Non-Equilibrium Ionization (NEI) State and Electron-Ion Two-Temperature (2T) structure as a Probe of Shocks in Merging Galaxy Clusters (GCs)

Special Thanks
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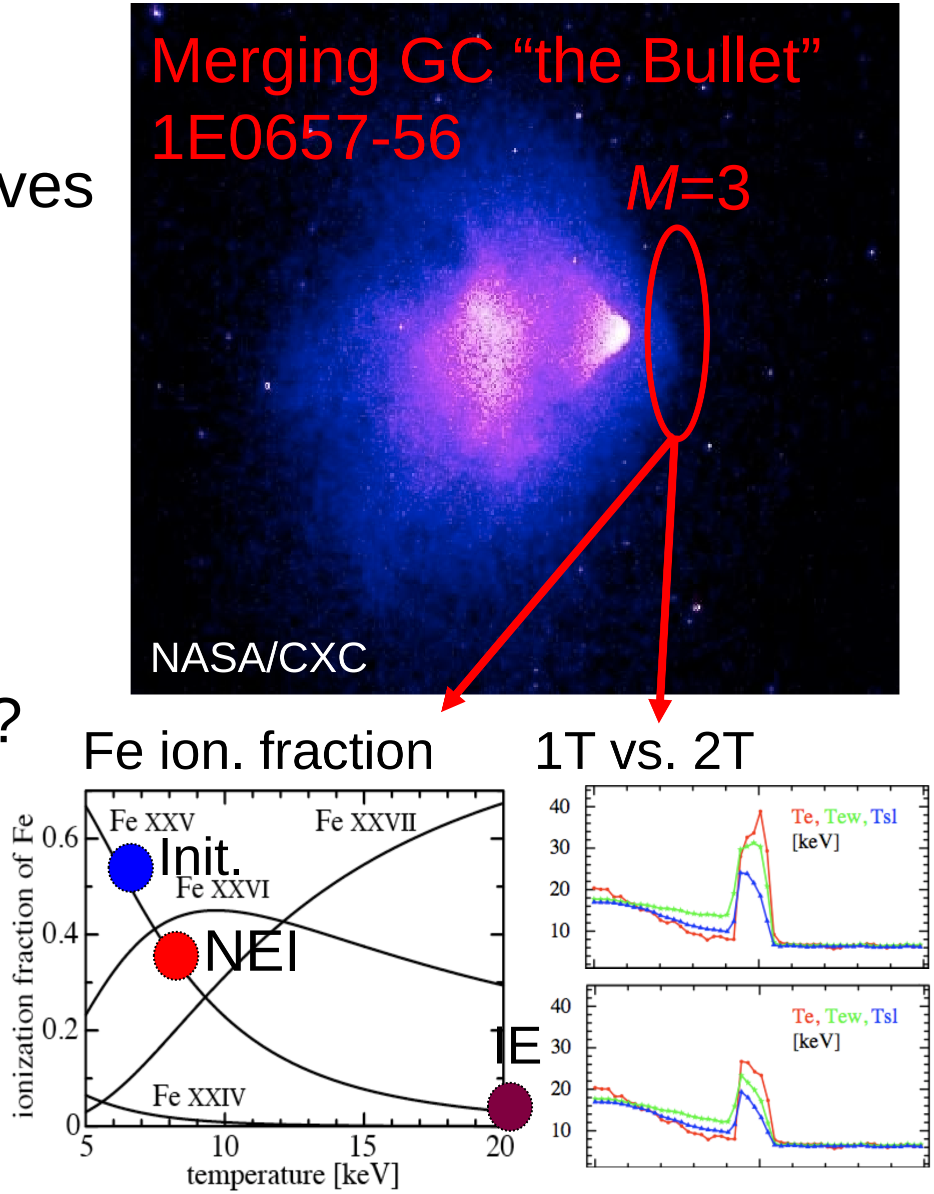
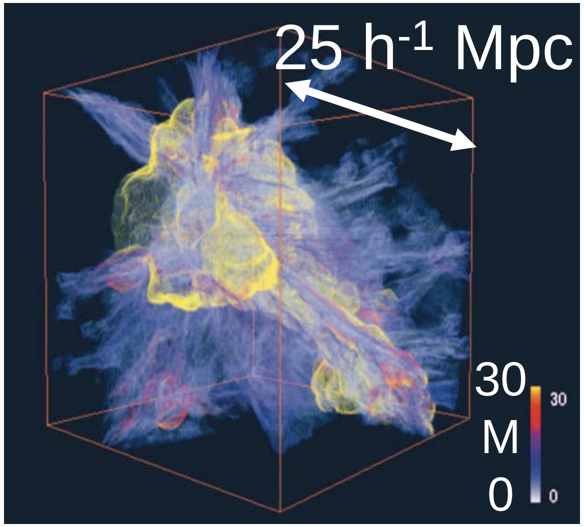


