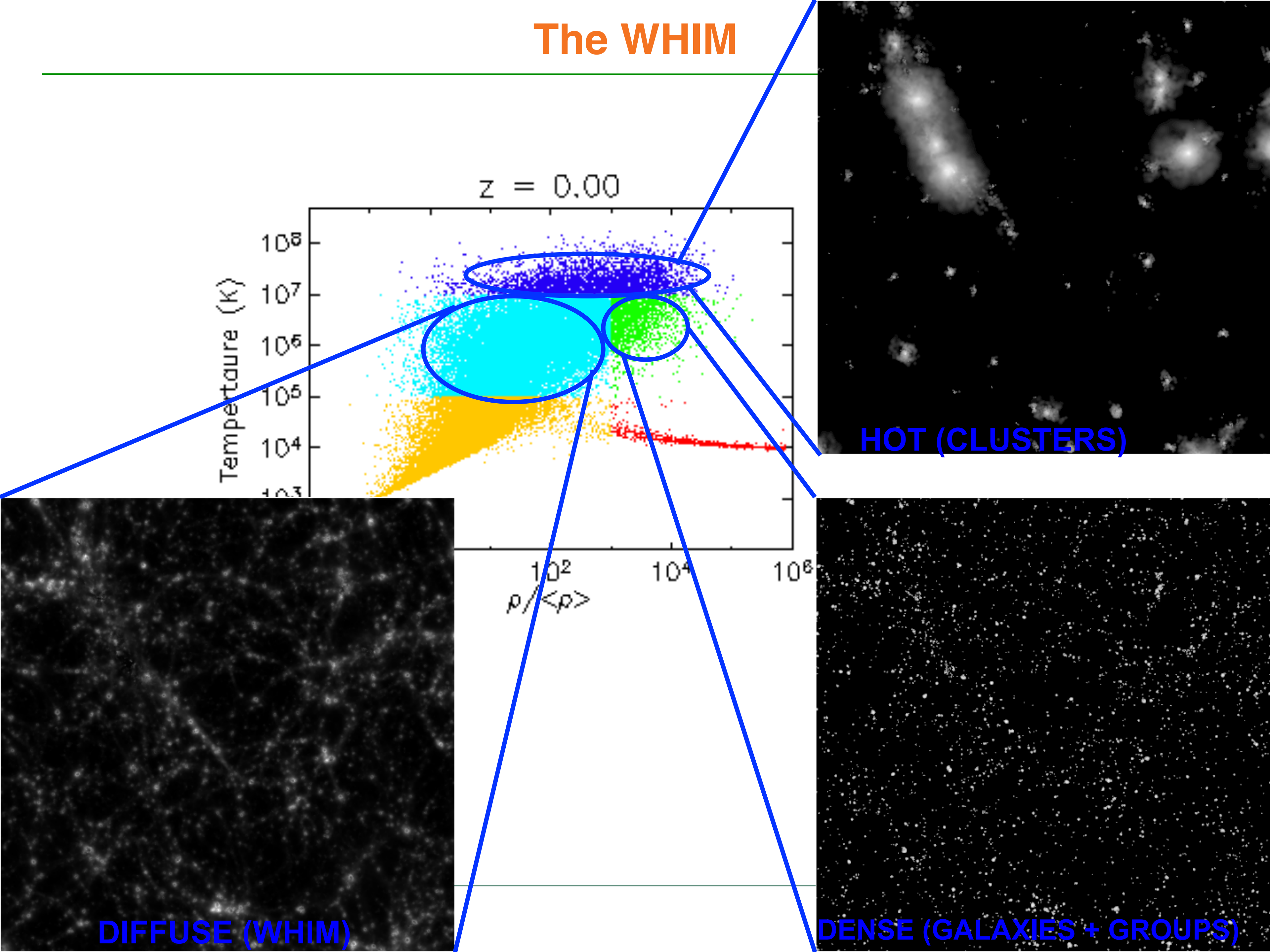
STUDYING THE WHIM THROUGH X-RAY EMISSION

Massimiliano Galeazzi

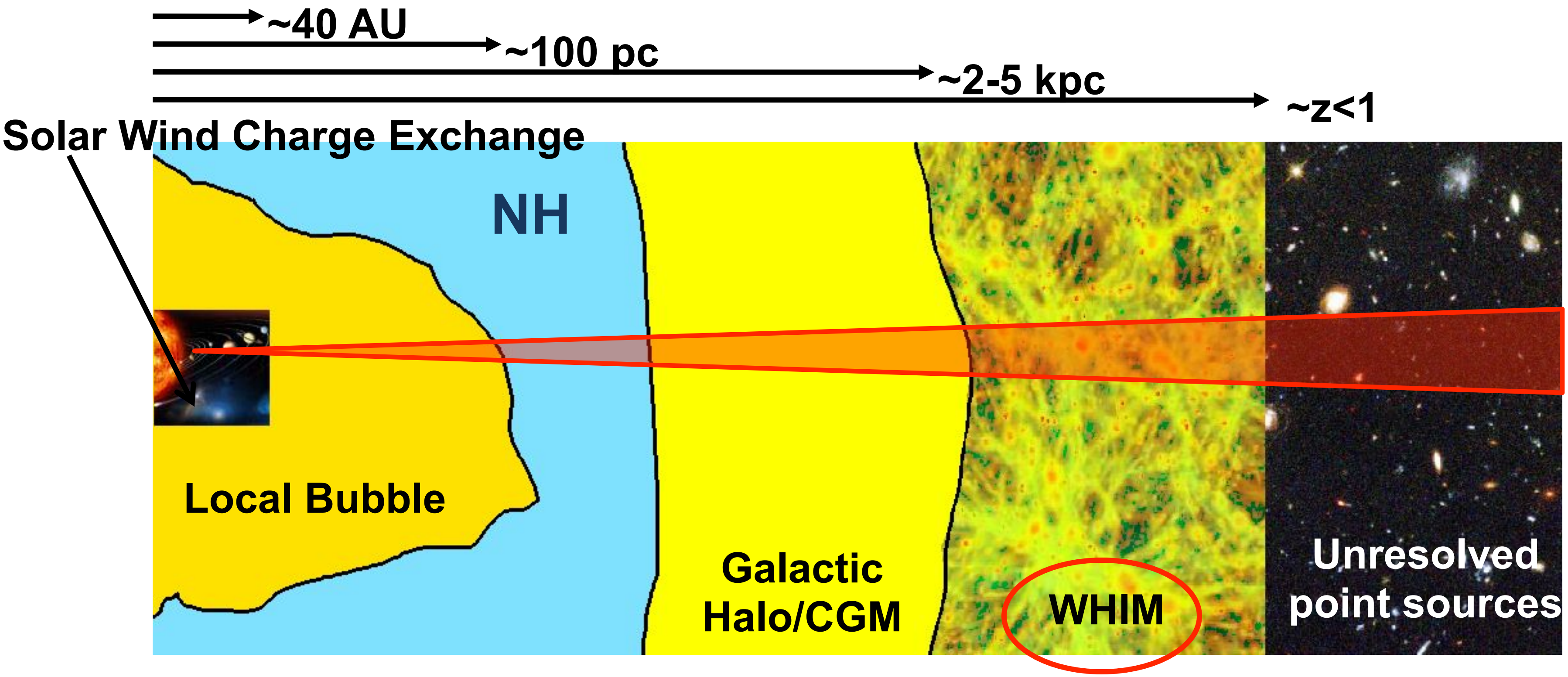
University of Miami

Enzo Branchini, Alexis Finoguenov, Anjali Gupta, Rich Kelley, Wenhao Liu, Ikuyuki Mitsuishi, Takaya Ohashi, Mauro Roncarelli, Kosuke Sato, Eugenio Ursino, Tomikkutty Velliyedathu AND the Athena WHIM Science Working Group.

