# Galaxies, filaments and clusters from MeerKAT to SKA

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in happy collaboration with

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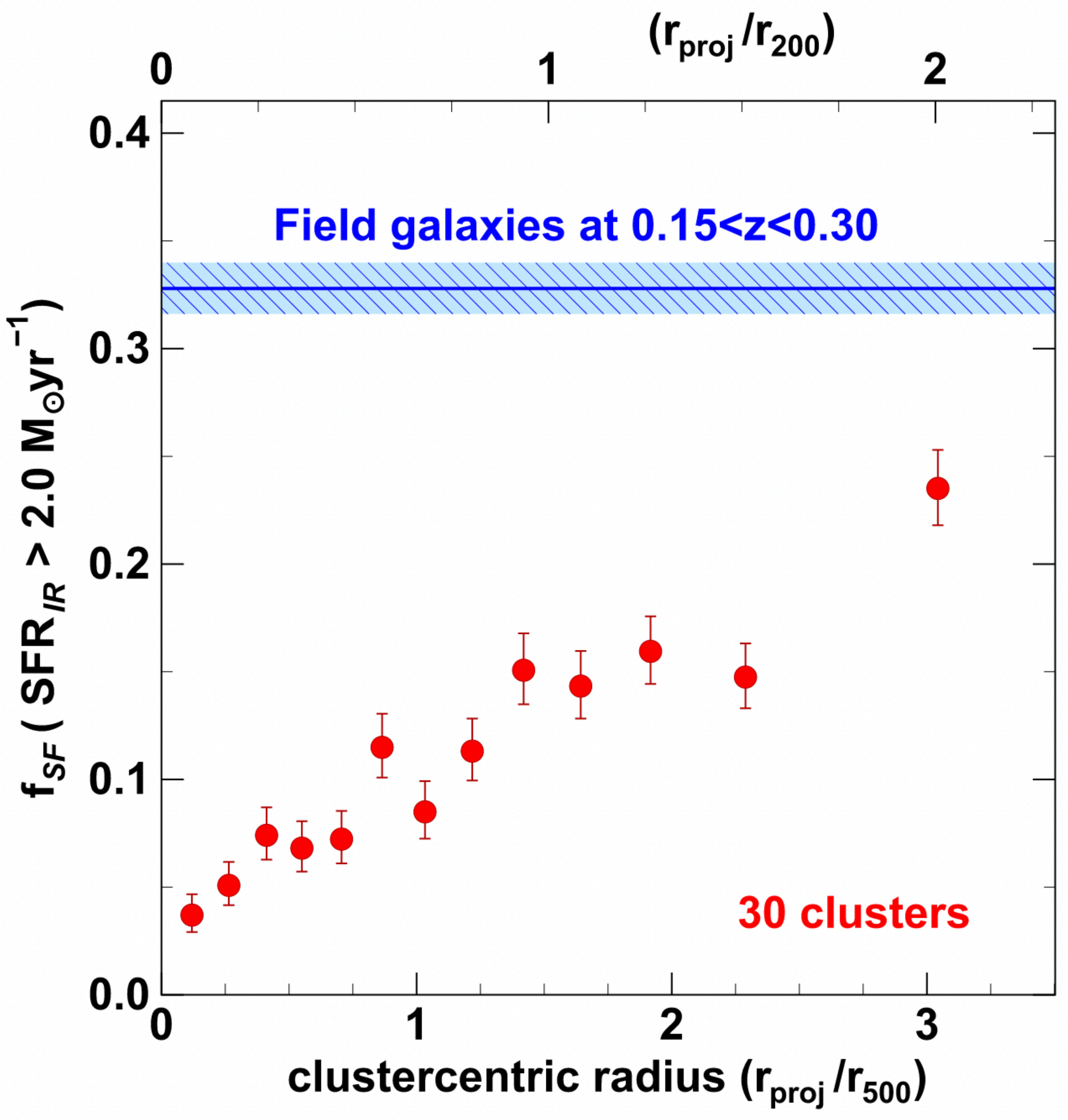
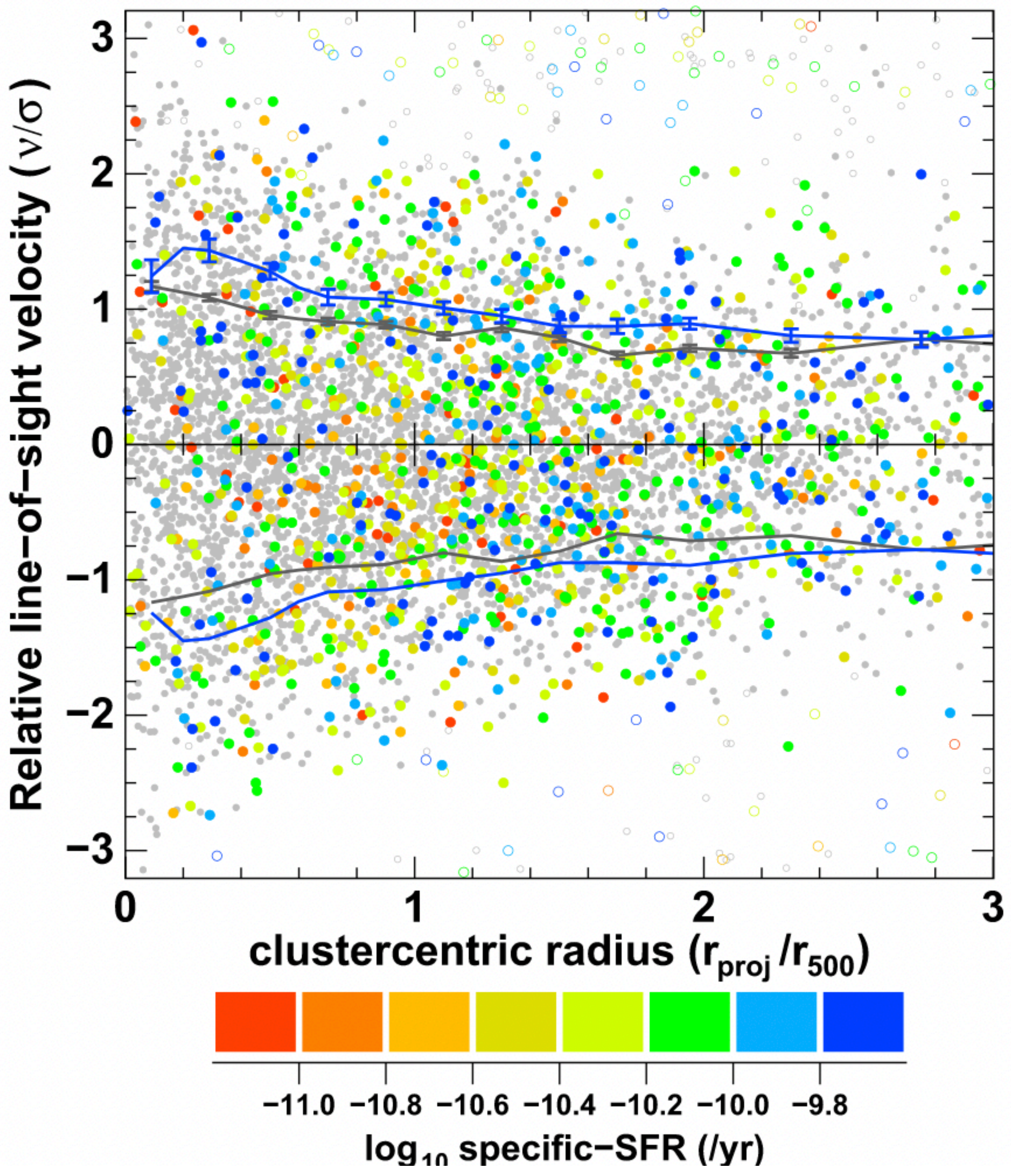
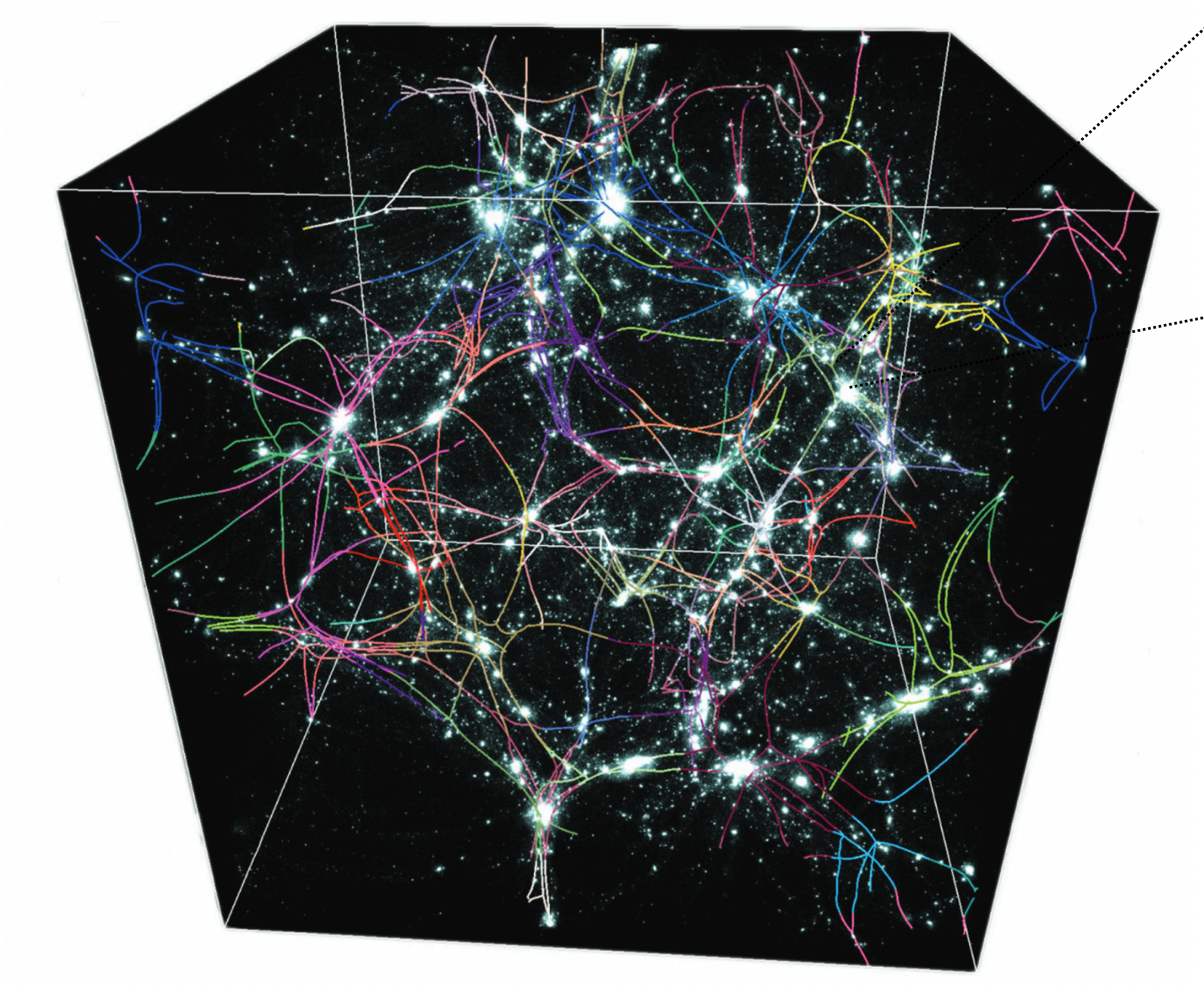
# Galaxy star formation activity



