# The Planetary Nebulae populations in the MW, Local Group and beyond


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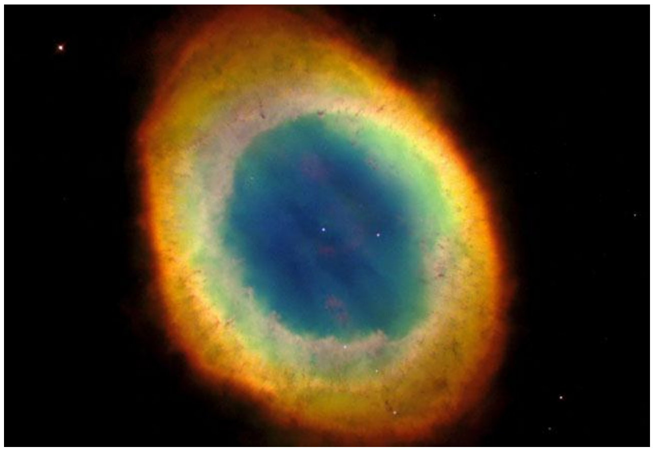
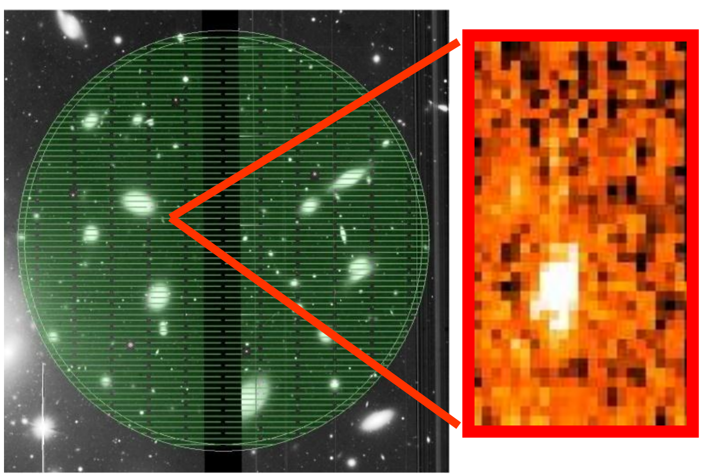
Chemical and dynamical evolution of the Milky Way and Local Group galaxies

Sesto, January 21st, 2015

# Planetary Nebulae

Ring nebula M57





- A typical Galactic PN has an average diameter of 0.3 pc; when observed in external galaxies (D> 1 Mpc), PNs are unresolved emission of green light at 5007 Å ([OIII] ).
- About 2000 PN are known in the MW out of 200 billion stars, mostly in the MW plane.
- 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.

# Outline

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

# Motivation I. PNLF in [OIII]@5007Å

[OIII] fluxes of a PN population:

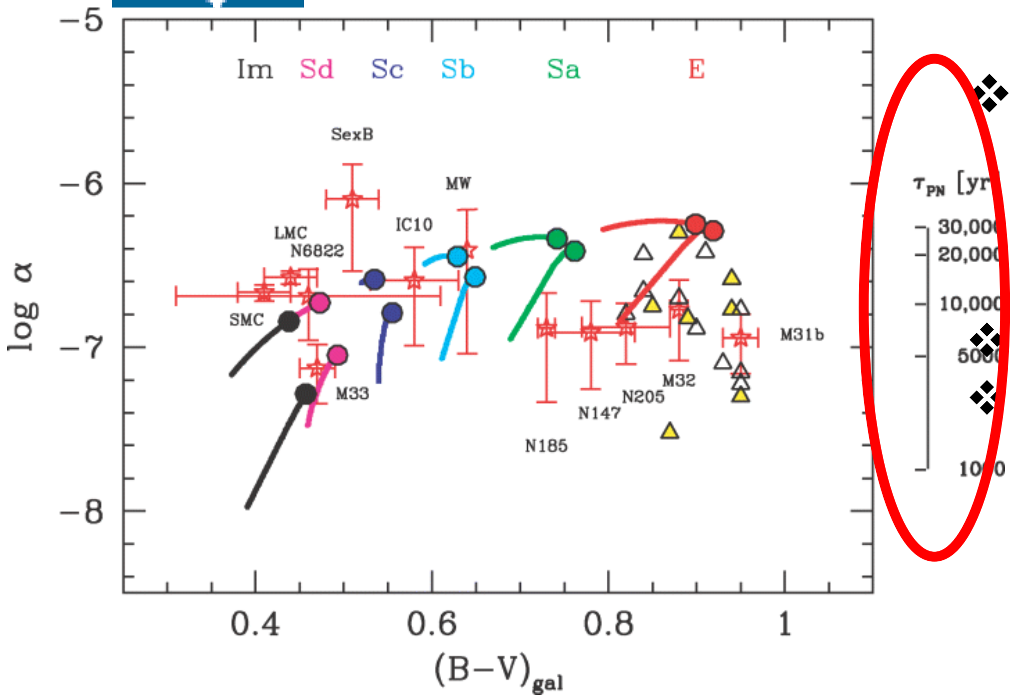
$$m_{5007} = -2.5 \log F([OIII]_{5007}) - 13.74 \quad \text{(Jacoby 1989)}$$

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

- $F^*([OIII]_{5007})=3.2\text{x } 10^{-10}$ 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.

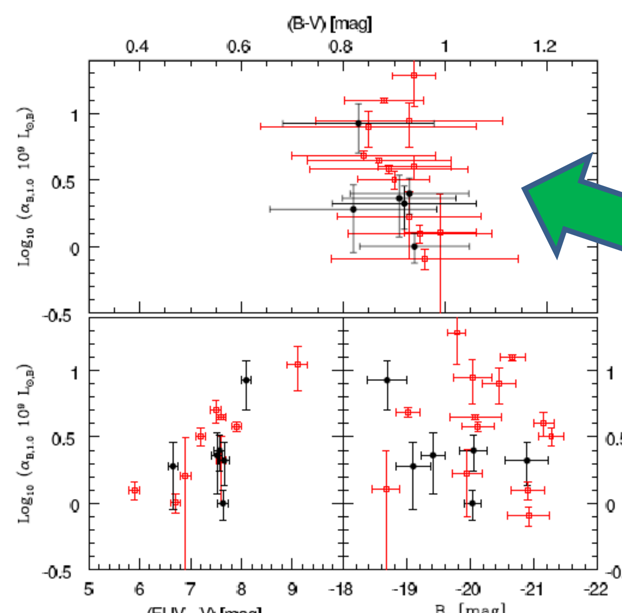
[OIII] fluxes from PNs in Virgo and beyond are of the same order of the Lyα@z=3.14, [OII]3727Å@0.34 emissions. Small HII regions in ETGs halo may also mimic bright PNs (Gerhard et al. 2002, ApJL, 589, 121; Ryan Weber et al. 2004, AJ, 127, 1431)

# Motivation II. PN visibility lifetime and PNLF



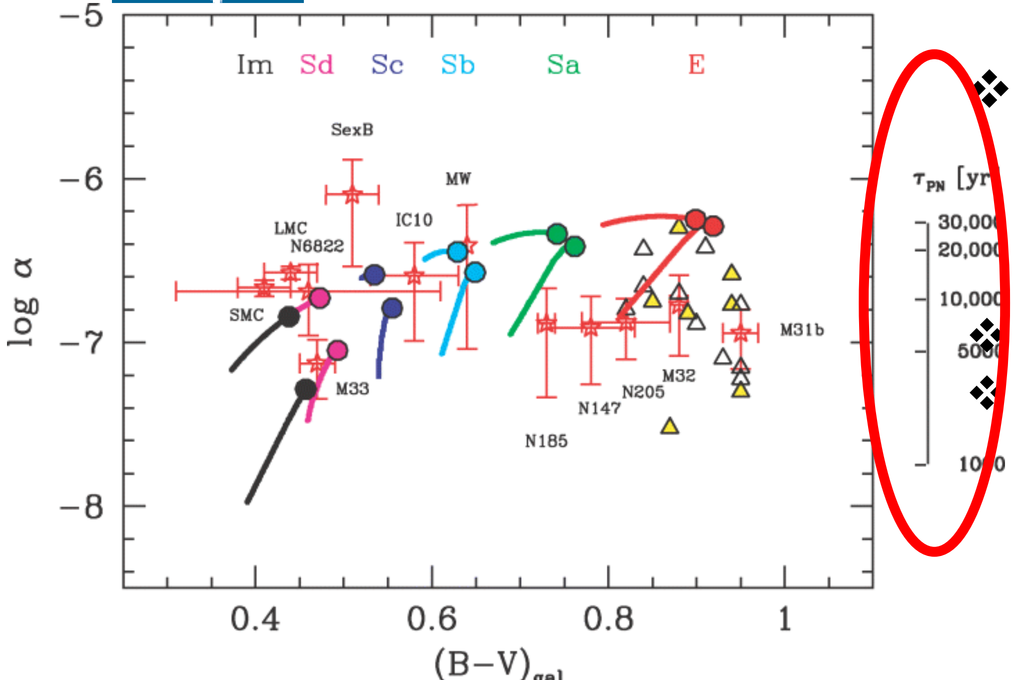

Buzzoni+2006, MNRAS, 368, 877

- The luminosity specific PN number
  $\alpha = N_{PN}/L_{bol,gal} = B\tau_{PN}$
- 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.




