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# CAN AGN FEEDBACK BREAK THE SELF-SIMILARITY OF GALAXIES, GROUPS, AND CLUSTERS?

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## ABSTRACT

It is commonly thought that AGN feedback can break the self-similar scaling relations of galaxies, groups, and clusters. Using high-resolution 3D hydrodynamic simulations, we isolate the impact of AGN feedback on the $L_{\rm x} - T_{\rm x}$ relation, testing the two archetypal and common regimes, self-regulated mechanical feedback and a quasar thermal blast. We find that AGN feedback has severe difficulty in breaking the relation in a consistent way. The similarity breaking is directly linked to the gas evacuation within $R_{500}$, while the central cooling times are inversely proportional to the core density. *Breaking self-similarity implies thus breaking the cool core*, morphing all systems to non-cool-core objects, which is in clear contradiction with the observed data populated by several cool-core systems. Self-regulated feedback, which quenches cooling flows and preserves cool cores, prevents the dramatic evacuation and similarity breaking at any scale; the relation scatter is also limited. The impulsive thermal blast can break the core-included $L_{\rm x} - T_{\rm x}$ at $T_{500} \lesssim 1$ keV, but substantially empties and overheats the halo, generating a perennial non-cool-core group, as experienced by cosmological simulations. Even with partial evacuation, massive systems remain overheated. We show the action of purely AGN feedback is to lower the luminosity and heating the gas, perpendicular to the fit.

*Keywords:* galaxies: active — galaxies: clusters: intracluster medium — galaxies: groups: general — galaxies: jets — hydrodynamics — methods: numerical

## 1. INTRODUCTION

In the last decade, feedback due to active galactic nuclei (AGN) has allowed to solve crucial astrophysical problems. The supermassive black hole (SMBH) at the center of galaxies, groups, and clusters can indeed release a terrific amount of energy ($> 10^{61}$ erg), providing an efficient source to quench cooling flows and star formation (McNamara & Nulsen 2007). In particular, mechanical AGN feedback in the form of jets/outflows is able to regulate for several Gyr the thermodynamical state of the system core (Gaspari et al. 2013a for a review). However, it is far from clear if AGN feedback is able to strongly modify the large-scale gas halo, as the total X-ray luminosity and temperature, in other words, breaking the self-similar scaling relations.

If gravity were the single driver of the evolution (Kaiser 1986; Kravtsov & Borgani 2012), all systems would scale only with mass, $M_\Delta = (4\pi/3)\Delta\,\rho_{\rm c}\,R_\Delta^3$, where $\Delta$ is the chosen overdensity. The critical density of the universe evolves in redshift as $\rho_{\rm c}(z) \propto E^2(z)$, where $E^2(z) \simeq \Omega_{\rm m}\,(1+z)^3 + \Omega_\Lambda$, giving a characteristic radius $R_\Delta \propto M_\Delta^{1/3}\,E^{-2/3}(z)$. Via hydrostatic equilibrium ($M_\Delta \propto T\,R_\Delta$), we can retrieve $M_\Delta \propto T^{3/2}E^{-1}(z)$. Since the bolometric X-ray luminosity scales as $L_{\rm x} \propto n^2\,T_{\rm x}^{1/2}\,R_\Delta^3$ (in the Bremsstrahlung regime), using gas number density $n \propto M_\Delta/R_\Delta^3 \propto \rho_{\rm c}(z)$ and the above relations, we find the well-known self-similar scaling $L_{\rm x} \propto T_{\rm x}^2\,E(z)$. However, cluster observations show a slope steeper than 2 (∼3; e.g., Pratt et al. 2009; Maughan et al. 2012), further sharpening in the group regime, ∼4 - 5 (Mulchaey et al. 2003; Osmond & Ponman 2004; Helsdon & Ponman 2000a,b; Sun et al. 2009; Sun 2012; see Fig. 1).

