# Clusters of Galaxies (and some Cosmology)

## Scientific and Data Analysis Issues

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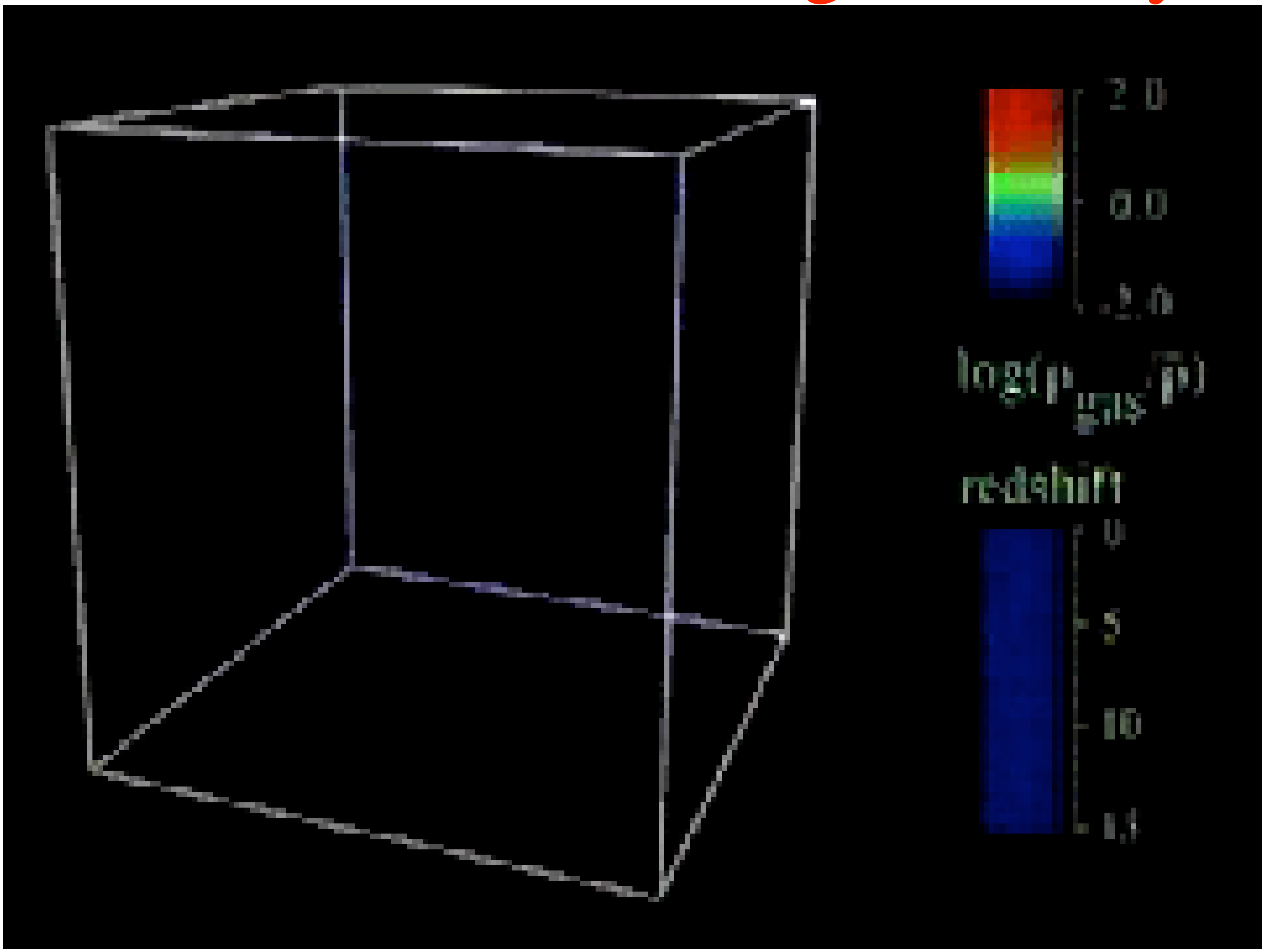
X-ray Astronomy School 2007

