Star formation quenching in cluster galaxies from integrated and spatially resolved spectra

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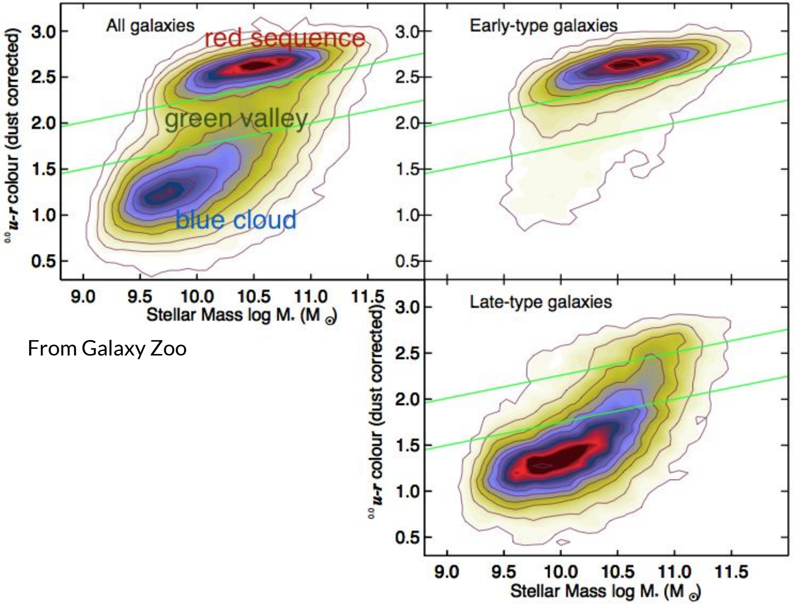
http://web.oapd.inaf.it/gasp/

Outline

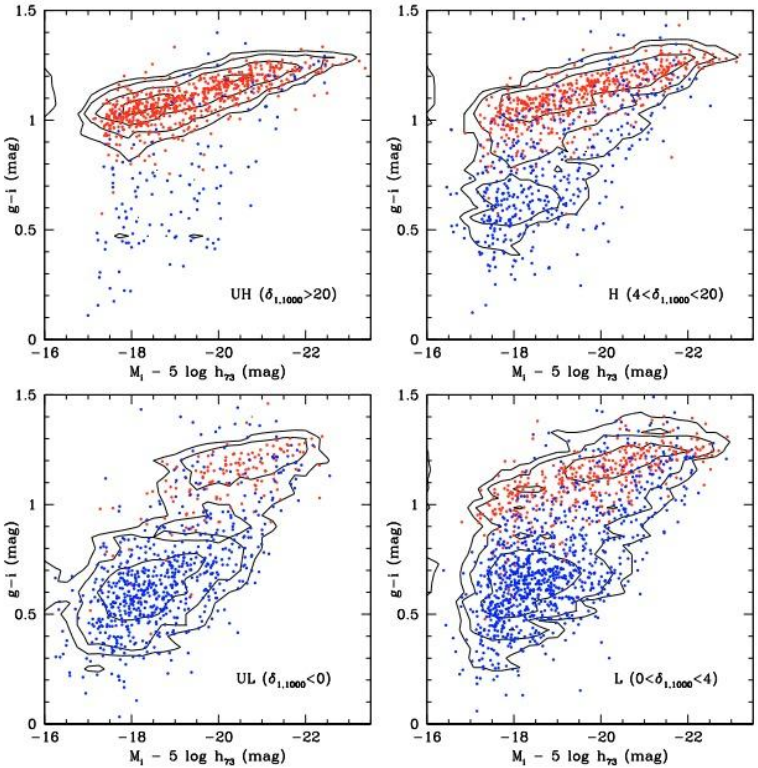
- → Galaxies and environment (color, SFR)
- → The WINGS/OMEGAWINGS survey
- → (OMEGA)WINGS results (MD relation, SFR-Mass)
- → Quenching mechanisms and GASP motivation
- → The GASP survey: prototypical JF and other animals
- → GASP results (so far) and future

Galaxies bimodality & environment



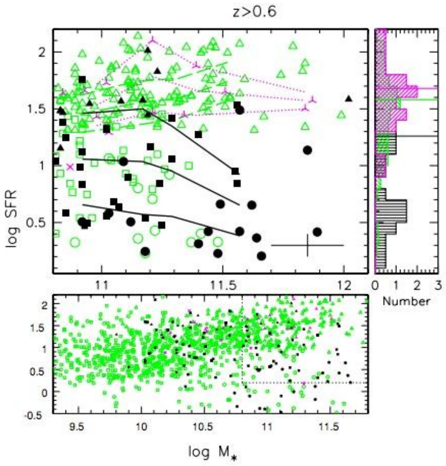
From Galaxy Zoo

Gavazzi et al., 2010 [Coma]

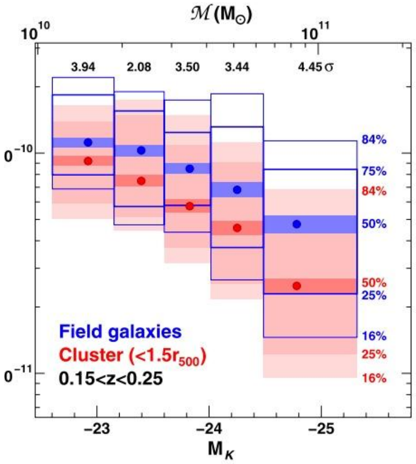


High luminosity ET in place in all environments
Low luminosity ET grow with LD (as LT disappear):
RP?

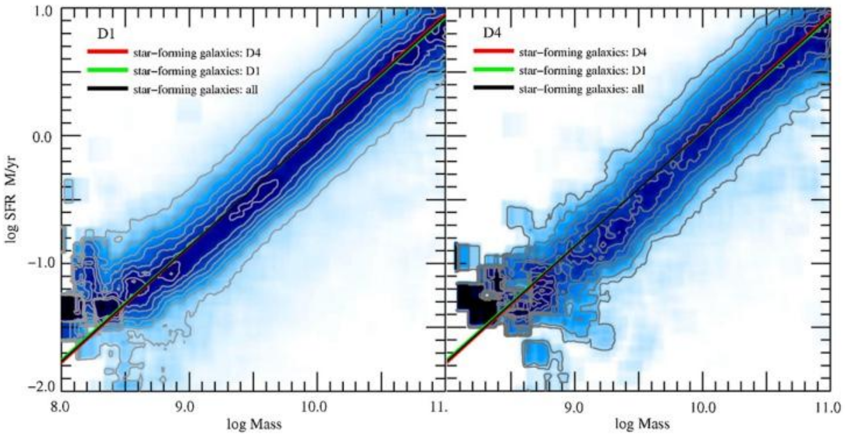
Statistical properties of cluster galaxies



Vulcani et al., 2010
z>0.6



Haines et al., 2013
0.15<z<0.25



Peng et al., 2010
SDSS

How does the SFR proceed with galaxy mass/environment?
Is the quenching due to mass/environment/both?
What is the mechanism acting in different conditions?

The WINGS/OmegaWINGS contribution

Fasano et al., 2002, Fasano et al., 2006, Moretti et al., 2014

→ Started back in 2001 to fill the redshift gap between Virgo/Coma and high-z clusters.

→ Survey of 76 X-rays selected clusters at z=[0.04-0.07] with **30′ x 30′** FoV: B,V imaging

→ 48 clusters have spectroscopic follow-up (~6000 redshifts, ~5300 SFH)

→ Complemented by NIR/U imaging

→ Images and catalogs available (VO tools)

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Gullieuszik et al., 2015, Moretti et al., 2017

→ B, V imaging with OmegaCAM@VST to cover **1 sq. deg** around cluster centers -> beyond R_{200}

→ 46/76 original clusters

→ 50% completeness at V=23

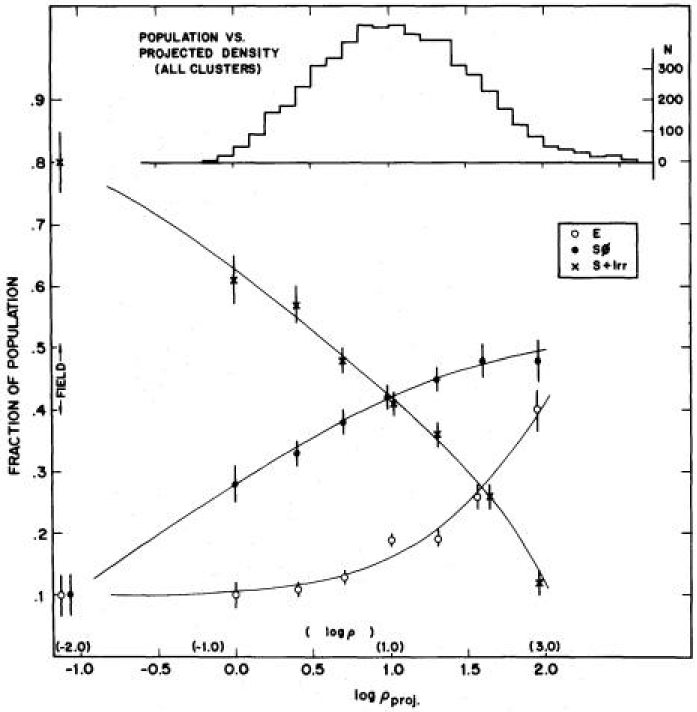
→ σ_v=[500-1300 km/s]

→ Lx=[0.2-5.5 x 10^{44} erg/s]

→ 33 clusters have spec. Follow up (~18000) with 90% completeness at V=20 (7500 new members)

The cluster environment

MD relation

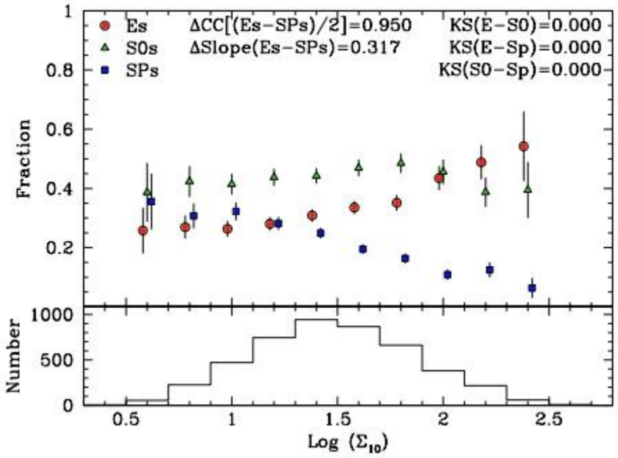


Dressler, 1980

→ ET galaxies dominant in high density regions (55 clusters)

The cluster environment: WINGS results

MD relation in WINGS



→ ET galaxies dominant in high density regions (55 clusters)

→ MD relation still holds

Fasano et al., 2015

The cluster environment: WINGS results

MD relation in WINGS

→ ET galaxies dominant in high density regions (55 clusters)

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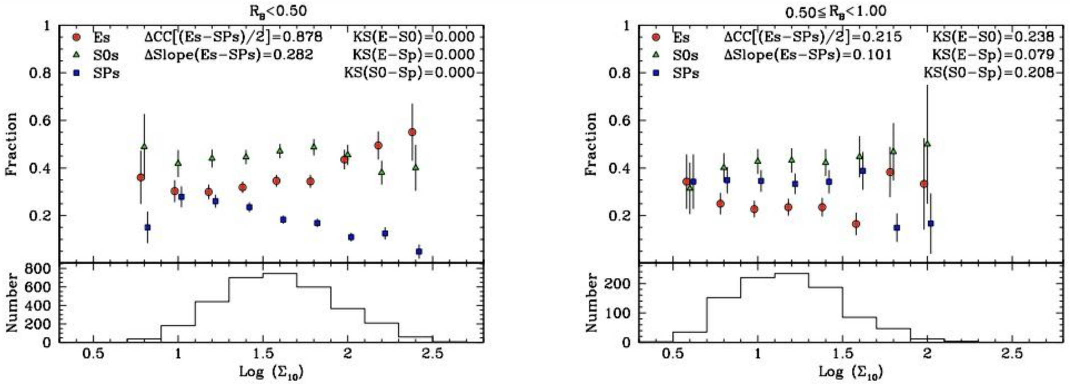
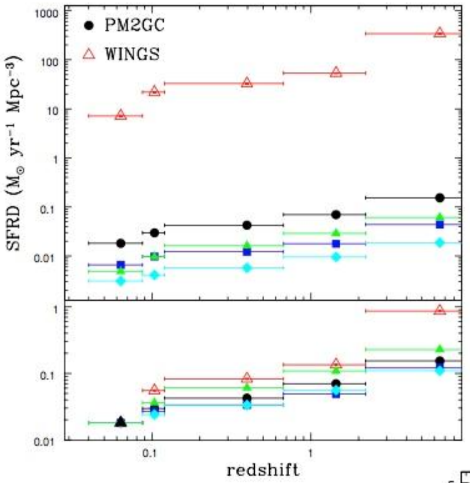


→ MD relation disappears at large R

Global environment?

