COSMIC JELLYFISH

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OUTLINE

- The importance of gas removal processes in galaxies
- What are jellyfish galaxies and why is it fun to study them
- Integral-field spectroscopy unveils the rich physics involved in gas stripping
- What happens in the tentacles: star formation and multiphase gas
- AGN-stripping connection
- Final remarks and open questions

Gas Stripping Phenomena in galaxies

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MUSE ESO Large Programme + ALMA/APEX (CO), JVLA/MeerKAT (HI), UVIT@ASTROSAT (UV), HST

where, how, why is gas removed from galaxies?
what is the effect on the galaxy SFH?

114 galaxies at z=0.04-0.07, with masses 10^9-10^11.5 Msun, in clusters, groups, filaments and isolated

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

Progetto Premiale MITiC (PI B. Garilli)

ESKAPE HI

PI L. Hunt

European Research Council
Established by the European Commission

GALAXIES ARE FULLY OPENED BOXES

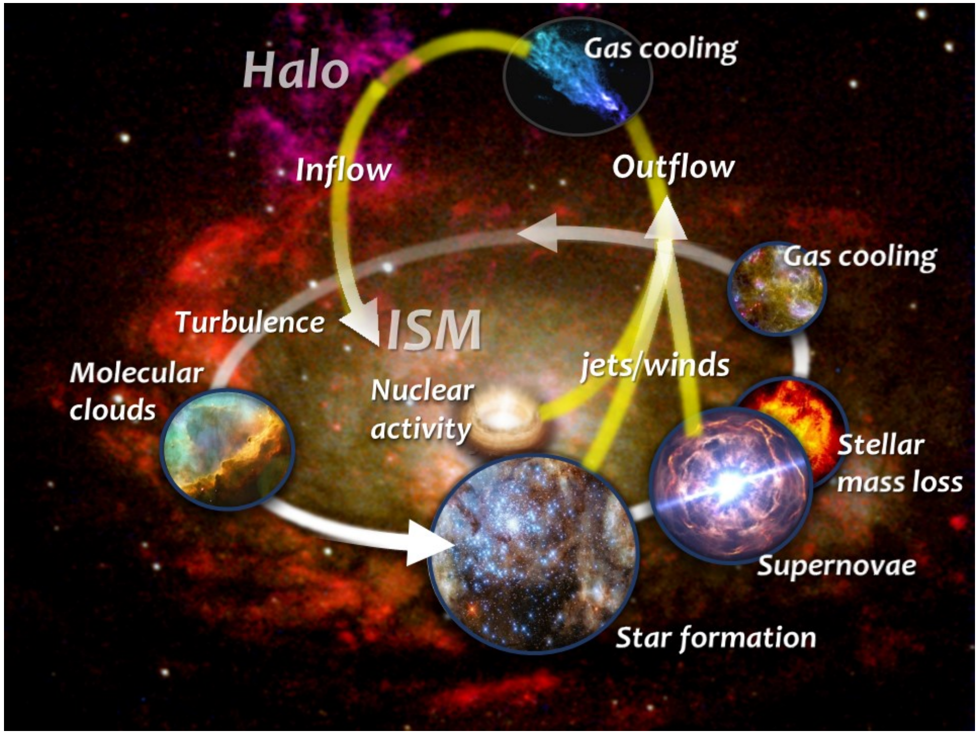
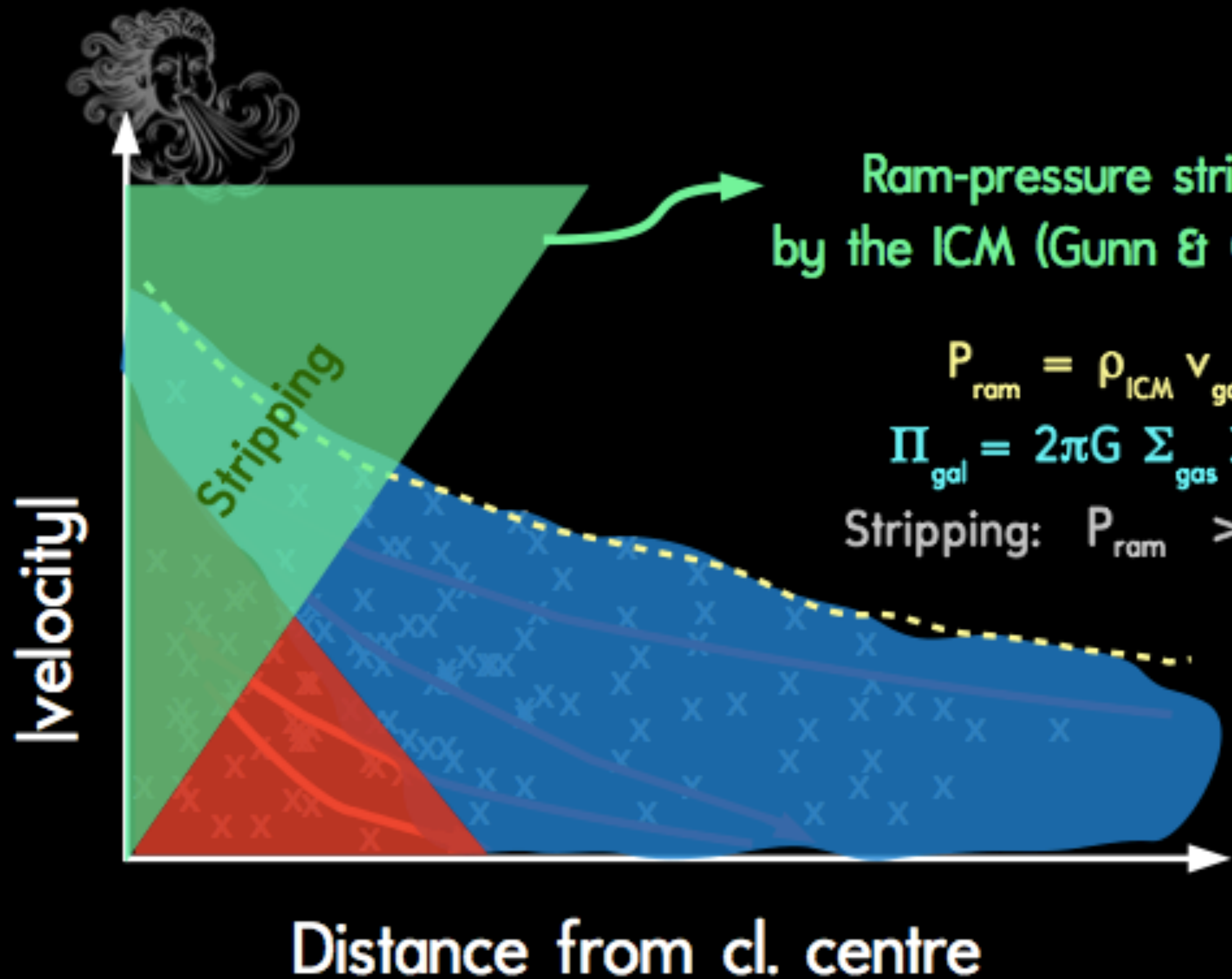


Image credits: SPICA mission

- The gas supply regulates the stellar histories of galaxies
- Several processes can affect the gas content:
  - -- shock-heating of circumgalactic gas, that stops cooling in a DM halo
  - -- galactic winds due to star formation or an active galactic nucleus
  - -- affecting gas and stars: tidal interactions, mergers
  - -- affecting only gas: ram pressure stripping and strangulation
- Gas removal processes can lead to the interruption of the star formation activity (quenching)



Ram-pressure stripping
by the ICM (Gunn & Gott 1972):

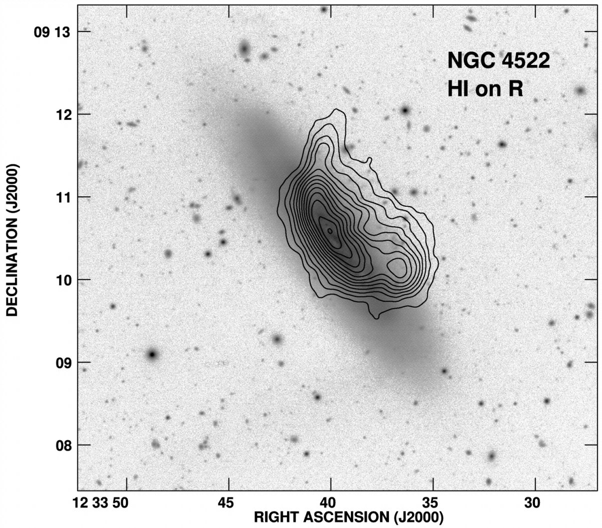
$$P_{ram} = \rho_{ICM} v_{gal}^2$$

$$\Pi_{gal} = 2\pi G \Sigma_{gas} \Sigma_{stars}$$

Stripping: $P_{ram} > \Pi_{gal}$

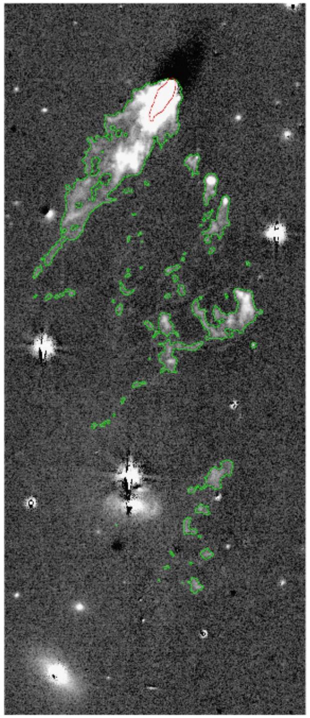
OBSERVATIONS OF RAM PRESSURE STRIPPING

Observational evidence for gas stripping in clusters from:

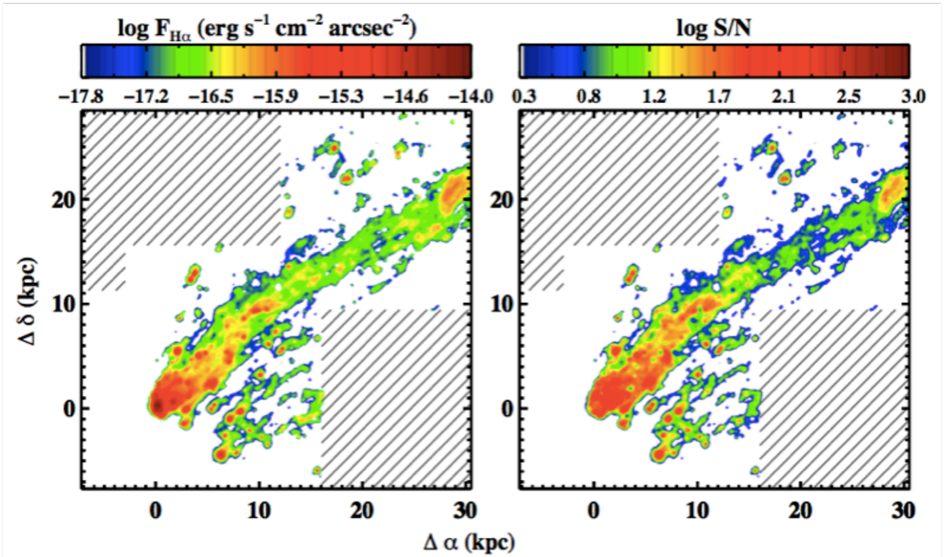


HI - Kenney, van Gorkom and Vollmer 2004, Virgo cluster

HI
H-alpha narrow band imaging
X-ray
IFU spectroscopy
……and even UV and optical images



Halpha imaging, Yagi + 2010, 2017, Coma cluster



ESO137-001, Fumagalli+ 14, Fossati et al. 2016, in Abell 3627

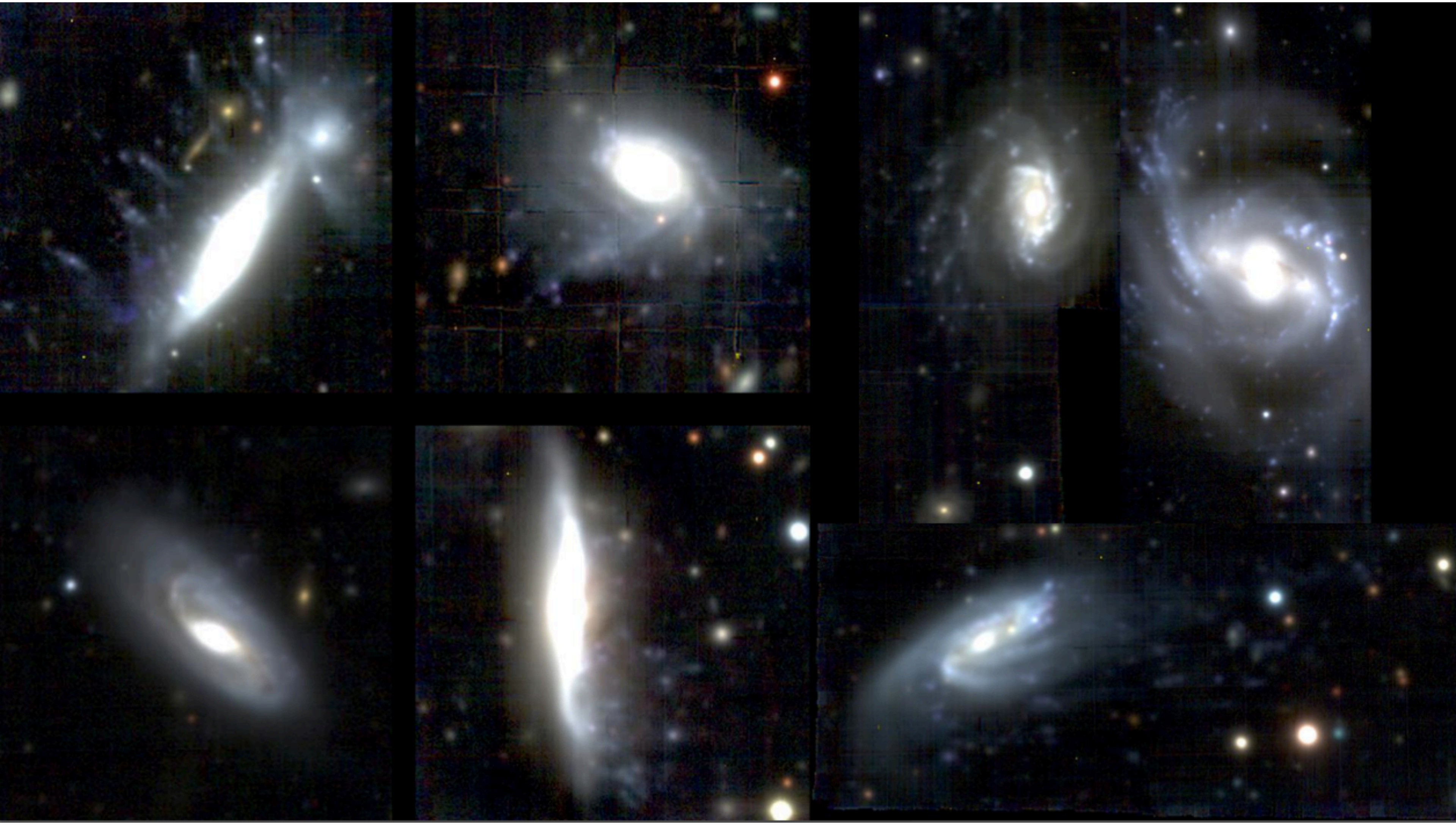
JELLYFISH GALAXIES

"Galaxies with clearly distorted images with optical data resolving multiple filaments offset asymmetrically from the galaxy " (Smith+, 2010)