# 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.

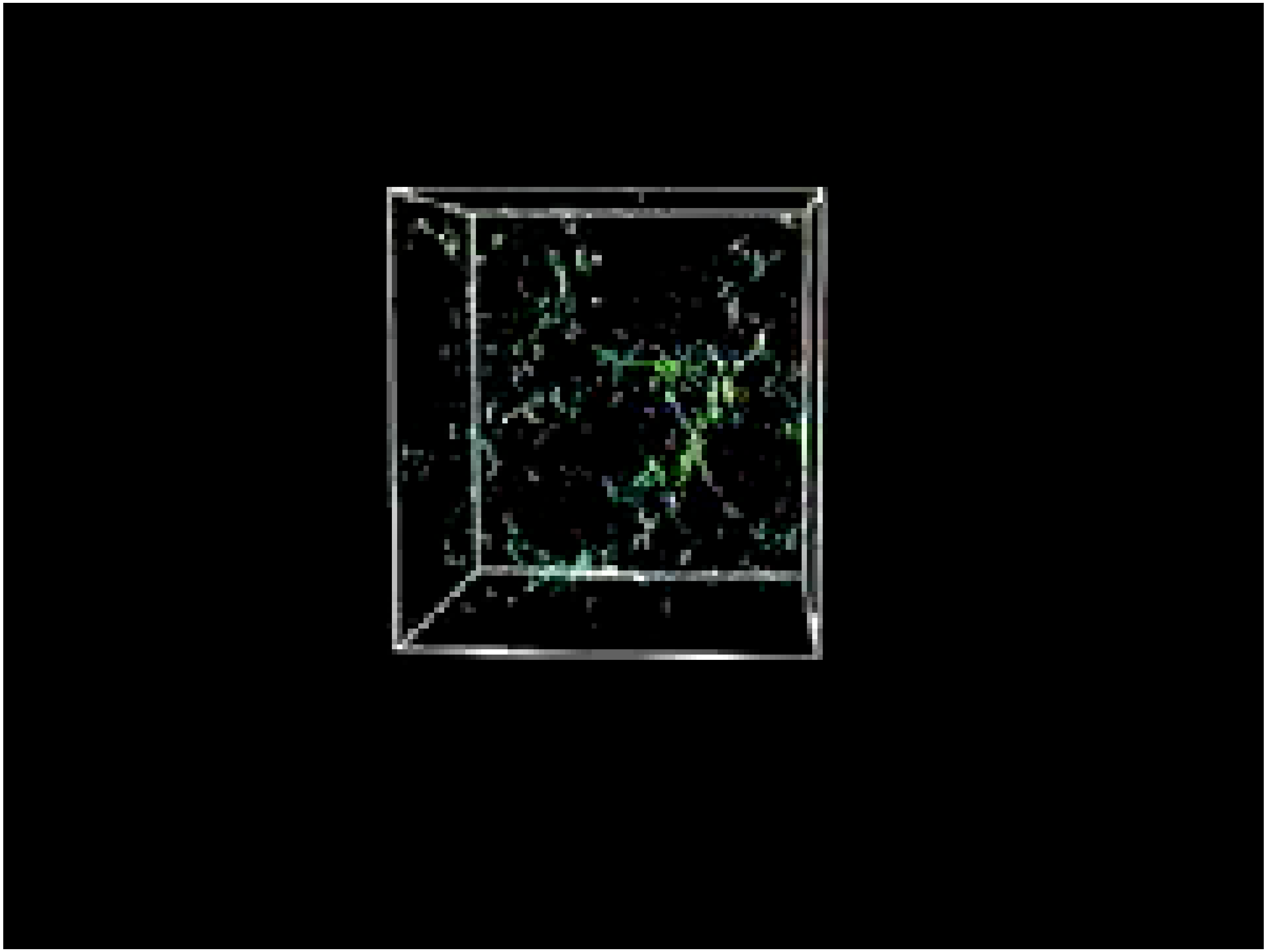
# NCSA simulation - gas density





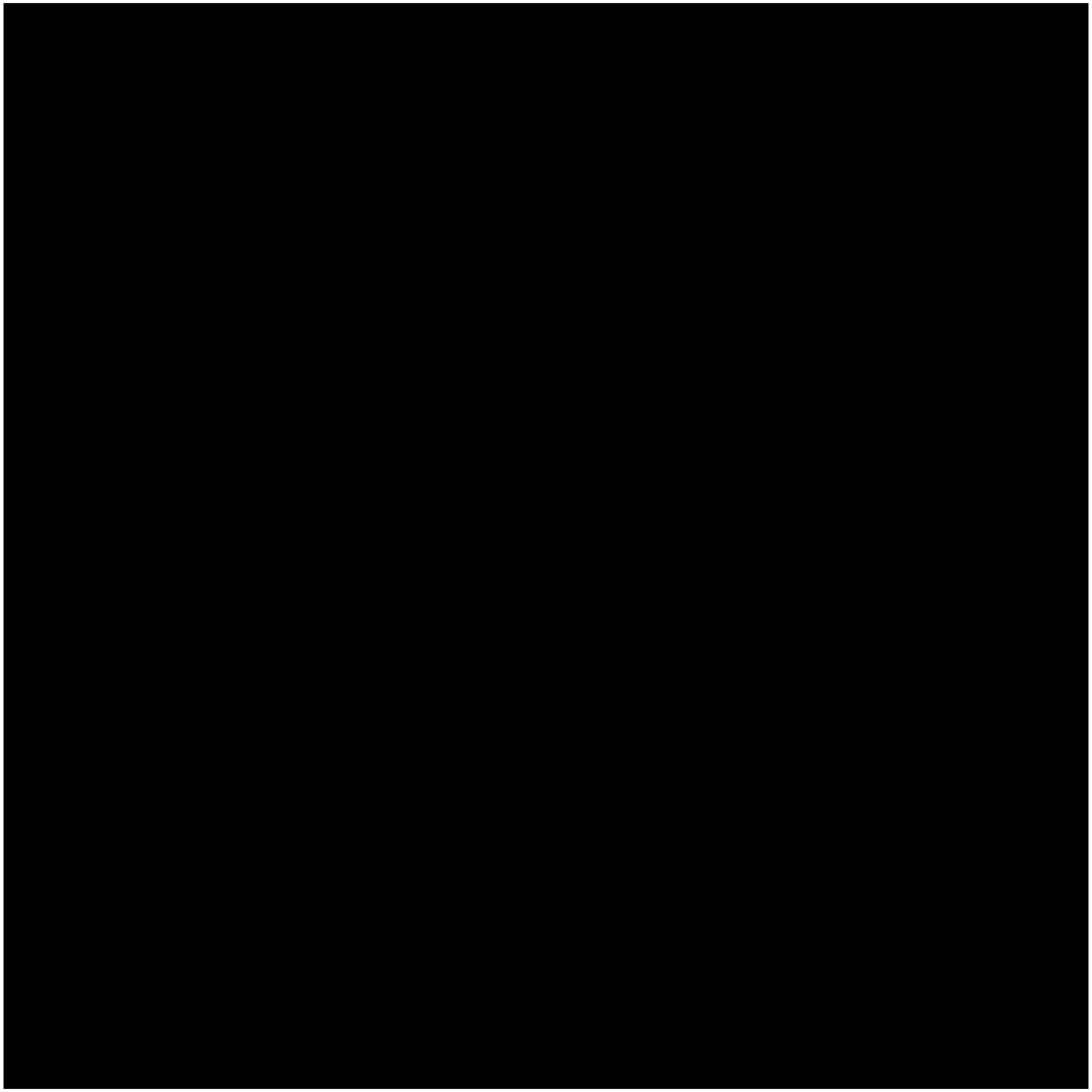

Bryan & Norman

# NCSA simulation - X-ray luminosity



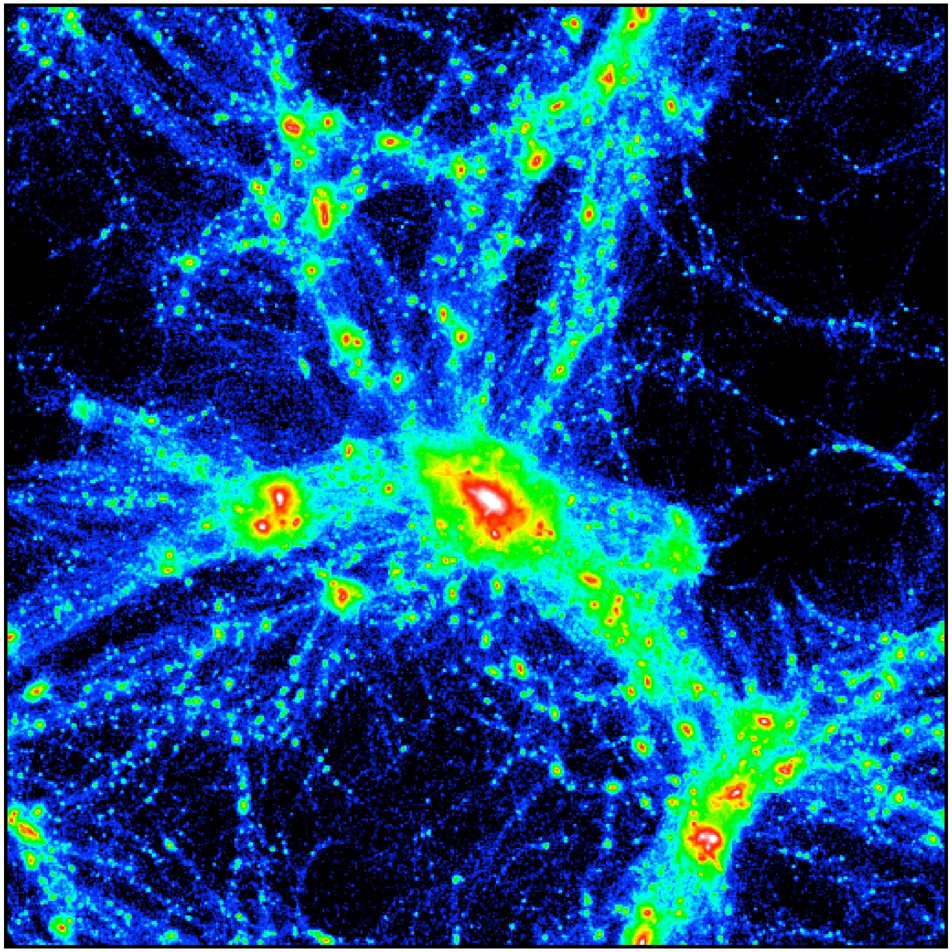
Bryan & Norman

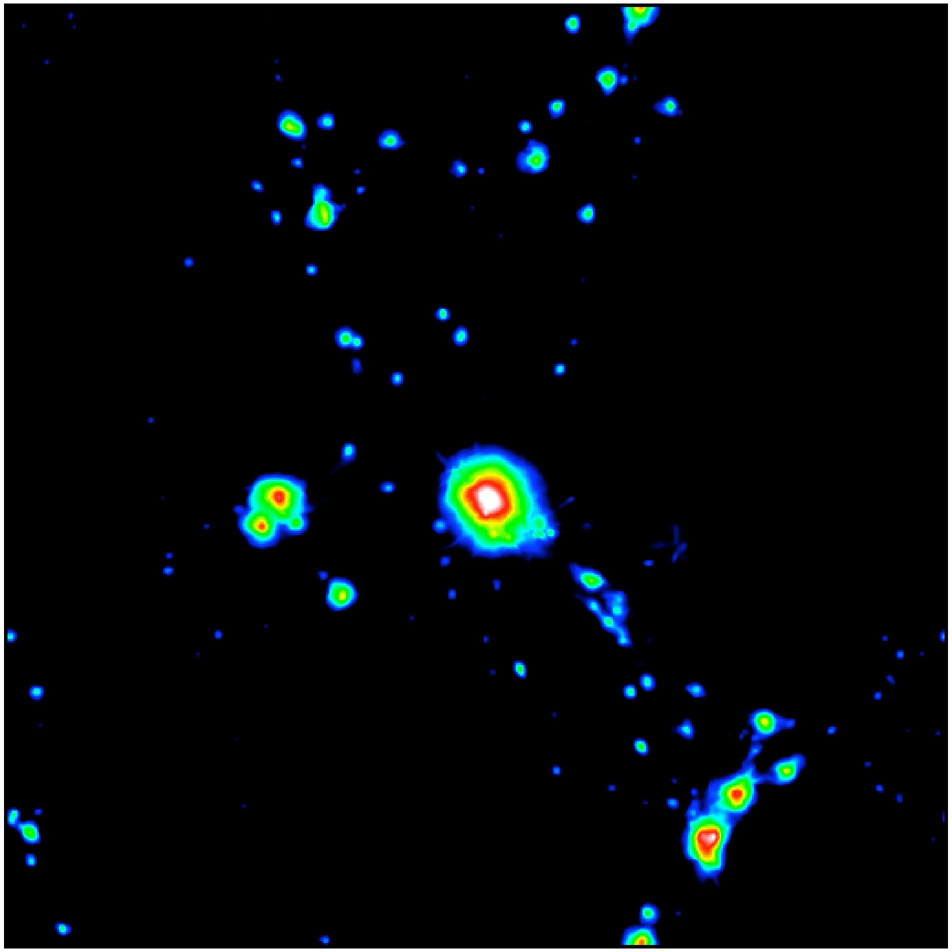
# Formation of dark matter halo



Moore et al.

# Dark matter and X-ray emission simulation





# Structure in the Universe II

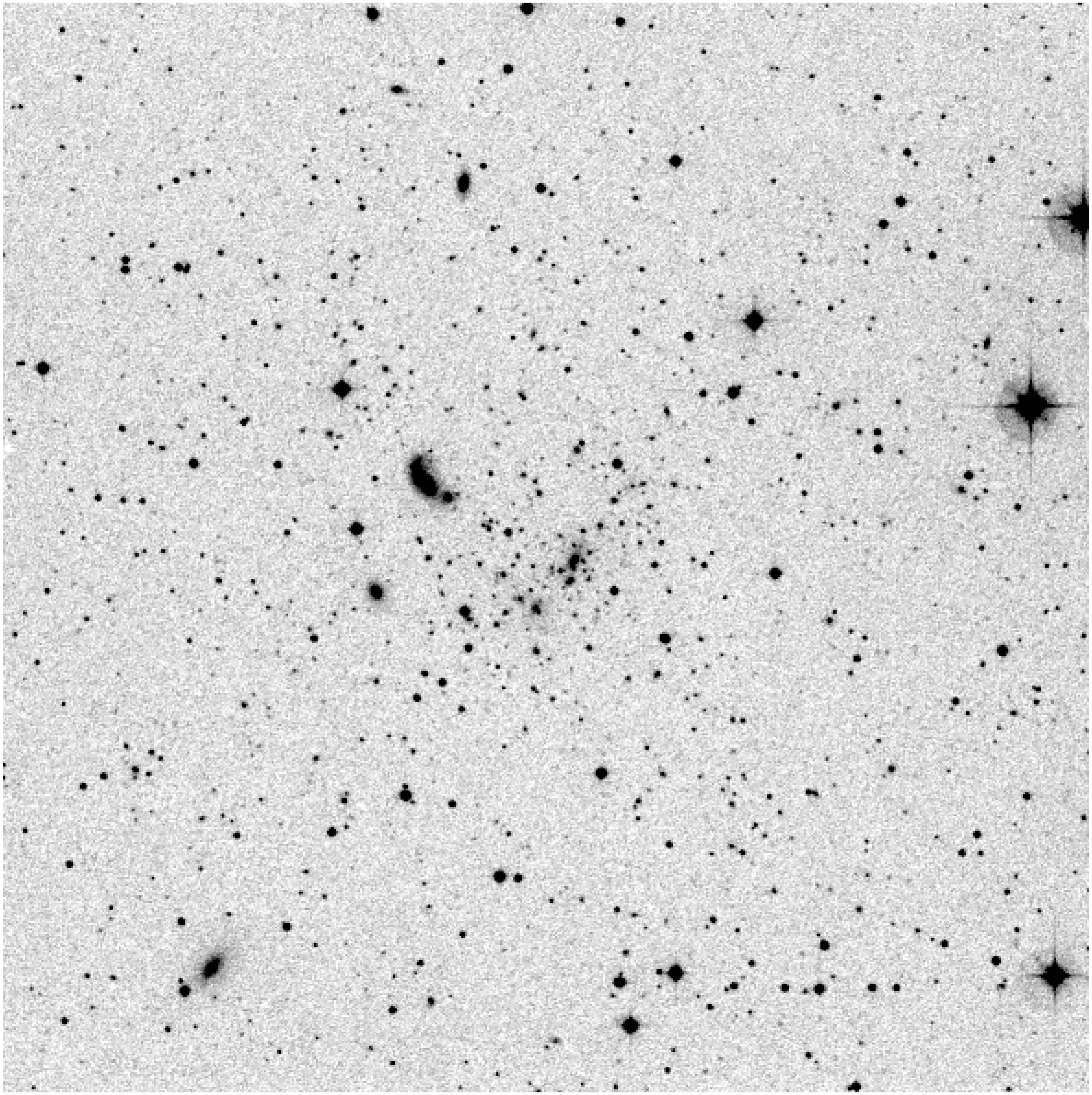
- Clusters of galaxies are formed from the extreme high end ("high sigma peaks") of the initial fluctuation spectrum. They exist at the intersections of the Cosmic Web.

- The way that structure evolves depends on the geometry and contents of the Universe (total density, dark matter density, dark energy density,…).

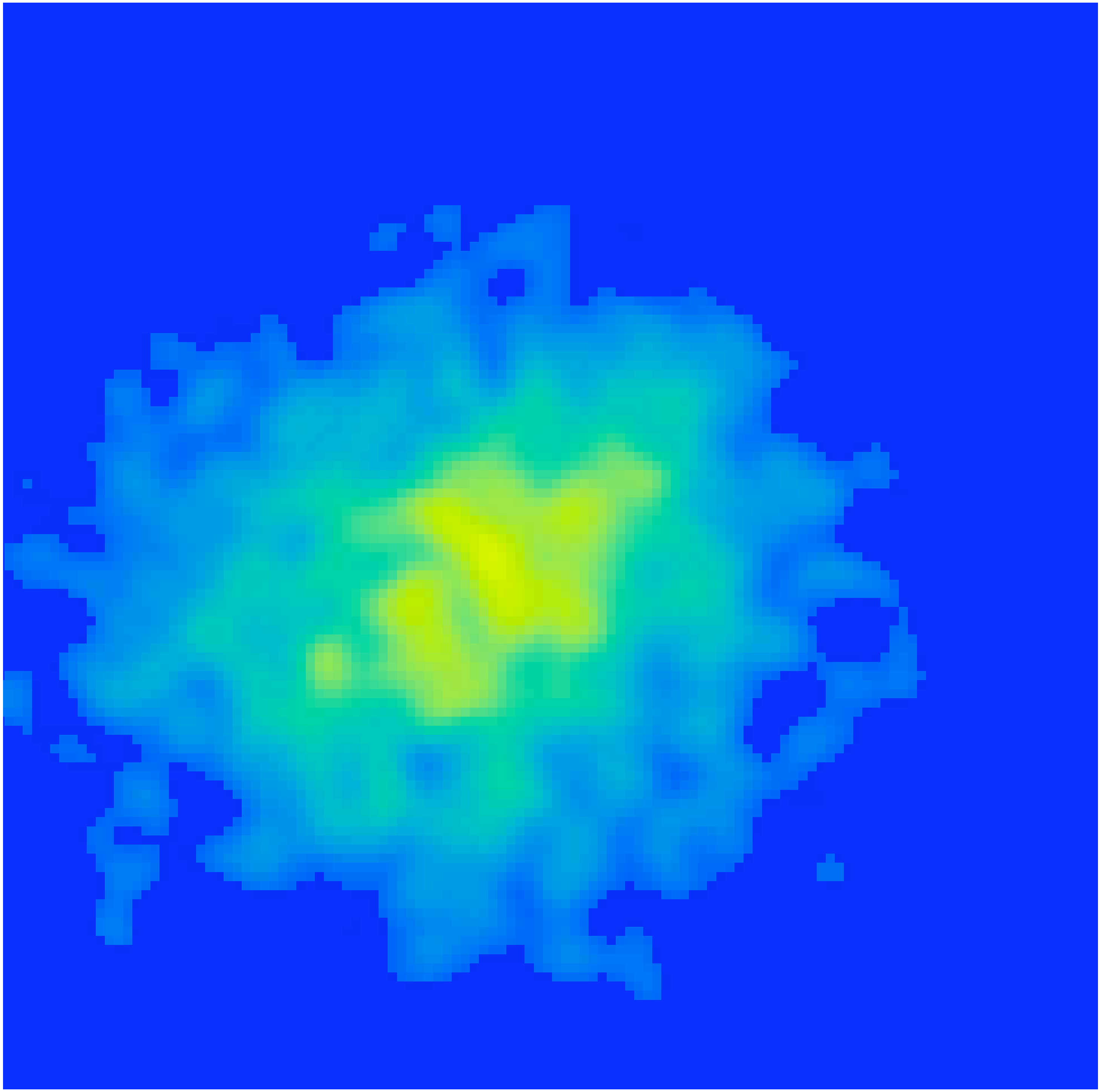
- Because clusters are formed from the high sigma peaks their numbers and evolution in time depend sensitively on cosmological parameters.

