Mapping Fossil and non-Fossil systems out to their Virial Radii

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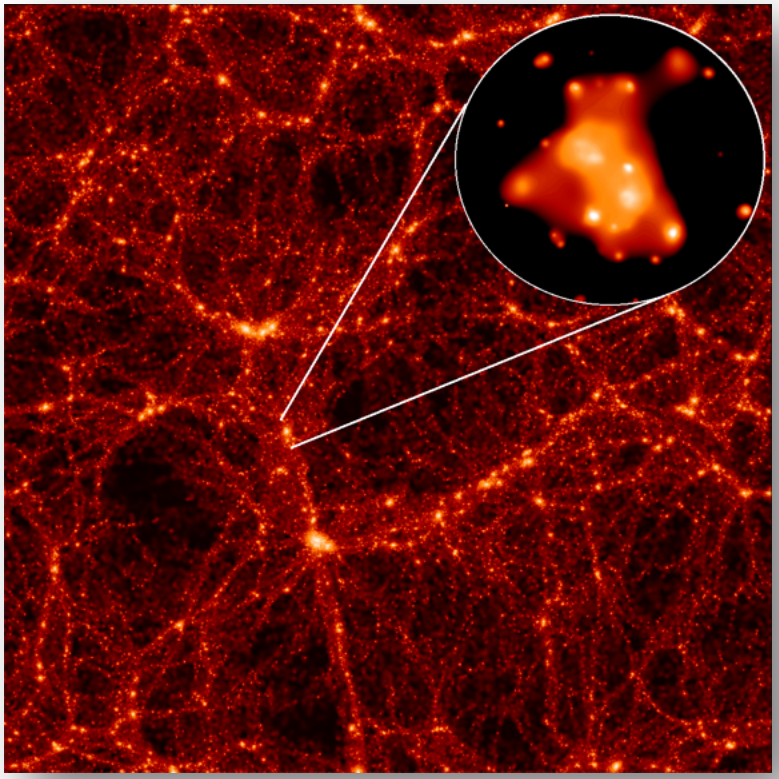
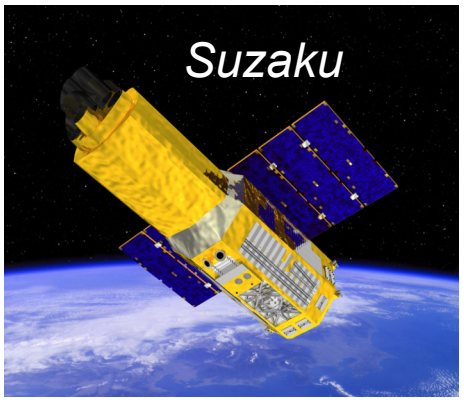
Continuing growing



A computer simulation of a large volume of the Universe.
XMM image of the Virgo Cluster is superimposed.
Jenkins et al. (2008)

Motivation: cluster outskirts



0.5 ~ 1.0 virial radius (R_{vir} ~ R_{200})

low and stable
instrumental background

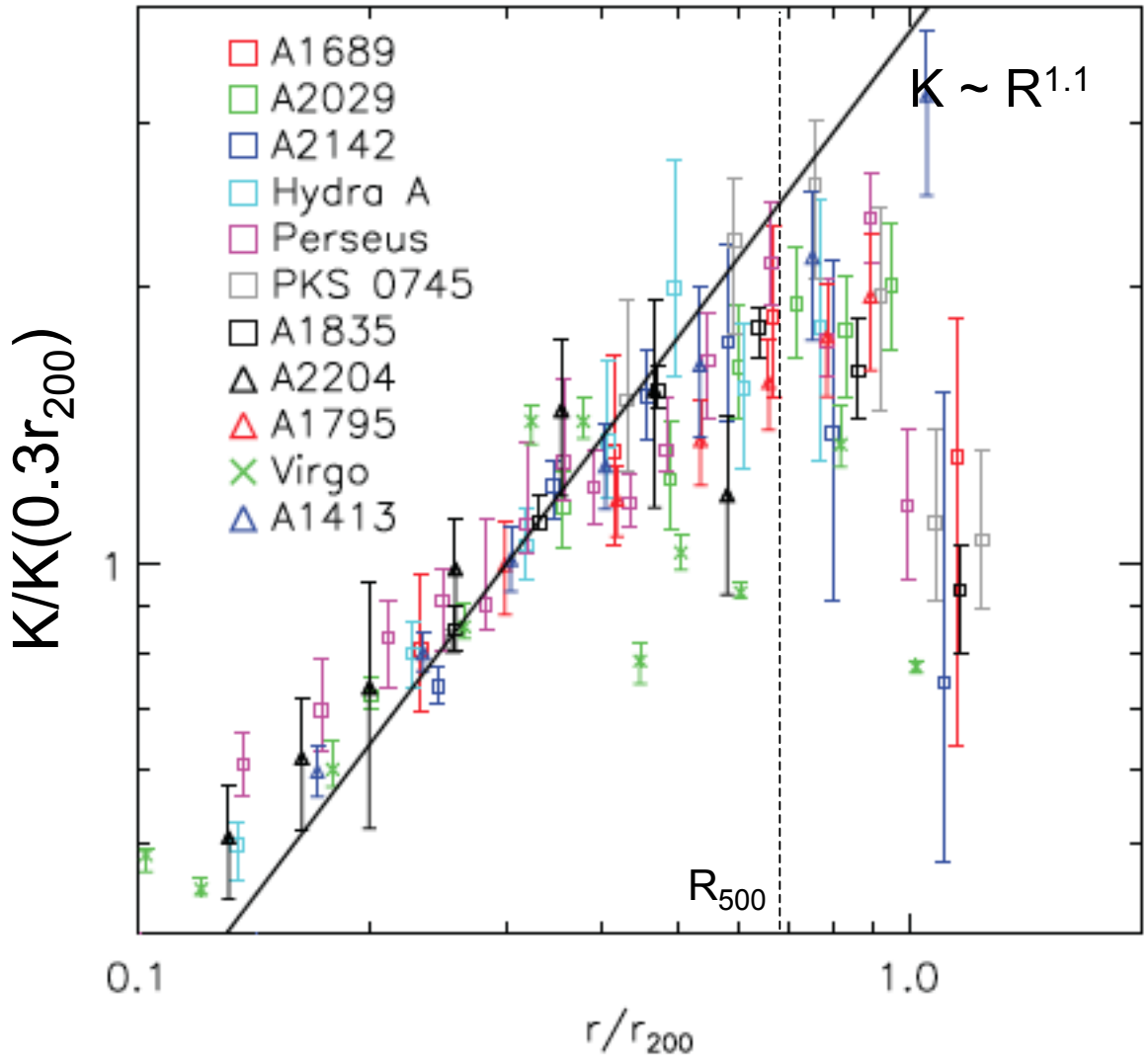
Large volume: majority of dark matter/baryons
- structure formation, enrich history

Still accreting: site for various astrophysics
- gas clumping, turbulence, non-equilibrium

Outline

- Cluster outskirts review
  - flat entropy profiles
- Fossil groups as bench mark
  - RXJ 1159+5531 (azimuthal)
  - ESO 3060170
- Impact of large scale environment

galaxy clusters at R_{vir}



Entropy profiles
Flatten at large radii
by R_{500} (0.6 virial radius)

Walker et al. (2012)

Explanation #1: gas clumping

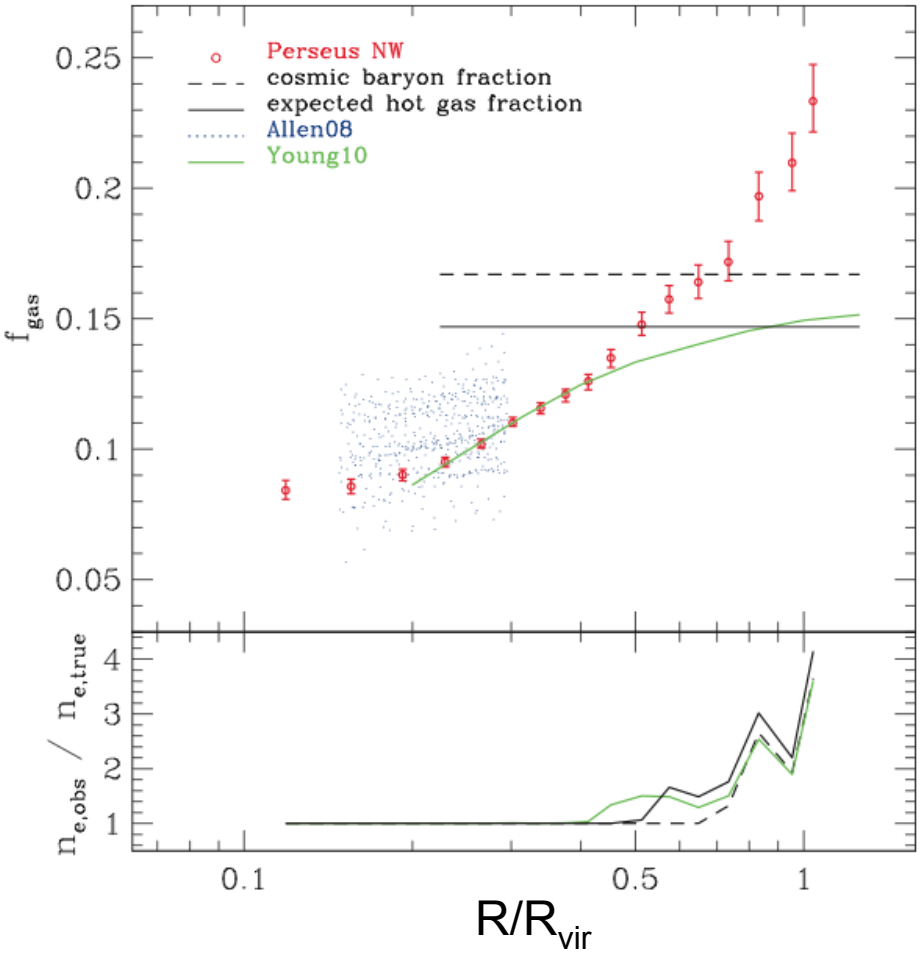
$K = kT_e / n_e^{2/3}$

observe $\langle n^2 \rangle$ instead of $\langle n \rangle^2$

$\Rightarrow$ density overestimate

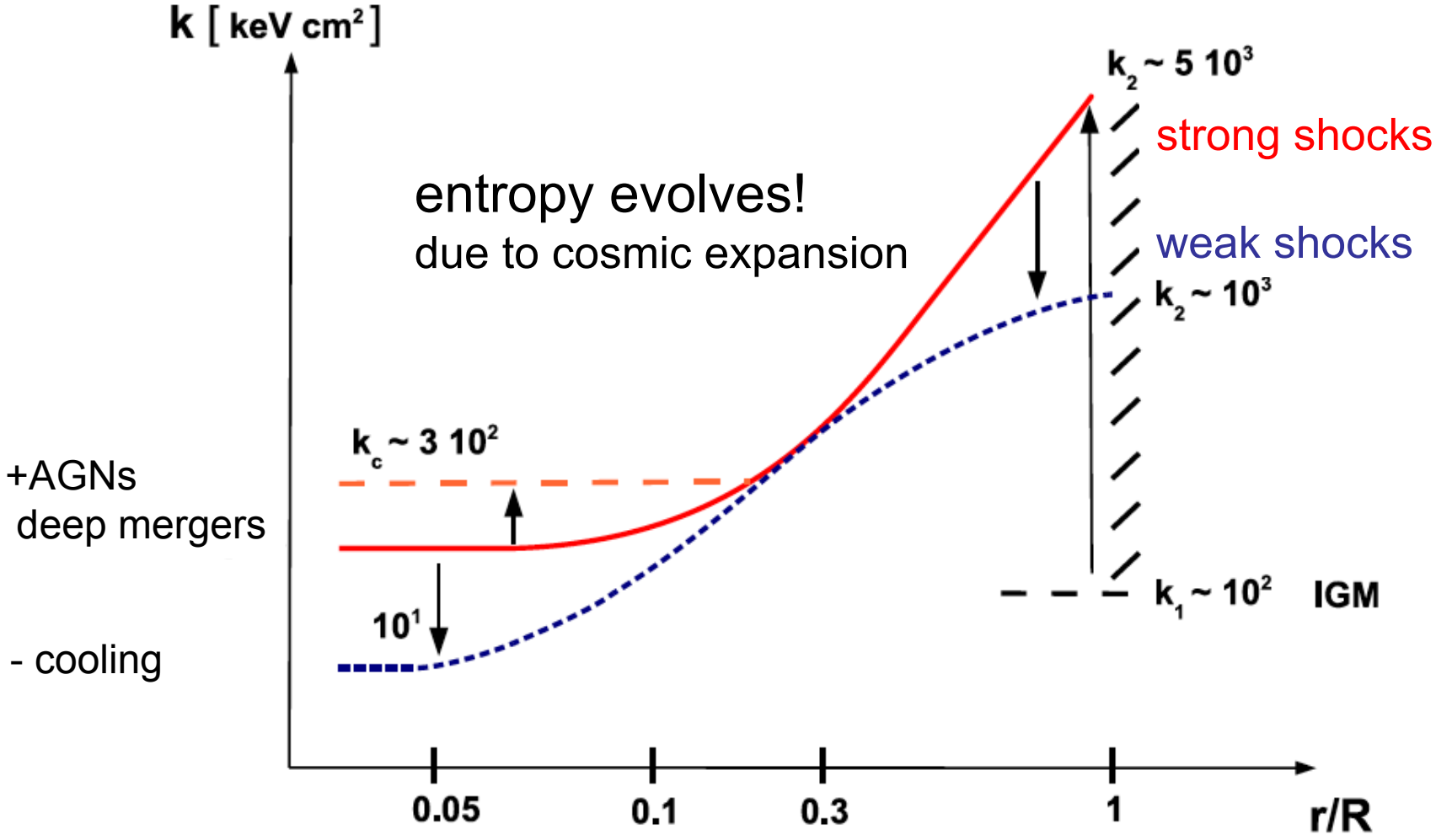
$C = \langle n^2 \rangle / \langle n \rangle^2$