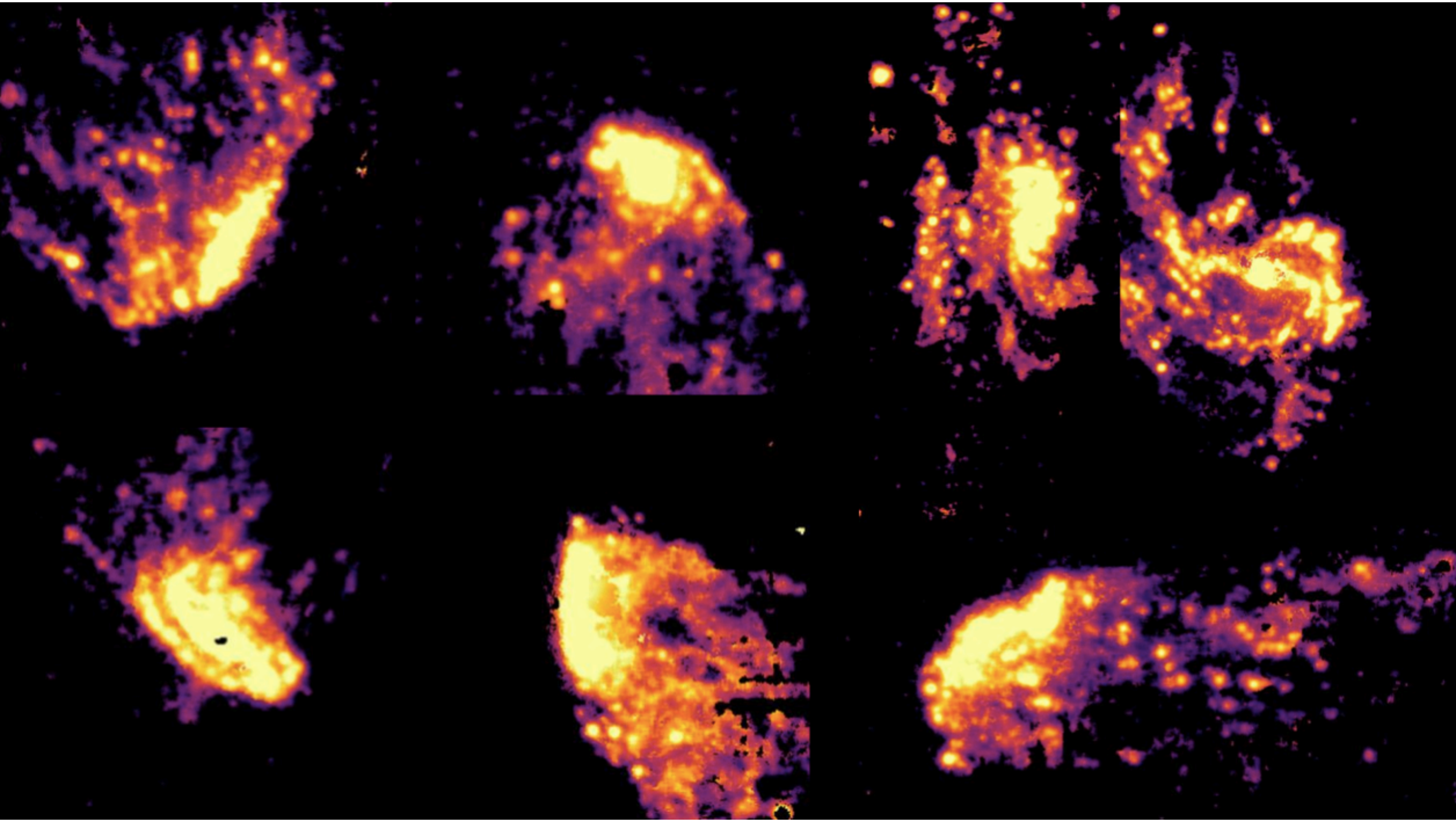
GASP definition:

"Tails at least as long as the stellar disk diameter"

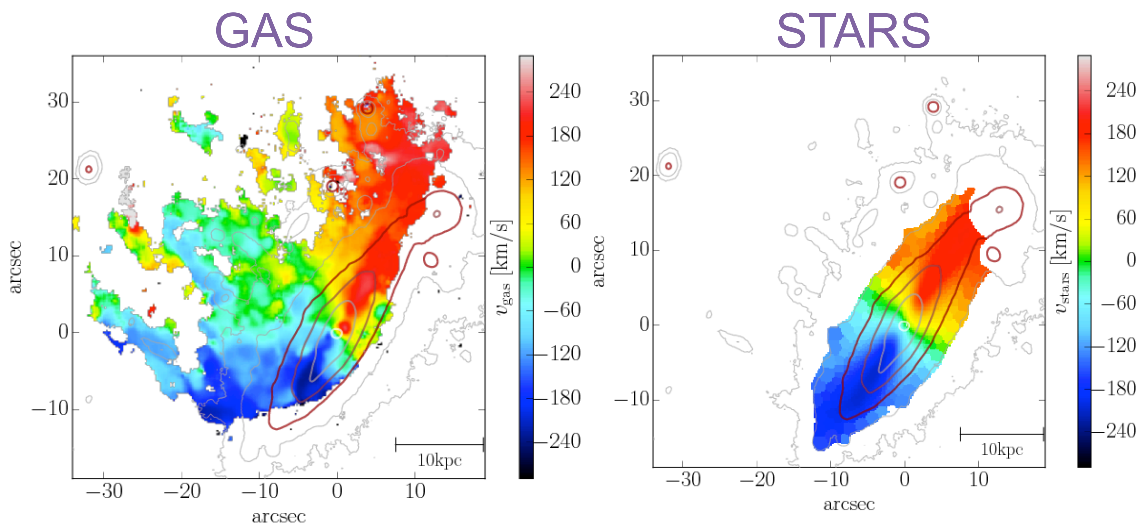
ESO Press Release n. 1725



M. Gullieuszik and the GASP collaboration



INTEGRAL-FIELD SPECTROSCOPY AND RAM PRESSURE: GAS and STELLAR KINEMATICS

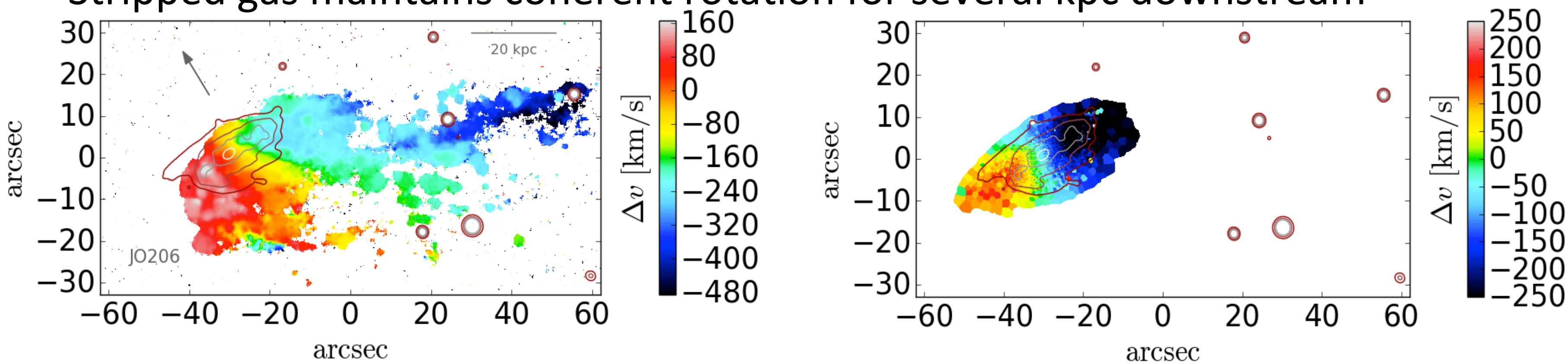


See also e.g. Fumagalli+ 2014

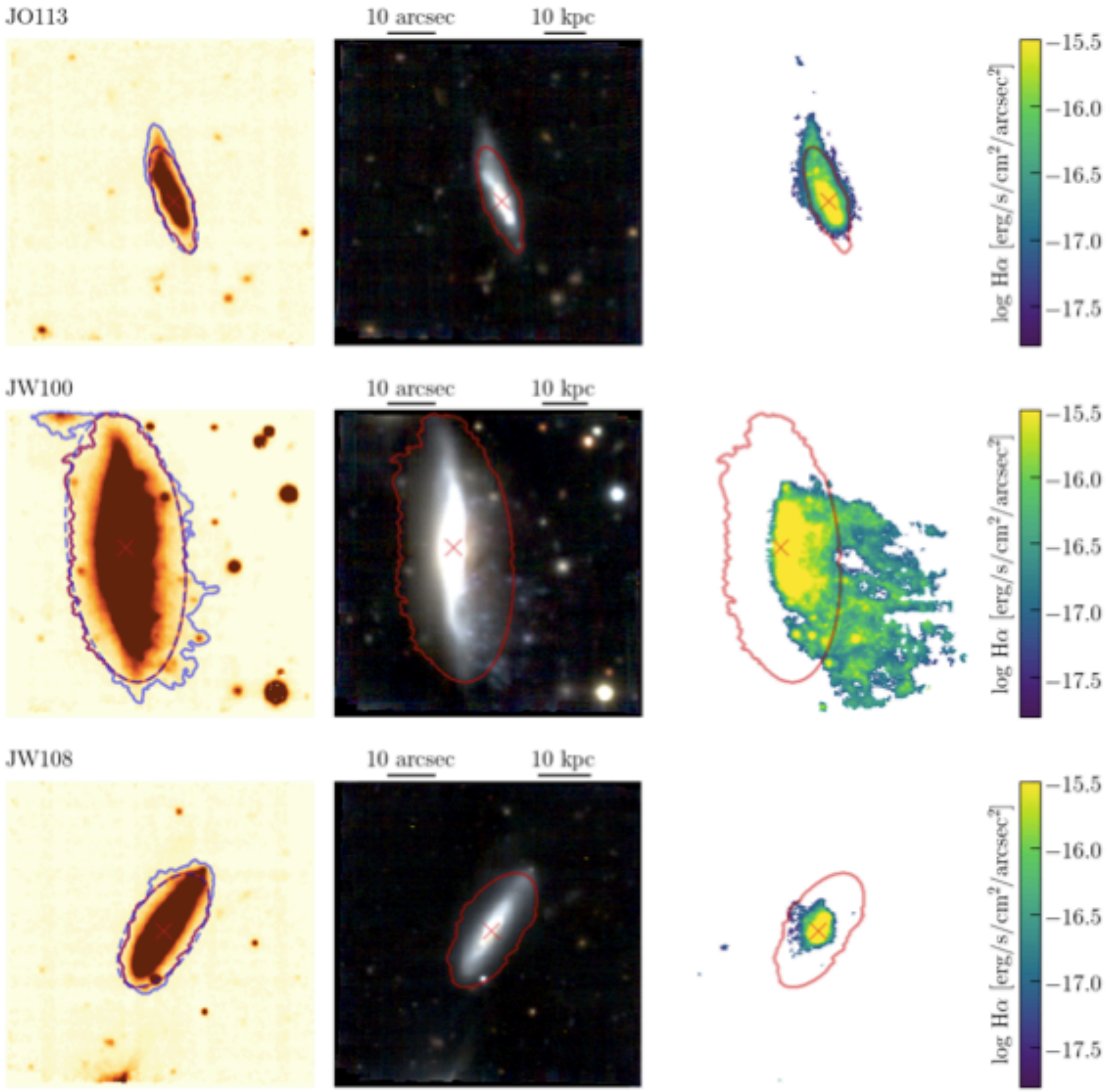
Gullieuszik+ 2017

The stellar component is not disturbed, regular stellar kinematics: gas-only stripping

Stripped gas maintains coherent rotation for several kpc downstream



Poggianti+ 2017

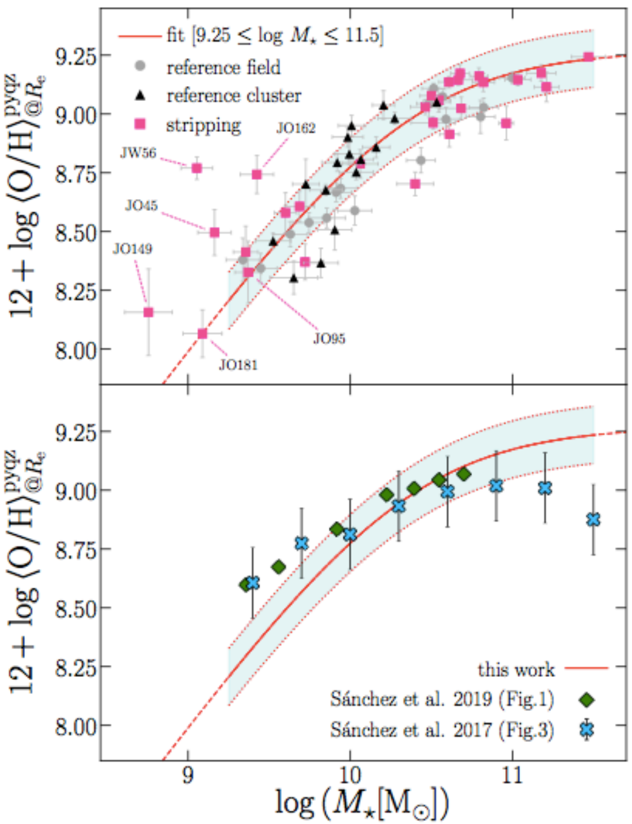


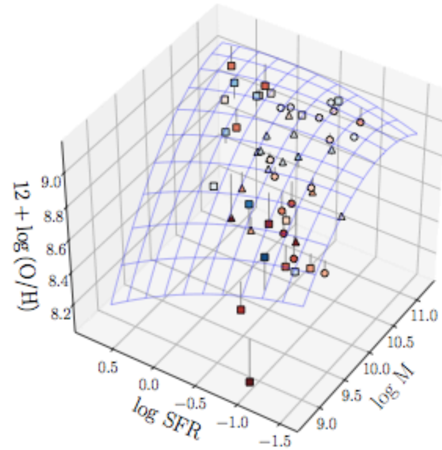
Various stages of stripping

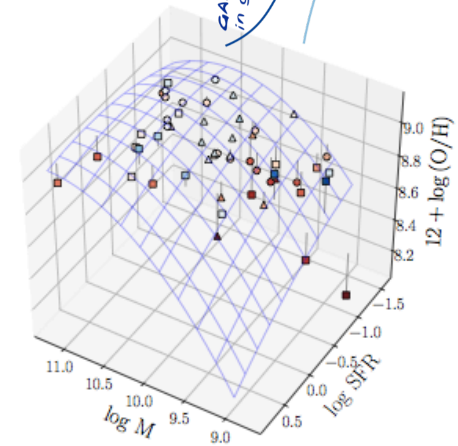
Gullieuszik+ 2020

GAS METALLICITIES

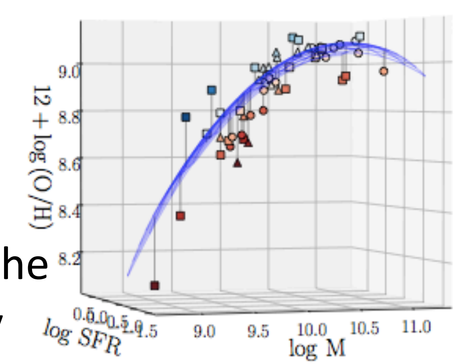
Jellyfish galaxies, and stripping galaxies in general, follow the mass-metallicity relation of non-stripped cluster galaxies.
At low galaxy masses, metallicities in clusters are higher than in the field.







