

XMM 20th anniversary: Galaxy Clusters Structure and Feedback

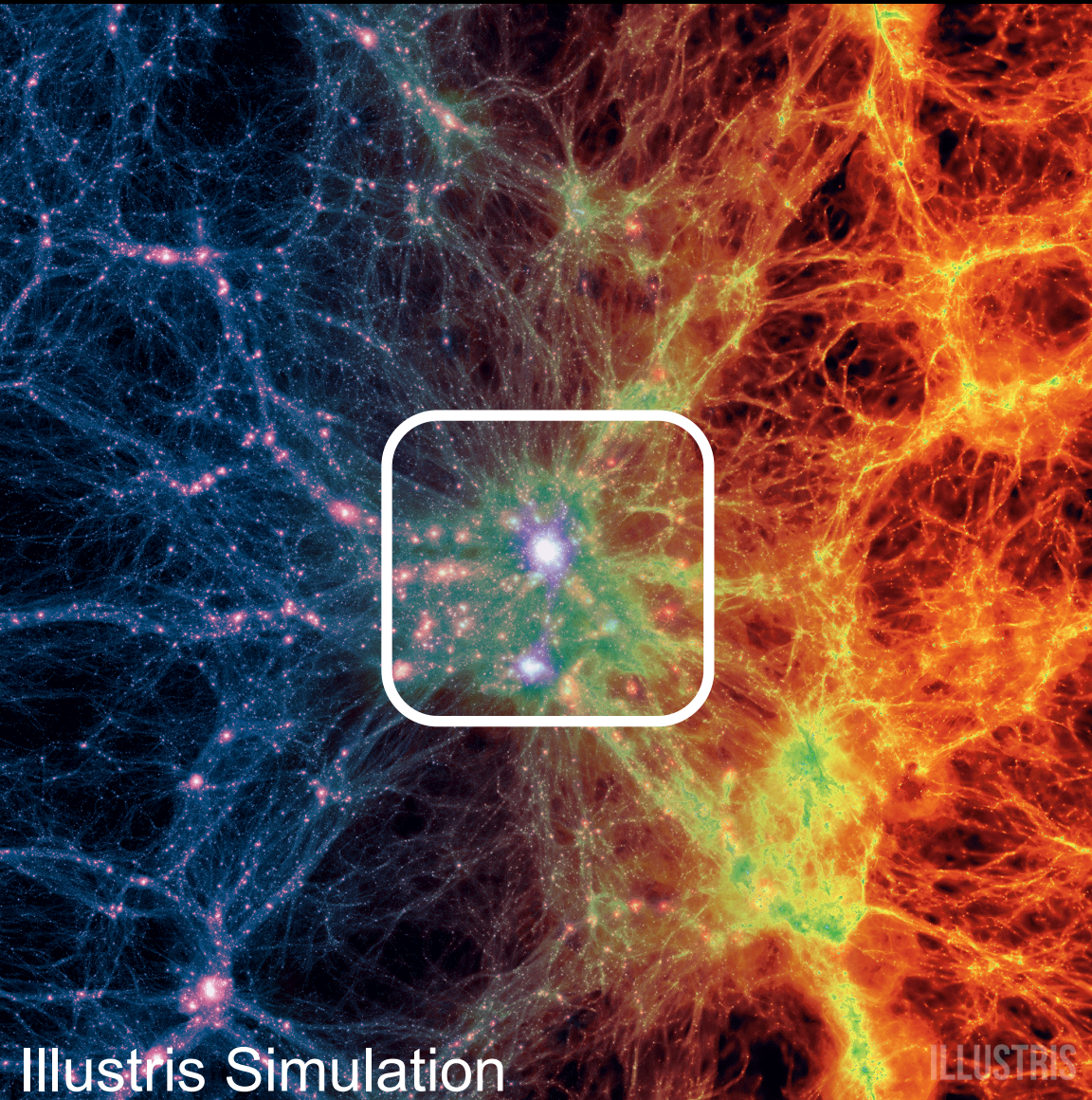
Fabio Gastaldello (INAF-IASF Milano)

Why Galaxy Clusters ?



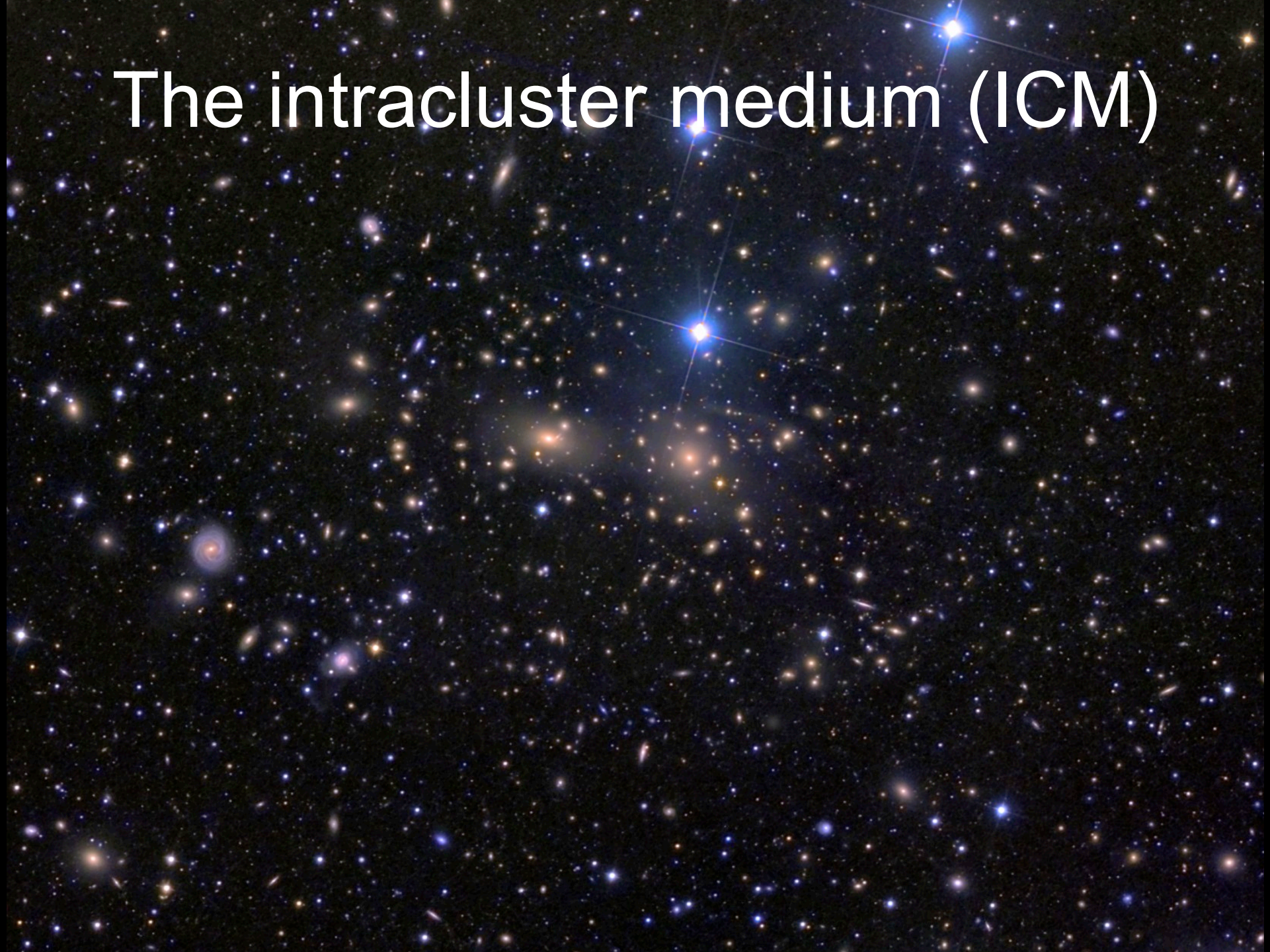
- Clusters as cosmological probes: structure formation and cosmological parameters estimate (next talk by M. Arnaud)
- Clusters as astrophysical laboratories: structure formation, chemical enrichment, DM properties, plasma physics

Clusters of galaxies

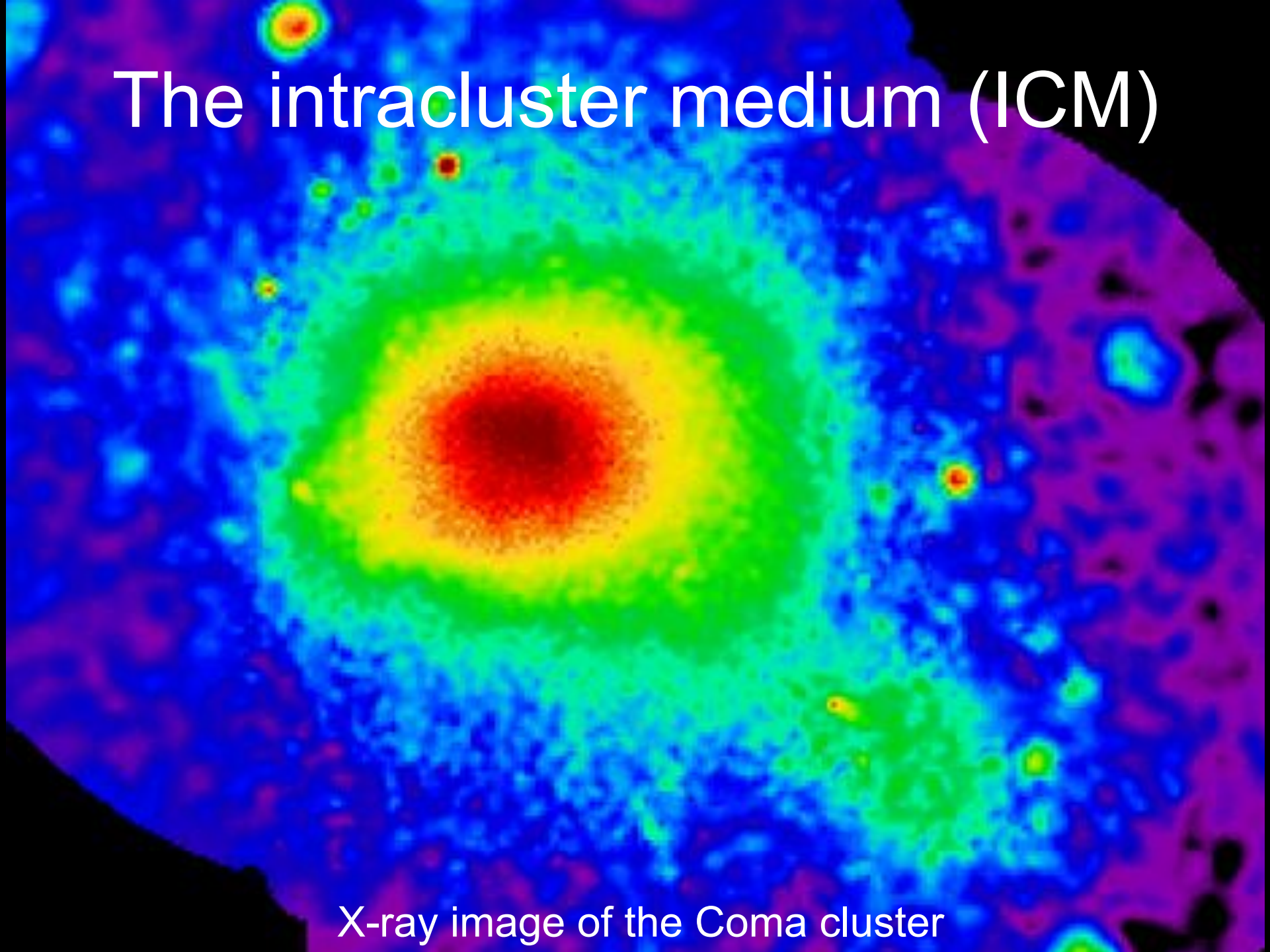


- They form at the intersection of the cosmic web
- The greatest structures to decouple from the Hubble flow
- Dimension of the order of the Mpc
- Masses 10^{14} - $10^{15} M_{\text{sun}}$ (75-90% Dark Matter)

The intracluster medium (ICM)

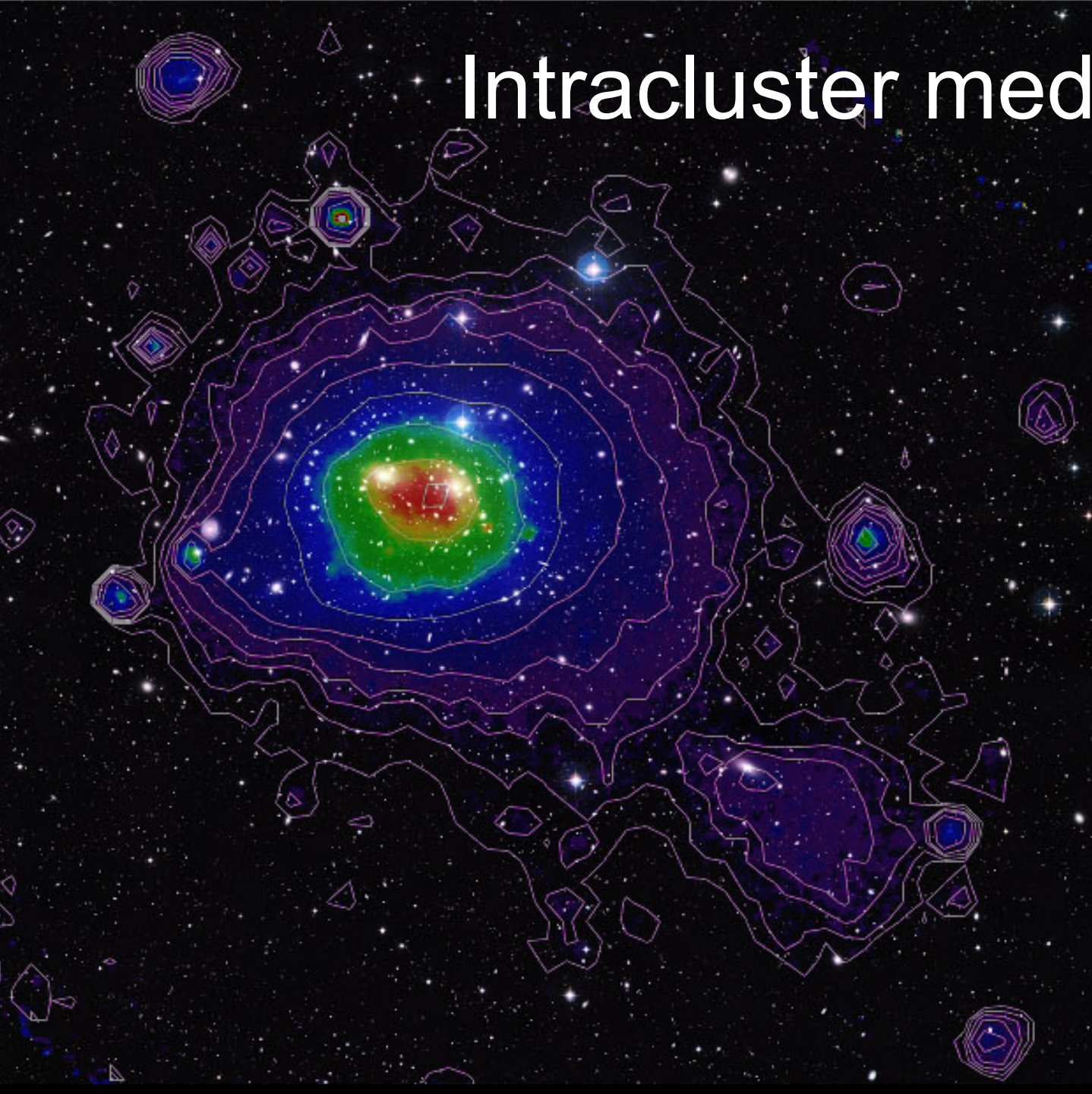


The intracluster medium (ICM)



X-ray image of the Coma cluster

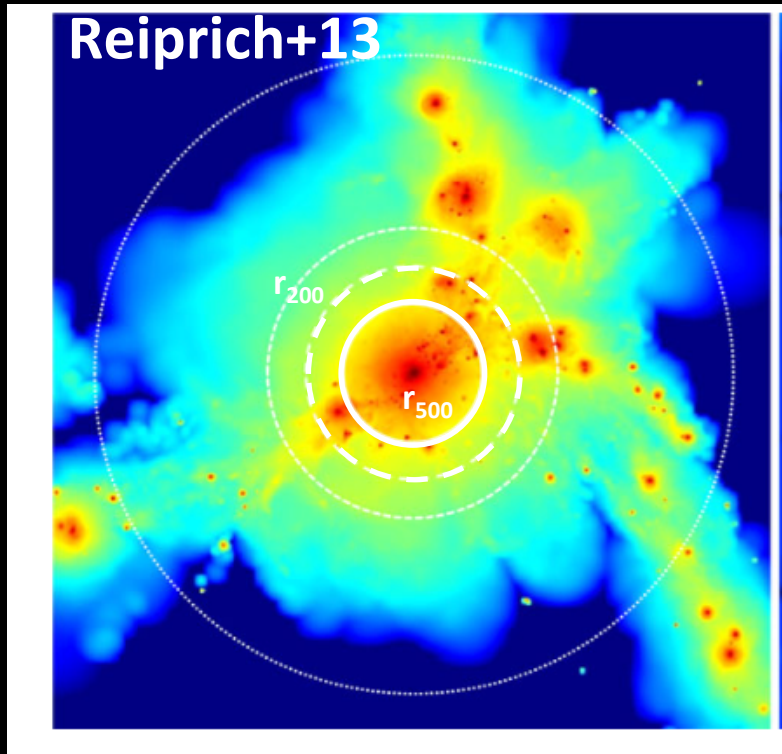
Intracluster medium (ICM)



