The Mass in Galaxy Clusters from X-ray/SZ observables

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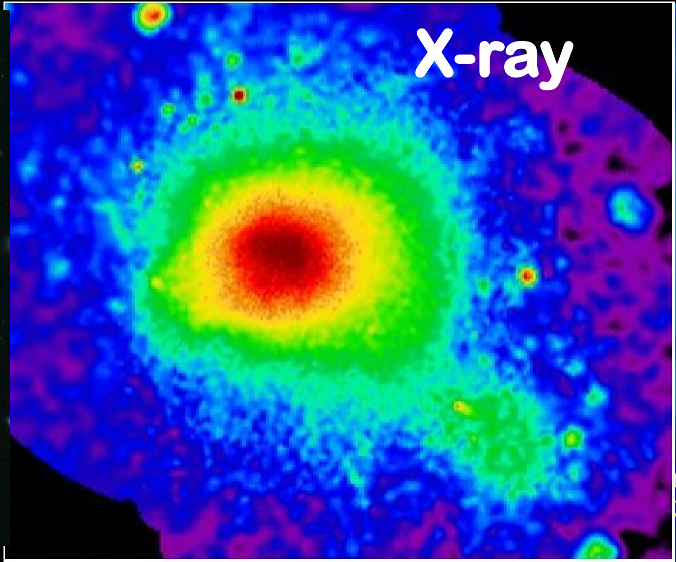
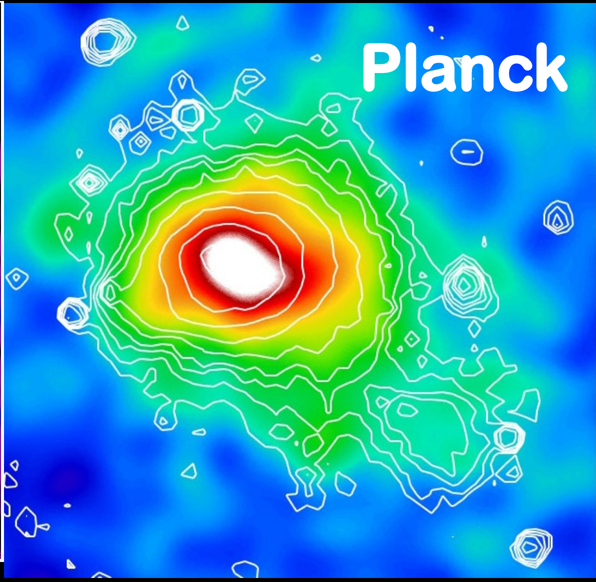
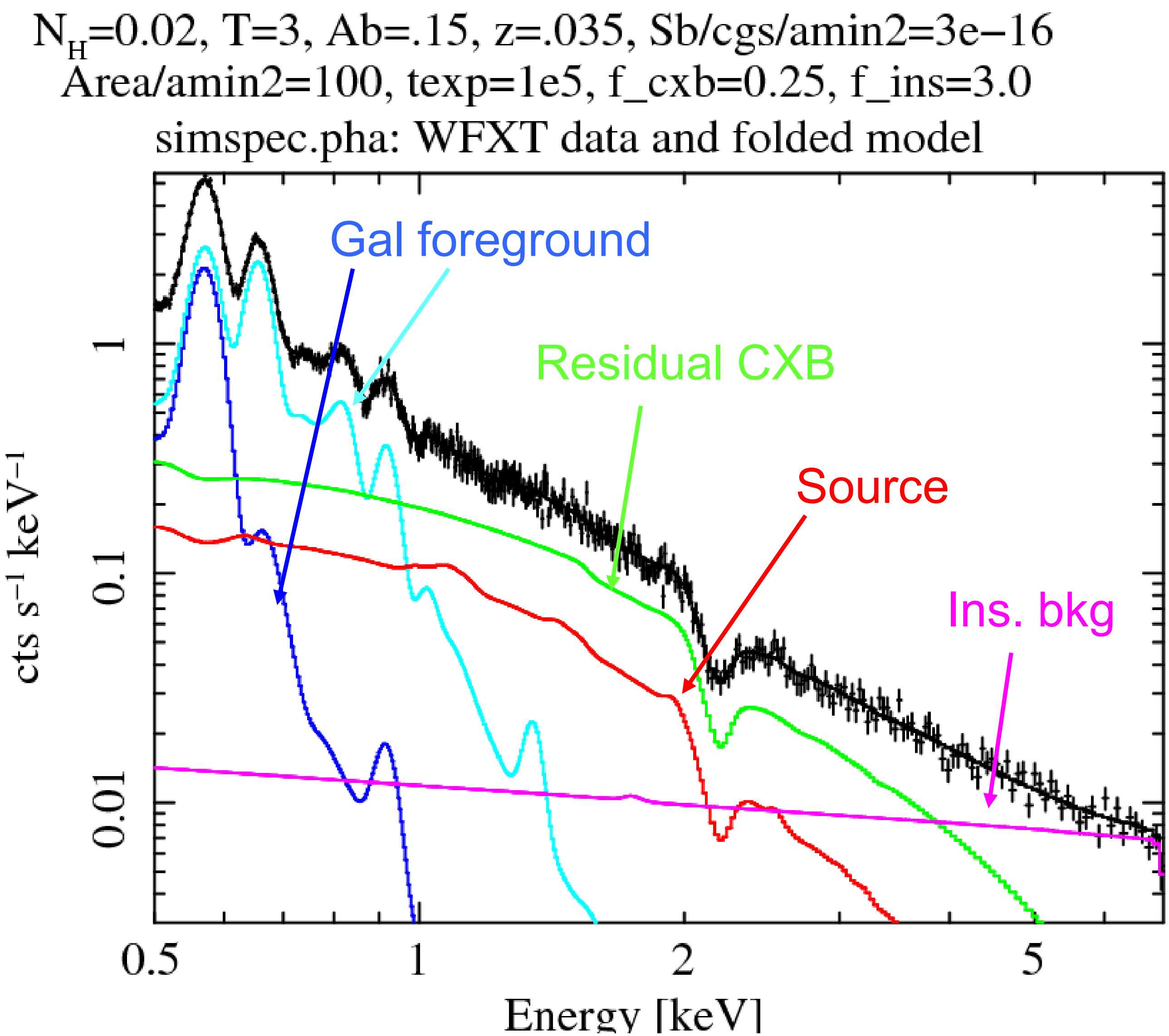
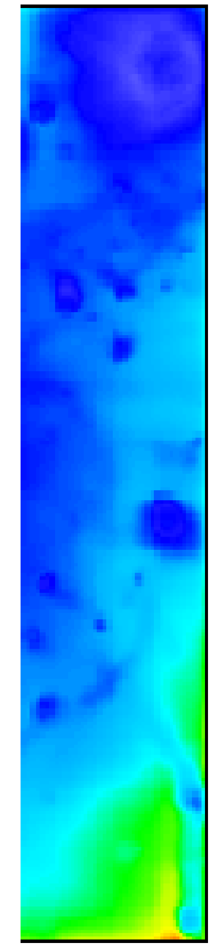




X-ray view of the ICM

[redacted]





Simulation for 3keV cluster @ R200 (Ettori & Molendi arXiv:1005.0382)

Total mass from SZ/X-rays

- *high counts statistic*: **mass profiles**

(calibration & hydrostatic bias; *~200 out of 1743 obj known*, *Piffaretti et al. 11*)
Ettori et al., 2013, SSRv, arXiv:1303.3530

$$M_{tot}(<r) = -\frac{kT_{gas}(r)\ r}{G\mu m_p}\left[\frac{\partial \ln n_{gas}}{\partial \ln r} + \frac{\partial \ln T_{gas}}{\partial \ln r}\right]$$

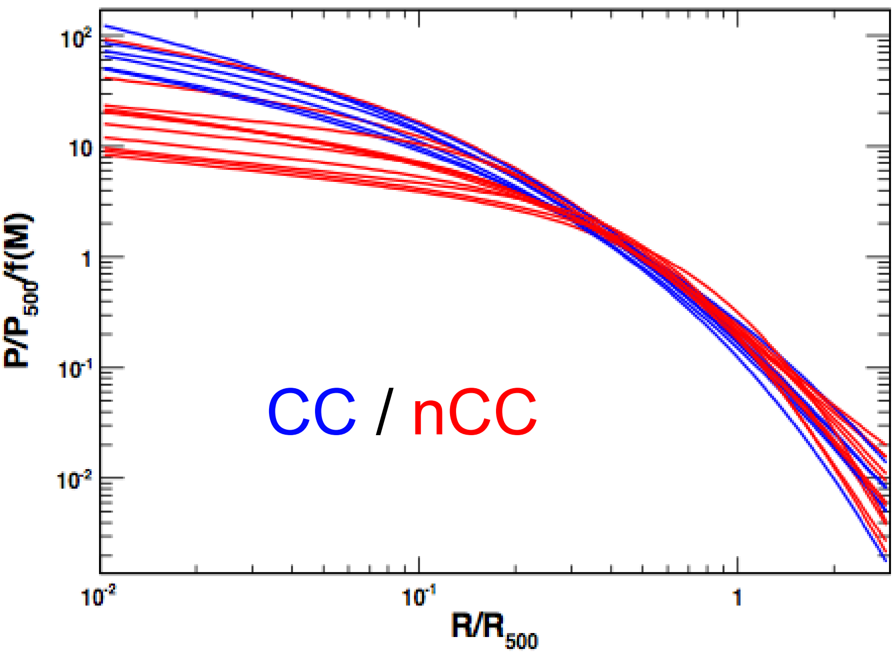
- *low counts statistic*: **scaling relations**

