UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
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Where are the baryons?

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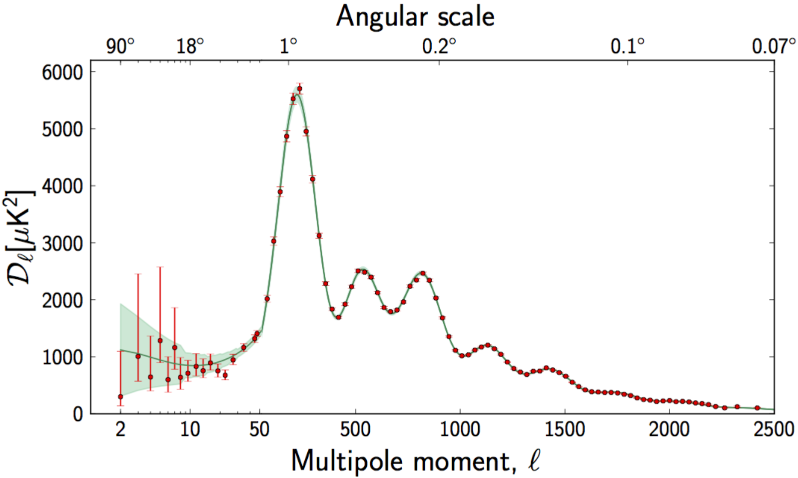
Main collaborators: S. Ettori, M. Jauzac, J. Coupon, C. Tchernin, J.-P. Kneib, S. Molendi, E. Pointecouteau, M. Ramos, G. Hurier, F. Vazza, H.Y. Shan, S. Paltani
...

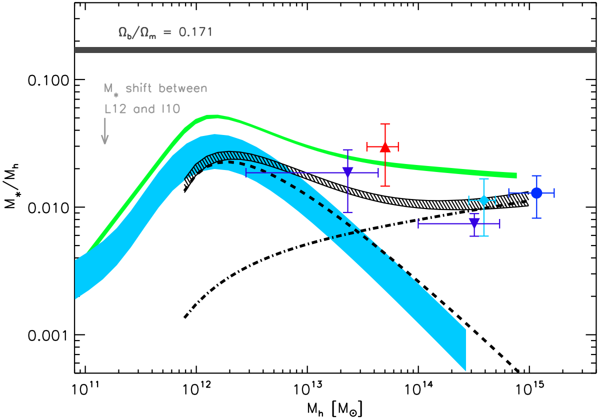
September 29, 2016

The cosmic baryon fraction



Planck 2015 release: $\Omega_b/\Omega_m = 0.156 \pm 0.003$; 2% uncertainty!

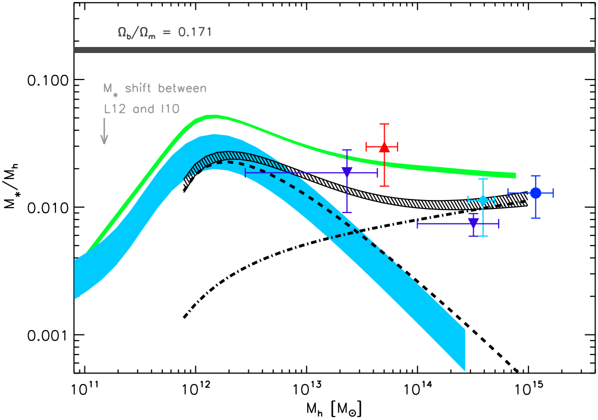
Star formation in the Universe is inefficient



Coupon et al. 2015

Where are the Universe's baryons?

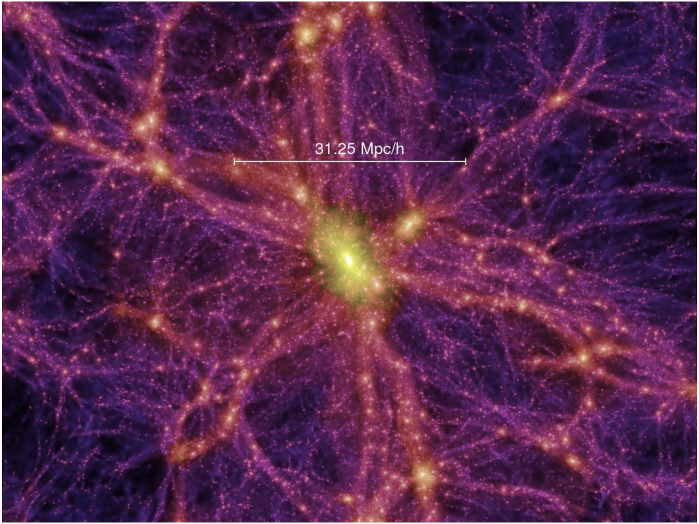
Star formation in the Universe is inefficient



Coupon et al. 2015

At all mass scales the stellar fraction only represents a small fraction ($< 20\%$) of the cosmic baryon fraction

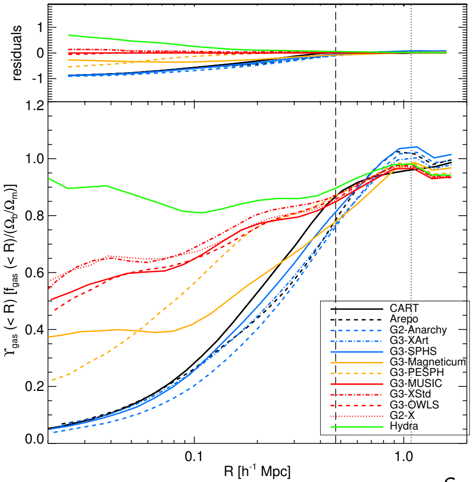
Formation and evolution of a galaxy cluster



Millenium Simulation, Springel et al. 2005

Most of the baryons should be in the hot gas

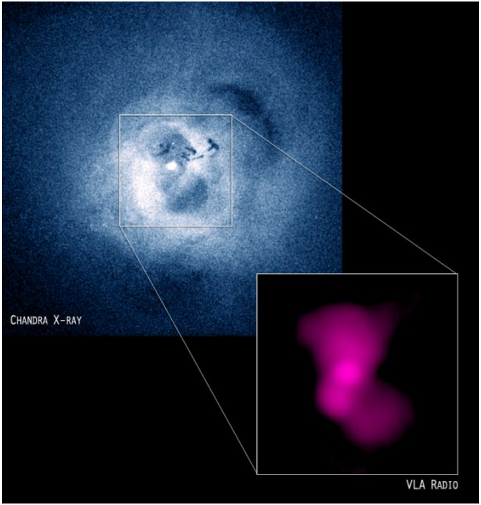
Comparison between 13 non-radiative codes



Sembolini et al. 2015

The baryon fraction should be close to the cosmic value

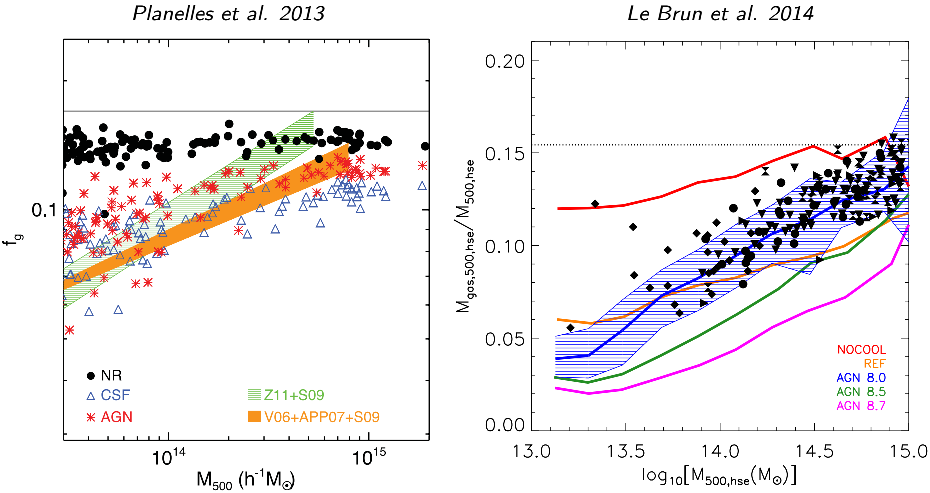
AGN feedback in massive halos



Perseus cluster, Fabian et al. 2000

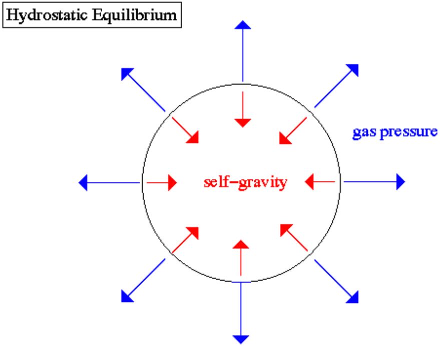
Feedback from the central AGN reheats the surrounding medium

