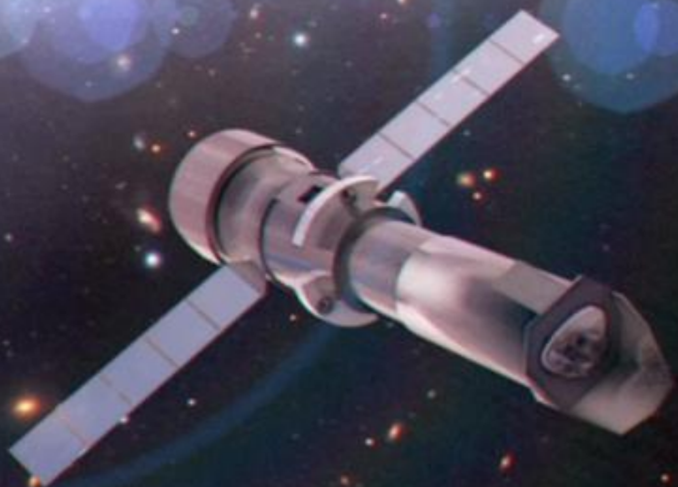
ATHENA

Studying AGN feedback in galaxy clusters and groups with *Athena*



Jeremy Sanders

Max Planck Institute for Extraterrestrial Physics

On behalf of the Athena topical panel for AGN feedback in clusters and groups
(co-chaired by J. Croston, B. McNamara and J. Sanders)

Acknowledgements

- This talk is based on the Athena supporting paper *AGN Feedback in Galaxy Clusters and Groups*, arXiv:1306.2323

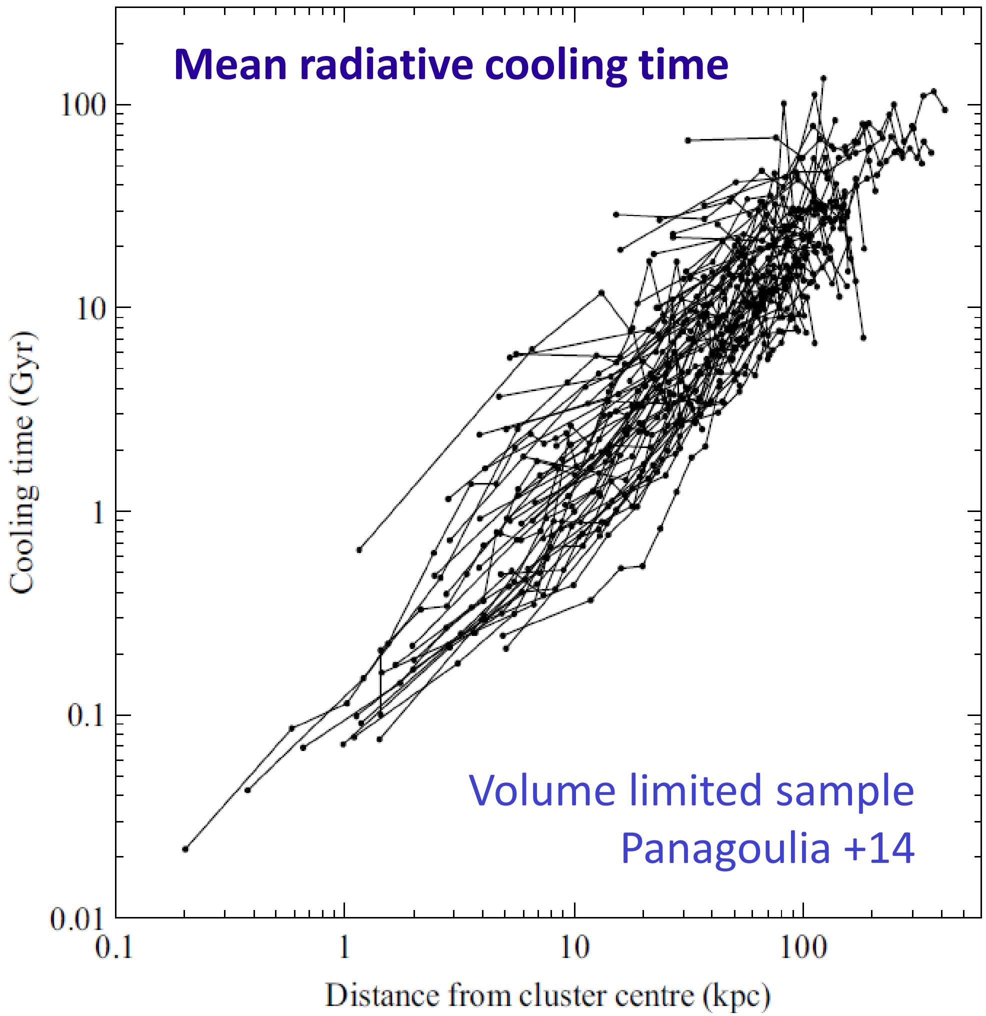
  J.H. Croston, **J.S. Sanders**, S. Heinz, M.J. Hardcastle, I. Zhuravleva, L. Bîrzan, R.G. Bower, M. Brüggen, E. Churazov, A.C. Edge, S. Ettori, A.C. Fabian, A. Finoguenov, J. Kaastra, M. Gaspari, M. Gitti, P.E.J. Nulsen, B.R. McNamara, E. Pointecouteau, T.J. Ponman, G.W. Pratt, D.A. Rafferty, T.H. Reiprich, D. Sijacki, D.M. Worrall, R.P. Kraft, I. McCarthy, M. Wise

Many clusters, groups and elliptical galaxies have steeply-peaked X-ray surface brightness profiles

(X-ray brightness $\propto$ density-squared integrated along LoS)

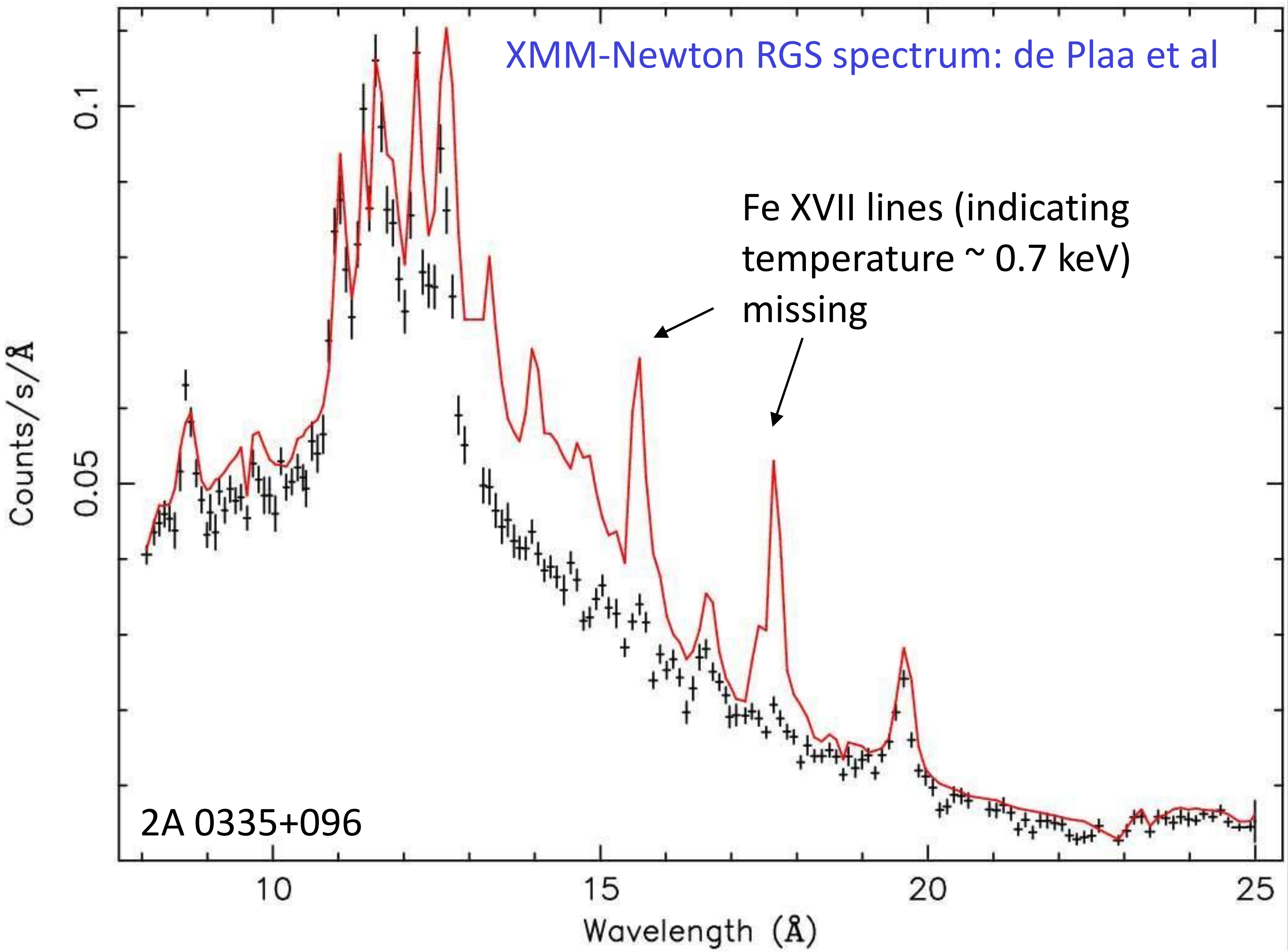
Abell 1835 observed by Chandra

Cooling times in cluster cores



- Mean radiative cooling times in centre of many cluster and group cores < 10^9 yr
- Rapid cooling of 10s-1000s $M_\odot$ yr^{-1} if the X-ray luminosity is not replaced (i.e. cooling flow; Fabian 1994)

