

Cold gas formation triggered by active galactic nucleus jet feedback in galaxy cluster cores

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ABSTRACT

Extended warm and cold gas nebulae, with complex morphologies and kinematics, have been observed in the centres of cool-core galaxy clusters. Their origin within the hot intracluster medium (ICM) is still puzzling, and among many mechanisms, positive feedback from the central active galactic nucleus (AGN) has been proposed. In this work, we performed a suite of very high-resolution hydrodynamic simulations of a Perseus-like cool-core galaxy cluster subject to self-regulated AGN jet feedback, which leads to realistic ICM properties. By explicitly following warm ionised, neutral, and molecular gas phases, we studied the complex interplay between AGN activity and the multi-phase ICM. While AGN feedback globally heats the ICM, we find that during the individual AGN jet bursts, hot material is also injected laterally to the jet axis, within the turbulent mixing layer. This material, as it expands, compresses the surrounding hot ICM, reducing the local cooling time, and leads to the formation of cold clumps on a characteristic timescale of ~ 30 Myr. By employing tracers, we explicitly track cooling within the affected regions, finding that very hot gas identified in high-compression, low-vorticity zones condenses in situ to form cold clumps. A statistical analysis reveals that the condensation of cold gas is highly promoted once the local turbulent Mach number, $\sigma_{\text{hot}}/c_{s,\text{hot}}$, in the hot gas component ($T \geq 10^7$ K) takes values of around ~ 0.3 . The presented process is a further important step in understanding the physical mechanisms that lead to the formation of cold gas in the cluster core. Our measured values of the characteristic turbulent Mach number, together with detailed multi-phase gas kinematics predictions, provide important theoretical tools to interpret future X-ray spectroscopy and deep radio data, ultimately to constrain the origin of cool-core cluster nebulae.

Key words. turbulence – galaxies: clusters: general – galaxies: clusters: intracluster medium – intergalactic medium – galaxies: jets

1. Introduction

Within cool-core galaxy clusters, the feedback from the central active galactic nucleus (AGN) has been firmly identified as the fundamental process regulating intracluster medium (ICM) thermodynamic properties by providing an energy supply sufficient to combat gas radiative cooling losses (see e.g. McNamara & Nulsen 2007; Fabian 2012; Hlavacek-Larrondo et al. 2022; Bourne & Yang 2023). However, surrounding the cluster-Dominant (cD) galaxy, large, clumpy, filamentary, and multi-phase gas structures have been widely observed. The warm ionised phase ($T \simeq 10^4$ K) has been detected through H α , [N II], [O II], OI, and [Si II] emission lines, revealing structures with highly variable sizes that range from a few kiloparsecs up to ~ 80 – 100 kpc (Fabian et al. 2008, 2016; Fabian 2012; Olivares et al. 2019, 2022; Gingras et al. 2024; Tamhane et al. 2026). Co-spatial with these structures is a molecular component observed in CO and H₂ emission (Salomé et al. 2011; Pulido et al. 2018; Olivares et al. 2022). The mass of the molecular gas in these filaments ranges between 10^8 – 10^{10} M $_{\odot}$, and the mass of the ionised gas is of the same order of magnitude. Furthermore,

these filaments also contain dust and are permeated by magnetic fields (Fabian et al. 2008; Donahue et al. 2011; Reefe et al. 2025). Previous work has suggested that the magnetic fields may stabilise the filaments against gravitational collapse (Fabian et al. 2008), but some observations also reveal the presence of star formation (Fogarty et al. 2015, 2019).

Observations of cold gas kinematics reveal line-of-sight velocities ranging from ± 50 to ± 600 km/s (Gendron-Marsolais et al. 2018; Olivares et al. 2019, 2022; Ganguly et al. 2023; Gingras et al. 2024; Li et al. 2025). The complex morphologies and kinematics allow, in a few cases, for it to be determined whether the gas is infalling or outflowing with respect to the central supermassive black hole (SMBH). The main caveats here are projection effects and the determination of the filling factor. Understanding the detailed kinematics of the hot phase is, however, more challenging. So far, only a select number of measurements have been taken of the hot ICM velocity dispersion using X-ray spectroscopy, and they have a lower spatial and spectral resolution compared to the cold phase measurements. Somewhat surprisingly perhaps, these observations have revealed relatively quiet environments for the few cluster cores observed so far, with velocity dispersion values between

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150–200 km/s (Hitomi Collaboration 2016; Fujita et al. 2025; XRISM Collaboration 2025a,b).

Given this complex observational picture, the nature and formation of these cold filaments are still not well understood, notwithstanding a large theoretical body of work. Linear stability analysis (e.g., Malagoli et al. 1987; Balbus & Soker 1989; Loewenstein 1999) showed that in a stratified galaxy cluster atmosphere, thermal instability cannot form localised clouds of cold gas too distant from the halo centre: perturbations are either over-stable or their cooling time is larger than their free-fall time.

However, the evolution of non-linear perturbations, generated by AGN feedback, for instance, seems more relevant in this context. It is plausible that a strong enough perturbation could rapidly cool and form a cold clump (e.g., Joung et al. 2012; Beckmann et al. 2019), with the density (or entropy) contrast threshold for localised cooling being determined both by the properties of the background medium and the nature of the perturbation. Voit et al. (2017) summarised the basic underlying theoretical understanding of the cold gas cycle in the ICM subject to AGN feedback. As the gas is uplifted by the central AGN activity, new cold gas may form through thermal instability at larger radii caused by turbulence and mixing of the uplifted low-entropy gas. Several groups suggested that this happens when the minimum of the ratio between the cooling time, t_{cool} , and the free-fall time, t_{ff} , in the cluster is approximately equal to or below 10 (e.g., Gaspari et al. 2012; McCourt et al. 2012; Voit & Donahue 2015; Choudhury & Sharma 2016), even though cold gas is also found in simulations with different values of this ratio, and it is not entirely clear whether this captures the whole physics involved in this process (McNamara et al. 2016; Voit et al. 2017; Beckmann et al. 2019). For example, higher values of the ratio $t_{\text{cool}}/t_{\text{ff}}$ can still lead to the condensation of cold gas if large density perturbations are present, as shown by Choudhury et al. (2019) using 2D hydrodynamical simulations, or if there is enough turbulence in the medium to make buoyancy oscillations thermally unstable (Voit 2018). Furthermore, Voit (2021) studied cold gas condensation and precipitation due to different astrophysical processes in cluster and galactic halos, generalising previous findings. Entropy fluctuations, which in turn are directly linked to density and temperature perturbations (see also e.g., Fielding et al. 2020), and the tails of the respective distributions, have been found to be the key in driving the cold gas precipitation from a hot atmosphere.

A large body of theoretical work, studying cold gas formation due to AGN jet or cavity propagation, found that the complex multi-phase medium can extend to tens of kiloparsecs from the cluster centre (e.g., Brighenti & Mathews 2002a; Revaz et al. 2008; Gaspari et al. 2012, 2013, 2018; Li & Bryan 2014b; Brighenti et al. 2015; Beckmann et al. 2019; Qiu et al. 2020; Fournier et al. 2024; Sotira et al. 2025). Part of this cold gas is expected to infall towards the innermost regions, accrete onto the central SMBH on a dynamical time, and hence sustain the AGN feedback cycle. For example, Revaz et al. (2008) used an idealised simulation setup to show how cold gas can condense at the edges of rising cavities, falling back towards the centre of the gravitational potential. Brighenti et al. (2015) showed using two-dimensional simulations that cold clumps can form in the wake of a rising cavity and suggested that large vortexes generated around the buoyantly rising cavities lead to sustained, long-lasting compression. Rhea et al. (2025) studied the impact of magnetic fields on the survival of cold filaments, which can also help to promote cold clump filamentary morphology (Wang et al. 2021; Ehlert et al. 2023; Das & Gronke 2024; Fournier et al. 2024). Furthermore, Li & Bryan (2014b), Beckmann et al.

(2019), and Fournier et al. (2024) conducted a detailed analysis of the properties of the cold gas substructures in AGN feedback simulations and found that the AGN activity has a positive impact on the cold gas formation, with an important fraction of the cold gas forming during the uplift or condensing during the fallback toward the centre. Jennings et al. (2023) also found that the filaments are likely to experience a natural fragmentation in the hot ICM and that the resulting small clumps are sites for further condensation.

Investigating these phenomena with numerical simulations has, however, many limitations. The relevant temperature range is very large, since the ICM contains multi-phase gas from the X-ray emitting hot plasma at $\sim 10^8$ K to the very cold molecular phase at 10–100 K. Furthermore, when reaching the very cold phases of the gas, it is necessary to take care of the numerous (non-equilibrium) thermochemical processes happening at these low temperatures, as well as the complex physics of star formation and stellar feedback. To circumvent these difficulties, numerical simulations of galaxy clusters often introduce an artificial gas temperature floor of 10^4 K, with the obvious drawback that this does not allow a complete view to be obtained of the formation of the cold clumps (e.g., Li & Bryan 2014b), and also likely limits our understanding of AGN fuelling.

Another critical point is the AGN feedback implementation: even high-resolution zoom-in simulations of galaxy clusters cannot inject AGN-driven jets from first principles and instead have to employ subgrid models (for a review see Bourne & Yang 2023). While some works compute the AGN power from the accretion of the hot gas based on the Bondi-like formula (e.g., Sijacki et al. 2007; Dubois et al. 2011), in other works the AGN feedback power is calculated taking into account the quantity of gas below a temperature threshold (usually a few 10^4 Kelvin) or above a given density threshold, within a region close to the sphere of influence of the SMBH (e.g., Gaspari et al. 2011a,b, 2015; Li & Bryan 2014a,b; Prasad et al. 2015; Yang & Reynolds 2016; Ehlert et al. 2023).

In our first work, Sotira et al. (2025), through numerical simulations based on the approach of Li & Bryan (2014a) and adopting the ENZO code, we found that the hot gas velocity dispersion in the cluster core is strongly linked to the AGN activity and that, even though the kinematics of the hot and the colder phases are roughly correlated, to the first order, they can show large discrepancies when analysed in detail. Furthermore, we found that the formation of cold gas is promoted by kinetic jet feedback and further aided by jet precession. However, a fully self-consistent model that explains how the colder phases can be formed in the hot environment of the cluster core is still lacking, and is the aim of the present study.

