Sloshing, merging and feedback velocities in the intracluster medium

Efrain Gatuzz (MPE, Garching, Germany)

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Why measuring velocities in the ICM is important?

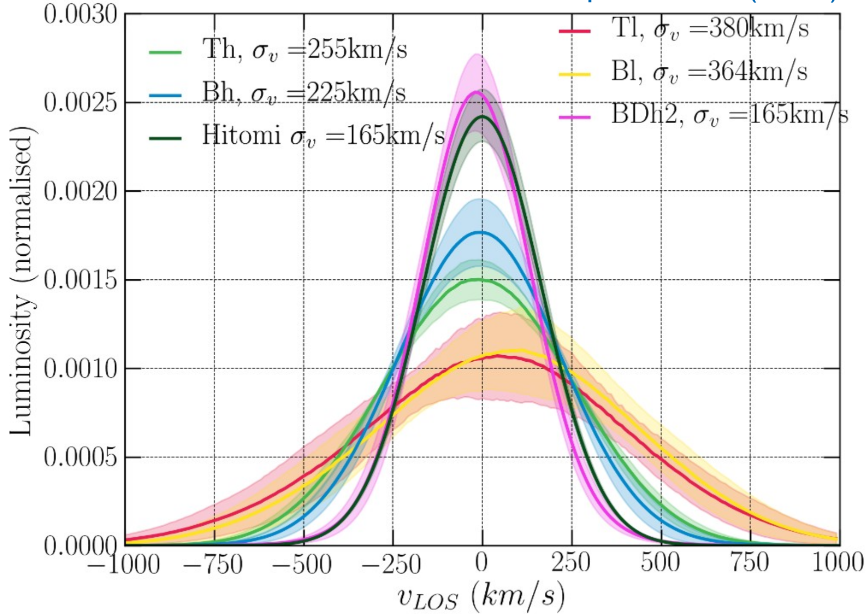
- Turbulent motions, particularly at large radii, affect calculations of hydrostatic equilibrium and cluster mass estimates.

- Simulations predict a close connection between entropy, temperature, density, pressure, and velocity power spectra.

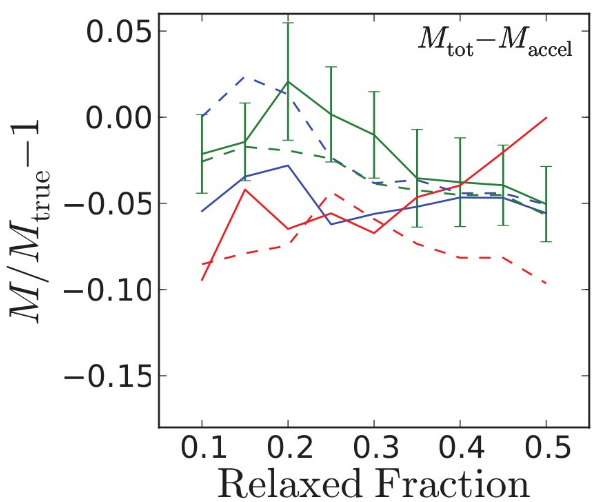
- Motions will cause the transport of metals within the ICM, due to sloshing and uplift of metals by AGNs.

- Measuring velocities should directly indicate gas sloshing in cold fronts, which can remain for several Gyr.

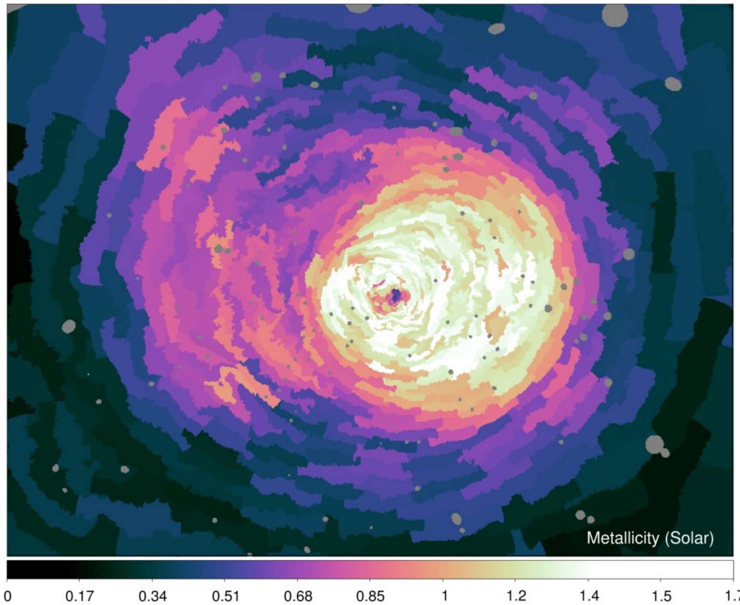
Mohapatra et al. (2019)



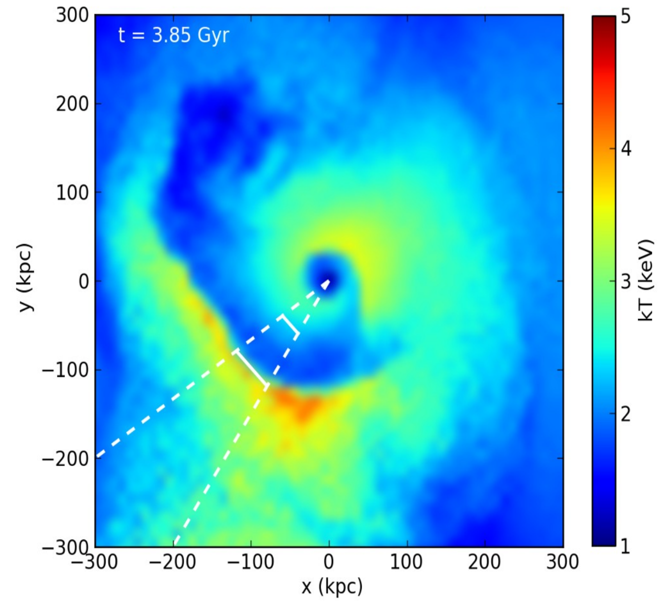
Kayela et al. (2014)



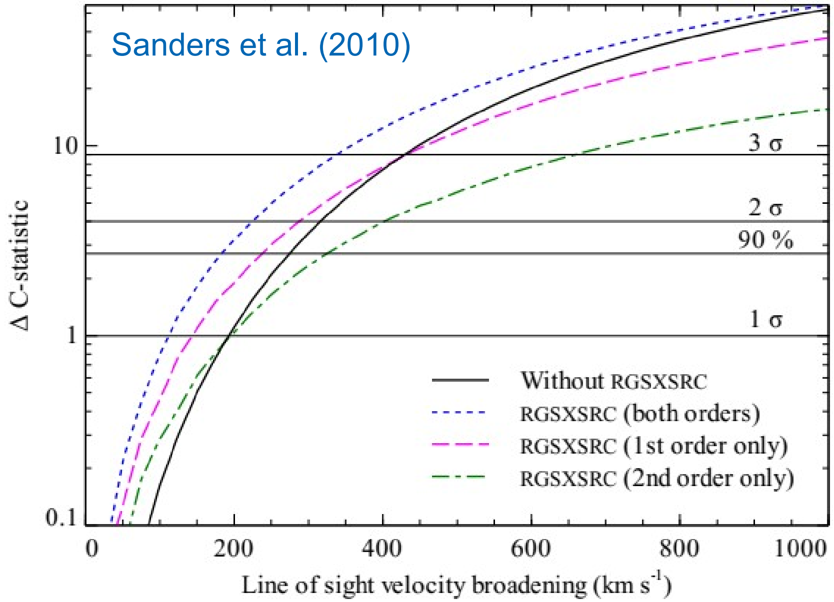
Sanders et al. (2016)

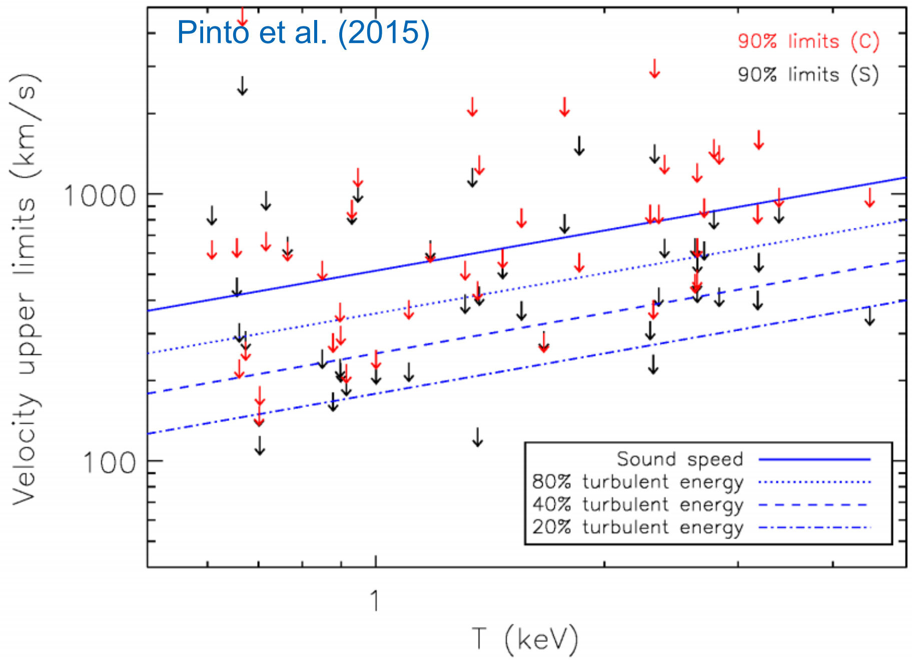


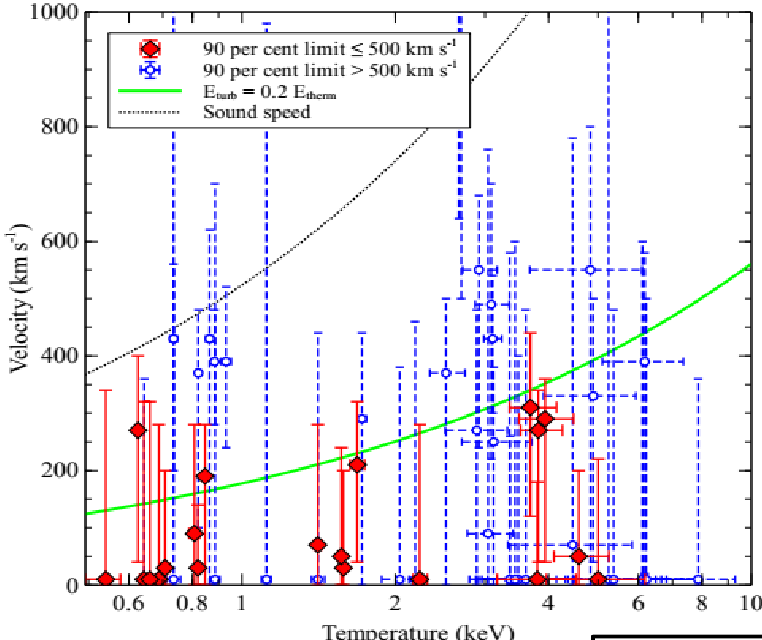
Machado et al. (2015)



Line broadening and resonant scattering

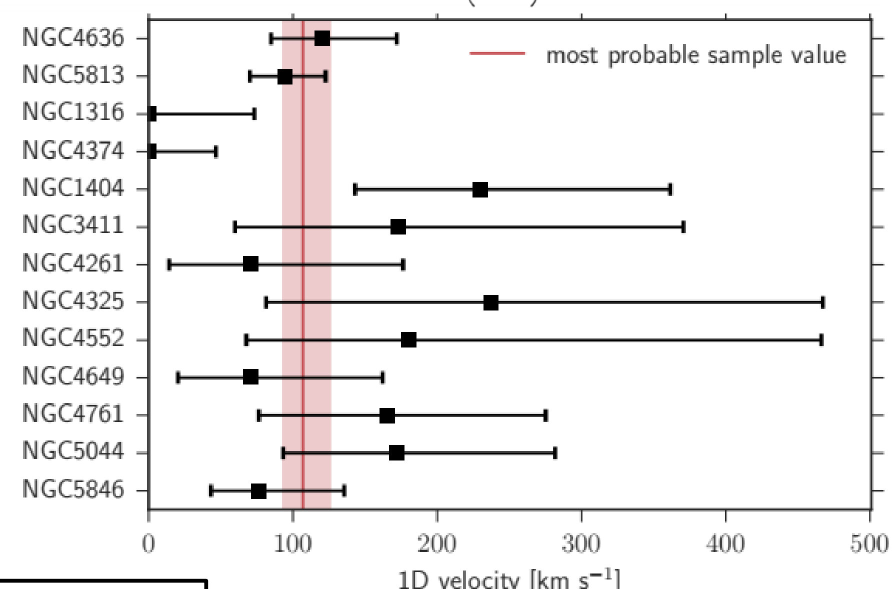






Sanders & Fabian (2013)

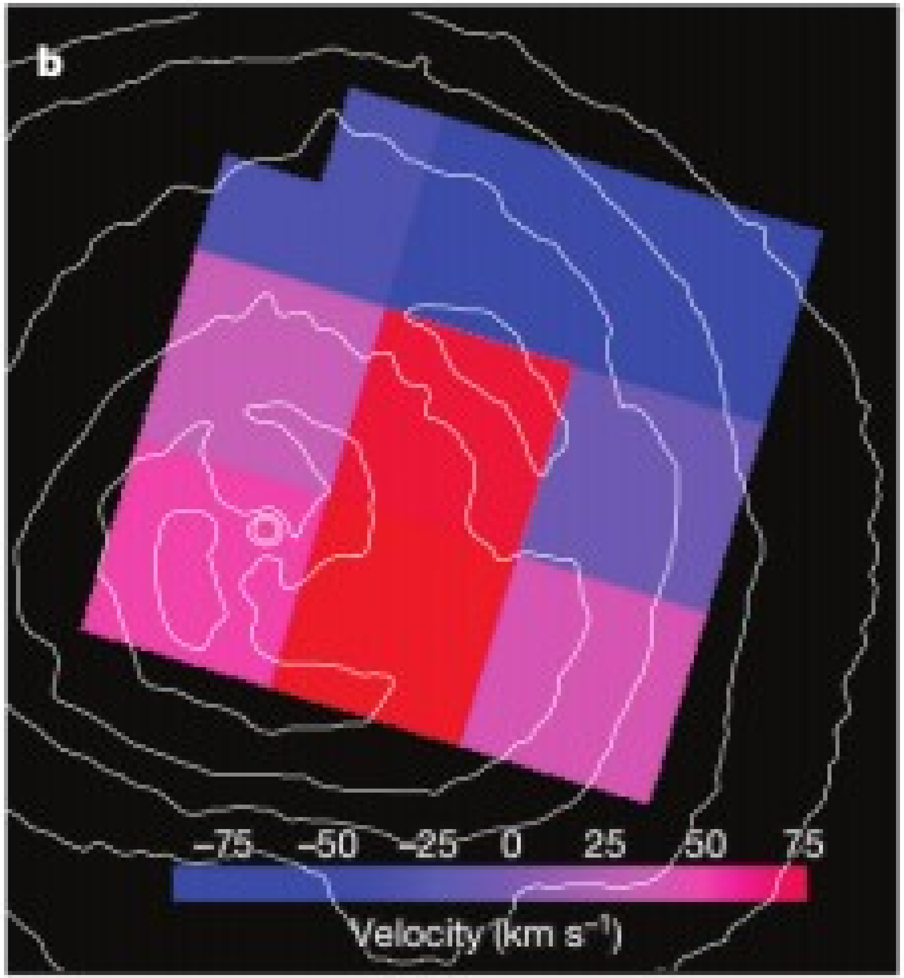
v ~ 100-300 km/s

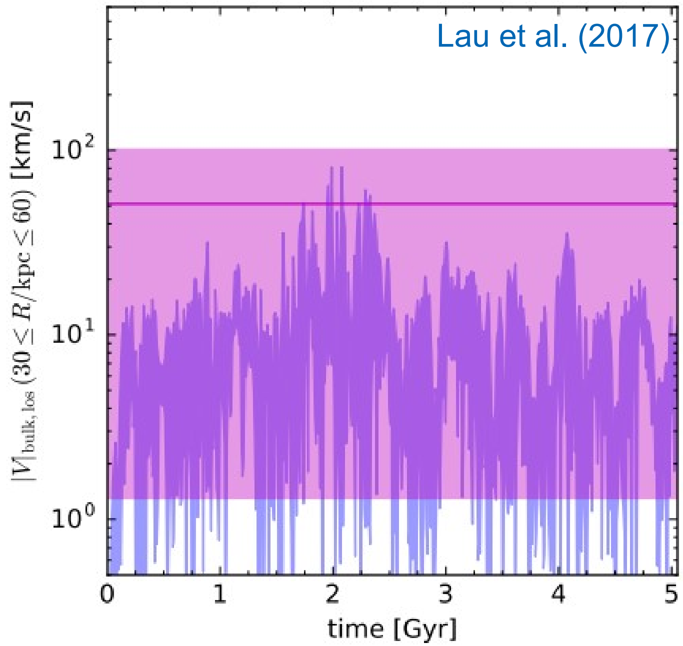


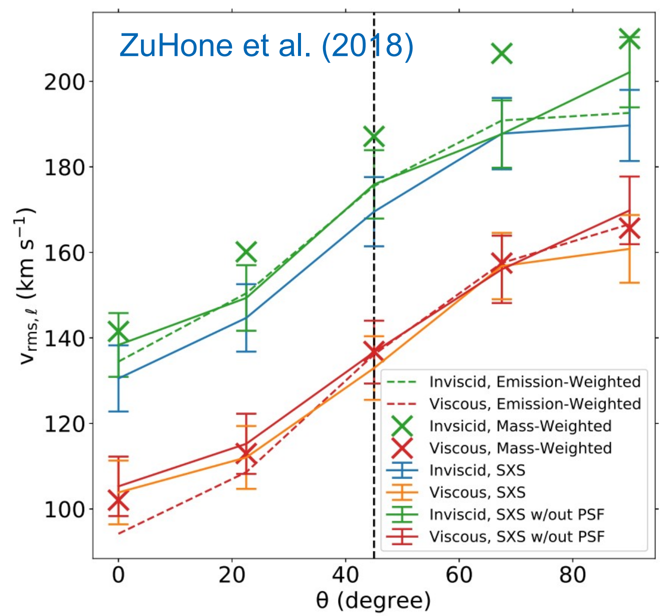
Orgorzalek et al. (2017)

