How Were Cold Fronts Formed in Abell 496?

Raymond White (*University of Alabama*)
Renato Dupke (*University of Michigan*)
Joel Bregman (*University of Michigan*)

Abstract: Cold fronts, discontinuities in X-ray surface brightness accompanied by continuous gas pressure distributions, are often found in relaxed galaxy clusters. Explaining cold fronts as remnant cores of head-on subcluster mergers does not generally work for such clusters, which has led to competing models invoking gas sloshing. We use a deep Chandra exposure of Abell 496 to test predictions of these sloshing models by analyzing the spatial distributions of density, temperature, metal abundances and abundance ratios. We confirm that the temperature and chemical discontinuities in this cluster are not consistent with being directly identified with a core merger remnant. Nonetheless, we find that these structures could have been caused by sloshing induced by an off-center collision with a dark matter halo. We find a relatively cool "arm" of gas, with different abundance ratios than its surroundings, stretching from the central regions. The spiral shape of this arm emanating from the center is reminiscent of structures induced by off-center encounters with less massive dark matter halos, as found in recent numerical simulations of Ascasibar and Markevitch (2006).

Cold fronts are sharp X-ray surface brightness discontinuities, accompanied by jumps in gas temperature (e.g. Markevitch et al. 2000; Vikhlinin et al. 2001). Despite the temperature and density jumps, the gas pressure remains continuous across such fronts, so they are not created by shocks. They were originally interpreted as being the result of subsonic (transonic) motions of head-on merging substructures with suppressed thermal conduction (Markevitch et al. 2000, 2001; Vikhlinin et al. 2001).

However, subcluster merger models do not account for the increasing number of cold fronts (sometimes multiple cold fronts in the same cluster) found in apparently non-merging clusters such as A496 (Dupke & White 2003), A1795 (Markevitch et al. 2001), RXJ1720.1+2638 (Mazzotta et al. 2001). This suggests their are other mechanisms for generating cold fronts, such as oscillation of the cD and the low entropy gas around the bottom of the cluster potential well (Lufkin et al. 1995; Dupke & White 2003), hydrodynamic gas sloshing (Ascasibar & Markevitch 2006), or dark matter peak oscillation due to scattering of a smaller dark matter system (Tittley & Henriksen 2005).

Cold fronts are found with relatively high frequency: Chandra archival images reveal that more than 40% of observed clusters have cold front-like features. Their presence, depending on how they are generated, may have significant physical implications for the physics of their host cluster cores, such as gas heating, generation of bulk and turbulent velocities, constraining conduction, etc.

Different models for cold front formation can be discriminated through the analysis of chemical gradients across the front. If the cold front is a due to a head-on merger core remnant, we expect the front to be accompanied by a discontinuities in elemental abundances and abundance ratios (e.g. Mushotzky et al. 1996; Dupke & White 2000a,b). The expected discontinuity in this case would be symmetric with respect to the merger axis and asymmetric with respect to the perpendicular direction to the merger axis.

Abell 496 provides an excellent opportunity to test different scenarios for cold front generation given its physical and observational characteristics. It is a bright, nearby ($z \approx 0.032$), apparently relaxed cluster with a cool core. The X-ray peak coincides very well with the cD optical centroid. The gas temperature varies from 5–6 keV in the outer regions to 2–3 keV in the central arcmin (e.g. Tamura et al. 2001, Dupke & White 2003). The presence of a central abundance enhancement has been established with previous instruments including Ginga and Einstein (White et al. 1994), ASCA (e.g. Dupke & White 2000a), BeppoSAX (Irwin & Bregman 2001) and XMM (Tamura et al 2001), showing an overall radial enhancement from ~0.2-0.25 solar in the outer regions to ~ 0.4-0.7 solar in the central arcminute.
At the distance of Abell 496, 1" ≈ 0.66 kpc & 1' = 40 kpc.

Here we report the results of a deep (76 ksec) observation of Abell 496 (**Fig.1**) that allowed us to produce high quality maps of the gas parameters and to compare closely the observations with the predictions given by different models for cold front formation.

We investigate radial distributions & 2D maps of temperature & abundances to see if there are discontinuities in abundances &/or abundance ratios at cold front interfaces. We find that cold fronts (**Fig.1**) are generally NOT associated with abundance discontinuities (**Figs. 3-6**), therefore are likely not due to the merger of a gas-rich subcluster. This confirms the previous analysis of a shallow Chandra observation by Dupke & White (2003).

However, a 2D temperature map (**Fig. 5**) reveals a cool spiral "arm" emanating from the central region. The shape and extent of this cool arm is similar to those generated in Nbody-SPH simulations (see **Fig. 8**) of off-center encounters of pure dark matter halos with cluster cores (Ascasibar & Markevitch 2006). Such pure dark matter subclusters may represent subclumps which were stripped of their gas when they were further out in the cluster.