Here, using the moving-mesh code AREPO (Springel 2010; Pakmor et al. 2016), we performed a new simulation suite following the AGN feedback cycle in a Perseus-like galaxy cluster. We used the GRACKLE library (Smith et al. 2016), which models non-equilibrium primordial chemistry, as well as metal cooling via look-up tables, and allows for low temperature cooling to follow the formation of the warm ionised, neutral, and molecular phases, with a minimum temperature threshold at 10 K. This approach allowed us to conduct a more reliable and detailed analysis of the formation and kinematics of the cold, warm ionised and molecular phases, and their connections with the hot medium. We furthermore incorporated jet-driven AGN feedback based on work by Bourne & Sijacki (2017); Bourne et al. (2019) and Bourne & Sijacki (2021), together with a novel sink-particle-based model for SMBH accretion (Ortame et al. 2026), allowing us to simulate very high-resolution

hydrodynamical jets and resolve the lobe and ICM turbulence thanks to targeted super-Lagrangian refinement schemes. These high-resolution, light jets do not ‘drill’ through the ICM, but can be deflected by the cold gas phase present in the ICM.

The paper is organised as follows: in Section 2, we introduce the simulation setup, describing the initial conditions and the feedback implementation; in Section 3, we present the global properties of our simulation suite, verifying the validity of the outcomes; and in Section 4, we discuss the physical model responsible for the cold gas formation. Finally, in Section 5, we discuss the critical aspects of the model and present our conclusions.

2. Methodology and simulation suite

2.1. Numerical code and initial conditions

Simulations presented here were performed using the moving-mesh code AREPO (Springel 2010; Pakmor et al. 2016). Our simulated galaxy cluster has physical properties that closely resemble those of the Perseus cluster. The initial gas density profile was taken from the X-ray fitting of Churazov et al. (2004):

$$n(r) = \left(\frac{0.046}{\left[1 + \left(\frac{r_{\text{kpc}}}{57}\right)^2\right]^{1.8}} + \frac{0.00479}{\left[1 + \left(\frac{r_{\text{kpc}}}{200}\right)^2\right]^{0.87}} \right) \text{ cm}^{-3}. \quad (1)$$

We assumed an analytic dark matter halo that follows the NFW distribution with a mass profile of

$$M_h(r) = \frac{4\pi}{3} \rho_c R_s^3 d_c \left(\log(1 + r/R_s) - \frac{r/R_s}{1 + r/R_s} \right), \quad (2)$$

and density profile of

$$\rho_h(r) = \rho_c \frac{d_c}{\frac{r}{R_s}(1 + r/R_s)^2}, \quad (3)$$

where $c = 5$, $R_s = R_{200}/c$, $R_{200} = 1.9$ Mpc, $\rho_c = 3H_0^2/8\pi G$, and $d_c = 200c^3/(\log(1+c) - c/(1+c))$. The gas metallicity profile follows the observational fit by Rebusco et al. (2005),

$$Z(r) = 0.3 \frac{2.2 + (r/80)^3}{1 + (r/80)^3} Z_\odot, \quad (4)$$

where $Z_\odot = 0.127$ is the solar metallicity (Asplund et al. 2009).

The whole simulated domain is a box with side $6R_{200} = 11.5$ Mpc. We set the minimum allowed volume, V_{min} , for a cell to be the same as a sphere of radius 100 pc. The target mass of the gas cells is $m_{\text{cell}}^{\text{target}} = 10^8 M_\odot$, although we note that, due to novel refinement schemes (discussed below), a much higher mass resolution is achieved in and around the jets and SMBH regions, reaching minimum cell masses of around 10^2 – $10^3 M_\odot$. The SMBH has an initial mass of $M_{\text{BH}} = 4 \times 10^9 M_\odot$, and was placed at a fixed position at the centre of the cluster. At the beginning of the simulation, we evolved the cluster adiabatically for 2 Gyr to relax the initial conditions and to allow temperature and entropy to settle into a hydrostatic equilibrium. This procedure also introduces to the ICM a low-level turbulence with velocities of around 10 km/s.

2.2. Cooling processes: Neutral gas, molecular gas, and dust

Since the aim of the work is the study of the cold gas phases, we want to follow the formation of low-temperature gas below the typical temperature floor adopted by many numerical approaches (e.g., Sotira et al. 2025). In this work, we focus on the formation channels of neutral and molecular gas, while we shall address detailed dust and star formation processes in a future work.

We used GRACKLE (Smith et al. 2016), which tracks non-equilibrium primordial chemistry and cooling for nine species of H and He, including H₂ formation on dust grains, and has tabulated metal-line cooling rates also in the presence of an ultra-violet background radiation field. We note that, although the simulations reach a high spatial resolution, the cooling length and internal structure of cold clouds are not fully resolved (e.g., Rey et al. 2024); consequently, the exact partitioning of the cold gas into neutral and molecular components, presented below, should be interpreted as an indicative diagnostic of the model behaviour, as opposed to a strict quantitative prediction.

Detailed modelling of dust evolution, growth, and destruction in the ICM is beyond the scope of this paper. However, dust acts as an important catalyst for the formation of molecular hydrogen. Therefore, we employed a simplified dust model within our simulations. The dust is present only in cells in which more than half of the cell mass (considering both hydrogen and helium) is composed of neutral gas, where a local dust-to-gas ratio is assumed to be $M_{\text{dust}}/M_{\text{gas}} = 0.009387$ (Pollack et al. 1994). This assumption takes into account the initial condition of a dust-poor, hot ICM, due to grain sputtering, and dust growth by accretion in cold, dense gas. The main cooling process of the hot gas component is Bremsstrahlung cooling for all ionised species (Black 1981).

2.3. Star formation prescription

Detailed modelling of star formation and stellar feedback is beyond the scope of this study. However, to prevent excessive dense gas formation, it is advantageous both from a physical and numerical viewpoint to convert the densest gas cells, which reside in the interstellar medium (ISM) of the cD galaxy, into stars. At the mass and spatial resolutions that can be achieved even in high-resolution isolated galaxy cluster simulations, it is extremely difficult to employ realistic star formation and feedback models, where the multi-phase nature of the ISM is unresolved. On the other hand, employing models that treat the ISM by employing an effective equation of state (see e.g., Springel & Hernquist 2003) also presents difficulties as star formation often proceeds at relatively low gas density thresholds, and gas cooling to low temperatures on the equation of state is often not considered. Therefore, we employed here a different and simple approach that allowed us to hydrodynamically follow cold, dense gas to sufficiently high densities, as follows. Following Bourne et al. (2015), whenever a gas cell is colder than its Jeans temperature, defined as

$$T_J = \rho^{1/3} \frac{\mu m_p G}{\pi k_B} (N_{\text{ngb}} m_{\text{cell}})^{2/3} \text{ K}, \quad (5)$$

where ρ is the gas cell density, m_{cell} its mass, and $N_{\text{ngb}} = 8$, and the cell has a density higher than the threshold density, $n_{\text{SF}} = 2 \times 10^4 \text{ cm}^{-3}$, it is converted into a star particle. No stellar feedback is produced by the star particles, which act as pure N -body particles after their formation. While this is certainly a significant simplification, for the purpose of this work our concern is for the amount of dense gas formed to be realistic in the

simulation, so that we can study the interplay between the AGN-driven jet and the multi-phase ICM (see Section 4.1 for details), while we postpone the development of a more sophisticated star formation module to a future work. Simulations with AGN feedback and detailed star formation models in galaxy clusters can be found in Li et al. (2015).

2.4. SMBH accretion and AGN feedback implementation

The feedback implementation is based on the model presented in Bourne & Sijacki (2017) and Bourne & Sijacki (2021), with some modifications to account for interactions between the jet and cold gas and SMBH accretion modelling. Here, SMBH accretion is tracked based on the sink particle model presented in Ortame et al. (in prep). Specifically, for the purpose of this work, it captures the accretion of cold gas within the accretion radius of the SMBH on a fixed accretion timescale (see also e.g., Li & Bryan 2014a,b and Sotira et al. 2025). The gas cells are drained following a mass-weighted Gaussian kernel if the following requirements are satisfied:

- They have a temperature below $T_{\text{cold}} = 10^4$ K;
- They are located within the accretion region with radius $r_{\text{acc}} = 500$ pc centred on the SMBH;
- The sum of the masses of these cells is greater than a minimum mass of $M_{\text{acc}} = 10^7 M_{\odot}$.

The consequent mass that flows toward the SMBH, $\dot{M}_{\text{in}}$, is the total kernel-weighted¹ mass of these cells, multiplied by an accretion efficiency, $\eta = 0.1$, divided by an accretion time, $\tau_{\text{acc}} = 5$ Myr, approximately the free-fall time of the accretion region. It is assumed that half of this mass goes into accretion and half is launched in the jet such that $\dot{M}_{\text{acc}} = \dot{M}_{\text{J}} = \dot{M}_{\text{in}}/2$.

When the AGN feedback is active, inside the accretion region, an ‘injection cylinder’ with radius r_{jet} and height $2h_{\text{jet}}$ is defined centred on the SMBH, in which mass, momentum, and energy are injected into the gas cells in order to launch the jet. The cylinder aspect ratio is fixed such that $r_{\text{jet}}/h_{\text{jet}} = 1$. The cylinder target size was determined such that each half cylinder contains a fixed gas mass of $10^4 M_{\odot}$ or at least ten gas cells. An additional criterion was enforced such that the injection region cannot extend beyond the sink boundary. The cylinder and thus the jet axis do not take into account any precession effects, i.e. the jet is always launched along the z axis.

