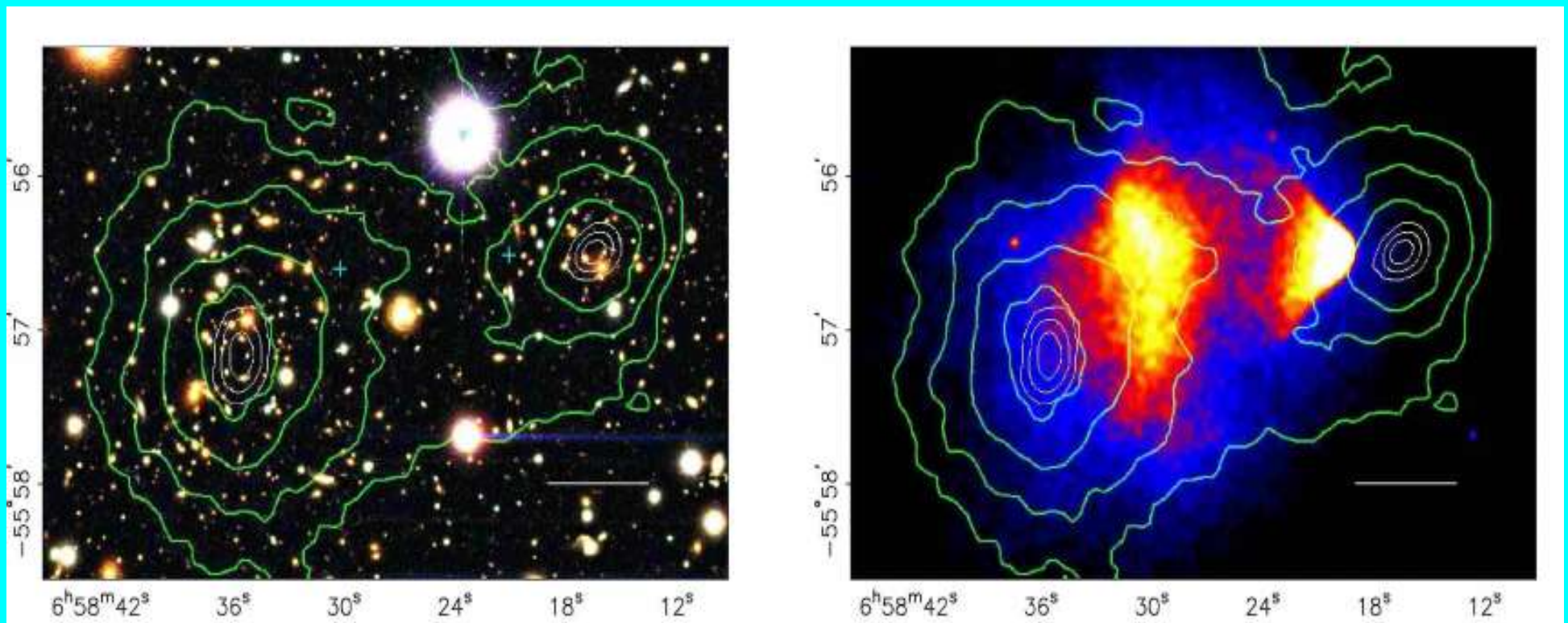


Direct evidence for dark matter in “bullet” cluster 1E 0657-56

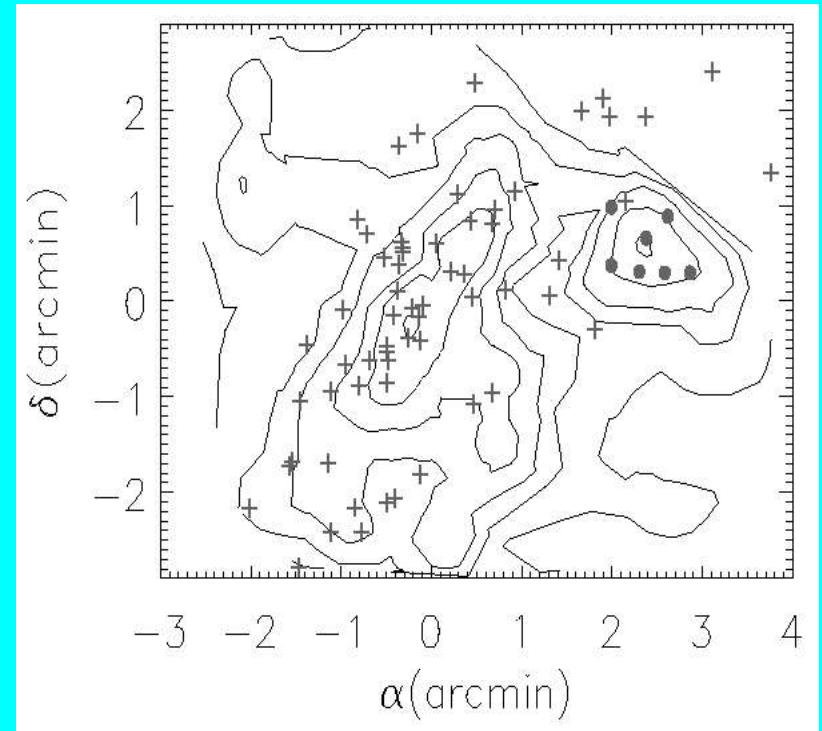


“Bullet” cluster

- Clusters form by merging of subclusters
- In mergers, dark matter and baryons can be segregated due to different particle properties
- Bullet cluster is special merger because the merging happens in the plane of the sky →
- merger signatures are sharp and the dynamics can be accurately determined