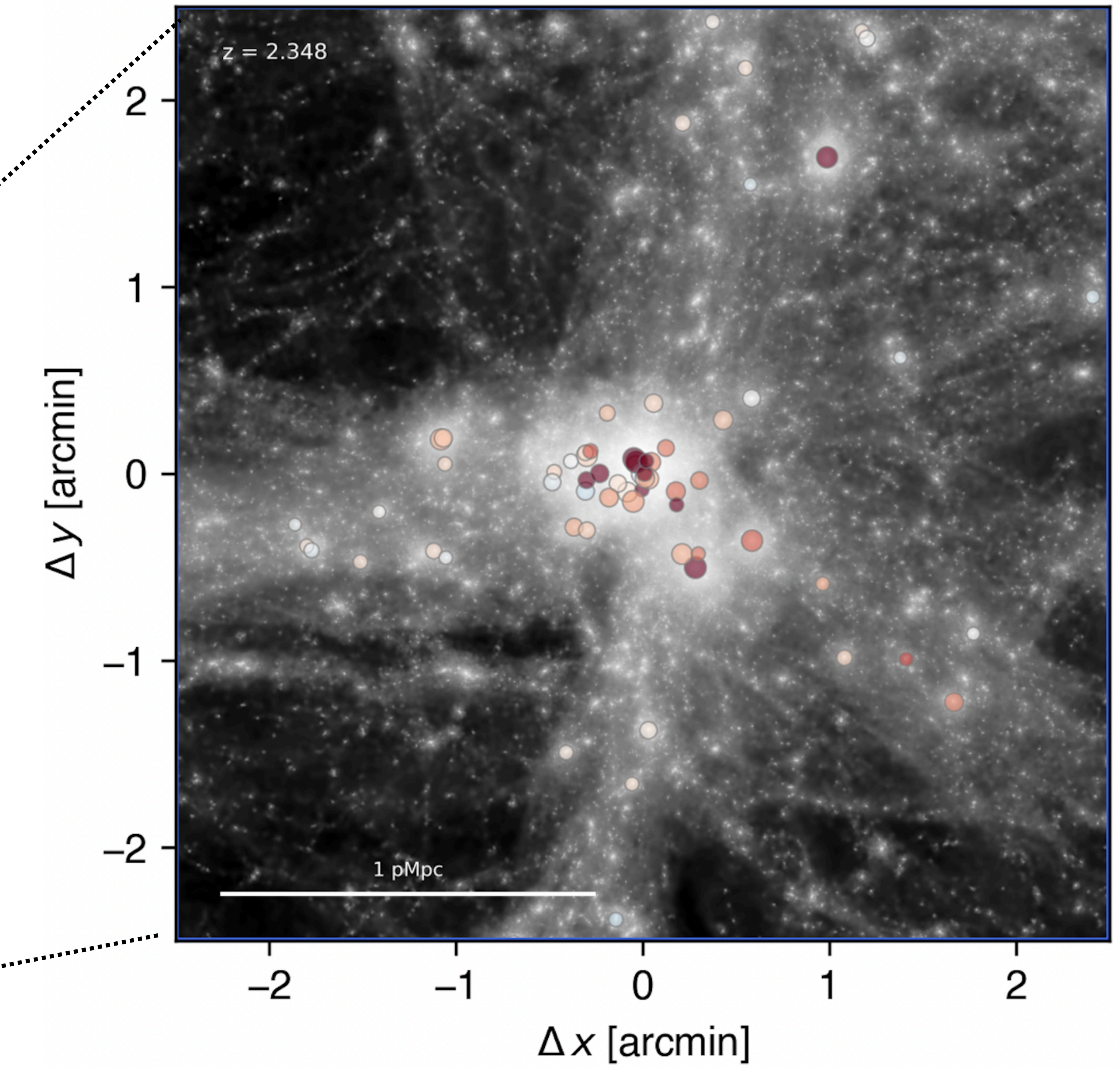



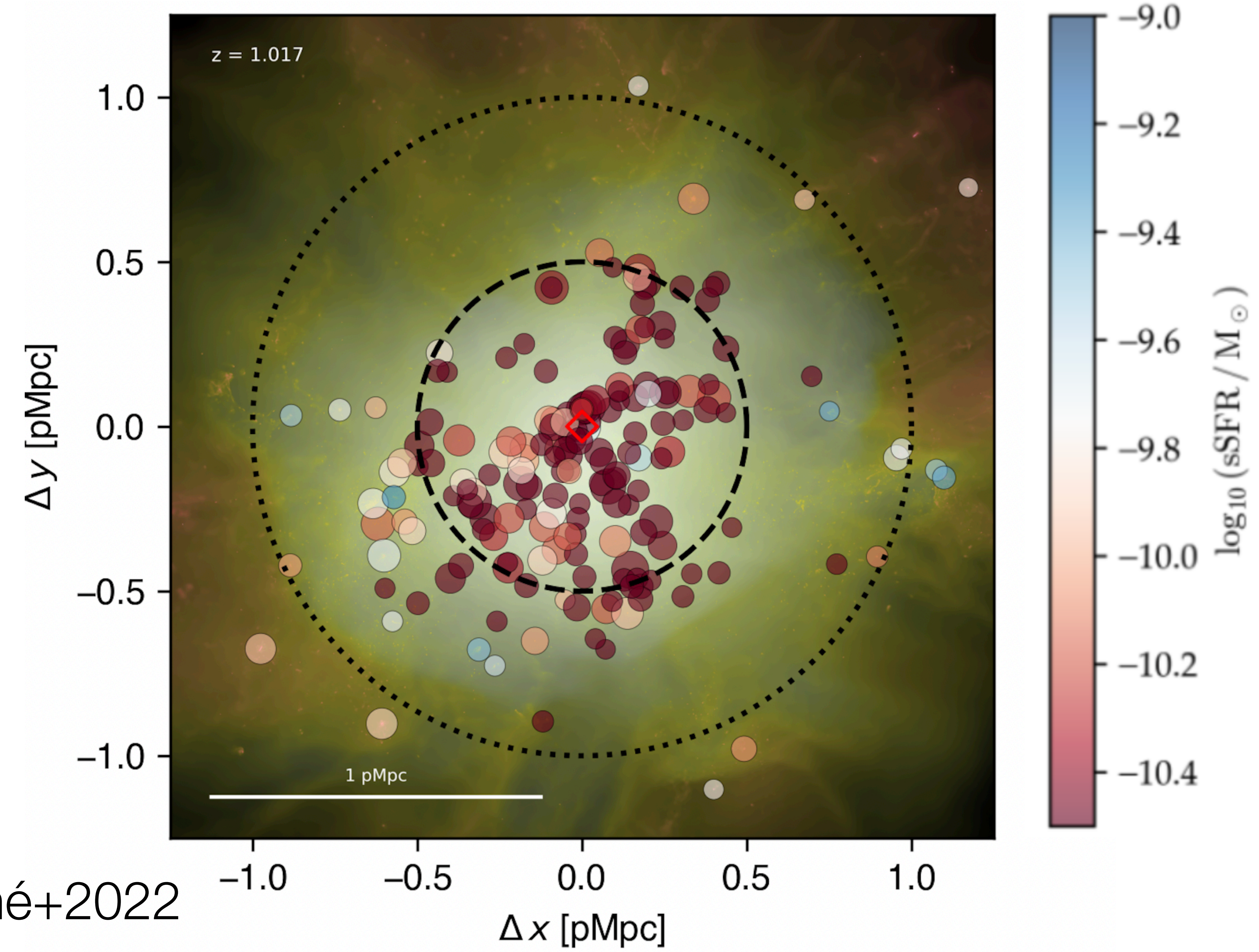

Haines+2015

# Structure & evolution of the cosmic web



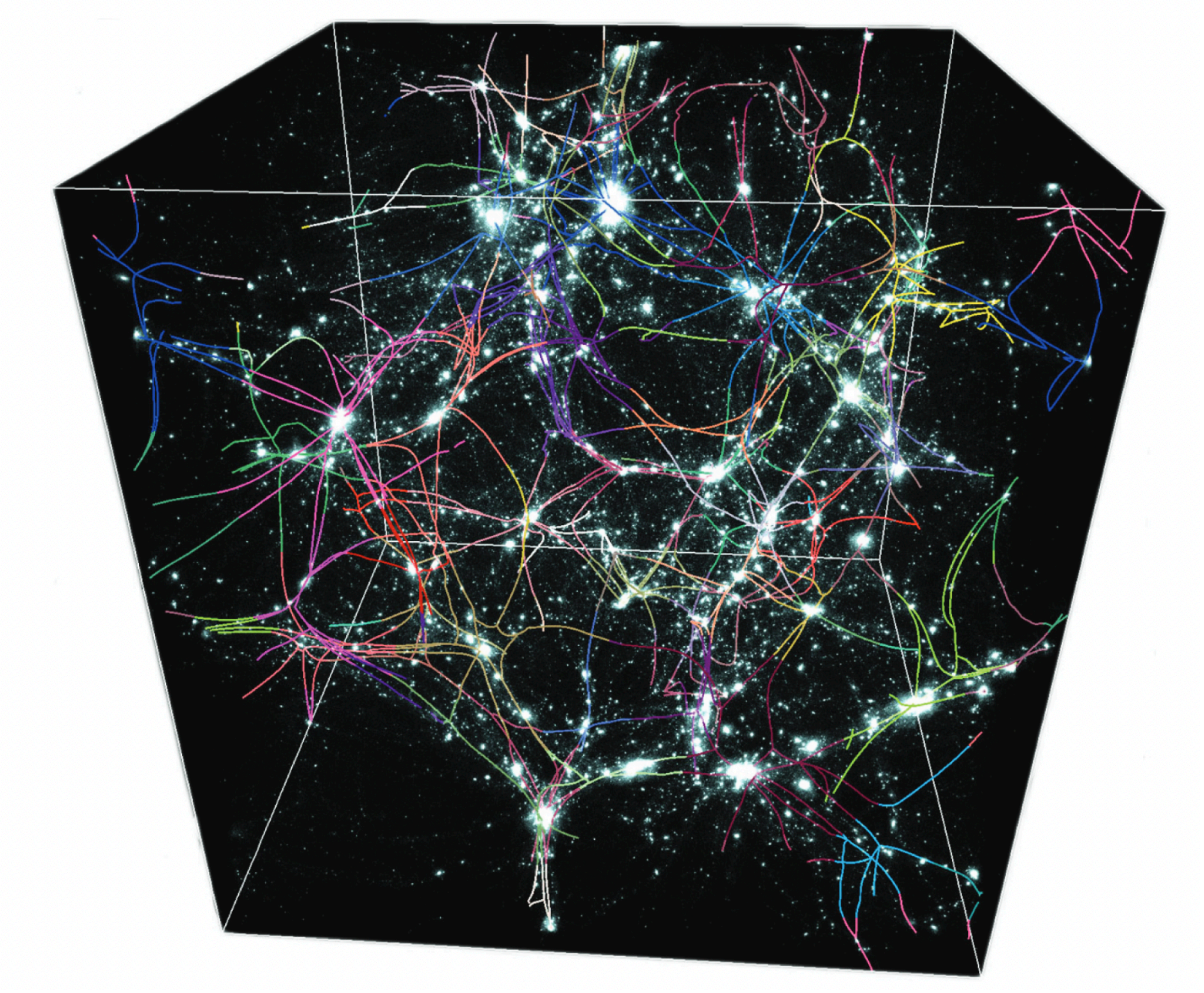
Sousbie+2009

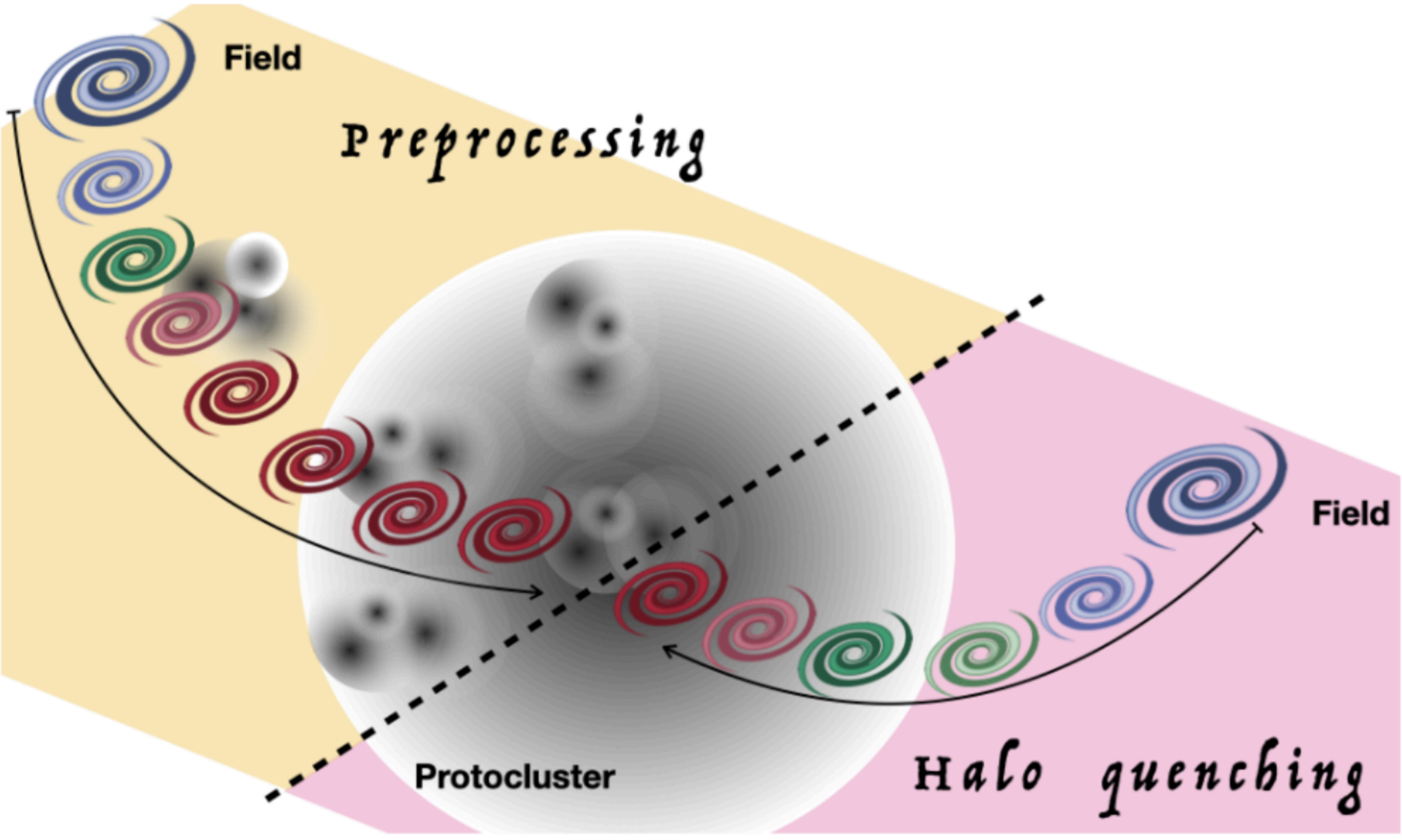



Hydrangea, Bahé+2022

