A census of cool core galaxy clusters in IllustrisTNG

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ABSTRACT
The thermodynamic structure of hot gas in galaxy clusters is sensitive to astrophysical processes and typically difficult to model with galaxy formation simulations. We explore the fraction of cool-core (CC) clusters in a large sample of 370 clusters from IllustrisTNG, examining six common CC definitions. IllustrisTNG produces continuous CC criteria distributions, the extremes of which are classified as CC and non-cool-core (NCC), and the criteria are increasingly correlated for more massive clusters. At $z = 0$ the CC fraction is systematically lower than observed for the complete sample, selecting massive systems increases the CC fraction for 3 criteria and reduces it for others. This result is partly driven by systematic differences between the simulated and observed gas fraction profiles. The simulated CC fraction increases more rapidly with redshift than observed, independent of mass or redshift range, and the CC fraction is overpredicted at $z \geq 1$. The conversion of CCs to NCCs begins later and acts more rapidly in the simulations. Examining the fraction of CCs and NCCs defined as relaxed we find no evidence that CCs are more relaxed, suggesting that mergers are not solely responsible for disrupting CCs. A comparison of the median thermodynamic profiles defined by different CC criteria shows that the extent to which they evolve in the cluster core is dependent on the CC criteria. We conclude that the thermodynamic structure of galaxy clusters in IllustrisTNG shares many similarities with observations, but achieving better agreement most likely requires modifications of the underlying galaxy formation model.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – X-rays: galaxies: clusters – methods: numerical

1 INTRODUCTION
Galaxy clusters are the most massive collapsed structures at the current epoch; forming hierarchically under gravity via the accretion of matter and merging with other collapsed haloes. This formation process shock-heats the intracluster medium (ICM) to $10^7 - 10^8$ K, resulting in the emission of X-rays. Early X-ray observations of the ICM revealed that the cooling time in the cores of some clusters was significantly shorter than the Hubble time (Lea et al. 1973; Fabian & Nulsen 1977; Cowie & Binney 1977; Mathews & Bregman 1978). Clusters with short central cooling times are also associated with more relaxed morphologies and drops in central temperatures, reaching only a third of the virial temperature (Ikebe et al. 1997; Lewis et al. 2002; Peterson et al. 2003; Vikhlinin et al. 2005). These systems are known as cool-core (CC) clusters.

The fraction of the cluster population that host a CC depends strongly on the method of selection, due to the so-
called ‘cool-core bias’ (Eckert et al. 2011). CCs are associated with a strong peak in their X-ray surface brightness and a higher X-ray luminosity at fixed mass compared to non-cool-core (NCC) clusters, making them more easily detected in flux-limited X-ray samples. Hence, the fraction of CCs in X-ray samples is likely overestimated. For example, ≈ 60 per cent of 207 clusters detected with Einstein, over 59 per cent of 55 clusters observed with ROSAT and 72 per cent of 64 clusters in the HIFLUGCS sample were found to host a CC (White et al. 1997; Peres et al. 1998; Hudson et al. 2010). However, the success of Sunyaev-Zel’dovich (SZ) surveys (Hasselfield et al. 2013; Bleem et al. 2015; Planck Collaboration et al. 2016b) has enabled clusters to be selected avoiding the cool-core bias (see Lin et al. 2015). Using the Planck SZ sample, Planck Collaboration et al. (2011) found that 35 per cent of the sample hosted a CC, Rossetti et al. (2017) found a CC fraction of 29 per cent and Andrade-Santos et al. (2017) found that, depending on the defining criterion, 28–39 per cent of Planck clusters hosted a CC.

Observational results suggest that CCs have evolved little since z ~ 1.6. The central electron number density, entropy and cooling time of CC clusters have not evolved during this epoch (Cavagnolo et al. 2009; McDonald et al. 2013, 2017), suggesting that thermal equilibrium in the cluster core is established very early in its formation history. These results are consistent with the observation that the fraction of strong CCs, defined by cuspiness of the electron number density (Vikhlinin et al. 2007) or concentration of the surface brightness (Santos et al. 2008, 2010), decreases with increasing redshift. This is because the majority of the cluster volume evolves self-similarly around a CC, increasing in density and reducing the contrast to the core with increasing redshift (McDonald et al. 2017).

Reproducing the observed CC/NCC fractions in numerical simulations has been a significant challenge (Borgani & Kravtsov 2011). Idealized simulations have examined the physical processes in idealized CC setups (e.g. McCourt et al. 2012; Sharma et al. 2012; Gaspari 2015; Li et al. 2015), but have not reproduced how CCs form or how they are maintained in a cosmological setting. Cosmological simulations give conflicting results on CC formation and maintenance. Kay et al. (2007) found that almost all clusters hosted a CC at both z = 0 and z = 1. Burns et al. (2008) also found that the fraction of CCs as a function of redshift was roughly constant, but that only ≈ 15 per cent of systems hosted a CC. The predicted fraction of CC clusters is inconsistent with the observed fraction and the lack of evolution in the fraction of CC systems is in tension with the mild evolution that is observed. Early work also proposed that the difference between CCs and NCCs was driven by activity at high redshift (z > 1), with significant early mergers (Burns et al. 2008) or preheating (McCarthy et al. 2008) resulting in the production of NCC clusters and late time mergers being unable to turn a CC into a NCC (Poole et al. 2008). This is in contrast to more recent numerical work that has shown that late time mergers are capable of destroying CCs (Rasia et al. 2015), with Hahn et al. (2017) advocating that the angular momentum of the merger is critical in determining whether the CC is disrupted. Rasia et al. (2015) argue that the lack of AGN feedback in early work, which leads to over-cooling, made the cores too resilient to late time mergers. In addition, the conflicting numerical results are further complicated by the use of different criteria when defining a CC cluster.

In this paper, we examine the fraction of CC and NCC galaxy clusters in the IllustrisTNG simulations, a follow-up to the Illustris project that contains an updated galaxy formation model and larger simulation volumes. Compared to previous theoretical work our study has the advantages of: being a significantly larger sample of clusters than many previous studies; being at higher numerical resolution compared to many previous works; employing a state-of-the-art galaxy formation model that shows good agreement with observational results from dwarf galaxies to cluster scales. This enables us to study the fraction of clusters defined as CC and NCC for a variety of criteria commonly used in the literature. We examine the fraction of CC clusters produced by the IllustrisTNG model at z = 0 and compare the criteria distributions to those from low-redshift observational samples. We then study how the fraction of CC systems evolves with redshift and how the fraction of CCs defined as relaxed evolves with redshift, in comparison to those defined as NCC or the complete sample of clusters. Finally, we examine how cluster cores evolve compared to the rest of the cluster volume by comparing the hot gas profiles at z = 0 and z = 1.

The paper is structured as follows. In Section 2 we briefly describe the IllustrisTNG model and the simulation volume we use. We present the CC criteria that we use throughout this work in Section 3. In Section 4 we examine the criteria as a function of mass and the correlation between them. We then investigate how the CC fraction, defined by the different criteria, evolves with redshift and the fraction of CC systems that are defined as relaxed in Section 5. In Section 6 we study how the profiles of CCs evolve compared to NCCs. We then present our conclusions in Section 7.

2 NUMERICAL METHOD

IllustrisTNG (Springel et al. 2017; Marinacci et al. 2017; Naiman et al. 2017; Pillepich et al. 2017a; Nelson et al. 2017) is a follow-up project to the Illustris simulation (Vogelsberger et al. 2014a,b; Genel et al. 2014; Sijacki et al. 2015), which reproduces the galaxy size-mass relation (Genel et al. 2017) and the metallicity content of the ICM (Vogelsberger et al. 2017). The IllustrisTNG suite contains three simulation volumes, TNG50, TNG100 and TNG300, each at three different resolution levels (1, 2 and 3). All simulations use a cosmological model with parameters chosen in accordance with the Planck Collaboration et al. (2016a) constraints: \(\Omega_0 = 0.3089\), \(\Omega_b = 0.0486\), \(\Omega_{\Lambda} = 0.6911\), \(\sigma_8 = 0.8159\), \(H_0 = 100 \, h \, \text{km s}^{-1} \text{Mpc}^{-1} = 67.74 \, \text{km s}^{-1} \text{Mpc}^{-1}\) and \(n_s = 0.9667\).

In this work, we analyze the clusters that are present in the TNG300-1 periodic volume. The TNG300-1 volume has a side length of 302.6 Mpc and a dark matter and baryonic mass resolution of \(5.9 \times 10^7 M_\odot\) and \(1.1 \times 10^7 M_\odot\) respectively. The collisionless particles, i.e. stars and dark matter, have a softening length of 1.48 kpc, which is comoving for \(z > 1\), and a fixed physical length for \(z \leq 1\). The gas cells employ an adaptive comoving softening length that reaches a minimum of 0.37 kpc. The simulation was performed with the moving-mesh code Arepo (Springel 2010), and evolved
the magneto-hydrodynamics equations (Pakmor & Springel 2013). IllustrisTNG employs an updated version of the Illustris galaxy formation model (Vogelsberger et al. 2013; Torrey et al. 2014; Vogelsberger et al. 2014a,b; Genel et al. 2014), a comprehensive set of subgrid physical models that now include a new radio mode AGN feedback scheme (Weinberger et al. 2017a), a re-calibrated SN wind model and an extension to the chemical evolution scheme (Pillepich et al. 2017b) and refinements to the numerical scheme to improve the convergence properties (Pakmor et al. 2016). We analyze a mass-limited sample and select all haloes with $M_{500} > 10^{13.75} M_\odot$ at each redshift. At $z = 0$ ($z = 1$) this yields a sample of 370 (77) clusters with a median mass of $M_{500} = 8.8 \times 10^{13} M_\odot$. X-ray luminosities, $L_X$, are computed using the Astrophysical Plasma Emission Code (APEC; Smith et al. 2001) via the pyATOMDB module with atomic data from ATOMDB v3.0.3 (last described in Foster et al. 2012). We compute mock X-ray spectra for each individual chemical element tracked by the simulation in the rest-frame energy band 0.05 – 100 keV for each gas cell, using its density, temperature, and metallicity. We then sum the spectra for the elements to produce an X-ray spectrum for each cell. X-ray luminosity within an aperture is then calculated by summing the spectra in the desired energy band for the gas cells that fall within the aperture, see Le Brun et al. (2014); Barnes et al. (2017a) for further details.

