Suzaku and XMM study of the Warm-Hot Intergalactic Medium in cluster vicinities

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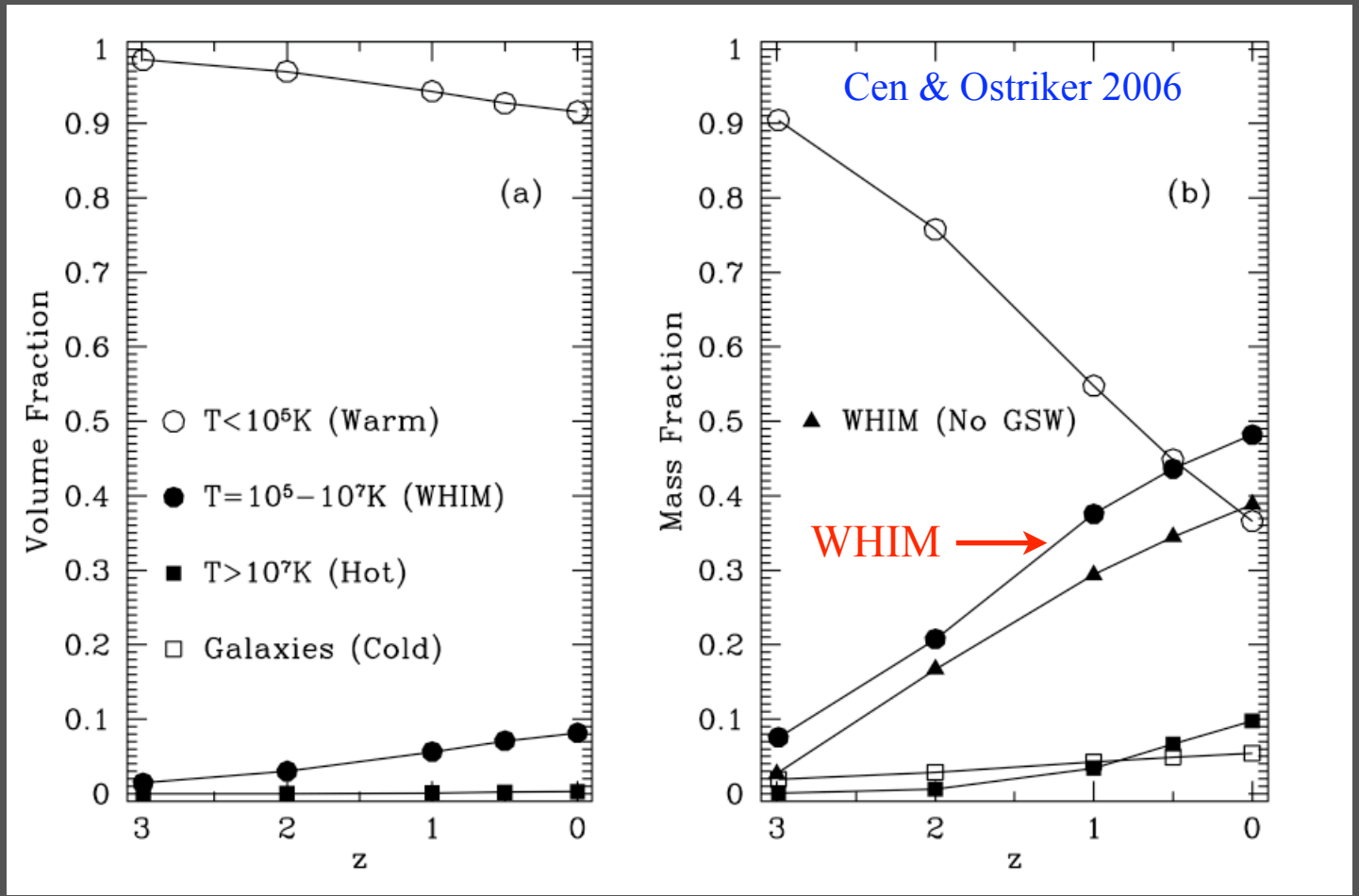
Missing baryon problem and the Warm-hot intergalactic medium (WHIM)

- About a half of the baryons in the local universe is 'missing' (assuming standard model...).
- Most of the remaining baryons are thought to reside in a form of Warm-hot intergalactic medium (WHIM).

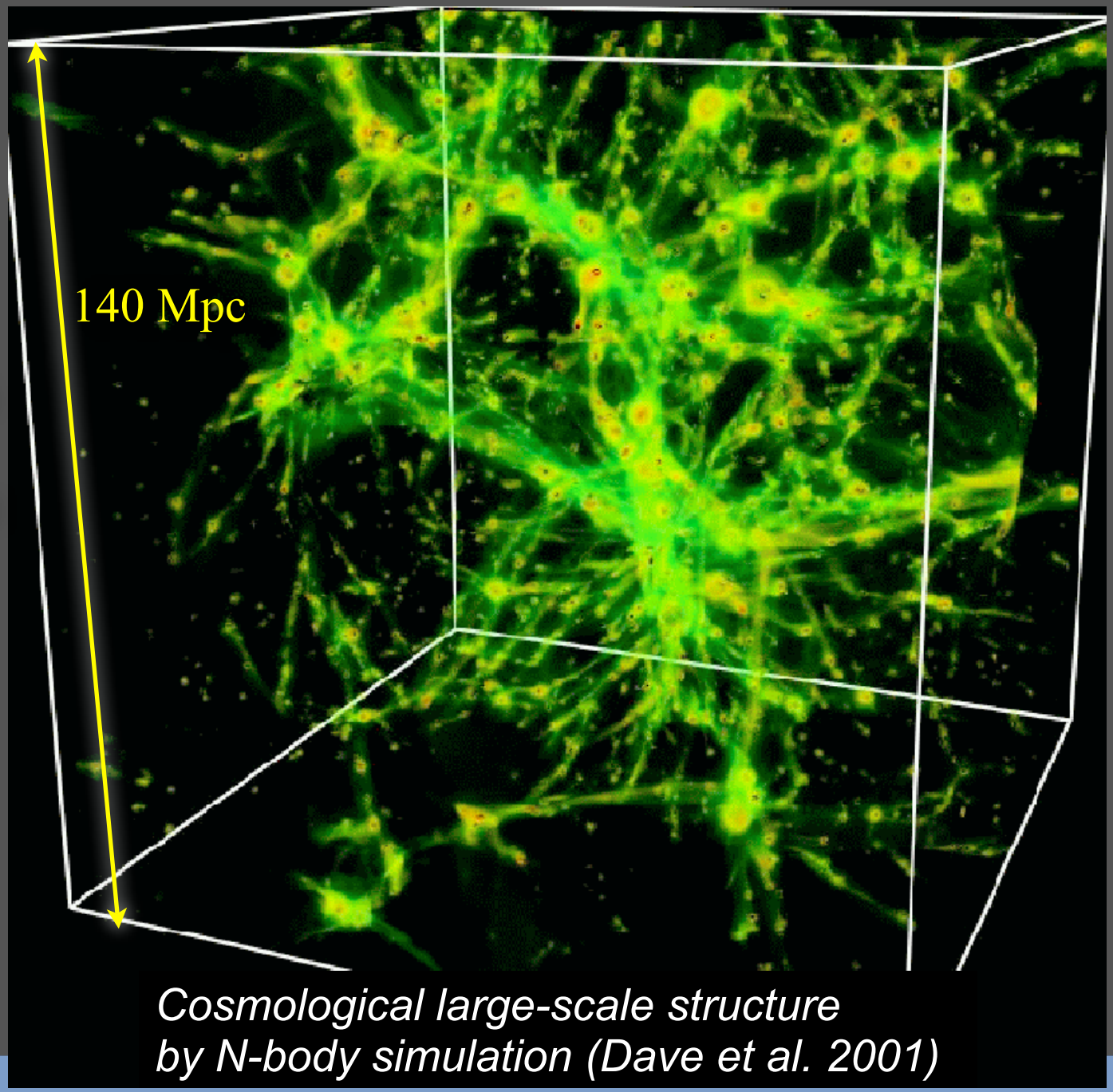
WHIM: IGM with
- $T = 10^5$-10^7 K
- $n_H = 10^{-6}$-10^{-4} cm^{-3} (δ = 10-1000)
  - $\delta = \rho/\rho_{mean}$