The feedback implementation employs a hybrid mix of thermal and kinetic energy injection, which adapts the feedback based on its interplay with different gas phases (i.e. dense vs dilute gas). Mechanical feedback from hot high-speed jets acts in a different way on the hot ICM and cold, dense clouds, the former being accelerated and the latter being heated or destroyed. Klein et al. (1994) and more recent works (Armiglotta et al. 2017; Gronke & Oh 2018) through analytical studies and idealised hydrodynamic simulations indicate the conditions under which a cold gas cloud is destroyed, or can survive and be accelerated, when hit by a rarefied hot wind, even though the survival of cold clouds in a hot wind tunnel in the presence of radiative cooling, magnetic fields, and transport processes is still not well understood (Jennings et al. 2023). For this purpose, we injected kinetic energy into the hot cells, while we injected thermal energy plus momentum into the cold, dense gas cells near the SMBH (see, Bourne & Sijacki 2017, for a comparison of kinetic energy versus momentum conserving injection techniques), under the assumption that cold, dense clouds are only

affected by the ram pressure of the outflow (Bourne et al. 2014, 2015). To separate the two feedback coupling behaviours, we used the density as a discriminant, with a density threshold of $n_{\text{th}} = 10 \text{ cm}^{-3}$.

All quantities were updated in the injection cylinder weighted through a kernel function, $W_{\text{J}}(r, z) \propto \exp(r^2/2r_{\text{jet}}^2)|z|$. The expected total mass and energy injected in the i -th cell are given by

$$dE_i^{\text{tot}} = \frac{\dot{E}_{\text{J}} dt}{2} \frac{V_i W_{\text{J}}(r, z)}{V_{\text{weight}}}, \quad \text{and} \quad dm_i = \frac{\dot{M}_{\text{J}} dt}{2} \frac{V_i W_{\text{J}}(r, z)}{V_{\text{weight}}}, \quad (6)$$

respectively, where $\dot{E}_{\text{J}} = \epsilon \dot{M}_{\text{acc}} c^2$ with $\epsilon = 0.1$, V_i is the cell volume and V_{weight} is the kernel normalisation. In the kinetic coupling regime, the momentum added to the cell, with an initial energy, mass, and momentum of $E_{i,0}$, $m_{i,0}$, and $\mathbf{p}_{i,0}$, respectively,

was calculated as $|d\mathbf{p}_i^{\text{tot}}| = \sqrt{2(m_{i,0} + dm_i)(E_{i,0} + dE_i^{\text{tot}}) - |\mathbf{p}_{i,0}|^2}$.

This is designed to conserve the injected energy in kinetic form. Due to potential momentum cancellation, if the actual gain in a cell’s total energy is less than dE_i^{tot} , the internal energy will be increased by an appropriate amount to ensure energy conservation. For the thermal coupling regime, we instead directly injected the assumed jet momentum, with each cell receiving a momentum of

$$d\mathbf{p}_i = \frac{\dot{\mathbf{p}}_{\text{J}} dt}{2} \frac{V_i W_{\text{J}}(r, z)}{V_{\text{weight}}}, \quad (7)$$

where $\dot{\mathbf{p}}_{\text{J}} = \sqrt{2\dot{M}_{\text{J}}\dot{E}_{\text{J}}}\hat{\mathbf{k}}$. This results in an increase in the kinetic energy of

$$dE_i^{\text{kin}} = \frac{(\mathbf{p}_{i,0} + d\mathbf{p}_i)^2}{2(m_{i,0} + dm_i)} - \frac{\mathbf{p}_{i,0}^2}{2m_{i,0}} \quad (8)$$

due to the effect of mass loading, and therefore, to conserve the total injected energy, each cell receives a thermal energy injection of $dE_{\text{therm},i} = dE_{\text{tot},i} - dE_{\text{kin},i}$. We used two tracers to track jet material. The first one, f_{J} , is set equal to 1 whenever a cell is in the jet cylinder, and the jet is active. It is subsequently advected with the gas and decays exponentially with time with a decay time of 3 Myr. The primary purpose of this tracer is for the jet refinement scheme (see below). The second tracer, f_{JM} , tracks the mass injected in each cell that belongs to the jet (Eq. (6b)), which, similarly to the former tracer, is advected with the gas. This tracer does not decay with time and was used for our analysis (Section 4.2).

In addition to the standard AREPO refinement criteria based on maintaining an approximately constant gas cell mass, as in Bourne & Sijacki (2021), additional criteria were implemented to ensure the jet injection region and jet material maintained a high resolution. Specifically, we adopted the super-Lagrangian refinement schemes of Curtis & Sijacki (2015) and Bourne & Sijacki (2021) to resolve the region around the SMBH. These schemes ensure that within both the accretion region and the jet cylinder there is a sufficiently high resolution, while maintaining a smooth transition between high- and low-resolution regions. To ensure that the jets and lobes maintain a high resolution, we applied additional jet tracer and property gradient-based refinement criteria similar to those described in Bourne et al. (2019) and Bourne & Sijacki (2021), which cap the volume of jet and lobe cells based on their tracer fraction, f_{J} .

¹ The fraction of mass each eligible cell contributes to M_{acc} is given by $\min\left[0.9, \exp\left(-4\frac{r^2}{R_{\text{acc}}^2}\right)\right]$.

3. Results: Overview of simulations

We begin this section by visualising the multi-phase ICM, outlining the gas kinematics and comparing the ICM radial profiles against the relevant observational sample.

3.1. Visuals of the multi-phase ICM

In Fig. 1, we show three representative simulation snapshots (columns from left to right) at different AGN powers and warm and cold gas masses present. The bottom panel shows the total amount of gas with temperatures below 5×10^4 K and the AGN power (smoothed using a Gaussian filter with a standard deviation of 20 Myr), as a function of time. The times at which panels in each column are produced are indicated by the purple bands. The first row shows the X-ray surface brightness (black-red colour tones), computed as $\Sigma_X(x, z) = \int n_H^2 \Lambda_X(T) dy$, where n_H is the hydrogen number density of the ionised gas and $\Lambda_X(T)$ is the free-free function in the X-ray wavelengths, having non-zero values only in the temperature range $10^6 \text{ K} \leq T \leq 3 \times 10^8 \text{ K}$. Projected jet tracer surface densities are shown by overlaid black contours, which are smoothed using a Gaussian filter with a standard deviation of 350 pc to reduce noise.

The three time instances were taken, respectively: (1) in a period of low AGN activity preceding an AGN outburst; (2) soon after a strong AGN outburst; and (3) in a period of mid activity after the AGN outburst. The X-ray maps reveal large cavities that are filled with the jet lobe material, with larger cavities corresponding to higher AGN activity. At these three different times, we can find, respectively: (1) a relatively low amount of warm and cold gas mostly confined to the centre; (2) a large quantity of warm and cold gas spread throughout the central 30 kpc; and (3) warm and cold gas less spread out and instead more distributed around the cavities. In general, significant fractions of the warm ionised gas (second row) are located in the cluster centre, although this gas component extends throughout all of the core, reaching cluster-centric distances of around 40 kpc. Warm ionised gas has both filamentary and clumpy appearance with some of the gas tracing cavity rims. The molecular gas is mostly confined within the inner 10–15 kpc, but it can also be found in smaller amounts within warm clumps. This is in line with observations of warm and molecular gas in cluster centres (Salomé et al. 2011; Olivares et al. 2019).

3.2. Warm ionised gas kinematics

While a detailed analysis of the kinematics of the multi-phase gas will be tackled in an upcoming work (Sotira et al., in prep), we give here a cursory exploration of the complexity of gas flows. The fourth row of Fig. 1 shows the emission-weighted projected velocity along a line of sight perpendicular to the jet axis for the warm ionised gas component. Our simulated gas velocities, in the range of ± 50 to ± 300 km/s, are comparable to those measured in observed clusters (Gendron-Marsolais et al. 2018; Rhea et al. 2025). Specifically, Gendron-Marsolais et al. (2018) studied the kinematics of this phase in the Perseus cluster (see their Figure 5), with the simulation results being in very good agreement with their findings, matching both the velocity range and kinematic map topology.

3.3. ICM radial profiles

In Fig. 2, we show the profiles of X-ray emission-weighted electron number density, temperature, and entropy, from left to right, respectively, colour-coded to mark different time instances in

the simulation, and compared to the observed profiles for the Perseus cluster (Churazov et al. 2004), as well as for selected cool-core clusters from the ACCEPT sample (Cavagnolo et al. 2008), which includes clusters with similar properties to the Perseus cluster. Note that the observed Perseus cluster profiles, used to create our initial conditions, are towards the edge of the distribution of cool-core clusters in the ACCEPT sample. Across the entire 4 Gyr span of our simulation, the simulated cluster does not experience any excessive cooling flow, while due to the self-regulatory AGN feedback, it maintains the characteristic cool-core features, as can be seen from the temperature and entropy profiles.

Around the epoch of $t = 2$ Gyr, however, in the central 20 kpc, the core is almost one order of magnitude denser with respect to the observed distribution, resulting in a lower central entropy. In this phase, our system appears as a strong cool-core cluster, although the emission from the denser and colder X-ray emitting phase might be absorbed by the warm ionised gas in the ICM (see, e.g., Fabian et al. 2022). At $t = 3$ Gyr, the density and entropy profiles settle closer to the Perseus values, and they remain in agreement with observed values until the end of the simulation at 4 Gyr.

3.4. Jet density and velocity

In this section, we illustrate key physical properties of the jet and describe its interaction with the ICM. In the left-hand panels of Fig. 3, we show the average gas number density of a 1 kpc thick projection centred at $y = 0$ at two epochs during the jet outbursts in the simulation. Close to the SMBH, the jet is less dense than the ICM, having density values of around 10^{-2} cm^{-3} , with a jet-to-ICM density ratio of around 10^{-2} . Also, compressed regions with a higher density are clearly visible around the jet lobes.

The middle panels of Fig. 3 show the corresponding vertical gas velocity maps, v_z . The jet material velocities reach up to $\sim 10^4$ km/s. At larger radii, when the jet material thermalises and is slowed down, the bulk-outward velocity within the turbulent jet lobes decreases to values of around several $\sim 10^2$ km/s to $\sim 10^3$ km/s.

With these properties, the jet is capable of compressing the ICM while propagating within it. Indeed, if we consider, at the moment of the injection, $\rho_{\text{jet}} \approx 10^{-26} \text{ g cm}^{-3}$ and $v_{\text{jet}} \approx 10^4$ km/s, the ram pressure of the jet is $P_{\text{ram}} = \rho v^2 \approx 10^{-8} \text{ erg cm}^{-3}$, while during the jet propagation later on, $\rho_{\text{jet}} \approx 10^{-25} \text{ g cm}^{-3}$ and $v_{\text{jet}} \approx 10^3$ km/s, and thus $P_{\text{ram}} = \rho v^2 \approx 10^{-9} \text{ erg cm}^{-3}$. These jet ram pressure values are significantly larger than the characteristic thermal pressure of the ICM in the cluster core, $P_{\text{ICM}} \approx nk_B T \approx 10^{-10} \text{ erg cm}^{-3}$, with $n \approx 10^{-1} \text{ cm}^{-3}$ and $T \approx 10^7 \text{ K}$.

