Intracluster Planetary Nebulae

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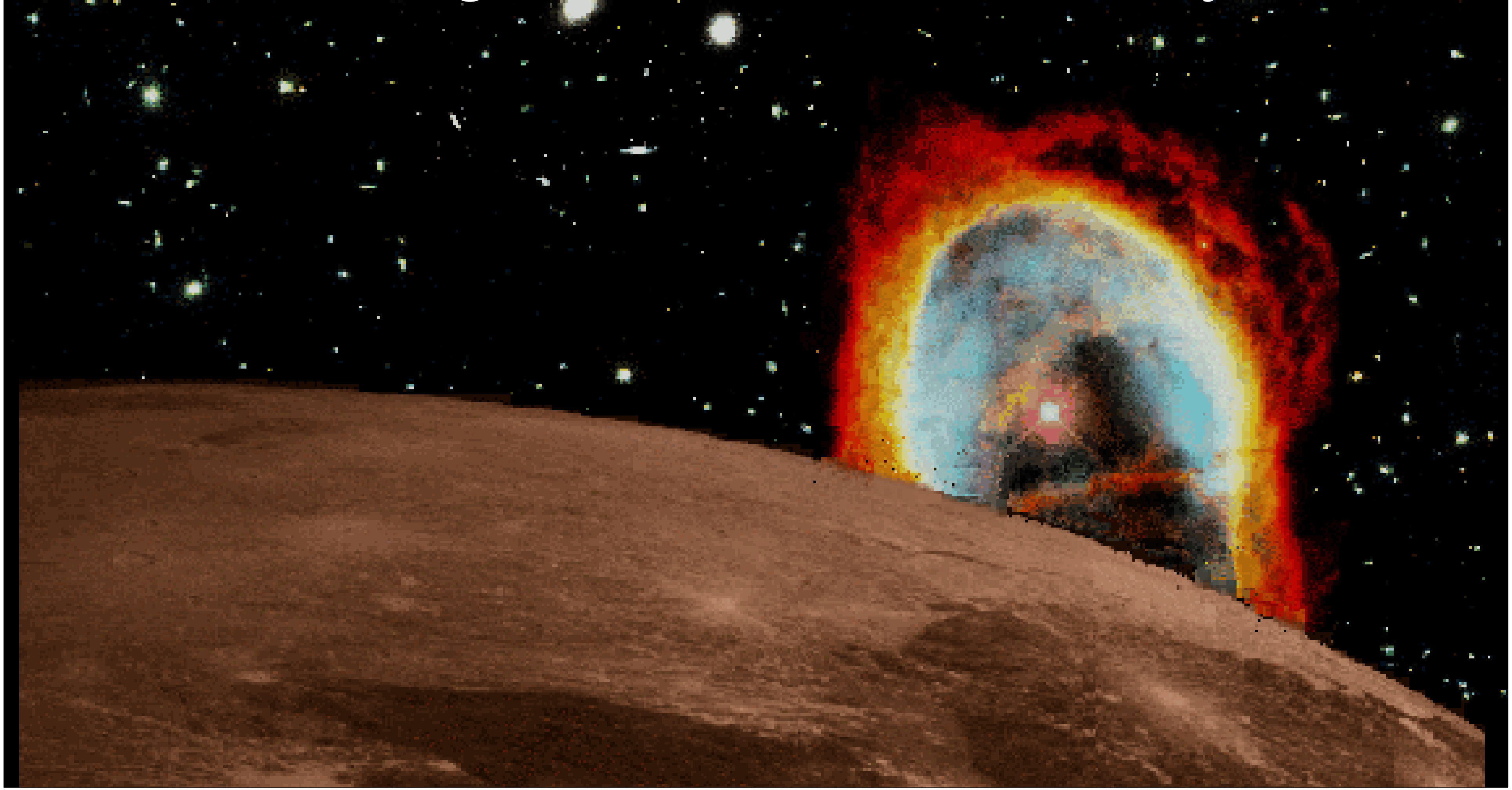

Collaborators: Robin Ciardullo (PSU), George Jacoby (WIYN), Pat Durrell (YSU), Chris Mihos (CWRU), Kelly Holley-Bockelmann (PSU), Heather Morrison (CWRU), Paul Harding (CWRU), Ben Williams (PSU), Caryl Gronwall (PSU), Steinn Sigurdsson (PSU)

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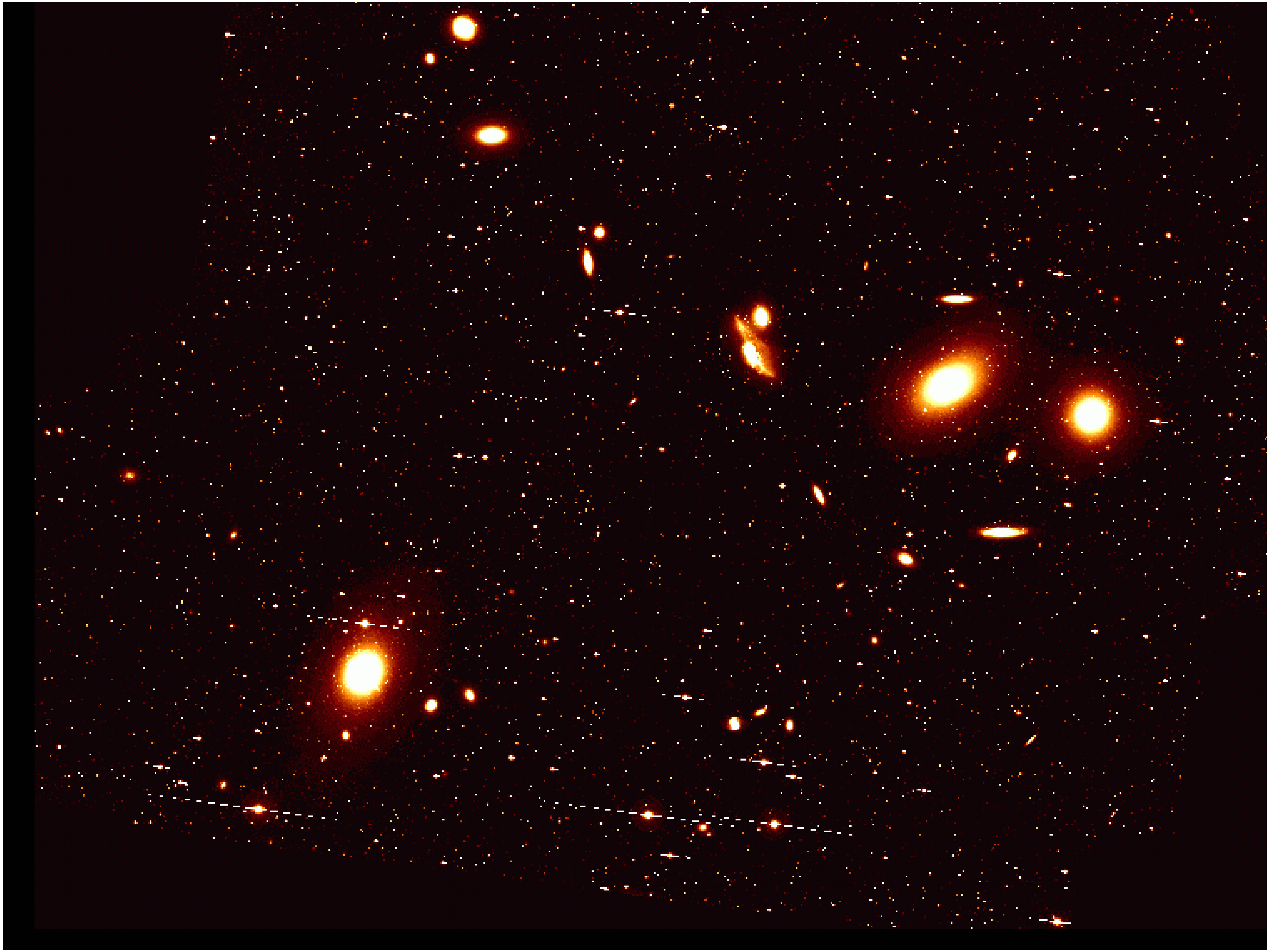
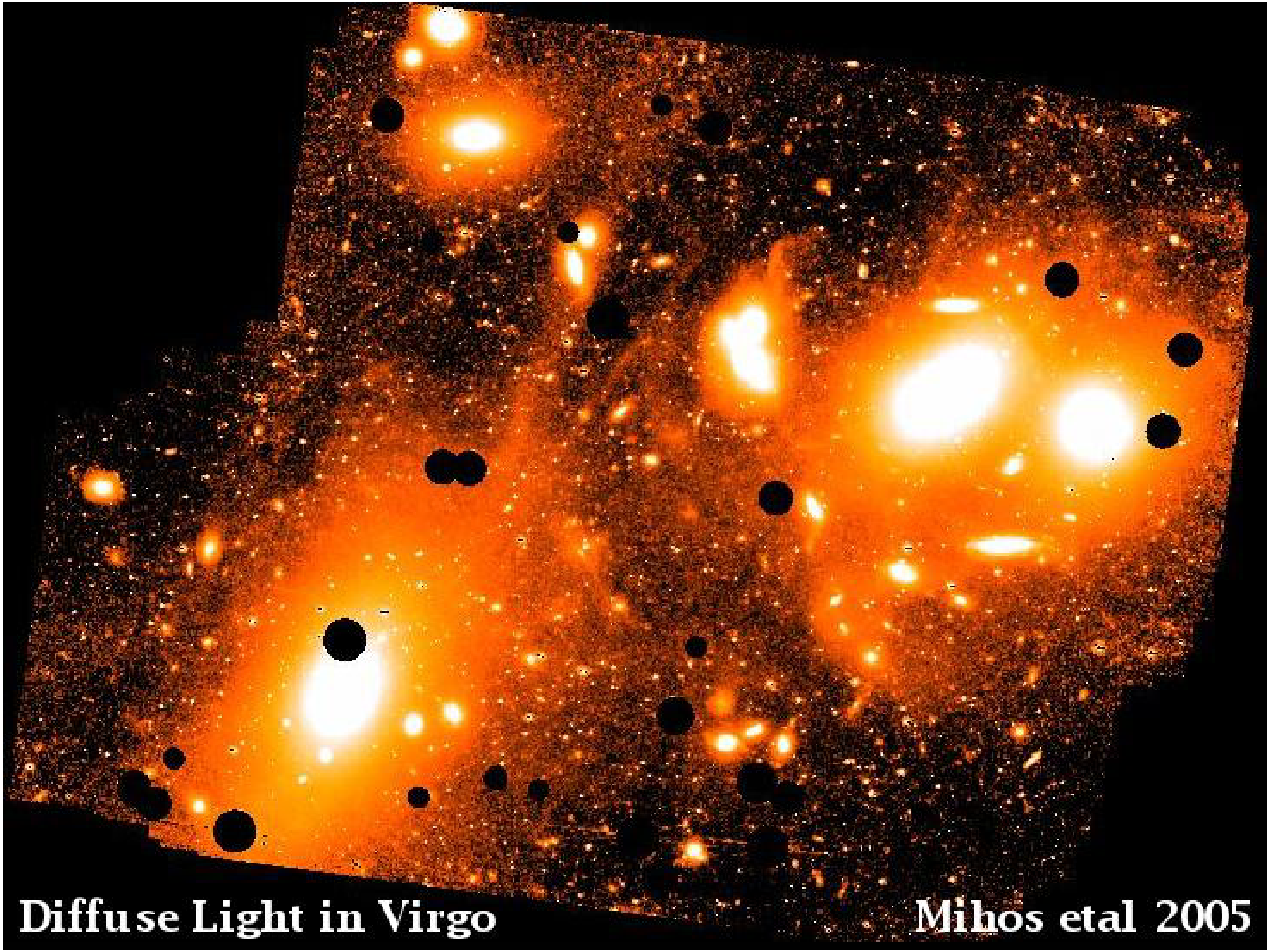
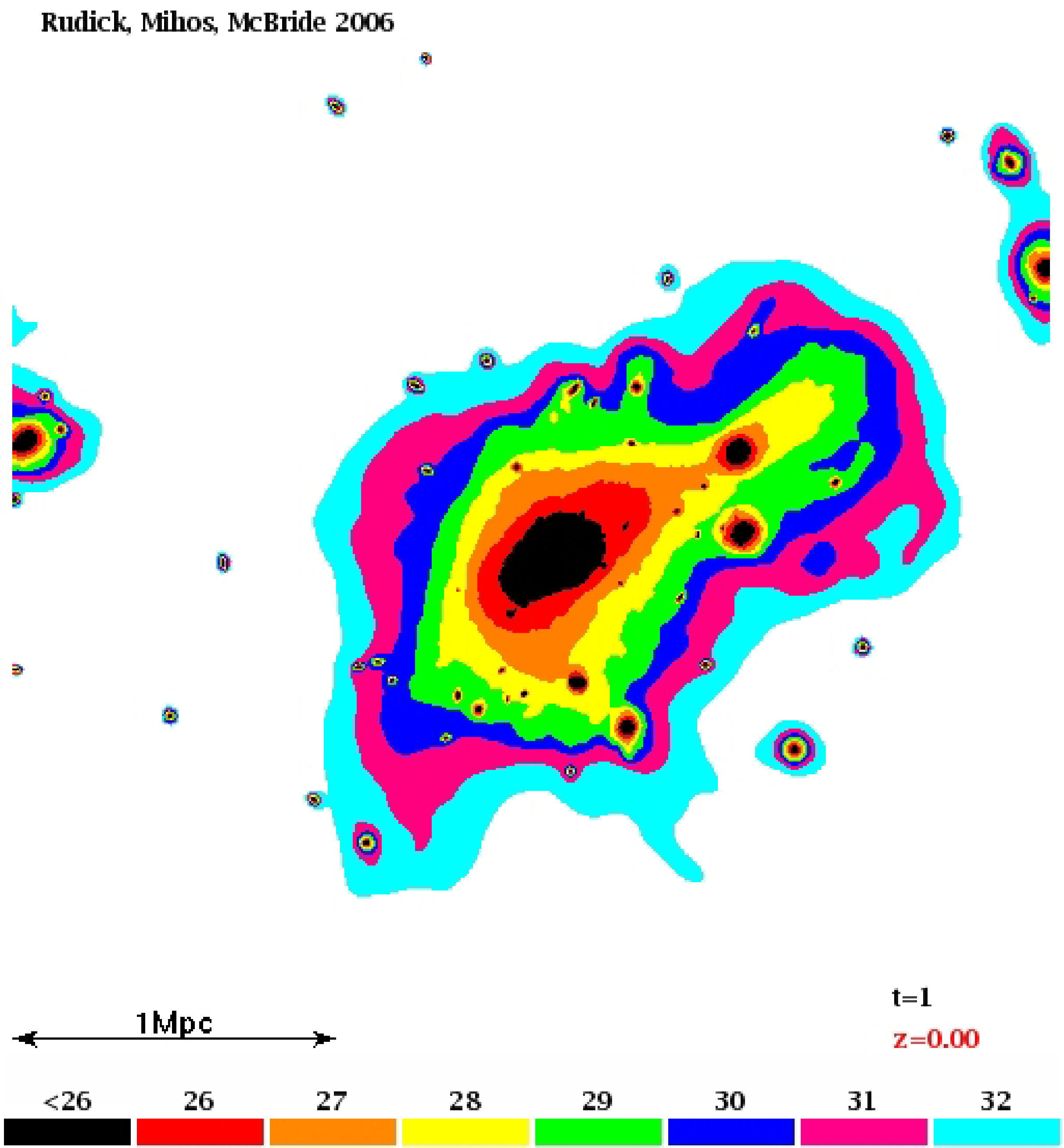



