GAS STRIPPING IN CLUSTERS

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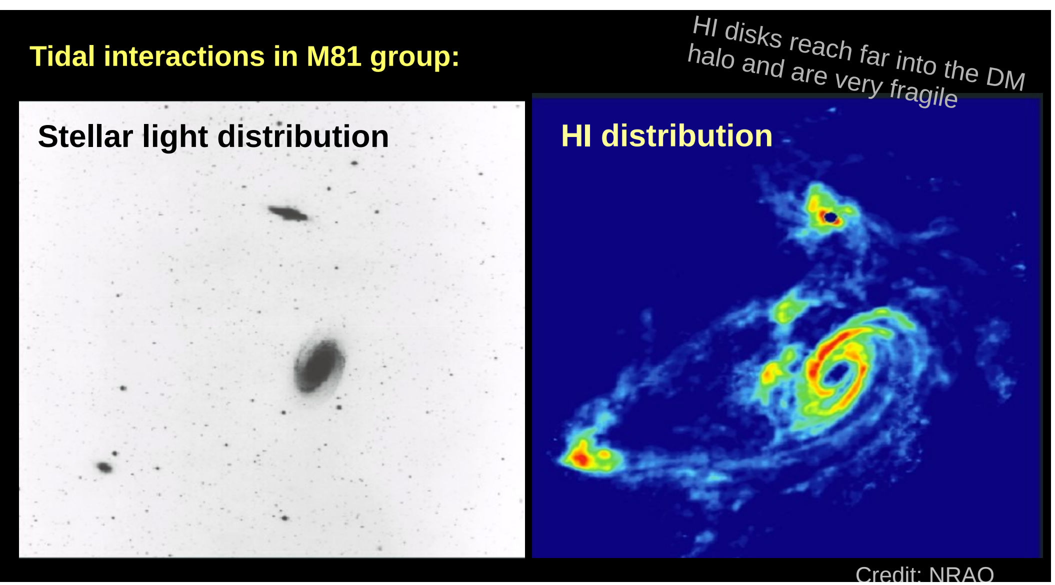
and the BUDHIES and WINGS collaborations

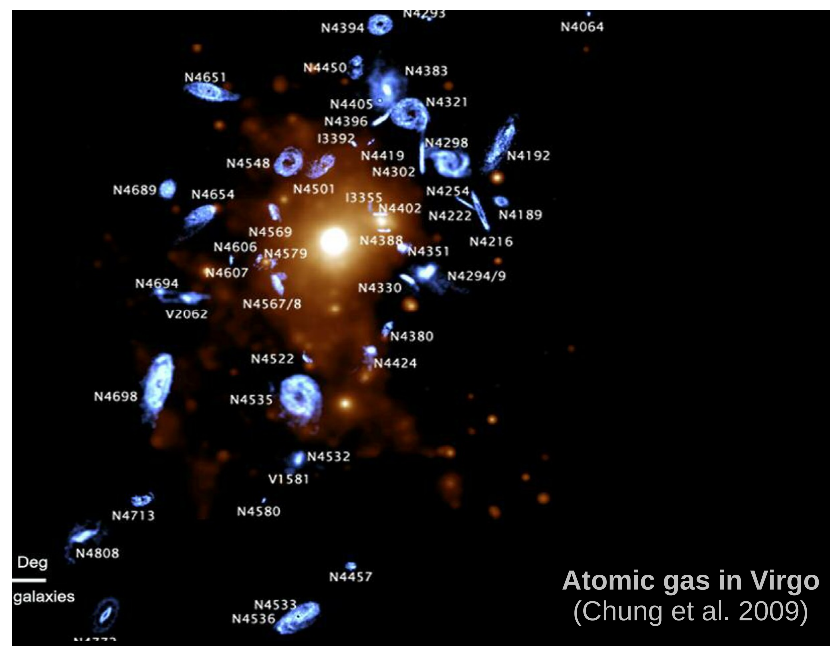
ATOMIC GAS:
A KEY INGREDIENT TO UNDESTAND GALAXY EVOLUTION

Fuel for star formation

Sensitive tracer of different environmental processes, such as ram pressure stripping and tidal interactions, but also harassment and eventual preprocessing in infalling groups

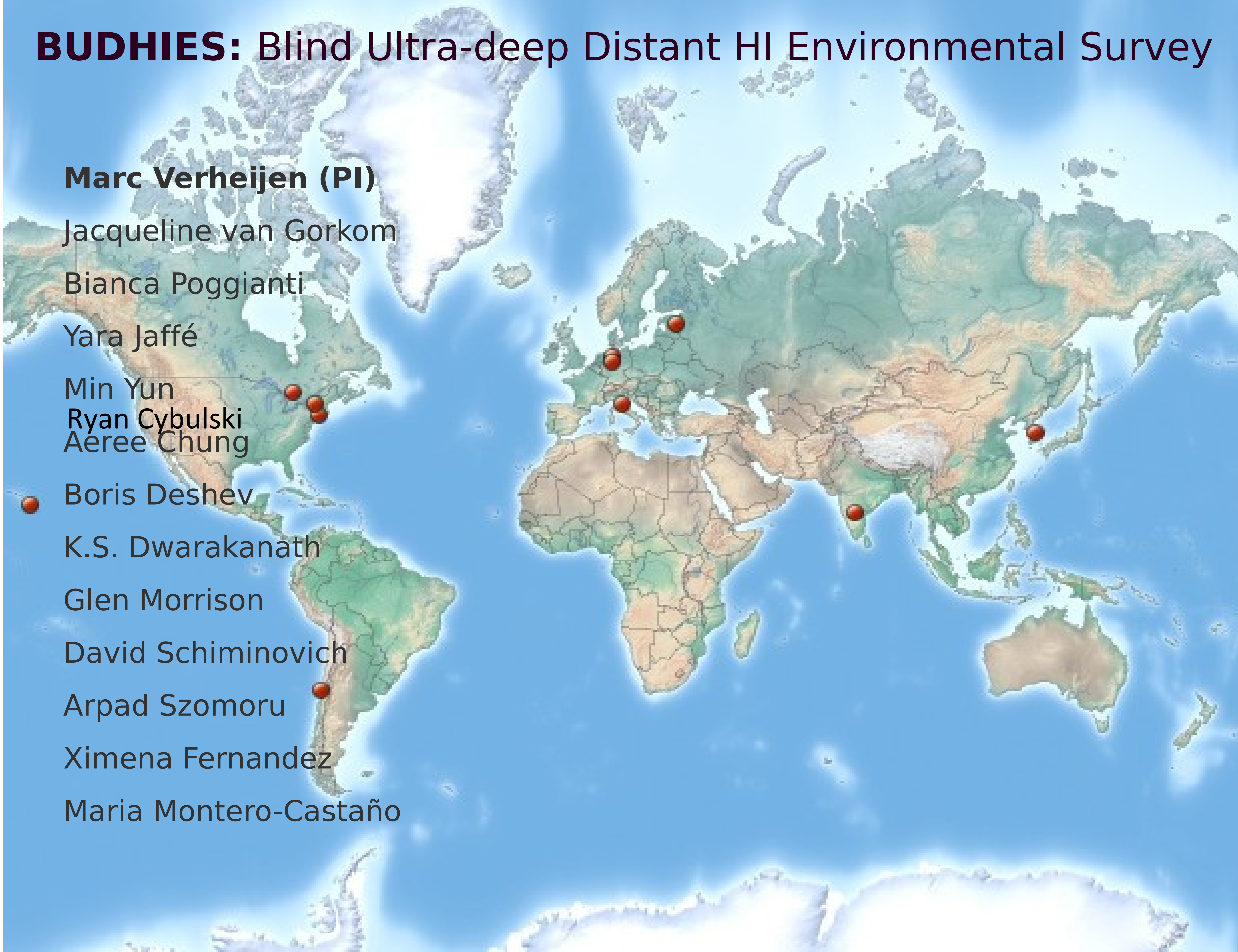
Observations have shown that the HI gas is disturbed and eventually truncated and exhausted in galaxies in low-z clusters





Atomic gas in Virgo
(Chung et al. 2009)