3 COOL-CORE CRITERIA

The literature contains many ways of defining a CC cluster and the fraction of clusters defined as CC depends on the chosen criterion. Observationally, the choice of criterion used will depend on the quality and resolution of the data, for example, the ability to extract a temperature profile. In this section we define the CC criteria that we will consider in this work. The thresholds for defining a cluster as CC for the different criteria are summarized in Table 1. When calculating the criteria we only include non-star forming gas that is cooling and has a temperature $T > 1.0 \times 10^8$ K. The choice of halo centre can impact the recovered CC fraction and in this work we always centre on the cluster’s potential minimum.

3.1 Central electron number density

A rapidly cooling core will be colder than its surrounding material and, therefore, must be denser than its surroundings in order to maintain pressure equilibrium. Observationally, the electron number density is extracted from the measured surface brightness profile and requires significantly fewer counts than other CC criteria, such as the cooling time. Following Hudson et al. (2010), we define a cluster as CC if the average density $n_e < 0.012 r_{500}^{-3}$ cm$^{-3}$. We choose to measure the quantity inside a 3D aperture of $0.012 r_{500}$ to mimic observational apertures (e.g. Hudson et al. 2010; McDonald et al. 2017; Andrade-Santos et al. 2017). Those clusters with a central density in the range $0.5 \times 10^{-2} < n_e(< 0.012 r_{500}) \leq 1.5 \times 10^{-2}$ cm$^{-3}$ are defined as MCC clusters and the remaining are defined as NCC.

3.2 Central cooling time

Classically, clusters have been defined as CCs if the cooling time of their central region is short compared to the age of the Universe. Cooling time is defined as

$$t_{cool} = \frac{3}{2} \frac{n_e + n_i}{n_e n_i} k_B T \frac{T}{n_e n_i (T, Z)},$$

(1)

where $n_i$ is the ion number density, $k_B$ is Boltzmann’s constant, $T$ is the temperature of the gas and $\Lambda$ is the cooling function, which is a function of temperature and metallicity, $Z$. Mimicking observations, we measure the average cooling time inside a 3D aperture of $r < 0.012 r_{500}$ (e.g. McDonald et al. 2013). We define those clusters with a cooling time less than 1 Gyr as CCs. We define our second threshold for those clusters considered as MCCs as $t_{cool} < 7.7$ Gyr to make the definition independent of redshift. Observationally, this has a negligible impact on the recovered cooling properties of the clusters (McDonald et al. 2013). Those clusters with $t_{cool} \geq 7.7$ Gyr are defined as NCCs.

3.3 Central entropy excess

The central entropy excess of a cluster is another method of defining whether it is a CC or not. To measure the central entropy excess we follow the method of Cavagnolo et al. (2009). We first compute the 3D radial entropy profile, where the entropy $K = k_B T n_e^{2/3}$. We then fit the entropy profile in the range 0.01 – 1.0$r_{500}$ with a power-law of the form

$$K(r) = K_0 + K_{100} \left( \frac{r}{100 \text{kpc}} \right)^a,$$

(2)

where $K_0$ is the excess entropy above the best-fitting power-law, $K_{100}$ is the normalization of the entropy at 100 kpc, $a$ is the power-law index and $r$ is the radial distance from the cluster’s potential minimum. We then use $K_0$ as the measure of the central entropy excess. We define CC clusters as those with $K_0 < 30$ keV cm$^2$, MCCs as those in the range $30 \leq K_0 < 60$ keV cm$^2$ and the remaining as NCCs.

3.4 Concentration parameter

As the X-ray emissivity is proportional to the gas density squared, and only weakly depends on temperature, CC clusters should have X-ray bright cores. Therefore, the ratio of the X-ray luminosity within the core compared to the luminosity within a larger aperture should clearly demonstrate the presence of a CC. First proposed by Santos et al. (2008), this criterion is commonly known as the concentration parameter. We define the concentration parameter as

$$C_{\text{phys}} = \frac{L_X^{\text{soft}}(r_p < 40 \text{kpc})}{L_X^{\text{soft}}(r_p < 400 \text{kpc})},$$

(3)

where $L_X^{\text{soft}}$ is the soft band X-ray luminosity in the energy range 0.5 – 5.0 keV and $r_p$ is the projected radial distance from the cluster’s potential minimum. Those clusters with $C_{\text{phys}} > 0.155$ are defined as CCs, those in the range

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defining CC clusters. Following the literature, we compute the electron number density profile is a common metric for Cusps. For the scaled concentration parameter we define CCs as those with $\alpha > 0.75$, MCCs in the range $0.2 < \alpha \leq 0.75$, and the rest as NCCs.

### 3.5 Cuspiness parameter

First proposed by Vikhlinin et al. (2007), the cuspiness of the electron number density profile is a common metric for defining CC clusters. Following the literature, we compute the cuspiness parameter of the 3D density profile via

$$\alpha = -\frac{d \log n_e(r)}{d \log r} \bigg|_{r=0.04r_{500}}. \tag{5}$$

We define CCs as those with $\alpha > 0.75$, MCCs in the range $0.5 < \alpha \leq 0.75$ and the remaining are classified as NCCs.

Using these common CC criteria we now examine the fraction of CC clusters produced by the IllustrisTNG model at $z = 0$.

### 4 LOW-REDSHIFT COOL-CORES

#### 4.1 CC fractions

In Fig. 1 we plot the different CC criteria presented in Section 3 as a function of $M_{500}$ at $z = 0$. Clusters that are defined as CC are denoted by blue triangles, MCCs as black circles and NCCs as red squares. The CC metrics all produce continuous distributions with no obvious bimodality or dichotomy, suggesting that CC and NCC clusters are the two tails of the distribution. Excluding the concentration parameter within scaled apertures, the CC criteria distributions all show minimal mass dependence. We examine the reason for the mass dependence of the scaled concentration parameter in Section 4.2. In Appendix A we examine the impact of numerical resolution on the criteria distributions using the TNG100 level 1 volume.

To examine the mass dependence of the CC fraction we divide the sample into three mass bins: low-mass ($M_{500} < 9 \times 10^{13} M_\odot$), intermediate-mass ($9 \times 10^{13} \leq M_{500} < 2.0 \times 10^{14} M_\odot$) and high-mass ($M_{500} \geq 2.0 \times 10^{14} M_\odot$). The mass bins contain 191, 139 and 49 clusters and have median $M_{500}$ values of $6.9 \times 10^{13} M_\odot$, $1.2 \times 10^{14} M_\odot$ and $2.7 \times 10^{14} M_\odot$, respectively. A summary of the CC, MCC and NCC fractions defined by the 6 criterion at $z = 0$ for the complete sample and each mass bin is given in Table 2. Errors on the CC, MCC and NCC fractions are calculated by bootstrap resampling 10,000 times.

### Table 1. Table summarizing the criteria used throughout this work with the CC and MCC definitions.

| Criterion                        | Notation | CC limit         | MCC limit         |
|----------------------------------|----------|------------------|------------------|
| Central electron density         | $n_e$    | $> 1.5 \times 10^{-2} \text{ cm}^{-3}$ | $> 0.5 \times 10^{-2} \text{ cm}^{-3}$ |
| Central cooling time             | $t_{\text{cool}}$ | $< 1 \text{ Gyr}$ | $< 7.7 \text{ Gyr}$ |
| Central entropy excess           | $K_0$    | $< 30 \text{ keV cm}^{-2}$ | $< 60 \text{ keV cm}^{-2}$ |
| Concentration parameter (physical) | $C_{\text{phys}}$ | $> 0.155$ | $> 0.075$ |
| Concentration parameter (scaled) | $C_{\text{scal}}$ | $> 0.5$ | $> 0.2$ |
| Cuspiness parameter              | $\alpha$ | $> 0.75$ | $> 0.5$ |

0.075 < $C_{\text{phys}}$ ≤ 0.155 as MCCs, and the rest as NCCs. We calculate the luminosity by projecting the gas cells along the $z$-axis and summing the mock spectra of the gas cells that fall within the given physical 2D apertures. We have examined different projection axes, or using the mean or median of the projections, and find that it makes negligible difference to the distribution of concentrations. We also consider the modification to this parameter proposed by Maughan et al. (2012), a scaled concentration parameter where the apertures are scaled by the cluster’s characteristic radius $r_{500}$.

$$C_{\text{scal}} = \frac{L_{\text{phys}}(r_p < 0.15r_{500})}{L_{\text{phys}}(r_p < r_{500})}. \tag{4}$$

For the scaled concentration parameter we define CCs as those with $C_{\text{scal}} > 0.5$, MCCs as $0.2 < C_{\text{scal}} \leq 0.5$, and the rest as NCCs.

In the upper left panel of Fig. 1, we plot the central electron number density as a function of $M_{500}$ for the complete sample, that suffers from CC bias. Andrade-Santos et al. 2017). Selecting clusters with $0.5 < z < 0.25$, the observed sample has a CC fraction of $41 \pm 4$ per cent. This is a factor of 3 larger than the CC fraction of the complete sample. However, due to the Planck selection function, the ESZ sample has a larger median mass compared to the complete simulated sample. Selecting only clusters in the high-mass bin the simulated CC fraction rises to $35 \pm 6$ per cent, which is in good agreement with the observed fraction. Although the criteria distribution shows relatively little mass dependence, when split into the three mass bins we find that the CC fraction increases with increasing mass.

