HUNTING FOR COLD FRONTS IN GALAXY CLUSTERS

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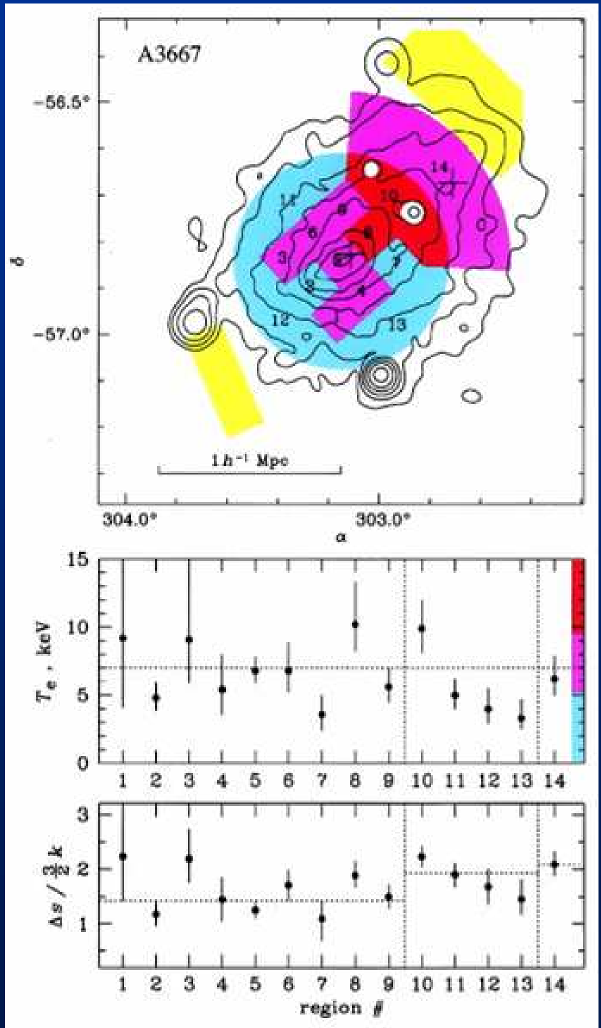
Outline

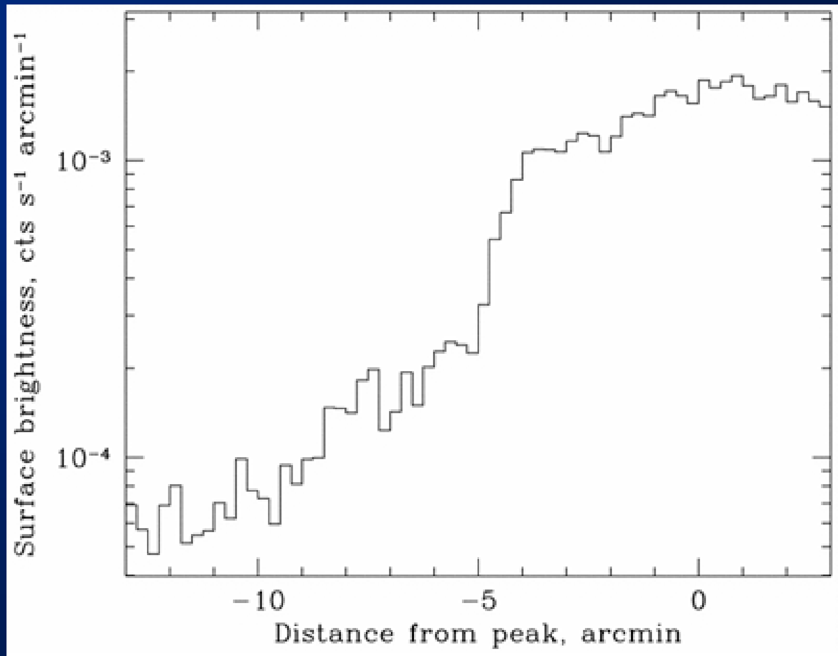
- The discovery of cold fronts
- Description of the origin and the evolution of cold fronts through simulations and models
- Hunting for cold fronts in a sample of galaxy clusters.

A candidate shock in A3667

The history of cold fronts: once upon a time there was a (candidate) shock..



Measurements with ASCA and ROSAT of A3667 seem to detect a shock in the SE region.

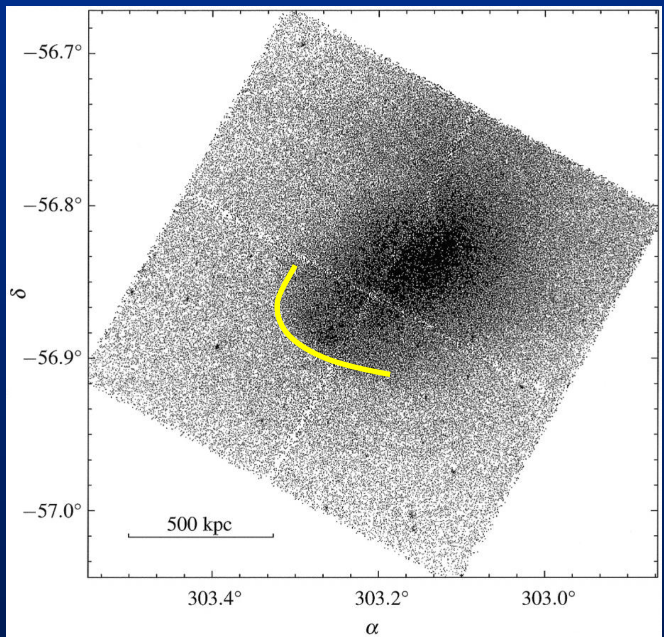


The surface brightness shows a sharp decrease. The temperature jump is uncertain.

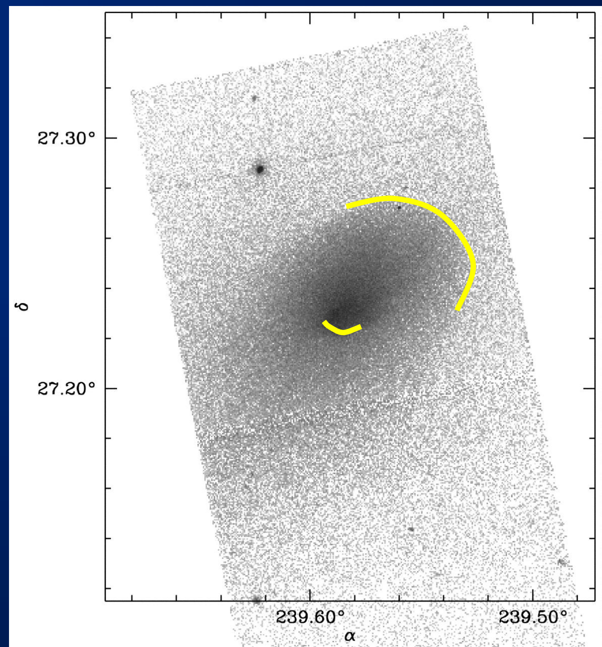
Markevitch et al 1999

Chandra observations of shocks ?

First observations of some merging galaxy clusters with Chandra confirm surface brightness edges.



A3667

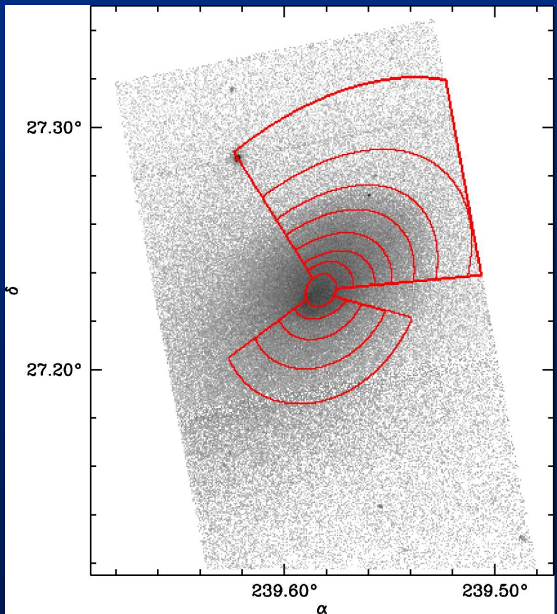


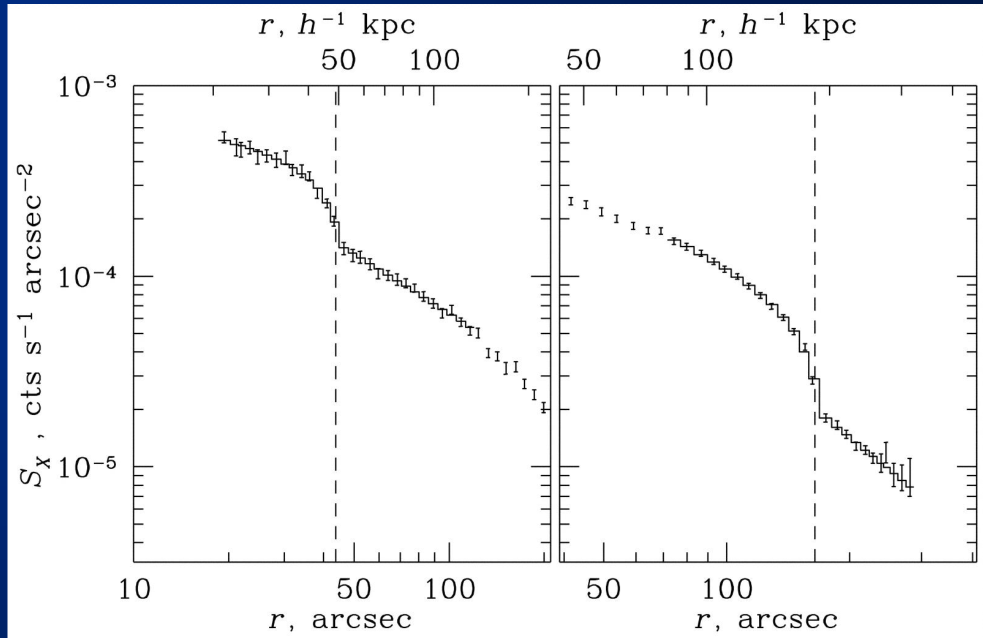
A2142

Are these the first Chandra observations of shocks??