# X-rays from Clusters of Galaxies

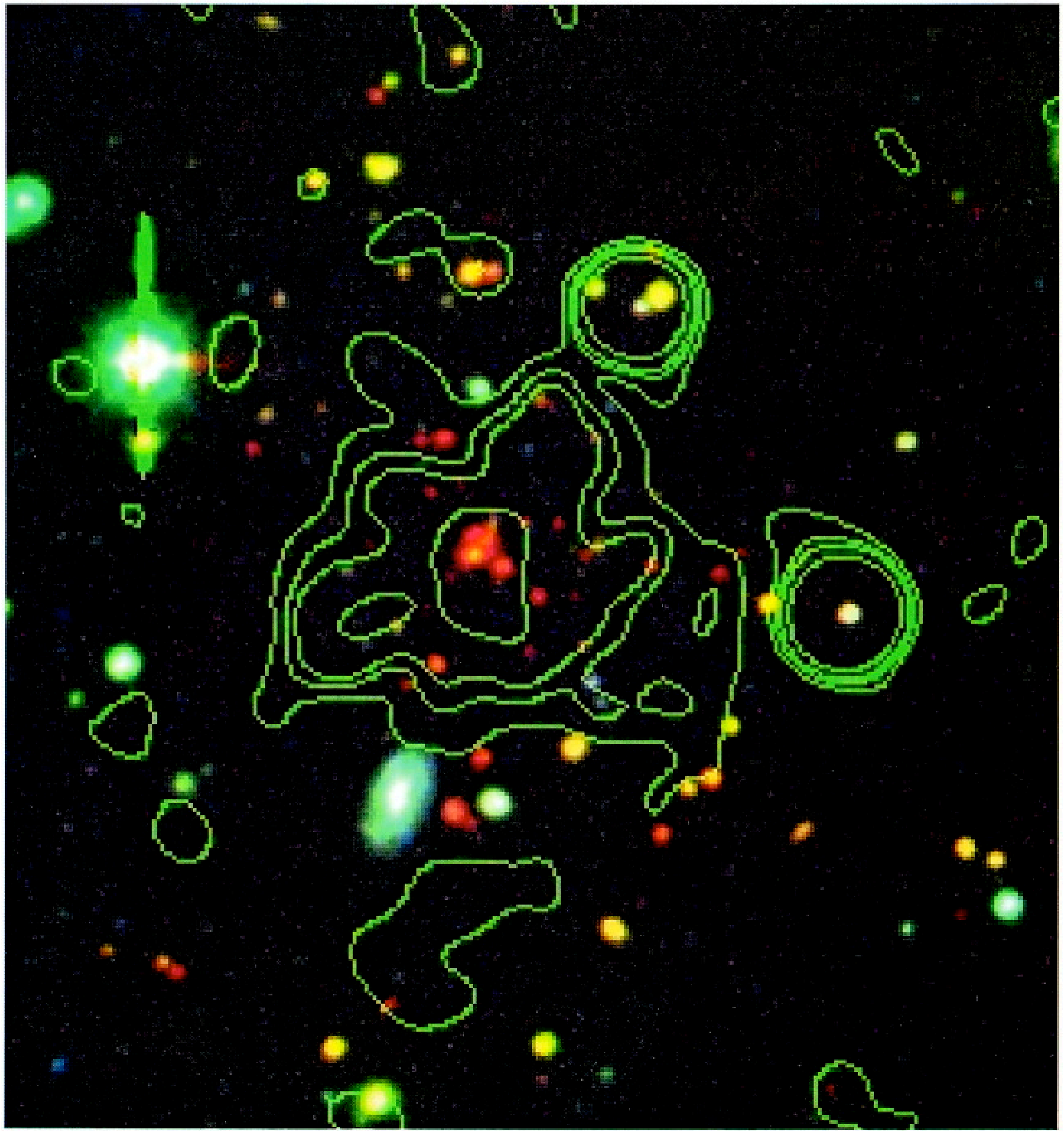
- The baryons thermalize to > $10^6$ K making clusters strong X-ray sources.
- Most of the baryons in a cluster are in the X-ray emitting plasma - only 10-20% are in the galaxies.
- Clusters of galaxies are self-gravitating accumulations of dark matter which have trapped hot plasma (intracluster medium - ICM) and galaxies. (the galaxies are the least important constituent)



Optical
image



X-ray image



z=1.26 cluster observed using Chandra and Keck

# What we try to measure

- 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.

# What we try to measure II

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.

$$\nabla P = -\rho_{gas} \nabla \Phi$$

where

$$P = -\rho_{gas} T$$

There are two other ways to get the gravitational potential :

- The galaxies act as test particles moving in the potential so their redshift distribution provides a measure of total mass.
- The gravitational potential acts as a lens on light from background galaxies.

For “regular” clusters these measures agree.

# Top Questions on Clusters of Galaxies

- 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 ?

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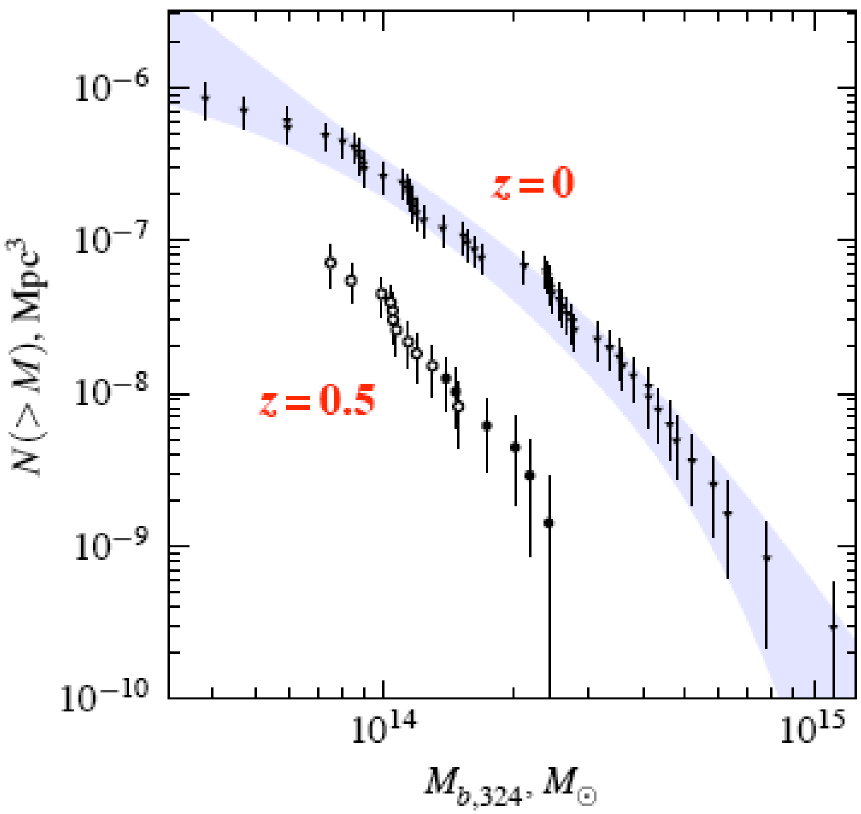
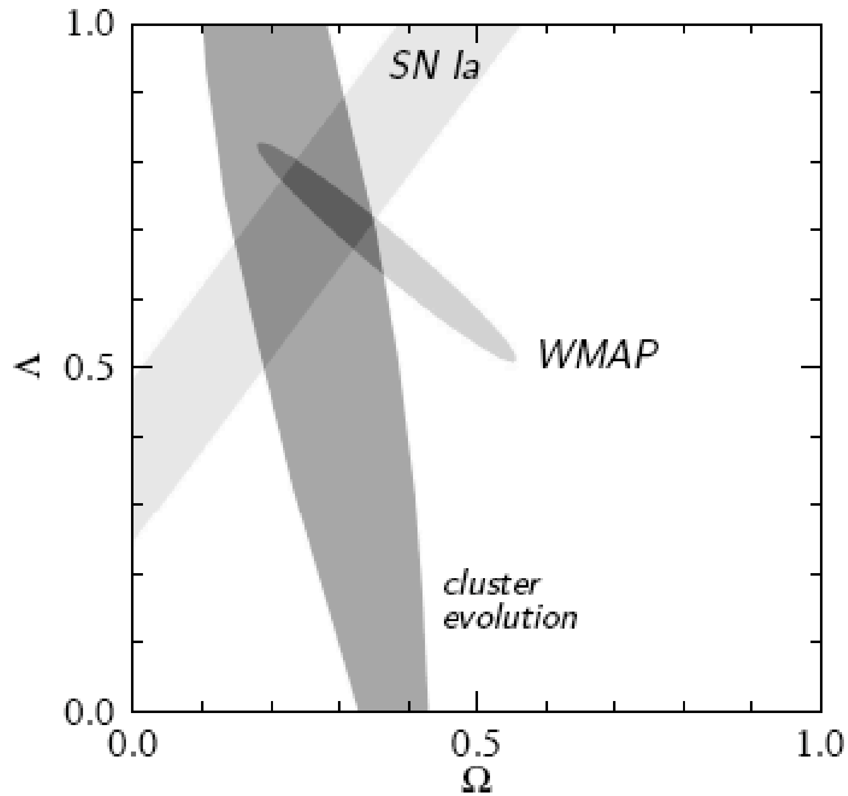
# Why do we care ?

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.