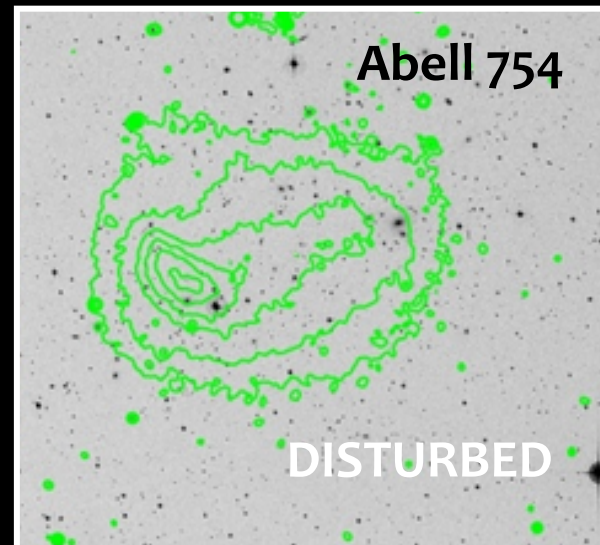
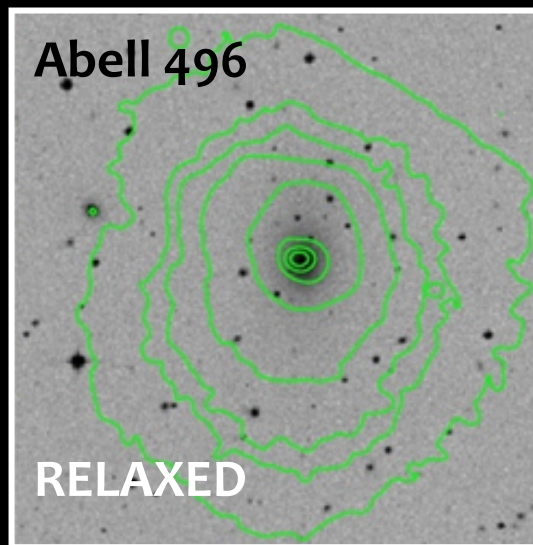
- Hot with temperatures 10^7 - 10^8 K or 1-10 keV
- Low density (10^{-2} - 10^{-4} particles/cm³)
- Mainly H and He completely ionized. Chemically enriched with heavy elements (C, O, Si, Fe)
- Dominant baryonic component
- Bremsstrahlung: n^2 dependence

Glossary

Credits:
B. Maughan

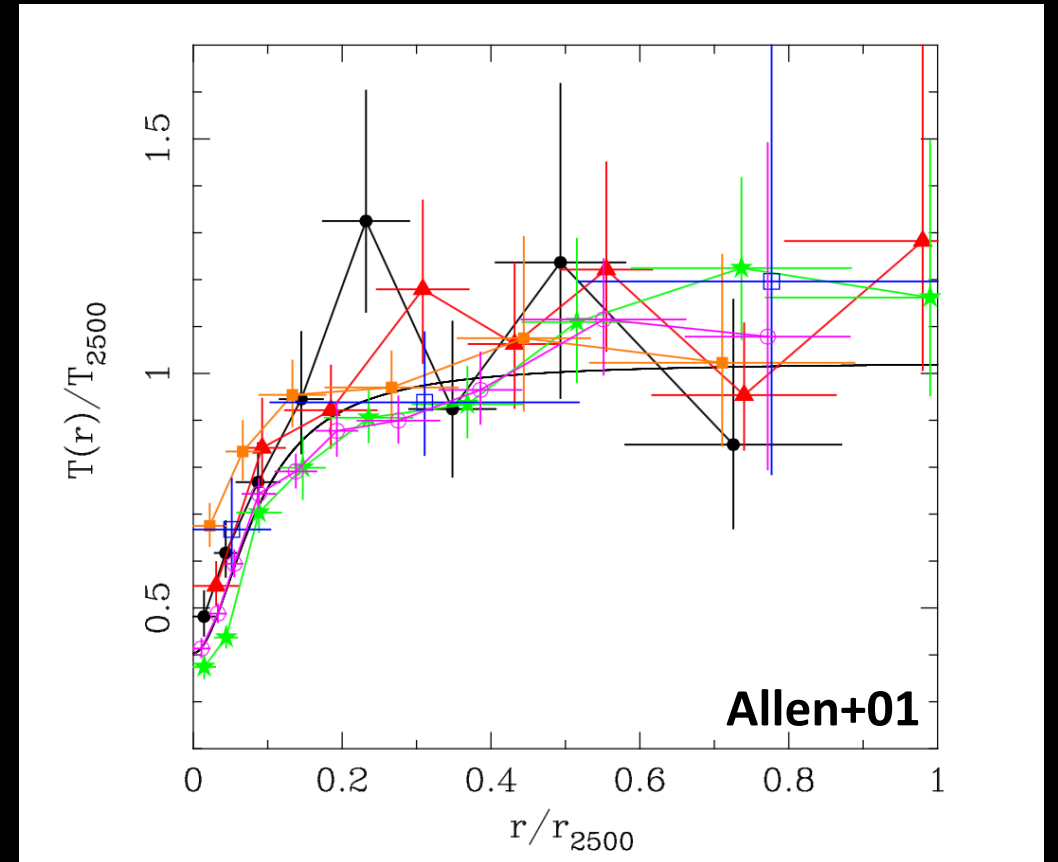
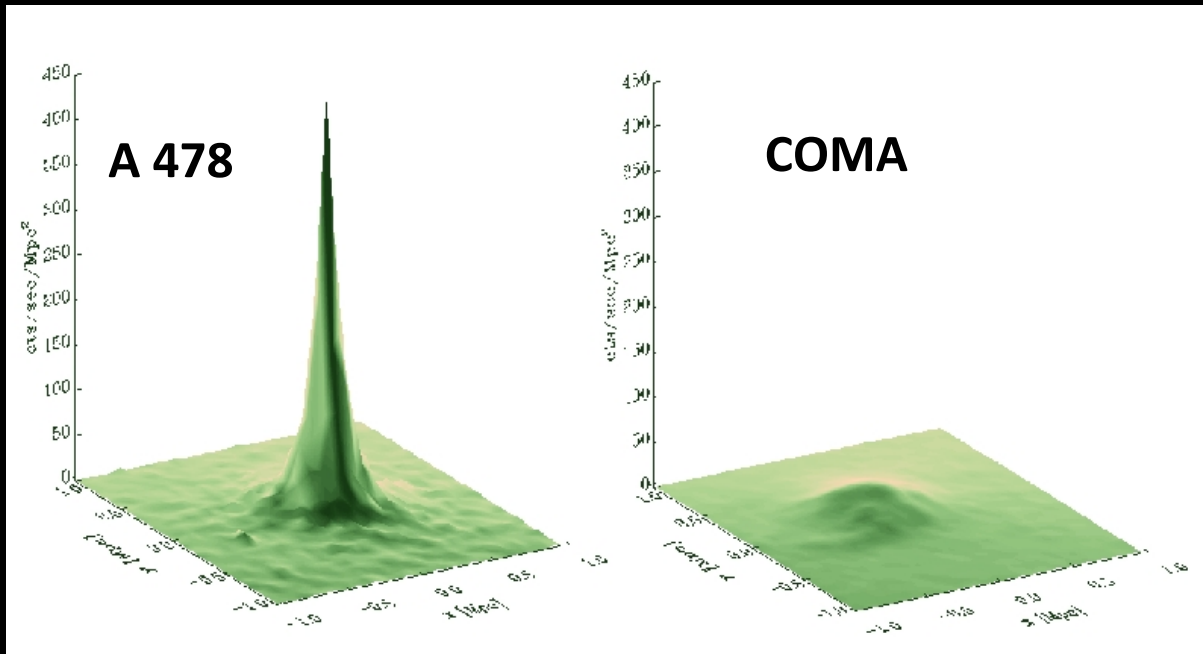


If only gravity works, clusters of different masses are scaled versions of each other and we expect power-laws relations between observables (L, T, etc.) and mass (Kaiser 86)



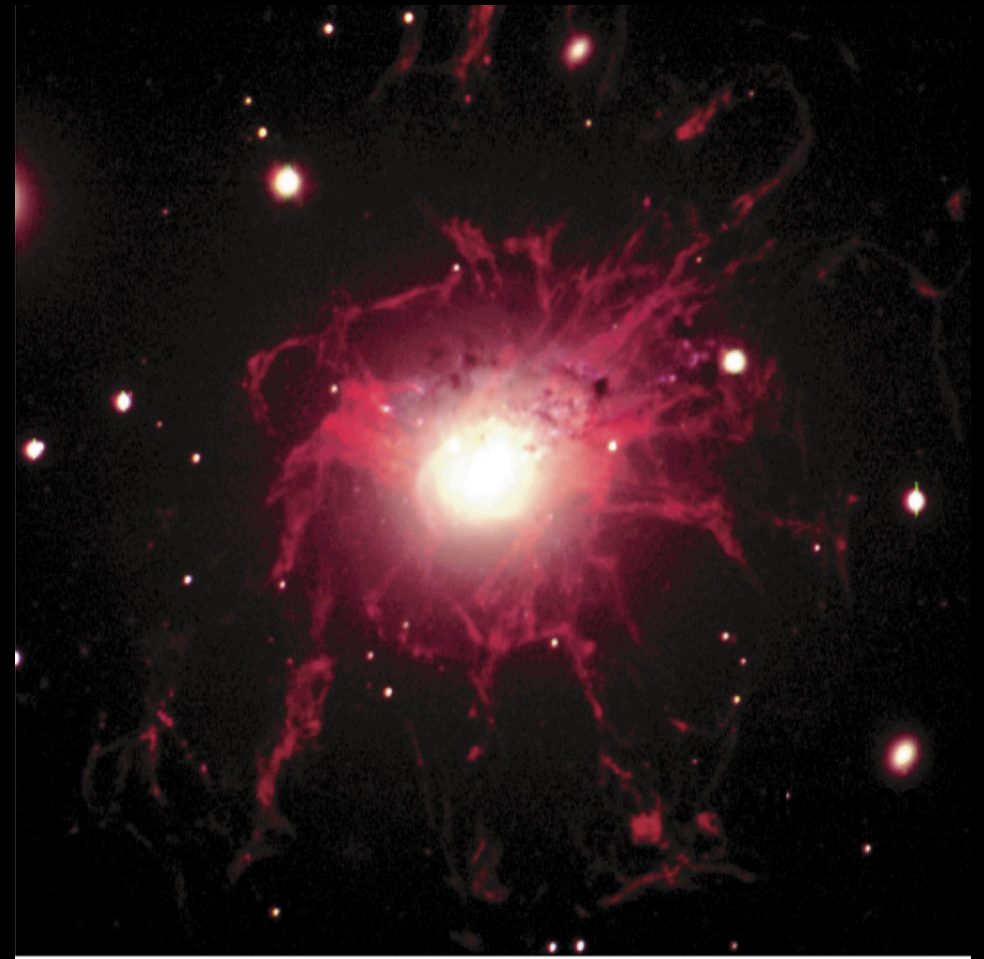
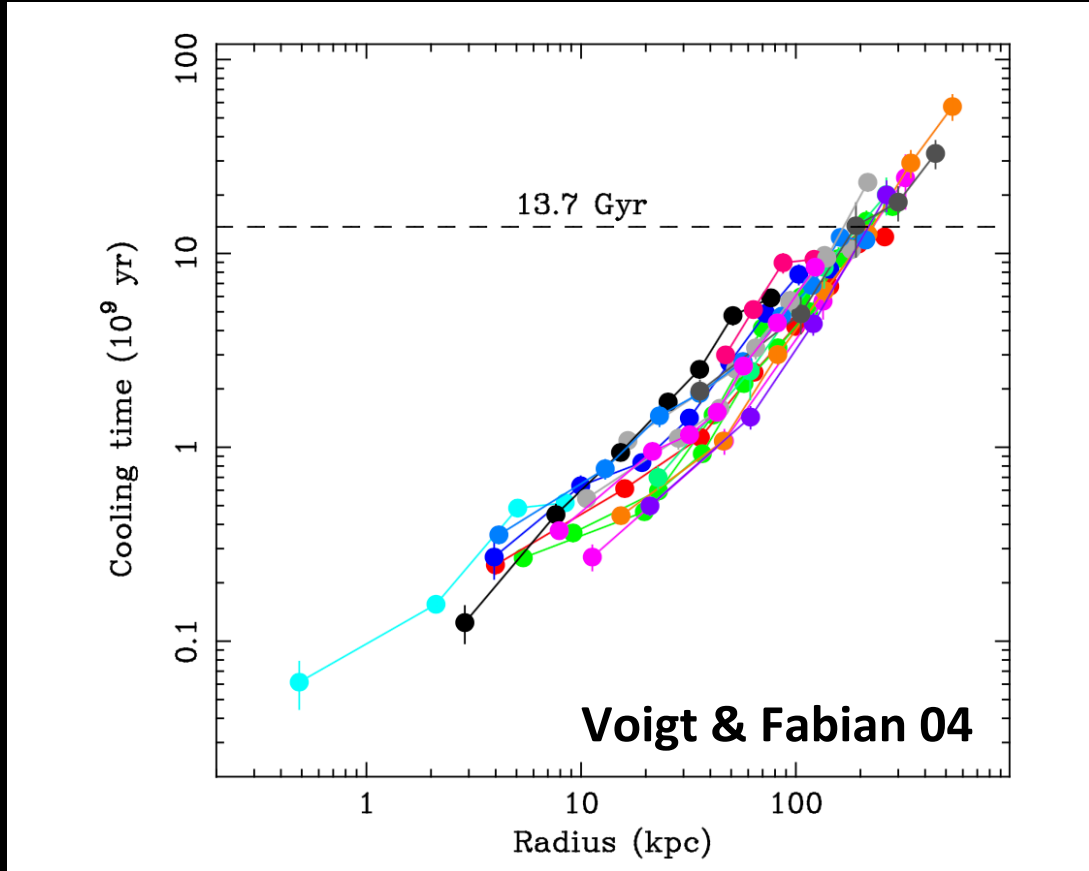
1. Falsification of the steady cooling flow model

- Great debate until the early 2000s: there was evidence of cool temperatures in the center of the peaked surface brightness clusters with cooling times smaller than the Hubble time



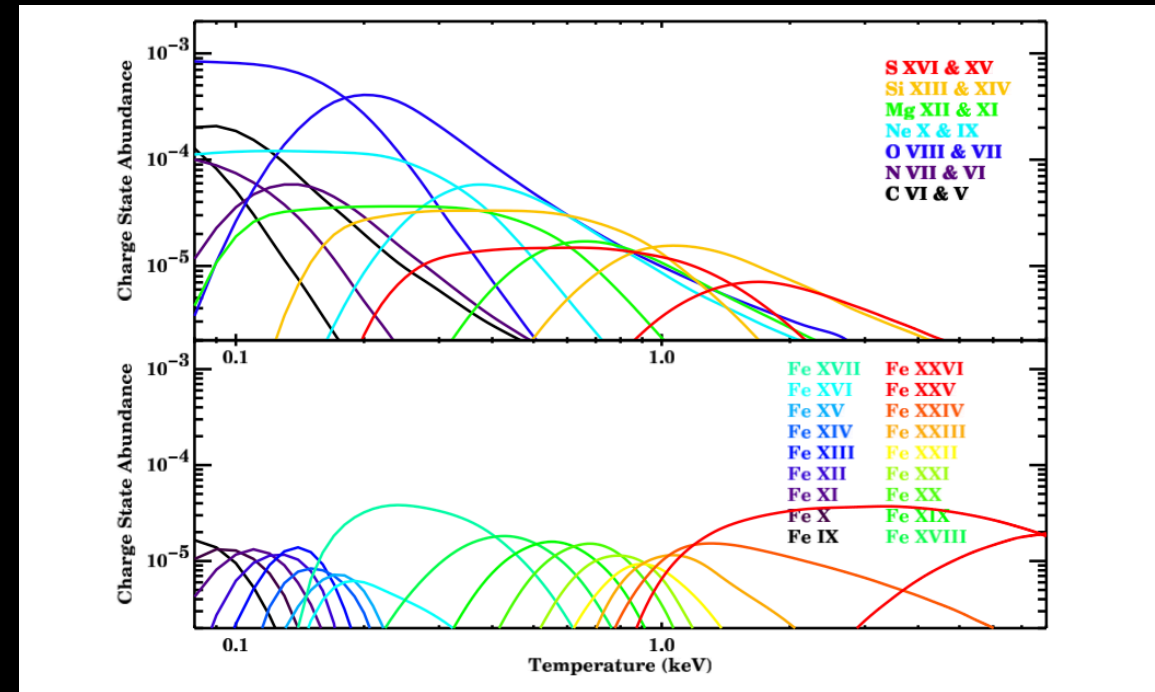
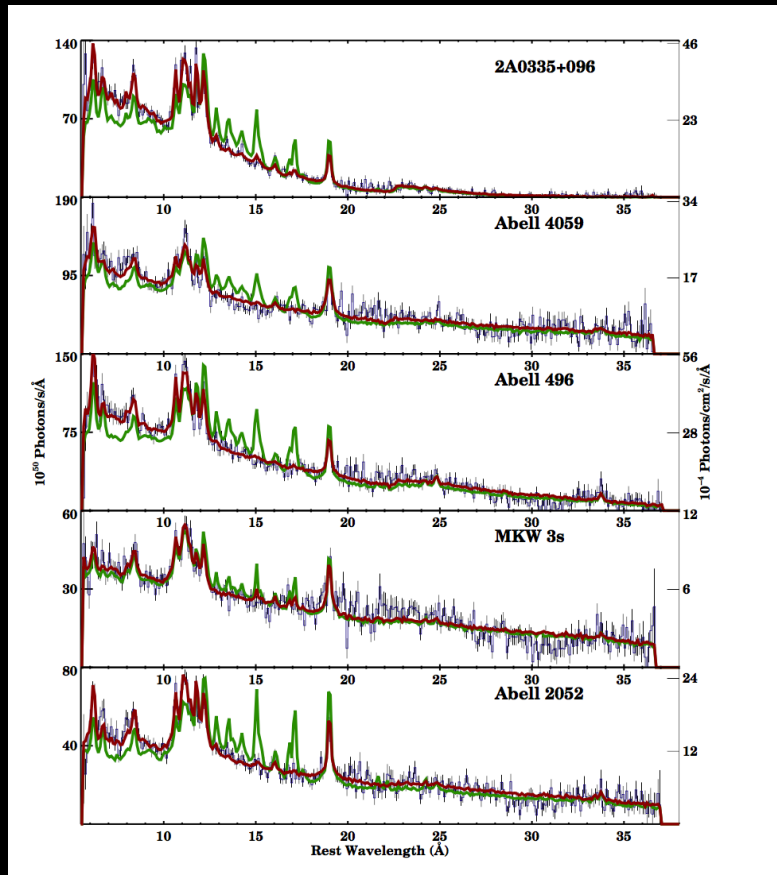
1. Falsification of the steady cooling flow model

