

Processing of gas in galaxies within the cosmic web

Gianluca Castignani



Cosmology and Astrophysics with Clusters

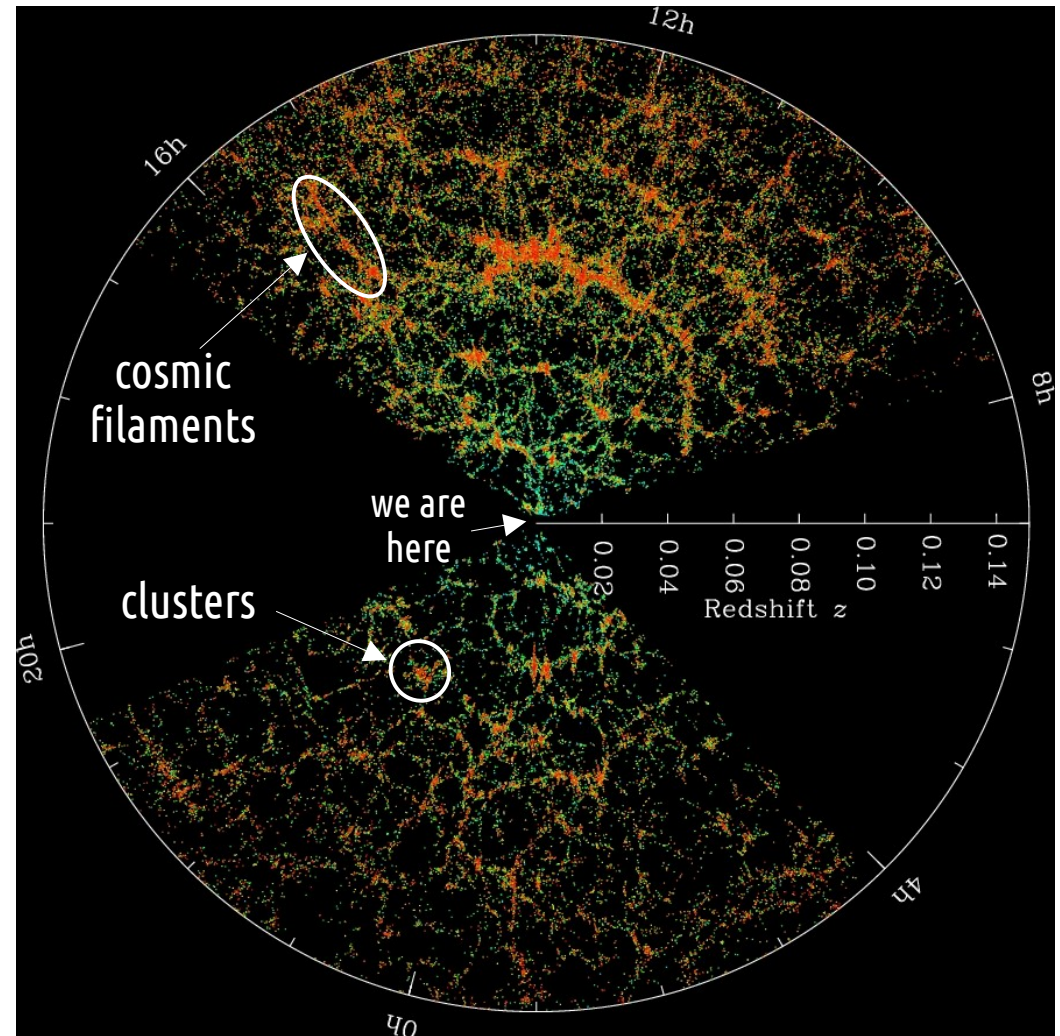
▶ Cosmic Web

- filamentary network of galaxies
- visible matter : ~4%
- the rest is **dark** (DM, DE)

▶ Clusters of galaxies

the most massive gravitationally bound systems

- cosmological probes (e.g. via cluster counts)
- cluster physics : dark matter, gas, galaxies
- structure formation



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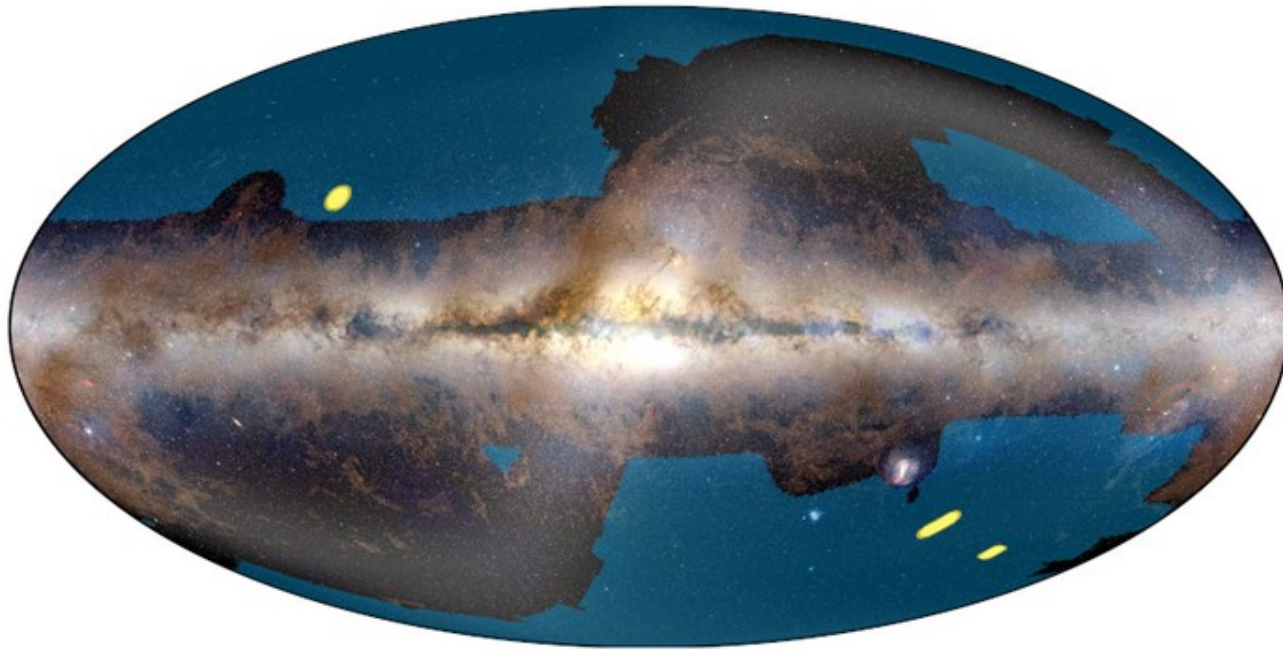
Distant clusters and ongoing missions

► Distant clusters at $z > 1$

- Their number is currently limited to a few tens
- Thousands will be discovered in the next years (*Euclid*, Vera Rubin LSST) [Euclid : Adam+19 ; Sartoris+16 ; Euclid : Barghava+25]

precision cosmology with clusters

Legacy value : astrophysics of clusters and galaxies

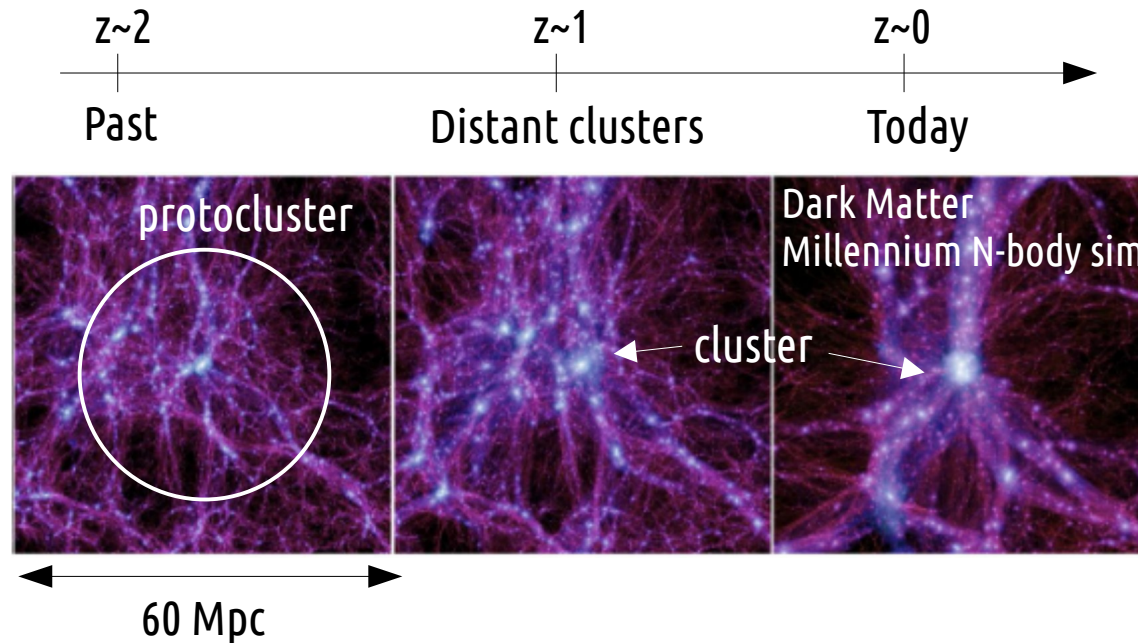


► *Euclid*

- 6 yr mission (~ 2023-2029)
- Blue : wide field survey (13 000 deg²) - $H < 24$
- Yellow : deep fields (53 deg²) - $H < 26$

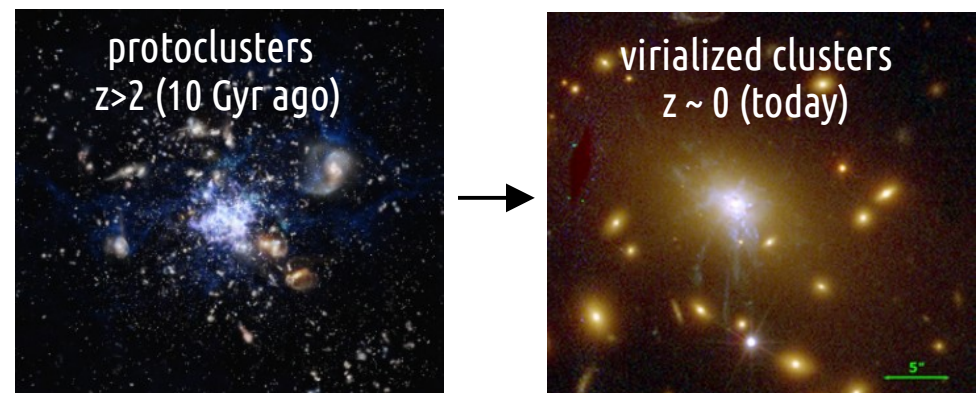
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The co-evolution of galaxies with their cluster environments



Open Questions

- How do **massive ellipticals** form and evolve ?
- How do **Brightest Cluster Galaxies (BCGs)** evolve ?
- What regulates the evolution of **black holes** ?
- What is the impact of the **environment** on the evolution of galaxies ?
- How did the **first clusters** form ?



Fogarty+15

Search for molecular gas in and around clusters

- **Large ongoing campaign** : IRAM facilities at millimeter wavelengths.
- **Goal** : search for CO in galaxies in dense environments over 10 Gyr of cosmic time

CO as a tracer of ongoing star formation



• Campaign studies

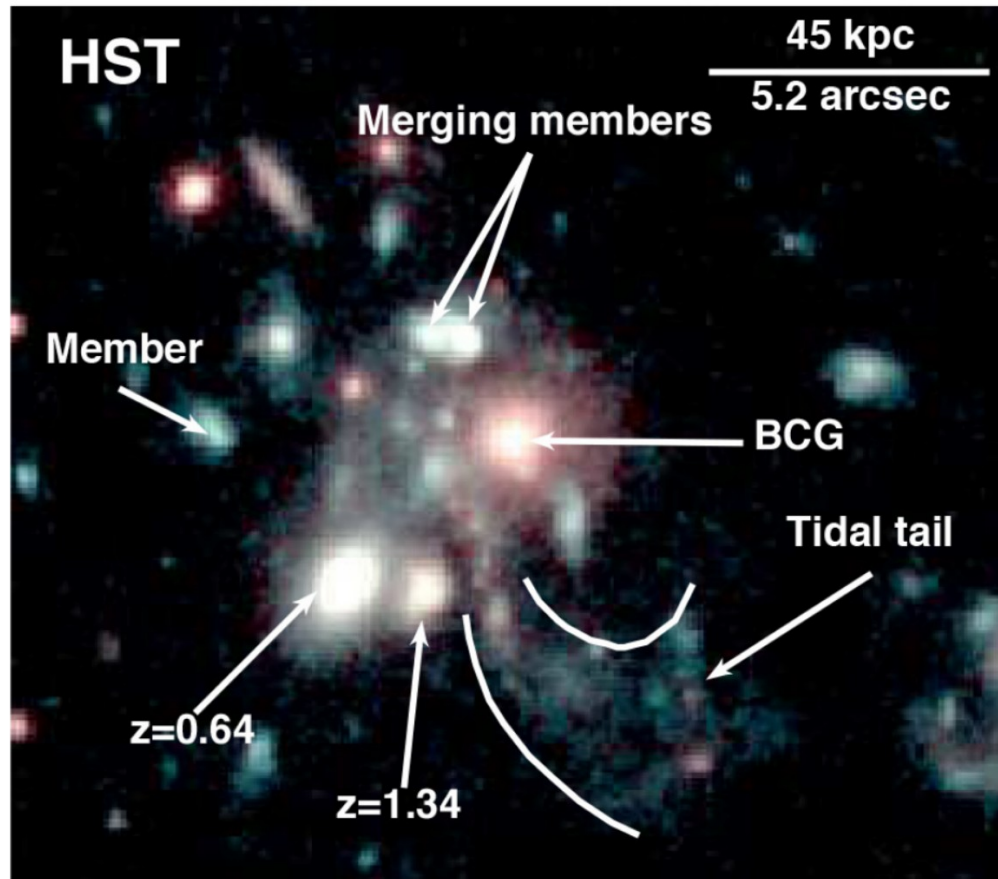
Castignani, Radovich et al. (2022, 2023) ; Castignani, Meyer et al. (2022) ; Castignani, Combes et al. (2018, 2019, 2020ab, 2022, 2025) ; Castignani, Pandey-Pommier et al. (2020) ; Castignani, Jablonka et al. (2020)

