# The diffuse intra-cluster component in the Virgo cluster


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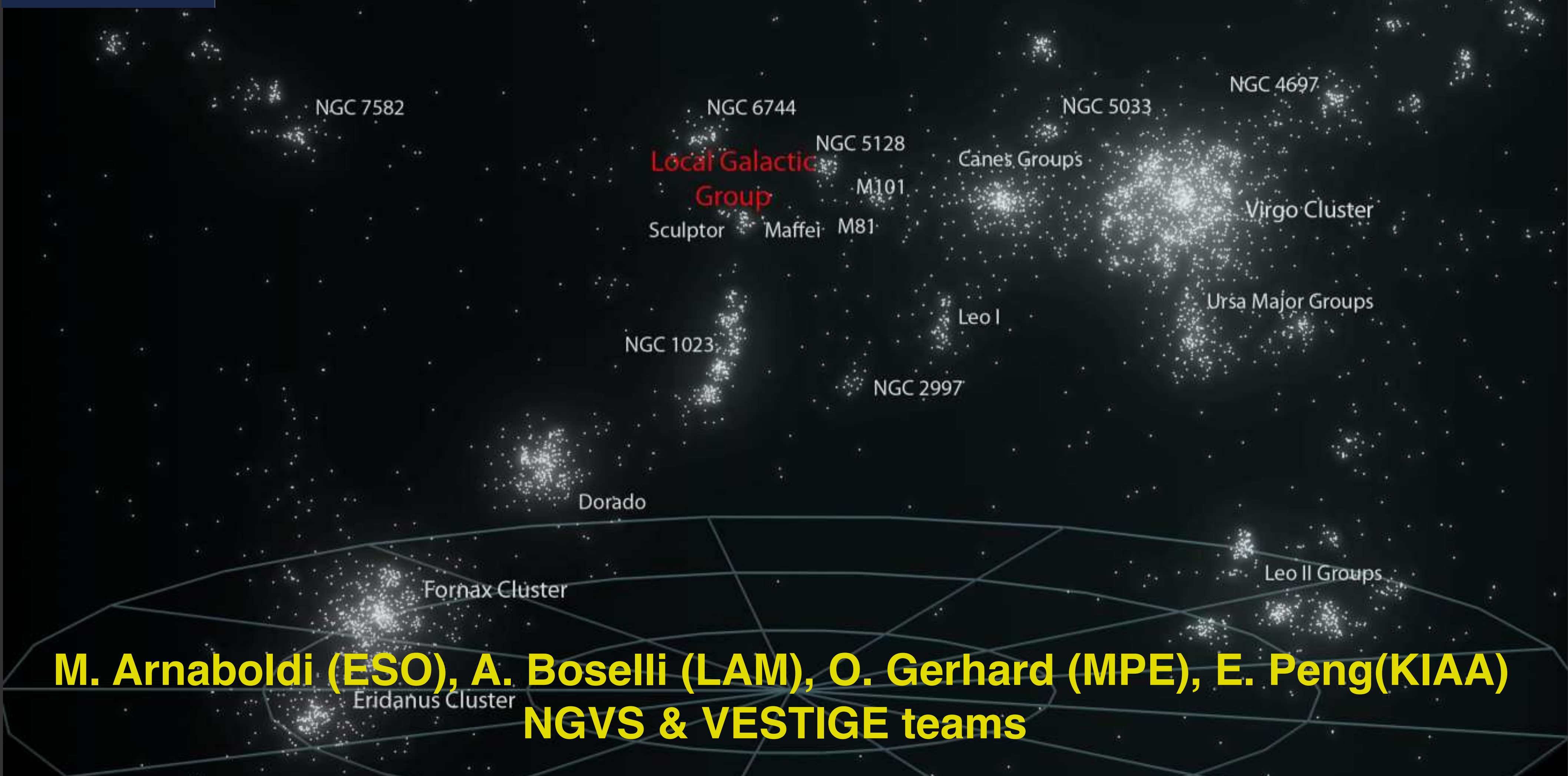




**M. Arnaboldi (ESO), A. Boselli (LAM), O. Gerhard (MPE), E. Peng(KIAA)**

**NGVS & VESTIGE teams**

# Outline:

**1. Introduction:** What is it the intra-cluster component and where and how we can trace it

**2. Previous results :** *Where stellar halos coexist with intra-cluster light: a case study of the giant Virgo-central galaxy M87*

**3. Moving forward:** *A panchromatic view of the Virgo intra-cluster component: diffuse dust in the Virgo intra-cluster medium*

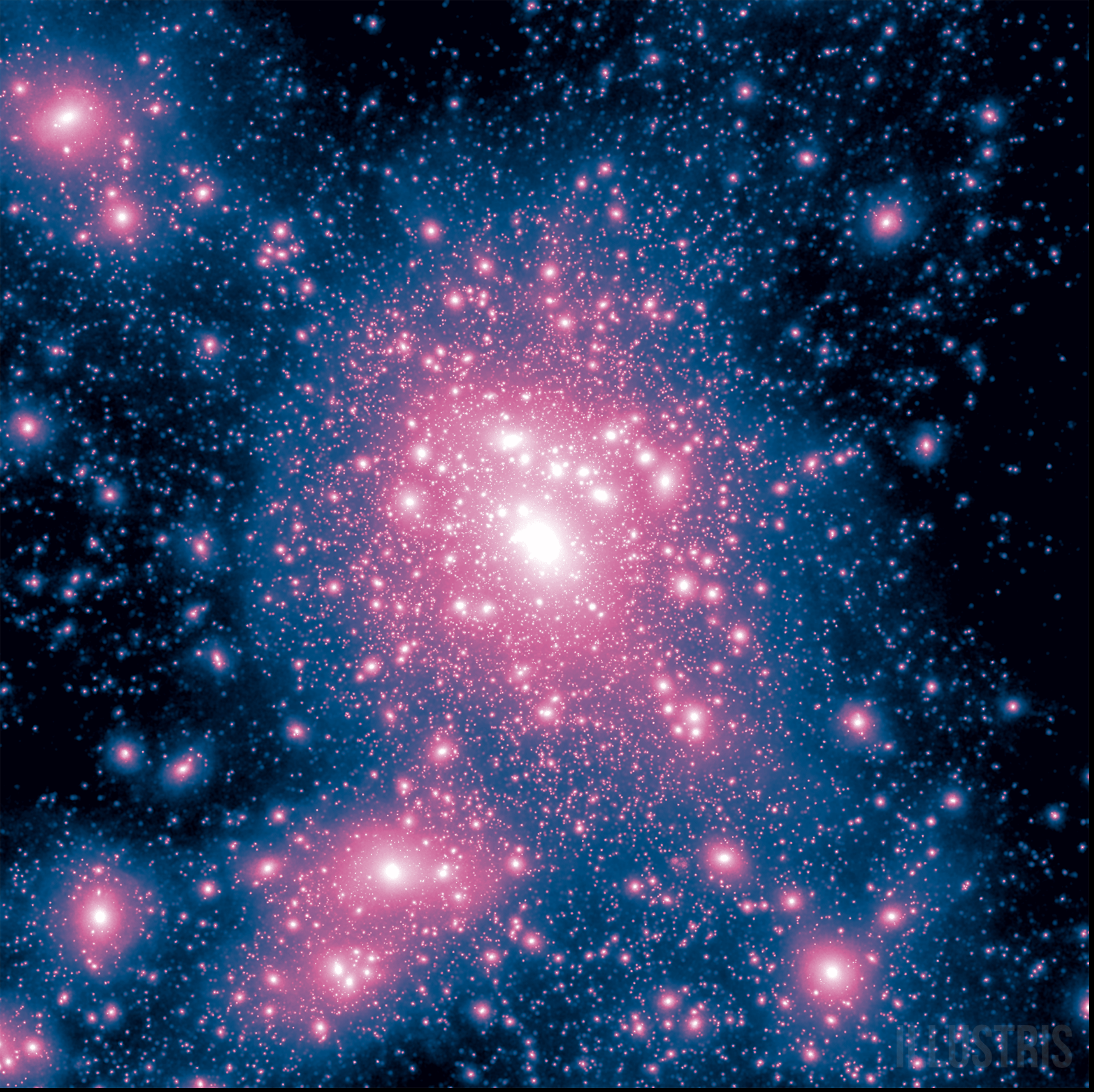


Image Credit: *Illustris* simulation

# The intra-cluster component

Up to ~50% of the baryonic matter in a cluster

•Galaxy interactions

•Tidal interactions between galaxies and the cluster potential

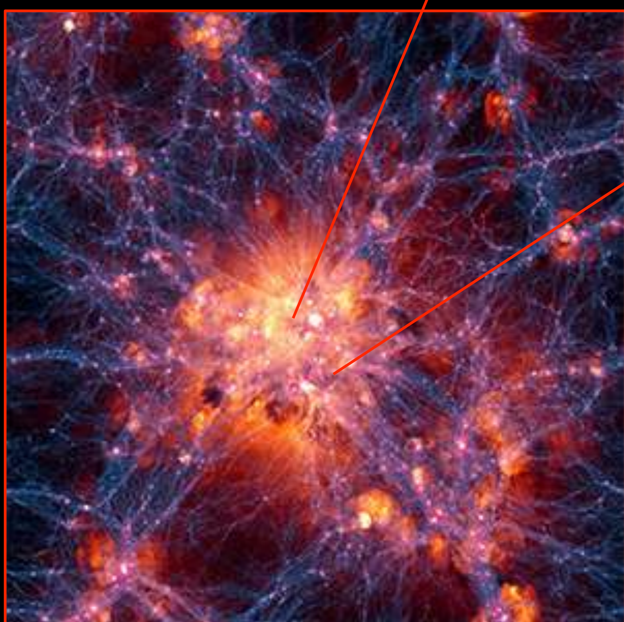
•In-situ formation

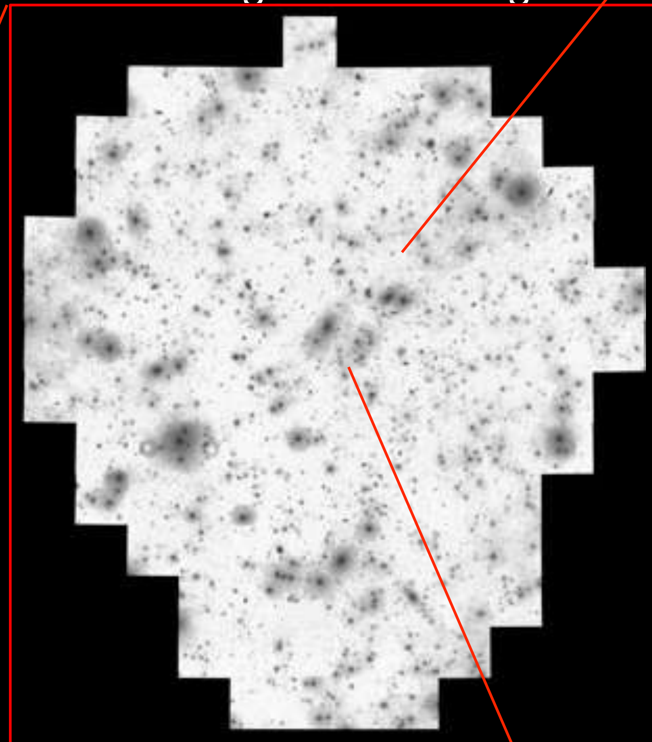
From the study of the luminosity, distribution and kinematics of the IC component we get information on the evolution of galaxies and hosting clusters

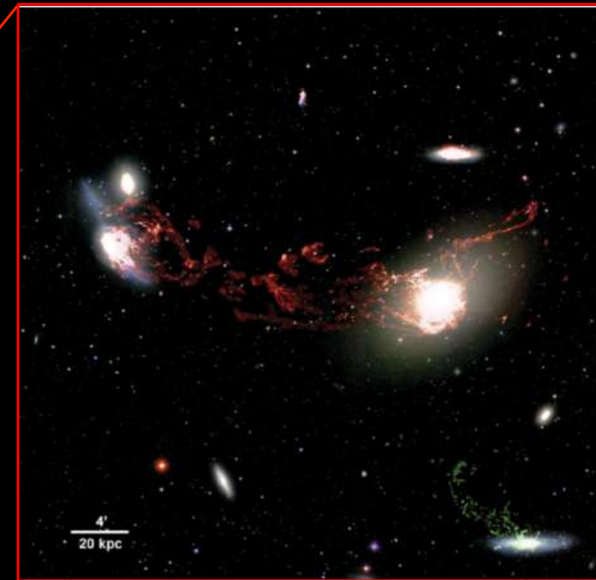
# How do structures form and evolve ?

Local universe as analogue of the over-dense regions in the high-redshift universe

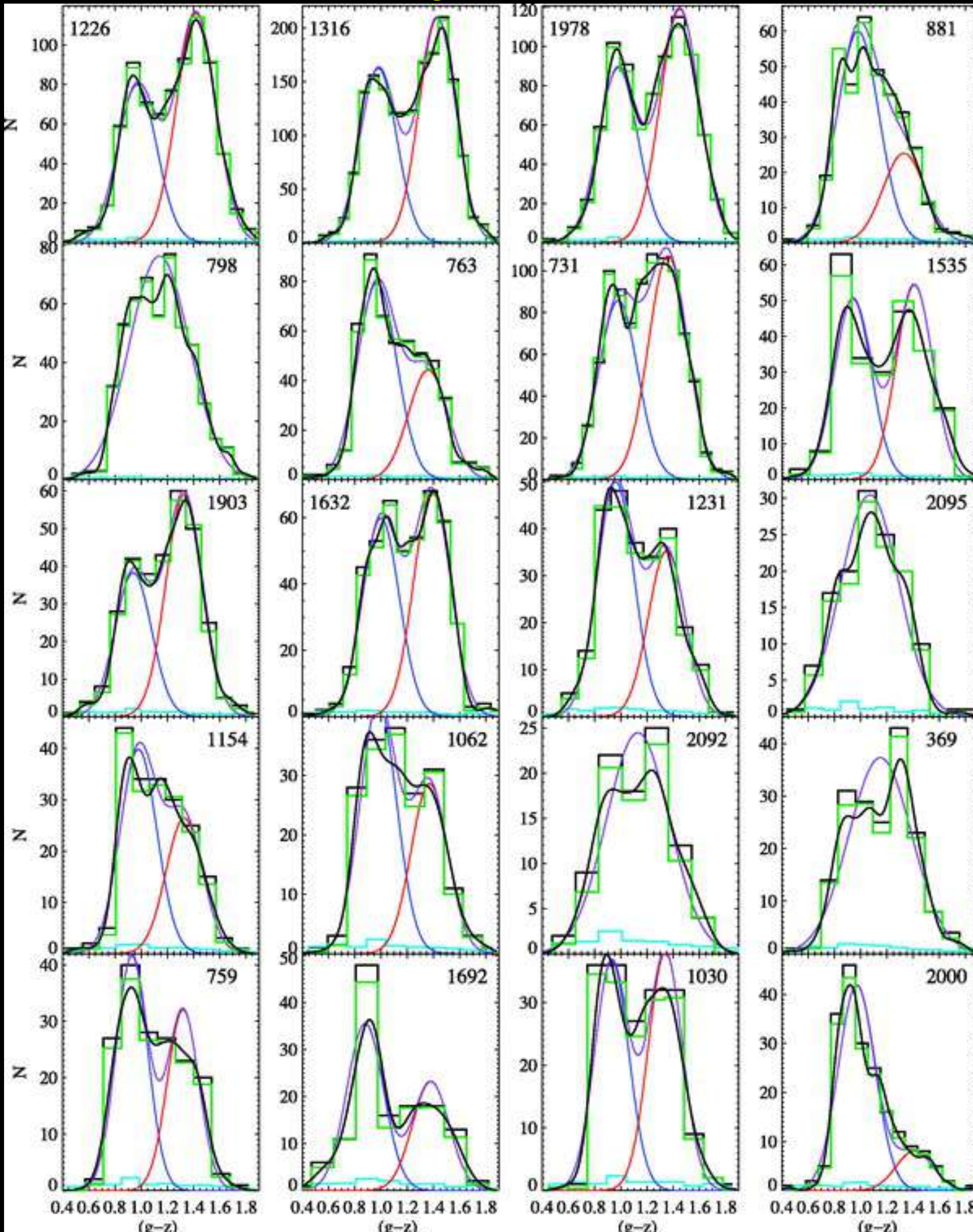
Ideal laboratories for studying (at high resolution) the perturbing mechanisms that shaped galaxy evolution.