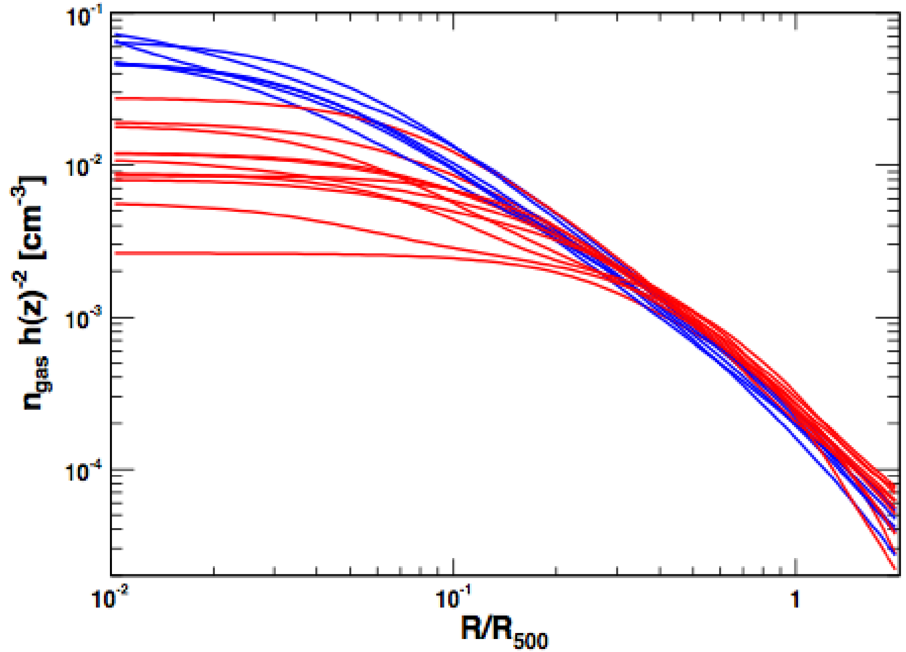
(for galaxy clusters mass function: M_{tot} vs L/T/M_{gas}/Y_X *or* ***a combination of these***…)
Ettori et al., 2012; Ettori, 2013 & 2015

$$M_{tot} \propto \Delta R_\Delta^3 \propto T^{3/2} \propto M_g \propto L^{3/4} \propto Y_{SZ}^{3/5}$$

The X-ray/SZ view out to R_{200}

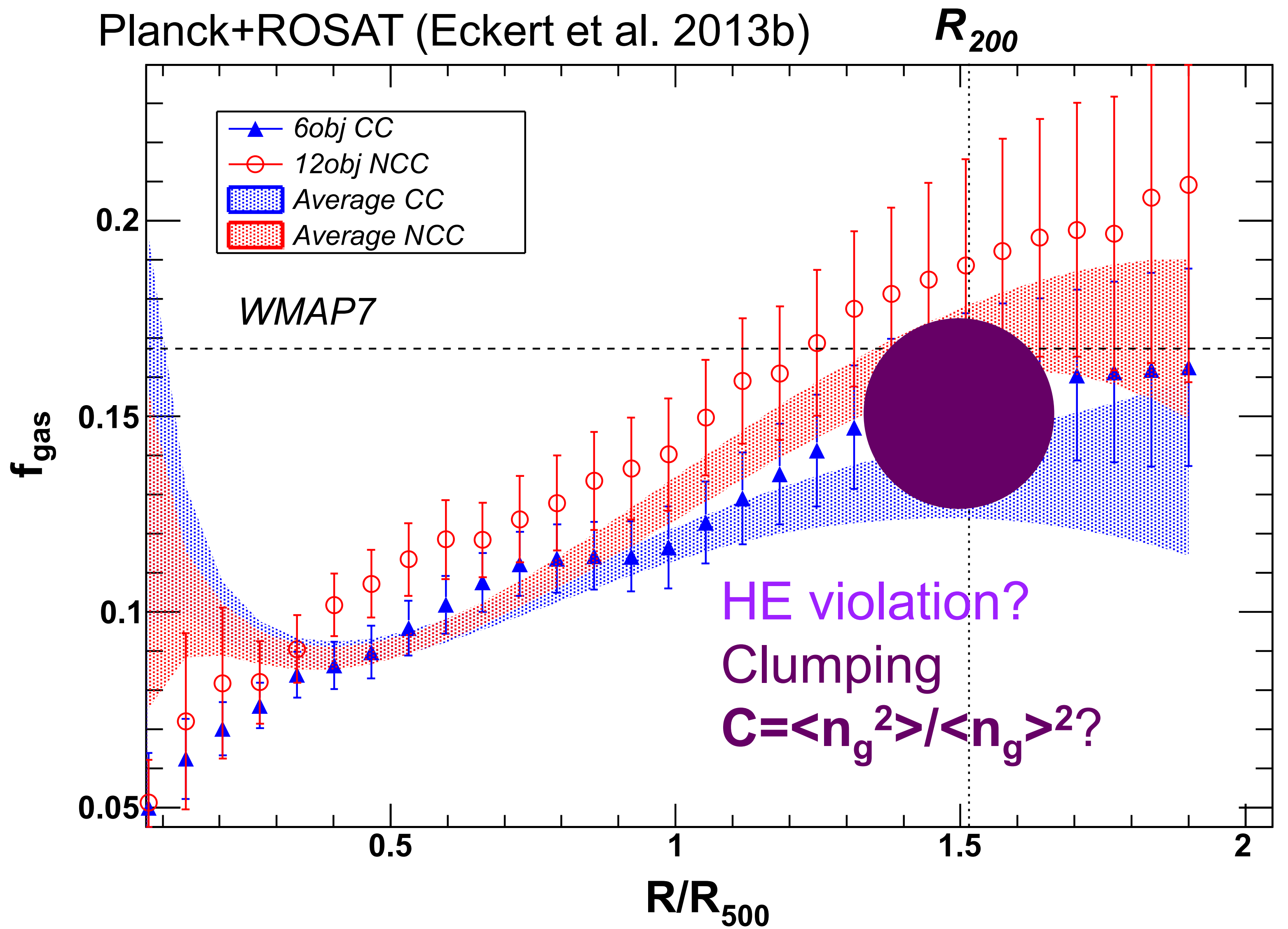
Thermodynamic properties of the ICM for 18 objects in common with Planck SZ thermal pressure and the ROSAT X-ray gas density profiles (Eckert et al. 13a & 13b)





$\mathbf{T} = \mathbf{P}/\mathbf{n}$ $\quad$ $\mathbf{K} = \mathbf{P}/\mathbf{n}^{5/3}$ $\quad$ $\mathbf{M} = -r^2/(G\ \mu\ m\ \mathbf{n})\ d\mathbf{P}/dr$

The X-ray/SZ view out to R_{200}

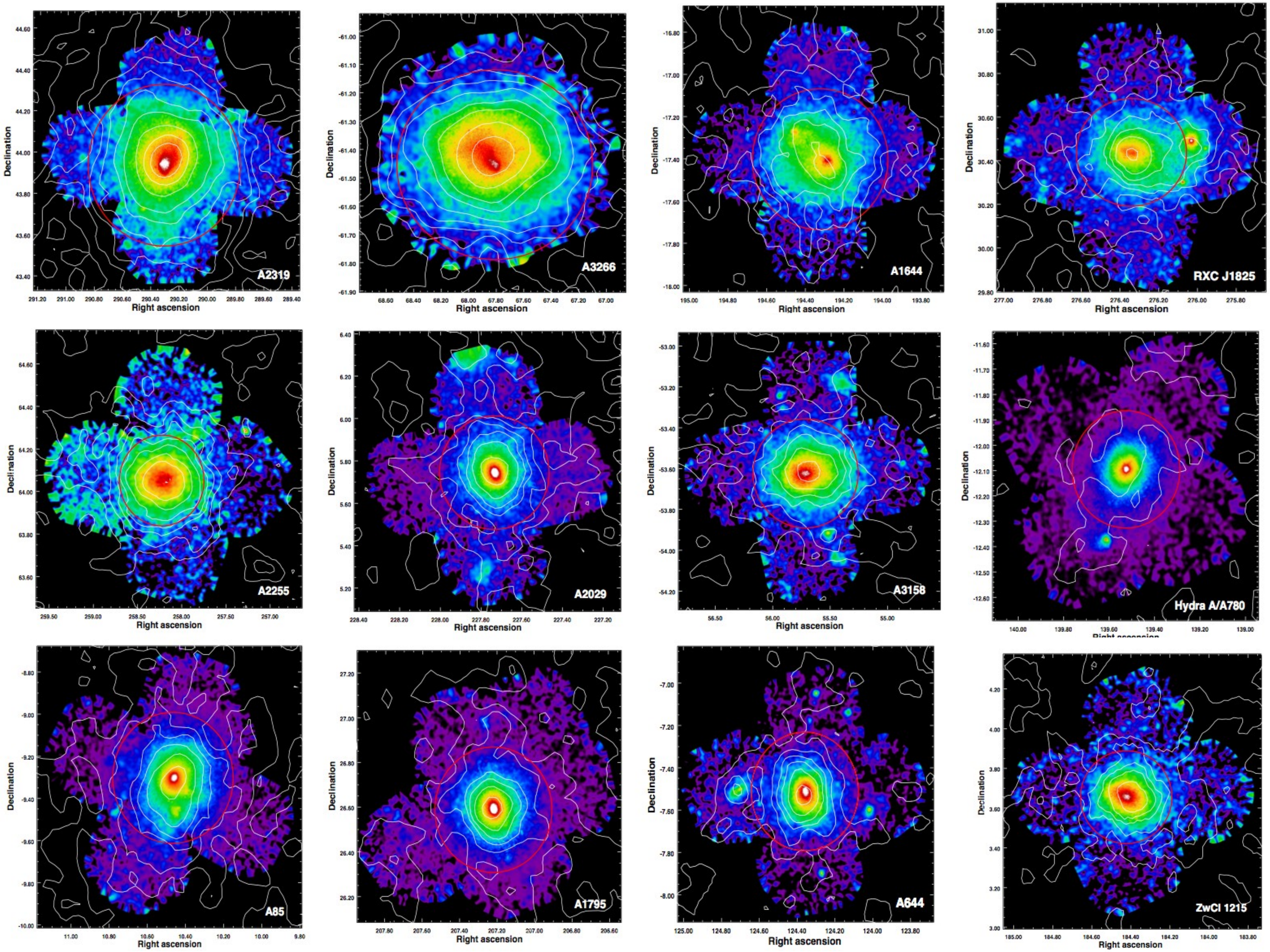


X-COP
The XMM Cluster Outskirts Project

- X-COP is a ***very large program*** (PI: Eckert), approved in *XMM-Newton* AO-13 for a total observing time of 1.2 M-sec; co-I: Ettori, Molendi, Pointecouteau, Gastaldello, Hurier, Vazza, Roncarelli, Rossetti, Kneib, Paltani, Ghizzardi, De Grandi, Bartelmann Tchernin

