Merging Galaxy Clusters, Cluster Outskirts, and Large Scale Filaments

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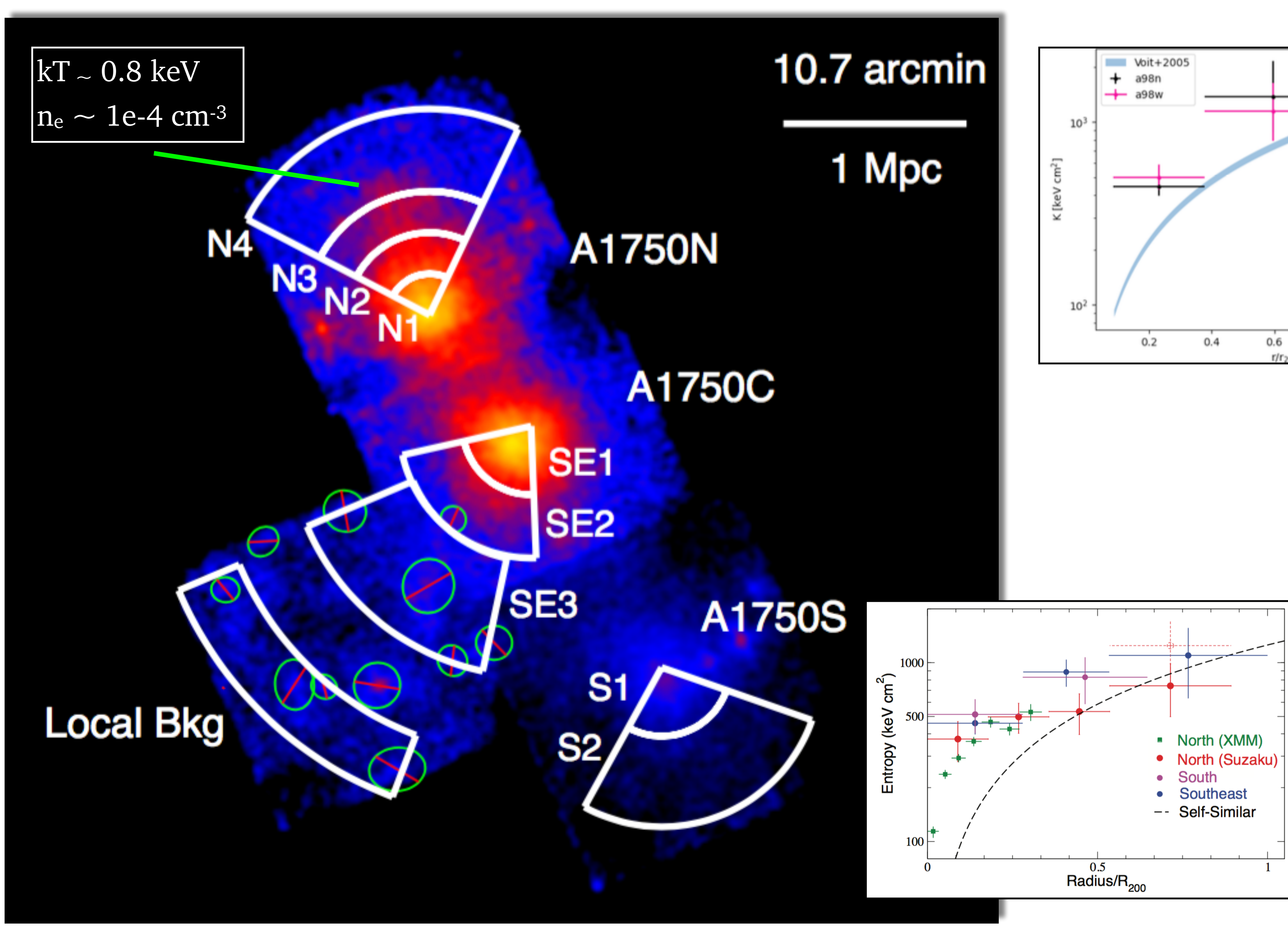
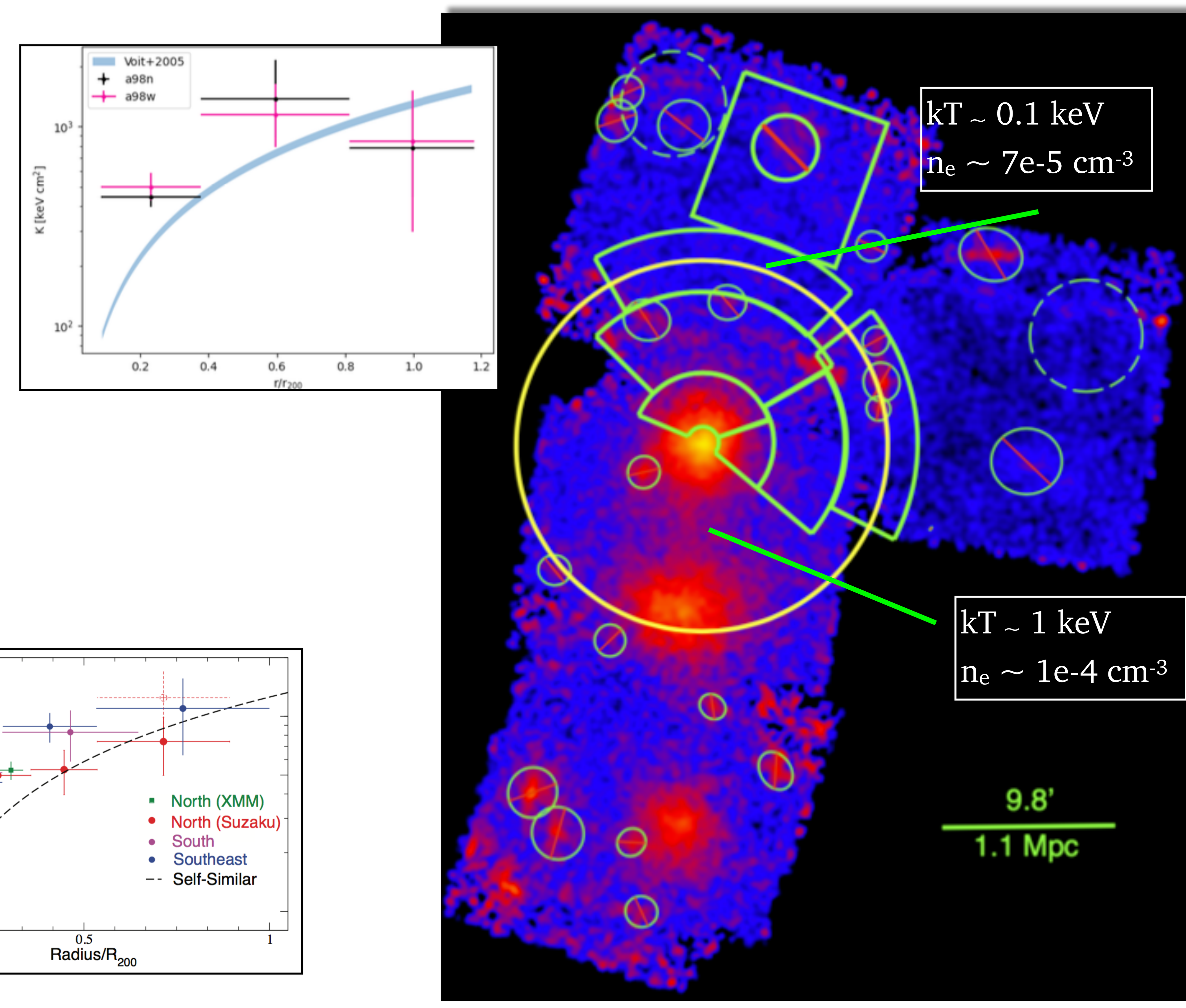
Recent X-ray observations of the outskirts of clusters, particularly with Suzaku, show that entropy profiles of the intracluster medium (ICM) generally lie below what is expected from purely gravitational structure formation near a cluster's virial radius. Possible explanations include electron/ion non-equilibrium, accretion shocks that weaken during cluster formation, and (most favored) the presence of unresolved cool gas clumps. Some of these mechanisms are expected to correlate with large scale structure (LSS), such that the entropy is lower in regions where the ICM interfaces with LSS filaments and, presumably, the warm-hot intergalactic medium (WHIM). Major, binary cluster mergers are expected to take place at the intersection of LSS filaments, with the merger axis initially oriented along a filament. Thus, X-ray observations of the virialization region of early stage major merger clusters provide an opportunity to explore the effects of LSS filaments on cluster outskirts via a direct comparison of on- and off-filament regions in the same system. We present results from deep X-ray observations of the virialization regions of a set of binary (and triple), early-stage merging clusters, including a possible detections of the dense end of the WHIM along a LSS filaments.