References

Ascasibar & Markevitch 2006 ApJ 650 102
Dupke & White 2000a ApJ 537 123
Dupke & White 200b ApJ 528 139
Dupke & White 2003 ApJ 583 L13
Irwin & Bregman 2001 ApJ 546 150
Lufkin, Balbus & Hawley 1995 ApJ 446 529
Markevitch et al 2000 ApJ 541 542
Markevitch, Vikhlinin & Mazzotta 2001 ApJ 562 L153
Mazzotta et al 2001 ApJ 555 205
Mushotzky et al 1996 ApJ 466 686
Tamura et al 2001 A&A 379 107
Tittley & Henriksen 2005 ApJ 563 673
Vikhlinin, Markevitch & Murray 2001 ApJ 563 673

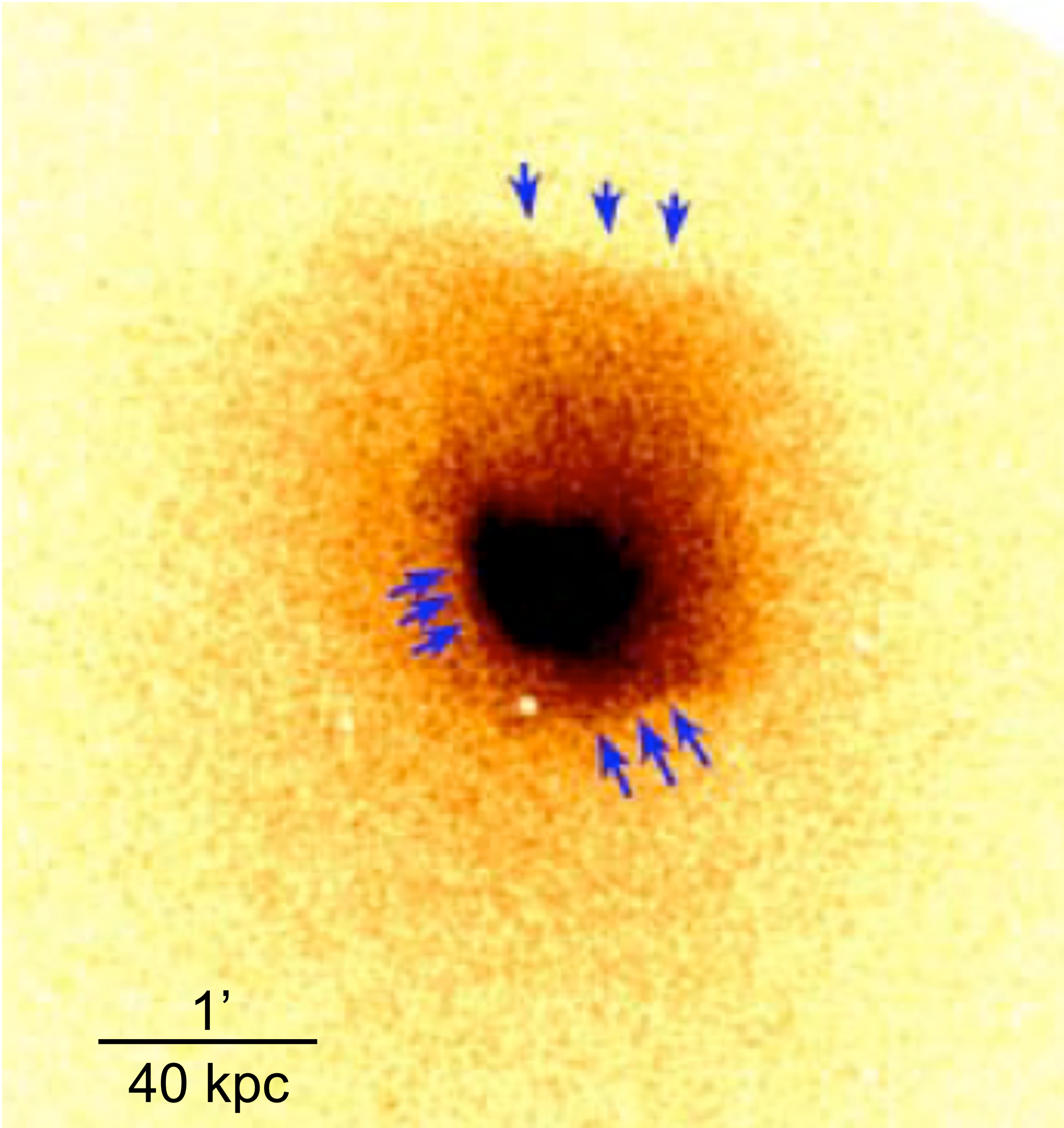

Figure 1

Surface brightness edges
In Abell 496

Surface brightness
drops by 30-50%
In several directions

76 ksec exposure
ACIS S3 shown

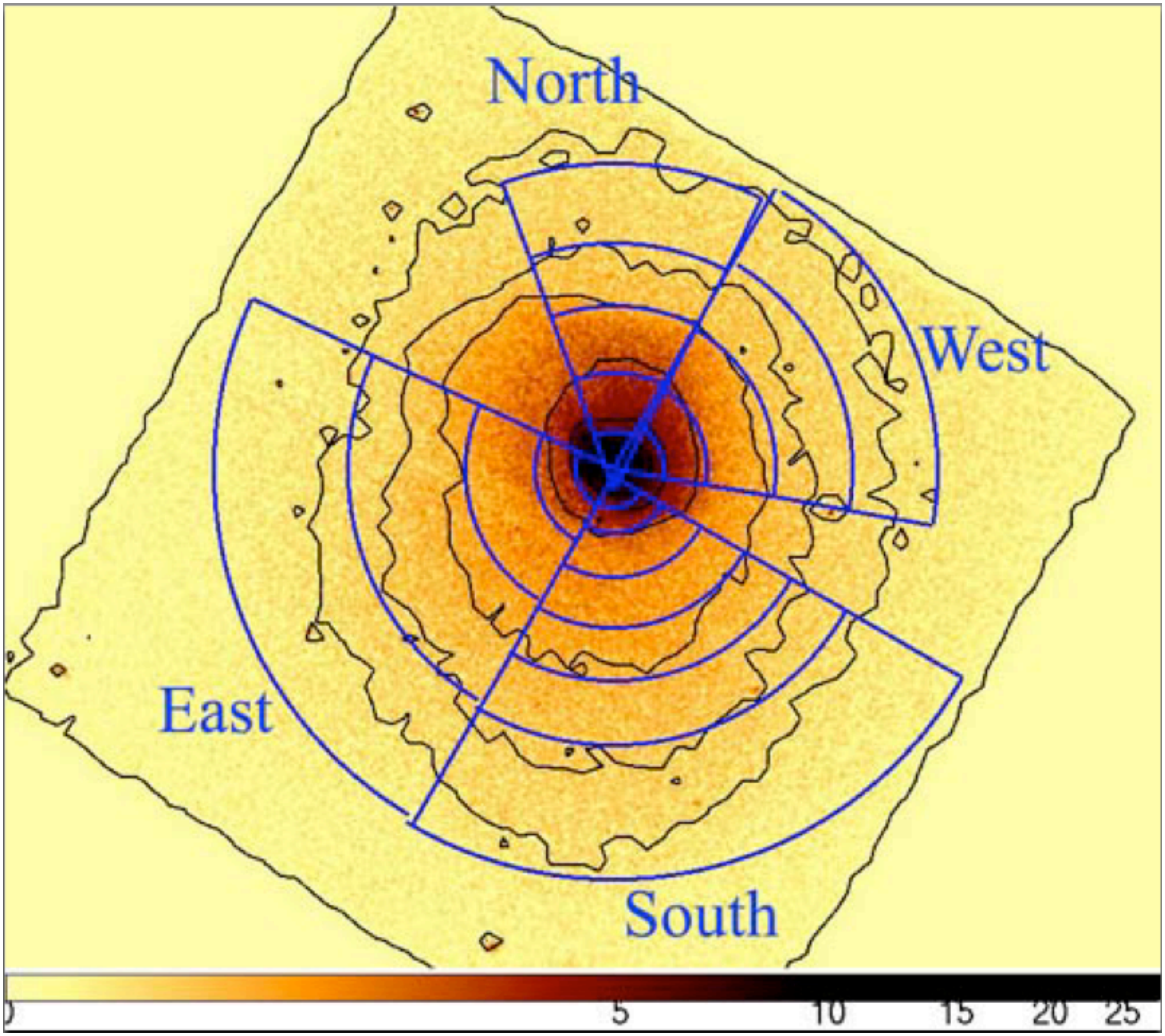

Figure 2

Pie **regions** used for radial temperature & abundance plots