Lack of cool X-ray emitting gas



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

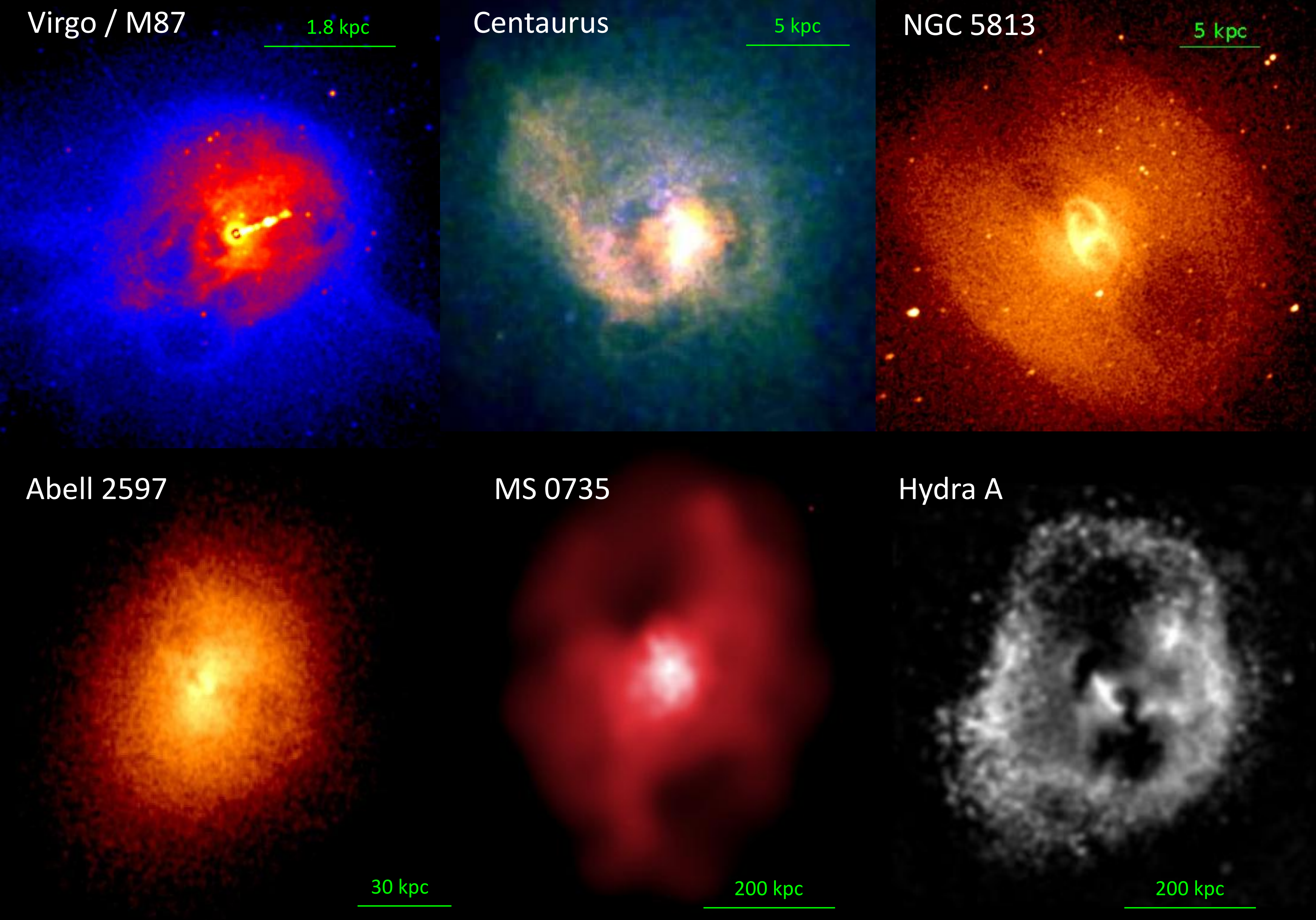
Image courtesy of Jelle de Plaa, SRON, NL.

European Space Agency

Spectra imply less than 10% of cooling rates expected from luminosity profiles

Typically only significant gas down to 1/2 to 1/3 of outer temperature

see also Peterson+01, 03, Kaastra +01, 03, Tamura+01, Sanders+08, 10…

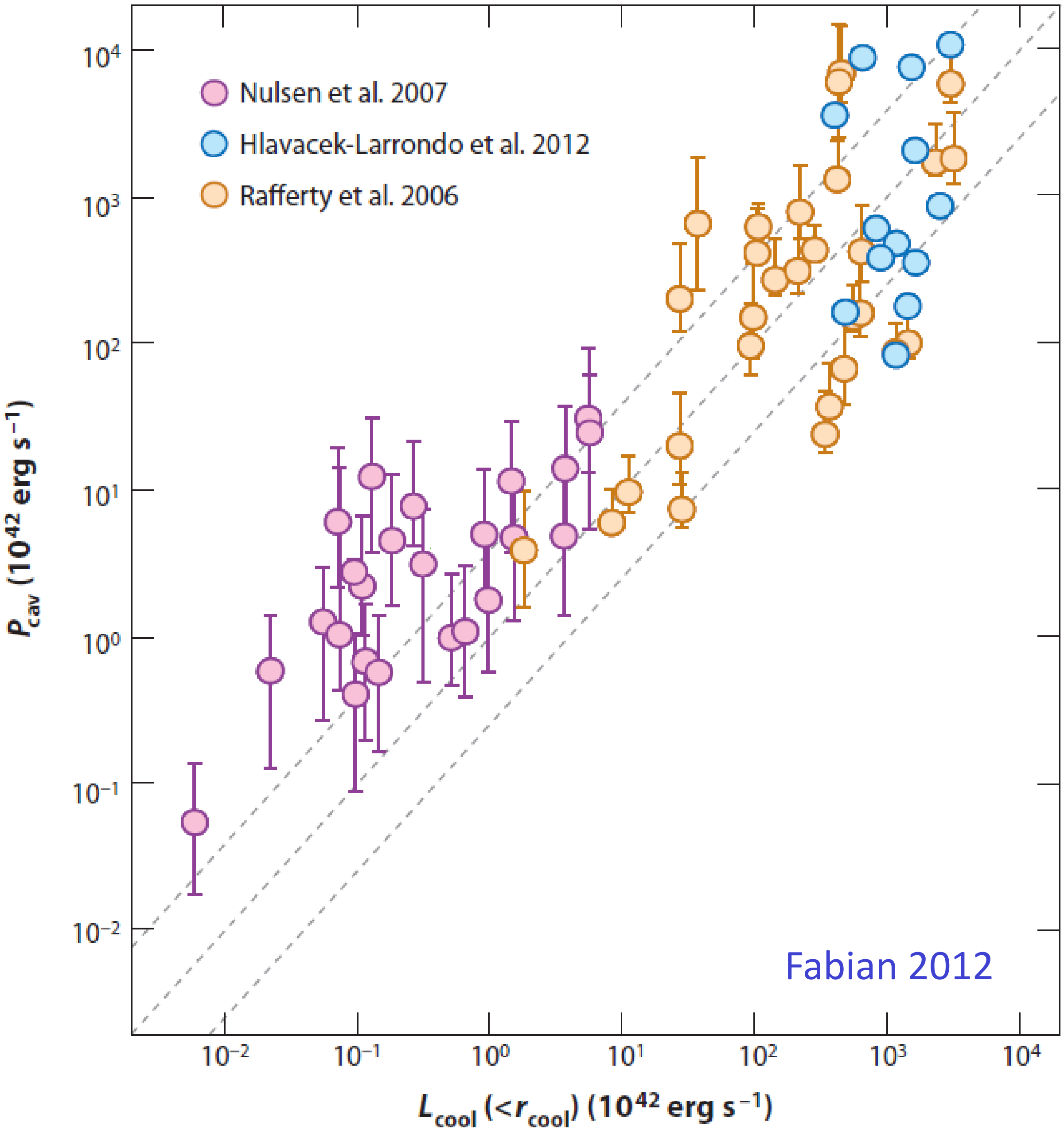


Cavities seen in cluster X-ray images, filled with radio emission and inflated by AGN jets

What impact do these cavities have?

