Search for WHIM in X-rays

Warm-hot intergalactic medium

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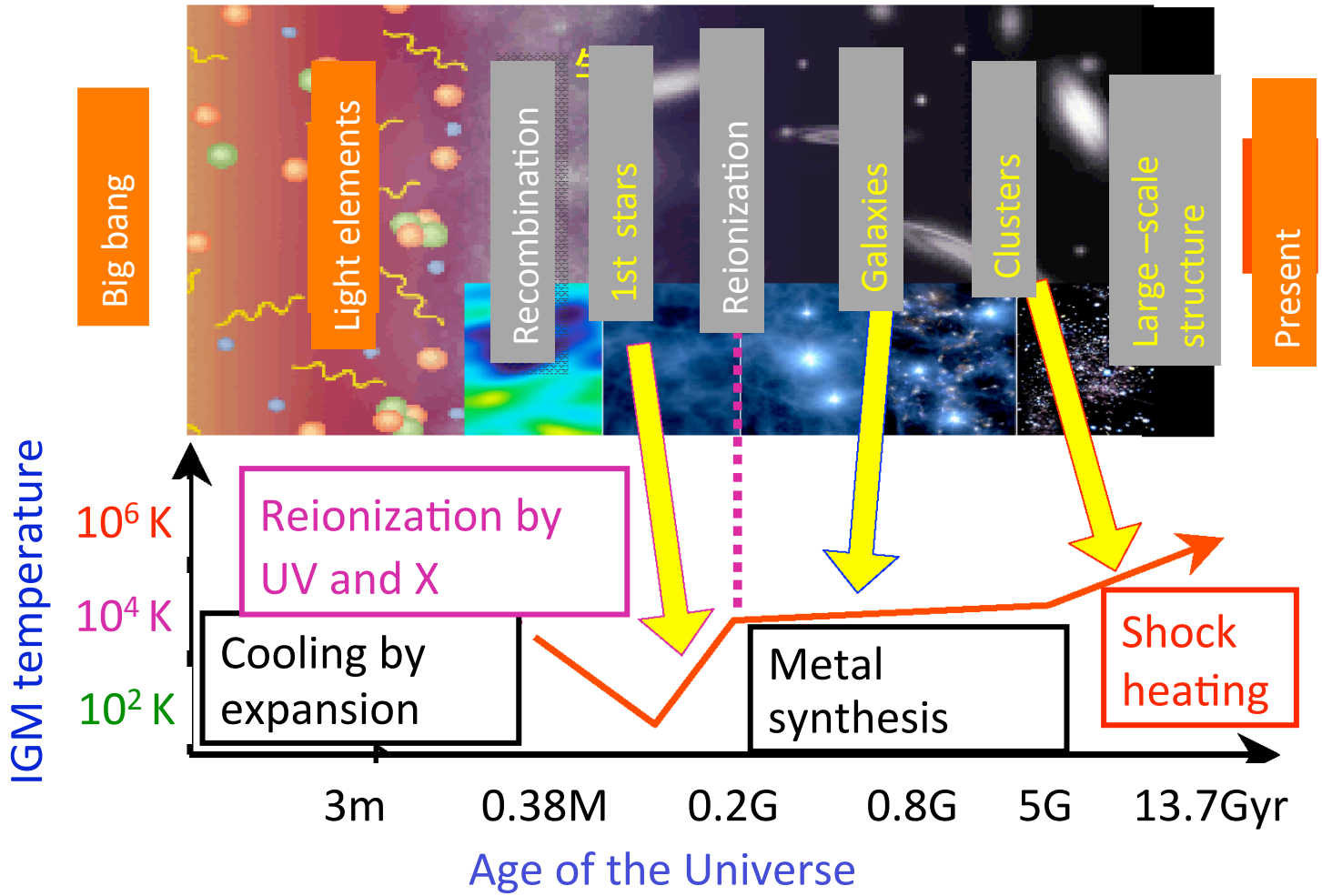
- Science of WHIM
- Status of WHIM search
- Suzaku study of superclusters, cluster outskirts and a near-by filament
- Future missions for WHIM study
- Summary

Thermal history of the universe

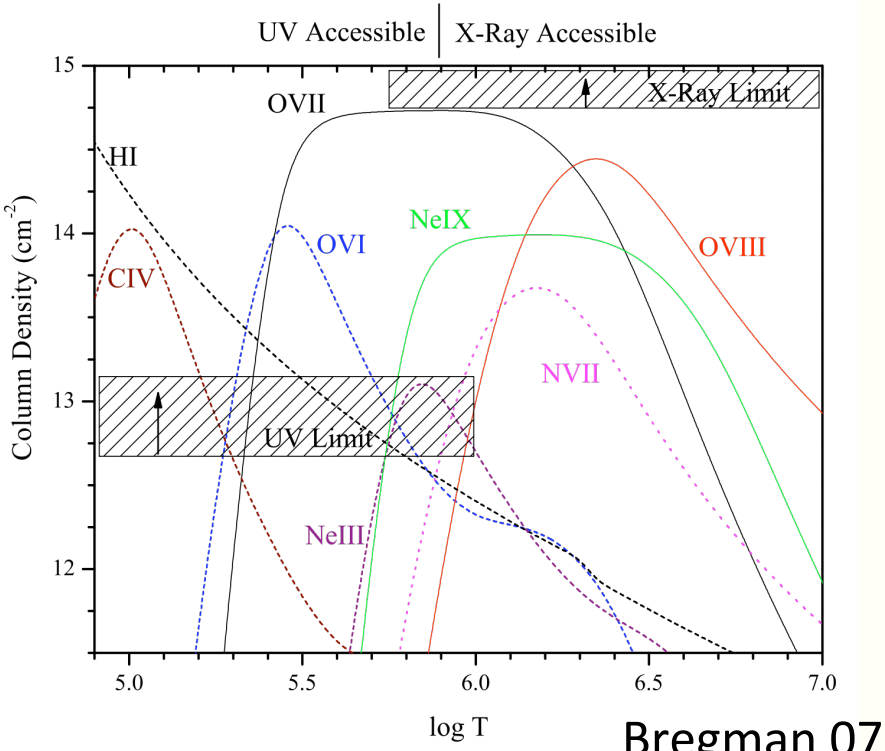


WHIM (warm-hot intergalactic medium) will tell us the evolution of the hot-phase material in the universe

Baryon phase

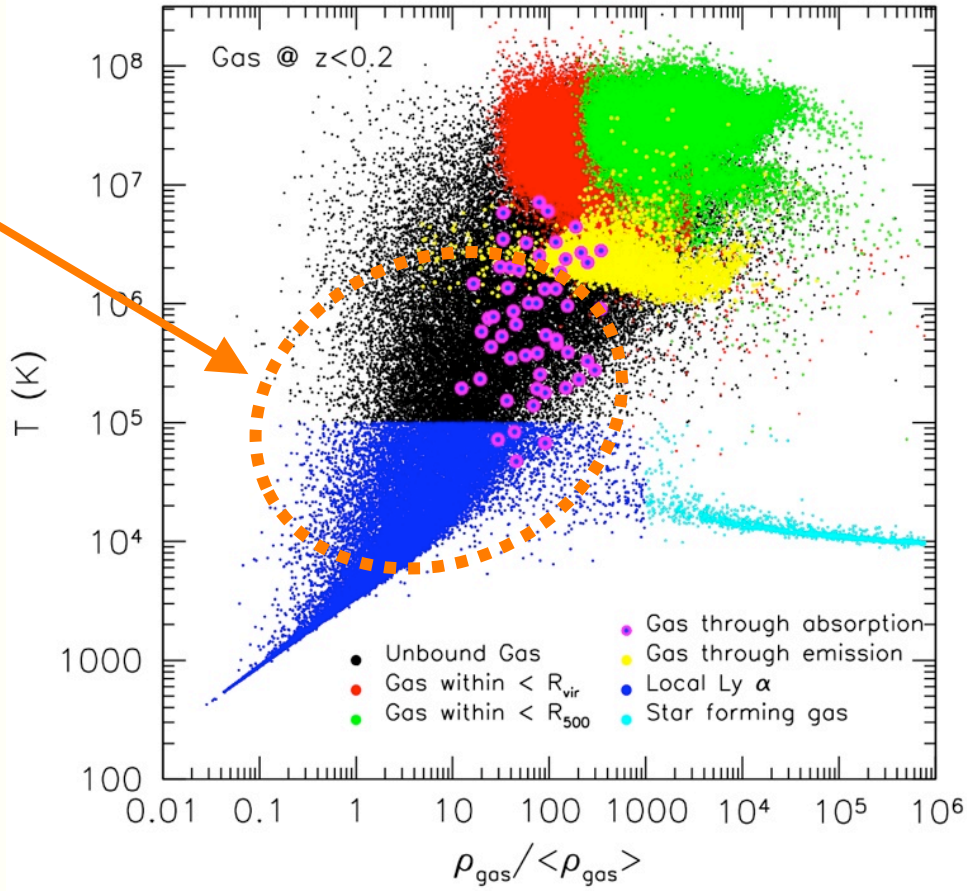
Wide area in the baryon phase space is unexplored

