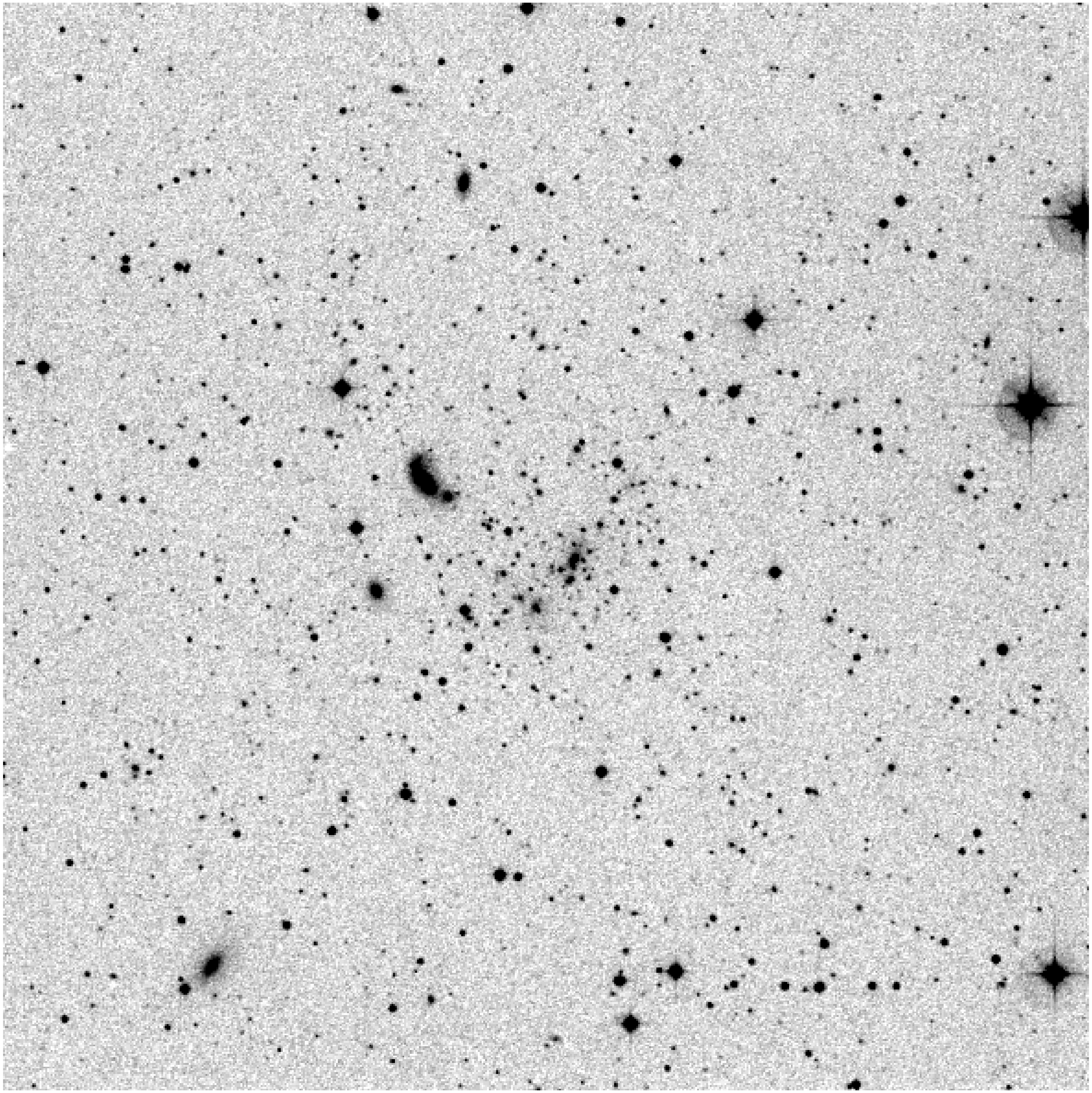
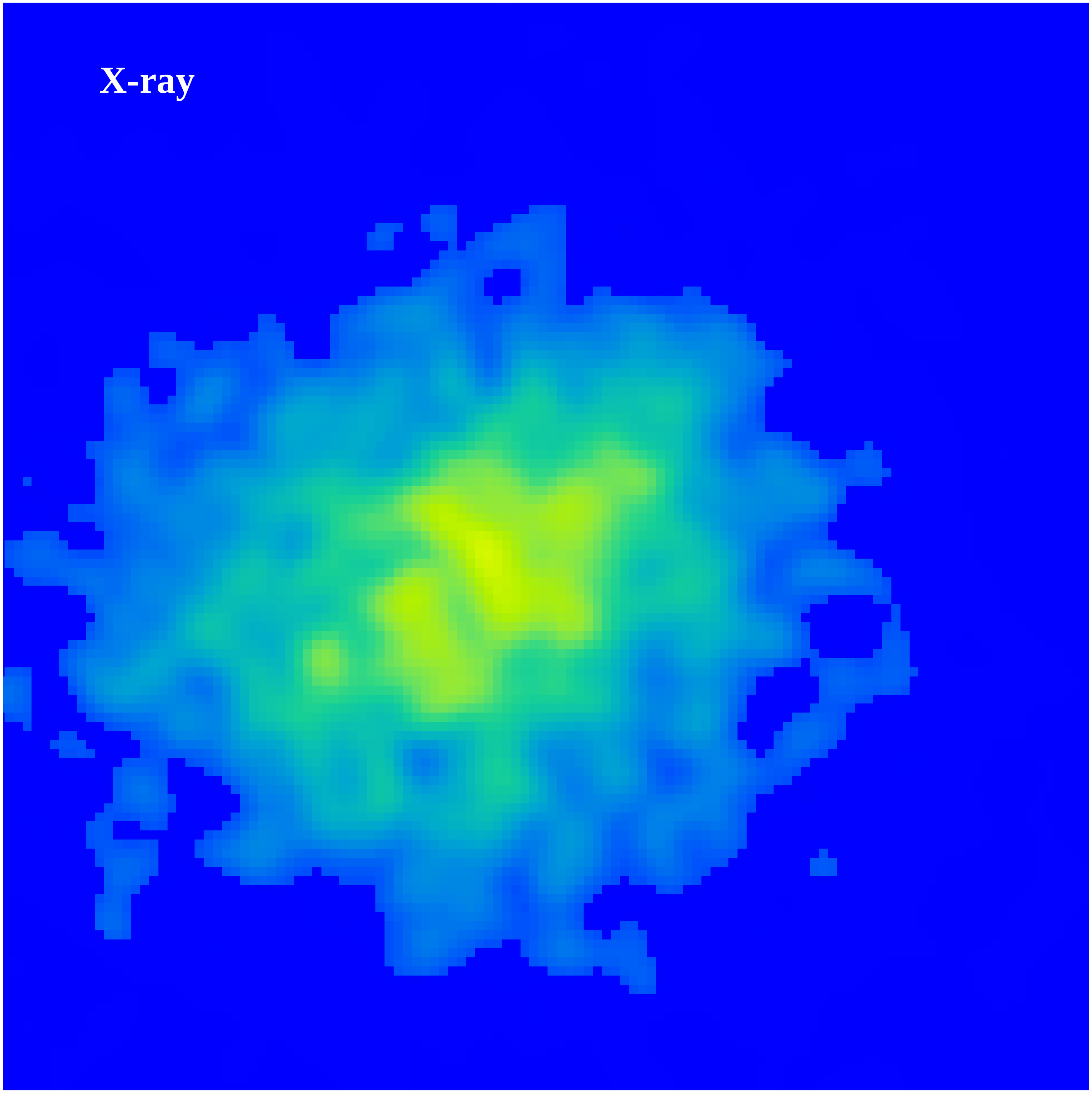
Galaxy clusters:

Science and *Chandra* analysis

M. Markevitch

August 2005, X-ray astronomy school, Cambridge, Mass.




X-ray

Clusters contain:

- **1–3% of mass in stars**
- **10–20% in hot gas** ($\sim$ **10 keV,** $\sim 10^{-3}$ **cm**$^{-3}$**)**
- **80–90% in dark matter** ($\sim 10^{15} M_\odot$)

Gas is in hydrostatic equilibrium in the dark matter's grav. potential:

$$\nabla p = -\rho_{\rm gas} \nabla \Phi$$

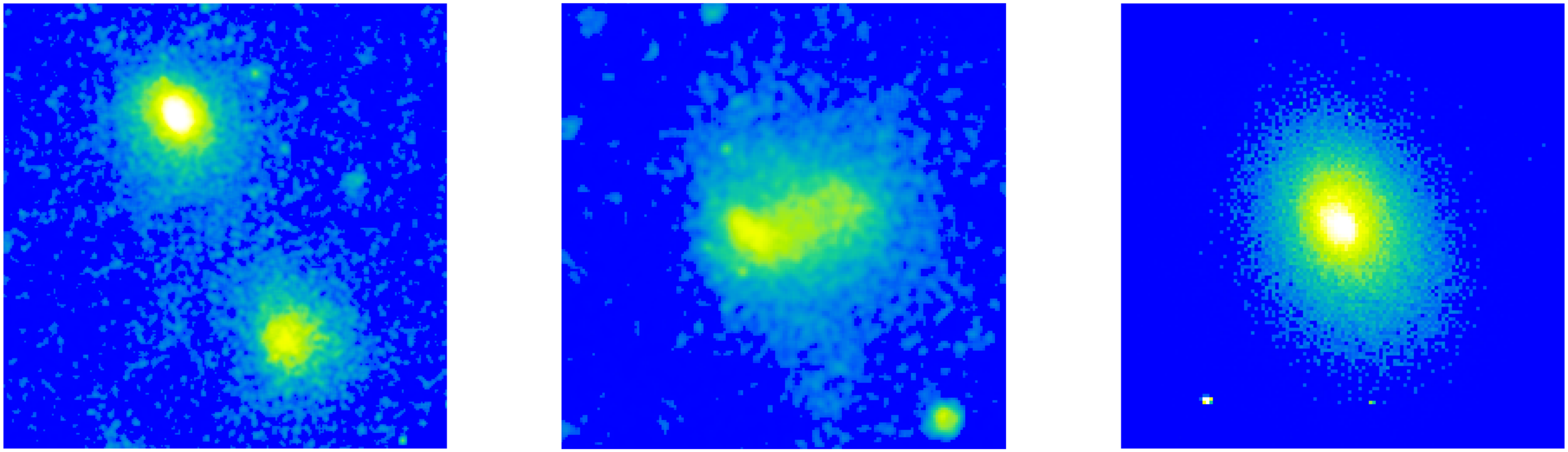
$p = \rho_{\rm gas} T$ **can be derived from X-rays, so can measure cluster total masses.**

