Planetary nebulae as tracers of motions and light in the outer halos of galaxies

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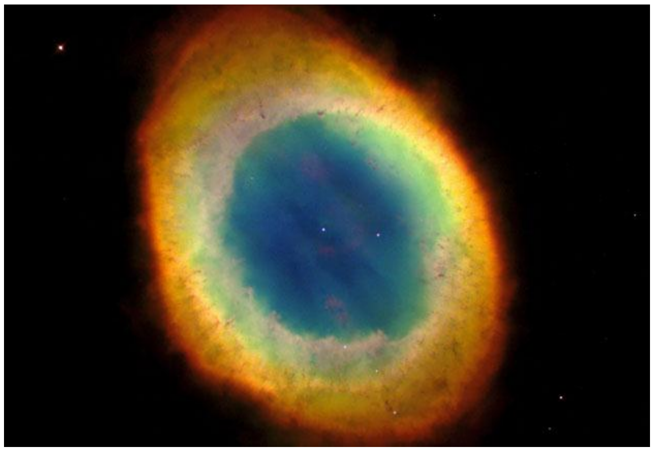
ESO, Garching

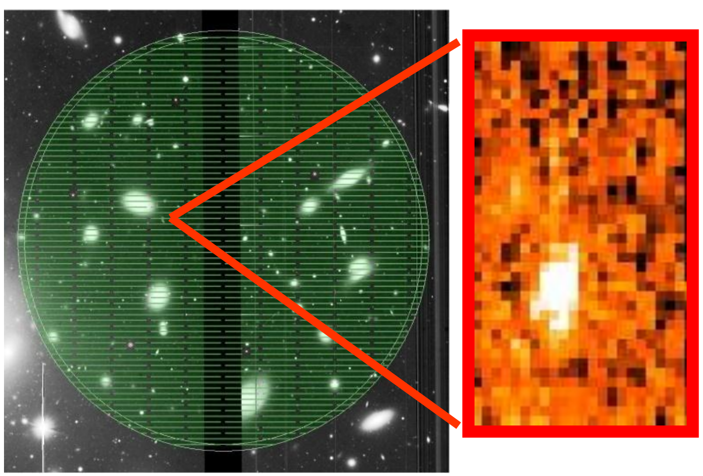
Baryons at low densities: the stellar halos around galaxies

ESO Garching, February 26th, 2015

Planetary Nebulae

Ring nebula M57





- About 2000 PNs are known in the MW out of 200 billion stars, mostly in the MW plane.
- A typical Galactic PN has an average diameter of 0.3 pc.
- In MW 95% of the stars end their lives as PNs, the remaining 5% as SN.
- Up to 15% of the UV energy from the core star is re-emitted in the [OIII] 5007 Å line.
- When PNs are detected in external galaxies (D> 1 Mpc), they are unresolved emission of monochromatic green light at 5007 Å ([OIII]).

Outline

1. **Motivation: PNs as distance indicators, tracers of stellar populations & kinematics**
2. PN Visibility Lifetime and Luminosity Functions in the MW & Local Group galaxies
3. The PN populations in the Virgo cluster core
4. Conclusions

Motivation I. PNLF in [OIII]@5007Å

[OIII] fluxes of a PN population:

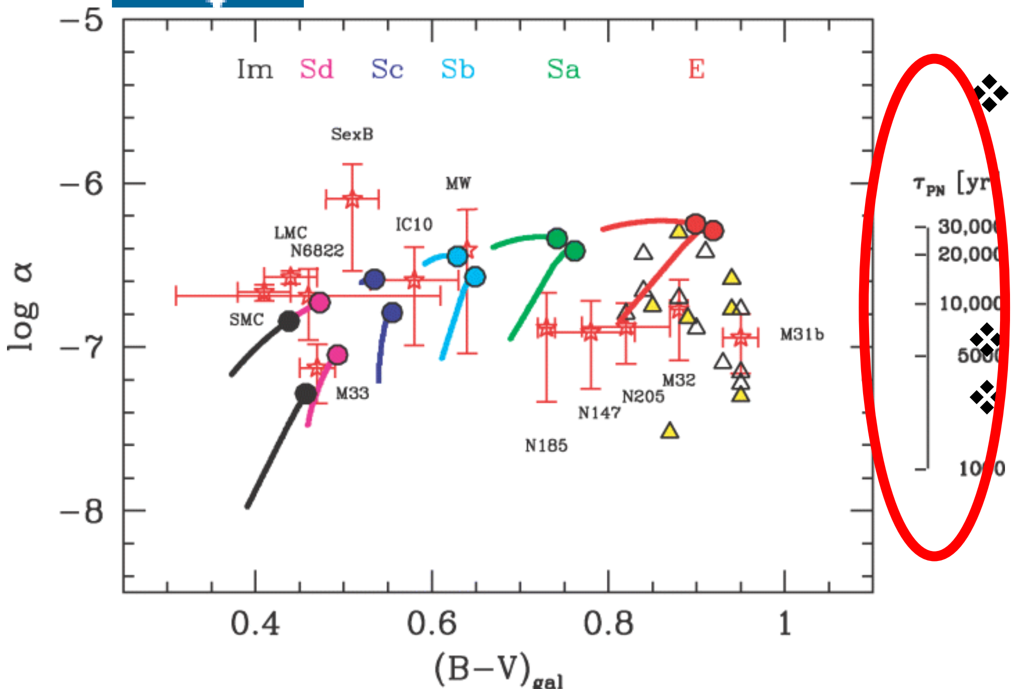
$$m_{5007} = -2.5 \log F([OIII]_{5007}) - 13.74 \quad \text{(Jacoby 1989)}$$

$$N(M) \propto e^{0.307M} x (1-e^{3(M^{*}-M)}); \; M^{*}=-4.51 \quad \text{(Ciardullo+1989)}$$

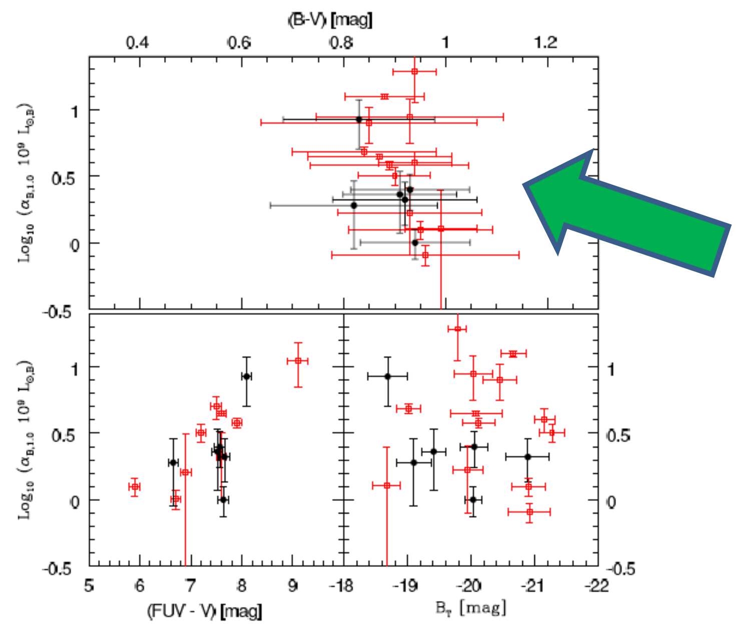
- $F^{*}([OIII]_{5007})=3.2\text{x } 10^{-10}$ erg/s/cm^2 @MW Bulge
- $F^{*}([OIII]_{5007})=2.4 \text{ x } 10^{-14}$ erg/s/cm^2 @M31
- $F^{*}([OIII]_{5007})=9.6 \text{ x } 10^{-17}$ erg/s/cm^2 @Virgo
- $F(^{*}[OIII]_{5007})=2.2 \text{ x } 10^{-18}$ erg/s/cm^2 @Coma => it corresponds to ~2 photons/min on 8m tel.

[OIII] fluxes from PNs in Virgo and beyond are of the same order of the Lyα@z=3.14, [OII]3727Å@0.34 emissions. Small HII regions in ETGs halo may also mimic bright PNs (Gerhard et al. 2002, ApJL, 589, 121; Ryan Weber et al. 2004, AJ, 127, 1431)

Motivation II. PN visibility lifetime and PNLF



- The luminosity specific PN number
  $\boldsymbol{\alpha = N_{PN}/L_{bol,gal} = B\tau_{PN}}$
- The observed values of α show a strong scatter in red and old stellar populations (Hui+93, Ciardullo+05, Coccato+09, Cortesi+13)
- Inverse correlation between α & FUV-V
- It is a function of metallicity and age of the parent stellar populations.

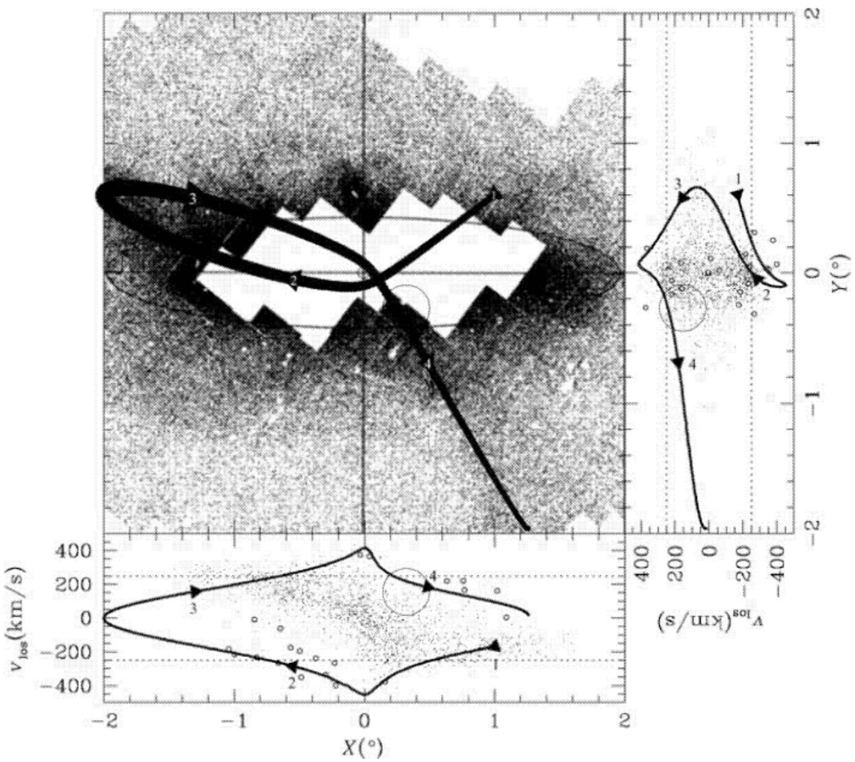


τ_{PN} can be estimated using v_{exp} and D_{PN}, as $\tau_{PN} = D_{PN} / v_{exp}$