Chandra observation of A2142

- Chandra observation of A2142 (Markevitch et al. 2000)
- SB profiles in two opposite regions of the cluster





south **north-west**

- Clear detection of surface brightness discontinuities

- Density jumps are given by factors

  1.85 +/- 0.10 (S edge) and

  2.0 +/-0.1 (NW edge)

Chandra observation of A2142

- Chandra observation of A2142 (Markevitch et al 2000)
- What can we expect if this is a shock?
  - SB (and density) jump: ✓
  - Temperature jump

    - What do we expect for the outer temperature from the Rankine-Hugoniot jump conditions if this is a shock???

- For the NW edge the inner temperature is $T_1 \sim 7.5$ keV :

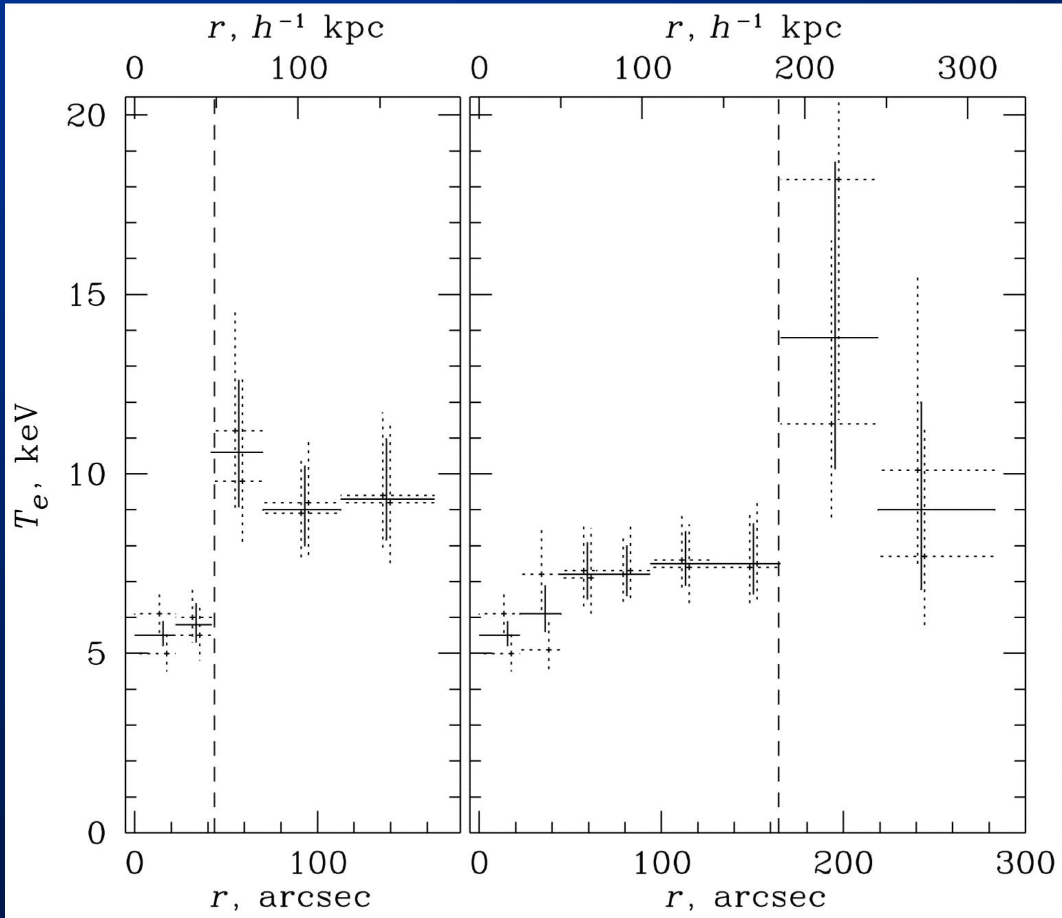
- $\rho_0/\rho_1=[\frac{1}{4}\,\zeta^2(T_1/T_0-1)^2 - T_1/T_0]^{1/2} - \frac{1}{2}\,\zeta(T_1/T_0-1)$

with $\zeta = (\gamma+1)/(\gamma-1)$ ⟶

- We expect an external temperature of $T_0 \sim 4$ keV

$\gamma=5/3$ adiabatic index of monoatomic gas

Chandra observation of A2142



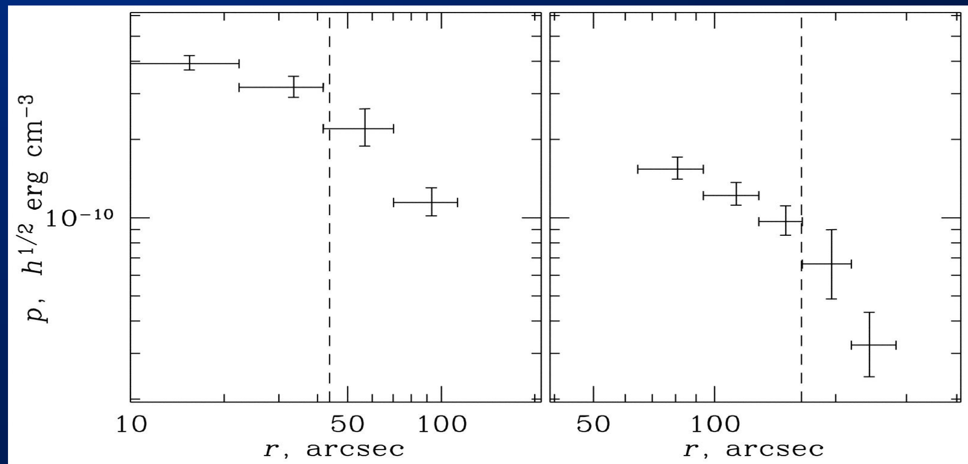
south

north-west

A temperature jump is detected, but the temperature increases across the front.

Chandra observations of shocks

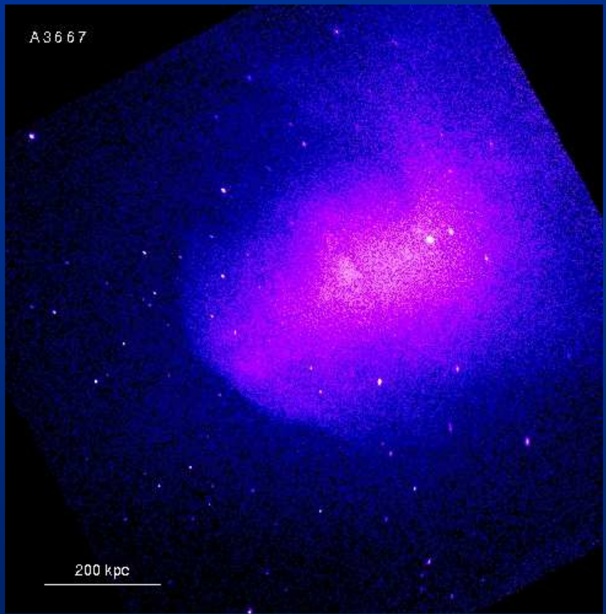
- Chandra observation of A2142 (Markevitch et al 2000)
- What can we expect if this is a shock?
  - SB (and density) jump: ✓
  - Temperature jump: ✗
  - Pressure jump: ✗



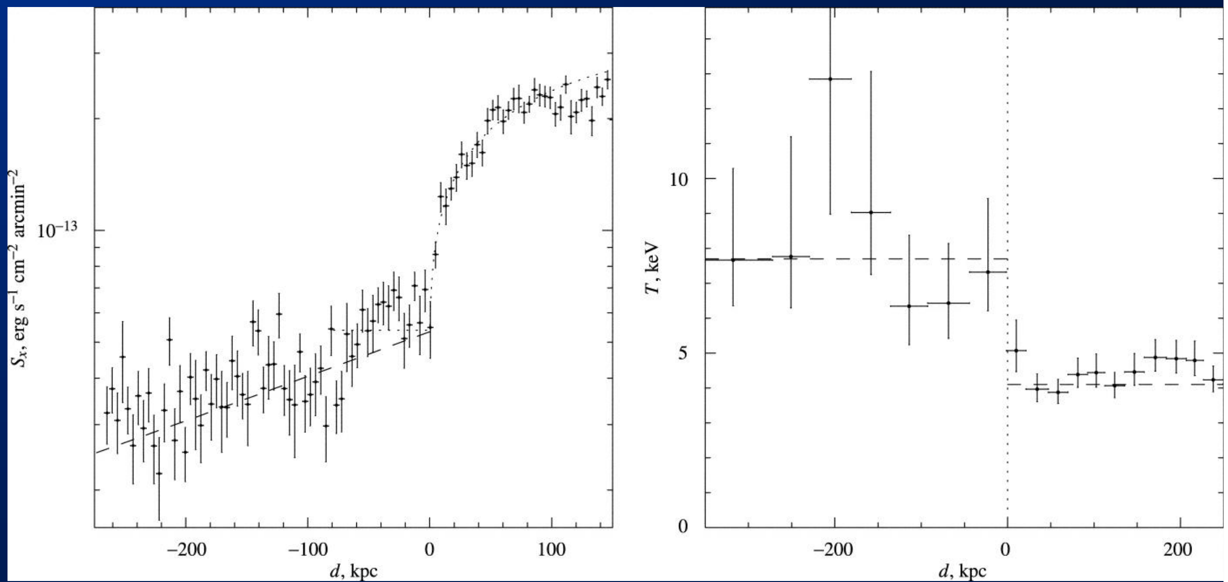
south north-west

- This definitively rules out the shock interpretation.

Chandra observation of A3667



- Chandra observes A3667 (Vikhlinin, Markevitch and Murray 2001)



- Also the hypothetical shock in A3667 is definitively not a shock.

Chandra discovers cold fronts

What are these sharp edges then??