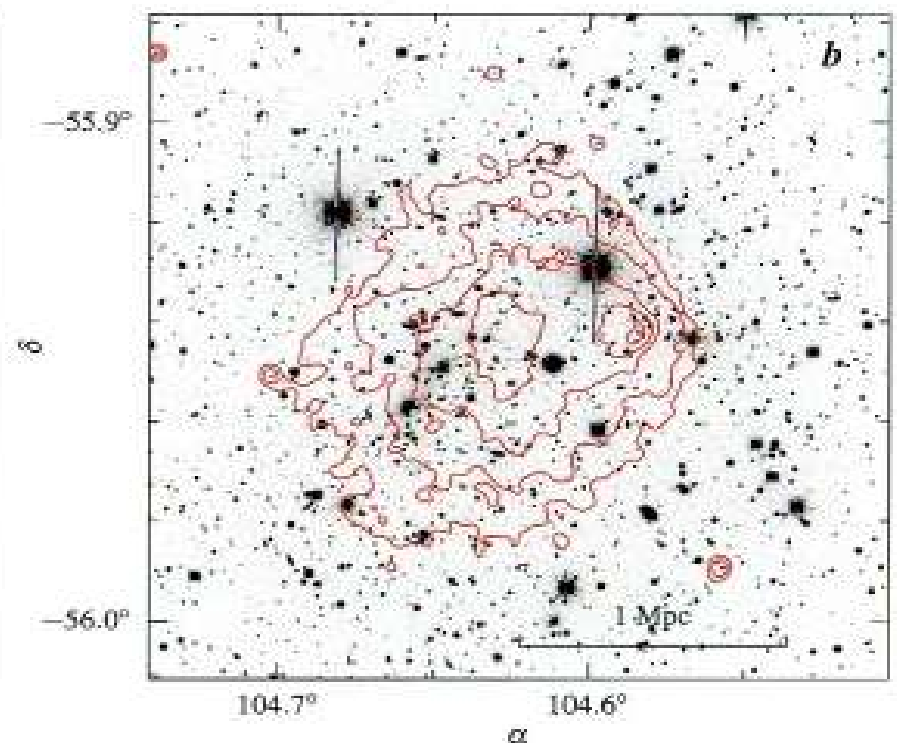
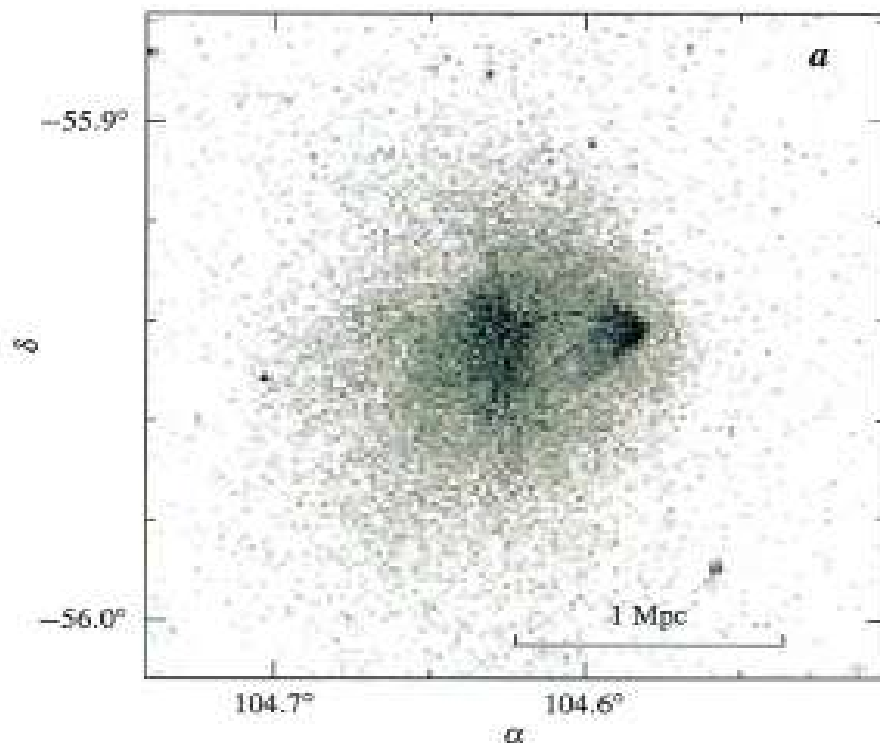
Galaxy distribution

- ESO spectra of 129 galaxies
- elongated main cluster ; subcluster at 0.7 Mpc
- same redshifts and spectral types: same origin
- line of sight velocity difference 600 km s^{-1}



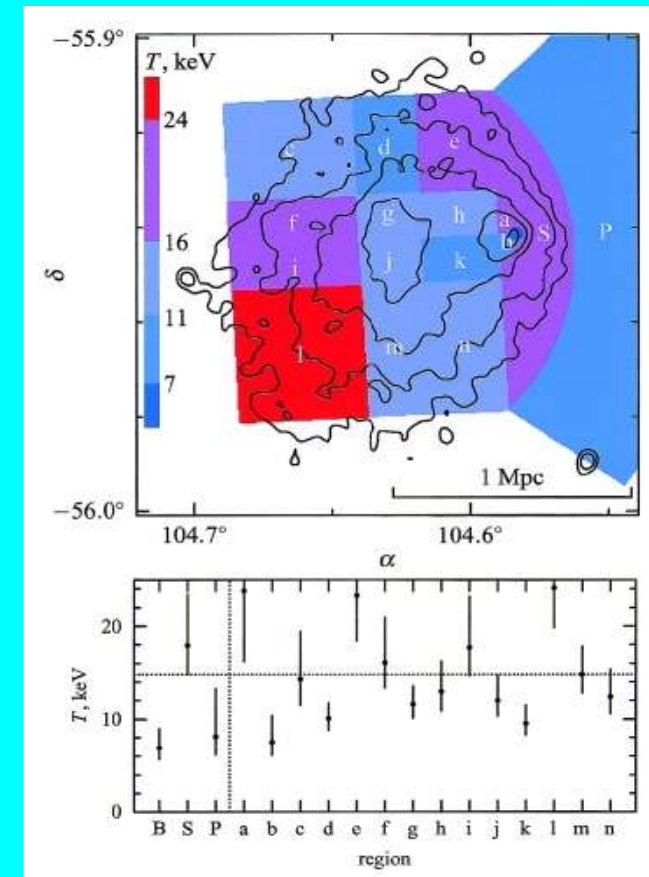
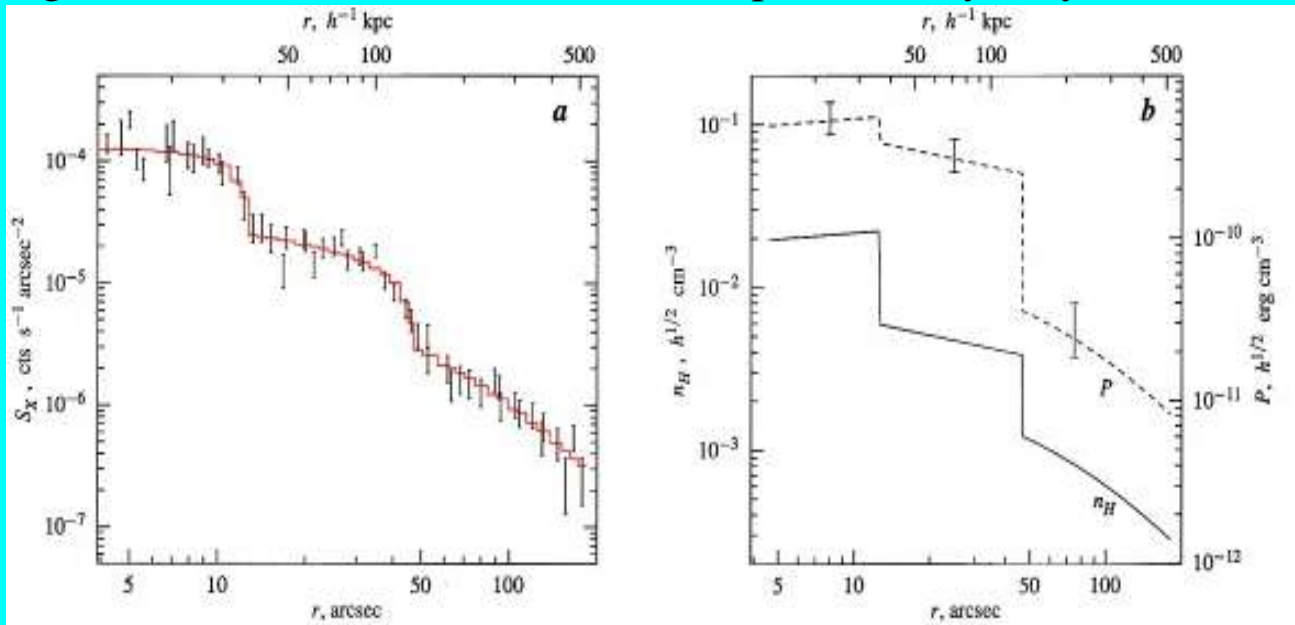
Baryon distribution from X-rays