Cosmological Shock Waves

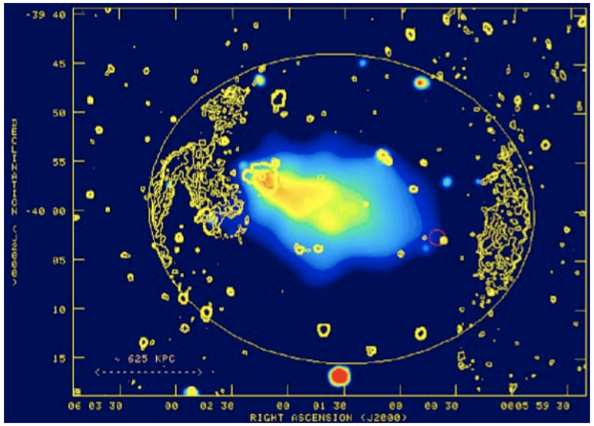
- According to the ΛCDM cosmology, **accretion shocks** are ubiquitous and occur in **magnetized plasma**
  - Usually, Infall V > Sound Cs

	GCs	filaments
Mach number V/Cs	a few	10-100 (a few)
Magnetic Fields B	a few μG	10-100 nG
Density n	$10^{-2\text{-}4}$ cm^{-3}	$10^{-4\text{-}7}$ cm^{-3}
Temperature T	$10^{7\text{-}8}$ K	$10^{5\text{-}7}$ K

- Shocks heat up the plasma, but **observational evidences… a few**
- **Merging GCs** are targets/laboratories
  - to find cosmological shocks
  - to understand shock mechanisms
  - to discuss interesting phenomena around shocks (CR accel., IC, synchrotron,…)



Ryu+ 03



Bagchi+ 06

NEI/2T: Relaxation of Heated Plasma

Structure Formation → Present

Shock, Turbulence, Particle Acceleration

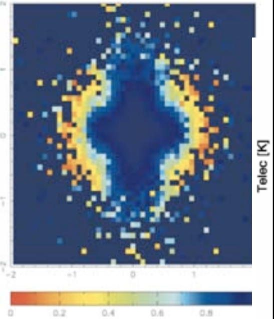
Relaxation when?where?how?

Thermal Plasma is predominant in GCs

2T $t_{e\text{-}i} \sim 2$ Gyr $(n$ $^{-4})^{-1}(T$ $^{8})^{3/2}$

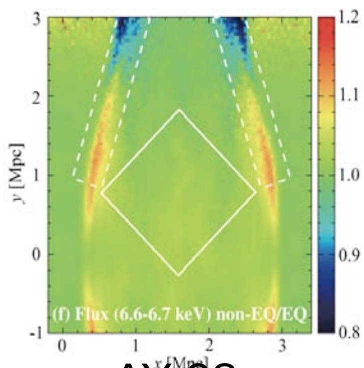
NEI t ~ 0.3 Gyr $(n_e^{-4})^{-1}$

g., Masai '84)

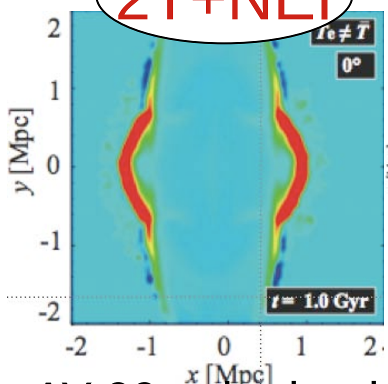


Takizawa 98, 99, 00

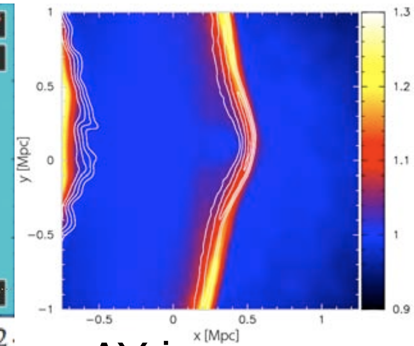
2T+NEI



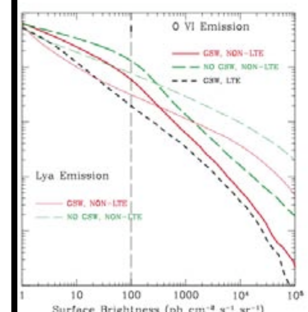
AY 08



AY 09 submitted



AY in prep.



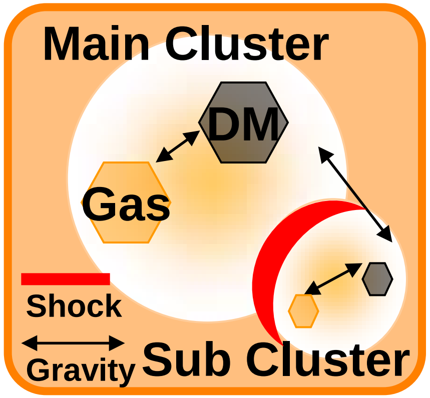
Cen, Fang 06

■ Importance

– 2T: fundamental properties for discussing shock structure

– NEI: misread X-ray analysis -> affect Te (and Ti in future) estimations

Model and Calculation



SPH + N-body

Hydrostatic Model (e.g., Sarazin 02)
Infall from turn-around (e.g., Sarazin 02) or free

\+

Shock Capture estimated

by the entropy generation at the shock (Pflommer+ 06)

$$1+\frac{f_h h}{M_1 c_1 A_1}\frac{dA_1}{dt}=\frac{2\gamma M_1^2-(\gamma-1)}{\gamma+1}\left[\frac{(\gamma-1)M_1^2+2}{(\gamma+1)M_1^2}\right]^{\gamma}$$