Vikhlinin et al. 2003



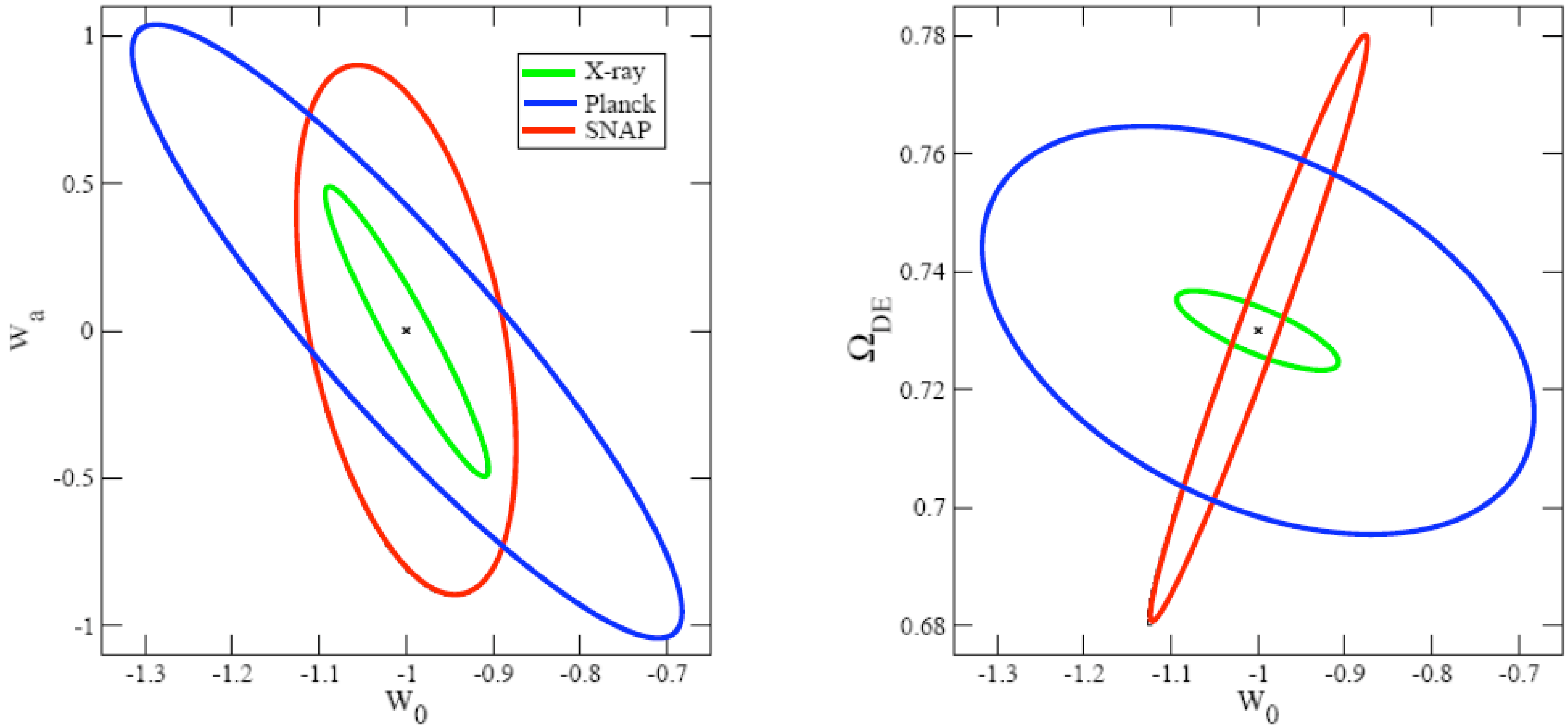




# Cosmology from cluster evolution

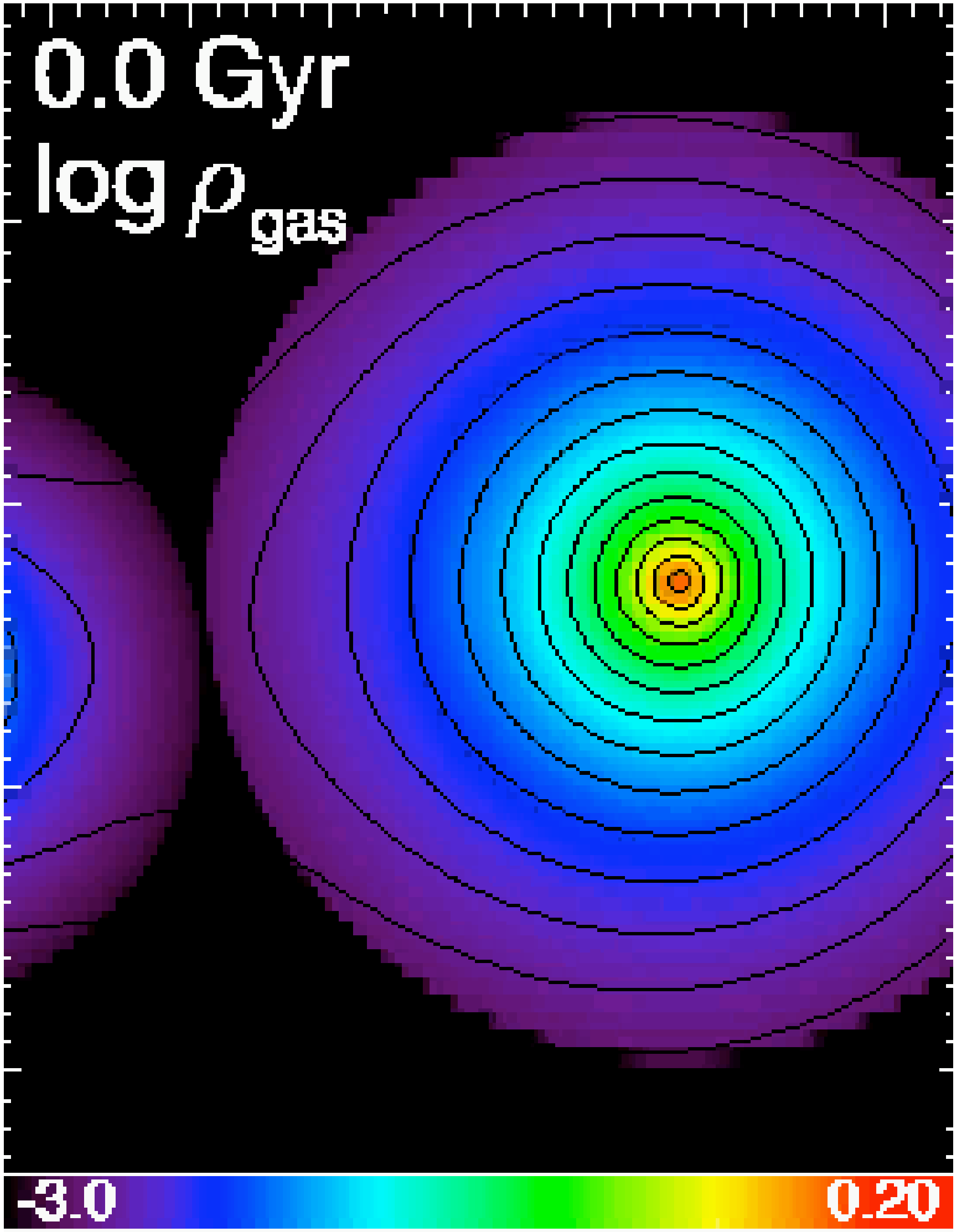
# Constraints from 100K Cluster Survey

**Time dependence of $w_x$**

$w_{x(z)} = w_0 + w_a \cdot z$  $p(z) = w_x(z) \cdot \rho(z)$

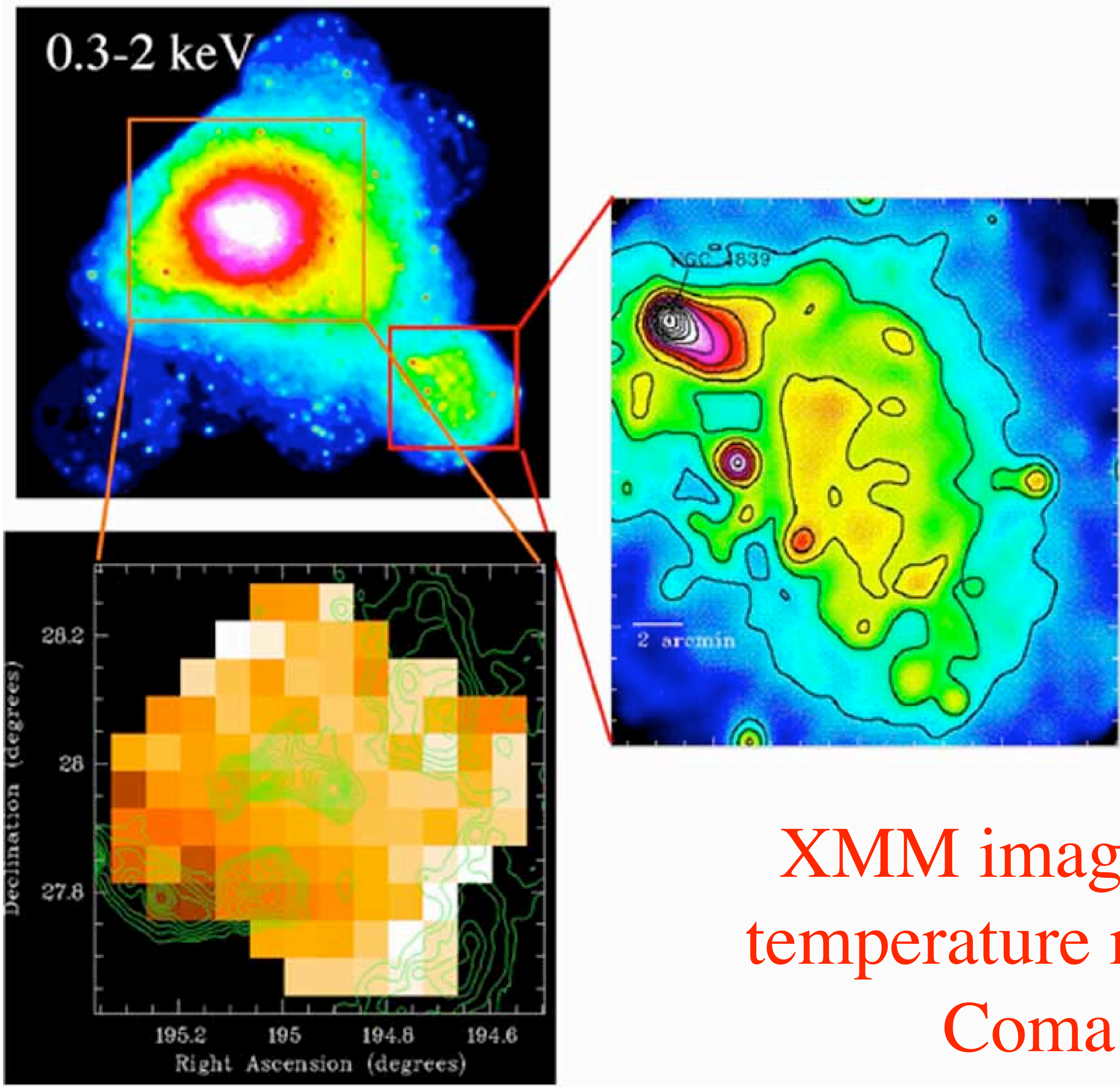



Results from the White Paper submitted to the NASA/DOE Dark Energy Task Force: Haiman et al., 2005, astro-ph/0507013




Ricker et al.

