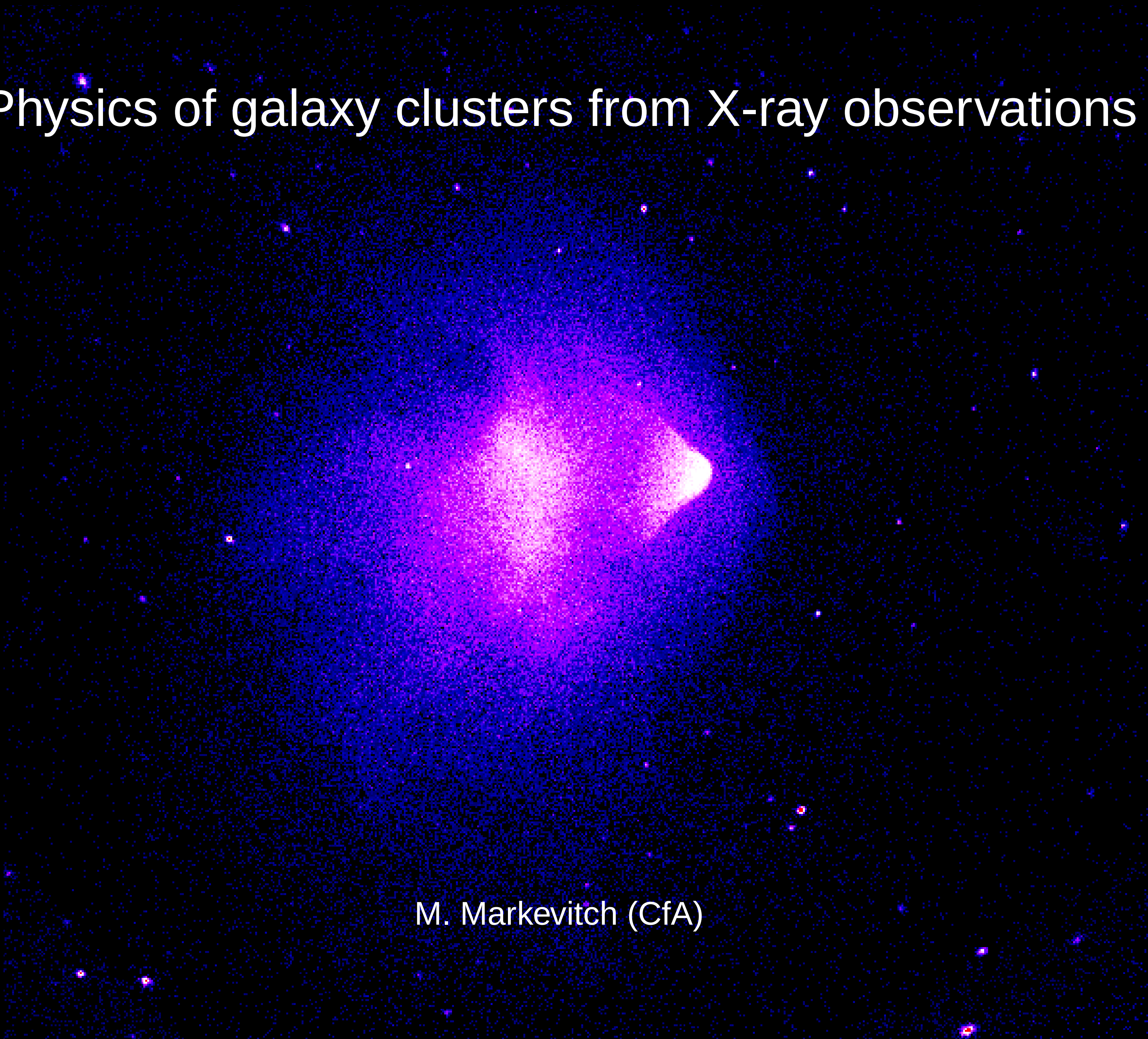
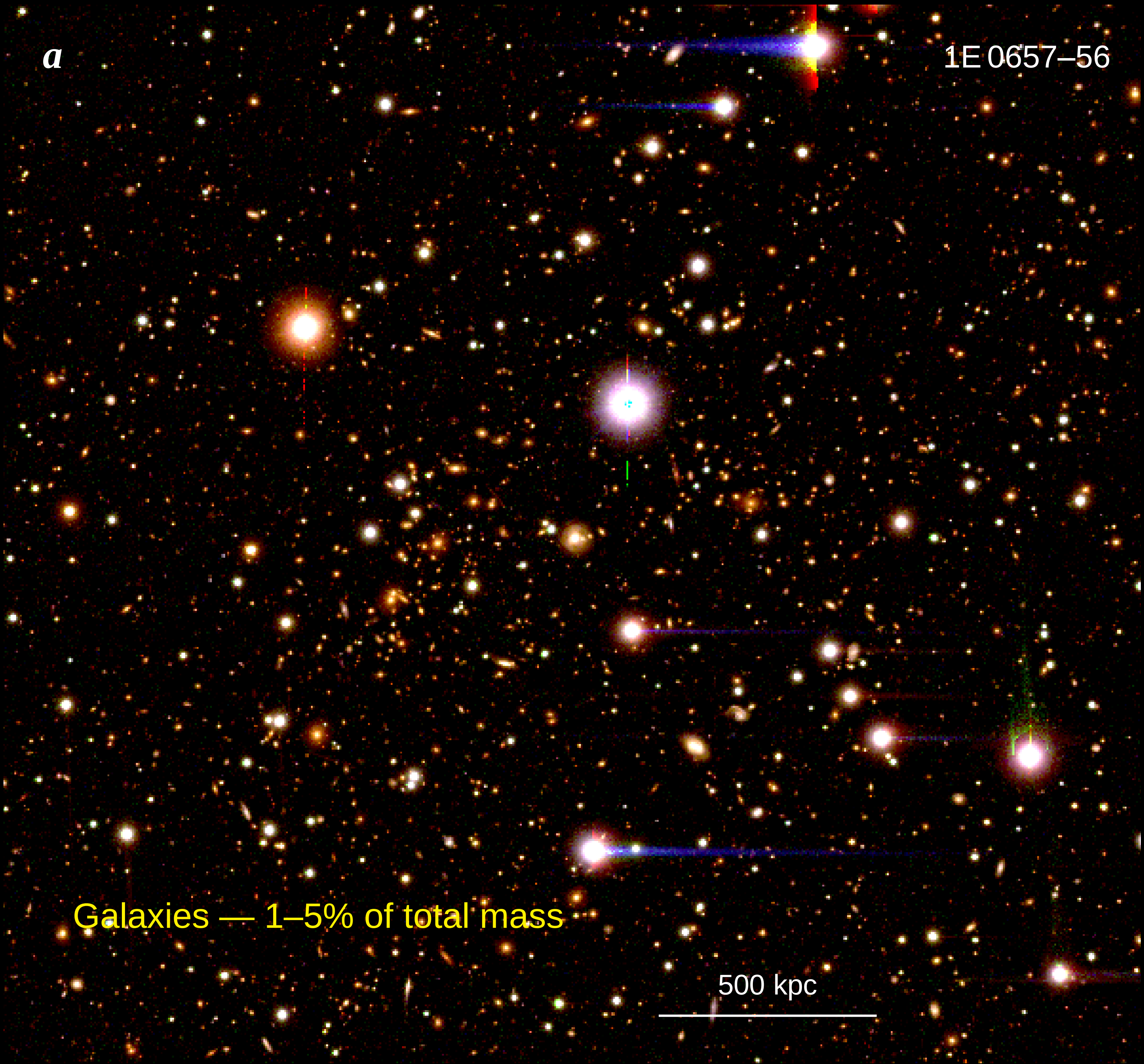
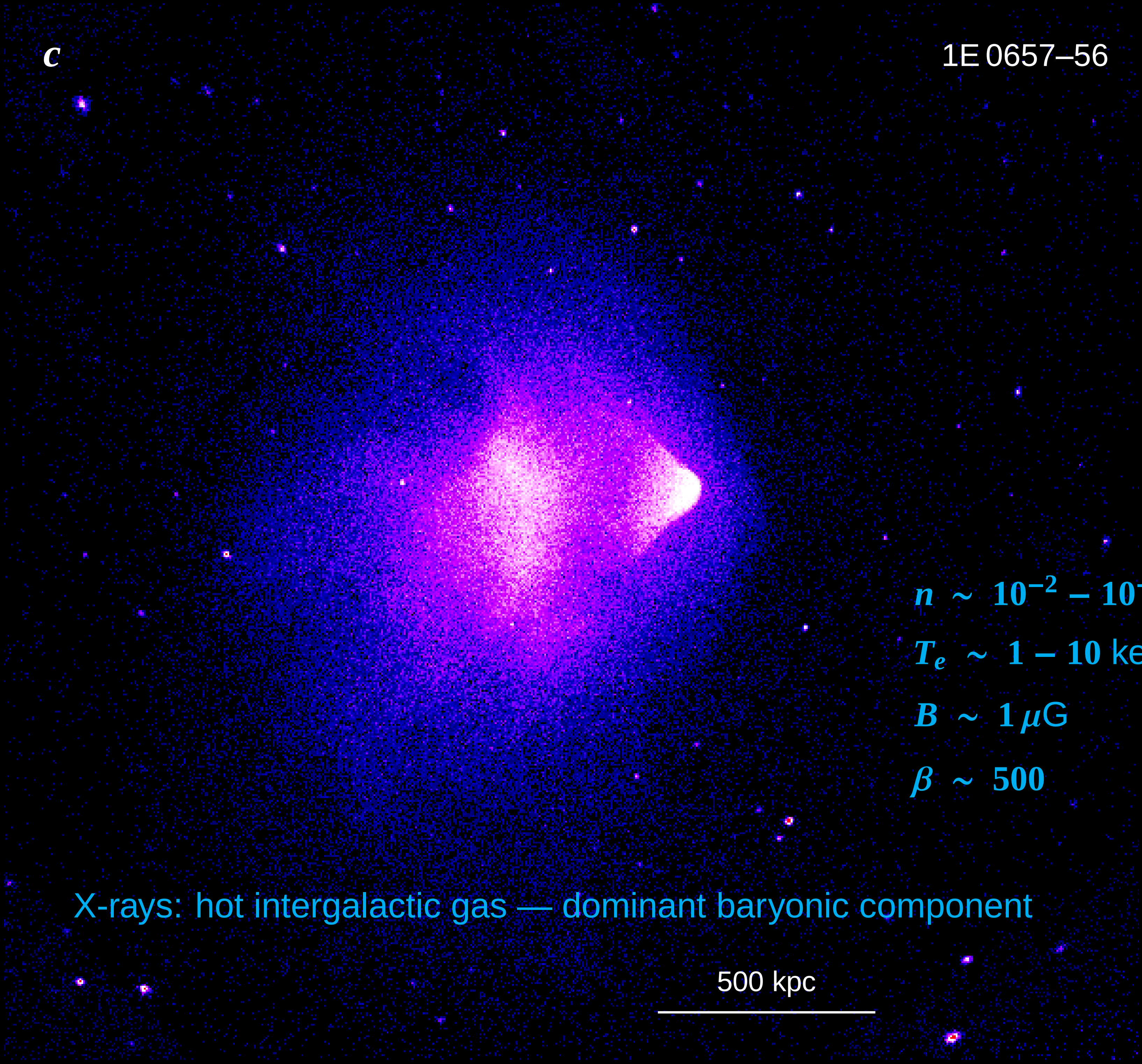
Physics of galaxy clusters from X-ray observations