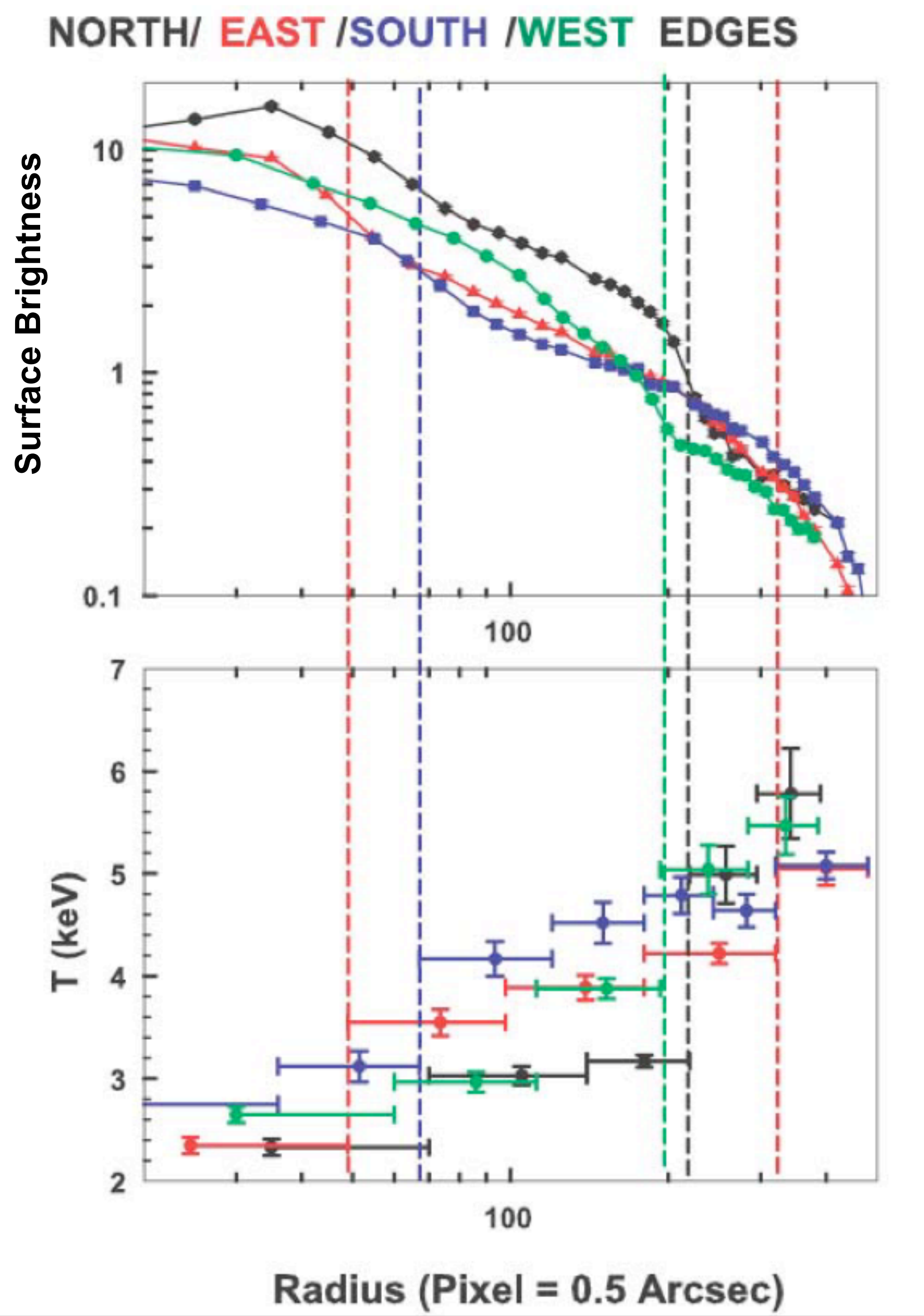

Figure 3

Radial distributions of
surface brightness (top) &
gas temperature (bottom)
in wedges indicated In Fig. 2

Wedge data (see Fig. 2) are color coded

Vertical dashed lines connect surface brightness jumps to temperature jumps

Strongest surf br & temperature jumps are in **North** (**black**) and **West** (**green**) wedges