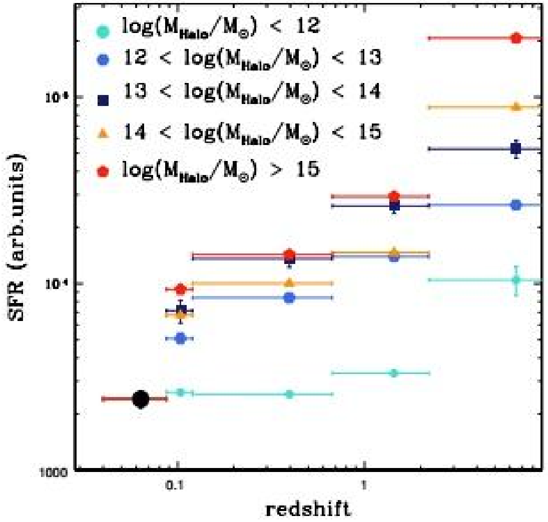
Fasano et al., 2015

The WINGS results: SFR

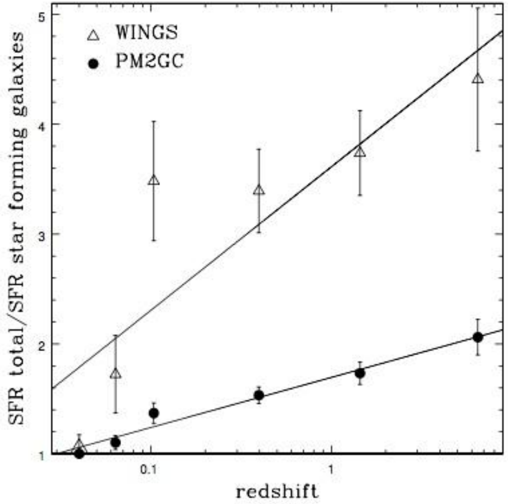


SFR shows a steeper decline in clusters than in the field (not due to the mass)

And this is true also if considering DM halo masses



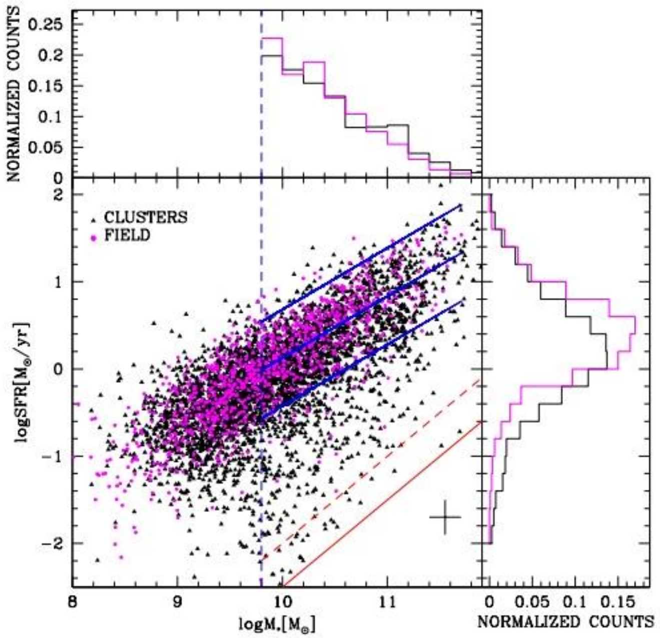
SFR at high z due to quenched galaxies (and even more so in clusters)



Guglielmo et al., 2015, WINGS

The OMEGAWINGS results

Low-z clusters possess a population of transition galaxies, which are seen in the act of being slowly quenched (strangulation/starvation?)

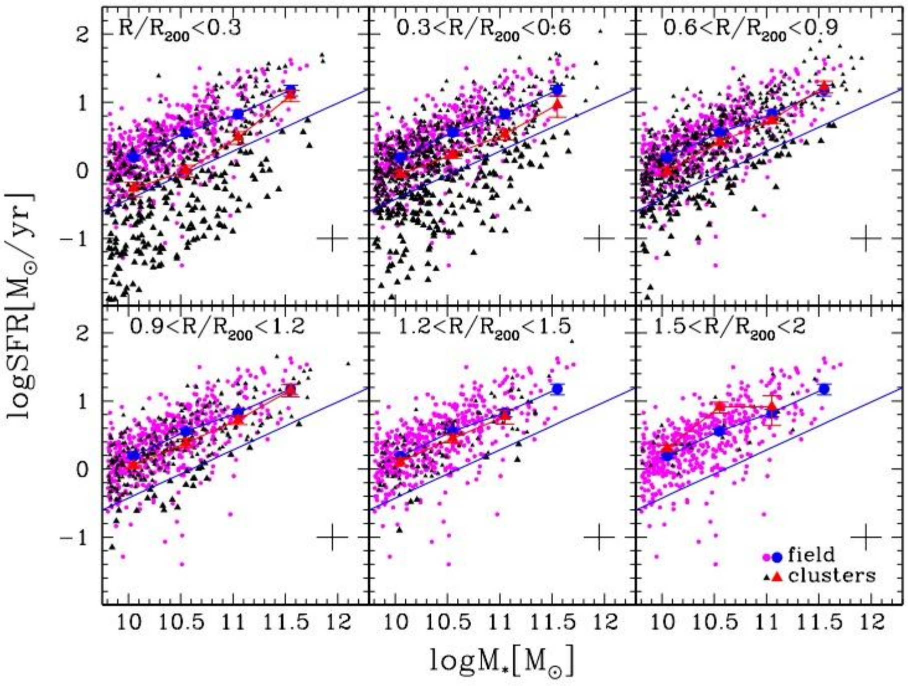


Paccagnella et al., 2016 OmegaWINGS

The OMEGAWINGS results

Low-z clusters possess a population of transition galaxies, which are seen in the act of being slowly quenched (strangulation/starvation?)

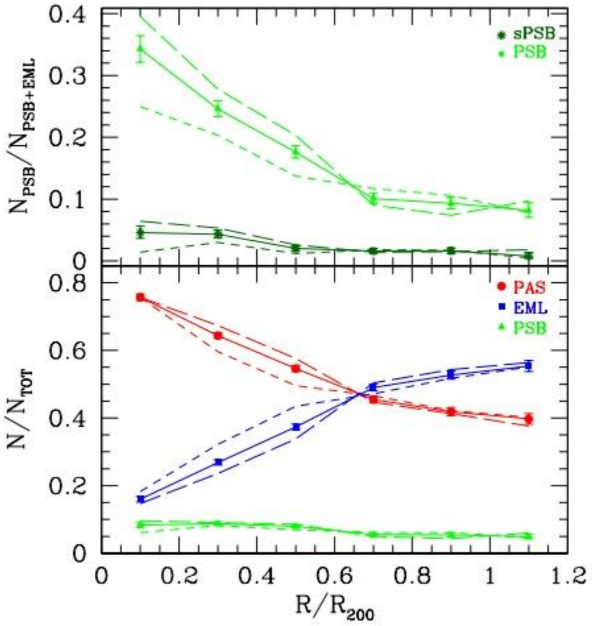
Transition galaxies are mainly found within $0.6R_{200}$ (30% of SF) where environment plays a major role

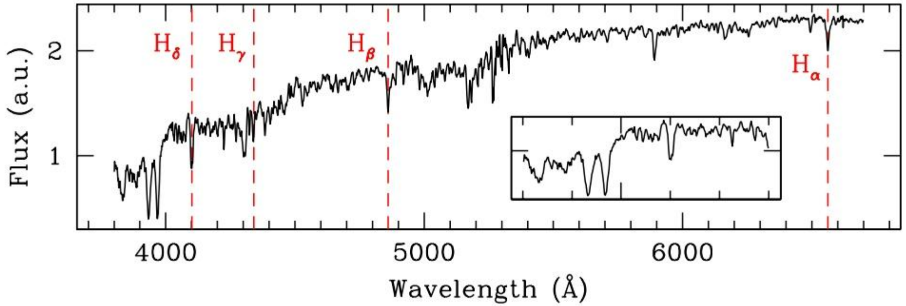


Paccagnella et al., 2016 OmegaWINGS

The OMEGAWINGS results

First characterization of PSB galaxies (tracers of fast quenching - 1 Gyr) in clusters out to 1.2 R_{200}





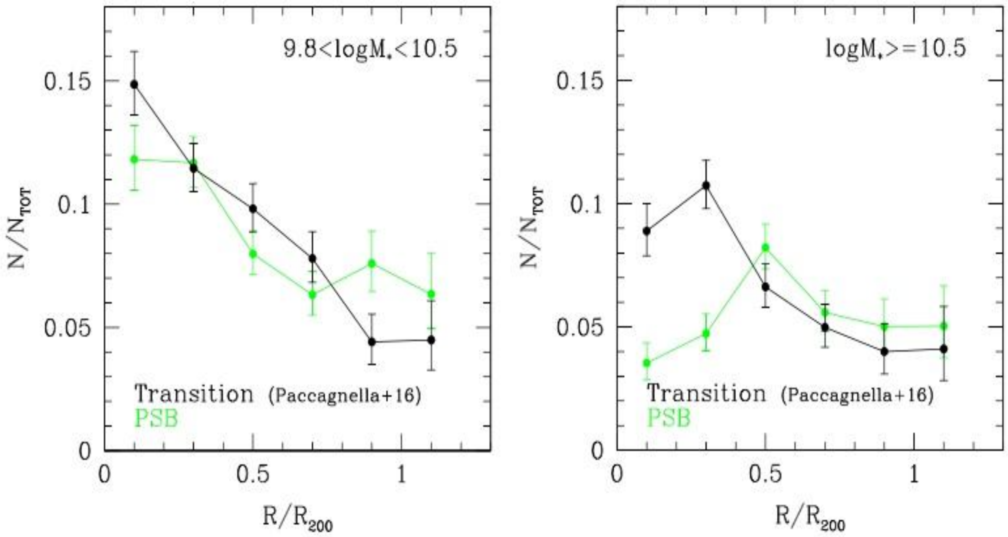
Galaxy type	PAS		PSB		sPSB		EML	
	N	%	N	%	N	%	N	%
Clusters	8162 (4235)	55.7±0.4	1057 (560)	7.2±0.2	154 (80)	1.1±0.3	5441 (3029)	37.0±0.4
Field	415 (225)	19.7±0.8	28 (15)	1.3±0.2	7 (3)	0.3±0.1	1667 (923)	79.0±0.9

More frequent toward cluster centers and in more massive/relaxed clusters
If common progenitor, given the timescales the fast quenching is twice more efficient than the slow quenching channel in the build up of the passive population

Paccagnella et al., 2017 OmegaWINGS

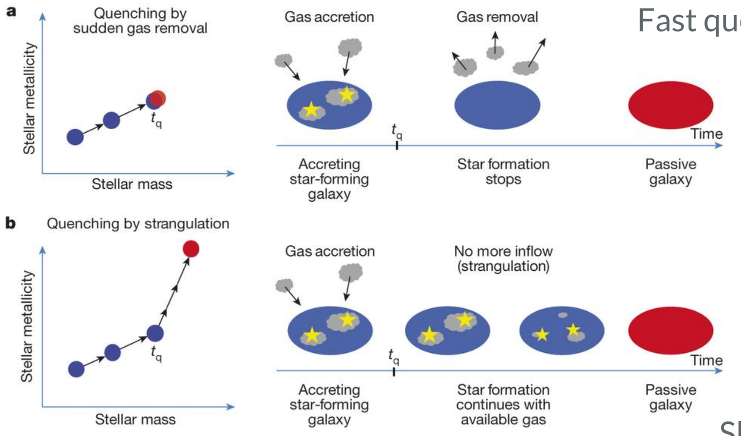
The OMEGAWINGS results

~7800 local cluster galaxies (WINGS+OmegaWINGS)
Spectral features analysis:
PSB and transition galaxies show the same frequency (7.3% and 9%)
The radial trend is similar for low mass galaxies
High mass transition/PSB are missing in clusters cores



Paccagnella et al., 2017

Quenching mechanisms



Fast quenching

Slow quenching

Peng et al., 2015

Quenching related to gas supply/removal

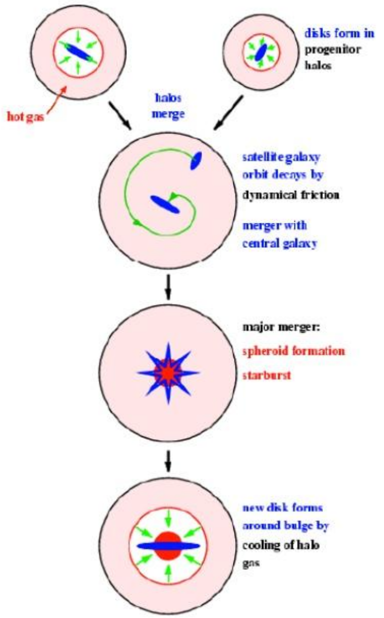
→ RPS, strangulation (fast and slow gas-only removal)

→ mergers, tidal interaction (gas and stars)

→ internal mechanisms (AGN, stellar winds)

26000 SDSS galaxies
Stellar metallicity analysis:
Most galaxies with $M<10^{11}\,M_{\odot}$ are quenched due to strangulation

