The Lack of Non-Thermal Motions in Galaxy Cluster Cores

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ABSTRACT

We report the non-thermal pressure fraction ($P_{\text{nt}}/P_{\text{tot}}$) obtained from a three-dimensional triaxial analysis of 16 galaxy clusters in the CLASH sample using gravitational lensing (GL) data primarily from Subaru and HST, X-ray spectroscopic imaging from Chandra, and Sunyaev-Zel’dovich effect (SZE) data from Planck and Bolocam. Our results span the approximate radial range 0.015–0.4R_{200m} (~35–1000 kpc). At cluster-centric radii smaller than 0.1R_{200m} the ensemble average $P_{\text{nt}}/P_{\text{tot}}$ is consistent with zero with an upper limit of nine per cent, indicating that heating from active galactic nuclei and other relevant processes does not produce significant deviations from hydrostatic equilibrium (HSE). The ensemble average $P_{\text{nt}}/P_{\text{tot}}$ increases outside of this radius to approximately 20 per cent at 0.4R_{200m}, as expected from simulations, due to newly accreted material thermalizing via a series of shocks. Also in agreement with simulations, we find significant cluster-to-cluster variation in $P_{\text{nt}}/P_{\text{tot}}$ and little difference in the ensemble average $P_{\text{nt}}/P_{\text{tot}}$ based on dynamical state. We conclude that on average, even for diverse samples, HSE-derived masses in the very central regions of galaxy clusters require only modest corrections due to non-thermal motions.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – X-rays: galaxies: clusters – gravitational lensing: weak – gravitational lensing: strong – galaxies: active

1 INTRODUCTION

Given the hierarchical buildup of structure in the Universe, galaxy clusters are the largest and most recent objects to form (Davis et al. 1985; Kravtsov & Borgani 2012). Their evolution is dictated mainly by gravity (Kaiser 1986, 1991), but a range of more complicated processes, including core sloshing (Markevitch & Vikhlinin 2007), dynamical friction from galaxy motions (El-Zant et al. 2004), and conduction and turbulent mixing (Ruszkowski & Oh 2010), feedback from centrally located active galactic nuclei (AGN) is thought to be the primary heating source (McNamara & Nulsen 2007; Gitti et al. 2012). This feedback is dynamic: AGN jets inflate bubbles in the gas and transfer energy via multiple mechanisms, such as shocks, cavity heating, and convective mixing (Yang & Reynolds 2016).

Recently, Hitomi used high resolution X-ray spectroscopy to measure the gas velocity structure of Perseus’s core. Surprisingly, despite its active AGN and the presence of features like a sloshing cold front (Simionescu et al. 2012), the gas was found to be remarkably quiescent, with a non-thermal pressure fraction $P_{\text{nt}}/P_{\text{tot}} \approx 4$ per cent (Hitomi Collaboration et al. 2016). More recently, a multi-probe observational study of five galaxy clusters at $z \approx 0.35$ with extremely round morphologies from the Joint Analysis of Cluster Observations (JACO) project found $P_{\text{nt}}/P_{\text{tot}} \leq 6$ per cent within R_{2500c} (corresponding to $\sim 0.2R_{200m}$, Siegel et al. 2018).¹ This suggests that Perseus is not unusual, although the strict selection of the JACO sample may not be representative of the overall population.

External to these central regions, simulations predict that $P_{\text{nt}}/P_{\text{tot}}$ increases with radius as a result of the series of shocks required

¹ We refer to radii, and corresponding masses, that enclose an average density defined by the subscript. The number in the subscript denotes the overdensity relative to the background critical (c) or matter (m) density of the universe. All physical values described in this work were computed assuming a flat ΛCDM cosmology with $\Omega_{\text{m}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $h = 0.7$.}

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to thermalize newly accreted material (Miniati et al. 2000; Molnar et al. 2012; Nelson et al. 2014; Shi & Komatsu 2014; Lau et al. 2015; Shi et al. 2015). Recently, JACO (Siegel et al. 2018) and the XMM-Newton Cluster Outskirts Project (X-COP, Eckert et al. 2019), which included 12 local galaxy clusters, both found $P_{\text{tot}}/P_{\text{th}} \lesssim 10$ per cent at $R_{200m} \sim 0.5R_{200m}$. These results are in some tension with simulation-based predictions of 15–25 per cent at this radius (Nelson et al. 2014; Angelinelli et al. 2020; Gianfagna et al. 2020), and potentially imply more efficient thermalization.

