Mapping the mass distribution and scaling in galaxy clusters with *Chandra*

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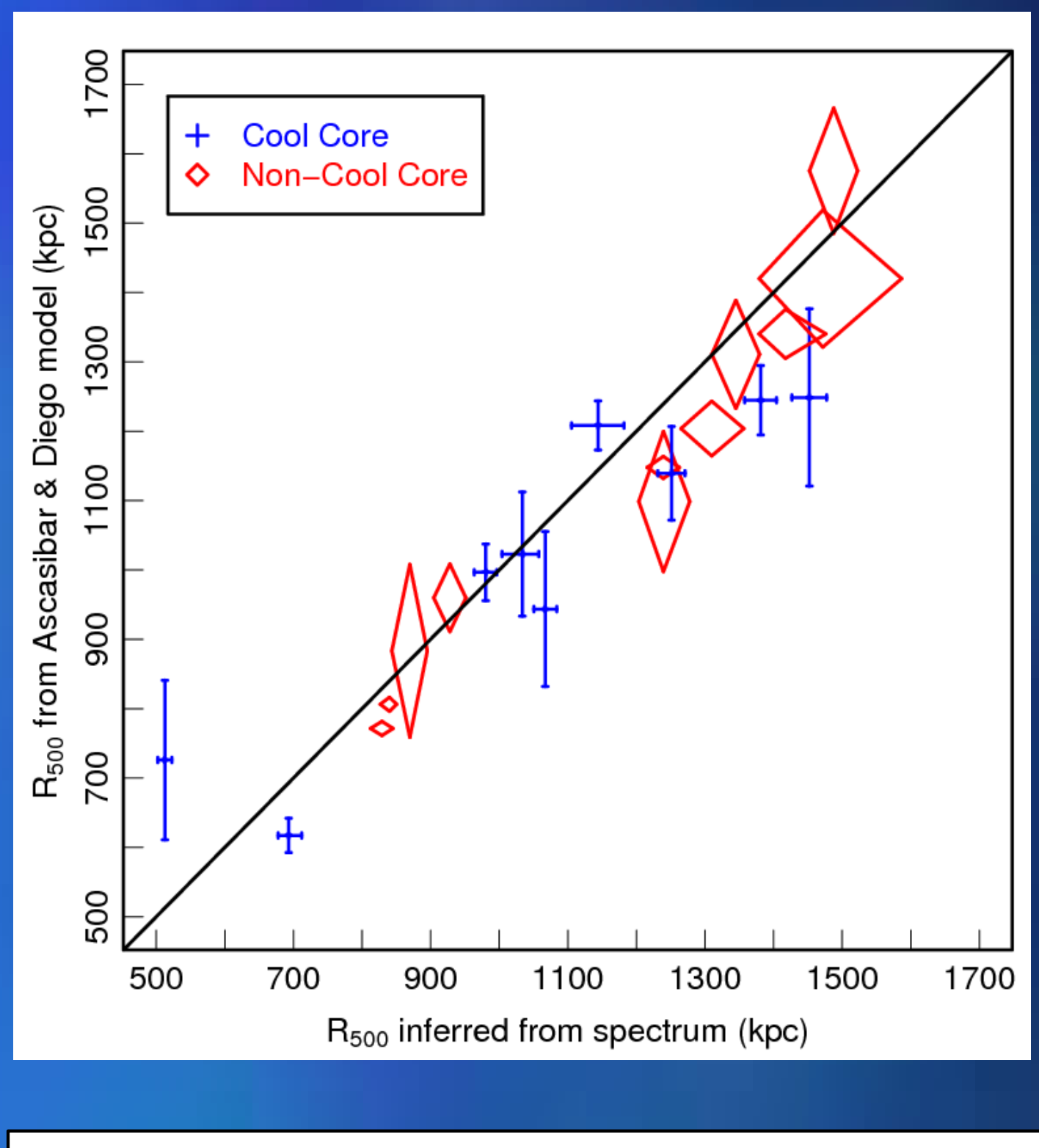
Overview

The mass profiles of clusters of galaxies are of great cosmological importance, but measuring them is challenging. X-ray imaging spectroscopy observations of the hot intracluster medium allow the temperature and density structure of the hot gas to be mapped in detail. This enables the gravitating mass distribution, *M(r)*, to be inferred, under the assumption of hydrostatic equilibrium; numerical simulations demonstrate that this assumption holds for the majority of clusters, to ~5-20% accuracy (e.g. Nagai et al., 2007).