Oxygen line probes the dark baryon efficiently



Bregman 07

Branchini et al. 09



EDGE consortium

Cosmic structure

WHIM (10^5-10^7 K) traces the cosmic large-scale structure

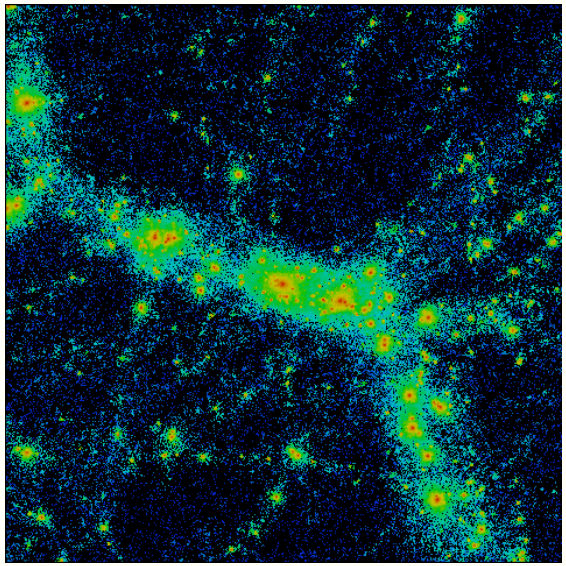
= "Missing baryon"

Typical matter density:
δ (=$n/\langle n_B \rangle$) = 10 - 100

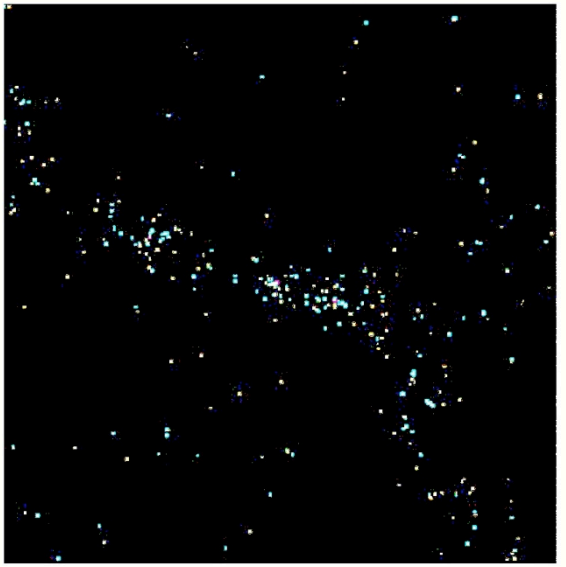
Yoshikawa et al. 2001, ApJ, 558, 520

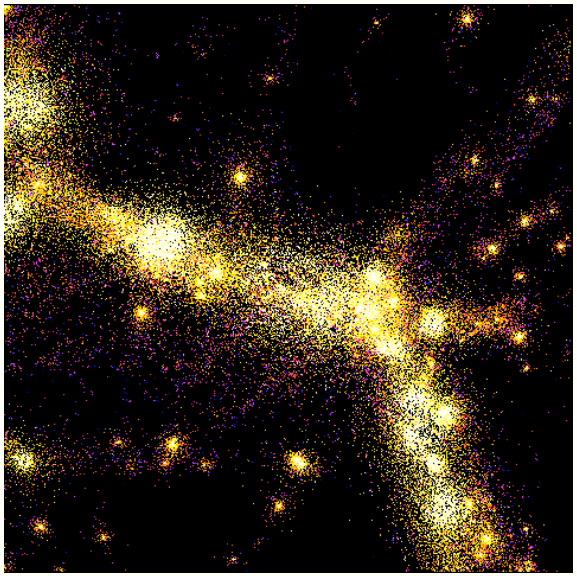
size = 30 h^{-1} Mpc
≈ 5 deg at z=0.1

Dark matter

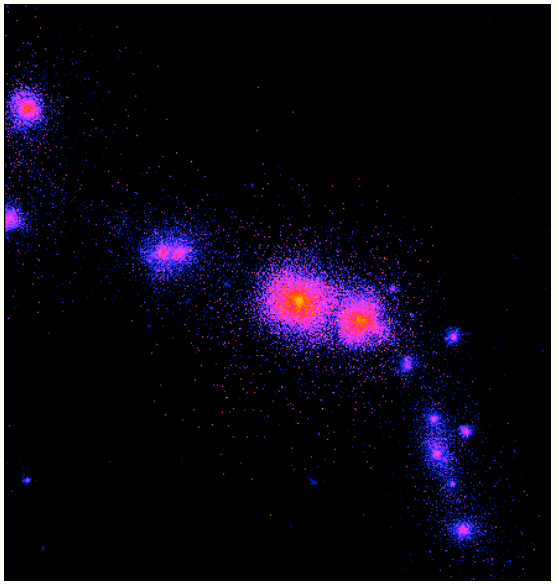


Galaxies (~10^4K)





IGM (10^5-10^7K)

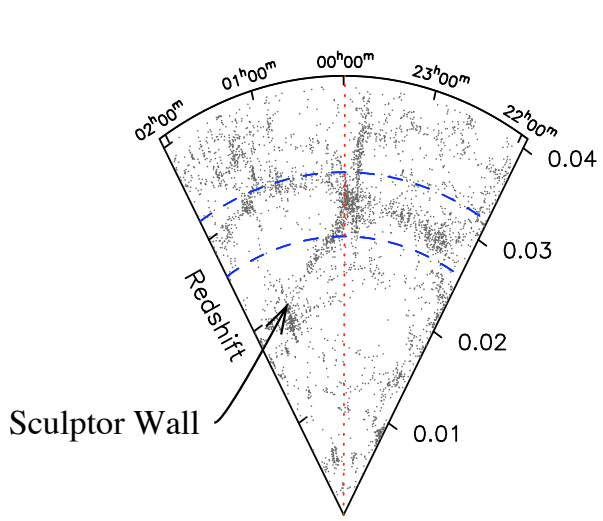


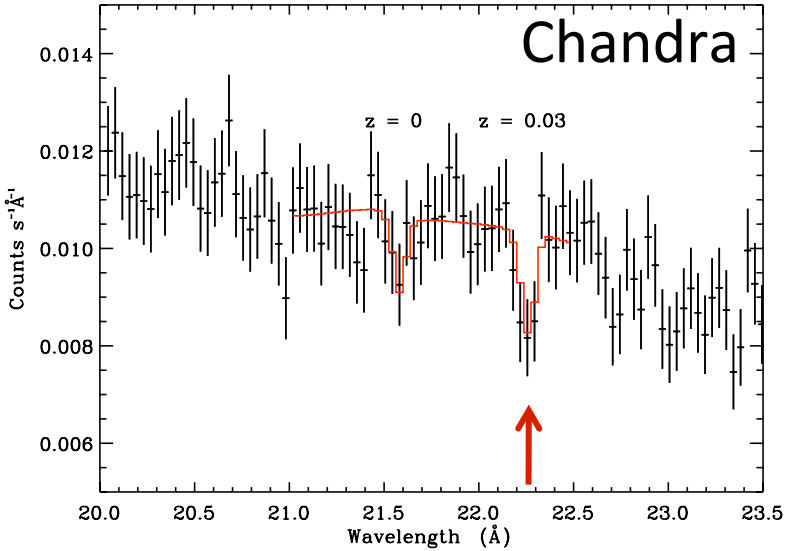
Cluster gas (10^7K)

Sculptor Wall by Chandra and XMM

Fang et al. 2010, ApJ 714, 1715

- Scupltor wall (z = 0.03 ± 0.002) via absorption of blazar H2356-309 (z = 0.165)
- XMM RGS (130 ks) + Chandra LETG (520 ks) combined
- OVII (21.6 A) absorption line detected at z = 0.03 with 4.0σ significance (EW = 26 mA)
- If depth of L = 15 Mpc (filling the wall) and Z_O = 0.1 solar assumed, overdensity becomes $\delta \sim 30$
- Consistent with WHIM filling the filament

