# The X-Ray Universe

## Potsdam University

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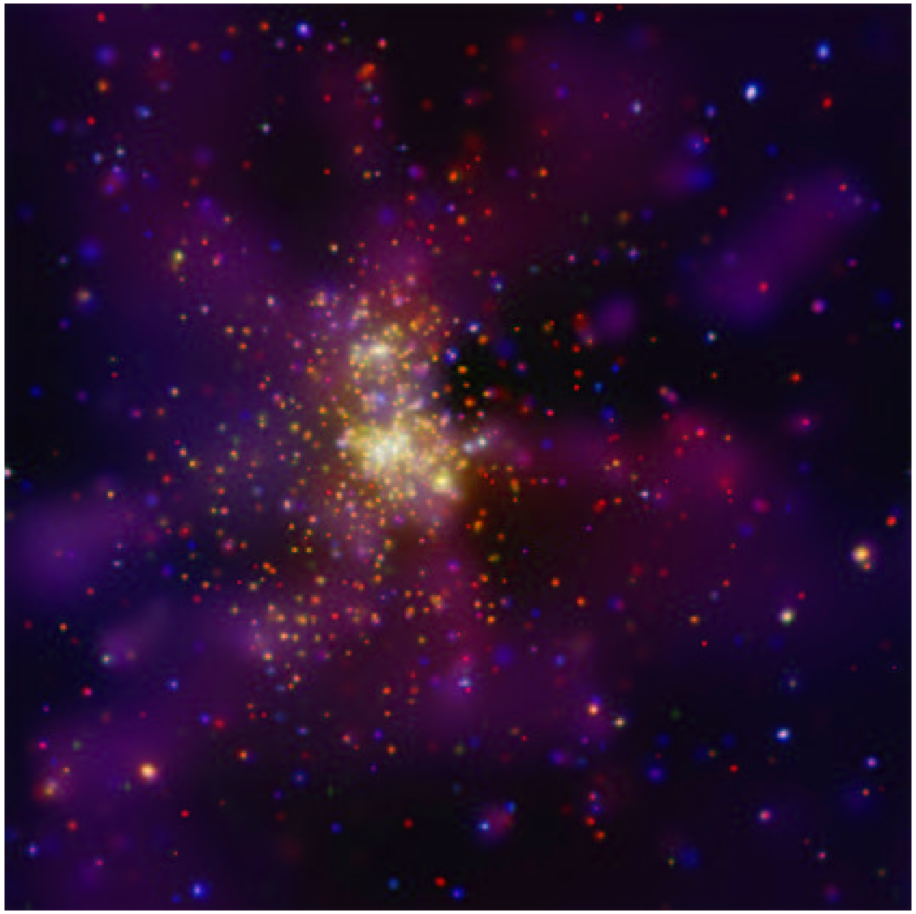
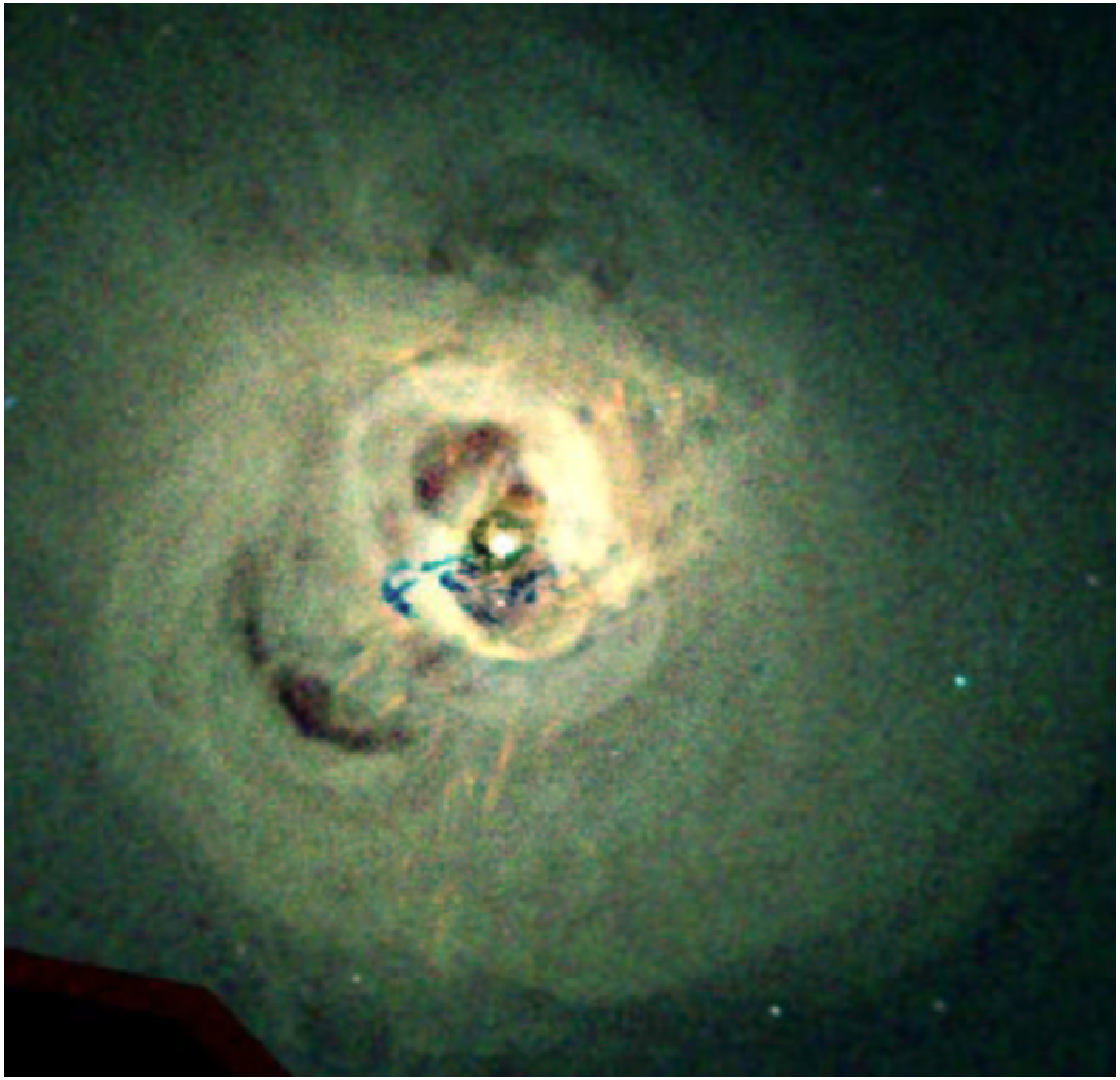


Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d= $2 \times 10^4$ ly

# X. Clusters of galaxies



http://chandra.harvard.edu/

# 01a Galaxy clusters


HST Coma cluster z=0.023

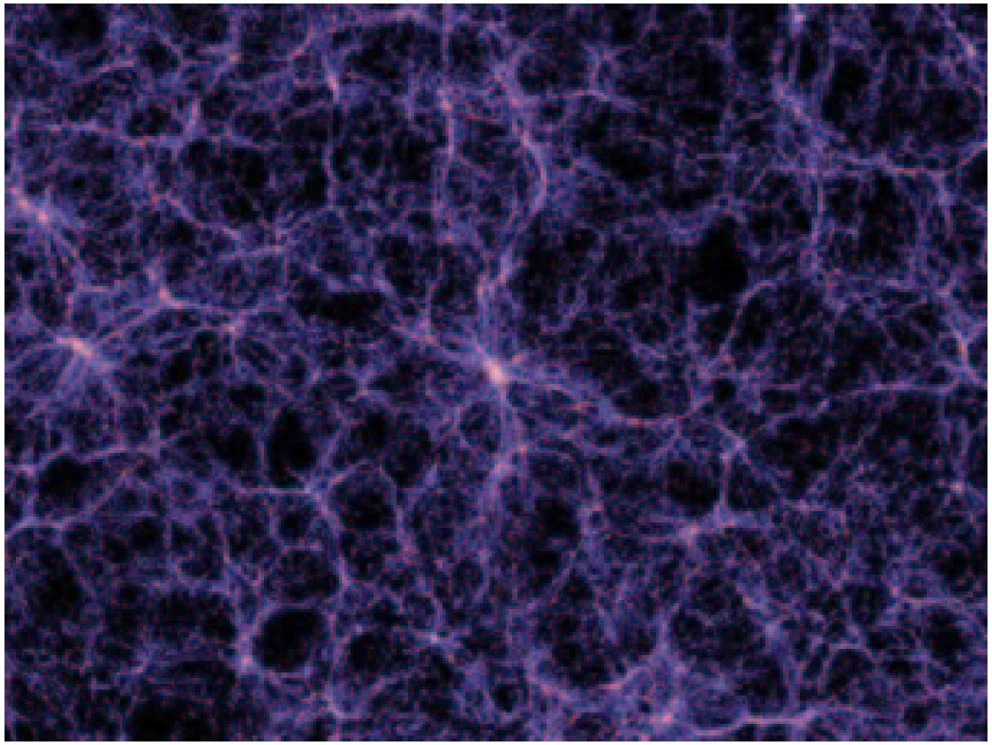
- Total masses of $10^{14}$ to $10^{15}$ solar masses.
- Largest gravitationaly bound objects in the Universe
- Diameter from 2 to 10 Mpc
- They contain 50 to 1000 galaxies, Intra Cluster Matter (ICM) and dark matter
- The MW belongs to the Local Group: over 35 galaxies. The MW is the most massive and second largest in the Local Group,