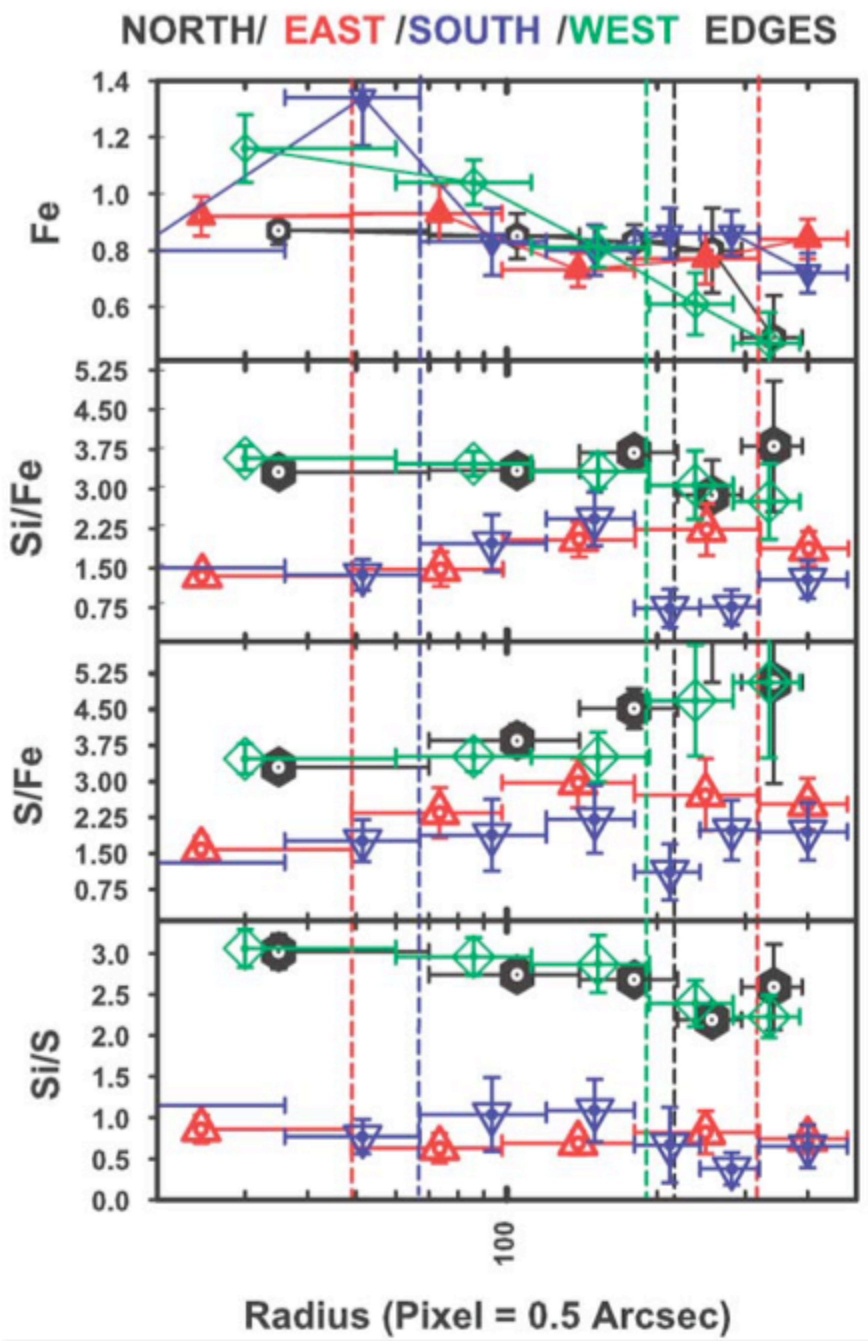

Figure 4

Radial distributions of **abundance** (Fe) (top) & **abundance ratios** (Si/Fe, S/Fe, Si/S) in spatial wedges indicated In Fig. 2

Note general lack of discontinuities in abundance & abundance ratios at vertical lines, which mark where surface brightness & temperature jumps occur.

The lack of discontinuities in abundance & abundance ratios suggests that the cold fronts are NOT due to a gas-rich subcluster merger, which would likely have different chemistry to go along with its different temperature structure.