The right-hand panels of Fig. 3 illustrate this point by showing the total gas pressure composed of ram and thermal pressure. Jets and bow shocks generated by their inflation are clearly visible, highlighting the ICM compression caused by AGN feedback. This results in an overall heating of the ICM and in a localised formation of overdensities (see Section 4.2). This will be a crucial point for the remainder of the paper.

4. Results: Properties of warm and cold gas components

4.1. Warm and cold gas evolution

During the entire simulation timespan of 4 Gyr, we identify several different stages of AGN feedback. In the first transient phase

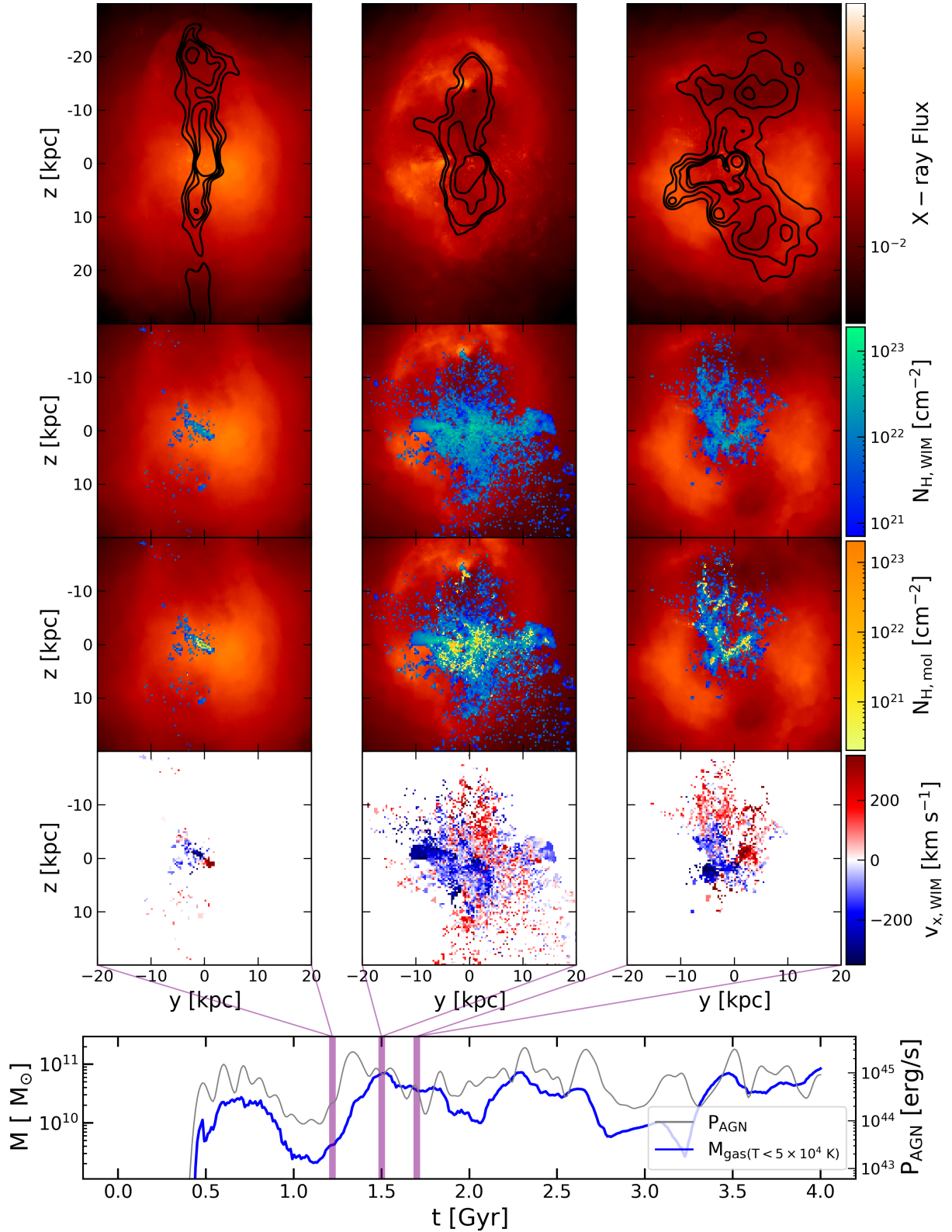


Fig. 1. Top panels: overview of the gas phases of interest during three particular moments of the simulation (columns from left to right). First row: X-ray emission shown with black-red colour tones (see the main text for the emission calculations) and jet tracer projections contours (black colour). X-ray cavities coincide with the locations where jet tracer material is prevalent. Second row: warm ionised gas ($3 \times 10^3 \text{ K} < T < 5 \times 10^4 \text{ K}$) column density superimposed on the X-ray image, shown with blue-green colour tones. Third row: molecular gas column density, superimposed on the previous two images, shown with yellow-orange colour tones. Fourth row: projected velocity along a line-of-sight of the warm ionised gas phase, which is in good agreement with observations. Bottom plot: Total mass of gas with temperature below $5 \times 10^4 \text{ K}$ (blue curve) and AGN power (grey curve), plotted as a function of time. Purple bands indicate the corresponding time instances of the maps shown. The amount of warm and cold gas correlates with the AGN power because the cold gas, accreting onto the central SMBH, ignites the AGN feedback. The AGN-driven jets propagating through the multi-phase ICM create further perturbations, leading to the renewed formation of cold clumps and filaments.

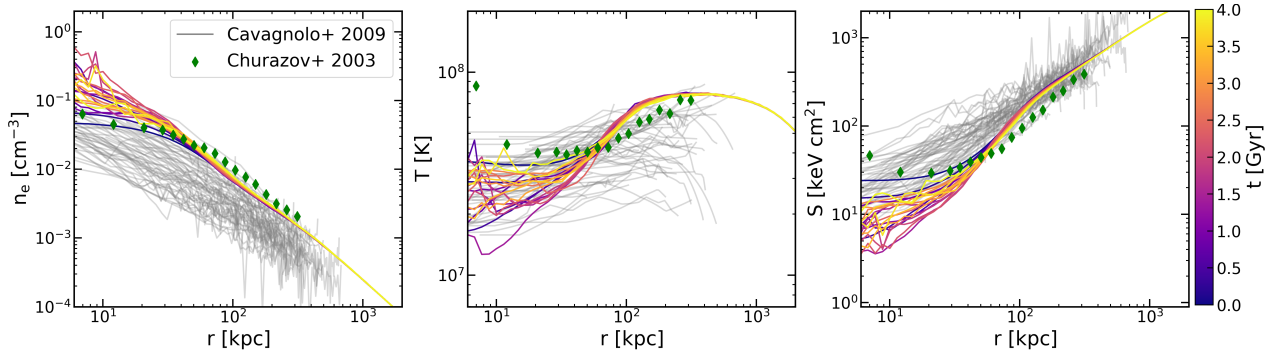


Fig. 2. From left to right: X-ray emission-weighted profiles of electron number density, temperature, and entropy of our simulations, colour-coded with respect to time (purple–yellow colour bar), and compared with: the Perseus cluster derived by Churazov et al. (2004) (green diamonds); cool-core clusters from the ACCEPT sample by Cavagnolo et al. (2008) (grey lines), with a central temperature in a range of $1.5 \times 10^7 \text{ K} \leq T \leq 5 \times 10^7 \text{ K}$ and a central entropy of less than 50 keV cm^{-2} , i.e. similar properties to the Perseus cluster. We find that our simulated galaxy cluster profiles are in good agreement with the observed Perseus-like cool-core clusters.