# Merger simulation - gas density




XMM image and temperature map of Coma

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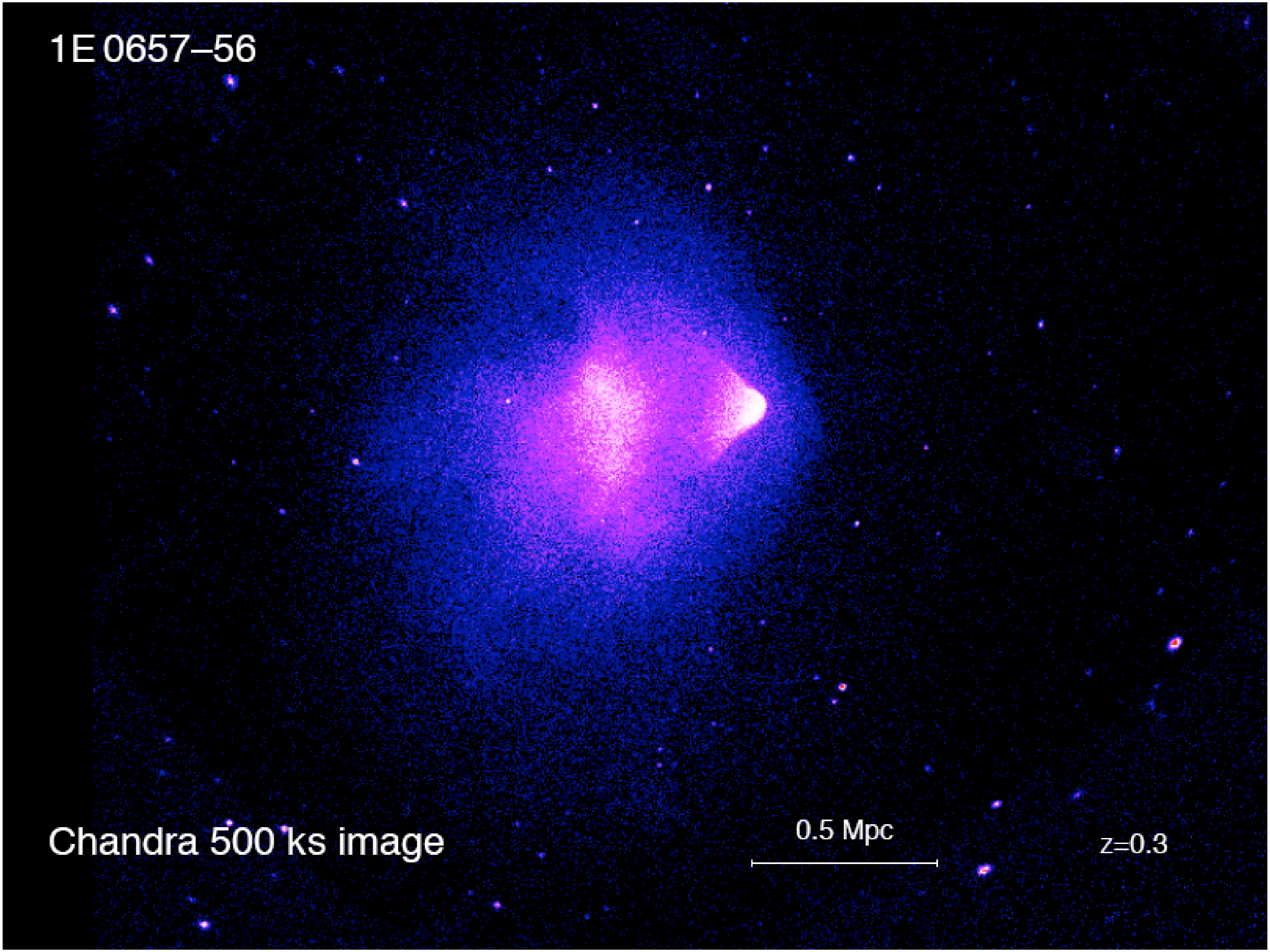
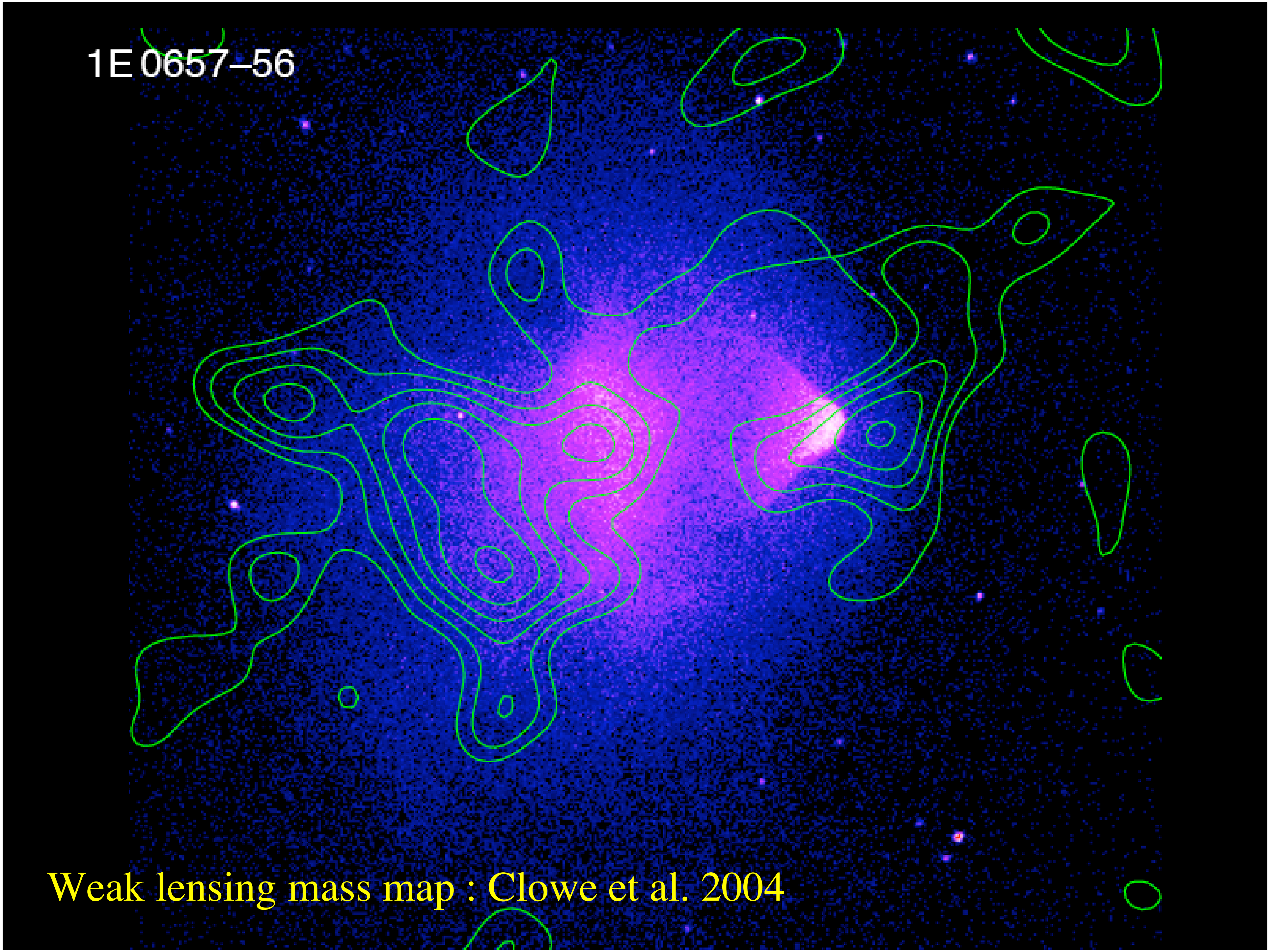

1E 0657–56
Chandra 500 ks image
0.5 Mpc
z=0.3


1E 0657–56
Weak lensing mass map : Clowe et al. 2004

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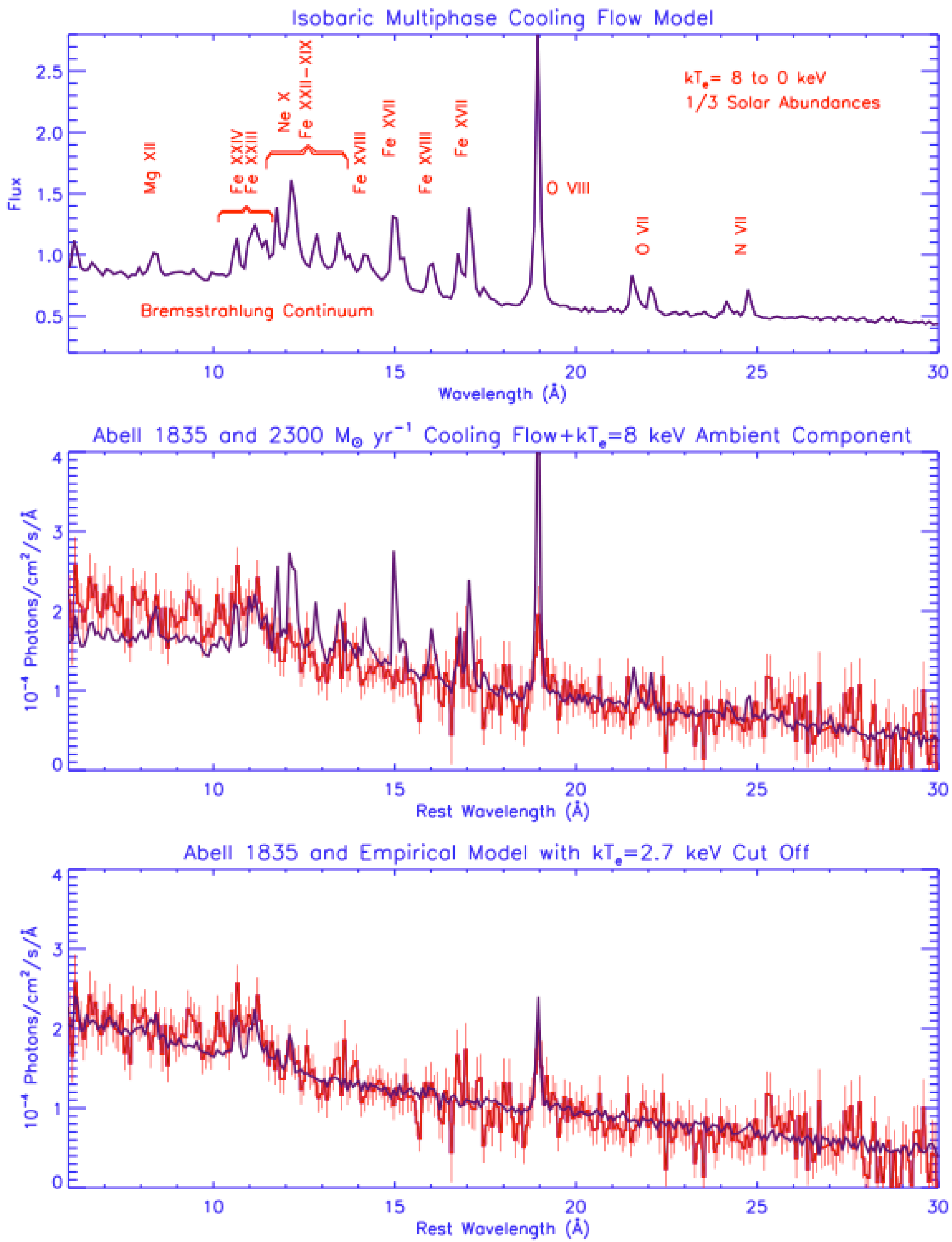
# Why do we care ?

We used to have a simple model for the cores of clusters :

- Clusters were spherically symmetric balls of plasma that evolved in isolation.
- In their centers they would lose energy by radiating X-rays - 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.