Suzaku image of A1750, with regions for the entropy profile extraction. Inset: entropy profile in sectors, as compared with the self-similar prediction.



Suzaku image of the three subclusters in A98, with regions for the entropy profile extraction. Inset: entropy profile in sectors, as compared with the self-similar prediction.

Abell 1750

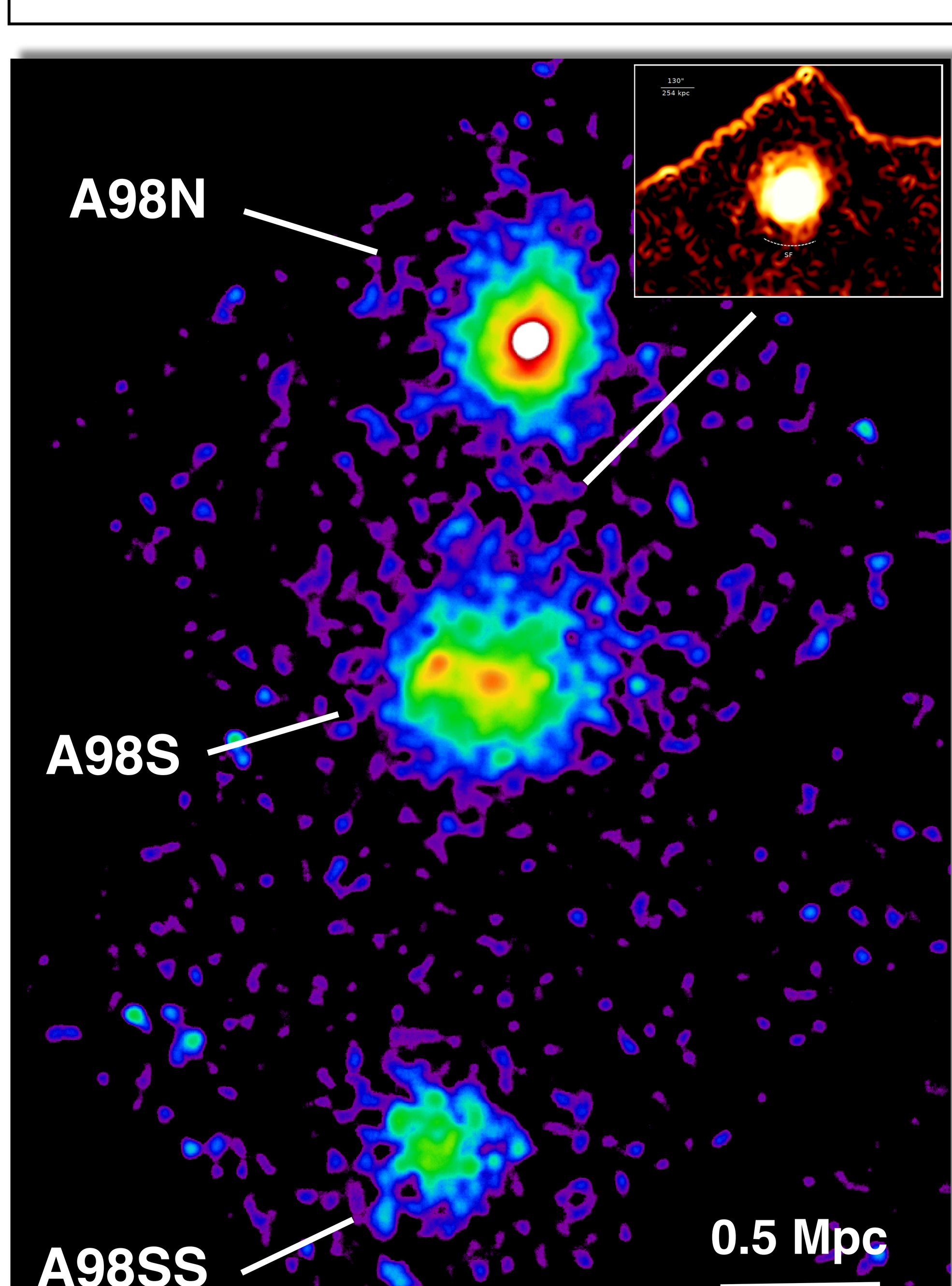
This is a 3-4 keV triple system at a redshift of z=0.085. Main findings are [2]:

- No evidence for entropy lower than the self-similar expectation, either along or perpendicular to the putative LSS filament.
- Evidence for a cool (≈ 0.8 keV) component near the viral radius along the LLS filament that is not present in the off-filament region. Its temperature and density are consistent with what is expected for the WHIM at the interface region with cluster outskirts.

Abell 98

This is a ≈ 3 keV triple system at a redshift of z=0.104. Main findings are [1,3,5]:

- No evidence for entropy lower than the self-similar expectation, either along or perpendicular to the putative LSS filament.
- Evidence for a cool (≈ 0.1 keV) component along the LLS filament that is not present in the off-filament region, both at the virial radius to the north and in the intercluster filament (with a somewhat higher density and temperature). The temperatures and densities are consistent with what is expected for the dense end of the WHIM.



Smoothed, source-cleaned, mosaic Chandra image of A98. Inset: Gaussian gradient magnitude (GGM) filtered image, which reveals a pre-merger shock front

Pre-merger shock in A98

- Deep Chandra observations [5] reveal the first ever detected pre-merger axial shock front.
- The magnitudes of the density and temperature discontinuities across the shock front (lower right) imply a Mach number of M = 2.3 ± 0.3.
- A98S is experiencing and ongoing, later stage merger.
- The temperature profile behind the shock front is more consistent with instant electron heating at the shock front, as opposed to subsequent collisional heating (lower right figure). However, the current observations cannot rule out either model. The electron heating mode in merger shocks remains an unsettled question.

Take aways

- Early-stage, binary pre-mergers should typically be aligned with a large scale structure filament. Cluster-filament connection regions are where we expect to find the greatest impact of entropy flattening in the ICM.
- We find no evidence for entropy flattening in the cluster outskirts, either along or off putative filaments, in contrast with what is generally found in massive clusters. In [2], we suggest that cluster mass may play a larger role in processes that lead to entropy flattening, since the systems we consider are all relatively low mass.
- We do find evidence for very low density, low temperature gas in filament regions that is *not* detected in off-filament regions. The properties of this emission are consistent with the dense end of the WHIM, as expected where filaments interface with clusters. Such direct detections of the WHIM are extremely rare.
- Chandra observations reveal the first ever detected axial pre-merger shock in A98. The temperature profile across the shock front is more consistent with instantaneous (versus collisional) heating of electrons in the post-shock region, although both models are allowed by the data.

[1] Alvarez et al. 2022, ApJ, 938, 51
[2] Bulbul et al. 2016, ApJ, 818, 131
[3] Paterno-Mahler et al. 2014, ApJ, 791, 104
[4] Sarkar et al. 2022, ApJL, 935, 23
[5] Sarkar et al. 2023, ApJ, 944, 132