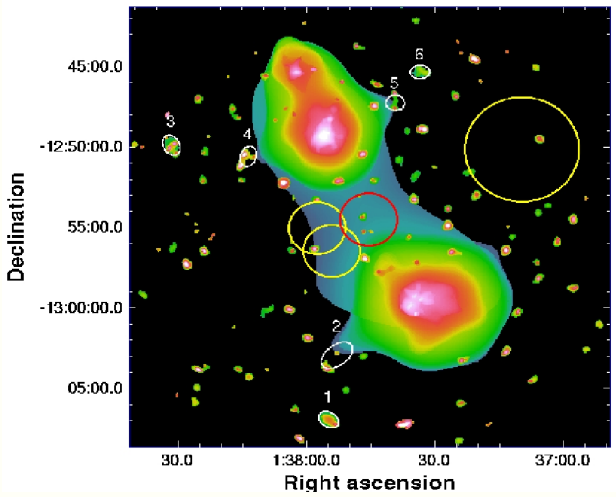




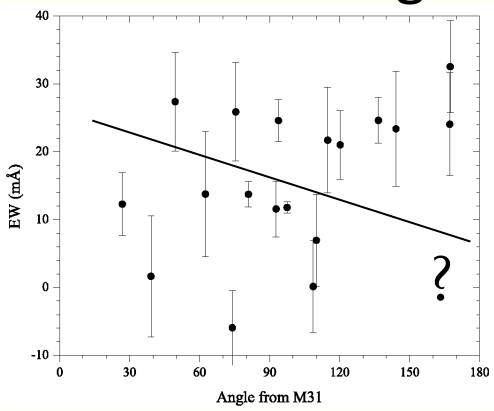
XMM study of WHIM

- Werner et al. 2008: X-ray bridge between A222 and A223 (z = 0.21)
  - kT ~ 0.9 keV, δ ~ 150 (L = 15 Mpc), continuum only
- Bregman & Lloyd-Davis 2008: Local OVII absorption is due to Galactic halo (not by Local group medium)

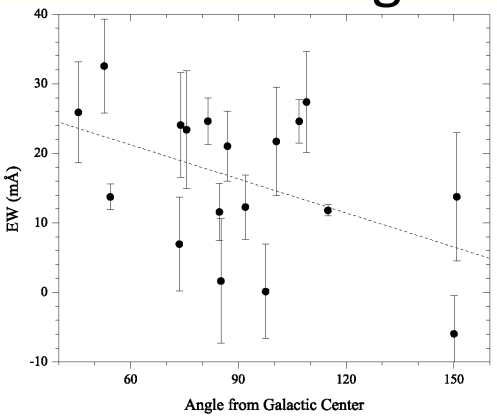
A222-A223 bridge



EW vs M31 angle

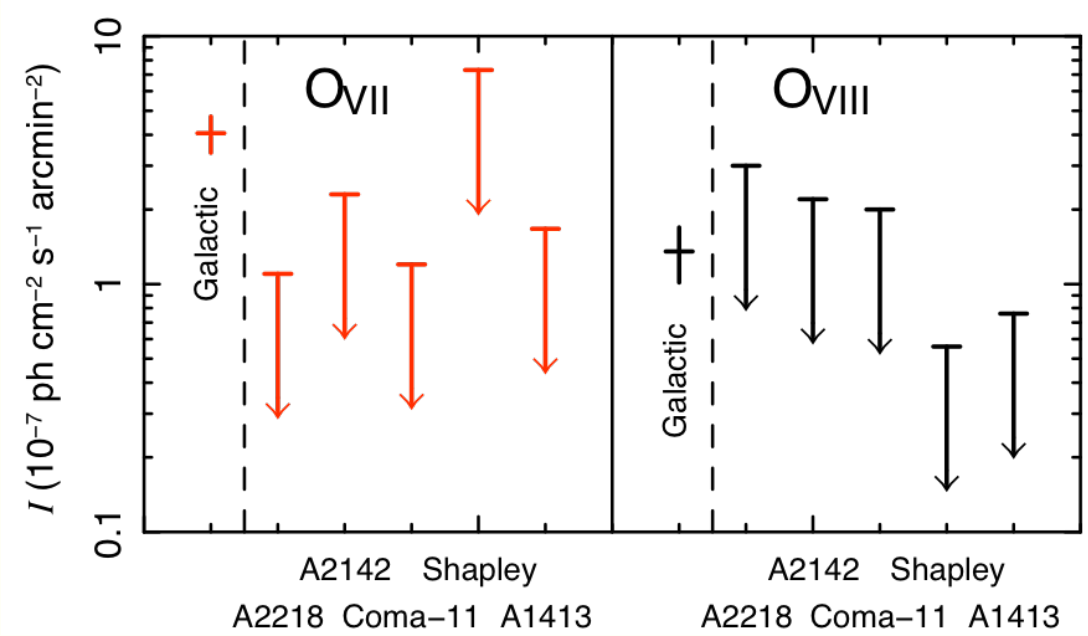


EW vs GC angle



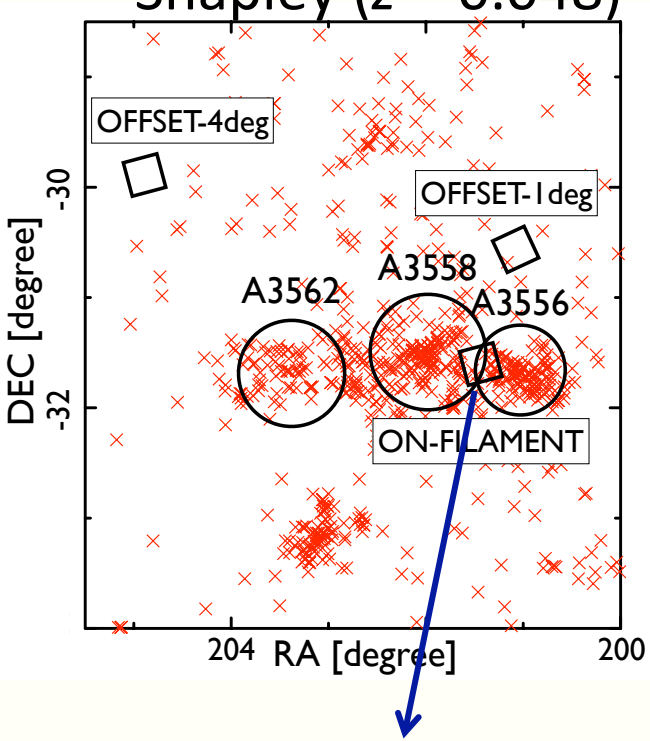
Suzaku search for WHIM

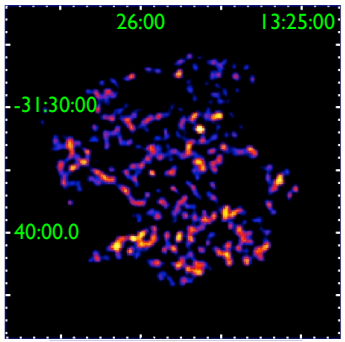
- Suzaku has been searching for WHIM in superclusters, cluster outskirts and in known filaments
- No positive detection of redshifted O lines yet
- Suzaku is giving fairly low upper limits: $\delta < 300\ (L/2\ \mathrm{Mpc})^{-0.5}$ for $Z_O = 0.1$ solar



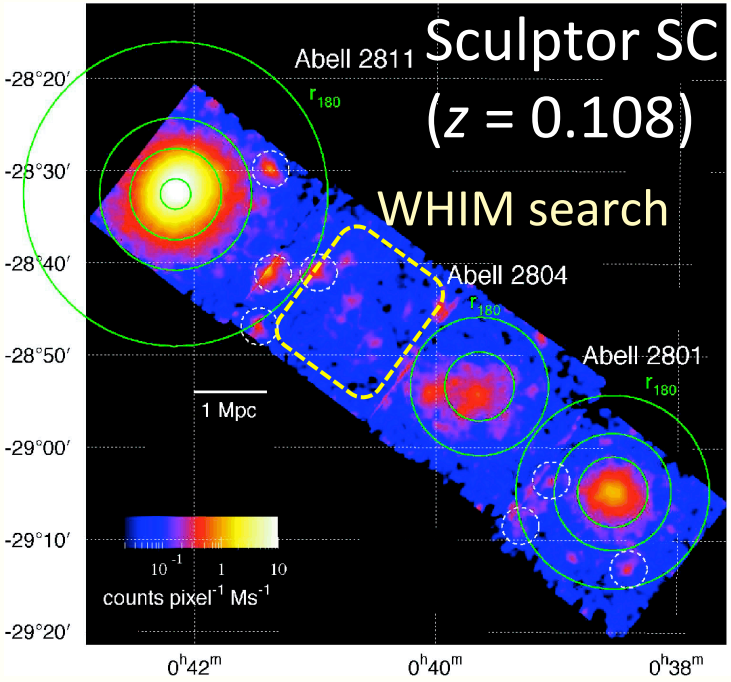
Superclusters

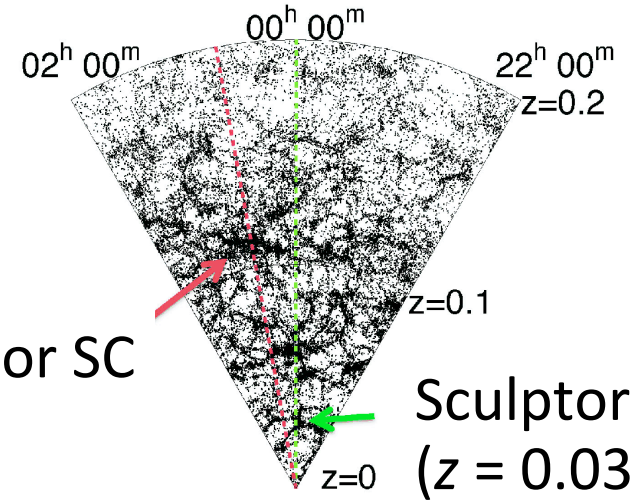
Shapley (z = 0.048)