\+

One Temperature Model

Instantaneous Relaxation

Set Te=Ti always

Two Temperature Model

Coulomb Relaxation
(Fox, Loab 98, Takizawa 99)

Te≠Ti

$$\frac{d\tilde{T}_{\rm e}}{dt}=\frac{\tilde{T}_{\rm i}-\tilde{T}_{\rm e}}{t_{\rm ei}}-\frac{\tilde{T}_{\rm e}}{u}Q_{\rm sh}$$

\+

NEI/Spectra Calculations

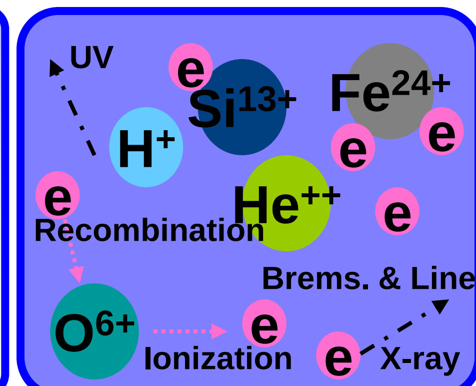
Backward difference formula
(Yoshikawa, Sasaki 06)

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

Reaction rates are calculated by using

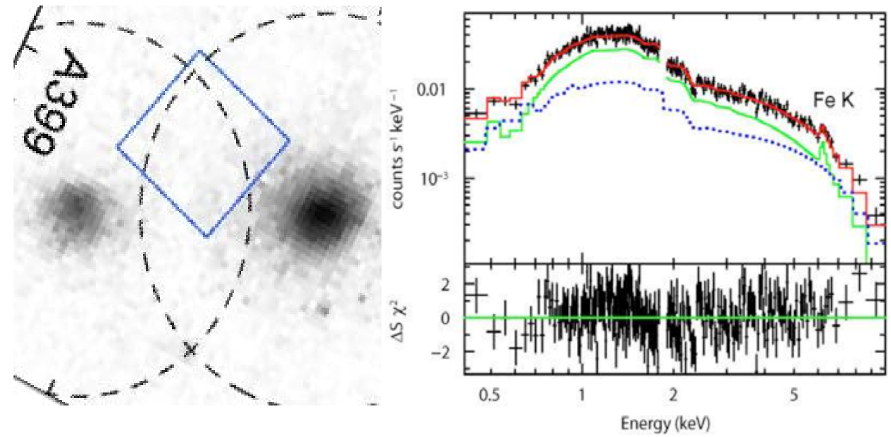
Te

H,He,C,N,O,Ne,Mg,Si,S,Fe
SPEX ver. 1.10
CUBA (Haardt, Madau 01)

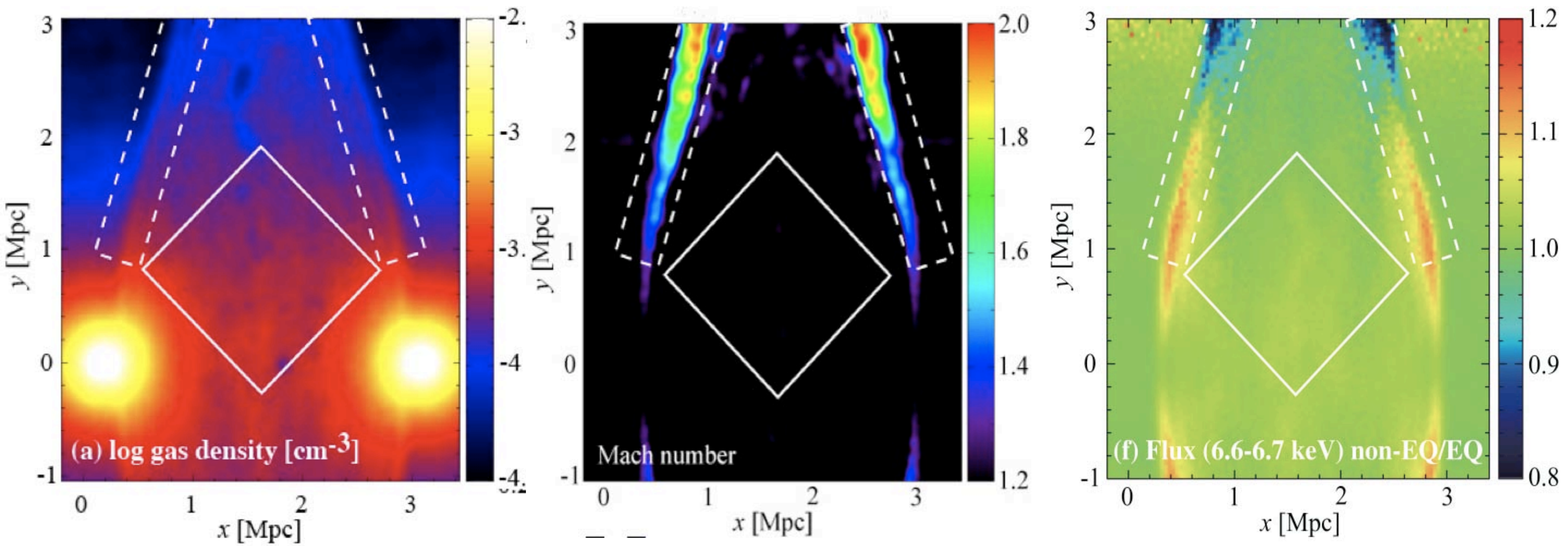


Linked Region of Abell 399/Abell 401

- Linked (compressed) region with $n_e \sim 1.5 \times 10^{-4}$ cm^{-3}
- Suzaku field→ NO shocks!
- Shock layers at the edge of the linked region



