衝突銀河団における非平衡電離過程と二温度構造

Non-equilibrium Ionization and Two-Temperature Structure in Merging Galaxy Clusters

「銀河団の物理」ワークショップ

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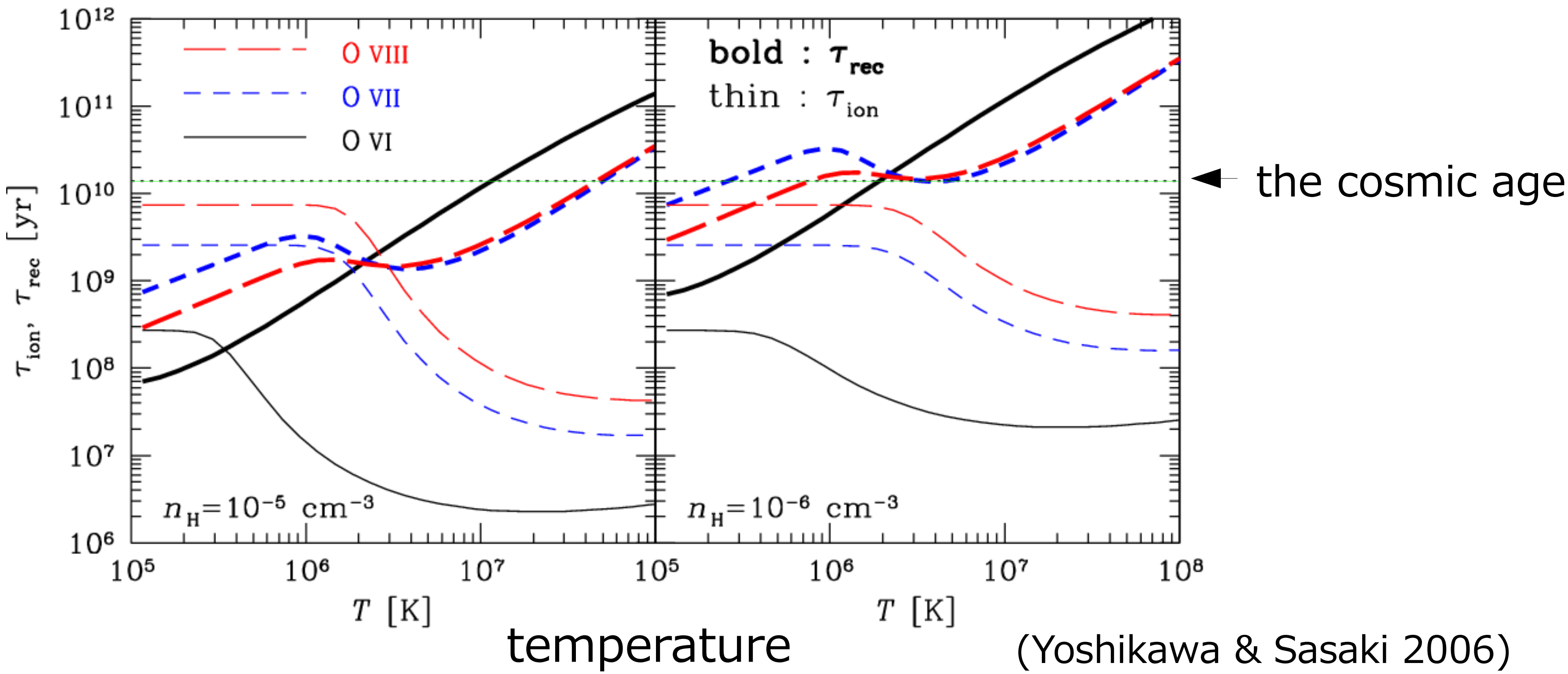
Non-equilibrium Ionization State



(Yoshikawa & Sasaki 2006)

- Timescales for recombination >> timescales for ionization at T>10^7 K
- Even longer than the cosmic age for low-ρ and high-T plasma
  - → important for WHIM and IGM (Yoshikawa, Sasaki 2006)

Evolution of Ionization States

$$\frac{df_j}{dt} = \sum_{k=1}^{j-1} S_{j-k,k} f_k - \sum_{i=j+1}^{Z+1} S_{i-j,j} f_j - \alpha_j f_j + \alpha_{j+1} f_{j+1}$$

f_j : ionization fraction

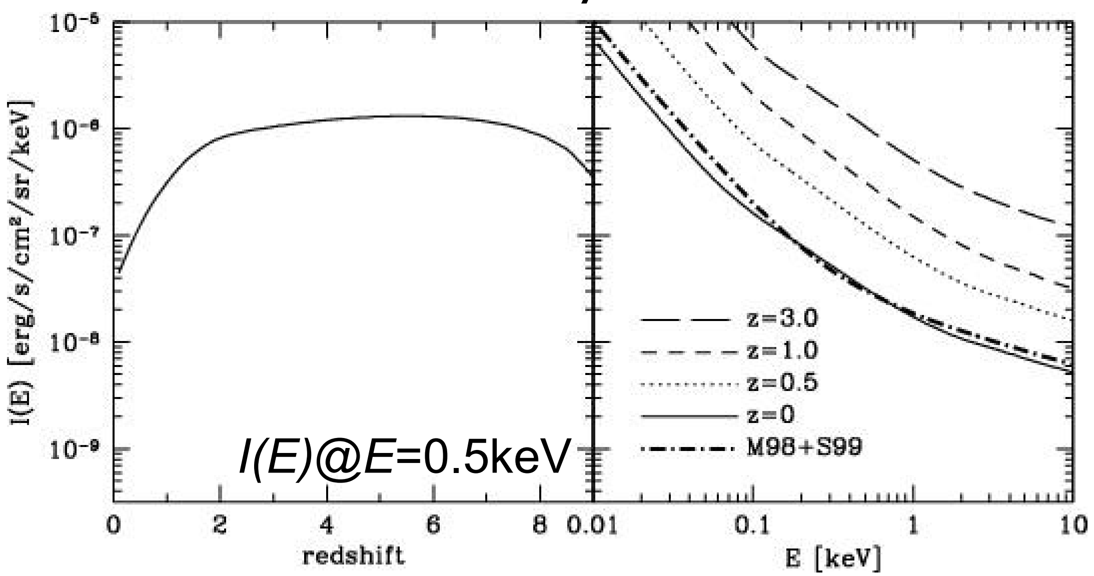
S_{ij} : ionization rates (collisional, auger, photo, C-T)

α_j : recombination rates (radiative, dielectronic, C-T)

(solved for C, N, O, Ne, Mg, Si and Fe as well as H and He)