Part 1

Search for molecular gas in distant BCGs

- ▶ SpARCS 1049+56 at $z=1.7$
- ▶ GW recoil candidate 3C186 at $z=1.06$
- ▶ cool-core BCGs at $z=0.4$

SpARCS 1049+56 : one of the most distant BCGs @ $z=1.7$



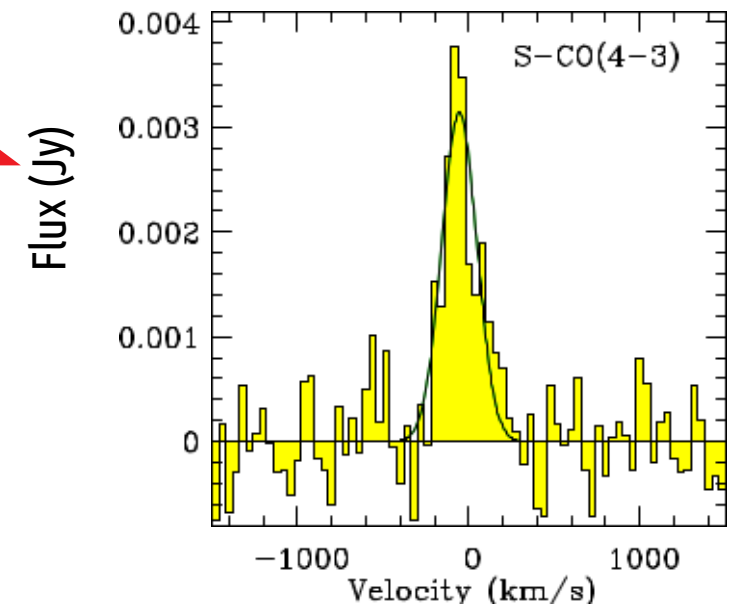
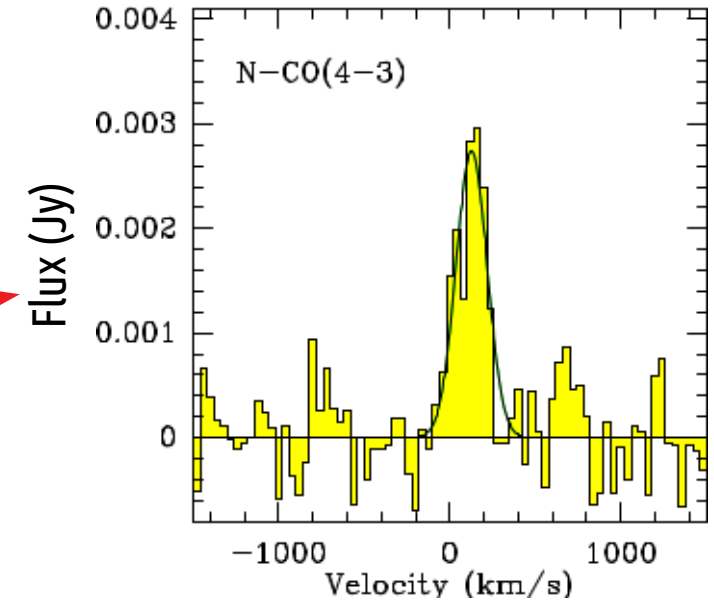
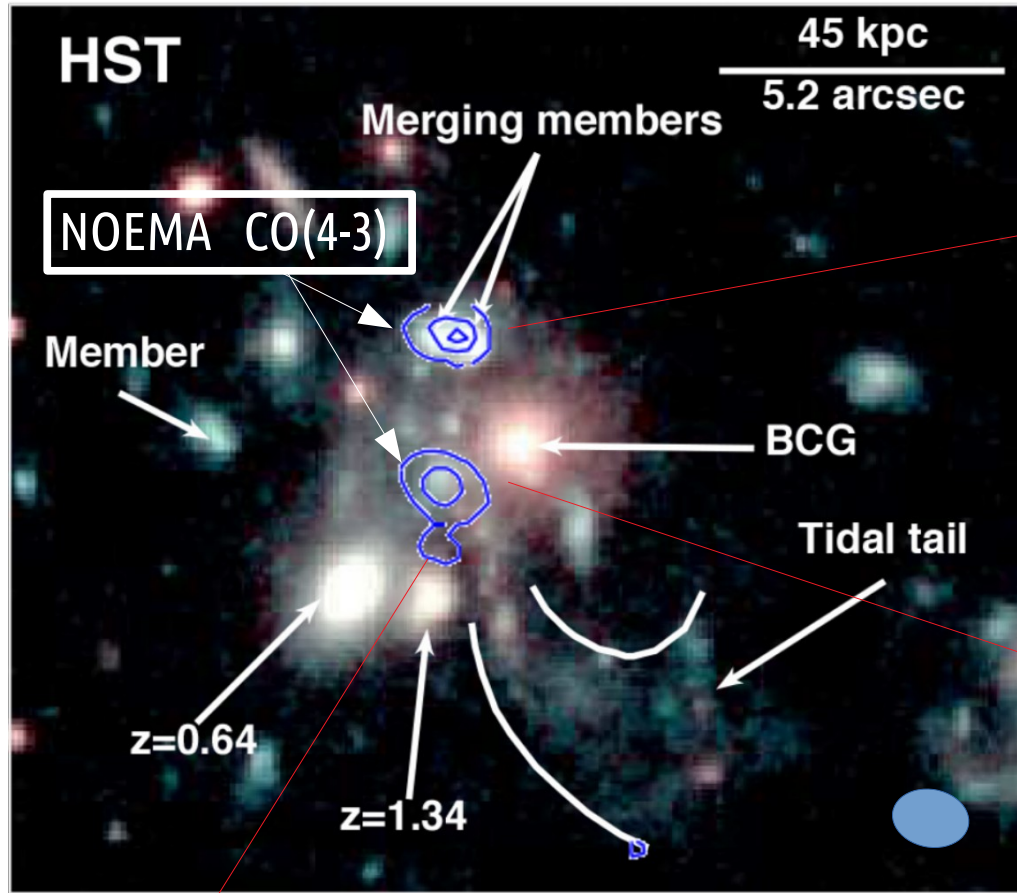
▶ Starbursting core

- $\text{SFR} = (860 \pm 130) M_{\odot}/\text{yr}$
Spitzer MIPS $24\mu\text{m}$ (Webb+2015)
- BCG claimed to be gas rich
LMT single dish observations (Webb et al. 2017)

Trudeau et al. (2019)

NOEMA observations and results

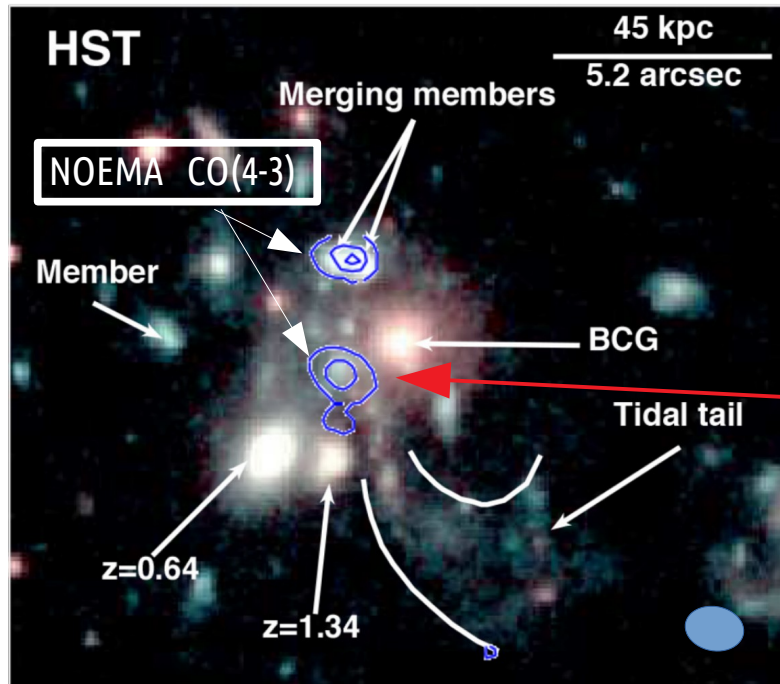
Castignani, Combes & Salomé (2020)



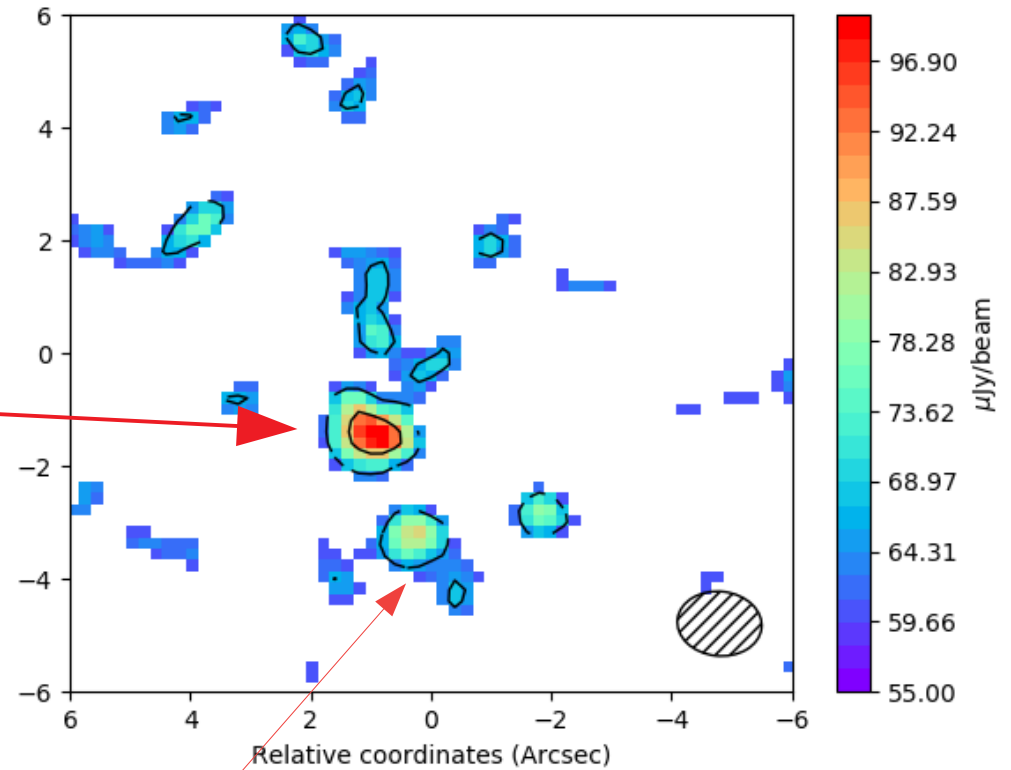
Tail in CO and in continuum!
Possibly the most distant jelly-fish galaxy

NOEMA observations and results

Castignani, Combes & Salomé (2020)



