Search for the Missing Baryons

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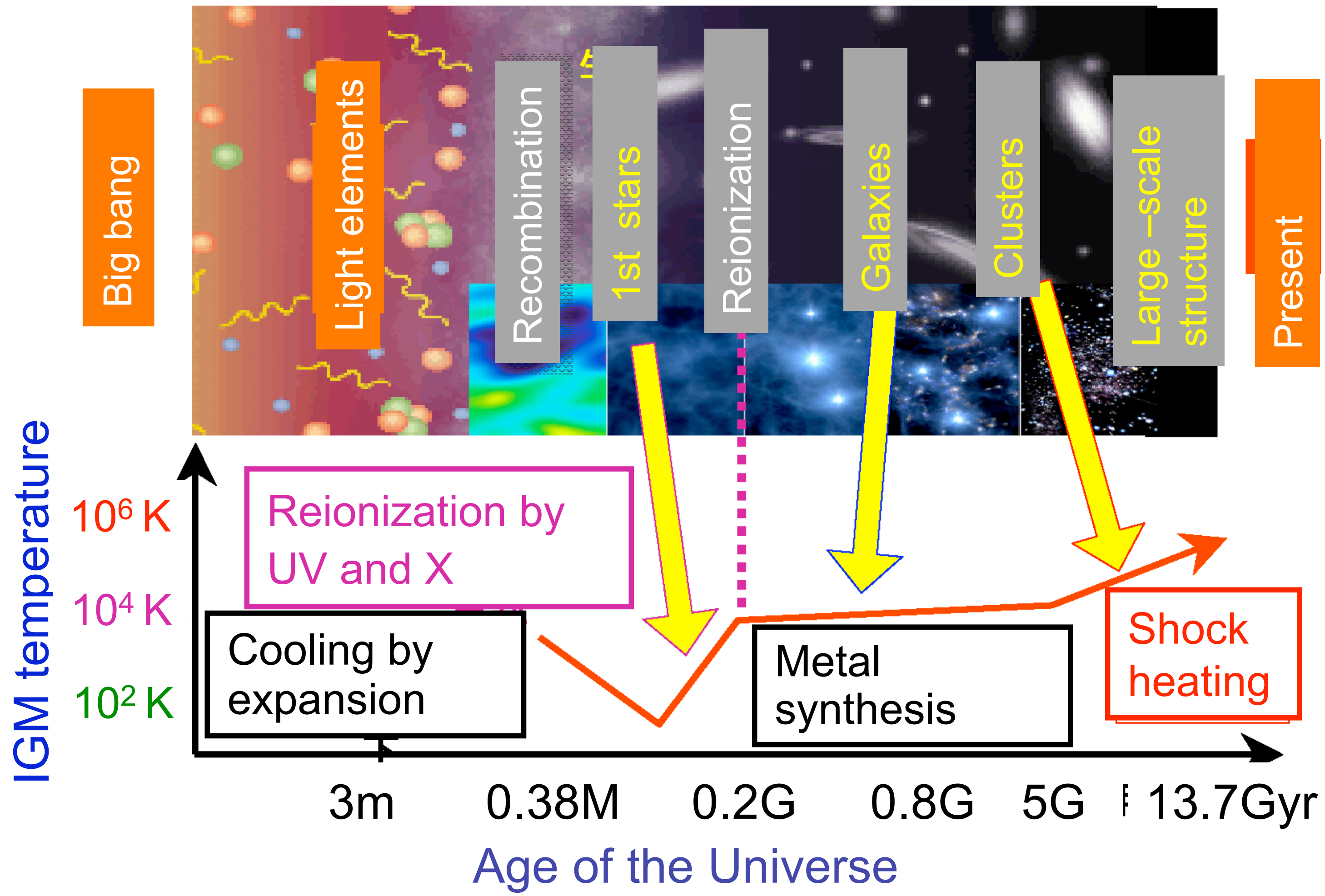
1. Science of WHIM
2. Suzaku search for WHIM
3. Future prospects

With Y. Takei, K. Sato, T. Tamura, A. Hoshino, and others

Thermal history of the universe



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

Cosmic structure

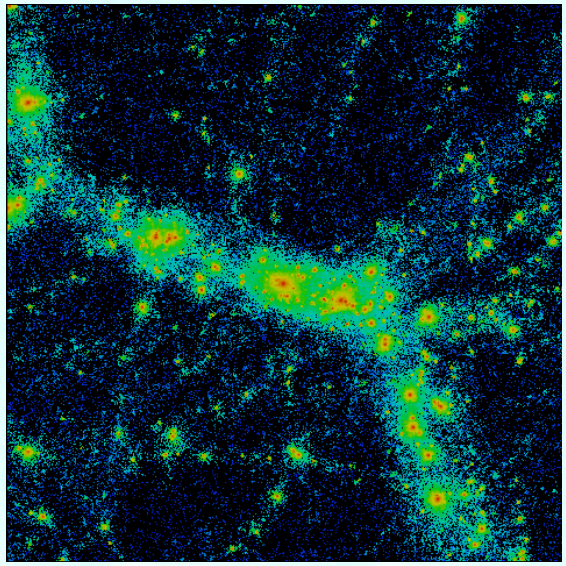
WHIM (10^5-10^7 K) traces the cosmic large-scale structure
= "Missing baryon"

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

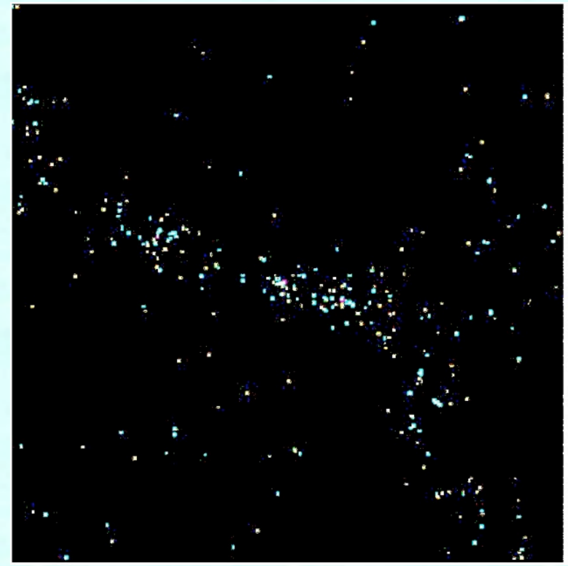
Yoshikawa et al. 2001, ApJ, 558, 520

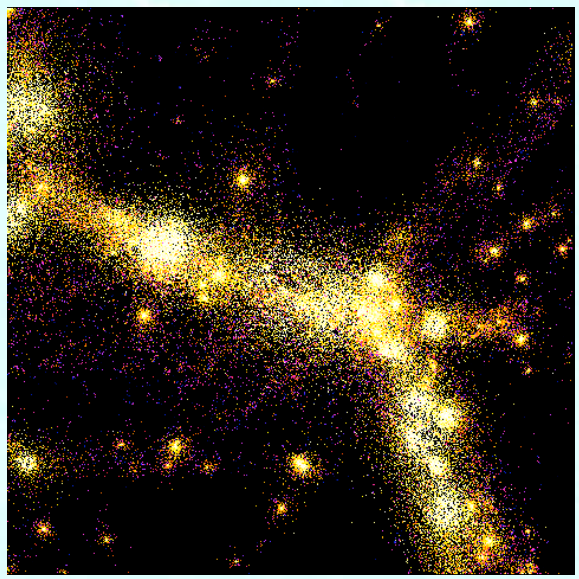
size = 30 h^{-1} Mpc
≈ 5 deg at z=0.1

Dark matter

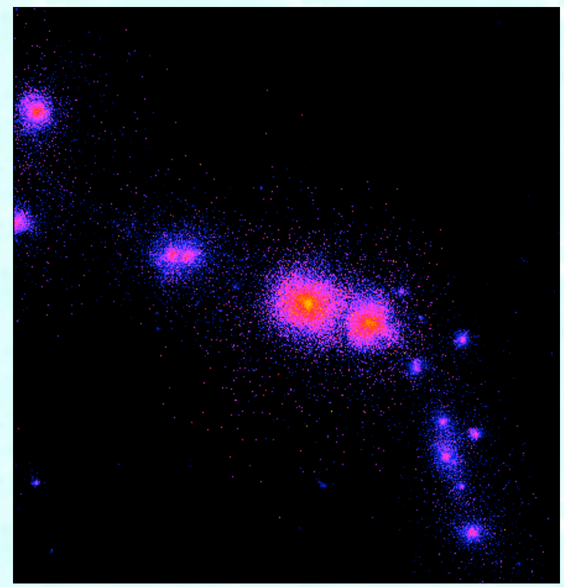


Galaxies (~10^4K)





IGM (10^5-10^7K)



Cluster gas (10^7K)

