XRISM observations of the velocity field in merging galaxy clusters

Yuki Omiya (ISAS/JAXA)

XRISM

JAXA

Galaxy clusters in the cosmic web

Galaxy clusters:

- Nodes of the cosmic web
- Largest gravitationally bound systems
- High-mass end of structure formation
- Cosmological probes through abundance and mass

But clusters are not static systems: their hot gas is continuously disturbed by energy injection.

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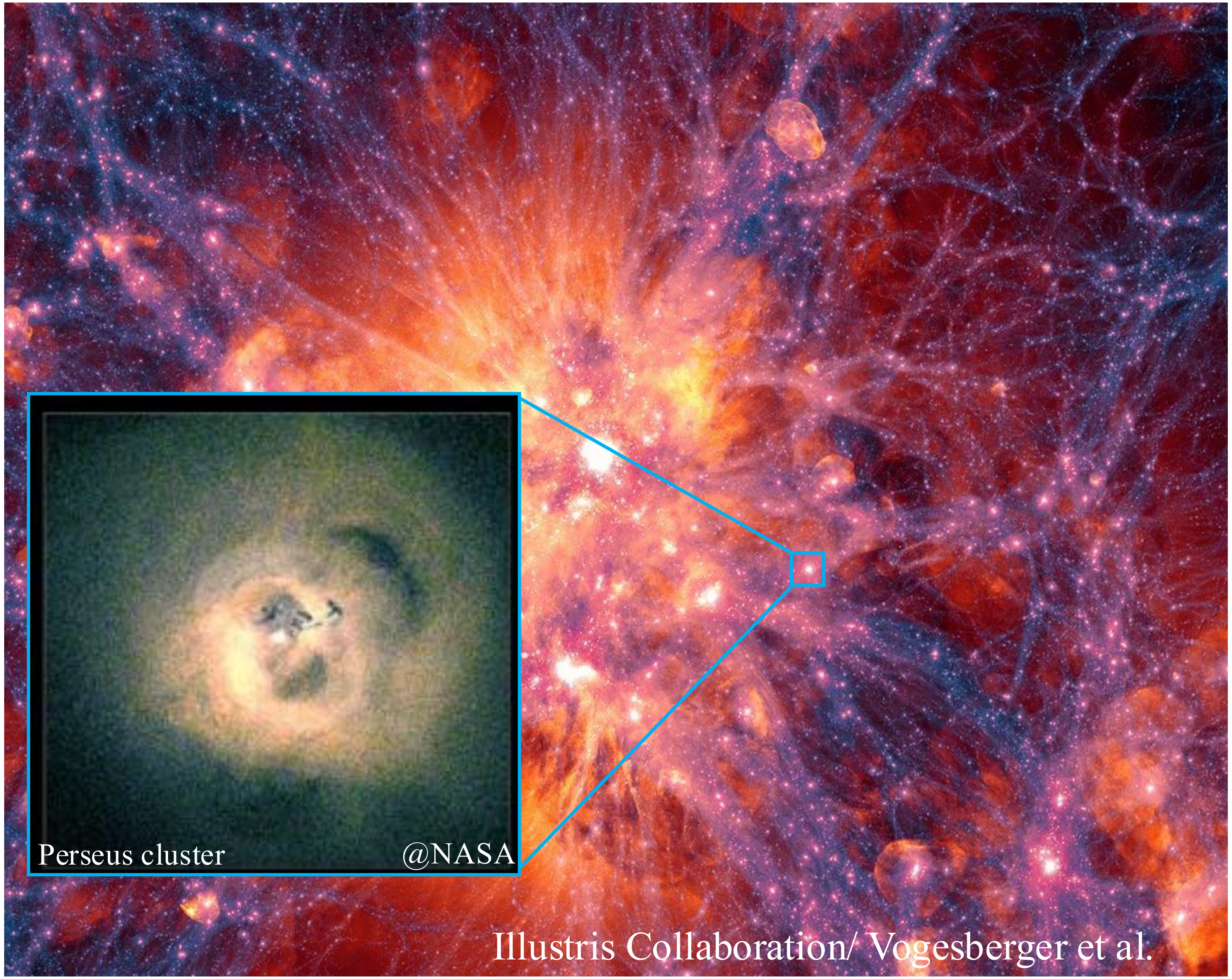
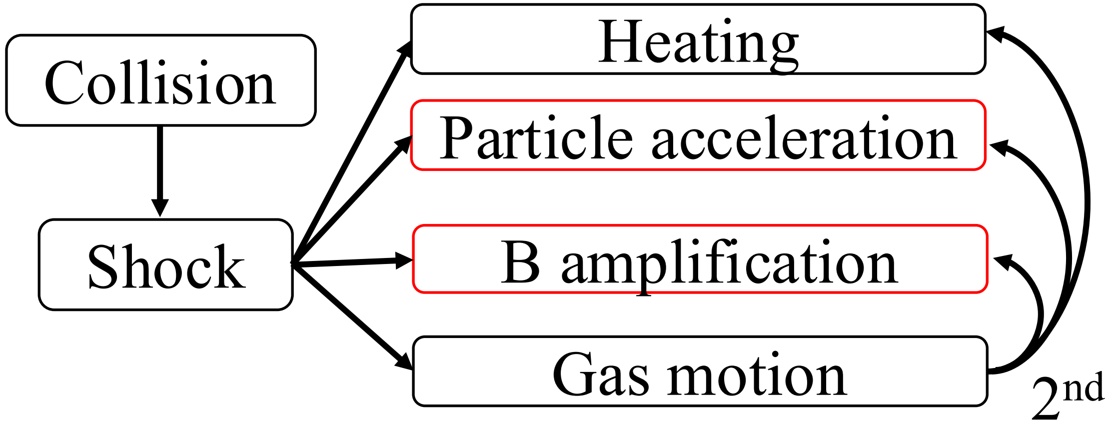
1. AGN feedback
→ compact central engine
→ jets, bubbles, cavities
2. **Cluster mergers**
→ Mpc-scale gravitational engine
→ shocks, bulk motions, turbulence

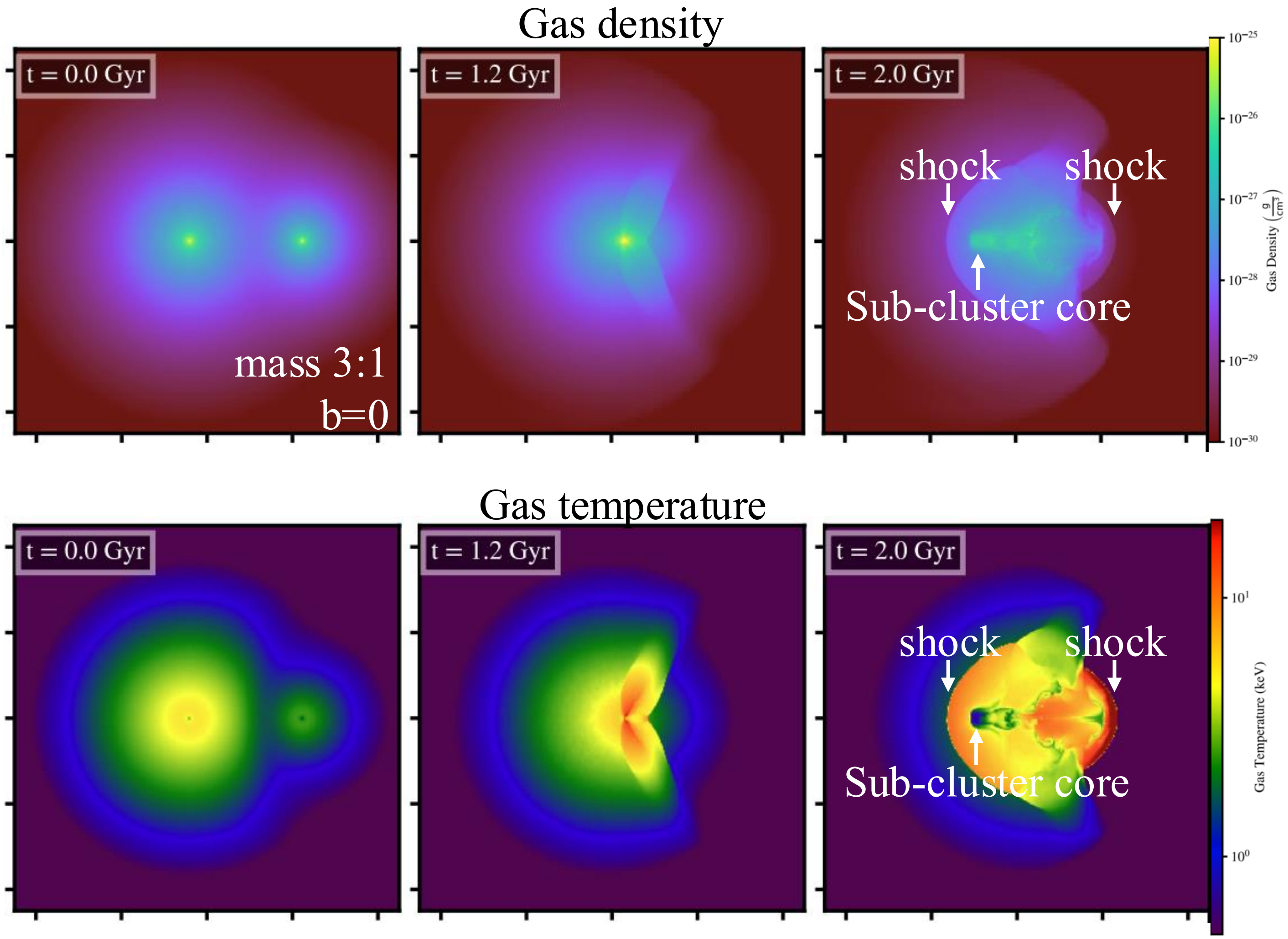


Physics among merging galaxy clusters

Cluster merger:

- Most energetic events (>10^{63} erg)
- Driving Mpc-scale merger shocks





Brzycki et al. 2019

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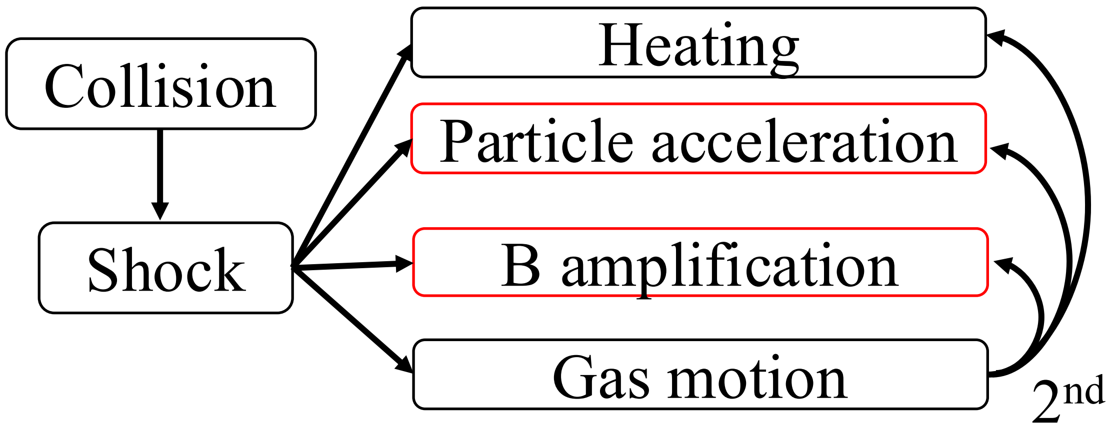

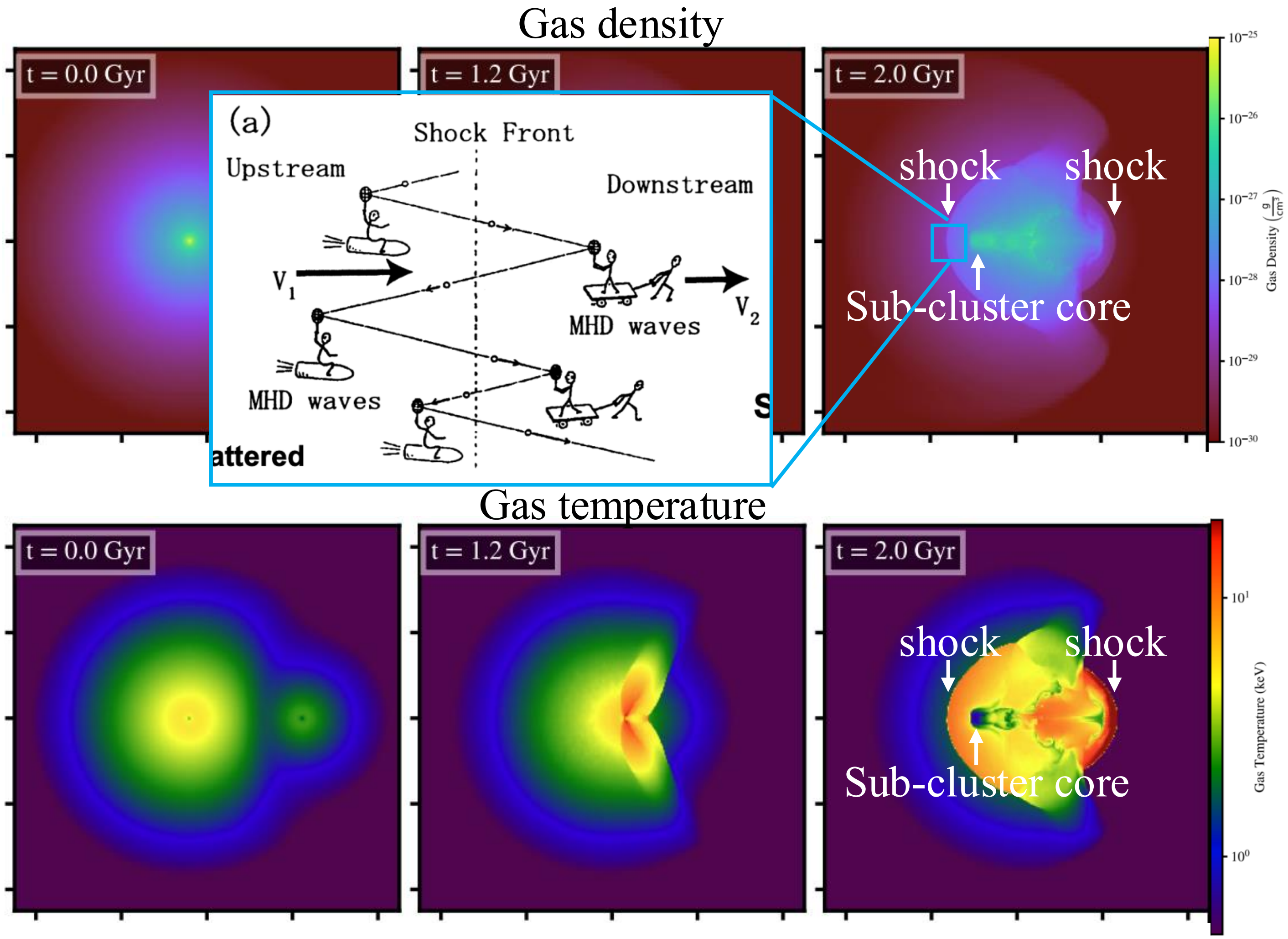

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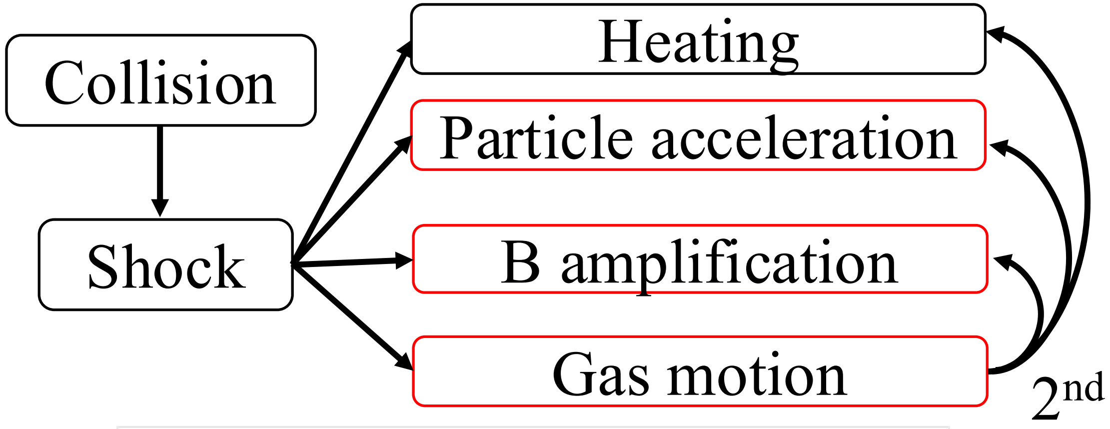
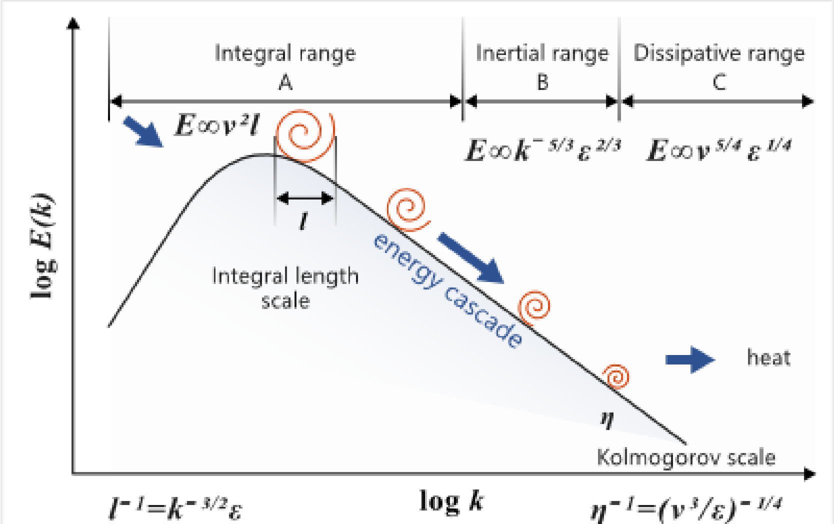
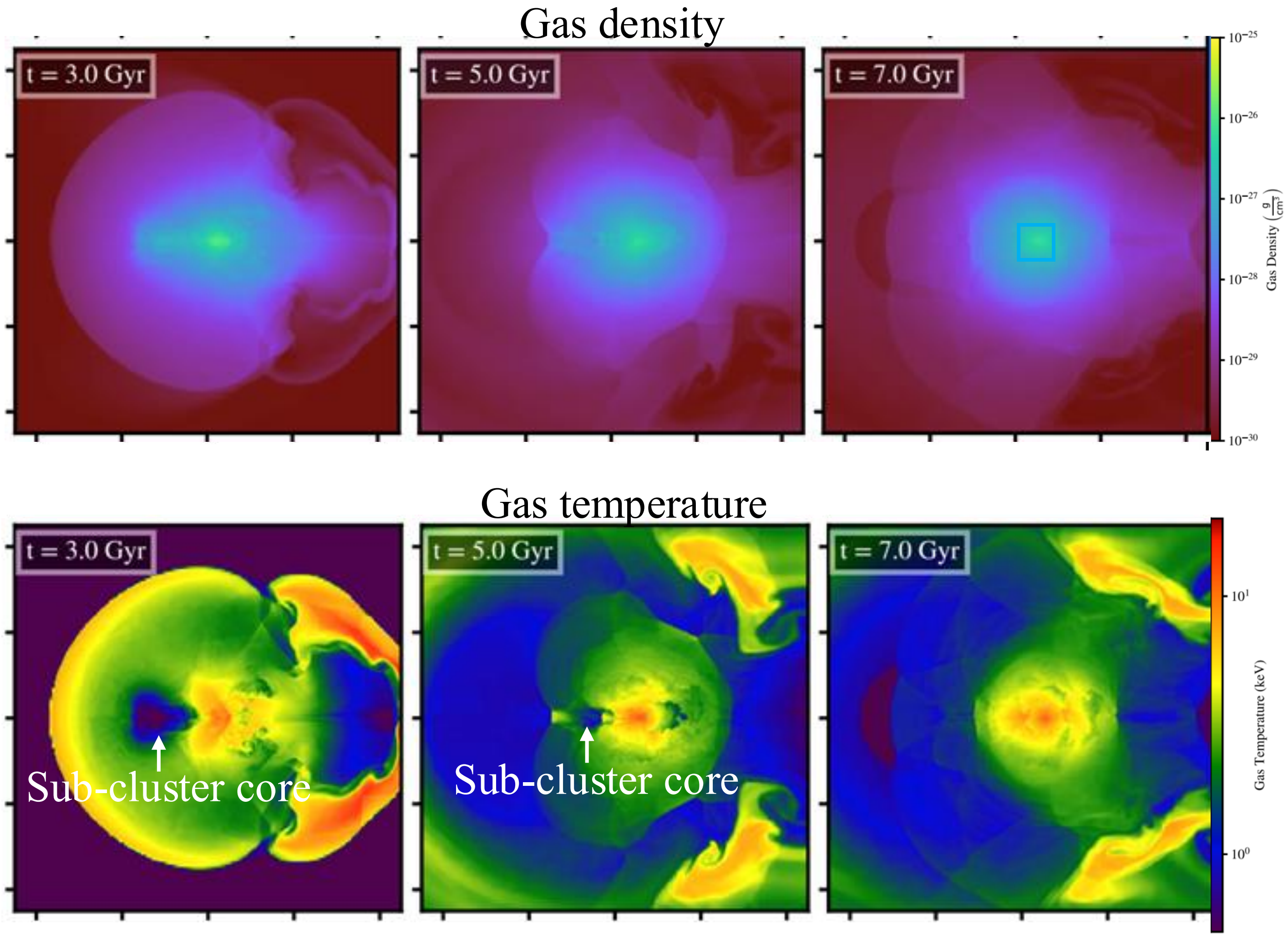




Altair Engineering, Inc. 2025,



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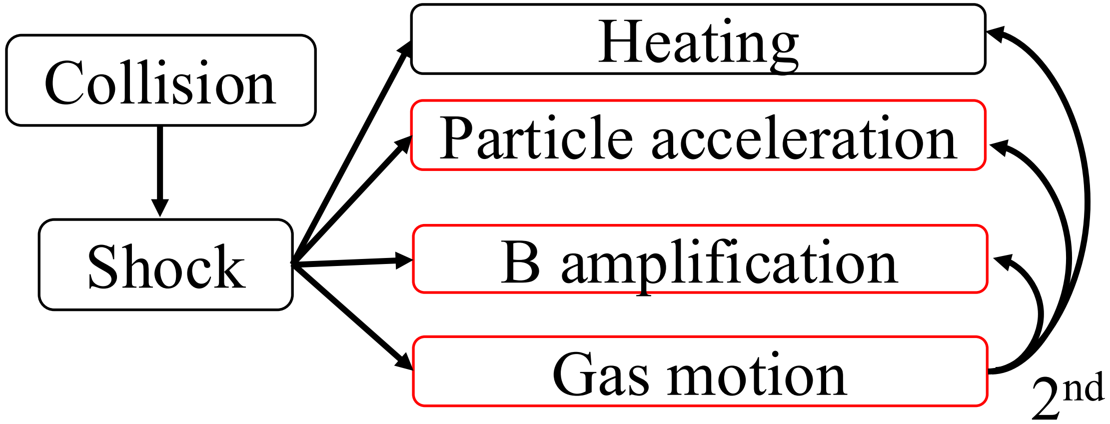

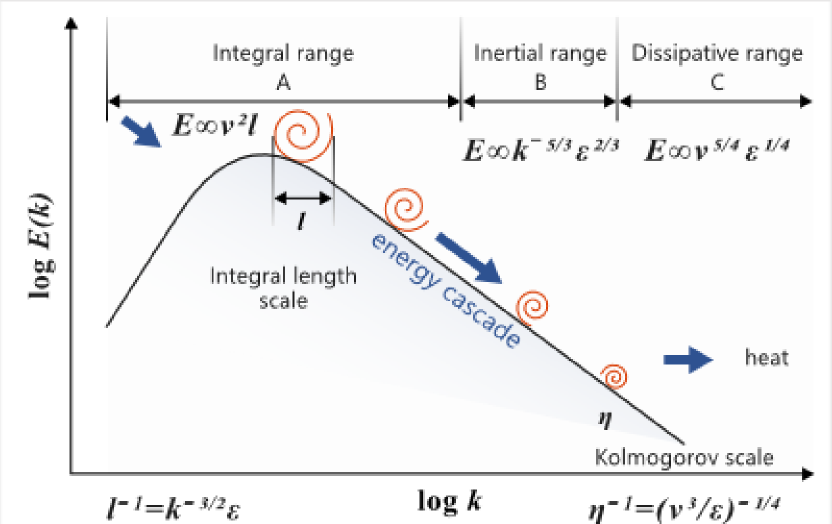

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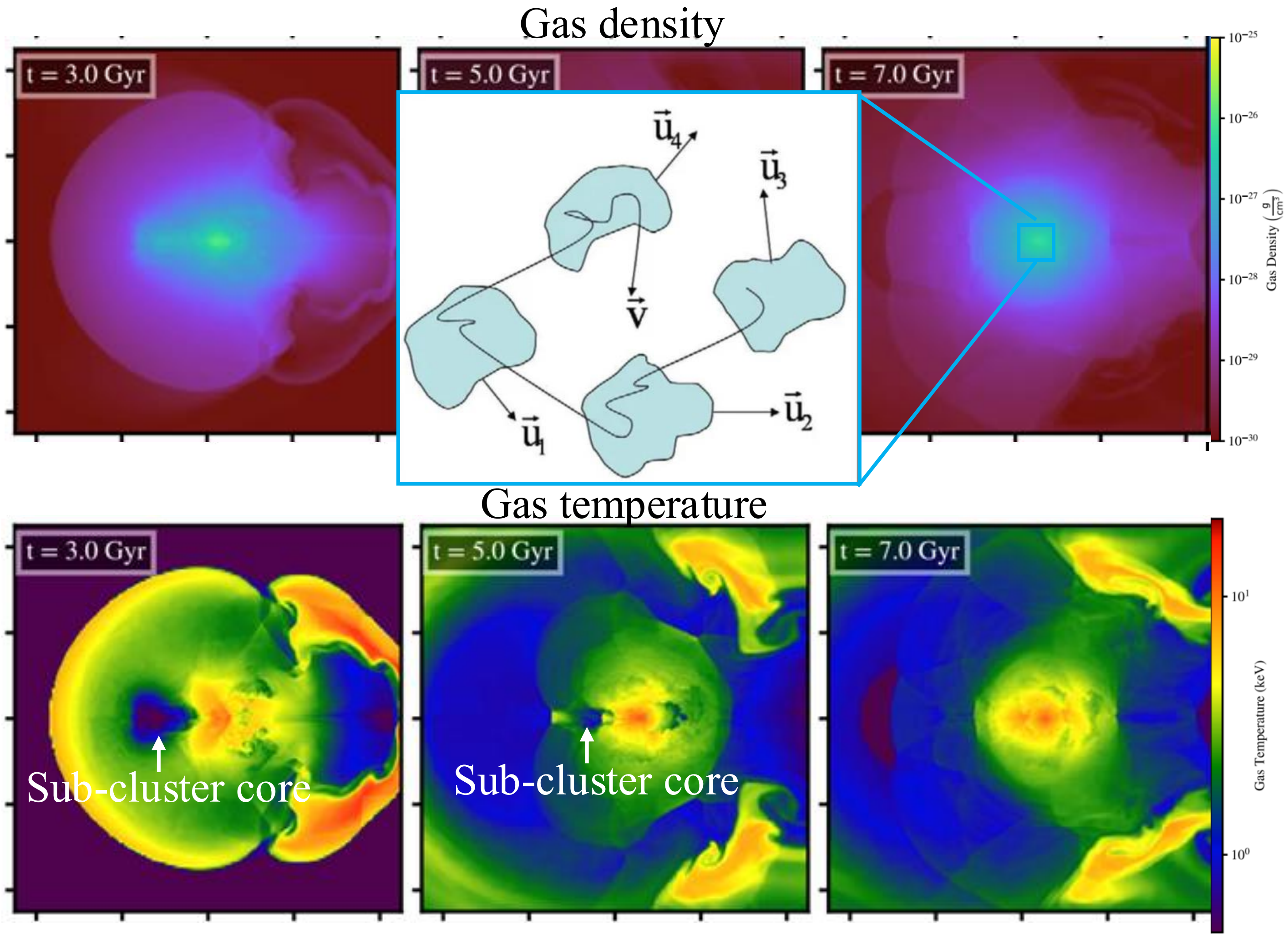

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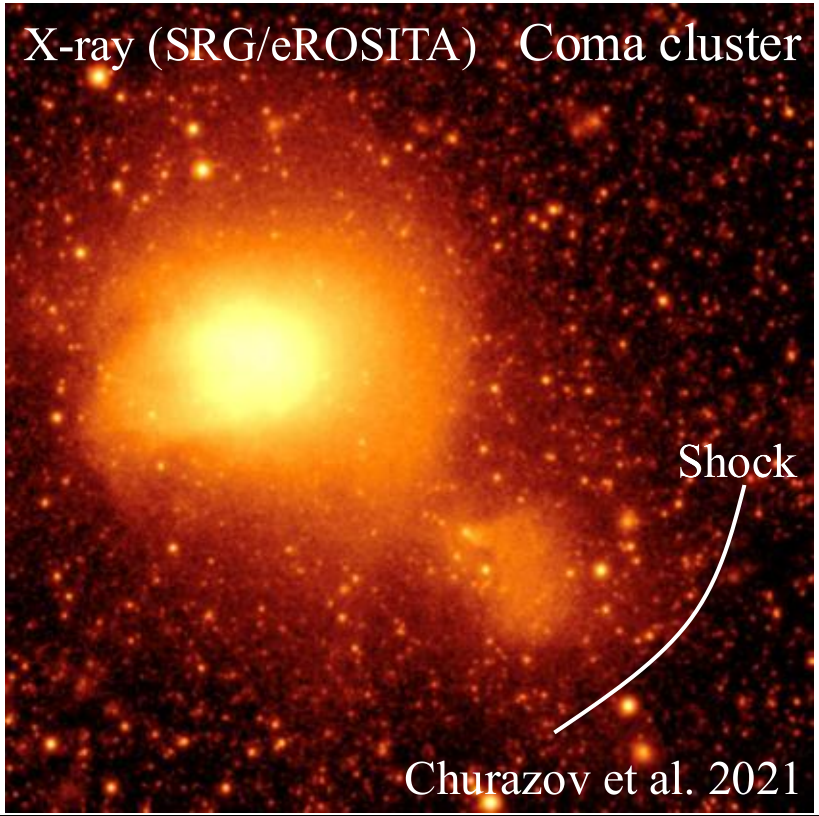
Observational probes of merging clusters

X-ray

Thermal component

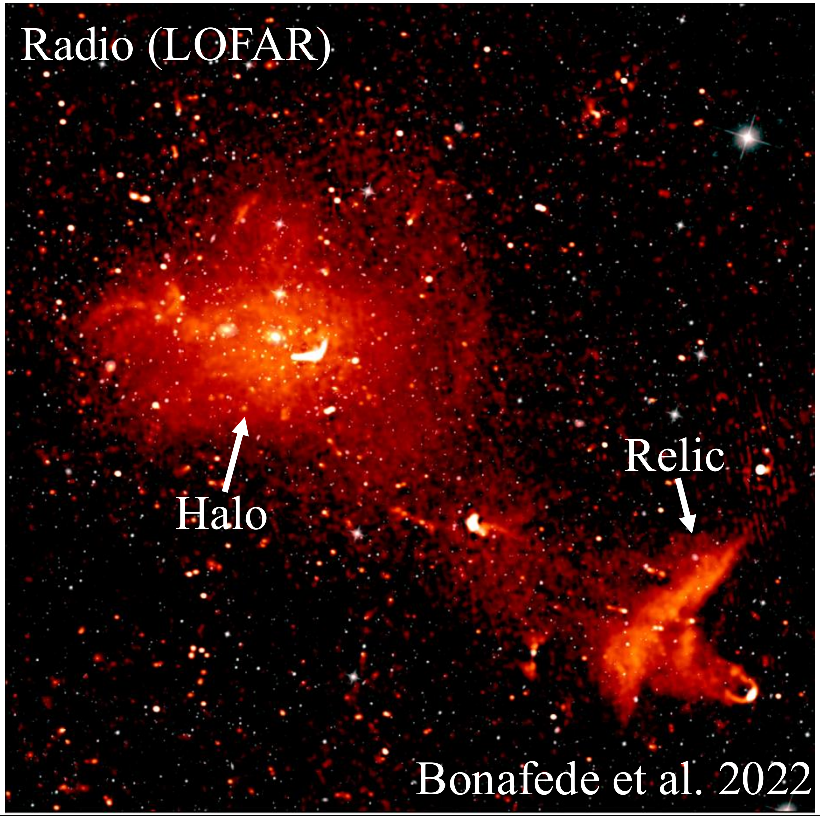
- Temperature structures
- Shocks, stripped gas, etc.