Simulations predict smaller $C \sim 1.5$
Nagai & Lau (2011)
Mathiesen et al. (1999)



the Perseus Cluster
Simionescu et al. (2011)

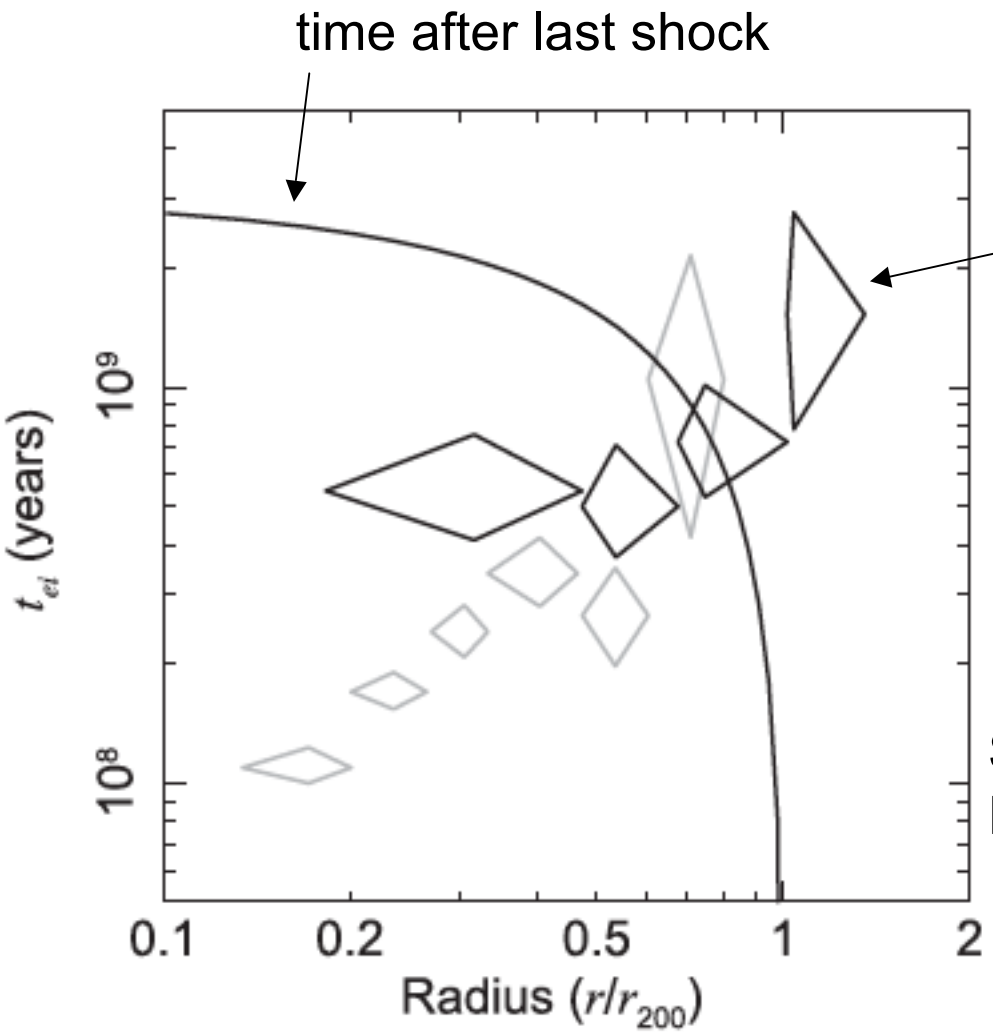
Explanation #2: weakening of accretion shock



A grand design for galaxy clusters

Cavaliere, Lapi, & Fusco-Feminao (2011), also see Walker et al. (2012), (2013)

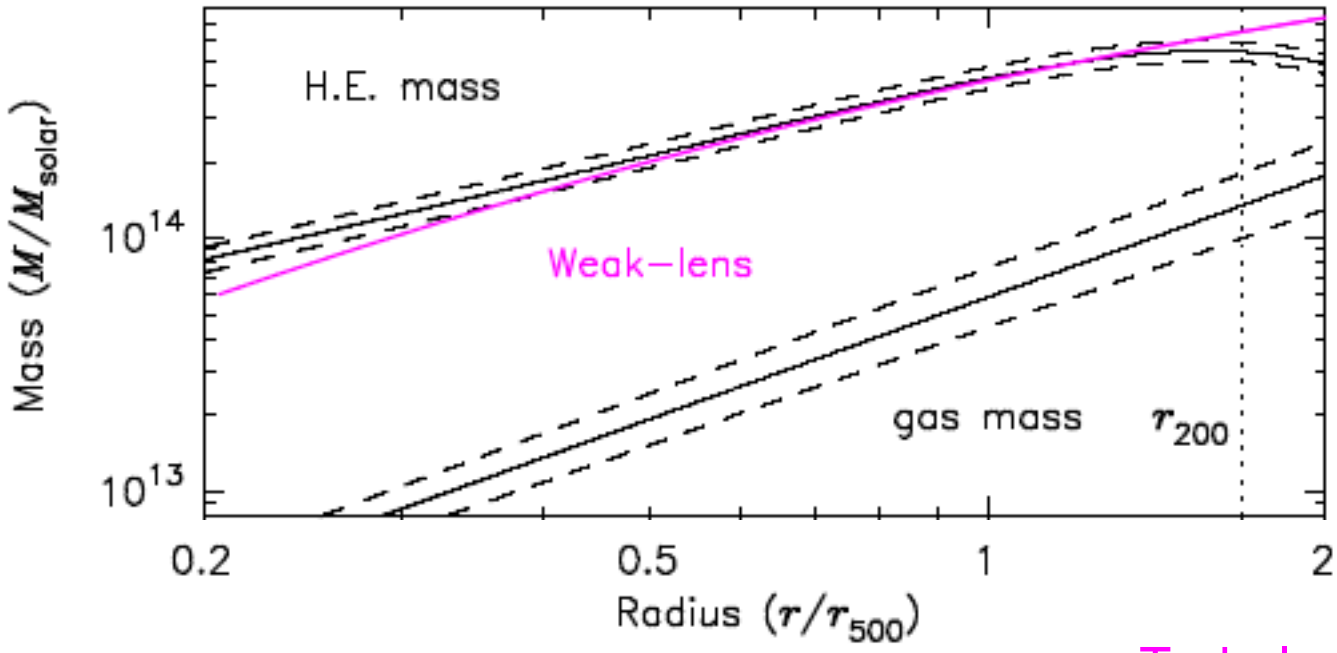
Explanation #3: $kT_i > kT_e$



$K=kT_e/n_e^{2/3}$

Suzaku observations of Abell 1413
Hoshino et al. (2010)

Explanation #4: non-thermal support



Turbulence?

Abell 1246
Sato et al. (2014)

Hydrostatic mass too small

$$M_{<R} = -\frac{kTR}{\mu m_{\rm p} G}\left(\frac{d\ln\rho_{\rm gas}}{d\ln R} + \frac{d\ln T}{d\ln R}\right)$$

entropy flattening,
caused by temperature steepening,
rather than gas density flattening
also see Okabe et al. (2014)

test various possible explanations

- more relaxed systems - fossil groups

  less clumpy gas, less accretion/merger (weaker shock), hydrostatic equilibrium, thermal equilibrium …

- less relaxed systems - galaxy groups, non-cool core clusters

  clumpier gas, more accretion/merger (stronger shock), out of hydrostatic equilibrium, out of thermal equilibrium …

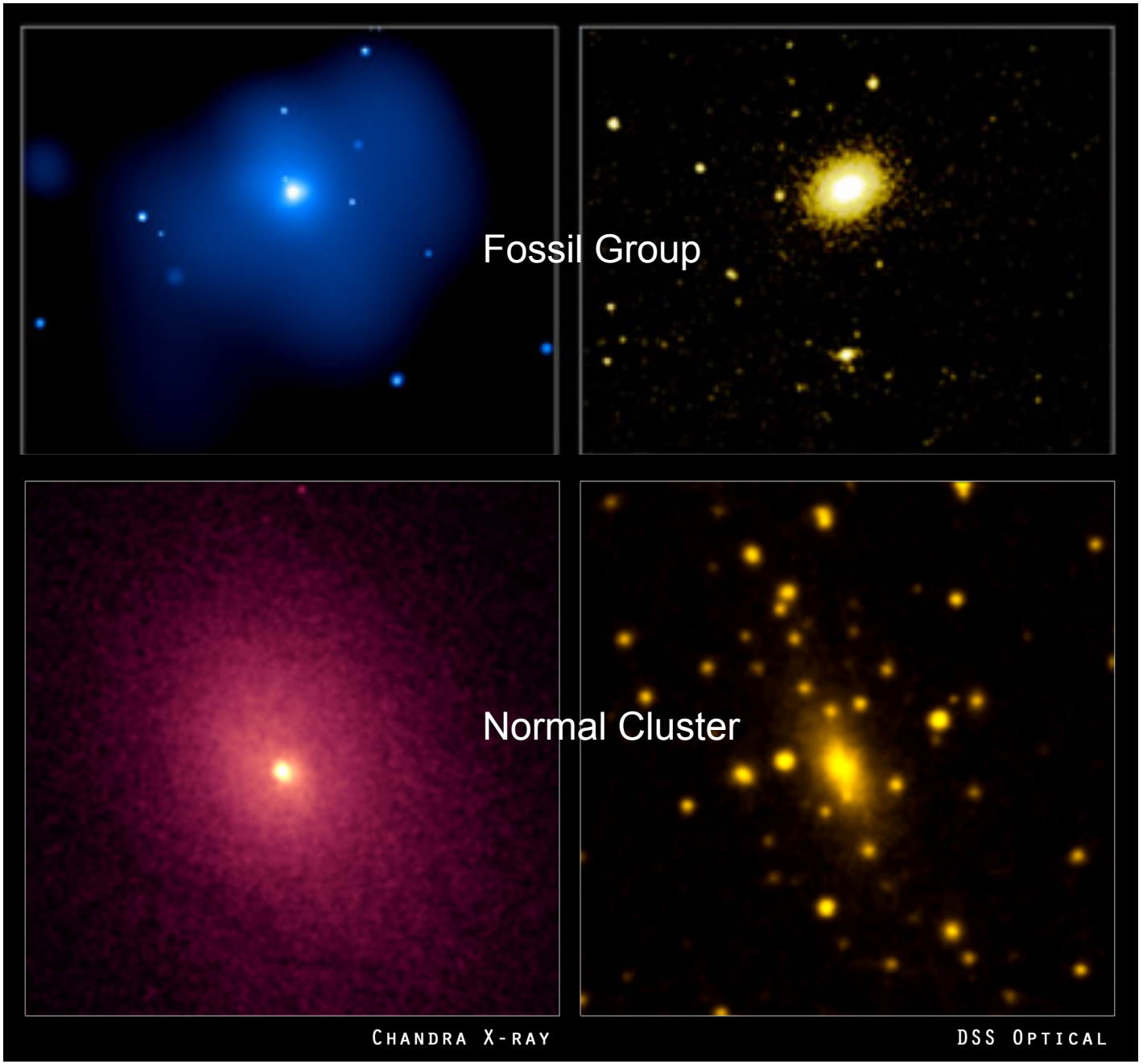
Fossil groups as bench mark

Central dominant galaxy much more luminous than 2nd brightest gal

- undisturbed: less mergers/accretions (weakening of shocks), less azimuthal variations

- highly relaxed: put constrains on gas clumping and non-thermal processes

- in equilibriums, spherical shape: more robust measurements



X-ray Optical

Fossil groups as bench mark

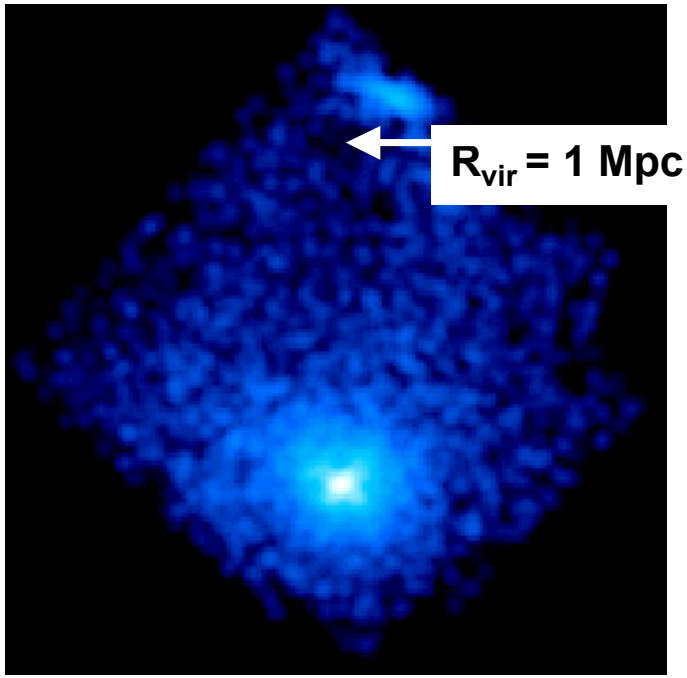
Central dominant galaxy much more luminous than 2nd brightest gal