- Chandra X-ray analysis (Markevitch et al., 2002, ApJ, 567, L27):
- two peaks, bullet-like subcluster

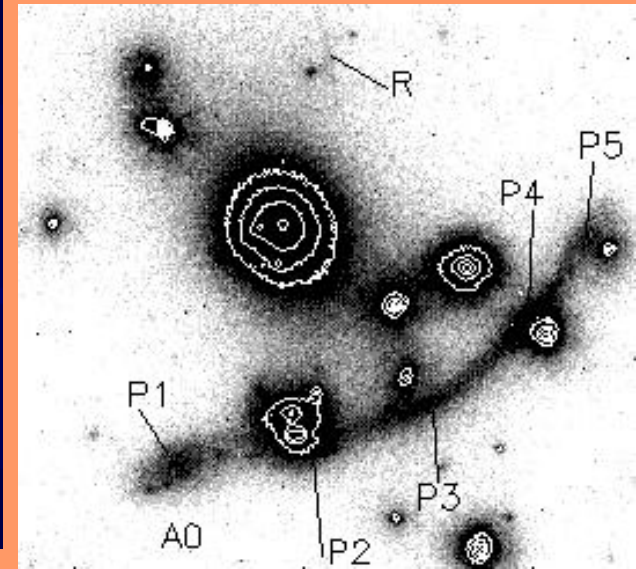
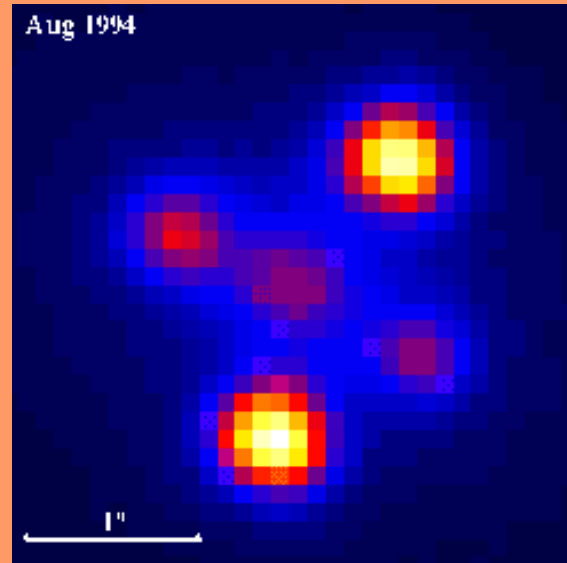
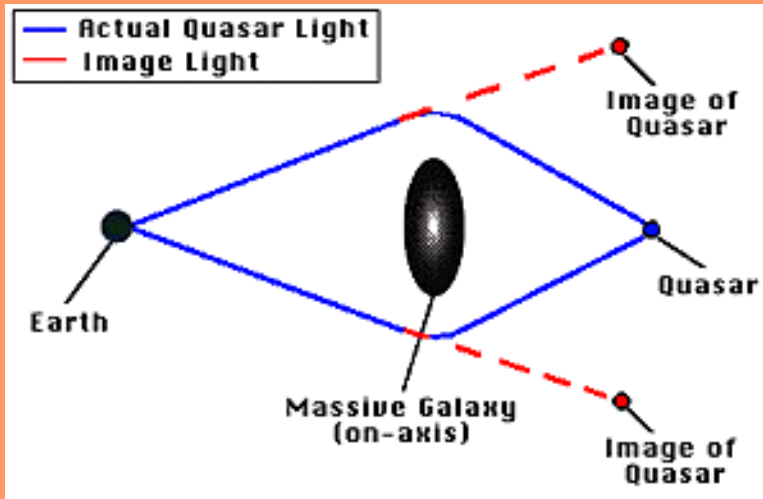


Baryon distribution from X-rays

- cool bullet-like subclump (7 keV), hot shock (18 keV) , cool perimeter (8 keV)
- gas density jumps by a factor of 3-4 at shock edges: UNSTABLE →
- Mach number 2-3, $v = 3000-4000 \text{ km s}^{-1}$, passed core 0.1 Gyr ago
- V_{shock} high compared to V_{LOS} difference (600 km s) →
- angle between direction of motion and plane of sky only 8°