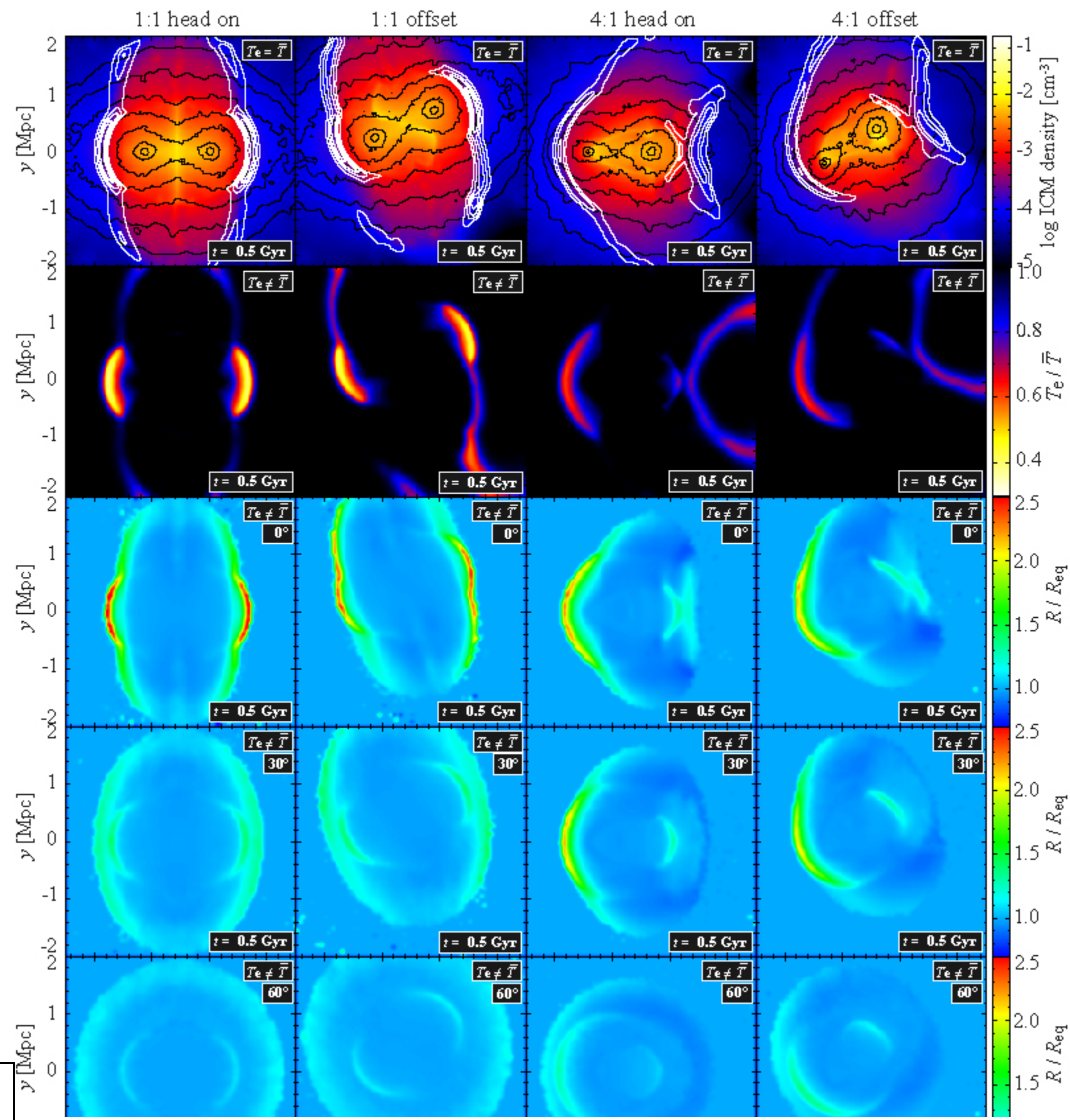
Suzaku Observation (Fujita+ 08)



The gas density, Mach number, and deviation of He-like Fe K line intensity (AY 08)

Various Merging Simulation

- Shock layers:
  - M~1.5-2 (outskirts)
  - M~2-4 (cores)
- $T_{electron}/T_{mean}$:
  - 0.8-0.9 (outskirts)
  - 0.5-0.8 (core)
- R/R_{CIE}*:
  - 1.2-1.4 (outskirts)
  - 1.6-2.2 (core)
- Viewing angle
  - Non-EQ effects are diluted significantly