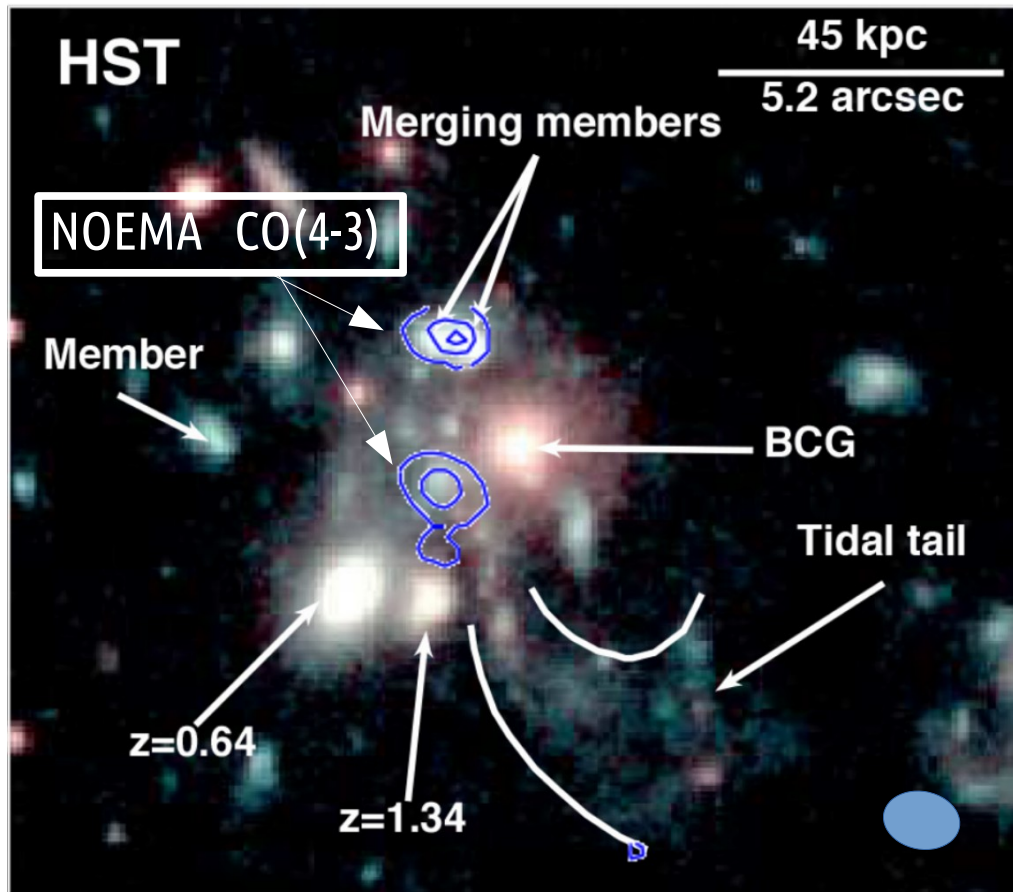
NOEMA: continuum detection



Tail of stripped gas ALSO in continuum, cospatial with the stellar stream

The stellar mass assembly of the BCG at play

Castignani, Combes & Salomé (2020)



► SpARCS 1049+56

- Gas rich companions detected :
 - in CO(4-3)
 - continuum

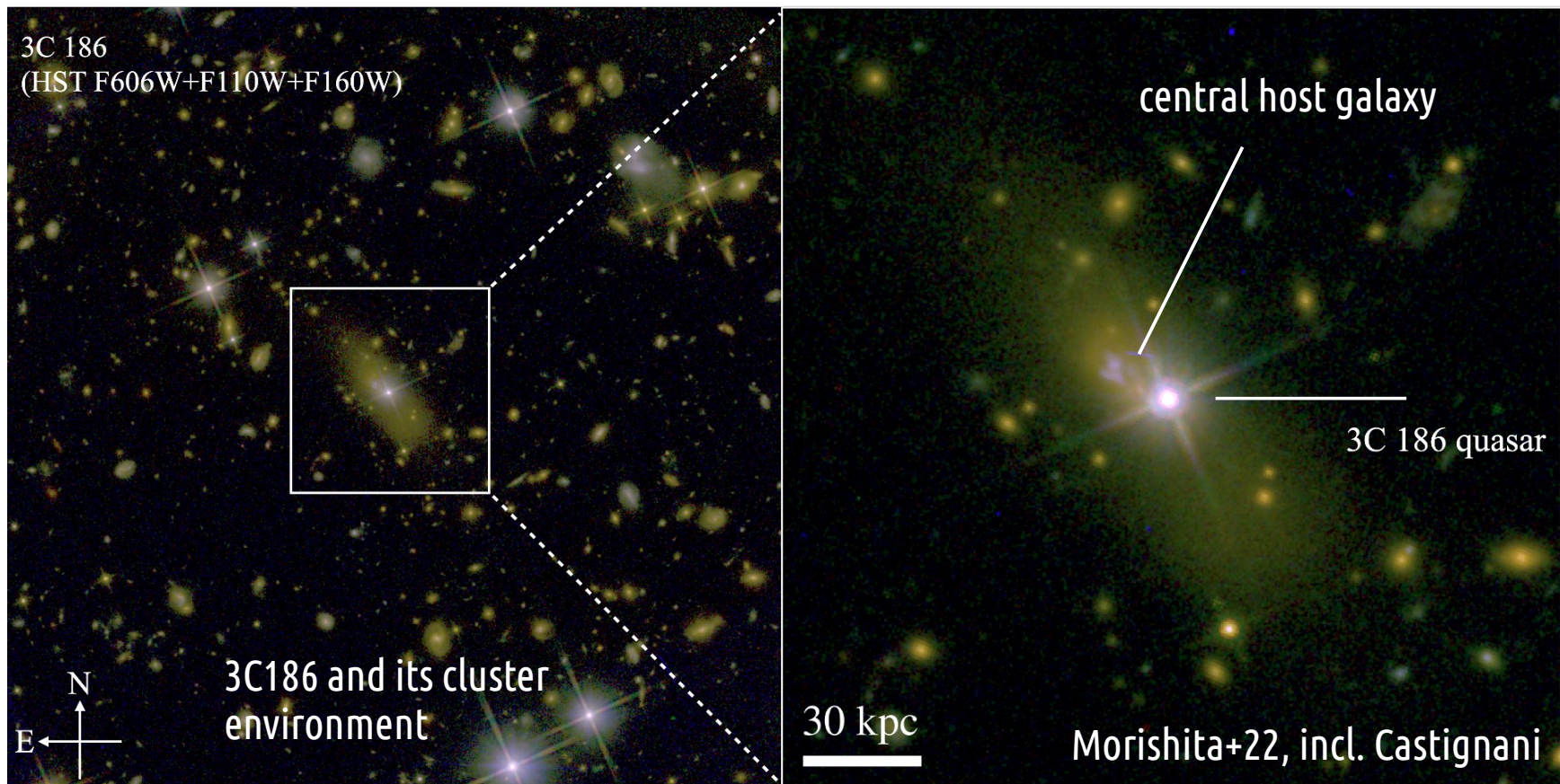
► Results

- Gas-rich systems will likely merge with the BCG
- Possible reversal of the SF – density relation
- Assembly of high-z BCG in great detail

► Alternative

- ICM run-away cooling results in gas condensation, observed in CO (Capucine et al. 2022)

3C186 at $z=1.06$



► BCG properties

- radio-loud quasar
- in a cool-core cluster at $z=1$ (Siemiginowska+05,10)
- GW recoil candidate (Chiaberge+17,18)

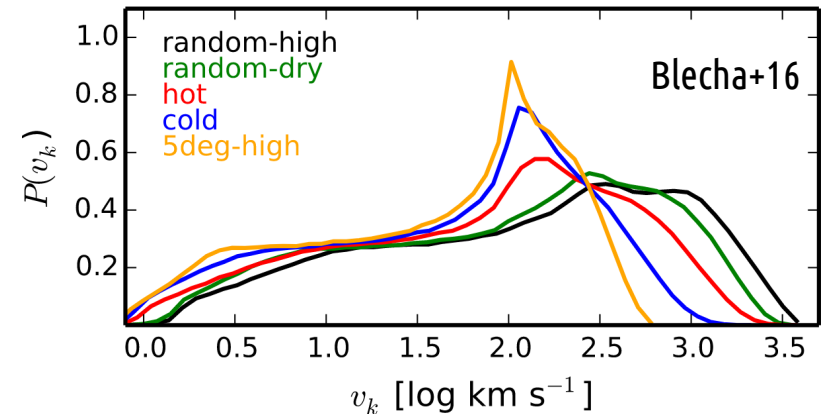
► Offsets

- 1.4'' (12 kpc) offset (galaxy vs. QSO)
- 2000 km/s shift (NLR vs BLR)

Gravitational-Wave recoils

► SMBH mergers

- Depending on their relative spin orientation and SMBH mass ratio the GW radiation may be anisotropic resulting in a kicked SMBH (Centrella+10; Komossa 2012)
- Merged SMBH : kick velocities up to 5000 km/s (Campanelli+07; Lousto & Zlochower 2011)
- Among the most energetic events (Colpi 2014)
- A small fraction of the binding energy is converted into a large GW energy

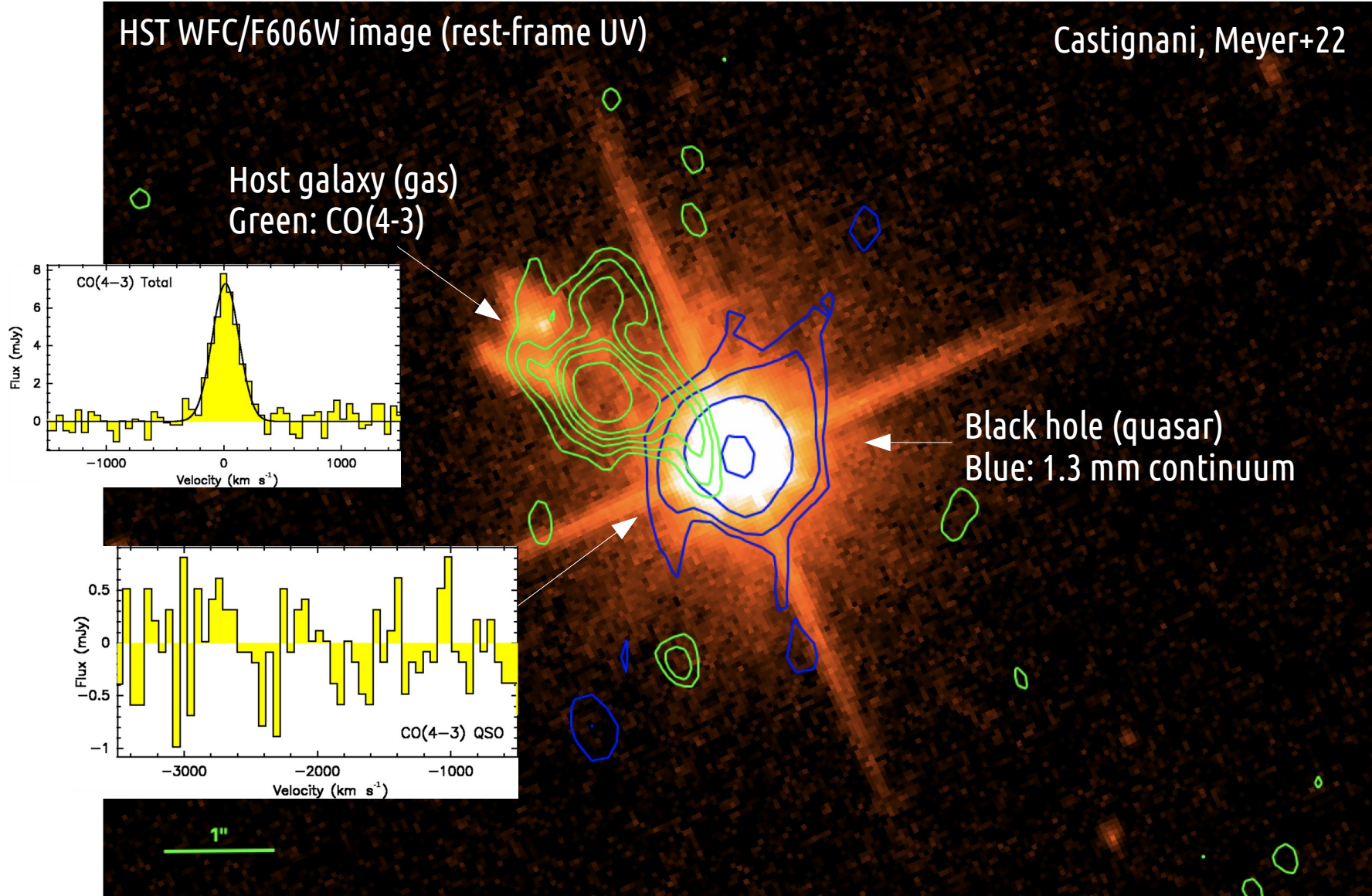


$$\frac{\Delta E}{M_{\bullet} c^2} \simeq 10^{-5} \left(\frac{M_{\bullet}}{10^6 M_{\odot}} \right)^{1/4} \quad \sim 10^{55} \text{ erg} \left(\frac{M_{\bullet}}{10^6 M_{\odot}} \right)^{5/4}$$

- Clear observational evidence of GW recoils is still missing
- Final parsec problem (Milosavljević & Merritt 2003)

NOEMA observations

Castignani, Meyer et al. (2022)