The WHIM


z = 0.00
Tempertaure (K)
ρ/<ρ>
HOT (CLUSTERS)
DIFFUSE (WHIM)
DENSE (GALAXIES + GROUPS)

WHIM X-RAY EMISSION



- Relatively Small Signal on top of background and foreground due to Galactic emission and unresolved point sources
- Grasp of current X-ray missions makes detection nearly impossible other than in a few specific cases
  - ⇒ Statistical approach using Angular Autocorrelation Function (AcF)
  - ⇒ Look in regions where a WHIM filament is expected (e.g., between clusters of galaxies)

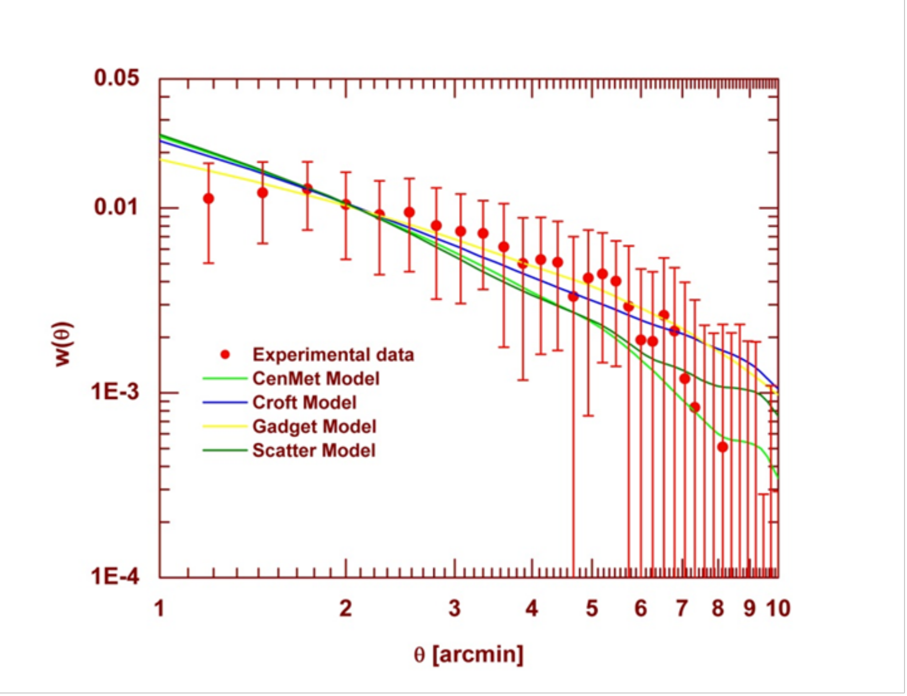
UNIVERSITY OF MIAMI

WHIM AcF WITH XMM-NEWTON

AcF

$$w(\theta) = \frac{\langle I(n)I(n')\rangle}{\langle I\rangle^2} - 1$$

AcF of 6 XMM-Newton empty fields in the 0.4-0.6 keV range



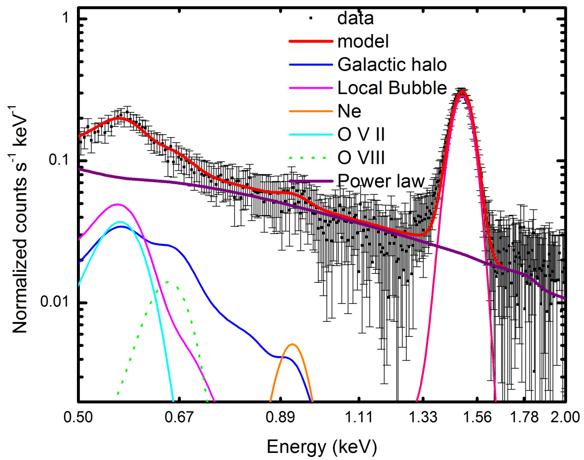
The fraction of X-rays due to the WHIM in the energy range 0.4-0.6 keV is 12±5% of the total diffuse X-ray emission

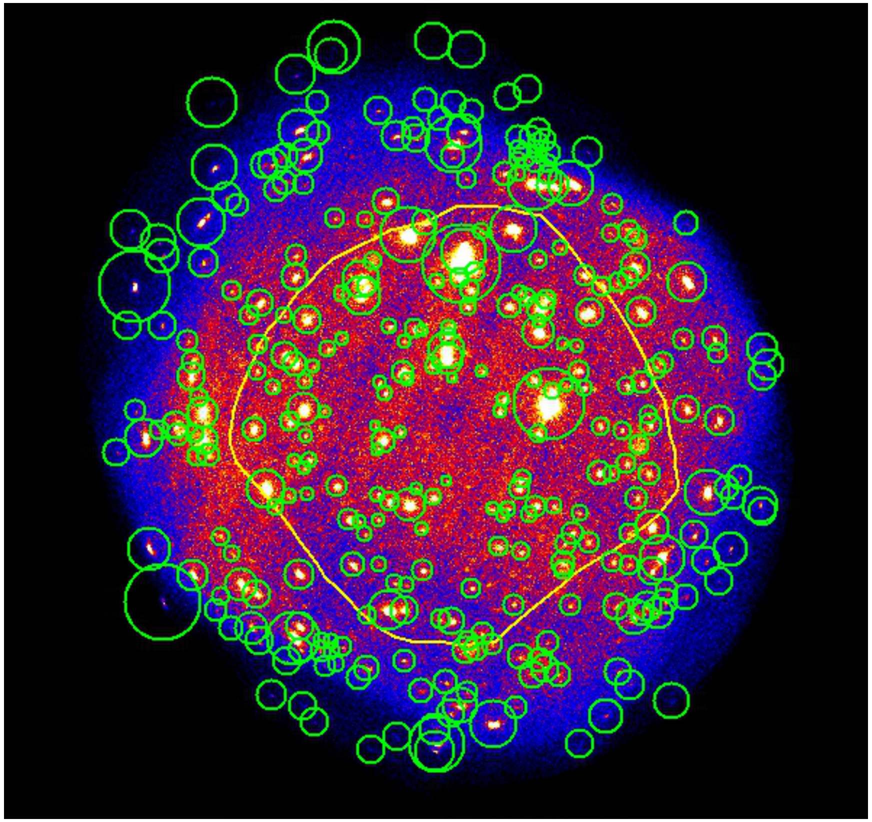
UNIVERSITY OF MIAMI

Galeazzi et al. 2009

The AcF in the CDFS with XMM-Newton

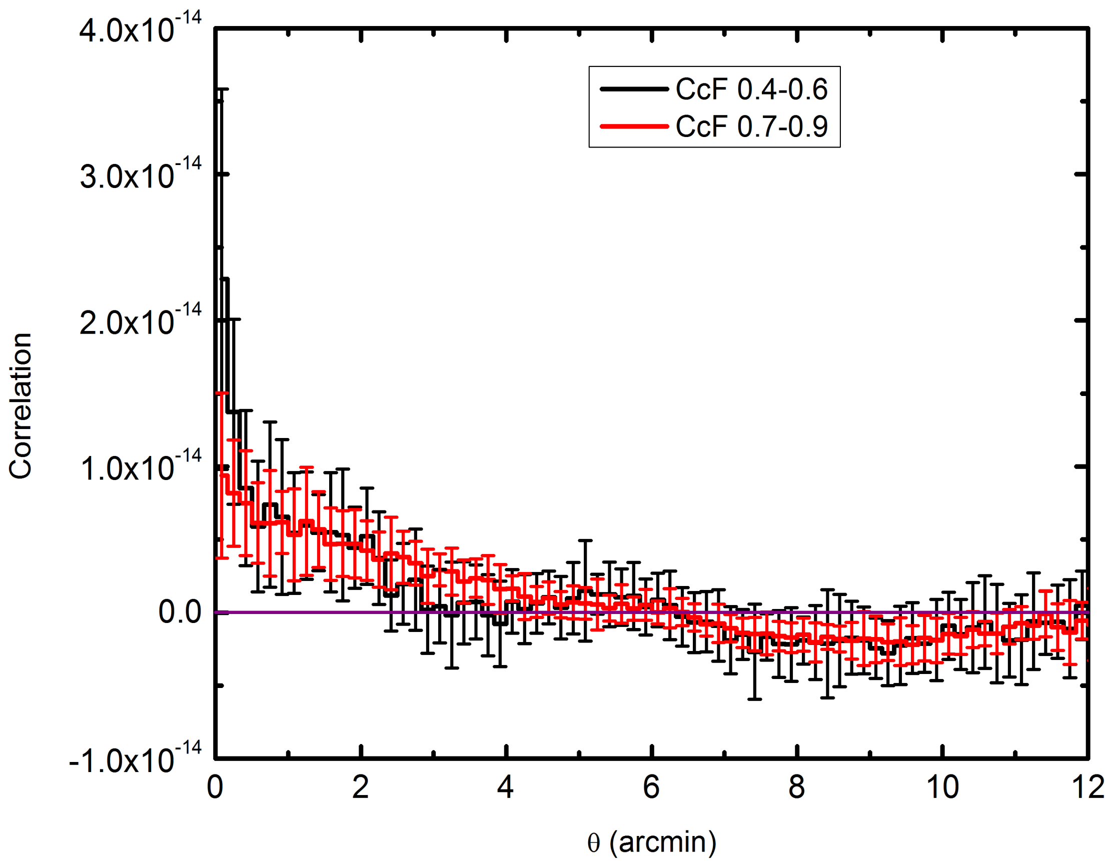
- 4 MS
- 33 pointings
- 2 different sets of roll-angle (180 deg apart)
- Chandra-detected point sources
- Diffuse sources from Alexis Finoguenov
- Diffuse emission consistent with other work