I. Cluster physics

- **Mergers**
- **Cool central regions**

II. Clusters as cosmological probes

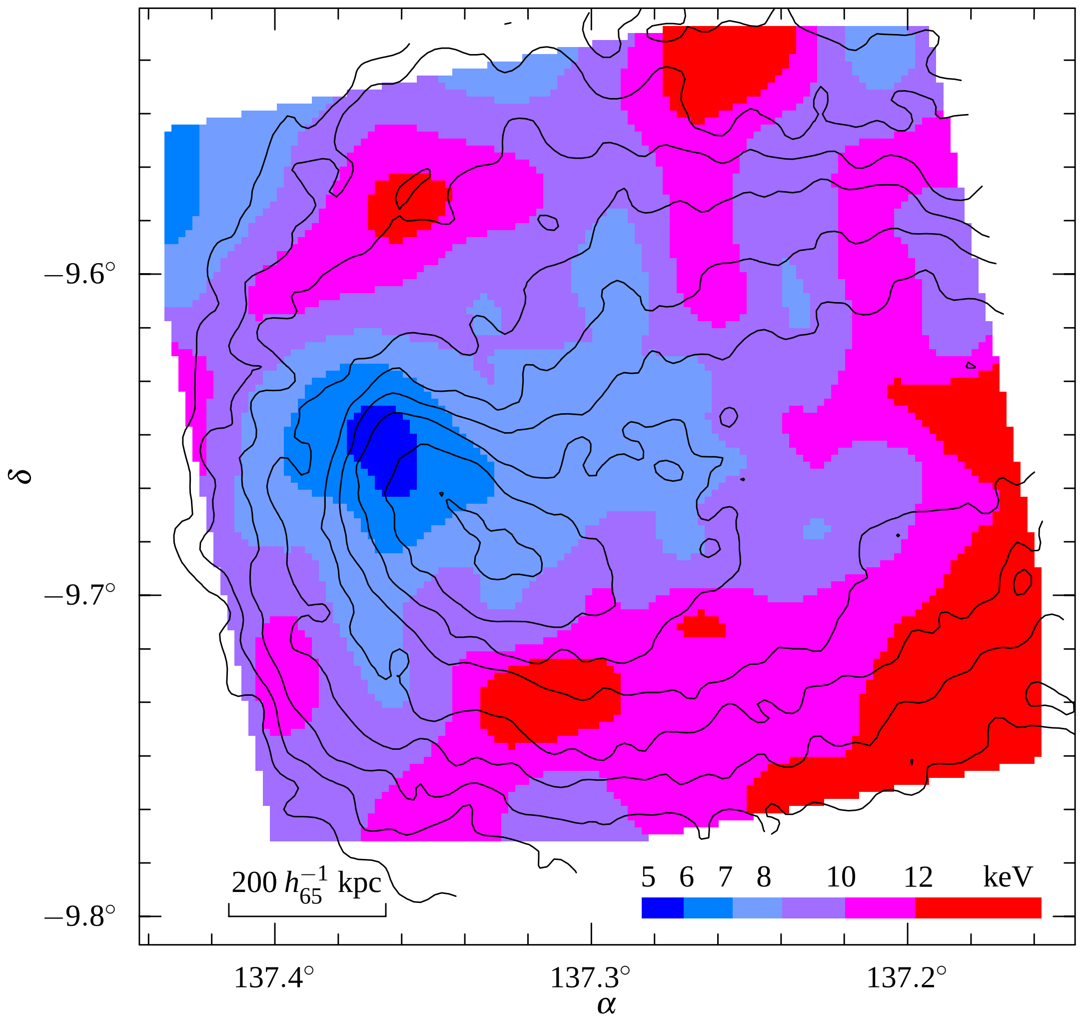
Cluster mergers



The most energetic events since the Big Bang:
two $10^{15}\,M_{\odot}$ clusters carry $E_{\rm kin} \sim 10^{63-64}$ ergs

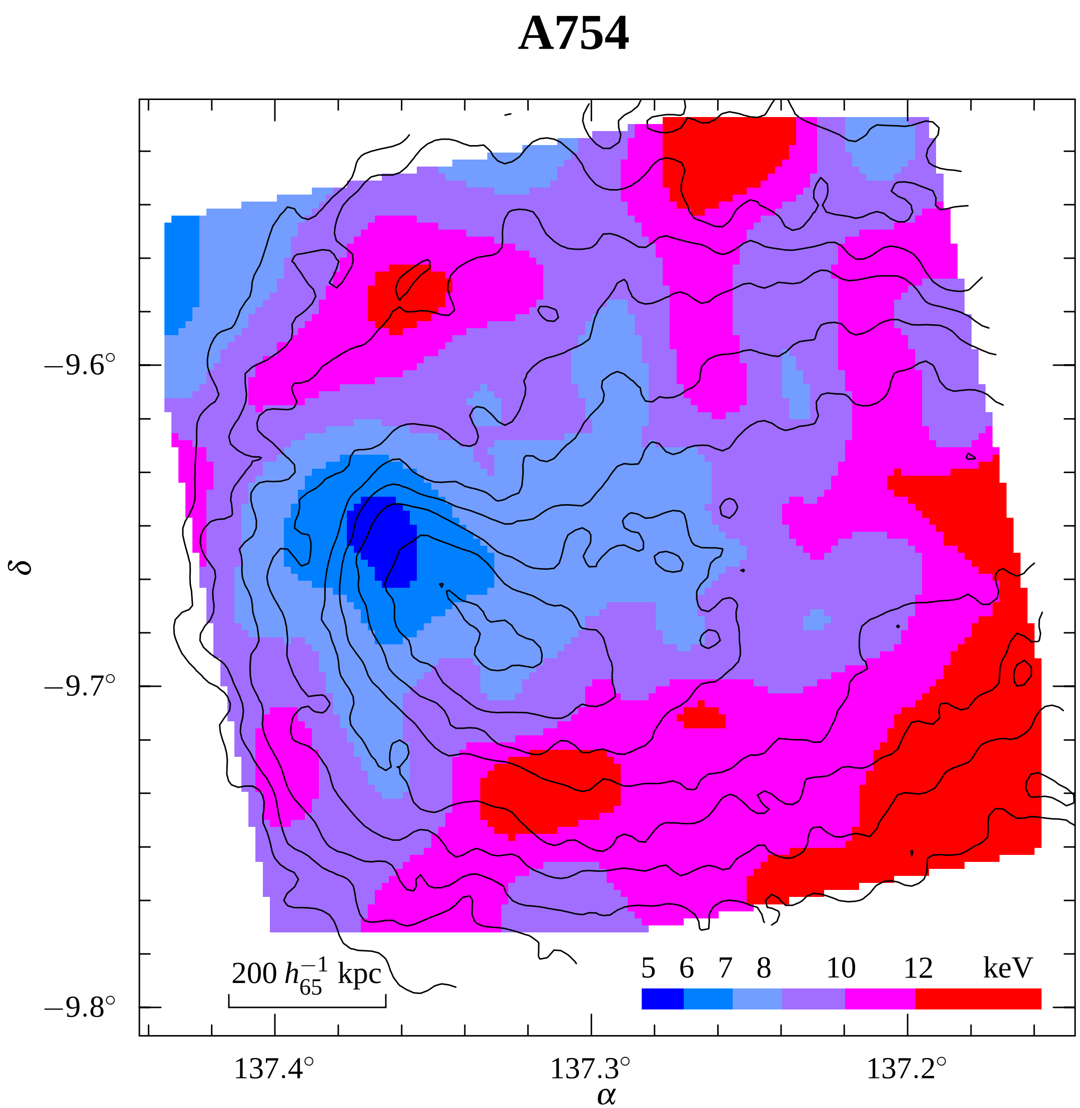
Great laboratory for studying intracluster gas:
shocks, instabilities, transport processes, particle accelertion,
amplification of magnetic fields

A754



(Markevitch et al. 2003)

Thermal conductivity of the intracluster gas



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:

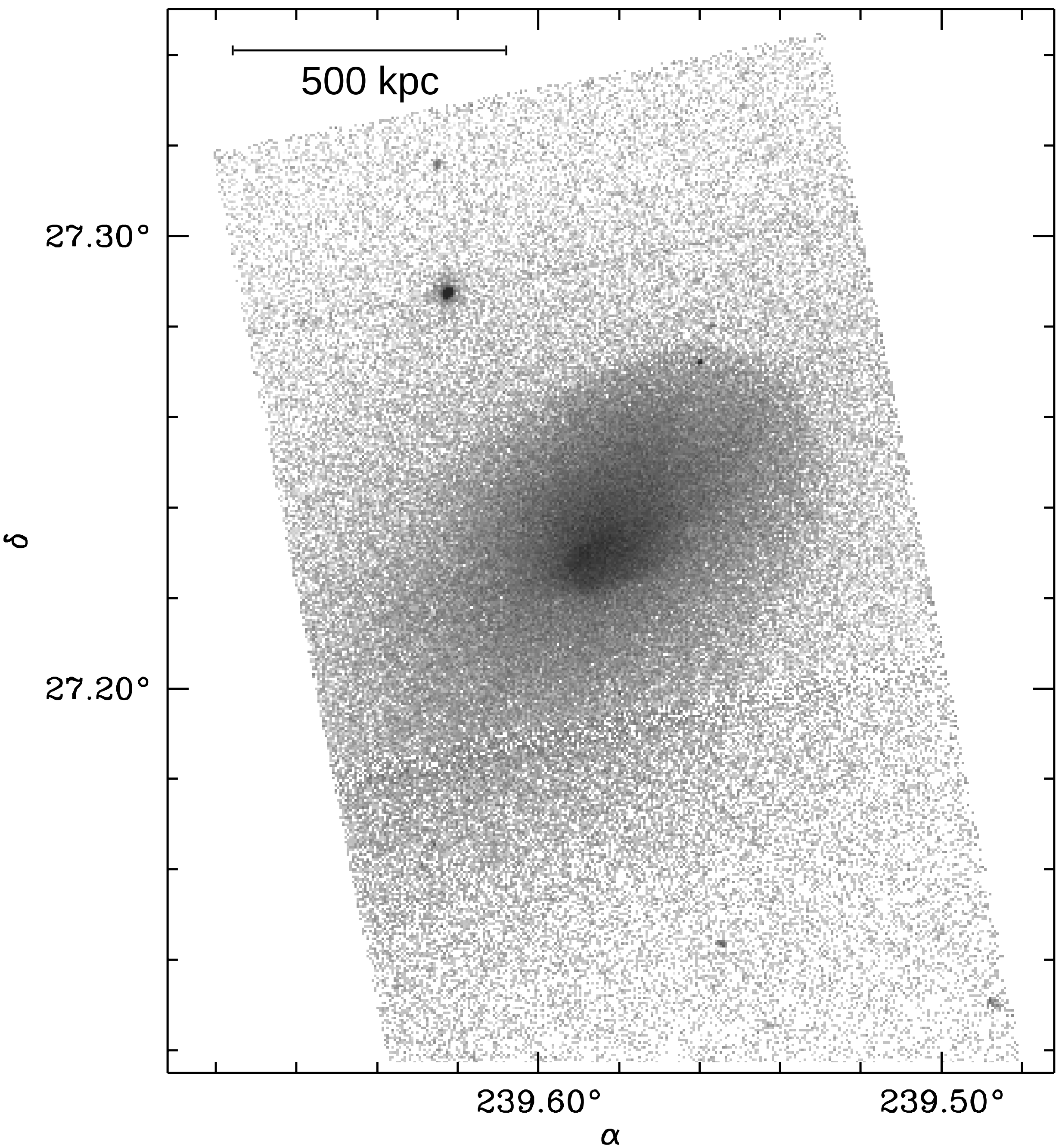
$$t_{\rm age} \sim \frac{L}{c_s} \sim 5 \times 10^8 \text{ yr}$$