The approximate pressure equilibrium across the density jump suggests (Markevitch et al. 2000) that these features are contact discontinuities at the boundaries of a cool and dense gas cloud moving sub- or transonically through a hotter and less dense surrounding gas

This feature has been called COLD FRONT

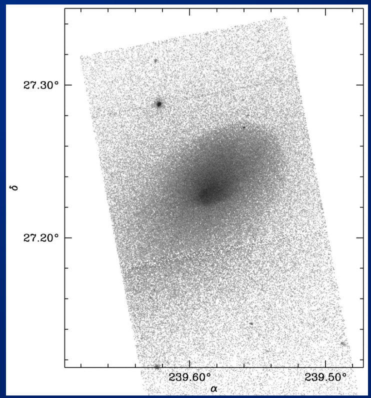
(Vikhlinin, Markevitch and Murray, 2001)

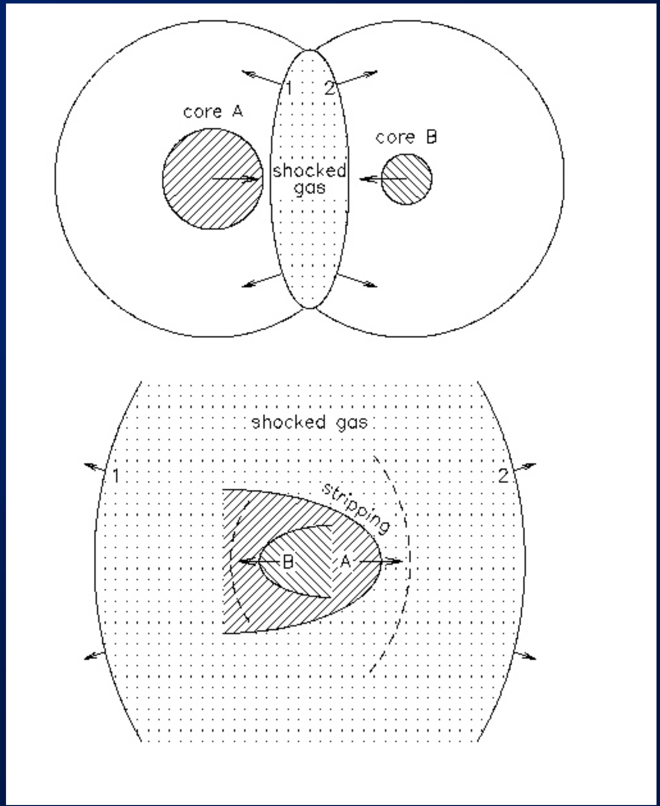
A possible scenario:

survival of subcluster core after the shock of a merger.

These dense gas clouds are remnants of the cool cores of the two merging subclusters

The dense core we observe has been stripped of the outermost gas by the less dense surrounding gas.





The observed edge should be the surface where the pressure in the dense core gas is in balance with the thermal plus ram pressure of the surrounding gas:

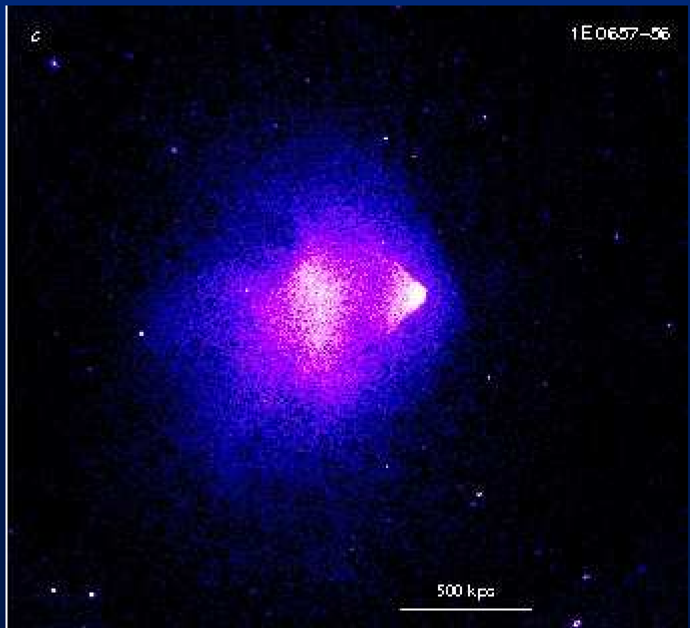
$$p_1 = p_2 + \rho_2 v^2$$

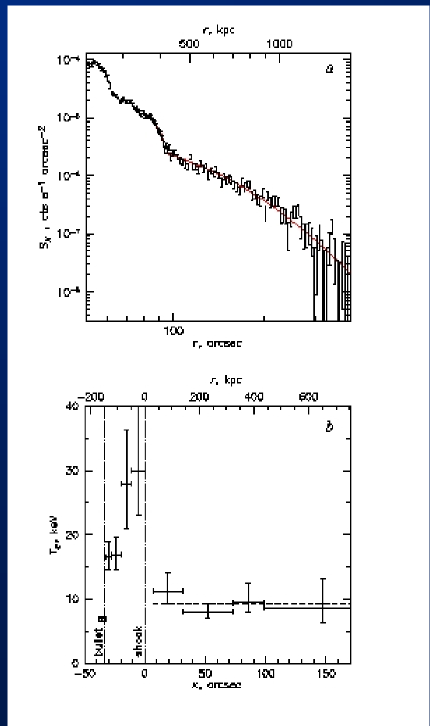
Ram pressure

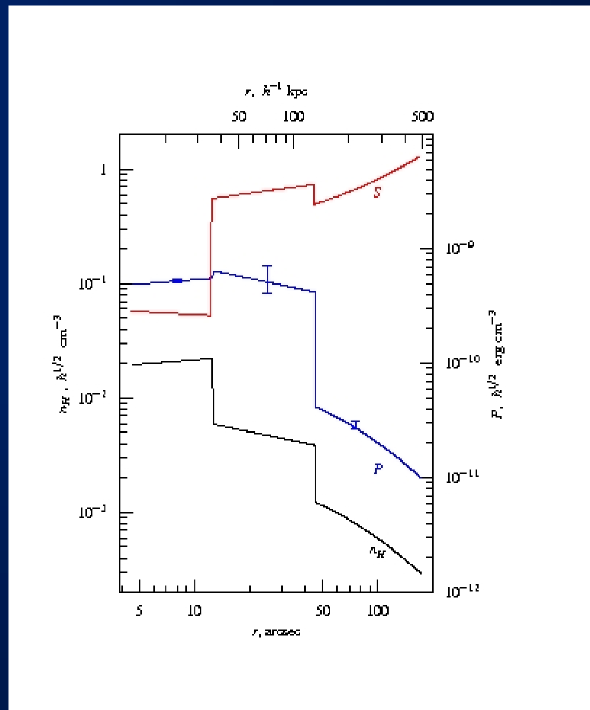
Cold front and bow shock

In front of the cold front the moving gas can generate a bow shock: the gas bullet in 1E0657-56 has developed the sharp edge at the west side (which is the cold front).

Ahead of it a genuine bow shock is observed





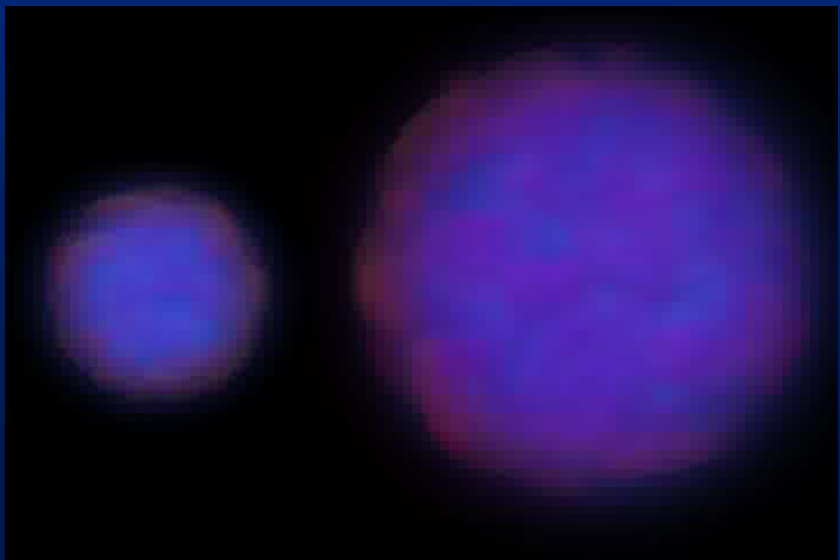


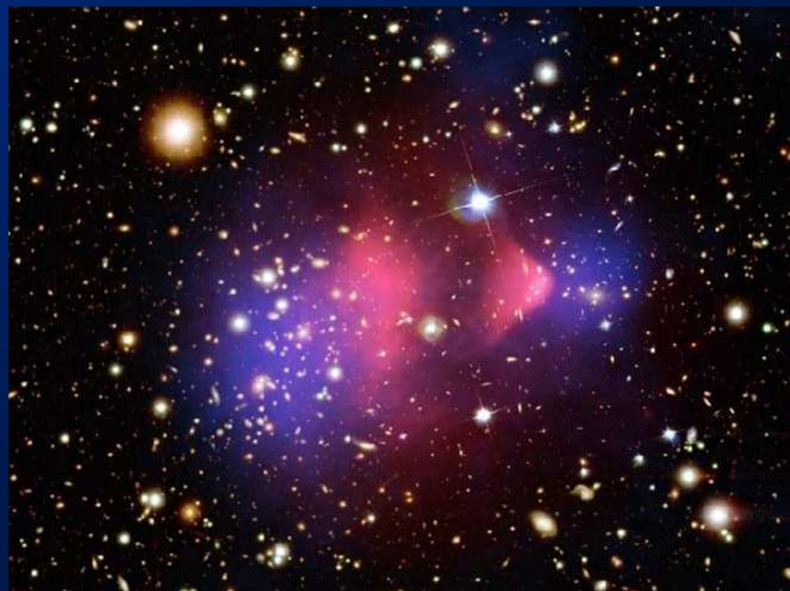
Markevitch et al 2002; Markevitch 2006

Ram pressure stripping: the bullet cluster

If the gas of the subcluster is not completely stripped by the ram pressure, the cool dense core is dragged along by the gravity of the subcluster, initially slightly lagging behind its dark matter peak. The ambient shocked gas flows around it, separated by a sharp contact discontinuity (the cold front). This is the stage at which we observe the bullet cluster