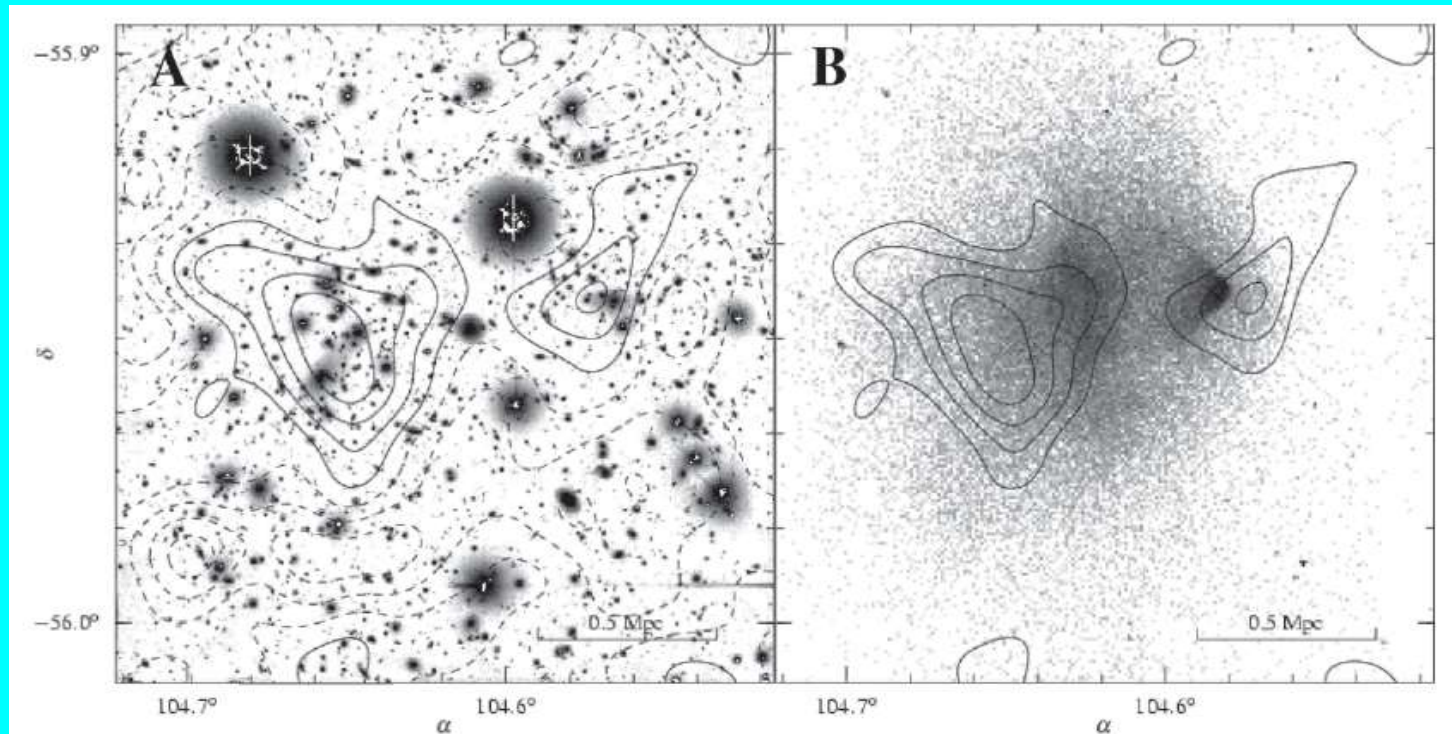
Gravitational lenses (I)



- Mass bends the light
- Strong lensing: many images of the same object
- Weak lensing: image distortions (arcs, elongations)

Total mass from weak lensing I

- A: VLT I-band image used to measure galaxy shapes
- A: 2 distinct mass peaks , same redshift
- B: weak lensing mass contours and Chandra X-ray image