Conduction suppressed by factor

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

(Markevitch et al. 2003)

A2142: cold fronts



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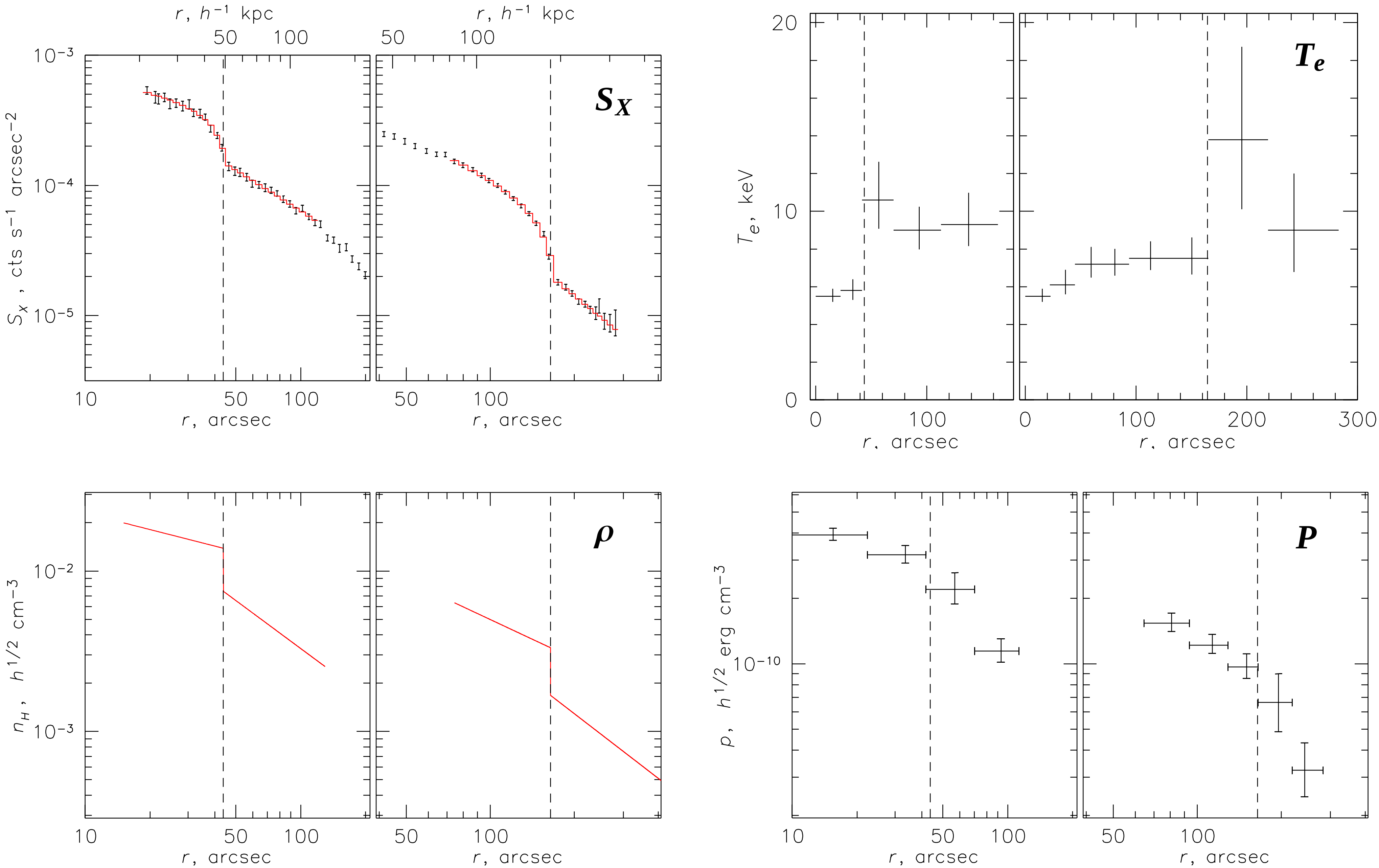
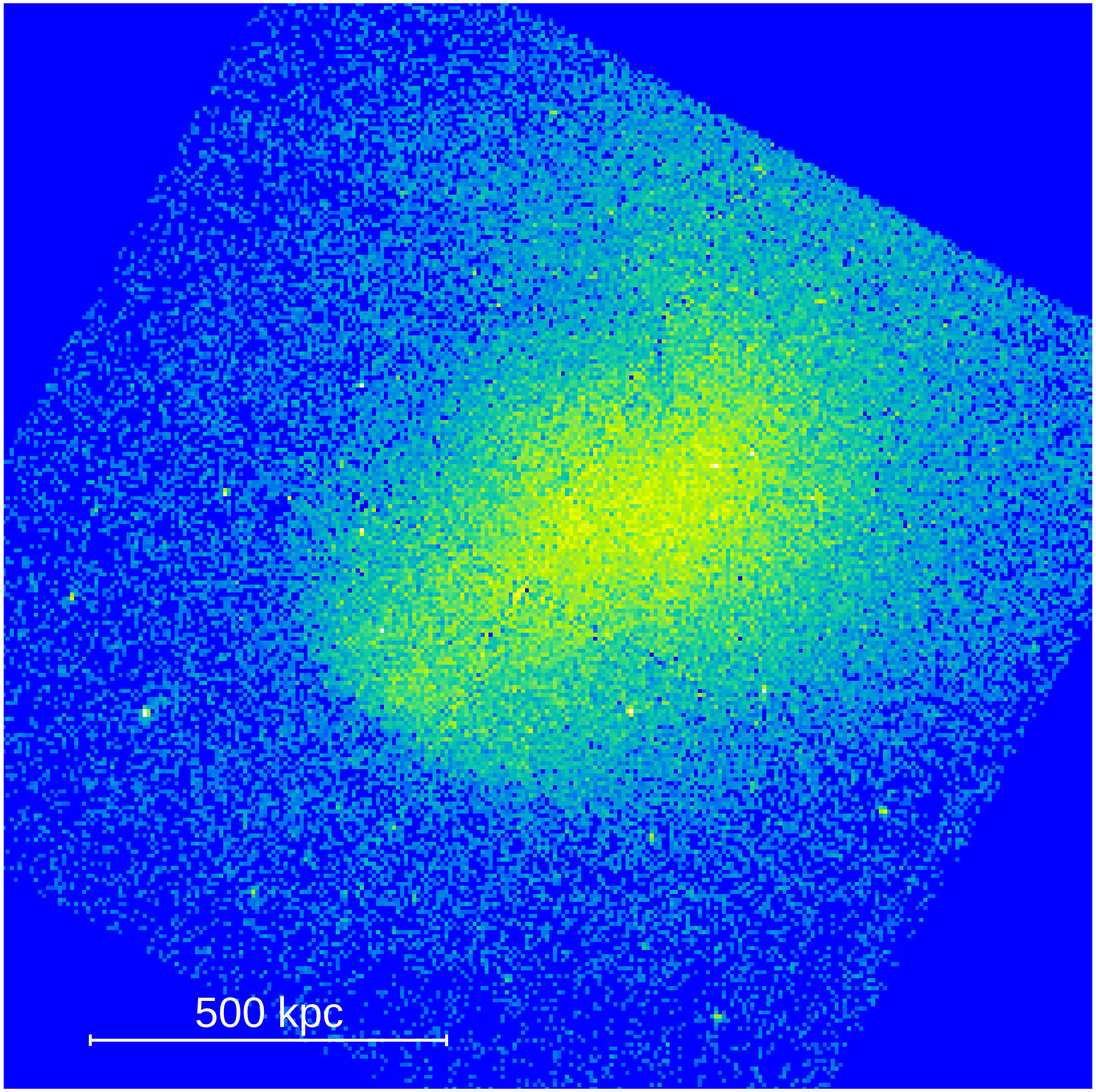
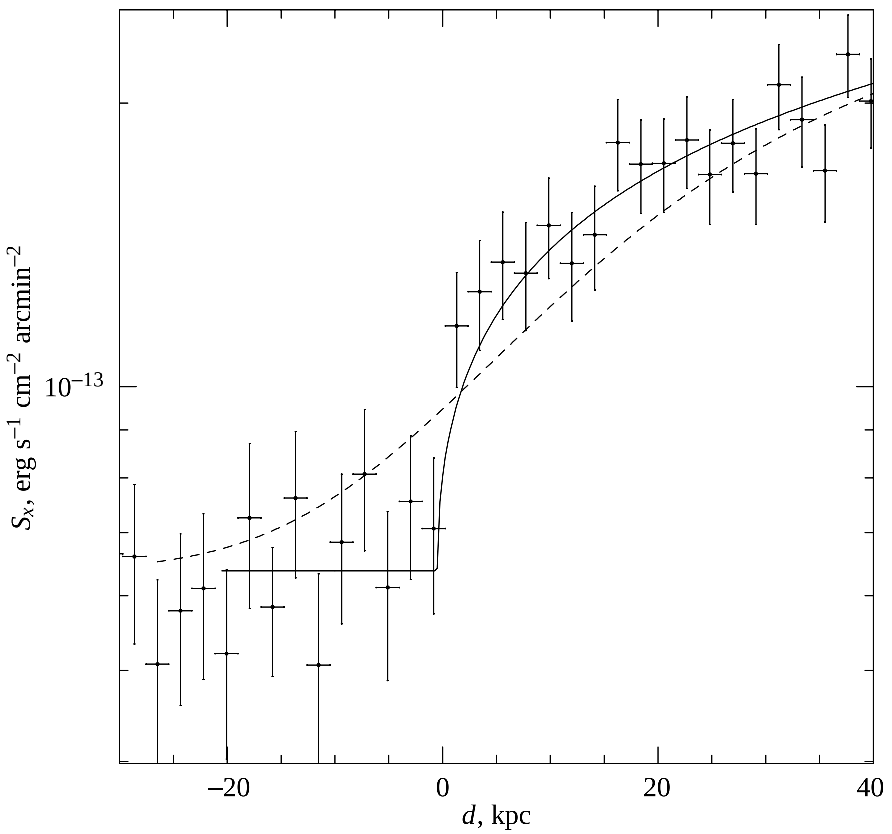


Markevitch et al. (2000)

