“Brick” or “Mist”? Investigating Cold Gas Dynamics in Cool-core Clusters

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Introduction

Multi-phase gas in cool-core (CC) galaxy clusters:

1) **Intracluster medium (ICM, hot gas)**: diffuse and ionized gas, emitting X-rays with a temperature around 10^7 to 10^8 K (Fig 1a).
2) **Cold gas**: T$\sim 10^4$ K, formed through ICM radiative cooling, emitting transition lines in optical wavelengths, e.g., $H\alpha$, [O II], etc. (Fig 1b).

Motivation. The characteristic size of cold gas (on pc scales) is typically unresolved in observations and simulations. To address this, we perform hydrodynamic simulations assuming two scenarios for cold gas: the dense, clumpy ”Brick” and the light, passively evolving “Mist”.

Aims. We investigate the kinematics of gases and compare the results with the latest observations (Fig 1). Our goal is to gain insights into the nature of cold gas in CC clusters and to offer explanations of quiescent cluster atmospheres revealed by recent XRISM observations.

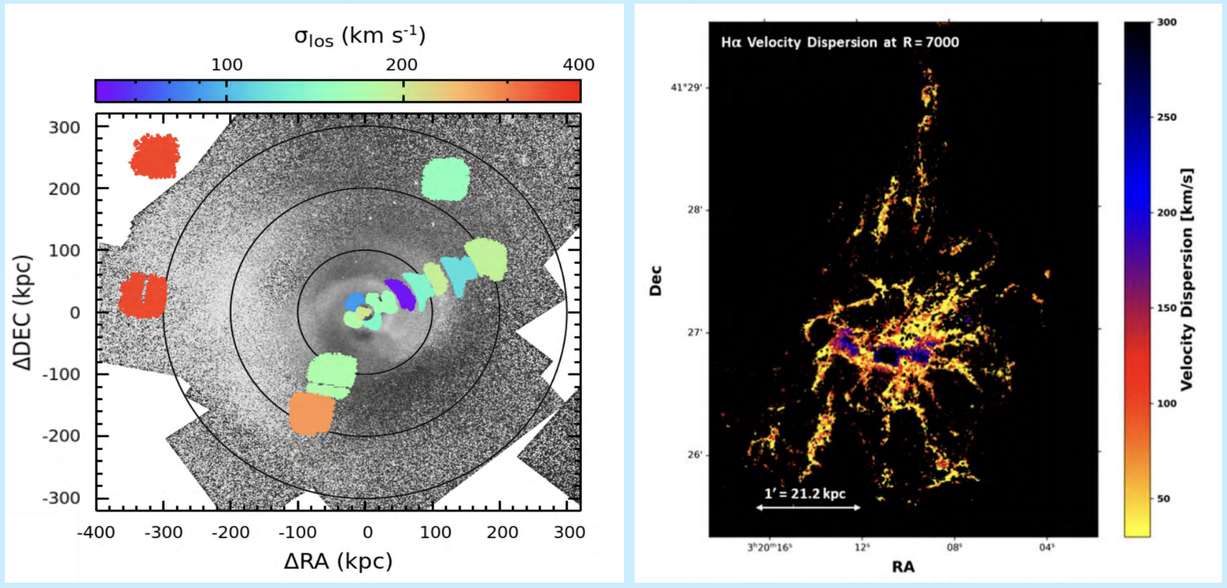


Fig 1a (left), 1b (right): Hot gas (a) and cold gas (b) velocity dispersion observations at the central region of the Perseus cluster by Zhang et al., 2025 and Vigneron et al., 2024. Hot gas is observed in X-ray by XRISM, while cold gas observation used $H\alpha$ line as tracer.

Methods

Our simulations used the FLASH code with adaptive mesh refinement (AMR) and the initial condition of the Perseus cluster. The AGN feedback is modelled using kinetic-energy or cosmic-ray (CR)-energy dominated jets. The implementation of cold gas behaviors in the two simulations:

1) **Brick**: gas motions and interactions follow the typical hydrodynamic equations, representing dense cold gas clumps (Wang & Yang, 2022). The cold gas snapshot colored with LOS velocity is shown in Fig 2a.
2) **Mist**: cold gas clumps are removed from the grid and replaced by a tracer particle, representing light, passively evolving cold gas mists that are unresolved in the simulations (Yang & Reynolds, 2016b). The mist-like cold gas is shown in Fig 2b.