Radio

Relativistic electrons + B fields

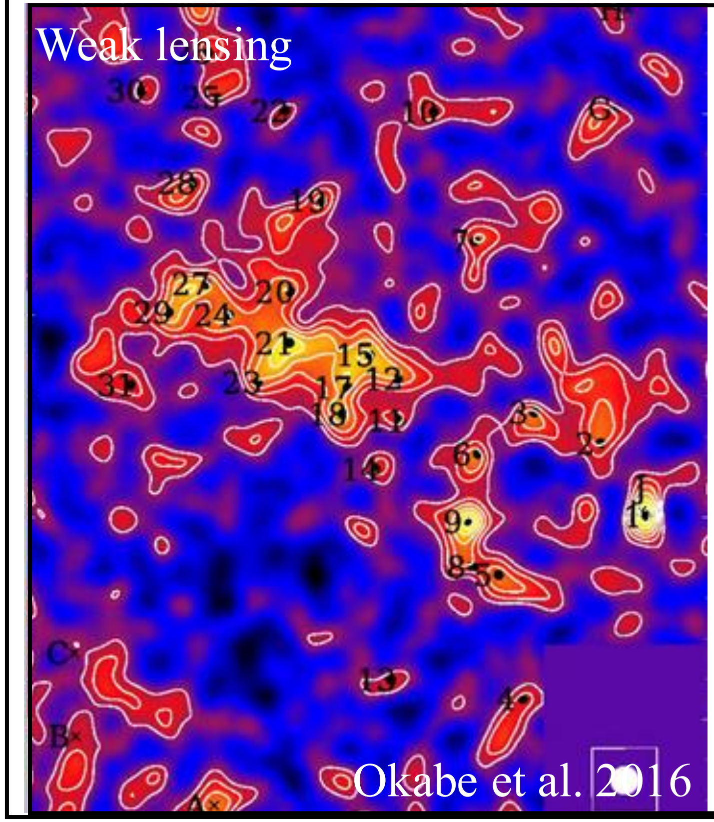
- Relics: merger shocks
- Halos: turbulent re-acceleration



Weak lensing

Dark matter distribution

- Mass peaks and substructures
- Merger geometry



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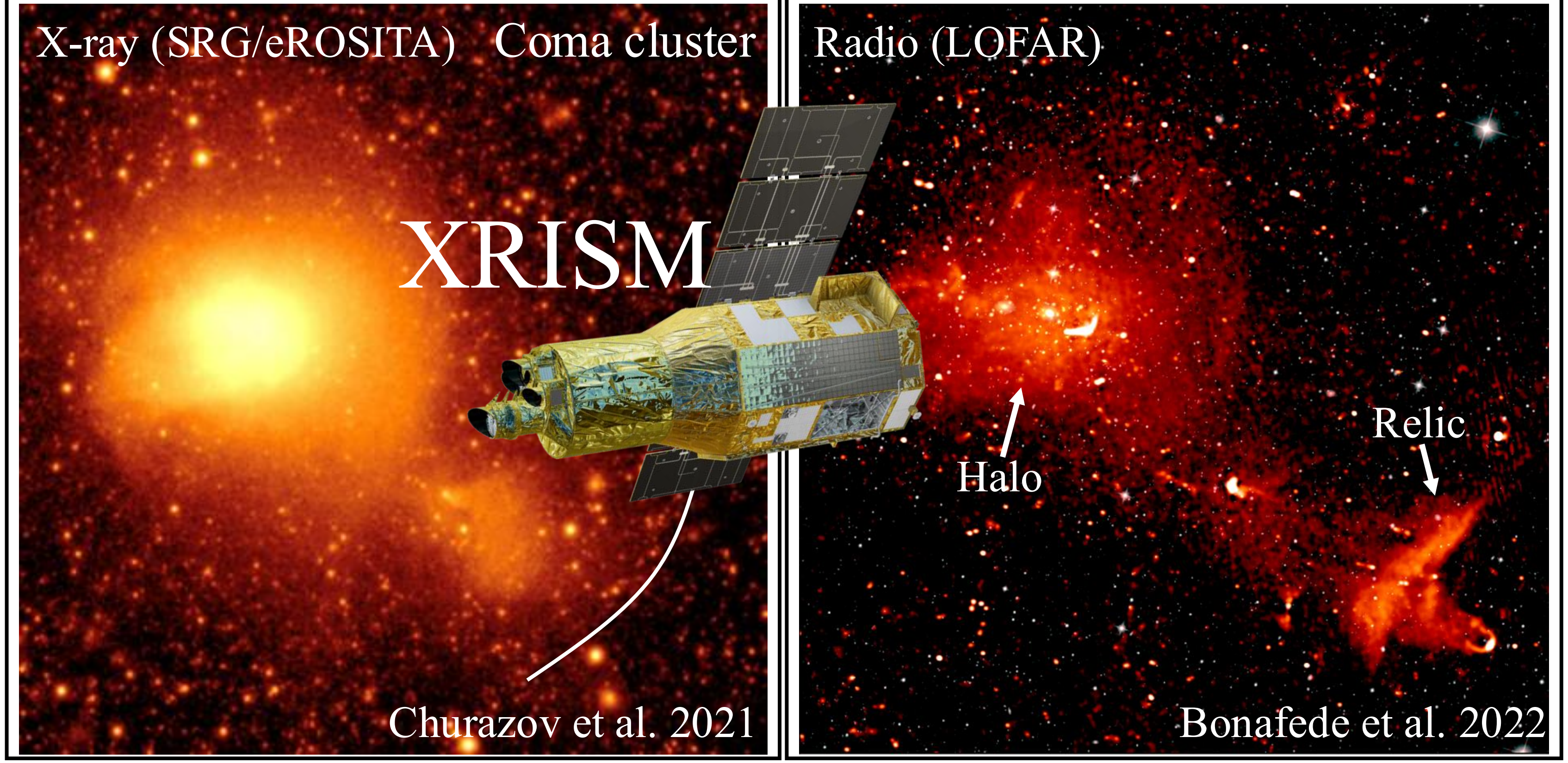

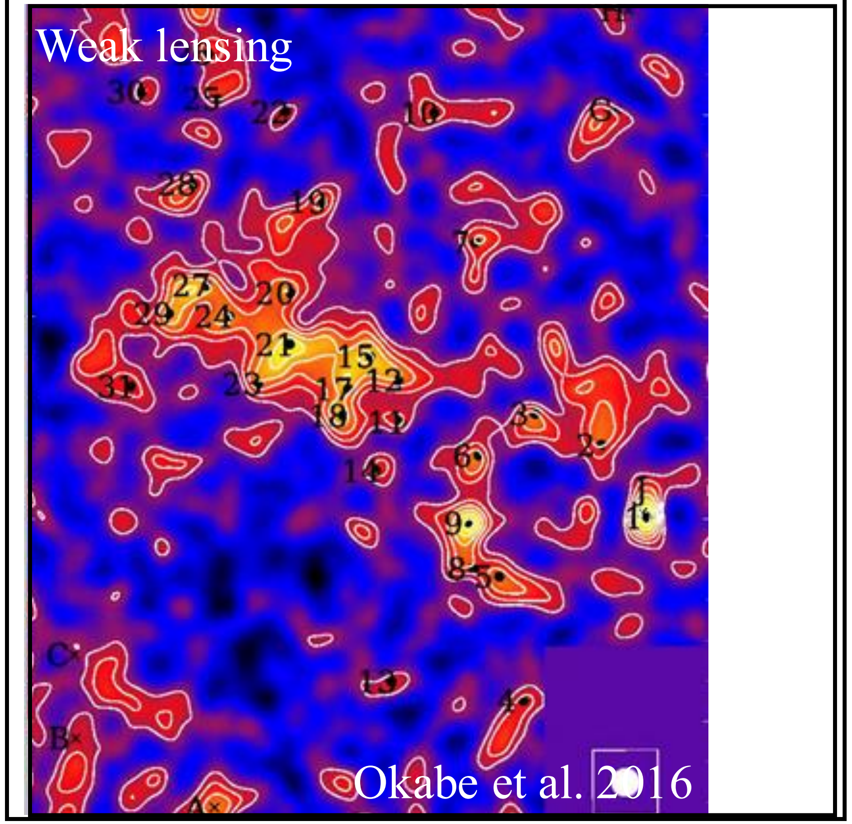

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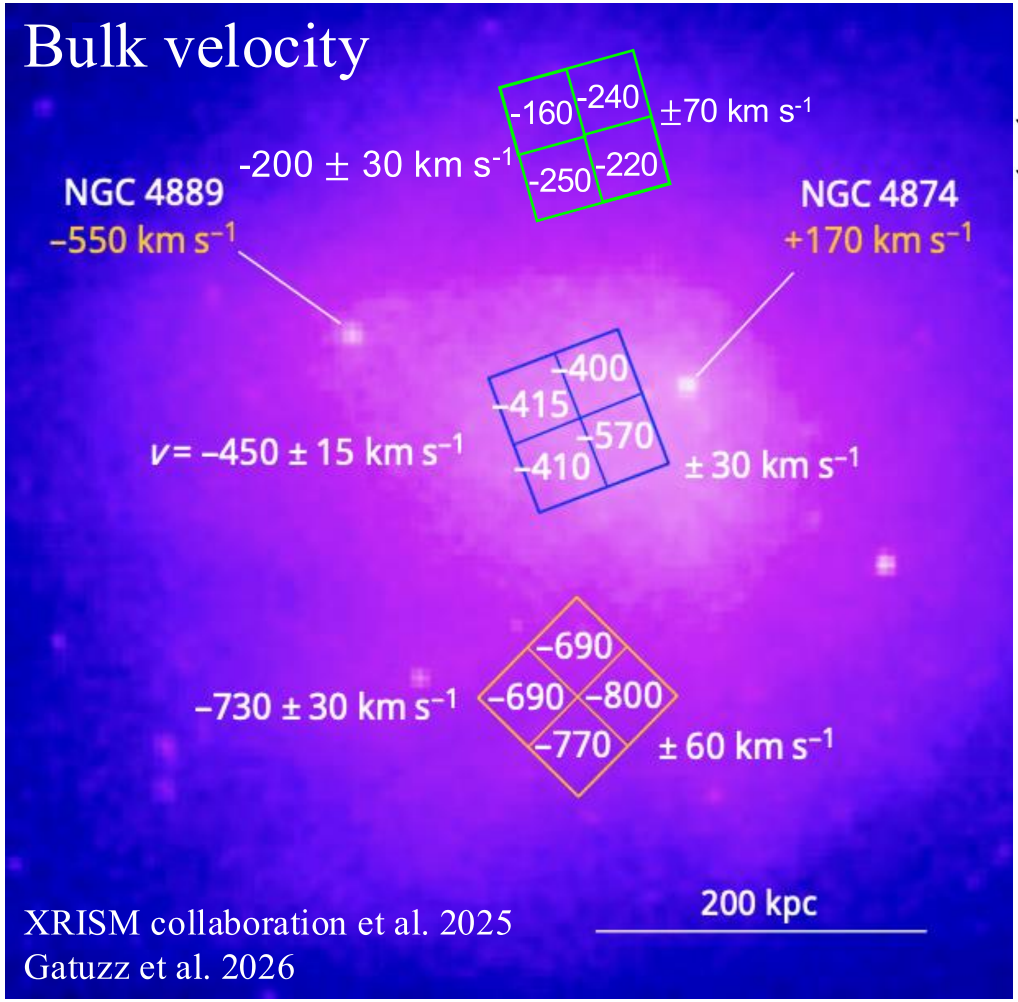
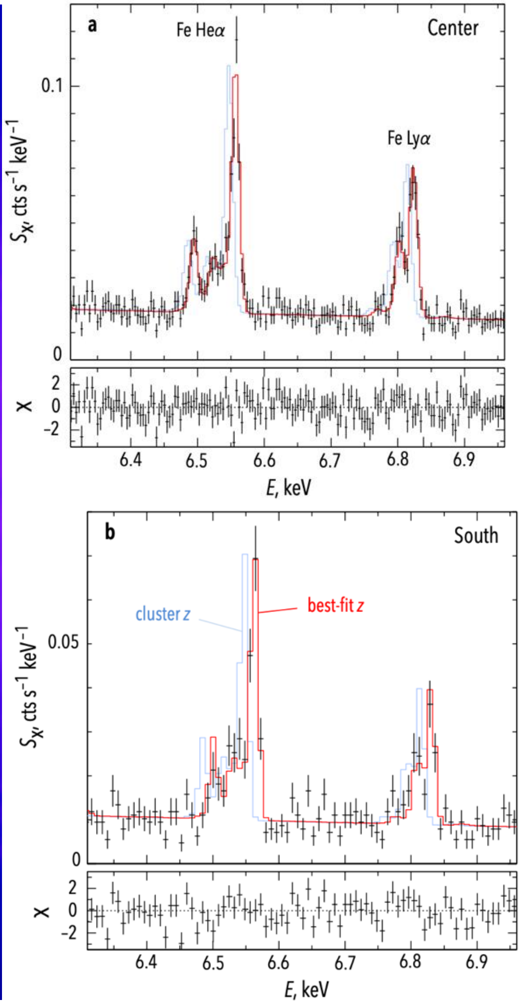
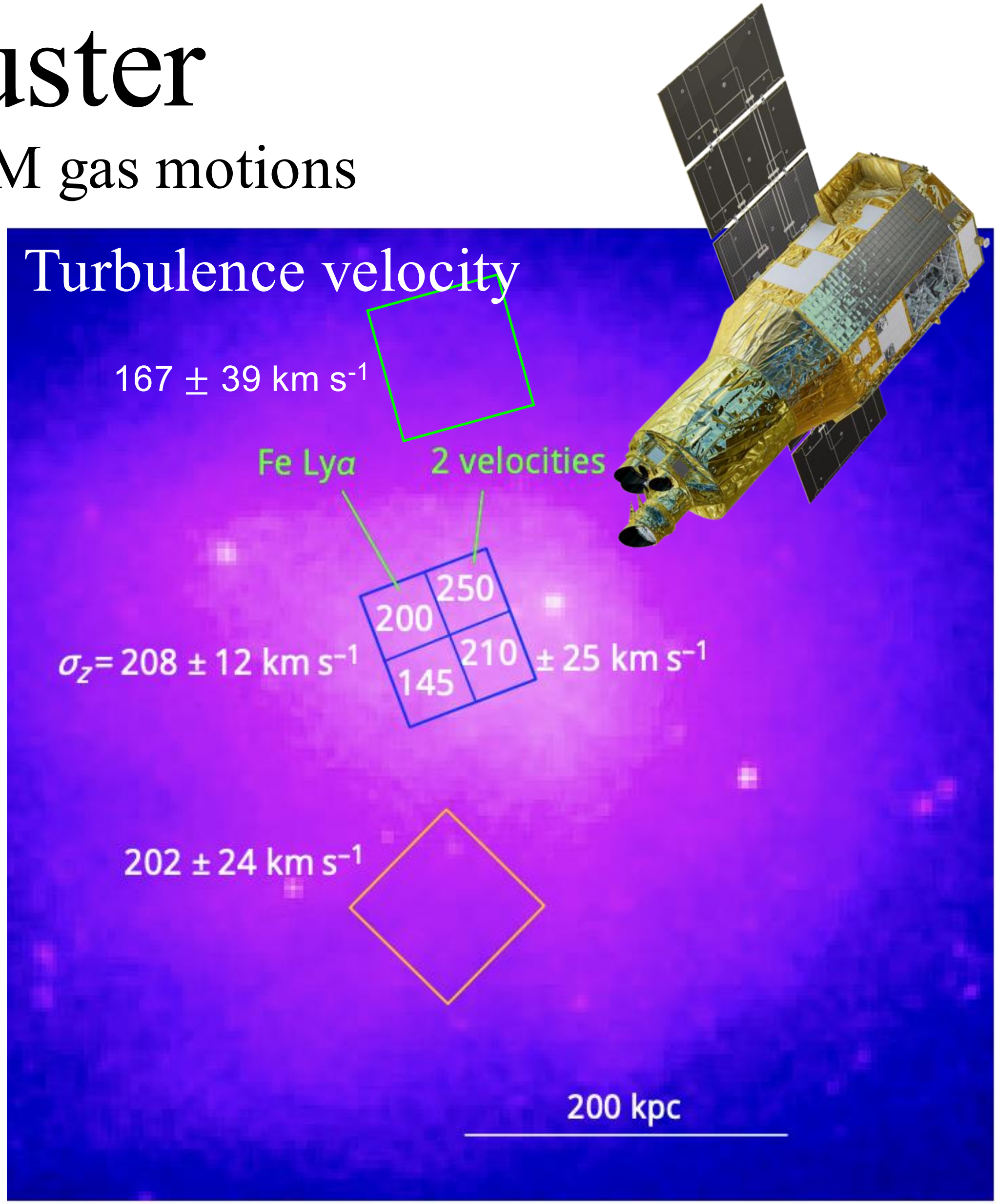
XRISM view of the Coma cluster

$\Delta E \sim 4.5$ eV over a ~3′ FoV, enabling measurements of ICM gas motions







Large-scale bulk motions (500-600 km s^{-1}) are clearly detected across Coma, while small-scale turbulence remains modest (about 200 km s^{-1}).

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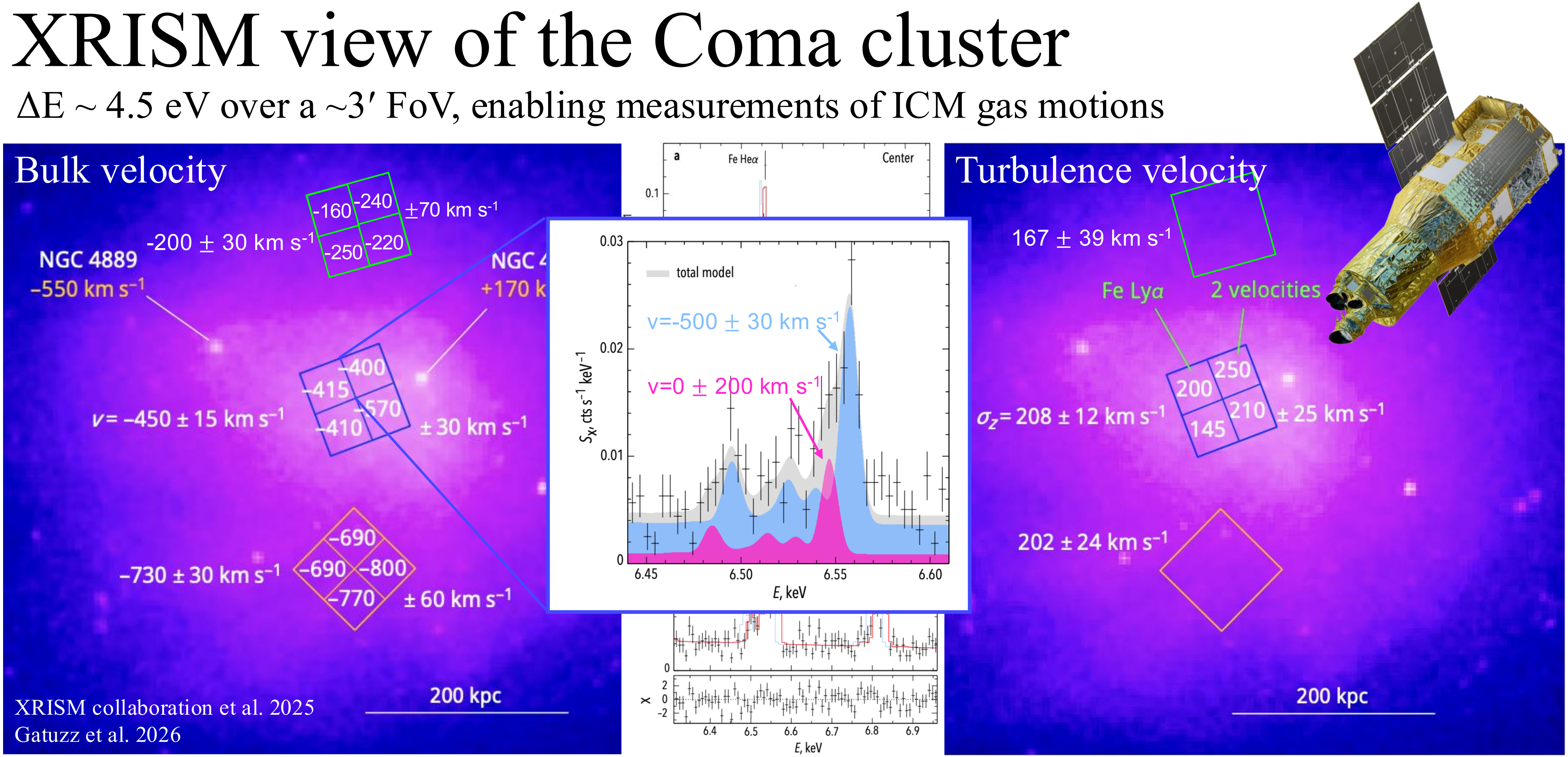

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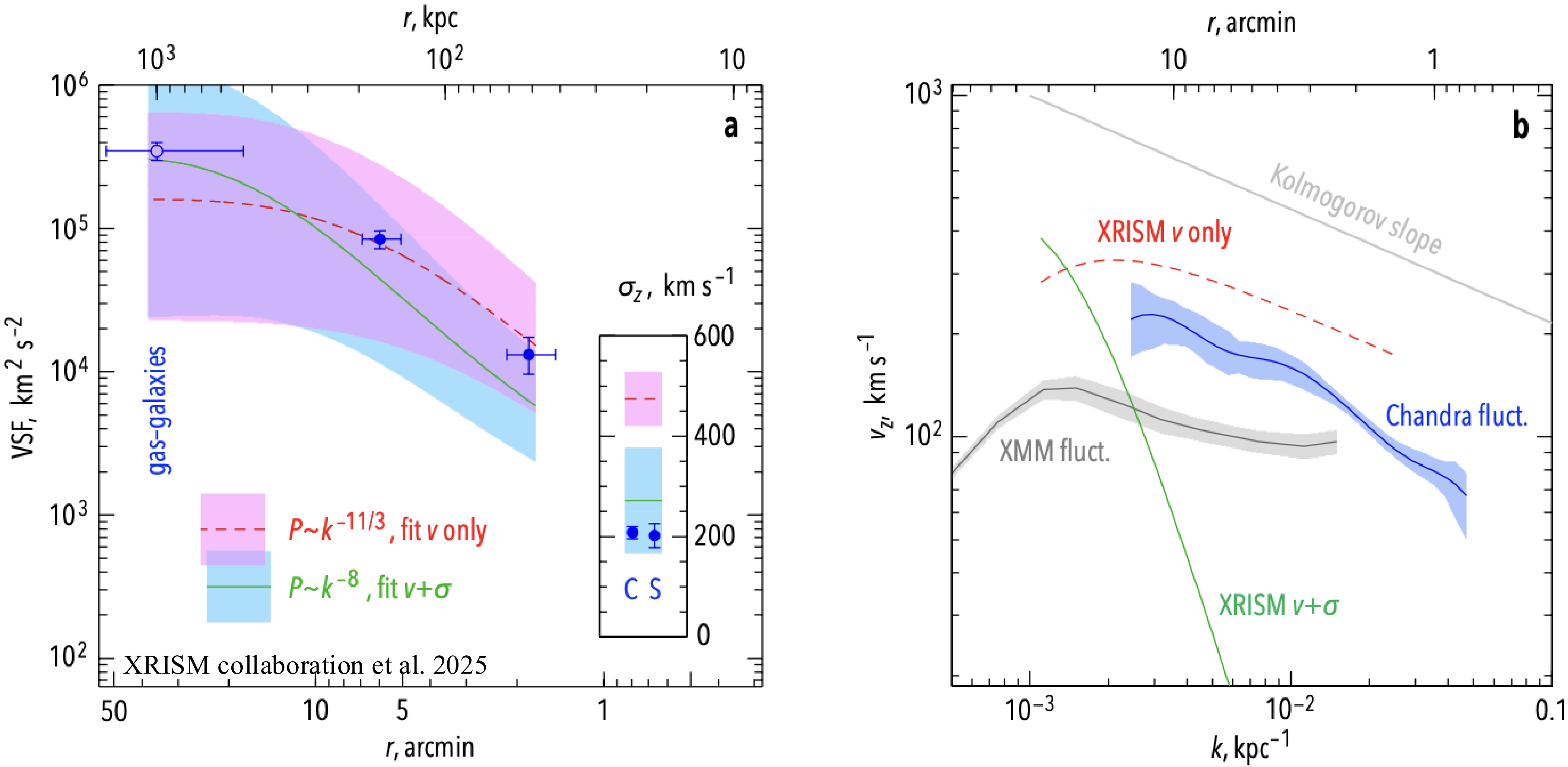
ICM velocity power spectrum in Coma cluster



- Current XRISM data favor a steep velocity power spectrum.
- Coma is in an ongoing/recent merger stage?, with kinetic energy still dominated by large-scale gas motions.

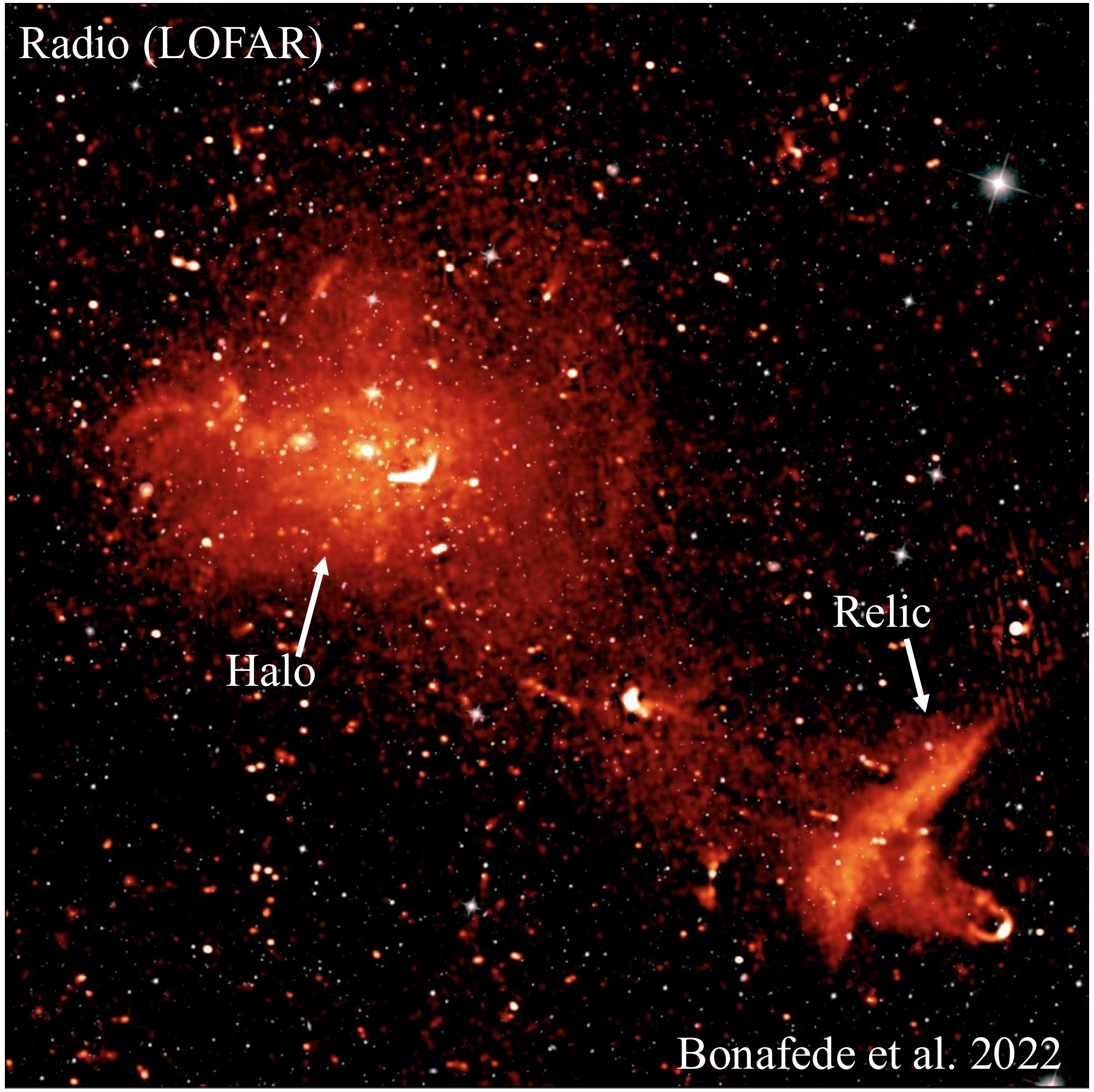
Non-thermal energy budget in the Coma ICM

Sakai and Nakazawa et al. submitted

Region	Center		South
component	1st	2nd	1st
$u_{\rm B}$ [eV cm^{-3}]	~ 0.55		~ 0.42
$u_{{\rm CR}e}$ [eV cm^{-3}] [1]	$\sim 7.0 \times 10^{-4}$		$\sim 5.9 \times 10^{-4}$
$u_{\rm th}$ [eV cm^{-3}]	82.9 ± 1.8		$55.9^{+1.9}_{-2.0}$
$u_{\rm turb.3D}$ [eV cm^{-3}]	$1.9^{+0.6}_{-0.7}$		$2.2^{+0.5}_{-0.4}$
$u^{\rm ave}_{\rm bulk.1D}$ [eV cm^{-3}][2]	$4.1^{+0.4}_{-0.6}$	$0.00^{+0.10}_{-0.00}$	$8.5^{+0.5}_{-0.5}$
$u^{\rm ICM}_{\rm bulk.1D}$ [eV cm^{-3}][3]	0	$0.6^{+0.6}_{-0.4}$	$1.1^{+0.3}_{-0.4}$

- Cooling time at 144 MHz in 5μG B →0.25 Gyr
- Turbulence dissipation rate
  $Q_{\rm terb} \sim 5\rho v_{\rm turb.1D}/l_t$ (Zhuravleva et al. 2014)
  l_t: length scale at which velocity is measured
  $\rightarrow \tau = v_{turb.3D}/Q_{turb} \sim 0.14$ Gyr ($l_t = 3' \sim 84$ kpc)
  If $l_t = 500$ kpc, $\tau = 1.0$ Gyr

Turbulence decays comparable to radio-electron cooling. Continuous energy supply from large-scale bulk motions is needed to sustain the radio halo.



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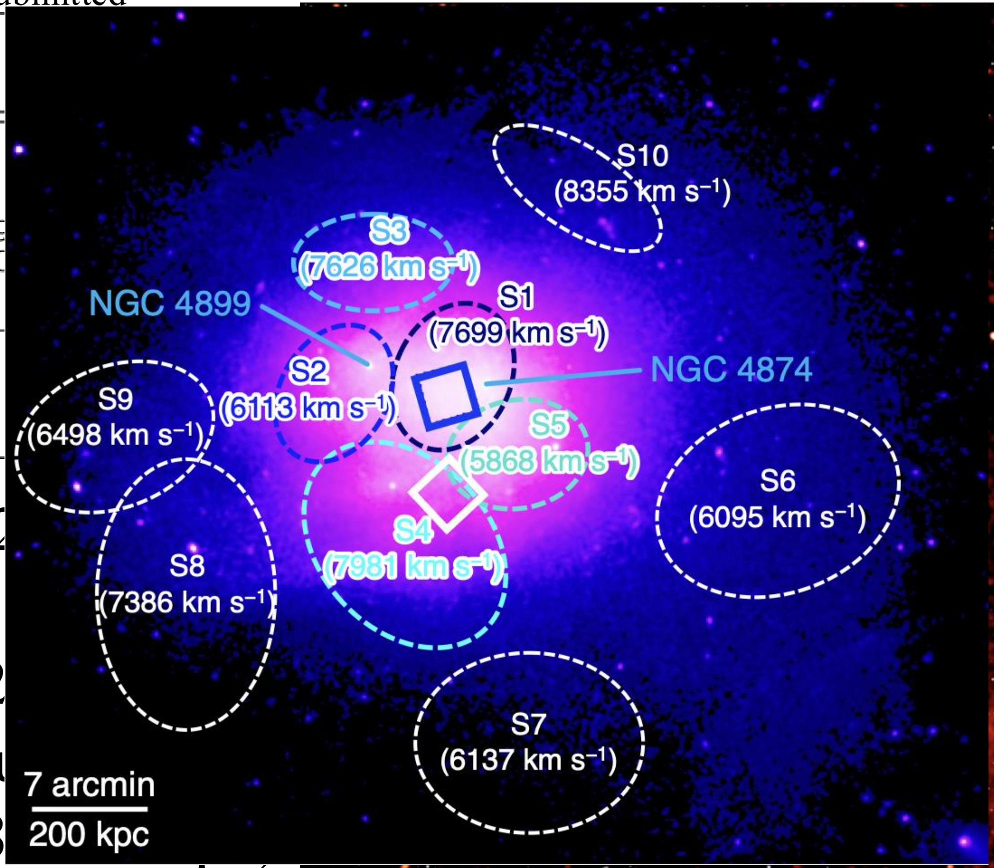
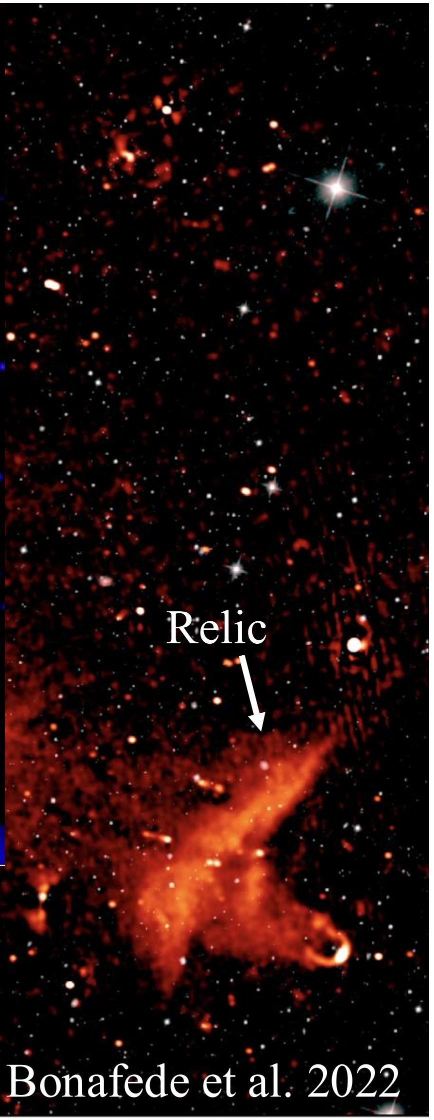


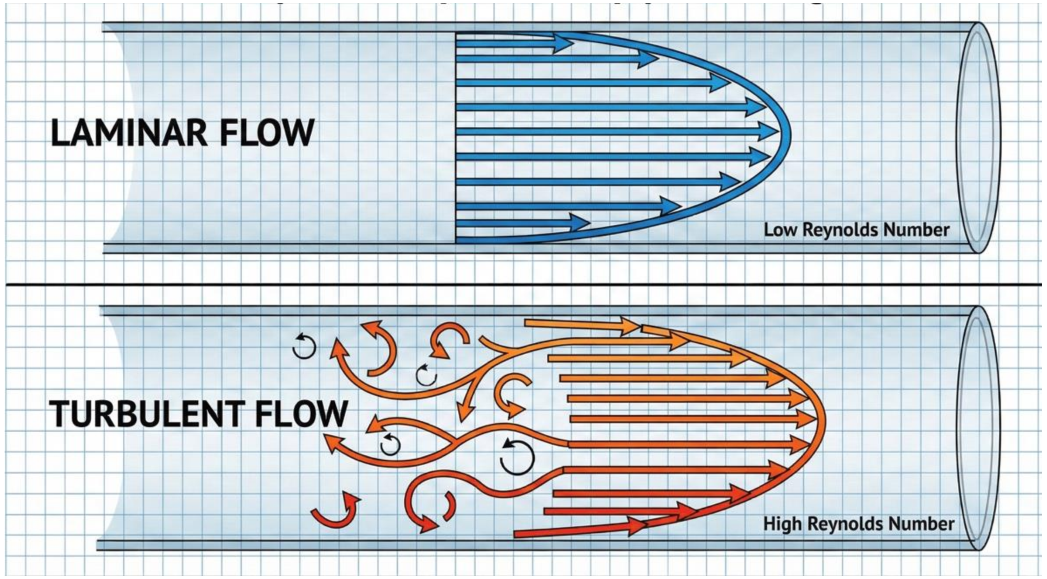


Bonafede et al. 2022

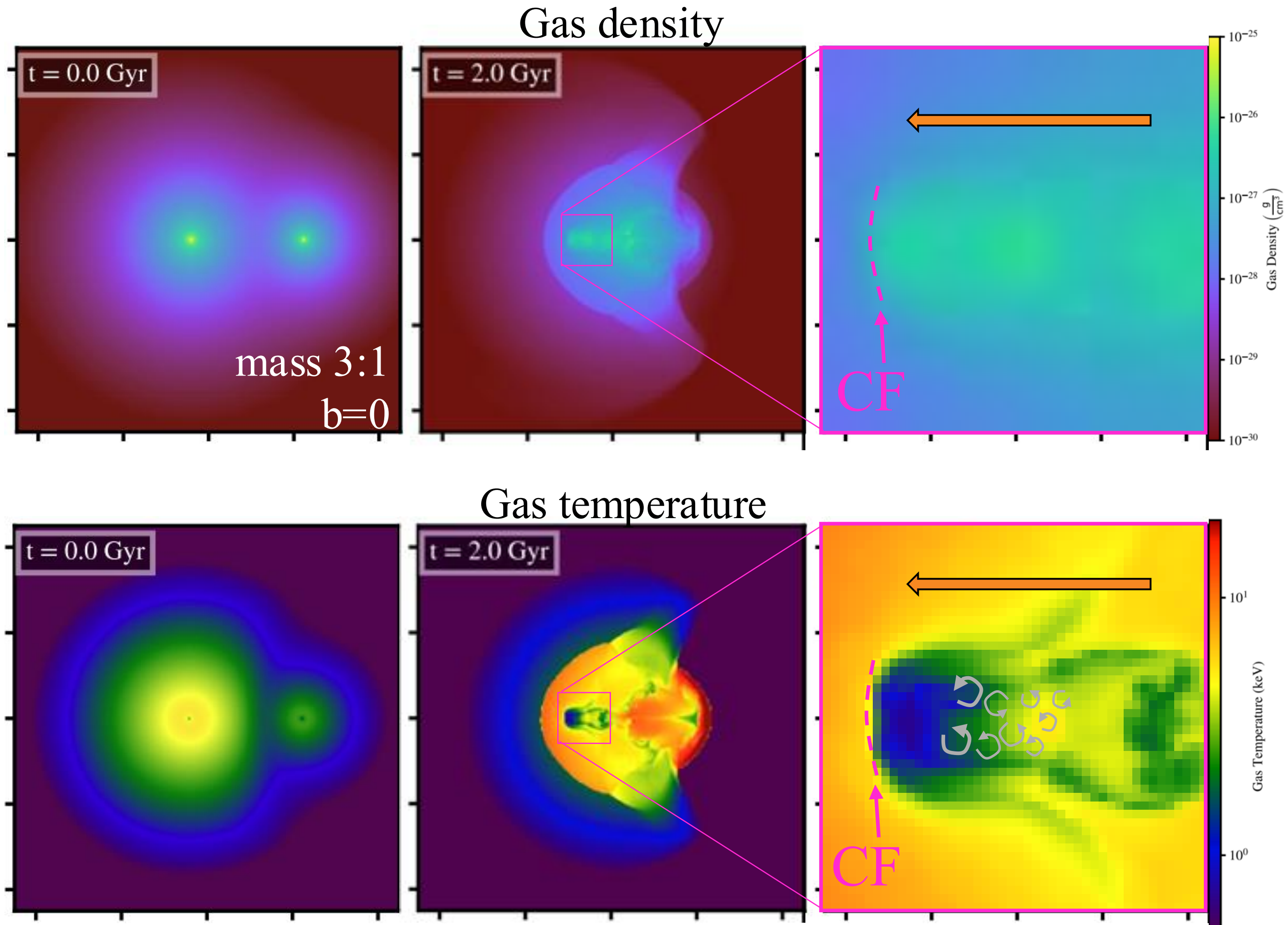
Coma: complex merger geometry
→ need dynamically clearer systems