In recent years, different authors have studied the scaling relations by means of large cosmological simulations with AGN feedback (e.g., Sijacki et al. 2007; Fabjan et al. 2010; McCarthy et al. 2010; Short et al. 2010). In general, they find that the implemented AGN feedback is able to break the self-similarity, lowering luminosities by orders of magnitude and, surprisingly, decreasing the global temperature (Puchwein et al. 2008, fig. 2). Often overlooked, the simulated systems are however non-cool-core objects (Planelles et al. 2013, fig. 7, for a critical discussion). Even no-feedback runs produce negative temperature gradients, due to extreme adiabatic heating, which are not present in high-resolution simulations (e.g., Li & Bryan 2012). Besides the under-resolved black hole/feedback physics and subgrid numerics (see the analysis in Barai et al. 2014), it remains difficult to disentangle and isolate the action of feedback in the complex evolution shaped by mergers, filaments, star formation, sink particles, and other prescriptions.

The objective of this study is to critically examine if AGN feedback itself can break the self-similarity of galaxies, groups, and clusters, in a way consistent with observations. Via controlled high-resolution 3D (mesh) simulations, we study how the main scaling, $L_{\rm x} - T_{\rm x}$ is shaped by the two archetypal and commonly adopted feedback models, self-regulated kinetic feedback and a quasar thermal blast. In a forthcoming work, we explore other models and different relations (Gaspari et al. 2014, in prep.).

A crucial constraint driven by observations is the presence of a (strong or weak) cool core in the majority of observed systems ($\gtrsim$ 65 per cent, Peres et al. 1998; Mittal et al. 2009; Sun et al. 2009; Hudson et al. 2010; Zhao et al. 2013). Such systems show, in the core, cooling times $< 7$ Gyr, positive temperature gradients, and low gas entropy ($<$ 10s keV cm$^2$). Moreover, cool cores appear to be long lived and in place since $z > 1$ (McDonald et al. 2013). AGN feedback, or inside-out heating, intrinsically evacuates the central regions, before touching the periphery of the system. Although the AGN feedback energetics is in principle capable to breaking the group self-similarity (Cavaliere & Lapi 2008; Giodini et al. 2010), the energy deposition and hydrodynamics is crucial. We show that breaking self-similarity via AGN feedback implies disrupting the cool core, morphing the system into perennial non-cool-core objects; vice versa, self-regulation preserves the core and the large-scale structure.

## 2. PHYSICS & NUMERICS

### 2.1. *Initial conditions*

In order to fully isolate the role of feedback in altering the scaling relations, we start with a virialized group/cluster having a formed cool core, which characterizes the majority of observed systems (§1). Groups and clusters share many common properties, allowing to build an initial 'universal' system defined only by its mass. Following Vikhlinin et al. (2006)[1], the observed average temperature profile can be modeled as

$$T(r) = T_0 \, \frac{0.45 + (\hat{r}/0.045)^{1.9}}{1 + (\hat{r}/0.045)^{1.9}} \, \frac{1}{(1 + (\hat{r}/0.6)^2)^{0.45}}, \quad (1)$$

where $\hat{r} = r/R_{500}$; the normalization is $T_0 \simeq 1.4\, T_{500} \simeq 3$ keV $(M_{500}/10^{14}\,\mathrm{M}_\odot)^{0.6}$ (cf., Sun et al. 2009). Eq. 1 models the positive gradient of the cool core and the gentle decrease at large $r$; the peak temperature ($r \sim 0.15\, R_{500}$) is $\sim$2× the central value, which is reached again at $r \sim R_{500}$. Albeit some groups have slightly higher $T$ peak and steeper decrease (Sun et al. 2009), such minor differences have no impact on the results.

The system is initially in hydrostatic equilibrium within the gravitational potential $\phi$, dominated by dark matter, modeled via the usual NFW profile in the concordance $\Lambda$CDM universe. The halo concentration is linked to the virial mass as $c \simeq 8.5\, (M_{\rm vir}/10^{14}\ \mathrm{M}_\odot)^{-0.1}$ (e.g., Bullock et al. 2001). In addition, each group/cluster is dominated by a central massive elliptical galaxy ('BCG'), modeled with a de Vaucouleurs stellar density profile. The BCG $K$-band luminosity increases with the halo mass as $L_K \simeq 4.7 \times 10^{11}\, (M_{\rm vir}/10^{14}\ \mathrm{M}_\odot)^{0.39}\, \mathrm{L}_\odot$ (e.g., Lin & Mohr 2004). The stellar mass is then retrieved adopting $M_*/L_K \sim 1$ (e.g., Mannucci et al. 2005). Since BCGs are large ellipticals, we keep the effective radius $R_{\rm eff} \simeq 9$ kpc. As described in Gaspari et al. (2012b), the BCG injects a low amount of energy and mass due to SNIa and stellar winds; however, the energetics is dominated by the AGN feedback.