Image of Oxygen lines (ΔE=2 eV)

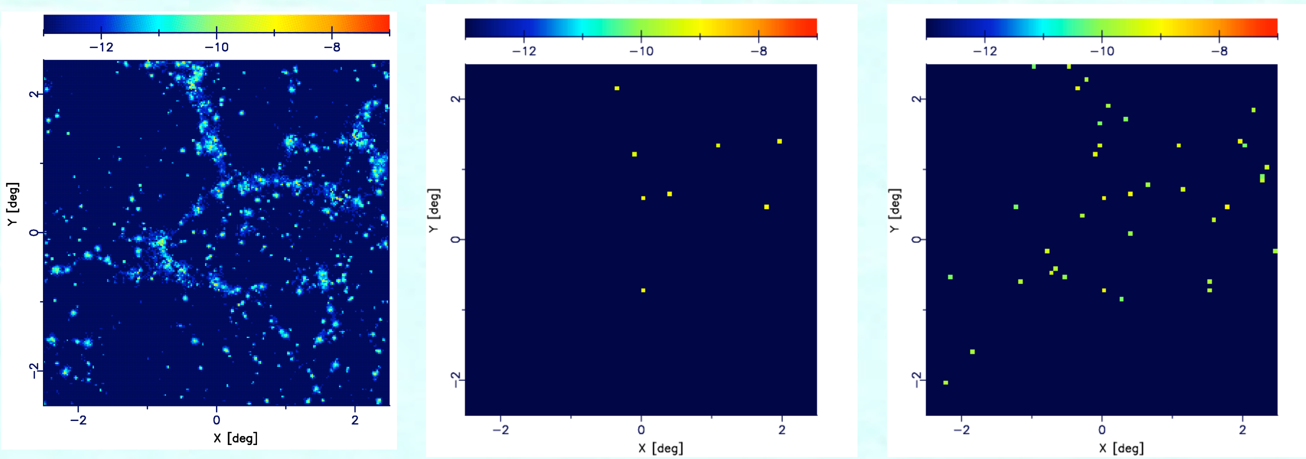
Significance > 5σ

Effective area = 1000 cm^2

OVII line

10^5 sec

10^6 sec



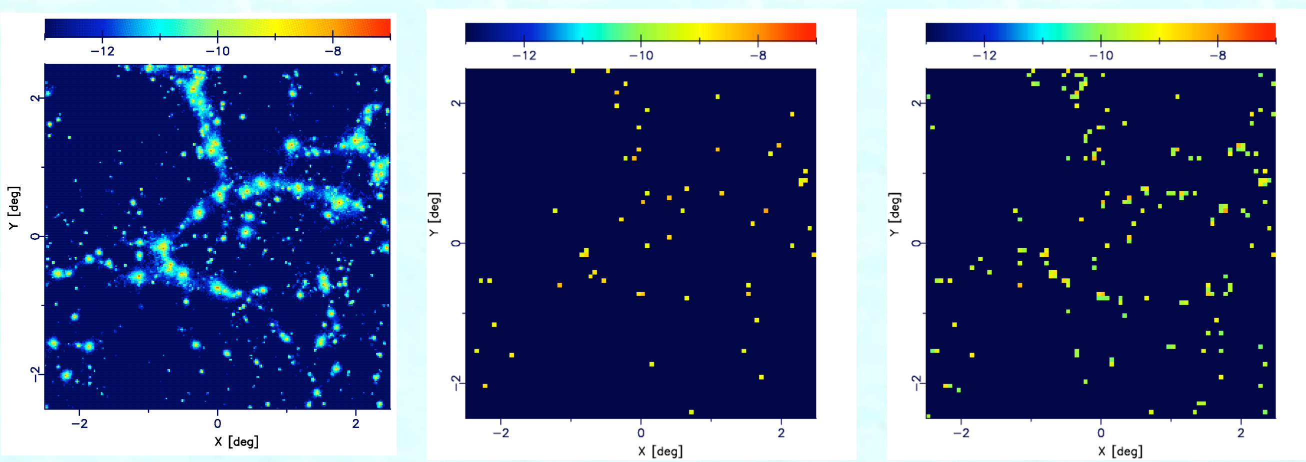
5°

z=0.24

Depth

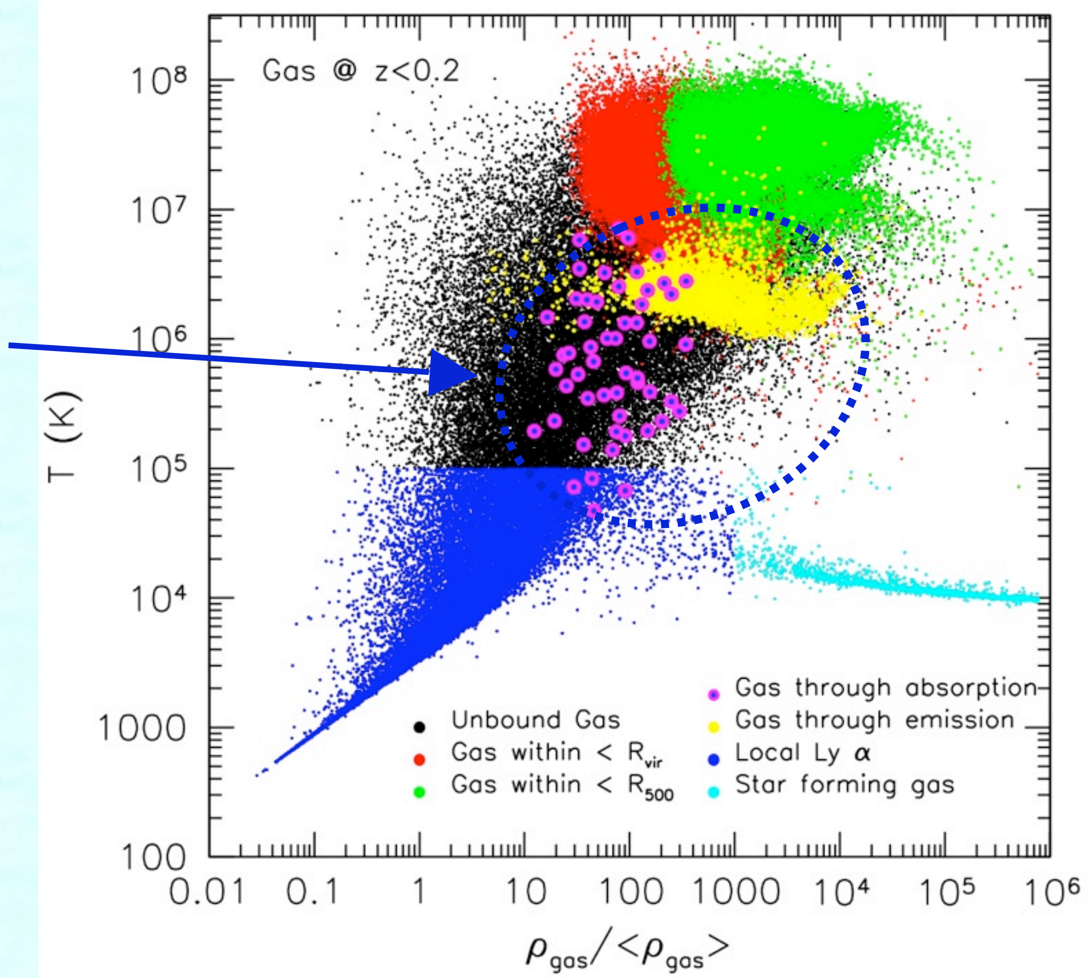
~40 Mpc

OVIII line



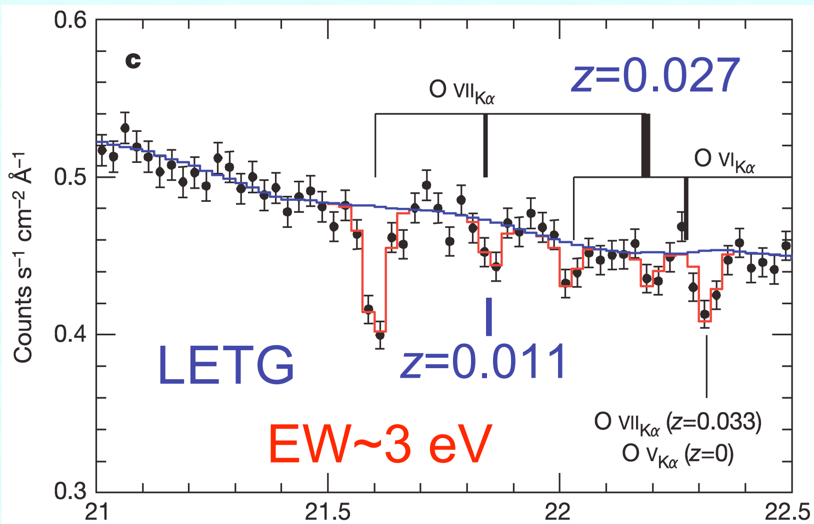
Baryon phase

With X-ray absorption and emission lines, a wide area in the baryon phase space can be probed



