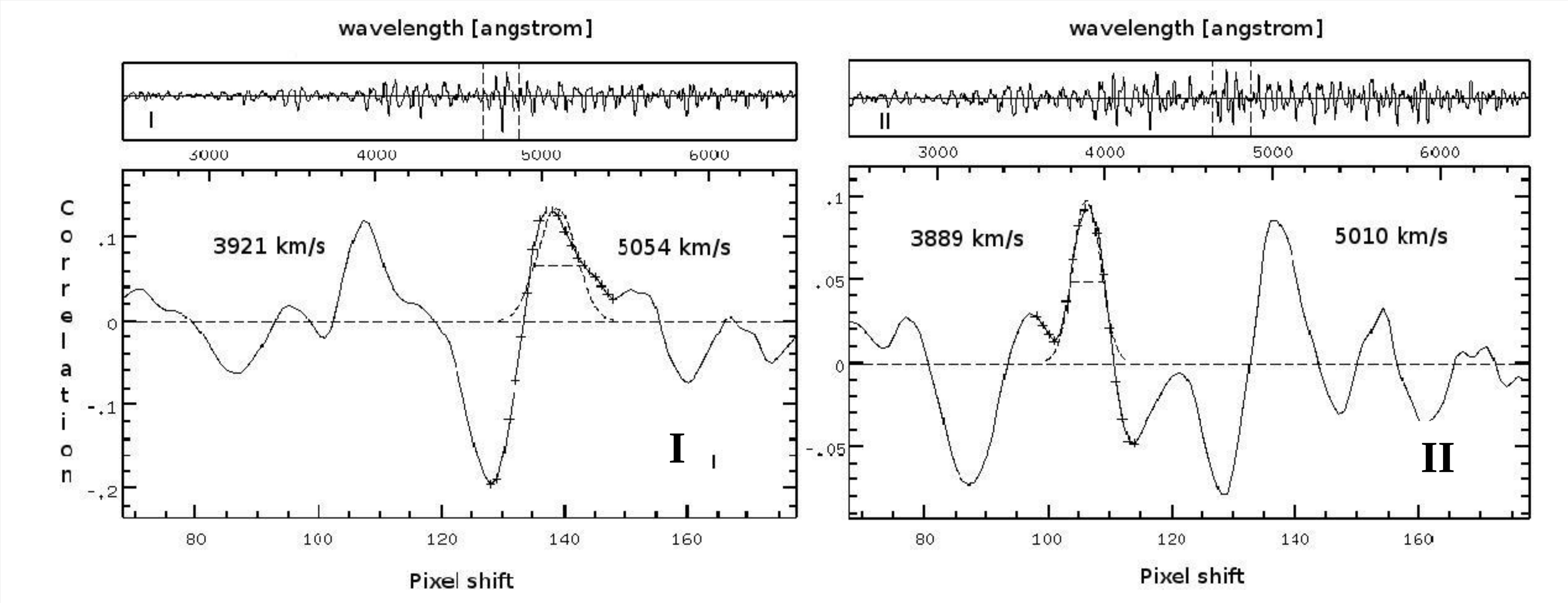
- DWs' V_{los} = 4479 - 5735 kms^{-1}
- Concentrated in the NE quadr. & at the same location of the red peak PNs.
- No other DWs within (100 kpc)^2 of NGC 3311
- Light excess is 12% of light in slit region.

Spectra of light excess obtained from slit regions I,II as $S_{ex} = S_{1D} - 0.9 * S_{NGC\,3311}$, where $S_{NGC\,3311}$ is halo template



5.4 Light Excess in the halo of NGC 3311 – cont.

In spectra I and II , v_{LOS} of the light excess is at 5032 kms^{-1} (±38 kms^{-1})!