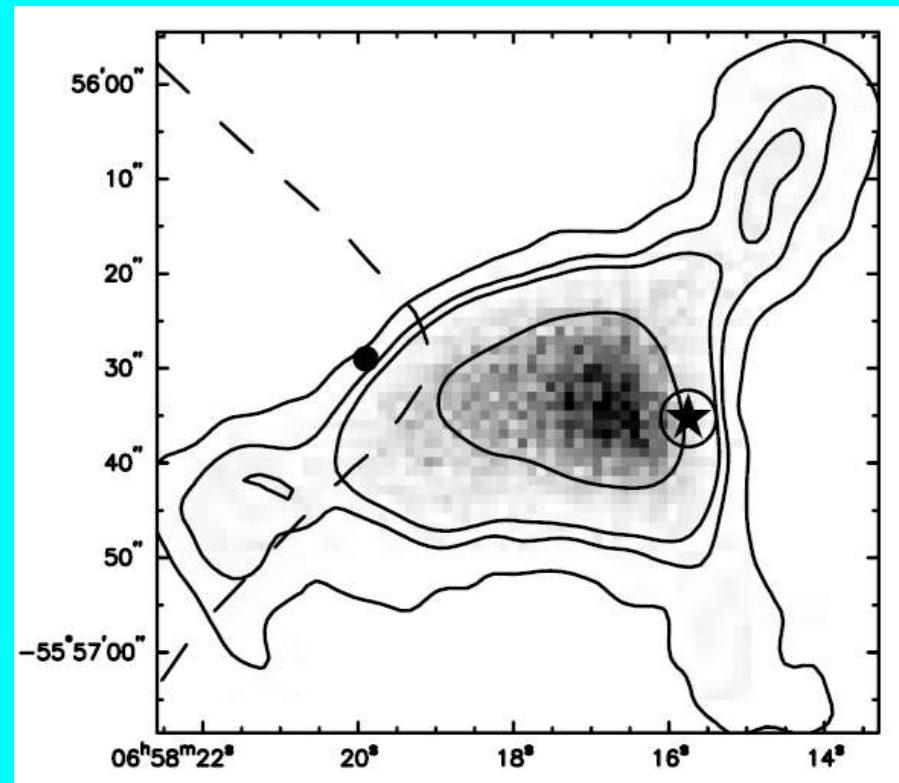


Clowe et al., 2004, ApJ, 648:L109

Total mass from weak lensing I

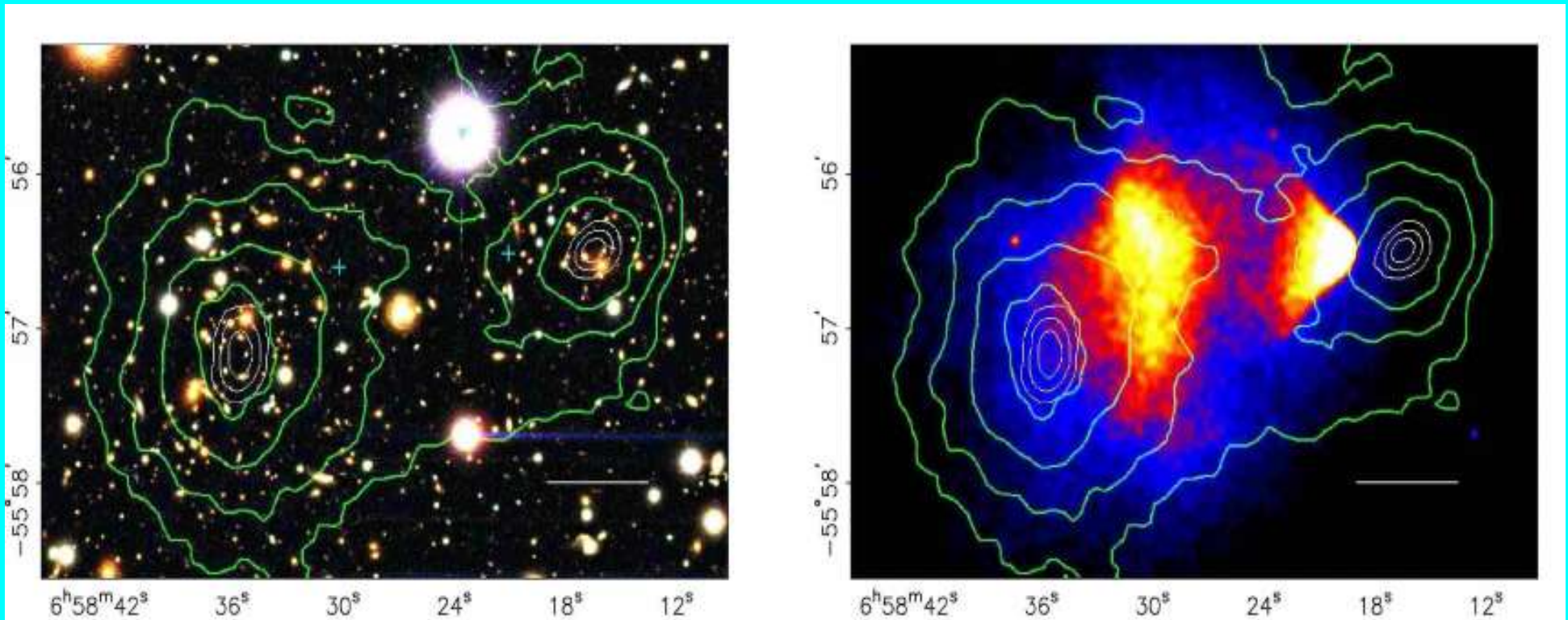
- Centroid of the weak lensing mass peak of the bullet (contours)
- 23'' (= 100 kpc) offset (3.4σ) from gas centroid (•)
- consistent with the centroid of the galaxy distribution (★)
- $M_{\text{tot}} / M_{\text{gas}} = 10$; $M_{\text{tot}} / M_{\text{gal}} = 100$
- total mass is not where the baryons are →
- non-baryonic dark matter exists
- galaxies and DM collisionless, pass-through
- gas haloes interact, slow down by ram pressure

Clowe et al., 2004, ApJ, 648:L109



Total mass from weak lensing II

- Optical data from HST + ESO + Magellan, Chandra 500ks re-observation
- total mass peaks co-incide with galaxy concentrations
- total mass peaks offset from X-ray peaks by $\sim 8\sigma$