The result presented here is obtained from modeling multi-probe observations using the CLUMP-3D package (Sereno et al. 2017). These data enable independent measurements of the thermal pressure ($P_{\text{th}}$) and total mass distribution (which sets the total pressure, $P_{\text{tot}}$, required to offset gravity). The non-thermal pressure ($P_{\text{nt}}$) is the difference between $P_{\text{tot}}$ and $P_{\text{th}}$. While this basic formalism is common to CLUMP-3D, JACO, and X-COP, our model relies on fewer assumptions. We do not require spherical symmetry and we allow for intrinsic cluster-to-cluster scatter in $P_{\text{nt}}/P_{\text{tot}}$. Unlike JACO, we do not assume a fixed radial form for $P_{\text{nt}}/P_{\text{tot}}$. Unlike X-COP, we measure the total mass with gravitational lensing (GL). Like JACO, we use strong lensing (SL) constraints to reliably probe mass profiles near the core. In sum, our technique enables a more flexible, data-driven approach that can address larger and more diverse samples.

### 2 DATA

Because of the deep multi-probe observations required for this type of analysis, previous applications of similar methods have been limited to individual galaxy clusters (e.g., Morandi et al. 2012; Limousin et al. 2013; Sereno et al. 2013). In this work, we use the datasets obtained as part of the Multi-Cycle Treasury program Cluster Lensing and Supernova survey with Hubble (CLASH, Postman et al. 2012) to model 16 individual objects. While CLASH includes 25 galaxy clusters, five were selected based on lensing strength and appear to be dynamically complicated systems that may not be accurately modeled within the CLUMP-3D formalism (i.e., at least four of these five objects are undergoing major mergers between at least two distinct sub-clusters, see Mann & Ebeling 2012; Postman et al. 2012). Of the remaining 20, four lack the requisite ground-based wide-field GL data required for our analysis (Umetsu et al. 2018), leaving a sample of 16 for this work (see Table 1).

All of these clusters have a regular X-ray morphology, which indicates a slightly higher than average probability of being dynamically relaxed (Meneghetti et al. 2014). None of the galaxy clusters appear to be undergoing a major merger. However, eight of the 16 show potential signs of some merger activity in at least one systematic search for such objects based on X-ray imaging, location of the central galaxy, and member-galaxy velocity dispersions (Gilmour et al. 2009; Postman et al. 2012; Mann & Ebeling 2012).

Observational data available for the full sample include: X-ray spectroscopic imaging from *Chandra* with a median exposure time of 44 ksec (Sereno et al. 2018); Sunyaev-Zel’dovich effect (SZE) imaging from Bolocam and *Planck* with a median combined signal-to-noise ratio of 12.3 (Sayers et al. 2016); wide-field ground-based weak lensing (WL) constraints from an average background source density of 12 arcmin$^{-2}$ after stringent color–color cuts (mainly using *Subaru* imaging from ≥ 3 bands, Umetsu et al. 2014, 2018); and 16-filter HST imaging providing a median of 18 effective SL constraints per galaxy cluster and an average background source density of 50 arcmin$^{-2}$ for WL (Zitrin et al. 2015).

### 3 METHODS

The CLUMP-3D model assumes an elliptical triaxial geometry, with co-alignment and co-centering of the major, intermediate, and minor axes of both the total mass and gas distributions. The eccentricities are allowed to separately vary, with the well-motivated prior that the galaxy cluster. Independently, the gas temperature ($T_{\text{gas}}$) determined from X-ray spectroscopy. The SZE brightness is proportional to the total mass. Specifically, the X-ray surface brightness is related to the gas, while the GL data enumerate the total mass. Specifically, the X-ray surface brightness is related to the gas, while the GL data constrain the total mass. Specifically, the X-ray surface brightness is related to the gas, while the GL data constraint the model using the brightest cluster galaxy as the centre (Sereno et al. 2017, 2018). Background and exposure-corrected *Chandra* surface brightness images are produced in the 0.7–2.0 keV band using the CIAO 4.8 software and the calibration