EDGE consortium

Absorption in Mrk421 spectrum

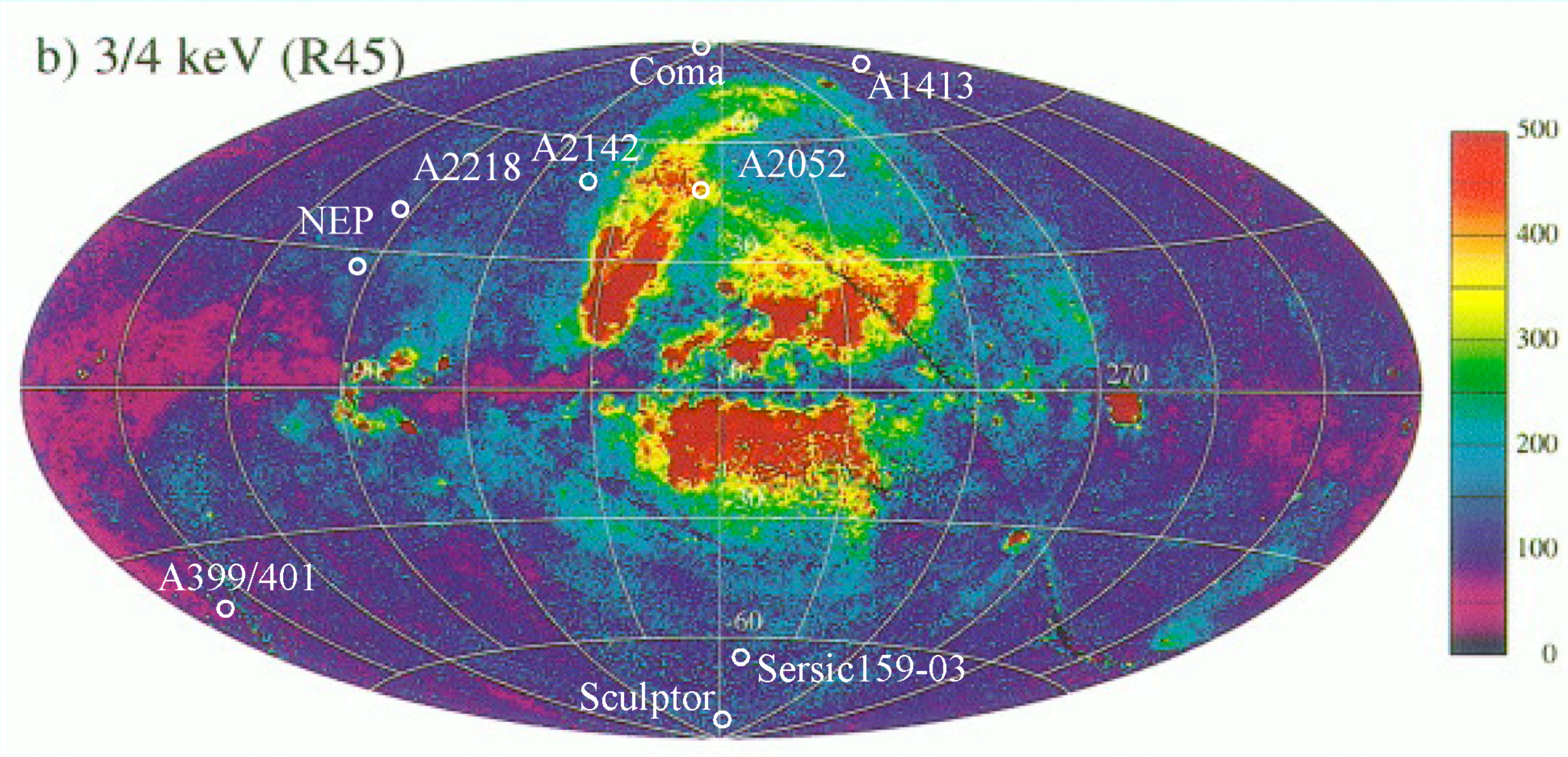


RGS

Nicastro et al. 05,Nature & ApJ
Kaastra et al. 06, ApJ
Rasmussen et al. 06, ApJ
Nicastro et al. 07, submitted

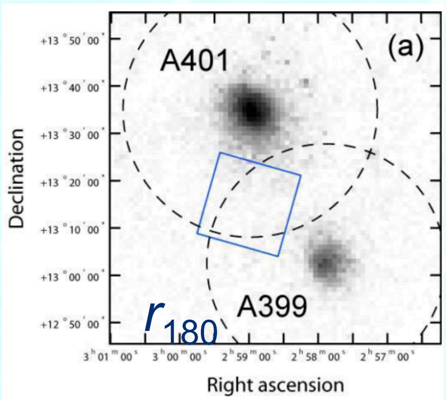
- LETG: OVII (z=0.011) detection significance = 3.9σ (P*52bin=10^{-6})
- Not significant if behavior of $\Sigma(\Delta\chi^2)$ for 7 lines with redshift trials is considered
- No absorption sign in RGS data
- LETG feature might be transient? (outflow from Mrk421?)
- Much more convincing evidence needed: with EDGE and XEUS