Recently, Ascasibar and Diego (2008) have developed a phenomenological model to describe the dark matter density, gas density and gas temperature profiles of galaxy clusters using just 5 parameters, each with a clear physical meaning (see lower right panel), which can be used to determine any physical property of the gas or dark matter in the halo with good accuracy. Moreover, this model is very easy to fit robustly to discrete gas temperature and density profiles obtained from non-parametric deprojection of X-ray data, even with relatively poor statistics and sparse sampling. This allows it to be used to map the mass profiles of a wide range of objects.



A comparison of R_{500} calculated directly from the mass profile of the best-fit Ascasibar & Diego cluster model and as estimated from the mean temperature in an aperture of 0.15-0.2 R_{500}, determined iteratively and calibrated to the *M-T* relation of Vikhlinin et al. (2006). Clusters are identified according to their cool-core status and the solid line depicts the locus of equality; there is close agreement between the two methods.

The Ascasibar & Diego (2008) cluster model

The model comprises a Hernquist density profile for the dark matter plus a polytropic gas in hydrostatic equilibrium, with a variable central cooling component to allow for the presence of a cool core.

Model parameters

- Characteristic temperature of the dark matter halo, $\boldsymbol{T_0}$
- Characteristic scale radius of the dark matter halo, ***a***
- Cooling radius of the gas, in units of ***a***, $(0 < \boldsymbol{\alpha} < 1)$
- Central gas temperature, in units of $\boldsymbol{T_0}$ $(0 < \boldsymbol{t} < 1)$
- Asymptotic baryon fraction, in units of the cosmic value (***f*** ~1)