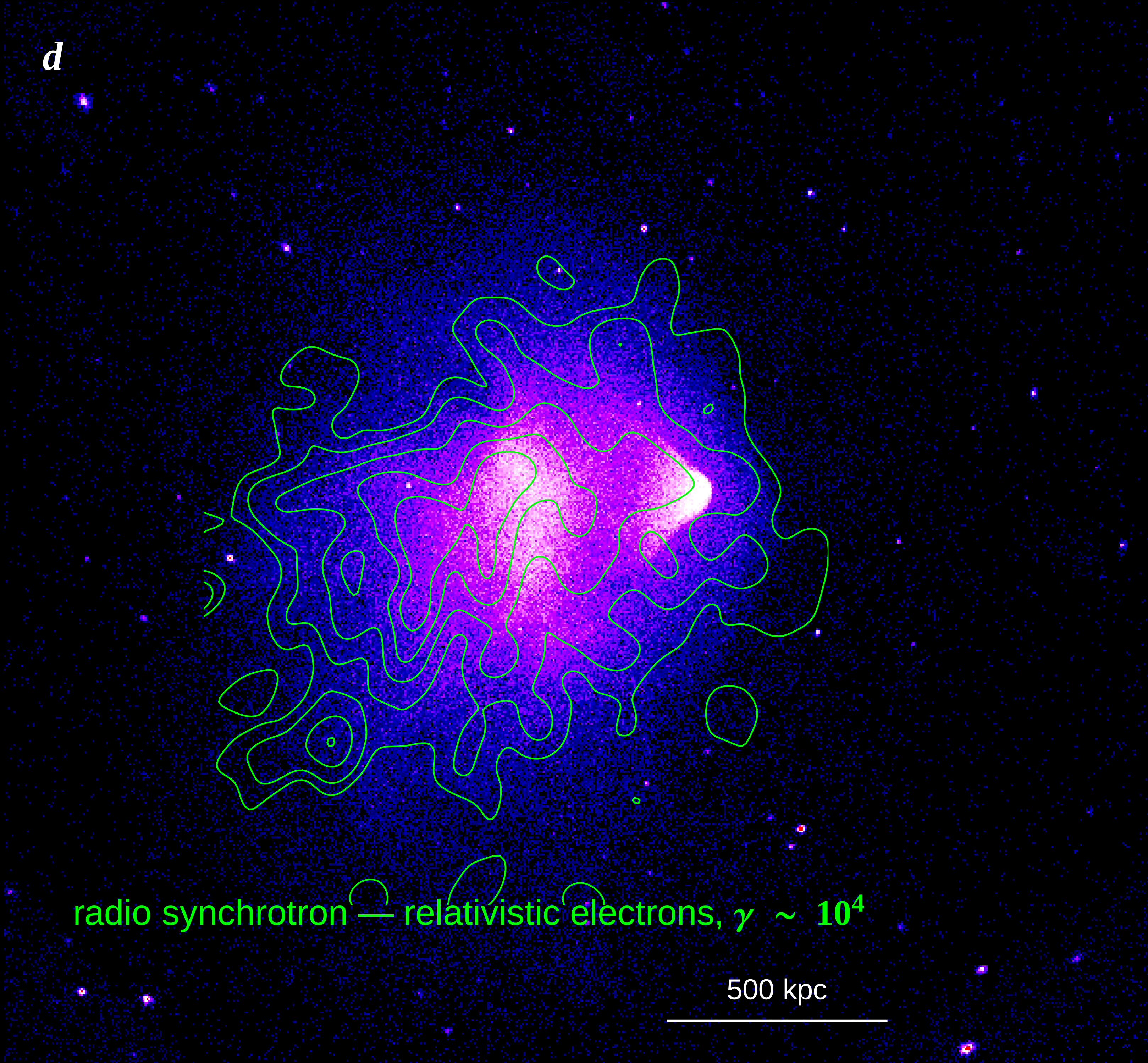


M. Markevitch (CfA)

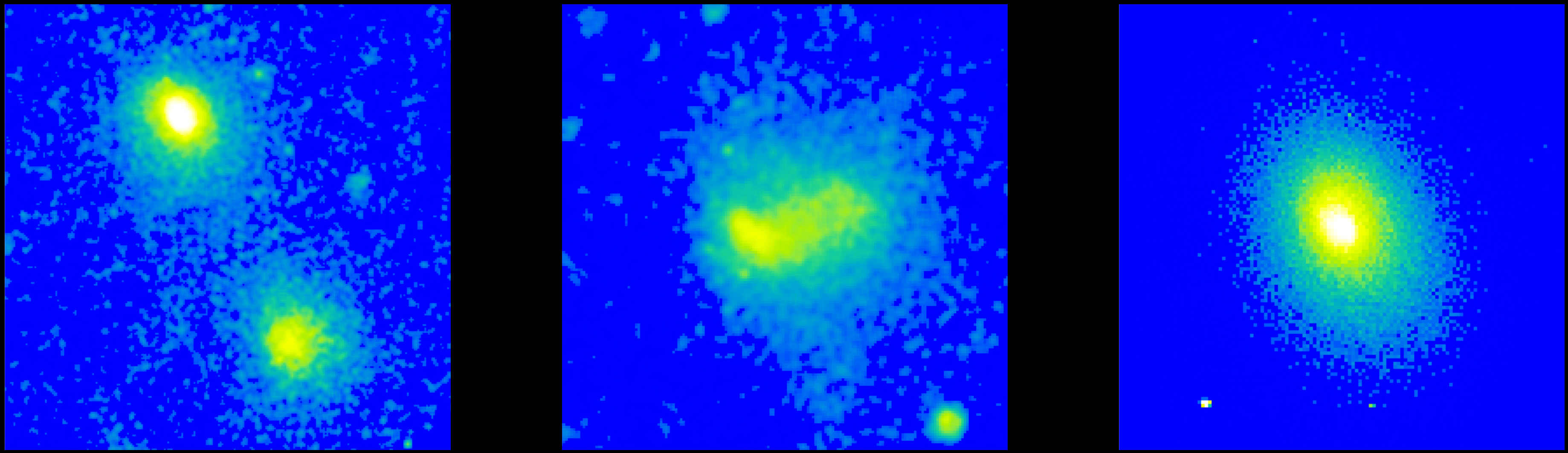

a
1E 0657–56
Galaxies — 1–5% of total mass
500 kpc


b
Total mass from lensing — 85% dark matter
500 kpc


c
1E 0657–56
$n \sim 10^{-2} - 10^{-3}$ cm^{-3}
$T_e \sim 1 - 10$ keV
$B \sim 1\,\mu$G
$\beta \sim 500$
X-rays: hot intergalactic gas — dominant baryonic component
500 kpc


d
radio synchrotron — relativistic electrons, γ ~ 10^4
500 kpc

Galaxy cluster formation



Mergers are the most energetic events since the Big Bang:

E_{kin} up to $\sim 10^{63-64}$ ergs

Unique laboratory of cluster physics:

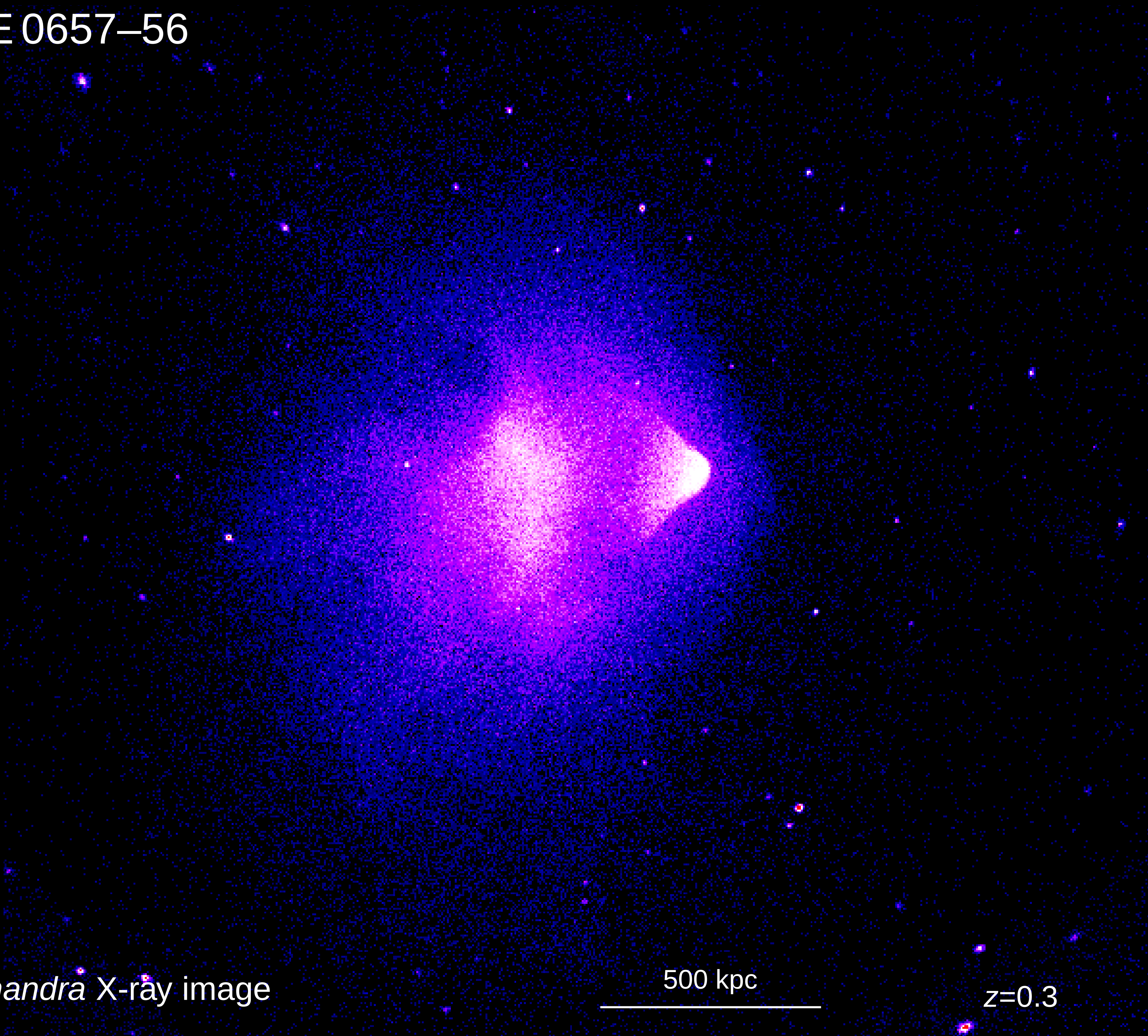
shocks, “cold fronts”, gasdynamic instabilities, turbulence;

particle acceleration, dynamic effects of magnetic field;