The Hitomi observations

Hitomi collaboration et al. (2016)

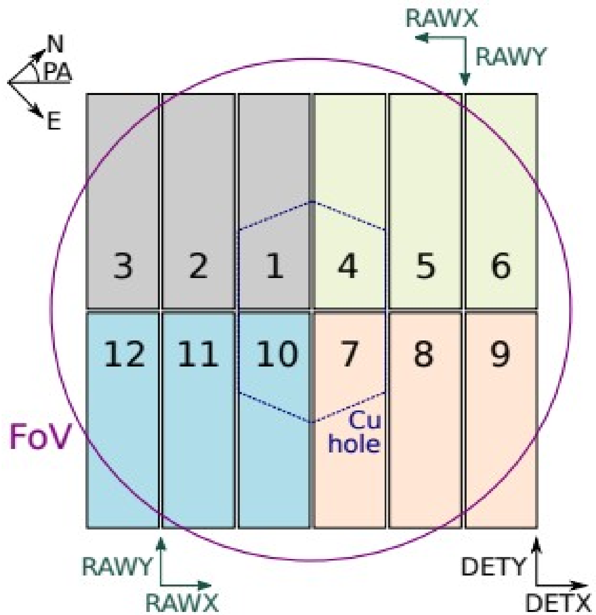


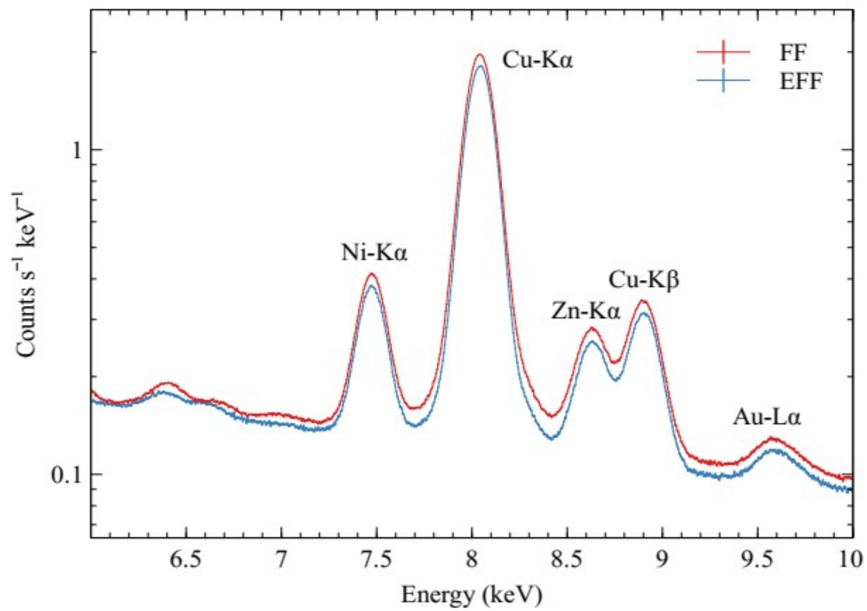


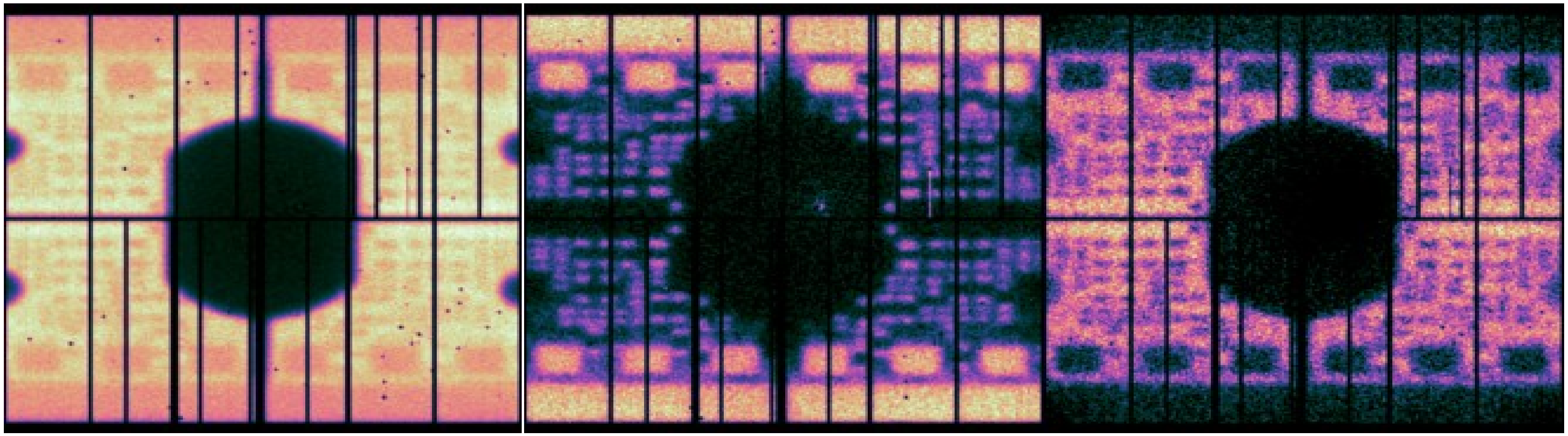


We will not be able to make further measurements!!!
Future missions:
XRISM (2023), LEM(2032)
Athena (2035)

Measuring velocities with XMM-Newton







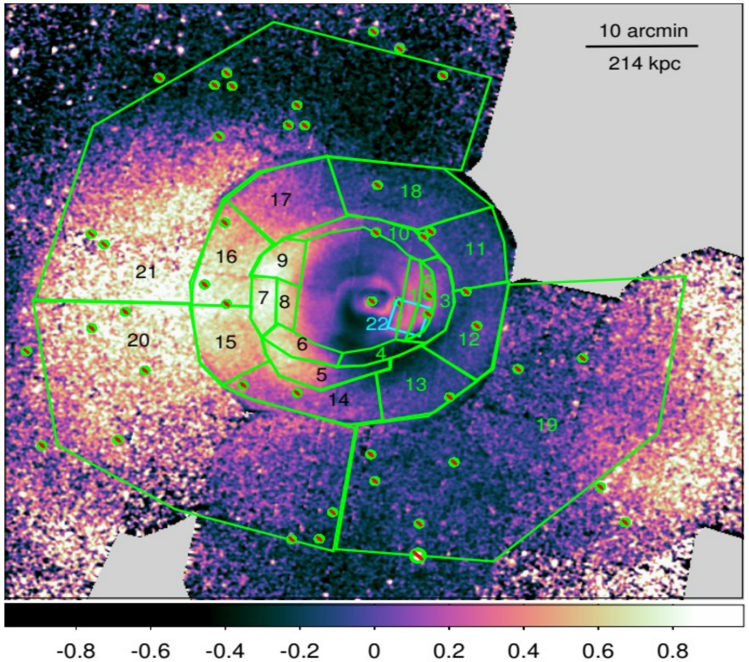
Sanders et al. (2020)

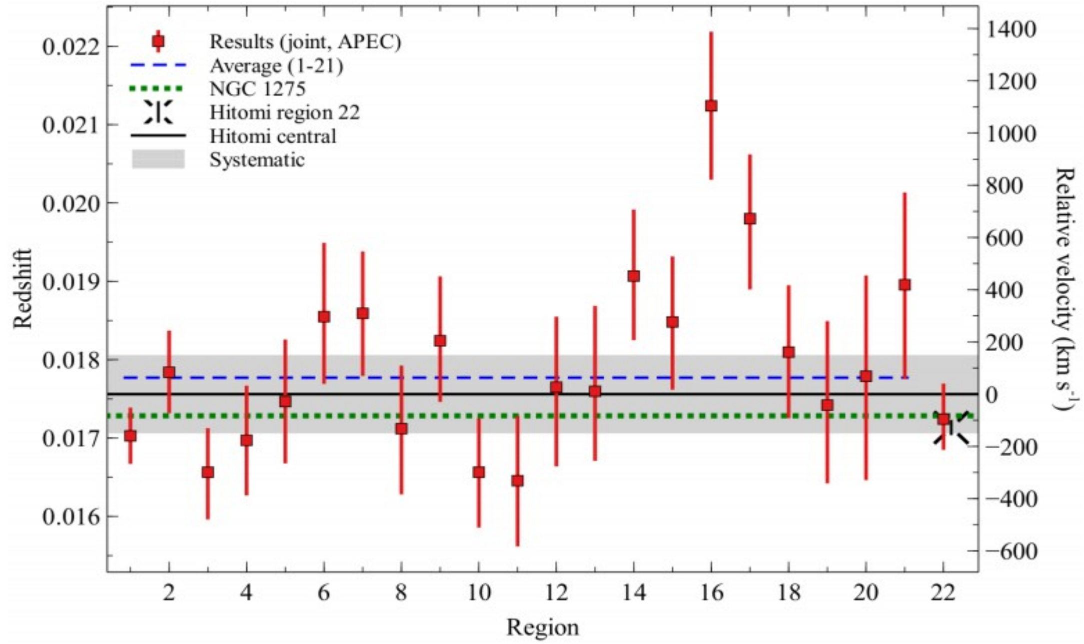
We can use the instrumental background to calibrate the energy scale and obtain velocities down to 100 km/s!

The Perseus and Coma cluster

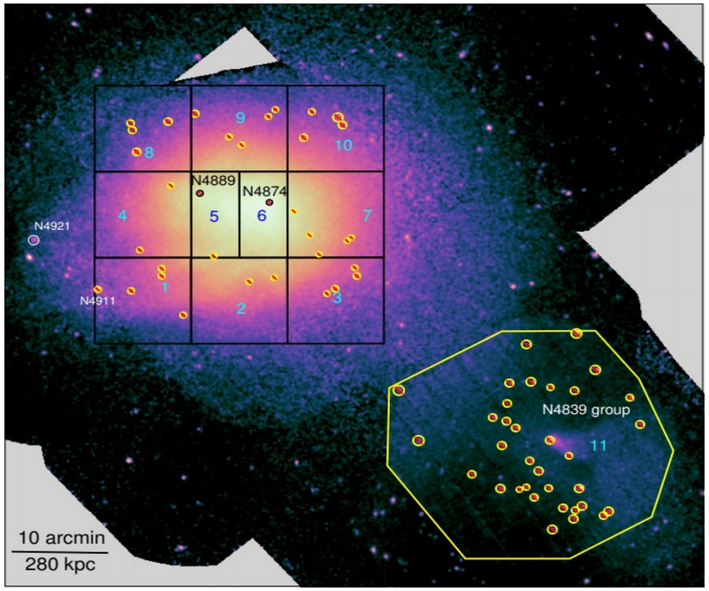
Sanders et al. (2020)

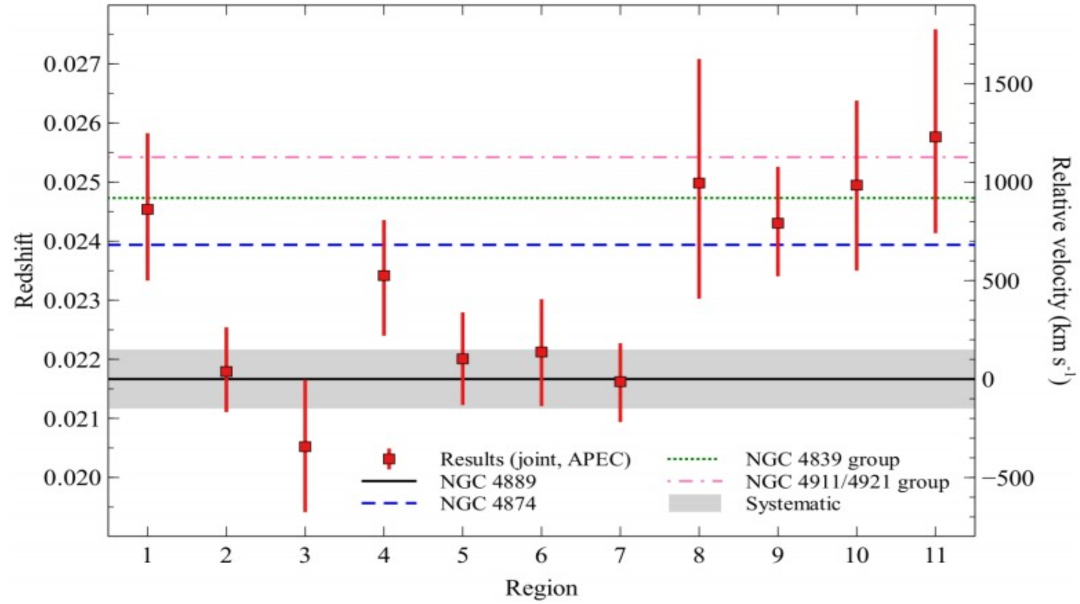
Perseus clsuter



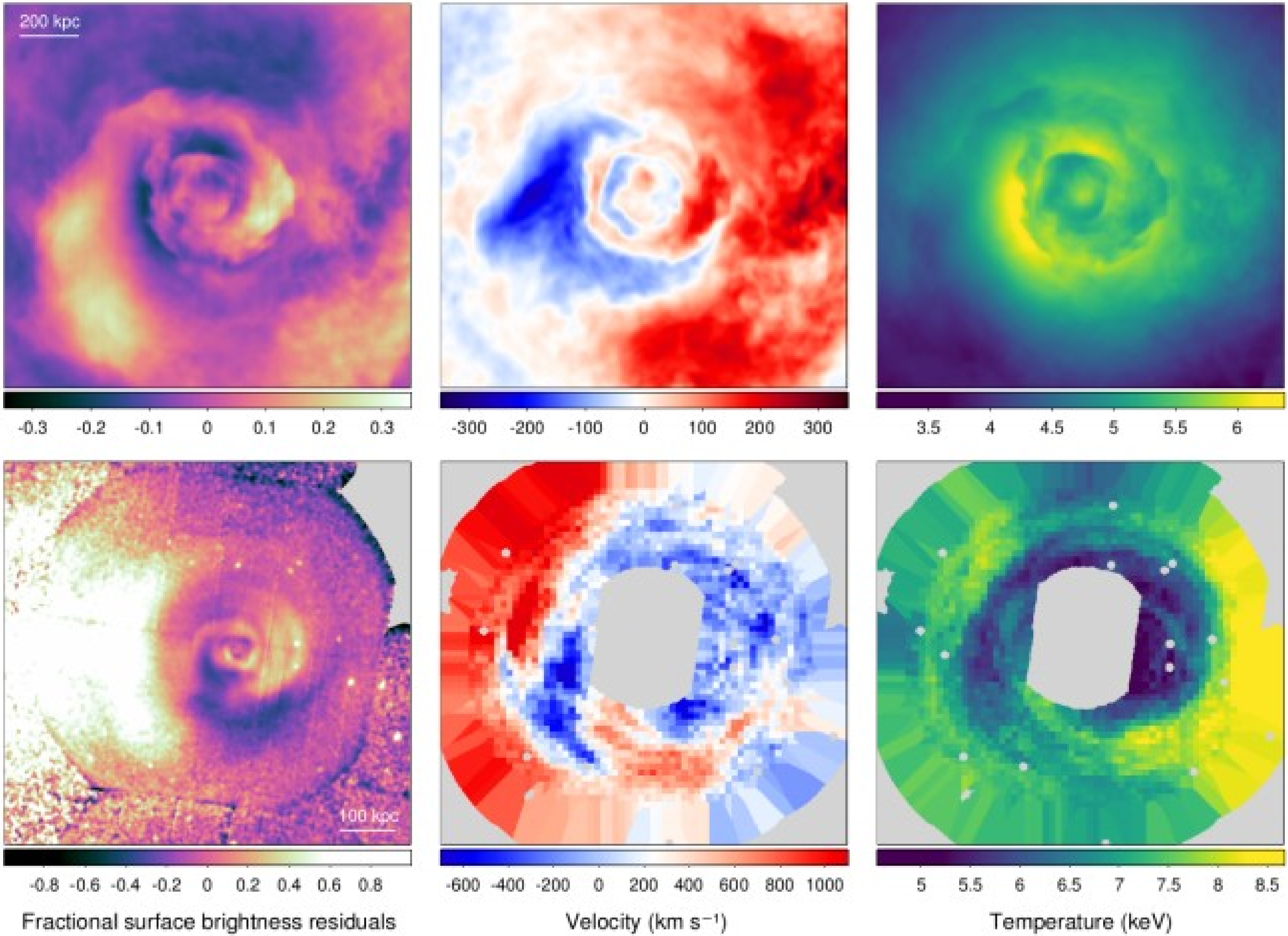


Coma clsuter





The Perseus and Coma cluster



Sanders et al. (2020)

These results provide direct evidence of the ICM sloshing in the cluster potential well

Virgo, Centaurus and Ophiuchus galaxy clusters

- **Virgo** shows a central jet and large extended radio bubbles. There is a heavy interaction between the ICM and the AGN.

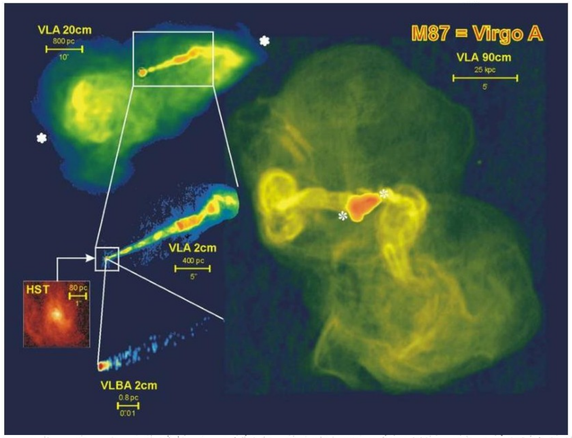
- **Centaurus** contains two dynamic components, Cen 30 and Cen 45. The AGN appears to have been repeatedly active over long time-scales with periods of Myr.

- **Ophiuchus** is a massive and relatively relaxed cluster. Cold fronts have been observed, as well as a truncated cool core.