The normalization of the density profile is set by the gas fraction at the virial radius, $f_{\rm gas,vir} \simeq 0.15$. The initial gas fraction is intentionally high, near the cosmic value (Planck Collaboration et al. 2013), since we want to test if AGN feedback is the original cause of gas evacuation and hence self-similarity breaking. Using lower values (e.g., 0.1) does not change the conclusions.

### 2.2. *Hydrodynamics, cooling and heating*

Using FLASH4 code, we integrate the 3D equations of hydrodynamics in conservative form, including total gravity, gas radiative cooling, and feedback heating. The latter two source terms are implemented following the unified self-regulation model, as described in Gaspari et al. (2012b). Transport mechanisms, as conduction, are not included since data suggest a strong suppression (e.g., Gaspari & Churazov 2013). The cubical box fully covers the virial radius, $\sim$1.2 - 4.6 Mpc (groups to clusters). We use concentric grid levels with radius of $\sim$60 cells, centered on the BCG, where the maximum resolution reaches $\approx$ 290 pc. The system is integrated for at least 5 Gyr. Boundary conditions are set in diode mode.

#### 2.2.1. *Self-regulated mechanical feedback*

In Gaspari et al. (2011a,b, 2012a,b, 2013a,b) was found that the most consistent model able to solve the cooling flow problem is mechanical feedback, self-regulated by cold accretion. In turbulent regions where the cooling time drops below $\sim$10× the free-fall time, thermal instabilities become quickly nonlinear, leading to the condensation of cold gas out of the hot phase. Such cold clouds and filaments collide in an inelastic and chaotic way while raining on to the black hole, boosting the accretion rate. Bipolar massive sub-relativistic outflows are then triggered with kinetic power proportional to the central cooling rate, $P_{\rm jet} = \epsilon\, \dot{M}_{\rm cool}\, c^2$ (Gaspari et al. 2012b for the numerical details), with optimal mechanical efficiencies $\epsilon \sim 5 \times 10^{-4} - 5 \times 10^{-3}$. The self-regulated outflow generates the cocoon shock, two buoyant bubbles, and gas/metal uplift. The kinetic feedback rises the central gas entropy, quenching cooling and stifling the accretion rate; the self-regulated loop starts then over again.

The gentle self-regulation with either kinetic or thermal injection (the latter commonly used in cosmological simulations[2]) produces analogous impact on the scaling relations, although thermal feedback induces again excessive core overheating (Brighenti & Mathews 2003; Gaspari et al. 2011b).

#### 2.2.2. *Quasar thermal blast*

In the opposite spectrum of feedback models resides the sudden and powerful release of thermal energy. This can be justified by a quasar event, emitting large radiative power absorbed by highly dense clouds, or in alternative, by an Eddington wind fully thermalizing in the inner core. Numerically, the thermal energy is injected in the inner $\sim$4 kpc, with Eddington power $P_{\rm Edd} \simeq 1.5 \times 10^{47} (M_{\rm bh}/10^9\, \mathrm{M}_\odot)$ erg s$^{-1}$ lasting $\sim$ 6 Myr. The total released energy is $E_{\rm AGN} \equiv \eta\, M_{\rm bh}\, c^2 \simeq 3 \times 10^{61}$

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[1] Note a typo in the published version, missing the 0.45 exponent; A. Vikhlinin, private communication (see astro-ph version).

[2] In some cosmological works, the 'quasar mode' is simply quasi-continuous thermal feedback.

