Suzaku Observations of the Outskirts of A399/A401

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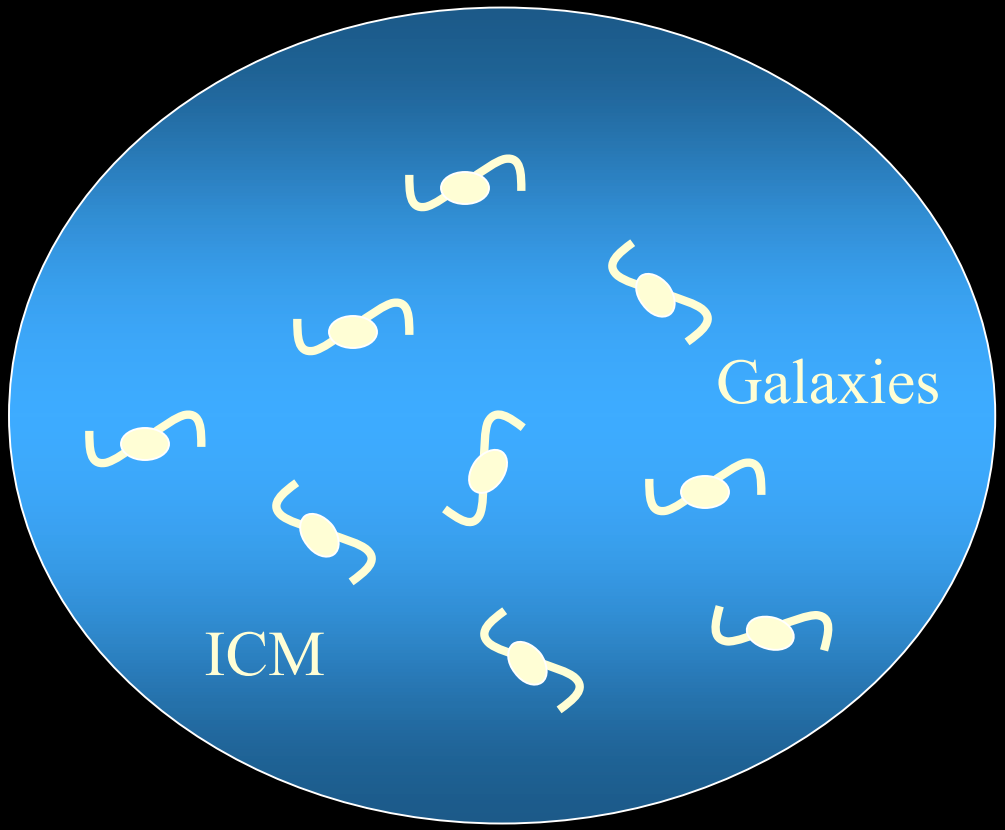
Outline

- Metal Abundance of intracluster medium (ICM) in the outskirts of binary clusters, A399/A401.
  - Metal transfer from galaxies to the ICM
- Warm-hot intergalactic medium (WHIM)
  - Missing baryon around clusters
- Summary

Metal Transfer

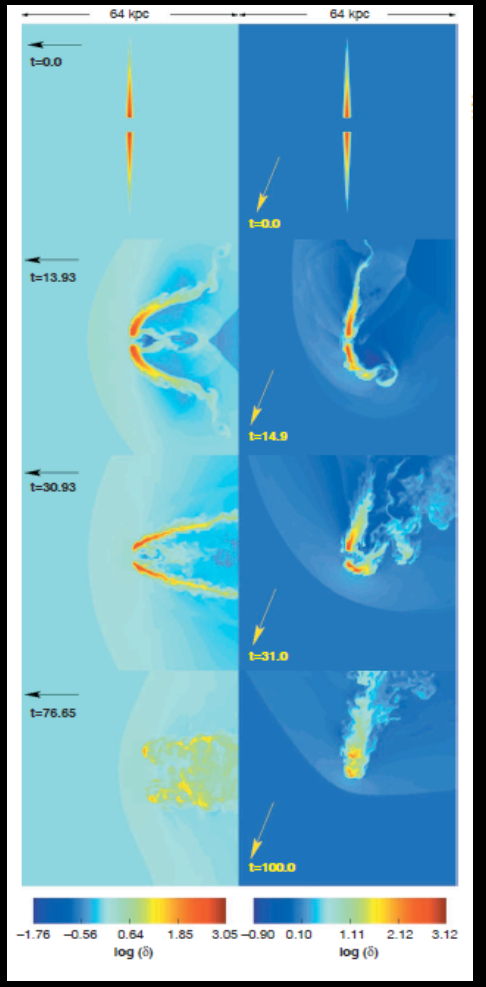
- Metals in the ICM come from galaxies
- What transfers metals from galaxies to the surrounding ICM?
  - Ram-pressure stripping
  - Galactic winds
- Which is the main mechanism?