Mitsuishi et al. 2011, PASJ, submitted

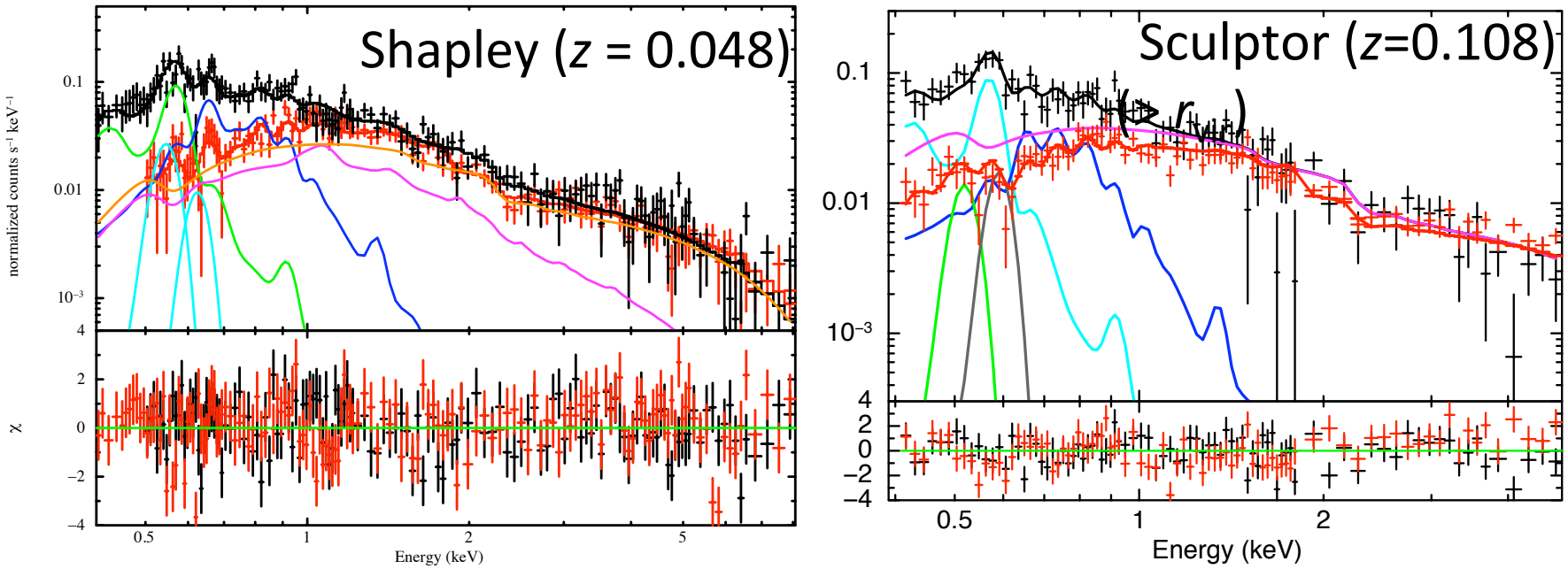




Wedge diagram in R.A. vs. redshift

Sato et al. 2010, PASJ, 62, 1423

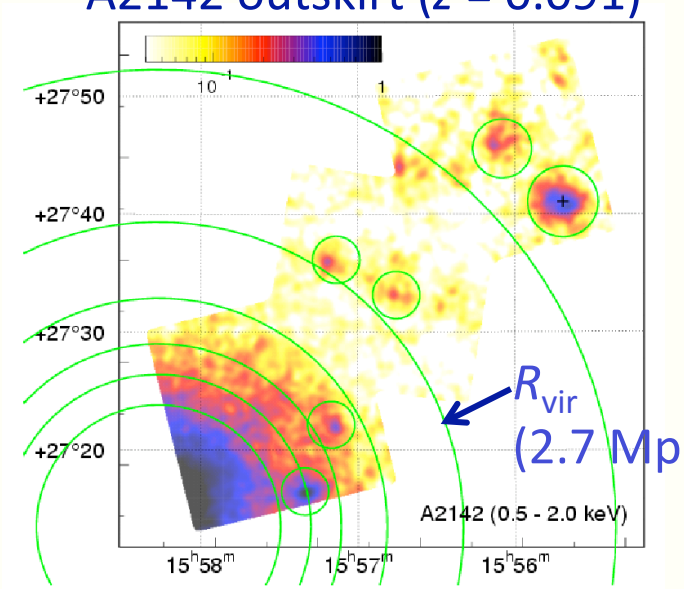
Superclusters



- Emission in supercluster space is explained by the sum of cosmic background (CXB) and Galactic emission (LHB + MWH)
- Weak cluster emission is seen in Shapley (A3558, A3556)
- Tight upper limits are given for redshifted OVII and OVIII lines → Overdensity $\delta < 340$ (Sha) and 210 (Scu) for L = 2 Mpc and Z_O = 0.1 solar

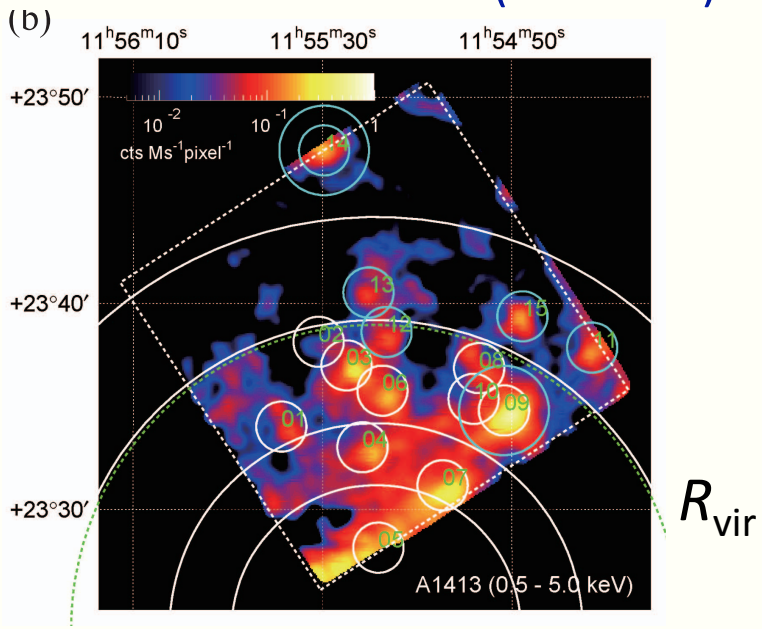
Cluster outskirts with Suzaku

A2142 outskirt (z = 0.091)



Akamatsu et al., arXiv:1106.5653

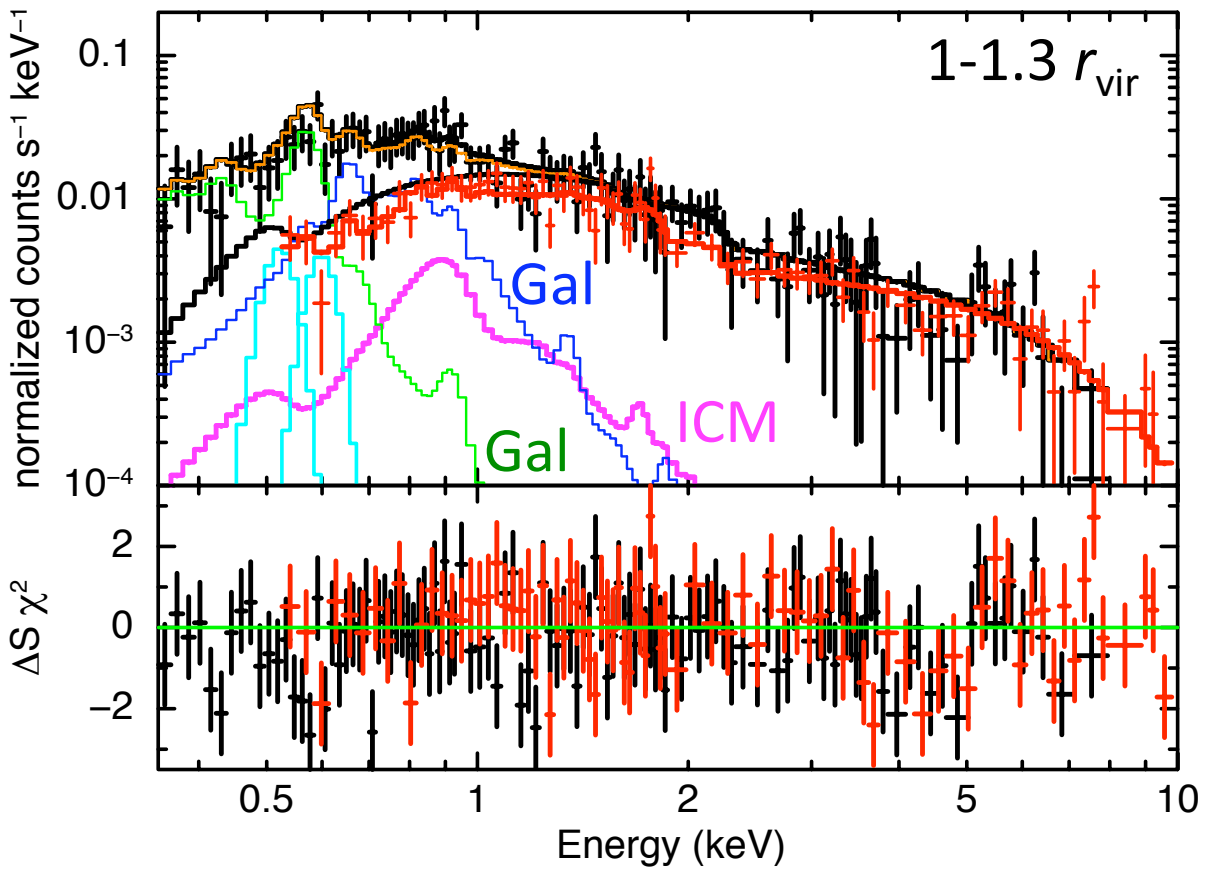
A1413 outskirt (z = 0.143)



