

(Almost) TEN YEARS OF MUSE GASP DISCOVERIES

Bianca M. Poggianti
INAF-Astronomical Observatory of Padova



This project has received funding from the European Research Council under the Horizon 2020 research and innovation programme (grant agreement GASP N. 833824)



GAs Stripping Phenomena in galaxies

How do environmental processes remove gas from galaxies?

What is the effect on the galaxy star formation history?

First MUSE ESO Large Programme, ALMA/APEX (CO),
JVLA/MeerKAT/LOFAR/ATCA (HI, radio cont., polariz.), HST
(H α , UV to I) , UVIT@ASTROSAT (UV) + simulations

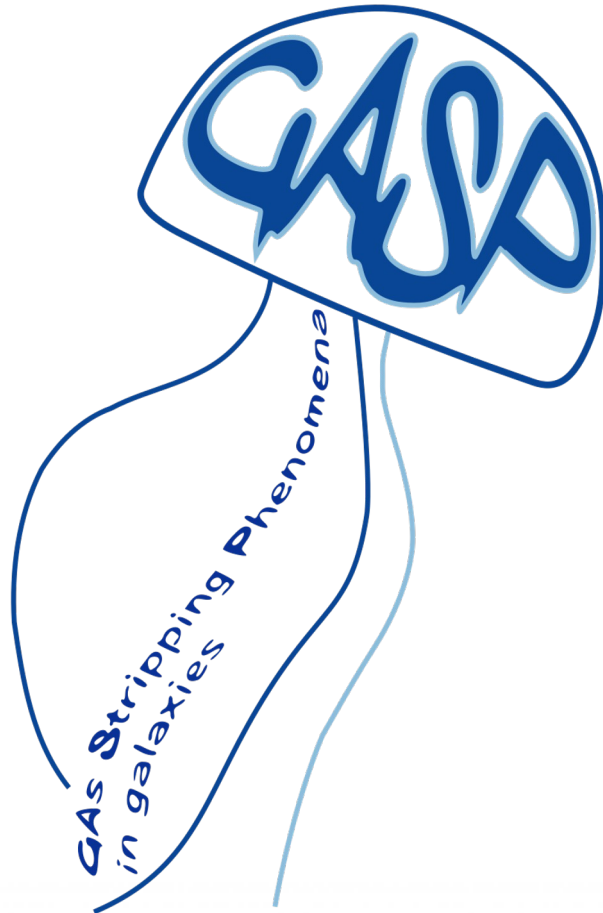
MUSE data for 114 galaxies at $z=0.04-0.07$
galaxy stellar masses $10^9-10^{11.5}$ Msun
in 39 clusters + groups, filaments and isolated

Diskly “disturbed” galaxies (with signs of extraplanar debris in
B-band images) + control sample (~ 30 undisturbed disk
galaxies).

MUSE coverage out to $7 R_e$ on average
MUSE and ALMA sp. res. ~ 1 kpc
HST resolution 70 pc

70 papers so far

N. Akerman
C. Bacchini
C. Bellhouse
D. Bettoni
T. Deb
A. Biviano
J. Fritz
K. George
E. Giunchi
M. Gullieuszk
A. Ignesti
A. Kulier
Y. Jaffe'
A. Lourenco
A. Marasco
S. McGee
M. Mingozi
A. Moretti
A. Mueller
A. Omizzolo
R. Paladino
G. Peluso
M. Radovich
M. Ramatsoku
P. Serra
R. Smith
N. Tomicic
S. Tonnesen
J. Van Gorkom
M. Verheijen
B. Vulcani
A. Werle
A. Wolter



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

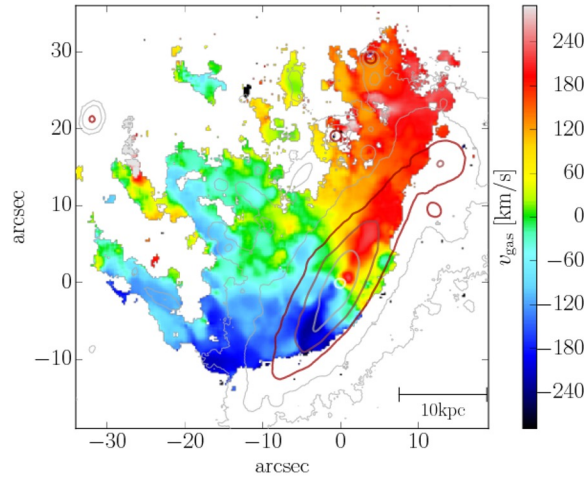


RAM PRESSURE STRIPPING DOMINATES IN CLUSTERS

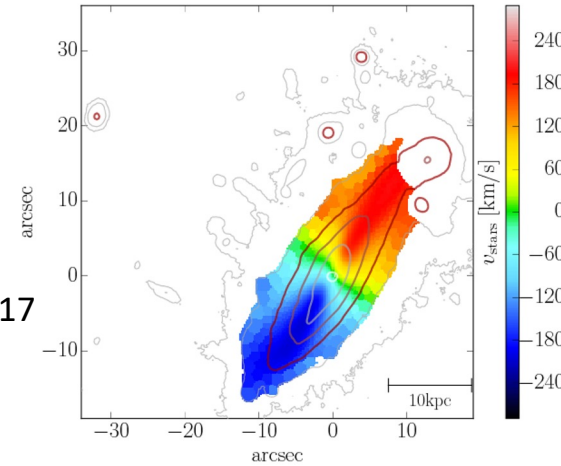
GAS and STELLAR KINEMATICS



GAS (H α)



STARS

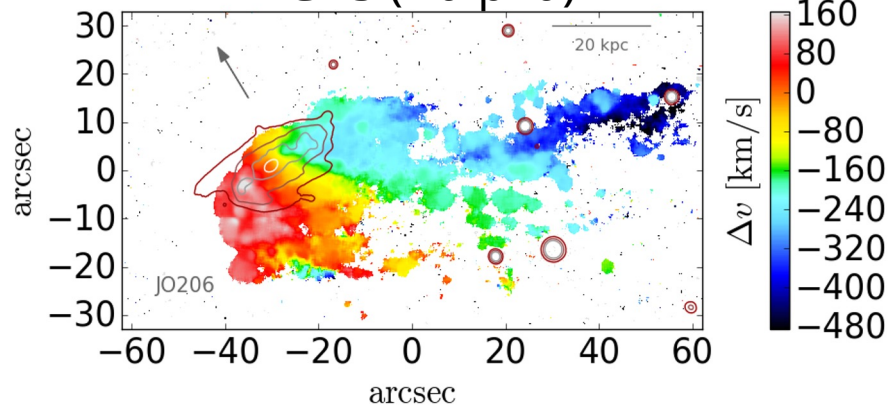


Gullieuszik+ 2017

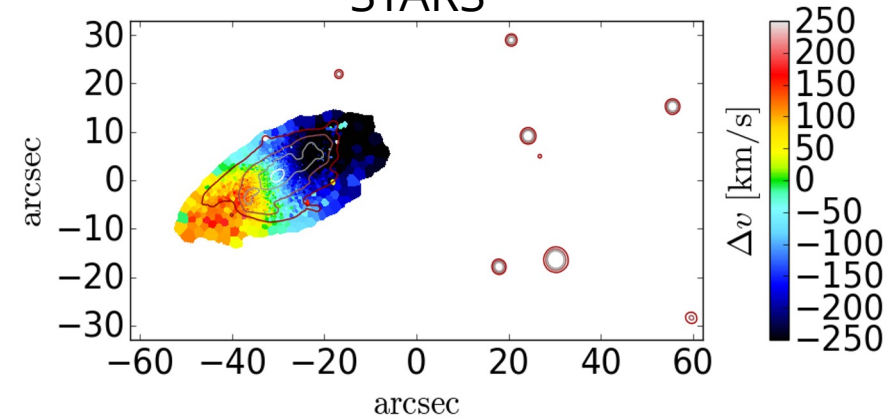
See also ESO137-001 Fumagalli+ 2014,
Fossati+ 2016

The stellar component is not disturbed, regular stellar kinematics: gas-only stripping
Stripped gas maintains coherent rotation for several kpc downstream

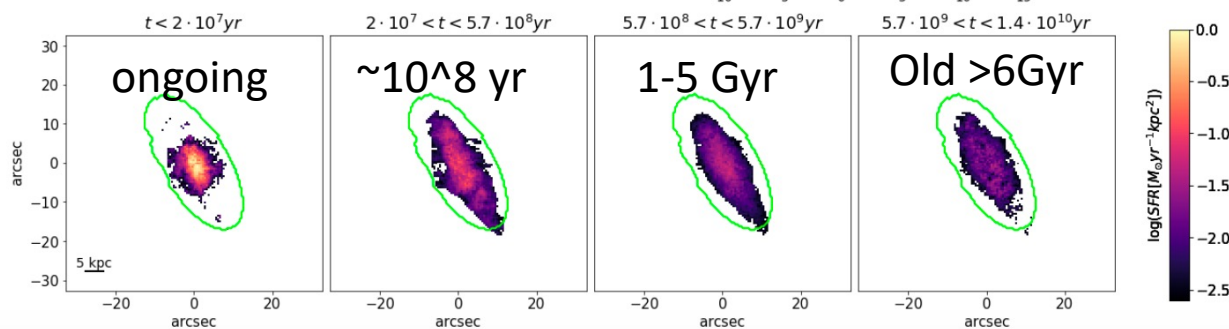
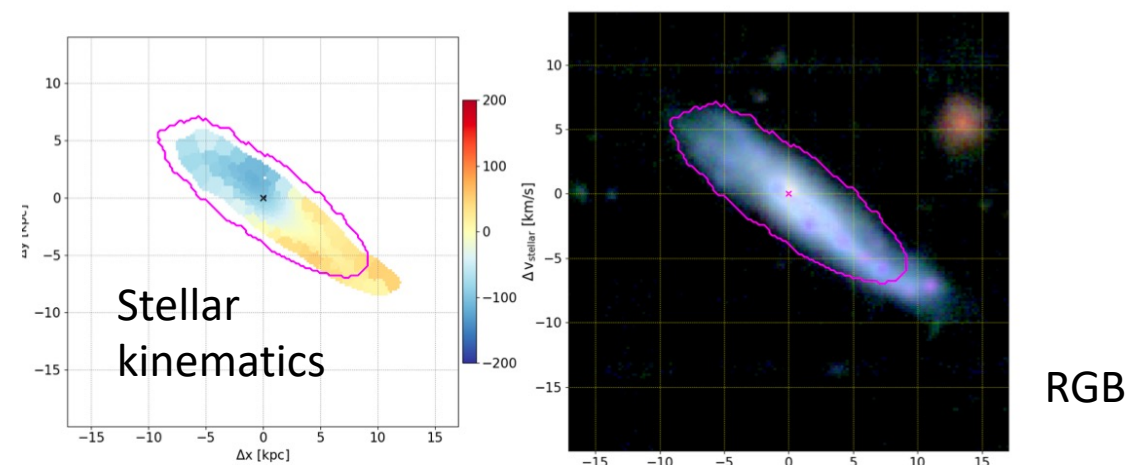
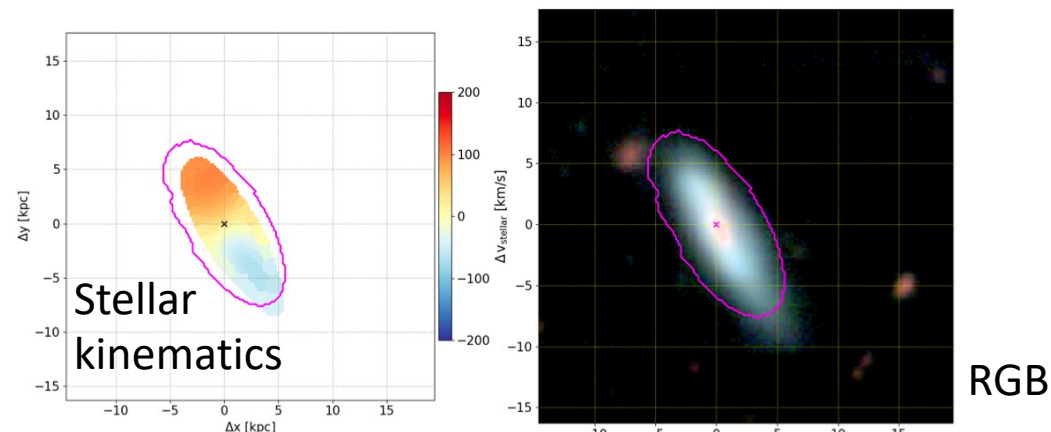
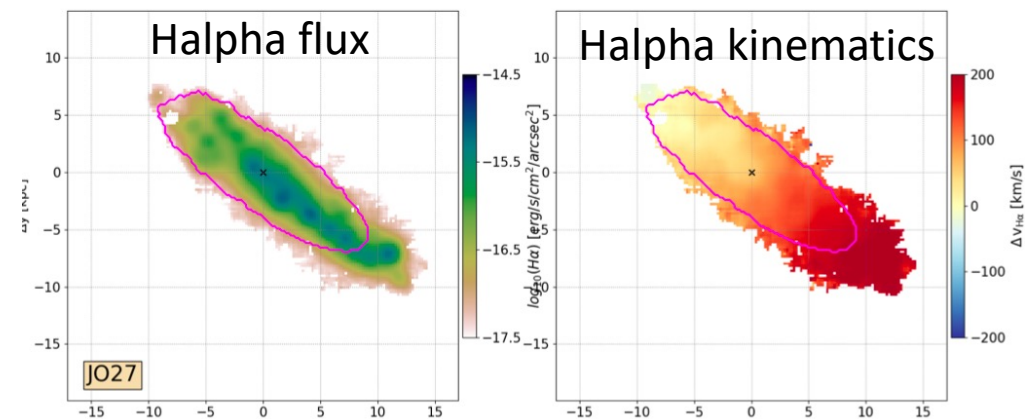
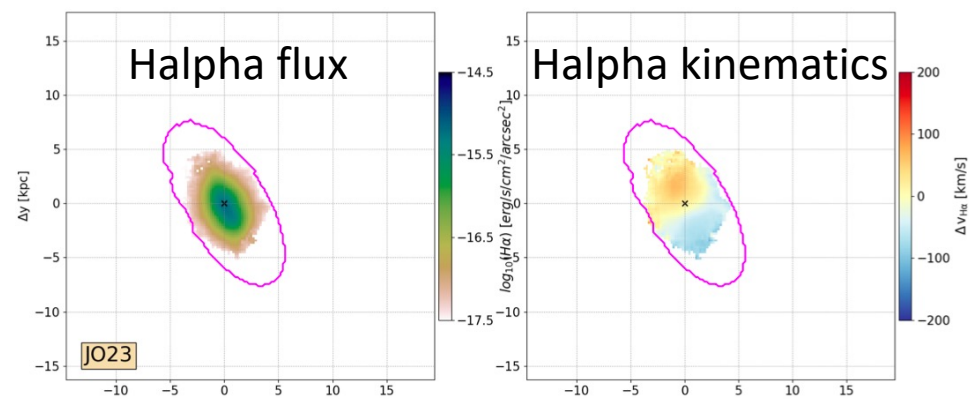
GAS (H α)