Ram-pressure stripping

- Galaxies in a cluster are moving in the ICM (~1000 km s^{-1})
- Metal-enriched gas in the galaxies are stripped by the ram-pressure from the ICM
- Effective in the central region of a cluster
  - Large velocities of galaxies
  - Large density of the ICM

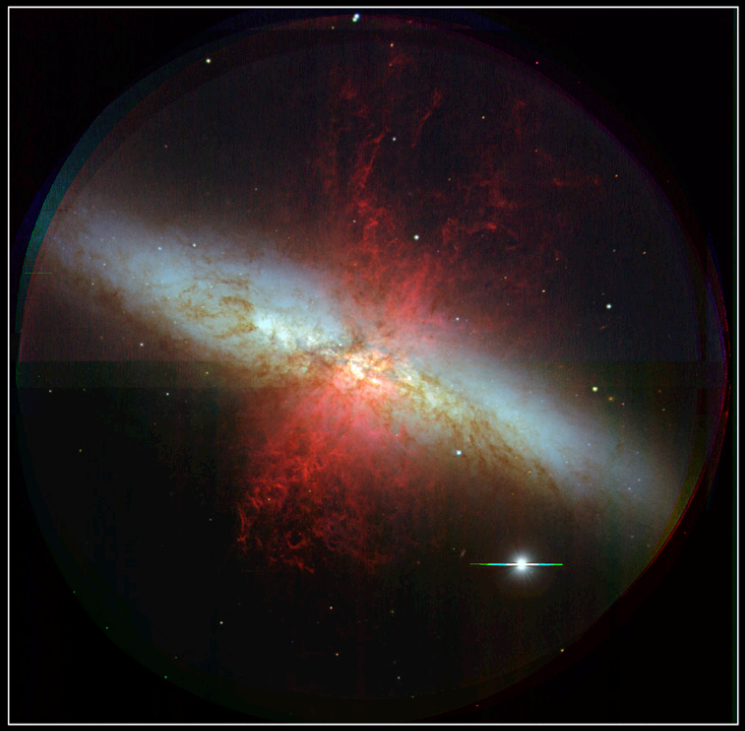
    → Large ram-pressure



Quilis et al. (2000)

Galactic winds

- Winds from galaxies
  - Supernova explosions followed by starburst cause winds of metal-enriched gas from a galaxy
- Effective in the outskirt of a cluster or in an immature cluster
  - External pressure from the ICM, which prevents the development of the winds, is small



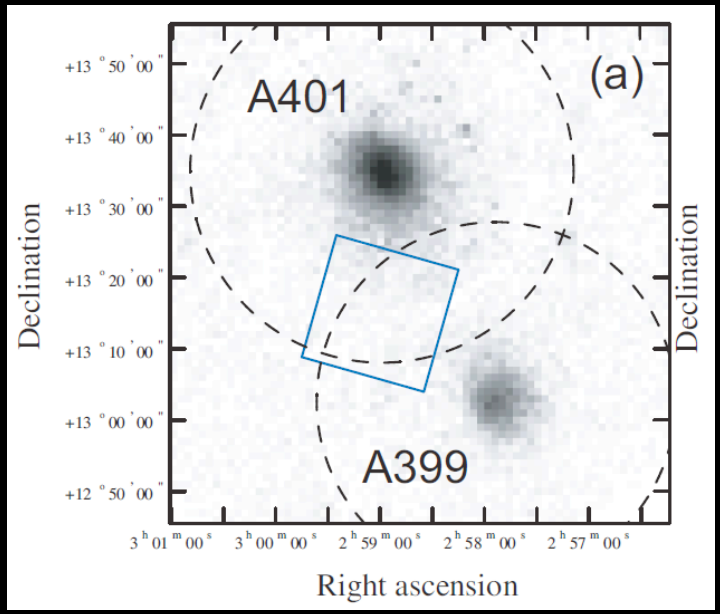
Outskirts of clusters

- Metal abundance of the ICM in the outskirts of clusters tells us which mechanism is important for metal transfer from galaxies to the ICM
  - Ram-pressure stripping
    - Almost no metals in the outskirts
  - Galactic winds
    - There should be some amount of metals in the outskirts

A399/A401

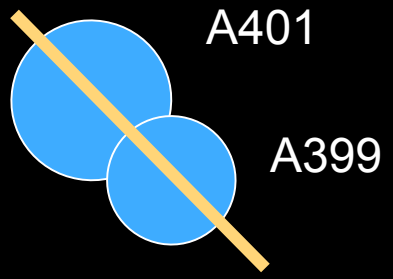
- Binary clusters with a projection distance of ~3 Mpc
  - Redshift
    - 0.0718 (A399)
    - 0.0737 (A401)
  - Temperature in their central regions
    - 7.23 keV (A399)
    - 8.47 keV (A401)

    (Sakelliou & Ponman 2004)
    - Massive clusters
  - In the early stage of a cluster merger