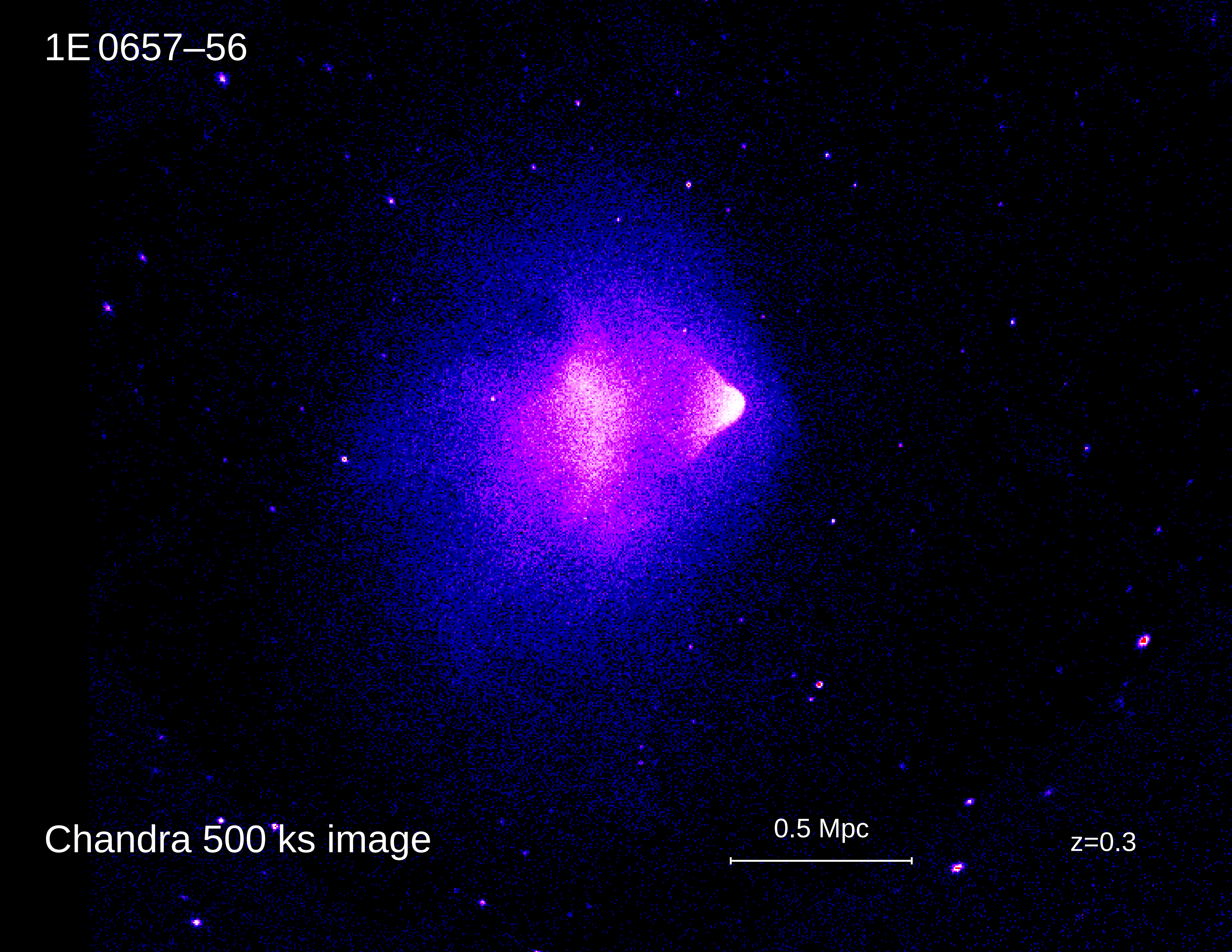
A3667: cold front



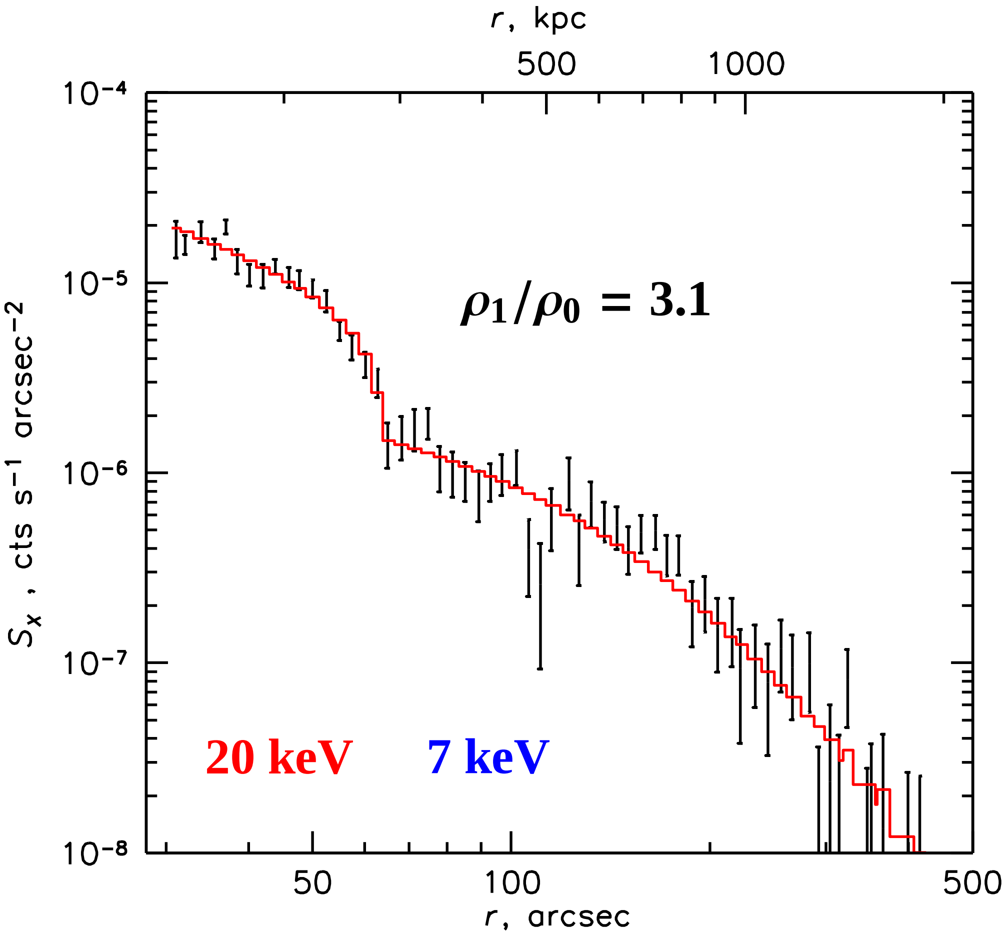
A3667: brightness profile across cold front



Width of the density jump ***d*** **< 5 kpc (3.5′′), that is,** $d < \lambda_e$ **(Coulomb)**
(Vikhlinin et al. 2001)