- undisturbed: less mergers/accretions (weakening of shocks), less azimuthal variations

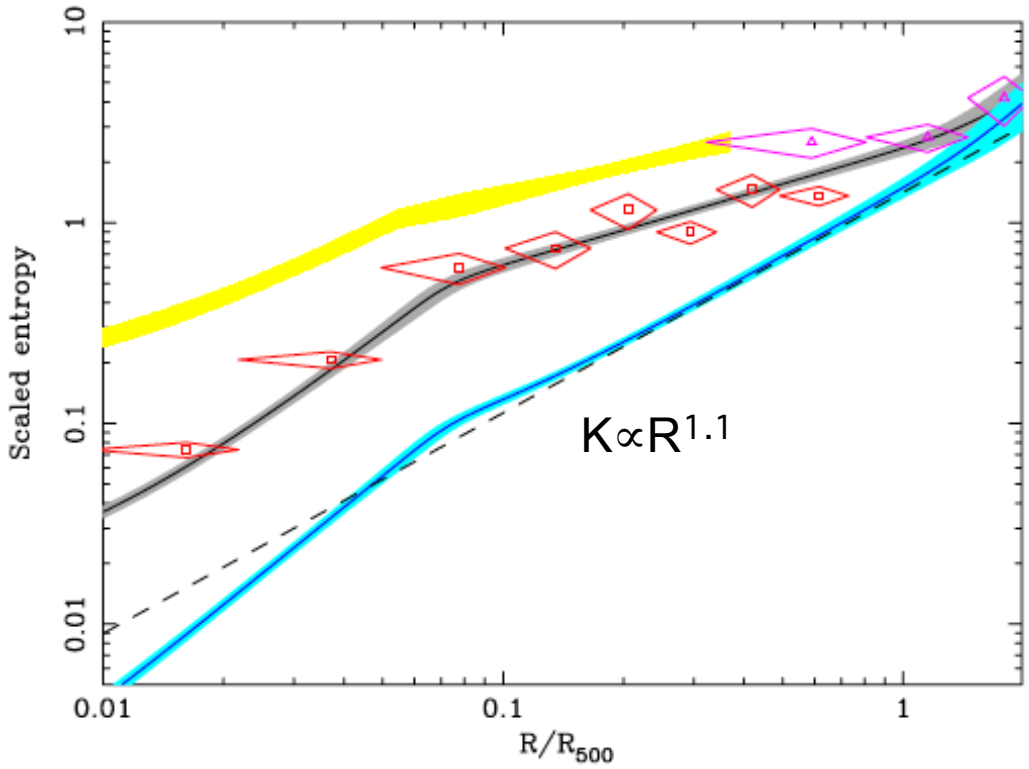
- highly relaxed: put constrains on gas clumping and non-thermal processes

- in equilibriums, spherical shape: more robust measurements

Fossil group RXJ1159+5531 kT ~ 2 keV



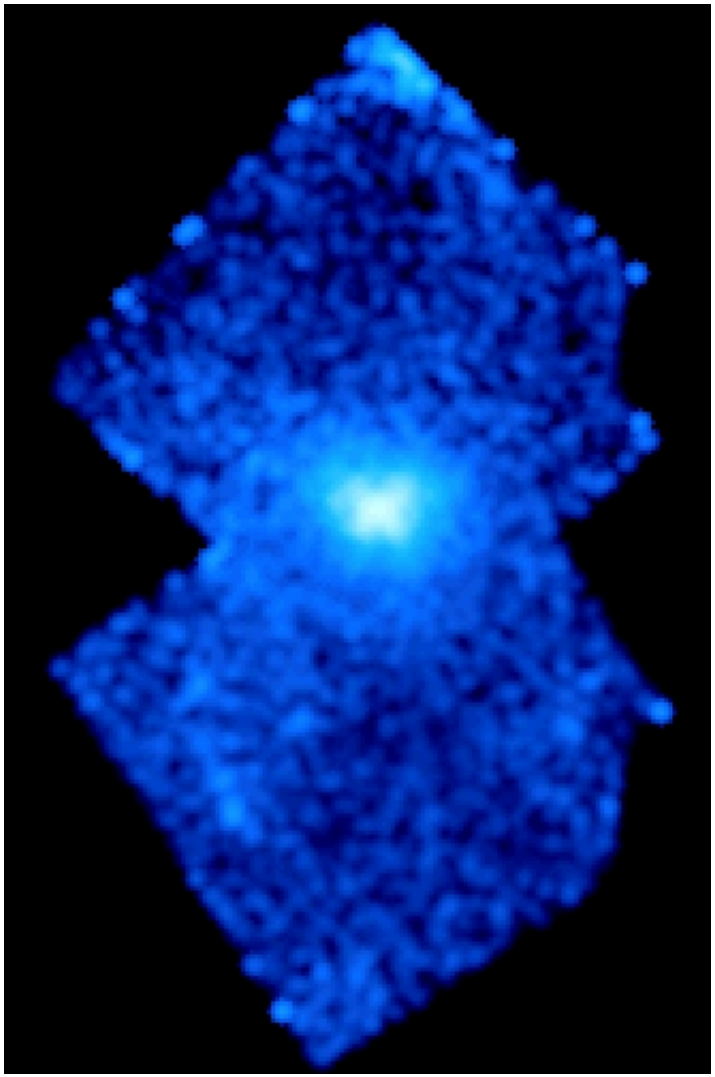
Suzaku X-ray Image

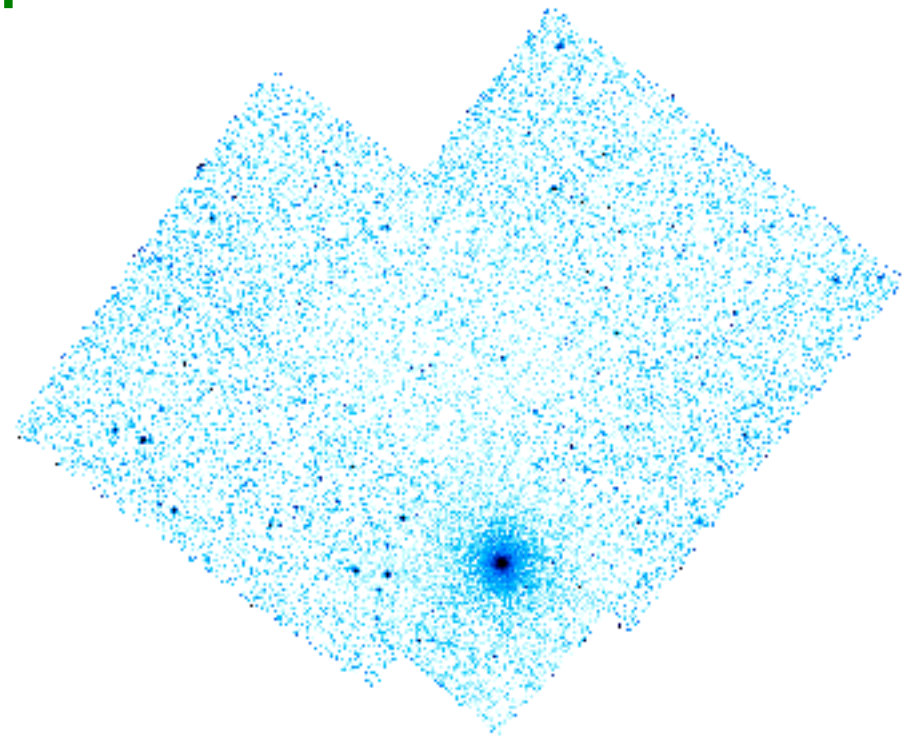


Humphrey et al. (2012)

Counter example of entropy profiles found in other galaxy clusters!