UV/X-ray Background Radiation

CUBA model by Haardt & Madau (2001)



right : spectra of background radiation

left : intensity evolution at E=0.5keV

- rapid decay of background radiation at z<2

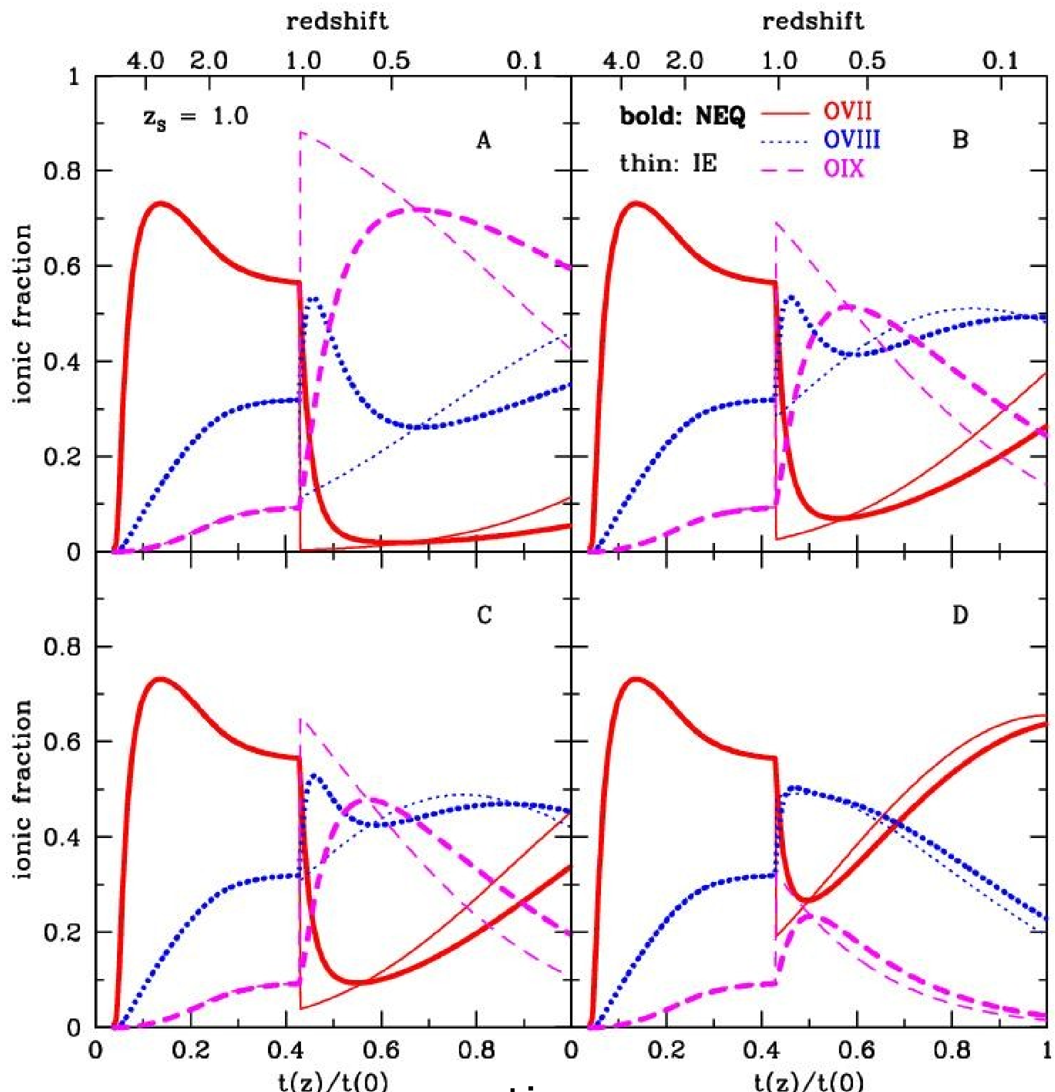
Evolution of Ionization Fractions

bold lines : non-equilibrium states thin lines : equilibrium states

high-T

low-T

Ionization Fraction

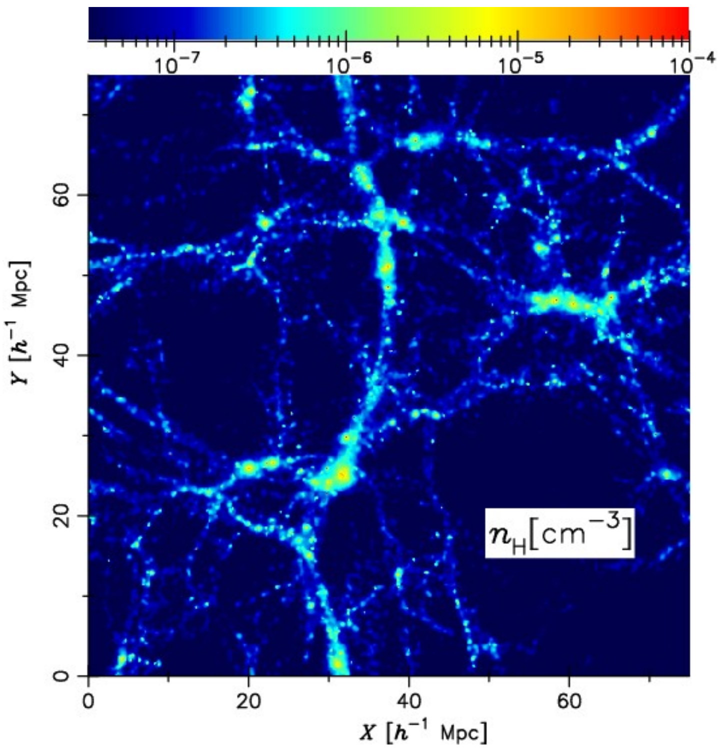


time

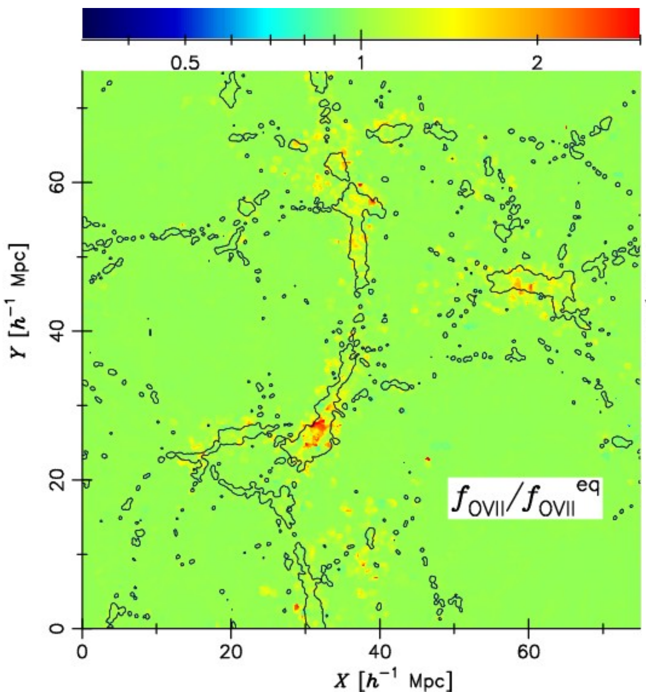
low-ρ high-ρ

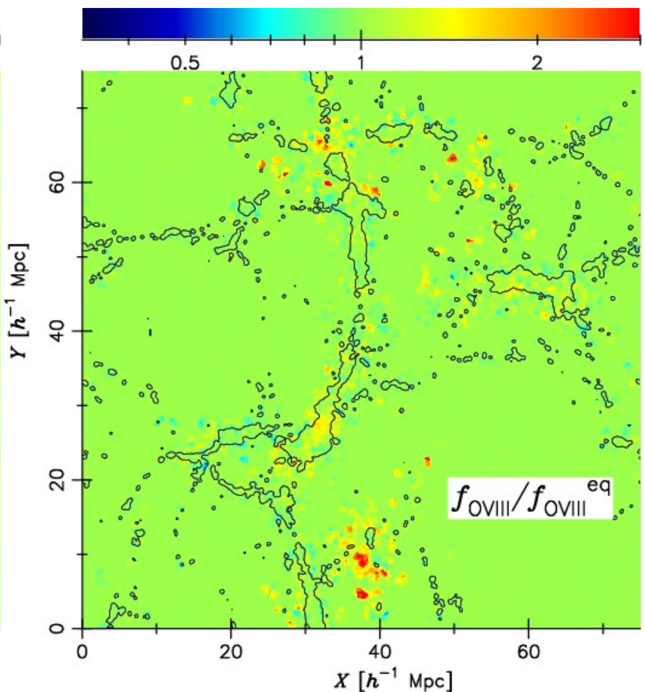
Non-equilibrium Ionization

- Non-equilibrium ionization state in large-scale structure formation
- Strong deviation from ionization equilibrium at the outskirts of galaxy clusters and filaments