- “In the absence of heating a cooling flow must occur”. Cooling flow rates could be 10^2 - 10 M/yr. Only smaller fraction (few %) of all this gas was found at various wavelengths



1. Falsification of the steady cooling flow model

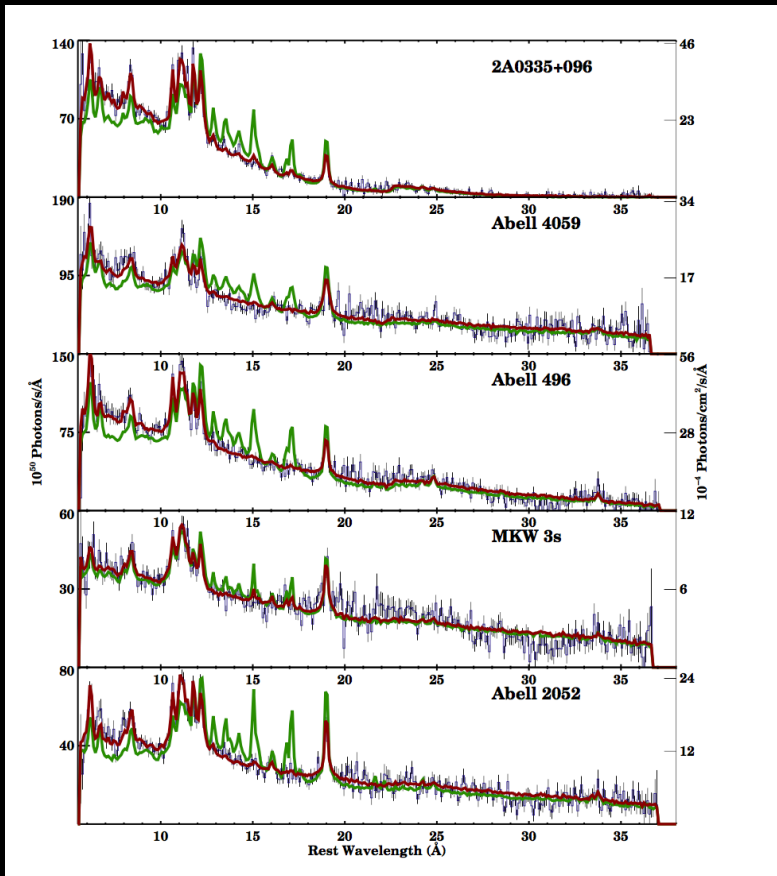
- RGS and EPIC spectra of the core of the clusters found no evidence for gas cooling at low temperatures below $T_{\text{vir}}/3$. There must be a heating source !



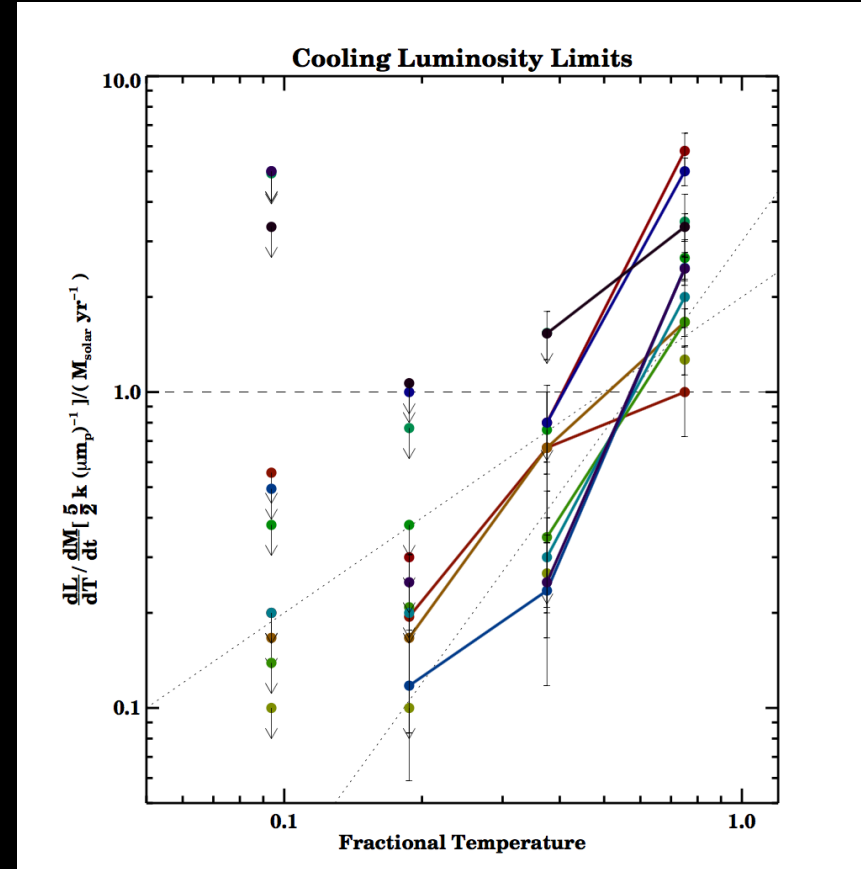
Peterson+03

1. Falsification of the steady cooling flow model

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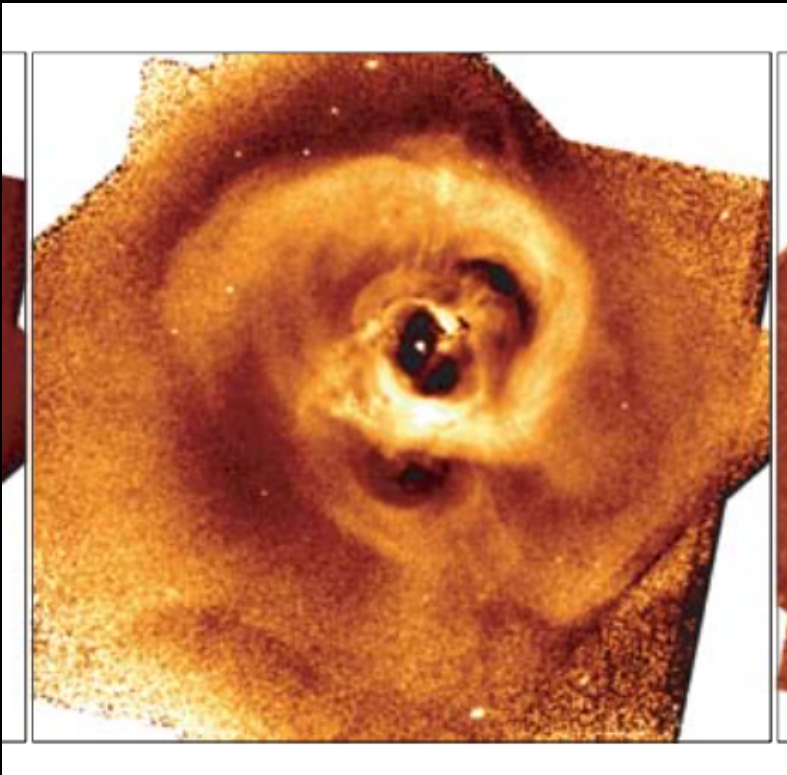


Peterson+03

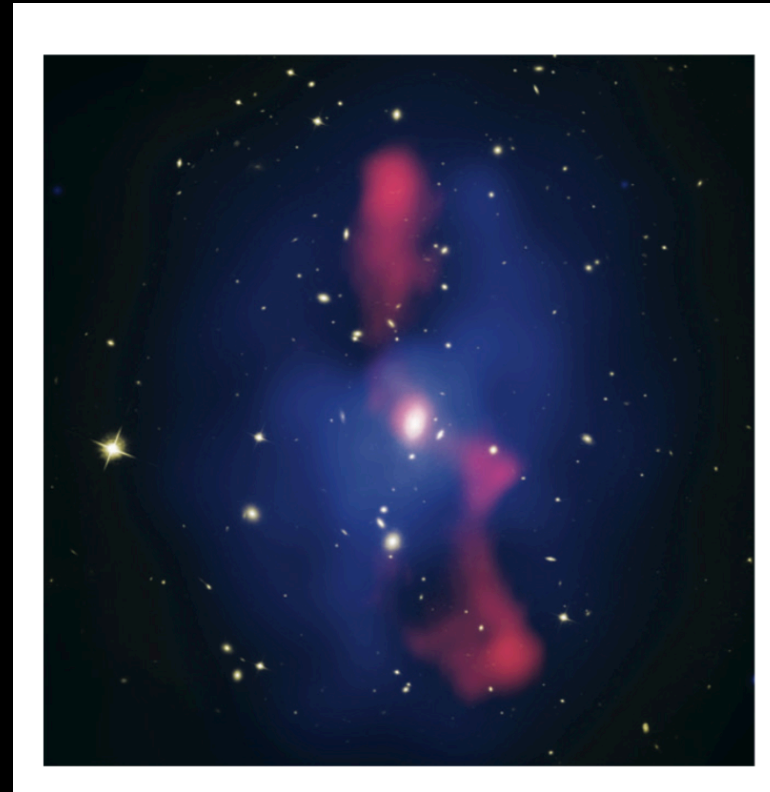


AGN feedback in the ICM

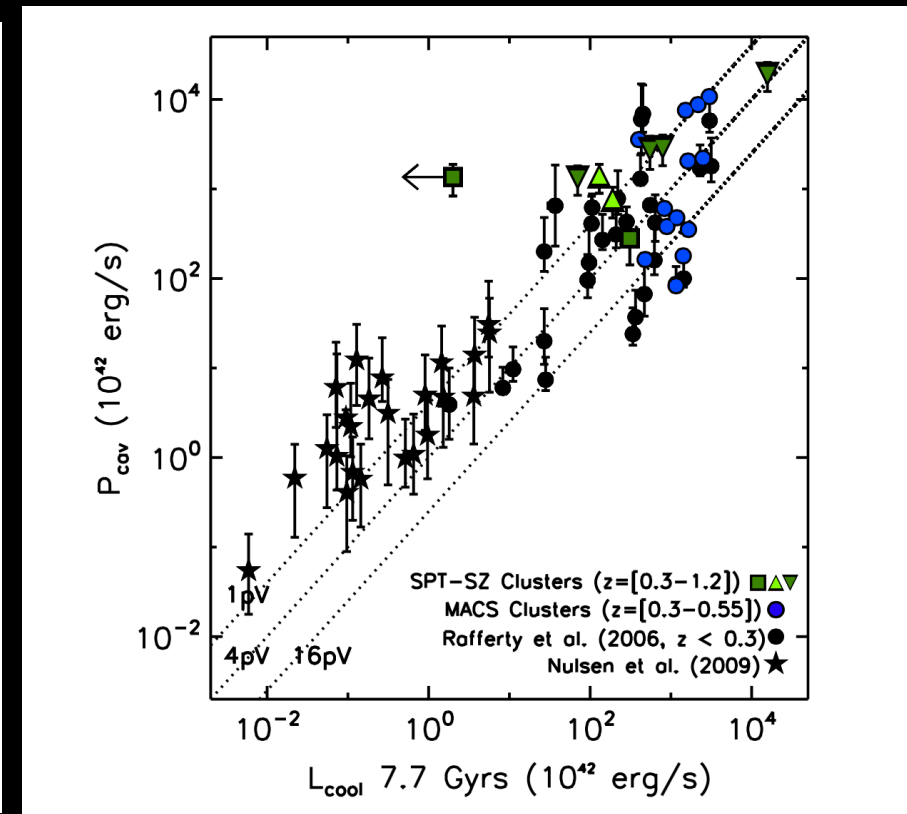
- Feedback from the central supermassive BH by means of cavities mechanically inflated by its radio jets, weak shocks and possibly turbulence is the way to balance cooling and heating



Perseus Sanders+07



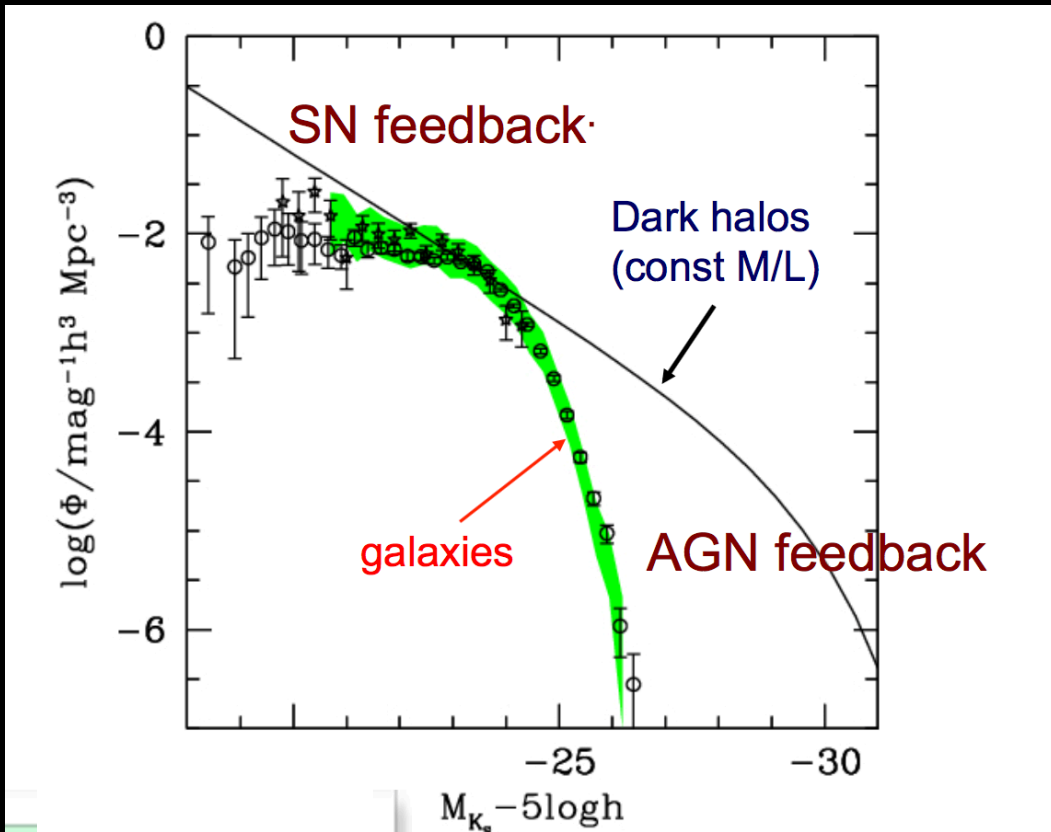
MS 0735+7241 McNamara+05



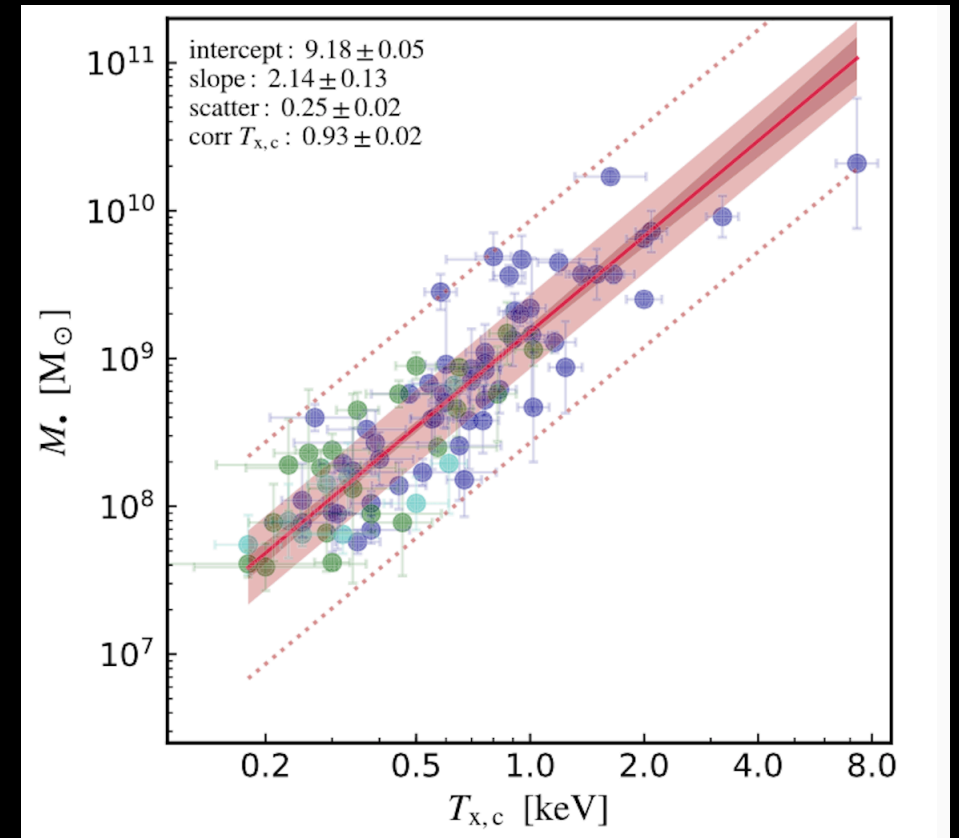
Hlavacek-Larrondo+15

AGN feedback in the ICM

- AGN feedback has broad astrophysical implications for galaxy formation, explaining the truncation of the high end of the luminosity function, the symbiosis of BHs and stellar and gaseous halos