- X-COP targets the outer regions of a sample of 13 massive clusters ($M_{500} > 3 \times 10^{14}\ M_{\odot}$) in the redshift range 0.04-0.1 at uniform depth. The sample was selected based on the signal-to-noise ratio in the *Planck* Sunyaev-Zeldovich (SZ) survey with the aim of combining high-quality X-ray and SZ constraints throughout the entire cluster volume

X-COP

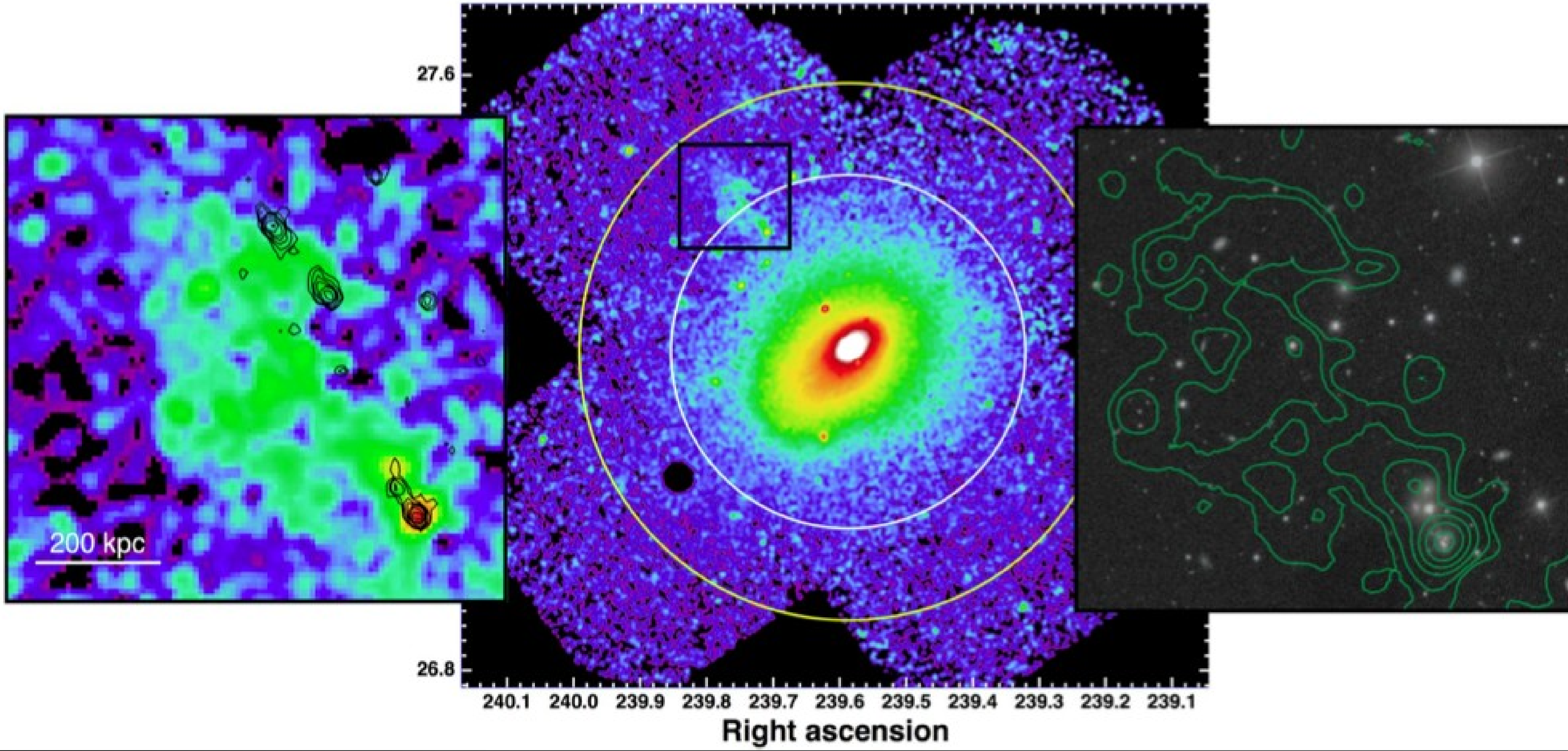

A2319
A3266
A1644
RXC J1825
A2255
A2029
A3158
Hydra A/A780
A85
A1795
A644
ZwCl 1215
Declination
Right ascension

X-COP: A2142

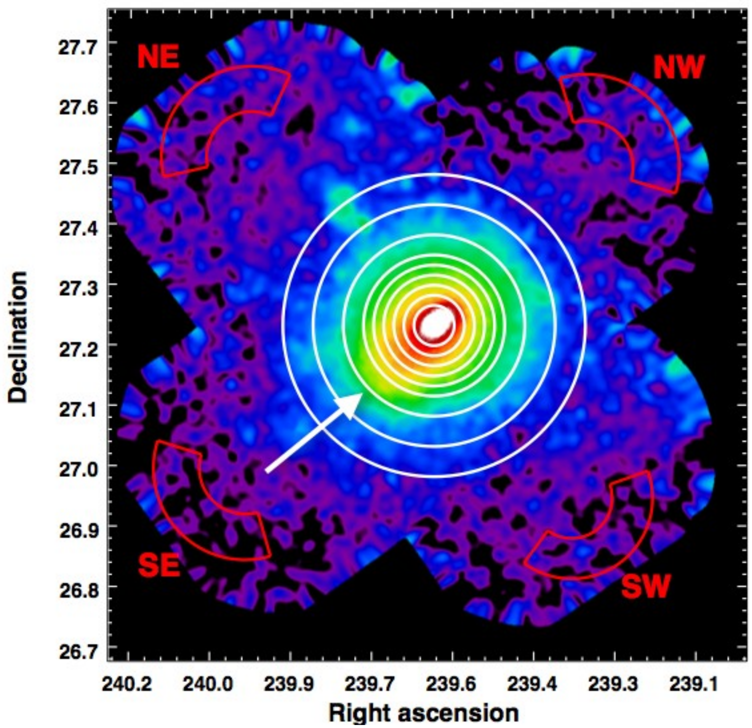
A2142 (~1.3e15 $M_{\odot}$, z=0.09; Eckert+14)

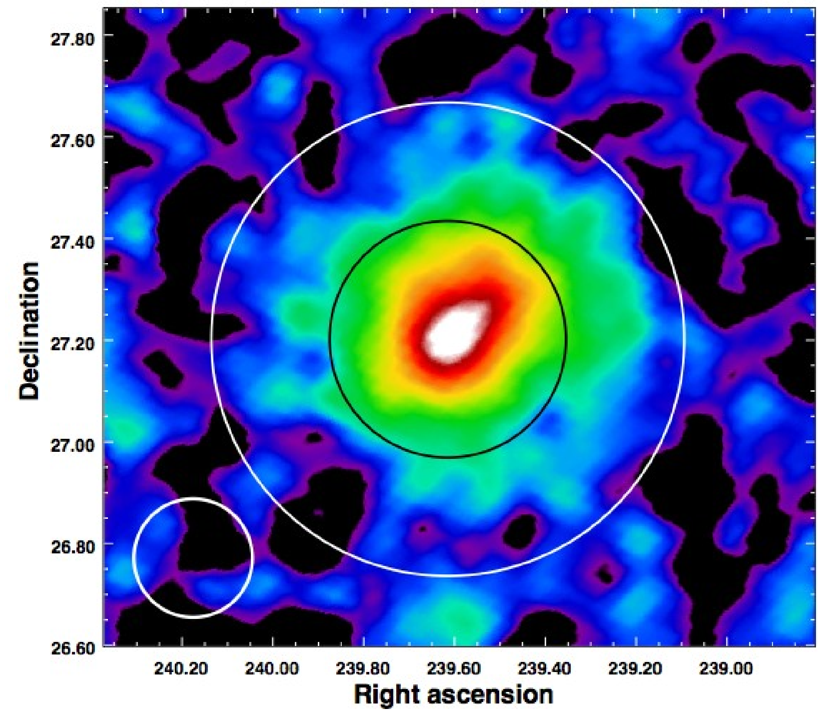
Direct observation of the accretion of a clump with M~1/100 M_{halo}

