Processing of gas in galaxies within the cosmic web

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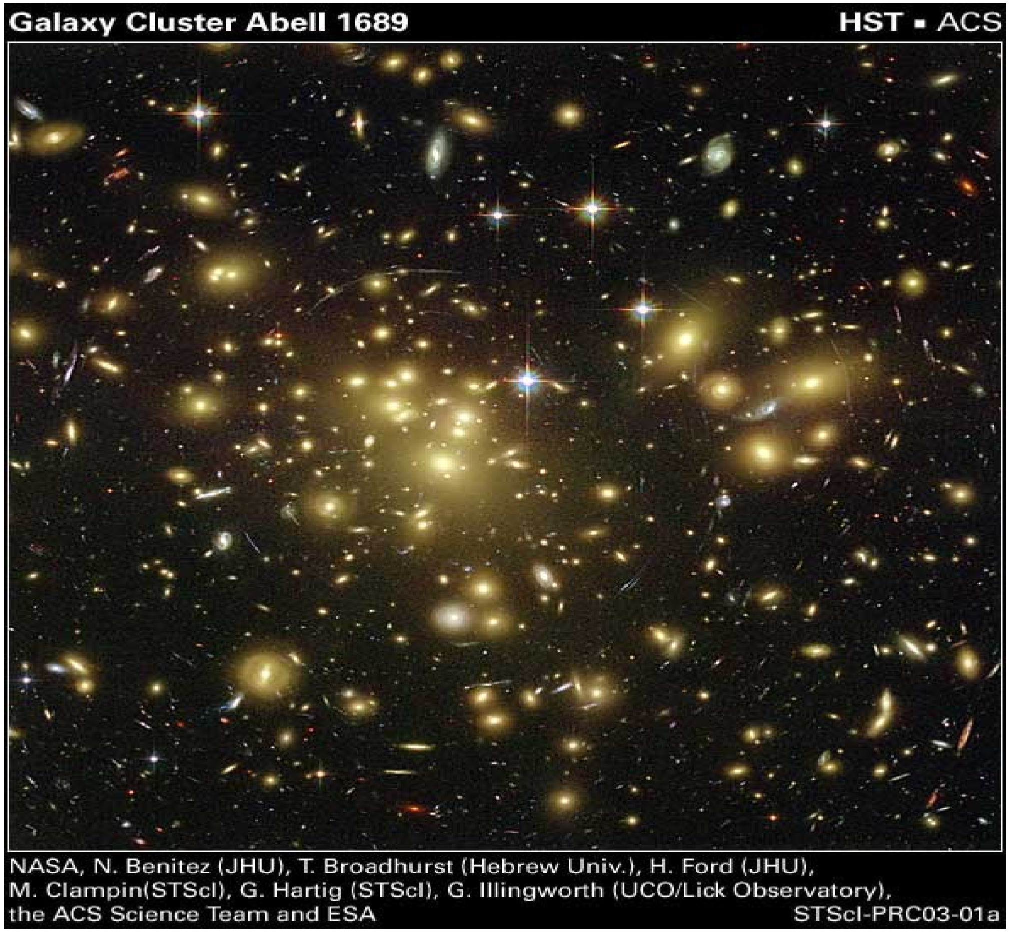
Galaxy Clusters

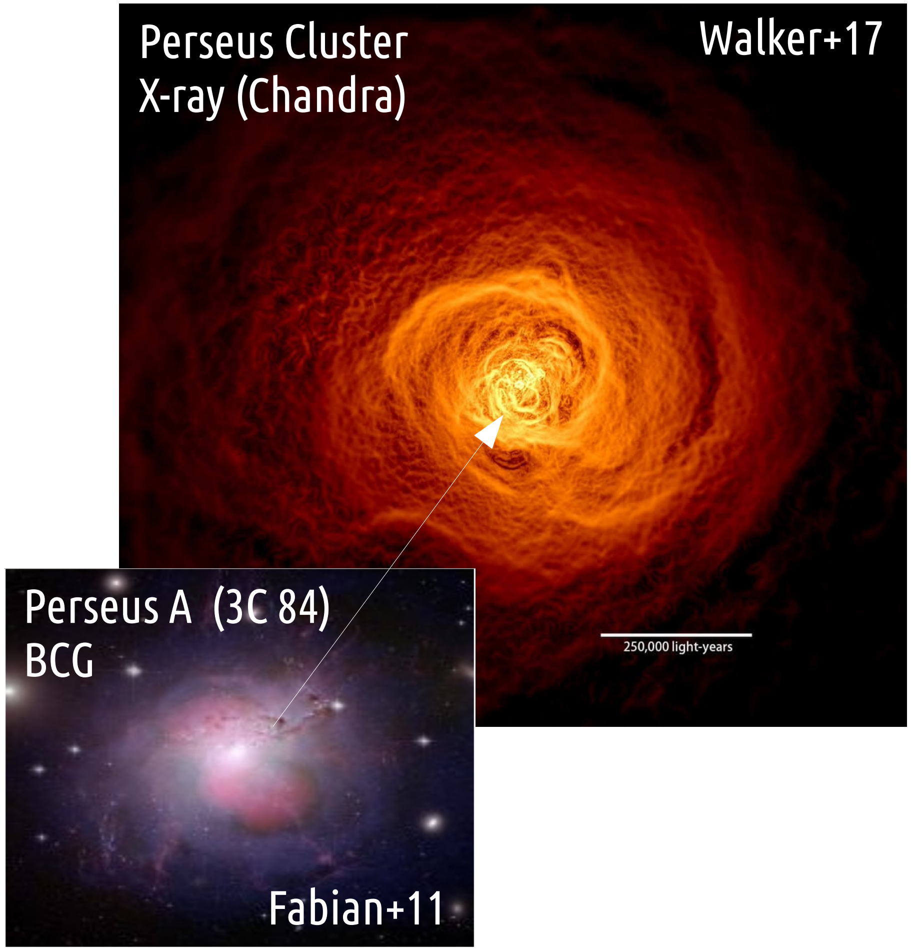


- **Gravitationally bound systems** originated from primordial perturbations in the gravitational density field (Peebles 1993, Peacock 1999)

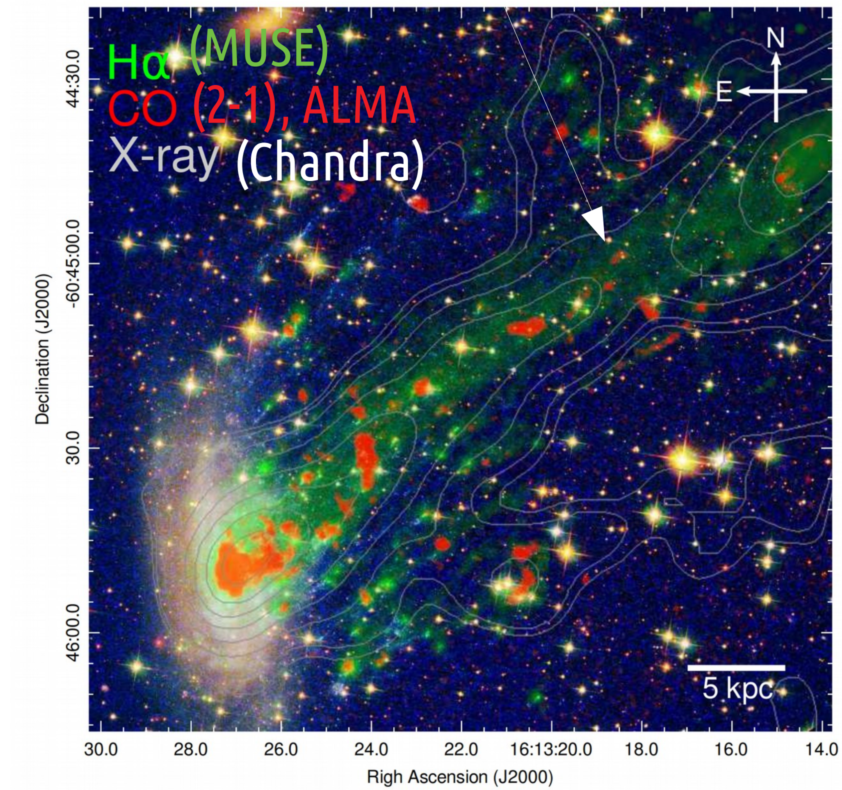
- Masses ~$10^{14\text{-}15}$ solar masses
- Sizes ~1-10 Mpc
- N ~ 50-1000 galaxies

Galaxy clusters as sites of galaxy gas processing

Radio Mode AGN feedback



Ram pressure stripping

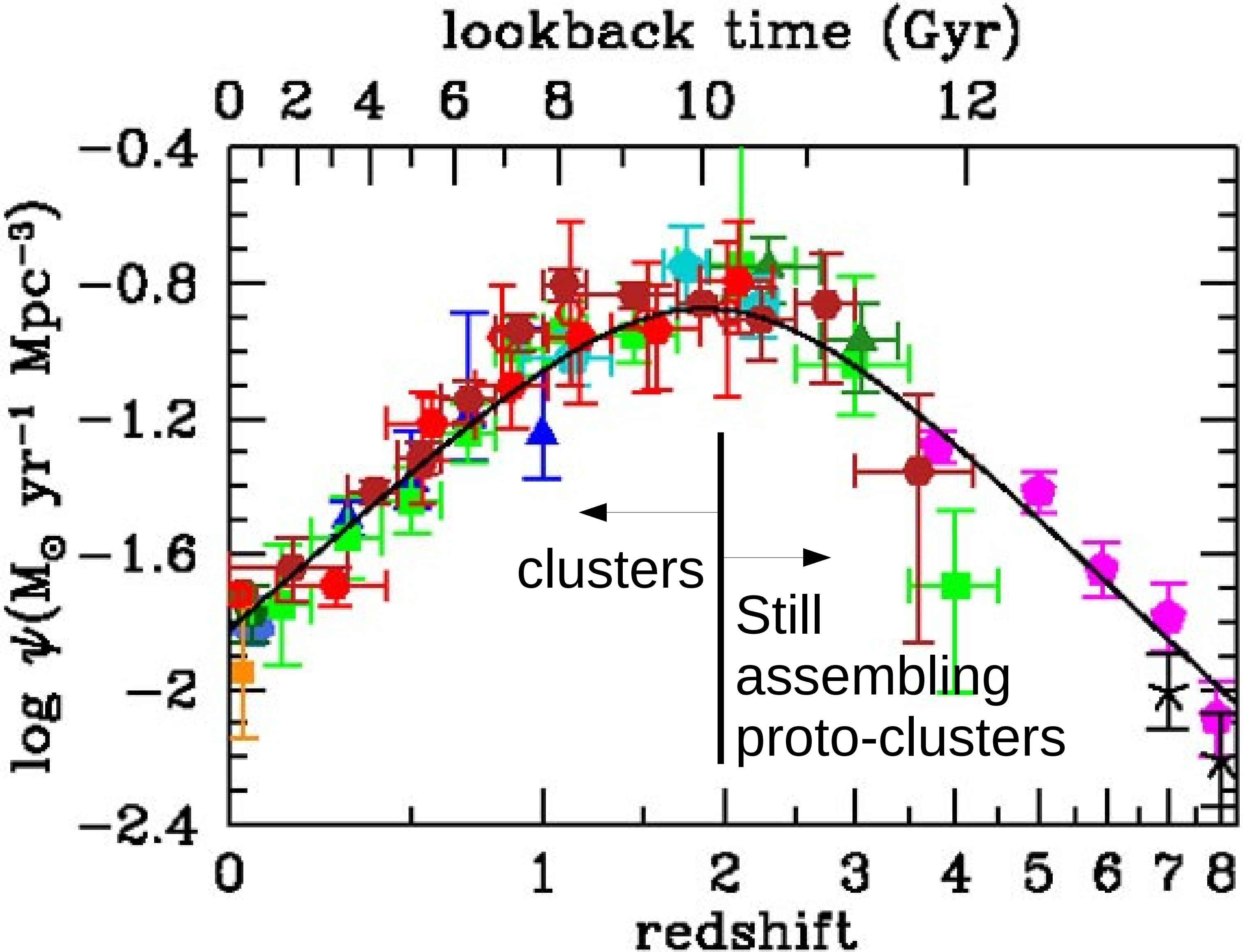


Jellifish galaxy in the Norma cluster (Jachym+19)

Dense environments influence galaxy star formation properties (Dressler+80, Baldry+06, Peng+10,12...)