BUDHIES: Blind Ultra-deep Distant HI Environmental Survey



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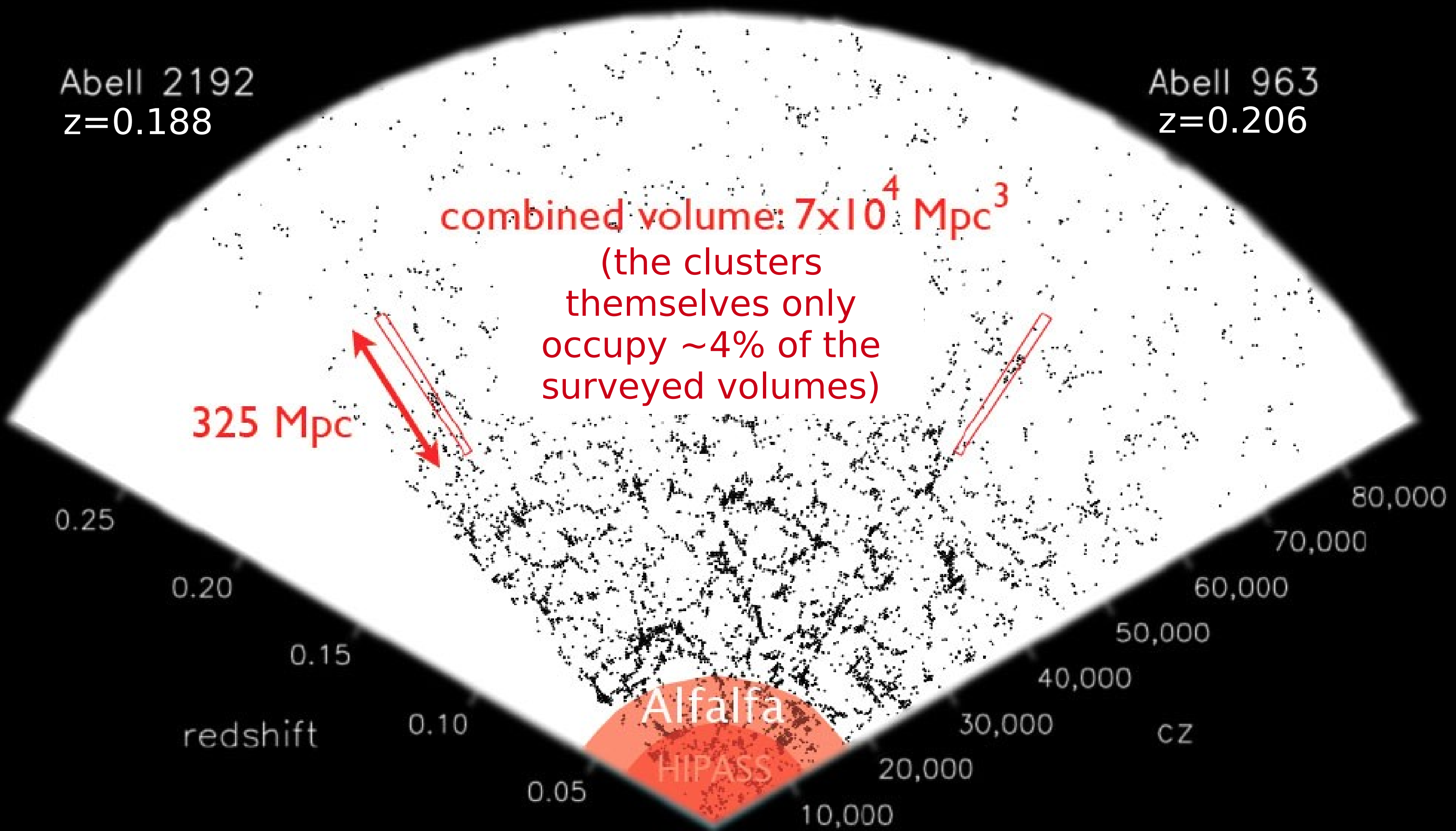
BLIND ULTRA DEEP HI ENVIRONMENTAL SURVEY

BUDHIES

HI ultradeep survey of ~2400hrs with Westerbork Synthesis Radio telescope in and around two clusters at z~0.2, A963 and A2192

Effective volume depth of 328 Mpc, a coverage on the sky of ~12 X 12 Mpc

BUDHIES: Blind Ultra-deep Distant HI Environmental Survey with the Westerbork Synthesis Radio Telescope



BLIND ULTRA DEEP HI ENVIRONMENTAL SURVEY

BUDHIES

127 HI detections in A963 and 36 in A2192 $M_{HI} \geq 2 \times 10^9$ Msun

Ancillary data: WHT and WIYN spectroscopy, B+R imaging INT, NUV +FUV Galex, Spitzer imaging

GOAL: where, how and why star-forming late-type galaxies get transformed into passive early-types

Uniqueness of this study: a) very large volume sampling clusters and all the large scale structure around them, sampling all environments; b) first direct imaging study of neutral hydrogen gas at a redshift when evolutionary effects start to show

Jaffe' et al.

GAS RESERVOIRS AND STAR FORMATION IN A FORMING GALAXY CLUSTER AT $z \simeq 0.2$

ApJLetter 756 L28, 2012

BUDHIES I: characterizing the environments in and around two clusters at $z \simeq 0.2$

MNRAS 431, 2111, 2013

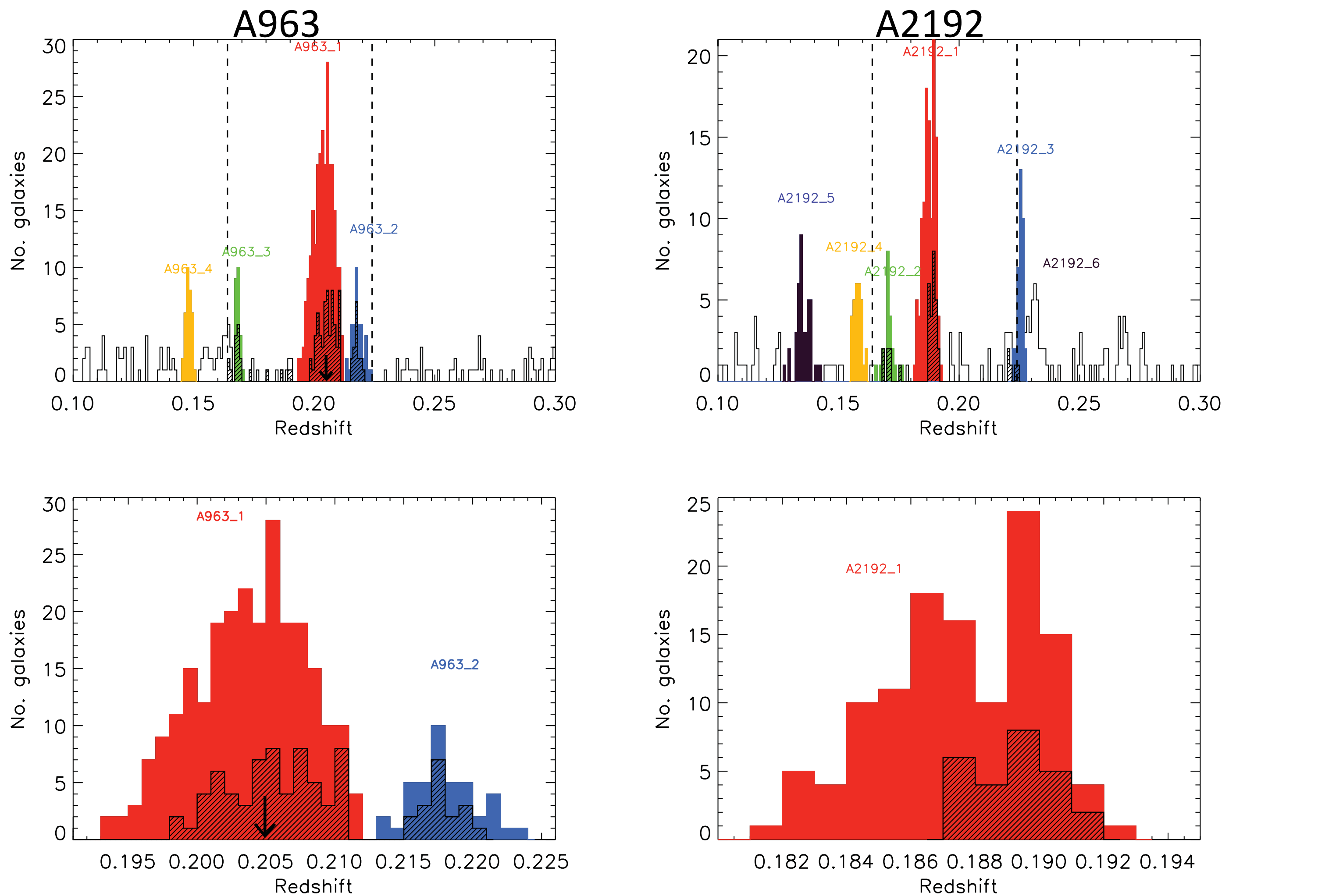
BUDHIES II: A phase-space view of gas stripping and galaxy quenching in a cluster at $z \sim 0.2$