Moving cores as laboratories for ICM turbulence

Moving body in a high-Re flow
→ wake, eddies, and turbulence



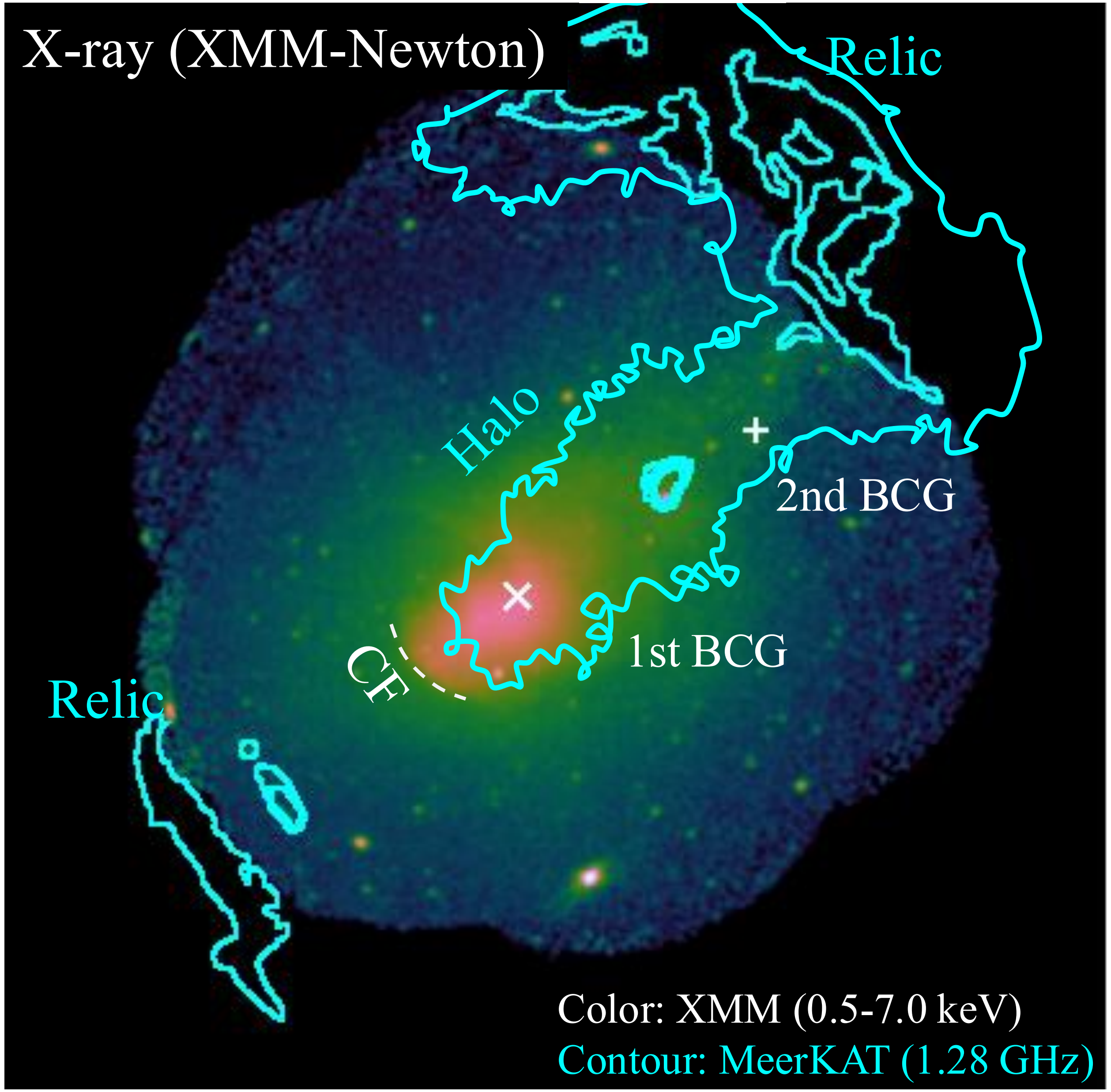
In merging clusters:
cool core moving through the ICM
→ Cold Fronts (CFs), wake, and turbulent gas motions

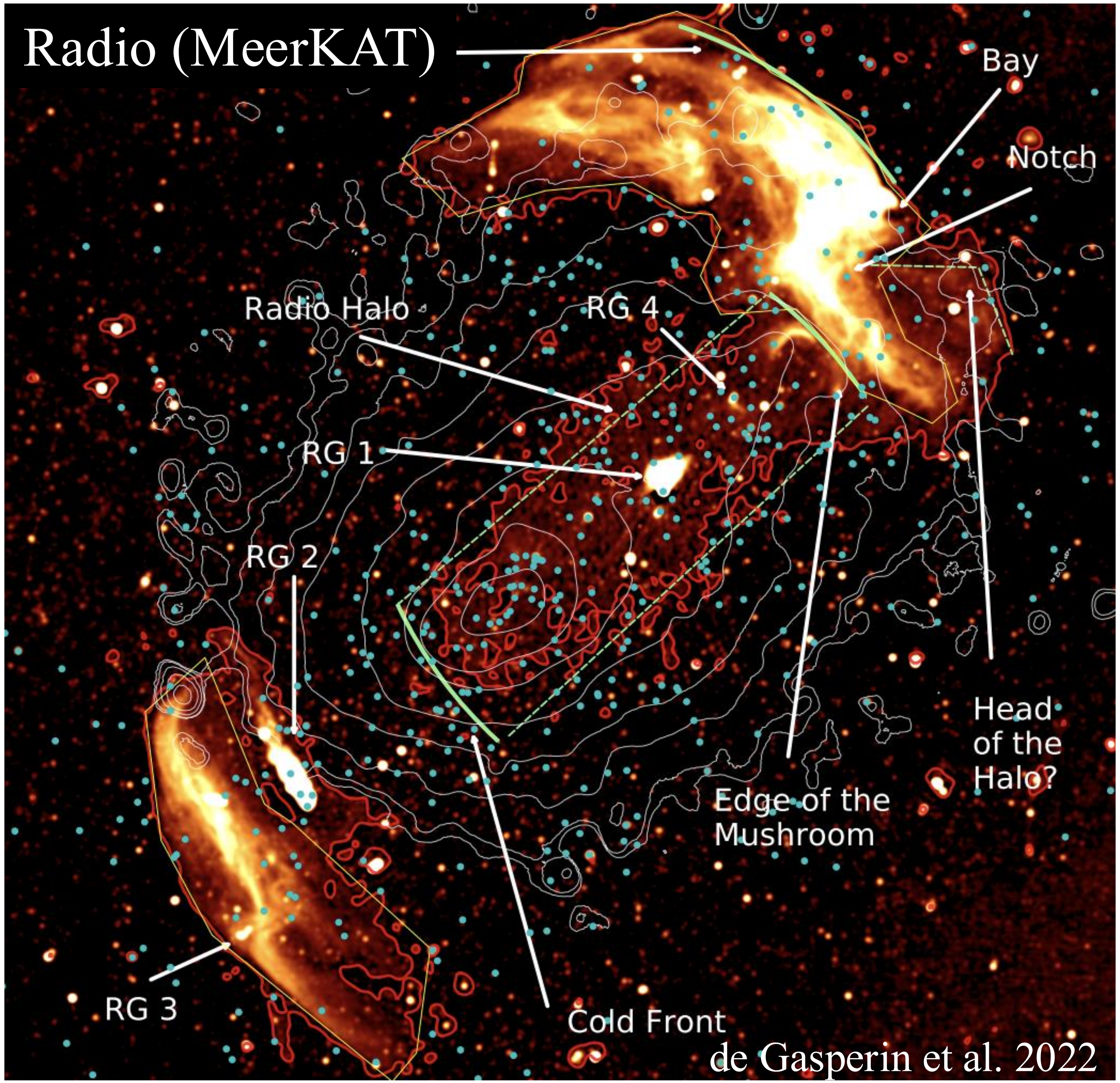


Brzycki et al. 2019

CFs (Moving cluster cores) provide a test case for tracing merger-driven gas motions → turbulence → particle acceleration

Prototypical cold-front cluster: Abell 3667





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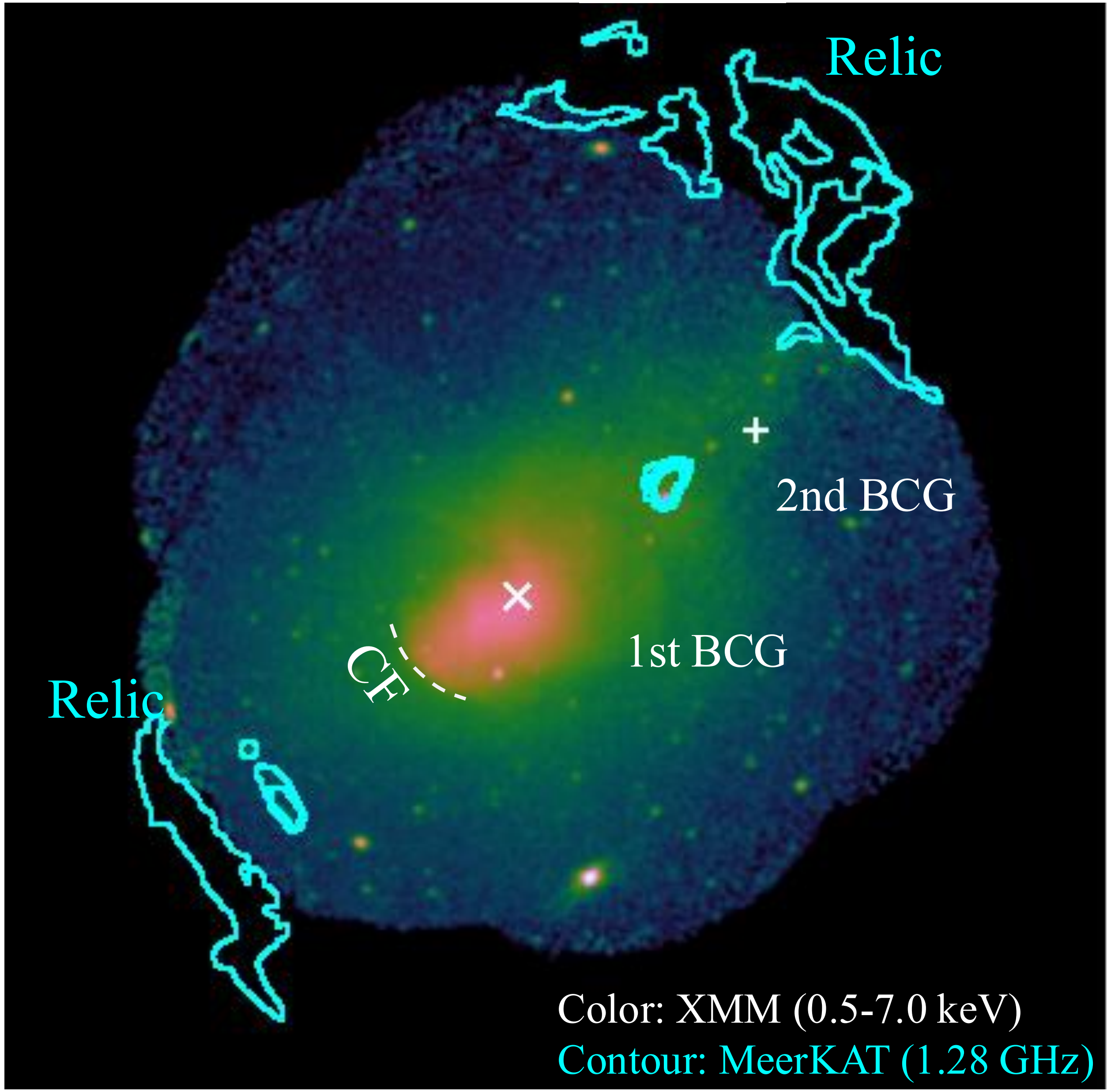

Abell 3667

- Binary merger system
  - SE/NW BCGs: z = 0.0556 / 0.0560
  - Radio-relic pair with X-ray shocks
- Brightness jump of ~1:5

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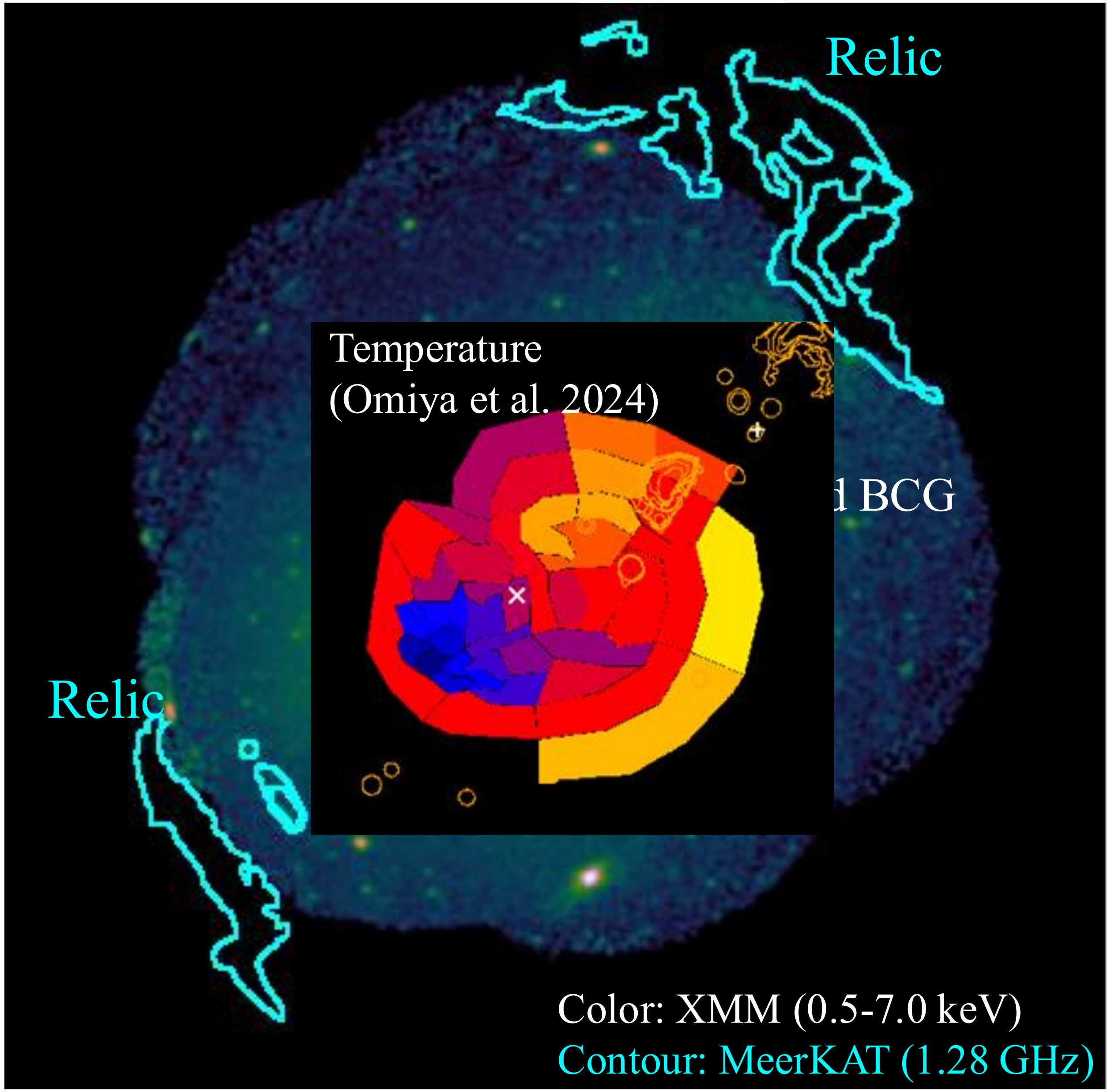

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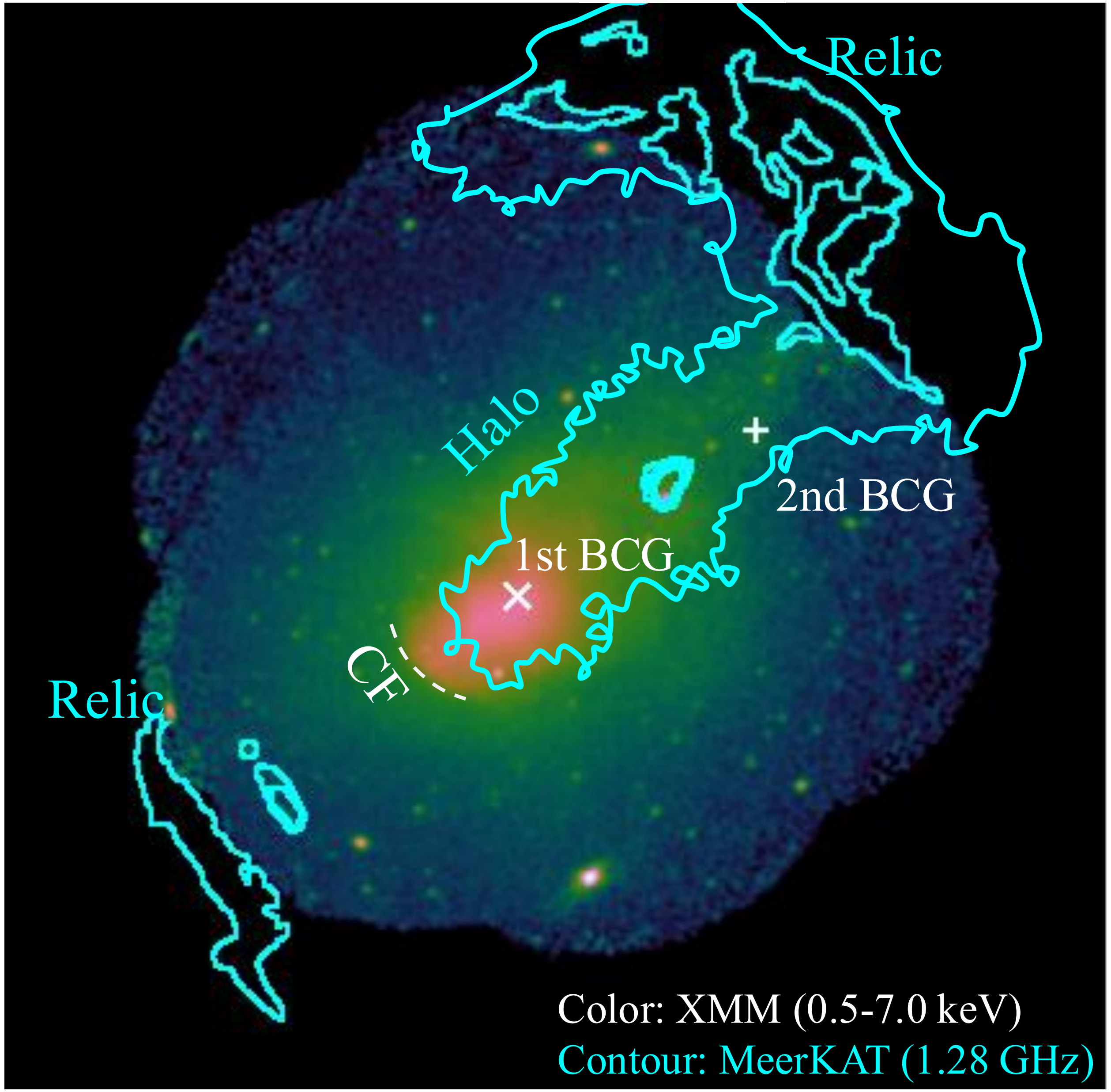

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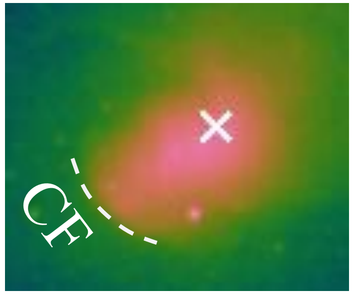

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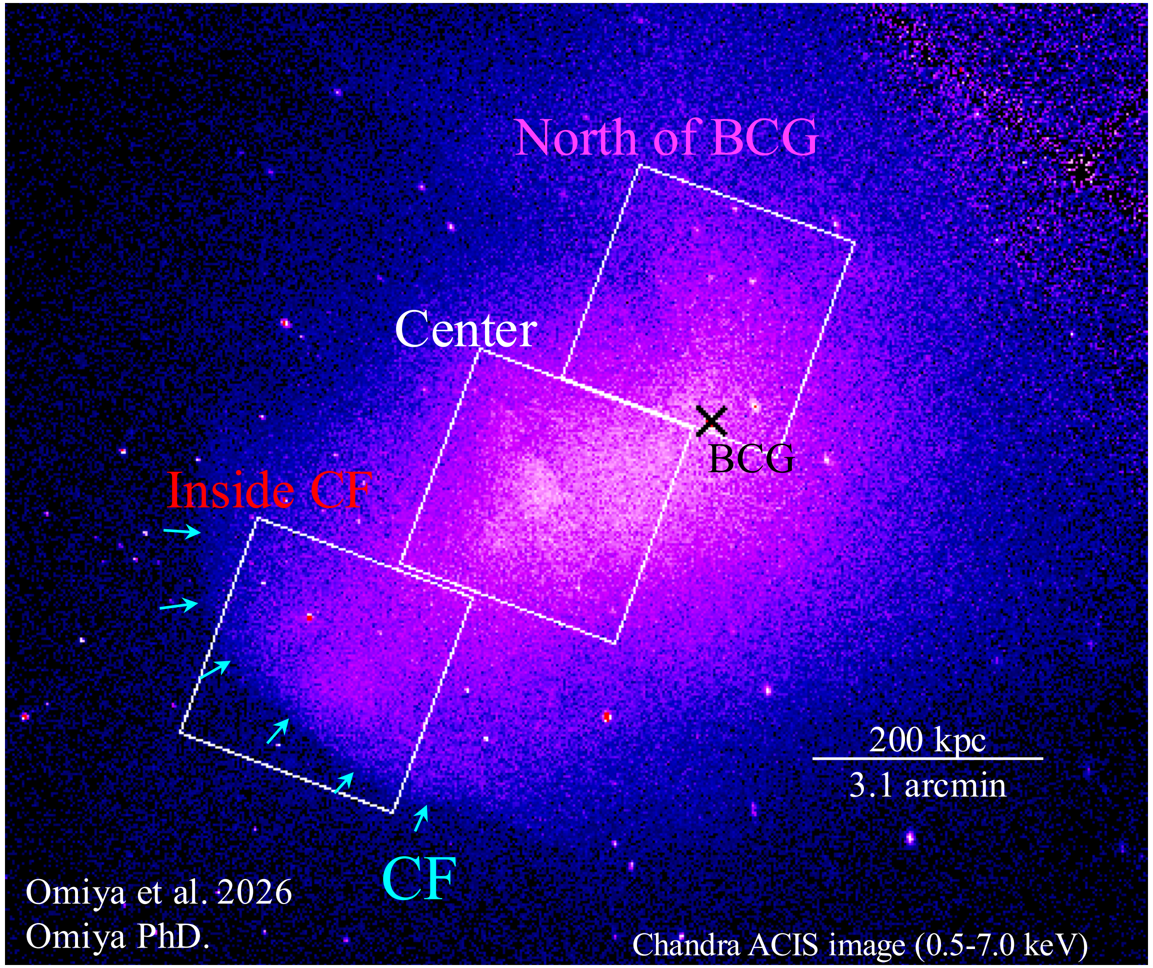
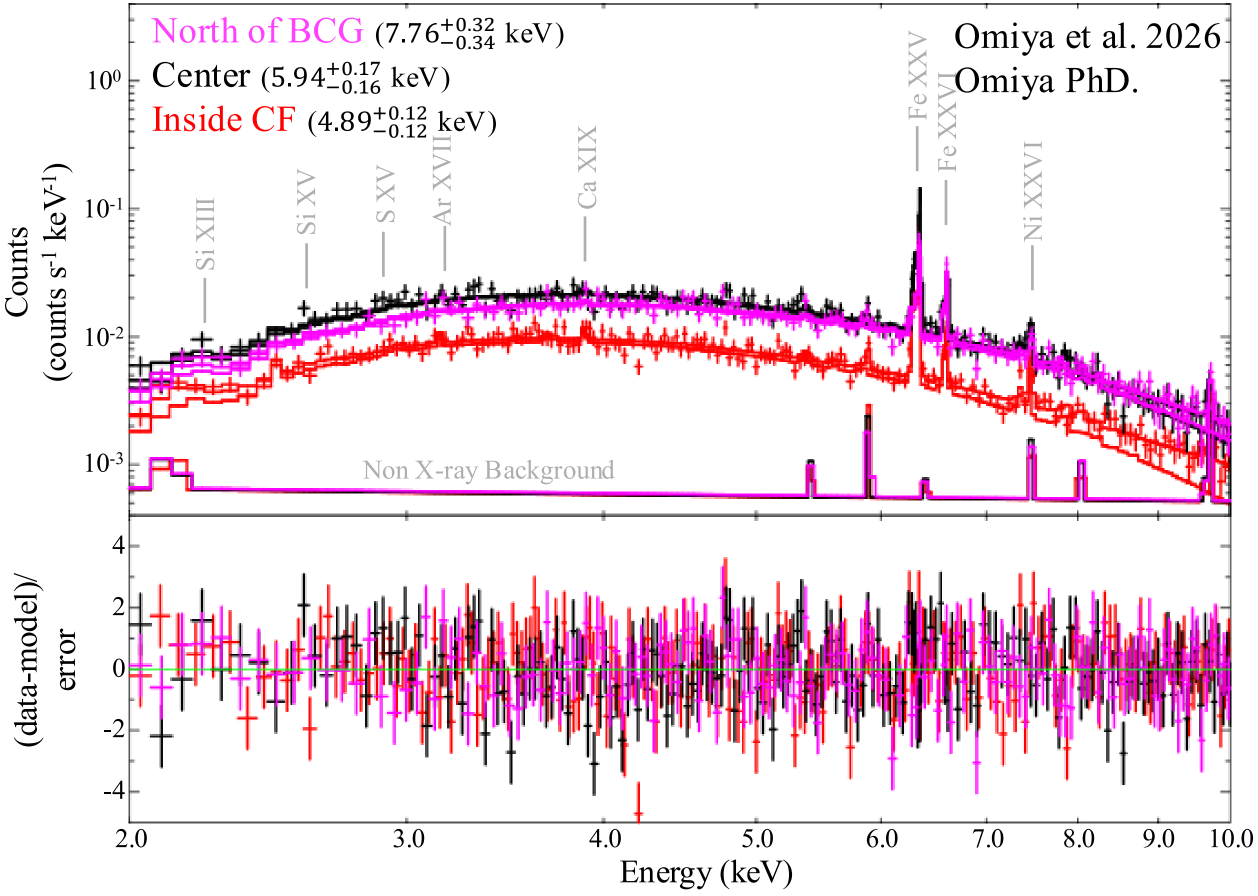
With XRISM:
- determine the merger geometry from ICM velocity fields
- trace turbulence development in the wake of the moving CF

XRISM view of Abell 3667

Pointing	Observation date	Exposure	PI
North of BCG	2025/10/14	98 ks	Y. Omiya
Center	2024/11/1	276 ks	Y. Ichinohe
Inside CF	2024/10/30	105 ks	Y. Ichinohe





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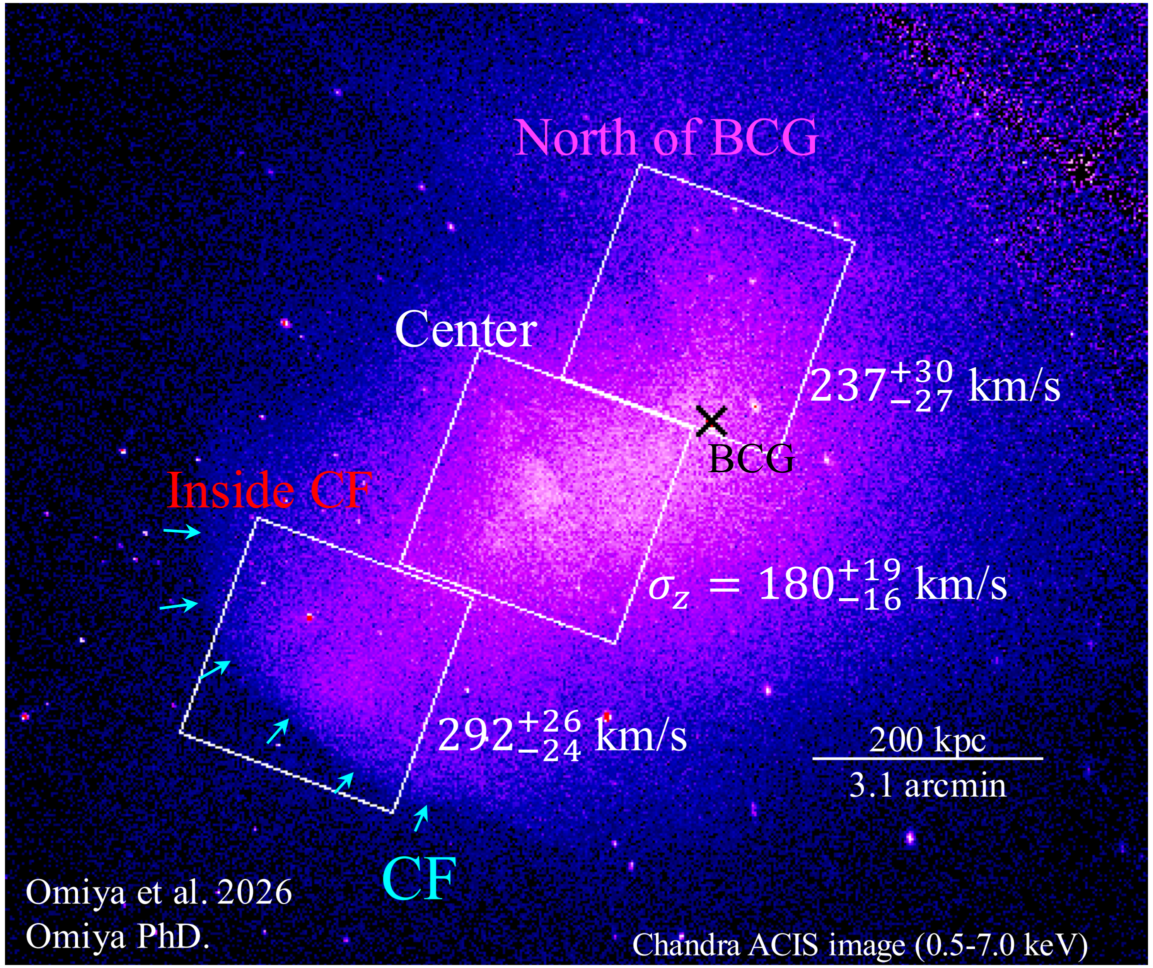

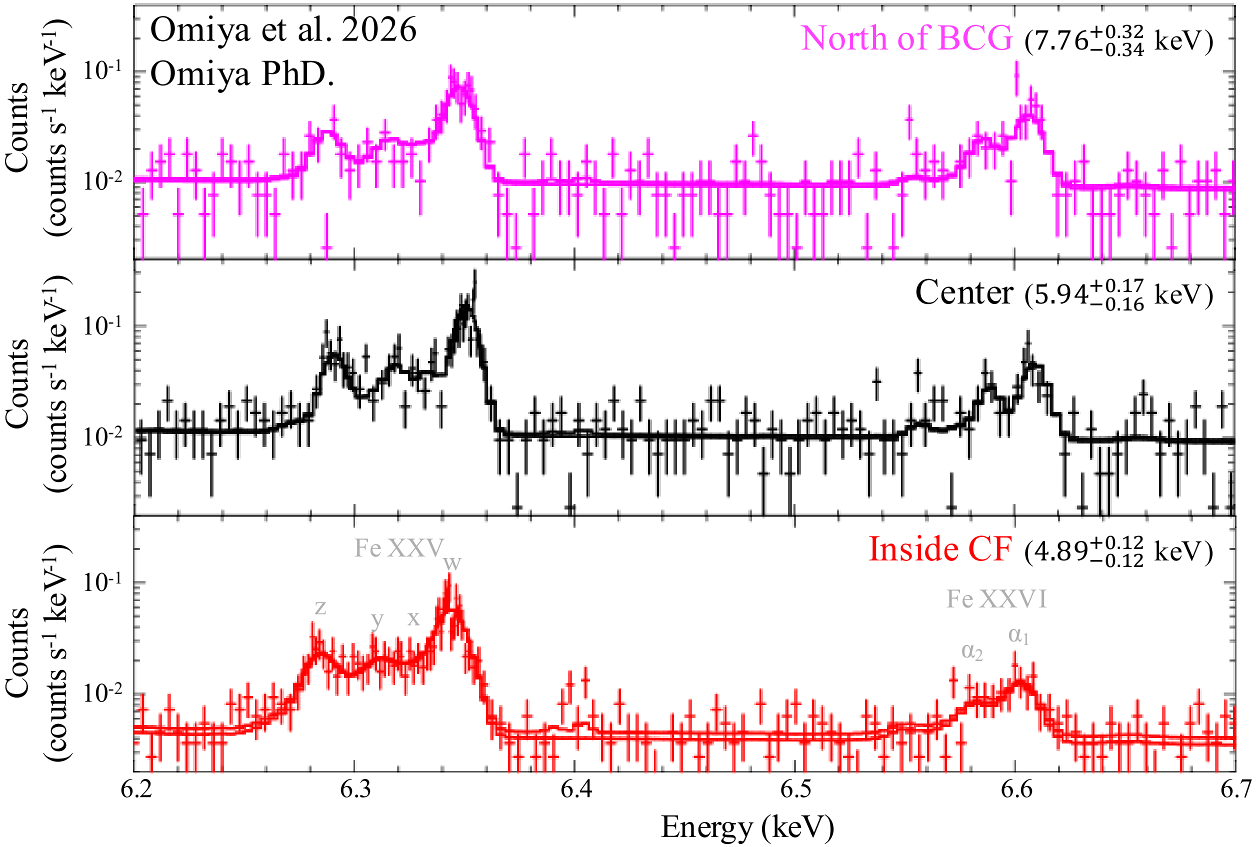

1σ c.l.	Inside CF	Center	North of BCG
Bulk velocity (km/s)	$+146^{+28}_{-25}$	-177^{+19}_{-17}	-62^{+33}_{-29}
Velocity dispersion (km/s)	292^{+26}_{-24}	180^{+19}_{-16}	237^{+30}_{-27}

※Bulk velocities are measured relative to the 1st BCG redshift (z = 0.05567).