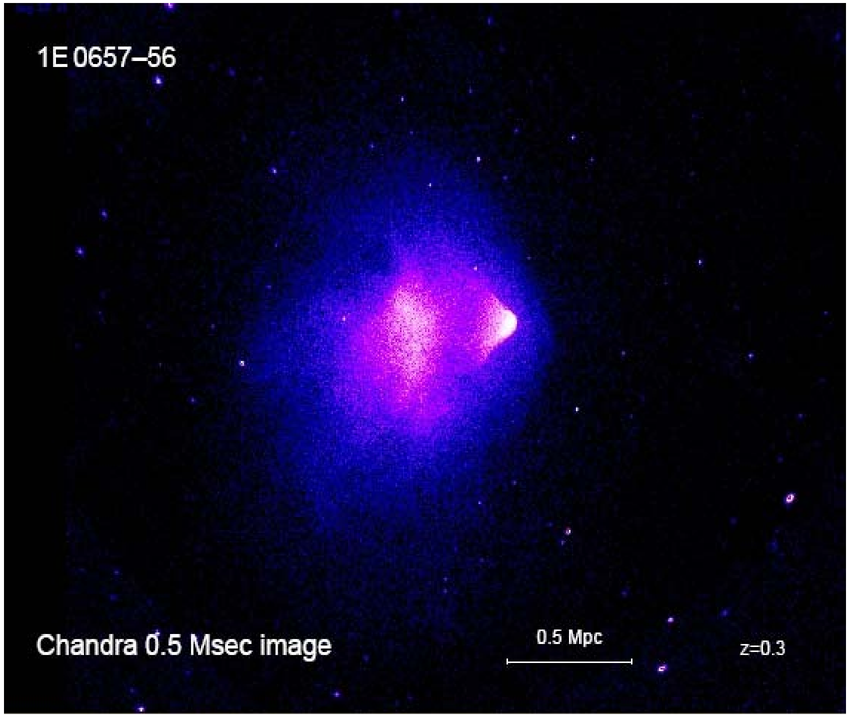


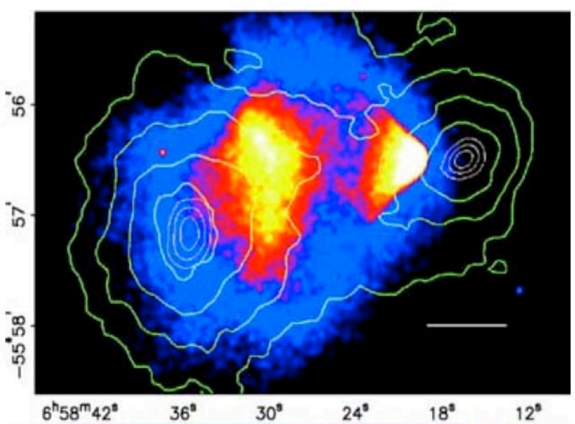
ICM density + Mach num., Te/T, R/Req, and viewing angle dependences of R/Req (AY 09 submitted)

*He vs. H-like Fe K line ratio $R = \frac{F(6.6-6.7keV)}{F(6.9-7.0keV)}$

The Bullet Cluster Simulation

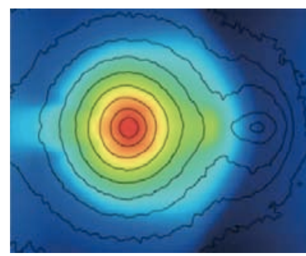
What's the "Bullet" cluster?



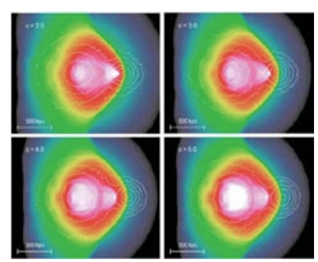


Clowe+ 04

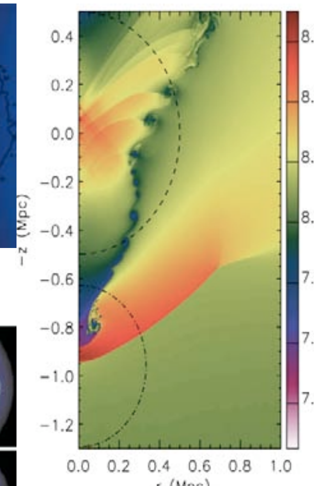
- X-ray substructure, "Bullet"-like shape
- Gas/Mass peaks offset
- Jump Condition: M= **3.0±0.4** (Markevitch 06)