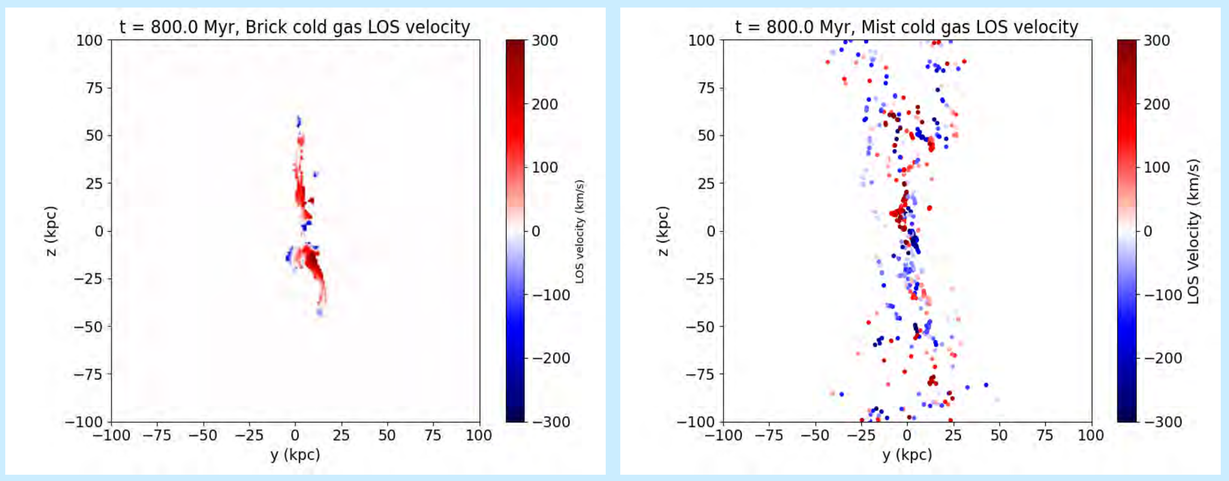


Fig 2a (left), 2b (right): Cold gas snapshot colored with LOS velocity in the Brick (a) and the Mist simulation (b) at t = 800 Myr.

Results & Discussion

1) Time evolution (Fig 3a, 3b) shows that the **hot gas in the Mist model is less disturbed** than in the Brick. In the Mist simulation, the jet activity is the only stirring source, while both the cold gas and jet are stirring the hot gas in the Brick simulation.
2) In central regions of CC clusters, observed hot gas velocity dispersion values are consistent with Brick 1-sigma range but outside the Mist simulation predictions (Fig 4). On the other hand, TNG-Cluster, Three Hundred Project cosmological simulations overpredict the velocity dispersion values between 150 to 300 km/s (XRISM collaboration, 2025).
3) Despite the consistency from the Brick hot gas results, we focus on the evolution of a single, isolated cluster without large-scale disturbance and accretion. Therefore, accounting for these environmental contributions, the true velocity dispersion should be greater than the current results.
4) Simulation implementing **CR-mode feedback also presented smaller velocity dispersion** compared with kinetic-mode feedback used in the Brick and Mist simulation (Fig 5). The feedback is relatively gentle, since most of the jet energy is in the form of CR energy rather than kinetic energy (Ruszkowski, Yang & Reynolds, 2017).