dark matter effects

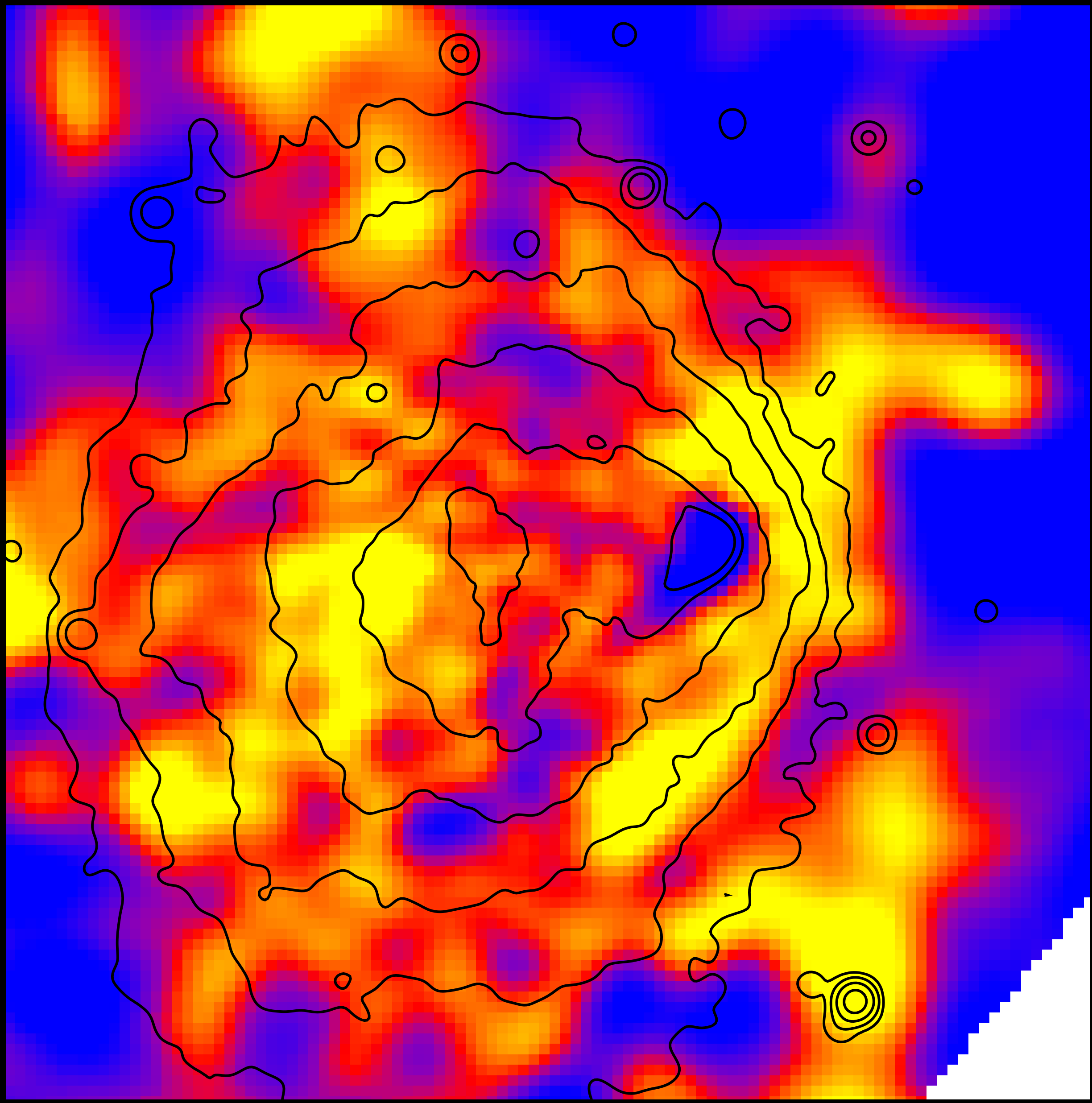
Merger shock fronts

1E 0657–56



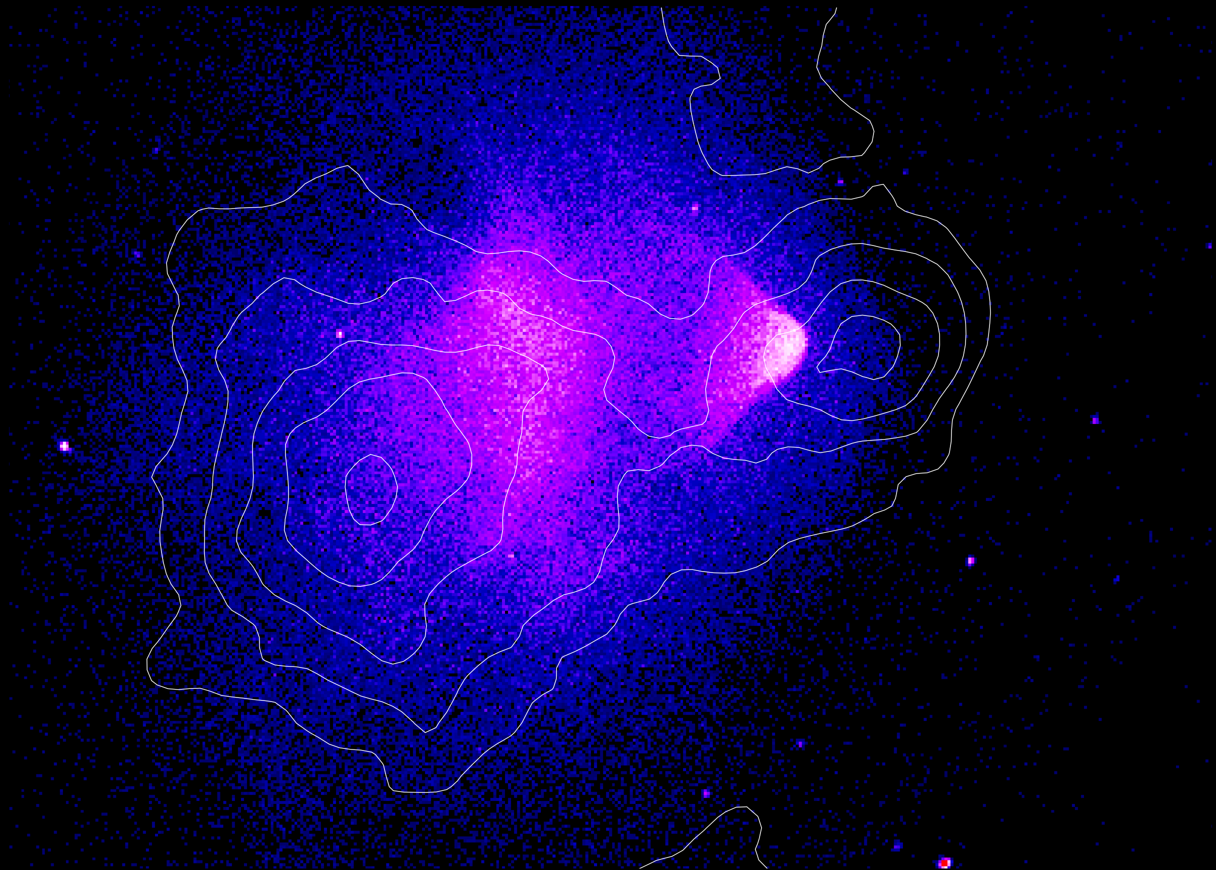
Chandra X-ray image

1E 0657–56



Chandra gas temperature map

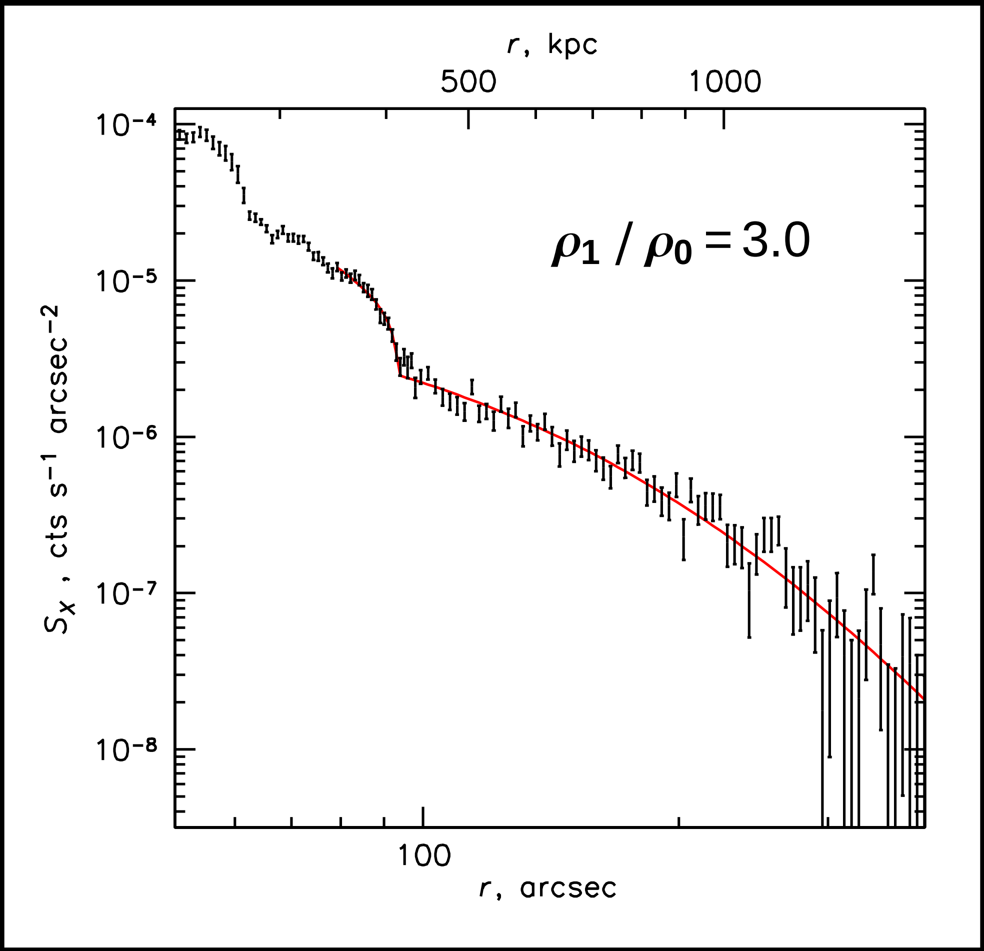
1E 0657–56

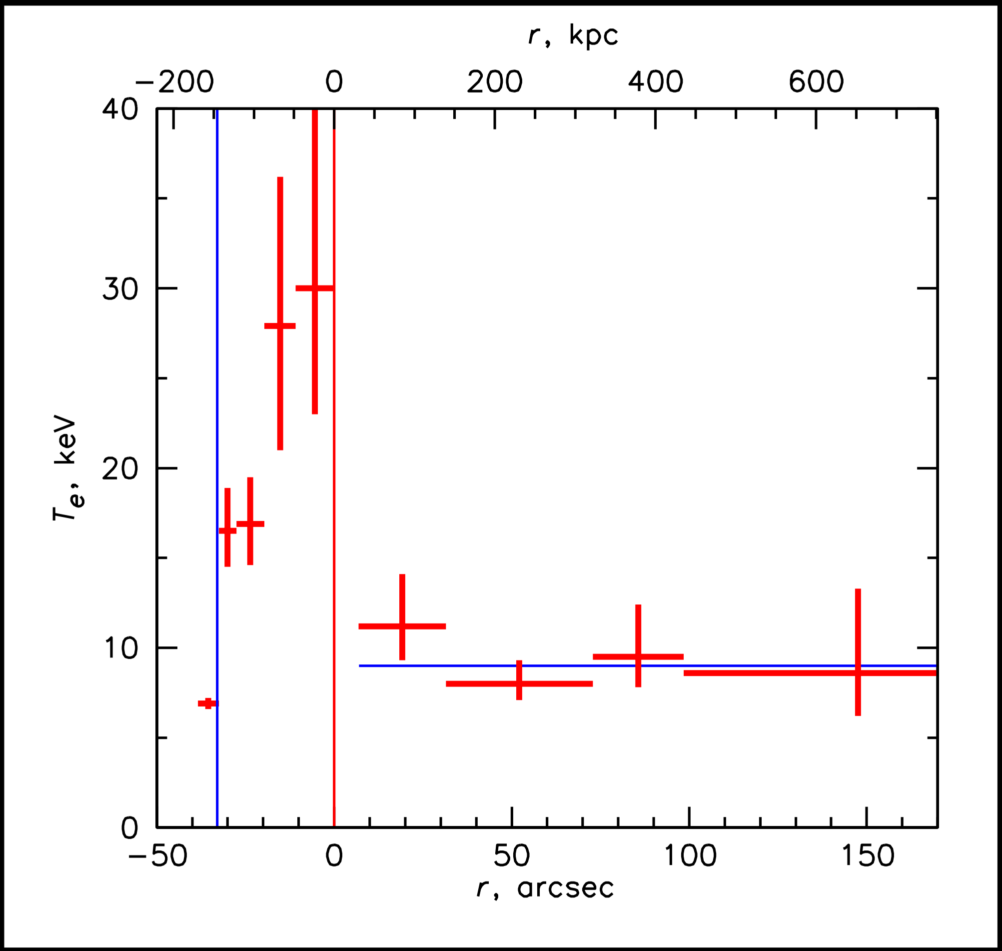


Chandra X-ray image

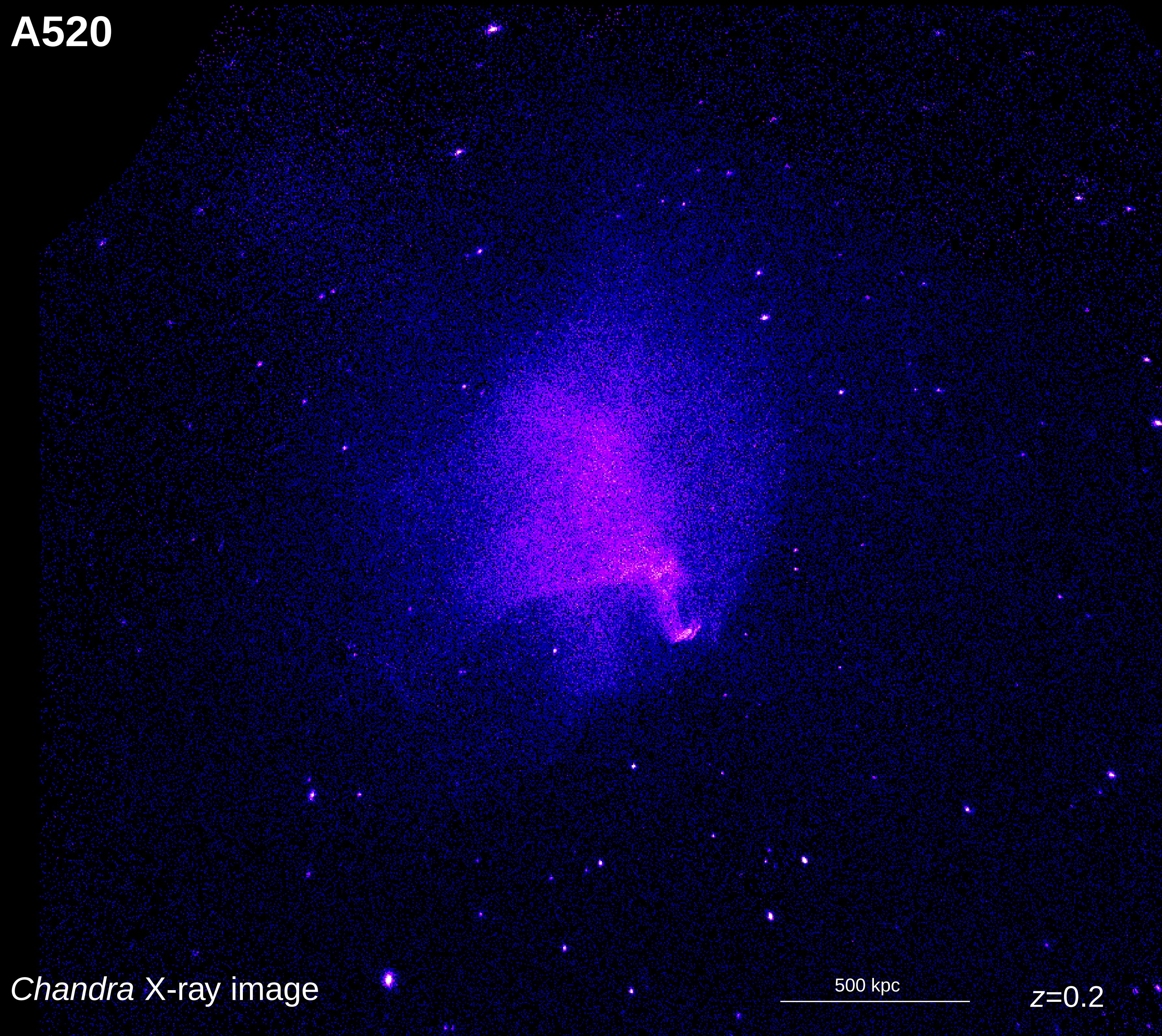
weak lensing mass contours (Clowe 06)