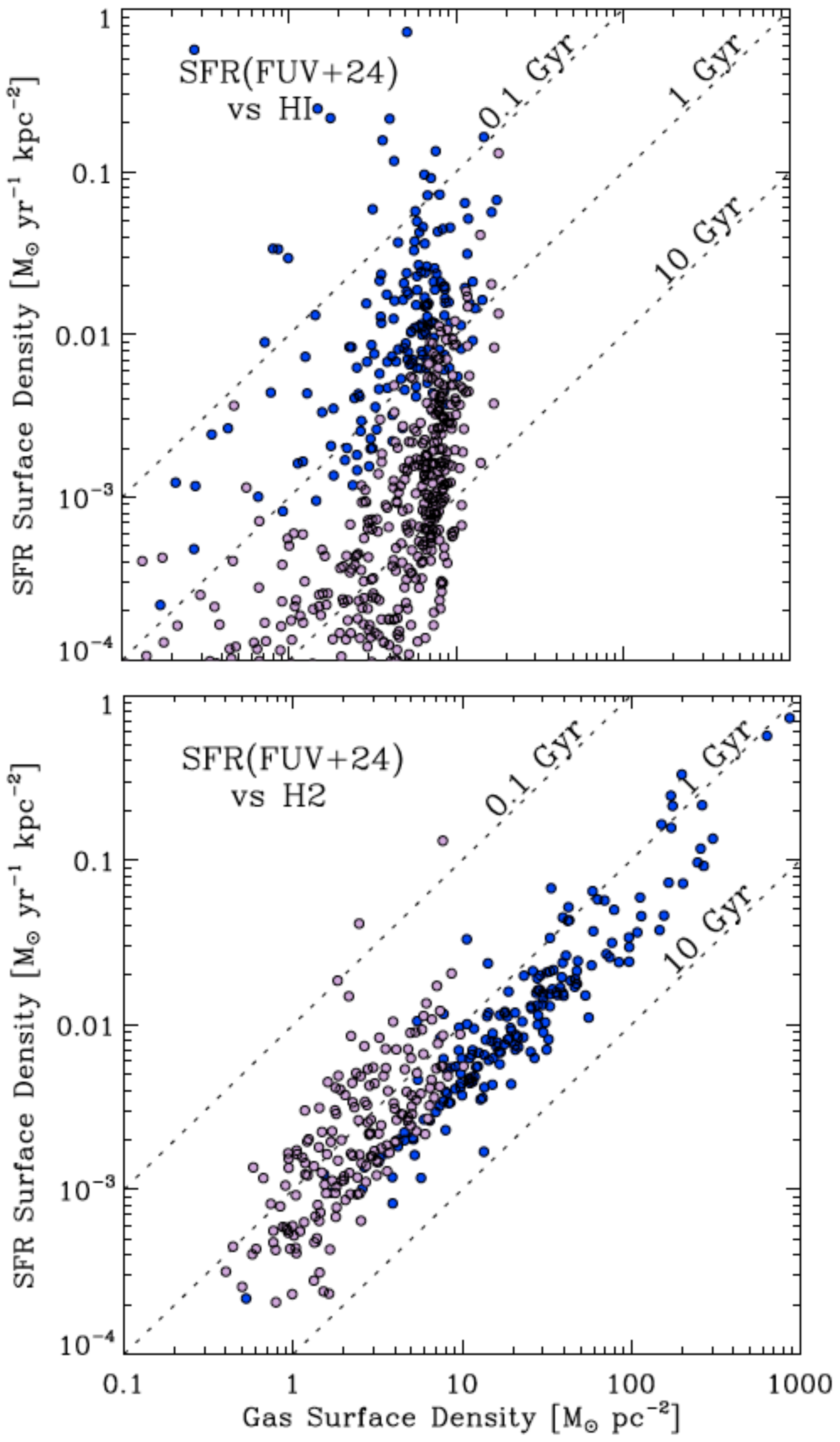
# Where do galaxies stop forming stars?






Sousbie+2009

# Origin of SF quenching



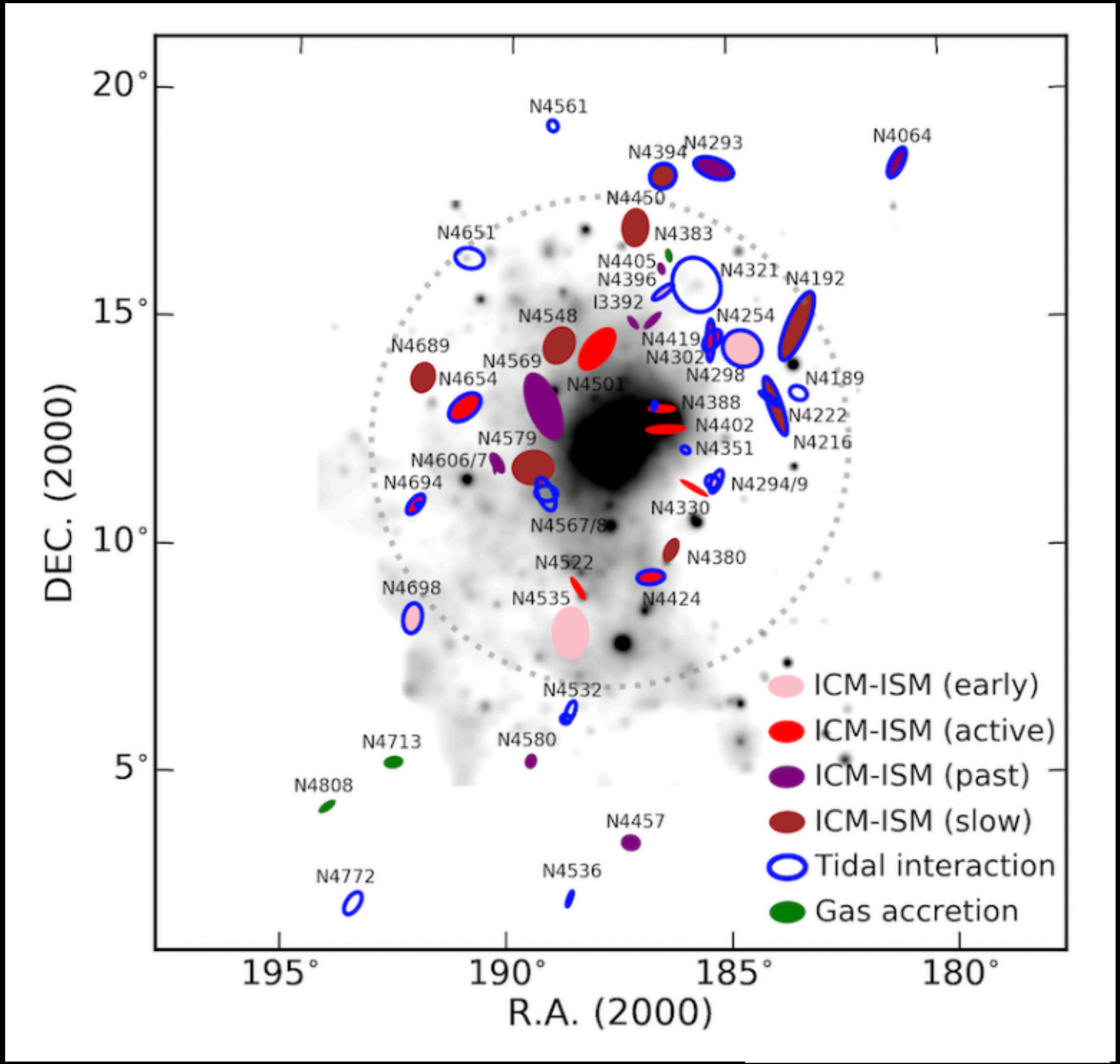

These features
are driven by physical
processes in the gas that
fuels star formation
(Schruba et al. 2011, AJ, 142,37).