Adding baryonic physics and AGN feedback



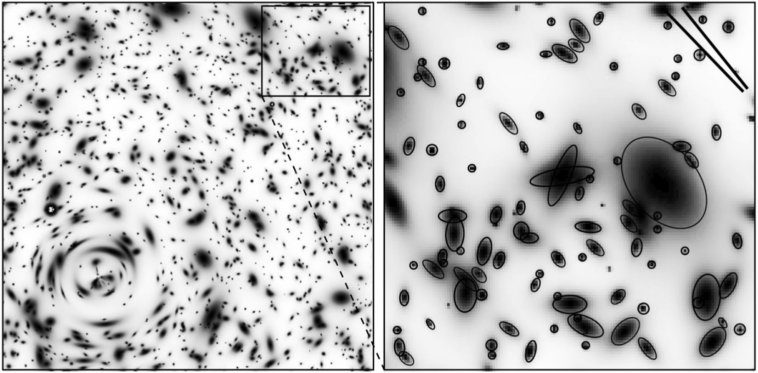
Cooling transforms some of the baryons into stars
AGN feedback makes the gaseous atmosphere expand

A word on mass measurement techniques



- Hydrostatic: $\frac{dP}{dr} = -\rho \frac{GM(<r)}{r^2}$; assumes that all the energy is thermalized

A word on mass measurement techniques



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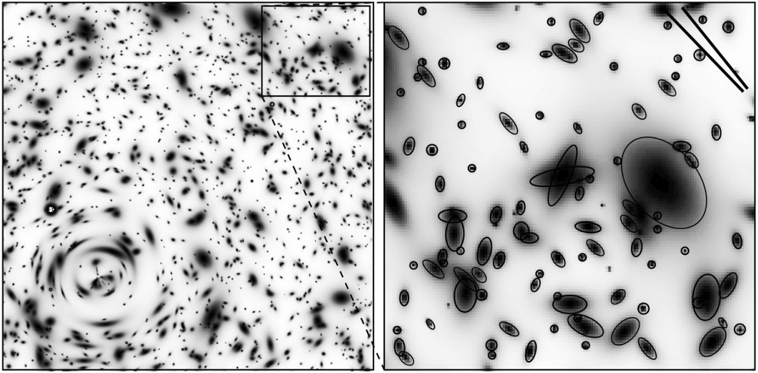
- Weak lensing: requires precise shape measurements, sensitive to projection effects

A word on mass measurement techniques



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$\boxed{\textbf{All current measurements of } f_{\rm bar} \textbf{ assumed HSE}}$

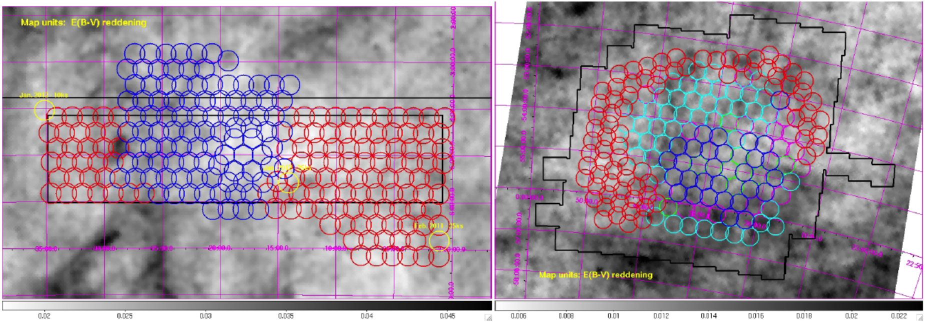
Outline

A large fraction of the Universe's baryons is escaping our census...
This talk:

- A census of baryons in XXL-selected galaxy clusters
- The baryon content of optically-selected massive galaxies
- Pushing X-ray and SZ observations towards the outskirts
- Hot gas filaments in the outskirts of Abell 2744

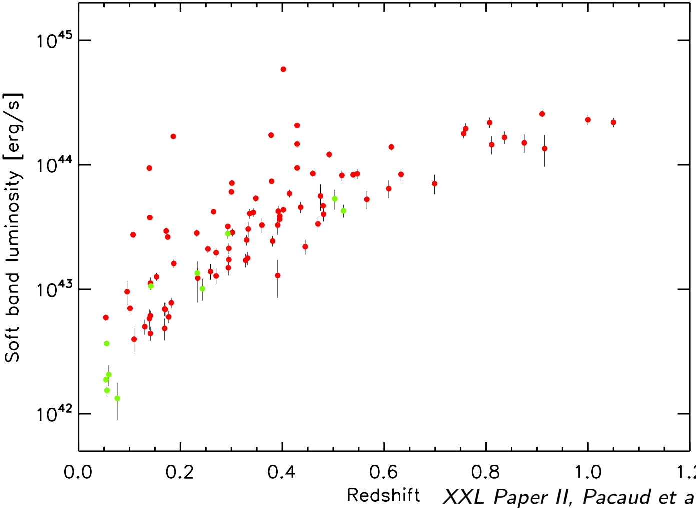
The XMM-XXL survey

XXL (PI: M. Pierre) covers an area of 50 square degrees with uniform 10 ks XMM exposure



- Survey sensitivity: 5×10^{-15} ergs cm^{-2} s^{-1} (0.5-2.0 keV band)
- Observations completed in December 2013

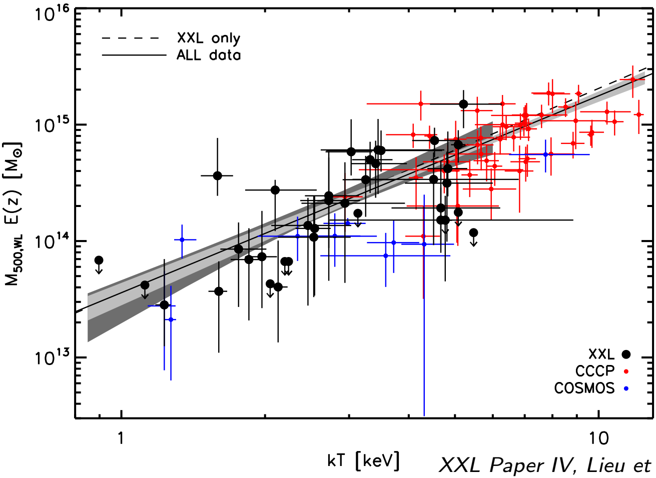
The XXL-100 sample



XXL Paper II, Pacaud et al. 2016

Sample used to calibrate mass-observable scaling relations

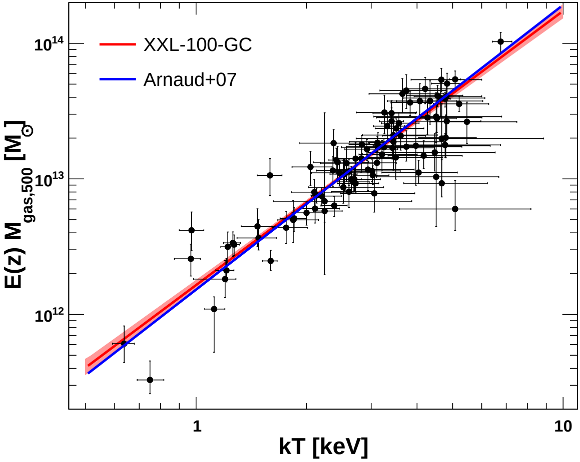
Weak lensing mass - X-ray temperature relation