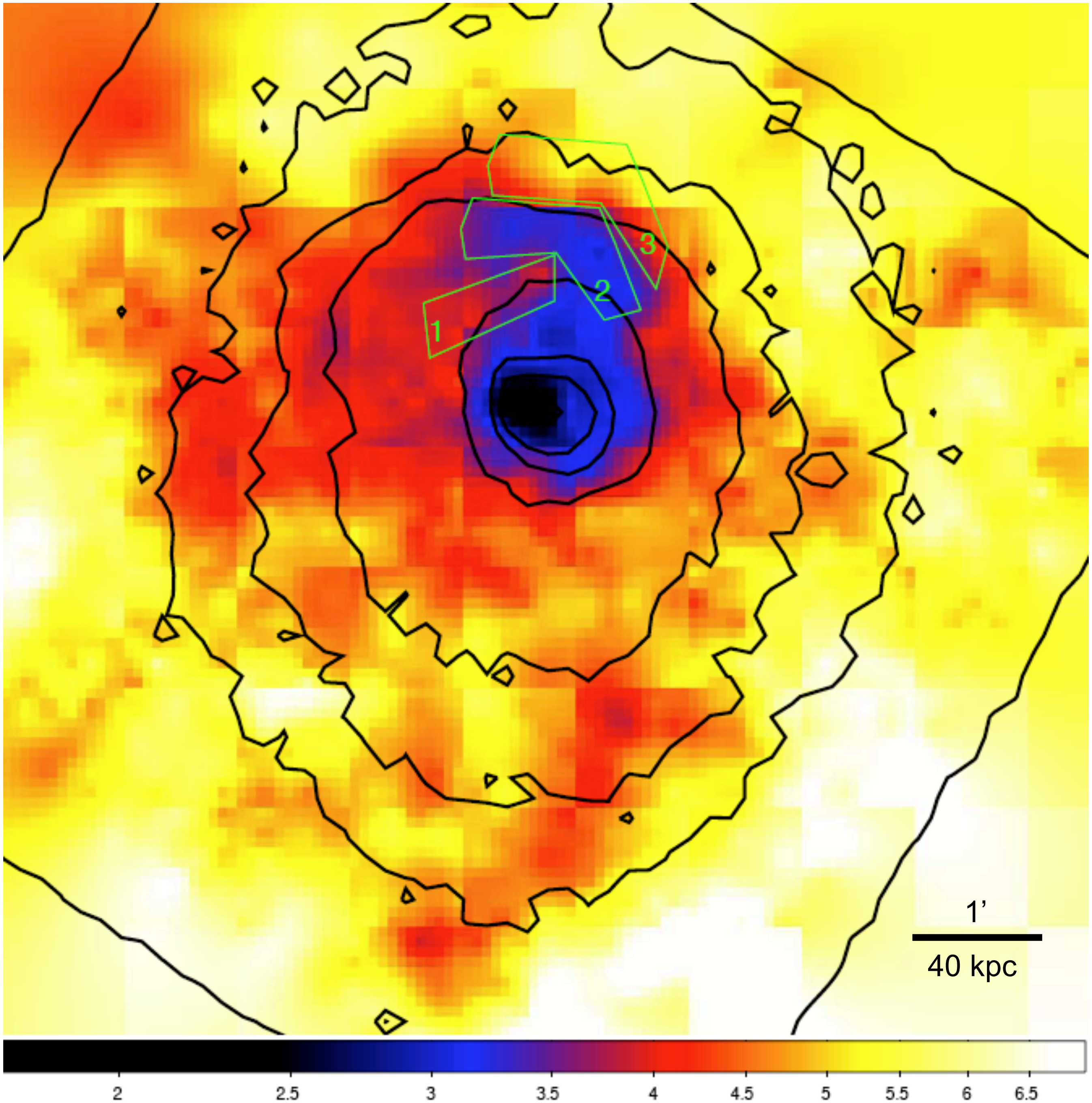

Figure 5

Temperature map

3000 cnt minimum per cell

Note cool “arm” extending to N, then NE

cool arm = 3 keV
adjacent gas = 4-5 keV

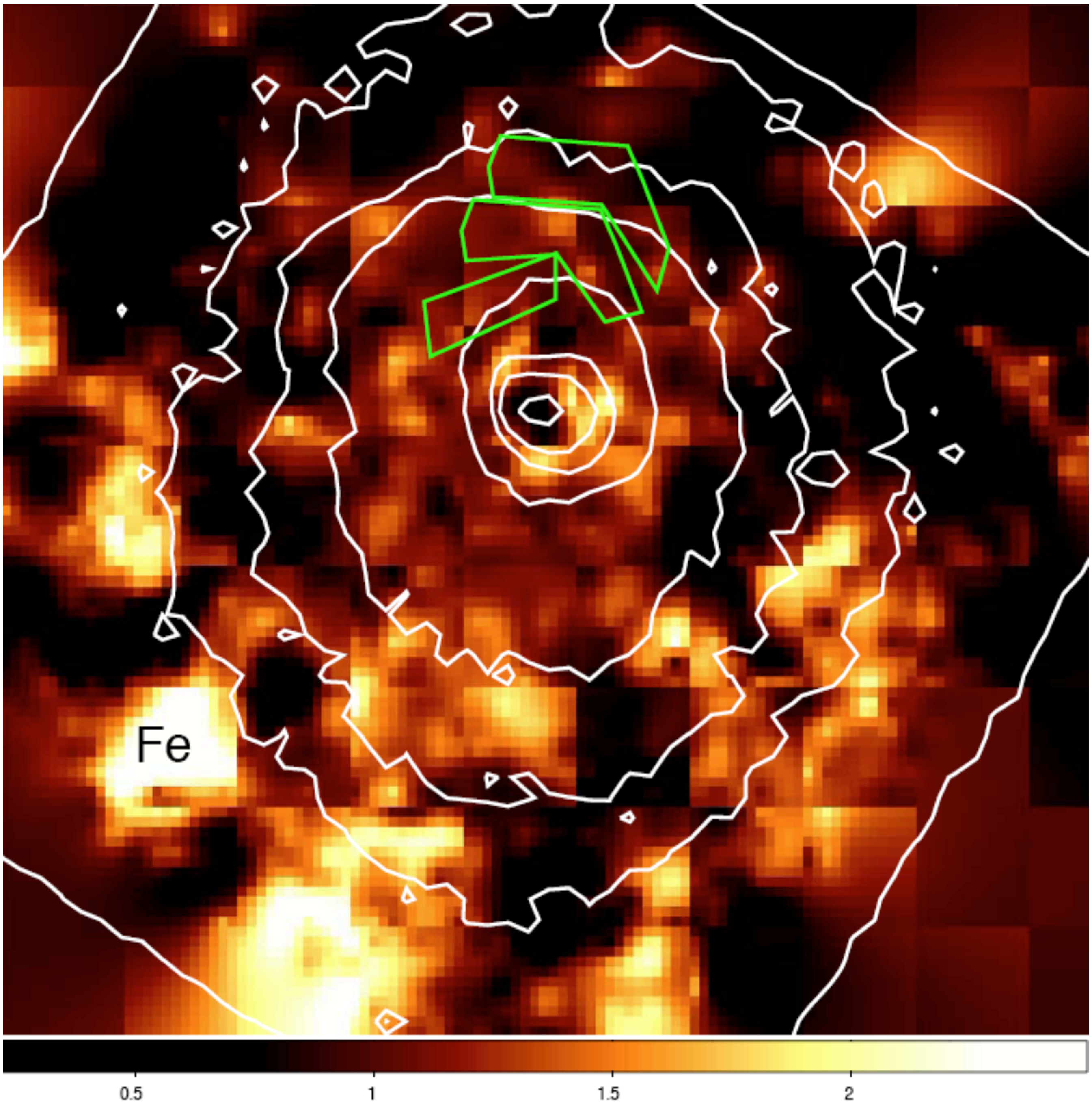

Figure 6

Abundance (~Fe) map

3000 cnt minimum per cell