Clowe et al 2006





http://chandra.harvard.edu/photo/2006/1e0657/animations.html#1e0657_bullet_anim

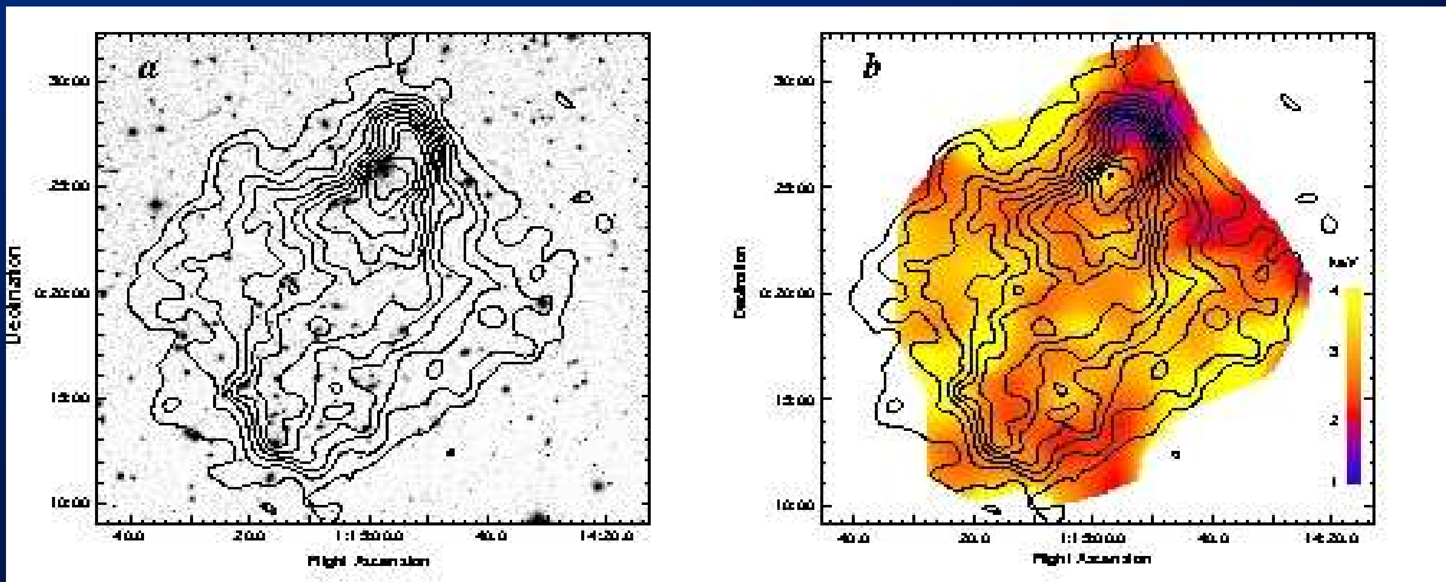
Ram pressure slingshot: A168

As the subcluster moves away from the core and slows down, it enters in regions where the gas density and the ram pressure ($p_{ram} = \rho\, v^2$) drop rapidly. The cool gas rebounds under the effect of gravity and overtakes the DM. It is kept at high pressure, expands adiabatically and cools, further enhancing the temperature contrast at the front. The merging cluster A168 is observed at this stage.

Hallman and Markevitch 2004

contours= X-ray

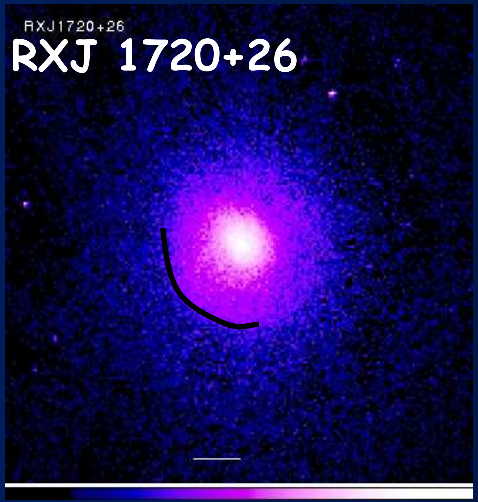
Optical

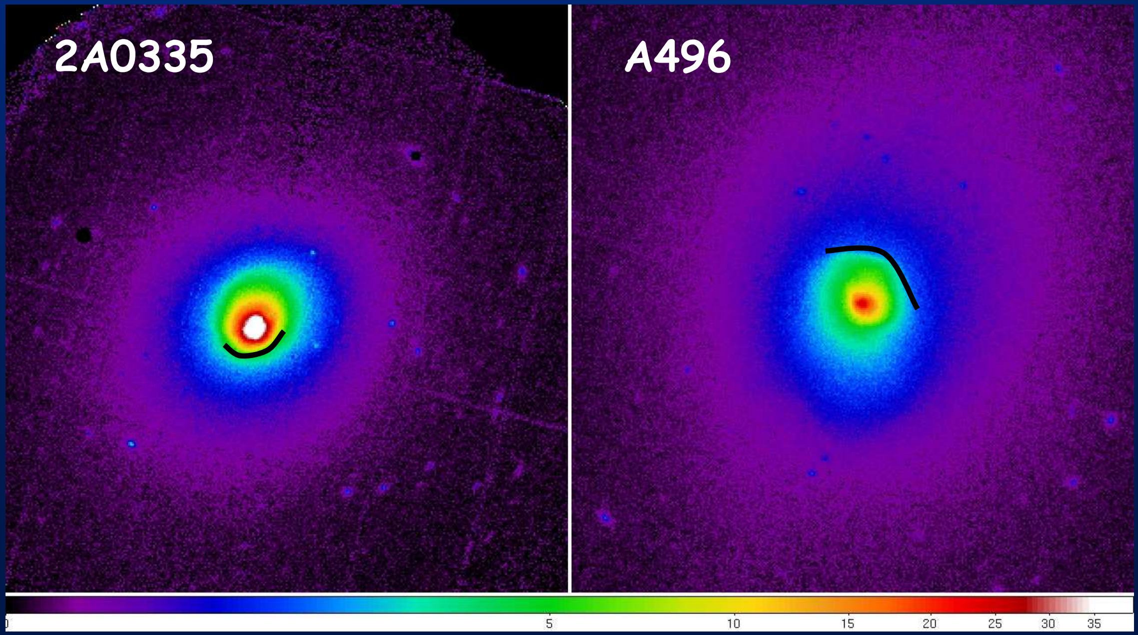


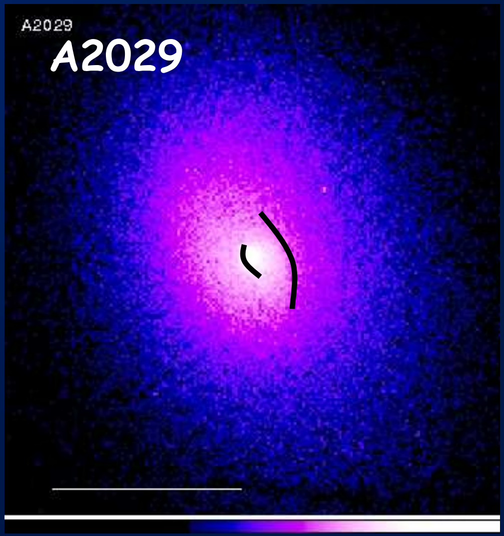
Colors=T

COLD FRONTS IN COOL CORES

In a merging event, the gas flow and the corresponding moving remnants which give rise to cold fronts are expected. Surprisingly cold fronts have been observed also in several relaxed clusters which show no or little sign of recent merging.







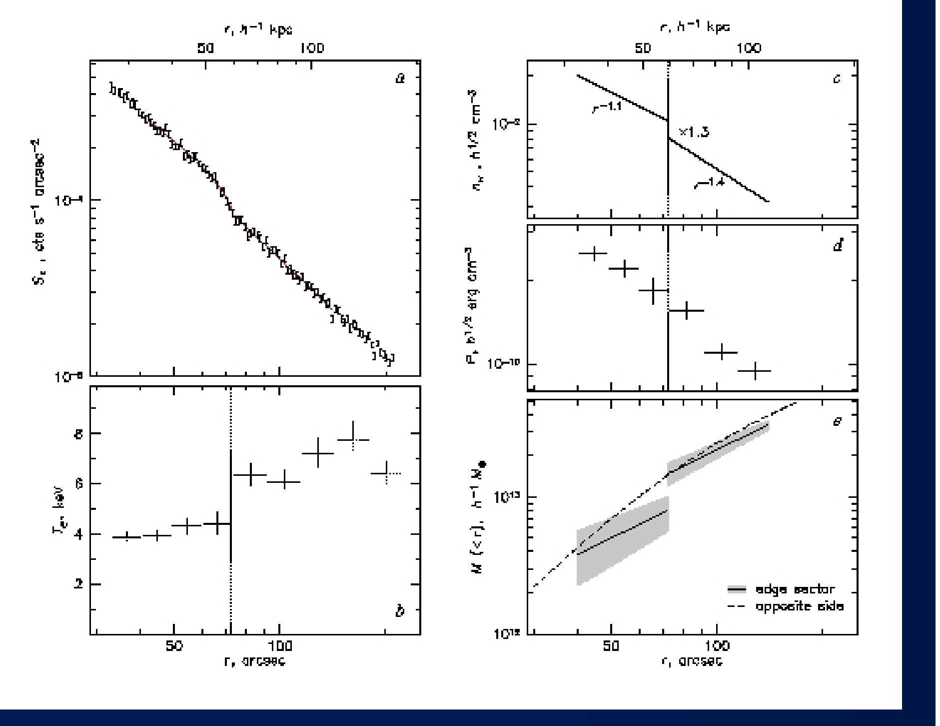
A1795 and sloshing

A1795 hosts a CF at 70 kpc in the south sector. The surface brightness jump is moderate and it corresponds to a density jump of a factor 1.3

The pressure is almost continue.

The total mass profile presents an unphysical discontinuity of a factor of 2.

The gas is not in hydrostatic equilibrium!!