STARS



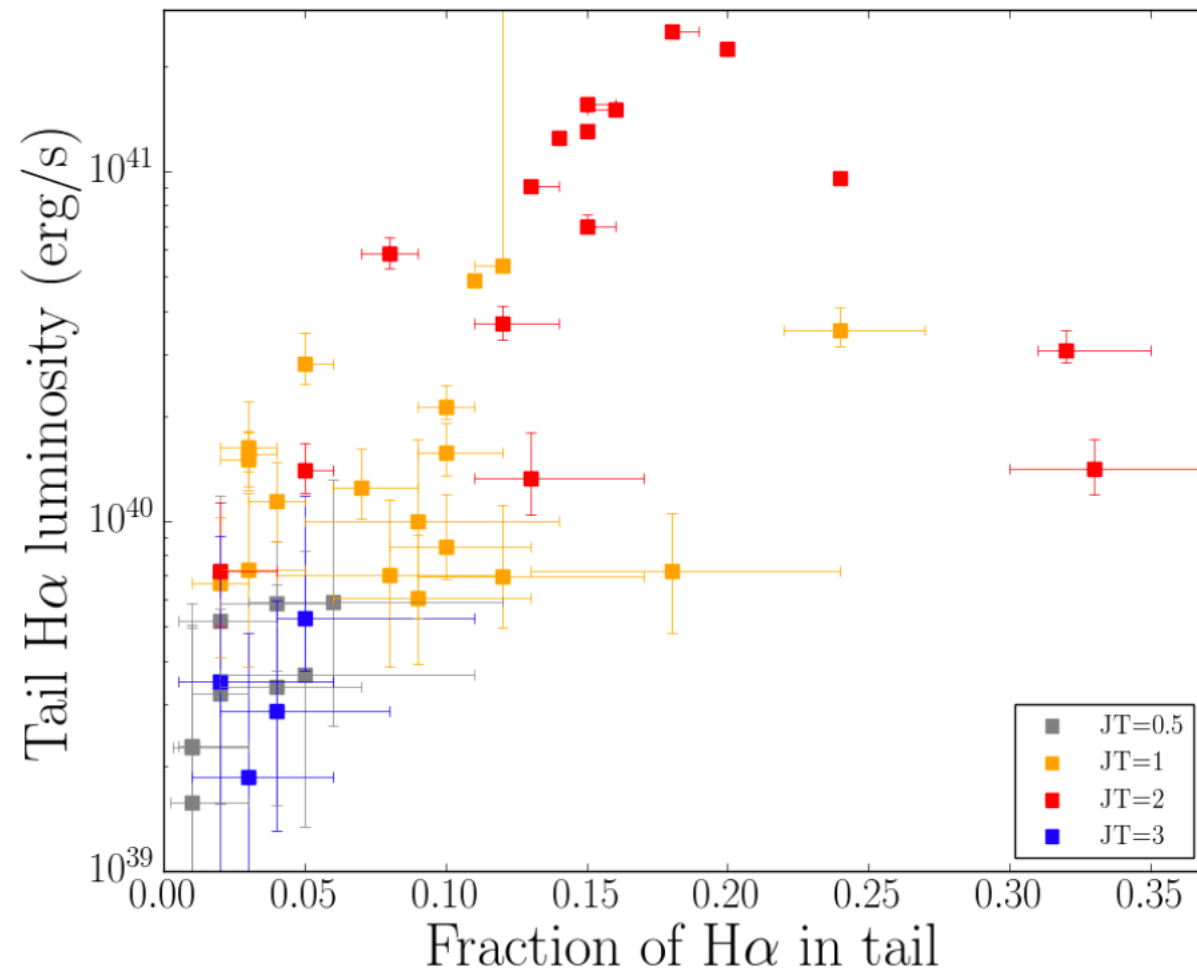
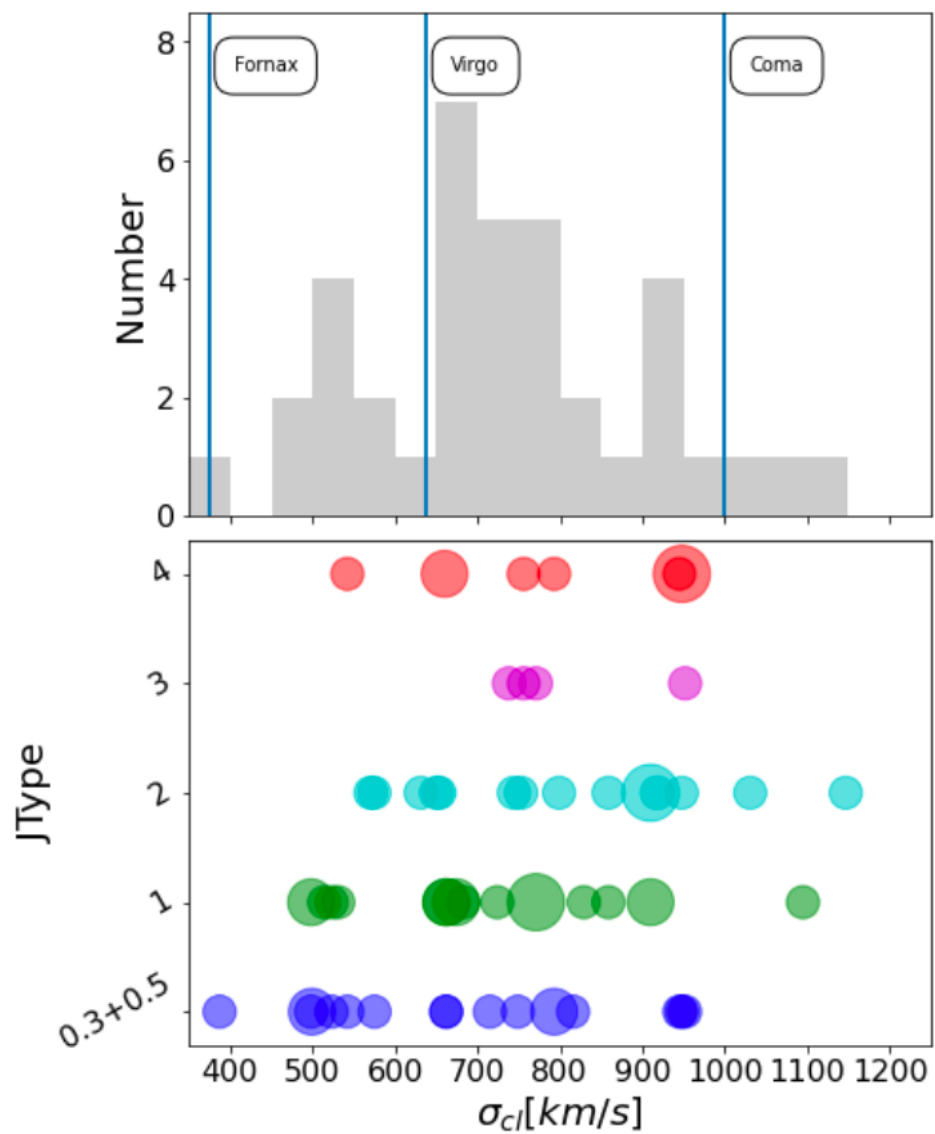
Poggianti+ 2017



Poggianti+ subm.

Star formation history: 4 age bins

CLUSTER GALAXIES: RAM PRESSURE STRIPPING



Poggianti+ subm.

IN SITU STAR FORMATION IN THE STRIPPED TAILS

Long extraplanar H α tails (20-100 kpc long):
the dominant ionization mechanism of gas in the tails in many cases is dominated by photonization by young massive stars (MUSE BPT diagrams).