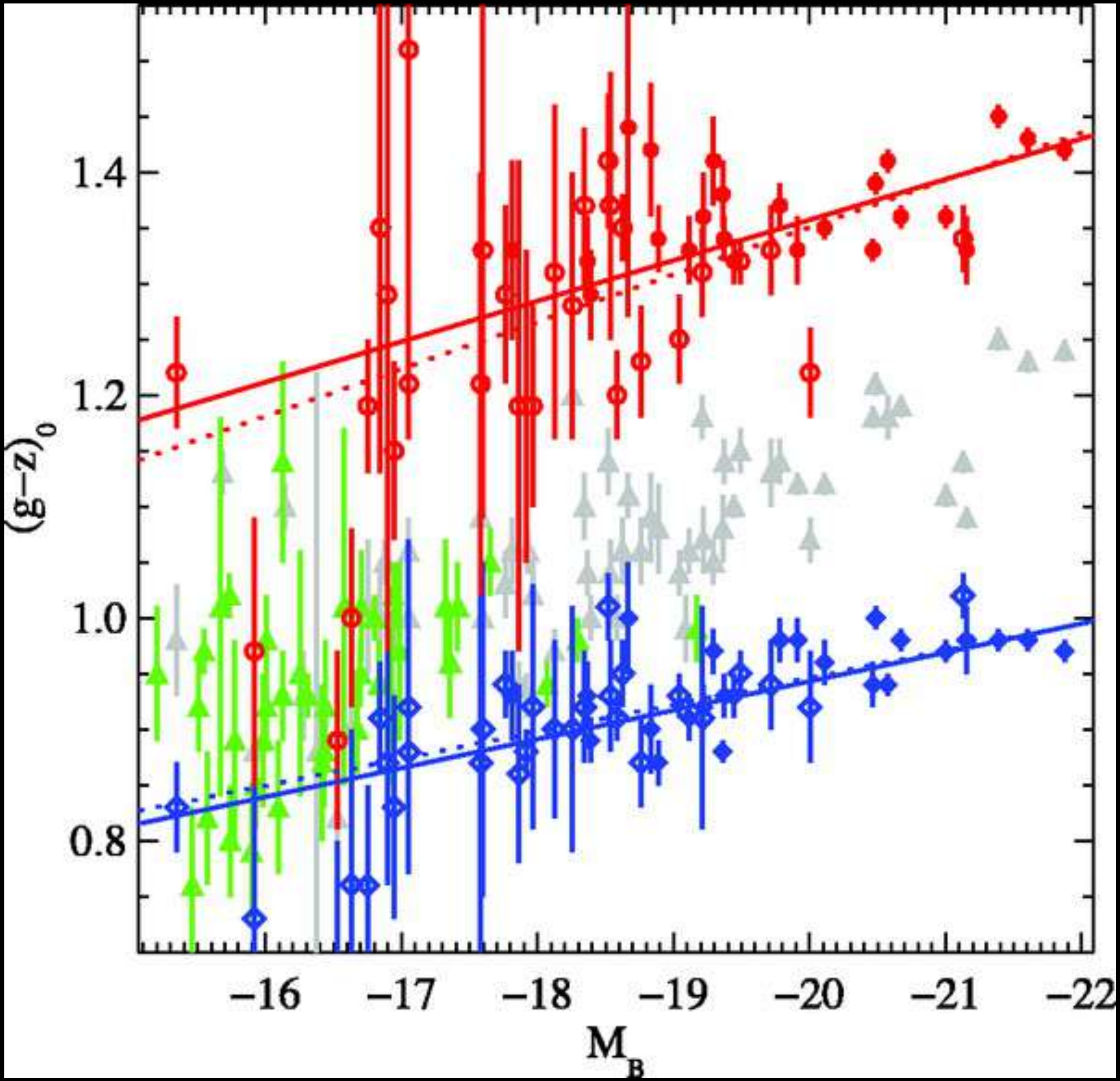



Peng et al. 2006



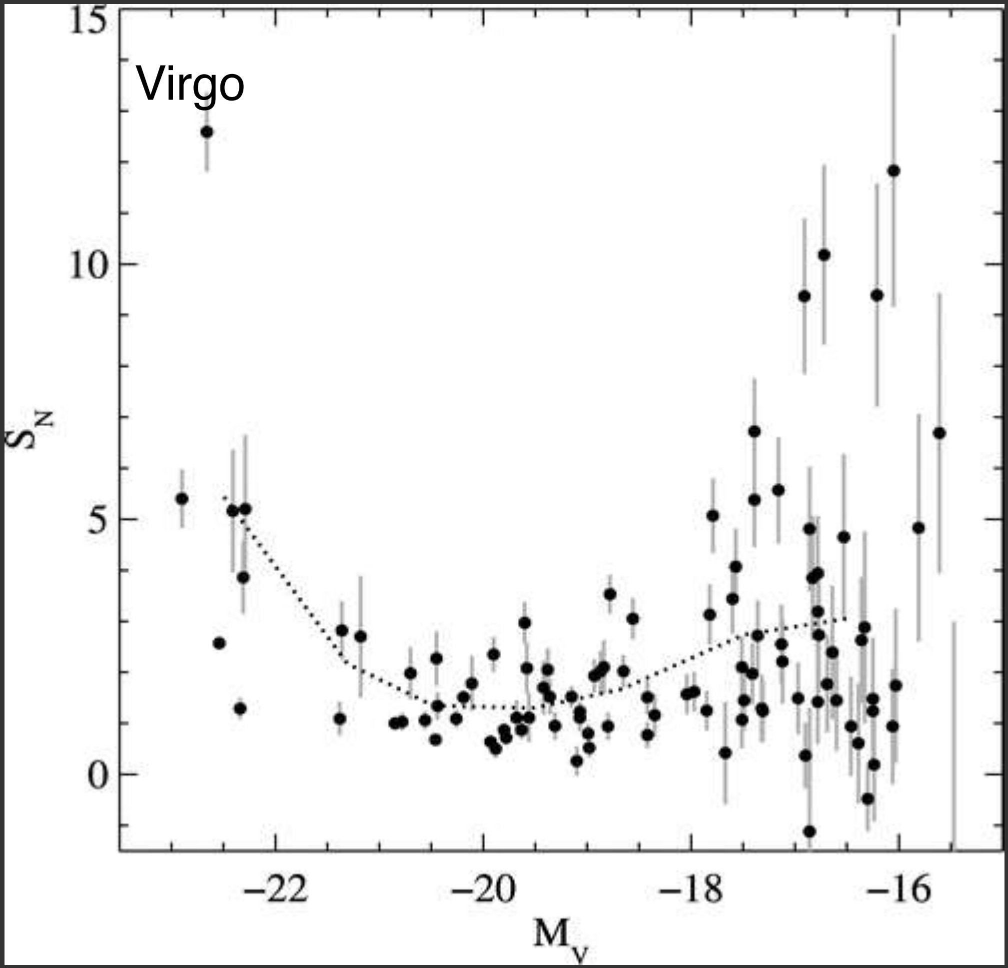

GC Color bimodality is a common property in massive early type ellipticals (e.g. Gebhardt +1999)

Peng et al. 2006



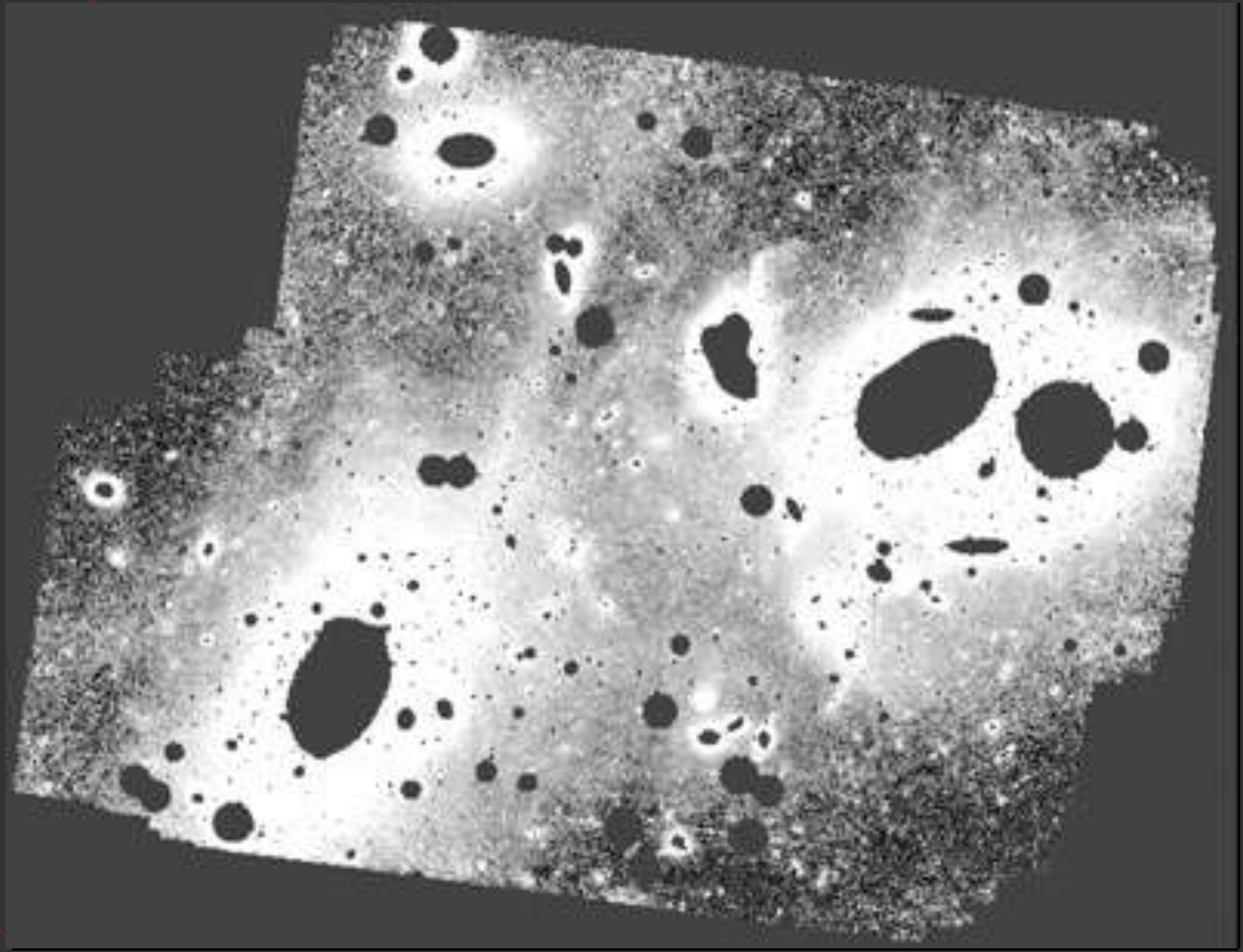

Continuous trends across galaxy properties

Peng et al. 2006




- Early-type dwarf galaxies have a large spread in $S_N$ .
- Both dwarf and giant ellipticals appear to be subject to the same family of processes that drive the formation and evolution of GC systems

# Where stellar halos coexist with intra-cluster light



Mihos+05

•Complex network of extended tidal features in the outer regions (Mihos+05, Mihos+17)

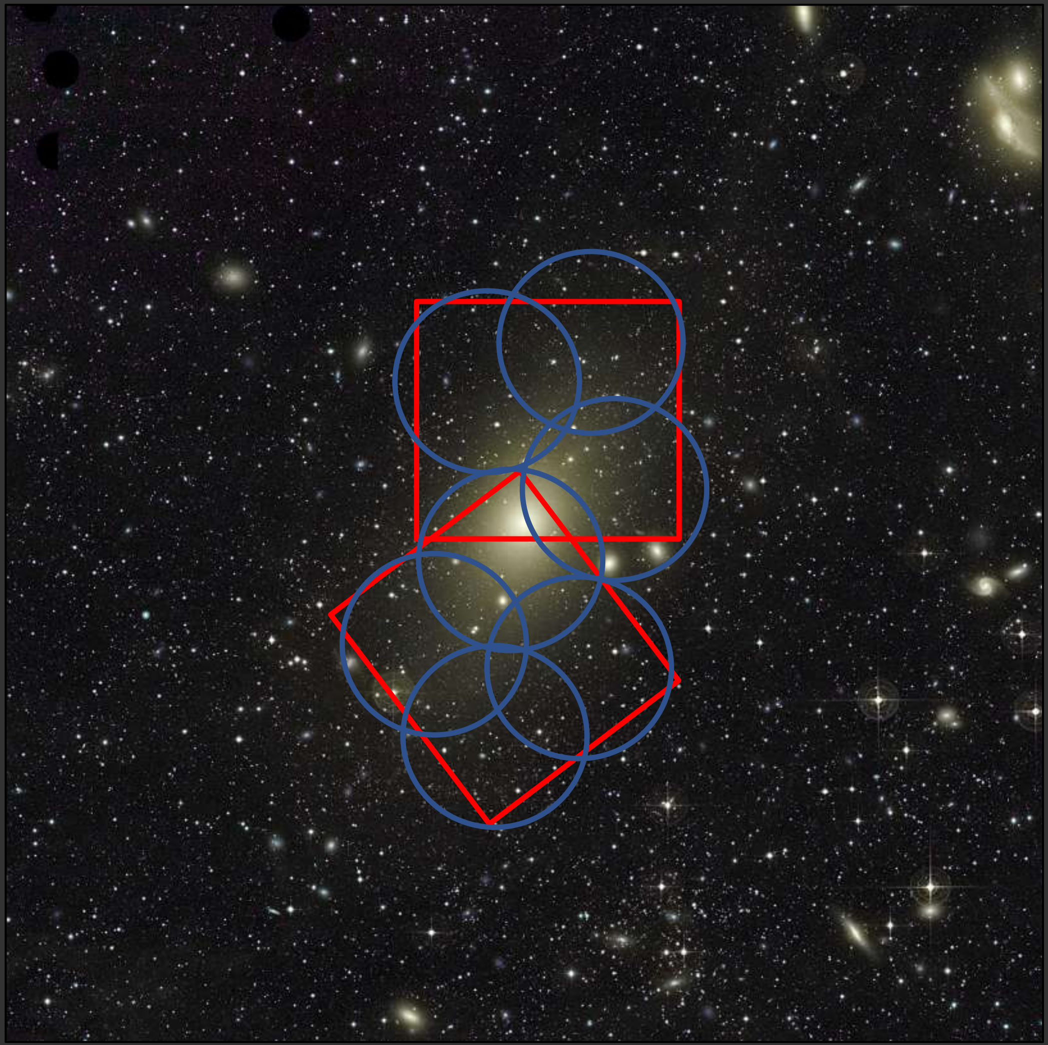
•M87 is expected to have its majority of stars accreted (Cooper+15)

•Observed gradients in colour and inferred age and metallicity gradients support the hierarchical scenario (Rudick+10,Montes+14)

