The Virgo cD galaxy M87 and its environment as revealed by Planetary Nebulae

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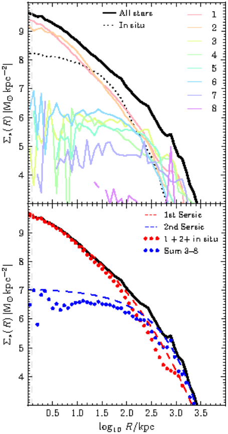
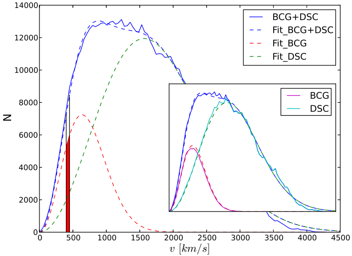
Outer regions of galaxies and structure formation

- Formation of intracluster light (ICL) and extended halos around BCGs closely related to the morphological transformation of galaxies in clusters (Murante+07,Puchwein+10)
- Simulations show that mergers and accretion are driving mechanisms for galaxy characteristics at the current epoch (Naab+09,Van Dokkum+10,Oser+10).
  At the centre of cluster the majority of stars are acrreted (Cooper+14)
- Outer regions of galaxies preserve fossil records of the accretion events that characterise the hierarchical assembly of galaxies (William+04,Rudick+09)
- Therefore, from the study of the physical properties and kinematics of galaxy halos we get information on the evolution of galaxies and hosting clusters

BCG and ICL single entity or discrete components?

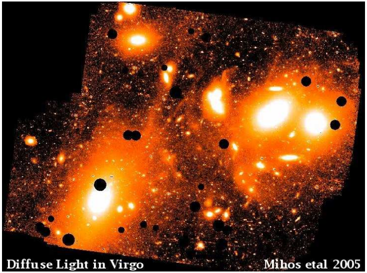


Single entity consisting of all stars not bound to any subhalos (Zibetti+05,D'Souza+14,Cooper+14)



Two **distinct dynamical components** with different parent stellar systems in terms of spatial distribution, age and metallicity (Cui+14, Dolag+2010)

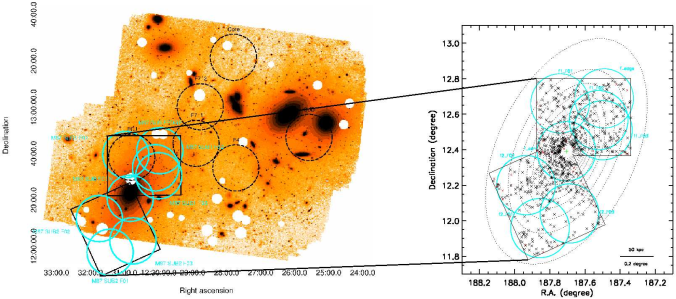
M87 in Virgo Cluster



Ultra-deep wide field (1.5° $\times$ 1.5°) image of the Virgo cluster core (Mihos et al. 2005)

- At the centre of the subcluster A in the Virgo cluster (Binggelli et al. 1987)
- Extended stellar halo down to $\mu_V \sim 27.0$ mag arcsec^{-2} (Kormendy+09)
- Observed gradients in colour and inferred age and metallicity gradients support the hierachical scenario (Rudick+10,Montes+14)
- Complex network of extended tidal features in the outer regions (Mihos+05)

Surveyed Area $\sim 0.5\text{deg}^2$



Suprime-Cam@Subaru Two fields covering the halo of M87 out to 150 kpc (FOV 34'×27') Fields observed through the NB503 narrow-band ([OIII] 5029 Å 74 Å) and broad-band V filter (Longobardi+13)

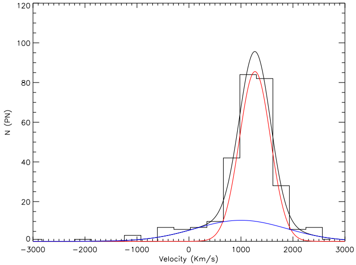
FLAMES@VLT
high-resolution grism HR08
$\lambda_c = 5048\text{Å}$
spectral resolution of 22 500
FWHM=0.29 Å (17 km/s)
λ_{err}= 0.0025 Å (150 m/s)
(Longobardi+15a)