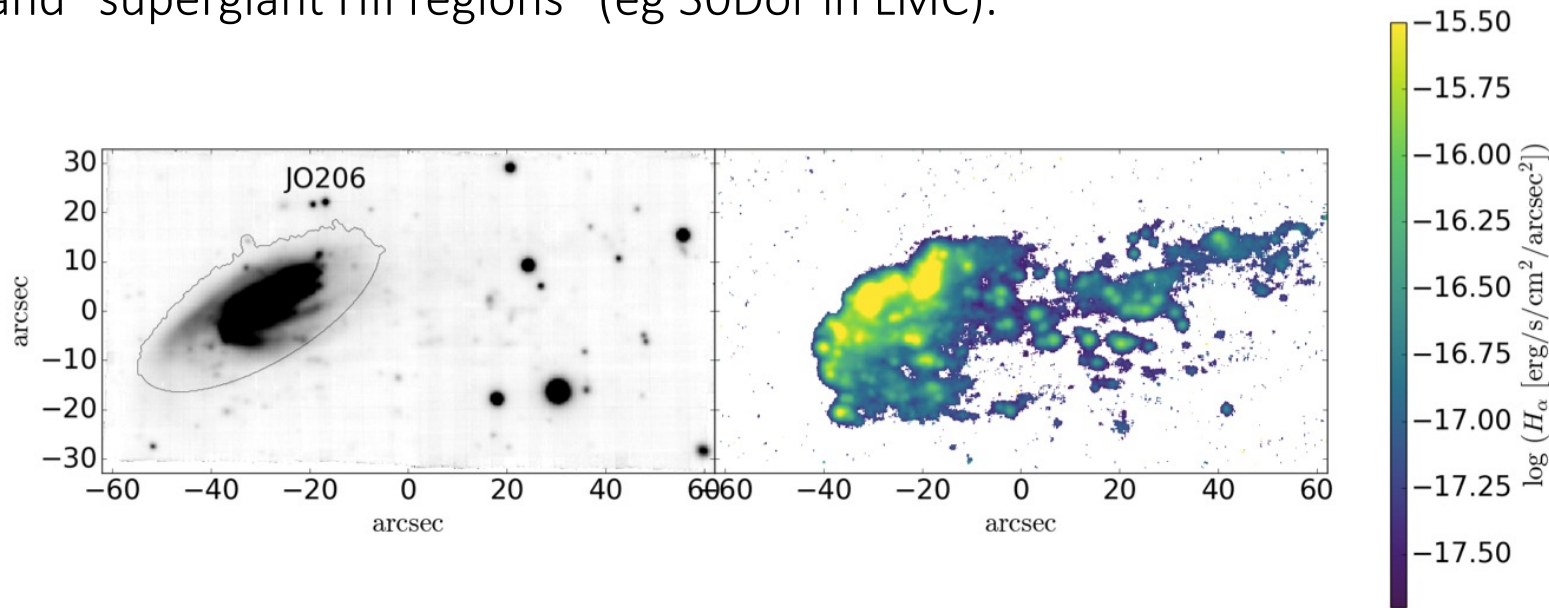
The SF takes place in H α bright, dynamically cold (median $\sigma=27$ km/s):
star-forming clumps forming in-situ in the tails.

Clump H α luminosities typical of “giant HII regions” (eg Carina Nebula) and “supergiant HII regions” (eg 30Dor in LMC).

Tail clumps give us the opportunity to study the star formation process without an underlying galaxy disk

The SFR in the tails is typically a few percent (2-5%), and up to 20%, of the total SFR.

16 galaxies,
Poggianti+ 2019



see also Smith+ 2010, Hester+ 2010, Yoshida+ 2008 Abramson+ 2011, Merluzzi+ 2013, 2016, Fumagalli+ 2014, Fossati+ 2016, 2019, Boselli+ 2018



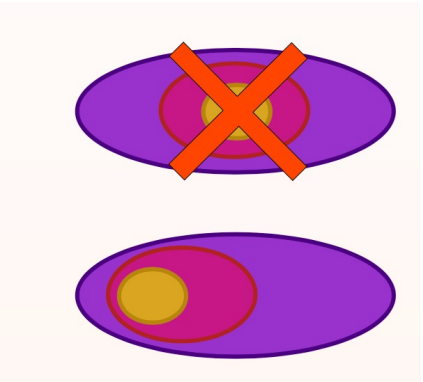
MUSE + HST

F275W, F336W, F606W, F814W
and Halpha narrow band



HST

Gullieuszik+ 2023

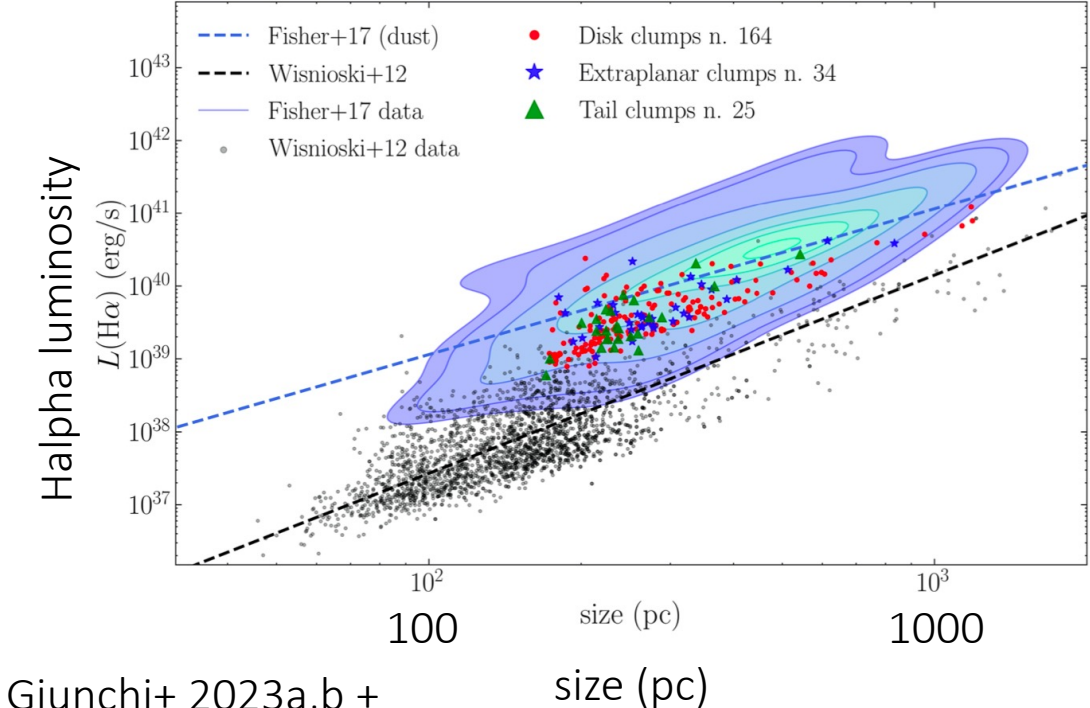
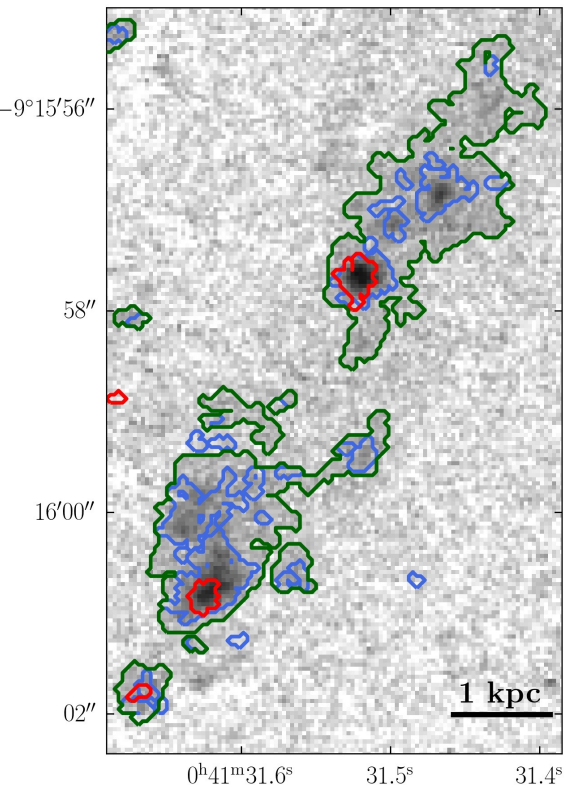


Red = H α
 Blue = UV
 Green = F606

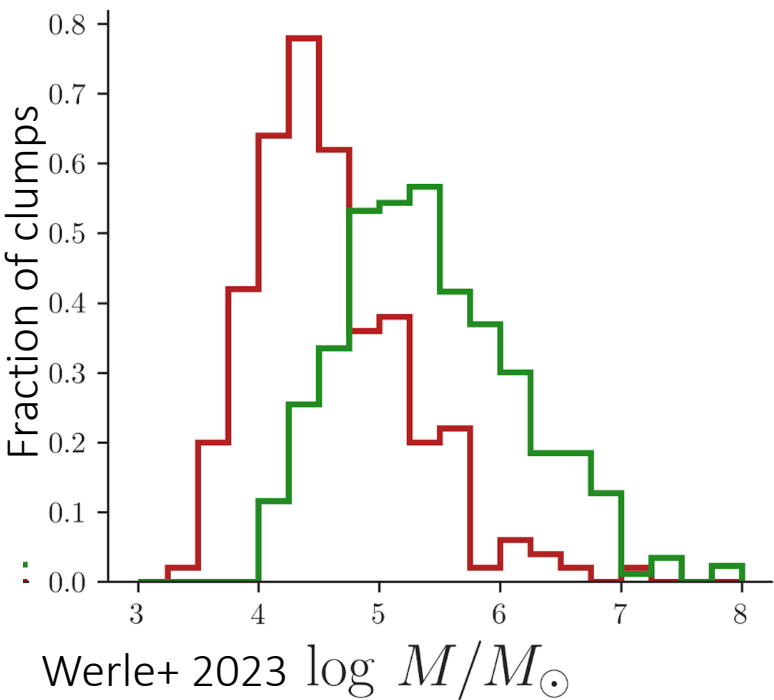
STAR-FORMING CLUMPS IN THE TAILS

In HST data **~2400 (H α) and ~3700 (UV) clumps** identified and studied in detail: sizes, luminosities, stellar masses, stellar histories, scaling relations, morphologies...

Massive stellar complexes, 10^4 -- 10^7 M $_{\text{sun}}$
 Their stellar surface densities consistent with cluster dwarfs and local dwarf spheroidals.
 Are we witnessing the formation of *dark-matter-free* quenched dwarf galaxies?



Giunchi+ 2023a,b +
 submitted



Werle+ 2023 $\log M/M_{\odot}$

Can the AGN activity be triggered by ram pressure?

AGN fraction higher among ram-pressure stripped galaxies than in non-ram-pressure-stripped similar galaxies, after controlling for galaxy mass (Poggianti+ 2017, Peluso+ 2022)