1E0657–56: textbook example of a shock front



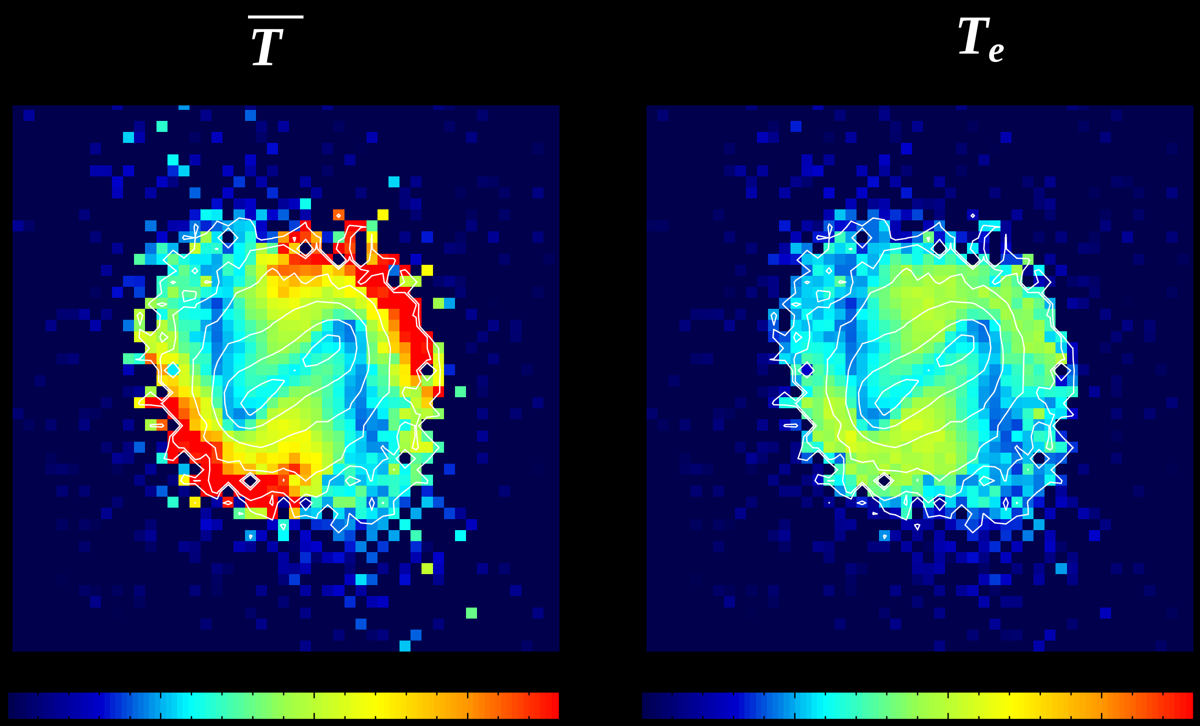


$M = 3.0 \pm 0.4$, shock $v = 4700$ km/s


A520
500 kpc
z=0.2
Chandra X-ray image

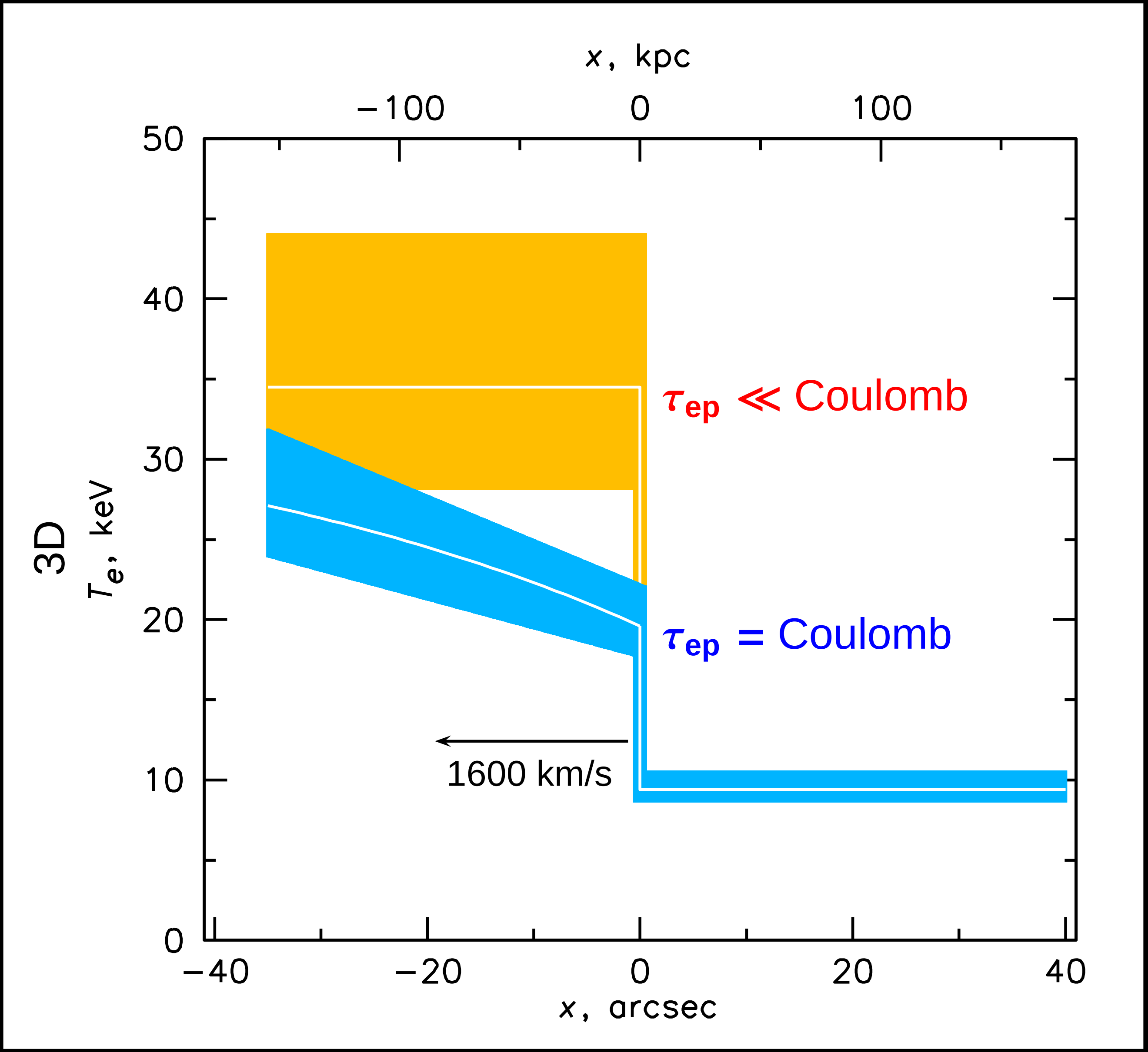
Physics from shocks I. Electron-ion nonequilibrium?

- At shock, protons heated dissipatively
- Electrons heated adiabatically and then reach equilibrium with protons on $t \sim \tau_{ep}$

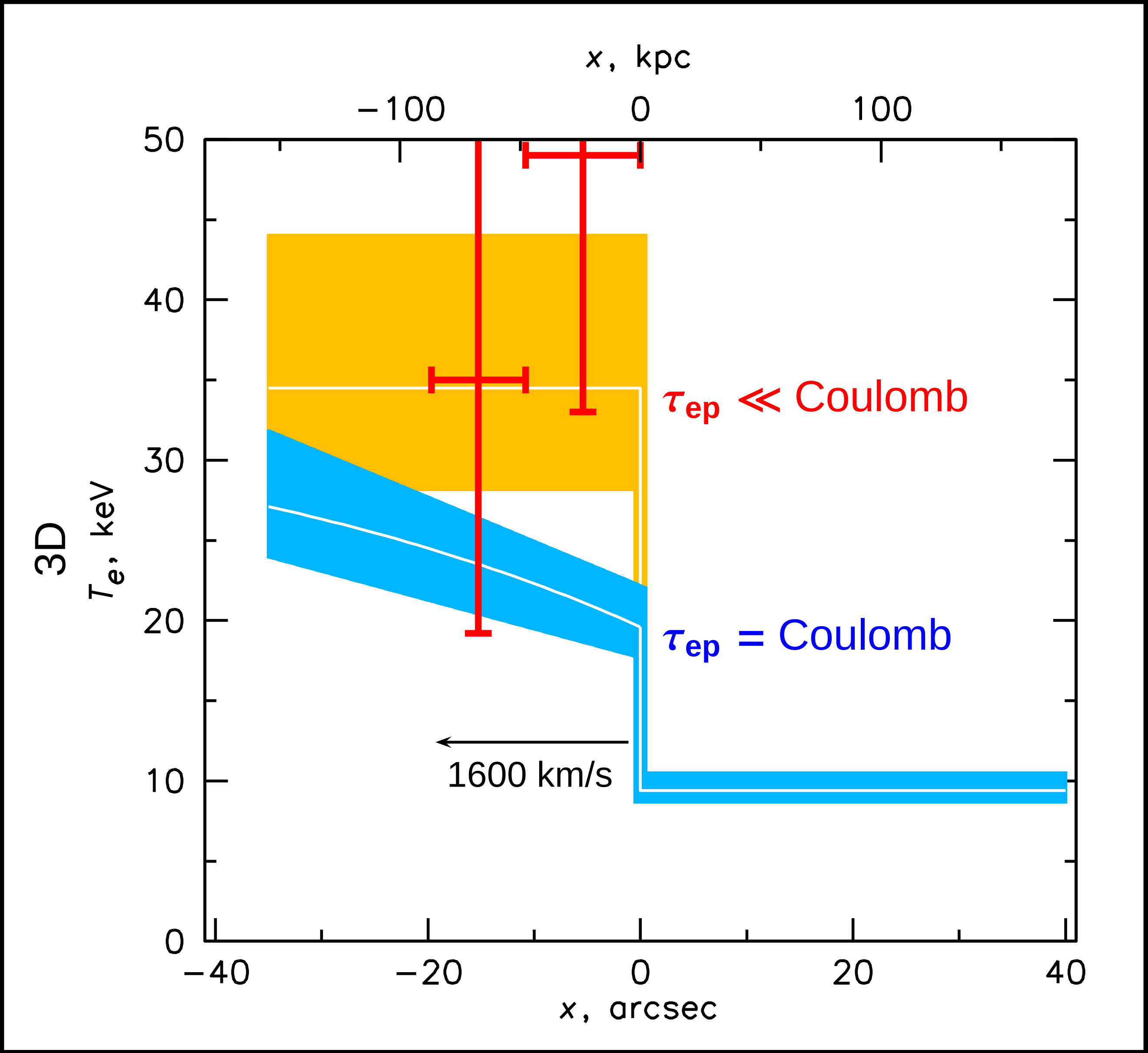


Collisional (Coulomb) τ_{ep} (simulations by Takizawa 1999)

Model predictions for Bullet cluster shock:

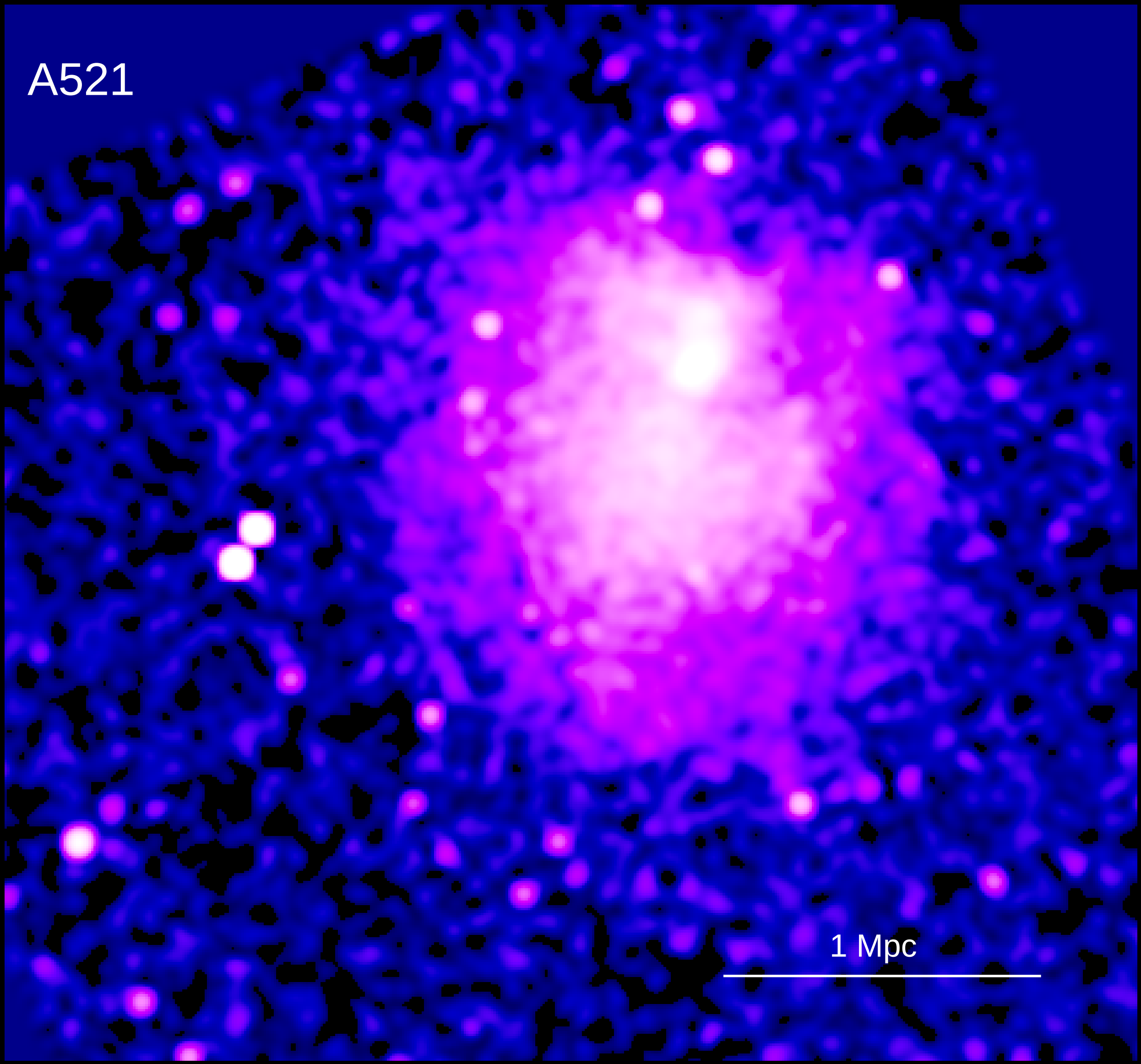


Model predictions for Bullet cluster shock:



- 95% confidence: $\tau_{ep} \ll$ Coulomb

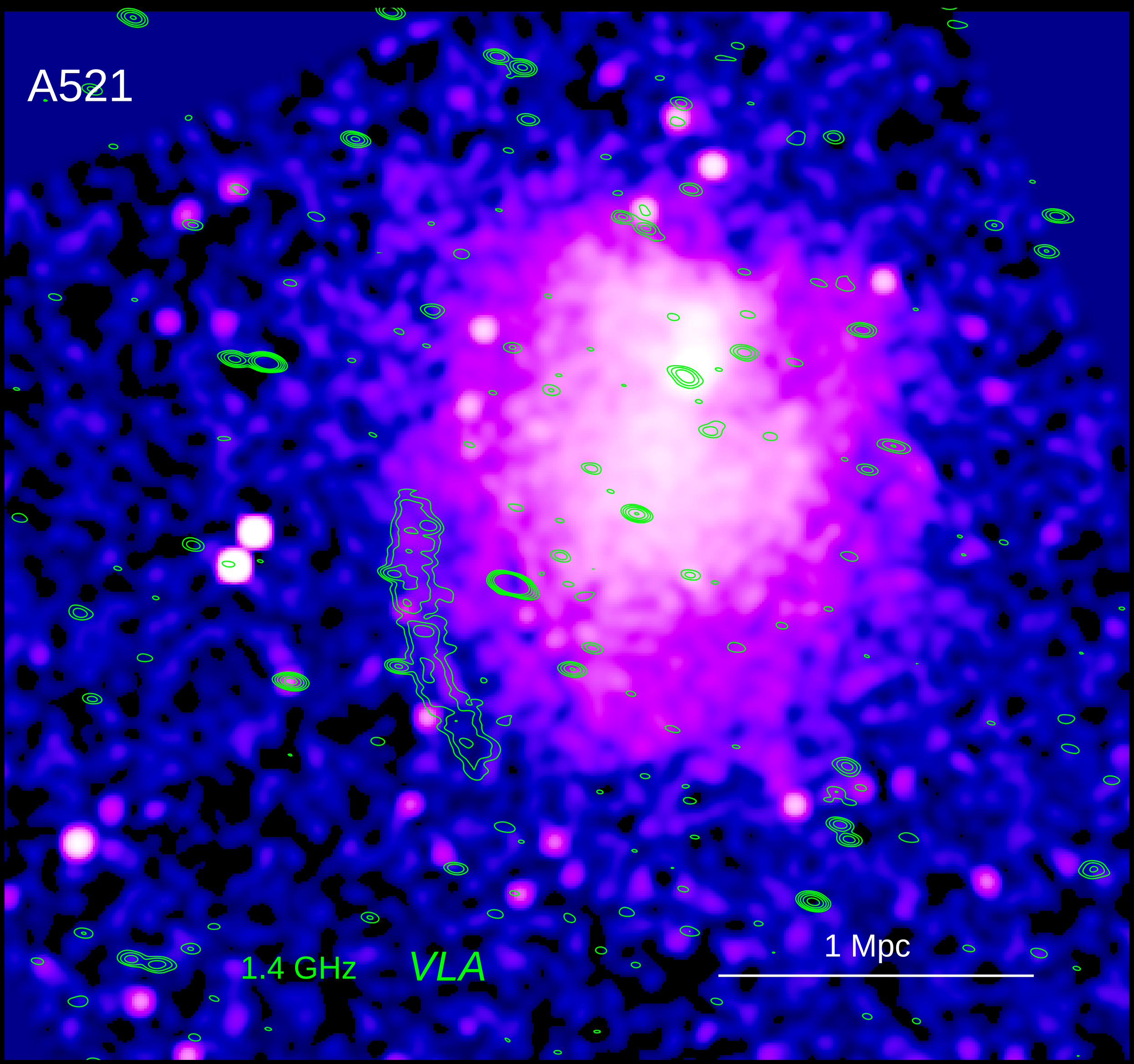
Physics from shocks II. Particle acceleration



Chandra X-ray image

Giacintucci et al. 08

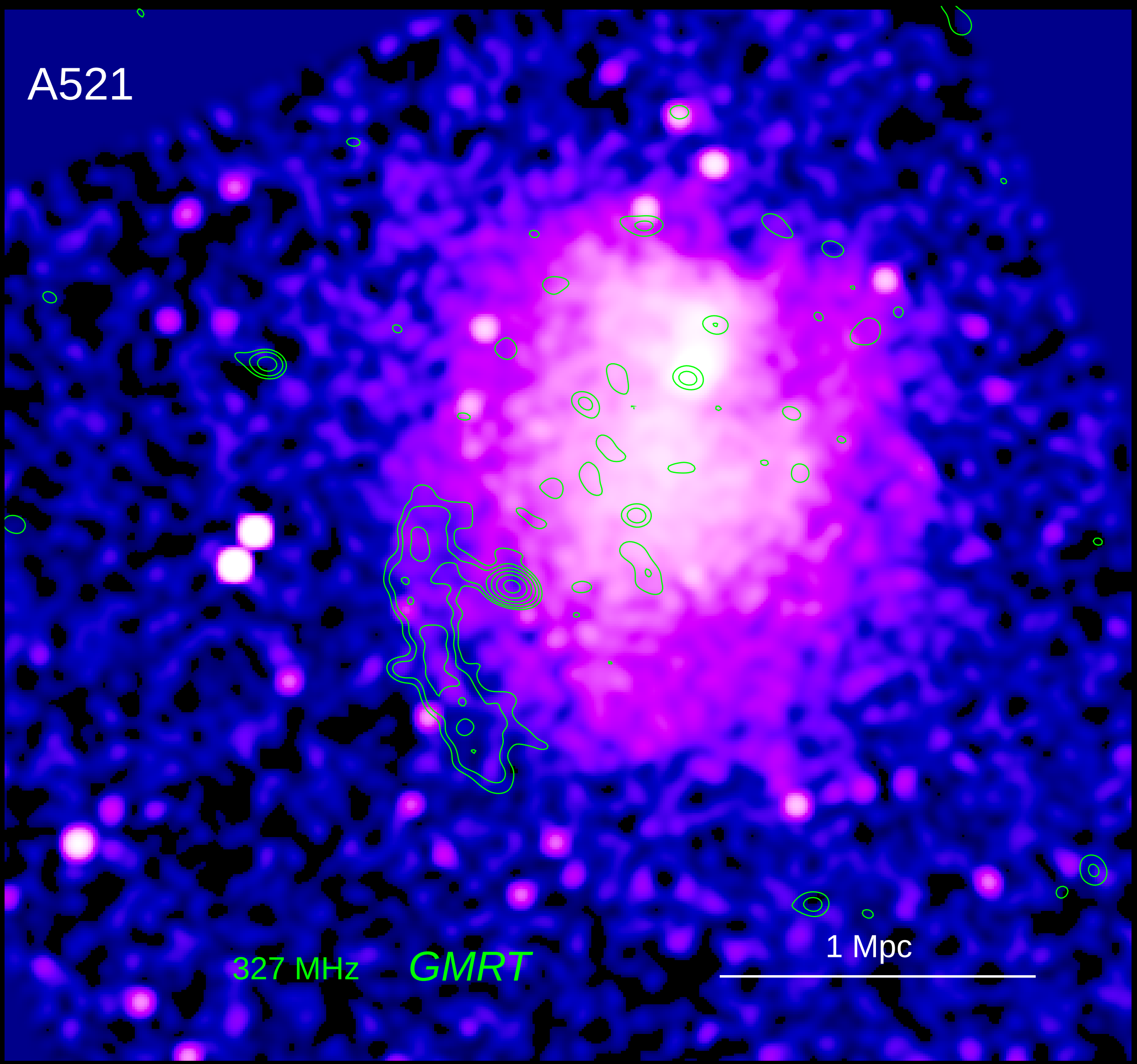
Physics from shocks II. Particle acceleration



Chandra X-ray image

Giacintucci et al. 08

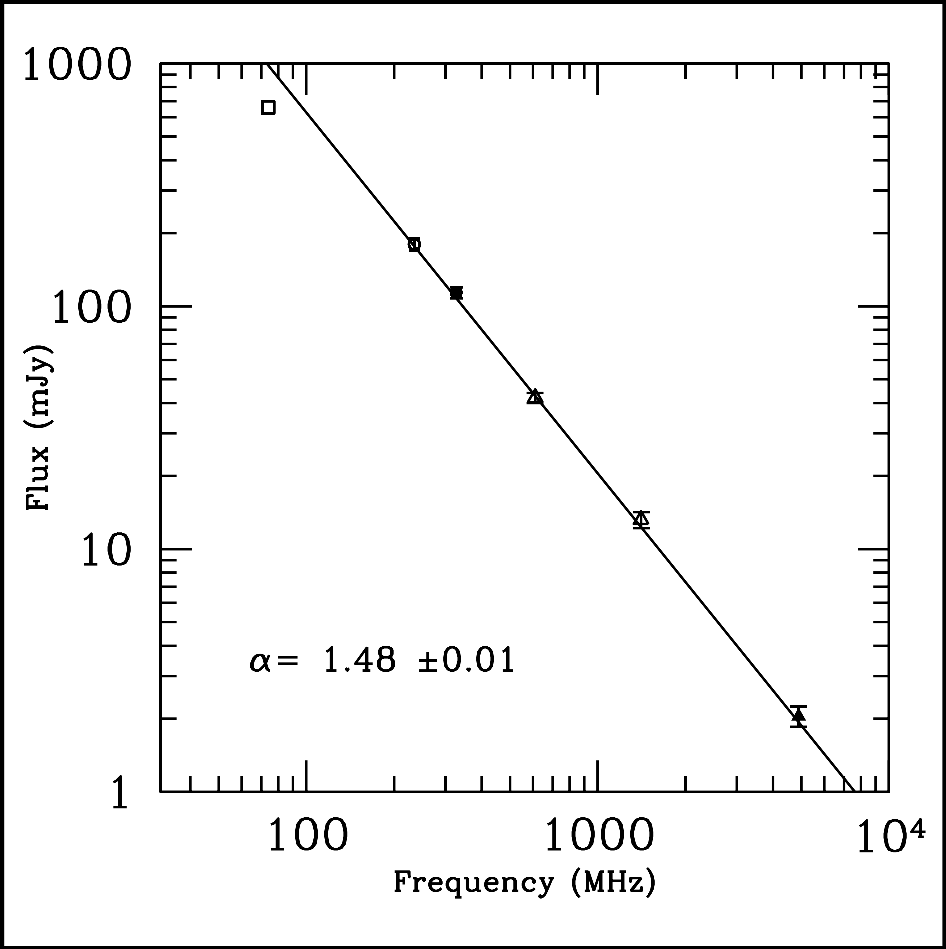
Physics from shocks II. Particle acceleration