The central cooling time as a function of $M_{500}$ is plotted in the upper centre panel of Fig. 1. Defining CCs via this criterion we find that $12 \pm 2$ per cent of clusters are defined as CC for the complete sample. The CC fraction has the opposite mass dependence to the central electron number density and reduces with increasing mass. The high-mass bin has a CC fraction of $6 \pm 4$ per cent. We compare the simulated CC fraction to those clusters from the ACCEPT sample (Cavagnolo et al. 2009) with $z < 0.25$, noting that the median mass of the observed sample is more massive than the complete sample. The observed clusters yield a CC fraction of $52 \pm 4$ per cent. However, the ACCEPT clusters are taken from the Chandra archive and in effect form an X-ray selected sample, that suffers from CC bias. Andrade-Santos et al. (2017) quantify the selection effects by assuming that the mass function and X-ray luminosity-mass relation are power laws. Using values from Vikhlinin et al. (2009a) and Vikhlinin et al. (2009b) they estimate that CCs are over-represented by a factor of $\sim 2.2$. This reduces the observed CC fraction to $0.24$ per cent, which is a factor of 2 and 4 times larger than the complete and high-mass samples respectively.
Comparison of common CC criteria as a function of $M_{500}$ at $z = 0$. We plot the central electron number density (top left), central cooling time (top centre), central entropy excess (top right), the concentration parameter within physical apertures (bottom left) and scaled apertures (bottom centre), and the cuspiness parameter (bottom right). CCs are denoted by blue triangles, MCCs by black circles and NCCs by red squares. We set $K_0 = 2 \text{ keV cm}^2$ for those clusters whose central entropy excess falls below this value, making them visible on the plot, and denote these systems by open symbols. The dashed black lines denote the mass bins and the (red) blue circles and NCCs by red squares. We set $K_0$ and scaled apertures (bottom centre), and the cuspiness parameter (bottom right). CCs are denoted by blue triangles, MCCs by black circles and NCCs by red squares. We set $K_0 = 2 \text{ keV cm}^2$ for those clusters whose central entropy excess falls below this value, making them visible on the plot, and denote these systems by open symbols. The dashed black lines denote the mass bins and the (red) blue numbers give the fraction of (non-)cool-core systems in each bin. We note the y-axis is inverted for the central cooling time and central entropy excess, such that CCs always appear at the top of a panel.

### Table 2

Table of the fraction of clusters defined as CC, MCC or NCC for the criteria presented in Section 3 for the complete sample and the different mass bins. All errors are computed by bootstrap resampling 10,000 times.

| Sample | Fraction | $n_e$ | $t_{\text{cool}}$ | $K_0$ | $C_{\text{phys}}$ | $C_{\text{scal}}$ | $\alpha$ |
|--------|----------|------|-----------------|------|-----------------|-----------------|---------|
| Complete | CC | $0.14 \pm 0.02$ | $0.12 \pm 0.02$ | $0.18 \pm 0.02$ | $0.01 \pm 0.01$ | $0.04 \pm 0.01$ | $0.21 \pm 0.02$ |
| ($M_{500} > 10^{13.75} \, M_\odot$) | MCC | $0.39 \pm 0.03$ | $0.58 \pm 0.03$ | $0.10 \pm 0.01$ | $0.20 \pm 0.02$ | $0.62 \pm 0.02$ | $0.09 \pm 0.01$ |
| | NCC | $0.46 \pm 0.02$ | $0.30 \pm 0.03$ | $0.72 \pm 0.02$ | $0.79 \pm 0.02$ | $0.34 \pm 0.03$ | $0.70 \pm 0.02$ |
| Low-mass | CC | $0.07 \pm 0.02$ | $0.15 \pm 0.03$ | $0.28 \pm 0.04$ | $0.00 \pm 0.01$ | $0.00 \pm 0.01$ | $0.31 \pm 0.04$ |
| ($M_{500} < 9.0 \times 10^{13} \, M_\odot$) | MCC | $0.36 \pm 0.03$ | $0.55 \pm 0.03$ | $0.12 \pm 0.02$ | $0.22 \pm 0.04$ | $0.54 \pm 0.04$ | $0.10 \pm 0.03$ |
| | NCC | $0.57 \pm 0.04$ | $0.30 \pm 0.04$ | $0.60 \pm 0.04$ | $0.78 \pm 0.03$ | $0.46 \pm 0.04$ | $0.59 \pm 0.04$ |
| Intermediate-mass | CC | $0.13 \pm 0.03$ | $0.10 \pm 0.02$ | $0.05 \pm 0.03$ | $0.00 \pm 0.01$ | $0.02 \pm 0.02$ | $0.12 \pm 0.03$ |
| ($9.0 \times 10^{13} \leq M_{500} < 2.0 \times 10^{14} \, M_\odot$) | MCC | $0.49 \pm 0.05$ | $0.62 \pm 0.05$ | $0.06 \pm 0.02$ | $0.16 \pm 0.04$ | $0.73 \pm 0.04$ | $0.09 \pm 0.03$ |
| | NCC | $0.38 \pm 0.05$ | $0.28 \pm 0.05$ | $0.88 \pm 0.02$ | $0.84 \pm 0.03$ | $0.25 \pm 0.04$ | $0.79 \pm 0.03$ |
| High-mass | CC | $0.35 \pm 0.06$ | $0.06 \pm 0.04$ | $0.10 \pm 0.06$ | $0.08 \pm 0.06$ | $0.29 \pm 0.06$ | $0.10 \pm 0.06$ |
| ($M_{500} \geq 2.0 \times 10^{14} \, M_\odot$) | MCC | $0.33 \pm 0.06$ | $0.59 \pm 0.06$ | $0.14 \pm 0.06$ | $0.22 \pm 0.06$ | $0.59 \pm 0.06$ | $0.06 \pm 0.05$ |
| | NCC | $0.33 \pm 0.06$ | $0.35 \pm 0.06$ | $0.76 \pm 0.05$ | $0.69 \pm 0.06$ | $0.12 \pm 0.06$ | $0.84 \pm 0.07$ |
CCs are defined by the central entropy excess in the upper right panel of Fig. 1. This yields CC fractions of 18 ± 2 per cent and 10 ± 6 per cent for the complete and high-mass bins respectively. Many of the simulated clusters defined as CC have very small central entropy excesses, which increases the simulated CC fraction and is further discussed below. To make these clusters visible on the plot we have set their central entropy excess to 2 keV cm$^2$ and denoted them by open triangles. For the same CC definition clusters in the ACCEPT sample with $z < 0.25$ yield a CC fraction of 48 ± 3 per cent. However, we note that the limited resolution of the temperature profiles for some ACCEPT clusters have been shown to induce an artificial floor in the entropy profile (Panagoulia et al. 2014; Hogan et al. 2017). This may lead to some clusters being incorrectly classified as NCC and the observed CC fraction should be viewed as a lower limit. Assuming that CCs are over-represented in the observational sample by a factor 2.2 the observed CC fraction of 22 per cent is in good agreement with the complete sample and a factor 2 larger than the high-mass CC fraction. However, we caution that this is likely driven by limitations of the simulations and observations. Examining the three mass bins we find that the CC fraction decreases with increasing mass.

In the left and central bottom panels of Fig. 1 we plot the concentration parameter within physical, $C_{\text{phys}}$, and scaled, $C_{\text{scal}}$, apertures as function of $M_{500}$, respectively. Measured within physical apertures the concentration parameter produces CC fractions of 1 ± 1 per cent and 8 ± 6 per cent for the complete sample and high-mass bin, respectively. These fractions are lower than the CC fraction of 36 ± 5 per cent found the clusters in the Planck ESZ sample with $z < 0.25$. Scaled by $r_{500}$ the concentration parameter produces CC fractions of 4 ± 1 per cent and 29 ± 6 per cent. The high-mass bin is good agreement with the value of 28 ± 4 per cent found for the Planck ESZ sample. The CC fractions of both concentration parameters show strong mass dependencies, with the fraction of CCs increasing with increasing mass, and we further discuss this below.

Finally, in the bottom right panel of Fig. 1 we plot the cuspiness parameter, $\alpha$, as a function of $M_{500}$. The complete sample yields a CC fraction of 21 ± 2 per cent, while the high-mass bin produces a fraction of 10 ± 6 per cent. This is lower than the 35 ± 5 per cent found for those clusters in the Planck ESZ sample with $z < 0.25$. The cuspiness parameter has a decreasing cool-core fraction with increasing mass, reducing from 28 ± 3 per cent in the low-mass bin to 10 ± 6 per cent in the high-mass bin.

Compared to other recent numerical work with modern hydrodynamic solvers and more developed subgrid prescriptions, we find that IllustrisTNG yields similar CC fractions. Rasia et al. (2015) found at $z = 0$ that 38 per cent (11/29) of clusters were classified as CC, defined by pseudo-entropy and a central entropy excess criterion of $K_0 < 60$ keV cm$^2$. Although we do not calculate a pseudo-entropy for our clusters, if we make the same cut based on the central entropy excess we find that 34 ± 3 per cent of the complete sample at $z = 0$ are classified as CCs. In comparison, 57 ± 4 per cent of clusters with $z < 0.25$ in the ACCEPT sample are defined as CC, corrected to 26 per cent assuming a CC bias correction factor of 2.2. Hahn et al. (2017) defined a cluster as CC if the central entropy excess measured at 40 kpc was $K_0 < 40$ keV cm$^2$. They find that 40 per cent (4/10) of their clusters at low-redshift ($z \leq 0.37$) are classified as CC. Making the same cut in the central entropy excess the complete sample produces a CC fraction of 19 ± 2 per cent at $z = 0$ and 49 ± 3 per cent at $z = 0.4$. With the same criterion the ACCEPT cluster sample at $z < 0.25$ yields a CC fraction of 50 ± 3 per cent (23 per cent corrected). The c-EAGLE project (Barnes et al. 2017b; Bahé et al. 2017) resimulated 30 clusters using the state-of-the-art EAGLE galaxy formation model (Schaye et al. 2015; Crain et al. 2015), at a similar resolution to the TNG100 level-1 volume. However, the clusters had low-density, high-entropy cores compared to the REXCESS sample, making it unlikely that any of these clusters would be classified as CCs. The low-density, high-entropy cores were thought to be due to the AGN feedback being ineffective at high redshift, resulting in some overcooling, and too active at late times, increasing the central entropy of the clusters. In summary, we find that the IllustrisTNG model yields a sample of clusters that, in general, has a lower CC fraction than observed when compared to low-redshift SZ selected samples, where the impact of observational selection effects are expected to be less than 1 per cent (Pipino & Pierpaoli 2010; McDonald et al. 2013; Lin et al. 2015). However, the simulated CC fractions are consistent with other recent numerical work.