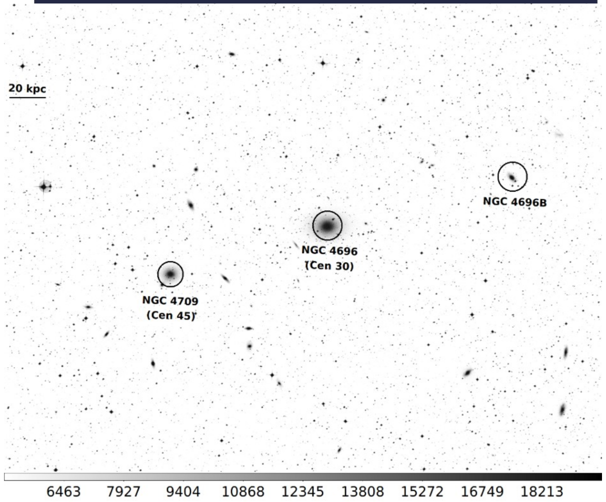
<u>XMM-Newton approved proposals:</u>

Virgo cluster (080367,PI Sanders, J.)
Centaurus cluster (082358, PI Sanders, J.)
Ophiuchus cluster (88028, PI Gatuzz, E.)

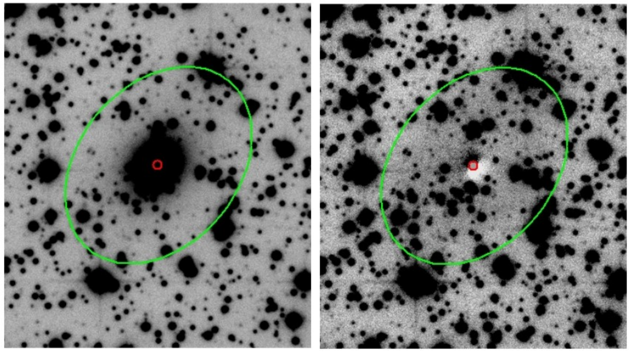
Virgo clsuter



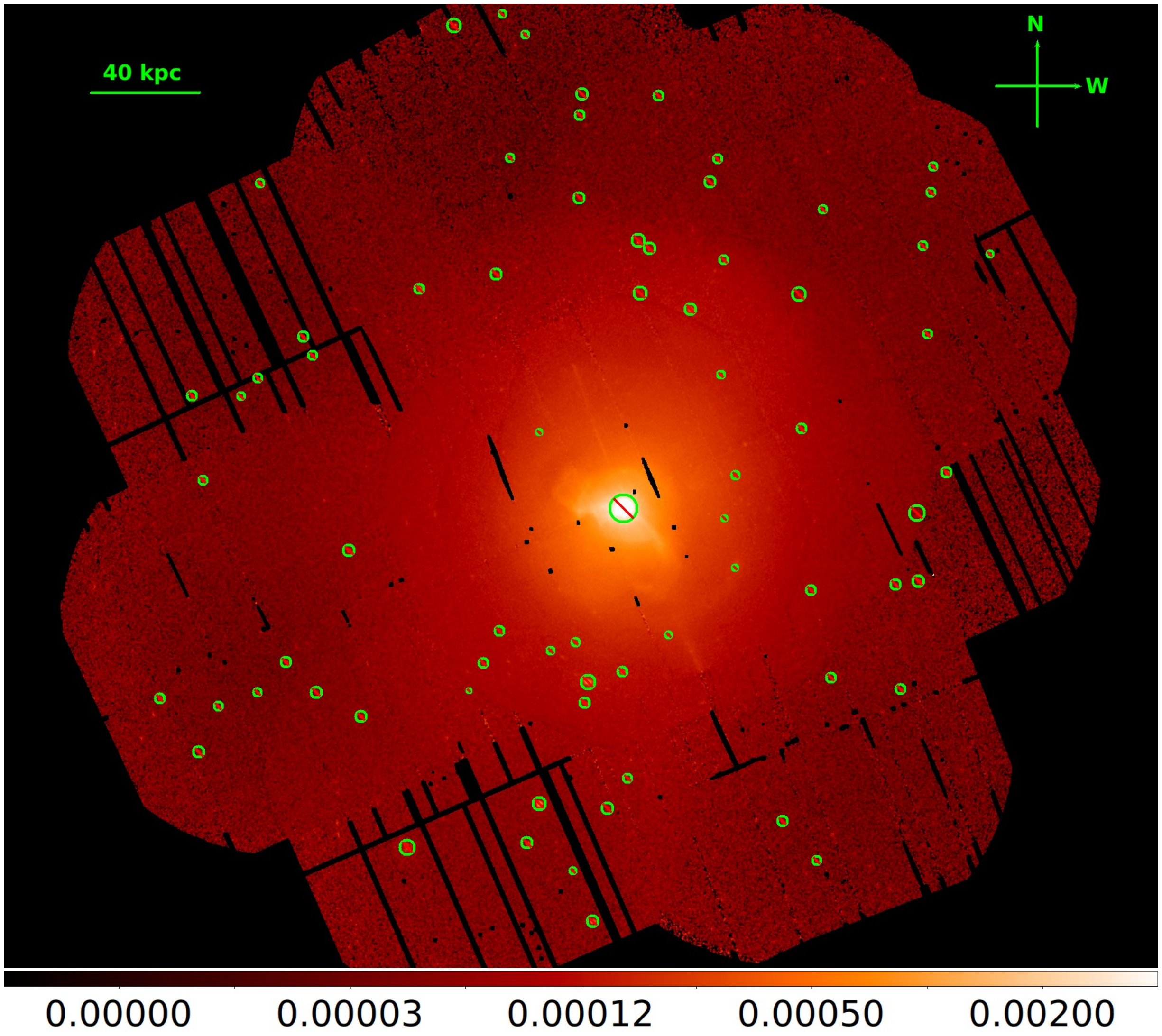
Centaurus clsuter



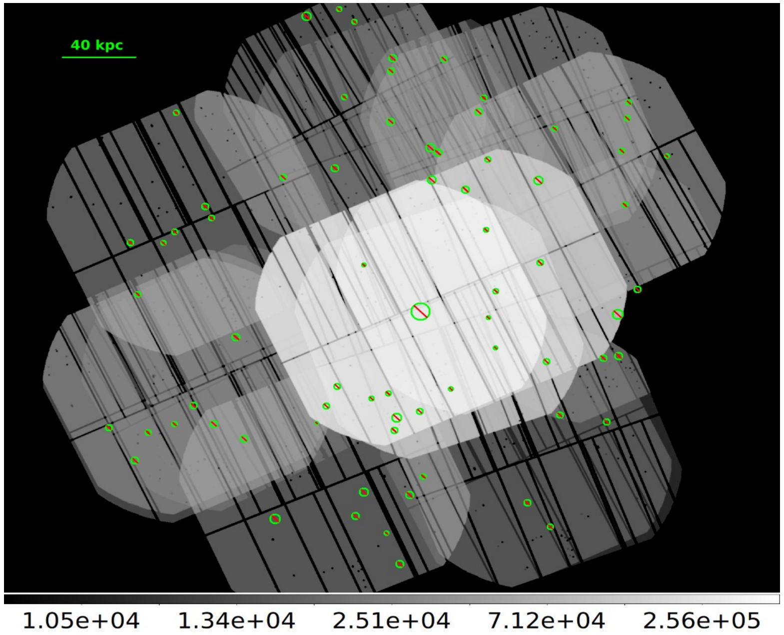
Ophiuchus clsuter

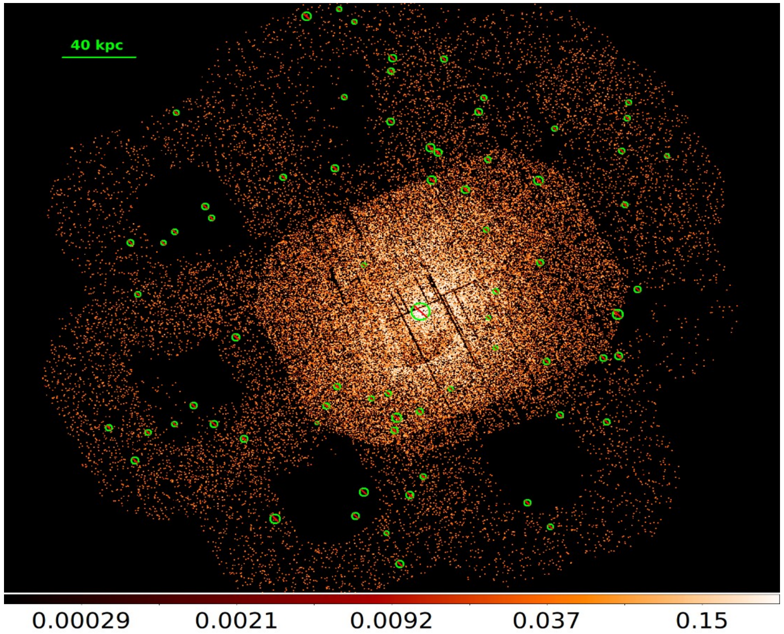


The Virgo cluster: X-ray observations

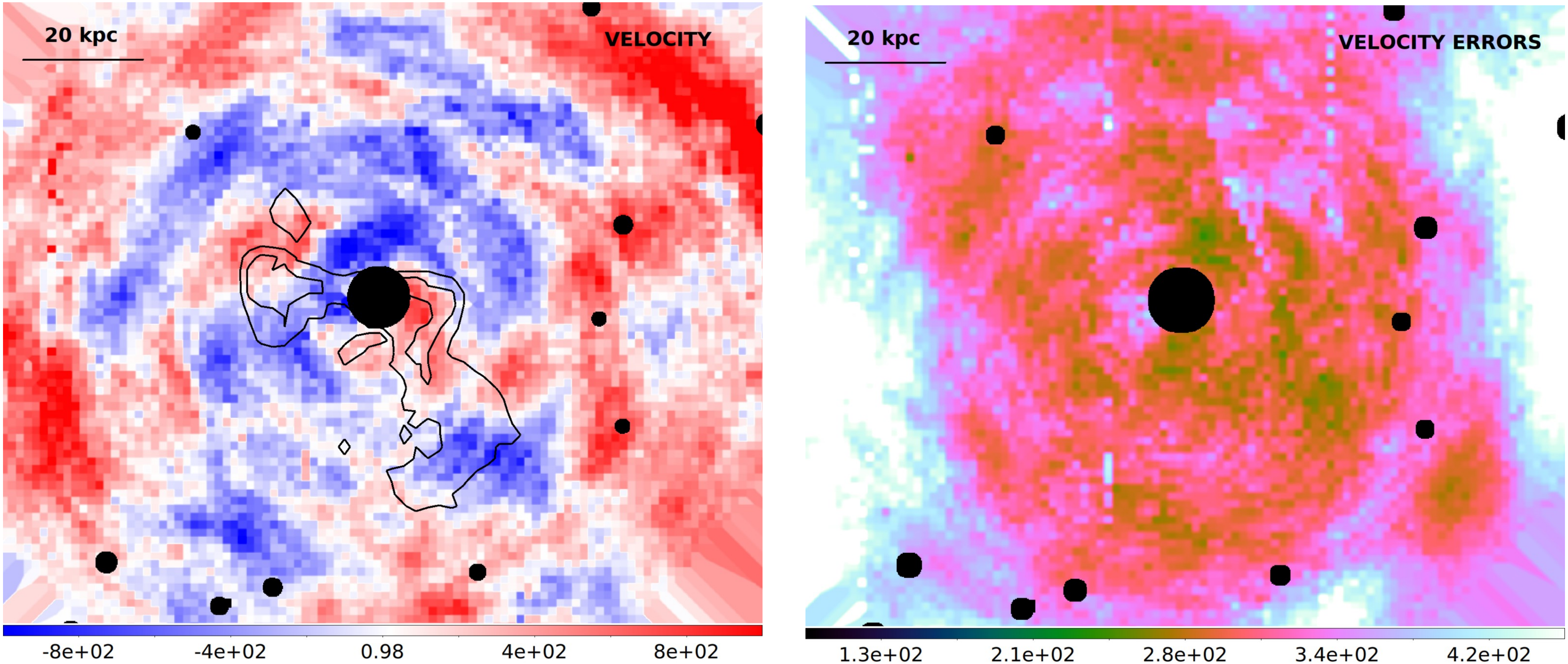


Gatuzz et al. (2022a)





The Virgo cluster: spectral maps

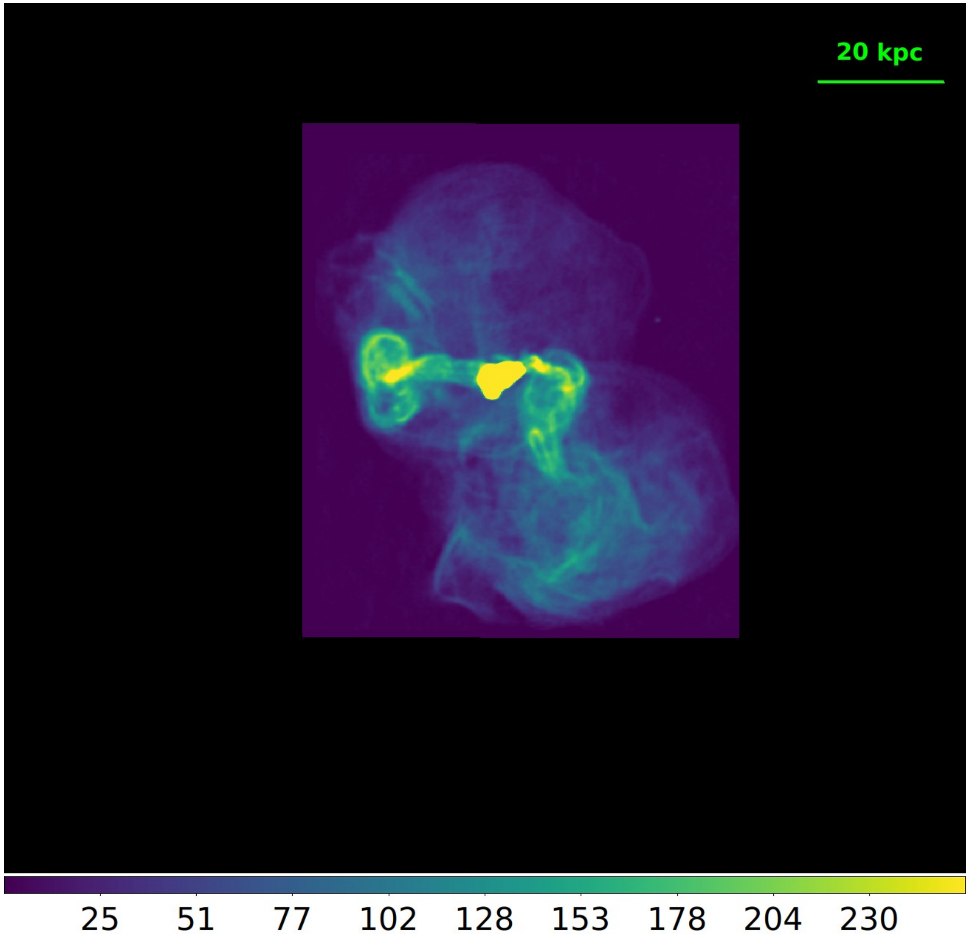


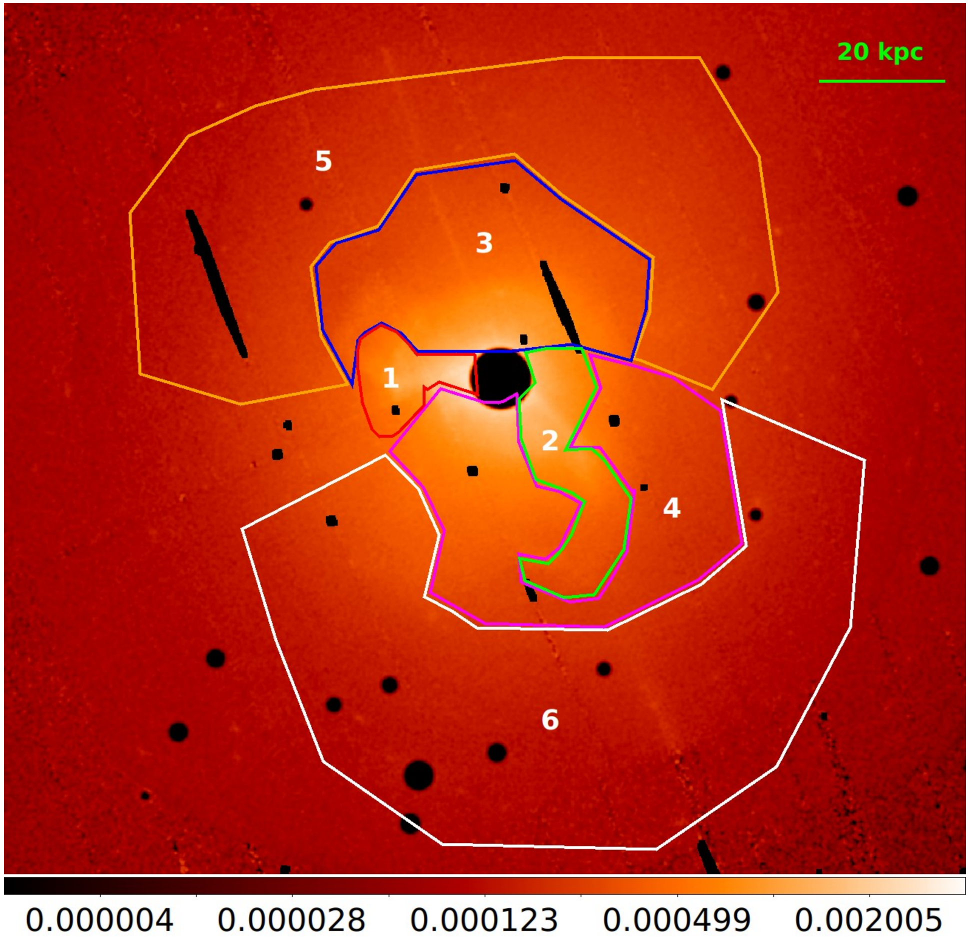
Gatuzz et al. (2022a)

- The gas moves around the cluster core in different directions, following the arms identified in the soft X-ray/radio image.

- Typical spiral patterns observed in some gas sloshing simulations cannot be identified.