# 02 Structure in the Universe

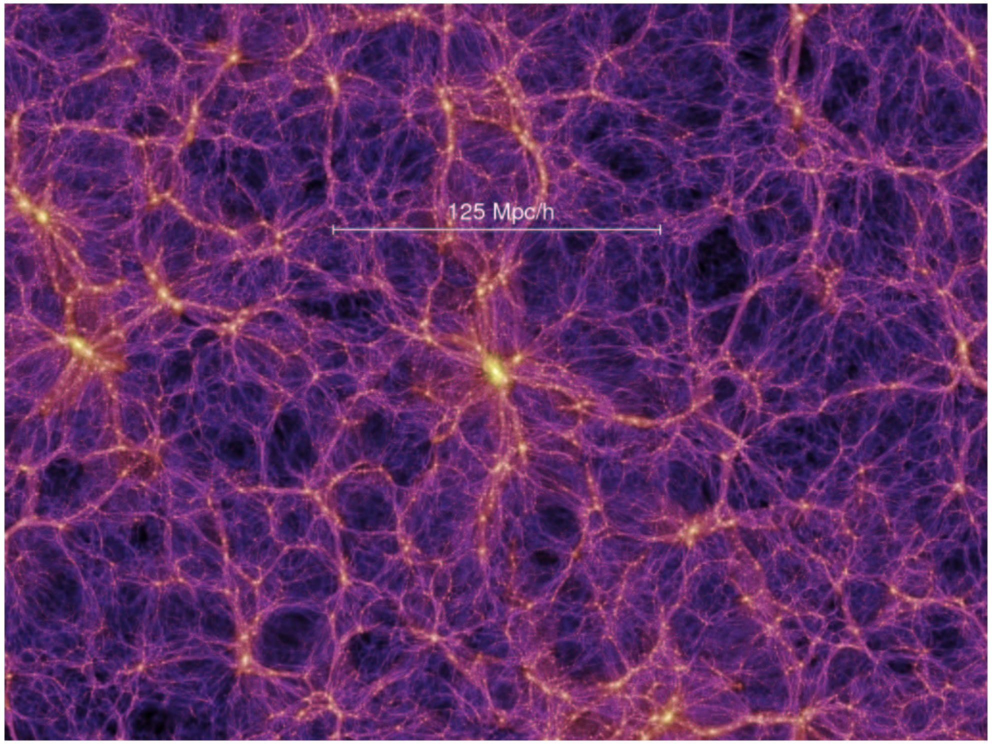
- Fluctuations in density are created early in the Universe.
- These fluctuations grow in time. At recombination (when the Universe has cooled enough for atoms to form from electron-proton plasma) they leave their imprint on the microwave background. COBE, WMAP
- Fluctuations continue growing as overdense regions collapse under their own gravitational attraction.
- Baryons fall into the gravitational potential wells produced by the dark matter. Potential energy is converted to kinetic then thermalized -> hot plasma.

# 03 Structure in the Universe

A cluster of galaxies: DM distribution



A cluster of galaxies: DM distribution



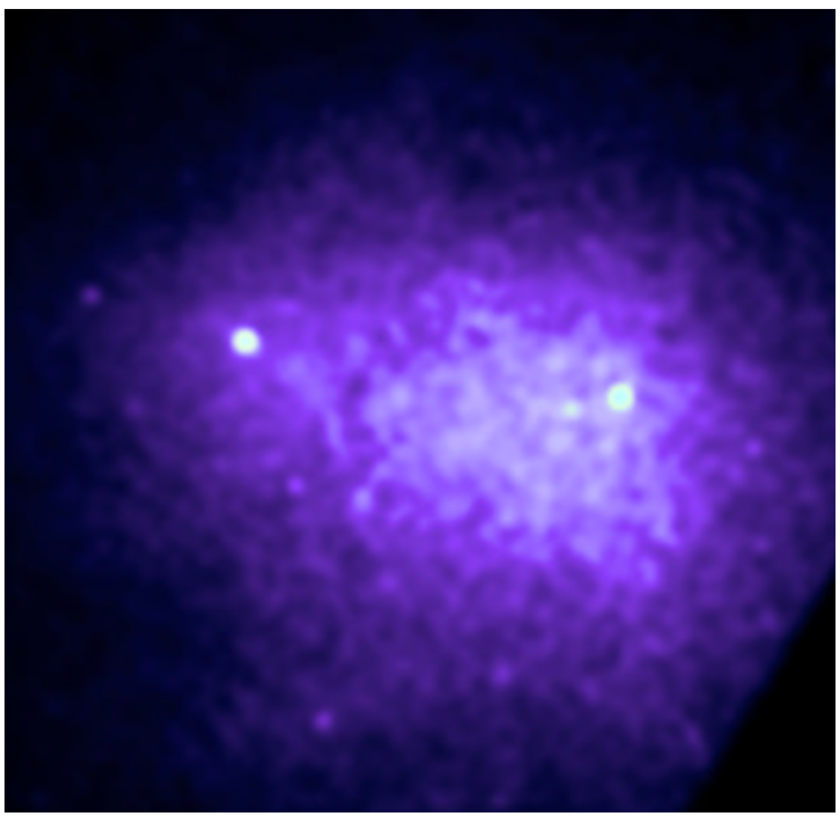

Millennium Simulation, Nature 2005, 435, 629

- Clusters of galaxies are formed from the extreme high end (high σ peaks ) of the initial fluctuation spectrum. They exist at the intersections of the Cosmic Web.
- The way that structure evolves depends on the geometry and contents of the Universe (total density, dark matter density, dark energy density).
- Because clusters are formed from the high sigma peaks their numbers and evolution in time depend sensitively on cosmological parameters.

# 04 X-rays from Clusters of Galaxies

Coma cluster HST: 9 arcmin wide


Coma cluster CXO: 17 arcmin wide



NASA/CXC/SAO/A.Vikhlinin et al.

- Virial Theorem: $U_{pot} = -2T_{kin}$ .

  $$\overline{v^2} = \overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2} = 3\overline{v_{pj}^2}$$

  $$\rightarrow T = \frac{1}{2}\sum_i m_i \vec{v}_i^2 = \frac{3}{2}M\overline{v_{pj}^2}$$

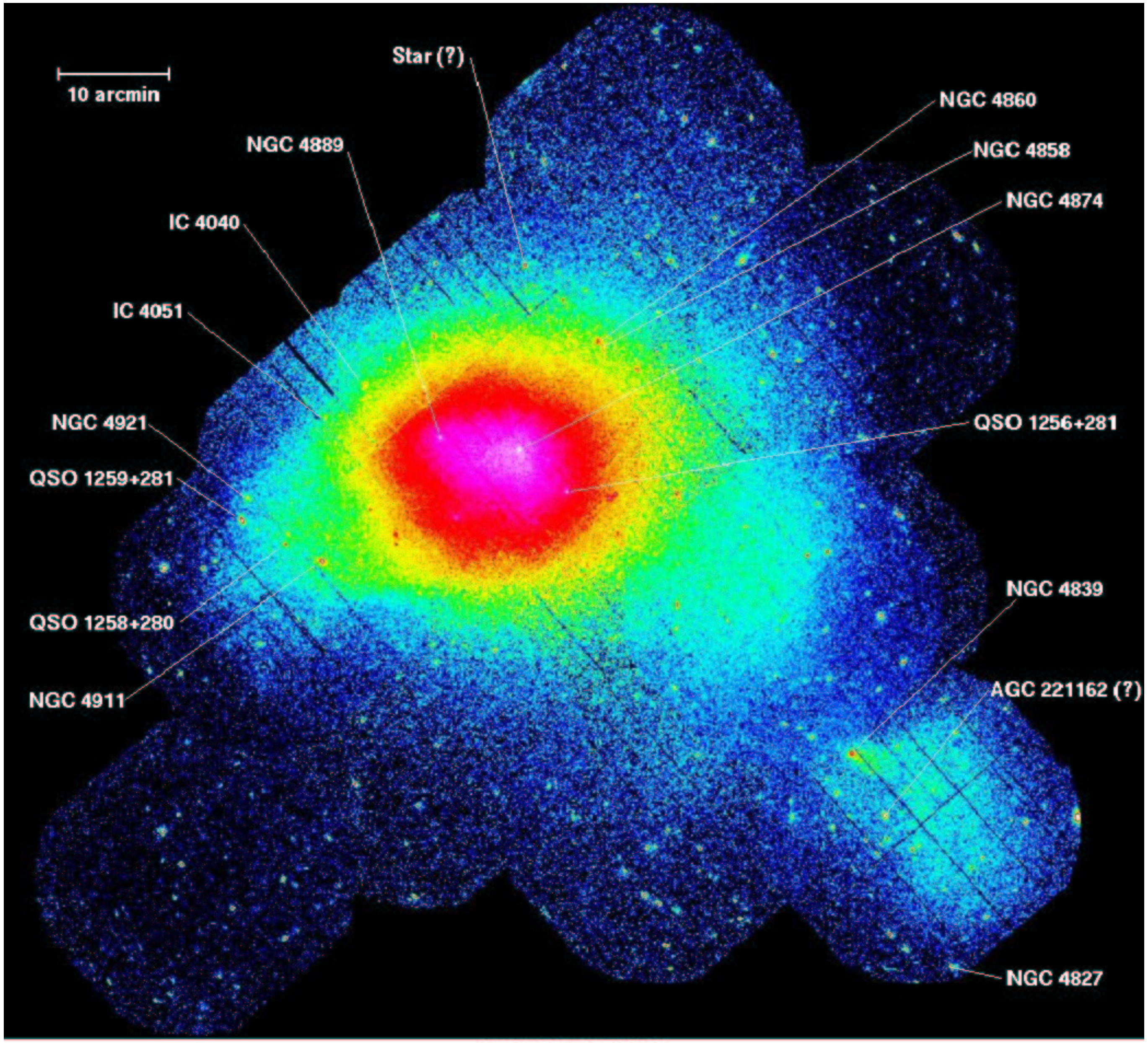
- $U = \frac{GM^2}{R} \rightarrow \quad M = \frac{3}{G}\overline{v_{pj}^2}R$ , where R is mean separation

- The baryons thermalize to > $10^6$ K making clusters strong X-ray sources.

- Most of the baryons in a cluster are in the X-ray emitting plasma - only 10-20% are in the galaxies.

- Clusters of galaxies are self-gravitating accumulations of dark matter which have trapped hot plasma (ICM) and galaxies.

# 05 X-ray measurments




Coma Cluster of galaxies

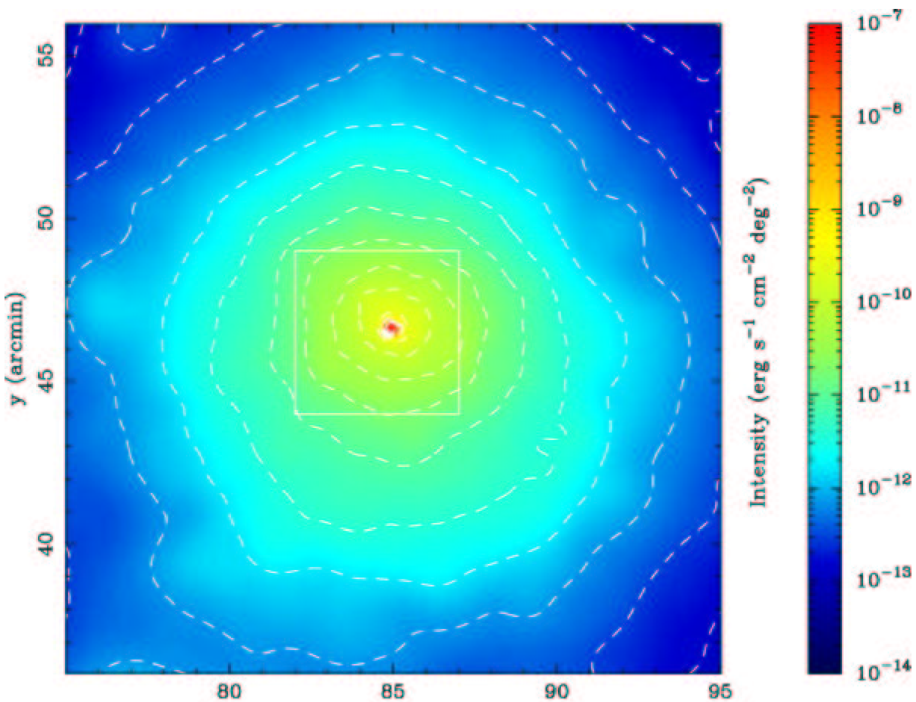
Image courtesy of U. Briel, MPE Garching, Germany

European Space Agency

- From the spectrum we can measure a mean temperature, a redshift, and abundances of the most common elements (heavier than He).
- With good S/N we can determine whether the spectrum is consistent with a single temperature or is a sum of emission from plasma at different temperatures.
- Using symmetry assumptions the X-ray surface brightness can be converted to a measure of the ICM density.