Quenching mechanisms



Star formation induced by merger takes place not only in the center (gas inflows + ISM turbulence + fragmentation)

Quenching related to gas supply/removal

→ RPS, strangulation (fast and slow gas-only removal)

→ mergers, tidal interaction (gas and stars)

→ internal mechanisms (AGN, stellar winds)

Quenching mechanisms

Quenching related to gas supply/removal

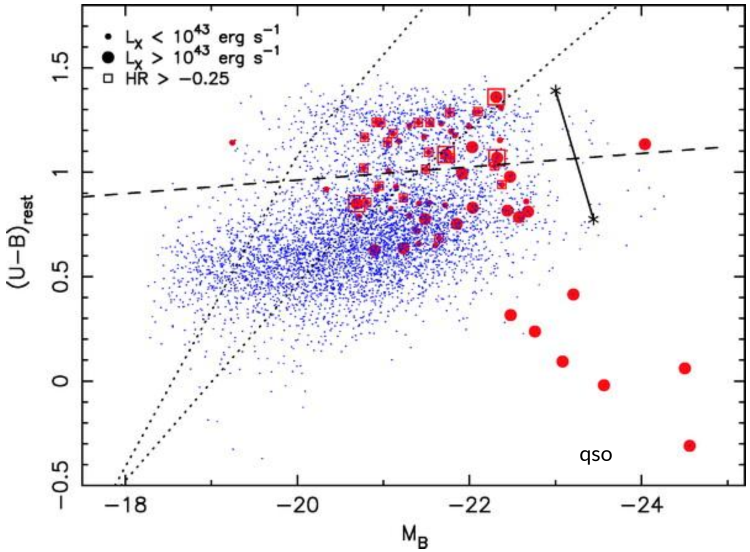
→ RPS, strangulation (fast and slow gas-only removal)

→ mergers, tidal interaction (gas and stars)

→ internal mechanisms (AGN, stellar winds)

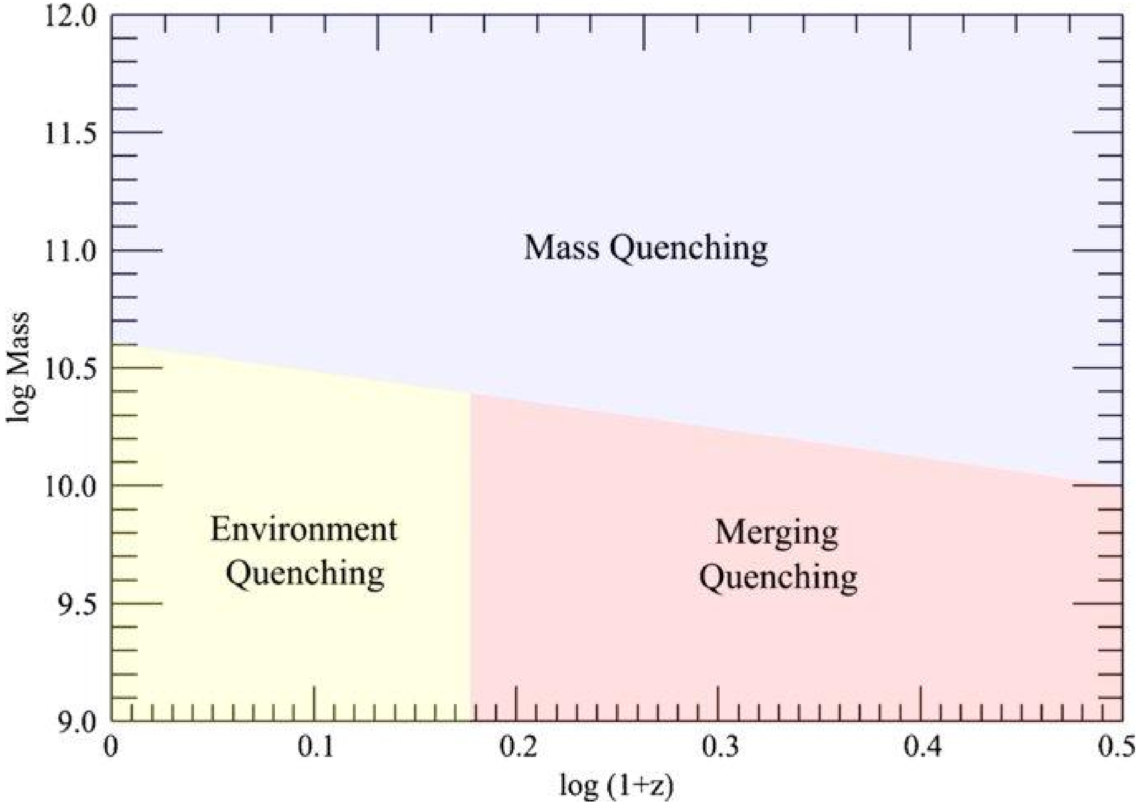
"The great majority of X-ray AGN lie in luminous, red galaxies in and around the transition region between the blue cloud of star-forming galaxies and the red sequence. This finding is consistent with AGN activity being associated with the process that quenches star formation in massive galaxies."

Nandra et al., 2006



[red] Chandra X-ray sources (AGN) at z=0.6-1.4
[blue] comparison sample from DEEP2 survey

Quenching mechanisms



At low redshift low mass galaxies are quenched due to environment, high mass due to mass quenching

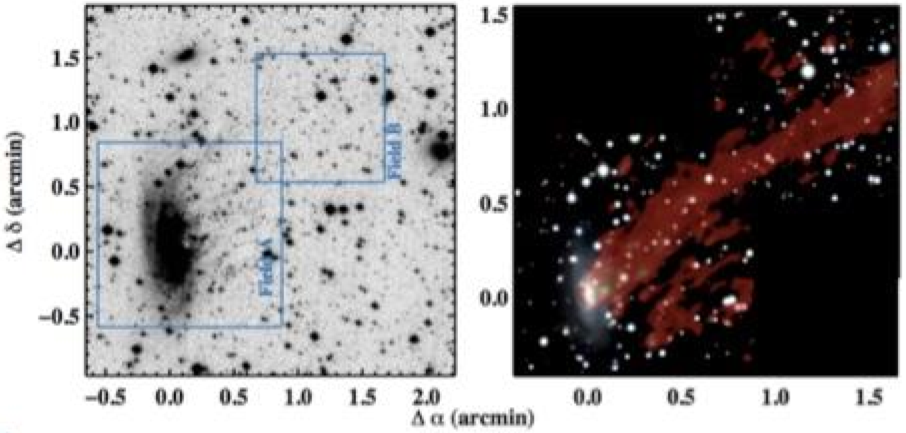
Peng et al., 2010

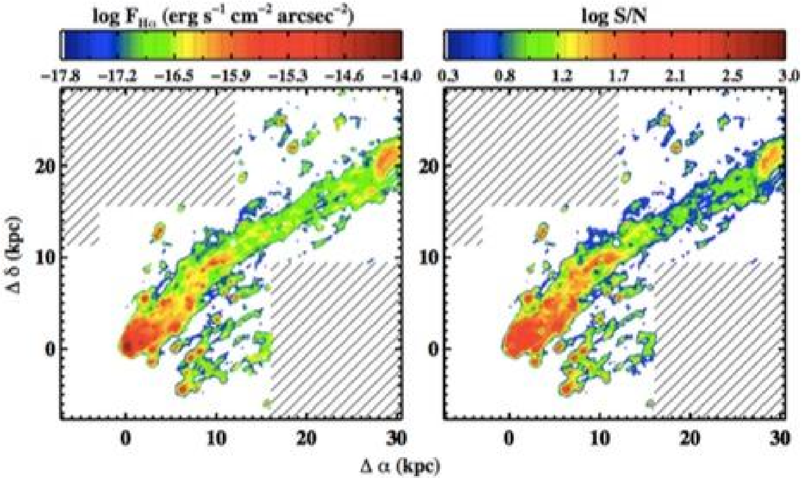
Jellyfish galaxies

"Galaxies with clearly distorted images, with optical data resolving multiple filaments offset asymmetrically from the galaxy " [Smith et al., 2010, UV asymmetry]

+ 60 kpc Hα tails in D110 (Coma) [Yagi et al 2007]

Virgo





z>0.2

Owen et al., 2006; Cortese et al., 2007; Owers et al., 2012 - ACS data

Fumagalli et al., 2014, Fossati et al., 2016 ESO137-001

The GASP survey [LP, PI B. Poggianti]: motivation

GAs Stripping Phenomena in galaxies with MUSE

The key drivers of GASP are:

1. measure the **time-scale** and the **efficiency of the stripping phenomenon in galaxies as a function of galaxy environment and galaxy mass**;
2. quantify the amount of stars formed in the stripped gas, contributing to the understanding of the formation of the intracluster and intragroup medium;
3. estimate the speed at which the galaxy moves in the IGM from the comparison between the velocity of the stripped gas and that of the main galaxy body;
4. identify the **physical process/es responsible for the gas outflow** among the possible external (ram pressure, tidal interactions, harassment, etc.) and internal (winds due to stars or AGN) mechanisms, clarifying where and how it happens;
5. monitor the evolution of the galaxies which are being depleted of their gas content, looking at their **transition from the blue cloud to the red sequence**;
6. derive the galaxy velocity and velocity dispersion maps, measure the total mass and Mass/Light ratio and estimate the **spatially resolved star formation history** and metallicity distribution.

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: candidates selection

GAs Stripping Phenomena in galaxies with MUSE

→ Galaxies in different environments (clusters, groups, field+control sample)

→ Galaxies with different masses (from 10^9 to $10^{11.5}$ $M_\odot$)

→ Galaxies with different stripping signatures (Jclass 1-5, taken from Poggianti et al., 2016)

→ 114 [94+20] gx, 120 hrs, 2700s/pointing, 1e5 spectra/pointing

→ 0.2”/px, 2.5 A FWHM, 4700-9300

→ Started in 2015, 50% observed

→ **Fov (1’x1’)~60x60 kpc^2**

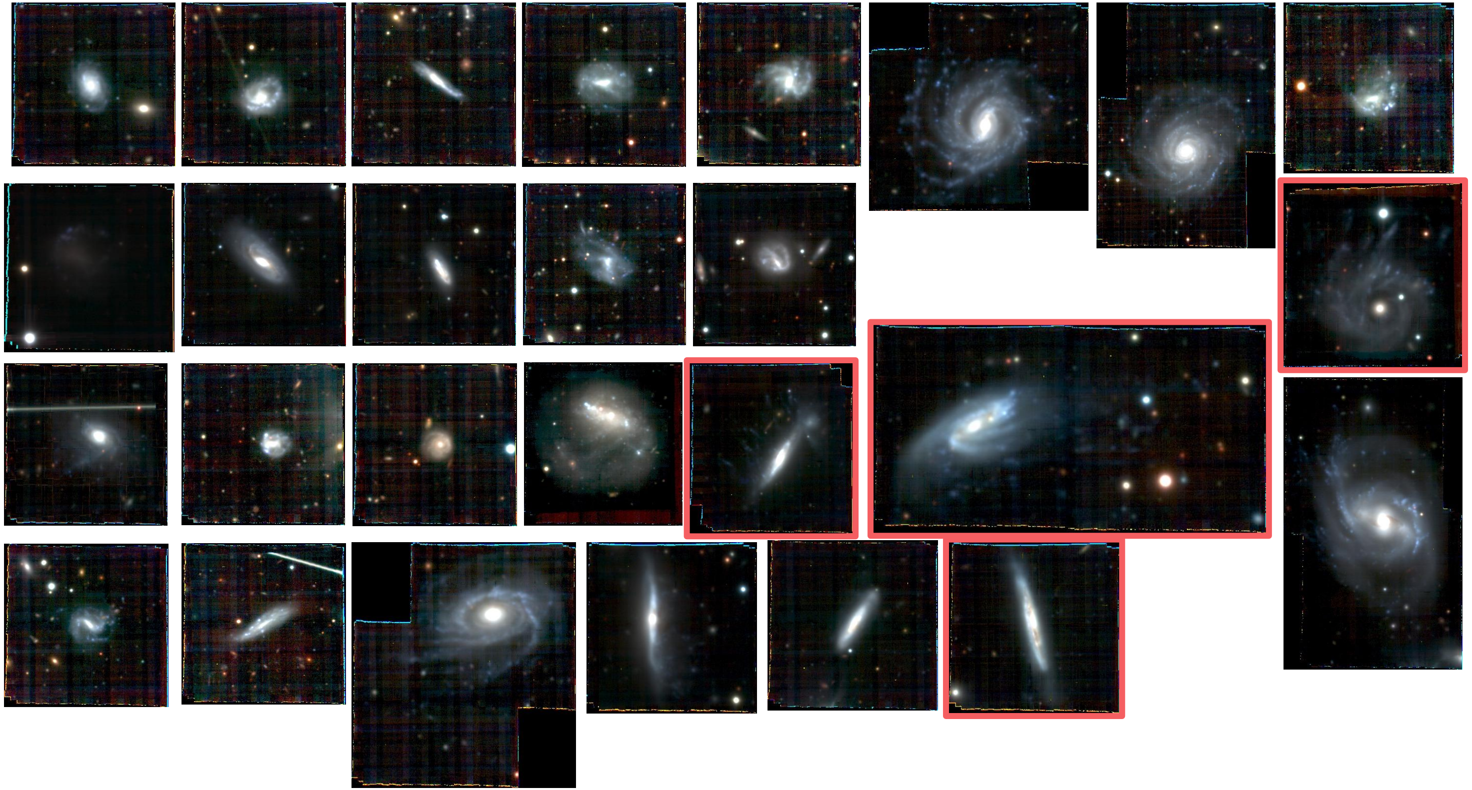
NB Target galaxies selected to have signatures of GAS-ONLY removal processes (no mergers, no tidal interactions)