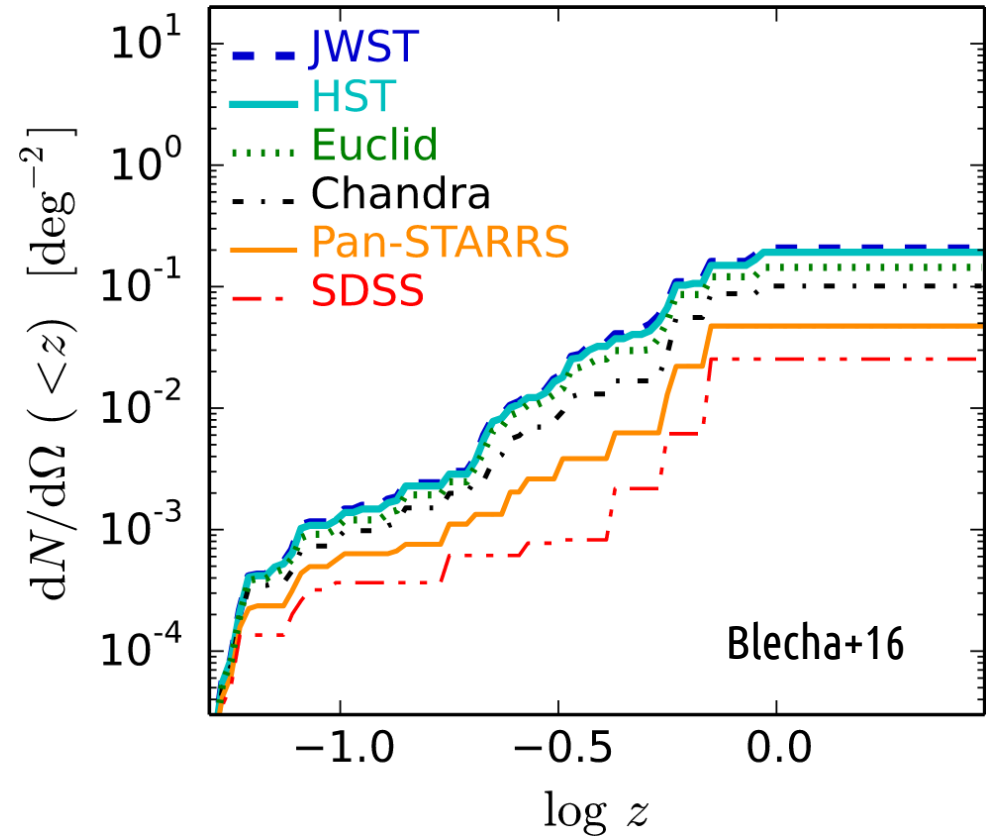
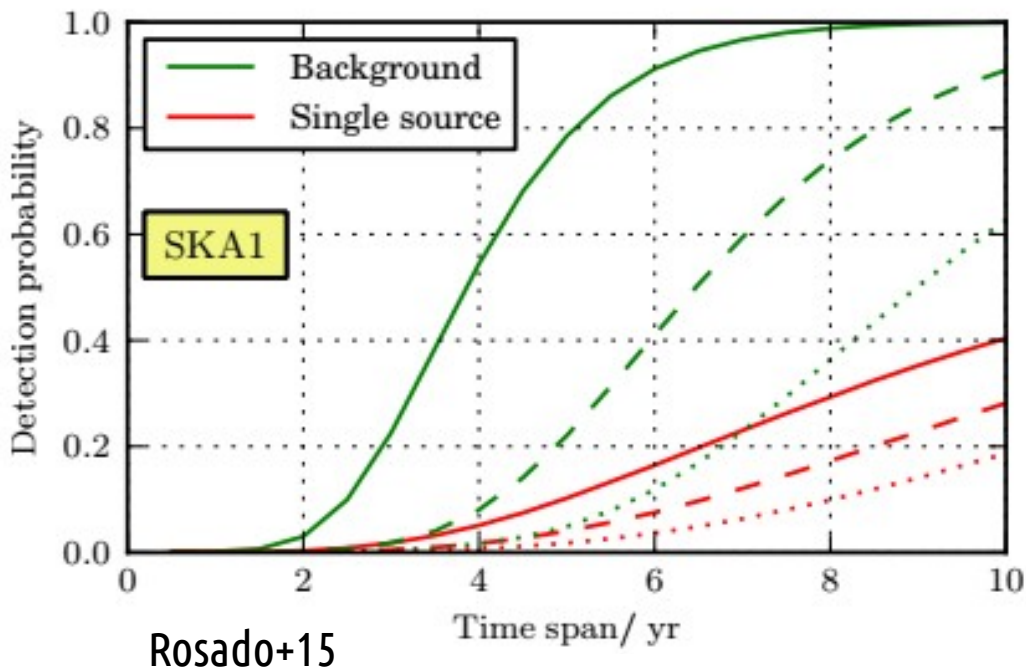


- Confirmed galaxy – QSO offset
- SMBH is expelled out of the galaxy after the merger of the parent galaxies

Perspectives : GW recoils in distant BCG

► *Euclid* and SKA

- Thousands of $z > 1$ BCGs are expected with *Euclid* (Sartoris+16 ; *Euclid* : Adam+19)
- Excellent targets to search for GW recoils with SKA PTA (Rosado+15)



Molecular gas in cool-core BCGs at $z=0.4$

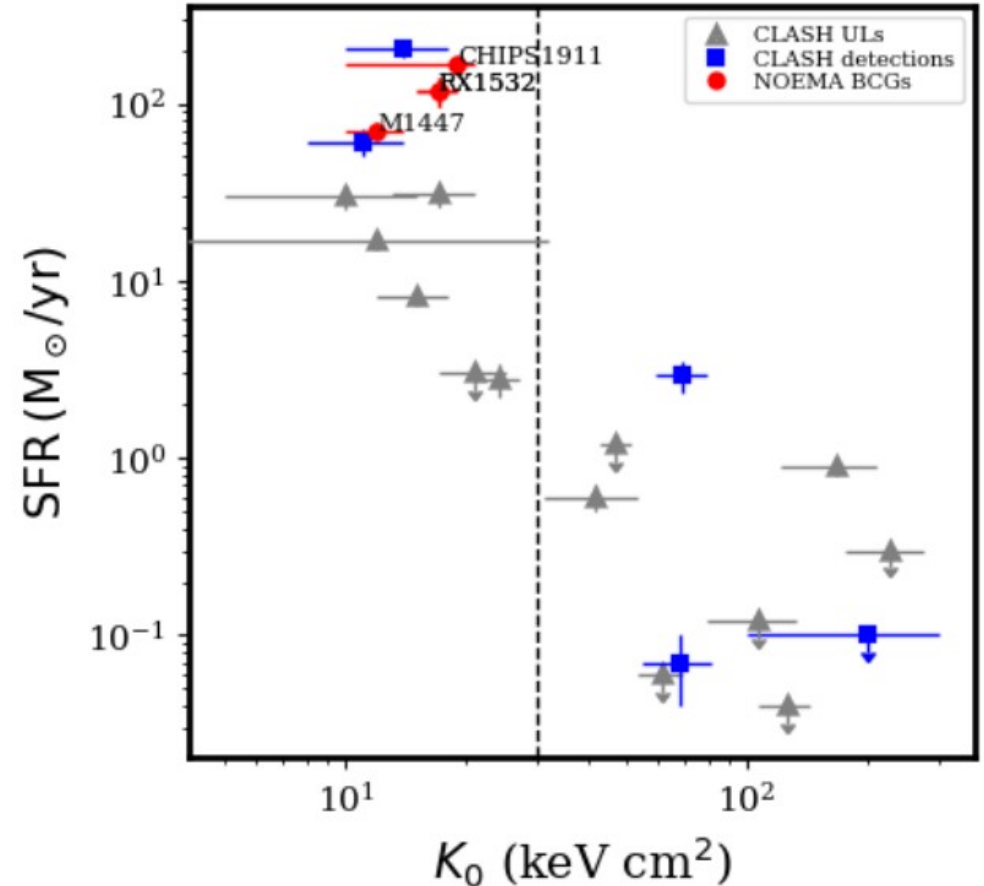
Castignani et al. (2025)

► The sample of BCGs

- Three cool-core and star forming BCGs at $z \sim 0.4$:
 - RX1532
 - MACS1447
 - CHIPS1911

► Star formation and cluster core entropy

- High SFR $\sim 80\text{-}160 M_{\odot} / \text{yr}$ (UV, Ha, [OII]) (Fogarty+15, Liu+12, Somboonpanyakul+21)
- Low K_0 from Chandra (Donahue+15, Prasow-Émond+20, Somboonpanyakul+21)



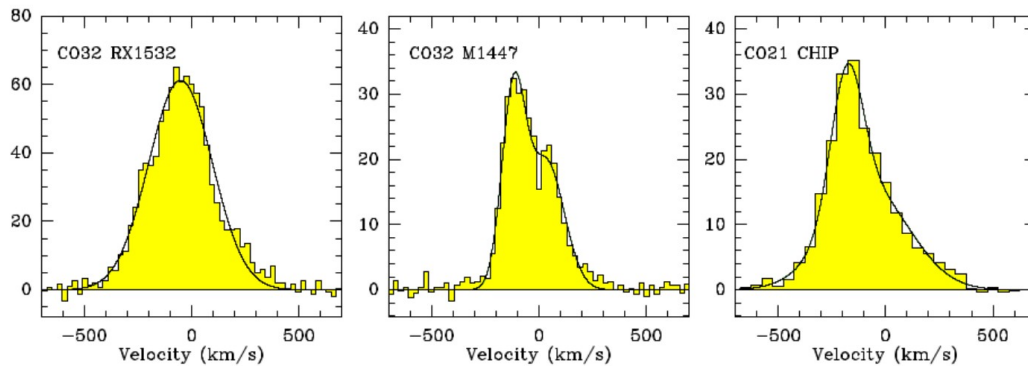
Adapted from : Castignani, Pandey-Pommier+20 and Fogarty+15

Molecular gas in cool-core BCGs at $z=0.4$

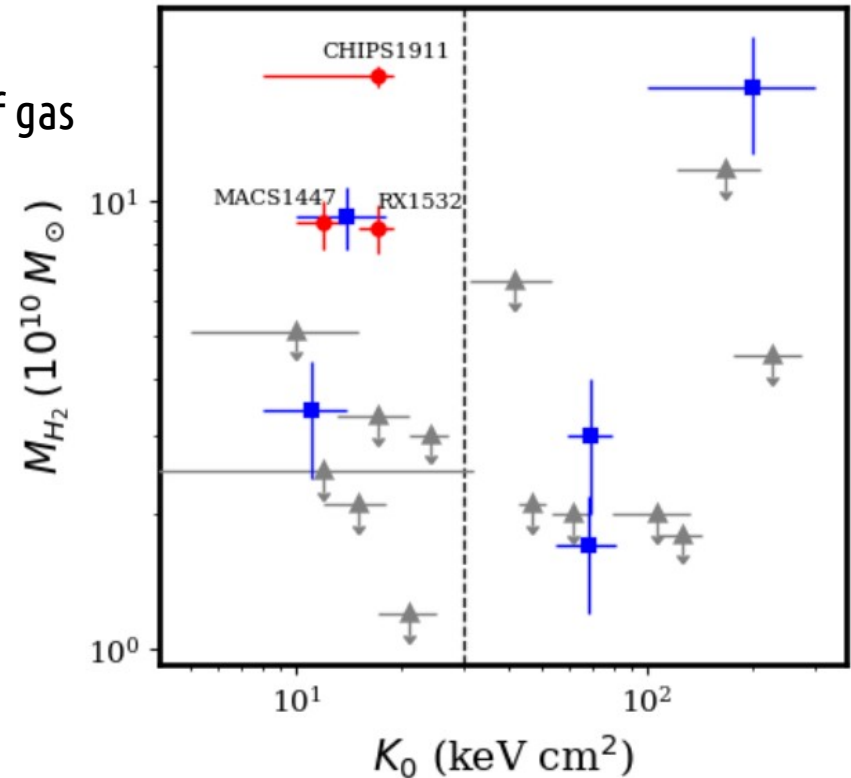
Castignani et al. (2025)

► Molecular gas and condensation

- Large $M(\text{H}_2) \sim 10^{11} M_\odot$ (NOEMA and IRAM 30m)
- Cool-core of clusters favor the condensation and infall of gas



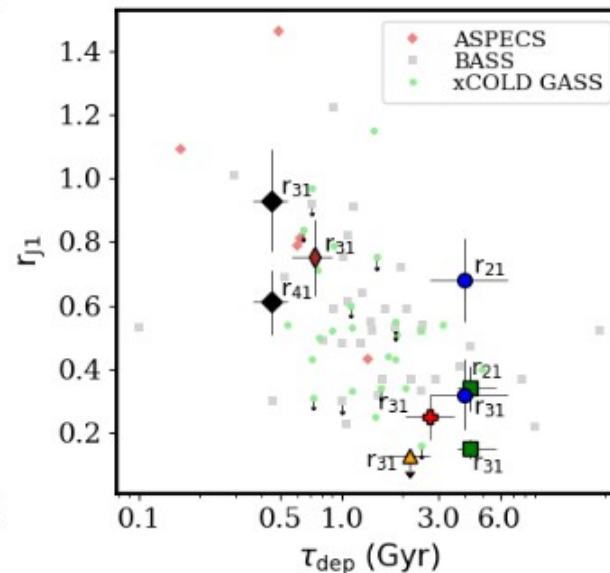
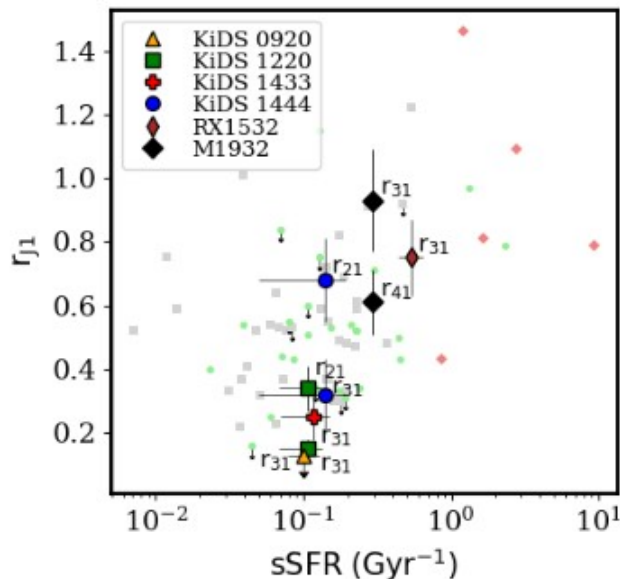
CO spectra, fluxes in mJy