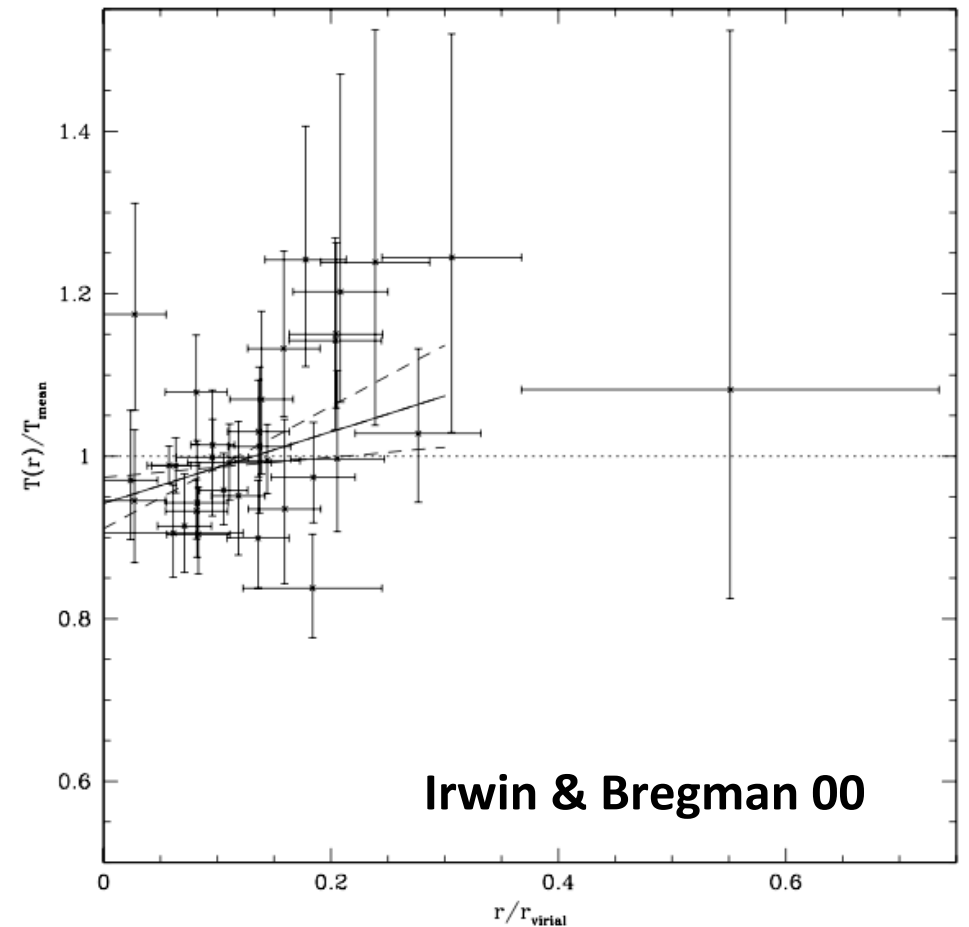
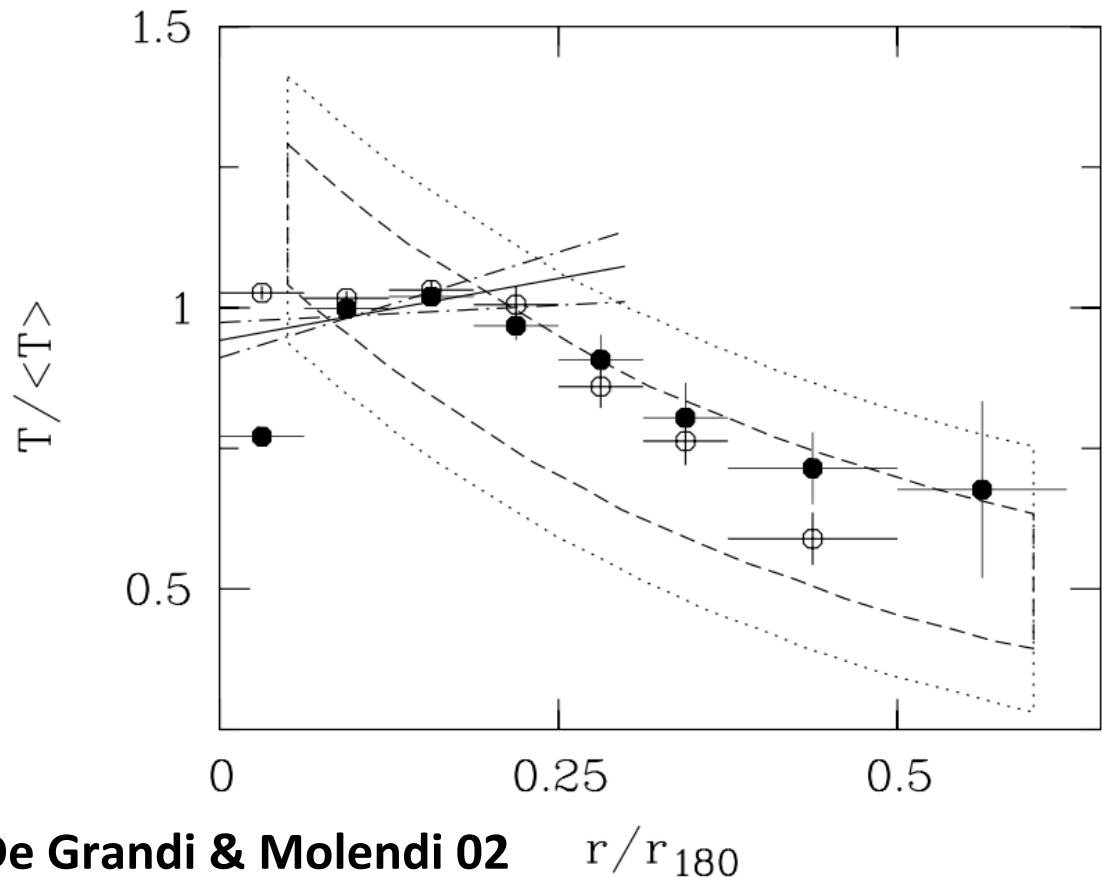
Benson+03



Gaspari+19

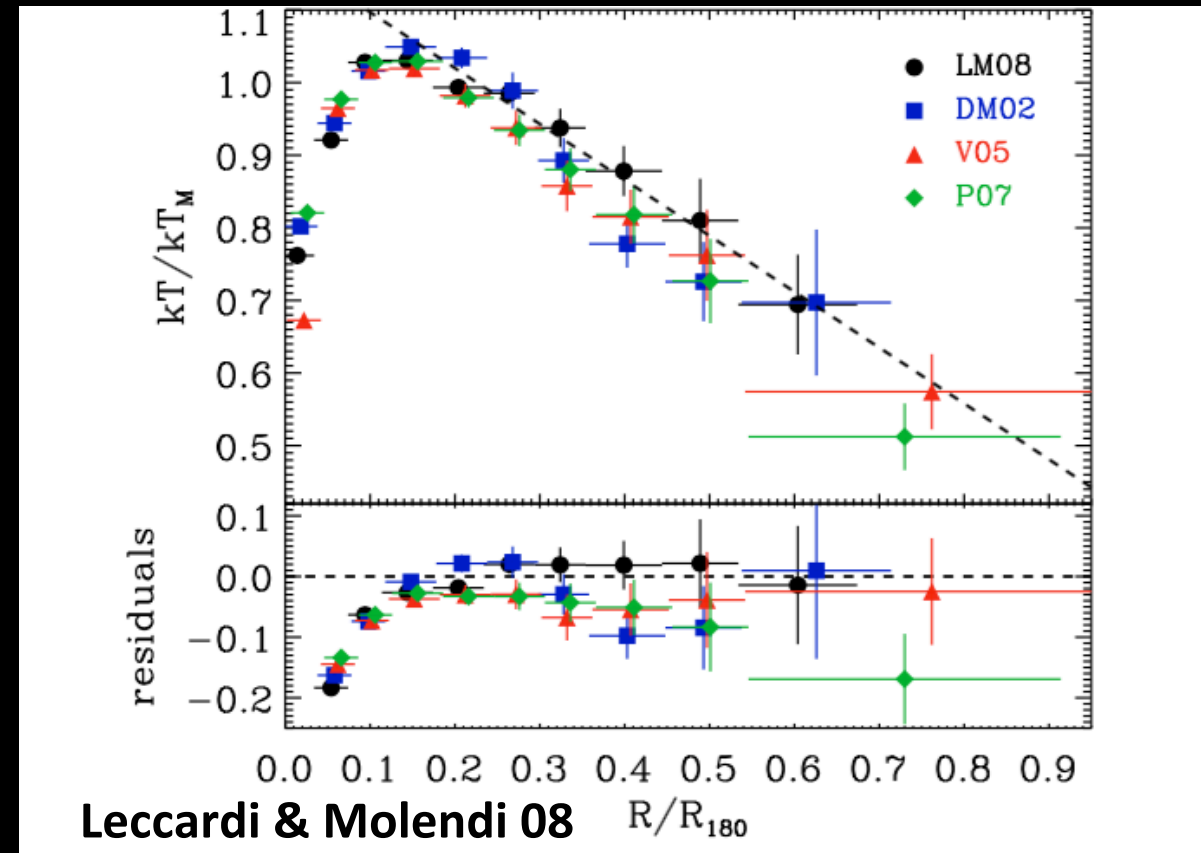
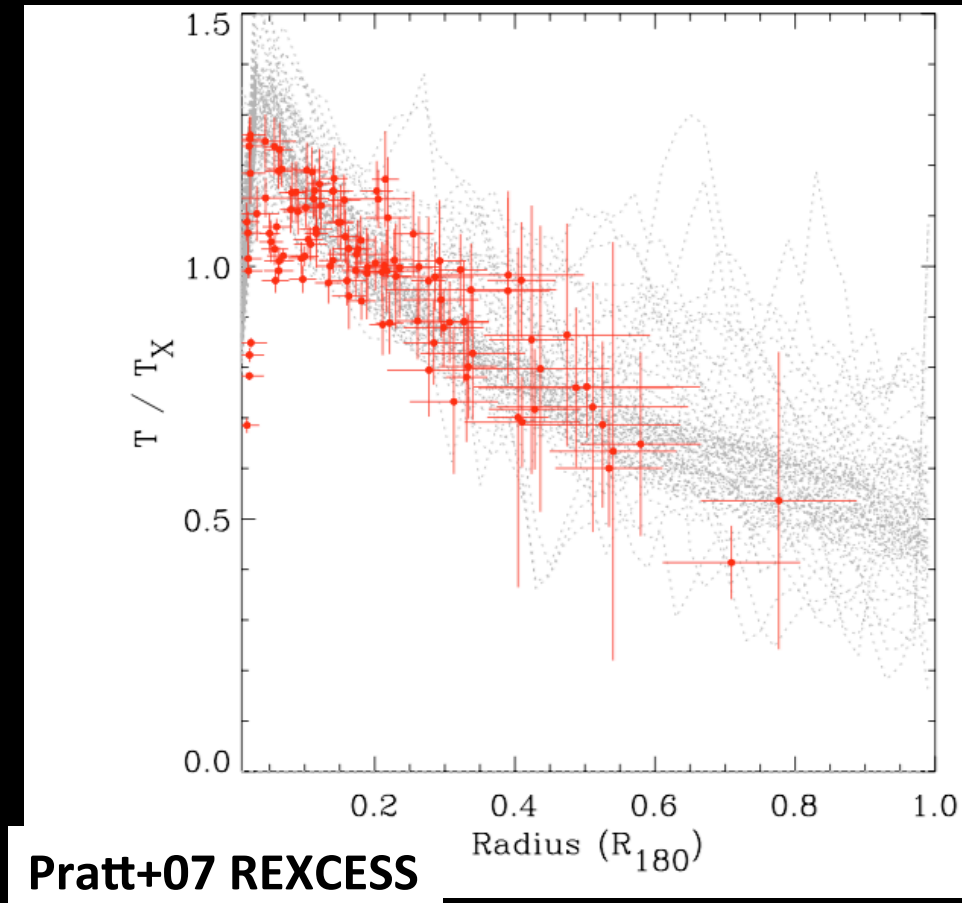
2. Shape of temperature profiles

- Conflicting evidence with SAX and ASCA data: isothermal or declining at large radii ?



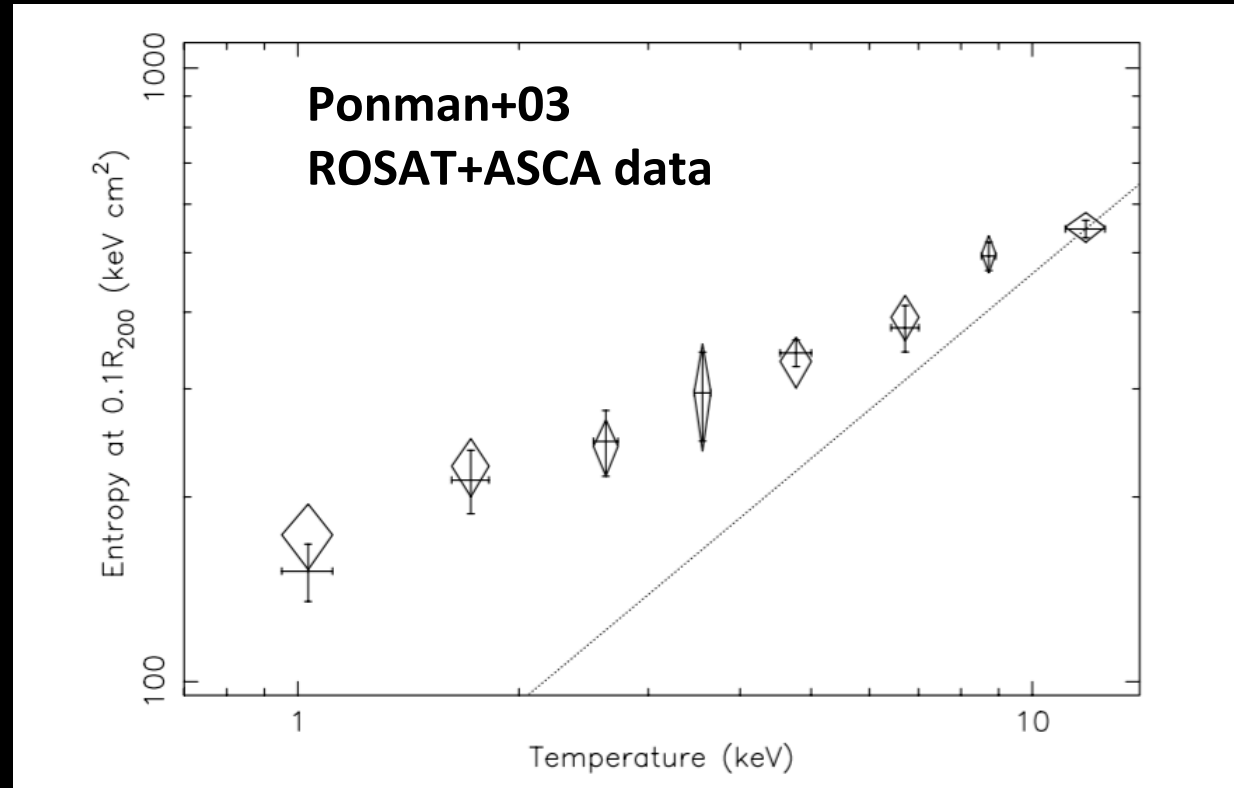
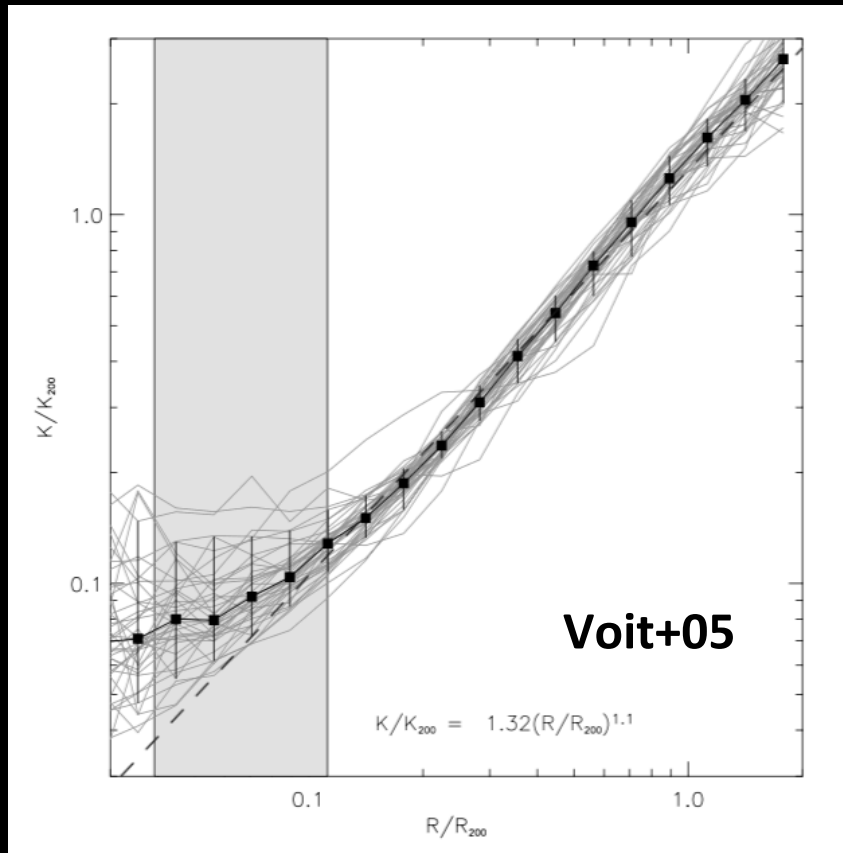
2. Shape of temperature profiles