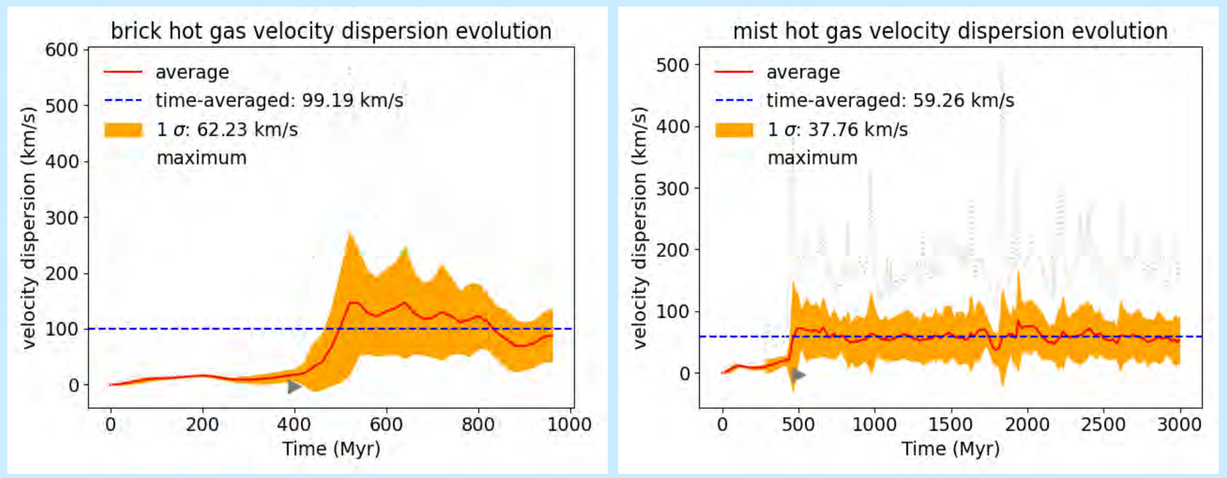


Fig 3a (left), 3b (right): Evolution of hot gas velocity dispersion throughout the Brick (a) and the Mist (b) simulation. Averaged values (red solid), standard deviation (orange shaded), and maximum (light grey dashed) are derived after smoothing over 20 kpc to simulate the lower spatial resolution in X-ray observations. The time-averaged values (blue dashed) are counted since the system reached quasi-equilibrium (grey triangle).

Conclusions

We perform hydrodynamic simulations, modeling the cold gas as dense, clumpy “Brick”, or light, passively evolving “Mist” and compare gas kinematics with observations as well as CR-mode feedback simulation. From our results, we suggest either using a Mist-like cold gas or considering CR-mode feedback in cosmological simulations will decrease the predicted hot gas velocity dispersion values.

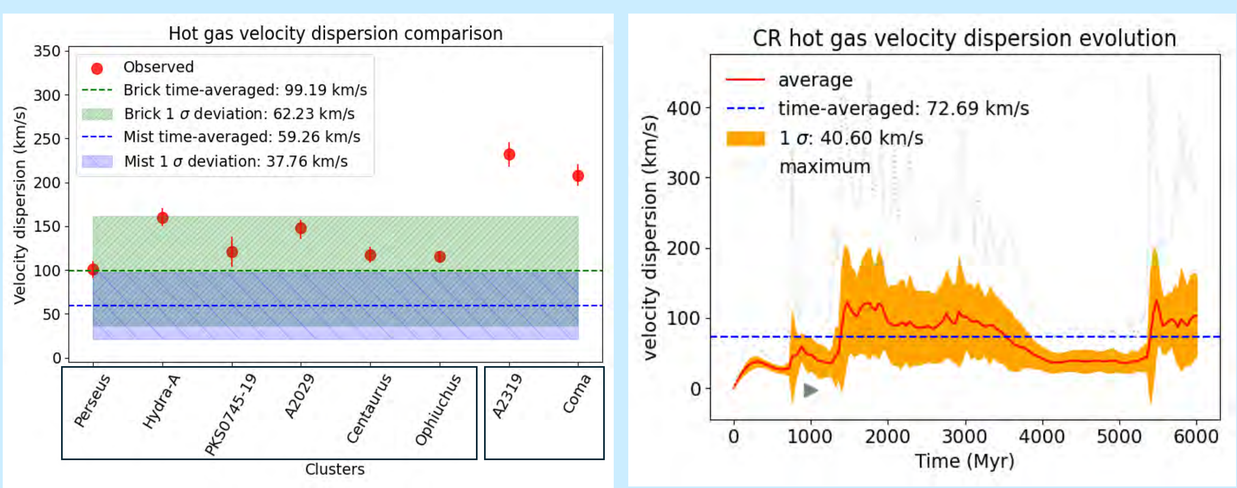


Fig 4. (left): Central velocity dispersion in CC (left rectangle) and non-CC clusters (right rectangle) observed by XRISM (red) overplotted with average and 1-sigma deviation from the Brick’s (green dashed and striped) and the Mist’s prediction (blue dashed and striped).

Fig 5. (right): Evolution of hot gas velocity dispersion in the CR simulation. Notations are same as Fig 3a, 3b.

References

[1] Wang & Yang 2022, MNRAS, 512, 5100

[2] Yang & Reynolds 2016b, ApJ, 818, 181

[3] XRISM collaboration et al, 2025, ApJL, 993, L11

[4] Ruszkowski, Yang & Reynolds, 2017, ApJ, 844, 13

[5] Zhang et al., 2025, A&A submitted

[6] Vigneron et al., 2024, ApJ, 962, 96