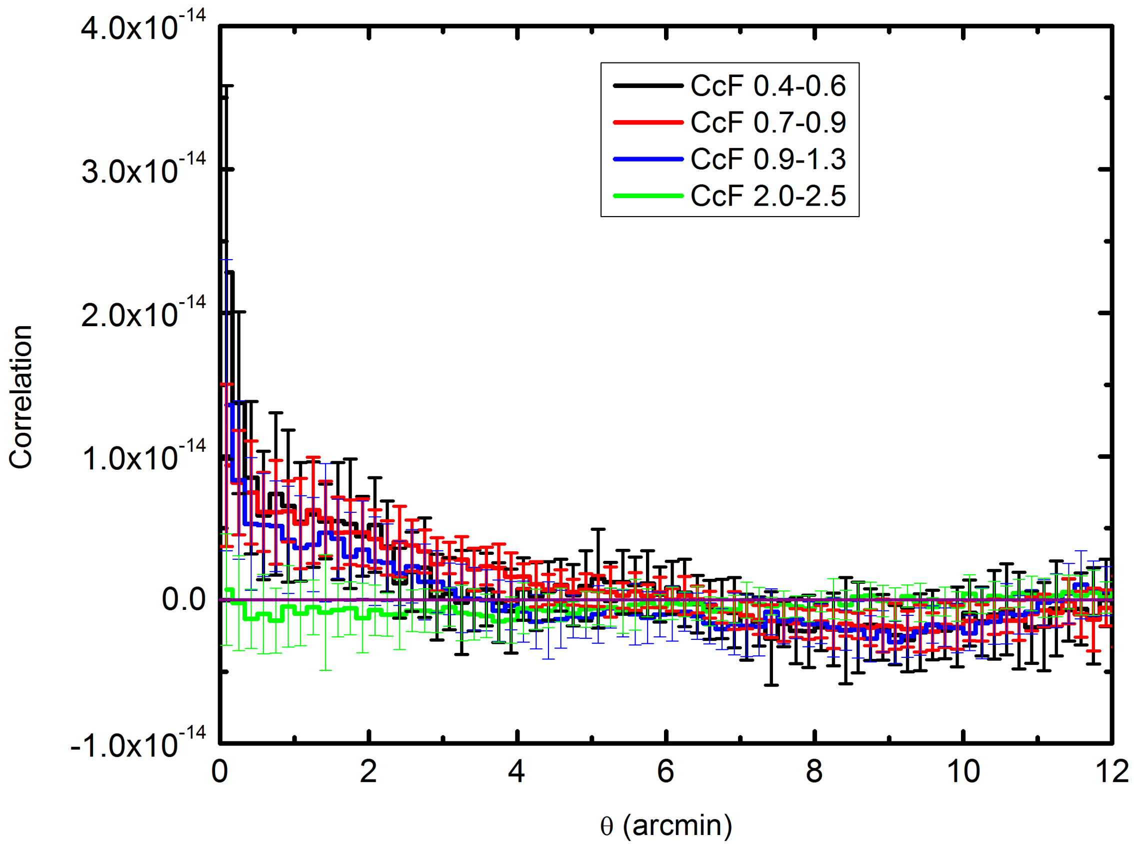
UNIVERSITY
OF MIAMI

The AcF in the CDFS with XMM-Newton



- **<u>Small correlation signal detected</u> in both 0.4-0.6 keV and 0.7-0.9 keV band**
- **We ruled out a systematic origin of the signal**
- **Negligible correlation at high energy**
- **The signal in the two soft bands is correlated → <u>same origin</u>**
- **T~9x10^6 K**

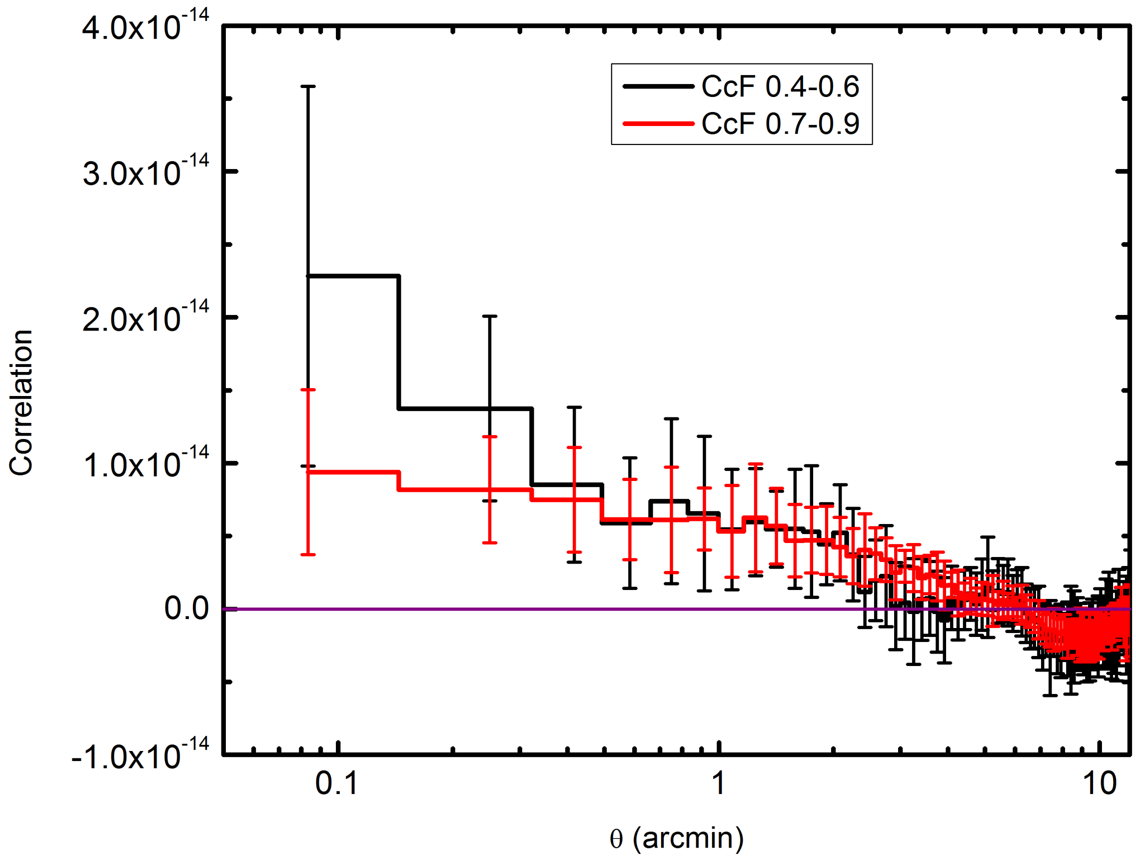
The AcF in the CDFS with XMM-Newton



- **Small correlation signal detected in both 0.4-0.6 keV and 0.7-0.9 keV band**
- **We ruled out a systematic origin of the signal**
- **Negligible correlation at high energy**
- **The signal in the two soft bands is correlated → same origin**
- **$T \sim 9 \times 10^6$ K**