Jellyfish/stripping galaxies sit on the Fundamental Metallicity relation (the metallicity anticorrelates with the SFR – and the galaxy size)



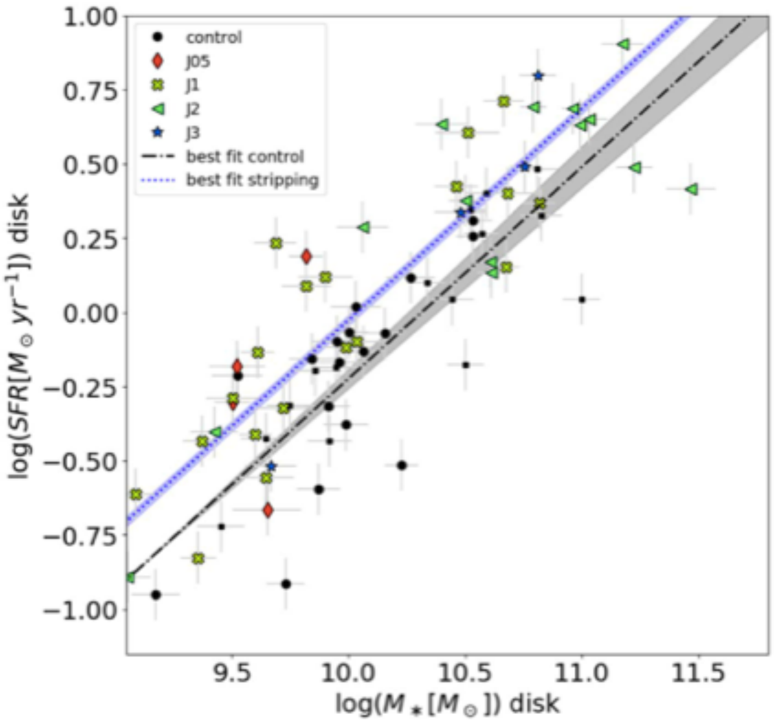
Franchetto+ 2020

STAR FORMATION

ENHANCED GLOBAL STAR FORMATION

RPS can moderately enhance the SFR in the disk before quenching

Log SFR (disk)

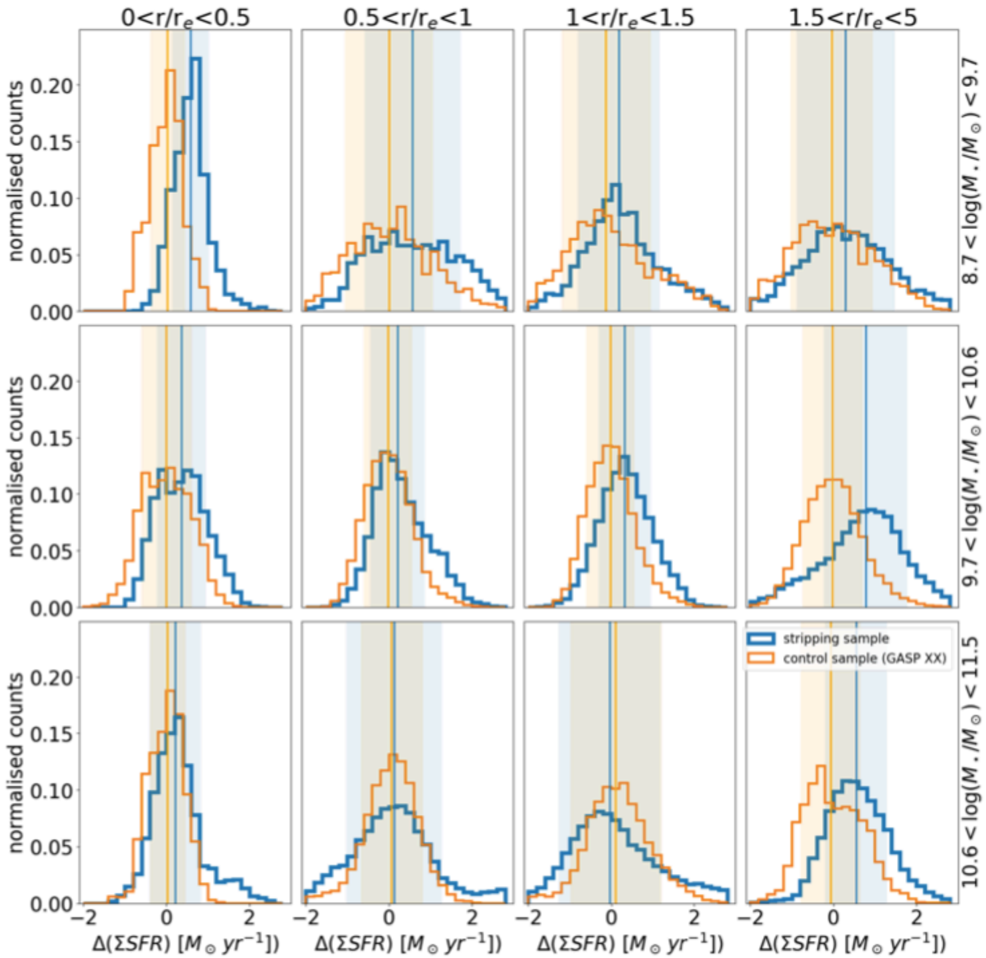


Log M*

Galaxies undergoing stripping show a systematic enhancement of the *disk* SFR at fixed disk galaxy stellar mass (0.2dex)

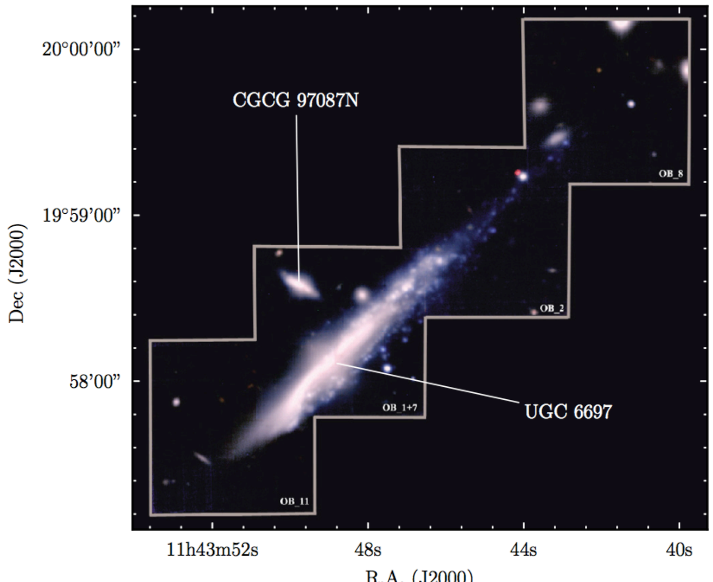
Vulcani+ 2018c,
Roberts & Parker 2020

Systematic enhancement of SFR surface density at a given stellar mass surface density – at all galactocentric distances – suggesting SF enhancement induced by compression waves from ram pressure

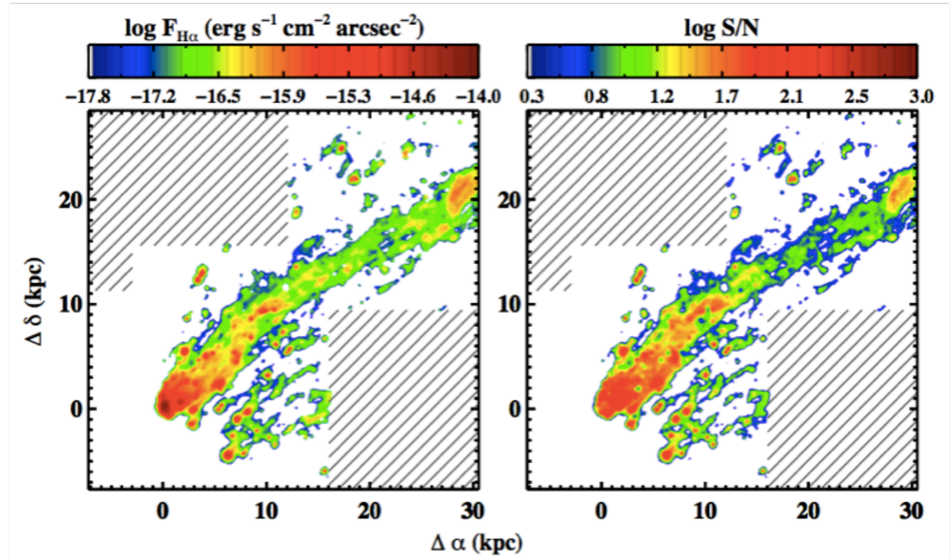


Vulcani+ 2020b

STAR FORMATION IN STRIPPED TAILS

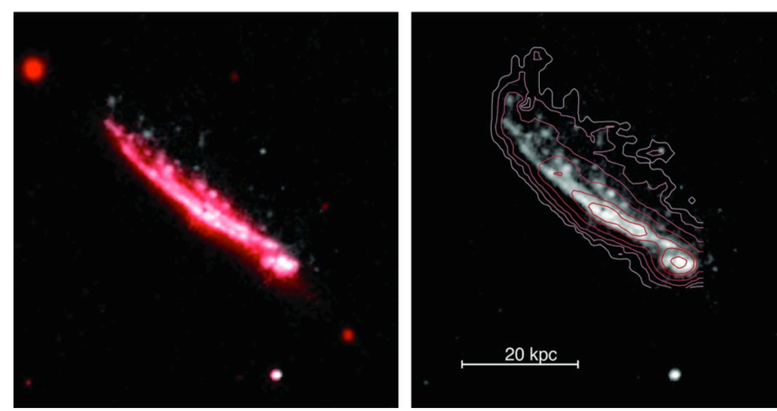


UGC6697, Consolandi et al. 2017, Abell 1367



ESO137-001, Sun et al. 2010, Fumagalli+ 14, Fossati et al. 2016, in Abell 3627

IFU data allow us to assess gas ionization mechanism from multiple line ratios.



SOS 114372, Merluzzi+2013, 2016, Shapley supercluster

See also Fossati+ 2019.

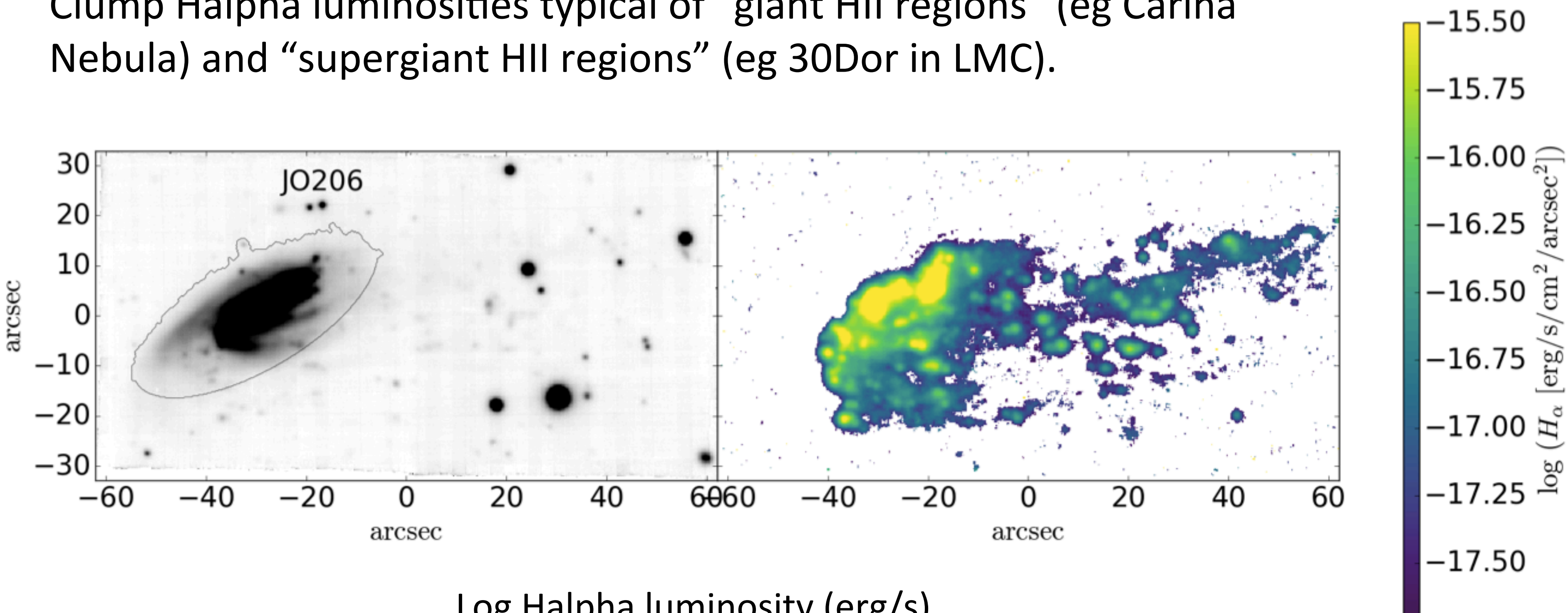
SF evidence also from UV+Halpha (Boselli+ 2018, Abramson+ 2011), UV-only of post-SB (Hester+ 2010, Yoshida+ 2008), and UV-only or Halpha-only surveys (Smith+ 2010, Yagi and Gavazzi's works)

STAR FORMATION IN THE STRIPPED TAILS

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

The SF takes place in Halpha bright, dynamically cold (median σ=27 km/s):
star-forming clumps forming in-situ in the tails.

Clump Halpha luminosities typical of "giant HII regions" (eg Carina Nebula) and "supergiant HII regions" (eg 30Dor in LMC).