Markevitch Vikhlinin Mazzotta 2001

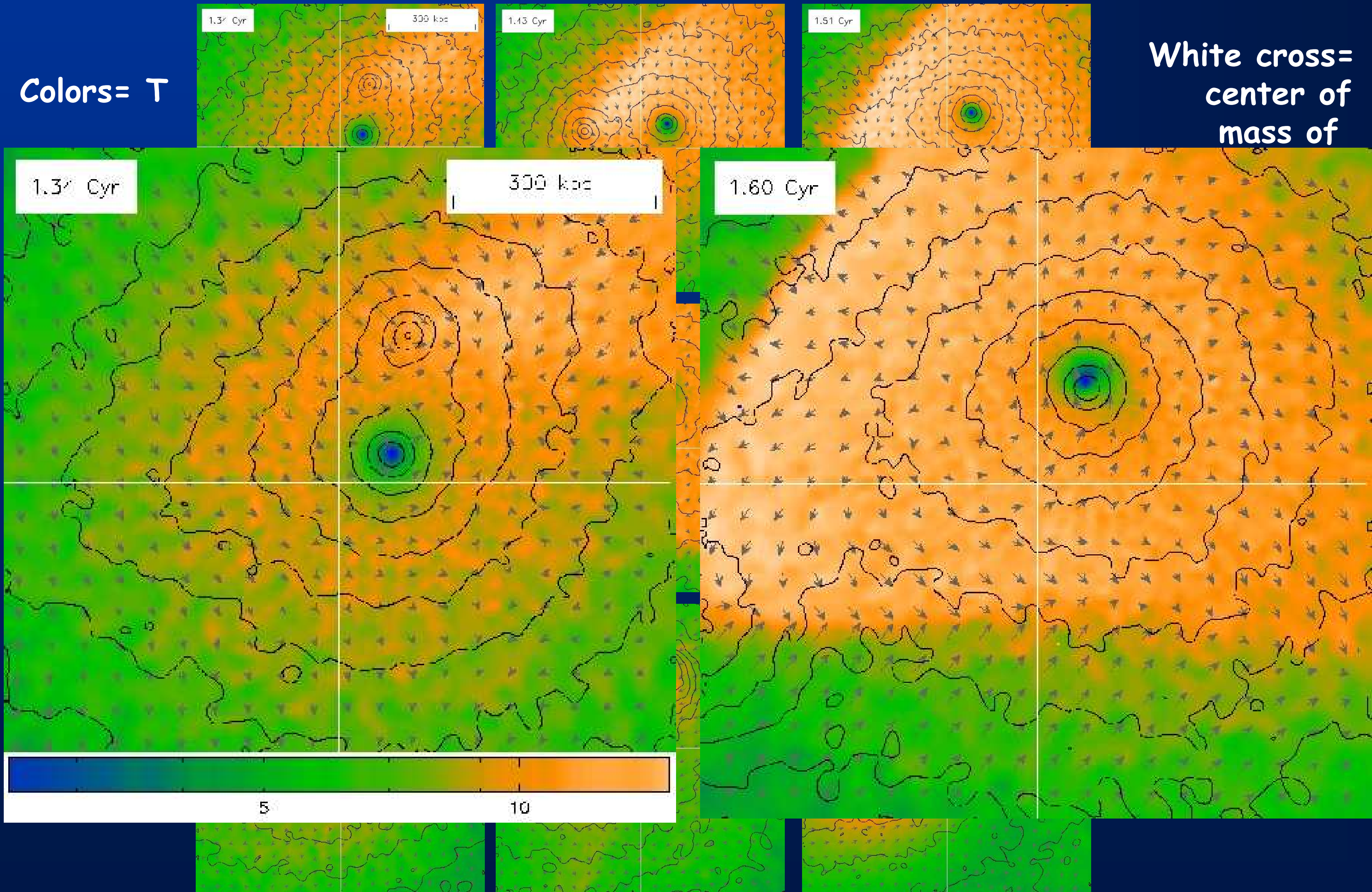
The low entropy central gas is sloshing in the central potential well. The gas is near the maximum displacement with zero velocity but nonzero acceleration.

Simulations of gas sloshing

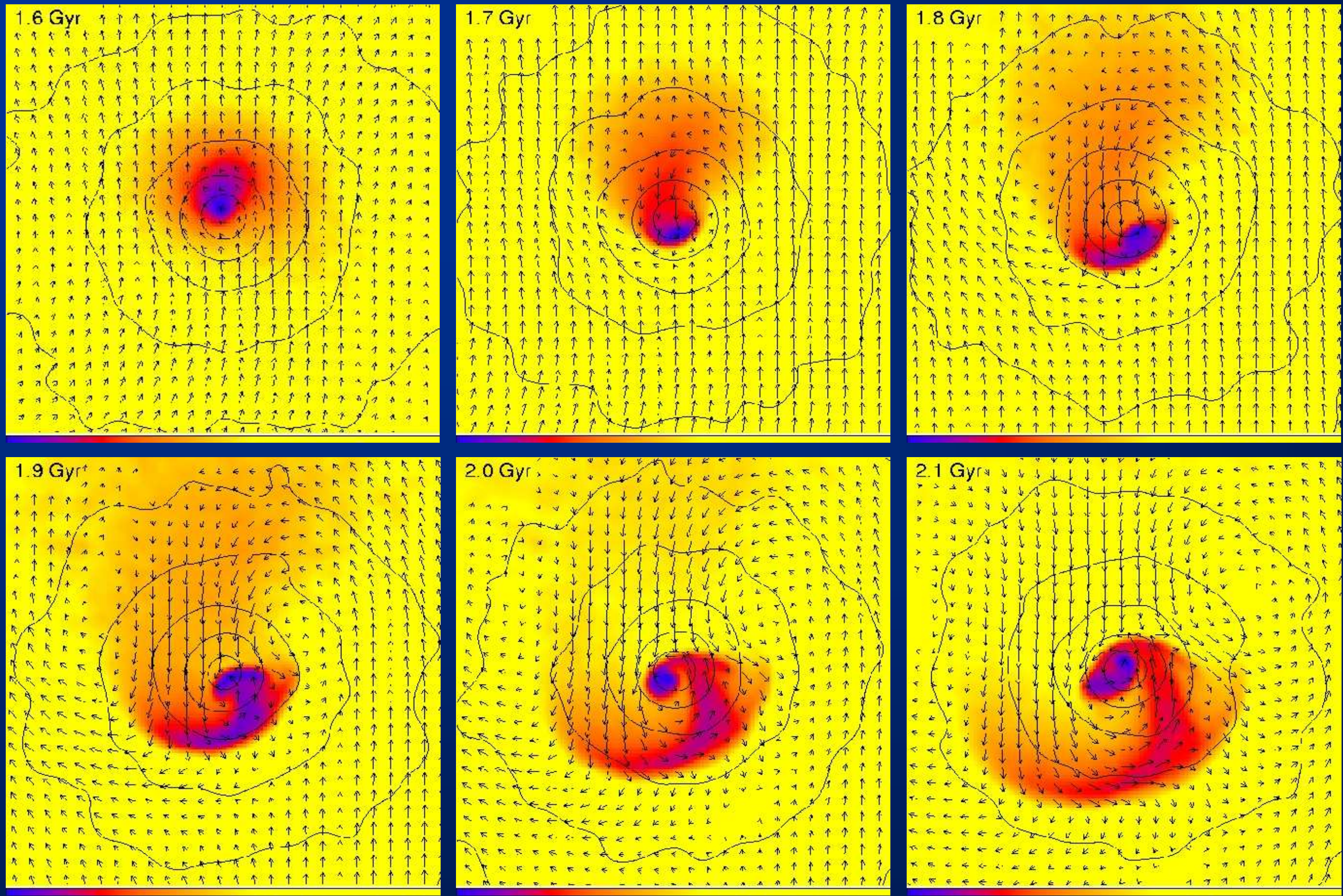
(Ascasibar and Markevitch 2006)