UNIVERSITY OF MIAMI

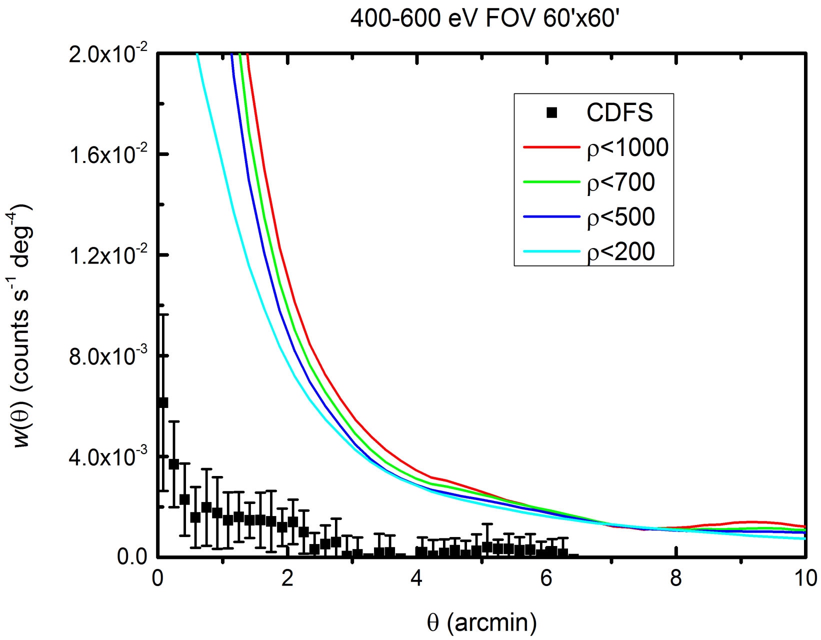
The AcF in the CDFS with XMM-Newton

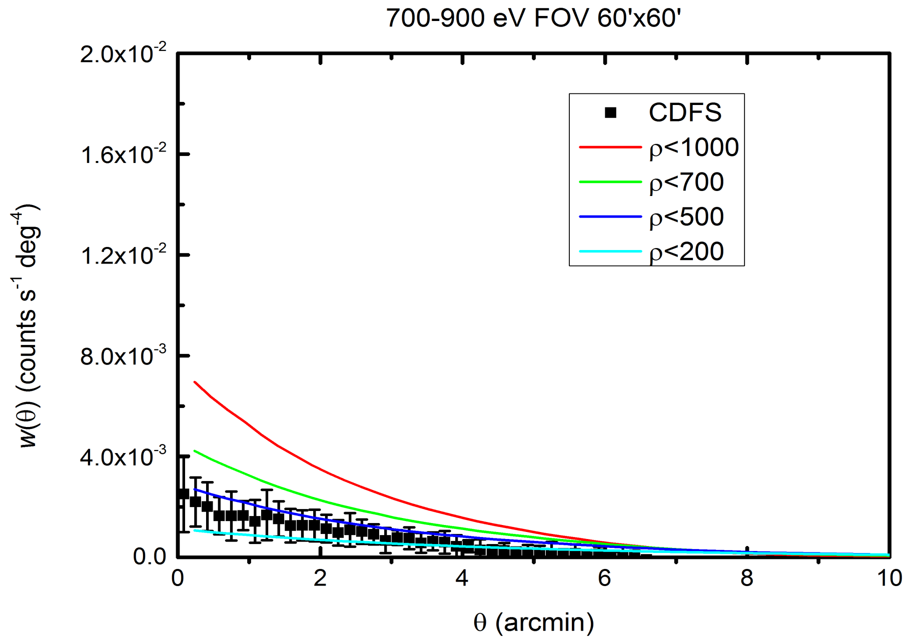


- **Small correlation signal detected in both 0.4-0.6 keV and 0.7-0.9 keV band**
- **We ruled out a systematic origin of the signal**
- **Negligible correlation at high energy**
- **The signal in the two soft bands is correlated → same origin**
- **T~9x10^6 K**

UNIVERSITY OF MIAMI

Comparison with models





Signal in 0.4-0.6 keV band inconsistent with models

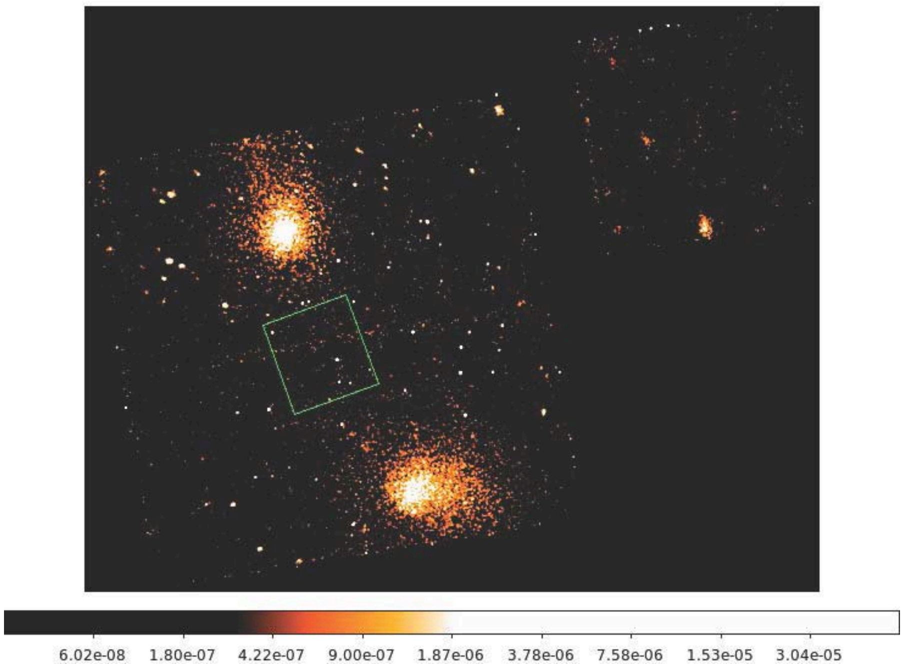
- Cosmic variance (it is known the the CDFS is devoid of significant structures)
- Problem with the models
  - Metal diffusion? (but what about UV data?)
  - Temperature distribution?
  - ???

UNIVERSITY OF MIAMI

Models from Ursino et al. 2010

SEARCH FOR INTERCLUSTER FILAMENTS

A222-A223



- z=0.21
- identied as a possible filament through weak lensing and as an overdensity of color selected galaxies
- The clusters are separated by 14’ (2.8 Mpc)
- Projected distance 15 Mpc
- 144 ks pointing with XMM-Newton