Radio Galaxies are often hosted by Brightest Cluster Galaxies (BCGs). Both locally and in the distant Universe.
Zirbel 1996, von der Linden+2007, Yu+2018, Castignani+19

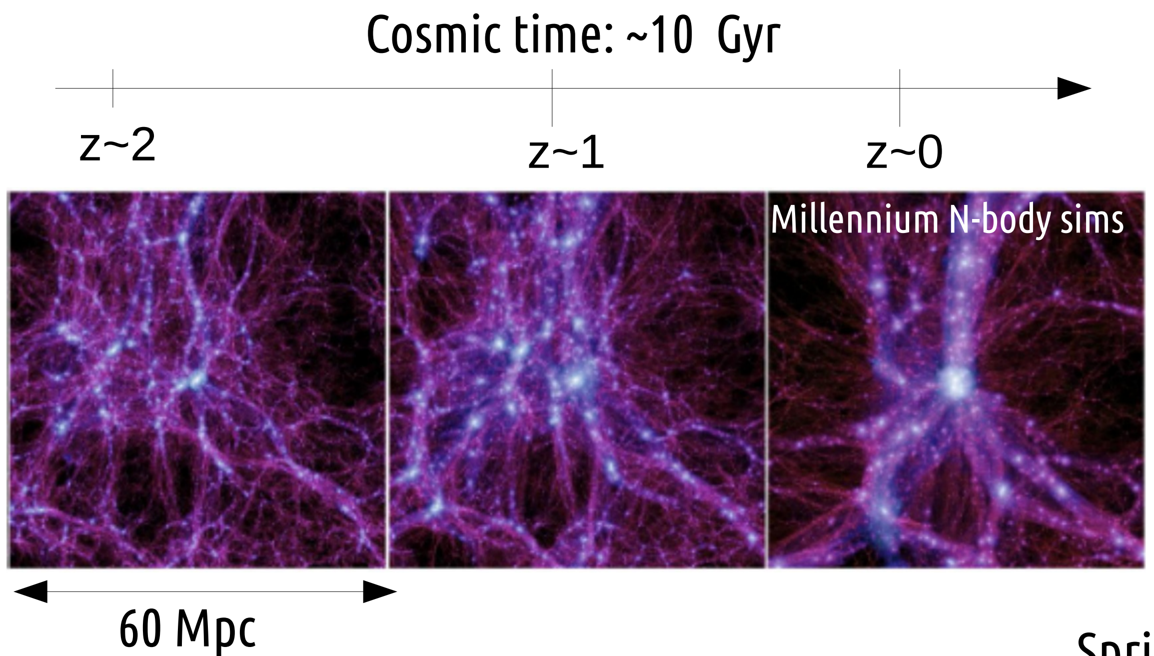
Star formation and cosmic time



Madau & Dickinson (2014)

Large Scale Structures and the Cosmic Web

Galaxies are distributed in a complex filamentary network of matter, the cosmic web, with a large dynamic range of local density (Kitaura et al., 2009; Darvish et al., 2014)



Springel et al. (2005)

The formation of clusters from their progenitor protoclusters is debated

- Only a few confirmed **protoclusters** are known (Overzier et al. 2016)
- They form early, even close to the **epoch of reionization** (Morishita et al. 2022, Laporte et al. 2022)
- Great science cases for **next generation facilities** (*JWST* and next generation spectrographs)

Galaxy evolution in clusters

Some open questions

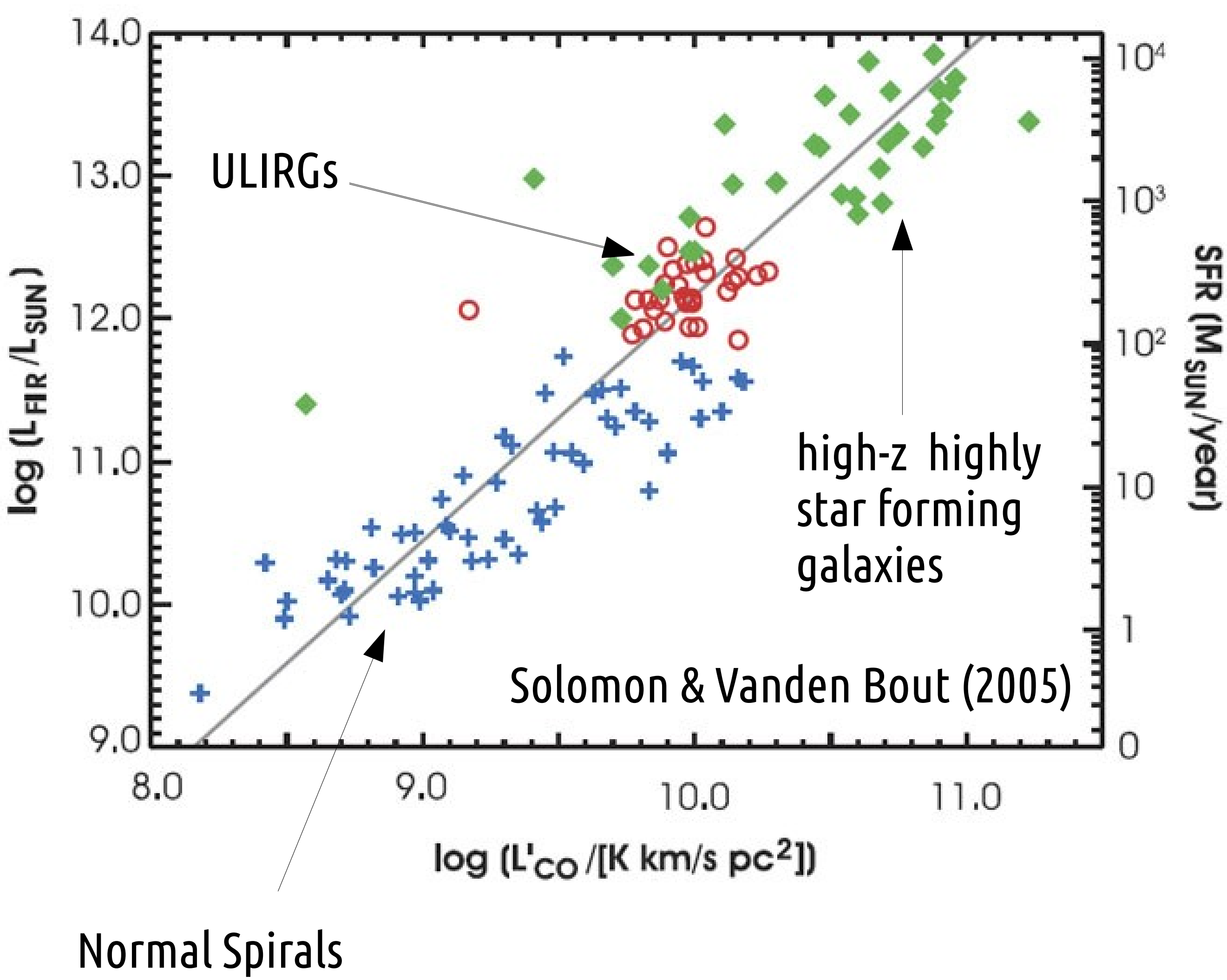
- **BCG evolution is unknown**
  Formation at high-z followed by dry mergers?
  Several episodes of enhanced star formation, even at z<1?
  (e.g., De Lucia & Blaizot 2007, Lidman+12,McDonald+16)

-At high-z (z>~1.5?) the **reversal of the star formation vs density relation** is somehow expected (Smith+10; Tran+10; Webb+13, Alberts+16, Wang+16)

-What is the impact of the environment in **processing the gas galaxies**, as they move in the cosmic web?
(Haines+15, Malavasi+16, Laigle+18, Castignani,Jablonka+20a)

-What's the **fate of molecular gas reservoirs** observed in distant proto-clusters ?
(Papadopoulos+00, De Breuck+05, Emonts+11)

Molecular gas as tracer of star formation activity



The interstellar molecular gas is the raw material from which stars form

H_2 forms in dust grains and is found in dense molecular gas

However, difficult to detect, it does not have a strong dipole

CO : strong dipole moment.

$M_{H2} = \alpha_{CO} L'_{CO}$

α_{CO} ~ 1 – 10 std. units

Search for molecular gas in galaxies in and around clusters over 10 Gyr of cosmic time

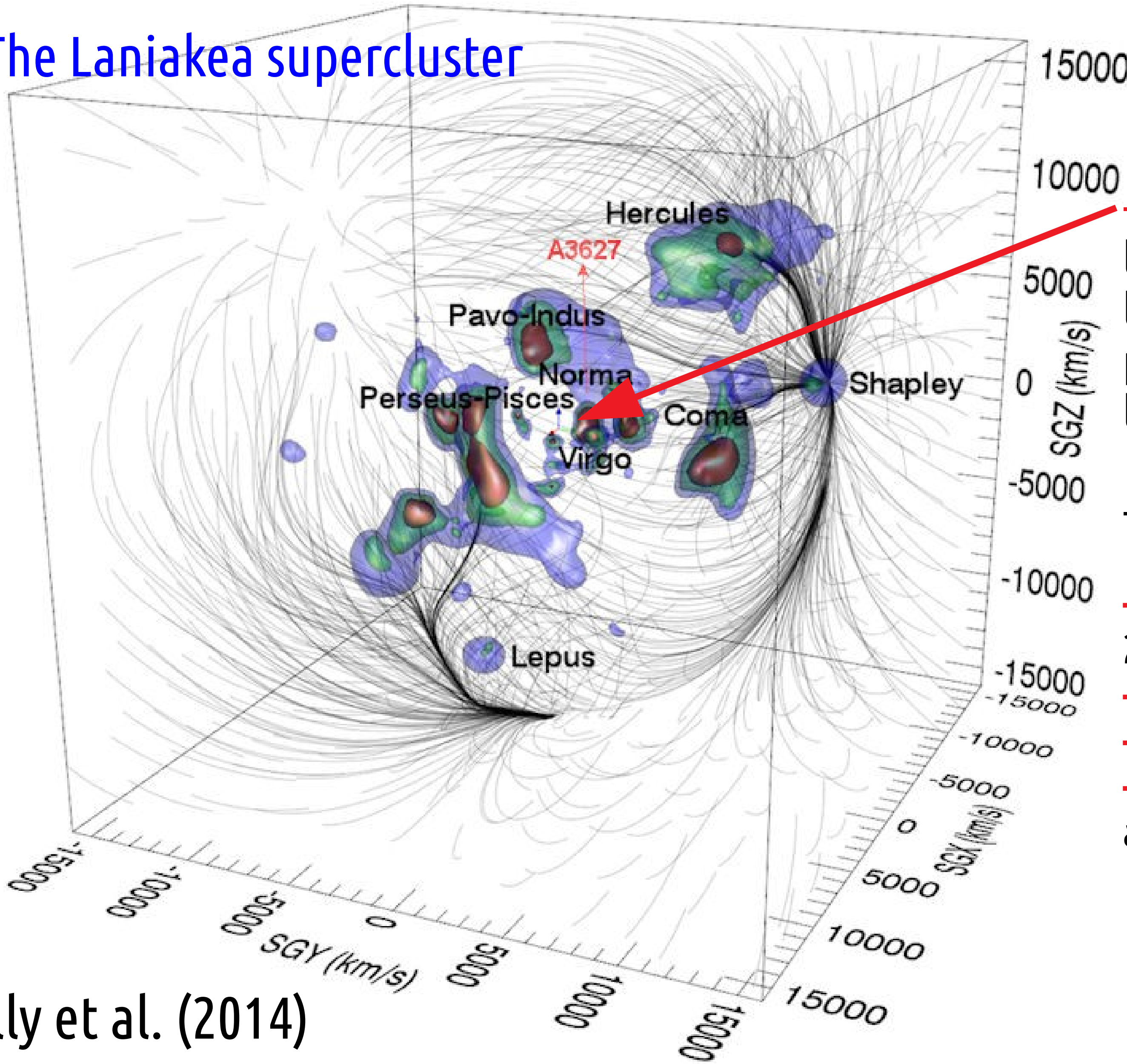
Large observational campaign with IRAM facilities at millimeter wavelengths

I. The local Universe.

Preprocessing in cosmological filaments

I. The local Universe.
Preprocessing in cosmological filaments

The Laniakea supercluster



- Virgo: benchmark cluster in the local Universe optimal laboratory to evaluate pre-processing of galaxies in the local universe

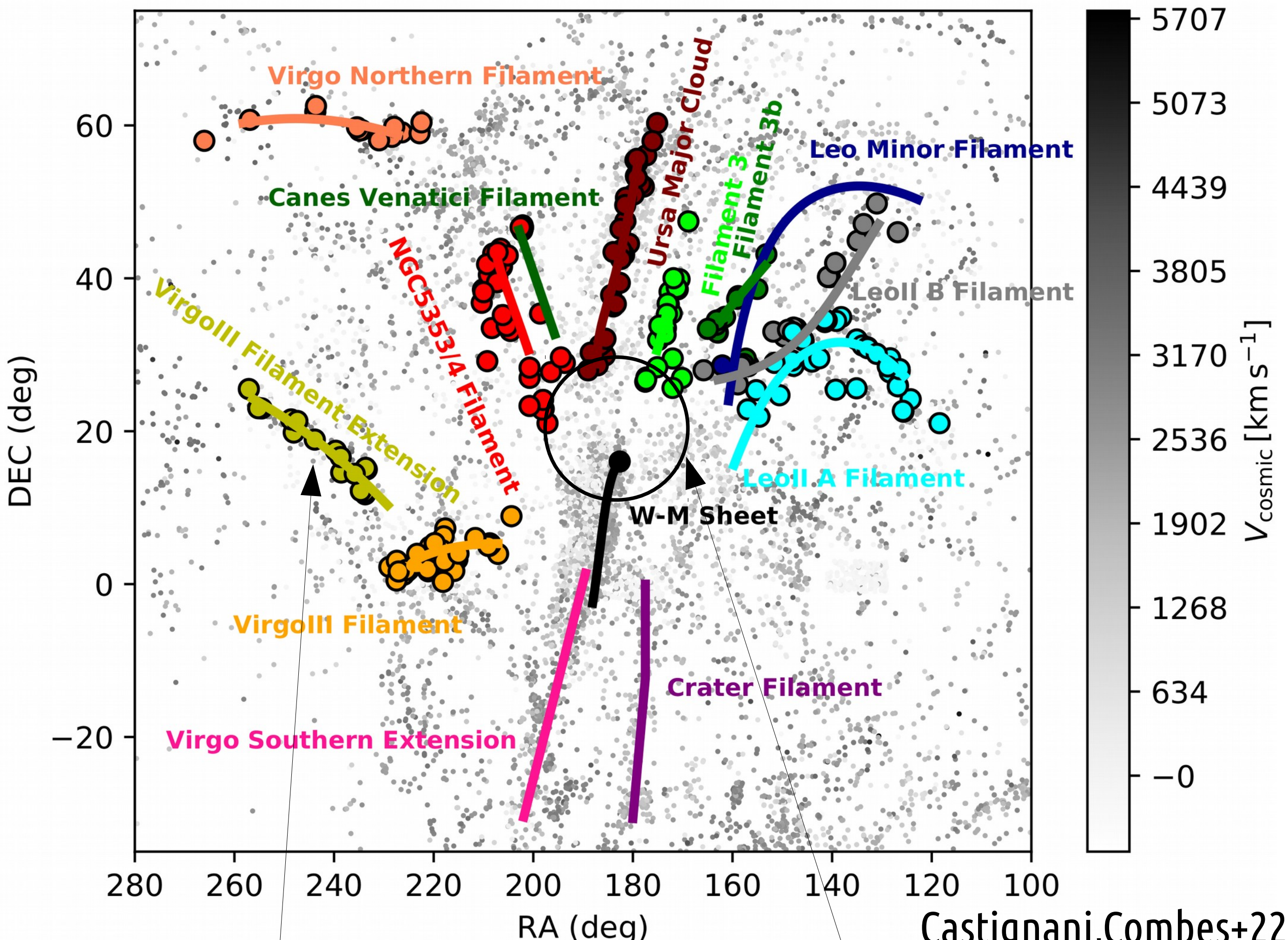
-Virgo cluster: existing data

- **Atomic gas**, HI: (VLA, Chung et al 2009; ALFALFA, Giovanelli et al 2005)
- **dust**: (Herschel; Davies et al 2010),
- **stellar masses** (Ferrarese et al 2012)
- **SFR** (UV, GALEX GUViCS, Boselli et al 2011).