Submitted, 2014

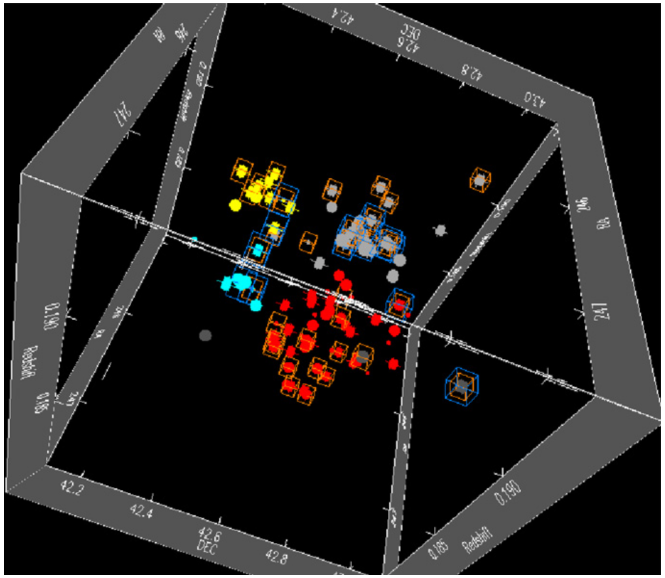
See also pilot study in Verheijen+ 2007

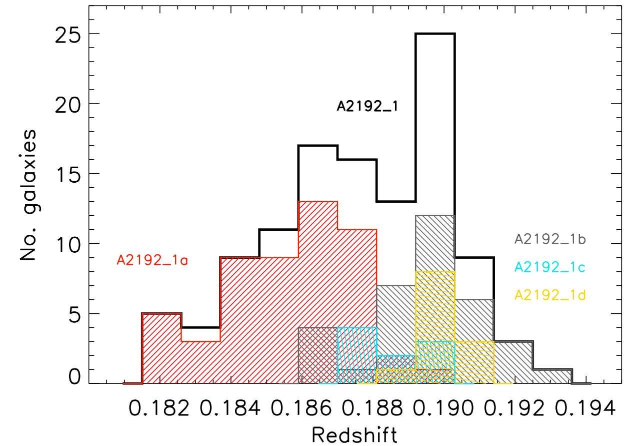
A2192: z=0.1876, intermediate-mass cluster, sigma=530 km/s, L_X= 7 X 10^43 erg/s, dynamical mass = 1.6 X 10^14 Msun, weak X-ray

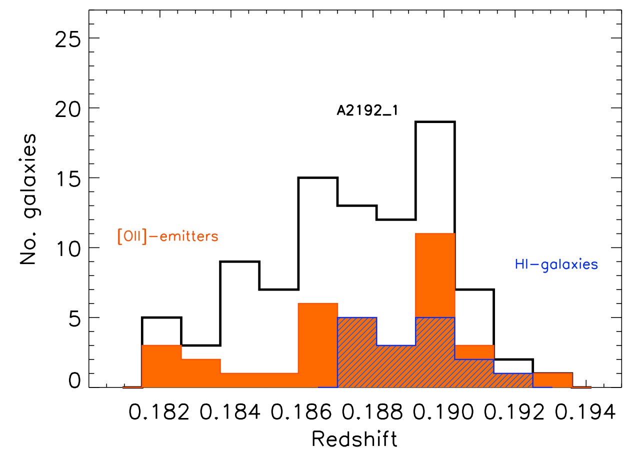
A963: z=0.2039, sigma=993 km/s, dynamical mass 1.1 X 10^15 Msun, regular and centrally concentrated in X-ray and weak lensing,



A2192: THE BABY CLUSTER







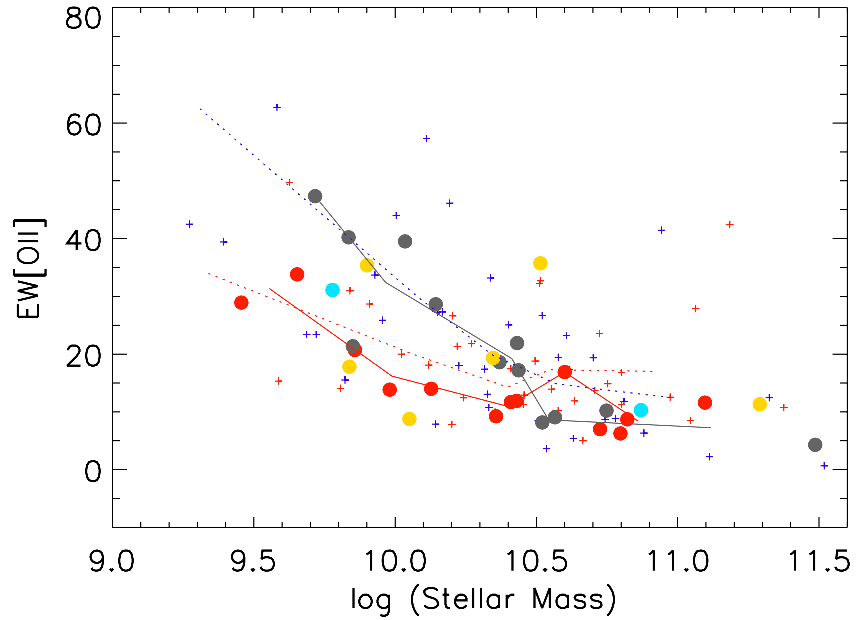
Four distinct structures, all within turnaround radius
---- main cluster, Gaussian, virialized, least HI-rich (2%), but 28% with OII emission
---- rich ensemble of "field" galaxies, very dispersed in space, not bound – late-types: 40% with HI, 80% with OII
---- not bound, "field" spatially segregated structure, HI-rich
---- compact galaxy group, 161 km/s, 6.3 X 10^12 Msun, mainly late-types: 63% OII, ~15% HI in the outskirts (>1R200) – intermediate between "cluster" and "field"

A2192: A CLUSTER IN FORMATION, ACCRETING PRE_PROCESSED GALAXIES

The main cluster is practically devoid of galaxies with M_HI>= 2 X 10^9 Msun, has suppressed star formation, and a core of red early-type galaxies that coincides with the X-ray center.

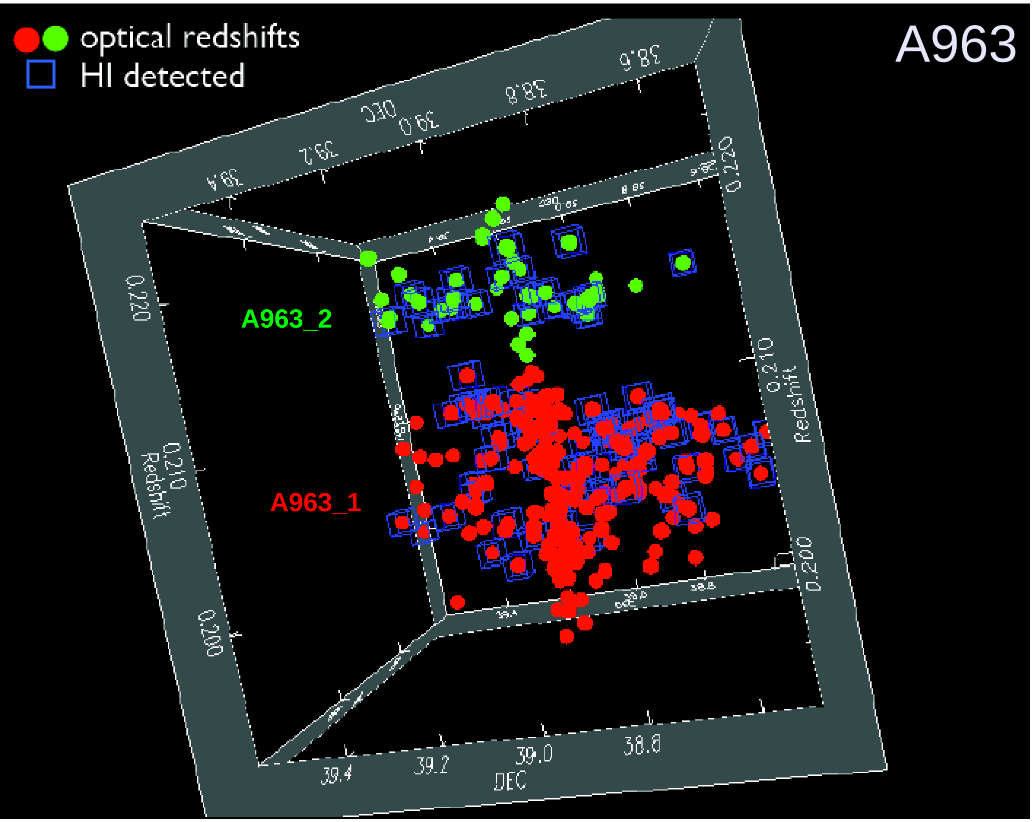
Surrounded by a scattered “field” of mostly late-type galaxies that are actively star-forming and preserve their HI reservoir.