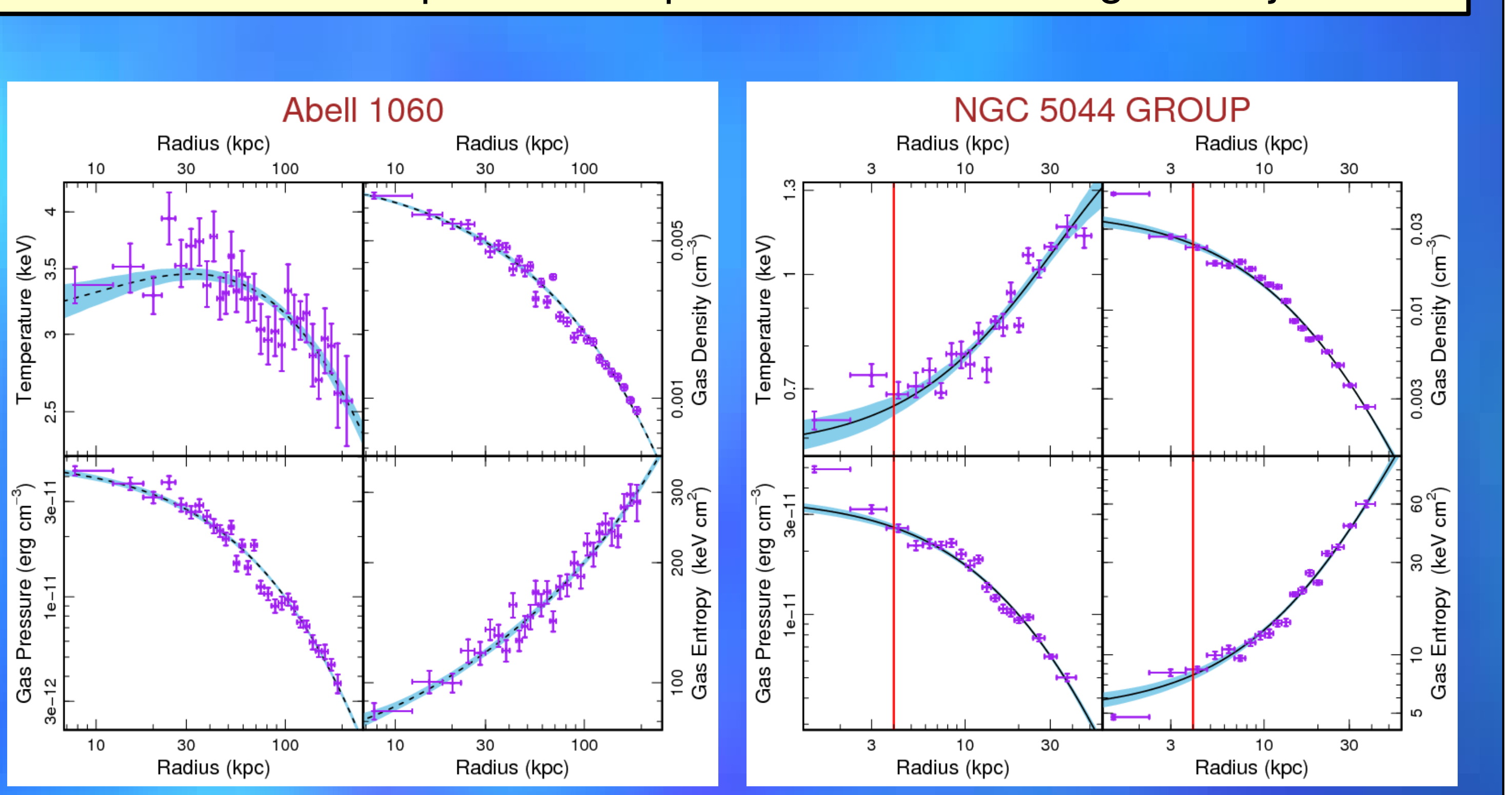
Profile equations

- Hernquist mass density: $$\rho(r) = \frac{M}{2\pi r^2}\frac{1}{(r/a)(1+r/a)^3}$$
- Gas temperature: $$T(r) = \frac{T_0}{1+r/a}\frac{t+r/(\alpha a)}{1+r/(\alpha a)}$$
- Gas density: $$\rho_{gas}(r) = \rho_{gas}(0)\left(\frac{