# 06 Mass determination

Simulation of X-Ray Emission




Fang et al.2003, 623, 612

ICM: bremsstrahlung emission

$$\epsilon(E) \propto \sqrt{\left(\frac{m_e}{kT}\right)} g N^2 \exp -E/kT$$

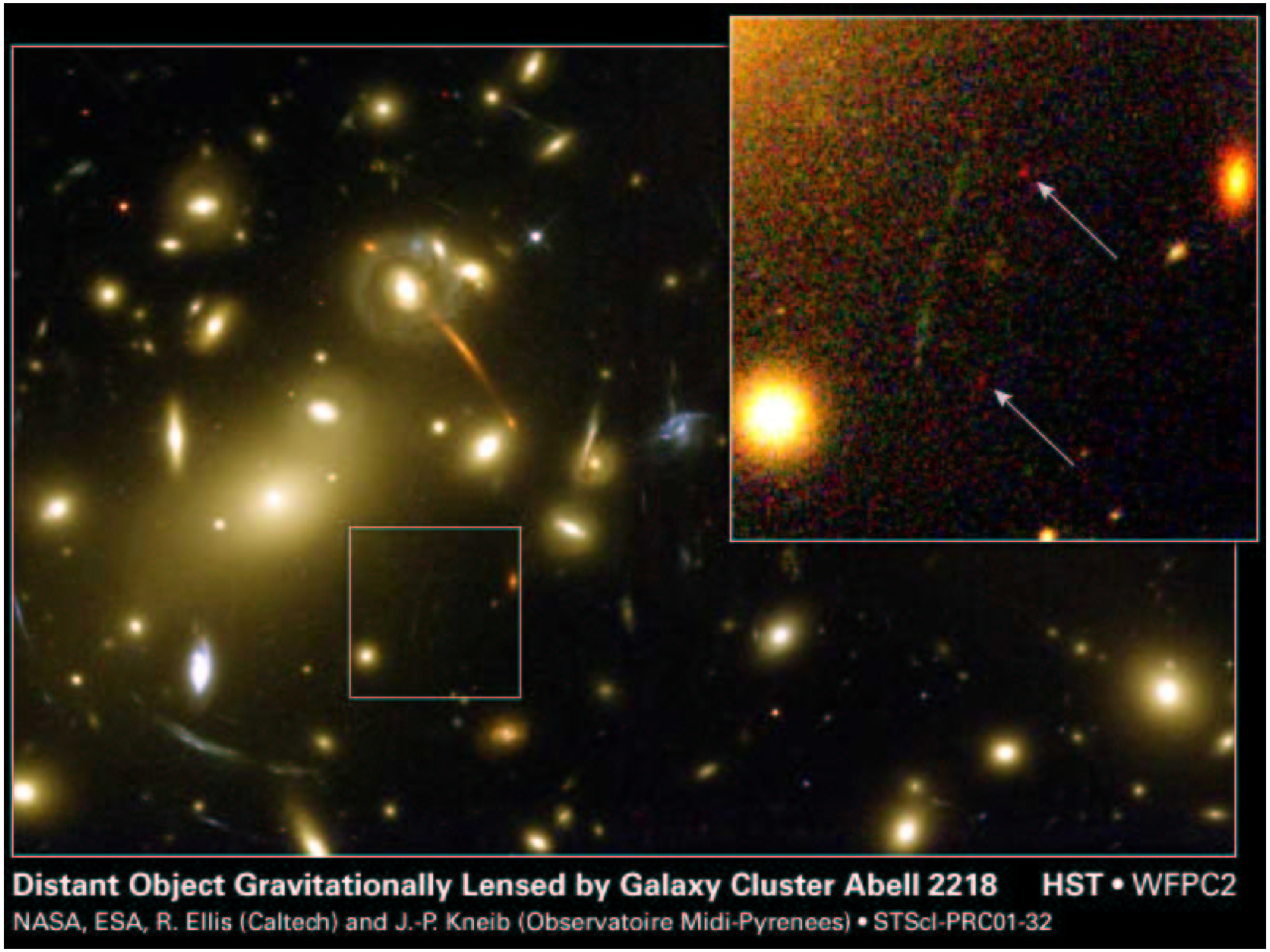
- If we can measure the temperature and density at different positions in the cluster then assuming the plasma is in hydrostatic equilibrium we can derive the gravitational potential and hence the amount and distribution of the dark matter. (e.g. Sarazin 1998)
    - $\nabla P = -\rho_{\rm gas} \nabla U = -\frac{GM}{r^2}\rho$ , $P = \rho_{\rm gas} T = \frac{\rho k T}{\mu m_{\rm H}}$
    - $\frac{dP}{dr} = \frac{k}{\mu m_{\rm H}}\left(T\frac{d\rho}{dr} + \rho\frac{dT}{dr}\right)$
    - $= \frac{\rho k T}{\mu m_{\rm H}}\left(\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right)$
    - $M = -\frac{kTr^2}{G\mu m_{\rm H}}\left(\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right)$

**T, N from X-ray spectra → mass**

# 06a Mass determination

- X-ray observations allow **two** mass determinations for a relaxed galaxy cluster
- Mass of gas is proportional to square of X-rays emission, because the emission is thermal Bremsstrahlung.
- Total mass is proportional to the gas temperature, because this defines the cluster potential.
- Temperature profile can be used to constrain the cluster potential and find $\mathbf{f_{gas}=M_{gas}/M_{total}}$
- Eck (1998): the mean baryonic mass fraction b within the virial radius of a cluster is similar to the universal baryon fraction. Because $R_{vir}$ separates the region where shells of material are infalling for the first time.
- From X-ray data gas fraction is only about 82% of average barion fraction → clusters loose some gas when they form, it decreases with z.

# 07 Other ways to detrmine cluster mass




-- The gravitational potential acts as a lens on light from background galaxies.

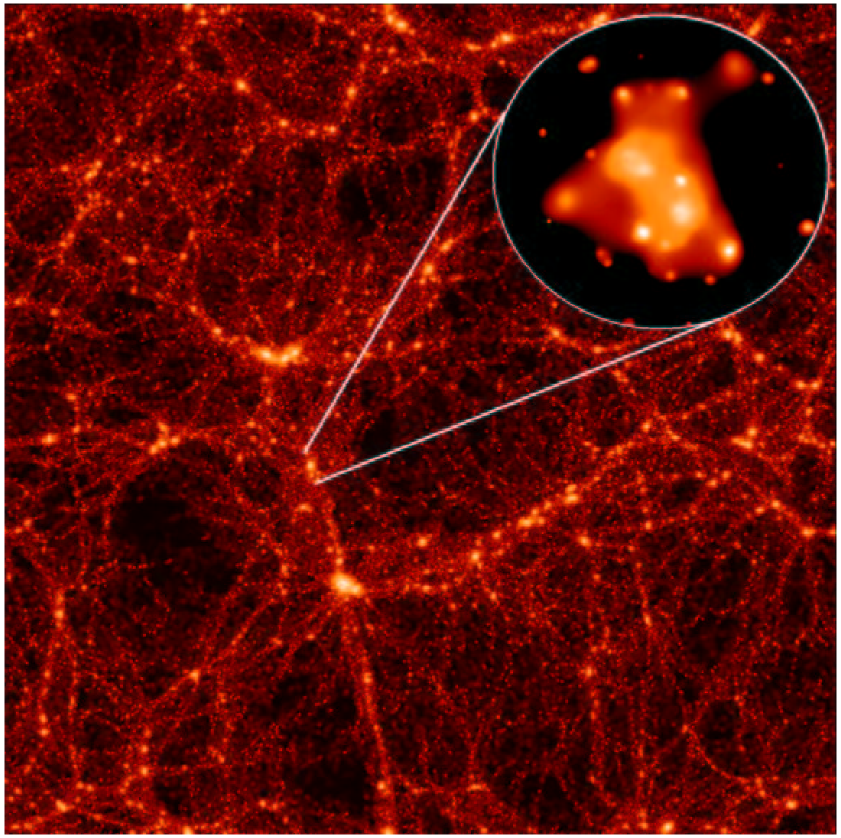
-- The galaxies act as test particles moving in the potential so their redshift distribution provides a measure of total mass.

For regular clusters these measures agree.

## 08 Top questions on Clusters of Galaxies (after Keith Arnaud 2007)

- Are clusters fair samples of the Universe ?
- Can we derive accurate and unbiassed masses from simple observables such as luminosity and temperature ?
- Does the gravitational potential have the same shape as the baryons (stars and gas) ?
- What is happening in the centers of clusters - how does the radio galaxy and the cluster gas interact ?
- What is the origin of the metals in the ICM and when were they injected ? What is the origin of the entropy of the ICM ?