4.2 Cumulative gas fractions

To further understand the lower fraction of CCs present in the IllustrisTNG volume we now examine the cumulative and differential gas fractions. In Fig. 2 we plot the median cumulative (left panel) and differential (right panel) gas fraction as a function of radius at $z = 0$. We compare to the observed profiles from Pratt et al. (2010) and Landry et al. (2013) for the cumulative and differential profiles respectively. These have median masses of $M_{500} = 2.8 \times 10^{14} M_\odot$ and $M_{500} = 5.4 \times 10^{14} M_\odot$. We calculate the median simulated profile for those clusters with $M_{500} > 2 \times 10^{14} M_\odot$, which yields a sample with a median mass of $M_{500} = 2.78 \times 10^{14} M_\odot$.

The observed cumulative median gas fraction increases by a factor of 3.1, from 28 per cent of the universal baryon fraction ($\Omega_b/\Omega_M = 0.157$) at 0.1$r_{500}$ to 83 percent at $r_{500}$. Although the median simulated profile increases by a similar factor between 0.1 – 1$r_{500}$, it rises more rapidly and reaches 80 per cent of the universal fraction at 0.6$r_{500}$. Between 0.6 – 1$r_{500}$ the median profile flattens to a constant value of 90 per cent of the universal fraction. The simulated and observed differential profiles are similarly different, with the simulated profile rising much more rapidly than the observed profile and peaking at smaller radii compared to the observed profile. These differences between the observed and simulated profiles suggest that the simulated AGN feedback is more violent than in reality. This drives gas from the centre and results in a steepening of the gas fraction profiles, though we note that the feedback is significantly gentler than the previous Illustris model which removed the gas from the potential entirely (Genel et al. 2014). Additionally, the cumulative profiles show that the gas fraction within $r_{500}$ is higher than observed by ~ 10 per cent. This may indicate that the AGN is not efficient enough at removing gas from the potential at high-redshift, and ejected gas then is reac-
creted at low redshift. Similar gas fraction results were found in the c-EAGLE cluster simulations (Barnes et al. 2017b).

The gas fraction profiles help to explain why we find a lower simulated CC fraction than observed, especially for the concentration parameter. A gas fraction that rises more rapidly will result in a greater fraction of the X-ray emission coming from larger radii. This will result in systematically lower concentration parameter values. In the inset of Fig. 2 we plot the gas fraction on a log scale and we find that the median simulated gas mass enclosed in 0.01r500 is 70 per cent lower than observed. Therefore, the central electron number density in the simulated clusters is systematically lower and fewer clusters will be defined as CCs by this criterion. From eq. 1, it is clear that a lower central number density will

Figure 2. Median cumulative (left panel) and differential (right panel) gas fraction profiles as a function of r/r500 at z = 0. We plot the observed profiles from Pratt et al. (2010) and Landry et al. (2013) (dashed gray line) for the cumulative and differential profiles respectively, with the shaded regions encompassing 68 per cent of the sample. To ensure a fair comparison, we compute the median simulated profile for those clusters with M500 > 2×10^14 M⊙ (solid purple line). The universal baryon fraction (ΩB/ΩM ≡ 0.157) is denoted by the black dotted line. The inset in the left panel shows the gas fraction profiles on a log scale to clarify the difference at small radii. The median simulated profiles rise more steeply than the observed profiles, before flattening at larger radii.

Figure 3. Median cumulative gas fractions at z = 0 for CCs (solid blue line) and NCCs (red dashed line) defined by the central electron number density (left panel), central cooling time (centre panel) and cuspiness parameter (right panel). The shaded (hashed) region denotes 68 per cent of the sample for CCs (NCCs) and the dotted line denotes the universal baryon fraction. We find that CCs and NCCs have very similar gas profiles regardless of the defining criterion.
also produce longer cooling times and result in fewer clusters being defined as CCs by the cooling time criterion.

We examine the difference between the cumulative gas mass profiles for CCs and NCCs for the complete sample in Fig. 3, where CCs are defined by the central electron number density (left panel), cooling time (middle panel) and cuspiness parameter (right panel) criteria. In general, we find that CC and NCC clusters have very similar profiles, regardless of defining criteria. This is in contrast to previous numerical work by Hahn et al. (2017) who found that their simulated CCs had significantly higher central gas fractions compared to NCCs, but in agreement with Eckert et al. (2013) who observed little difference between the CC and NCC gas fraction profiles of 62 clusters. Defining CCs by their central cooling time, the median profiles and the region denoting 68 per cent of the population are almost identical at all radii. Defining CCs by their central electron number density results in the CC profile having a higher median gas fraction at a fixed radius compared to the NCC median profile, 70 per cent at 0.1r500, and larger variation in the region denoting 68 per cent of the sample. This most likely reflects the inclusion of a greater fraction of more massive objects in the CC profile, as the CC fraction increases with increasing mass for this criterion. Defining CCs by the cuspiness parameter results in the opposite trend, with NCC clusters having a marginally higher gas fractions at a fixed radius. The cuspiness parameter has a decreasing CC fraction with increasing mass, and fewer massive clusters are included in the CC profile.

4.3 CC criteria distributions

We now compare the observed and simulated CC criteria distributions, which are plotted in the diagonal panels of Fig. 4. For the central electron number density, the concentration parameters and the cuspiness parameter we compare to Planck ESZ sample (Andrade-Santos et al. 2017) and for the central cooling time and central entropy excess we compare to the ACCEPT cluster sample (Cavagnolo et al. 2009). Excluding the observed central entropy excess distribution, we find both the observed and simulated distributions are reasonably well described by log-normal distributions. The observed central entropy distribution is clearly bimodal. However, as noted, previous work by Panagoulia et al. (2014); Hogan et al. (2017) has shown that the peak at 15 keV cm² appears to be generated by the limited resolution of the temperature profiles, which complicates a direct comparison.

A sizable fraction of the simulated clusters have a very low central entropy excess (< 2 keV), which may suggest that physical processes are missing from the IllustrisTNG model. All cosmological simulations currently lack the resolution and the physics to correctly capture the multi-phase nature of the ICM. Idealized simulations have shown a cluster’s entropy floor is set by the ratio of the cooling time to the free-fall time (McCourt et al. 2012; Sharma et al. 2012; Gaspari et al. 2012; Li & Bryan 2014). Once \( \frac{\text{cool}}{t_{\text{ff}}} \approx 10 \), cold gas begins to precipitate out of the hot gas, triggering AGN feedback events that maintain the central entropy. This result is supported by multiwavelength observations of filamentary molecular gas structures surrounding brightest cluster galaxies (BCGs) (McDonald et al. 2010, 2011; Werner et al. 2014; Tremblay et al. 2015; Suess et al. 2017). Cosmological simulations may need to model AGN triggering by cold phase precipitation to reproduce the minimum entropy floor. However, observations by Panagoulia et al. (2014) have shown that the entropy profiles are almost pure power-laws at radii that are sufficiently well resolved. However, the overall fraction of objects with these almost pure power-law profiles is uncertain as this study is X-ray selected and likely suffers from CC bias.

The simulated and observed central cooling time distributions are significantly different. The simulated distribution is strongly peaked with a mean value of 6.23 Gyr and standard deviation of 0.63. In contrast, the observed distribution is very broad with a standard deviation of 1.90. Although selection effects, which we do not account for, will impact the observed distribution, the central cooling time is a balance between radiative losses, thermal conduction and heating by feedback processes and merger events. Therefore, it is unlikely the simulations will be able to reproduce the observed distribution without accurately modelling all of these processes.

The simulated central electron number density distribution has a smaller mean value of 0.50 \( \times 10^{-2} \) cm⁻³ and standard deviation \( \sigma = 0.97 \) compared to the observed distribution, which has a mean value of 1.07 \( \times 10^{-2} \) cm⁻³ and a slightly larger standard deviation \( \sigma = 1.13 \). The higher observed mean value combined with the wider distribution leads to an observed CC fraction that is twice the simulated fraction. The simulated and observed mean values of the concentration parameter within physical apertures are in reasonable agreement, yielding values of 4.74 \( \times 10^{-2} \) and 4.33 \( \times 10^{-2} \) respectively. However, the observed distribution has a significantly larger standard deviation of \( \sigma = 0.99 \), compared to \( \sigma = 0.43 \) for the simulated distribution, and this results in a larger fraction of observed clusters being classified as CC. Measuring the concentration parameter within scaled apertures there is a larger offset between the simulated and observed mean values, yielding 0.22 and 0.52 respectively. We also find that the simulated distribution is significantly wider, with a standard deviation of 0.43 compared to 0.26 for the observed distribution. The larger mean value leads to a higher fraction of observed clusters being classified as CC. The fits to the simulated and observed distributions of the cuspiness parameter are in good agreement, with mean values of 0.46 and 0.41 and standard deviations of 0.75 and 0.69 respectively. However, the simulated cuspiness parameter distribution is poorest fit by a log-normal distribution, with a large number of clusters yielding values just below the MCC threshold. This leads to a larger number of simulated clusters being defined as NCC and a greater fraction of the observed distribution being defined as CCs.

In the upper off-diagonal panels of Fig. 4 we plot projected mass-weighted temperature maps of randomly selected simulated clusters that pass both CC criteria to demonstrate the range of systems that are classified as CCs. Each map is centred on the potential minimum of the cluster with a width of 2r500 × 2r500, a depth of 2r500 and is projected along the z-axis. All maps show a central core, but there is significant variation in the structures surrounding it.