- XMM (and Chandra) definitively settled the issue. Temperature declines in agreement with numerical simulations (simpler physics in external regions)



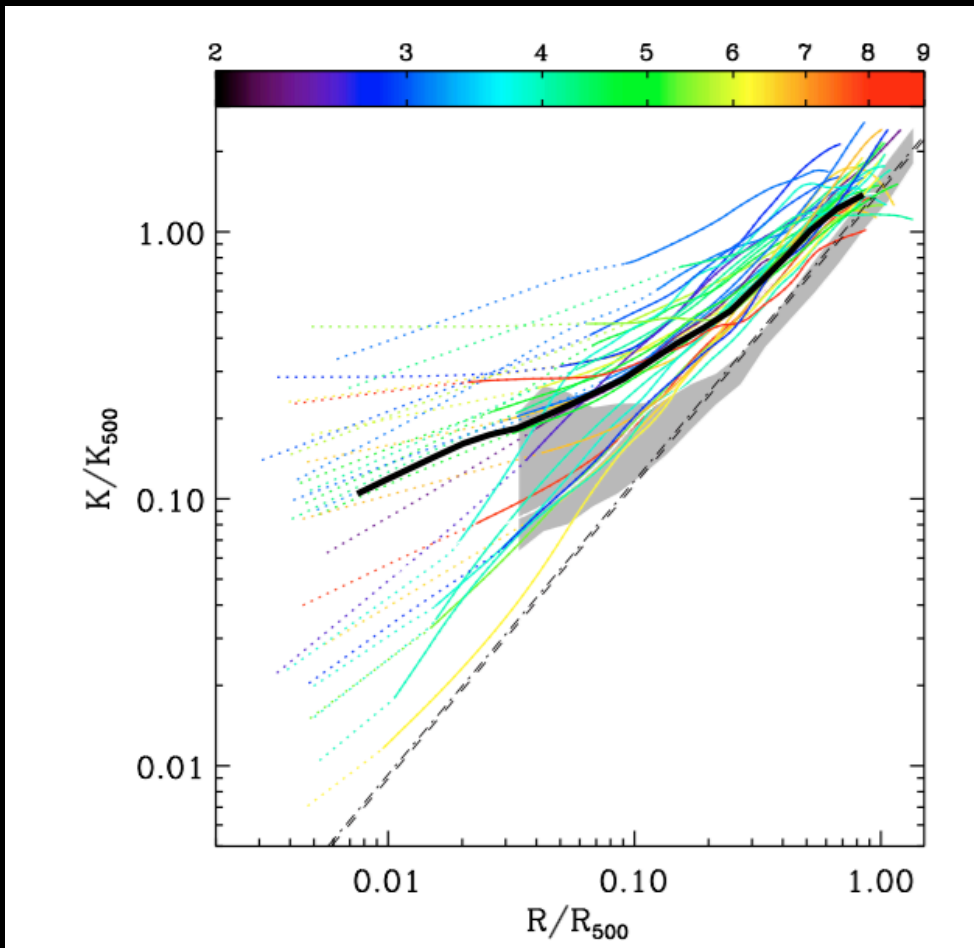
3. Entropy profiles

- Entropy, $S=kT/n_e^{2/3}$, is a key quantity related to non-gravitational feedback. Its radial profiles in objects of different masses reveals the details of the various astrophysical processes

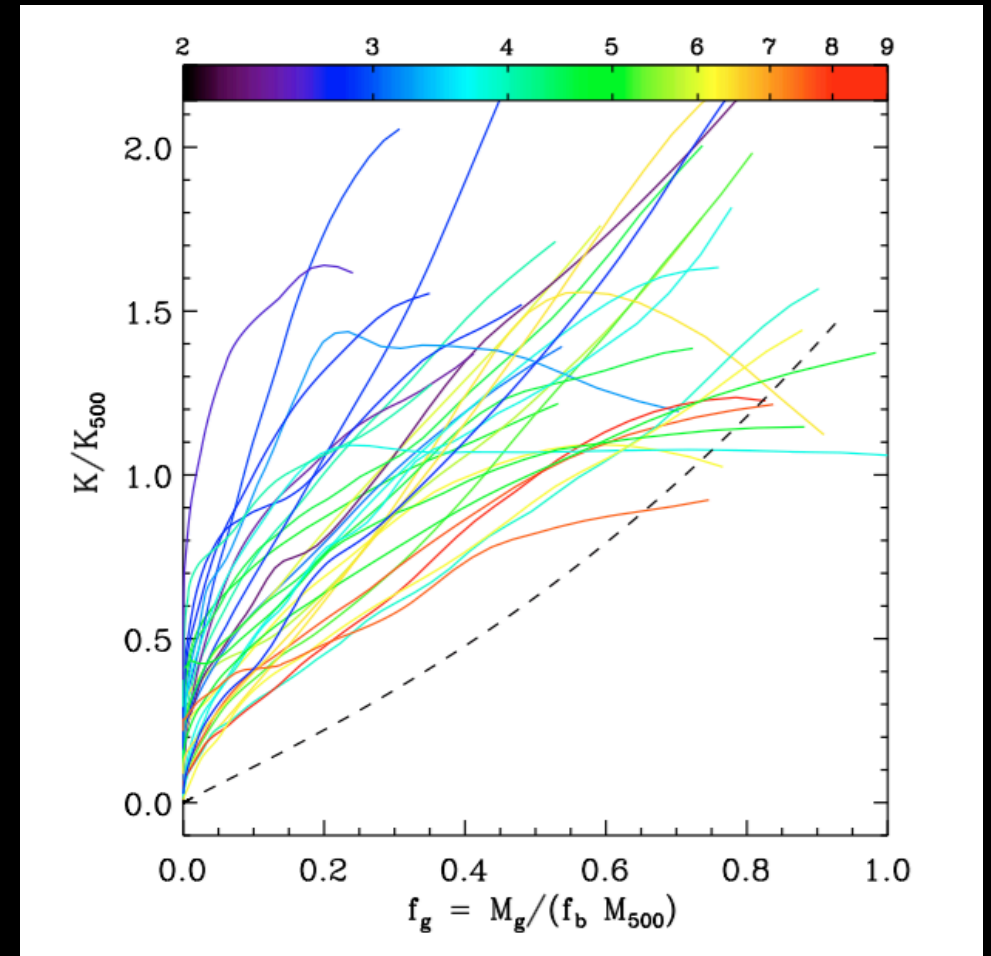


3. Entropy profiles

- In the REXCESS sample of 31 objects, XMM measurements allowed to show a radial and mass dependent excess entropy.

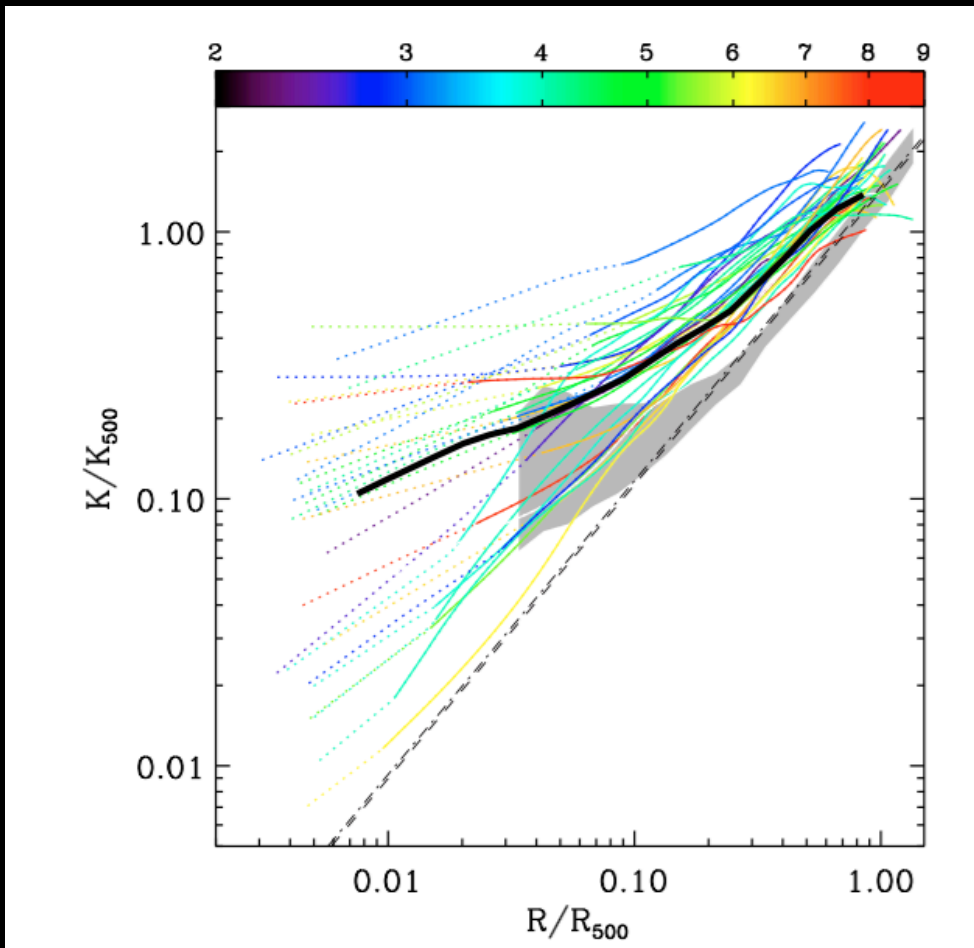


Pratt+10

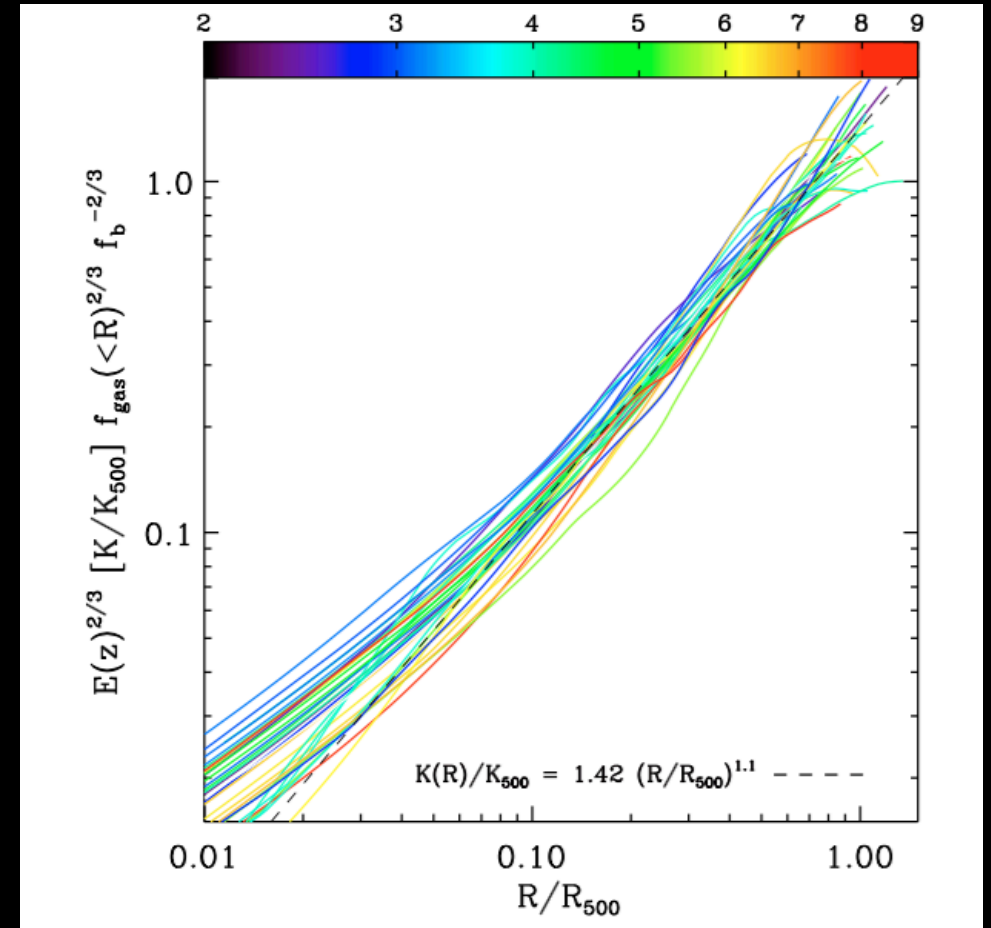


3. Entropy profiles

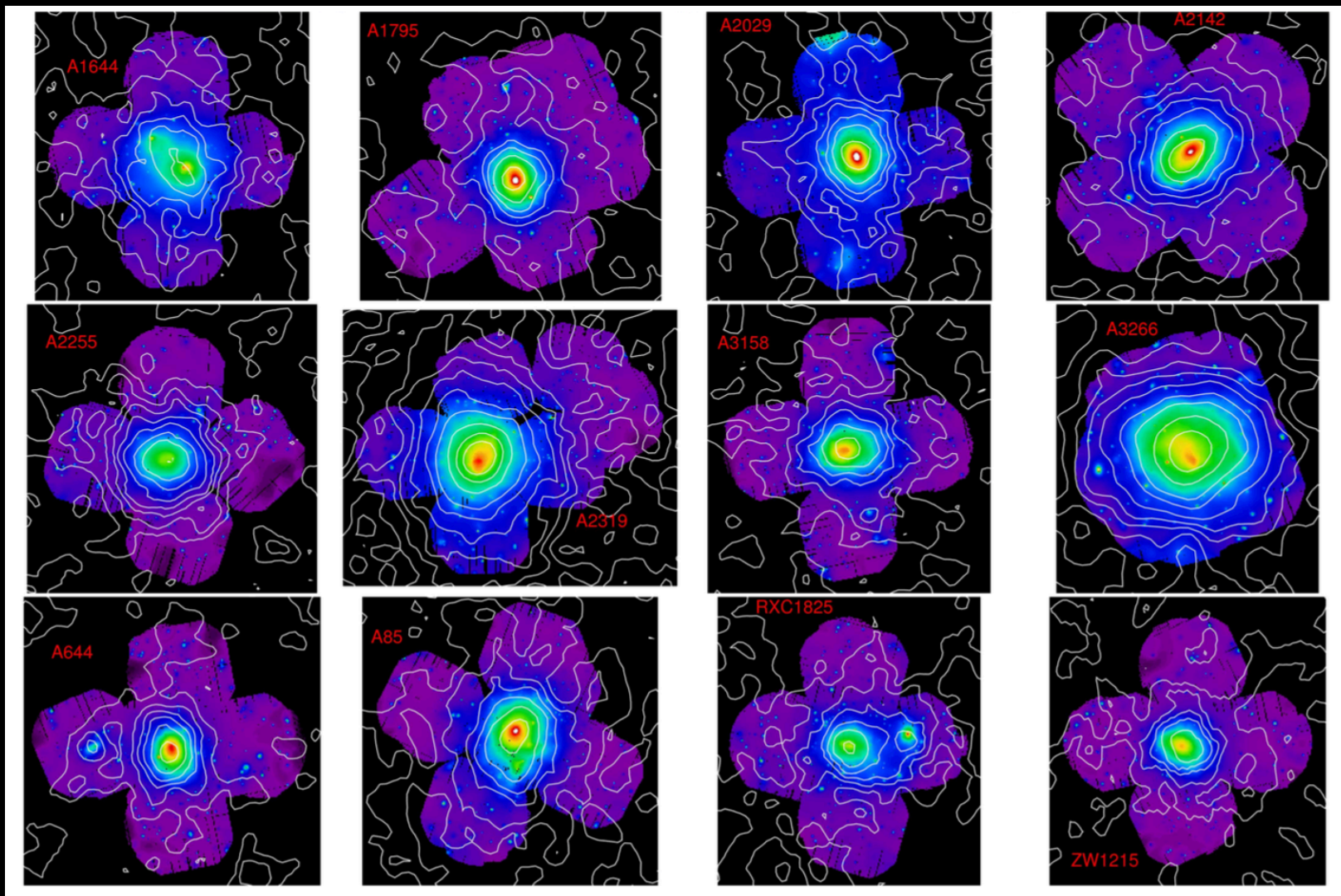
- When rescaled by the f_{gas} entropy profiles have a much reduced scatter in close agreement with gravity-only prediction.