1E 0657–56
Chandra 500 ks image
0.5 Mpc
z=0.3

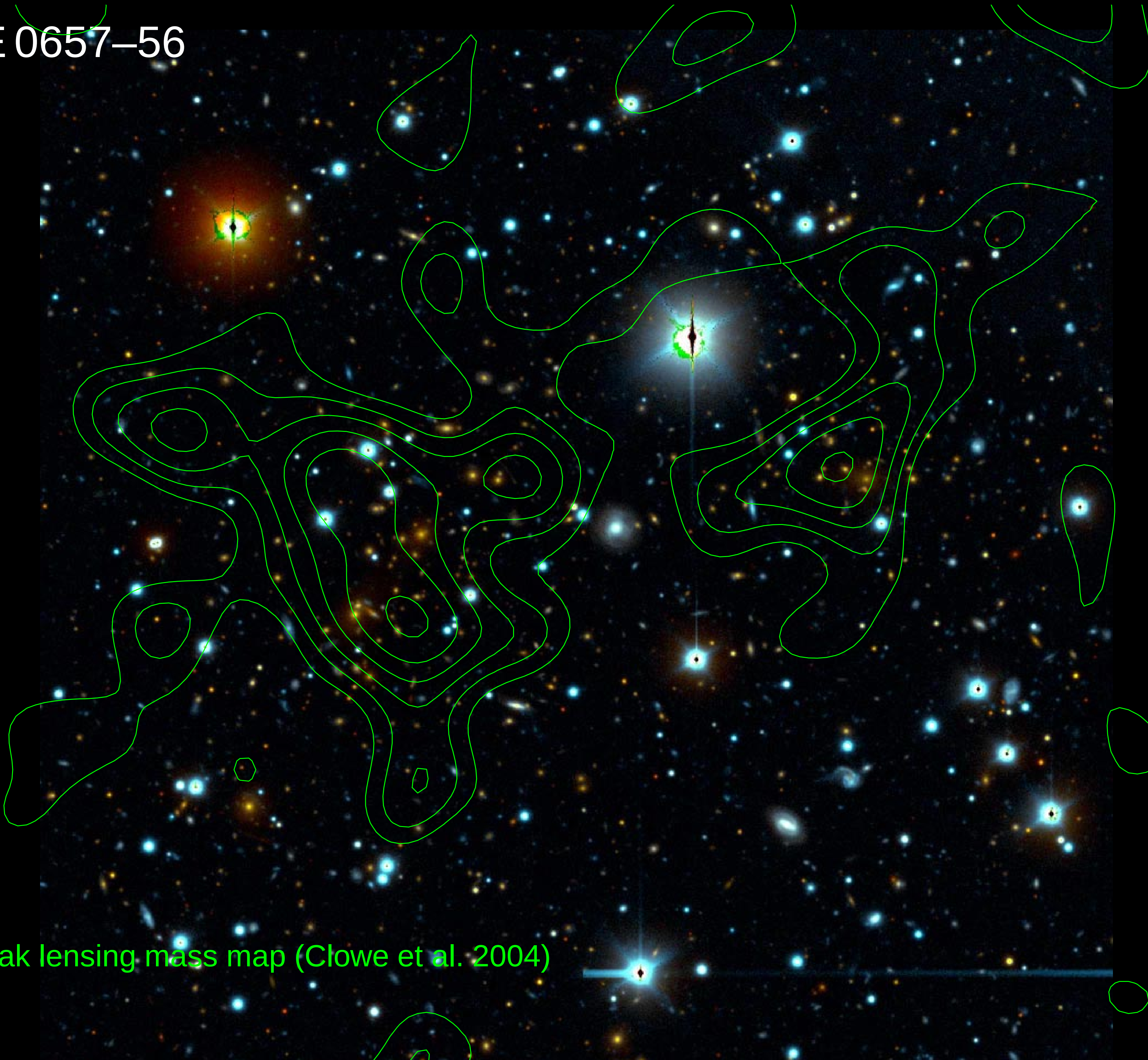
Bow shock in 1E 0657–56



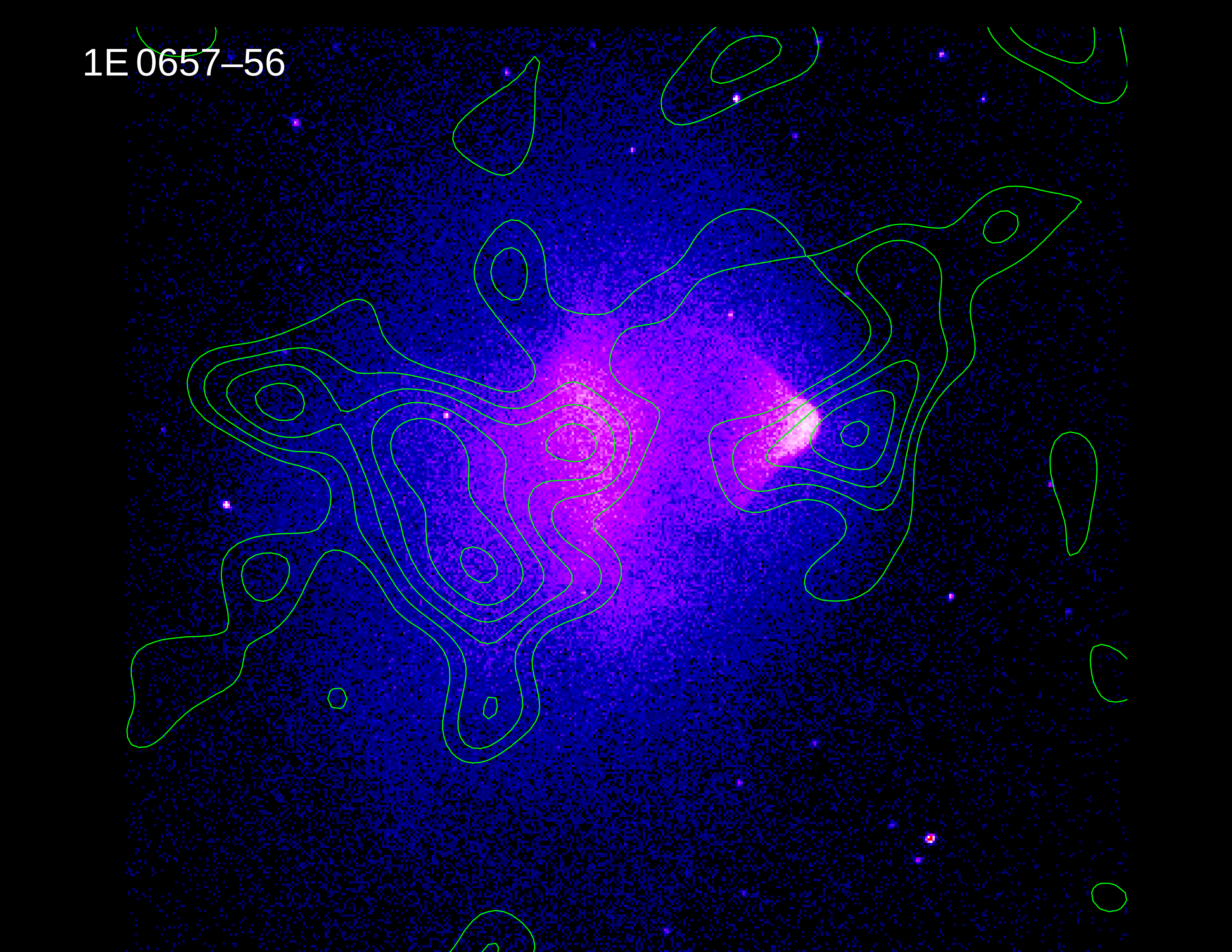
$M = 3.1 \pm 0.5, \quad v = 5000\ \mathrm{km\,s^{-1}}, \quad t \sim 0.1\ \mathrm{Gyr}$

1E 0657–56

1E 0657–56



Weak lensing mass map (Clowe et al. 2004)


1E 0657–56

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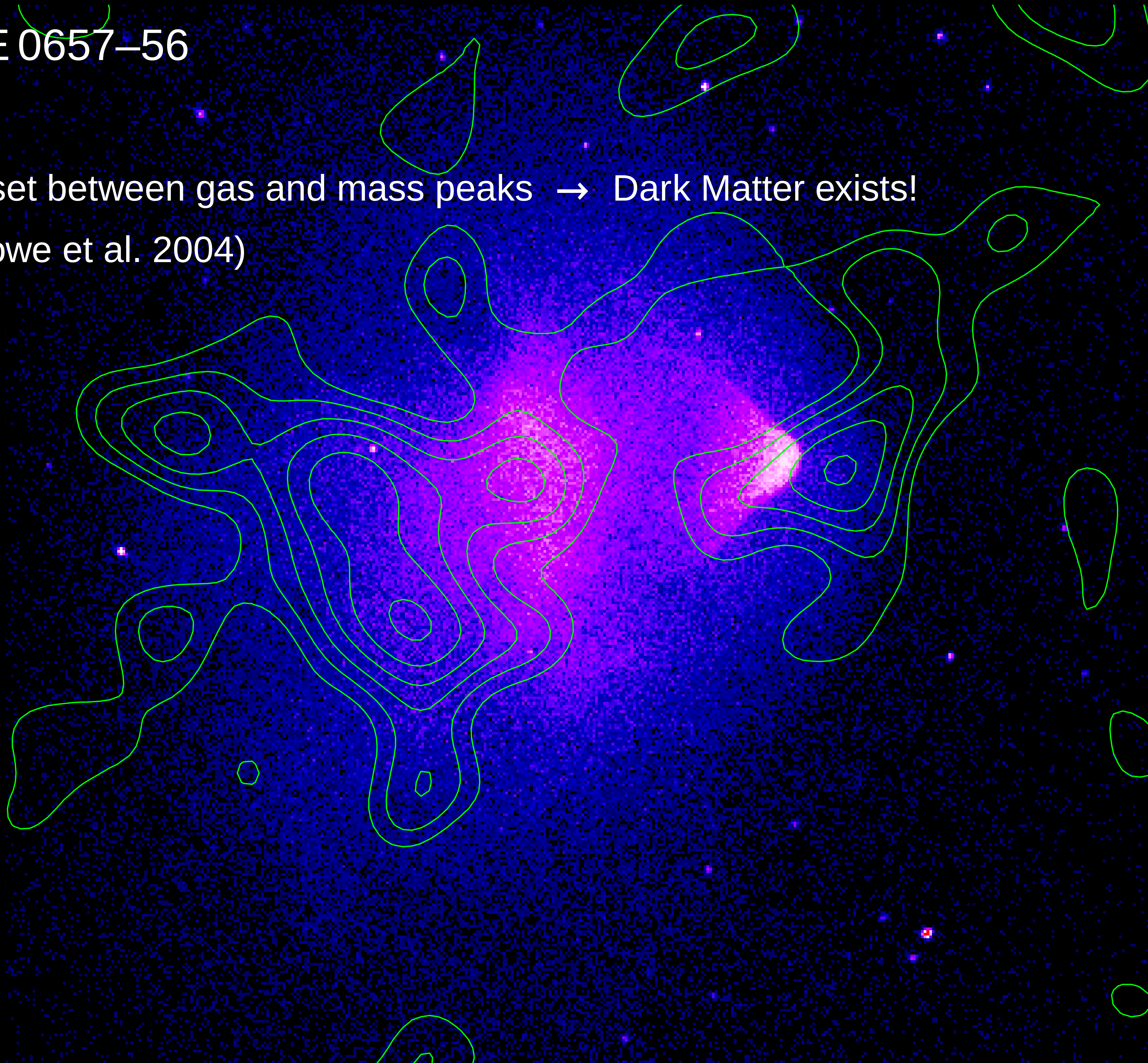
Offset between gas and mass peaks → Dark Matter exists!

(Clowe et al. 2004)



Cooling flows

$L_X \propto n^2 \, T^{1/2}$

At the cluster centers, $\frac{E_{\mathrm{th}}}{L_X} < 10^9$ yr ($\sim$ cluster age)

→ "cooling flow" (Fabian et al. 1980's)

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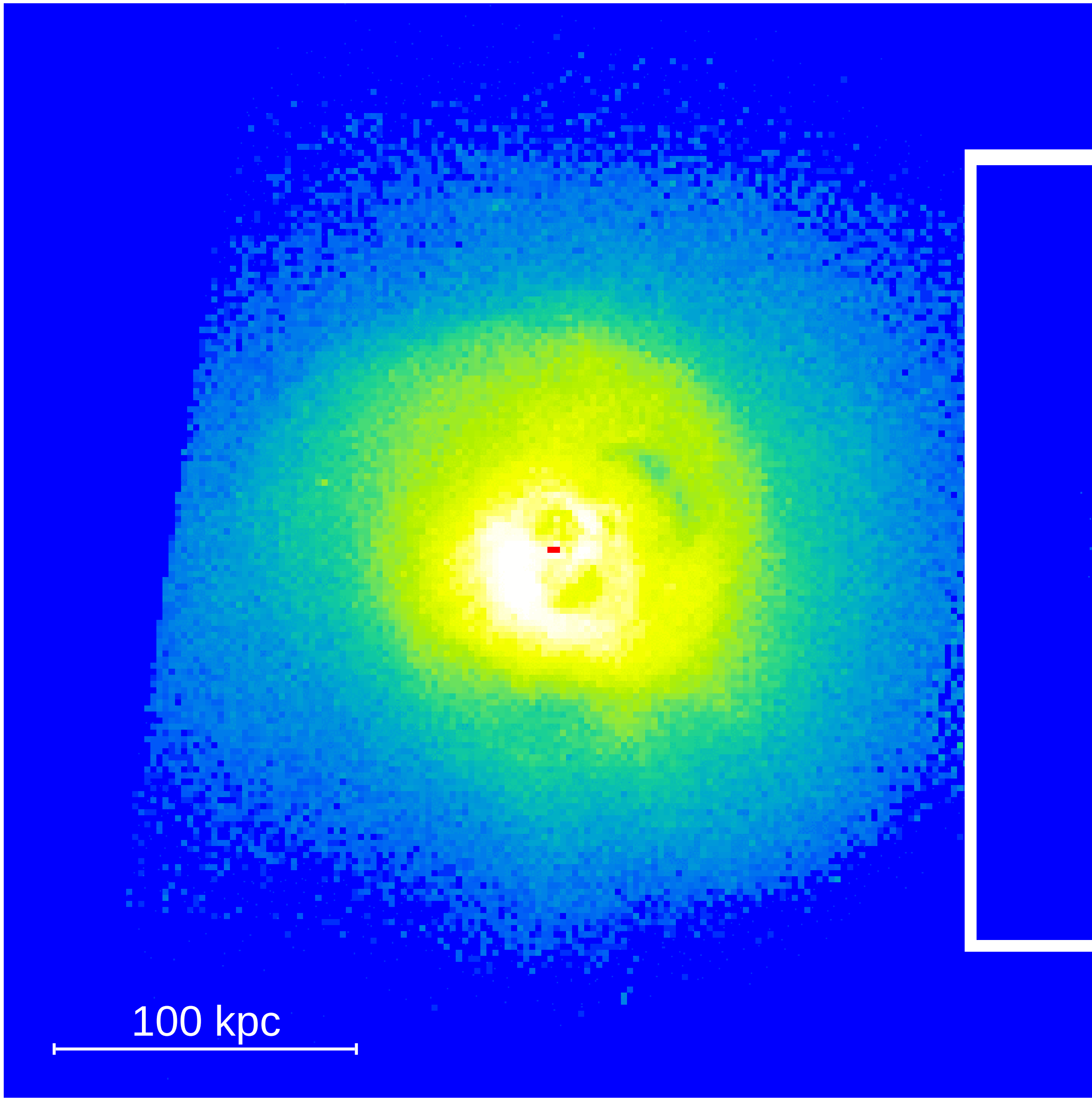
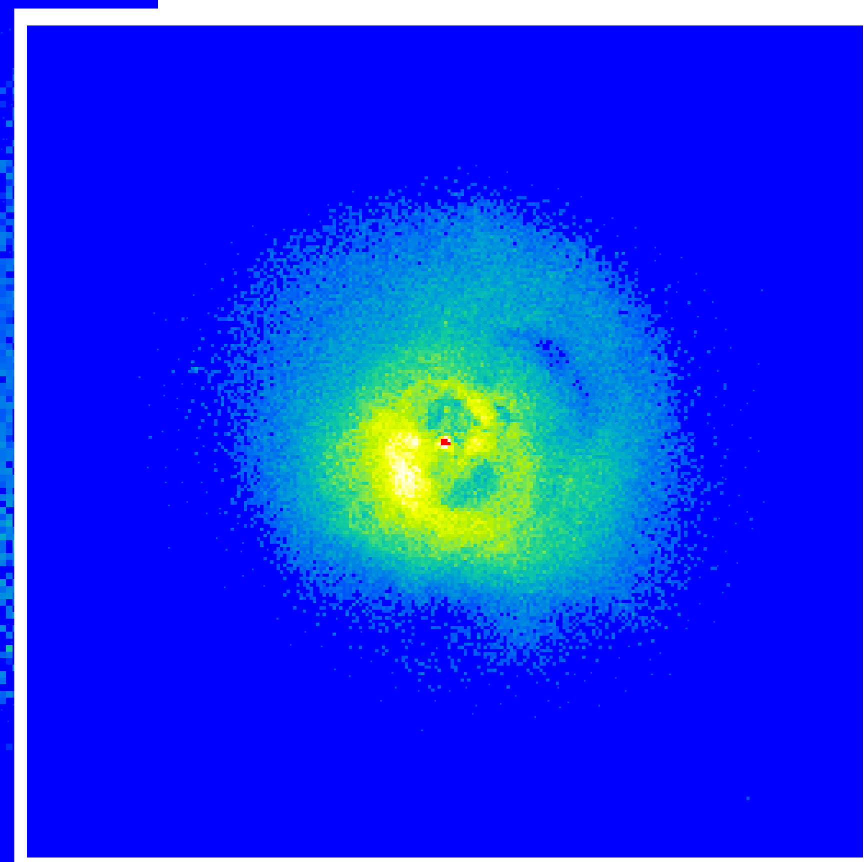
But: *XMM* and *Chandra* do not find the expected quantities of cool gas