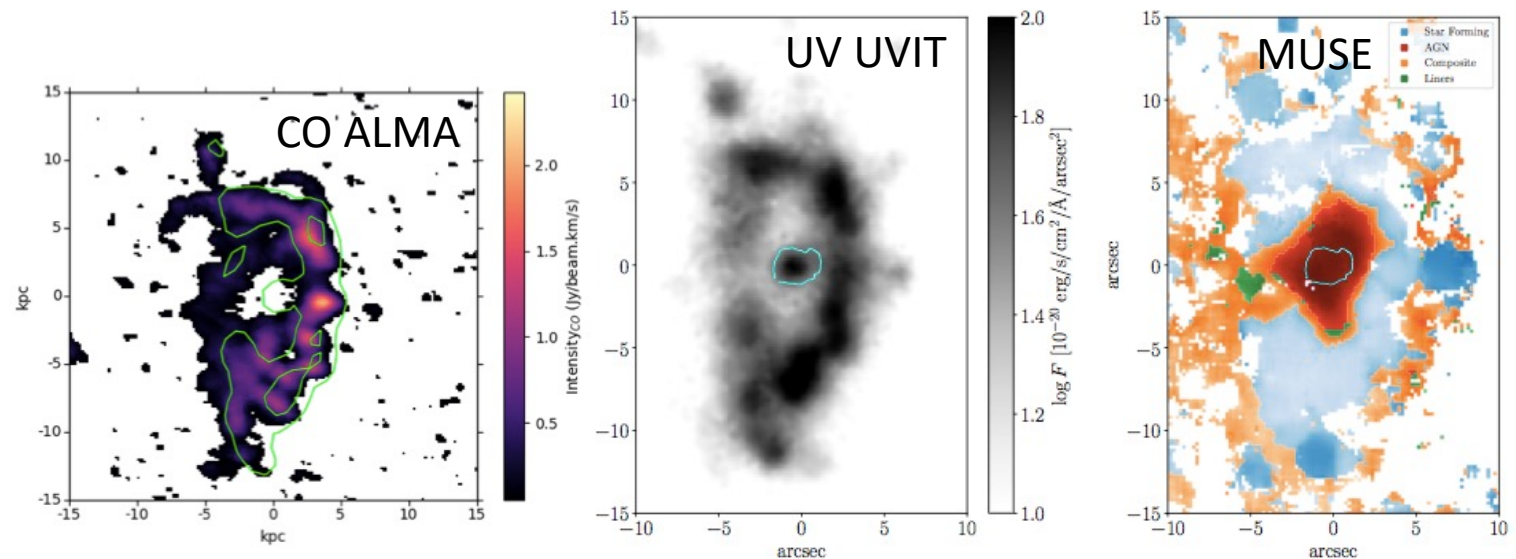
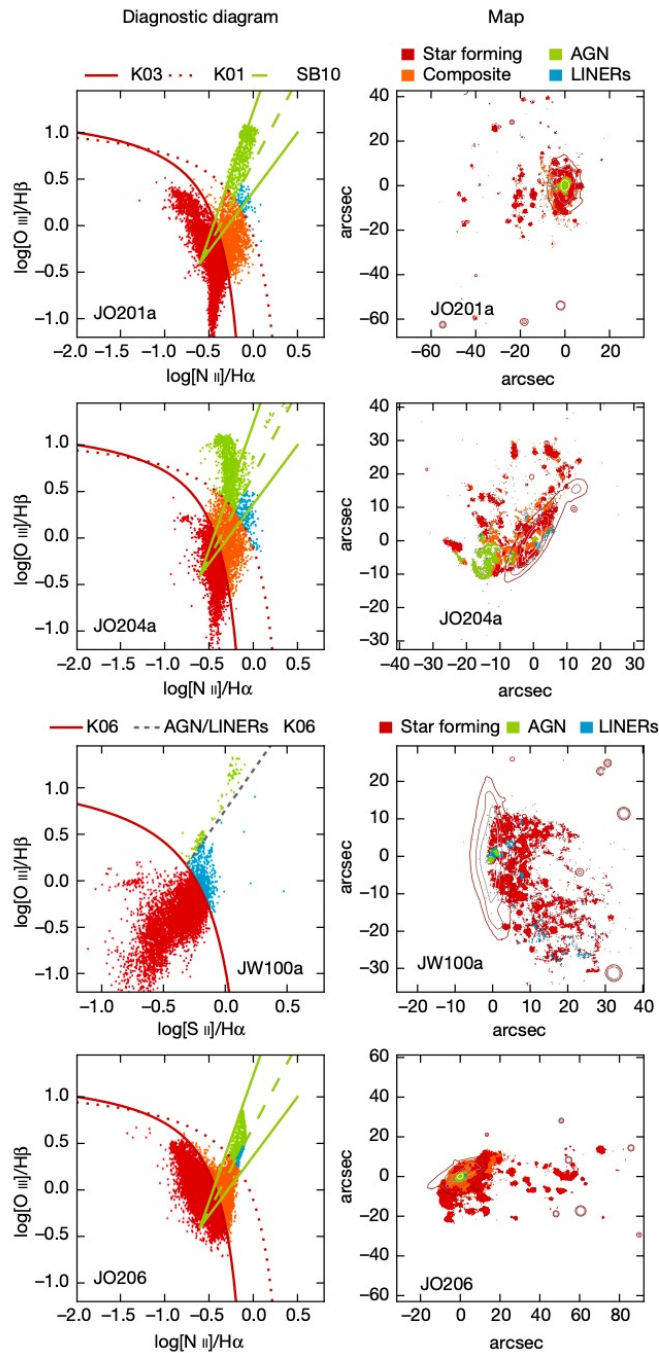
The AGN incidence is higher in galaxies with the longest tails

AGN outflows (Radovich+ 2019)

SF quenching by AGN feedback (George+ 2019)

Metallicity of ionized gas in AGN-powered, composite and SF regions (Peluso+ 2023)

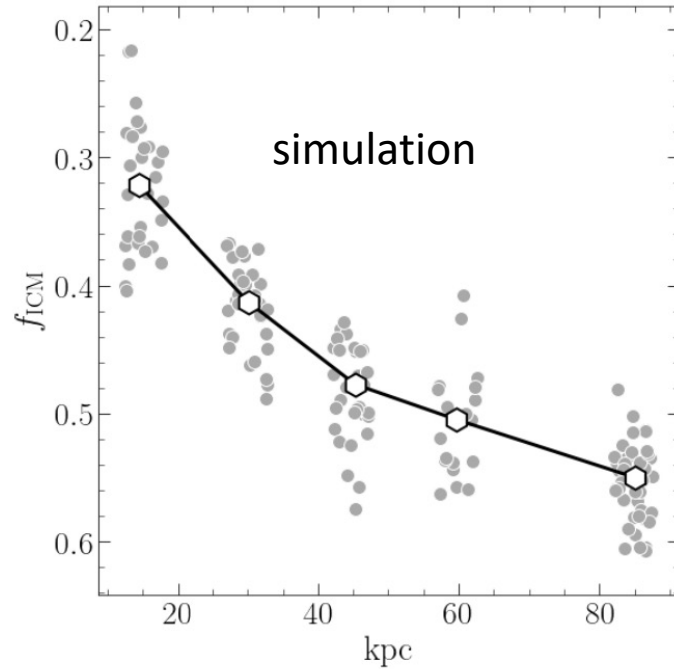
Hydrodynamical simulations clarify why (Akerman+ 2023 and refs. therein): RPS increases the inflow of gas to the galaxy center: mixing of rotating ISM and non-rotating ICM + increased torque of inner gas from local pressure gradients.



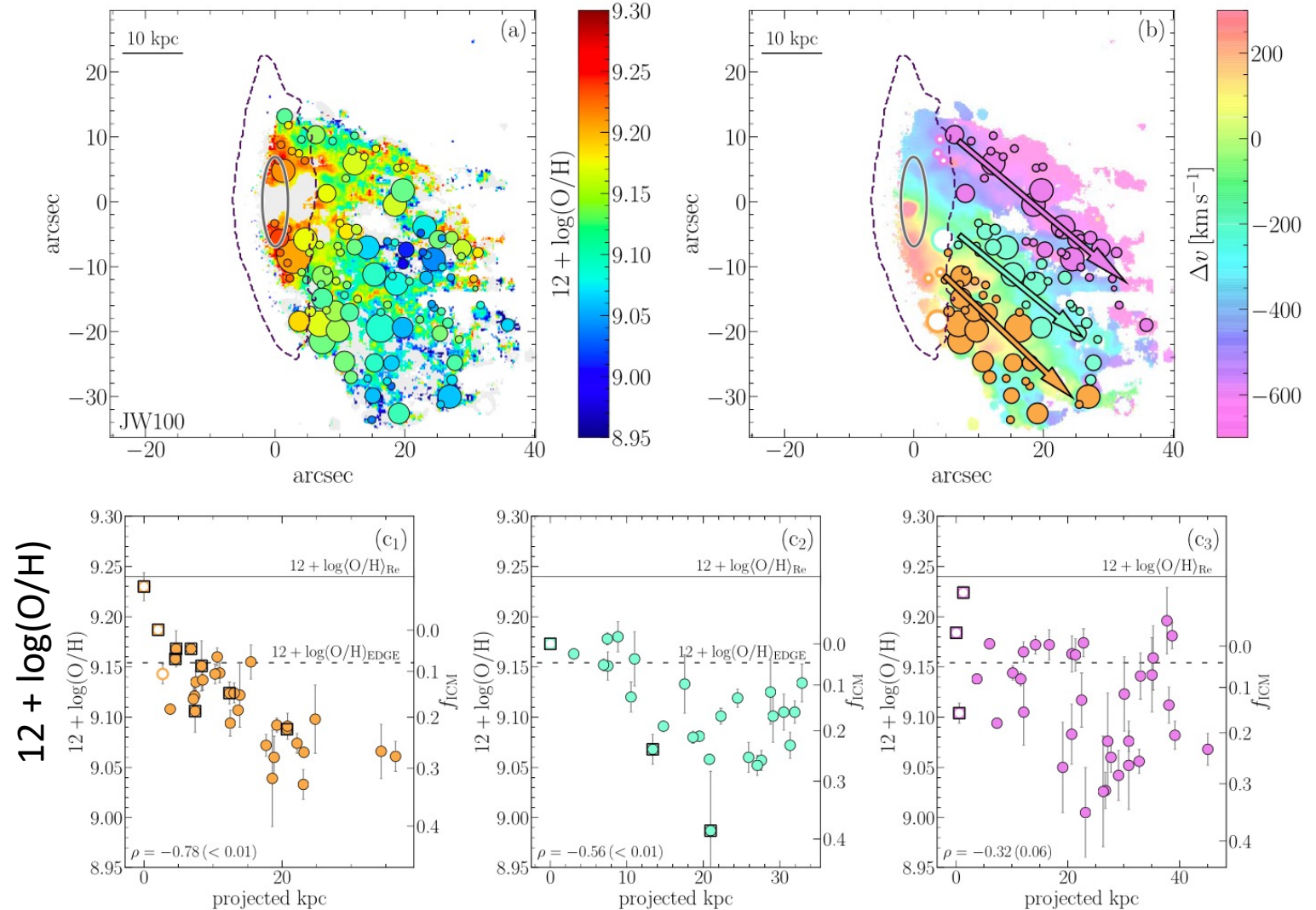
GAS METALLICITY GRADIENTS IN THE TAILS



The decline of metallicities along the tails is evidence for ISM-ICM mixing – as shown also in simulations



Franchetto+ 2021



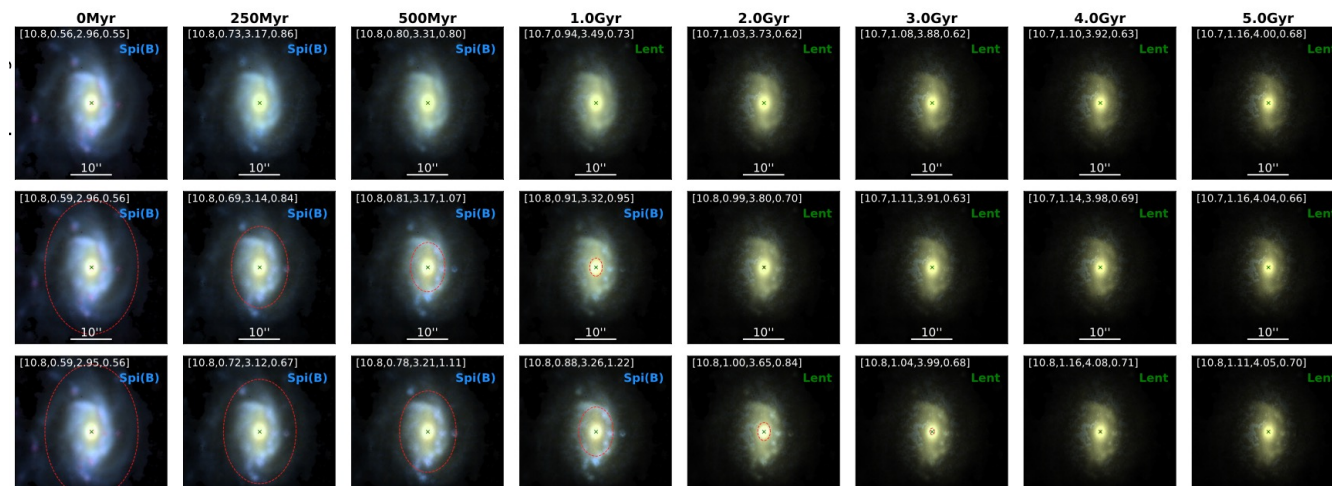
Projected kpc away from the disk

SPECTRO-MORPHOLOGICAL EVOLUTION: MUSE MOCK DATACUBES FROM SPIRALS TO S0 GALAXIES

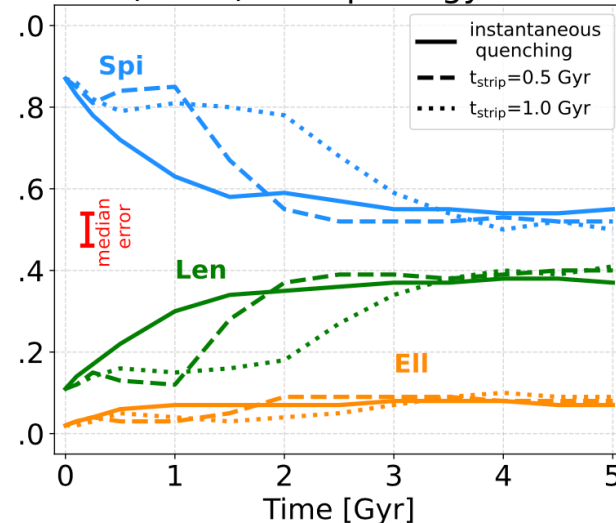
Using MUSE spatially resolved SFH, we produce mock MUSE datacubes considering a “realistic” spatially resolved quenching scenario and then reclassify the morphologies of the mock cubes.