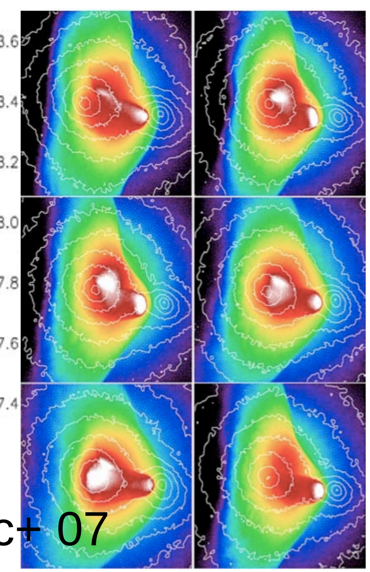
Takizawa 06



Springel, Farrar 07



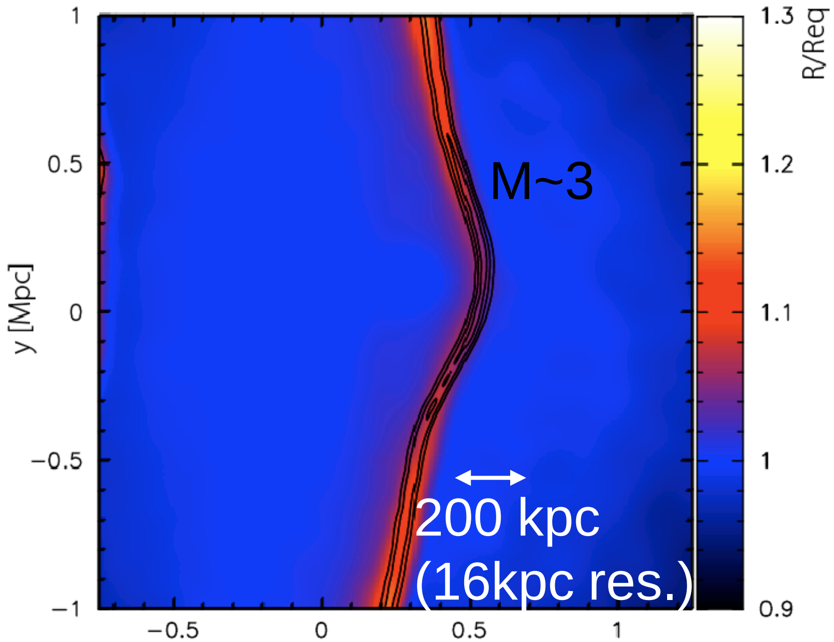
Milosavljevic+ 07



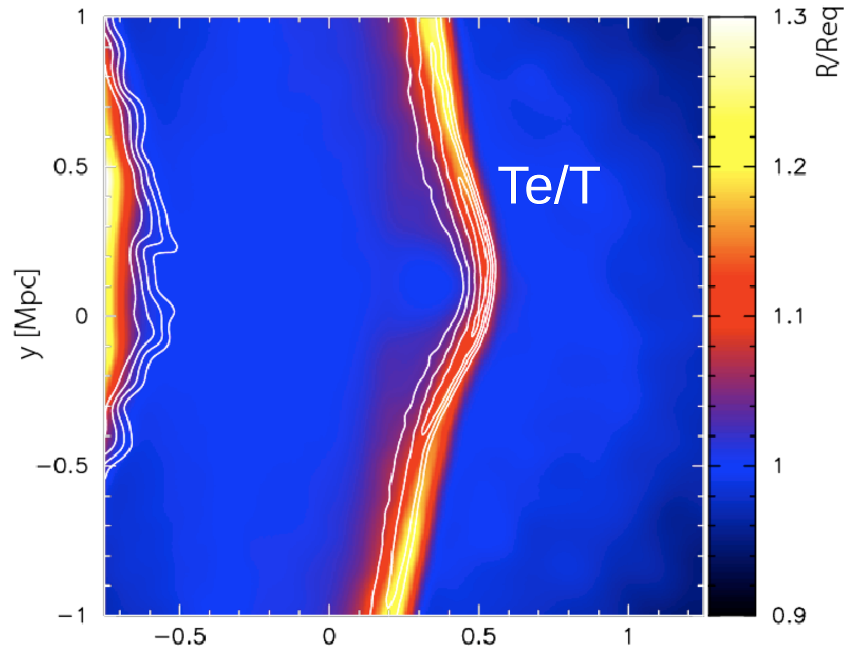
Mastropietro, Burkert 08

Result: Non-Equilibrium Ionization State

R/RCIE



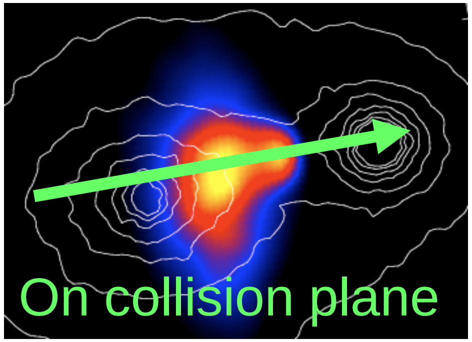
one temperature model
(Instantaneous relaxation)



two temperature model
(Coulomb relaxation)

- For V~3000 km/s, Mach~3, Tsl~8 keV@front (unperturbed region Chandra observed) → **R/R_{CIE}~1.1-1.3** is probable around the shock