XXL Paper IV, Lieu et al. 2016

$M_{\rm WL} - T_X$ using 37 CFHTLS systems. Low scatter $\sigma_{\rm int} \sim 20-30\%$

$M_{\text{gas}} - T$ relation

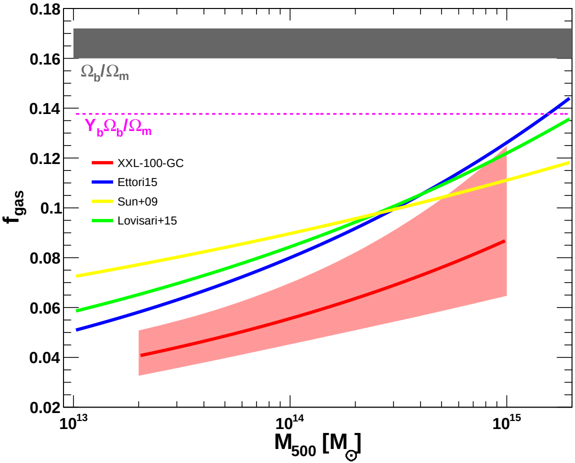


XXL Paper XIII, Eckert et al. 2016

M_{gas} correlates very well with temperature

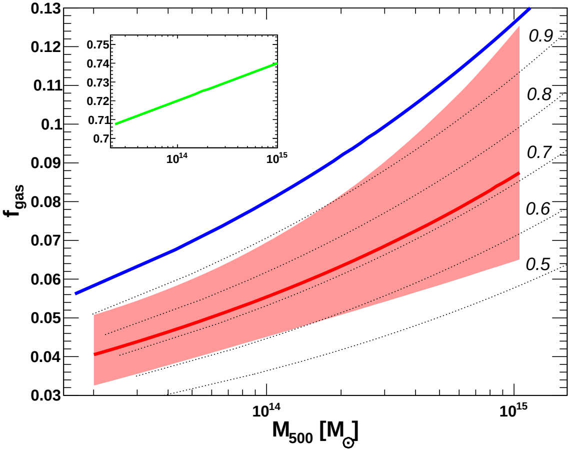
Gas fraction

We get $f_{\rm gas}$ by combining $M_{\rm WL} - T$ and $M_{\rm gas} - T$



Our $f_{\rm gas}$ is significantly lower than HSE-based measurements

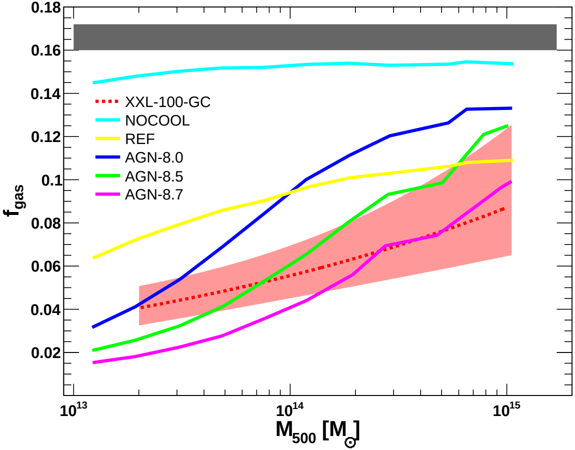
Hydrostatic bias?



Matching WL and hydrostatic relations would require a hydrostatic bias $1-b=0.72^{+0.08}_{-0.07}$

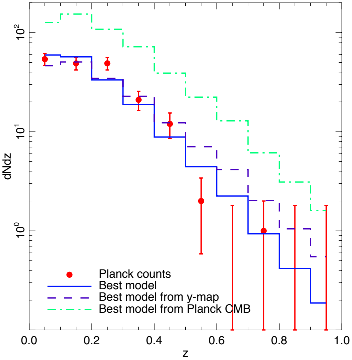
Comparison with numerical simulations

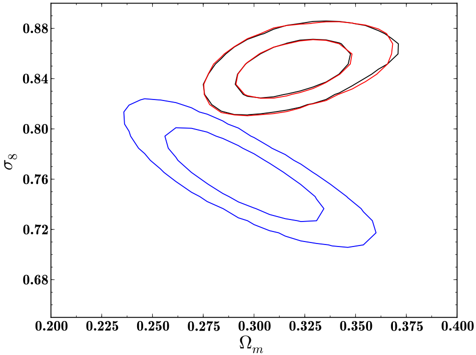
Comparison with hydrodynamical simulations (cosmo-OWLS, Le Brun et al. 2014)



Puzzling result not easy to explain for simulations

Planck: inconsistency between CMB and cluster counts



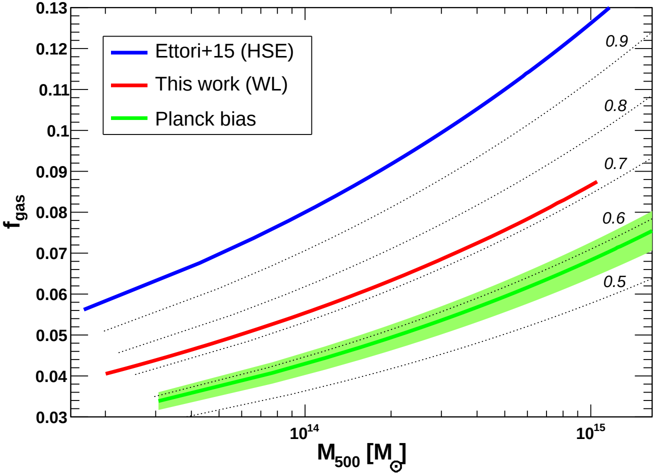


Planck Collaboration XX, 2013

The tension could be solved by invoking a very large HSE bias
$1 - b = 0.58 \pm 0.04$

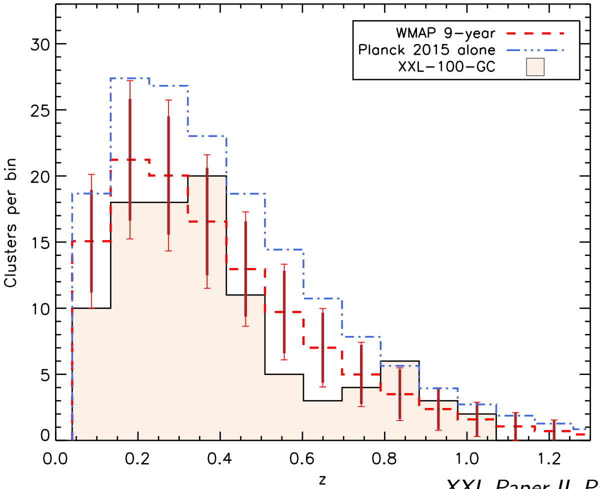
Implications for cosmology

Expected $f_{\rm gas}$ for $1-b=0.58$



Large HSE bias strongly disfavored by $f_{\rm gas}$ data

XXL vs Planck cosmology



XXL Paper II, Pacaud et al.