1+r/a}{t\alpha+r/a}\right)^{1+[(\alpha-t\alpha)/(1-t\alpha)](n+1)}\frac{\alpha+r/a}{(1+r/a)^{n+1}}, \quad where\ \ n=4$$

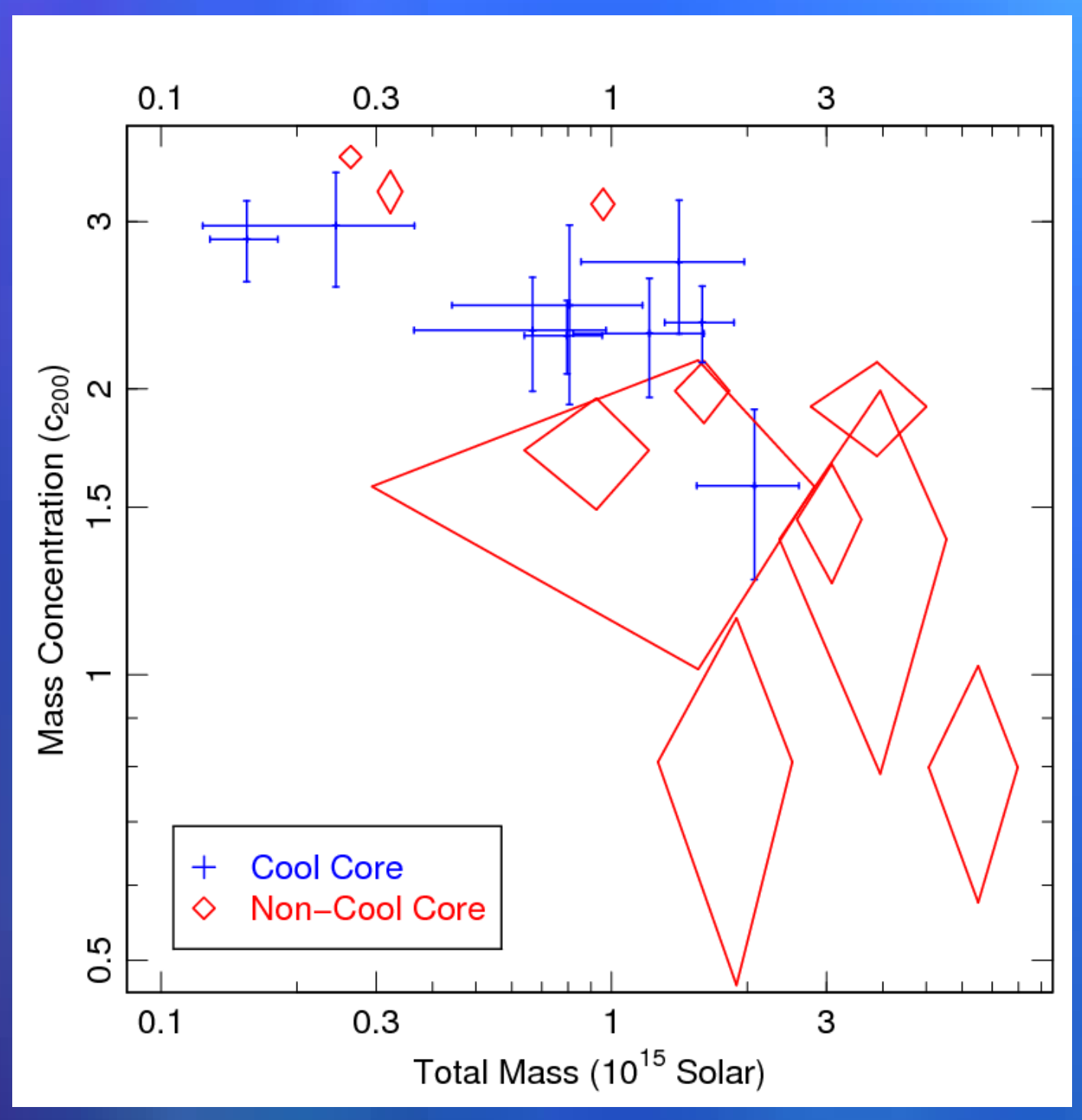
$$\rho_{gas}(0) = f\,\frac{\Omega_b}{\Omega_{dm}}\frac{M}{2\pi a^3}, \quad where\ \ \frac{\Omega_b}{\Omega_{dm}} = 0.133$$