Colors= T

White cross= center of mass of



The gas temperature during the sloshing



Color=T

Arrows= gas velocity field

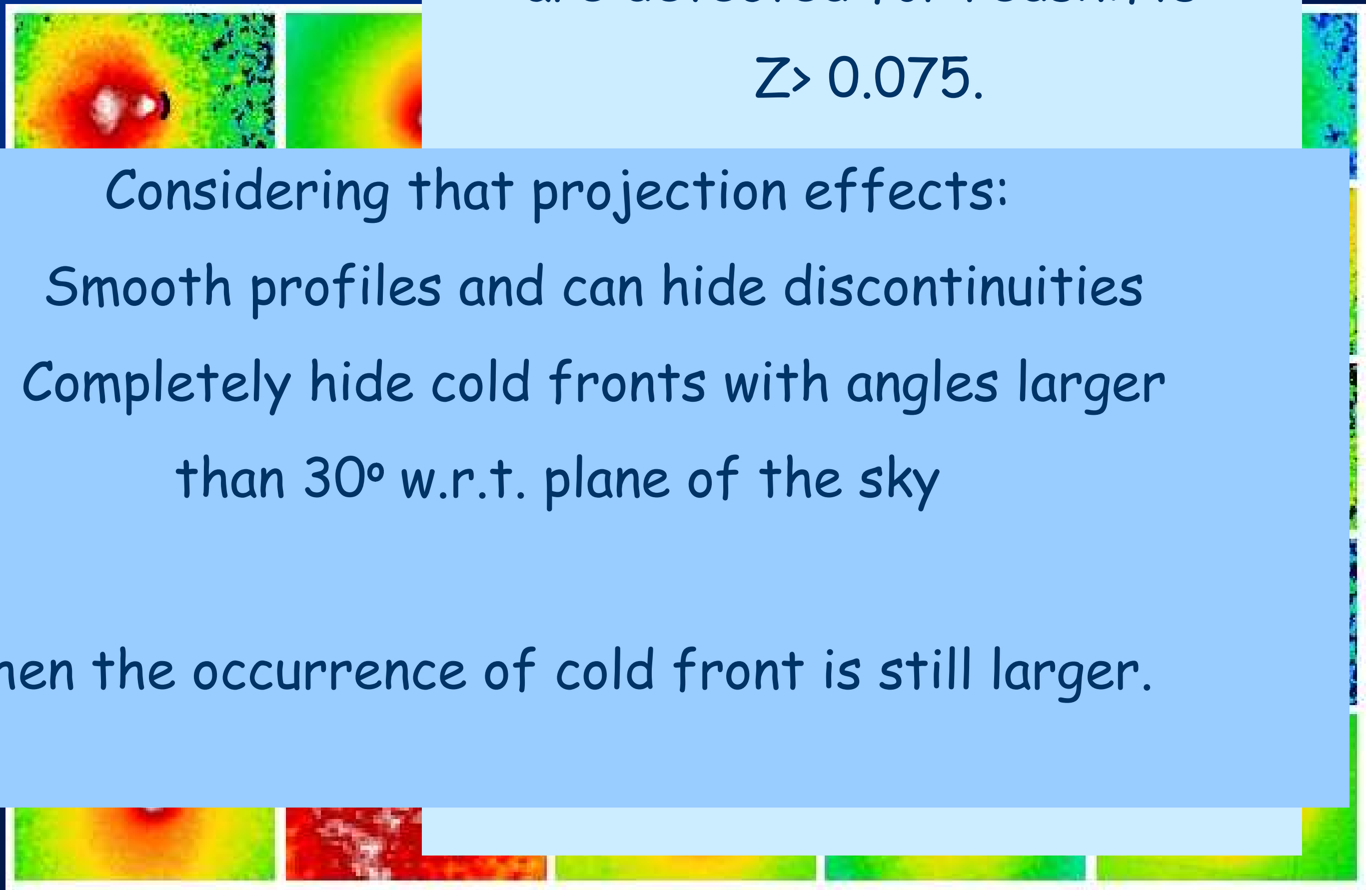
Contours= DM

Ascasibar and Markevitch 2006

The onset of the sloshing is due to a gravitational disturbance generated by the passage of a subcluster but the arise of the sloshing is due to ram pressure and to hydrodynamic mechanisms, even when the subcluster has been completely stripped of the gas. The most important condition for the onset of this mechanism is the presence of a low entropy core.

Hunting for cold fronts

A systematic search of ... ample shows that 47%(21/4 ... front (SG et al in prep)



No cold fronts

are detected for redshifts

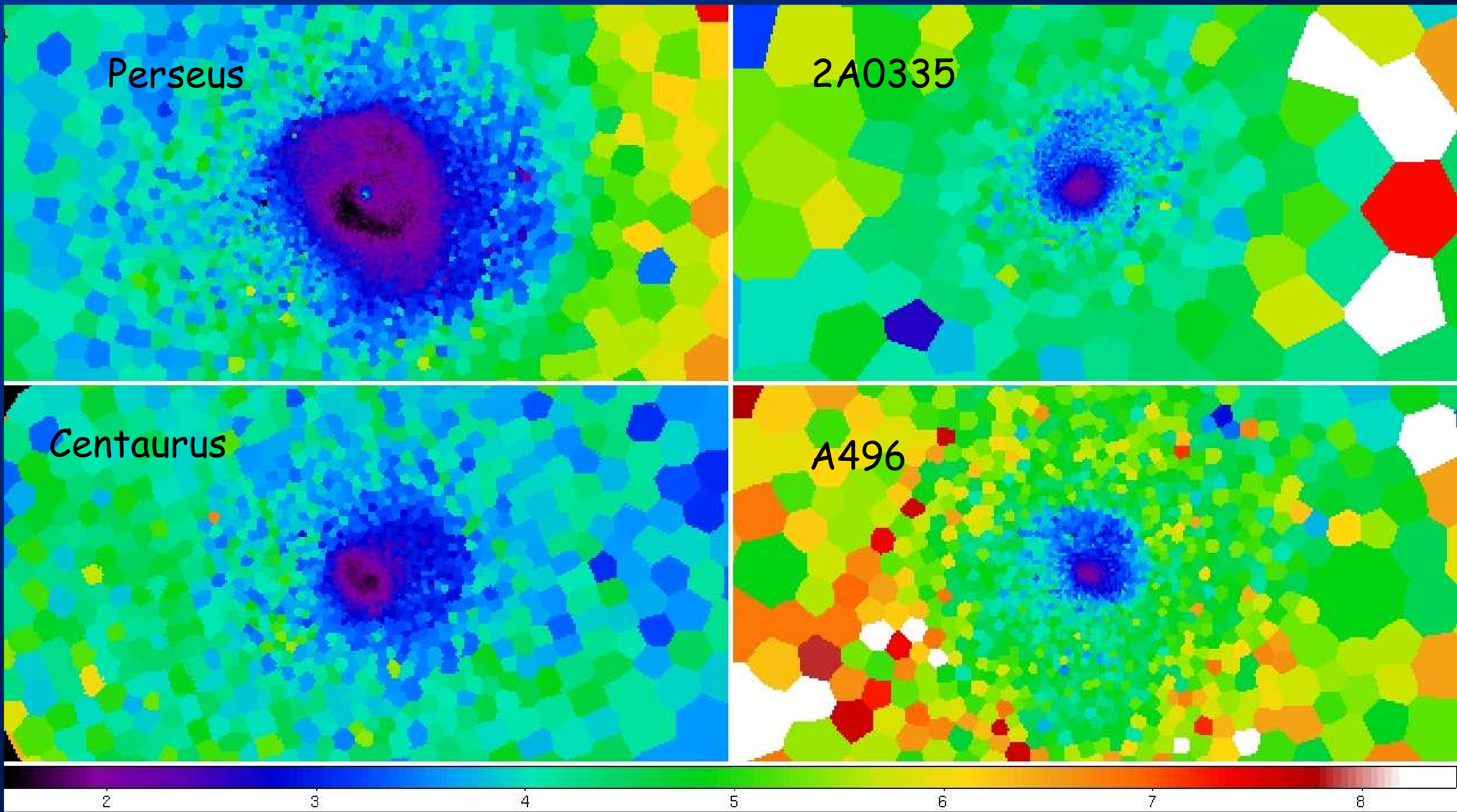
Z> 0.075.

Considering that projection effects:

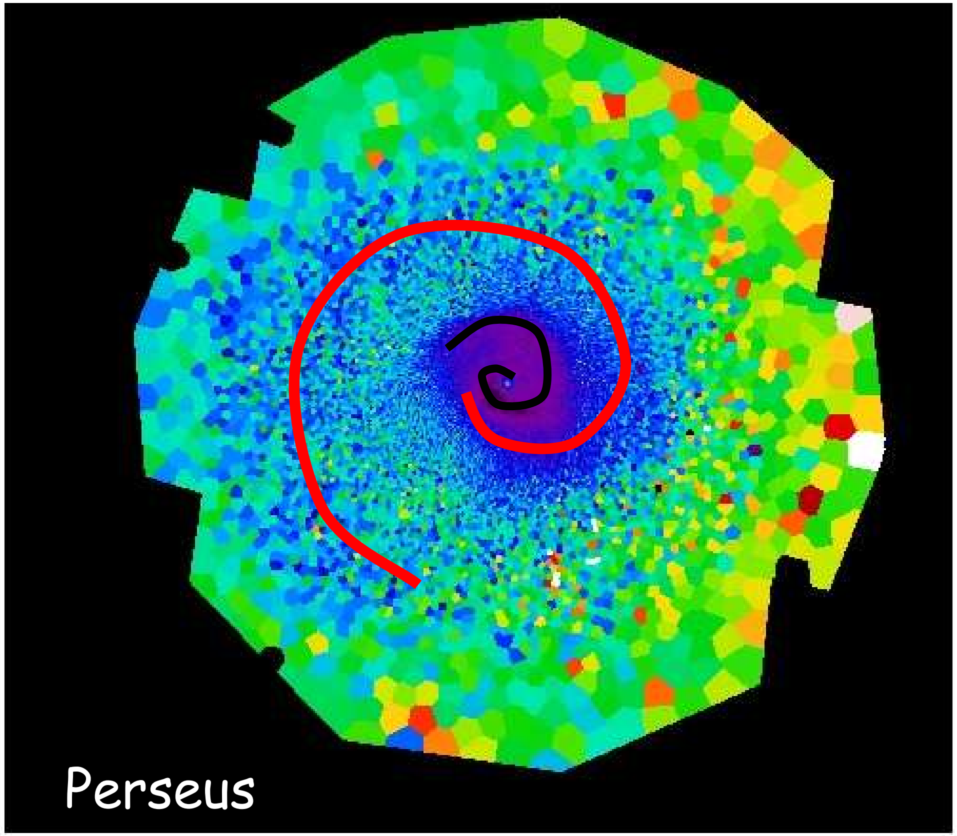
- Smooth profiles and can hide discontinuities
- Completely hide cold fronts with angles larger than 30° w.r.t. plane of the sky

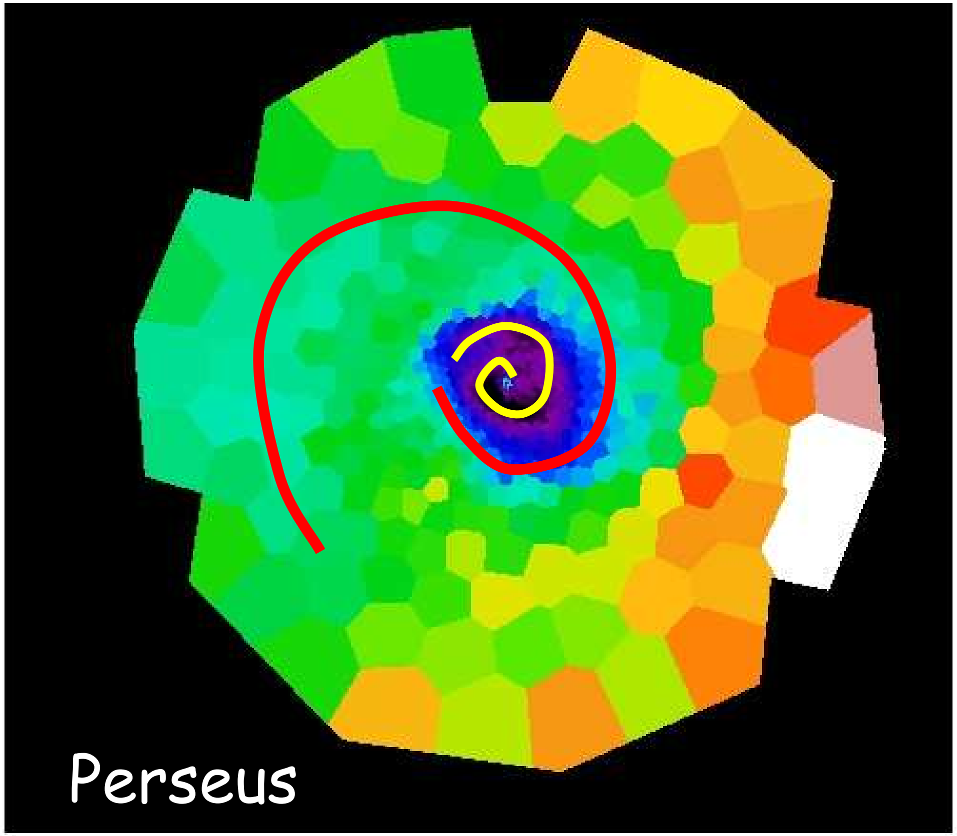
then the occurrence of cold front is still larger.