# 09 Galaxy Clusters have a lot in common

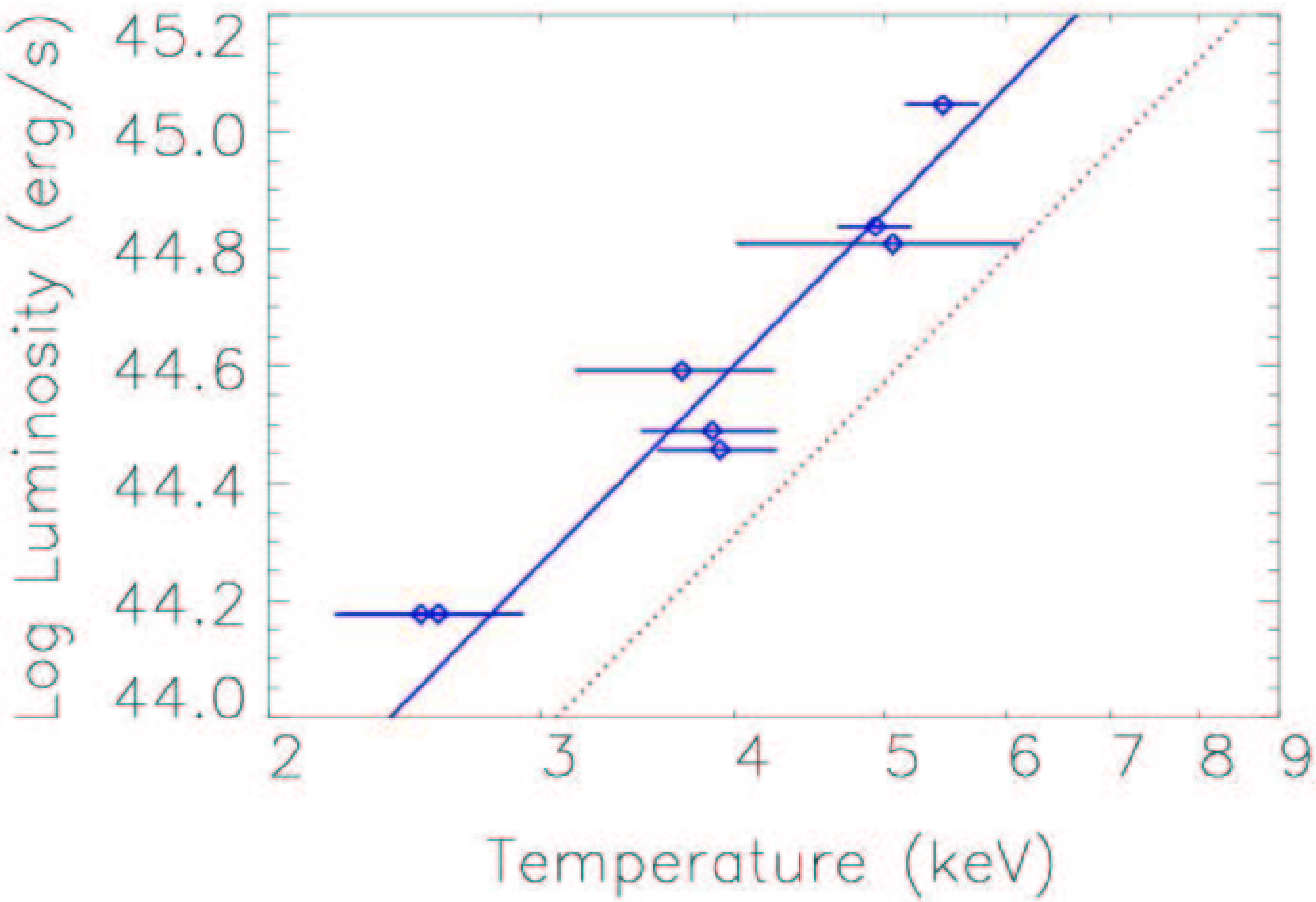


Virgo consortium; Jenkins et al. 1998

- Number of surveys with XMM and Chandra. E.g. z = 0.6-1.0 the Universe was half its present age.
- Icluding two merging clusters and an extremely massive "relaxed" cluster.
- **The galaxy clusters are weakly self-similar.**
- Vikhlinin et al. 2002, ApJ 578, 107
  Correlations between X-ray temperature, luminosity, and gas mass for a sample of 22 z>0.4 clusters: evolution in all three correlations between z>0.4 and the present epoch. In the $\Omega$=0.3, $\Lambda$=0.7 cosmology, the luminosity corresponding to a fixed temperature scales approximately as $(1+z)^{1.5}$ the gas mass for a fixed luminosity scales as $(1+z)^{-1.8}$ and the gas mass for a fixed temperature scales as $(1+z)^{-0.5}$.

The observed M-T-L correlations → high-redshift clusters were denser than at present - hotter and more luminous for a given mass, as expected in a theory of the hierarchical self-similar formation. However, the details of the observed evolution contradict the self-similar predictions.

# 10 Redshift evolution of the L-T relation for clusters of galaxies




Redshift evolution of the lt relation for clusters of galaxies

Image courtesy of D. H. Lumb, J.G. Bartlett et al.,

European Space Agency

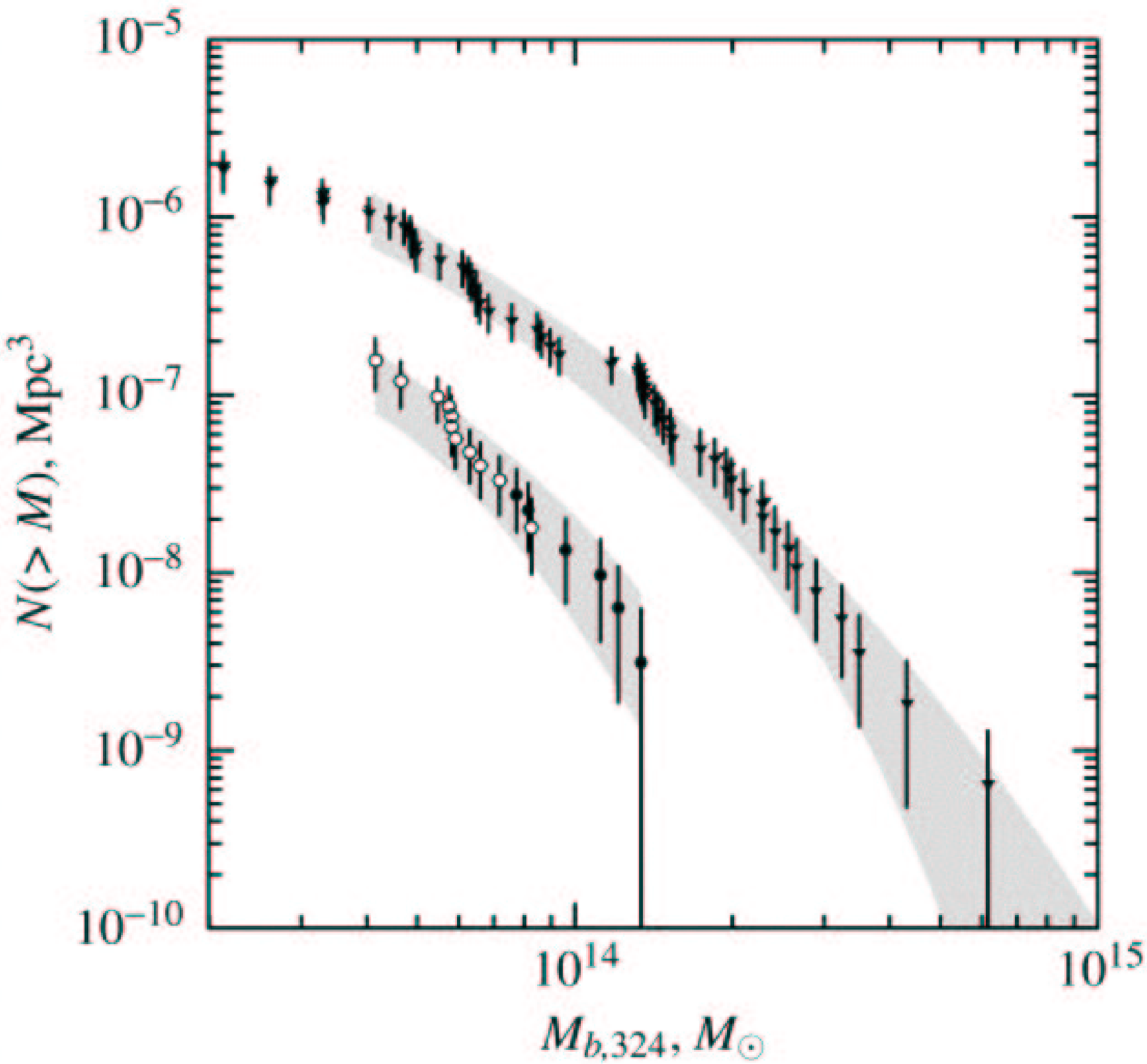
- galaxy clusters for a redshift range 0.45<z<0.62
- Low-Redshift clusters there is evolution with redshift

Cosmological simulations predict distributions of masses. If we want to use X-ray selected samples of clusters of galaxies to measure cosmological parameters then we must be able to relate the observables (X-ray luminosity and temperature) to the theoretical masses.

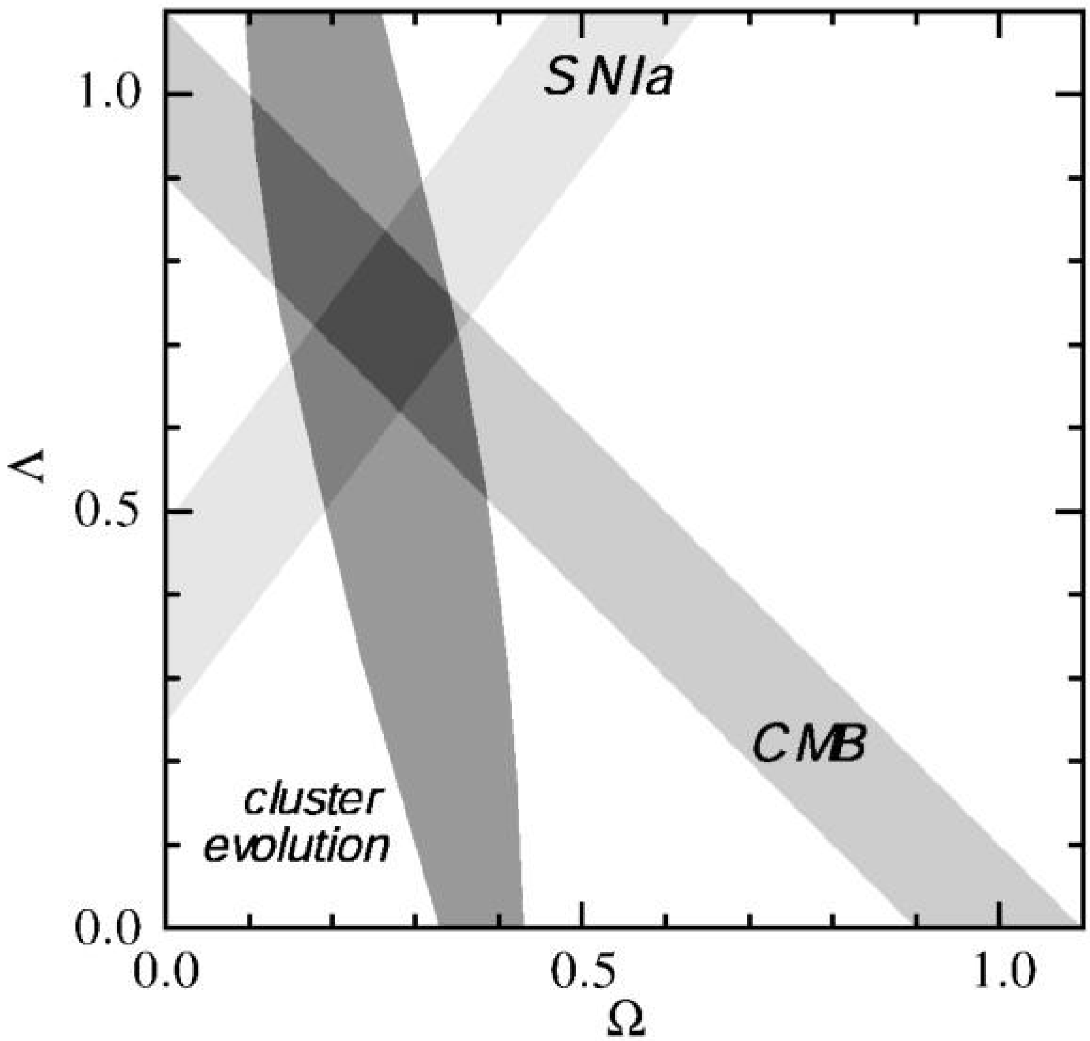
# 11 Cosmology from cluster evolution (Vikhlinin et al. 2003)

- Barion mass fraction from measuring $T_X$ and $L_X$ and used as a proxy for total M
- Cosmological simulations predict the cluster mass function at any redshift
- Constraining N of cluster of given mass with redshift constarins cosmological models.
- Most of the difficulties are on the observational side.