XXL prefers lower σ_8 compared to *Planck* CMB, agreement with clusters and WL shear

Hot halos of massive galaxies

Hot halos are a generic prediction of structure-formation models (e.g. Vogelsberger et al. 2014)

NGC 5746, Pedersen et al. 2006

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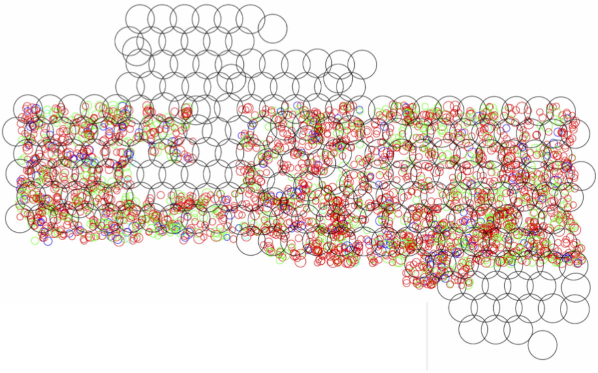
NGC 5746, Pedersen et al. 2006

The mass and occurrence of hot halos is essentially unknown

Stacking optically-selected galaxies in XXL-N

Step 1: We selected a catalogue of $\sim 3,000$ massive galaxies ($M_\star > 10^{11} M_\odot$) from WIRCAM and CFHTLS data



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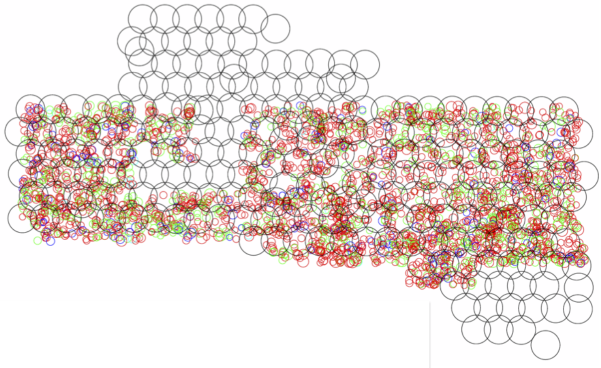
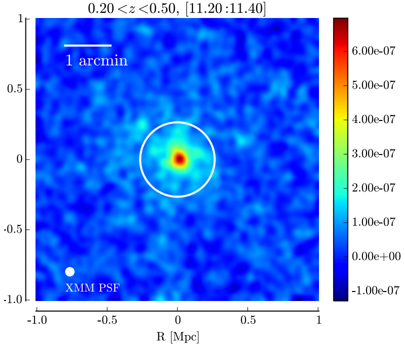
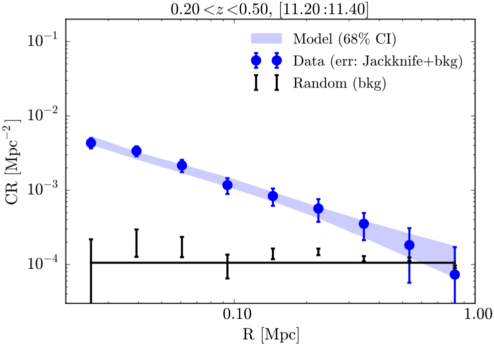


Step 2: We stacked XXL images in bins of $M_\star$

Low-z sample ($0.2 < z < 0.5$)



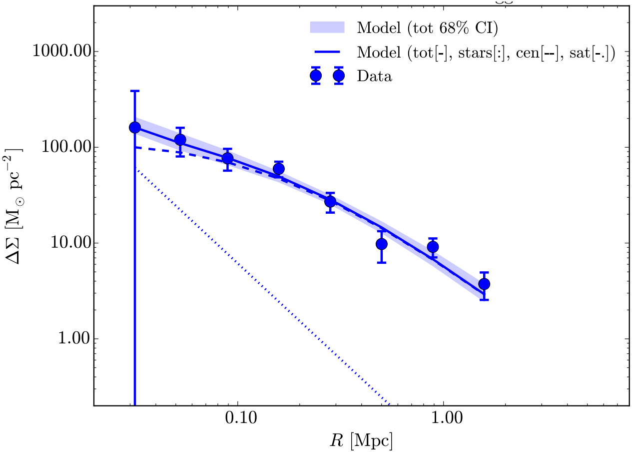


Coupon et al. in prep.

Strong X-ray signal detected down to $M_\star = 10^{11} M_\odot$!

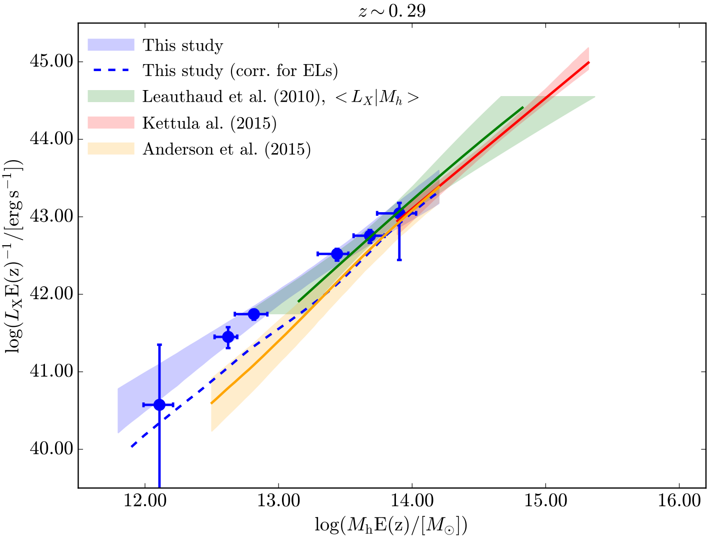
Galaxy-galaxy lensing

High-S/N lensing signal detected in all mass bins



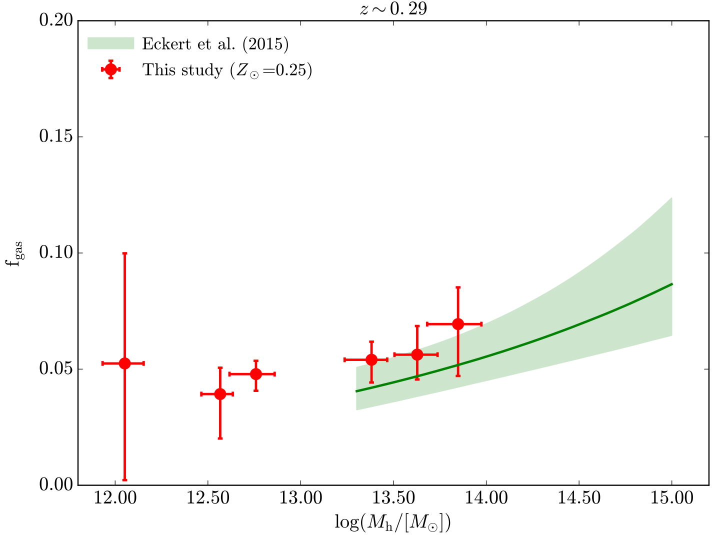
Here: $11.2 < \log M_\star < 11.4$

$L_X - M$ relation



The $L_X - M$ relation extends *with no break* down to $M_h \sim 10^{12.5} M_\odot$

$L_X - M$ relation

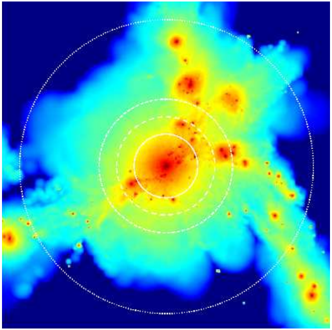


The gas fraction

The outskirts of galaxy clusters

Why pushing toward the outskirts? ($R > R_{500}$)

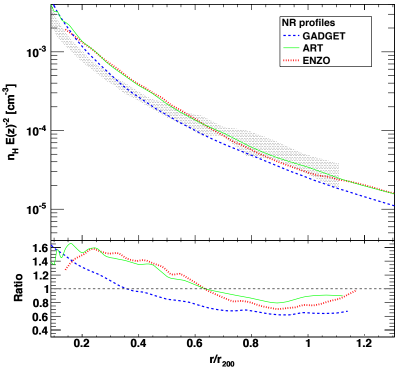
- Contain $\sim 90\%$ of the volume and $\sim 50\%$ of the mass!
- Understand the build-up of galaxy clusters
- Test hydrostatic mass measurements
- Estimate the global baryon budget



Roncarelli et al. 2006

ROSAT density profiles

- We analyzed a sample of 31 nearby clusters ($0.04 < z < 0.2$)
- Emission-measure and deprojected density profiles for all clusters
- In average density profiles *steepen* beyond R_{500}
- Non-radiative simulations predict *too steep* density slopes