➢ Filament outside the virial radius of the clusters

➢ emission measure (n_e x n_p x V) =1.72 x 10^{65} cm^{-3}

➢ Temperature: kT = 0:91 keV

➢ Metallicity of 0.2 solar

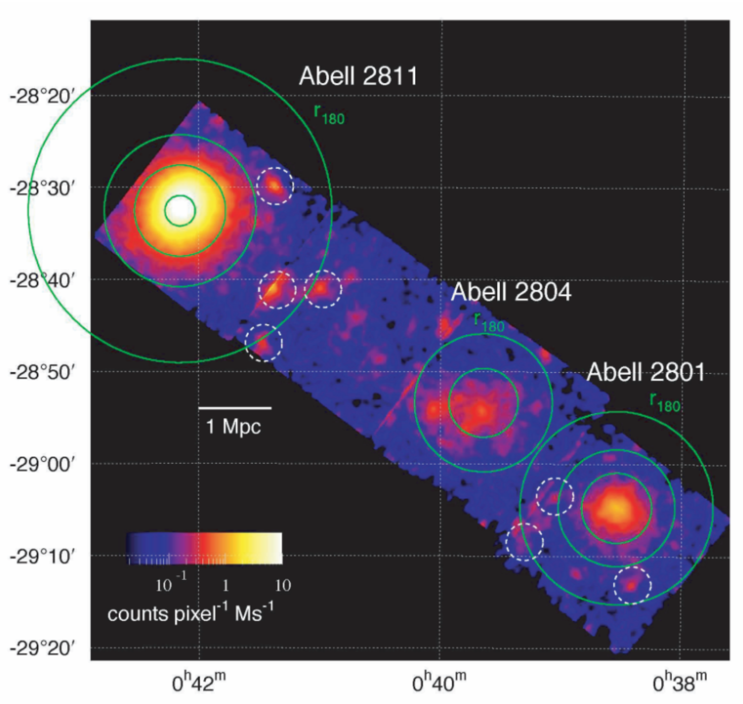
UNIVERSITY OF MIAMI

Werner et al. 2008

See also SZ, de Graaff+ 2017

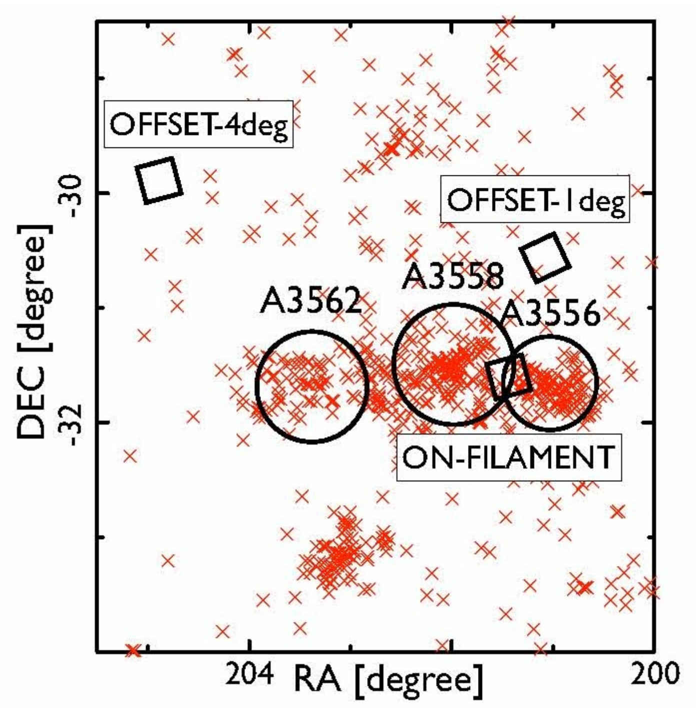
SEARCH FOR INTERCLUSTER FILAMENTS

Sculptor Supercluster



K. Sato et al., 2010

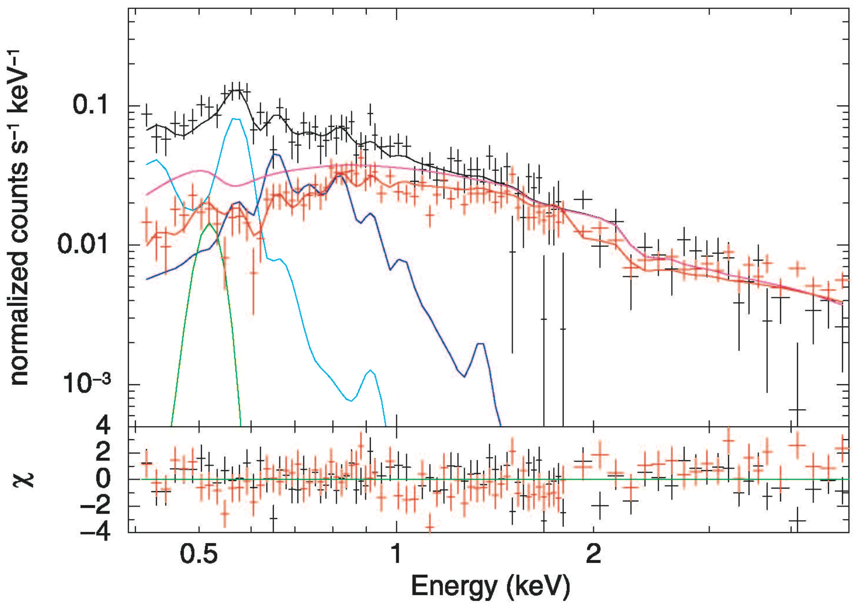
Shapley Supercluster



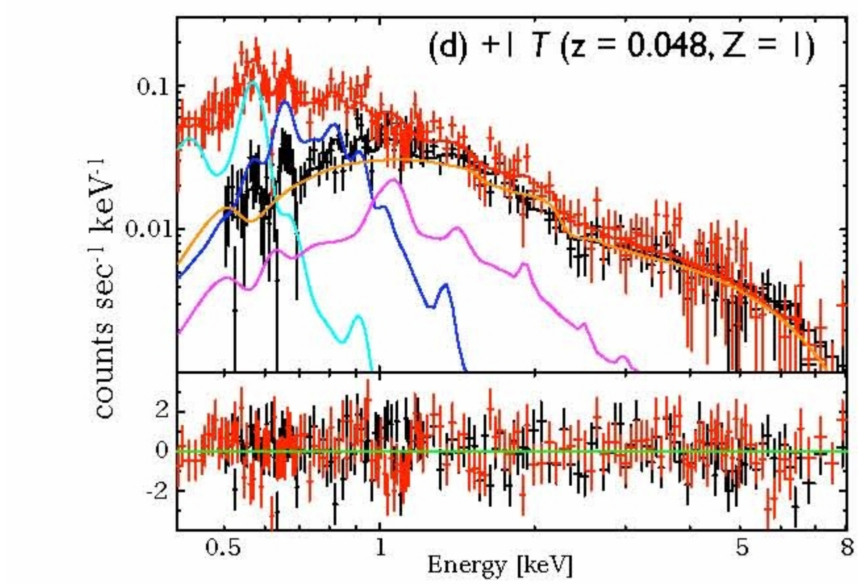
I. Mitsuishi et al., 2012

X-RAY EMISSION FROM INTERCLUSTER FILAMENTS

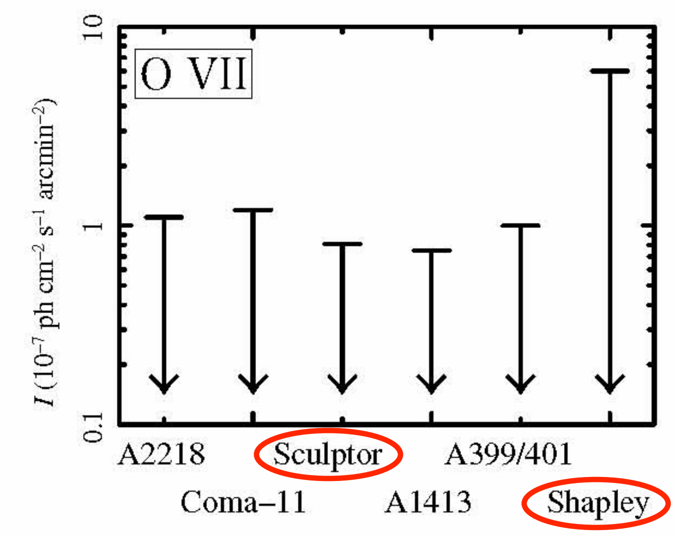
Sculptor Supercluster

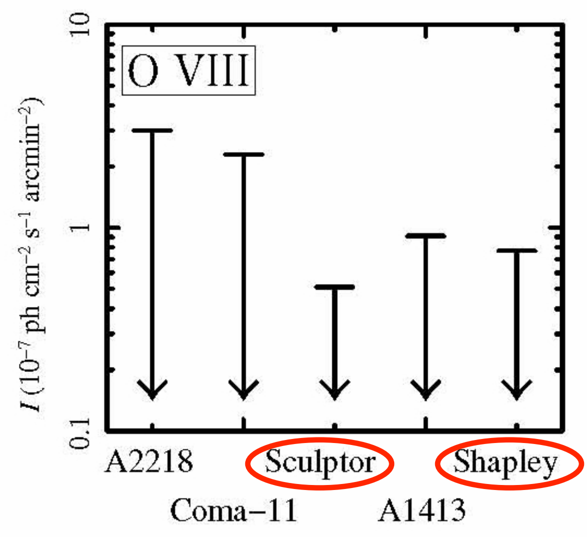


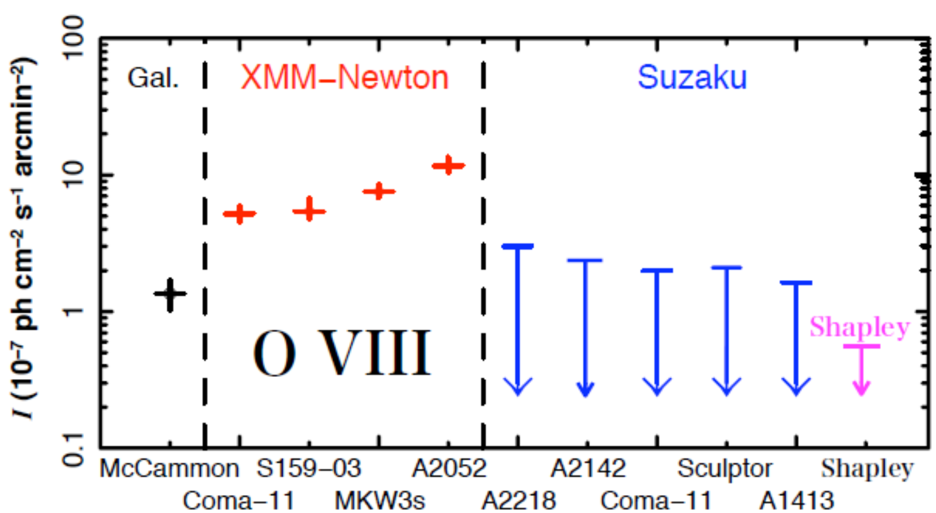
Shapley Supercluster



X-RAY EMISSION FROM INTERCLUSTER FILAMENTS



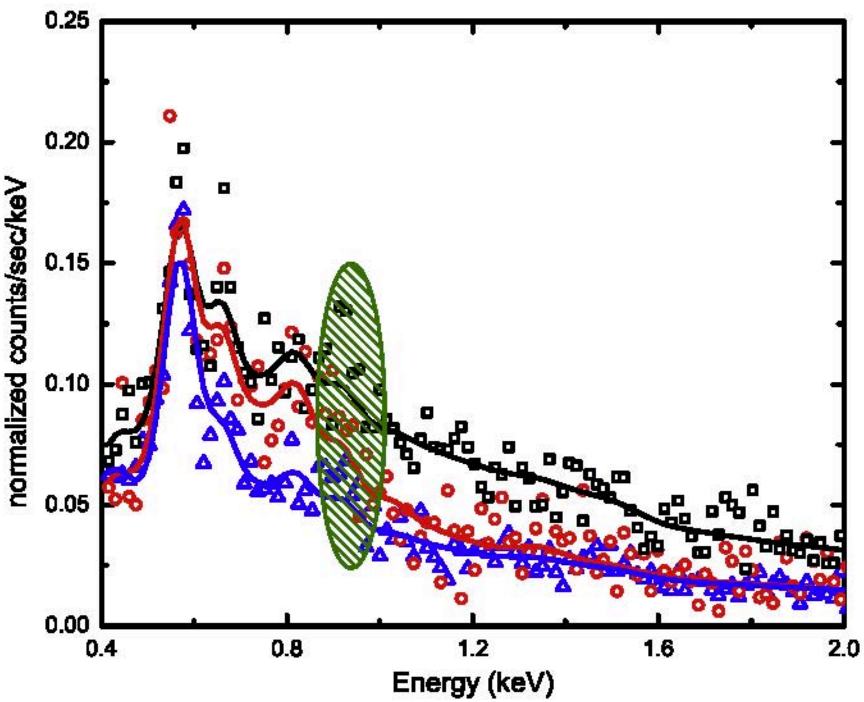


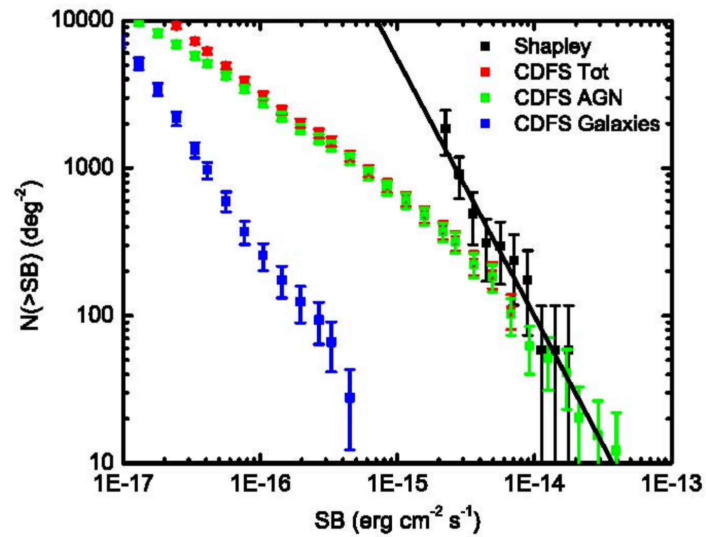


Shapley

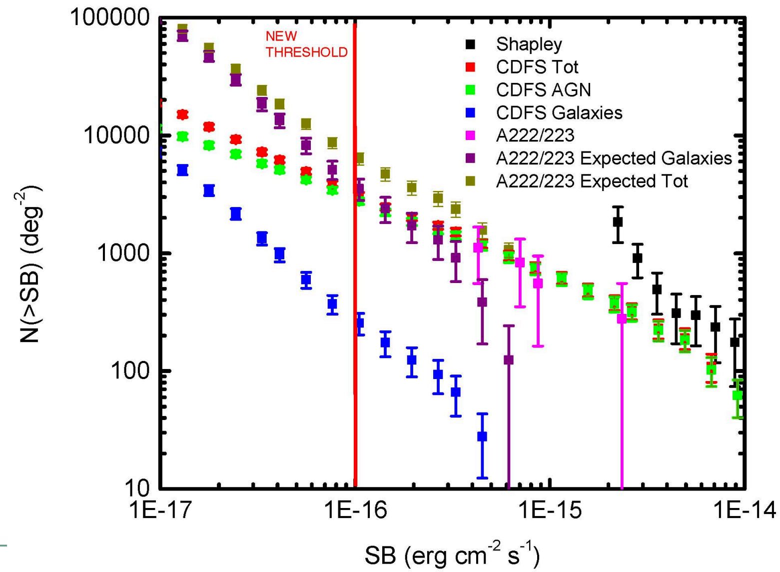
SEARCH FOR INTERCLUSTER FILAMENTS

Shapley point sources





Excess emission due to galaxies in the filament between the two clusters!



UNIVERSITY OF MIAMI

Ursino et al. 2015

What can we do next?

1) SHORT TERM:
   Look at other deep fields with XMM-Newton (e.g., COSMOS – in progress)

2) SHORT-MEDIUM TERM:
   Use other tracers to highlight the x-ray signal
   - Cross-correlation with galaxy maps
   - Cross-correlation with SZ

3) MEDIUM-LONG TERM:
   High energy resolution studies with Athena

