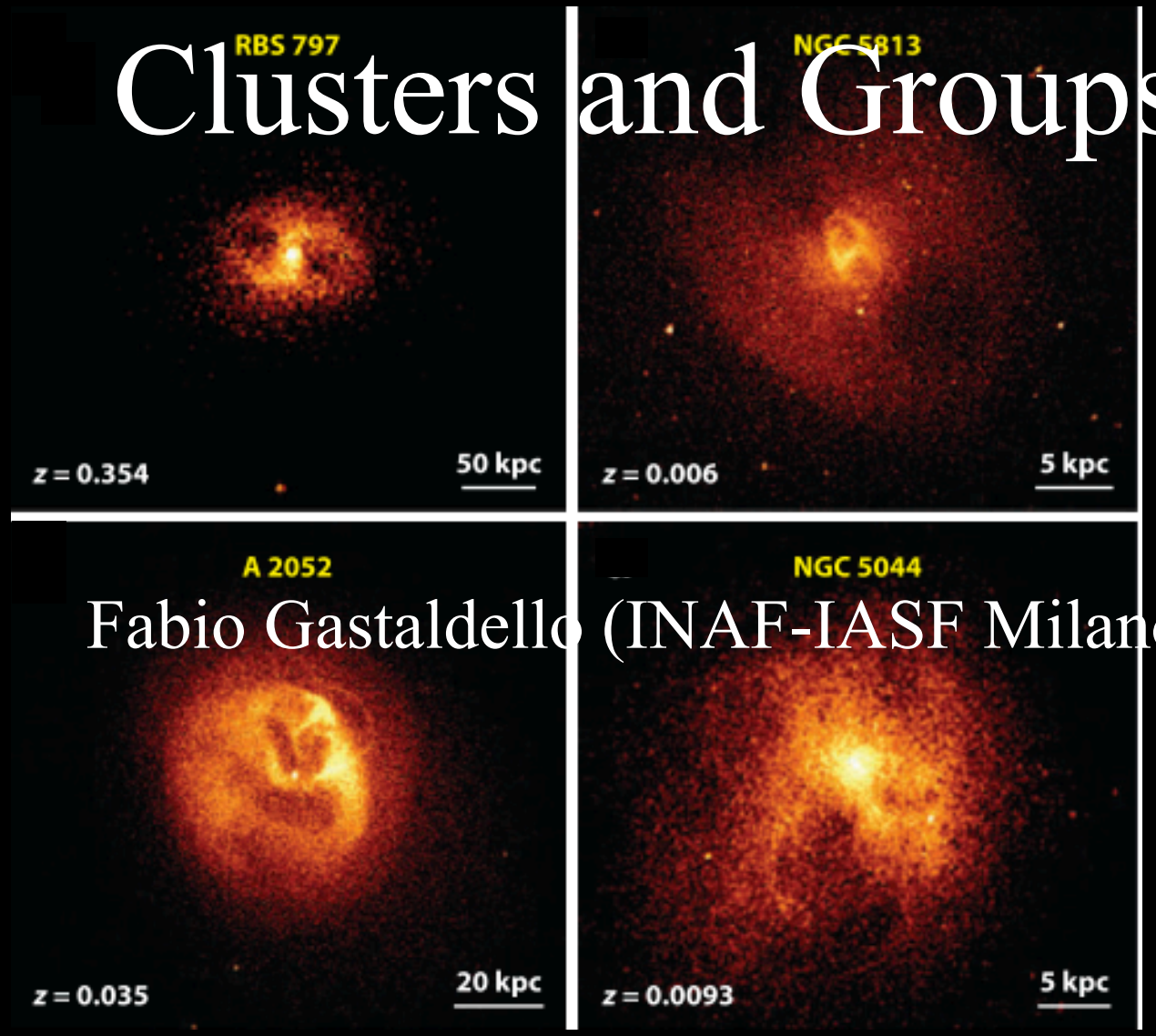
# AGN Feedback in Galaxy Clusters and Groups




Fabio Gastaldello (INAF-IASF Milano)