WHIM and the large-scale structure

Red: Clusters

Yellow/green: WHIM



Cosmological large-scale structure by N-body simulation (Dave et al. 2001)

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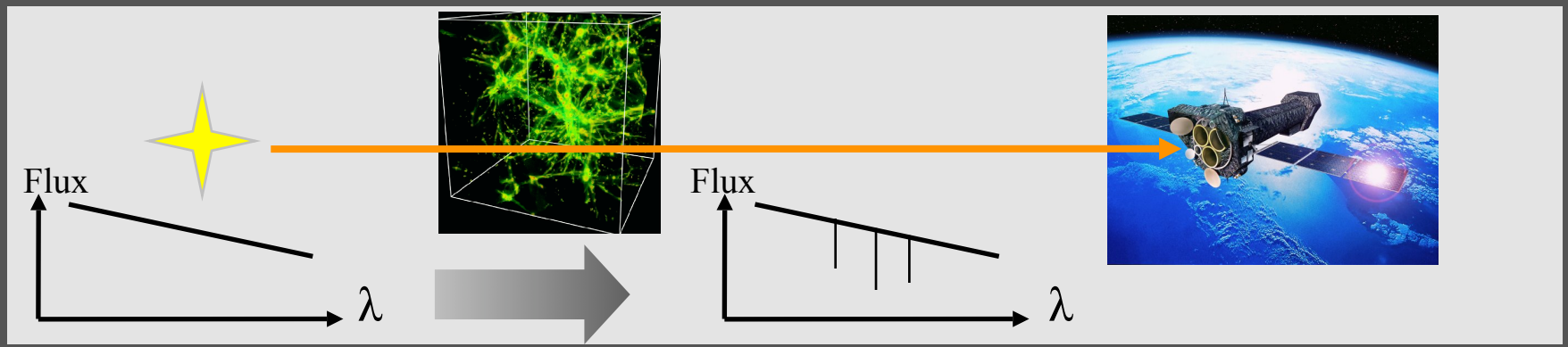
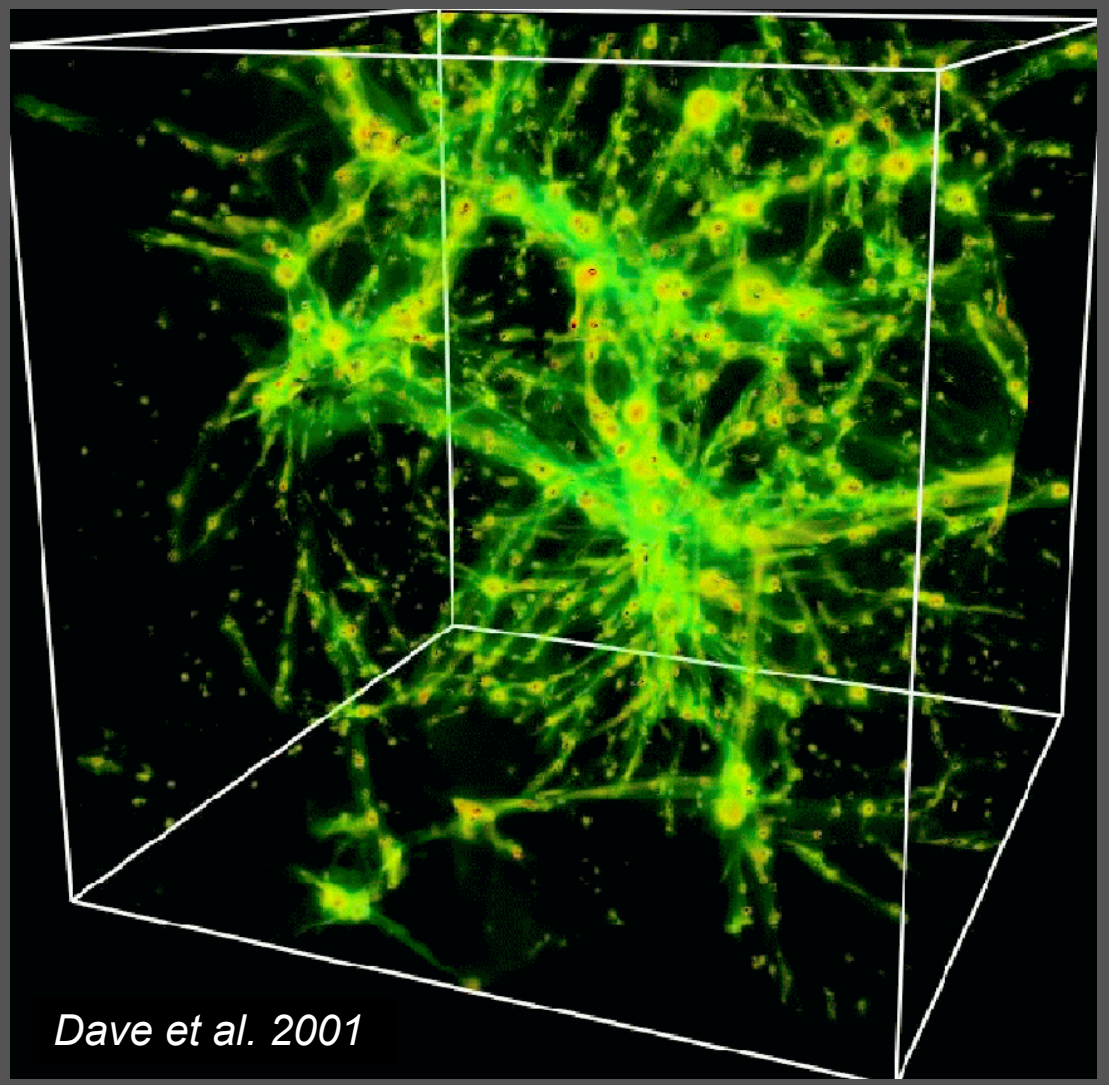
How to detect the WHIM

- Through emission/absorption lines of ionized *metals* in the WHIM.
  - O, Ne, N, C, Fe...
- UV and X-ray spectroscopy is essential.
- Warm (~10^6 K) WHIM have been detected via OVI absorptions in UV.
  - About 10% of the total baryons (e.g., Tripp et al. 2004).
- Most missing baryons seems to be hotter (10^{6-7} K).
  - Should be detected in X-ray; more difficut due to sensitivity limits.
  - Only one controversial detection in absorption (Nicastro et al. 2005).



X-ray Emission study of the WHIM

- Dense region (around clusters) may be observable.
- Energy resolution of the CCDs limits the sensitivity.
- Possible origin of the `soft excess' observed in soft X-ray and UV spectra of clusters (e.g., Lieu et al. 1996).
- Detection of redshifted lines is essential, though difficult.