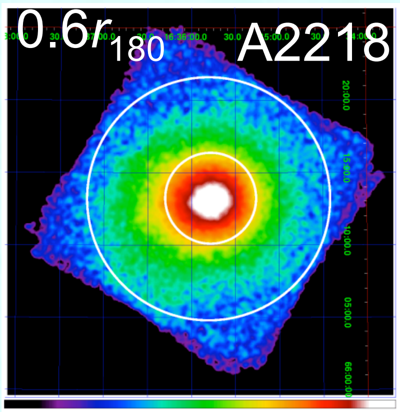
Suzaku clusters studied

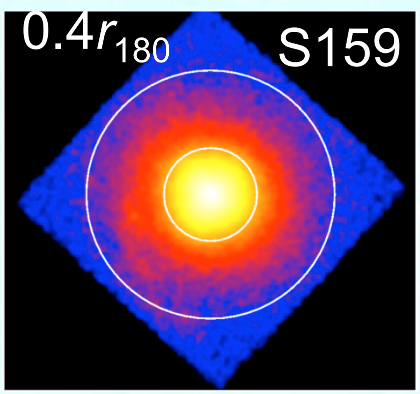


Snowden et al. 1995,1997

A2218, Sérsic159 and A399/401

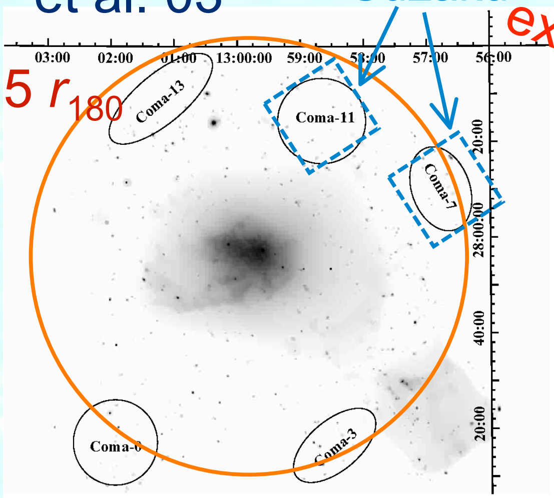


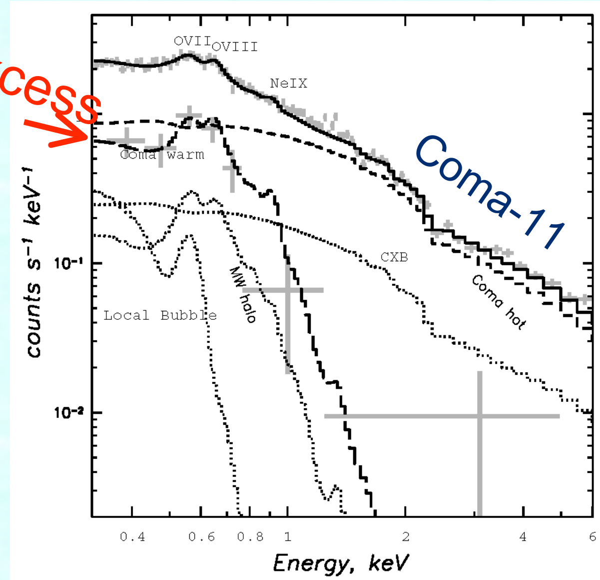


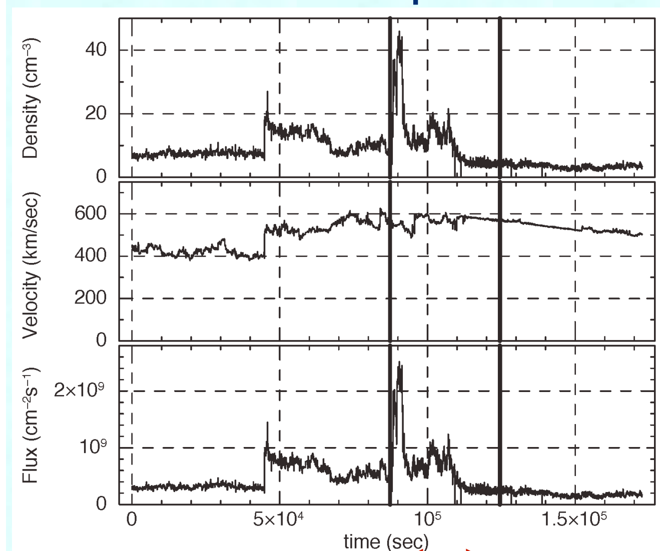


- A399/A401 (Fujita et al. 07 PASJ Suzaku #2): Binary cluster at z=0.072 before merging
  - OVII line < 1 x 10^{-7} $cm^{-2}s^{-1}arcmin^{-2}$
  - δ < 310 ($0.1Z_\odot$, L = 2 Mpc, 2 x10^6K)
- A2218 (Takei et al. 07): z = 0.1756
  - OVII line < 1 x 10^{-7} $cm^{-2}s^{-1}arcmin^{-2}$
  - δ < 270
- Sérsic 159-03 (Werner et al. 07, A10): z = 0.0564
  - Non-thermal excess over the cluster
  - OVII line < 1.7 x 10^{-7} $cm^{-2}s^{-1}arcmin^{-2}$
  - δ < 410

Coma outskirts



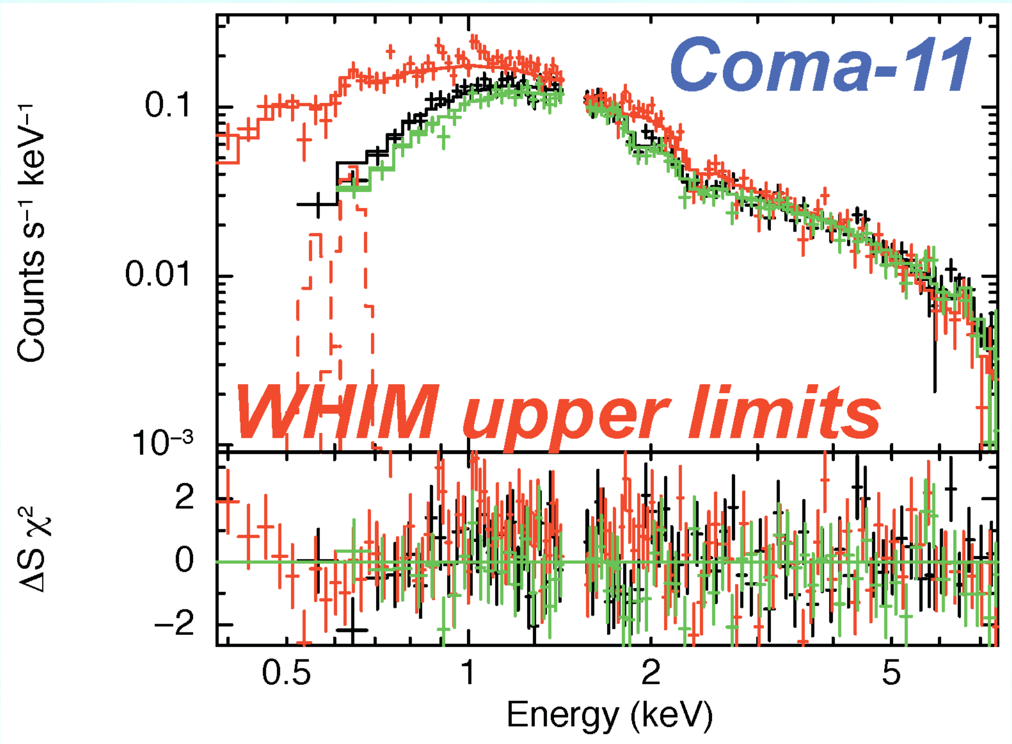


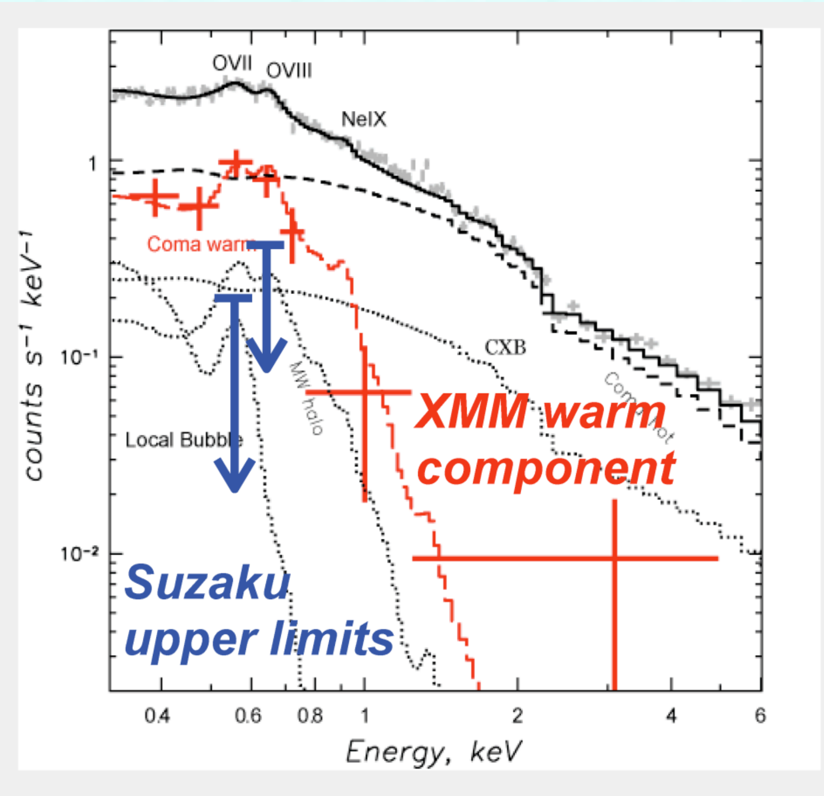


- XMM observation of Coma-11 field showed strong excess with OVII and OVIII lines, which are a few times stronger than the Galactic emission
- But, solar wind proton flux showed a flare-like feature during the XMM observation, which might be causing solar wind effect.

Takei et al. Poster A14

Coma-11 Suzaku result

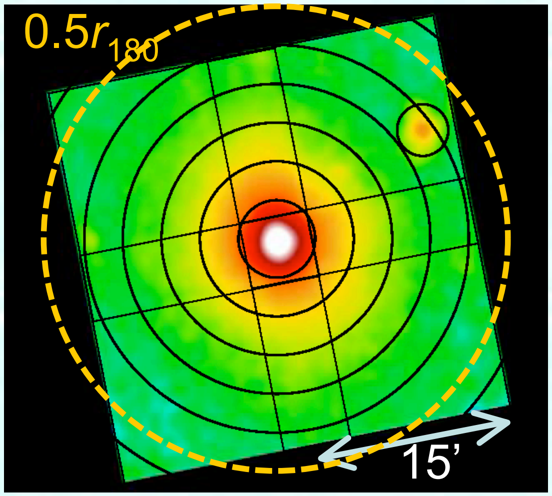




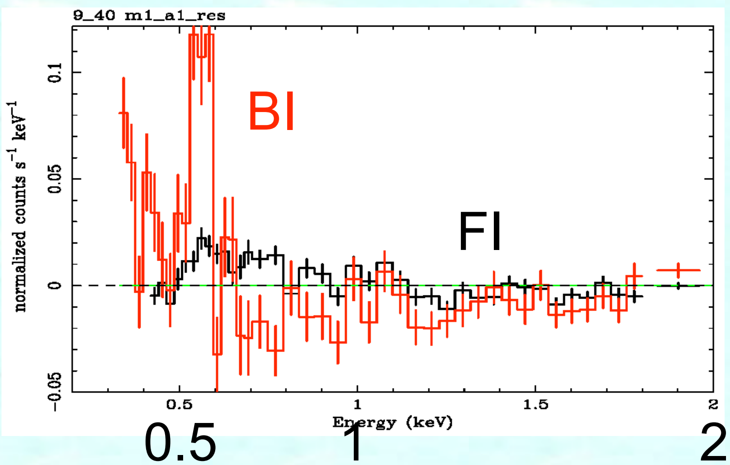
- Suzaku data do not show significant OVII or OVIII feature, with an upper limit 3 - 4 times lower than the XMM flux.
- Overdensity: $\delta < 300\ (L/2\mathrm{Mpc})^{-1/2}\ (Z/0.1Z_{\odot}\mathrm{solar})^{-1/2}$

Tamura et al. 2008?