1. Debris trails, tails or surrounding debris on one side of the galaxy
2. asymmetric/disturbed morphology
3. Distribution of star forming knots/region suggesting induced SF on one side

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: observed galaxies [clusters]

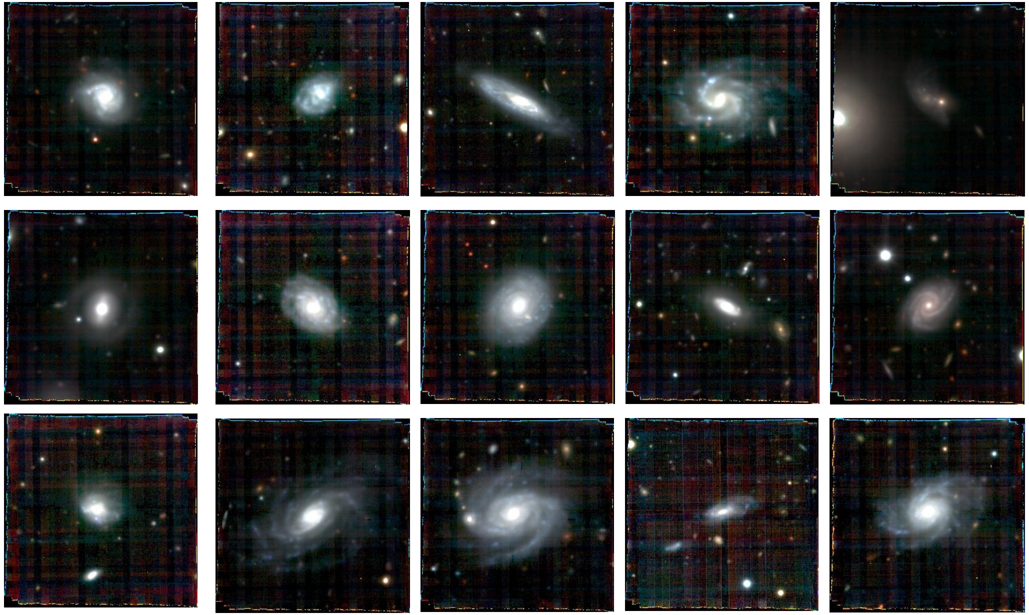
GAs Stripping Phenomena in galaxies with MUSE

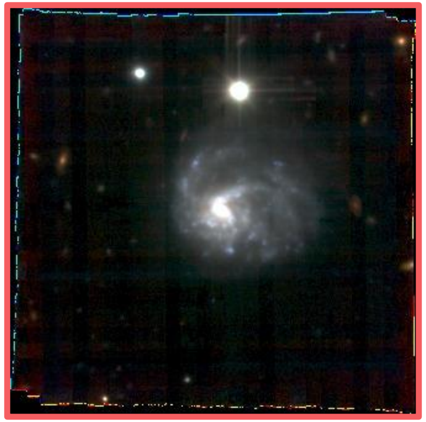


http://web.oapd.inaf.it/gasp/index.html

The GASP survey: observed galaxies [groups/field]

GAs Stripping Phenomena in galaxies with MUSE

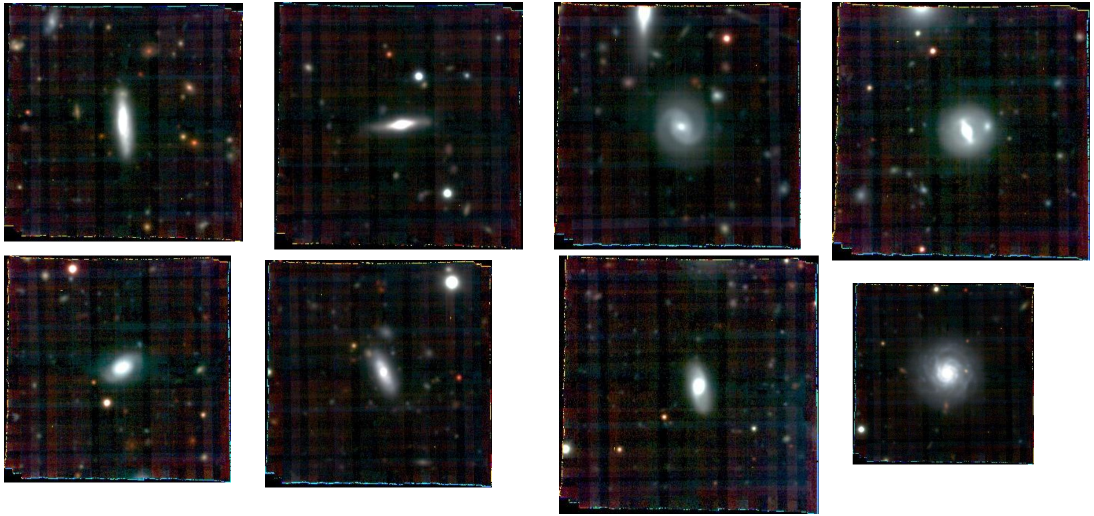


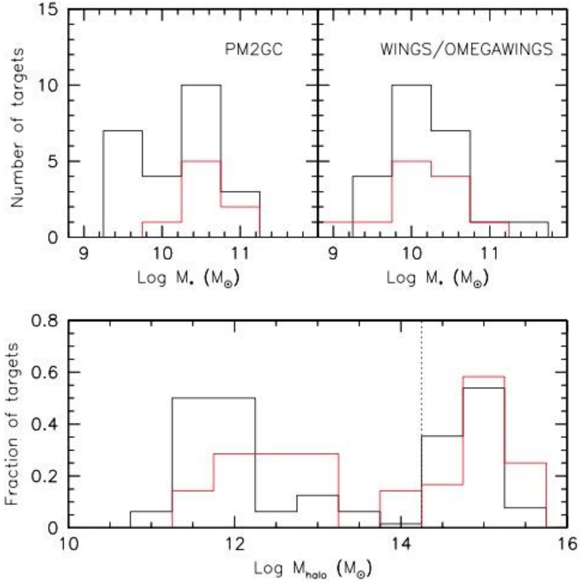


http://web.oapd.inaf.it/gasp/index.html

The GASP survey: observed galaxies [control sample]

GAs Stripping Phenomena in galaxies with MUSE

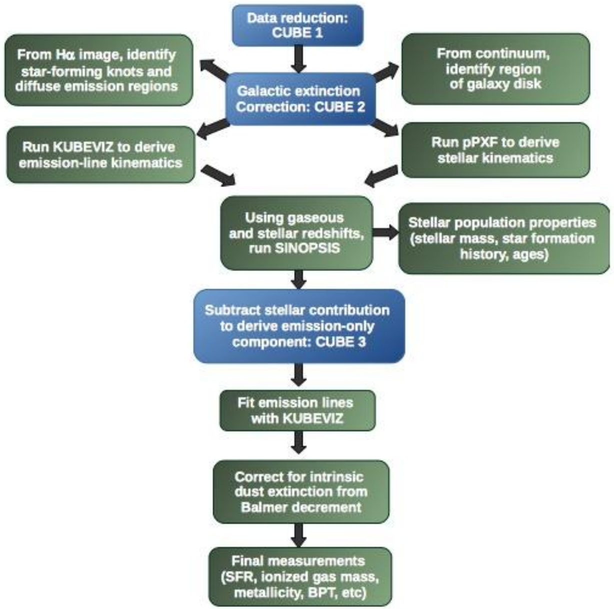




http://web.oapd.inaf.it/gasp/index.html

The GASP survey: Data analysis

GAs Stripping Phenomena in galaxies with MUSE



Poggianti et al., 2017

→ Initial cube (CUBE1) corrected for galactic extinction (CUBE2) and spatially smoothed (5x5 pixels kernel, 0.7-1.3 kpc)

→ Emission lines fitting on the original cube and on the emission only cube (CUBE3) [Kubeviz, Fossati et al., 2016]

→ Gas and stellar kinematics maps [pPXF, Cappellari & Emsellem, 2004]

→ Stellar population properties [SINOPSIS, Fritz et al., 2017]

→ Dust extinction from Balmer decrement

→ Metallicity [pyqz, Dopita et al., 2013] and BPT classification from line ratios

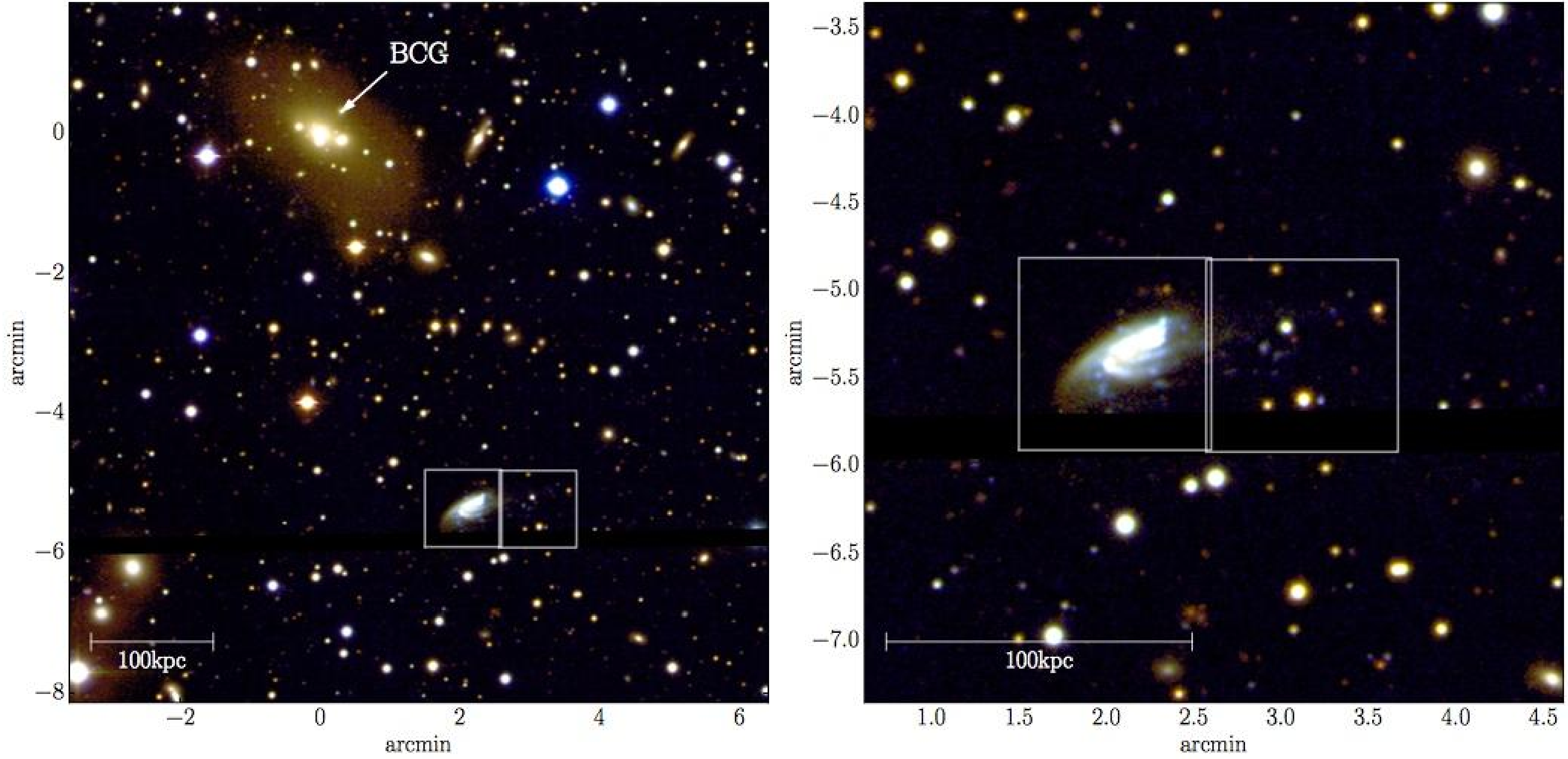
→ SFR from Hα flux using Kennicutt (1998) relation