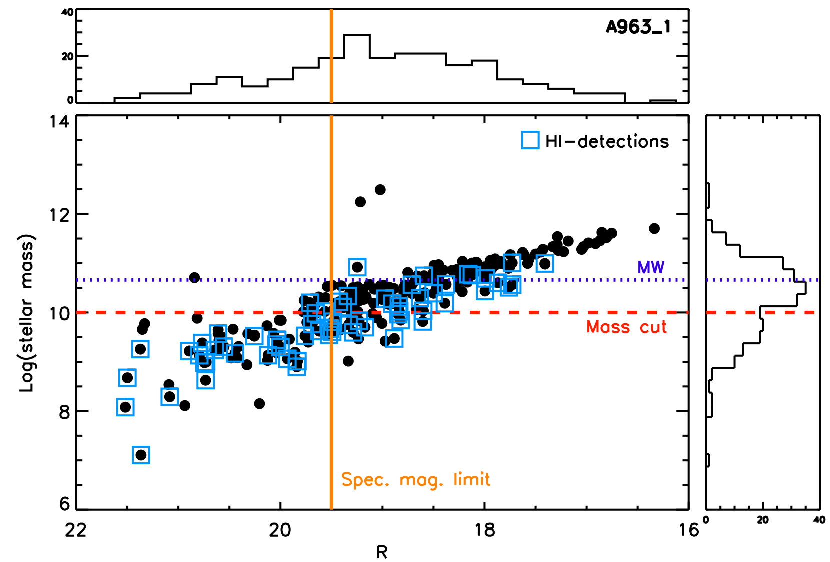
Moreover, there is a spatially segregated compact group where galaxies show signs of pre-processing: effects on HI start to kick in in low-mass groups

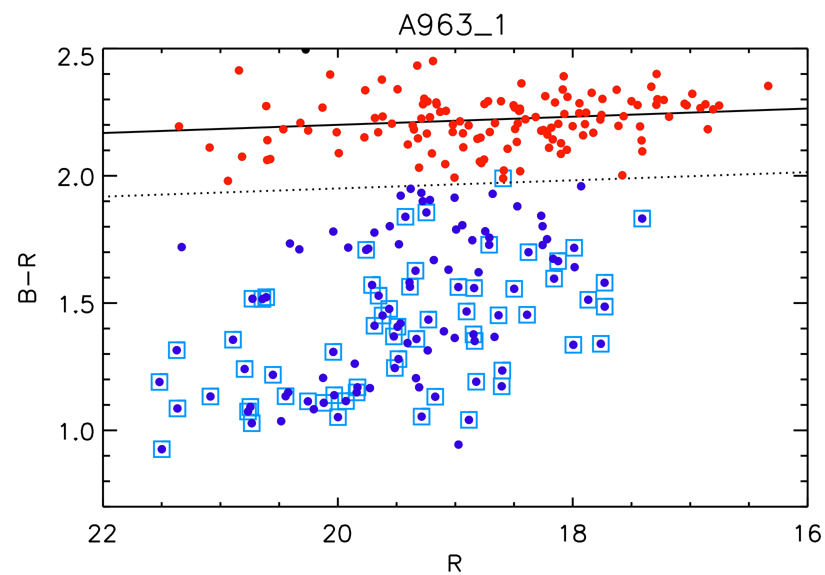


Progressive removal of HI and suppression of SF from low-mass galaxy groups to cluster-sized structures

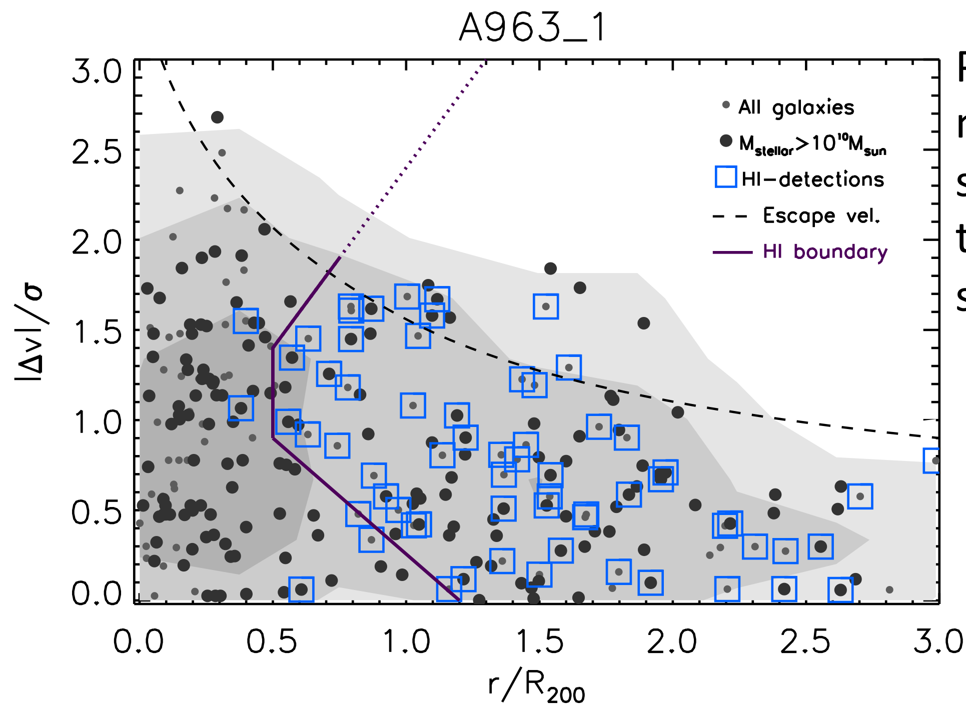
ON TO A963: RAM PRESSURE AT WORK







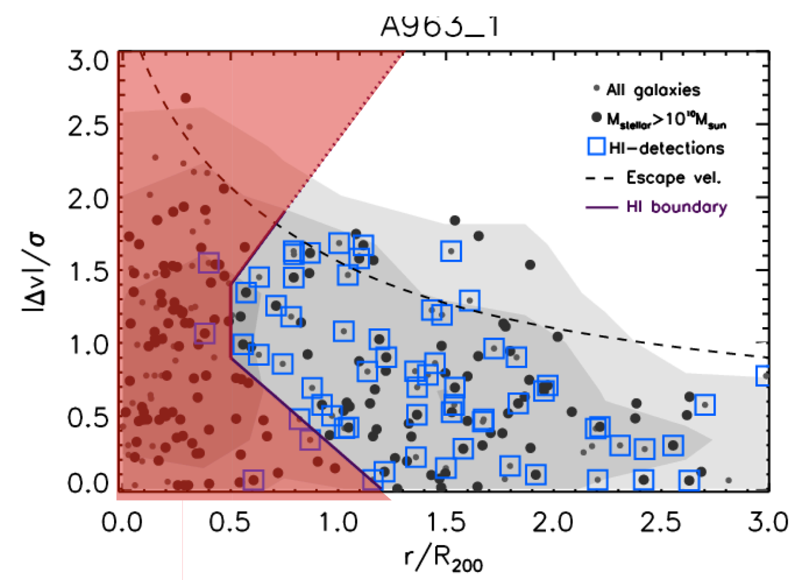
THE ORBITAL HISTORIES OF THE DIFFERENT GALAXY POPULATIONS



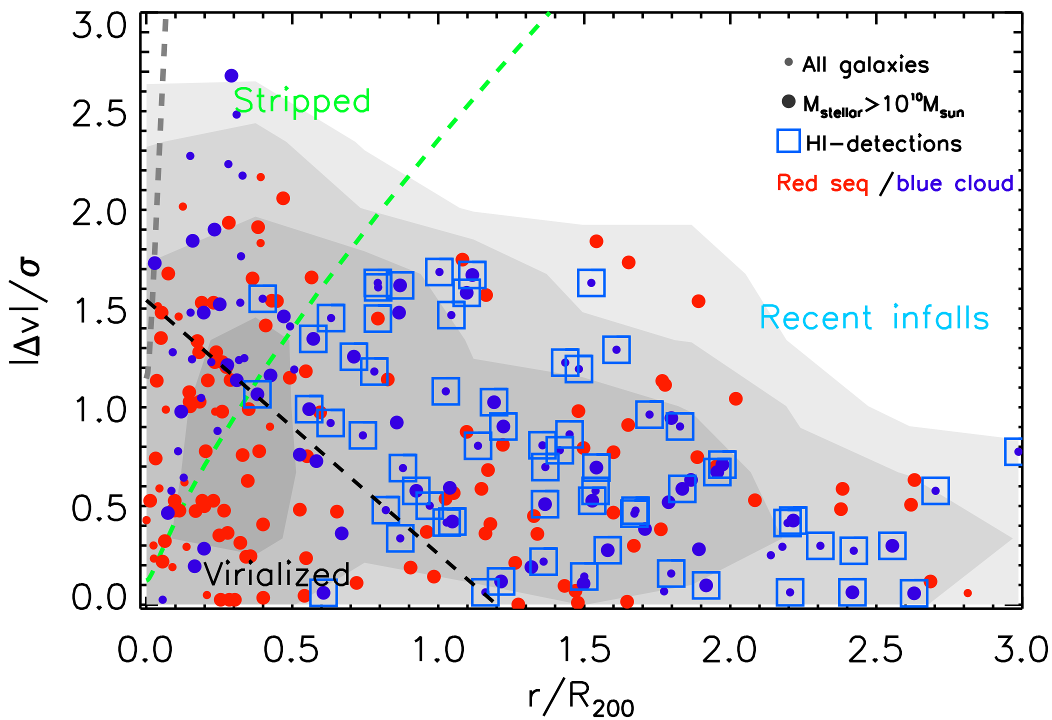
Projected distance from cluster center normalized by R200 vs the peculiar line-of-sight velocity of each galaxy with respect to the cluster recessional velocity normalized by sigma

Grey contours = galaxy number density distribution
Dashed line: escape velocity in a NFW halo, projected
Solid line delimits the region where the vast majority of HI detections are

What is removing the gas in galaxies in the red region?