- Energy required to make a cavity is its enthalpy
  - Thermal energy + energy to inflate cavity
  - 4PV for relativistic gas
- Buoyancy causes cavity to rise
- Energy is converted into heat on a similar size to the cavity, via viscosity or turbulence (e.g. Nulsen+07)
- Plausible timescales for work done on surroundings are similar
  - Sound crossing time
  - Buoyancy rise time
  - Refill time

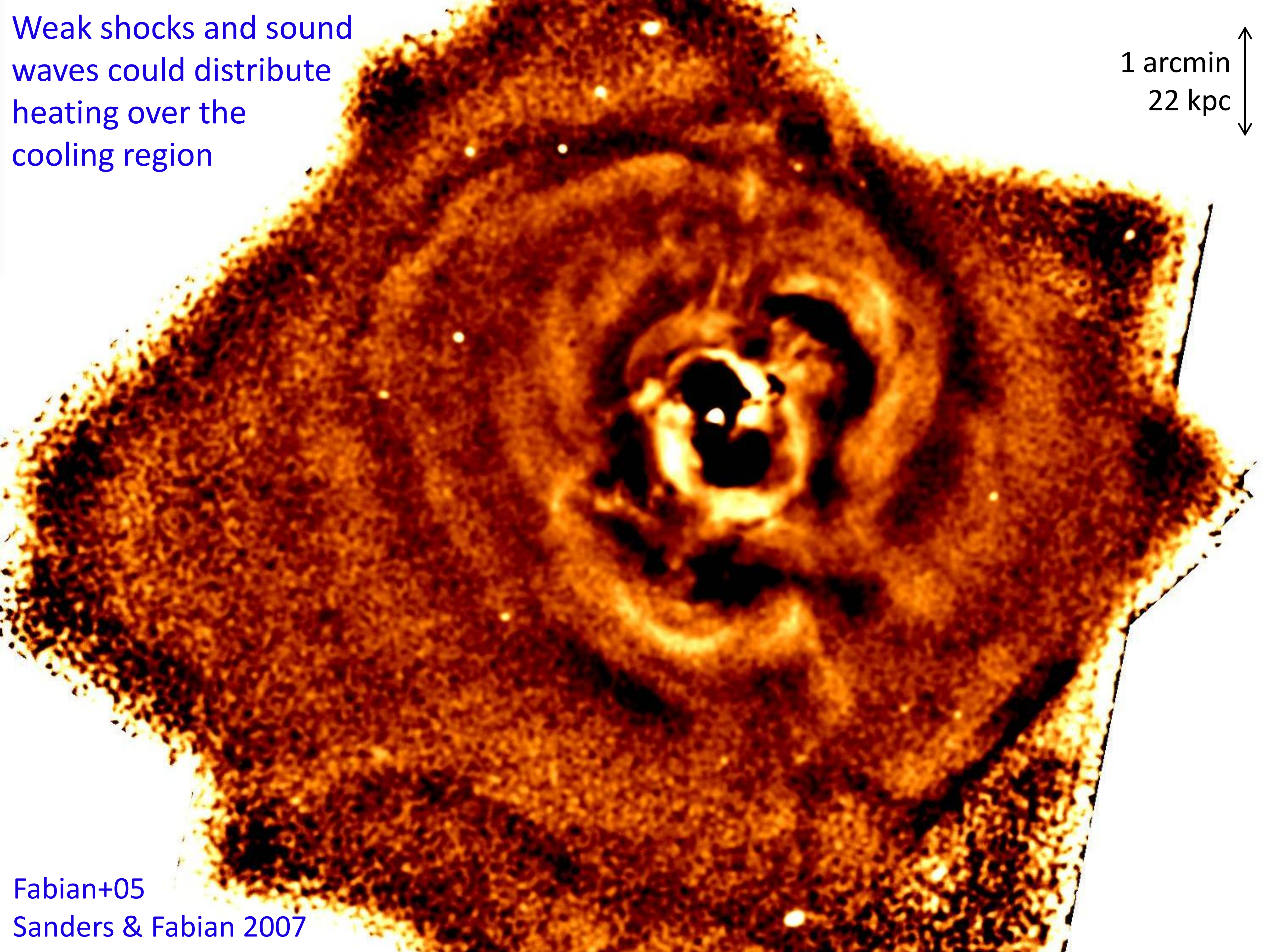
Heating power vs cooling luminosity



Comparison of bubble heating power to X-ray luminosity

Energetically, AGN can prevent cooling in the majority of objects over a wide range in X-ray luminosity

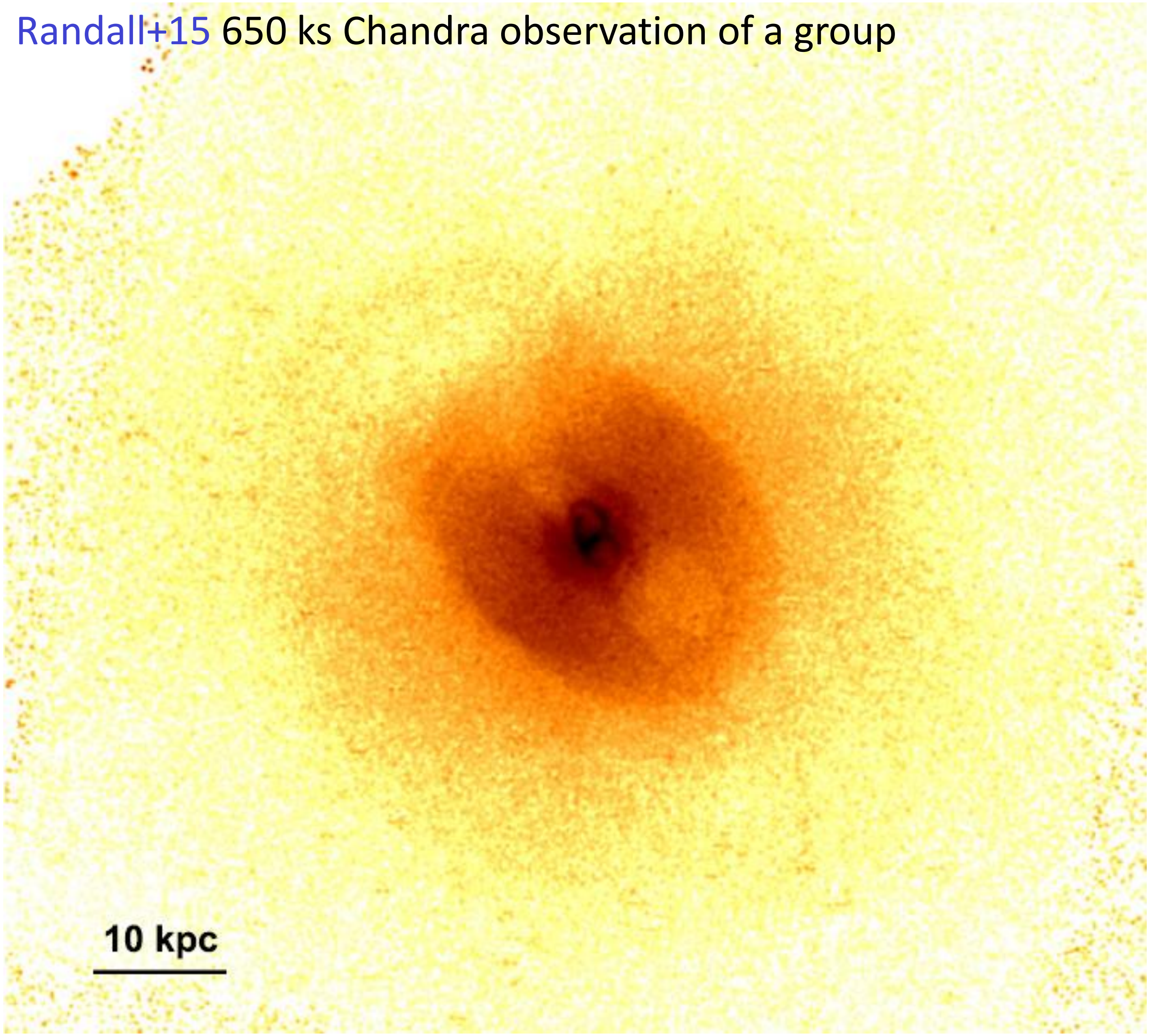
Weak shocks and sound waves could distribute heating over the cooling region