# The galaxy halo-intracluster light dichotomy: the PN perspective

**Suprime-Cam@Subaru** program to image Virgo within 0.5 deg$^2$ from its centre

**Flames@VLT** program to get Planetary Nebulae velocities



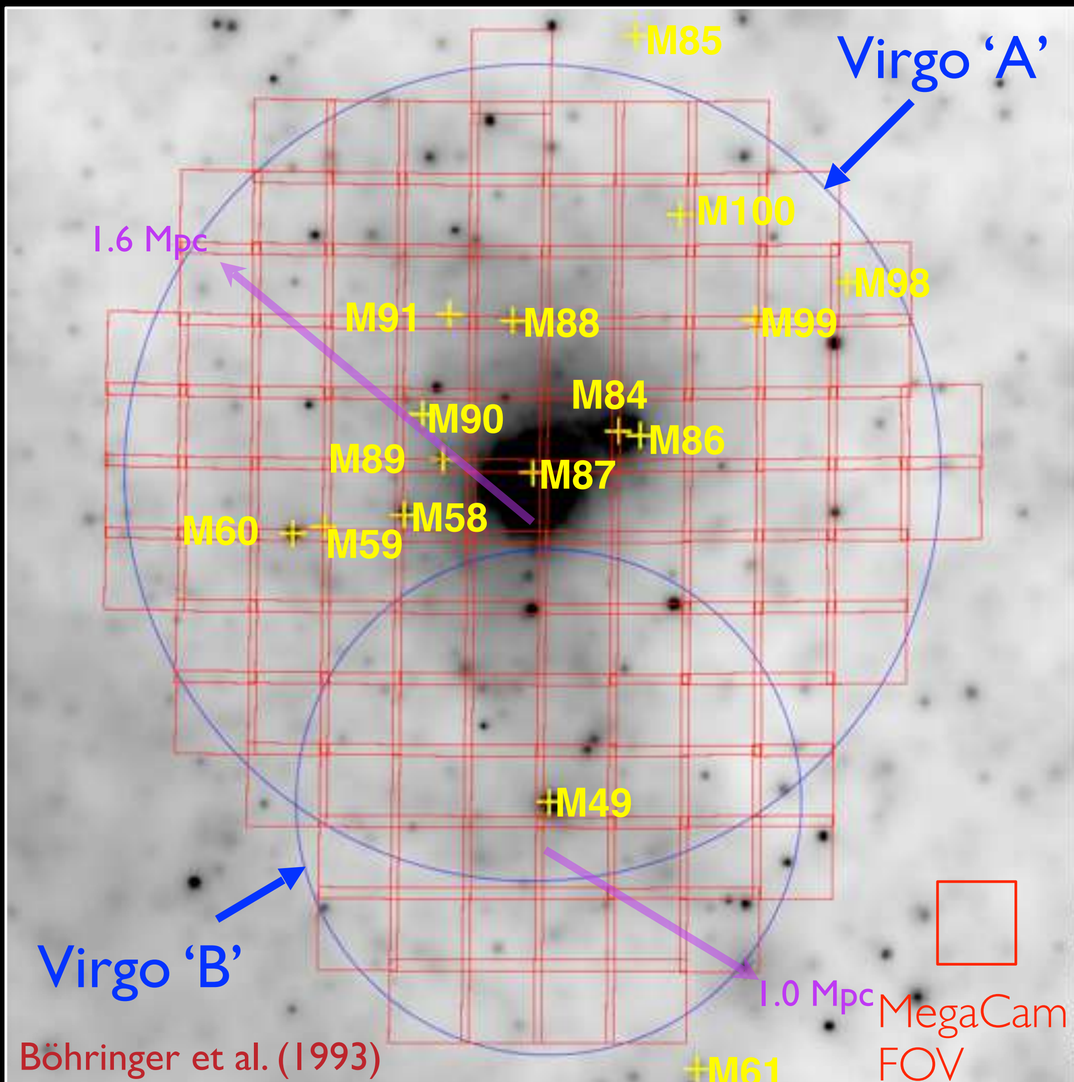
Imaging fields observed through a narrow-band ([OIII] 5029 Å) and broad-band V filter

High resolution spectroscopy : velocity accuracy of 4 kms$^{-1}$

# The CFHT Next Generation Virgo Cluster Survey

- **CFHT MegaCam** program to fully image Virgo within $R_{200}$ for its two main sub-clusters.

Virgo in X-rays




- $\Omega = 104\ \mathrm{deg}^2 \approx 8.6\ \mathrm{Mpc}^2$
- **Five filters** (*u*g'r'i'z'*)
- **g ≈ 25.7 mag** (10-σ depth) ➡ corresponding to a mass of $M \sim 4\times10^4\ M_\odot$ for old stellar populations
- $\mu_g \approx 29\ \mathrm{mag\ arcsec}^{-2}$ (2-σ depth) ➡ corresponding to $\Sigma \sim 0.1\ M_\odot\ \mathrm{pc}^{-2}$ for old stellar pops
- **sub-arcsec resolution** in all filters (0.55" in i-band)
- shallow and long exposures for optimal surface brightness profile analysis

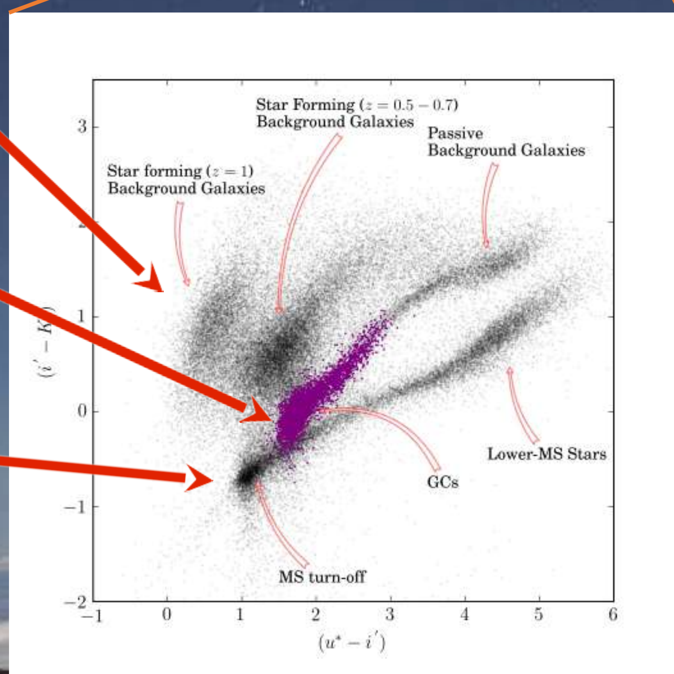
**For details, see Ferrarese et al. 2012**

# The galaxy halo-intracluster light dichotomy: the GC perspective

NGVS@CFHT program to fully image Virgo in the u*g'r'i'z' filters within R200 for its two main sub-clusters

For NGVS pilot region K-band photometry: Accurate identification of GCs against contaminants

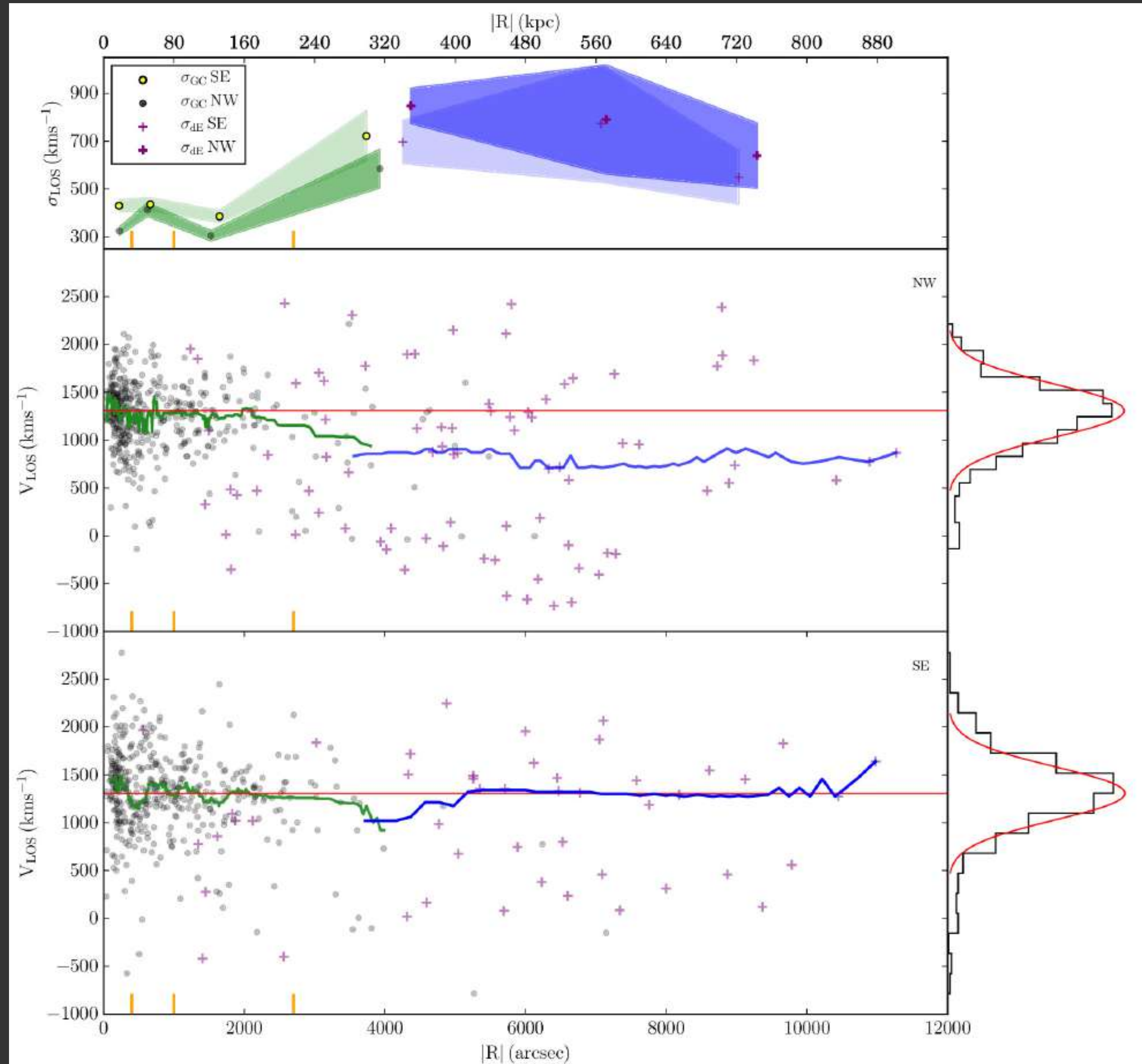
2 deg




The Next Generation Virgo Cluster Survey

*The NGVS as it would appear in the sky*
*Photo Jean–Charles Cuillandre (2010)*

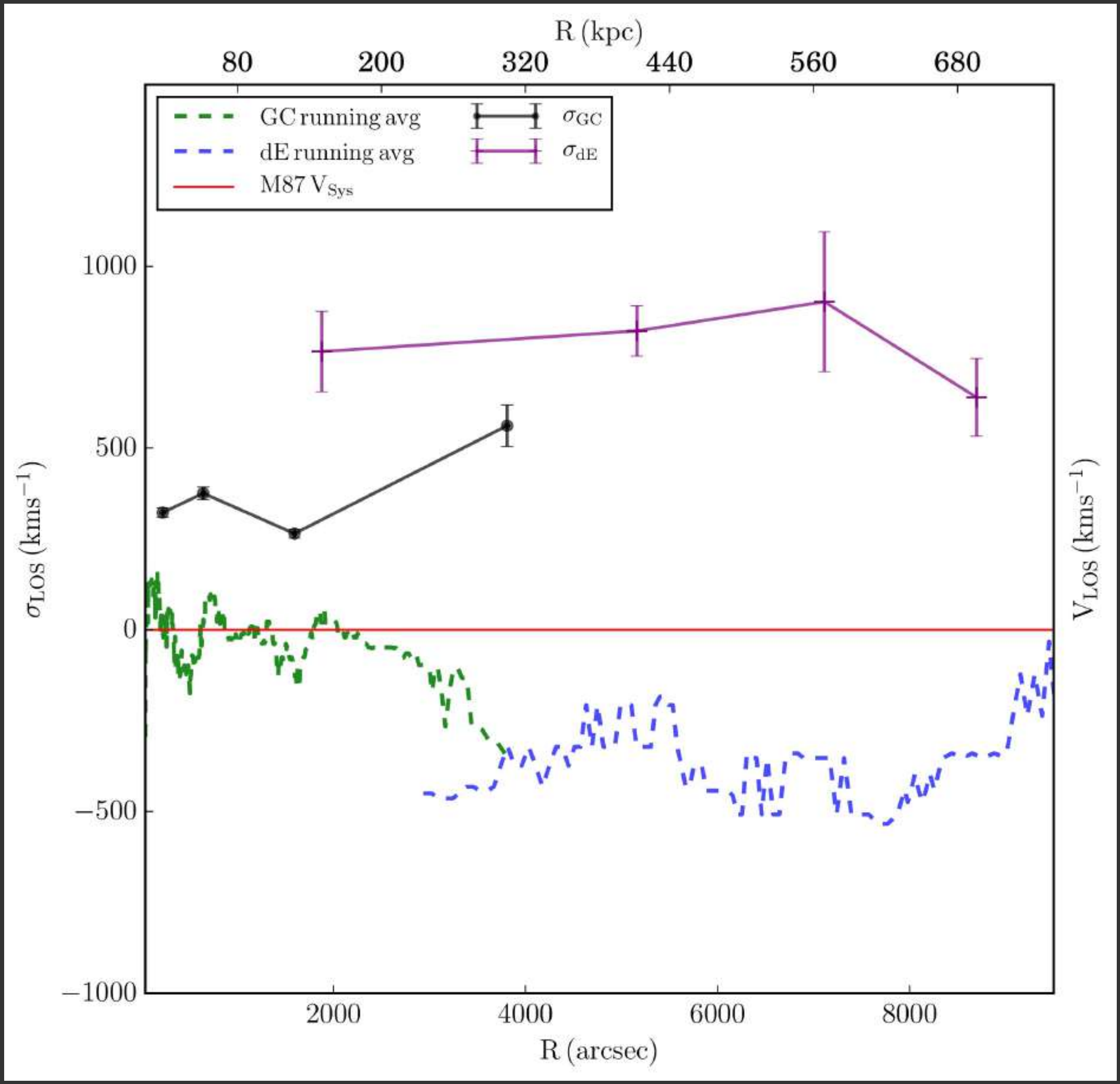
Longobardi + 2018a




- GC kinematics eventually becomes indistinguishable from the kinematics of Virgo dwarf galaxies at major axis distances of R > 320 kpc.