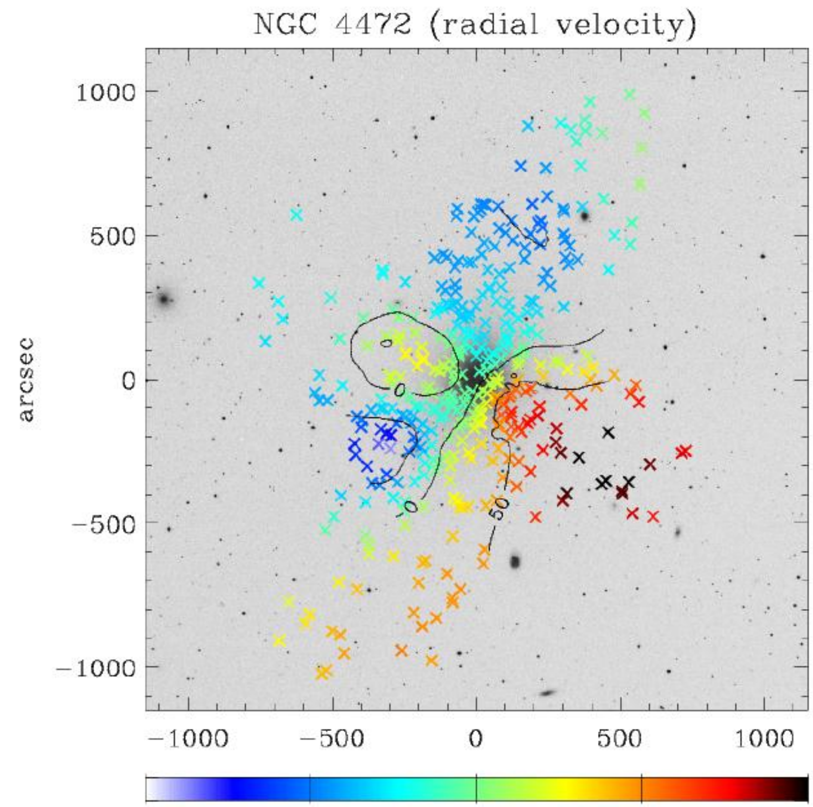
Motivation III. PNs as kinematical tracers

	TYPE	D Mpc	cz km/sec	B_T mag	PA deg	N_{PNe}	R_{LAST} arcmin	Reference
NGC 221 (M31)	Sb	0.77 ± 0.02	-295	3.36	35	2615	120.0	Merrett et al. (2006)
NGC 1316	S0	20 ± 1.6	1793	9.40	50	796	11.0	Mc Neil-Moylan et al. (2012)
NGC 5128	S0	4.2 ± 0.3	547	7.30	35	1267	8.4	Walsh et al. (2015)
NGC 4697	E6	10.9 ± 0.7	1236	10.07	70	535	6.6	Mendez et al. (2001)
NGC 4374	E1	17.1 ± 0.9	1060	10.01	135	450	6.9	Coccato et al. (2009)
NGC 2768	E6/S0	22.4	1335	10.84	95	315	5.5	Cortesi et al. (2013)
NGC 4649	E2	16 ± 1	1117	9.70	105	298	7.0	Teodorescu et al. (2010)
NGC 4494	E1	15.8 ± 0.8	1344	10.55	0	255	7.6	Napolitano et al. (2008)
NGC 1344	E5	18.4 ± 2.5	1169	11.24	165	194	6.7	Teodorescu et al. (2005)
NGC 3115	S0	9.68	663	9.87	70	192	6.5	Cortesi et al. (2012)
NGC 3379	E1	9.8 ± 0.5	889	10.18	70	186	7.2	Douglas et al. (2007)
NGC 1023	S0	10.6 ± 0.8	637	10.08	87	183	10.8	Noordermeer et al (2008)
NGC 5236 (M83)	SBc	4.8 ± 0.1	516	8.31	46	162	18	Herrmann et al. (2009)
NGC 3377	E5	10.4 ± 0.4	665	11.07	35	151	10.0	Coccato et al. (2009)
NGC 1399	E1	18.5 ± 1.4	1447	10.44	110	146	10.0	Mc Neil et al. (2010)
NGC 4736 (M94)	Sab	4.4 ± 0.2	310	8.99	115	127	5.8	Herrmann et al. (2009)
NGC 821	E6	22.4 ± 1.8	1735	11.72	25	123	6.8	Coccato et al. (2009)
								+ Teodorescu et al. (2010, 167 PNe)
NGC 5846	E0	23.1 ± 2.1	1714	10.91	70	123	6.0	Coccato et al. (2009)
NGC 7457	S0	13.2	812	12.09	130	121	2.0	Cortesi et al. (2013)
NGC 628 (M74)	Sc	8.6 ± 0.3	656	9.95	25	102	4.8	Herrmann et al. (2009)
IC 342	Scd	3.5 ± 0.3	34	9.1	39	99	4.8	Herrmann et al. (2009)
NGC 3384	SB0	10.8 ± 0.7	704	10.75	53	95	3.8	Cortesi et al. (2013)
NGC 3608	E2	21.3 ± 1.4	1253	11.69	75	87	6.8	Coccato et al. (2009)
NGC 3489	S0	12.1	690	11.12	70	60	2.4	Cortesi et al. (2013)
NGC 4564	E6/S0	13.9 ± 1.1	1142	12.05	47	49	7.5	Coccato et al. (2009)
NGC 5457 (M101)	Scd	7.7 ± 0.5	241	8.31	35	48	8	Herrmann et al. (2009)
NGC 4406	E3	16 ± 1	-244	9.74	130	16	4.0	Arnaboldi et al. (1996)

Motivation III. PNs as kinematical tracers



Substructure in the halo of M31
Merrett+2006,MNRAS,369,120



Dissolving satellite in the halo of M49

See talks by Gerhard, Longobardi, Napolitano for the use of PNs as kinematical tracers and Talks on the use of globular clusters by Brodie, Durrell, Hilker and Harris

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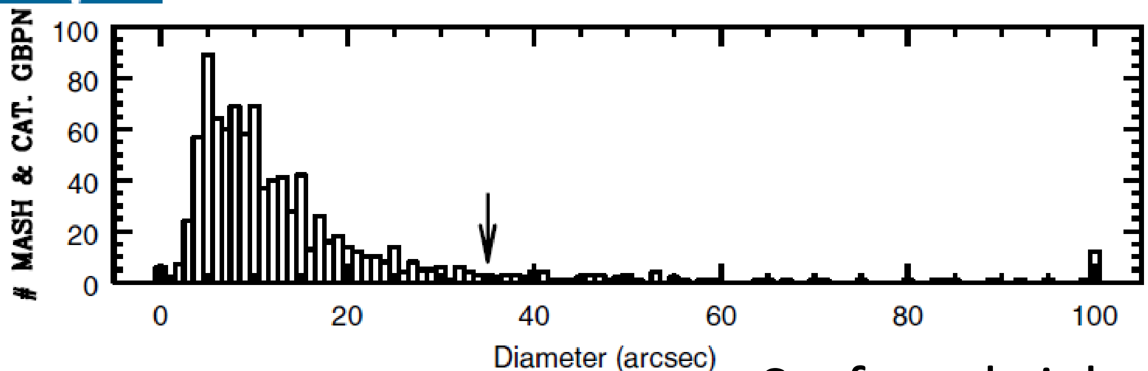
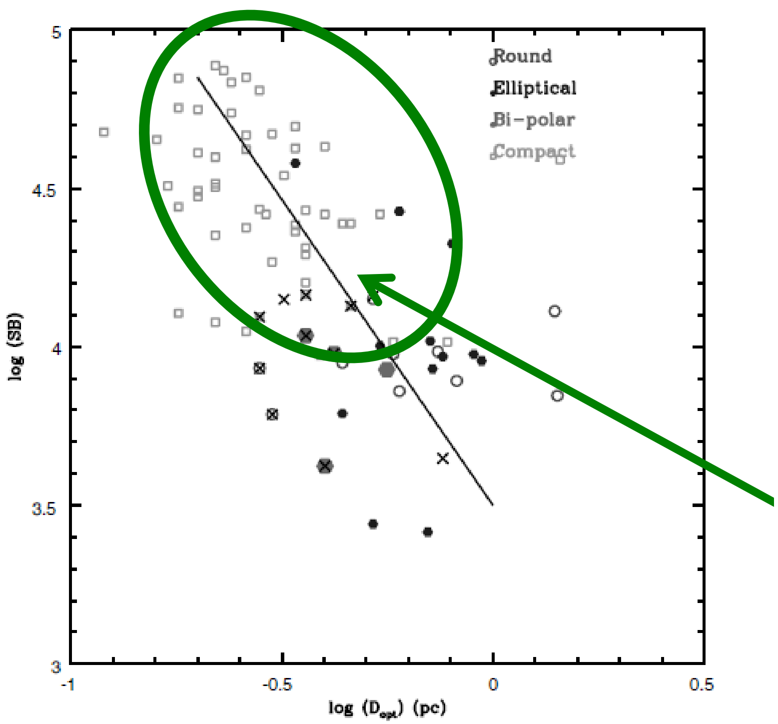
The Galactic Bulge PNs



Angular diameter for Bulge and Disk PNs (MASH I + II and Acker+1992)



Surface brightness vs. diameter in parsecs for 133 Bulge PNs: the surface brightness appears to be linked to size, morphology, and the ratio $R = (I[NII]_{6548} + I[NII]_{6584})/I(H\alpha)$.

D_{ave}~0.3pc-> Extragalactic PNs are selected preferentially from these high SB PNs.