4.4 Criteria correlations

In the lower off-diagonal panels of Fig. 4 we plot the correlation of the different CC criteria for the simulated clusters,
Figure 4. Comparison of the different CC criteria at $z = 0$. In the diagonal panels we plot the simulated (blue) and observed (grey) criteria distributions. We compare to the Planck ESZ sample (Andrade-Santos et al. 2017) [A-S+17] (for central electron number density, physical and scaled concentration parameter and cuspiness parameter) and the ACCEPT sample (Cavagnolo et al. 2009) [C+ 09] (for cooling time and central entropy excess). The solid blue and dashed grey lines show the best-fit log-normal distributions for the simulations and observations, respectively. The lower-off diagonal panels show the simulated criteria correlations with color denoting cluster mass, where we find increased scatter for low-mass systems, and the dashed lines denoting CC and MCC thresholds. In the upper off diagonal panels we plot $2r_{500} \times 2r_{500}$ mass-weighted temperature maps of randomly selected clusters that are defined as CC by both criteria.
with the point colour denoting \( M_{500} \). We note that for easier comparison we have inverted the \( t_{\text{cool}} \) and \( K_0 \) axes, therefore CC clusters will always appear at the top or right side of a panel. Additionally, those clusters with \( K_0 < 2 \text{ keV cm}^2 \) are denoted by an open symbol and made visible by setting \( K_0 = 2 \text{ keV cm}^2 \). We quantify the correlation between criteria using the Spearman rank correlation coefficient, \( r_s \). In addition, we fit a simple power-law of the form

\[
\log_{10}(Y) = A + B\log_{10}(X/X_{\text{piv}}),
\]

where \( A \) and \( B \) set the normalisation and slope of the power-law, respectively, and \( X_{\text{piv}} \) is the pivot point, which is set to the median value of the criterion \( X \). This enables us to compute the scatter about the best-fit via

\[
\sigma_{\log_{10}} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left[ \log_{10}(Y_i) - \log_{10}(Y_{\text{mod}}) \right]^2},
\]

where \( N \) is the number of clusters in the sample, \( Y_i \) is the measured criterion value, \( Y_{\text{mod}} \) is the expected criterion value for a cluster with a value of \( X_i \) for criterion \( X \) and we note that \( \sigma_{\log_{10}} = \ln(10)\sigma_{\log_{10}} \). All errors are computed by bootstrapping the complete sample yields a correlation coefficient of \( 0.31 \pm 0.06 \) with a scatter of \( 0.52 \pm 0.05 \) and \( 0.62 \pm 0.04 \). The central electron number density criterion, \( n_e \), is strongly correlated with \( t_{\text{cool}} \), \( C_{\text{phys}} \) and \( C_{\text{scal}} \), yielding correlation coefficients of \( 0.88 \pm 0.04 \), \( 0.58 \pm 0.04 \) and \( 0.57 \pm 0.04 \), respectively. These correlations are not unexpected as the cooling time depends on the central number density, see equation (1), and clusters with higher central densities should have higher central X-ray luminosities, due to its \( n_e^2 \) dependence. There is no obvious separation in the criteria space with cluster mass. The correlation of \( t_{\text{cool}} \) with the \( C_{\text{phys}} \) and \( C_{\text{scal}} \) criteria is significantly weakened by the increased scatter in these values for low-mass clusters, with correlation coefficients of \( 0.49 \pm 0.05 \) and \( 0.27 \pm 0.05 \) and scatter values of \( 0.51 \pm 0.03 \) and \( 0.54 \pm 0.03 \) for \( t_{\text{cool}} \) and \( C_{\text{phys}} \), respectively. Lower mass clusters systematically scatter to shorter central cooling times for a given concentration parameter.

The central entropy excess, \( K_0 \), is strongly correlated with \( n_e \), \( t_{\text{cool}} \) and \( \alpha \), producing correlation coefficients of \( 0.62 \pm 0.04 \), \( 0.86 \pm 0.02 \) and \( 0.62 \pm 0.04 \), respectively. There is a reasonable correlation with the concentration parameter measured within physical apertures with coefficient of \( 0.41 \pm 0.5 \), but we find no correlation between \( K_0 \) and \( C_{\text{scal}} \) with a coefficient value of \( -0.06 \pm 0.06 \). Low-mass clusters have increased scatter to smaller values of \( K_0 \) for a given value of \( C_{\text{scal}} \) and many have a central entropy excess of zero, which results in no statistical correlation. We find a mild trend with mass for the \( K_0 \) and \( C_{\text{scal}} \), with \( n_e \) and \( C_{\text{scal}} \) values increasing with mass for a given \( K_0 \) value.

We find a strong correlation between the physical and scaled concentration parameters, which is not that surprising. For the complete sample we find \( r_s = 0.74 \pm 0.03 \) with a small level of scatter of \( 0.12 \pm 0.01 \), which is not surprising. We find a mass dependence for this correlation, with more massive clusters having a larger concentration parameter within physical apertures, \( C_{\text{phys}} \), for a given concentration parameter within scaled apertures, \( C_{\text{scal}} \). As noted above, this may be due to the distribution of gas with radius.

The cuspinness parameter, \( \alpha \), is strongly correlated with \( t_{\text{cool}} \) \( r_s = 0.63 \pm 0.04 \) and \( K_0 \) \( 0.60 \pm 0.04 \), and weakly correlated with \( n_e \) \( r_s = 0.33 \pm 0.06 \) and \( C_{\text{phys}} \) \( r_s = 0.23 \pm 0.06 \). However, it has some of the largest levels of scatter, with \( t_{\text{cool}} \) and \( K_0 \) producing values of \( 0.52 \pm 0.05 \) and \( 0.62 \pm 0.04 \), respectively.

In summary, we find that the correlation between different CC criteria is mass dependent, with an increasing correlation between criteria for more massive clusters. Low-mass clusters appear to scatter to lower central entropy excess values. Although correlated with other criteria the cuspinness parameter has some of the largest levels of scatter. The two quantities that are most correlated are the central electron number density and the central cooling time.

### 5 EVOLUTION WITH REDSHIFT

#### 5.1 CC fraction evolution

Having examined the CC fraction at \( z = 0 \) for the different criteria, we now compare the evolution of the CC fraction with redshift. The success of large SZ surveys with dedicated follow-up has resulted in a large number of clusters being detected out to \( z \approx 2 \), due to the redshift independence of the SZ effect. This provides a large sample of clusters that is free from CC bias (Lin et al. 2015) and enables a fair comparison of the redshift evolution of the simulated and observed CC fractions. We use the Planck ESZ and ACCEPT samples as a low-redshift \( (z < 0.25) \) bin, with the latter’s CC frac-
The complete sample has a lower median mass than the observational samples, due to observational selection functions. Therefore, for each criterion we compare how the observed CC fraction evolves with redshift to both the complete and high-mass samples. Additionally, we also examine the evolution only over the redshift range of the SPT-XVP sample (0.25 < z < 1.2) to ensure that differing low-redshift samples and low number statistics at z > 1.2 do not impact the result. We do not examine the evolution of the concentration parameter with scaled apertures as there are no high-redshift (z > 0.25) observational constraints. To enable a quantitative comparison we fit both the observed and simulated CC fraction as a function of redshift with a linear relation that accounts for the uncertainty.

In Fig. 5 we plot the CC fraction, defined by the central electron number density, for the complete sample (left panel) and the high-mass sample (right panel). As noted in the previous section the high-mass sample leads to higher normalization at low-redshift and the high-mass sample has a consistently greater CC fraction at fixed redshift. With best-fit slopes of 0.64 ± 0.05 and 0.55 ± 0.10, respectively, the complete and high-mass samples have a consistent redshift evolution. This is significantly steeper than the observed evolution, which has a slope of 0.24 ± 0.08. If we only compare to the SPT-XVP sample (0.25 < z < 1.2) we find that the simulated slope steepens further for the complete sample. The observed CC fraction slowly decreases from z = 2 to z = 0. In contrast, the reduction in the CC fraction for the complete sample begins later and results in a much more rapid decline. For the high-mass sample the process begins at even lower redshift and then proceeds at the same rate, leading to a higher normalization.

We examine the evolution of the CC fraction defined by the central cooling time criterion with redshift in Fig. 6. The simulated samples have consistent redshift evolutions, corrected for the expected CC bias. The SPT-XVP sample is then divided into 3 bins over the redshift range 0.25 < z < 1.2, with CC criteria values taken from McDonald et al. (2013). For the central electron number density we additionally include the SPT-Hiz sample to form a high-redshift bin (1.2 < z < 1.9). For the SPT samples we plot the CC fractions based on the peak emission centring as this is the fairest comparison to the potential minimum centred simulation values. We note that the redshifts of SPT clusters have been updated since McDonald et al. (2013) and this results in slightly different CC fractions compared to the original paper (Bleem et al. 2015). The 1σ confidence intervals on both the observed and simulated samples are calculated via the beta distribution quantile technique (Cameron 2011), due to low number statistics at high redshift. We note that McDonald et al. (2013) find similar low-redshift CC fractions to other low-redshift observations when analyzing the Vikhlinin et al. (2009a) cluster sample with the SPT pipeline, indicating that the systematic impact of using different observational samples at low-redshift is likely small.

The complete sample has a lower median mass than the observational samples, due to observational selection functions. Therefore, for each criterion we compare how the observed CC fraction evolves with redshift to both the complete and high-mass samples. Additionally, we also examine the evolution only over the redshift range of the SPT-XVP sample (0.25 < z < 1.2) to ensure that differing low-redshift samples and low number statistics at z > 1.2 do not impact the result. We do not examine the evolution of the concentration parameter with scaled apertures as there are no high-redshift (z > 0.25) observational constraints. To enable a quantitative comparison we fit both the observed and simulated CC fraction as a function of redshift with a linear relation that accounts for the uncertainty.

In Fig. 5 we plot the CC fraction, defined by the central electron number density, for the complete sample (left panel) and the high-mass sample (right panel). As noted in the previous section the high-mass sample leads to higher normalization at low-redshift and the high-mass sample has a consistently greater CC fraction at fixed redshift. With best-fit slopes of 0.64 ± 0.05 and 0.55 ± 0.10, respectively, the complete and high-mass samples have a consistent redshift evolution. This is significantly steeper than the observed evolution, which has a slope of 0.24 ± 0.08. If we only compare to the SPT-XVP sample (0.25 < z < 1.2) we find that the simulated slope steepens further for the complete sample. The observed CC fraction slowly decreases from z = 2 to z = 0. In contrast, the reduction in the CC fraction for the complete sample begins later and results in a much more rapid decline. For the high-mass sample the process begins at even lower redshift and then proceeds at the same rate, leading to a higher normalization.