Note lack of abundance features in vicinity of cool arm & other cold fronts

This suggests that the cold fronts are NOT due to a gas-rich subcluster merger

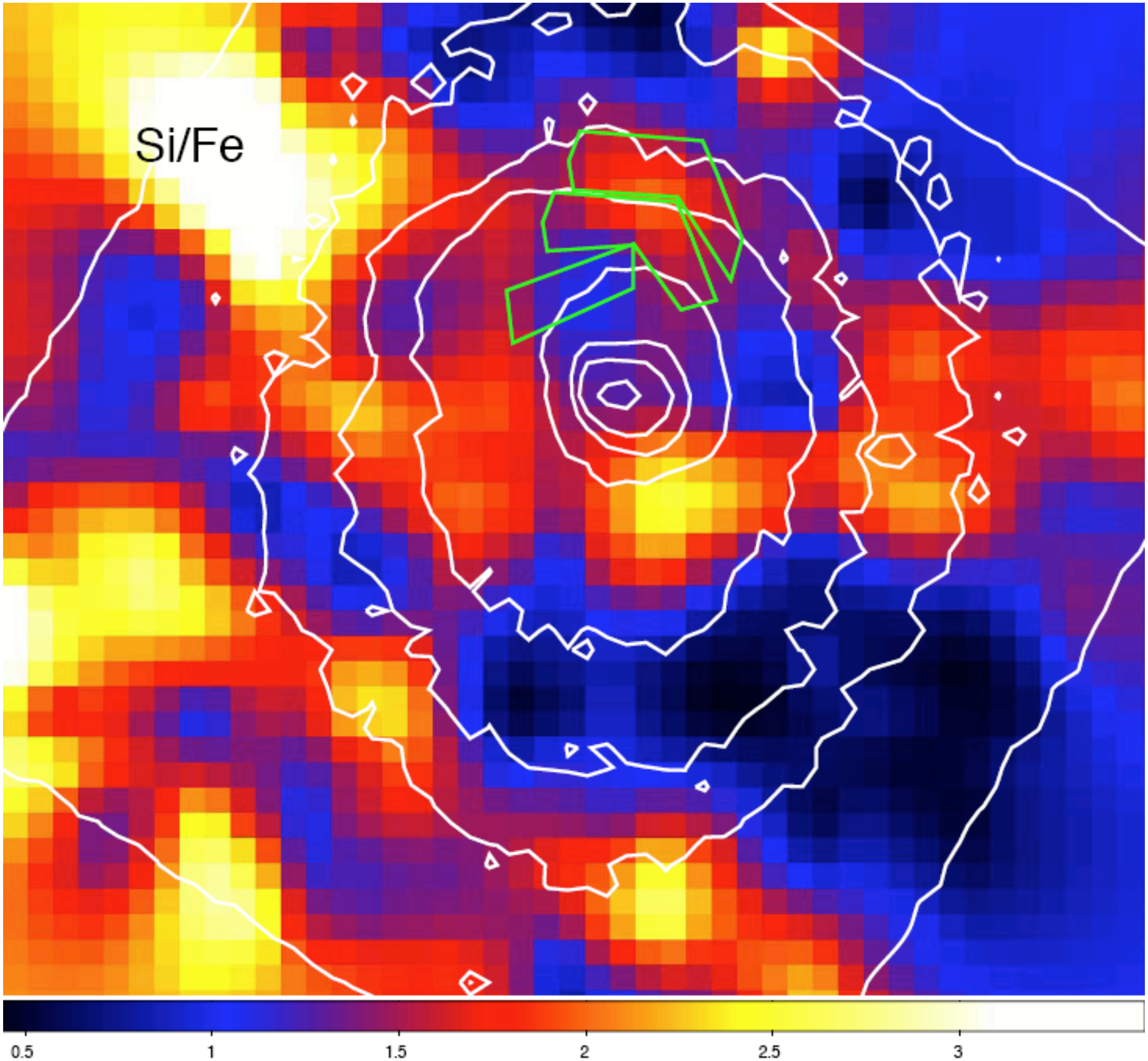

Figure 7

Map of Si/Fe abundance ratio

7000 cnt min/cell

Cold arm (middle green outline) may be associated with clump of high Si/Fe material.