Tully et al. (2014)

Pre-processing in Virgo filaments

Virgo: benchmark cluster in the local Universe
(Laniakea supercluster)



Castignani,Combes+22

Dots: filament galaxies with CO and HI observations

Virgo cluster core (r_{200})

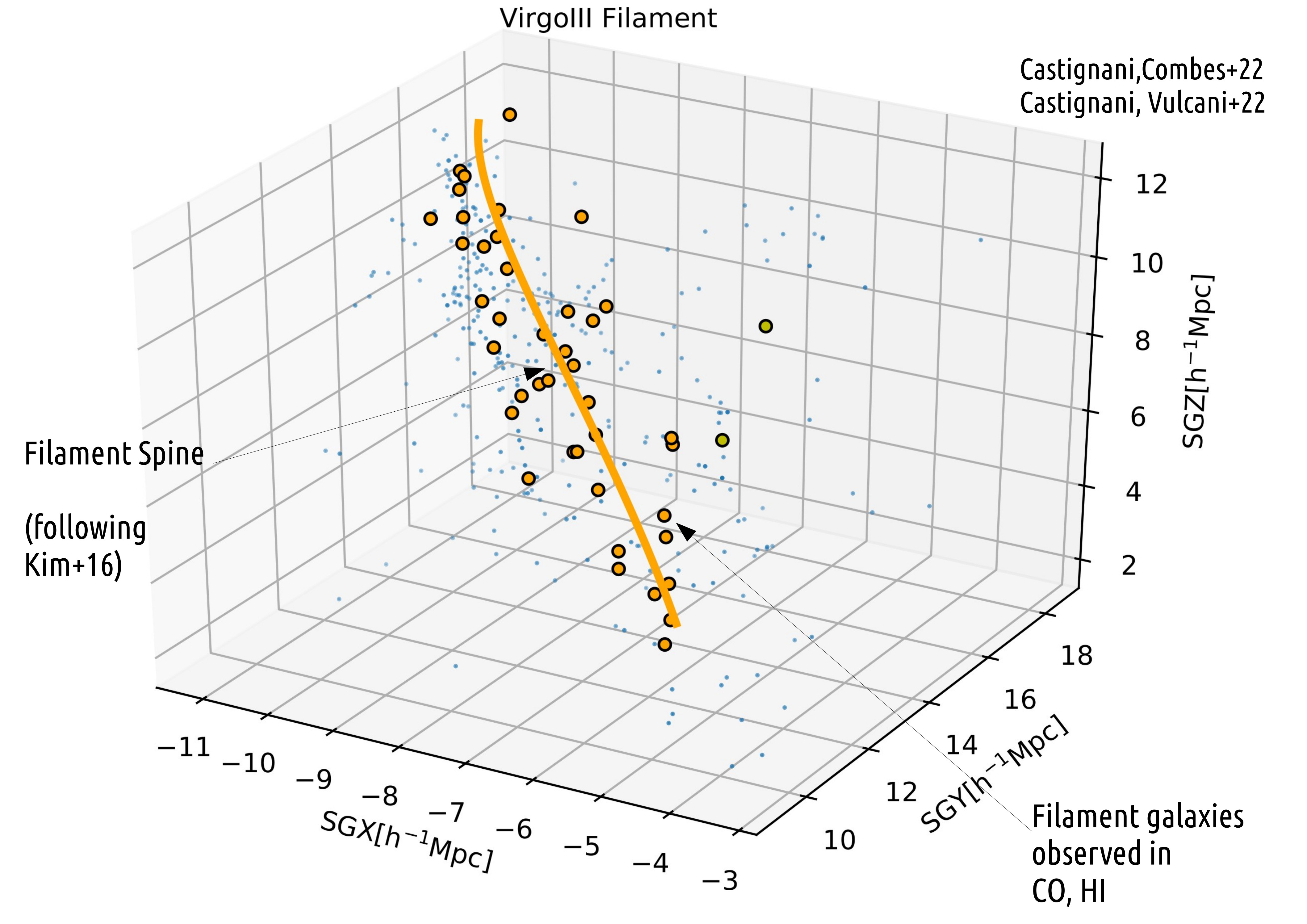
Galaxies also experience pre-processing, before they fall into the cluster cores.
(e.g., Malavasi+16, Laigle+18, Cortese+06, Poggianti+99)

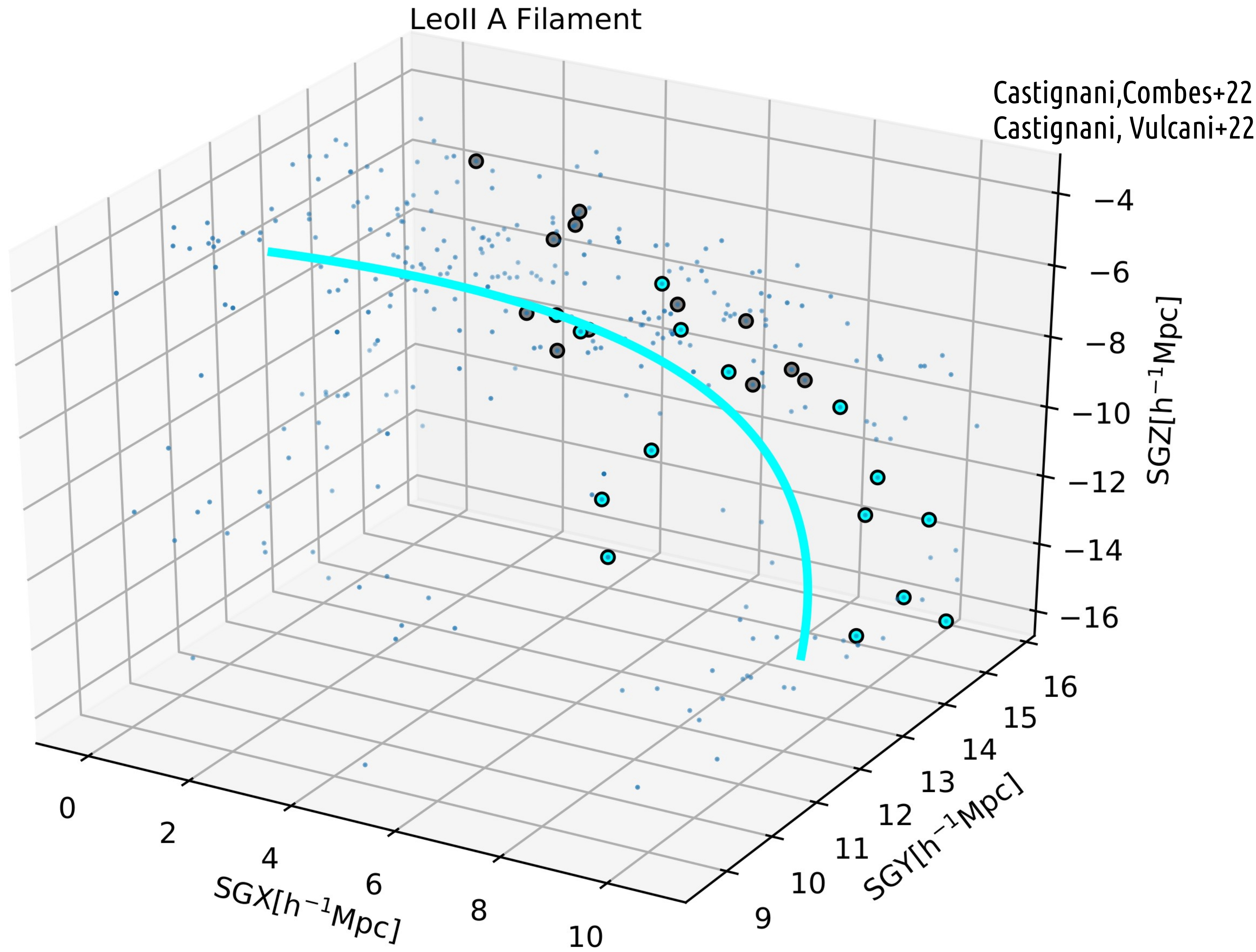
Virgo Filament Survey

-**Mass complete sample of filament galaxies**
Mstar = $10^{9\text{-}11}$Msun
245 sources

- **Molecular gas :**
CO(1-0) and/or CO(2-1)
85% from our IRAM30m survey

- **Atomic Gas: HI**
24% from our Nancay survey


VirgoIII Filament
Castignani,Combes+22
Castignani, Vulcani+22
Filament Spine
(following
Kim+16)
Filament galaxies
observed in
CO, HI
SGX[h⁻¹Mpc]
SGY[h⁻¹Mpc]
SGZ[h⁻¹Mpc]
−11 −10 −9 −8 −7 −6 −5 −4 −3
10 12 14 16 18
2 4 6 8 10 12


LeoII A Filament
Castignani,Combes+22
Castignani, Vulcani+22
SGX[h^{-1}Mpc]
SGY[h^{-1}Mpc]
SGZ[h^{-1}Mpc]
0
2
4
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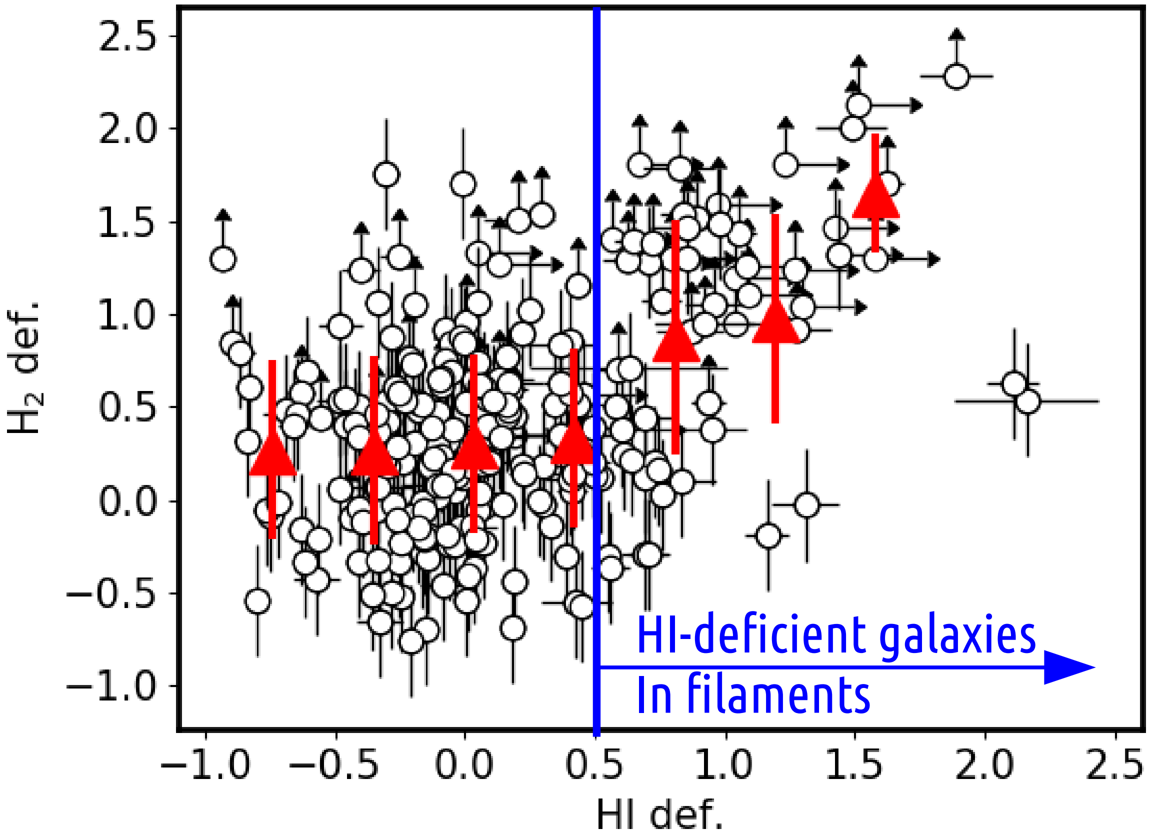
−16

Pre-processing in Virgo filaments



H2-def and HI-def correlation for filament galaxies

↓

Environment-driven pre-processing of cold gas in galaxies in groups well before they fall into Virgo

Castignani, Combes et al. 2022

M_{HI} → HI-deficiency

M_{H2} → H_2-deficiency

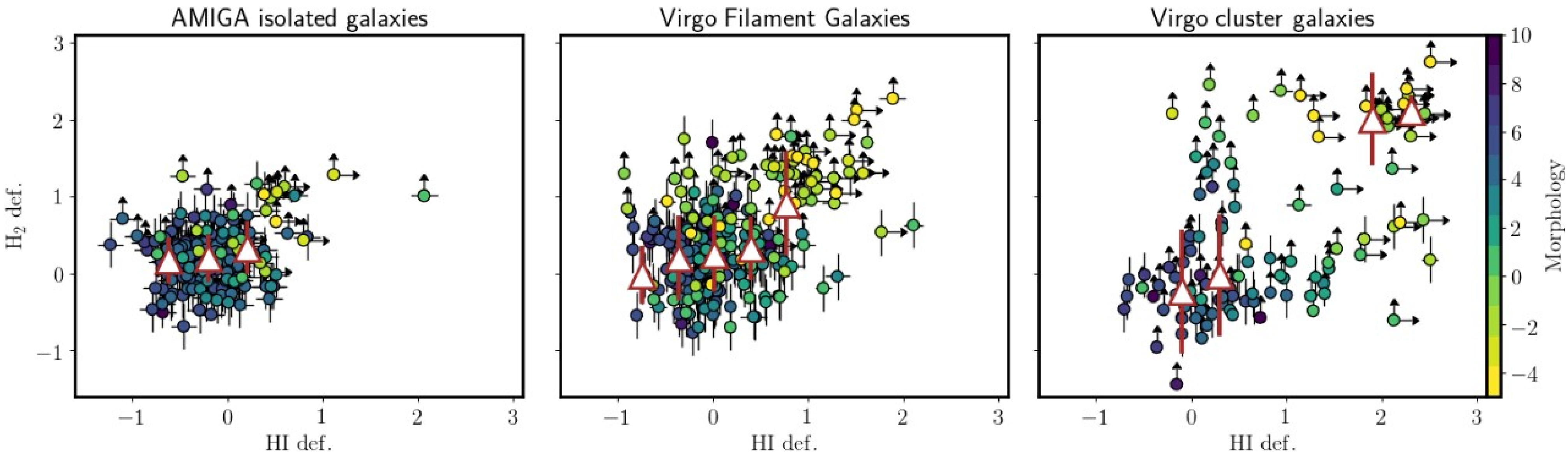
New high-resolution CO maps with NOEMA/SMA will give insights on the physics of the processing (starvation, stripping, etc…) – PI: Castignani