The WHIM with Athena

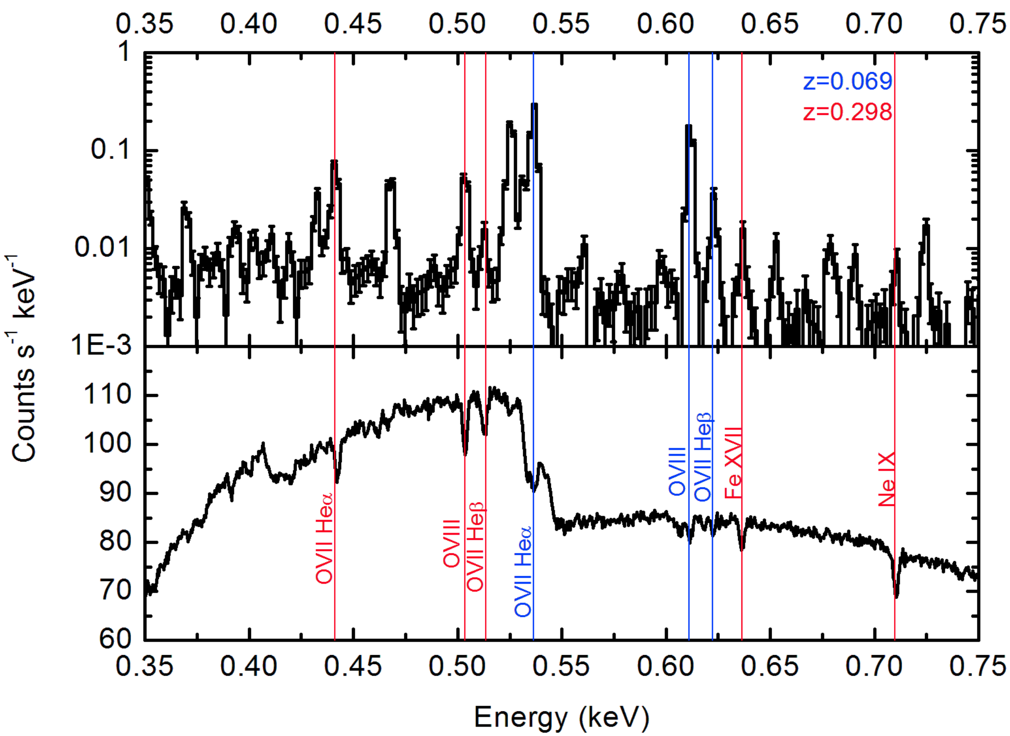


Figure 1: Simulated emission and absorption line spectra captured in a single *Athena+* observation for two filaments at different redshifts. Lower panel: absorption spectrum from a sight line where two different filamentary systems are illuminated by a bright background source. Upper panel: corresponding emission from a 2'x2' region from the same filaments for 1 Ms exposure time. The high spectral resolution allows us to distinguish both components. *Athena+* will be able to study dozens of these sight lines in detail.

Kaastra et al. 2013

The WHIM with Athena

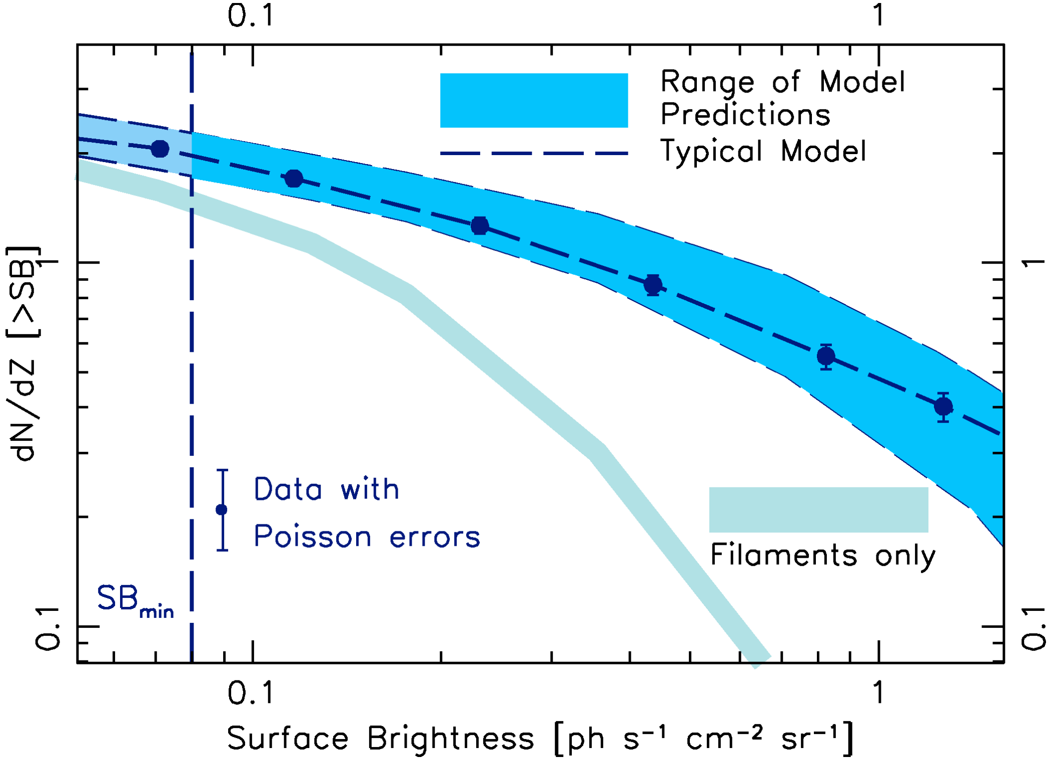


Figure 3: Same line statistics as in Fig. 2 but referring to filaments detected in emission as a function of line surface brightness (Takei et al. 2011). We expect to detect serendipitously about 4 filaments in the field of view of X-IFU for observations longer than 100 ks. We have conservatively assumed that for about 30% of the systems detected in absorption, the associated X-ray line emission will be detected. The upper band illustrates the scatter in model predictions and refers to simultaneous detections of O VII and O VIII from all the baryons. The lower band refers to line emission from baryons in filaments only. This component increasingly dominates low SB. For observations longer that 100 ks, we expect that about 50% of the filaments detected are due to the WHIM.