The cluster sample

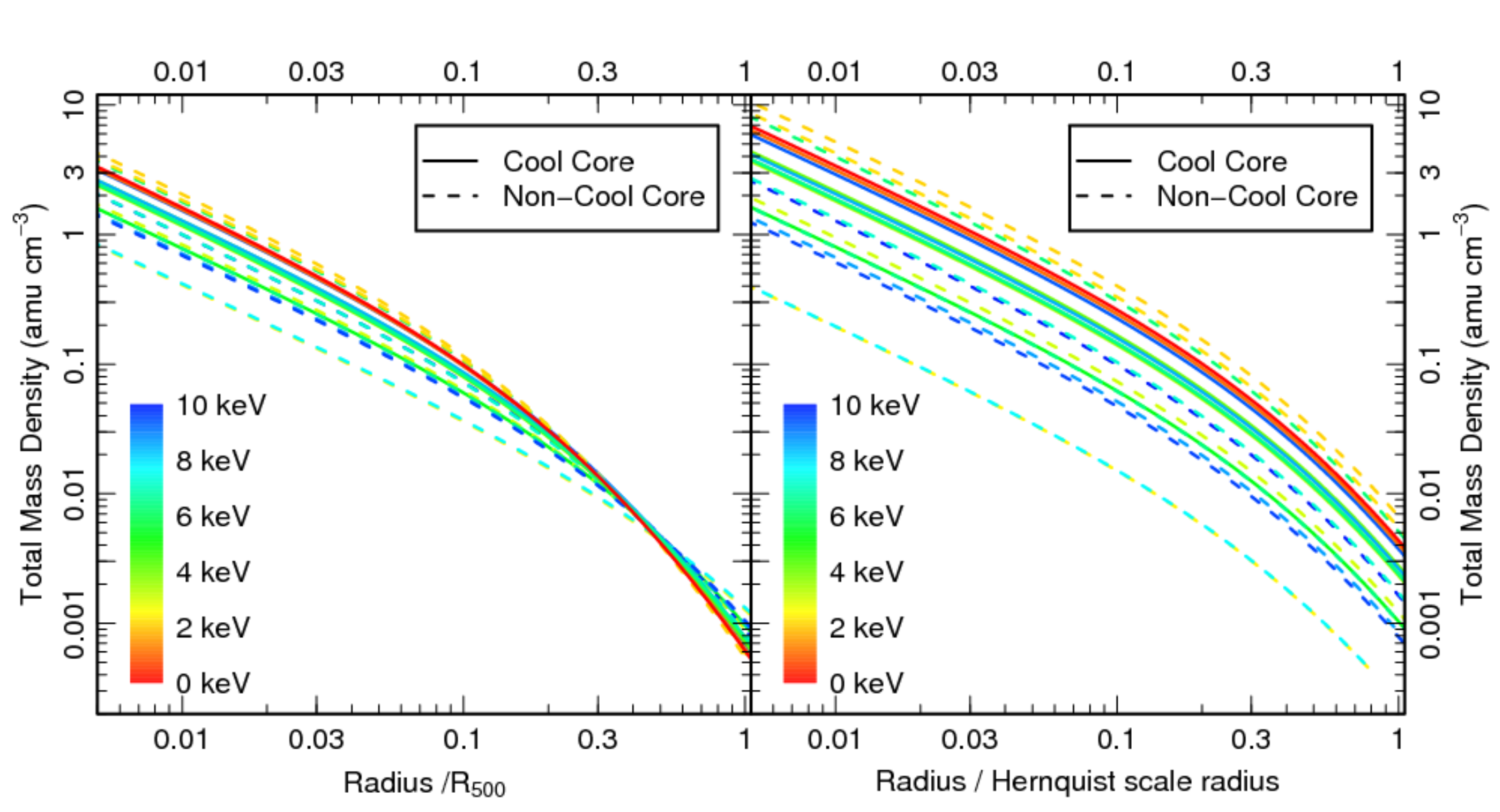
The data used in this study are a statistical sample of 20 clusters, presented in Sanderson et al. (2006), for which a full deprojection analysis of *Chandra* X-ray observations has been made, using a non-parametric annular spectral analysis (using the "projct" model in the XSPEC spectral analysis package).