Fabian+05
Sanders & Fabian 2007

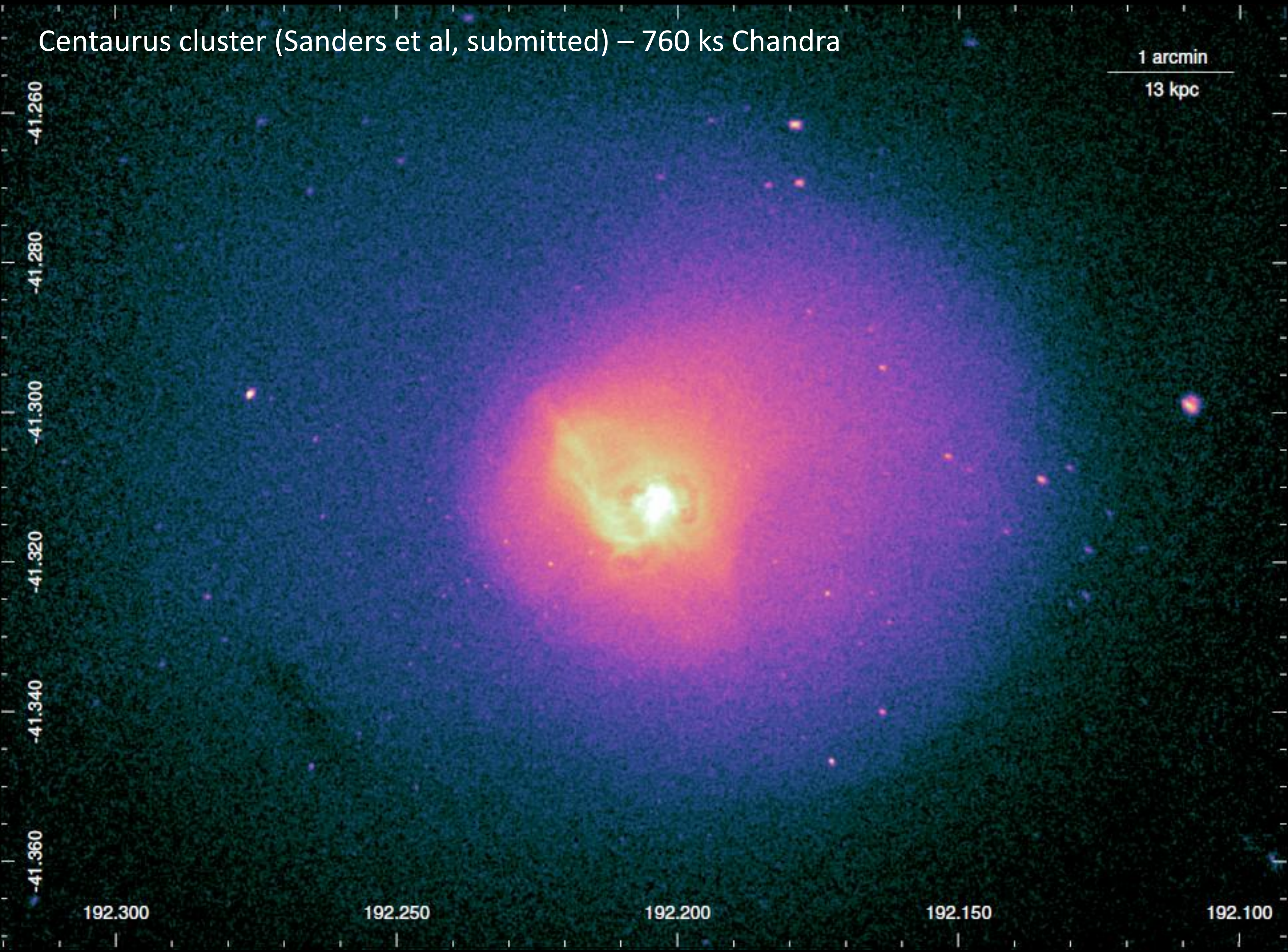
Shock and bubble heating in NGC 5813

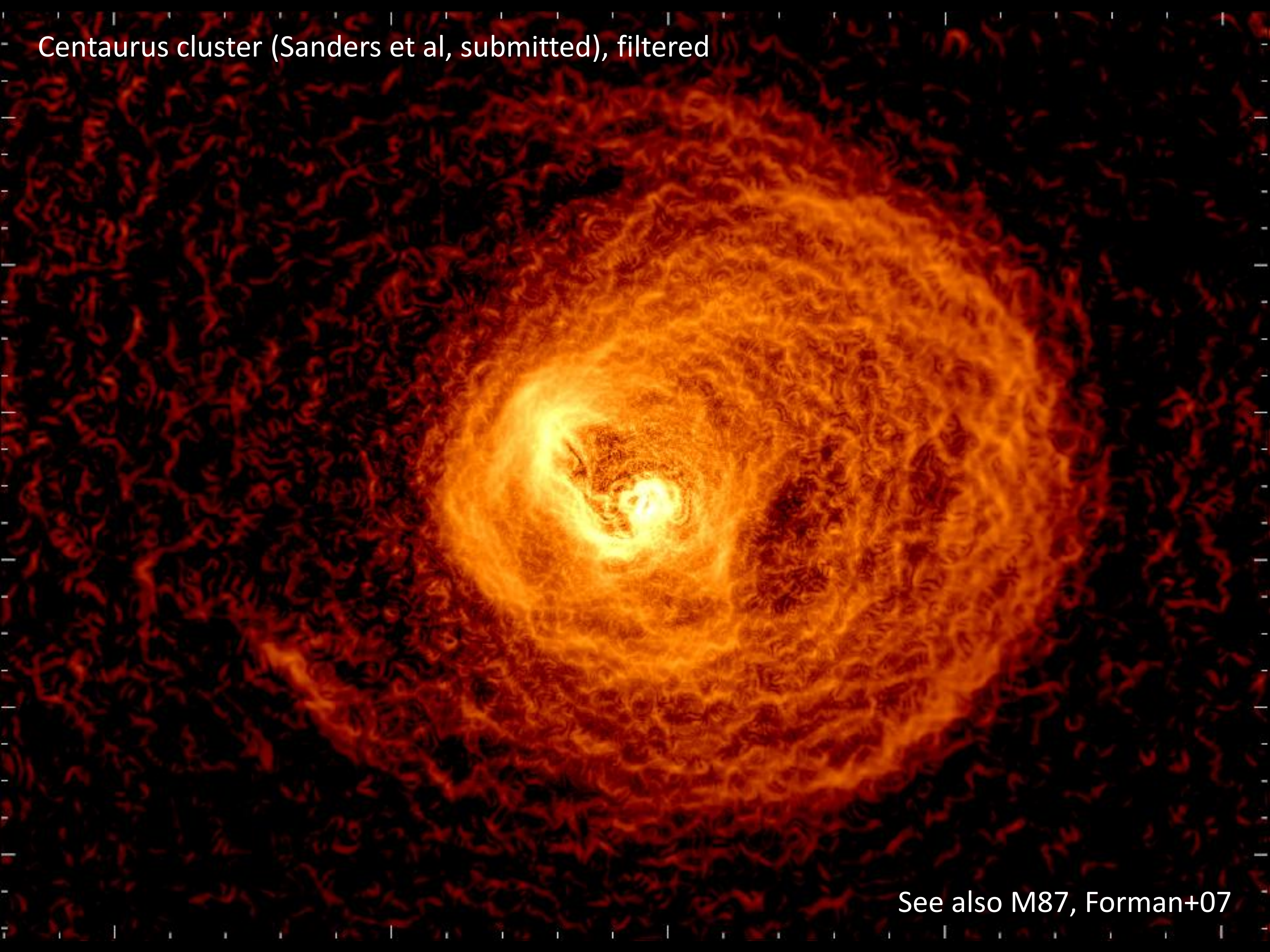
Randall+15 650 ks Chandra observation of a group