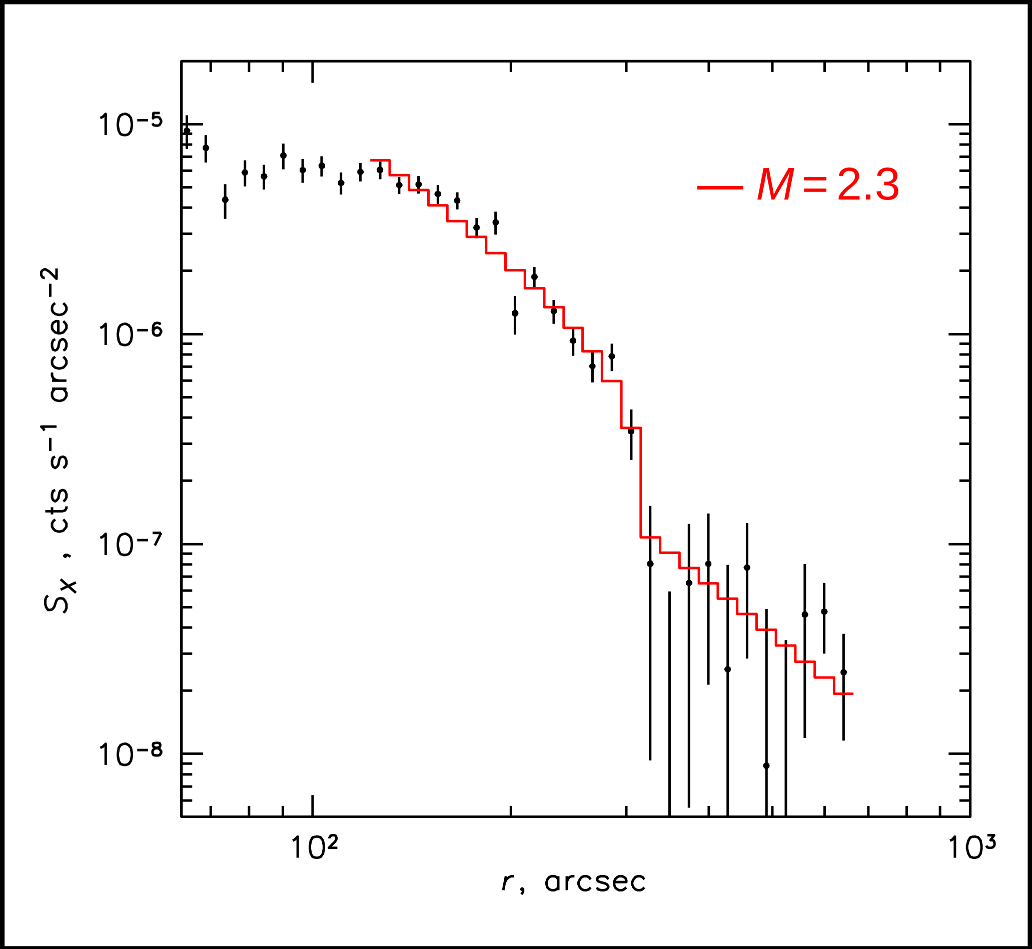
Chandra X-ray image

Giacintucci et al. 08

A521 relic radio spectrum



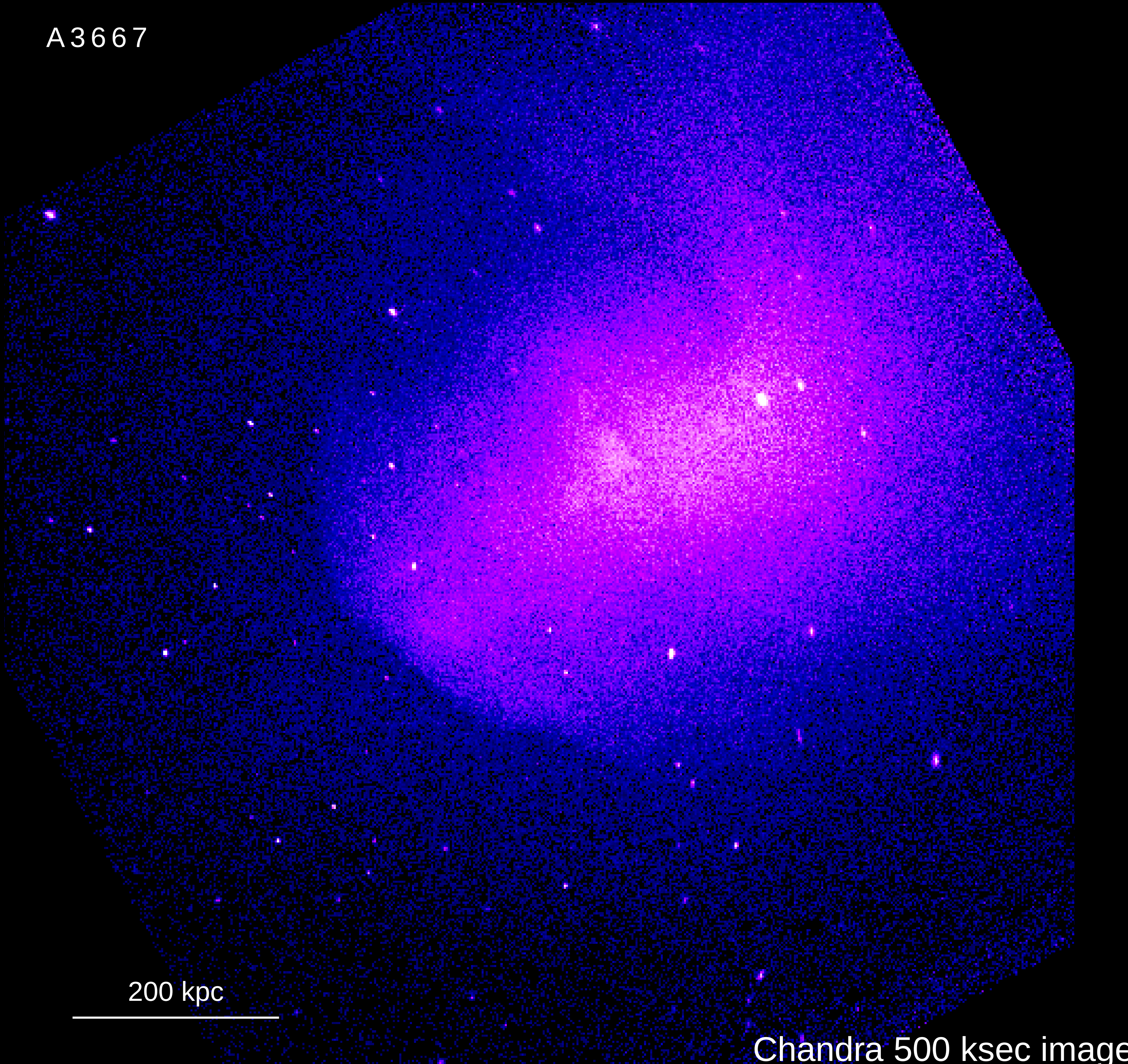
shock X-ray brightness profile

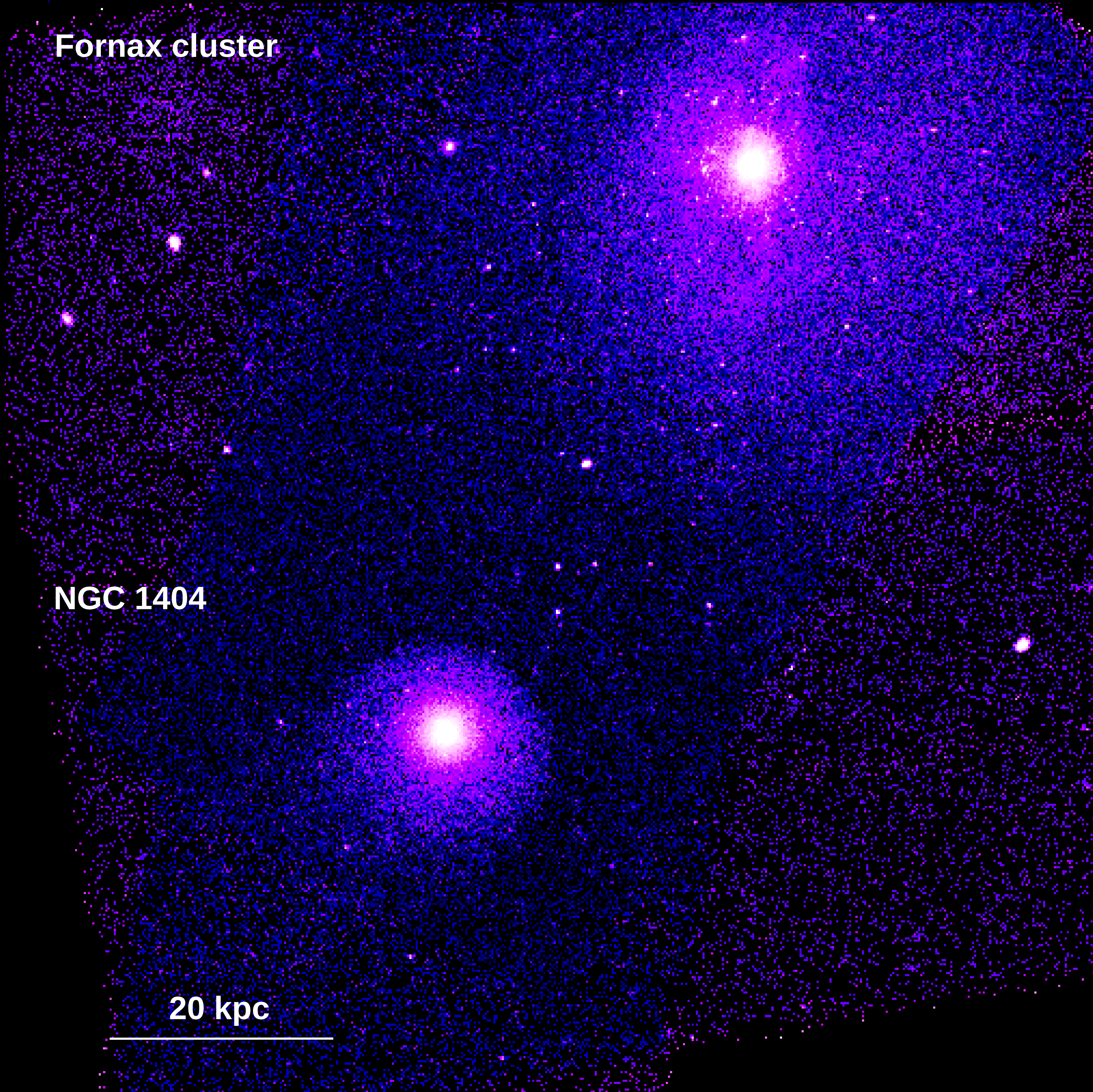


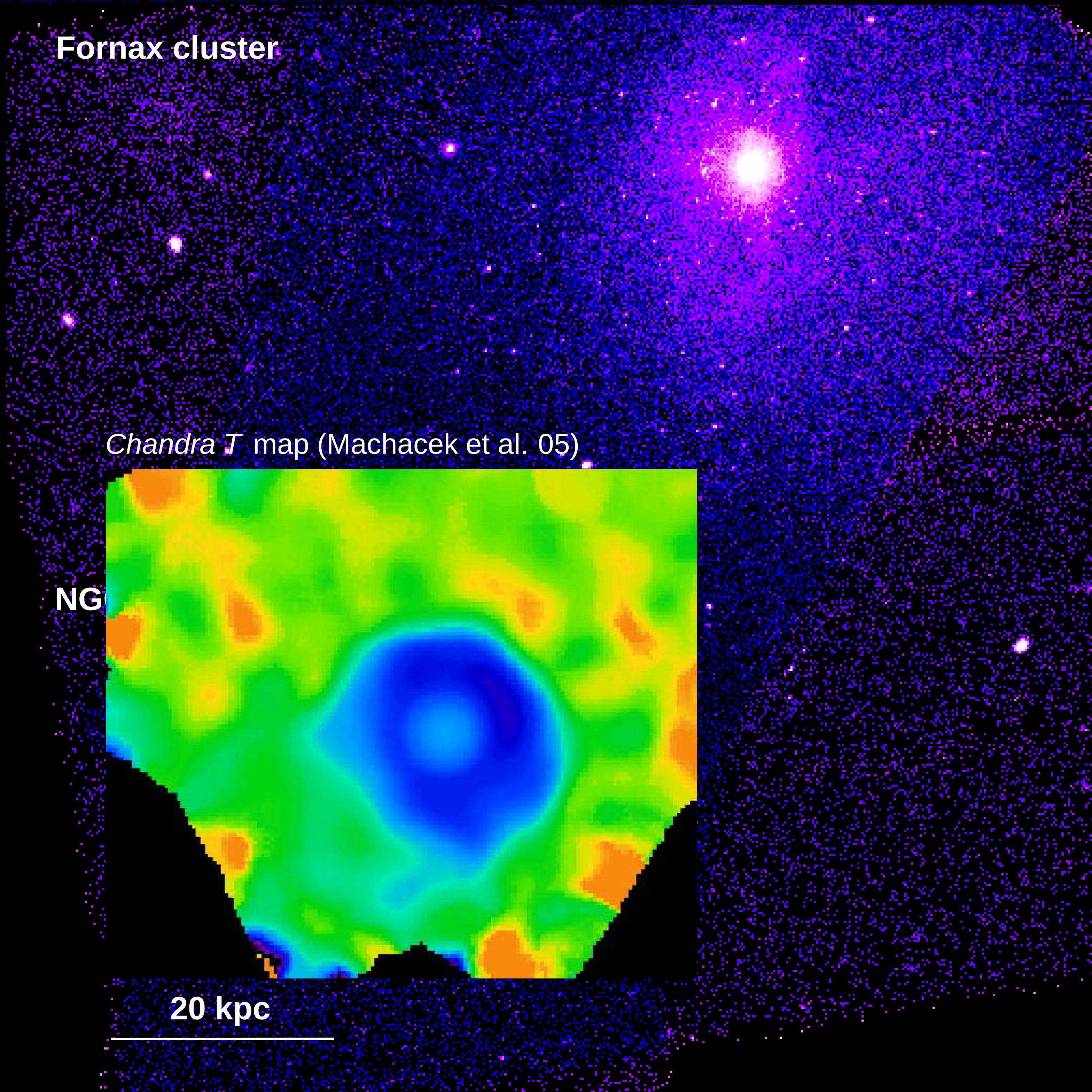
consistent with Fermi acceleration
on a $M = 2.3$ shock