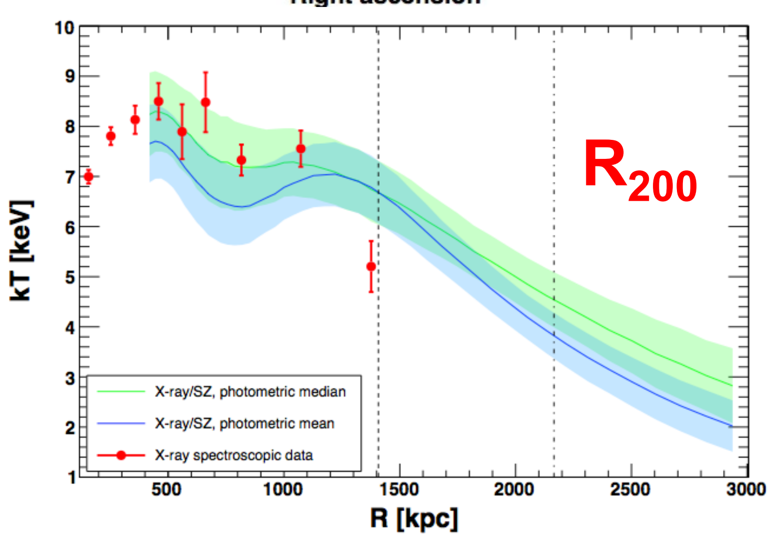
Simulations predict ~1 per local clusters

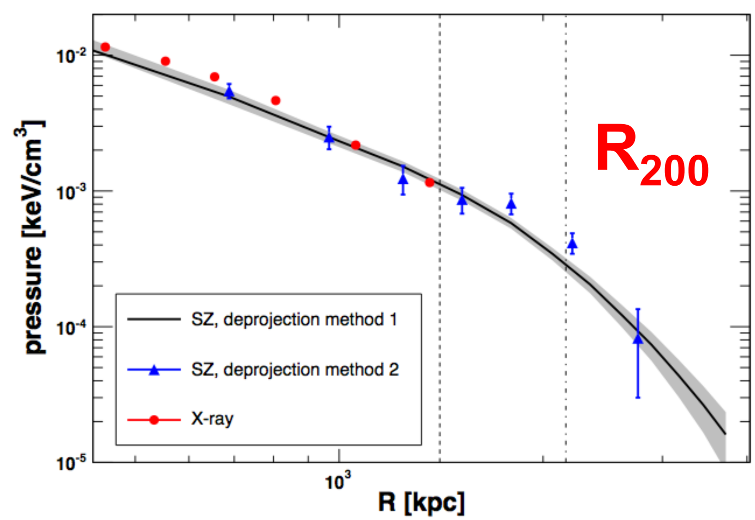


X-COP: A2142 (Tchernin+16 subm)









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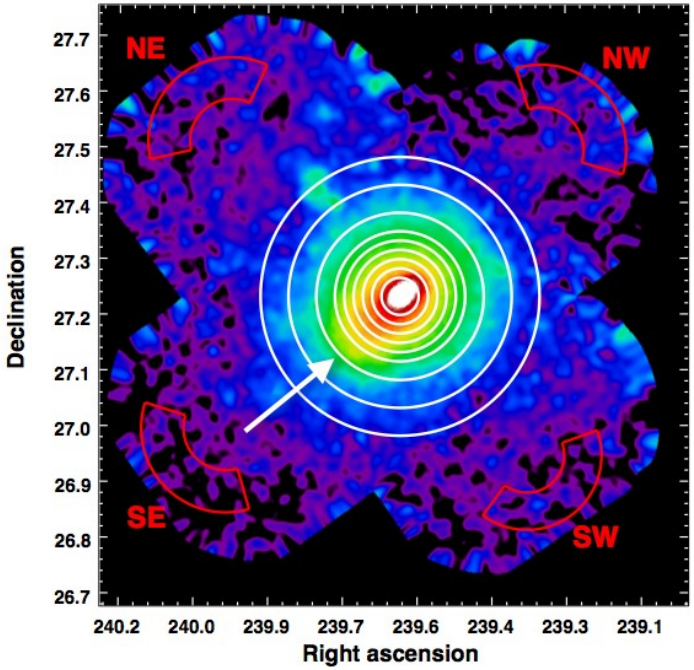
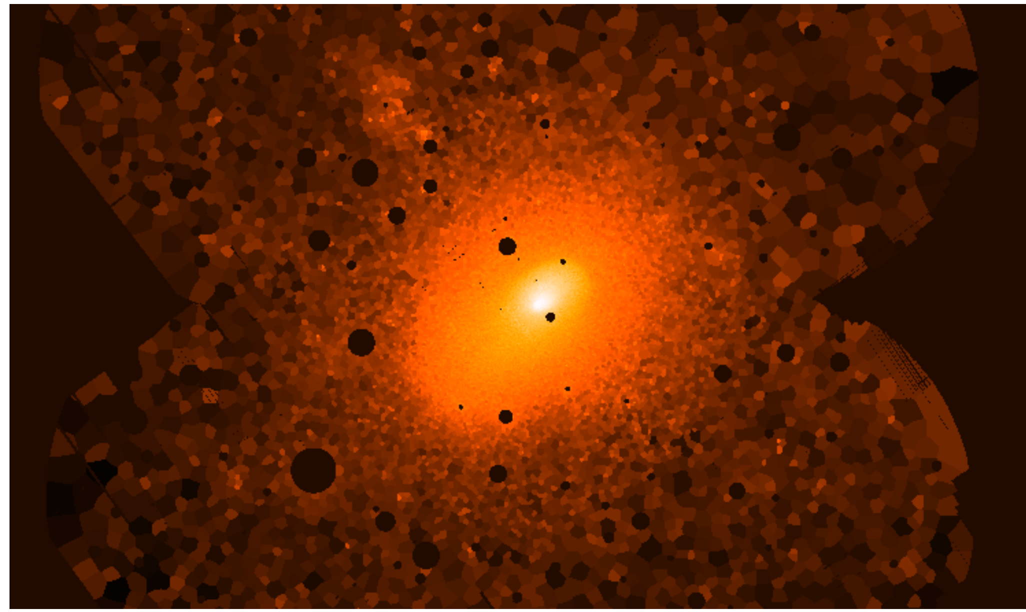
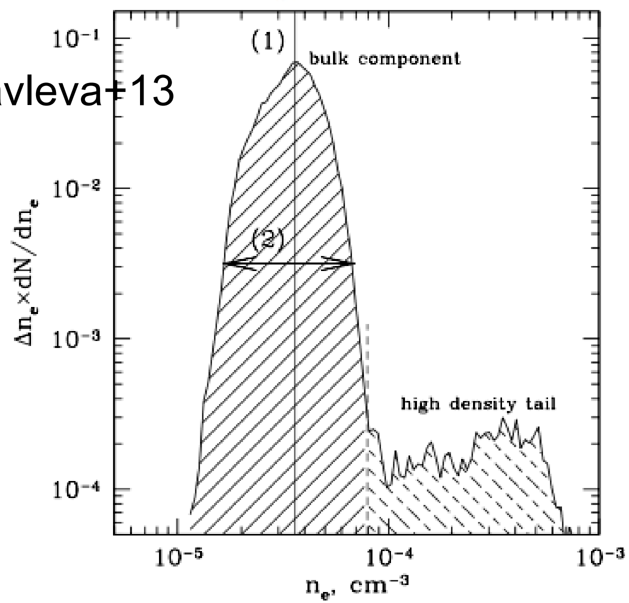
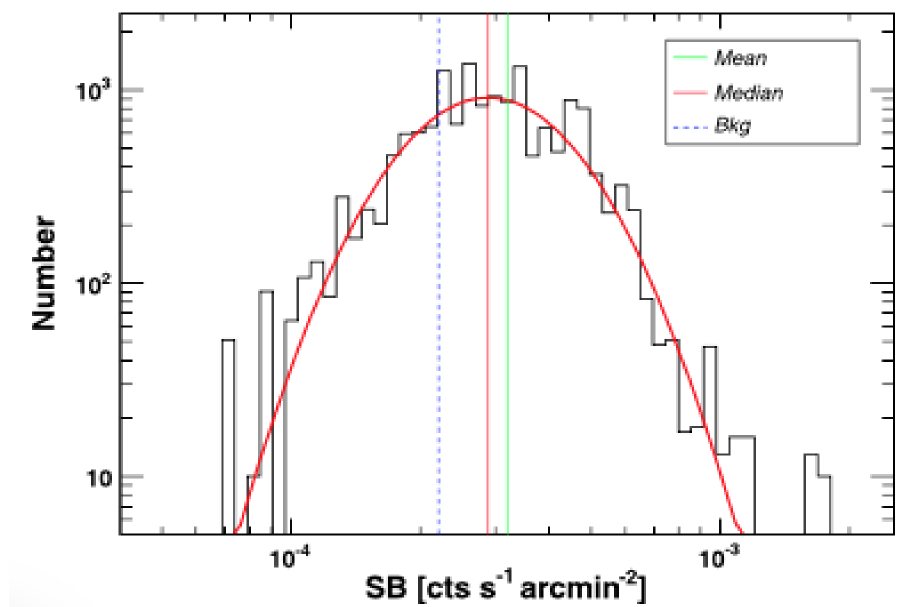