Log Halpha luminosity (erg/s)

Poggianti+ 2019

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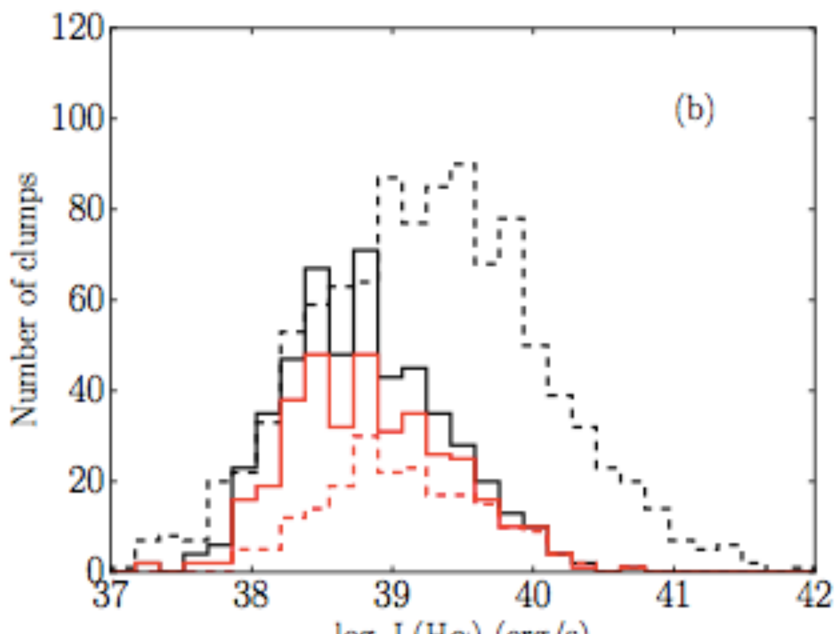


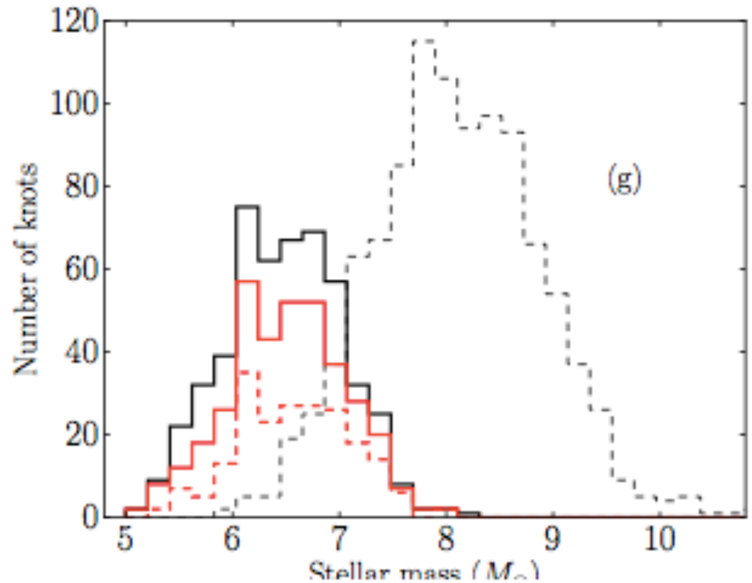
Log Halpha luminosity (erg/s)

Poggianti+ 2019

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

Median stellar mass of the clumps in the tails 3X10^6Msun

Are we witnessing the formation of UltraCompact Dwarf Galaxies / Globular Clusters?



Stellar mass (Msun)

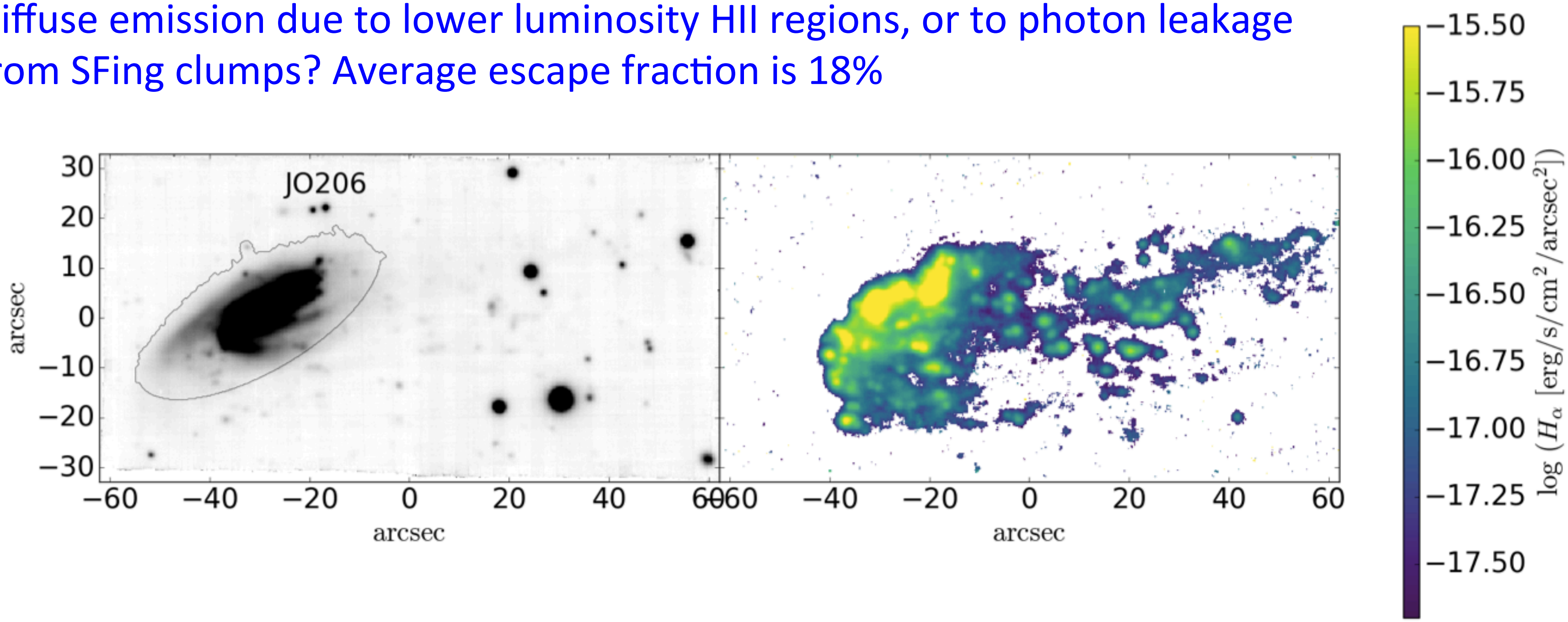
Poggianti+ 2019

DIFFUSE Halpha-emitting IONIZED GAS (DIG)

In tails, 50% of emission is Halpha clumps and 50% is DIG.

DIG mostly due to photoionization by young massive stars + "LINER-like" emission component from [OI] line: thermal heating from ICM? Or mixing? Or shocks?

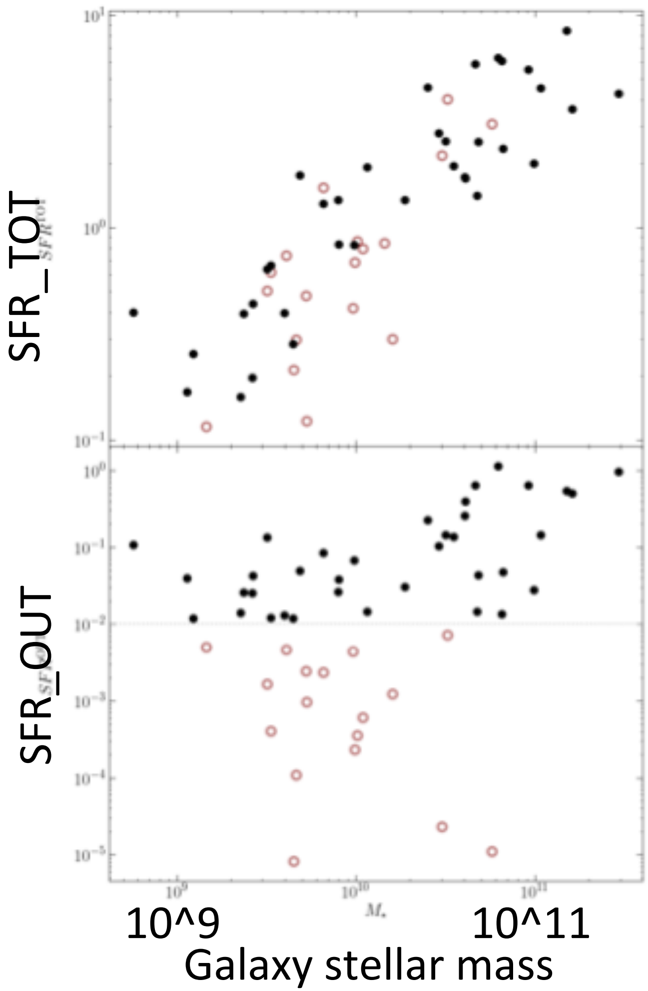
Diffuse emission due to lower luminosity HII regions, or to photon leakage from SFing clumps? Average escape fraction is 18%



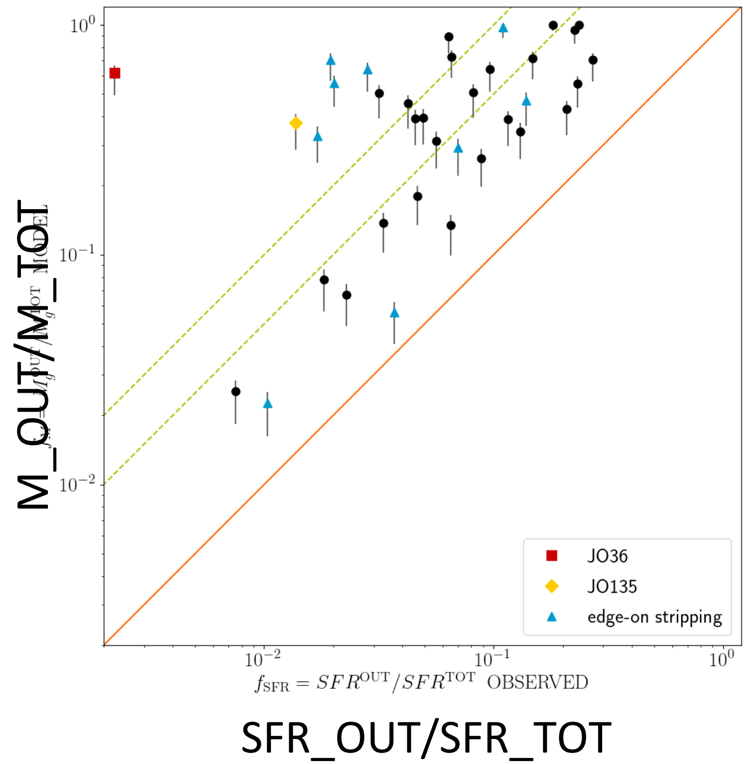
Poggianti+ 2019a

What does the amount of SF in the tail depend upon?

Not simply the galaxy stellar mass…



The fraction of SFR that is "out" follows the fraction of gas mass that is expected to be stripped according to the Gunn&Gott formulation…



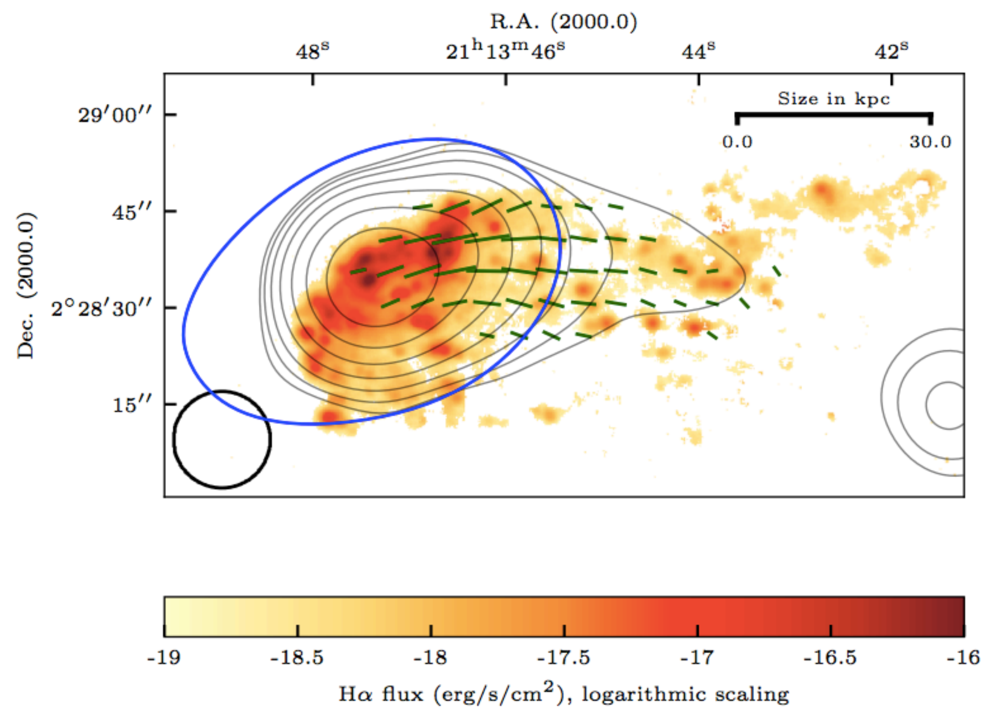
With 4 observed quantities (galaxy mass, cluster mass, v and r) SFR_OUT can be roughly predicted, in a statistical sense

Gullieuszik+ 2020

FIRST OBSERVATION OF THE MAGNETIC FIELD IN A JELLYFISH TAIL!!!

The magnetic field vectors are aligned with (are parallel to) the direction of the ionized gas tail and stripping direction.

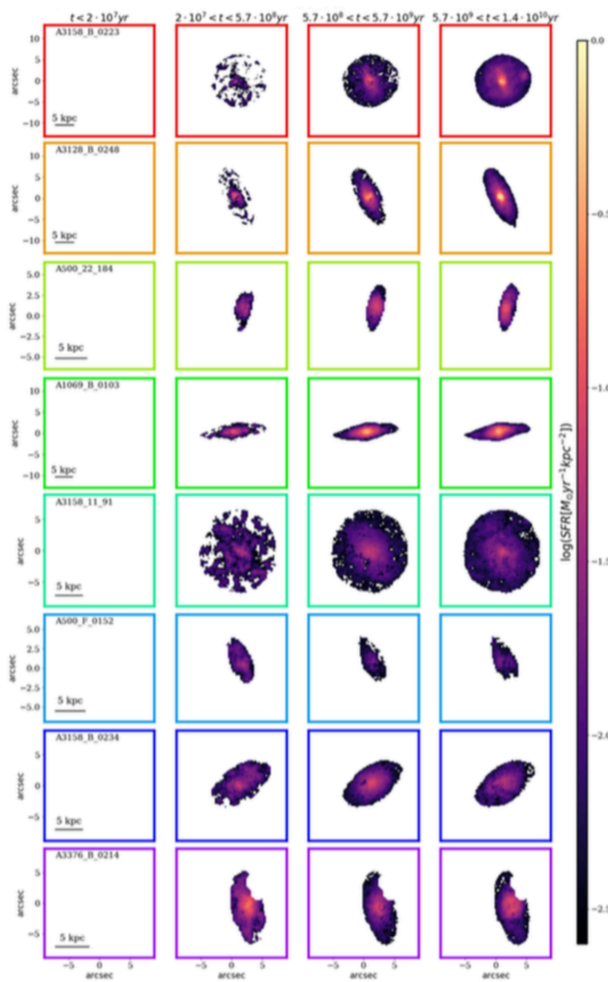
A key factor in allowing in-situ SF?