# $\alpha_{B,1.0}$ for ETGs: Ellipticals and S0s

# Motivation II. PN visibility lifetime and PNLF

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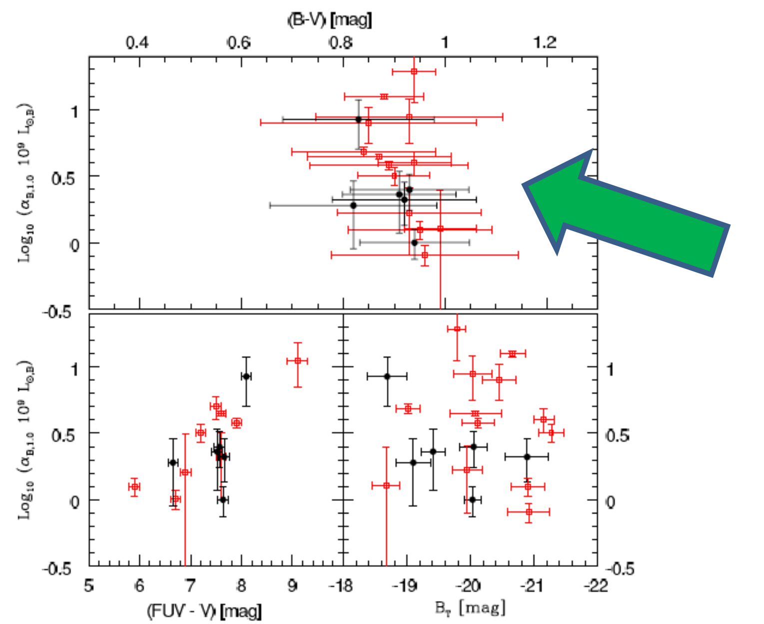


$\tau_{PN}$ can be estimated using $v_{exp}$ and $D_{PN}$, as $\tau_{PN} = D_{PN} / v_{exp}$

1. Motivation: PNs as distance indicators & tracers of stellar populations
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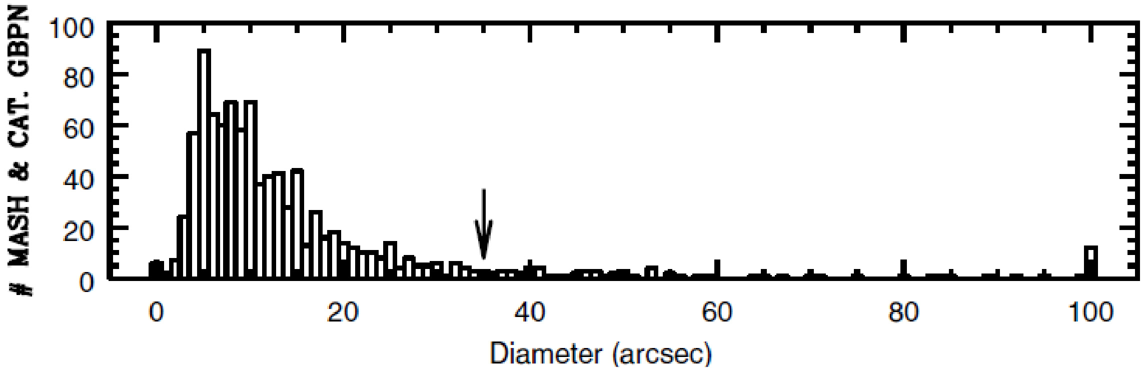
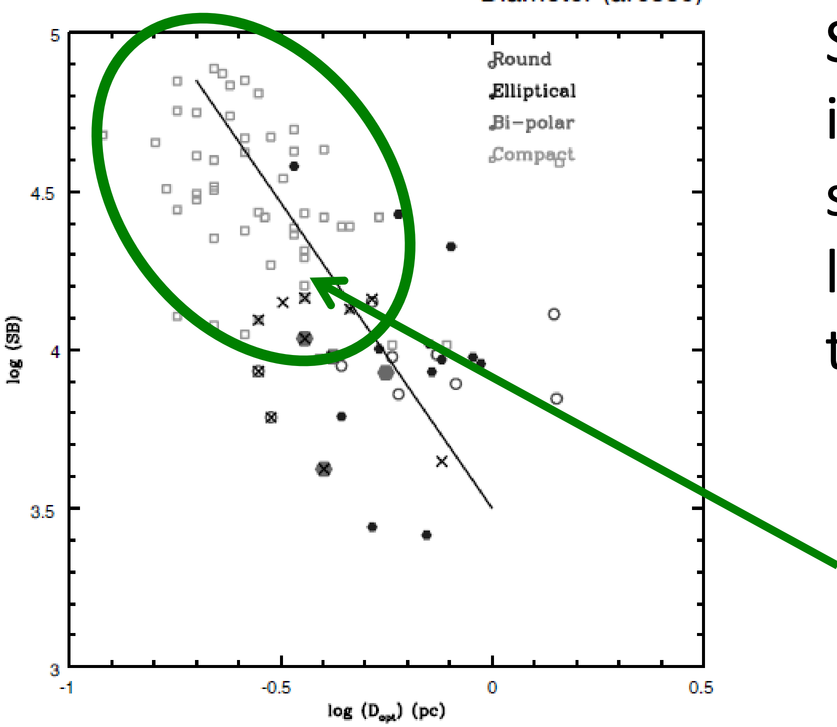
# The Galactic Bulge PNs




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.**

# The Galactic Bulge PNs

- There are 560 PN in the galactic Bulge with average diameter about 0.3 pc
- The average expansion velocity of Bulge PNs is 30 $kms^{-1}$
- $\tau_{PN}$ can be estimated using $v_{exp}$ and $D_{PN}$ , as $D_{PN} / v_{exp}$
- Thus the observable lifetime of a Galactic Bulge PN is then only a few $10^3$ years
- **Consistent with visibility lifetime for PN in early-type galaxies**

# 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, $\alpha$-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**

# 2. Surveys of PNs in the Local Group

| Name | Type | Mv | Dist. [kpc] | PNe 2006 | PNe 2011 | Ref (old) 2006 | Ref (new) 2011 |
|---|---|---|---|---|---|---|---|
| M31 | Sb | -21.2 | 785 | 2766 | 2766 | Merrett 2006 | |
| Milky Way | Sbc | -20.9 | | 2400 | 3000 | Acker *et al.* 1996 | Parker *et al.* 2006; Miszalski *et al.* 2008 |
| Andromeda I | IDsPH | -11.8 | 810 | | | | |
| Andromeda II | dSph | -11.8 | 700 | | | | |
| Leo A | dIr | -11.5 | 690 | 1 | 1 | Magrini *et al.* 2003 | |
| DD 210 | dIr | -11.3 | 1025 | | | | |
| Sag DIGD | dIr | -10.7 | 1300 | | | | |
| Pegasus II | dSph | -10.6 | 830 | | | | |
| Pisces (LGS3) | dIr | -10.4 | 810 | | | | |
| Andromeda V | dSph | -10.2 | 810 | | | | |
| Andromeda III | dSph | -10.2 | 760 | | | | |
| Leo II (Leo B) | dSph | -10.1 | 210 | | | | |
| Cetus* | dSph | -9.9 | 755 | | | | |
| Phoenix | dSph | -9.8 | 395 | | 1 | | Saviane *et al.* 2009 |