Hoshino et al. 2010 PASJ, 62, 371

- Significant X-ray emission detected out to R_{vir}
- Systematic errors due to fluctuation of CXB, Galactic background, non X-ray background, XIS filter contamination evaluated
- Effect of stray light from bright center less than 7% of the observed flux

A2142 spectrum around r_{vir}

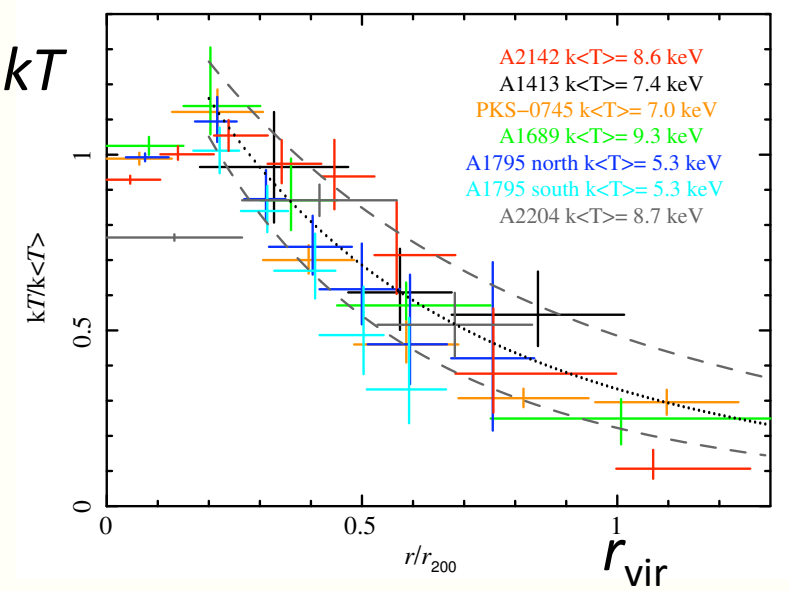


Akamatsu et al., arXiv: 1106.5653

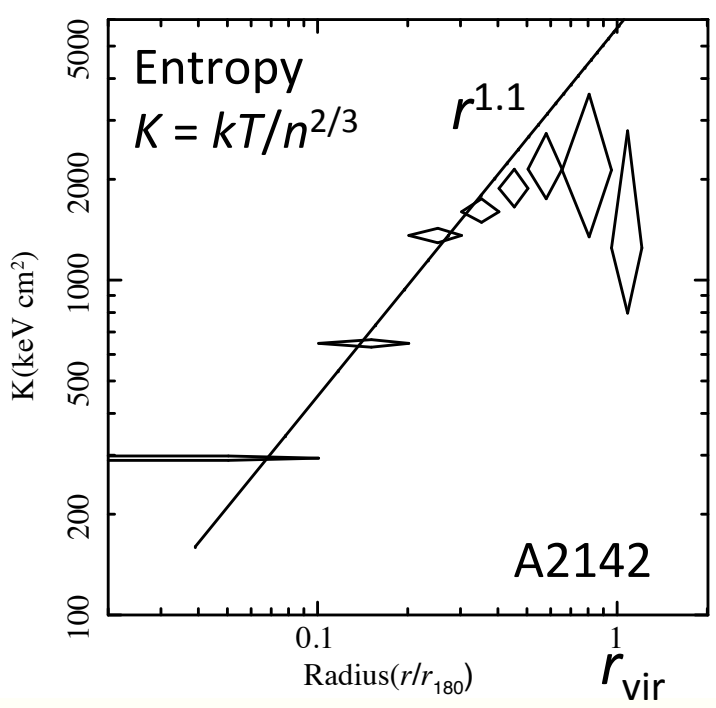
- *kT* and brightness lie along the smooth declining extension
- OVII and OVIII line upper limits are mostly determined by the intense Galactic emission
- $\delta < 280\ (L/2\ \mathrm{Mpc})^{-0.5}$ for Z_O=0.1 solar

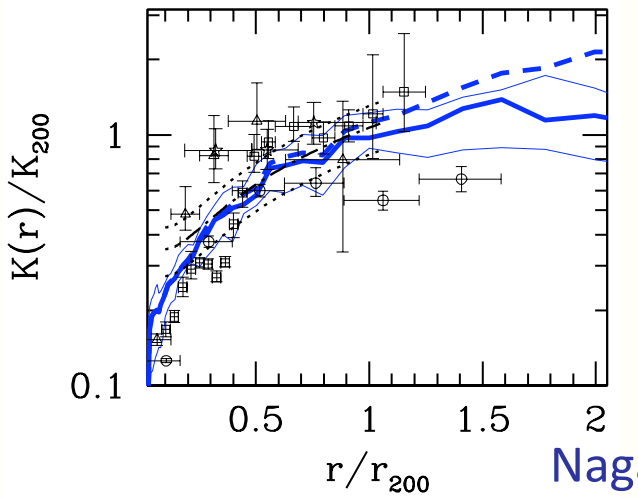
Cluster outskirts with Suzaku

"Uniform" temperature profile
by Burns et al. 2010, ApJ 721, 1105



Akamatsu et al., arXiv:1106.5653





- Entropy deviation at > 0.5 r_{vir} is seen in several clusters
- Clumpiness explains only ~10% drop
- Non equilibrium ($T_i > T_e$) more likely?

Nagai and Lau 2011 ApJL

Filament junction by Suzaku

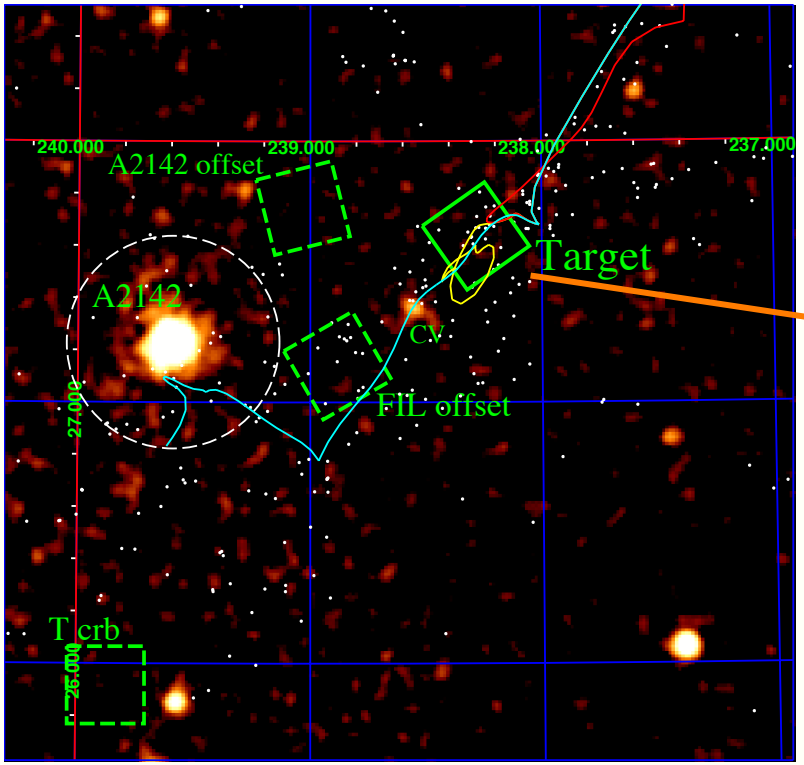
Search for (and detection of) X-ray emission from large-scale junction of filaments at $z \approx 0.08$