Emission Statistics

Kaastra et al. 2013

Future plans

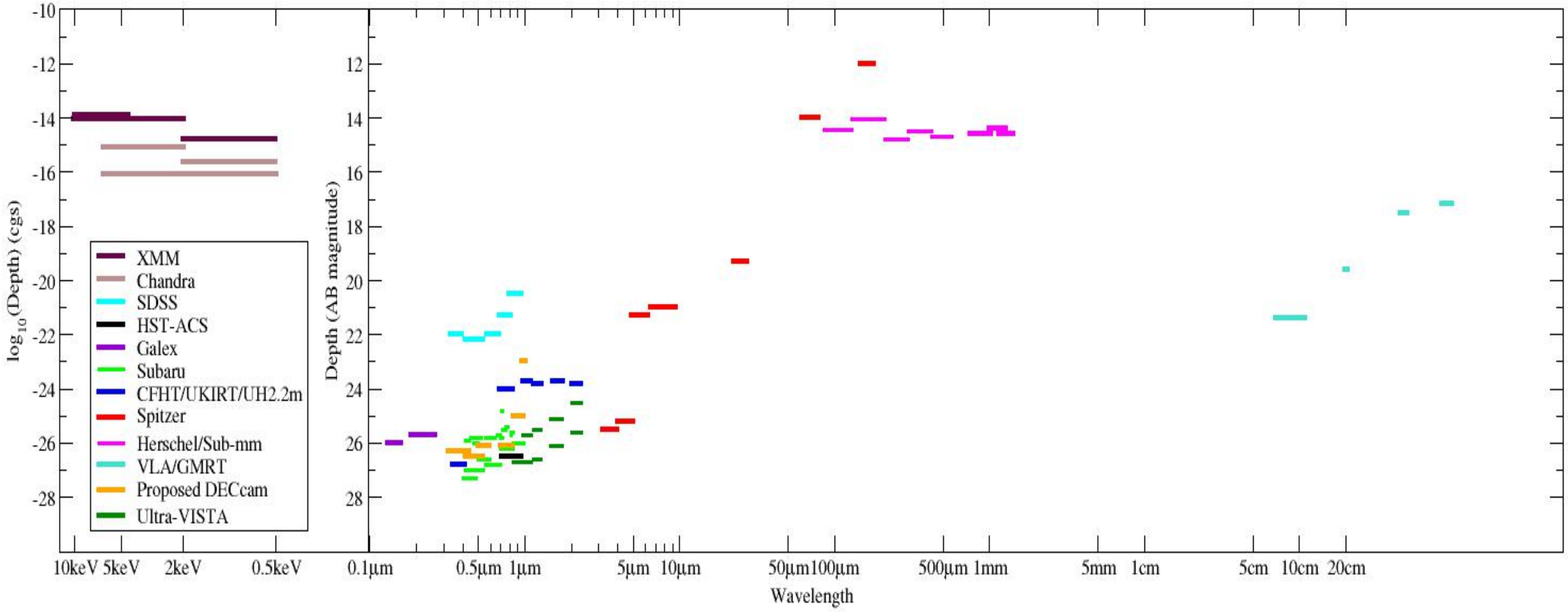
- Cross correlation with galaxies
- Multi-wavelength study (correlation with other bands)
- Extend XMM-Newton work to investigate cosmic variance

Table 1. Summary of XMM-Newton Deep and Extended targets that will be used in the investigation.

Target	Area	Total Exposure	Avg Exposure	Sensitivity (0.5-2.0 keV)
	deg^2	Ms	ks	10^{-15} erg s^{-1} cm^{-2}
XMM-CDFS[7]	0.25	3.45	3.45	0.66 (2-10 keV)
XMM-XLL [1]	50[*]	6.9	~10	5
XMM-Cosmos [2]	2	1.5	~68	1.7
XMM-Stripe 82 [3,4]	20	~0.8	4.5	5
Lockman Hole [5,6]		~0.7	~700	1.9

[1] Pierre et al., 2015, A&A, in press, D.O.I. 10.1051/0004-6361/201526766
[2] Cappelluti et al., 2009, A&A, 497, 635
[3] LaMassa et al., 2013, MNRAS, 436, 3581
[4] XMM AO13 proposal summary
[5] Worsley et al., 2004, MNRAS, 352, L28
[6] Brunner et al., 2008, A&A, 479, 283
[7] Ranalli et al., 2013, A&A, 555, A42
[*] The XMM-XLL survey covers two fields of 25 deg^2 each. One field is in the northern galactic hemisphere, roughly at the anticenter position. The second field is in the southern hemisphere close to the edge of the galactic bulge.

Future plans



Multi-wavelength coverage and sensitivity in the COSMOS field

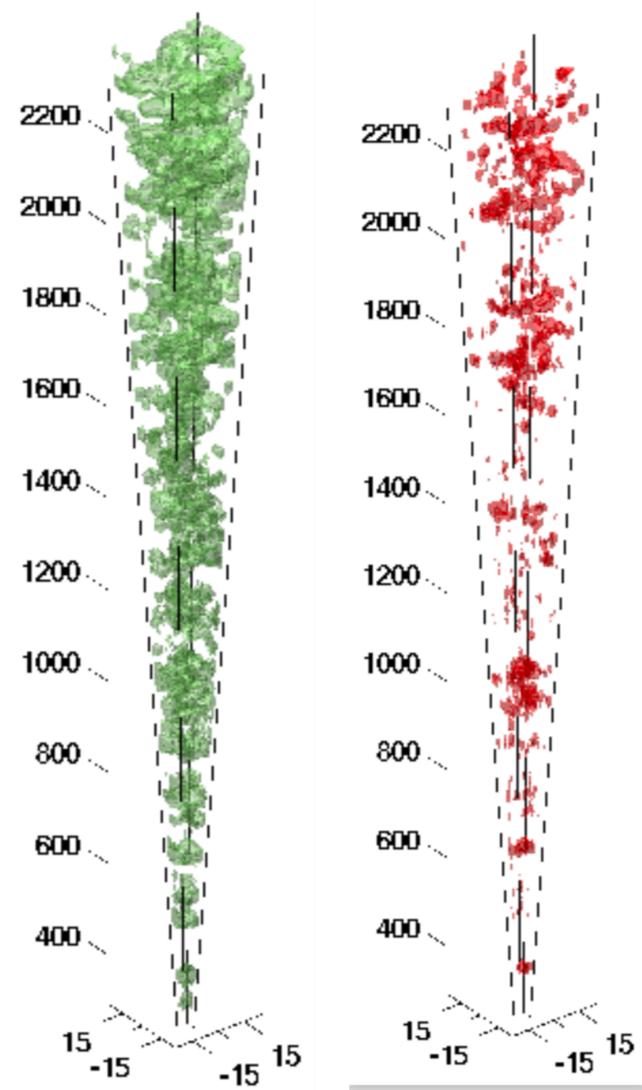
WHIM in emission. COSMOS

Spatial information

Correlation with galaxies can beat down the foreground

$$\sigma_{\rm line} = \frac{f_{\rm line}}{\sqrt{[f_{\rm line} + (f_{\rm CXB} + \cancel{f_{\rm G}} + f_{\rm inst})\Delta E]}}\sqrt{\Delta\Omega t_{\rm exp} A_{\rm eff}},$$

20K galaxies in the ZCOSMOS survey (+20K with photometric redshifts) to trace the galaxy density field up to z=1. (Kovac+ 2010).
Several large scale structures already detected. Most notably at z~0.4 and at z~0.7. For the latter, Wall-like, a dedicated redshift survey of galaxies galaxies has been done to increase sampling.