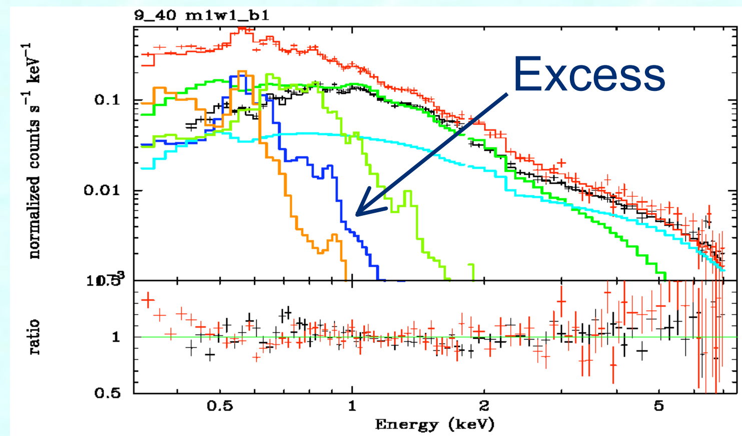
A2052



- A nearby cluster: z = 0.0355 and kT = 3 keV
- Soft excess observed with XMM (Kaastra et al. 03)
- Suzaku observation: August 19-21, 2005 (very low contamination on XIS filter)
- 4 deg offset observation: July 14-15, 2007



Residual over ICM (1.5 keV), CXB and nominal Galactic emission

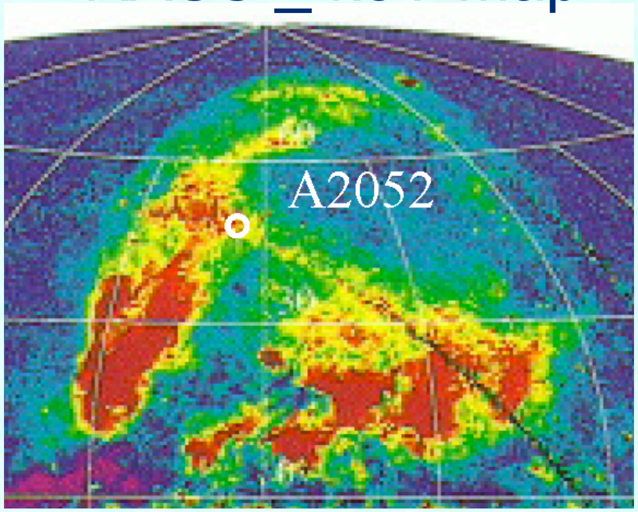


Residual spectrum can be fit with either brighter Galactic foreground or redshifted emission (kT ~ 0.2 keV)

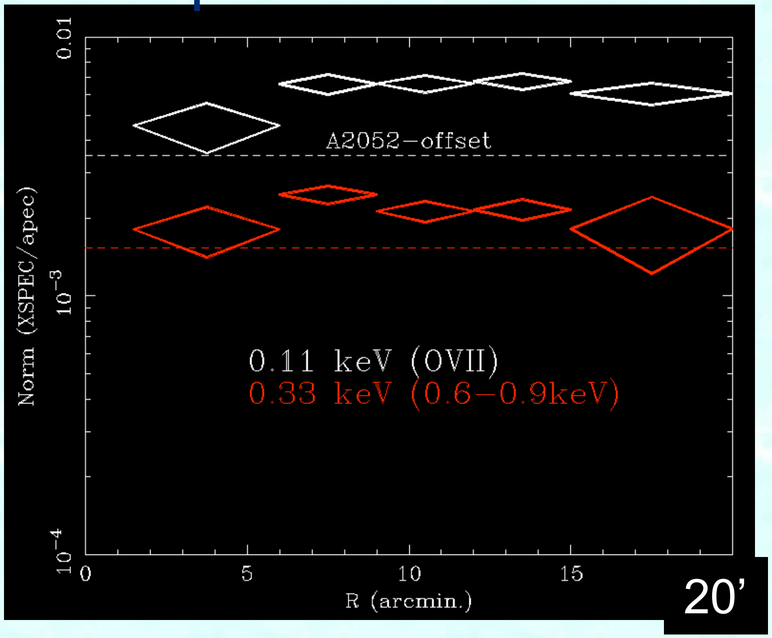
More A2052

- Both A2052 and BGD regions are near the North Polar Spur, and the emission is rather strong
- If the 0.2 keV excess is due to WHIM at the cluster redshift with L = 2 Mpc, Z = 0.1 solar, $n_H \sim 2 \times 10^{-4}$ cm^{-3} ($\delta \sim 1000$)
- The excess component looks spatially extended