COMPARING WITH A SIMPLE RAM PRESSURE MODEL



a simple model following Gunn & Gott prescription, a beta cluster model and galaxy parameters for the Milky Way

Dashed grey line: to the left of which MW-like galaxies are expected to be completely stripped of HI gas

Solid green where galaxies are stripped enough to fall below our HI detection limit

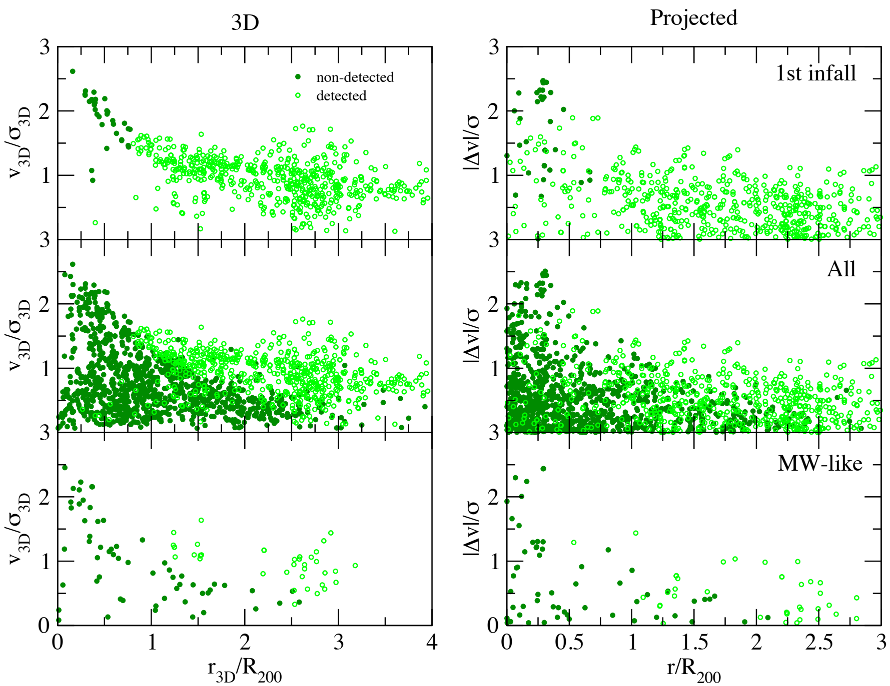
These are effects on first infall galaxies

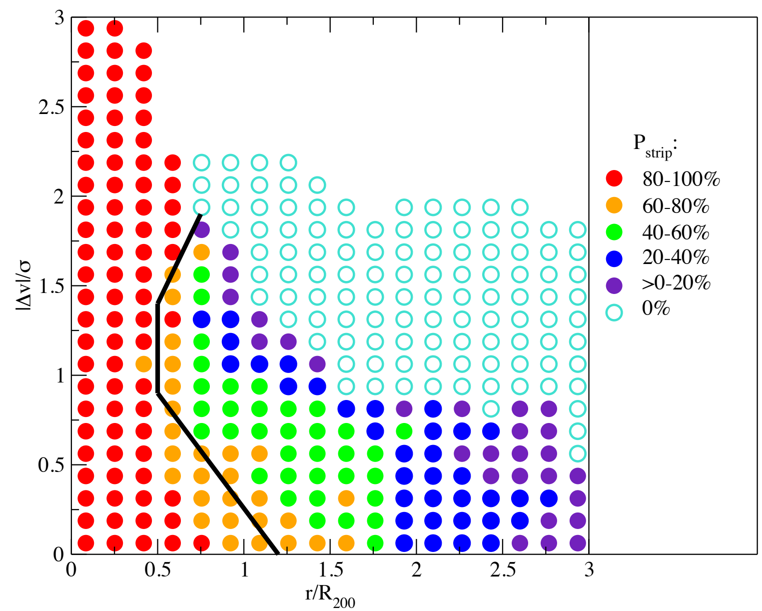
"Virialized region roughly at r<R200 and Av<1.5sigma, where many of the galaxies have passed pericenter more than once, thus have been in the cluster for > 2 Gyr

HIGH-RES N-BODY SIMULATIONS WITH ADAPTIVE MESH REFINEMENT CODE

(Warnick+ 2006, 2008, Knebe+ 2001)

We follow the orbits of individual haloes in the cluster, and apply our ram pressure model



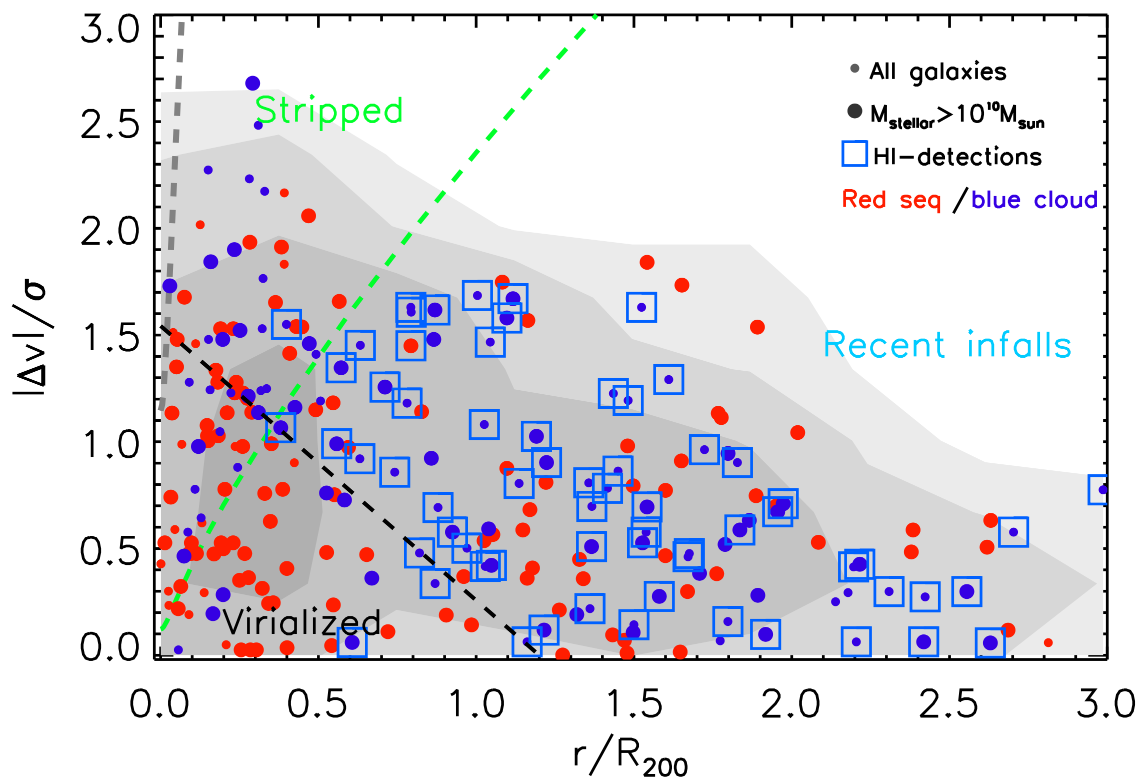


Top: only haloes that are infalling for the first time

Middle: as cluster evolves and becomes virialized, galaxies end up at low r and low v for dynamical friction -- so galaxies in this region are stripped because they are virialized, and have been in the cluster for more than a pericentric passage (> 2 Gyr) – they have already been in the "stripping region" of the diagram

Bottom,only for MW-like galaxies (subsampling our haloes)

COLORS



only a few of the blue galaxies in the stripped and virialized zones have HI, while most of the blue galaxies in the recent infall zone are detected in HI

Also, noticeable fraction of red HI poor galaxies in the recent infall zone, possibilities:

---- preprocessing

---- wide scatter in ram pressure strength at fixed radius, non-smooth ICM

---- backsplash galaxies, but insignificant at r> 2 R200

---- “mass-quenching”? (discussing with Kovac…)

BUDHIES TAKE-AWAY MESSAGES

- in the forming cluster A2192 we see effect of gas stripping both in the main virialized cluster and in a compact infalling group

- In the massive A963 cluster, we have investigated the cause and the timescale of gas stripping and subsequent quenching

  - clear segregation of HI-stripped and non-stripped galaxies, with HI-detected galaxies avoiding the regions they "should avoid" based on ram pressure model + cosmological N-body simulations – combination of stripping on first infall + getting virialized due to dynamical friction

  - trends of other properties (colors, OII) also segregate, but less clearly than the HI, consistent with galaxies losing their HI and having still blue colors for a while (did not show NUV colors analysis)

  - presence of quenched, HI-poor galaxies in the infall region might indicate preprocessing, or some backsplashing