- ***The velocity of HCC26 (v_{sys} = 4225 kms^{-1}) and those of dwarf galaxies in the same regions as the PNs are consistent with the red subcomponent at ~ 5000 kms^{-1} in the PNs LOSVD. Light excess at the same location and LOS velocity.***
- ***Blue peak traces the NGC 3311 halo.***

5.5 The Hydra I cluster – Results

- The stellar halo of NGC 3311 becomes hotter at large radii - accreted origin.
- Presence of discrete velocity subcomponents in PNs LOSVD - substructures not phase mixed yet (*).
- The PNs in the red peak are associated in velocity and space with a group of dwarf galaxies at v_{mean} = 5000 kms^{-1}
- Presence of a light excess at the same location & v_{LOS} of dwarfs galaxies and red peak PNs in the halo of NGC 3311.
- L_{excess}= 2.3 $\cdot 10^9$ $L_\odot$, a factor 2 times luminosity in dwarfs
- Results consistent with the light excess tracing debris by disrupted dwarfs galaxies as they fall and interact with the Hydra I core gravitational potential (**).

(*) Poster from G. Ventimiglia.

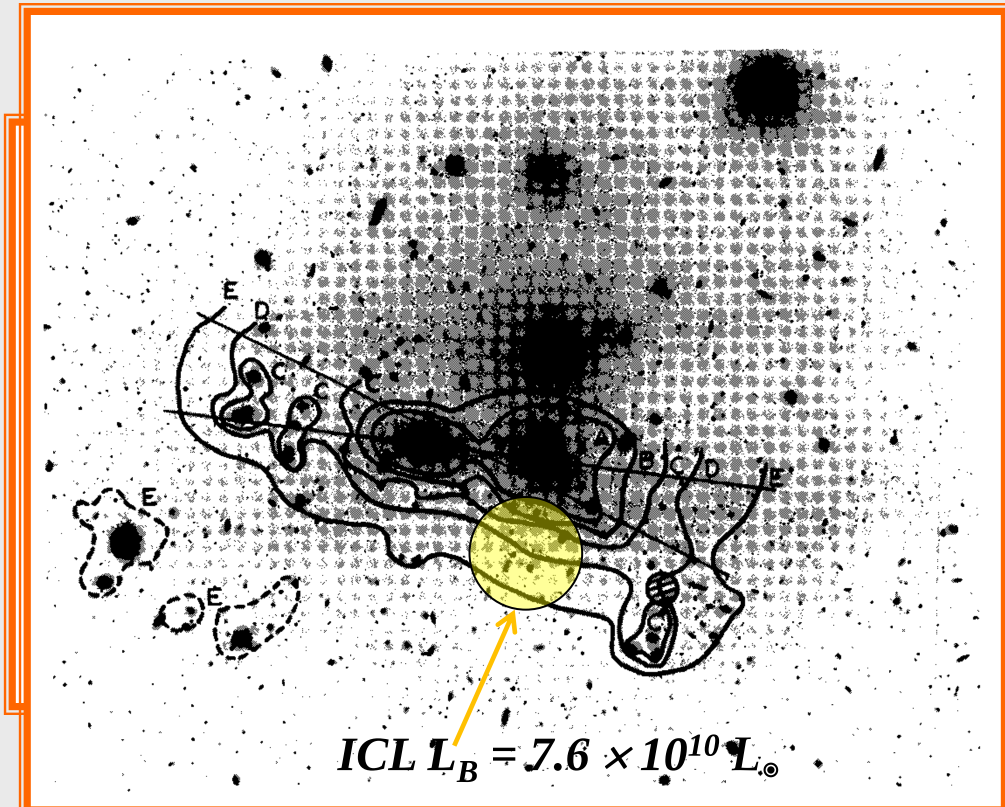
(**) see L. Coccato's poster on stellar populations in BCGs

6. Diffuse light in the Coma cluster

Coma is one of the best studied nearby clusters; of these, it is the richest and the most compact one. It provides a laboratory for studying the effects of a dense environment on galaxy evolution.