The Virgo cluster: X-ray/radio structures



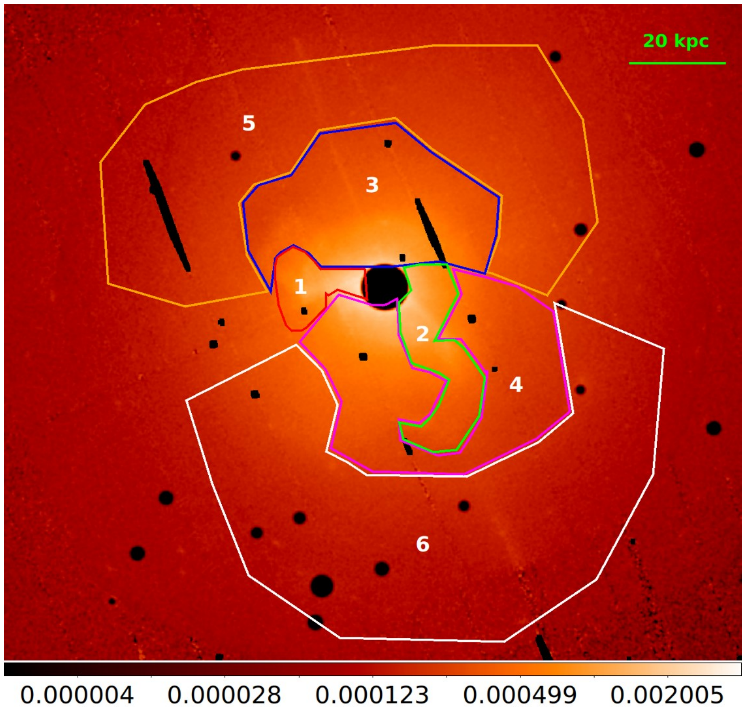


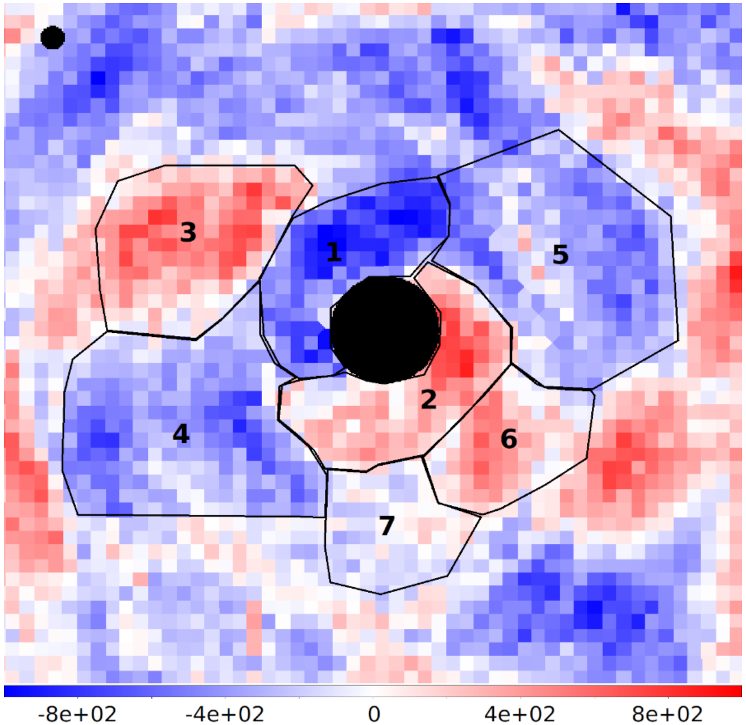
Gatuzz et al. (2022a)

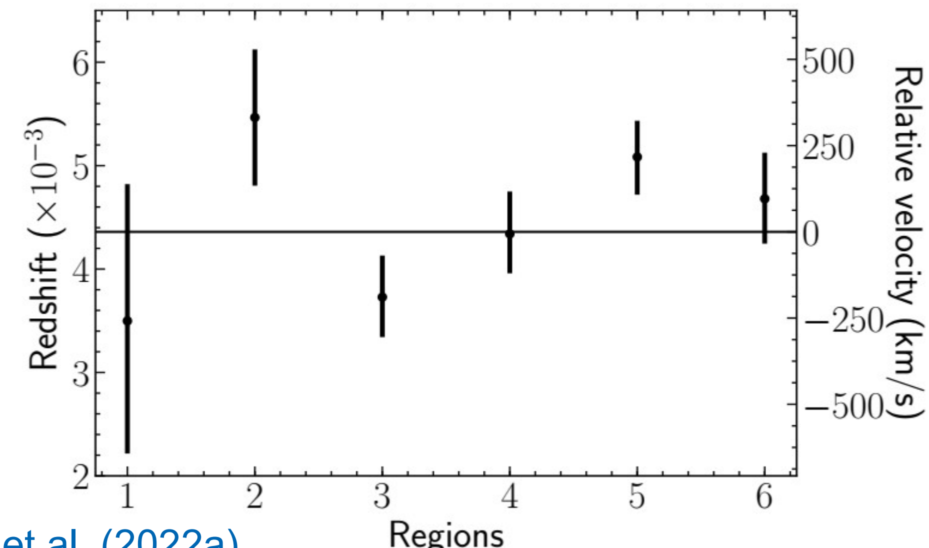
Main structures in the radio images:

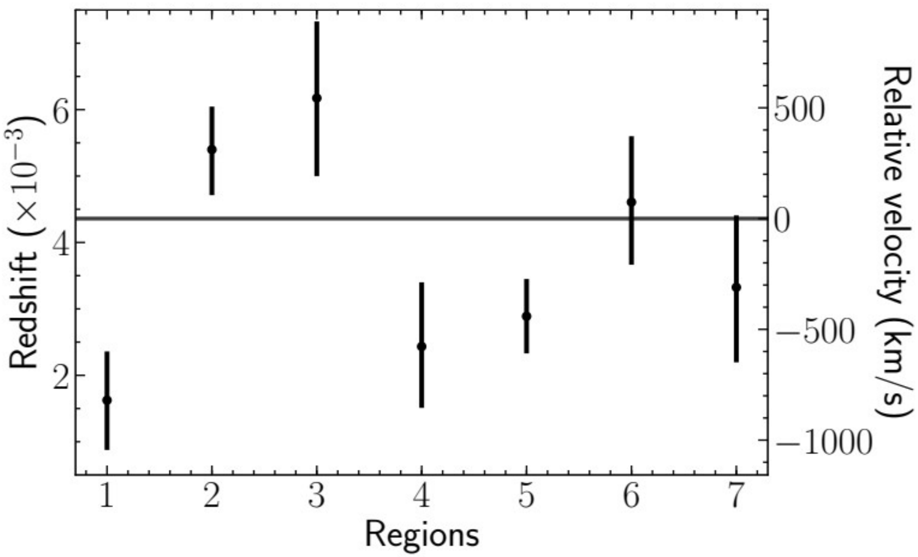
Central radio low, eastern, and western flows and large bubbles

The Virgo cluster: X-ray/radio structures





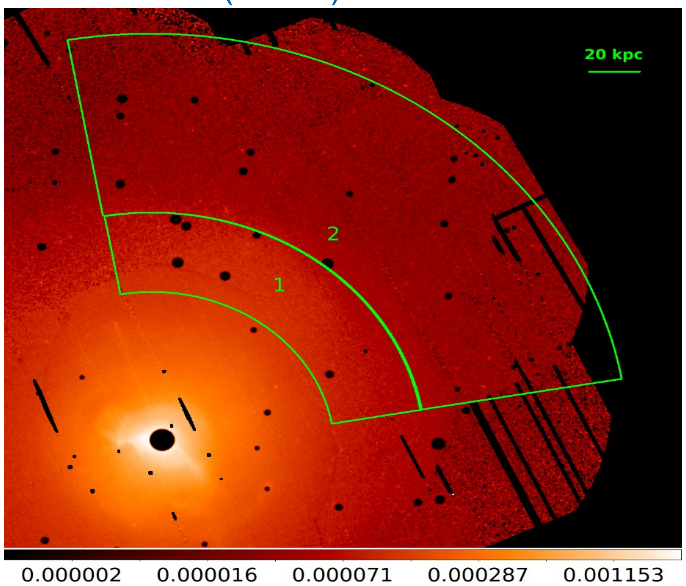


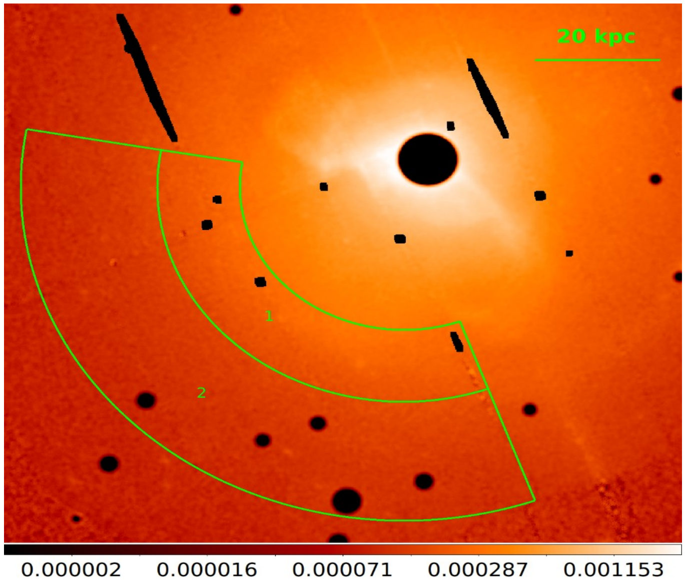


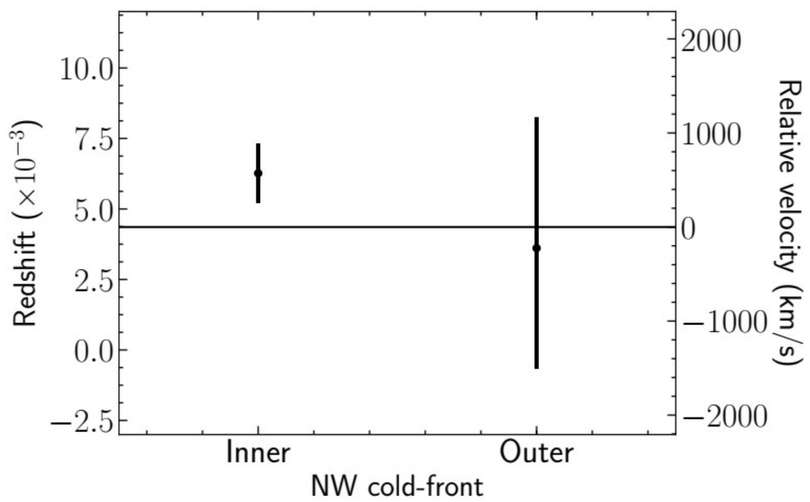
Gatuzz et al. (2022a)

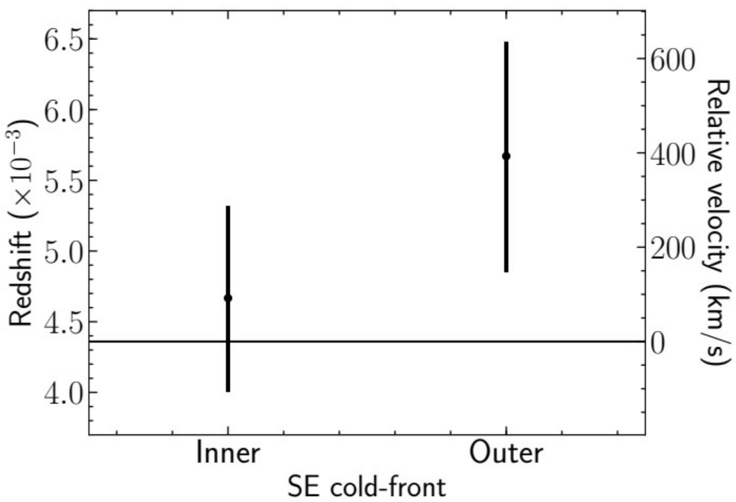
The Virgo cluster: Cold Fronts

Gatuzz et al. (2022a)



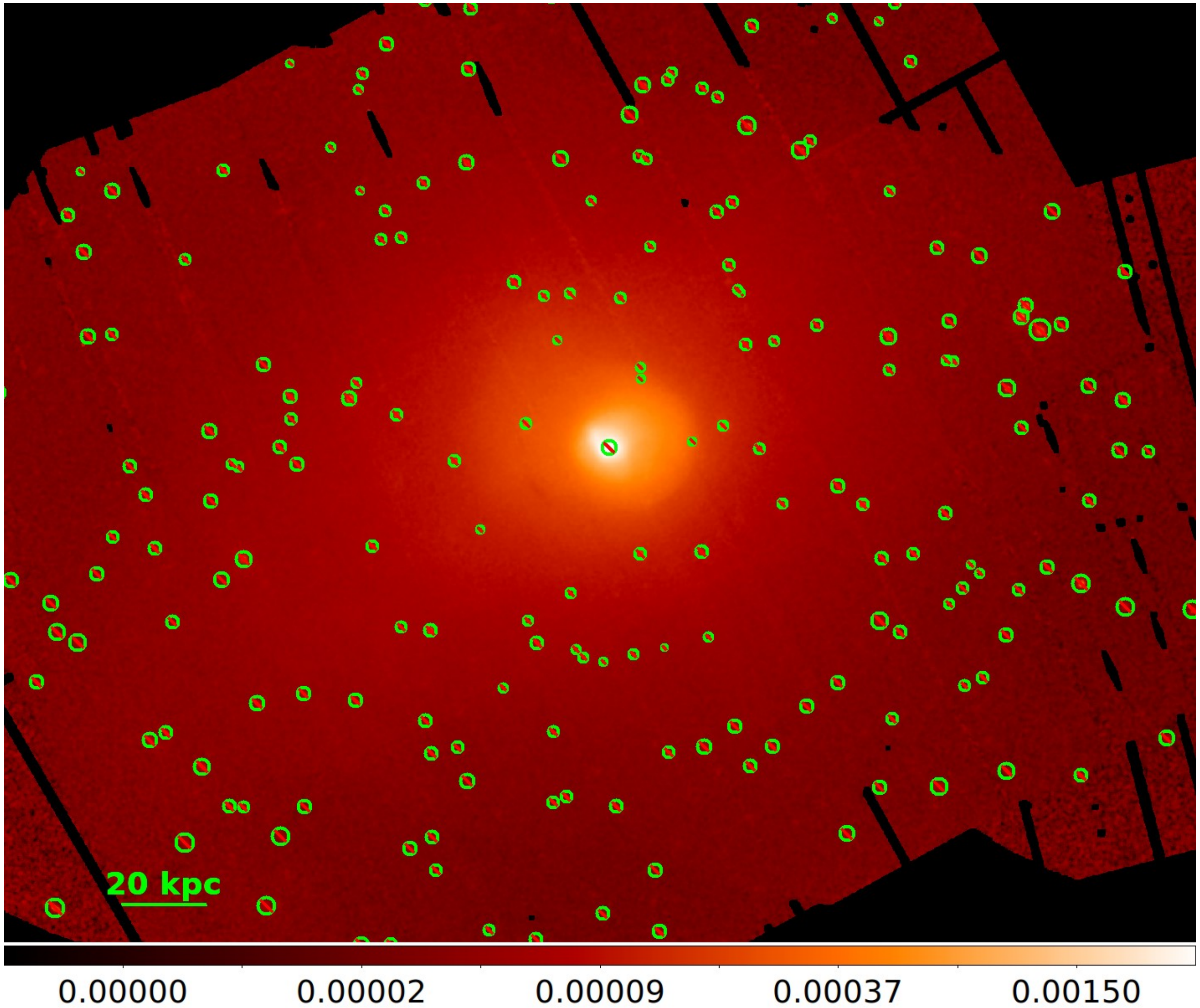


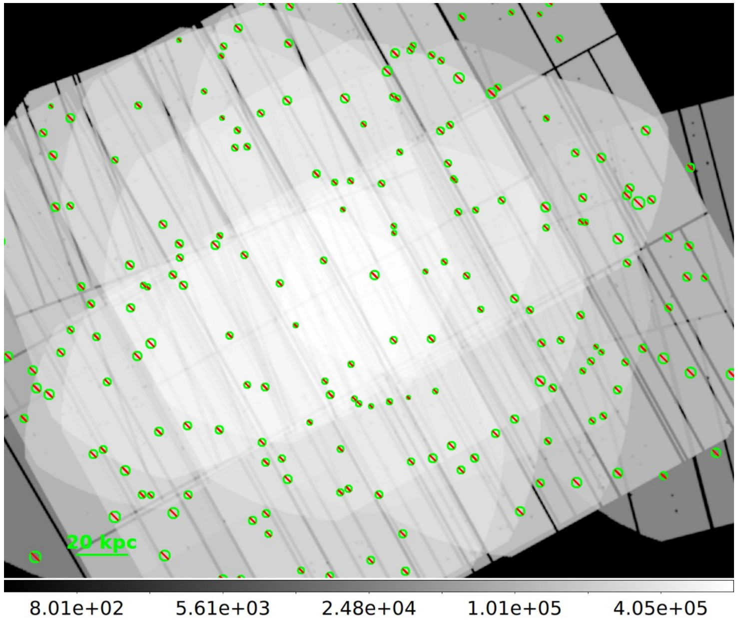


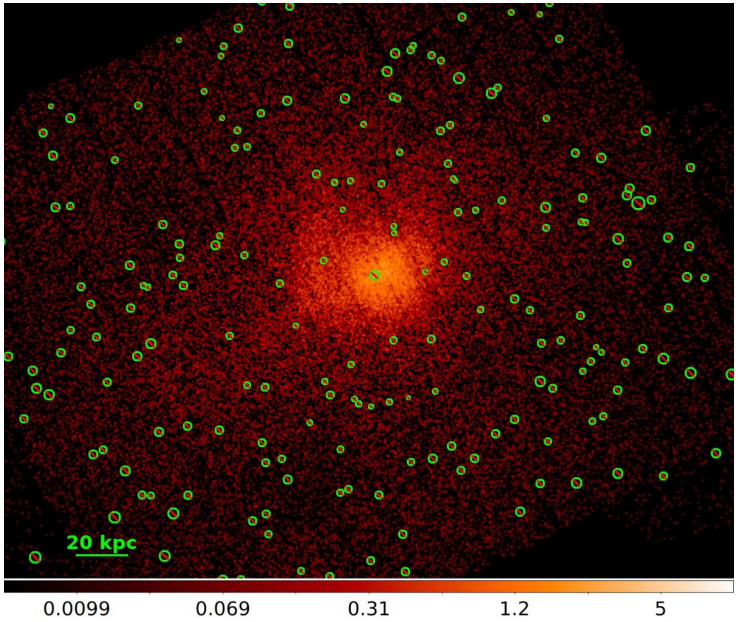


- Simulations predict very low velocities, with large uncertainties, in the outer regions.
- The SE cold-front, closer to the cluster core, is more influenced by the AGN.
- We found a significant difference in metallicities due to gas sloshing (Roediger et al. 2011)