Mueller+ 2020

POST-STARBURST/POST_STARFORMING GALAXIES: NO (ionized) GAS and NO SF LEFT

OUTSIDE-IN QUENCHING

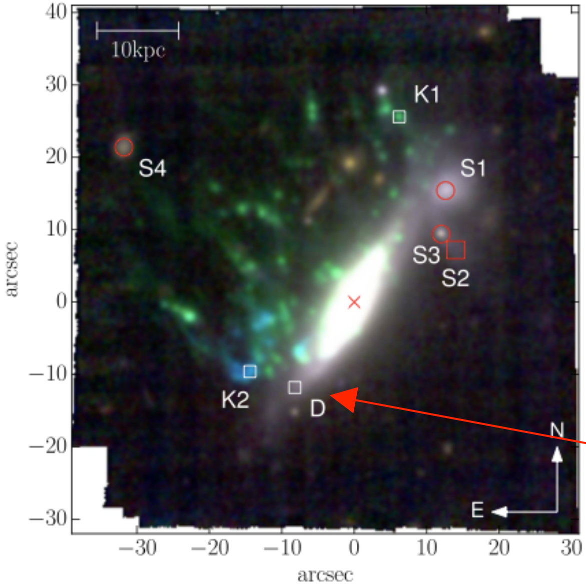


Post-starburst spirals, with strong Balmer absorption and no emission lines

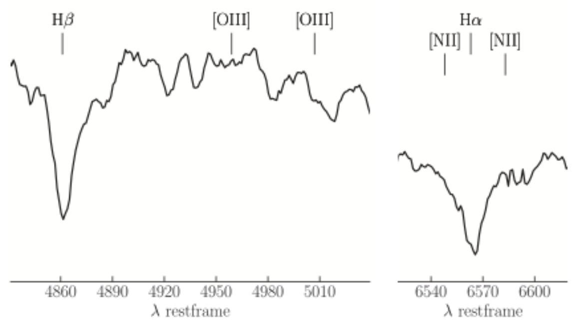
typically located between 0.5 and 1 cluster virial radii (r200)

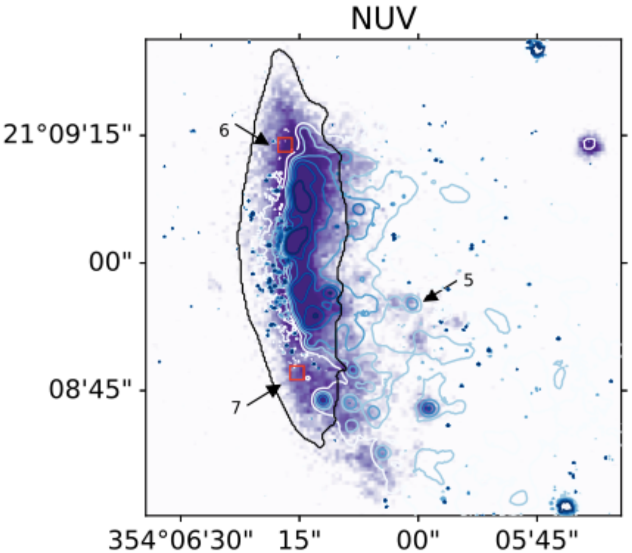
Vulcani et al. 2020

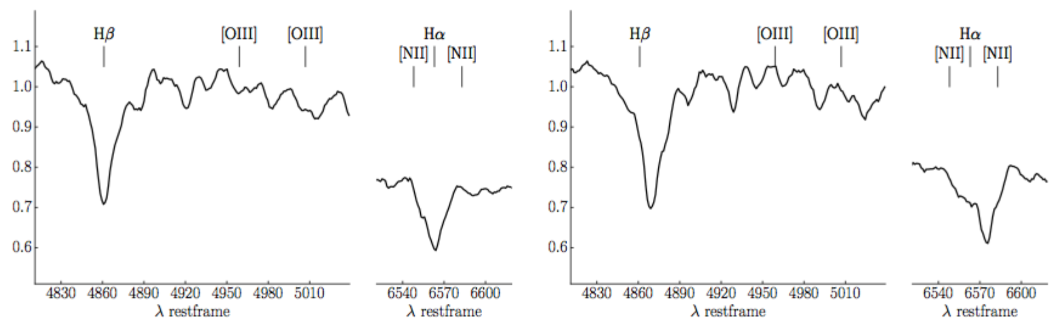
QUENCHING:
POST-STARBURST SIGNATURES



“Local post-starburst” signature: outer regions of disks undergoing stripping



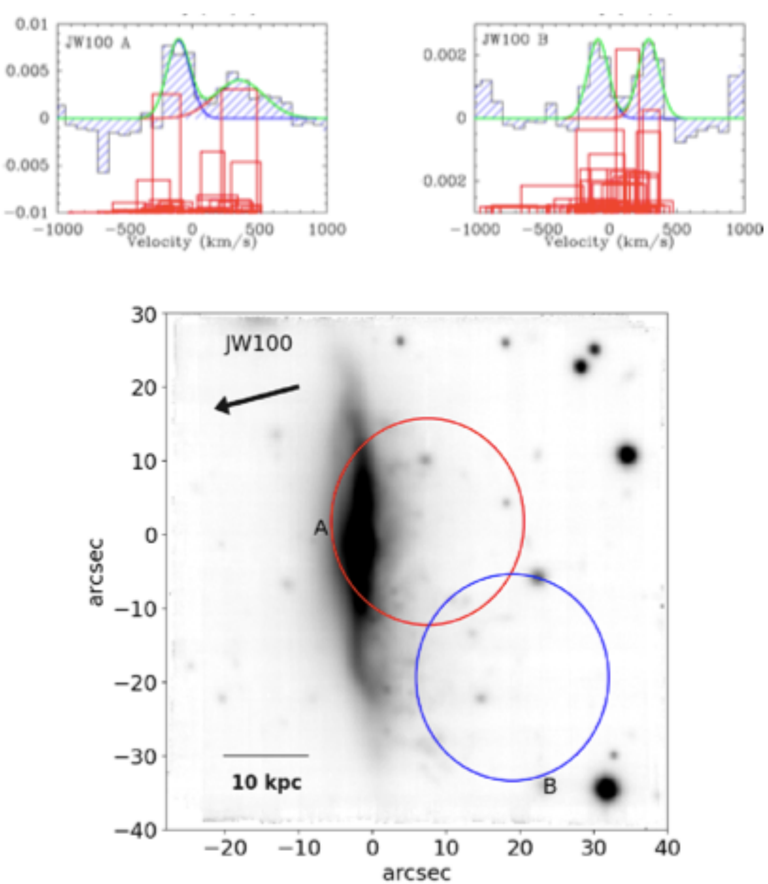




Gullieuszik+ 2017 – Poggianti+ 2019b

MULTI-PHASE GAS AND SF

MOLECULAR GAS IN TAILS: SINGLE DISH STUDIES



Moretti+ 2018

Large molecular gas masses (CO) in the tails, and in the disks

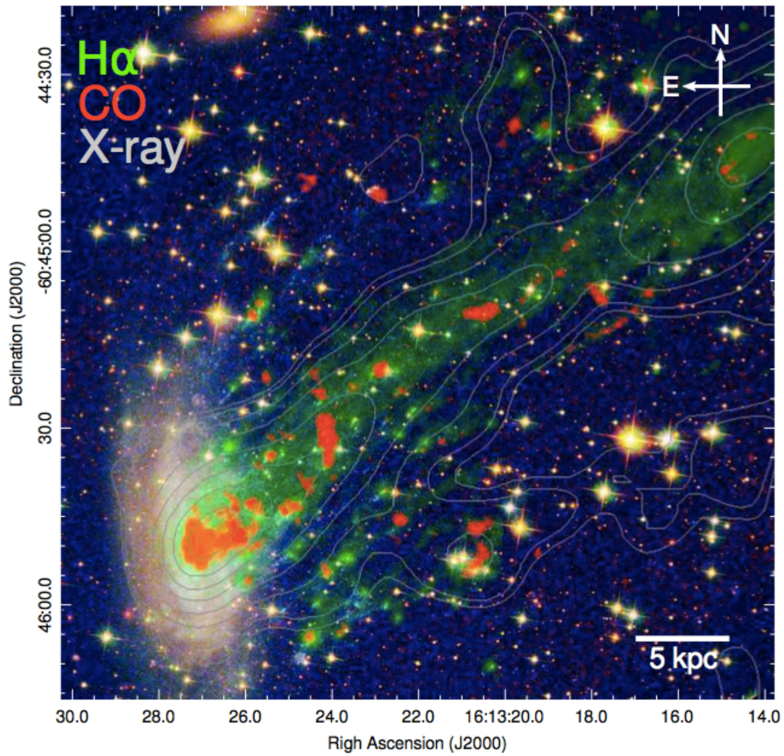
Until recently, 8 galaxies detected (large beam, low spatial resolution)

Jachym+ 2014, 2017, Verdugo+ 2015, Lee+ 2018, Moretti+ 2018

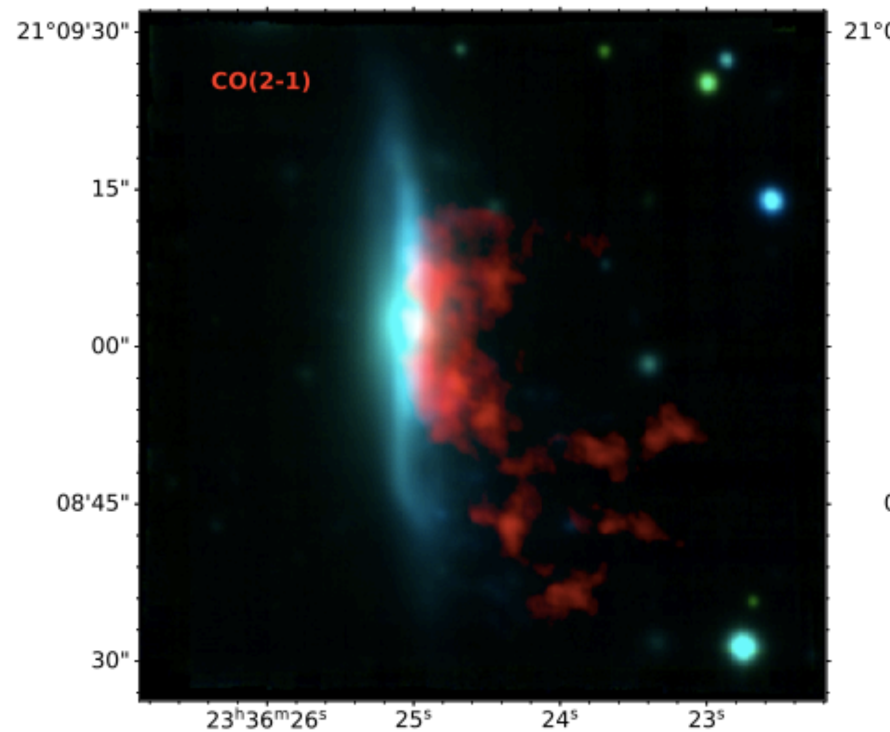
ALMA DETECTIONS OF MOLECULAR GAS IN THE TAILS

Individual CO clumps can be studied: from 10^6 to 10^9 Msun clumps.
In the tail, mol. gas much more diffuse (larger scales)

Molecular gas formed in the tails (close to the disk can be stripped gas).