Pratt+10

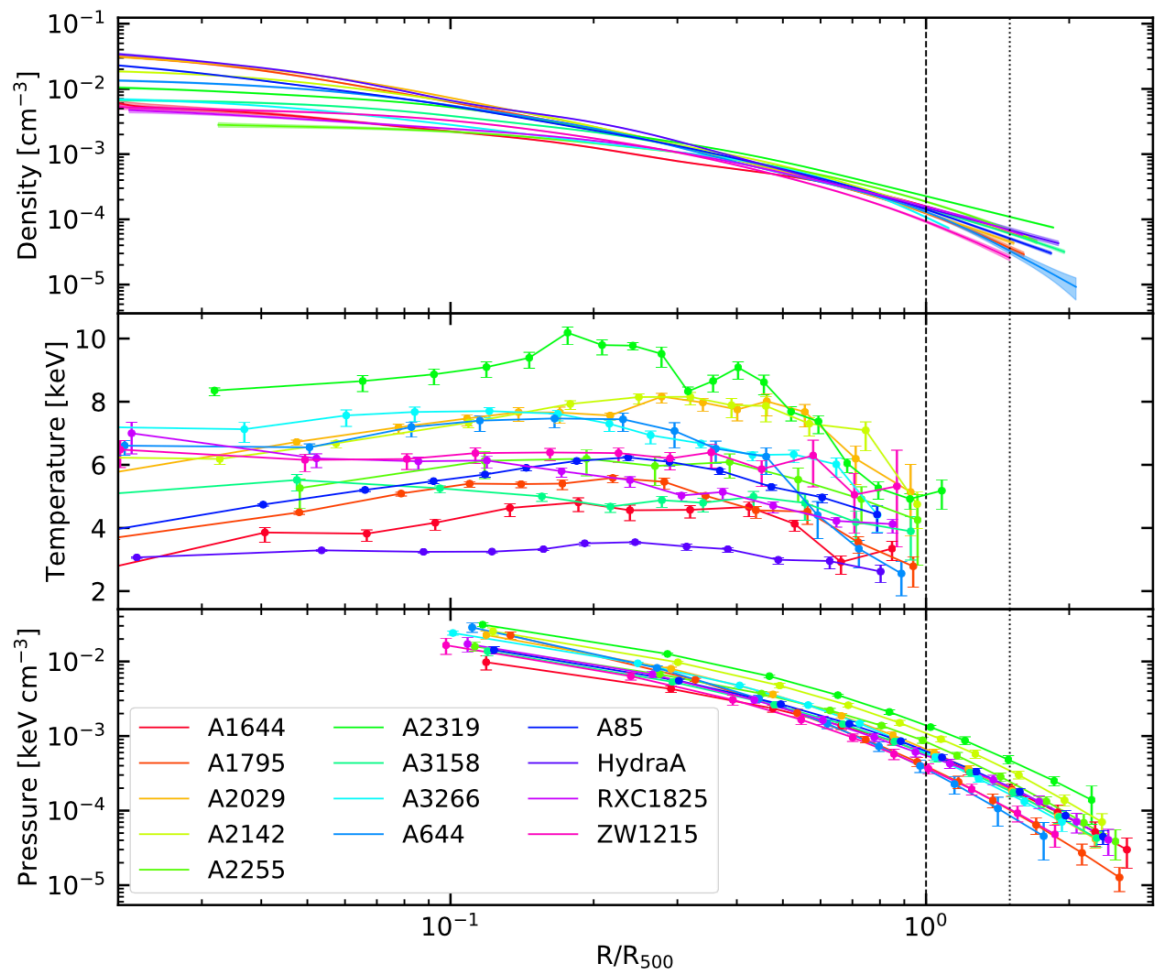


4. Reaching the outskirts

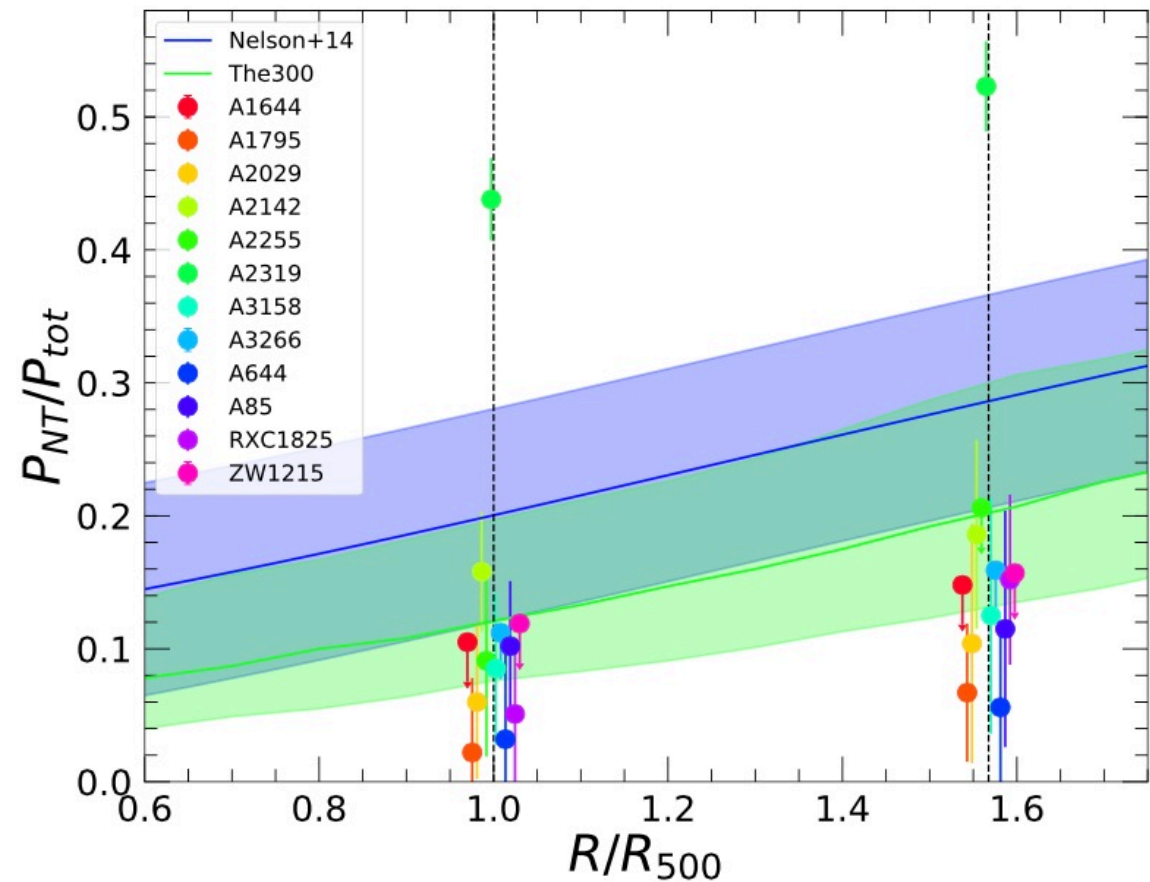


XCOP sample
specifically designed
to reach r_{200}

4. Reaching the outskirts



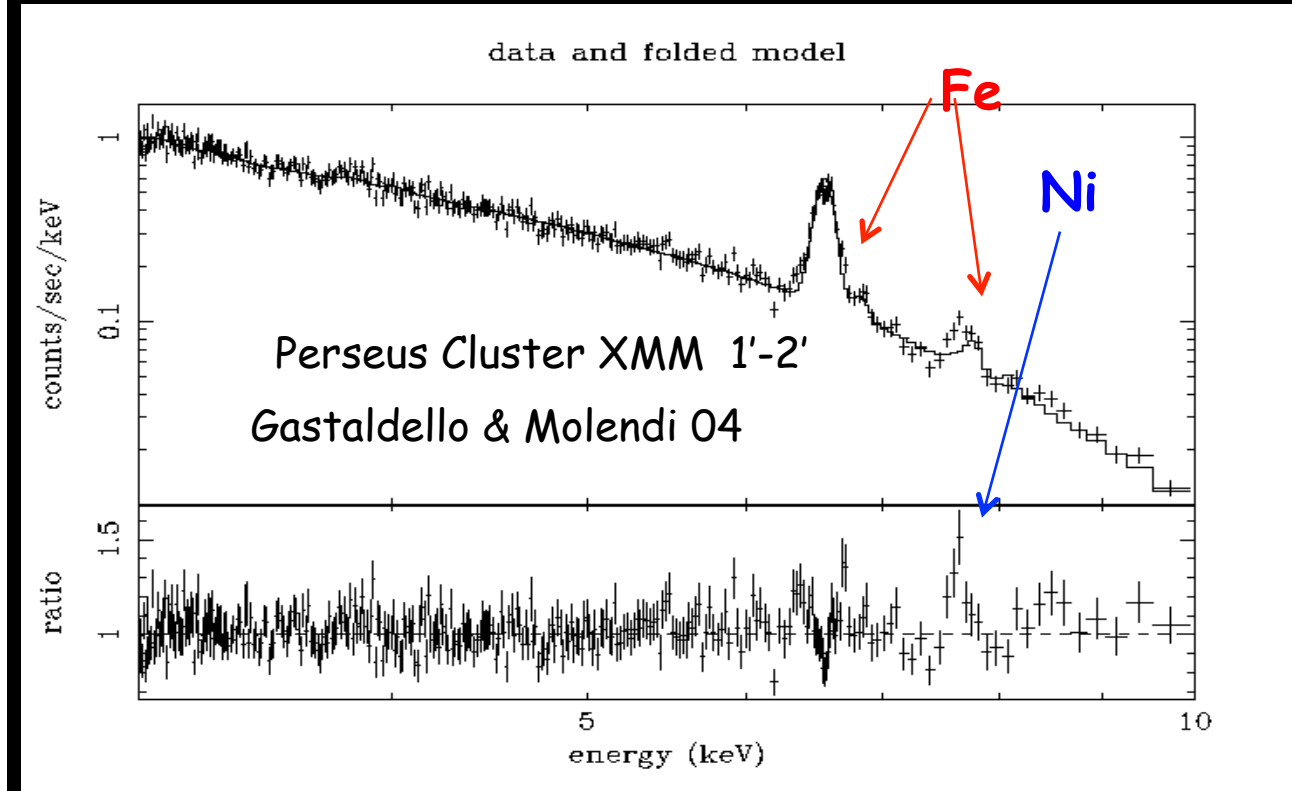
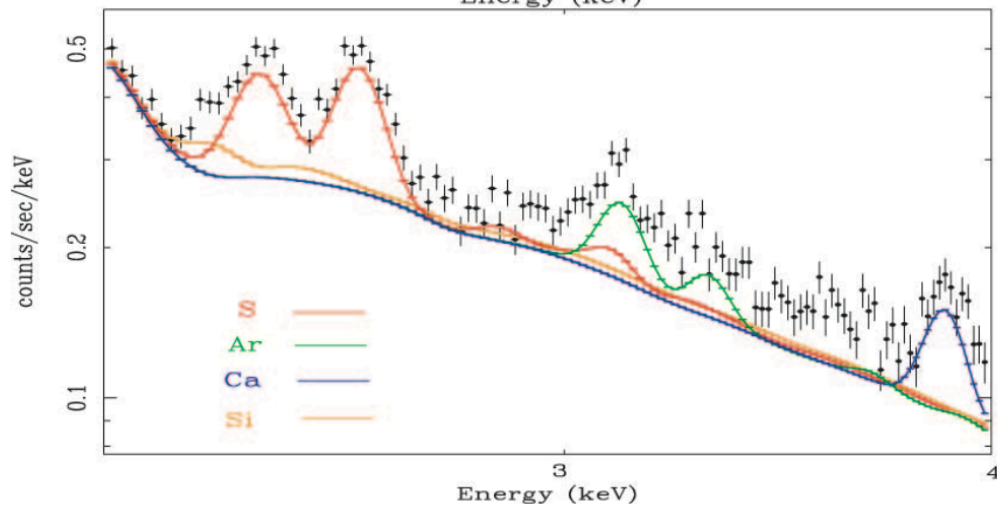
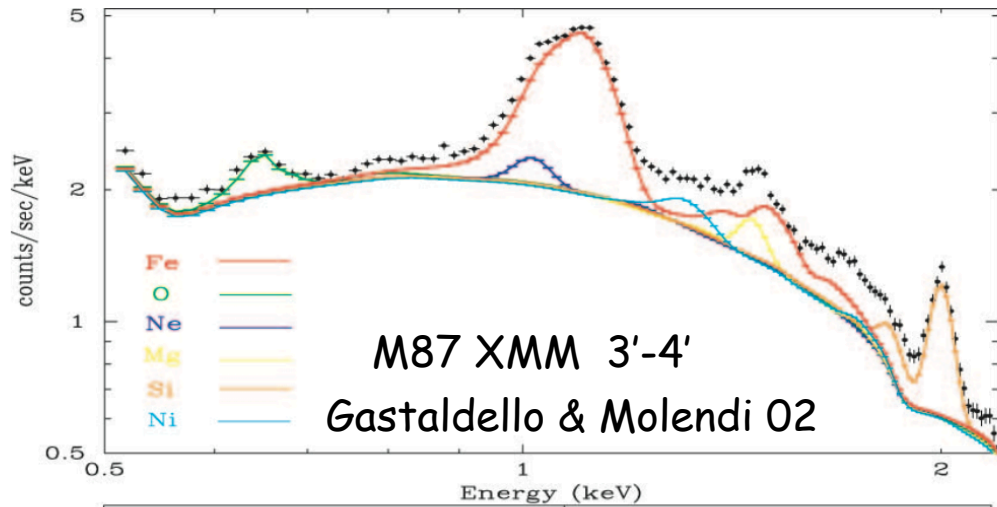
Ghirardini+19