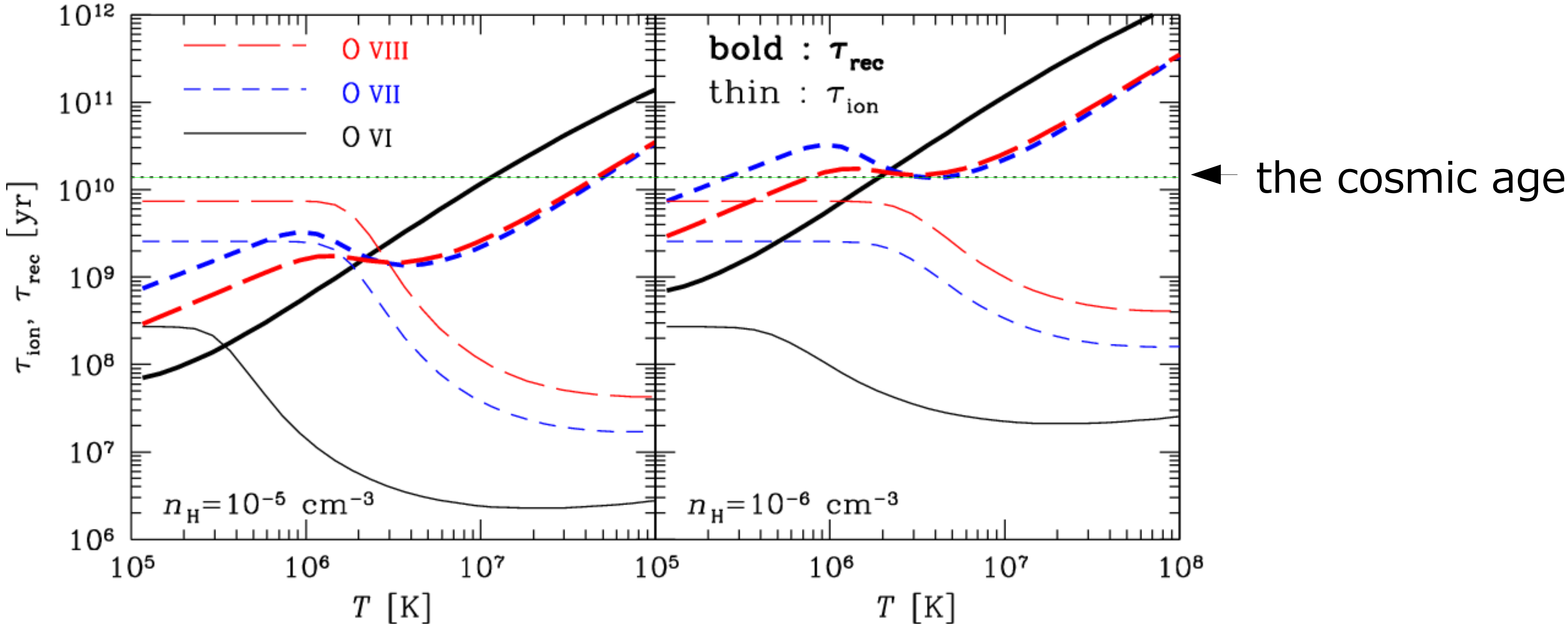


Yoshikawa & Sasaki 2006





Non-equilibrium Ionization State



temperature (Yoshikawa & Sasaki 2006)

- Timescales for recombination >> timescales for ionization at T>10^7 K
- Even longer than the cosmic age for low-ρ and high-T plasma

  ⇨ important for WHIM and IGM (Yoshikawa, Sasaki 2006)

- **also important for merging galaxy clusters**

Two-Temperature Structure in the ICM

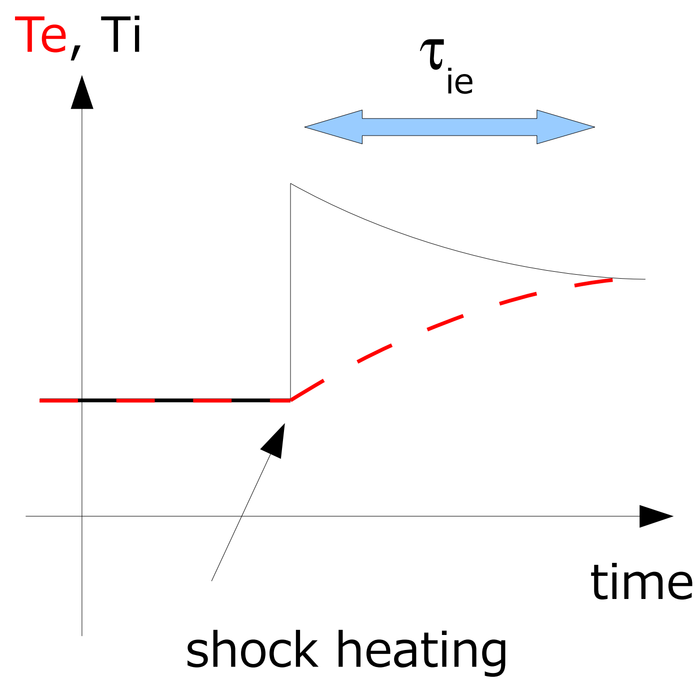
- Thermal relaxation between ions and electrons

relaxation timescale : $\tau_{\rm ee} \ll \tau_{\rm ii} \ll \tau_{\rm ie}$

$$\frac{dT_{\rm e}}{dt} = \frac{T_{\rm i} - T_{\rm e}}{\tau_{\rm ie}}$$

$$\tau_{\rm ie} = 6.3 \times 10^8 \left(\frac{T_{\rm e}}{10^7 {\rm K}}\right)^{3/2} \left(\frac{n_{\rm e}}{10^{-5}{\rm cm}^{-3}}\right)^{-1} [{\rm yr}]$$

(Fox & Loeb 1997, Takizawa 1999)



- Ionization and recombination rates depend on Te
  - → lower ionization rates
  - → larger deviation from ionization equilibrium

- Effect of radiative cooling also depends on the temperature structure.

Two-Temperature Structure in the ICM

- observational probes

X-ray continuum spectra, SZ effect → electron temperature

width of emission / absorption lines → ion temperature + turbulence

- more effective relaxation processes other than the Coulomb scattering ?