The Centaurus cluster: X-ray observations

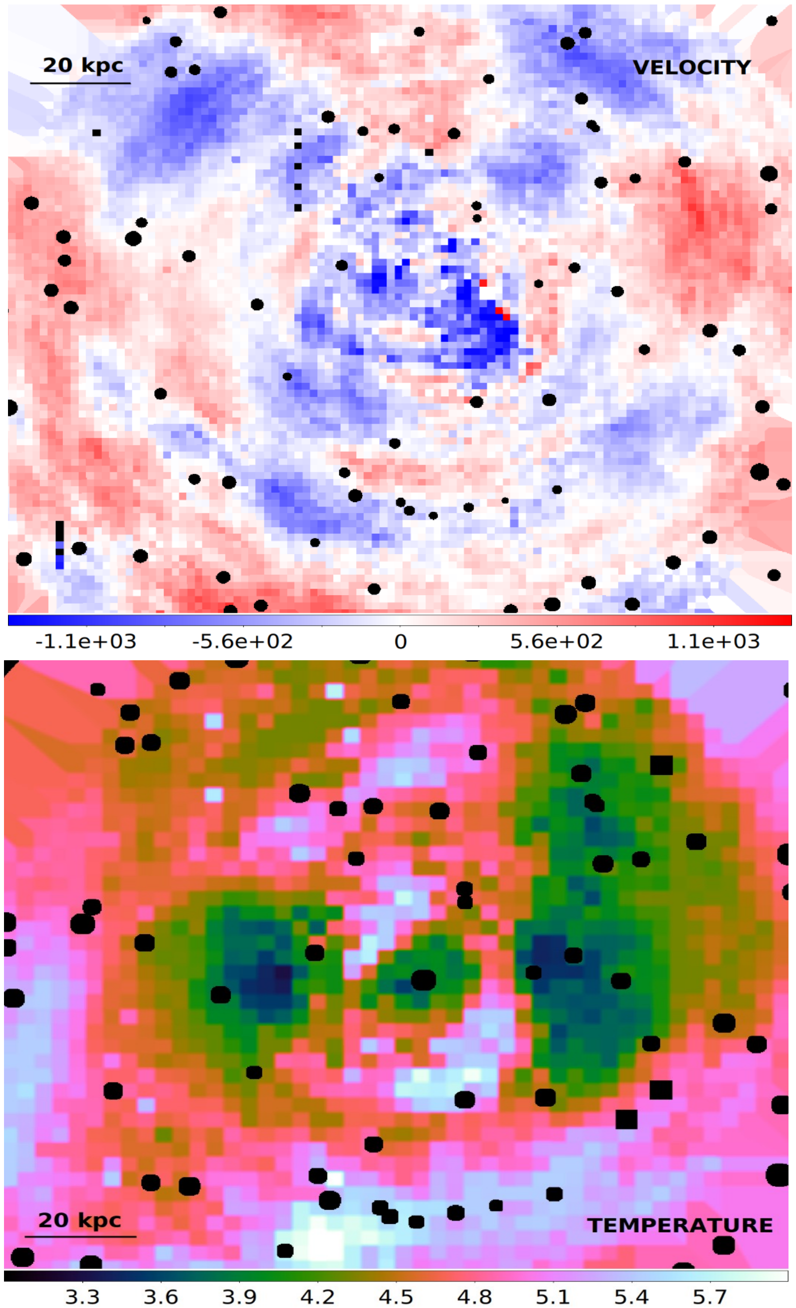






Gatuzz et al. (2022b)

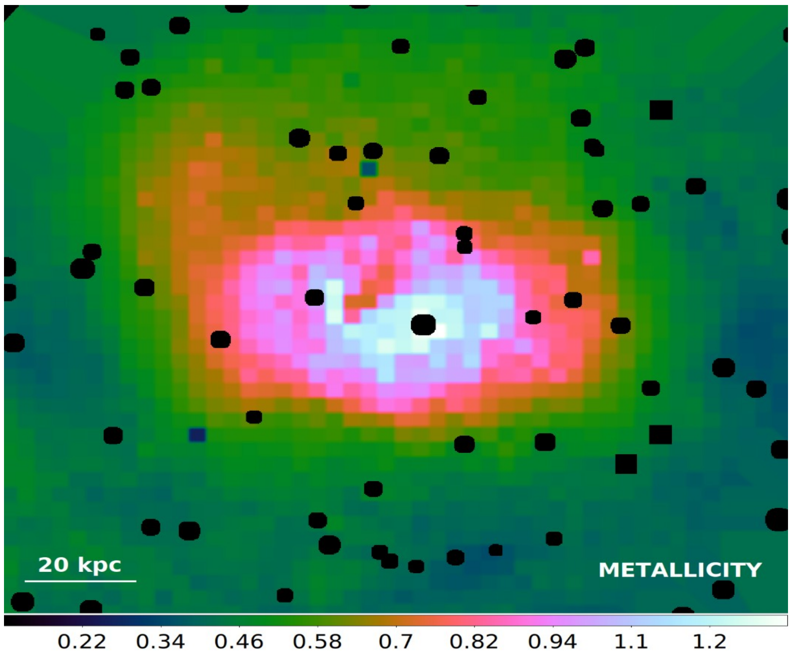
The Centaurus cluster: velocity maps



- No clear spiral pattern (LOS perpendicular to the sloshing plane?)

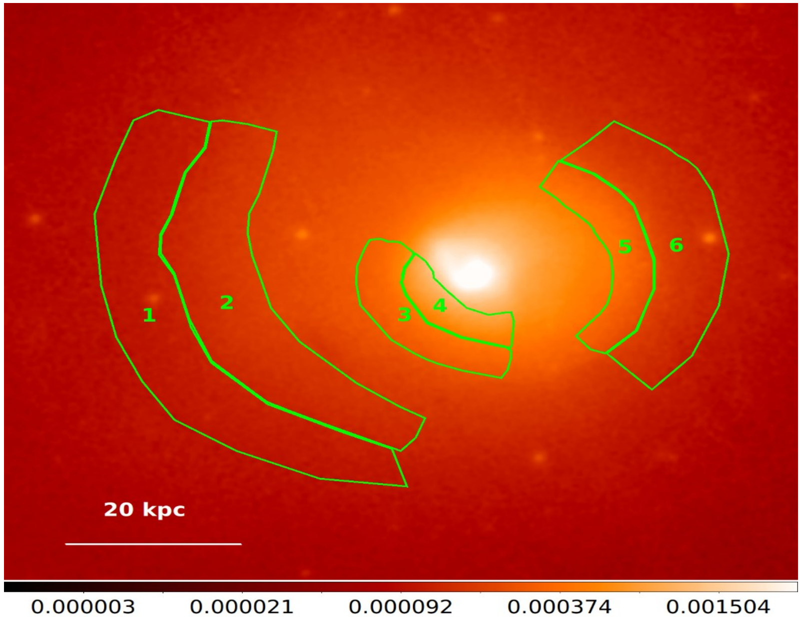
- Blue structure south-west direction: impact of AGN outflows from NGC 4969

- Blueshifted gas X-shape?



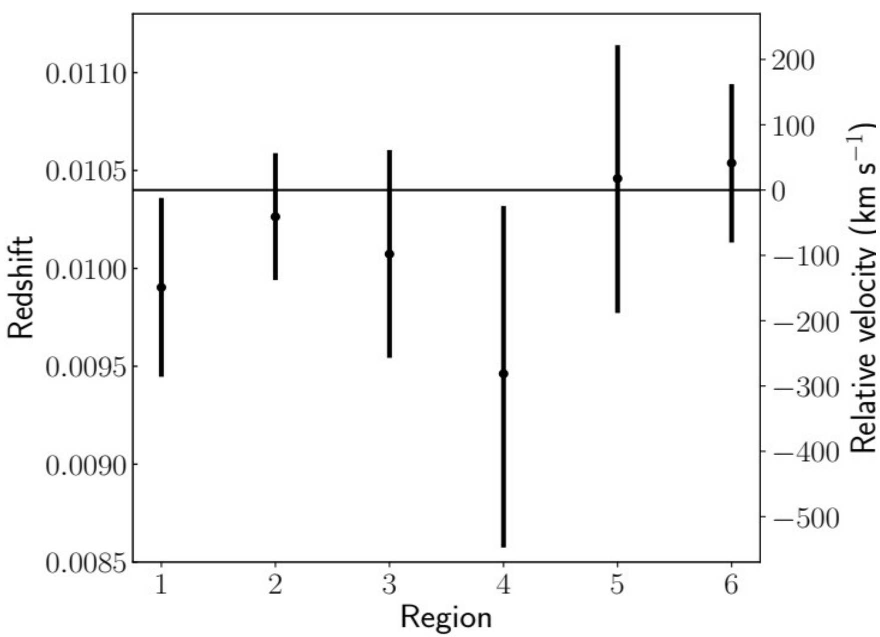
Gatuzz et al. (2022b)

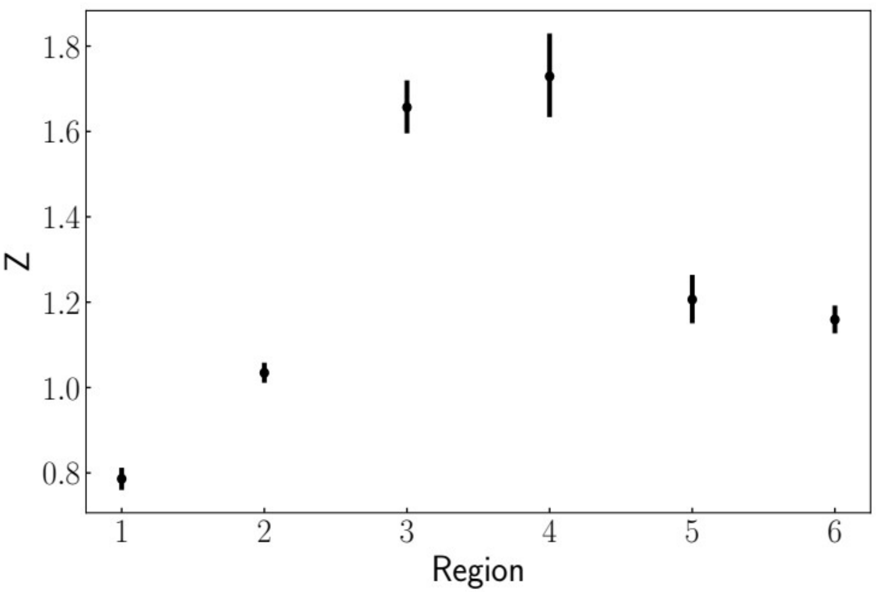
The Centaurus cluster: cold fronts



- Discontinuity in metallicity.

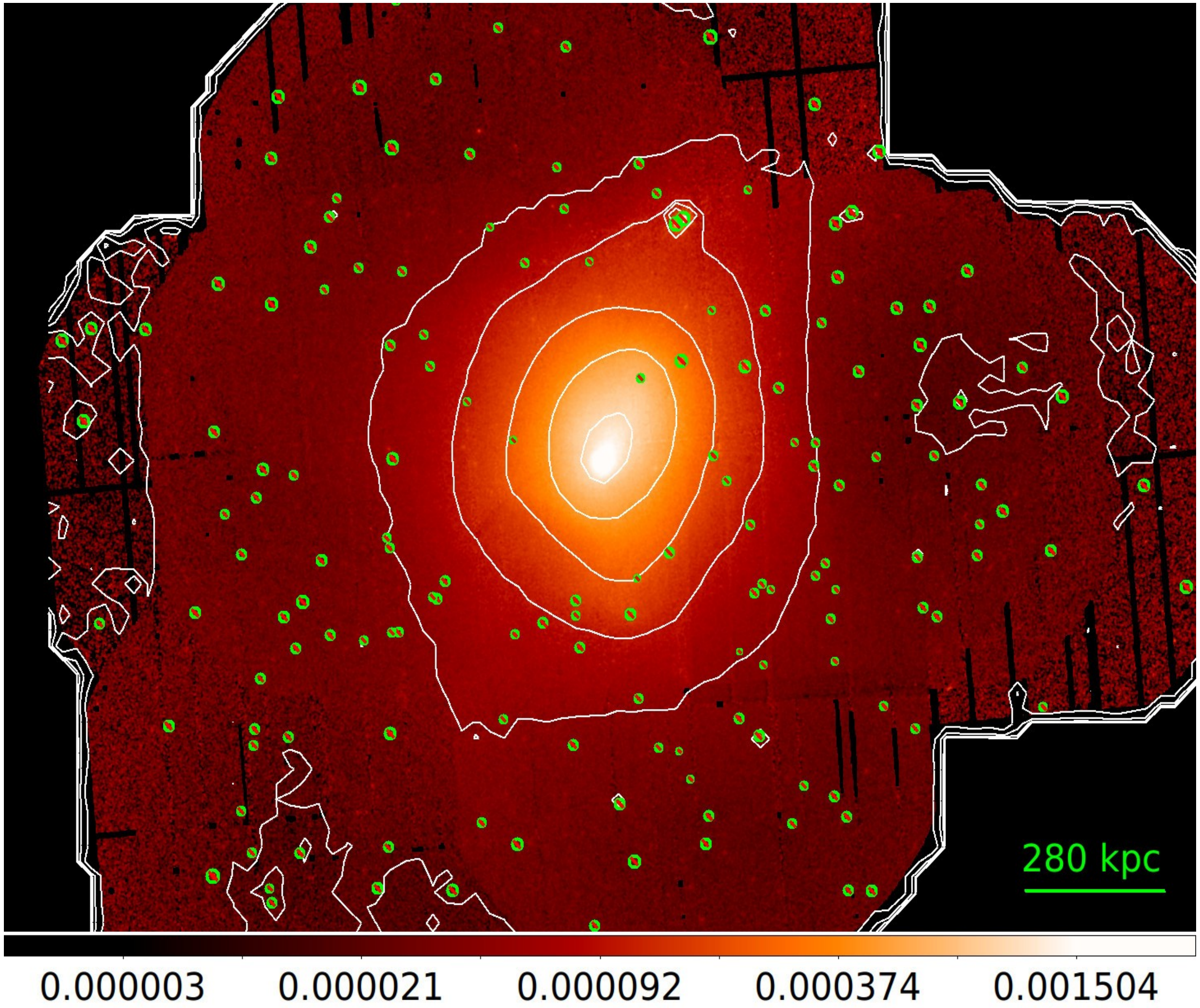
- There are changes in velocities and temperatures, but the uncertainties are large.

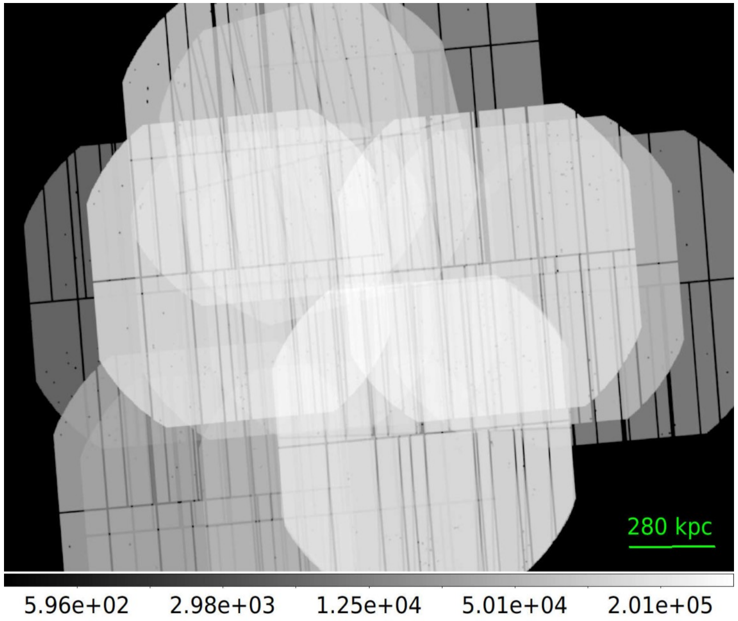


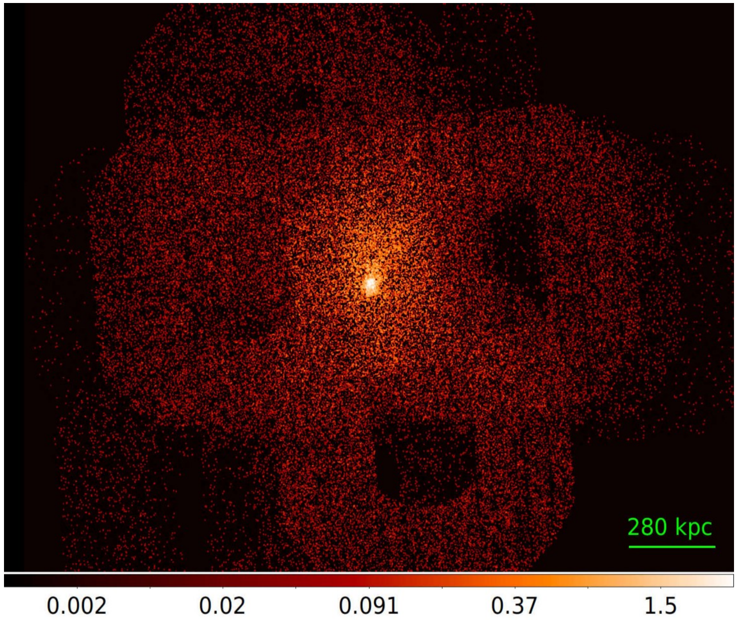


Gatuzz et al. (2022b)