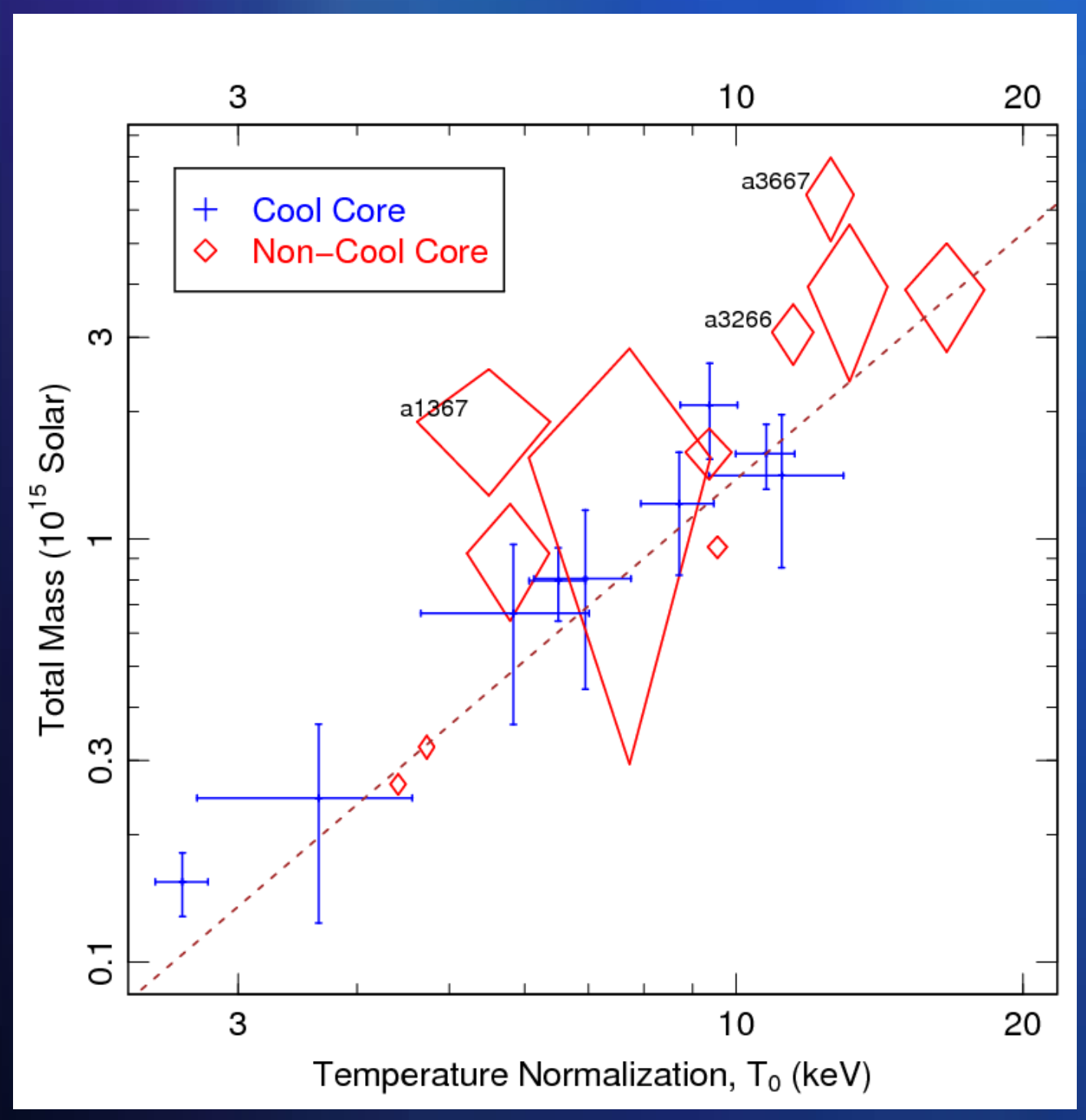
Gas profiles for a non-cool core cluster (left) and cool-core group (right) showing the non-parametric deprojected data points (errorbars) and the best-fit Ascasibar & Diego (2008) model + 1σ envelope from 200 bootstrap resamplings of the original data. The red line in the right panel marks the radius within which data were excluded from the fit, due to the effects of complex baryon physics in the core of the central galaxy (radius < 4 kpc).