Dave et al. 2001

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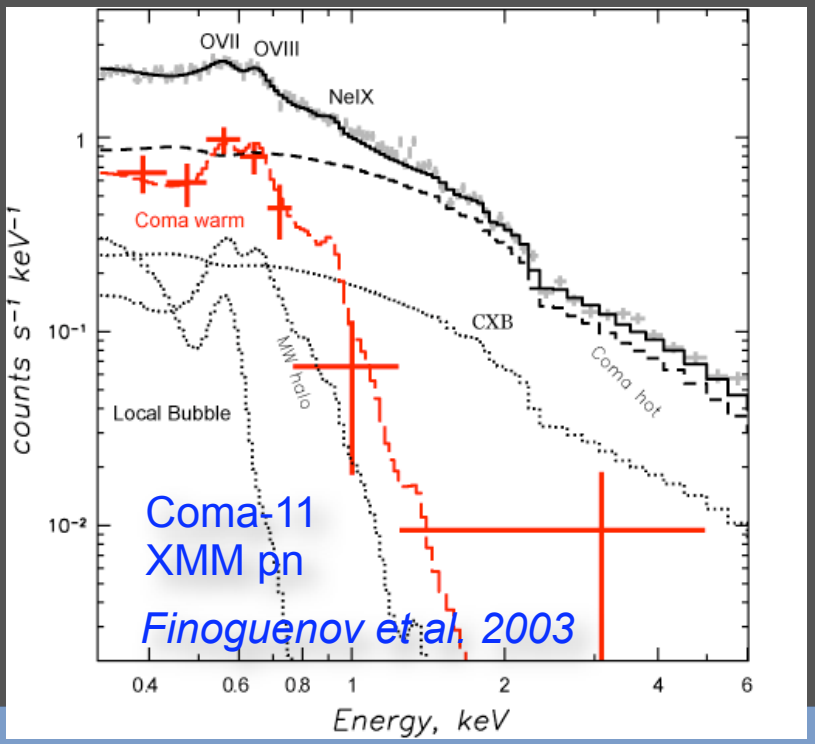
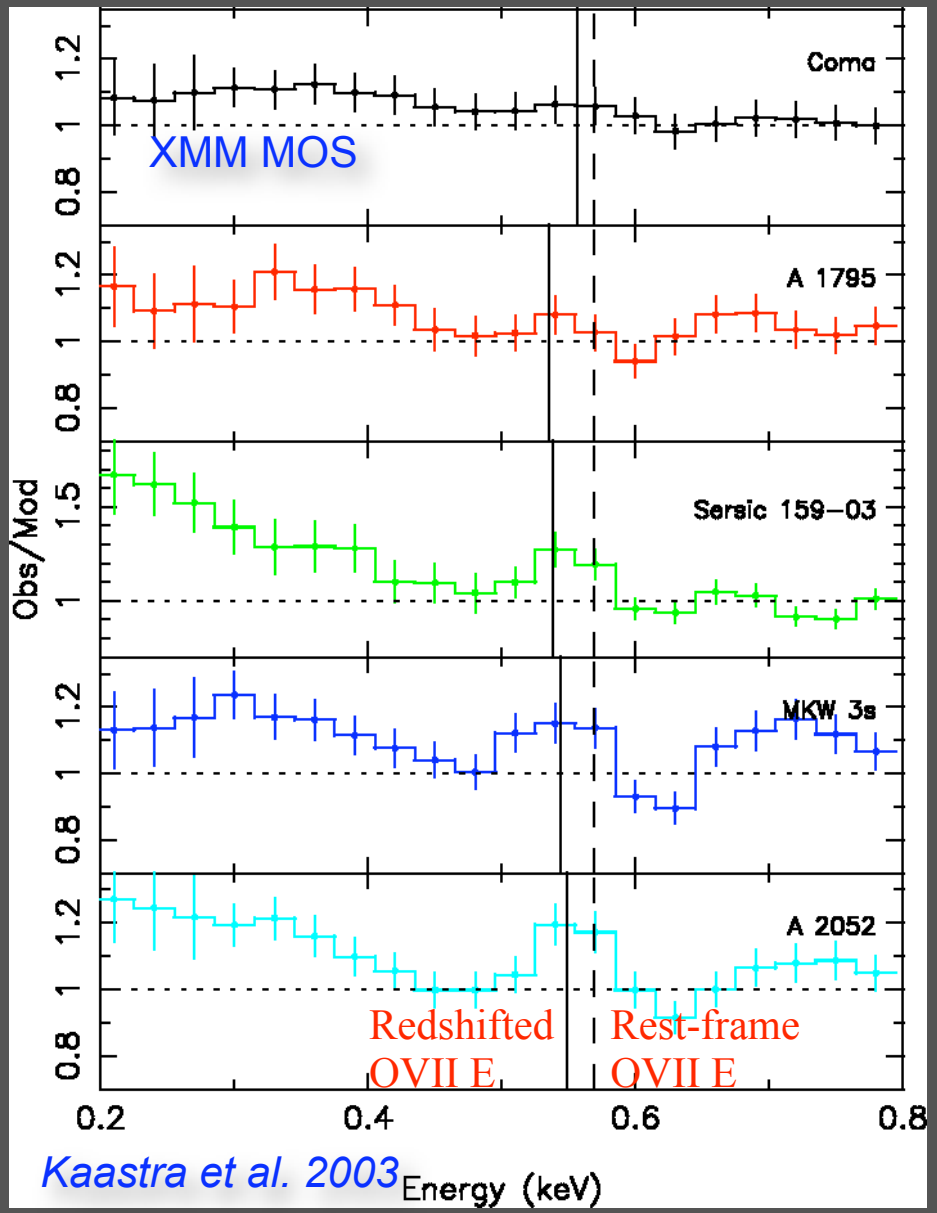
Emission in cluster outskirts

- Soft excess with OVII lines (Kaastra et al. 2003, Finoguenov et al. 2003).
- Counterarguments...
  - Bonamente et al. (2005); Bregman & Lloyd-Davies (2006); Nevalainen et al. (2006)
- Should be careful: foreground Galactic emission, ICM emission, instrument calibration.