So has to be a constant heat source ~ 10^{44} erg s^{-1}

Perseus cluster: AGN bubbles



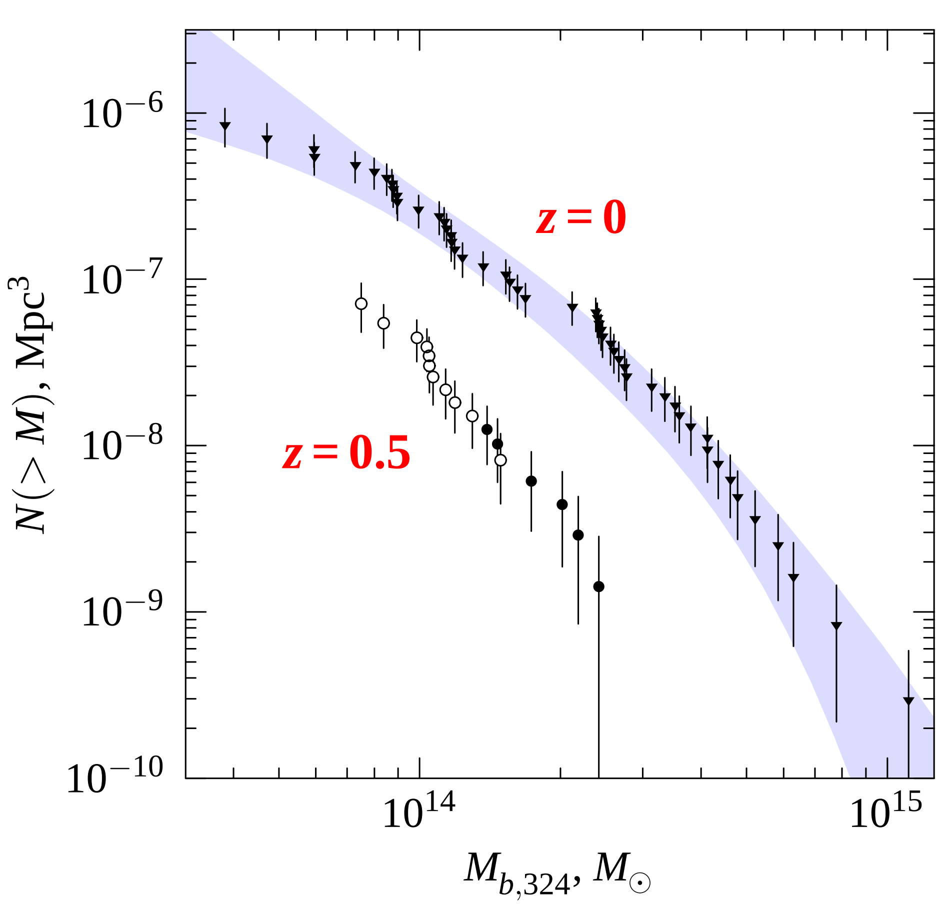


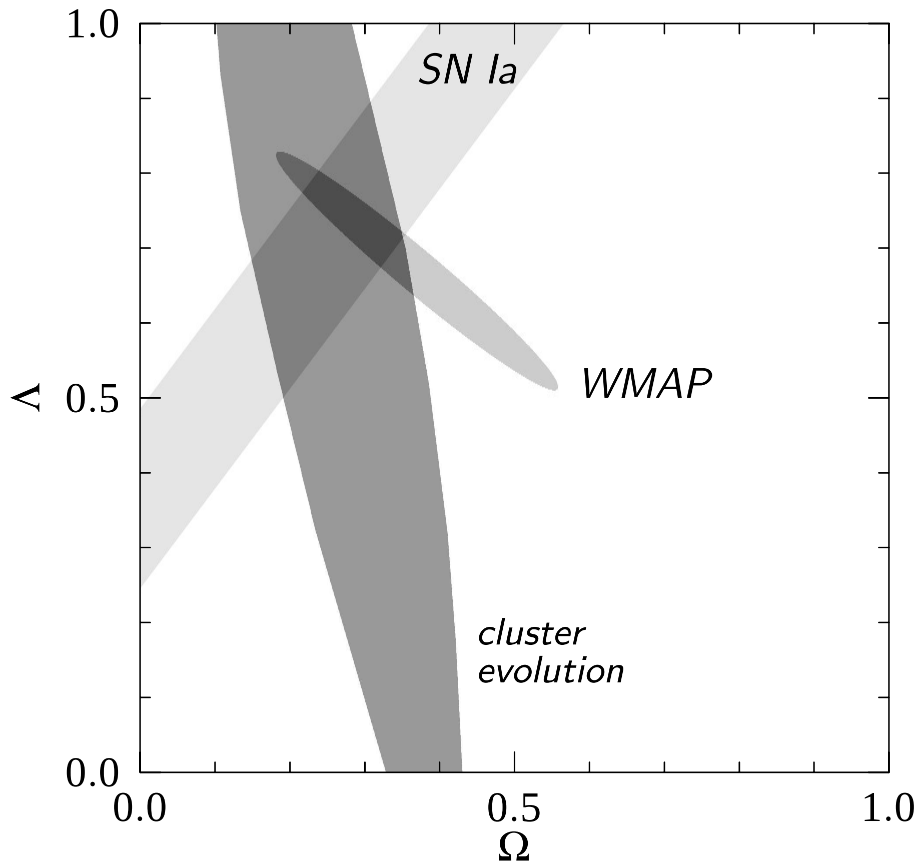
Clusters as cosmological tools

- **cluster mass function and its evolution:** σ_8, Ω_m, Ω_Λ **(even** w **?)**

- **cluster baryon fraction** f_b**:**
  - Ω_b **from nucleosynthesis,** $f_b \rightarrow \Omega_m = 0.3$ **(White et al. 93)**
  - $f_b(z) = \text{const} \rightarrow \Omega_m, \Omega_\Lambda$ **(Sasaki 1996; Allen et al. 2004)**

Evolution of cluster mass function

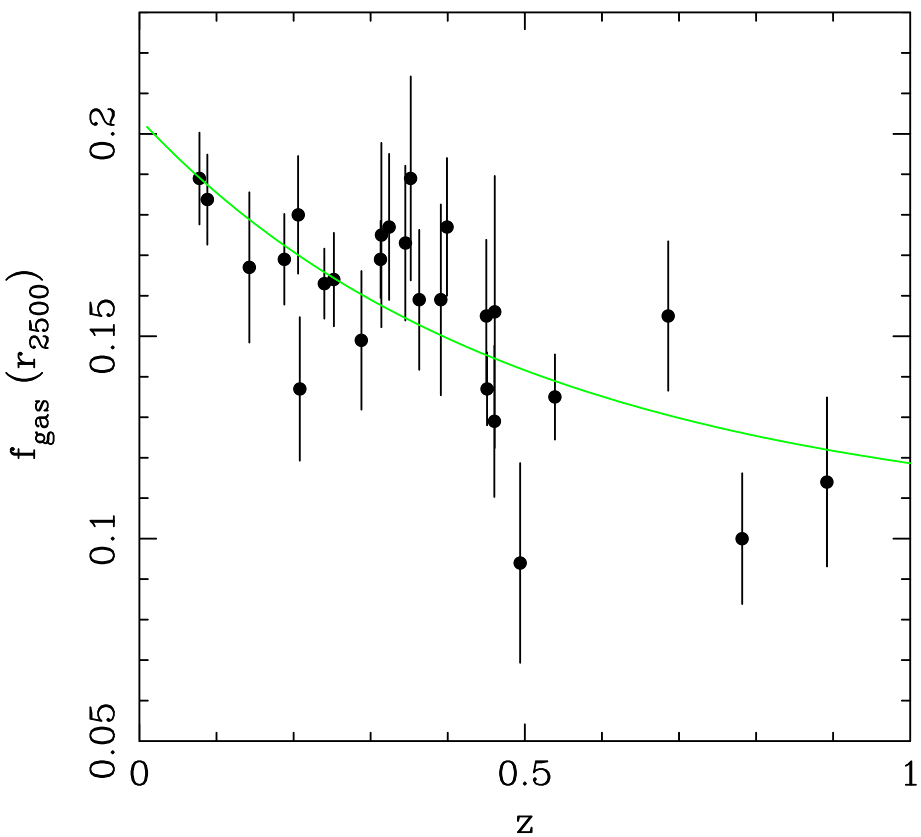




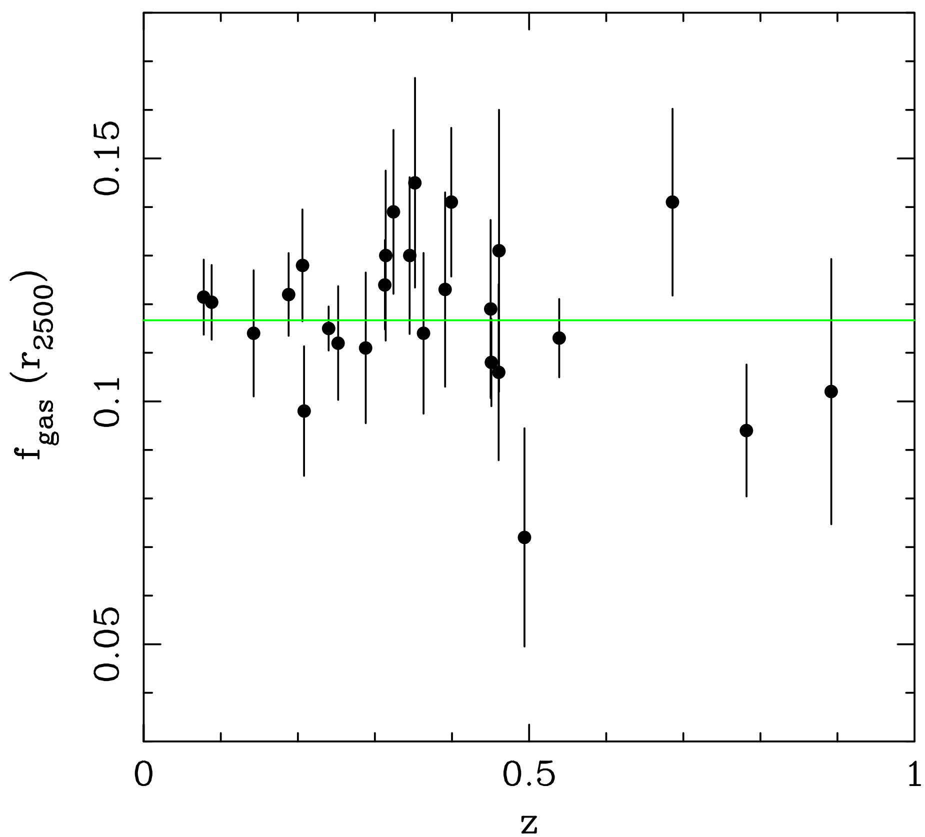
Vikhlinin et al. (2003), using baryon mass as a measure of total mass