Zhuravleva+13





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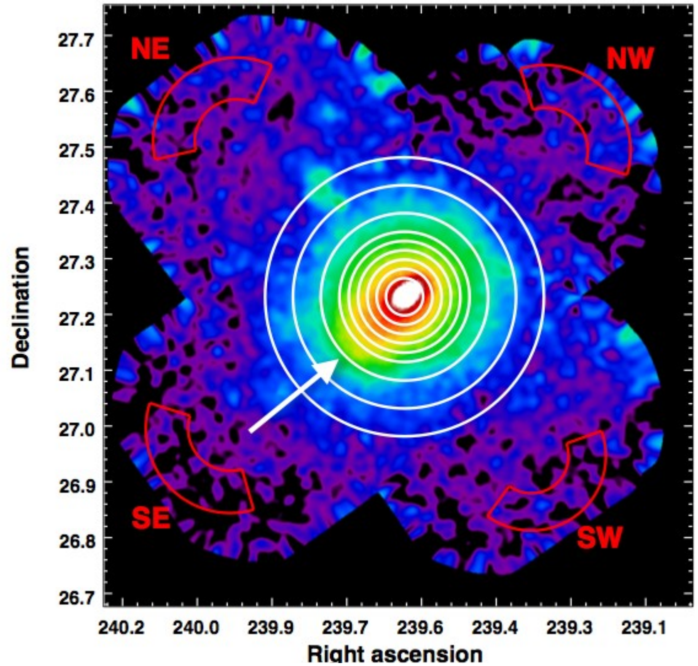

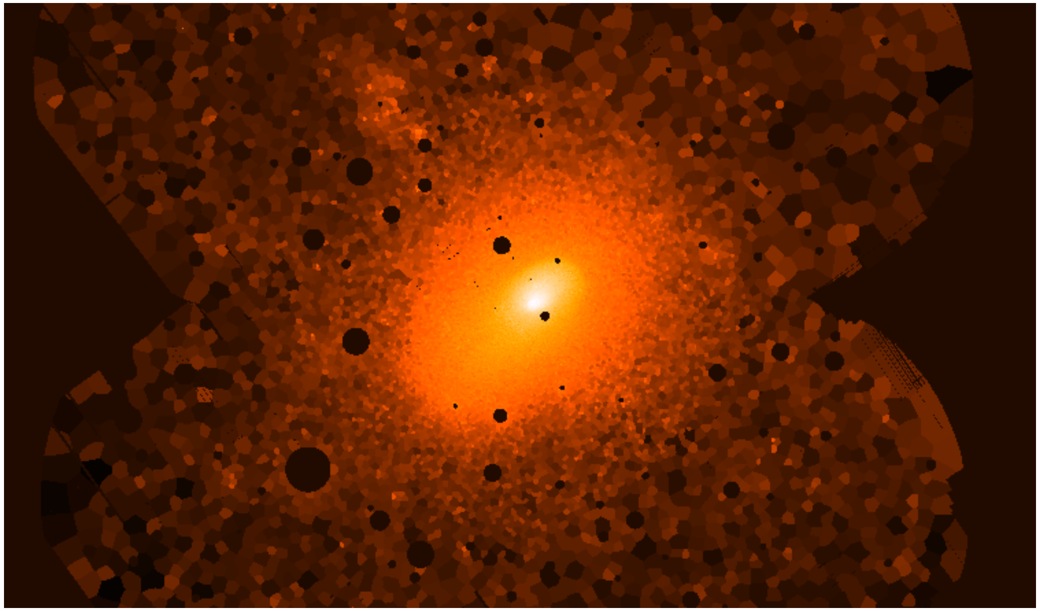

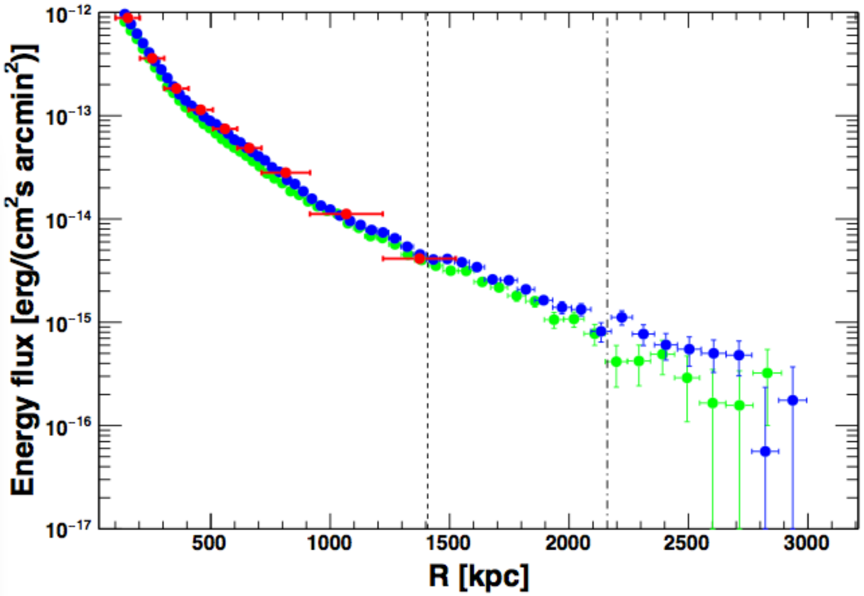

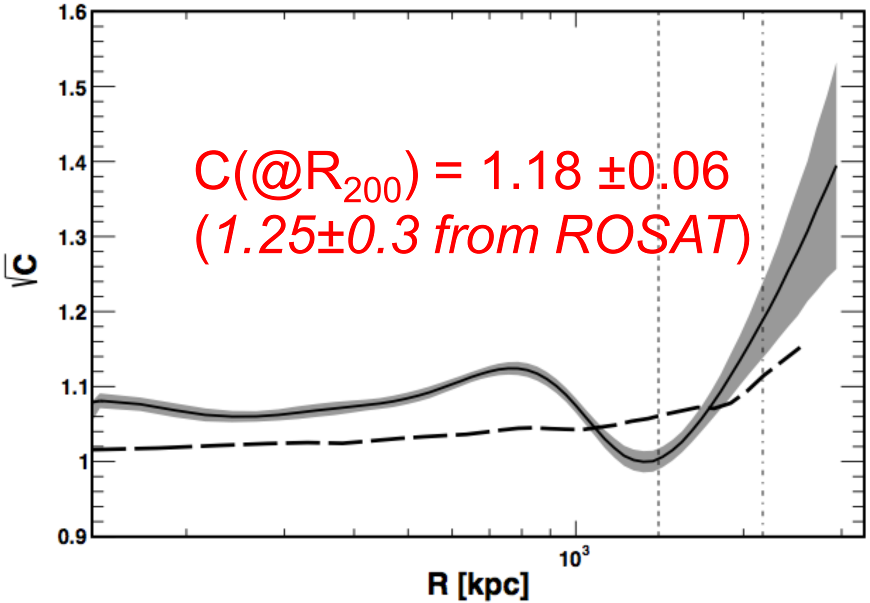

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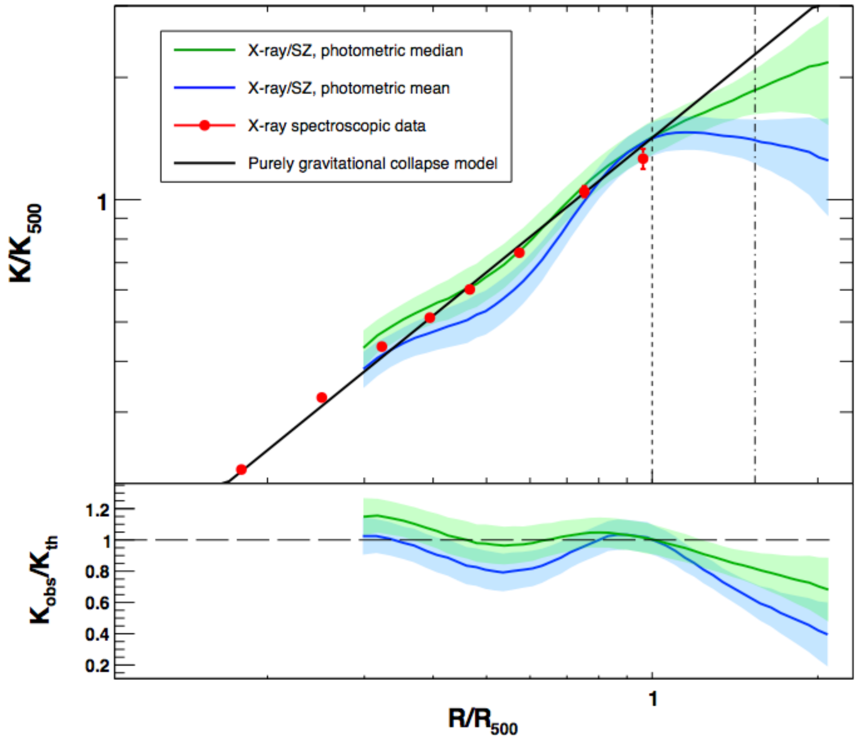
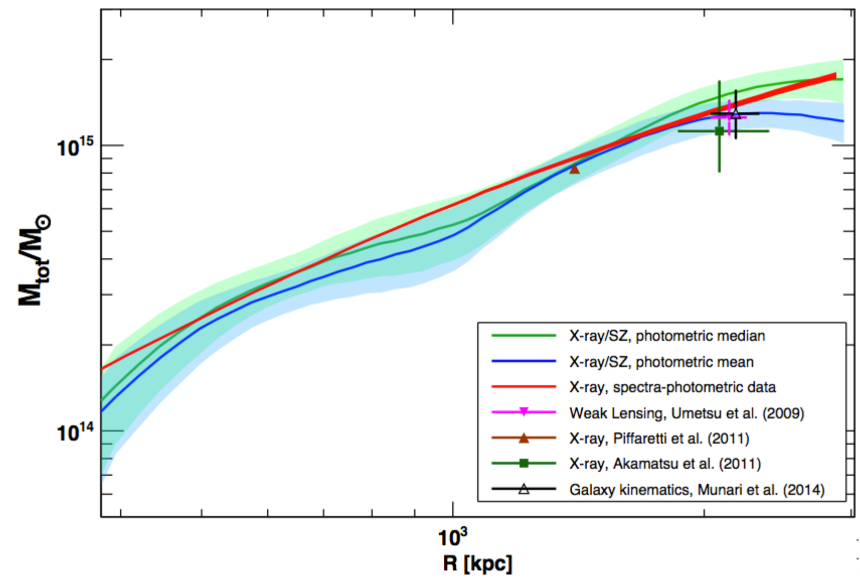
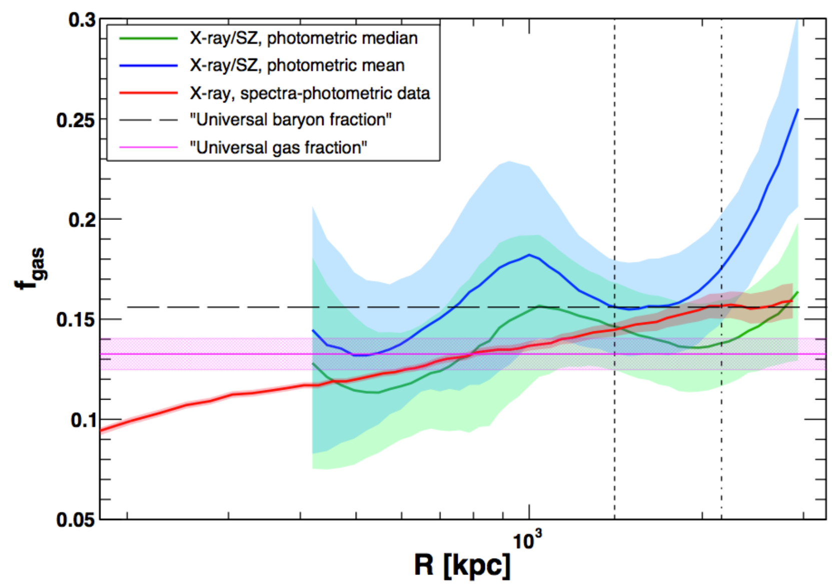