Adapted from Fogarty+15, Castignani, Pandey-Pommier+20

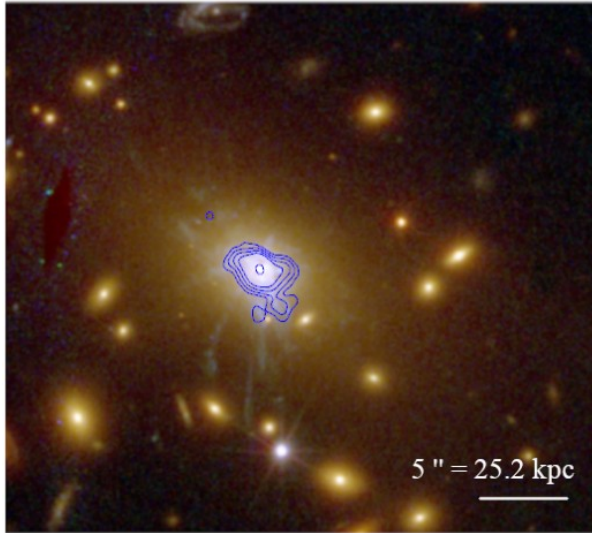
BCGs caught in a rare phase of their evolution

- ▶ **Cool-core cluster environments favor the condensation and infall of gas resulting in**
 - high SFR
 - high excitation ratio ($r_{31} \sim 0.8$, Castignani+20, 23)
 - large cold gas reservoirs feeding SF
- ▶ **Counterparts of low-z star forming BCGs such as Perseus A** [see e.g., Olivares+19]



Extended CO emission : three gas processing mechanisms at play

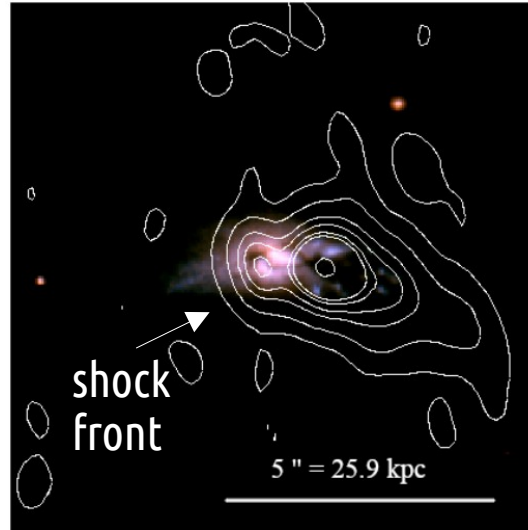
RX 1532



CO(3-2)

Filamentary flows of cold gas

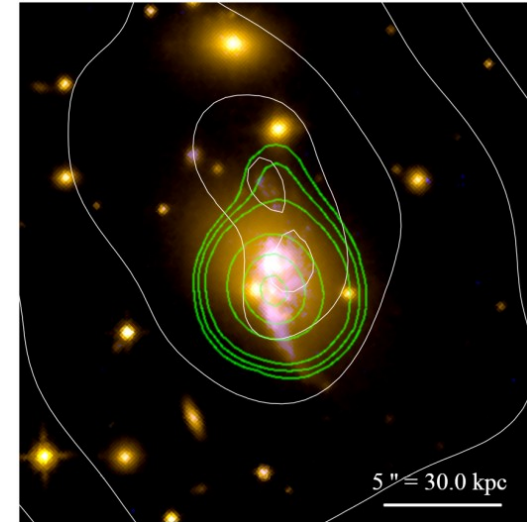
MACS 1447



CO(3-2)

Ram pressure stripping

CHIPS 1911



CO(2-1)

Tidal interaction and tails

- Optical images from *HST* filters. **Ionized gas** (Ha and [OII]) tracing SF (Fogarty+15 ; Prasow-Émond+20 ; Somboonpanyakul+21)

- Contours : CO detections

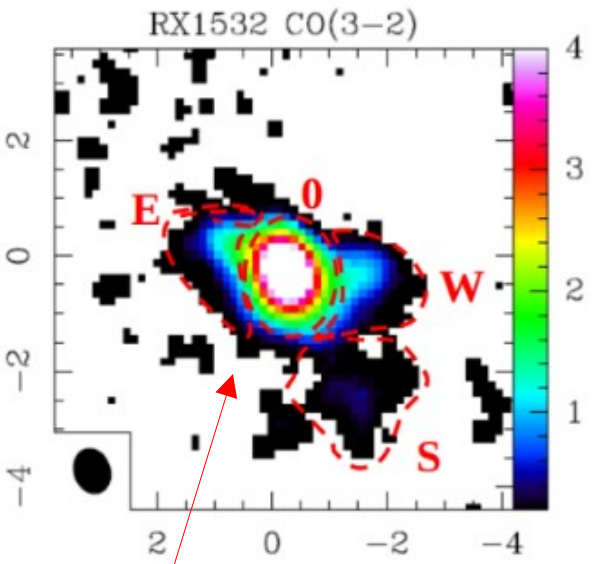
- Three NOEMA programs : 24h

- Resolution : 0.8", 1.7" [1" ~ 5 kpc]

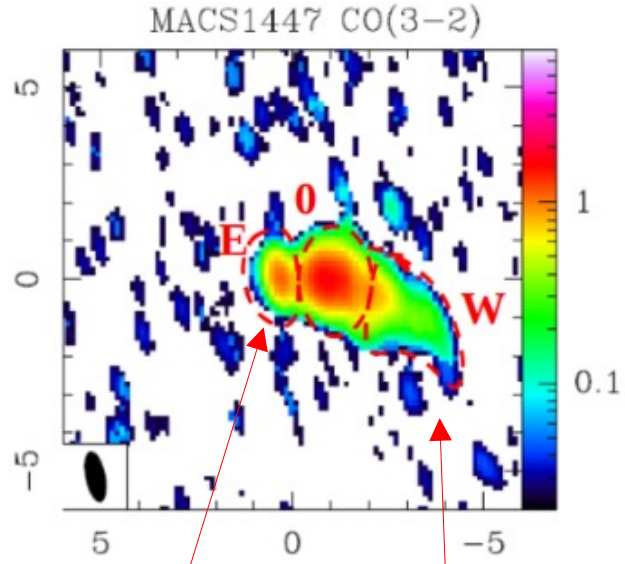
PIs : Castignani, Combes, Salomé

CO intensity maps

Several CO emitting components identified



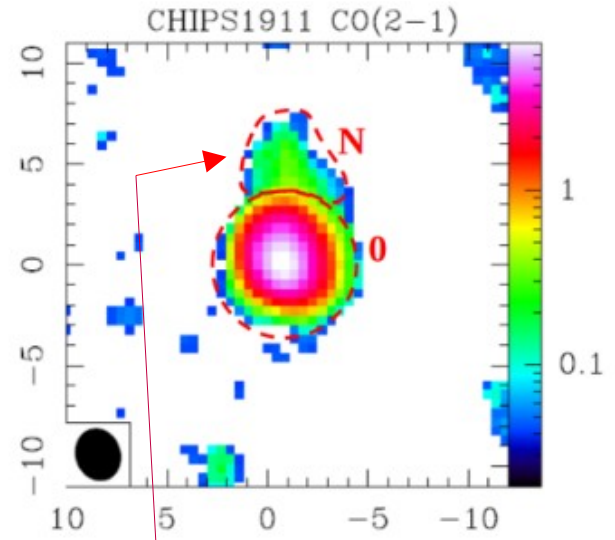
Filamentary structures (E, W, S)



E : compressed gas at the shock front

W : tail of RPS gas

Castignani et al. (2025)



N : tidal tail in molecular gas

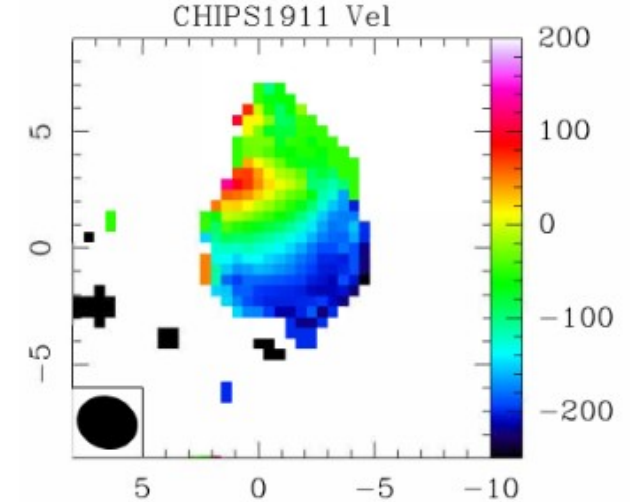
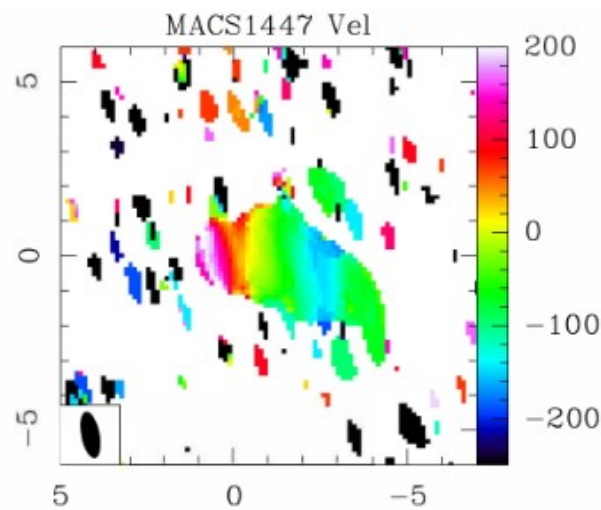
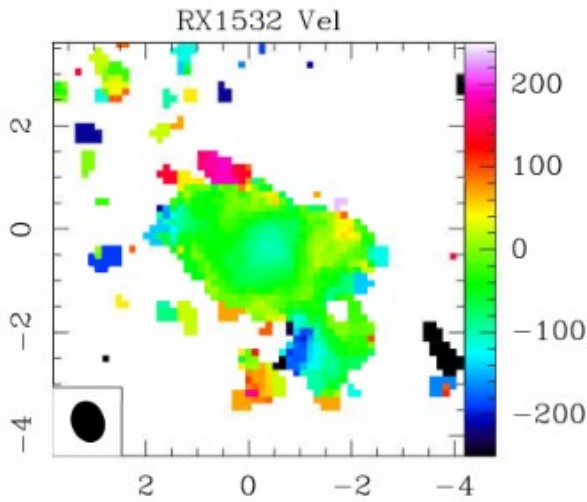
Castignani et al. (2025)

Components 0 :
molecular gas feeding star formation within the host

Relative coordinates in arcsec
color bar : fluxes in Jy km/s

CO velocity maps

Castignani et al. (2025)