We also have new MeerKAT observations in HI – PI: Jablonka

Deficiency: H_2 vs HI

M_{HI} → HI-deficiency
M_{H2} → H_2-deficiency

Castignani, Combes et al. (2022)



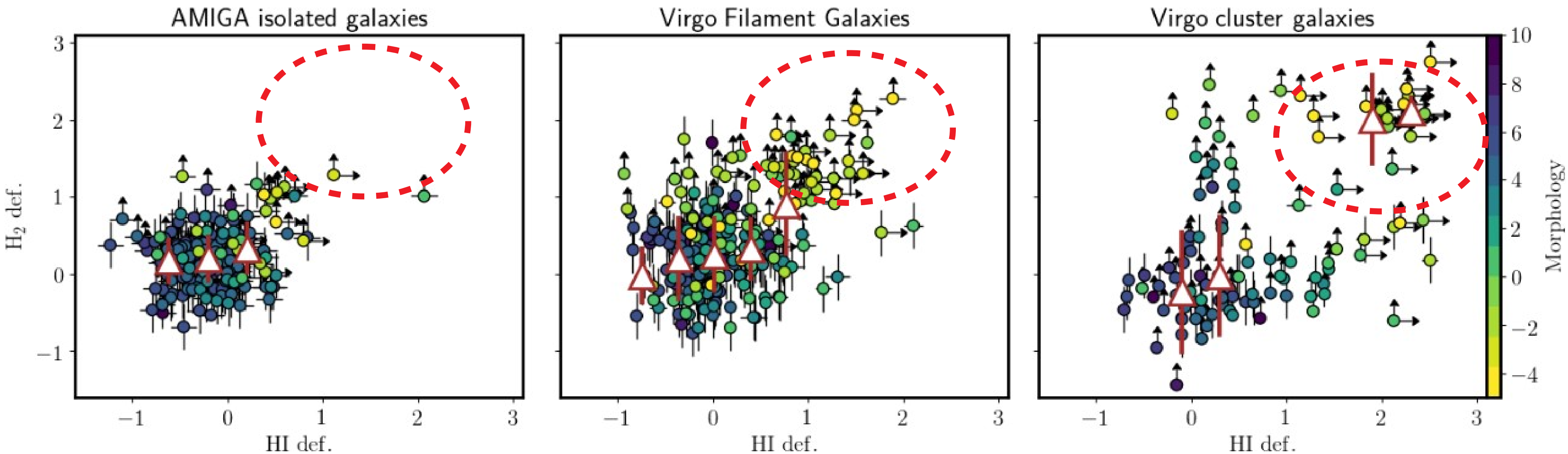
- Emergence of ETGs as we move to the field (left) to filaments (center)

- Increase scatter as we move from field, filaments, to the cluster

Deficiency: H_2 vs HI

M_{HI} → HI-deficiency
M_{H2} → H_2-deficiency

Castignani, Combes et al. (2022)



Gas reservoirs (both HI, H_2) in ETGs in filaments have likely already experienced environmental preprocessing (e.g., dry mergers, starvation, HI ram pressure stripping), which favored the exhaustion of H2 gas and the removal of the HI envelope.

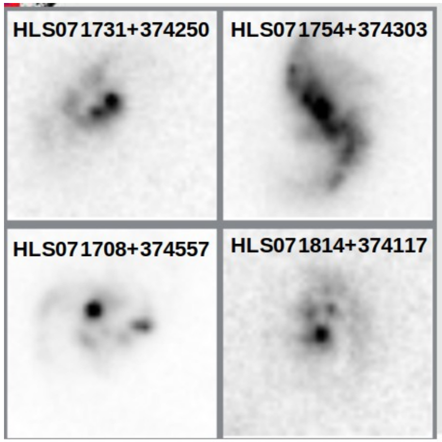
Virgo cluster then finalizes the processing.

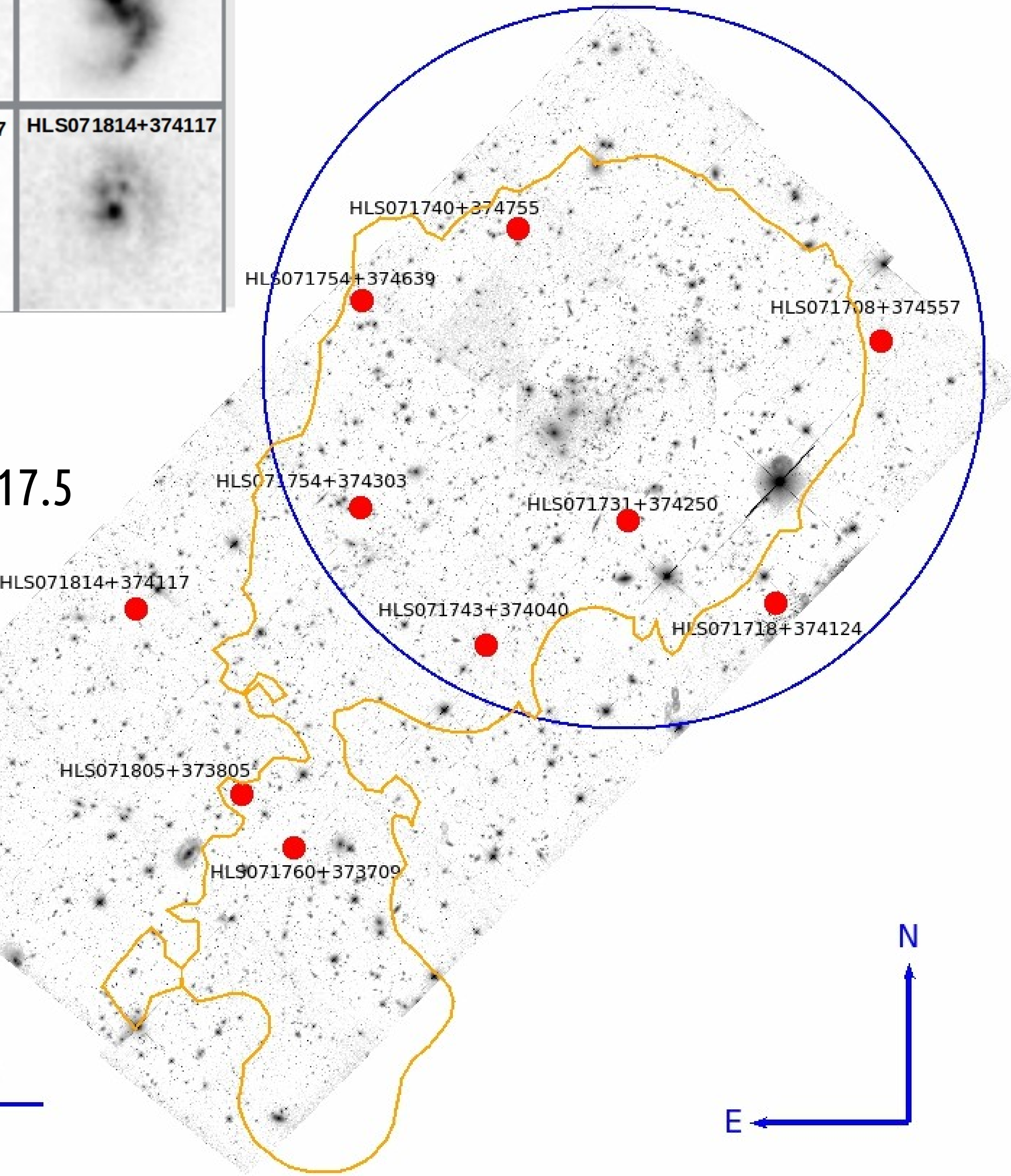
I. Intermediate redshifts.

Processing of gas in and around clusters

(pre-)processing in cluster Luminous Infrared Galaxies (LIRGs)

Castignani, Jablonka et al. (2020)



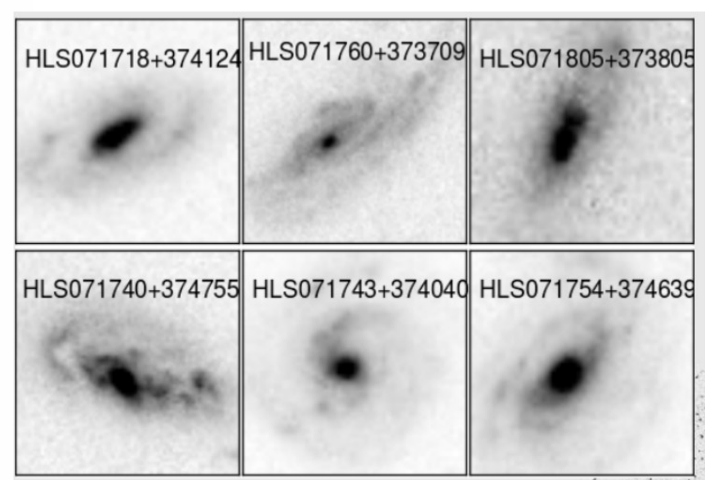


MACS J0717.5
(z=0.55)

→ 20 LIRGs (HLS, LoCuSS)

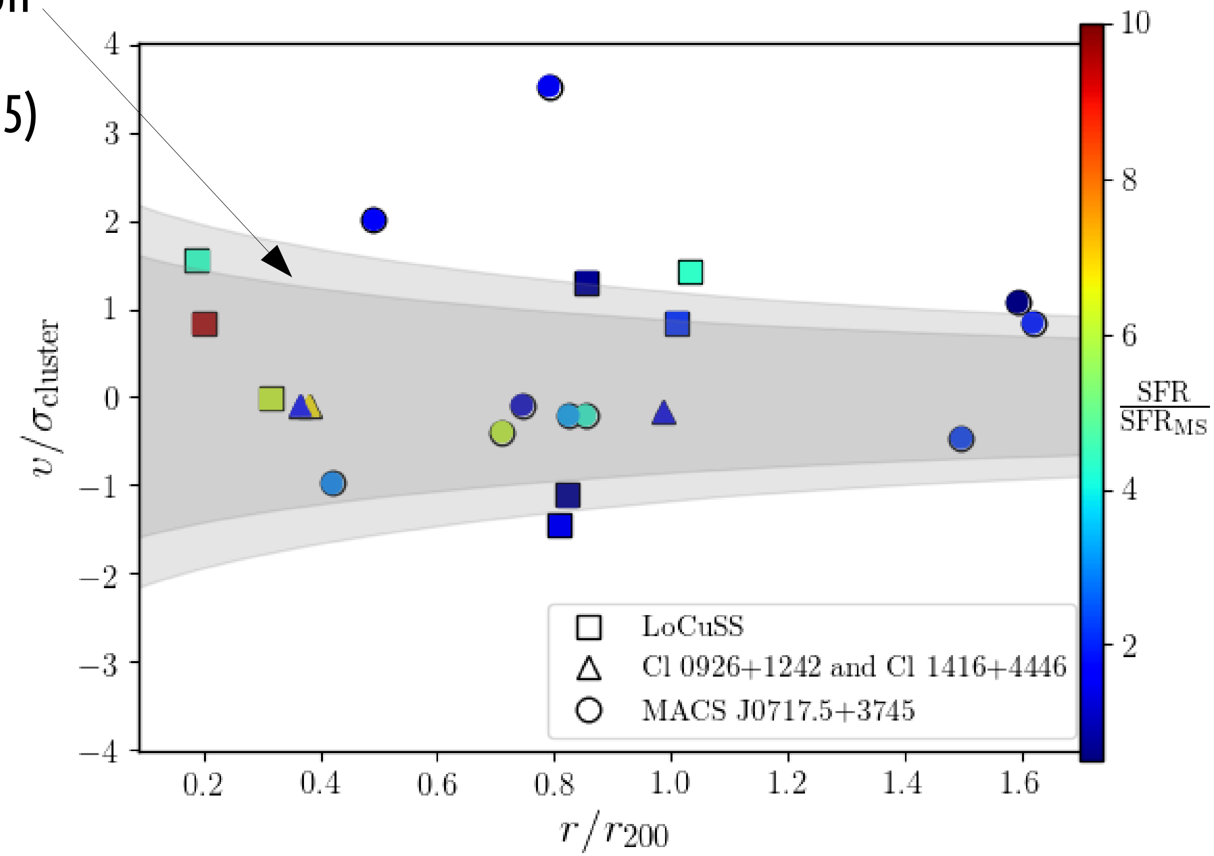
→ Five intermediate z~0.2-0.5 clusters: A2219, 1763, 697, 963, and M0717

→ 5 NOEMA/PdBI programs targeting CO(1-0) or CO(2-1)