Diffuse Light in Virgo
Mihos etal 2005



Models by:

Rudick, Mihos & McBride (2006),

Stanghellini, Gonzales-Garcia, Manchado (2006),

Sommer-Larsen et al. (2005),

Murante et al. (2004),

Willman et al. (2004), and

Napolitano et al. (2003)

show that intracluster light is common in galaxy clusters

However, direct imaging observations are incredibly time-consuming and do not probe the lowest surface brightness features!

Detection of individual intracluster stars:

- Intracluster Red Giants – thousands of candidates found in Virgo (Ferguson, Tanvir, and von Hippel 1998; Durrell et al. 2002; Williams et al. 2006)

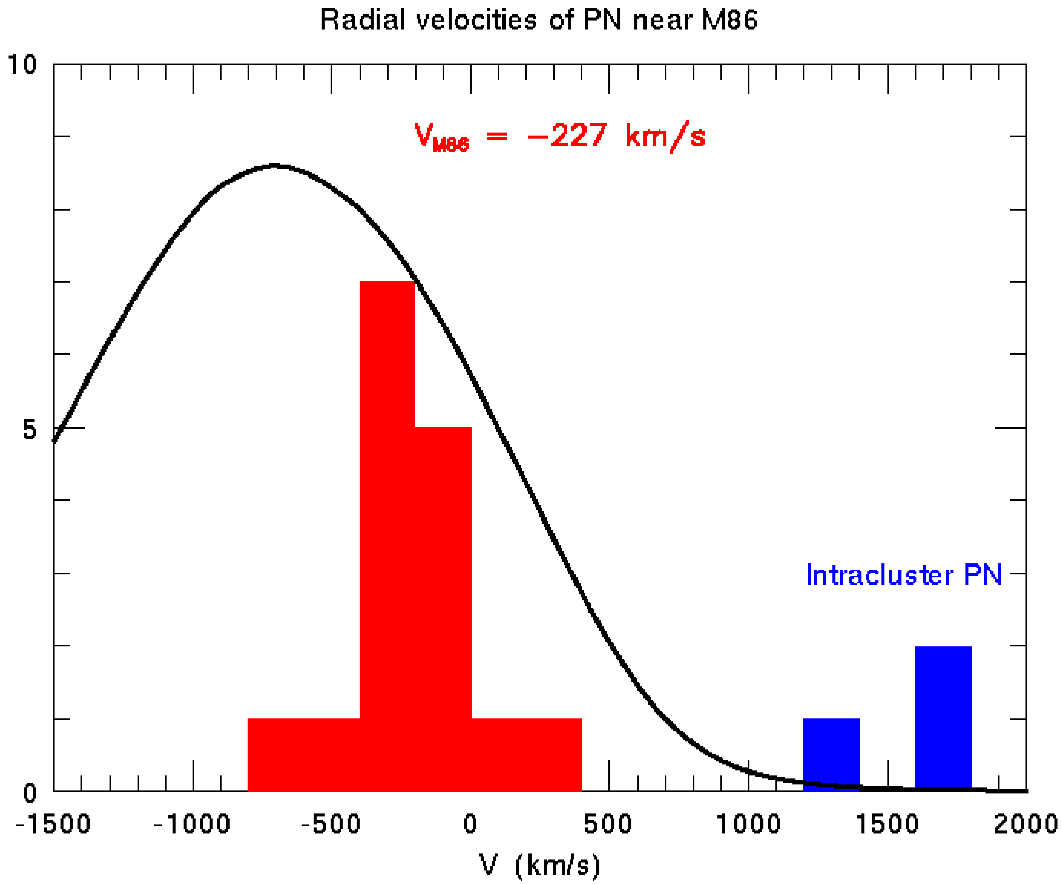
- Intracluster HII regions, Intracluster Novae and Intracluster Supernovae – Found in Virgo, Fornax, and more distant clusters and groups (Gerhard et al. 2002; Ryan-Weber et al. 2004; Gal-Yam et al. 2003; Neil, Shara, & Oegerle 2005)

- Intracluster Planetary Nebulae

Some Advantages of Intracluster Planetary Nebulae (IPN)

1. Since IPN are luminous emission objects, they can be detected by 4-m class and larger telescopes from the ground. – large surveys are possible
2. The number of PN is proportional to the amount of stellar luminosity within a field, making it possible to measure the amount of the intracluster starlight.
3. With spectroscopic follow-up, the IPN’s radial velocities can be measured, leading to dynamical studies of intracluster starlight

History of Intracluster Planetary Nebulae - 1



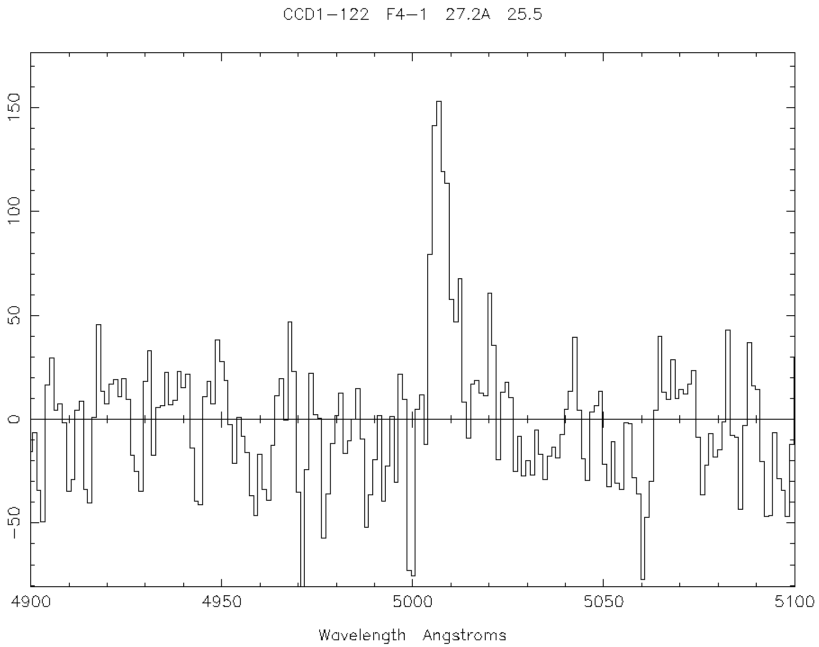
Arnaboldi et al. (1996) – First time “Intracluster Planetary Nebulae” enters the literature