Halo and ICL in Virgo: Kinematical separation

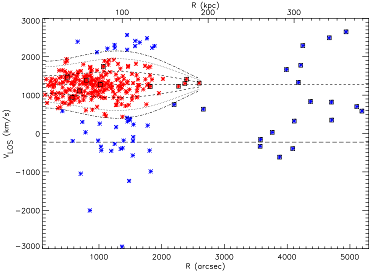
Sample of ∼ 300 spectroscopically confirmed PNe out to 200 kpc

Red: halo PNe (bound)

Blue: intracluster PNe (unbound) Black squares: PN data from Doherty+09



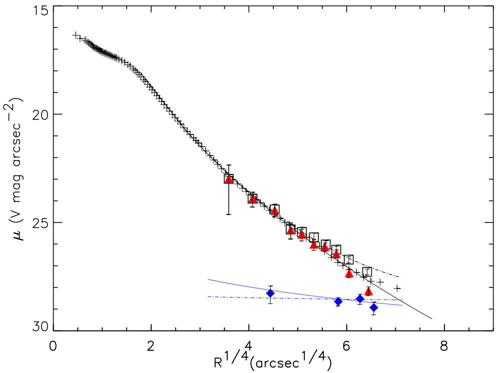
PN LOSVD for halo (red) and IC (blue) components (Longobardi+15a)



V_{LOS} vs major axis distance (Longobardi+15a)

- M87 halo and Virgo ICL are dynamically distinct components

PN Surface Density profile



$$\mu_{\rm PNe}(R) = -2.5\log_{10}\left(\Sigma_{\rm PNe}(R)\right) + \mu_0$$

The halo component is more centrally concentrated and less extended than the ICL

Two component photometric model

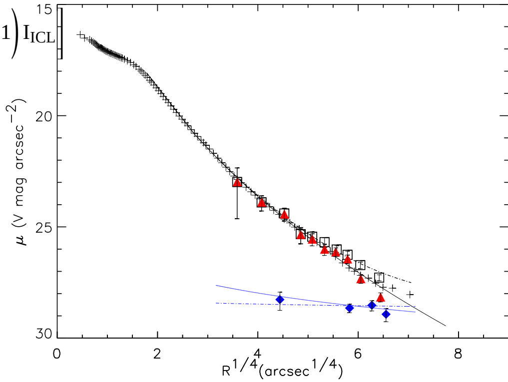
$$\tilde{\Sigma}(R) = \alpha_{2,5,\mathrm{halo}} \left[I(R)_{K09} + \left(\frac{\alpha_{2,5,\mathrm{ICL}}}{\alpha_{2,5,\mathrm{halo}}} - 1 \right) I_{\mathrm{ICL}} \right]$$

$$\alpha_{2.5,\mathrm{halo}} = (1.07 \pm 0.12) \times 10^{-8} \mathrm{PNL}_{\odot}^{-1}$$

$$\alpha_{2.5,\mathrm{ICL}} / \alpha_{2.5,\mathrm{halo}} \sim 2.5$$

$$\alpha_{2.5,\mathrm{ICL}} = (2.72 \pm 0.63) \times 10^{-8} \mathrm{PNL}_{\odot}^{-1}$$

$$\mathbf{I}_{\mathrm{ICL}} \propto \mathbf{R}^{\gamma}$$

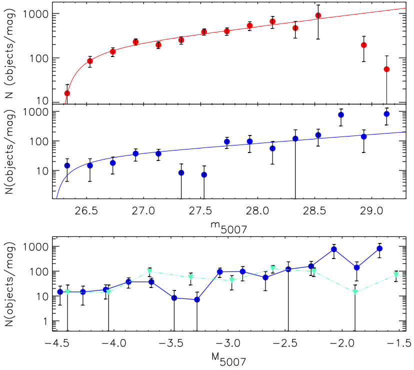


M87 azimuthally averaged colour profile becomes bluer at larger radii (Rudick+10) in the same regions where we observe the α parameter increment

