Galaxies, Clusters & Groups

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University of Maryland College Park
and
NASA’s Goddard Space Flight Center

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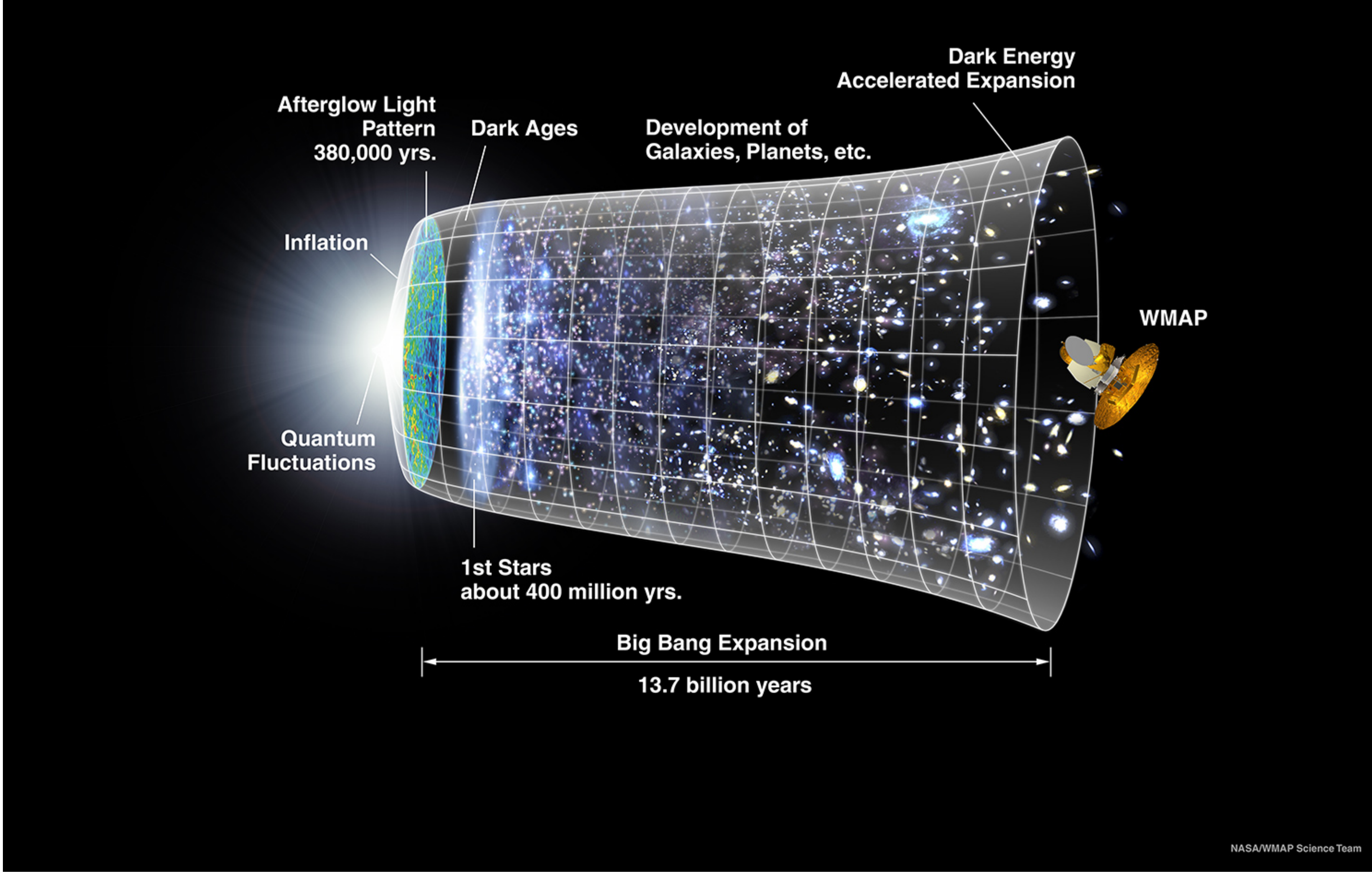
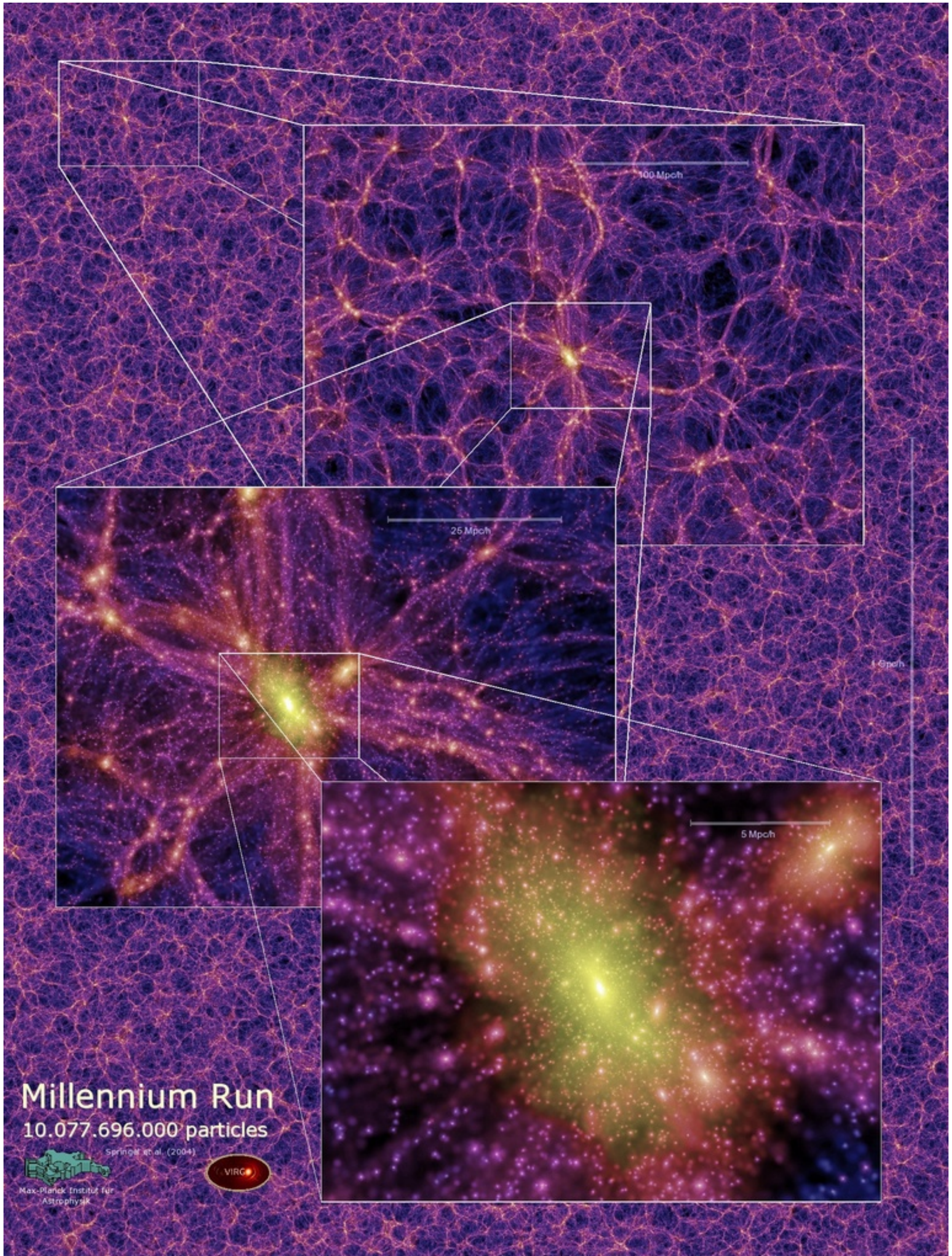


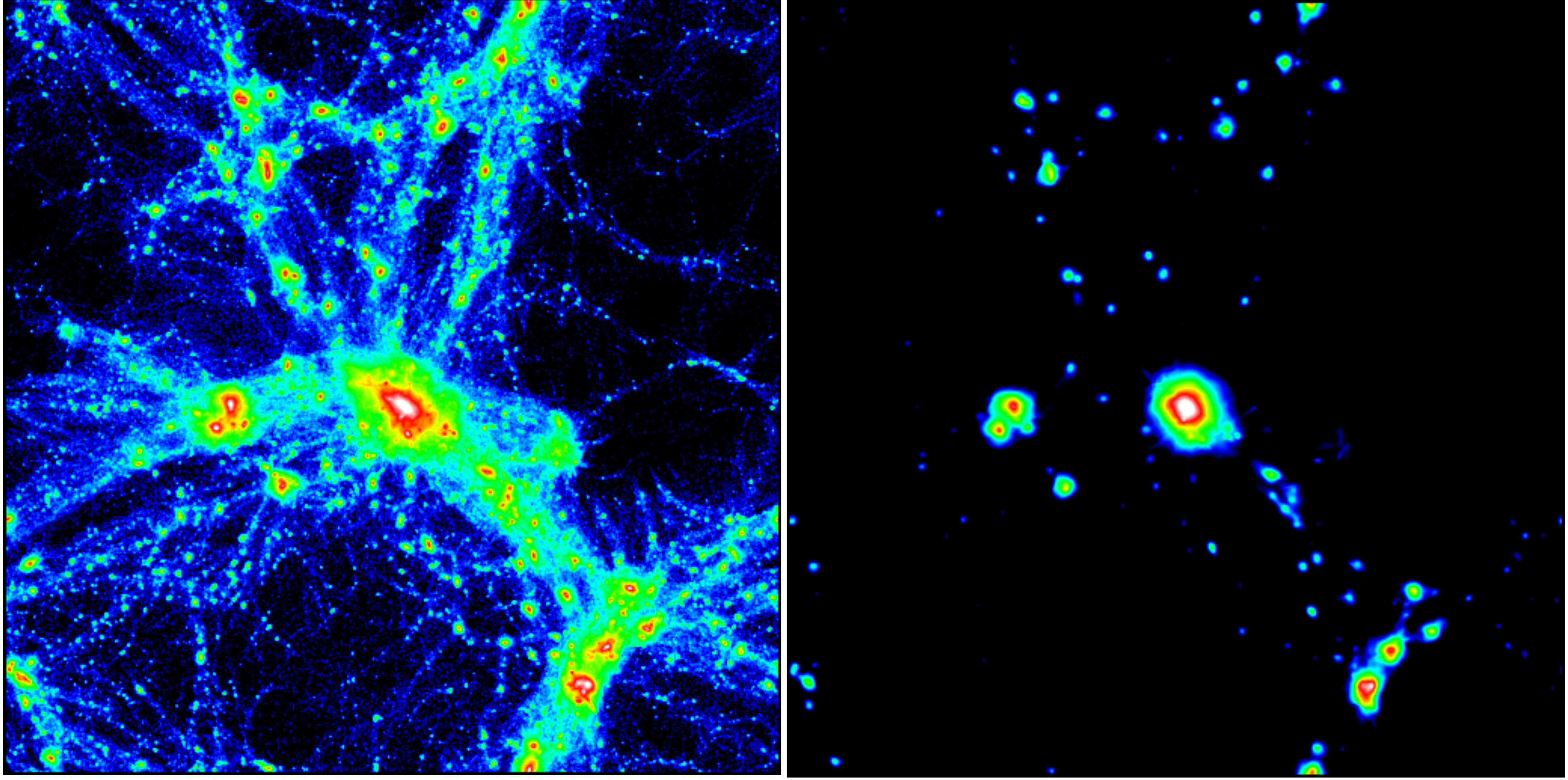
NASA/WMAP Science Team

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, Planck,...

Fluctuations continue growing, over-dense regions collapse under their own gravitational attraction.

Baryons fall into the gravitational potential wells produced by dark matter. Potential energy is converted to kinetic then thermalized -> hot plasma.


100 Mpc/h
25 Mpc/h
5 Mpc/h
1 Gpc/h
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck Institut für Astrophysik
VIRGO



- 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.

- 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).

- Total masses 10^{14} — 10^{15} M_o (10% ICM)
- X-ray luminosities 10^{43} — 10^{46} erg/s
- Temperatures 10^{6} — 10^{8} K
- Central densities 10^{-2} — 10^{-3} cm^{-3}
- Extent several Mpc
- $L_X \; \alpha \; T^3$

- The X-ray temperature is linearly correlated with the velocity dispersion of the galaxies.

- Clusters with a central, large galaxy (cD) have X-ray emission sharply peaked on the location of the galaxy.

- More luminous clusters have more galaxies with a smaller fraction of spirals.

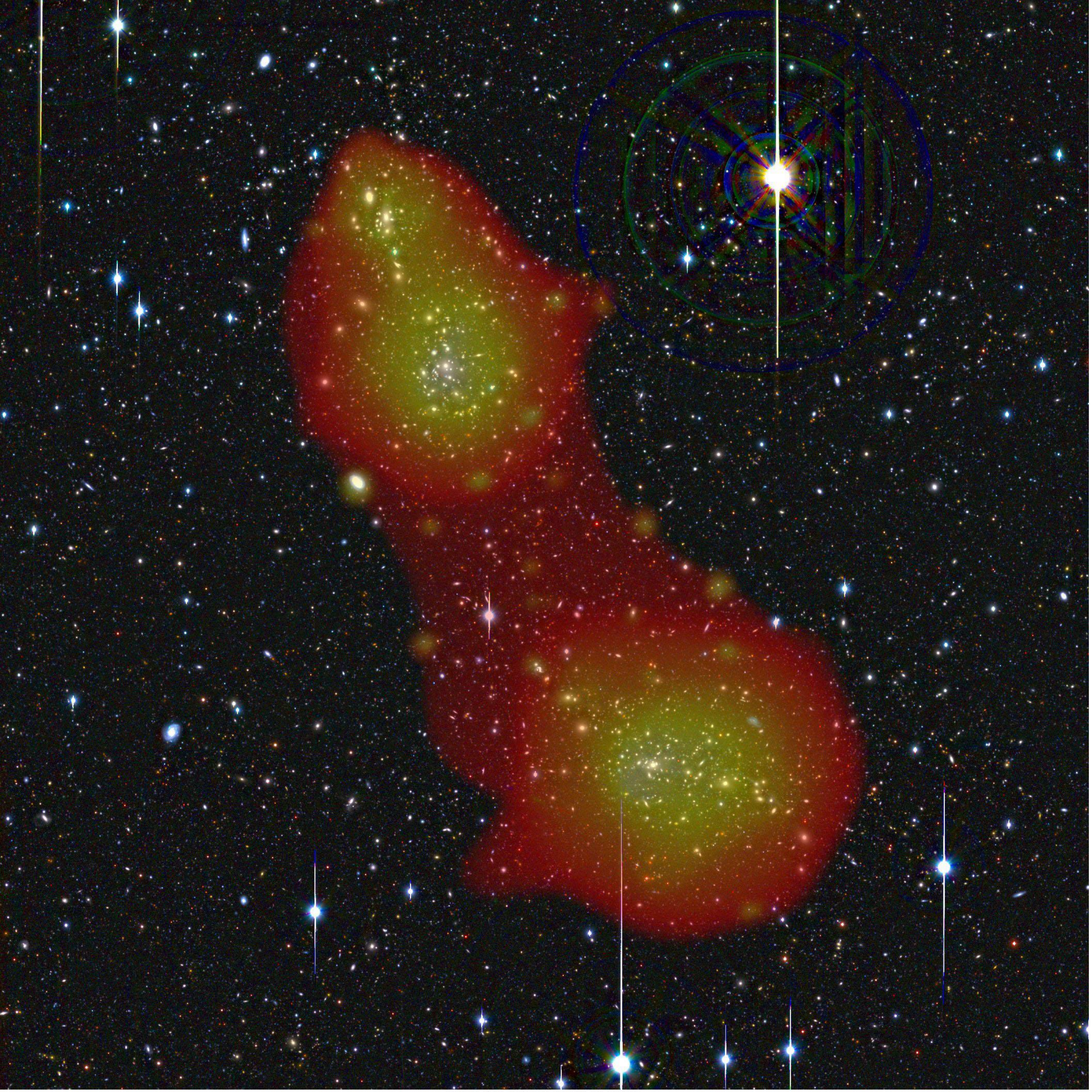
- More luminous clusters have a larger proportion of their baryons in the X-ray emitting plasma.

- Clusters of galaxies were first identified (in the 1930s) by looking for groupings of galaxies on photographic plates.

- Modern optical surveys (using eg SDSS data) combine colour and spectroscopic redshifts to identify clusters.

- In the X-ray, clusters are easy to find - just look for extended sources outside the Galactic plane. Follow-up optical spectroscopy then supplies the redshift.

- CMB surveys are now finding clusters based on their S-Z effect signal. This is a good way of finding high-z clusters.