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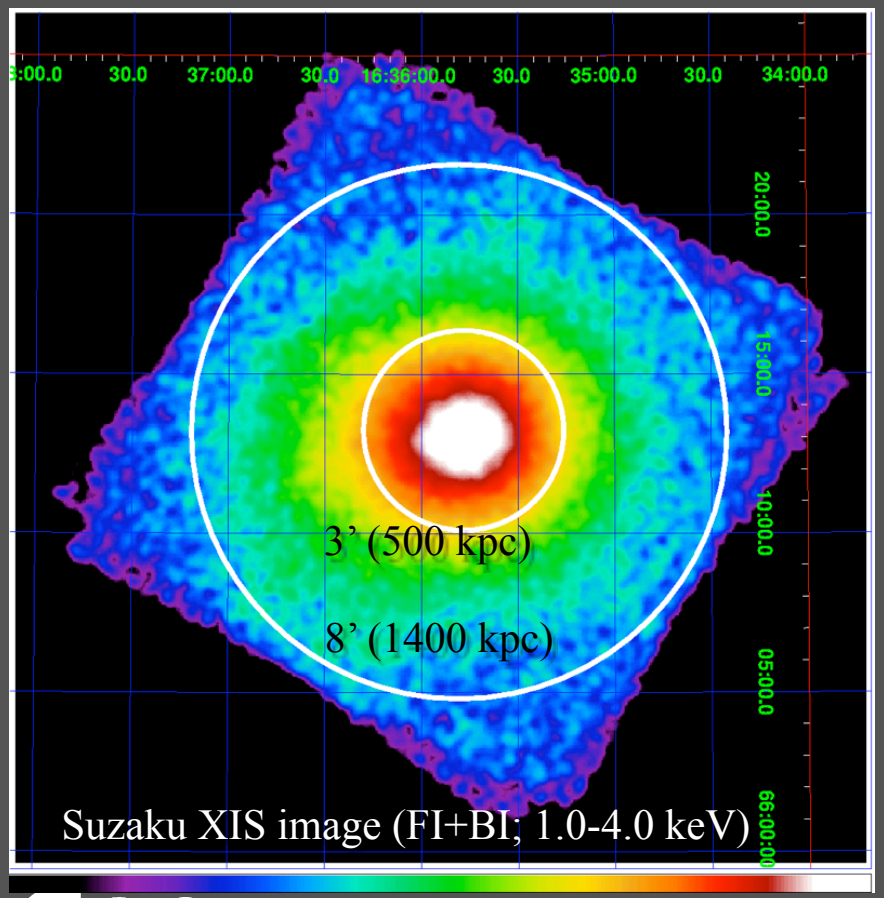
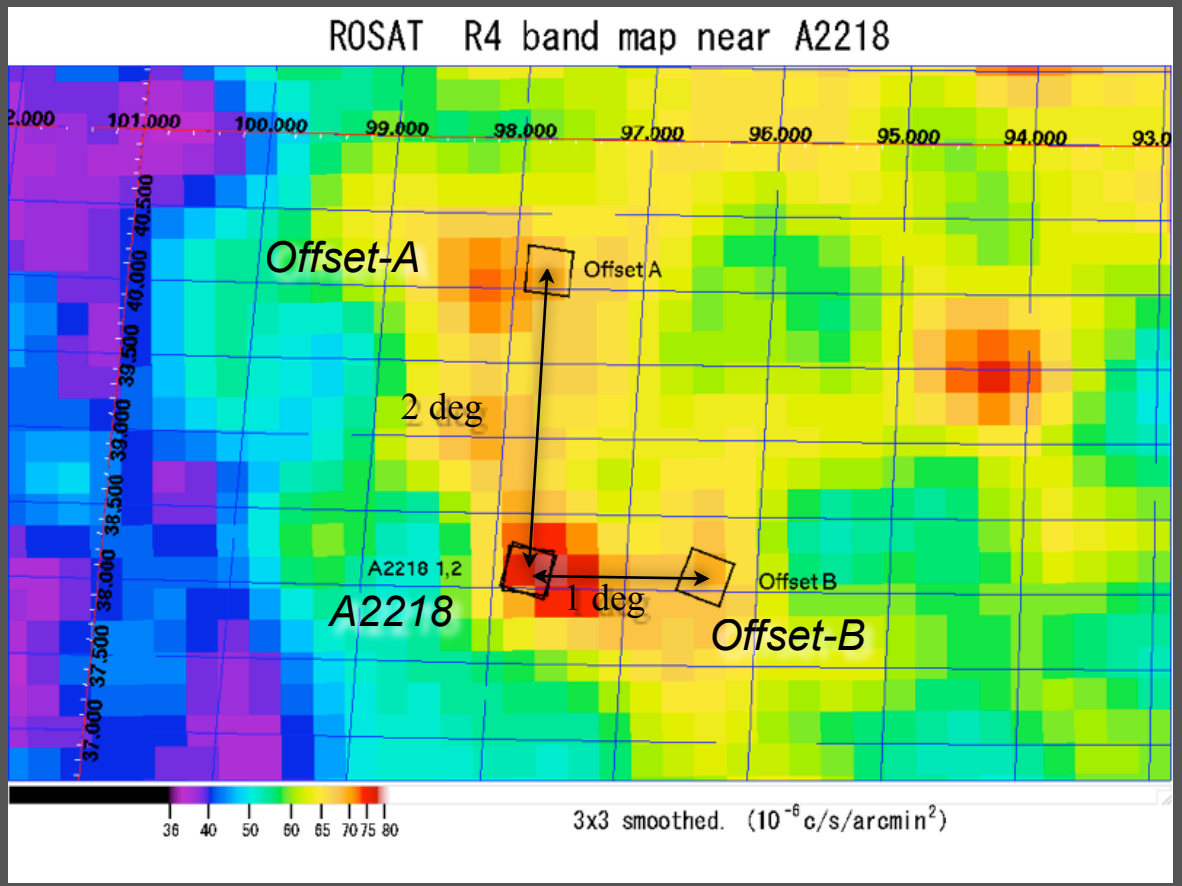
Suzaku observations of A2218

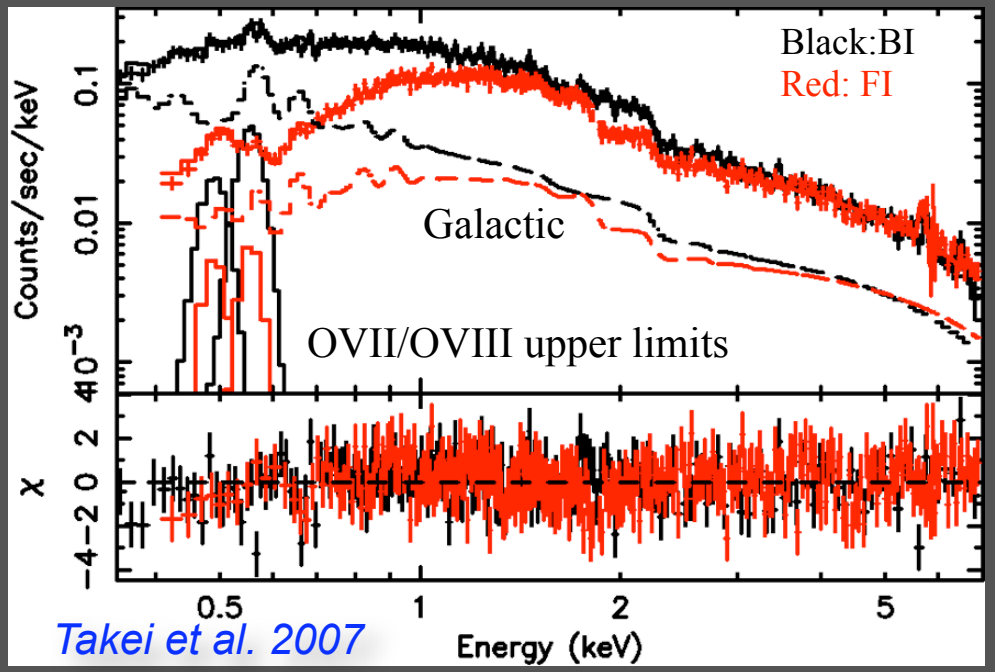
- Study a moderate redshift (0.18) cluster to see redshifted O lines.
- Suzaku: better energy spread function. (Imaging capability is worse).
- On-source/offset observations to estimate Galactic foreground emission.