→ M(ionized gas) from Hα

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE



JClass=5

8.5e10 $M_{\odot}$

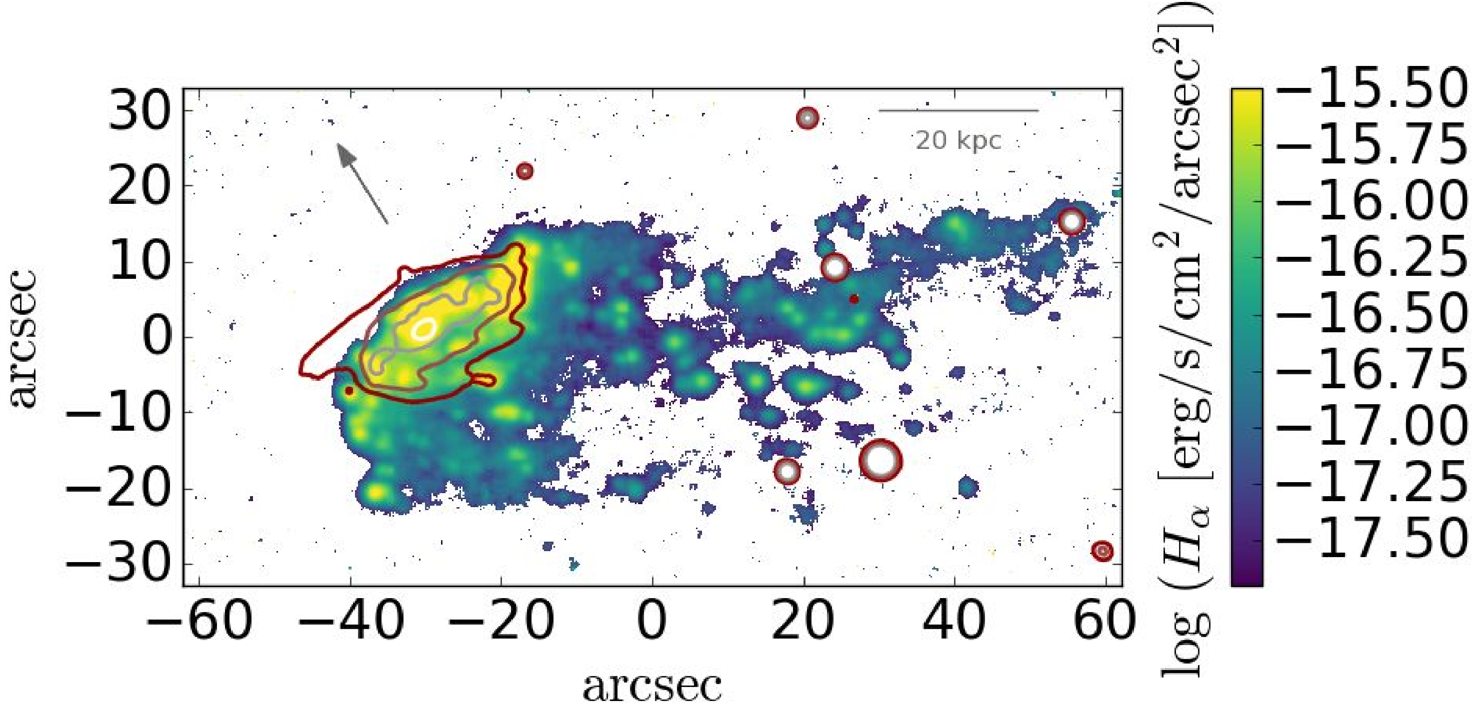
In IIZw108 (low mass)

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE

JO206 [8.5e10] in
IIZW108 [1.9e14]
at ~350 kpc
JClass=5



S/N(Hα)=5÷50

Hα tails out to ~90 kpc (and more?)

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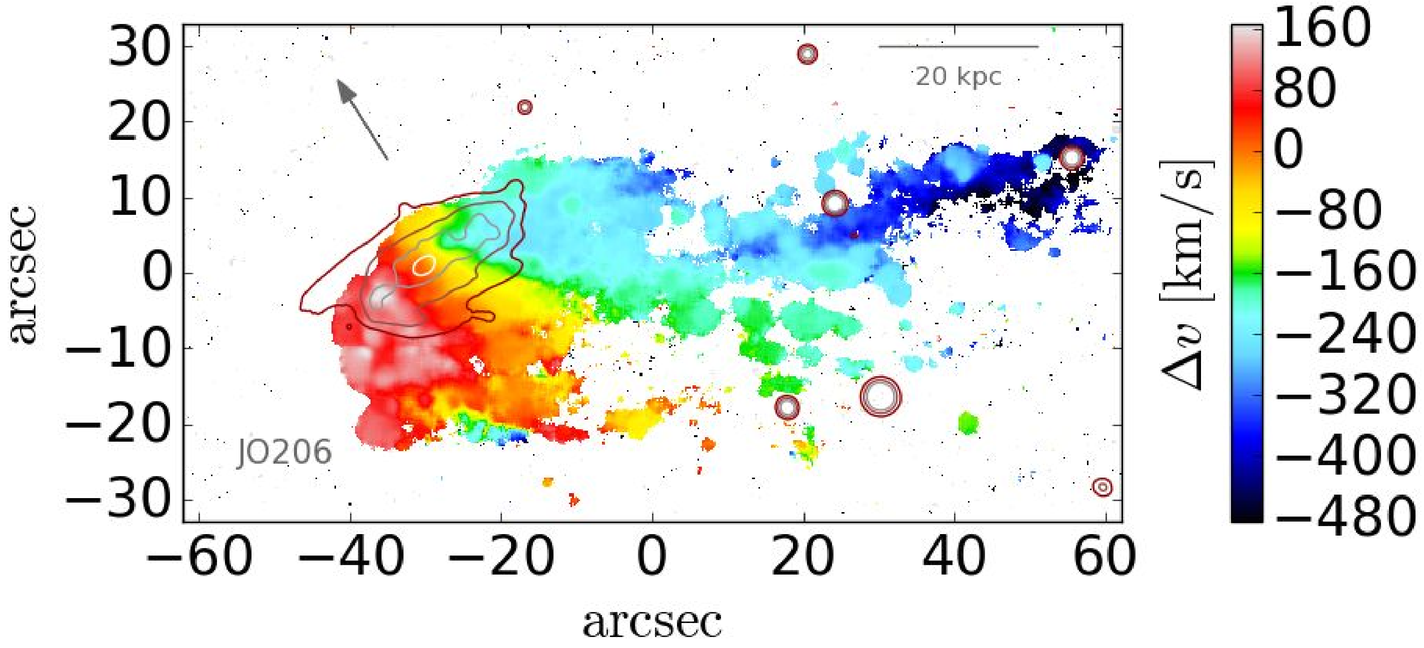
The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE



S/N(Hα)=5÷50

Hα tails out to ~90 kpc (and more?)

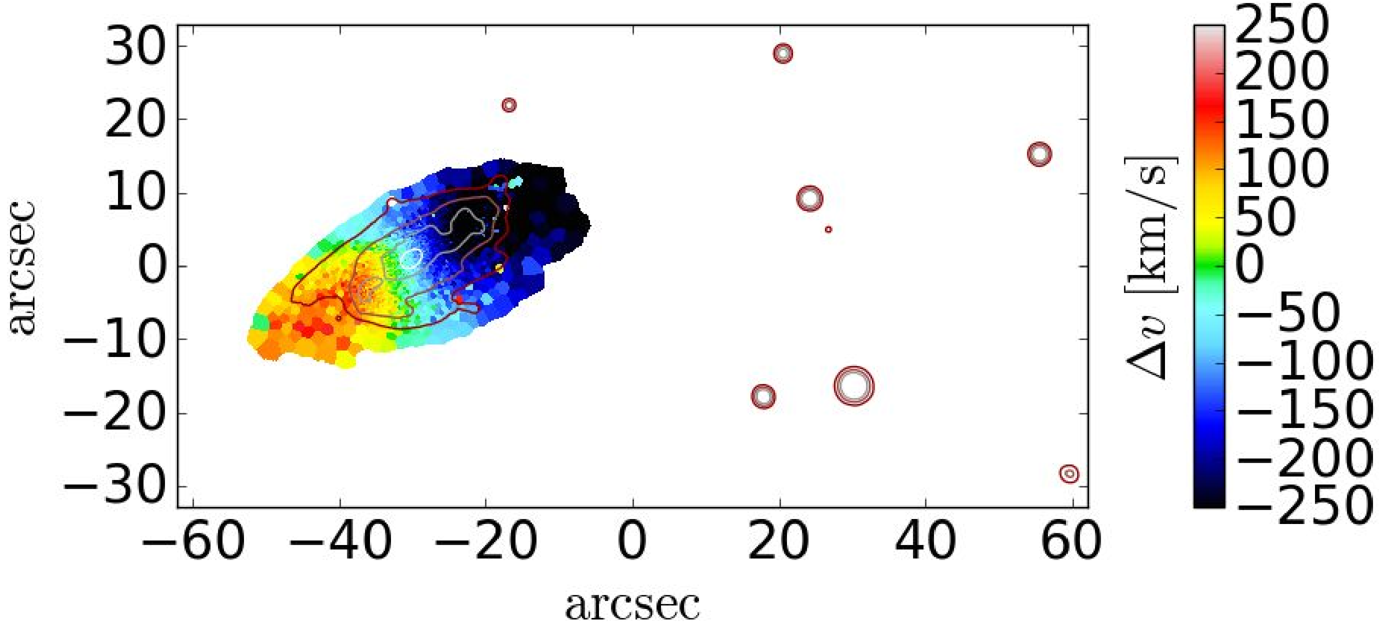
Stripped gas has coherent rotation

Velocity dispersion generally low (but in the center--AGN)

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE



S/N(Hα)=5÷50

Hα tails out to ~90 kpc (and more?)

Stripped gas has coherent rotation

Velocity dispersion generally low (but in the center--AGN)

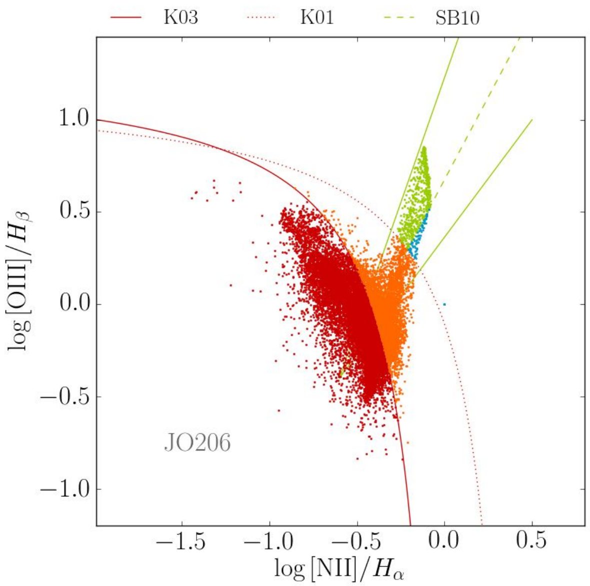
Regular stellar kinematics

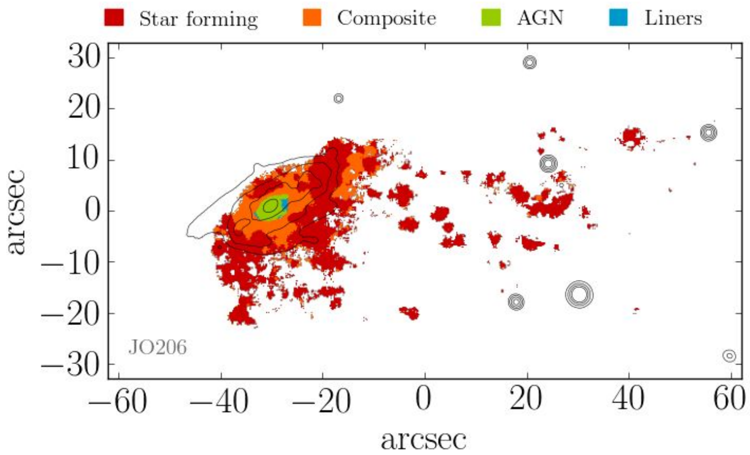
Evidence of ram pressure stripping

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE





Central AGN emission from BPT diagram(s)

Star forming disk

Origin of SF in the tails (from massive stars formed in the last 10^7 yr)

→ new stars in situ (compatible with measured stellar continuum and stellar ages)

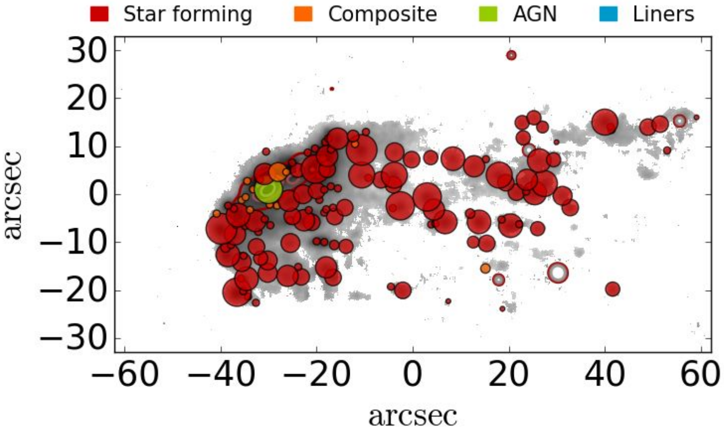
→ ionizing radiation from stars in the disk