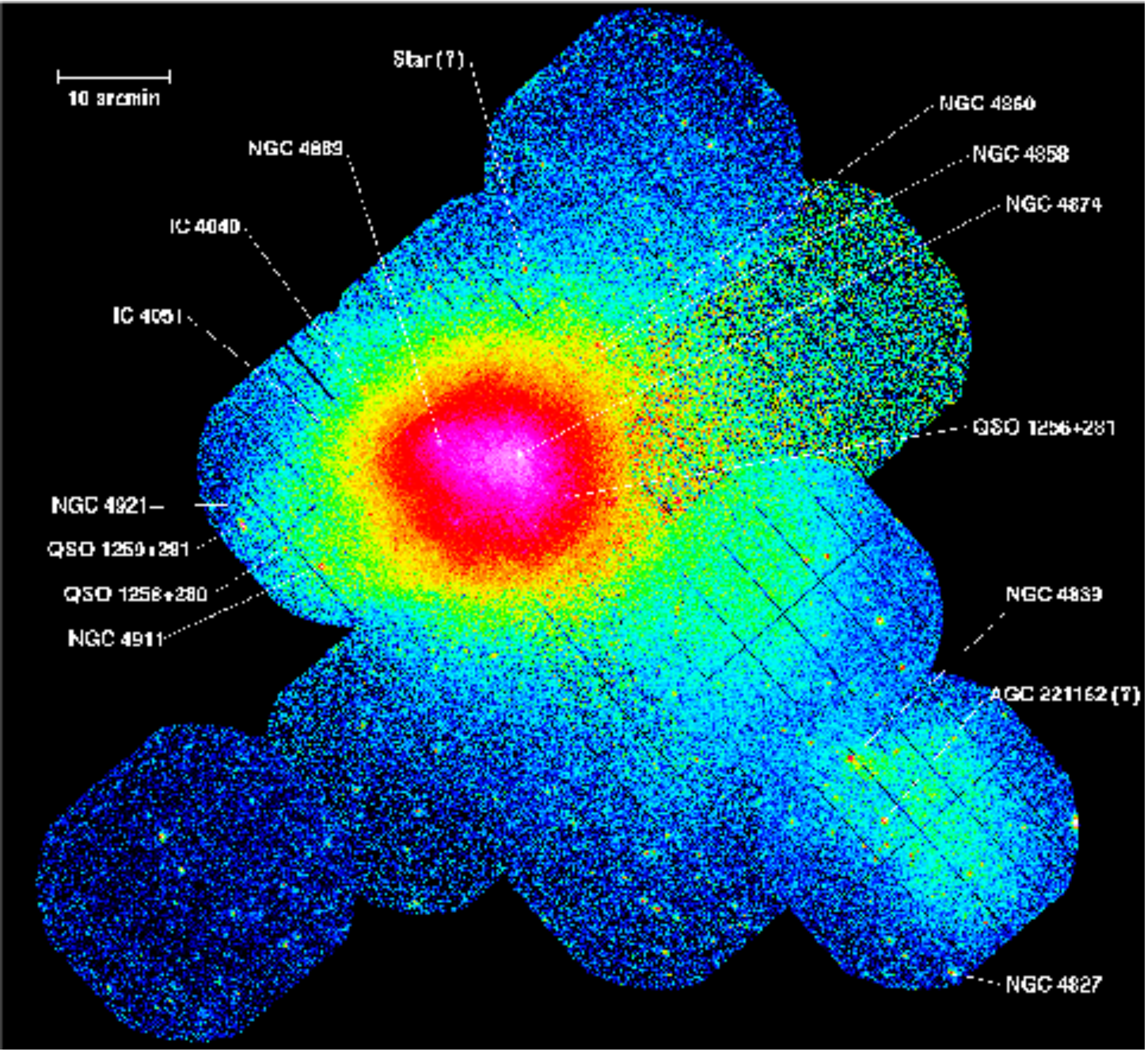
A bridge of hot gas between Abell 222 and Abell 223

Image courtesy of N. Werner (SRON, Netherlands Institute for Space Research), A. Finoguenov, A. Simionescu, H. Boehringer (MPE, Germany), J. Kaastra (SRON, Netherlands Institute for Space Research and Utrecht University), J. Dietrich (ESO, Germany)

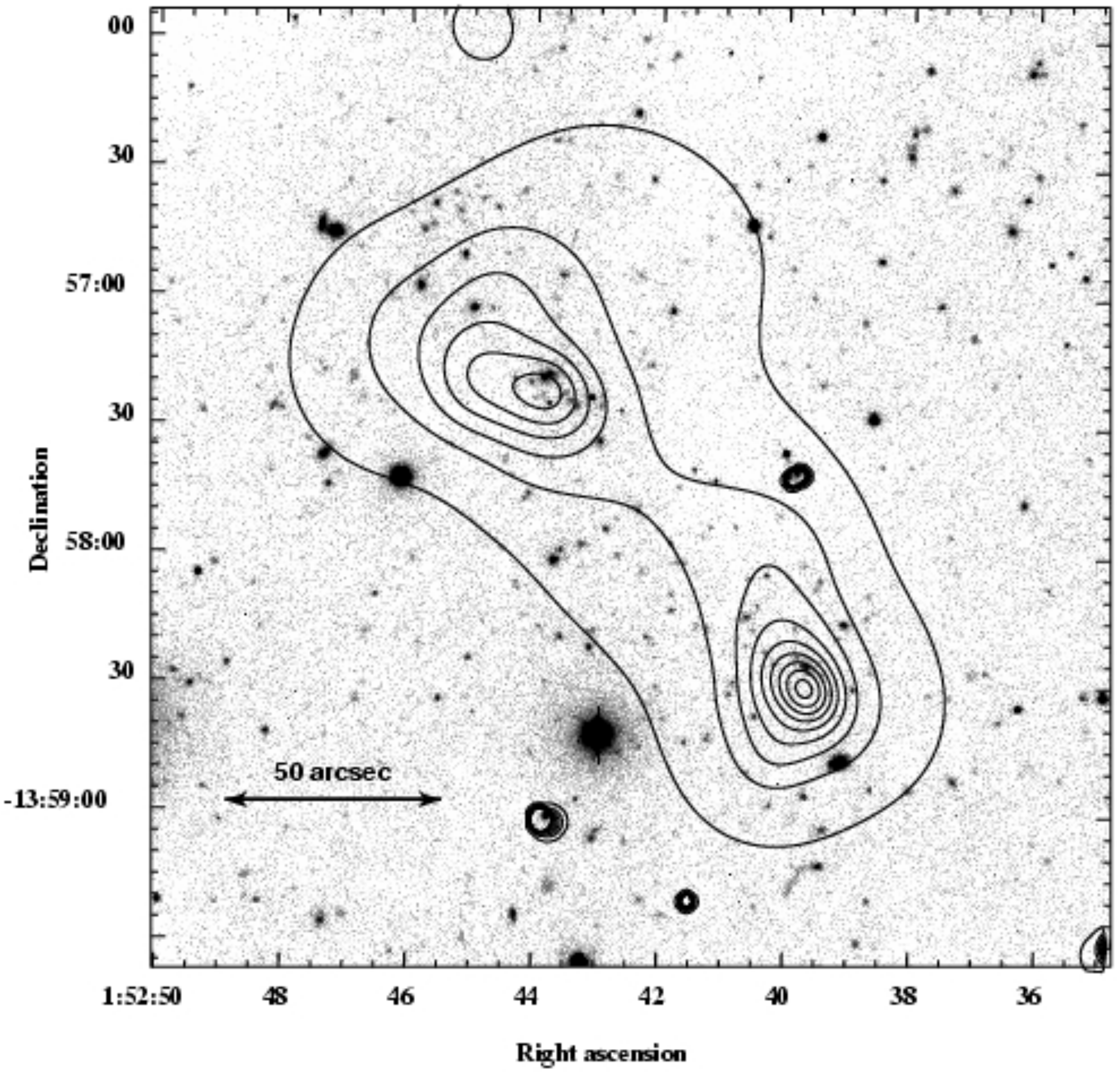
European Space Agency

Werner et al. (2008)
XMM-Newton and
Subaru.

Coma cluster with XMM

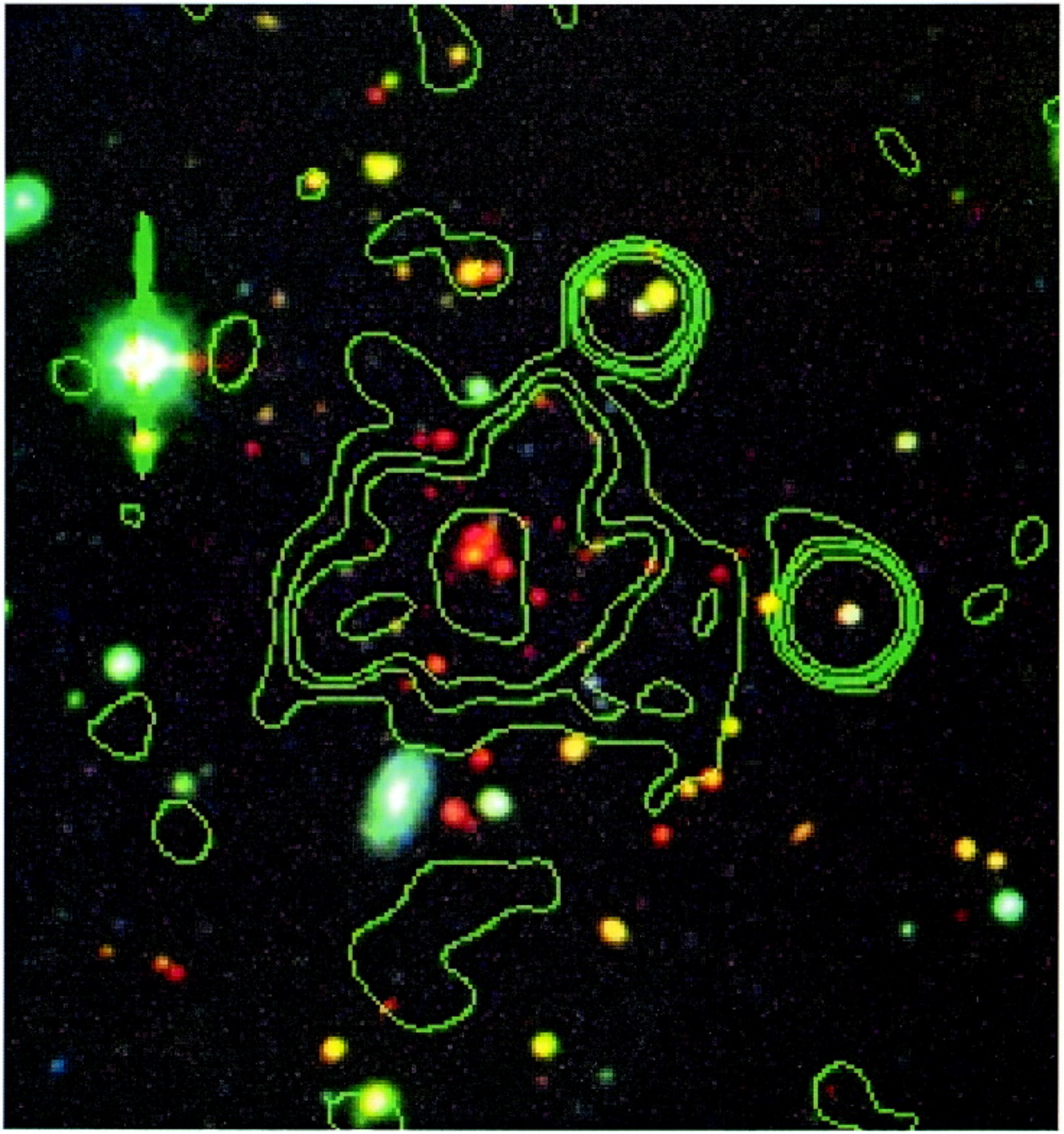


Briel et al. 2001



z=0.83 cluster with Chandra

Jones et al. 2004



z=1.26 cluster observed using Chandra and Keck

- From the spectrum we can measure a mean temperature, a redshift, and abundances of the most common elements (heavier than He).

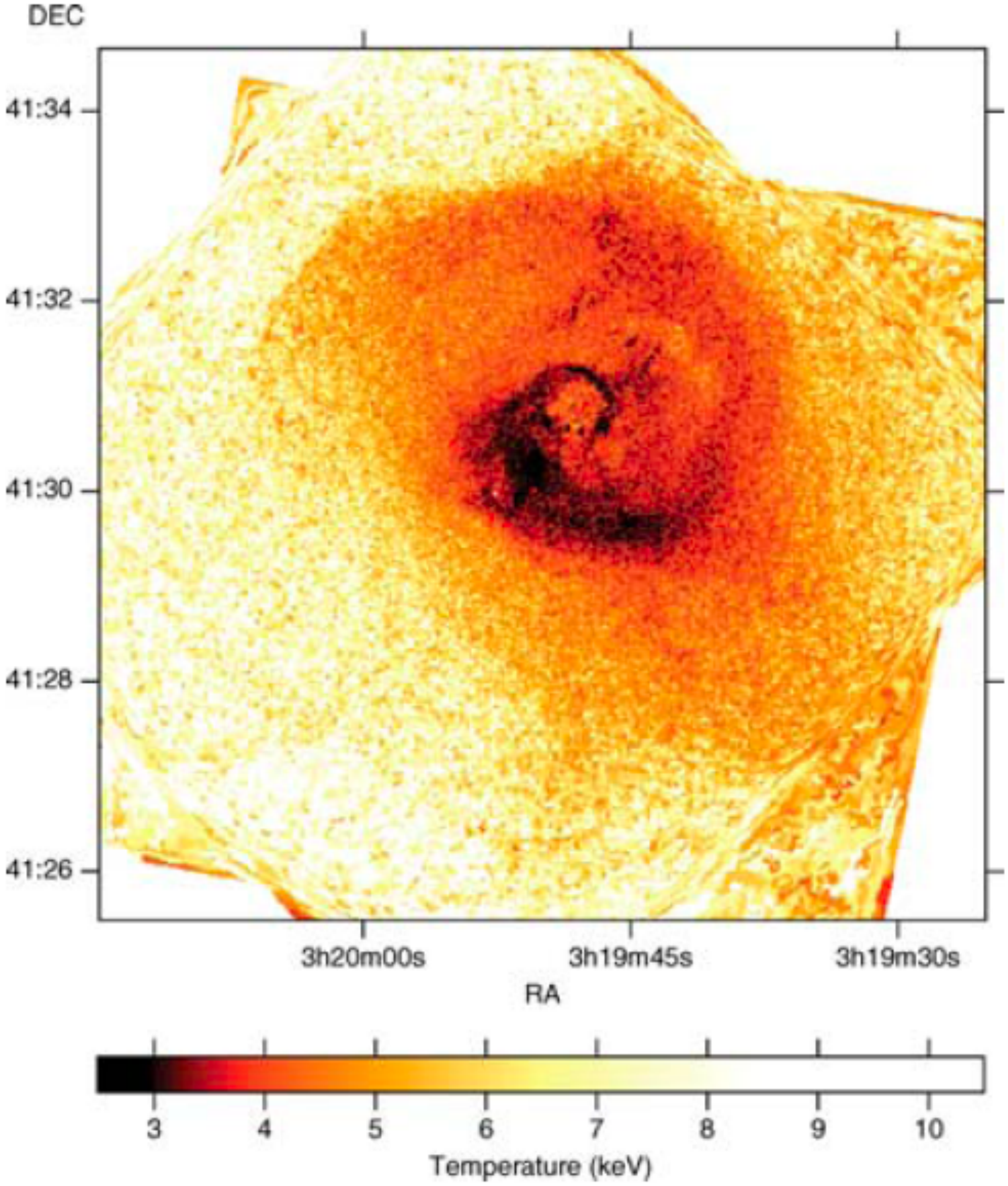
- With good S/N we can determine whether the spectrum is consistent with a single temperature or is a sum of emission from plasma at different temperatures.

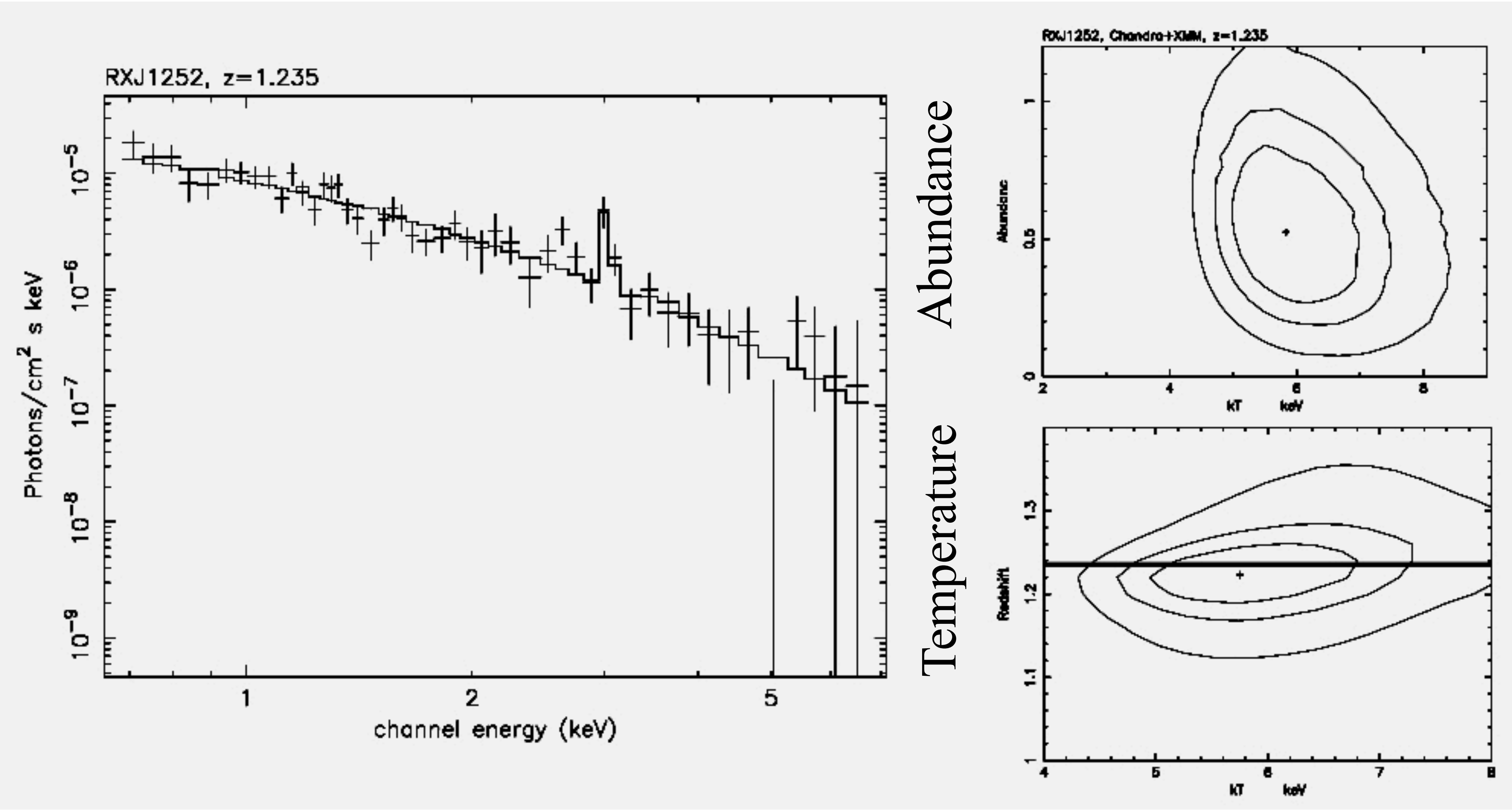
- With enough S/N this can be determined at many places in the cluster image.

- Using symmetry assumptions the observed X-ray surface brightness and temperature measurements can be converted to the ICM density and temperature.

Perseus cluster
Chandra 900 ksec
Fabian et al. 2006

Temperature map





Spectrum of RXJ1252

Rosati 2004

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.

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

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 undisturbed clusters these measures agree.

- Can we derive accurate and unbiassed masses from simple observables such as luminosity and temperature ?
- What do clusters tell us about dark matter ?
- 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 ?

Can we derive accurate and unbiassed masses from simple observables such as luminosity and temperature ?

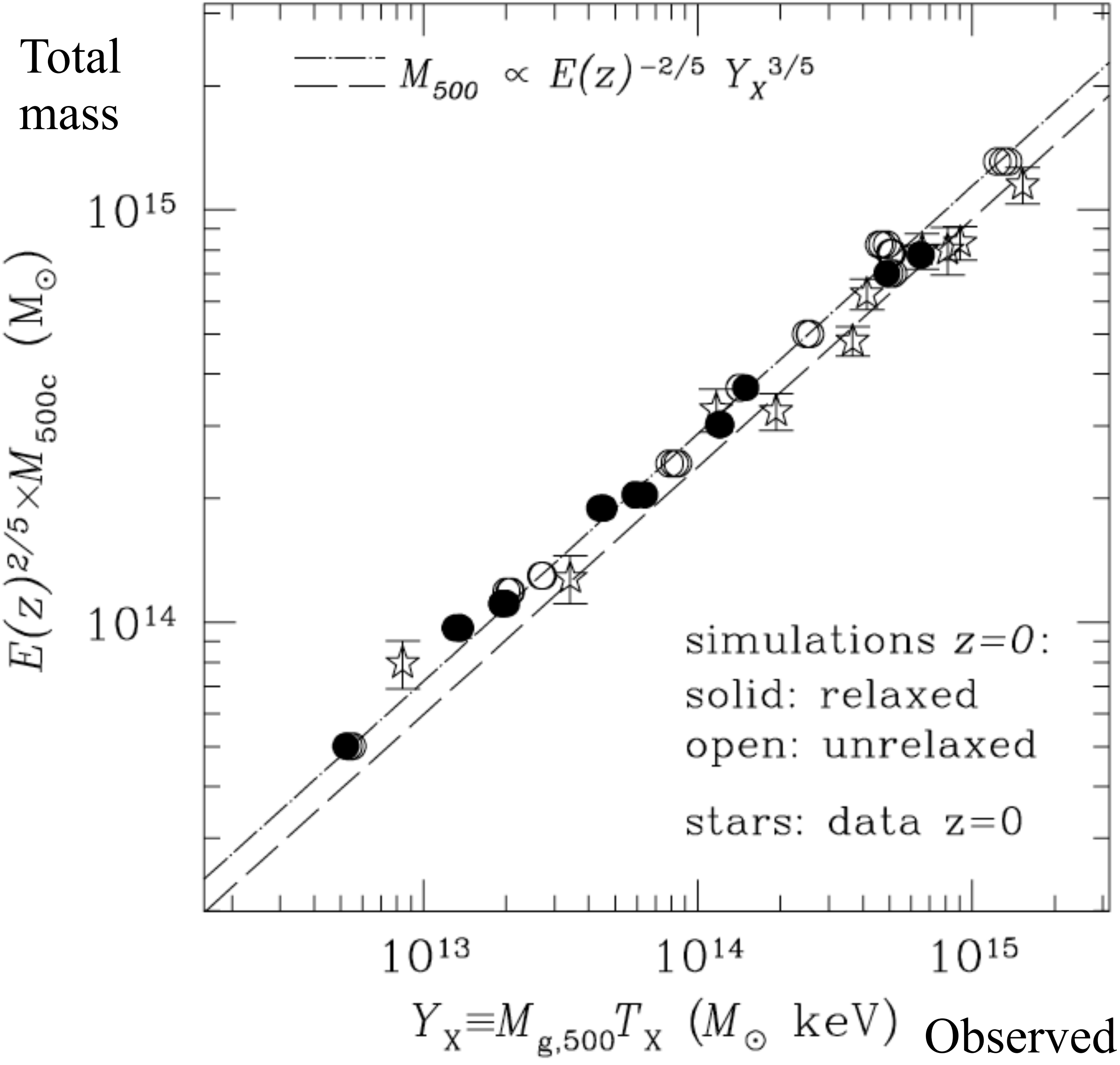
Why do we care ?