The Ophiuchus cluster: X-ray observations

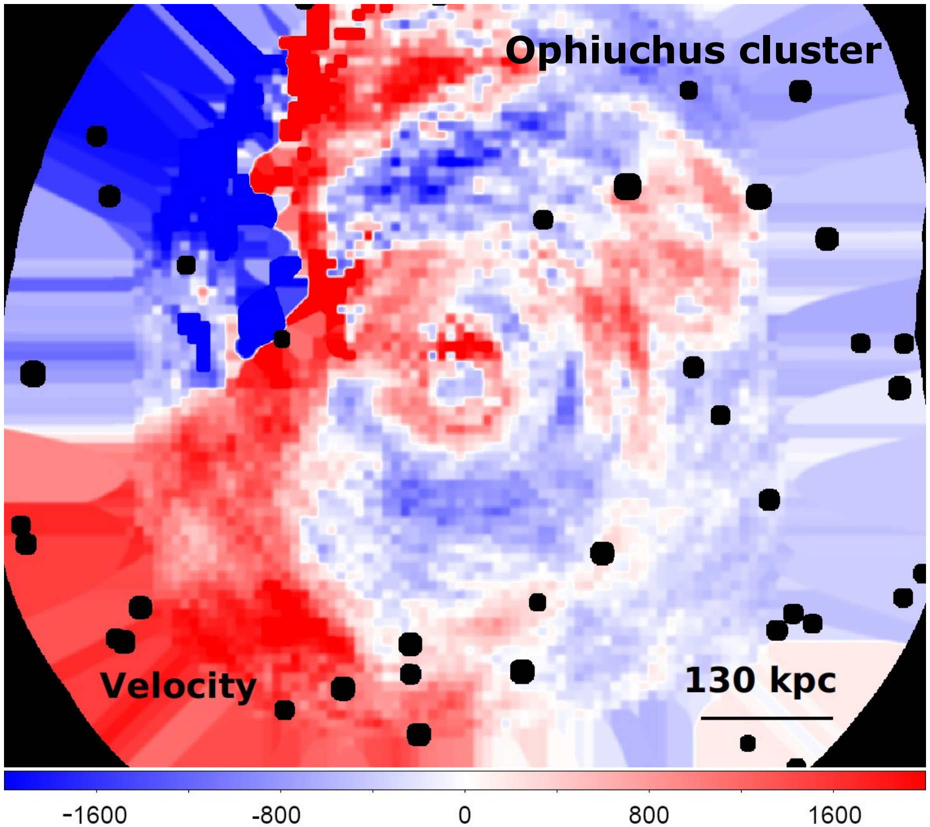


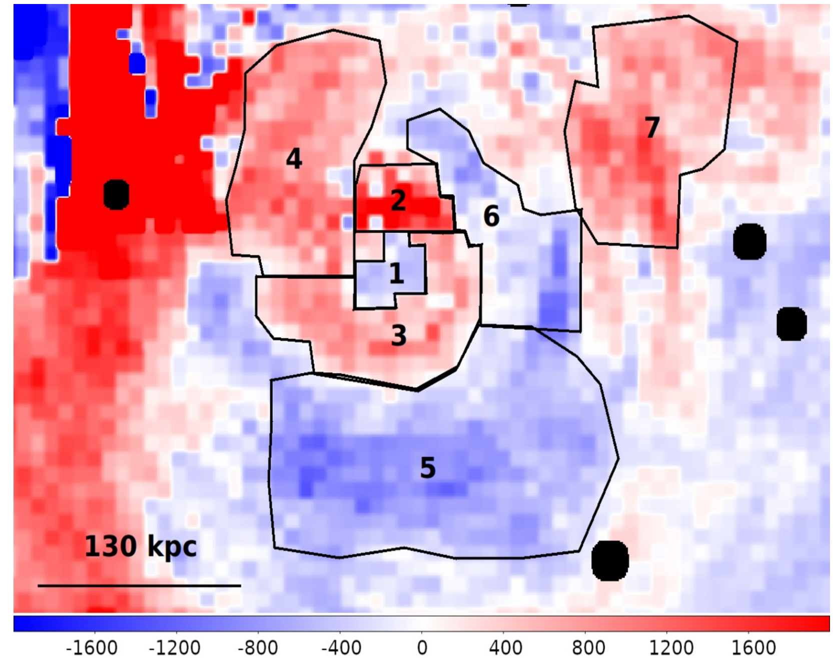


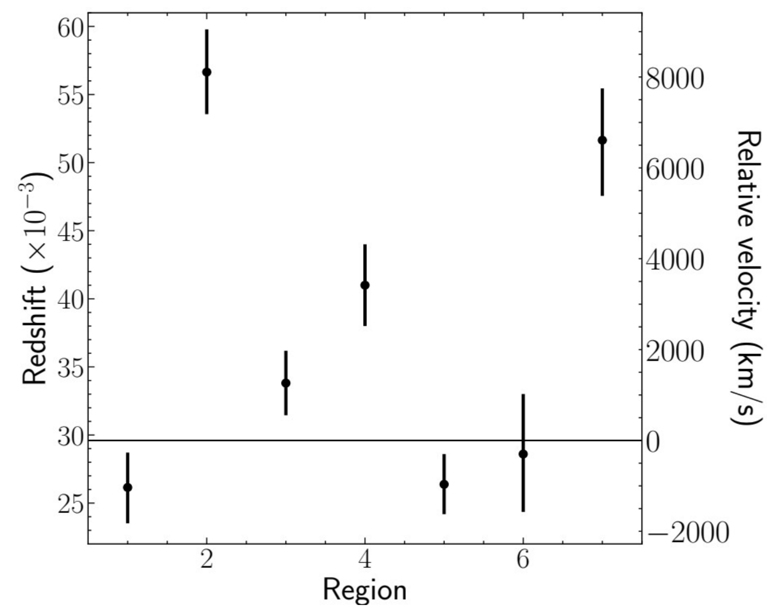


Gatuzz et al. (2023b)

The Ophiuchus cluster: velocity maps





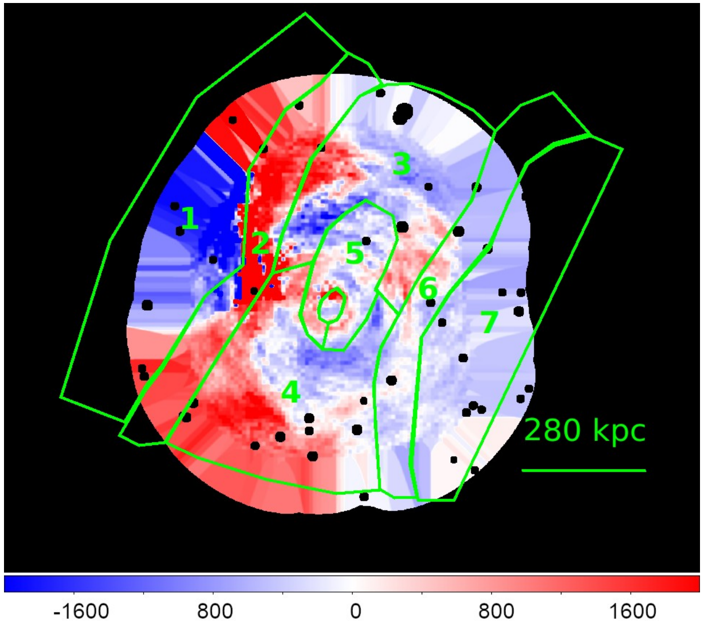


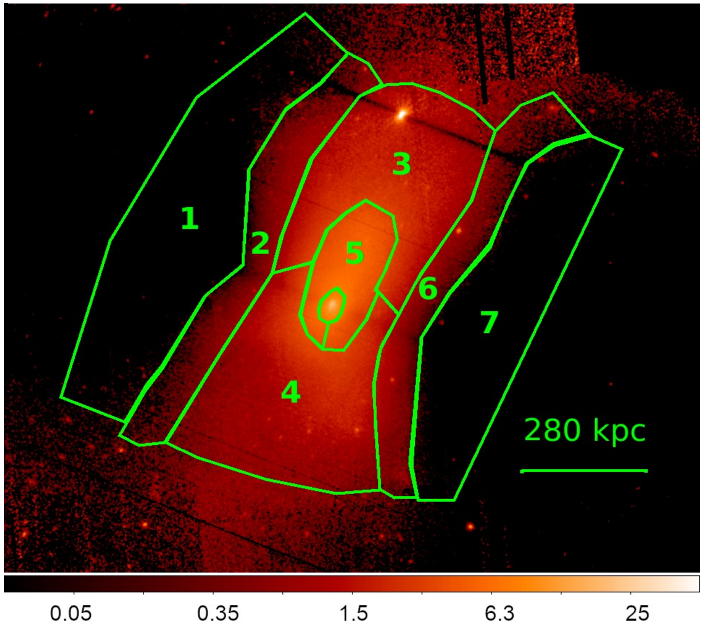
- We have found a large redshifted-blueshifted interface located ~150 kpc in the E direction from the cluster core.

- We found large velocity differences between some regions near the cluster core, with departure from systematics >5σ.

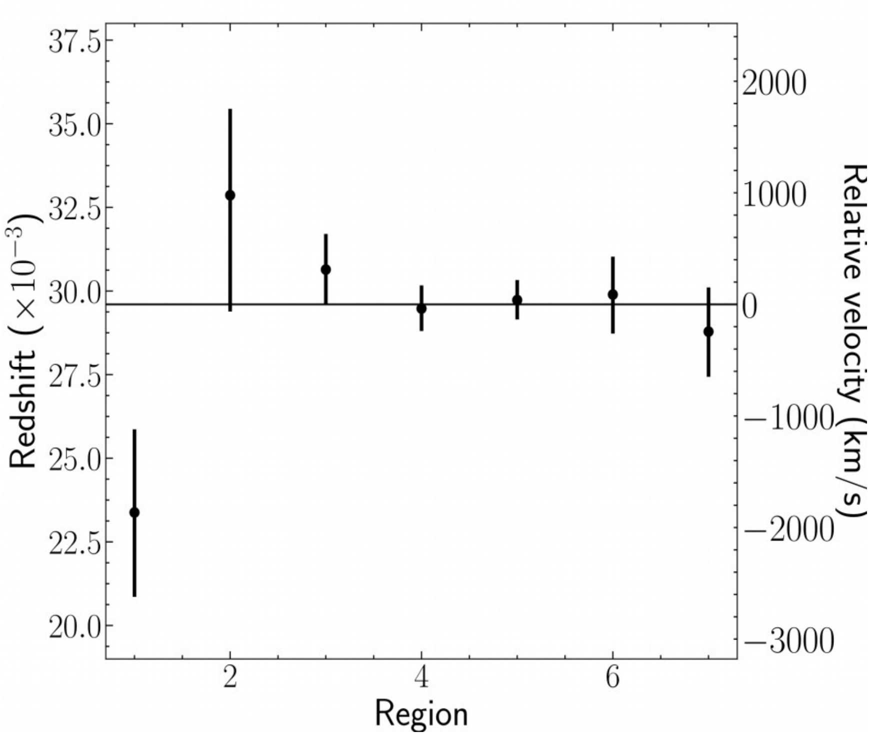
Gatuzz et al. (2023b)

The Ophiuchus cluster: velocity maps





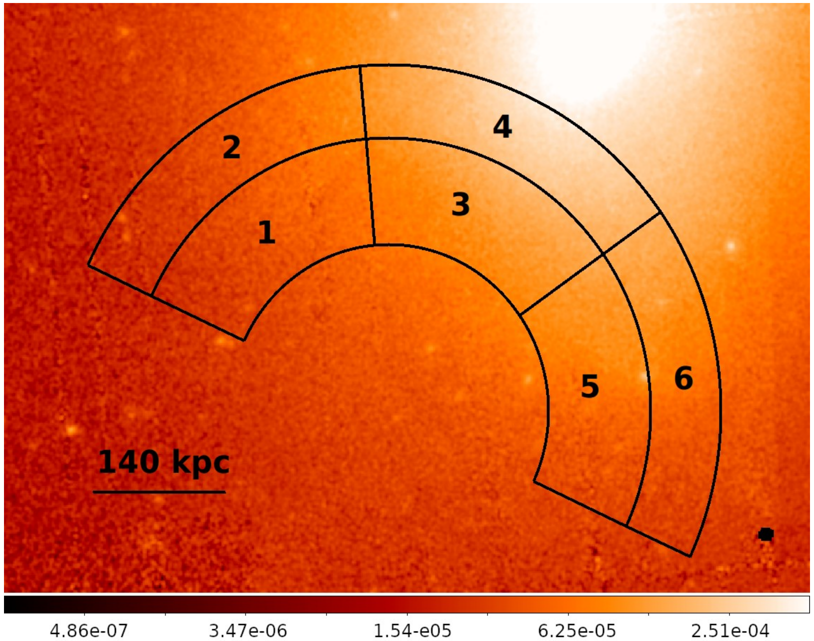
Gatuzz et al. (2023b)

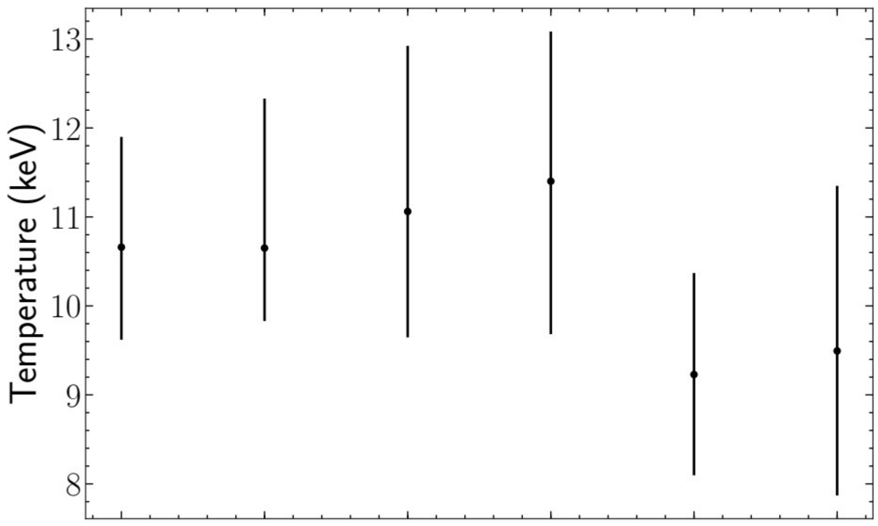


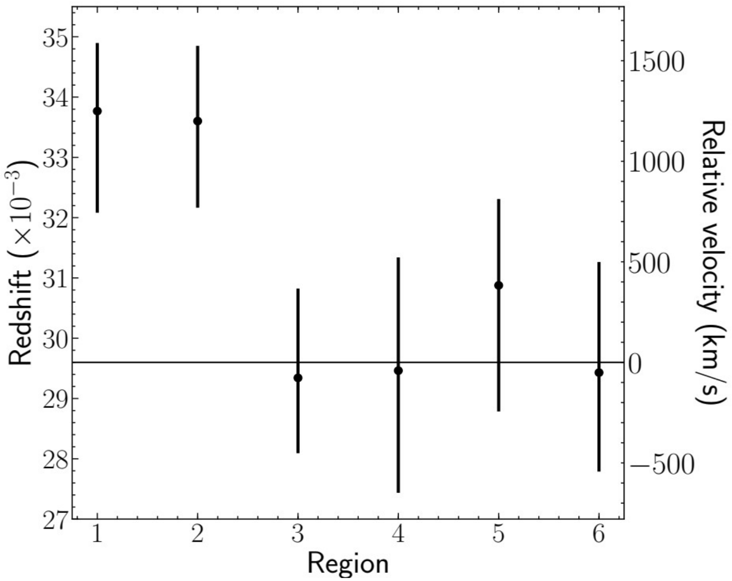
- We found a rapid change in the velocities between regions 1 and 2.

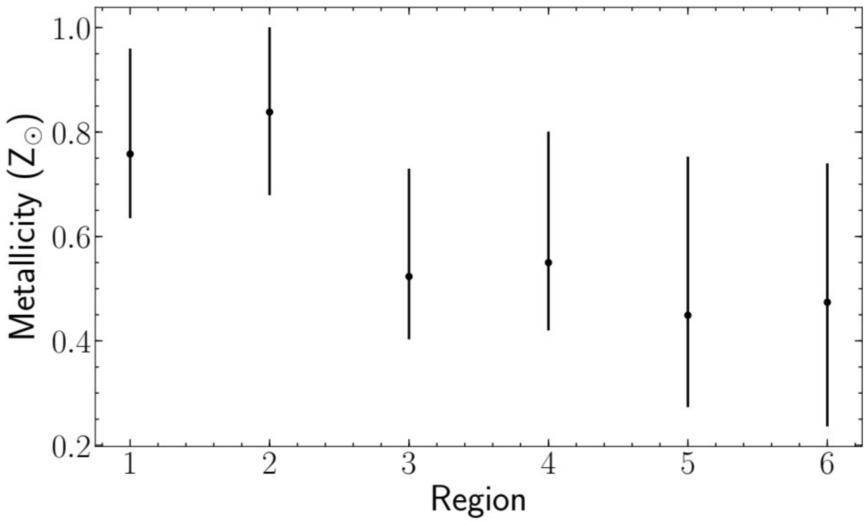
Sharp surface brightness discontinuities observed away from the core are most likely due to gas dynamics associated with a merger instead of an extraordinary AGN outburst (Werner et al. 2016)