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- Large-scale bulk motions of ~300 km s^{-1} within the cluster.
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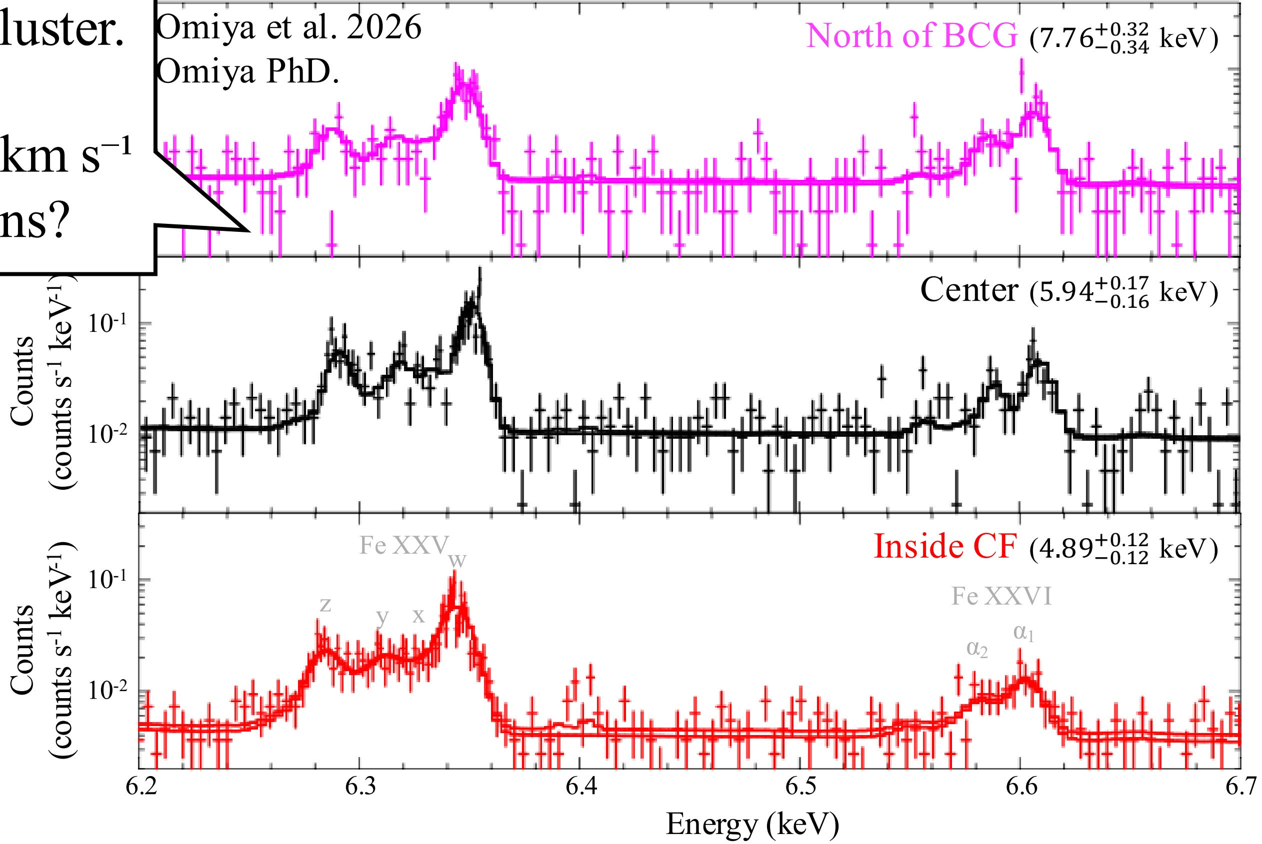
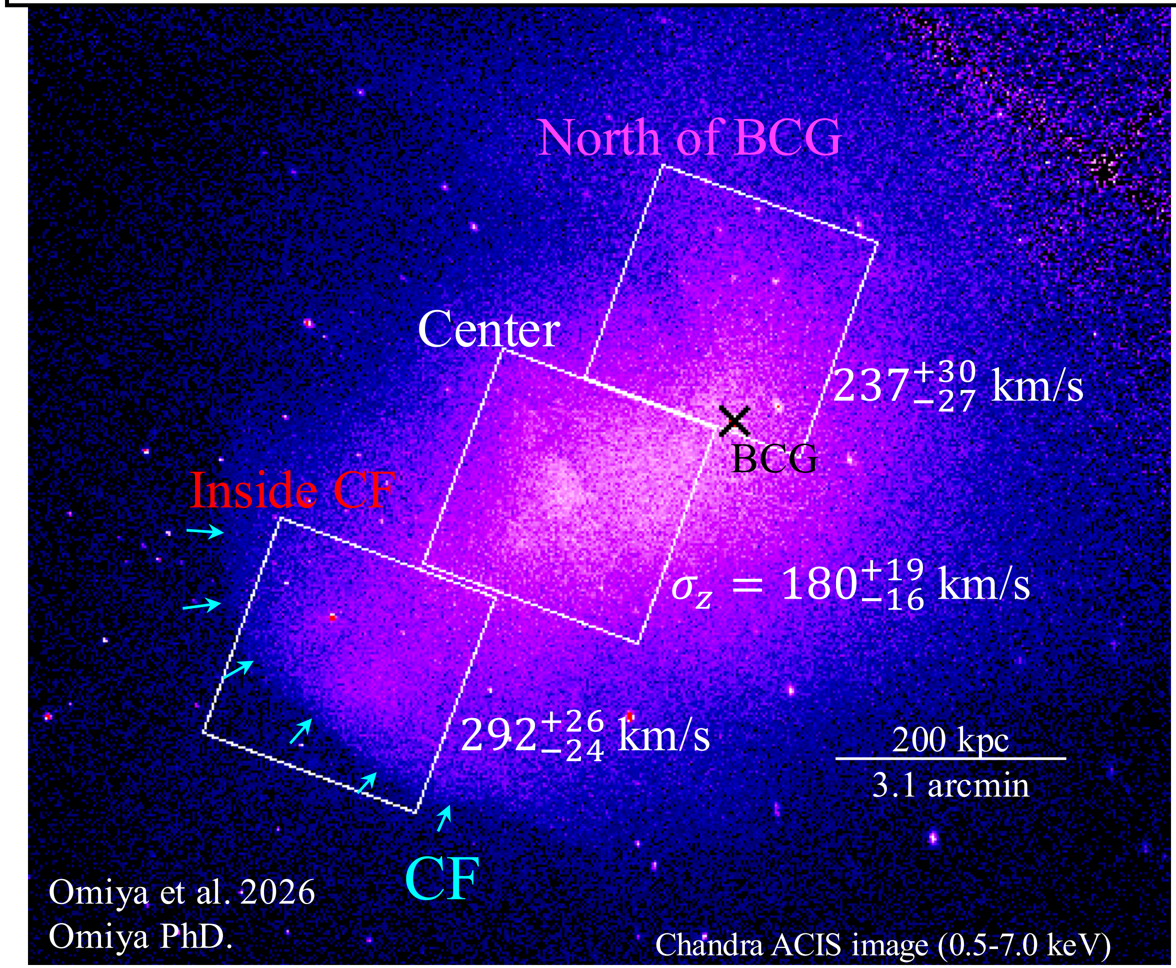
What is the velocity structure in physically defined regions?





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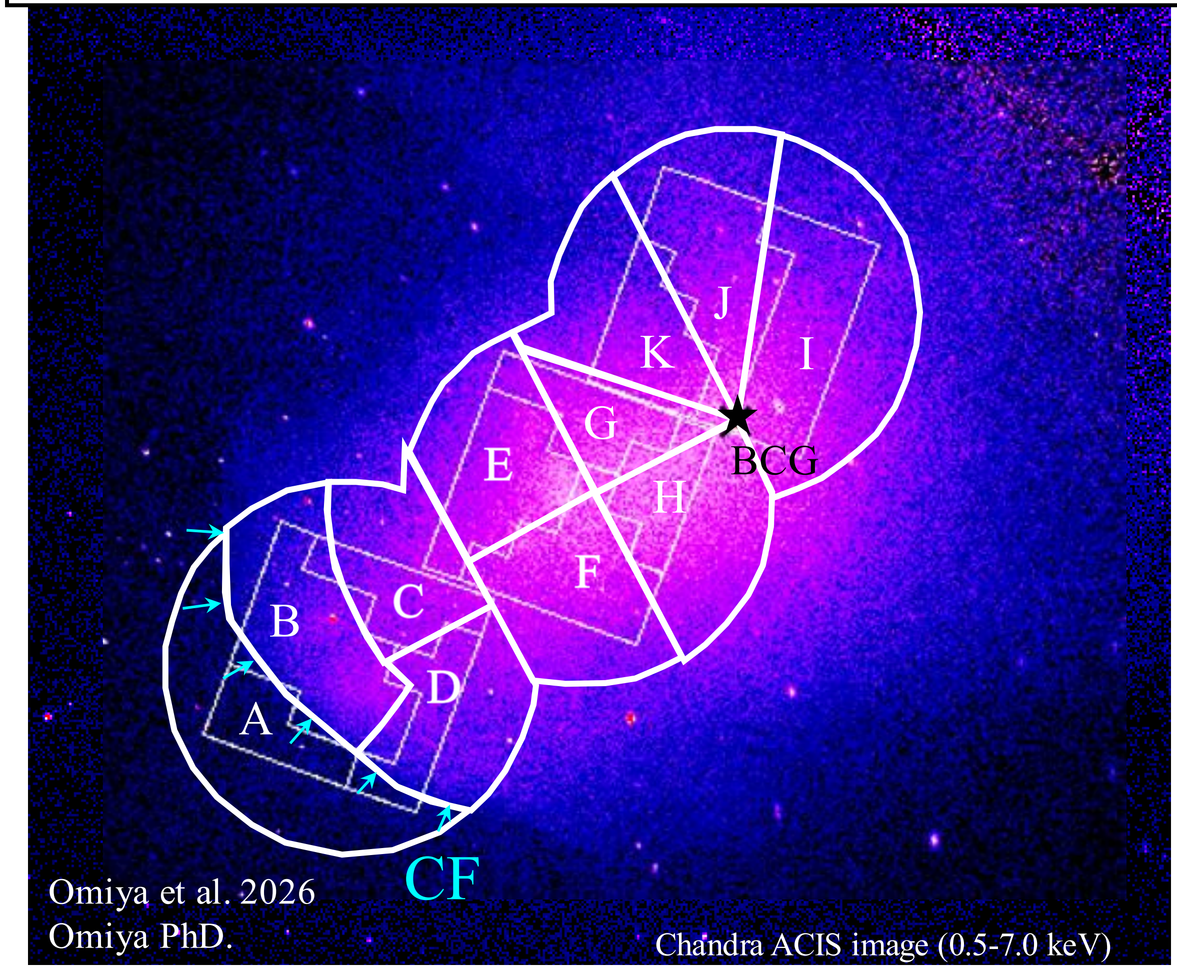

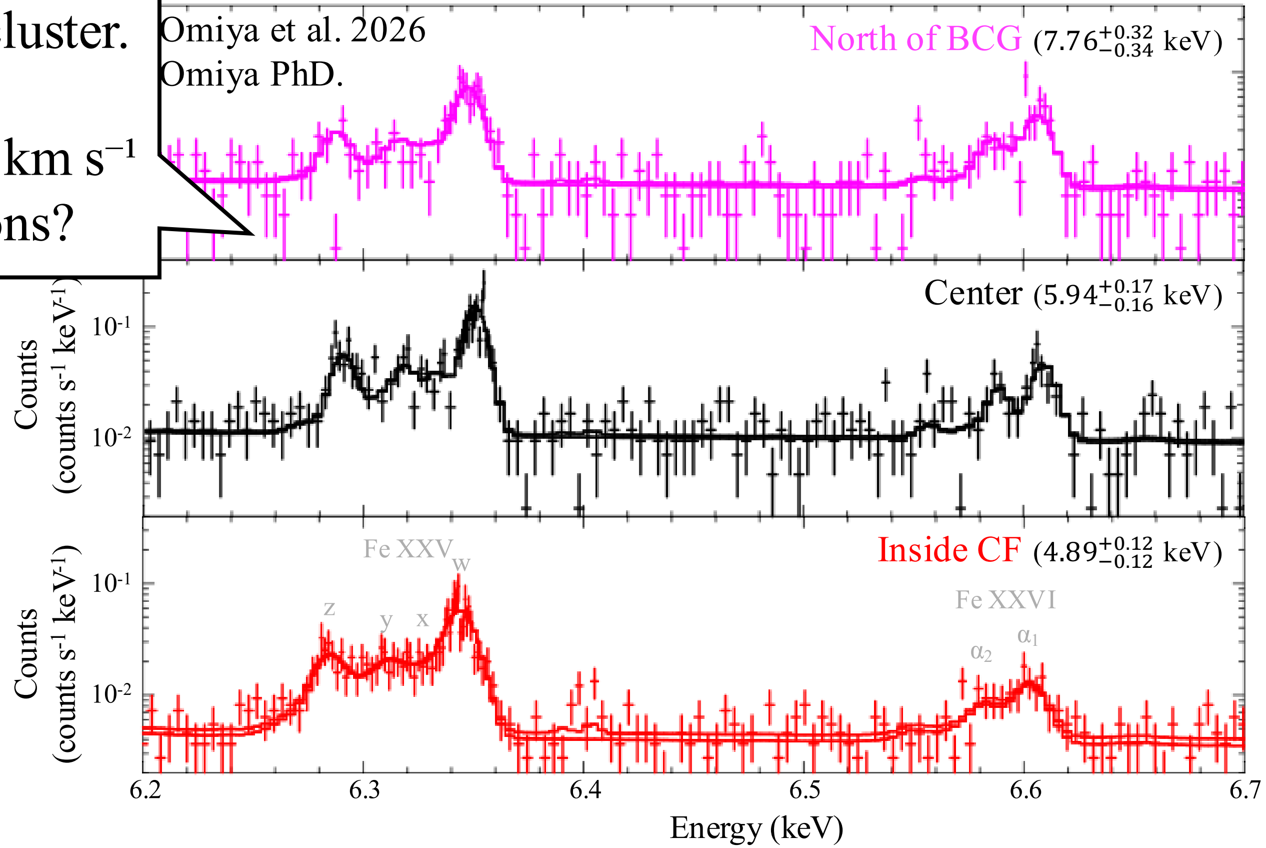

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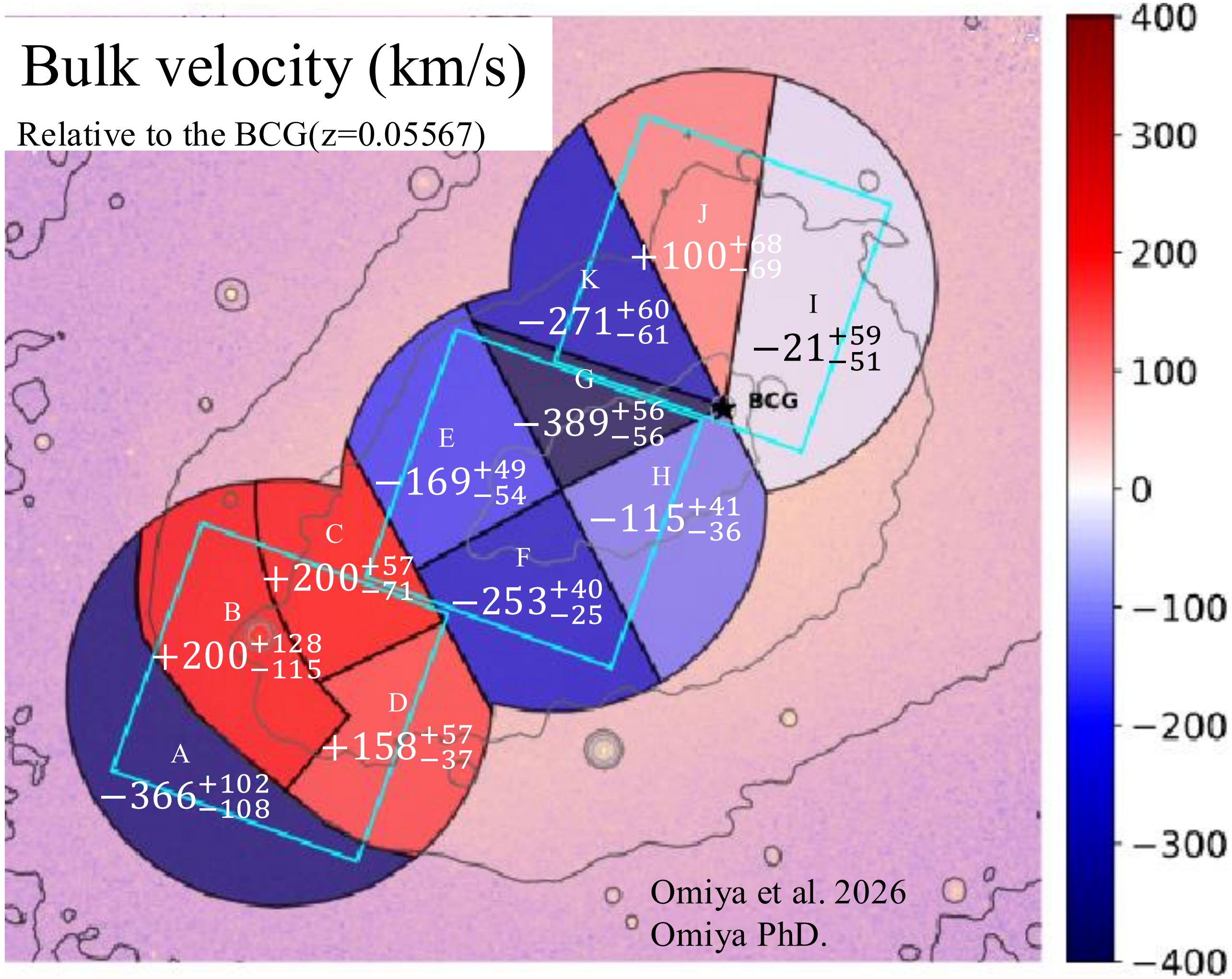

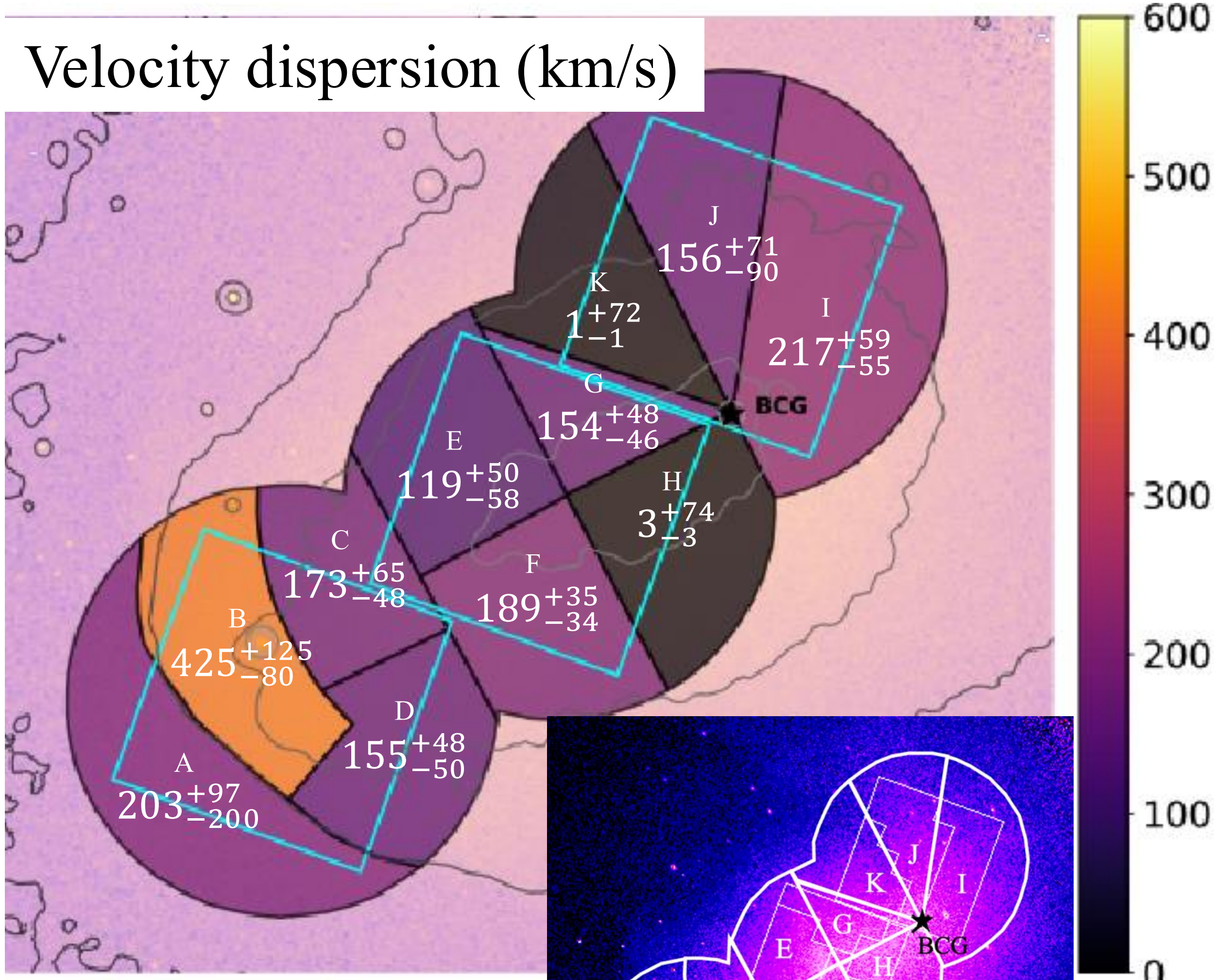

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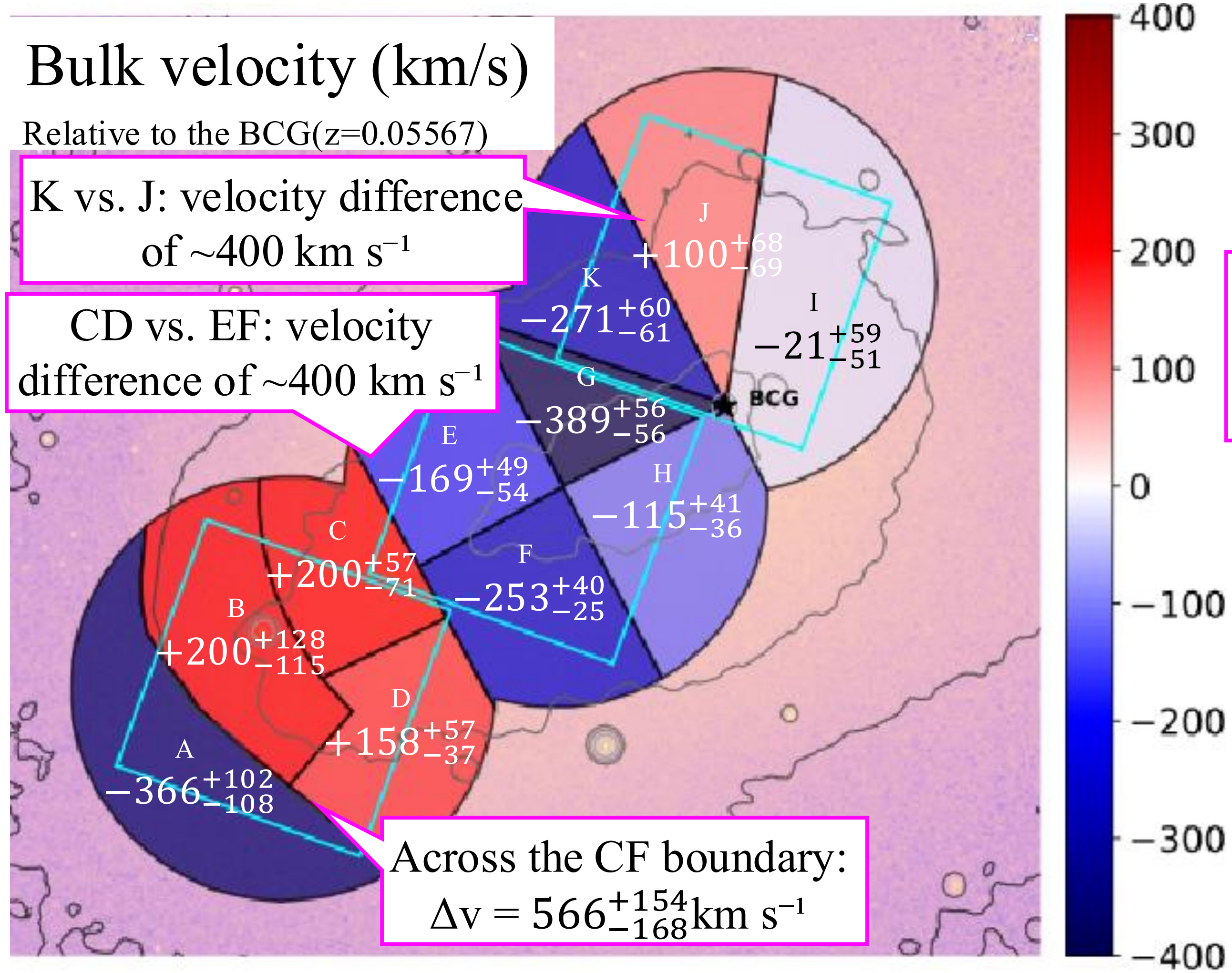

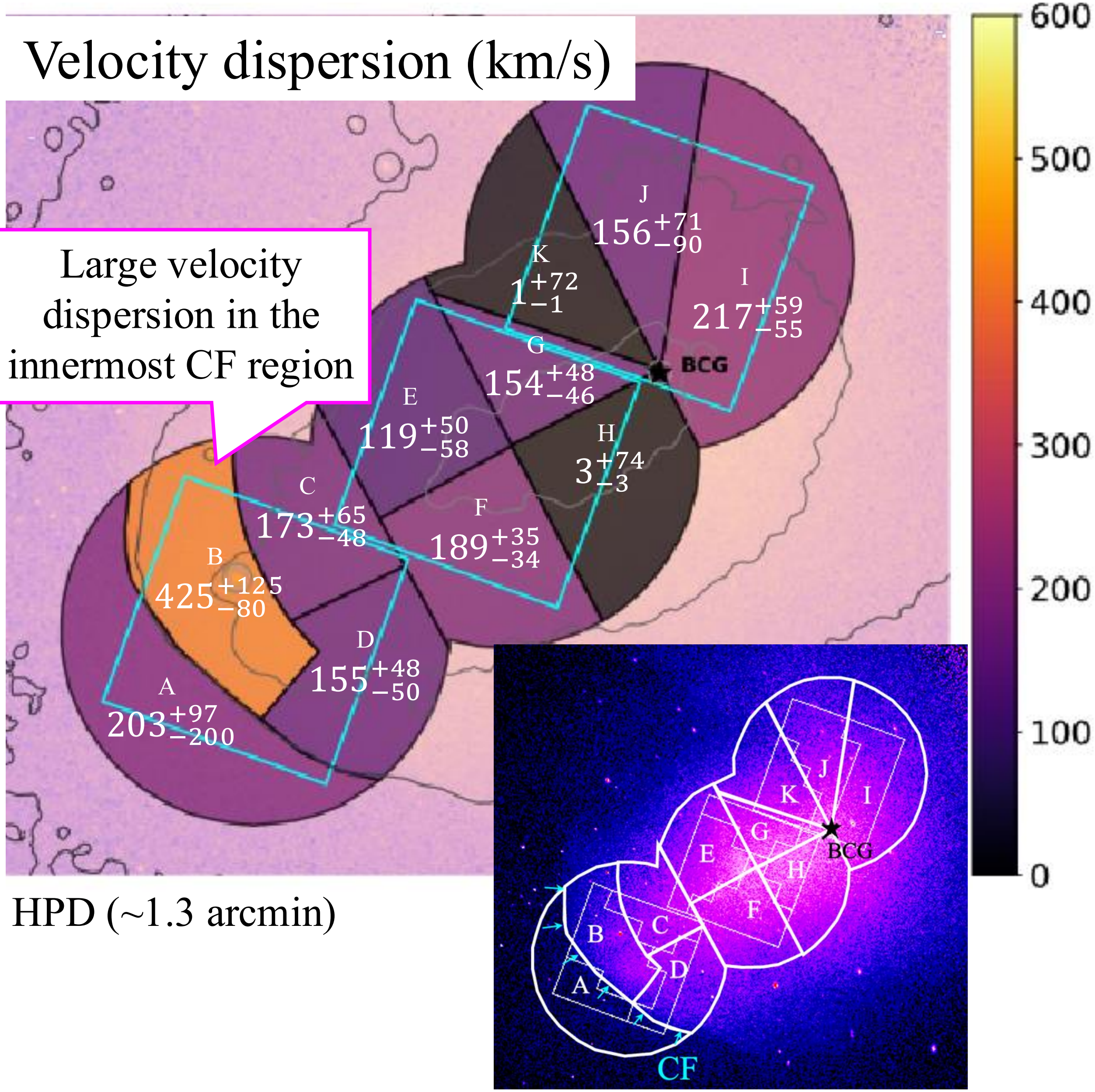

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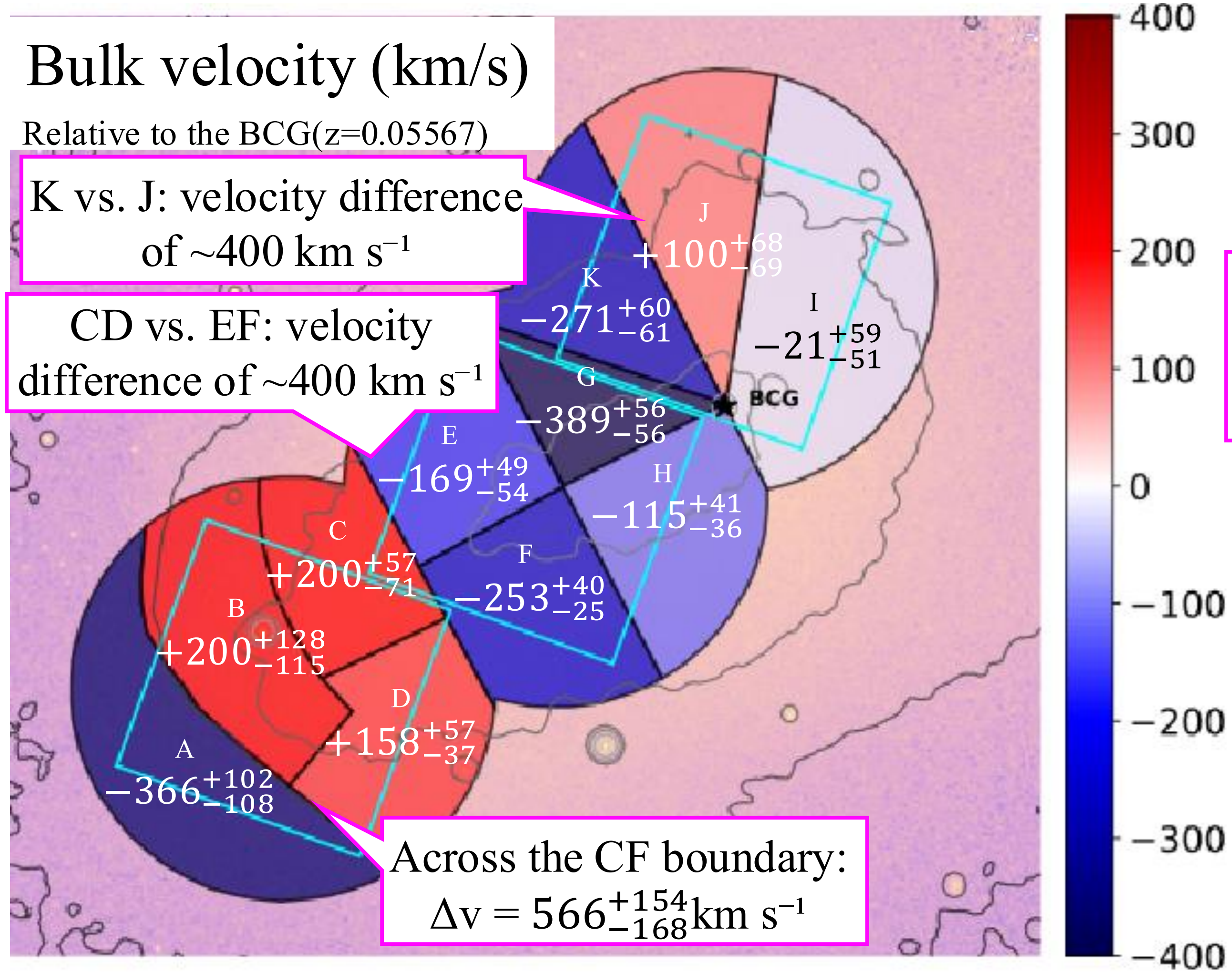