| Cluster Name | Redshift | $M_{200m}$ | $R_{200m}$ | $R_{\text{max}}$ |
|--------------|----------|------------|------------|---------------|
| ABELL 0744.9+3927 | 0.451 | 0.391 | 0.363 | 0.348 |
| MACS J1347.5-1144 | 0.60 | 0.440 | 0.411 | 0.39 |
| MACS J0329.6-0211 | 0.71 | 0.356 | 0.326 | 0.31 |
| MACS J1206.2-0847 | 0.225 | 0.234 | 0.222 | 0.206 |
| MACS J1720.2+3536 | 0.225 | 0.234 | 0.222 | 0.206 |
| MACS J1115.8+0129 | 0.27 | 0.391 | 0.371 | 0.352 |
| MACS J1931.8-2635 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J1532.8+3021 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J1270.2+3536 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J0429.6-0253 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J1026.2-0847 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J0329.6-0211 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J1347.5-1144 | 0.14 | 0.371 | 0.352 | 0.333 |
| MACS J0744.9+3927 | 0.14 | 0.371 | 0.352 | 0.333 |
database CALDB 4.7.1. Point sources are filtered out, and the two-dimensional image is restricted to the circular region enclosing 80 per cent of the total source emission. Spectra used to constrain the gas temperature are extracted from circular annuli and analyzed with the XSPEC v.12.9 software. The SZE brightness is computed in circular annuli using publicly available maps from Bolocam (Sayers et al. 2013) and Planck (Planck Collaboration et al. 2016) via a combined analysis of both datasets (Sayers et al. 2016). For the ground-based wide-field WL, two-dimensional projected mass maps and their pixel–pixel covariance matrices are obtained from a joint analysis of the shear and magnification bias over a 24 arcmin × 24 arcmin square region (Umetsu et al. 2018). Using the Hubble Space Telescope WL and SL data, projected masses are computed in circular annuli between 5 arcsec and twice the Einstein radius from the publicly available CLASH PIEMDeNFW maps (Zitrin et al. 2015).

To compare with these products generated from the observational data, the CLUMP-3D model is used to create projected GL mass maps, X-ray surface brightness and temperature maps, and SZE brightness maps from a given set of parameter values. A Bayesian inference scheme is used to assess the probability distributions of the parameters (Sereno et al. 2017). Priors spanning large regions of parameter space, with uniform distributions in either linear or logarithmic spaced intervals, are assumed. Some priors span the full range of physically motivated or allowed values. For example, the major axial ratio of the total mass density has a uniform linear prior between 0.1 and 1.0 (Jing & Suto 2002). All other priors span a sufficiently large range to include any reasonable derived value.

From these fits, we compute probability densities for the values of $\rho_{gas}$ and the gravitational potential $\Phi_{mat}$ in three dimensions. Here, we assume the gas to be in equilibrium, and so the ICM axial ratios are set equal to the average ratios of the gravitational potential. We then determine $P_{tot}$ from the HSE equation ($\nabla \Phi_{tot} = -\rho_{gas} \nabla \Phi_{mat}$). Using the three discrete values for $P_{th}$ and $P_{tot}$, we compute the average for each within a set of discrete logarithmically spaced spherical annuli. We find that the probability densities are well described by a Gaussian distribution for $\ln(P_{th}/P_{tot})$, and so profiles are generated in this quantity for each galaxy cluster. Finally, the radial coordinate is scaled relative to $R_{200m}$, which simulations indicate minimizes the cluster-to-cluster scatter in $P_{th}/P_{tot}$ (Nelson et al. 2014). Plots of $P_{th}/P_{tot}$ for all 16 galaxy clusters are shown in Figure 1.

From these radially scaled profiles, we constrain the ensemble-average profile at each discrete radius using the log likelihood

$$\mathcal{L}(X|\mu, \sigma_{int}) = -\frac{1}{2} \sum_{i} \left[ \frac{(x_i - \mu)^2}{\sigma_i^2 + \sigma_{int}^2} + \ln(\sigma_i^2 + \sigma_{int}^2) + \ln(2\pi) \right]$$

(1)

where $x_i = \{x_1, \ldots, x_N\}$ are the values of $\ln(P_{th}/P_{tot})$ with measurement uncertainties $\sigma_i$ for the $N$ objects in our sample, $\mu$ is the ensemble average, and $\sigma_{int}$ is the intrinsic scatter about the average. This likelihood is evaluated using a grid of $\mu \in [-2, 2]$ and $\sigma_{int} \in [0, 1]$ to obtain probability distributions for $\mu$ and $\sigma_{int}$.

To mitigate the impact of any outlier values, particularly at small radii where our assumption of coagulation between the gas density and the potential may be invalid, we discard any $x_i$ that fails the goodness-of-fit criteria suggested by Feldman & Cousins (1998). To ensure consistency with the physically allowed region based on this procedure, any individual $x_i$ with

$$\int_{x_i}^{\infty} \mathcal{L}(X|\mu=0, \sigma_{int}=0) dx < 0.01$$

(2)

is removed from the analysis. This occurs at a subset of radii for five galaxy clusters, primarily at $R \leq 0.1 R_{200m}$ (see Figure 1). To further mitigate contamination from outliers, we also remove any $x_i$ that sufficiently differs from the maximum likelihood value of $\mu$ such that they would be expected to occur less than one per cent of the time given the maximum likelihood value of $\sigma_{int}$. This removal is performed in an iterative manner until no such $x_i$ remain. From a total of 16 values, the number of $x_i$ removed at a given radius is between 2–6, and so the majority of the sample is retained for the ensemble fits. The value of $\mu$ is largely insensitive to the above data cuts, even if no $x_i$ are removed. However, the value of $\sigma_{int}$ does increase if fewer $x_i$ are removed, particularly at small radii where it can be up to a factor of $\approx 1.5$ larger when all the $x_i$ are retained.