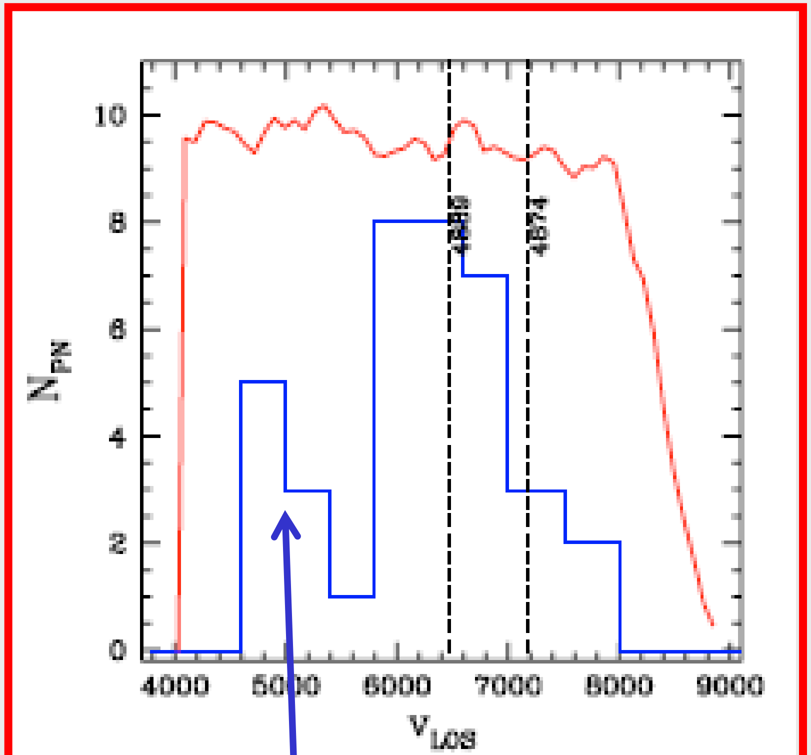
Presence of diffuse light is established from SB measurements:

- ***extended halo around NGC 4874 and NGC 4889 (Thuan & Kormendy 1977; Bernstein+95). $\mu_v \sim r^{-1.3}$ for r > 40″ from center of NGC 4874***
- ***This extended halo is not uniform: there is presence of plumes and tidal tails (Gregg & West 1998, Adami+05a)***
- ***Outside this halo, giant arcs and debris are also detected (Trentham & Mobasher 1998, Gregg & West 1998)***
- ***(*) Recent surf. phot data – contrib. by Adami, Durret, Okamura - & GCs – E. Peng***