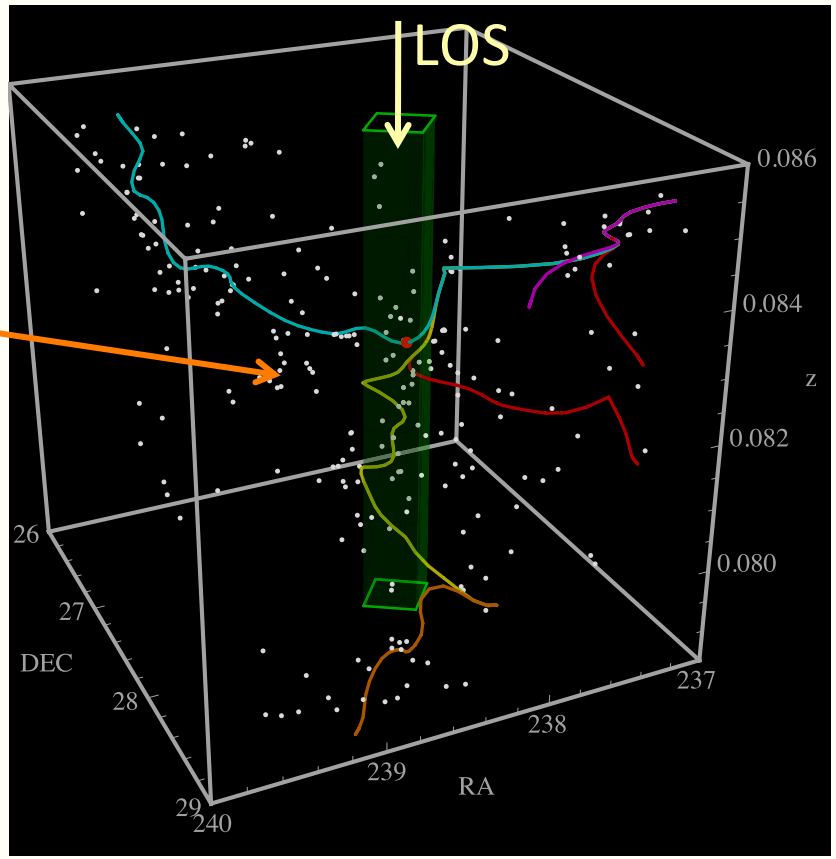
Kawahara et al. 2011 ApJL 727, L38

DisPerSE : filament extractor

Sousbie 2010, Sousbie, Pichon, & Kawahara 2010

RASS map with SDSS galaxies

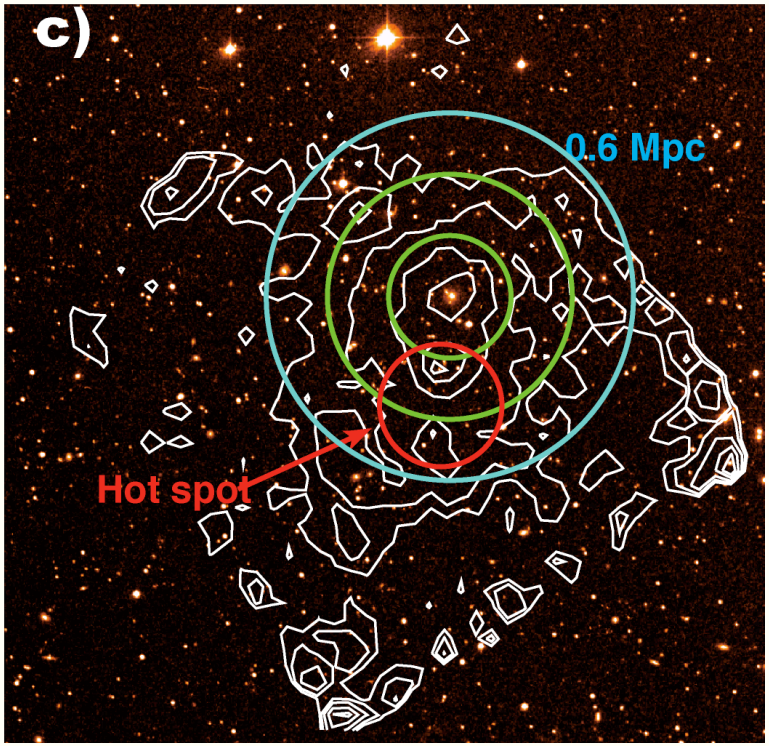




Suzaku J1552+2739: a group of galaxies

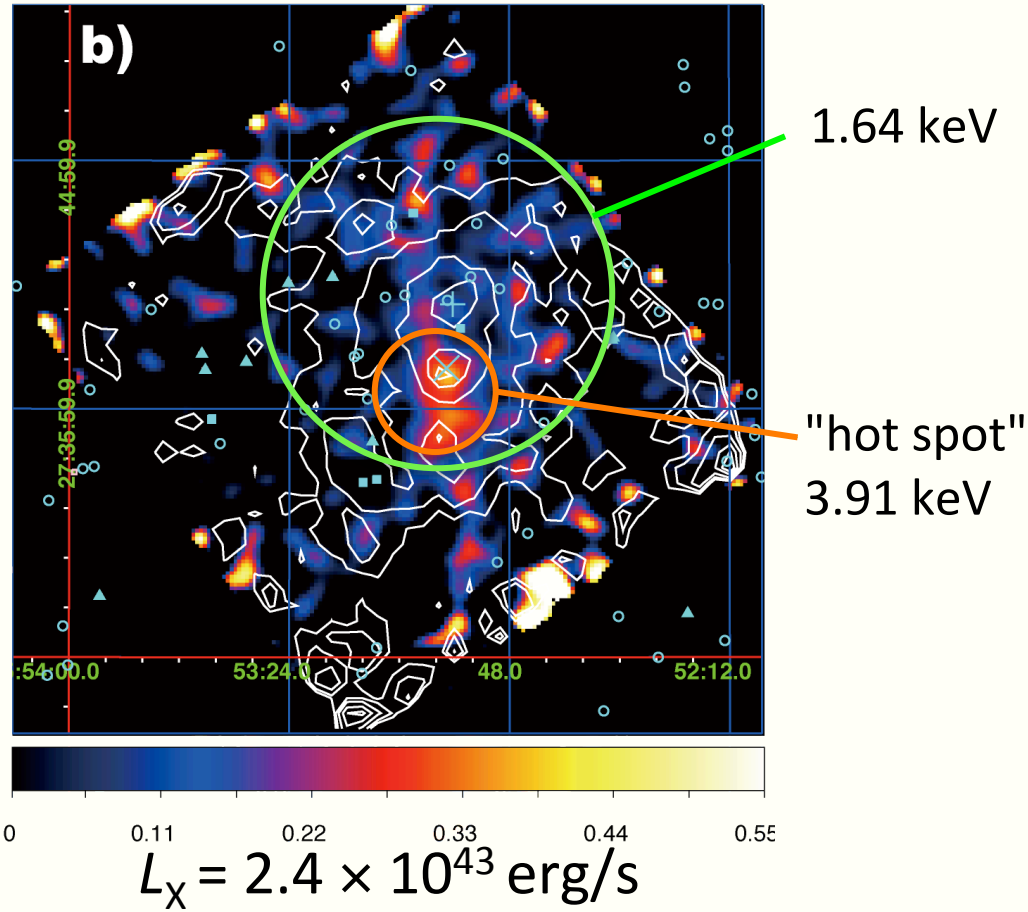
Kawahara et al. 2011 ApJL 727, L38

X-ray intensity contour



NXB subtracted & vignetting corrected image

Hardness ratio map



$L_X = 2.4 \times 10^{43}$ erg/s

- Likely to be a group undergoing major merger
- Filament junction could host many undetected X-ray groups
- These should explain some of the missing baryons