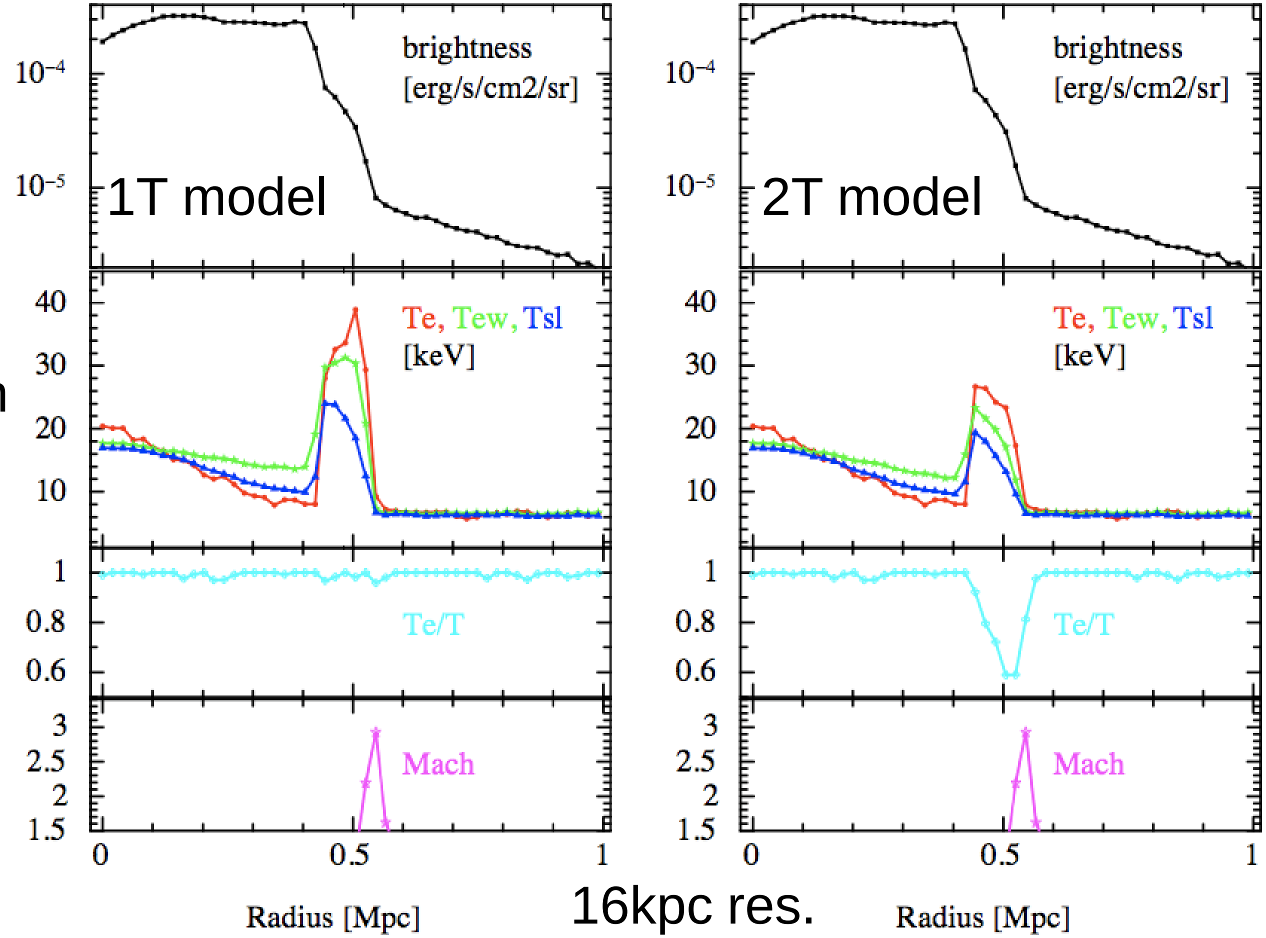
Result: Two-temperature Structure



Radial profile through the bullet and shock

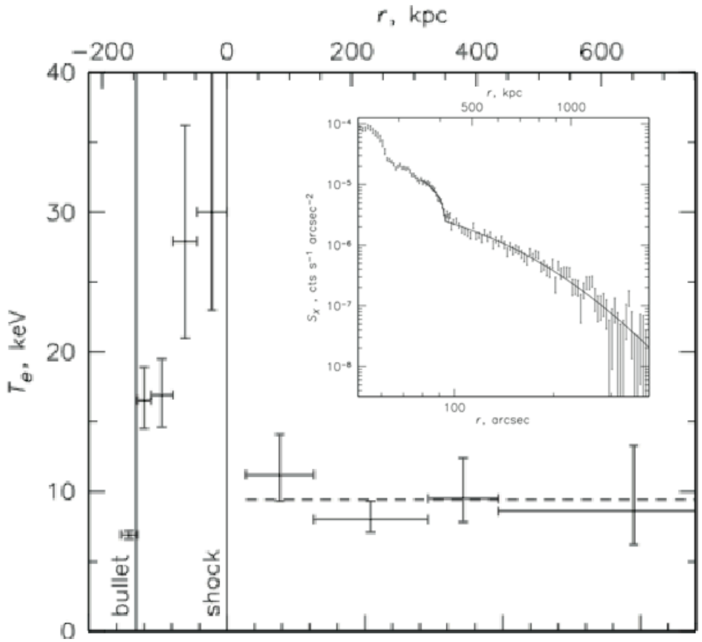
$$Tew = \frac{\int T \cdot n^2 T^{1/2} dV}{\int n^2 T^{1/2} dV}$$

