A tale of two papers

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Stability of Cool Cores during Galaxy Cluster Growth: A Joint Chandra/SPT Analysis of 67 Galaxy Clusters along a Common Evolutionary Track Spanning 9 Gyr

F. Ruppin[1], M. McDonald[1], L. E. Bleem[2,3], S. W. Allen[4,5,6], B. A. Benson[7,3,8], M. Calzadilla[1], G. Khullar[8], and B. Floyd[9]
[1] Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
ruppin@mit.edu
[2] High Energy Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Lemont, IL 60439, USA
[3] Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
[4] Kavli Institute for Particle Astrophysics & Cosmology, P.O. Box 2450, Stanford University, Stanford, CA 94305, USA
[5] Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305, USA
[6] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
[7] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA
[8] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
[9] Department of Physics and Astronomy, University of Missouri, 5110 Rockhill Road, Kansas City, MO 64110, USA
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Abstract

We present the results of a joint analysis of Chandra X-ray and South Pole Telescope (SPT) Sunyaev–Zel'dovich (SZ) observations targeting the first sample of galaxy clusters at $0.3 < z < 1.3$, selected to be the progenitors of well-studied nearby clusters based on their expected accretion rate. We develop a new procedure in order to tackle the analysis challenge that is estimating the intracluster medium (ICM) properties of low-mass and high-redshift clusters with ~150 X-ray counts. One of the dominant sources of uncertainty on the ICM density profile estimated with a standard X-ray analysis with such shallow X-ray data is due to the systematic uncertainty associated with the ICM temperature obtained through the analysis of the background-dominated X-ray spectrum. We show that we can decrease the uncertainty on the density profile by a factor varying between 2 and 8 with a joint deprojection of the X-ray surface brightness profile measured by Chandra and the SZ-integrated Compton parameter available in the SPT cluster catalog. We apply this technique to the whole sample of 67 clusters in order to track the evolution of the ICM core density during cluster growth. We confirm that the evolution of the gas density profile is well modeled by the combination of a fixed core and a self-similarly evolving non-cool-core profile. We show that the fraction of cool cores in this sample is remarkably stable with redshift although clusters have gained a factor of ~4 in total mass over the past ~9 Gyr.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); High-redshift galaxy clusters (2007); Sunyaev-Zeldovich effect (1654); X-ray astronomy (1810); Intracluster medium (858); Cool cores (302)

1. Introduction

Galaxy clusters are the end result of a hierarchical process starting from matter density peaks at the end of inflation that first grew through the smooth accretion of surrounding material (e.g., Press & Schechter 1974; Cooray & Sheth 2002; Mead et al. 2015). Merger events with smaller halos then contributed to both the galaxy cluster growth and the heating of their baryonic matter content called the intracluster medium (ICM) up to a few keV (e.g. Sarazin 2002; Markevitch & Vikhlinin 2007; Bourdin et al. 2013). Studying the evolution of the ICM thermodynamic properties with cluster redshift and mass is essential to unveiling the multiphase and multiscale physical mechanisms at play during their growth (e.g. Voit et al. 2008, 2015; McNamara et al. 2016; Tümer et al. 2019; Gaspari et al. 2020). Such understanding is key to using galaxy clusters as tracers of the history of large-scale structure formation (e.g. Voit 2005; Planelles et al. 2015; Vallés-Pérez et al. 2020) and as probes of the underlying cosmology (e.g. Allen et al. 2011; Hasselfield et al. 2013; Bocquet et al. 2015; Ade et al. 2016a; Hilton et al. 2018; Bocquet et al. 2019).

Unveiling the properties and evolution of the ICM and the active galactic nucleus (AGN)–star formation–halo connection in early-forming systems all the way back to $z \sim 3$ will be among the primary science goals of both Athena (Barret et al. 2020) and Chandra successor missions such as Lynx (The Lynx Team 2018) or the Advanced X-ray Imaging Satellite (Mushotzky et al. 2019). While many of the most exciting questions about the initial formation of galaxy clusters must wait for these next-generation X-ray missions, the current X-ray observatories can lay an important foundation now by studying clusters in the $1 < z < 2$ range, where to date only a dozen of the most massive systems have been observed.

Until recently, studies of distant galaxy clusters were limited to a small number of extreme systems, discovered serendipitously in deep X-ray observations (e.g. Schwope et al. 2004; Kolokotronis et al. 2006; Finoguenov et al. 2010). However, the successes of Sunyaev–Zel'dovich (SZ) surveys (Hasselfield et al. 2013; Bleem et al. 2015; Ade et al. 2016b; Hilton et al. 2018; Bleem et al. 2020; Huang et al. 2020; Hilton et al. 2021) have rapidly altered the landscape of galaxy cluster astrophysics and cosmology. In particular, the South Pole Telescope (SPT; Carlstrom et al. 2011) has surveyed 5000 deg^2 of the southern sky over the past 10 yr, leading to the discovery of 1066 galaxy clusters, including 72 at $z > 1$. The combination of SPT selection, which is redshift independent and only limited by the survey sensitivity, with relatively shallow Chandra follow-up has proven an extremely efficient way of studying the growth and evolution of the most massive clusters (e.g. McDonald et al. 2013b, 2014, 2016, 2017).

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The history of metal enrichment traced by X-ray observations of high-redshift galaxy clusters

Anthony M. Flores,[1,2★] Adam B. Mantz,[2] Steven W. Allen,[1,2,3] R. Glenn Morris,[2,3] Rebecca E. A. Canning,[1,2,4] Lindsey E. Bleem,[5,6] Michael S. Calzadilla,[7] Benjamin T. Floyd,[8] Michael McDonald[7] and Florian Ruppin[7]
[1] Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305, USA
[2] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 452 Lomita Mall, Stanford, CA 94305, USA
[3] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
[4] Institute of Cosmology and Gravitation, University of Portsmouth, Burnaby Road, Portsmouth PO1 3FX, UK
[5] HEP Division, Argonne National Laboratory, Argonne, IL 60439, USA
[6] Kavli Institute for Cosmological Physics, University of Chicago, 5640 S Ellis Ave, Chicago, IL 60637, USA
[7] Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[8] Department of Physics and Astronomy, University of Missouri, 5110 Rockhill Road, Kansas City, MO 64110, USA

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ABSTRACT

We present the analysis of deep X-ray observations of 10 massive galaxy clusters at redshifts $1.05 < z < 1.71$, with the primary goal of measuring the metallicity of the intracluster medium (ICM) at intermediate radii, to better constrain models of the metal enrichment of the intergalactic medium. The targets were selected from X-ray and Sunyaev–Zel'dovich effect surveys, and observed with both the *XMM–Newton* and *Chandra* satellites. For each cluster, a precise gas mass profile was extracted, from which the value of r_{500} could be estimated. This allows us to define consistent radial ranges over which the metallicity measurements can be compared. In general, the data are of sufficient quality to extract meaningful metallicity measurements in two radial bins, $r < 0.3r_{500}$ and $0.3 < r/r_{500} < 1.0$. For the outer bin, the combined measurement for all 10 clusters, $Z/Z_\odot = 0.21 \pm 0.09$, represents a substantial improvement in precision over previous results. This measurement is consistent with, but slightly lower than, the average metallicity of 0.315 solar measured at intermediate-to-large radii in low-redshift clusters. Combining our new high-redshift data with the previous low-redshift results allows us to place the tightest constraints to date on models of the evolution of cluster metallicity at intermediate radii. Adopting a power-law model of the form $Z \propto (1 + z)^\gamma$, we measure a slope $\gamma = -0.5^{+0.4}_{-0.3}$, consistent with the majority of the enrichment of the ICM having occurred at very early times and before massive clusters formed, but leaving open the possibility that some additional enrichment in these regions may have occurred since a redshift of 2.

Key words: galaxies: clusters: intracluster medium – X-rays: galaxies: clusters.