We examine the evolution of the CC fraction defined by the central cooling time criterion with redshift in Fig. 6. The simulated samples have consistent redshift evolutions,
Figure 6. Evolution of the CC fraction with redshift for the complete (left panel) and high-mass (right panel) samples (solid black line), defined by the central cooling time criterion. We compare to the observed evolution from the combination of bias corrected Cavagnolo et al. (2009) (open circle) and McDonald et al. (2013) (open squares). The fit line styles are the same as in Fig. 5. The evolution with redshift for both simulated samples is steeper than the observed evolution.

Figure 7. Evolution of the CC fraction with redshift for the complete (left panel) and high-mass (right panel) samples (solid blue line), defined by the central entropy excess criterion. We compare to the observed evolution from the combination of bias corrected Cavagnolo et al. (2009) (open circle) and McDonald et al. (2013) (open squares). The fit line styles are the same as in Fig. 5. The evolution with redshift for both simulated samples is steeper than the observed evolution.
Figure 8. Evolution of the CC fraction with redshift for the complete (left panel) and high-mass (right panel) samples (solid grey line), defined by the concentration parameter within physical apertures. We compare to the observed evolution from the combination of Andrade-Santos et al. (2017) (open circle) and McDonald et al. (2013) (open squares). The fit line styles are the same as in Fig. 5. Selecting high-mass clusters results in a flatter and positive evolution with redshift that is more consistent with the observed evolution, however the normalization of the CC fraction is 0.15 lower than observed.

Figure 9. Evolution of the CC fraction with redshift for the complete (left panel) and high-mass (right panel) samples (solid yellow line), defined by the cuspiness parameter. We compare to the observed evolution from the combination of Andrade-Santos et al. (2017) (open circle) and McDonald et al. (2013) (open squares). The fit line styles are the same as in Fig. 5. The evolution with redshift for both simulated samples is consistent, however the evolution of the observed sample has a positive slope towards low-redshift and the simulated evolution is negative.
with the complete and high-mass samples yielding slopes of $0.60 \pm 0.05$ and $0.37 \pm 0.09$, respectively. The redshift evolution for both samples steepens when only considered in the redshift range $0.25 < z < 1.2$. The observed sample produces a shallower evolution with redshift, yielding a slope of $0.17 \pm 0.10$. Defining clusters via the central entropy excess yields the same result, as shown in Fig. 7. The simulated samples yield a steeper evolution with redshift, regardless of redshift range selected, compared to the observed sample. In addition, we note that the low-redshift CC fraction is likely a lower limit due to limited resolution of the observed temperature profiles and an increase in this would further flatten the observed CC fraction evolution with redshift.

In Fig. 8 we plot the observed and simulated CC fraction evolution with redshift for clusters defined as CCs by the concentration parameter within physical apertures. It is clear that the complete sample does not evolve linearly with redshift, producing a more rapid increase in CC fraction with increasing redshift. This in contrast to the observed evolution, which produces a mildly declining CC fraction with redshift. The high-mass sample shows significantly better agreement with the observed evolution, producing a slope in reasonable agreement with the observation sample. However, the normalization is a factor $\sim 0.15$ lower than the observed CC fraction at all redshifts. Defining clusters by the cuspiness parameter, the complete sample does not produce a linear redshift evolution, as shown in Fig. 9. The CC fraction rises with increasing redshift before flattening and then reducing at $z \approx 2$. Although significantly noisy, the high-mass sample produces a CC fraction that increases with increasing redshift, reaching a similar CC fraction of $\approx 0.50$ at $z \approx 1$. In contrast, the observational sample produces a CC fraction that steadily declines with increasing redshift.

If the entire cluster volume evolves in a self-similar manner it is not unexpected that the fraction of clusters defined as CC should rise with increasing redshift. The critical density of the Universe increases with redshift and we define clusters as overdensities relative to it. Therefore, clusters at a fixed mass increase in density with increasing redshift. When measuring the central electron number density at a fixed fraction of the critical radius this will result in an increasing number density with redshift and a greater fraction of clusters being defined as CC for a fixed physical threshold.

From equation (1), it is clear that an increasing number density will result in a decreasing cooling time and for a fixed threshold the fraction of clusters defined as CC via their central cooling time should increase with redshift. The concentration parameter within physical apertures should yield a greater CC fraction with redshift because the inner aperture will include an increasing fraction of the X-ray emission and the outer aperture will remain roughly unchanged due to the $n_e^2$ dependence of the emission. The lack of evolution in the observed CC fractions suggest that the cluster core significantly deviates from the expected self-similar evolution (McDonald et al. 2017).

### 5.2 Relaxed fraction

CC clusters are often associated with more spherical and relaxed X-ray morphologies. Previous numerical work has shown that close to head-on major mergers can disrupt a CC (Rasia et al. 2015; Hahn et al. 2017), which suggests that a greater fraction of NCC clusters should be disturbed at low-redshift. Additionally, radio haloes that are associated with recent merger activity have, to date, only been observed in NCC clusters, which suggests that a greater fraction of NCC clusters should have undergone recent mergers (Cassano et al. 2010). We now examine the fraction of clusters that are defined as relaxed and the fraction of CC and NCC clusters that are defined as relaxed as a function of redshift. Theoretically, there are many ways of defining a relaxed cluster (Neto et al. 2007; Duffy et al. 2008; Klypin et al. 2011; Dutton & Macciò 2014; Klypin et al. 2016). We follow Barnes et al. (2017b) and define a cluster as relaxed if

$$E_{\text{kin},500}/E_{\text{therm},500} < 0.1,$$

where $E_{\text{kin},500}$ is the sum of the kinetic energy of the gas cells, with the bulk motion of the cluster removed, inside $r_{500}$. This should account for any motions generated by substructures or the centre of mass being offset from the potential minimum. $E_{\text{therm},500}$ is the sum of the thermal energy of the gas cells within $r_{500}$. As clusters relax they will thermalize, converting kinetic energy to thermal energy via weak shocks (e.g. Kunz et al. 2011) and potentially turbulent cascades (Zhuravleva et al. 2014). We demonstrate in Appendix B that using other metrics to define a relaxed cluster, such as substructure fraction or centre of mass offset, yields a similar result.

In Fig. 10 we plot the relaxed fraction as a function of redshift in both panels, where we have split the criteria for clarity. The fraction of the complete sample defined as relaxed decreases with increasing redshift, from 45 ± 3 per cent at $z = 0$ to 3 ± 1 per cent at $z = 1$. The increased kinetic energy of the cluster gas with increasing redshift has been shown in previous numerical work (Stanek et al. 2010; Barnes et al. 2017a; Le Brun et al. 2017), which is consistent with the picture that the merger rate at higher redshift is larger (McBride et al. 2009; Fakhouri et al. 2010; Giocoli et al. 2012) and that clusters have had less time to thermalize at high-redshift. This picture is consistent with observational results if the crossing time of clusters decreases with increasing redshift (Mantz et al. 2015; Nurgaliyev et al. 2017; McDonald et al. 2017), which it does if we assume self-similar evolution (Carlberg et al. 1997).

In addition, we plot the fraction of CCs and NCCs that are classified as relaxed, defined by the central electron number density and the central entropy excess in the left panel, and the central cooling time and cuspiness parameter in the right panel. We do not show the concentration parameter because it is noisy as it only defines a small number of clusters as CC. We are limited to $z \leq 1$ due to small number statistics at high redshift. Defining CCs and NCCs by the central electron number density, we find that the fraction of relaxed clusters in both samples is broadly consistent with the complete sample, decreasing from $42 \pm 7$ per cent and $39 \pm 4$ per cent at $z = 0$ to $13 \pm 5$ per cent and $14^{+14}_{-5}$ per cent at $z = 0.5$ for the CC and NCC samples respectively. For $z > 0.5$ no clusters are defined as NCC. We find that the fraction of CCs defined as relaxed is consistent within $2\sigma$ of the fraction of NCCs defined as relaxed at all redshifts. Defining clusters as CC or NCC by their central entropy excess, there is some evidence that the fraction of NCC clusters
Figure 10. Fraction of clusters defined as relaxed as a function of redshift. The relaxed fraction is plotted for the complete (purple line), CC (filled) and NCC (open) samples. CCs are defined via the central electron number density (red square), cooling time (black circle), central entropy excess (blue triangle) and the cuspiness parameter (yellow diamond) criteria. Shaded region and error bars denote the $1 \sigma$ confidence interval, calculated via the beta distribution quantile technique. The CC and NCC points are divided between the two panels and marginally offset for clarity. We find no evidence that CCs, defined by any criteria, have a greater fraction of objects defined as relaxed compared to the NCC or complete samples.

defined as relaxed is greater than the fraction of CC clusters defined as relaxed, but the fractions are consistent within $2 \sigma$. We find that $37 \pm 6$ per cent and $49 \pm 3$ per cent at $z = 0$ and $10 \pm 3$ and $23 \pm 5$ per cent at $z = 0.5$ of clusters are defined as relaxed for the CC and NCC samples, but we note that many CCs have a central entropy excess of zero. For $z > 0.5$ no clusters are defined as NCC.

Using central cooling time as the defining criteria, we find that the fraction of the CC sample defined as relaxed is consistent with the relaxed fractions for the NCC and the complete samples. At $z = 0$, $38 \pm 7$ per cent of CC clusters are defined as relaxed, compared to $36 \pm 5$ per cent for the NCC sample. In contrast, defining CCs via the cuspiness parameter we find that at low-redshift ($z < 0.25$) the fraction of CC clusters defined as relaxed is lower than for the NCC sample. We find that $41 \pm 5$ per cent and $50 \pm 3$ per cent of CCs and NCCs, respectively, are defined as relaxed at $z = 0$. At higher redshifts the fraction of CCs and NCCs defined as relaxed are consistent with each other and the relaxed fraction of the complete sample. Overall, we find little evidence that the simulated CCs samples have a higher relaxed fraction compared to either the NCC sample or the complete sample for any of the CC criteria that we have examined. We stress this result holds for other theoretical methods of defining a relaxed cluster, such as substructure fraction and centre of mass offset. For the central entropy excess and the cuspiness parameter criteria we find hints that the fraction of CCs defined as relaxed is lower for the NCC sample, but we would require a significantly larger sample to investigate this further.