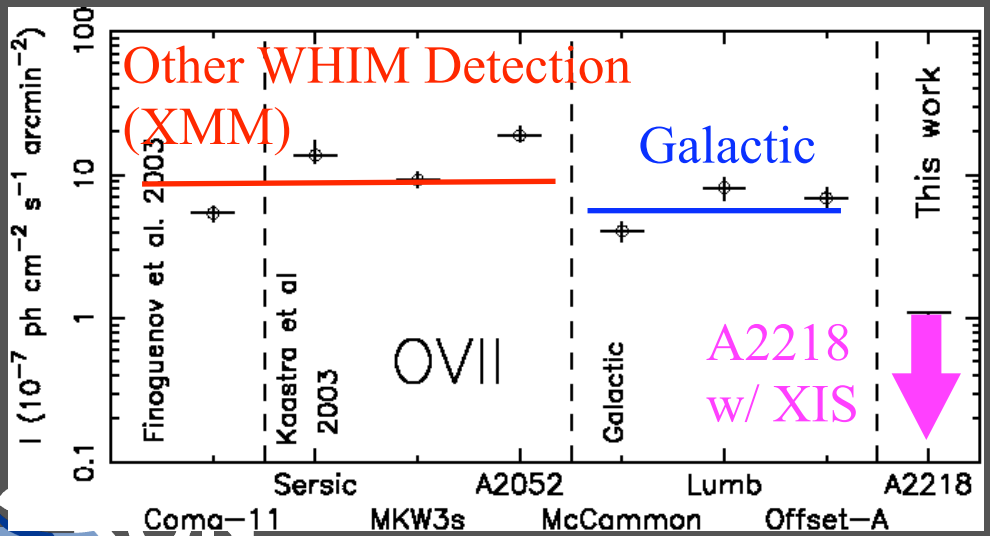


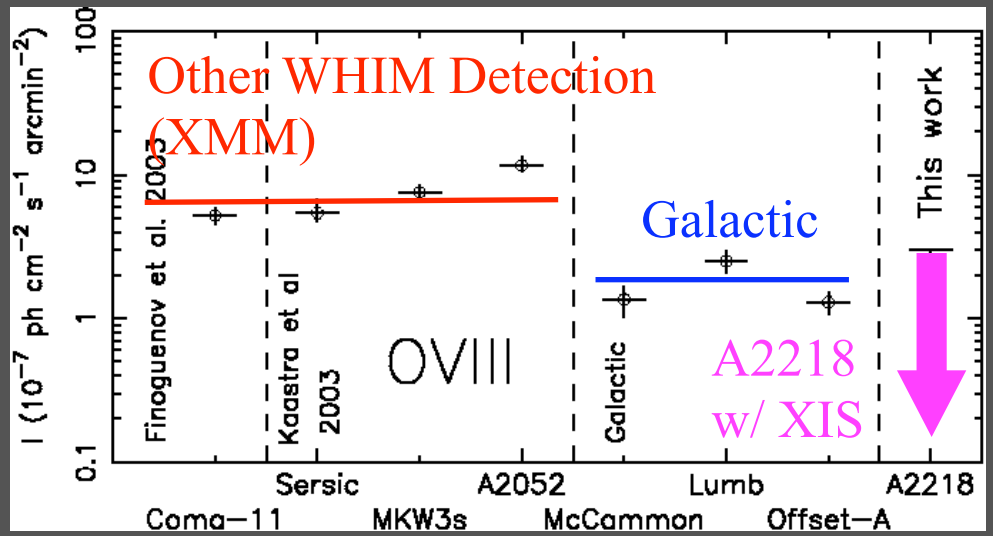


Suzaku observations of A2218 (cont.)

- No redshifted lines are observed
- Tight upper limit on the OVII/ OVIII intensity
  - corresponding to $\delta<270$ (assuming 2×10^6 K)

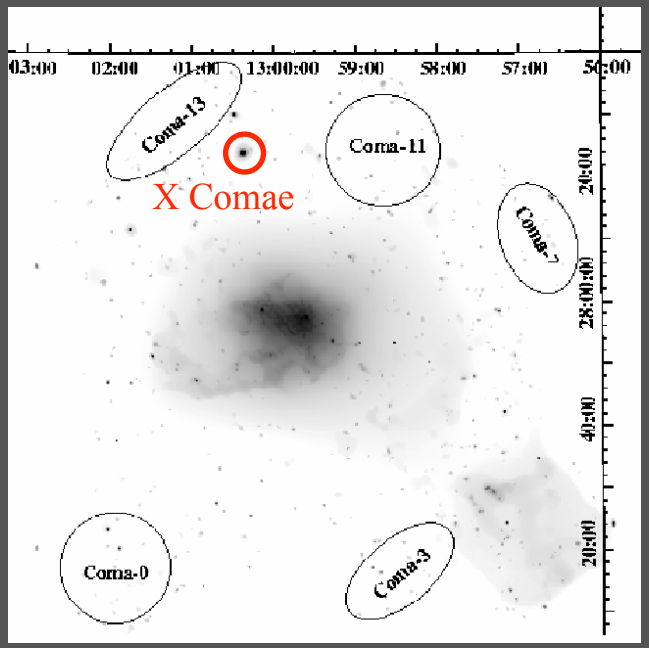


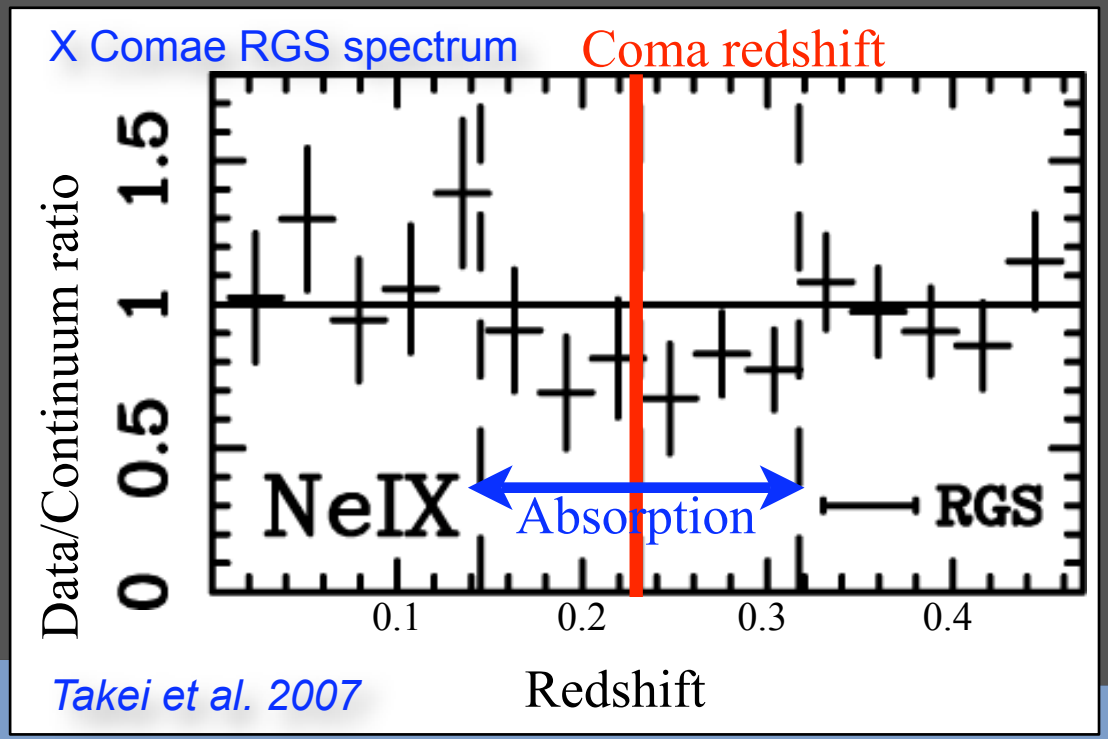


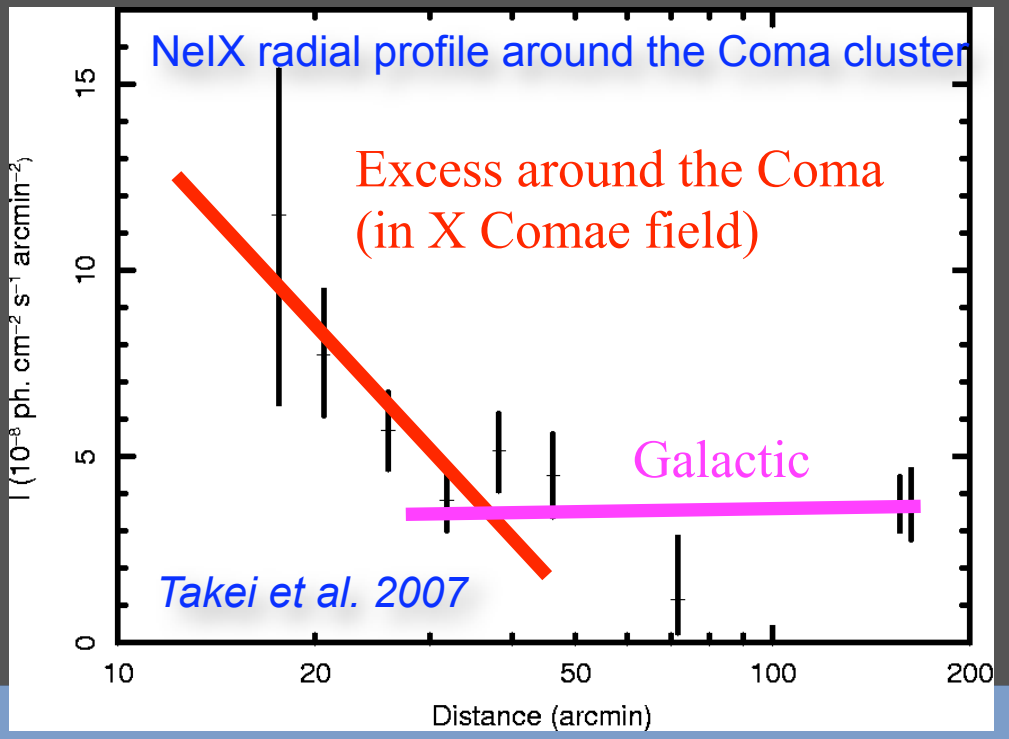


Absorption/emission combination

- Fortunate orientation of a bright QSO (X Comae) behind the Coma cluster (Takei et al. 2007).
- NeIX absorption/emission were detected, though not very significant (~3 sigma).
- Redshift of the absorption line is consistent of the Coma cluster.