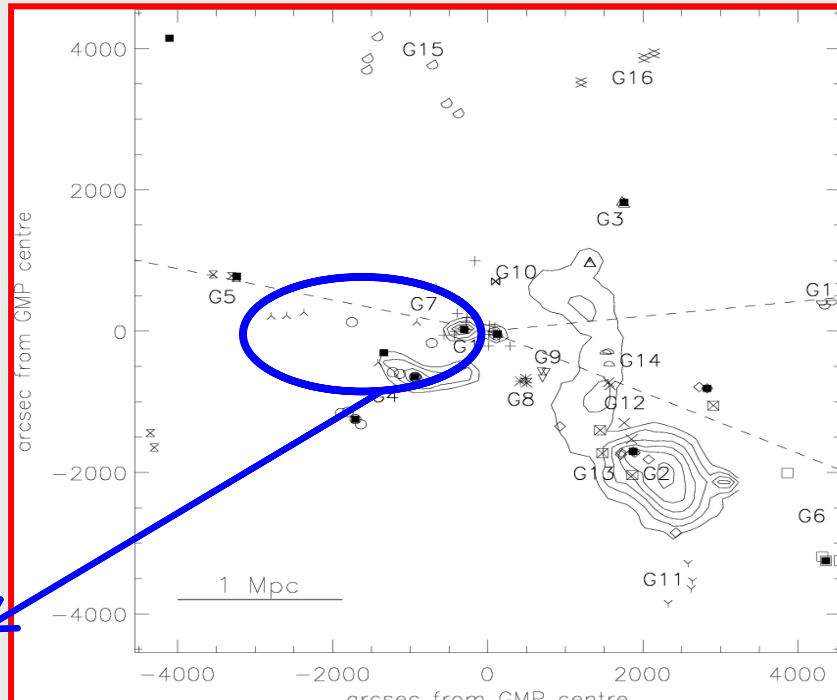


Diameter ~200 kpc **Thuan & Kormendy 1977**

PNs LOSVD in the Coma field

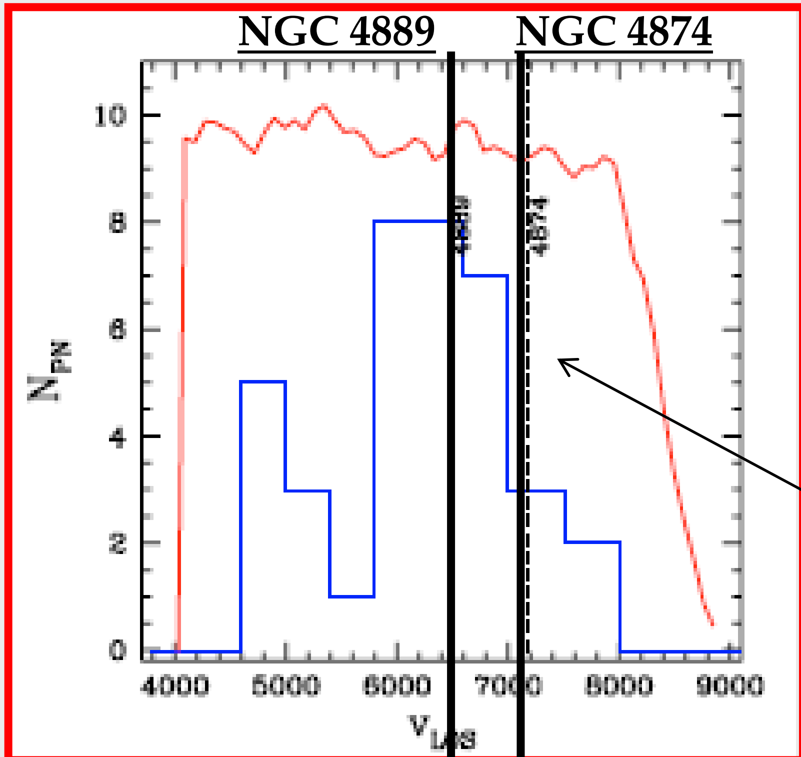


- *37 PNs detected*
- *Their LOSVD is not a single Gaussian*
- *Multi peaked – secondary bluer peak associated with nearby substructure G7*
- *Main peak of the PN LOSVD is at 6450 kms^{-1}*



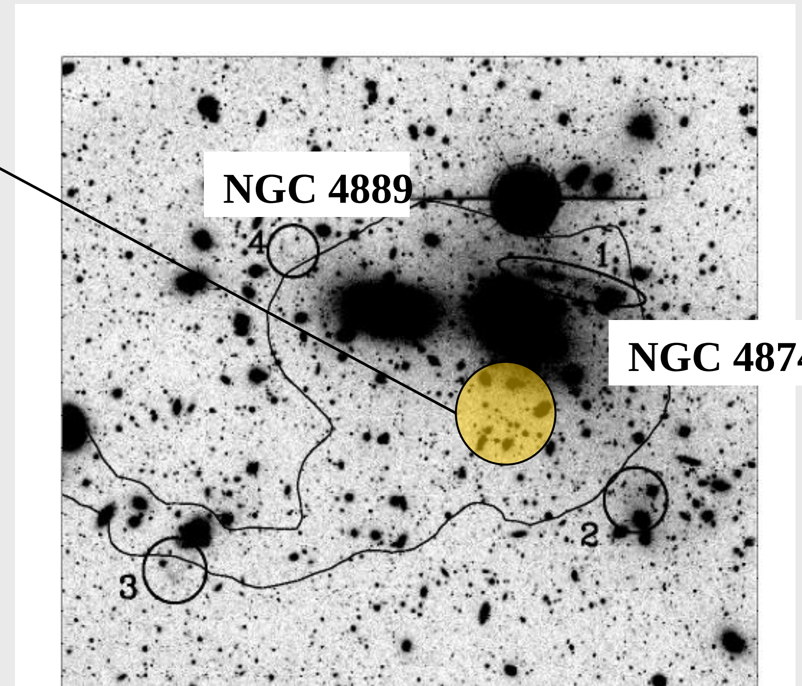
G7 sub-group V_{LOS} < 5500 km/s
Adami+05b, A&A 443, 17

PNs LOSVD in the Coma field



NGC 4874 σ_0 = 300 kms^{-1}
NGC 4889 σ_0 = 400 kms^{-1}

- *37 PNs detected*
- *Their LOSVD is not a single Gaussian*
- *Multi peaked – secondary bluer peak associated with nearby substructure G7*
- *Main peak of the PN LOSVD is at 6450 kms^{-1}*
- *Coma core is not virialized*



We measure the v_{LOS} of stars in the diffuse stellar halo in a region near to NGC 4874, but stars' v_{LOS} histogram is peaked at -700 kms^{-1} from its systemic velocity - Halo velocities flipped!