→ faster relaxation between ions and electrons or single-temperature structure

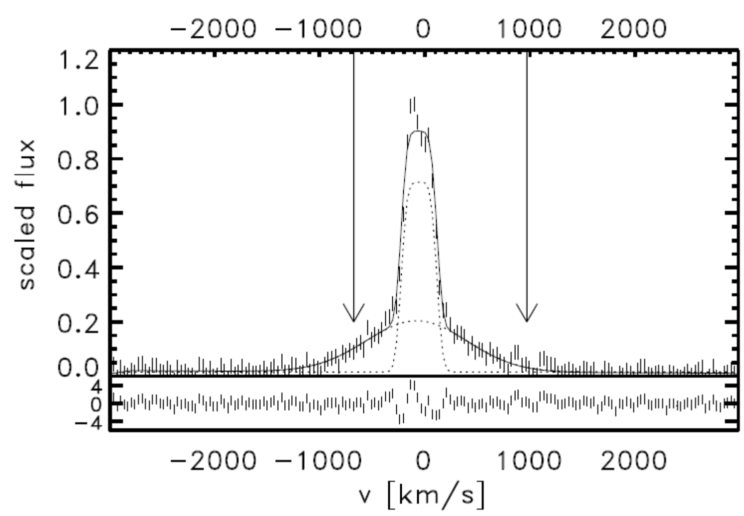
- two-temperature structure in astrophysical plasma

solar corona

BH accretion disk

SN remnant

H-alpha line in balmer-dominated shock

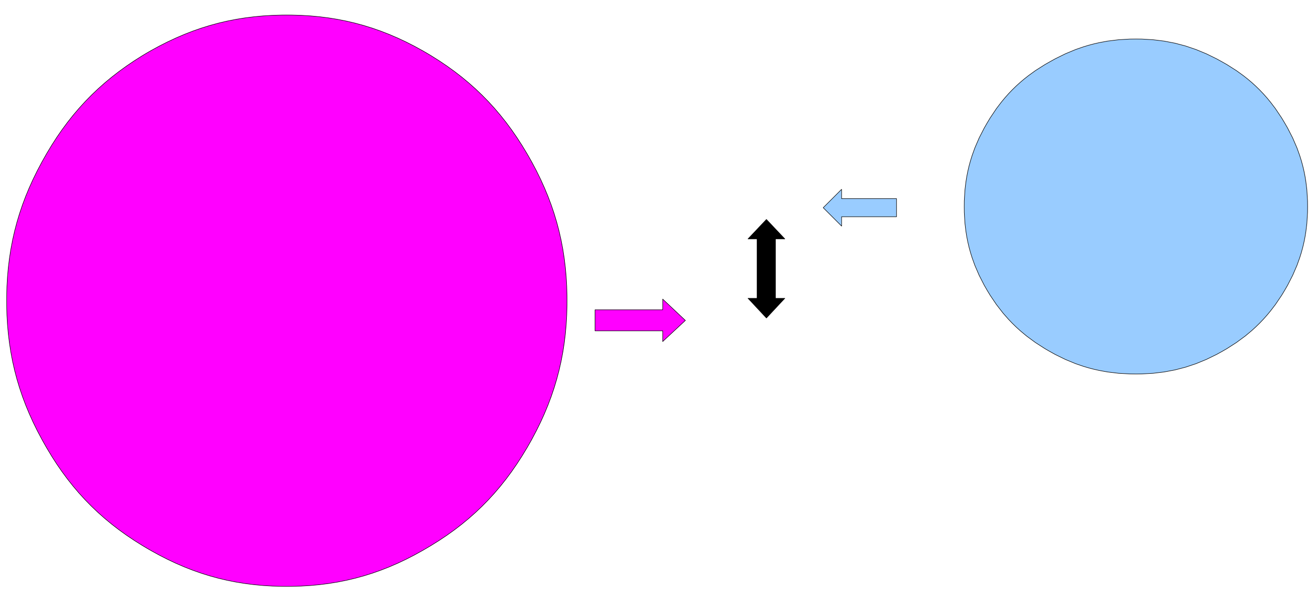


Non-eq. Ionization & Two-Temp. Structure in Merging Galaxy Clusters

- Systematic N-body + SPH simulations of merging galaxy clusters with non-eq. ionization and two-temperature plasma.

$$M = 8 \times 10^{14} M_{\odot}$$

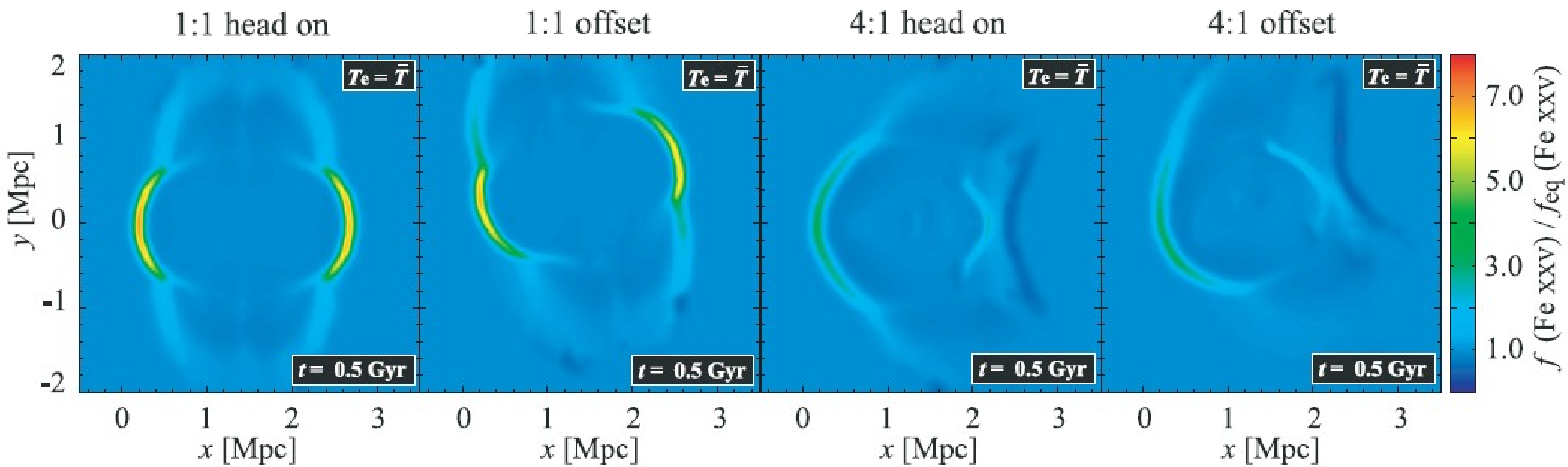
$$M = 8 \text{ or } 2 \times 10^{14} M_{\odot}$$