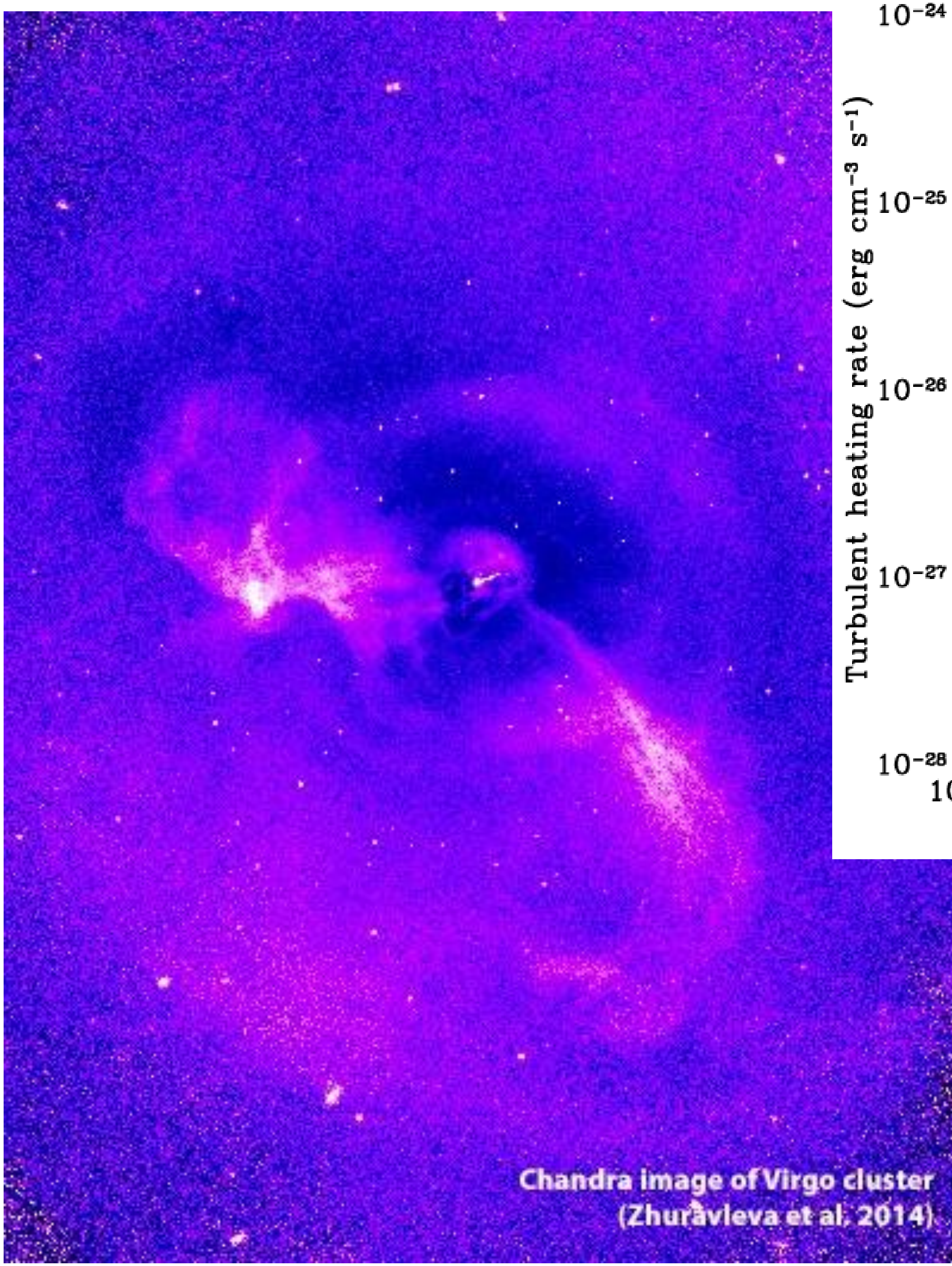


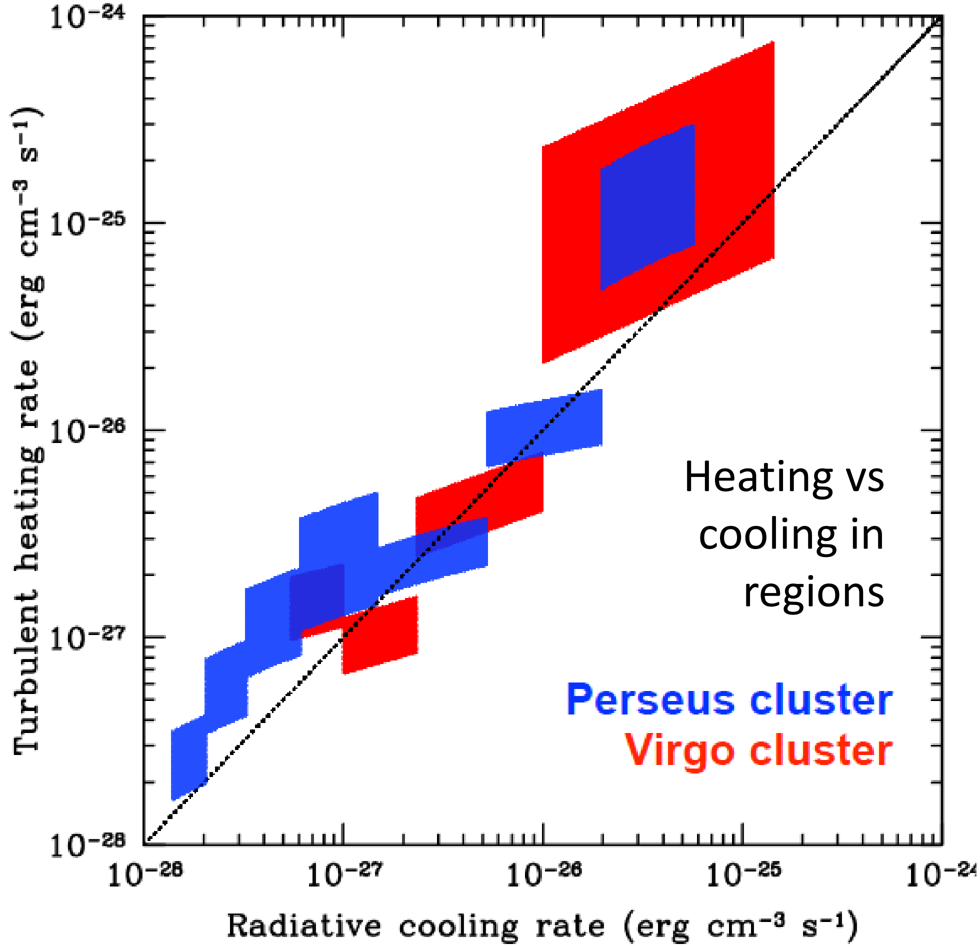
3 sets of cavities and shocks, with ages of 1.7, 15 and 50 Myr. Cooling rates and heating rates balanced at each front.