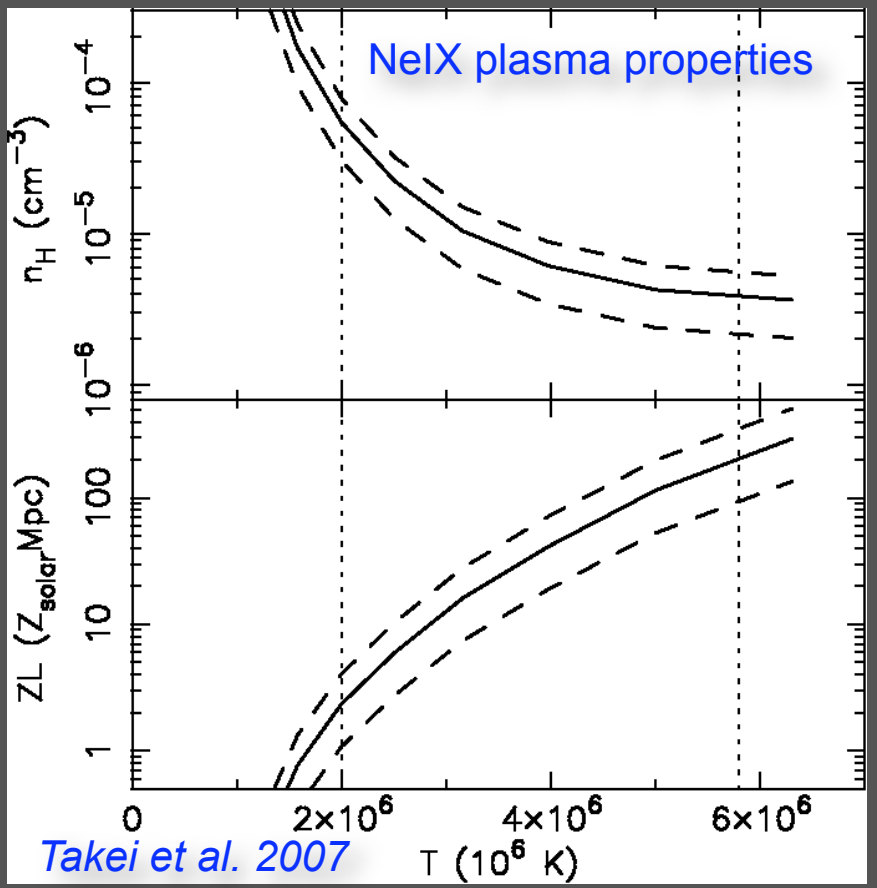
Absorption/emission combination (cont.)

- Constraint on the density and the line-of-sight length of the plasma.
  - with simple assumptions (uniform, isothermal, in CIE).

$$N_{\rm ion} \propto Z n_{\rm H} L \qquad I \propto Z n_{\rm H}^2 L$$

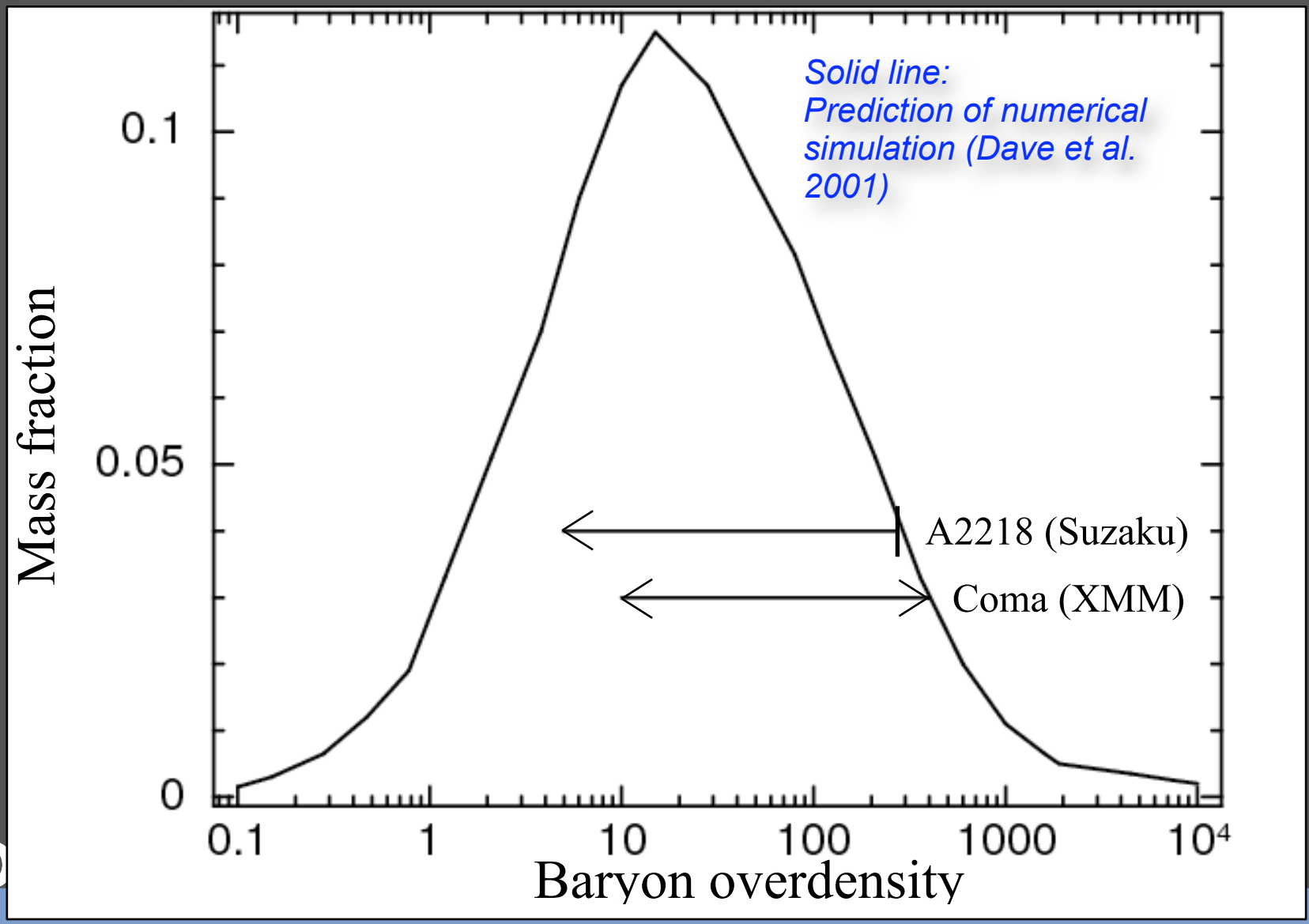
$$\Rightarrow \quad n_{\rm H} \propto \frac{I}{N_{\rm ion}} \qquad ZL \propto \frac{N_{\rm ion}^2}{I}$$

- NeIX plasma extends over the scale of r_{vir} in line-of-sight direction.
  - T = 2-6 x 10^6 K
  - L > r_{vir} = 2.4Mpc
  - n_H > 2x10^{-6} cm^{-3}
- WHIM origin is supported.