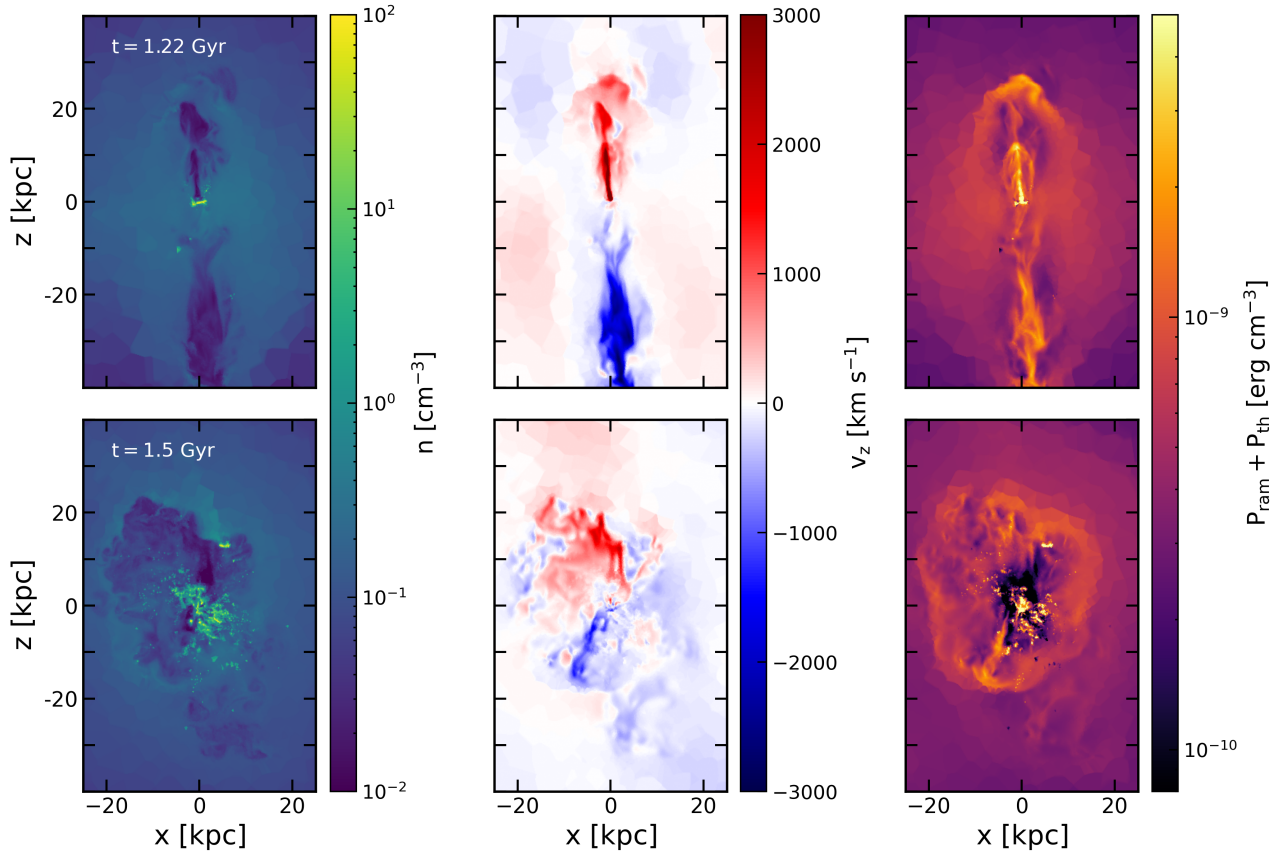


Fig. 3. From left to right: maps of the average gas number density, average vertical component of gas velocity, and average total gas pressure (i.e. ram plus thermal) of a 1 kpc thick projection centred at $y = 0$ during the two AGN jet outbursts, at $t = 1.22 \text{ Gyr}$ (top) and $t = 1.50 \text{ Gyr}$ (bottom). With non-relativistic velocities ($v_{\text{jet}} \lesssim 0.1c$), the jets are able to compress the ICM, heating the cluster core and leading to the formation of localised overdensities (see Section 4.2).

lasting $\sim 500 \text{ Myr}$, influenced by the assumed initial conditions, the ICM is gradually cooling down, and as such there is not enough cold gas to trigger the AGN activity. When only gravity and cooling processes are at play, the cold gas is mostly concentrated in the centre, as expected in classical cooling flow models, while during or shortly after AGN outbursts, it is distributed within larger and more extended structures. Both configurations are seen in observed galaxy clusters, and either one or the other can happen in the cluster centre, due to the long-term interaction with the AGN feedback (or lack thereof). The correlation,

amount, and morphologies of the cold gas with respect to the AGN power are not simple, as this interaction develops across a range of time and spatial scales.

When the AGN is activated by a sufficient quantity of cold gas reaching the accretion region, AGN power oscillates in the range of $\sim 10^{44} - 10^{45} \text{ erg s}^{-1}$ (bottom plot of Fig. 1, grey curve). These values are consistent with observations (e.g., Fabian 2012; McNamara & Nulsen 2012). The AGN activity and the formation and evolution of cold gas in our simulation are two interconnected processes for the following reasons: a) as the cold gas

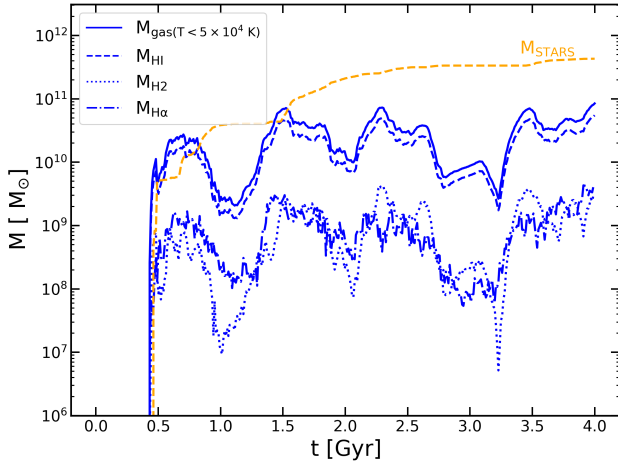


Fig. 4. Total mass of gas with temperature below 5×10^4 K (solid blue line), as well as mass of neutral hydrogen HI (dashed blue line), molecular hydrogen H₂ (dotted blue line), and warm ionised phase (dash-dotted blue line). Note that the total amount refers to both hydrogen and helium, while the different phases refer only to hydrogen. For completeness, the total stellar mass (dashed orange line) is also shown. All the quantities are largely consistent with the values observed in real systems.

forms in the ICM, a fraction of it falls onto the accretion region around the central SMBH, and ignites the AGN feedback; and b) when the AGN is on, its outbursts move a fraction of cold or cooling gas from the central region to larger radii, through uplift and entrainment, favouring further condensation (Voit et al. 2017; Jennings et al. 2023). Furthermore, as we discuss later in greater detail, the AGN-driven jets create perturbations and compression regions in the hot ICM, leading to the formation of cold clumps and filaments (see also Gaspari et al. 2018).

The amount of cold gas present in the ICM strongly correlates with the AGN power, due to both of the aforementioned effects. Indeed, the evolution of the jets is very sensitive to the presence of cold gas in the central ~ 10 kpc region. Specifically, we observe deflection and redirection of the jets, induced by interactions and collisions with dense cold clouds² (see also Ehlert et al. 2023). These deflections appear to be essential to distribute heating from jets, and to avoid the ‘dentist drill’ effect: perfectly collimated jets, digging through the ICM, will travel a long path in the clusters and inject energy at large distances, as we found in Sotira et al. (2025), (see also Vernaleo & Reynolds 2006 and Li & Bryan 2014a). While in Sotira et al. (2025), precession of jets was introduced by the numerical setup; here, jet redirection is spontaneously induced by the interaction with the dense, multi-phase gas. In the observed clusters, both the AGN jet precession, redirection via collisions with the dense clouds, and displacement by cluster weather (e.g., Heinz et al. 2006; Bourne et al. 2019; Bourne & Sijacki 2021) are likely at play.

To verify that the multi-phase ICM properties are realistic, in Fig. 4 we show the evolution of gas mass for the different phases of the hydrogen below 5×10^4 K, as well as the cumulative mass of the stars formed. At the end of the simulation, the total stellar mass formed is $3 \times 10^{11} M_{\odot}$, 99% being within a 30 kpc radius, while the small remainder resides in filaments or clumps at larger radii. The total stellar mass, somewhat surprisingly, matches the cD galaxy of Perseus despite our simple stellar model; of course, in real systems, the central galaxy is not

formed by a direct cooling flow as it happened in the initial stage of our simulation. After the cooling flow stage, the average star formation rate is $\approx 100 M_{\odot}/\text{yr}$. This value would mostly produce a blue star-forming central galaxy rather than a massive red passive galaxy as observed. Several key aspects that can suppress the star formation are missing in the simulation, such as most importantly stellar feedback. Furthermore, our simulations assume a simple prescription for star formation, while the injection of turbulence from the AGN itself and the presence of a magnetic field can drastically reduce the star formation efficiency of the molecular phase (Alatalo et al. 2015; Tabatabaei et al. 2018). We again stress the simple nature of the star formation model employed in our simulations, which is, at least partly, employed for numerical reasons, to avoid excessively dense gas formation. Importantly, the realistic stellar mass in conjunction with the reasonable black hole and cold gas mass we find in our simulation demonstrates the self-regulated nature of our AGN feedback implementation, where the numerical overcooling is avoided. The SMBH mass is quite constant during the whole simulation, growing by roughly 10% from its initial mass of $M_{\text{BH}} = 4 \times 10^9 M_{\odot}$.

Approximately 90% of the warm-cold gas is neutral, while the remainder is in molecular form, with masses in the range of 10^7 – $2 \times 10^9 M_{\odot}$. The mass of the warm ionised hydrogen component is of the same order of magnitude as the molecular gas. These values are compatible with observations of observed systems (Salomé et al. 2011; Olivares et al. 2019, 2022; Gingras et al. 2024), except for the warm ionised gas, which appears to be higher in our model with respect to observations by Gingras et al. (2024), who found ionised gas masses in the range of 10^6 – $10^8 M_{\odot}$ in a small sample of cool-core clusters.

4.2. Cold gas formation model

In this section, we quantitatively investigate the formation scenario of cold clumps. Once non-linear density perturbations are generated, they can undergo rapid localised cooling. Such perturbations preferentially originate in regions of sustained compression in the ICM, due to bulk motions and turbulence, naturally driven by the central AGN-driven outflows (Revaz et al. 2008; Brighenti & Mathews 2002b; Gaspari et al. 2013, 2018; Brighenti et al. 2015; Li et al. 2015; Sotira et al. 2025).

In Fig. 5, we show central slices of the jet mass fraction, i.e. the mass added to the launching cells in the injection cylinder over the total mass of the cells, which is displayed by the yellow-red colour tones³, at different times. The yellow tone mostly marks material from the newly injected jet, while redder tones mark older and more diluted jet material⁴. Notice the presence of the jet redirection due to encounters with cold clumps.

Fig. 5 also shows the column density of the gas with temperatures below 5×10^4 K (blue-green colour tones). The cold clumps are found displaced from the jet main axis, with some of them spatially located within the laterally expanding jet lobes edges. The displacement is due to the fact that, soon after an AGN jet outburst, small amounts of cold gas follow the jets as a result of entrainment and ram pressure (Voit et al. 2017); other condensation can be further enhanced during fragmentation of the cold clouds by the hot jets (Jennings et al. 2023; Ghosh et al. 2026). Another proposed mechanism is the cold cloud formation in situ due to the AGN-induced turbulence (e.g.; Gaspari et al. 2018); we explore these ideas further by linking the formation of

² We recall that in our adopted implementation, the SMBH has no natural precession and the jet axis is fixed.

³ The fraction of the jet mass is low, because this mass is added to cells already present in the injection cylinder, i.e. it is only the dm in Eq. (6b).

⁴ For clarity, we do not display here jet material with a fraction of less than 10^{-4} .