Cosmological simulations predict distributions of total masses.

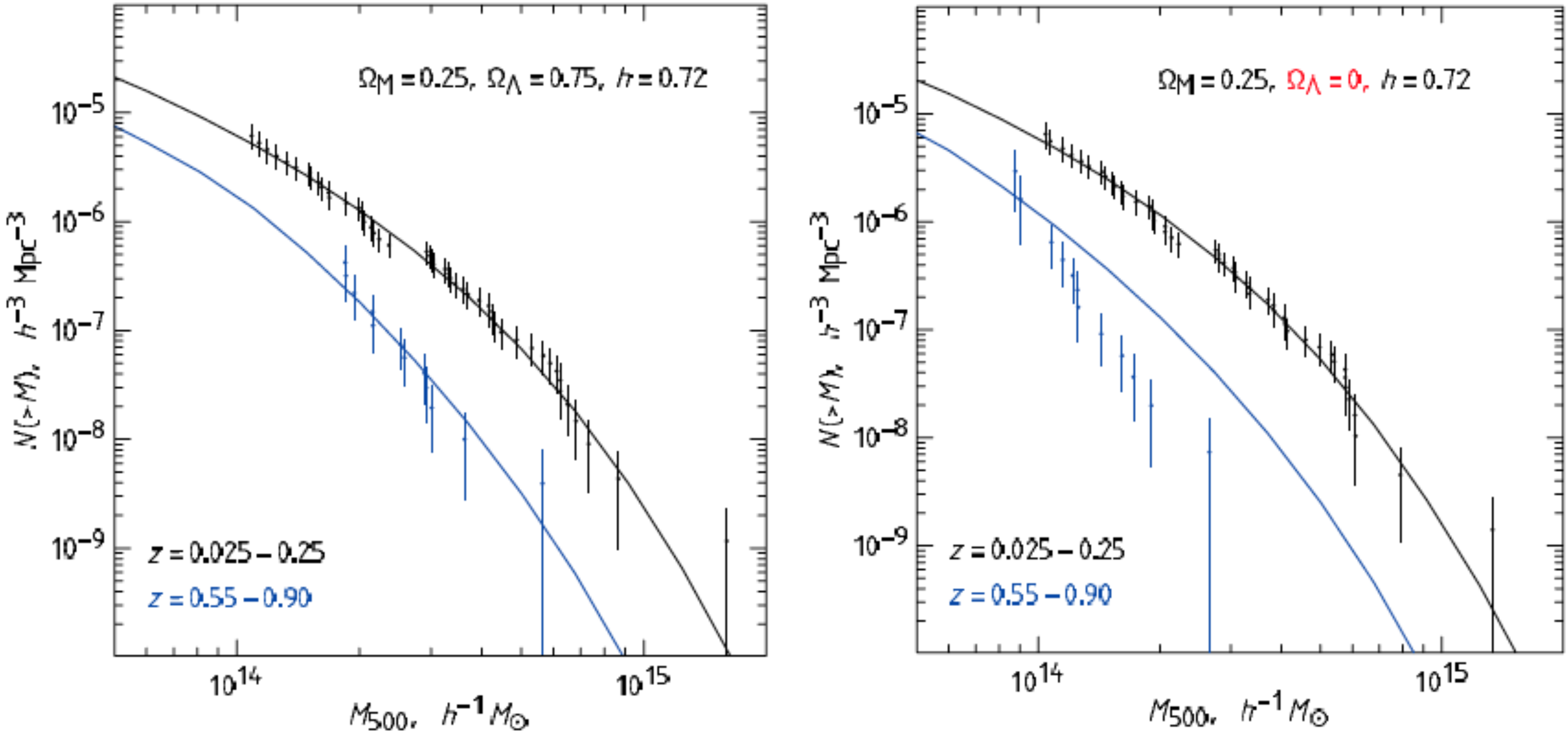
If we want to use X-ray selected samples of clusters of galaxies to measure cosmological parameters then we must be able to relate the observables (X-ray luminosity and/or temperature) to the total mass.

Total
mass

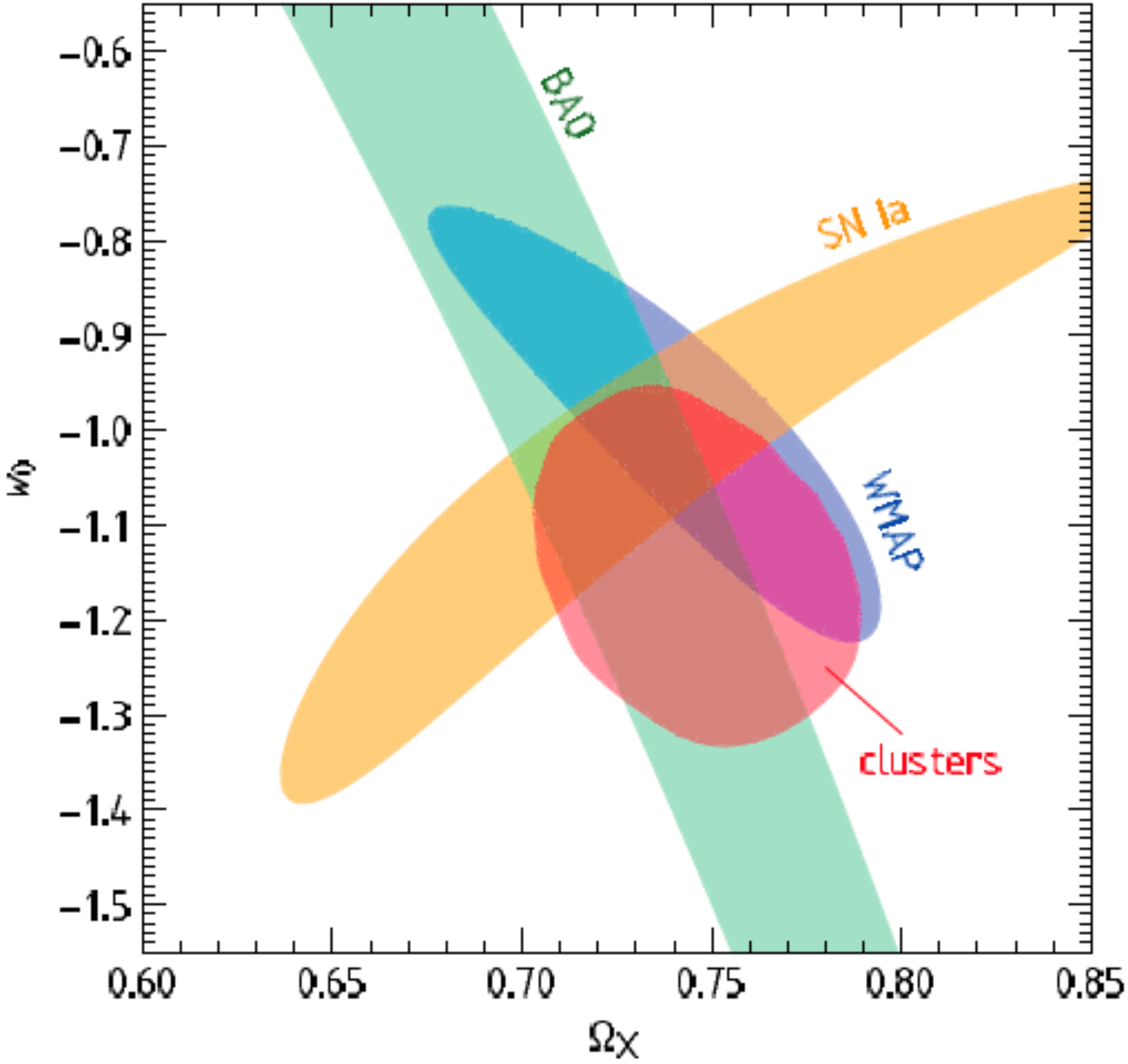
Kravtsov et al. 2006



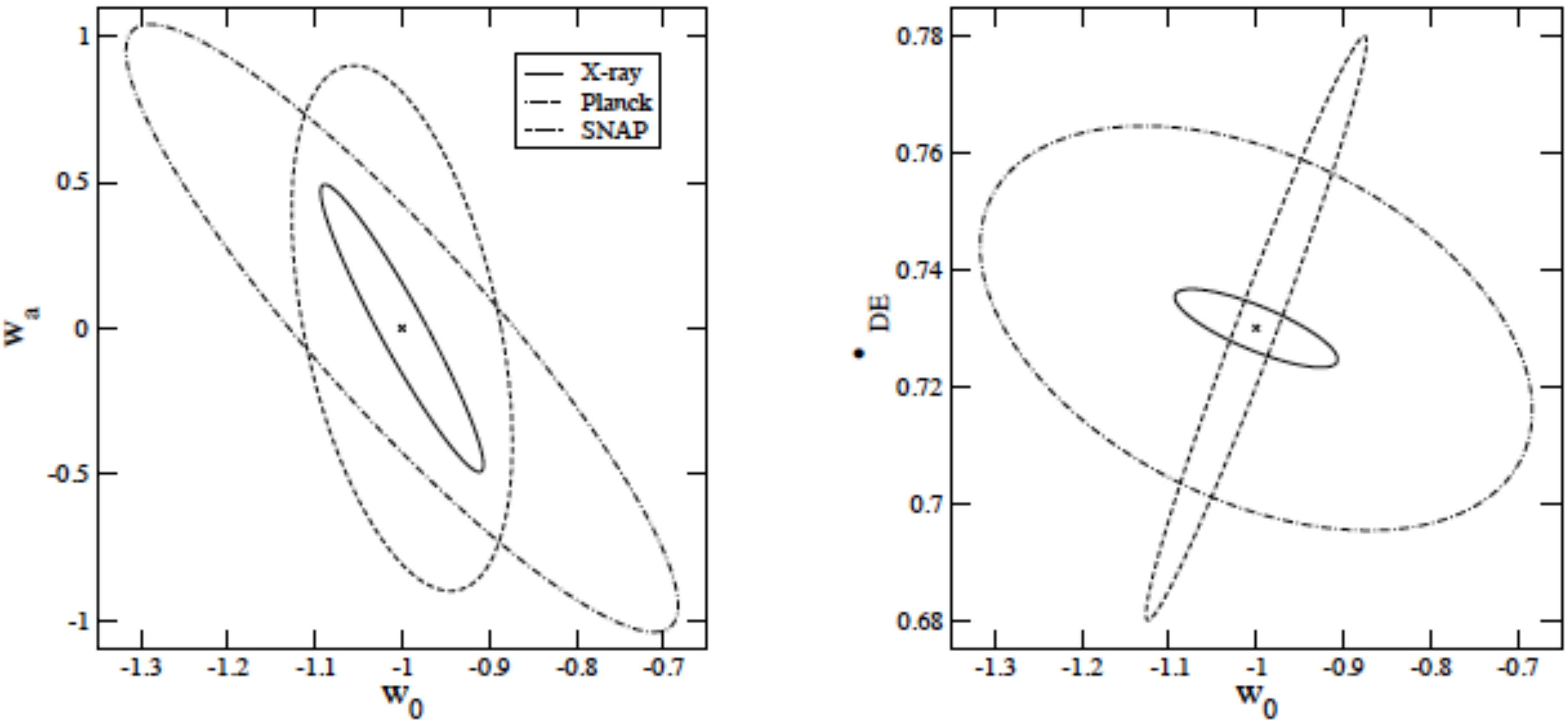
Observed



Vikhlinin et al. 2009



Vikhlinin et al. 2009

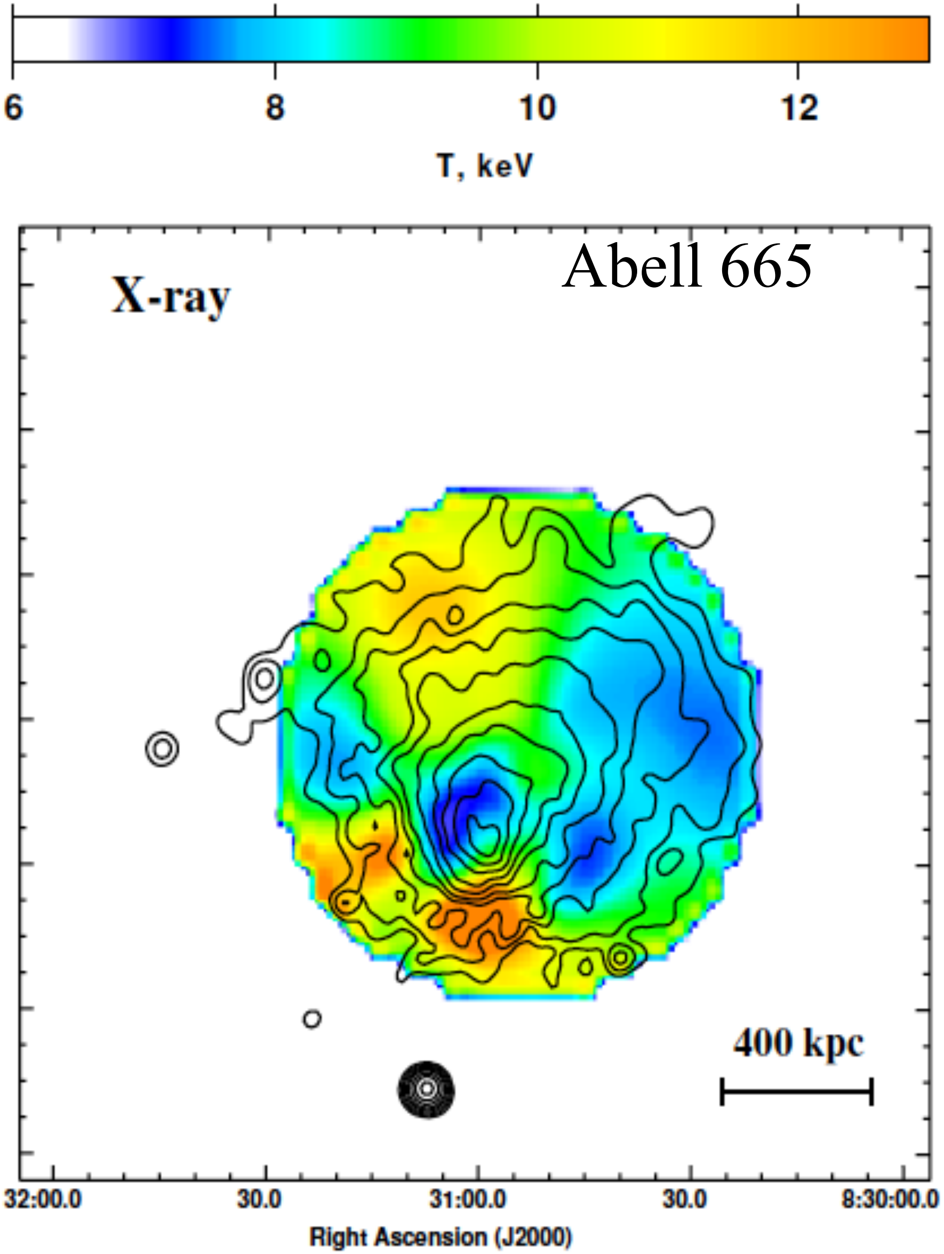


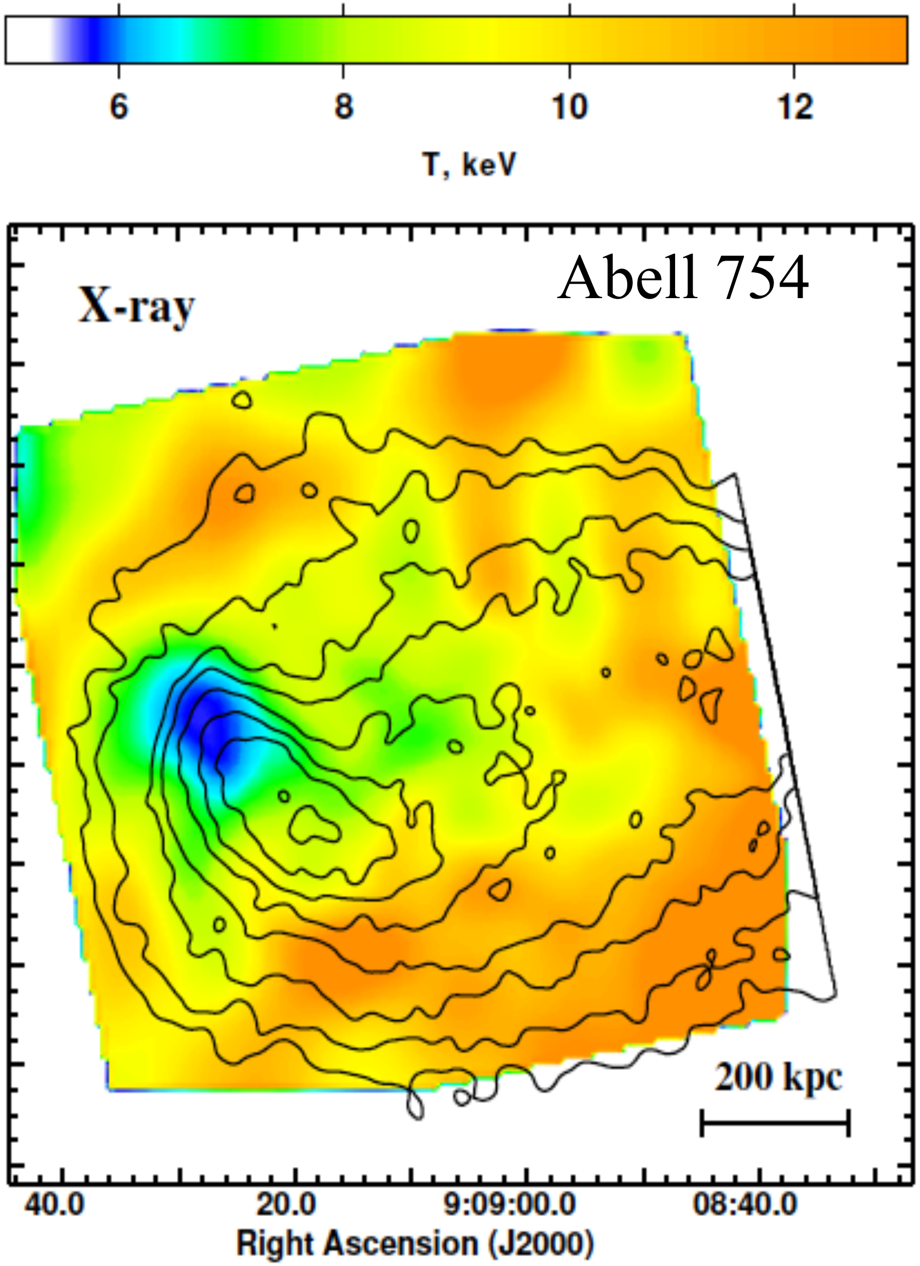
Simulated result for 100,000 clusters with X-ray observations.