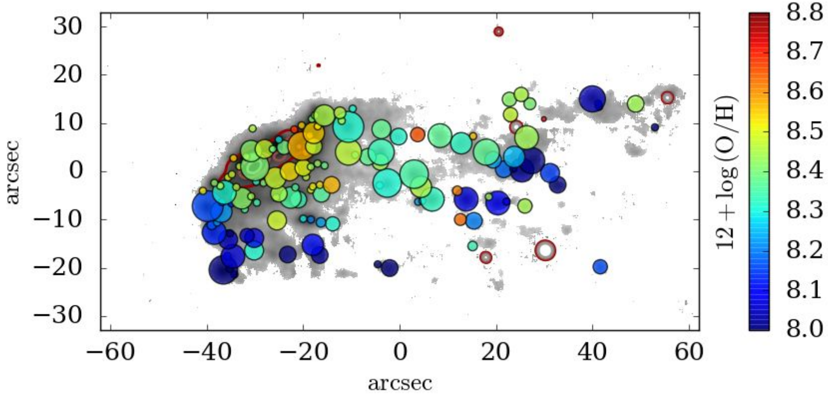
→ stripping of ionized gas (recombination time too short, or implying gas traveling at ~9000 km/s)

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE





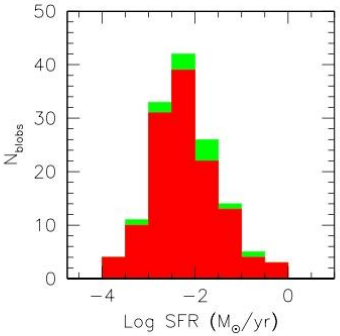
139 knots found on Ha image: 1 AGN dominated, remaining SF

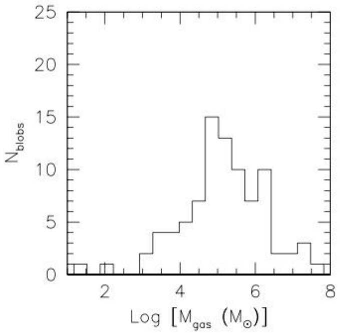
Knots in the tails are giant HII regions (as in other JF - Fossati et al., 2016; Yagi et al., 2013; Cortese et al., 2004 etc) photoionized by stars [at odds with NGC4569 ionized by shocks, see Boselli et al., 2016]

Knots metallicity follows the resolved one

SF[AGN] = 1 $M_{\odot}$/yr
SF[Knots]= 4.2 $M_{\odot}$/yr

Total gas mass = 1.7e8 $M_{\odot}$





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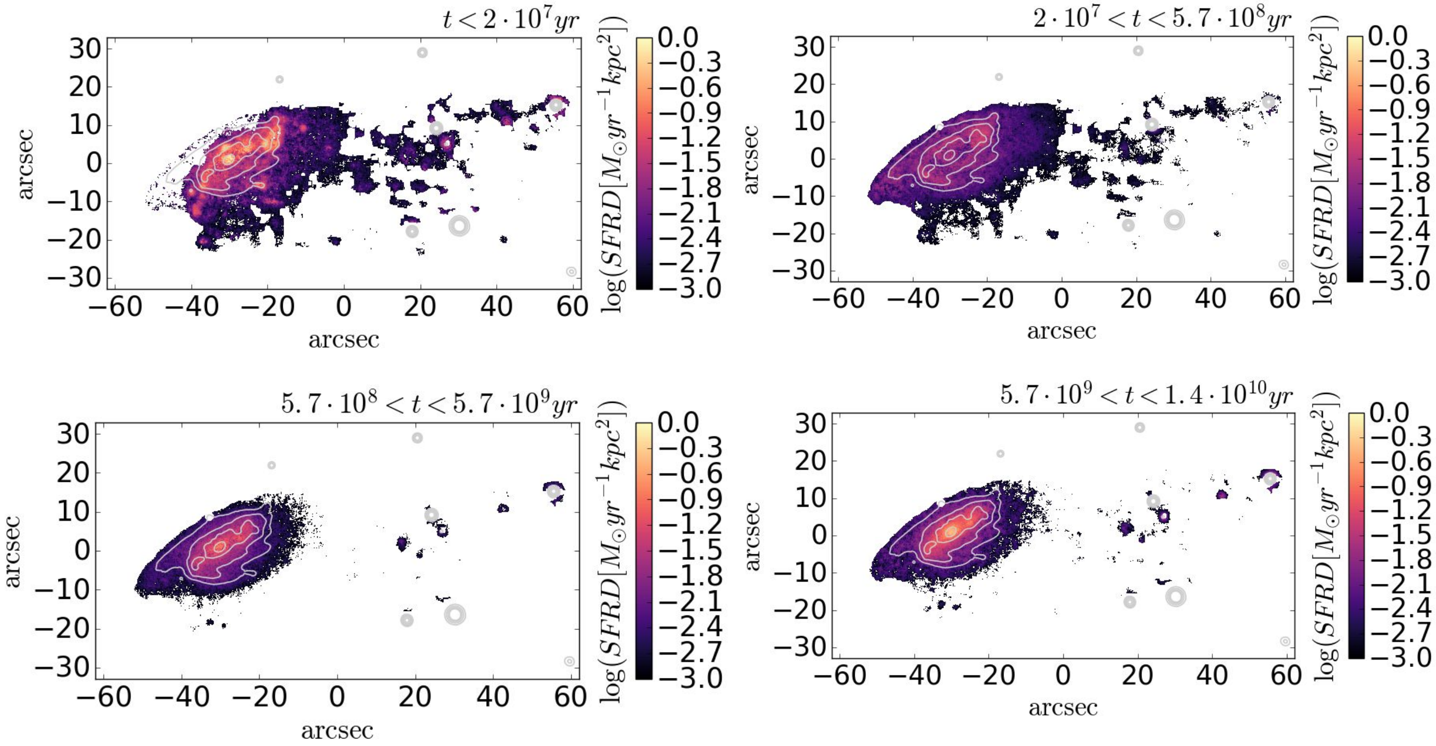
The GASP survey: JO206, a JF prototype

GAs Stripping Phenomena in galaxies with MUSE



Ongoing and recent SF in the tails

Older stars confined to the main galaxy body

SF in the stripped gas started during the last $5x10^8$ yrs

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The GASP survey: JO206, a JF prototype

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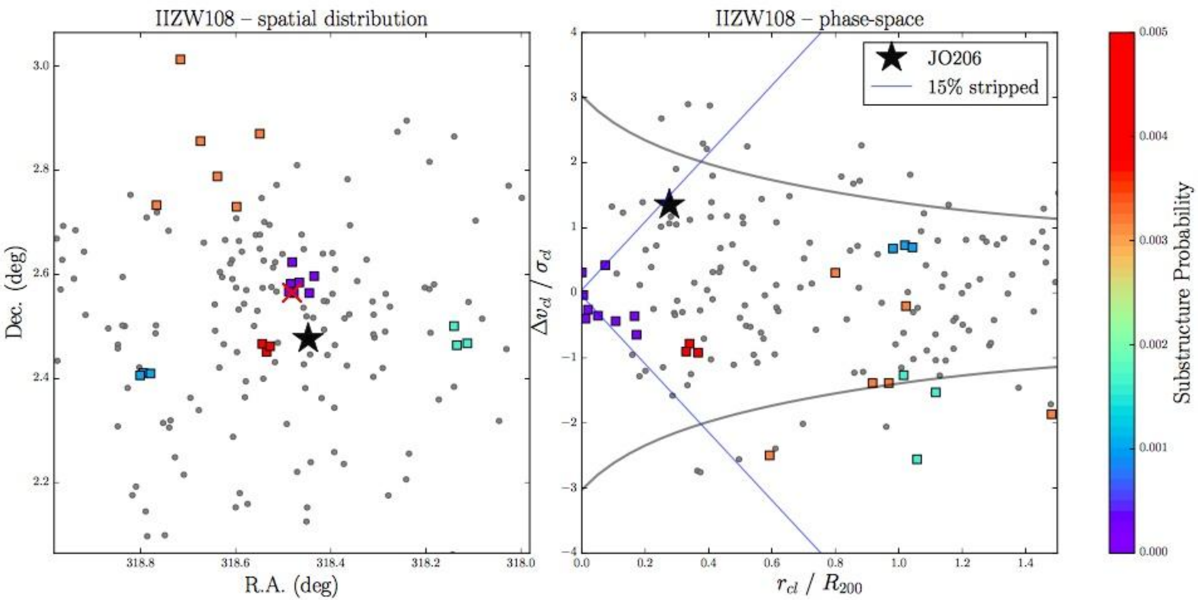


Cluster dynamics from WINGS/OmegaWINGS dataset (Moretti et al., 2017, Biviano et al., in preparation) on 171 spectroscopic members

M_{200}=1.9 x 10^{14} $M_{\odot}$, R_{200}=1.17 Mpc

JO206 does not belong to any substructure

Located at 0.3 R_{200} with Δv~1.5 σ_{cl} → ideal conditions for RPS

By comparing P_{ram} with the anchoring force of a disk galaxy as JO206 → condition for stripping met at r~20 kpc

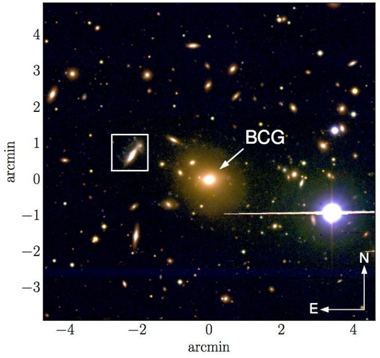
The estimated gas mass fraction lost to the ICM is ~15%

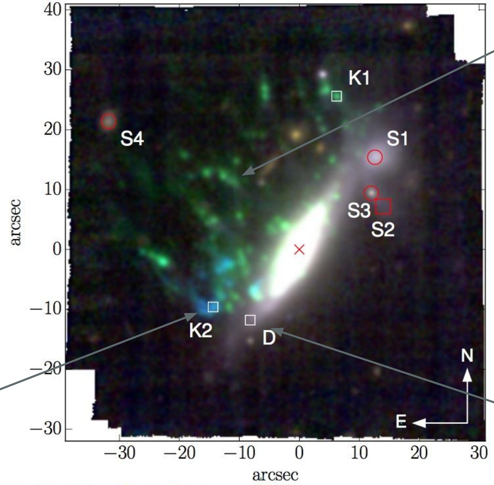
Caveat
→ Only projected measurements
→ Idealized exp. Disk for JO206
→ Assumed homogeneous ICM
→ Hα used as gas tracer

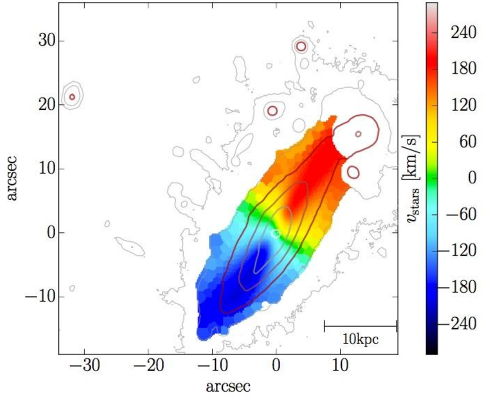
The GASP survey: Galaxy zoo

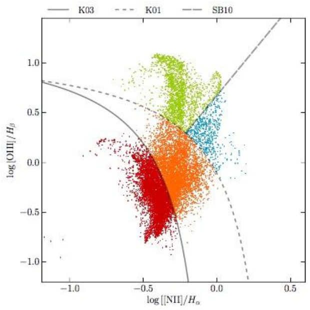
GAs Stripping Phenomena in galaxies with MUSE

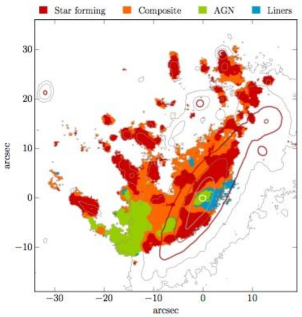
JO204 [4e10] in A957 [4.4e14] at 132 kpc JClass=5