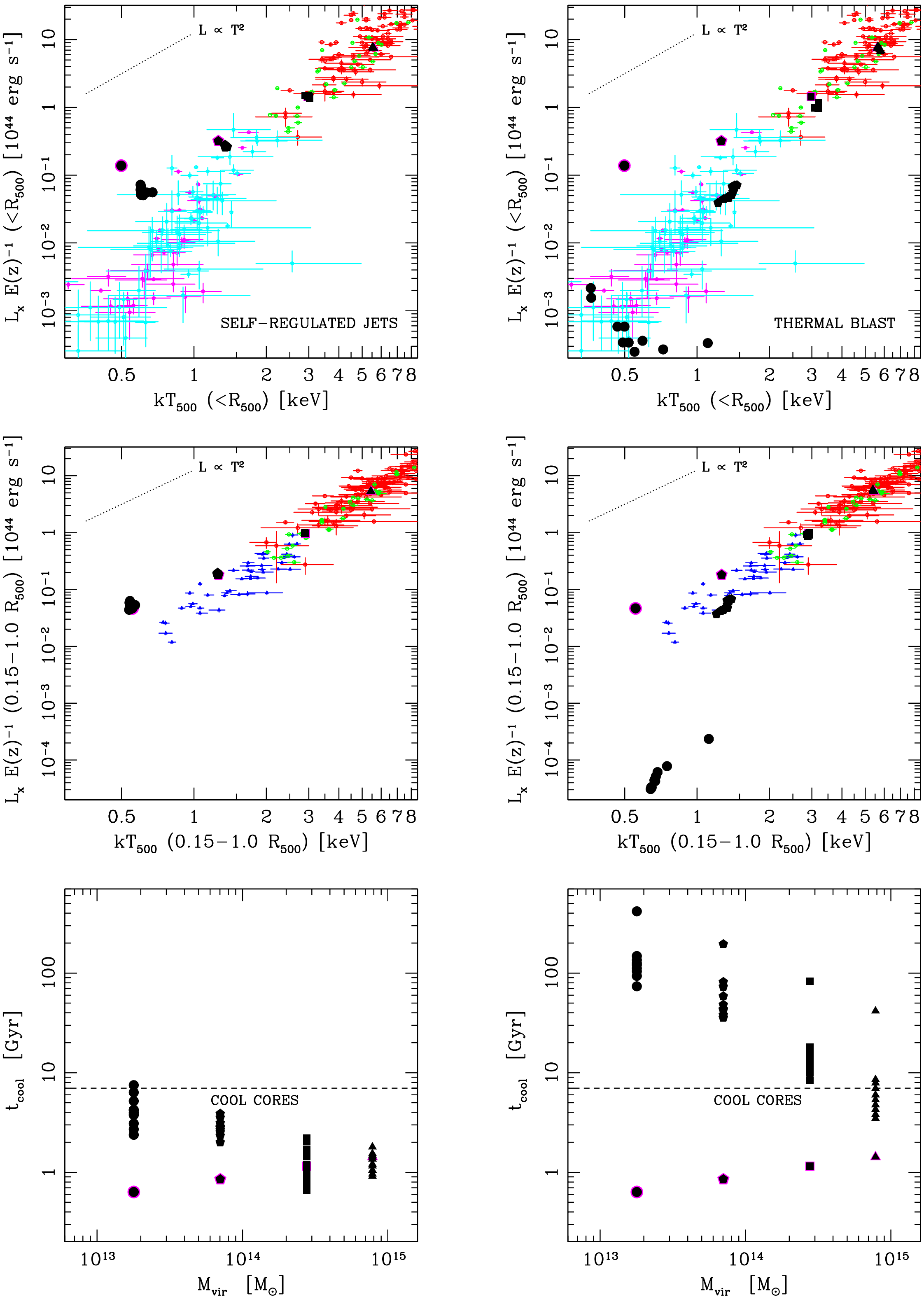

**Figure 1.** X-ray bolometric luminosity versus X-ray temperature, including (top) or excising (middle) the core, $r < 0.15\,R_{500}$. The bottom panels show the central cooling time (∼15-20 kpc), with the cool-core threshold $t_{\rm cool} \sim 7$ Gyr. Left: self-regulated kinetic models (§2.2.1; $\epsilon = 5 \times 10^{-3}$). Right: quasar thermal blast (§2.2.2); the black points show the simulated 5 Gyr evolution every 500 Myr (the initial point has magenta contour). The observational data are from Maughan et al. (2012, *Chandra*; red), Pratt et al. (2009, *XMM*; green), Sun et al. (2009, *Chandra*; blue), Mulchaey et al. (2003) and Osmond & Ponman (2004; magenta), Helsdon & Ponman (2000a,b, *ROSAT*; cyan); we always use $h = 0.7$ (e.g., for $L_{\rm x} \propto h^{-2}$). The self-regulated AGN feedback prevents overheating, at the same time avoiding the self-similarity breaking. Conversely, the powerful thermal blast can break the $L_{\rm x} - T_{\rm x}$ relation at the group scale, but morphing the system into a perennial non-cool-core object.