Phase space diagram

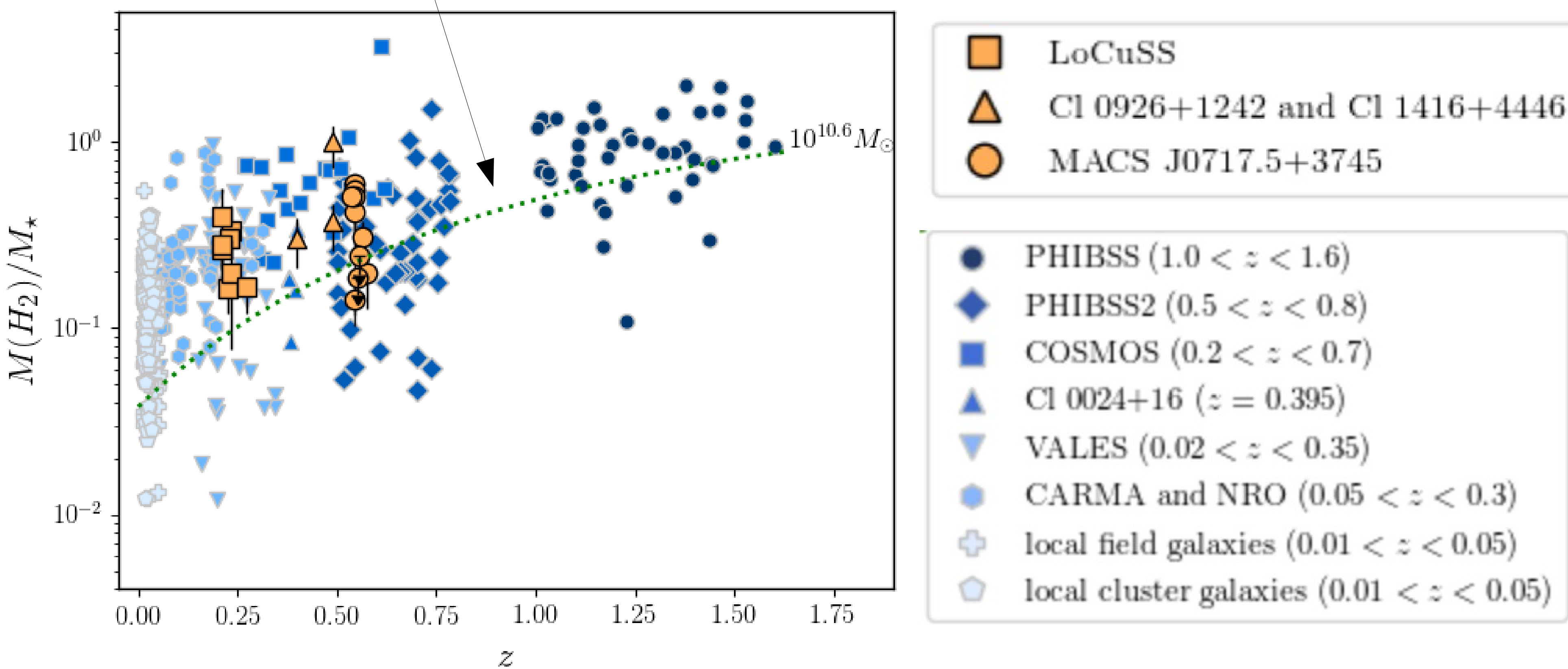
Virialized region
of the clusters
(Jaffé et al. 2015)



Castignani, Jablonka et al. (2020)

Molecular gas content

Main sequence relation
Tacconi et al. 2018

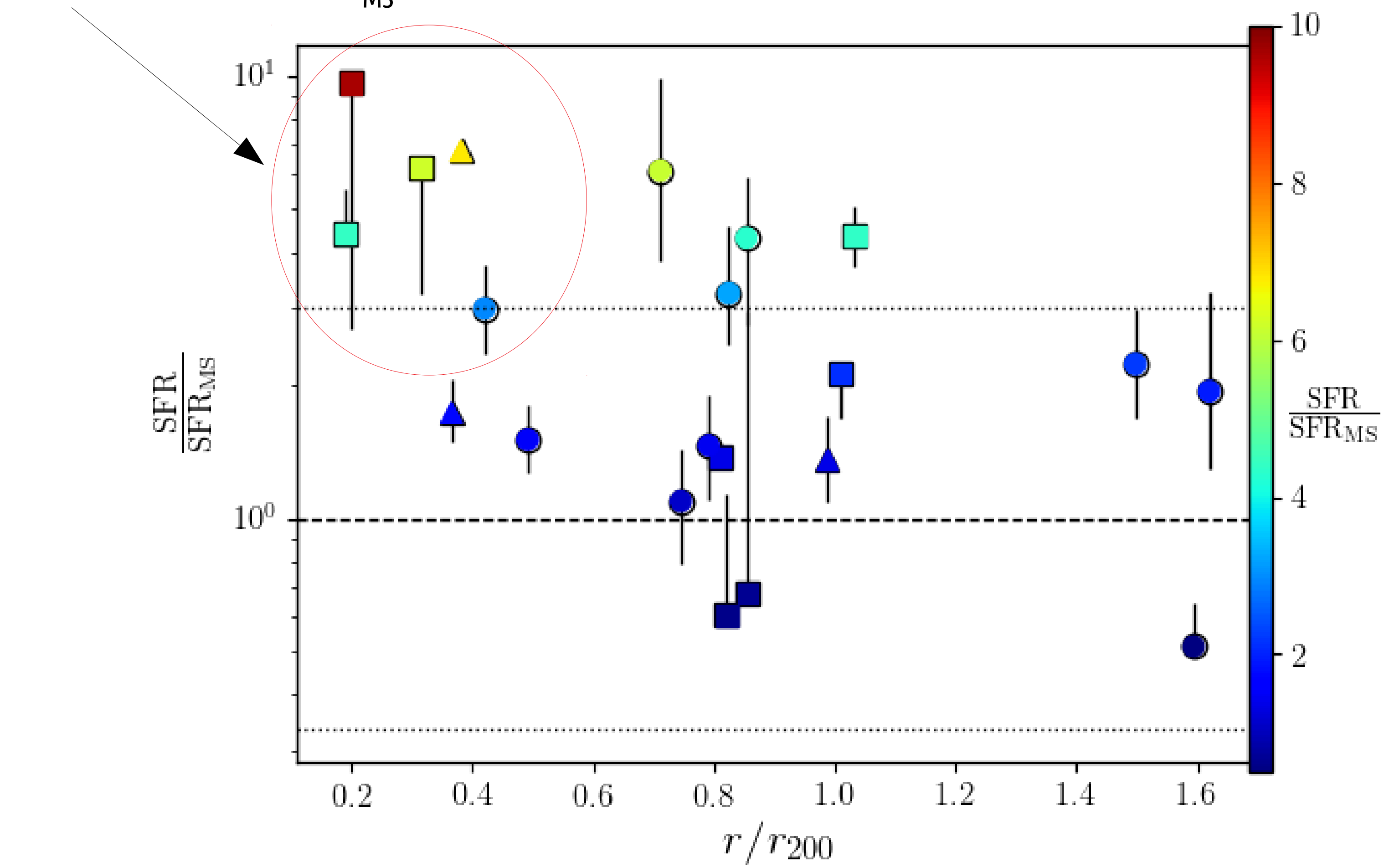


$M_{H2} \sim (1\text{-}5)\ 10^{10}\ M_\odot$

Castignani, Jablonka et al. (2020)

Molecular gas content

Excess of SFR >~ SFR_{MS} sources

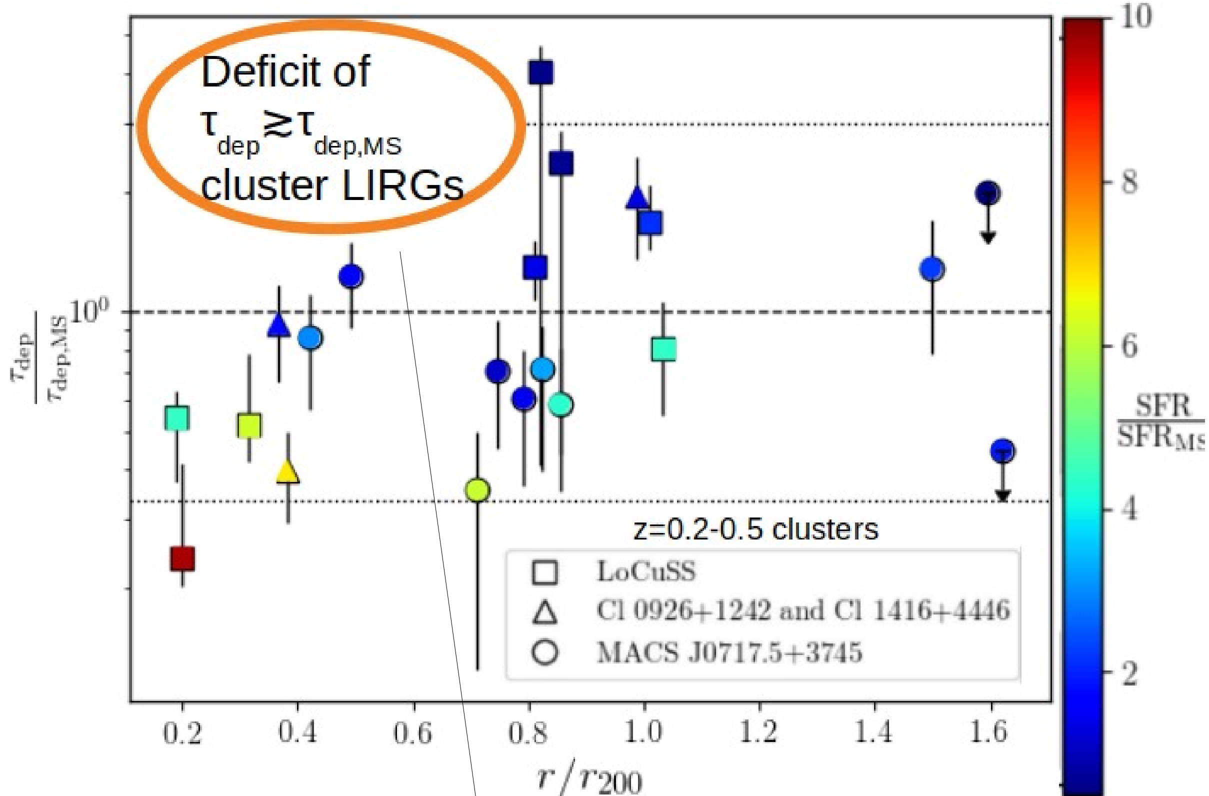


Castignani, Jablonka et al. (2020)

(pre-)processing in cluster Luminous Infrared Galaxies (LIRGs)

Castignani, Jablonka et al. (2020)

$t_{dep} = 1/SFE = M_{H2}/SFR$



→ processing in LIRGs as they fall into the cluster core.

This exhaustion may explain the exponential decrease of the fraction of cluster LIRGs with cosmic time (Finn+08)

1- SF enhancement
2- H_2 not altered

→ Rapid exhaustion of H_2 gas, possibly via gas compression induced by ICM shocks

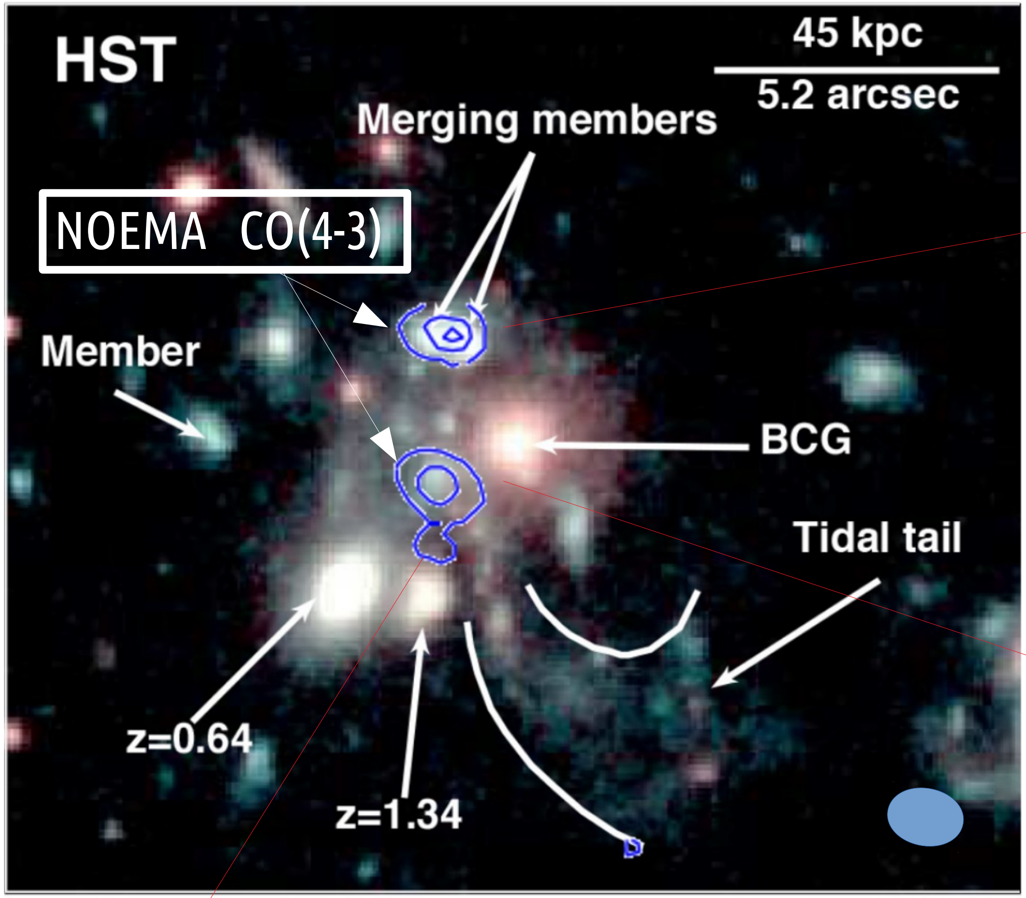
III. Search for molecular gas in distant Brightest Cluster Galaxies (BCGs)

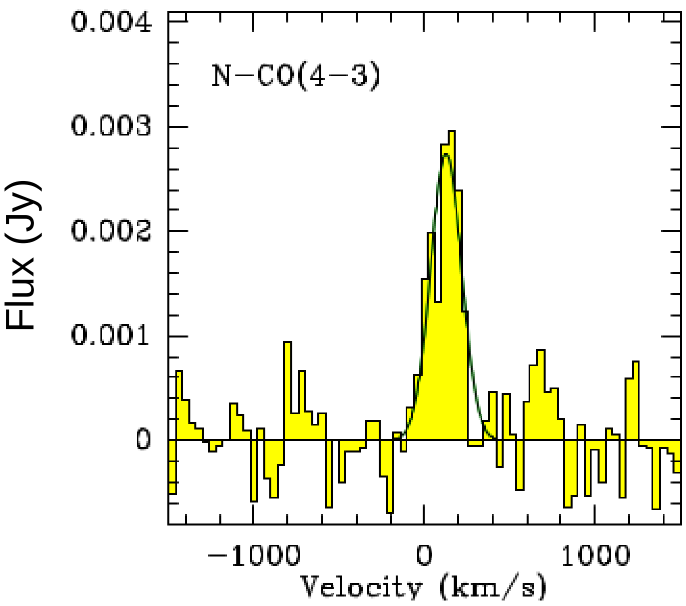
Evolution and mass assembly of the most massive galaxies (at the center of clusters) is still a matter of debate, in particular at $z>1$, where cluster cores undergo strong evolution