Results - the sub-cluster merger in the Coma Cluster

Summary

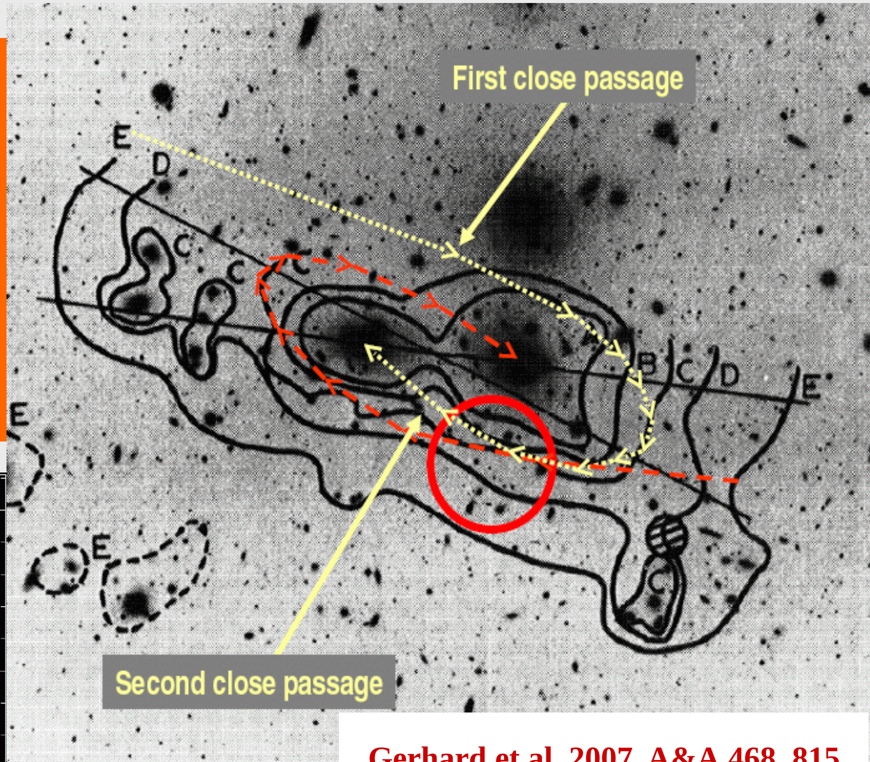
- *The sub-clumps in the galaxy distribution centred on the two supergiant galaxies (Fitchett & Webster 1987, Biviano et al. 1996) have the average velocity of the other BCG (Colless & Dunn 1996)* ***=> Halo velocities flipped****.*
- *Elongation of ICL and the MSIS PN kinematic measurements make a strong case that this ICL is in highly dynamically evolving state.*
  - *Early binary model (Valtonen & Byrd 1979).*
  - *Head on collision of cDs (Korchagin,Tsuchiya &Miyama 2001),*

Implications

- *In these nearly head on collisions, the outer envelopes of both structures merge in a slow oscillatory fashion along an essentially unchanging orbital direction.*
- ***By contrast, the interaction of the cores is faster stronger and may involve a significant impact parameter****.*

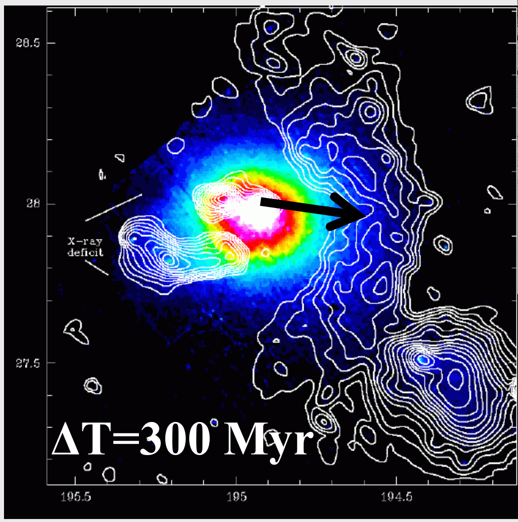
Results - the sub-cluster merger in the Coma Cluster