Jachym+ 2019 ESO 137-001



Moretti+ 2020   JW100

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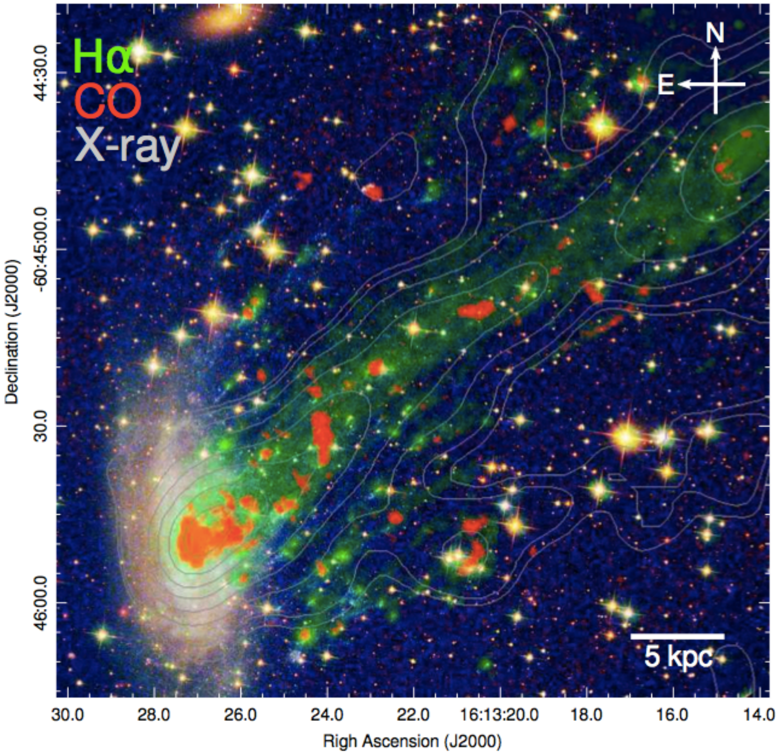
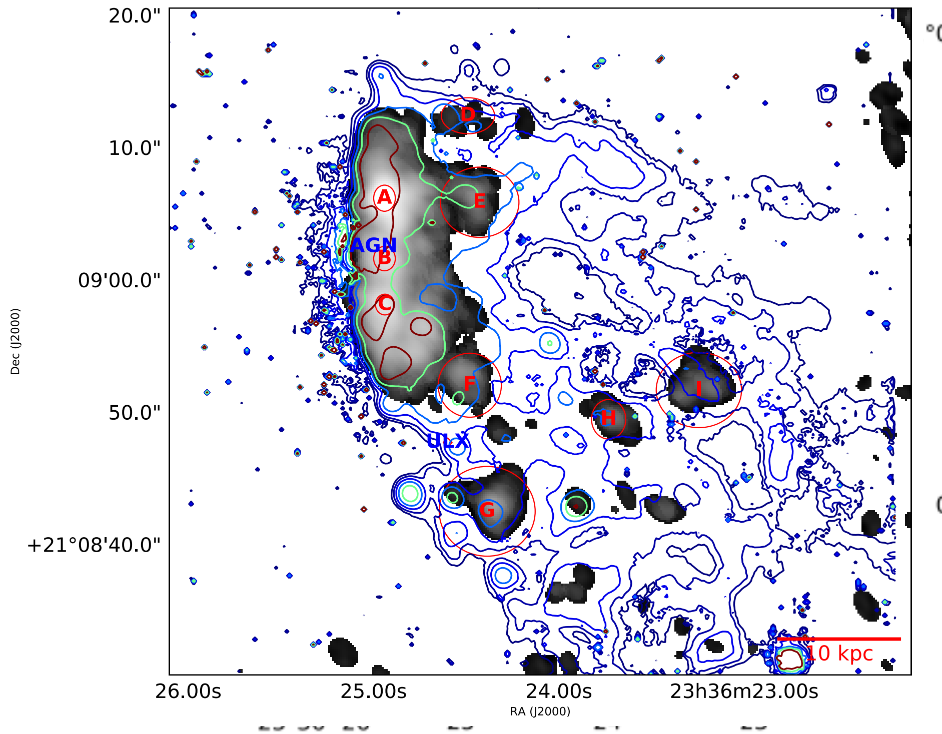
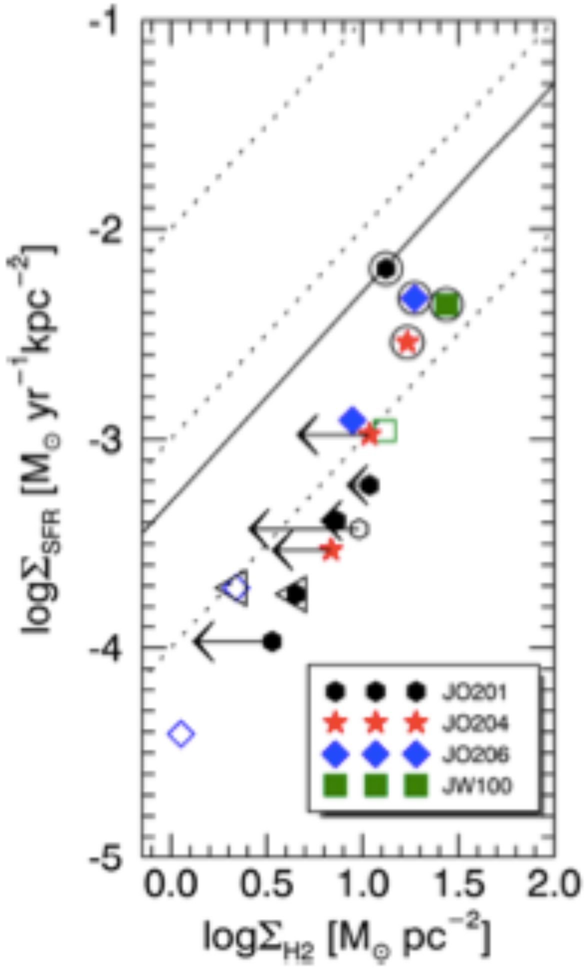


Jachym+ 2019 ESO 137-001



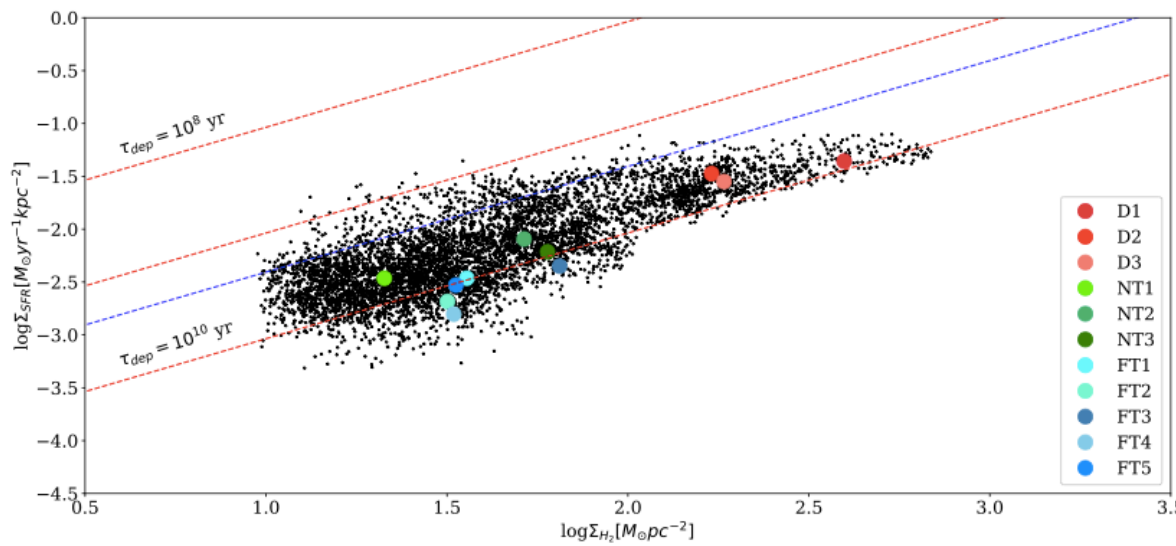
Moretti+ 2020 JW100

LOW CO-STAR FORMATION EFFICIENCY (SFR surface density per unit of molecular gas mass surface density)



Moretti+ 2018

Globally, lower than in spiral disks.
Lower in tails than in jellyfish disks.

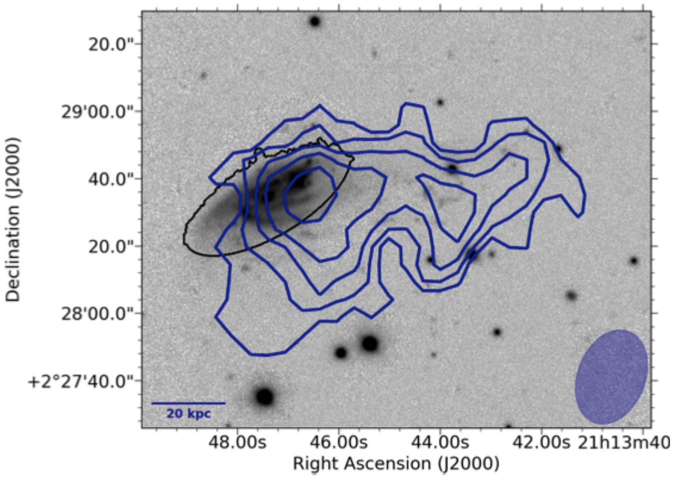


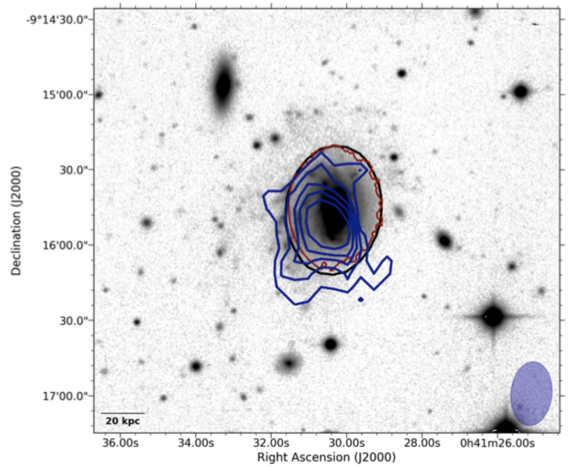
Moretti+ 2020

Long depletion times, several Gyr

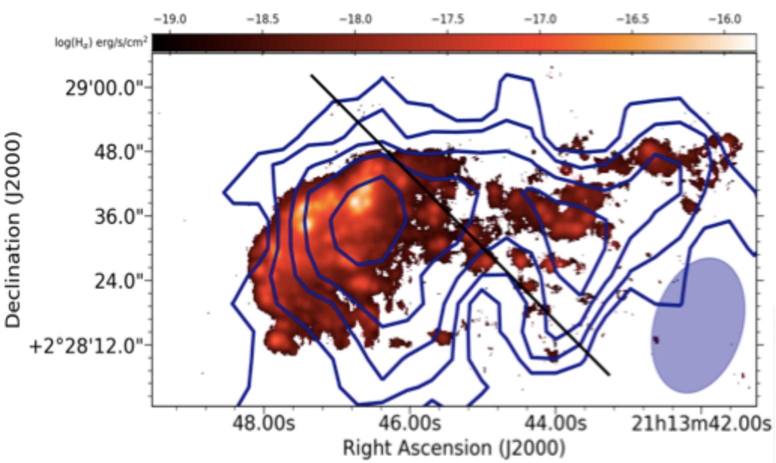
HI GAS

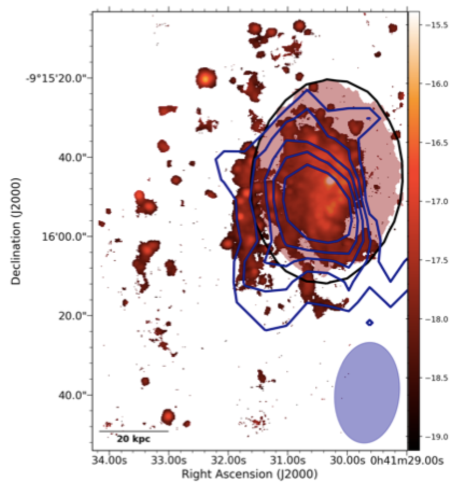
Generally, HI tails present in galaxies with Halpha tails – but HI and Halpha tail morphologies can be very different (but always for a reason…)