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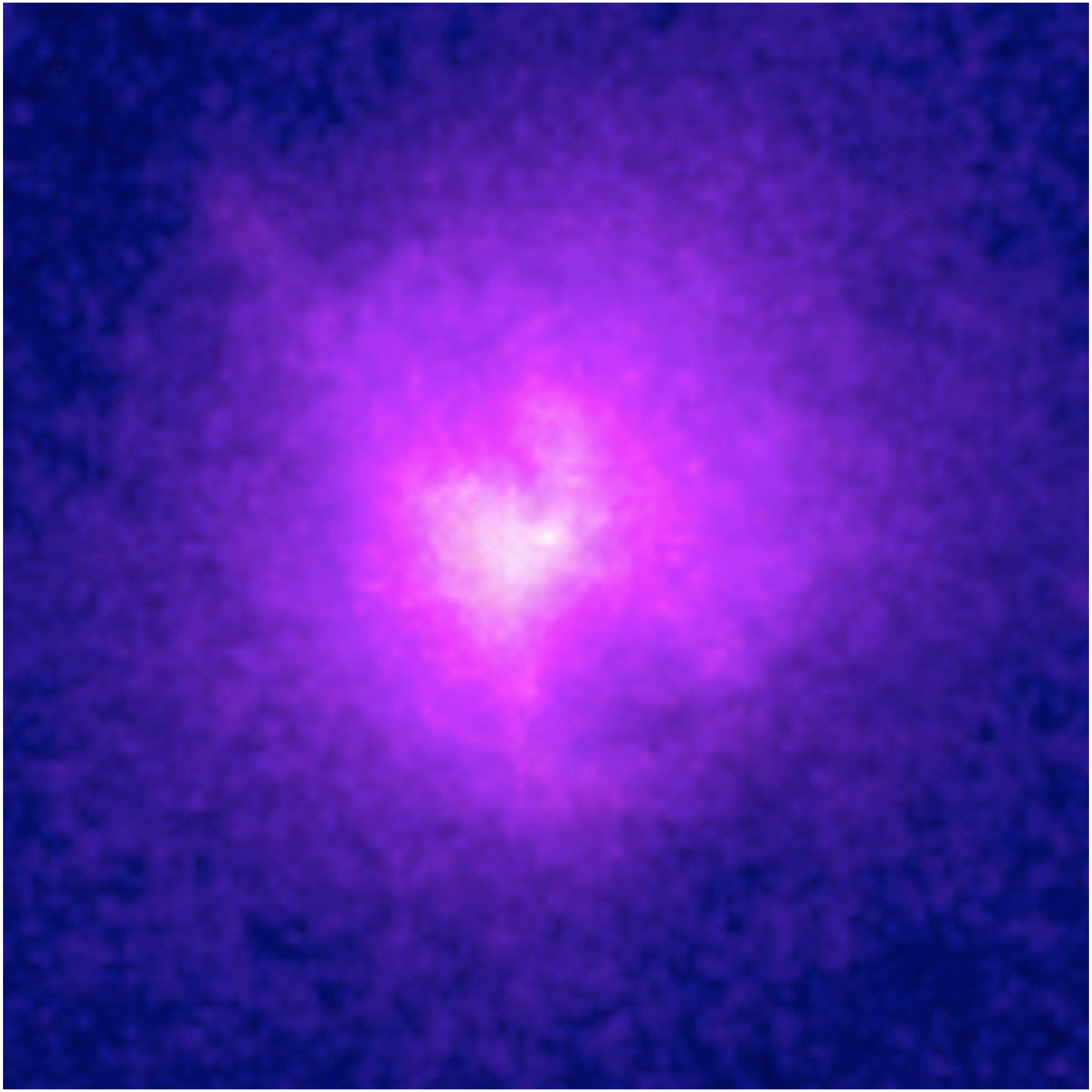
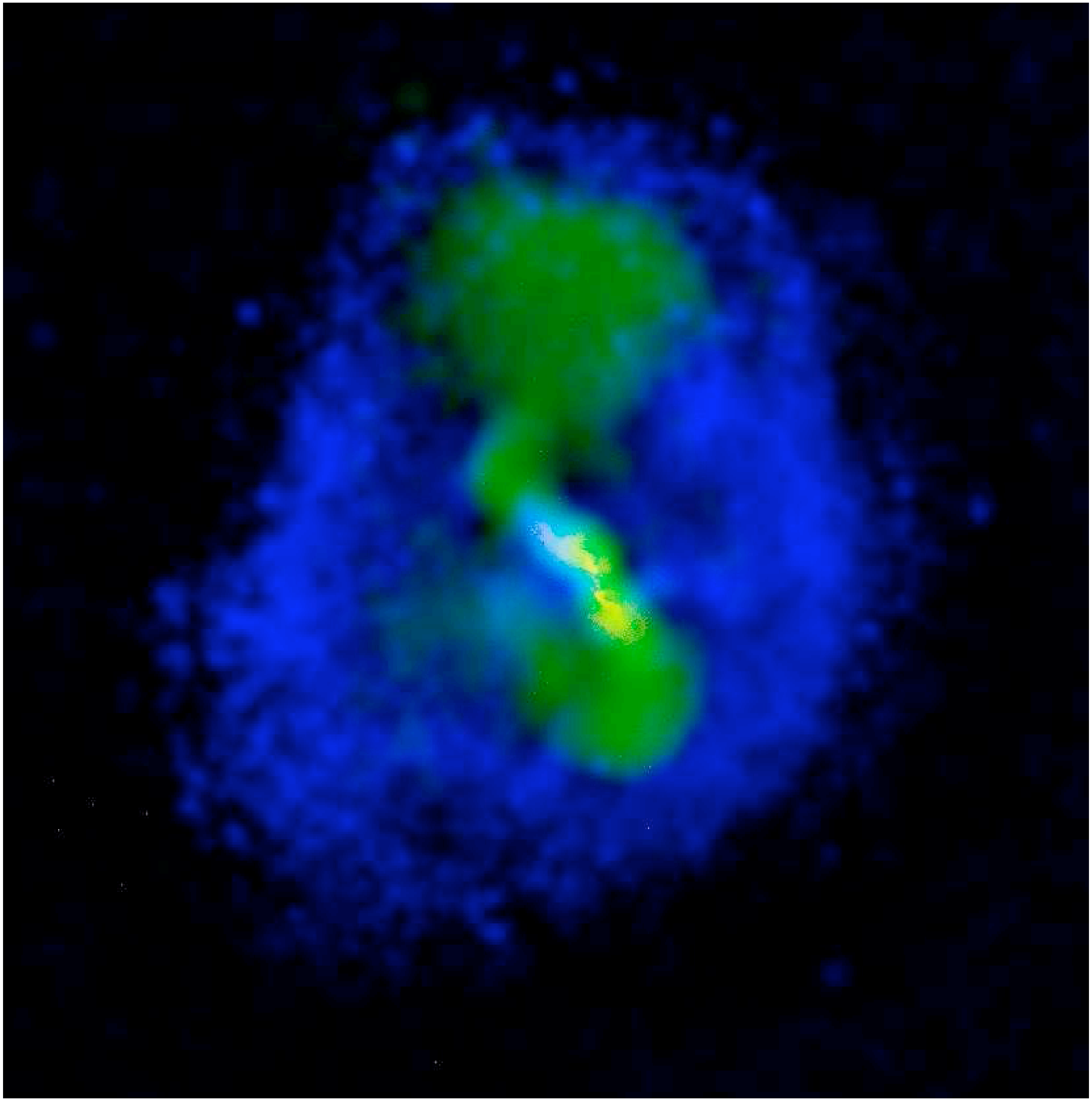
Peterson et al.