1 INTRODUCTION

As the most massive gravitationally bound structures in the Universe, the deep gravitational wells of galaxy clusters trap essentially all baryonic matter present during their formation and subsequent evolution (Allen, Evrard & Mantz 2011; Kravtsov & Borgani 2012). Metals produced by stellar processes and ejected from galaxies within these volumes mix with the hot intracluster medium (ICM). X-ray spectroscopic techniques allow us to determine accurate elemental abundances for the ICM (Böhringer & Werner 2010; Mernier et al. 2018) and, by making measurements across a range of redshifts, construct the histories of star formation and metal enrichment in our Universe.

The metallicity of the ICM in the centres of low-redshift clusters is often centrally peaked (Allen & Fabian 1998; De Grandi & Molendi 2001; De Grandi et al. 2004) and has been shown to evolve moderately with redshift, albeit with substantial intrinsic scatter (e.g. Mantz et al. 2017) indicative of ongoing and somewhat sporadic enrichment and mixing in these regions. In contrast, the metallicity at intermediate-to-large radii is observed to be remarkably uniform and shows no evidence of evolution. In particular, detailed *Suzaku* observations of the nearest, X-ray brightest galaxy clusters, including the Perseus (Werner et al. 2013), Coma (Simionescu et al. 2013), and Virgo (Simionescu et al. 2015) clusters, among others (Thölken et al. 2016; Urban et al. 2017), found a remarkably uniform distribution of iron, with a metallicity of $Z/Z_\odot \sim 0.315 \pm 0.008$ solar [combining the independent *Suzaku* measurements of Werner et al. (2013) and Urban et al. (2017), and using the Asplund et al. (2009) solar abundance table]. These results extended earlier findings with, in particular, *BeppoSAX* and *XMM–Newton* that determined consistent results at intermediate radii, when scaled to the same solar abundance table (e.g. De Grandi & Molendi 2001; De Grandi et al. 2004; Leccardi & Molendi 2008; for a recent review, see Mernier et al. 2018).

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★ E-mail: aflores7@stanford.edu

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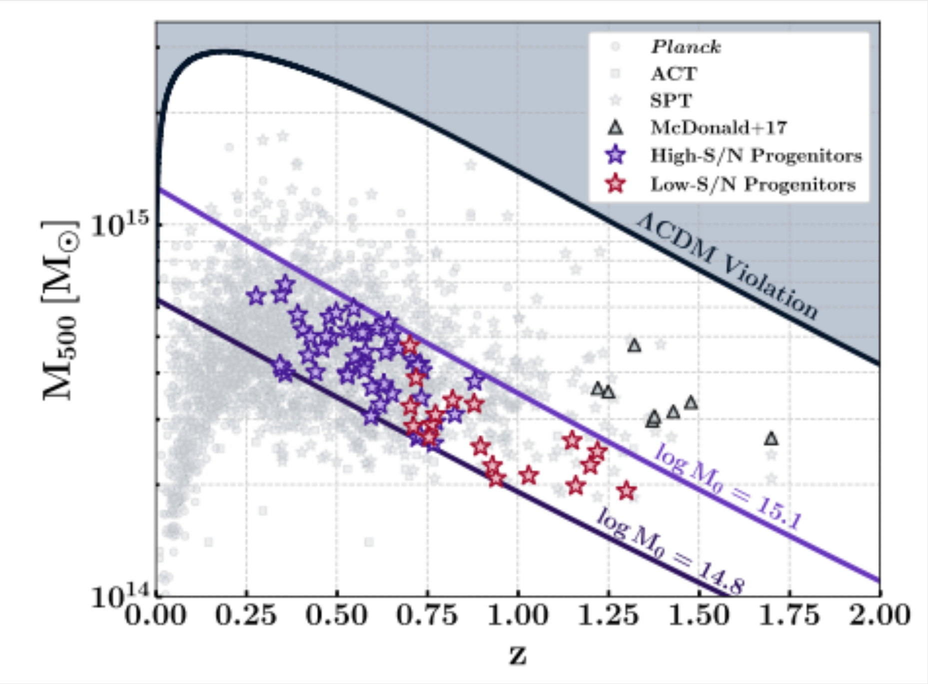
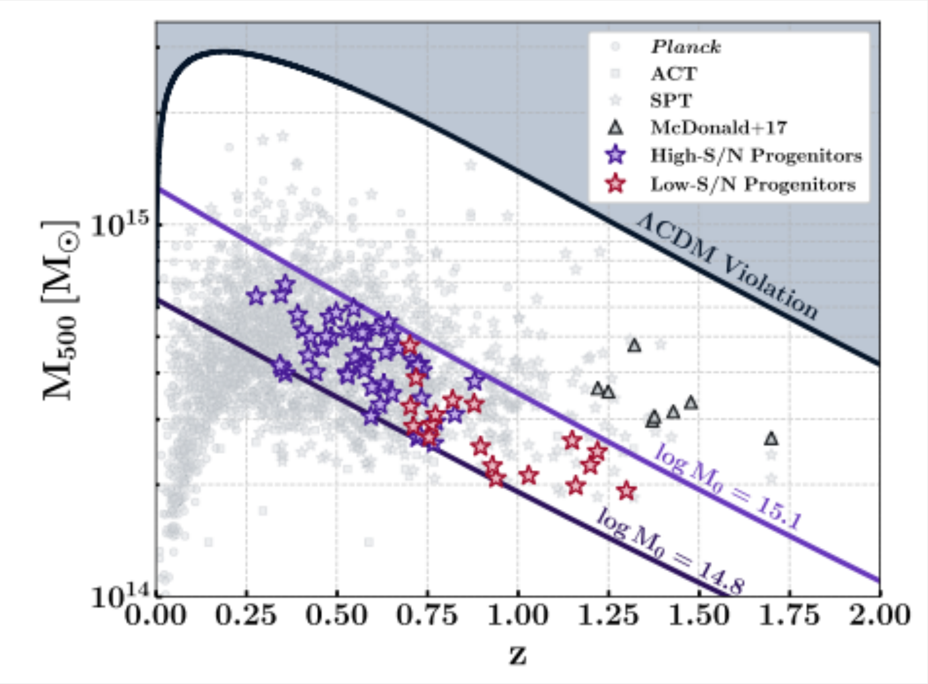
A common approach

- Study evolution of cluster properties
- Previous work focused on comparing the properties of the brightest high z clusters with those of local systems
- However massive distant systems do not (on average) evolve into massive local systems.
- Investigate less massive clusters which are (on average) the progenitors of massive local systems.