ICPN and galaxy velocities in surveyed field are concentrated around NGC 4889 velocity

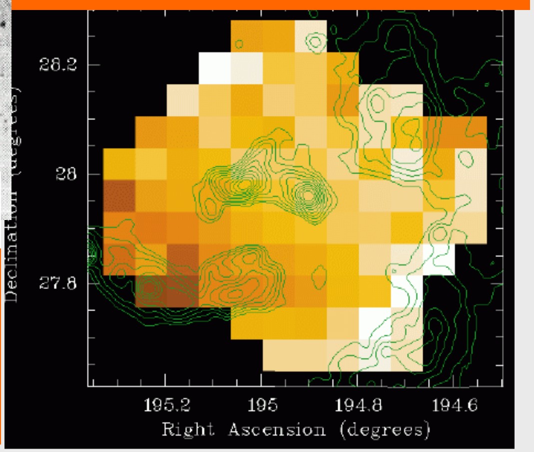


Gerhard et al. 2007, A&A,468, 815

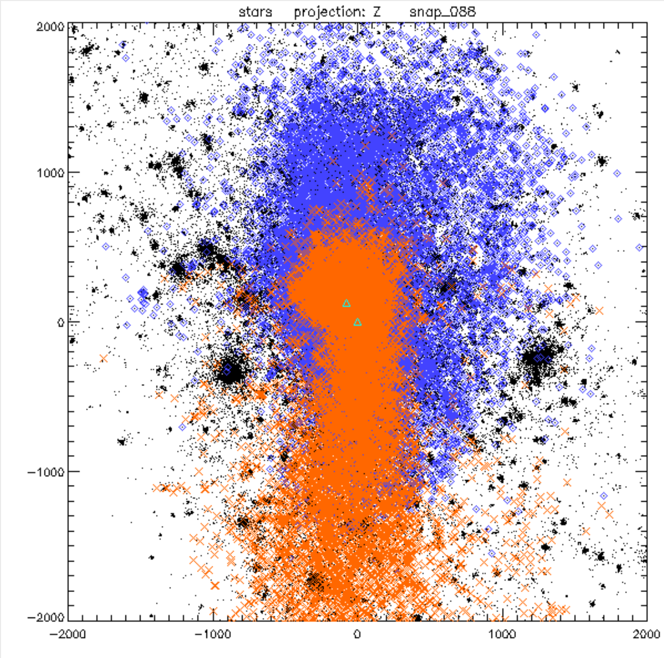
With the near head-on geometry of the collision, it is likely that a pre-existing cooling core in the cluster would have been heated by the collision. <u>This is consistent with the absence of a cooling core in the Coma custer now</u>



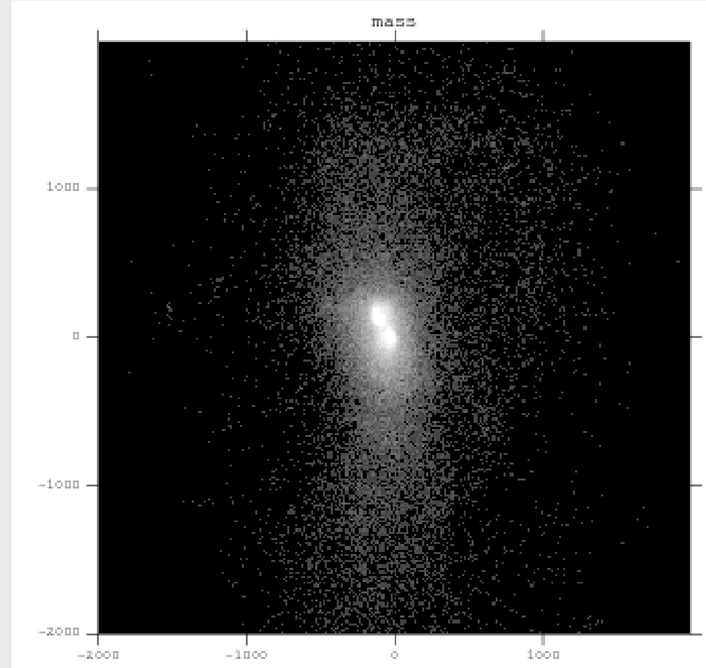
Residual X-ray emission and temperature map indicate arc shock following collision