τ_{PN} for MW bulge PN population is only a few 10^3 years

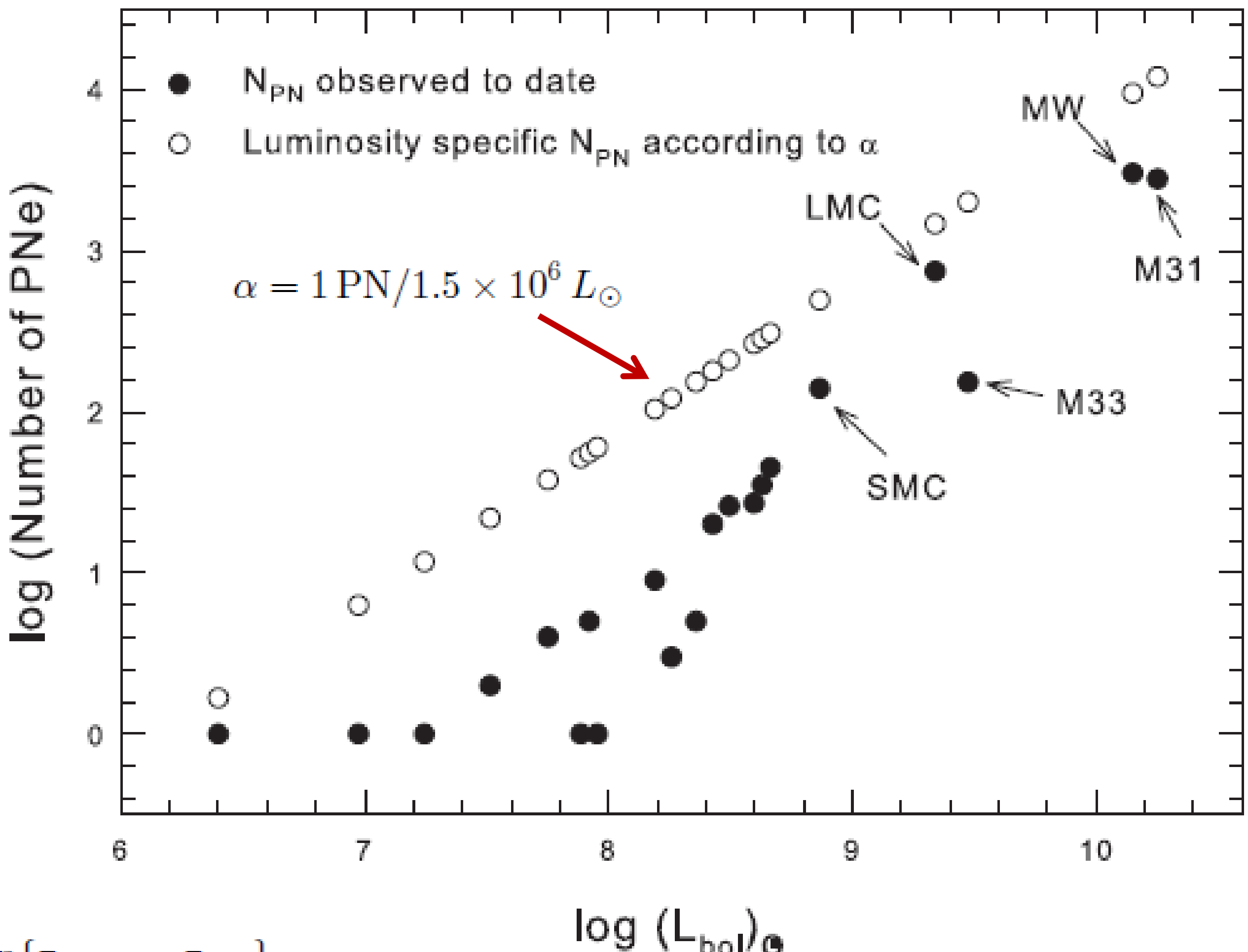
PNs from different stellar populations

- We require self-contained systems at known distances whose PN populations are sufficiently nearby to permit investigation into their physical properties.
- The galaxies in the Local Group (LG) represent valid proxies to study the late phases of evolved stellar populations with a spread of metallicities, α-element enhanced (Bulges in MW & M31 - as in ETGs halos) and star formation histories (star forming, e.g. LMC, M33 vs. passive evolving stellar populations) **=> Surveys of PNs in LG and beyond**

PNs populations in the Local Group

- PN populations in the LG galaxies show systematic variations of the α values and the expansion velocity of the nebulas.

PNs populations in the Local Group



Upper limit

$\alpha_{max} \simeq 1$ PN/1.5 × 10^6 $L_\odot$

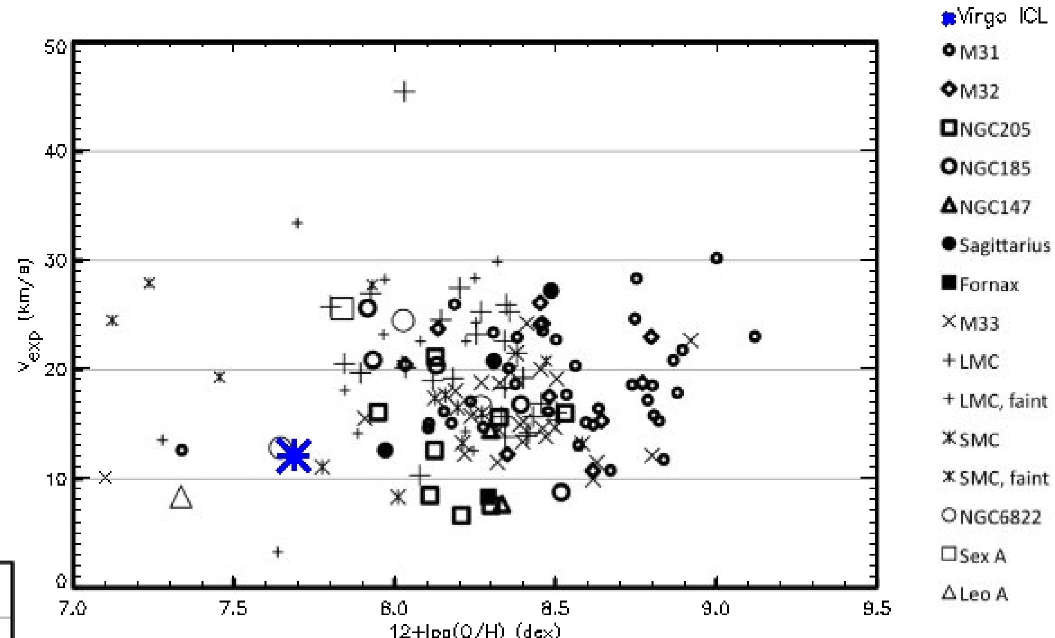
$$\alpha = \frac{N_{\rm PN}}{L_{\rm SSP}} = \beta\,\tau_{\rm PN} = \beta\,\min\{\tau_{\rm HPAGB}, \tau_{\rm dyn}\}$$

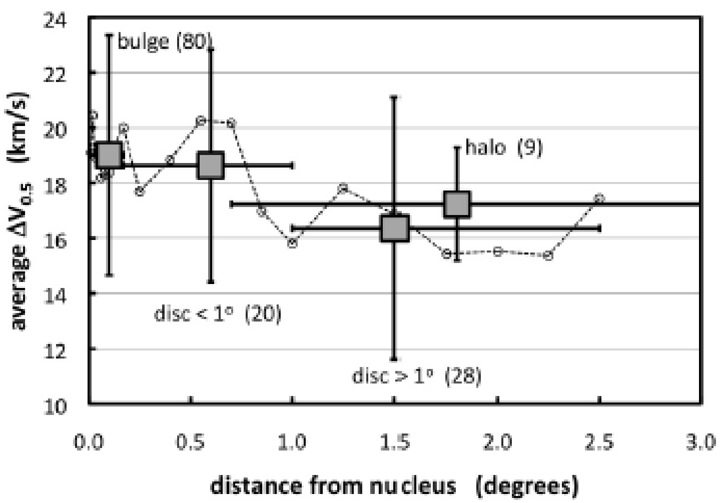
PNs populations in the Local Group

Expansion velocity of a PN is measured from V_{HWHM} of the [OIII] 5007 emission.

$V_{exp} \geq 2 \times V_{HWHM}$

Distribution of V_{exp} for PNs in LG members (Richer+2010).





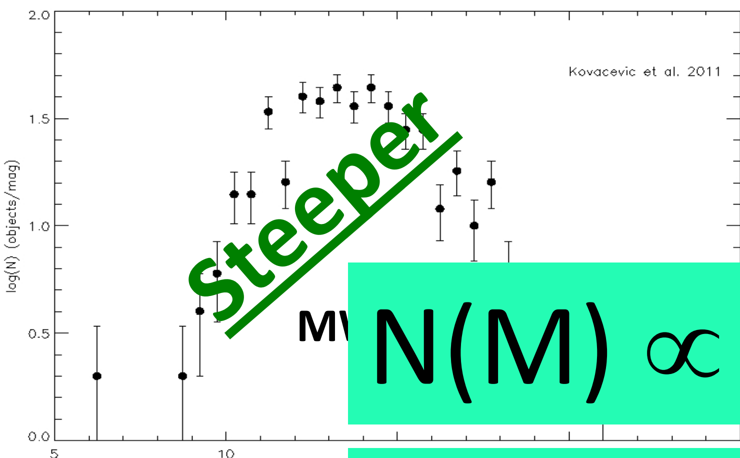
Expansion velocity of a PN is measured from V_{HWHM} of the [OIII] 5007 emission.
Distribution of V_{exp} for PNs in M31
PNLF at different radii in M31: strong deviations in the central region (Sarzi+2012)!

PNs populations in the Local Group

- PN populations in the LG galaxies show systematic variations of the α values and expansion velocity of the nebulas.
- PNLFs show systematic variations: 1) gradient within 2.5 mag below brightest is negative/ flatter/positive according to the star formation history and 2) presence of a dip within 2-4 magnitudes below the brightest.

PNs populations in the Local Group

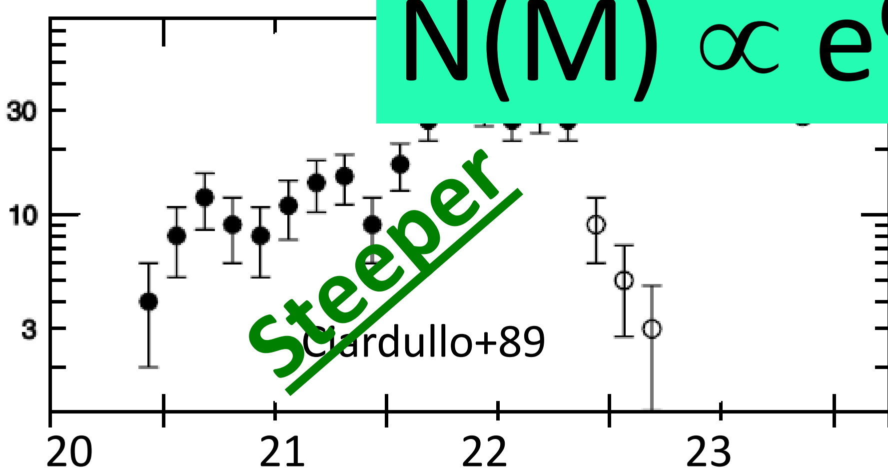
Different gradients between m*-m*+2.5 in the PNLFs !