Eckert et al. 2012

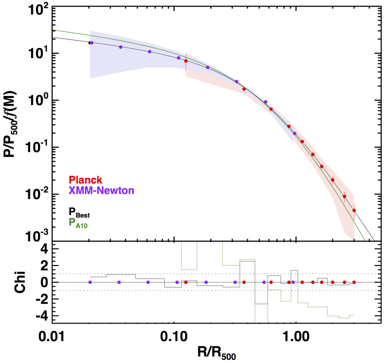
Planck Sunyaev-Zeldovich measurements

- Recently: *Planck* measures the SZ effect beyond the virial radius
- Combined with X-ray data, we can reconstruct:

$$kT = \frac{P_{SZ}}{n_{X-ray}}, \quad K = P_{SZ} n_{X-ray}^{-5/3}$$

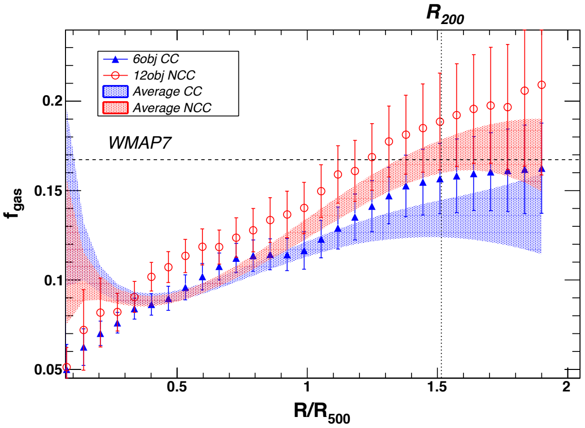
- Assuming hydrostatic equilibrium we can also reconstruct mass profiles:

$$\frac{dP}{dr} = -\rho \frac{GM(<r)}{r^2}$$



Planck Collaboration V 2012

Gas fraction in relaxed/unrelaxed systems

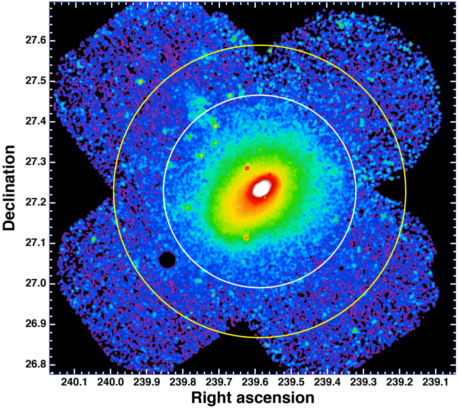


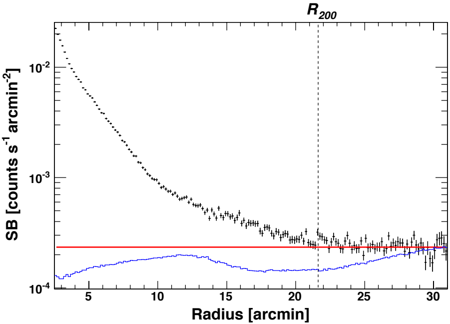
Eckert et al. 2013b

- For relaxed (CC) systems f_{gas} reaches the expected values ($\Omega_b/\Omega_m - 15\%$)
- For unrelaxed (NCC) systems f_{gas} **exceeds** the cosmic value

Mapping clusters out to R_{vir} with XMM and Planck

Abell 2142 ($z = 0.09$): XMM mosaic program (Eckert et al. 2014)

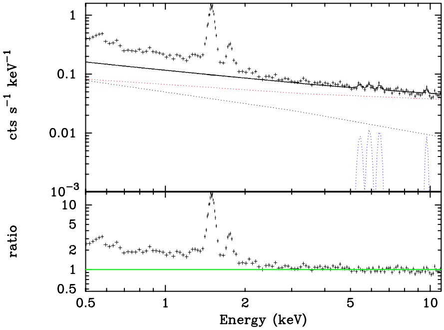


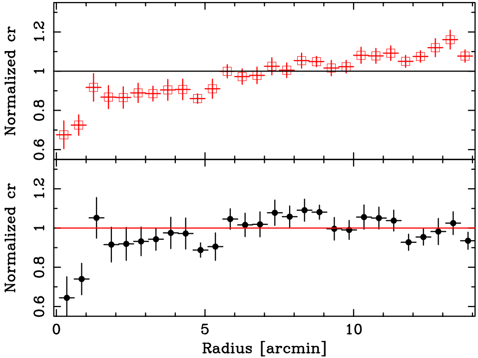


With the appropriate bkg modeling XMM can trace efficiently the ICM out to R_{vir}

Calibration using deep fields

Mean radial profiles for 22 blank fields (total 1.3 Ms)



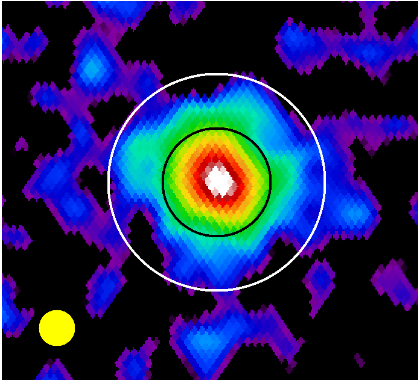


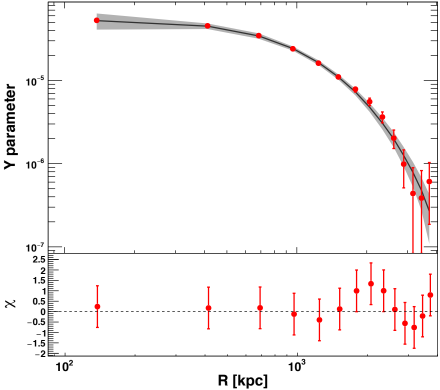
Eckert et al. subm.

Quiescent soft protons must be taken into account; with new calibration we reach a precision of 5% on background subtraction

Mapping clusters out to R_{vir} with XMM and Planck

Abell 2142 ($z = 0.09$): MILCA component separation (Hurier et al. 2013)

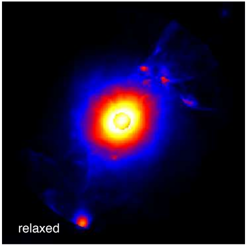




Planck nicely detects several individual clusters out to R_{vir}

Gas clumping

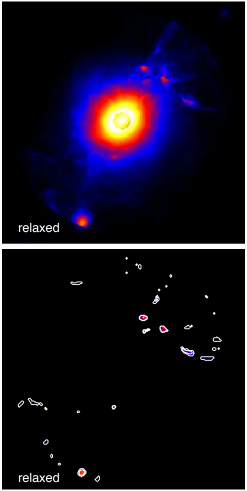
- Possible interpretation: gas clumping
- The accretion flow on galaxy clusters is *clumpy* and *asymmetric*



Vazza, DE et al. 2013

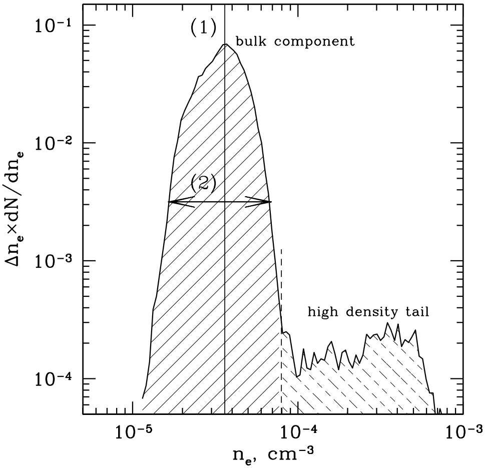
- Possible interpretation: gas clumping
- The accretion flow on galaxy clusters is *clumpy* and *asymmetric*
- X-ray signal biased towards high-density, cool regions:

$$C^2 = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} > 1$$



Vazza, DE et al. 2013

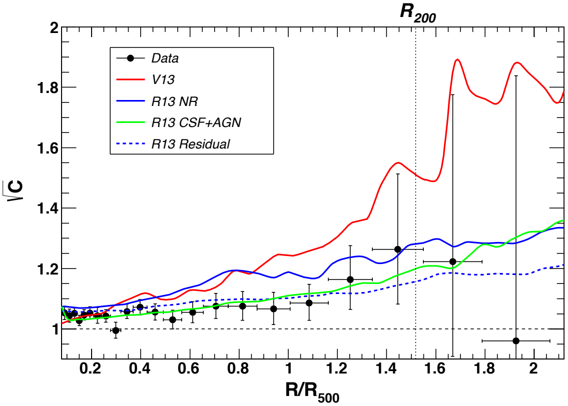
Azimuthal median is robust against inhomogeneities