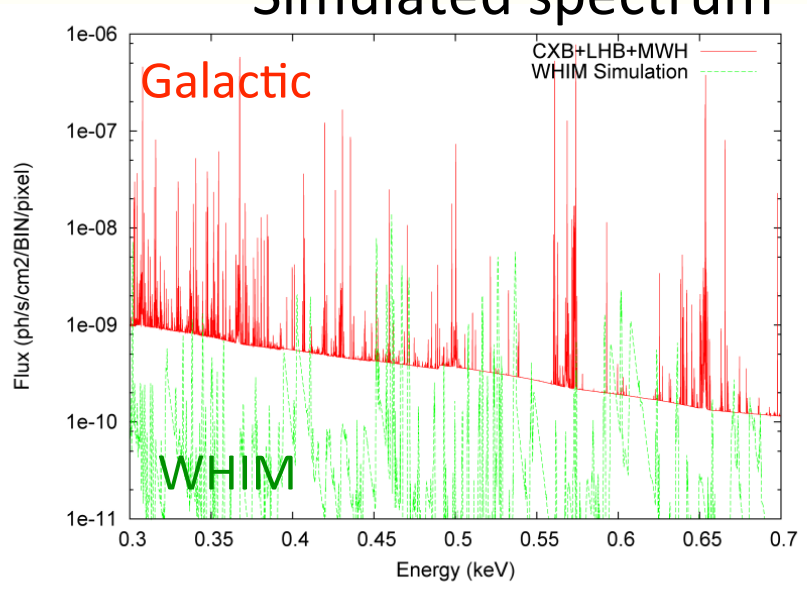
Future X-ray study of WHIM

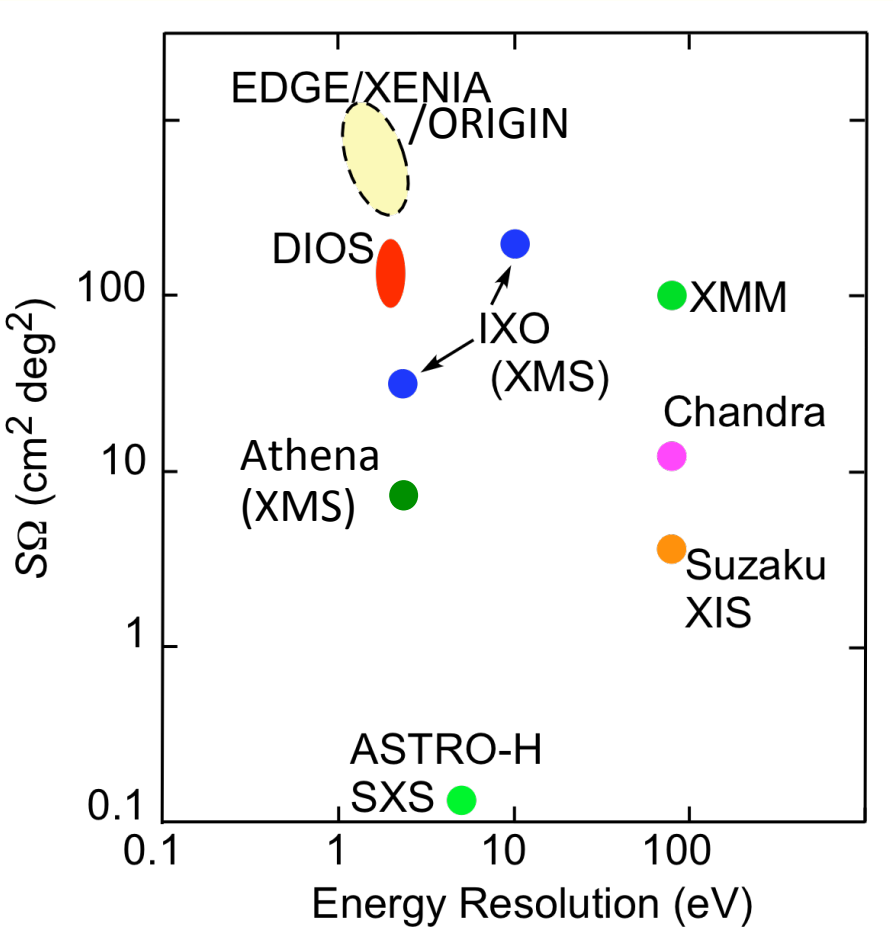
- Requirements
  - Superior energy resolution: a few eV
  - Wide field of view (for emission study): ~ deg
  - Good angular resolution: ~ 10 arcsec
- Large f.o.v. is not compatible with large X-ray observatories such as ASTRO-H and Athena
  - Dedicated X-ray mission is desirable
- The mission can be realized as a medium/small satellite program
- Many additional sciences are possible: clusters, SNRs, Galactic ISM, SWCX etc

WHIM emission with Athena

- Grasp of XMS: moderately large and 100 times of ASTRO-H SXS
- 10″ angular resolution resolves 32 kpc at z = 0.2 (galactic outflow scale)