erg, i.e., the characteristic energy of a SMBH with typical $M_{\rm bh} \sim 10^9$ M$_\odot$ and radiative efficiency $\eta \simeq 1.5\times10^{-2}$ (Novak 2013). The isotropic blast triggers once the necessary mass of cold gas has been accreted; due to the powerful heating, no second event ever occurs. Conclusions are unaltered with different $E_{\rm AGN}$ and compact deposition windows.

Boosting $\epsilon$ above the optimal values (e.g., $\sim$ 0.1) transforms the previous gentle self-regulated feedback in the impulsive blast. Conversely, significantly lowering $E_{\rm AGN}$ morphs the feedback in the self-regulated regime. The presented models constitute thus the two opposing archetypes of inside-out feedback.

## 3. RESULTS

Figure 1 presents the key results of the high-resolution hydrodynamic simulations, testing kinetic or thermal AGN feedback in the range of systems with $T_{500} \simeq 0.5$ - 6 keV ($M_{\rm vir} \sim 10^{13}$ - $10^{15}$ M$_\odot$). In the top and middle panels, we show the X-ray luminosity versus X-ray temperature[3] within $R_{500}$, including or excising the core ($r < 0.15\,R_{500}$), respectively. The bottom panel depicts the gas central cooling time (in the shell ∼15 - 20 kpc, contained within $\lesssim 0.06\,R_{500}$). The $L_{\rm x} - T_{\rm x}$ relation is shaped by the global amount of cooling and heating, while $t_{\rm cool} \propto T/n\,\Lambda$ assesses the core thermal state ($\Lambda$ is the cooling function; see Gaspari et al. 2012b).

The self-similar relation is expected to be $L_{\rm x} \propto T_{\rm x}^2$, even shallower in the group regime due to line emission ($L_{\rm x} \propto T_{\rm x}^{3/2}\Lambda \propto T_{\rm x}$). Figure 1 (top) reveals that the observational data relative to the cluster regime (red, green) are already deviating, with a slope $\alpha \sim 3$. Below 2 keV, i.e., for small and massive groups, the relation steepens further, reaching $\alpha \sim$ 4 - 5, with a much more significant scatter. Excising the core in both quantities reduces the scatter and the steepness ($\alpha \sim 2.5$), avoiding an abrupt decline. The relation becomes nearly self-similar considering only cool-core clusters (Maughan et al. 2012). Unfortunately, the excised relation for small groups is not covered by observational data.

In the left column, the simulations (black; the initial state has magenta contour) show that the impact of self-regulated jet feedback ($\epsilon = 5\times10^{-3}$) on the $L_{\rm x} - T_{\rm x}$ relation is limited. The remarkable aspect is that no break – a deviation of orders of magnitude – occurs, even at the scales of small halos. In the massive group (pentagons), the maximum deviation in luminosity/temperature is ∼30/10 per cent (0.1/0.05 dex), strongly diminishing to ∼10/1 per cent in massive clusters. In the compact group (circles), the luminosity decreases by ∼2.8×, while temperature increases by ∼80 per cent. $T_{500}$ shows the weaker scatter; the main action of feedback, especially kinetic, is to evacuate gas and, secondarily, to heat the global atmosphere.

Excising the core within $0.15\,R_{500}$ (middle panel), significantly reduces the scatter to $\lesssim 1/3$ of the previous values. By removing the core separately for each variable, we see that internal heating can only move the points towards lower luminosities and higher temperatures. Similarly, radiative cooling moves the system towards higher $L_{\rm x}$ and lower $T_{500}$ (cf., Ettori & Brighenti 2008). In other words, the $L_{\rm x} - T_{\rm x}$ secularly moves due to heating/cooling perpendicular to the fit, particularly as the core is included. Works based on cosmological simulations (§1) show instead a decrease of $T_{500}$, adding subgrid AGN feedback. This could be linked to the reduction of the extreme adiabatic heating present in the under-resolved pure cooling flow. A more serious problem is that, although the similarity breaking occurs, no object can be observationally described as a cool core with the positive $T$ gradient depicted in §2.1.