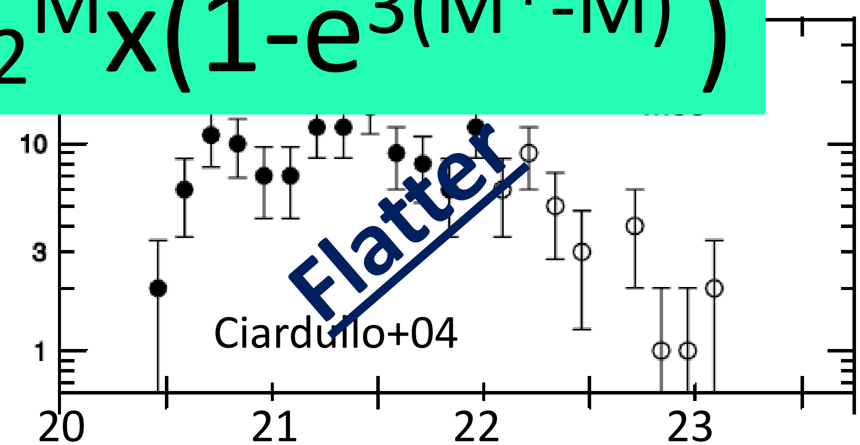


PN population from old metal rich /passive evolving vs. intermediate metal poor/star

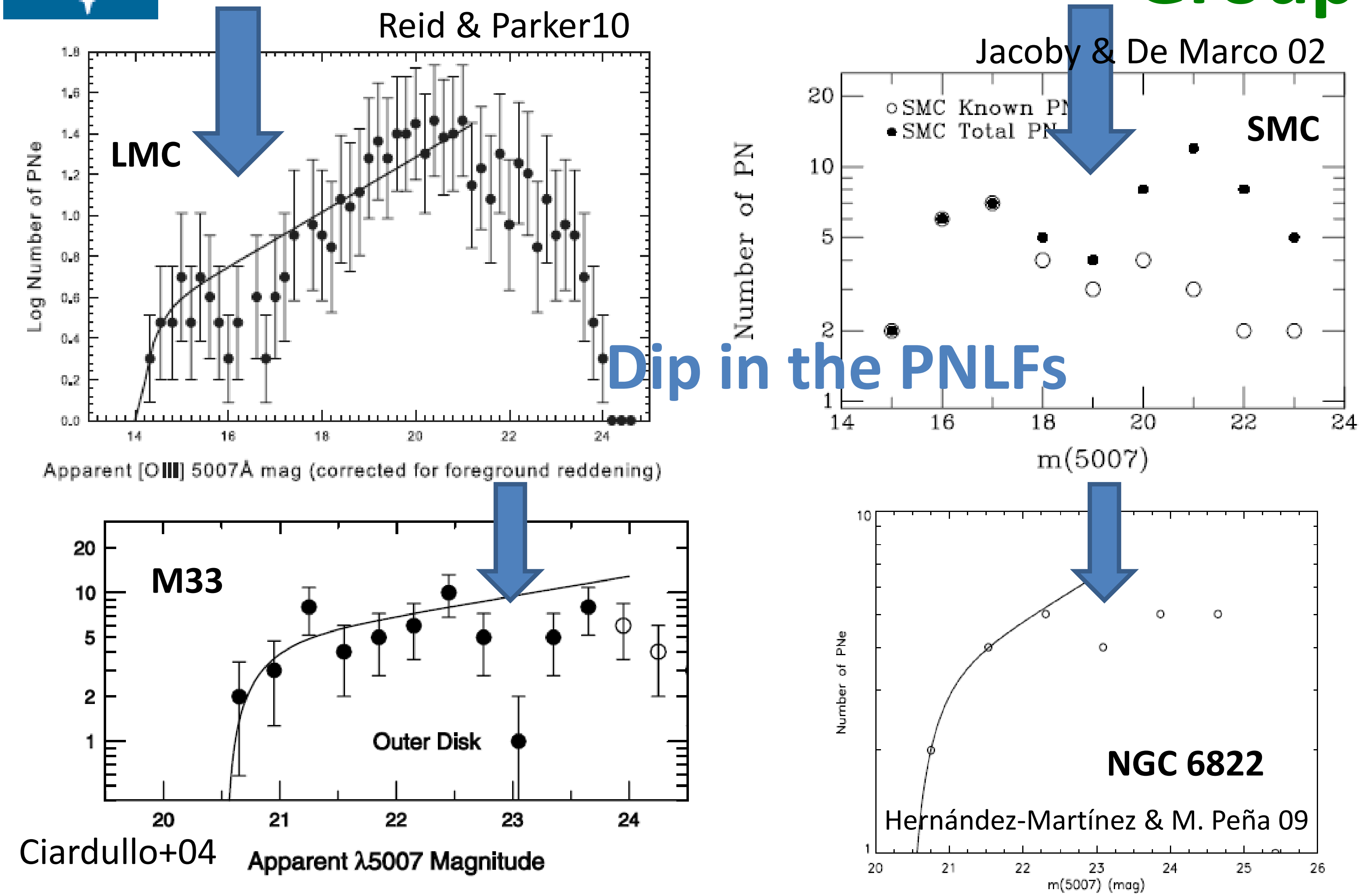
$$N(M) \propto e^{0[illegible]7M} x(1-e^{3(M^*-M)})$$

$$N(M) \propto e^{c_2 M} x(1-e^{3(M^*-M)})$$





PNs populations in the Local Group



PNs populations in the Local Group

- PN populations in the LG galaxies show systematic variations of the α values and expansion velocities.
- PNLF show systematic variations: 1) gradient within 2.5 mag below brightest is negative/flatter/steeper according to the star formation history and 2) presence of a dip in the magnitude range 2-4 below the brightest.
- We can use the properties of the PN population (PNLF gradient, dip, α value) to identify passive evolving/metal rich from star forming /metal poor stellar populations, when individual stars cannot be resolved (Arnaboldi et al. 2015).

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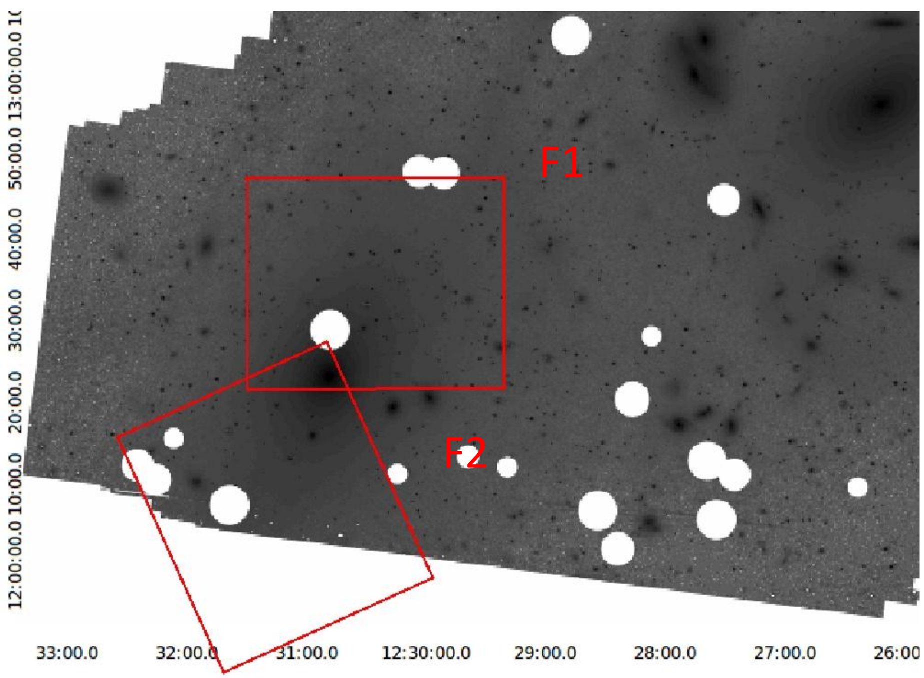
The PN populations in the Virgo cluster core

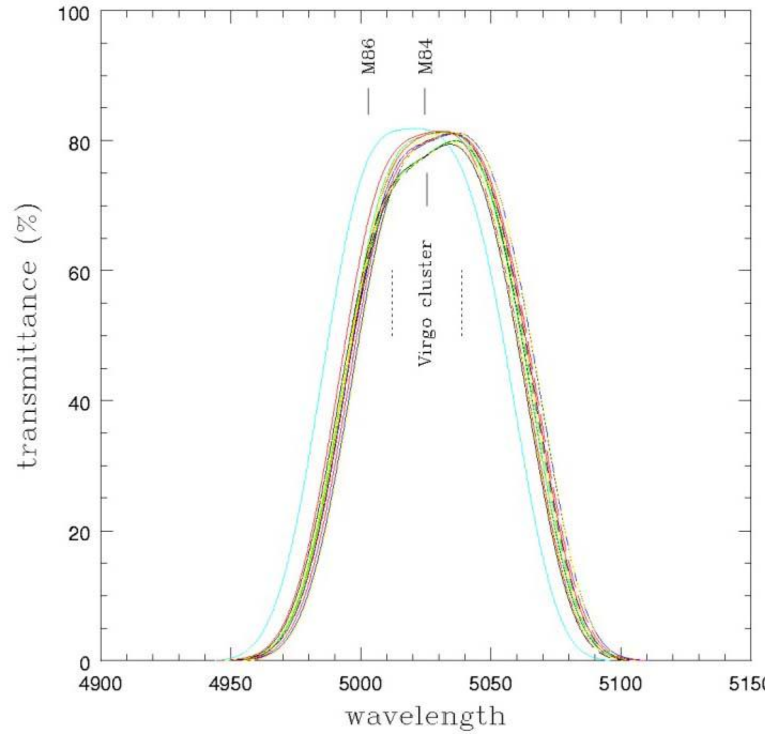
- In 2010 we started a project to study the dynamics and substructures of the M87 stellar halo using PNs as tracers, out to 150 kpc
- Imaging project with SuprimeCAM@Subaru to cover 0.5 deg^2 in the M87 outer halo.
- Deep [OIII] and deep off-band V images.
- Identify PN candidates as [OIII] point-like emissions with no continuum.
- Spectroscopic follow-up with FLAMES@VLT.
- **Ph.D Thesis of Alessia Longobardi (IMPRS@Garching) – and Longobardi et al. 2015a, A&A, sub. (arXiv1502.02032)**

PNs in the Virgo cluster core

- SuprimeCAM observations of M87. For each field:
  - Total exposure [OIII] NB 6 hrs
  - Total exposure in V band 1.23 hrs
- Seeing in [OIII] & V images < 0''.8