- LOSVD with strong and asymmetric tails

Longobardi + 2018a

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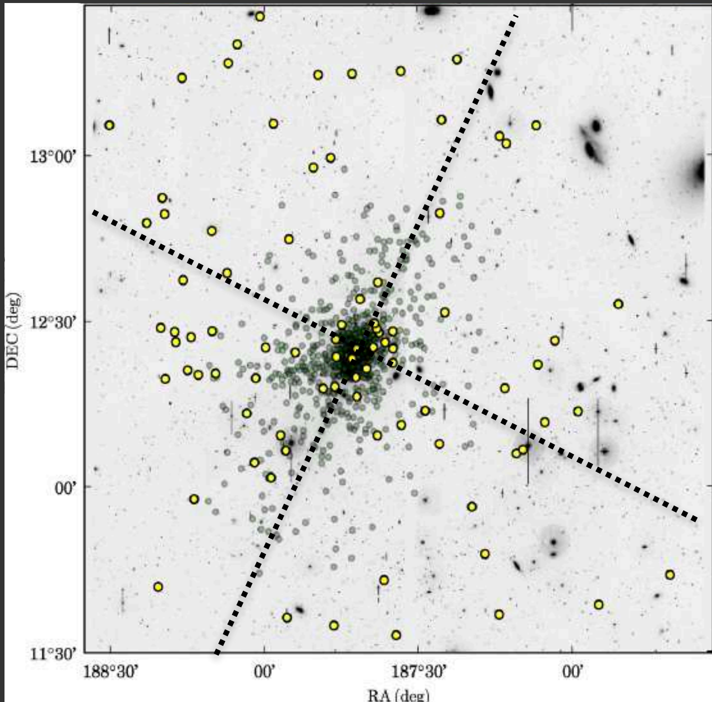
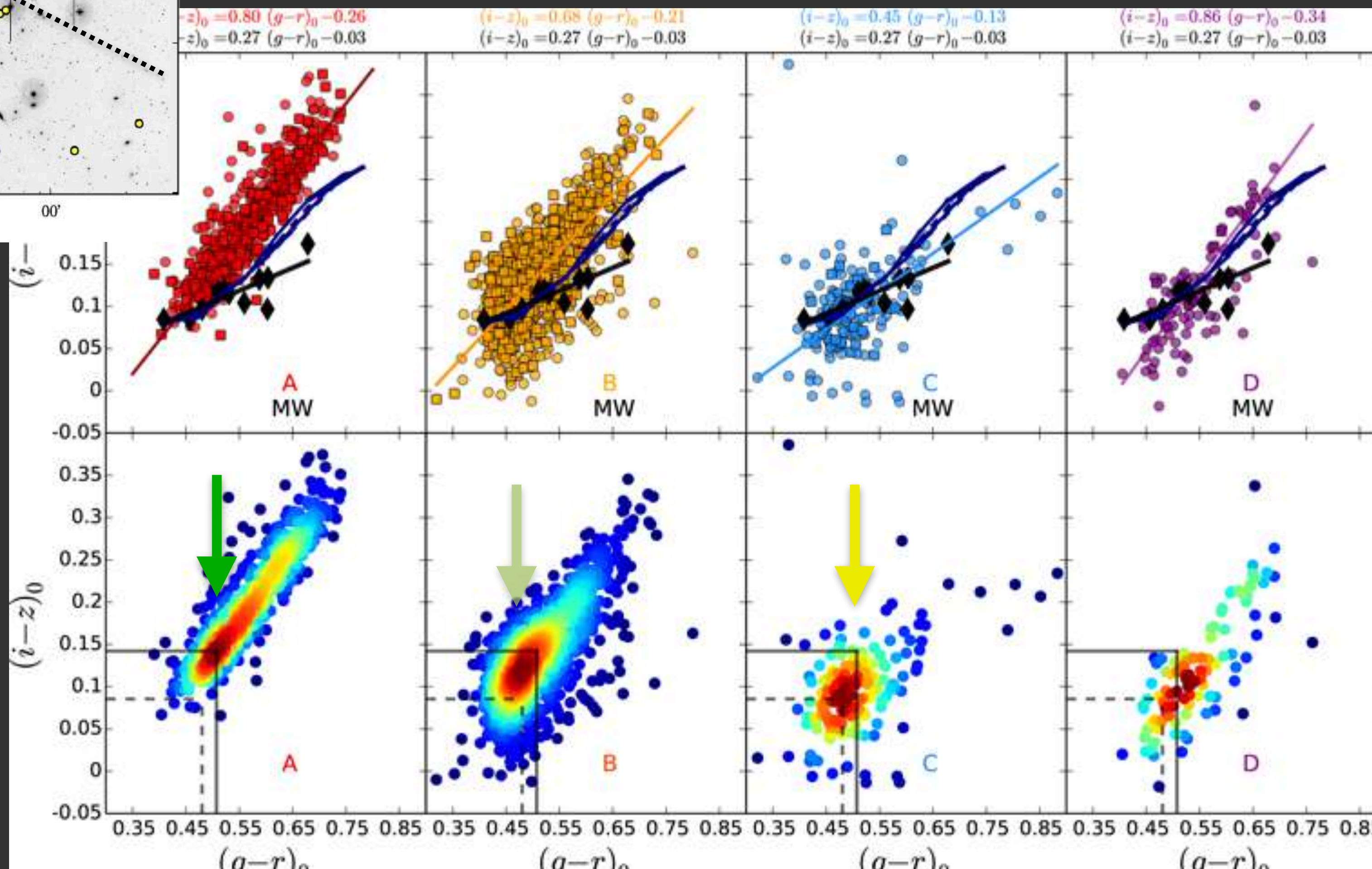
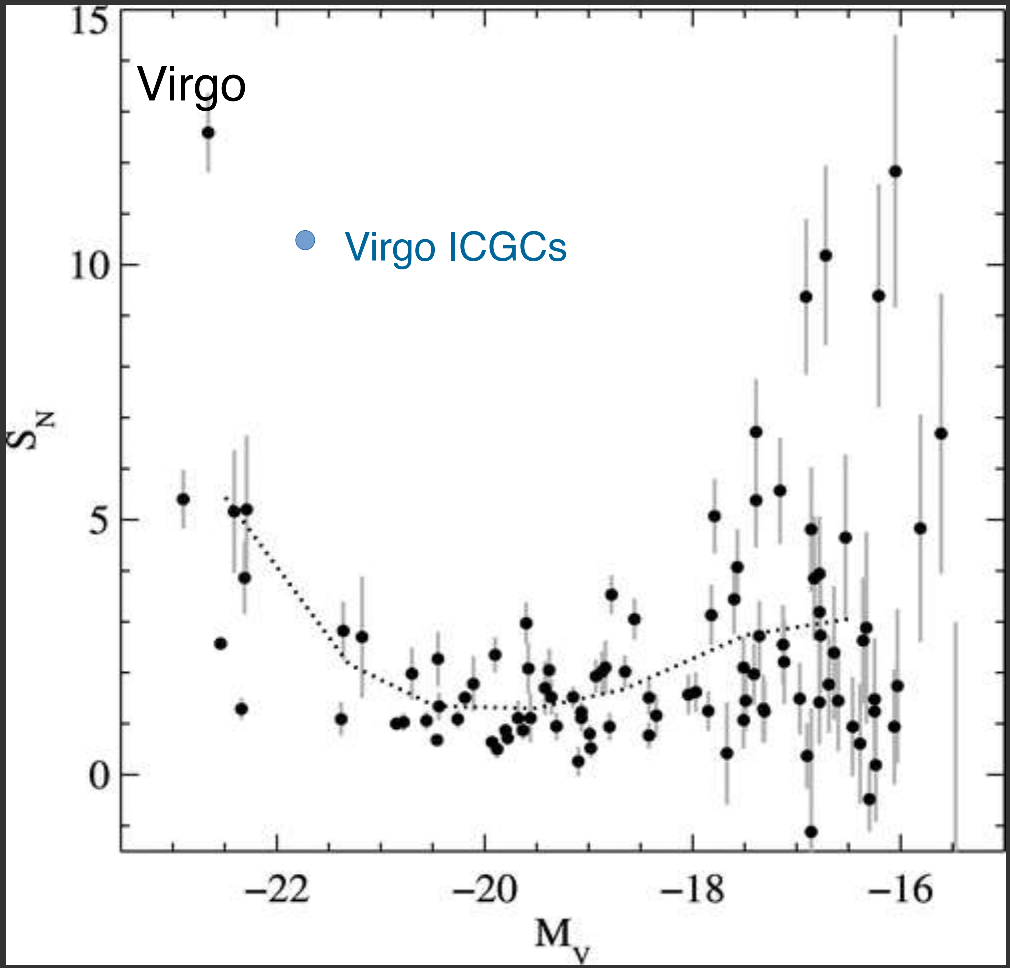



Correlation between GC color-color relations and environment
Interpreted as driven by different stellar abundance ratios
(Powalka et al. 2016B,2018)

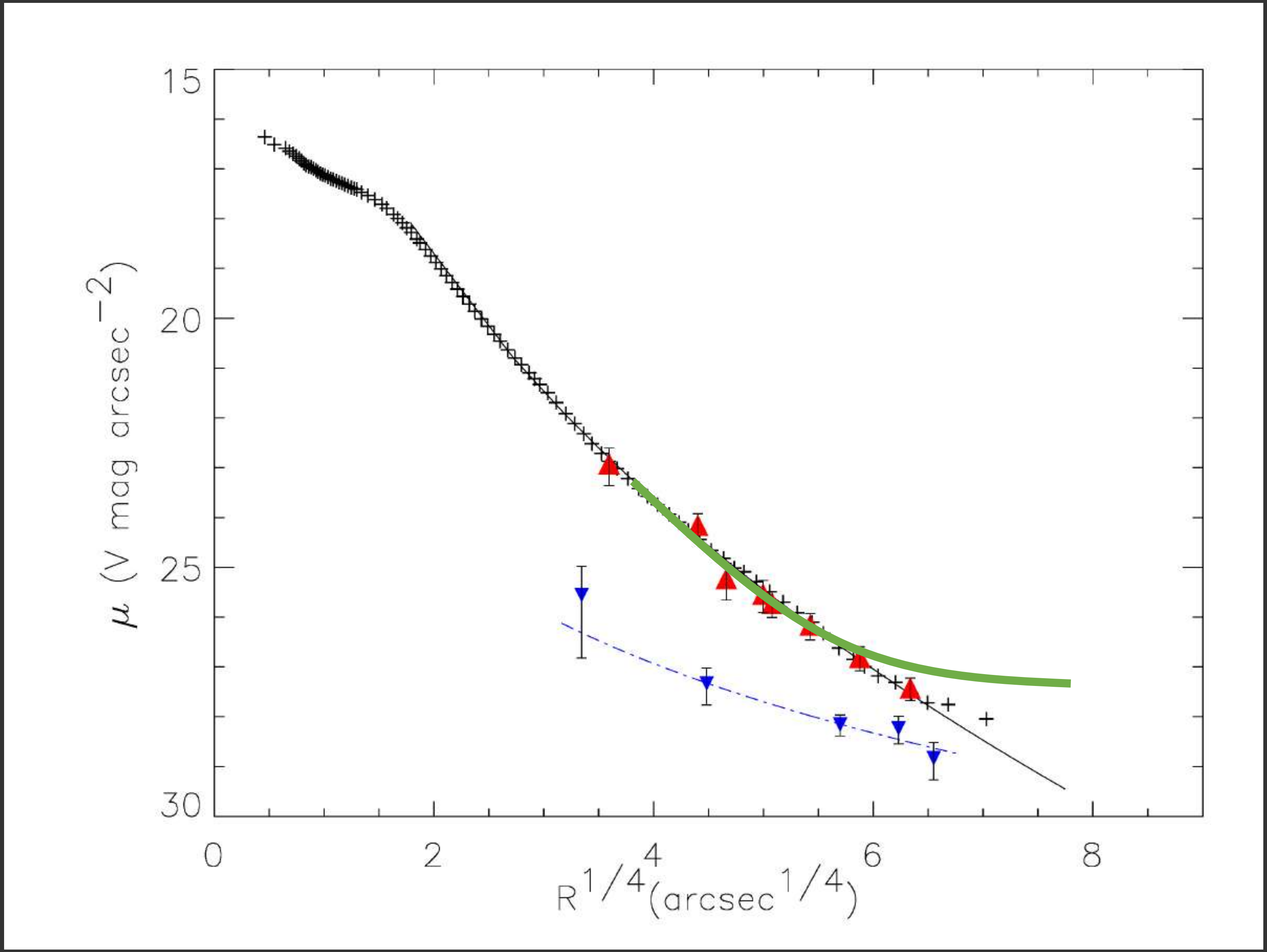


Peng et al. 2006




Early-type dwarf galaxies have a large spread in $S_N$ . Data outside Virgo show that fainter dwarf ellipticals can have an even larger range of specific frequency

$S_{N,ICL}$ = 10.2 ± 4.7, consistent with what is observed for the population of low-mass galaxies within 1 Mpc from the cluster's center (Longobardi+18b)

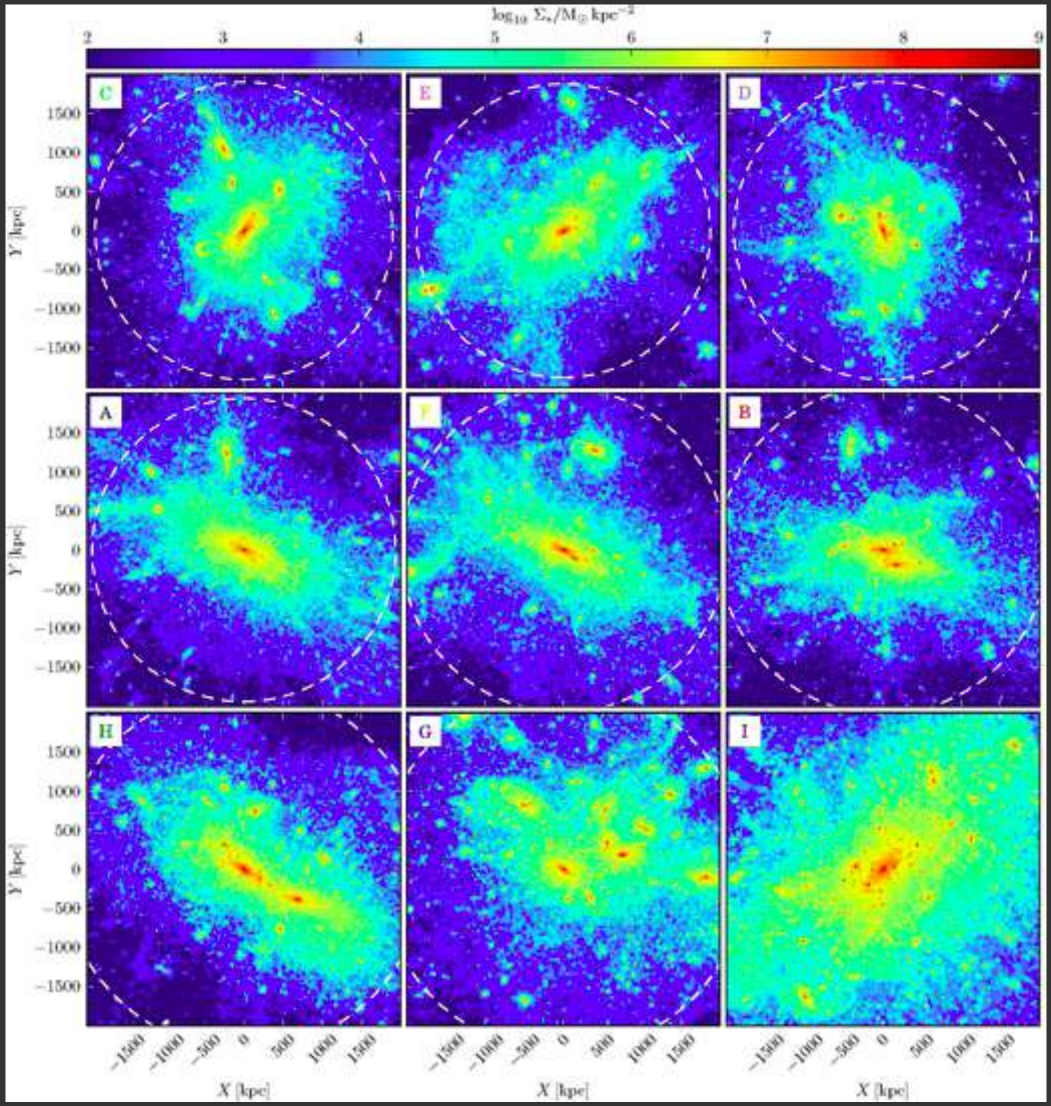


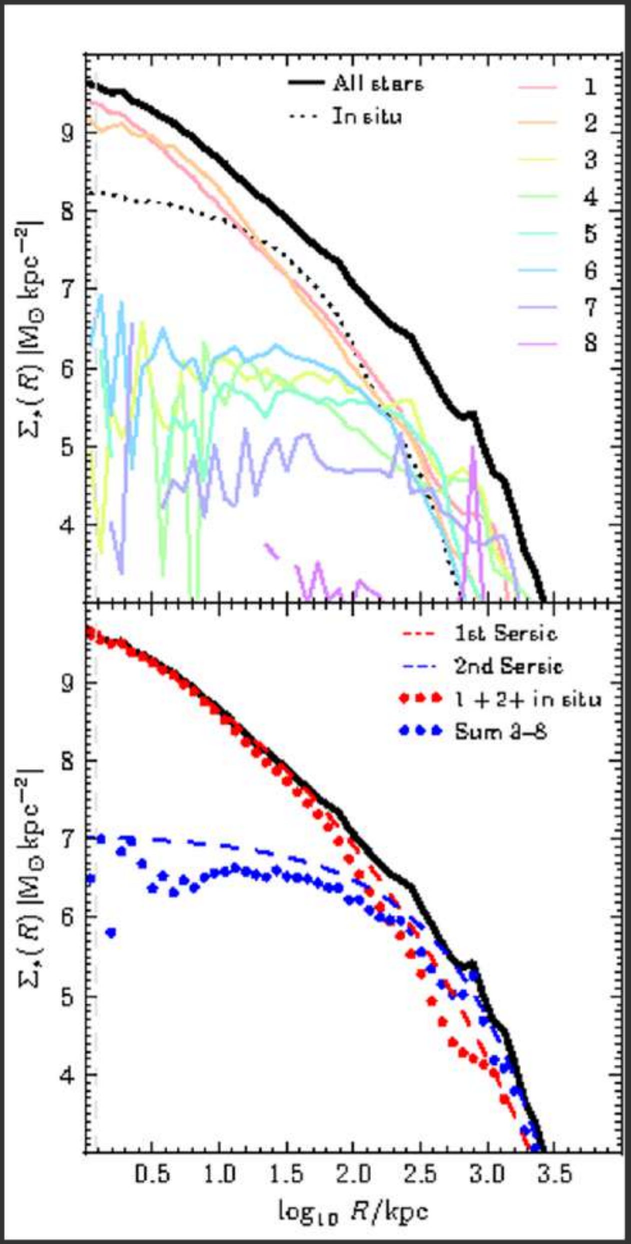
M87 halo (red) and intracluster (blue) density profiles (Longobardi+13,15a)