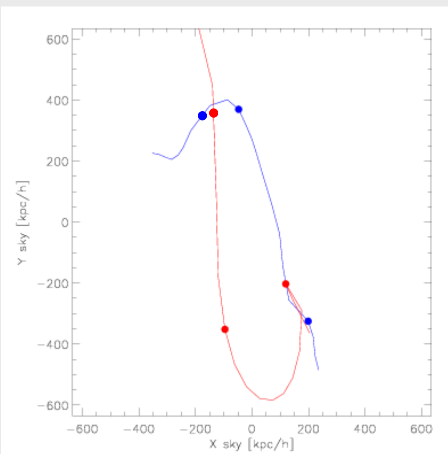


A similar merger is currently ongoing more nearly along the LOS in cluster CL0958+4702 (z=0.39, Rines, Finn & Vikhlinin 2007). Elongated plume of old stars from BCG seen in Spitzer IRAC images.



Simulated BCG Merger





Blue galaxy is at (0,0) with “green” velocities

Halo velocities flipped

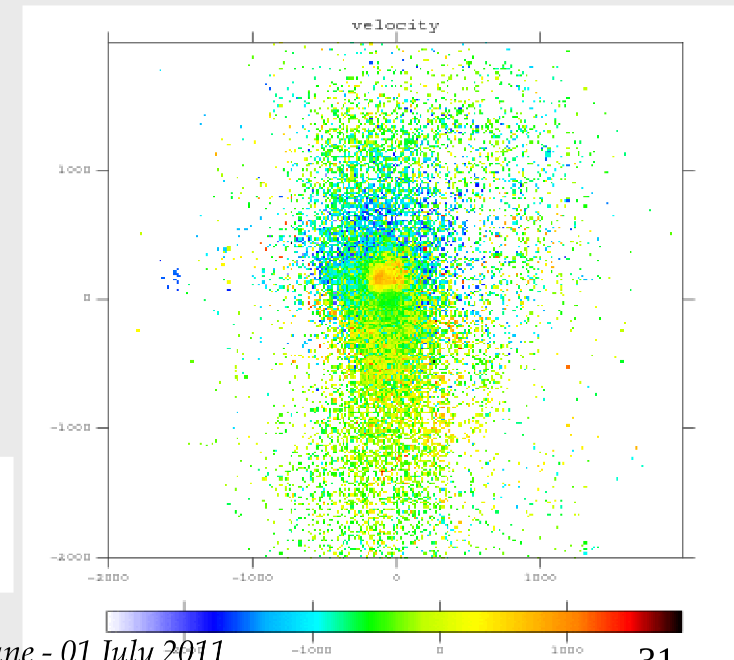
z ~ 0.034

$|V1 - V2|$ ~ 1600 km / sec

$|V1 - V2|_{SKY}$ ~ 1200 km/sec

D ~ 215 kpc

D_{SKY} ~ 145 kpc



Cluster simulation from K.Dolag, analysis from L. Coccato (2011, in prep.)

7. Conclusions

- **Diffuse light in cluster cores ubiquitous – deep photometry and kinematics from PNs show it is made up of genuine ICL and extended, luminous halos of BCGs. On average, ICL contains ~10% of cluster stellar light, BCG halos further ~10%; substantial variations depending on cluster evolutionary state.**
- **Kinematics from PNs show that ICL is un-relaxed with discrete velocity components (Virgo, Coma, Hydra) over cluster σ scale. BCG halos are colder; constant (NGC 4889), decreasing (M87, NGC 1399), or increasing (Hydra, collapsed ICL) σ's. Together with morphology: dynamically distinct components.**
- **Formation of ICL and outer halos, how and when? Evidence for BCG mergers (Coma+) and tidal disruption/accretion (Hydra) in cluster cores – build-up of BCG halos and nearby ICL continues. Formation of ICL and outer halos on-going and long-lasting process.**

- **Stellar population characteristics of the halos and the ICL? – more work needed lots to learn: see contributions by L. Coccato, O. Gerhard, I. Loubser**