The Ophiuchus cluster: radio fossil



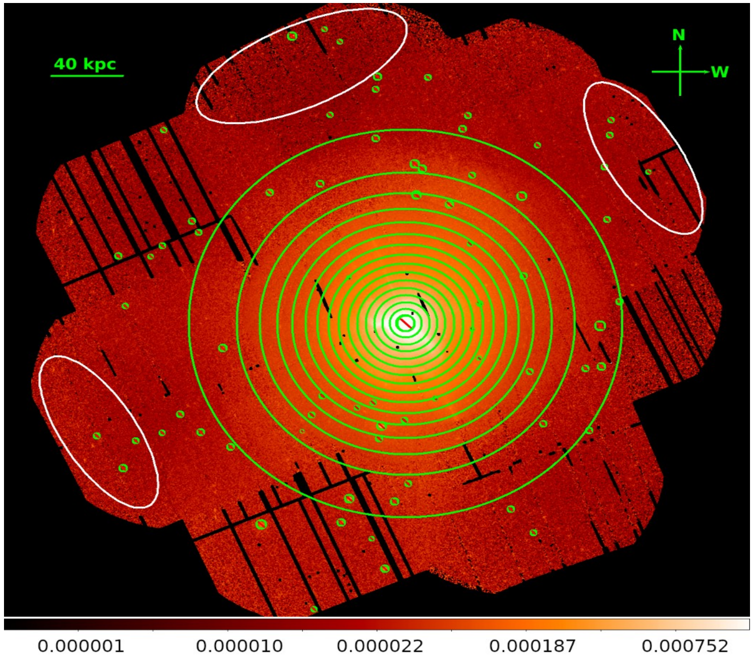


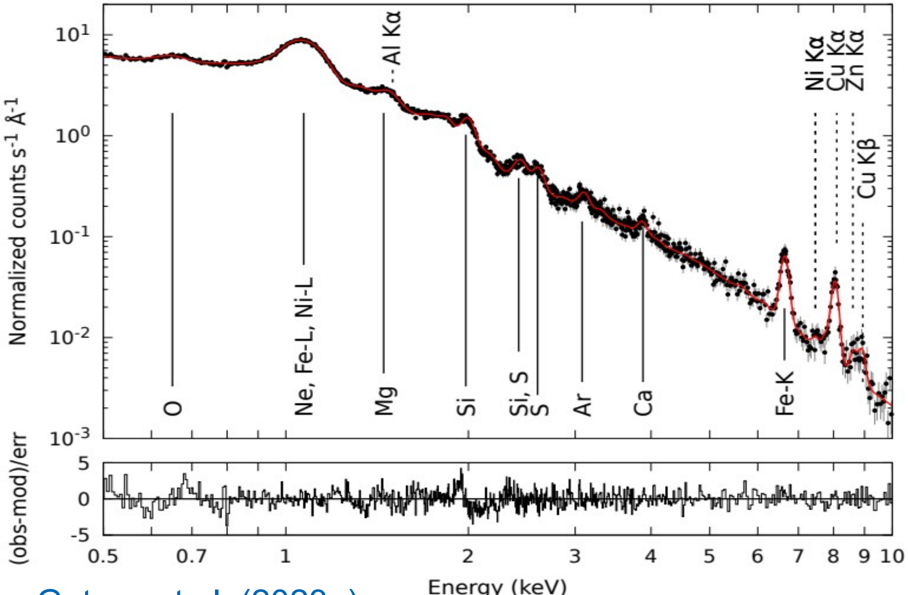




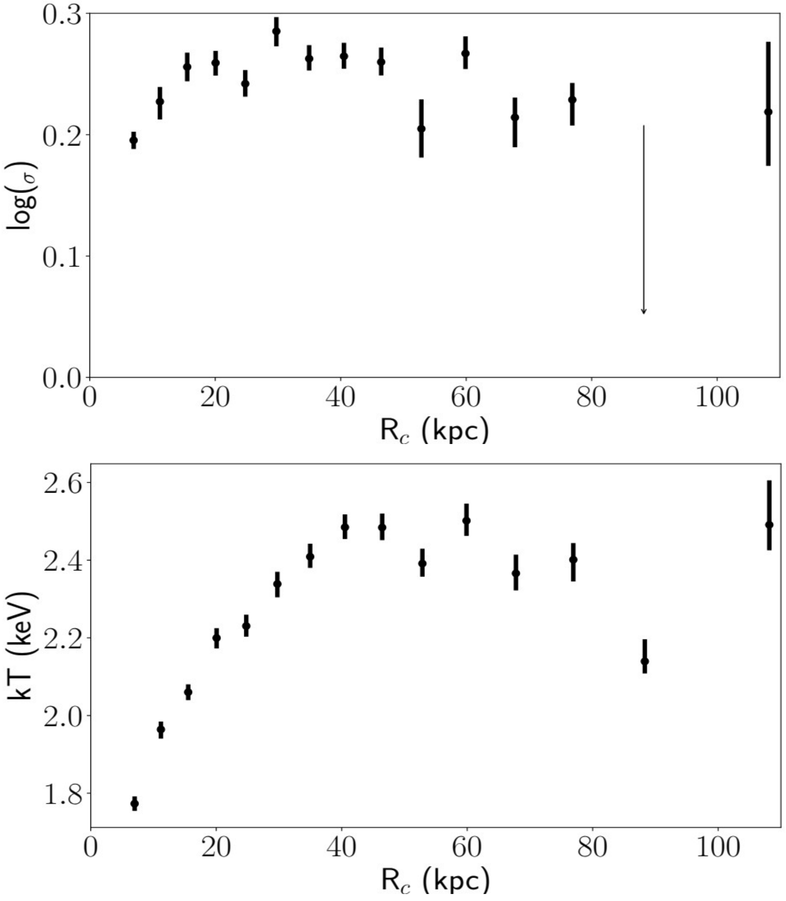
Gatuzz et al. (2023b)

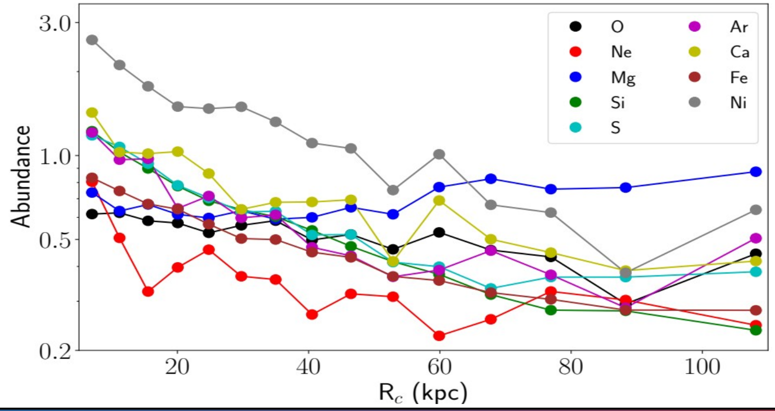
The Virgo cluster: radial profiles



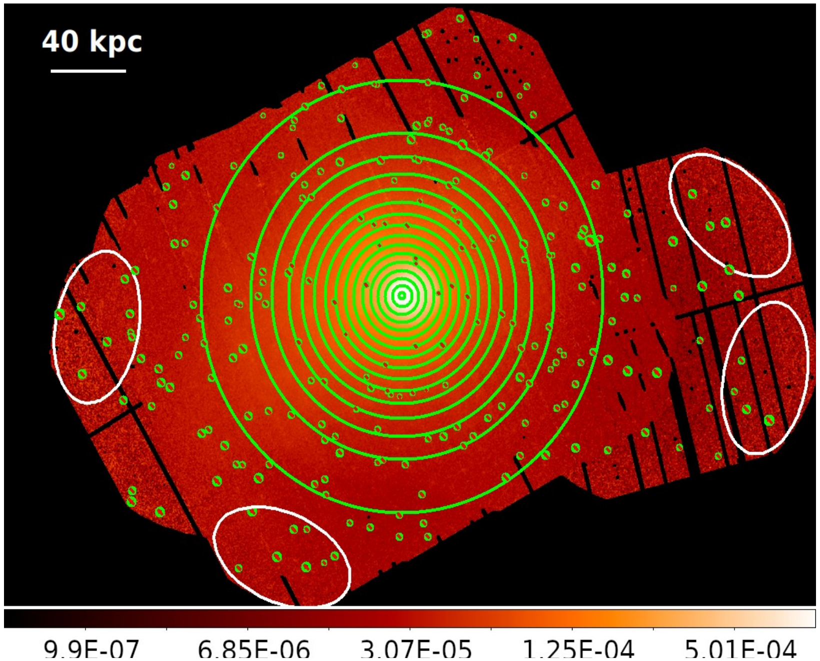


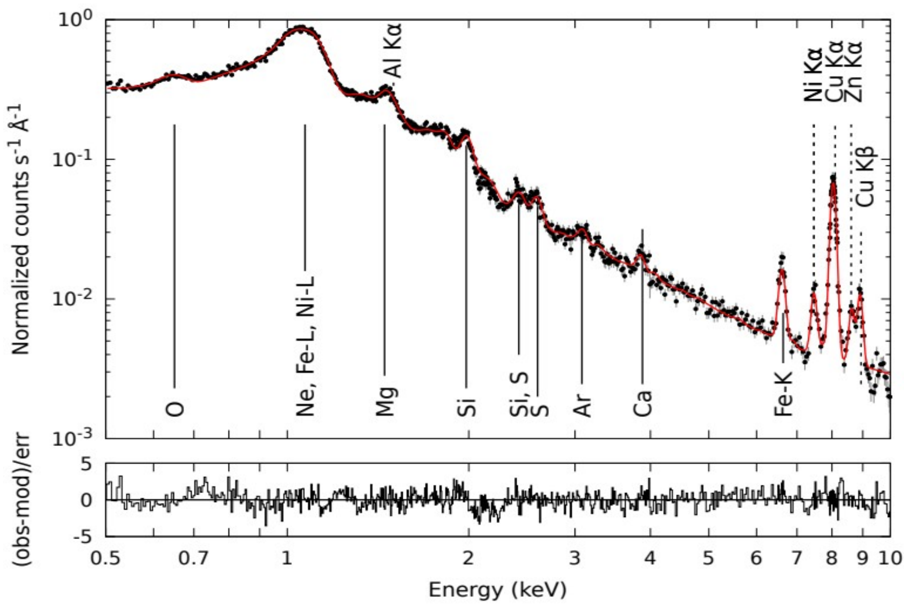
Gatuzz et al. (2023a)

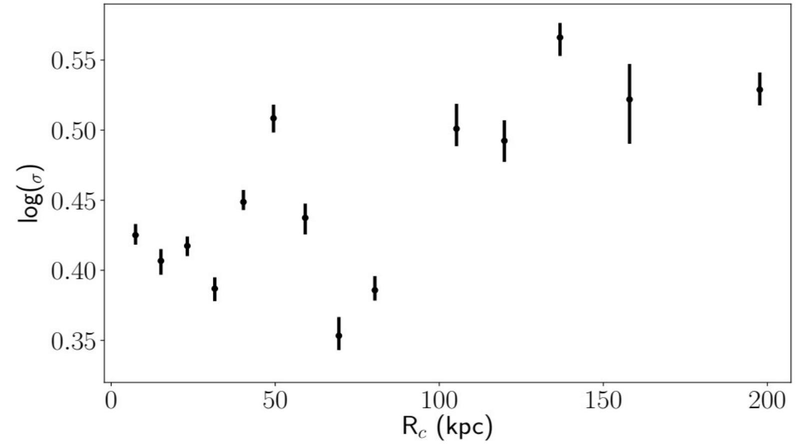


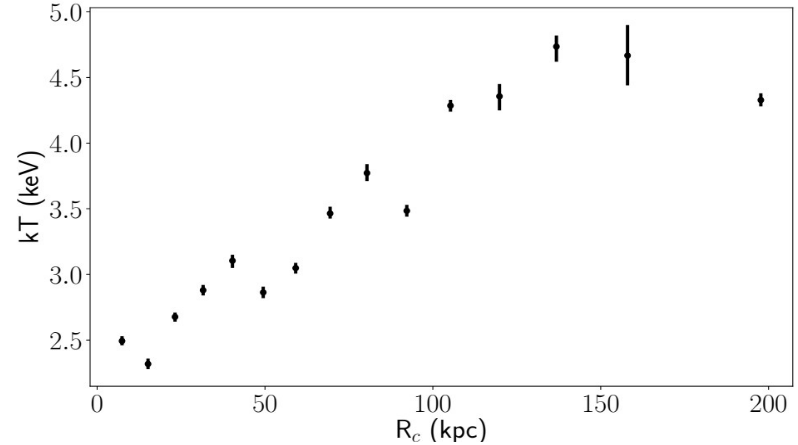


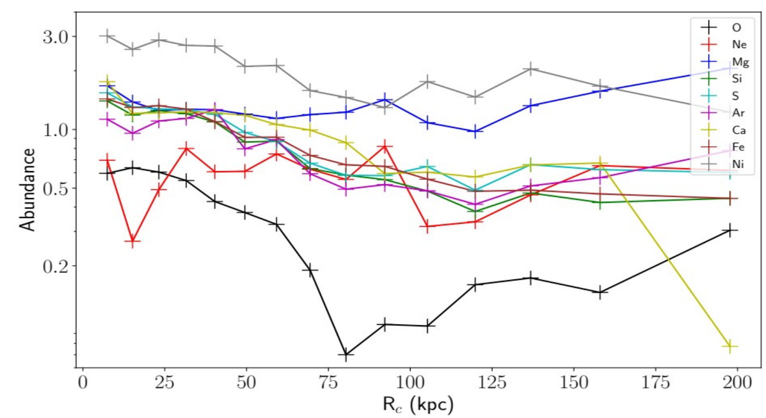
The Centaurus cluster: radial profiles I





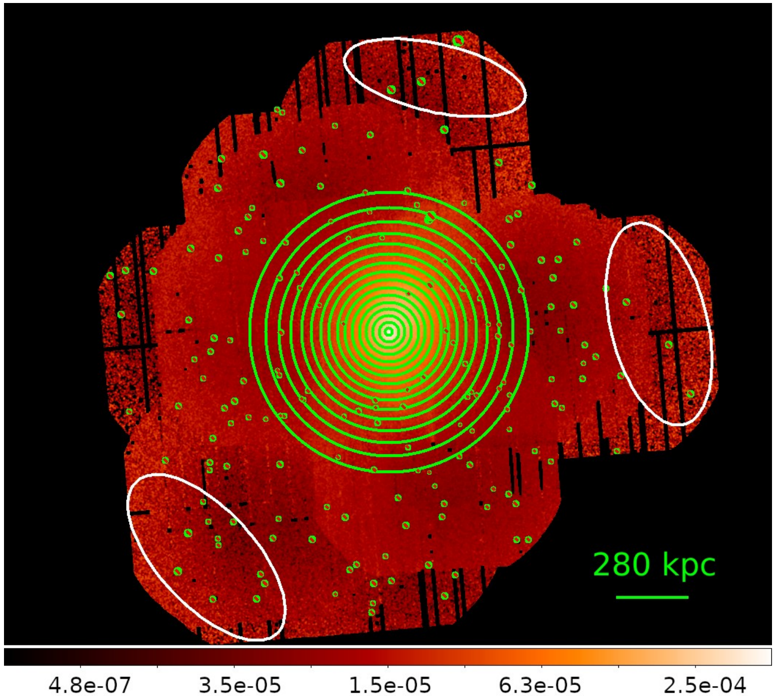


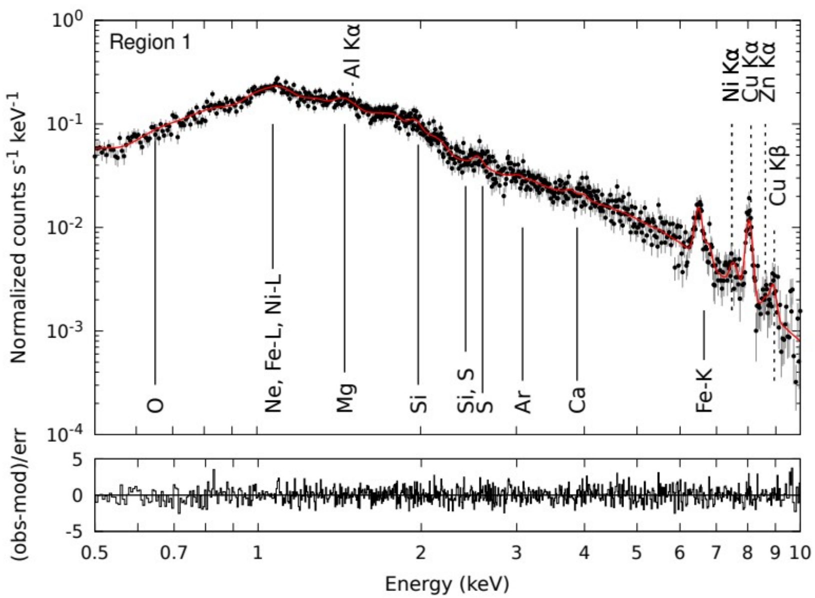




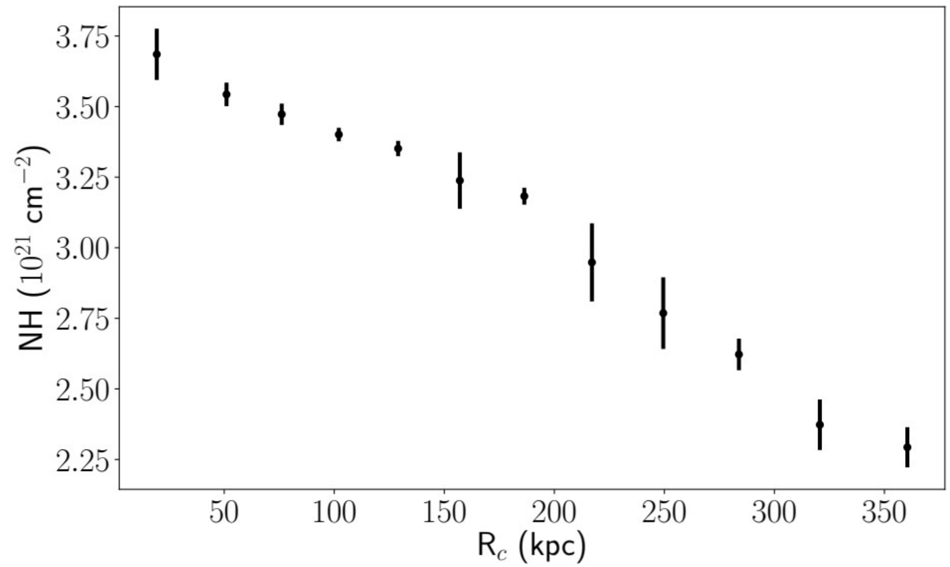
Gatuzz et al. (2023b, submitted)

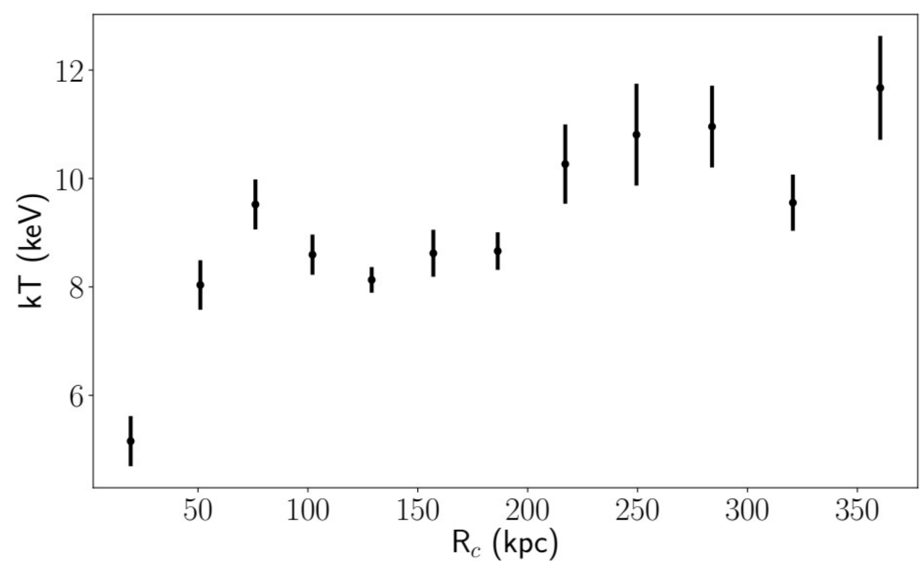
The Ophiuchus cluster: radial profiles I