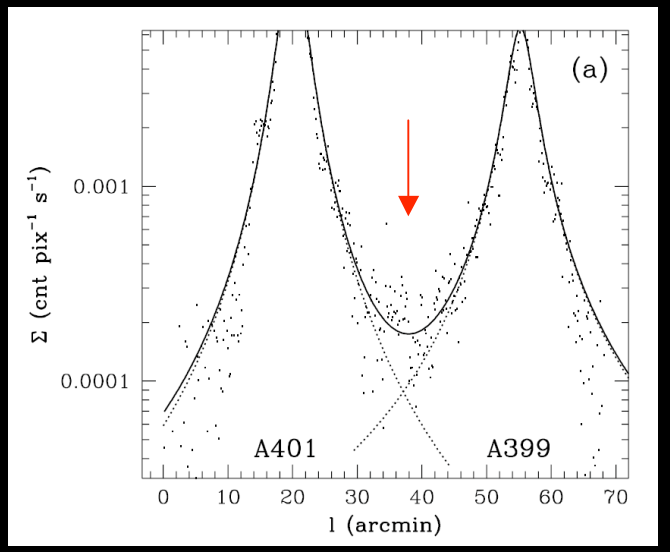


ROSAT X-ray image. Dashed lines are the virial radii. Blue square is the Suzaku field

Link region



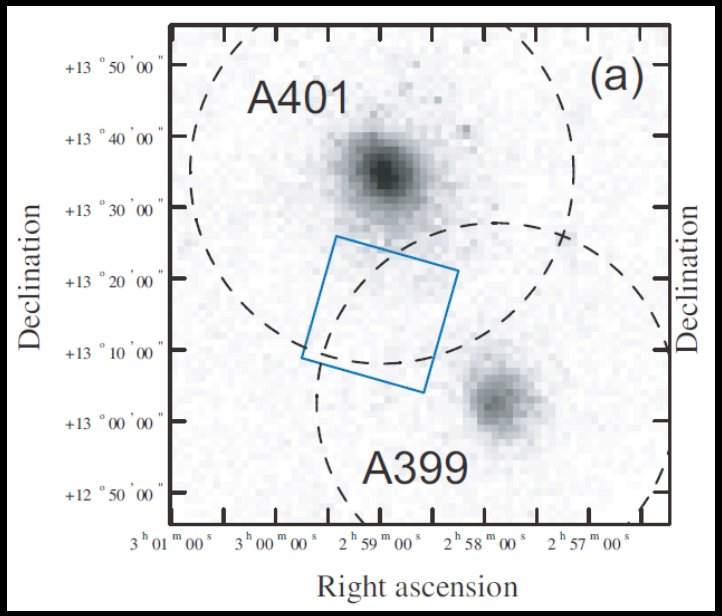
- We observed the link region between the two clusters
- The region is brighter than that is expected from simple superposition of the two clusters
  - The clusters are interacting
  - Compressed filament gas?
    - Some of the gas was in a cosmological filament that had connected the two clusters
  - In spite of the distance from the cluster centers (τ1Mpc) , the region is bright
    - Suitable to study the nature of the ICM in the outermost region of clusters



Surface brightness profiles along a 1-arcmin wide stripe that intersects the two cluster centers (Sakelliou & Ponman 2004)

Suzaku Observation

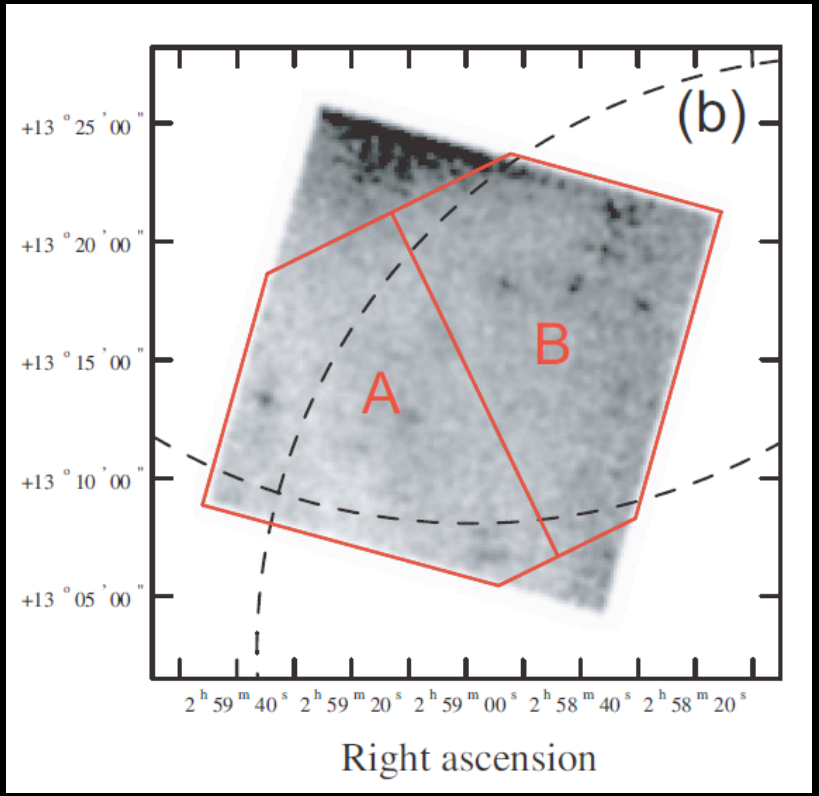
- Suzaku XIS
  - High sensitivity
  - Low background
- We observed a region where the virial radii of the two clusters ($r = r_{vir}$) cross each other
  - With Chandra and XMM-Newton, $r < 0.5r_{vir}$ is the limit for the observation of metal abundance of the ICM