With Recently Acquired Observations

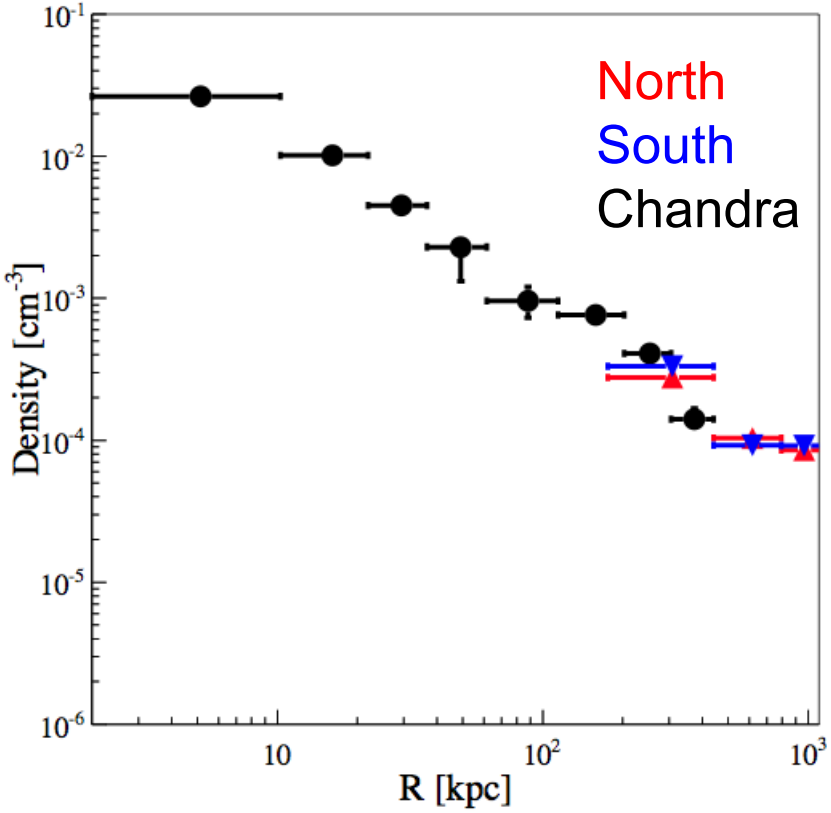


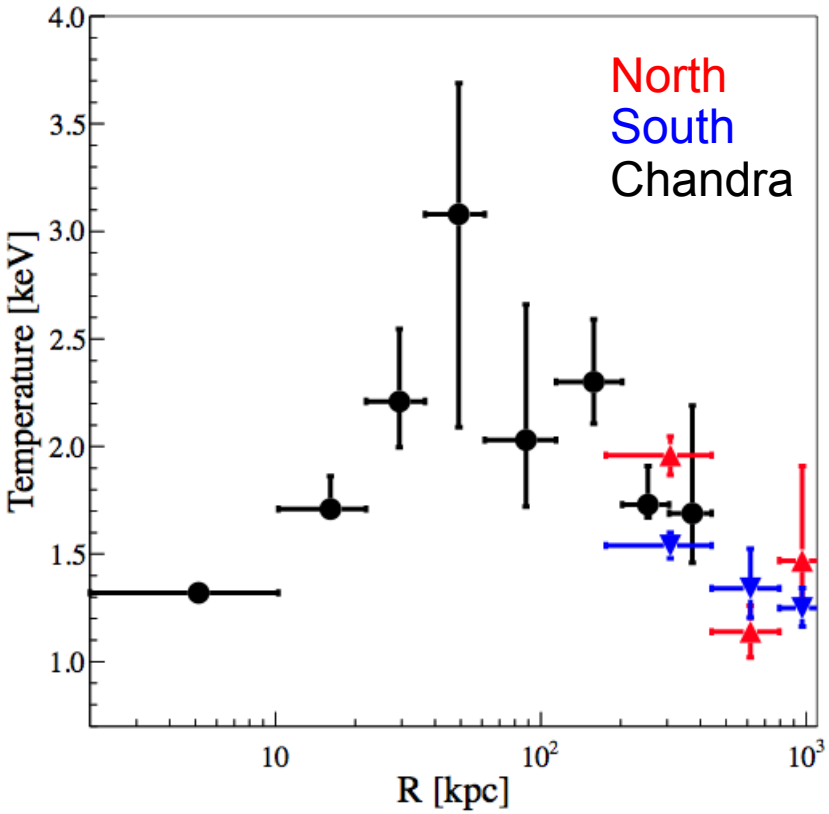


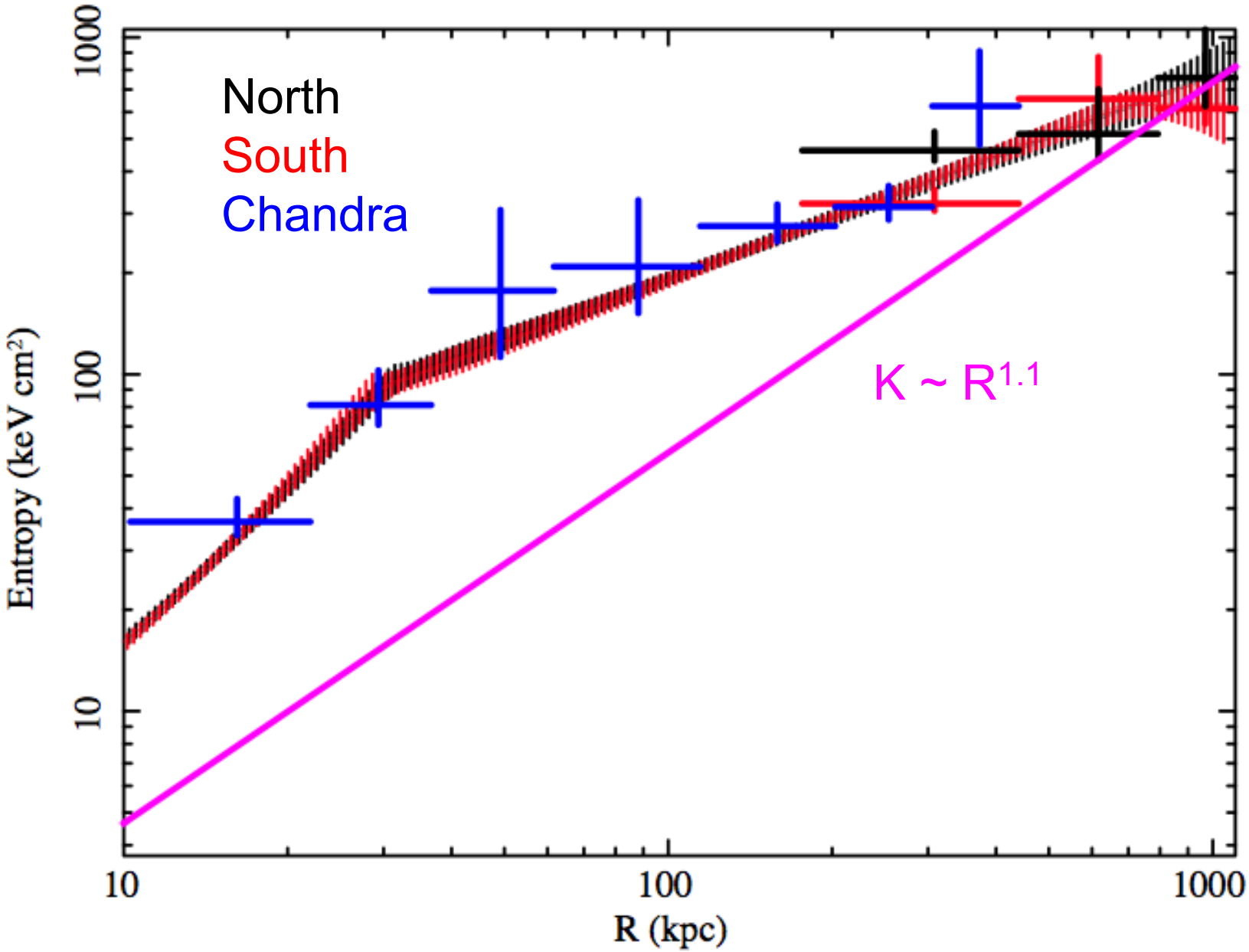
- Suzaku observation of the opposite direction
- Point sources resolved by deep Chandra observation

Su et al. 2014, in prep

gas properties out to R_{vir}

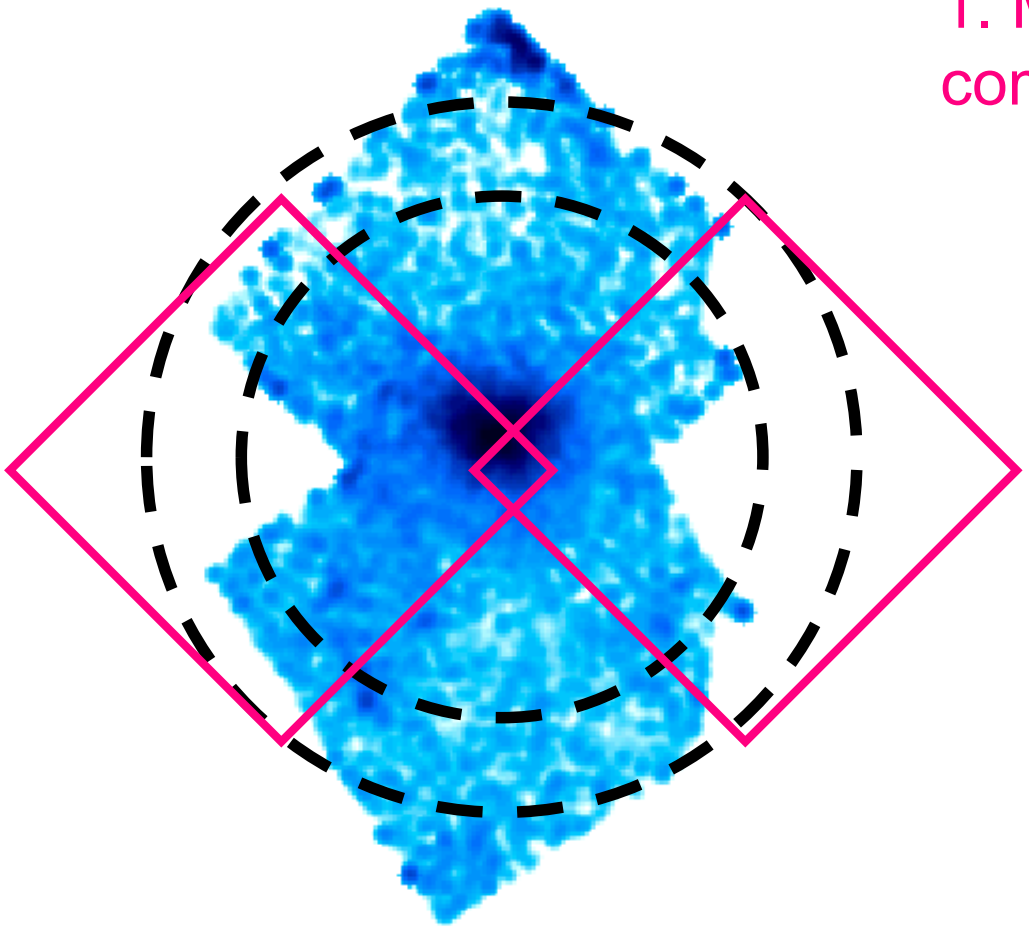





North
South
Chandra
K ~ R1.1
Entropy (keV cm2)
R (kpc)
10
100
1000
10
100
1000

RXJ 1159+5531 More Suzaku observations

PI: Y. Su



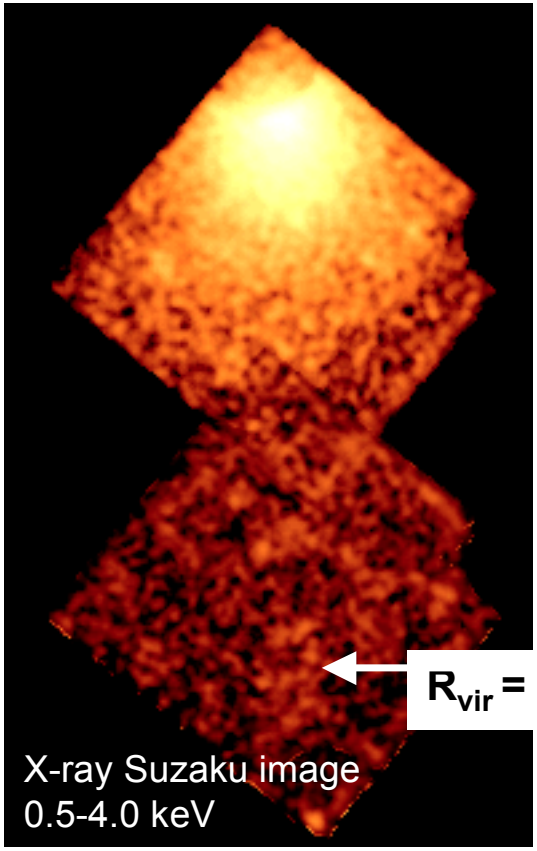
1. More azimuthally complete coverage

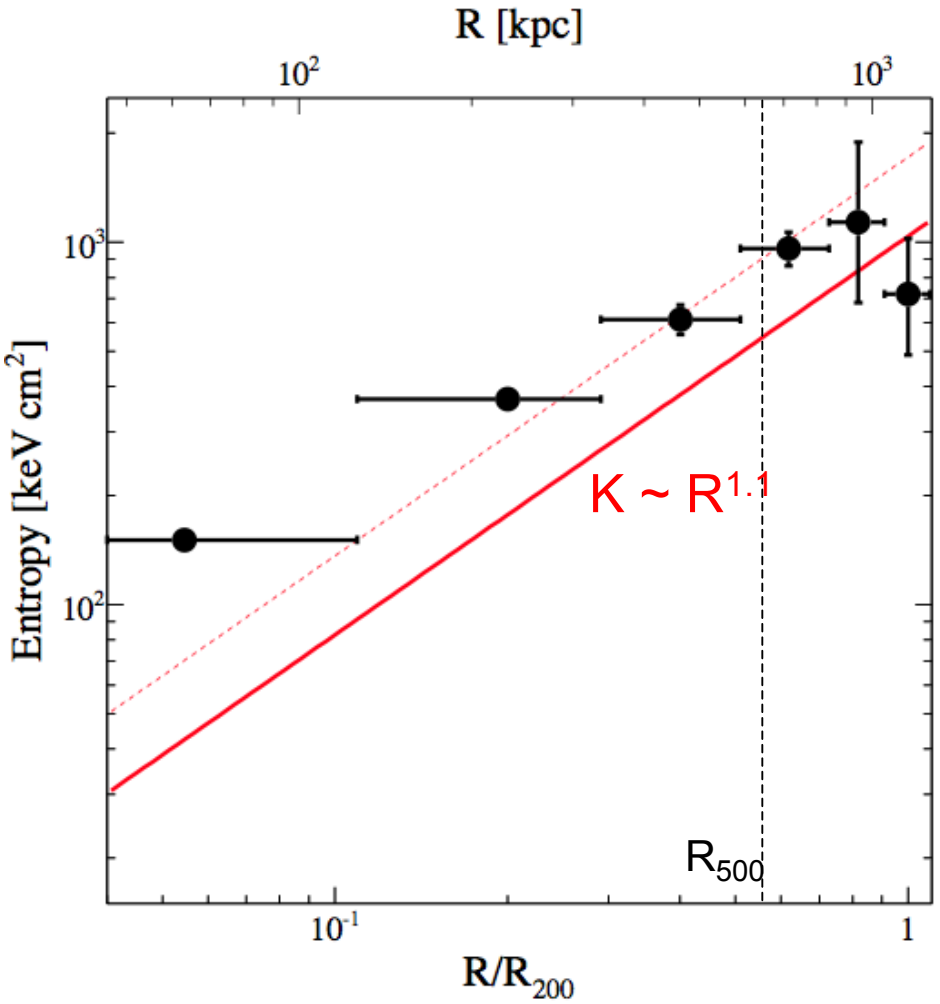
2. Determine hot gas metal abundance out to the virial radius

likely non-clumping gas (no Fe-bias)

Fossil Group ESO 3060170 kT ~ 3 keV

PI: Y. Su





Su, White, & Miller (2013)

test various possible explanations

- more relaxed systems - fossil groups

  less clumpy gas, less accretion/merger (weaker shock), hydrostatic equilibrium, thermal equilibrium …

- less relaxed systems - galaxy groups, non-cool core clusters

  clumpier gas, more accretion/merger (stronger shock), out of hydrostatic equilibrium, out of thermal equilibrium …

test various possible explanations

- more relaxed systems - fossil groups - little flattening

favor clumping/non-equilibrium explanations,
disfavor weakening of accretion shock

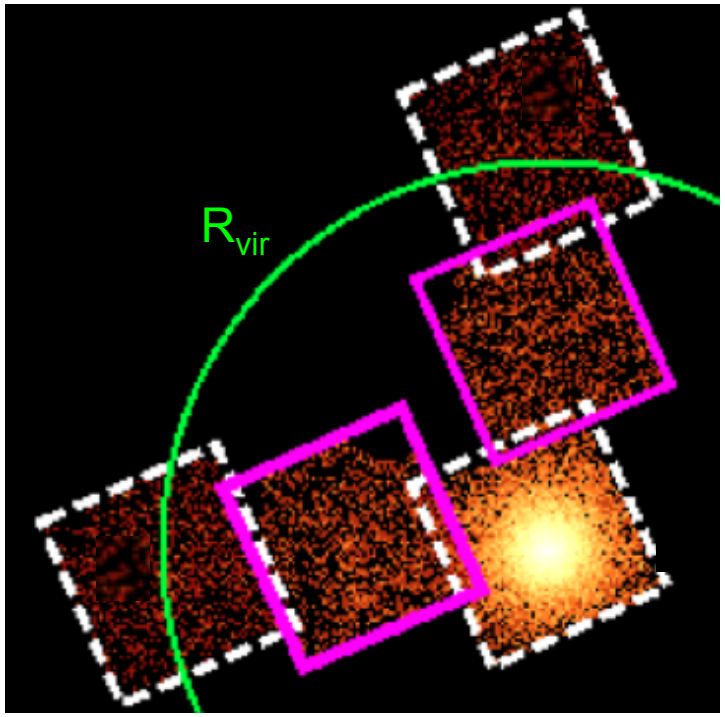
- less relaxed systems - galaxy groups, non-cool core clusters

clumpier gas, more accretion/merger (stronger shock),
out of hydrostatic equilibrium, out of thermal equilibrium
…