- The ICPNs contribute 3 times more PNs per unit bolometric luminosity, i.e. larger α parameter

- Consitent with the galaxy halo being redder and more metal rich than the ICL

# The hierarchical structure formation

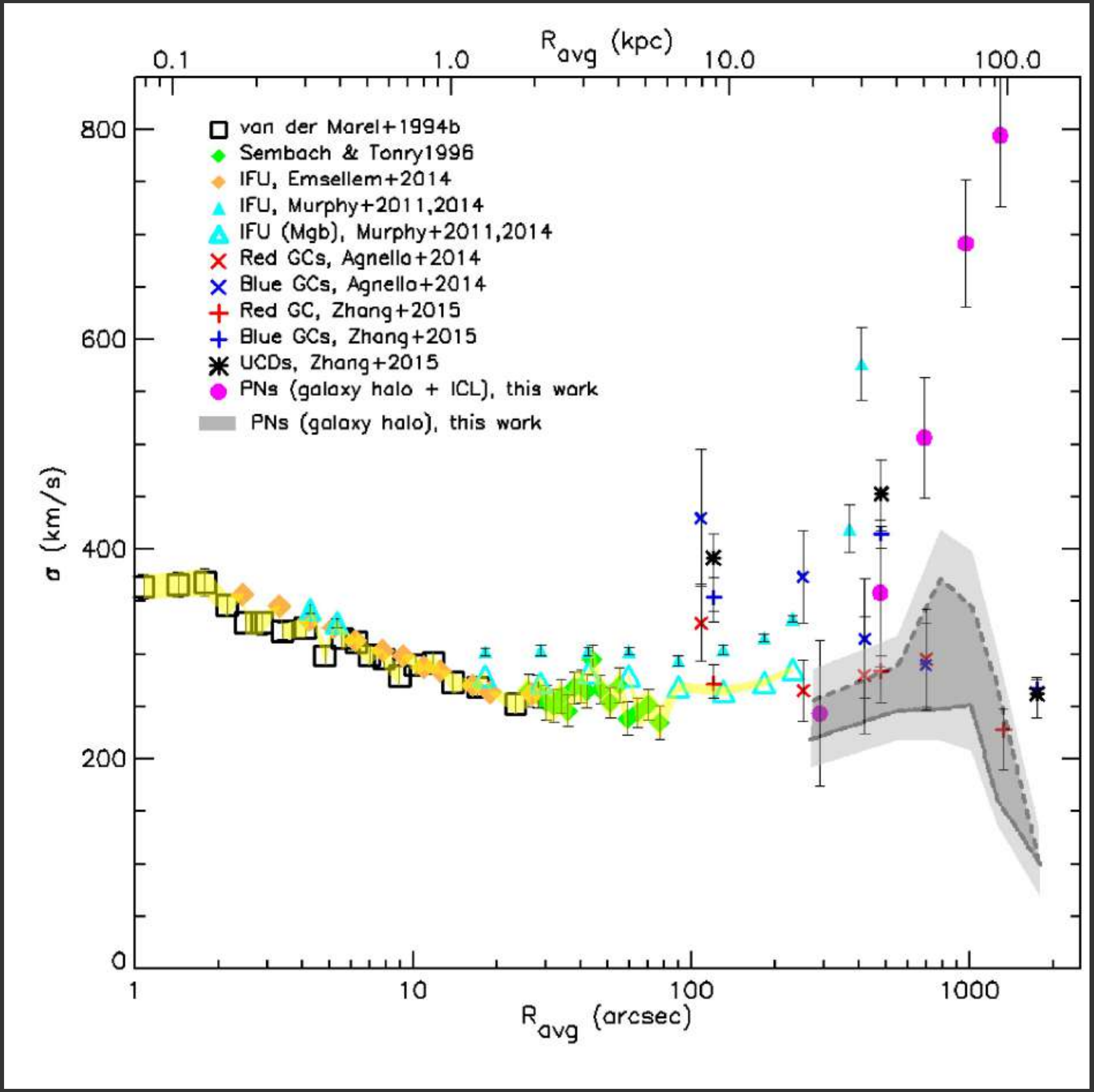



ΛCDM simulation of central cluster galaxies and their light profiles (Cooper+15)

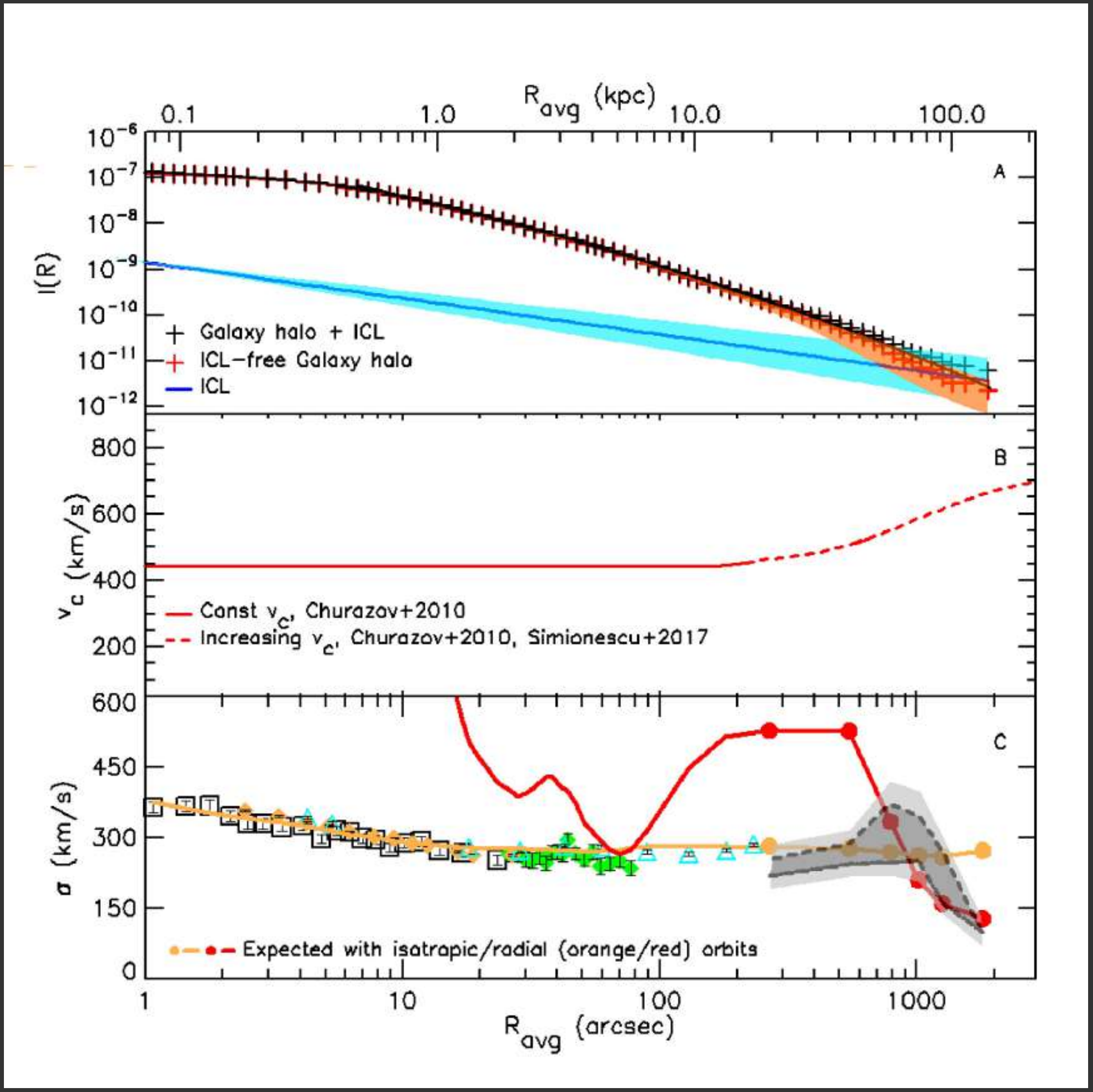
The system central galaxy+intracluster light is treated as a single entity consisting of all stars which are not bound to any sub-halos.

Simulations suggest masses of a few x $10^9$ $M_{sun}$ for the ICL progenitors




M87 composite velocity dispersion profile (Longobardi et al. 2018b)

The presence of sub-components in the LOSVD and of ICL at large radii can systematically bias the estimates of the total enclosed mass in bright cluster galaxies like M87.




M87 orbital distribution(Longobardi et al. 2018b)

The M87 surface density and velocity dispersion profiles are in approximate dynamical equilibrium in the X-ray gravitational potential

The anisotropy of the halo stellar orbits change from an approximately isotropic distribution to a strongly radially anisotropic configuration

# Outline:

**1. What we know :** *Where stellar halos coexist with intra-cluster light: a case study of the giant Virgo-central galaxy M87*

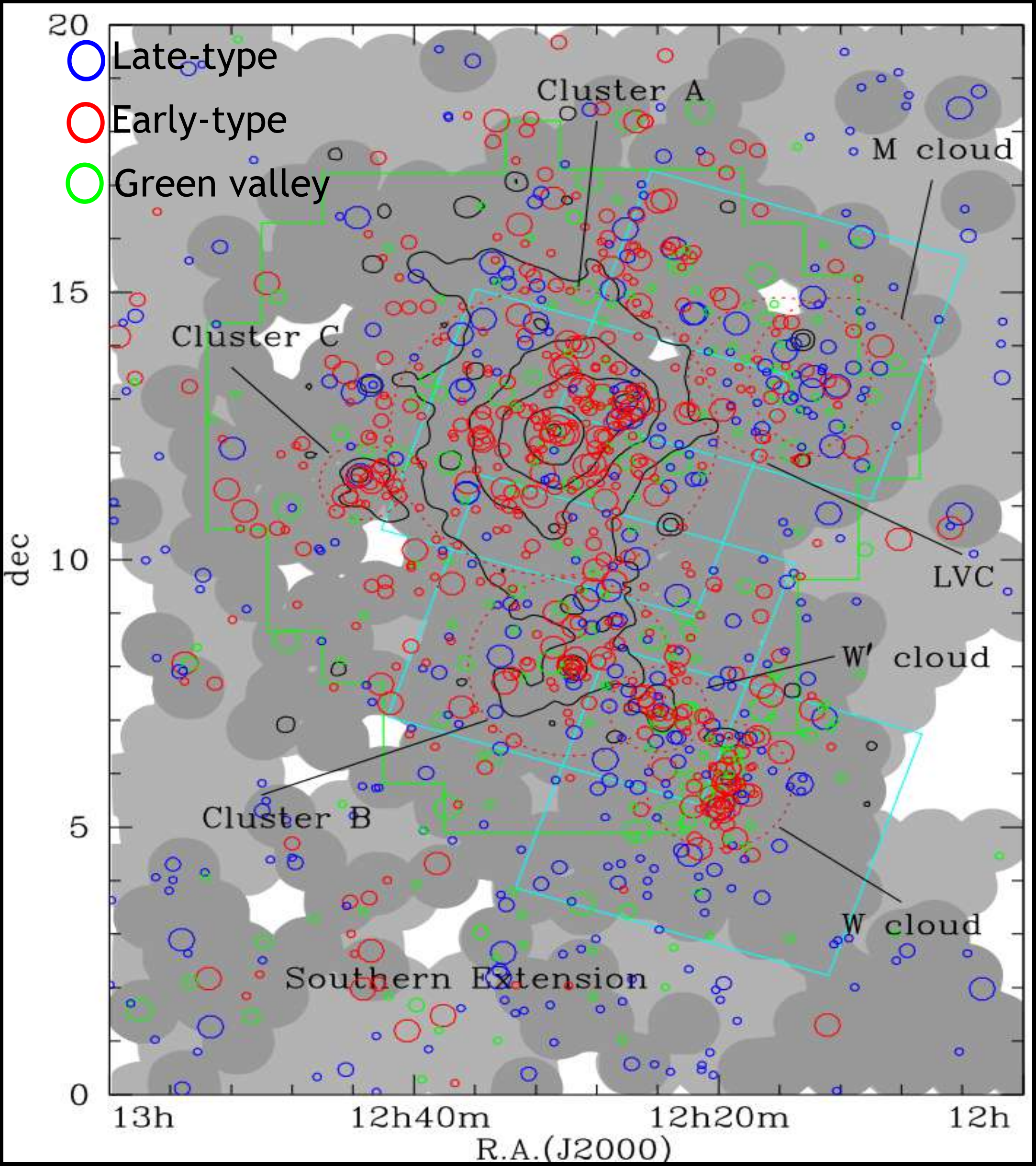
The synergy between photometry and spectroscopy revealed the galaxy halo-ICL dichotomy

The ICL is the cluster accreted component from low and intermediate mass star-forming and dwarf-ellipticals galaxies

**2. Moving Forward:** *A panchromatic view of the Virgo intra-cluster component*

**Deep surveys**

map the Virgo cluster at different wavelengths.