ROSAT X-ray image. Dashed lines are the virial radii. Blue square is the Suzaku field

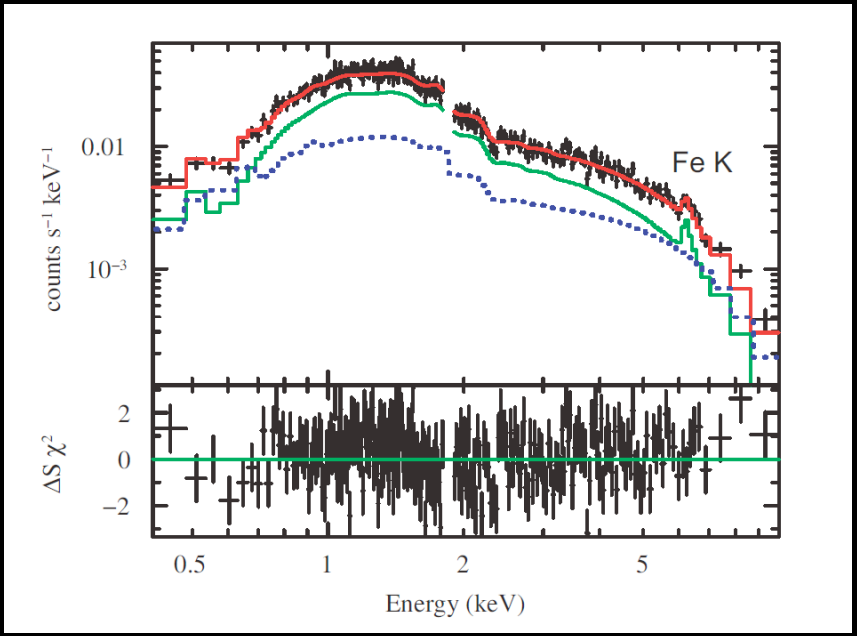
XIS Image

- No prominent objects
  - No group of galaxies that could eject metals
  - For regions A and B, we analyzed the spectra



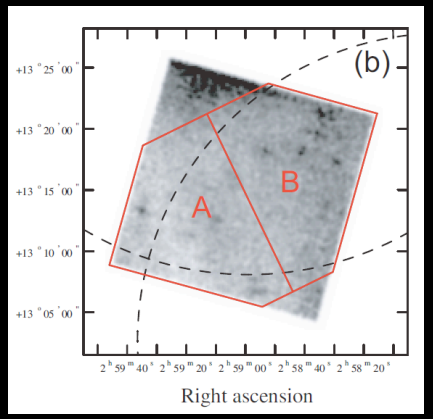
Spectrum

- Spectrum for region A
  - Summed spectrum of the three FI chips
    - Exposure time is 150 ks
  - Fe K is clearly seen

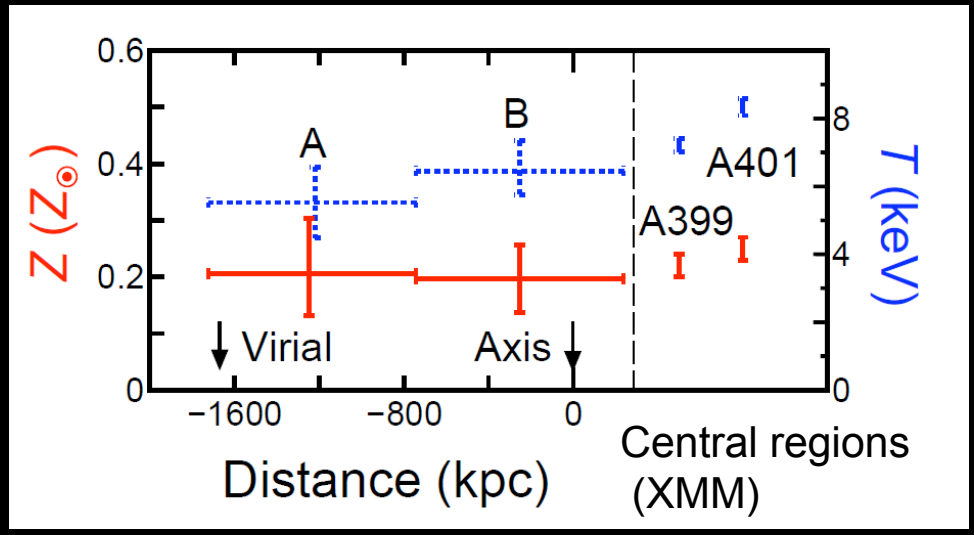


Cross： observations
Red line： fitting results
Green line： ICM
Blue line： other components (Galactic, CXB)