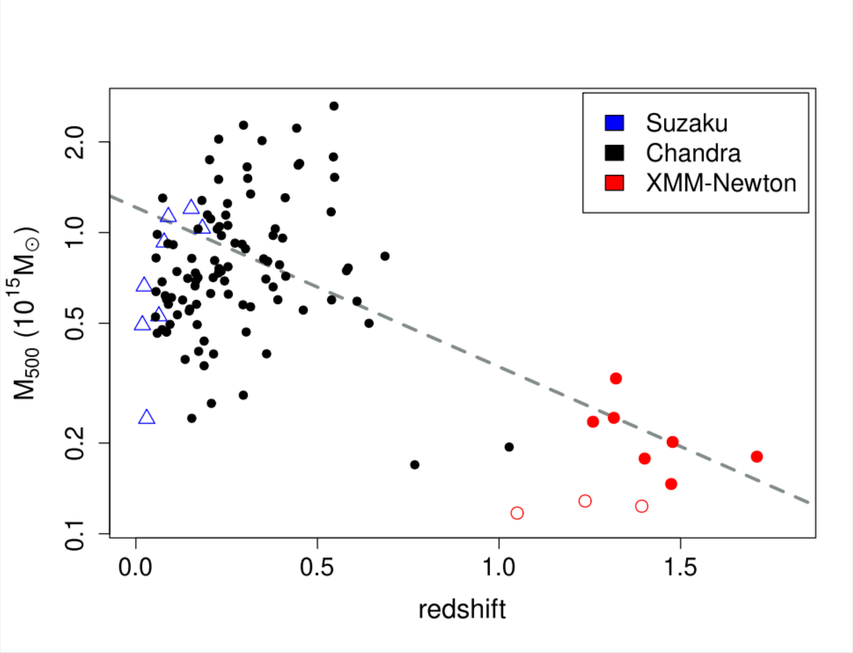
Different Goals and Samples

R21 Evolution of Cool Core fraction across cosmic time



50 H-S/N +17 L-S/N SPT sample Chandra follow up

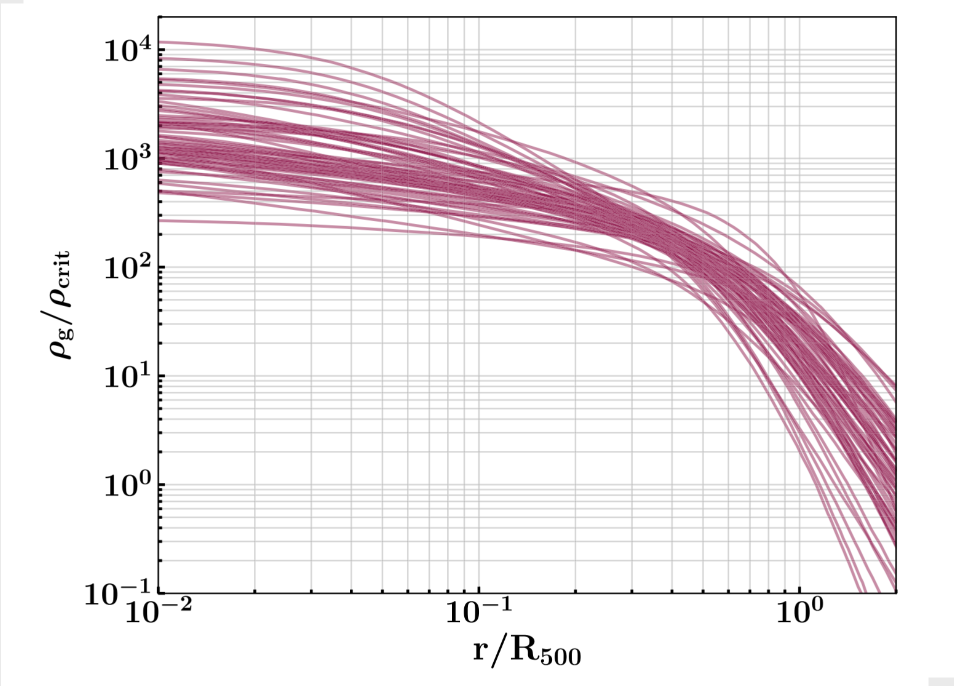
F21 Evolution of Metal Abundance across cosmic time



7 SPT sample, 3 AC XMM follow up

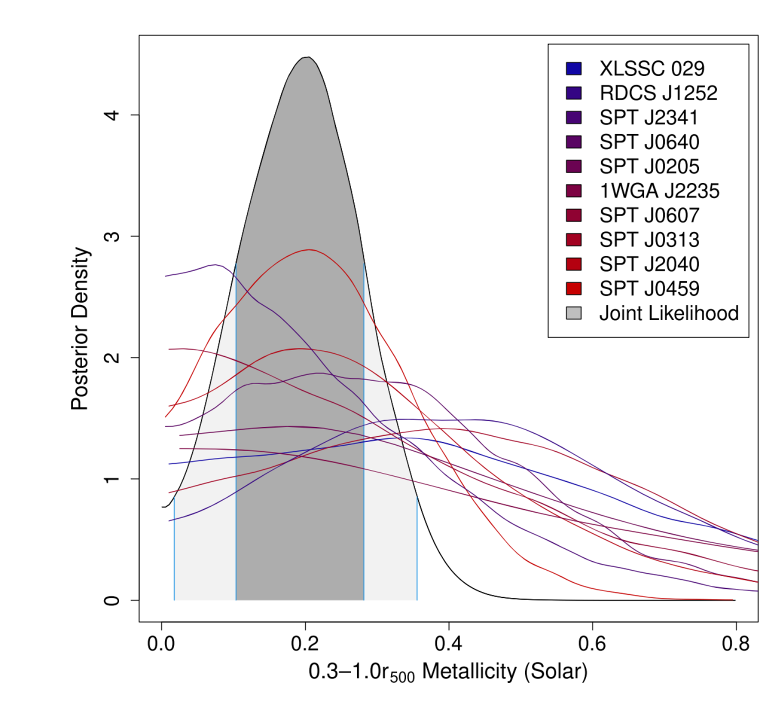
Different Goals and Samples

Density profiles



50 H-S/N +17 L-S/N SPT sample
Chandra follow up

Metal abundances in 0.3-1.0 r500

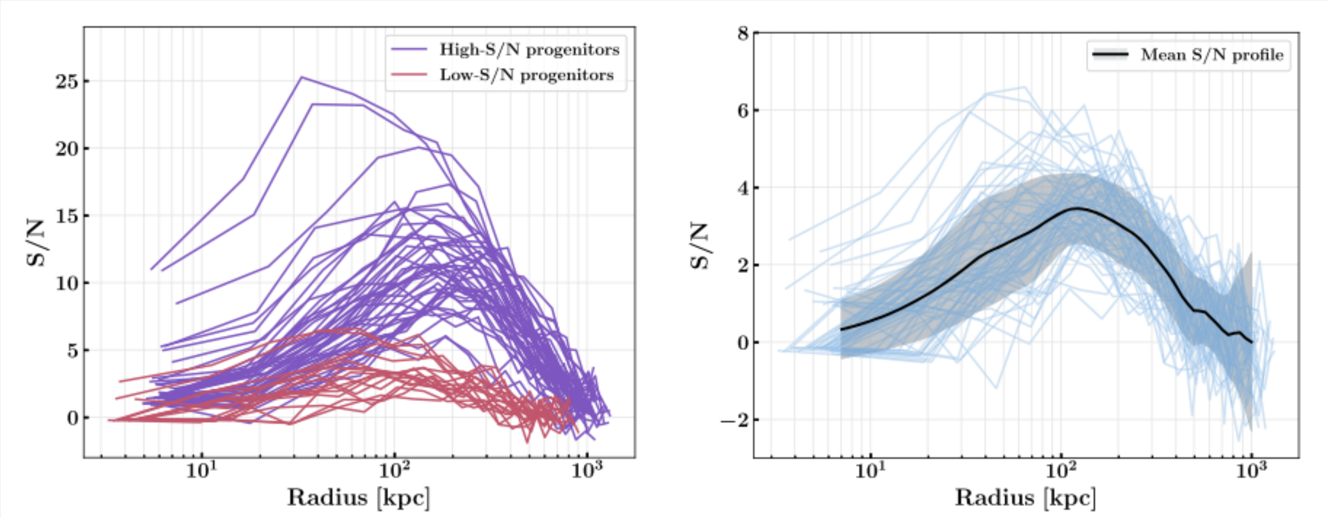


7 SPT sample, 3 AC XMM follow up

Combining High S/N & Low S/N samples

Careful and creative treatment of several issues

Correcting H S/N - L S/N bias



H S/N data used only for preparatory analysis, not for establishing if a system is CC or not

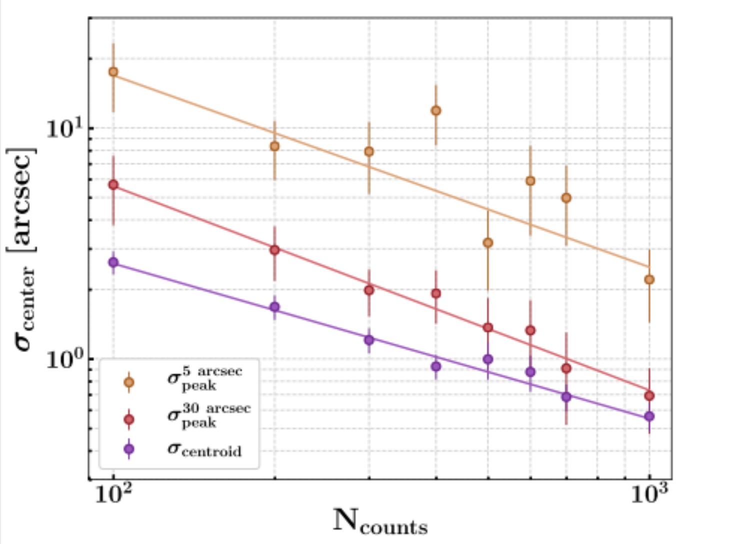
Is throwing away ~90% of your data really the best approach?