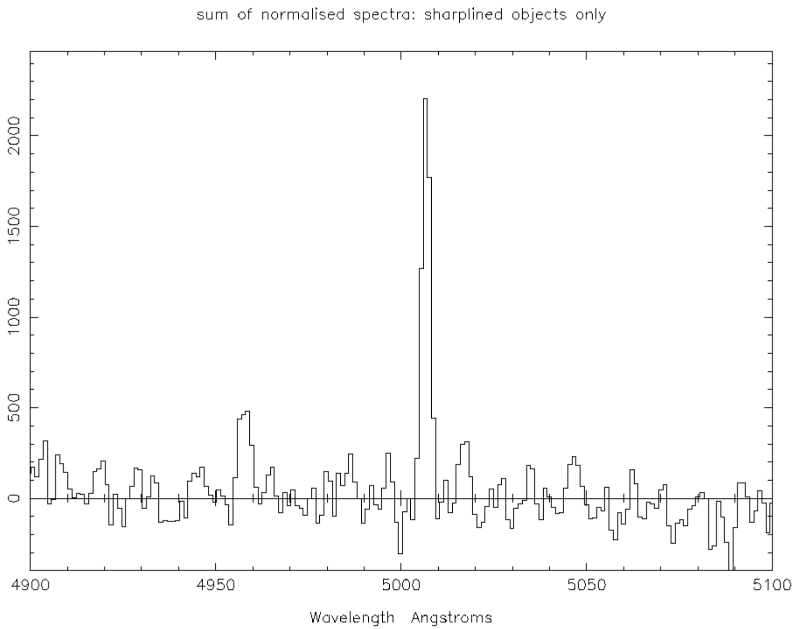
(see also Theuns & Warren (1997), Fornax IPN)

History of Intracluster Planetary Nebulae - 2

Follow-up observations confirmed large numbers of IPN candidates in Virgo

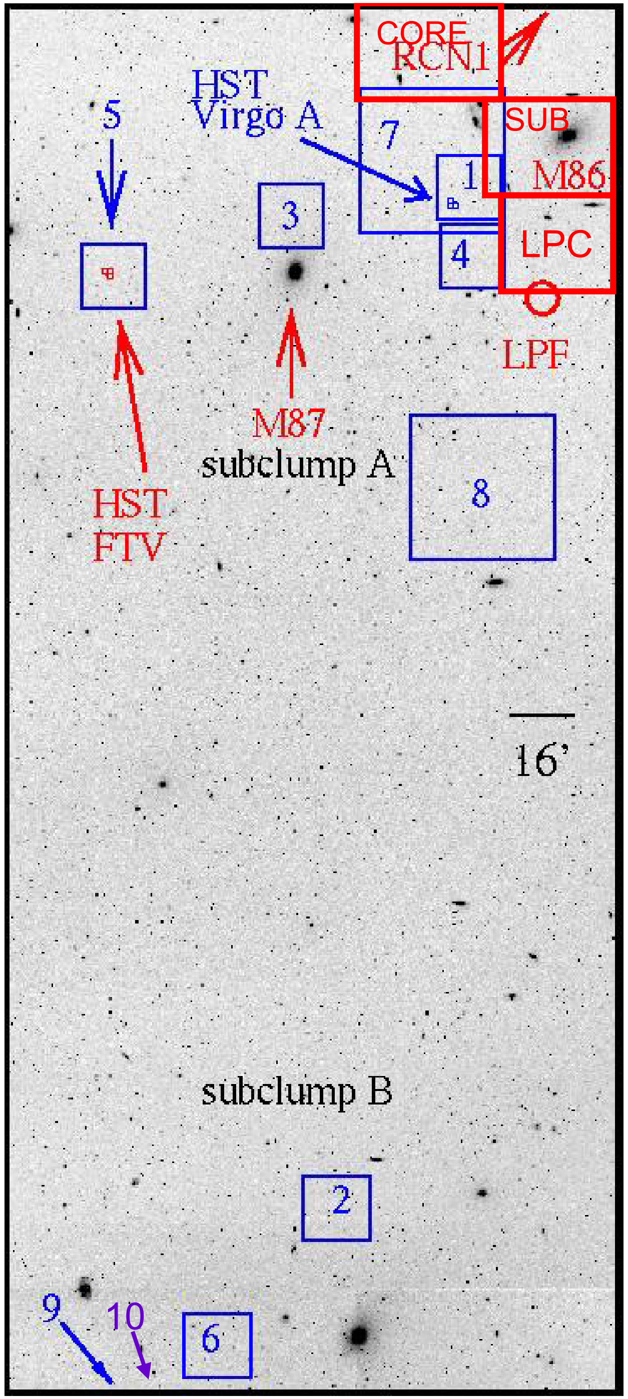
(Mendez et al. 1997; Ciardullo et al. 1998; Feldmeier, Ciardullo, & Jacoby 1998)





However, surveys for IPN are not pristine. There is contamination from background sources (most notably Lyman-alpha galaxies at z=3.13)

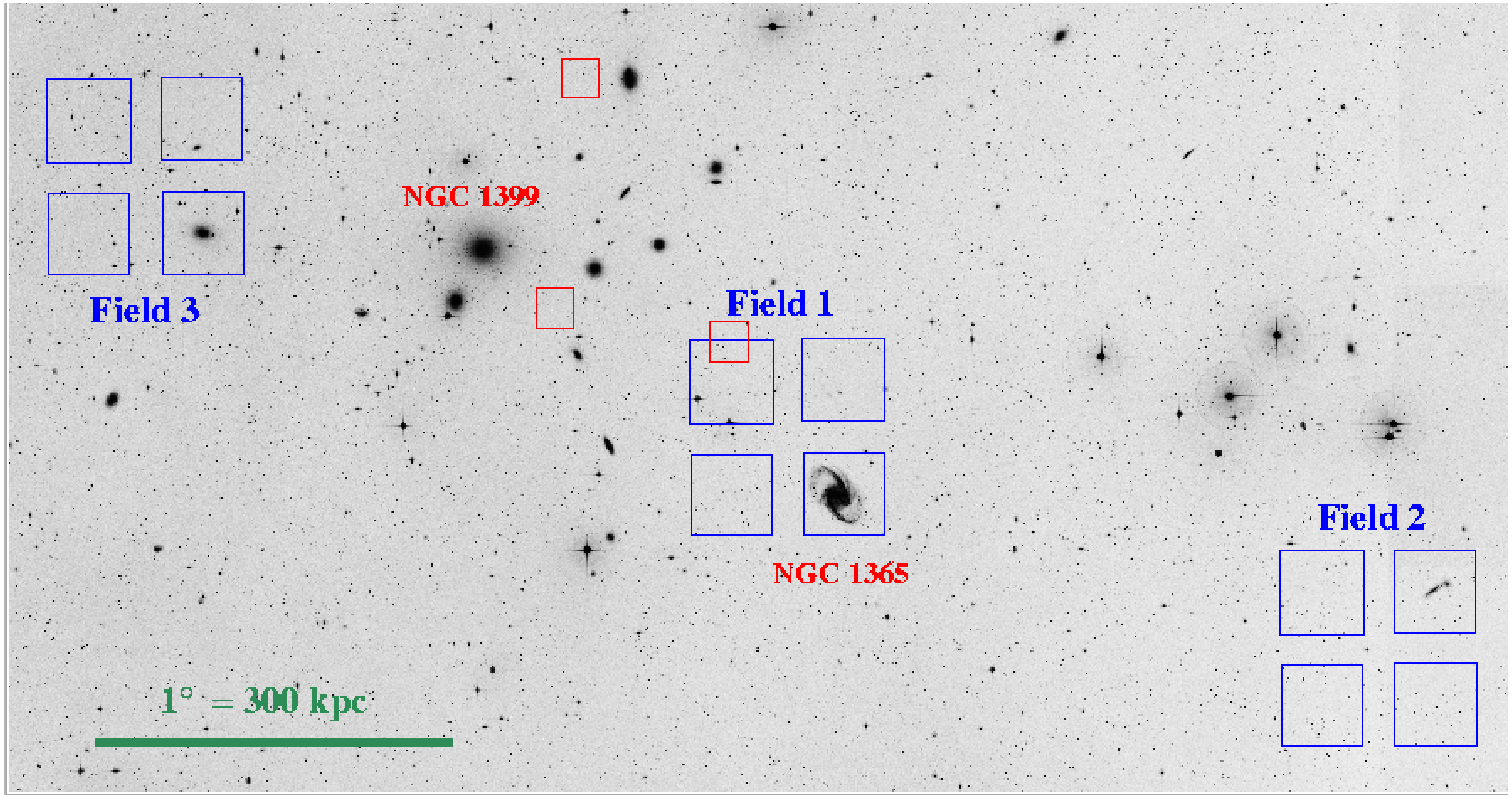
See Kudritzki et al. 2000; Freeman et al. 2000



Virgo Cluster results (D = 15 Mpc)