Sensitivity of the emission study

- Sensitivity is reaching to detect the dense end of the WHIM.
- Larger sample of cluster vicinities is important to statistical discussion.



(Possible) impact on structure formation

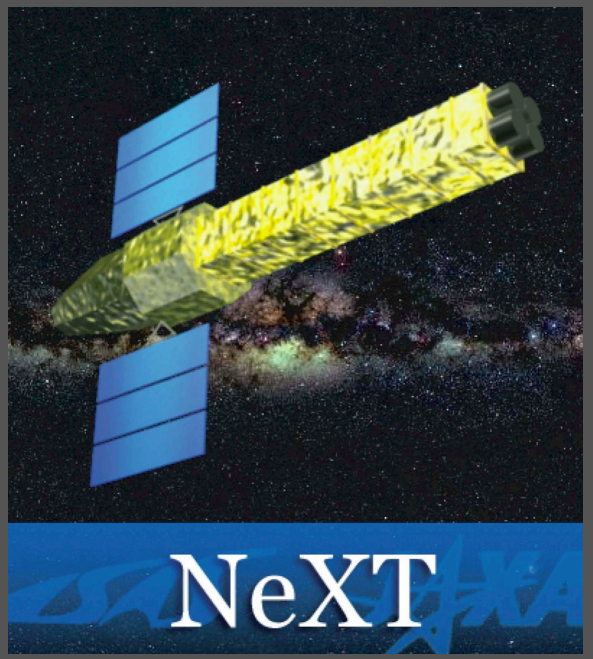
- Direct constraints on metal budget in the universe.
  - Observations are sensitive to *metals* in the WHIM.

- A useful clue to the metal enrichment history of the IGM.
  - One of the key questions of the structure formation/evolution.
    - Not a direct gravitational effect (i.e., difficult to predict).
    - Little knowledge. No concensus so far.

- The study of the WHIM will answer:
  - What is the real structure of the (warm/hot) universe?
  - How and how much metals pollutes IGM?
  - (Possibly) how much missing baryons resides in the WHIM?

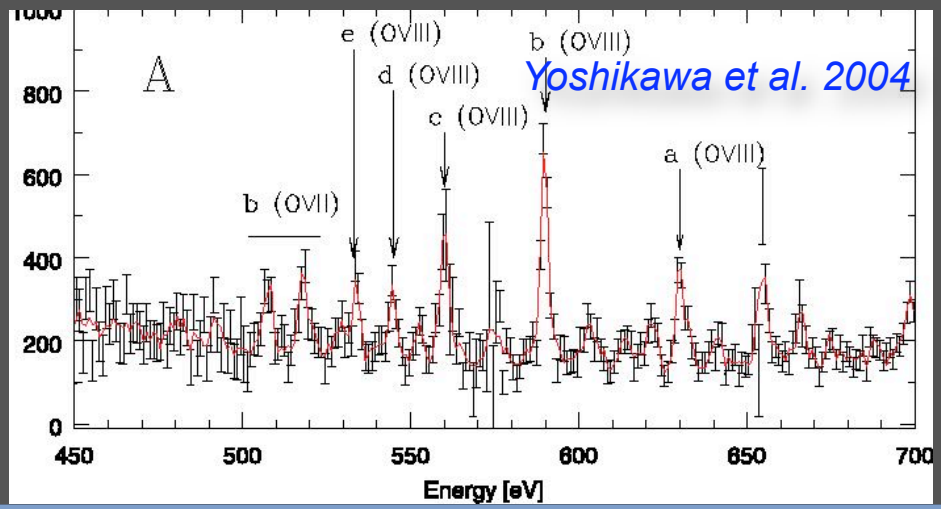
Future study with microcalorimeters

- Microcalorimeters can achieve 2 eV energy resolution (60 times better than CCD).
- Galactic and low-redshift (z~0.01) emission lines can easily be distinguished.
- NeXT: Japanese middle class satellite (2013?).
  - Main science: cluster dynamics.
- EDGE: Europe middle class satellite. Will be proposed to cosmic vision program (2017?).
  - Main science: mapping WHIM emission and study WHIM absorption using GRBs.
  - Large FOV/A_{eff} (1000cm^2/~1deg^2)
  - Fast slew capability (~60s)



EDGE

Explorer of Diffuse Emission and Gamma-ray burst Explosions



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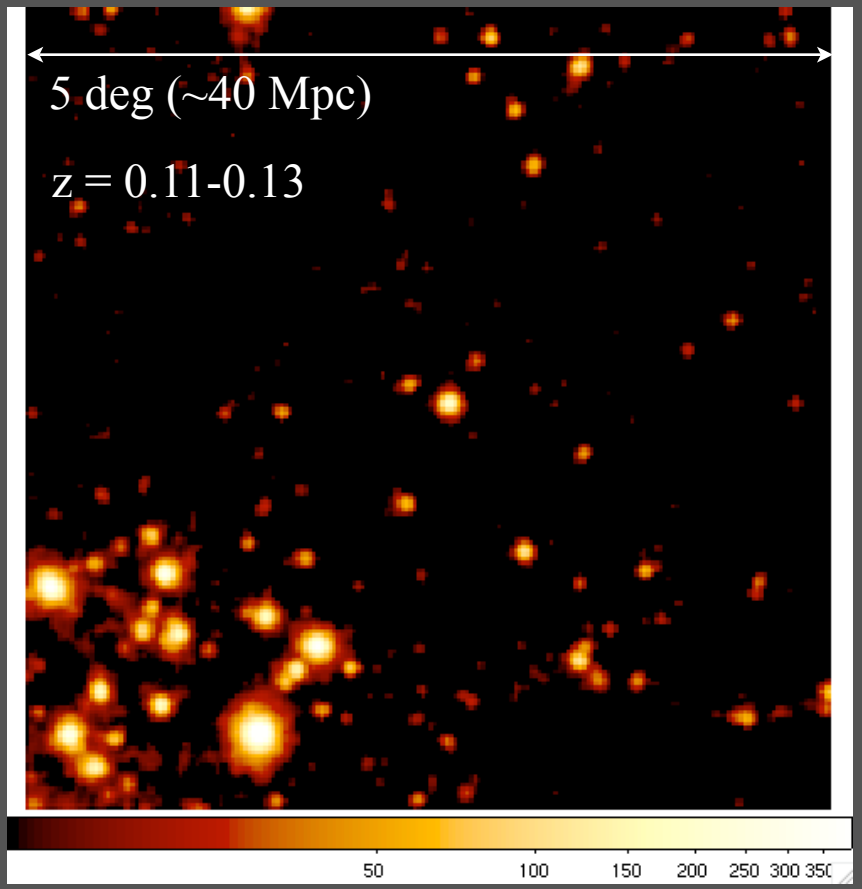
Example of observation with EDGE mission

- WHIM with δ>100 (possibly δ>20) can be detected with redshift resolution of 0.003.