Centroid vs Peak

Center SB profiles on Centroid or Peak?

Use 30 obj with highest S/N to investigate how stable Centroid and Peak are in low S/N regime

Centroid appears to be more stable



However, is this really the question?

More fundamental questions:

1. Does Centroid or Peak best identify the CC?
2. How distant are Centroid and Peak?

Not Addressed

Centroid vs Peak

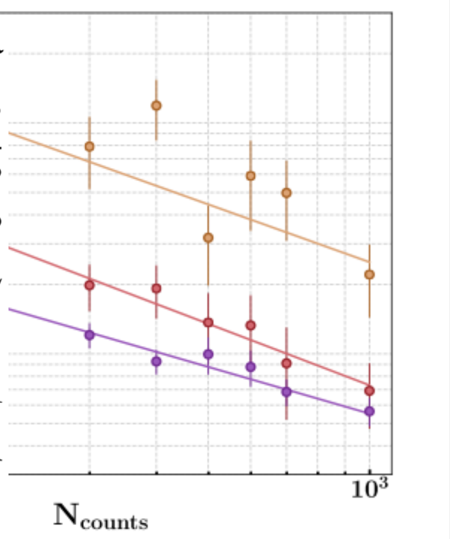
Center SB profiles on Centroid or Peak?

Use 30 obj with highest S/N to investigate how stable Centroid and Peak are in low S/N regime

Centroid app

However, is t

If a cool-core cluster has a core that is significantly offset with respect to its centroid (see, e.g., McDonald et al. 2014; Ruppin et al. 2020), then choosing the centroid may induce a misclassification of such a cluster as a system with a disturbed core. However, there are only 2 clusters out of 30 in this subsample that satisfy this condition. Therefore, following McDonald et al. (2013b), we will consider in this paper that a cool-core cluster is a system with an overdense cool gas region located at its barycenter.



More fundamental questions:

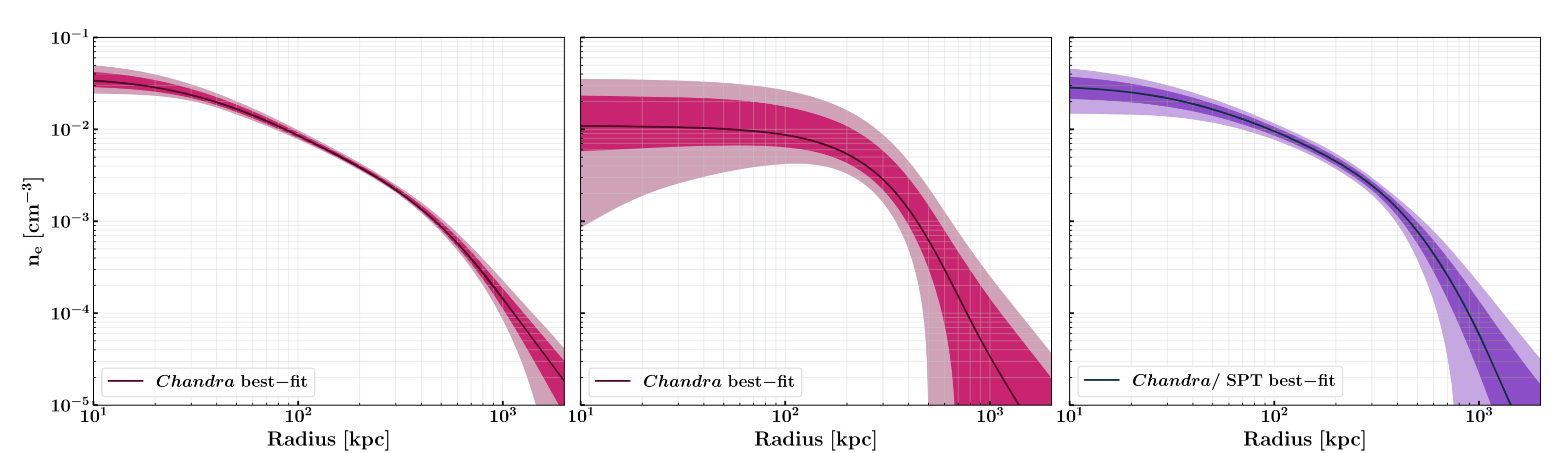
1. Does Centroid or Peak best identify the CC?
2. How distant are Centroid and Peak?

Not Addressed

Reconstruction of density profile

50 high S/N "Standard" X-ray analysis (forward fitting MCMC) to SB and spectra in annuli to derive n_e profiles

17 low S/N X-ray + SZ (forward fitting MCMC)



Use of sophisticated statistical analysis tools

Reconstruction of density profile

50 high S/N "Standard" X-ray analysis (forward fitting MCMC) to SB and spectra in annuli to derive n_e profiles

17 low S/N X-ray + SZ (forward fitting MCMC)

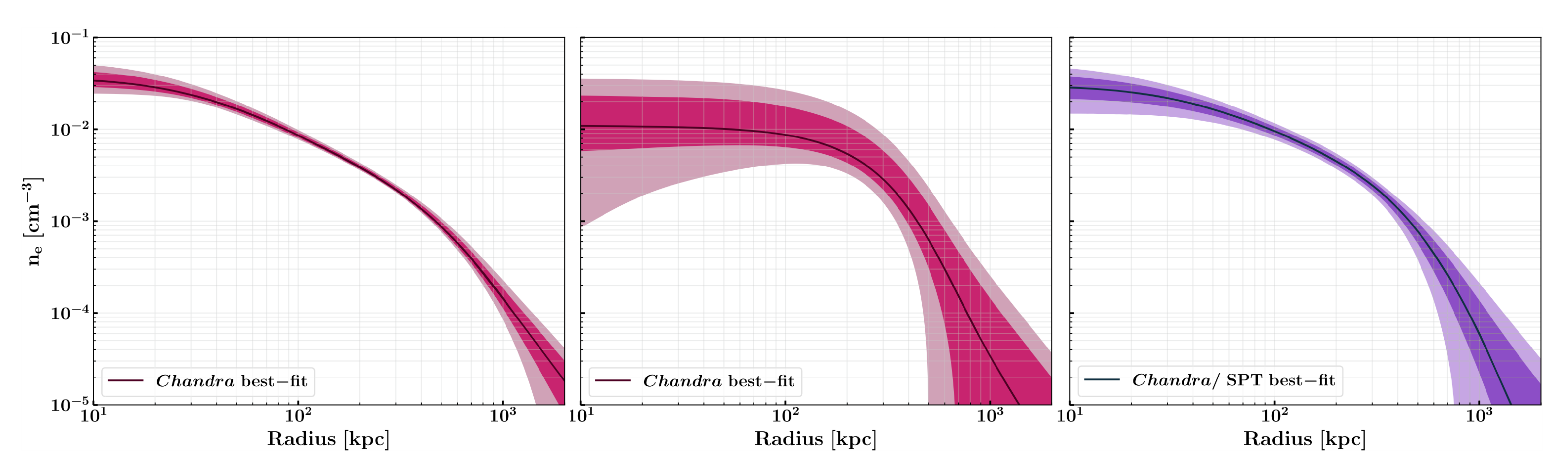
Use of sophisticated analysis tool.

Great care in handling statistical issues

Same approach is not followed when dealing with systematic issues.