Fabian 12 Review

RBS 797 Cavagnolo+11, NGC 59813 Randall+11, A2052 Blanton+11, NGC 5044 David+11

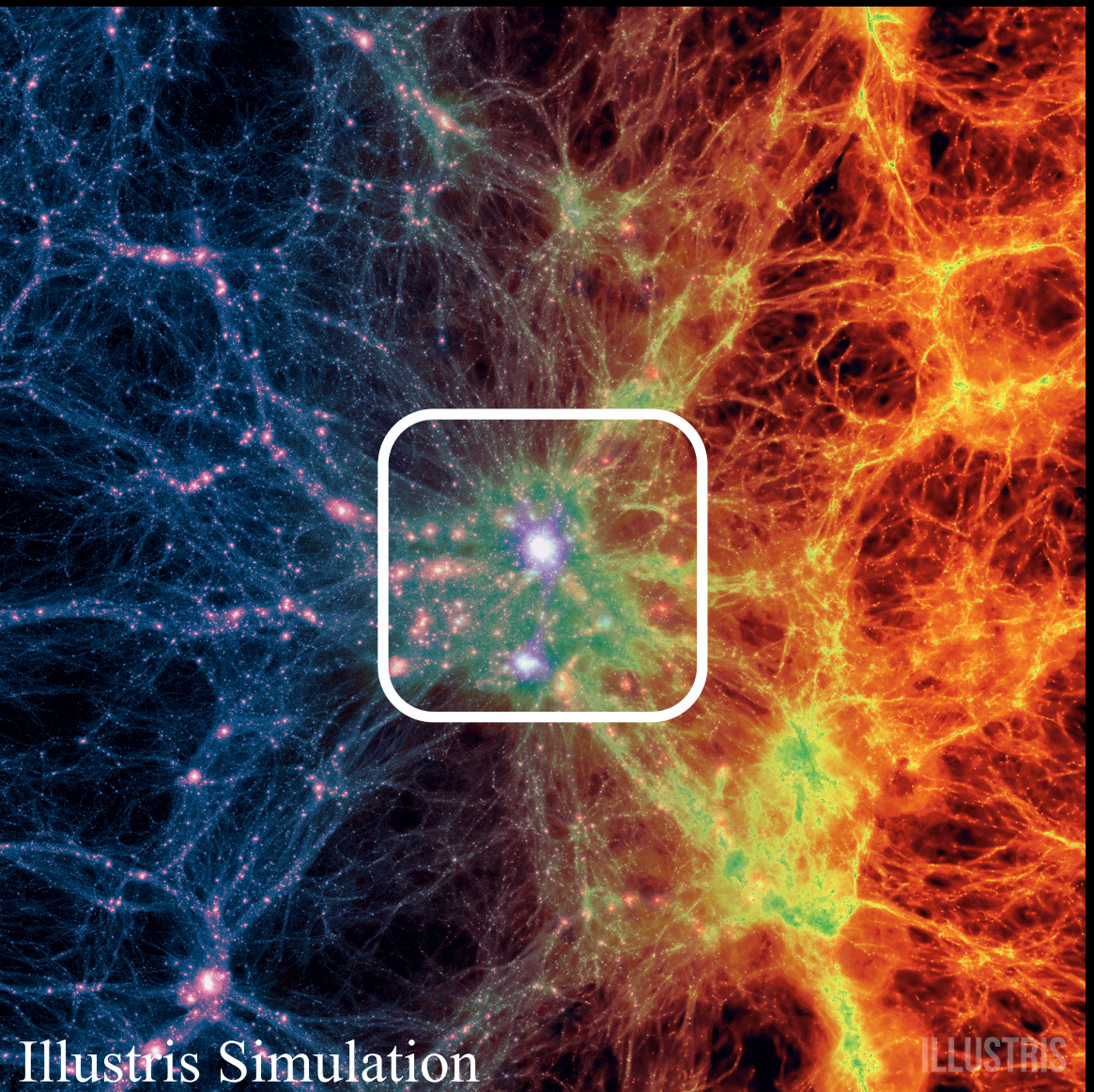
# Why Galaxy Clusters ?