Simulated overdensity map
(Kawahara et al. 2007 in prep)

Simulated OVIII intensity map
1 Ms observation with 1000 cm^2

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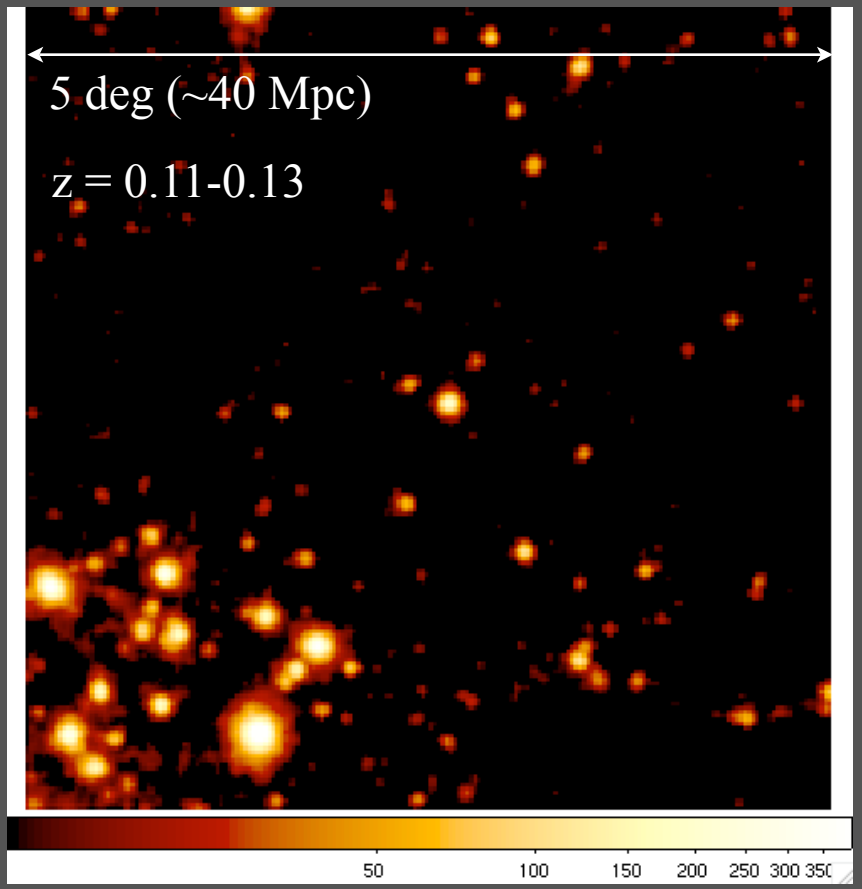

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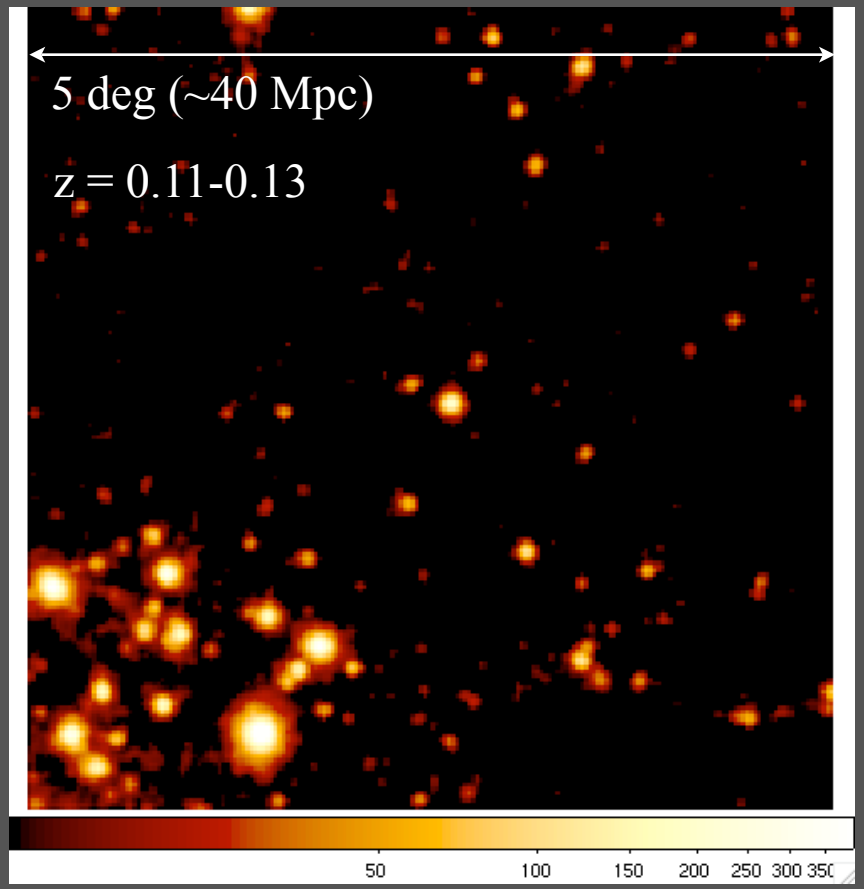

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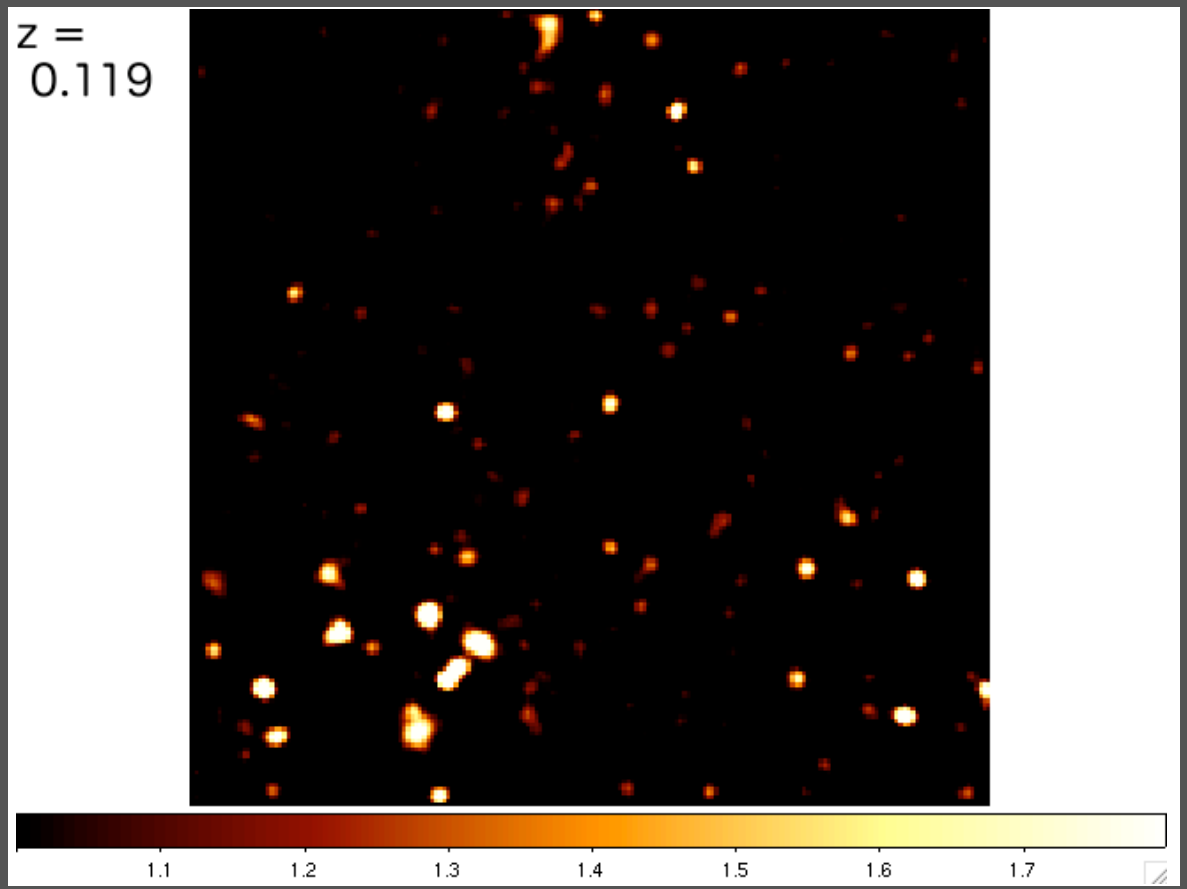

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Summary

- Warm-hot intergalactic medium is a key to understand:
  - where the missing half of baryons resides
  - the structure of the warm/hot universe
  - how and how much metals are diffused in IGM

- Currently available instruments can probe high-density WHIM clouds.
- Larger sample of cluster vicinity observations will enable us to constrain N-body simulations or cosmology models.

- Observations with microcalorimeters are expected to map the WHIM in detail.