Zhuravleva et al. 2013

Gas clumping factor

ROSAT/PSPC ENZO NR GADGET NR GADGET CSF+AGN

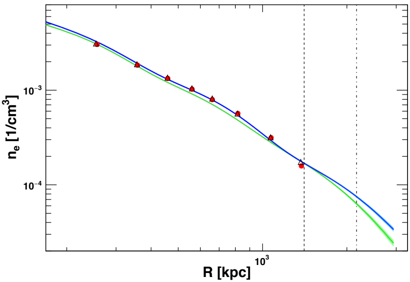


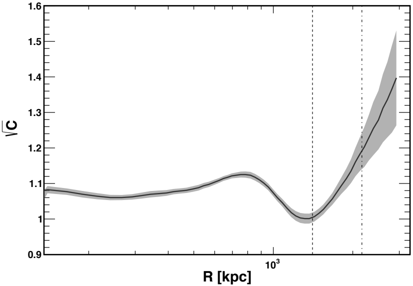
Eckert et al. 2015

- Non-radiative simulations predict *too many* substructures in the outskirts
- Including AGN + SN feedback improves the match

A2142 clumping factor

By comparing mean and median SB we can recover the gas clumping factor

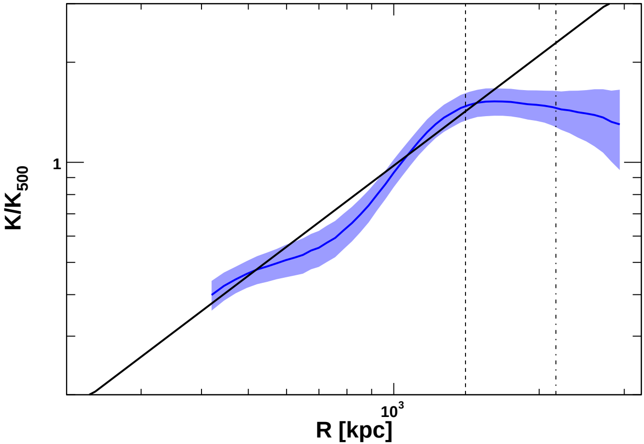




Tchernin, DE et al. 2016

We observe significant clumping beyond R_{500}

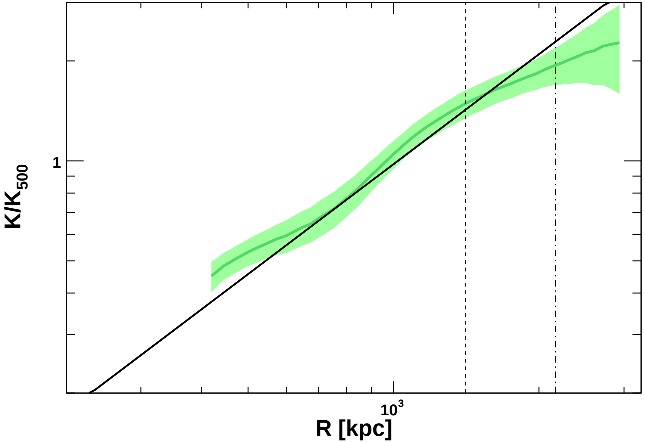
A2142 entropy profile



Tchernin, DE et al. 2016

The entropy flattens beyond R_{500} when clumps are not excised...

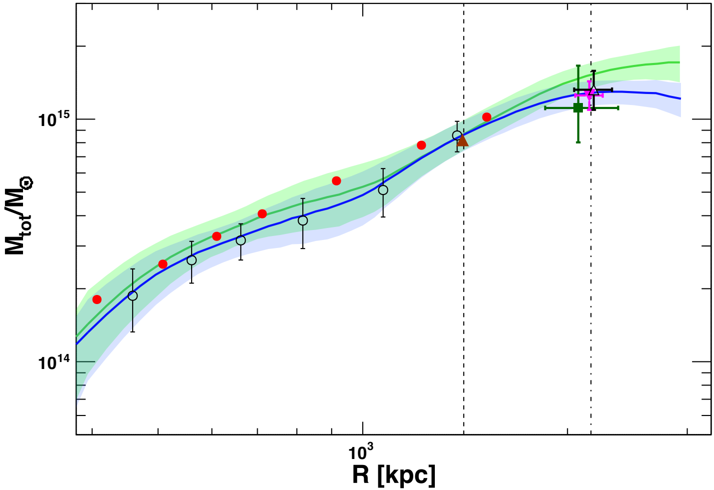
A2142 entropy profile



Tchernin, DE et al. 2016

The entropy flattens beyond R_{500} when clumps are not excised...
but not when clumping is taken into account!

A2142 mass profile



Tchernin, DE et al. 2016

Hydrostatic profiles consistent with weak lensing, galaxy dynamics; $f_{\rm gas}$ converges to the cosmic value

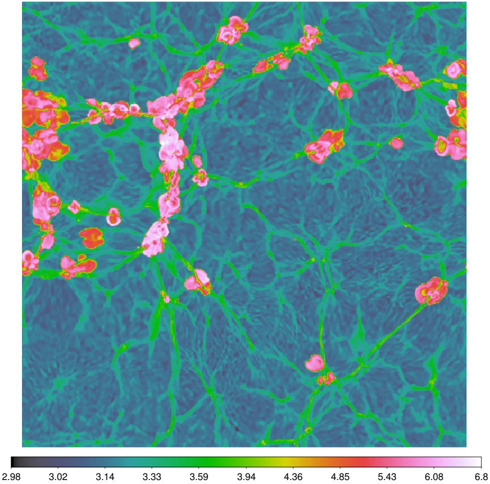
The XMM Cluster Outskirts Very Large Programme (X-COP)

XMM AO-13 VLP, total 1.5 Ms: Construct a sample of 13 clusters at $0.04 < z < 0.1$ with high-S/N *Planck* detection and XMM mapping of the entire azimuth

Cluster	**Redshift**	**Mass [10^{14} $M_\odot$]**	***Planck* S/N**
A2319	0.0557	5.83	30.8
A3266**	0.0589	4.56	27.0
A2142*	0.090	8.15	21.3
A2255	0.0809	3.74	19.4
A2029	0.0766	7.27	19.3
A3158	0.059	3.65	17.2
A85	0.0555	5.32	16.9
A1795	0.0622	5.53	15.0
A644	0.0704	3.88	13.9
RXC J1825	0.065	2.62	13.4
A1644	0.0473	2.93	13.2
ZwCl 1215	0.0766	3.59	12.8
A780*	0.0538	1.89	-

The Warm-Hot Intergalactic Medium (WHIM)

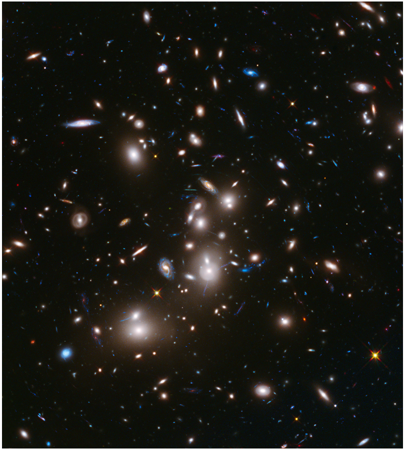
- Numerical simulations predict that $\sim 50\%$ of the baryons should be located in intergalactic filaments
- Temperatures in the range $10^{5.5} - 10^7$ K
- Density, temperature, gas mass scale with filament mass