X-ray: **ROSAT** (Nulsen & Bohringer, 1995)

OPTICAL : **NGVS** (Ferrarese et al. 2012)
S: ~ *g* 25.9 mag ; ~ g 29 mag arcsec$^{-2}$
R: < 1“

OPTICAL - Hα: **VESTIGE** (Boselli et al. 2018)
*S: f(Hα)* ~ 4x10$^{-17}$ erg sec$^{-1}$ cm$^{-2}$ (5σ) for point sources; *Σ(Hα)* ~ 2x10$^{-18}$ erg sec$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (1σ) for ext. sources at 3” res

UV: **GALEX UV Virgo Cluster Survey** (GUViCS; Boselli et al. 2011)
S: ~ 21.5 mag; ~27.5 mag arcsec $^{-2}$
R:4”-5”

Near-IR: **SPITZER** (Werner et al. 2004)

Far-IR: Herschel Virgo Cluster Survey (HeViCS; Davis et al. 2010)
S: 6.8, 3.1 MJy/sr (PACS)
1.0, 0.7, 0.3 MJy/sr (SPIRE)
R: ~7”-35”

radio HI: **VIVA** (Chung et al. 2009)

S: 3-5 x 10$^{19}$ cm$^{-2}$ @ 10 km s$^{-1}$
R: 15”

# Dust in the ICM of clusters

Dust is expected to survive sputtering by the harsh X-ray emitting gas for a typical timescale of $\sim 10^8$ yr
(Draine & Salpeter 1979)

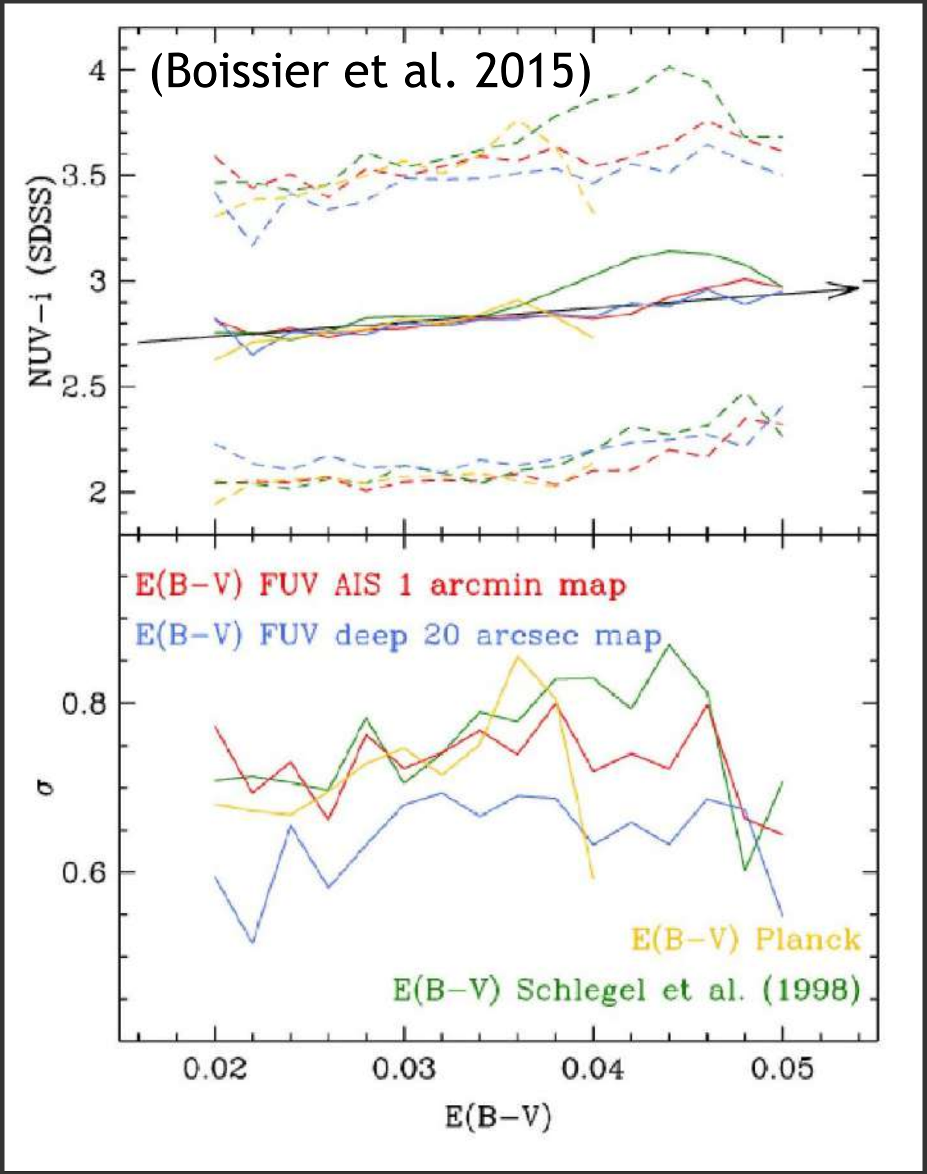
Dust detection can give us clues to the different injection mechanisms and their efficiencies and to the current accretion rate of the cluster
(e.g. Popescu 2000)

Detectable either searching for thermal dust emission (FIR, submillimeter studies ) or searching for extinction and reddening of background sources
(e.g. Giard et al. 2008, Gutiérrez & López-Corredoira 2017)

$A_V$ values attributed to the presence of ICD vary significantly, $0.004 < A_V < 0.5$,
(e.g. Muller et al. 2008)

Only a small amount of dust in the ICM of clusters , 1–3% of the Galactic value
(e.g. Chelouche et al. 2007; Giard et al. 2008; Planck XLIII 2016)

# Contamination by Galactic Cirrus in the Virgo direction




NUV−*i* colour of SDSS background galaxies in the Virgo direction as a function of the Galactic dust reddening

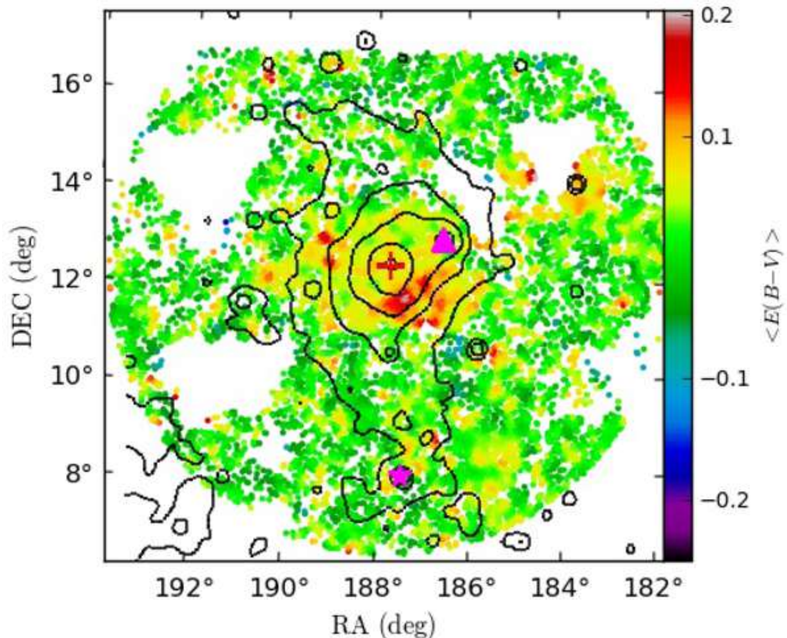
Linear correlations between NUV−*i* colour and E(B-V)

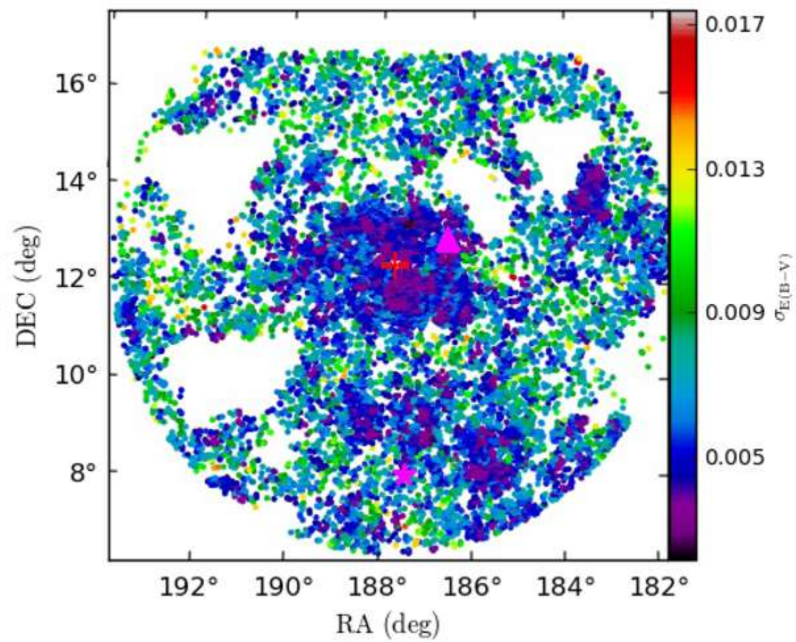
Opportunity of studying the distribution of the background galaxy colours after correction for Galactic contamination

# Diffuse Dust in the Virgo intra-cluster space

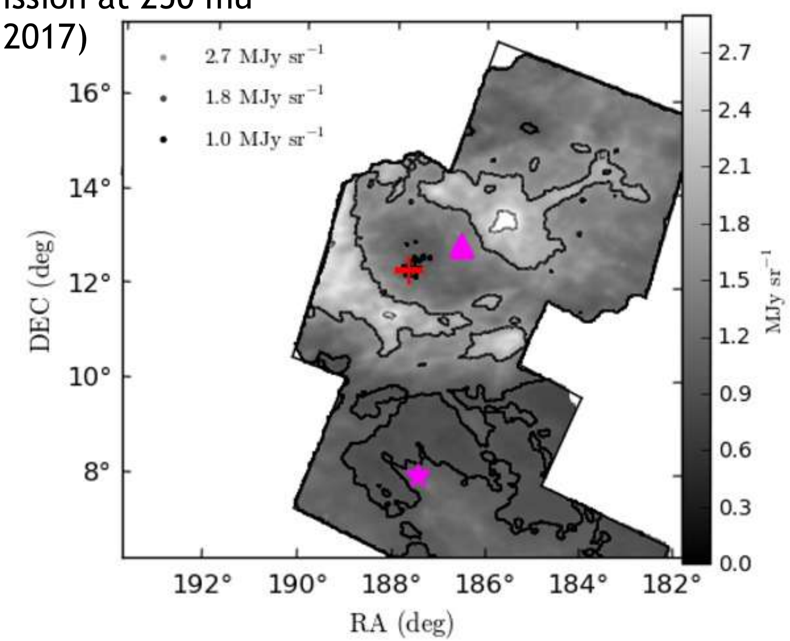
Longobardi et al. 2020a

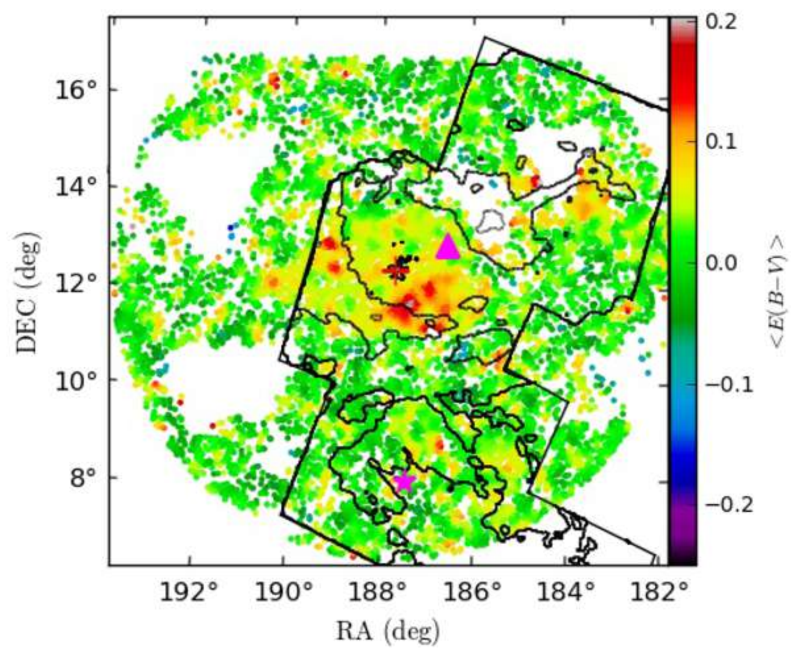
Virgo Dust reddening



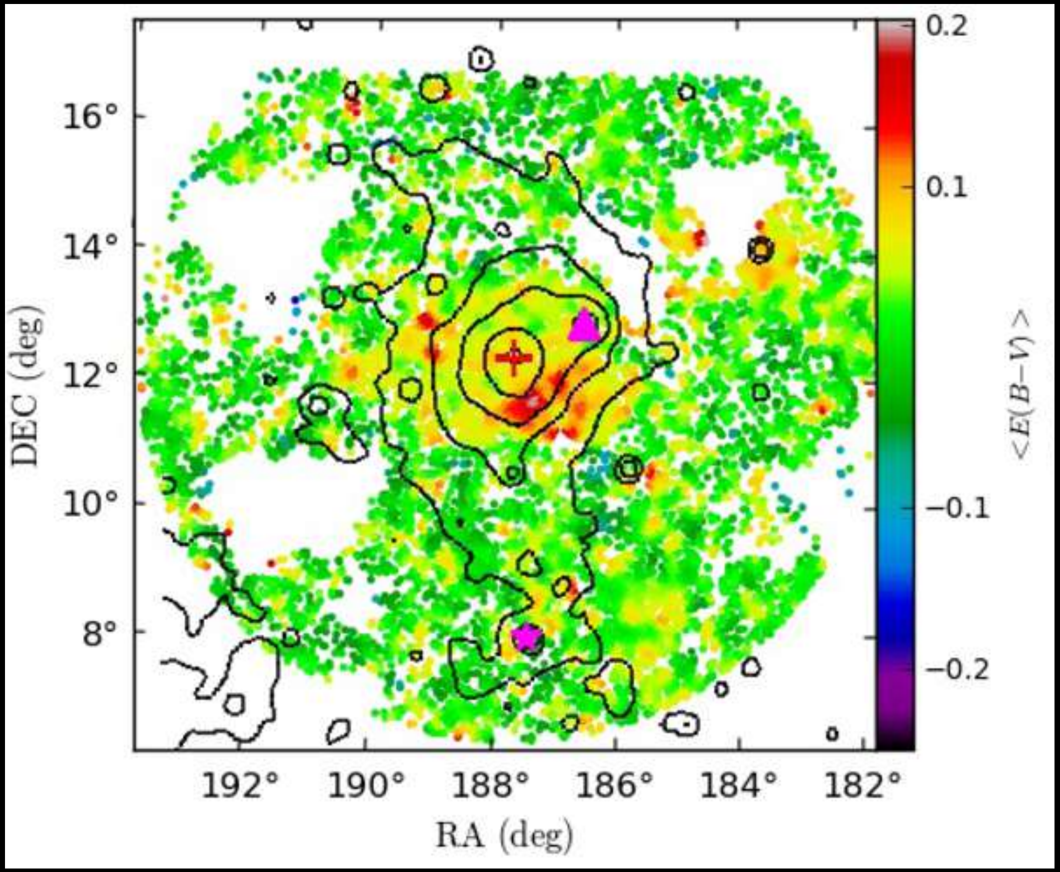

MW dust IR emission at 250 mu
(Bianchi et al. 2017)