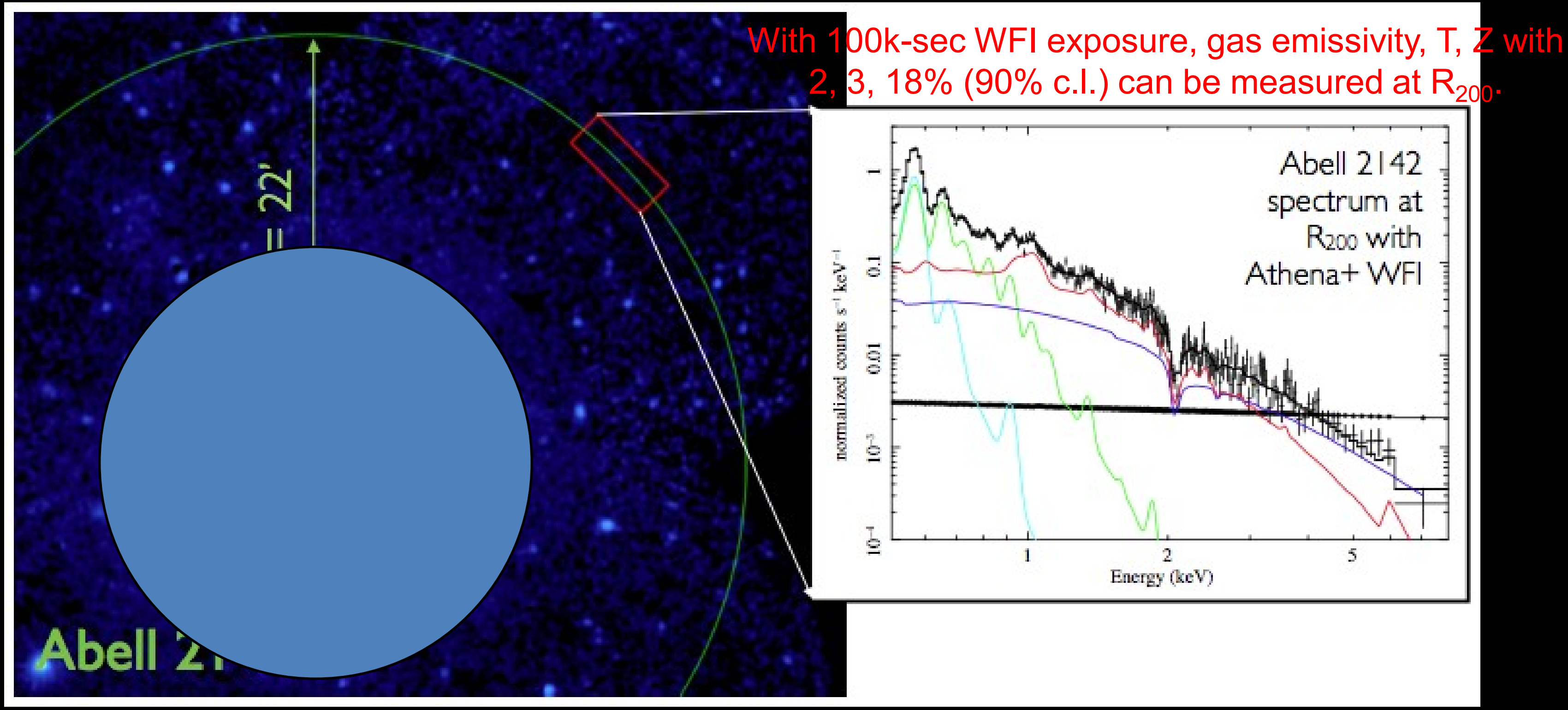


- **clumping can explain the entropy flattening** observed by *Suzaku* in the outskirts of several clusters
- M_{HE} recovered using joint X-ray/SZ data agrees with M reconstructions obtained through weak lensing and galaxy kinematics: **no hydrostatic bias**

The formation and evolution of clusters and groups of galaxies

How and when was the energy contained in the hot intra-cluster medium generated?

Ettori, Pratt et al., 2013 arXiv1306.2322



How does ordinary matter assemble into the large-scale structures that we see today?

ATHENA

The formation and evolution of clusters and groups of galaxies

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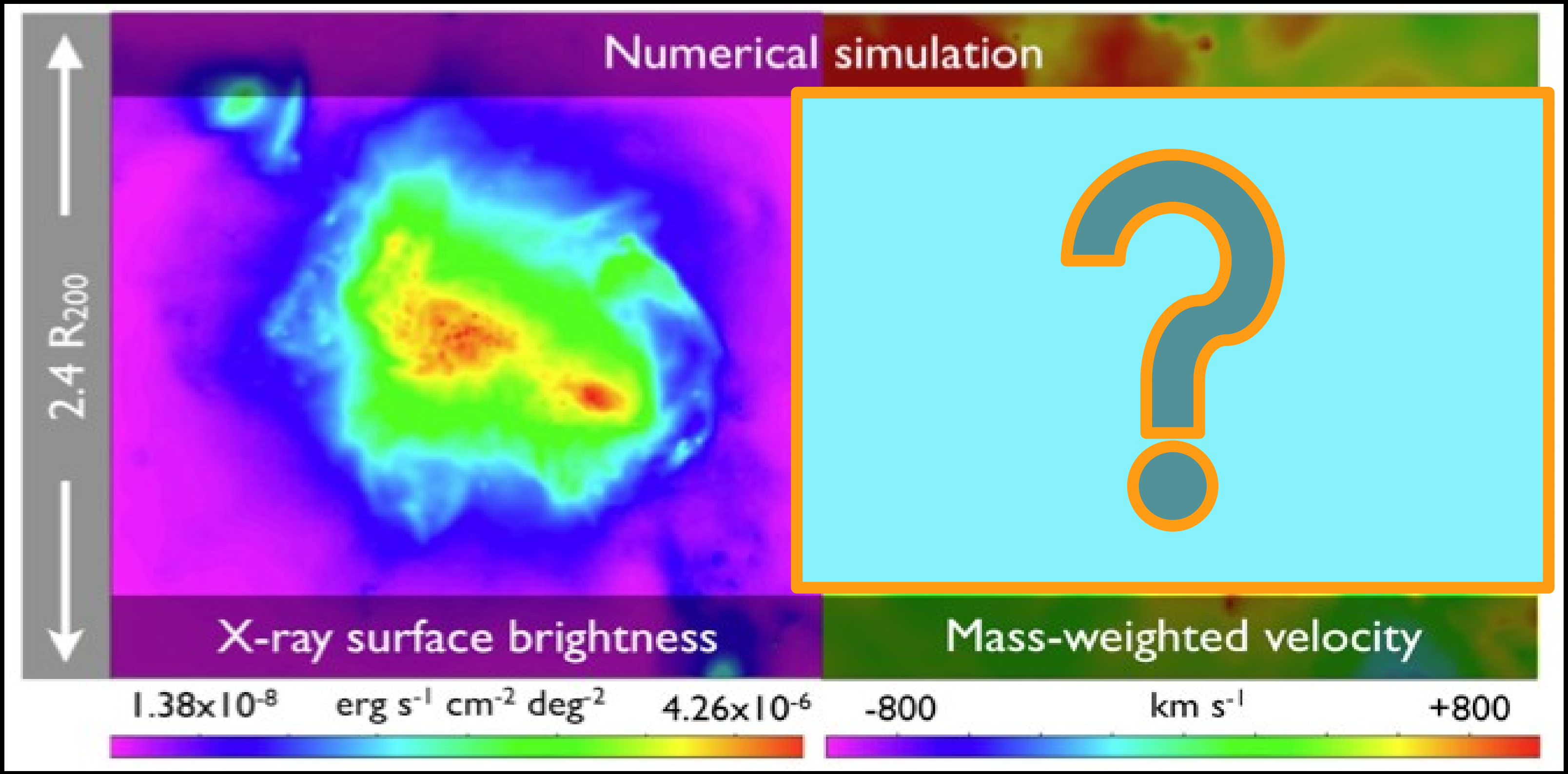