In summary, we find that the simulated CC fraction evolves significantly more with redshift than the observed fraction. The process that converts CCs to NCCs appears to begin later in the simulations but acts much more rapidly. We find no evidence that the relaxed fraction of CCs is greater than NCCs or the complete cluster sample, suggesting that mergers are not solely responsible for disrupting CCs.

### 6 Core Evolution

We now examine how the properties of the simulated cluster cores evolve for CC, MCC and NCC clusters. McDonald et al. (2017) demonstrated that the cores of CC clusters present in the SPT samples have evolved little since $z \geq 1.5$, with the rest of the cluster volume evolving in a manner consistent with the self-similar expectation. For all profiles we only include non-star forming gas that is cooling and has a temperature $T > 1.0 \times 10^6$ K.

#### 6.1 Electron number density profiles

In Fig. 11 we plot the median electron number density profiles at $z = 0$ in the top row of panels. We divide the clusters into CC, MCC and NCC samples via the central electron number density, central cooling time and cuspiness parameter in the left, centre and right panels respectively. The
median CC, MCC and NCC profiles defined by the central electron number density criterion are in good agreement for \( r > 0.2r_{500} \), but inside of this radius they diverge. The CC central density is a factor \( \approx 2.5 \) greater than the MCC profile, which in turn is 30 per cent higher than the NCC profile. Dividing clusters by their central cooling time the profiles begin to diverge at \( r = 0.1r_{500} \), reach a central density that is a factor 2 lower than central electron number density criterion, and have a significantly larger spread. The profiles split by the cuspiness parameter diverge in the range \( 0.01-0.1r_{500} \), but then combine again to produce a similar normalization in the very centre of the core.

In the bottom row of panels we plot the ratio of the median CC, MCC and NCC profiles at \( z = 0 \) over the median profiles at \( z = 1 \). Note the samples are redefined at \( z = 1 \) and clusters can change from a CC to NCC, vice versa, or disappear from the sample between the two redshifts. If the profile has not evolved we would expect the ratio to be unity. Assuming profiles evolved in line with the self-similar expectation the ratio would produce a value of \( 1/E^2(z = 1) = 0.316 \), where \( E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_{\\Lambda}} \). All profiles evolve in reasonable agreement with the self-similar expectation for \( r > 0.1r_{500} \). Inside this radius the profiles diverge when separating clusters by their central electron number density. The CC ratio begins to rise at \( r = 0.1r_{500} \) and reaches a peak value of 0.60, while the MCC and NCC ratios begin rising at \( r = 0.03r_{500} \) and reach peak values of 0.60 and 0.42, respectively. In contrast, using the central cooling time or the cuspiness parameter as the CC criterion results in all ratios being consistent with expected self-similar evolution at all radii. We conclude that the extent to which the cluster cores have evolved is dependent on the CC criteria used. For the central electron number density the profiles have evolved more than observed since \( z = 1 \), but less than the self-similar expectation.

6.2 Temperature profiles

We plot the median CC, MCC, and NCC temperature profiles at \( z = 0 \) in the top row of Fig. 12. For \( r > 0.1r_{500} \) the median profiles are consistent within the scatter for all CC criteria. Inside this radius, the central cooling time criterion produces a CC profile that reduces to a third of the peak value, while the MCC and NCC profiles are flat to the centre. Classifying clusters by the cuspiness parameter produces a central CC profile that reduces by a third, a MCC profile that shows a modest reduction and a flat NCC profile. The central electron number density criterion produces three median profiles that all flatten in the core, but the CC profile shows significantly more scatter compared to other criteria. This increased scatter reflects the differing mass dependence of the criteria, with the central cooling time and cuspiness parameter preferentially selecting low-mass clusters and the central electron number density selecting equally across the mass range. All profiles begin to rise again at \( \sim 0.005r_{500} \), which may be a sign of ongoing AGN activity.

The bottom panels show the ratio of median temperature profiles at \( z = 0 \) and \( z = 1 \). If the profile has evolved...
self-similarly this would be $1/E^{2/3}(z = 1) = 0.681$. For $r \geq 0.1r_{500}$ all profiles are consistent with the expected self-similar evolution. The exception is the central electron number density CC profile which has cooled less than expected, but we note this profile has a very large scatter at $z = 0$. Inside this radius the ratios defined by the central electron number density and cuspiness parameter criteria rise to values consistent with or greater than no evolution, suggesting the cores have gotten hotter since $z = 1$. This is consistent with the observed evolution from McDonald et al. (2014), who defined CCs by the cuspiness parameter and demonstrated that the temperature in the cluster core has increased towards lower redshift. In contrast, classifying clusters by the central cooling time leads to central profiles that have cooled slightly, but still less than the self-similar expectation. The CC profile is noisy and it is less evident that the ratio in the core region deviates from self-similar.

6.3 Pressure profiles

In the top row of Fig. 13 we plot the median CC, MCC and NCC pressure profiles for the different criteria at $z = 0$. A linear combination of density and temperature, for $r > 0.2r_{500}$ the profiles are in good agreement for all criteria, as expected from the density and temperature profiles. Inside this radius the classification of CCs by the central electron number density yields a CC profile with a central pressure that is 30 per cent larger than the MCC profile, a result of the increased central density. For the central cooling time and cuspiness parameter the decrease in central temperature offsets the modest increase in central density and all profiles have similar central pressures.

In addition, we plot the CC and NCC universal pressure profiles for the Planck ESZ sample (Planck Collaboration et al. 2013). CCs were defined as having a central electron number density $n_e \geq 4 \times 10^{-2} \text{cm}^{-3}$ (Planck Collaboration et al. 2011). We calculate the observed profile using the listed parameters and calculating the virial pressure, $P_{500}$, using the median mass of each simulated sample. For all criteria the simulated and observed NCC profiles show good agreement. A like-with-like comparison classifying clusters by the central electron number density results in observed and simulated CC profiles that are in good agreement. However, using a different criterion produces a difference between the CC profiles in the core, due to the differing mass dependence of the criteria.

In the bottom row we plot the ratio of the median pressure profiles at $z = 0$ and $z = 1$. The self-similar evolution is given by $1/E^{8/3}(z = 1) = 0.215$. All profiles for the central cooling time and cuspiness parameter criteria are consistent with the self-similar expectation throughout the cluster volume. Classifying clusters by the central electron number density yields profiles consistent with the self-similar expectation for $r > 0.1r_{500}$. Inside this radius the clusters evolve less than expected, with central values of 0.76, 0.68 and 0.58 at 0.01$r_{500}$ for the median CC, MCC and NCC profiles, respectively. This deviation is driven by the lack of evolution in both the temperature and density profiles.

6.4 Entropy profiles

We plot the median CC, MCC and NCC entropy profiles for the different criteria at $z = 0$ in Fig. 14. For $r > 0.1r_{500}$ the profiles are in good agreement with each other for all

![Figure 12. Median gas temperature profiles at $z = 0$ (top row) and the ratio of the median temperature profiles at $z = 0$ and $z = 1$ (bottom panel). The line styles are the same as in Fig. 11. For the central electron number density profiles consistent with the self-similar expectation.](image-url)
Figure 13. Median gas pressure profiles at $z = 0$ (top row) and the ratio of median pressure profiles at $z = 0$ and $z = 1$ (bottom row). The line styles are the same as in Fig. 11. We plot the observed universal pressure profile (yellow) for the CC (solid) and NCC (dot-dash) clusters using the median mass for each simulated sample (Planck Collaboration et al. 2013). Using the same criterion the observed and simulated profiles show good agreement, but the differing mass dependence of other criteria results in different CC profiles.

Figure 14. Median gas entropy profiles at $z = 0$ (top row) and the ratio of the median entropy profiles at $z = 0$ and $z = 1$ (bottom row). The panels and line styles are the same as in Fig. 11. Additionally, we plot the non-radiative simulations of Voit et al. (2005) (yellow dotted) and find that all profiles asymptote to this result at $0.6r_{500}$. The entropy profiles between $z = 1$ and $z = 0$ increase by at least the self-similar expectation, rising beyond that in the core due to the temperature increase.
criteria and asymptote to the non-radiative result at $0.6r_{500}$ (Voit et al. 2005). Inside $0.1r_{500}$ the increased density and decreased temperatures of the CC profiles yield a drop in the entropy profile compared to the NCC profiles. The extent of the drop depends on the defining criteria, with central cooling time CC profiles a factor of 5 lower than the NCC profile at $0.01r_{500}$, but the cuspiness parameter CC profile is only a factor 2 lower.

The bottom panels show the ratio of the median profiles at $z = 0$ and $z = 1$ for the different CC criteria. The expected self-similar entropy evolution is given by $1/E^{-2/3}(z = 1) = 1.468$. We find that all profiles produce ratios that are consistent with the self-similar expectation when classifying clusters by their central cooling time, and greater than self-similar in the core of clusters defined by the central electron number density and cuspiness parameter. The entropy inside $r = 0.1r_{500}$ increases faster than expected because the clusters increase in temperature between $z = 1$ and $z = 0$.

### 6.5 Metallicity profiles

Finally, we examine the median metallicity profiles for the different criteria in the top row of Fig. 15. The profiles are normalized to the solar abundances of Anders & Grevesse (1989). Although examined in Vogelsberger et al. (2017), here we examine how the metallicity evolution changes for different CC criteria. Classifying clusters by their central cooling time we find that the CC profile is cored for $r < 0.1r_{500}$ with a central metallicity that is 25 per cent higher than the MCC and NCC median profiles. The CC and MCC profiles are cored when defined by the cuspiness criterion and have marginally higher central metallicities compared to the NCC profile. The profiles are in good agreement throughout the cluster volume when split by their central electron number density, with all of them showing some hints of a core.