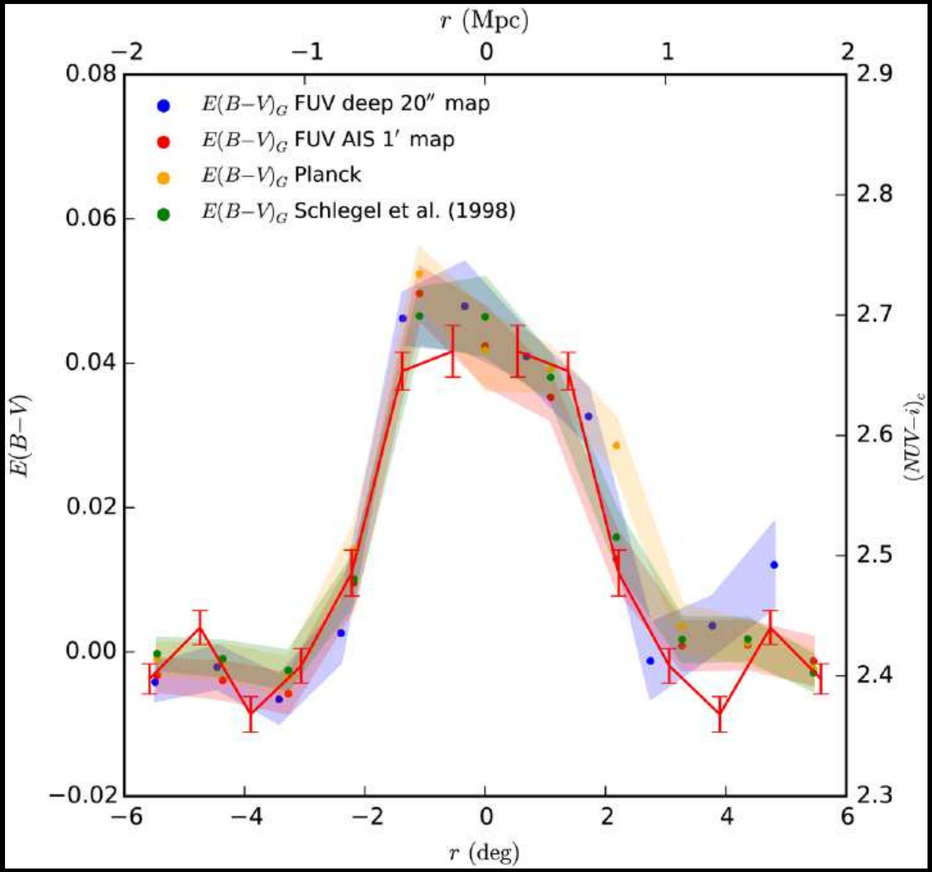


# Diffuse Dust in the Virgo intra-cluster space

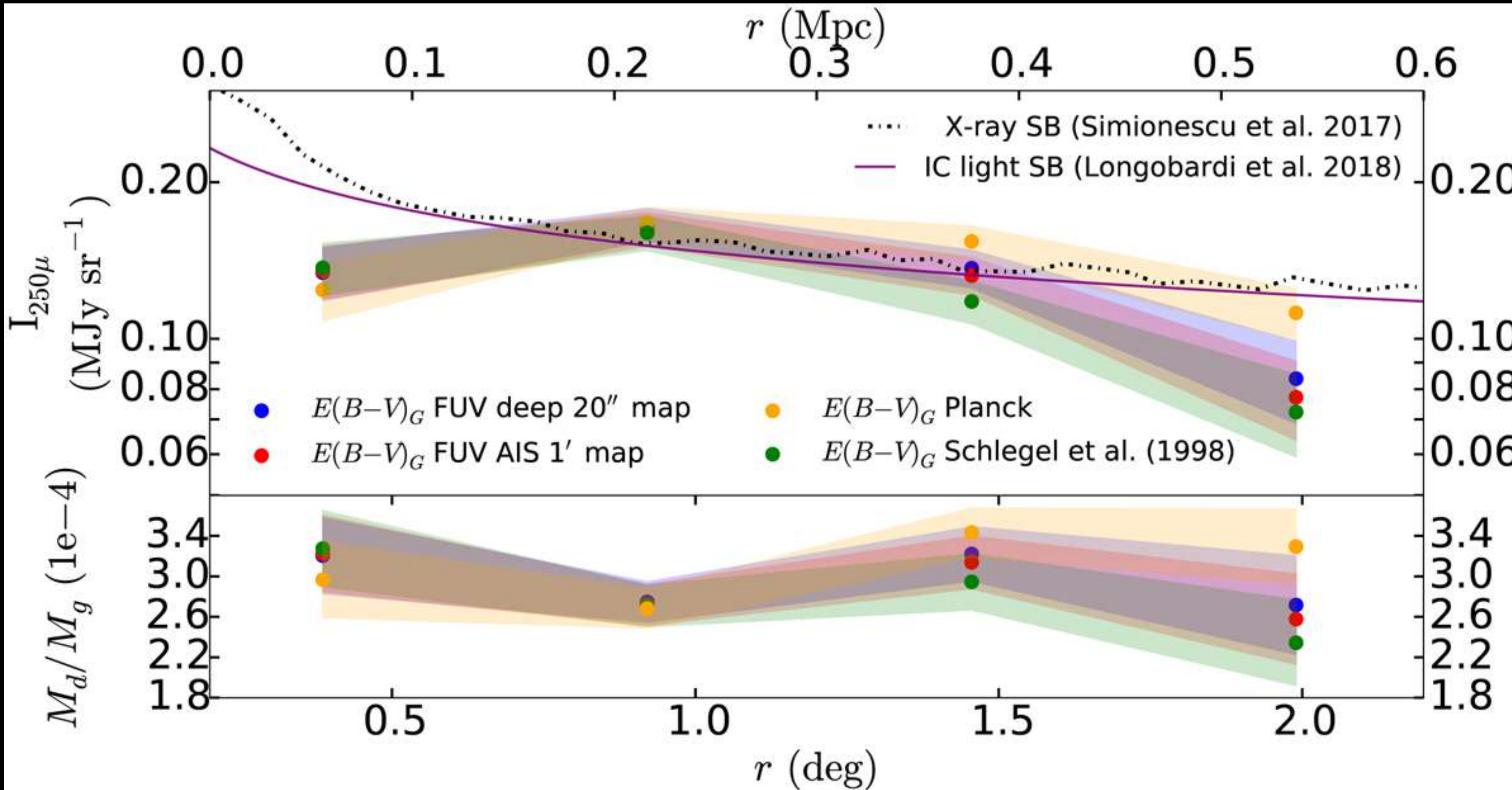
Longobardi et al. 2020a




- *E(B – V)* values are higher going closer to the cluster's centre
- *E(B – V)* ~ 0.042 ± 0.004 mag or $A_V$ = 0.14 ± 0.01within 1.5 degrees (~0.3 $r_{\mathrm{vir}}$)

Longobardi et al. 2020




- Radial profile similar to the one characterizing the diffuse ICL
- $M_d = 2.5 \pm 0.2 \times 10^9\, M_\odot$ ; $M_d/M_g = 3.0 \pm 0.3 \times 10^{-4}$ within 1.5 deg (~0.3 $r_{vir}$)
- Dust in the Virgo ICM constitutes an additional cooling agent of the gas

# Stripped tails and their connection with the intra-cluster component

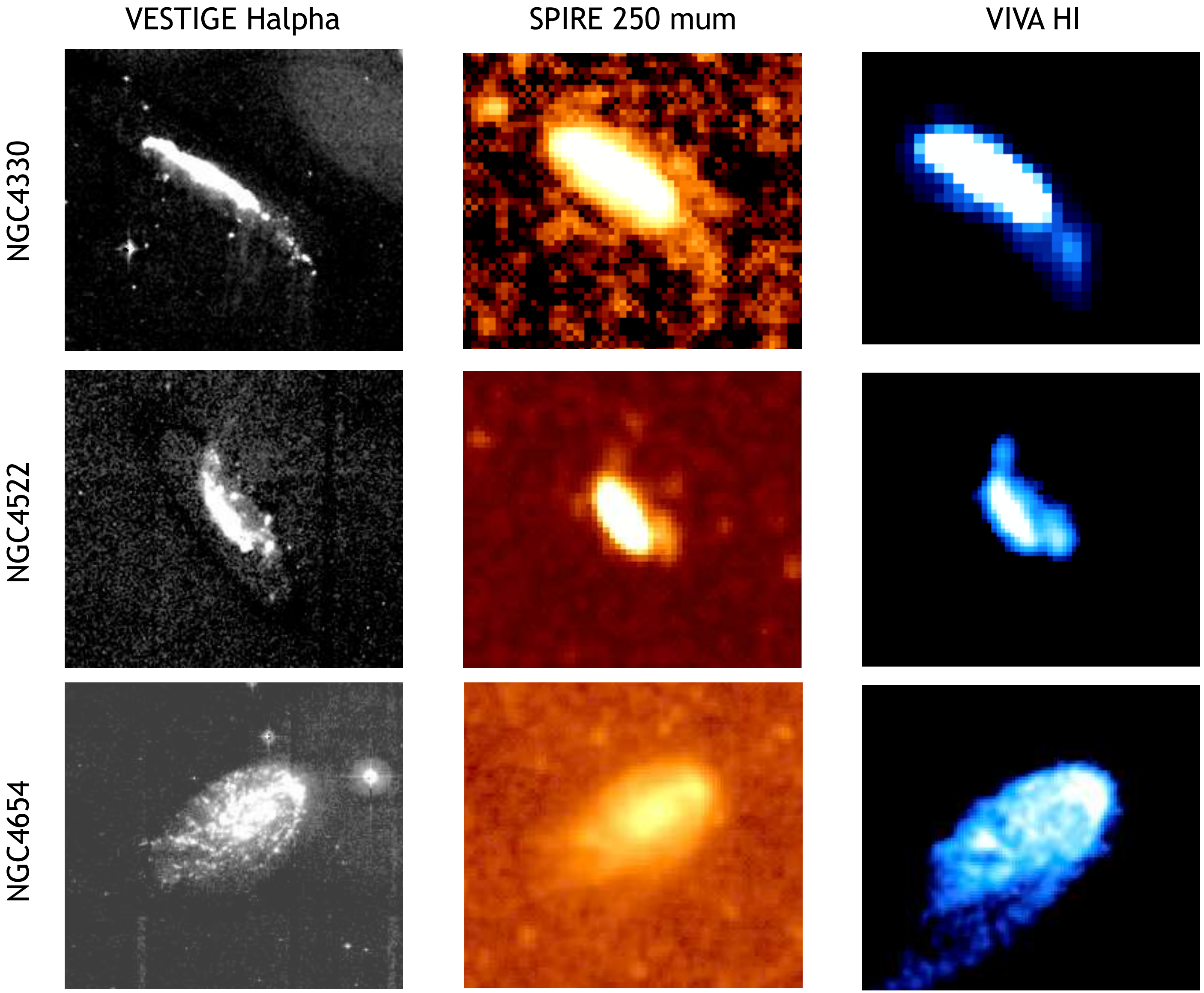
## The galaxy sample

- Virgo galaxies with asymmetric morphologies in the HI, Halpha and FIR emission
- All within 4 deg from the cluster's centre

- NGC4330 (1563 km/s)
- NGC4522 (2329 km/s)
- NGC4654 (1046 km/s)

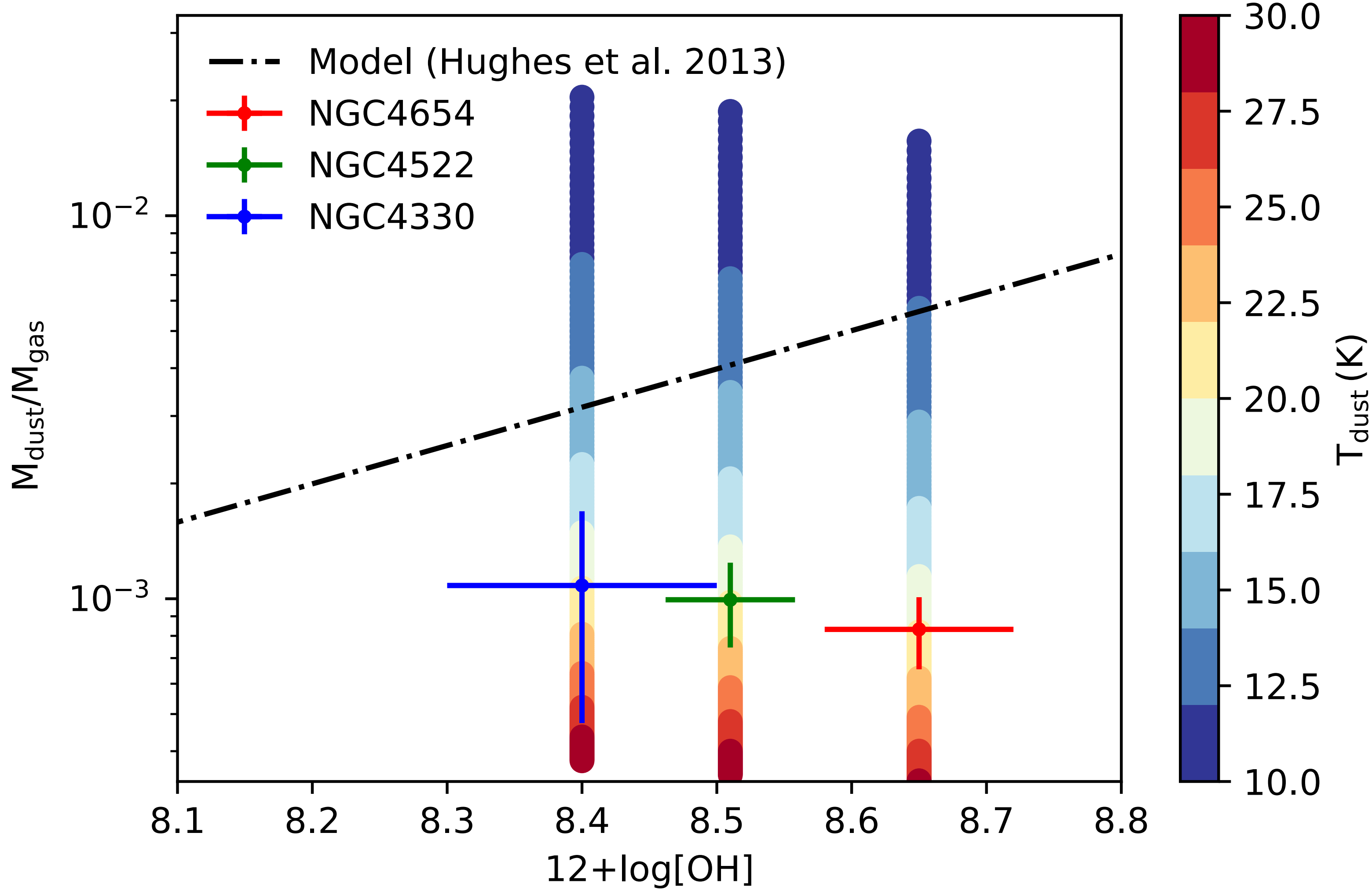
Image by A. Chung

Longobardi et al. 2020b




- Detection of stripped tails of dust allows us to study the interplay between the different baryonic components at a different stage of galaxy evolution

Longobardi et al. 2020b




- The dust-to-gas ratios as measured in the main body of the galaxies do not apply to the tails of processed systems.

# Conclusions:

The synergy between photometry and spectroscopy of bright tracers revealed the galaxy halo-ICL dichotomy

The Virgo ICL is the cluster accreted component from low and intermediate mass star-forming and dwarf-ellipticals galaxies

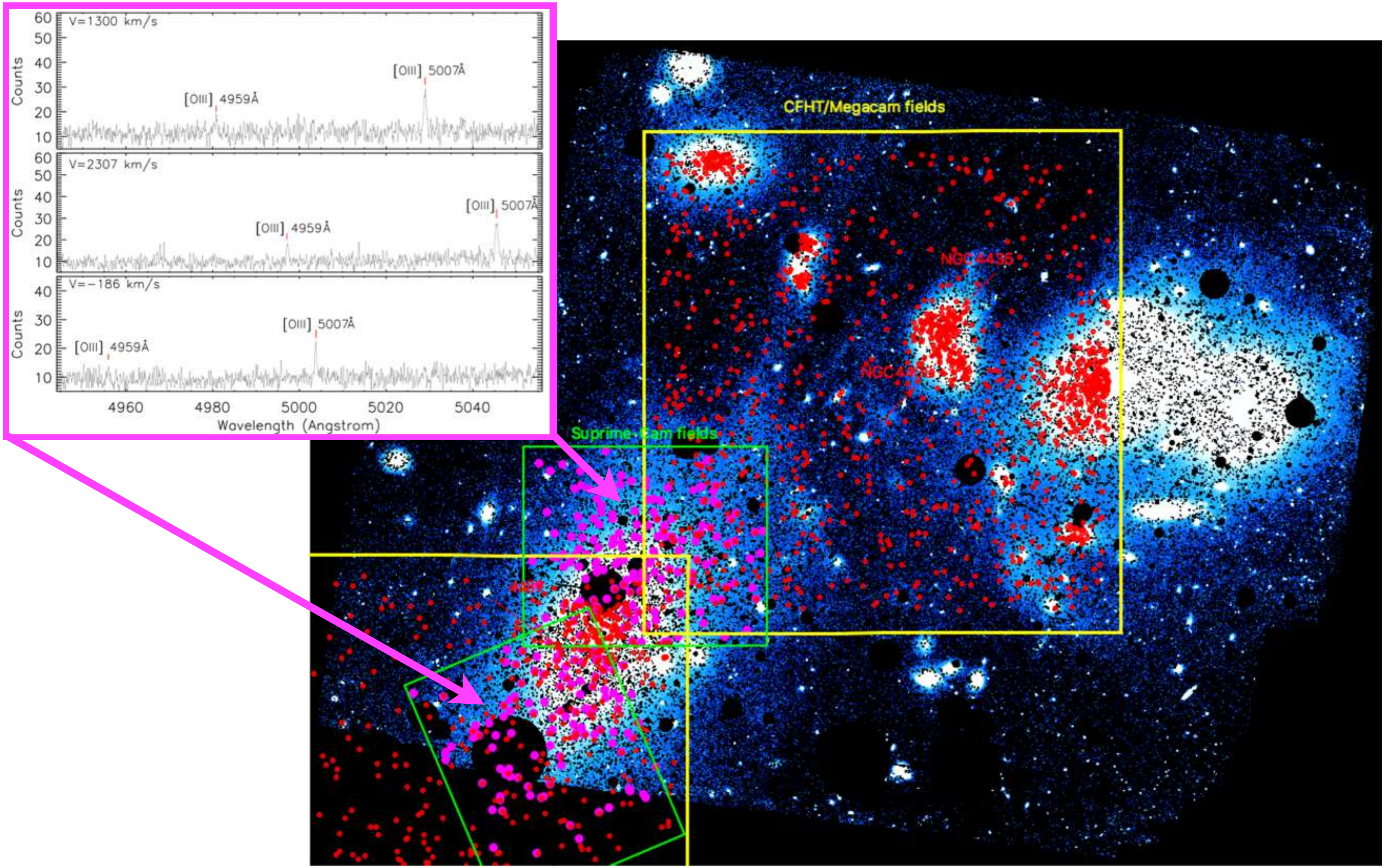
There is diffuse dust in the Virgo cluster transported into the cluster space through similar phenomena as those building up the Virgo ICL

The reddening values imply variations in the physical properties of the Virgo ICD either in terms of temperature (colder for the ICD) or in terms of emissivity (higher for the MW)

Tails of stripped dust are visible in processed Virgo galaxies. Their values of dust-to-gas ratios differ from those characterising the main body of the galaxies.