Relative coordinates in arcsec
color bar : velocities in km/s

Molecular gas seen almost face on

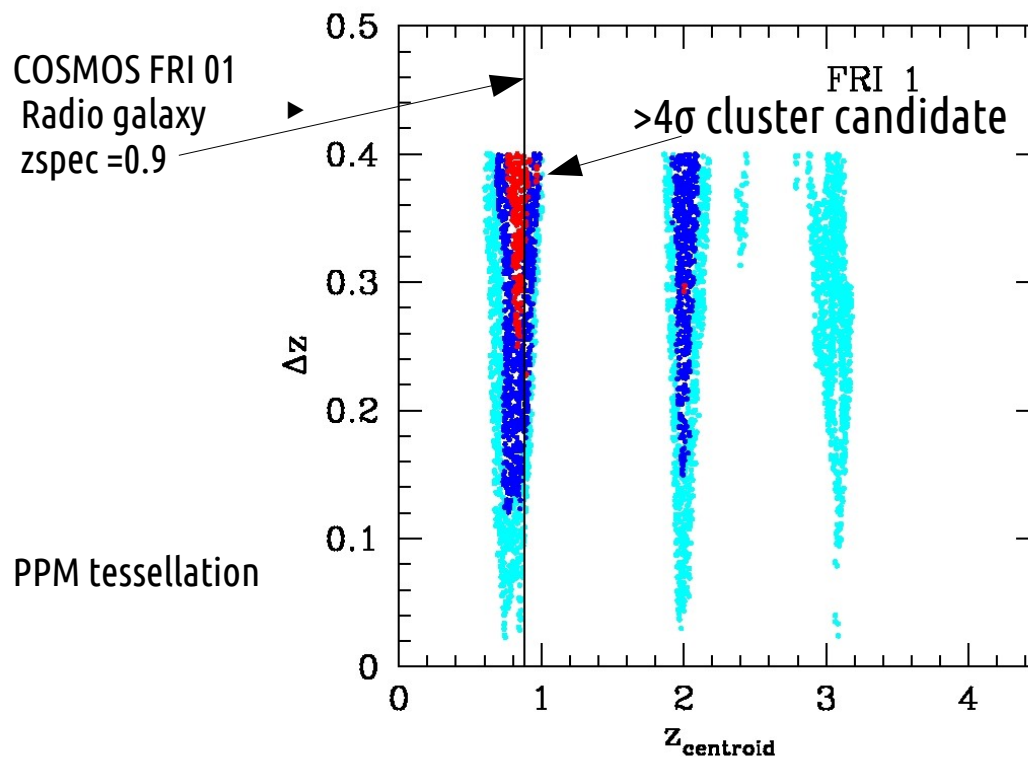
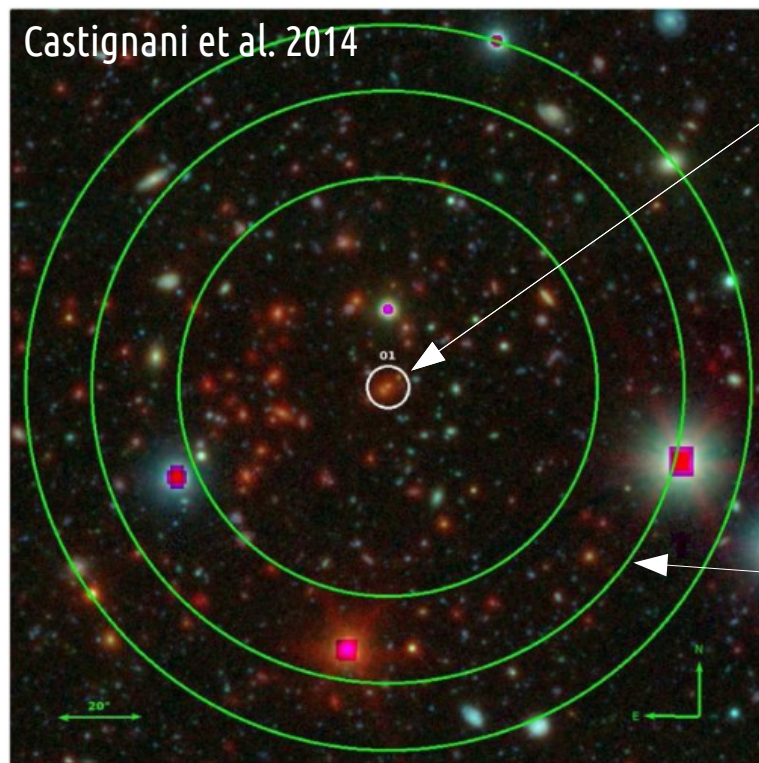
- **RX1532** : low los velocity ~ 100 km/s \ll free fall vel. \rightarrow flows of cold gas
- **MACS1447** : disturbed kinematics \rightarrow ram pressure
- **CHIPS1911** : two large scale components \rightarrow tidal tails

Part 2

Search for and characterization of (proto)clusters at $z > 2$

The Poisson Probability Method (PPM) cluster finder

- ▶ **mathematical / physical basis:**
effective theory defined on the ensemble of the z_{phot} . Realizations (Castignani+14)
- ▶ **positional prior** (e.g., radio galaxies, SMGs)
- ▶ **tailored to find distant proto-clusters :** COSMOS-FRI70 $z=2.6$ (Castignani+19)
COSMOS-FRI 03 $z=2.5$ (Castignani+14, Diener+13,15, z_{spec} confirmation)
Euclid Q1 (Euclid : Dusserre et al. 2025)



Sub-millimeter Galaxies (SMGs) as tracers of proto-clusters

Motivation

- ▶ Numerous studies show clustering of sub-mm galaxies at $z > 2$, around the peak of the cosmic SFR density
 - ▶ However, it is still debated if SMGs are good tracers of proto-clusters
- [Smail+13, Dannerbauer+14, Casey+16, Oteo+18, Harikane+19, Zhou+20, Umehata+20, Chapman+09, Miller+15]



First systematic study of the environments of SMGs

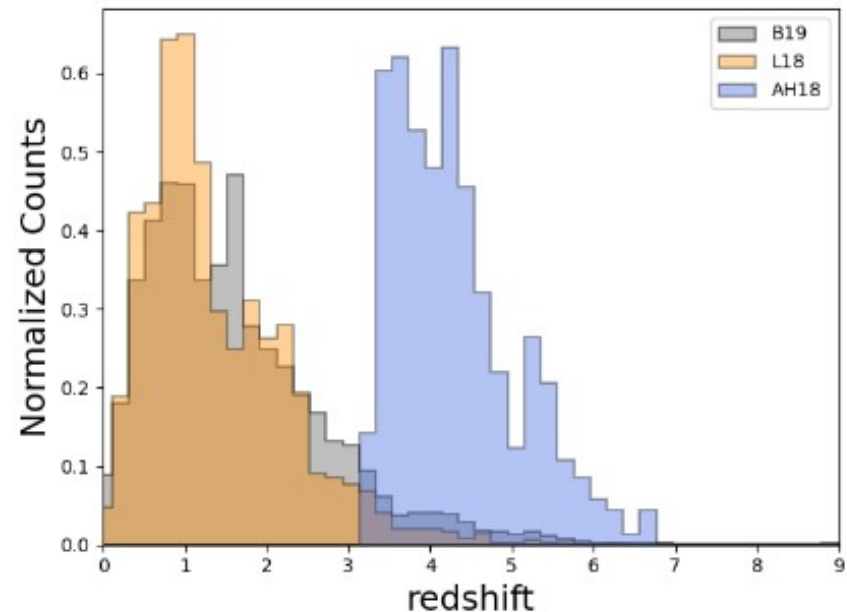
Calvi, Castignani & Dannerbauer (2023)

▶ The SGM sample

- 12 spectroscopically confirmed SMGs in the GOODS-N field
- $z_{\text{spec}} \sim 2-5$ from the literature (CO-based)

▶ Three photo-z catalogs

- Barro+19, Liu+18, Arrabal-Haro+18
- Complementary in redshift, star formation properties.

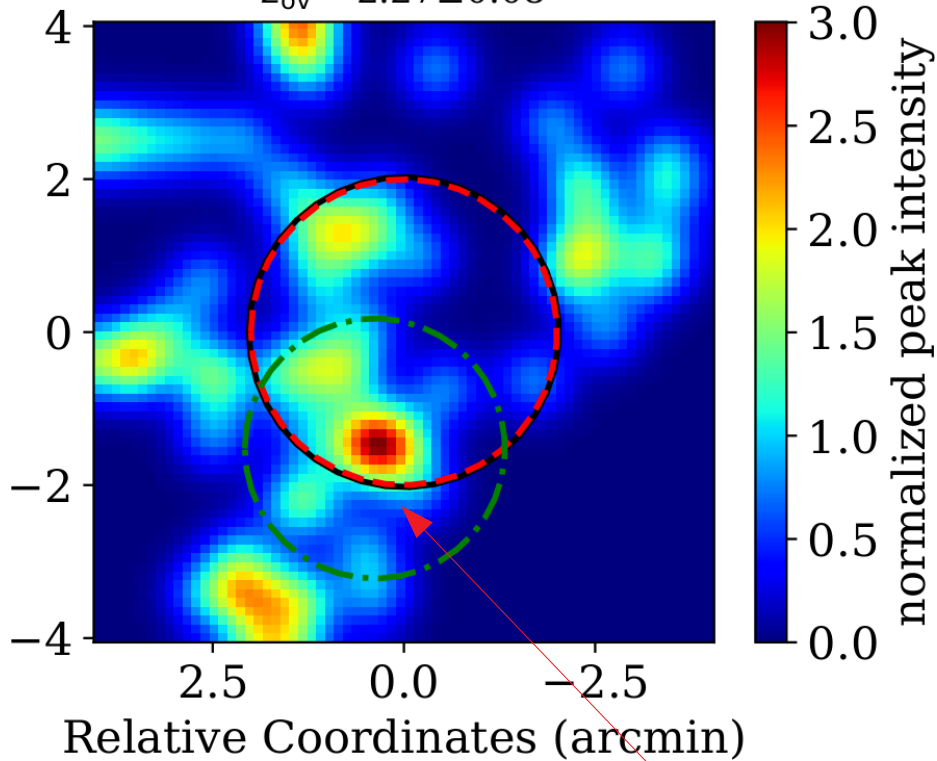


Some New Protoclusters

Calvi, Castignani & Dannerbauer (2023)

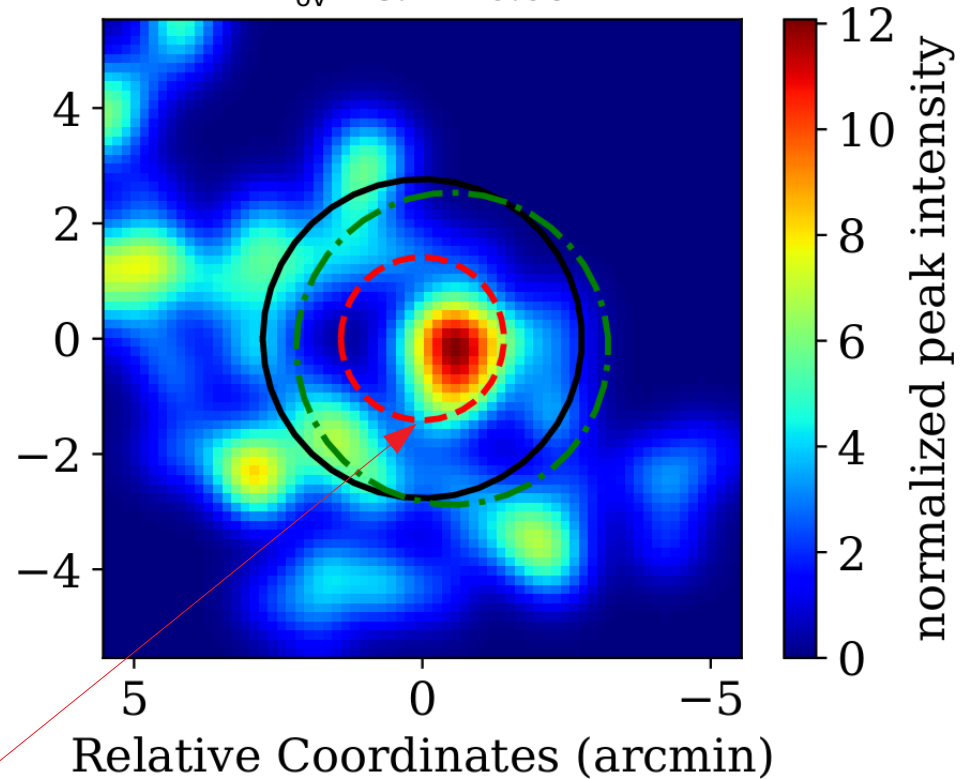
Field of SMM J123712

$$z_{ov} = 2.27 \pm 0.08$$



Field of GN10 (SMG)

$$z_{ov} = 5.44 \pm 0.06$$



Overdensity peak

complex proto-cluster structure around the SMGs (compact, clumpy or filamentary)