Haiman et al. 2005

These results are great but for these large surveys we don’t get much information for each cluster so we depend on average properties.

We must observe a subsample of clusters in greater detail to check the large surveys. We can’t assume that clusters are always simple objects with a hydrostatic equilibrium between gas pressure and gravity. There may be bulk velocities, turbulence, magnetic fields, relativistic particles, …





Markevitch et al 2004

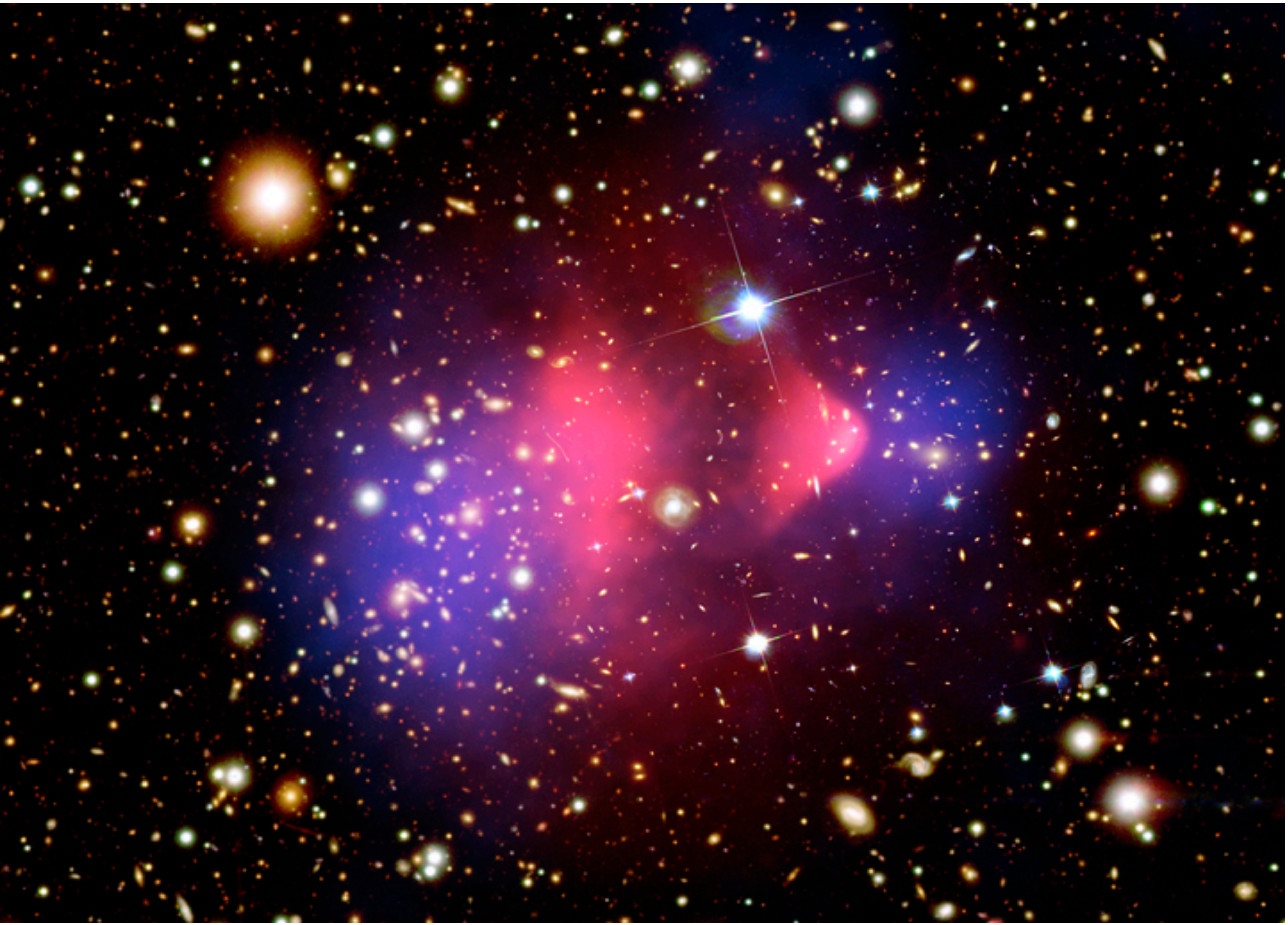
- What do clusters tell us about dark matter ?

Why do we care ?

We know in clusters of galaxies that the observed baryons (gas + galaxies) cannot explain the gravitational field inferred. We usually take this as evidence for dark matter.

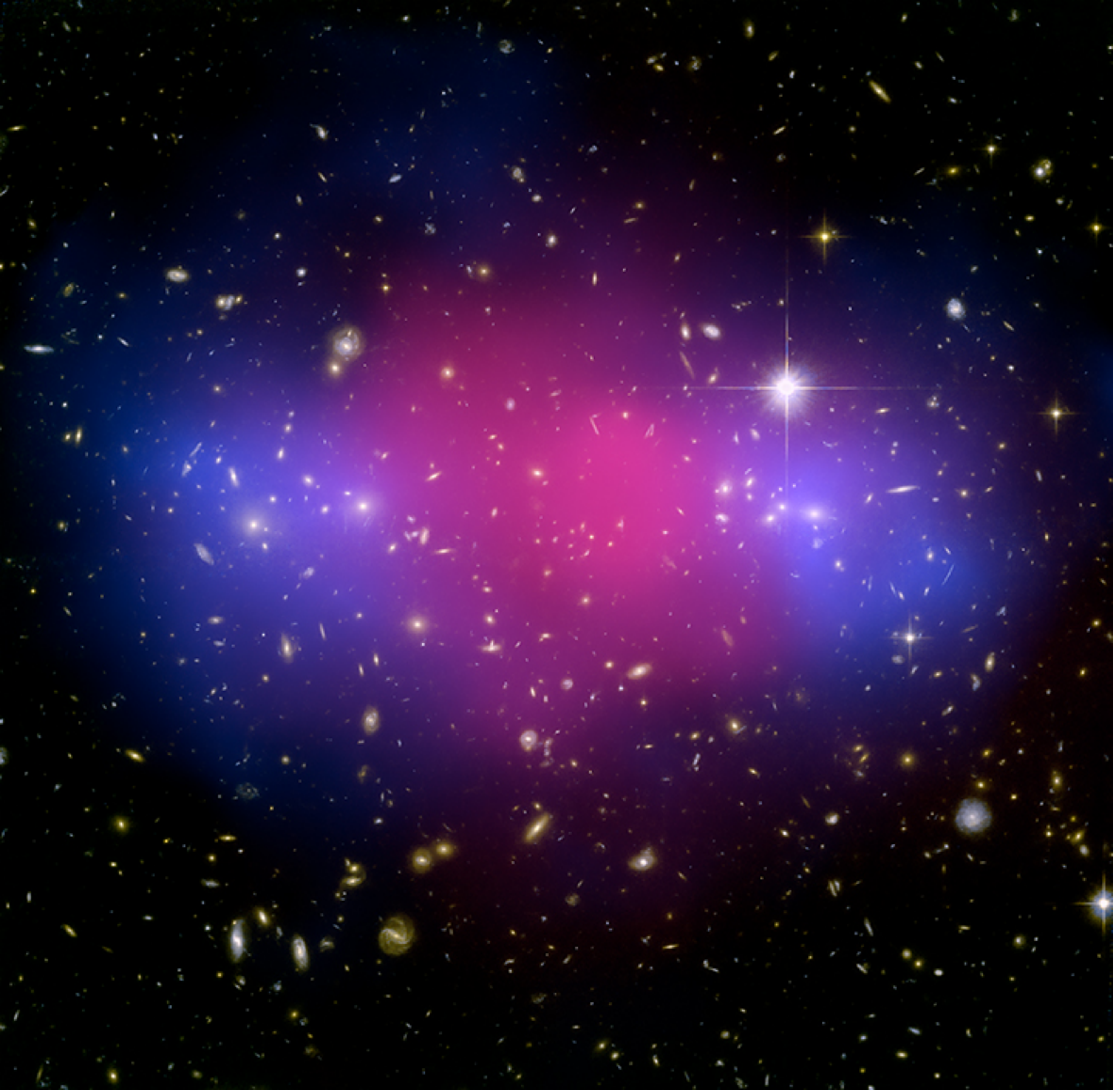
However, another possibility is that gravity is not strictly 1/r^2 on large-enough scales as originally suggested by Milgrom and formulated in a relativistic theory by Bekenstein.

If modified gravity is correct then the shape of the gravitational field **must** be the same as the shape of the baryon distribution. This provides a definitive test.



Bullet cluster

Markevitch et al., Clowe et al.



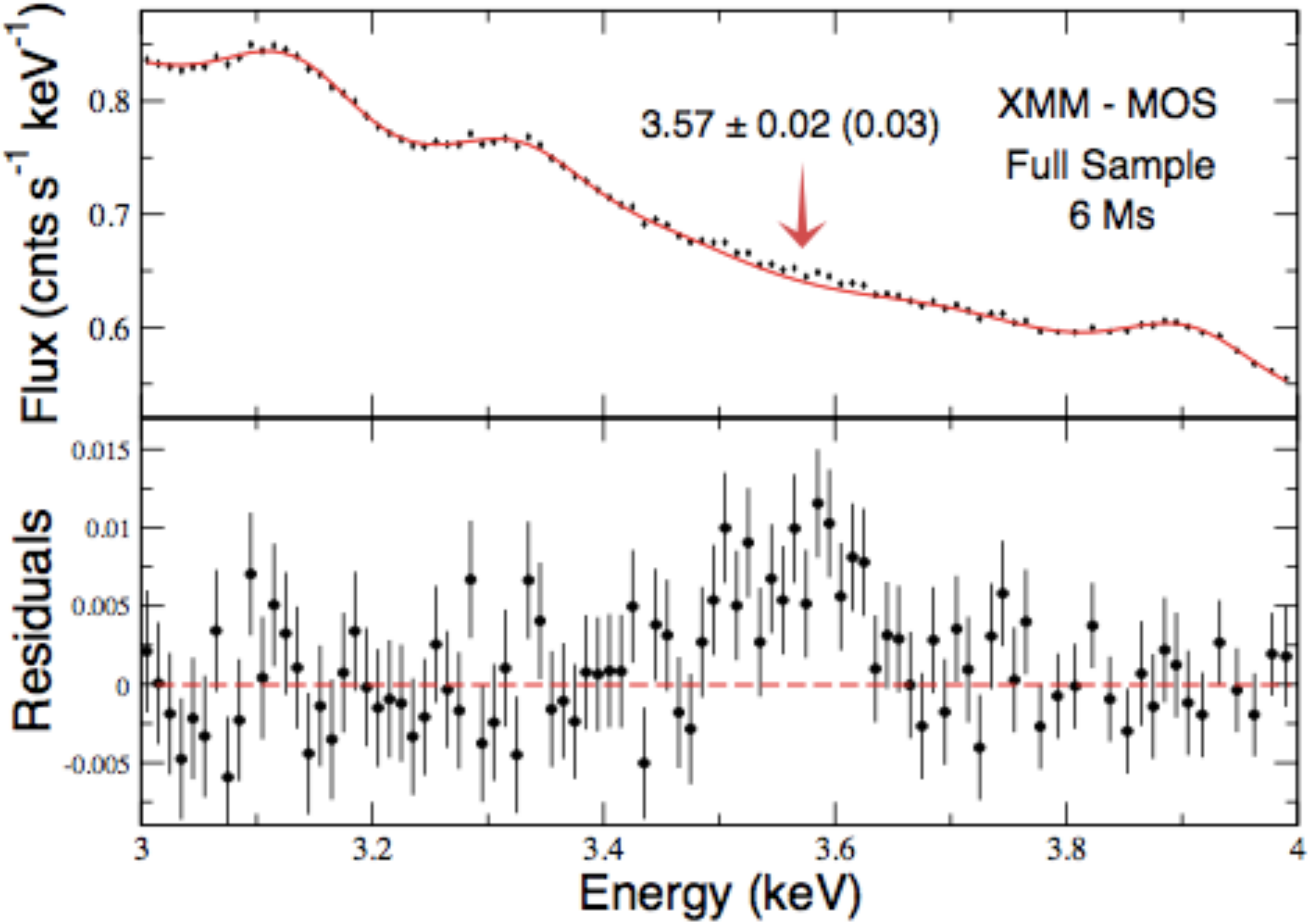
MACS J0025.4-1222

Bradac et al., 2008

In high-velocity collisions of clusters the gravitational mass is distributed in the same way as the galaxies and not the X-ray emitting plasma, which contains most of the baryons. So, an alternative gravity theory does not work and the mass must be in collision-less particles.

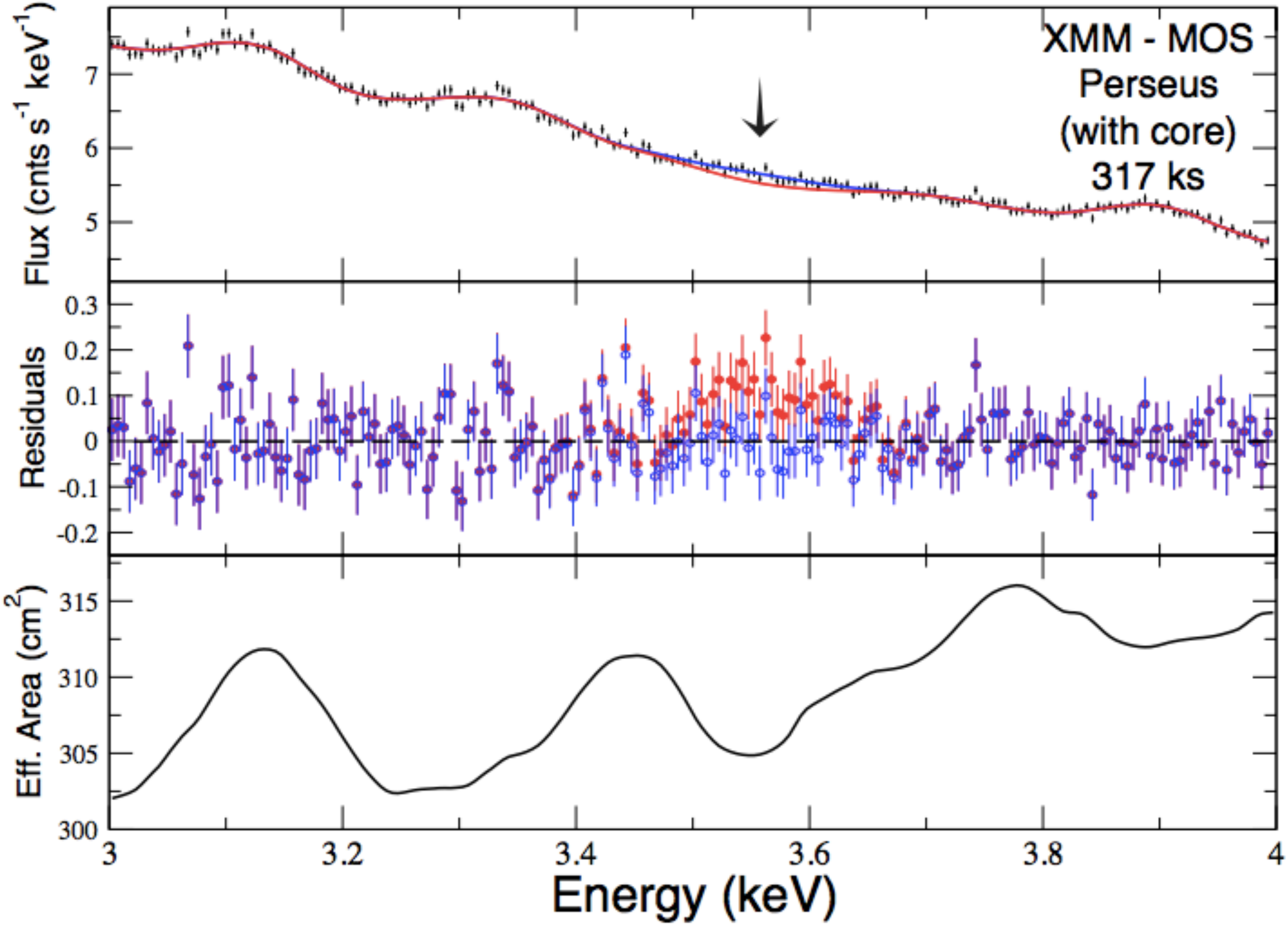
This argument will only be finally settled by the direct detection of dark matter particles. One popular candidate is the sterile neutrino which is predicted to have a decay line in the X-ray energy range ...