Apparent gas fraction as a function of *z*

Ω = 1

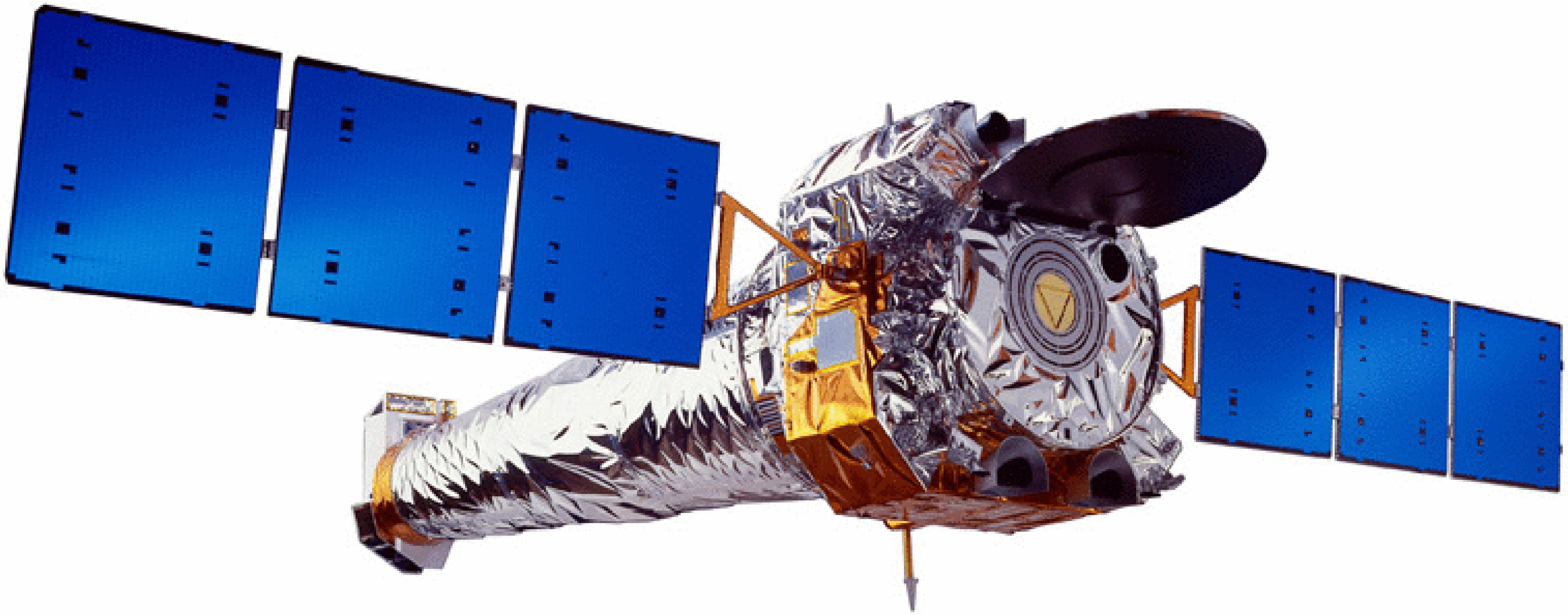


ΛCDM



Allen et al. (2004)

Chandra X-ray Observatory



ACIS detector:

- **0.3 – 8 keV energy band**
- **$16' \times 16'$ FOV**
- **$1''$ on-axis angular resolution**

Chandra data preparation

0. Write a winning proposal (or go to archive)

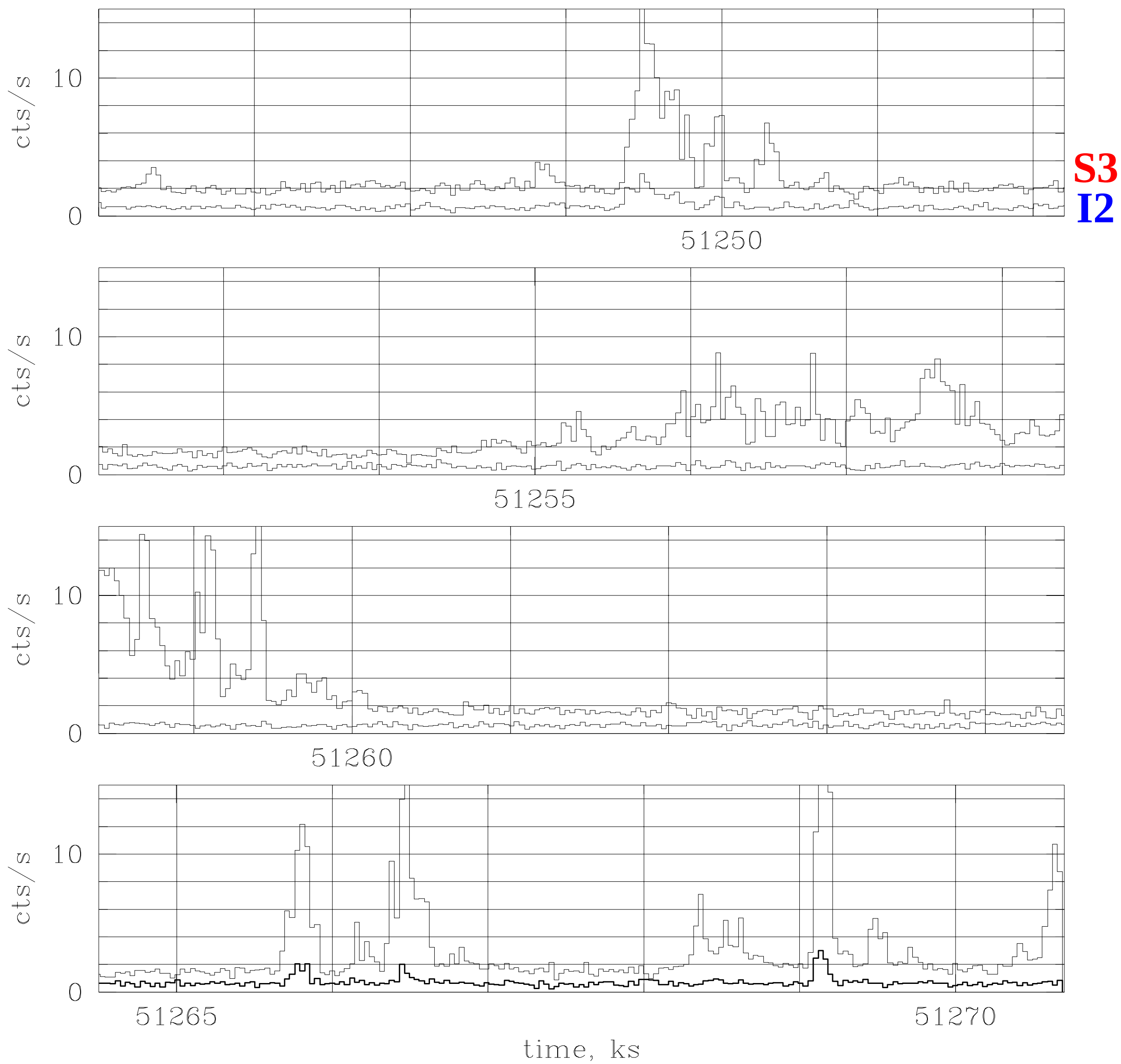
1. Get data:
   - List of all events recorded by detector (X-ray photons and cosmic ray hits)
   - Aspect file (pointing vs. time)
   - Calibration products

2. Reprocess event file applying latest cal. products (if needed)

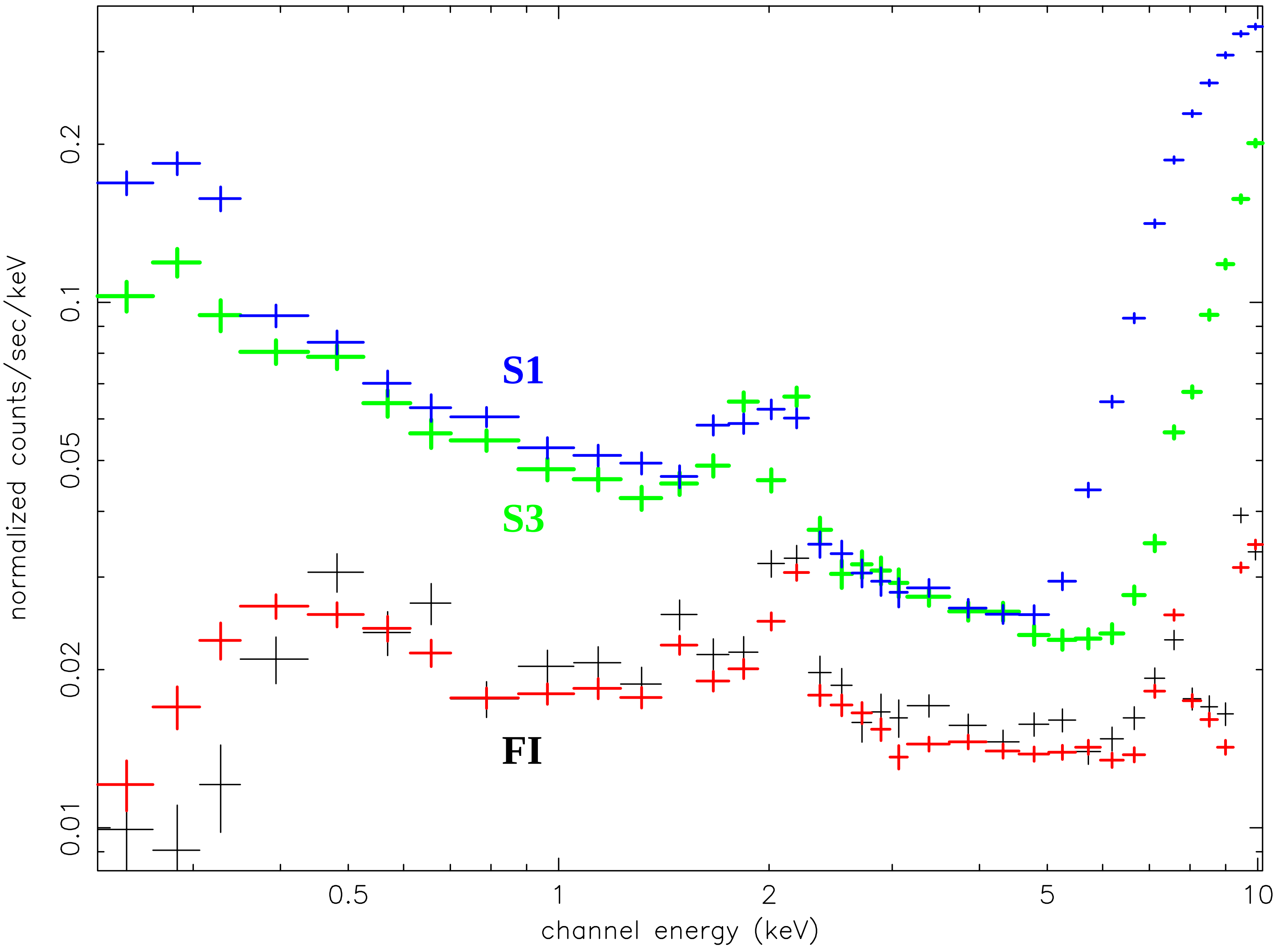
3. Clean data:
   - Most cosmic ray events (removed by event grade filtering) √
   - Bad pixels and columns √
   - Cosmic ray afterglow events
   - If VFAINT mode, additional cosmic ray rejection
   - Occasional periods of bad aspect √
   - Periods of elevated detector background