Results



Blue: temperature
Red: abundance

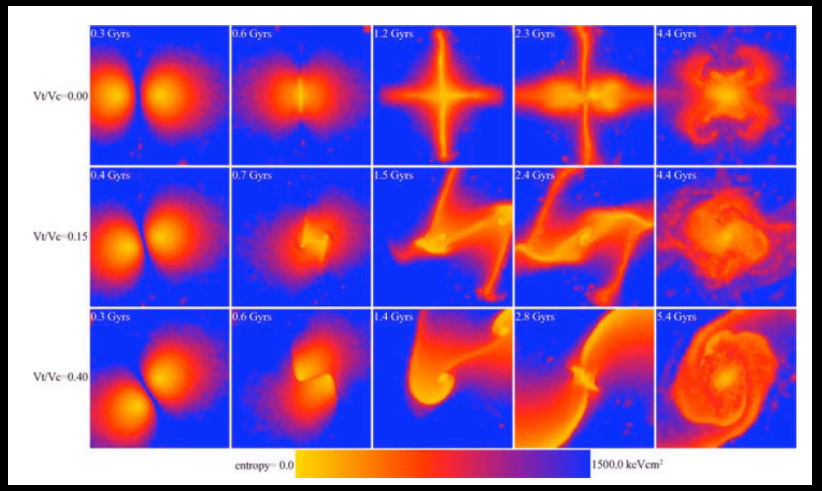


- Temperature and metal abundance
- Abundance in this region (close to the virial radii) is not much different from that at tha cluster centers
  - $Z \sim 0.2\ Z_{\odot}$

Cluster Merger

- Are A399/A401 clusters that have passed each other?
  - The ICM is mixed up and the metal abundance becomes uniform?
  - No!
- Simulations
  - At a collision, dark matter and galaxies can pass the other cluster because they are collision-less
  - The ICM cannot
    - The ICM is stripped from dark matter and galaxies
    - This not the case for A399/A401

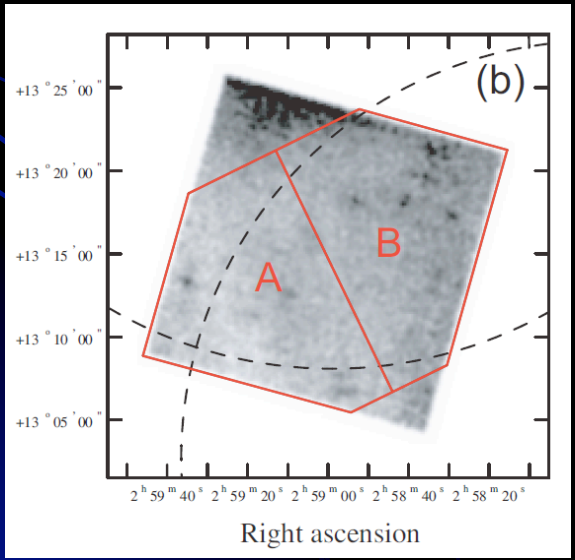
Simulation of a cluster merger (gas distribution)

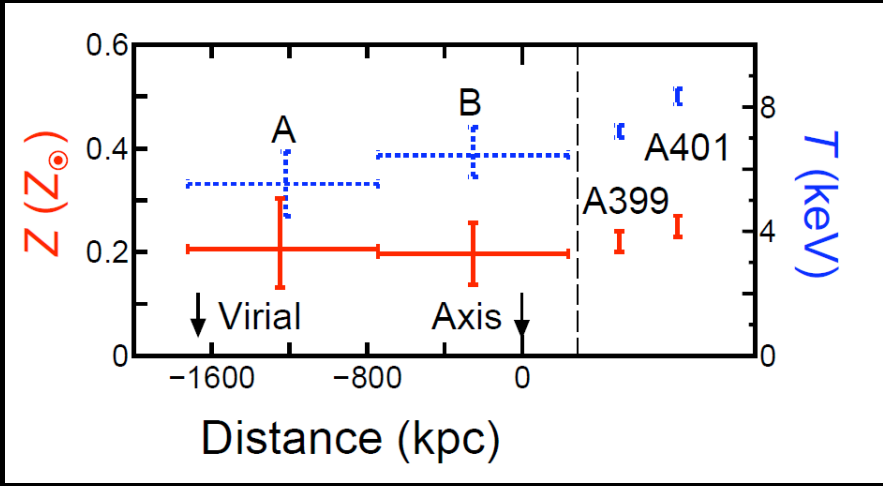


Poole et al. (2006)

Object that Eject Metals?

- Suzaku image
  - No objects that can eject large amount of metals
- Abundance is almost the same between region A and B
  - Abundance is uniform at least on a scale of ~1 Mpc
    - High Abundance is not a local phenomenon





What do we know from the high metal abundance

- Ram-pressure stripping (RPS) is not the main mechanism of metal transfer from galaxies to the ICM
  - RPS is not effective in the outskirts of a cluster
    - Condition of RPS

$$\begin{aligned}
&\rho_{\rm ICM} v_{\rm rel}^2 \\
&> 2\pi G \Sigma_\star \Sigma_{\rm H\,I} \\
&= v_{\rm rot}^2 R^{-1} \Sigma_{\rm H\,I} \\
&= 2.1 \times 10^{-11} {\rm dyn\,cm^{-2}} \left(\frac{v_{\rm rot}}{220\ {\rm km\ s^{-1}}} \right)^2 \\
&\quad \times \left(\frac{R}{10\ {\rm kpc}} \right)^{-1} \left(\frac{\Sigma_{\rm H\,I}}{8 \times 10^{20} m_{\rm H}\ {\rm cm^{-2}}} \right)
\end{aligned}$$

ρ_{ICM} : ICM
v_{rel} : galaxy velocity
v_{rot} : galaxy rotation velocity
R : radius of a galaxy
Σ_{HI} : column density of galaxy gas
(Fujita & Nagashima 1999)

- In the outskirt region, the ICM density is ~ 3.4×10^{-4}cm^{-3}
  - RPS requires v_{rel} > 2000 km s^{-1} and it is unlikely to happen in the region far from the cluster centers

Galactic winds?