- Baryon mass function for the cluster survey with 0.4<z<0.8. measured by Chandra barion mass measurments: data points
- Grey: computed theoretical mass function ($\Omega_m$=0.3, $\Lambda$=0.7) includng error bars.
- Upper curve: local Universe, cosmology independent



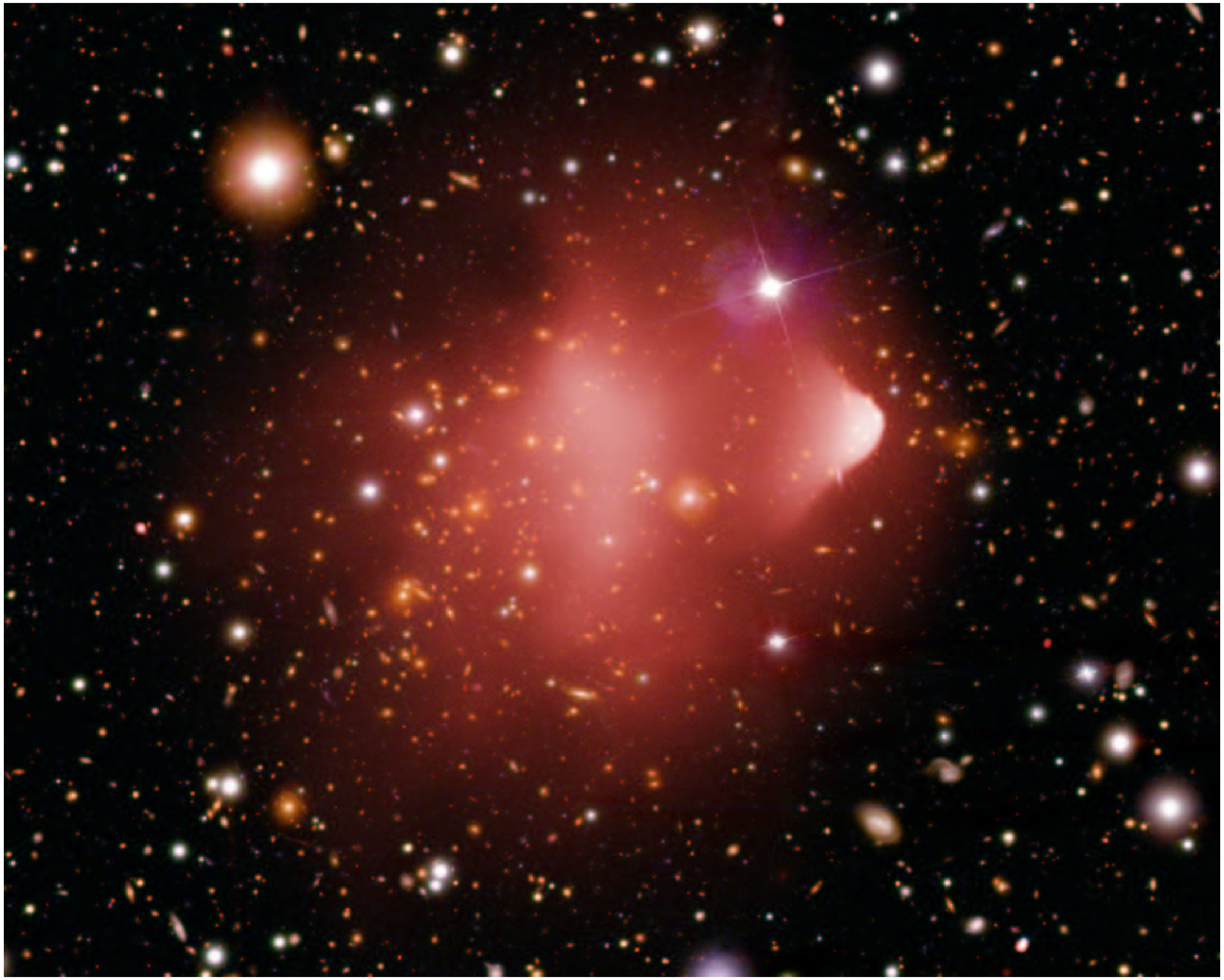
# 12 Cosmology from cluster evolution (Vikhlinin et al. 2003)




-- Independent on other methods

-- New surveys are underway

# 13 The Bullet Cluster (two interacting clusters)

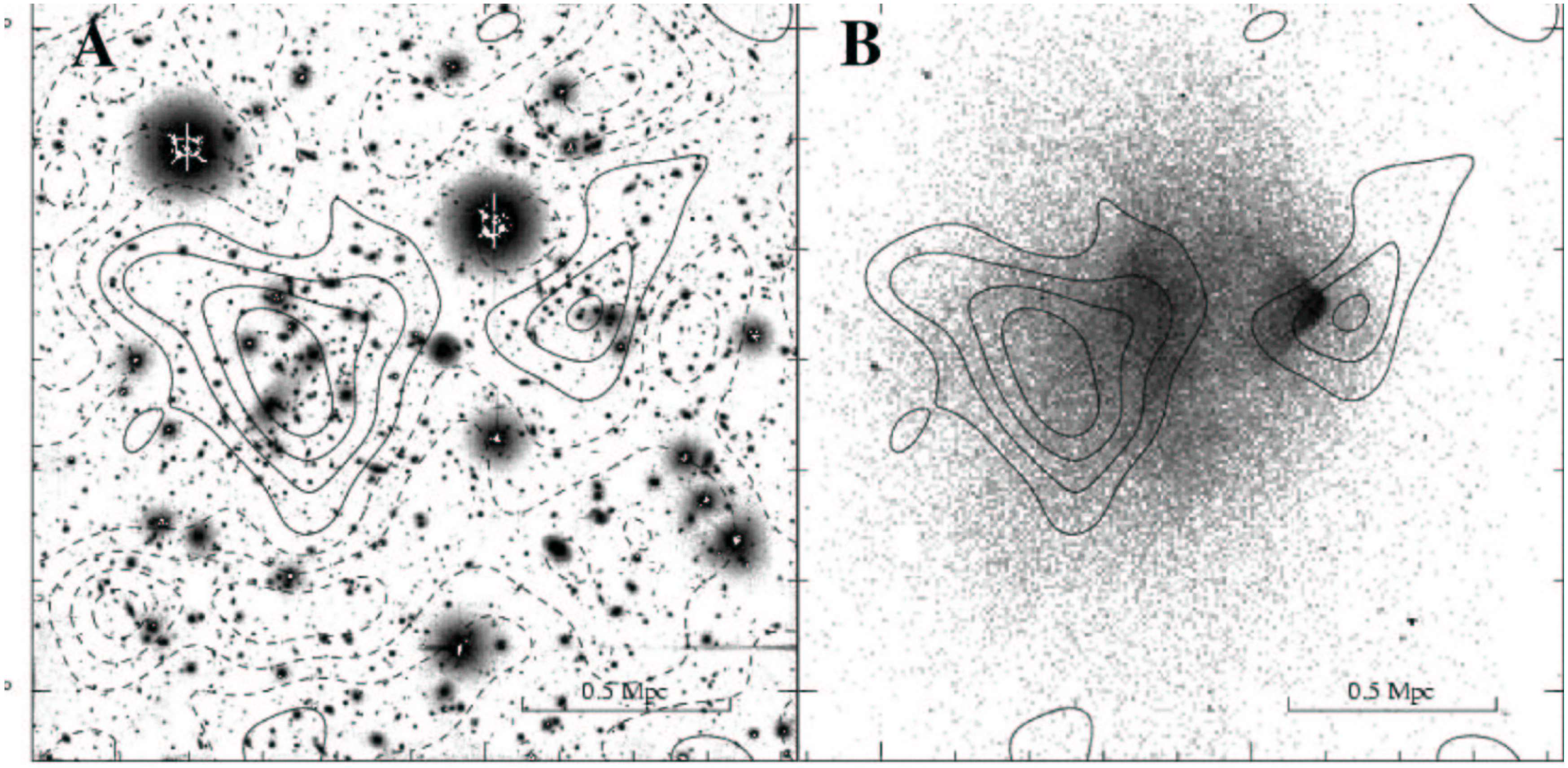


X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et

- System has just undergone pass-through: the two clusters are now moving away from one another.
- no $\gamma$-rays, no antimatter!