Bulbul et al. 2014

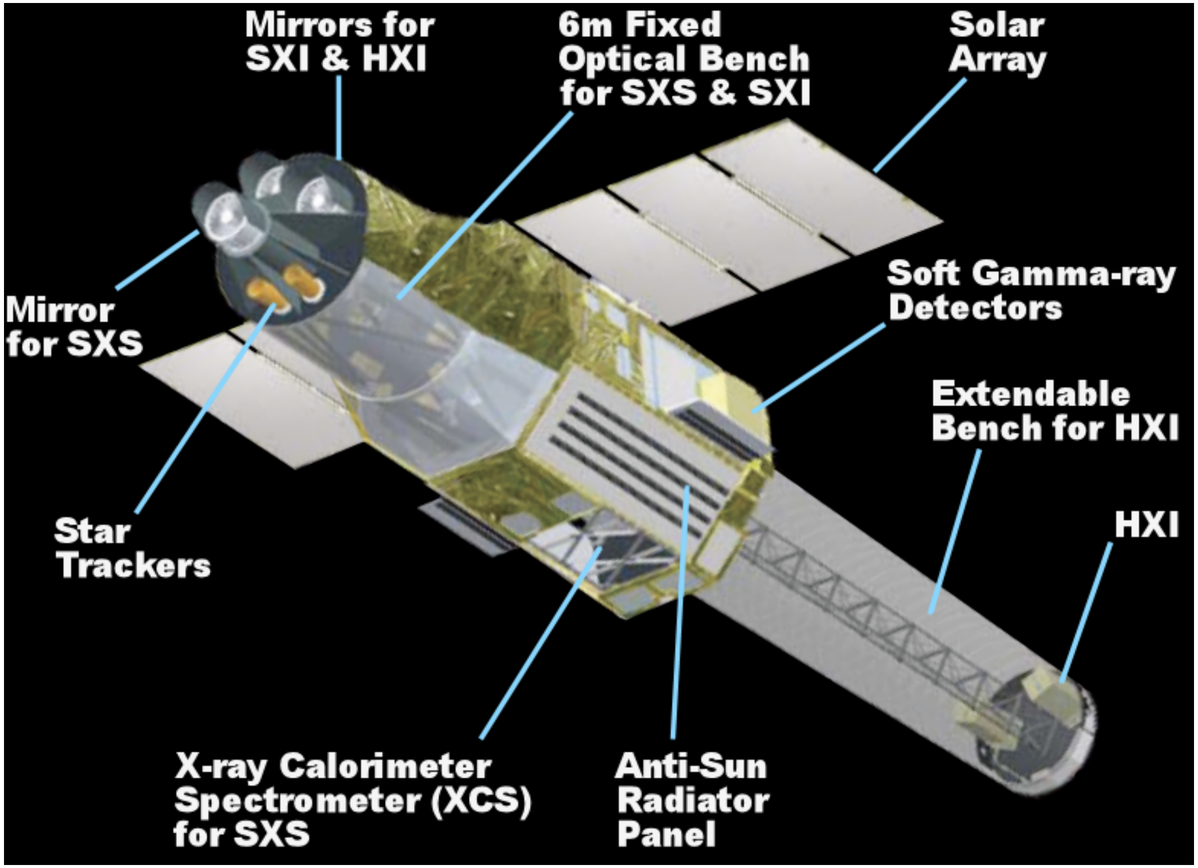


Stacked redshifted spectra from 73 clusters

Bulbul et al. 2014



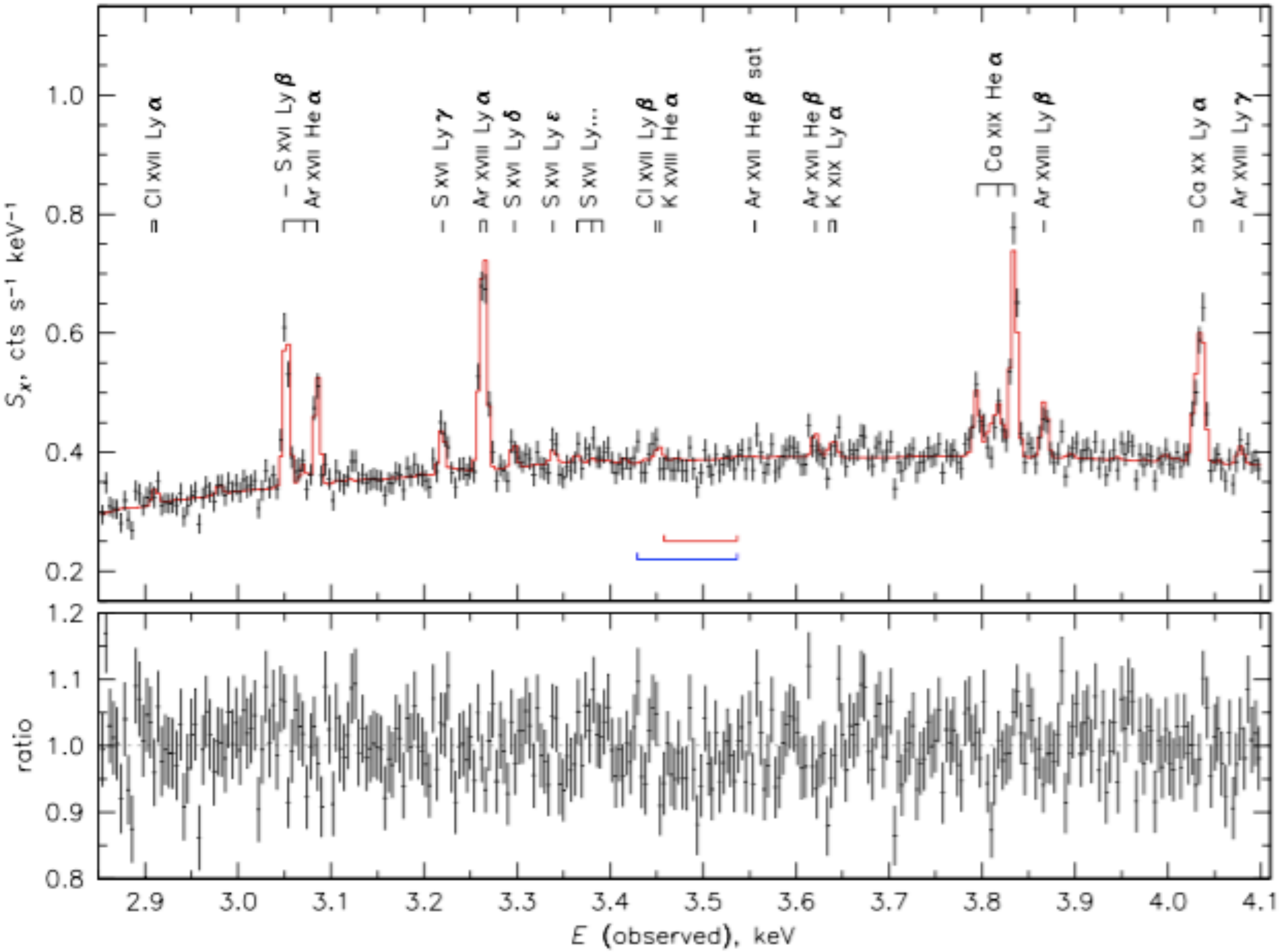
Perseus spectrum – this line is several times brighter than predicted from the total cluster sample.

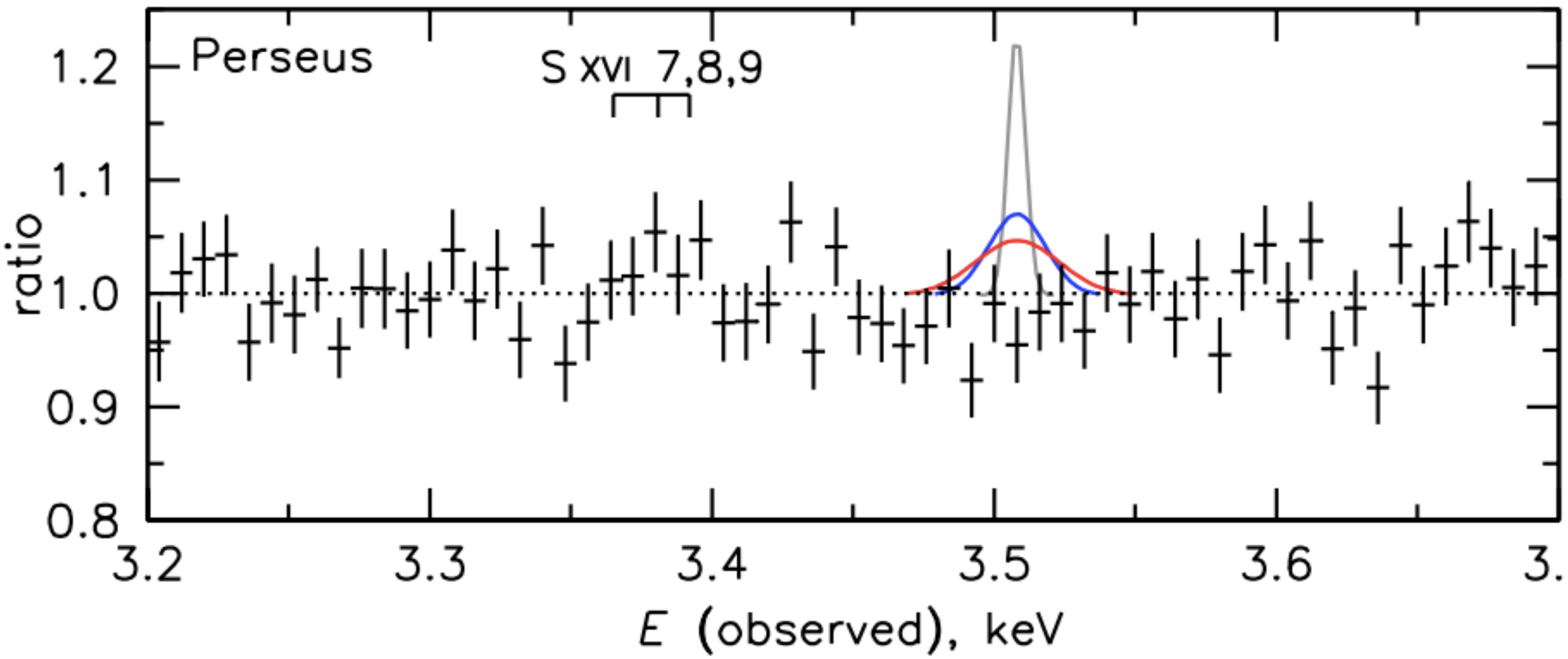


Hitomi was launched on February 17th 2016 and failed on March 26th 2016.

In this brief life we obtained 230 ksec on the Perseus cluster core.

The calorimeter had a resolution of 4.9 eV, about 60x better than XMM, so a weak line found using XMM should be much easier to detect using the calorimeter.


Cl XVII Ly α
S XVI Ly β
Ar XVII He α
S XVI Ly γ
Ar XVIII Ly α
S XVI Ly δ
S XVI Ly ε
S XVI Ly...
Cl XVII Ly β
K XVIII He α
Ar XVII He β sat
Ar XVII He β
K XIX Ly α
Ca XIX He α
Ar XVIII Ly β
Ca XX Ly α
Ar XVIII Ly γ
S_x, cts s^{-1} keV^{-1}
1.0
0.8
0.6
0.4
0.2
ratio
1.2
1.1
1.0
0.9
0.8
2.9
3.0
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4.0
4.1
E (observed), keV



Assumed line-of-sight velocity dispersion of 180 km/s (gray), 800 km/s (blue), 1300 km/s (red). So XMM MOS claim of line from Perseus cluster is not confirmed. However, the Perseus result was anomalously high compared to the other stacked clusters and we cannot rule out a line at the flux of the stacked clusters.

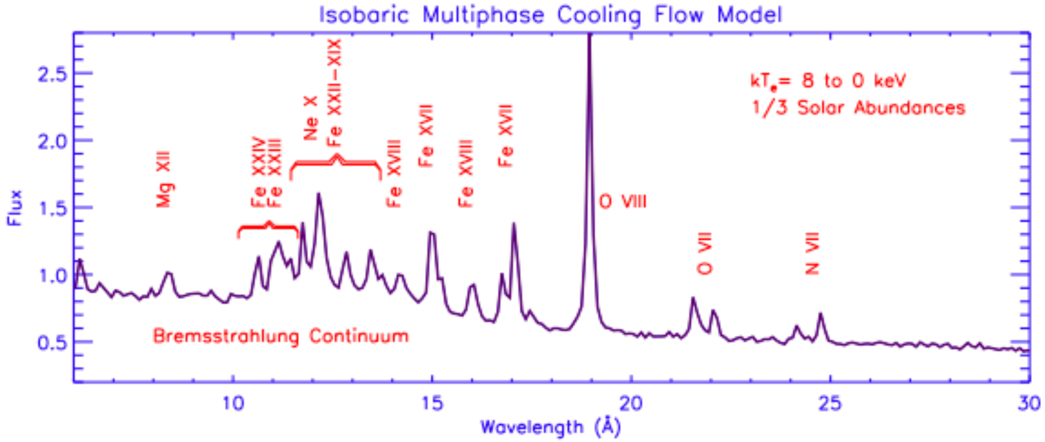
What is happening in the centers of clusters - how does the radio galaxy and the cluster gas interact ?

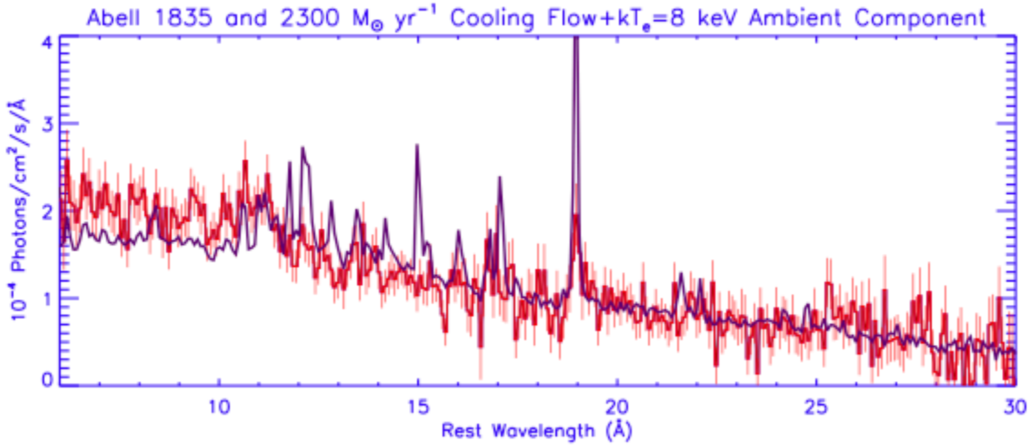
Why do we care ?

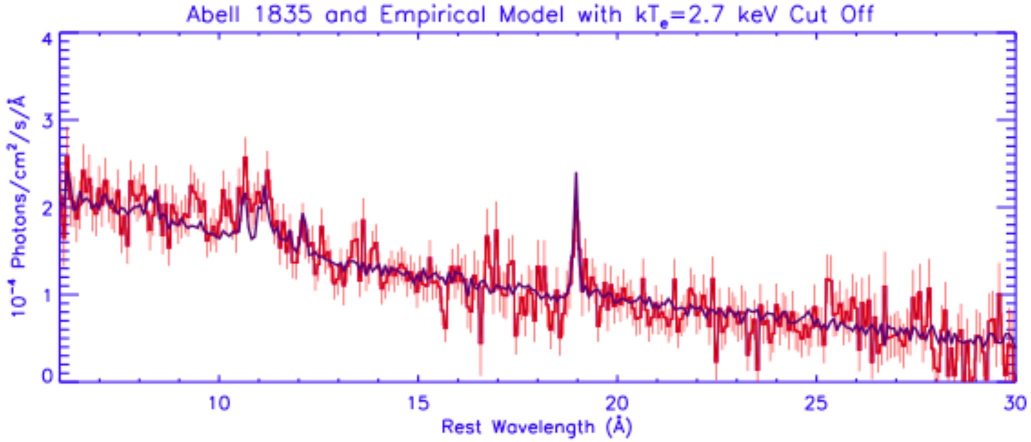
We used to have a simple model for the cores of clusters :

- 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.

Abell 1835
XMM RGS


Isobaric Multiphase Cooling Flow Model


Abell 1835 and 2300 $M_\odot$ yr^{-1} Cooling Flow+kT$_e$=8 keV Ambient Component

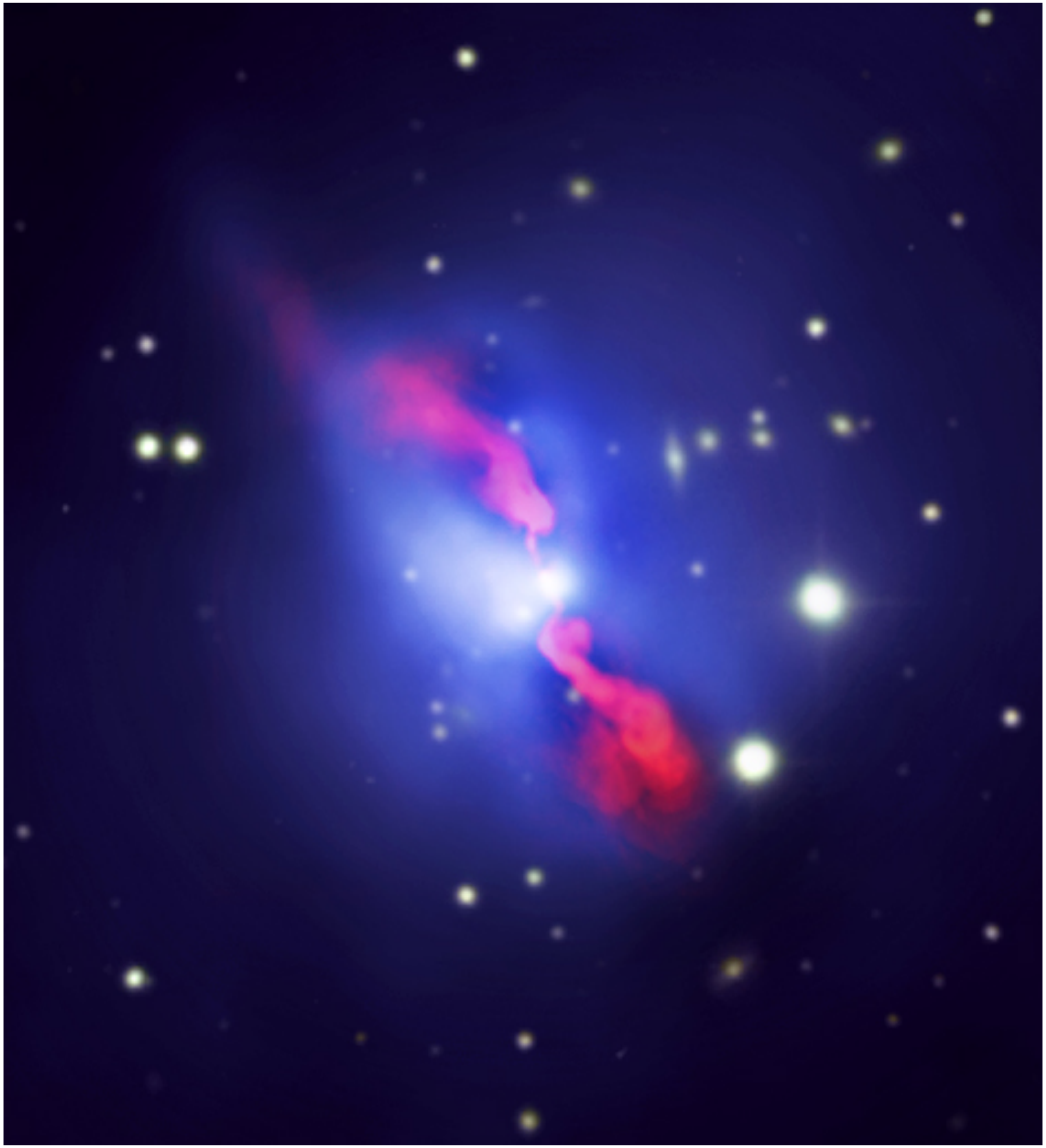

Abell 1835 and Empirical Model with kT$_e$=2.7 keV Cut Off

The RGS can be used for this extended source because the surface brightness is very sharply peaked at the cluster core.

Peterson et al.

So, XMM RGS spectra show that our model for the cores of clusters is wrong. Something is stopping the gas cooling but XMM can’t tell us what.