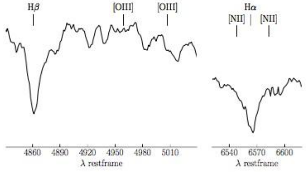


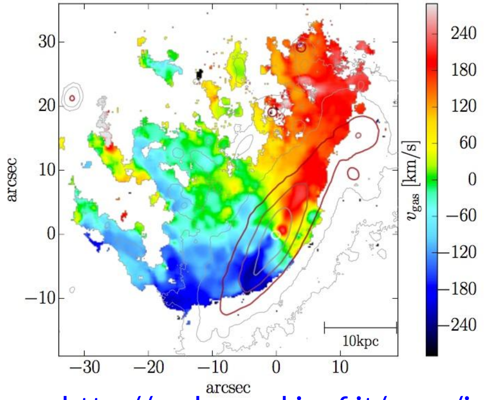










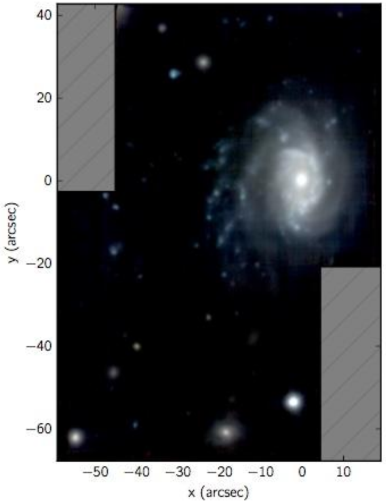


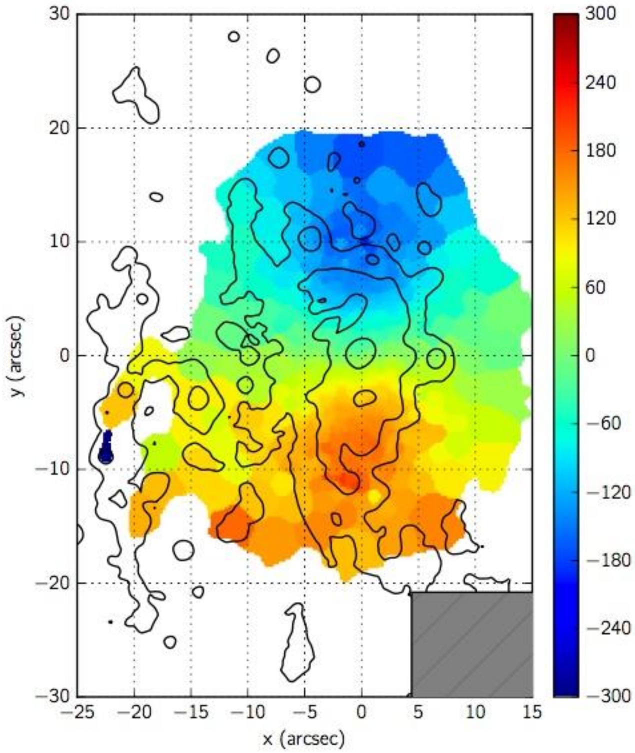
Gullieuszik et al., 2017, submitted

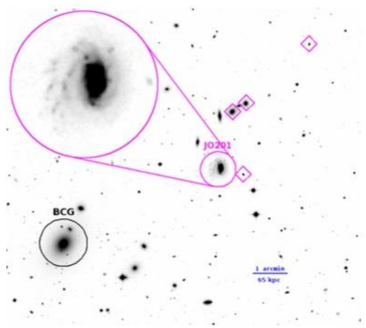
http://web.oapd.inaf.it/gasp/index.html

The GASP survey: Galaxy zoo

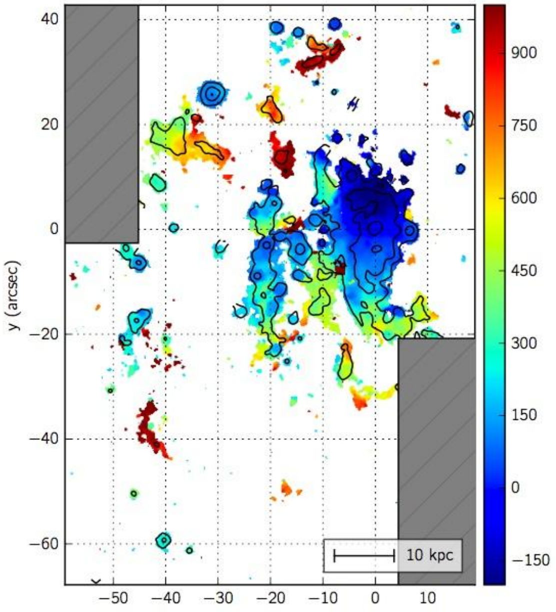
GAs Stripping Phenomena in galaxies with MUSE







JO201 [3.5e10] in A85 [1.58e15] at 360 kpc JClass=5



Is RPS causing unwinding arms?
Need for two components fitting: stripping along the line of sight

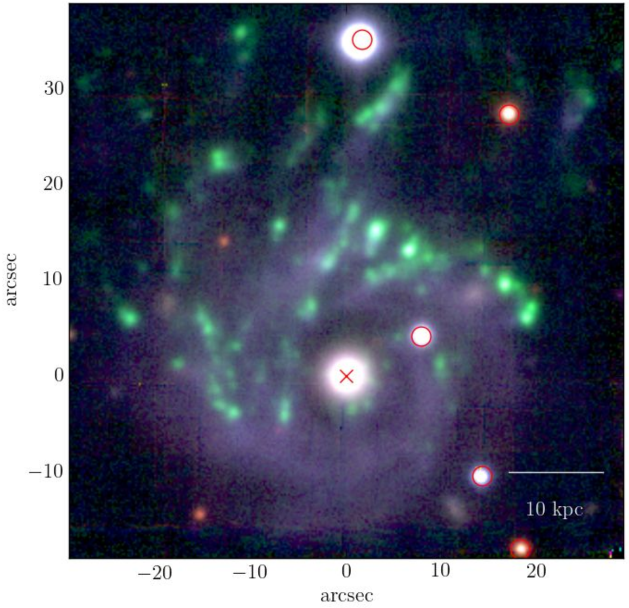
Bellhouse et al., 2017

http://web.oapd.inaf.it/gasp/index.html

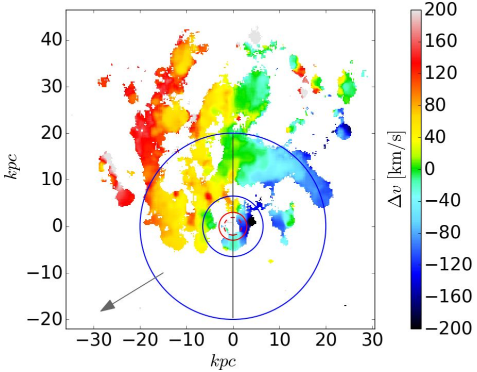
The GASP survey: Galaxy zoo

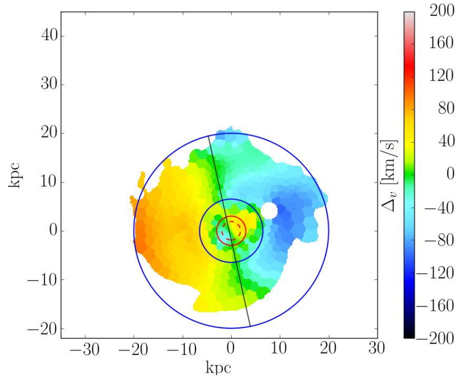
GAs Stripping Phenomena in galaxies with MUSE

JO171 [3.4e10] in A3667 [1.7e15] at 1.38 Mpc JClass=5



JO171 RGB image (I, Hα,B) resembling Hoag's galaxy: central spheroid+empty corona+gas ring (being stripped)

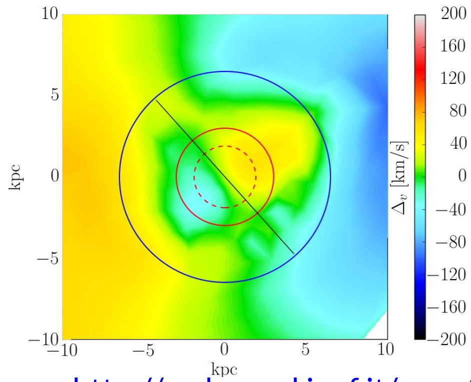




Gas only in the north region
Stars uniformly distributed
+
Counter-rotation!

No merger remnant, no bar

→ gas accretion? merger?

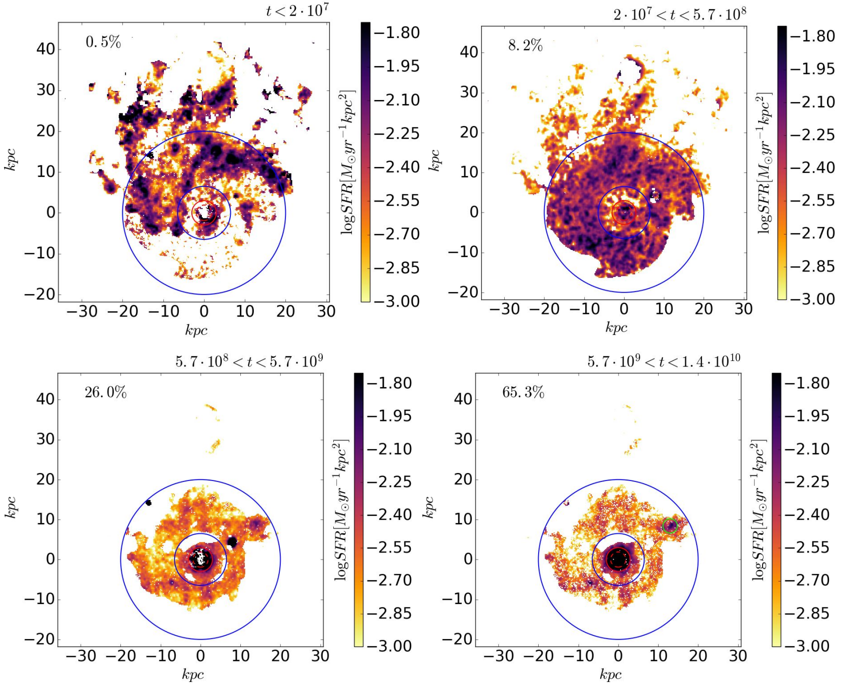


Moretti et al., 2017, submitted

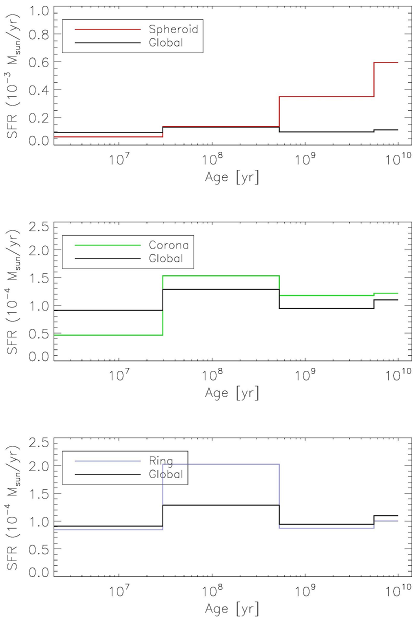
http://web.oapd.inaf.it/gasp/index.html

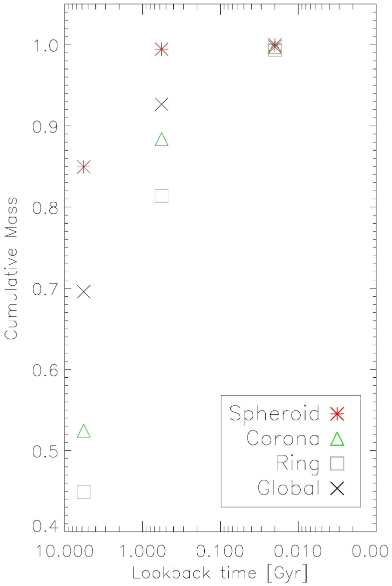
The GASP survey: Galaxy zoo

GAs Stripping Phenomena in galaxies with MUSE



SF history of different regions





→ ~90% of the total mass formed before the last 0.6 Gyr
→ no young stars in the central spheroid

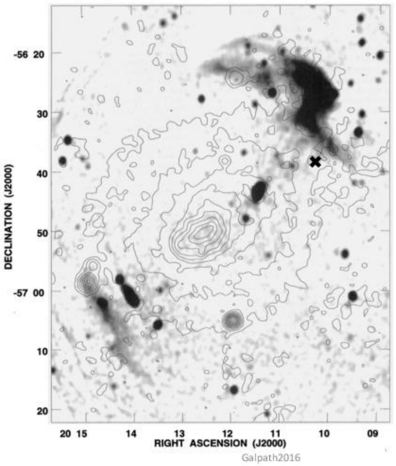
Old stars in the ring: low SFR for long time or single episode of SF?