Other cold fronts (use contours) NOT obviously associated with Si/Fe structure.

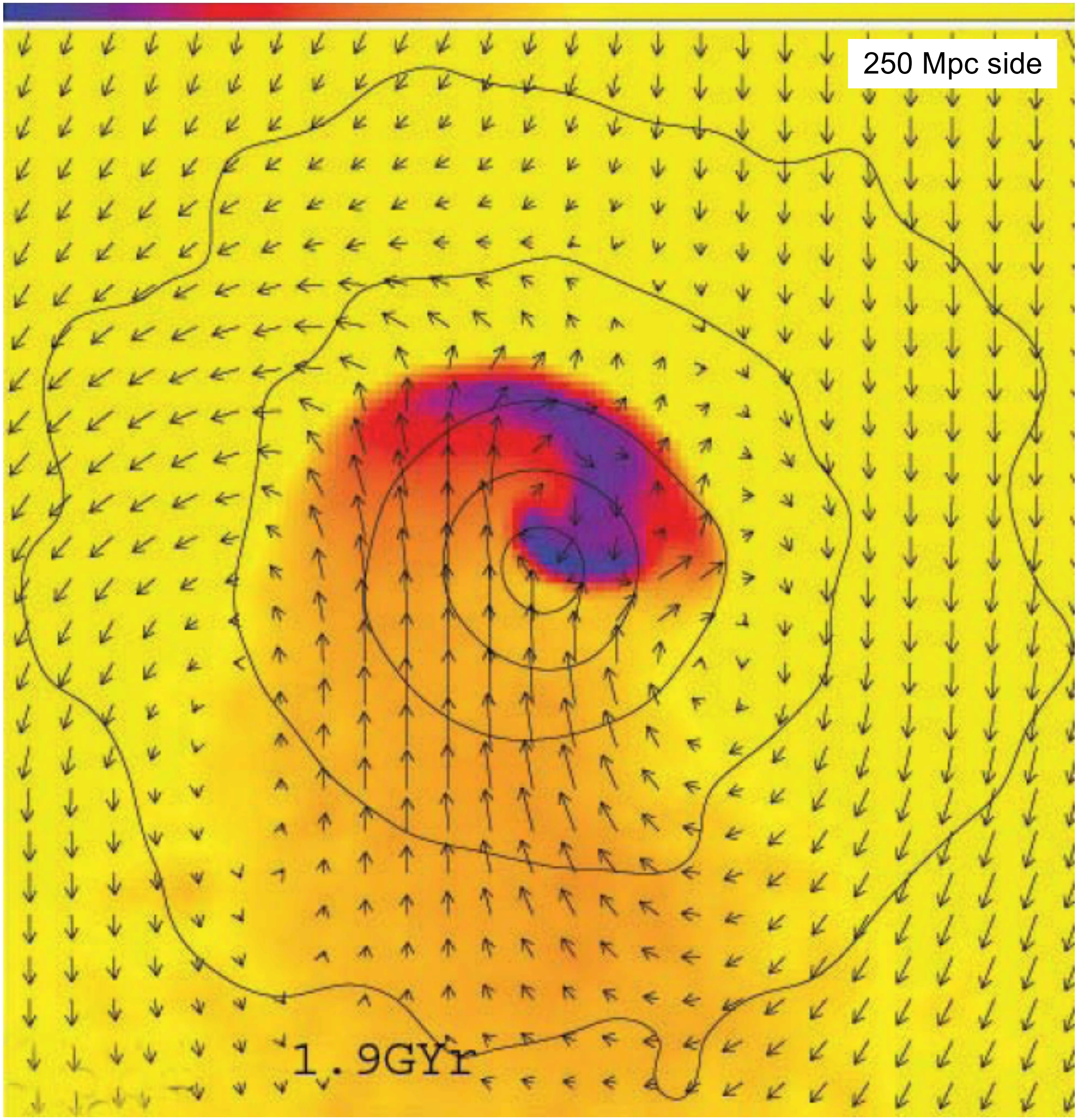

Figure 8

Temperature map from simulated pure DM halo offcenter encounter by Ascasibar & Markevitch 2006

Nbody (Tree particle-mesh) + SPH simulation using GADGET2 (Springel 2005)

pure DM halo encounter
⇒pre-stripped subcluster

Mdm = Mcluster / 5
Mtot = 1.7e15 Msun

500 kpc impact parameter
Closest approach = 1.37 Gyr

Cool arm = blue region = cool gas pulled from central regions in spiral following DM halo trajectory.

blue = 2 keV
yellow = 7-9 keV

This cool arm is similar to temperature structure seen in A496, on similar spatial scale