Newly discovered overdensities
Cluster core sizes $\sim (0.4-1)$ Mpc

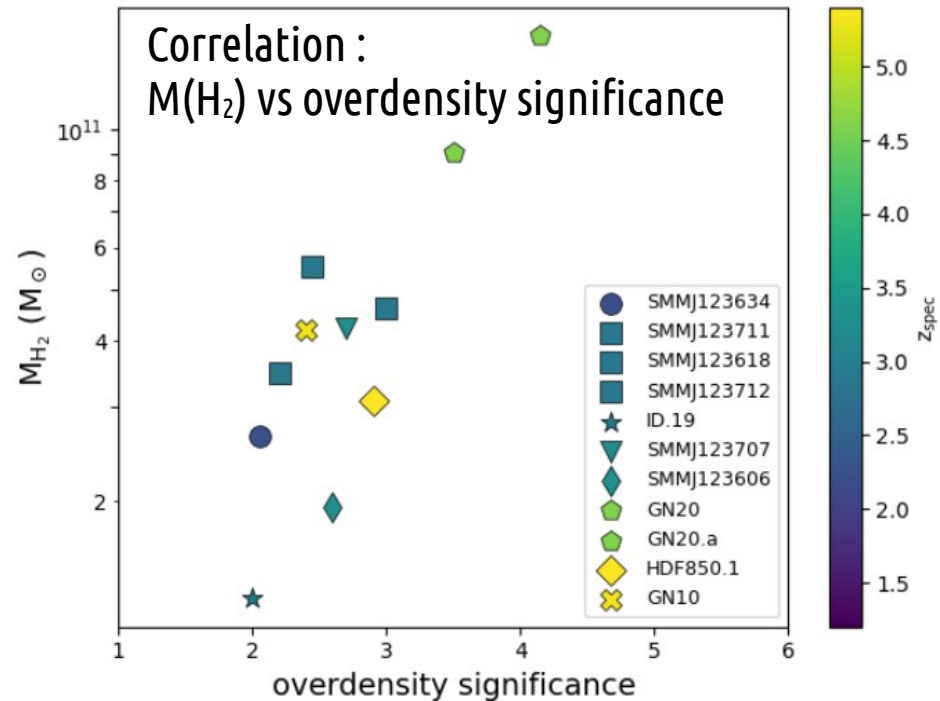
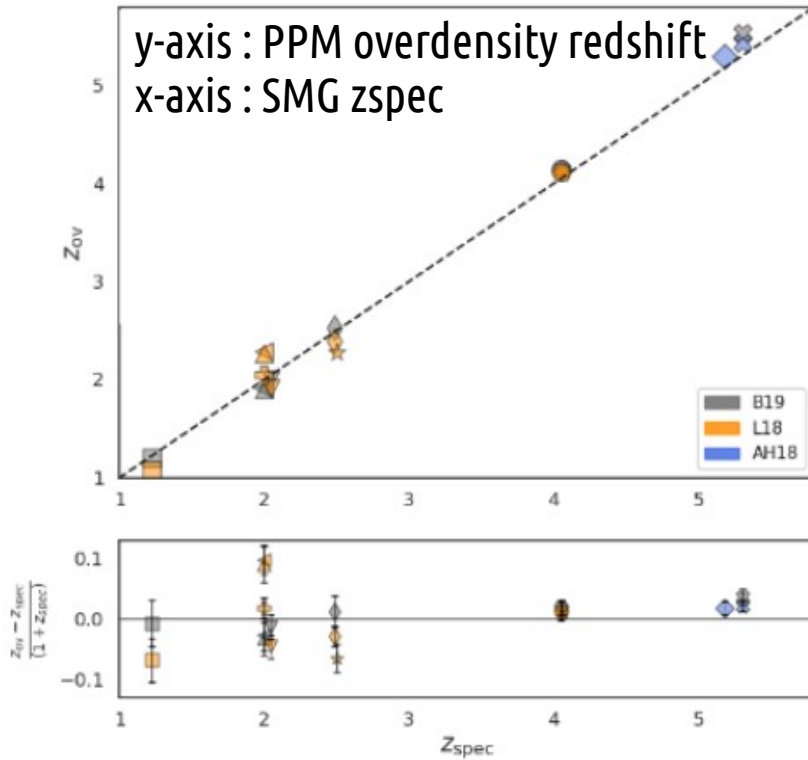
Main results

Calvi, Castignani & Dannerbauer (2023)

11 out of 12 SMGs are found in protoclusters ($z \sim 1.2-5.3$)

$92\% \pm 8\%$

Confirmation that SMGs are excellent tracers of distant protoclusters!

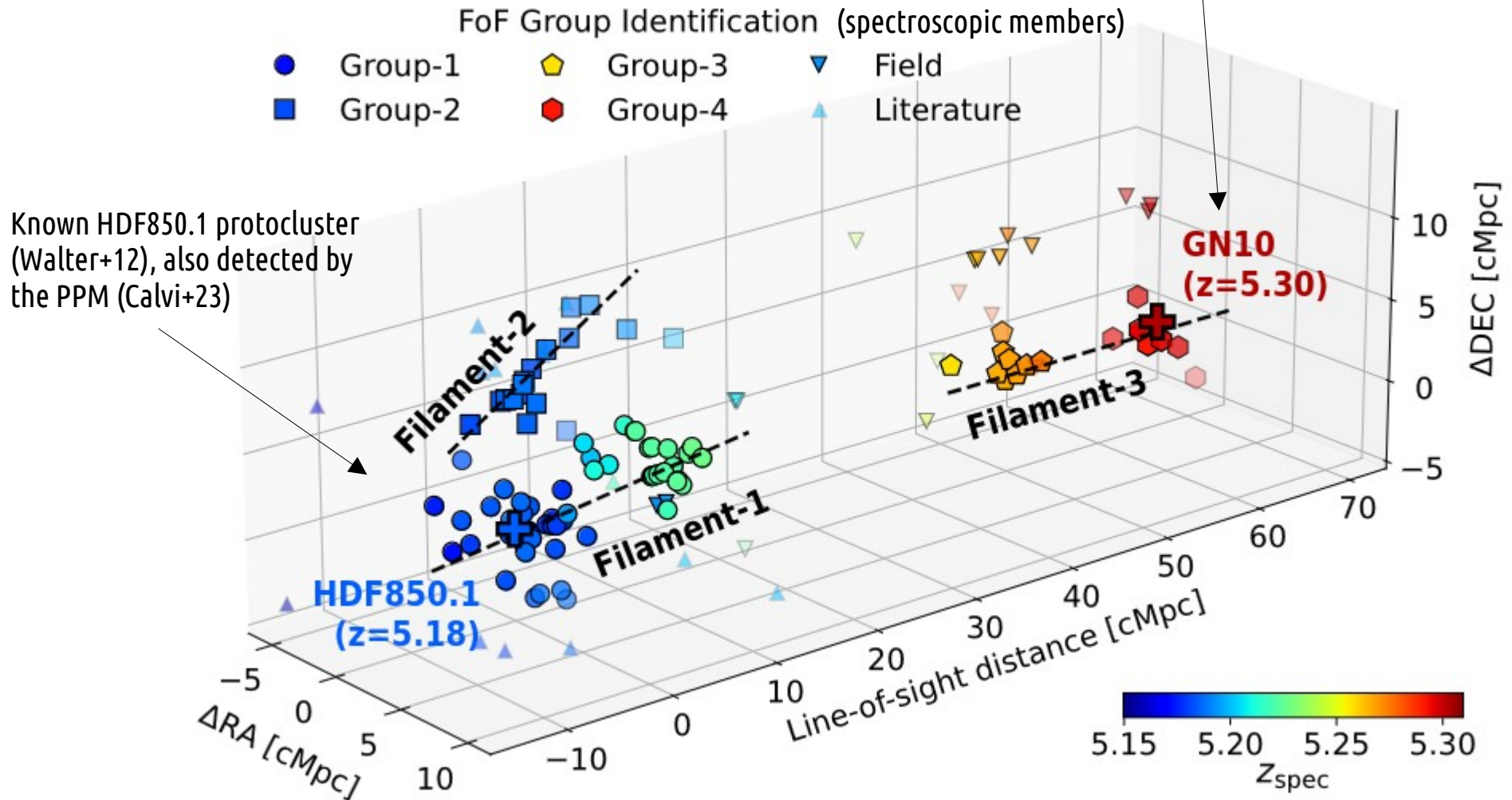


► good redshift accuracy $\sigma(z)=0.04(1+z)$

► SMGs in the strongest overdensities likely experienced most galaxy-galaxy interactions, which triggered gas infalls and high levels of star formation and gas content

Spectroscopic confirmation with *JWST*

- ▶ JADES program Ha NIRCам slitless spectroscopy (Sun et al. 2023)
- ▶ GN10 :
 - the most distant confirmed group in the GN field
 - first discovered with the PPM (Calvi+23)

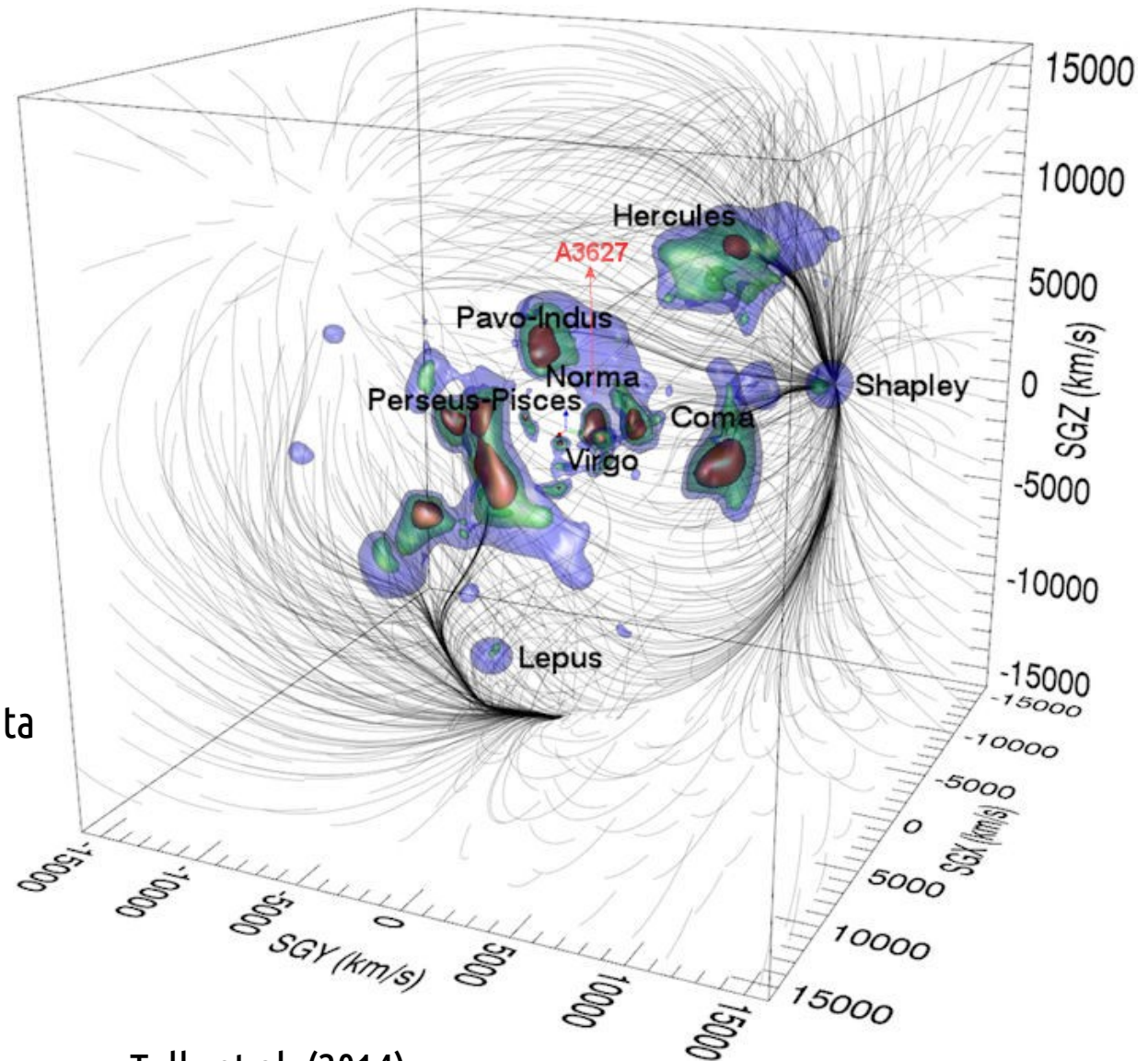


Part 3

Processing of gas in cosmological filaments in the local Universe

Virgo cluster and the Laniakea supercluster

- ▶ **Galaxies experience pre-processing,** before they fall into the cluster cores
 - The degree of such processing is debated (Malavasi+16, Laigle+18, Cortese+06, Poggianti+99)
- ▶ **Study of atomic (HI) and molecular (H₂) content in the cosmic filaments around Virgo**
 - the nearest cluster, with many ancillary data



Tully et al. (2014)