The self-regulated models show that avoiding the complete self-similarity breaking implies preserving the cool-core structure – at the same time reducing the cooling rate below 10 per cent of that of the pure cooling flow. In the bottom panel (left), the central cooling time stays in any halo below ∼7 Gyr, the common upper limit used to define cool-core systems (e.g., Hudson et al. 2010). These systems also preserve the positive temperature gradient and low central entropy. As found in Gaspari et al. (2011b, 2012b), $\epsilon \simeq 5\times10^{-3}$ is the best value for clusters; indeed, the two groups switch to a weaker cool core after the initial heating. Overall, optimal self-regulation induces the system to oscillate between a state of weak and strong cool core, preventing both the cooling *and* heating runaway. The duty cycle is very efficient with cold accretion, while much weaker with hot Bondi regulation (Gaspari et al. 2011b). Since most of the observed systems host a cool core (§1), self-regulated mechanical heating represents the long-term maintenance mode of AGN feedback, while avoiding the break of the scaling relations.

We test now the other extreme of AGN feedback models, i.e., the impulsive thermal blast (Fig. 1, right). The sudden isotropic energy release (∼$3\times10^{61}$ erg, comparable to that of a typical SMBH) can dramatically evacuate the atmosphere of the compact group, decreasing the X-ray luminosity by 2.5 orders of magnitude; $T_{500}$ initially increases by $\sim 2\times$ (the rightmost circle). The strong breaking occurs because the group total binding energy[4] is $\simeq 10^{61}$ erg. After the initial blast, the BCG is slowly replenished by the stellar mass loss, mildly increasing the luminosity ($< R_{500}$) to $\sim 10^{41}$ erg s$^{-1}$, while restoring $T_{500}$ near the initial value (this is not due to the action of AGN feedback). The system has completely morphed. The central $t_{\rm cool}$ (bottom) is always $> 60$ Gyr, in a perennial non-cool-core state. Excising the core (middle), aggravates the breaking, since the compact group is substantially devoid of gas outside the BCG, with an unrealistic drop down to $\sim 10^{40}$ erg s$^{-1}$ (cf., Sun 2012). Overall, the inside-out heating able to *fully* break self-similarity in the core-included $L_{\rm x} - T_{\rm x}$, violently alters the excised $L_{\rm x} - T_{\rm x}$ relation, which is instead observed to have tighter scatter.

In the massive group (pentagons), the total binding energy is $\simeq 10^{62}$ erg ($> E_{\rm AGN}$). The thermal blast can thus only partially evacuate the gas from the core ($\sim 0.1\,R_{500}$), halted by the extended atmosphere before reaching $R_{500}$. The result is a decrease in luminosity by

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[3] We computed both the emission-weighted $T_{500}$ with *Chandra* sensitivity ($T_{\rm x} \gtrsim 0.3$ keV; Gaspari et al. 2012b) and spectroscopic-like temperature (Vikhlinin 2006); since our flow is not multiphase, they are very similar. As in observations, we use the projected $T_{500}$; the difference with the spherical value is minor.

[4] Equal to the gravitational energy $E_{\rm b} = \int_0^{R_{\rm vir}} \rho_{\rm gas}\,\phi\,dV$.

maximum 0.9 dex and $T_{500}$ oscillating within 0.1 dex. The extended evacuation is confirmed by the excised relation. Both simulated $L_{\rm x} - T_{\rm x}$ are consistent with the observed data. However, the similarity deviation occurs again at the expense of the cool core. In fact, the central cooling time stays above tens Gyr, signaling a strong non-cool-core group. Analyzing the poor and massive cluster simulations (squares, triangles), we see no similarity breaking, due to the larger $E_{\rm b}$. The maximum deviation in the core-included relation is highly limited, $\sim 0.17/0.08$ dex in $L_{\rm x}$ and $\sim 0.03/0.015$ in $T_{500}$, for the poor and massive cluster, respectively. Excising the core stifles the scatter by at least 1/3. The powerful AGN heating has again the side effect of destroying the core ($t_{\rm cool} \gg t_{\rm H}$). Only the massive cluster can partially recover after several Gyr. Cool cores are common in the universe, hence this type of breaking should be rare. Notice that combining the two feedback mechanisms aggravates the core overheating.