An initial population that is 90% spirals turns into 40% lenticulars, 50-55% red spirals and ~5% of blue spirals in 1.5-3.5Gyr depending on quenching efficiency.

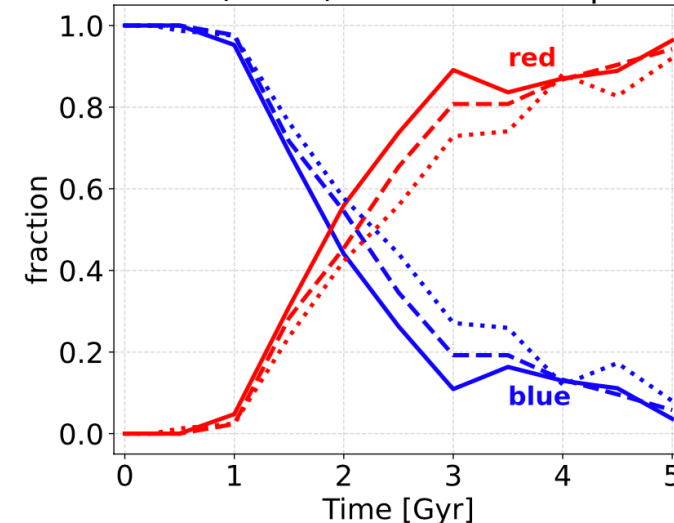
SF quenching caused by RPS can affect the morphology of the infalling galaxy population on timescales of a few Gyr.

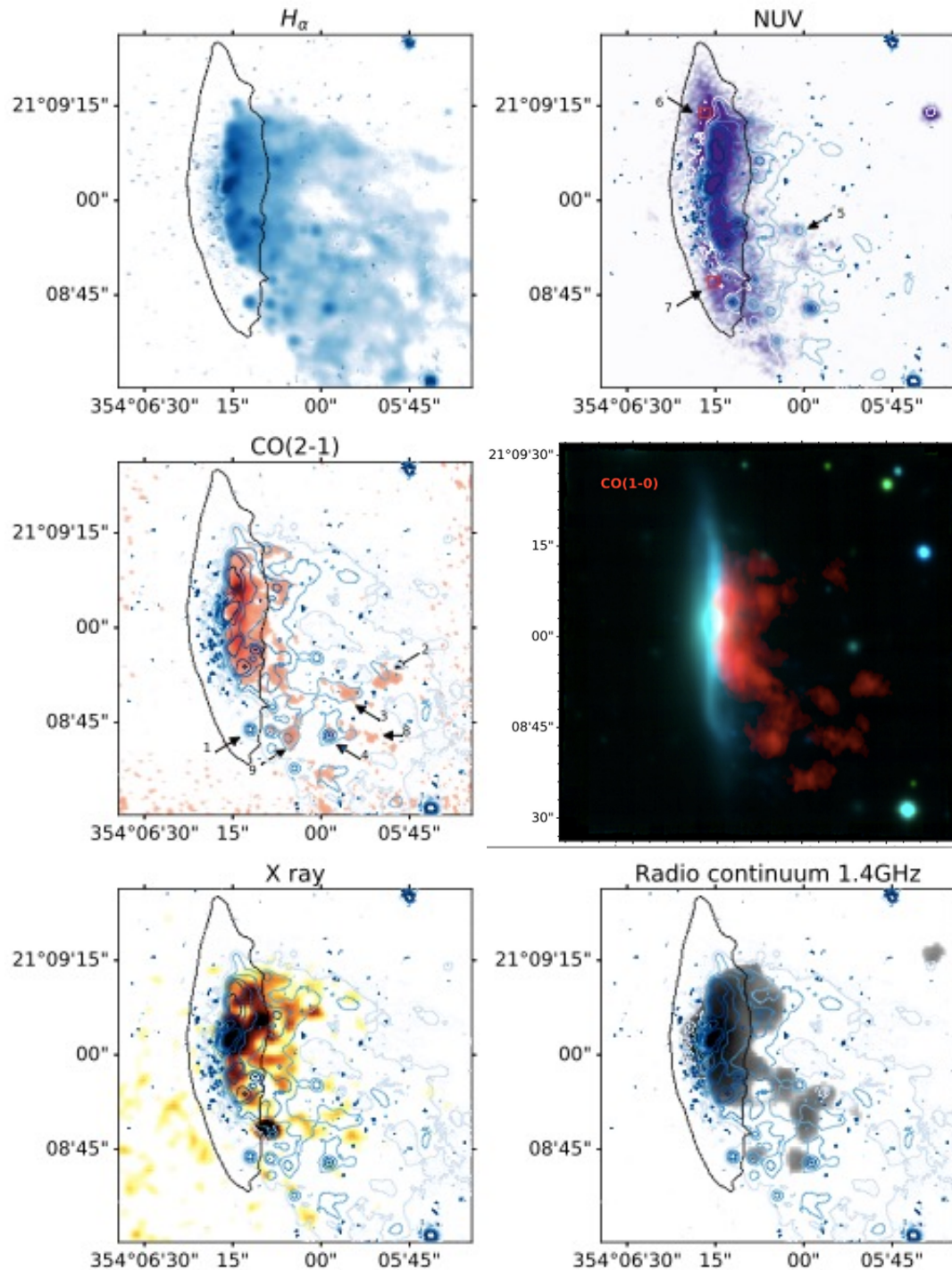


GASP (clean) - Morphology evolution



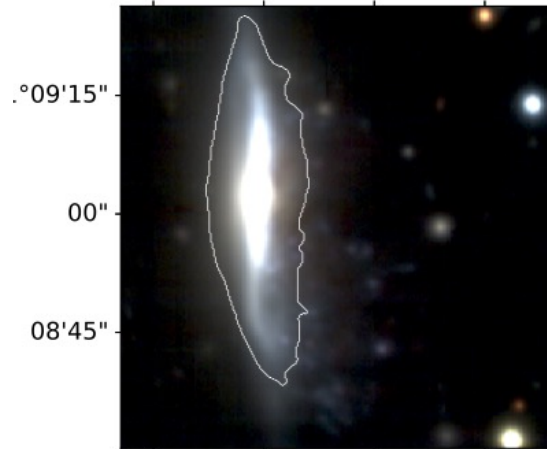
GASP (clean) - red vs blue spirals



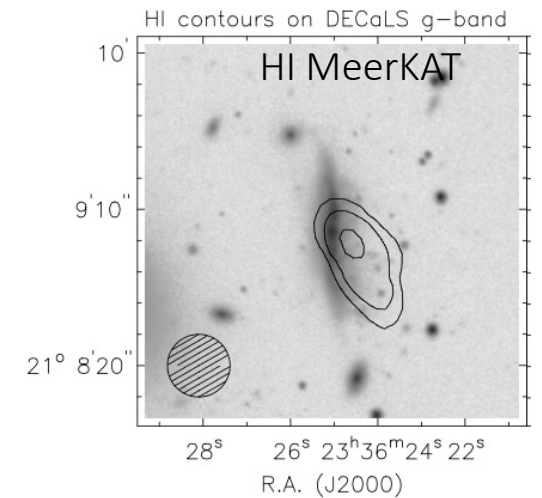
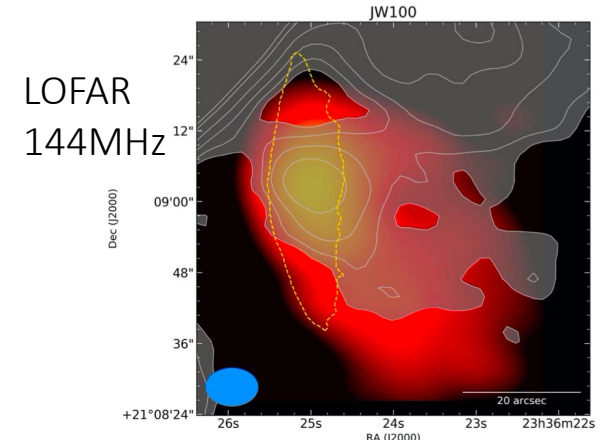
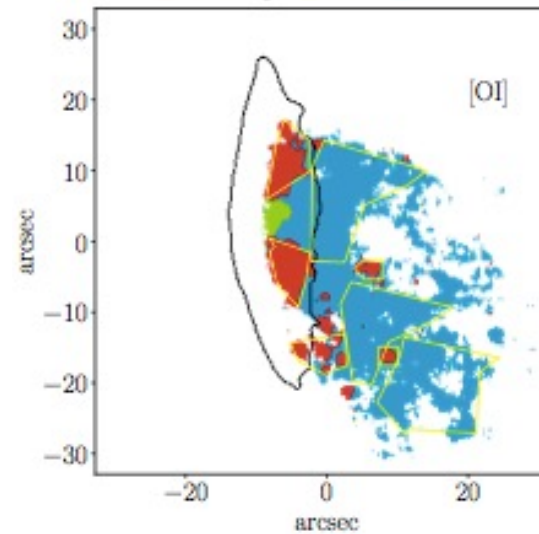


Multi-wavelength tails provide a plethora of information about star formation efficiency, baryonic cycle, HI_to_H2 conversion, ISM-ICM mixing, cosmic rays, radio cont. as SF indicator etc etc

About to come out: selecting at different wavelengths



Star forming AGN Liners



Poggianti+ 2019b, Moretti+ 2020, Ignesti+ 2022a,b, Deb+ 2022

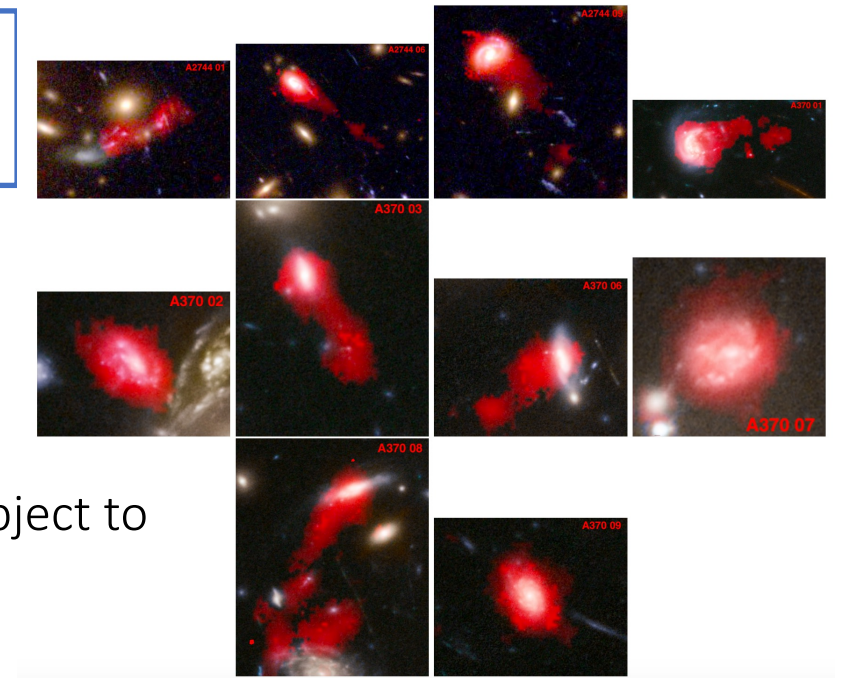
PUSHING STATISTICAL RAM PRESSURE STUDIES AT $z=0.3-0.5$: GASP - MUSE Lensing Cluster GTO COLLABORATION