Centaurus cluster (Sanders et al, submitted) – 760 ks Chandra

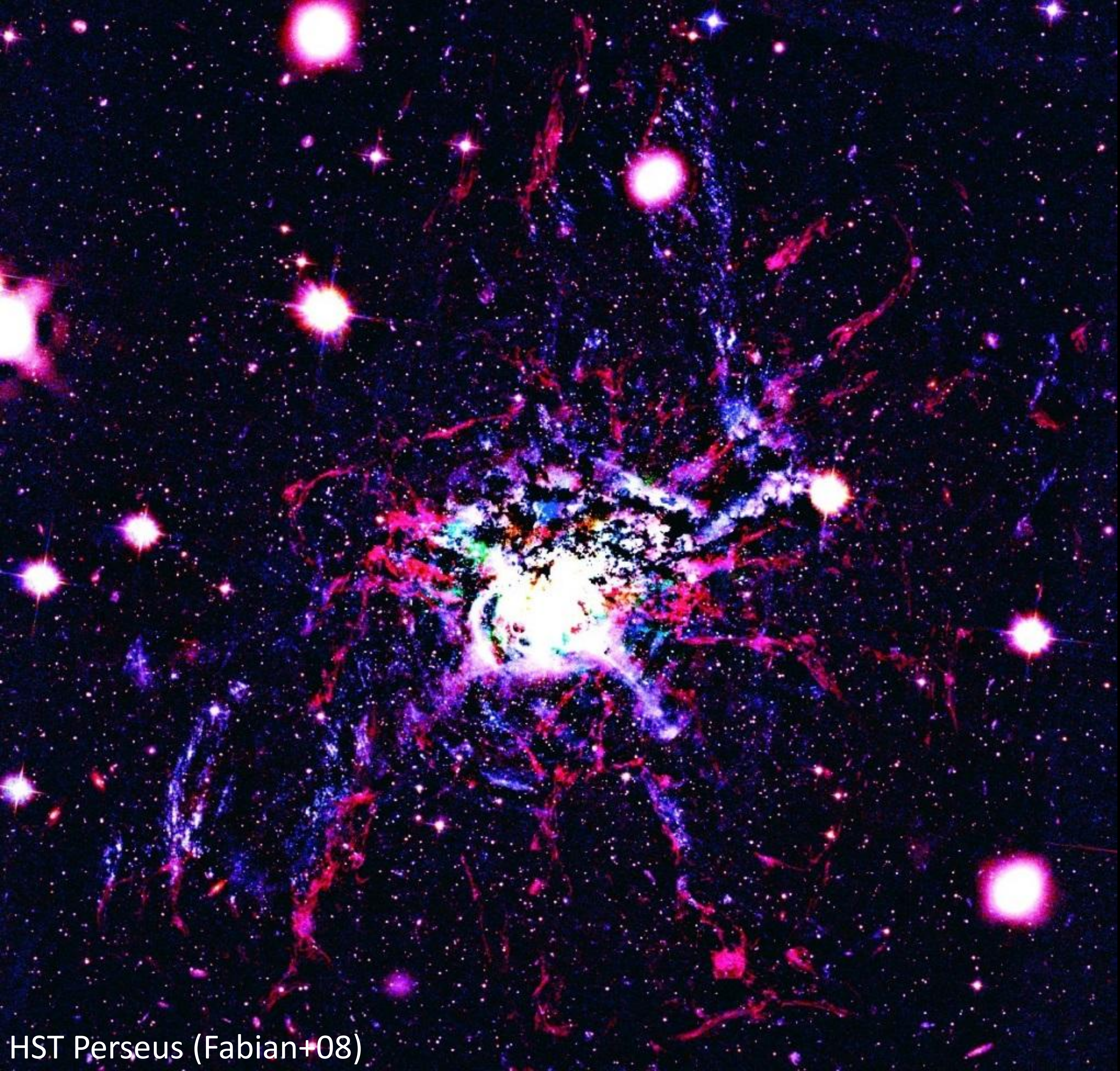



Centaurus cluster (Sanders et al, submitted), filtered
See also M87, Forman+07





Or turbulence, driven by the feedback, could do the heating (Zhuravleva+14)



HST Perseus (Fabian+08)

However, there is significant evidence of residual cooling in many objects:

- Emission line nebulae
- Star formation
- Atomic and molecular gas

Key questions identified for *Athena*

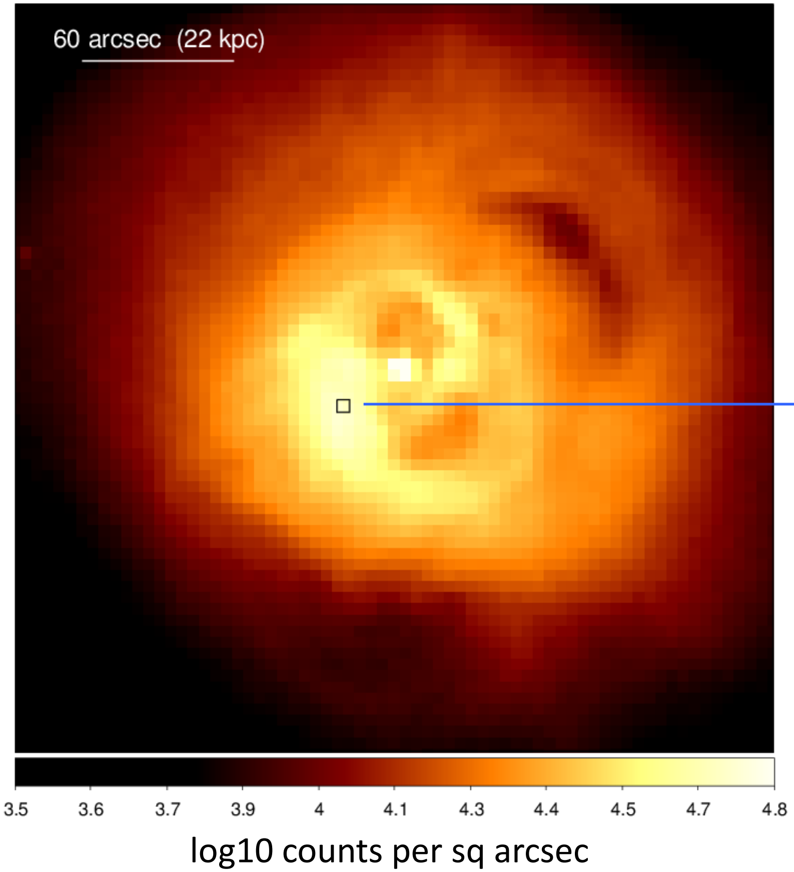
- How is the energy from AGN jets dissipated and distributed through the hot gas atmosphere of a cluster or group?
- How does feedback operate to regulate gas cooling and AGN fuelling?
- What is the cumulative impact of powerful radio galaxies on the evolution of baryons from group/cluster formation to now?

Q: *How is AGN energy dissipated?*

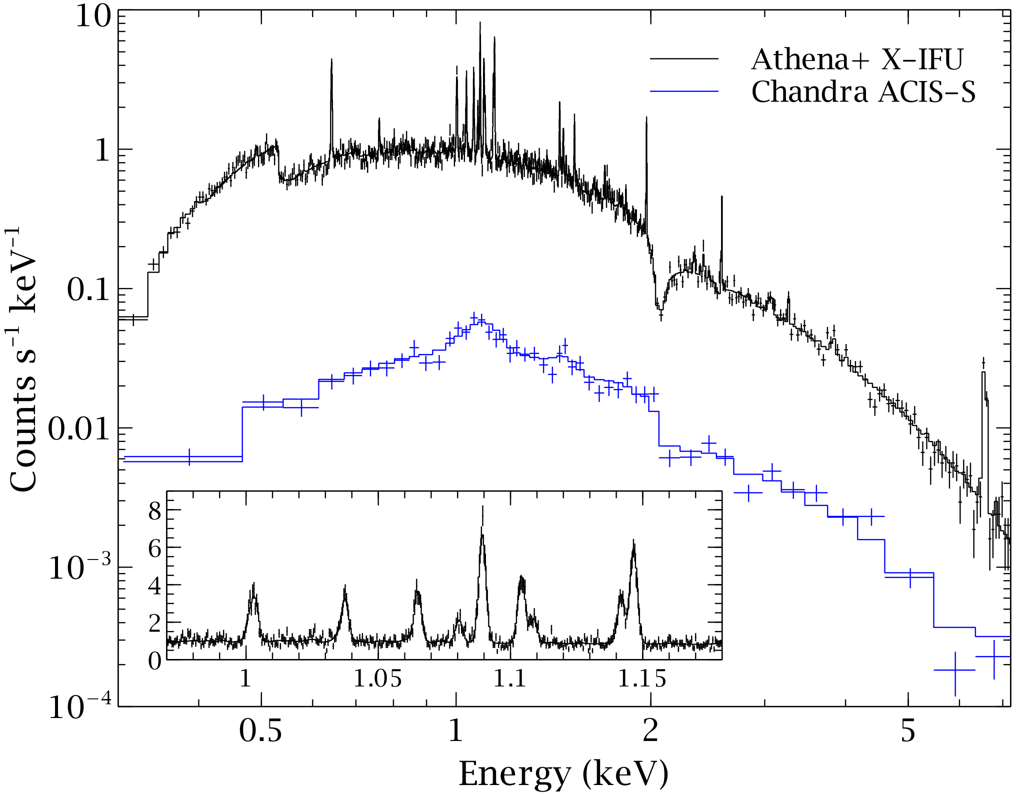
- The heat source in clusters, the AGN, must heat regions around 9 orders of magnitude larger than itself
- How is the energy from the jets and bubbles dissipated and distributed from the cluster?
- *Can only be examined in X-ray waveband*
- Will do spatially-resolved complete calorimetry in *several tens of nearby systems* to understand energy dissipation and heating mechanisms
  - Energy in cavities
  - Energy in motions to 10s km/s
  - Detailed temperature structure
  - Pressure and density fluctuations

Imaging spectroscopy with X-IFU

Perseus simulated X-IFU image (50 ks)