There are goods reasons to
concentrate on $H_2$

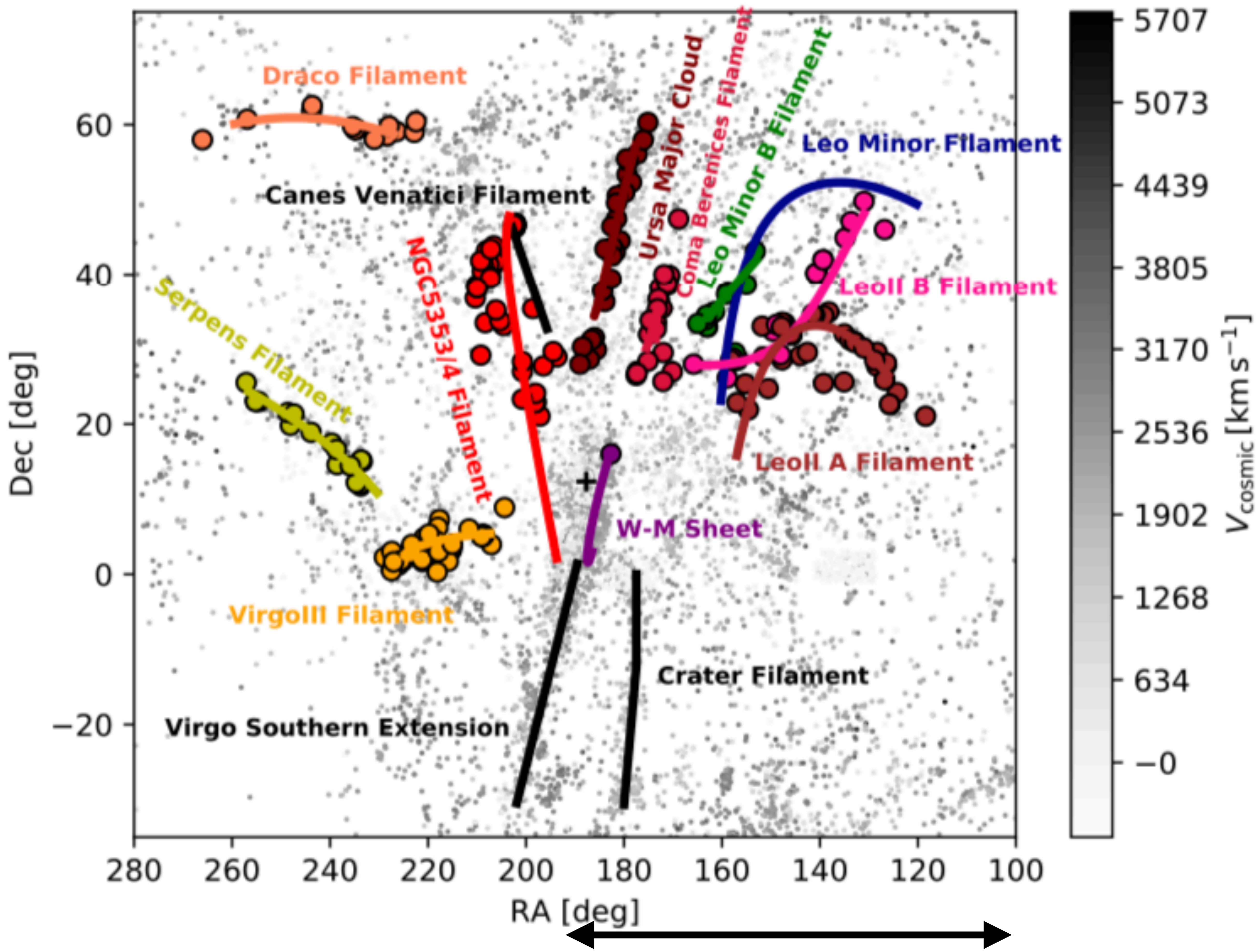
# Environmental impact in clusters


Van Gorkom

The impact of high density environments is documented



# Filaments around the Virgo cluster




12 virial radii

## Unique sample of ~7000 galaxies

- 100deg < RA < 280deg and −35deg < Dec < 75deg
- VH < 3300 km $s^{-1}$

Stellar masses: $10^9$ $M_\odot$ to $10^{11}$ $M_\odot$

## New datasets

integrated CO & HI

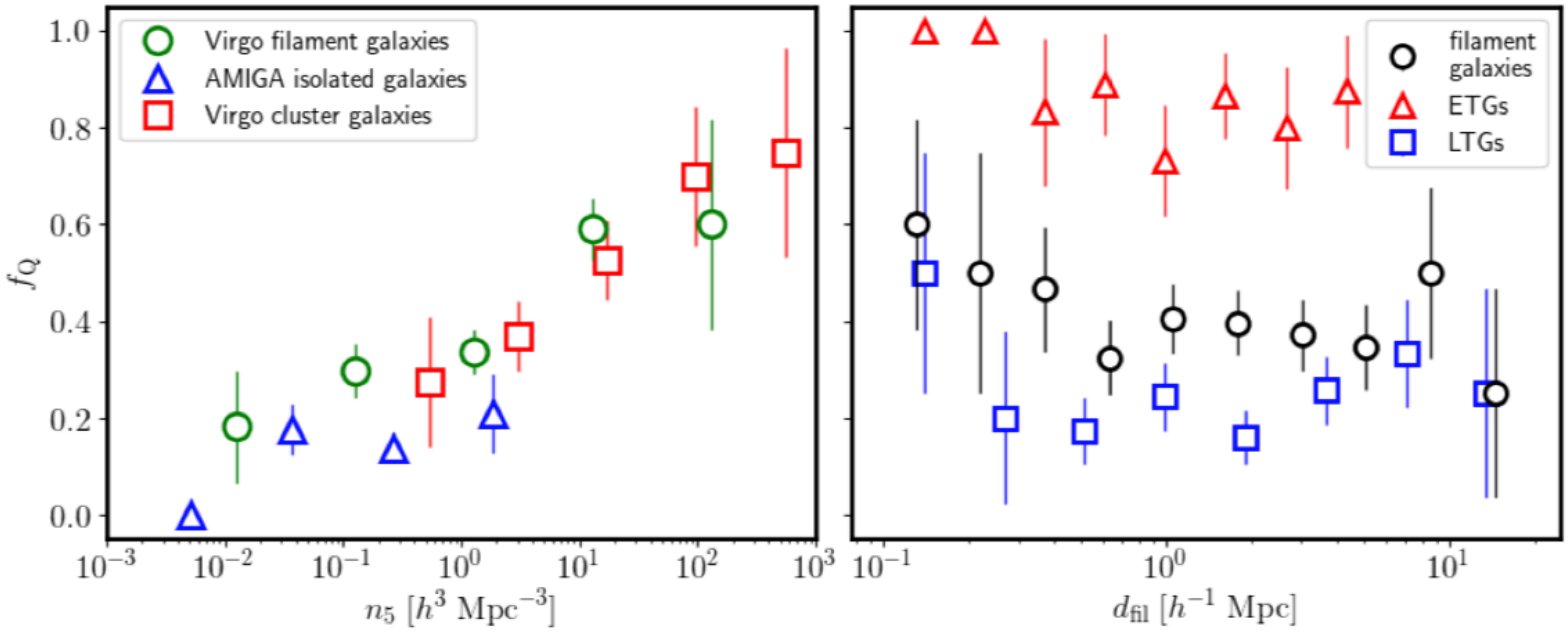
IRAM-30m (163/245 sources)
Nançay (69)/ Literature

Castignani+2022

# Filaments around the Virgo cluster


Plethora of multi-wavelength information, constraining the galaxy physical condition, as well as precise view of the morphological structures

# SFR, Mass, Morphology, density, distance to the filament spines




Density

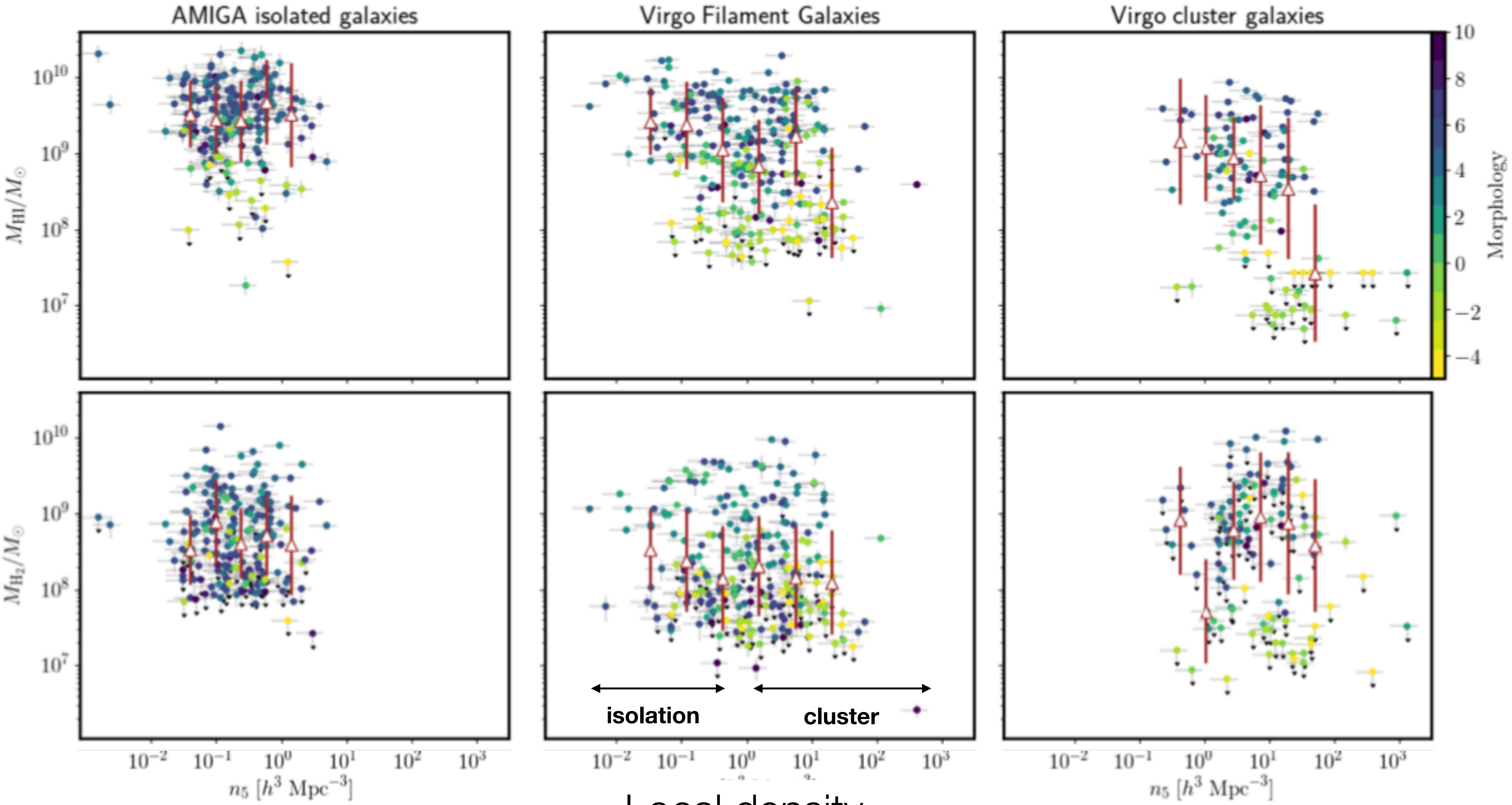
Distance to spline

Castignani+2022

# Gas content

HI mass

H2 mass




Local density

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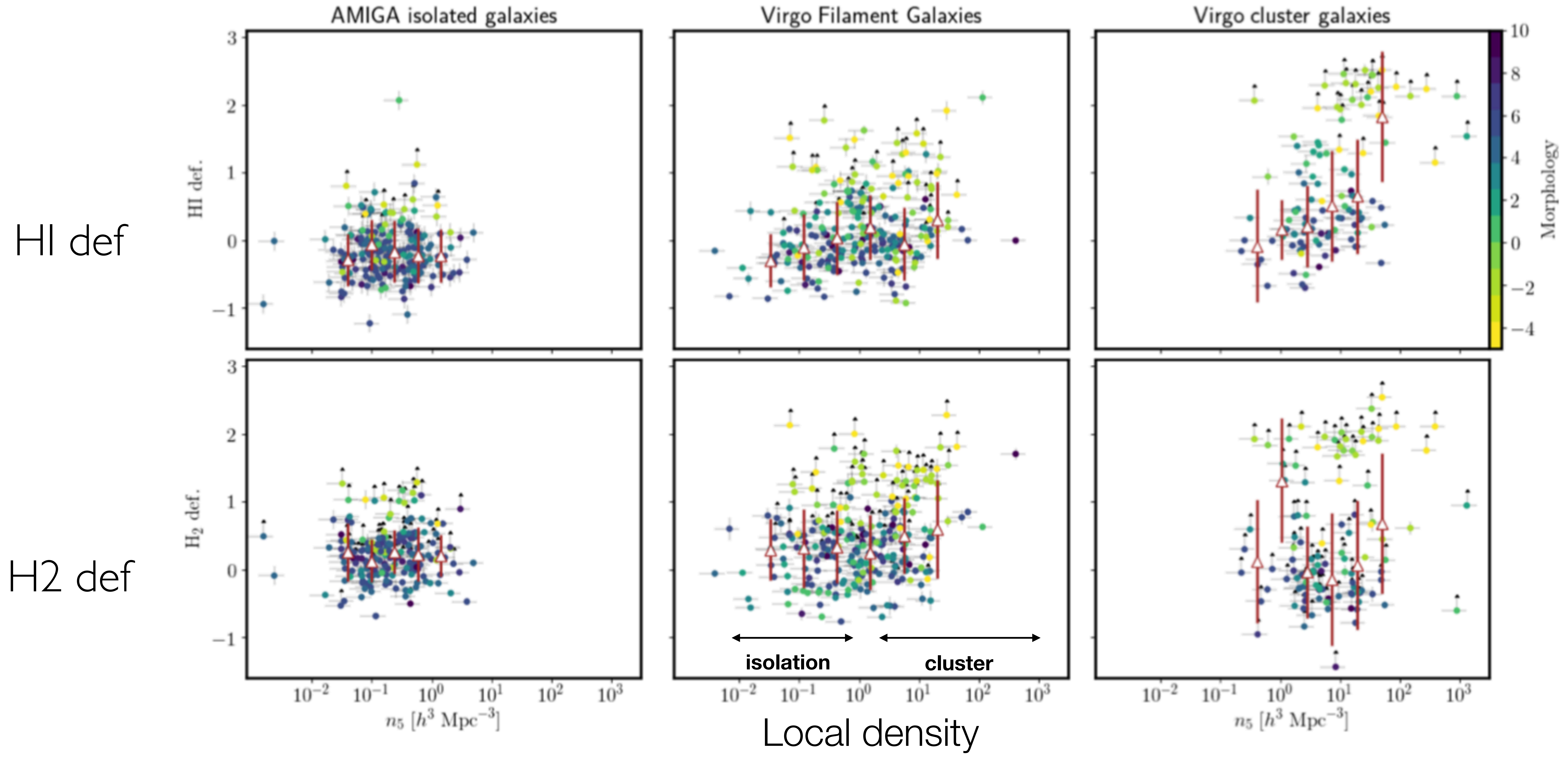
# Gas deficiency




Castignani+2022

# Status

- *Clear trends from isolation to dense environments*: change in morphologies, gas (HI & H2) content, star formation activity