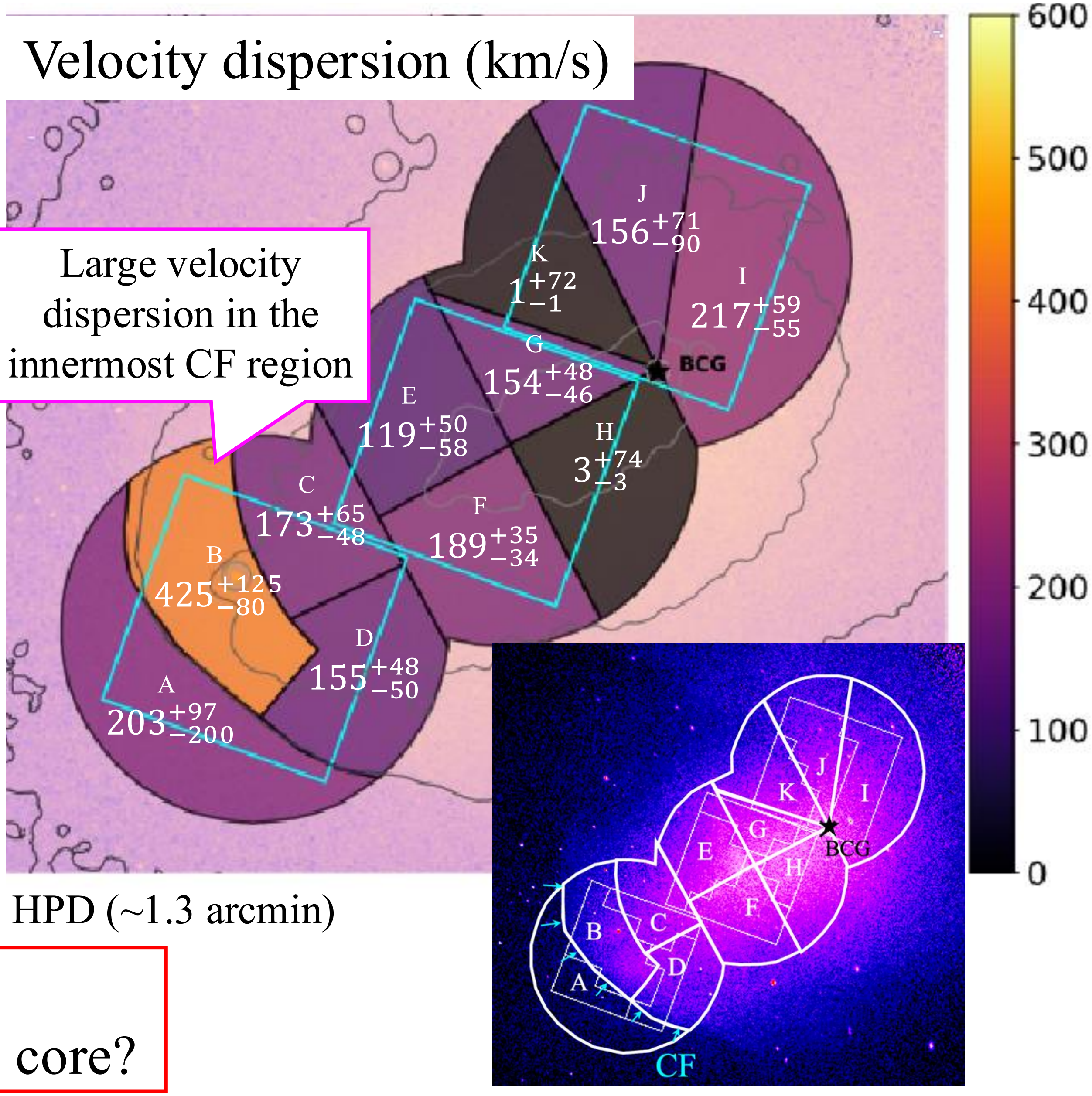

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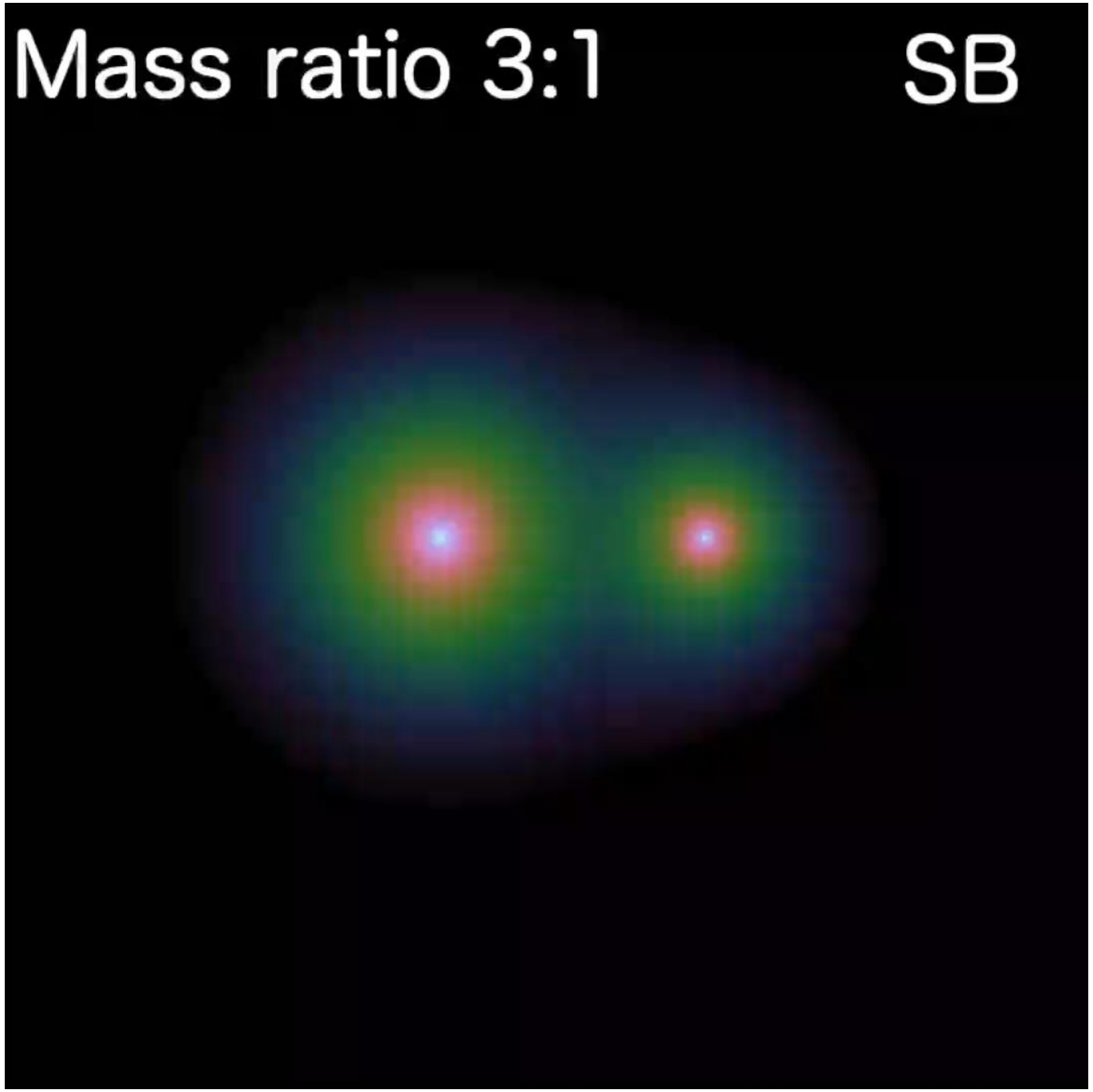
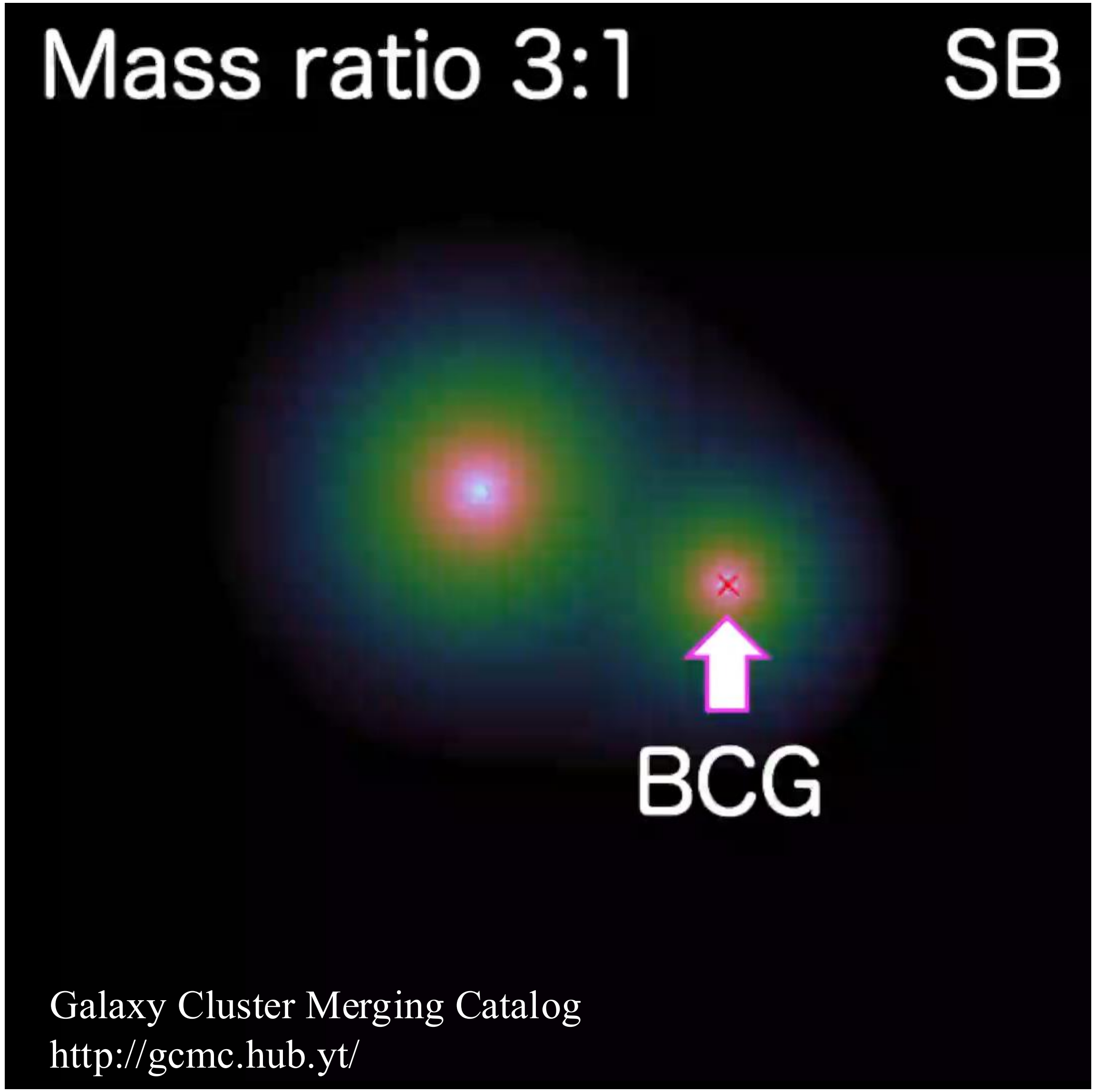
What merger geometry produces
300–400 km s⁻¹ velocity differences within the core?

Merger Geometry: Head-on or Offset?

head-on merger

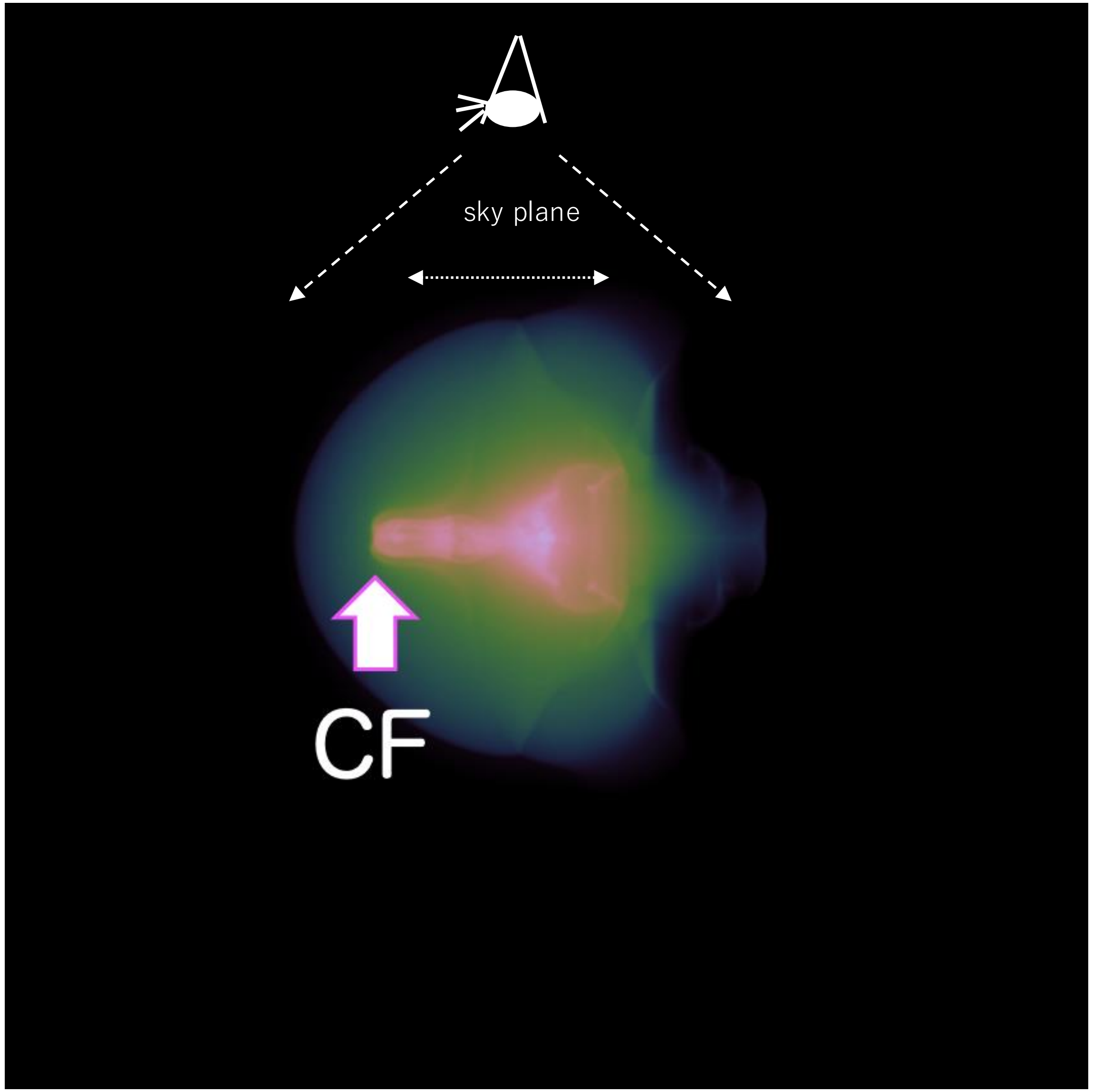


offset merger (sloshing)

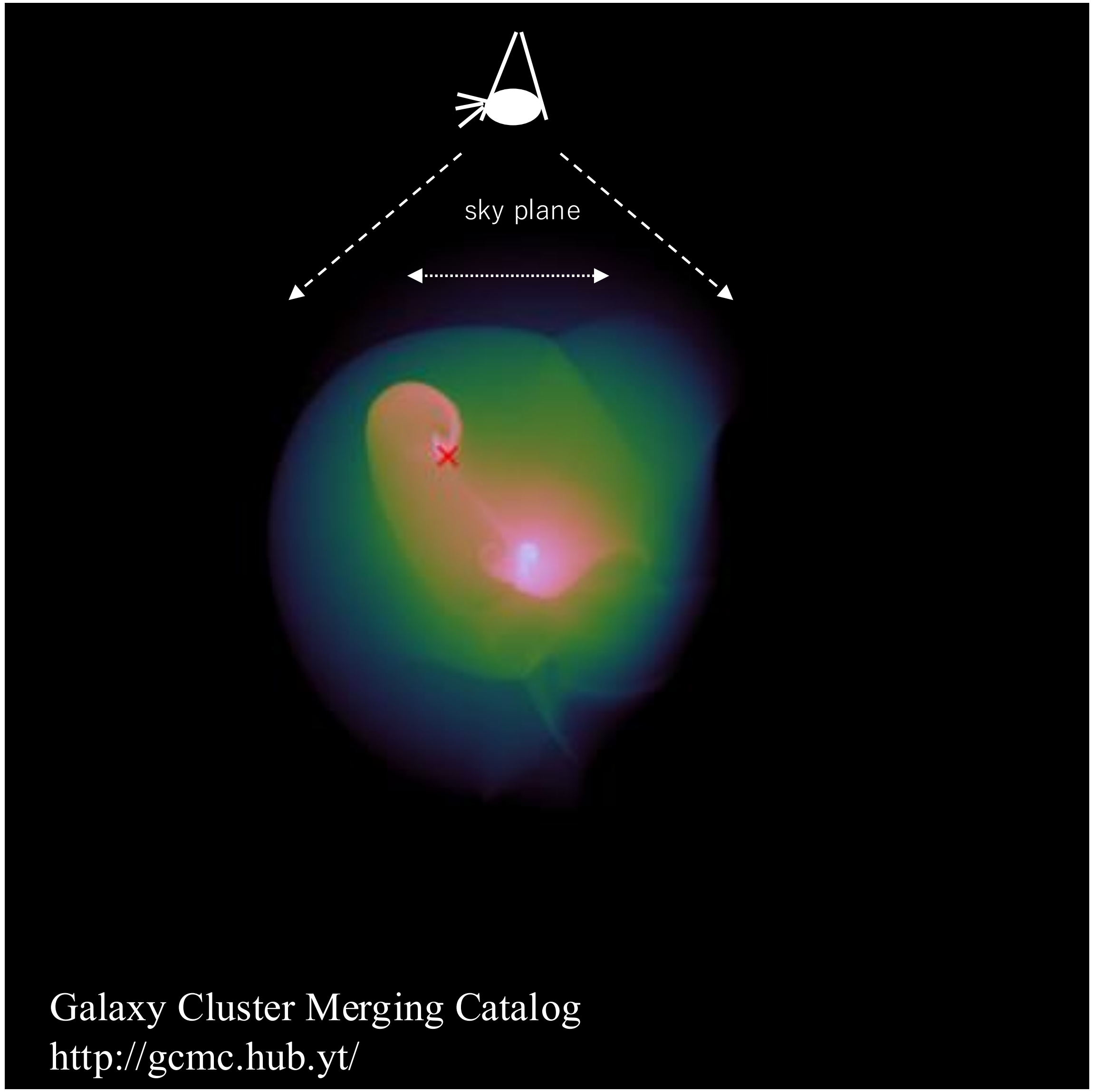


Merger Geometry: Head-on or Offset?

head-on merger



offset merger (sloshing)



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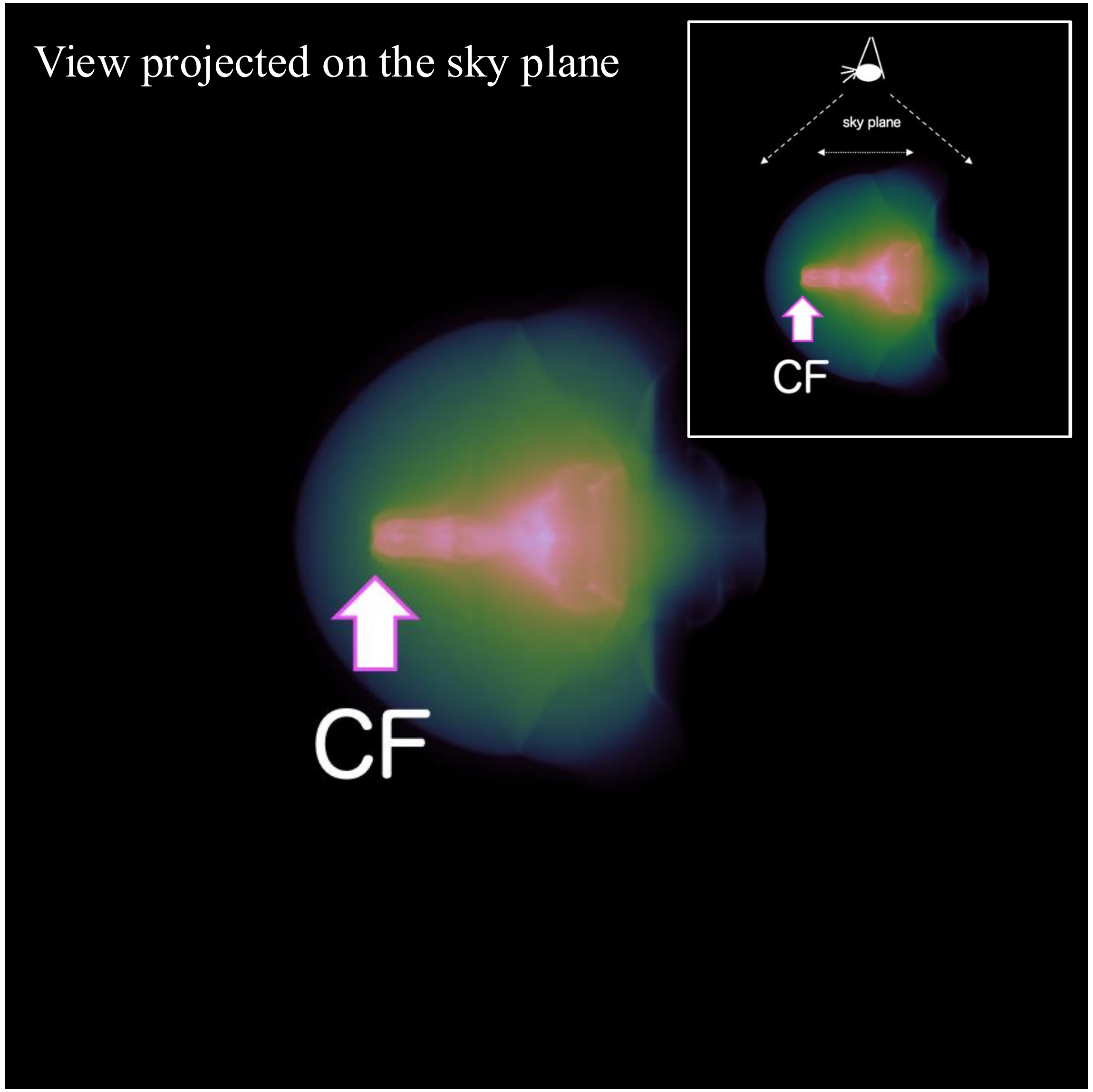
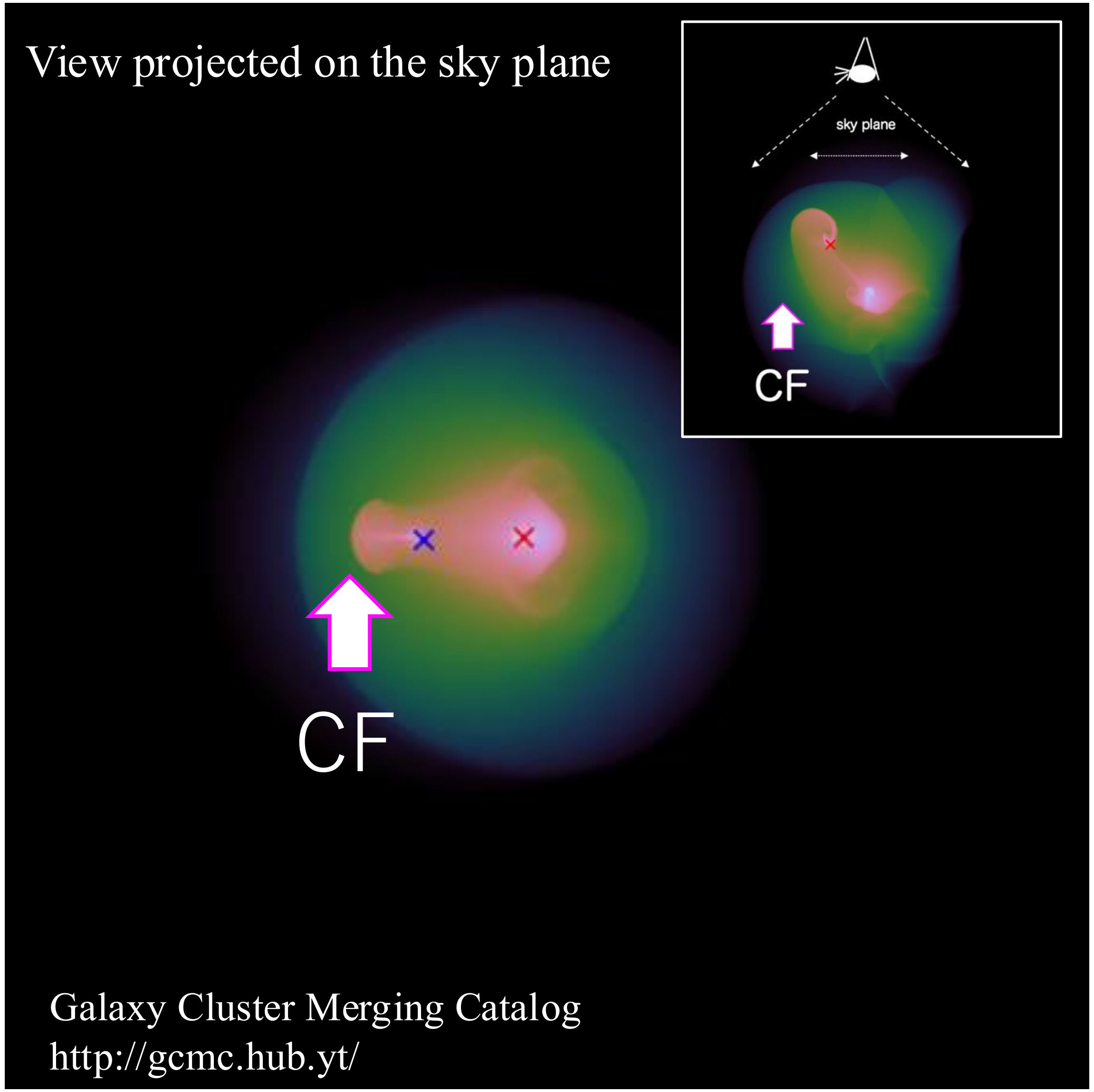
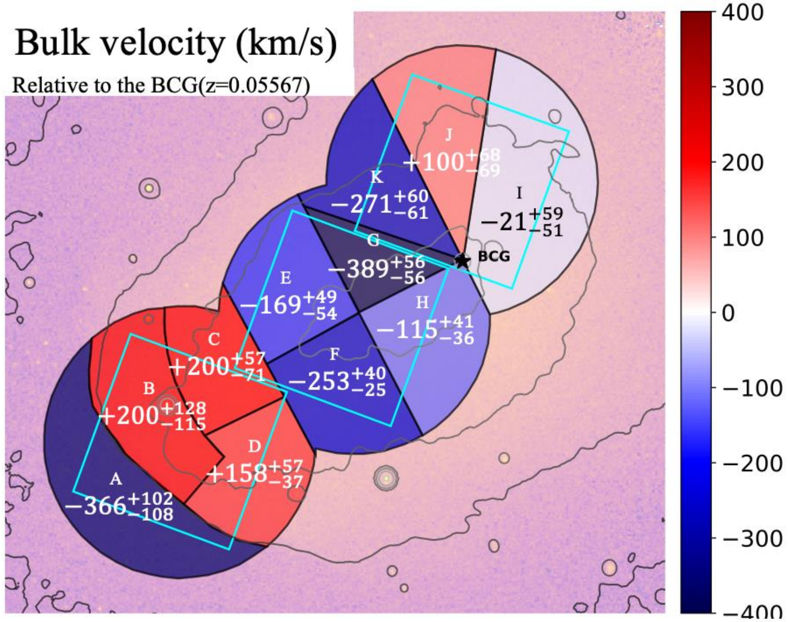
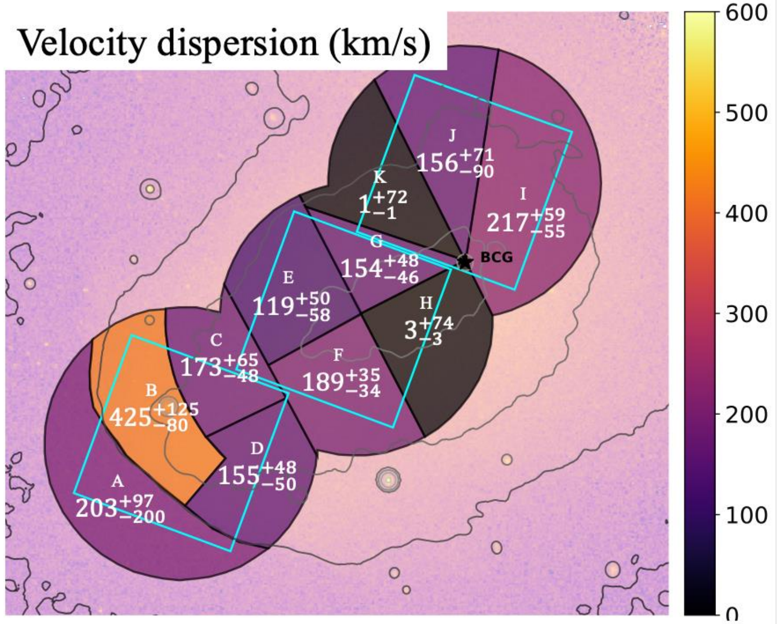


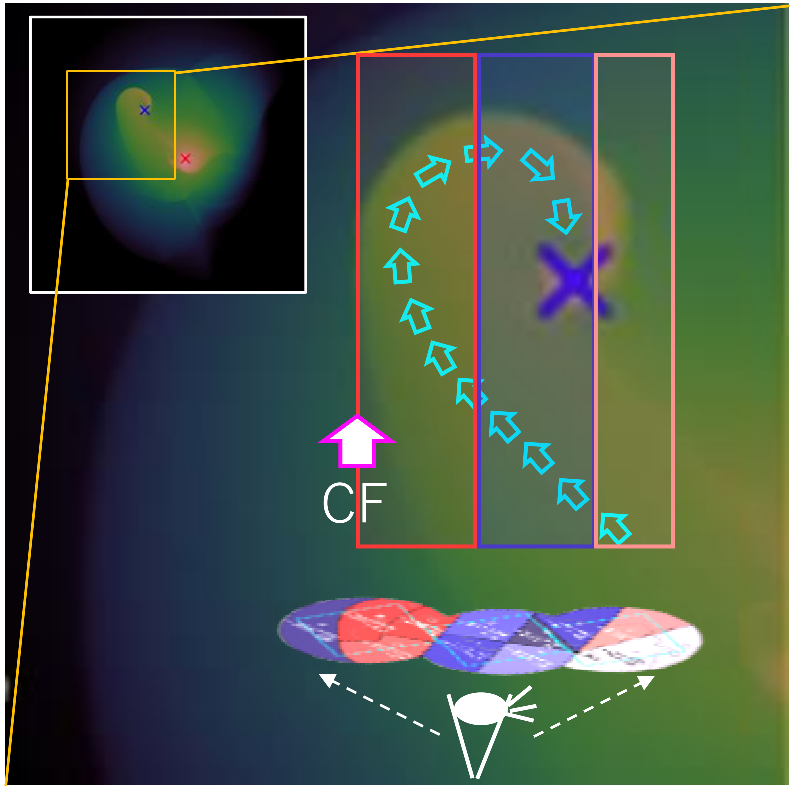
offset merger (sloshing)



Offset-merger geometry of Abell 3667







The core passed on the near side of the cluster :

1. redshift near the CF
2. blueshift around the BCG
3. redshift again in the wake

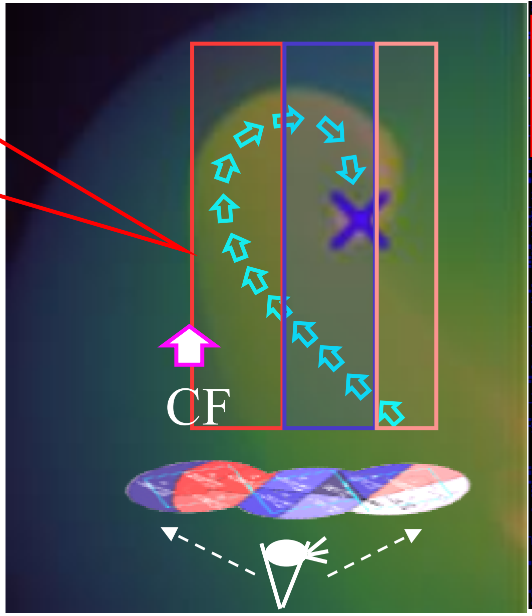
Gas expands outward near CF: Superposition of multiple bulk components → enhanced velocity dispersion

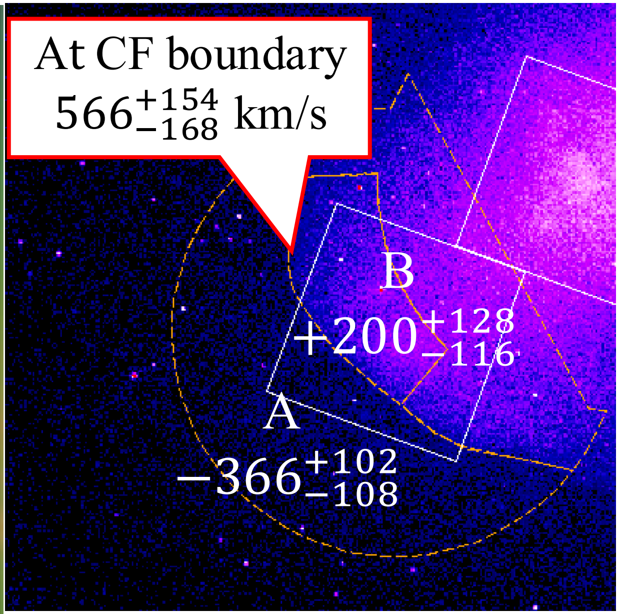
1. Velocity differences are symmetric with respect to the merger axis
2. CD–EF velocity difference: ~400 km s^{-1}
   → consistent with the expected rotational velocity

The core is rotating in a plane nearly perpendicular to the sky plane.

Cold-front shear and magnetic stabilization

Core rotation along the line of sight
Velocity difference across the CF boundary
566^{+154}_{-168} km/s =shear velocity at the CF interface.