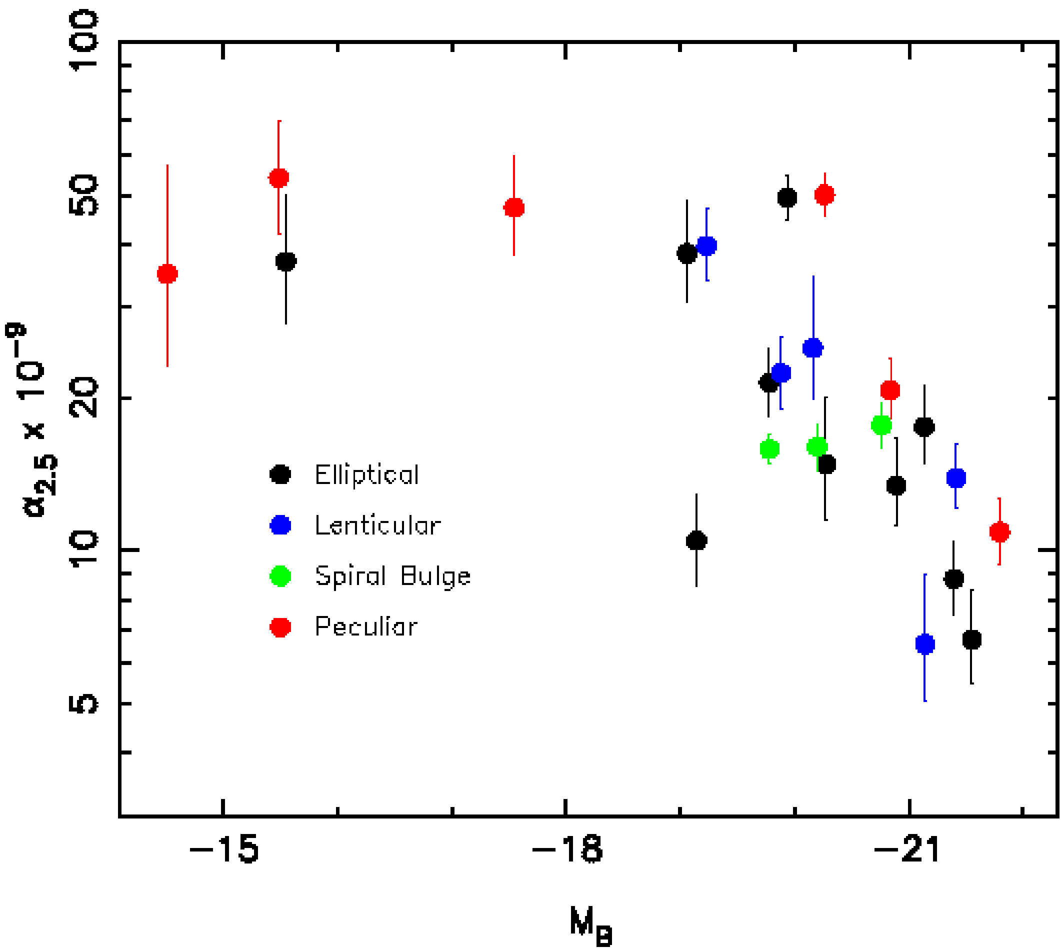
318 IPN candidates in 0.8% of Virgo (Feldmeier, Ciardullo, Jacoby 1998; Feldmeier et al. 2003, 2004) + at least 113 more (Arnaboldi et al. 2002; Okamura et al. 2003; Aguerri et al. 2005)

About 50 spectroscopically identified
(Freeman et al. 2000; Arnaboldi et al 2004)



Fornax Cluster (D = 17 Mpc) - 138 IPN candidates here (Ciardullo et al. 2006)

Converting IPN densities to Luminosity densities - 1



Ciardullo (1995)

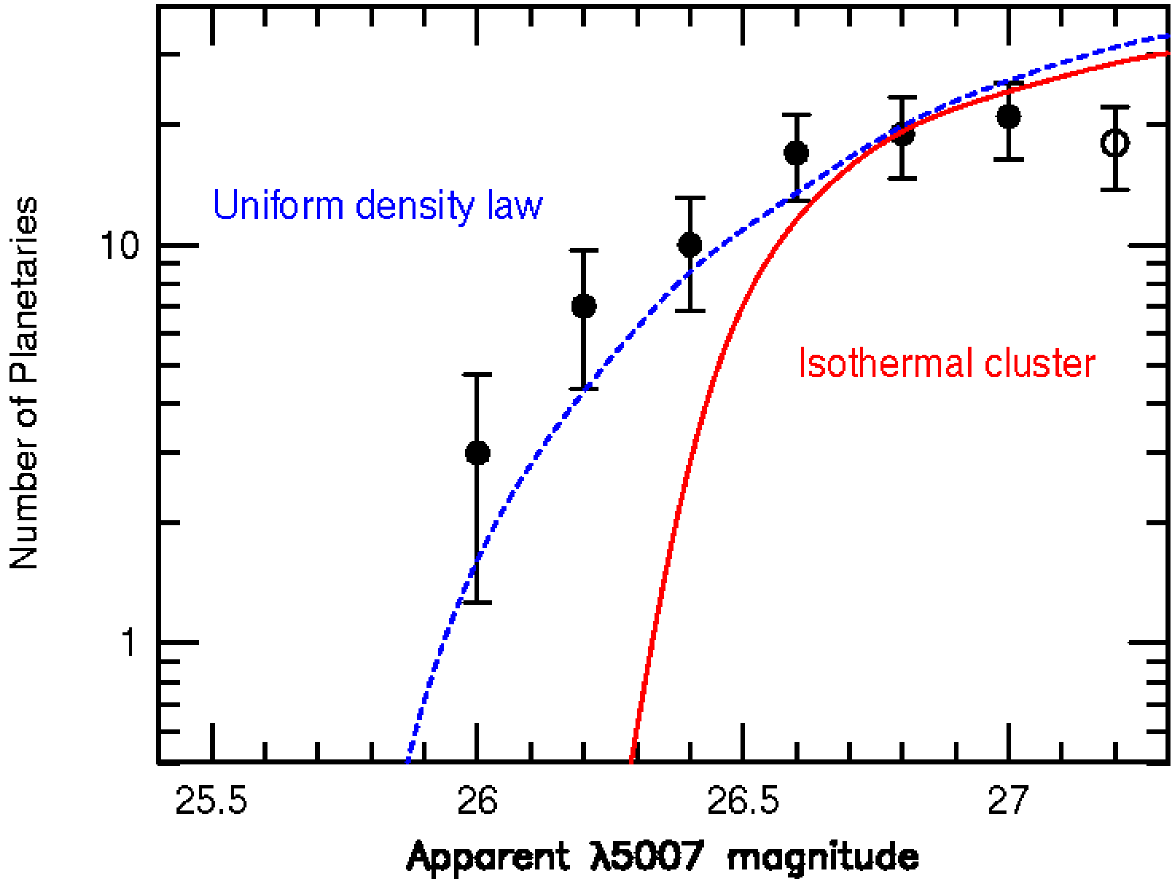
From comparing IPN densities to IRG densities, we found an empirical correction of:

$$\alpha_{2.5} = 23 \text{ +/-} 12$$

Durrell et al. (2002)

See also the theoretical analyses by Ciardullo et al. (2005) and Buzzoni, Arnaboldi & Corradi (2006)

Converting IPN densities to Luminosity densities - 2



Ciardullo et al. (1998)

Converting IPN densities to Luminosity densities - 3

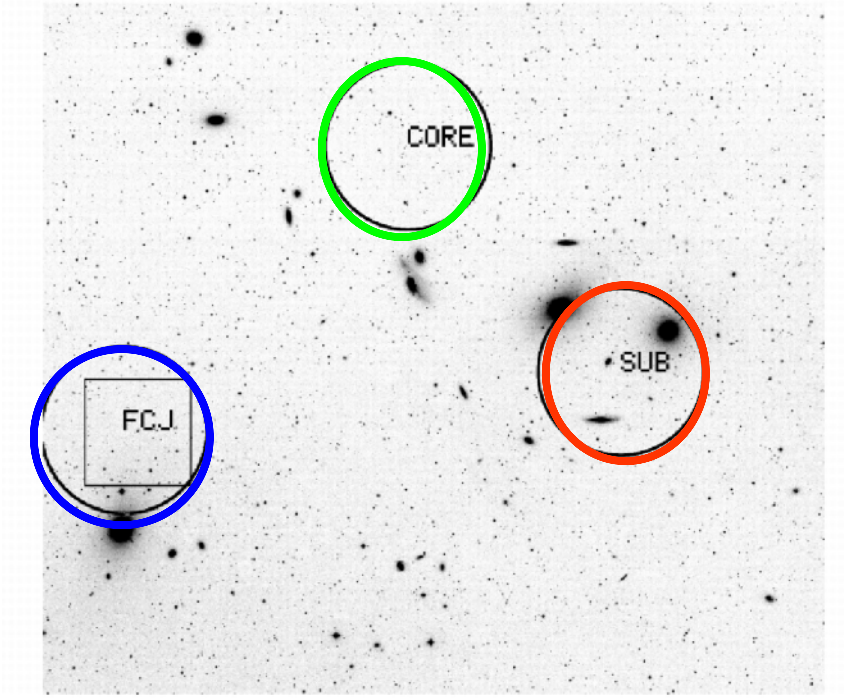
Averaging the Virgo results together, we find:

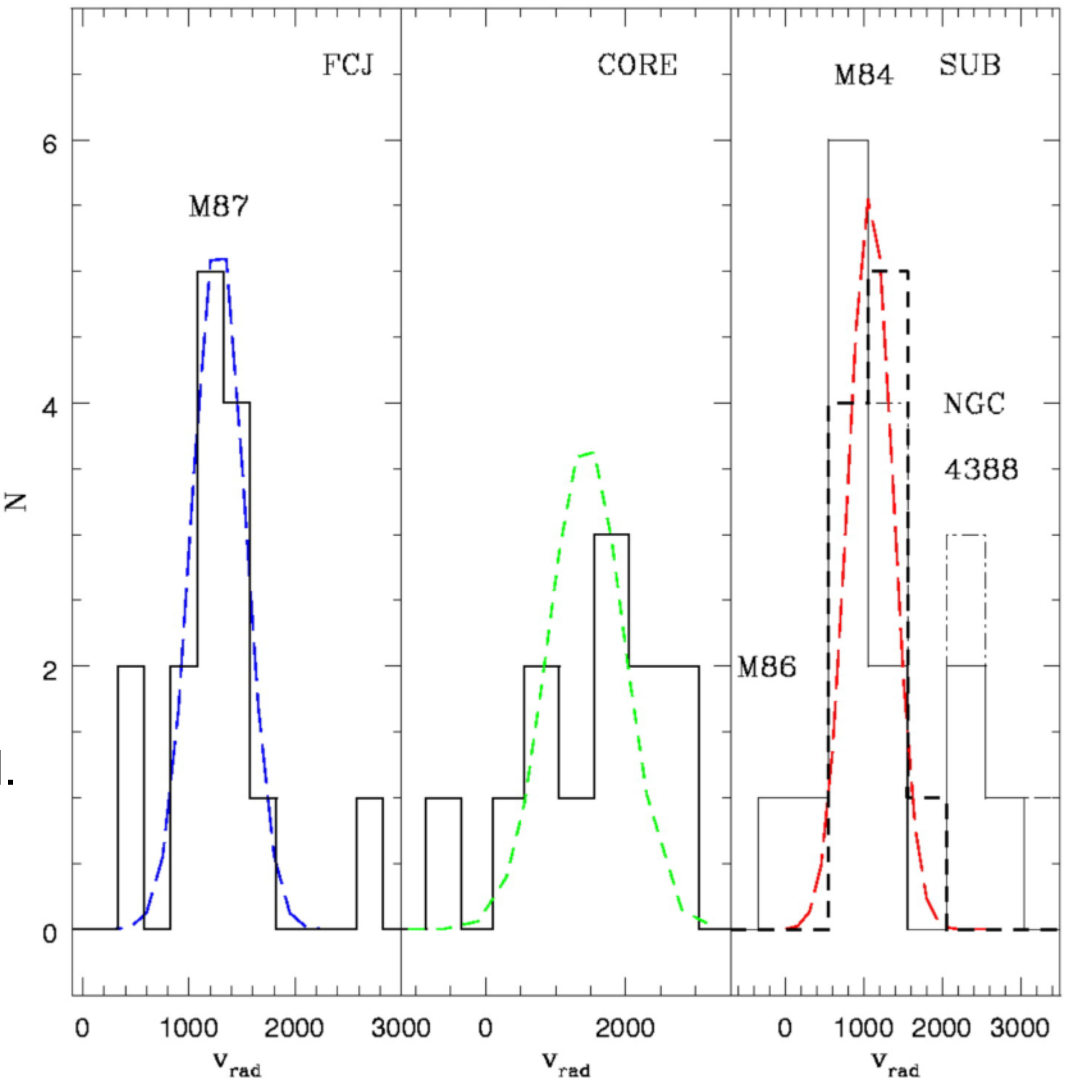
Fraction = 15.8% +/- 3.0% (statistical) +/- 5% (systematic)