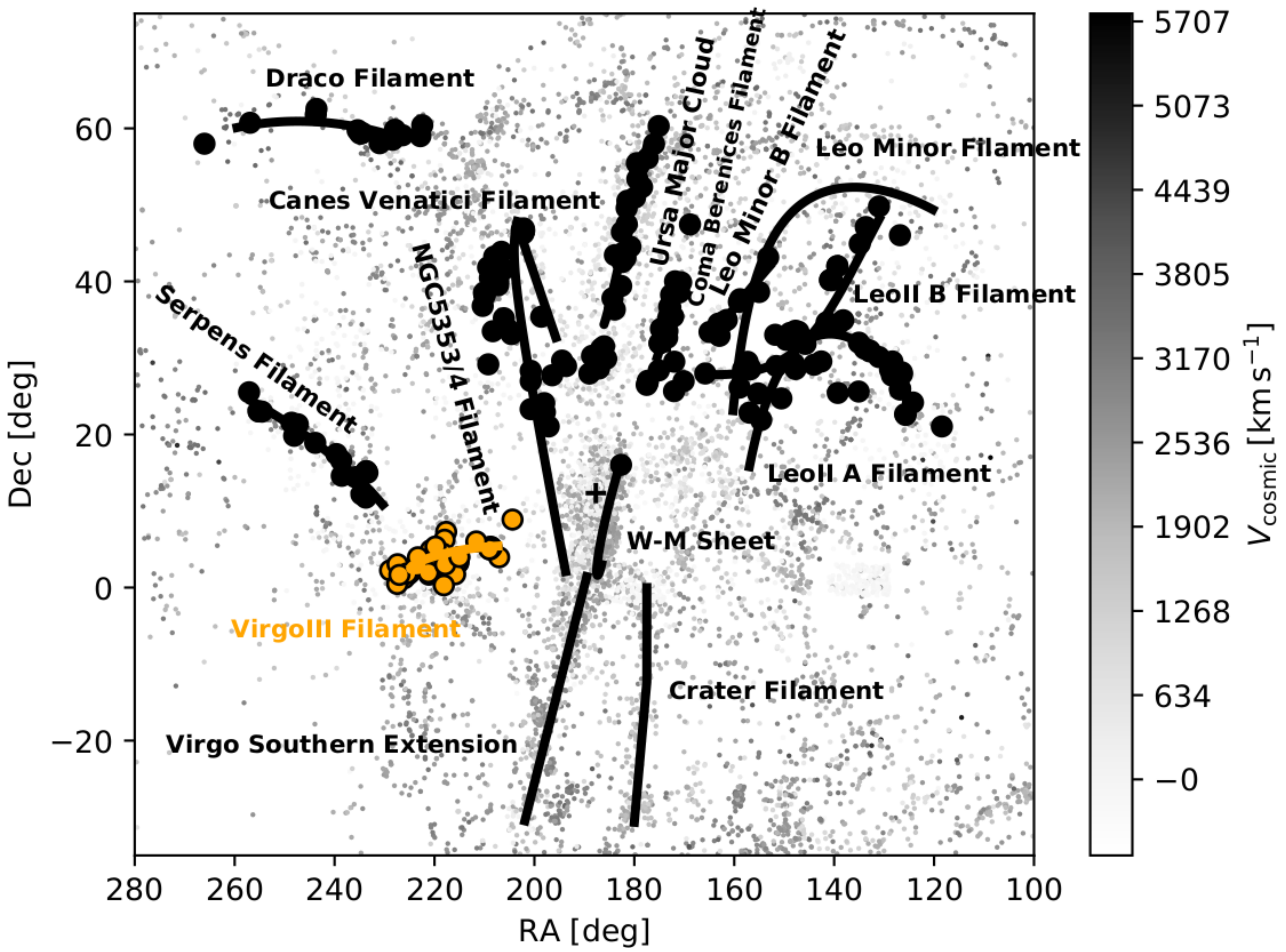
- *Density is not the only driver:* large scale structures do impact galaxy properties, possibly as a consequence of the build-up of the cosmic web with time.

- *Identifying physical processes at play requires spatial resolution*

# Filaments around the Virgo cluster

**MeerKAT**

## High spatial resolution view of the gas




Looking for evidence of:

- shocks due to ram-pressure, tidal interactions, and subsequent perturbations, as well as asymmetries in the main bodies of the galaxies. (HR - 9 arcsec beam)

- tails due to gas swept out by the filament or intra-group hot wind, or tidal tails in the outskirts of galaxies.

includes 1.4 GHz radio continuum star formation rate

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expectation: $\gtrsim N_{HI} \sim 2 \times 10^{20}$ atoms/cm2

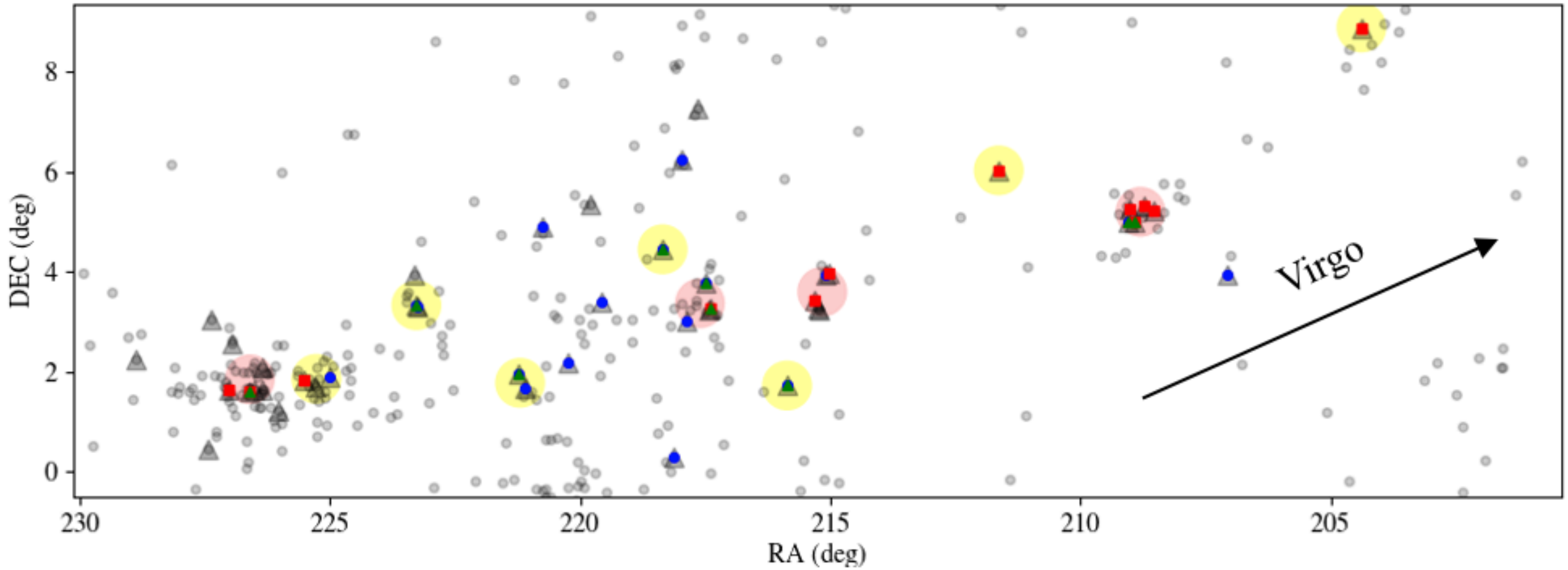
5 hours @ 3σ with 9arcsec (~0.9 kpc) 22km/s line width, 0.22mJy/bm
Smoothing the data to ~90 arcsec (9 kpc) …. $N_{HI} \sim 1 \times 10^{18}$ atoms/cm2