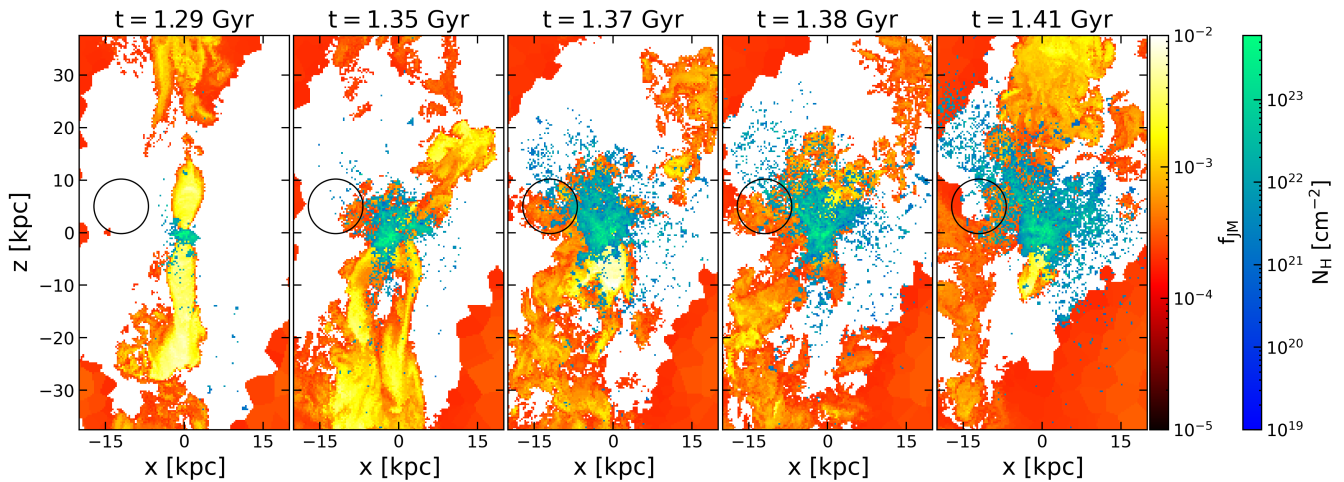


Fig. 5. Series of time instances showing the spatial distribution of the jet fraction in the meridional plane (red-yellow colour-coding). The column density of the gas with temperatures below 5×10^4 K is overplotted as well (blue-green colour-coding). The black circle indicates a 6 kpc radius region, centred at $(x, y, z) = (-3, -12, -5)$ kpc, in which the properties of Fig. 7 were computed. As the jet material propagates laterally towards the indicated region it initially drags some of the cold gas with it ($t \sim 1.34\text{--}1.38$ Gyr); meanwhile, by injecting turbulence, it creates the perturbations (Fig. 7) that, in the next 30 Myr, form fresh cold gas in situ (Fig. 9). The associated movie is available [online](#).

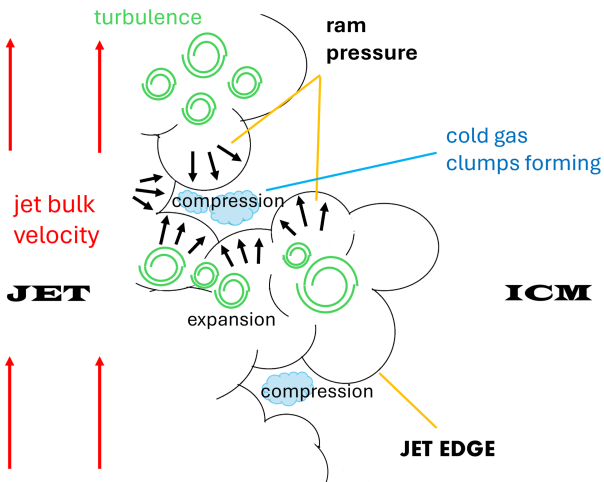


Fig. 6. Simplified sketch of the cold clumps formation model at the ‘edges’ of the main jet. Only a small vertical section of one jet is shown for simplicity. The red arrow indicates the main velocity of the jet (~ 1000 km/s), while the edges are expanding in a perpendicular direction at a lower speed (~ 300 km/s). The thin black line demarks the separation of the jet material from the ICM. The green curly regions indicate the presence of turbulence, and the bold black arrows indicate the pressure gradient direction. Turbulent vortices and black arrows marking pressure gradients are shown only in some parts of the sketch for clarity. The blue clouds indicate the new cold clumps that are forming.

cold clumps to the turbulent expansion and compression of the jet, especially when the jets expand or are re-directed towards unperturbed regions of the ICM.

As a representative example of this mechanism, we consider a spherical region that is centred at $(x, y, z) = (-3, -12, 5)$ kpc, has a radius equal to 6 kpc (highlighted by the black circle in Figs. 5), is unperturbed at $t = 1.29$ Gyr, and has small turbulence with velocity dispersion⁵, σ_{hot} , of the hot phase around

⁵ With $\sigma_{\text{hot}}^2 = 1/3(\sigma_x^2 + \sigma_y^2 + \sigma_z^2)$, where the terms on the right-hand side of the equation are mass-weighted velocity dispersions along each axis.

30 km/s $\approx 0.05\ c_{s,\text{hot}}$, where $c_{s,\text{hot}}$ is the mass-weighted sound speed of the hot phase in the region (see also Section 4.4). At $t = 1.35$ Gyr, part of the jet bends while hitting the cold gas in the cluster centre, and propagates in a perpendicular direction (x) with respect to the jet axis (z); in the time span $t = 1.35$ – 1.38 Gyr, the jet material enters the region injecting turbulence and creating the perturbations for the cold clumps that condense in the next 30 Myr, as we show in Section 4.3 (Fig. 9). At $t = 1.38$ Gyr, the velocity dispersion of the hot phase in the region is $\sigma_{\text{hot}} = 120$ km/s $\approx 0.2\ c_{s,\text{hot}}$.

The sketch in Fig. 6 represents a schematic view of the likely formation scenario for the cold clumps in our simulation, which we investigate quantitatively in the rest of this section. We find that at a given time, a jet cocoon can expand laterally with relatively low velocities, 300–500 km/s, with respect to the jet main axis (indicated by the red arrows), and move towards unperturbed portions of the ICM. The green curly regions denote the presence of turbulence, and the bold black arrows indicate the ram pressure (both are shown only in some parts of the sketch for clarity). In this configuration, the turbulent expansion triggers density enhancements in the ICM, which promote cooling into dense clumps. At later times, these structures can merge into larger clouds or filaments and, unless they get heated by an AGN outburst, they will migrate towards the cluster centre (see also [Gaspari et al. 2013](#)). At the front of the jet, there is instead no cold gas condensation as the jet moves supersonically, and even though there is compression, it is also associated with strong shock heating. So even in the case that gas clumps are present ahead of the expanding jet, their fate is to ultimately be disrupted and heated by the violent jet activity there.

The key physical driver of the cooling process is the increase in the gas velocity dispersion, which, combined with the particular geometry of the jet expansion, creates multiple zones of high compression, leading to thermally unstable portions of hot gas. This is quantitatively shown in Fig. 7 for the spherical region described above (highlighted by the black circle in Fig. 5). The left-hand panel shows the distribution of the hot gas mass ($T > 10^7$ K) with respect to the local overdensity. Here $\delta\rho/\bar{\rho} = (\rho_i - \bar{\rho})/\bar{\rho}$, where ρ_i and $\bar{\rho}$ are the density of the i -th cell and the average density (in the spherical region), respectively. The right-hand panel of Fig. 7 instead shows the

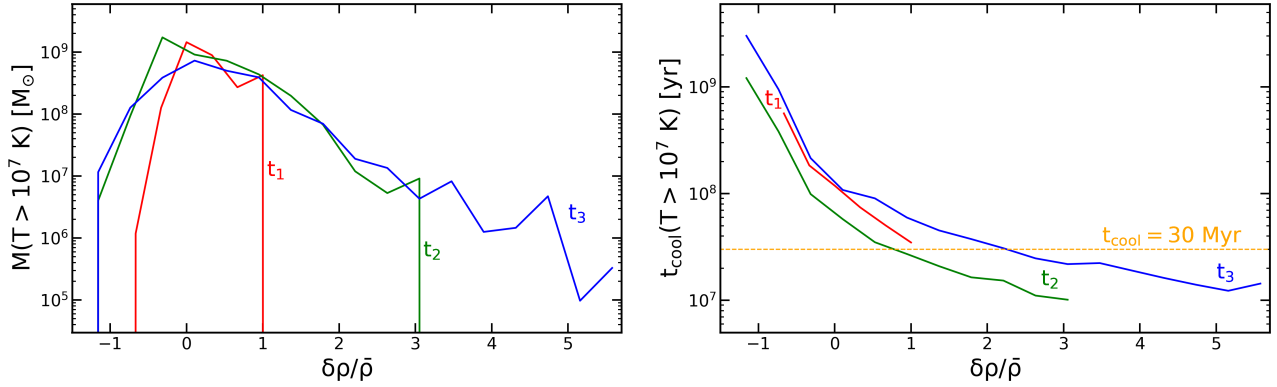


Fig. 7. Left: Distribution of the hot gas mass, i.e. with $T > 10^7$ K, binned as a function of overdensity, $\delta\rho/\bar{\rho} = (\rho_i - \bar{\rho})/\bar{\rho}$, where ρ_i and $\bar{\rho}$ are the density of the i -th cell and the average density, respectively. Right: Corresponding mass-weighted cooling time in each bin of overdensity. The distributions are computed in a spherical region that has a radius of 6 kpc and is centred at $(x, y, z) = (-3, -12, 5)$ kpc (highlighted by the black circle in Figs. 5 and 9) at $t_1 = 1.29$ Gyr before the jet passage (red line), $t_2 = 1.35$ Gyr and $t_3 = 1.38$ Gyr during the jet passage (green and blue lines). While the distribution of overdensities is very narrow at t_1 , at t_2 and t_3 there is a broad tail of much larger overdensities. The dashed orange line in the right panel separates bins that have average cooling times below 30 Myr. After the passage of the AGN jet, a significant fraction of the hot ICM mass exhibits low cooling times.

mass-weighted average cooling time in each overdensity bin⁶. The distributions in Fig. 7 are shown at three different times, before and during the jet passage. At t_1 , just before the passage of the redirected jet burst, the hot gas mass distribution (left-hand panel; red curve) is approximately symmetric and centred around $\delta\rho/\bar{\rho} \sim 0$, with a gas cooling time that never falls below 30 Myr (right-hand panel). After the jet passage, at t_2 and t_3 , the mass distribution has significantly changed (left-hand panel; green and blue curves); the distributions are now skewed towards densities much larger than the average, with large amounts of hot gas having $\delta\rho/\bar{\rho} = 3$ –5, indicating significant gas compression. Some of this compressed gas has a cooling time ranging in 10–30 Myr (right-hand panel; green and blue curves).