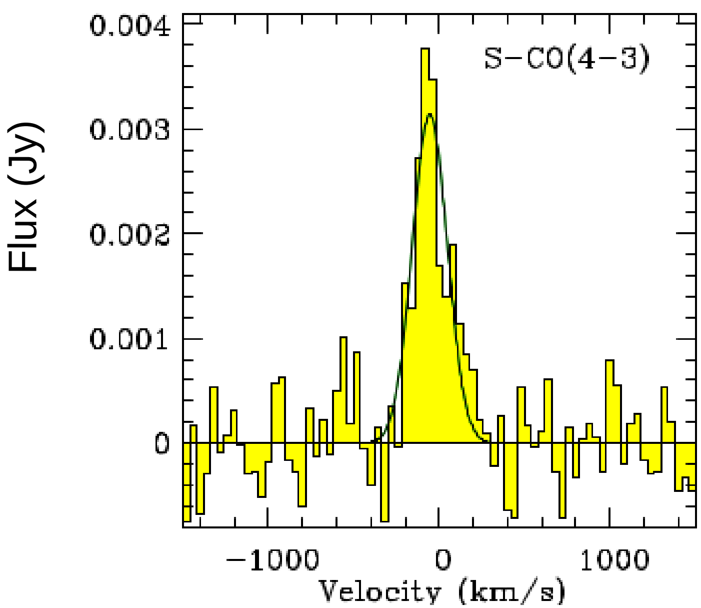
One of the most distant BCGs (z=1.7)

SpARCS1049+56

Castignani, Combes, & Salomé (2020)

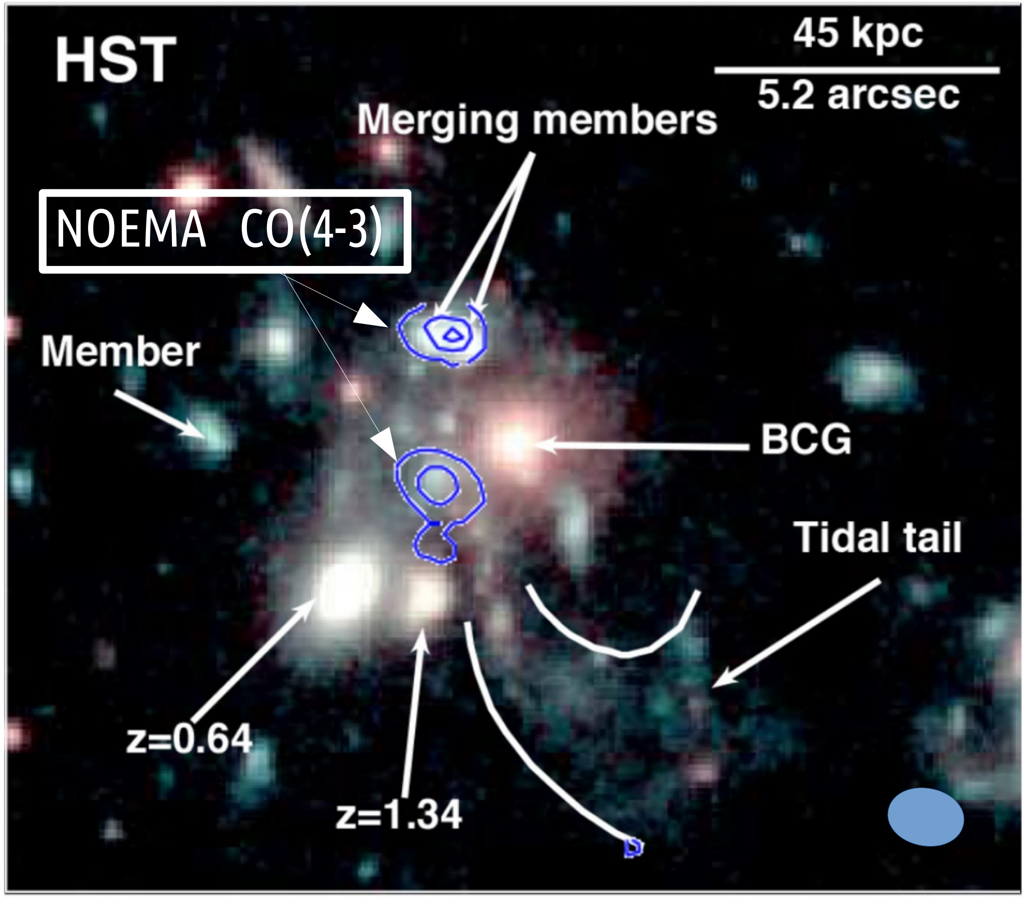






Tail in CO and in continuum!
Possibly the most distant jelly-fish galaxy

The stellar mass assembly of the BCG at play



Castignani, Combes, Salomé (2020)

SpARCS1049+56 BCG:

Gas rich companions are detected both in
→ CO(4-3)
→ continuum

A) These gas-rich systems will potentially merge with the BCG

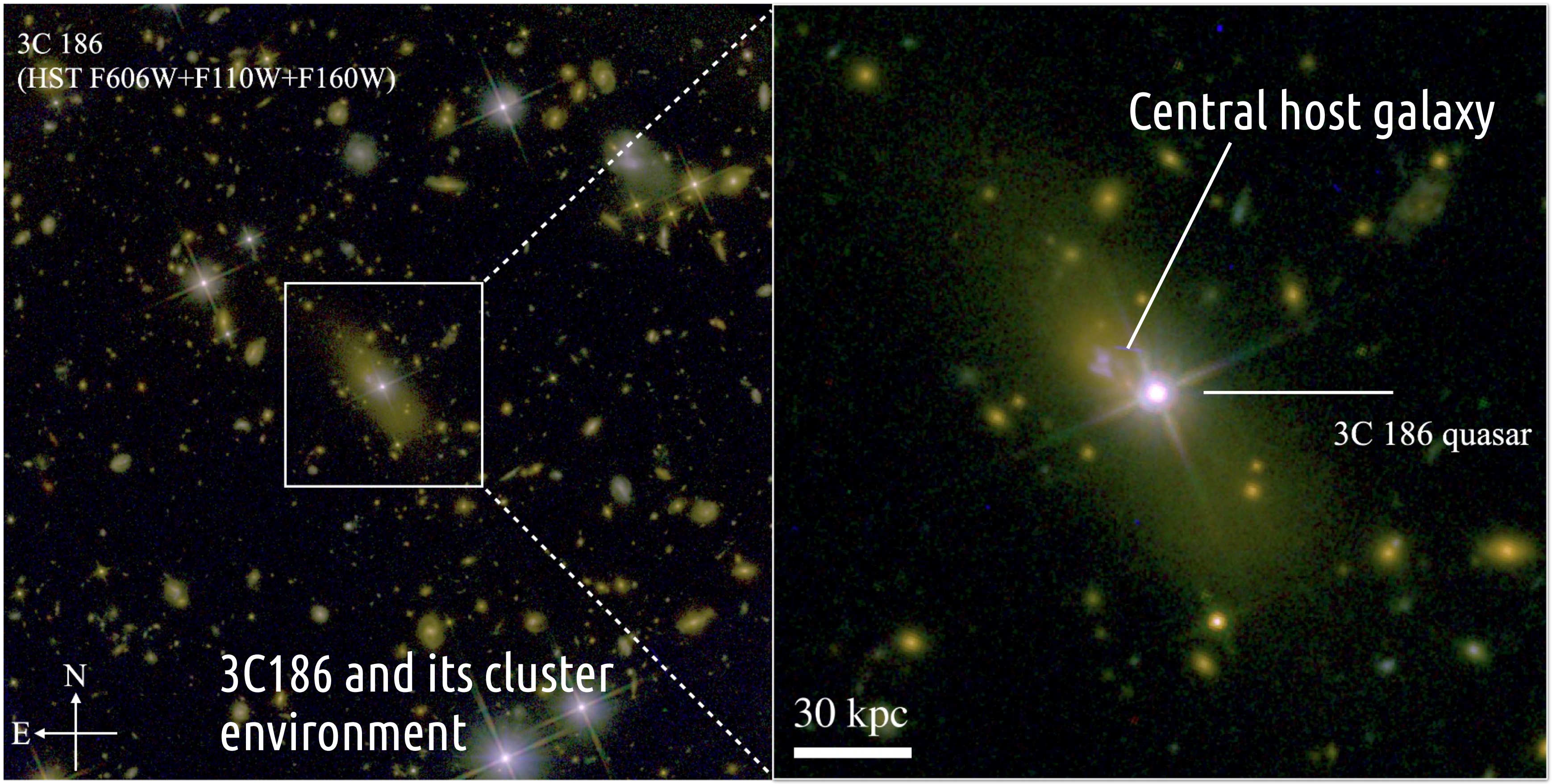
B) We may be seeing the reversal of the star formation - density relation

C) Assembly of high-z BCG in great detail

- Alternative proposed:
Strong ICM cooling of gas results in the observed CO emission (Capucine+22)

3C186 at z=1.06

Brightest Cluster Galaxy (BCG) of a z=1 cool-core cluster (Siemiginowska+05,10)

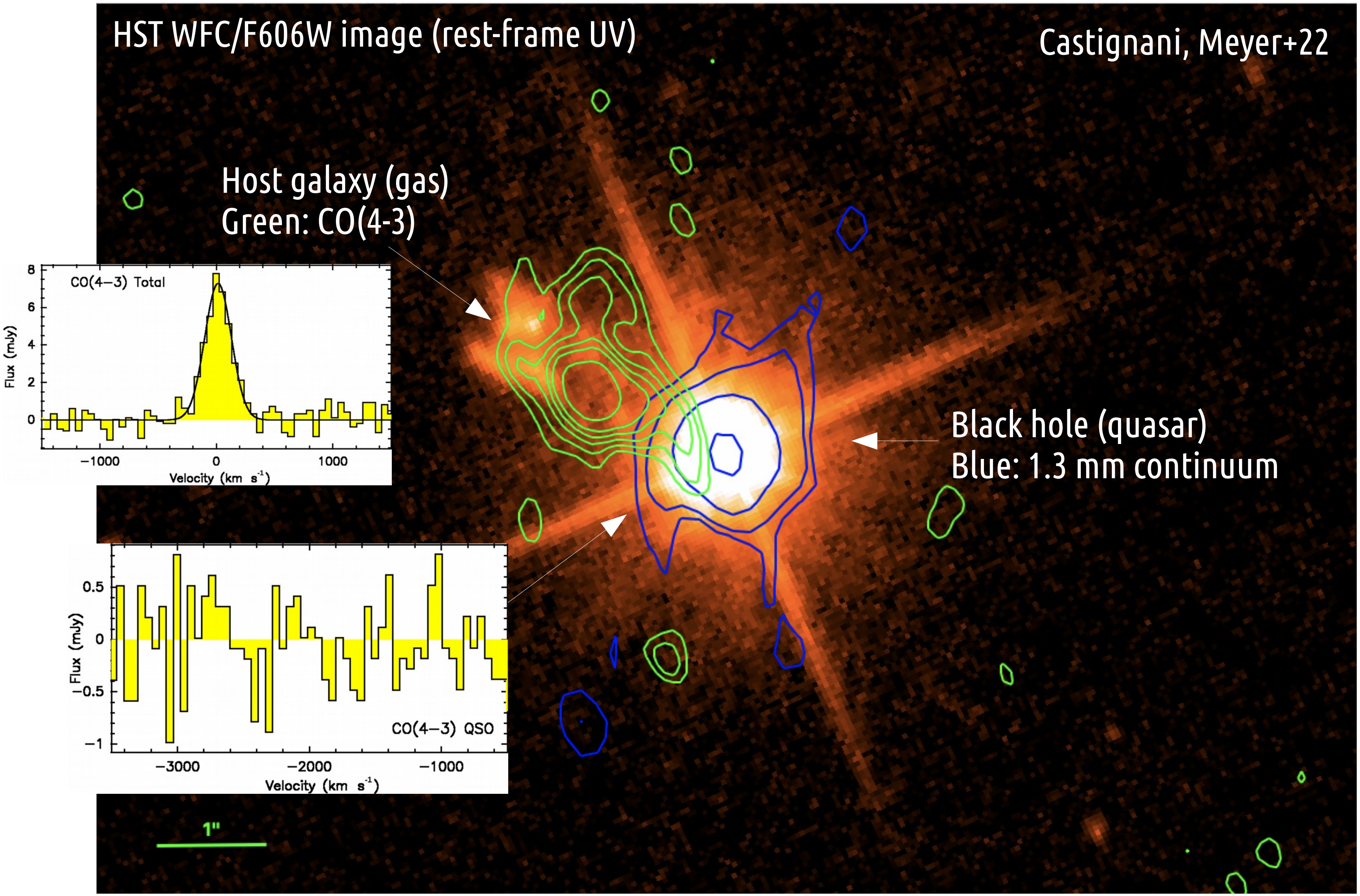


Morishita+22, incl. Castignani

- 1.4'' (12 kpc) projected offset between the galaxy center and the QSO
- 2000 km/s shift between the BLR and NLR

3C186 at z=1.06: the BCG of a cool core-cluster

GW recoil candidate:
The SMBH is expelled out of the galaxy after the merger of the parent galaxies (see also Chiaberge+17, 18)



Clear offset of 1.4'' = 12 kpc between the two.