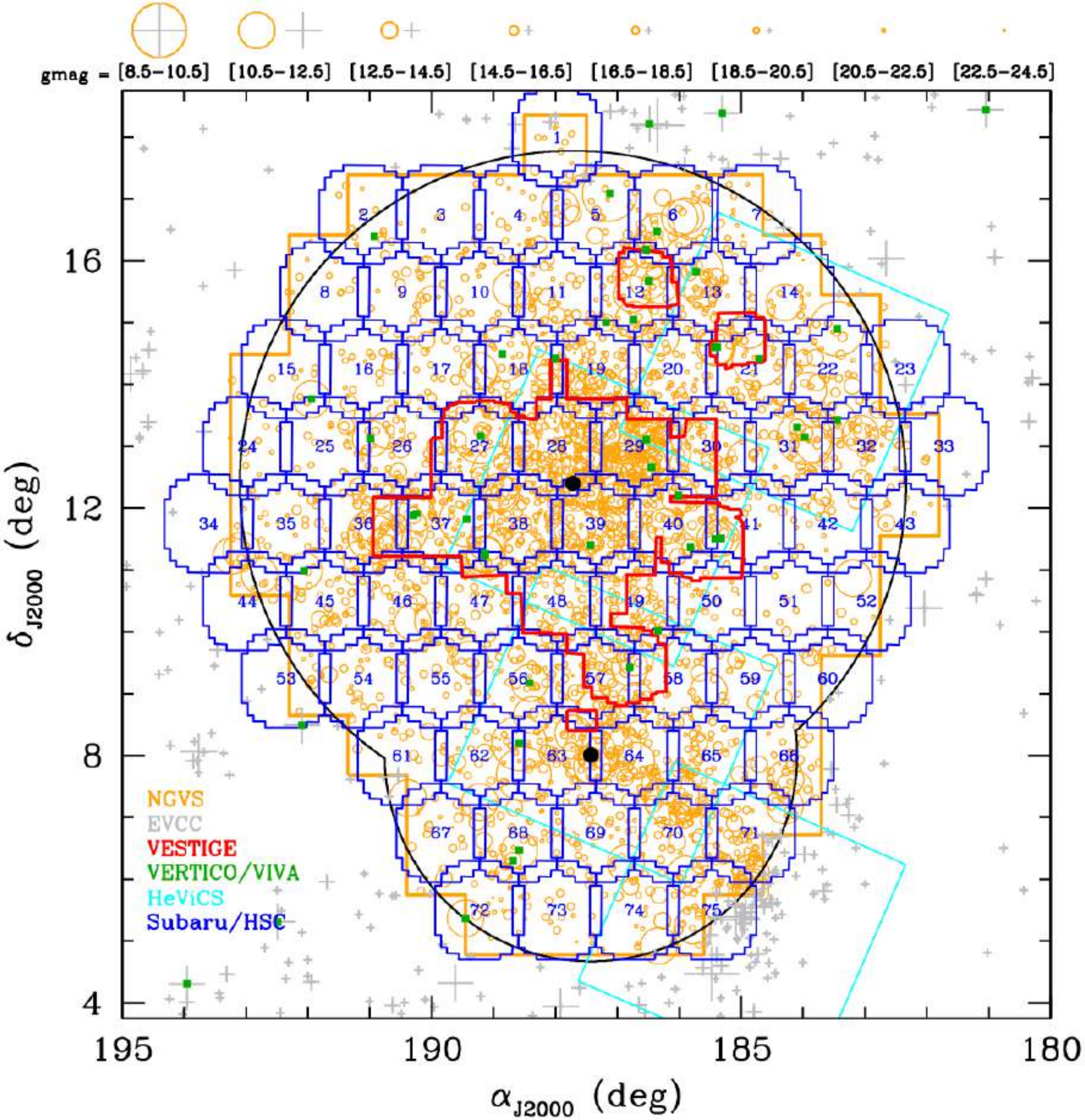
The properties between the different phases of the ISM change during the different stages of evolution

# Moving Forward: The Virgo PN survey




•3 nights on the MegaCam@CFHT in 2018A -> **3 nights A program -** Ω ~ 4 deg$^2$
•**Depth for [OIII] point sources ≈ 1.5x10$^{-17}$ erg sec$^{-1}$ cm$^{-2}$**
•able to detect a total of 4000 PNs down to m5007 = 28.2

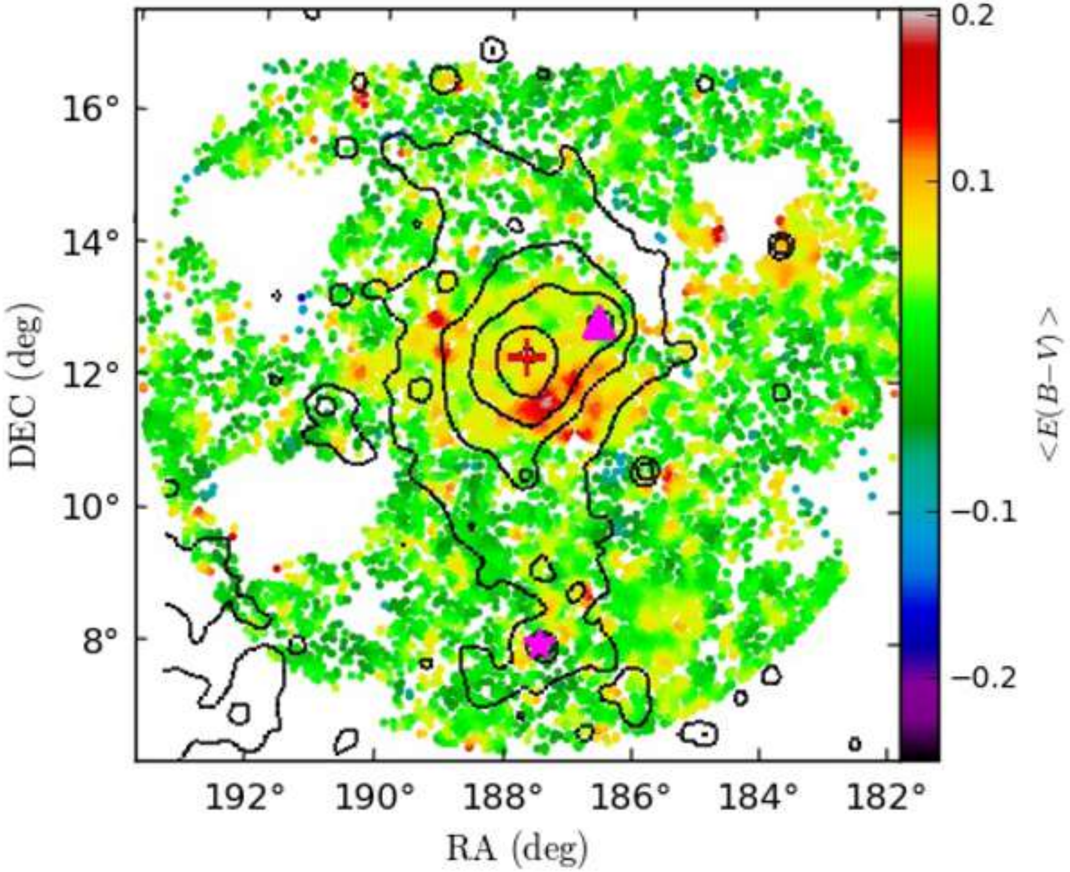
# Moving Forward: LP Subaru Intensive PN survey

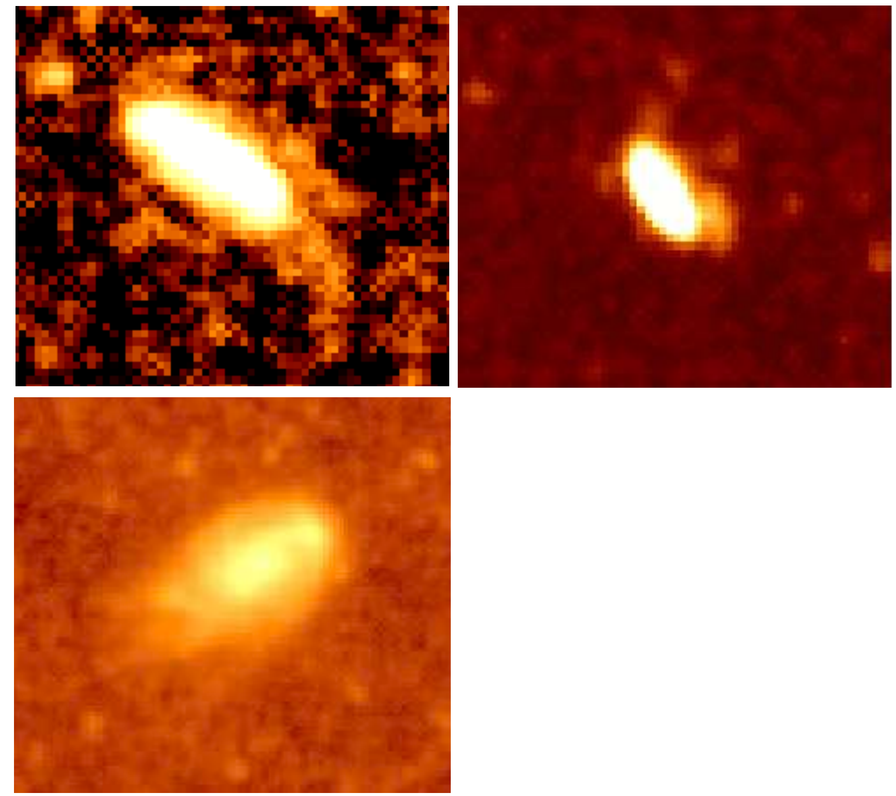



- 7.1 nights on the HyperSC@Subaru in 2020B - Ω ~ 104 deg$^2$
- **Depth for [OIII] point sources ≈ 1.5x10$^{-17}$ erg sec$^{-1}$ cm$^{-2}$ ->~ 10$^5$objects down to m5007 = 28.2**

# Future studies with ATHENA and SPICA

SPIRE 250 mum

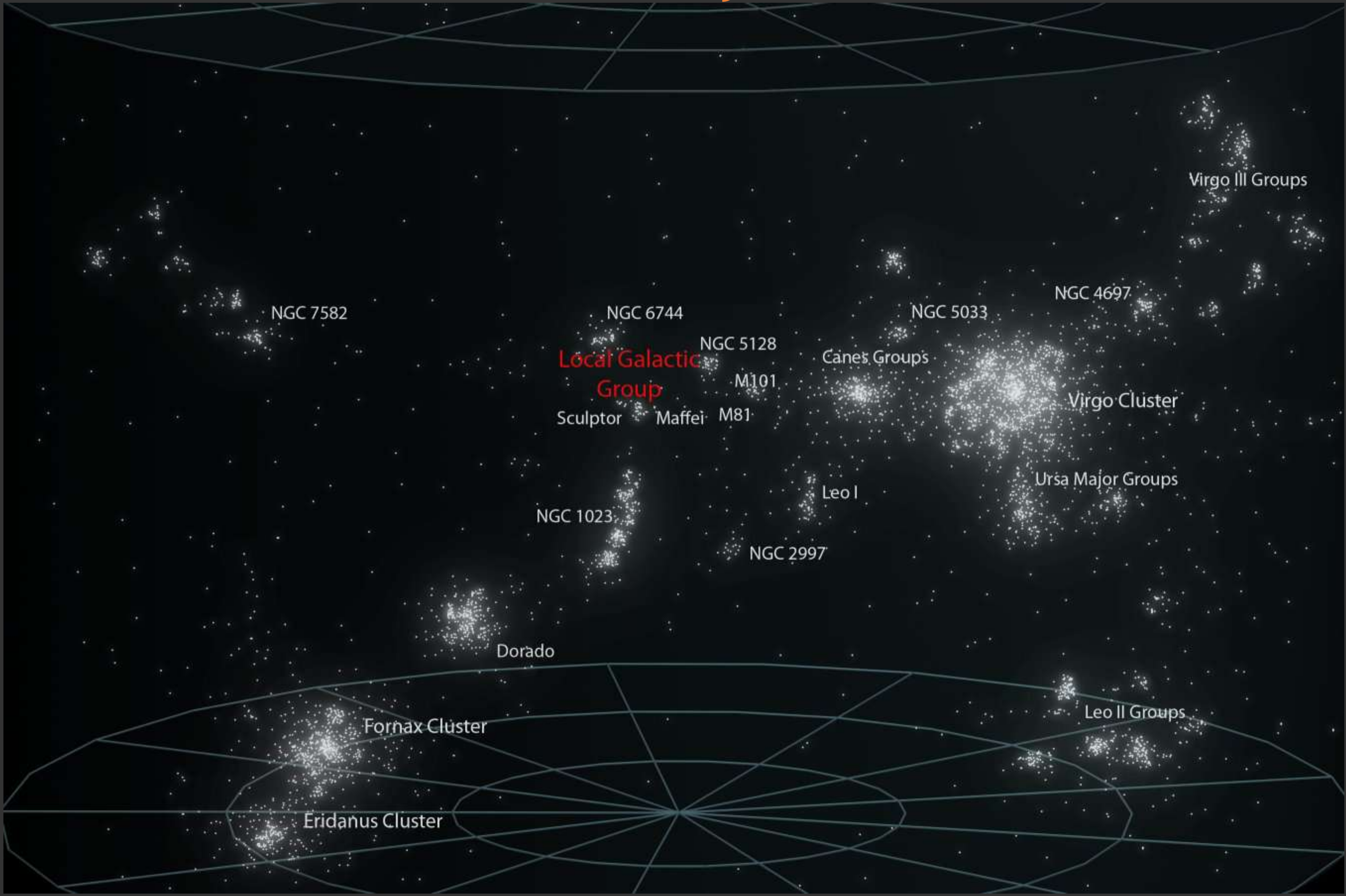


- *ATHENA follow-up studies:* ***The Athena eye on the dust in the Virgo intra-cluster medium*** (A. Longobardi, A. Boselli, M. Giard, C. Adami)

- *BeBOP SPICA follow-up studies:* ***The role of the interacting environment on polarised light*** (A. Longobardi, A. Hughes A. Boselli)

# Thank you



Virgo III Groups
NGC 7582
NGC 6744
NGC 4697
NGC 5033
NGC 5128
Local Galactic Group
Canes Groups
M101
Virgo Cluster
Sculptor
Maffei
M81
Ursa Major Groups
Leo I
NGC 1023
NGC 2997
Dorado
Leo II Groups
Fornax Cluster
Eridanus Cluster