# 14 Does gravitational potential trace barions?

Weak-lensing maps overlayed with X-ray image




Clowe et al. 2004 ApJ 604, 596

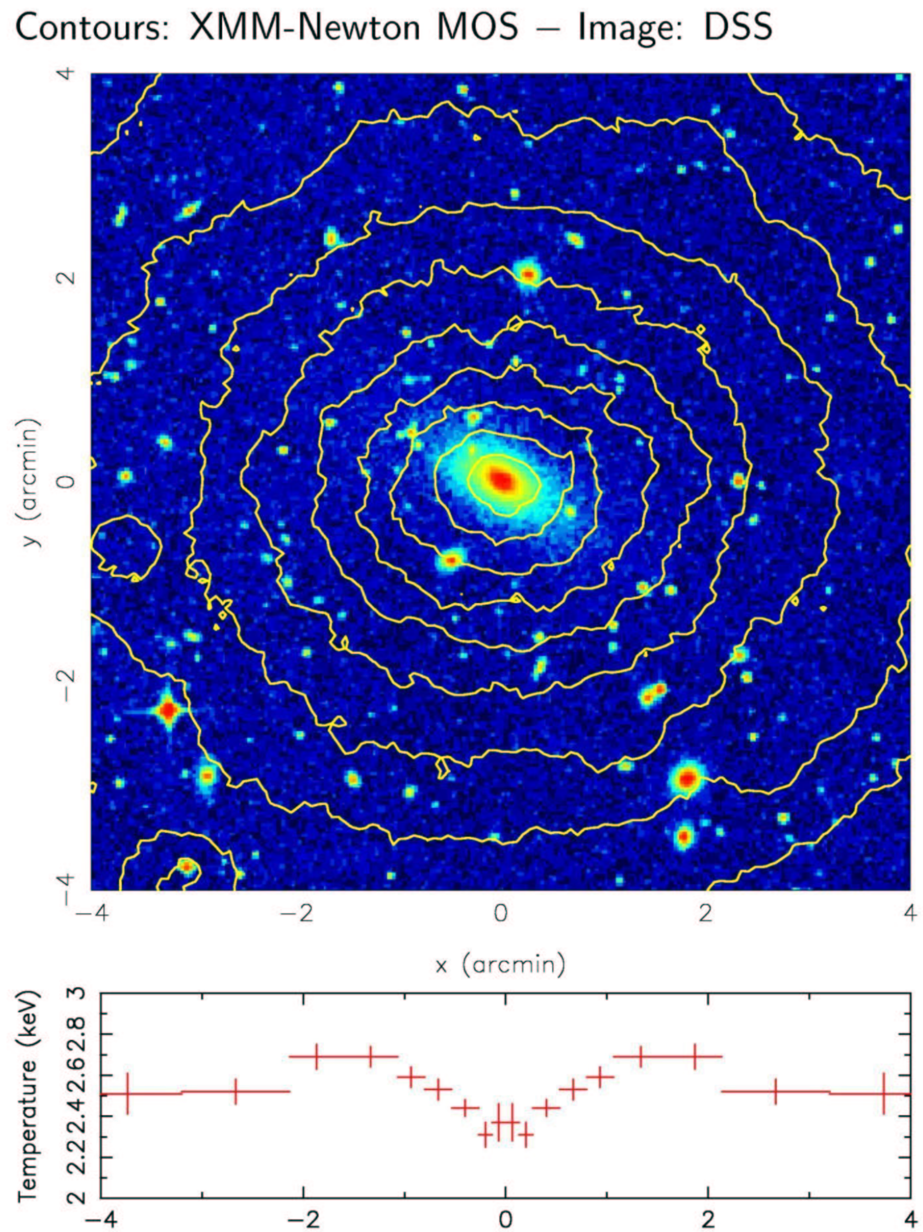
- Galaxies are collisionless particles in the pass-through
- There is agreement in position between the mass peak and galaxy overdensity
- The X-ray gas:the ram pressure of the interacting gas halos, it is slowed down during interaction
- There is offset between barionic density (X-ray) and mass density
- Bulk of the mass is collsionless as expected for the **dark matetr**

# 15 Central regions of galaxy clusters

- Basic model: Clusters were spherically symmetric balls of plasma that evolved in isolation.
- Gas density is highest at the center. $\varepsilon \sim N^2$, cooling time $t_{\rm cool} \propto T^{1/2}/n_{\rm e}$ smaller than the cluster age
- Gas is would lose energy by radiating X-rays → pressure drops → gets compressed by garvitational well → density and ε increase → leading to a steady cooling inflow of plasma cooling flow.
- So the X-ray spectra should show evidence for a range of temperatures from the ambient for the cluster down to zero.
- **But! They don't!** little cooling gas is found → CF-problem

# XMM-NEWTON SCIENCE RESULTS

## Sérsic 159-03



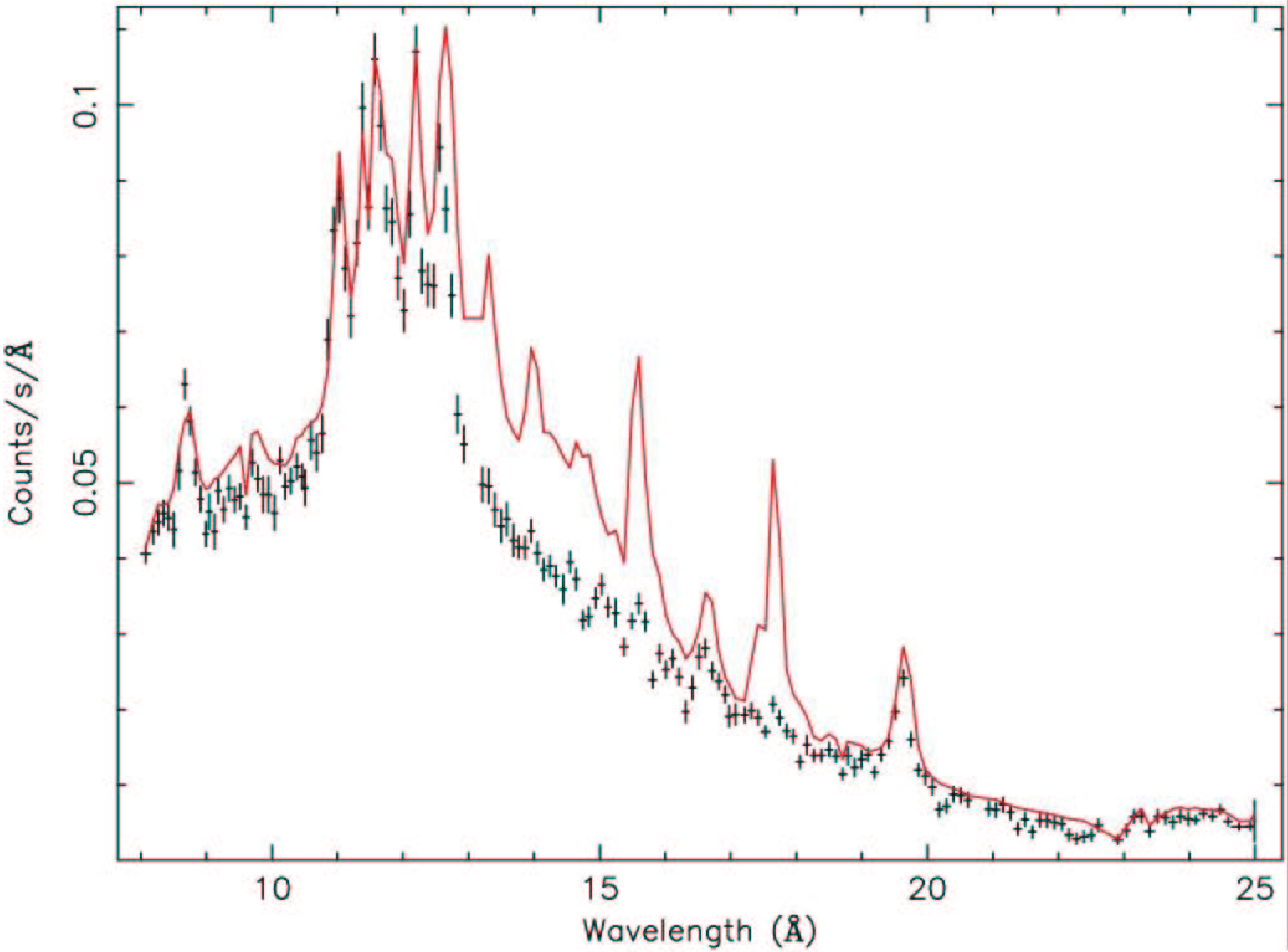

6 December 2000

Fig. 2

Abell S1101 (=Sersic 159-03)

Image courtesy of J. Kaastra, SRON, Utrecht, NL

16a




Slow cooling in the core of the galaxy cluster 2A 0335+096

Image courtesy of Jelle de Plaa, SRON, NL.

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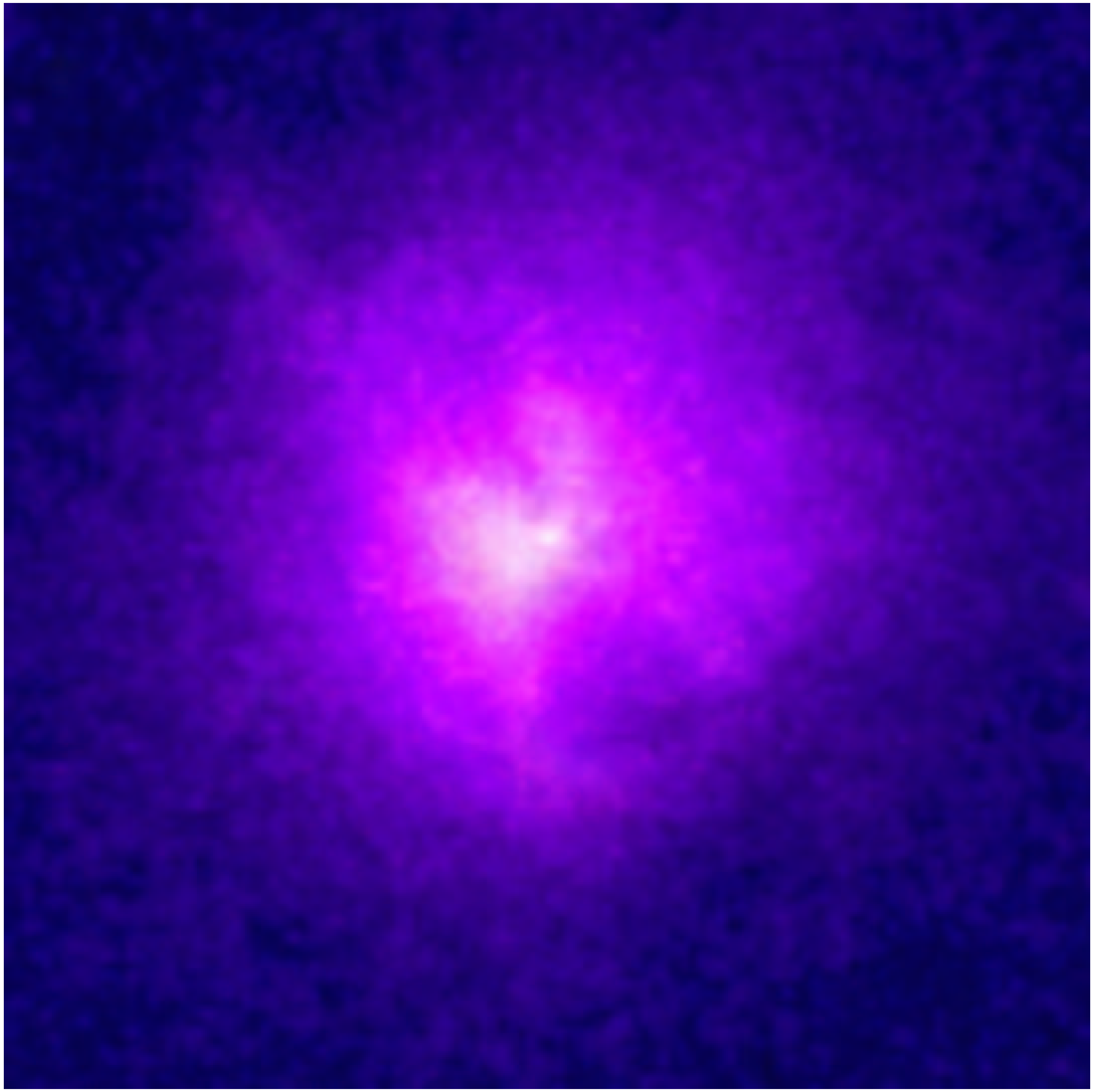
# 17 Hydra A: key to the CF problem?