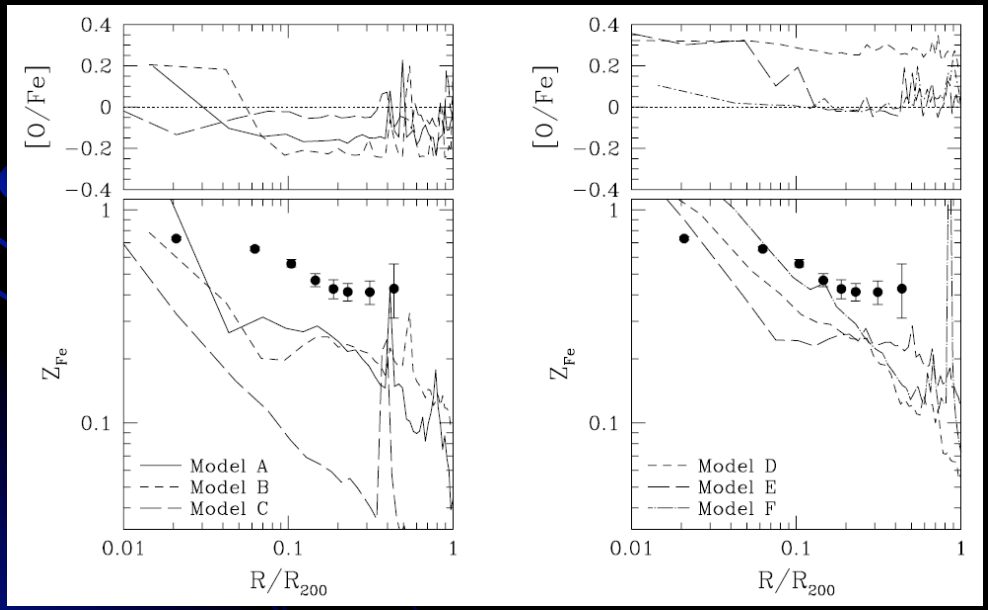
- At least they did not happen recently (z~0) inside the clusters
  - Energy of a galactic wind: $E_w \sim 10^{60}$ erg
  - The distance to which a wind can reach against the pressure from the surrounding ICM: d_w
    - $E_w \sim (4\pi/3)\, P\, d_w^3$
    - P : ICM pressure, $P = n\, k\, T$
  - For typical values of n and T inside a typical cluster

$$d_w \sim 86 \left(\frac{n}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1/3} \left(\frac{T}{8\,\mathrm{keV}}\right)^{-1/3} \left(\frac{E_w}{10^{60}\,\mathrm{erg}}\right)^{1/3} \mathrm{kpc}$$

    - Much smaller than the cluster size (~2 Mpc)
    - It is difficult for galaxies concentrated at the cluster centers (< 0.5 r_{vir}) at present to blow metals off to close to the virial radii

Theoretical Predictions

- Abundance distributions simulated with standard parameters for star formation
  - Steep abundance gradient



Tornatore et al. (2004)

Galactic Superwinds?

- Metals cannot reach the outskirts of a cluster through galactic winds after the cluster has grown up because the surrounding pressure is large
  - Winds must blow before the clusters grow (z ~ 2) and must be strong enough
    - Supernova explosions alone may not be enough?
    - Contribution of AGN activities?
      - So-called “superwinds”

Simulations for WHIM

- Yoshikawa et al. (2001)