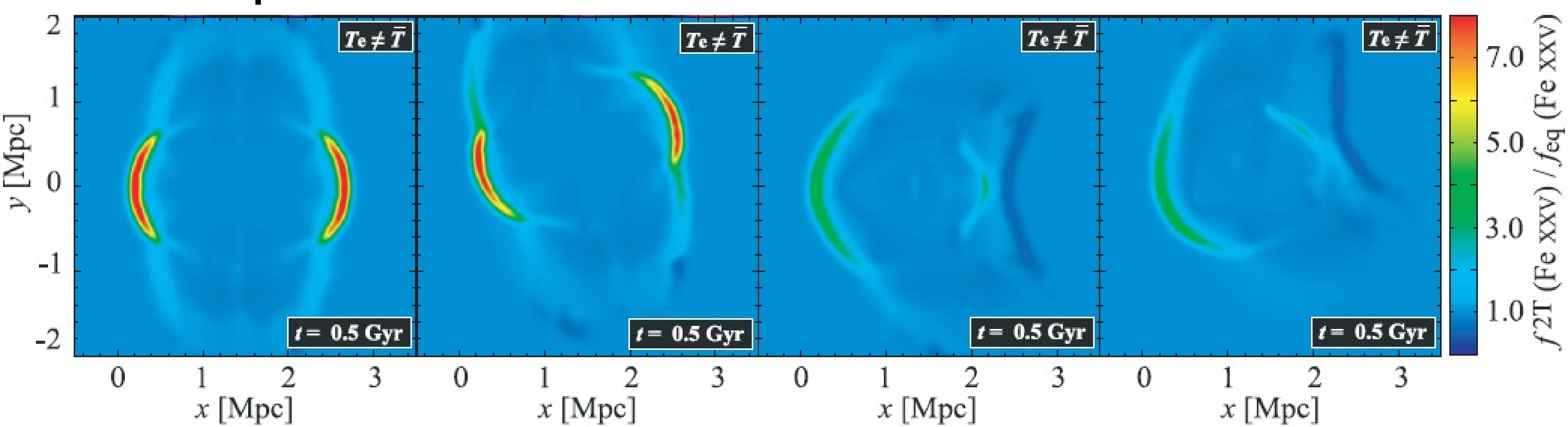
Akahori, T. & Yoshikawa, K. 2010, PASJ, 62, 335

Non-eq. ionization state in single- and two-temperature models

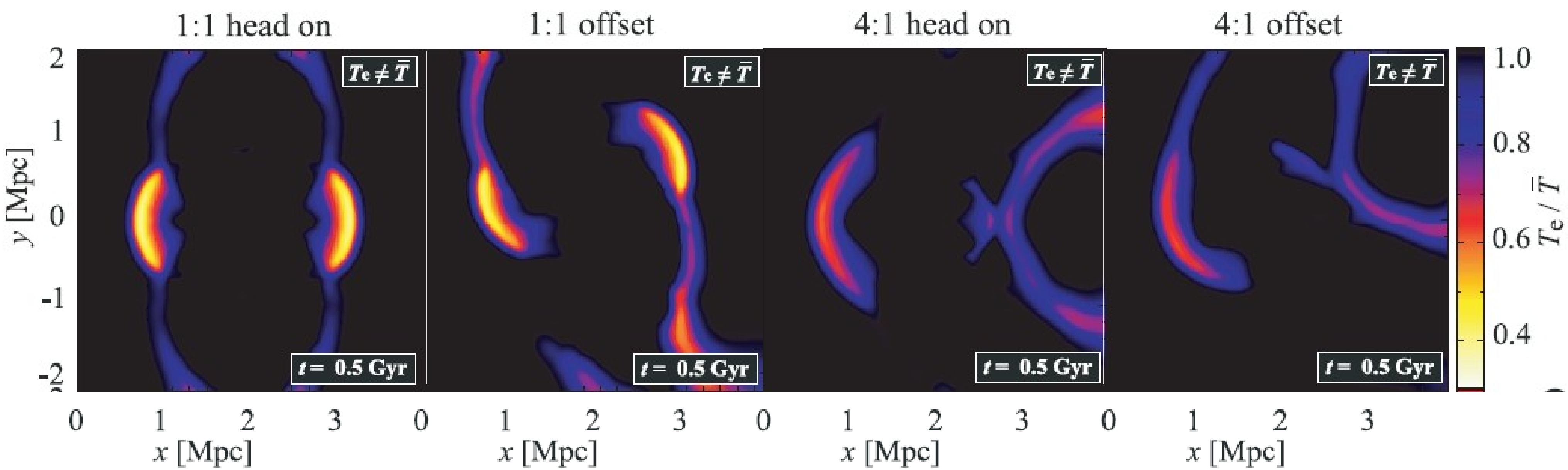
single-temperature



two-temperature

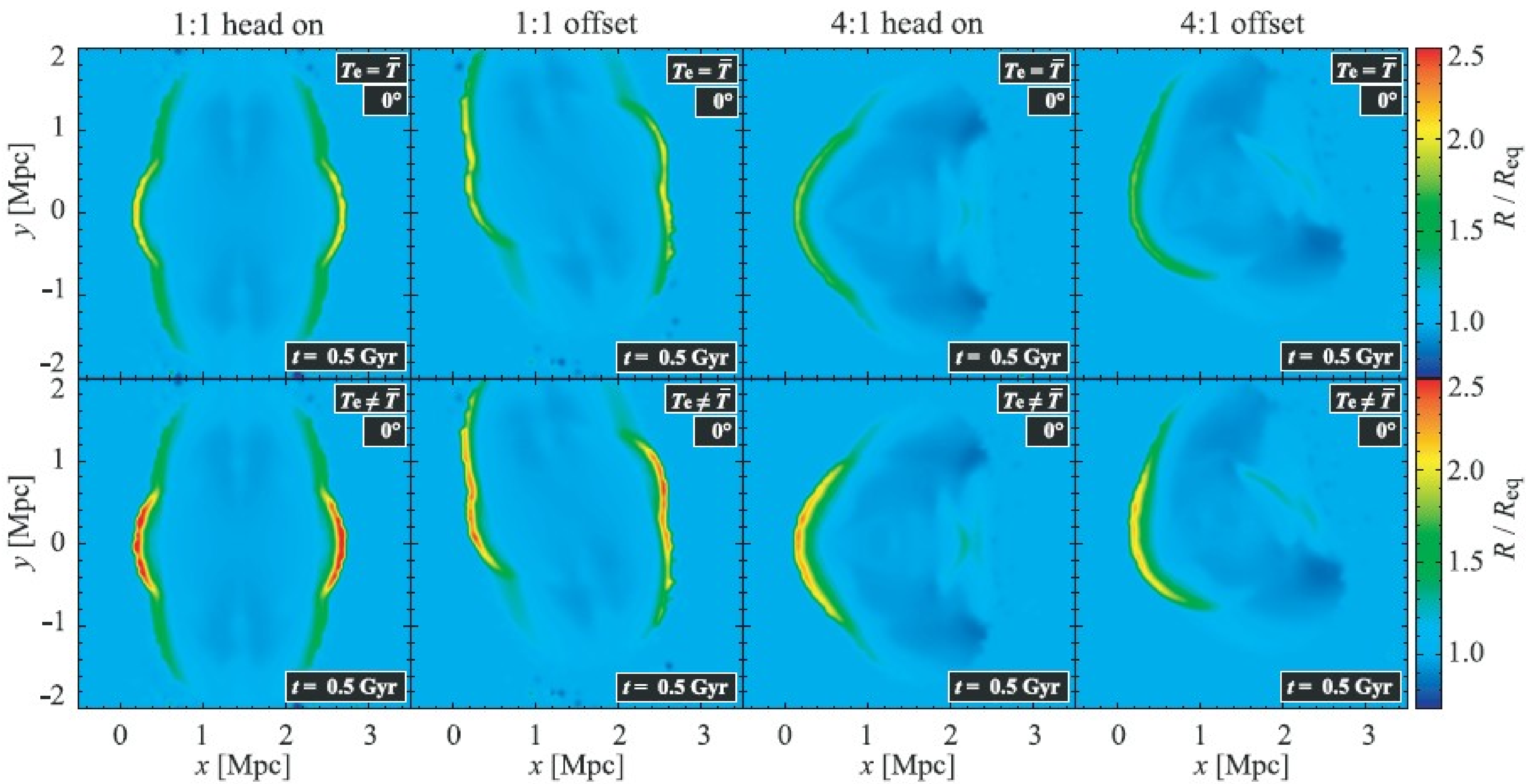


Two-temperature structure



- two-temperature structure could be found in shock regions
- they could have a width of a few 100 kpc.
- 30% ~ 50% decrement of electron temperature