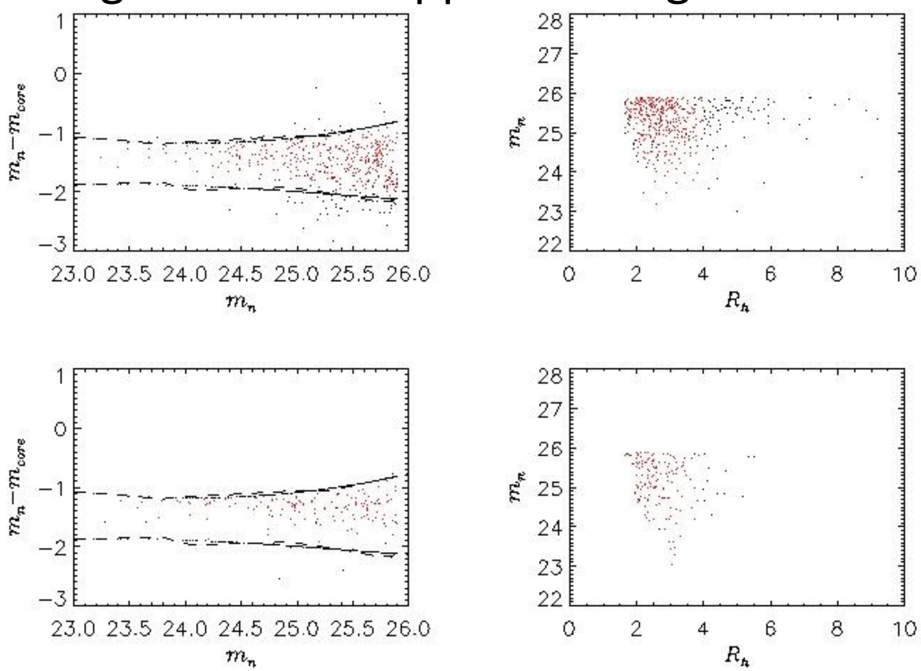


[OIII] filter transmission curve

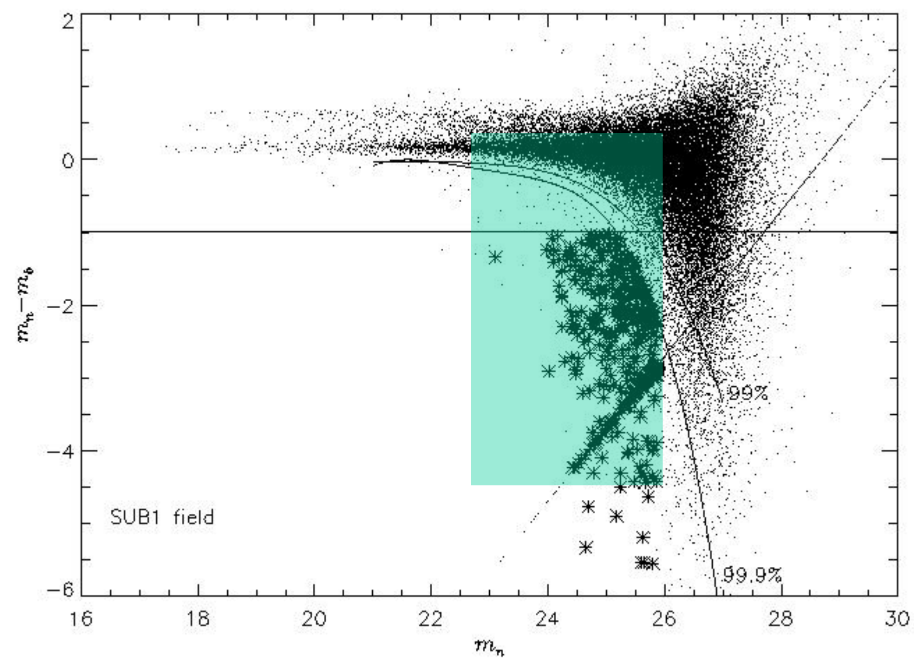


PNs in the Virgo cluster core

- Imaging data reduction: SuprimeCAM pipeline
- Catalogue extraction: SExtractor. Selection criteria for PN candidates from Arnaboldi+2002AJ123,760
- Final catalogue of 800 PN candidates in F1+F2, [OIII] limiting mags 28.8, i.e. 2.5 mags below the apparent magnitude of the PNLF cut-off for a distance modulus 30.8



Selection of point-like objects on the basis of the PSF shape



CMD for the selection of objects with a color excess in the [OIII] NB filter

PNs in the Virgo cluster core

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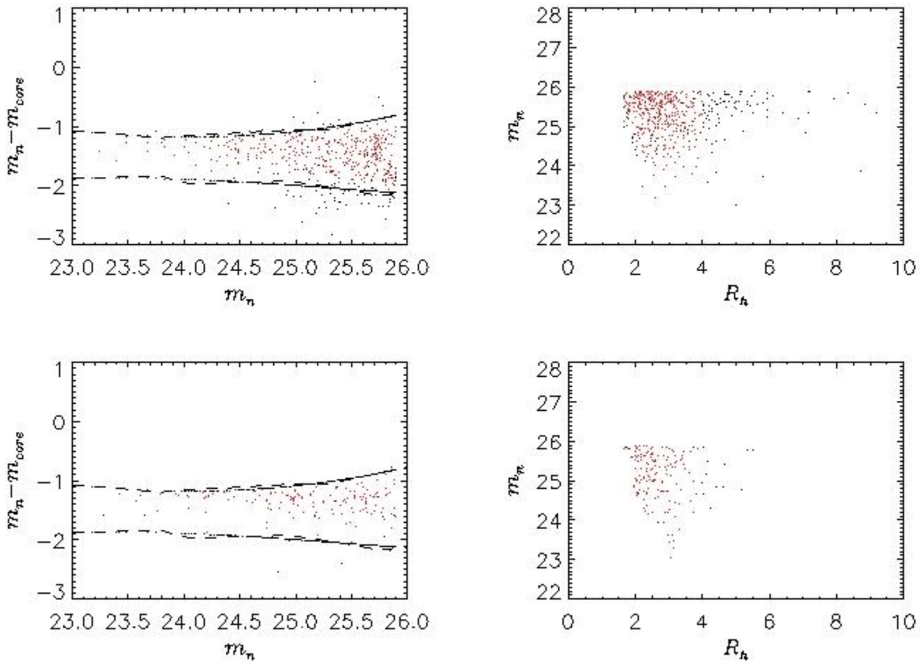

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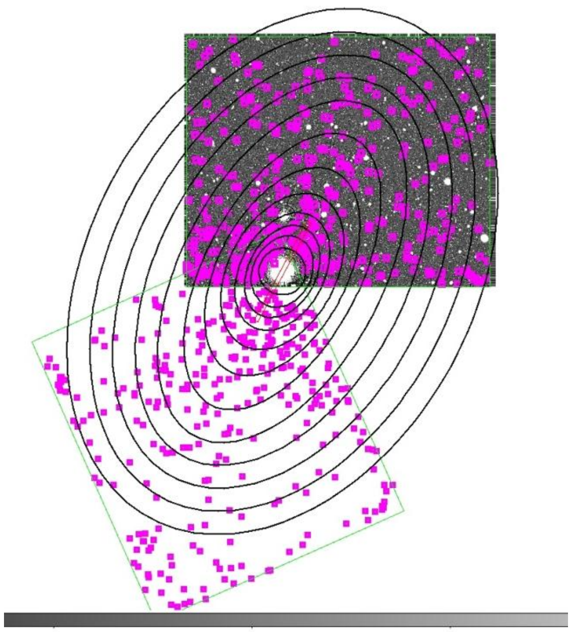
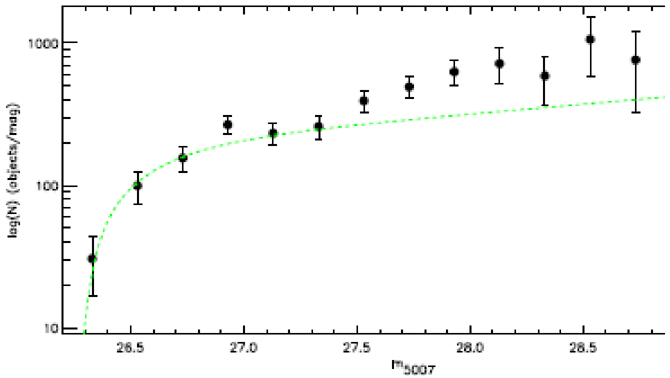
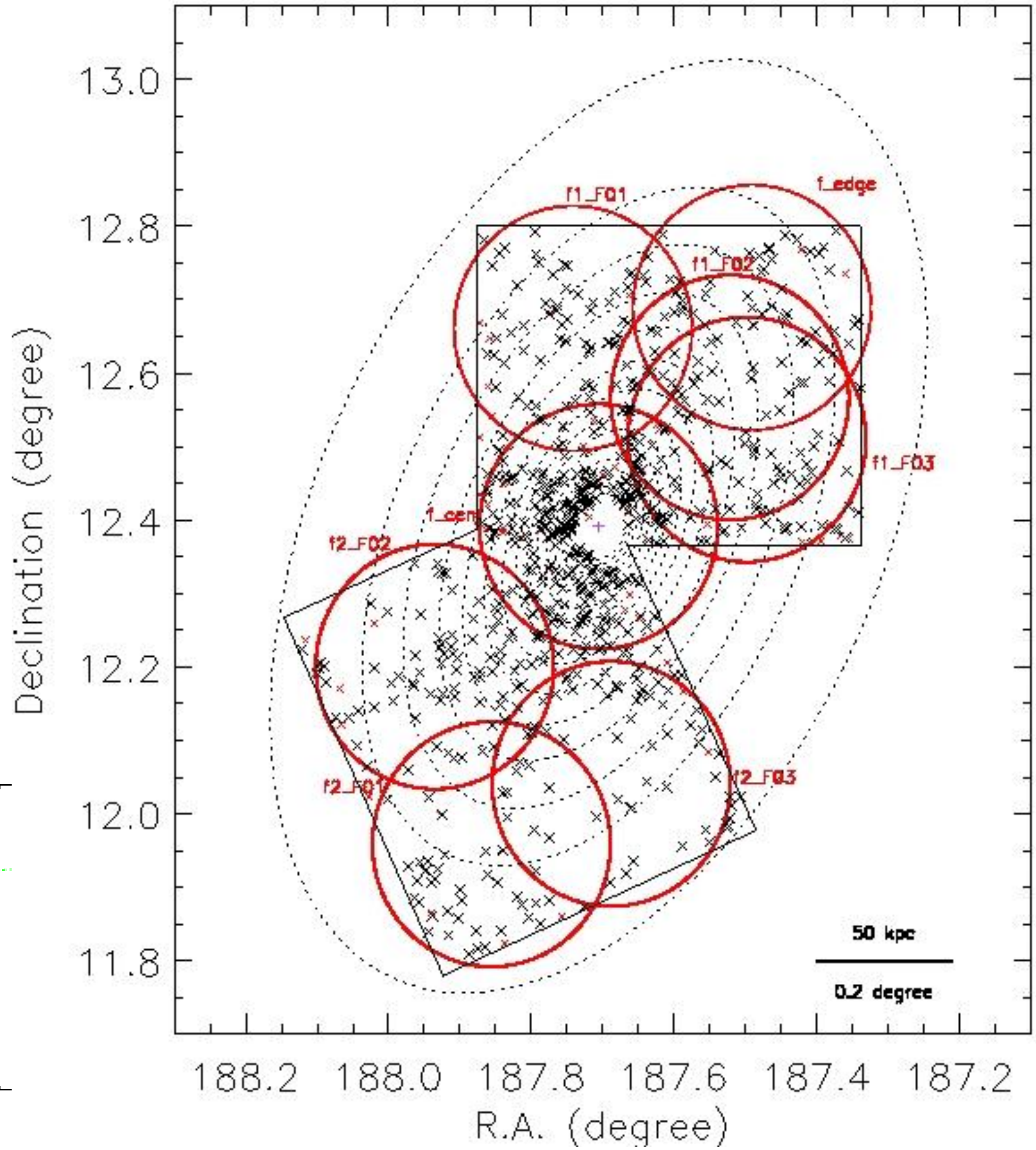