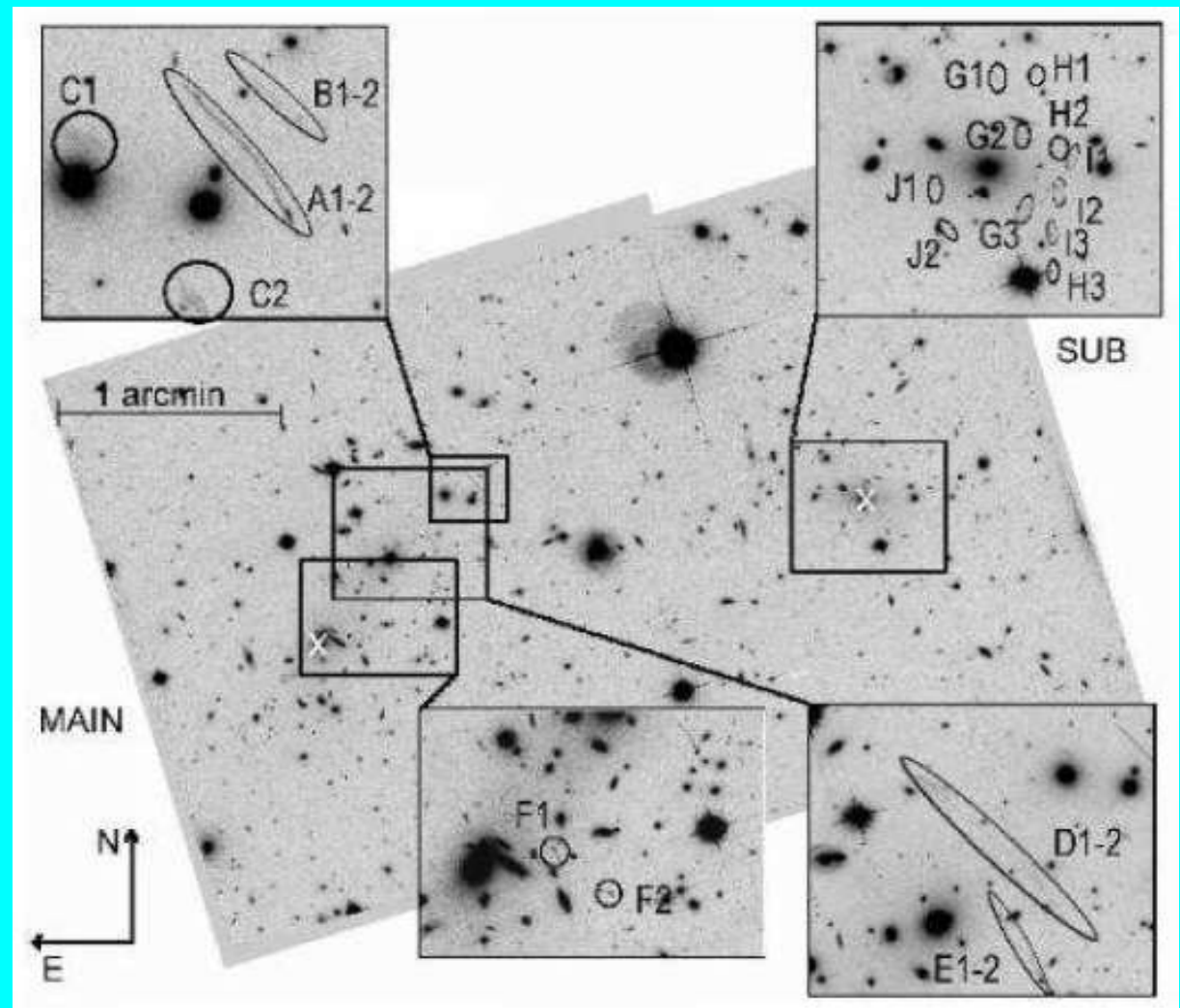


Clowe et al., 2006, ApJ, 648:L109

Weak + strong lensing

- HST ACS data
- 10 multiply imaged systems
- multiples identified by matching morphologies and surface brightness