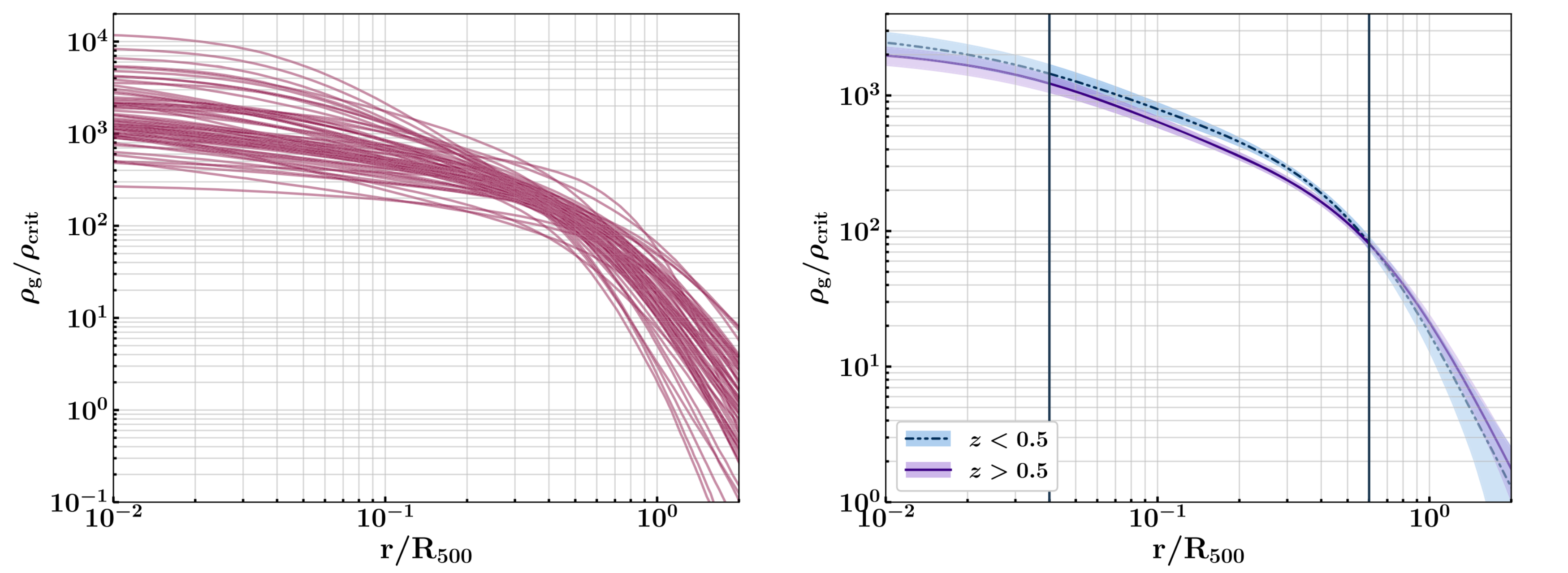
Example Instrumental bkg is subtracted not modeled

Using SZ to improve n_e profile



Non evolving cores in self-similarly evolving clusters

n_e profiles measured by combining X and SZ self sim scaled and averaged



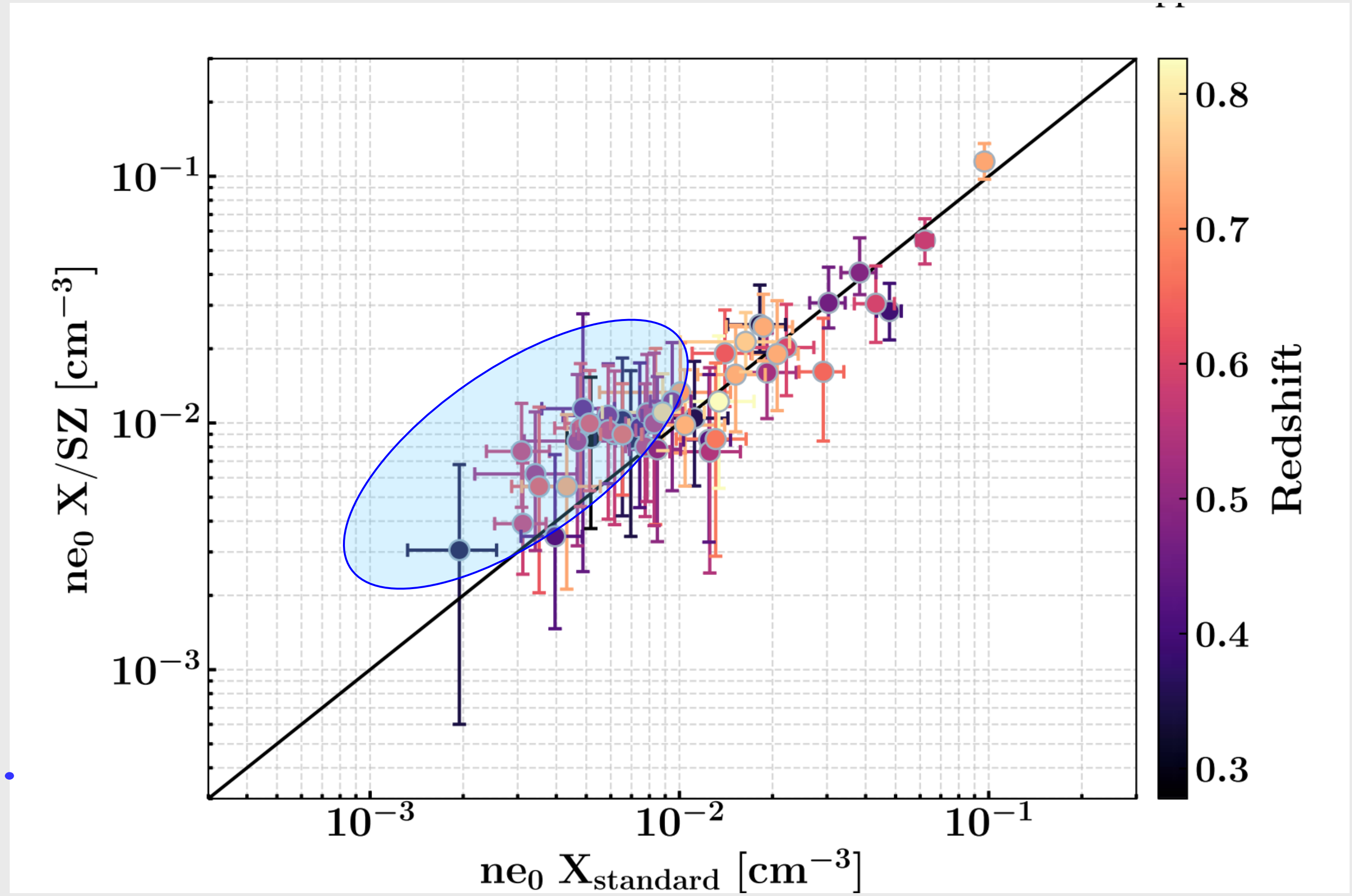
….

Comparison of n_e @ 10kpc for high S/N sample

n_e measured by combining X and SZ compared with those from standard X analysis for high S/N sample

"Although the available number of counts in the joint X-ray/SZ analysis is on average seven times lower than the one used in the standard X-ray analysis, we do not find any significant systematic deviation from the identity line (black) between the two estimates of the core density."