Next Step:
non-fossil, small mass systems
out to R_{vir}

- gas clumping, non-thermal support more prominent in groups
- more sensitive to non-gravitational process (e.g., AGN)
- most galaxies reside in groups
- more groups than clusters

galaxy group MKW4 kT < 2 keV
PI: Y.Su



Stay tuned

also non-cool core clusters

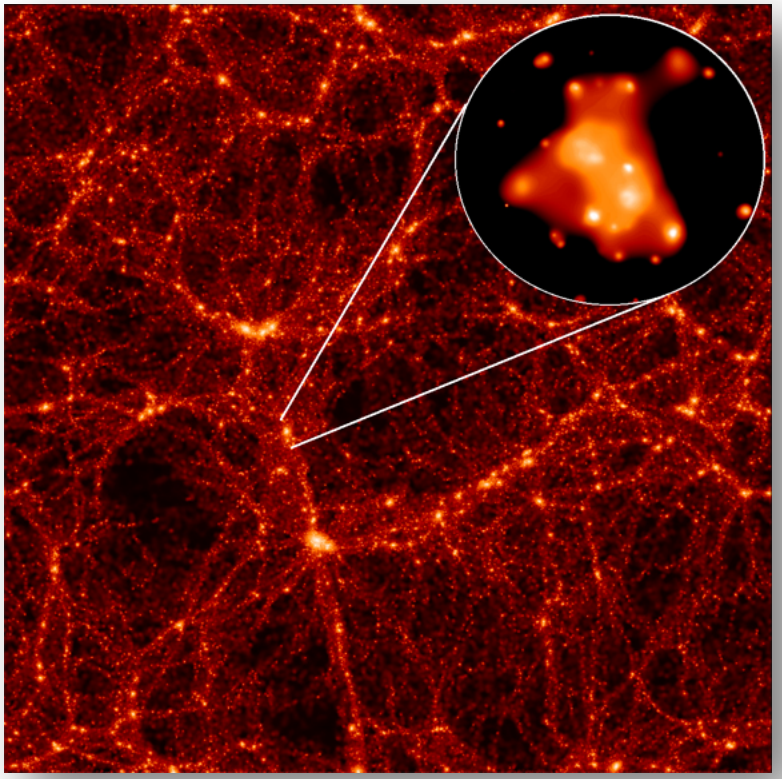
the *only* Suzaku observations out to the virial radius for a typical galaxy group

the *smallest* galactic system observed out to the virial radius with Suzaku

Small systems, BIG QUESTIONS:
(1) Self similar?
(2) The role of non-gravitational process?
since groups are more vulnerable

- Clumpier gas?
- Smaller baryon fraction?
- Smaller metallicity?
- Flatter entropy/pressure profile?

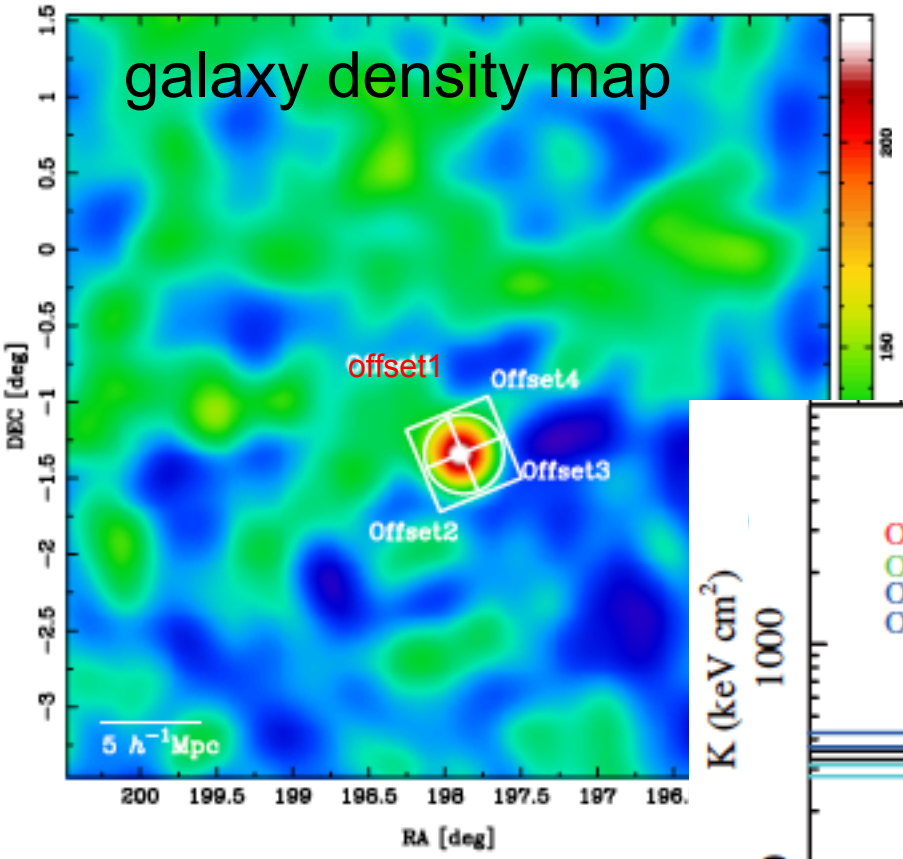
Effects of large scale environments



Jenkins et al. (2008)

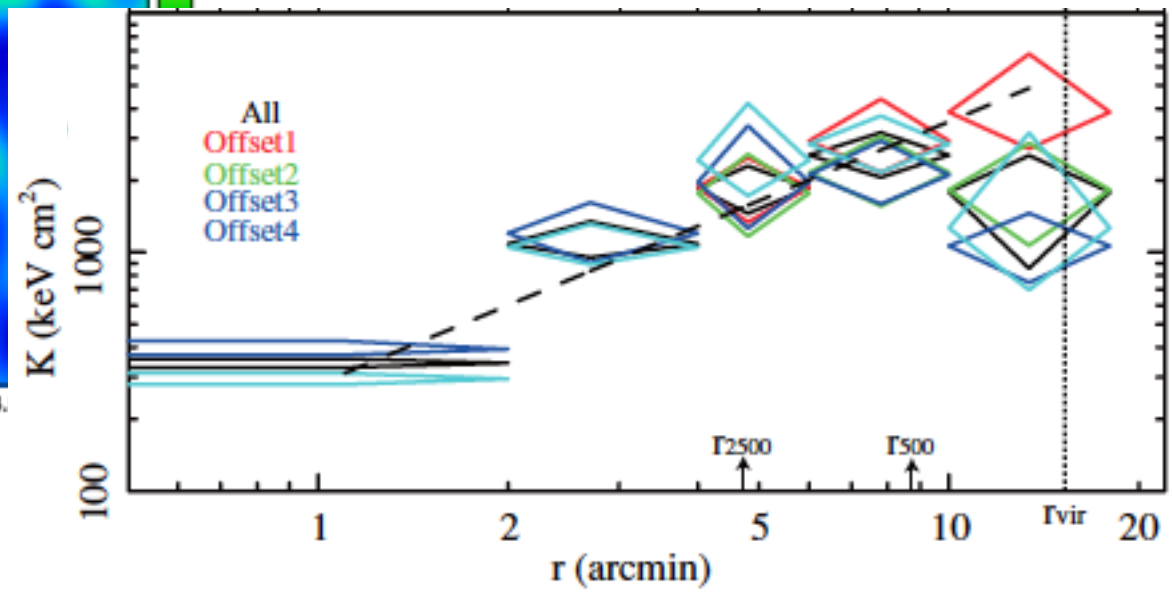
- Evolutionary stage
- Gas properties at outskirts
- Azimuthal variations
- Fossil vs non-fossil

39 Mpc x 39 Mpc

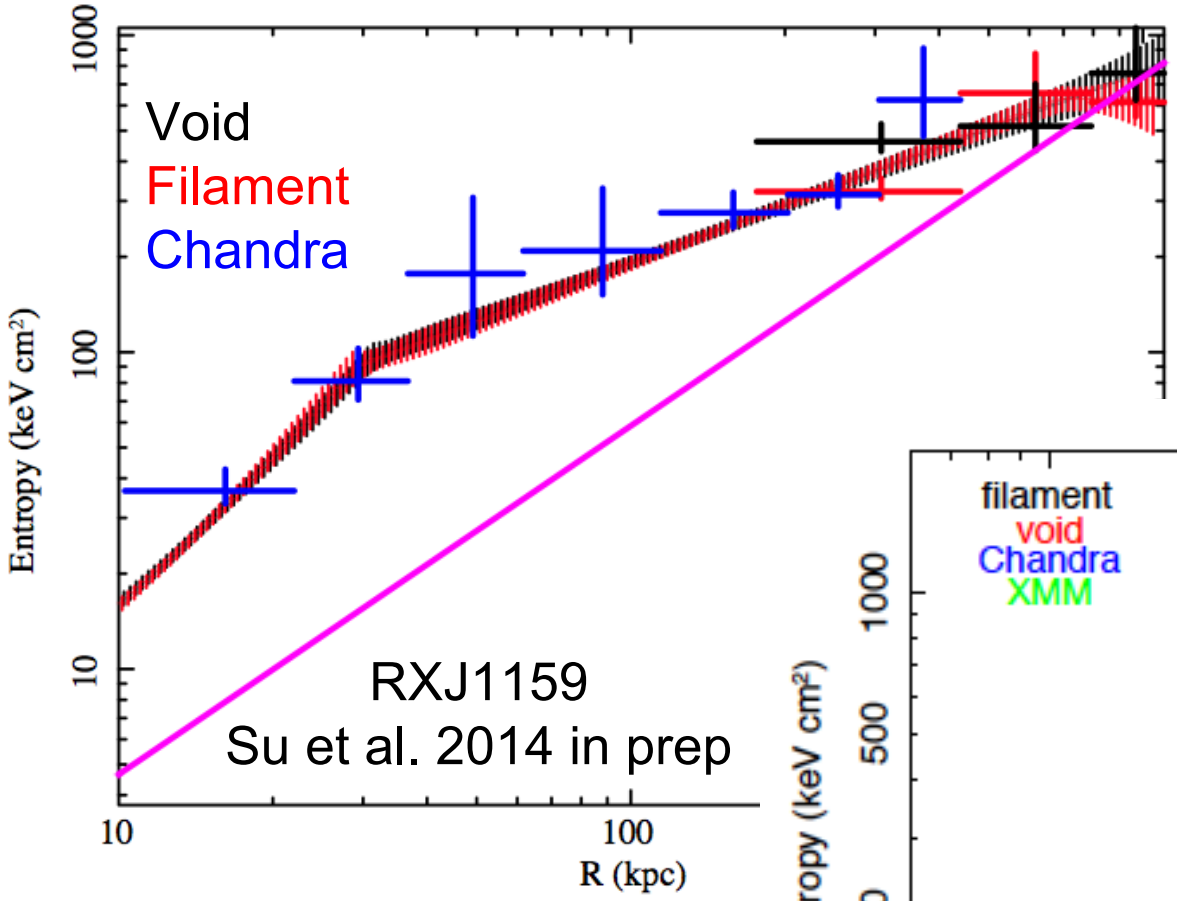


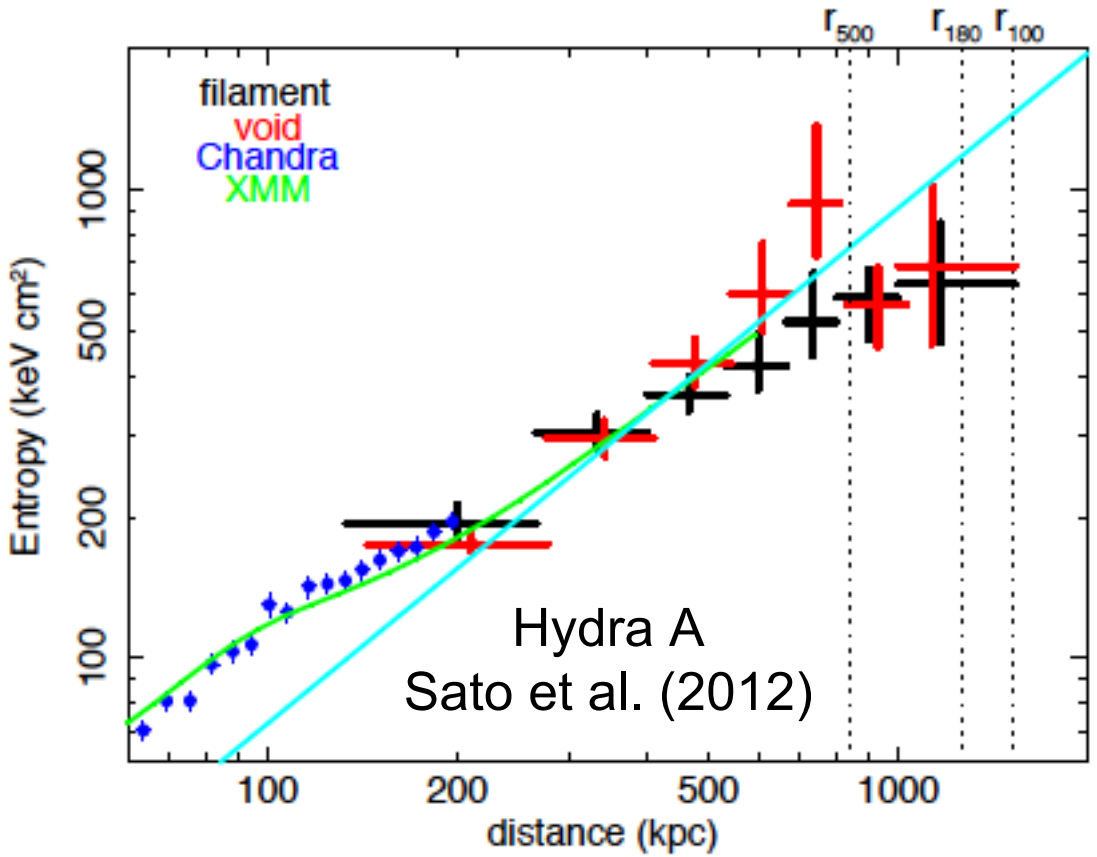
High galaxy density direction corresponds to large entropy

1. stronger shock keeps up entropy?
2. shock destroys clumpy gas?
3. evolves faster along filaments?