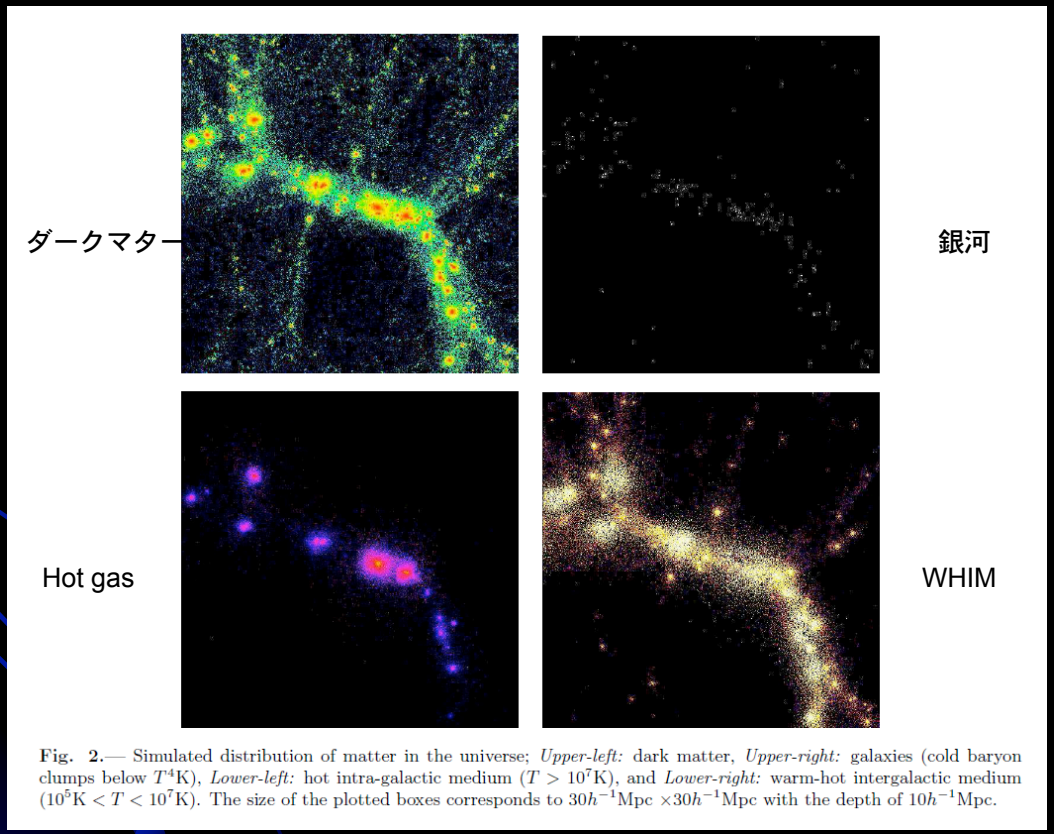
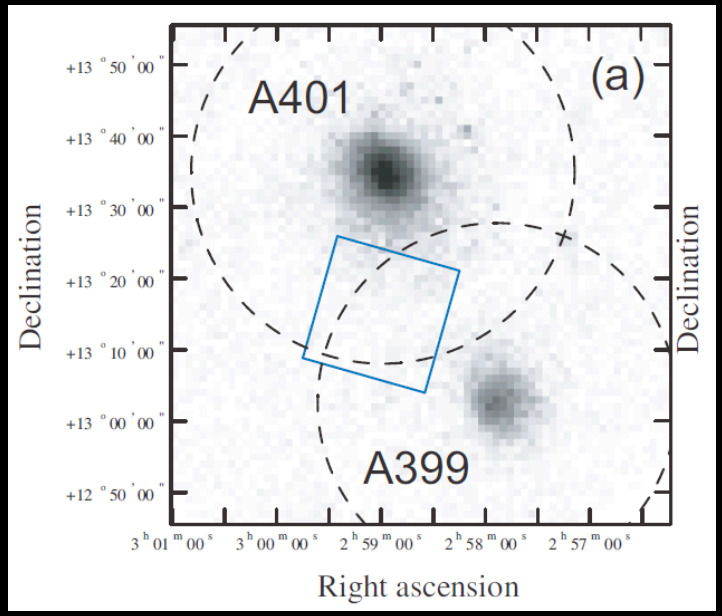


Fig. 2.— Simulated distribution of matter in the universe; *Upper-left:* dark matter, *Upper-right:* galaxies (cold baryon clumps below T^4K), *Lower-left:* hot intra-galactic medium ($T > 10^7$K), and *Lower-right:* warm-hot intergalactic medium ($10^5\text{K} < T < 10^7\text{K}$). The size of the plotted boxes corresponds to $30h^{-1}$Mpc $\times 30h^{-1}$Mpc with the depth of $10h^{-1}$Mpc.

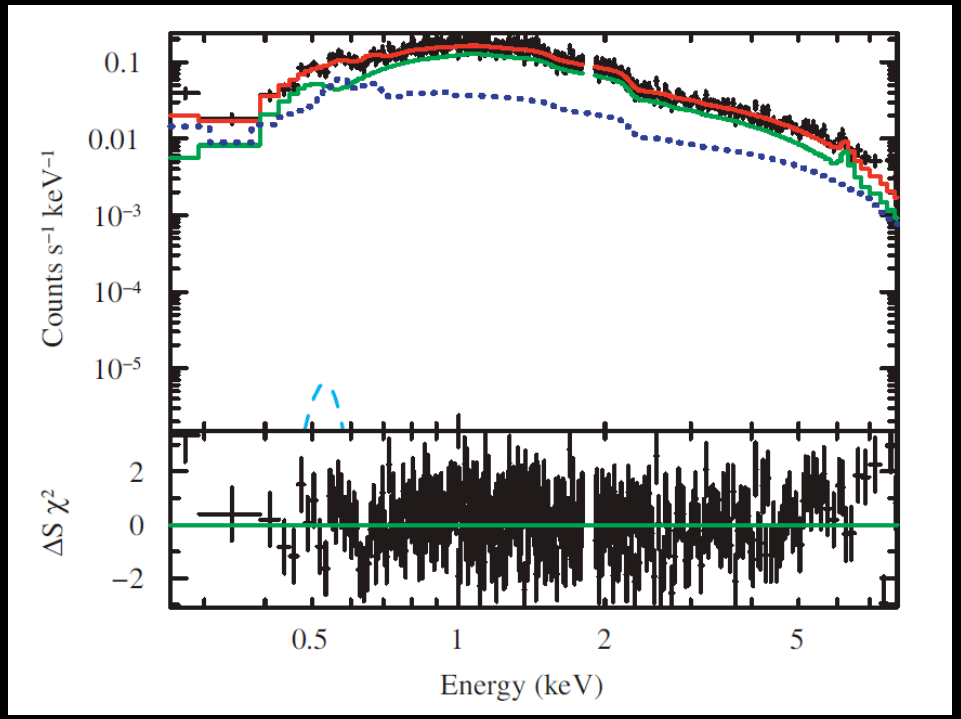
Observations of WHIM

- The region we observed was probably a cosmological filament that had connected the two clusters
  - WHIM may remain around the region
  - WHIM could be observed in the line of sight