We evaluate the likelihood at $\mu > 0$, which is in the physically disallowed region. Establishing confidence intervals on the values of $\mu$ requires care due to this physical boundary. For instance, imposing the physical boundary on the $x_i$ prior to computing $\mu$ can result in biases (Leccardi & Molendi 2008). Furthermore, Feldman & Cousins (1998) have argued that simple prescriptions such as Bayesian priors or renormalization of the Bayesian posterior can produce intervals without the desired coverage. For this analysis, we adopt the Feldman & Cousins (1998) approach for establishing frequentist confidence intervals in the physically allowed region.

Specifically, a value of $\mu$ should be included in the $\alpha$ per cent confidence interval if the data $X_0$ are in the $\alpha$ per cent most likely observational outcomes were $\mu$ the true underlying value. As described by Feldman & Cousins (1998), the statistic for evaluating whether an outcome is in the $\alpha$ per cent most likely outcomes is

$$R(X) = \mathcal{L}(X|\mu^*) / \mathcal{L}(X|\mu),$$

(3)

where $\mu^*$ maximizes the likelihood within the physically allowed region (i.e., $\mu^* \leq 0$) and $\mathcal{L}(X|\mu)$ is obtained from Equation 1. Absent a physical boundary, the denominator is independent of $X$ and $R(X) \propto \mathcal{L}(X|\mu)$. Because every potential observational outcome $X$ yields a value $R(X)$, $\mathcal{L}(X|\mu)$ maps into a likelihood $L^*(R(\mu))$. We
define a value $R_\alpha$ such that the integral of $L'(R)/\mu$ over $R(X) \geq R_\alpha$ is equal to $\alpha$. We include a value of $\mu$ in the $\alpha$ per cent confidence interval if $R(X_{\mu}/\mu) \geq R_\alpha$. To obtain the complete desired confidence interval, this process is performed over a grid of values of $\mu$.

We apply the same analysis to $P_{nt}$ and $P_{tot}$ profiles obtained in spherical annuli from 315 simulated galaxy clusters in the Three Hundred Project (hereafter “300”, Cui et al. 2018). This sample was selected based on the criteria described in Ansarifard et al. (2020), and excludes nine objects with at least one low-resolution particle, which are used to trace the large scale structure in which the galaxy cluster is embedded, within $R_{200m}$. These halos span the approximate mass range $M_{200m} \approx 10^{-15} \times 10^{14} M_\odot$, nearly identical to that of the CLASH clusters, and they were taken from a snapshot at $z = 0.333$, close to the median $z$ of 0.352 for our observational sample.

### 4 RESULTS AND DISCUSSION

Using the procedure detailed in Section 3, we obtain 95% confidence regions for $P_{nt}/P_{tot}$ profiles for all 16 individual galaxy clusters (see Figure 1), along with the ensemble average $P_{nt}/P_{tot}$ and the intrinsic scatter about this average (see Figures 2 and 3). When interpreting these profiles, note that the CLUMP-3D model assumes no inhomogeneities in the gas distribution (McNamara & Nulsen 2007). In addition, modeling of the Chandra data is generally more prone to systematic errors within approximately 50 kpc (~0.02R$_{200m}$) due to inhomogeneities in the gas distribution (McNamara & Nulsen 2007). The Chandra data also set the maximum radius that is fully constrained by GL, X-ray, and SZE data, with $R_{max} = 0.22 \pm 0.02 R_{200m}$ (see Table 1). In our ensemble analysis, the maximum radius considered is 0.42R$_{200m}$, outside of which more than half the sample lacks Chandra coverage.

Within 0.1R$_{200m}$, we measure an ensemble-average non-thermal pressure fraction consistent with zero (see Figure 2). The 95% confidence level upper limit takes on values in the range 8–18 per cent, with a volume-averaged upper limit of nine per cent. This is consistent with the Hitomi measurements of Perseus (Hitomi Collaboration et al. 2018) and the spherical JACO analysis of five galaxy clusters with extremely round morphologies (Siegel et al. 2018). Our analysis therefore suggests that those previous results are valid for a larger and more diverse sample. Recent simulations generally predict $P_{nt}/P_{tot}$ values close to our measured upper limit (i.e., ~10 per cent, Angelinelli et al. 2020; Gianfagna et al. 2020), in good agreement with our analysis of the 300 simulations.