# Filaments around the Virgo cluster

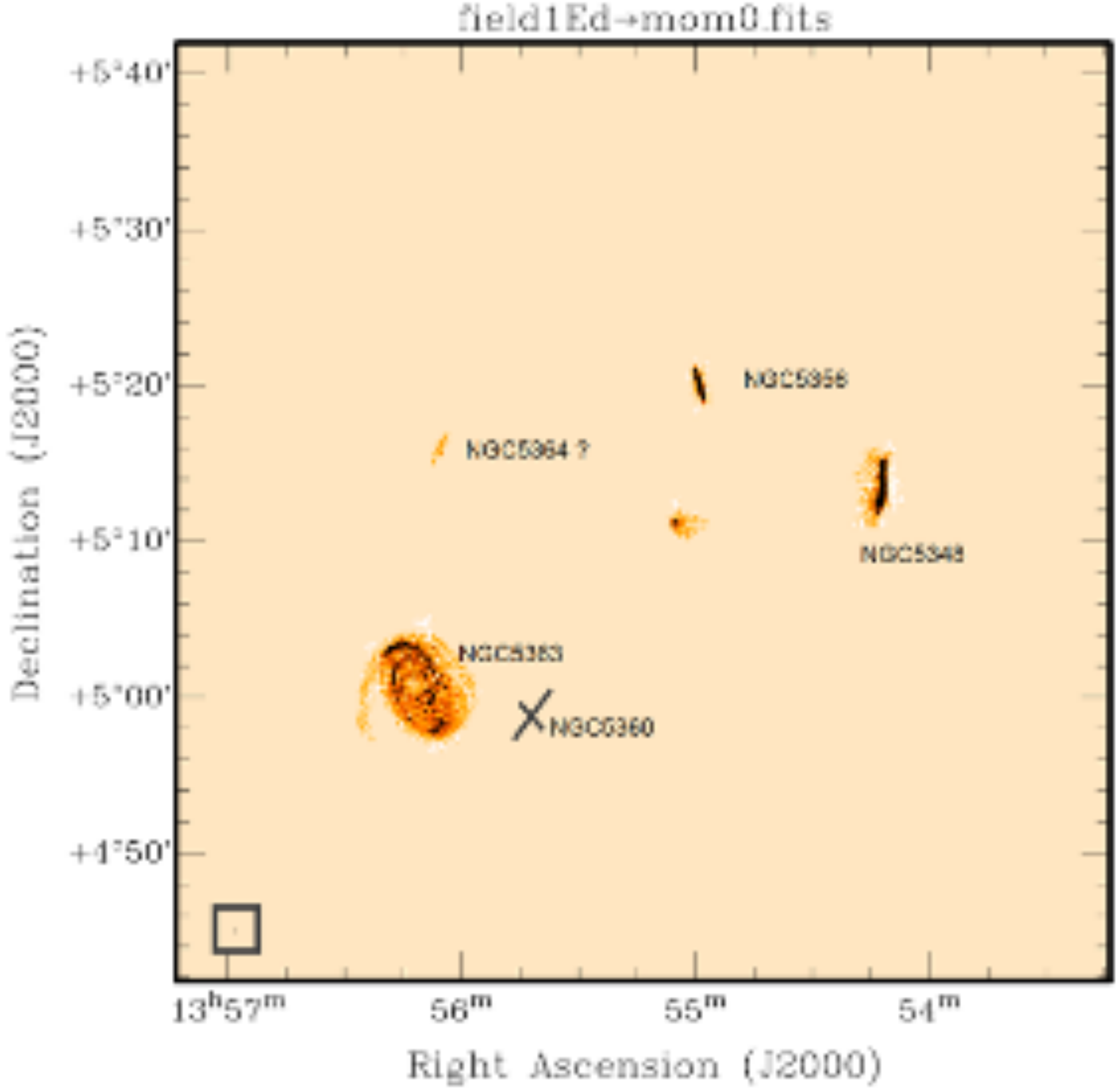
MeerKAT

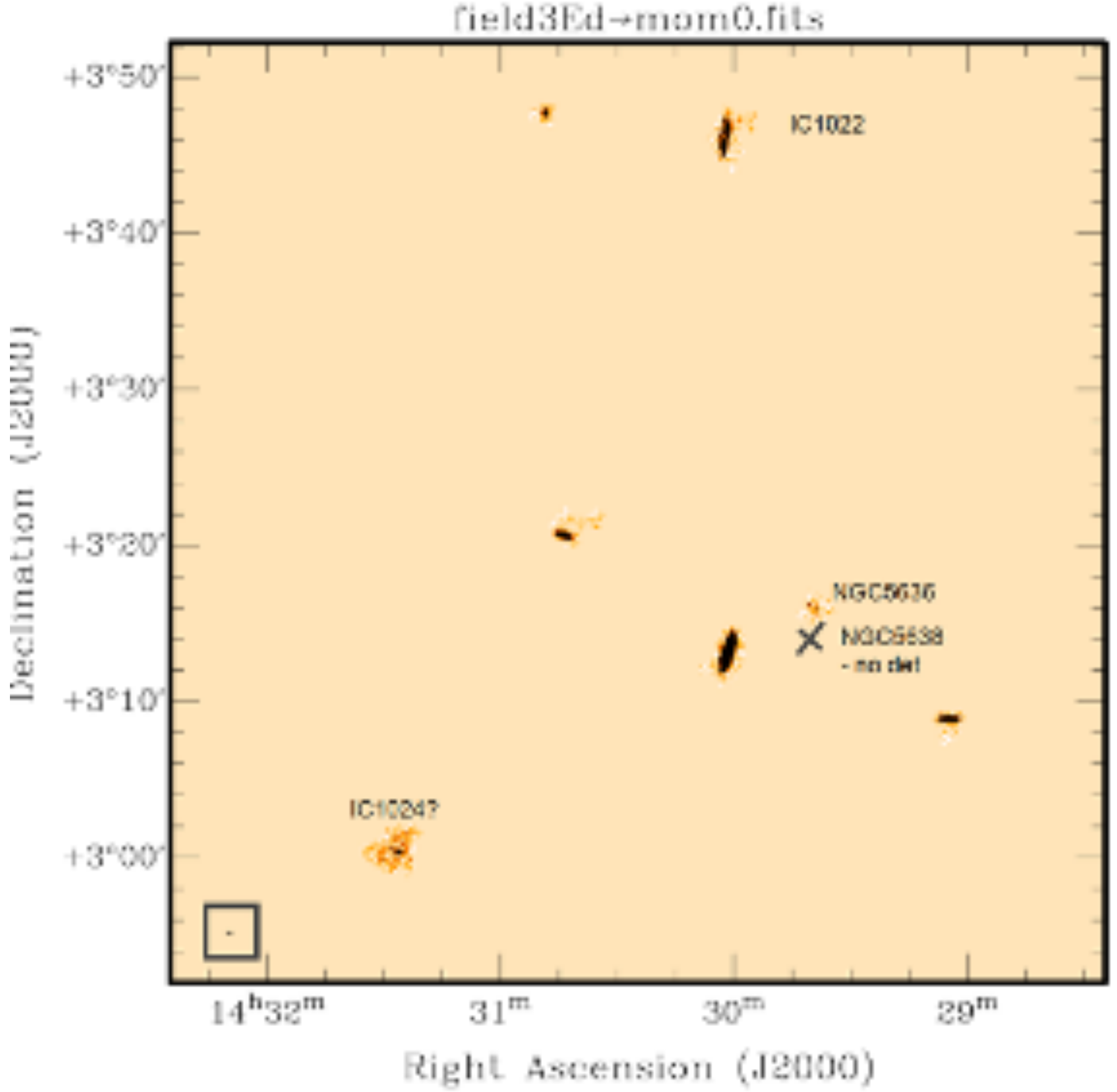
All
obs_HIdef > 0.4
obs_H2def > 0.4

MeerKAT 2022
MeerKAT 2020



# Filaments around the Virgo cluster



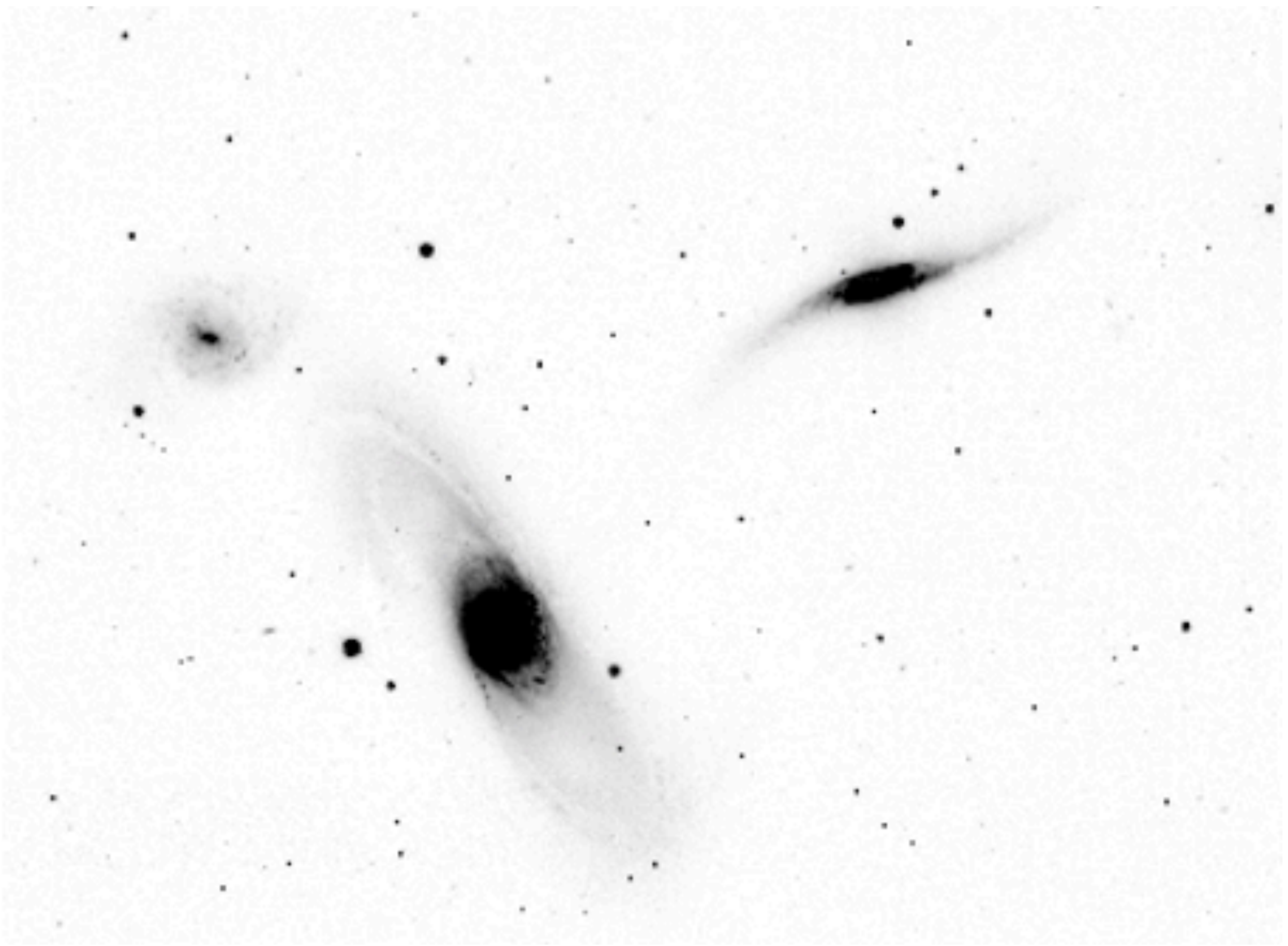

SoFiA J135412.17+051336.5
Dec (ICRS)
RA (ICRS)
$N_{HI} = 2^n$ x 1.5 x $10^{20}$ cm$^{-2}$ ($n$=0,1,...)
HI Intensity [Jy/beam*m/s]
Pixel SNR
$N_{HI}$ = 1.5 x $10^{20}$ cm$^{-2}$
$v_{sys}$ = 1440 $W_{50}$ = 177 $W_{20}$ = 197 km/s
$\Delta v_{contours}$ = 150 km/s
Topocent Radio Velocity [km/s]
Integrated Flux [Jy]
Topocent Optical Velocity [km/s]
Topocent Radio velocity [km/s]
Angular Offset [deg]
Kinematic PA = 175.3 deg


SoFiA J135503.19+051111.4
$N_{HI}$ = $2^n$ x 1.3 x $10^{20}$ cm$^{-2}$ ($n$=0,1,...)
$N_{HI}$ = 1.3 x $10^{20}$ cm$^{-2}$
$v_{sys}$ = 1390 $W_{50}$ = 41 $W_{20}$ = 56 km/s
HI Intensity [Jy/beam*m/s]
Pixel SNR
Topocent Radio Velocity [km/s]
$\Delta v_{contours}$ = 150 km/s
Dec (ICRS)
RA (ICRS)
Integrated Flux [Jy]
Topocent Optical Velocity [km/s]
Topocent Radio velocity [km/s]
Angular Offset [deg]
Kinematic PA = 269.9 deg


SoFiA J135610.41+050042.5
$N_{HI}$ = $2^n$ x 4.5 x $10^{20}$ cm$^{-2}$ (n=0,1,...)
$N_{HI}$ = 4.5 x $10^{20}$ cm$^{-2}$
$v_{sys}$ = 1239 $W_{50}$ = 263 $W_{20}$ = 282 km/s
Dec (ICRS)
RA (ICRS)
HI Intensity [Jy/beam*m/s]
Pixel SNR
$\Delta v_{contours}$ = 150 km/s
Topocent Radio Velocity [km/s]
Integrated Flux [Jy]
Topocent Optical Velocity [km/s]
Topocent Radio velocity [km/s]
Angular Offset [deg]
Kinematic PA = 30.5 deg

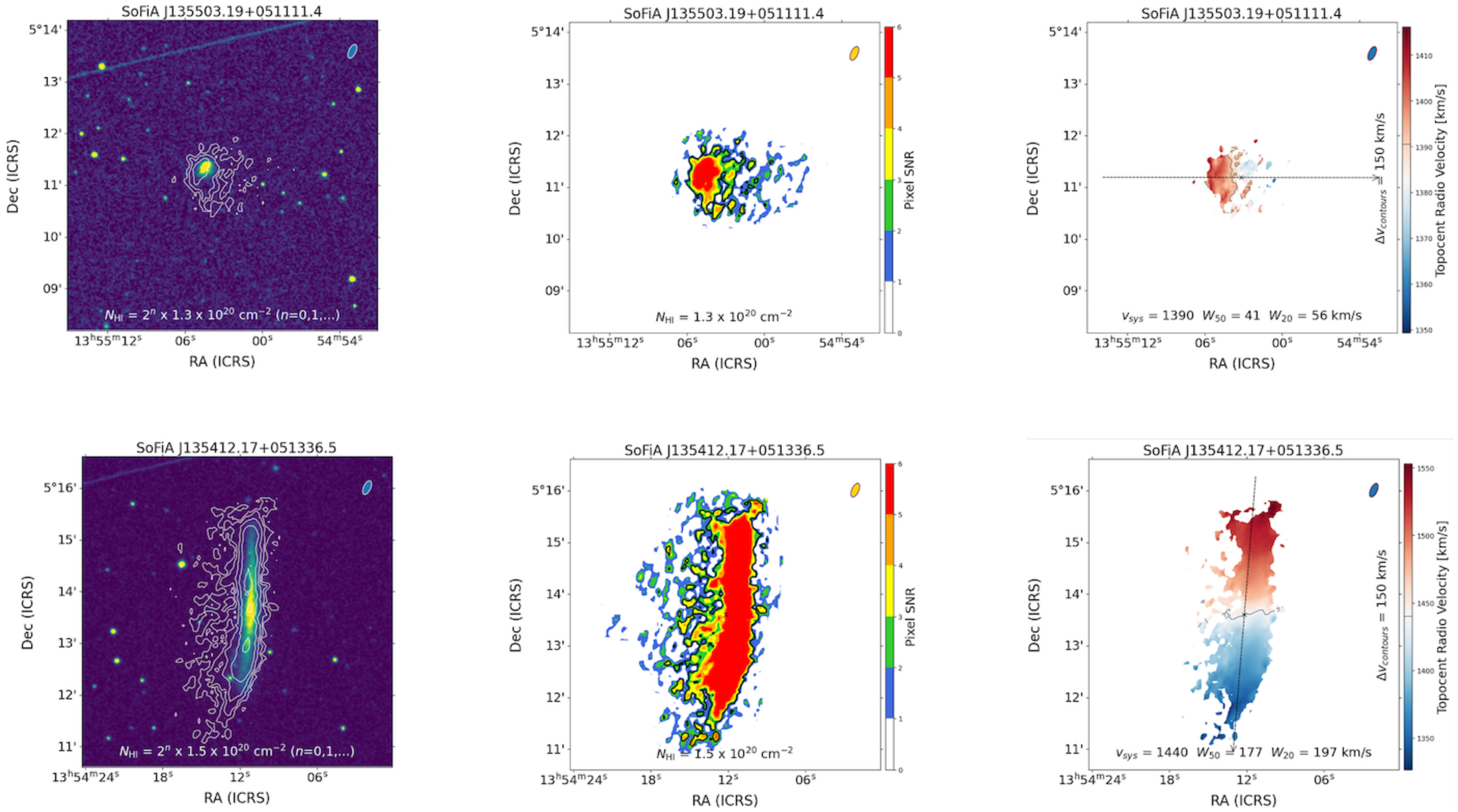
# A variety of cases: interactions in groups