Spectrum

- Spectrum obtained by XIS BI
  - At the redshift of the clusters, O VII line should be observed *at E* = 0.53 keV
    - No line is seen



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(Galactic, CXB)

Upper limit of WHIM

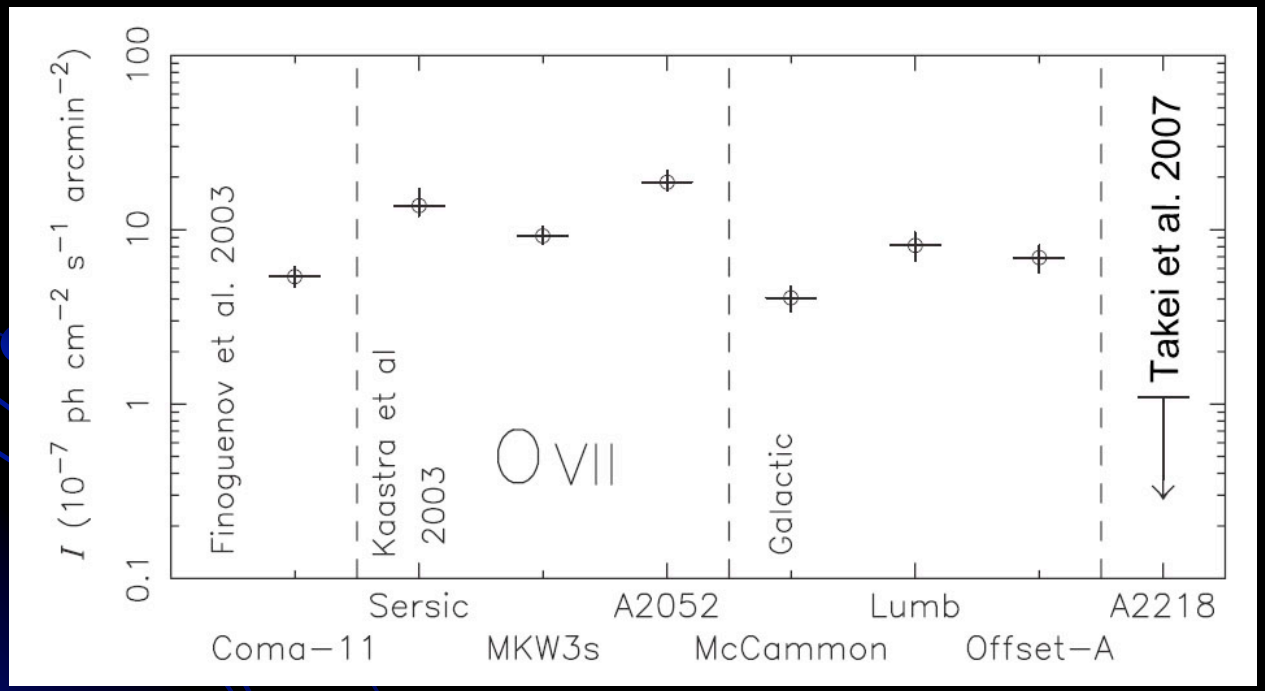
- Assuming $T = 2 \times 10^6$ K

$$n_{\rm H} = 9.2 \times 10^{-5} {\rm cm}^{-3} \left(\frac{I}{1 \times 10^{-7} {\rm ph\,cm^{-2}\,s^{-1}}} \right)^{1/2} \left(\frac{Z}{0.1\,Z_\odot} \right)^{-1/2} \left(\frac{L}{1\,{\rm Mpc}} \right)^{-1/2}$$

  - I : line intensity, Z: abundance, L: depth in the line of sight
- Observation
  - $I < 8.0 \times 10^{-8}$ photons cm^{-2} arcmin^{-2}
  - $n_{\rm H} < 4.1 \times 10^{-5}$cm^{-3} (for $Z = 0.2\,Z_\odot$, $L = 2$ Mpc)

Results

- For O VII line from WHIM
  - We obtained a strict upper limit



Takei et al. (2007)

Suzaku

Summary

- We observed the link region between A399 and A401 with Suzaku
  - The metal abundance of the ICM is not much different from that in their central regions ($Z \sim 0.2\ Z_{\odot}$)
    - Ram-pressure stripping is not the main mechanism of metal transfer from galaxies to the ICM
    - Strong galactic winds (superwinds) might have blown at high-redshift
      - The abundance may reflect that of gas in a cosmological filament
  - We could not detect WHIM in the link region
    - However, we obtained a strict upper limit