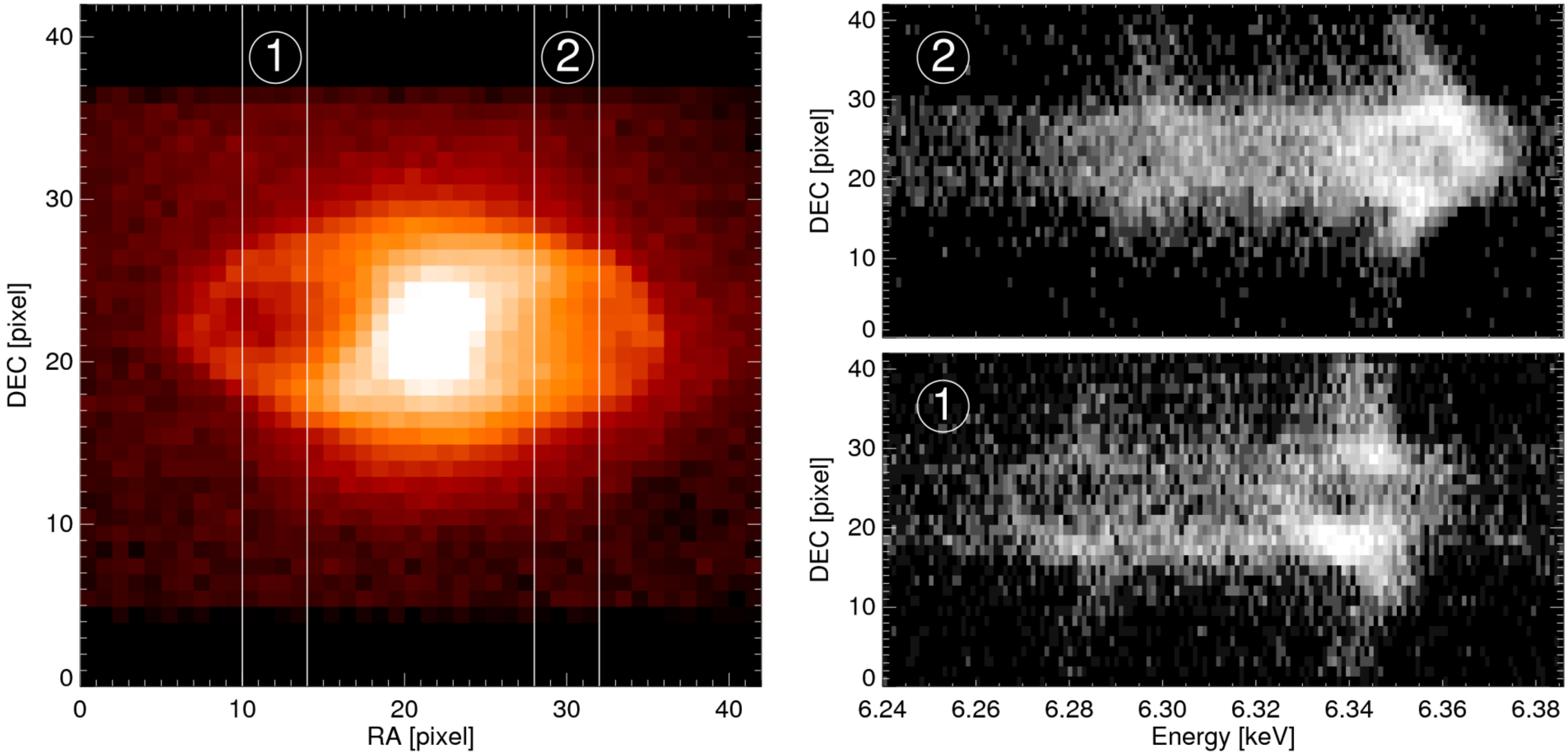


Spectrum for single 5x5 arcsec region in 50 ks



- Measure temperature to 1.5% and velocities to 10-20 km/s on scales <10 kpc in 20-30 nearby systems, and on scales of <50 kpc in hundreds of clusters and groups

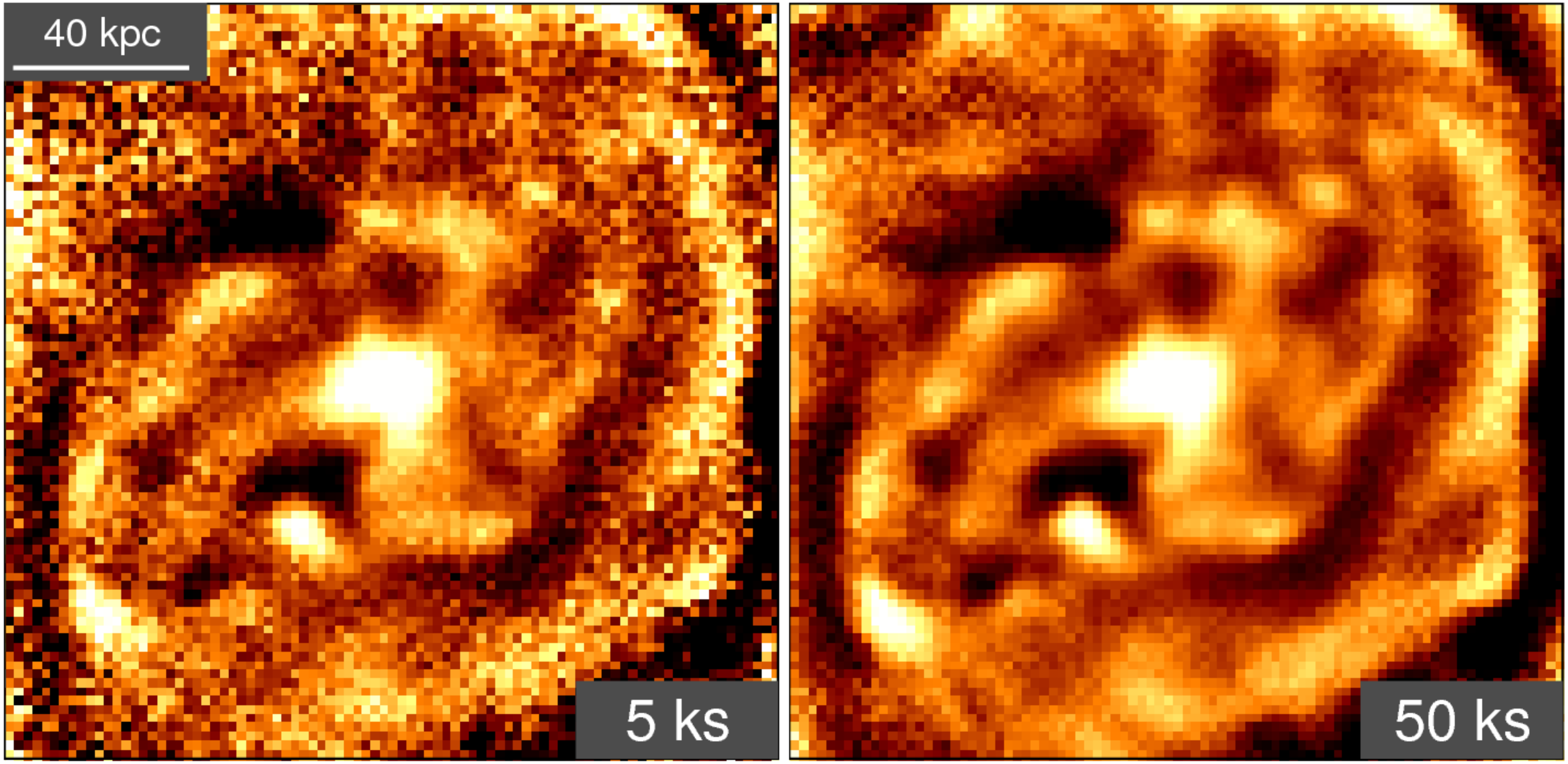
Spatially-resolved line profiles



Simulated 250ks Cygnus-A observation, based on hydro simulations of Heinz+10

- Characterise spatial scales and velocities of turbulent eddies (>kpc scales)
- Line width gives total kinetic energy in stochastic motions

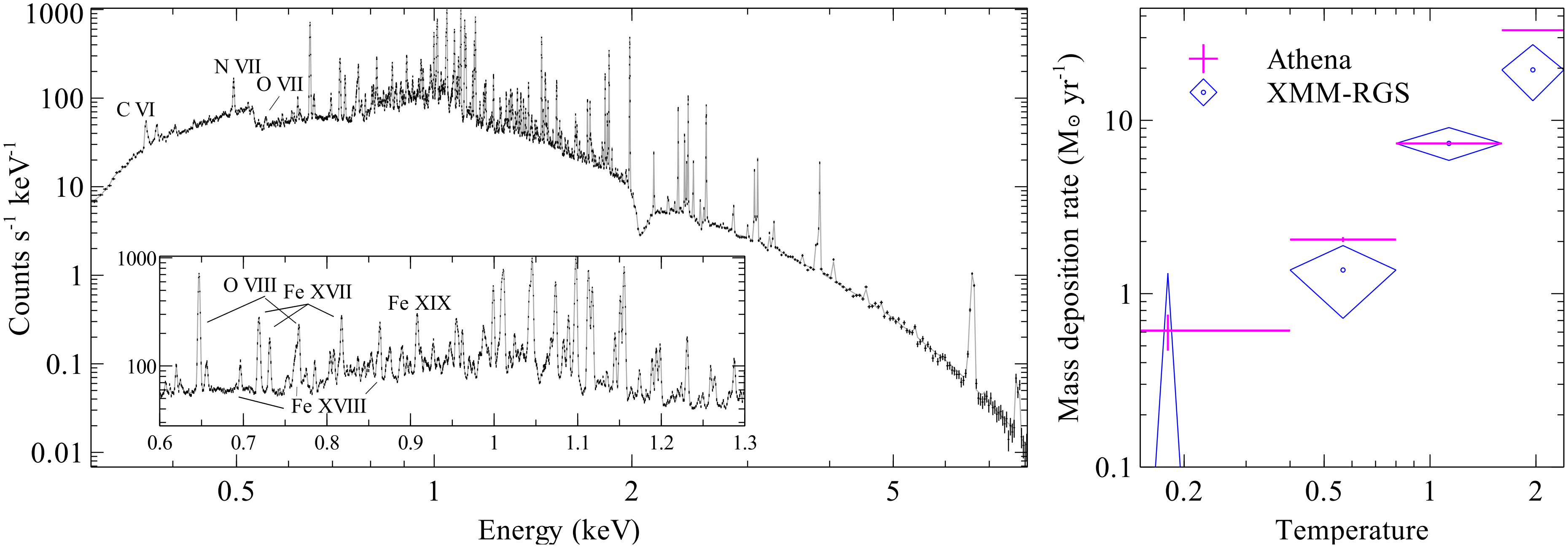
Characterising ripples and weak shocks



WFI-simulated core of a cluster *z* = 0.05, based on simulations of Morsony+10, applying unsharp-masking