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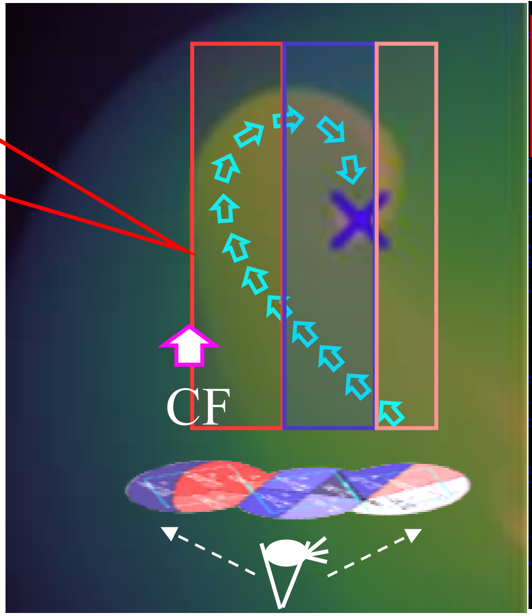

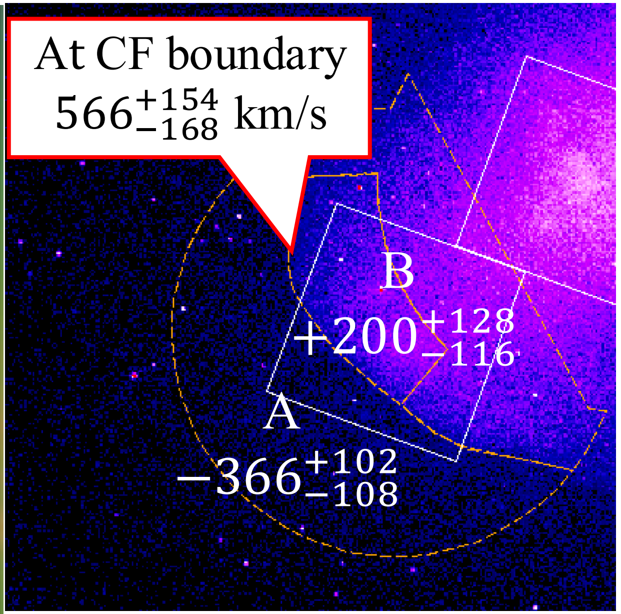

- Shear flow should amplify small perturbations (KHI) at the interface
- No clear KH-like waves are seen on the CF surface

Possible suppression mechanisms:
magnetic field / viscosity / gravity

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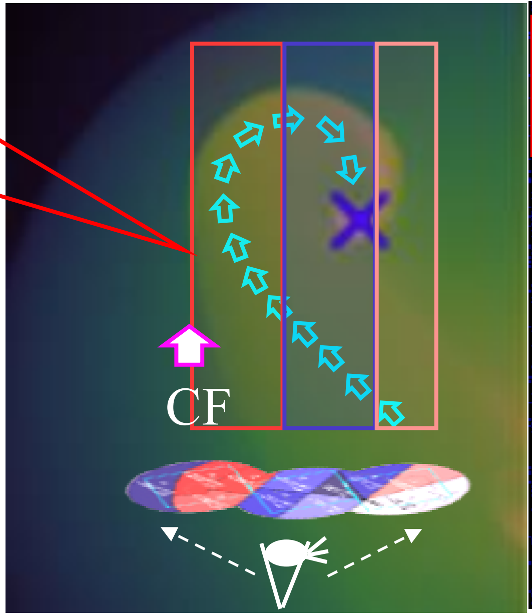

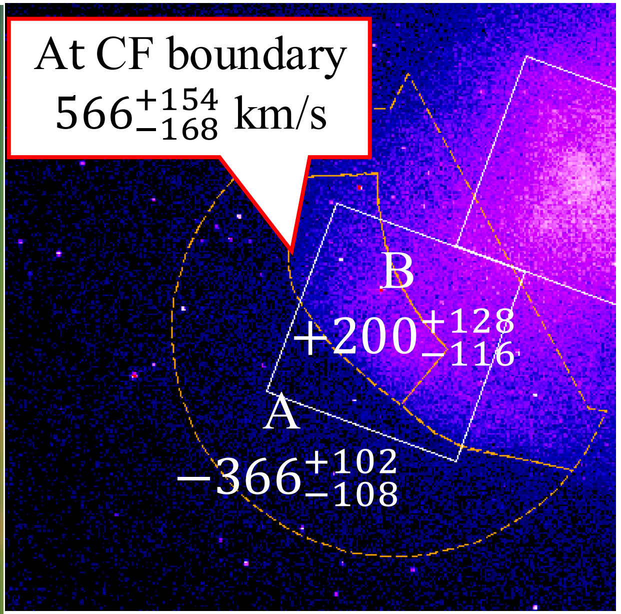

- Shear flow should amplify small perturbations (KHI) at the interface
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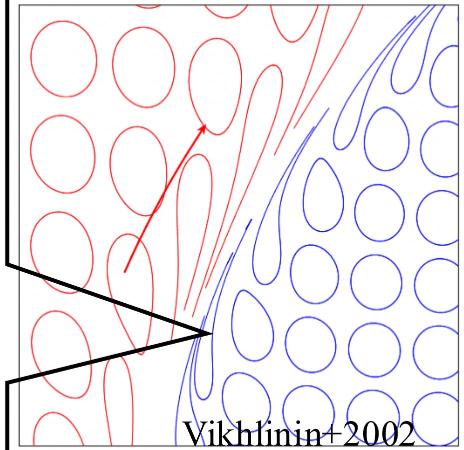
Possible suppression mechanisms:
magnetic field / viscosity / gravity

Draped magnetic field forms a layer parallel to the CF surface Magnetic tension acts like surface tension
→ suppresses shear-driven perturbations



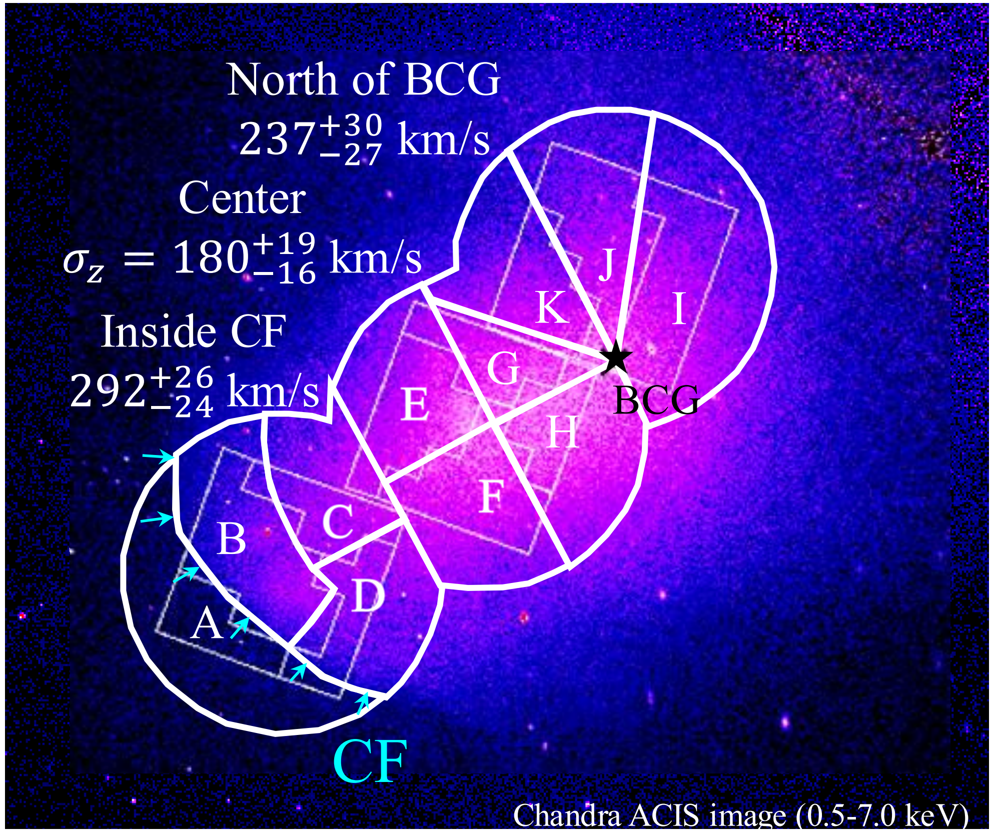
Ram pressure		Magnetic tension
$\frac{1}{2}\rho\Delta v^2$	$<$	$\frac{B^2}{8\pi}$

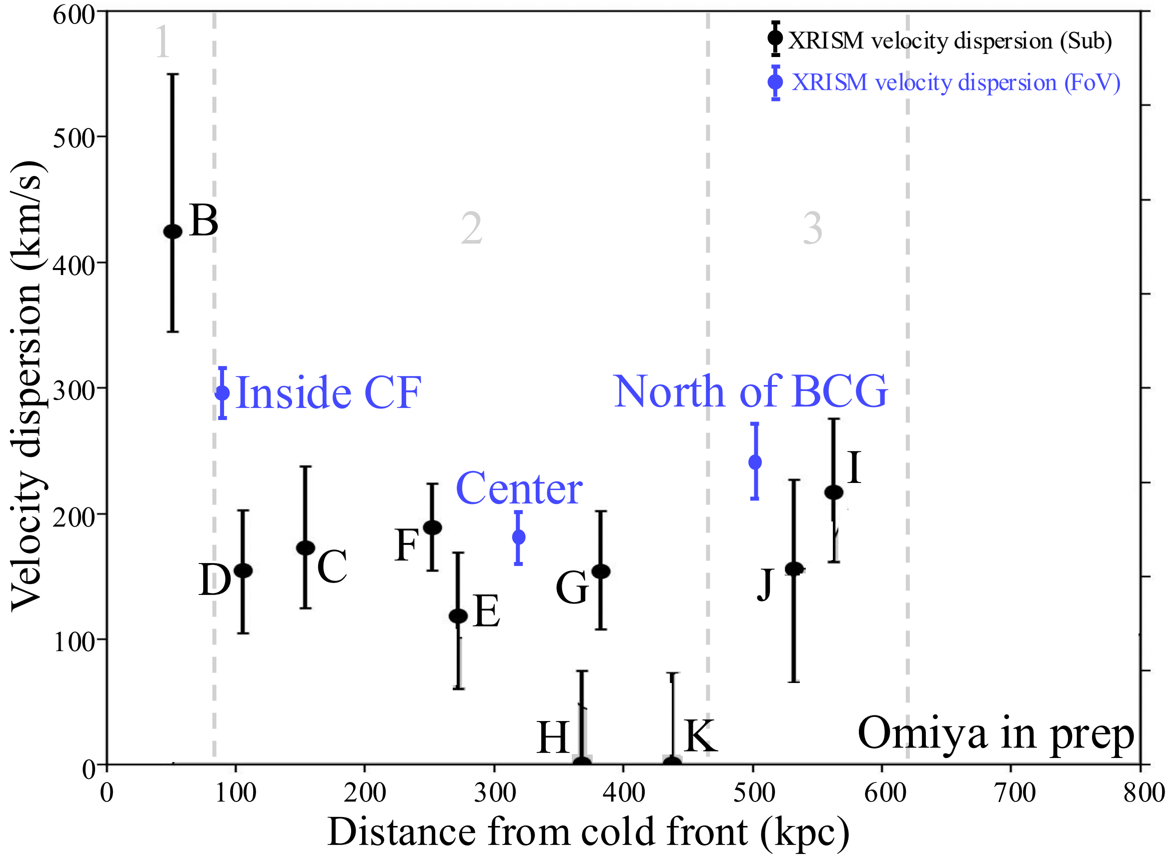
$\rho = 2.0 \times 10^{-27}$ g cm^{-3}
Using
$n_{\rm cold} = 3.2 \times 10^{-3}$ cm^{-3}
$n_{\rm hot} = 8.2 \times 10^{-4}$ cm^{-3}
(Vikhlinin+2000)

$B > 7.2^{+2.0}_{-2.1}$ μG

If magnetic tension alone stabilizes the CF:
B > 5.1 μG (1σ lower limit)

Tracing wake turbulence behind the moving CF



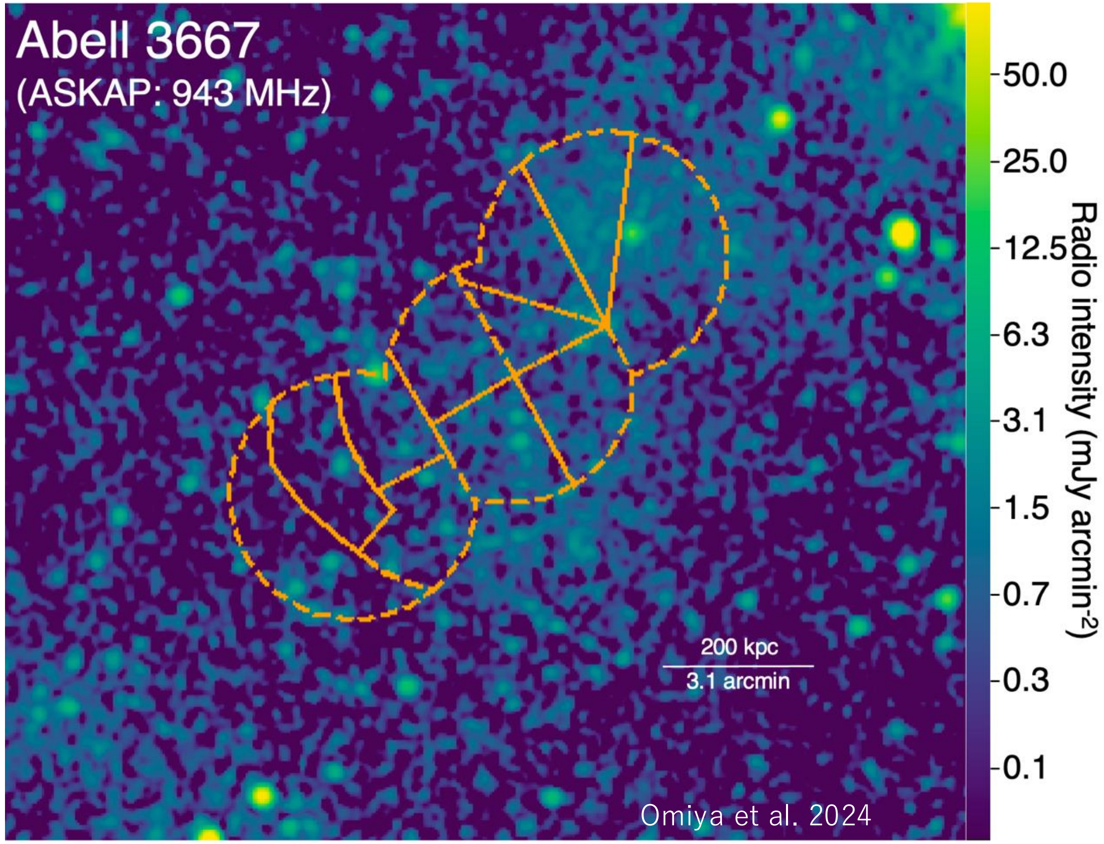


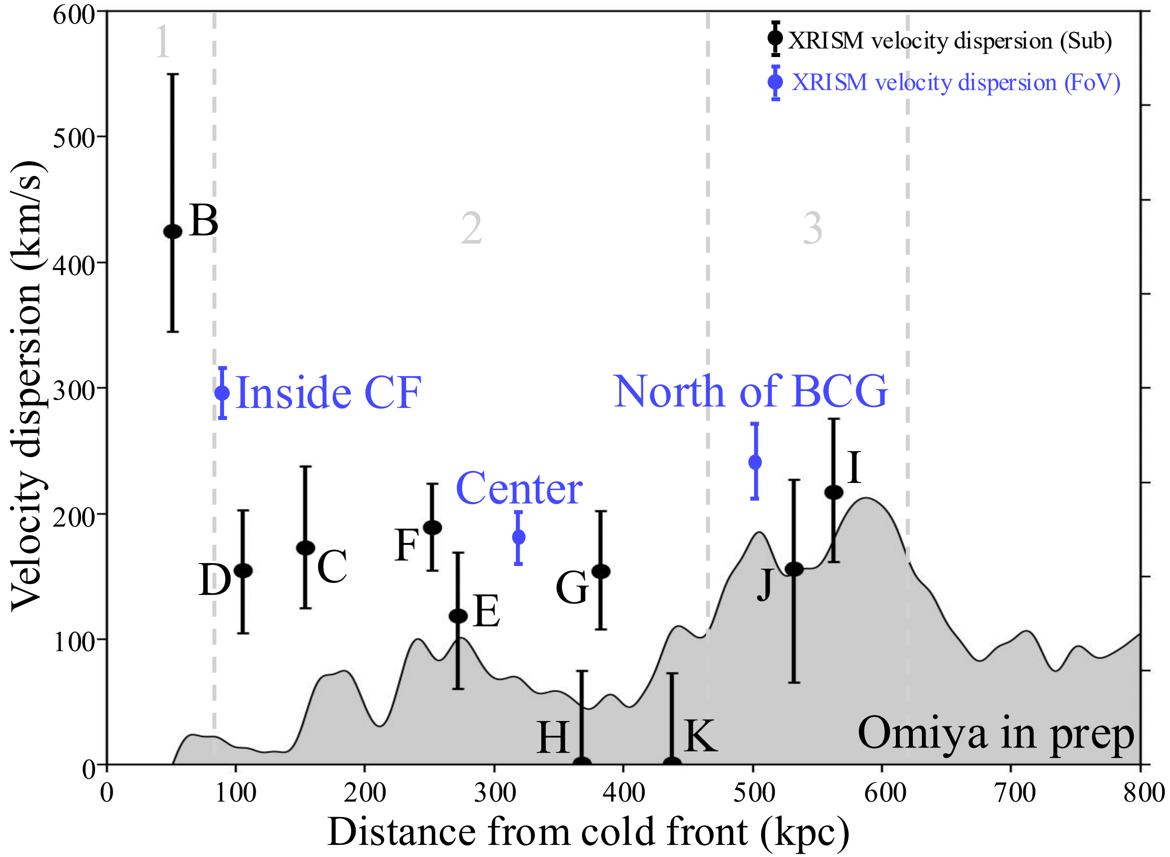
Velocity dispersion

1. Largest innermost the CF
   → possible superposition of multiple bulk
2. Decreases in the immediate wake
3. Increases again farther downstream (I, J)

Radio intensity

Comparison with the radio intensity

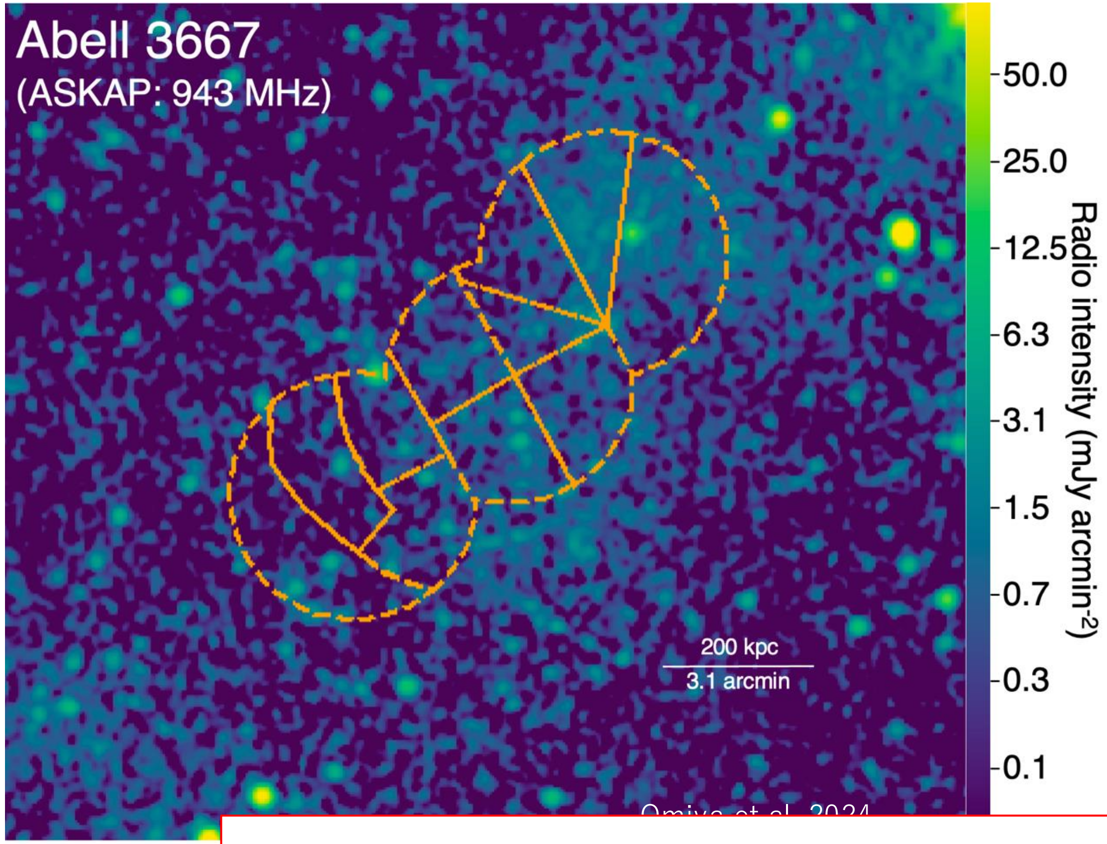


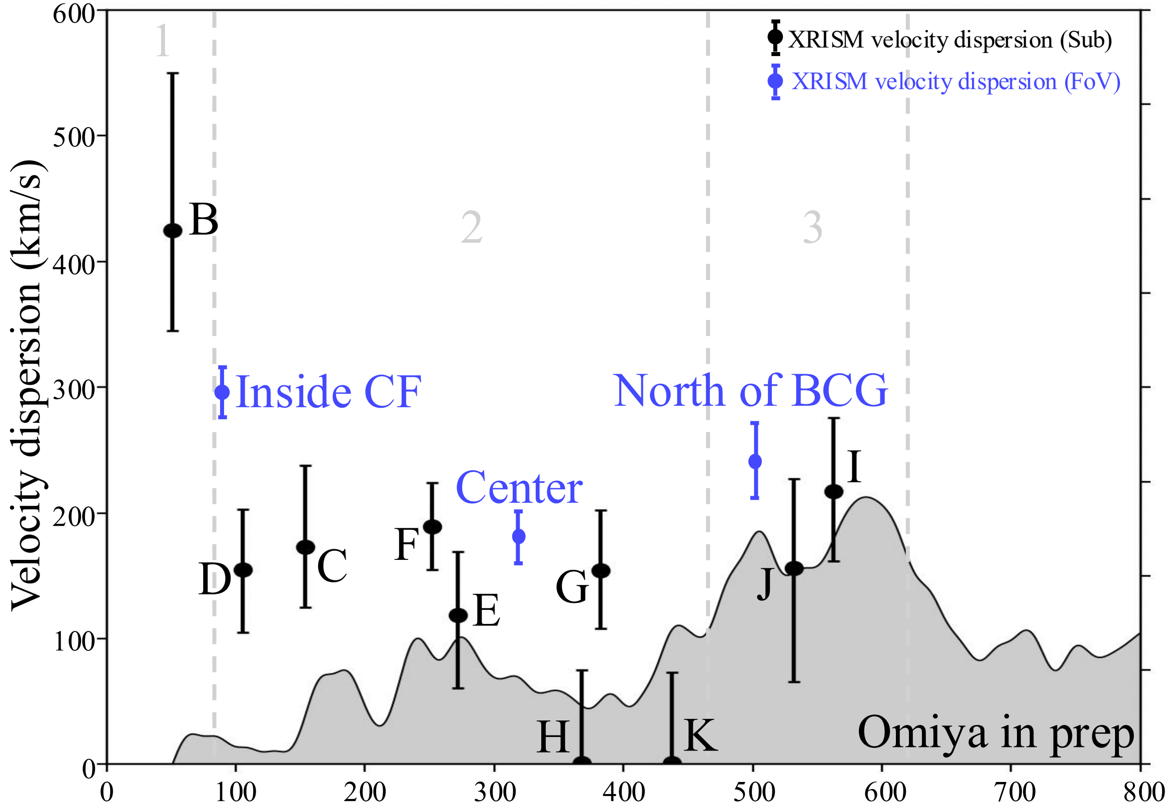


Velocity dispersion
1. Largest innermost the CF → possible superposition of multiple bulk 2. Decreases in the immediate wake 3. Increases again farther downstream (I, J)

Radio intensity
1. Weak near the CF 2. Increases downstream along the wake 3. Strong radio emission (I, J)

Comparison with the radio intensity





Possible link between wake turbulence and particle re-acceleration?

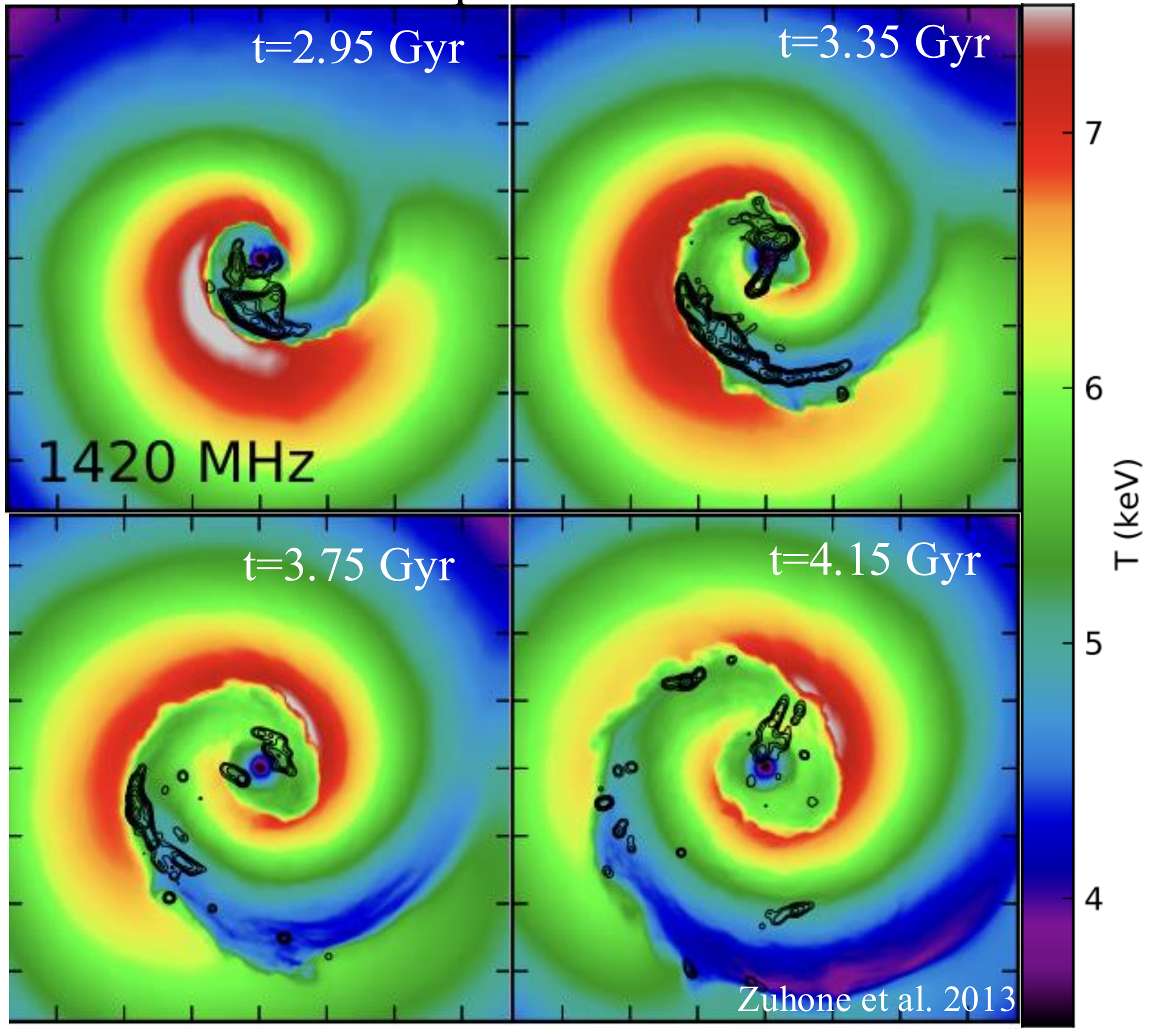
1. Largest innermost the CF
   → possible superposition of multiple bulk
2. Decreases in the immediate wake
3. Increases again farther downstream (I, J)

1. Weak near the CF
2. Increases downstream along the wake
3. Strong radio emission (I, J)

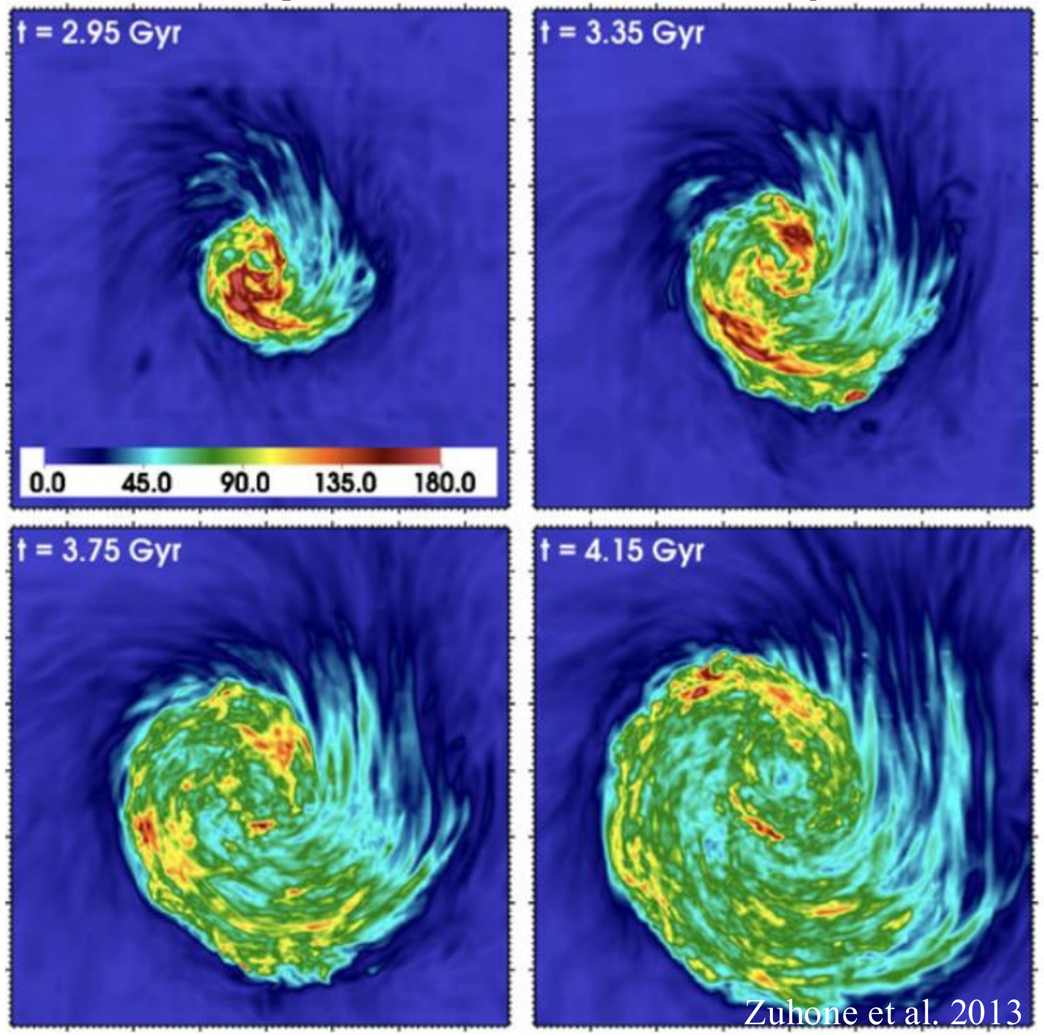
Can wake turbulence power the radio emission?

Zuhone et al. (2013) simulated cool-core sloshing induced by an offset merger, assuming seed relativistic electrons supplied by past AGN activity.

Temperature



Projected turbulence velocity



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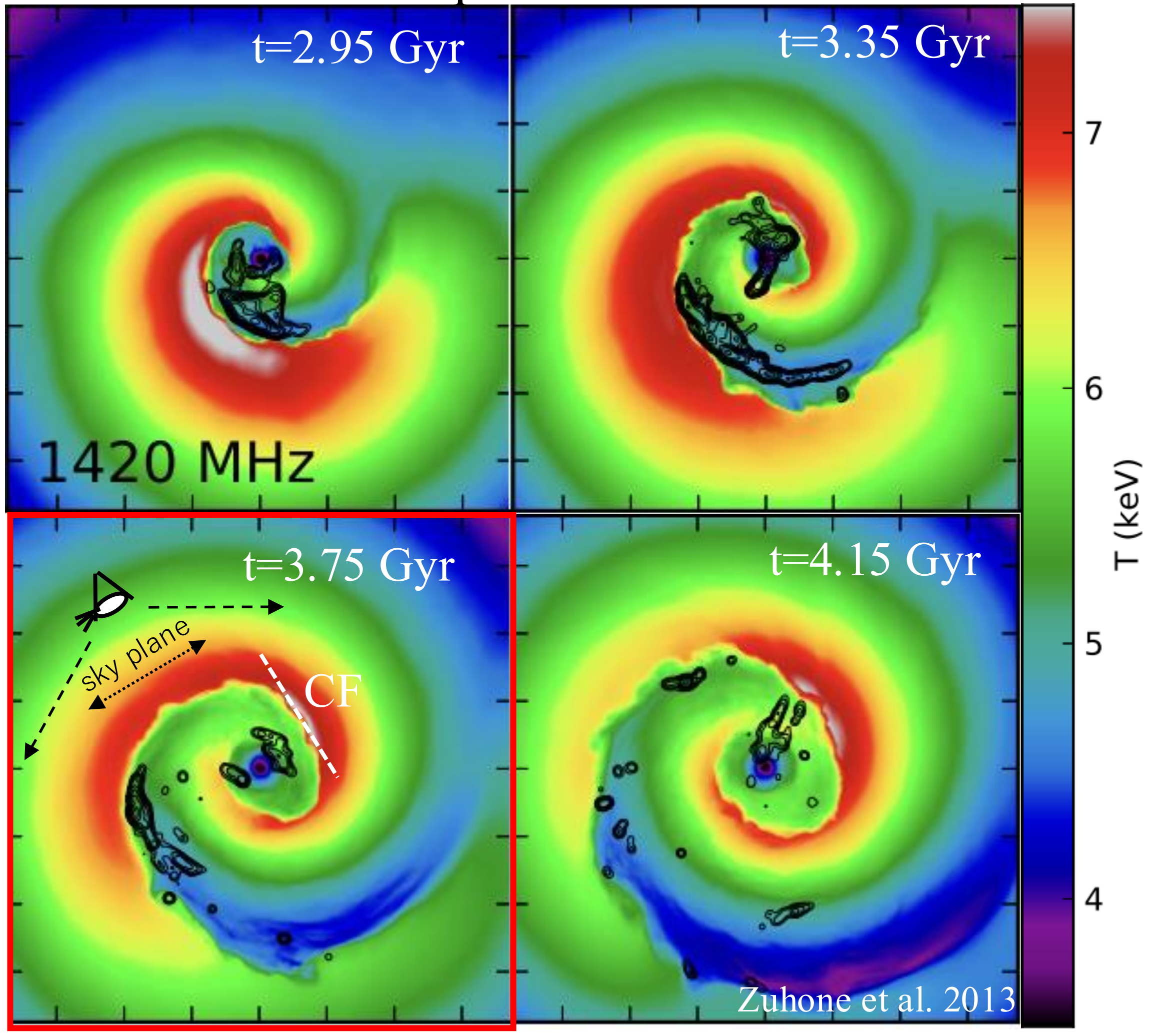

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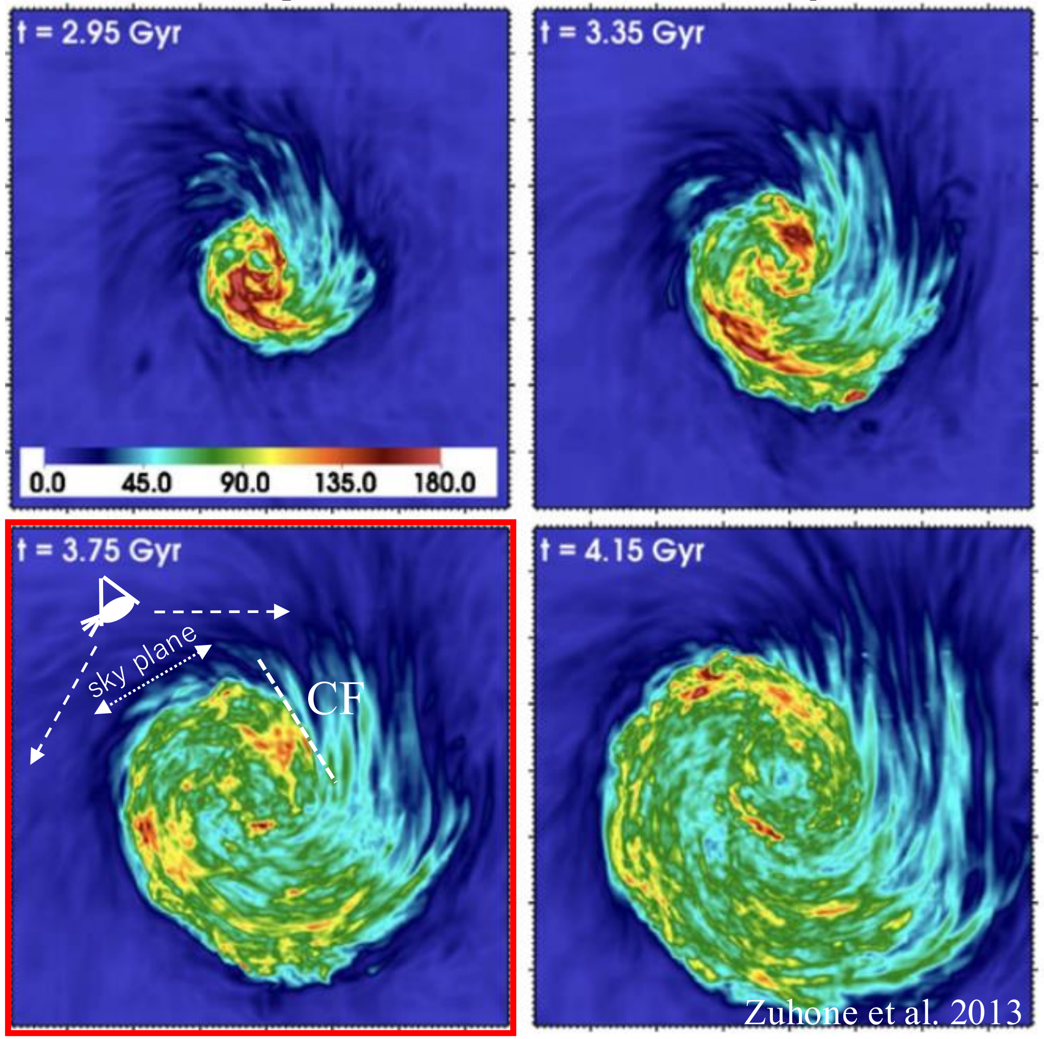
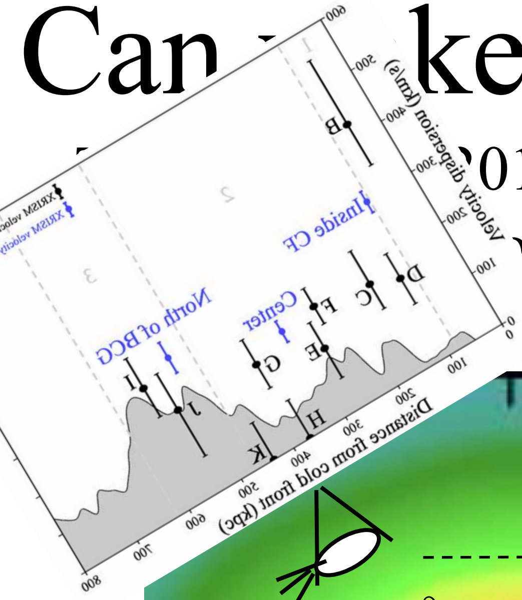
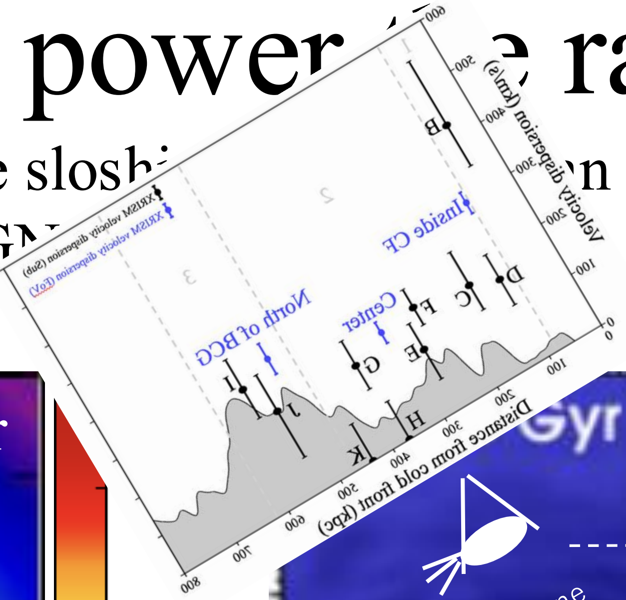


Can … ke turbulence power … e radio emission?