For the Fornax cluster, we find a similar result (20% +/- 5%)

Aguerri et al. (2005) performs a similar analysis, and finds 5-10% for their fields. This can be attributed to different field detections, different assumptions in α, corrections for contaminating sources, and possible depth effects.

These numbers are comparable to the Intracluster Red Giant results. The errors are dominated by the systematic uncertainties.





Spectroscopic follow-up of 40 IPN using VLT+FLAMES (Arnaboldi et al. 2004)

Results:

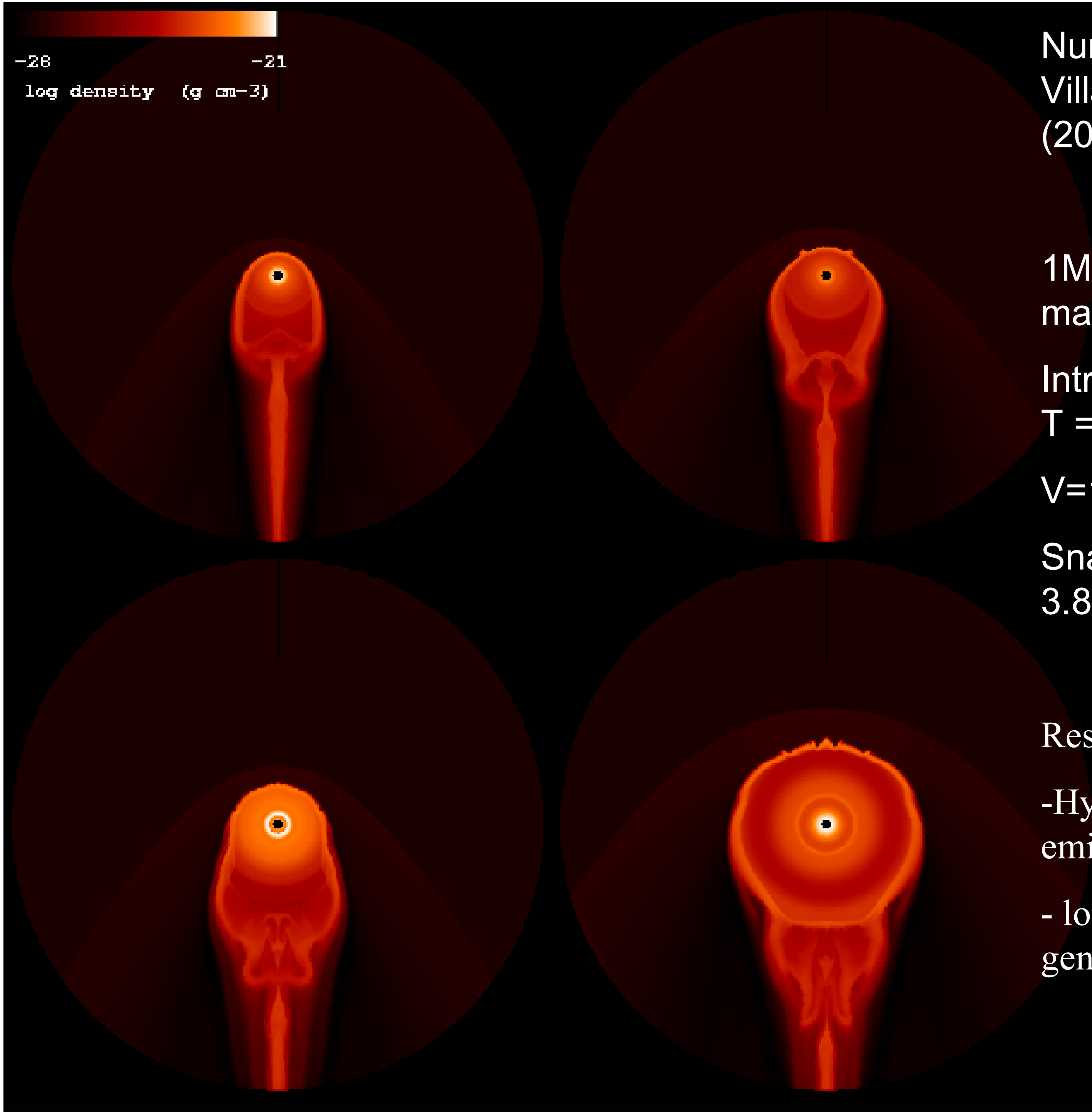
-Over 50% of the candidates have detected [OIII] λ 4959 emission in their individual spectra – others too faint to detect

-Noticeably different radial velocity structures in different fields – Virgo is still dynamically young

What is the effect of the intracluster environment on the planetary nebulae?

- Intracluster PN exist within the extremely hot intracluster medium of a galaxy cluster that emits strongly in the X-ray regime.

- Intracluster PN are moving with enormous velocities by Galactic and extragalactic standards ($v = 1000 – 2000$ km/s).



Numerical Simulations by Villaver & Stanghellini (2005)

$1M_\odot$ main-sequence mass progenitor

Intracluster medium
T = 10^7, n = 10^-4,

V=1000 km/s

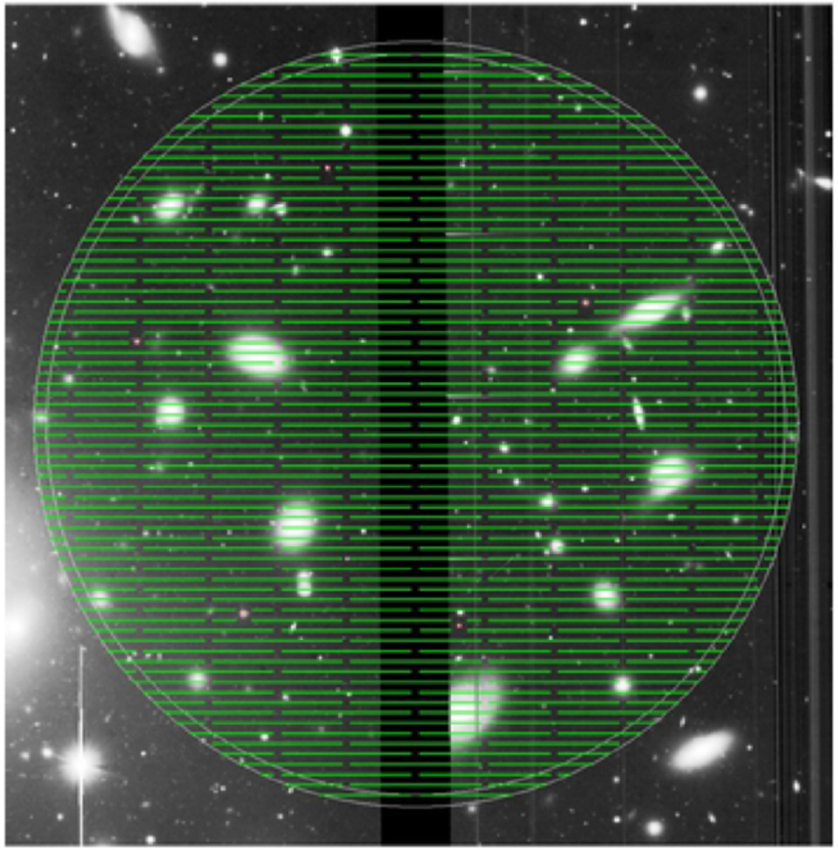
Snapshots at t= 2.8, 3.5, 3.8 and 4.1 x 10^5 years

Results:

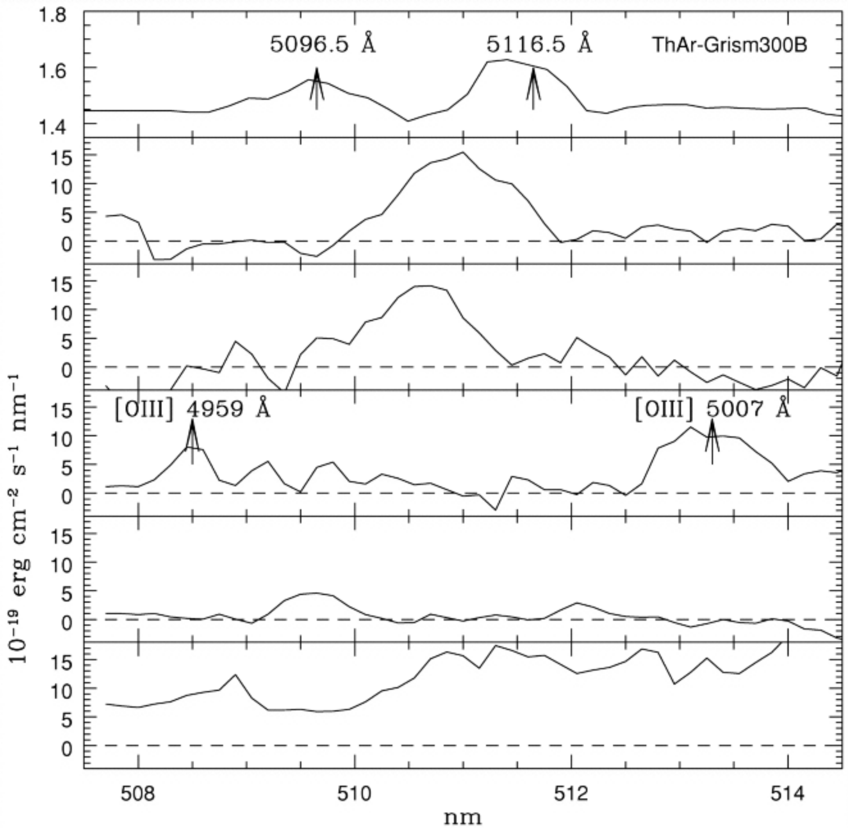
-Hydrogen-recombination emission unaffected