Wide-field Nearby Galaxy-cluster Survey

WINGS

A wide-field survey of 77 X-ray selected clusters at z=0.04-0.07

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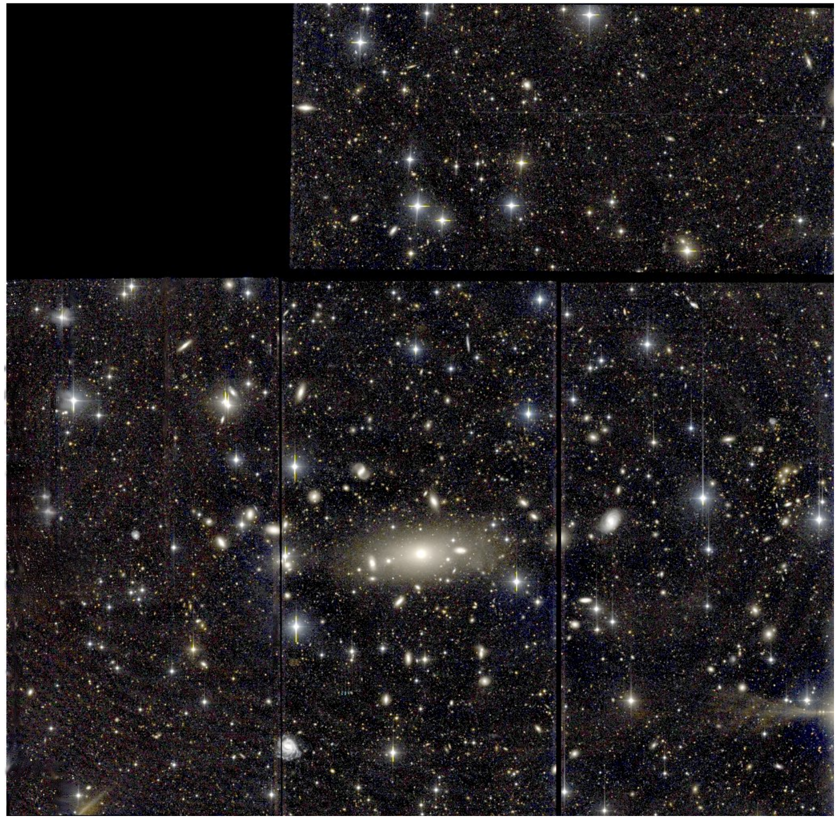
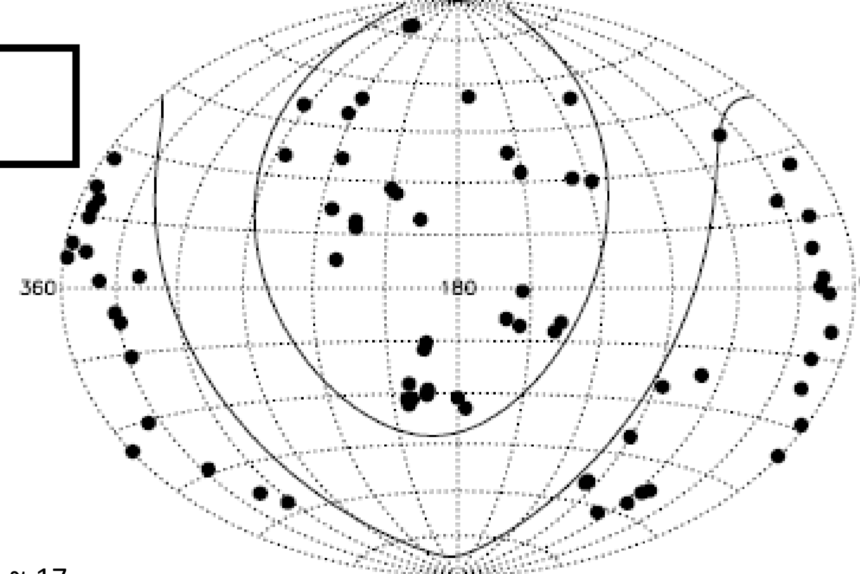
Jacopo Fritz+
Tiziano Valentinuzzi+
Jesus Varela+
Alessia Moretti
Benedetta Vulcani
Marco Guilleuszik
Angela Paccagnella
Valentina Guglielmo

Alan Dressler
Warrick Couch
Per Kjaergaard
Mariano Moles



THE WINGS DATASET



Sigma=500-1200+km/s, Log L_X=43.3-44.7 erg/s

B and V deep photometry on 34’X34’

FOV 1.2-2.7Mpc, res. 0.7-1.6kpc, M_V~-13
400.000 gal phot., 40.000 surf.phot + morph

Optical fibre spectroscopy

48 clusters, 6500 spectra, 100-200 galaxies/cluster, down to M_V~-17

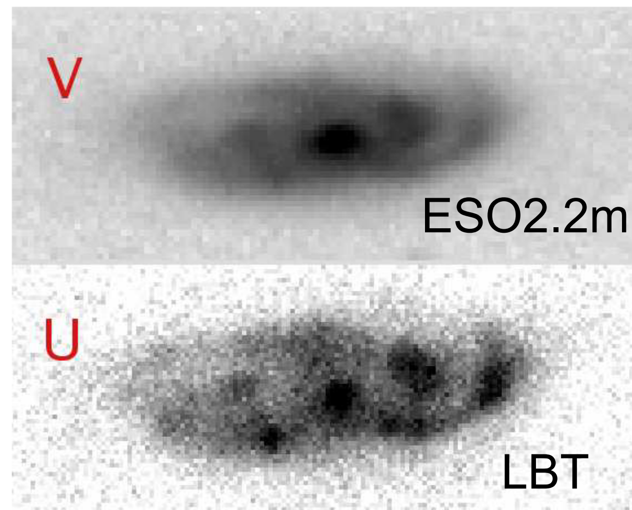
Near-IR deep photometry, J and K

36 clusters – galaxy masses, SED + struct.props

u, V and B on a 1deg sq. with Omegacam/VST + AAOmega/AAT spectroscopic follow-up – out to 2.5 virial radii, 90% spectr. completeness to V=20, 30k spectra