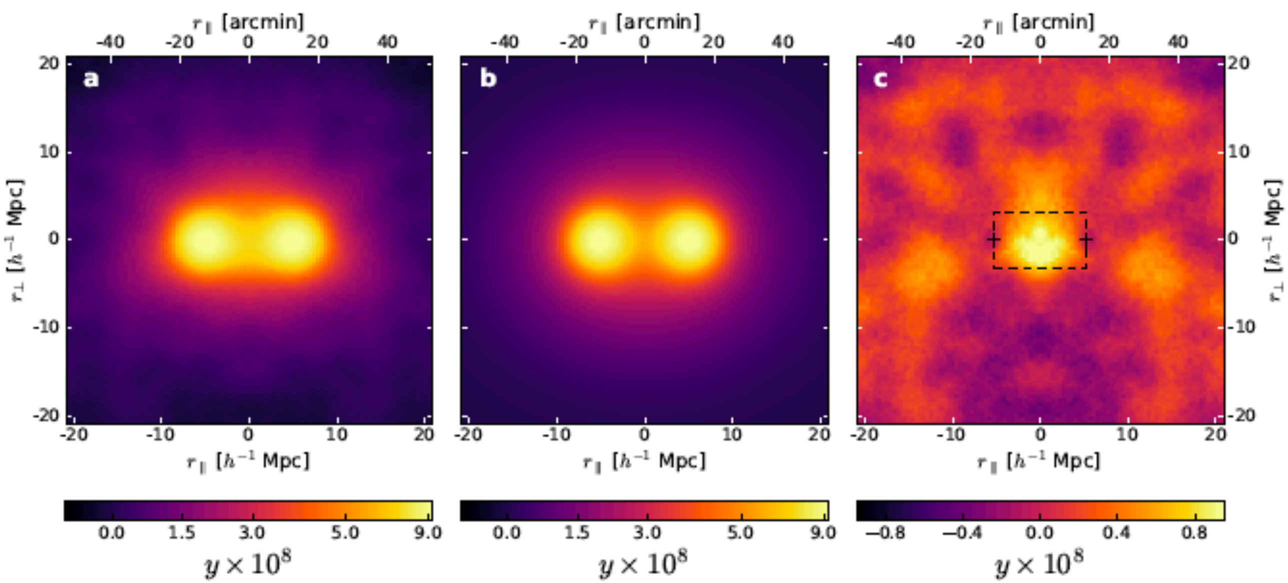


Branchini et al. 2018

WHIM in emission. Alternative probes

Probes different from galaxies are being used to statistically detect the WHIM signal. And could be combined with similar results obtained by Athena.

One example is the SZ-signal. An indirect, statistical WHIM detection has recently been claimed by de Graaff+ 2017 in filaments connecting galaxy pairs as a result of a stacking analysis.



A similar procedure can be repeated in the COSMOS field observed by Athena to look for a OVII/OVIII emission enhancement in between galaxy pairs. The resulting signal can be combined with the analogous SZ enhancement.

X-RAY/SZ CORRELATION

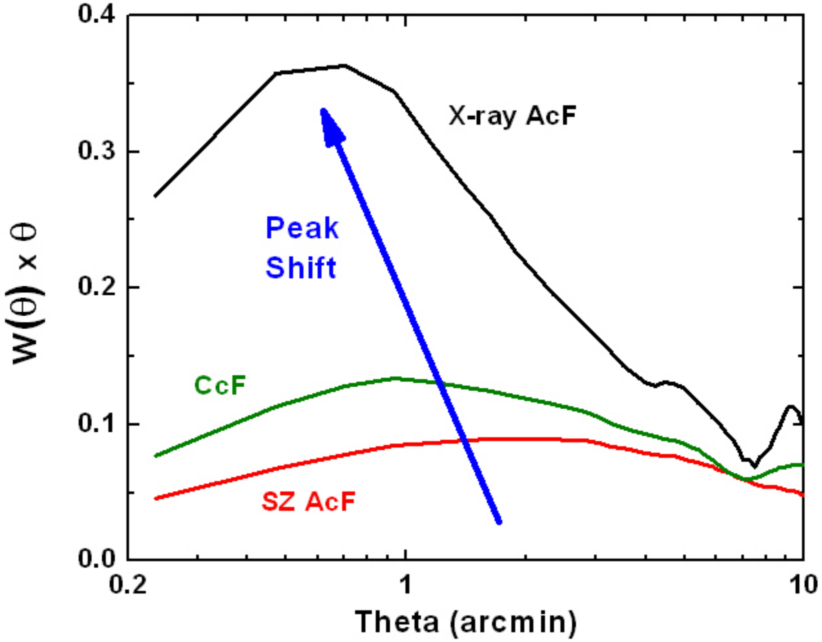
Sunyaev-Zel'dovich effect

$$\frac{\Delta T_{CMB}}{T_{CMB}} = g(x)y$$

$$y = \int \sigma_T n_e \frac{k_B T_e}{m_e c^2} dr$$

$$g(x) = x \coth\left(\frac{x}{2}\right) - 4, \quad \text{with} \quad x = \frac{h\nu}{k_B T_{CMB}},$$

$$F(X-rays) \propto n_e^2$$
$$\Delta T_{SZ} \propto n_e^{1.2}$$

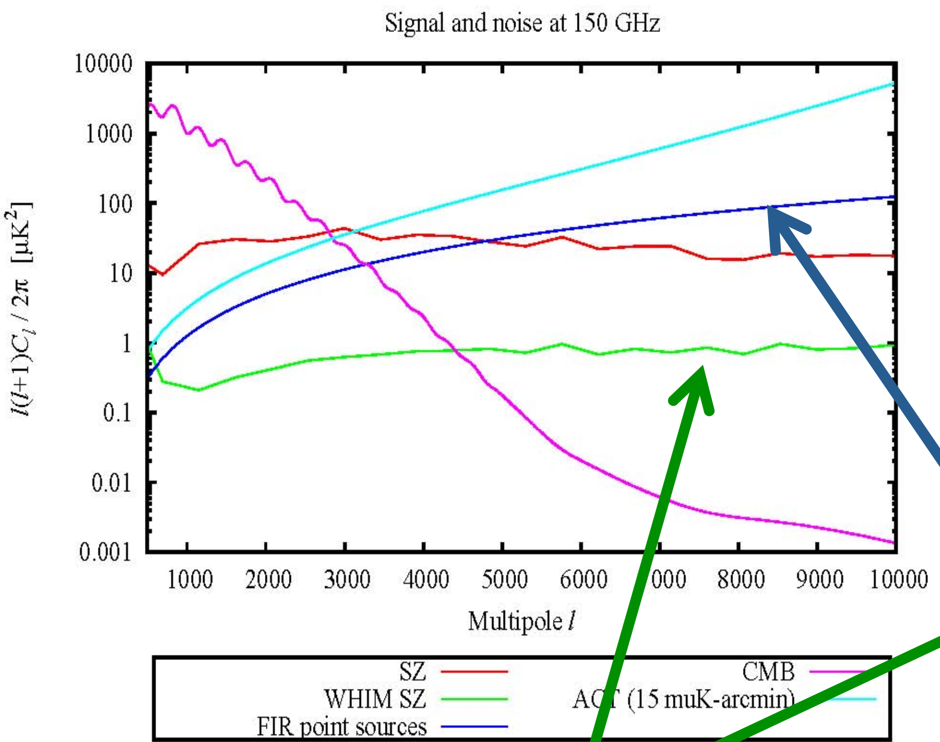


➔ **X-rays and SZ can probe different regions of the WHIM**

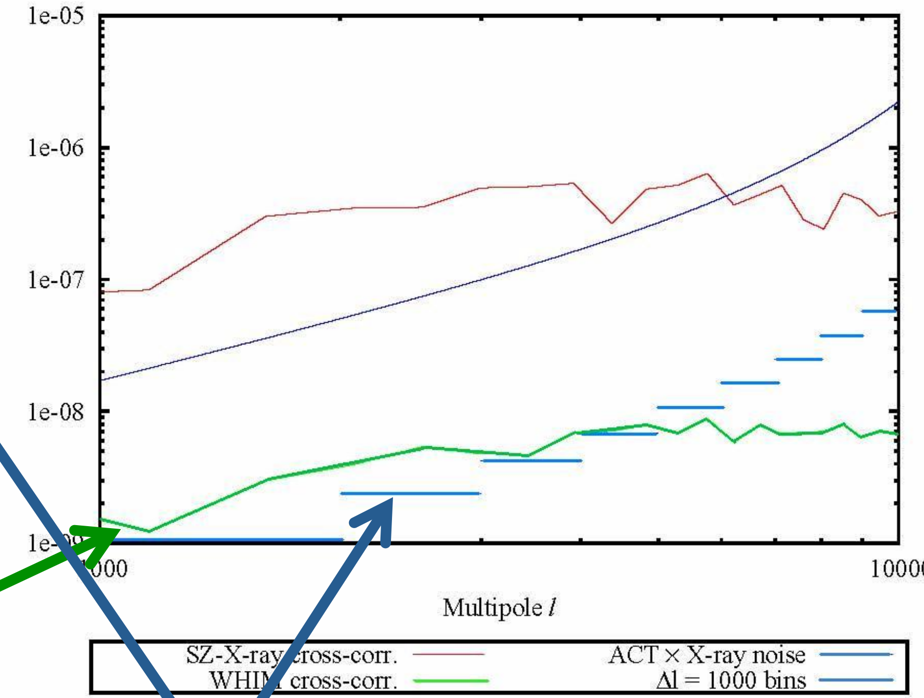
X-RAY/SZ CORRELATION

Simulated signal and background for 150 GHz ACT band and 100 ks XMM-Newton observation

SZ signal alone



SZ/X-ray cross coefficient



WHIM **BACKGROUND**

UNIVERSITY OF MIAMI

Ursino et al. 2014