- long stream of gas generated (up to ~ 130pc)

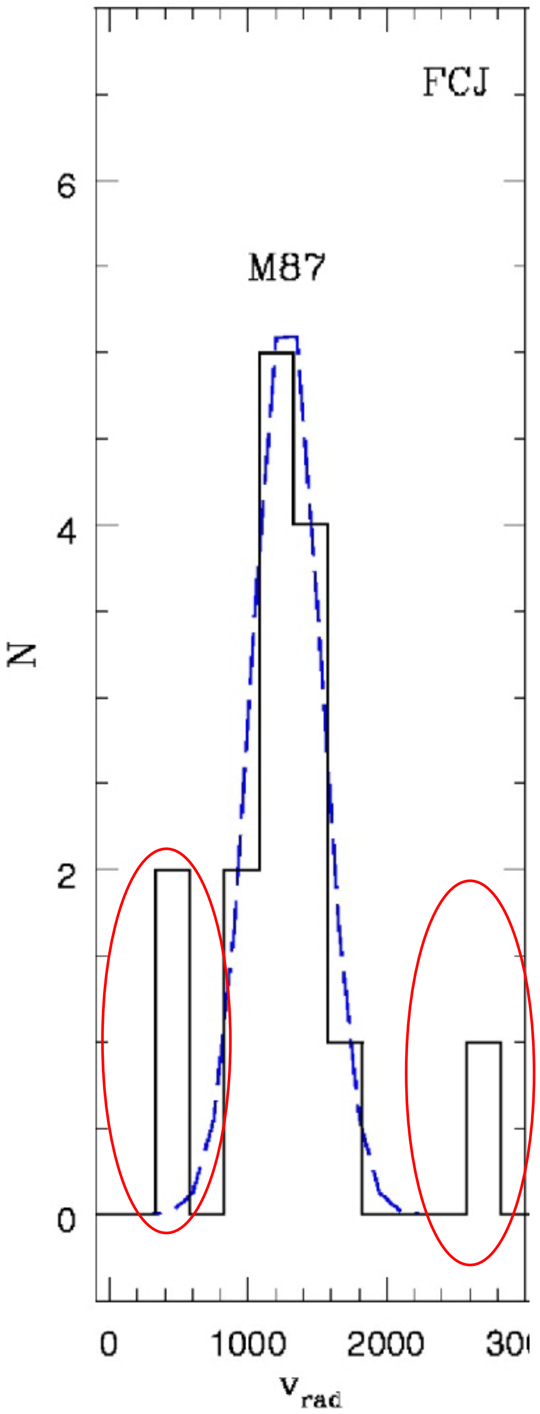
Detection of IPN in the Coma Cluster (D = 95 Mpc)



Gerhard et al. (2005)

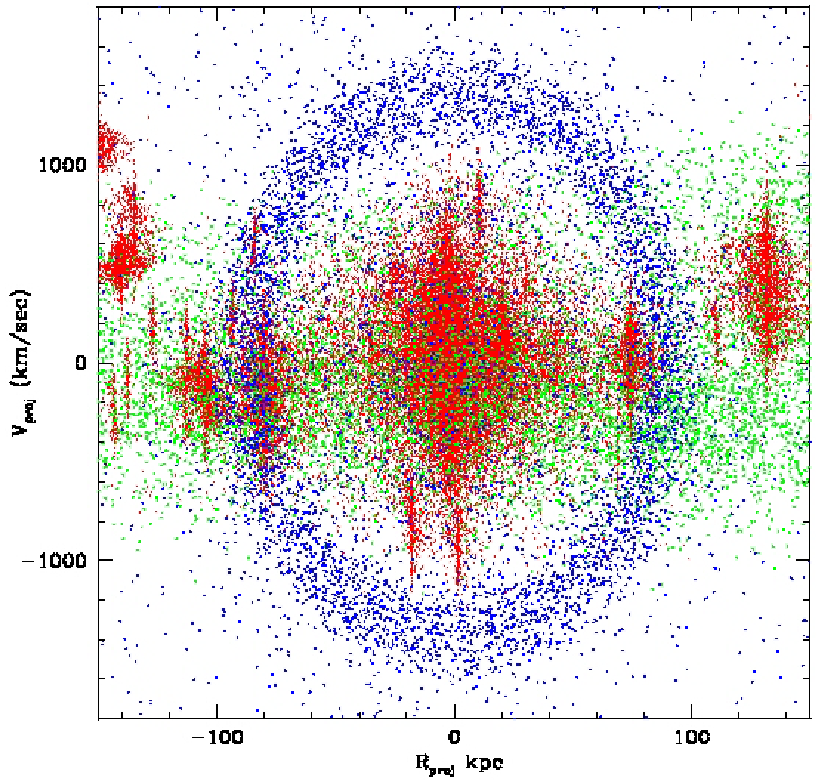


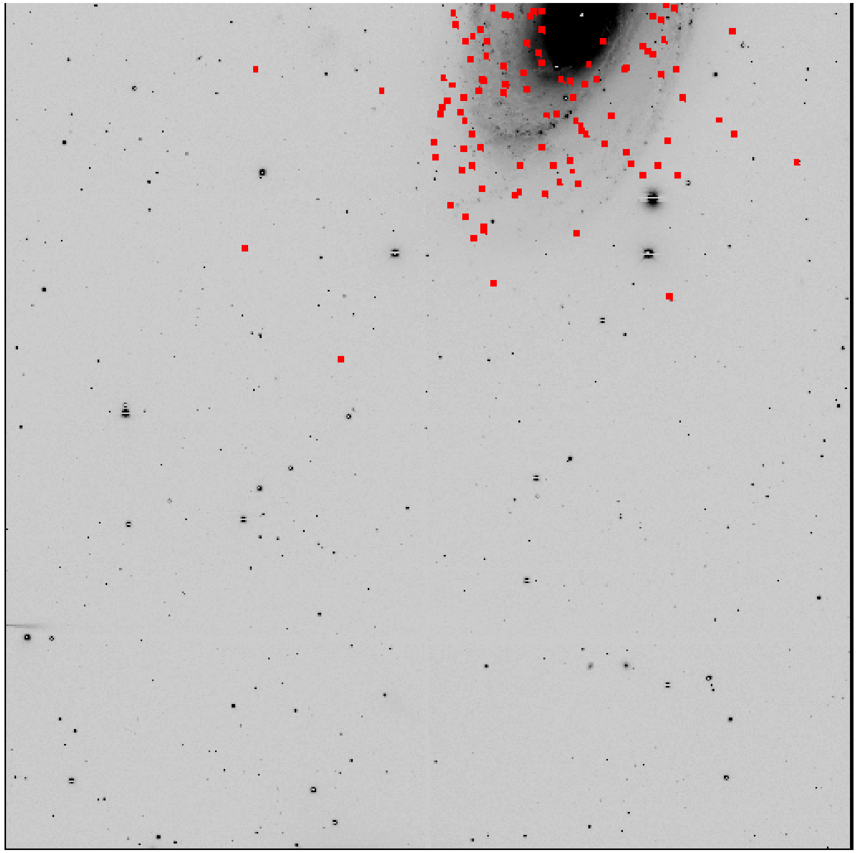
16 IPN candidates detected using Subaru + multislit imaging spectroscopy technique

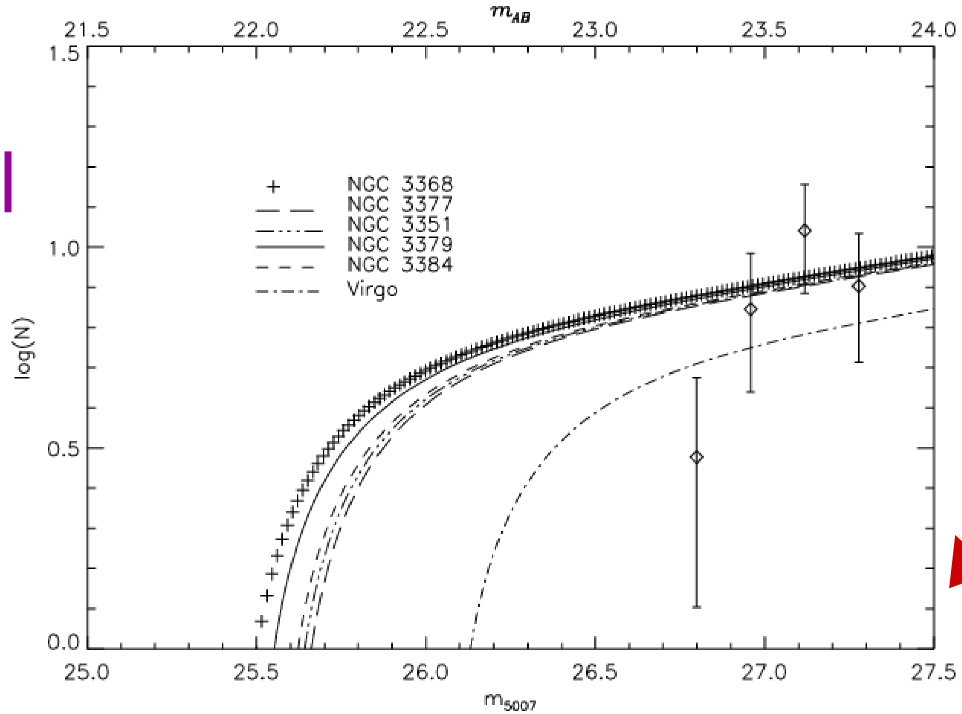


What is the origin of the extreme velocity Virgo IPN?

In a recent paper, Holley-Bockelmann et al. (2005) proposed that the three high velocity IPN observed by Arnaboldi et al. (2004) might be explained by stars being ejected by a supermassive binary black hole at the center of M87 – may account for up to 10% of the intracluster light!