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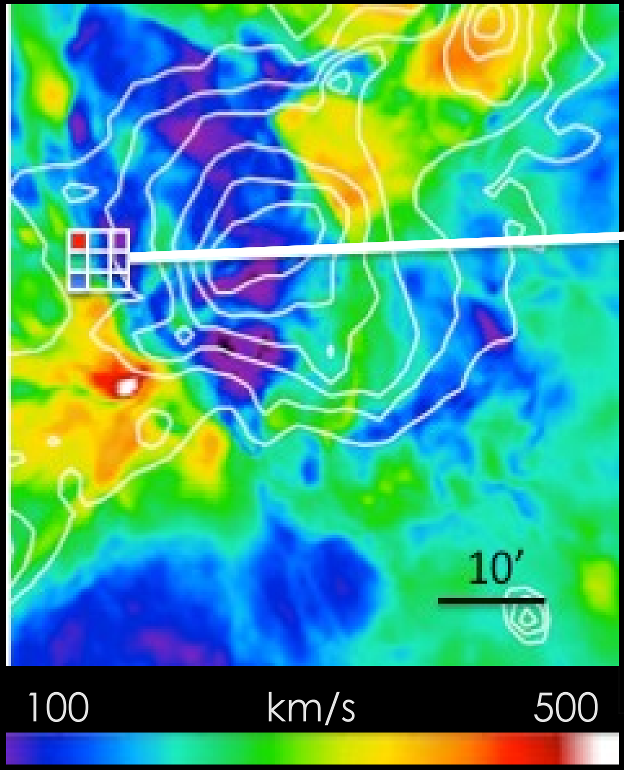
The formation and evolution of clusters and groups of galaxies

How and when was the energy contained in the hot intra-cluster medium generated?

Simulated Velocity map



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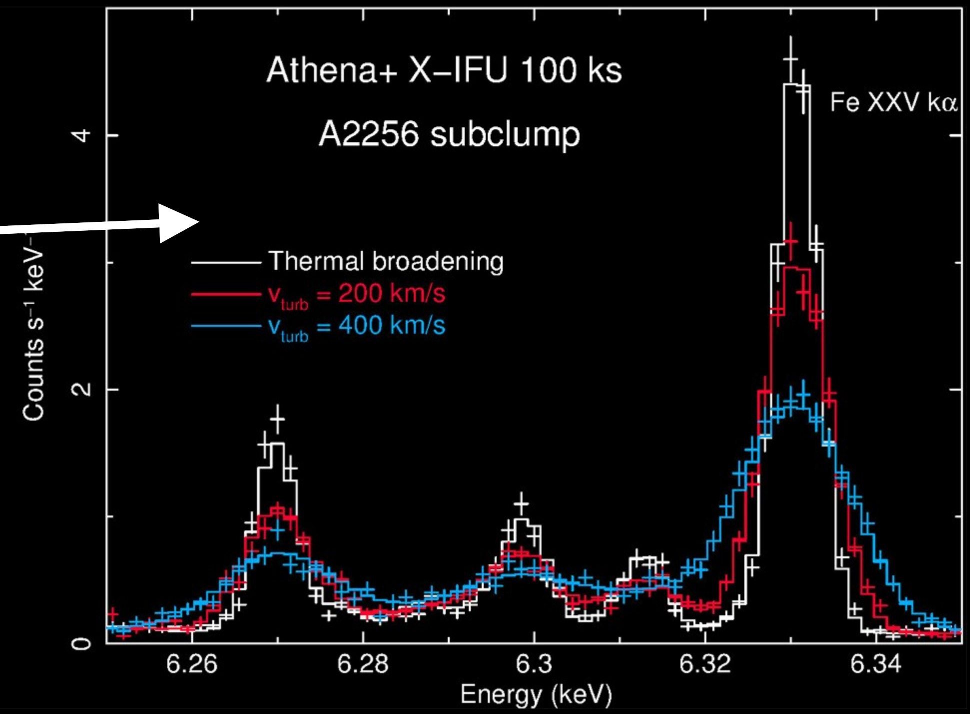


Bulk motion and turbulent broadening of FeXXV Ka line.

With 100k-sec X-IFU exposure, 0^{+20}, 200±5, 400±10 km/s can be resolved.

EWASS, Athens (Greece)

Symposium S6

4-5 July 2016

Exploring the outskirts of galaxy clusters

coordinators: Eckert, Ettori

S6

Webpage: http://eas.unige.ch/EWASS2016/session.jsp?id=S6

Total mass from SZ/X-rays

- *low counts statistic*: **scaling relations**

(for galaxy clusters mass function: M_{tot} vs $L/T/M_{gas}/Y_X$ *or* ***a combination of these***…)
Ettori et al. 2012; Ettori 2013 & 2015

Looking for the lowest scatter between X/SZ observables and Mass

$$M_{tot} \propto L^{\alpha} M_g^{\beta} T^{\gamma}; \quad 4\alpha + 3\beta + 2\gamma = 3$$

$M_{tot} \sim L^{\alpha}\ T^{-2\alpha+1.5}$

$\alpha = 0$ … $M_{tot} \sim T^{1.5}$
$\alpha = 3/4$ … $M_{tot} \sim L^{3/4}$
$\alpha = 1/2$ … $M_{tot} \sim (LT)^{1/2}$

$M_{tot} \sim M_{gas}^{\alpha}\ T^{-1.5\alpha+1.5}$

$\alpha = 0$ … $M_{tot} \sim T^{1.5}$
$\alpha = 1$ … $M_{tot} \sim M_{gas}$
$\alpha = 3/5$ … $M_{tot} \sim (M_{gas}\ T)^{3/5} \sim Y^{3/5}$

X-ray/SZ scaling relations:

Self-similar +{f_g, C, β}

The self-similar scenario predicts not only **slope** and **z-evolution** of the power-law relations between M_{tot} & X-ray/SZ observables but also the **normalization**

The ***self-similar*** prediction on **normalization & slope** can fully explain the ***observed X-SZ SL*** once **{f_g(M), β_P(M), C}** are considered

X-ray/SZ scaling relations:

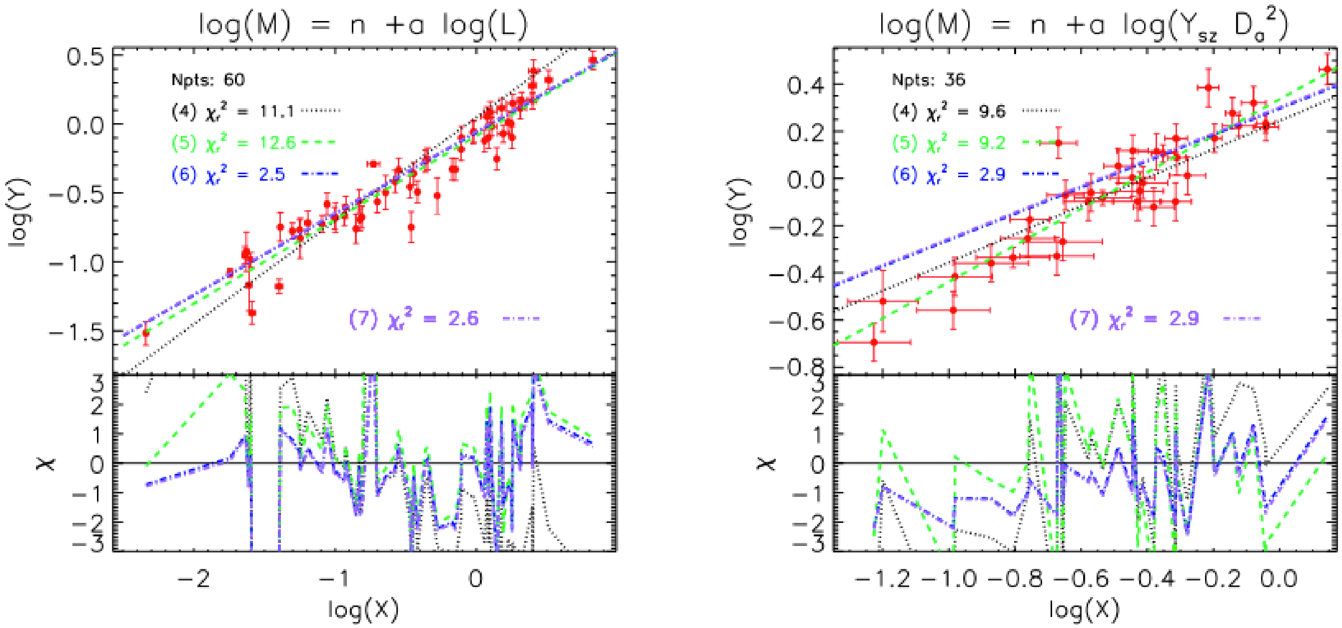
Self-similar +{f_g, C, β}

$$
\begin{aligned}
\frac{F_z M}{5\times 10^{14} M_\odot} &= 1.0 \left(\frac{C^{0.5} f_g}{0.1}\right)^{-1} \frac{F_z M_g}{5\times 10^{13} M_\odot} \\
&= 0.832 \left(\frac{\beta_P}{3}\right)^{3/2} \left(\frac{kT}{5keV}\right)^{3/2} \\
&= 0.962 \left(\frac{\beta_P}{3}\right)^{3/8} \left(\frac{C^{0.5} f_g}{0.1}\right)^{-3/2} \left(\frac{F_z^{-1} L_X}{5\times 10^{44}\mathrm{erg/s}}\right)^{3/4} \\
&= 1.748 \left(\frac{\beta_P}{3}\right)^{3/5} \left(\frac{f_g}{0.1}\right)^{-3/5} \left(\frac{F_z Y_{SZ} D_A^2}{10^{-4}\mathrm{Mpc}^2}\right)^{3/5} .
\end{aligned}
$$