Ongoing -

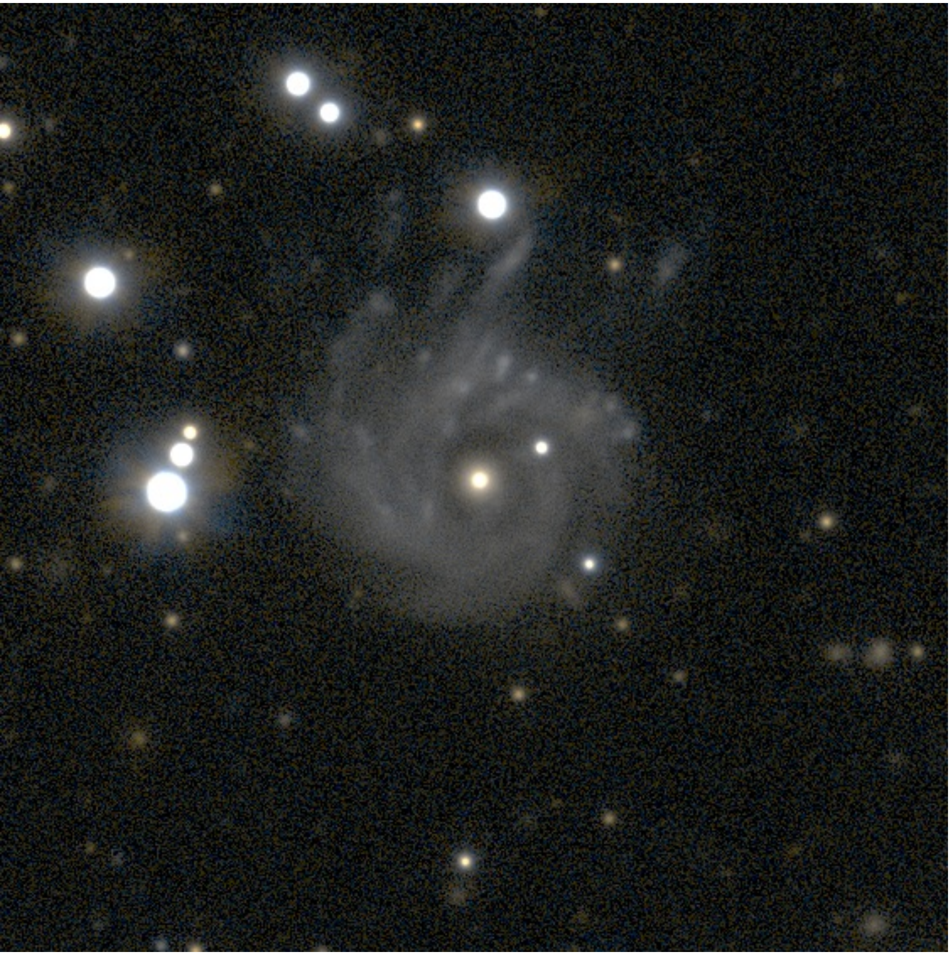
U-band with INT, LBT & Bok

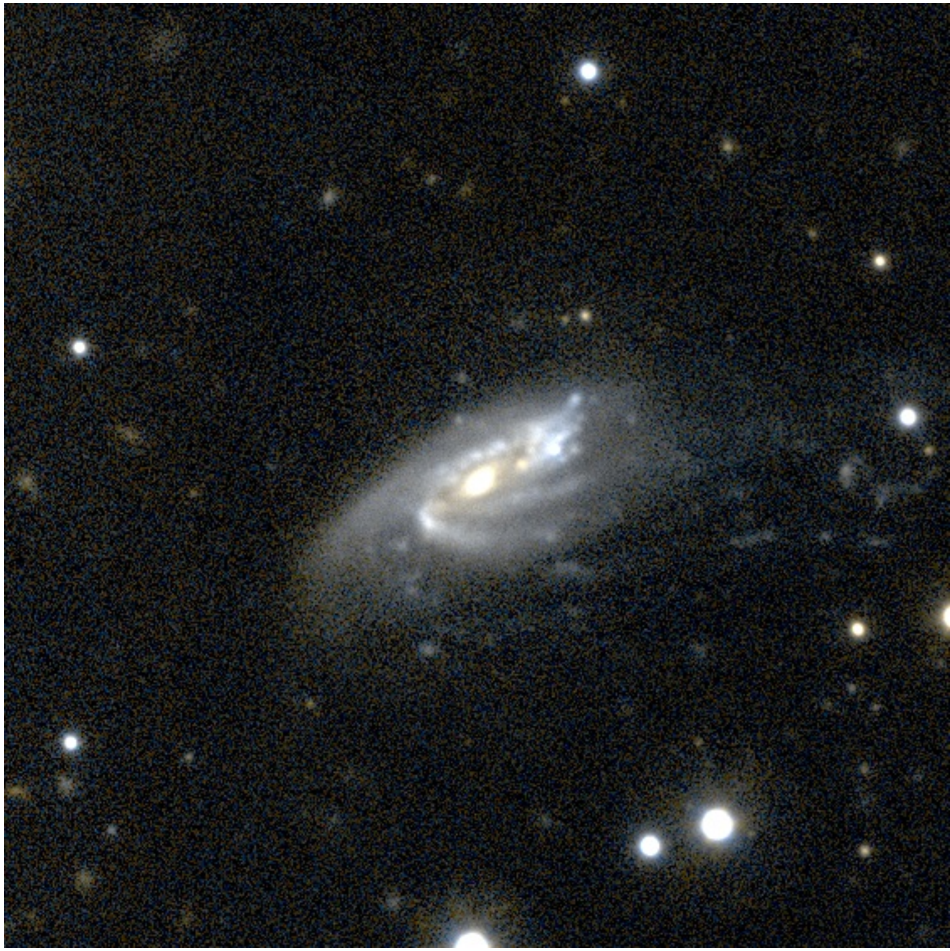


Large effort: 114 telescope nights, 28 refereed pubs so far, all wide-field – ALL PUBLIC on VO (Moretti+ 2014)

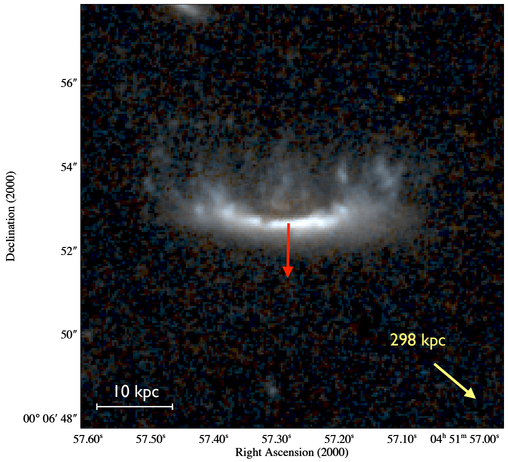
WFC/INT, WFC/ESO2.2, WYFFOS/WHT, 2dF/AAT, WFCAM/UKIRT, 90prime/Bok, LBC/LBT, Omegacam/VST, AAOMEGA/AAT,GMOS/Gemini,VIMOS/VLT

“JELLYFISH” GALAXIES IN OMEGAWINGS



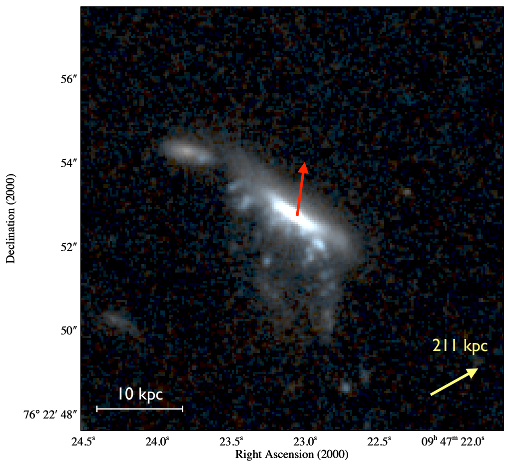


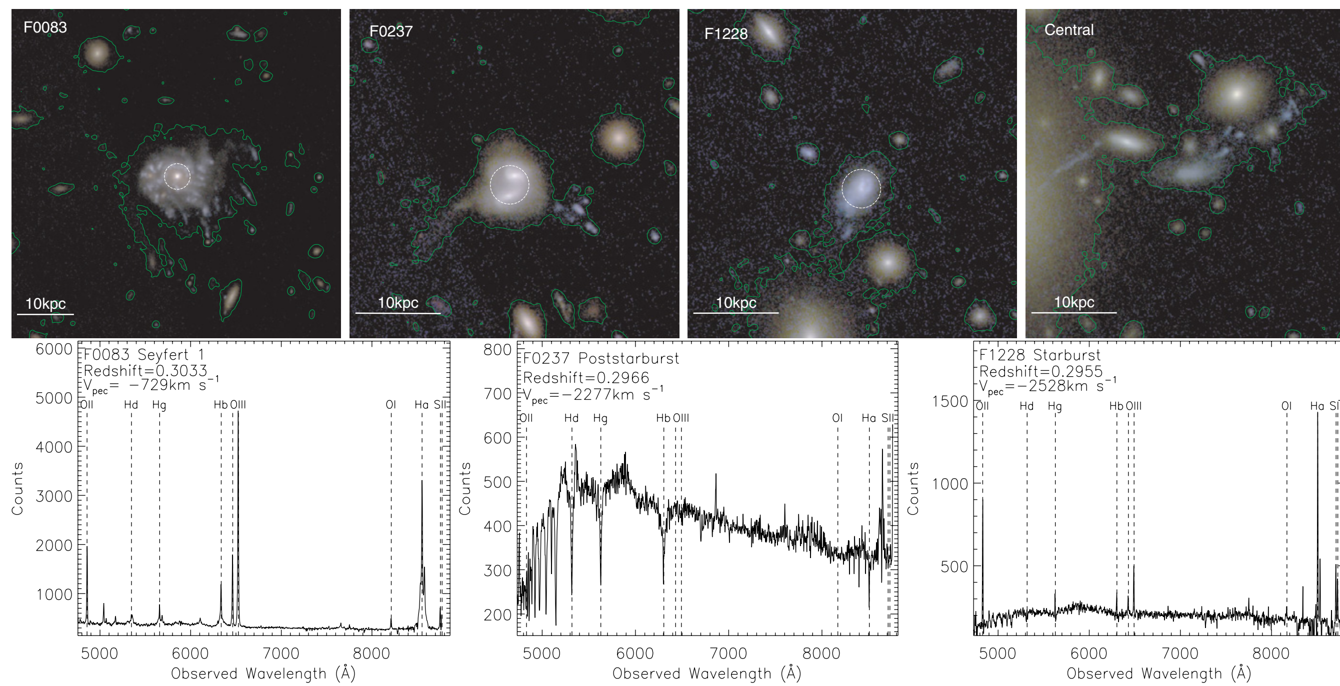
In prep.

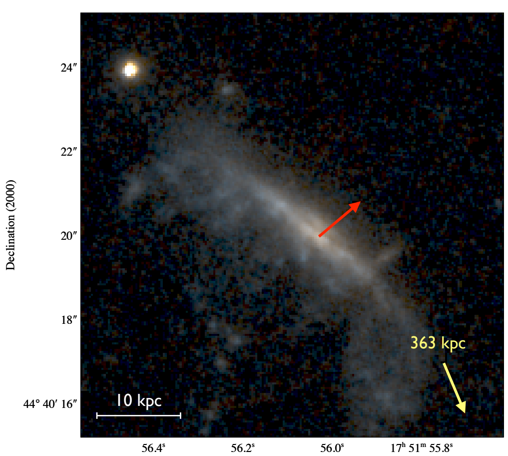


6 examples from Ebeling+ 2014in X-ray clusters at z=0.3-0.4

Figure 1. *HST* images of extreme cases of ram-pressure stripping in galaxy clusters at $z > 0.2$. From left to right: galaxy C153 in A2125 at $z = 0.20$ (WFPC2, F606W+F814W, Owen et al. 2006); galaxy 234144–260358 in A2667 at $z = 0.23$ (ACS, F450W+F606W+F814W, Cortese et al. 2007); galaxy F0083 in A2744 at $z = 0.31$ (ACS, F435W+F606W+F814W, Owers et al. 2012).