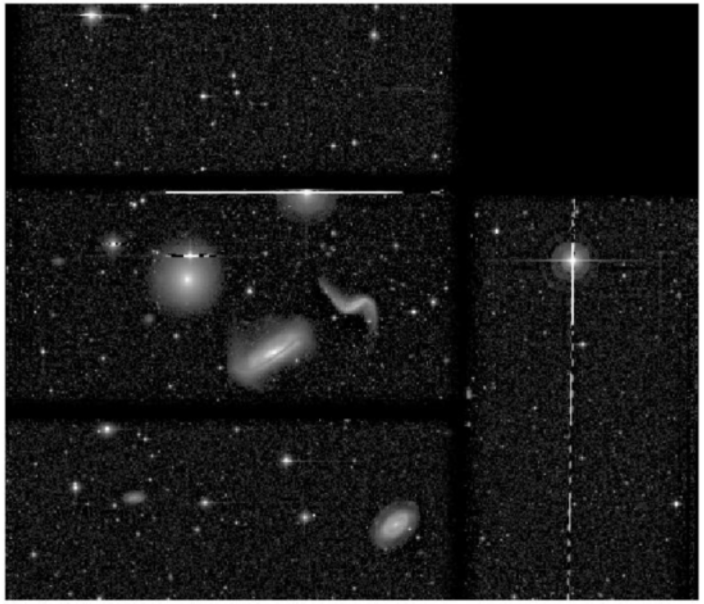






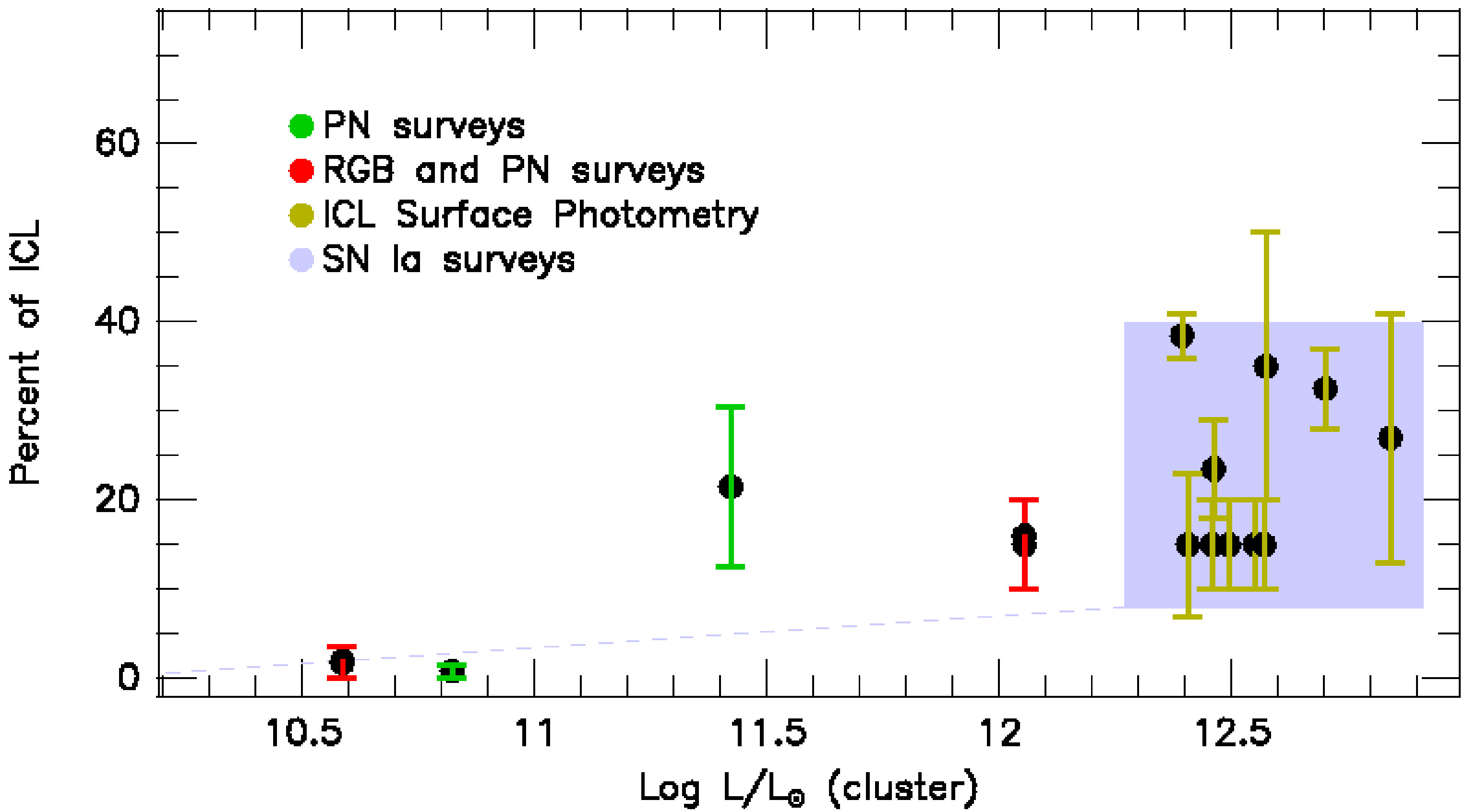
Leo I Group (Castro-Rodriguez et al 2003; < 1.6%)

M81 Group – (Feldmeier et al. 2001) < 1.3%

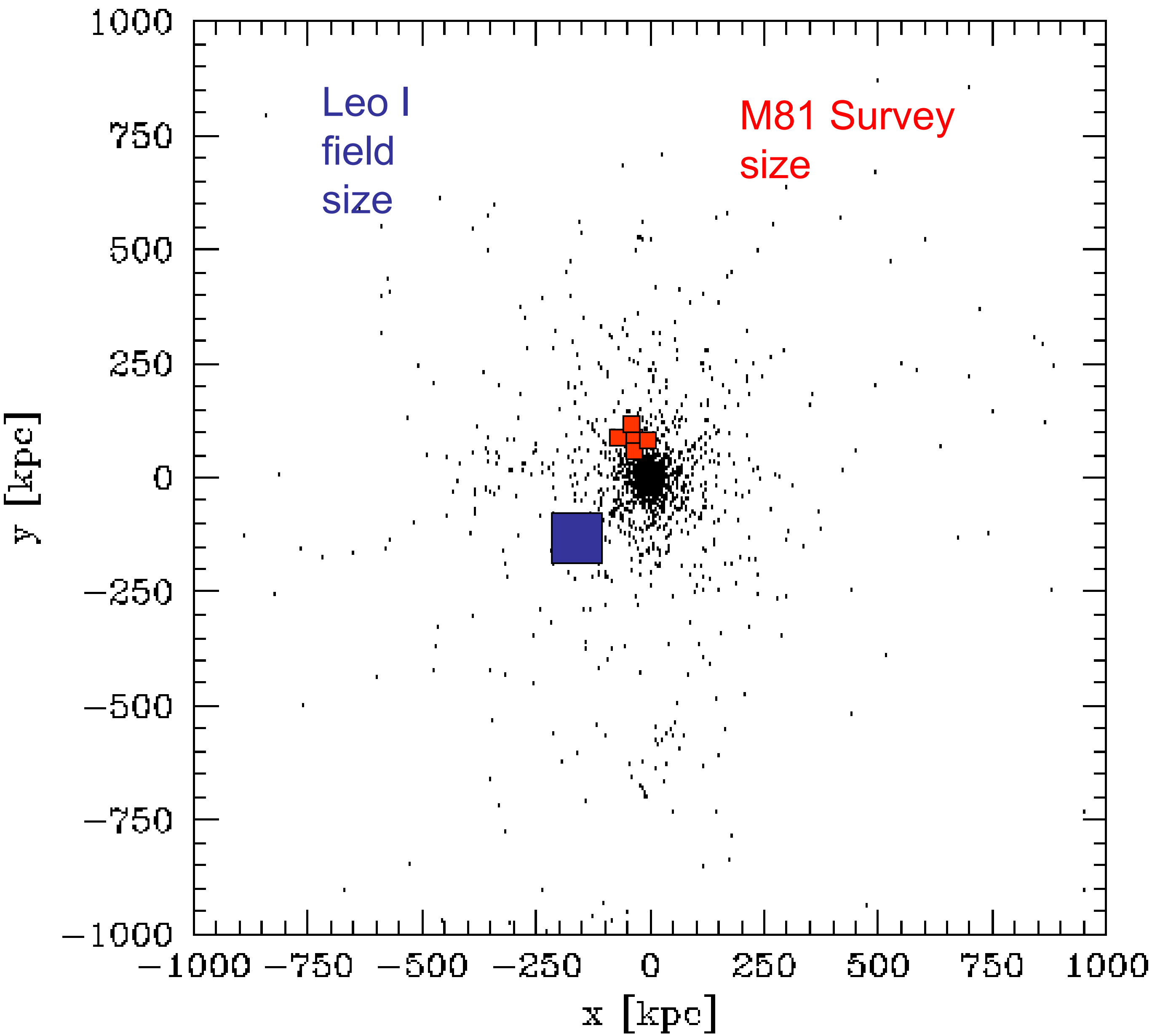


HCG 44 (Castro-Rodriguez et al. 2005)
< 0.6%

The Intracluster "cliff"



(Ciardullo et al. 2003)



Models of IPN within a fossil galaxy group by Sommer-Larsen et al. (2005)