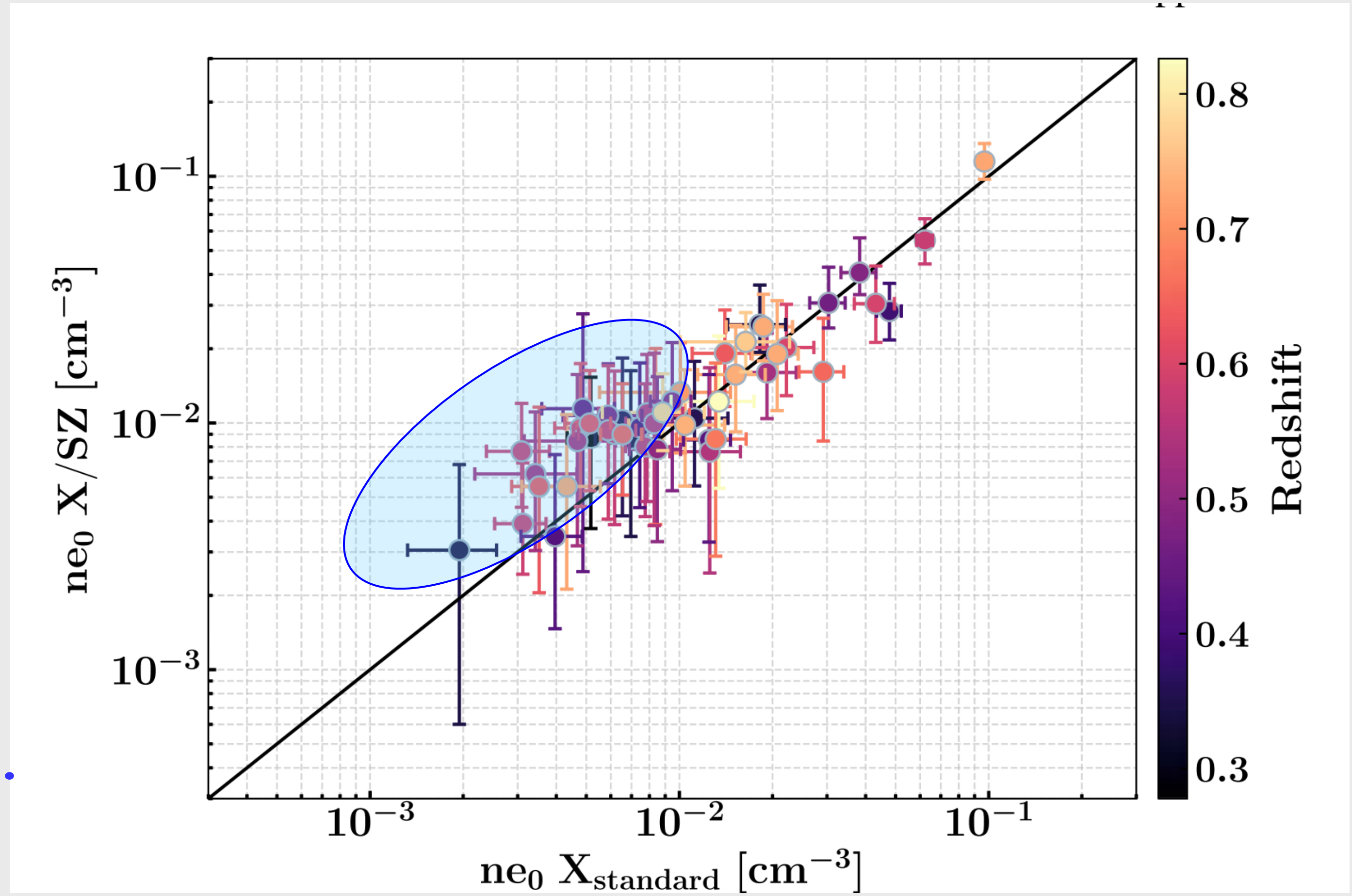
"We note however that this effect is taken into account in the uncertainties. Thus, this deviation with the line of equality is not significant."



Comparison of n_e @ 10kpc for high S/N sample

n_e measured by combining X and SZ compared with those from standard X analysis for high S/N sample

1. Do we buy this?
2. Why not?



"We note however that this effect is taken into account in the uncertainties. Thus, this deviation with the line of equality is not significant."

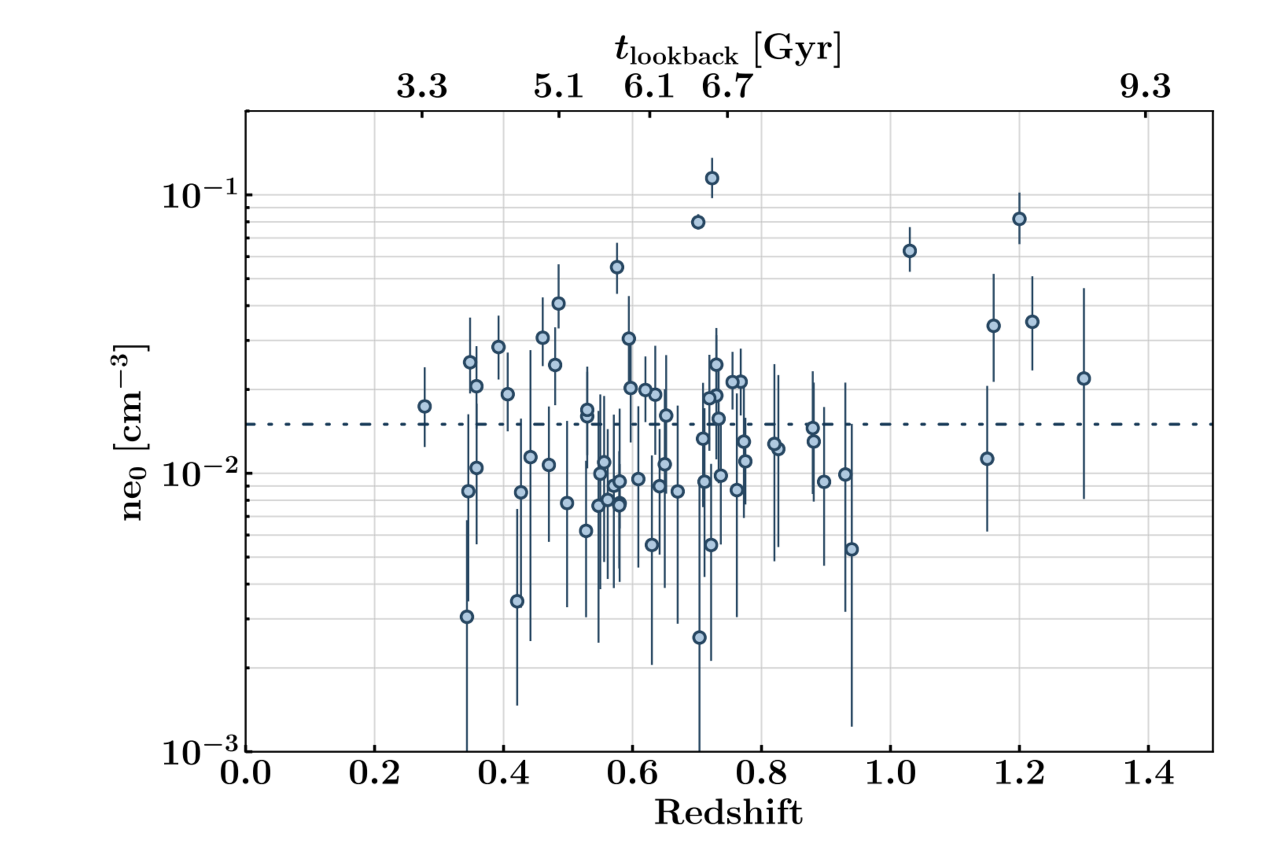
Core Density evolution

n_e @ 10 kpc from profiles measured by combining X and SZ

"Test the significance of a linear evolution of the ICM core density"