Distribution of PN candidates in the M87. Ellipses show isophote contours

Spectroscopic follow-up with FLAMES@UT2 on VLT; 289 spectroscopically confirmed PNs.

Additional 12 PNs from D09





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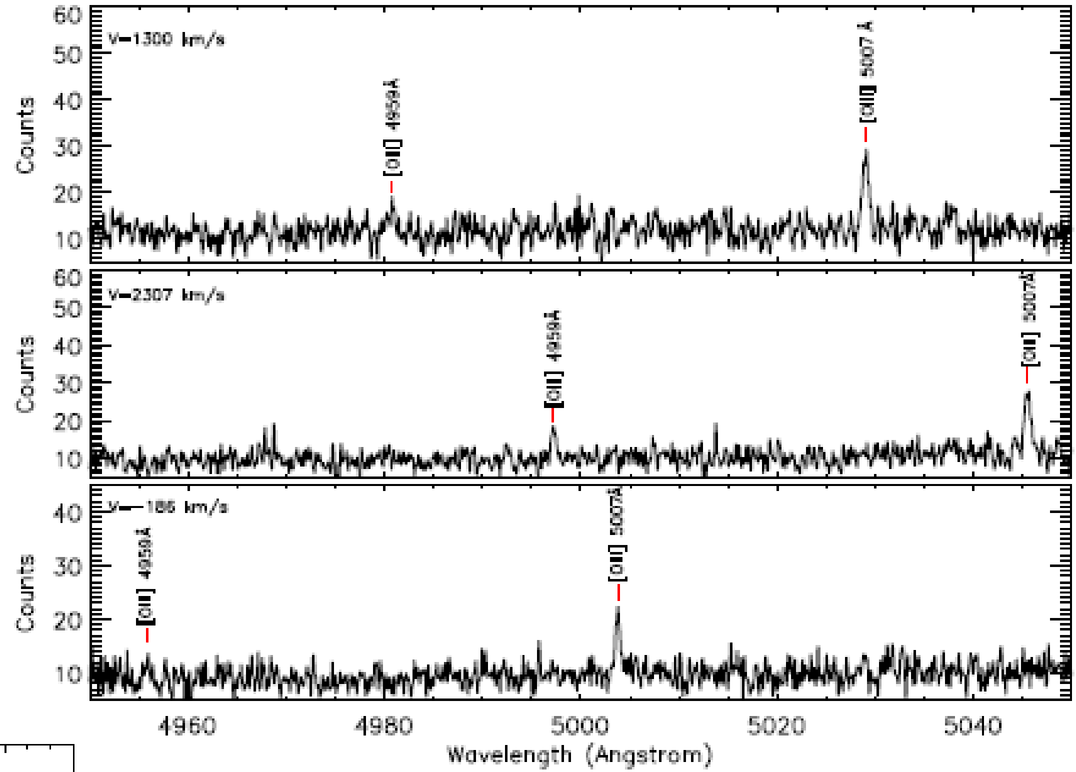
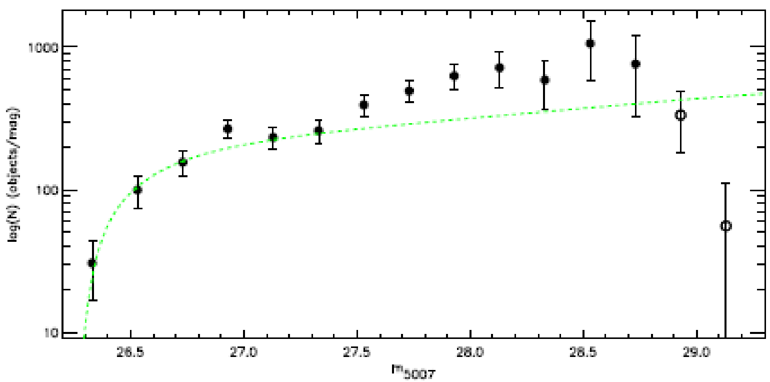




Single PN spectra – From Longobardi+2015a (arXiv150202032)

LF of spectroscopically confirmed PNs

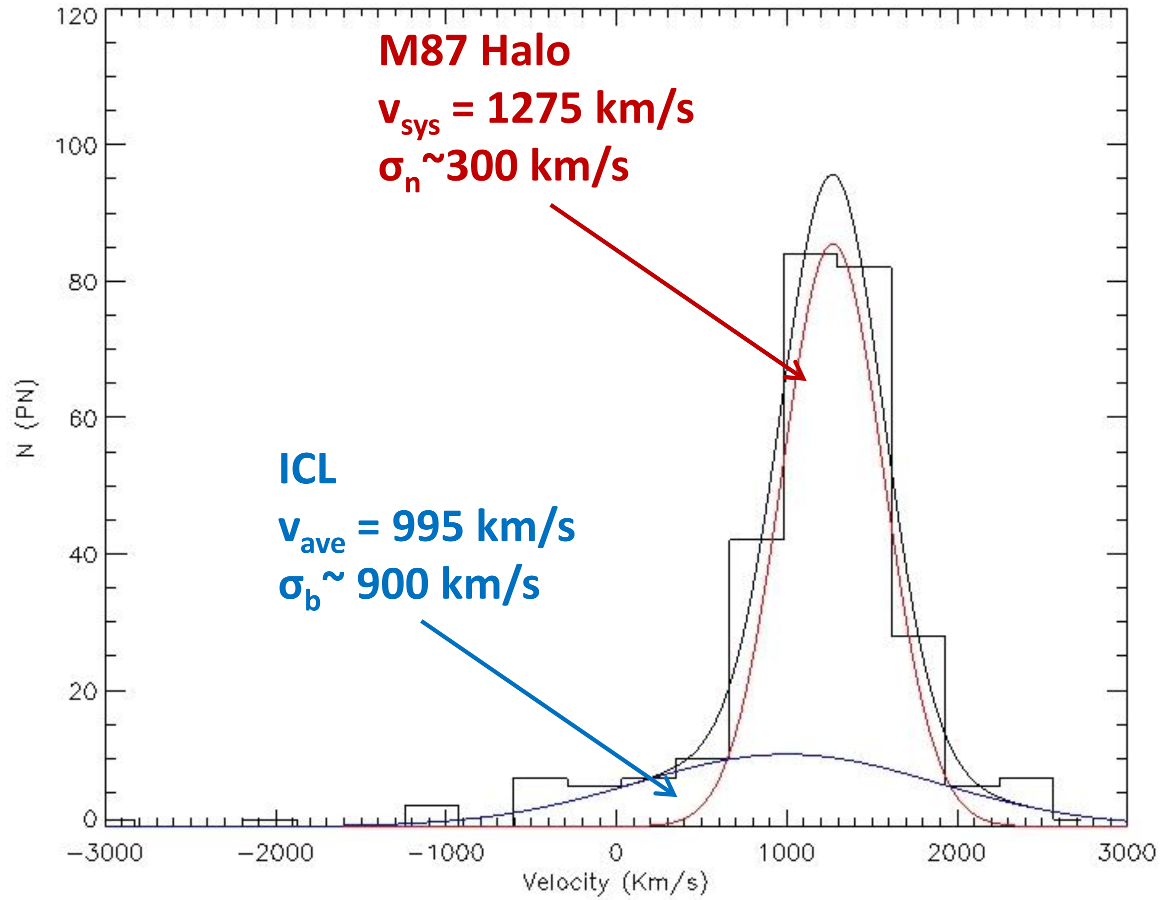
PNs in the Virgo cluster core

Spectroscopic follow-up with FLAMES@UT2 on VLT; 289 spectroscopically confirmed PNs. Additional 12 PNs from D09

Using their v_{los} PNs can be classified as M87 halo or intracluster population.