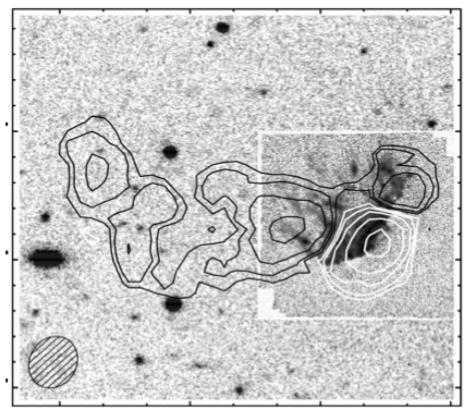




JVLA C-array



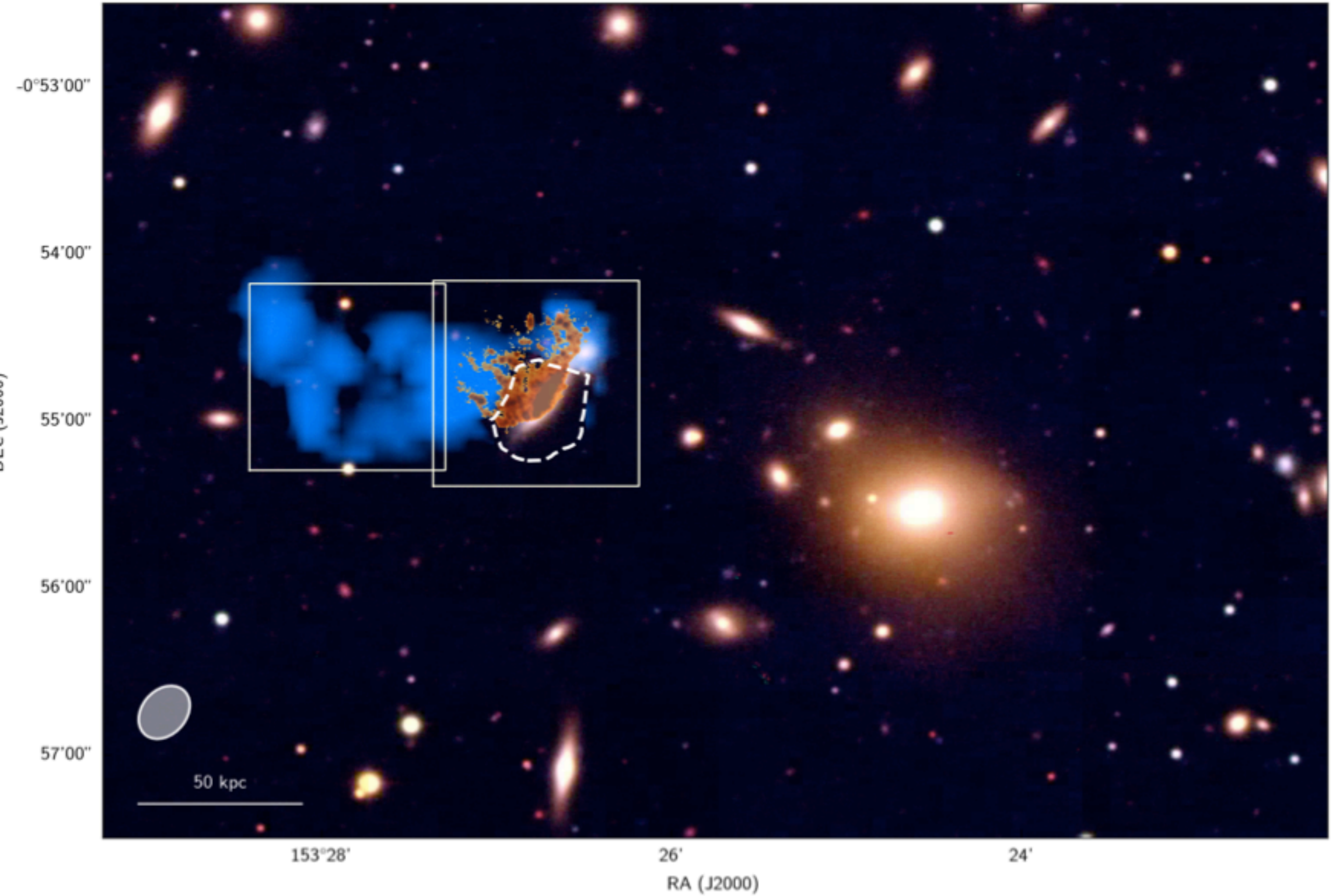




Ramatsoku+ 2019

Ramatsoku+ 2020

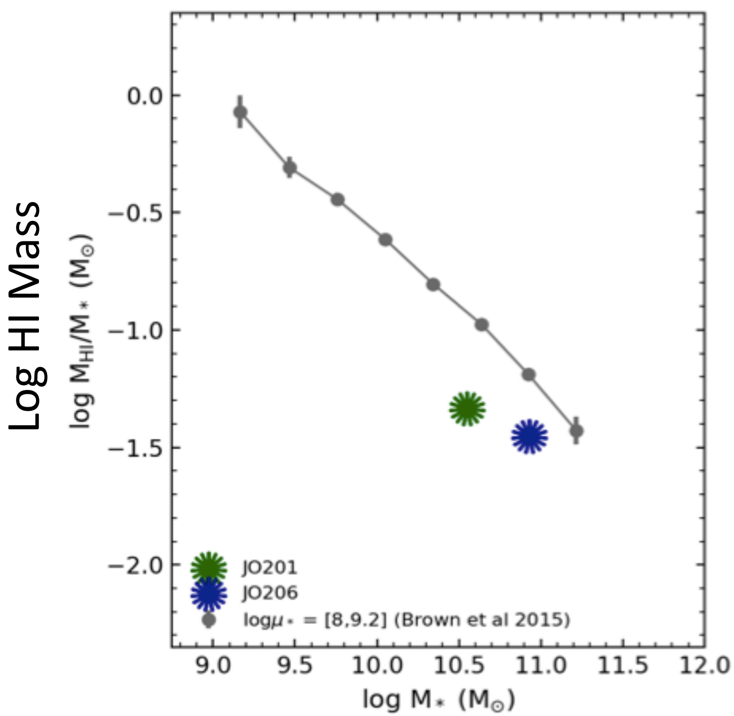
Deb, Verheijen+2020



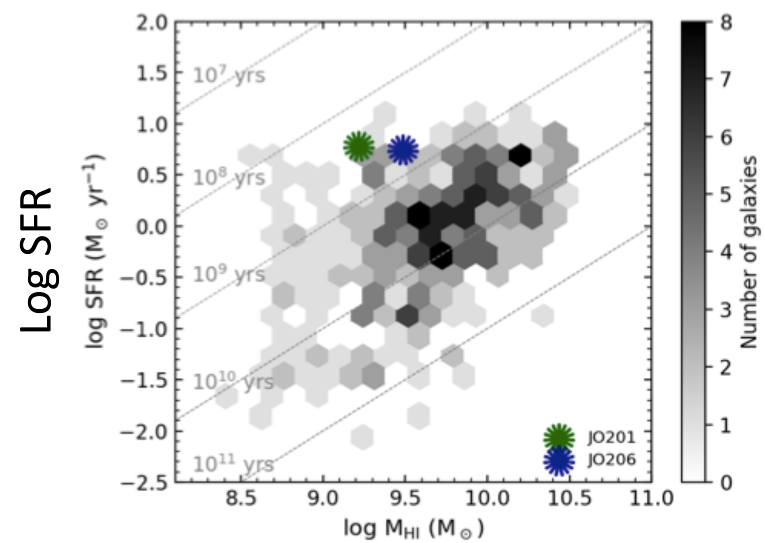
-0°53'00"
54'00"
55'00"
56'00"
57'00"
50 kpc
153°28'
26'
24'
RA (J2000)

Slightly HI-deficient

SF excess for their HI content – both globally and locally



Log stellar mass



Log HI Mass

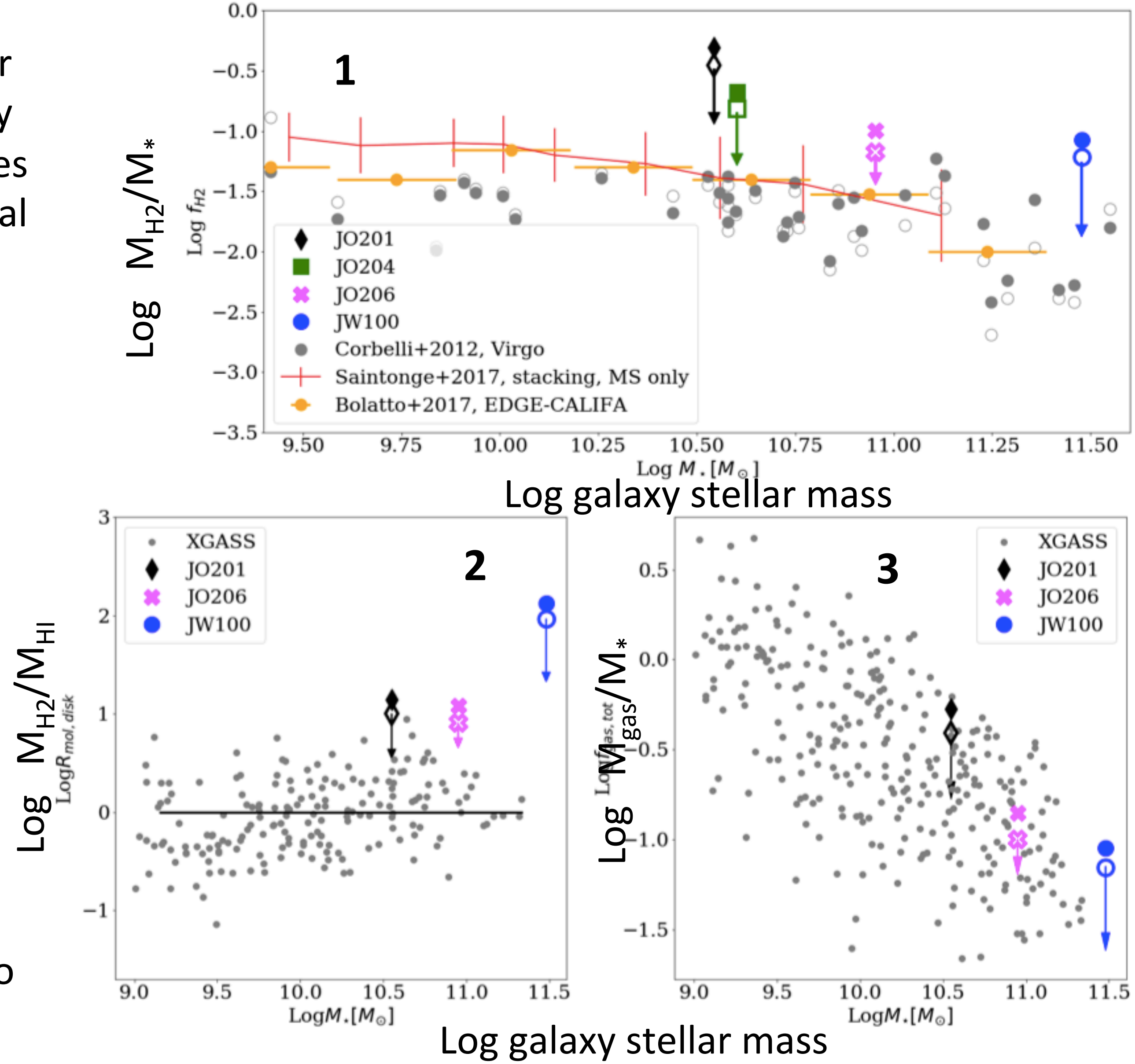
Ramatsoku+ 2020

MORE JELLYFISH SURPRISES

1. Ratio of molecular gas mass over galaxy stellar mass 4-5 times higher than in normal galaxies

2. The ratio of molecular gas mass over neutral gas mass in the disk is 4-100 times higher than in normal galaxies

3. The total (molecular+neutral) gas mass is similar to normal galaxies of similar stellar mass



Moretti+ 2020b

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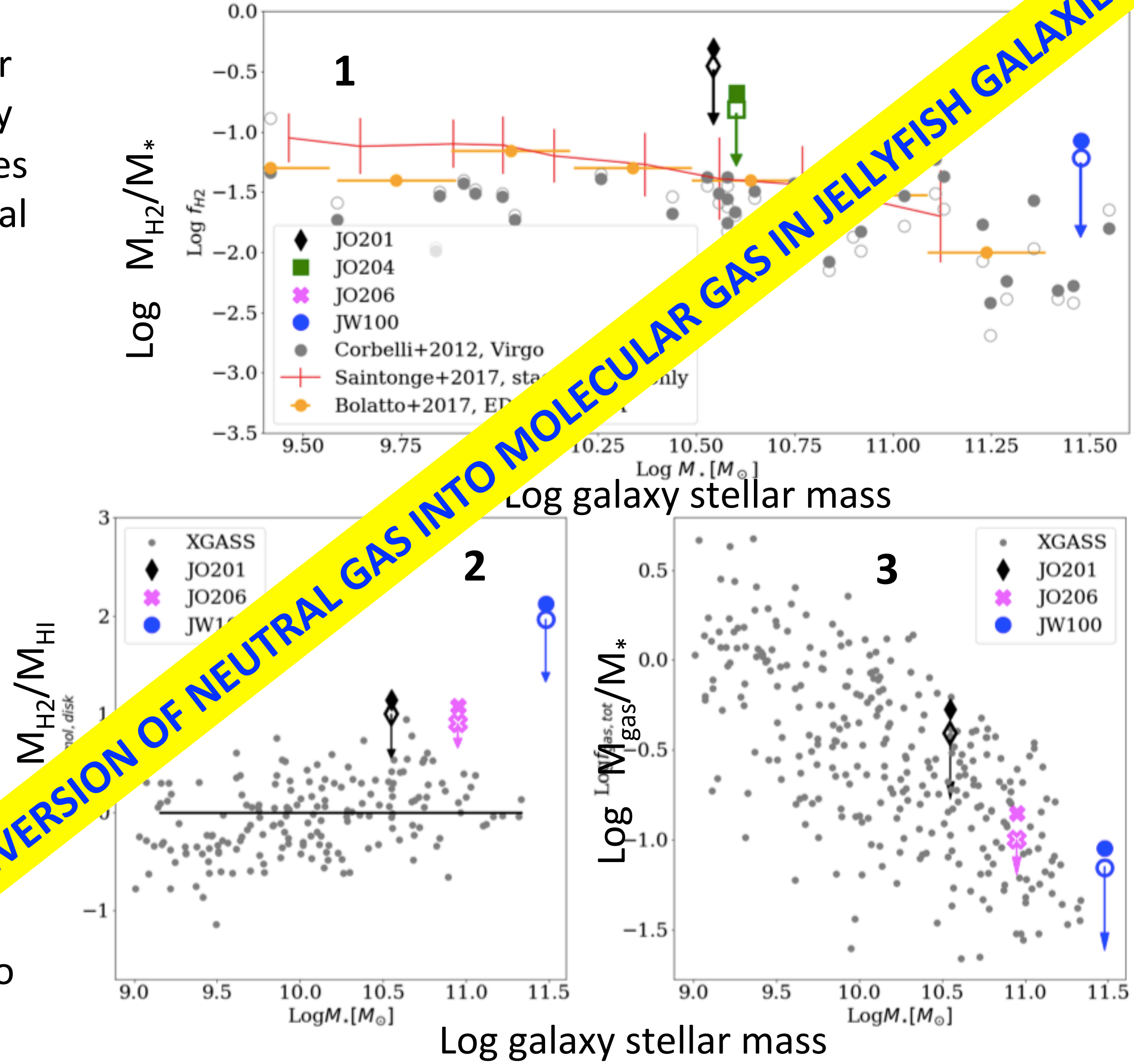


VERY EFFICIENT CONVERSION OF NEUTRAL GAS INTO MOLECULAR GAS IN JELLYFISH GALAXIES

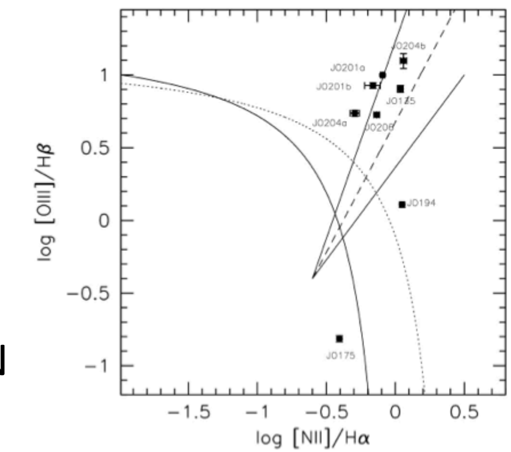
Moretti+ 2020b

AGN-RAM PRESSURE CONNECTION

HIGH FRACTION OF AGN IN JELLYFISH GALAXIES

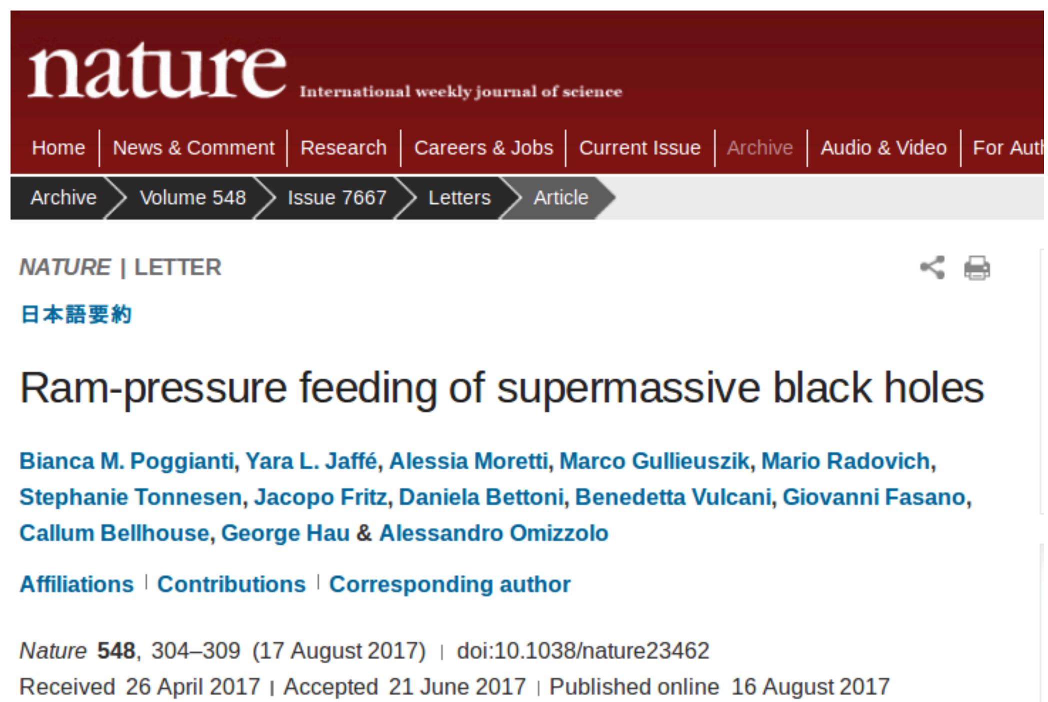
7 galaxies with Hα tentacles longer than the diameter of the stellar disk and stellar masses 4 * 10 ^{10} - 3 * 10 ^{11} Msun