Spiral pattern in temperature maps



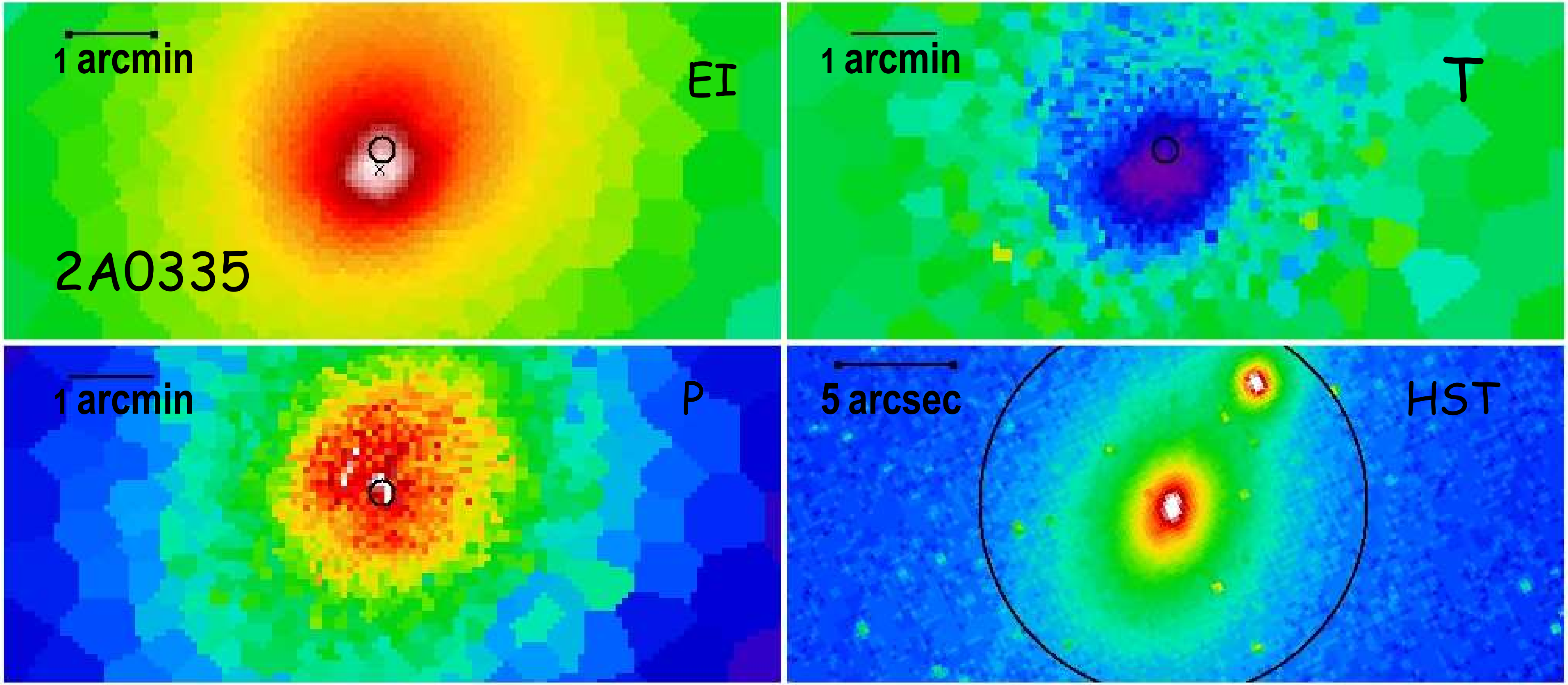
Spiral pattern in Perseus cluster





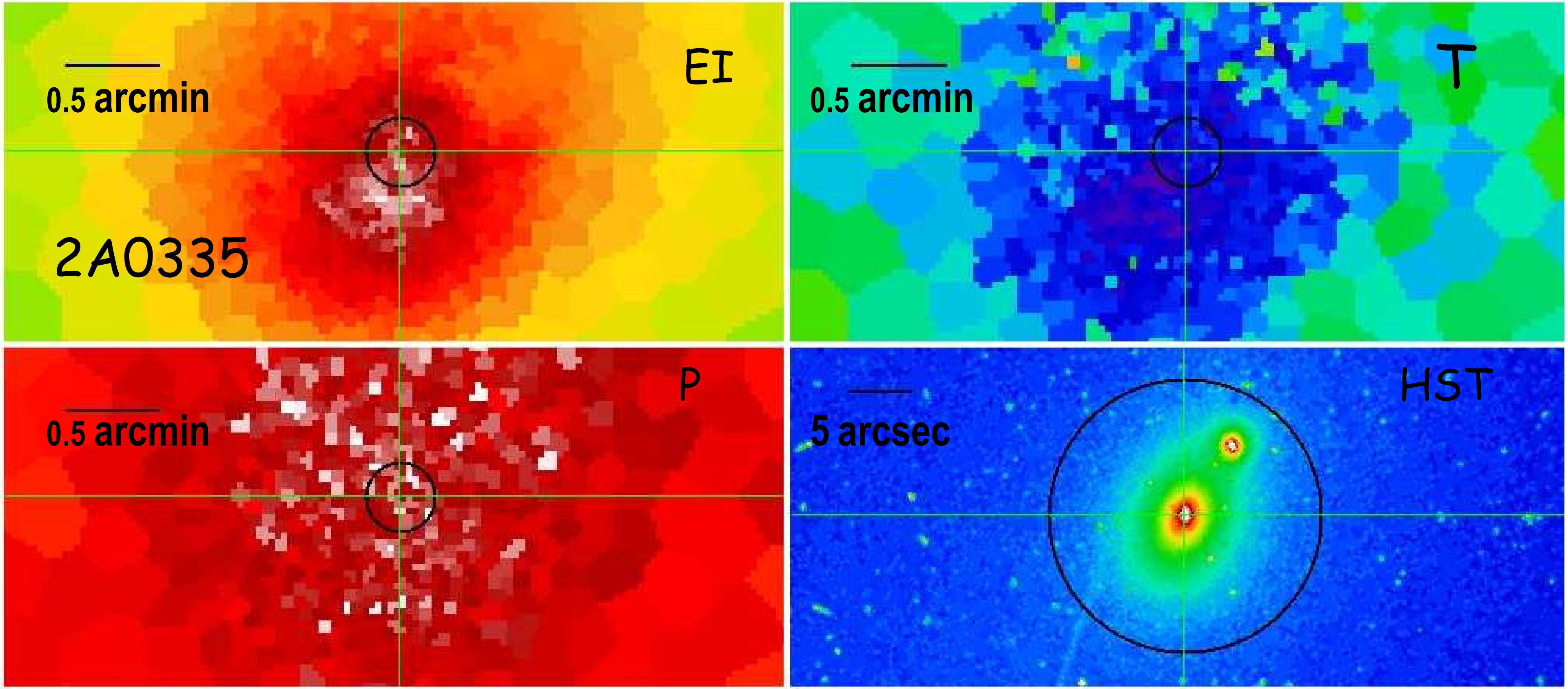
Perseus clusters shows a spiraling behavior on different scales

Displacement of the gas from the potential well



For some clusters we detect a displacement between the SB and the P peak, which perfectly matches with the position of cD galaxy observed with HST.

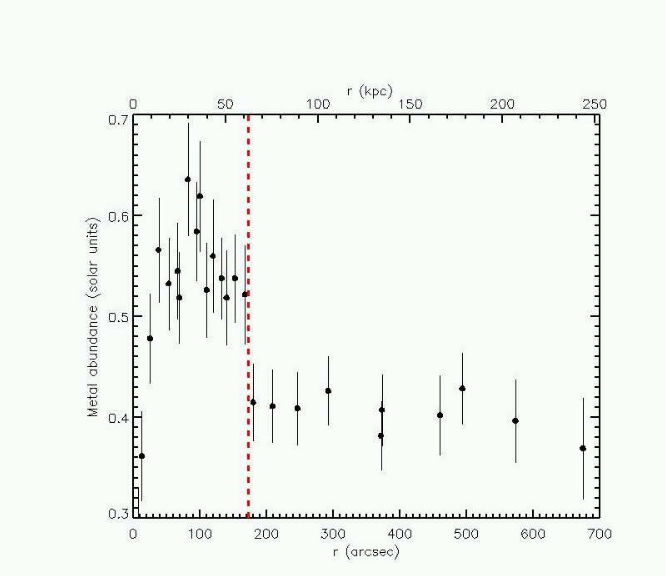
Displacement of the gas from the potential well



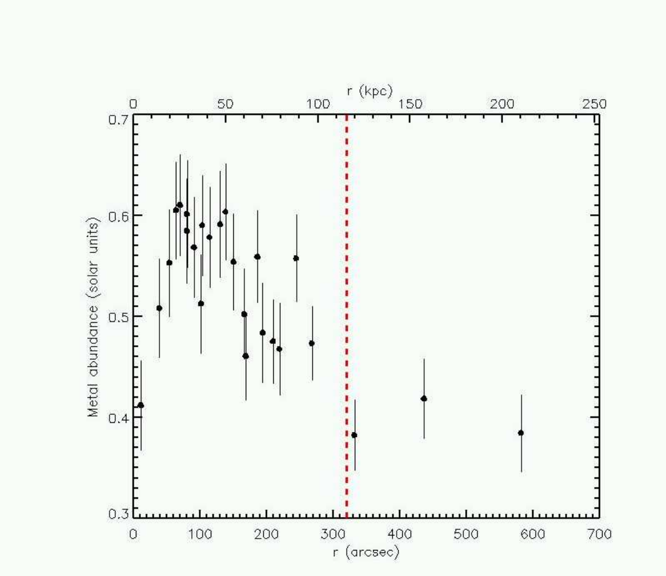
If we build maps for 2A0335 using Chandra data the displacement is still more evident