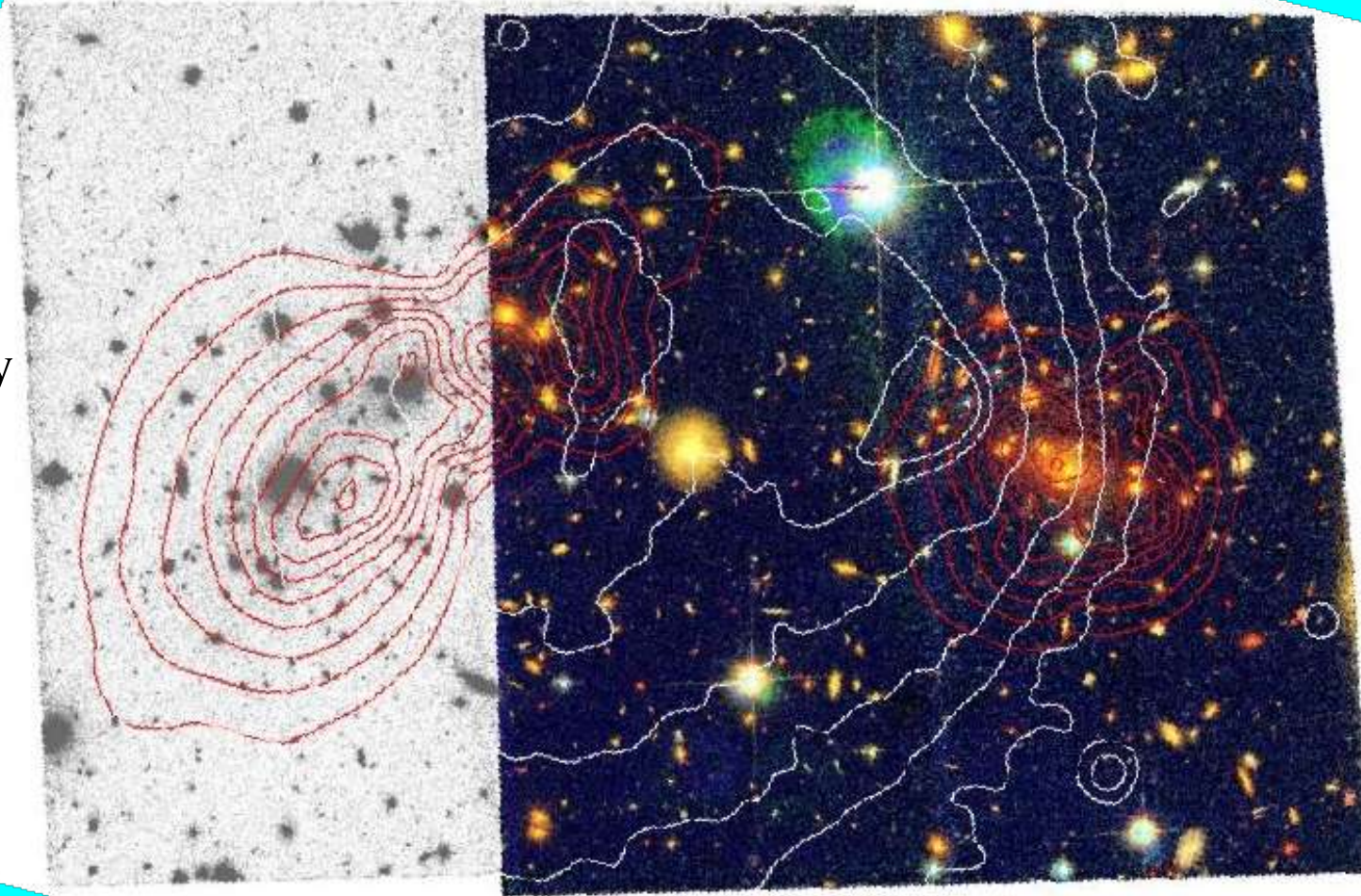
Bradac et al., 2006, ApJ, 652, 937



Weak + strong lensing

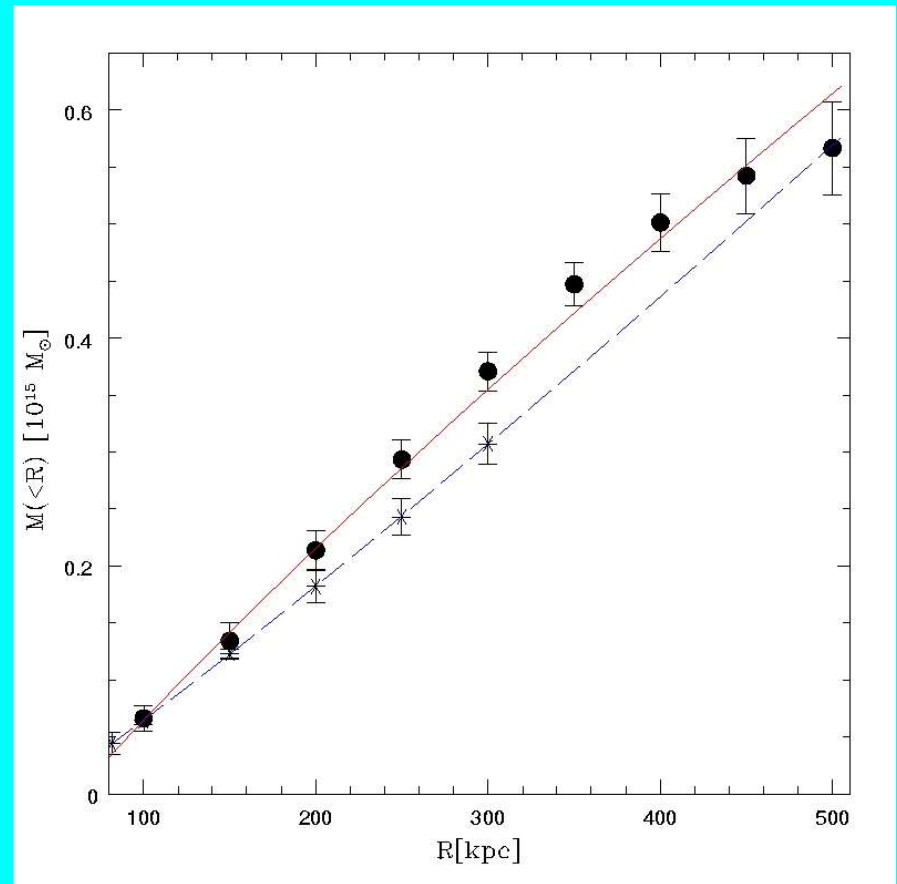
Bradac et al., 2006, ApJ, 652, 937

- red: total mass
- white: X-ray
- main cluster and bullet total mass and X-ray peaks offset by 10 and 6 σ



Weak + strong lensing

- $M_{\text{bullet}} (r < 300 \text{kpc}) = 3.0 \cdot 10^{14} M_{\text{sol}}$
- $M_{\text{main}} (r < 300 \text{kpc}) = 3.7 \cdot 10^{14} M_{\text{sol}}$
- $M_{\text{main}} (r < 500 \text{kpc}) = 5.6 \cdot 10^{14} M_{\text{sol}}$



Bradac et al., 2006, ApJ, 652, 937

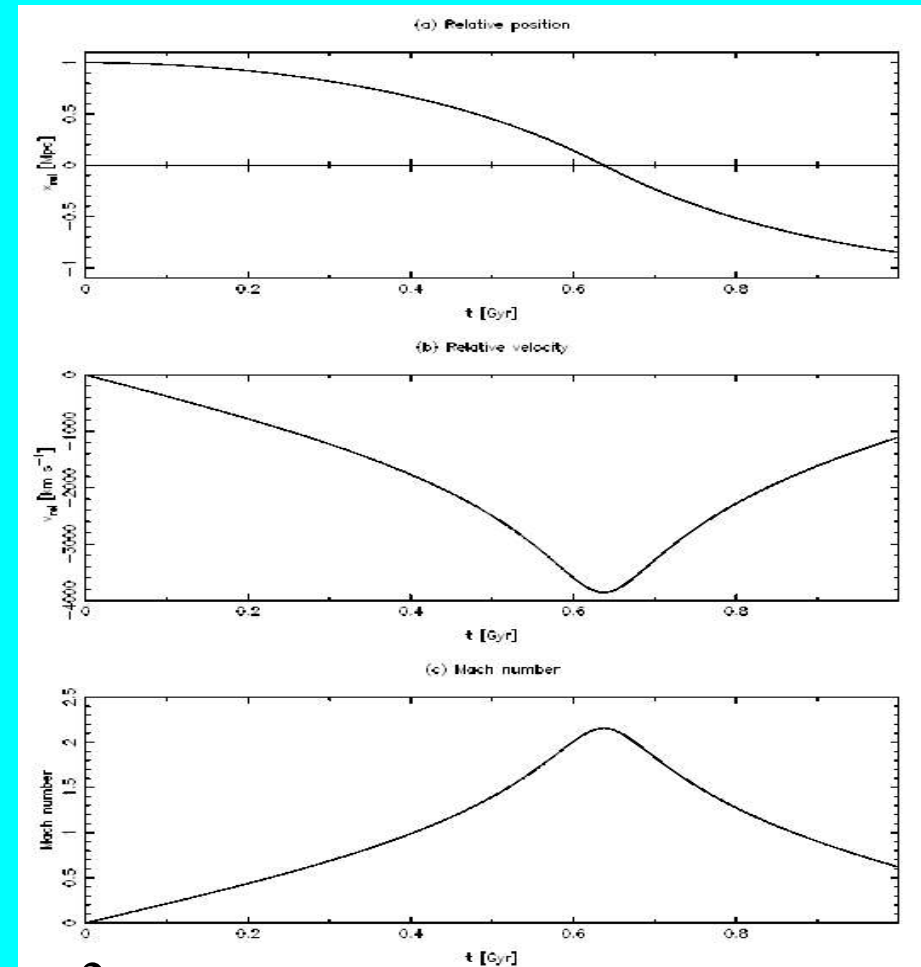
Evidence for dark matter?

- Within 100 kpc of the bullet BCG: $M_{\text{gas}}/M_{\text{tot}} = 4\%$, $M_{\text{gal}}/M_{\text{tot}} = 1\%$ → lots of dark matter (like in all clusters)
- Perhaps gravity law is wrong, correct one gives more power to baryons, and there is no dark matter?
- In the absence of dark matter, the gravitational potential will trace the dominant baryonic matter component, i.e. X-ray gas **in both Newtonian and modified gravity**. This is not the case → dark matter exists
- If dark matter is collisionless, the gravitational potential will trace the collisionless galaxies while gas lags behind. This is the case → dark matter is collisionless