√ removed in Level 2 event files

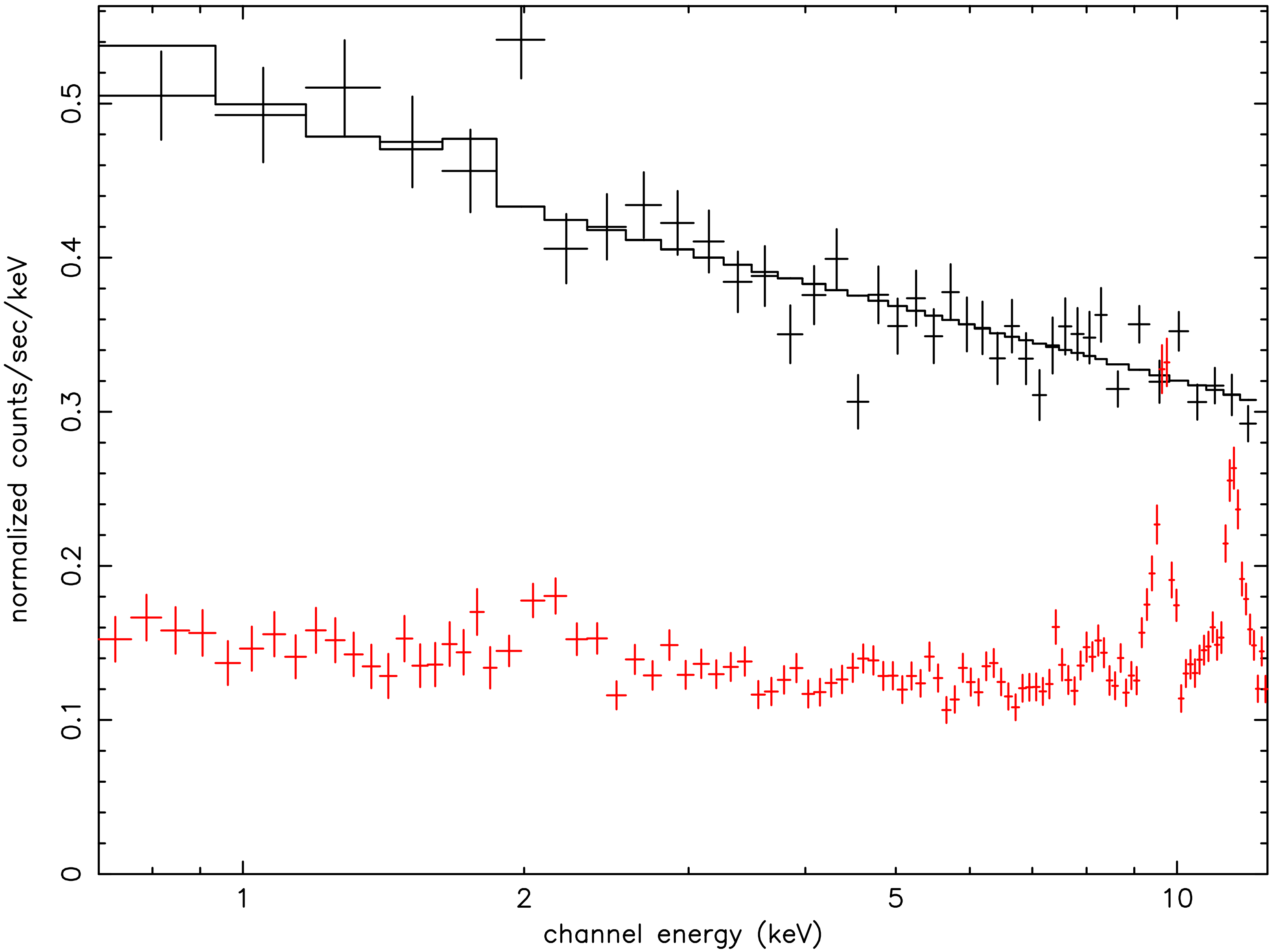
ACIS detector background: typical light curve



ACIS detector background: quiescent spectra

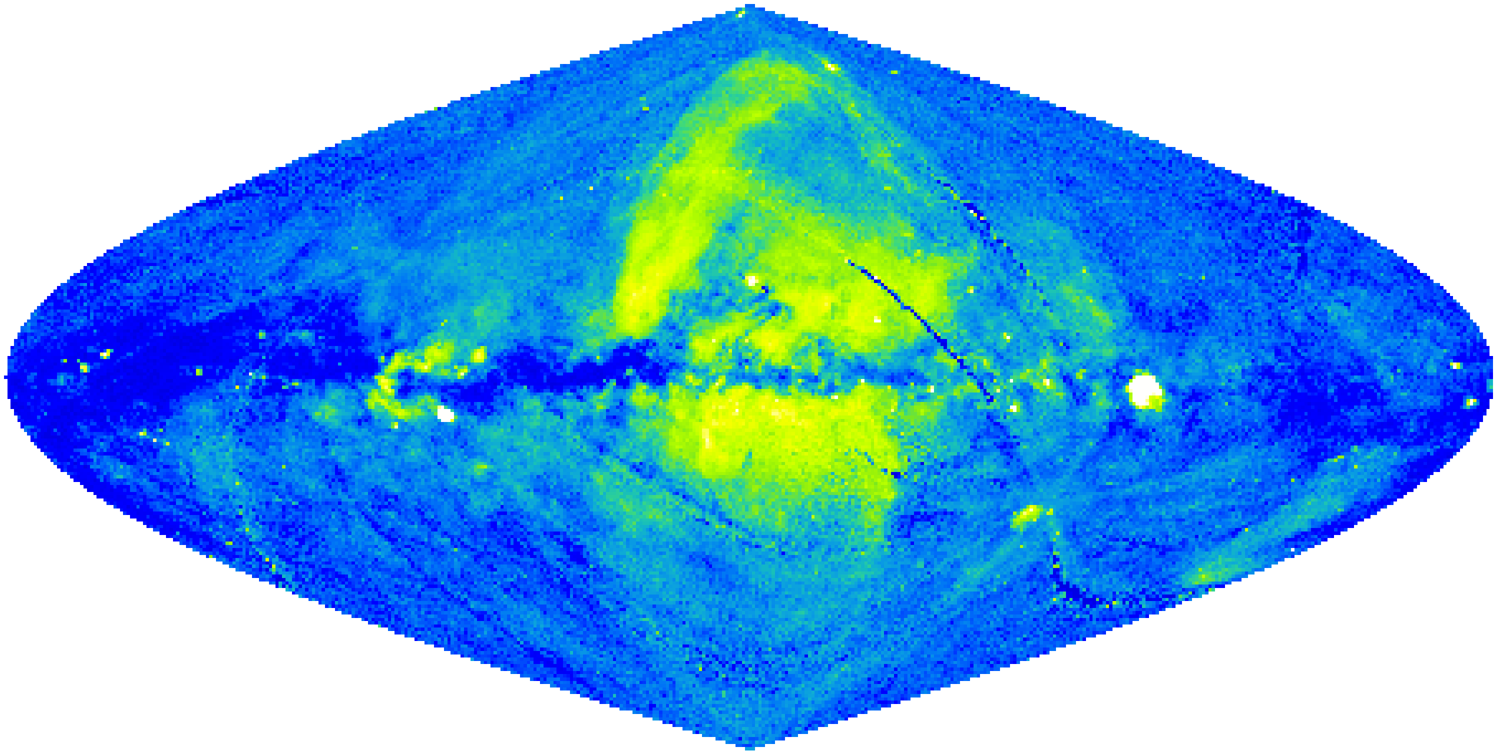


ACIS detector background: flare spectra



- **Very different from quiescent, so must be carefully excluded**

Soft sky background is nonuniform



ROSAT 3/4 keV all-sky CXB map (Snowden et al. 1997)

Chandra cluster analysis: images

- **Extract image from cleaned event file (create 2-D histogram)**
- **Reproject blank-sky background file into sky coords of this observation**
- **Extract image from bg file**
- **Calculate bg normalization using ratio of 9.5–12 keV rates; subtract bg image**
- **Create readout artifact model event file★; extract image; normalize by ratio of readout to frame exposures (0.0128) and subtract**
- **Create exposure map:**
  - **Detector map (includes mirror vignetting, CCD QEU and contamination maps for given energy; chip gaps, bad columns)**
  - **Convolve with aspect histogram**
- **Divide background-subtracted image by exposure map.**

★ **If cluster has sharp peak. Not in CIAO; make_readout_bg script in software exchange area**

Chandra cluster analysis: spectra

- **Select region in image; extract spectrum (PI histogram) from clean event file**

- **Create response files (weighted with cluster brightness within the extraction region):**
  - **ARF, includes mirror EA and vignetting and CCD efficiency vs. photon energy**
  - **RMF, energy redistribution matrix; converts photon energies into PI channels**

- **Extract spectra for same region from blank-sky and readout-artifact event files**
- **Adjust normalization of blank-sky spectrum (using 9.5–12 keV ratio)**
- **Use both as backgrounds in XSPEC**

- **If have source-free region, extract spectrum and check if need to model:**
  - **soft Galactic excess or deficit (mostly at $E < 1$ keV)**
  - **residual background flares (mostly at $E > 2$ keV)**

  If present, scale model norm. by region area and include as additional model components in the source fits

- **Fit source spectrum with favorite XSPEC model**
- **Vary bg normalization and propagate error into fit parameters**

Main differences between *Chandra* and *XMM*

- ***XMM* has 3 – 5× more effective area → more photons**

- ***XMM* is more strongly affected by background flares (Nevalainen et al. 2005)**
- ***XMM* has wider PSF, important for peaked clusters (astro-ph/0205333)**
- ***XMM* has stronger readout artifact (their “out of time events”)**