Red Gaussian : M87 halo; 244 PNs

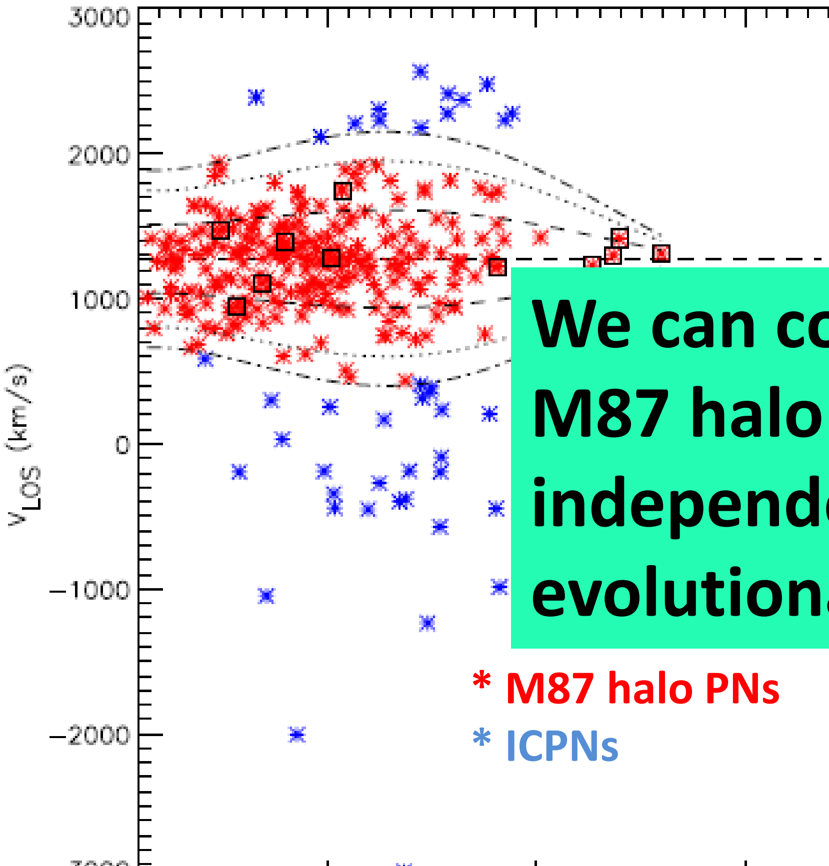
Blue Gaussian: ICL in Virgo core; 45 ICPNs

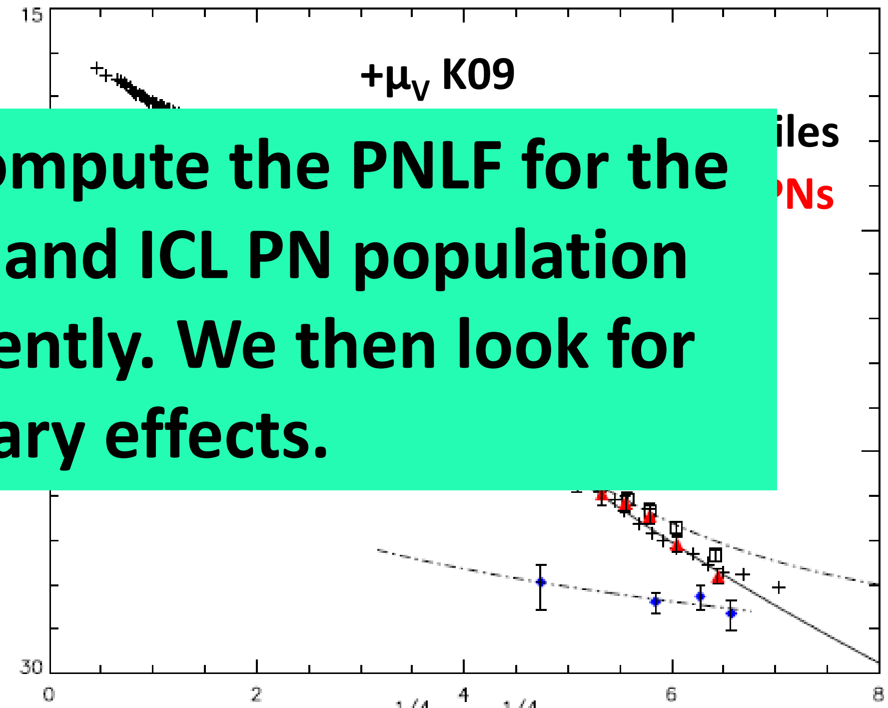


Line of sight velocity distribution of 301 PNs

PNs in the Virgo cluster core

Projected phase space diagram v_{los} vs R_{maj} for spec. conf. PNs



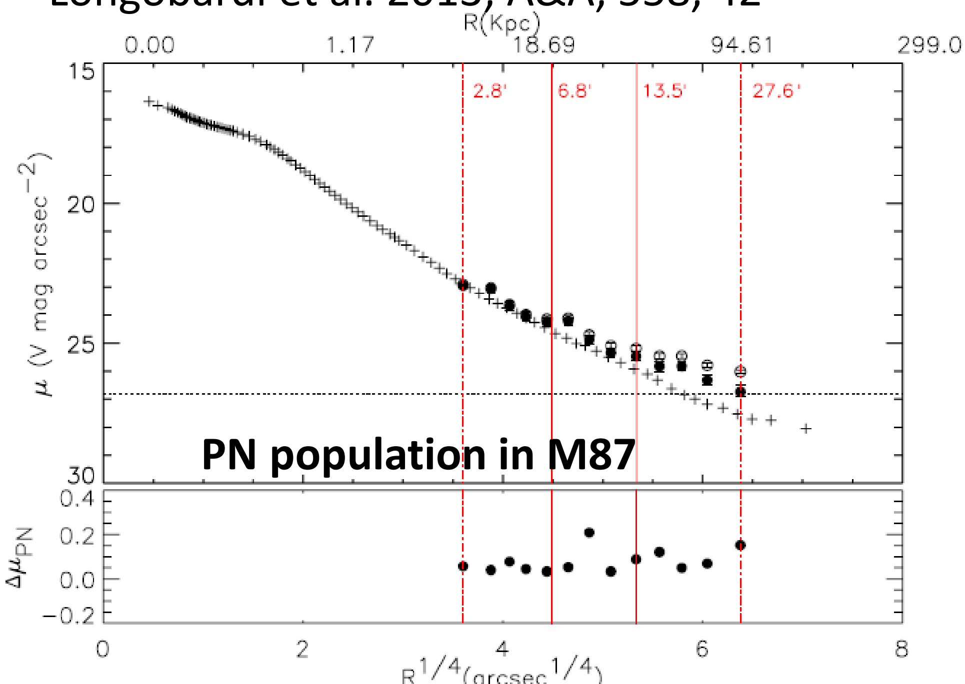


We can compute the PNLF for the M87 halo and ICL PN population independently. We then look for evolutionary effects.

Halo PNs and ICPNs have different spatial distributions: halo PNs have a steeper radial gradient; ICPNs $\propto R^{\Upsilon}$ with Υ=[-0.34,-0.04]

PNs in the Virgo cluster core

Longobardi et al. 2013, A&A, 558, 42



$$\tilde{\Sigma}(R) = [\alpha_{2.5,\mathrm{halo}} \mathrm{I}(R)_{\mathrm{halo,bol}} + \alpha_{2.5,\mathrm{ICL}} \mathrm{I}_{\mathrm{ICL,bol}}]$$

$$= \alpha_{2.5,\mathrm{halo}} \left[\mathrm{I}(R)_{\mathrm{K09,bol}} + \left(\frac{\alpha_{2.5,\mathrm{ICL}}}{\alpha_{2.5,\mathrm{halo}}} - 1 \right) \mathrm{I}_{\mathrm{ICL,bol}} \right]$$

Two component model: M87 halo and ICL

$\alpha_{2.5,ICL} = 3 x \alpha_{2.5,M87}$

The α values translate into <u>different</u> PN visibility lifetimes:

τ_{PN}=1.4 10^4 yr in ICL and 4.5 10^3 yr in M87 halo.

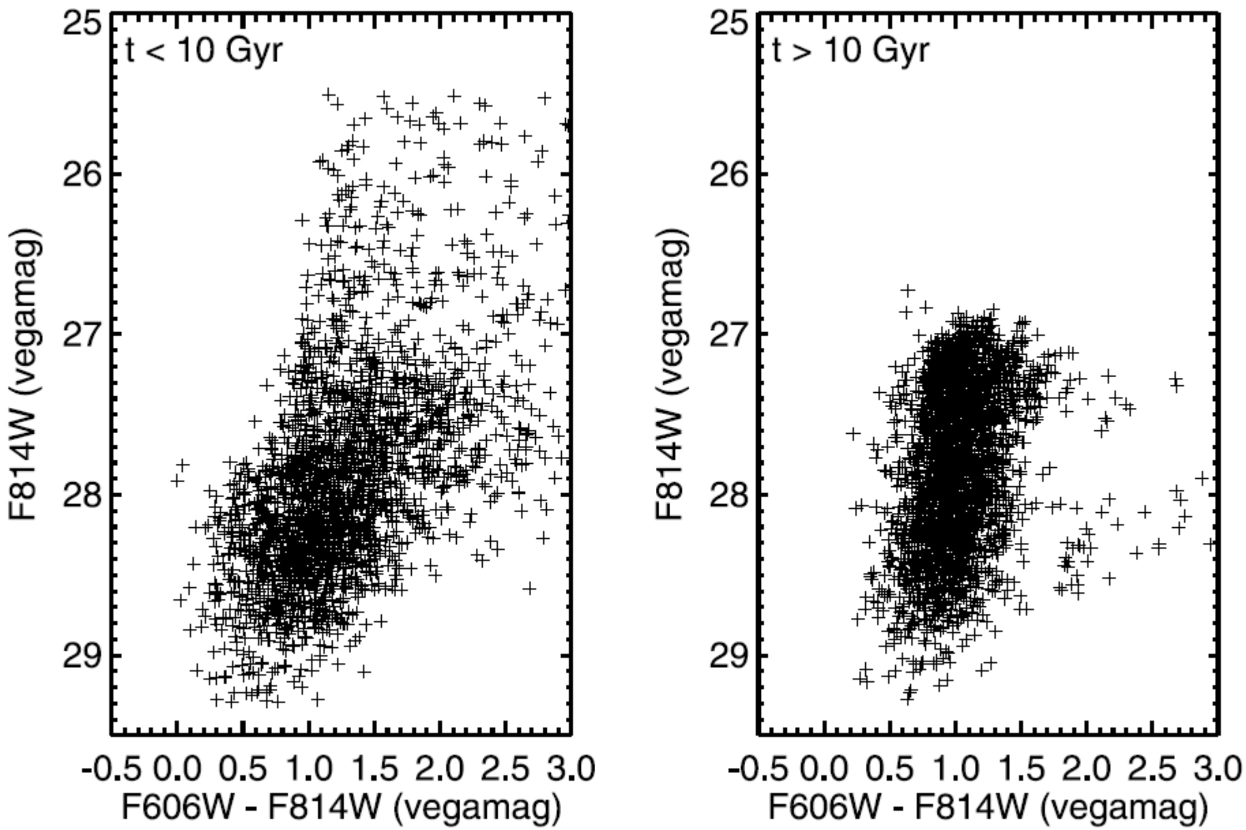
$Z_{halo} \cong 0.5$ (Liu+2005)

Z_{ICL} => [-1.0 :- 0.5] (Williams+07)

It is consistent with the existence of a color gradient towards bluer colors in the M87 halo (Liu+2005;Rudick+2010)

PNs in the Virgo cluster core

HST/ACS data for IC field in Virgo, half way between M87 and M86; 36 orbits.