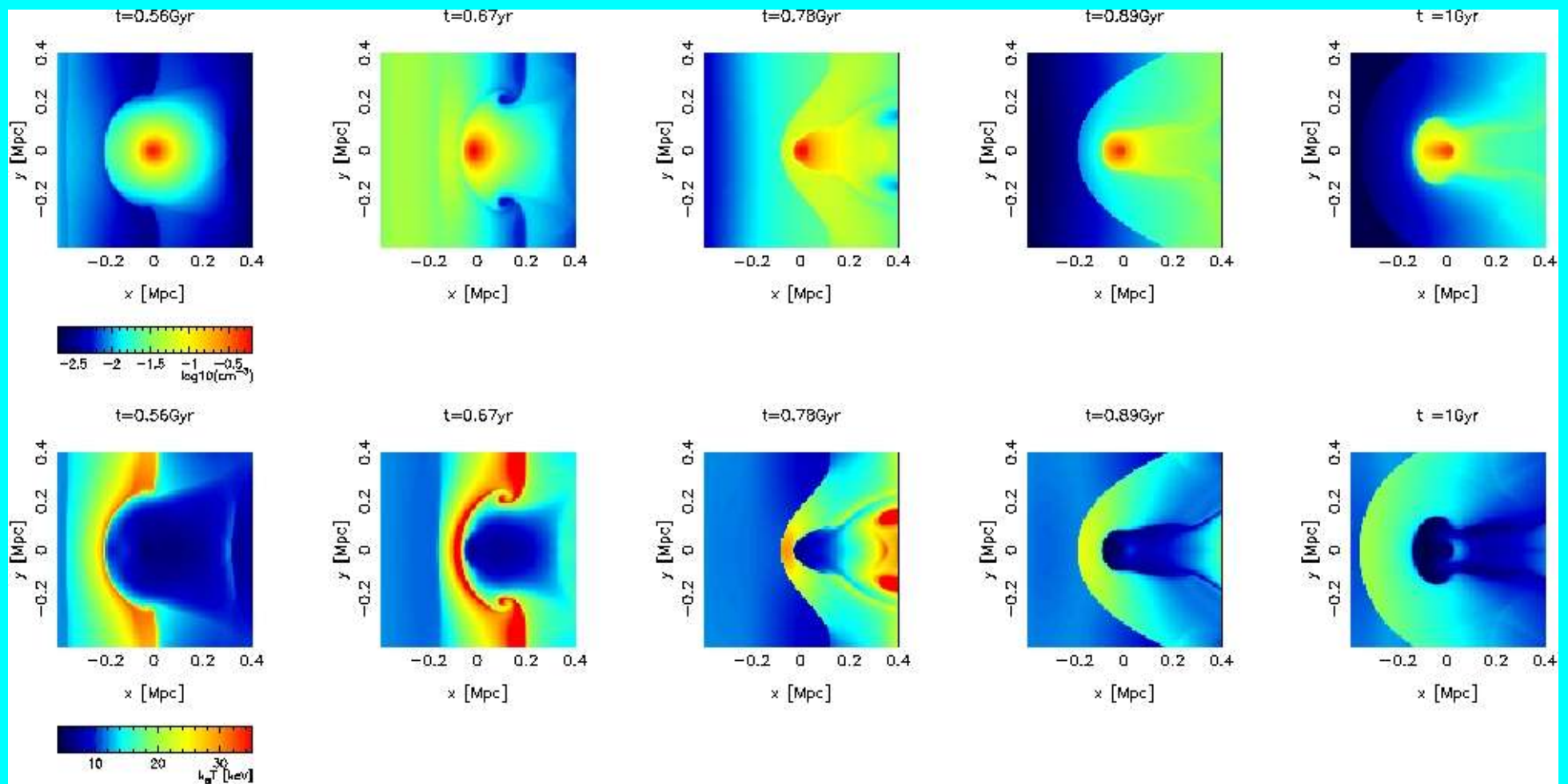
Simulations I

- 3D hydrodynamic simulation of a moving substructure in a cluster environment
- only gravitational interaction considered
- assumed: beta model for gas density,
King profile for DM density
- assumed: $\rho_{\text{gas}}(0) / \rho_{\text{DM}}(0) = 1 / 10$
- radial infall from the main cluster outskirts
- subcluster reaches main cluster's center at

$t = 0.64 \text{ Gyr}$, $T_{\text{max}} = -4000 \text{ km s}^{-1}$, Mach number ~ 2

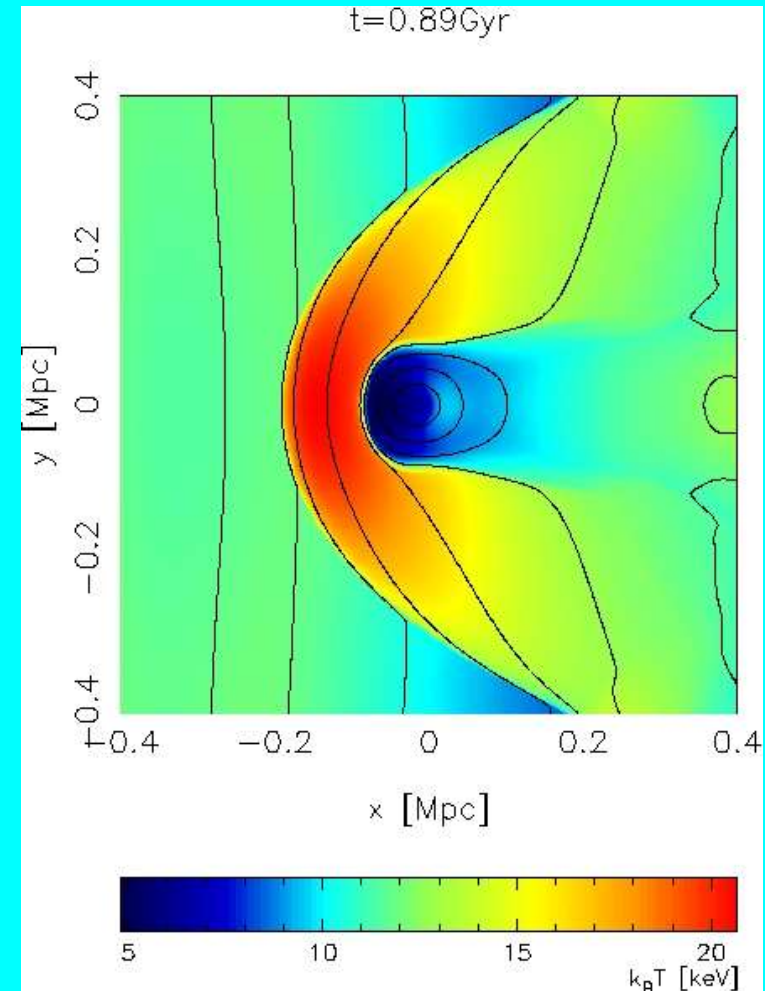


Simulations I



Simulations I

- At $t = 0.89$ Gyr (0.2 Gyr after passage), the bullet cluster features are produced:
- cold front, hot shock, cool bullet, 2 discontinuities of temperature and density around the shock



Simulations II

- subcluster mass-X-ray offset reproduced
(not the main cluster)

Takizawa, 2006, PASJ in press, astro-ph/0608693