- WFI capable of detecting and characterizing ripples and weak shocks in several tens of groups and clusters over a wide mass range
- Will allow mechanical energy to be related to environment and AGN properties

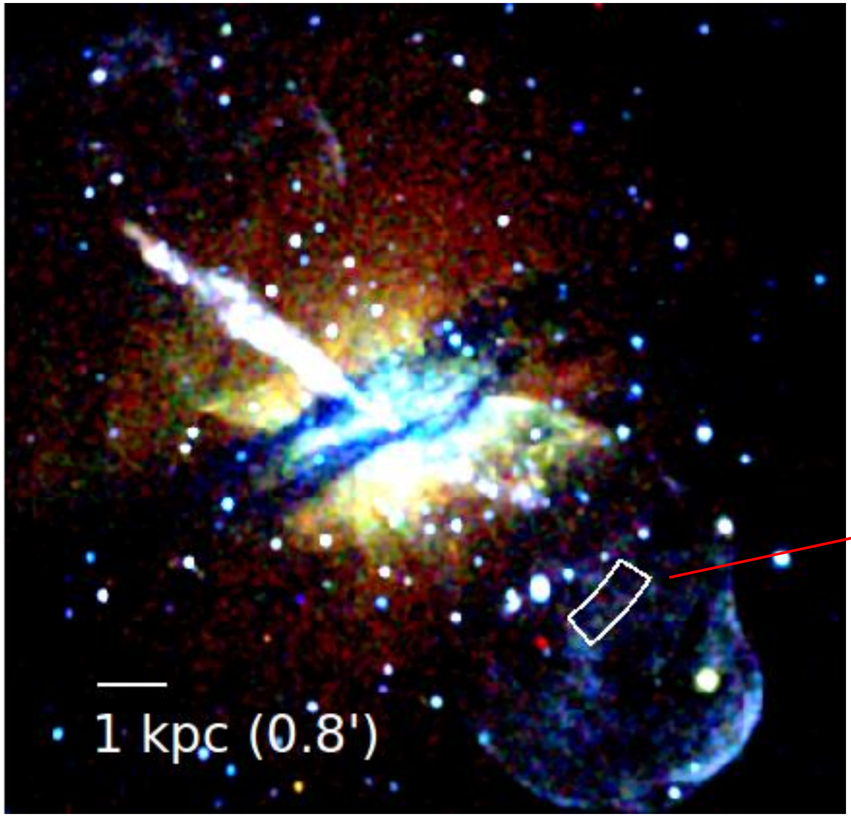
Q: *How does feedback regulate cooling?*



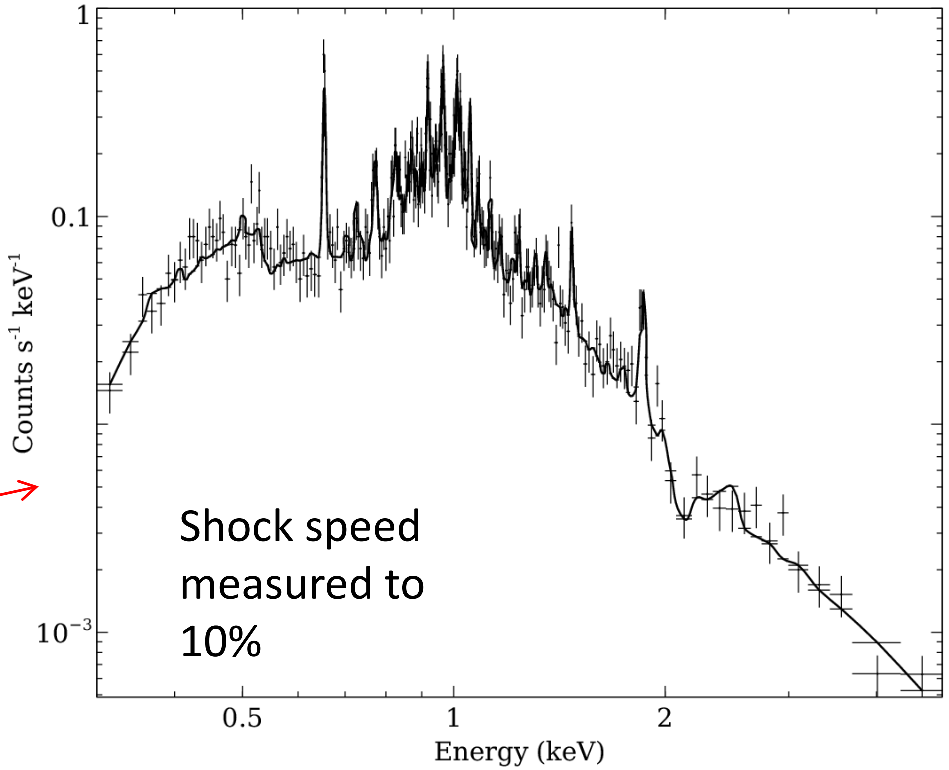
20 ks simulated X-IFU observation of the Centaurus cluster. The derived temperature distribution is compared to XMM-Newton RGS observations.

- Understand cooling from ICM and how this fuels the AGN (e.g. Bondi or molecular gas)
- Compare X-ray gas cooling rates down to a few MK and star formation rates
- Link these to ALMA and JWST measurements of cold gas in these systems
- Examine AGN-induced turbulence and its effect on feedback

Q: *What is the cumulative impact of powerful radio galaxies?*



WFI simulation of Centaurus A (50 ks)

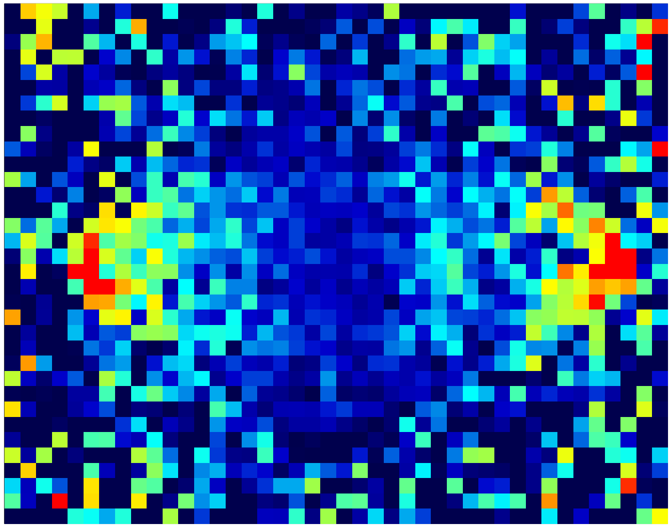


X-IFU spectrum of region shown

In poor environments, jets transfer more energy to their environment than required to prevent cooling (e.g. Ineson+13) – *possible explanation for entropy excess in groups*.

Athena will make first direct measurements of advance speed for a strong radio-lobe shock. Shocks can only be measured in X-rays.

Examining radio galaxies



Temperature map for group at z = 0.1 (20 ks exposure)

Inverse Compton measurements of magnetic fields and radio lobe electrons possible

- Athena will make possible precise measurements of shock conditions in large samples – identify shock locations, speeds and ages through temperature mapping – for first time

- Understanding radio galaxy evolution crucial for next generation radio surveys and for realistic modelling of AGN feedback in cosmological models

Conclusions

- A robust understanding of mechanical AGN feedback is essential for understanding galaxy evolution
- Requires a major advance in X-ray sensitivity and spectral resolution at high spatial resolution, i.e. *Athena*
- Jet feedback models can only be tested directly with X-ray observations
- Necessary to understand the future surveys of galaxies and AGN (Euclid, eROSITA, LOFAR, SKA)