# Abell 1835 XMM RGS



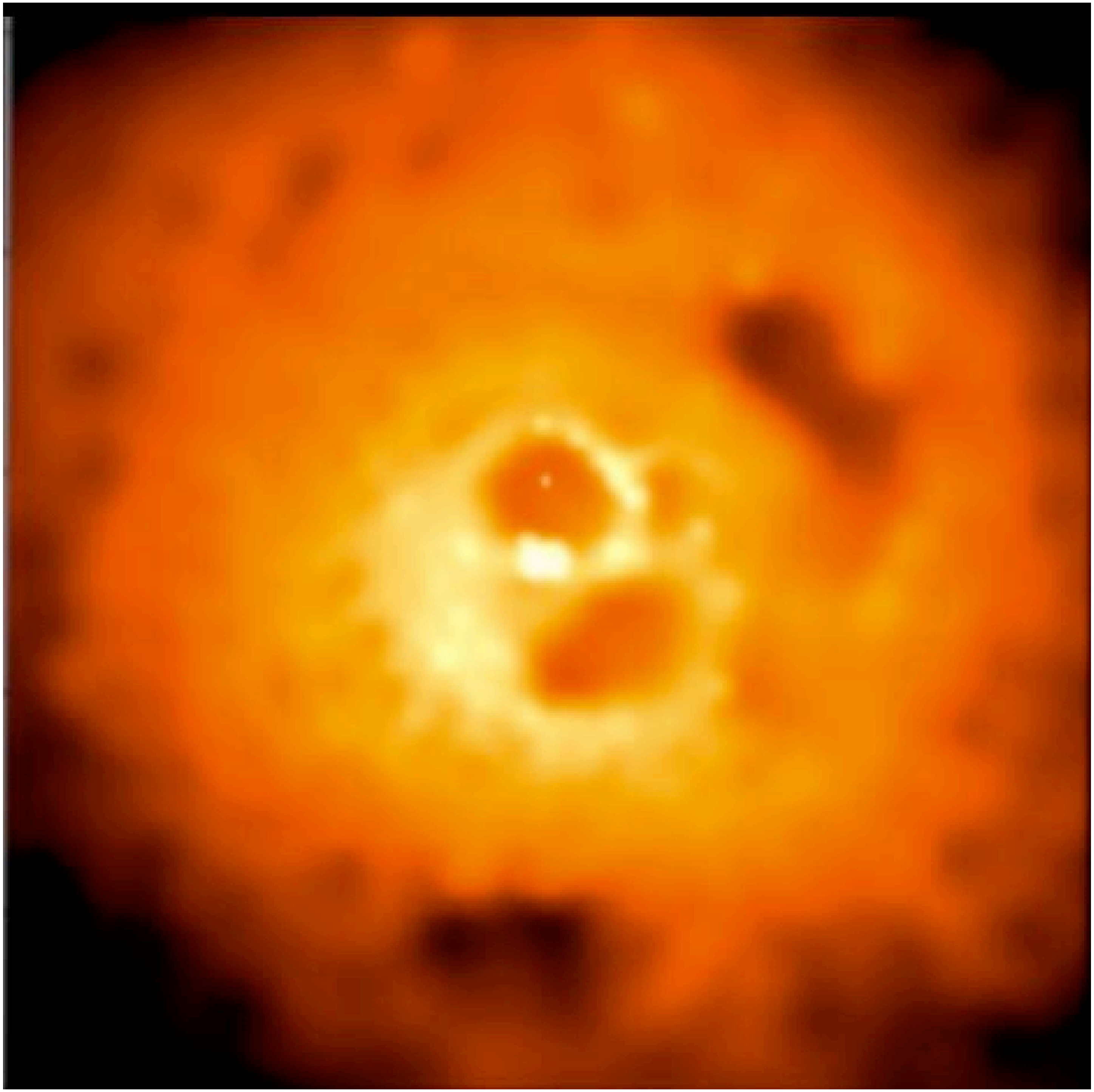
Chandra
image of
Hydra-A



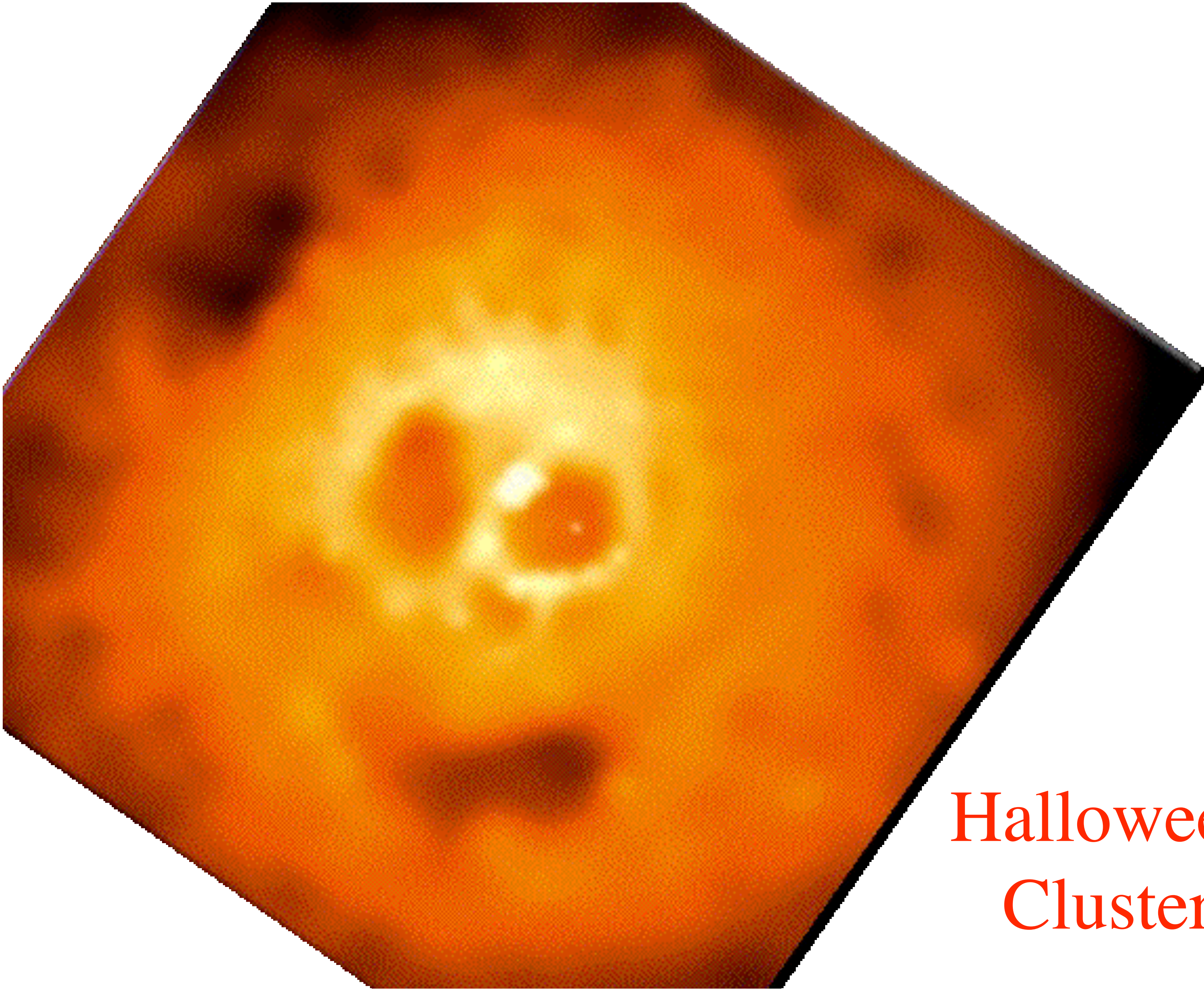
Wise et al. 2007

Blue: Chandra

Green: 330 Mhz



Chandra image of Perseus cluster

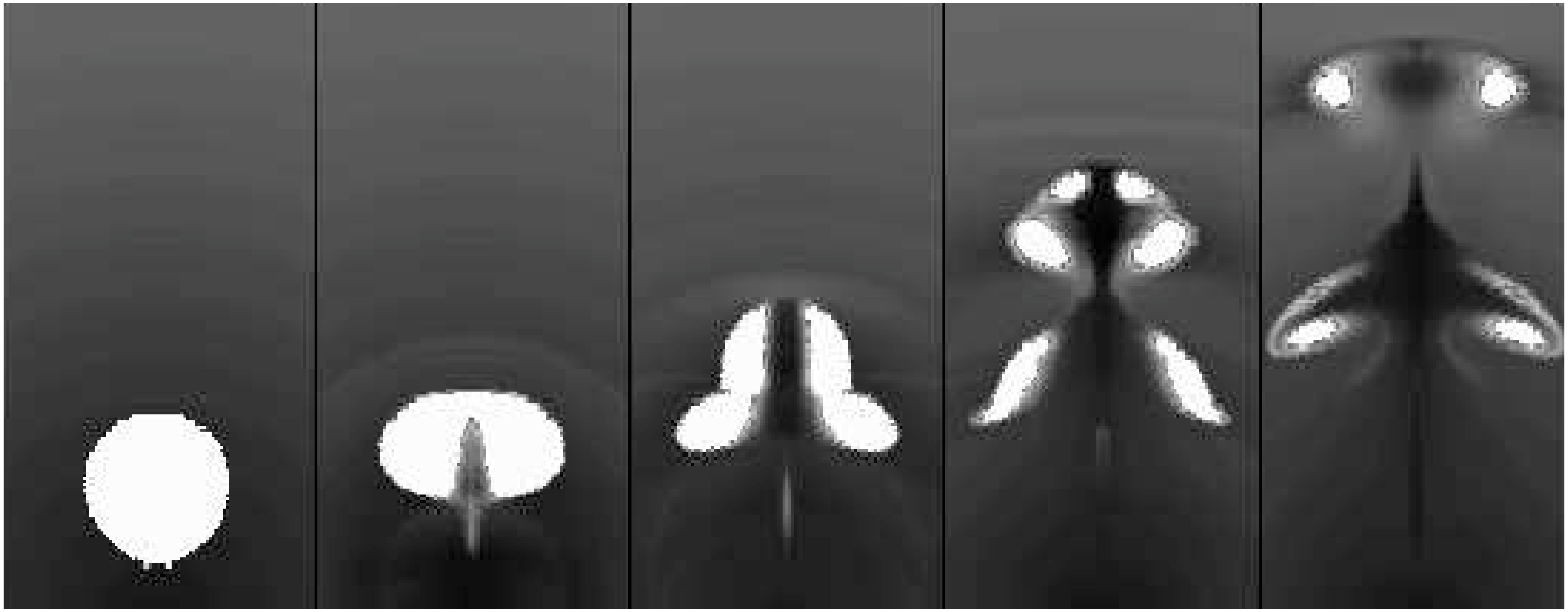


Halloween
Cluster

Churazov et al.

# Effect of a rising bubble of hot plasma

t = 0 t = 67 Myr



White is hot and black is cold - the coolest gas is produced from uplifted, adiabatically expanded gas.

# Cosmological Implications

Since all the gas in the Universe starts hot but we now observe some of it cold the process of galaxy formation must involve gas cooling.

Cosmological simulations have an “overcooling” problem ie clusters end up too cool (entropy too low). Solution is to find additional energy input into cluster gas.

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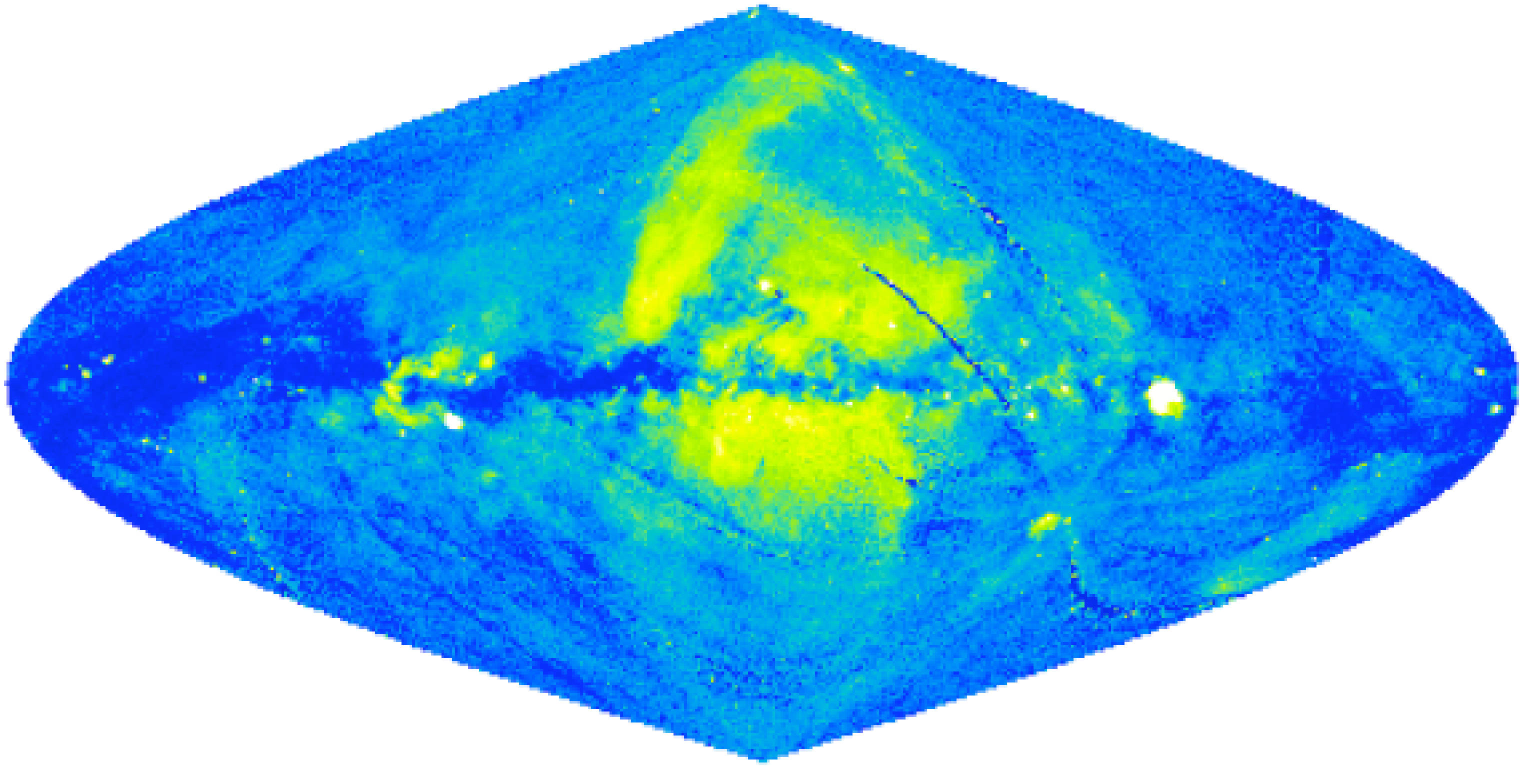
# Data Analysis Issues

- Background subtraction
- Corrections for PSF scattering
- 2D -> 3D
- Grating observations

# Background Subtraction

- Clusters of galaxies are large objects - they may well cover the entire field of view of the detector.

- To find a background you need to go to another observation - but the X-ray background varies with position on the sky at energies < 2 keV (see ROSAT all-sky survey maps).