Eckert+19

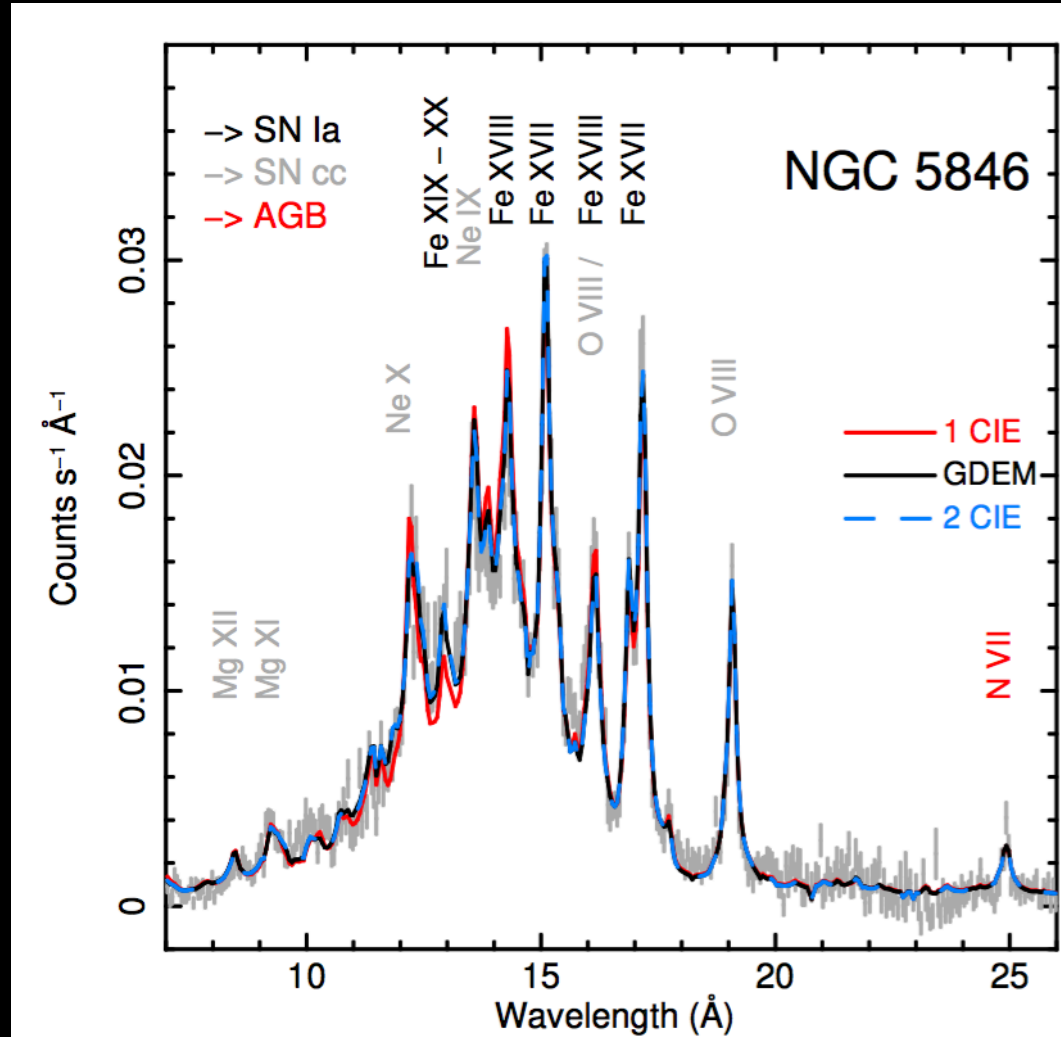
5. Metal abundances

- XMM has been showing exceptional line-rich spectra in clusters



5. Metal abundances

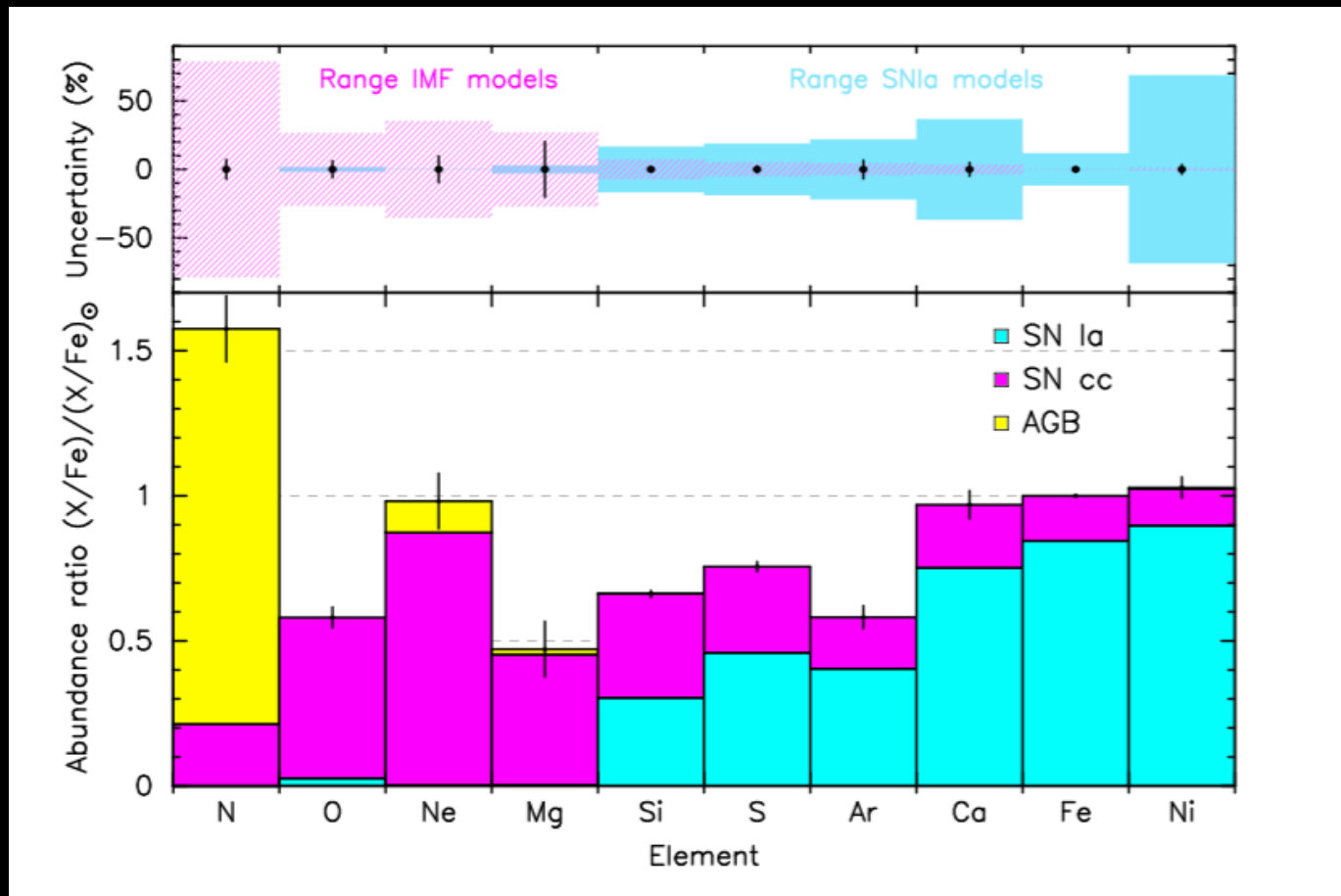
- XMM has been showing exceptional line-rich spectra in clusters



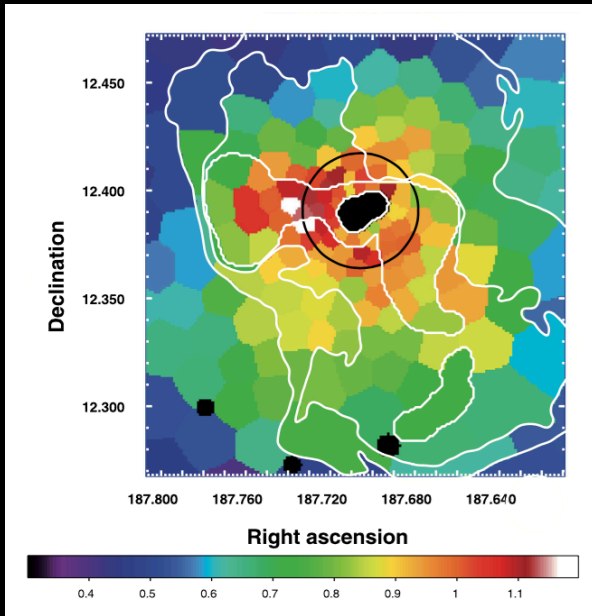
De Plaa+17
CHEERS sample

5. Metal abundances

- Abundances and metal distribution in the ICM encode the history of chemical enrichment of the Universe ...



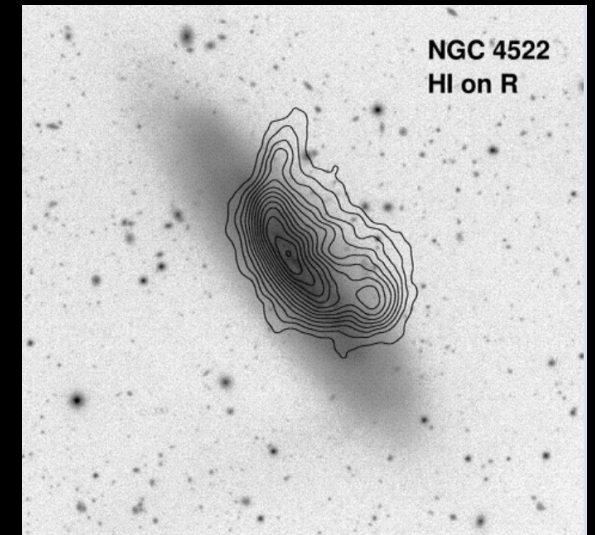
- ...and the process of transport of metals from galaxies to the ICM