If the stars in the M87 halo have a higher metallicity than the ICL, we might expect a variation of the luminosity specific PN number in the region of radii where the M87 stellar halo and the ICL are superposed along the LOS

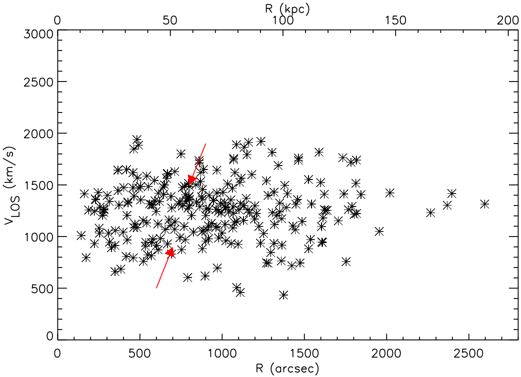
M87 Planetary Nebula Luminosity Function

Red: halo PNLF
Blue : ICL PNLF
cyan triangles : M33 PNLF



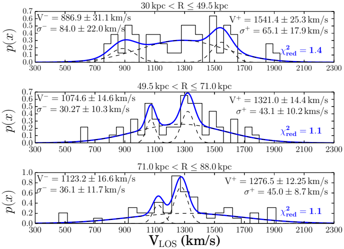
- Halo PNLF has steeper slope at fainter magnitude than ICPNLF
- Dip in the ICPNLF as observed for PN populations in star forming galaxies

M87 Halo Phase-space

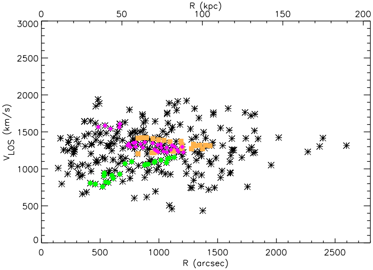


- The Halo phase-space shows a non uniform distribution of points
- Chevron-like substructure

PN tagging: Gaussian Mixture Models



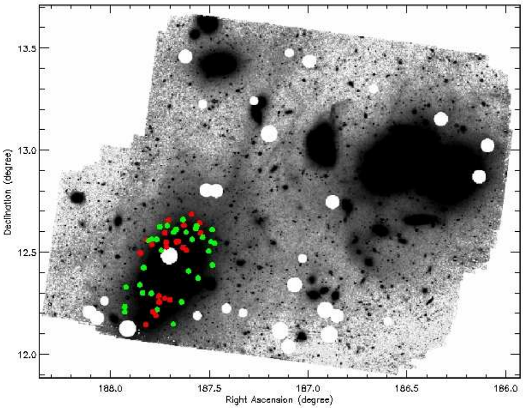
GMM assigns the contribution of each particle to the total (mixture) probability distribution



Chevron PNe (magenta, and green points; Longobardi+15c). Orange sqaures: GC substructure (Romanowsky+12)

- Chevron substructure extends over 700" along the major axis
- Asymmetry in number of PNe in the substructure