RASS _ keV map

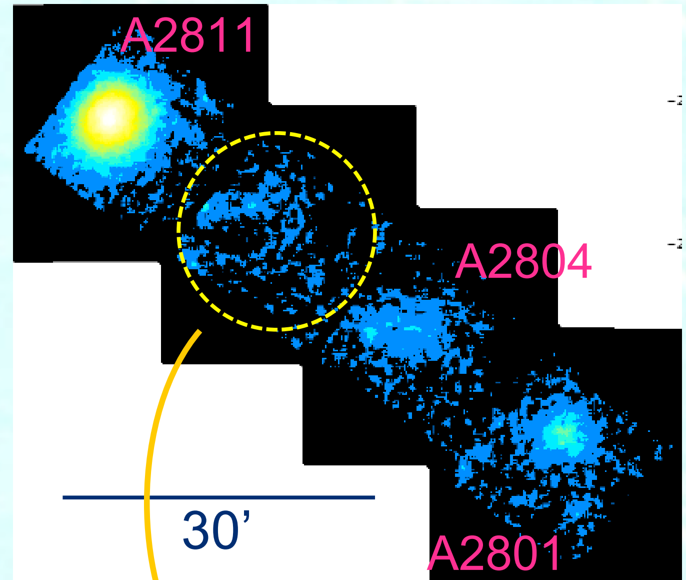


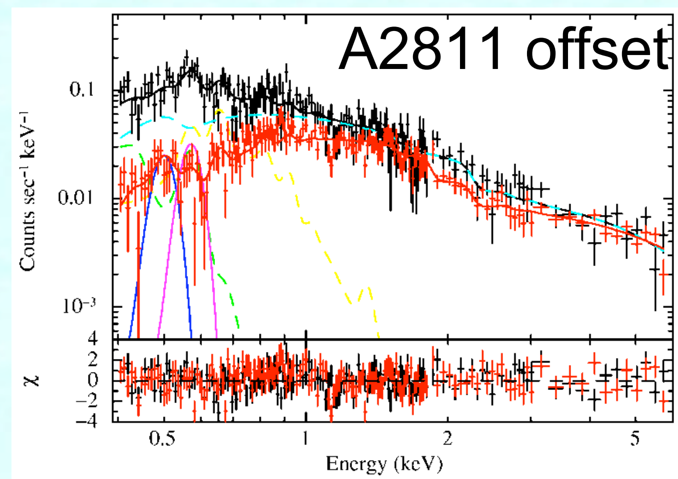
Radial profile of the excess



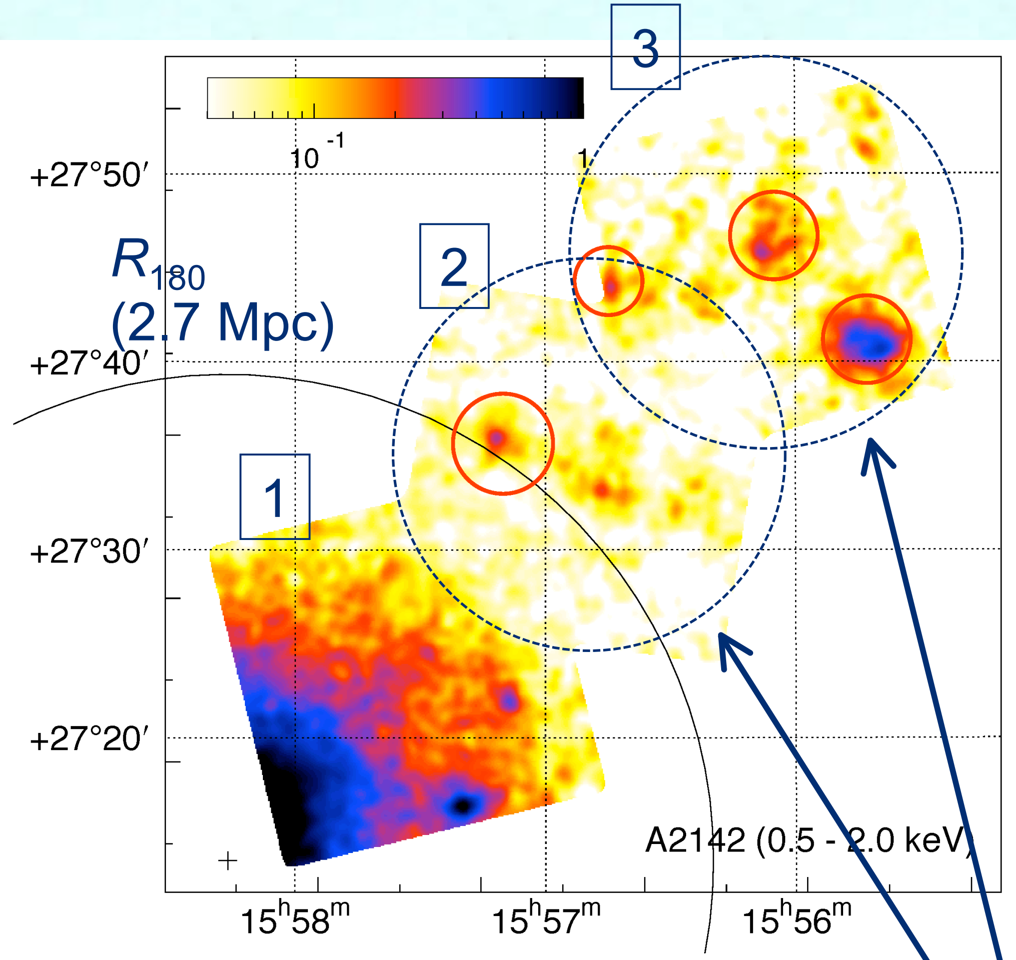
Sculptor supercluster

- 6 X-ray clusters at z = 0.11, observed in Nov. 27-29, 2005
- XIS data suggested excess emission with kT ~ 0.8 keV (Kelley et al.: Suzaku 2006)
- A2811-offset region was further analyzed
- Upper limits (2σ) to O lines:
  OVII: 1.2–1.4 x 10^{-7} $cm^{-2}s^{-1}$ $arcmin^{-2}$
  $\rightarrow \delta < 350$ ($2x10^6$K, 2Mpc, $0.1Z_\odot$)
  OVIII: 2–3 x 10^{-7} $cm^{-2}s^{-1}$ $arcmin^{-2}$





A2142 offset

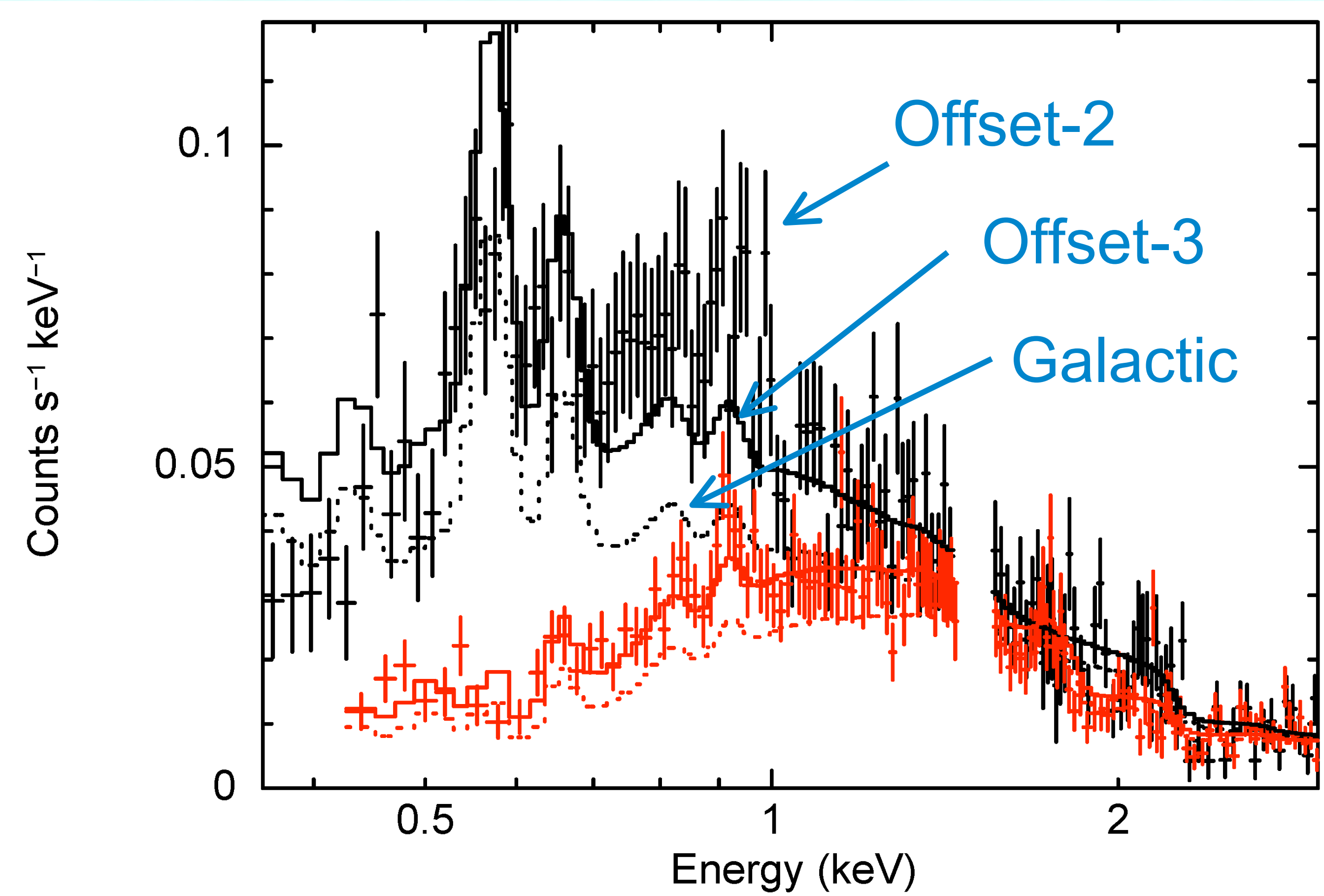


- The first cluster in which cold fronts were discovered by Markevitch et al. 2000.
- Offset regions along the merger axis were observed with Suzaku in August 2007
- *kT* = 9 keV, *z* = 0.0909 r_{vir}=2.66 Mpc =26.4'

Two offset regions show similar diffuse spectrum

A2124 Suzaku

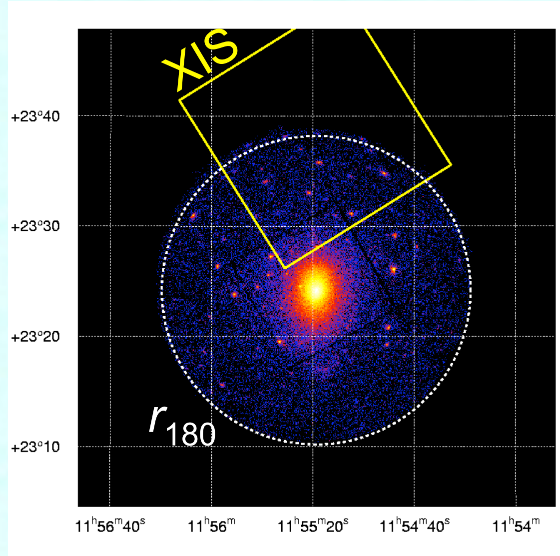
Preliminary

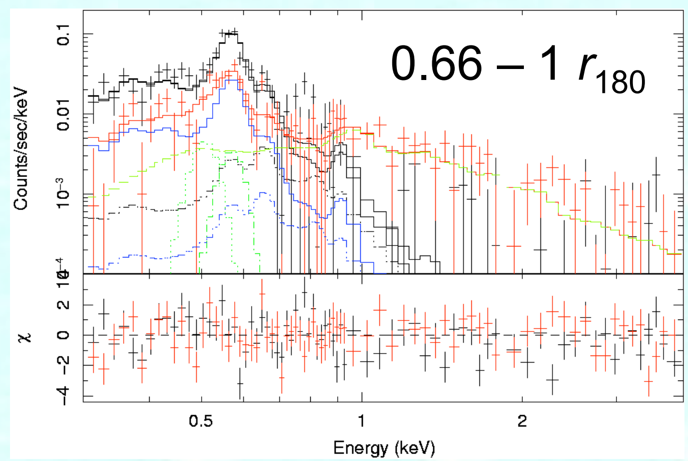


- Assuming the standard BGD (CXB and 2-T Galactic), the excess spectrum can be fit with $kT \sim 0.6$ keV thermal model
- Slight excess in offset-2 over offset-3 indicates OVII flux $< 0.7 \times 10^{-7}$ cm^{-2} s^{-1} arcmin^{-2} ($\rightarrow \delta < 250$).