Intensity ratio of Fe lines



$$R = \frac{I(6.6\mathrm{keV} < E < 6.7\mathrm{keV})}{I(6.9\mathrm{keV} < E < 7.0\mathrm{keV})}$$

FeXXV K-alpha

FeXXVI K-alpha

Bullet Cluster

Akahori, T., Yoshikawa, K. 2012 PASJ, 64, 12

smaller cluster

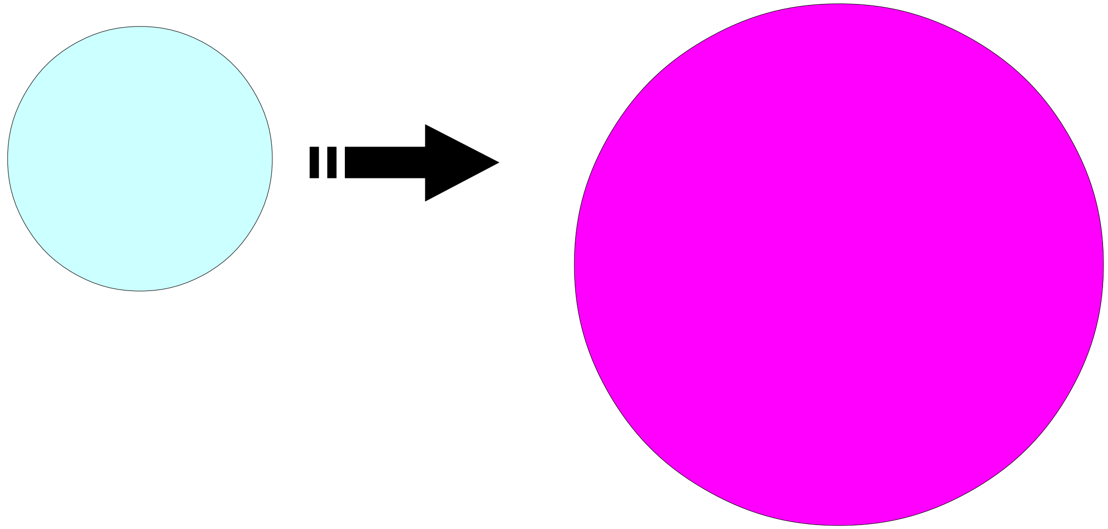
$M_{\rm vir} = 1.67 \times 10^{14} M_\odot$