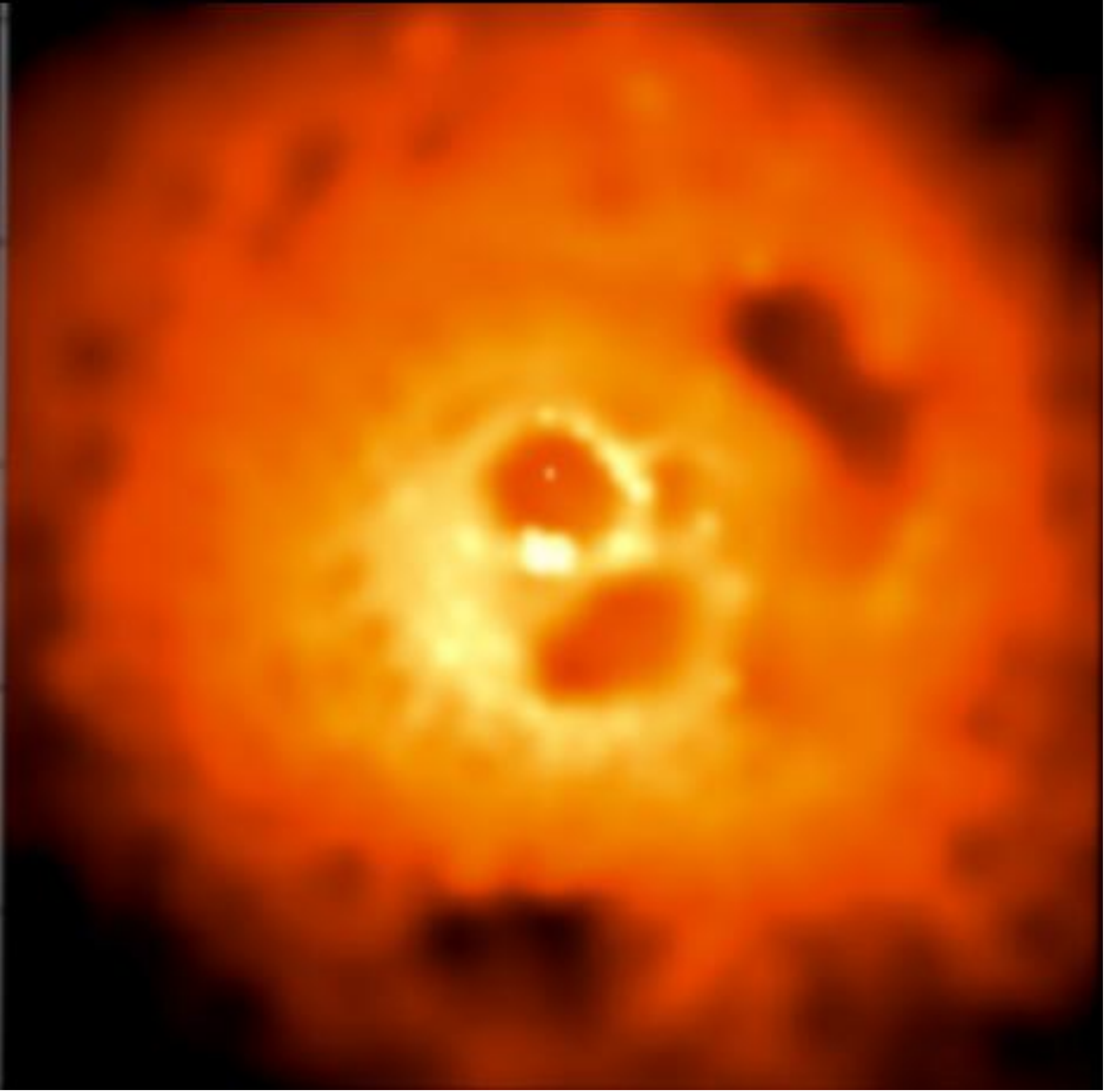
Chandra to the rescue ! High resolution imaging of cluster cores shows holes in the X-ray emission. Low frequency radio observations show structures that match these holes.



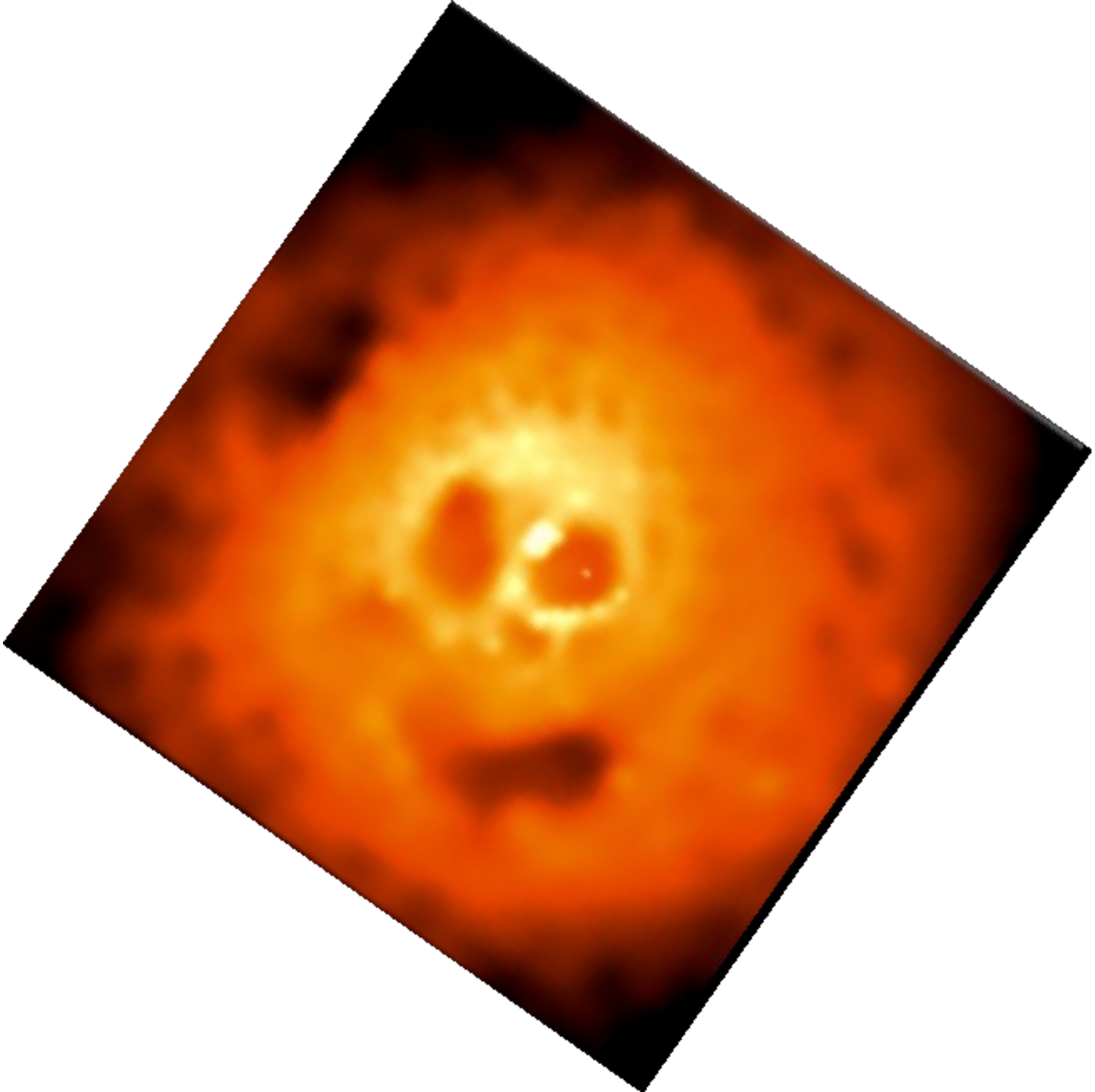
Hydra-A

Chandra blue
Radio red

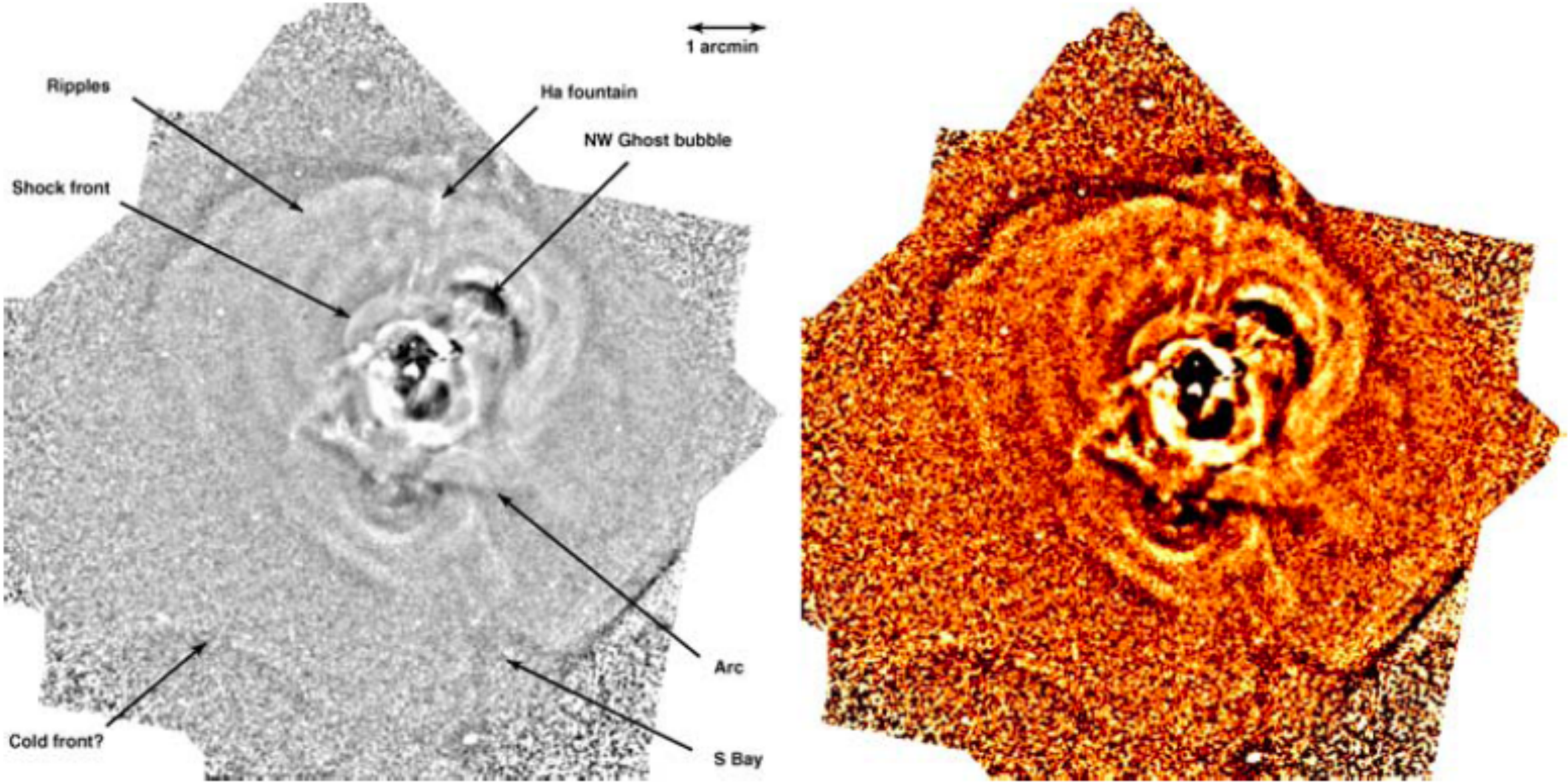
Kirkpatrick et al, 2009



Chandra
image of
Perseus
cluster



An AGN at the centre of the cluster is pumping bubbles of relativistic plasma into the intracluster medium. Can this stop the cooling flow ?



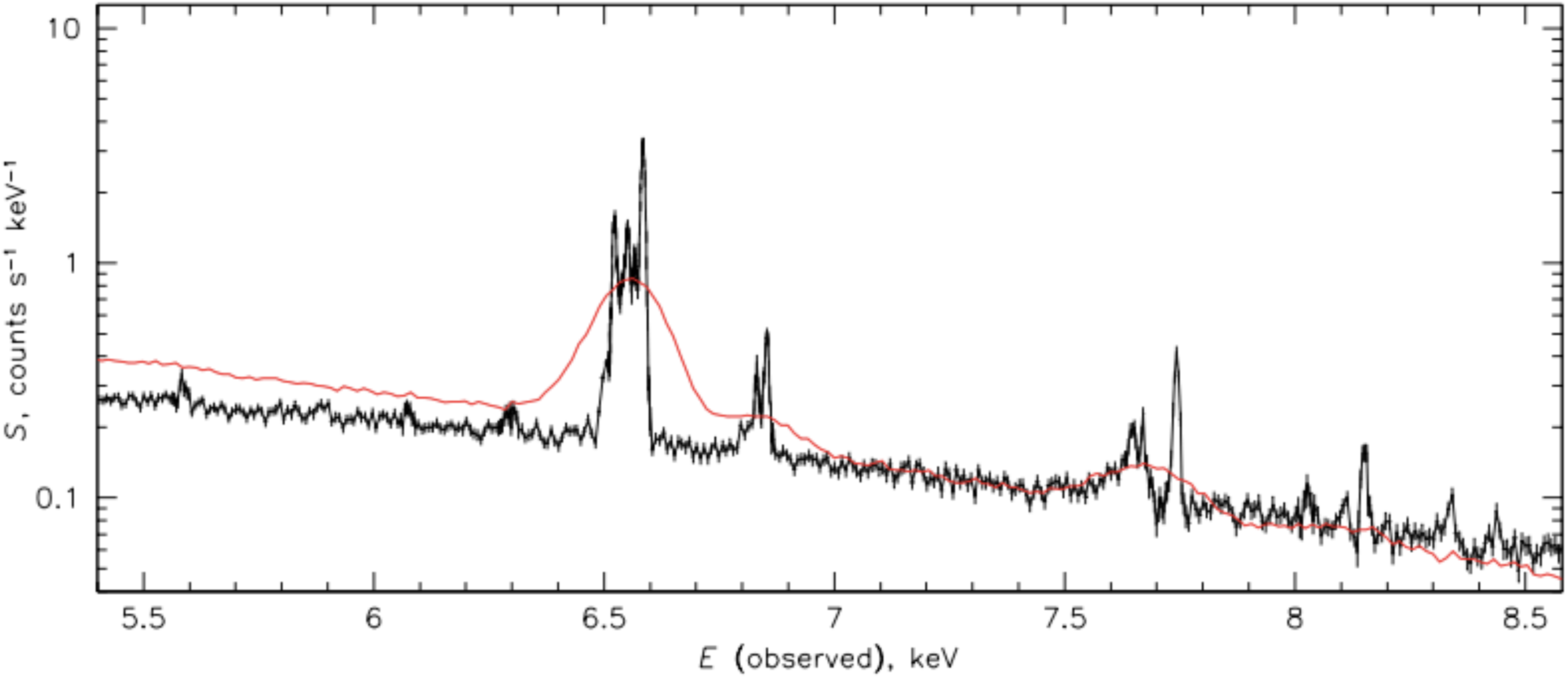
Perseus cluster unsharp masked. Evidence of energy propagating out into the cluster plasma in the form of waves.

Fabian et al., 2006

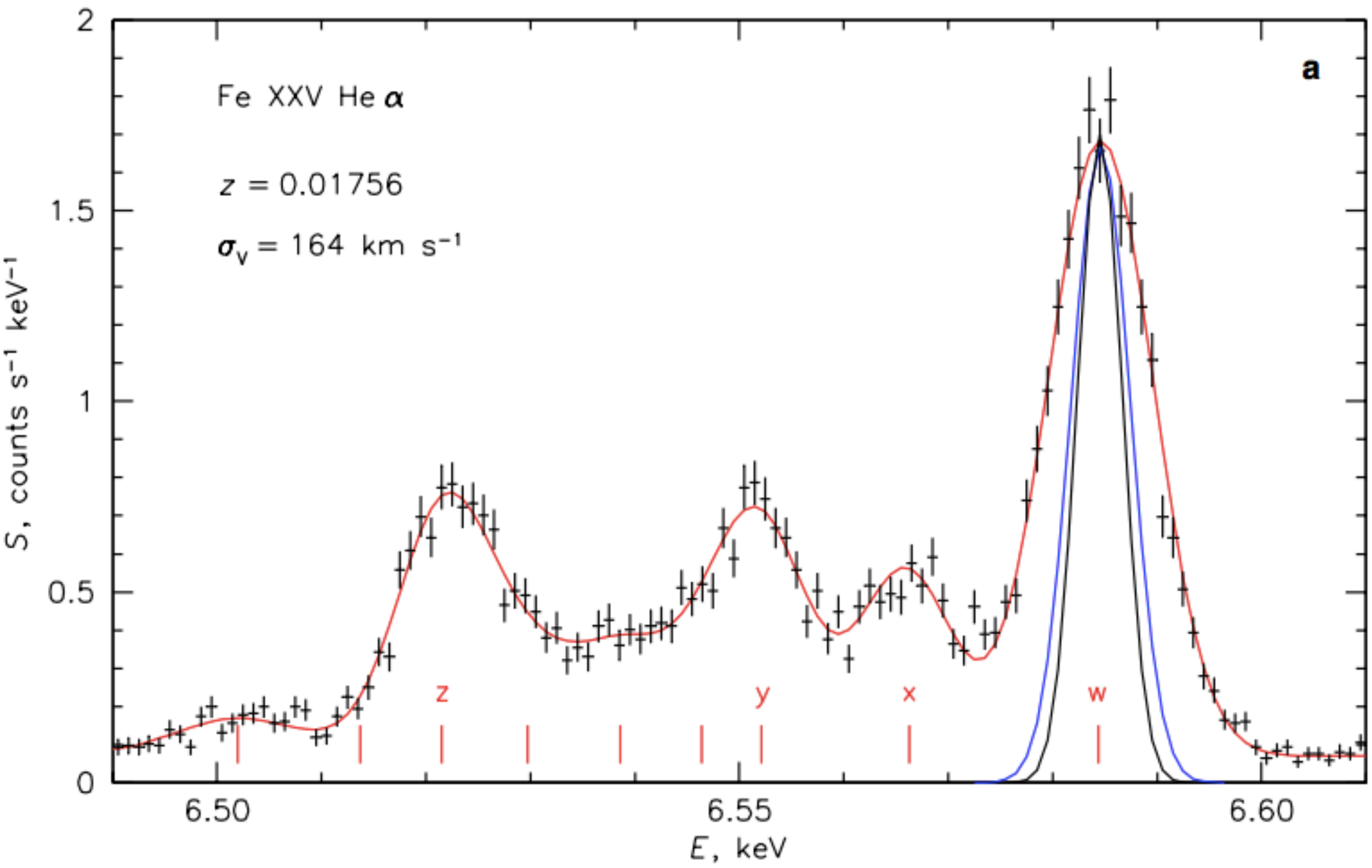
X-ray images show evidence for energy input from the AGN but we have no direct measurements of velocities and turbulence in the plasma to understand this in detail.

A major goal of Hitomi was to make such measurements, which require a calorimeter. The initial results were published in Takahashi et al., 2016, Nature 535, 117.

Takahashi et al.



Calorimeter spectrum of Perseus cluster core (in black) compared to Suzaku CCD spectrum of same region (in red).



Inner blue line includes instrumental resolution and natural line width, outer blue line also includes thermal broadening for a 5 keV plasma, red line also includes 164 km/s velocity broadening.

If the observed velocity dispersion is interpreted as turbulence on scales of the bubbles seen in Chandra images then turbulent dissipation of energy would be enough to offset radiative cooling.

However turbulent pressure is only 4% of thermal and such low velocity turbulence cannot spread energy far so an additional mechanism is required to distribute energy outside the region with bubbles.

The low level of turbulence and bulk motion in an active region with an AGN suggests that in these circumstances turbulence is difficult to generate and/or easy to damp.

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. If we can’t understand this process in nearby clusters how can we hope to understand it at high redshift ?