Halo concentration (R_{200}/***a***) vs. total mass. There is a clear trend for low-mass objects to have higher concentrations, consistent with an earlier formation epoch, as expected from hierarchical formation theories. Also, many of the non-cool core clusters have low concentrations, possibly as a result of recent merger-related disruption. Note that the commonly used NFW scale radius is half that of the Hernquist model, so the equivalent NFW c_{200} values are twice as large.

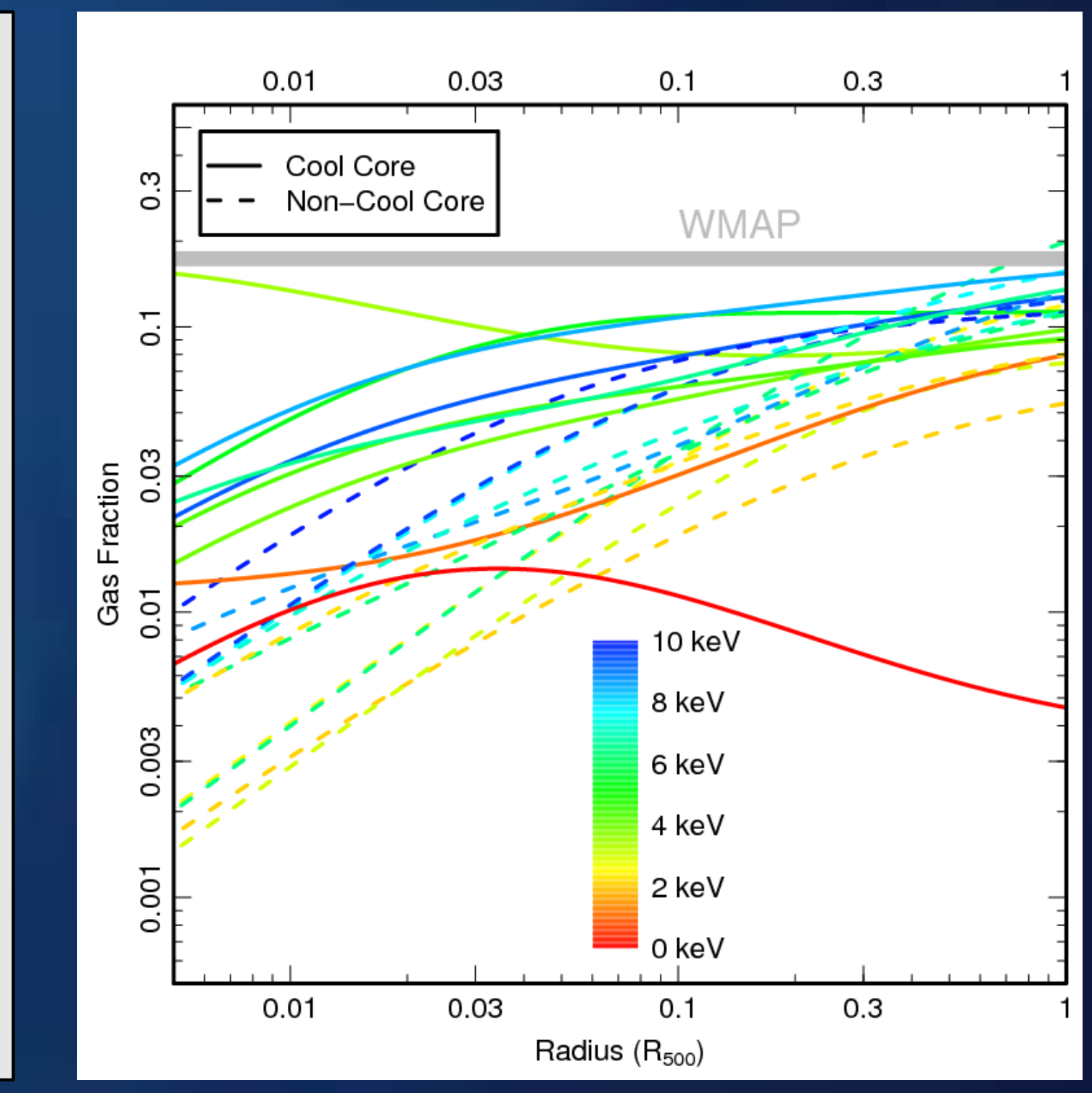


Total mass density profiles as a function of radius scaled by R_{500} (left panel) and the Hernquist scale radius, ***a***, (right panel), colour-coded by mean cluster temperature. Cooler clusters tend to have higher normalizations, while clusters without a cool core show much greater scatter in normalization.



The mass-temperature relation, from the cluster model total mass and T_0 parameter. The dashed line is the best-fit power-law model to the whole sample, fitted in log-log space with a weighted regression in the *y* direction only. This power law has a log slope of 1.93 +/- 0.17, which is ~2.5σ steeper than the self-similar prediction of 3/2, in disagreement with the findings of Vikhlinin et al. (2006). This could be caused by bias from non-relaxed clusters in this (statistical) sample, which were explicitly excluded from Vikhlinin et al.'s study; the outliers are indicated, and these are known merging (and non-cool core) clusters.

Integrated gas fraction profiles vs. scaled radius, colour-coded by mean cluster temperature, compared to the Universal baryon fraction determined by *WMAP*. In almost all cases f_{gas} rises monotonically with radius, flattening off after ~0.1 R500. Cool-core clusters tend to have higher gas fractions, while cooler clusters appear to be systematically depleted in gas mass, in agreement with the findings of Sanderson et al. (2003). This could result from mass drop out via cooling or gas displacement resulting from non-gravitational (pre)heating, e.g. from active galactic nuclei (AGN).



Conclusions

- The simple model of Ascasibar & Diego (2008) provides a good description of the gas density and temperature structure across the 20 cluster statistical sample of Sanderson et al. (2006).

- Non-cool core (NCC) clusters appear to be outliers in mass scaling relations, possibly due to departures from hydrostatic equilibrium and/or spherical symmetry, as a result of merging, for example. NCC clusters may be responsible for steepening the mass-temperature relation.

References

Ascasibar & Diego, 2008, MNRAS, 383, 369 -|- Nagai, Vikhlinin & Kravtsov, 2007, ApJ, 655, 98 -|- Sanderson et al., 2003, MNRAS, 340, 989 -|- Sanderson, Ponman & O'Sullivan, 2006, MNRAS, 372, 1496 -|- Vikhlinin et al., 2006, ApJ, 640, 691

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