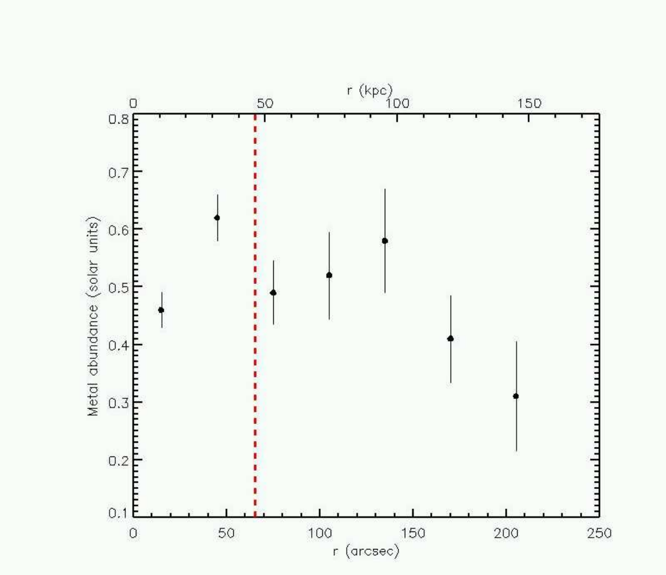
Metal abundances across the cold fronts

Perseus



Perseus





2A0335+096

A metal discontinuity is detected at the radius of the cold fronts for Perseus and 2A0335, but they have not been detected in A496.

SG at el astro-ph/0611390

Cold fronts and entropy

All the merging clusters of our sample host a cold front.

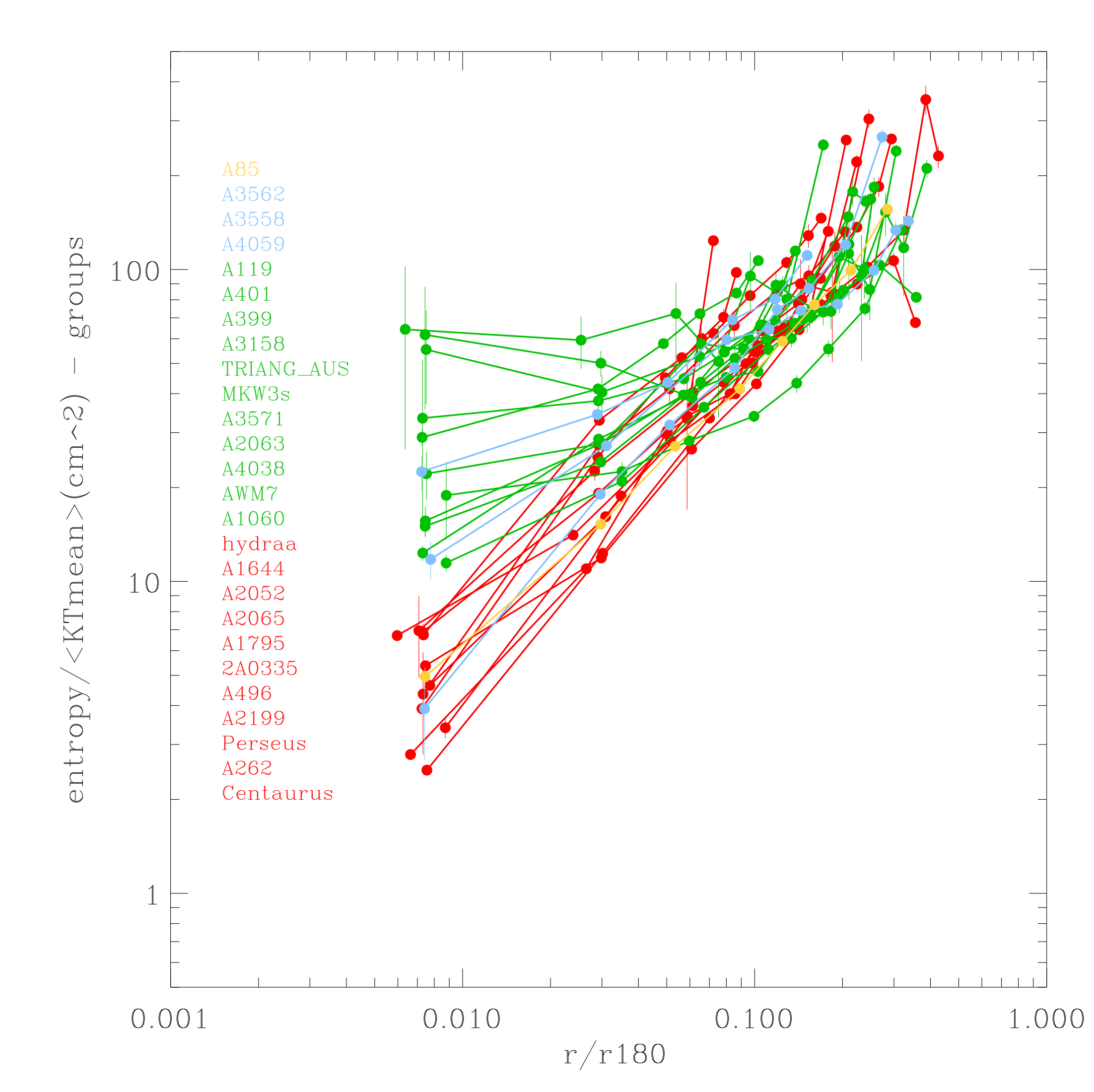
What about the others? Who hosts one?

Green: no cold front

Red: cold front

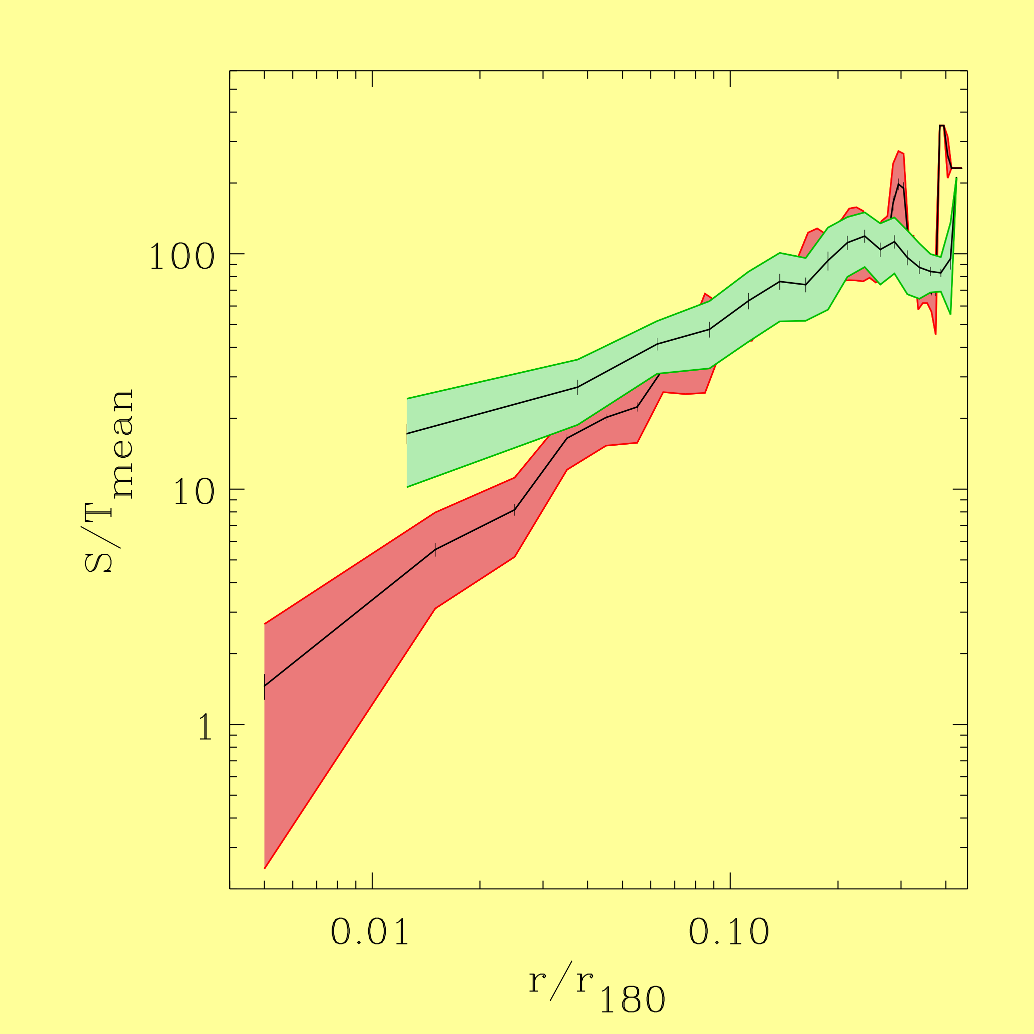
Orange: uncertain

Cyan: outliers



SG et al in prep

Cold fronts and entropy



Red: cold front

Green: non cold front

The entropy profiles of clusters hosting a cold front steepen in the central regions.

SG et al in prep

Summary

- Cold fronts in merging clusters correspond to the edge of the cool core of the merging substructure which is rapidly moving in the hotter surrounding ICM.
- Cold fronts are frequent also in cool core clusters. They originate from sloshing of the cool central gas. Sloshing is induced by minor merging events. Ram pressure makes the gas shoot up from the minimum of the potential well and then slosh back and forth in it. It is an hydrodynamic process.
- A systematic search of cold fronts in a sample of galaxy clusters shows that this is a common feature: at least ~50% of clusters host one (underestimation of occurrence).
- Some features supporting the sloshing models have been detected in clusters (displacements of the gas peak from the center of the potential well, spiral pattern in temperature maps…)
- Excluding merging clusters, a different behavior is detected for clusters hosting or not a cold front. Clusters with a cold front have an entropy profile which steepens in the central regions.