Cluster sample and data from Richard+ 2021

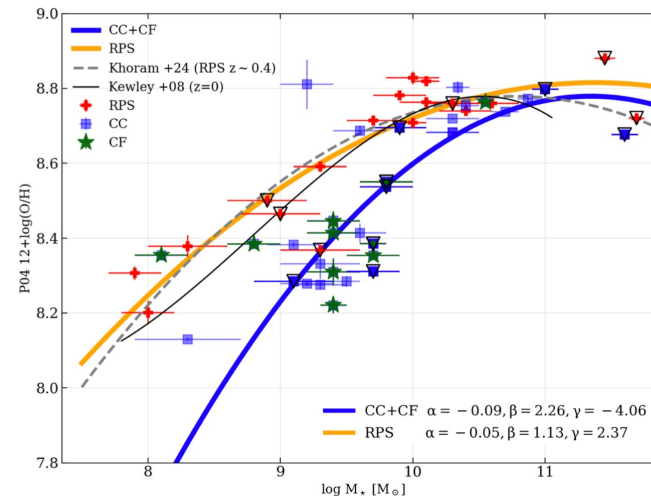
12 galaxy clusters at $z=0.3-0.5$, 80 galaxies studied in detail

In cluster cores at $z\sim 0.3-0.5$, essentially all star-forming galaxies are subject to strong RPS (Moretti+ 2022)

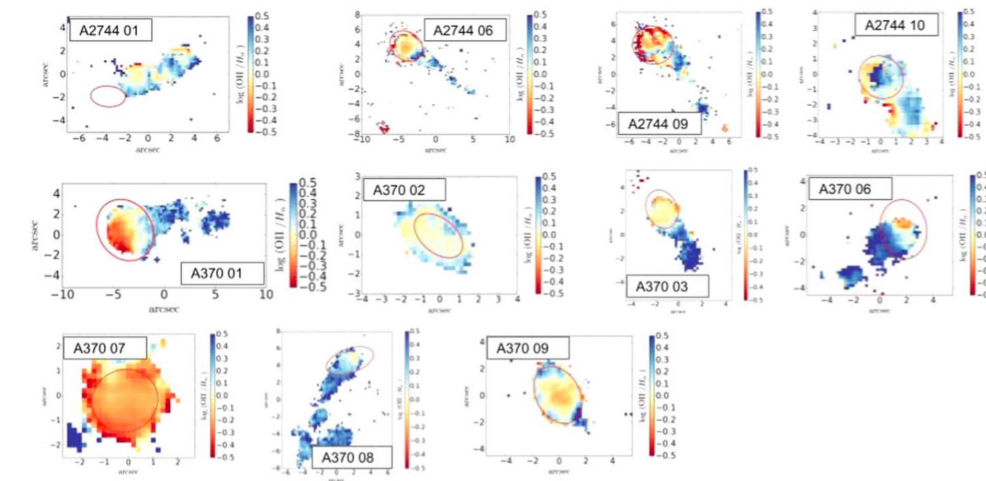
Results include: RPS tail characteristics, unusual optical line ratios, post-starburst, mass-metallicity relation vs environment, SFR-mass relation, methods to identify RPS galaxies morphologically



Moretti+ 2022



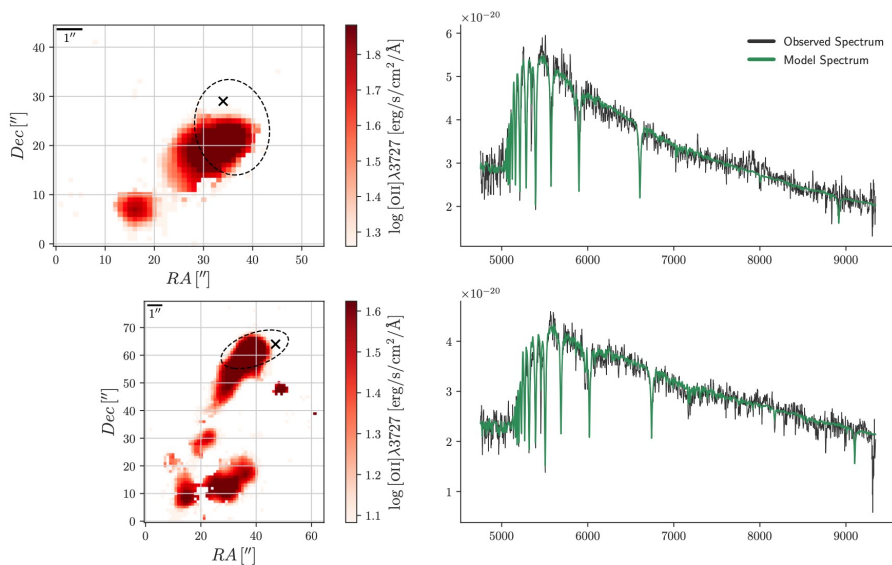
Khoram+ subm.



Unequivocal ram pressure stripping - - poststarburst connection

Figure 10 consists of two vertically stacked box plots. The top plot shows the distribution of t_Q [Gyr] for 20 different models. The y-axis ranges from 0.0 to 0.9. The bottom plot shows the distribution of $\mu_{1.5}$ [%] for the same 20 models. The y-axis ranges from 0 to 60. The x-axis for both plots lists the following models: A2744-01, A2744-02, A2744-05, A2744-07, A2744-08, A370-04, A370-05, MACS1206-06, MACS1206-09, MACS1206-11, MACS0257-01, MACS0257-03, MACS0257-04, MACS0257-05, RXJ1347-02, SMACS2011-02, SMACS2131-05, SMACS2131-06, A51063NE-01, A51063NE-02, and A51063SW-01. The box plots are green with black whiskers and medians.

See also Vulcani et al. 2020 $z=0.05$



Overall, mild global star formation enhancement in the disk (e.g. Vulcani+ 2018, 2024, Roberts & Parker + 2020) but locally starbursts (Werle+ 2022)

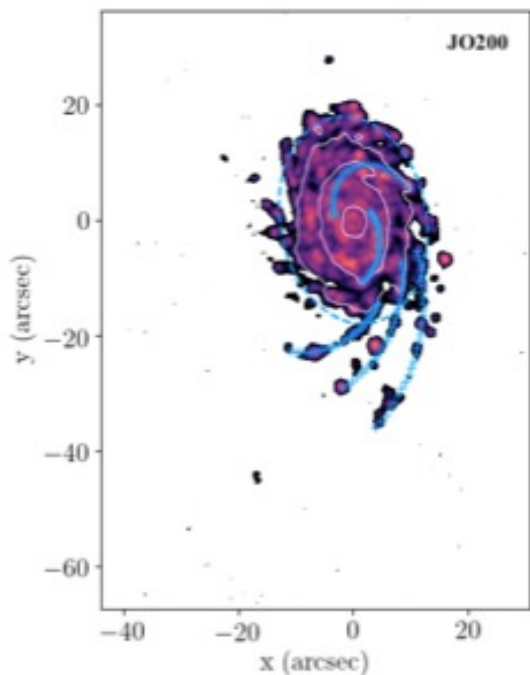
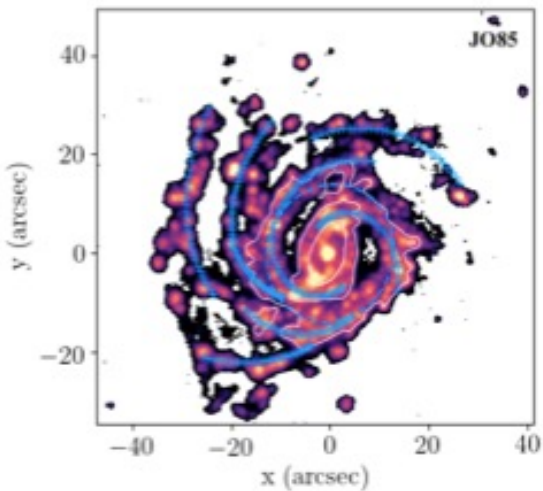
UNWINDING OF SPIRALS ARMS

UNWINDING OF SPIRAL ARMS can occur due to ram pressure stripping...as also shown by simulations (see also Roediger+ 2014)

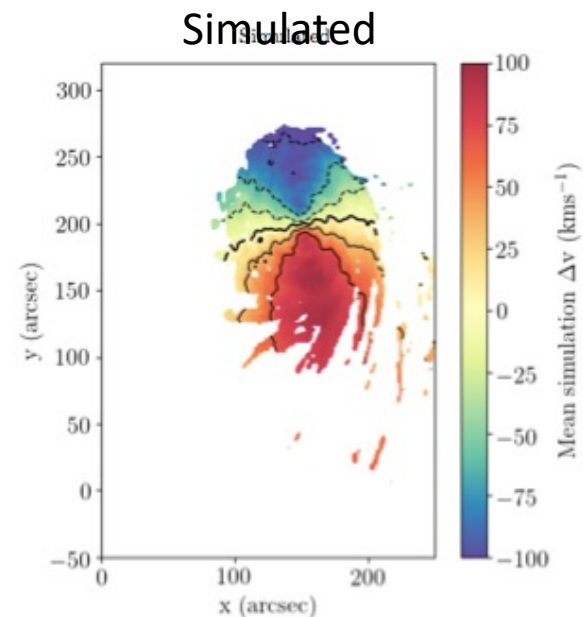
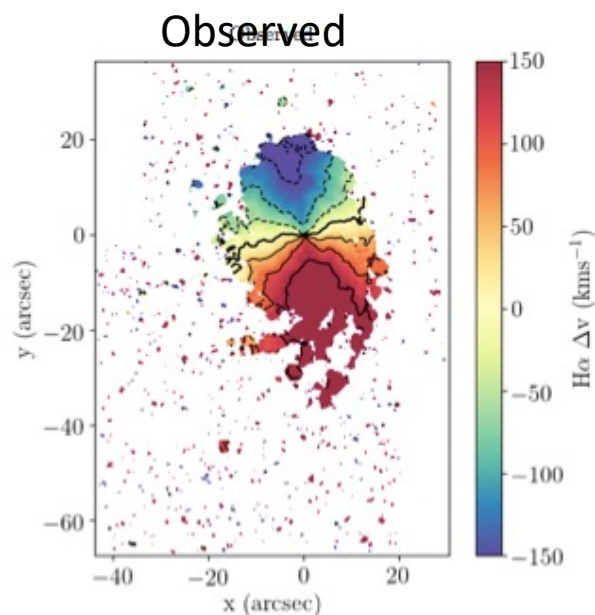
[Edge-on stripping: differential RP caused by disc rotation, stripped material slows and piles-up -
Face-on stripping: gas removed from outer edges falls to higher orbits]

Thus, galaxy lopsideness can arise from ram pressure stripping.