**PNs detected in 16 LG members**

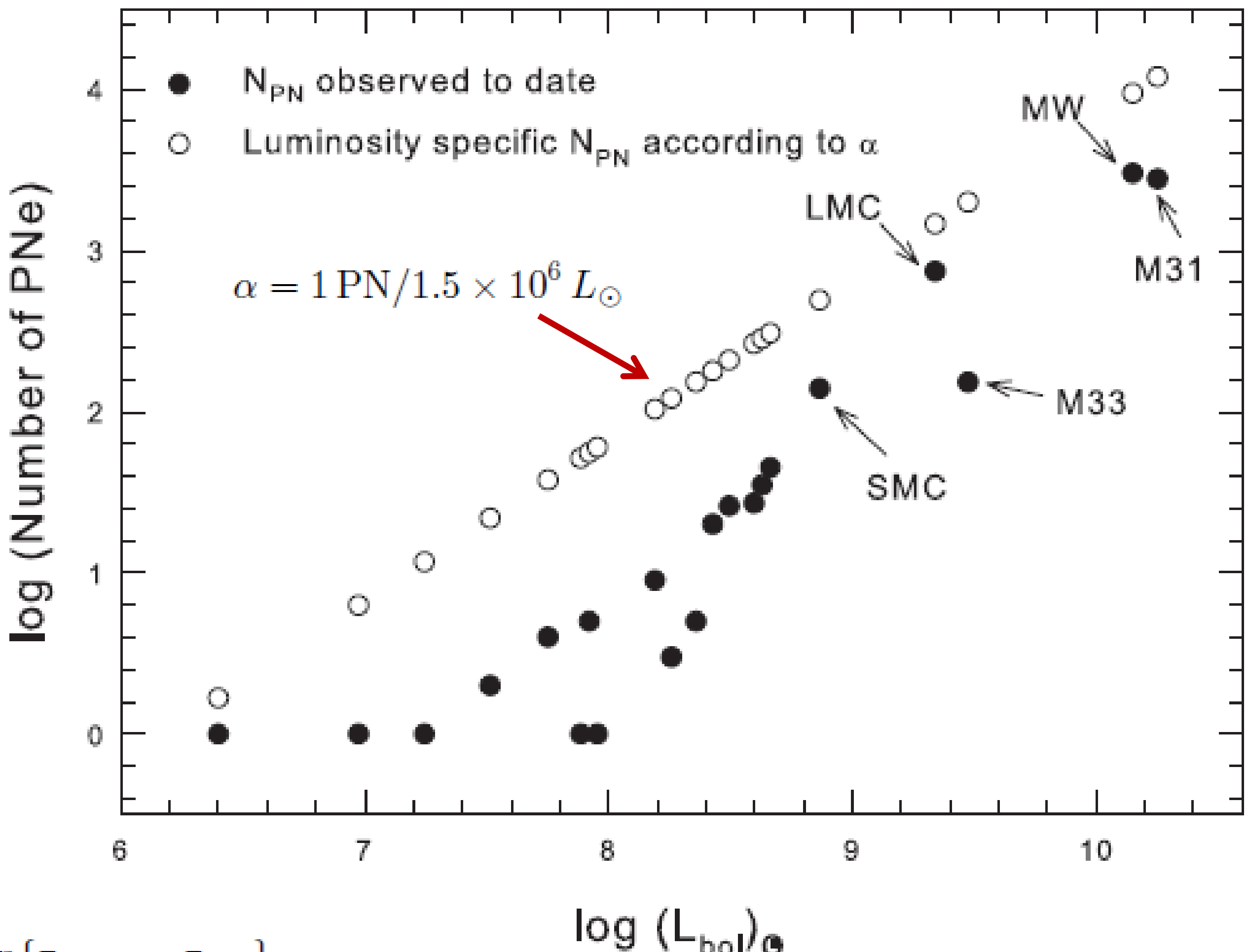
**There are no PN detected in LG galaxies with $M_V < -9.8$ ( $\approx 10^6 L_\odot$)!**

**Empirically, it is consistent with a maximum specific PN luminosity number of $\alpha_{max} < 1$ PN / $10^7 L_{bol,\odot}$**

# PNs populations in the Local Group

- PN populations in the LG galaxies, show systematic variations of the $\alpha$ values and the expansion velocity of the nebulas.

# PNs populations in the Local Group




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

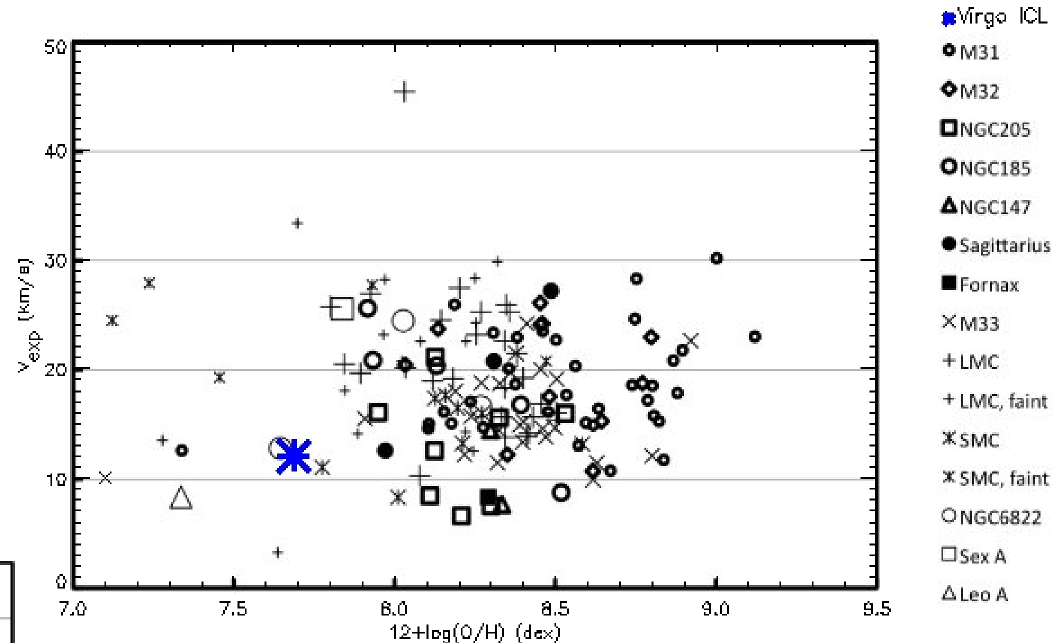
$$\alpha = \frac{N_{\rm PN}}{L_{\rm SSP}} = \beta\,\tau_{\rm PN} = \beta \min\{\tau_{\rm HPAGB}, \tau_{\rm dyn}\}$$

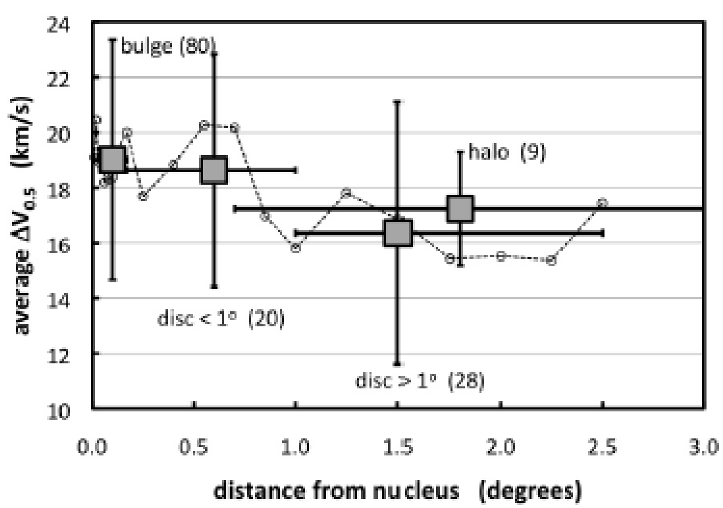
# PNs populations in the Local Group

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).



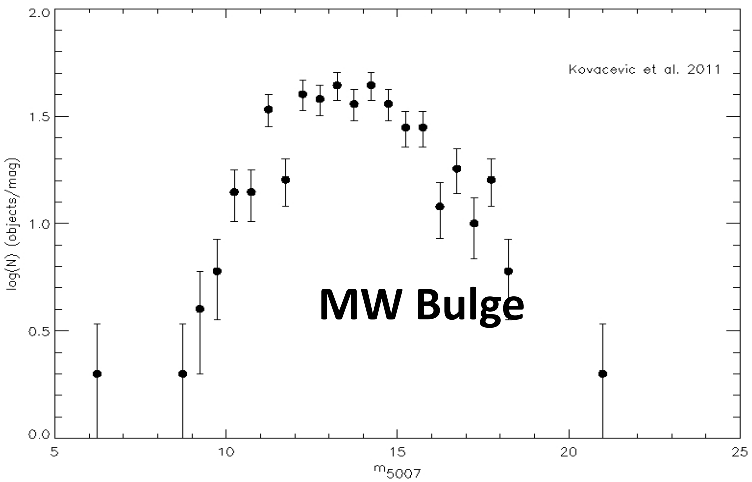

Expansion velocity of a PN is measured from $V_{HWHM}$ of the [OIII] 5007 emission.
Distribution of $V_{exp}$ for PNs in M31
PNLF at different radii in M31: strong deviations in the central region (Sarzi+2012)!