$$Tsl = \frac{\int T \cdot n^2 T^{-3/4} dV}{\int n^2 T^{-3/4} dV}$$

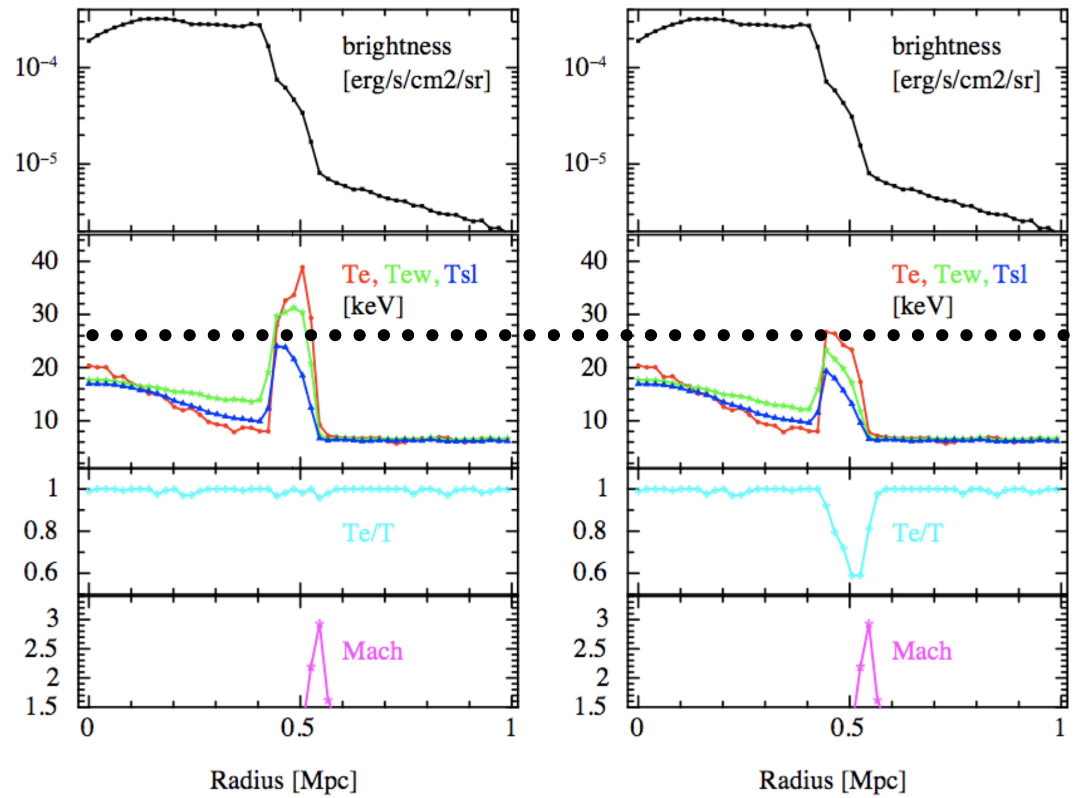


- For V~3000 km/s, Mach~3, Tsl~8 keV@front → **Te/T~0.6-0.7** is probable around the shock

Discussion



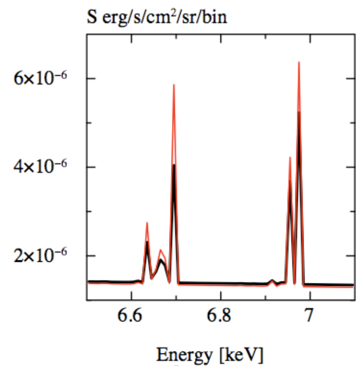
Markevitch 06



- Lower limit of Tx>25keV→1T model is acceptable
  - Imply the presense of rapid relaxation processes on M~3 shock
- Upper limit of Tx<25keV→2T model is acceptable
  - Imply the presence of very hot ion with Ti~40-50 keV
  - Broad Fe K lines, ionization Ti ≠ bremsstralhung Te

Future

- X-ray Observation
  - (201x~) eROSITA, NuSTAR, ASTRO-H,…
  - (202X~) IXO



AY in prep.

ASTRO-H

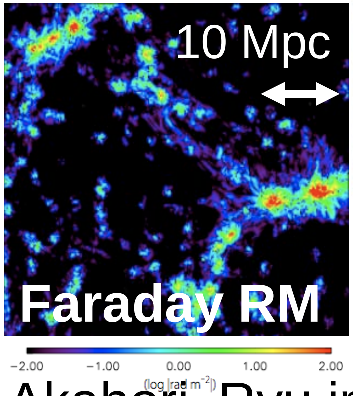
IXO

Calorimeter: ΔE=a few eV@7keV

Imaging: 1-2 order better sensitivity@10-80keV

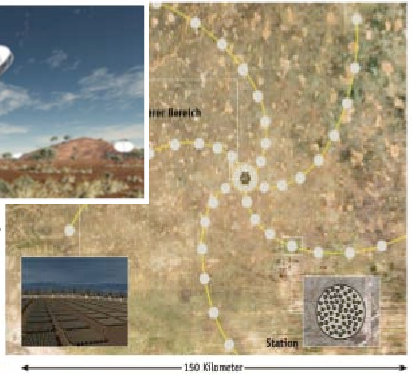
c.f….

- Radio Observation
  - (201x~) LOFAR, ASKAP, MEERKAT,…
  - (202x~) SKA



Akahori, Ryu in prep.

ASKAP



SKA

10^8 extragalactic radio sources@all-sky survey

Summary

- **Merging GC simulations**, relaxing the assumptions of
  the ionization equilibrium & the electron-ion temperature equipartition
- **Linked region of Abell 399 & Abell 401**
  - Non-equilibrium effects are significant around shock layers at the edge of the linked region (we newly predicted)
- **Systematic Study of Merging GCs**
  - Non-equilibrium effects are clearly seen at shock layers with Mach 1.5-2.0 (outskirts) and 2-4 (cores), at least within < 30°of the viewing angle
- **The Bullet Clusters 1E0657-56**
  - R/Req=1.1-1.3 and Te/T=0.6-0.7 are probable around the shock
  - If Tx>25keV→1T? Rapid thermal relaxation process on Mach 3
  - If Tx<25keV→2T? Broad line (Ti>40keV) & diff. from continuum Te

The non-equilibrium features (NEI/2T) is one of the certain evidences of shocks in merging GCs, and of the keys to know the nature of cosmological shock waves