5 AGN (Seyfert2) and 1 LINER
---- suggesting that ram-pressure stripping is triggering the AGN



ISM interacting with non-rotating ICM loses angular momentum

oblique shocks in a disk flared by magnetic field



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NATURE | LETTER

日本語要約

Ram-pressure feeding of supermassive black holes

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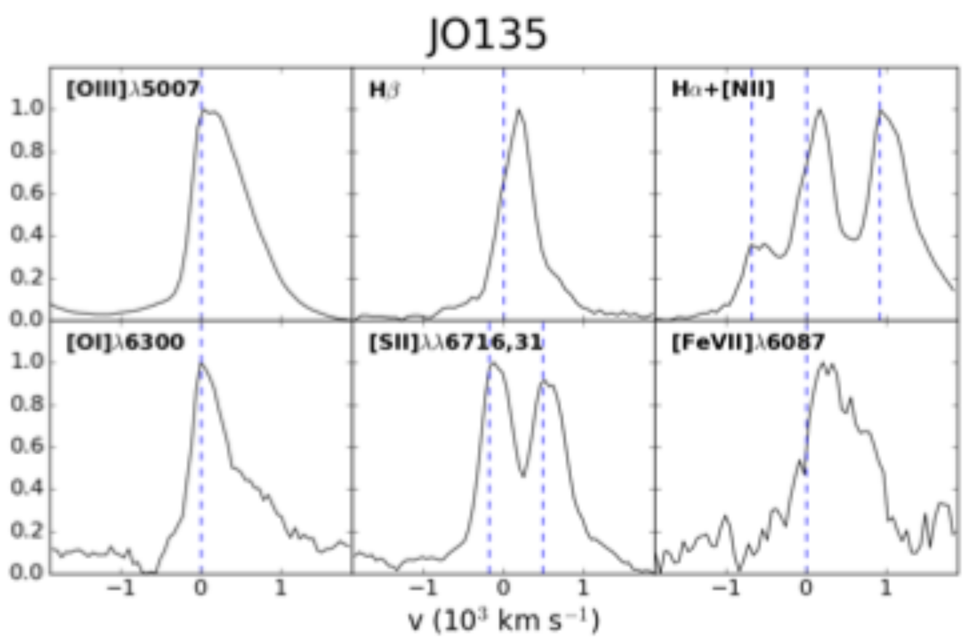
Poggianti+ 2017b

AGN and their OUTFLOWS in JELLYFISH GALAXIES

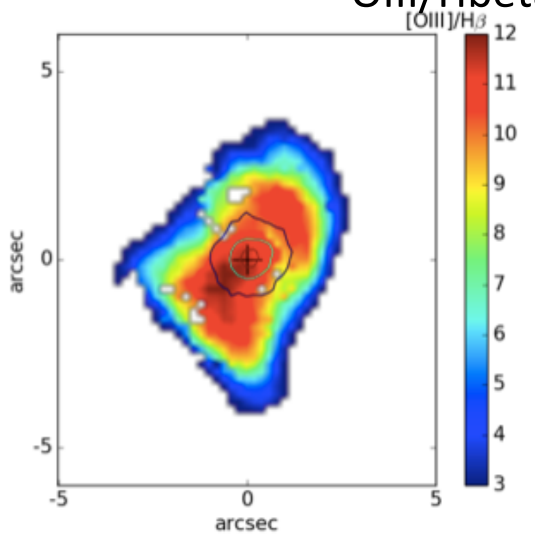
1) Comparison with AGN, shock and HII models using combination of line ratios confirms AGN. (+ HI absorption due to AGN in some cases…see later)

2) Nuclear iron coronal lines and extended (>10kpc) AGN-ionized regions in some of the galaxies.

3) AGN outflows in 4/6, extending out to 1.5-2.5kpc, with outflow velocities 250-550km/s

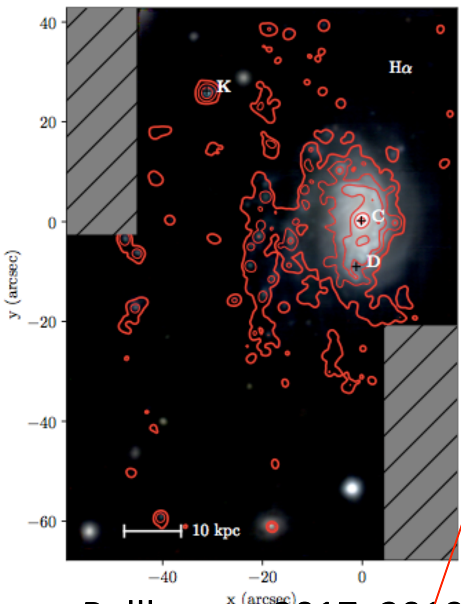


OIII/Hbeta



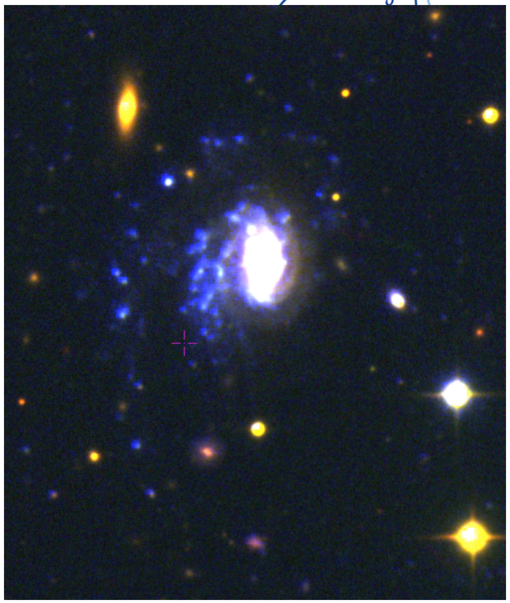
Radovich+ 2019

AGN FEEDBACK:
LACK OF UV, CO and SF IN THE CENTRAL REGION OF A JELLYFISH GALAXY
(MUSE+ALMA+UVIT)

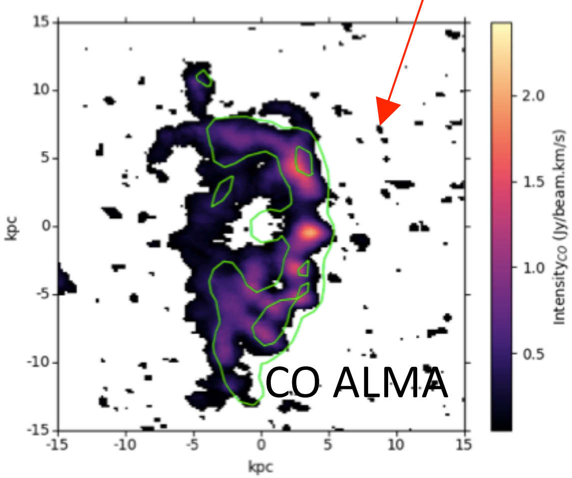


Bellhouse+2017, 2019

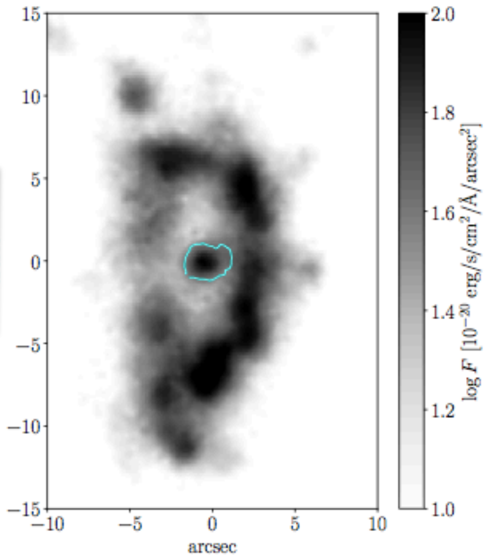
A central 8kpc-long region depleted of molecular gas and of star formation (central UV hole) – this region is filled with gas ionized by the AGN

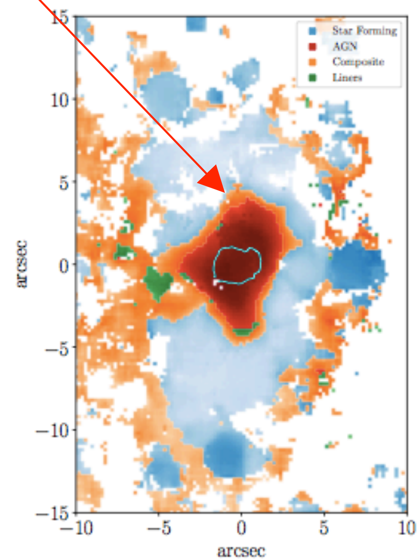


George+ 2018



8 kpc





George+ 2019

CONCLUSIONS

- Jellyfish galaxies, and galaxies undergoing stripping in general, are an excellent opportunity to study a plethora of physical processes, testing our knowledge of such processes under extreme environmental conditions

- Star formation: enhanced in the disks, and in-situ also in tails

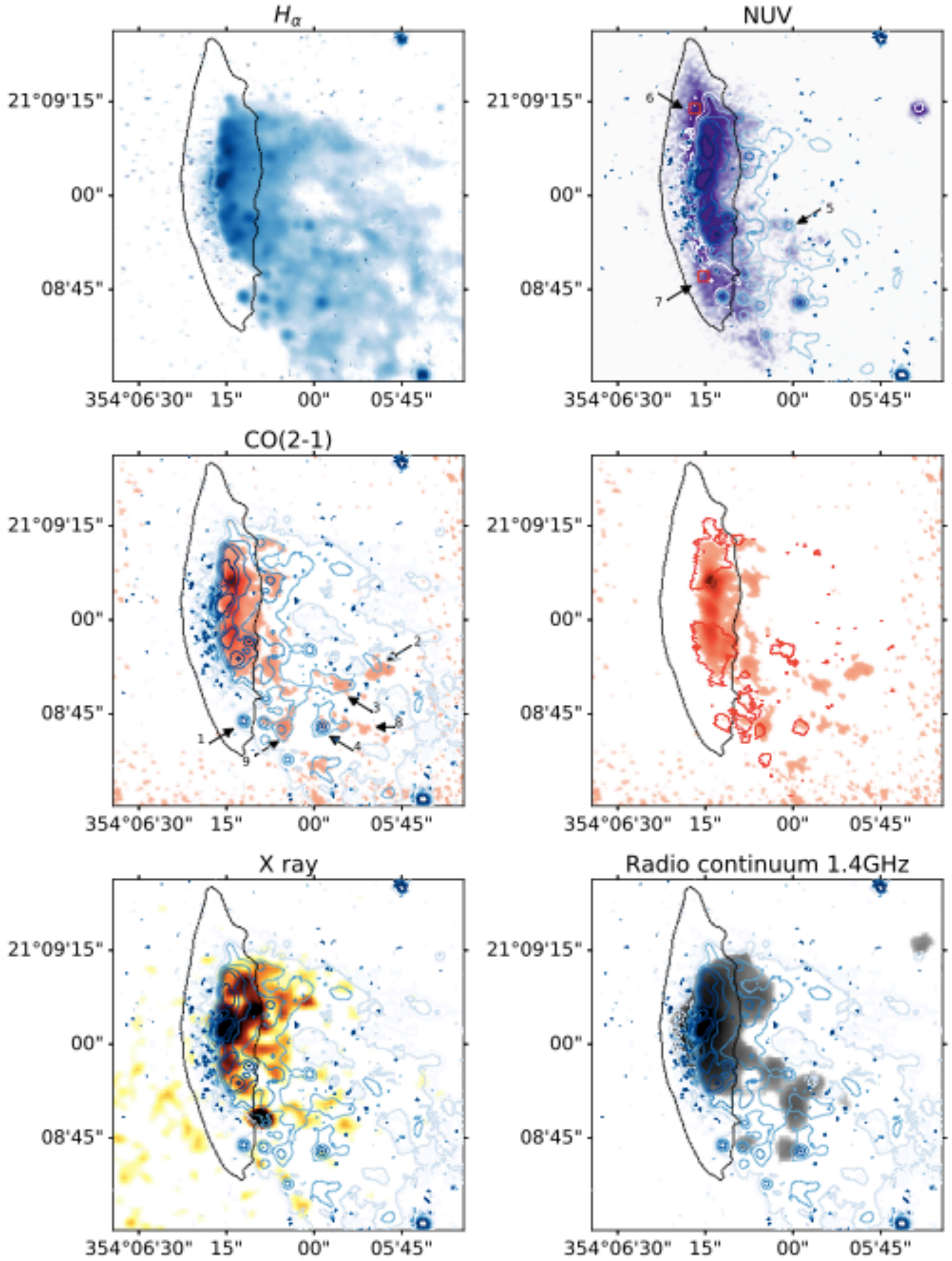
- Multi-phase gas in disks and tails:
  excess of molecular gas, likely efficient conversion of HI into H2
  star formation efficiency unusually high for HI, unusually low for H2

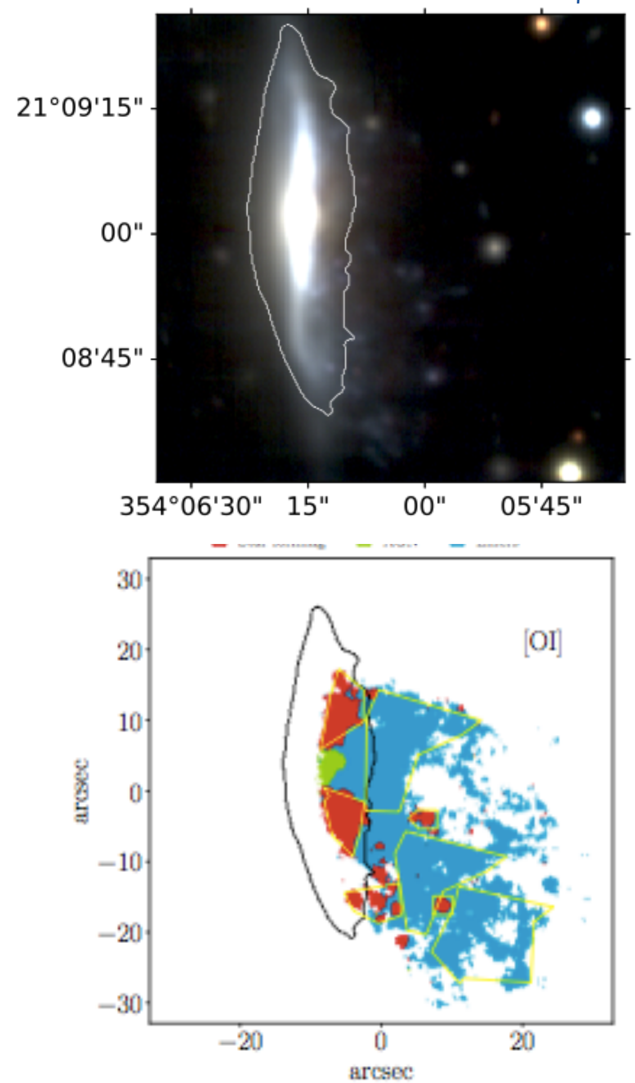
- Ram pressure – AGN connection

OPEN QUESTIONS and HOW TO TACKLE THEM

- When can tails at different wavelengths be observed?
    - How can we reach a complete census of ram pressure stripping?

Star-formation “sequence”





Poggianti+ 2019b

OPEN QUESTIONS and HOW TO TACKLE THEM

- When can tails at different wavelengths be observed?
  - How can we reach a complete census of ram pressure stripping?

- The universality of the SF process, versus the dependence of the various gas phases and the star formation efficiency on local conditions

- How does ram pressure trigger the AGN?

- Inside and outside clusters, what is the role of ram pressure stripping for the evolution of the overall galaxy population? What about other mechanisms?

- The nature and fate of the extraplanar star-forming clumps; the contribution to the intracluster light and the intracluster medium; the nature of the diffuse emission etc etc