Search for CO in intermediate-z BCGs

Star forming BCGs at intermediate-z :

- A transitioning population between local and z>1 BCGs
- High-z counterparts of local star forming BCGs (>40 Mo/yr, e.g. Perseus A, Centaurus A)

I. CLASH BCGs

Four IRAM-30m programs (2017-2020)

Castignani et al. (2020b)

II. KiDS BCGs

Two IRAM-30m programs (2021)

Castignani, Radovich et al. (2022ab)

The sample of CLASH BCGs

Cluster Lensing and Supernova Survey (CLASH) Postman+12

→ 25 massive clusters at z~0.2-0.9
→ Ideal survey for lensing studies

→ … but also for studies of galaxy evolution in clusters , with a lot of ancillary data: HST, Chandra, VLT, ... (Annunziatella+14,16, Burke+15; Yu+18; Durret+19, Donahue+16, ...)

IRAM 30m observations : 4 projects over 2017 – 2020 (Castignani, Pandey-Pommier et al. 2020)

→ 18 CLASH BCGs at z~0.2-0.9

→ 82% completeness in the Northern hemisphere

→ targeted lines CO 1-0, 2-1, 3-2, and/or 4-3

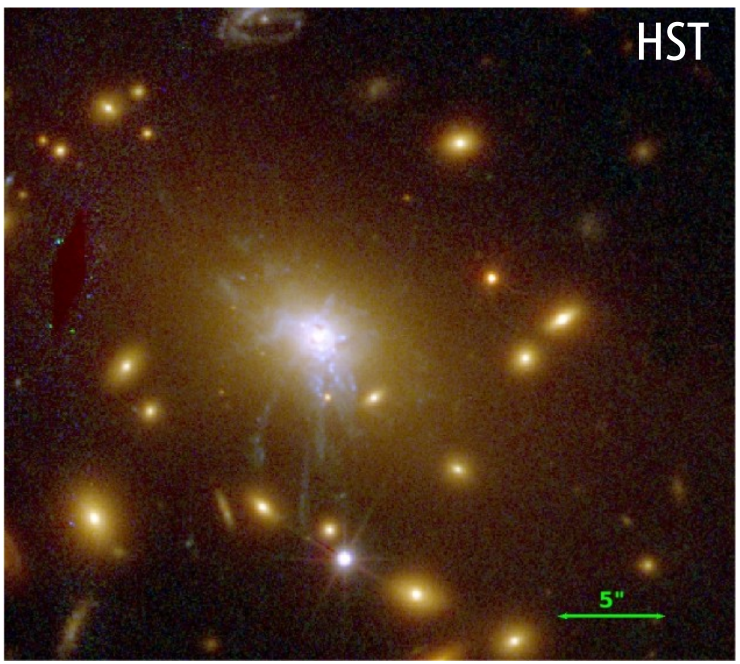
→ SFR (UV, Ha) by Fogarty+15

IRAM 30m results

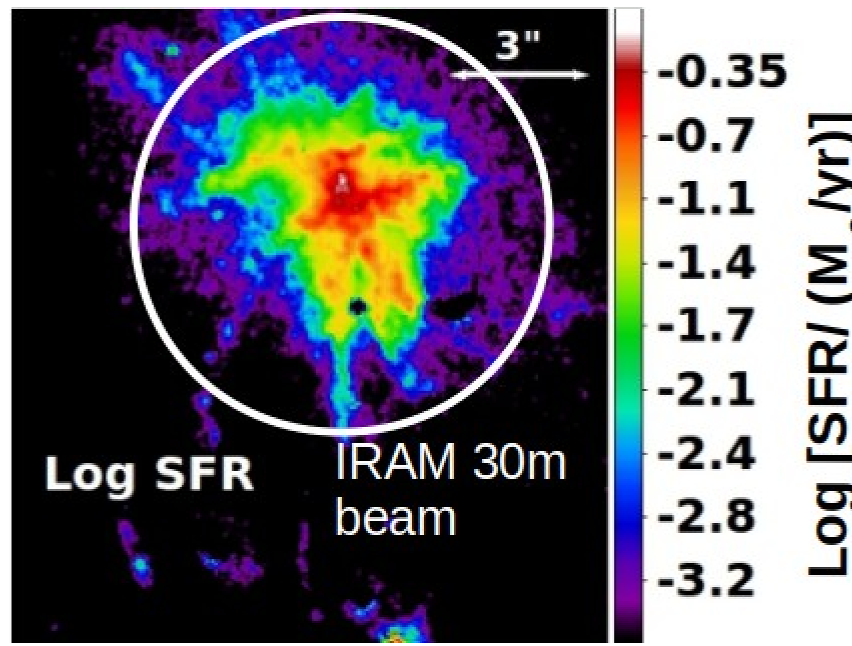
- Out of 18 BCGs 4 sources are tentatively detected in CO
- However… RX1532 at z=0.36 is clearly detected both in CO 1-0 and 3-2

→ Gas rich & star forming BCGs are rare!

RX1532 BCG



Fogarty+15



SFR (UV, Ha)>~100 $M_\odot$ /yr

IRAM 30m results

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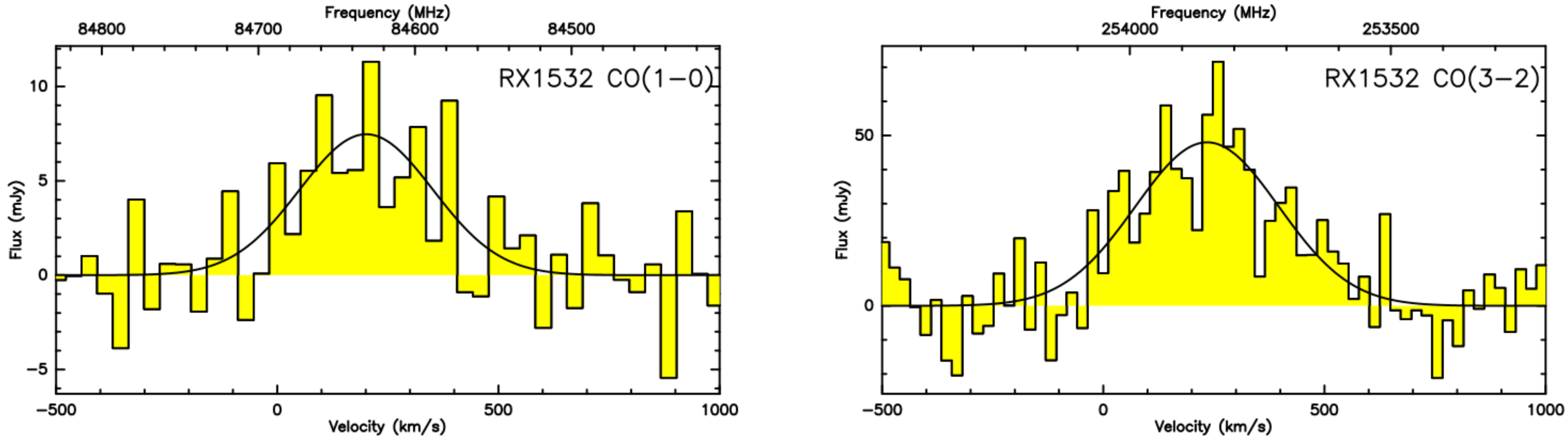
RX1532 BCG



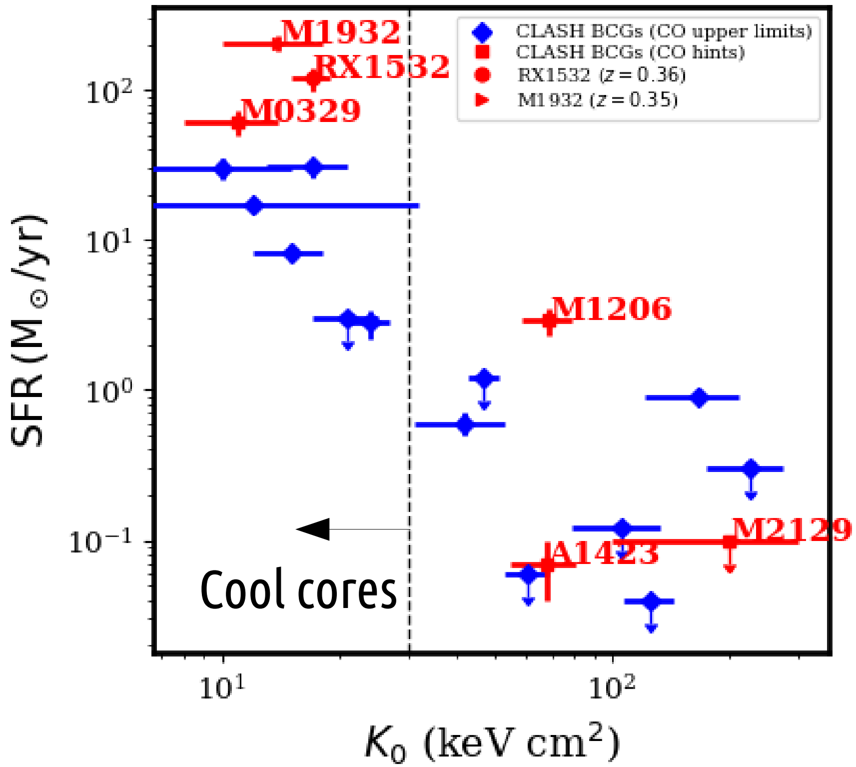
→ Large molecular gas reservoir: $M_{H2} = (8.7 \pm 1.1)\ 10^{10}\ M_{\odot}$

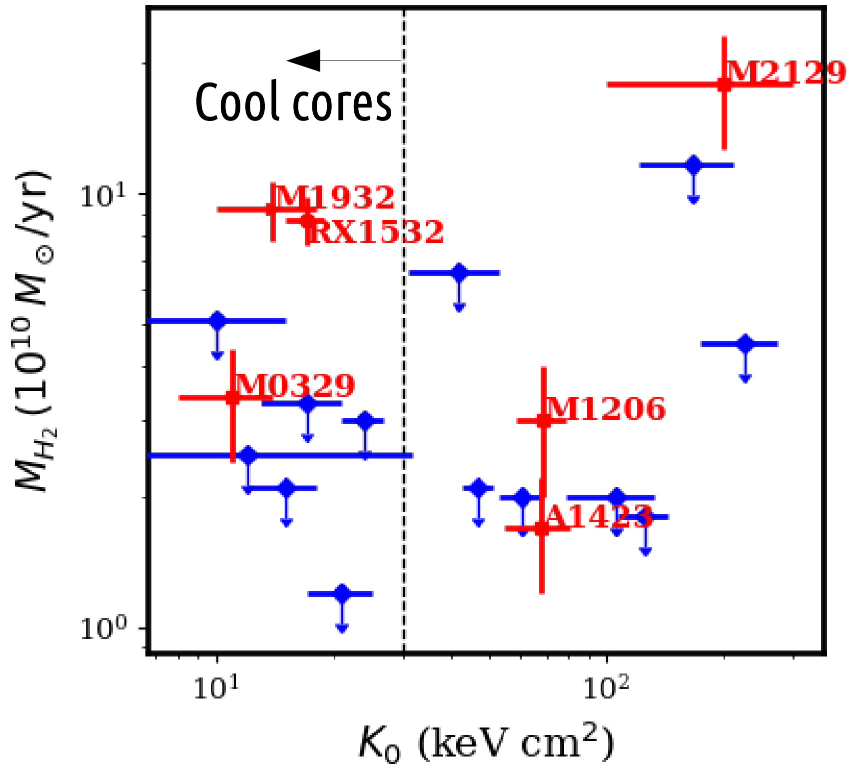
→ Strongly excited gas : $r_{31} = 0.75 \pm 0.12$

→ High $M_{H2}/M_{*} = 0.40 \pm 0.05$

Castignani, Pandey-Pommier et al. (2020)

Molecular gas reservoirs and the interplay with the ICM





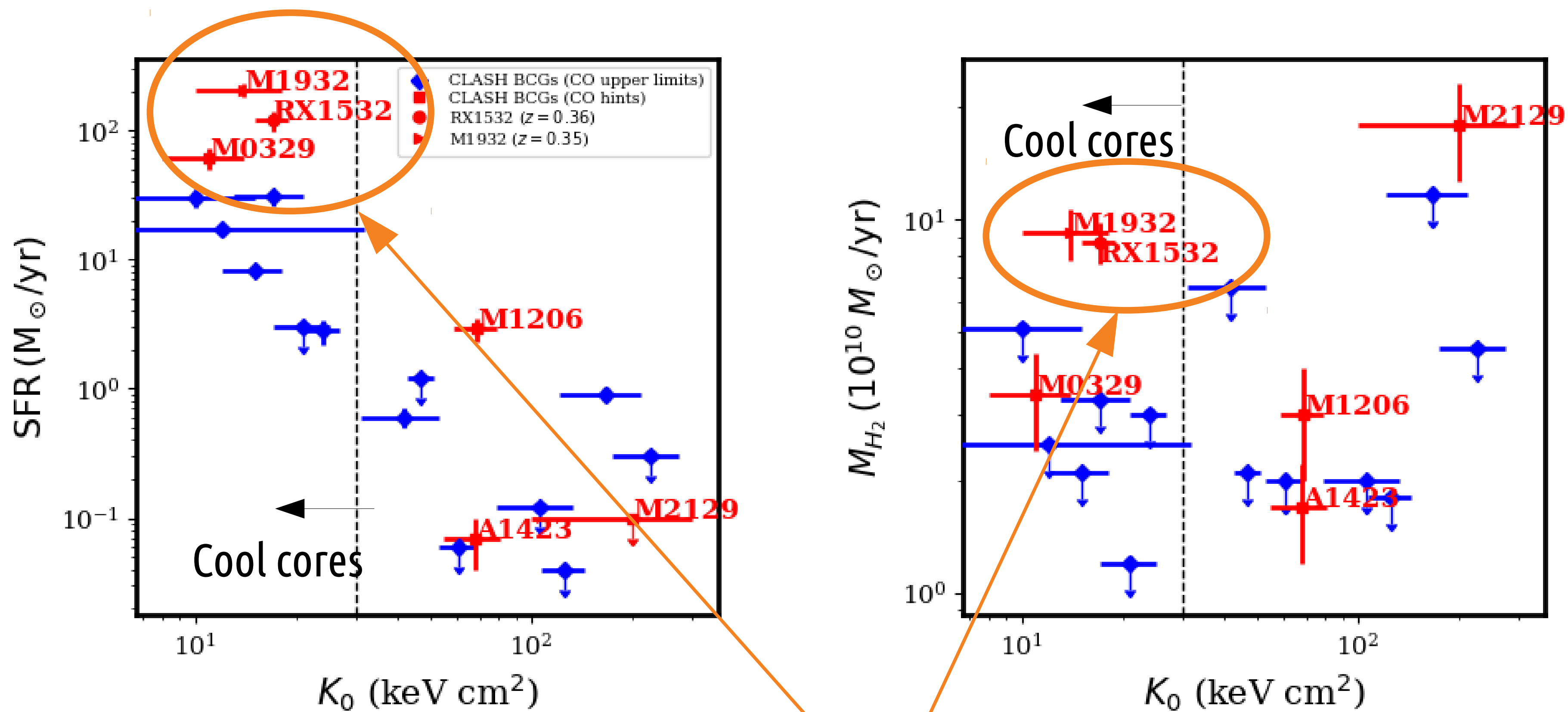
Red points = CO detections or hints by our campaign

M1932: in the Southern Hemisphere with
ALMA CO detections by Fogarty+19

Castignani, Pandey-Pommier et al. (2020)

Molecular gas reservoirs and the interplay with the ICM

Castignani, Pandey-Pommier et al. (2020)



The detection of large reservoirs of molecular gas in distant BCGs is possible when two conditions occur

i) high levels of star formation activity
ii) cool-core cluster cores, which favor the condensation and the inflow of gas

Star forming BCGs at z=0.4 in KiDS

Castignani, Radovich+22a, A&A in press
Castignani, Radovich+22b, submitted to A&A

Star forming and gas rich BCGs are rare!