# PNs populations in the Local Group

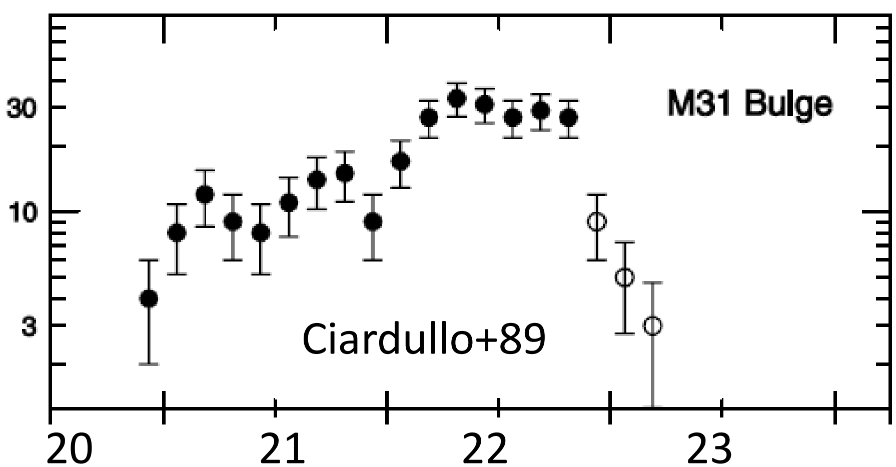
- PN populations in the LG galaxies, show systematic variations of the $\alpha$ values and expansion velocity of the nebulas.
- PNLFs show systematic variations: 1) gradient within 2.5 mag below brightest is negative/ flatter/steeper according to the star formation history and 2) presence of a dip within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

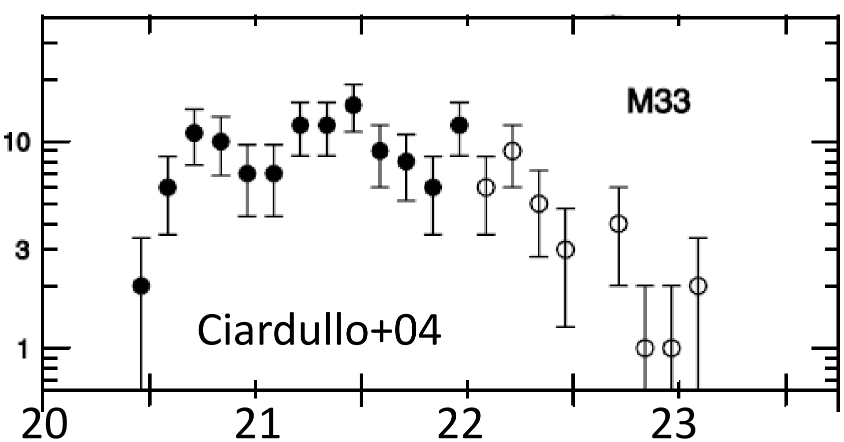
# PNs populations in the Local Group

## Different gradients in the PNLFs!



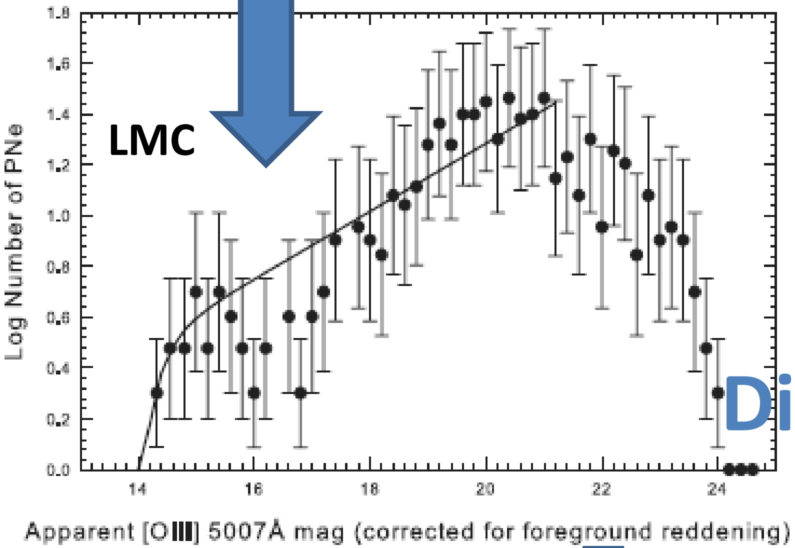

PN population from old metal rich /passive evolving stellar populations vs. intermediate metal poor star forming stars



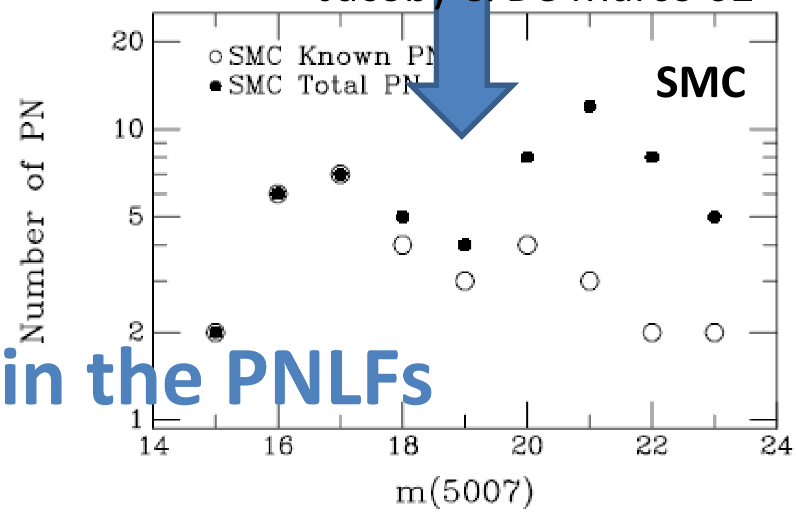



# PNs populations in the Local Group

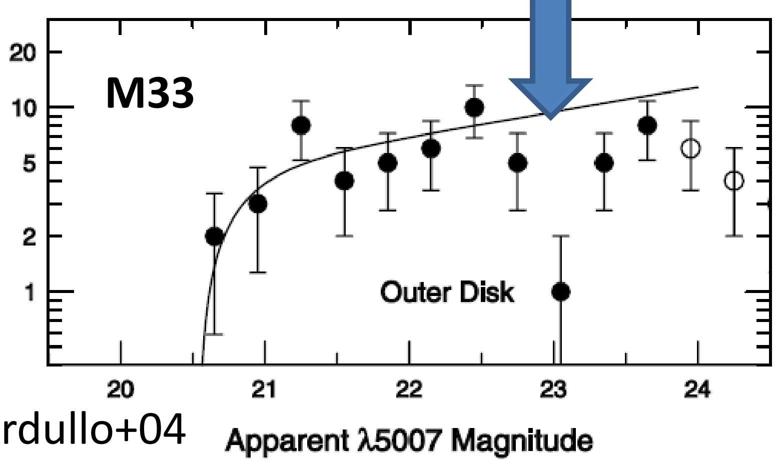
Reid & Parker10



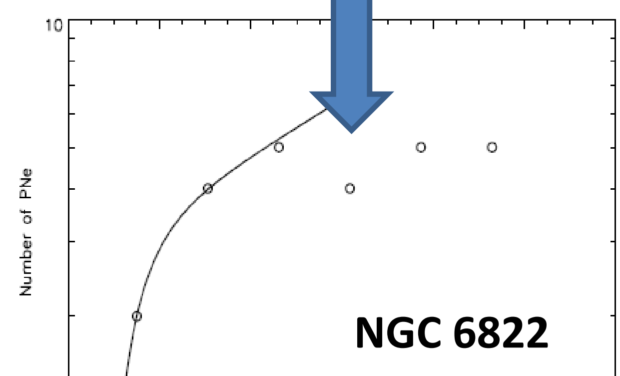

Jacoby & De Marco 02




Dip in the PNLFs




Ciardullo+04




Hernández-Martínez & M. Peña 09

# PNs populations in the Local Group

- PN populations in the LG galaxies show systematic variations of the $\alpha$ 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 gradients, dip, $\alpha$ value) to identify old/metal rich from star forming /metal poor stellar populations, when individual stars cannot be resolved (Arnaboldi et al. 2015).

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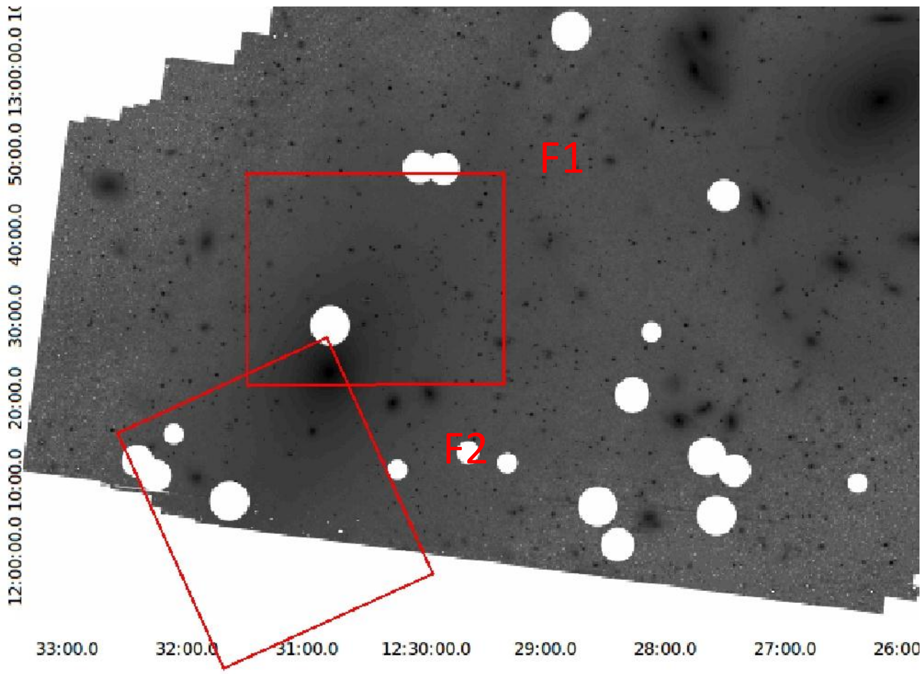
# The PN populations in the Virgo cluster core