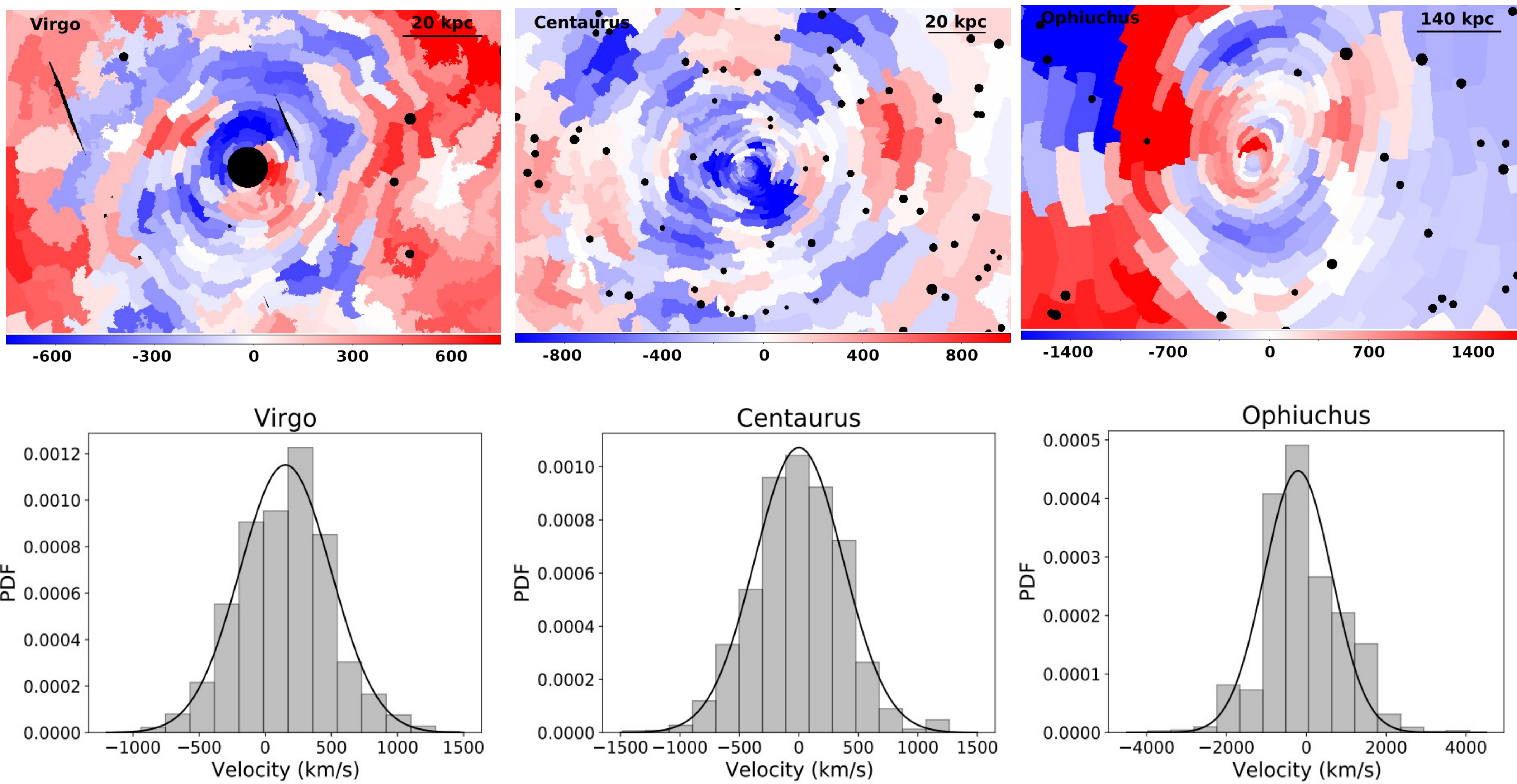


Gatuzz et al. (2023c, submitted)





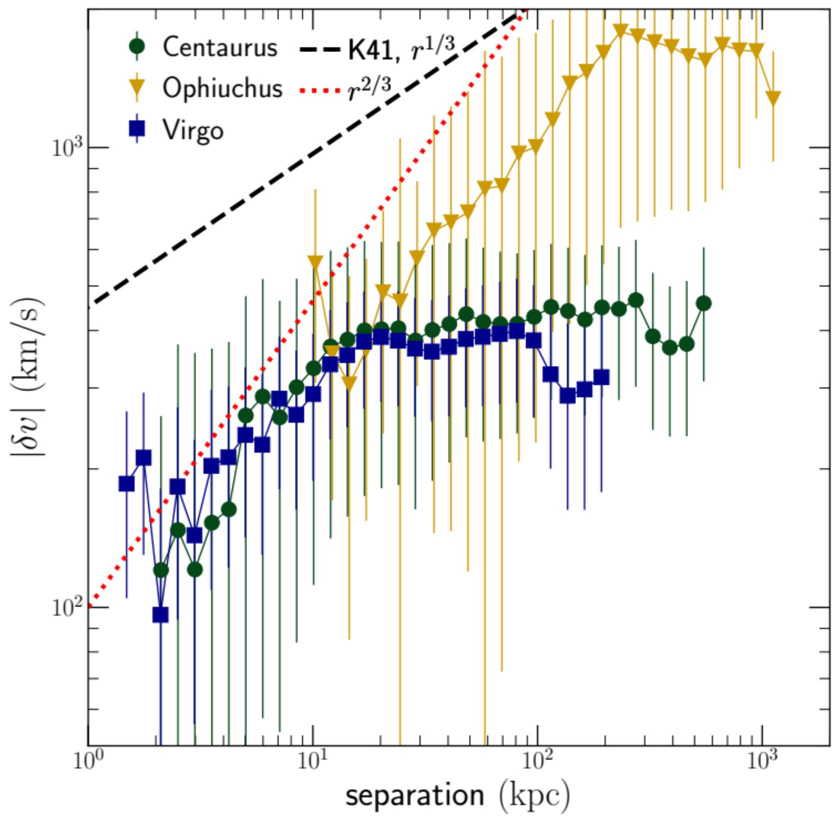
Hot ICM Velocity structure functions (VSF)

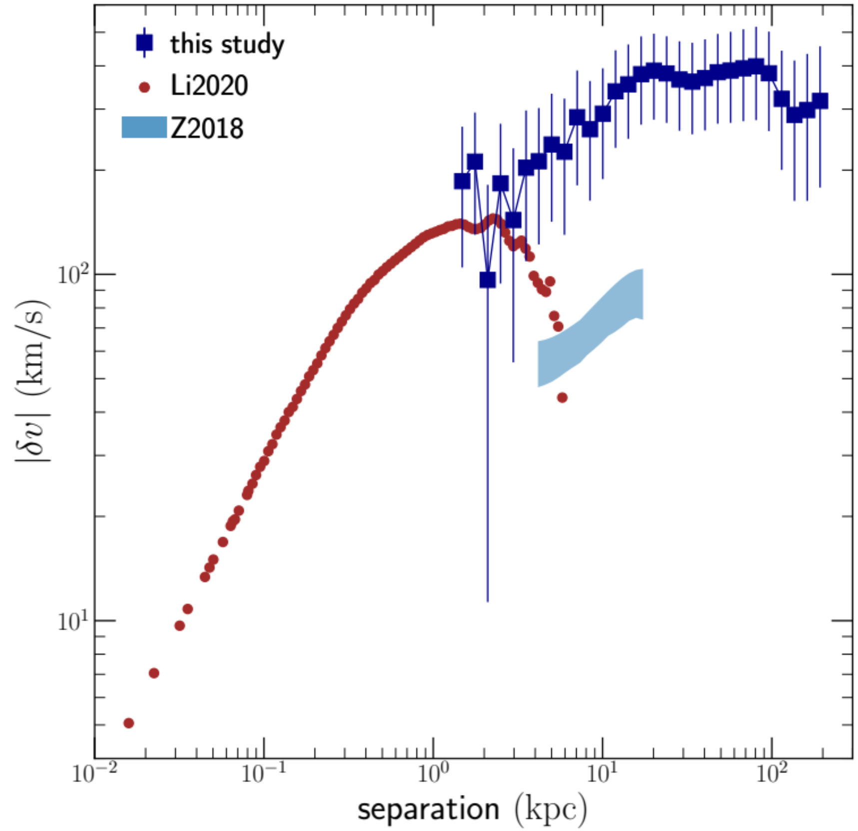


Gatuzz et al. (2023d, submitted)

Hot ICM Velocity structure functions (VSF)

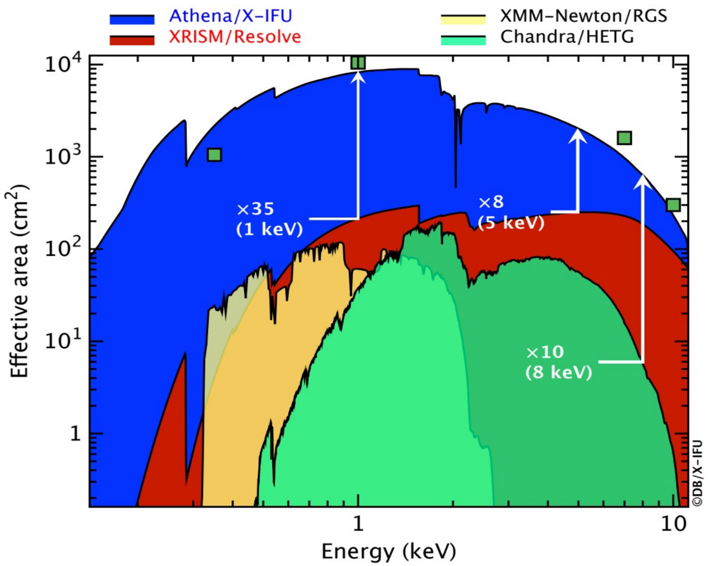
Gatuzz et al. (2023d, submitted)

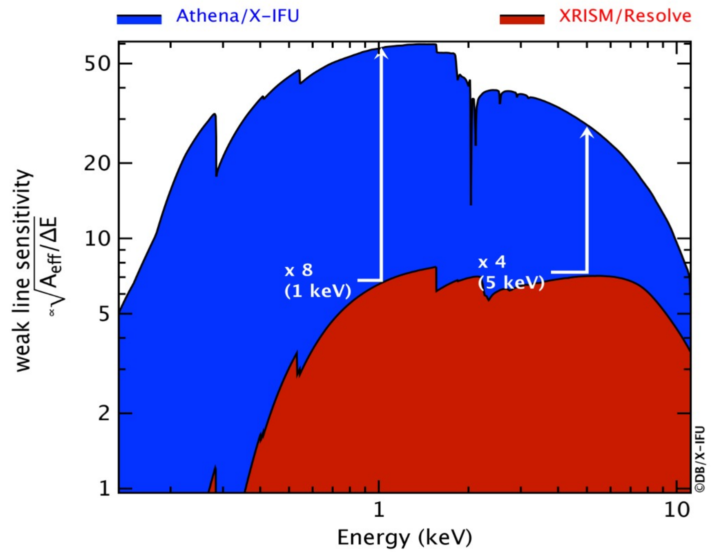




- PDFs follow a normal distribution with hints of a multimodal distribution for Ophiuchus.
- For Virgo and Centaurus, we found a driving scale of turbulence of ~10-20 kpc.
- The VSF reflects the absence of strong interactions between the ICM and a powerful AGN for the Ophiuchus cluster.
- The dissipation time is larger than the jet activity cycle (more heating processes, such as ICM mixing with hot bubbles, are required to reach equilibrium)

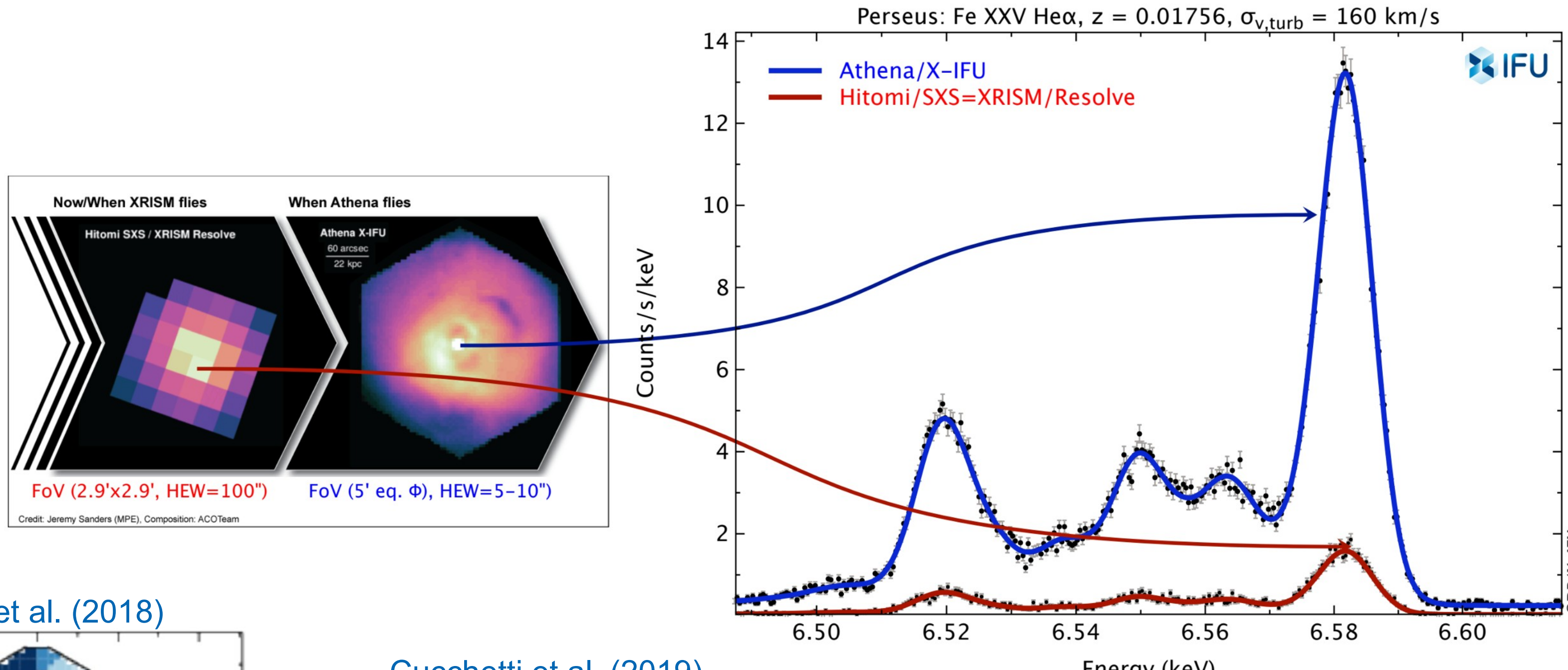
The ICM velocity structure as seen by Athena



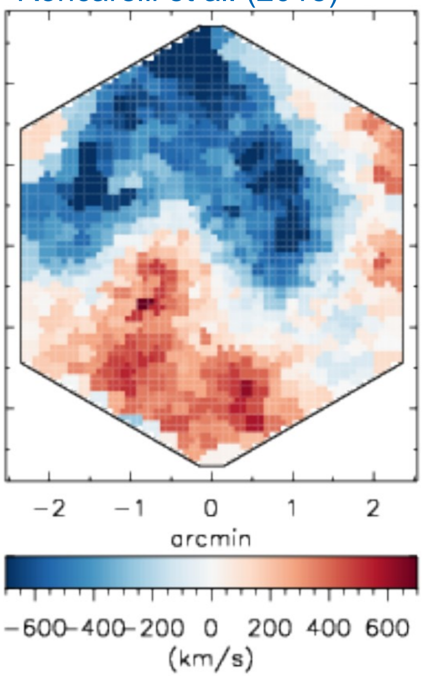


		LEM	XRISM Resolve	Athena XIFU*
Energy band, keV		0.2–2	0.4–12	0.2–12
Effective area, cm^2	0.5 keV 6 keV	1600 0	50 300	6000 2000
Field of view		30′	3′	5′
Grasp, 10^4 cm^2 arcmin^2	0.5 keV	140	0.05	12
Angular resolution		15″	75″	5″
Spectral resolution		0.9 eV (central 8′), 2 eV (rest of FOV)	7 eV	2.5 eV
Detector size, pixels (equiv. square)		118×118	6×6	50×50

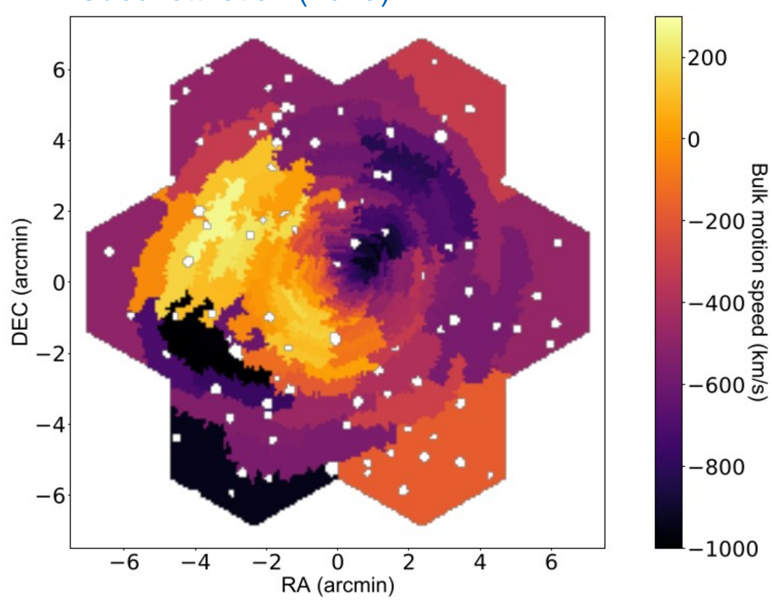
The ICM velocity structure as seen by Athena



Roncarelli et al. (2018)



Cucchetti et al. (2019)



- ICM velocity structure towards the cluster outskirts
- Line shifts and broadening down to ~ 20 km/s
- ICM viscosity (by measuring the dissipation scale of turbulence)
- Differential tests of the velocity structure for regions located in-/outside cold fronts.
- Velocities structure associated with AGN outflows

Conclusions

- The velocity structure in galaxy clusters is important.
- We can measure velocities with uncertainties down to 100 km/s using XMM-Newton observations.
- Our analysis of the Virgo and Centaurus cluster shows properties of both AGN outflows and gas sloshing. For Ophiuchus, we have found significant velocity differences between regions located near the cluster core and hints for the presence of the radio fossil.
- 2D spatial distribution of physical parameters is on the way!
- We will have new XMM-Newton observations of the A3266 galaxy clusters to apply this technique (#92188 PI: Gatuzz, E.)
- Athena observations are crucial in order to better understand the ICM velocity structure
- The synergy between numerical simulations, mock observations, and real data is necessary to interpret the measurements correctly.

THANK YOU!