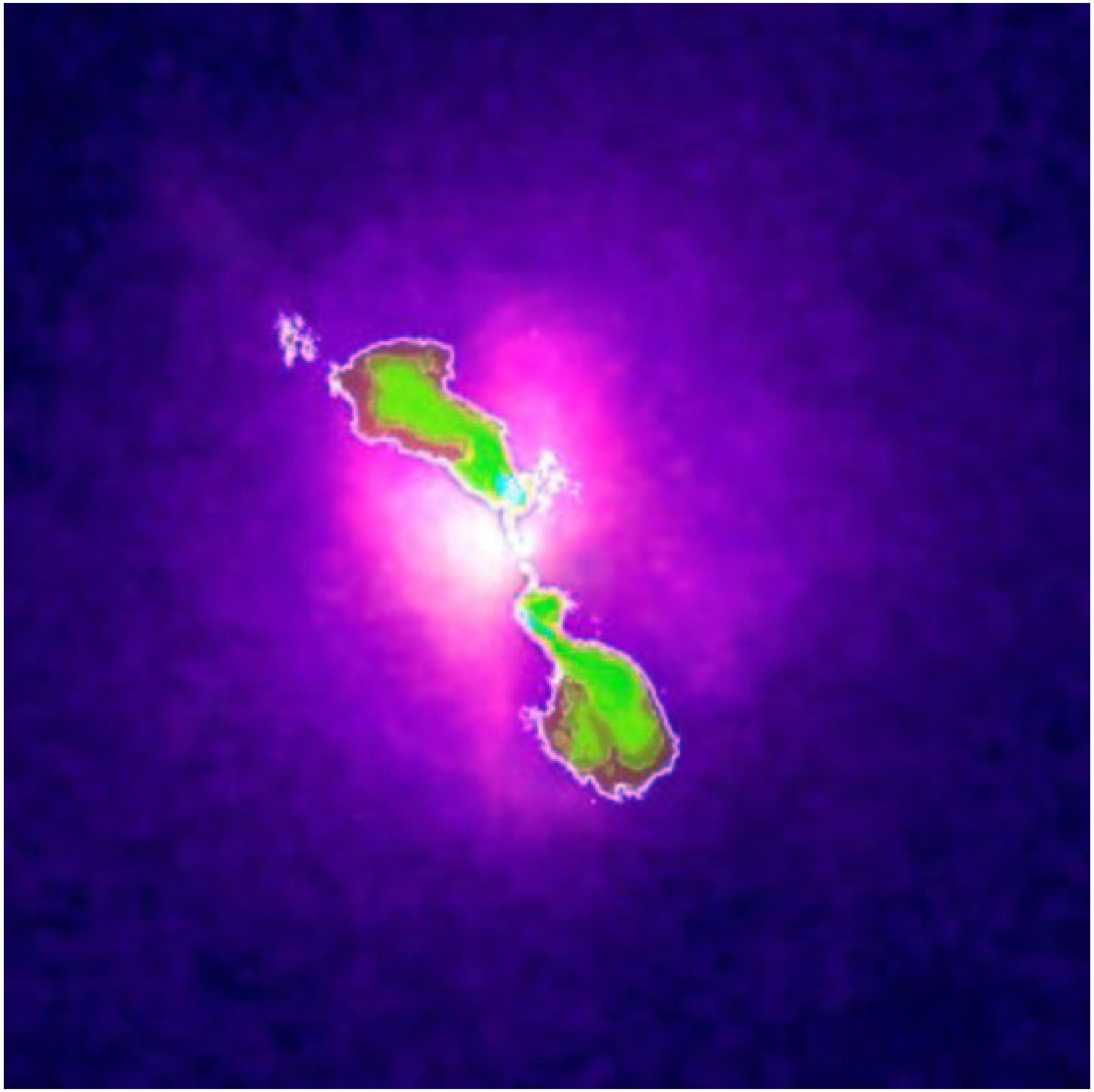
Chandra Image



NASA/CXC/SAO

# 18 AGN feedback - a key to the CF problem?

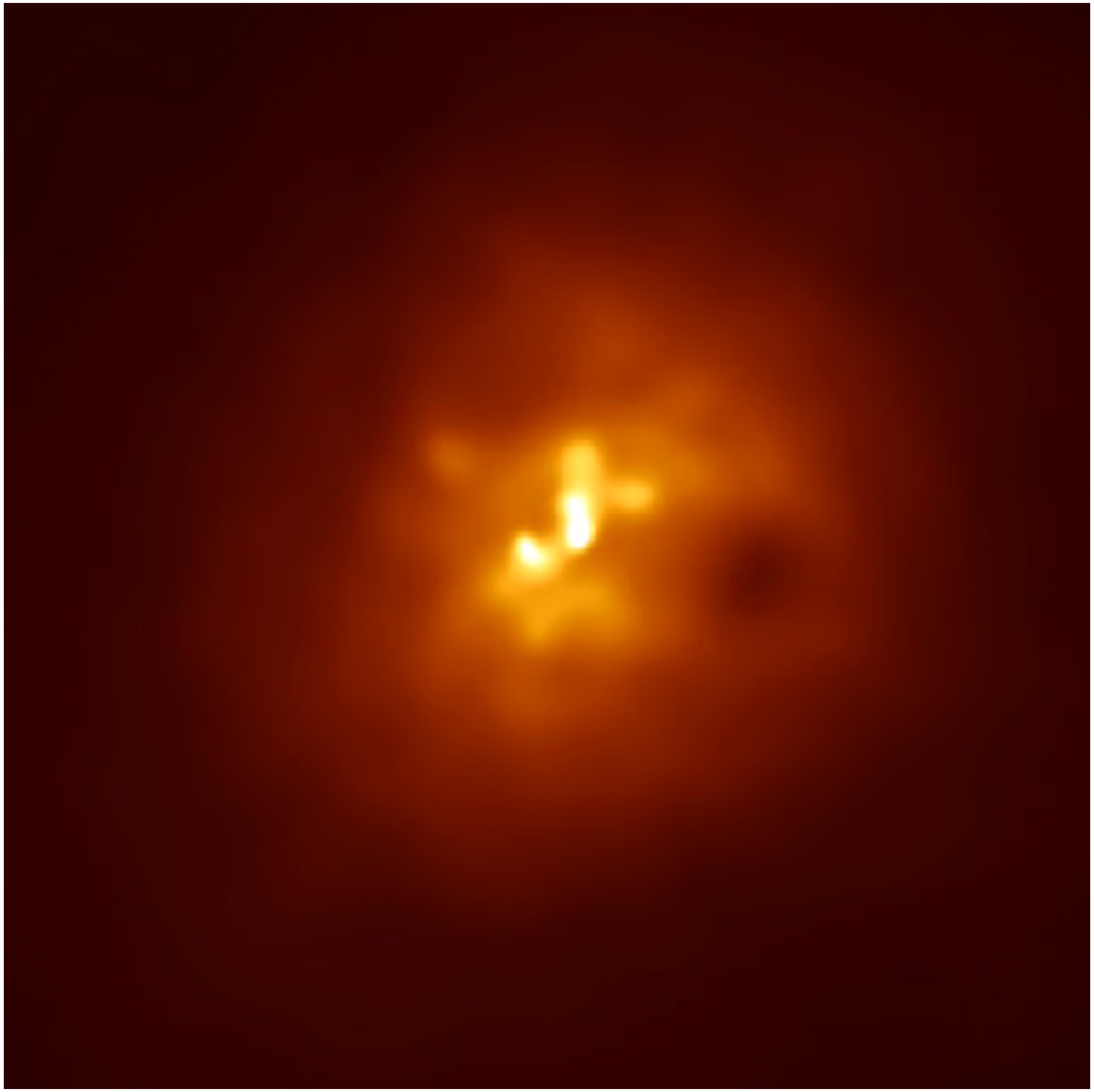
Chandra + Radio Image



NASA/CXC/SAO/NRAO

# 19 Bubbles in Abell 2597

Chandra X-ray image



NASA/CXC/SAO/NRAO

Ghost cavities are 100 million-year-old relics of an ancient eruption that originated around a massive black hole in the core of a centrally located galaxy.

Bubbles are hot gas, magnetized, high-energy particles → enough to support surrownding pressure.