Giacintucci et al. 08

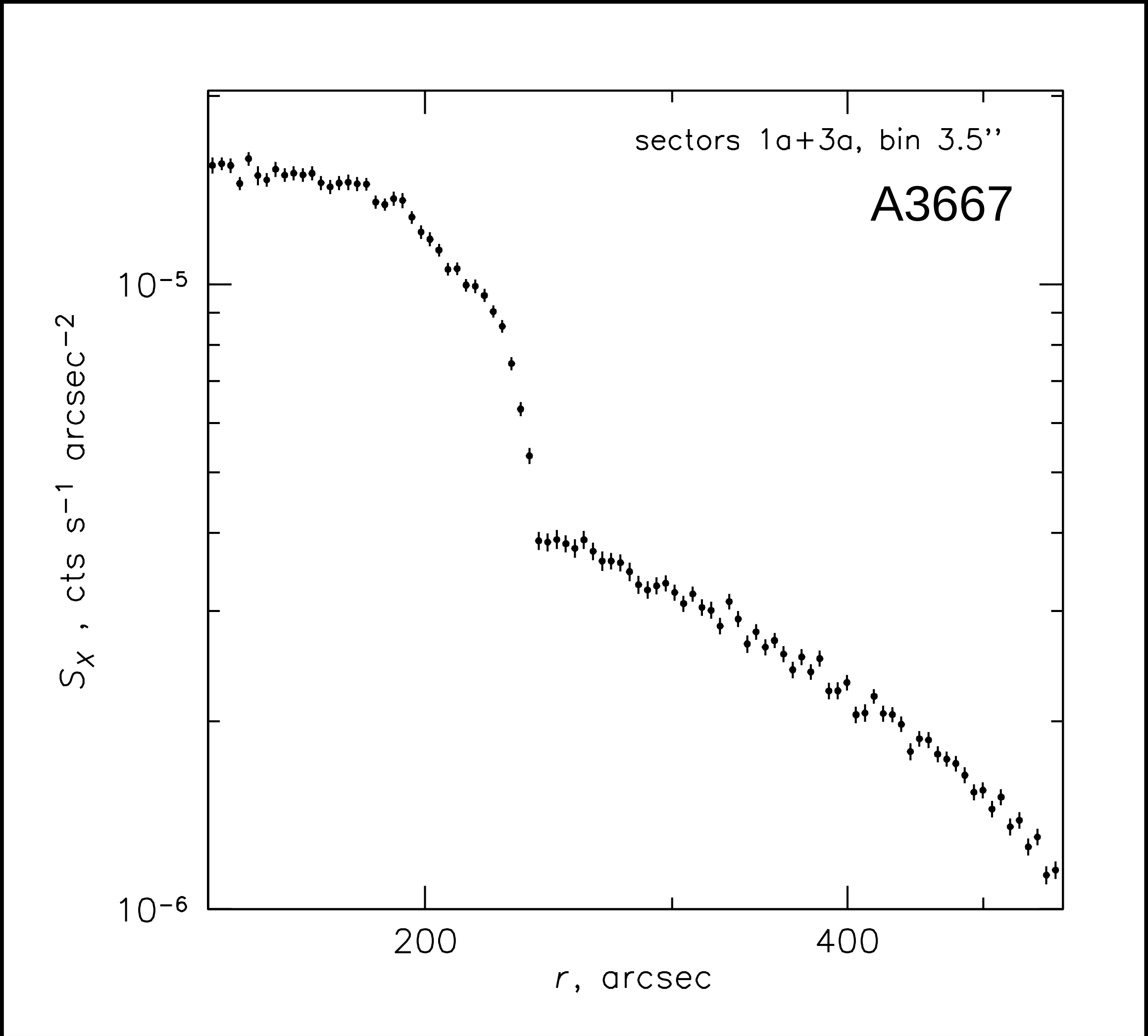
Cold fronts


A3667
200 kpc
Chandra 500 ksec image


Fornax cluster
NGC 1404
20 kpc


Fornax cluster
Chandra T map (Machacek et al. 05)
NG
20 kpc

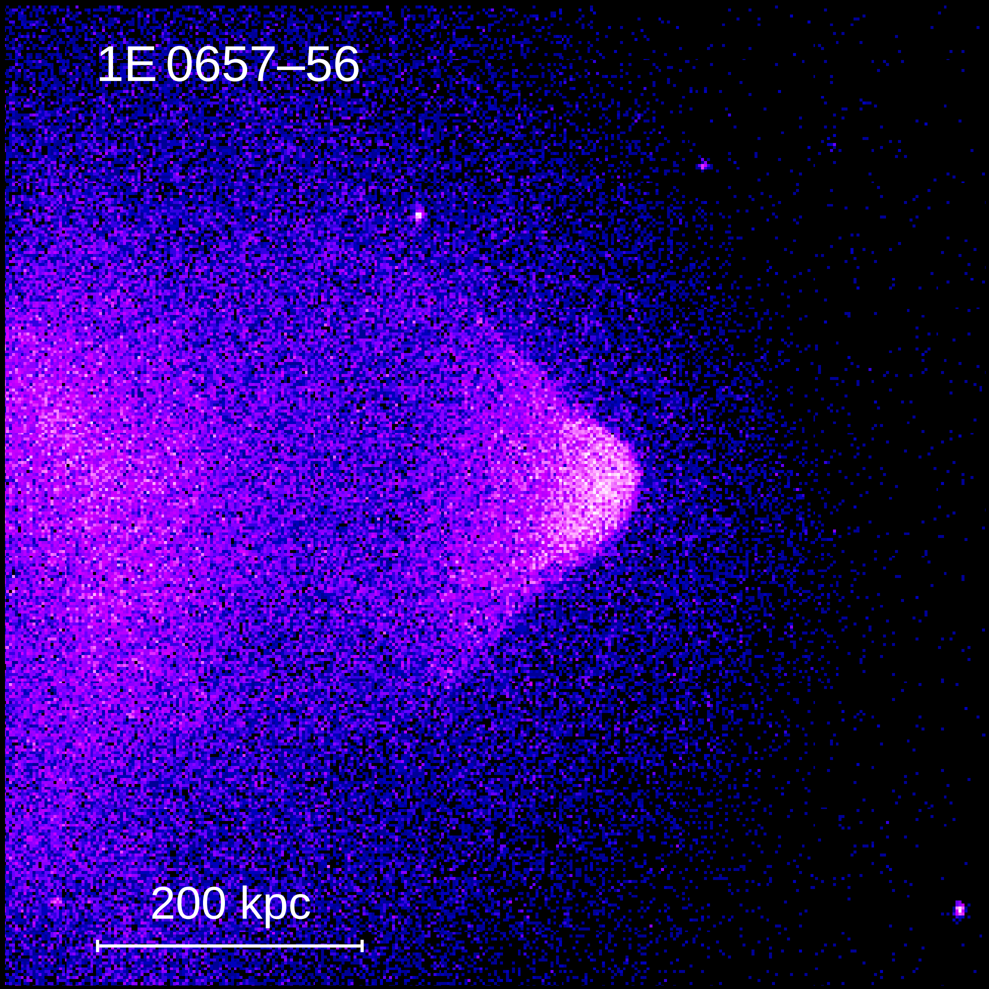
Physics from cold fronts I. Diffusion and conduction



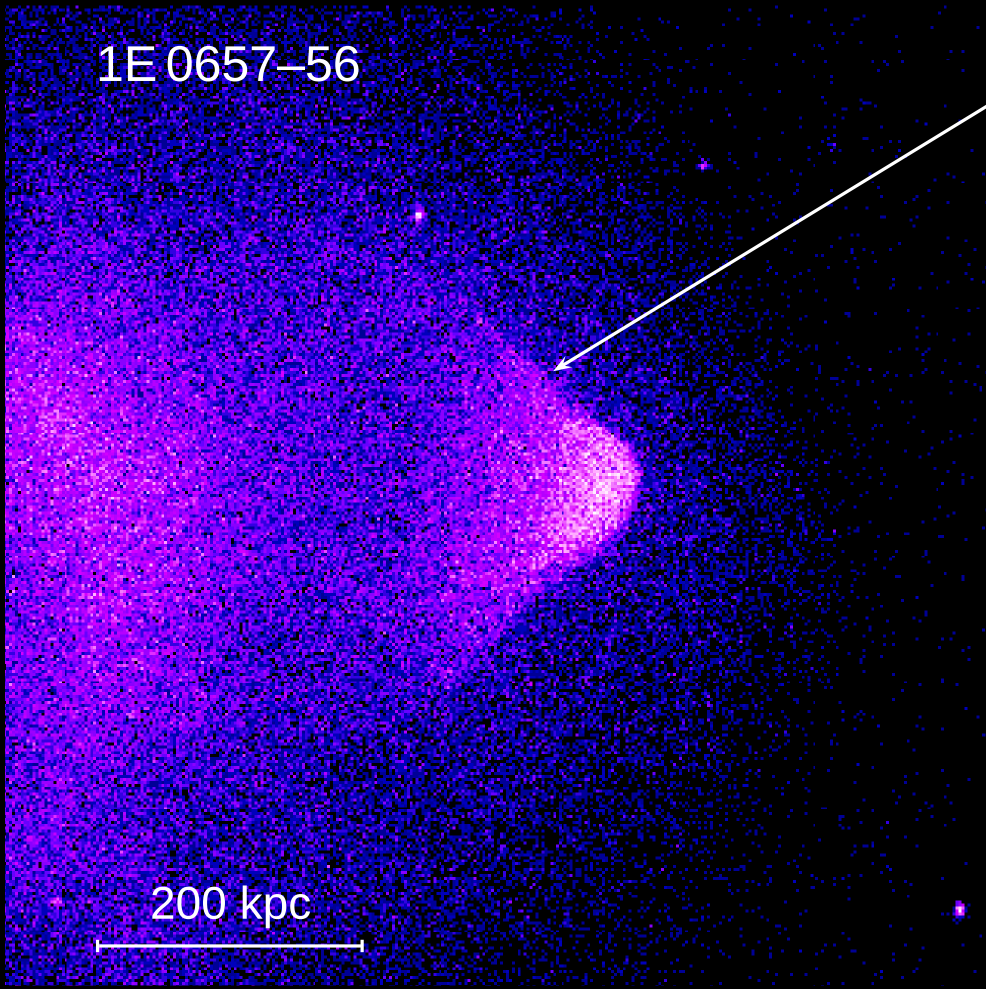
Width of density jump $\boldsymbol{d < 4}$ kpc $< \lambda_e$ (Coulomb) ≈ 10–15 kpc

→ diffusion across front is suppressed

Physics from cold fronts II. Viscosity



Physics from cold fronts II. Viscosity



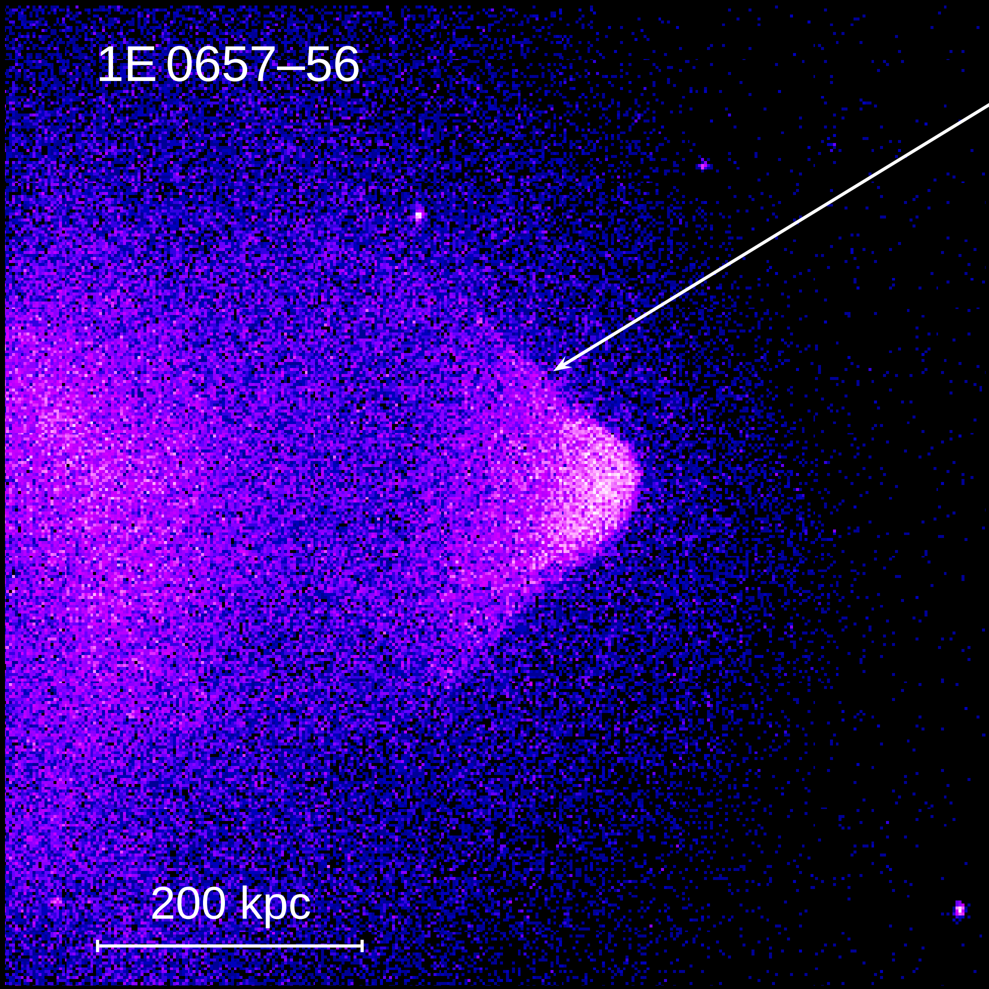
no turbulence → **Re < 10**

$$\mathrm{Re} \sim \frac{ML}{\lambda} \quad \rightarrow \quad \lambda > \text{few kpc}$$

Spitzer $\lambda_i = 1 - 10$ kpc

→ Plasma viscosity ≳ Spitzer

Physics from cold fronts II. Viscosity



no turbulence → **Re < 10**

$$\mathrm{Re} \sim \frac{ML}{\lambda} \quad \rightarrow \quad \lambda > \text{few kpc}$$

Spitzer $\lambda_i = 1 - 10$ kpc

→ Plasma viscosity $\gtrsim$ Spitzer

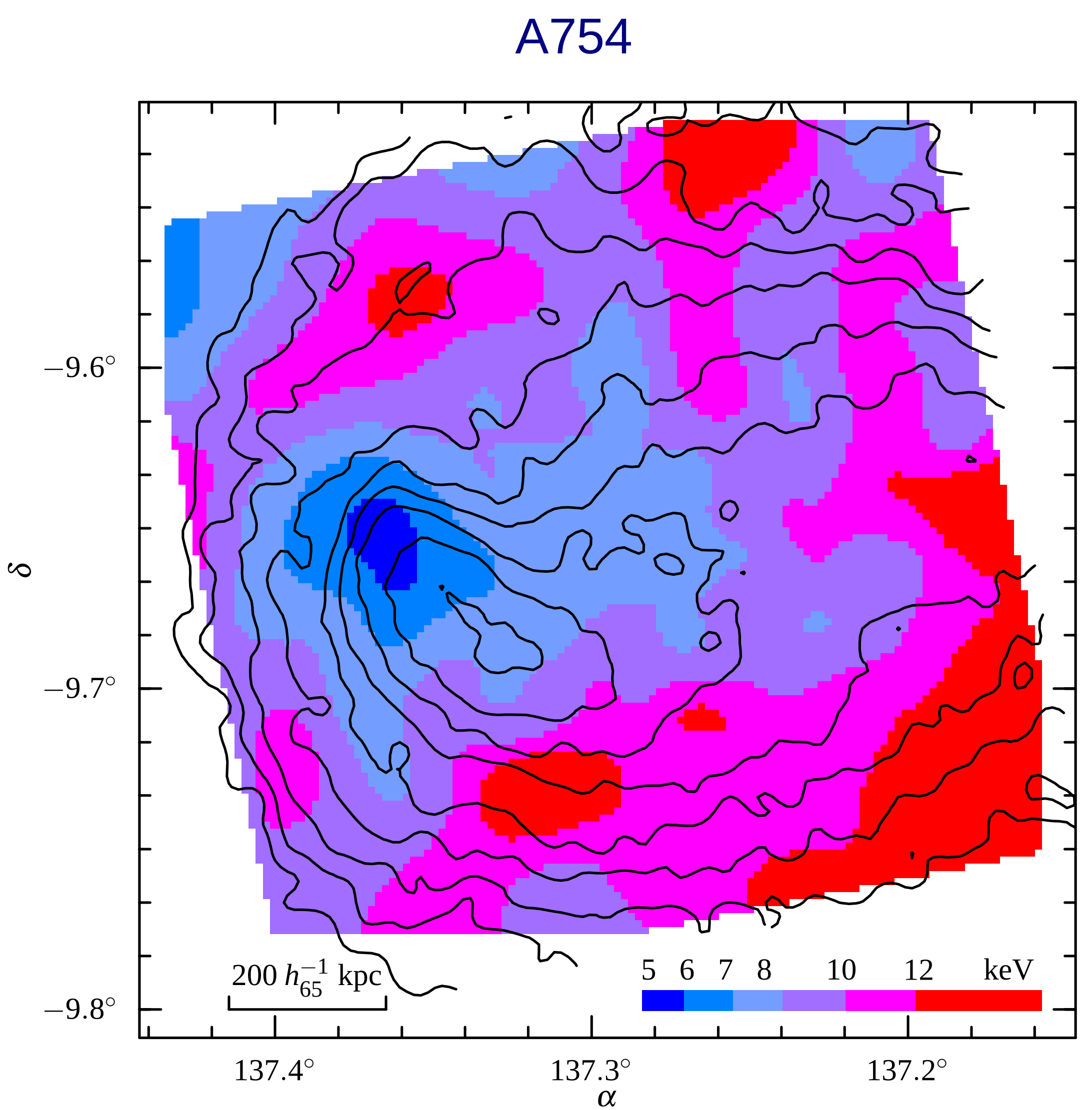
Upper limit: need turbulence to generate radio halos