Beyond 0.1R$_{200m}$, our measured ensemble-average $P_{nt}/P_{tot}$ increases. This is expected due to the series of shocks at varying radii that cause observable non-thermal material to be heated. This trend is consistent with what is seen in the 300 simulations and other published simulations (Nelson et al. 2014; Angelinelli et al. 2020; Gianfagna et al. 2020), indicating that they accurately reproduce the level of observed diversity.

With a relatively large measurement uncertainty, the CLASH data indicate an intrinsic cluster-to-cluster scatter on $P_{nt}/P_{tot}$ that is approximately constant with radius at a value of 15–20 per cent. This scatter is generally comparable to, or larger than, the ensemble average of $P_{nt}/P_{tot}$. Therefore, while the gas at small radii is highly quiescent on average, some galaxy clusters do contain significant non-thermal pressure support within that region. This suggests that AGN feedback may sometimes produce a larger amount of non-thermal pressure than typical and/or play a larger role (McNamara & Nulsen 2007; Markevitch & Vikhlinin 2007). In addition, modeling of the Chandra data is generally more prone to systematic errors within approximately 50 kpc (~0.02R$_{200m}$) due to inhomogeneities in the gas distribution (McNamara & Nulsen 2007). The Chandra data also set the maximum radius that is fully constrained by GL, X-ray, and SZE data, with $R_{max} = 0.22 \pm 0.02 R_{200m}$ (see Table 1). In our ensemble analysis, the maximum radius considered is 0.42R$_{200m}$, outside of which more than half the sample lacks Chandra coverage.

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For the 300 simulations, a sub-sample of 101 more relaxed systems was selected based on a centre-of-mass offset $\Delta \leq 0.04$ and a fraction of mass in subhaloes $f_s \leq 0.1$ within $R_{2500c}$ (Cui et al. 2018), with the remaining 214 objects forming the less relaxed sub-sample. It is not possible to robustly constrain the intrinsic scatter with only eight objects in the CLASH sub-samples. Therefore, for these sub-sample fits we fix the intrinsic scatter to the maximum likelihood value obtained from the full sample. At all radii, the profiles of the more relaxed and less relaxed sub-samples are consistent for both the CLASH galaxy clusters and the 300 simulations, indicating the ensemble average $P_{\text{nt}}/P_{\text{tot}}$ is largely insensitive to dynamical state and thus not strongly influenced by merger activity, at least for non-major mergers. This conclusion is consistent with the findings of a separate analysis of the 300 simulations focused on mass calibration (Ansarifard et al. 2020), but in contrast to what has been found in some recent simulations (Nelson et al. 2014; Gianfagna et al. 2020).

## 5 SUMMARY AND CONCLUSIONS

From a relatively diverse sample of 16 CLASH objects, we find that there is generally very little non-thermal pressure support in the core regions of galaxy clusters. Our result suggests that highly quiescent cores are not unusual nor restricted to a particular subset of galaxy clusters. This conclusion is further supported by the consistency of the non-thermal pressure fraction measured in two sub-samples of eight objects with and without potential merger activity. Therefore, AGN outbursts and other relevant heating mechanisms must typically operate in a gentle manner that preserves approximate HSE. Outside of the core, we find that the non-thermal pressure fraction increases with radius, as expected due to incomplete thermalization of newly accreted material. Furthermore, we find that the non-thermal pressure fraction varies significantly among the population, both within and external to the core region. Other than the 300 simulations suggesting a slightly higher ensemble average $P_{\text{nt}}/P_{\text{tot}}$ near the galaxy clusters’ centres, we find generally good agreement between the observational results from the CLASH sample and the results from those simulations. At the smaller radii where a difference does exist, we measure an average $P_{\text{nt}}/P_{\text{tot}}$ consistent with zero, with an upper limit similar to the average $P_{\text{nt}}/P_{\text{tot}}$ found in the 300 simulations. This suggests that the typical HSE mass bias found in the 300 simulations at those radii, for example 5–10 per cent at $R_{2500c}$ (Ansarifard et al. 2020), likely represents an upper limit.

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## DATA AVAILABILITY

The data underlying this analysis are available from repositories for CLASH [https://archive.stsci.edu/prepds/clash/], Chandra [https://cxc.cfa.harvard.edu/cda/], and Planck [https://irs.ias.caltech.edu/Missions/planck.html].

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