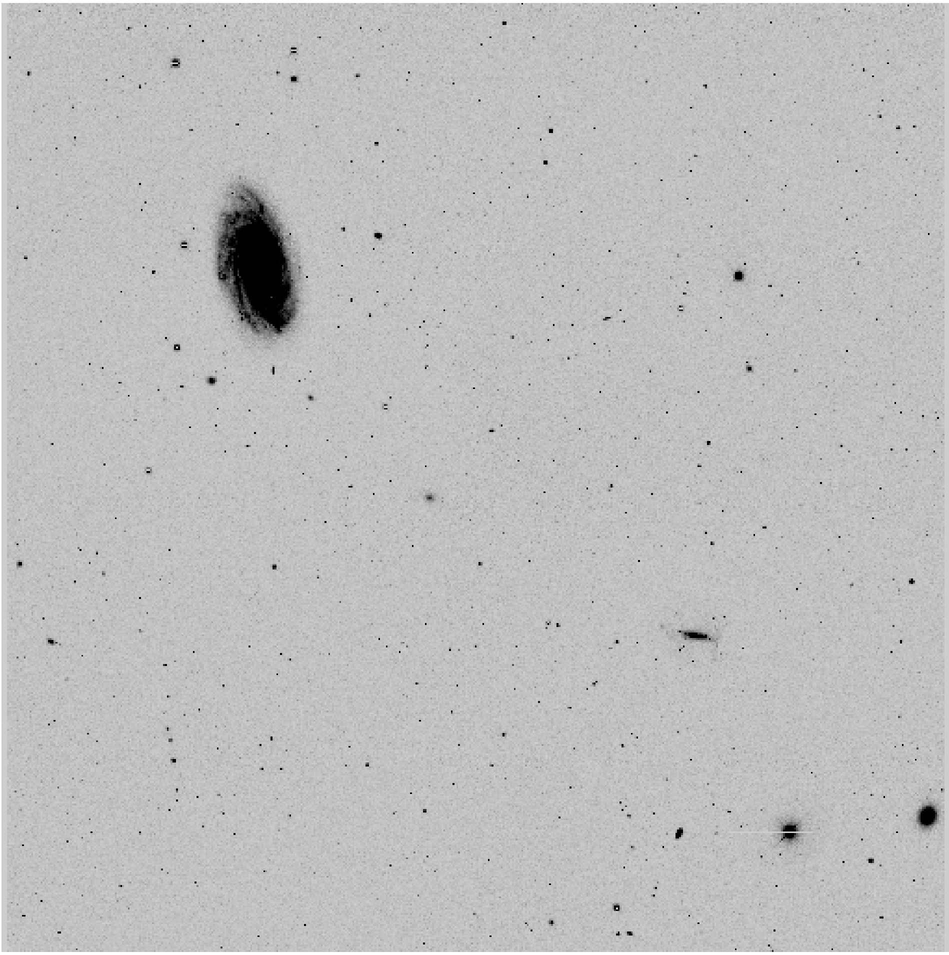
Simulations from Sommer-Larsen et al. (2005) predict intra-group star fractions of 12-45%!

What's the reason for the mismatch?

- Villaver & Stanghellini (2005) suggest that the intra-group medium might efficiently strip the IPN envelope

- Sommer-Larsen et al. (2005) claim that the IPN are widely scattered, and previous searches are not complete enough.

IPN Survey of the Ursa Major Cluster (D = 14 - 19 Mpc)



Two goals:

-Obtain distances to large-spiral galaxies to better calibrate the Tully-Fisher relation

- Search for IPN in an intermediate, spiral-rich cluster that is more luminous than the groups searched thus far for IPN

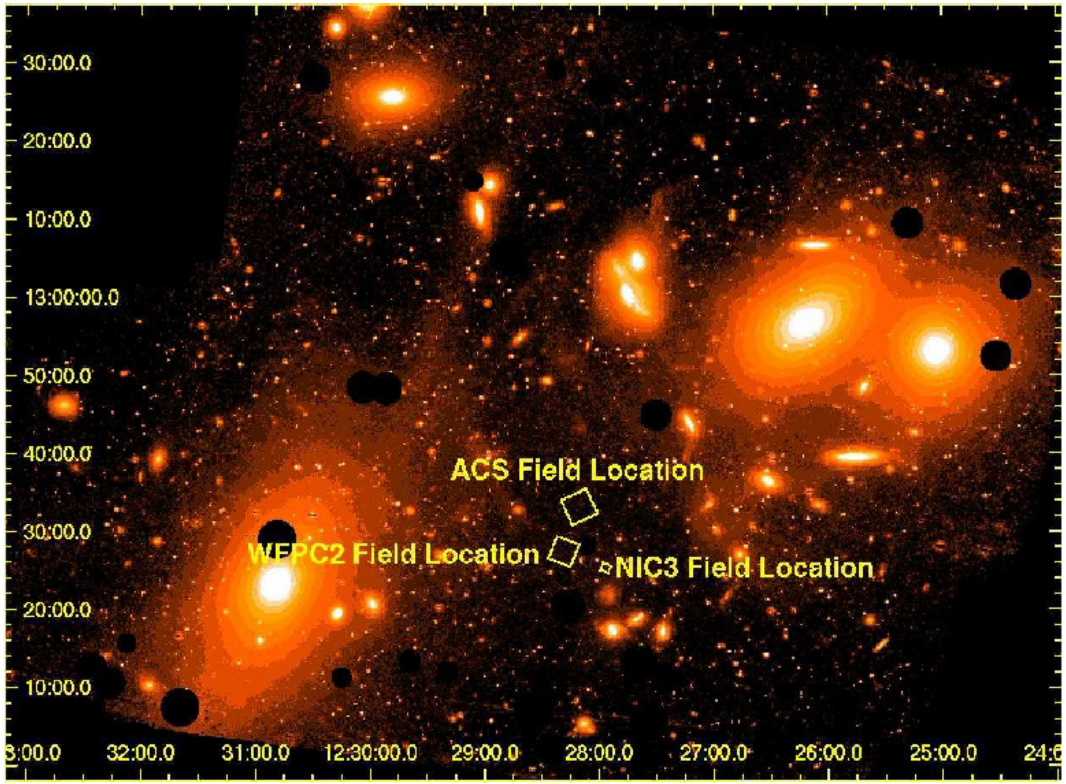
-Obtained data Spring 2005 on first field (7.5 hours in the on-band in 1.2” seeing from the KPNO 4-m)

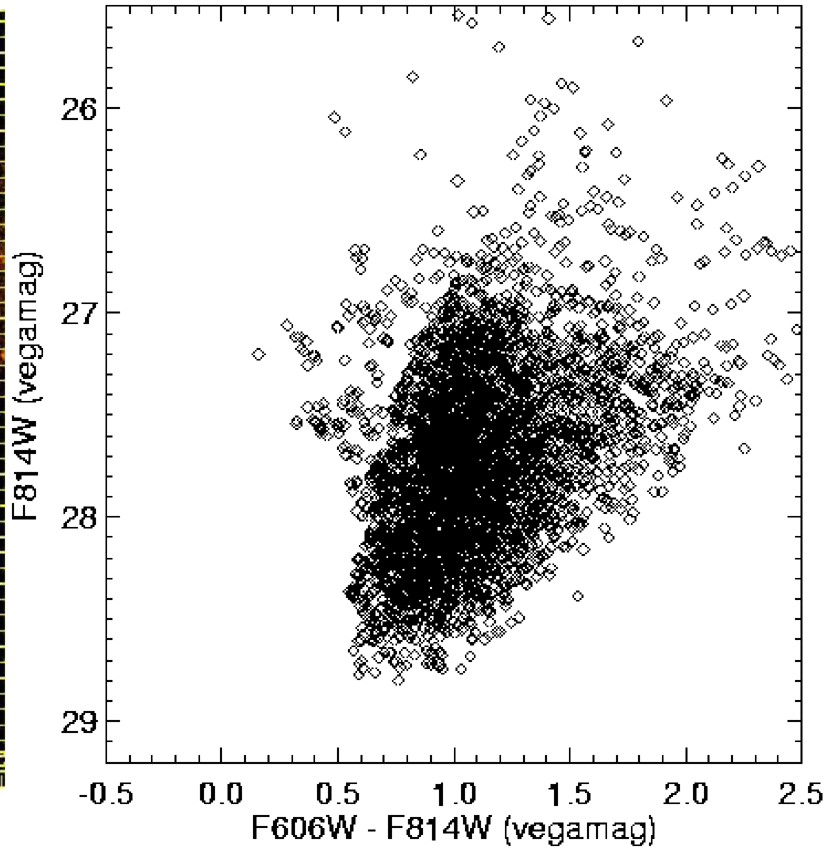
-PN-like objects being detected

Conclusions

- Intracluster planetary nebulae are among the most distant planetaries currently studied, and they are in the most hostile environment. They are an important tracer of intracluster starlight.
- Although significant systematic uncertainties exist, estimates show that 10-20% of all light in the Virgo and Fornax clusters is in an intracluster component.
- Limited spectroscopic follow-up observations indicates that the intracluster planetary nebulae in Virgo have a complex velocity structure.
- Intracluster planetary nebulae appears a common component of galaxy clusters, but not galaxy groups – why?
- More imaging and spectroscopic studies are needed to expand on these results. More modelling of the intracluster planetaries is also needed.

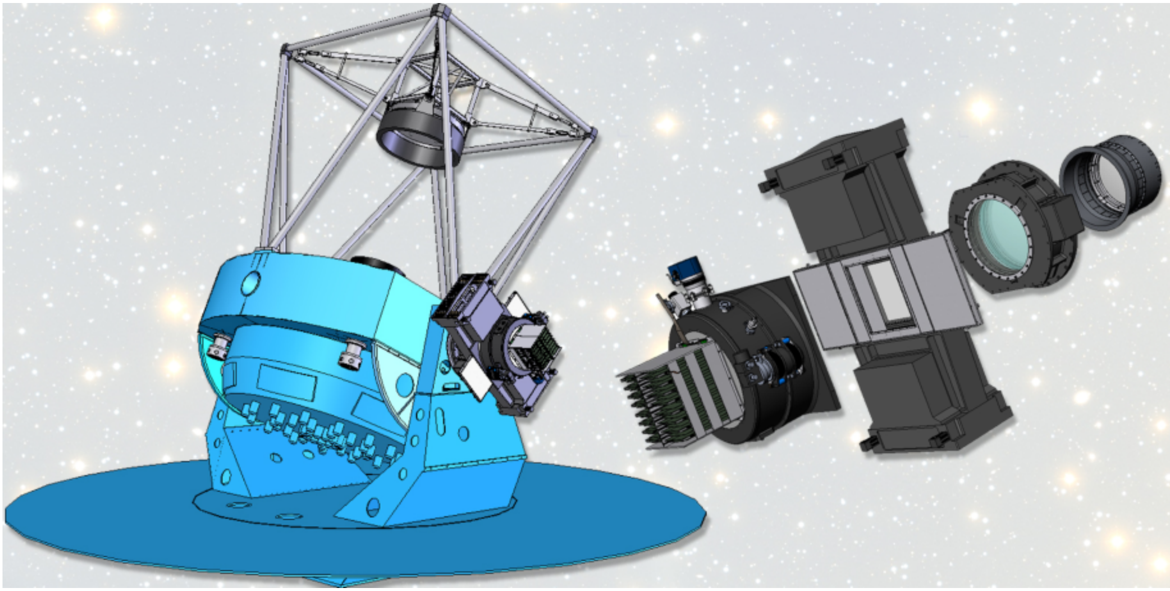
VICS: The **V**irgo **I**ntra**C**luster **S**urvey (PI: Ciardullo, T = 63.4ks)





Williams et al. (2006), in prep

WIYN One Degree Imager – The IPN machine (PI: Jacoby, Knezek, WIYN Consortium)



64 4k x 4k CCDs, using Orthogonal Transfer Arrays – Completion date 2008