Ongoing RPS can also affect (indirectly) the galaxy *stellar* structure



Bellhouse+ 2021



New MUSE data of 13 galaxies with unwinding arms

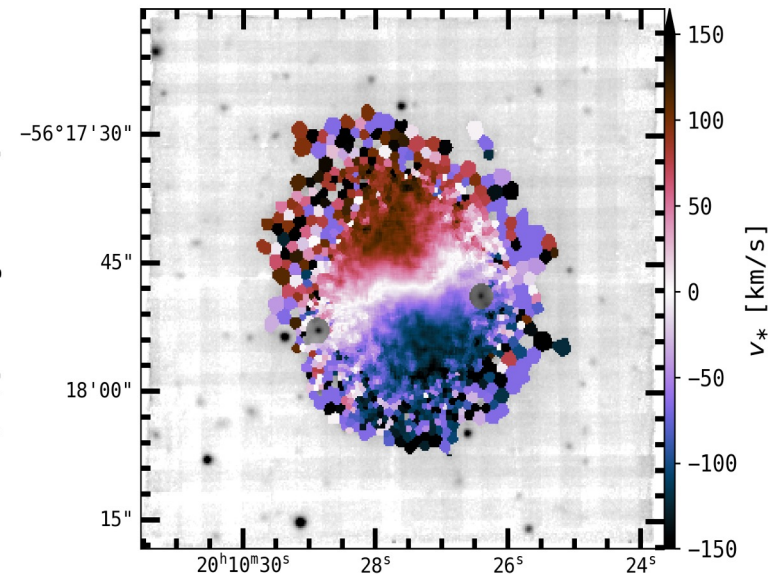
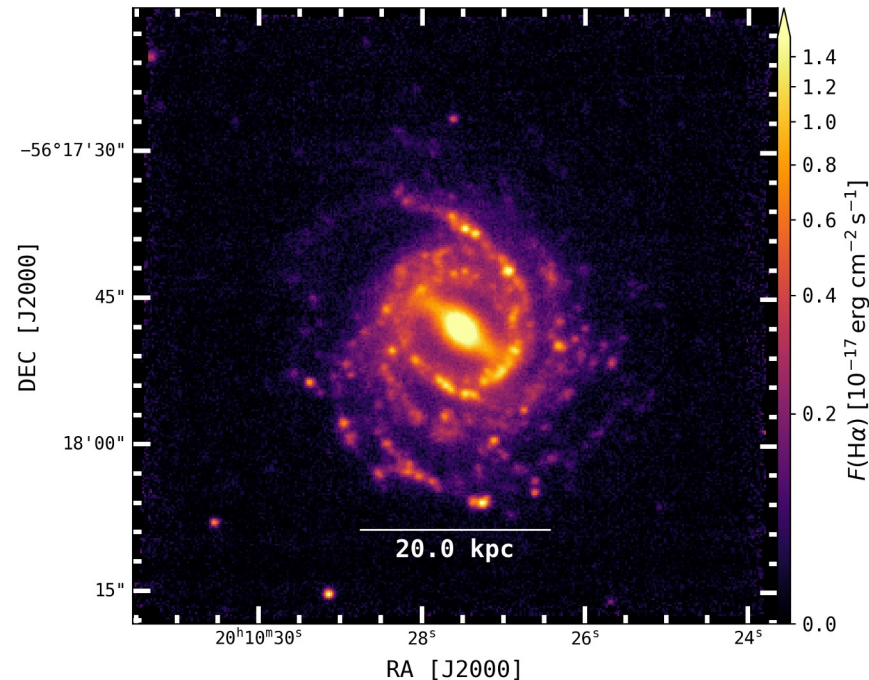
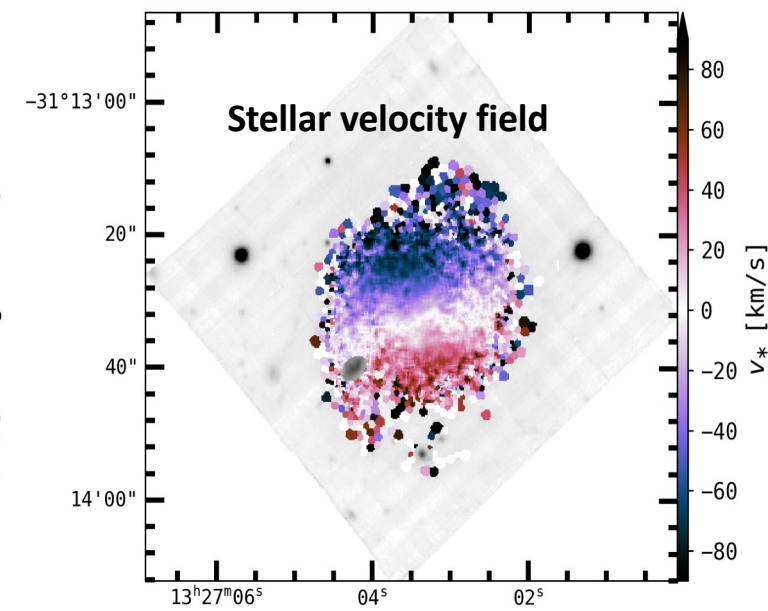
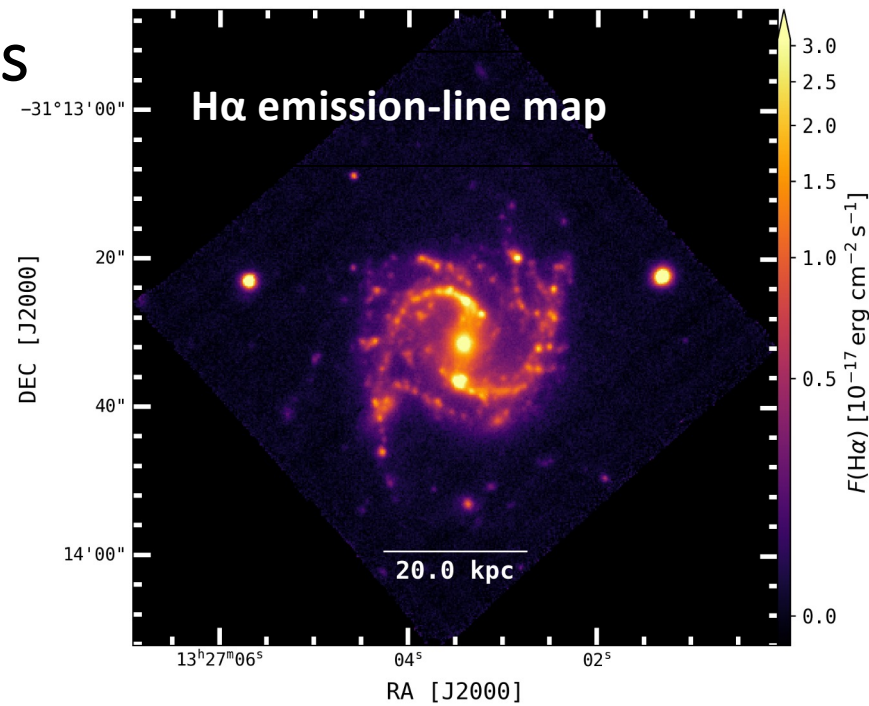


PI: **Benedetta
Vulcani**



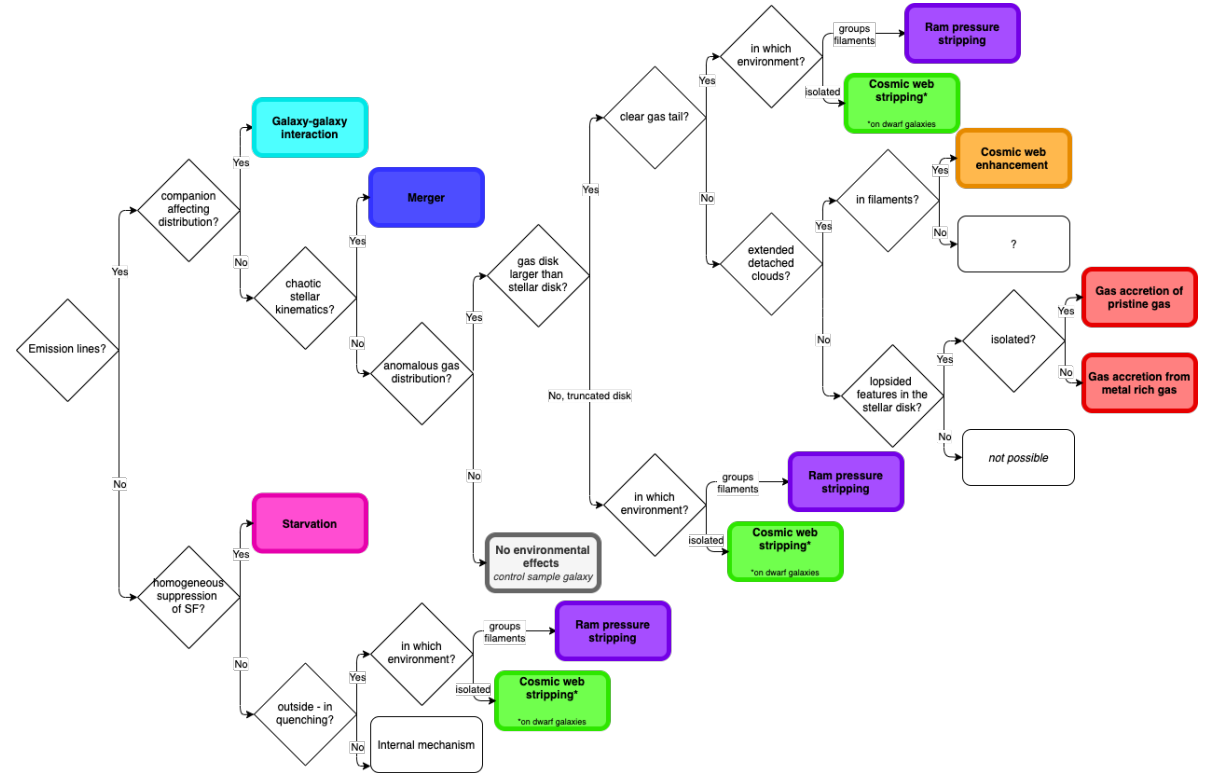
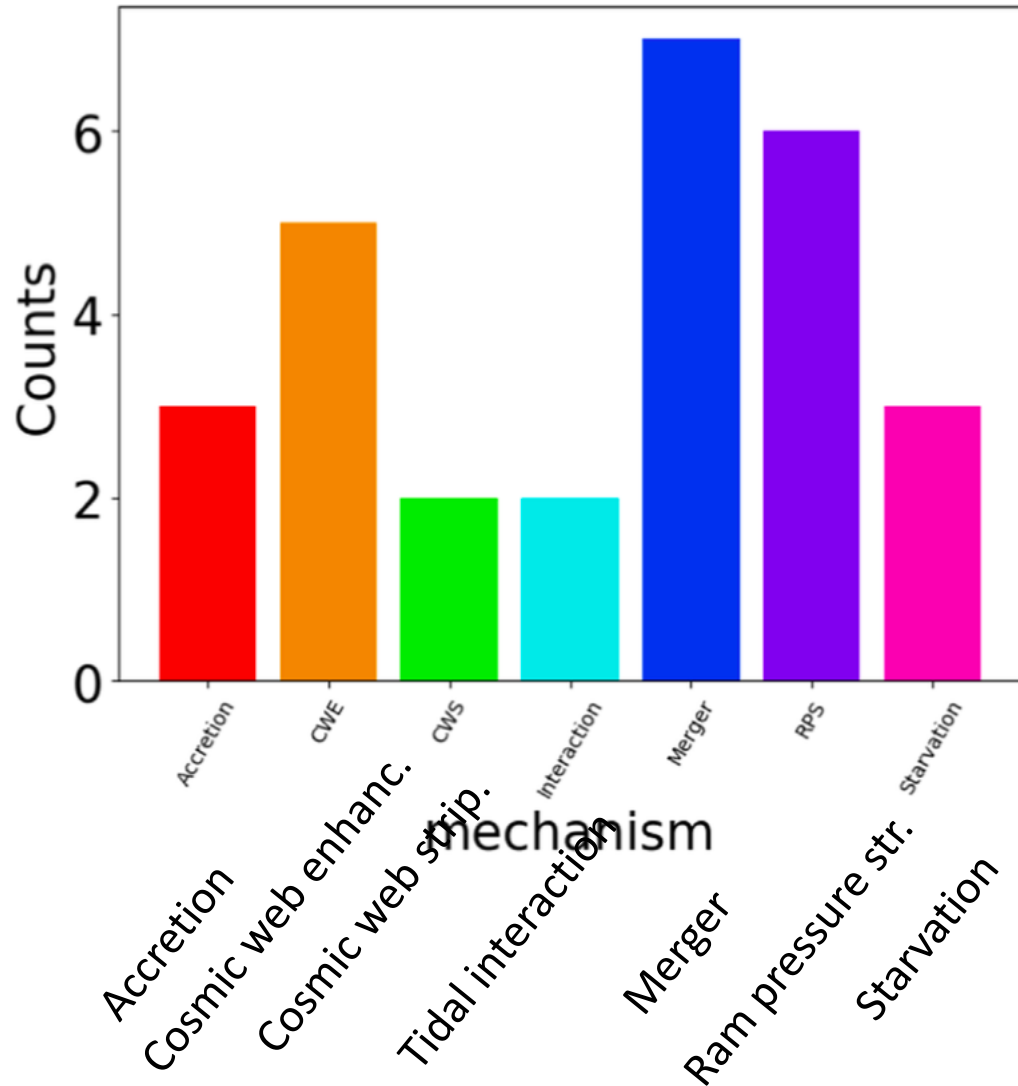
**Augusto
Lassen**

- ❑ RPS alone can unwind spiral arms in cluster galaxies (Bellhouse+21).
- ❑ Hydrodynamical effects (RPS) and gravitational interactions impact the stellar and ionized gas components in distinct ways.
- ❑ With a new sample of galaxies observed with MUSE we will determine if younger stars were formed in unwound arms after stripping or were rather displaced from the disk by tidal forces.