A1413

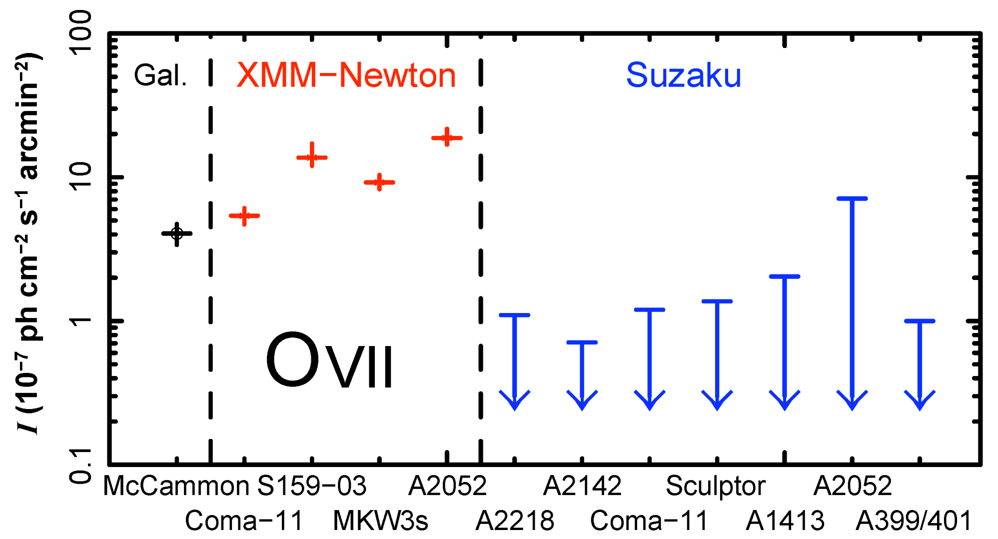
- A relaxed cluster at z = 0.143
- Suzaku offset pointing was done in Nov. 15-18, 2005
- 2σ upper limits to O lines in 0.66 – 1 r_{180}:
  OVII: 2.0 x 10^{-7} $cm^{-2}s^{-1}arcmin^{-2}$
  OVIII: 1.6 x 10^{-7} $cm^{-2}s^{-1}arcmin^{-2}$
  with BGD in the same field
- With the same assumption of 0.1 solar, 2 x 10^6 K and L = 2 Mpc, δ < 400 is implied by the OVII upper limit

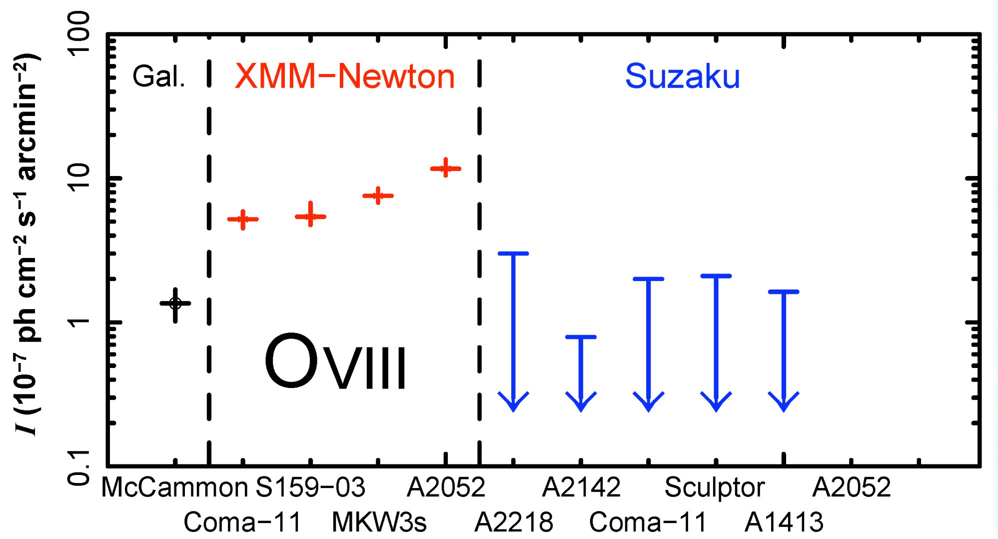




Hoshino et al. Poster A16

Summary of Suzaku constraints

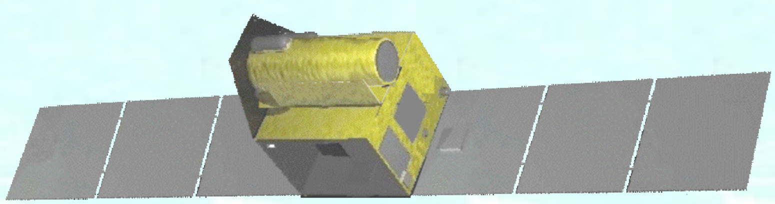




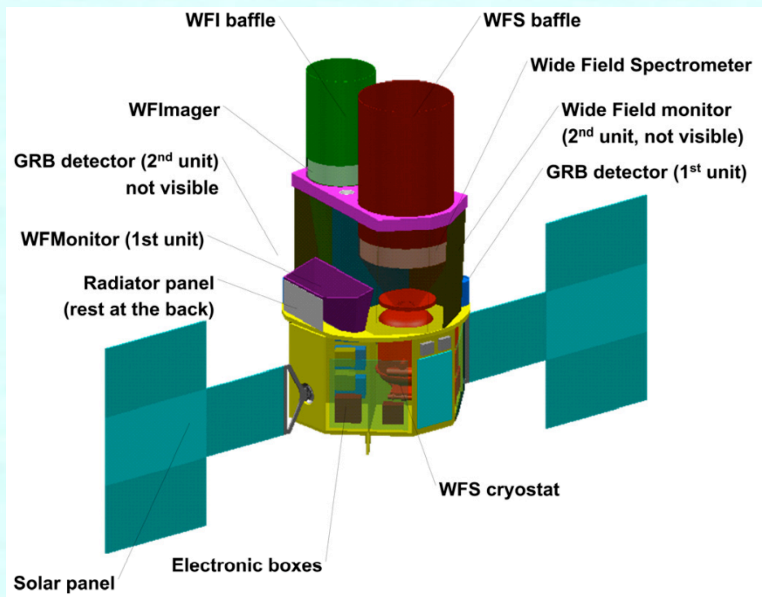
- Suzaku upper limits on Oxygen lines are factor of 3 -5 lower than the XMM “detection”.
- Understanding the spectrum of Galactic emission is most important
- Detector background and solar wind process also cause significant effect on oxygen measurement

XENIA/EDGE and DIOS

- TES calorimeter array with 1024 pixels
- <u>DIOS</u> (Diffuse Intergalactic Oxygen Surveyor, Japan) … small mission ~400 kg
- <u>EDGE</u> (Explorer of Diffuse emission and Gamma-ray burst Explosions) … medium size ~2000 kg
  ⇒ XENIA (Kouveliotou, Piro, ...)
- Launch: 2016 or later
- Very wide field of view (~ 1deg) with 4-reflection X-ray telescope
- Energy range < 2 keV



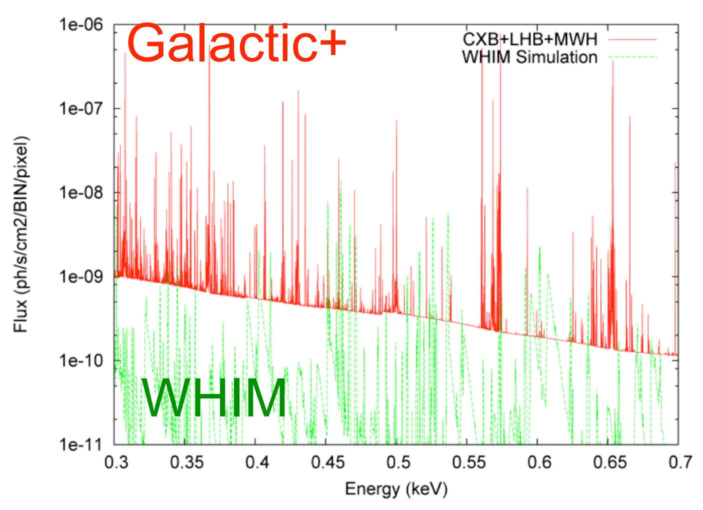
DIOS: Japanese small satellite



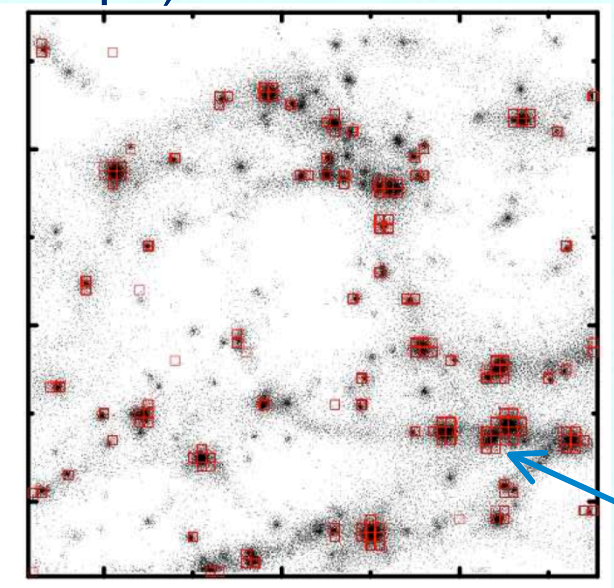
EDGE/XENIA: US-Europe-J

Expected results

Incident spectrum



5 deg x 5 deg at z = 0.2 (60 Mpc)