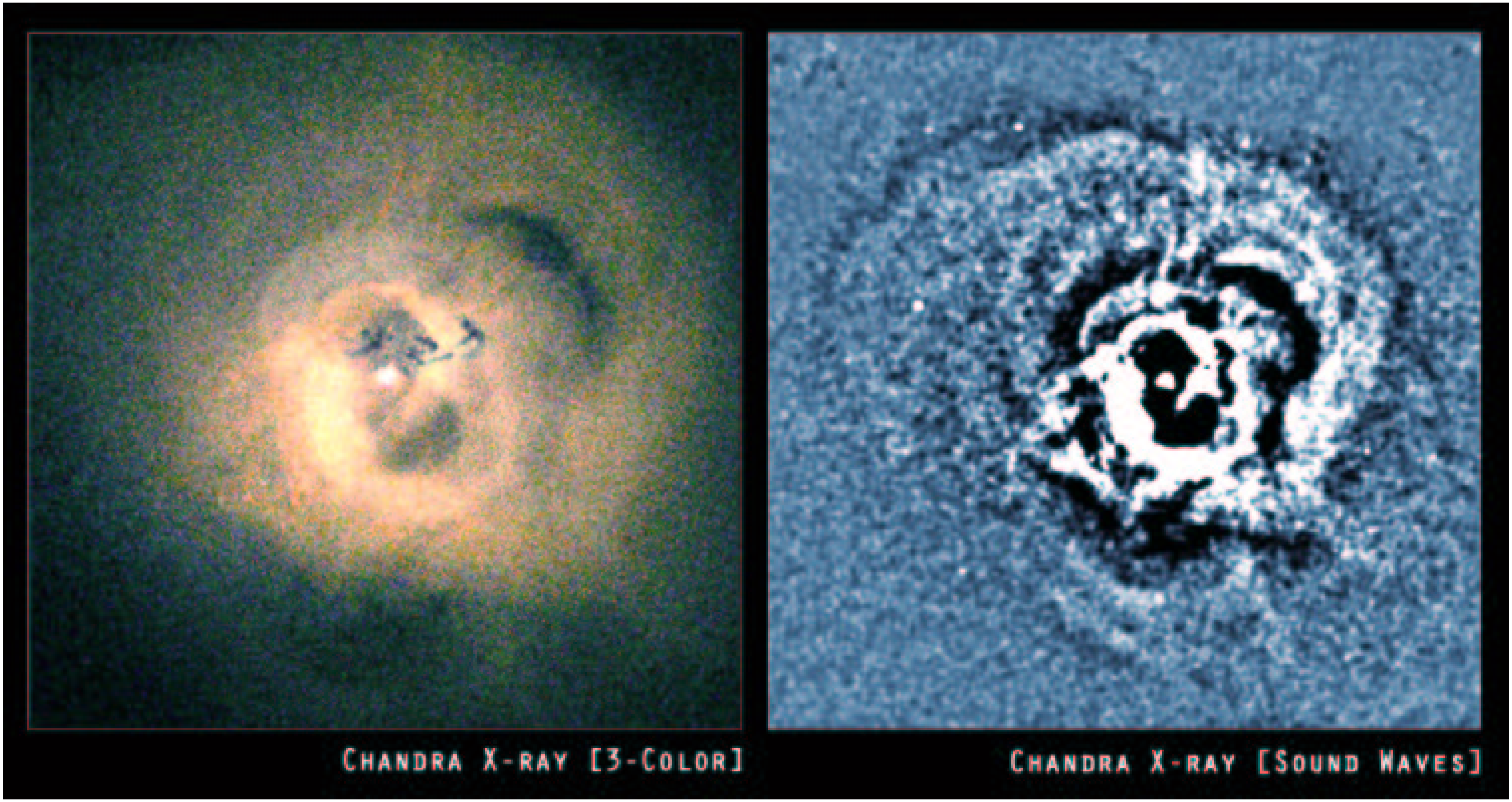
Multiple events → energy deposit into the ICM

# 20 Sound Waves in Perseus A

Sound waves from explosive events In the AGN in the central galaxy

Dissipation of sound waves → heating of ICM

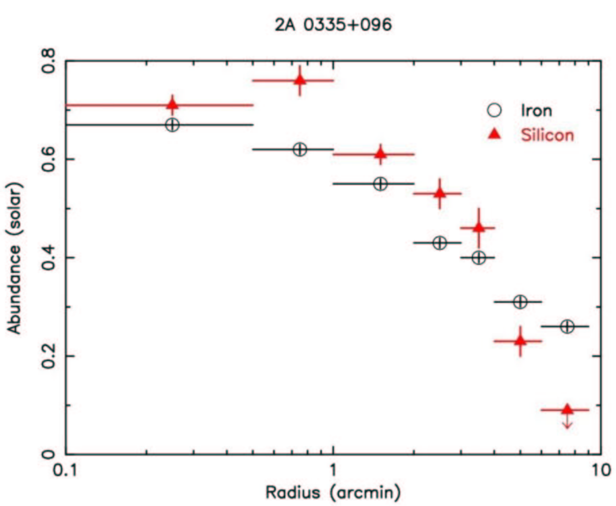
Cavities are radio sources, filled with high-energy particles and magnetic fields.

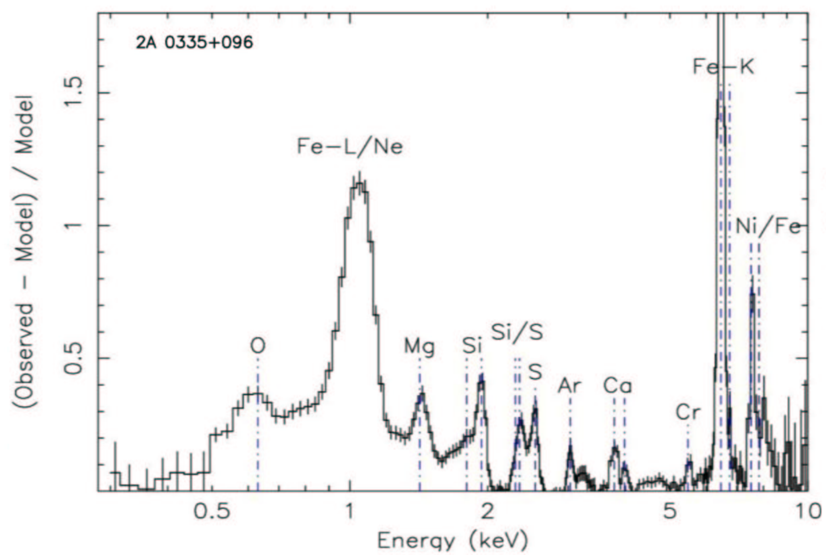



NASA/CXC/SAO/  see annimation

# 20a Chemical evolution of the Universe

What is the origin of the metals in the ICM and when were they injected ? What is the origin of the entropy of the ICM ?



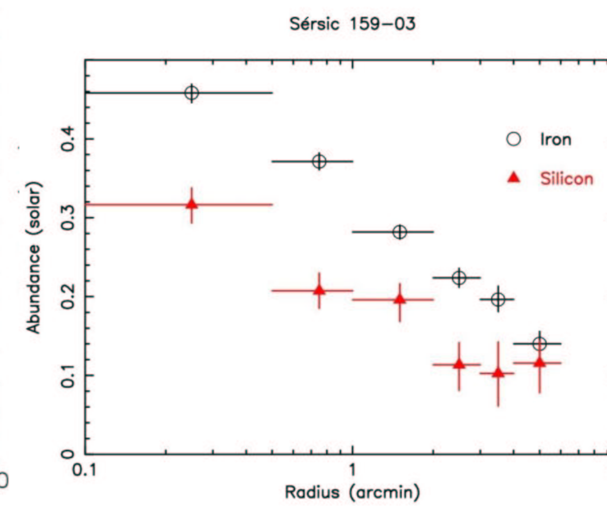
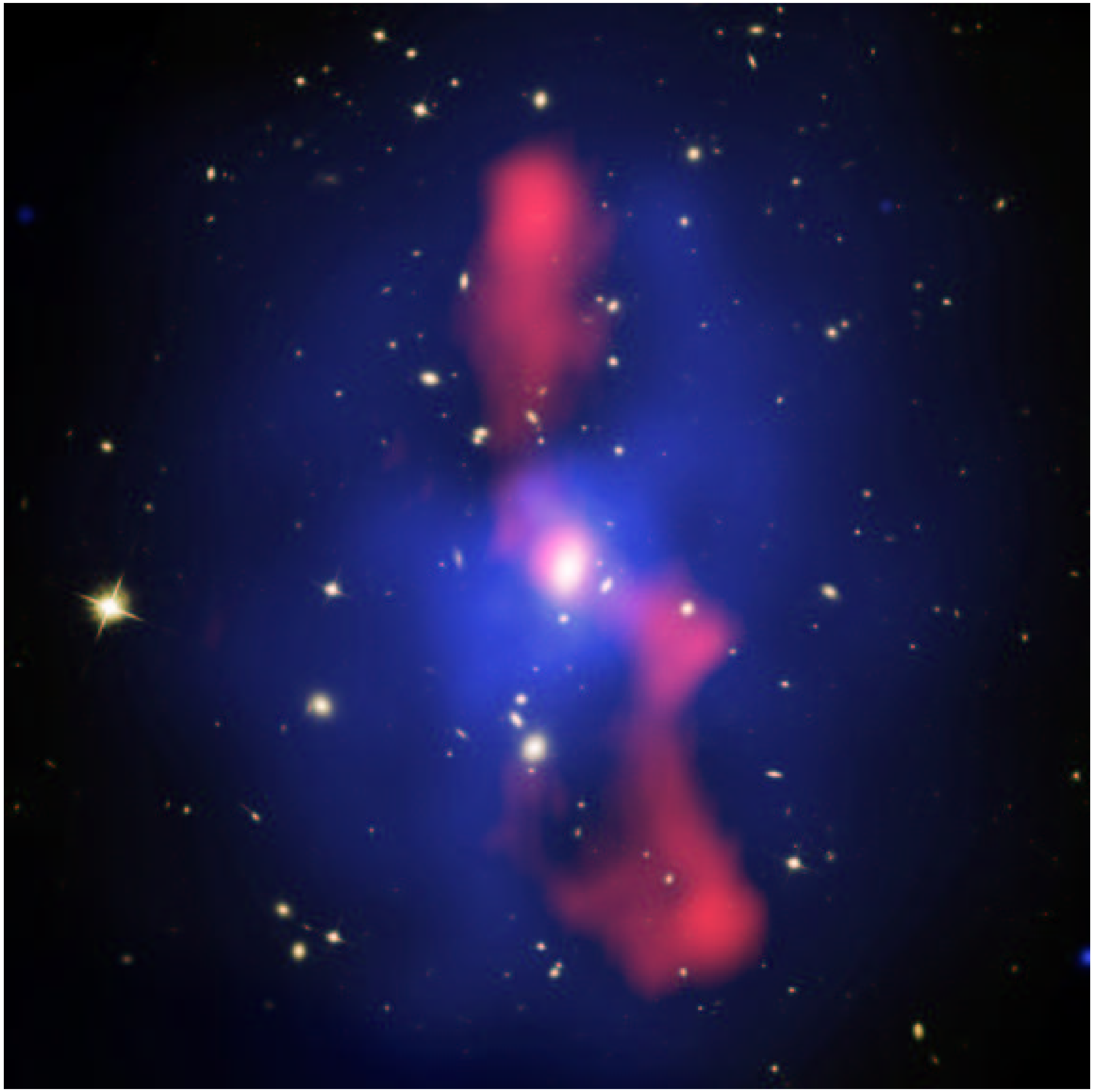




Image courtesy of J.S. Kaastra, J. de Plaa and N. Werner, SRON, Netherlands

**XMM-Newton reveals the origin of elements in clusters of galaxies**

European Space Agency

# 22 Summary



NASA/CXC/SAO/NRAO MS 0735.6+7421:

- Hot ICM in the potential well of galaxy cluster
- Most barions in the cluster are in the hot ICM gas
- Measuring X-ray flux and temperature profiles across cluster → density and temperature distribution → barionic mass
- Clusters are weakly self-similar (z-dependence)
- Can help to contstarin cosmological models
- Gravitational potnetial traces dark matter
- AGN feedback keeps centarl cluster regions hot