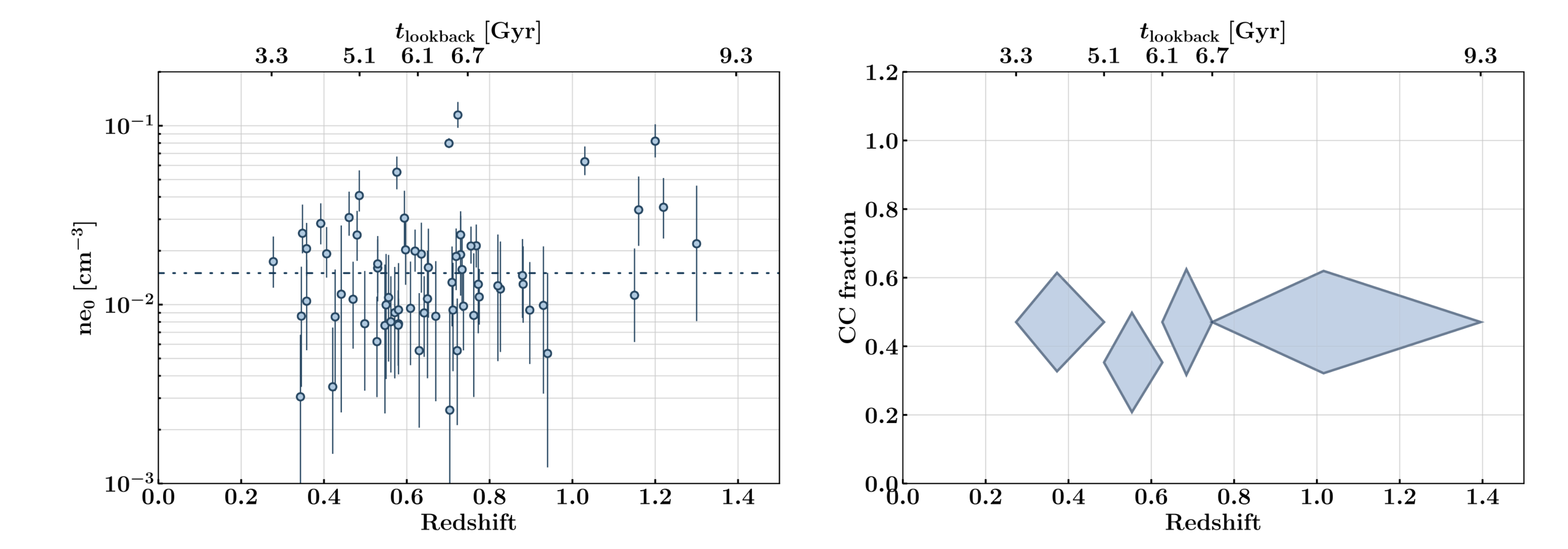
likelihood ratio analysis, which assumes data drawn from normal distribution

Result is consistent with no evolution



CC evolution

$n\_e(r=100kpc) = 1.5x10^{-2}\ cm^{-3}$ defined as threshold dividing CC from NCC



CC fraction consistent with being constant

Implications

- Solid evidence that mergers can disrupt CC, large fraction of NCC have gone through a CC phase

- The CC fraction does not change significantly with time.

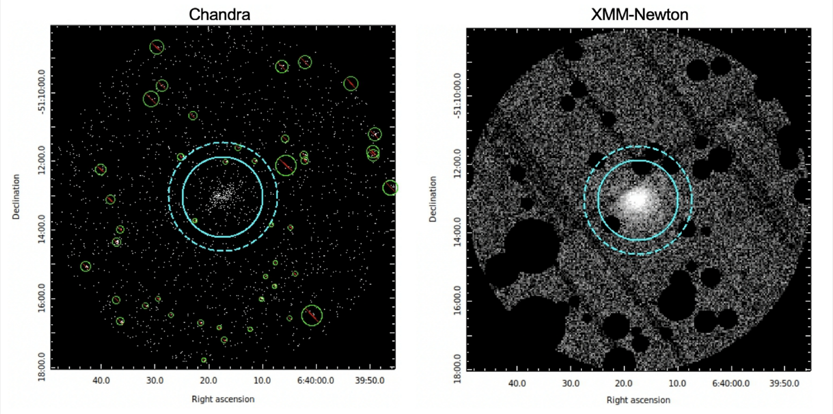
This also implies that cool-core disruption by mergers (e.g. Gomez et al. 2002; Douglass et al. 2018; Chadayammuri et al. 2021) has to be compensated by cool-core restoration mechanisms in timescales that are shorter than the Hubble time (Rossetti et al. 2011) in order to maintain a constant fraction of cool-core clusters with redshift.

Overall assesment

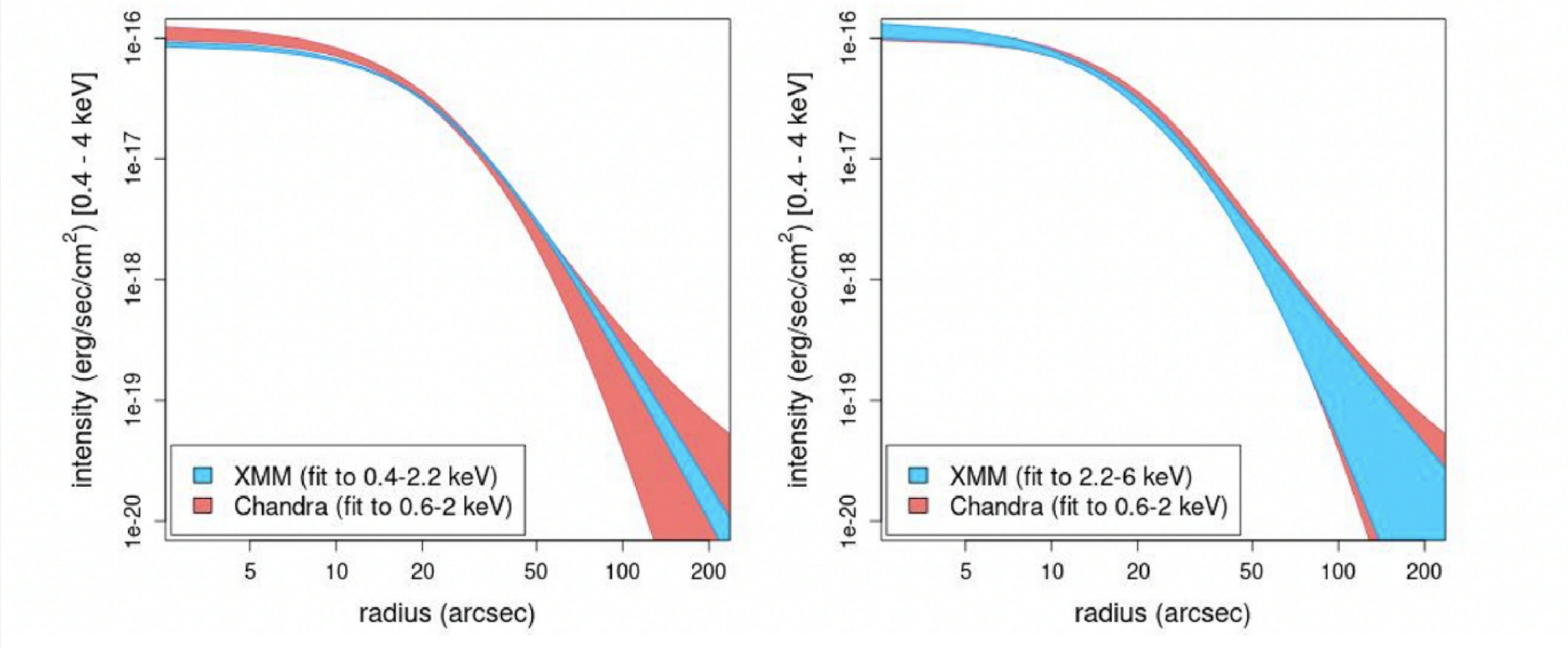
- Good selection of sample
- Important scientific issue
- Good understanding of statistical issues, perhaps sometimes excessive use of statistical tools and misunderstanding statistics is not an end but a means
- Limited understanding of systematic issues
- Very unlikely that either issue has any impact on main scientific result

Overall judgement very positive

Data analysis/imaging



- Chandra data too shallow to measure Z
- XMM data with supporting Chandra data
- Fit $S(r) = S_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta+0.5} + b,$ beta model to Chandra and XMM SB, model convolved with PSF for XMM



Data analysis/spectra

- Fit spectra in concentric annuli
- Use of a square mixing matrix that describes how much of the emission detected in a given annulus originates from each spherical shell.
- This mixing matrix is used to link normalizations of the APEC models fitted to the annuli appropriately for the deprojection analysis. It must also account for SB profile
- The temperatures and metallicities of neighbouring shells are linked over certain scales, depending on the specific analysis (i.e. density deprojection versus temperature and metallicity profiles).
- XMM PSF convolution included
- Modeling of instrumental and astrophysical background

Data analysis/spectra

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Highly sophisticated machinery, would have been nice to know what annuli were used for spectral extraction

- The temperatures and metallicities of neighbouring shells are linked over certain scales, depending on the specific analysis (i.e. density deprojection versus temperature and metallicity profiles).
- XMM PSF convolution included
- Modeling of instrumental and astrophysical background

Abundance estimate

- Derived Z from 2 spherical shells 0-0.3 r500 & 0.3-1.0 r500
- Uncertainties estimated using MCMC in XSPEC

Table 3. Values of r_{500} and M_{500} as well as inner and outer metallicity measurements for the 10 high-redshift clusters in this sample.