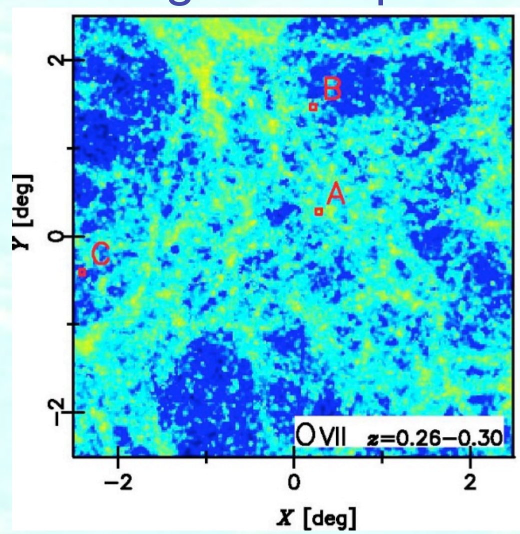
OVII & OVIII > 3σ

- 1 Msec exposure with EDGE/XENIA ($S\Omega$~ 1000 cm^2 deg^2) gives significant detection of WHIM filaments
- Combined detection of OVII and OVIII lines suppresses spurious features
- EDGE/XENIA has capability of absorption measuement against GRB afterglow → density and depth of the filament

Expectation from XEUS

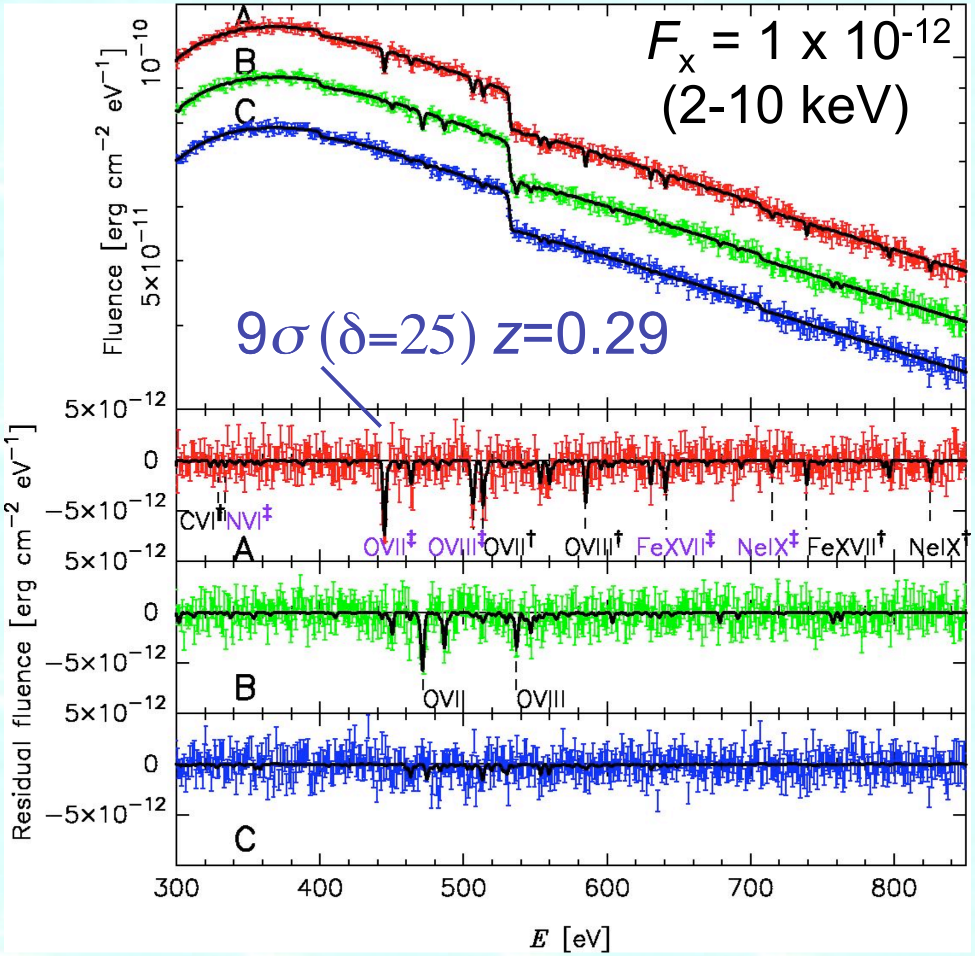
- Kawahara et al. 06 computed the mock transmission spectra of the WHIM based on hydrodynamic simulation data.
  - a light-cone output for $0 < z < 0.3$
  - mock spectra for a bright source
- Cosmological Hydrodynamic Simulation (Yoshikawa et al. 01)
  - PPPM/SPH (128^3 DM and gas particles, $L_{box} = 75h^{-1}$ Mpc)
  - $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.015h^{-2}$, $h = 0.7$, $\sigma_8 = 1.0$
  - note: Ω_b is ~30 % smaller than the recent estimate.

OVII: z=0.26-0.30, 5 deg = 76 Mpc



$N_{OVII}=10^{15}$-10^{16} cm^{-2}

Simulated spectra

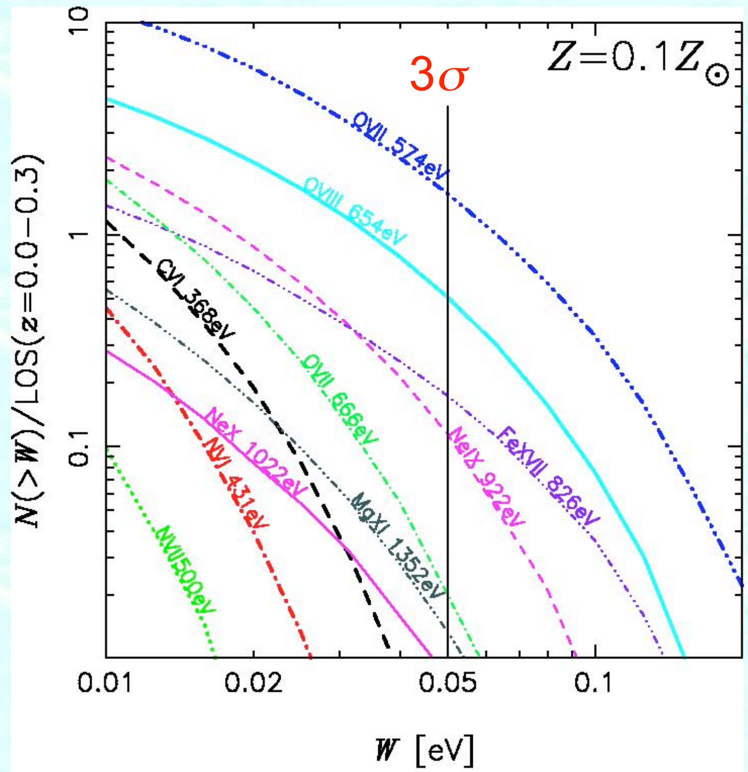


EW=0.05 eV ⇔ 3σ for 30 ksec with XEUS obs.

Expected number of absorption system per LOS

	$S/N \geq 3$
OVII (574 eV)	1.71
OVIII (654 eV)	0.43
OVII and OVIII	0.41

for 30 ksec obs.



Summary

- WHIM or missing baryons carry important science about structure formation and chemical/thermal evolution of the universe
- Its detection is a challenge for X-ray astronomy
- Suzaku is giving fairly low upper limits (δ < 300) , but real detection for δ <100 awaits either wide field (~ 1 deg) or large area (> 10^4 cm^2) microcalorimeters
- With Suzaku, we hope to find dense clamps of WHIM in cluster outskirts and in superclusters, which will be the first signature of WHIM