HI

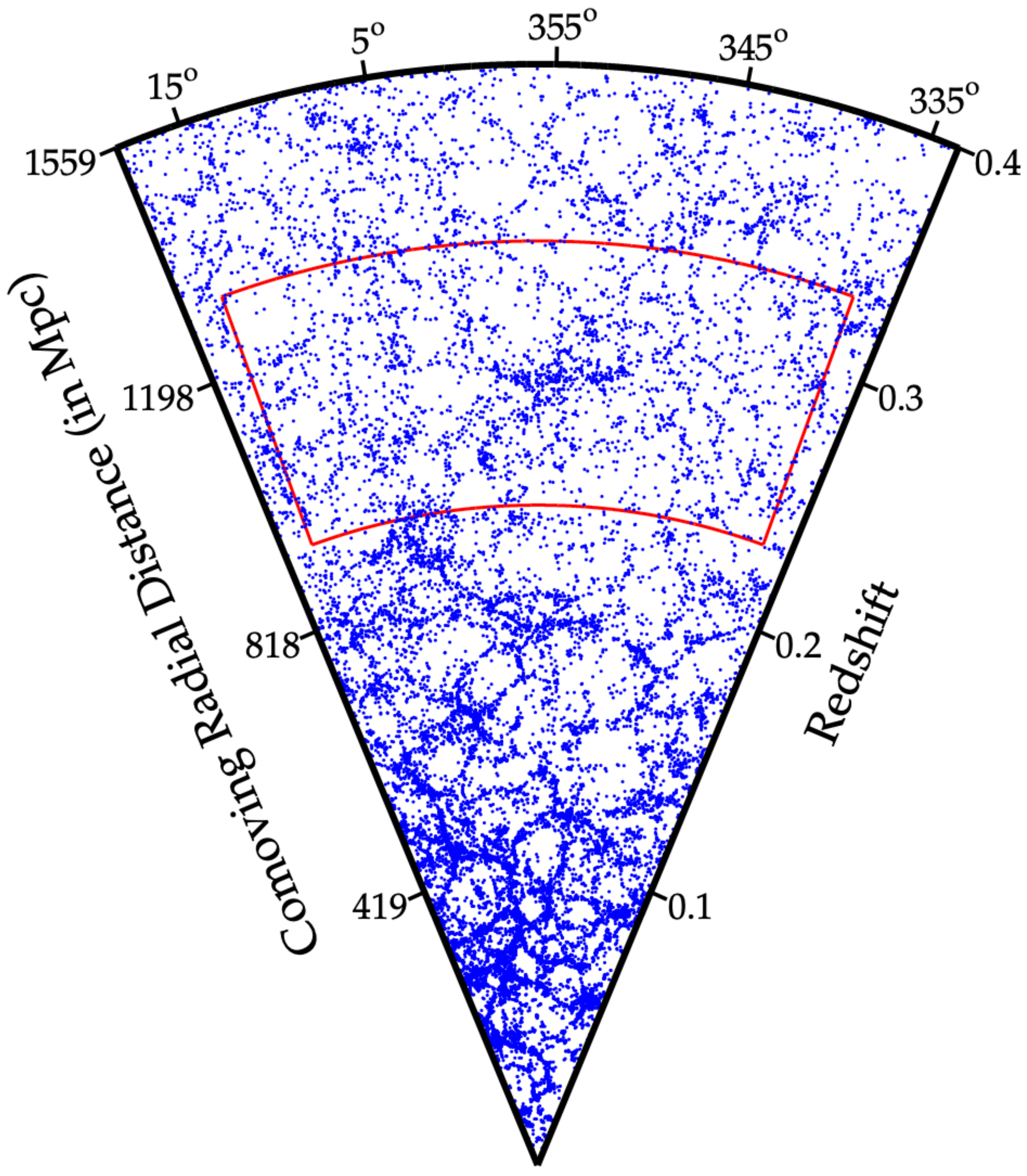


g-band

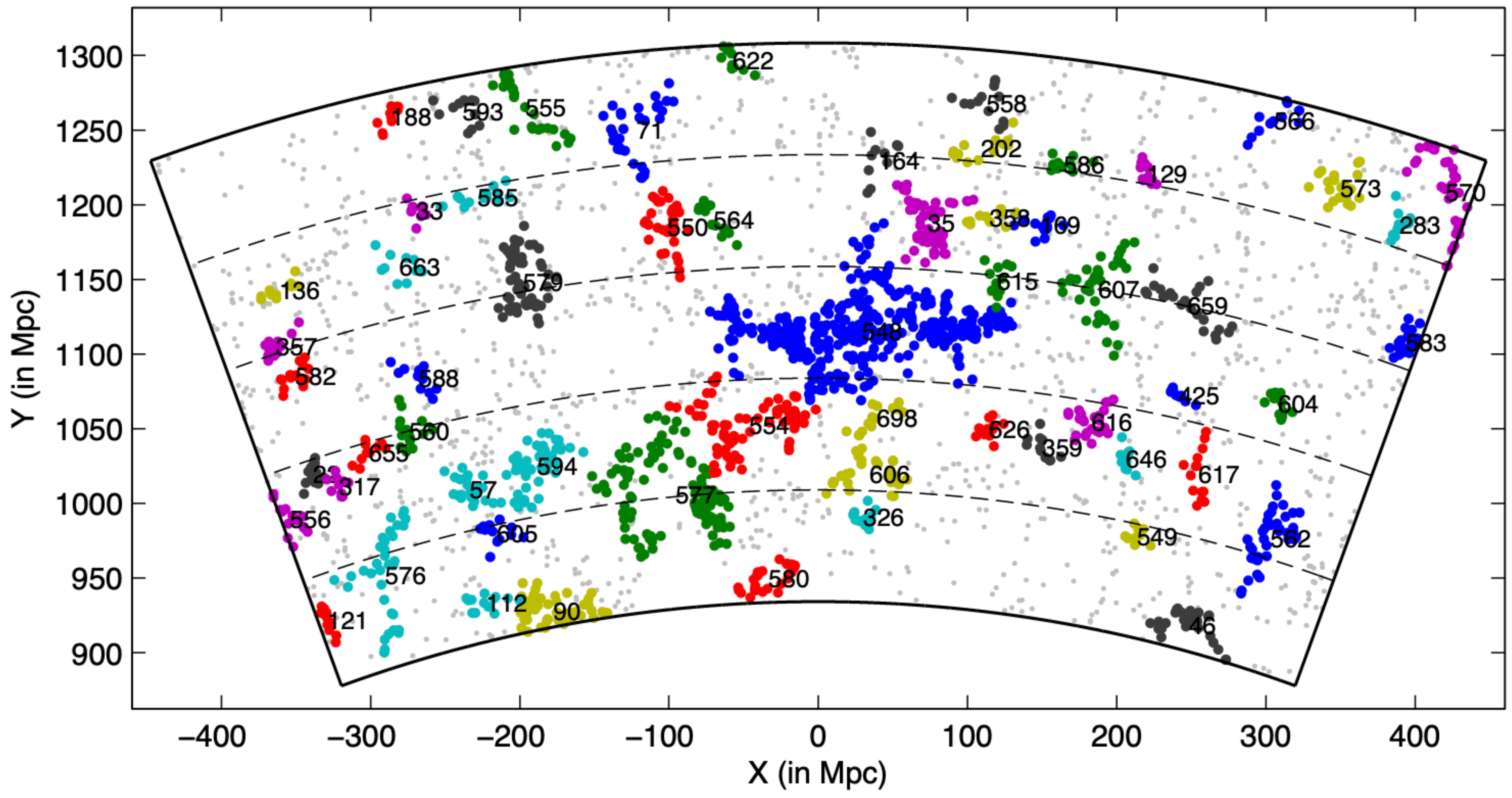
# A variety of cases: ram-pressure stripping



# Reaching higher redshift: The Saraswati supercluster



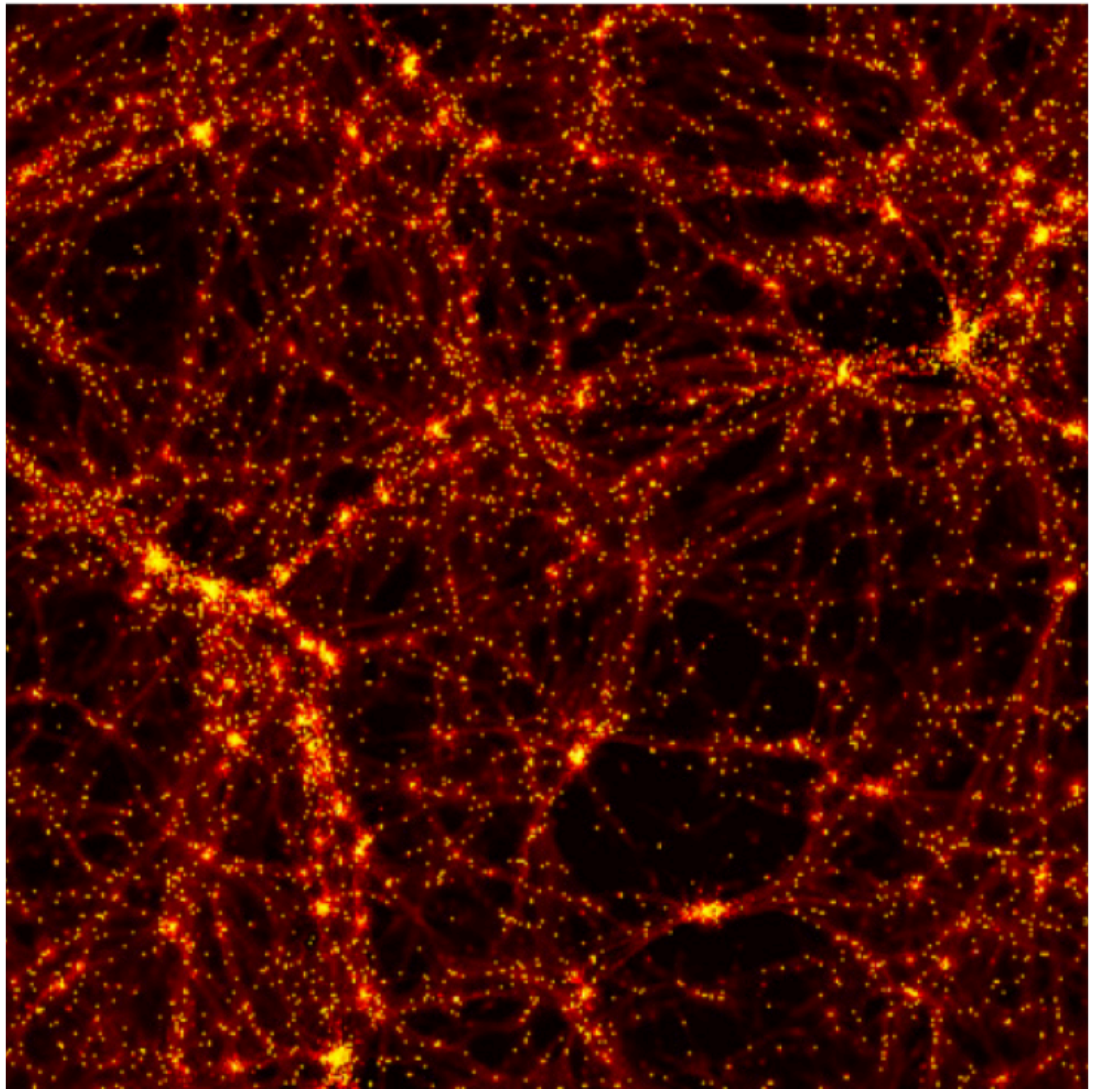

30 MeerKAT pointings - include several clusters.
Radio data in conjunction with optical surveys, both photometric and spectroscopic to provide a detailed characterization of this supercluster region through the mapping and study of the galaxy populations.




Bagchi et al. 2017

# Prospects with SKA:  Evolution of the gas filaments

## and their connection with galaxy evolution



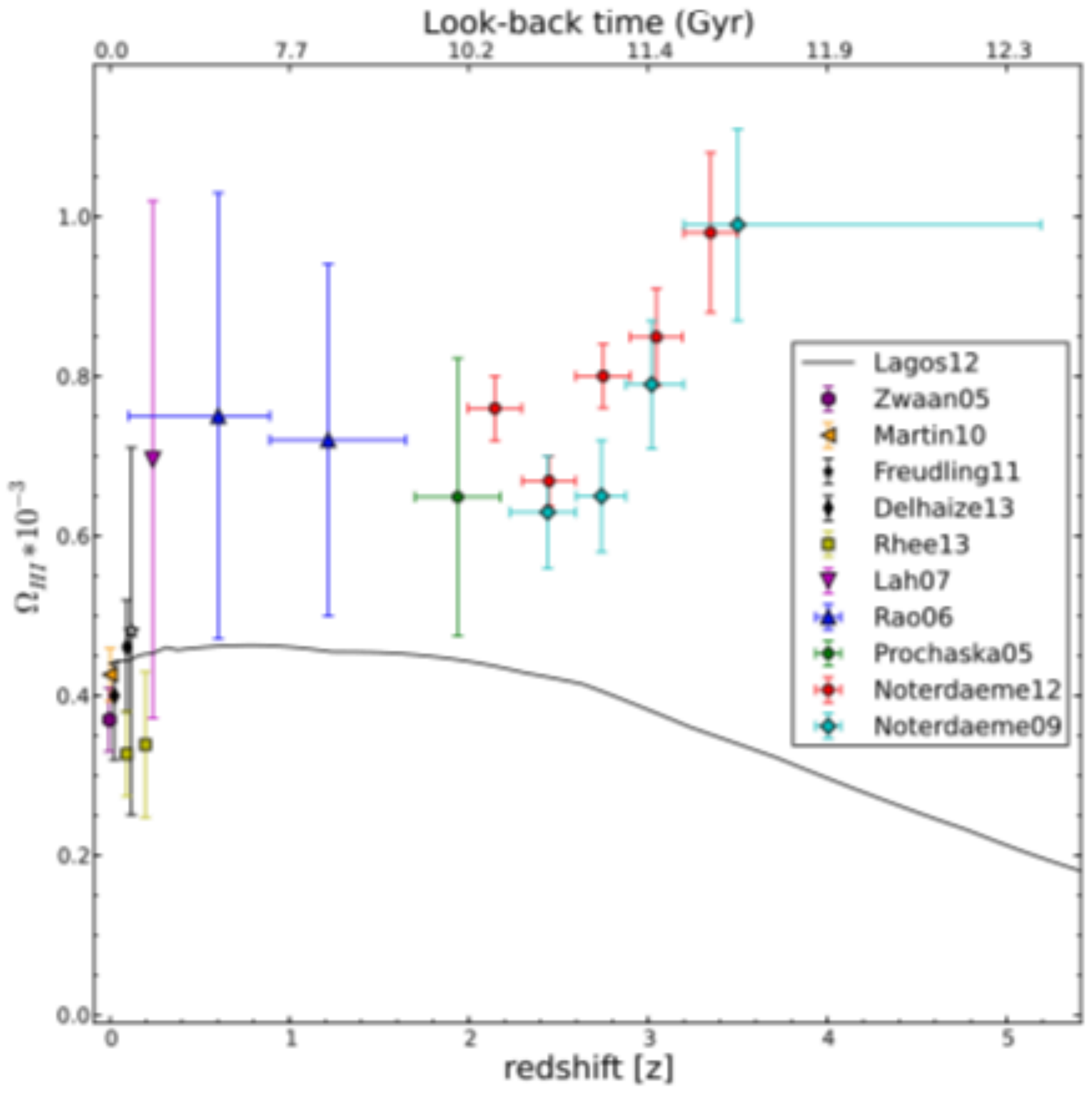



Figure 1: Recent compilation of cosmic H I gas density measurements as functions of redshift and look-back time. At z=0, the hexagon and triangle refer to direct observations from blind H I surveys (Zwaan et al. (2005); Martin et al. (2010)). All points above $z = 0.4$ are damped Ly-$\alpha$ measurements from HST and SDSS (Prochaska et al. (2005); Rao et al. (2006); Noterdaeme et al. (2009, 2012)). Bridging the gap between the two are the estimates from H I stacking of Parkes (diamonds)(Delhaize et al. (2013), WSRT (yellow squares) (Rhee et al. (2013)) and GMRT (magenta triangle) (Lah et al. (2007)) observations. The curve represents model predictions by Lagos et al. (2012).