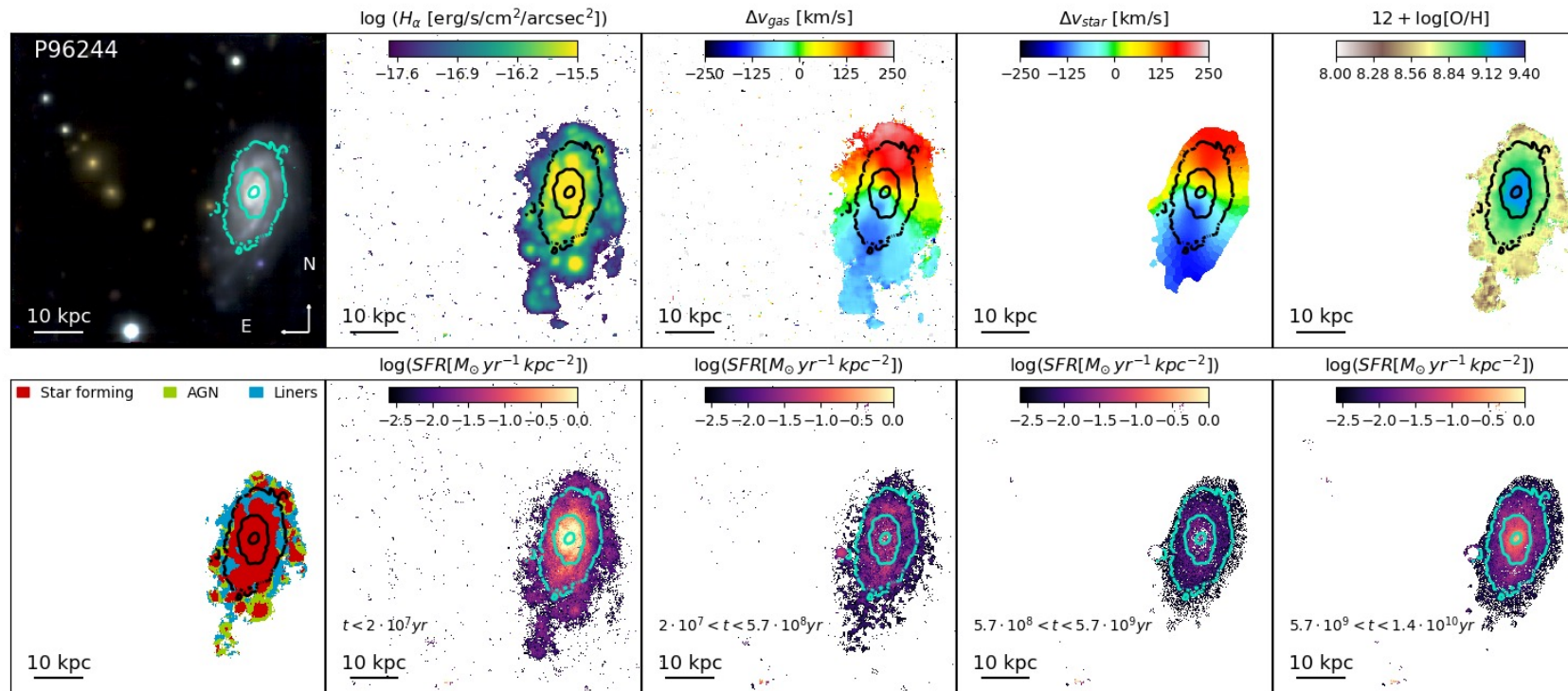
OUTSIDE OF CLUSTERS: CAN WE DISENTANGLE THE DIFFERENT PHYSICAL PROCESSES WITH MUSe DATA?

(the answer is mostly yes, but in some cases data at other λ s are vital...)



The combination of most of IFS diagnostics is crucial (gas and stellar kin., gas metallicity, SFH, etc.), as well as reaching the galaxy outer regions where processes show up more clearly

Ram pressure stripping yes in groups, but no extreme cases



Evidence for *H I* stripping in groups longstanding (see Cortese+ 2021)

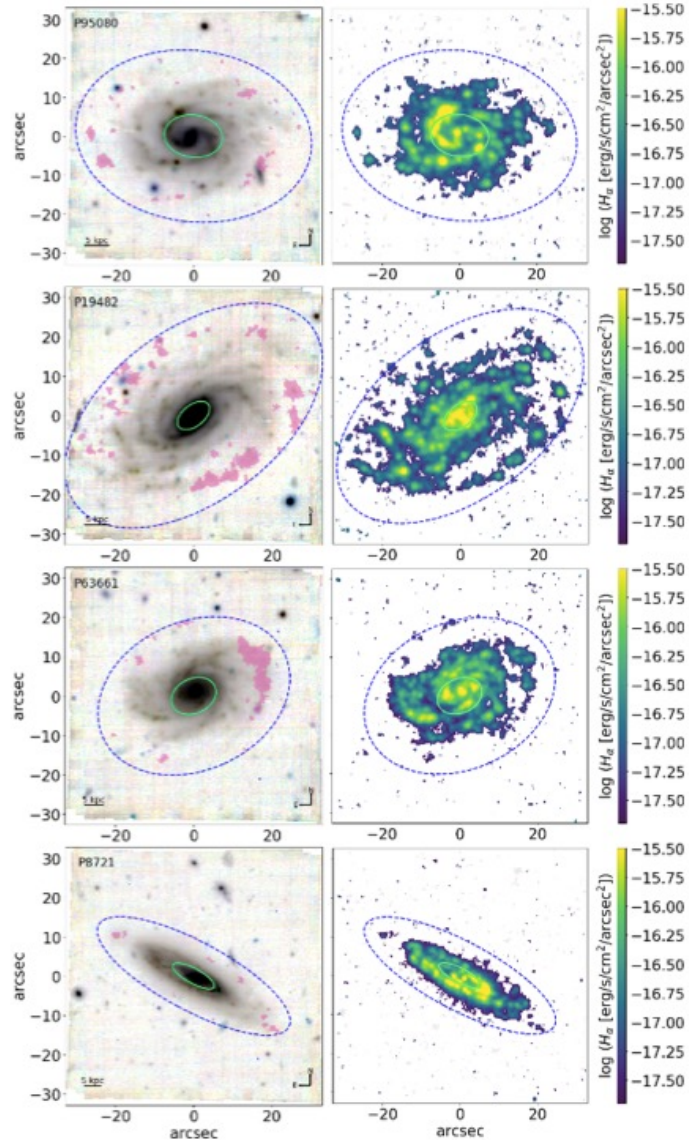
Still very limited IFS data

Relevance of RPS in groups?
Jury still out there....

In GASP we have examples of groups where multiple processes are at work in different galaxies of the same group (RPS, strangulation, gas accretion, cosmic web enhancement)

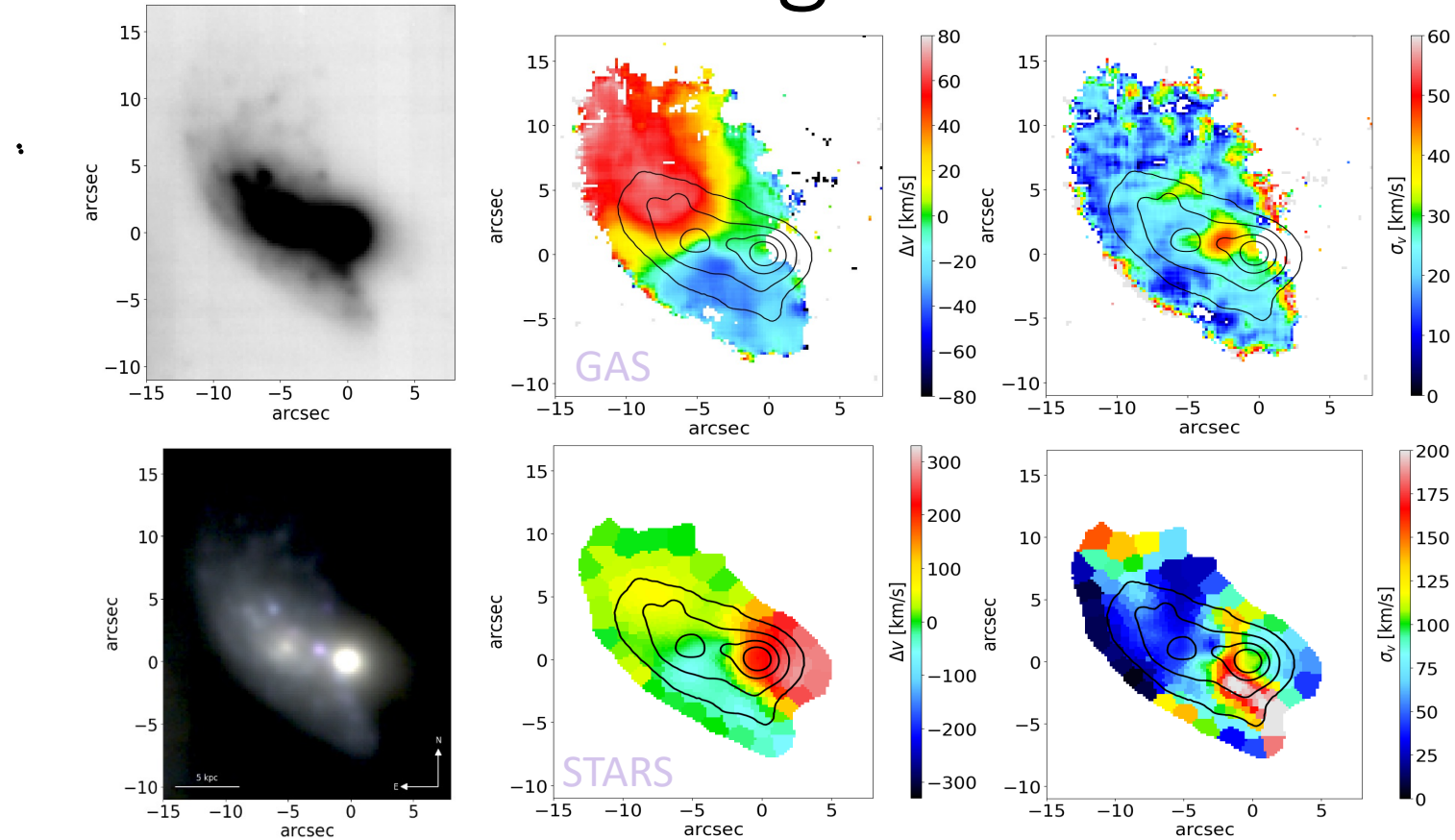
Vulcani+2018, Vulcani+2021

Cosmic web enhancement



“Cosmic web enhancement”: Galaxies passing through or flowing within filaments having an increase of SF in the densest regions of the circumgalactic gas - filaments assist gas cooling

Mergers



Vulcani+19, Vulcani+2021

WHAT'S NEXT ?

Coming up from GASP:

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

- Selecting at different wavelengths (HI, Halpha, radio continuum....) – it allows to pin down the stripping stages and their observability
- Several papers currently being refereed: clump mass function; AGN metallicity gradients; overall success and sample presentation; UVIT results for many more galaxies and clusters; mass-metallicity relation in clusters at $z \sim 0.4$ etc
- More studies almost ready: evolution from spirals to S0s across redshifts; Galaxy Zoo project results; hydrodynamical simulations of SF in tails etc
- All results on new unwinding MUSE sample

NO MUSE, NO GASP!

ONLY MUSE COULD ALLOW A LEAP FORWARD IN UNDERSTANDING THE PHYSICAL PROCESSES ACTING ON GAS IN LOW-Z GALAXIES, MOSTLY IN CLUSTERS SO FAR

MUSE, and MUSE SUCCESSORS, WILL BE ESSENTIAL TO TAKE THIS TO THE NEXT LEVEL