Cosmological simulations have an “overcooling” problem with galaxies and clusters ending up too cool. Current attempts to solve this involve energy input from AGN or SN. To know whether these are realistic we need to understand the amount and mechanism of the energy input.

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 ?

Why do we care ?

With the exception of some with low Z, all elements are made by nucleosynthesis in stars. This happens throughout the life of the star but most spectacularly in supernovae.

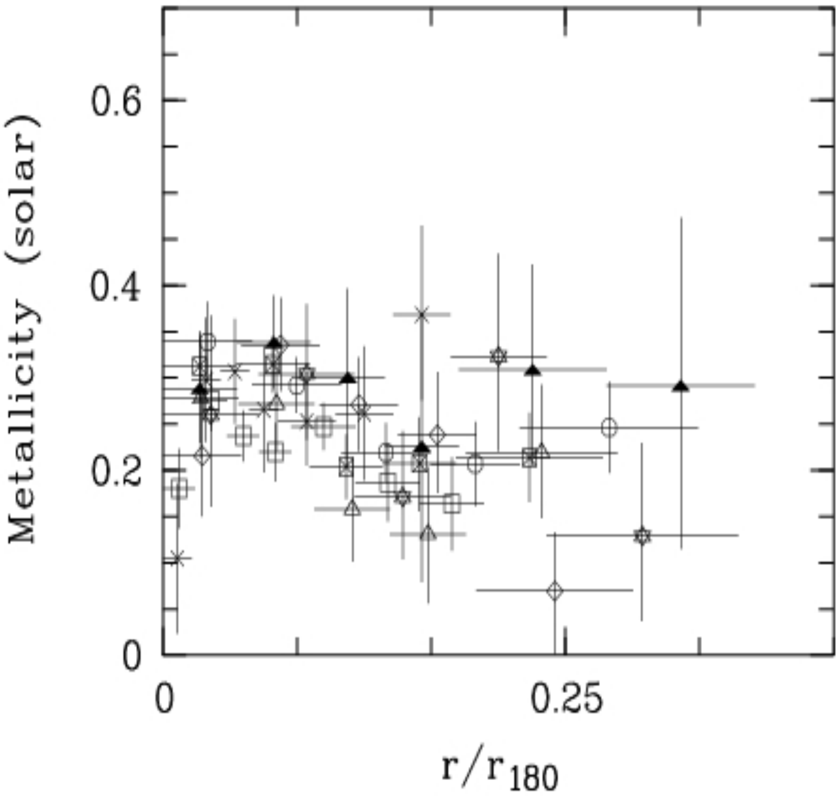
The “metals” in the cluster plasma are produced in stars in the cluster galaxies and are then expelled into the plasma.

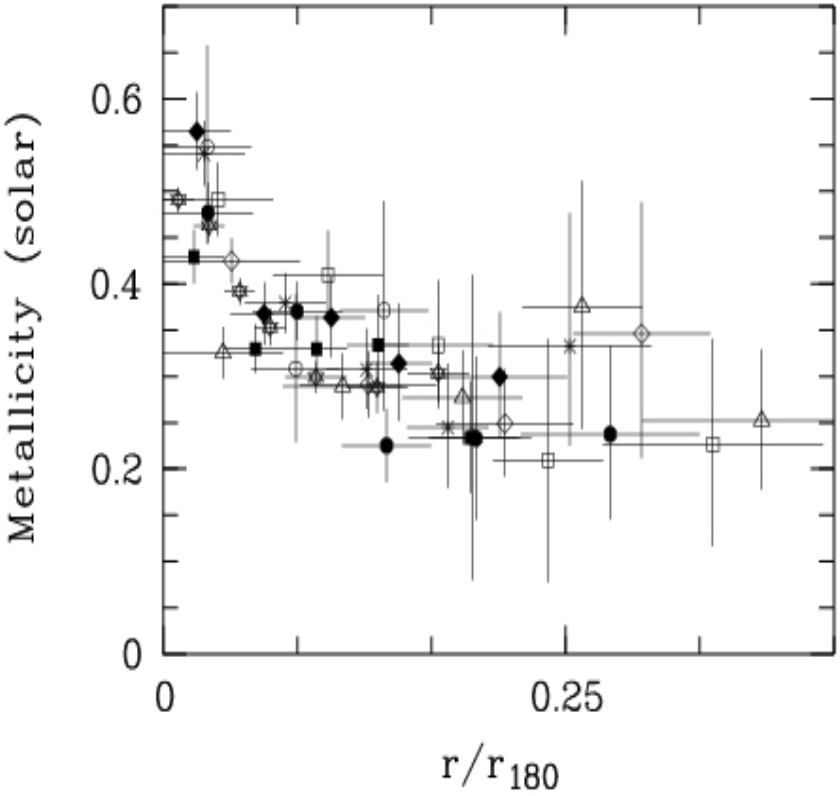
Clusters are “closed boxes” that store all the metals produce in their galaxies so provide an integrated measurement of star formation. It is easier to measure abundances of some elements in clusters than in Galactic SNR because the ICM is in collisional equilibrium.

Core collapse supernovae (SNII) occur relatively soon after star formation early in the life of the cluster. The elements from these supernovae will be expelled into the ICM by winds or stripping. We expect to see these elements throughout the cluster.

SNIa are the products of white dwarf stars and occur a billion years after star formation. The elements from these supernovae will be expelled into the ICM from galaxies in the dense core of the cluster. We expect to see these elements concentrated toward the core.

Iron abundance (mainly from SNIa) vs. radius



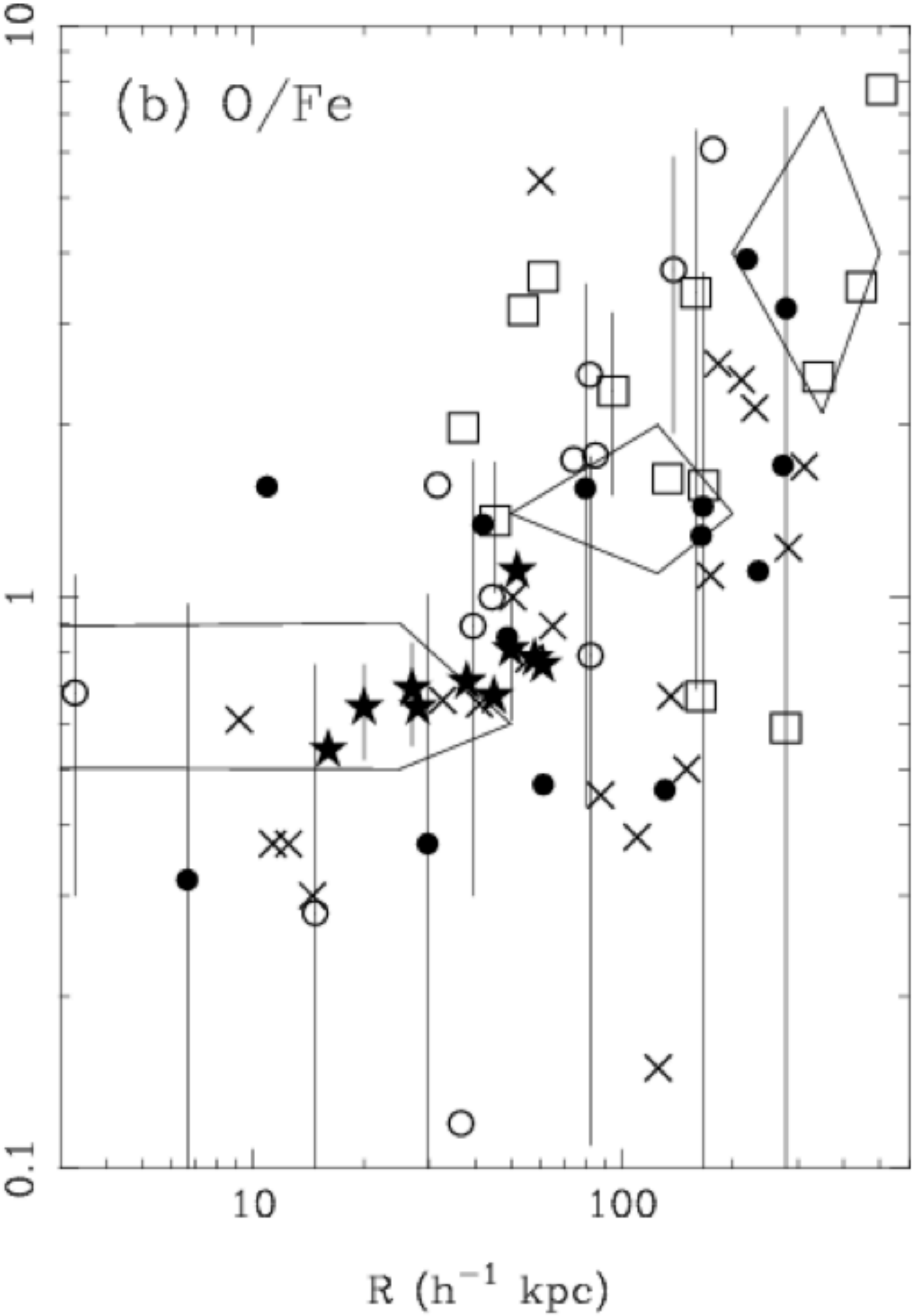


Non “cool core”
(recent merger)

“cool core”

Beppo-SAX observations

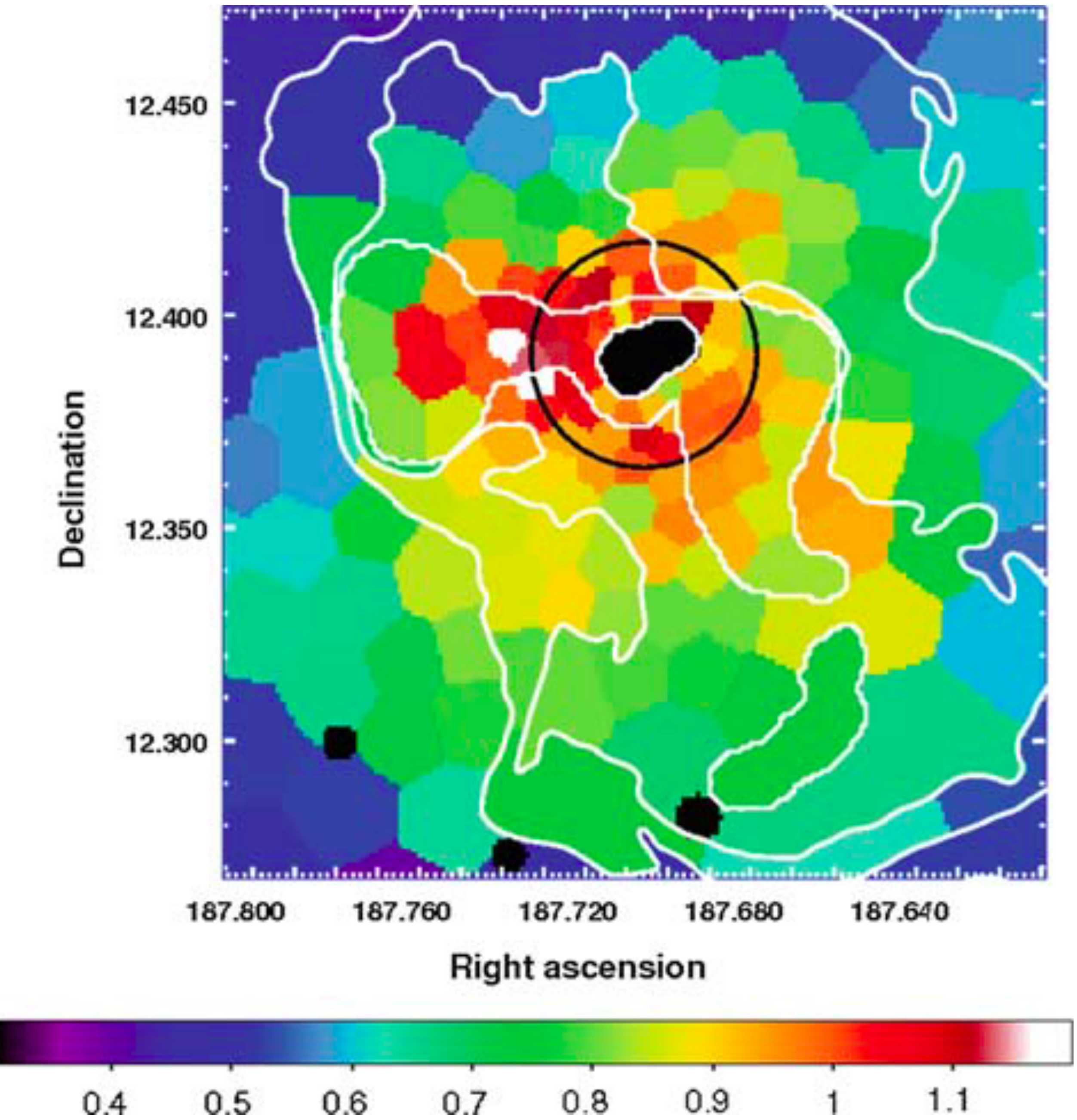
De Grandi & Molendi 2001



Oxygen relative to Iron

Most oxygen is produced in SNII.