In our simulation, such strongly non-linear overdensities are frequently formed by propagating jet material, and they eventually cool down to form the cold gas later found in the same region, before falling towards the centre. This happens despite the fact that the majority of the hot gas there has instead increased its cooling time: this means that the passage of the jet heats up overall the region, via mixing with hot jet material, (weak) shocks, and turbulent dissipation, while at the same time the same process promotes the localised formation of a significant amount of cold gas.

4.3. Tracking cold gas formation with tracers

To further explore the validity of this model, we re-ran the simulation introducing a passive tracer fluid into gas cells satisfying different physical criteria. This allowed us to determine the fraction of hot gas that, at any time in the simulation, was most likely to undergo the formation of cold clumps at later times. In particular, we re-ran the simulation in the time span $t = 1.38$ –1.5 Gyr, with a maximum time step of 2 Myr to follow the cooling processes in detail. We kept track of regions experiencing significant compression by introducing tracers based on specific ranges of values of velocity divergence and of the compressive ratio at the injection epoch. The compressive ratio was computed following

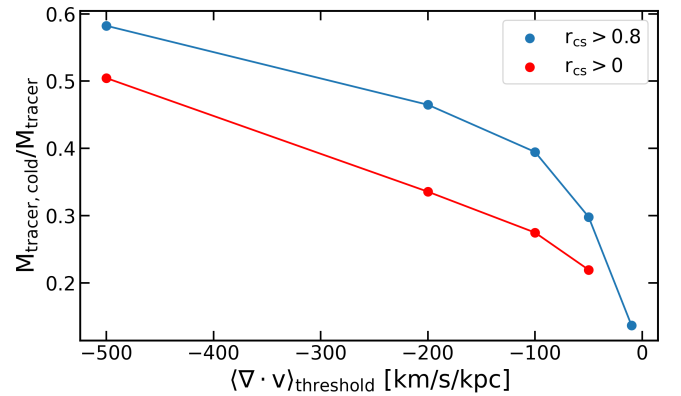


Fig. 8. Mass fraction of tracers that goes in the cold phase for every tracer re-run (dot symbols) performed with different divergence cuts from -10 km/s/kpc to -500 km/s/kpc (x axis) and with different compressive ratio cuts, $r_{cs} > 0.8$ (blue line) and $r_{cs} > 0$ (red line). The mass of tracers that condense in the cold gas increases when the divergence and compressive ratio cuts are higher, reaching up to $\sim 60\%$.

Iapichino et al. (2011); Bourne & Sijacki (2017), as

$$r_{cs} = \frac{\langle \nabla \cdot v \rangle^2}{\langle \nabla \cdot v \rangle^2 + \langle \nabla \times v \rangle^2}, \quad (9)$$

where the average $\langle \rangle$ was computed mass-weighting over 32 neighbouring cells. We ran a large number of simulations by considering gas cells that have a mass-weighted divergence, $\langle \nabla \cdot v \rangle$, lower than a series of values ranging from -500 to -10 km/s/kpc with (and without) $r_{cs} > 0.8$ to keep track of the jet compressive flow (Bourne & Sijacki 2017). We additionally ran two control simulations with $\langle \nabla \cdot v \rangle \geq 0$ and $> +100$ km/s/kpc, corresponding to barely or strongly expanding regions. For all the runs, the selection criteria, the initial selected mass tracked by the tracer fluid and the percentage of tracer mass that goes in the cold phase are listed in Table A.1 in the appendix.

In the selection process of the gas cells, a first selection considered cells with temperatures higher than 10^7 K. Their 32 neighbouring cells were then used to compute the average divergence and compression ratio, which we filtered on to localise compression zones. However, since by considering neighbouring cells gas with a range of temperatures may be included, we

⁶ Note that we excluded from this analysis gas with temperature ranging between $\approx 10^6$ and $\geq 10^4$ K, as it already has a short cooling time and a significant fraction of it will soon become a warm ionised medium with $T \approx 10^4$ K.

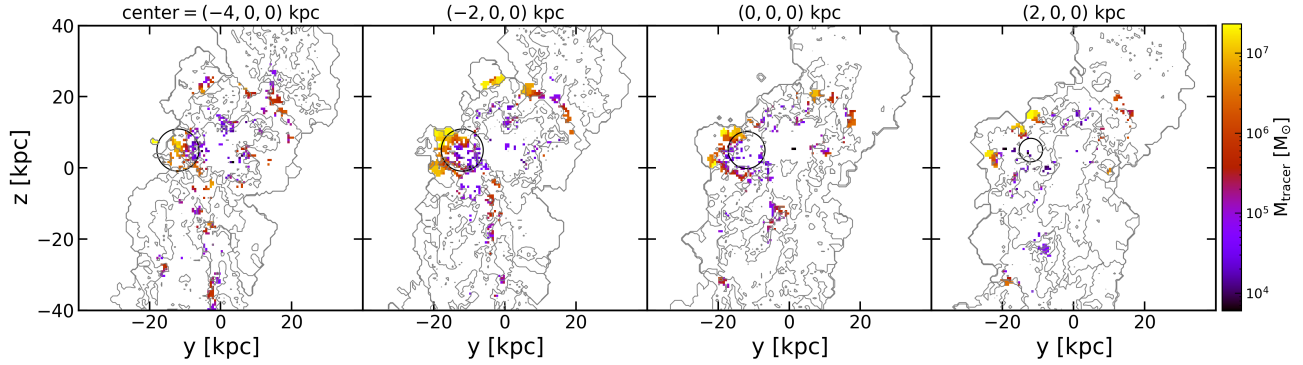


Fig. 9. Different slices in the y - z plane of the jet contours (grey) and tracer mass map at the time of the injection using the following criteria: $\langle \nabla \cdot v \rangle < -100$ km/s/kpc and $r_{cs} > 0.8$ (run A), centred at the cluster centre, and ± 2 , and 4 kpc away from the centre, from left to the right, respectively. The tracers are placed where the divergence is strongly negative (i.e. zones of compression) and where the compressive ratio is high (i.e. zones with low vorticity). The maps provide a simulation counterpart to the scenario explained in the sketch of Fig. 6. The black circle indicates the intersection of the spherical region of Figs. 5 and 7 with the different slices. The presence of tracers within it confirms the presence of perturbations that will condense in cold clumps. The associated movie showing the relation between jets, tracers, and cold gas is available [online](#).

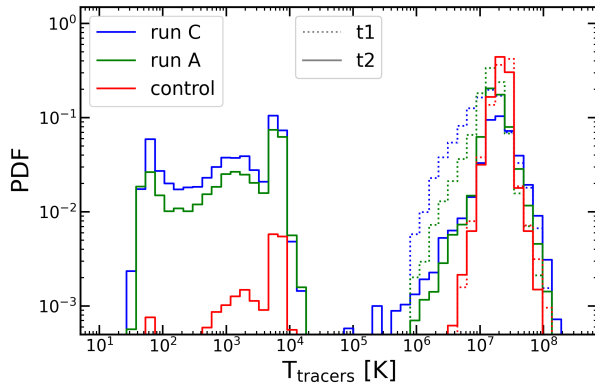


Fig. 10. Temperature PDF of the tracers at time of the injection (dotted lines) and after 30 Myr (solid lines), for runs A (green), C (blue), and control (red), corresponding to $\langle \nabla \cdot v \rangle$ lower than -100 , -500 km/s/kpc and $r_{cs} > 0.8$ for runs A and C, and $\langle \nabla \cdot v \rangle > 0$ without the r_{cs} cut for the control run. Our conditions on velocity divergence and compressive ratio successfully identify regions where cold clumps form in situ from the hot gas.

additionally removed cells with $T < 10^6$ K from our tracer injection region. We note that, after this cut, cells with a temperature of between 10^6 K $< T < 10^7$ K contribute only a small fraction of the total mass. The selected mass in which tracers were injected ranges from 2 to $8 \times 10^9 M_{\odot}$ for runs A, B, C, and is $2.8 \times 10^{11} M_{\odot}$ for the control run.

Fig. 8 summarises the main results of these tests and gives the mass fraction sampled by tracers which has condensed into cold ($\leq 5 \times 10^4$ K) gas after 30 Myr, as a function of the value of velocity divergence chosen for the initial selection. The blue and the red lines in the plot indicate runs with and without the compressive ratio cut, $r_{cs} > 0.8$, respectively. We can see a clear trend: the mass fraction of tracers that condense into warm and cold phases is higher when increasingly more negative values of divergence are used for the initial selection of tracers. Furthermore, the compressive ratio also plays a role since the fraction is always higher when the r_{cs} threshold is applied. In other words, the level of ongoing compression in the hot gas phase at a given epoch appears to be a good predictor of gas undergoing future condensation into cold clumps, after ~ 30 Myr.

While this trend can qualitatively be predicted a priori, we show that our selection criterion specifically determines cells

that are affected by the jet perturbation and therefore produces a tangible ‘positive’ feedback promoting cold gas formation. Let us consider our fiducial runs with $r_{cs} > 0.8$ and $\langle \nabla \cdot v \rangle$ lower than -100 (run A) and -500 km/s/kpc (run C), corresponding, respectively, to a compression time, $t_{comp} = \langle \nabla \cdot v_i \rangle^{-1}$, of 10 and 3 Myr. Fig. 9 shows different slices of the injected tracers at the initial time for run A, together with the jet contour in grey. The tracer presence indicates zones with a high negative divergence and relatively low vorticity (high compressive ratio). This selection marks regions highly perturbed by the jet, and the injected tracers are confined to localised regions at the edges of tangled jet contours. The location of such selected regions, i.e. at the tangled interface between laterally expanding jets and the ICM, qualitatively confirms the model already introduced in the sketch of Fig. 6. Furthermore, the black circle in the figure indicates the region analysed in the previous Section (Figs. 7 and 9). We note that at $t = 1.38$ Gyr, a large amount of tracer mass is present in the region, confirming what is pictured in Section 4.2.