Moretti et al., 2017, submitted

http://web.oapd.inaf.it/gasp/index.html

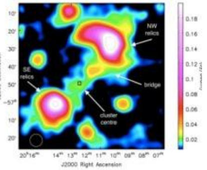
The GASP survey: Galaxy zoo

GAs Stripping Phenomena in galaxies with MUSE

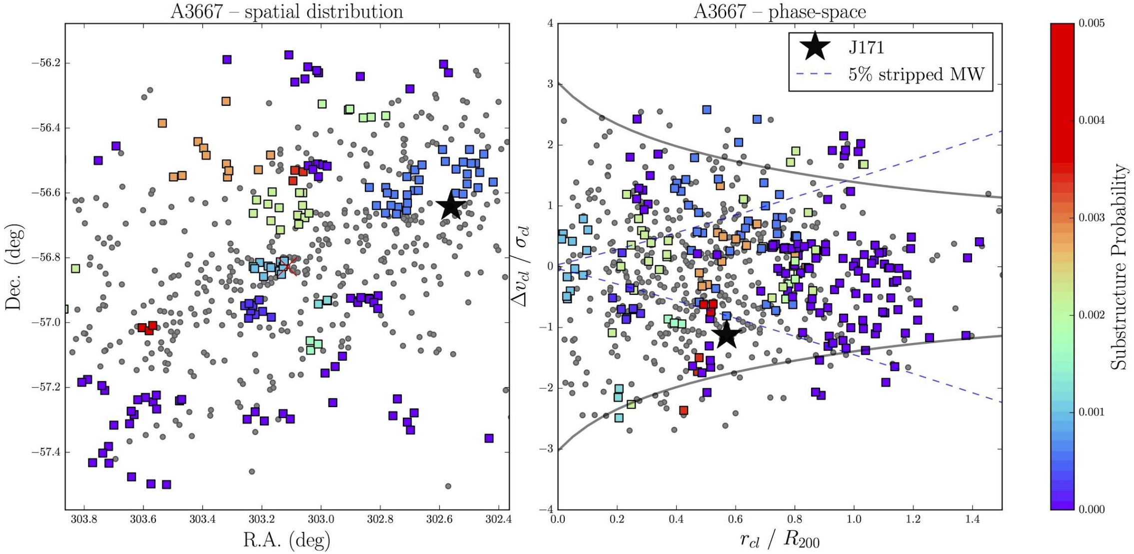


Contours: ROSAT
Grey-scale image:
radio relic

Rottgering et al.
1997



Radio bridge
Carretti et al.2013



In A3667, disturbed cluster (merging).
Close to the radio bridge

Analysis of members (dedicated spectroscopy from OmegaWINGS+literature): JO171 might belong to a substructure (only marginal evidence)
PPS location suggests recent accretion to the cluster + ram pressure stripping

Moretti et al., 2017, submitted

http://web.oapd.inaf.it/gasp/index.html

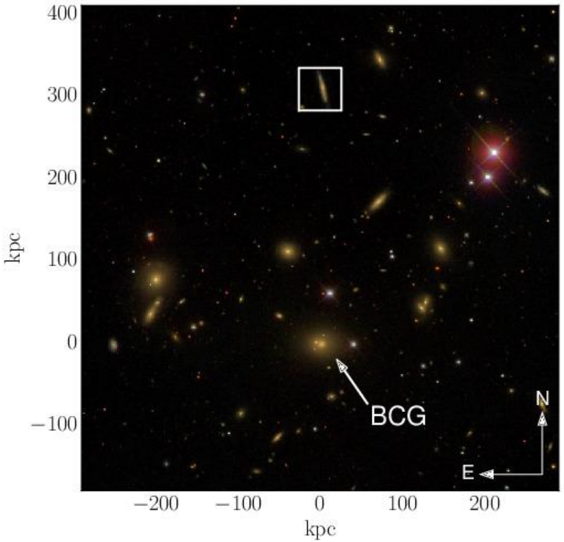
JO171 possible scenarios

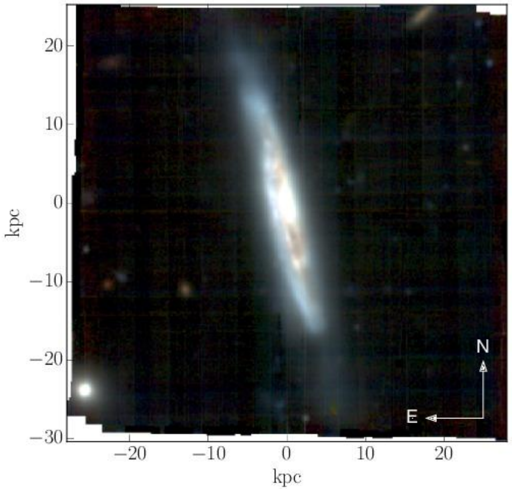
Internal origin	NO	Lack of bar
Collisional ring	NO	Counter-rotation
Major merger	NO	No young stars in the spheroid + round profile
Minor retrograde merger (1:2,1:5)	YES	~ 6 Gyr ago before entering into the cluster BUT no signatures of merger remnant
Cold Accretion	YES	Started early (old stars in the ring), confirmed by low metallicity

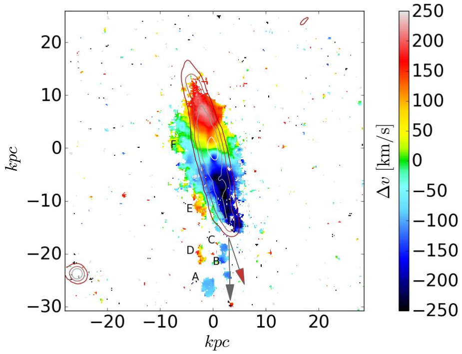
The GASP survey: Galaxy zoo

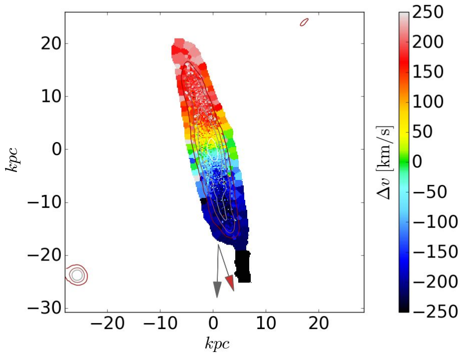
GAs Stripping Phenomena in galaxies with MUSE

JO36 [6.5e10] in A160 [2.9e14] at 310 kpc JClass=3







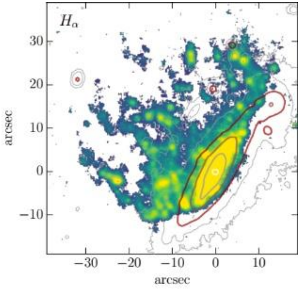


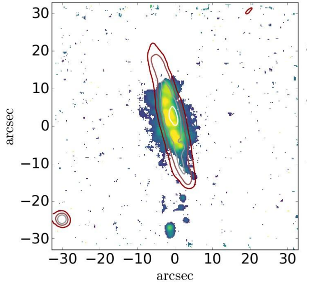
JO36 in A160: truncated Hα disk, with probable buried AGN (from Chandra data)
Gas kinematics is disturbed (see also Hα blobs)
Stellar tail towards the BCG (due to gravitational interaction)
Inside-out formation
Herschel data predict a normal total gas mass (~10^{10}), while ionized gas is 7×10^8
From PPS diagram 21% of gas mass stripped at ~13 kpc
Using also dust constraints → ~20-30% of the total gas mass has been stripped via RPS

Fritz et al., 2017, submitted

The GASP survey: General Results

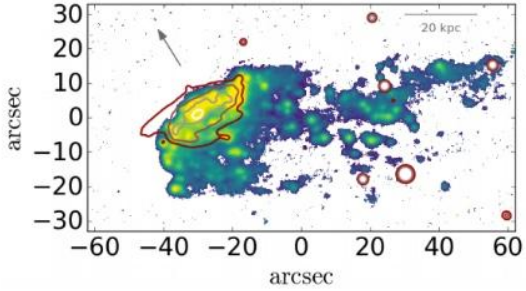
GAs Stripping Phenomena in galaxies with MUSE





Common phenomena:
→ Hα coincident with HII regions in the tails

→ SF ongoing in the stripped tails [WIP ICL, WIP Fraction of JF among spirals]



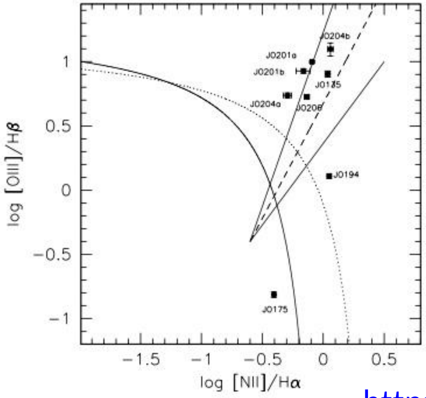
Success

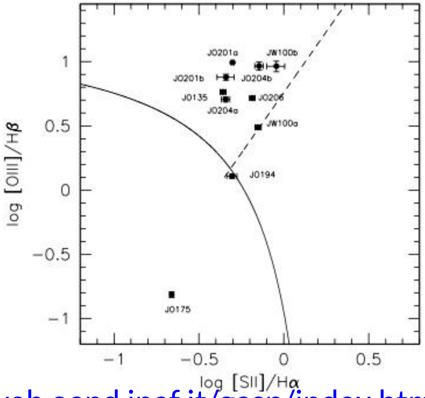
→ MUSE data able to infer RPS and date it

Results

→ RPS effective in low mass and high mass clusters, and
For massive and less massive galaxies

→ JF "degree" connected to AGN





GASP I : arXiv:1704.05086
GASP II: arXiv:1704.05087
GASP III: arXiv:1704.05088

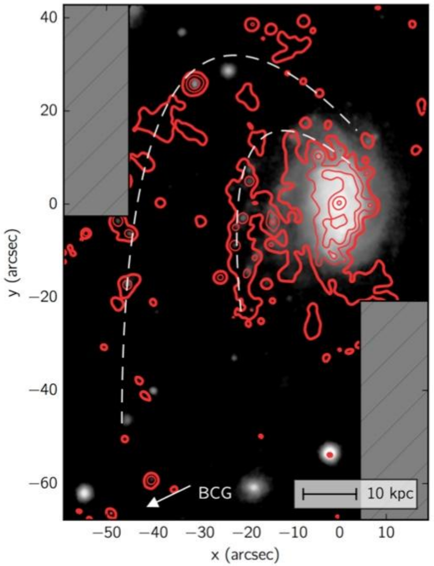
http://web.oapd.inaf.it/gasp/index.html

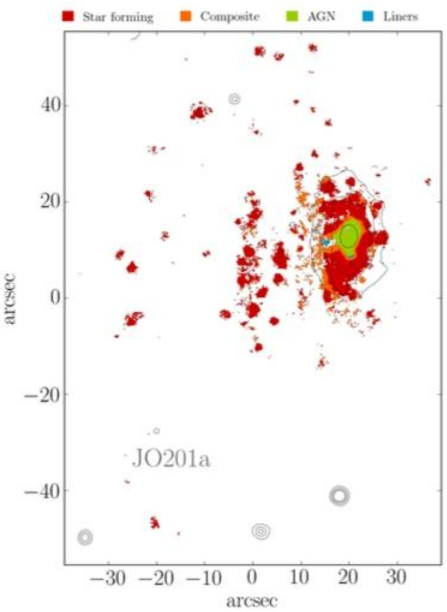
The GASP survey: JF/AGN connection?

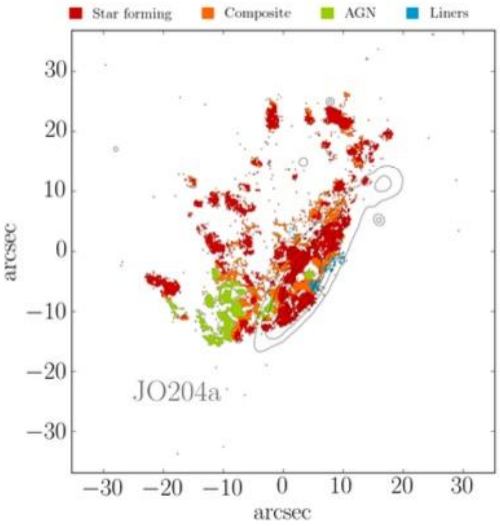
GAs Stripping Phenomena in galaxies with MUSE

→ selecting (observed) JF with Hα tails as long as the stellar disk diameter [masses between 4e10 and 3e11, estimated BH masses follows the relation between stellar masses and BH]

5/7 galaxies with emission line ratios typical of AGN (while only 3% of EL galaxies in WINGS clusters show AGNs) in the center and in an extended region of ~10 kpc. Chandra data confirm our results
1/7 LINER-like
1/7 with line ratios that can be explained in terms of star formation







Poggianti et al., Nature accepted

http://web.oapd.inaf.it/gasp/index.html

The GASP survey: future observations

GAs Stripping Phenomena in galaxies with MUSE

→ CO gas with APEX (33+44 hrs) for 5 galaxies to detect molecular hydrogen in the galaxies and in the tails: is the molecular gas stripped as well? How much molecular gas is present in the tails and left in the main body?
[molecular gas is present both in the disk and in the tails, with different velocities, Moretti et al., in preparation]

→ Deep HI observations of 15 JF in 5 clusters with JVLA (100 hrs, 15 kpc resolution)[mainly to study the interplay of the different gas phases, but also to correlate HI deficiency to the JF appearance and to discover interactions, if any.]

→ Ultraviolet view of RPS in action with Astrosat (24.4 ks)

→ Chandra observations [14 galaxies with masses >2e10 and JClass>=3, 40 ks each, 560 ks in total, 11 already show X-ray emission Nicastro et al., in preparation. To detect AGN signatures, shock fronts, ULXs]

→ ALMA observations [4 targets, 20 hrs requested, all with AGN, in different clusters. 1 kpc resolution would allow to resolve the knots as in GASP. CO21 and CO10]

http://web.oapd.inaf.it/gasp/index.html