The global $L_{\rm x} - T_{\rm x}$ property seems overall more likely linked to a primordial imprint that the group/cluster experienced, rather than an internal breaking after formation. However, we note that when the external 'preheating' at high redshift – whose agency is still unclear – is high enough to bring $L_{\rm x}$ consistent with observations, the gas entropy becomes usually too high, inhibiting cool cores to form ab initio (e.g., Brighenti & Mathews 2001).

## 4. CONCLUSIONS

We showed that AGN feedback has severe difficulty in breaking the self-similarity of galaxies, groups, and clusters, in a consistent way. Via high-resolution 3D simulations, we isolated the impact of the two common regimes of AGN feedback on the principal scaling relation $L_{\rm x}$–$T_{\rm x}$.

- Self-regulated kinetic feedback prevents the similarity breaking, inducing a limited scatter ($\lesssim 0.1$ dex). Self-regulation allows to properly quench cooling flows preserving the cool-core structure; avoiding overheating translates thus in a modest central gas evacuation, maintaining low core cooling times ($t_{\rm cool} < 7$ Gyr) and avoiding the $L_{\rm x} - T_{\rm x}$ breaking at any halo scale. Since the majority of observed systems display a cool core (§1), this mode should represent the long-term maintenance phase of AGN feedback.

- An impulsive quasar thermal blast, injecting the total energy of a typical SMBH, is able to break the core-included $L_{\rm x} - T_{\rm x}$ at scales $T_{500} \lesssim 1$ keV (where $E_{\rm AGN} \gtrsim E_{\rm b}$). However, after full breaking, the system is almost devoid of gas, also at large radii, in contradiction with the core-excised relation. Even with partial evacuation ($M_{\rm vir} \gtrsim 5 \times 10^{13}$ M$_\odot$), the central $t_{\rm cool}$ is raised to several times the Hubble time. In clusters, the scatter is again limited, $\lesssim 0.2$ dex. The imprint of the thermal blast is indelible, morphing the system into a perennial non-cool-core object. If existent, such a mechanism should be rare or occurring at very high redshift.

Breaking self-similarity via inside-out heating means to evacuate most of the gas from the region $\lesssim R_{500}$. Since central $t_{\rm cool} \propto n_0^{-1}$, lowering the gas density by one order of magnitude at large radii implies decreasing the core density $n_0$ by at least 10× more, inducing $t_{\rm cool} \gg t_H$. The problem is further aggravated by the increase of temperature ($t_{\rm cool} \propto T^{1/2}$). The direct action of AGN feedback is to lower the luminosity and heating the gas, not moving the system parallel to the $L_{\rm x} - T_{\rm x}$ fit. Overall, AGN feedback appears naturally suited to regulate the thermodynamical state of cosmic systems, in the core, but not over large radii ($r \gtrsim 0.2\, R_{500}$). We remark that any feedback mechanism, that is able to break the self-similarity, needs to properly solve the cooling flow problem.

In a forthcoming work, we discuss other heating models, parameters, and scaling relations. We found, nevertheless, that AGN feedback models fall in the two archetypal categories presented here: self-regulated heating, preventing the breaking, or strong impulsive heating, which breaks the scaling relations but destroys the core. For instance, using either thermal or kinetic feedback with self-regulation has the same minor impact on the scaling relations (§2.2.1). Injecting energy in the center or at a distance of a few 10 kpc ($\lesssim 0.05\, R_{500}$) has also the same effect, considering that the feedback must affect extremely large regions ($R_{500}$, several 100s kpc); a too distant injection allows instead central runaway cooling. Further, boosting $\epsilon$ transforms the self-regulated feedback into the quasar-like blast; vice versa, diminishing the impulsive $E_{\rm AGN}$ slightly lowers $t_{\rm cool}$, but prevents the similarity breaking. In other words, even with a different parametrization of the archetypal AGN feedback models, breaking self-similarity implies breaking the cool core.