# Prospects with SKA: Evolution of the gas filaments

## and their connection with galaxy evolution

- 13: Resolved HI kinematics and morphology of ~$10^{10}$ $M_\odot$ mass **galaxies out to z~0.8**
- 14: High spatial resolution studies of the **ISM in the nearby Universe**.
- 15: Multi-resolution mapping studies of the **ISM in our Galaxy**
- 16: **HI absorption studies** out to the highest redshifts.
- 17: The gaseous interface and accretion physics between **galaxies and the IGM**

### SKA1 science goals

| Science Goal | SWG | Objective | SWG Rank |
|---|---|---|---|
| 1 | *CD/EoR* | Physics of the early universe IGM - I. Imaging | 1/3 |
| 2 | *CD/EoR* | Physics of the early universe IGM - II. Power spectrum | 2/3 |
| 3 | *CD/EoR* | Physics of the early universe IGM - III. HI absorption line spectra (21cm forest) | 3/3 |
| 4 | *Pulsars* | Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection | 1/3 |
| 5 | *Pulsars* | High precision timing for testing gravity and GW detection | 1/3 |
| 6 | *Pulsars* | Characterising the pulsar population | 2/3 |
| 7 | *Pulsars* | Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies | 2/3 |
| 8 | *Pulsars* | Finding pulsars in the Galactic Centre | 2/3 |
| 9 | *Pulsars* | Astrometric measurements of pulsars to enable improved tests of GR | 2/3 |
| 10 | *Pulsars* | Mapping the pulsar beam | 3/3 |
| 11 | *Pulsars* | Understanding pulsars and their environments through their interactions | 3/3 |
| 12 | *Pulsars* | Mapping the Galactic Structure | 3/3 |
| 13 | *HI* | Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8 | 1/5 |
| 14 | *HI* | High spatial resolution studies of the ISM in the nearby Universe. | 2/5 |
| 15 | *HI* | Multi-resolution mapping studies of the ISM in our Galaxy | 3/5 |
| 16 | *HI* | HI absorption studies out to the highest redshifts. | 4/5 |
| 17 | *HI* | The gaseous interface and accretion physics between galaxies and the IGM | 5/5 |
| 18 | *Transients* | Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State | =1/4 |
| 19 | *Transients* | Accessing New Physics using Ultra-Luminous Cosmic Explosions | =1/4 |
| 20 | *Transients* | Galaxy growth through measurements of Black Hole accretion, growth and feedback | 3/4 |
| 21 | *Transients* | Detect the Electromagnetic Counterparts to Gravitational Wave Events | 4/4 |
| 22 | *Cradle of Life* | Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc | 1/5 |
| 23 | *Cradle of Life* | Characterise exo-planet magnetic fields and rotational periods | 2/5 |
| 24 | *Cradle of Life* | Survey all nearby (~100 pc) stars for radio emission from technological civilizations. | 3/5 |
| 25 | *Cradle of Life* | The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc. | 4/5 |
| 26 | *Cradle of Life* | Mapping of the sub-structure and dynamics of nearby clusters using maser emission. | 5/5 |
| 27 | *Magnetism* | The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields | 1/5 |
| 28 | *Magnetism* | Determine origin, maintenance and amplification of magnetic fields at high redshifts - I. | 2/5 |
| 29 | *Magnetism* | Detection of polarised emission in Cosmic Web filaments | 3/5 |
| 30 | *Magnetism* | Determine origin, maintenance and amplification of magnetic fields at high redshifts - II. | 4/5 |
| 31 | *Magnetism* | Intrinsic properties of polarised sources | 5/5 |
| 32 | *Cosmology* | Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales. | 1/5 |
| 33 | *Cosmology* | Angular correlation functions to probe non-Gaussianity and the matter dipole | 2/5 |
| 34 | *Cosmology* | Map the dark Universe with a completely new kind of weak lensing survey - in the radio. | 3/5 |
| 35 | *Cosmology* | Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology. | 4/5 |
| 36 | *Cosmology* | Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey. | 5/5 |
| 37 | *Continuum* | Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes | 1/8 |
| 38 | *Continuum* | Measure the Star formation history of the Universe (SFHU) - II. Thermal processes | 2/8 |
| 39 | *Continuum* | Probe the role of black holes in galaxy evolution - I. | 3/8 |
| 40 | *Continuum* | Probe the role of black holes in galaxy evolution - II. | 4/8 |
| 41 | *Continuum* | Probe cosmic rays and magnetic fields in ICM and cosmic filaments. | 5/8 |
| 42 | *Continuum* | Study the detailed astrophysics of star-formation and accretion processes - I. | 6/8 |
| 43 | *Continuum* | Probing dark matter and the high redshift Universe with strong gravitational lensing. | 7/8 |
| 44 | *Continuum* | Legacy/Serendipity/Rare. | 8/8 |

**Table 1. Collated list of science goals. Within each science area, the entries are ordered in the rank provided by the SWG Chairs. The eight different groups of SWG contributions are listed in the Table in an arbitrary sequence.**

**Braun et al, 2014,**
**SKA1 Science Priority Outcomes**

# Prospects with SKA1-mid & SKA2: Evolution of the gas filaments

## and their connection with galaxy evolution

Kooistra+2019 … predictions z~0.1

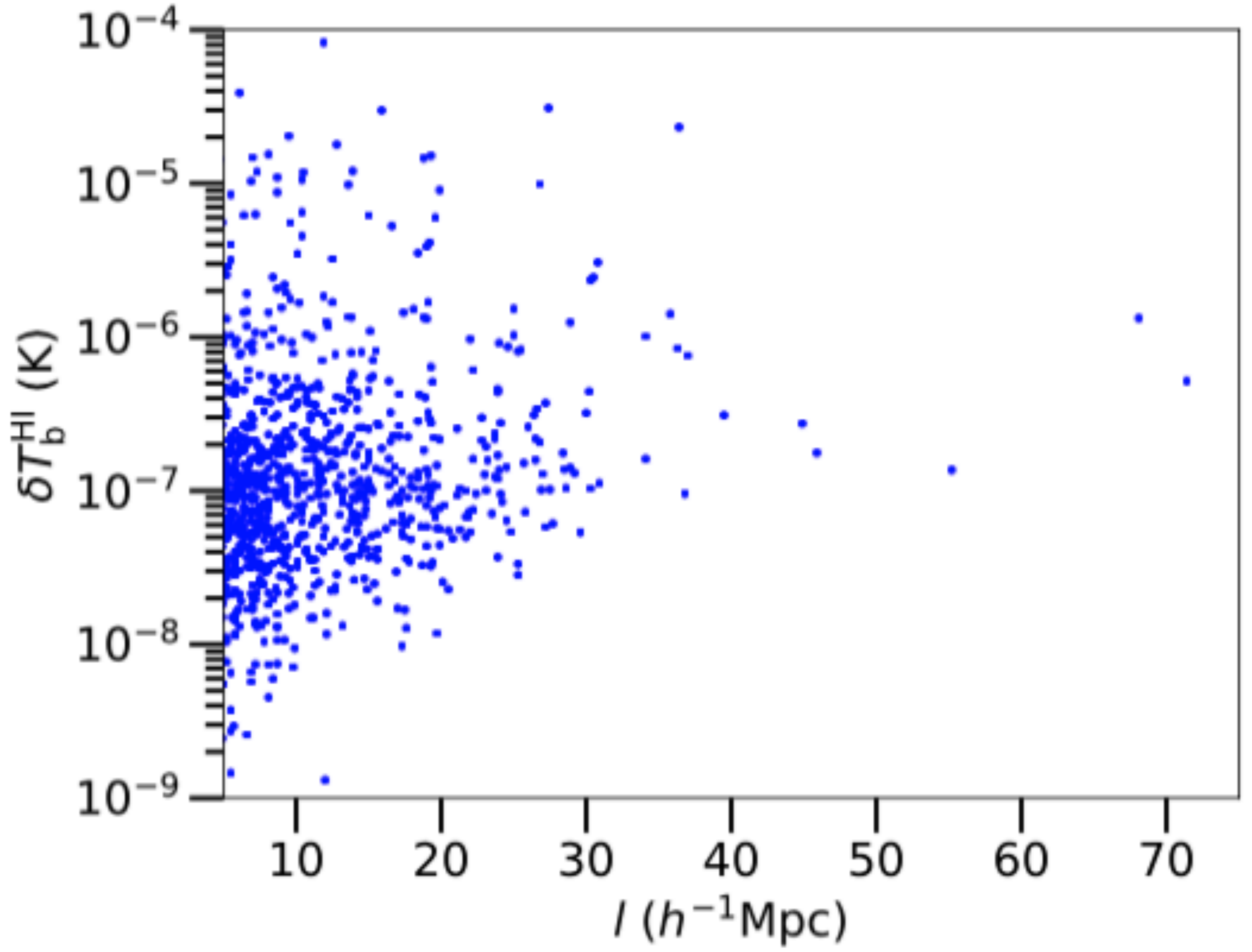



**Figure 3.** Distribution of the mean signal per cell in filaments as a function of their length for Bisous filaments longer than 5 $h^{-1}$Mpc in the EAGLE simulation box. A filament radius of 0.5 $h^{-1}$Mpc was adopted together with the HM01 UVB.

Large range of mean signals

Most of the low density gas at brightness temperatures $\boldsymbol{\delta}$T~ $10^{-7}$ K, i.e., HI column density of ~ $2-5\times10^{13}$cm$^{-2}$ for a 100 km s$^{-1}$ velocity width.

# Gas phases of cosmic filaments

Galárraga-Espinosa+2020

| | Density [$cm^{-3}$] | Temperature [K] | Comments |
|---|---|---|---|
| Diffuse IGM | $n_H \leq 10^{-4}$ | $T \leq 10^5$ | Gas in the lowest-density regions of the cosmic web. |
| WHIM | $n_H \leq 10^{-4}$ | $10^5 < T \leq 10^7$ | Gas that has been accreted onto cosmic structures and heated by shocks. |
| WCGM | $n_H > 10^{-4}$ | $10^5 < T \leq 10^7$ | In the surroundings of galaxies, sensitive to galactic physics. |
| Halo gas | $n_H > 10^{-4}$ | $T \leq 10^5$ | In the interstellar medium of galaxies, located inside or near them. |
| Hot gas | no cut | $T > 10^7$ | Shock-heated gas located in the denser regions of the cosmic web. |

TNG300-1 hydro-dynamical simulation @ redshift z = 0.
Filaments are essentially dominated by gas in the warm-hot intergalactic medium (WHIM), which accounts for more than 80% of the baryon budget at r ~ 1 Mpc, $T_{core} = 4-13 \times 10^5$ K
Pressure at cores of filaments is on average $P_{core} = 4-12 \times 10^{-7}$ keV.cm$^{-3}$, which is ~1000 times lower than pressure measured in observed clusters.

# Prospects with SKA1-mid & SKA2: Evolution of the gas filaments

and their connection with galaxy evolution

in a multi-wavelength approach

opens an avenue to improving our understanding
on how galaxies fuel and quench their star formation activity