$T = 2.5{\rm keV}$

main cluster

$M_{\rm vir} = 10^{15} M_\odot$

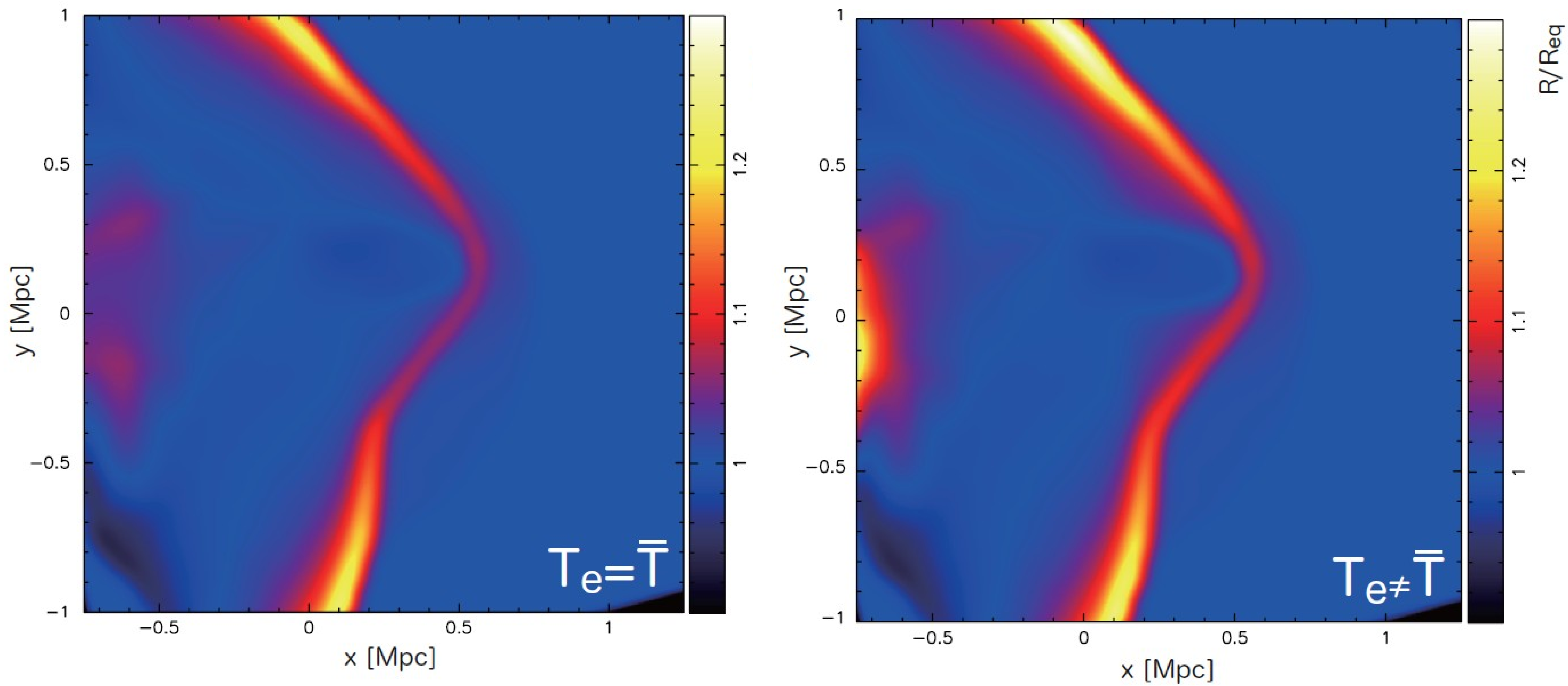
$T = 7{\rm keV}$



initial relative velocity : 3000km/s

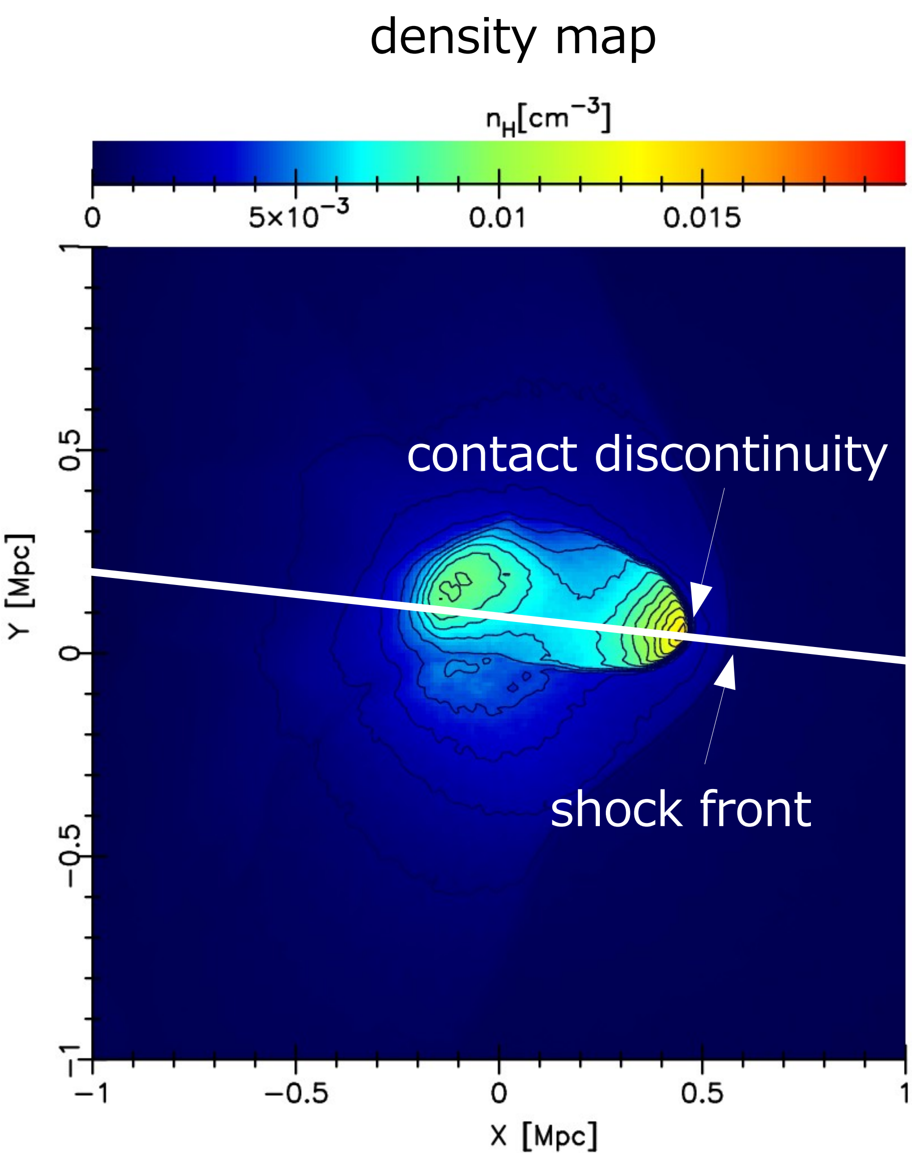
impact parameter : 0.24 Mpc

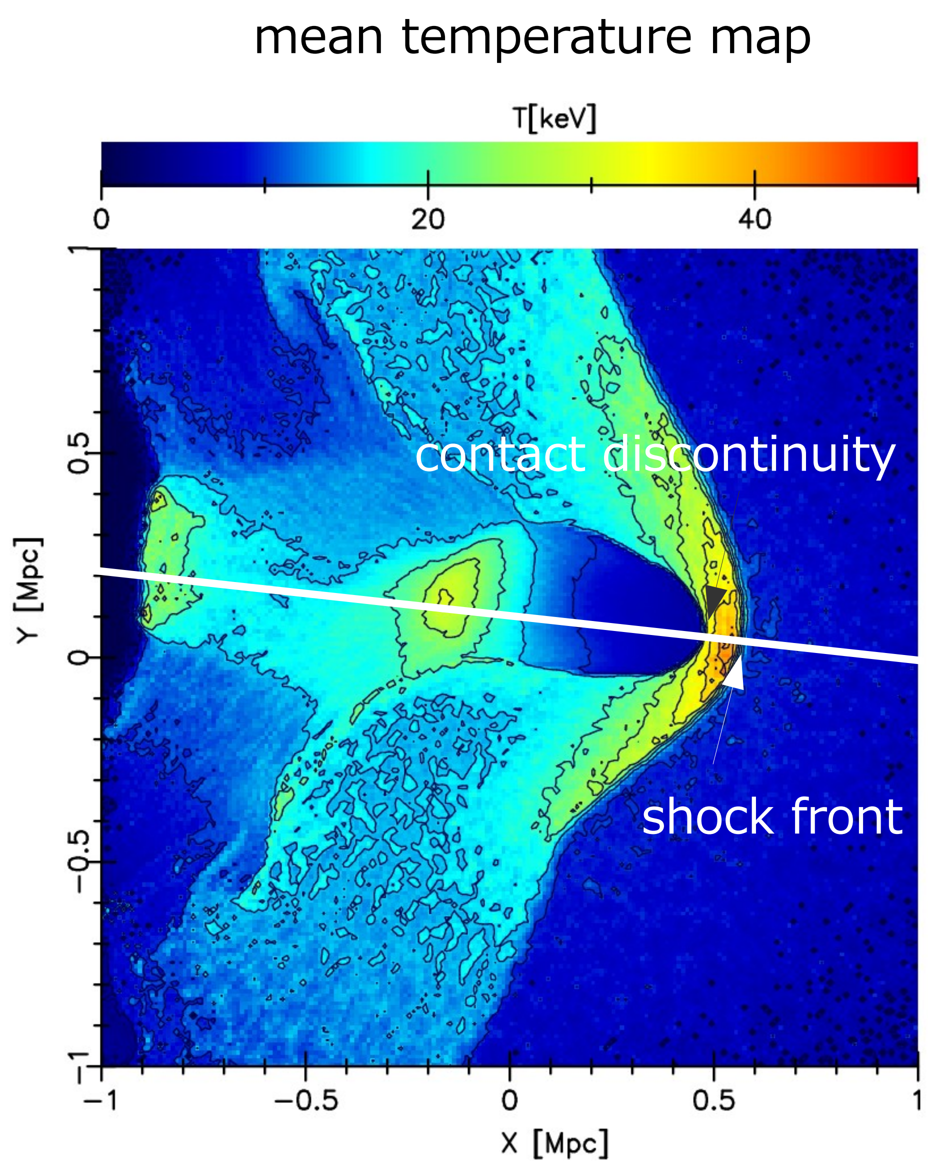
Fe line ratios



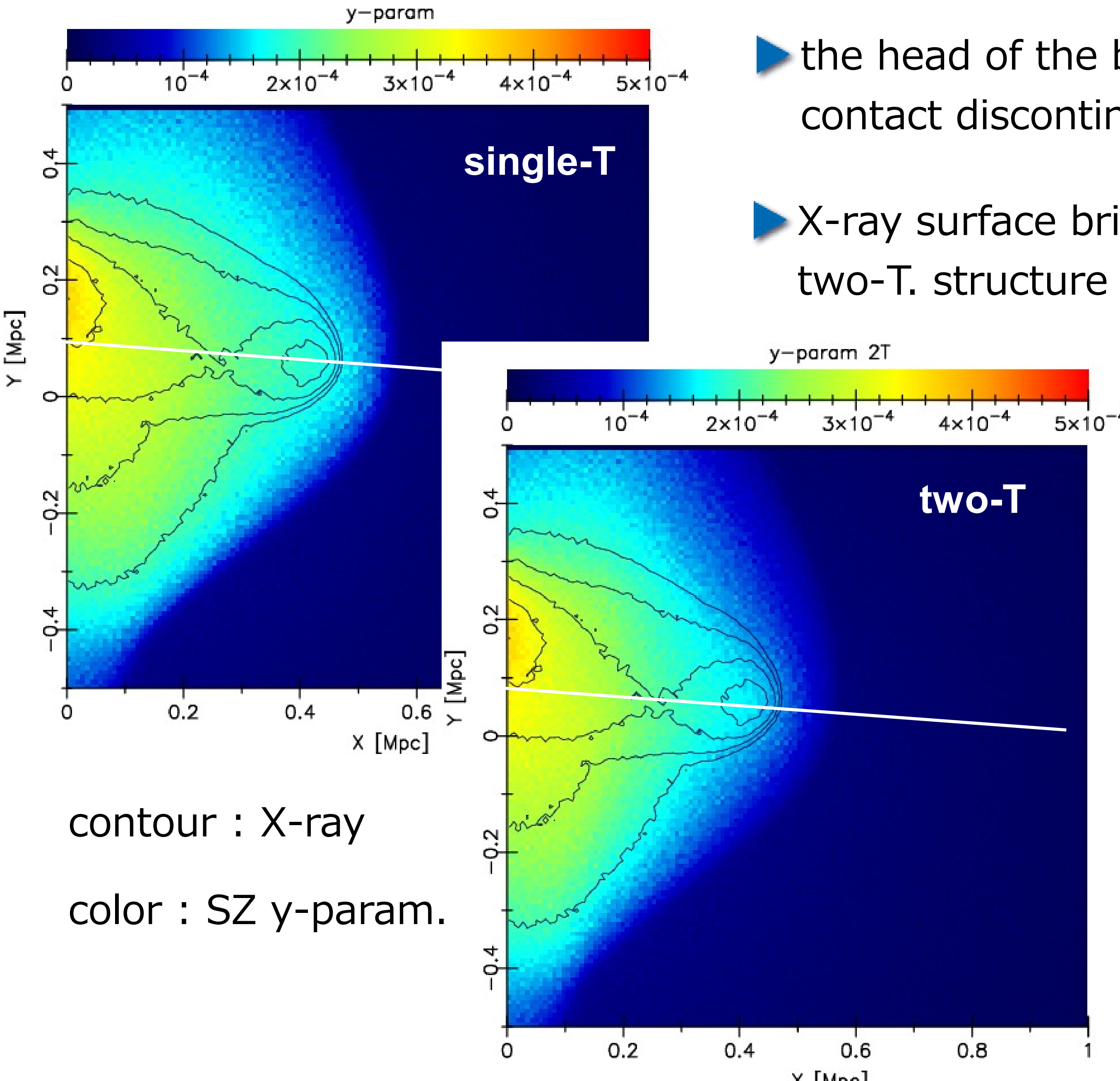
$$R = \frac{I(6.6\text{keV} < E < 6.7\text{keV})}{I(6.9\text{keV} < E < 7.0\text{keV})}$$

Structure of the bullet





Thermal SZ Effect of the Bullet Clusters



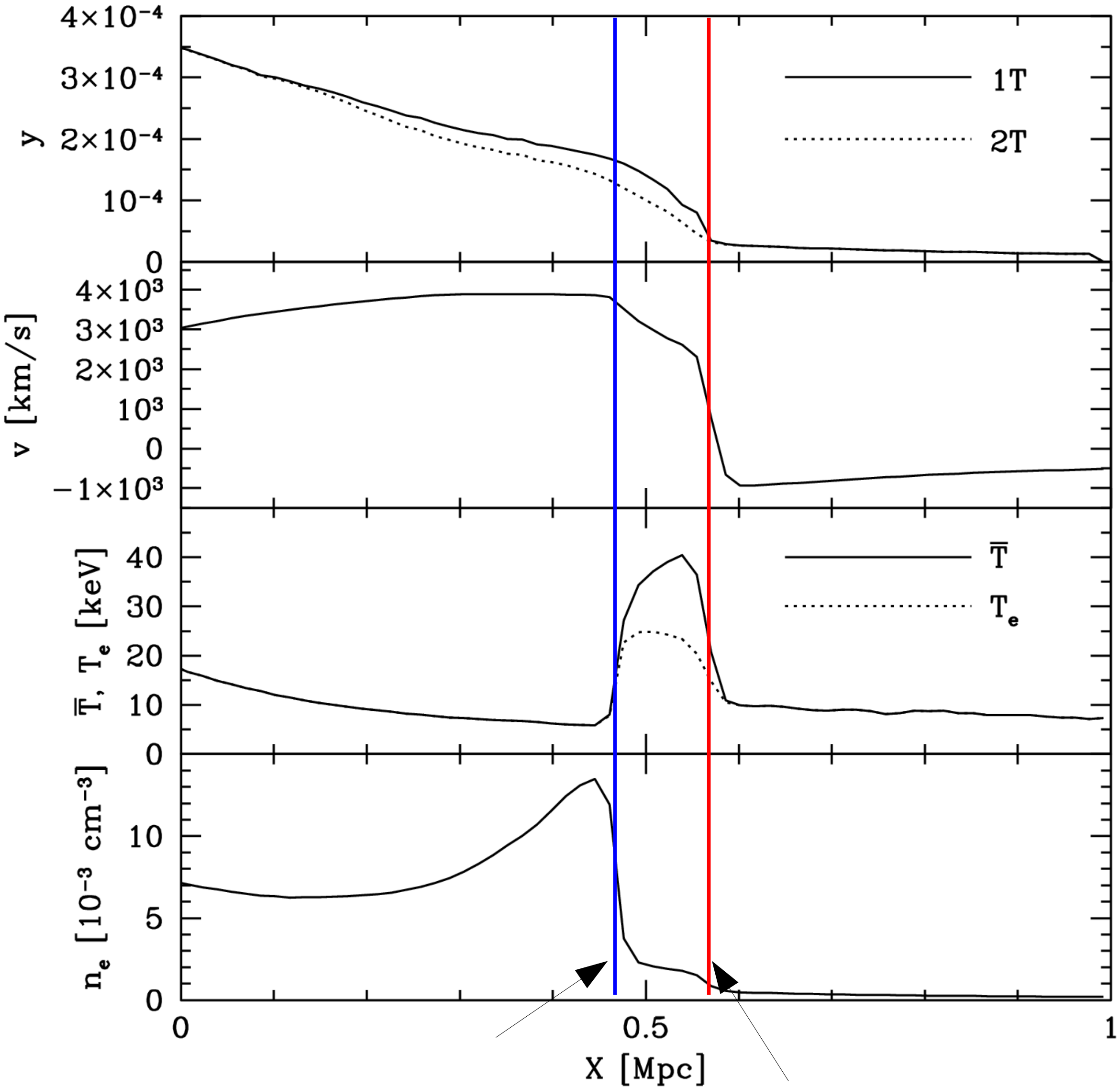
- the head of the bullet corresponds to the contact discontinuity.
- X-ray surface brightness is not affected by two-T. structure
- SZ signal depends on the temperature structure.
- The single-T model has strong SZ signals in the shocked regions.

contour : X-ray

color : SZ y-param.

Thermal SZ Effect of the Bullet Clusters

structure of the bullet



contact discontinuity

shock front

- $T_e \neq T_i$ between the shock front and the contact discontinuity
- $T_e = T_i$ behind the contact discont. because of the high density.
- high-resolution SZ observation of this region can discriminate the temperature structure.

Summary

- Non-equilibrium ionization and two-temperature structure of ICM are important for merging galaxy clusters

- Understanding of ionization state is important in analyzing the X-ray spectroscopic data

- Precise measurement of emission line ratios/ profiles also can constrain the temperature structure

- Observations of SZ effect of ICM in merging galaxy clusters with high spatial resolution can be a good probe for the temperature structure in merging galaxy clusters.