Chevron Spatial distribution

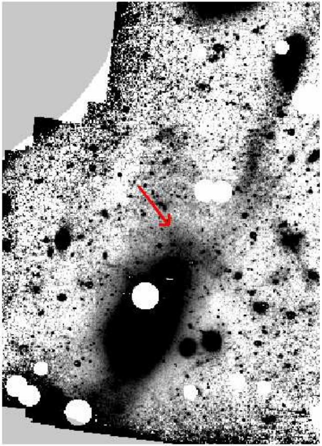


Longobardi+15c. Image from Mihos+05

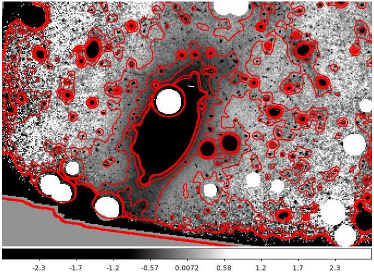
Suggestion the PNe trace tidal debris

Chevron Spatial distribution and M87 surface brightness: The Crown of M87

PN overdensity associated to a substructure in Surface brightness



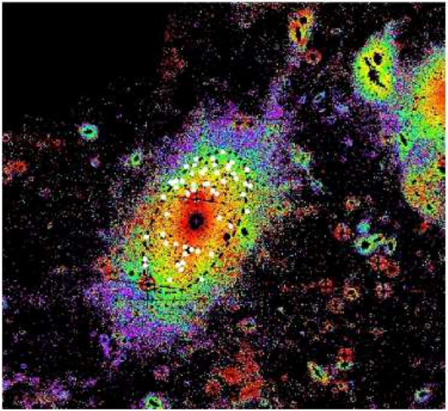
Masked Image that amplifies the high-frequency components.



Contours map on the unsharped masked image.
Contours go from -0.1 to -0.8 in steps of 0.2

Longobardi+15c

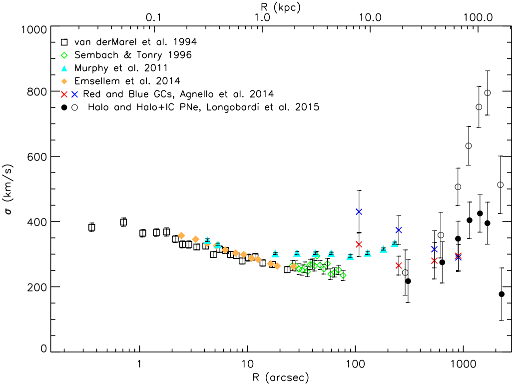
Chevron Spatial distribution and M87 colour



M87 (B-V) colour map (Mihos+15) with Chevron PN overplotted

- Correspondence to blue colours: (B-V)=0.76±0.05
- $\alpha = 1.8 \pm 0.7 \times 10^{-8}$ $N_{PN} L^{-1}_{\odot,bol}$, $L_V = 2.8 \pm 1 \times 10^9 L_{\odot,V}$, M= $6.4 \pm 2.3 \times 10^9 M_{\odot}$ (Longobardi+15c)

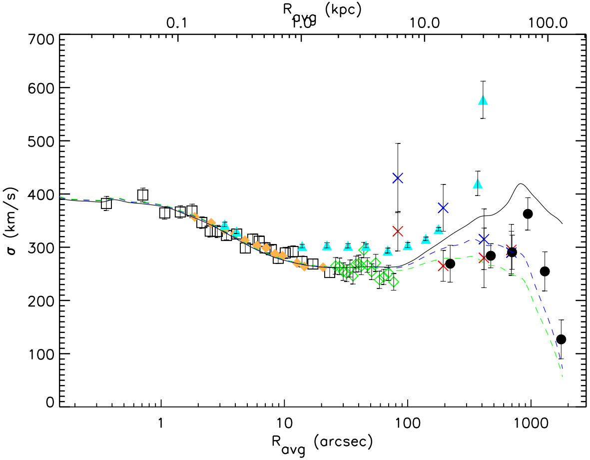
M87 velocity dispersion profile: PN data plus absorption line data and GC data



Longobardi+15b

- M87 σ profile consistent with halo PNe
- ICL may impact IFU kinematics
- Kinematics of red GCs closer to halo stars. Blue GCs discrepant

M87 velocity dispersion profile: comparison with Jeans models



- M87 velocity dispersion profile shows the dynamical complexity of a still assembling system

Summary

- We carried out a photometric and spectroscopic PN survey around the dominant Virgo elliptical galaxy M87 out to 150 kpc
- The BCG halo of M87 and the Virgo ICL are dynamically distinct components with different density profiles and velocity distributions and parent stellar populations.
- The observed properties of the halo and IC PN population, such as the α-parameter and the shape of the PNLF show that the M87 stellar halo is redder and more metal rich than the diffuse ICL.
- The halo PN phase-space shows signatures of a chevron-like substructure that can be seen in both surface brightness and colour maps.
- The substructure traces the azimuthal varience of the M87 colour
- The number of PNe associated to the substructure implies an accretion event of a LMC-like system.
- The M87 Kinematics as revealed by PNe supports the hierarchical scenario, consistent with a late build-up of its halo.
- M87 is still growing by accreting satellite galaxies.