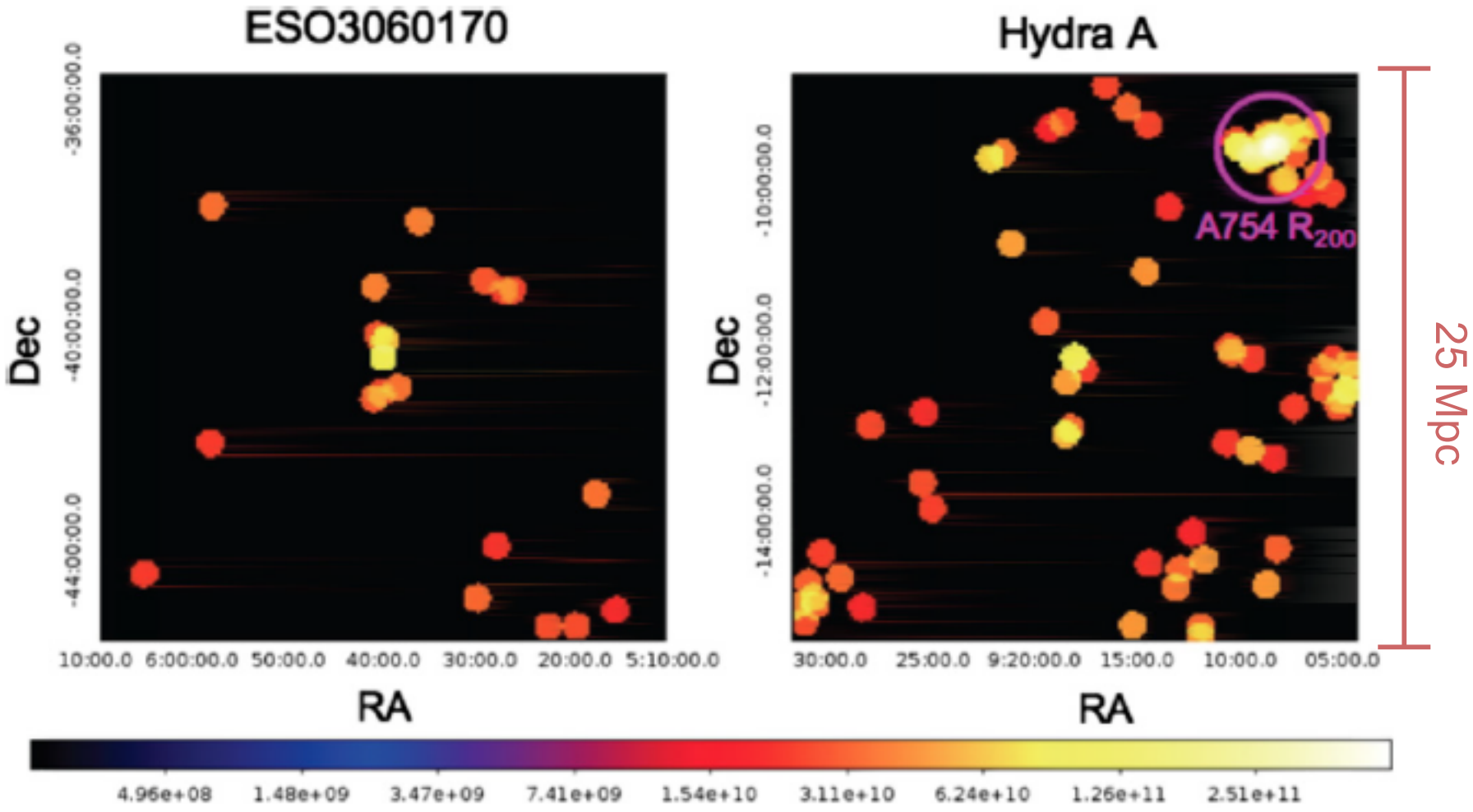
Abell 1689 - Kawaharada et al. (2010)
also see
the Perseus Cluster - Urban et al. (2014), Abell 1246 - Sato et al. (2014)



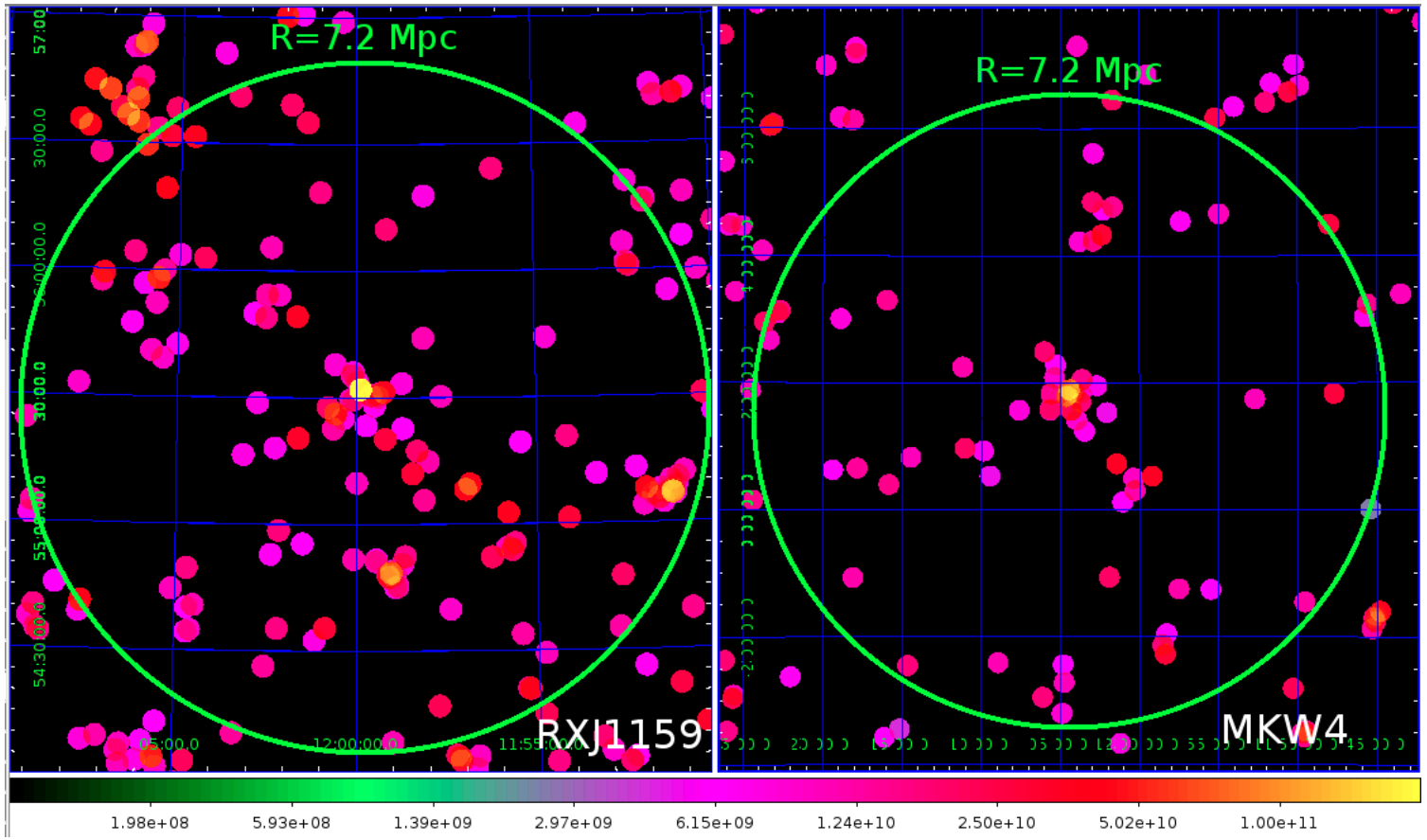


Maybe not be related
In other cases

Southern sky: 6dF galaxy density map



Northern sky: SDSS galaxy density map

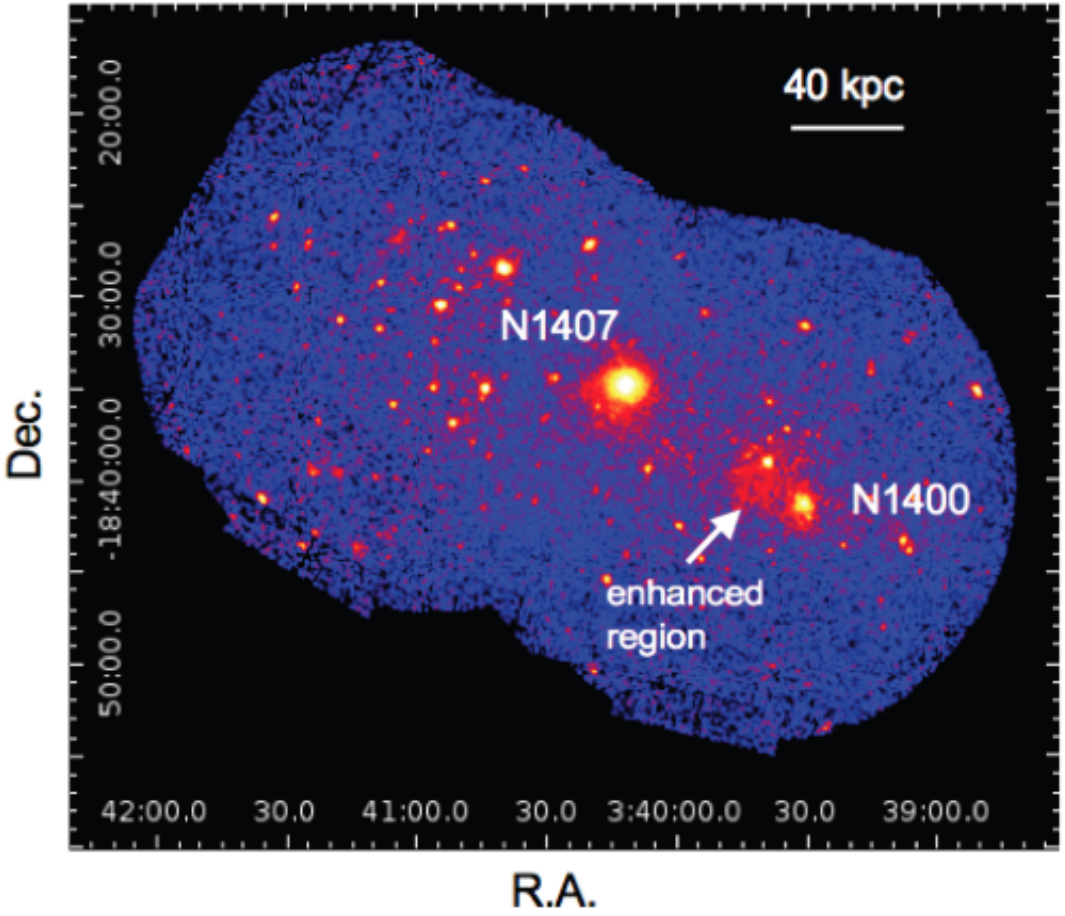


fossil

non-fossil

NGC1407/1400 complex PI: Y. Su

Su, Gu, White, & Irwin (2014)



Occasionally,
the infalling of new galaxies disqualify a group as a fossil group - transient

General Trend: a larger fraction of fossil groups at lower redshifts
Gozalisl et al. (2014)

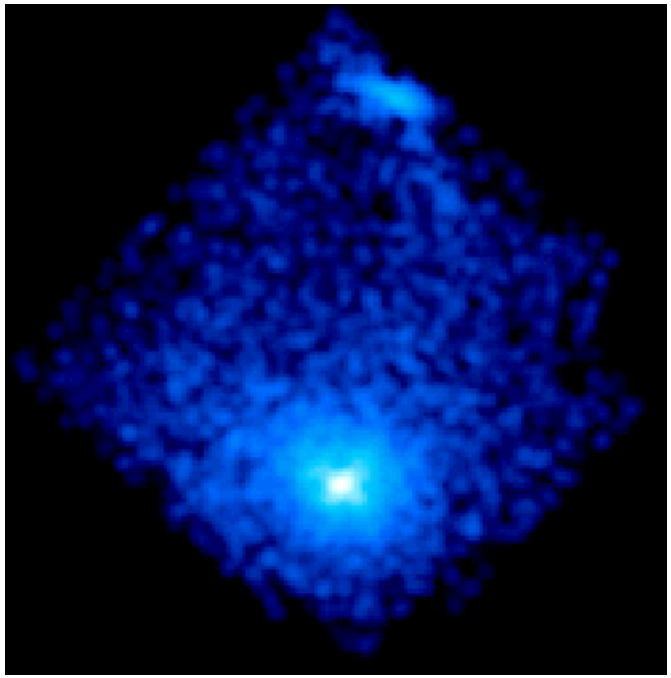
Summery

- Various explanations for flat entropy profiles found at the outskirts of galaxy clusters
- Fossil groups - bench mark of relaxed systems - more proper entropy behaviors