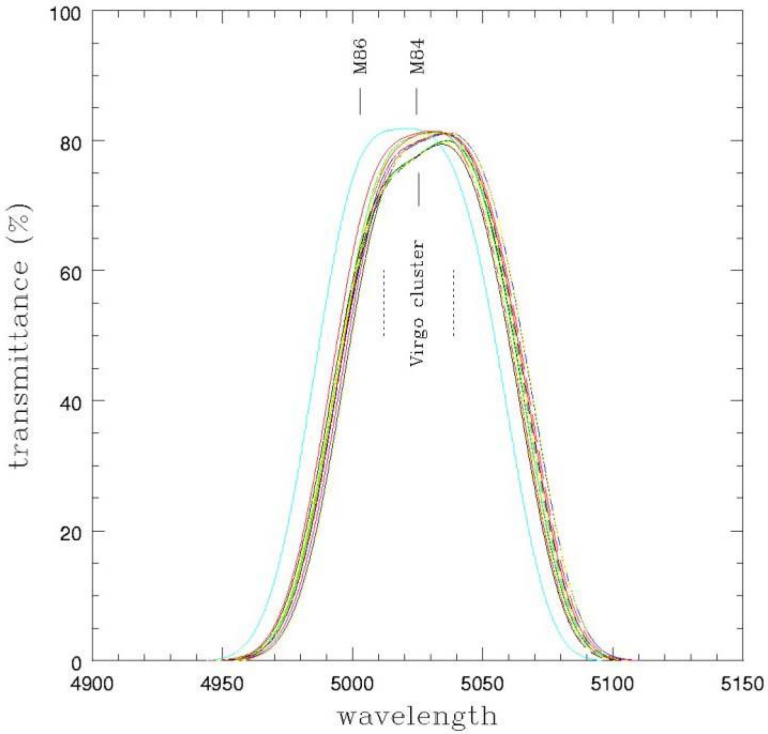
- In 2010 we started a project to study the dynamics and substructures of the M87 stellar halo using PNs as tracers, out to 150 kpc
- Imaging project with SuprimeCAM@Subaru to cover 0.5 $deg^2$ in the M87 outer halo.
- Deep [OIII] and deep off-band V images.
- Identify PN candidates as [OIII] point-like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

# 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

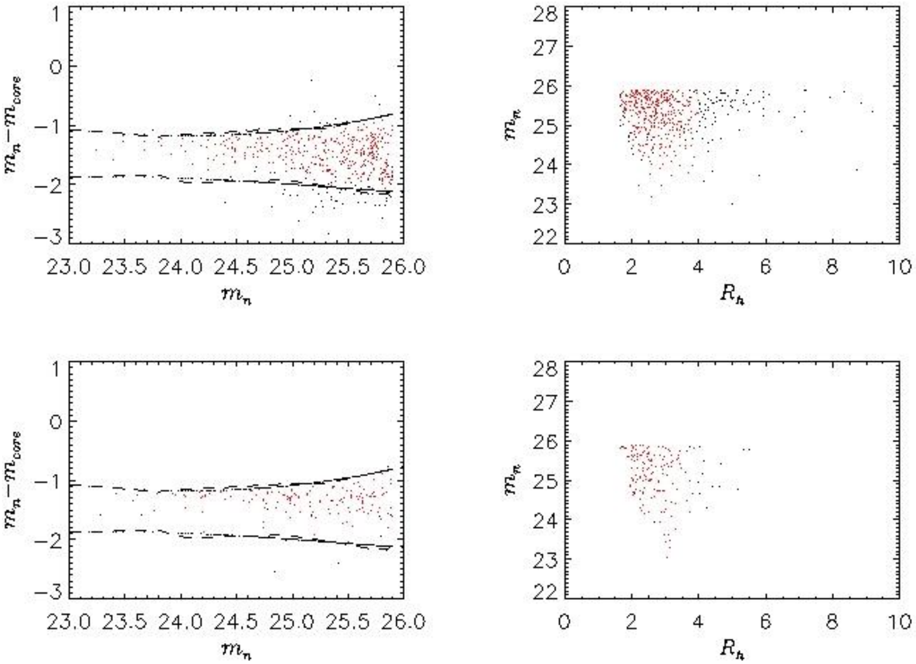



[OIII] filter transmission curve

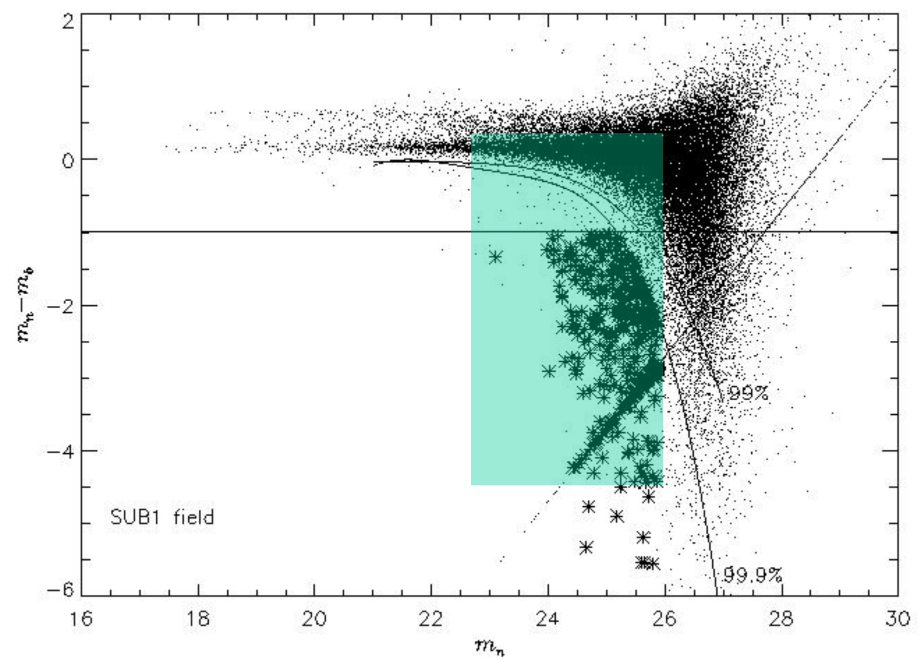


# PNs in the Virgo cluster core

- 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

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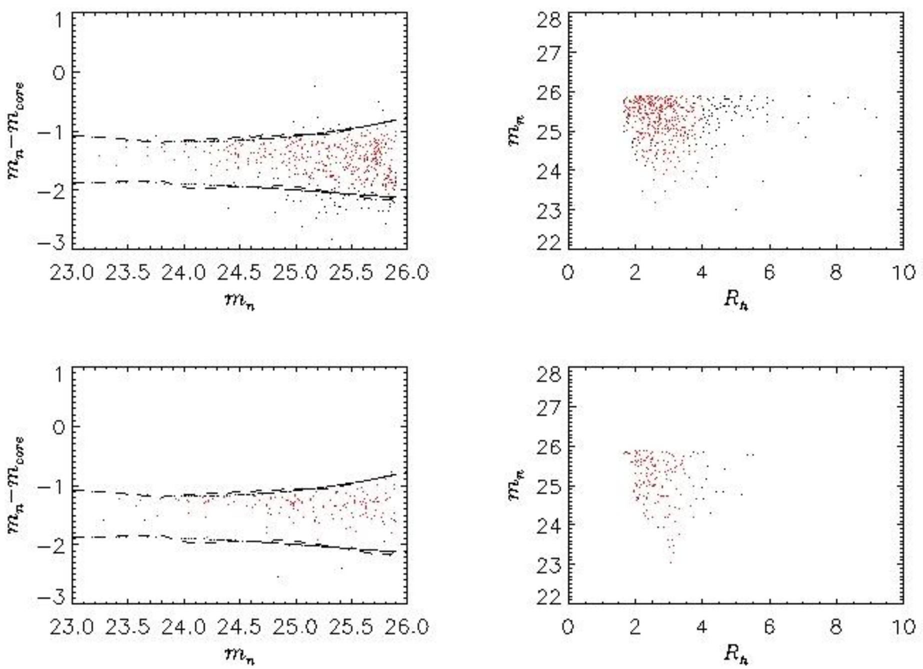