Gheller et al. 2015

Abell 2744 ($z = 0.306$): the Pandora cluster

Abell 2744 is one of the HST "Frontier Fields" clusters

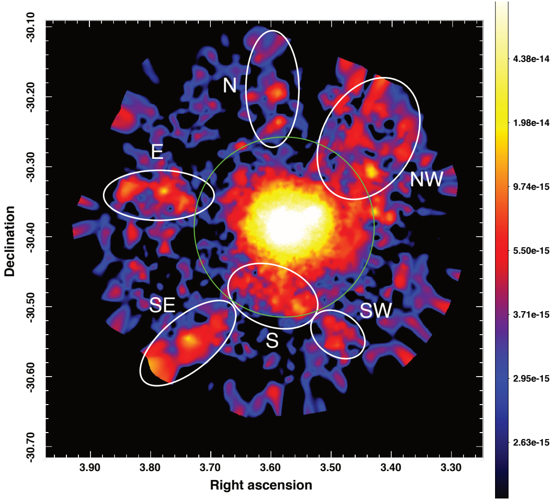


Jauzac et al. 2015

Jauzac et al. 2015: We detected ~ 50 lensed galaxies in this cluster, corresponding mass model known at 1% precision

XMM-Newton observation of Abell 2744

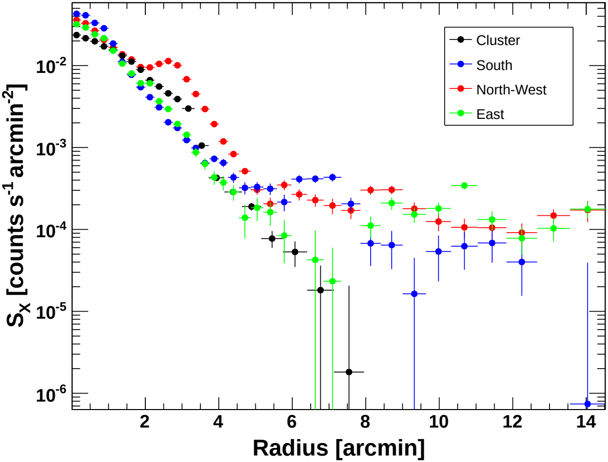
We discovered 5 regions of extended X-ray emission radially connected to the cluster



Eckert et al. 2015

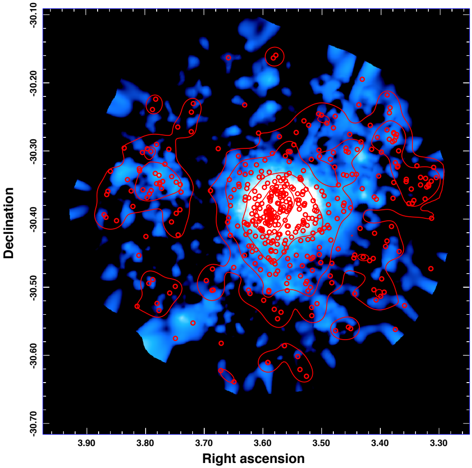
Hot gas filaments in Abell 2744

Significant extended emission detected in the direction of the filaments out to ~ 4 Mpc



Eckert et al. 2015

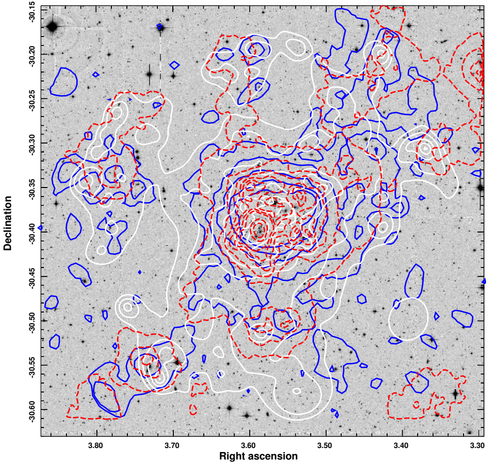
The filamentary structures correspond with overdensities of cluster galaxies (spectroscopically confirmed)...



Eckert et al. 2015

Hot gas filaments in Abell 2744

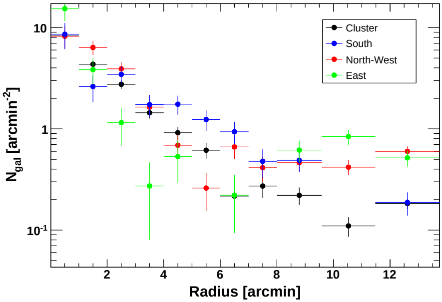
The filamentary structures correspond with overdensities of cluster galaxies ... and DM (CFHT weak lensing)!



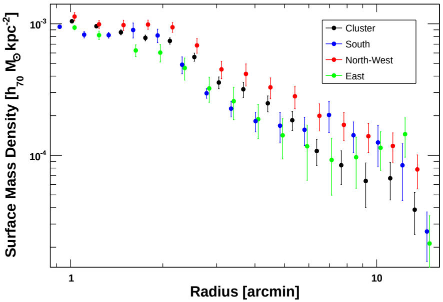
Eckert et al. 2015

Galaxies and DM overdensity in the filaments

Galaxy density



Lensing signal

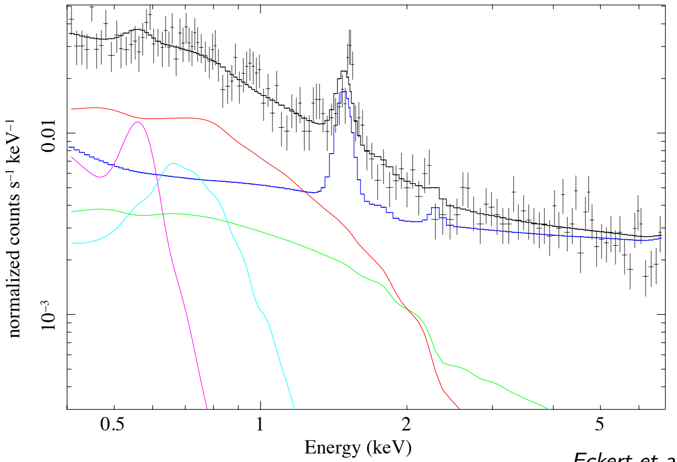


Eckert et al. 2015

Excess galaxy and DM density is observed in the regions encompassing the filaments. The gas fraction in the filaments is 5-10%

Nature of the filaments

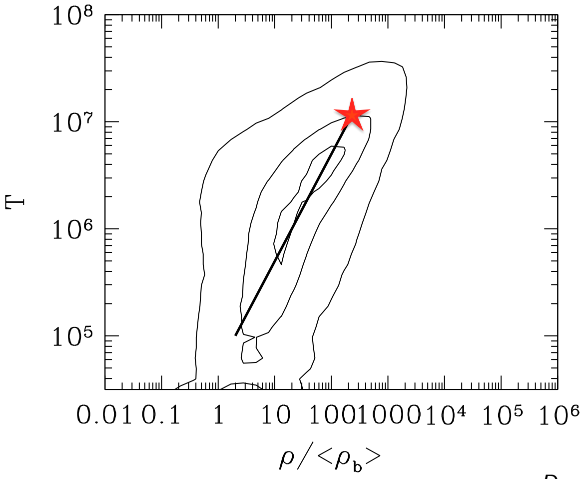
Spectral analysis reveals thermal gas with $T \sim 1$ keV