In the bottom row we plot the ratios of the median profiles at $z = 0$ and $z = 1$. All profiles show the metallicity inside $0.15r_{500}$ has decreased since $z = 1$, a result consistent with previous numerical work (e.g. Martizzi et al. 2016) but inconsistent with the latest observations (e.g. McDonald et al. 2016; Mantz et al. 2017). This may be due to differences in how the subgrid and real AGN shape the ICM and distribute metals or the result of systematic uncertainties in the idea of early enrichment. There are marginal changes in the size of the deficit radius when CCs are classified by different criteria.

In summary, we find that the thermodynamic profiles in the core of simulated clusters have evolved since $z = 1$. The extent of this evolution depends on the chosen CC criteria, as the mass dependence of the criterion impacts the median profiles. For example, defining CC via the same criterion as the observed profile yields a good agreement between the simulations and the observations, but differing criteria with opposite mass trends results in differing profiles. The departure of the simulated core profile evolution from the self-similar expectation is in agreement with the observed cluster core evolution, even if the exact scale of the departure differs between the simulations and the observations. Part of this discrepancy, e.g. the reduction in central metallicity, provides insight into how subgrid and real AGN differ in their shaping of the cluster volume. It may also be an indication that additional physical processes, such as anisotropic
thermal conduction, must be included to correctly capture the formation and evolution of the cores of clusters.

7 CONCLUSIONS

We have examined the fraction of clusters simulated with the IllustrisTNG model that host a CC. We focused on the TNG300 level-1 periodic volume, which has a side length of 302 Mpc and a mass resolution of $1.1 \times 10^7 M_\odot$ and $5.9 \times 10^7 M_\odot$ for the gas and dark matter components respectively. We selected all clusters with a mass $M_{500} > 10^{13.75} M_\odot$, which yielded a sample of 370 (77) clusters at $z = 0$ ($z = 1$). We then examined the CC fraction for 6 different criteria commonly used in the literature (Section 4), the evolution of the CC fraction with redshift (Section 5) and how the cluster core evolved in comparison to the rest of the cluster volume (Section 6). Our main results are as follows:

- The $z = 0$ CC fraction for the complete sample is in good agreement with previous numerical work (Rasia et al. 2015; Hahn et al. 2017), but is, in general, lower than the CC fractions observed in SZ selected samples (Fig. 1). Selecting a sample of high-mass ($M_{500} > 2 \times 10^{14} M_\odot$) objects improves the agreement with observed CC fraction for the central electron number density and concentration parameter, but worsens the agreement for the central cooling time, central entropy excess and the cusppiness parameter. This reflects the varying mass dependence of the CC fraction for different criteria, with the central electron number density and concentration parameter yielding an increasing CC fraction with increasing mass and the central cooling time, central entropy excess and cusppiness parameter all yielding a decreasing CC fraction with increasing mass.

- The simulated gas fractions are lower than observed at $0.01r_{500}$ and increase more rapidly than observed, with the cumulative profile reaching 86 per cent of the universal fraction at $0.6r_{500}$ compared to the observed fraction that reaches 83 per cent at $r_{500}$. This difference is likely due to the AGN feedback being more violent than in reality, explaining why the simulated CC fractions are lower than observed and some of the differences between the simulated and observed the criteria distributions (Fig. 4).

- The simulated central entropy excess distribution is single peaked, but a significant number of the clusters have effectively zero central entropy excess. Previous idealized numerical work and observations of filamentary molecular gas around BCGs support the idea that cold gas precipitates out of the hot phase once the ratio of the cooling time to the free-fall time reaches a small enough value and maintains a minimum central entropy. The simulated central entropy excess distribution may suggest that modelling the formation of a cold phase is an important component in reproducing cluster cores. However, we note that Panagoulia et al. (2014) found pure power laws entropy profiles if only radii that are sufficiently well resolved are considered, making the exact central profile of CC clusters uncertain.

- The correlations between different CC criteria is mass dependent, with the correlation increasing for more massive systems. For example, the correlation between central electron number density and the cusppiness parameter improves from 0.31 ± 0.06 for the full sample to 0.75 ± 0.10 when only clusters with $M_{500} > 2 \times 10^{14} M_\odot$ are selected.

- Examining the CC fraction as a function of redshift (Figs. 5-9) we find that the simulated CC fraction increases more rapidly with increasing redshift than observed. This result is independent of the mass range or redshift range selected. The exact normalization is dependent on the selected CC criteria and mass range. The simulations begin to convert CCs to NCCs later than observed, but then the conversion occurs much more rapidly.

- We found no evidence that the fraction of CCs defined as relaxed is greater than the fraction of NCCs defined as relaxed (Fig. 10). Defining relaxed clusters by the ratio of their kinetic to thermal energy, all samples yield a relaxed fraction that decreases with redshift, consistent with the expectation that the merger rate increases. The result holds for other theoretical definitions of a relaxed cluster. This result seems to be at odds with the idea that mergers solely drive the CC/NCC bi-modality and the observation that radio haloes only occur in NCC clusters.

- Comparing the pressure profiles to the observed universal pressure profile demonstrates that a like-with-like comparison is required. The differing mass dependence of the CC criteria leads to different central pressure profiles and either agreement or disagreement with the observed profile. A like-with-like comparison produces a good agreement between the simulated and observed CC pressure profiles.

- The thermodynamic profiles in the cores of simulated clusters have evolved to some extent between $z = 1$ and $z = 0$ (Figs. 11-15), with the extent of the evolution depending on the chosen CC criterion. The simulated core evolution departs from the self-similar expectation for many profiles, with the direction of the departure in agreement with recent observations of the evolution of cluster cores (McDonald et al. 2017). These results indicate that the heating and radiative losses in the centre of the simulated clusters are not in balance in the simulation and point to differences in the way the subgrid AGN and real AGN shape the cluster volume.

We conclude that the IllustrisTNG model matches the observed CC fraction between 0.25 < $z$ < 1.0, but converts CCs to NCCs too rapidly compared to the observations. This results in it overpredicting the fraction of CCs at $z > 1$ and underpredicting the CC fraction at $z < 0.25$. In future work we will investigate the mechanisms responsible for converting a CC to a NCC as we found that the fraction of CCs and NCCs defined as relaxed were similar, suggesting mergers may not be solely responsible for the dichotomy and in tension with previous numerical work (e.g. Hahn et al. 2017). It seems that subgrid models must continue to develop, especially for the treatment of AGN, and continue to include additional physical processes since essentially all numerical simulations, including IllustrisTNG, do not capture the evolution and thermodynamic profiles of clusters correctly. These physical processes include the impact of cosmic-rays (Pfrommer et al. 2017), anisotropic thermal conduction (Kannan et al. 2016, 2017, Barnes et al in prep.), outflows due to radiation pressure from the AGN (Costa et al. 2017a,b), the formation of dust (McKinnon et al. 2016, Vogelsberger et al. in prep.) and, as simulations push to higher resolution, and most importantly more accurate modelling of the interaction between the jet and the intracluster medium (English et al. 2016; Weinberger et al. 2017b).
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APPENDIX A: IMPACT OF RESOLUTION ON COOL-CORE CRITERIA

To examine the impact of numerical resolution on the CC criteria distributions we examine the clusters in the TNG100 level-1 volume. There are 20 clusters with $M_{500} > 10^{13.75} M_{\odot}$ at $z = 0$ in the TNG100 run, which has a dark matter and baryonic mass resolution of $7.5 \times 10^6 M_{\odot}$ and $1.4 \times 10^6 M_{\odot}$, respectively. In Fig. A1 we plot the objects from the TNG100 simulation on top of the clusters from the TNG300 volume. The clusters from the higher resolution TNG100 simulation have CC criteria values that are consistent with the distribution of values from the TNG300 simulation. For example, a two sample Kolmogorov-Smirnov test of the high-mass bin yields p-values of 0.34, 0.39, 0.61, 0.86, 0.76 and 0.29 for the central electron number density, central cooling time, central entropy excess, the concentration parameter within physical and scaled apertures and the cuspiness parameter, respectively. Therefore, we are unable to reject the hypothesis that the two samples are from the same distribution at much more than 1σ, even for the most discrepant criterion. This suggests that the CC criteria distributions are relatively insensitive to numerical resolution.

APPENDIX B: RELAXED FRACtIONS AND RELAXATION CRITERIA

In Fig. B1 we demonstrated that the fraction of CCs defined as relaxed was consistent with the fraction of NCC clusters and complete sample defined as relaxed. In Fig. B1 we plot the fraction of clusters defined as relaxed by a different theoretical criteria, the combination of the fraction of mass in substructures, $f_{\text{sub}}$, and the offset between the centre of mass and the potential minimum, $X_{\text{off}}$. Clusters are defined as relaxed if both $f_{\text{sub}} < 0.1$ and $X_{\text{off}} < 0.07$ (Neto et al. 2007). The overall fraction of clusters defined as relaxed has increased, however this can be reduced by making the relatively arbitrary threshold for relaxation stricter. In common with the relaxation criterion presented in Section 5, we find that the relaxed fraction decreases with redshift for all samples and, more importantly, that the fraction of CC clusters defined as relaxed is consistent with the fraction of the complete sample and NCC clusters defined as relaxed, regardless of the chosen CC criteria.

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Figure A1. CC criteria as a function of $M_{500}$ at $z = 0$. We plot the central electron number density (top left), central cooling time (top centre), central entropy excess (top right), the concentration parameter within physical apertures (bottom left) and scaled apertures (bottom centre), and the cuspiness parameter (bottom right). Clusters from the TNG300 (grey circles) and TNG100 (black squares) level 1 volumes are plotted. The CC criteria distributions from the different resolution volumes are consistent with each other.
Figure B1. Fraction of clusters defined as relaxed via the combination of substructure mass fraction and the offset between the centre of mass and potential minimum as a function of redshift. The line and marker styles are the same as in Fig. 10. The change of relaxation criteria does not impact the result that the complete sample, CC clusters and NCC clusters all have consistent relaxed fractions, regardless of CC definition.