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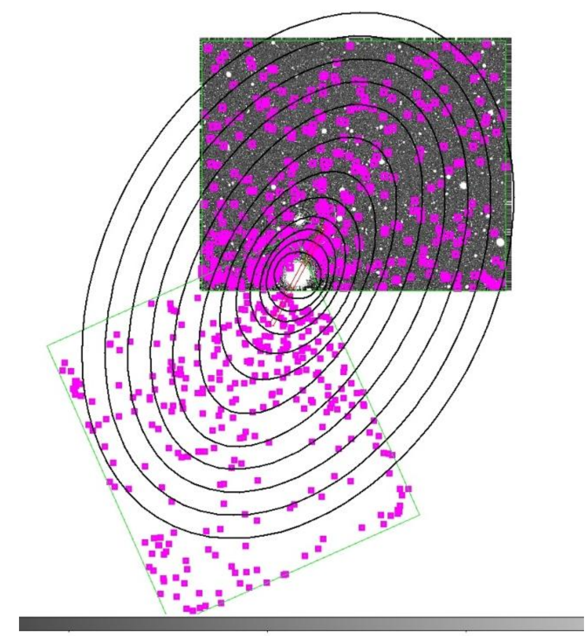
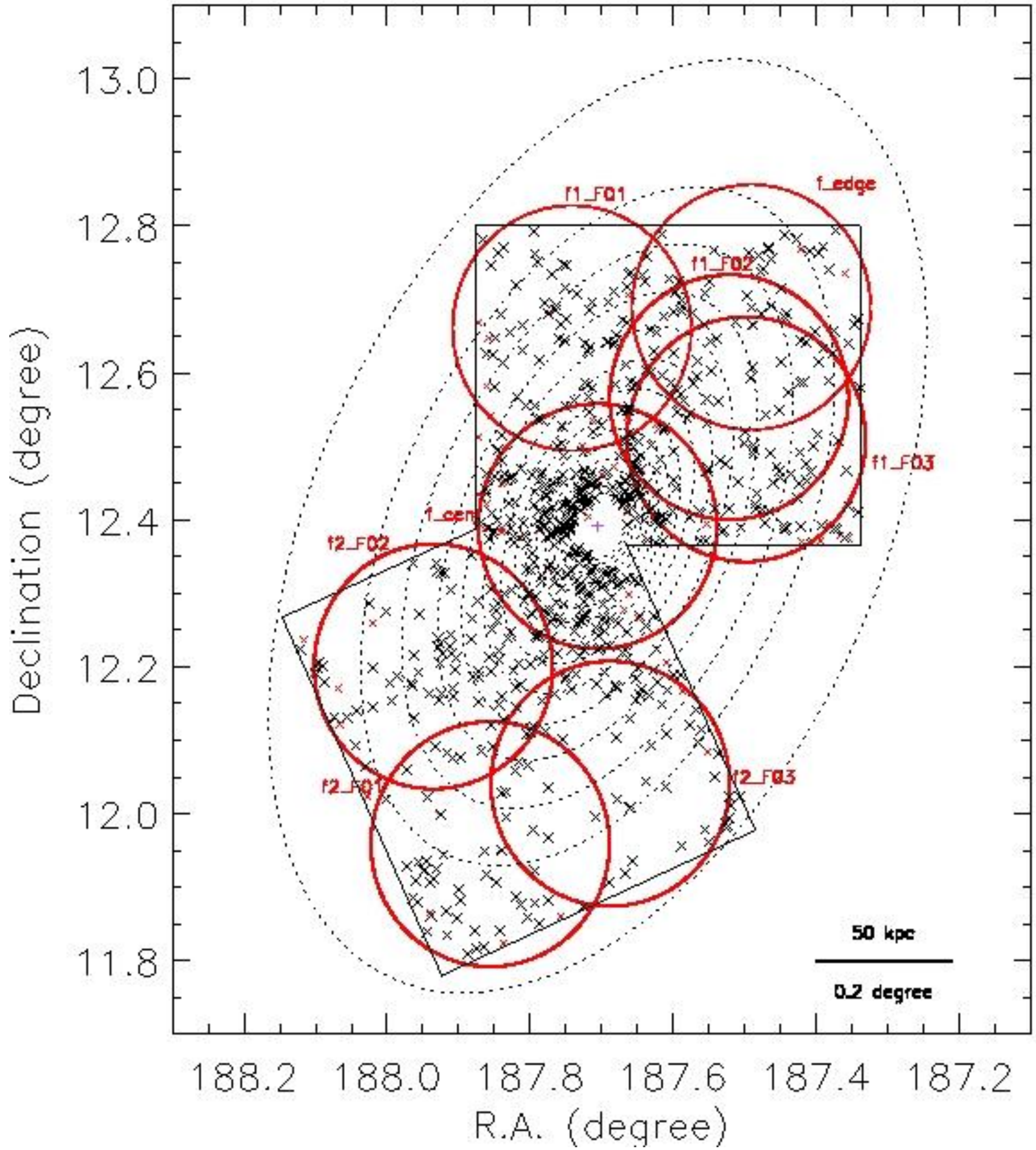


Distribution of PN candidates in the M87. Ellipses show isophote contours

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

Additional 12 PNs from D09



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

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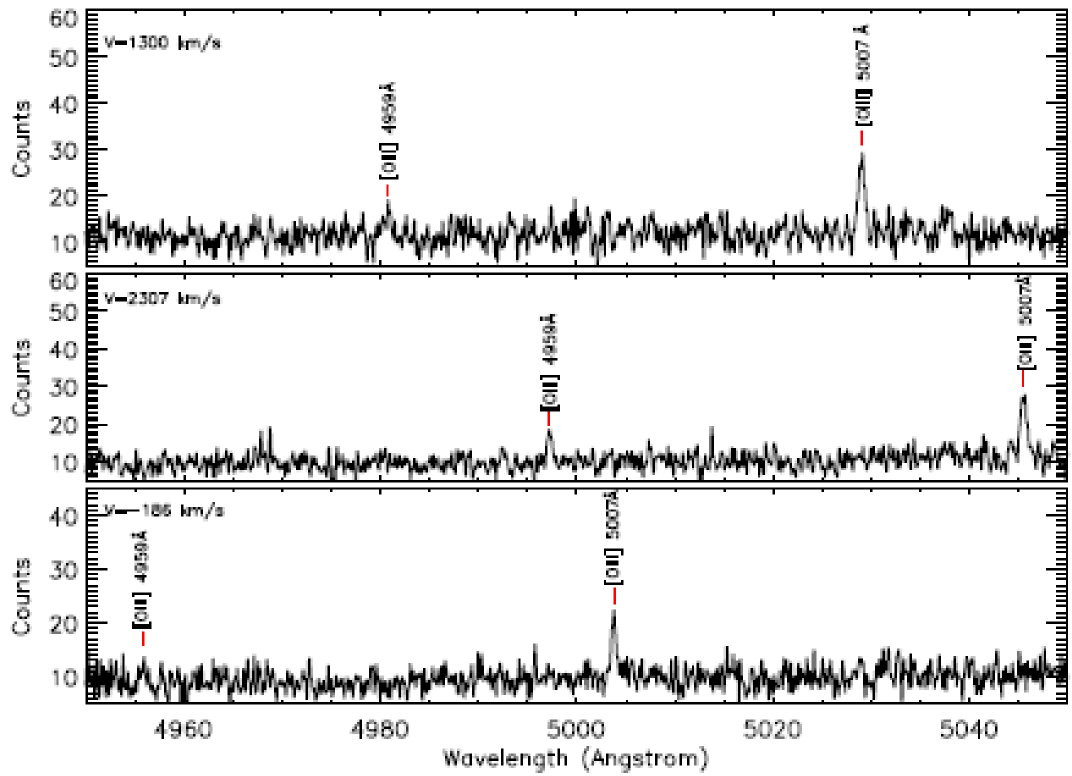