Summary

X-ray observations of intracluster shock fronts and cold fronts offer interesting tests of plasma properties:

- From the best-studied shock (Bullet cluster), $\tau_{ep} \ll$ Coulomb (first such measurement in any astrophysical plasma?)
- Directly see relativistic particle acceleration by shocks — even in relatively weak, $M \sim 2$ fronts
- From sharpness and stability of cold fronts:
  - diffusion and thermal conduction are suppressed
  - viscosity probably as high as Spitzer

Thermal conduction in the bulk of ICM



Chandra T map (Markevitch et al. 2003)

Time for T variations to disappear (for Spitzer $\varkappa$):

$$t_{\rm cond} \sim \frac{k n_e l^2}{\varkappa} \simeq 1.2 \times 10^7 \text{ yr}$$

Age of the structure:

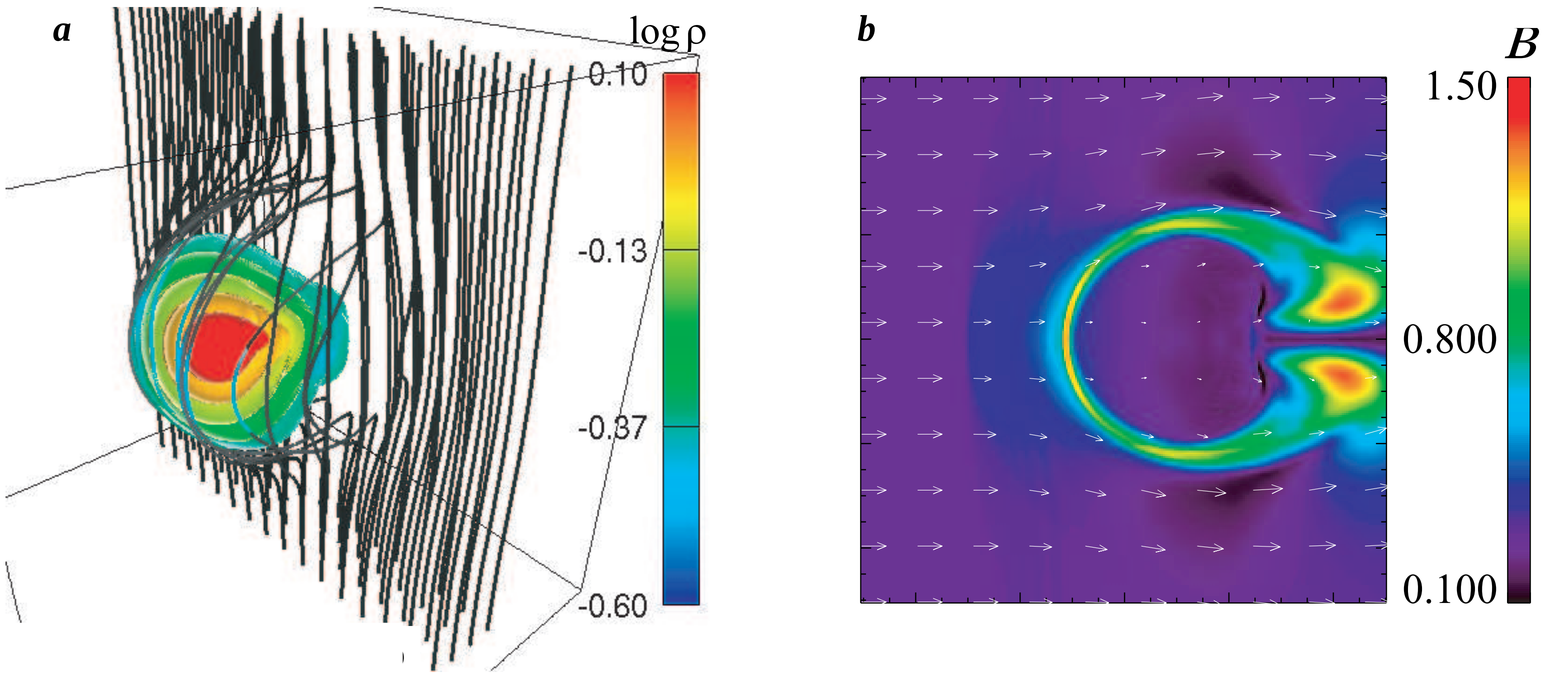
$$t_{\rm age} \sim \frac{L}{c_s} \sim 5 \times 10^8 \text{ yr}$$

Conduction suppressed by factor

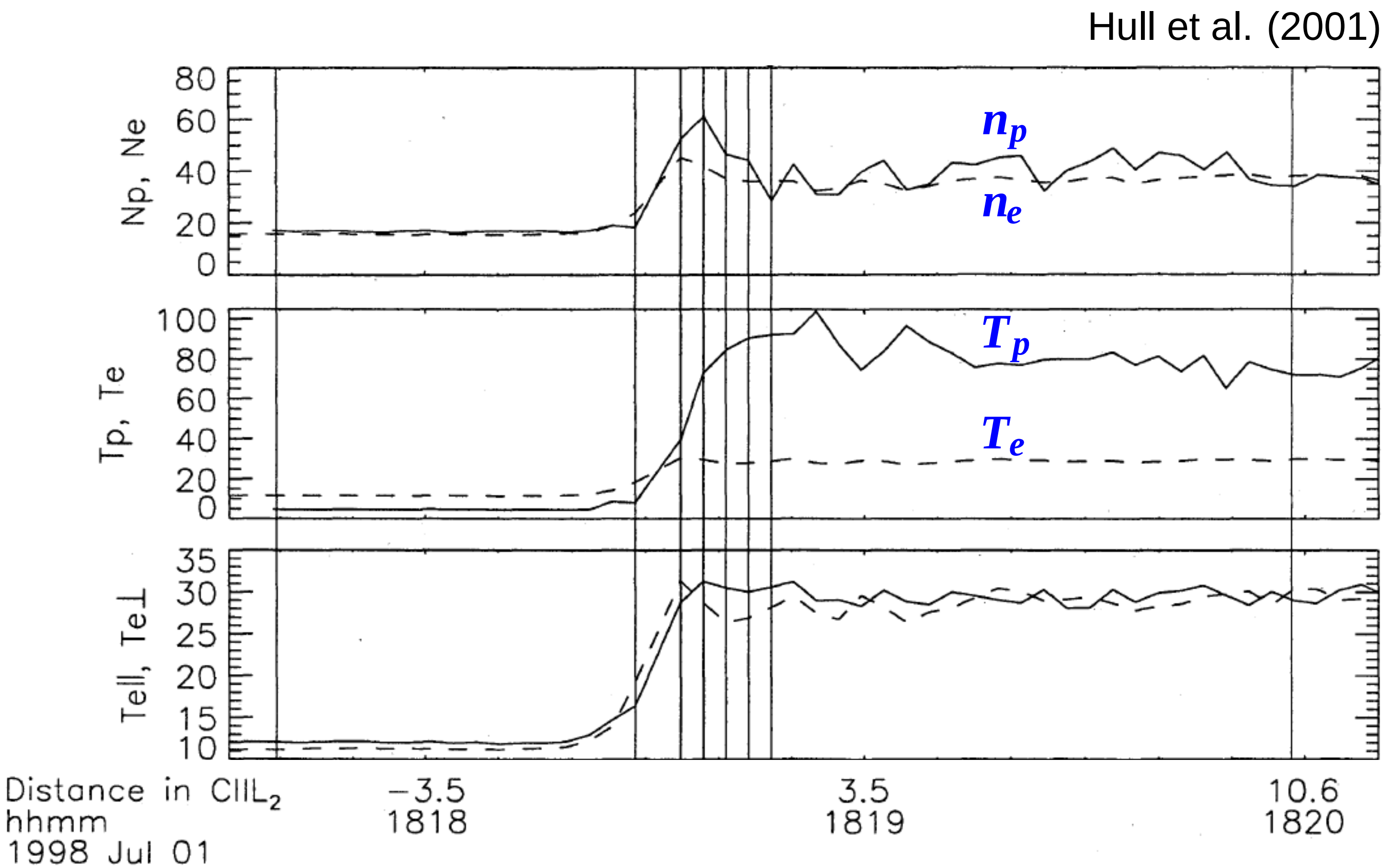
$$\frac{t_{\rm age}}{t_{\rm cond}} > 10$$

Magnetic draping

Simulation of magnetic field around cold front (Asai et al. 05)



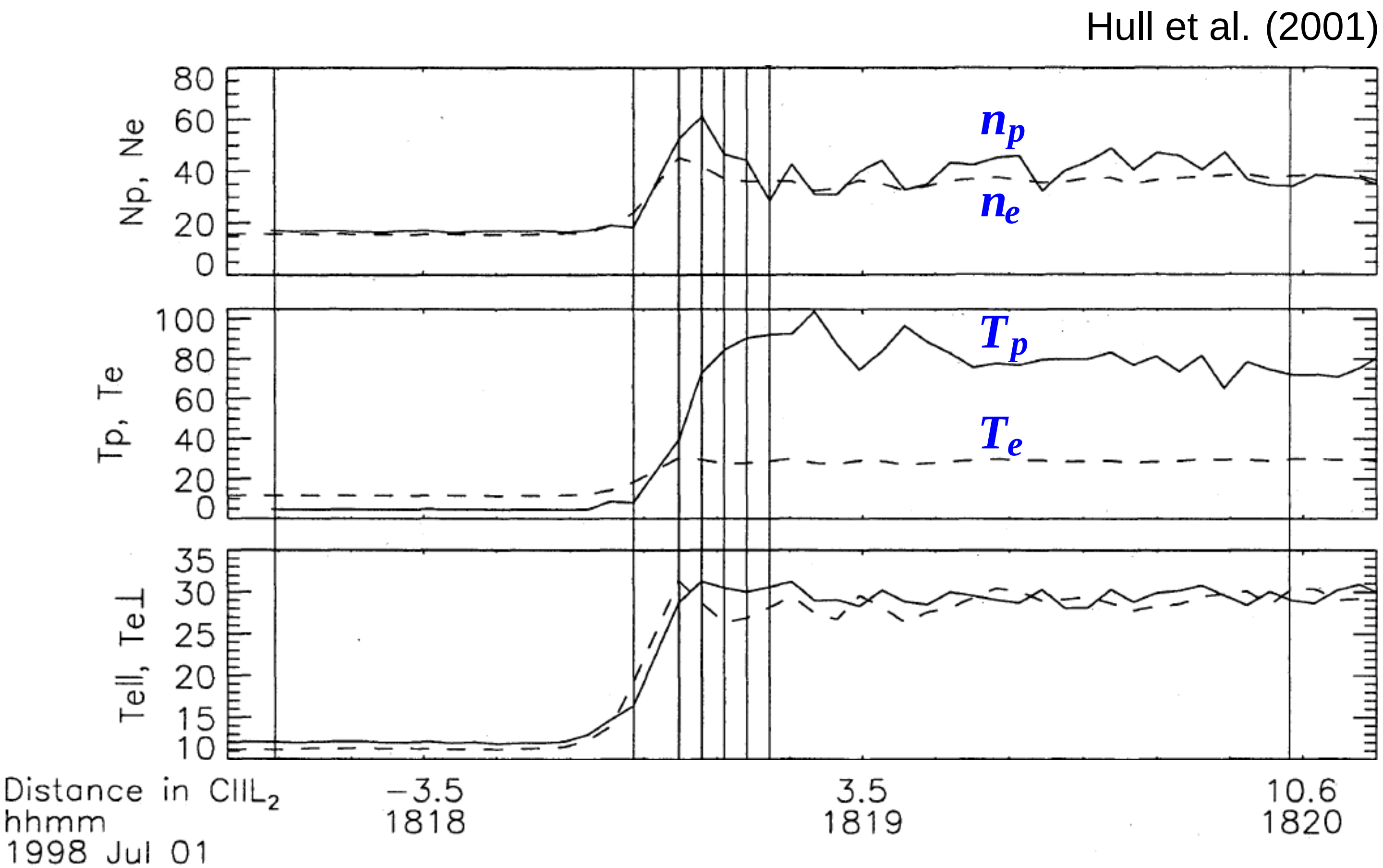
Typical Earth’s bow shock:



unit ~ $10^{-7}\ \tau_{coll}$

Electrons are not heated at shock

Typical Earth's bow shock:



unit ~ $10^{-7}\ \tau_{coll}$

Electrons are not heated at shock

→ fast $T_e - T_p$ equilibration outside shocks