Less then 20% of the stars in the VIRGO IC field have ages < 10 Gyrs

More than 80% of the stars have ages > 10 Gyrs

William et al. 2007, ApJ, 656, 756

PNs in the Virgo cluster core

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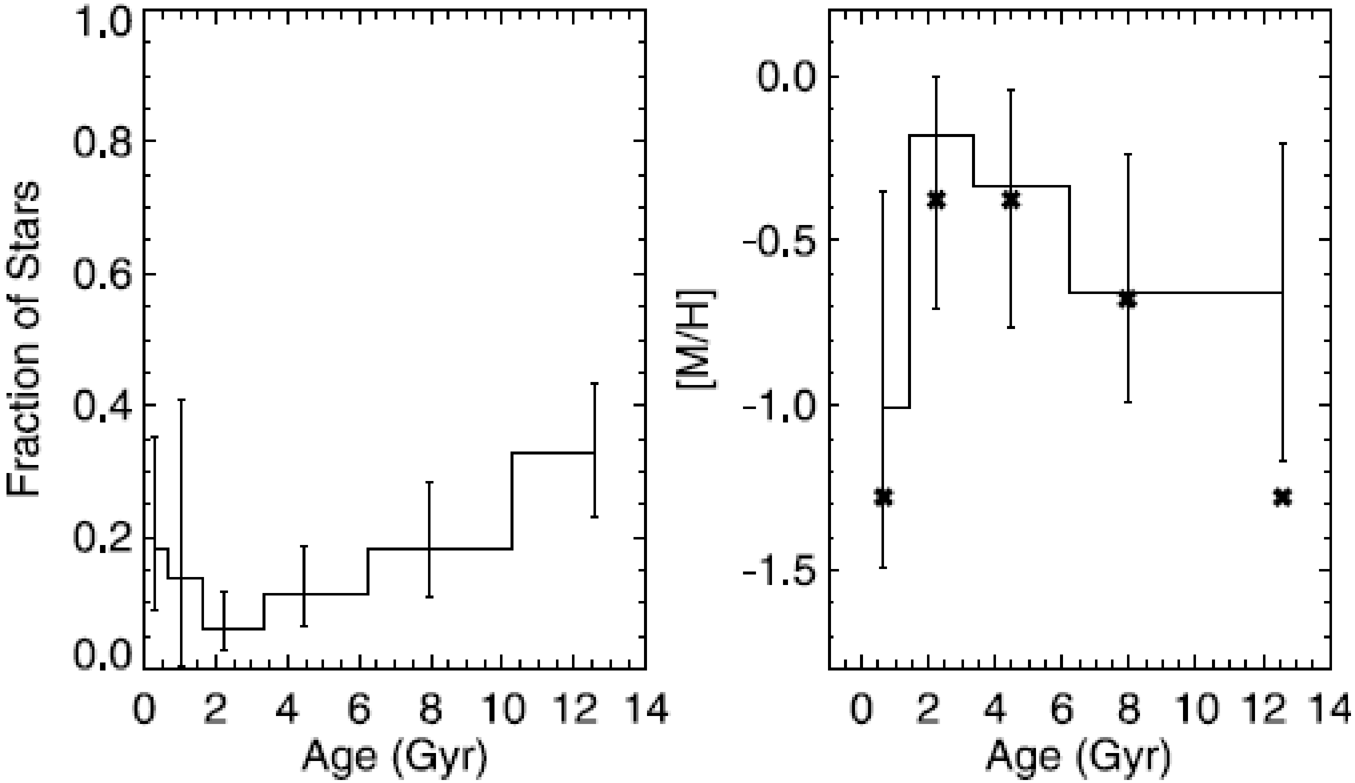


Age and metallicity distribution of the stellar population in the VIRGO ICL

Less then 20% of the stars in the VIRGO IC field have ages < 10 Gyrs

More than 80% of the stars have ages > 10 Gyrs

William et al. 2007, ApJ, 656, 756

PNLF in M87

Here we generalize Ciardullo'1989 formula and account for stellar populations effects:

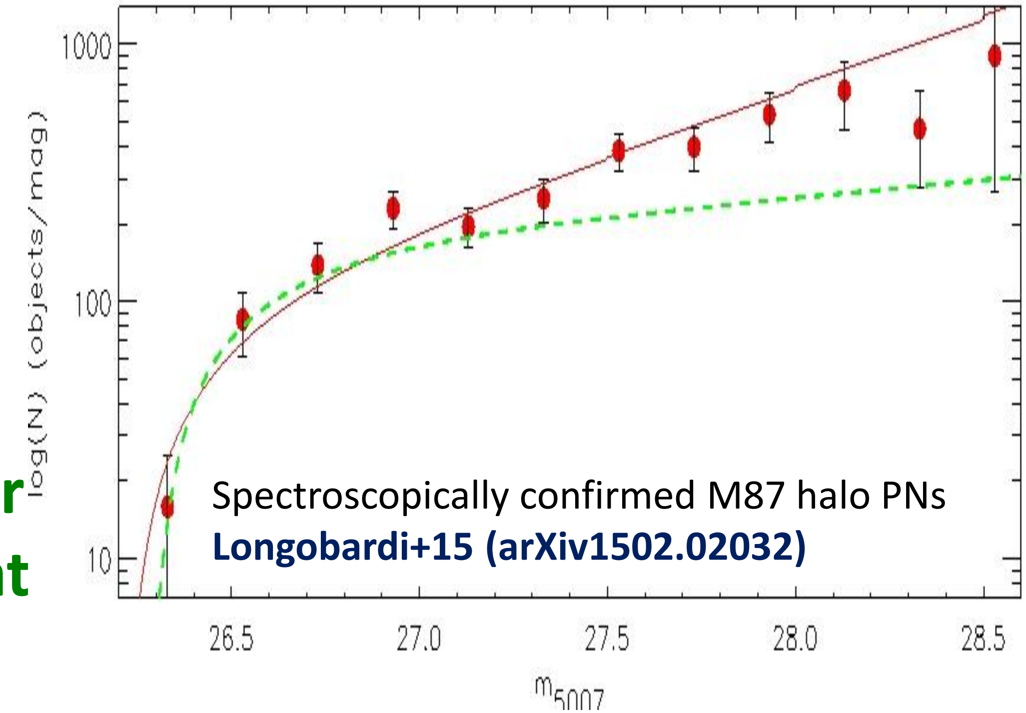
$N(M) = \mathbf{c_1} e^{\mathbf{c_2} M}(1-e^{3(M^*-M)})$;

$M^*=-4.51$ (Ciardullo+1989)

C_1 is related to α at first order

C_2 is related to the gradient at fainter m_{5007} than the cutoff

Longobardi et al. 2013, A&A, 558, 42



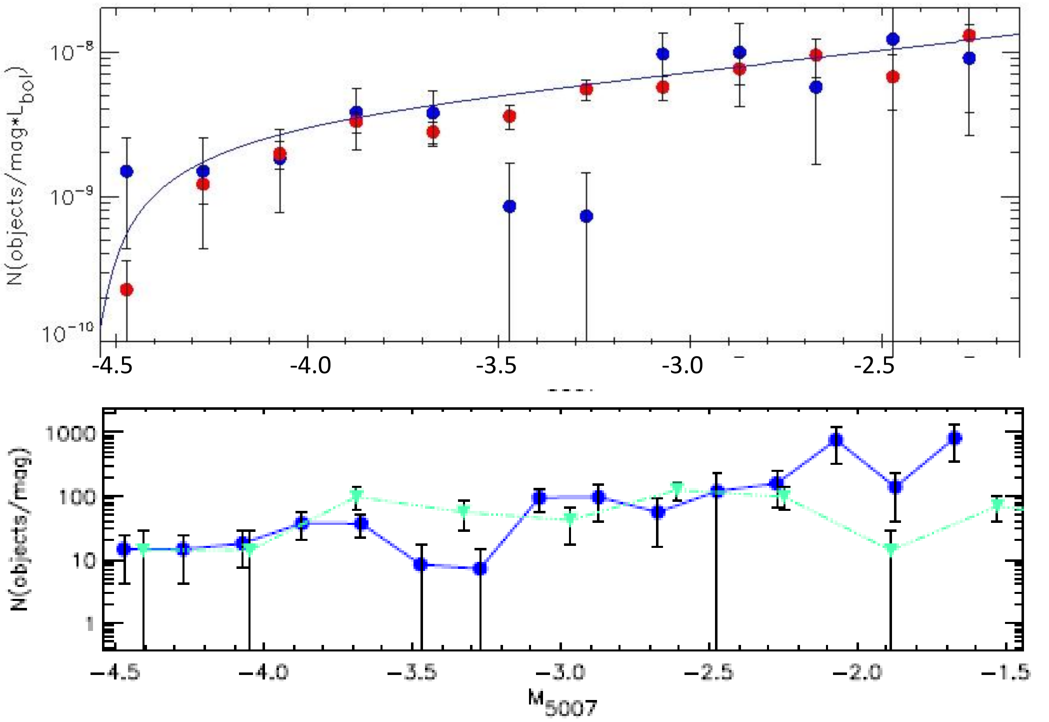
Spectroscopically confirmed M87 halo PNs

Longobardi+15 (arXiv1502.02032)

For M87: c_1 = 2017.1 and c_2=1.17 and m-M= 30.74

PNLF in Virgo ICL

Longobardi+15 (arXiv1502.02032)



Spectroscopically conf. PNLFs

- **M87 halo**
- **ICL**
- **M33**

ICL PNLF shows dip at 1-1.5 mag below brightest. Such an evolutionary feature is observed in PNLF pops. of low luminosity star forming galaxies.

For ICL PNLF: c_2=0.6 and m-M= 30.76 (blue curve)

Luminosity and Globular Clusters in Virgo ICL

- The number of ICPNs number density profile corresponds to a luminosity of $L_{ICL} = 0.53 \times 10^{10} L_{\odot}$
- It is equivalent to ~4*LMC or ~1.5*M33 on the whole surveyed area of $0.5deg^2$ or $(130\ kpc)^2$
- We can predict the number of ICGCs accreted with the ICPNs from Harris+2013 GCs specific frequencies as functions of M_K
- $N_{GC,ICL}$ = 80-90 with scatter of a factor ~2.5. In agreement with the lower limit of Σ_{IGC} ~0.2 $arcmin^{-2}$ from Durrell+2014 (total number of 100-430 ICGCs)

Concluding remarks

It is very important to establish the relation between PNs and their parent stars, because PNs will remain the single stars whose line of sight velocities can be measured at a distance of 15 Mpc (and beyond) even in the era of the E-ELT!

Conclusions

- Luminosity specific PN number (α), PN visibility lifetime τ_{PN}, and the PNLF shape (gradient down to m*+2.5, dip) are functions of the star formation history and metallicity of the parent stellar population
- <u>The M* at the bright cut off of the PNLF is invariant</u>
- In the Virgo core, there are two distinct PN populations, the M87 halo PNs and ICPNs. They trace different spatial & kinematic components, and stellar populations
- The progenitors of the Virgo core ICL are from <u>fading low luminosity, low metallicity, star forming/irregular galaxies,</u> which contain stars that are **different** from those found in the M87 halo!