Here, the normalizations & slopes are analytic.
The observed deviations from SS scenario can be ascribed to only 3 M-dependent physical quantities: gas clumpiness, f_{gas}, gradient of P_{gas} profile

X-ray/SZ scaling relations:

Self-similar +{f_g, C, β}



$$C^{0.5} f_{\mathrm{g}} = 0.110(\pm 0.002) \left(\frac{E_z M}{5 \times 10^{14}\,\mathrm{M}_\odot} \right)^{0.198(\pm 0.025)}$$

$$\beta_{\mathrm{P}} = -\frac{\mathrm{d}\ln P}{\mathrm{d}\ln r} = 3.14(\pm 0.04) \left(\frac{E_z M}{5 \times 10^{14}\,\mathrm{M}_\odot} \right)^{0.071(\pm 0.012)}$$

X-ray/SZ scaling relations:

Self-similar +{f_g, C, β}

$$\boxed{F_z M \sim \beta_{\rm P}^{\theta} f_{\rm g}^{-\phi} \, (F_z^{-1} L)^{\alpha} (F_z M_{\rm g})^{\beta} T^{\gamma}}$$

$$4\alpha + 3\beta + 2\gamma = 3$$

$$\theta = \alpha/2 + \gamma$$

$$\phi = 2\alpha + \beta$$

(Ettori15)

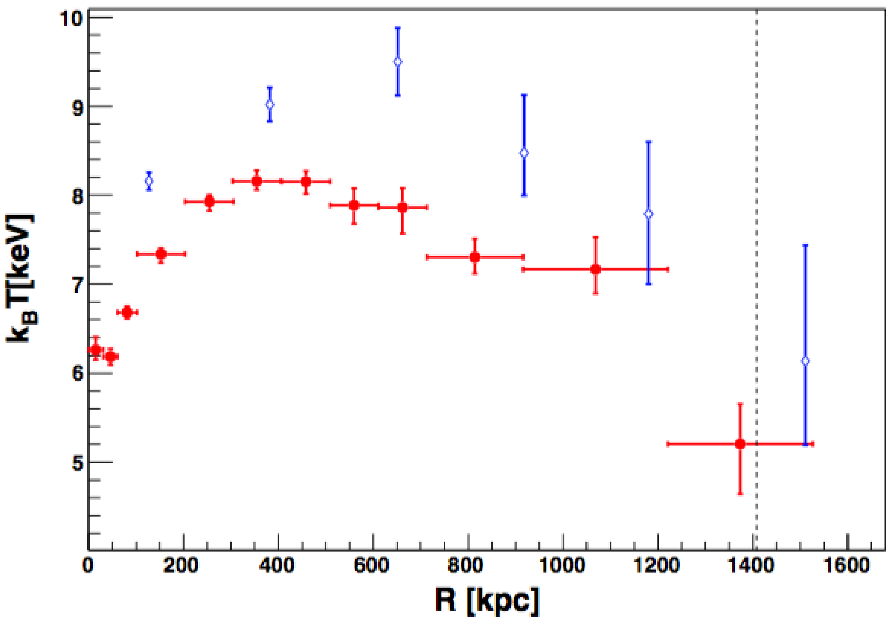
Conclusions
(waiting for *Athena*)

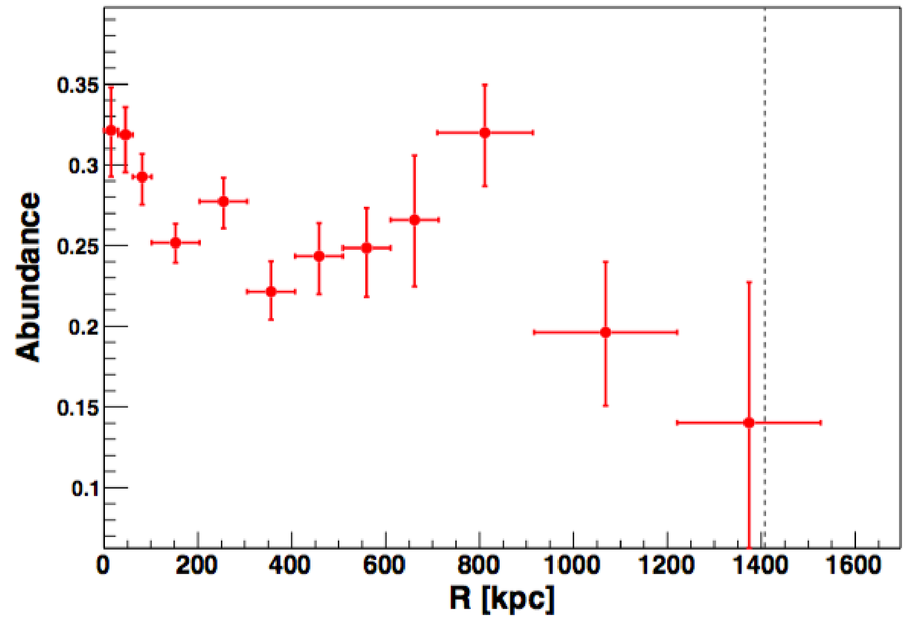
- Combining X-ray+SZ profiles is a promising tool to recover (possibly clumping-free) cluster physical quantities (and also M_{HE}):
  stay tuned for ***X-COP***…

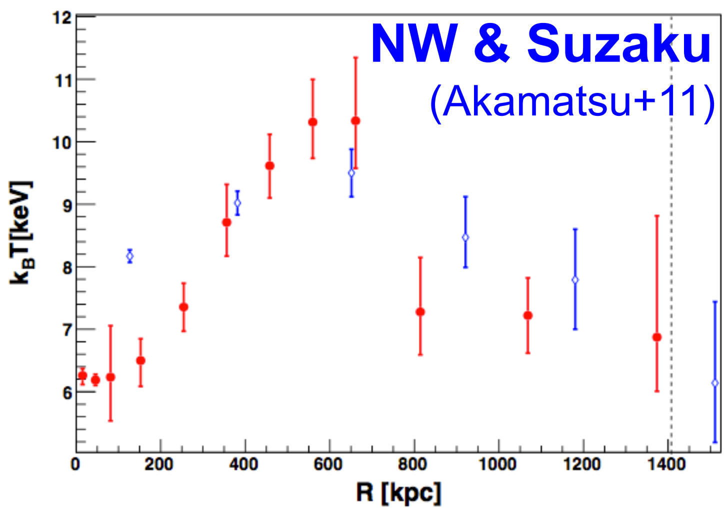
- *generalized-SRs* & *physical-SRs* define a framework for X-ray/SZ scaling laws that permit to reconstruct M with the lowest scatter
  (up to 50% lower than the one from standard-SRs)

FINE

X-COP: A2142 (Tchernin+16)







Conclusions
(waiting for *Athena*)

- from simulations & observations, we are understanding biases & scatter in M_{HE}-M_{WL} (still large deviations btw different samples); statistical tools are available to model many systematic effects

- Combining X-ray+SZ profiles is a promising tool to recover (possibly clumping-free) cluster physical quantities (and also M_{HE}): stay tuned for ***X-COP***…

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Ettori et al., 2010, A&A, 524, 68; Baldi, Ettori et al., 2012, A&A, 537, 142; Eckert et al., 2013, A&A, 551, 23; Planelles et al., 2013, MNRAS; Roncarelli et al., 2013, MNRAS; Ettori et al., 2013, SSRv, arXiv:1303.3530

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Ettori et al., 2012; Ettori, 2013 & 2015

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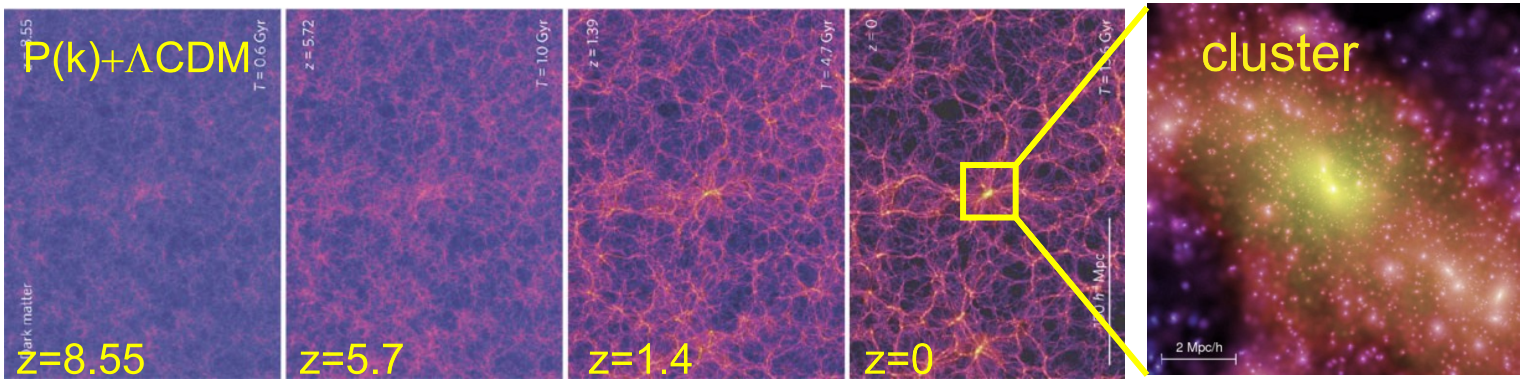
Structure formation in the Universe



We know how the gravity forms structures on cluster scales.
X-rays (SZ) provide a direct probe of the thermalized gas in a cluster's potential.