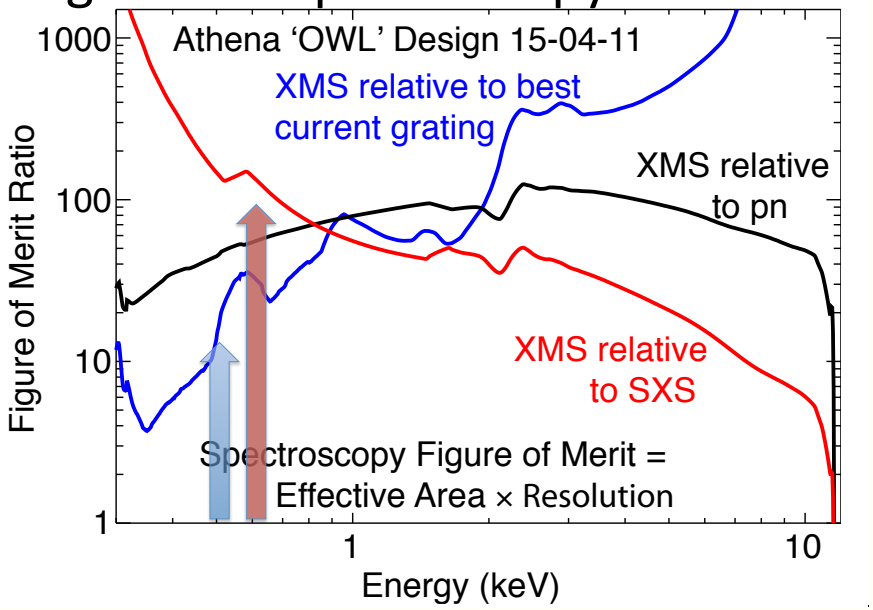
Simulated spectrum

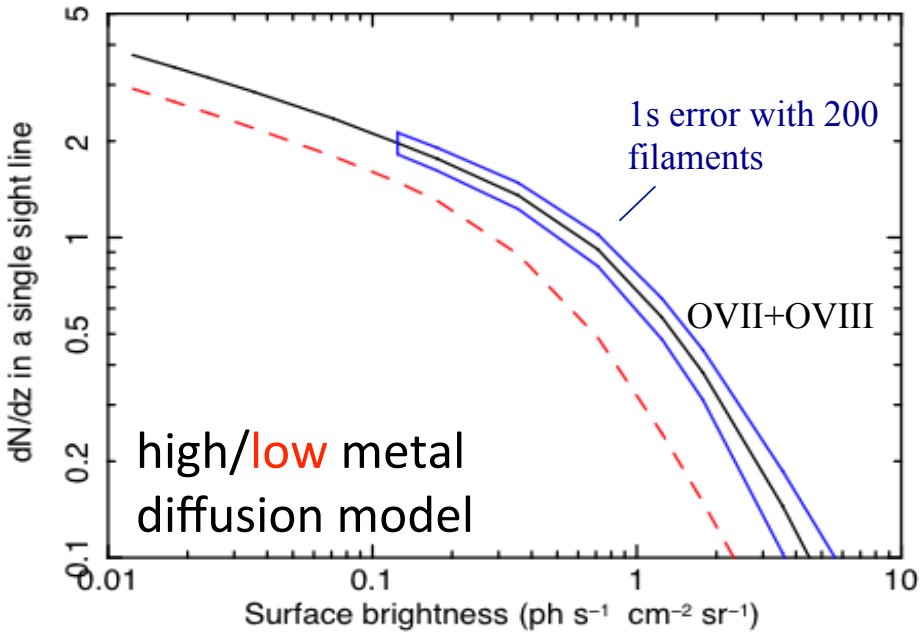




WHIM emission with Athena

Integral field spectroscopy with XMS



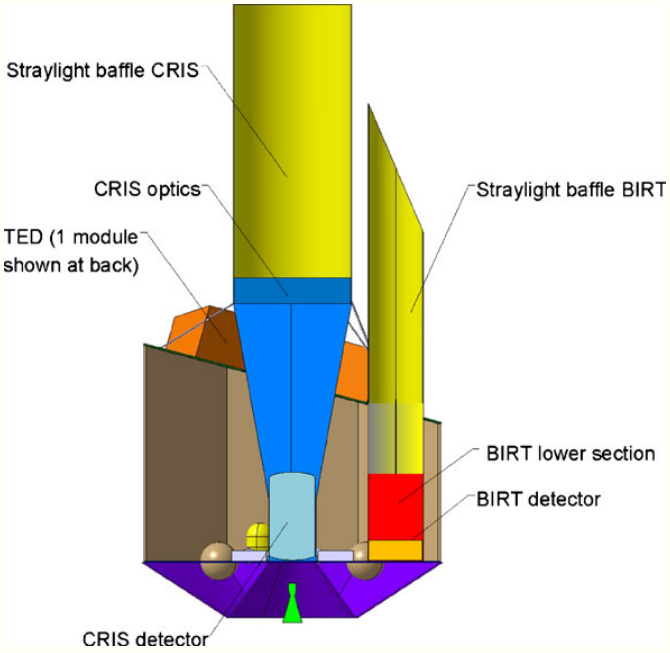


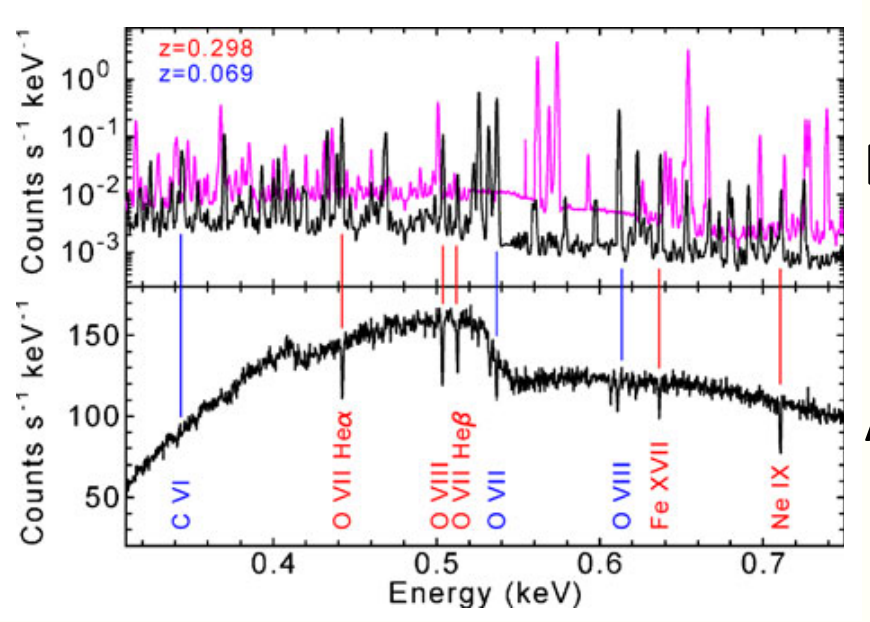
- Athena XMS:
  5000 cm^2 at 0.5 keV, f.o.v. 2.4' × 2.4', ΔE = 2.5-3 eV
- 1 emission system picked up in a 300 ksec pointing
  → 300 filaments with $\delta \sim 100$ in 5 yrs
- Simultaneous absorption and emission study can be done for 20-30 systems → cloud geometry can be constrained

ORIGIN

- metal creation and evolution from the cosmic dawn -

den Herder et al. 2011 Exp. Ast.





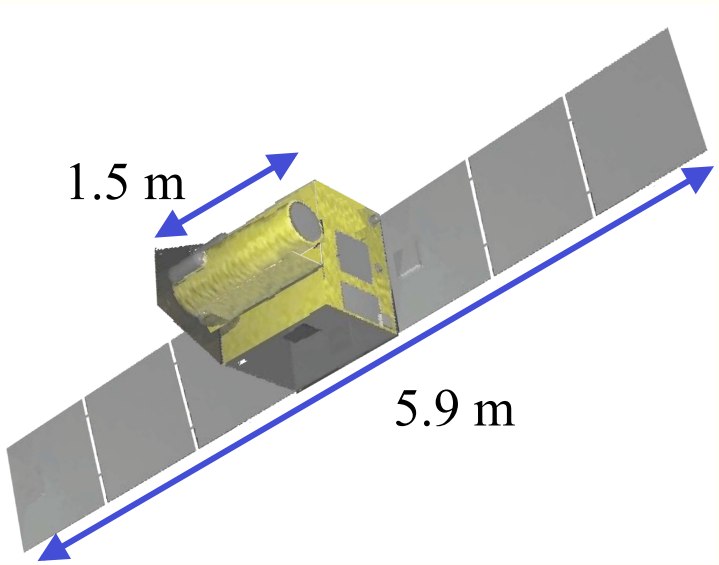
- Microcalorimeter: 1000 cm^2 at 0.5 keV, f.o.v. = 30',
  > 5000 pix (30 arcsec resol.), ΔE = 2.5 eV
- Fast repointing in 60 sec: GRB afterglow absorption line
- Joint emission/absorption stury: after GRB is faded out, WHIM emission can be studied
- Proposed to CV M-3, but ---

DIOS: Diffuse Intergalactic Oxygen Surveyor

Ohashi et al. 2010, SPIE, 7732

- To be proposed to JAXA's small satellite program for the WHIM survey study
- Satellite mass = 400 kg, low-earth orbit, mechanical coolers for ASTRO-H, TES calorimeter array with ~ 400 pix

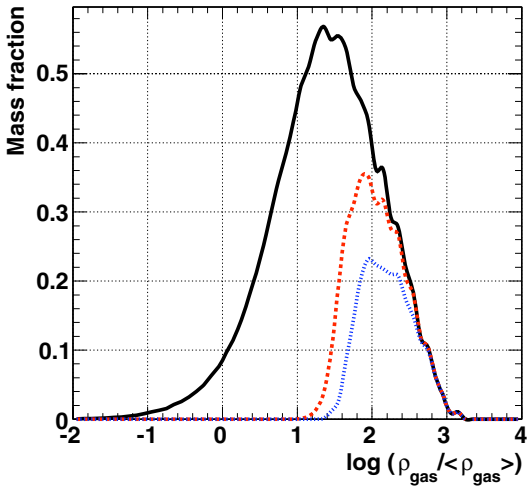
Effective Area	200 cm^2 (> 100 cm^2)
F. o. v	50′ diameter
$S\Omega$	~ 150 $cm^2 deg^2$
Angular resol.	3′ (16 x 16 pix)
Energy resol.	2 eV (FWHM)
Energy range	0.3 – 1.5 keV
Mission life	> 5 yr



Expected WHIM map

Takei et al. 2011 ApJ 734, 91

Probed fraction



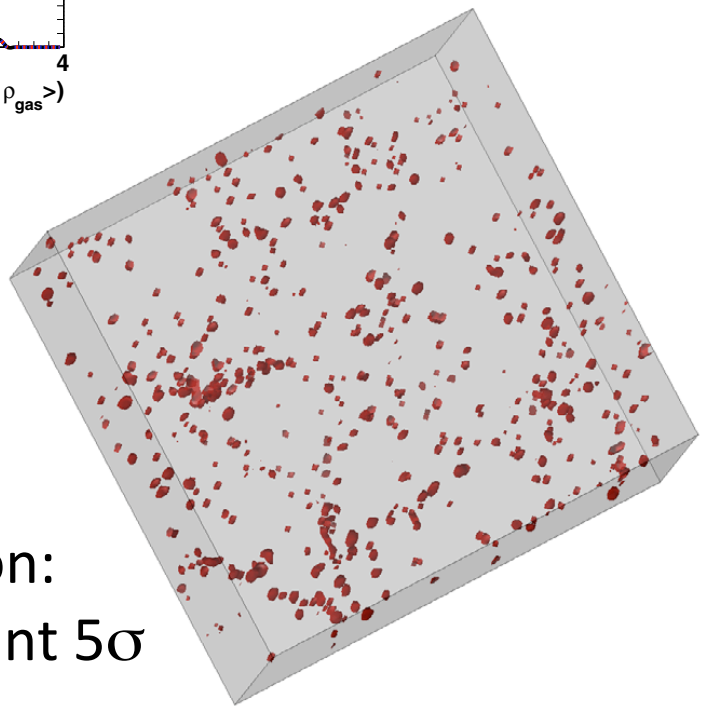
All gas

ORIGIN ~1Ms

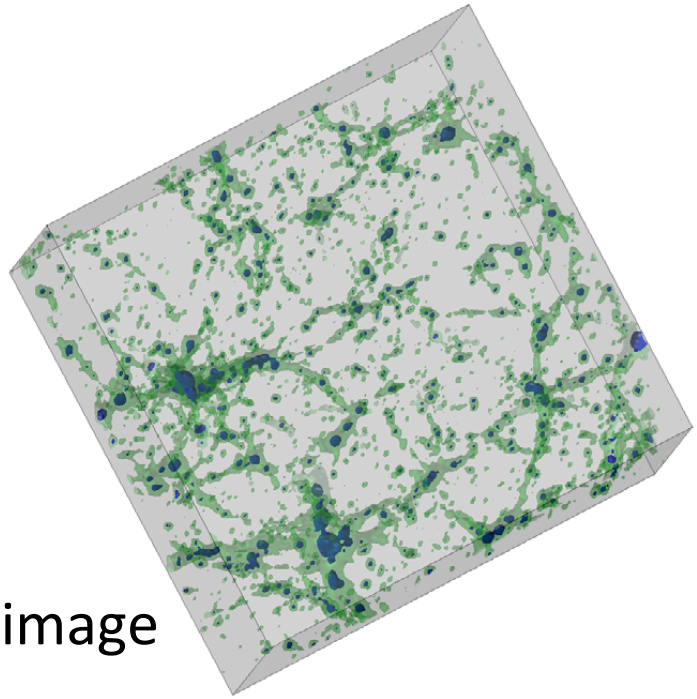
DIOS ~1Ms

- Survey of ~ 5 deg sky region can reveal dense knots in the filaments
- ≤ 20% of the whole gas can be probed

5.5° × 5.5° field at
z = 0.2117-0.2317



ORIGIN simulation:
OVII and OVIII joint 5σ



image

Summary

- WHIM will give us unique information about the thermal and chemical evolution of the universe
- Even though Suzaku is not detecting WHIM, it sets upper limits ($\delta < 300$ for $L = 2$ Mpc) based on OVII, OVIII line constraints in cluster outskirts and superclusters
- Suzaku also reveals temperature declining structure around r_{vir} of clusters and a new group in a near-by filament junction
- Future X-ray missions (Athena, ORIGIN, DIOS) with microcalorimeters will reveal WHIMand its spatial distribution
- X-ray mission with wide field and high spectral resolution can explore new frontiers of low density universe