Single PN spectra – From Longobardi+2015

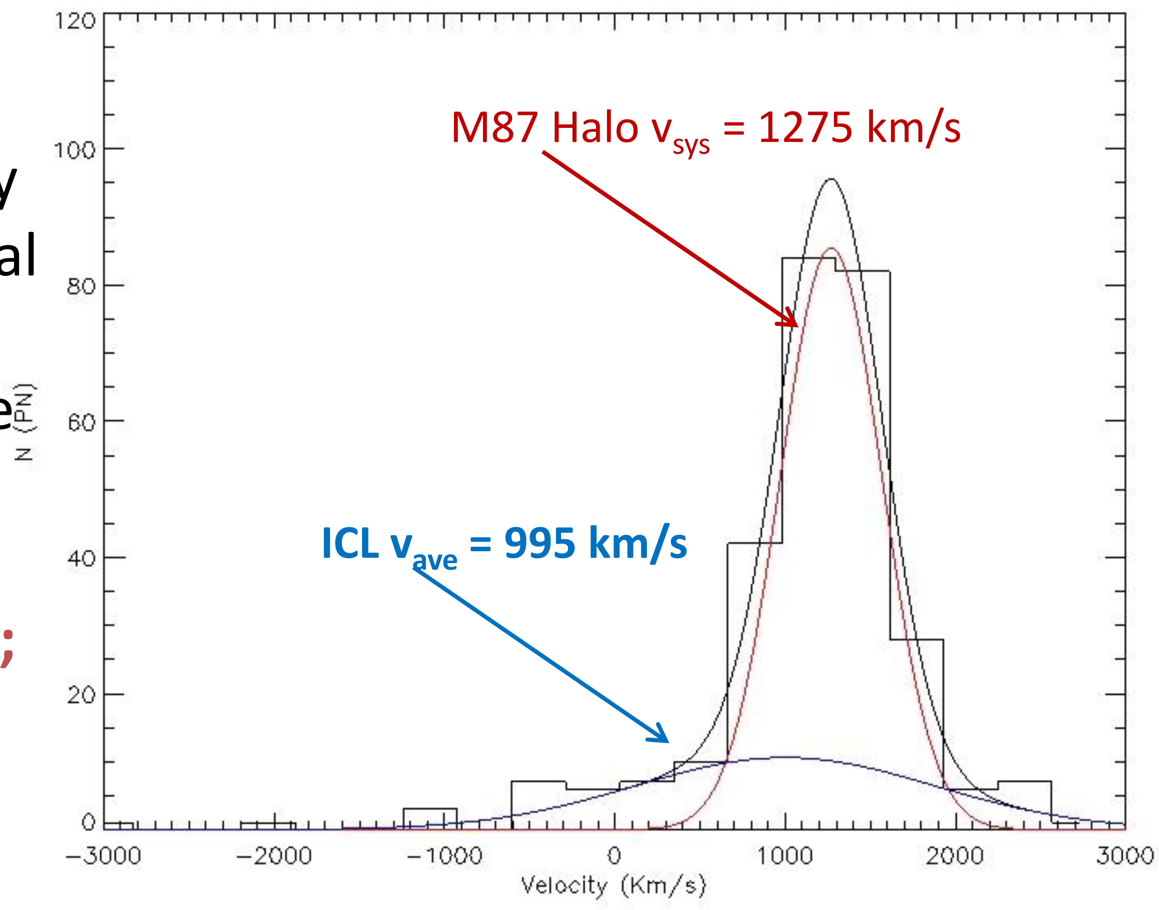
# PNs in the Virgo cluster core

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

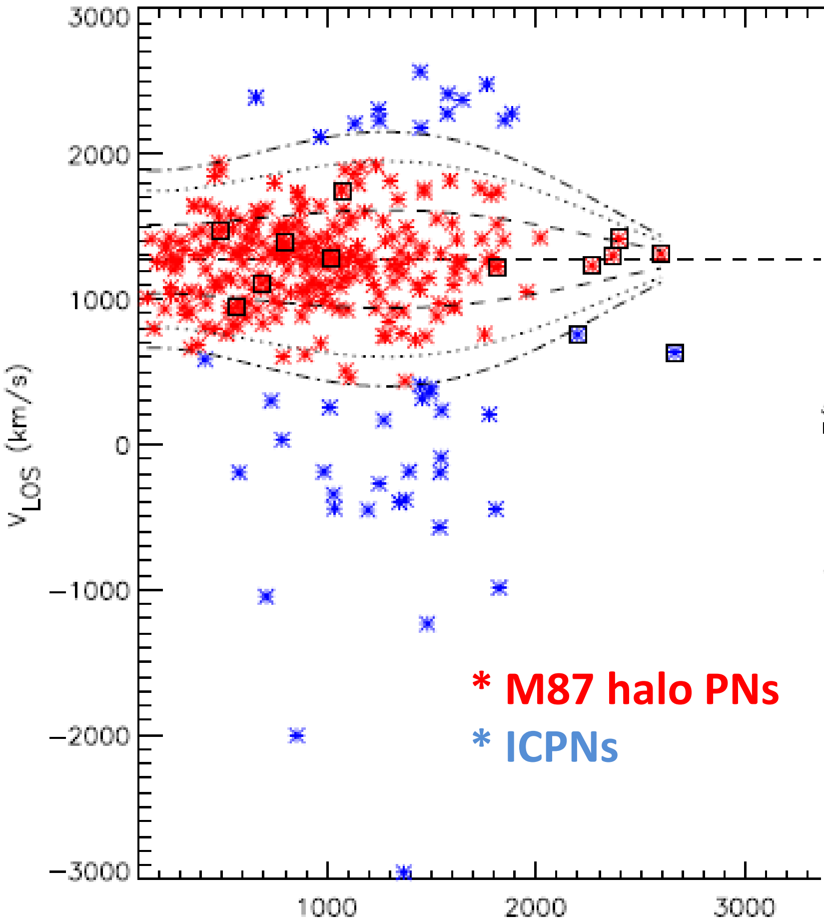
**Red Gaussian : M87 halo; 244 PNs**

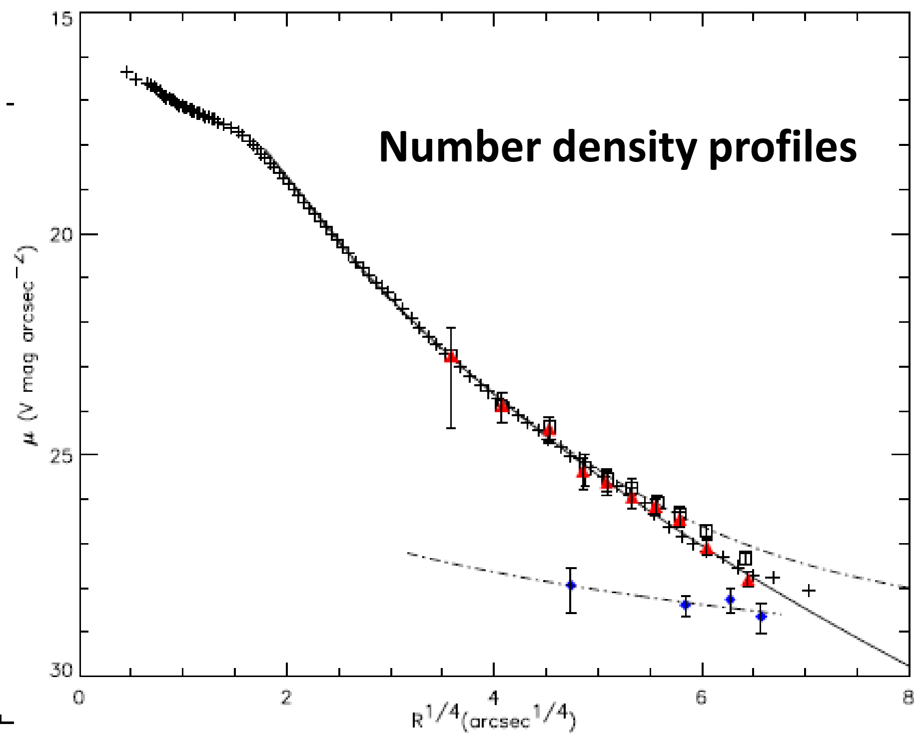
**Blue Gaussian: ICL in Virgo core; 45 ICPNs**



# PNs in the Virgo cluster core

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

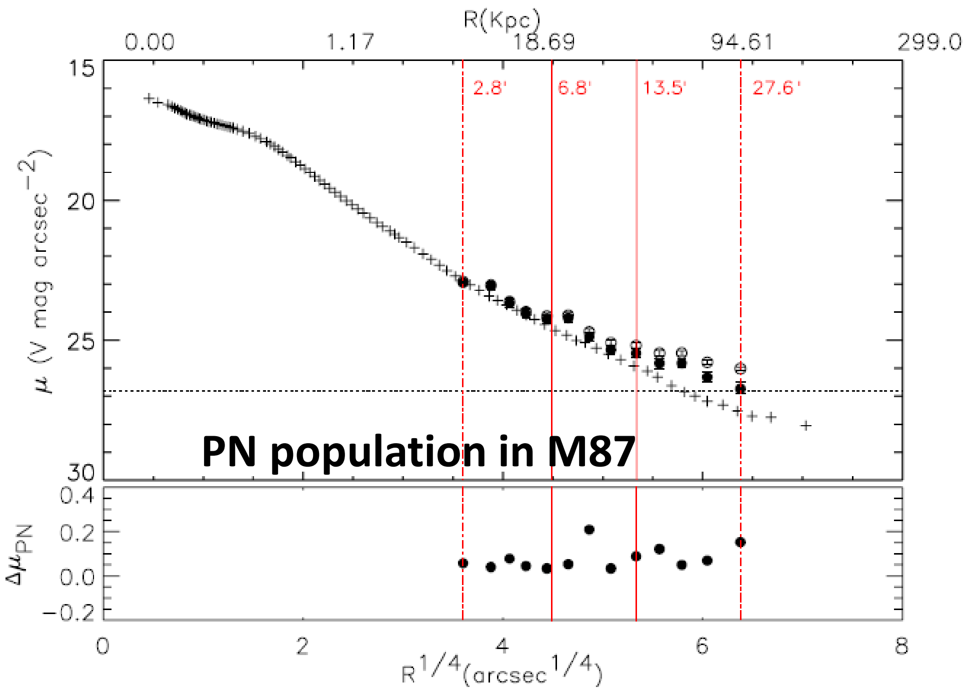


# PNs in the Virgo cluster core

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

# PNs in the Virgo cluster core




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

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

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

Two component photometric model

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

The α values translate into different PN visibility lifetimes:

**$\tau_{PN}$=1.4 $10^4$ yr in ICL and 4.5 $10^3$ yr in M87 halo.**

$Z_{halo} \cong -0.3$

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

# PNLF in M87

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

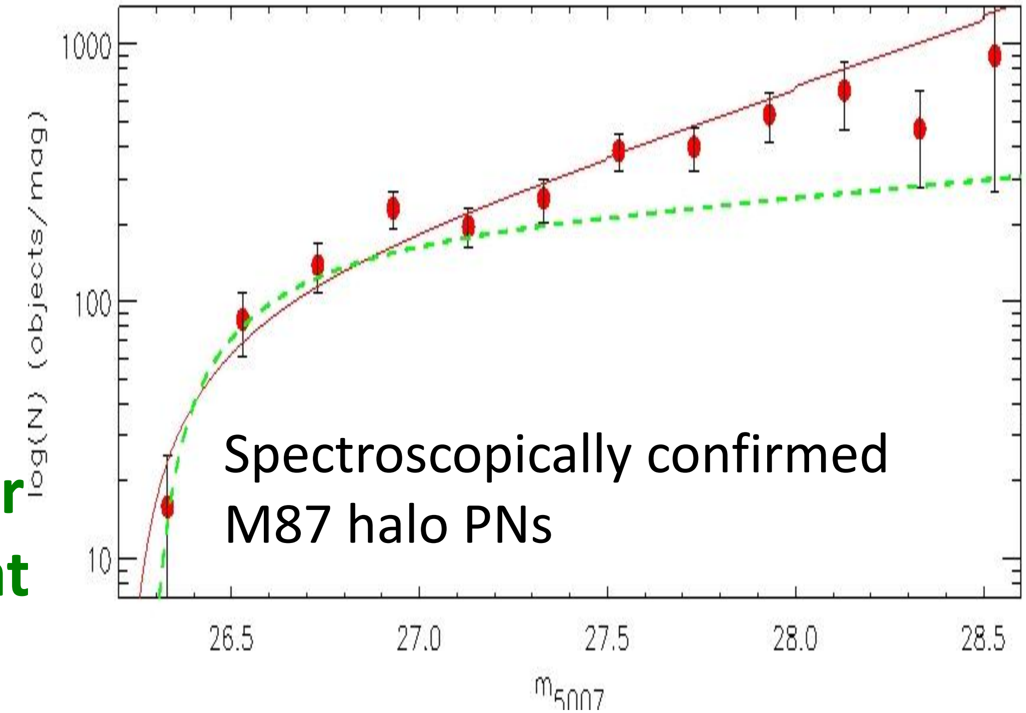
$N(M) = \mathbf{c_1} e^{\mathbf{c2}M}(1-e^{3(M^*-M)})$;

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

**$C_1$ is related to $\alpha$ at first order**

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

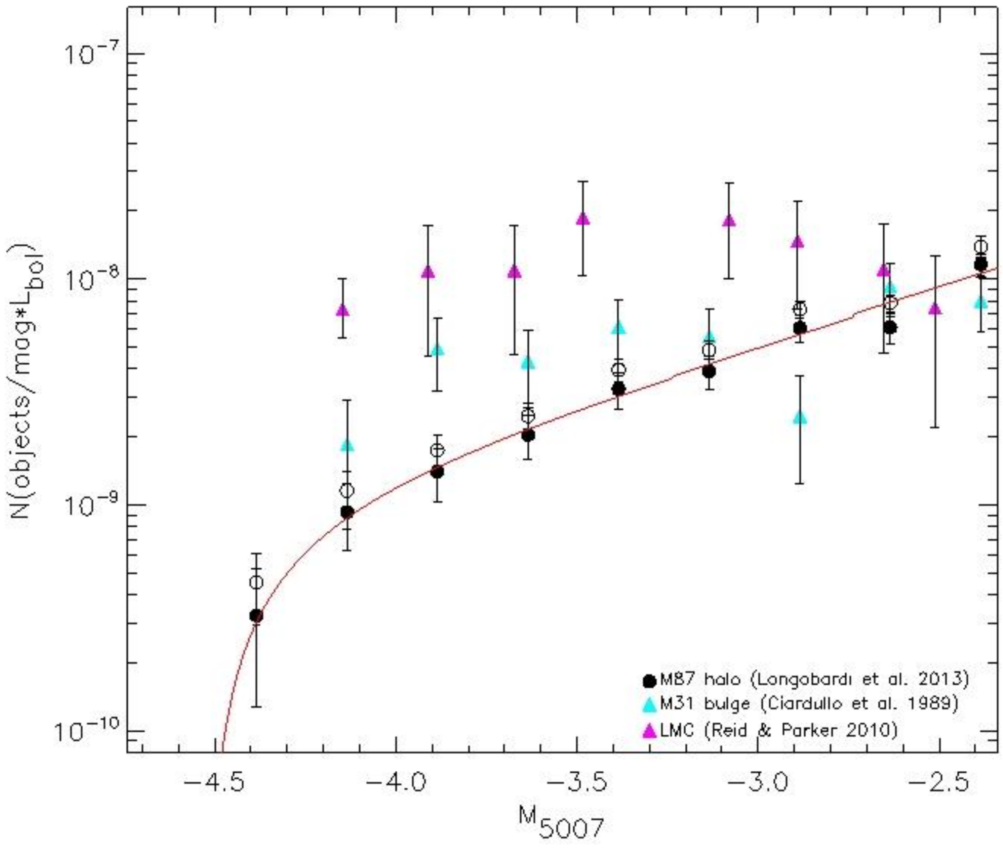
Longobardi et al. 2013, A&A, 558, 42




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

# PNLF in M87 halo

- PNLFs from different stellar populations
- Complete to 2.5 mag down the PNLF cut-off
- Normalize them by $L_{bol,\odot}$ of the light, in the same region where PNs are detected.
- PNLF for **LMC**, **M31** and **M87**




**M* is invariant, but gradient changes!**

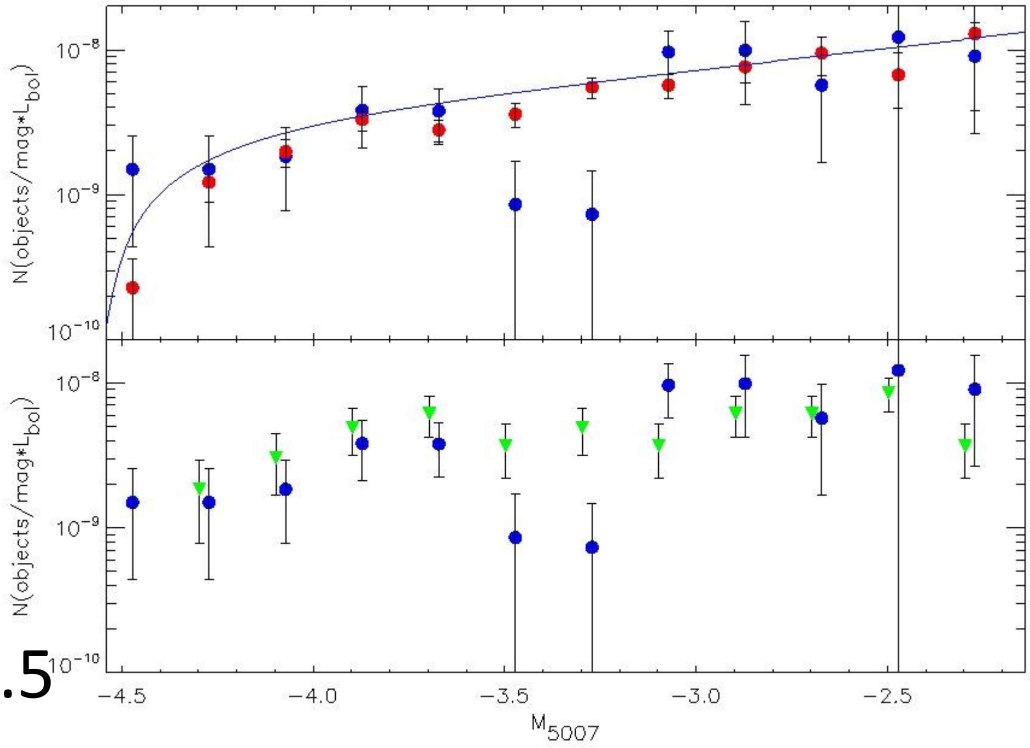
(Arnaboldi, Longobardi, Gerhard in prep.)

# PNLF in Virgo ICL

PNLF normalized by total bolometric luminosity of parent stellar population:

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

**ICL PNLF** shows dip at 1-1.5 mag below brightest. Such a evolutionary feature is observed in PNLF populations of star forming galaxies.




**Spectroscopically confirmed ICL PNs**

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

# 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 ($\alpha$), PN visibility lifetime $\tau_{PN}$, and the PNLF shape (gradient, dip) are functions of the star formation history and metallicity of the parent stellar population.
- The M* at the bright cut off is invariant!
- In the Virgo core, there are two distinct PN populations: the halo PNs and ICPNs.
- <u>The PN progenitors the Virgo core ICL are from fading star forming/metal poor populations, different from M87 halo stars!</u>