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

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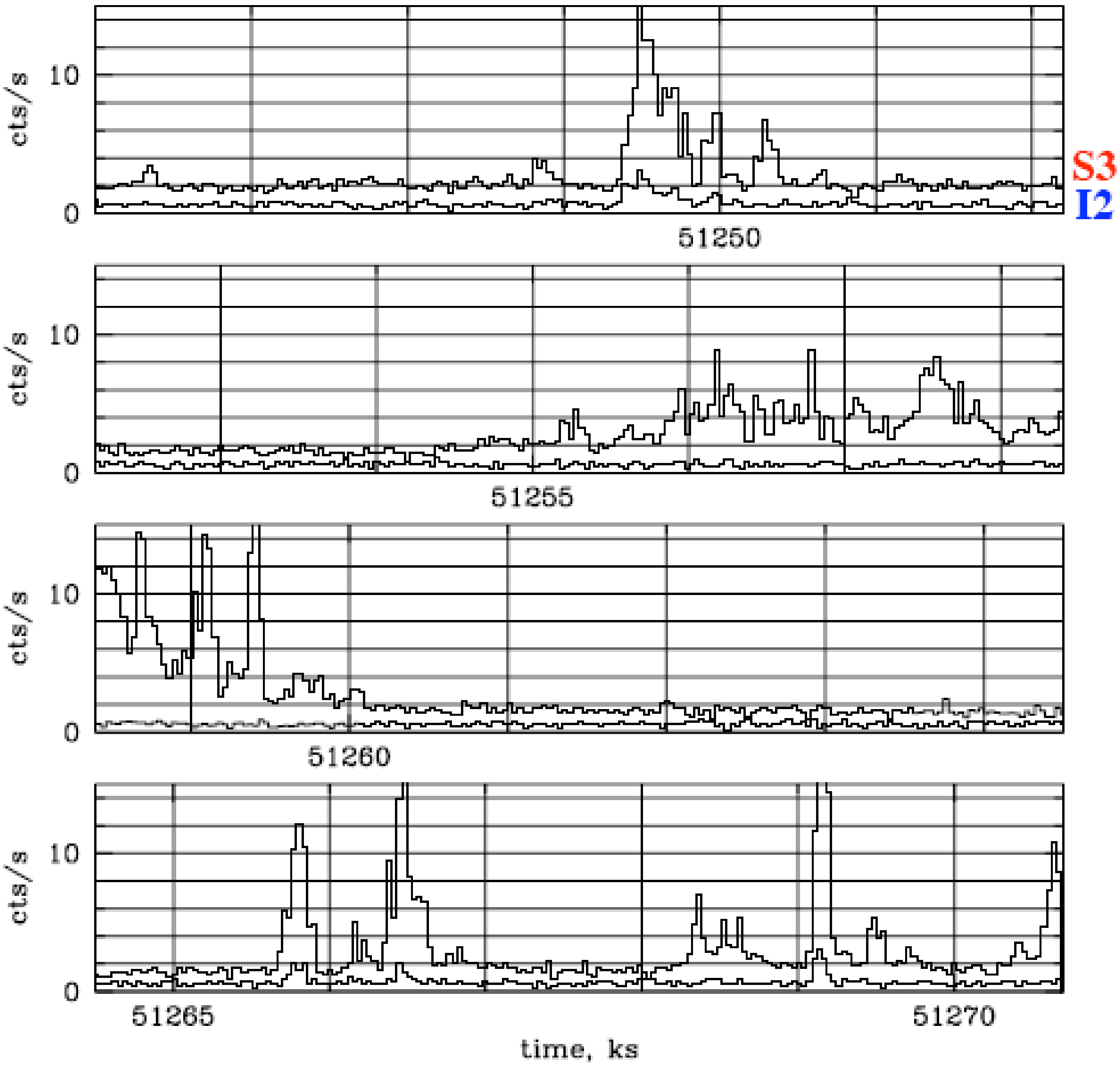
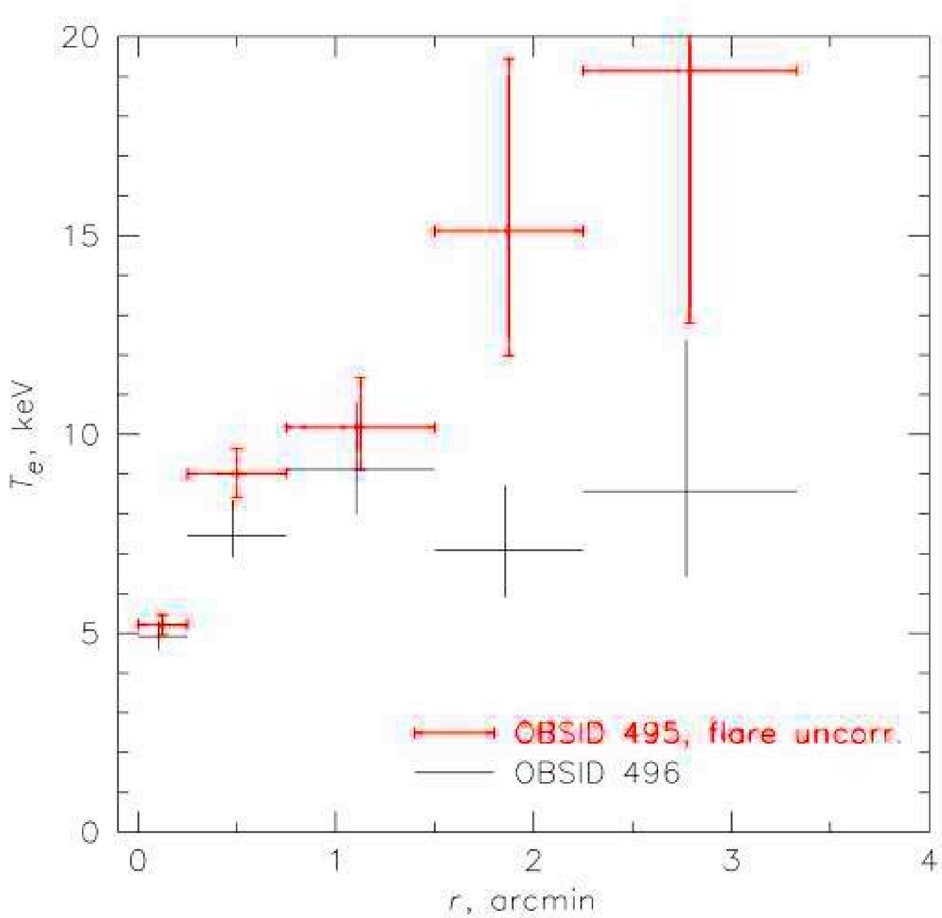
- To find a background you need to go to another observation - but the X-ray background varies with position on the sky at energies < 2 keV (see ROSAT all-sky survey maps).
- The background varies with time - big flares are easy to see and exclude but smaller flares are a problem.



cts/s
10
0
51250
S3
I2
51255
51260
51265
51270
time, ks

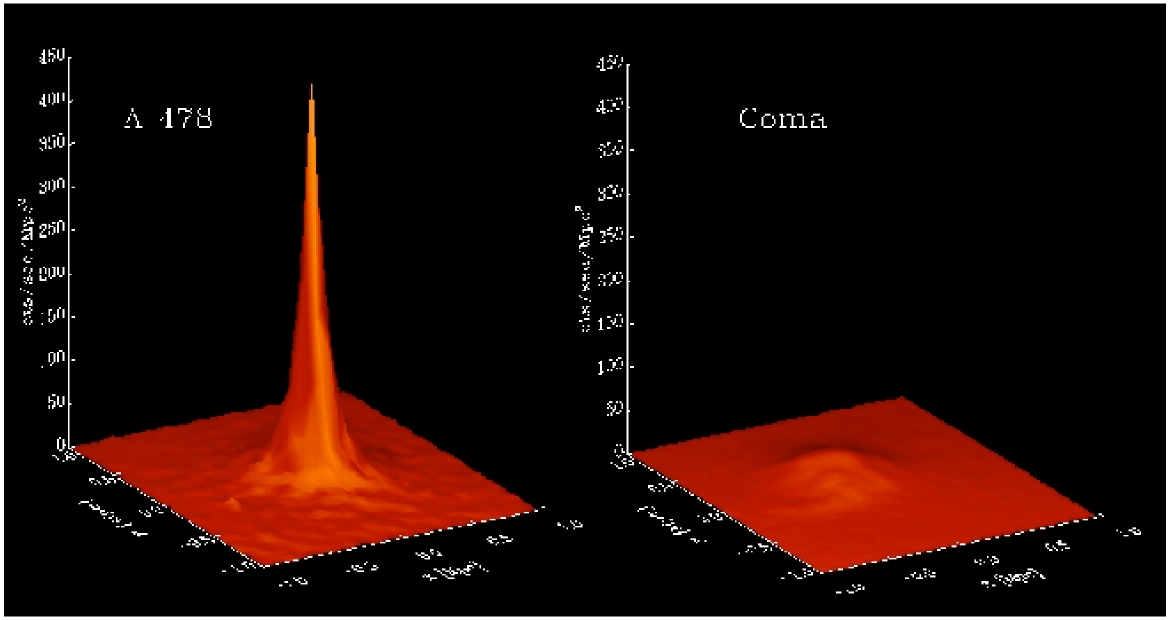
Markevitch




Abell 1835

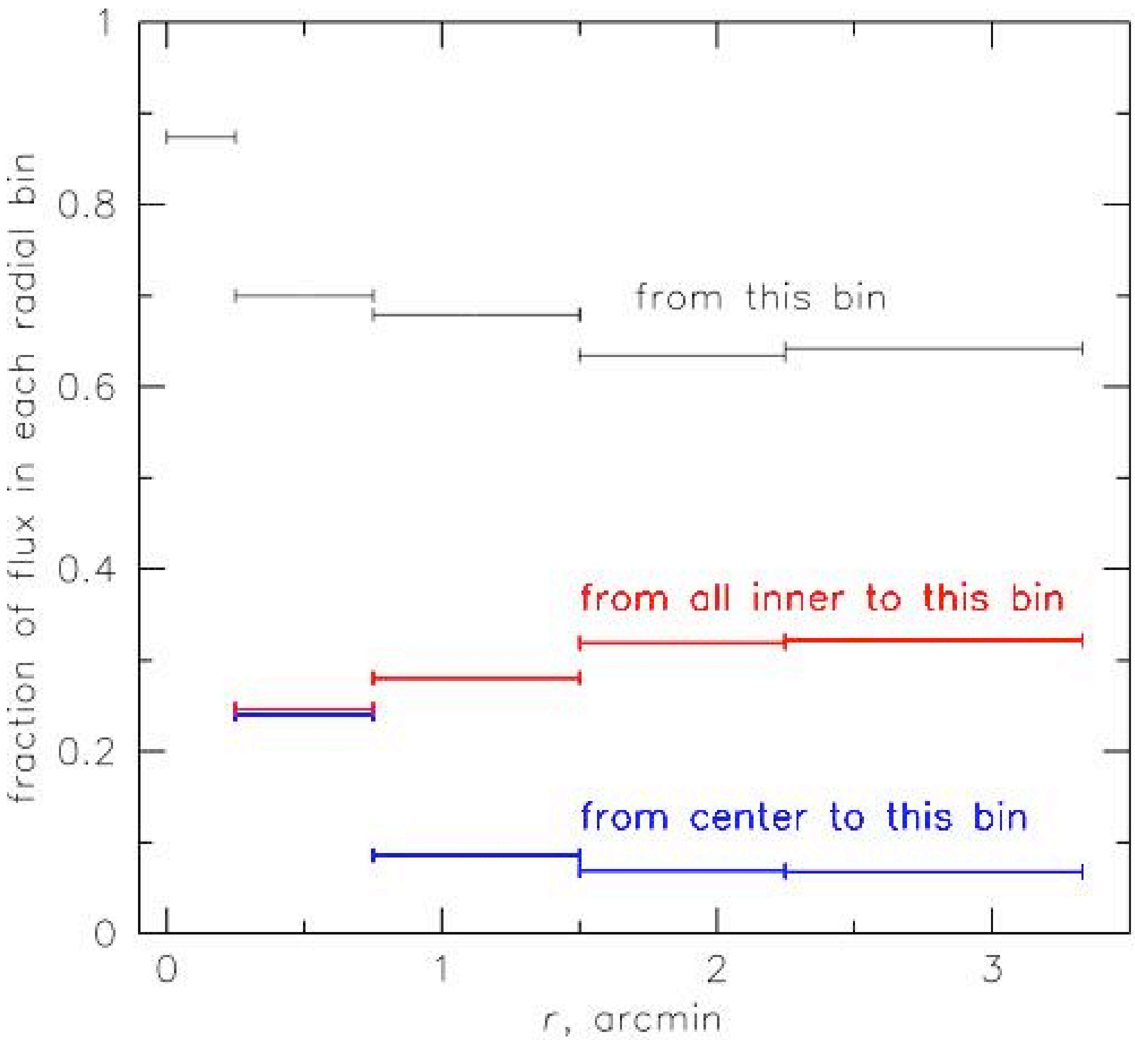
Comparison of two Chandra analyses

# Corrections for PSF scattering




Many clusters have very centrally concentrated X-ray emission.

If the telescope has a PSF with significant wings then emission from the cluster core will be scattered to its outer regions. This is a big problem with ASCA or BeppoSAX and a smaller problem with XMM-Newton.




# Effects of XMM PSF

I’ve written an XSPEC model to correct for this effect. Steve Snowden has developed a more sophisticated approach using new SAS features.

Markevitch

# 2D -> 3D

- Clusters are optically-thin 3-D objects. We would like to determine properties in 3-D but we observe them projected onto 2-D.

- For regular shapes it is possible to derive 3-D information from the 2-D observation. (There is a helpful XSPEC model called projct)

- But Chandra is showing us that there are many irregularities (at least in the cluster core). How do we derive 3-D information in this case ?

# Grating observations

- Gratings operate by dispersing a source along a line. If the source is a point this is straightforward. If the source is extended then the spatial and spectral dimensions get mixed together.

- The XMM grating does work very well for concentrated sources like the cores of clusters but the interpretation is non-trivial. An XSPEC model (rgsxsrc) helps in simple cases.

- Peterson et al. have developed a Monte Carlo code which predicts XMM spectra from 3-D properties of the cluster.