Virgo Filament Survey

► **Mass-complete sample of filament galaxies :**

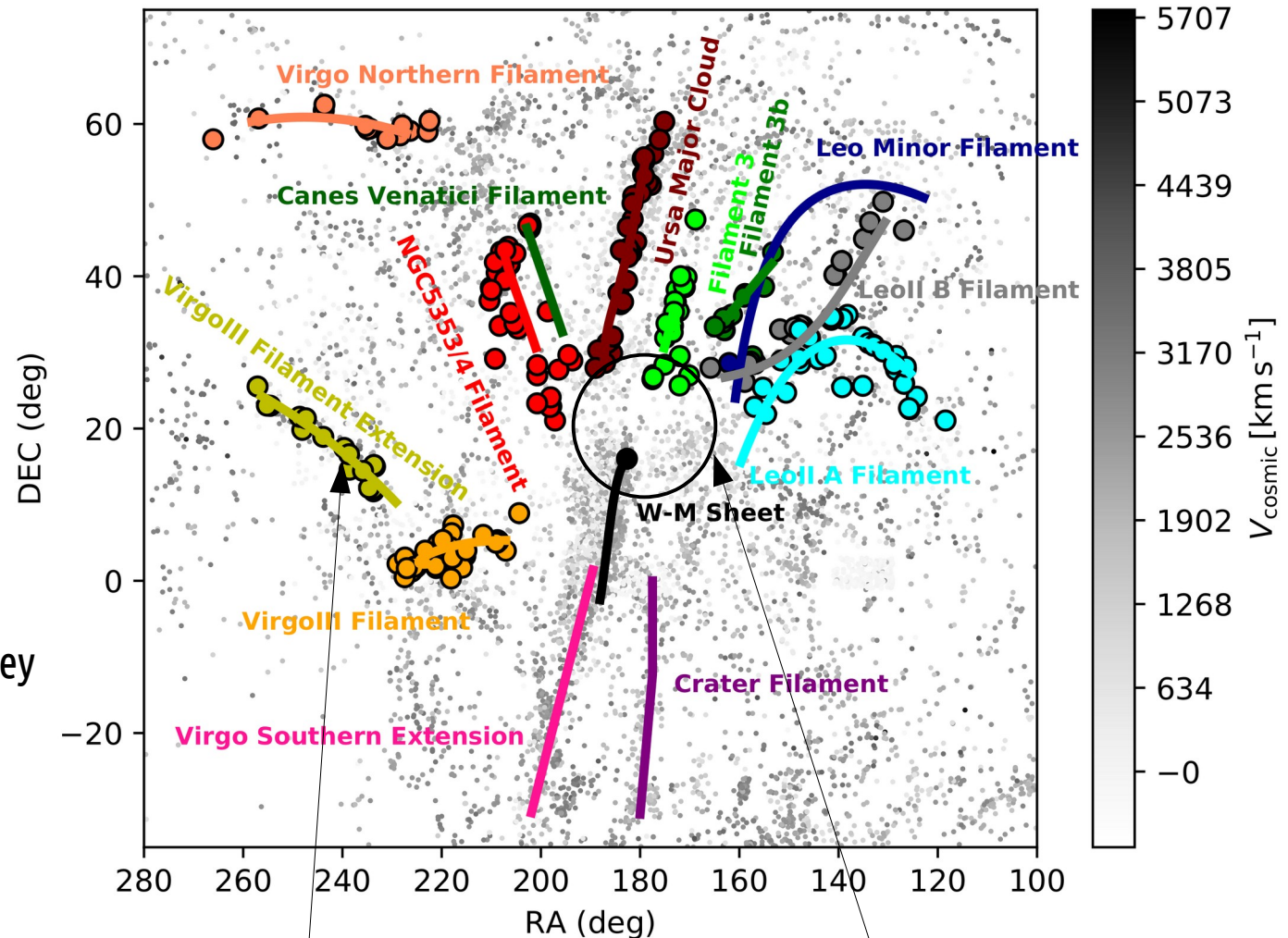
- 245 sources
- $M_{\text{star}} = 10^{9-11} M_{\text{sun}}$

► **Molecular gas :**

- CO(1-0) & CO(2-1)
- 85% from our IRAM 30m survey

► **Atomic HI gas :**

- 24% from our Nancay survey



Dots: filament galaxies with CO and HI observations

Virgo cluster core (r_{200})

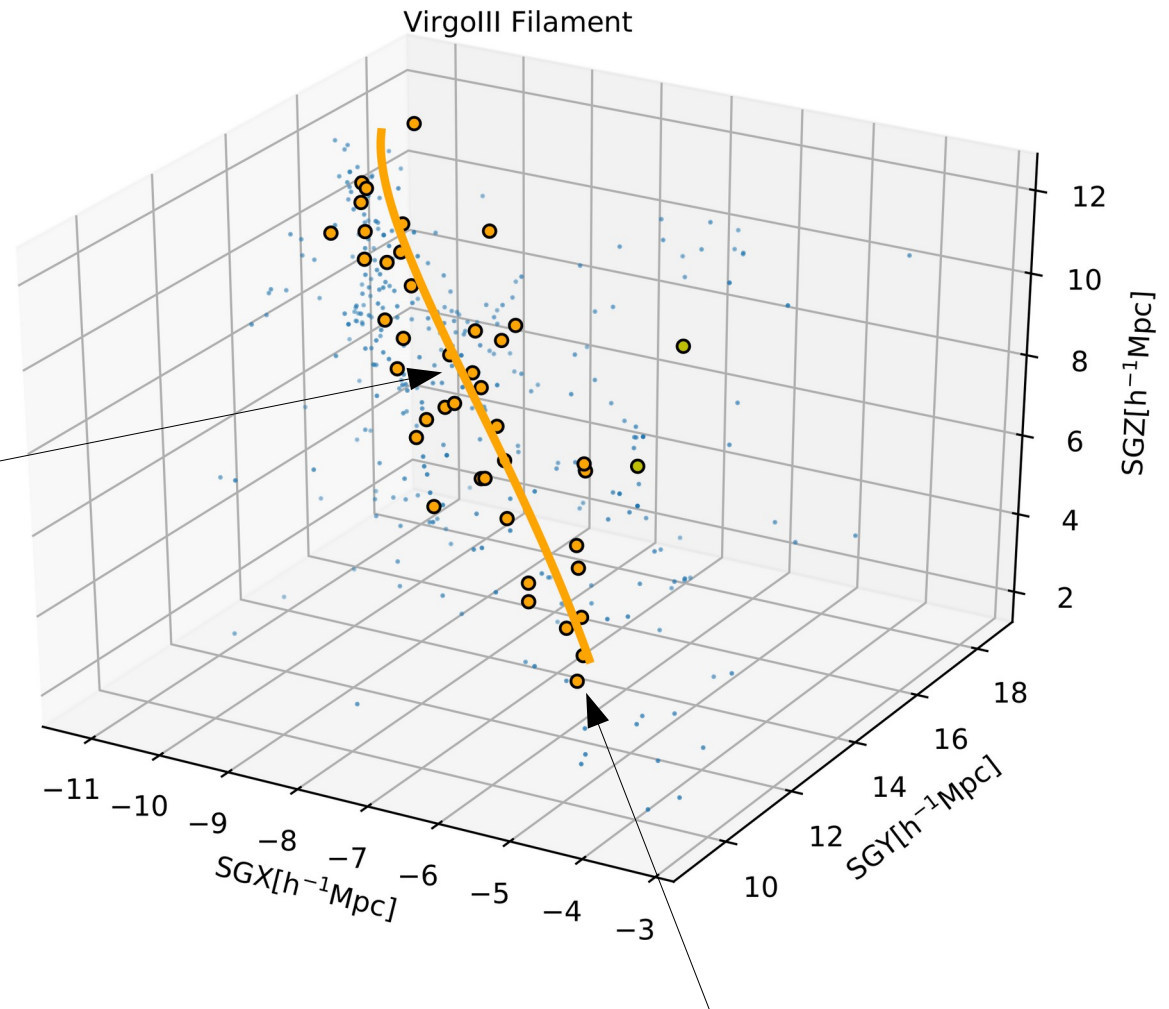
3D skeleton reconstruction : Super Galactic Coordinates

► Velocities

- z-independent distances (Steer+17)
- model corrected velocities (Mould 2000)

$$v_{\text{model}} = v_r + v_{\text{LG}} + v_{\text{in, Virgo}}$$

► Filament spines following Kim+16



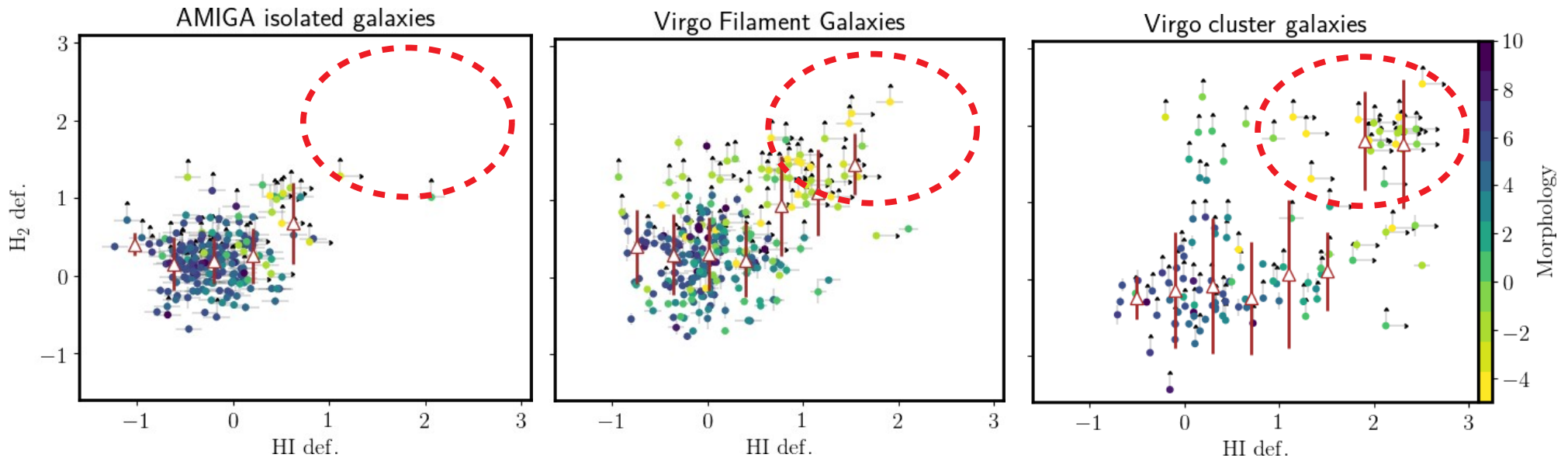
dots : filament galaxies observed in CO, HI

Castignani, Combes+22 ; Castignani, Vulcani+22

Preprocessing in Virgo Filaments : H₂ vs HI Deficiency correlation

$M_{\text{HI}} \rightarrow \text{HI-deficiency}$
 $M_{\text{H}_2} \rightarrow \text{H}_2\text{-deficiency}$

Castignani, Combes+22



- ▶ **Emergence of ETGs** as we move to the field (left) to filaments (center)
- ▶ **Increase scatter** as we move from field, filaments, to the cluster
- ▶ Virgo cluster then finalizes the gas processing.
- ▶ The degree of the **gas processing scales with local density**, then distance to the filament spine, then to Virgo cluster
- ▶ Cold gas reservoirs in ETGs in filaments have likely already experienced environmental pre-processing (e.g., dry mergers, starvation, HI ram pressure stripping), which favored the exhaustion of H₂ gas and the removal of the HI envelope.

Radio interferometry follow-up observations

- ▶ Follow up observations of a pilot sample of filament galaxies to spatially resolve the gas reservoirs
 - atomic HI gas : MeerKAT
PI : Jablonka
 - molecular gas (CO) : ALMA, SMA, NOEMA
PI : Castignani
 - they will provide insights on the physical mechanisms responsible for the gas processing (tidal tails, stripping, etc...)

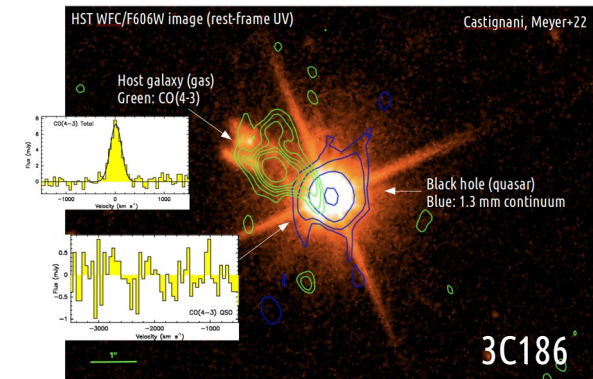
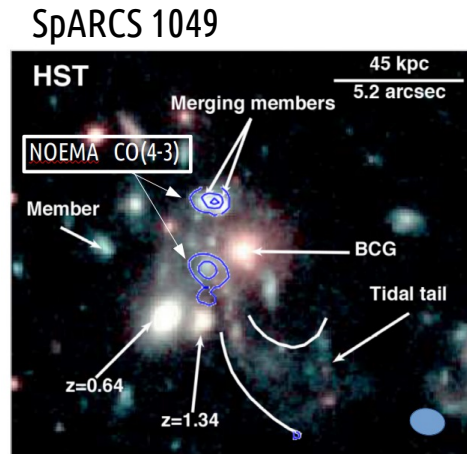
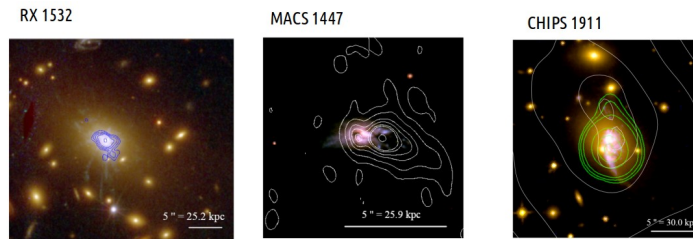
Conclusions and perspectives

Galaxy clusters

- High precision cosmology (e.g. cluster counts : *Euclid* , LSST)
- Astrophysical studies

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

- SpARCS 1049+56 at $z=1.7$
- 3C186 at $z=1.1$ (GW recoil candidate)
- Cool-core BCGs at $z=0.4$



SMGs are excellent tracers of protoclusters (PPM and GOODS-N)

Virgo clusters and large scale filaments

- environmental pre-processing of atomic and molecular gas, before galaxies fall into the cluster itself

Euclid / LSST / SKA synergy

- Thousands of $z>1$ clusters and BCGs with *Euclid* in the next years
- A revolution in the field of galaxy evolution is expected (radio-mode AGN feedback, formation of the first LSS)