**Galactic winds:
M82 starburst**



**Galaxy-galaxy
interaction**

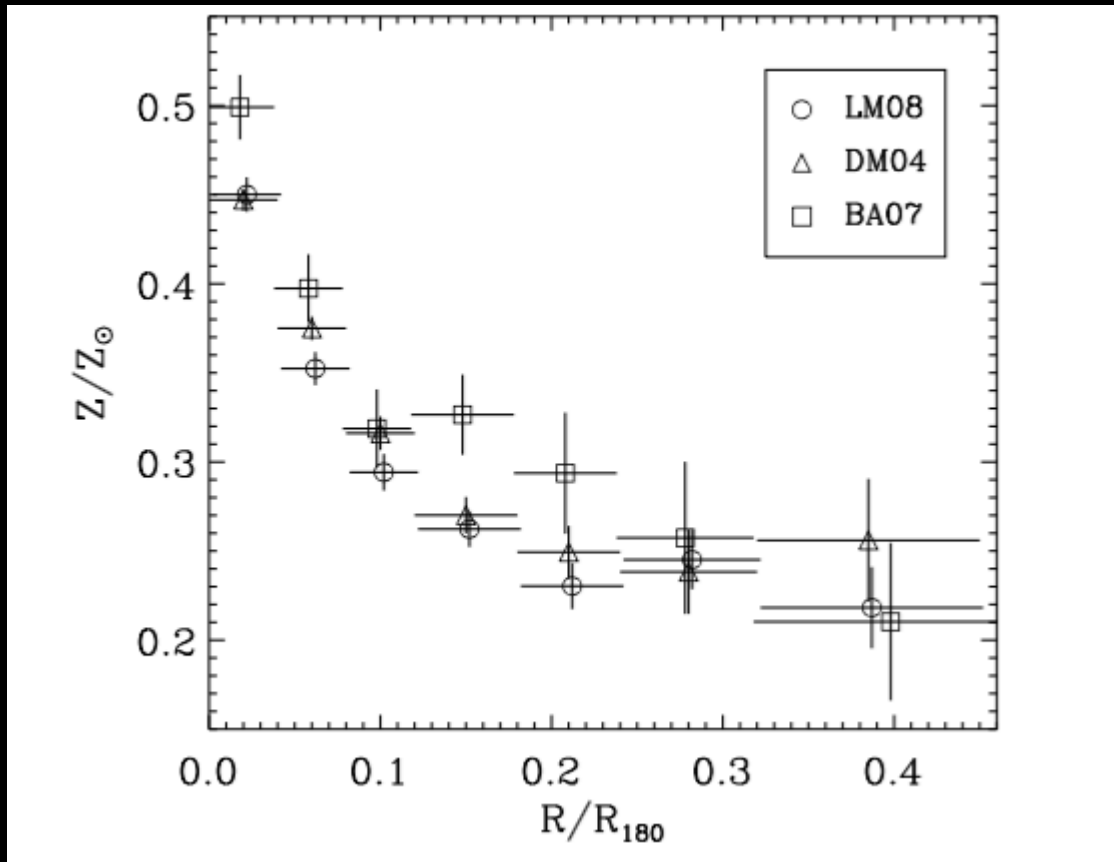


Ram pressure stripping

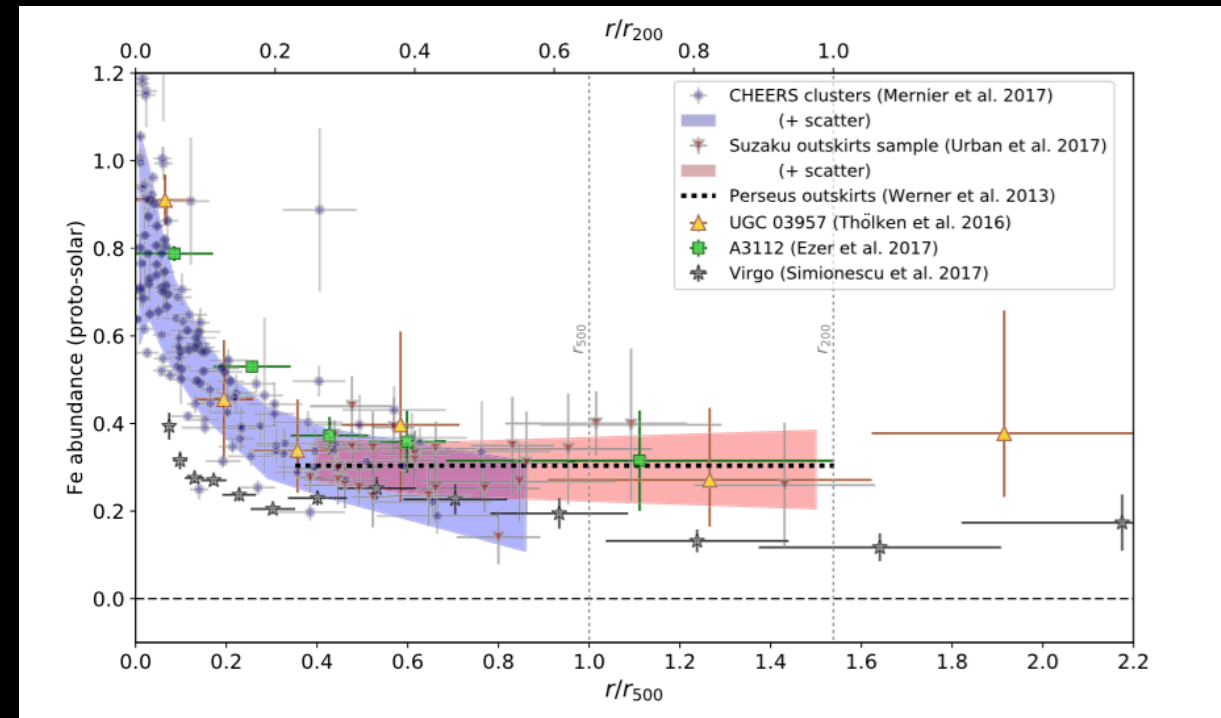
**AGN feedback:
Simionescu+08**

5. Metal abundances

- Clusters have uniform abundances almost over their entire volume



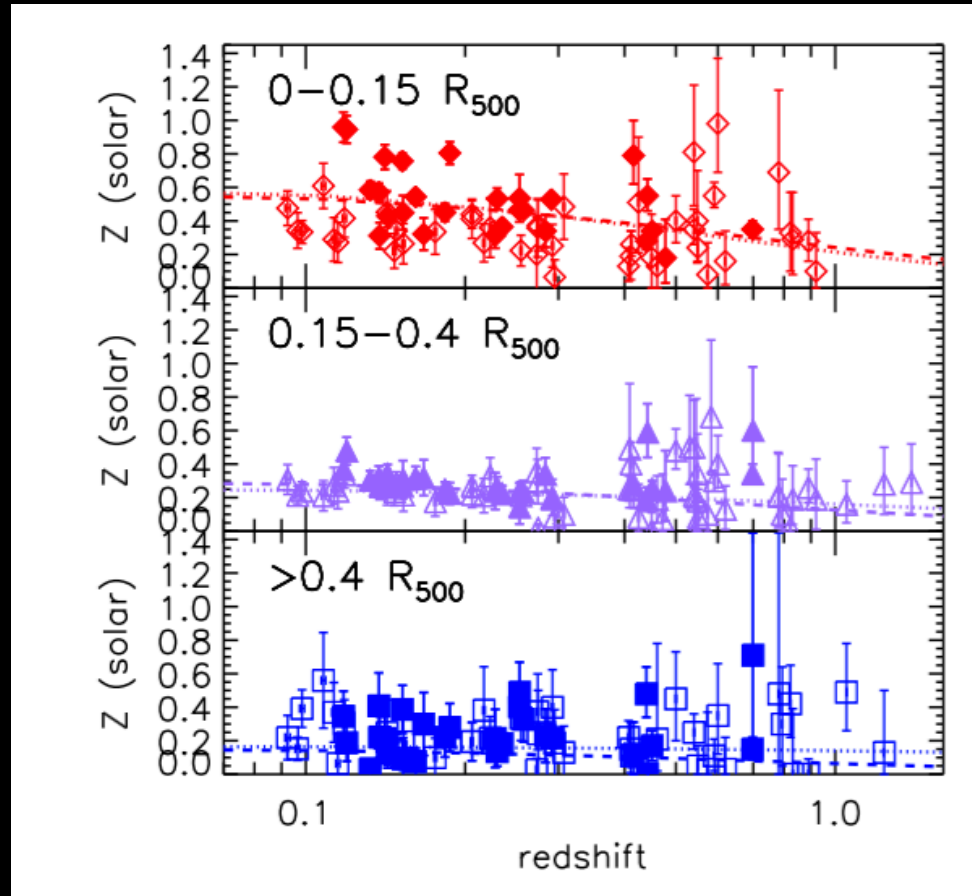
Leccardi+08



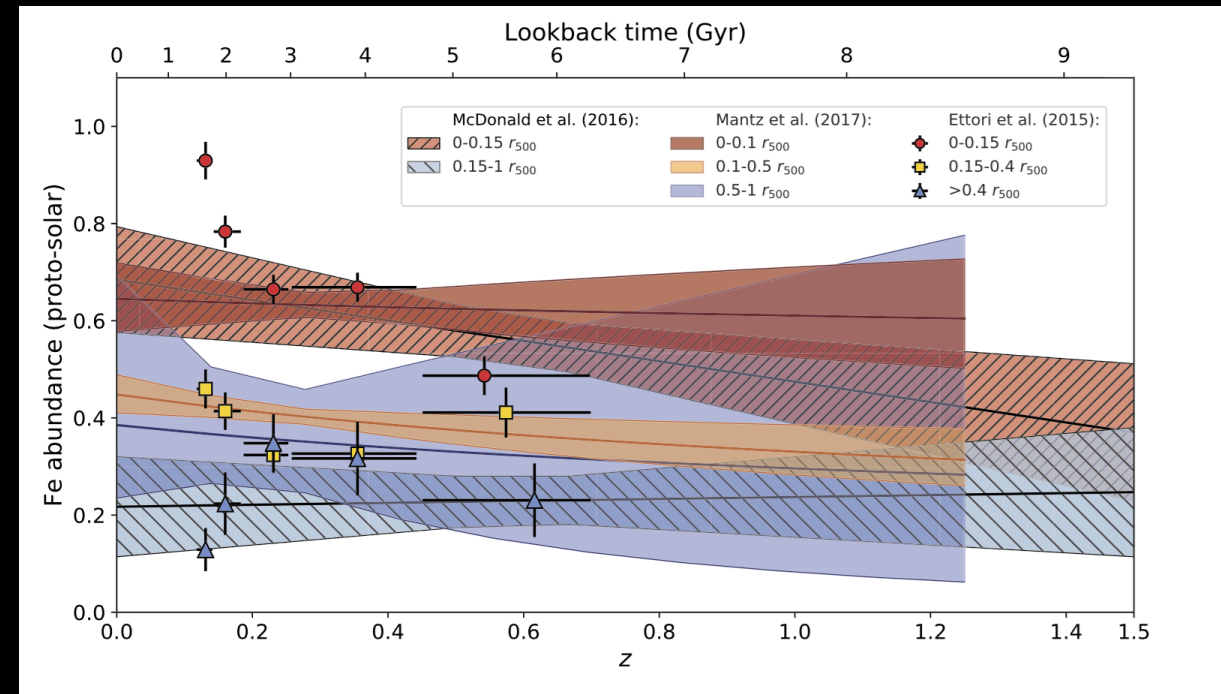
Mernier+18

5. Metal abundances

- Clusters have uniform abundances over their entire history



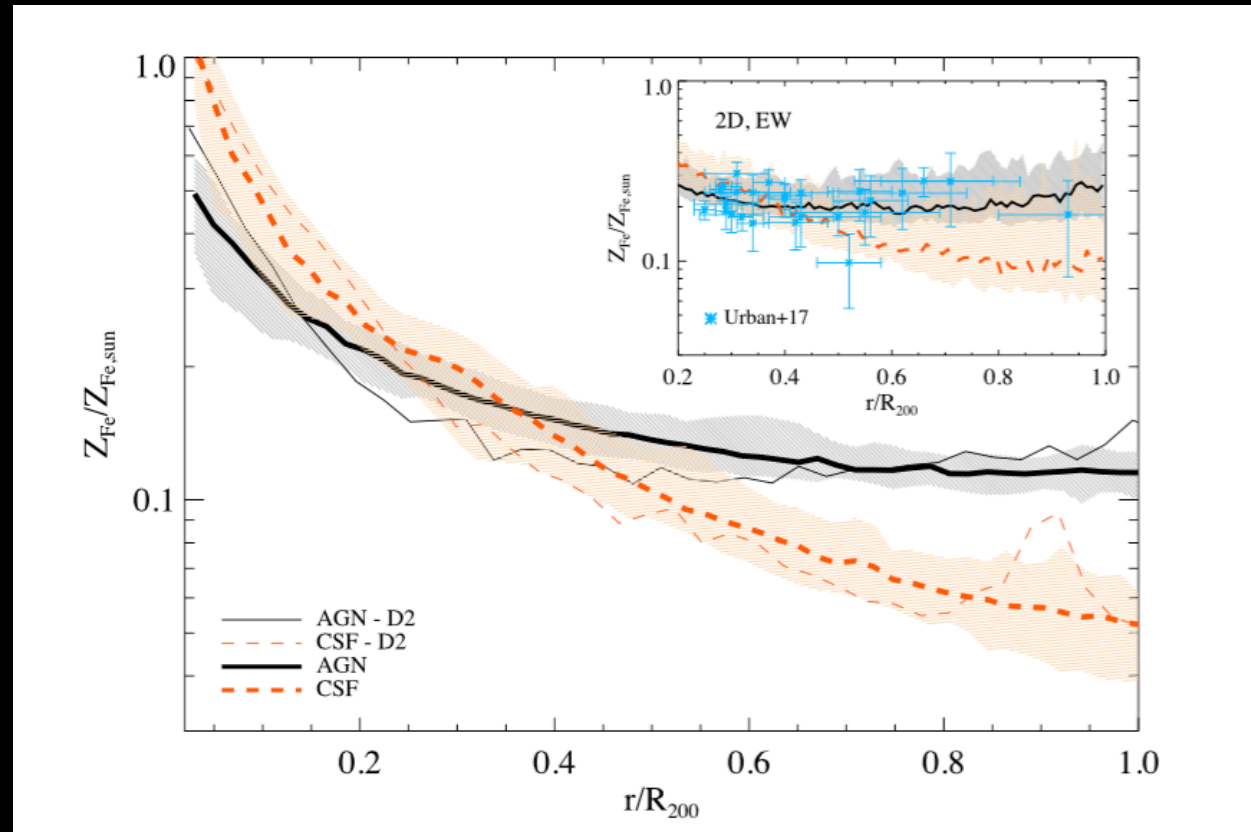
Ettori+15



Mernier+18

5. Metal abundances

- Chemical enrichment of clusters happened early ($z > 2$) with metals expelled from galaxy winds with the necessary help of AGN feedback.

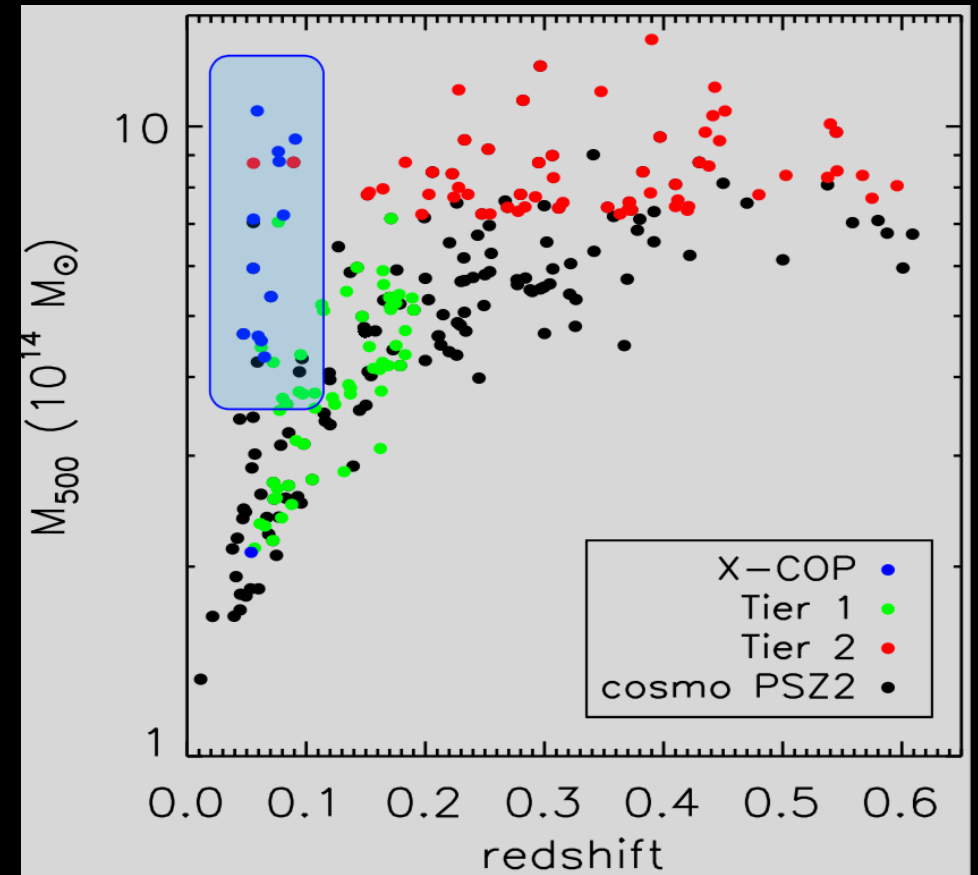


The future with XMM is happening now

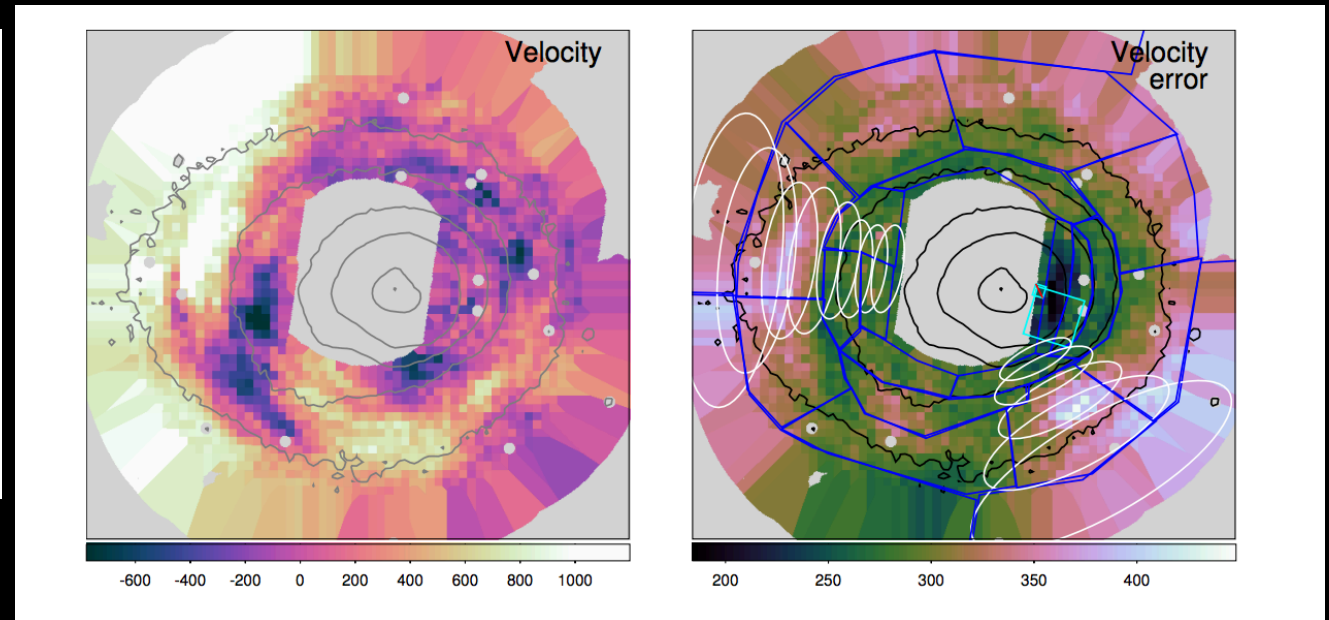
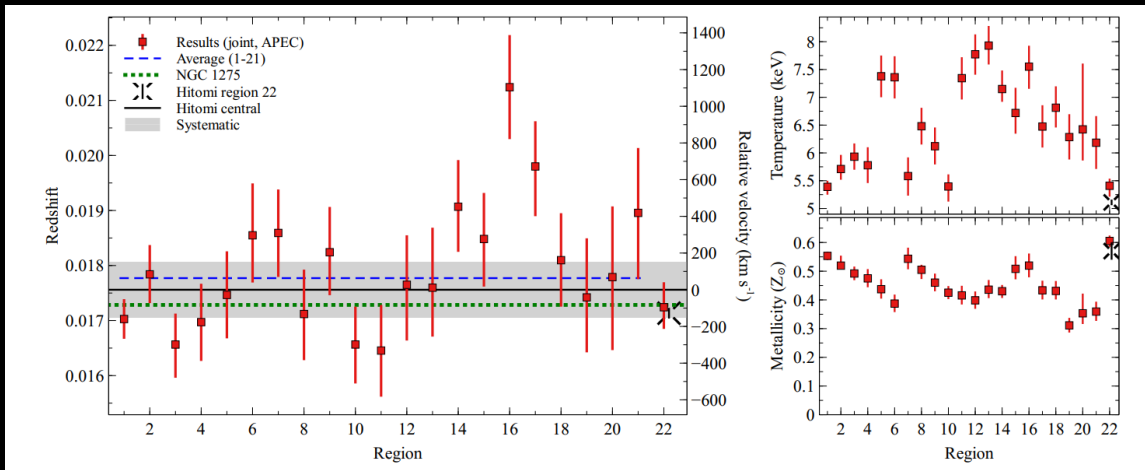
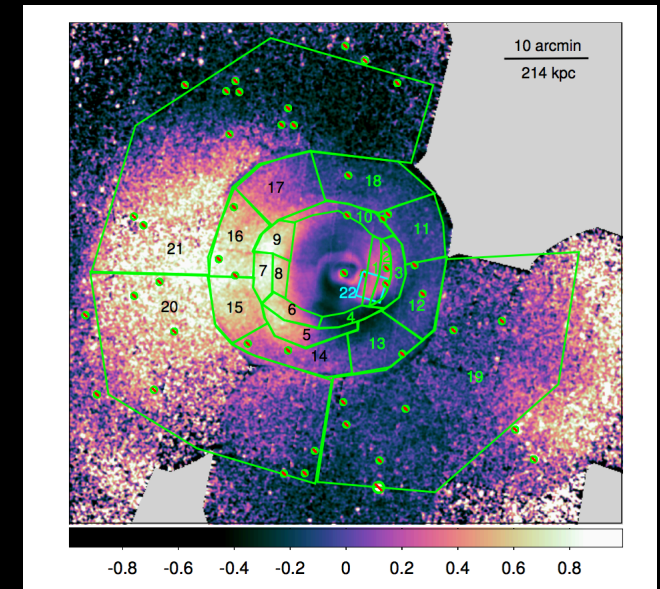
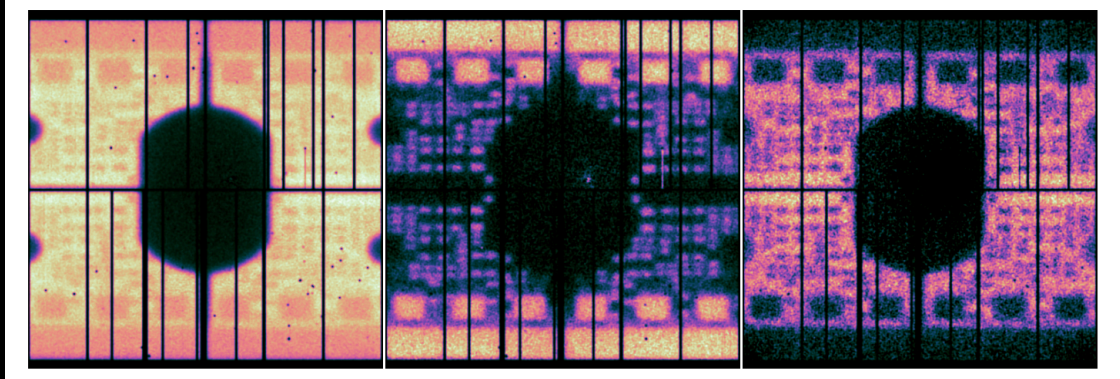
An XMM Heritage program: 3Ms of XMM time to observe 118 clusters

Witnessing the culmination of structure formation in the Universe
(co-PIs: Arnaud & Ettori) providing an unbiased census of

- The local population of clusters ($z < 0.2$)
- The most massive objects in the Universe



Bonus feature: velocity field !



Sanders+19

- 1  2014ApJ...789...13B 2014/07 cited: 508  
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X-ray spectroscopy of the cluster of galaxies Abell 1795 with XMM-Newton
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The XMM-Newton wide-field survey in the COSMOS field. The point-like X-ray source catalogue
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Gas entropy in a representative sample of nearby X-ray galaxy clusters (REXCESS): relationship to gas mass fraction
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A Spitzer-selected Galaxy Cluster at $z = 1.62$
Papovich, C.; Momcheva, I.; Willmer, C. N. A. *and 15 more*
- 14  2001A&A...365L..99K 2001/01 cited: 202  
XMM-Newton observations of the cluster of galaxies Sérsic 159-03
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Discovery of an X-Ray-luminous Galaxy Cluster at $z=1.4$
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- 16  2002A&A...382..804B 2002/02 cited: 173  
The new emerging model for the structure of cooling cores in clusters of galaxies
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Spatially resolved X-ray spectroscopy of cooling clusters of galaxies
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- 19  2006ApJ...646L..13S 2006/07 cited: 154  
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Calibration of the galaxy cluster M_{500} - Y_{X} relation with XMM-Newton
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LoCuSS: comparison of observed X-ray and lensing galaxy cluster scaling relations with simulations
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Radial temperature profiles for a large sample of galaxy clusters observed with XMM-Newton
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- 24  2008A&A...487..431C 2008/08 cited: 139  
Galaxy-cluster gas-density distributions of the representative XMM-Newton cluster structure survey (REXCESS)
Croston, J. H.; Pratt, G. W.; Böhringer, H. *and 7 more*
- 25  2015MNRAS.450.2143J 2015/06 cited: 135  
Discovery of a 3.5 keV line in the Galactic Centre and a critical look at the origin of the line across astronomical targets
Jeltema, Tesla; Profumo, Stefano