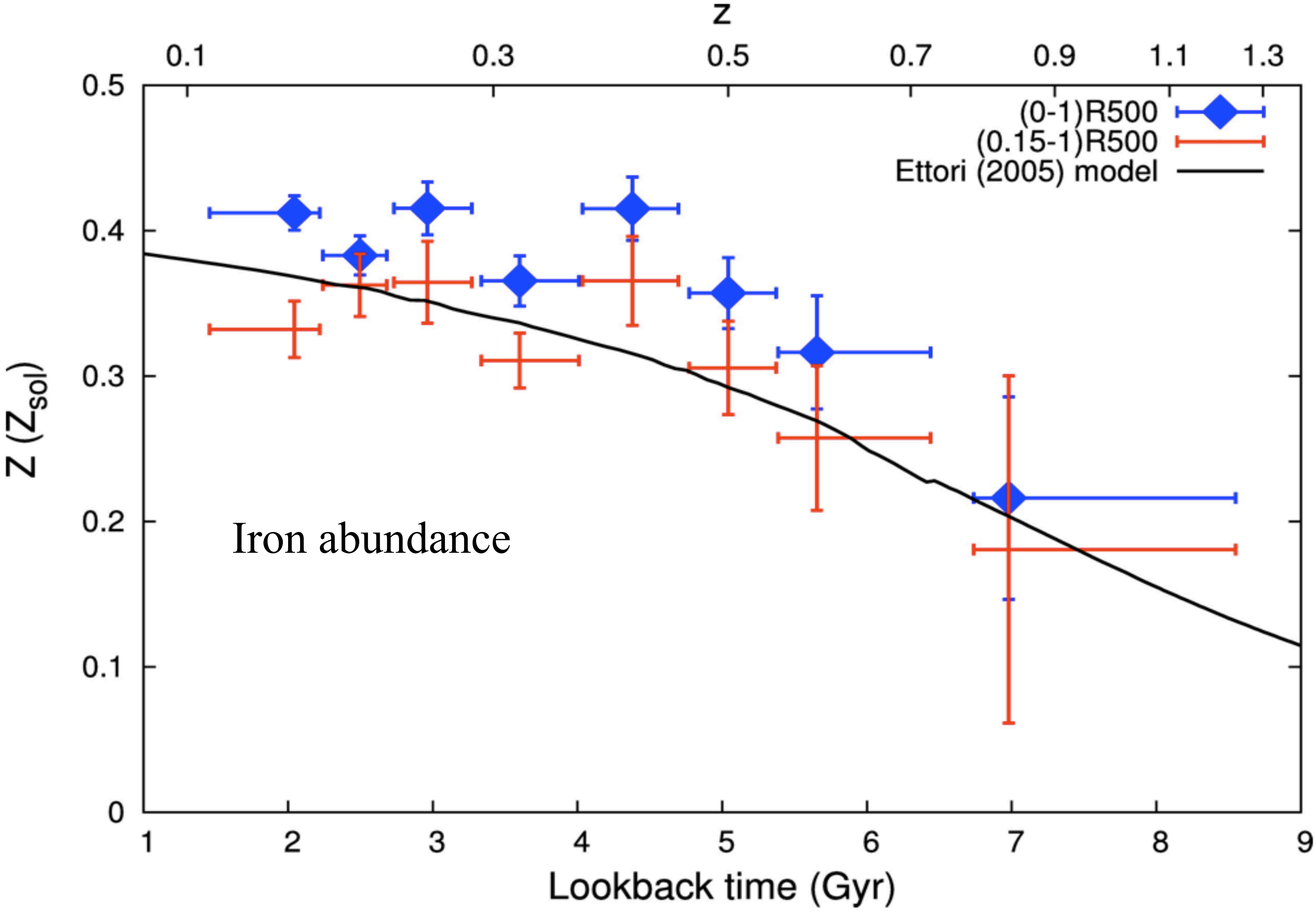
Tamura et al., 2004



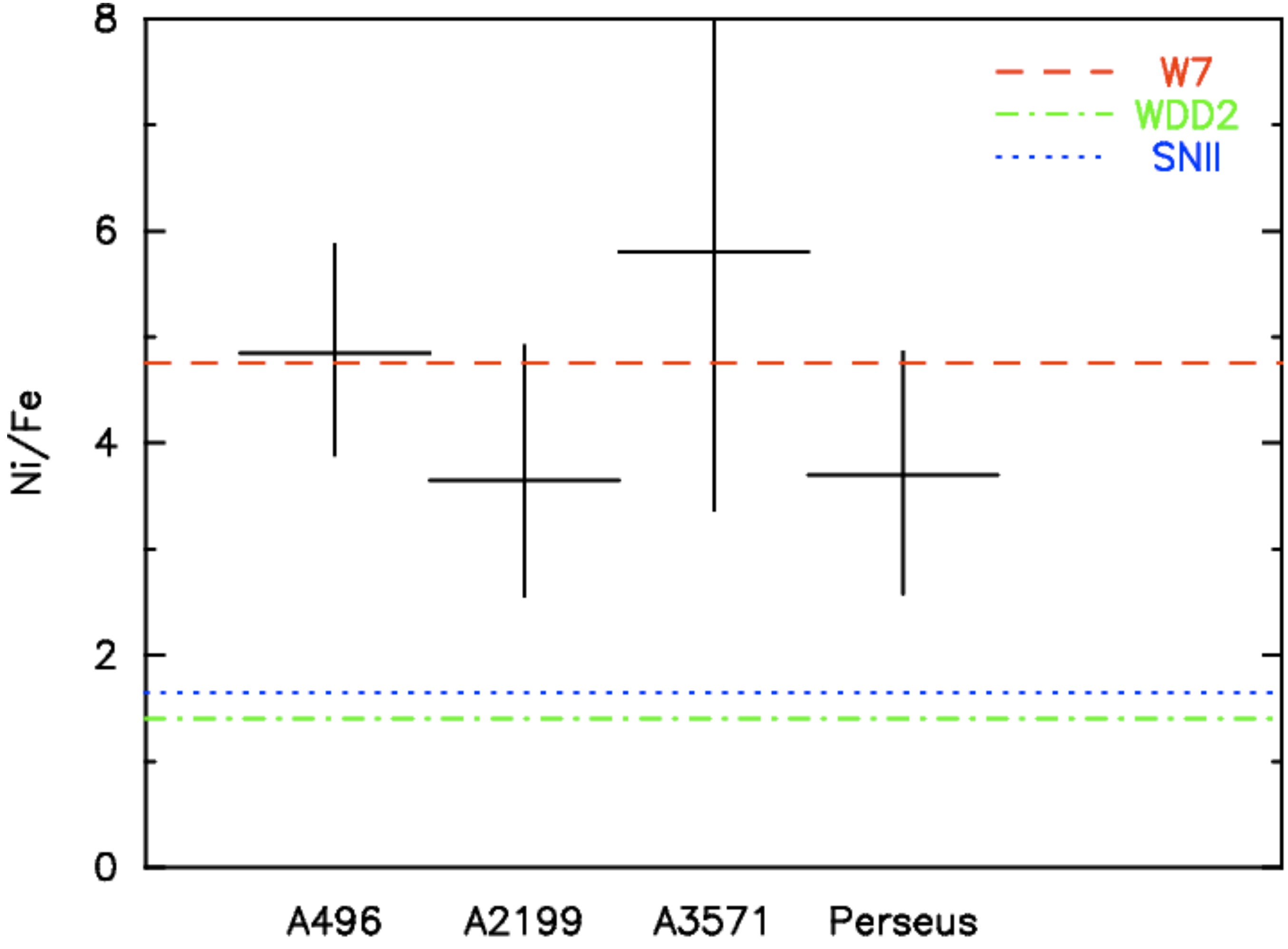
Map of iron abundance in M87

Contours are 90cm radio

Simionescu et al., 2008

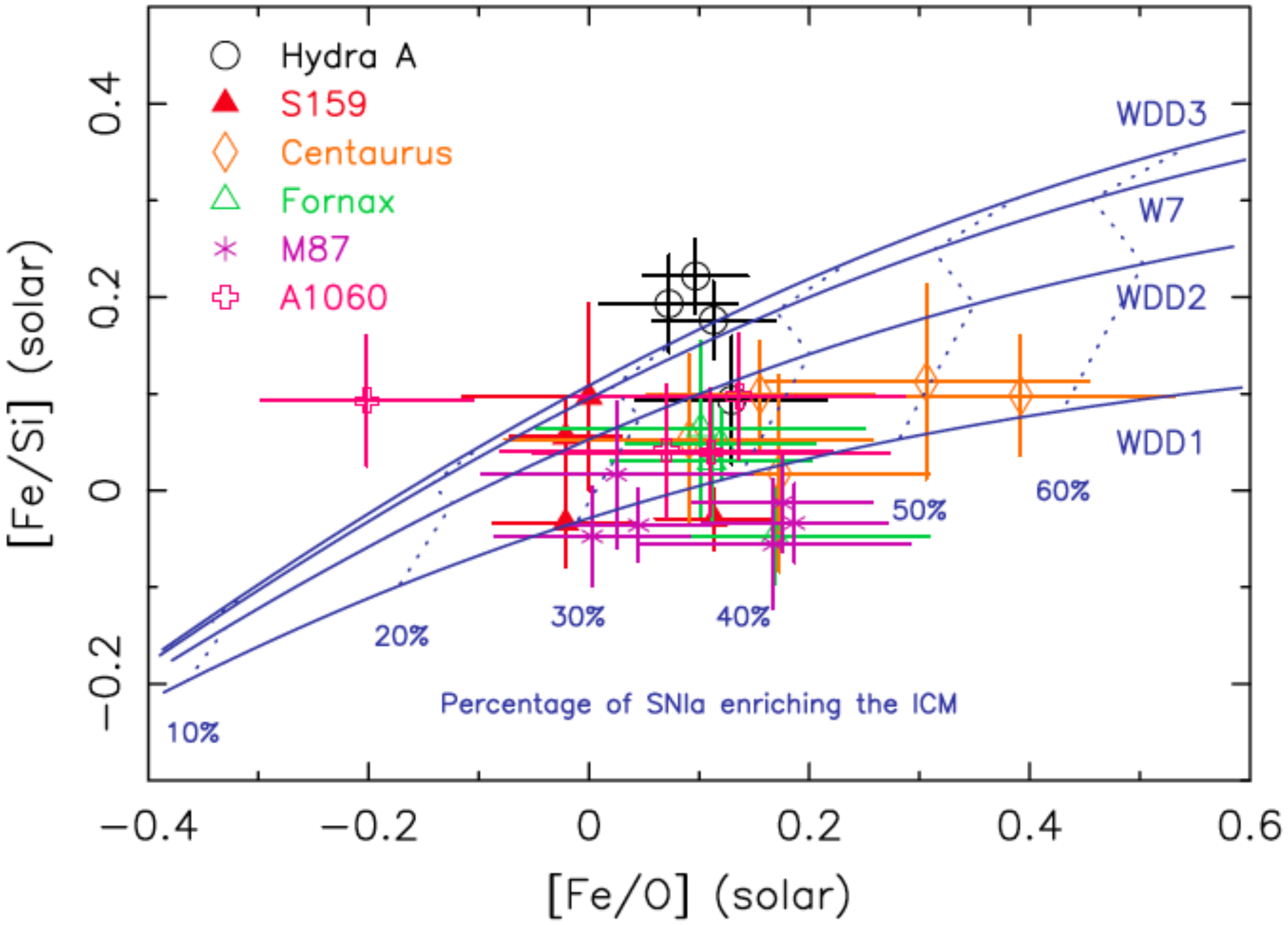


Maughan et al. 2008



W7 is sub-sonic nuclear burning front
WDD2 is super-sonic

Dupke & Arnaud 2001

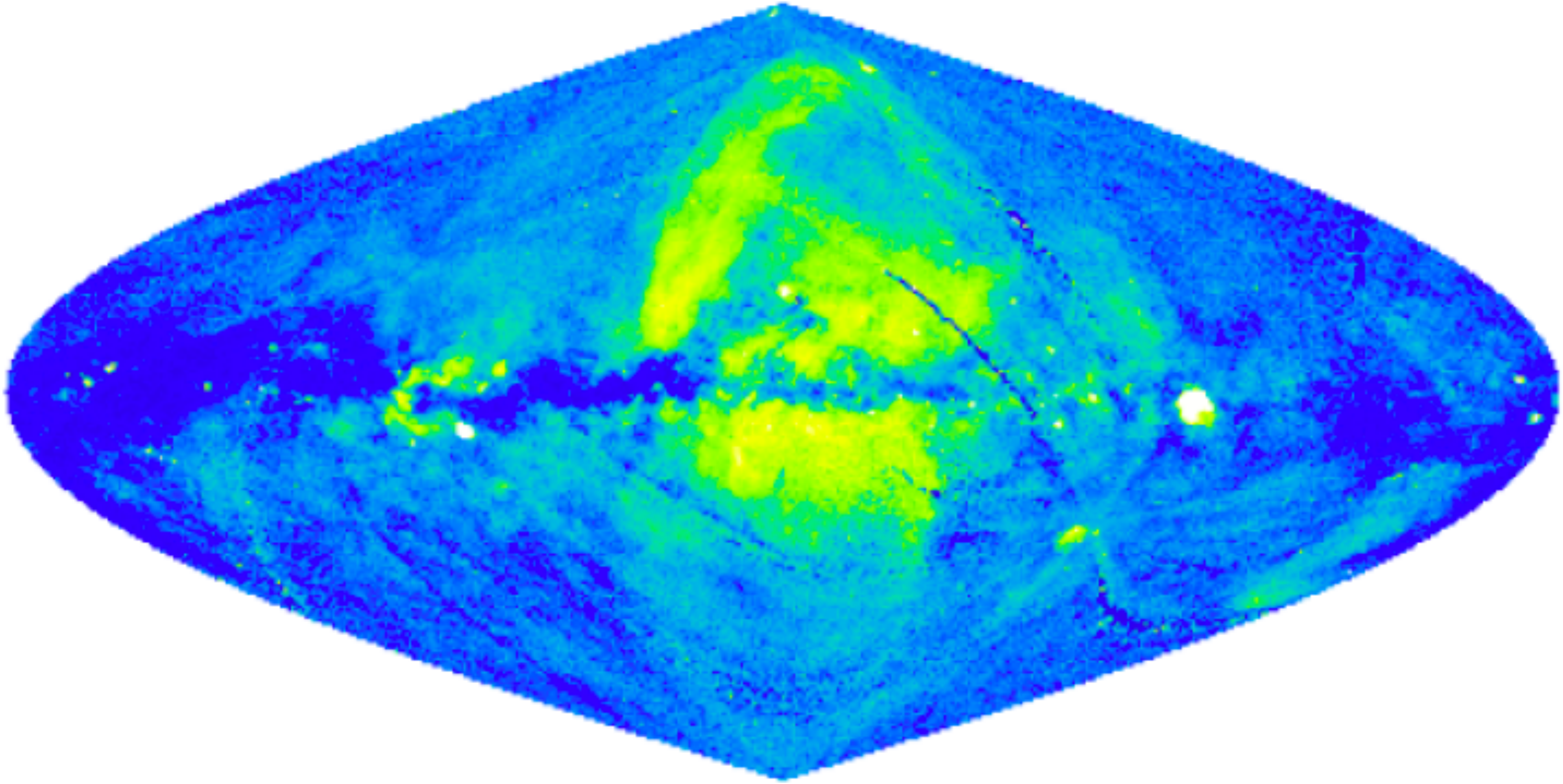


Bohringer & Werner 2010

Some Data Analysis Issues

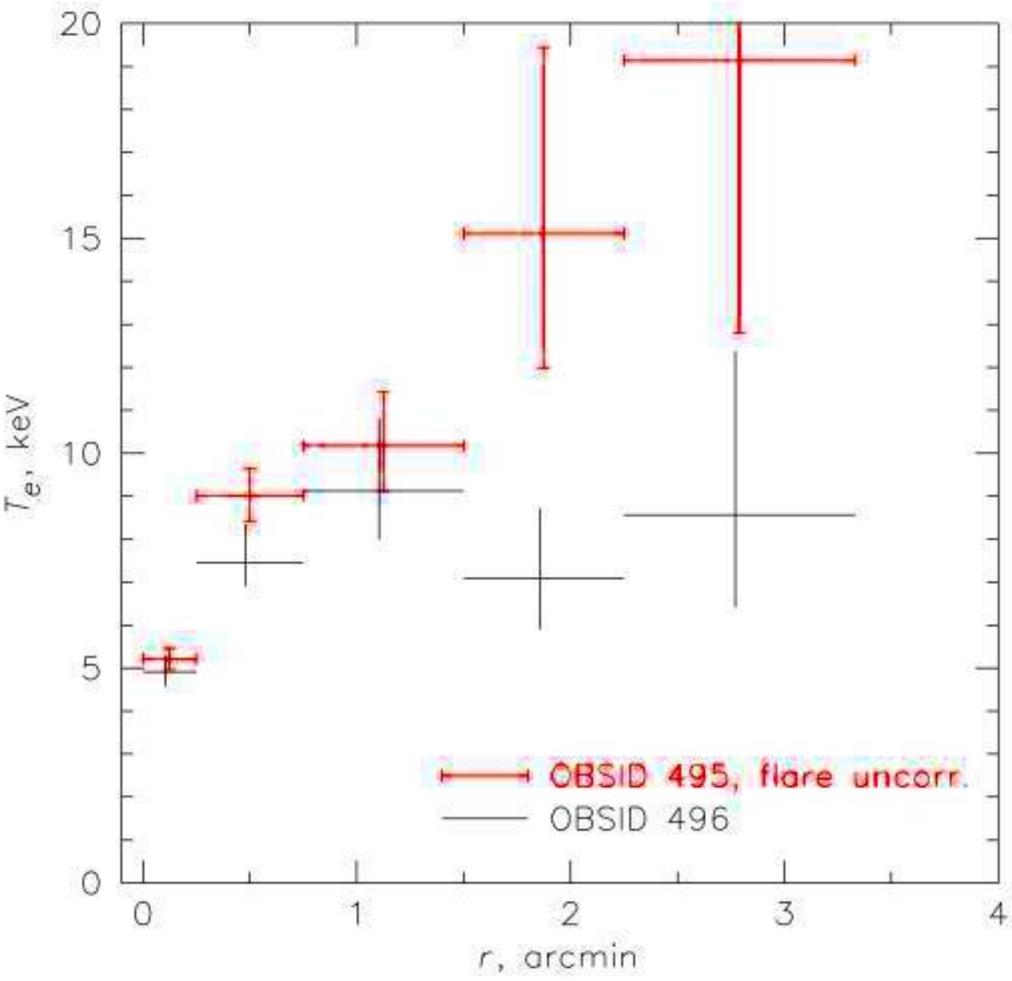
- Background subtraction
- Corrections for PSF scattering
- 2D -> 3D
- Grating observations

- 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)

The background varies with time - big flares are easy to see and exclude but smaller flares are a problem.



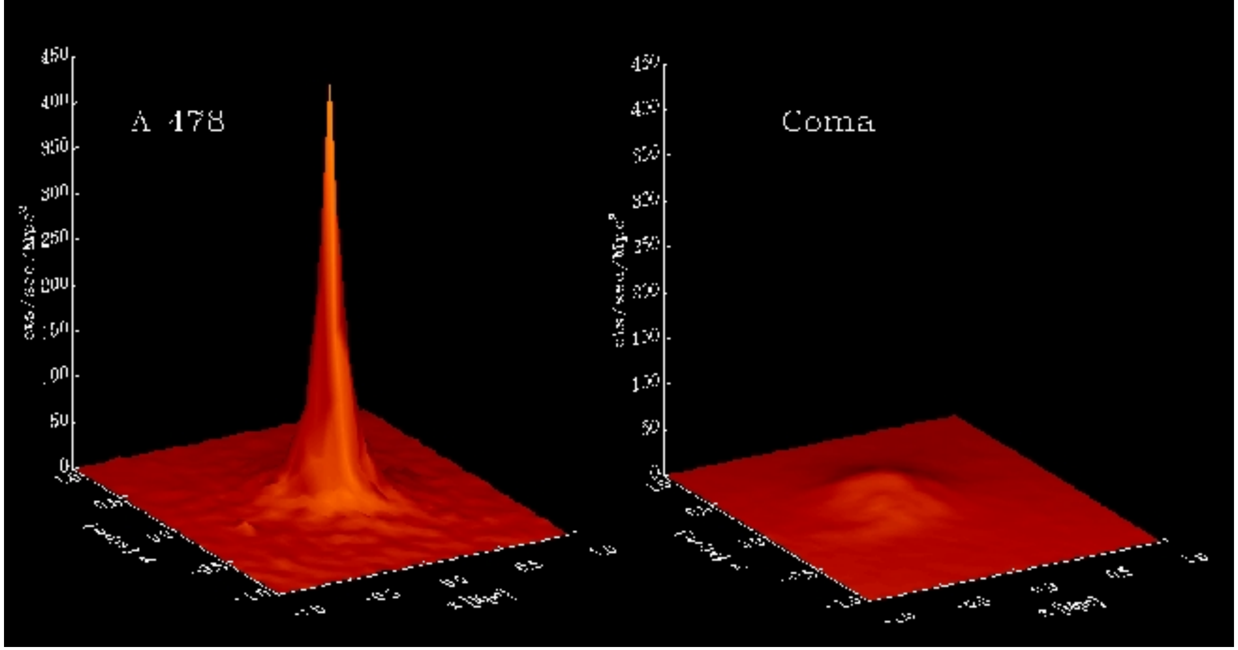
Abell 1835

Markevitch

Comparison of two Chandra analyses

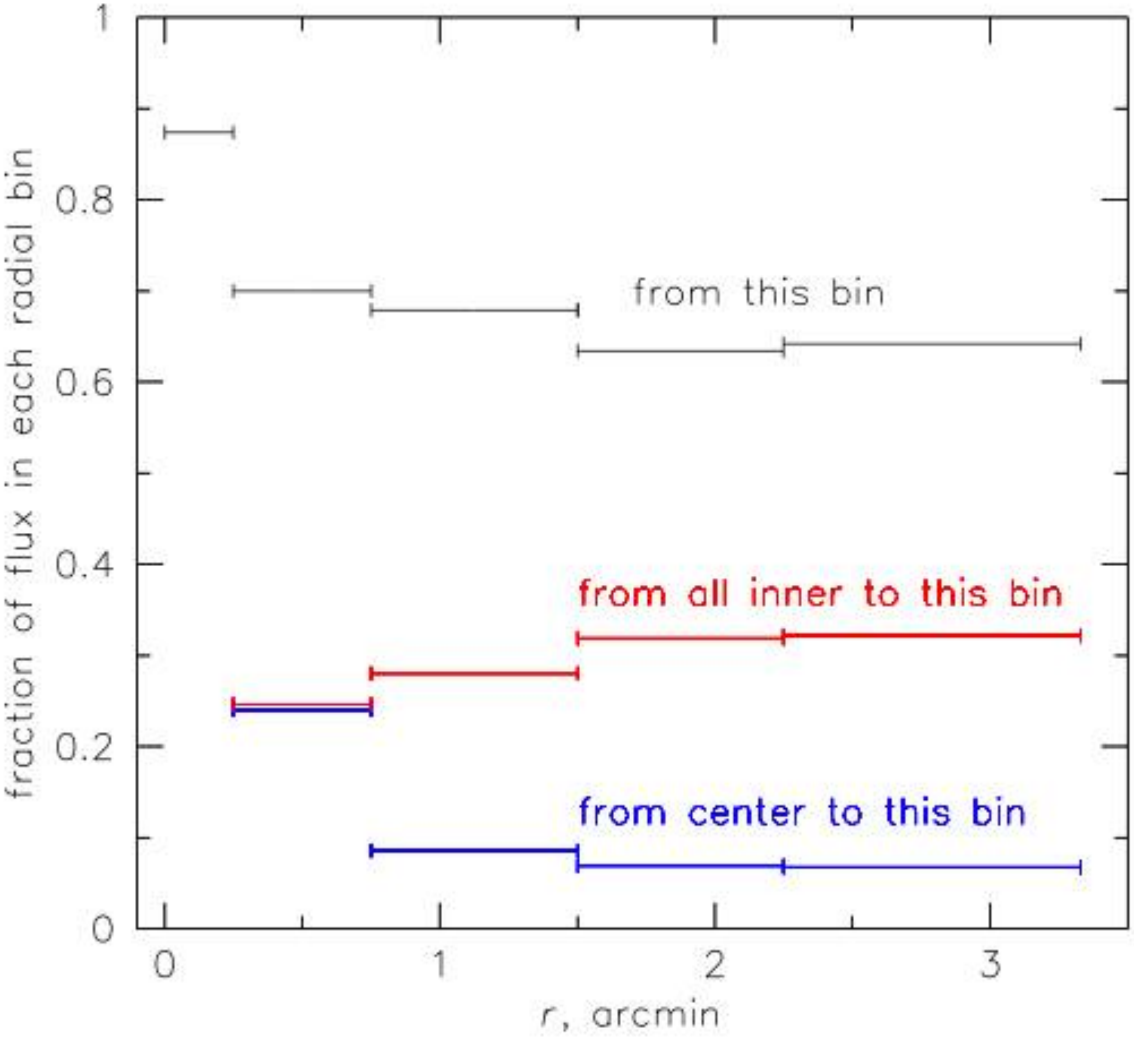
Snowden et al. 2008 (A&A 478, 615) includes a very complete discussion of performing background subtraction for XMM-Newton observations of large, extended sources.

I don’t know of such a comprehensive discussion for Chandra but see papers by Markevitch.



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, BeppoSAX or Suzaku 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 SAS features.I

Markevitch

- 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. The ftool rgsrmfsmooth or the XSPEC model rgsxsrc can be used to correct the RMF in this case.

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