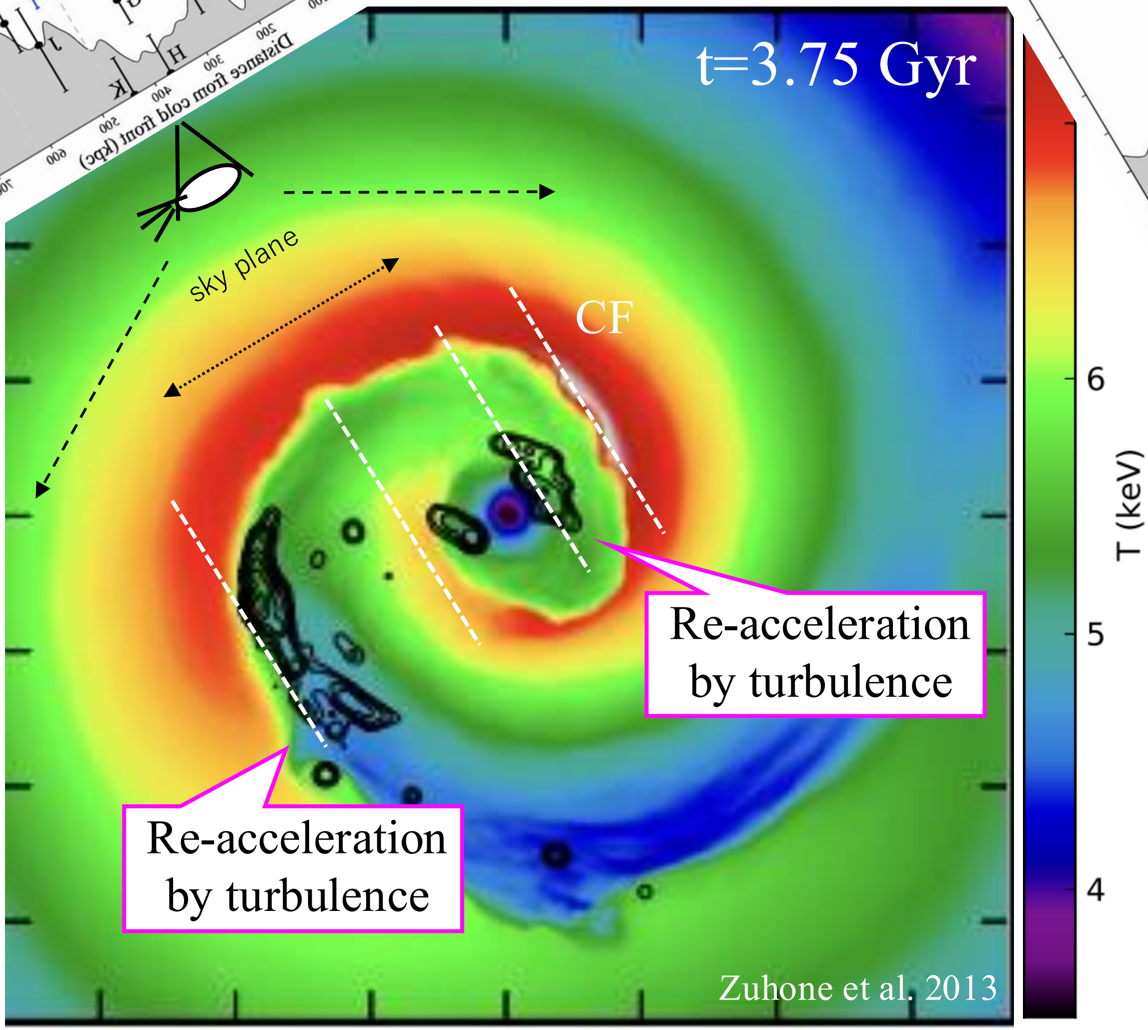
… 013) simulated cool-core sloshi … n offset merger, assuming seed

… ns supplied by past AG …

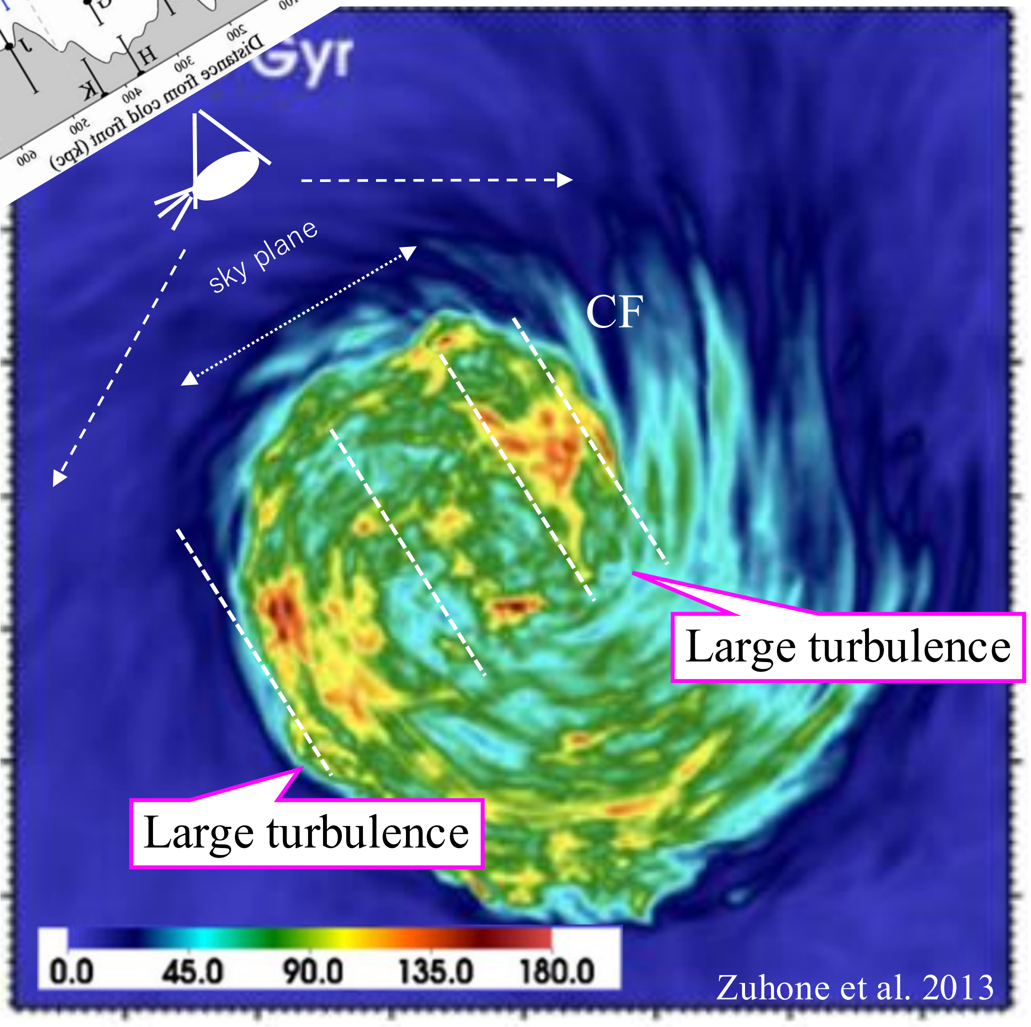




… mperature



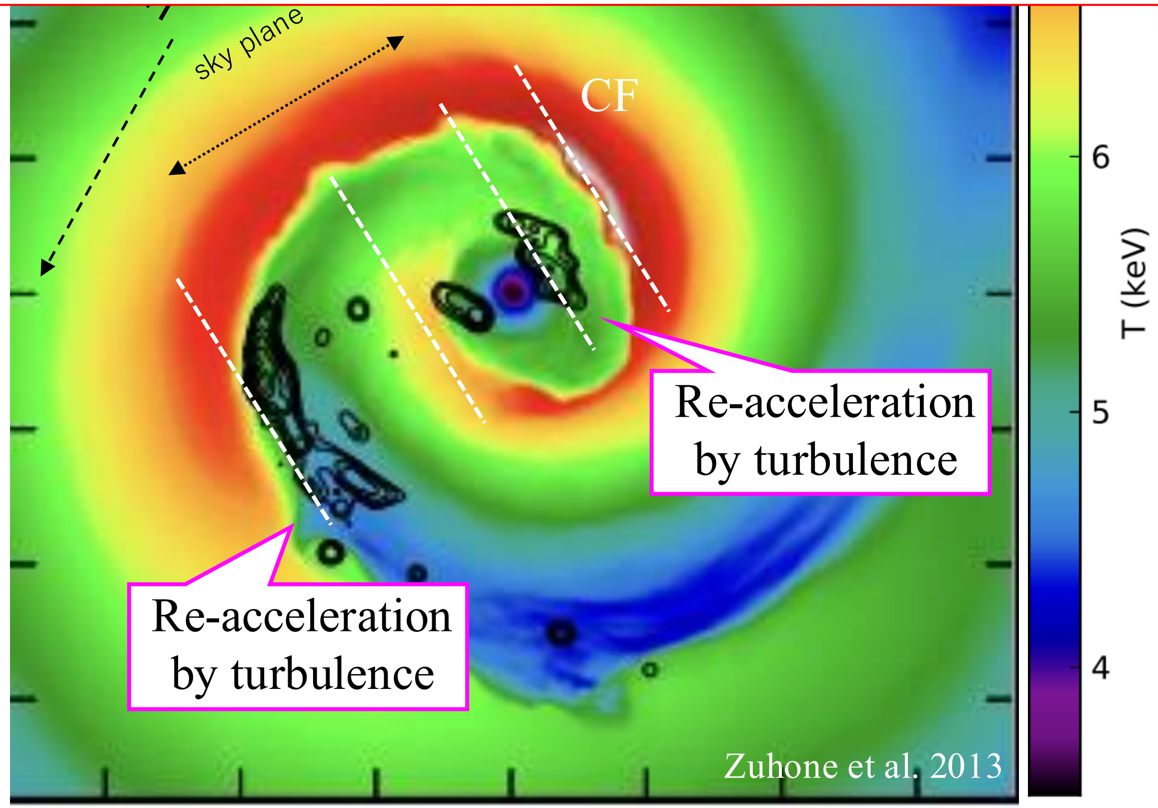
turbulence velocity

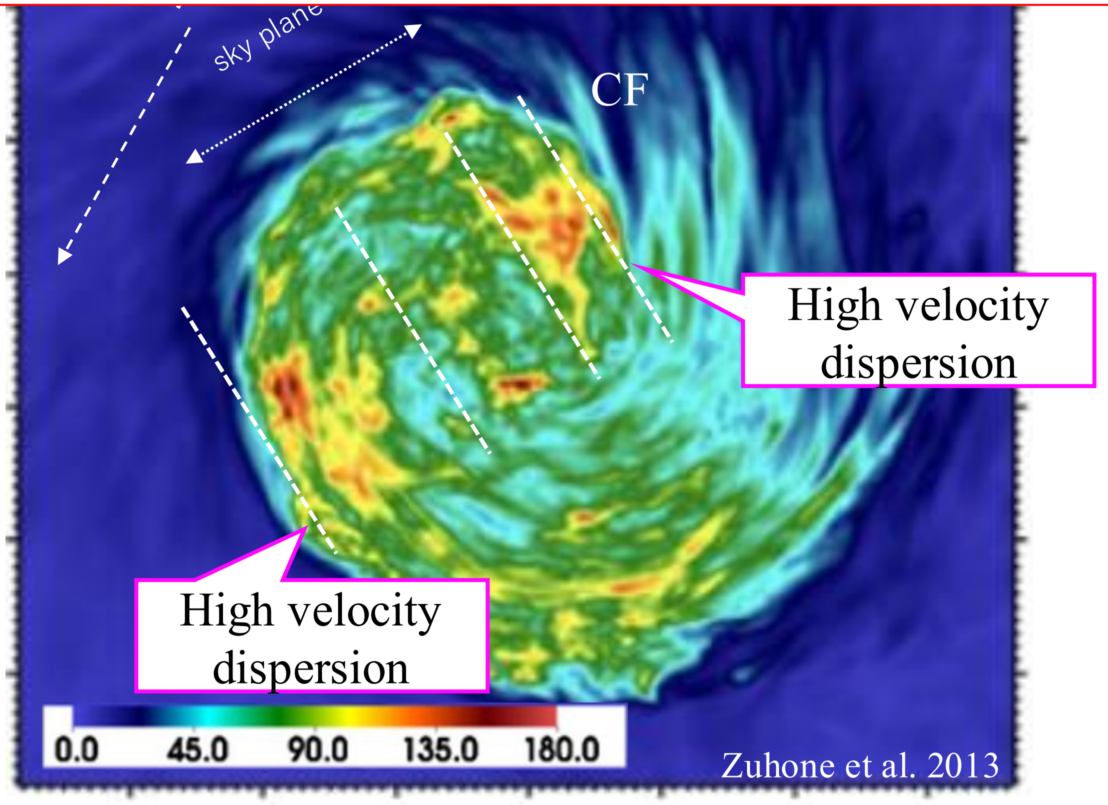


Can … ke turbulence power … e radio emission?

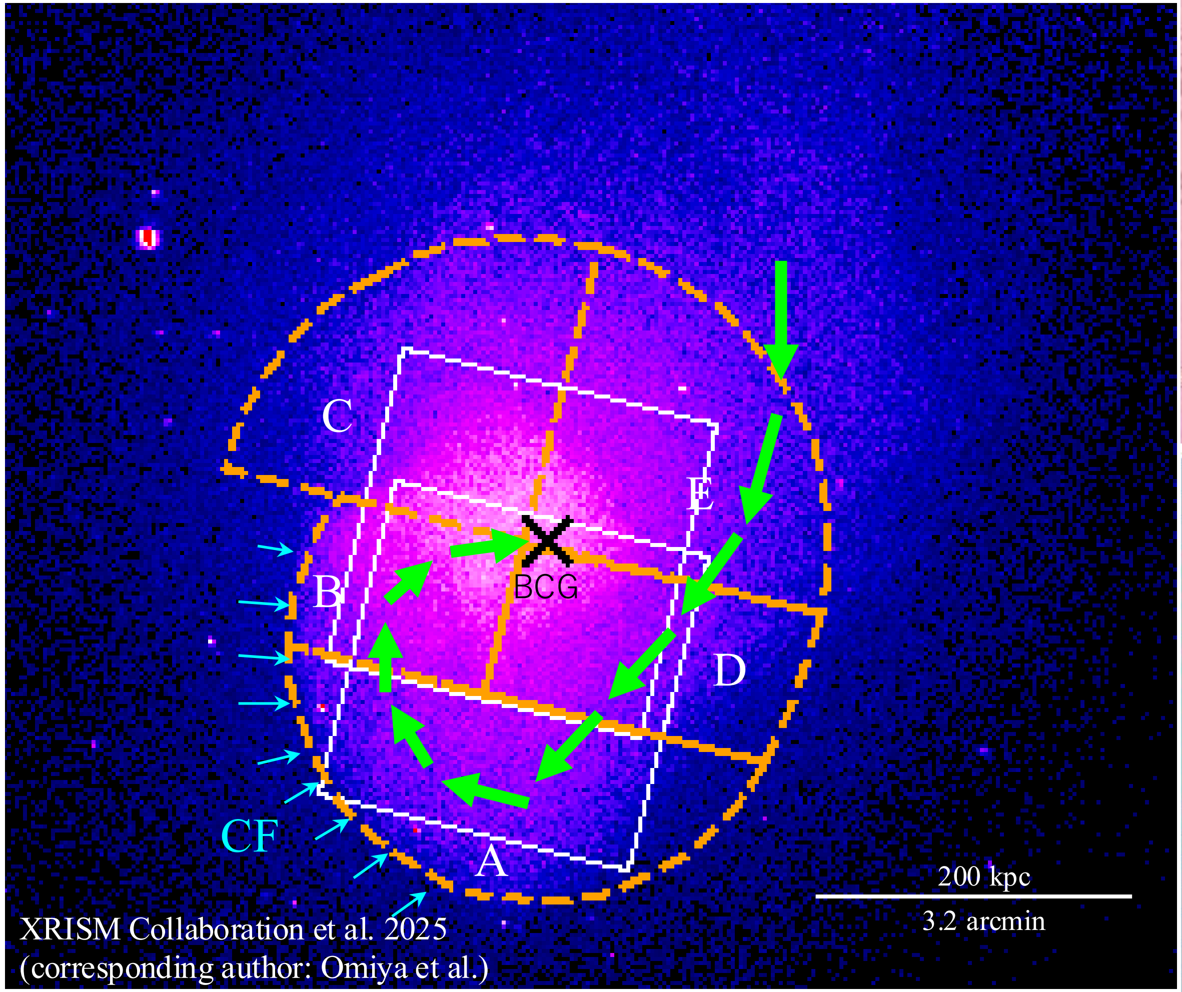
…2013) simulated cool-core sloshi… …n offset merger, assuming seed

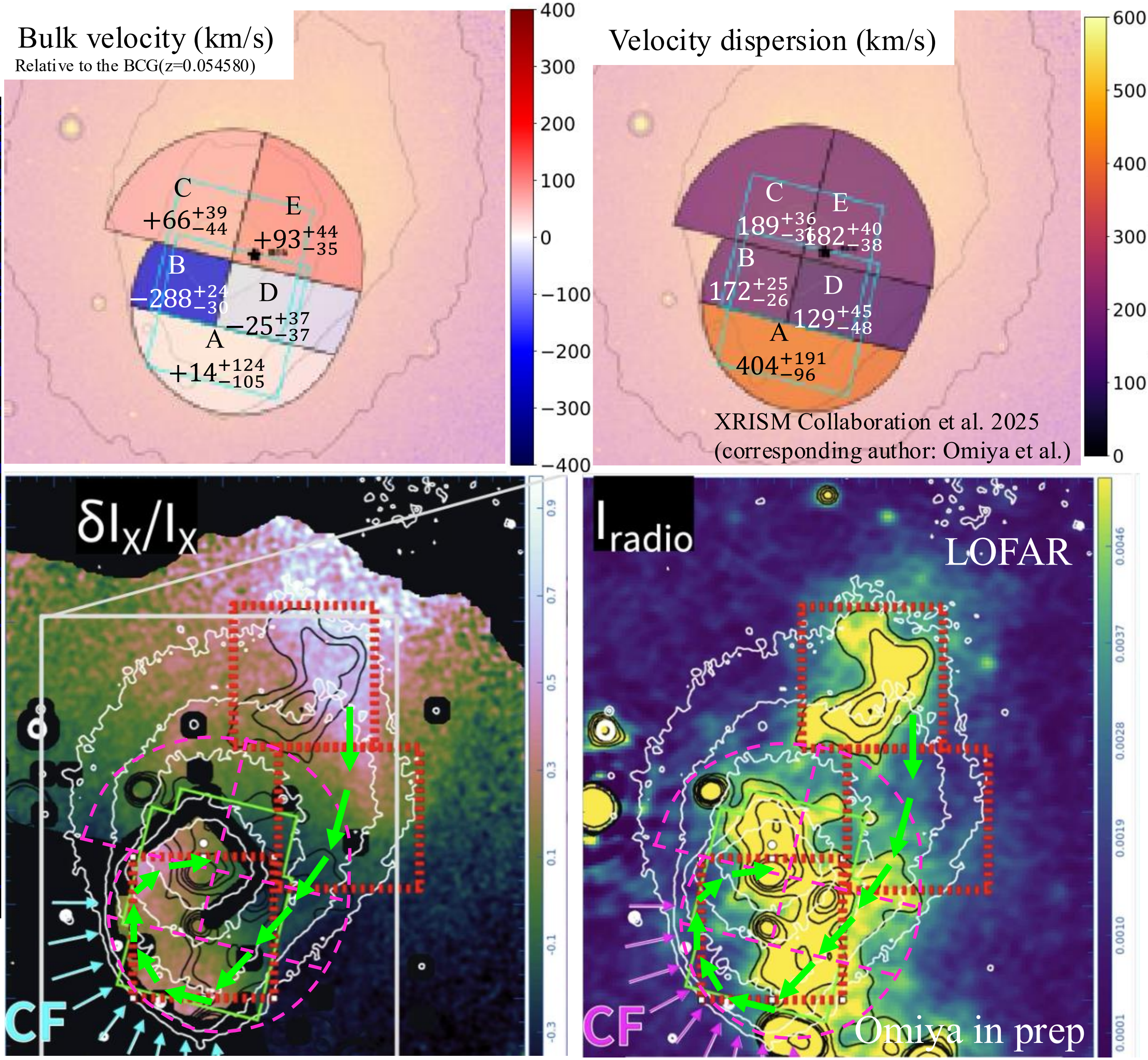
1. Detect velocity dispersion and radio brightness rise at downstream!
2. At the CF, simulation predicts radio emission from small sloshing perturbations, but Abell 3667 shows weak radio emission
→insufficient seed electrons or not enough time for particle re-acceleration?





XRISM view of sloshing core cluster: Abell 2319





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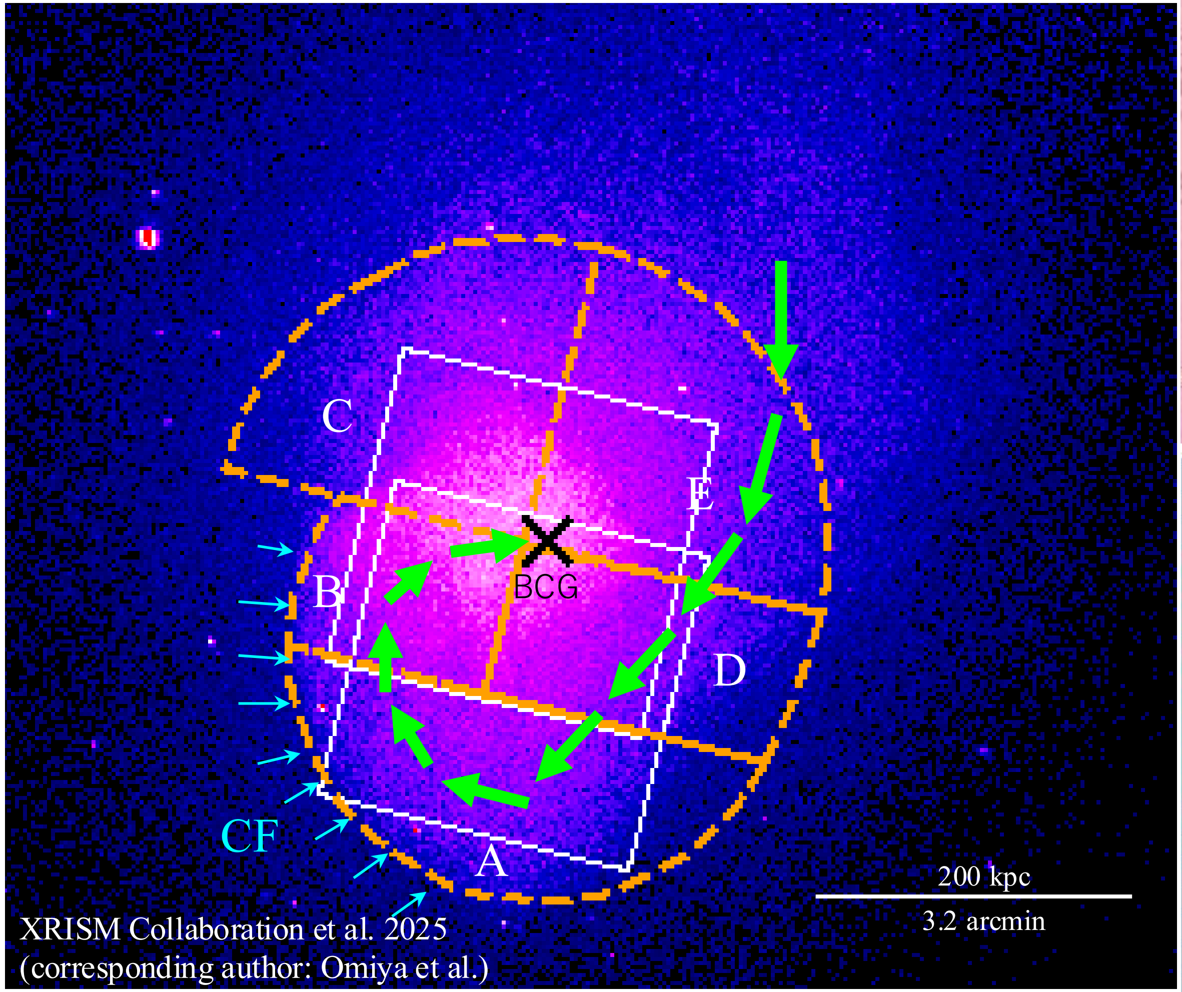