→ **Systematic search for star forming distant BCGs in the KiDS-N survey**

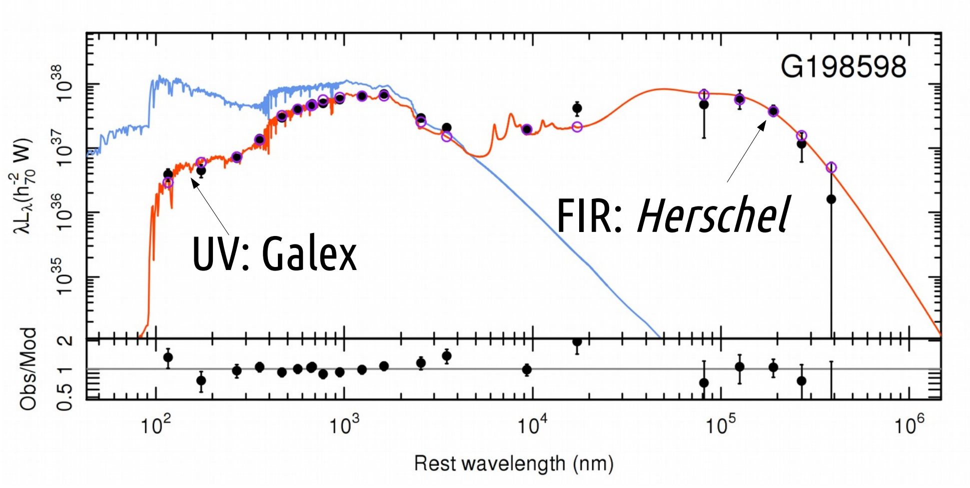
→ parent samples:
AMICO galaxy clusters and BCGs DR3 KiDS (Radovich+20, Maturi+19)

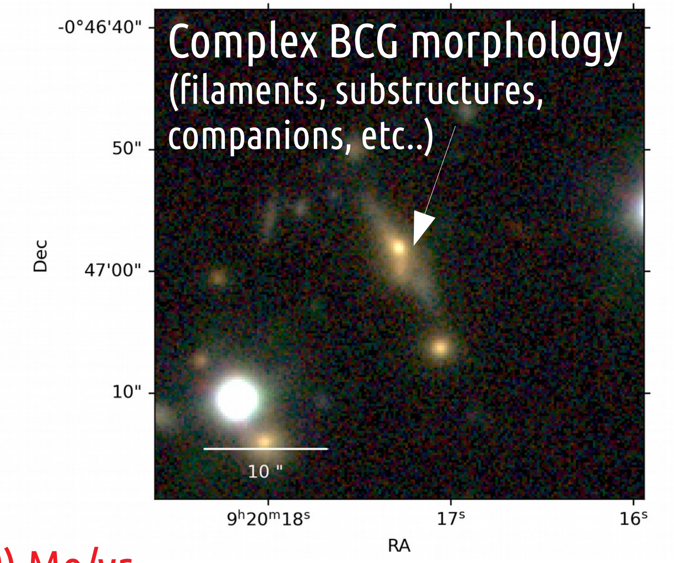
→ KiDS-N ~700 sq. deg.
- Multiwavelength photometry UV/opt/IR (VLT, VISTA, GALEX, Herschel, WISE)
- Spectra (GAMA, SDSS);

OUR SAMPLE
→ 6 BCGs at z~0.4 with WISE W4 emission, selected out of 1,484 with spectroscopic redshifts

Star forming BCGs at z=0.4 in KiDS

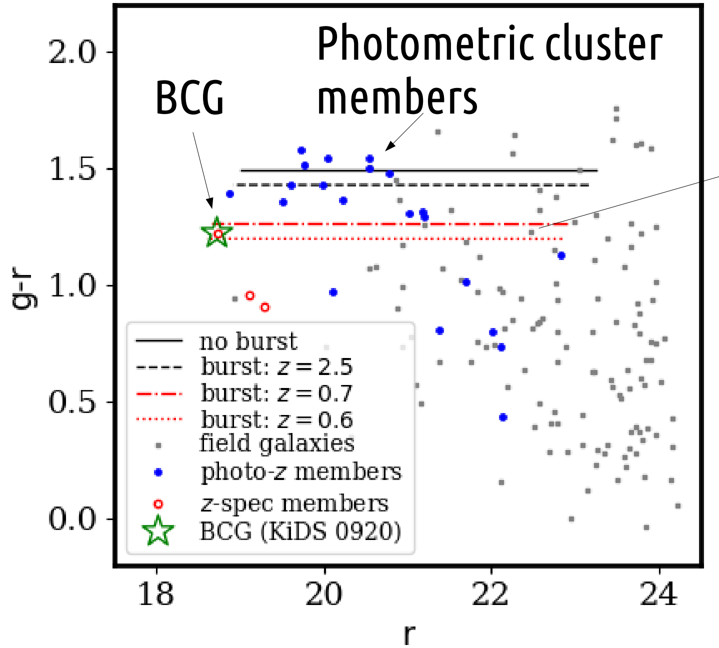
Castignani, Radovich et al. (2022ab)





GAMA DR3 SED modeling (Driver+18) → LIR >~1e+11 Lo → LIRGs

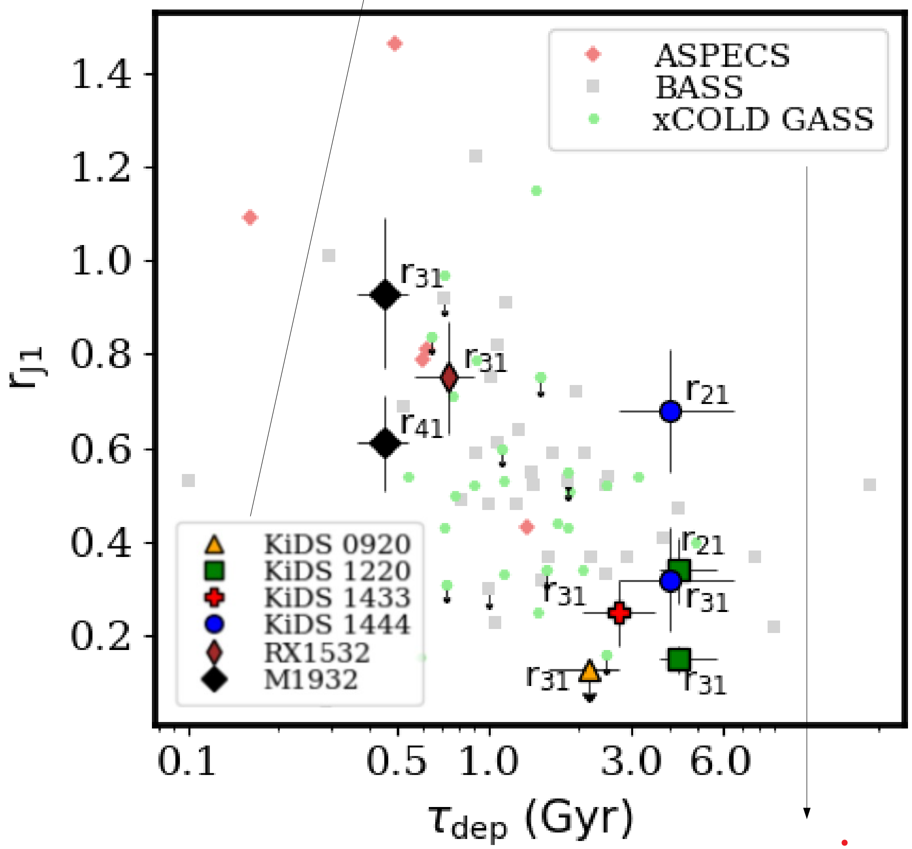
log Mstar / Mo >~ 11; SFR ~ (20-30) Mo/yr



GALEV (Kotulla+09) red sequence modeling predicts recent bursts of star formation for the BCGs

Molecular gas in KiDS BCGs at z~0.4

6 BCGs with multiple CO detections (5 of them from our CLASH+KiDS CO surveys)



comparison samples

→ IRAM 30m observations in multiple CO transitions

→ Highest CO detection rate for BCGs (4/6: 67%)

→ Large cold gas reservoirs: M_{H2} = (0.5-1.4) 10^{11} Mo

→ **BCGs caught in a peculiar phase: star forming and gas rich, before they ultimately undergo quenching.**

→ Largest sample of BCGs with multiple CO detections

→ The excitation ratio $r_{J1} = L'_{CO(J \to J-1)} / L'_{CO(1-0)}$ correlates with sSFR and SFE (first evidence for BCGs)

↓

Very excited gas is found only in highly star forming and cool core BCGs (gas infall favors high SF and high gas excitation)

Castignani, Radovich et al. (2022ab)

Conclusions and perspectives

→ Large campaign to search for molecular gas in galaxies in and around clusters over cosmic time

→ Evaluate the impact of the dense environments in processing the cold gas feeding star formation

→ I. Pre-processing in the local Universe.
Study of the cold gas in galaxies within cosmological filaments around Virgo
Filaments are able to process cold gas already before galaxies fall into Virgo

→ II. (pre)-processing of cluster LIRGs at intermediate-z.
Environment driven exhaustion of gas: low t_{dep} in the cluster core

→ III. Processing of gas in distant Brightest Cluster Galaxies (BCGs)
- SpARCS1049+56 BCG (z=1.7) → gas rich companions. Stellar mass assembly of the BCG at play
- 3C186 (z=1.06, cool core BCG) → strong support of the GW recoil scenario
- Intermediate-z gas rich and star forming BCGs (CLASH, KiDS) →
    a. BCGs caught in a peculiar phase: star forming and gas rich, before they ultimately quench.
    b. Cool cores of clusters favor gas infall sustaining high levels of star formation and gas excitation

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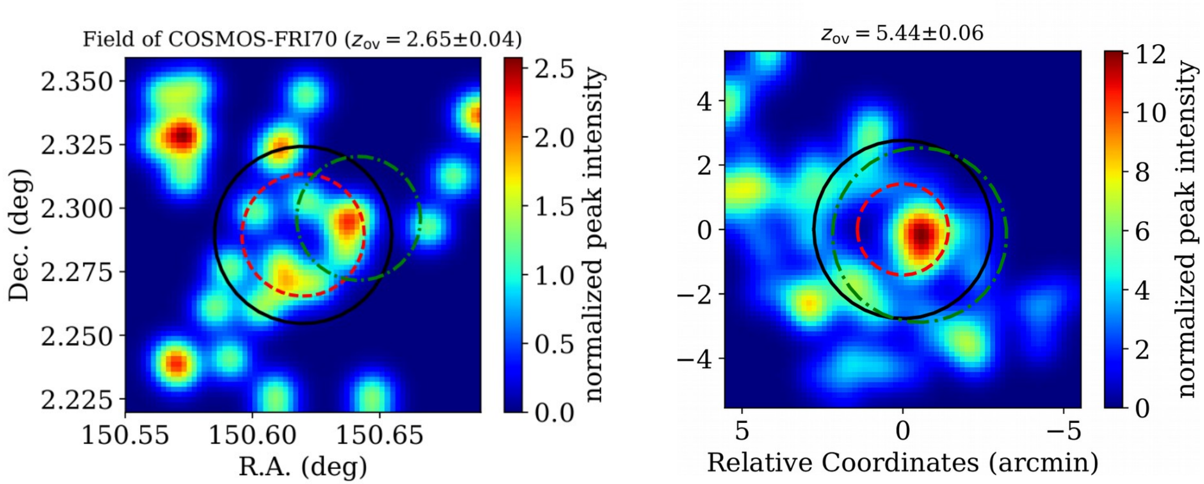
→ Ongoing interferometric observations will spatially resolve the molecular gas of distant BCGs (mergers, filaments and cooling flows, gas stripping, …)

Future Perspectives

- Samples described: optimal targets for high-resolution studies with NOEMA / ALMA as well as SKA (precurors/pathfinders).
- **Euclid / SKA** synergy: thousands of clusters and protoclusters around radio-loud BCGs at z>1. A revolution in the field of galaxy evolution in cluster is expected (radio-mode AGN feedback, formation of the first LSS, etc…)
- **Distant protoclusters at z>2. In collaboration with Lagrange cosmology team.**

  - **Excellent targets for MOONS spectrograph** (fov 500 arcmin^2). Maps of the large scale (10-20 Mpc) filamentary structures of protoclusters. Detection of targets for the MOONS GTO Extragalactic Survey (Maiolino et al. 2020).

  - **Excellent targets for *JWST*.** Discovery of new proto-clusters with the PPM cluster finder (Castignani et al. 2014ab) around radio and sub-mm galaxies (proto-BCGs)



Left: z=2.7 protocluster around the COSMOS-FRI70 radio galaxy (Castignani et al. 2019)

Right: New z=5.4 protocluster around a SMG in the GOOD-N field (Calvi, Castignani & Dannerbauer, to be submitted)