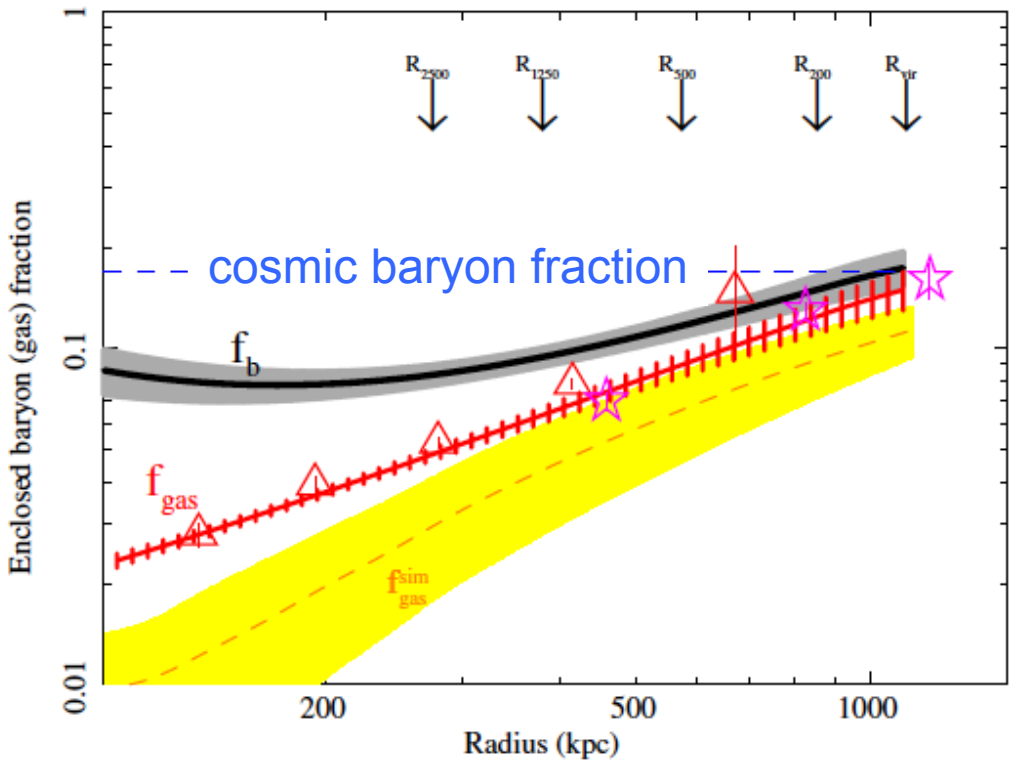
  - RXJ 1159+5531

  - ESO 3060170
- Next Step: galaxy groups, non-cool core clusters at R_{vir}
- Impact of large scale environment: unrelated? require larger sample

Fossil group RXJ1159+5531 kT ~ 2 keV



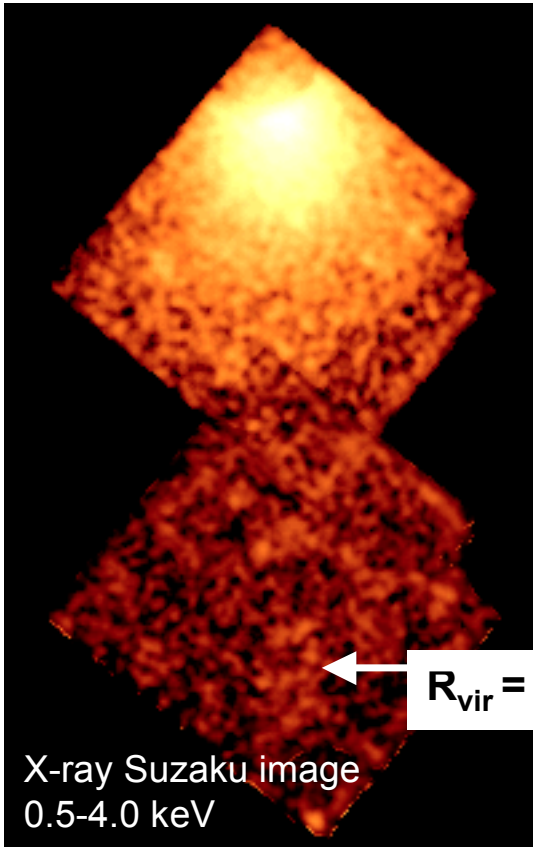
Suzaku X-ray Image

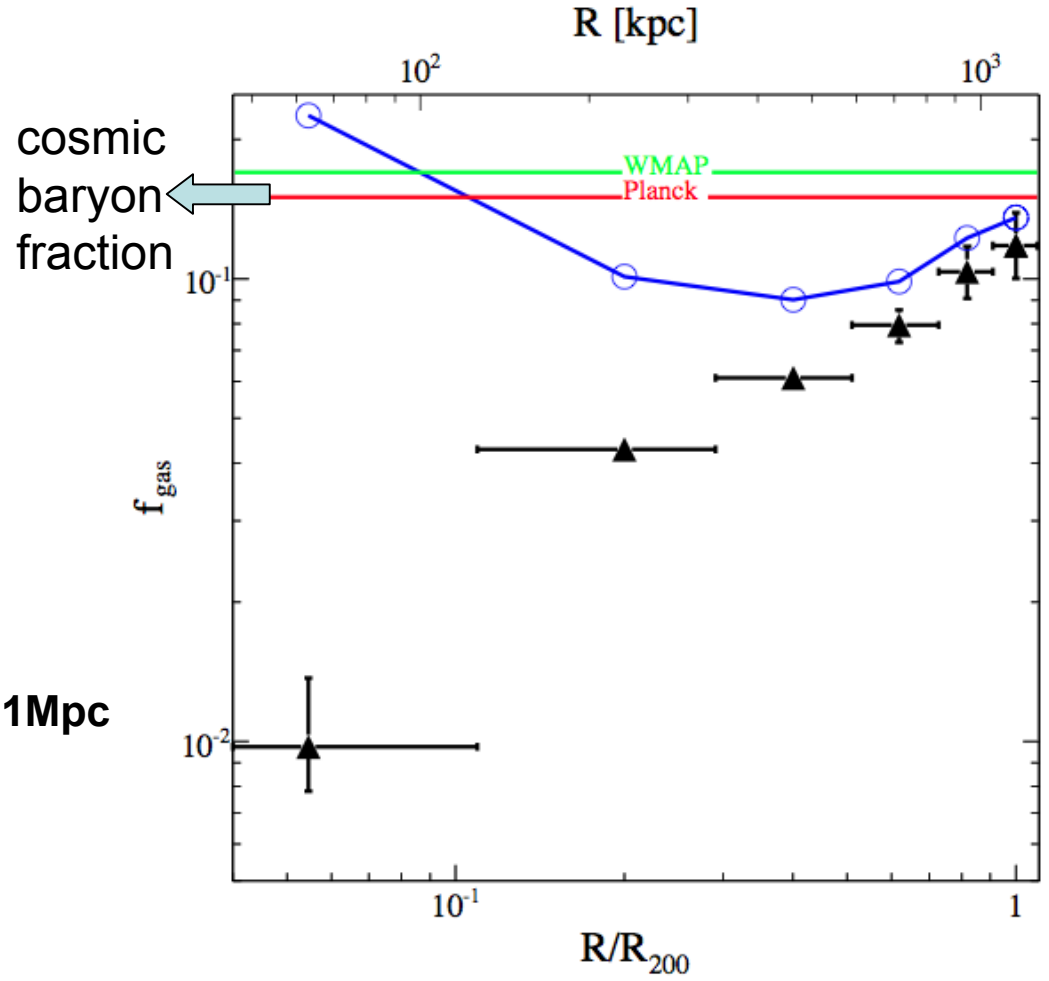


Humphrey et al. 2012

Fossil Group ESO 3060170 kT ~ 3 keV

PI: Y. Su



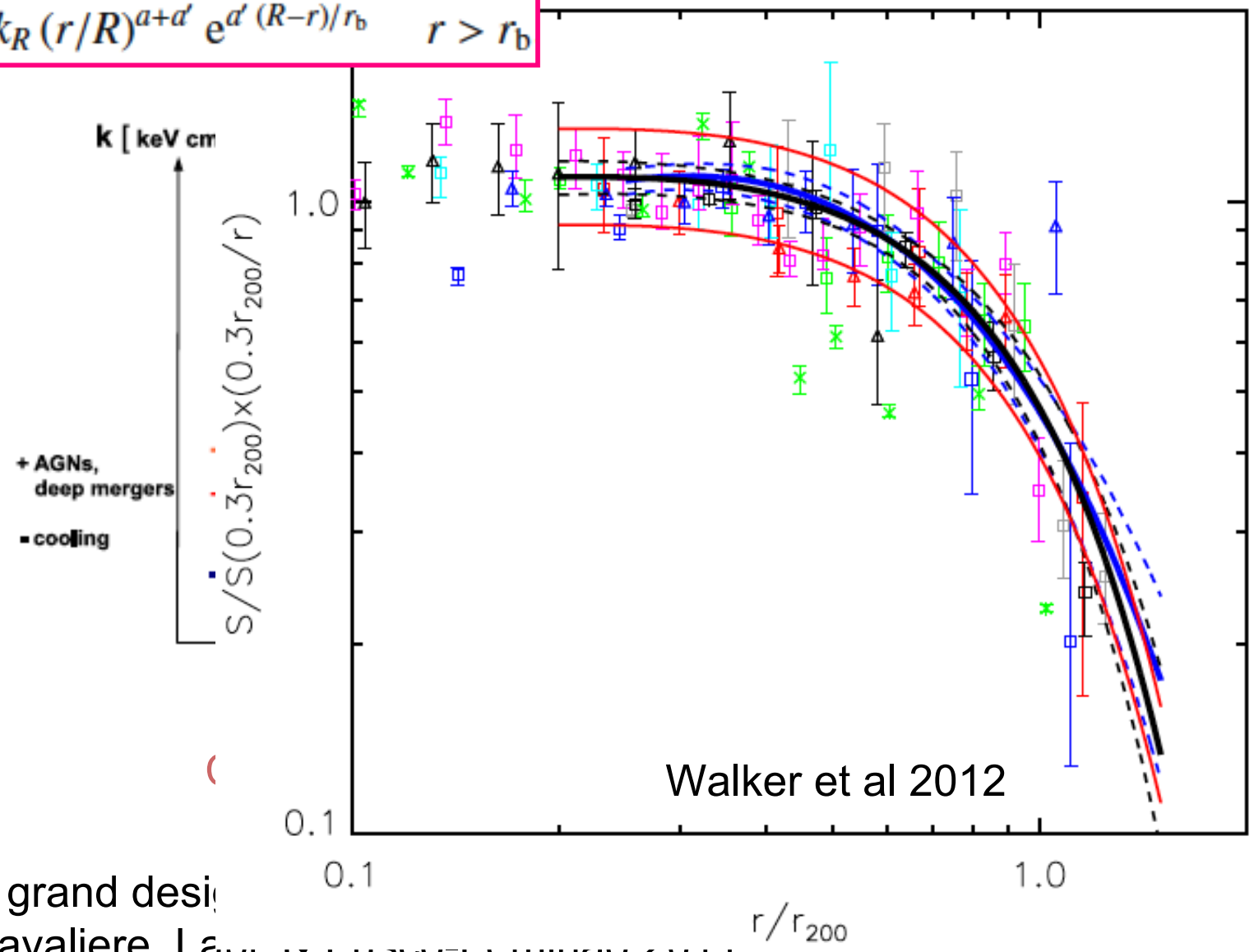


Su, White, & Miller 2013

True gas fraction should be even smaller!

$$k(r) = \begin{cases} k_c + (k_b - k_c)\,(r/r_b)^a & r \le r_b \\ k_R\,(r/R)^{a+a'}\,e^{a'\,(R-r)/r_b} & r > r_b \end{cases}$$