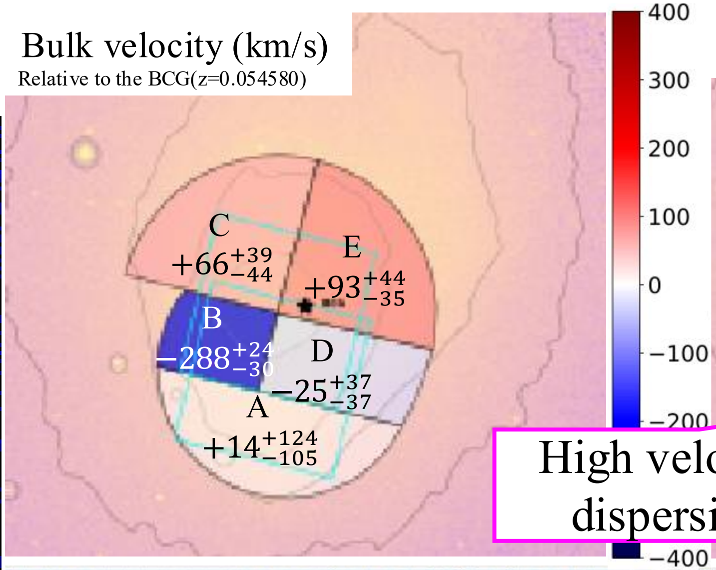

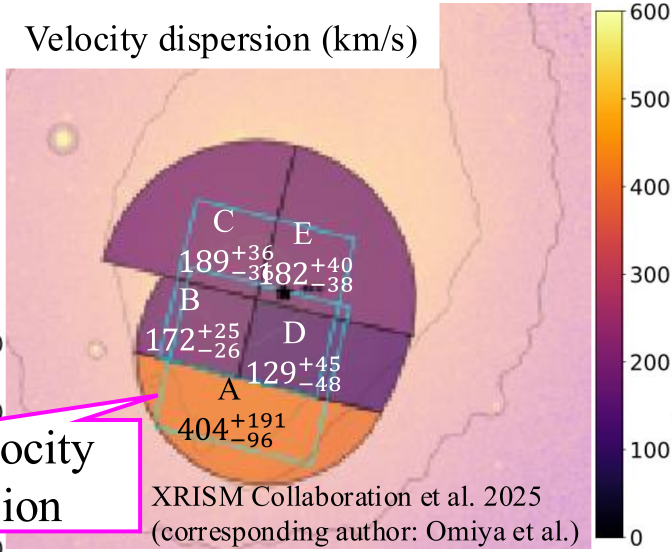

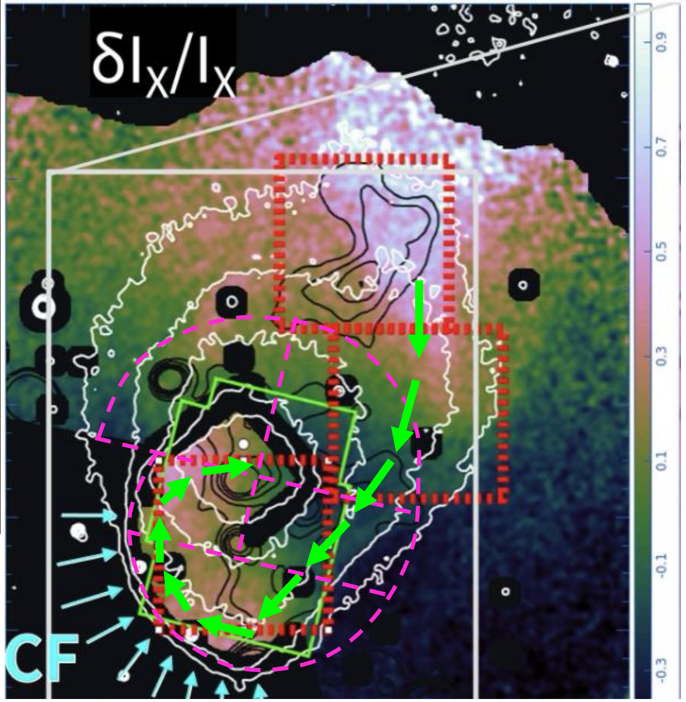

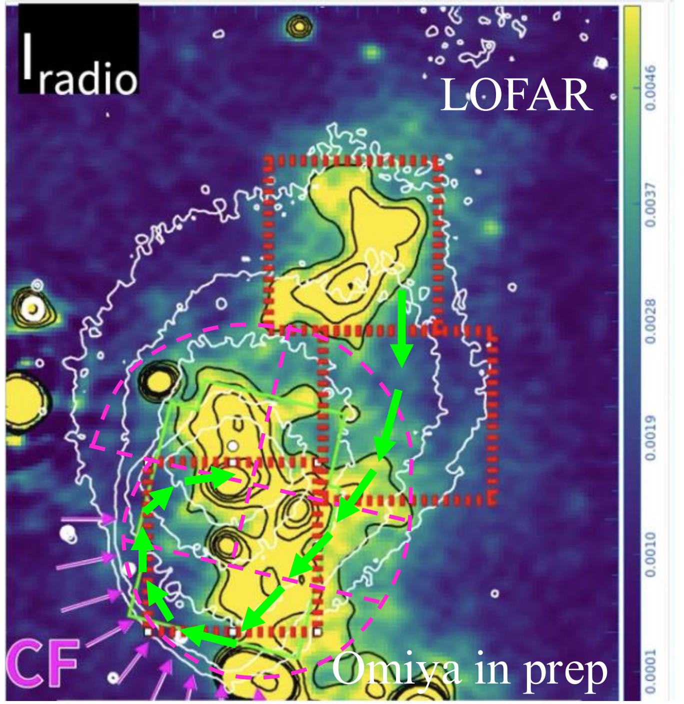

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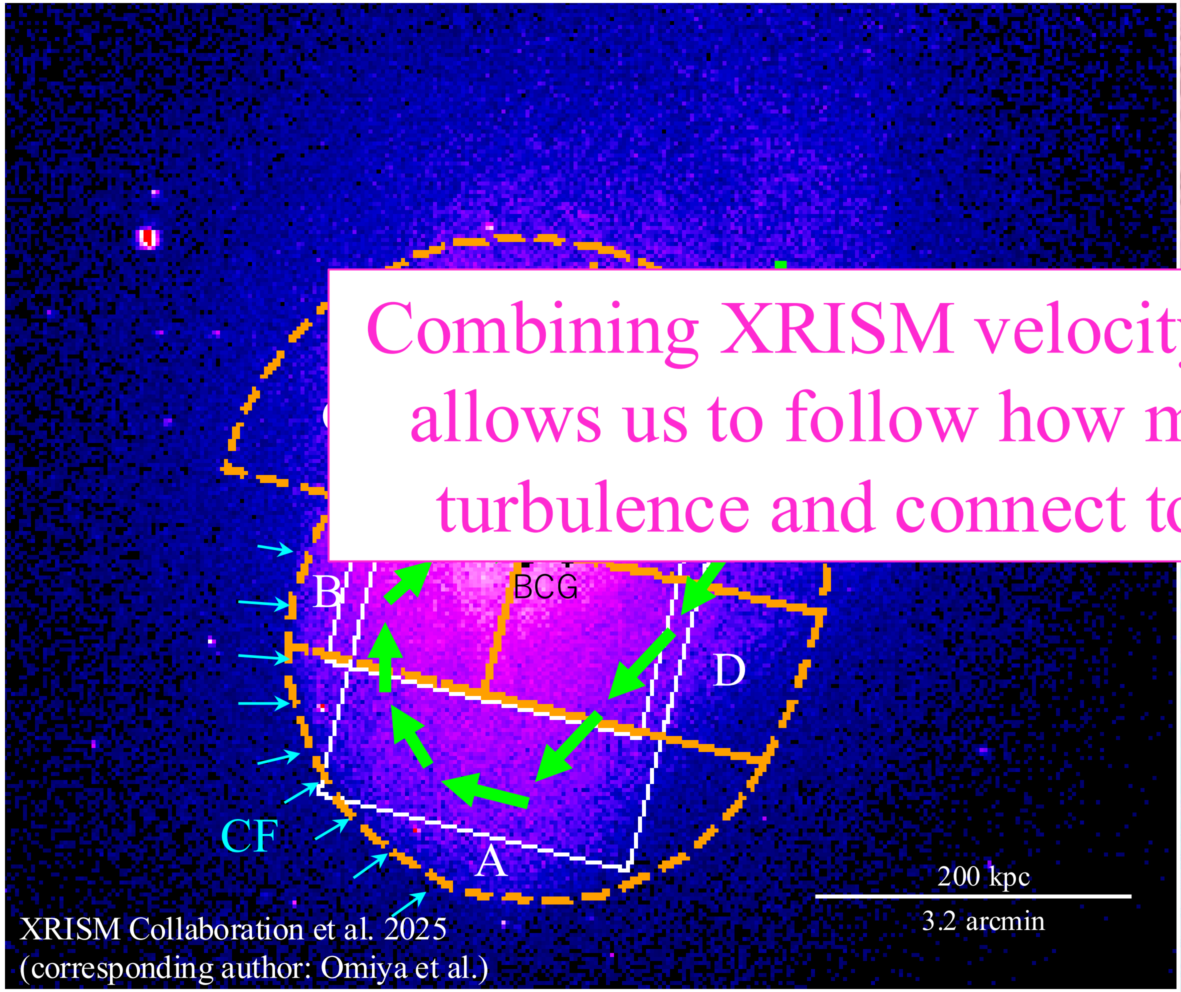
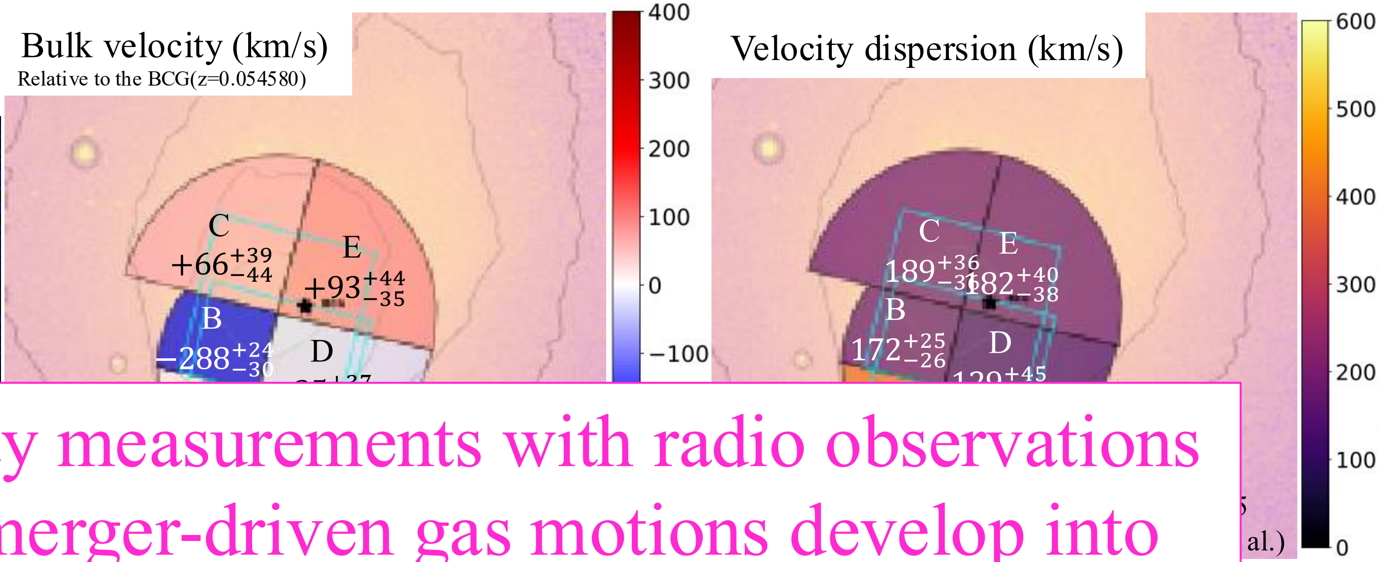
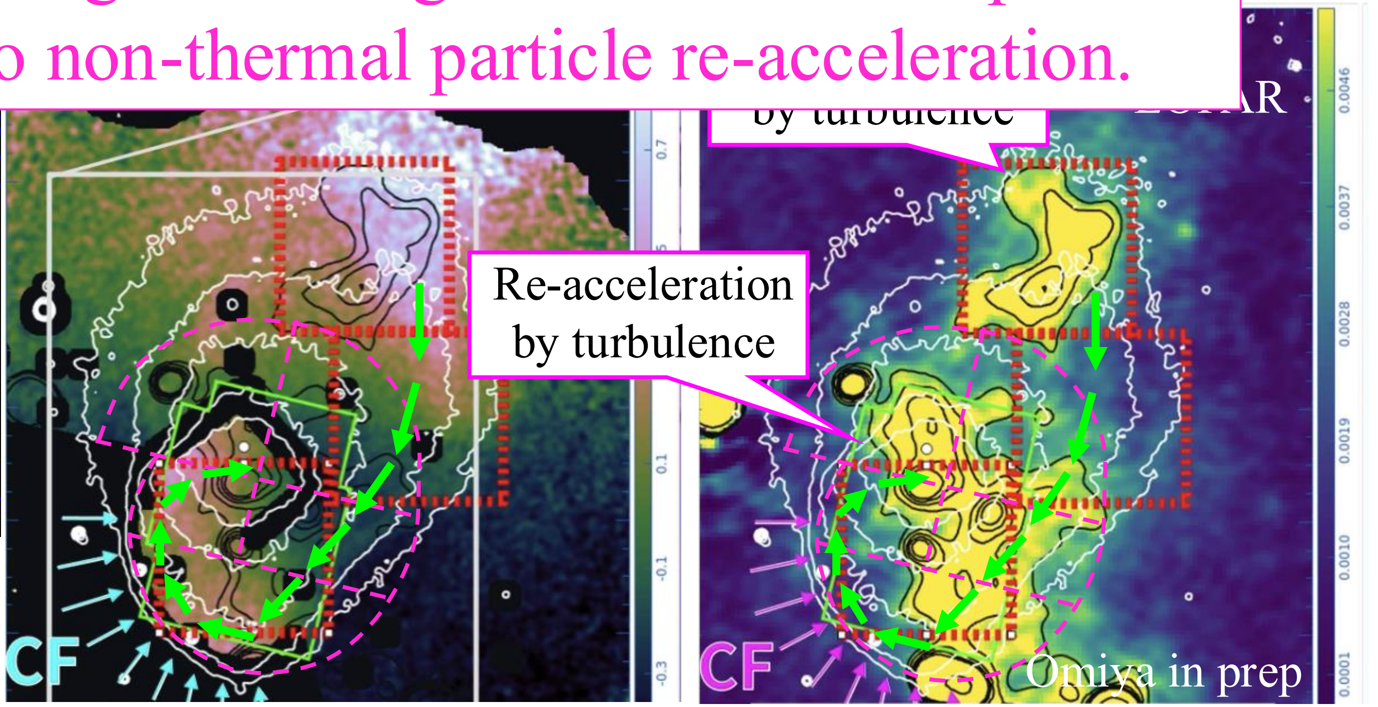




Combining XRISM velocity measurements with radio observations allows us to follow how merger-driven gas motions develop into turbulence and connect to non-thermal particle re-acceleration.

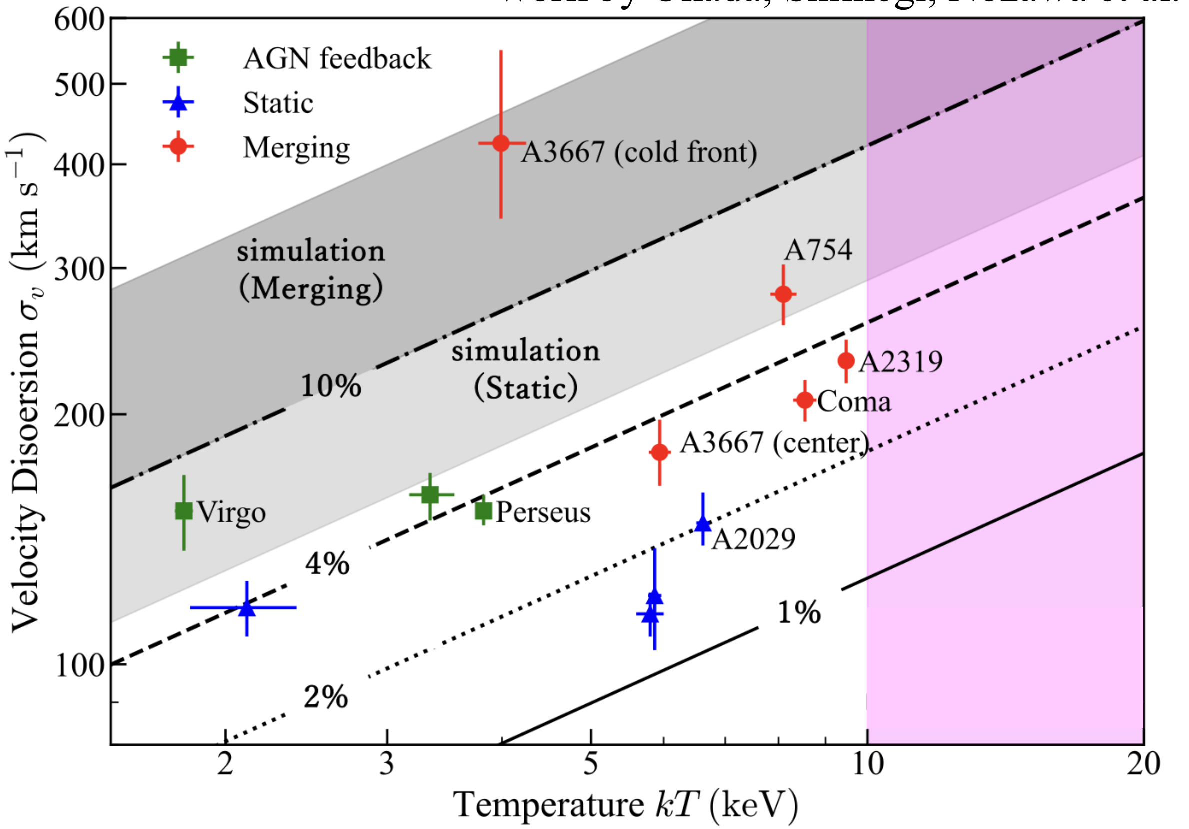


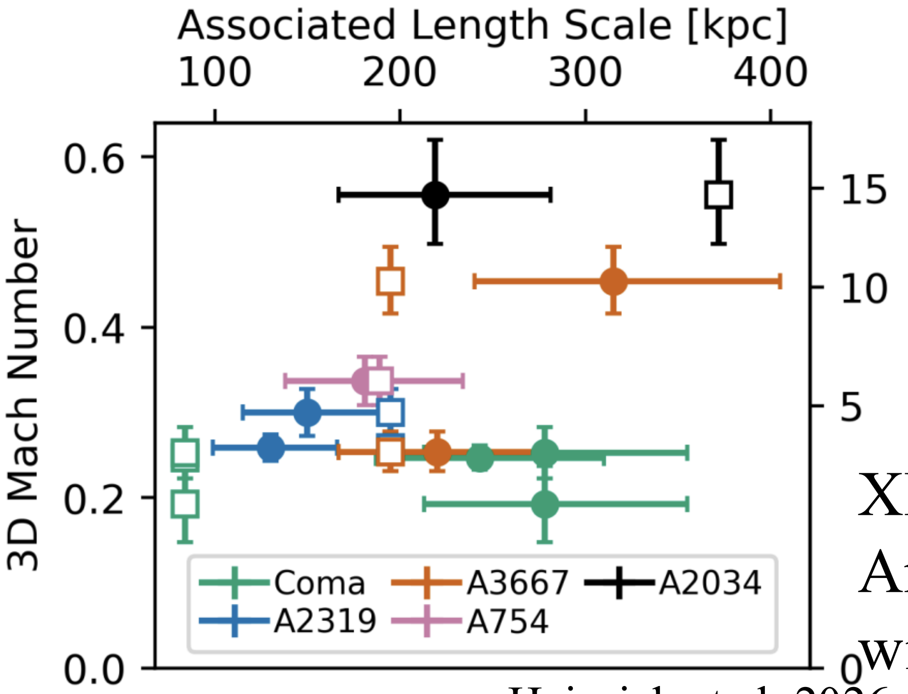
Toward a stacked XRISM sample of clusters

On June 3, XRISM reached 1000 days since launch！

Current five paper of merging clusters
Coma cluster; XRISM collaboration et al. 2025a
Abell 2319; XRISM collaboration et al. 2025b
Abell 3667; Omiya et al. 2026a
Abell 754; Omiya et al. 2026b
Abell 2034; Heinrich et al. 2026

Work by Okada, Shimegi, Nozawa et al.



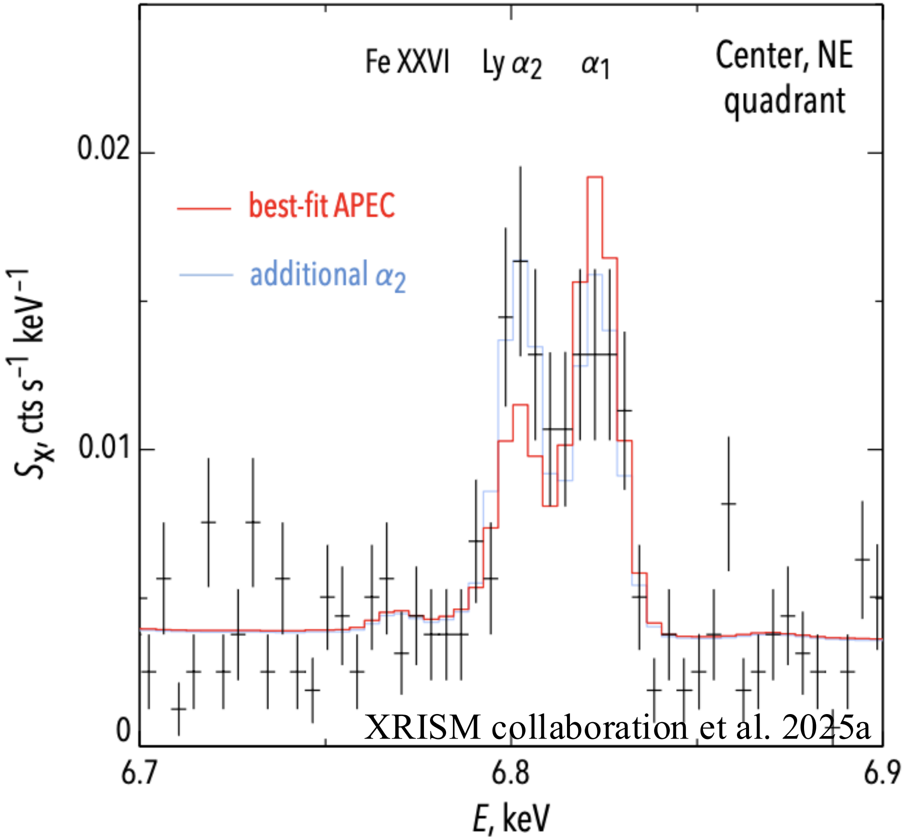


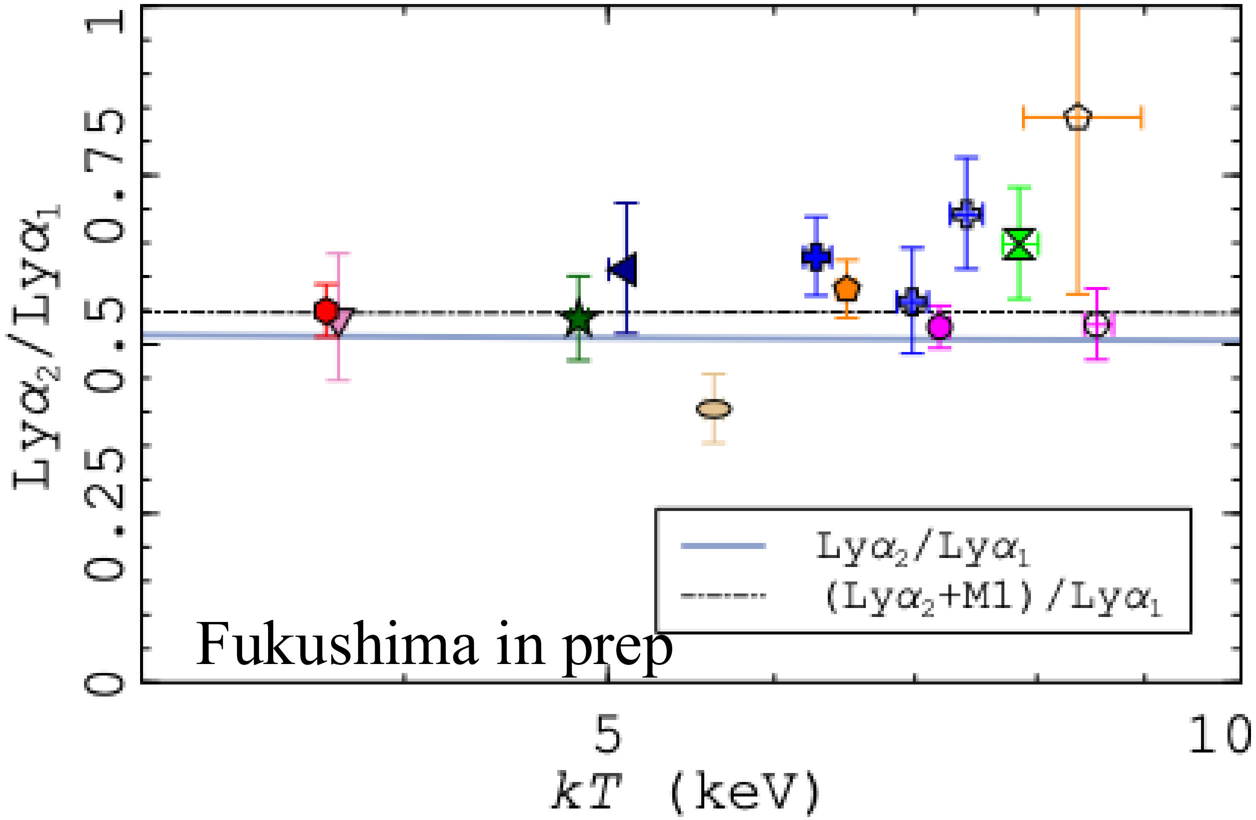
Heinrich et al. 2026

XRISM is planned to continue observation operations after 2026. An expanding sample will allow us to compare ICM gas motions with merger stage, cold fronts, shocks, and radio halos.

Stacking reveals Fe-line physics

Standard CIE predicts Fe Lyα2/Lyα1 ≃ 0.5.

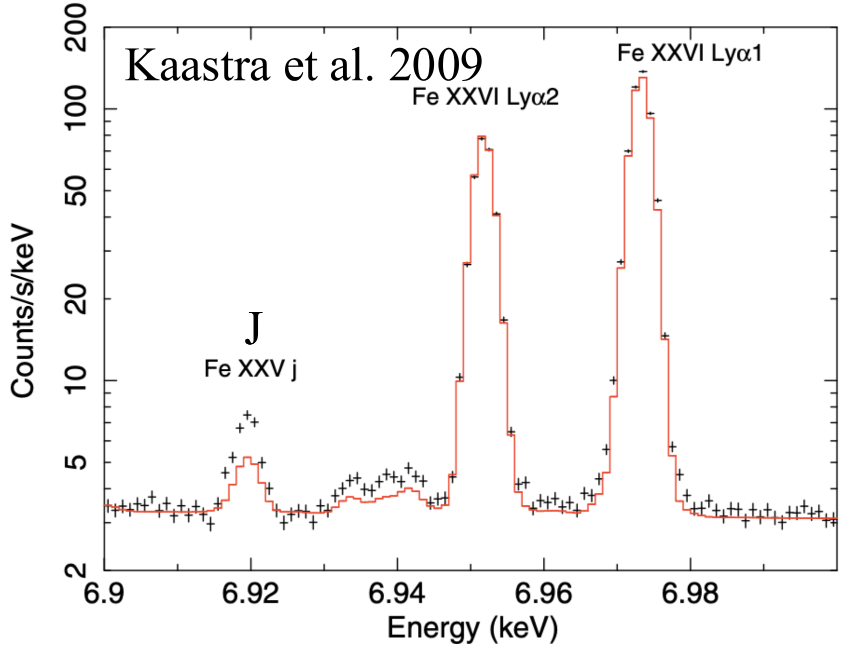


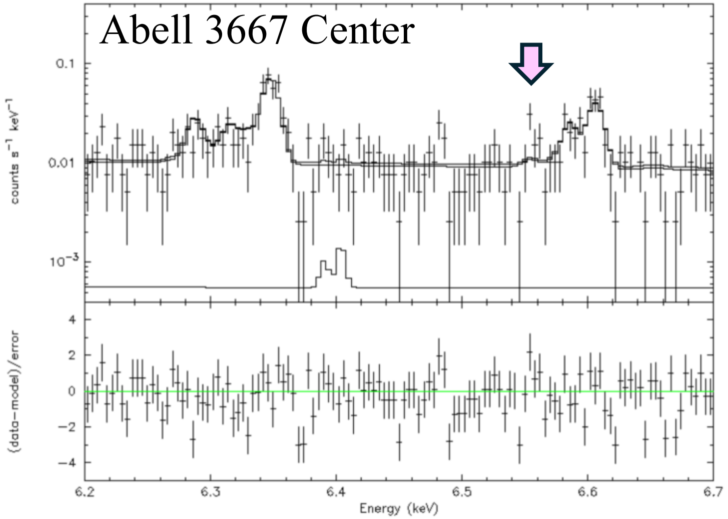


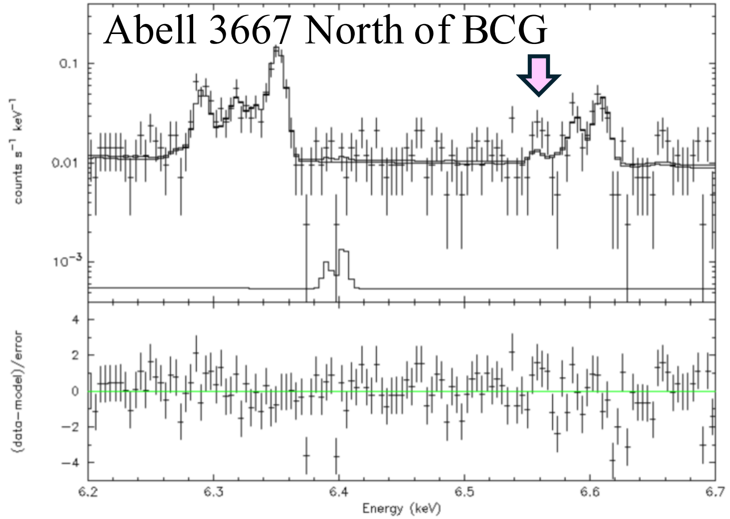
- Cluster samples suggest a possible excess in Fe Lyα2/Lyα1, especially above kT ≳ 6 keV.
- The anomaly may be caused by changes in the population of excited levels: unresolved M1 emission?, atomic uncertainties?, recombination/cascade processes?, charge exchange?, or non-Maxwellian electrons?

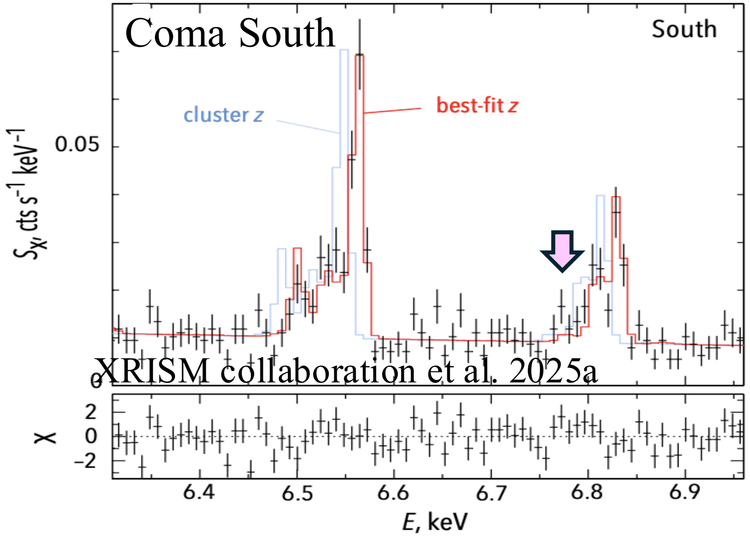
DR satellite lines as a probe of Non-Maxwellian

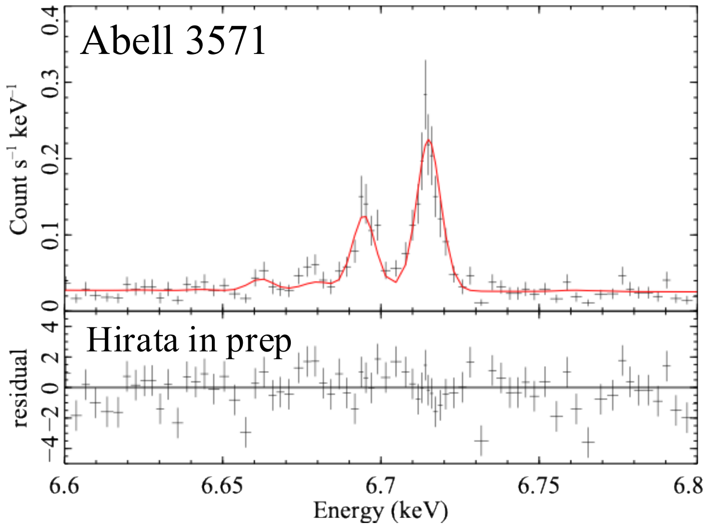
- DR satellite lines are sensitive to the electron energy distribution
- A high-energy tail, such as a kappa distribution, can enhance DR line emission.









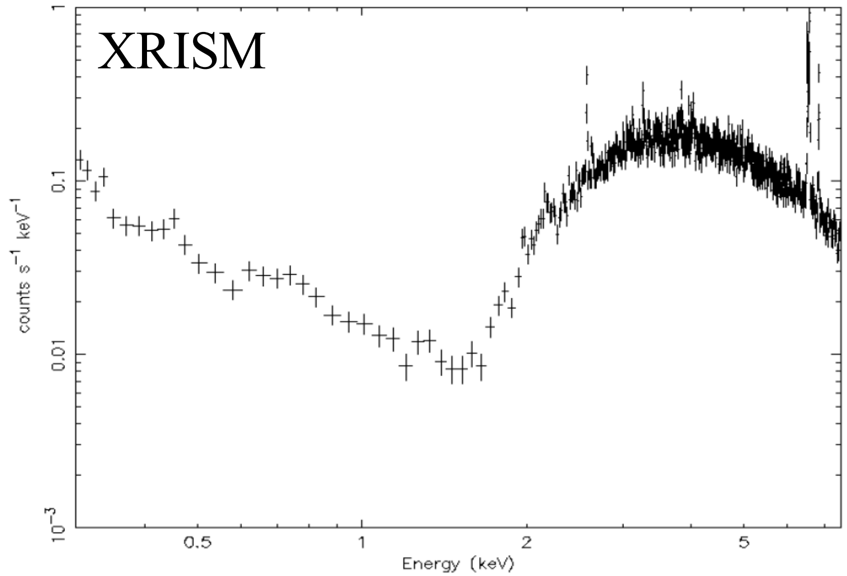


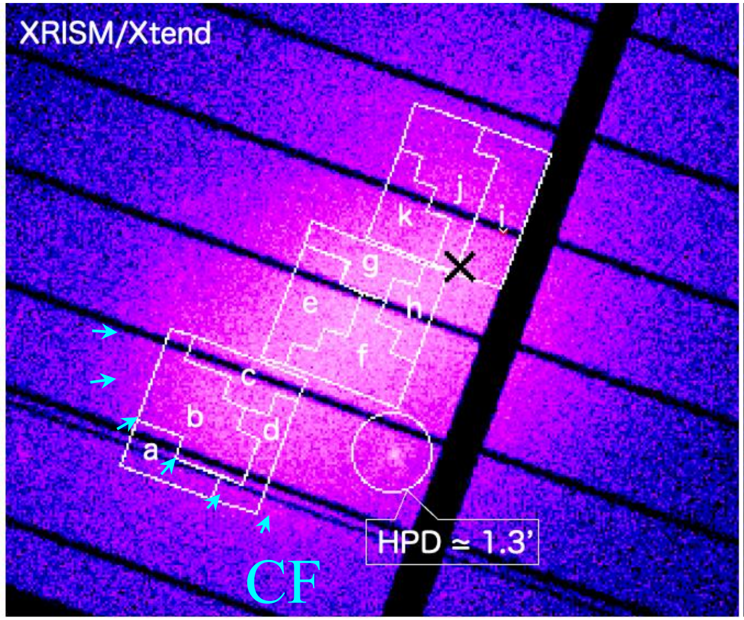
Hints of enhanced DR lines are seen in: part of observations.

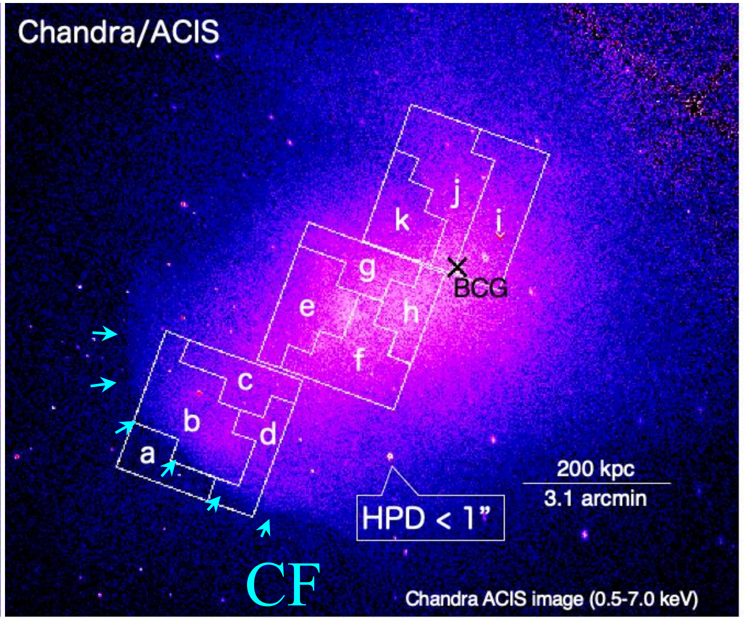
These trends are tentative and currently under investigation (Omiya in prep)

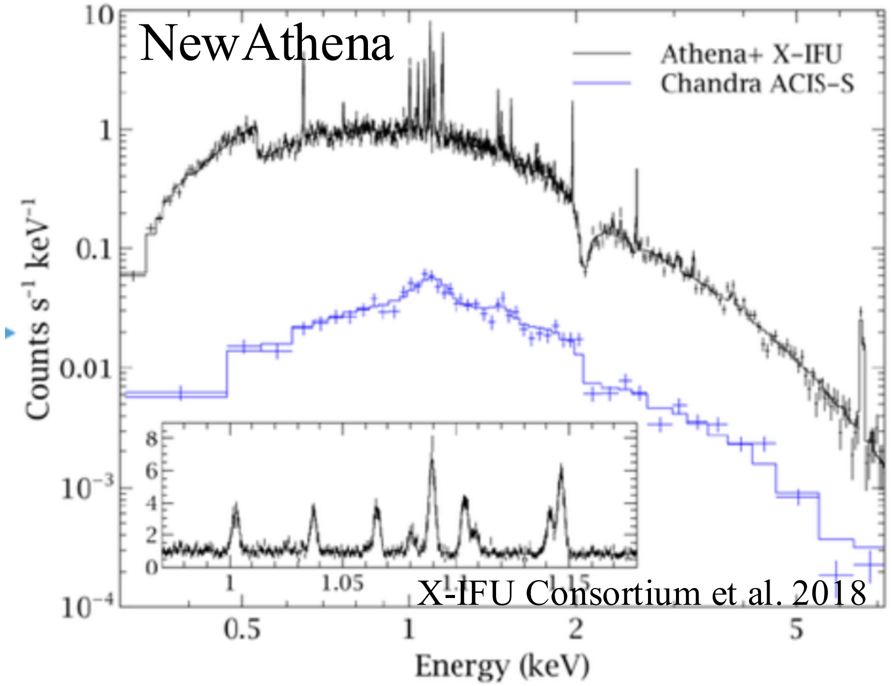
What can be done in NewAthena era

	XRISM/Resolve	NewAthena/X-IFU
Field of view	3′ × 3′	4′ FoV
Energy range	1.7–12 keV nominal	0.2–12 keV
Energy resolution	4.5 eV at 6 keV	< 4 eV up to 7 keV
Effective area	180 cm² at 6 keV	880 cm² at 7 keV
Angular resolution	1.3′ HPD	~9″ HEW
Detector format	6 × 6 array	~1500 pixels









Summary

- XRISM/Resolve directly measures ICM gas motions through Fe-K line shifts and broadening, revealing merger-driven bulk motions and velocity dispersion in clusters.
- In merging clusters such as Coma, A3667, A2319, A754, and A2034, XRISM shows larger gas motions than in relaxed systems, indicating non-negligible non-thermal pressure.
- In A3667, XRISM detects a large velocity shear across the cold front and enhanced velocity dispersion in the wake, suggesting that moving-core motions develop into turbulence and may connect to radio-halo emission.
- Stacked XRISM cluster samples are beginning to reveal not only ICM dynamics, but also Fe-line anomalies, including possible Fe Lyα doublet and DR satellite-line features.
- NewAthena/X-IFU will extend XRISM science by resolving cold fronts, shocks, wakes, and low-energy line diagnostics, linking cluster-scale merger dynamics to plasma microphysics.