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## REFERENCES

Barai, P., Viel, M., Murante, G., Gaspari, M., & Borgani, S. 2014, MNRAS, 437, 1456
Brighenti, F., & Mathews, W. G. 2001, ApJ, 553, 103
—. 2003, ApJ, 587, 580
Bullock, J. S., Kolatt, T. S., Sigad, Y., et al. 2001, MNRAS, 321, 559
Cavaliere, A., & Lapi, A. 2008, ApJ, 673, L5
Ettori, S., & Brighenti, F. 2008, MNRAS, 387, 631
Fabjan, D., Borgani, S., Tornatore, L., et al. 2010, MNRAS, 401, 1670
Gaspari, M., Ruszkowski, M., & Sharma, P. 2012a, ApJ, 746, 94
Gaspari, M., Brighenti, F., & Temi, P. 2012b, MNRAS, 424, 190
Gaspari, M., Brighenti, F., & Ruszkowski, M. 2013a, Astronomische Nachrichten, 334, 394
Gaspari, M., & Churazov, E. 2013, A&A, 559, A78
Gaspari, M., Ruszkowski, M., & Oh, S. P. 2013b, MNRAS, 432, 3401
Gaspari, M., Melioli, C., Brighenti, F., & D'Ercole, A. 2011a, MNRAS, 411, 349

Gaspari, M., Brighenti, F., D'Ercole, A., & Melioli, C. 2011b, MNRAS, 415, 1549
Giodini, S., Smolčić, V., Finoguenov, A., et al. 2010, ApJ, 714, 218
Helsdon, S. F., & Ponman, T. J. 2000a, MNRAS, 319, 933
—. 2000b, MNRAS, 315, 356
Hudson, D. S., Mittal, R., Reiprich, T. H., et al. 2010, A&A, 513, A37
Kaiser, N. 1986, MNRAS, 222, 323
Kravtsov, A. V., & Borgani, S. 2012, ARA&A, 50, 353
Li, Y., & Bryan, G. L. 2012, ApJ, 747, 26
Lin, Y.-T., & Mohr, J. J. 2004, ApJ, 617, 879
Mannucci, F., Della Valle, M., Panagia, N., et al. 2005, A&A, 433, 807
Maughan, B. J., Giles, P. A., Randall, S. W., Jones, C., & Forman, W. R. 2012, MNRAS, 421, 1583
McCarthy, I. G., Schaye, J., Ponman, T. J., et al. 2010, MNRAS, 406, 822
McDonald, M., Benson, B. A., Vikhlinin, A., et al. 2013, ApJ, 774, 23
McNamara, B. R., & Nulsen, P. E. J. 2007, ARA&A, 45, 117
Mittal, R., Hudson, D. S., Reiprich, T. H., & Clarke, T. 2009, A&A, 501, 835
Mulchaey, J. S., Davis, D. S., Mushotzky, R. F., & Burstein, D. 2003, ApJS, 145, 39
Novak, G. S. 2013, arXiv:1310.3833
Osmond, J. P. F., & Ponman, T. J. 2004, MNRAS, 350, 1511
Peres, C. B., Fabian, A. C., Edge, A. C., et al. 1998, MNRAS, 298, 416
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2013, arXiv:1303.5076
Planelles, S., Borgani, S., Fabjan, D., et al. 2013, MNRAS, 2889P
Pratt, G. W., Croston, J. H., Arnaud, M., & Böhringer, H. 2009, A&A, 498, 361
Puchwein, E., Sijacki, D., & Springel, V. 2008, ApJ, 687, L53
Short, C. J., Thomas, P. A., Young, O. E., et al. 2010, MNRAS, 408, 2213
Sijacki, D., Springel, V., Di Matteo, T., & Hernquist, L. 2007, MNRAS, 380, 877
Sun, M. 2012, New Journal of Physics, 14, 045004
Sun, M., Voit, G. M., Donahue, M., et al. 2009, ApJ, 693, 1142
Vikhlinin, A. 2006, ApJ, 640, 710
Vikhlinin, A., Kravtsov, A., Forman, W., et al. 2006, ApJ, 640, 691
Zhao, H.-H., Jia, S.-M., Chen, Y., et al. 2013, ApJ, 778, 124