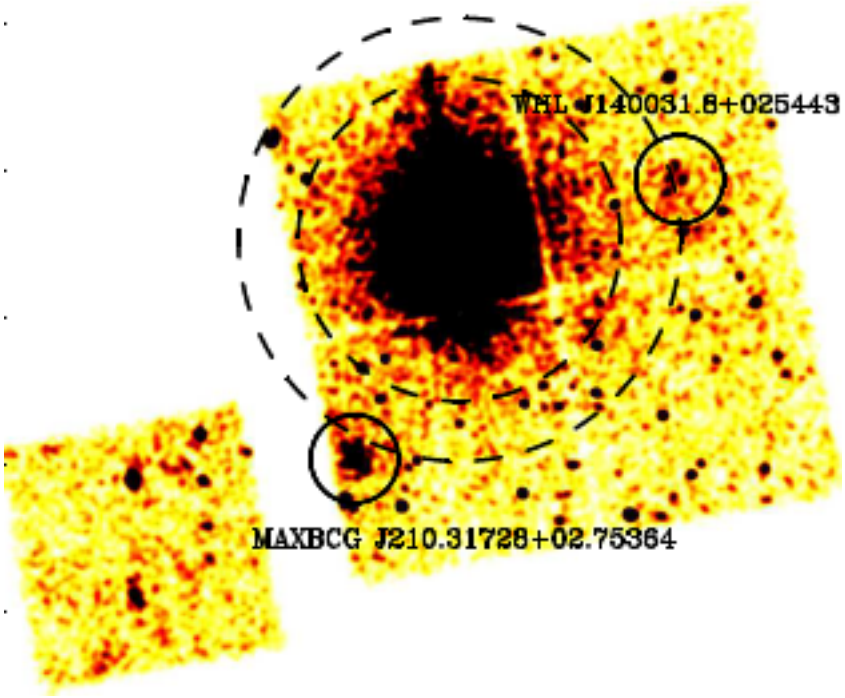
2: weakening of

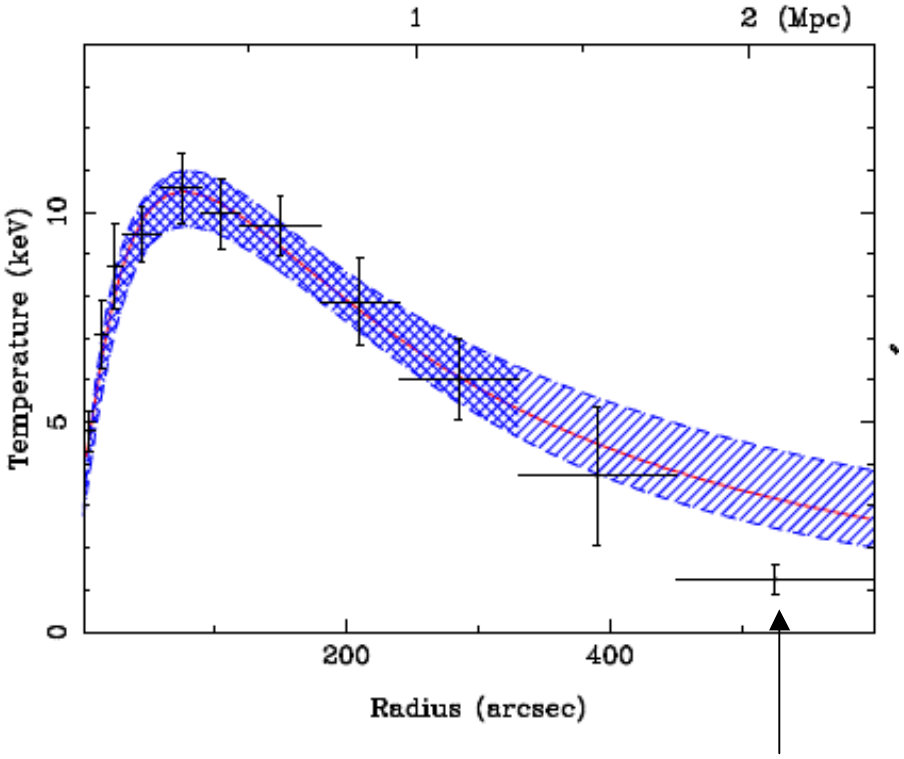


A grand desi

Cavaliere, La

Explanation #4: second phase of cold gas

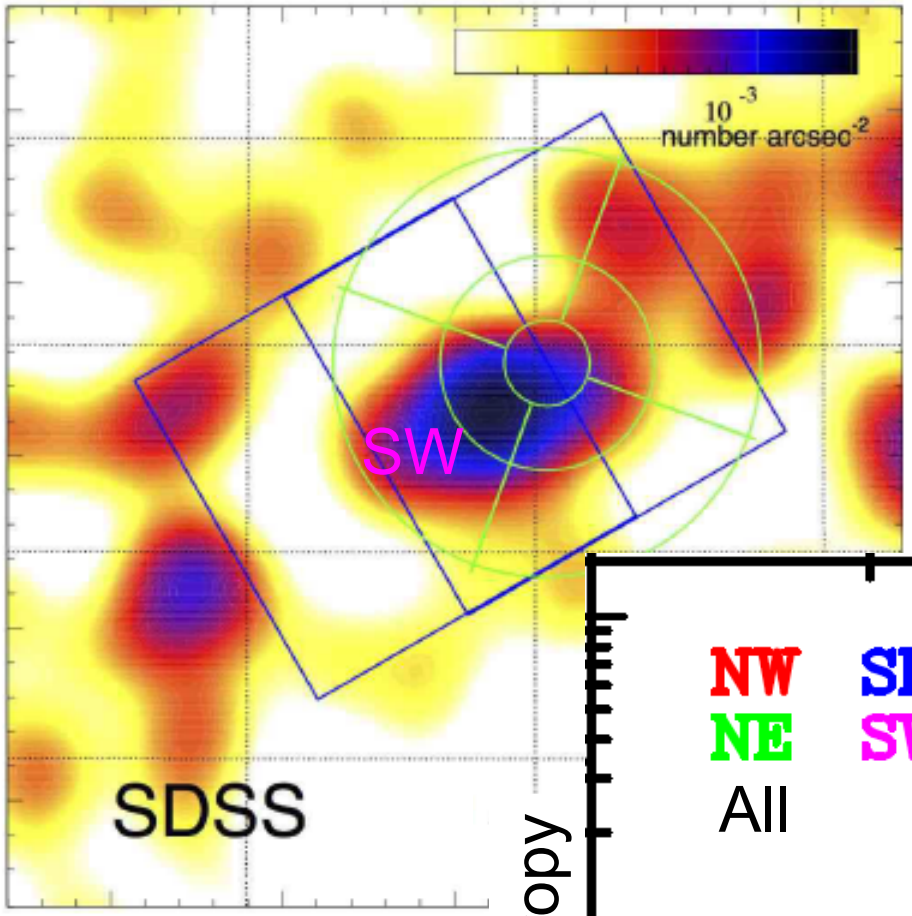




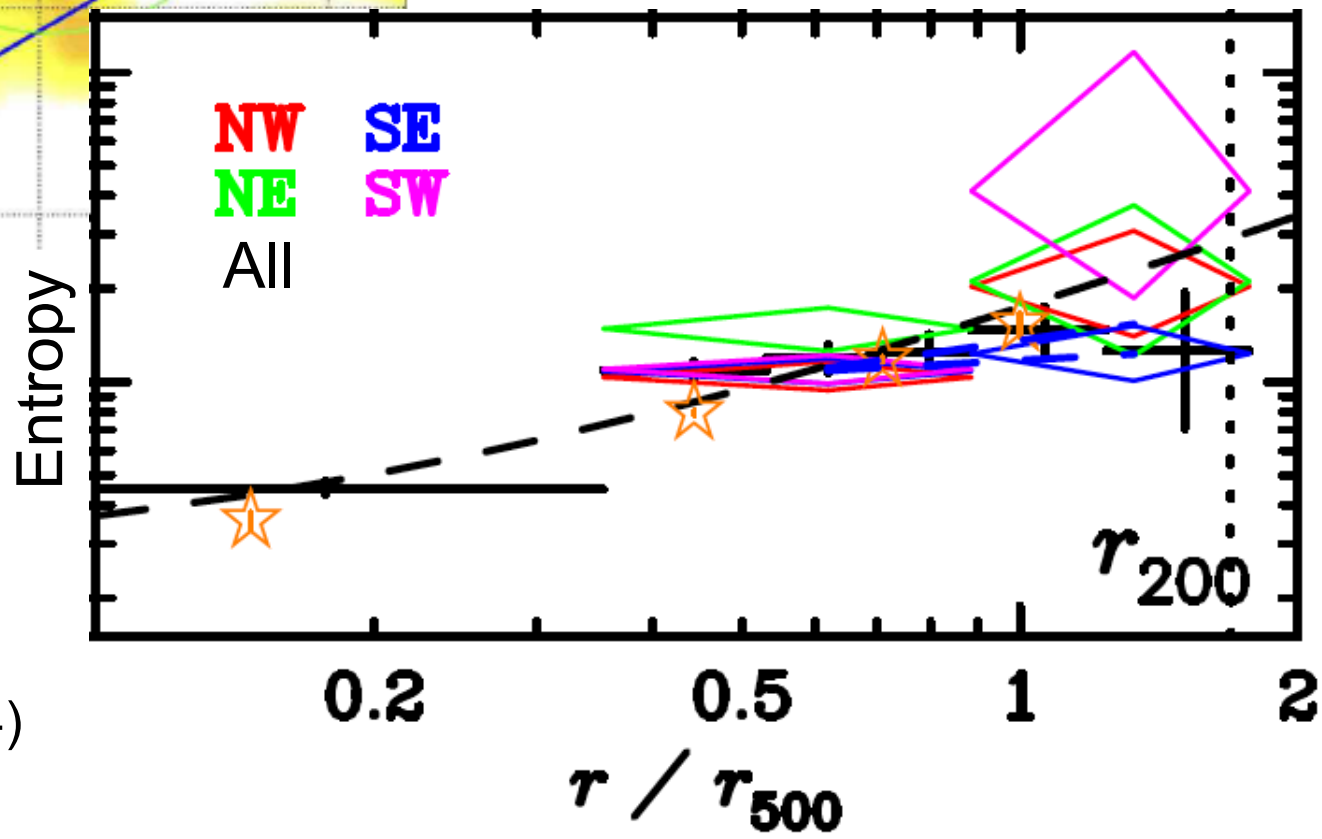
warm-hot gas at R_{vir}

Chandra observation of Abell 1835

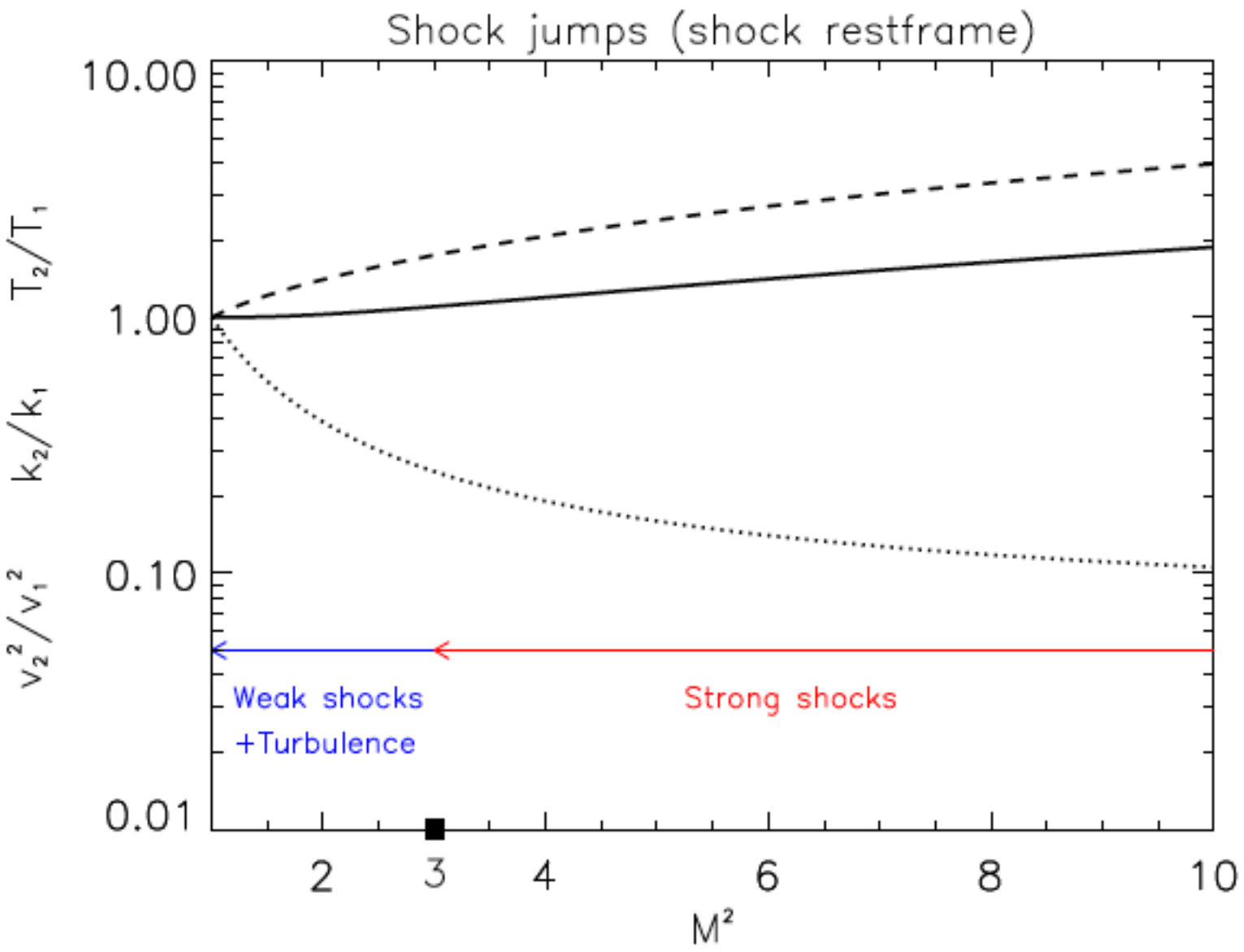
Bonamente et al. (2012)



High galaxy density direction corresponds to large entropy



Abell 1246
(Sato et al. 2014)


Shock jumps (shock restframe)
10.00
1.00
0.10
0.01
T_2/T_1
k_2/k_1
v_2^2/v_1^2
Weak shocks
+Turbulence
Strong shocks
2
3
4
6
8
10
M^2