Eckert et al. 2015

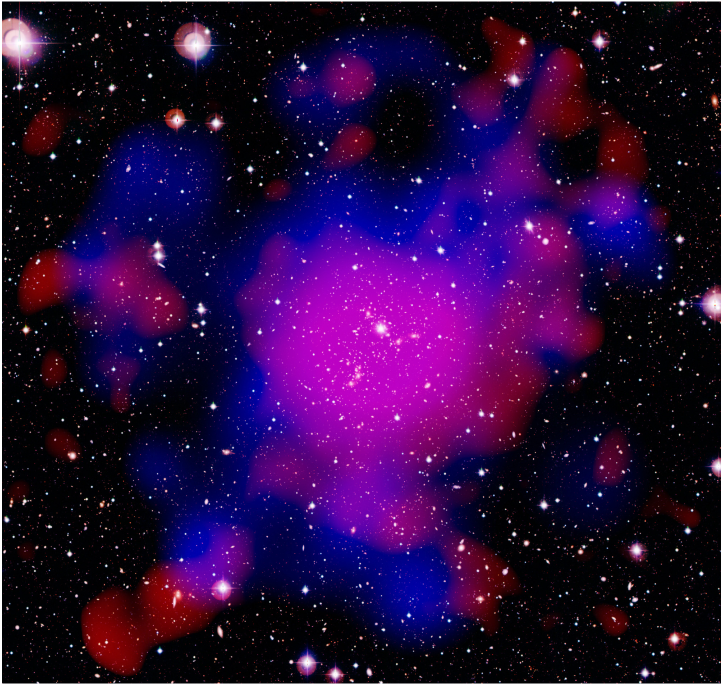
We are observing diffuse hot gas originating from the LSS and heated up by the gravitational pull of A2744

Is it the WHIM?

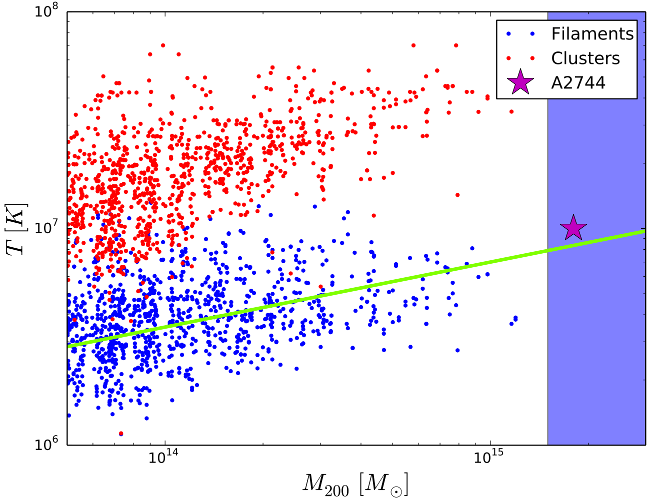


Davé et al. 2001

We are observing gas with overdensity ~ 200 and $T \sim 10^7$ K: consistent with predictions for the high-T part of the WHIM.



The WHIM temperature correlates with the mass of the halo



Idea: Target the most massive clusters at intermediate redshift

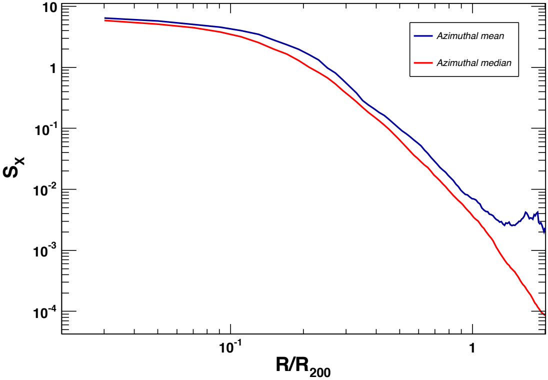
Summary

- Gas fraction of XXL-100 clusters lower than expected
- Trouble to explain this result using cosmological simulations; issue with WL masses?
- Stacking optically selected galaxies yields detection down to $10^{12.5} M_\odot$
- Combining X-ray and SZ data in cluster outskirts highlights the importance of clumping
- No sign of hydrostatic bias there
- Expect many more results on cluster outskirts with accepted XMM large programme
- We discovered 3 filaments radially connected to A2744
- Properties consistent with WHIM, gas fraction 5-10%
- In the future, ATHENA will revolutionize the field and make a census of hot baryons in the cosmic web, galaxies and clusters

Backup Slides

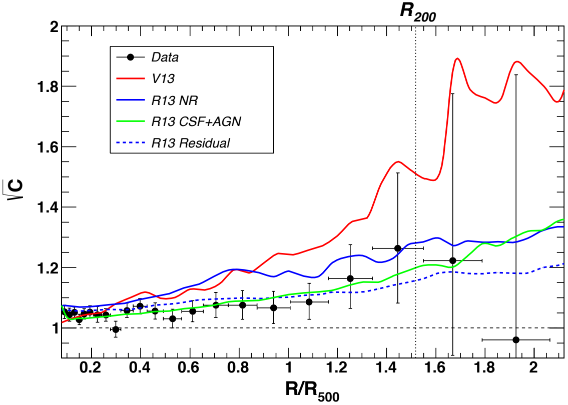
Gas clumping factor

Azimuthal median is robust against inhomogeneities



Eckert et al. 2015

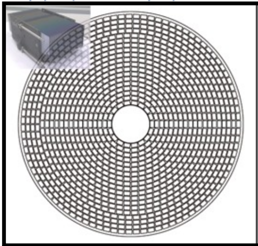
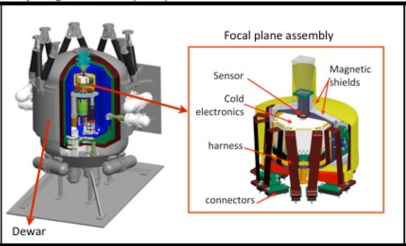
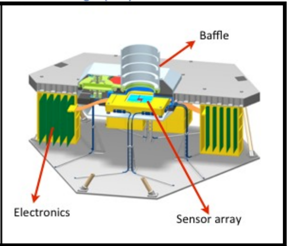
ROSAT/PSPC ENZO NR GADGET NR GADGET CSF+AGN

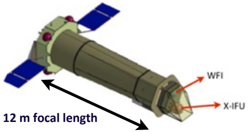


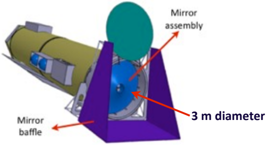
Eckert et al. 2015

- Hydrodynamical simulations predict *too many* substructures in the outskirts
- Including AGN + SN feedback improves the match

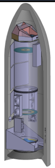
The ATHENA mission concept

X-ray optics (Silicon Pore Optics)	X-ray Integral Field Unit (X-IFU)	Wide-Field Imager (WFI)
		
2 m² at 1 keV, 5'' (3''), 0.3-12 keV	2.5 eV @ 6 keV (1.5 eV @ 1 keV), 5' FOV (7')	40' FOV (50'), < 150 eV @ 6 keV, sub-ms



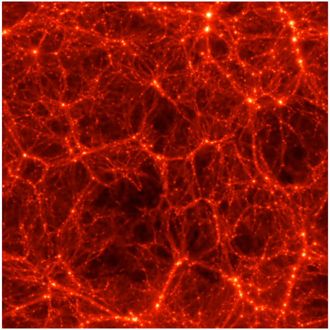


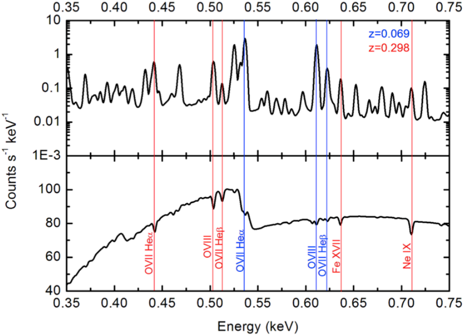
Ariane 5 fairing



The Warm-Hot Intergalactic Medium

About half of the baryons in the local Universe should be in the form of a high-T ($T = 10^5 - 10^7$ K) plasma in the cosmic web





Kaastra et al. 13, SP4

Finding and characterizing the missing baryons in the Universe requires high-resolution X-ray spectroscopy