Finally, Fig. 10 shows the temperature distribution functions for run A (green lines), C (blue lines), and control (red lines) at the moment of the injection (dotted lines) and the time of the peak of tracers in the warm and cold phases, i.e. 30 Myr later (solid lines). In runs A and C, the initial distribution of hot gas associated with tracers has been roughly halved after 30 Myr, with the other half of the initially selected mass being now in the cold phase. On the other hand, the initial temperature distribution of the control run remains almost the same, only with a small fraction of gas ($\leq 10\%$) collapsing into the cold phase.

4.4. Link to the ICM turbulence

The cold clumps formation scenario singled out by our simulation implies a tight relation with the turbulent motions episodically stirred by jets expanding in the ICM. Therefore, it is of interest to link the presence of positive AGN feedback with the macroscopic observables that are now potentially detectable via X-ray spectroscopy by the XRISM satellite (e.g. [Fujita et al. 2025](#)). To statistically study this, we sampled the central cluster volume by selecting seven spherical regions with a radius of 5 kpc. The regions are centred on $(0, 0, \pm 10)$, $(\pm 10, 0, 0)$, $(0, \pm 10, 0)$, and $(0, 0, 0)$, i.e. the cluster centre. In the time span 1.3–2.5 Gyr, we sum up the total gas mass of cells with temperatures $\geq 10^7$ K that have $\langle \nabla \cdot v \rangle < -500$ km/s/kpc and $r_{cs} > 0.8$ (as done in our tracer analysis) and plot the resulting mass as

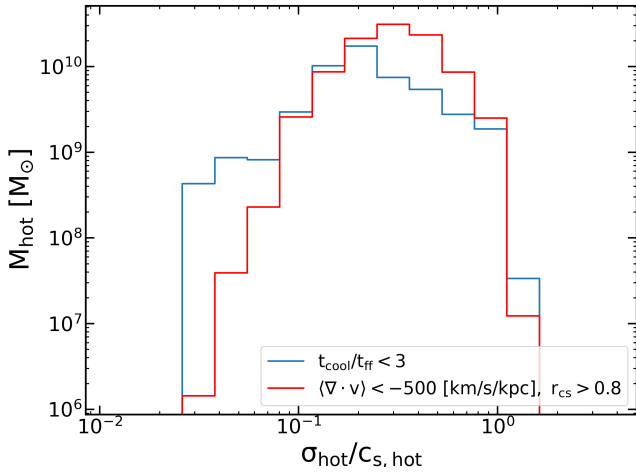


Fig. 11. Hot gas mass, i.e. with temperatures higher than $T > 10^7$ K, which has $\langle \nabla \cdot v \rangle < -500$ km/s/kpc and $r_{cs} > 0.8$ (red line) and $t_{cool}/t_{ff} < 3$ (blue line) computed for a sample of 5 kpc radius regions in the cluster core for $t = 1.3\text{--}2.5$ Gyr, computed against the total velocity dispersion of each region normalised to its mass-weighted average sound speed.

a function of the turbulent Mach number of the corresponding region at that moment in Fig. 11 (red line). The latter was calculated as the total gas velocity dispersion over the mass-weighted sound speed in the region, $c_{s,hot}$, at that moment. The turbulent Mach number was computed only for gas cells with temperatures $\geq 10^7$ K.

The resulting gas mass distribution has roughly a Gaussian shape, peaking at $\sigma_{hot} \approx 0.3 c_{s,hot}$. We also computed for each region the hot gas mass of cells that have free-fall times, computed as $t_{ff} = (2r^2/g)^{1/2}$ (where r is the distance of the region from the centre and $g = g(r)$ is the gravitational acceleration at that distance), shorter than three times the cooling time, i.e. $t_{ff}/t_{cool} < 3$ (blue line). Hot gas cells with the latter ratio of the order of unity are bound to condense and form cold clumps, before they can reach the cluster centre (Malagoli et al. 1987; Loewenstein 1999; Voit 2021). The two distributions in Fig. 11 are roughly the same, which is in line with the expectation of the cold clump formation scenario we outlined above.

This result indicates that values of σ_{hot} around 1/3 of the sound speed are necessary to promote cold gas condensation (Fig. 6), see also Gaspari et al. (2018). The condition on σ_{hot} must be interpreted as a necessary but insufficient condition to create cold clump condensation. Indeed, there are several periods of time during which regions have those values of turbulent Mach number, but not cells with the criteria for condensation. This can happen, for example, when the cold gas condensation has already occurred and the region maintains the same value of turbulence, but the gas is predominantly too hot.

Cells that are subject to strong compression are also associated with high local values of the velocity dispersion in the hot gas, and will be forming cold clumps given their short cooling time at a given radius; only the passage of AGN jets can promote such high values of velocity dispersion in the hot gas in our simulation, and this once more proves the positive feedback loop between jets, turbulence, compression, and cooling in this numerical model. In principle, using X-ray spectroscopy such as that provided by XRISM (XRISM Collaboration 2025a,b), future observations should be able to identify the regions of the ICM where cold gas clumps most likely undergo formation, promoted by the interaction with AGN jets. Spatially co-locating

these regions with deep, high-resolution radio maps may provide further evidence that lateral jet material expansion drives localised gas compression and in situ cold clump formation.

5. Discussion and conclusions

The idea that feedback from the central AGN enhances off-centre gas condensation in the ICM, and other astrophysical environments, has been often proposed in recent decades (Gaspari et al. 2012, 2018; Voit et al. 2017). In this work, we used advanced numerical simulations of high-resolution AGN jets in an isolated Perseus-like cluster to better investigate this phenomenon. Our model captures a self-consistent SMBH accretion and feedback cycle in a fully multi-phase ICM medium, ranging from the hot, X-ray emitting to the molecular gas, whereby the mass in different gas phases, ICM radial profiles, and AGN power are in very good agreement with observations.

We studied a specific mechanism whereby jet-induced off-axis turbulent motions in the hot gas lead to compression and in situ condensation into cold clumps, typically on a time scale of a few tens of millions of years. The proposed process happens simultaneously, while the jet heats up the ICM and increases its entropy to the levels consistent with the cool-core clusters. We assessed the validity of the proposed cold gas formation model by using tracers, which allowed us to directly link in the simulation localised compression regions in the hot gas (spatially associated with jet propagation sites) and the formation of cold clumps from the same perturbed gas after a cooling timescale.

After having highlighted and tested the validity of the proposed model, we want to stress that this scenario is not the only channel to produce cold gas in cluster cores. Indeed, the entire amount of warm and cold gas found outside of the innermost regions is not only generated starting from jet-induced compression, as it is unlikely that this mechanism alone has a sufficient efficiency for this task. For example, the advection and uplift of cold or low entropy gas from the centre, due to the jet expansion, has also been proposed to promote further cold clump formation, while entraining and mixing with the hotter and less dense gas outside of the cluster core (Gaspari et al. 2012; Voit et al. 2017; Jennings et al. 2023). Furthermore, in observed galaxy clusters, density fluctuations that lead to thermal instabilities can be generated by other astrophysical processes such as galaxy wakes, cosmological accretion, and compressive turbulence driven by other sources (Voit 2018, 2021; Choudhury et al. 2019; Fielding et al. 2020).

Our model is not in contrast with this global picture, but it highlights a further important effect, which we were able to isolate thanks to the very high spatial resolution of jet lobes in our simulation and detailed gas radiative cooling modelling down to the molecular phase. To summarise, our main conclusions are as follows:

- The compressive motion induced by the (lateral) jet expansion strongly widens the overdensity distribution and generates relatively dense localised regions in the ICM, where cold gas clumps form on a time scale of ~ 30 Myr;
- The regions of the hot ICM that experience this rapid cooling process are those characterised by significant compression and low absolute value of vorticity;
- Statistically, this process prevalently occurs when the local turbulent Mach number in the hot gas is $\sigma_{hot}/c_{s,hot} \approx 0.3$;
- The process of cold clump condensation (positive feedback) happens despite the presence of the AGN-driven jet distributed heating (negative feedback), which prevents the over-cooling catastrophe.

The formation process for cold gas clumps identified in this work is physically well motivated, although only future, more systematic studies will allow us to quantify its efficiency in converting hot into cold gas, as well as to generalise its validity to a larger number of host systems. However, integrated with a model that can explain how hot, rarefied jets can uplift cold gas from the centre to large distances, this study sets the basis for a more complete scenario that incorporates key physical mechanisms of cold gas formation and redistribution. Future observational data, including X-ray spectroscopy, molecular and warm gas kinematics, and deep, high-resolution jet lobe radio maps, in conjunction with detailed AGN-driven jet simulations, such as the ones presented here, will finally help us to unlock the nature of the puzzling filamentary nebulae residing in the centres of cool-core clusters.

Data availability

Movies associated with Figs. 5 and 9 are available at <https://www.aanda.org>.

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Appendix A: Table of the re-runs with tracers

	run <i>Y</i>	run <i>Z</i>	run <i>A</i>	run <i>B</i>	run <i>C</i>	run <i>D</i>	run <i>E</i>	run <i>F</i>	run <i>G</i>	control	control2
r_{cs}	> 0.8	> 0.8	> 0.8	> 0.8	> 0.8	-	-	-	-	-	-
$\langle \nabla \cdot v \rangle$	≤ -10	≤ -50	≤ -100	≤ -200	≤ -500	≤ -50	≤ -100	≤ -200	≤ -500	> 0	$\geq +100$
$M_{\text{in}} [10^9 M_{\odot}]$	51	15.5	8	5	2	28.4	15.9	8	2.4	279	16
$M_{\text{fin,cold}}$	13.7%	29.8%	39.5%	46.5%	58.2%	21.9%	27.5%	33.6%	50.5%	13.6%	12.2%

Table A.1. First and second rows: Compressive ratio and divergence criteria used to inject the tracers. Third row: Total gas mass selected using the above criteria. Fourth row: Percentage of tracer mass that condenses in warm and cold clumps ($T < 5 \times 10^4$ K) with respect to the total mass of tracer injected, for the various re-runs.