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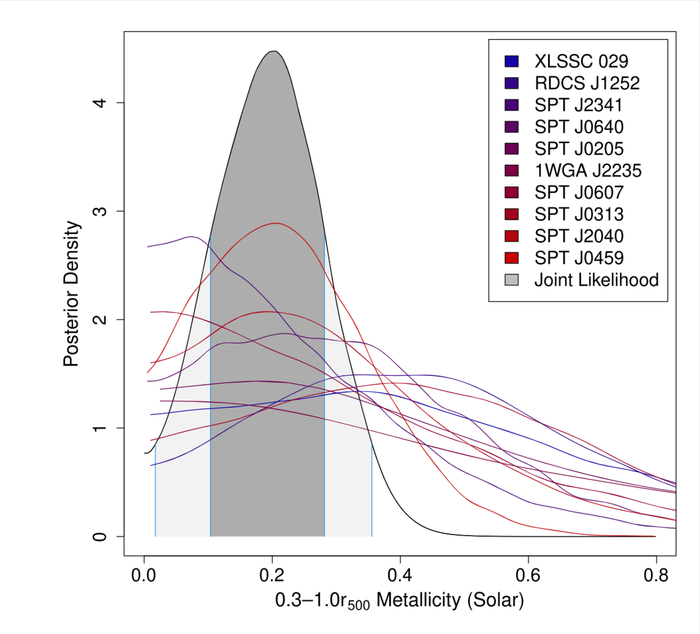
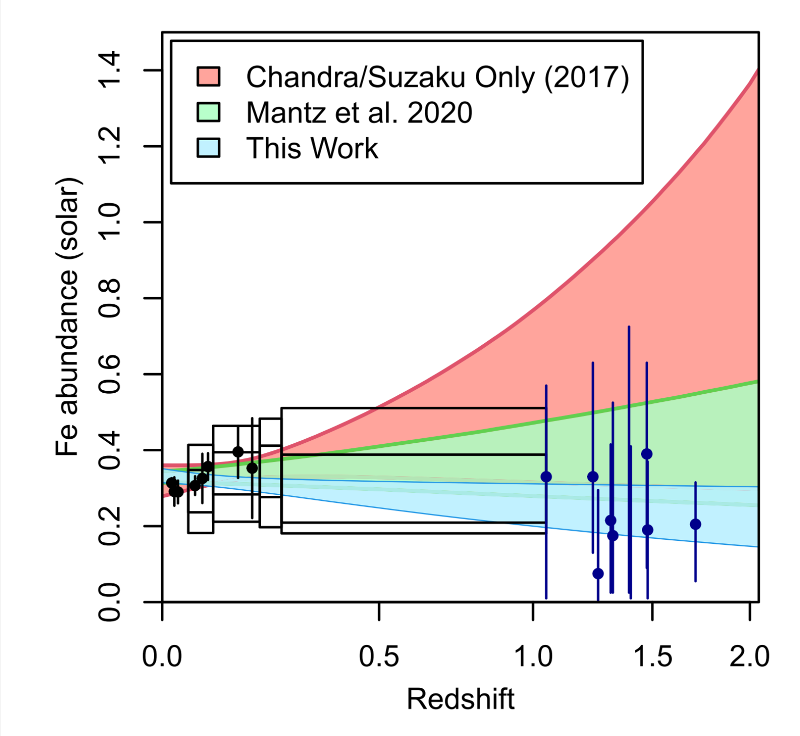
Cluster	r_{500} (Mpc)	M_{500} (10^{14} $M_{\odot}$)	$Z/Z_{\odot}$ ($0-0.3r_{500}$)	$Z/Z_{\odot}$ ($0.3–1.0r_{500}$)
XLSSC 029	0.50 ± 0.03	1.2 ± 0.2	$0.58^{+0.55}_{-0.50}$	$0.33^{+0.24}_{-0.32}$
RDCS J1252	0.48 ± 0.03	1.3 ± 0.3	$0.38^{+0.80}_{-0.35}$	$0.33^{+0.30}_{-0.20}$
SPT J2341	0.59 ± 0.03	2.4 ± 0.4	1.23 ± 0.50	$0.08^{+0.22}_{-0.07}$
SPT J0640	0.58 ± 0.03	2.4 ± 0.4	$0.31^{+0.26}_{-0.20}$	$0.22^{+0.20}_{-0.19}$
SPT J0205	0.64 ± 0.03	3.3 ± 0.5	$0.00^{+0.65}_{-0.00}$	$0.18^{+0.35}_{-0.15}$
1WGA J2235	0.45 ± 0.02	1.2 ± 0.2	$0.18^{+0.55}_{-0.15}$	$0.00^{+0.70}_{-0.00}$
SPT J0607	0.51 ± 0.04	1.8 ± 0.4	$0.58^{+0.35}_{-0.40}$	$0.03^{+0.38}_{-0.02}$
SPT J0313	0.46 ± 0.02	1.5 ± 0.2	$0.23^{+0.83}_{-0.20}$	$0.39^{+0.24}_{-0.30}$
SPT J2040	0.51 ± 0.03	2.0 ± 0.3	$0.28^{+1.25}_{-0.25}$	0.19 ± 0.18
SPT J0459	0.457 ± 0.018	1.8 ± 0.2	$0.67^{+0.30}_{-0.24}$	$0.21^{+0.11}_{-0.15}$



I am always amazed when I see this level of sophistication in the statistical machinery. I am equally puzzled by the lack of any analysis of systematics which potentially provide errors of comparable size.

Abundance evolution

Comparison of measurements with local sample



$$Z = Z_0 \left(\frac{1+z}{1+z_{piv}} \right)^{\gamma}$$

Consistent with no evolution of abundance

Confirmation of previous results on local systems: for Z to be so homogeneous in each clusters and for the cluster to cluster scatter to be so small, in Ghizzardi+21, we concluded that enrichment must have occured in the proto-cluster phase, this is confirmed by simulations and consistent with other observational results

Science is not wishful thinking

Flores+21 (although they do not cite us) share this conclusion, they discuss it profusely and yet...

At the same time, our results provide a first tantalizing indication (albeit at ∼68 per cent confidence) for a possible increase in the metallicity of the ICM at large radii from $\sim 0.2\,Z_\odot$ at $z \sim 2$ to $\sim 0.3\,Z_\odot$ today. This late-time enrichment, if confirmed, must occur in a way that preserves the spatial uniformity of metal abundances seen in well-studied, low-redshift clusters.

- They are aware that the statistical evidence is non-existent
- They also understand that a late enrichment would be difficult to reconcile with local measurements

and yet they speak of "tantalizing indication"

More spinning

While the tightening of the evolutionary model constraints with the addition of the data presented here is impressive,

Flores+21 claim their analysis leads to an impressive tightening of the evolutionary model, is this really the case?

- As previously stated, analysis of local samples points to enrichment in the protocluster phase
- F+21 provide the first confirmation from z=1-2 clusters of this
- Do they tighten evolutionary models? I do not see how, since the enrichment in the model is expected to occur at redshifts larger than those sampled.

Overall assesment

- Selection of sample not optimal
- Important scientific issues addressed
- Good understanding of statistical issues
- Limited understanding of systematic issues
- The result, consistent with expectations, is an important one, it stands on its own, spinning is unjustified

Overall judgement positive (particularly if you can read between the lines)