4 galaxies in merging cluster
Abell 2744 Owers+ 12

Also Rawle's poster, Shass etc

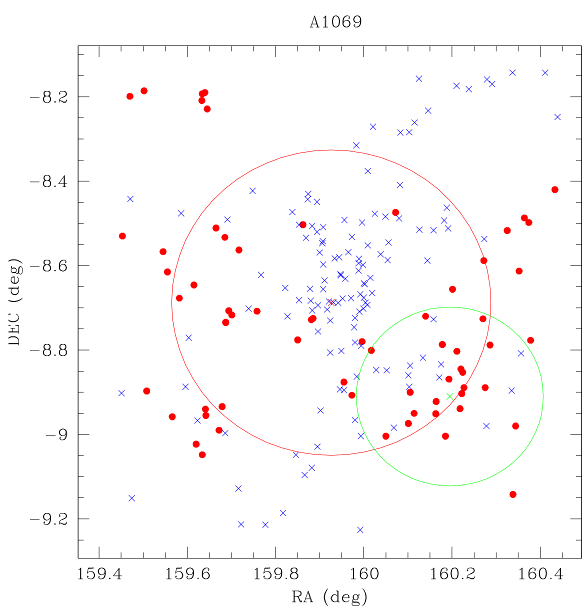
~300 candidates of jellyfishes in 44 clusters

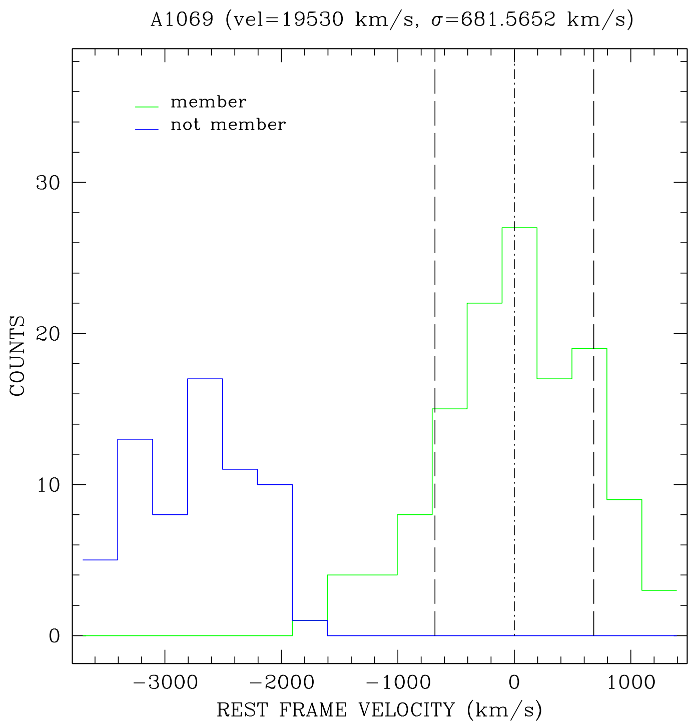
Some clusters have none, some have many: study vs.cluster properties

Phase-space study + position wrt Chandra maps/substructure and stellar population analysis:

- ---- detailed spectrophotometric modeling of fibre spectra
- ---- color maps (uBV) to see spatial distribution of star formation
- ---- IFU data pilot study in next semester

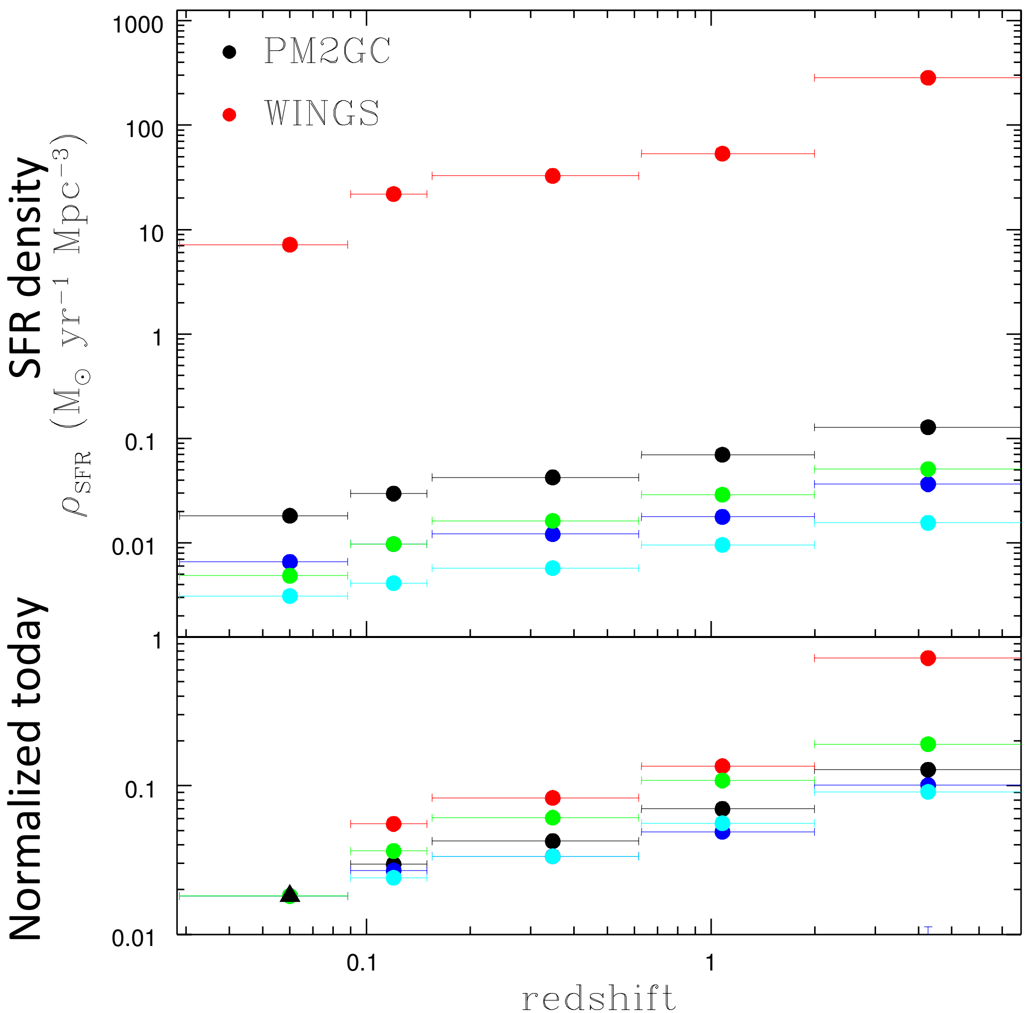
Not only in main WINGS cluster.....





Credit: Angela Paccagnella

COSMIC STAR FORMATION RATE DENSITY



MADAU PLOT IN GENERAL FIELD (black) vs. CLUSTERS (red,10^14-10^15 Msun)

and vs. GROUPS (green, 10^13 Msun), BINARIES (cyan, 10^12 Msun)), SINGLES (blue, 10^11.5 Msun)

2/3 of stars in clusters formed at z>= 2, while more than half of stars in the field formed at z< 2.

Guglielmo+ in prep.

FROM BLUE STAR-FORMING TO RED PASSIVE: GALAXIES IN TRANSITION IN DIFFERENT ENVIRONMENTS

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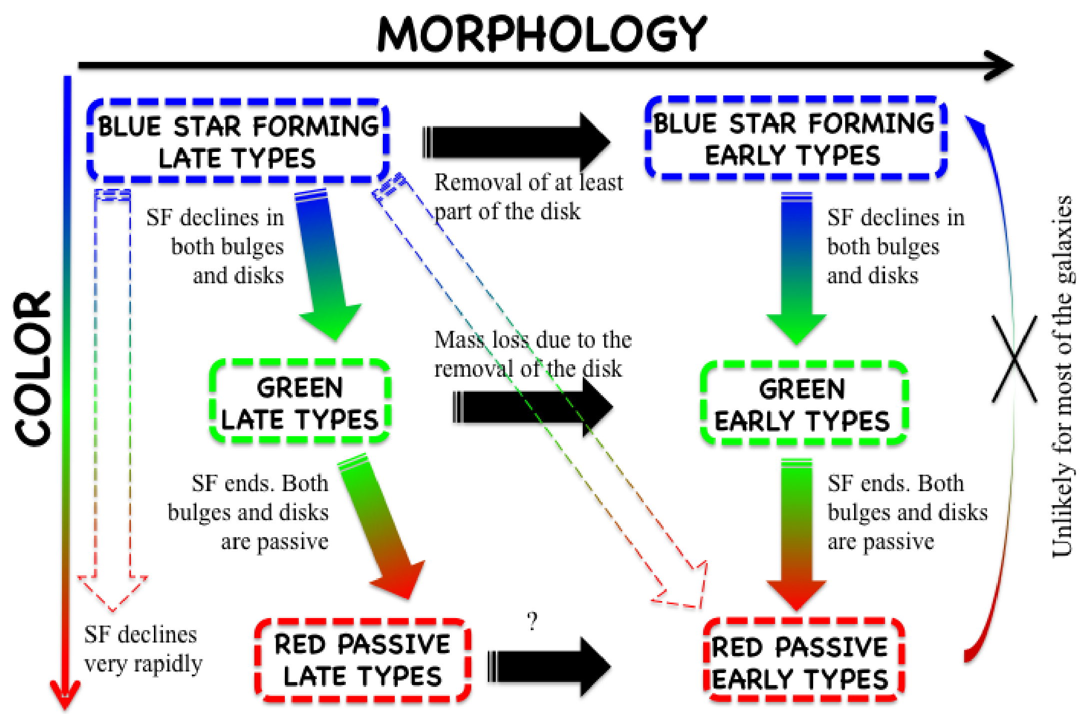

Vulcani+ submitted