- Clusters as cosmological probes: structure formation and cosmological parameters estimate (next talk by M. Arnaud)

- Clusters as astrophysical laboratories: structure formation, chemical enrichment, DM properties, plasma physics

# Clusters of galaxies



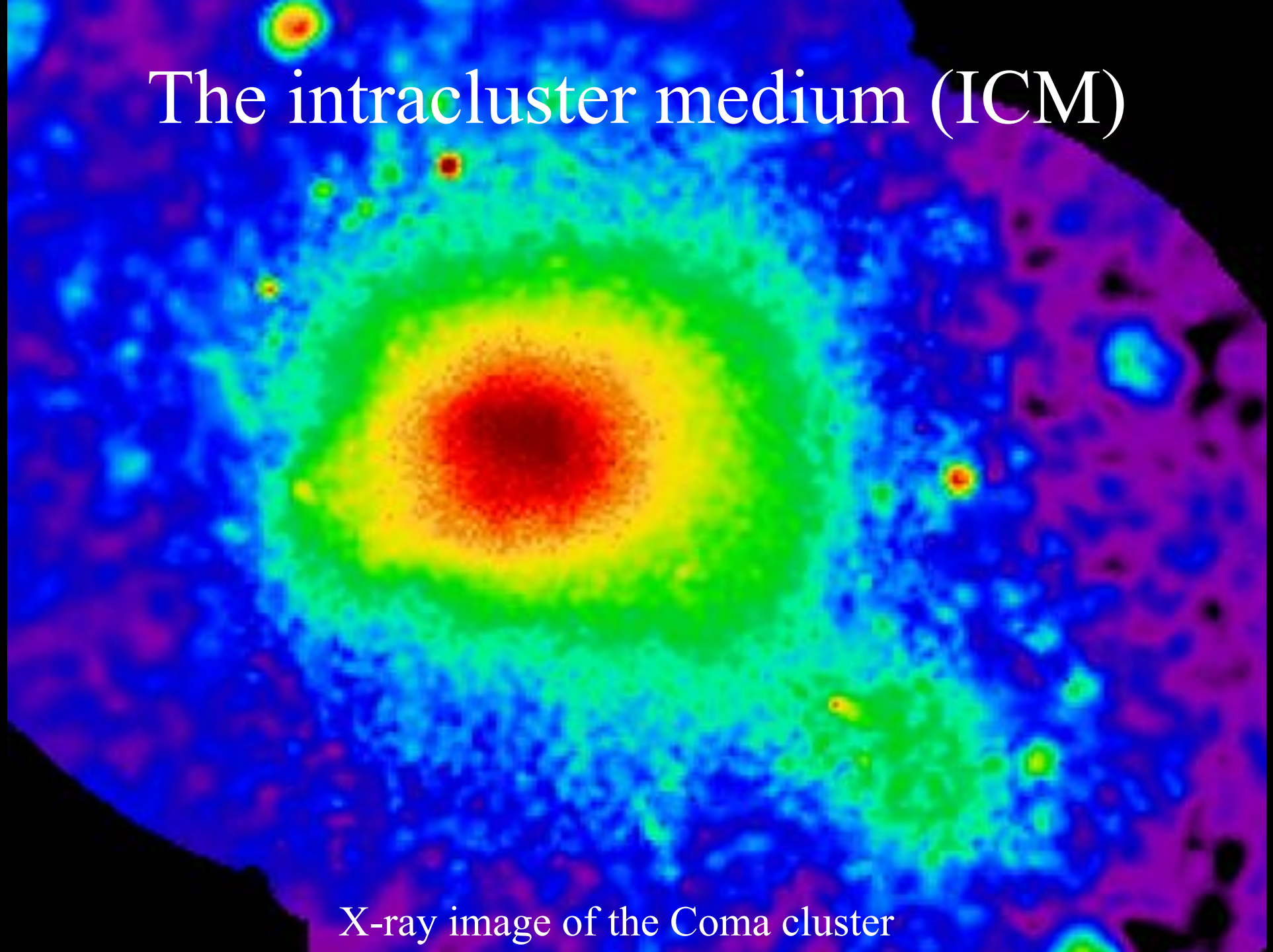
Illustris Simulation

- They form at the intersection of the cosmic web
- The greatest structures to decouple from the Hubble flow
- Dimension of the order of the Mpc
- Masses $10^{14}$-$10^{15}$ $M_{sun}$ (75-90% Dark Matter)

# Outline of the lesson

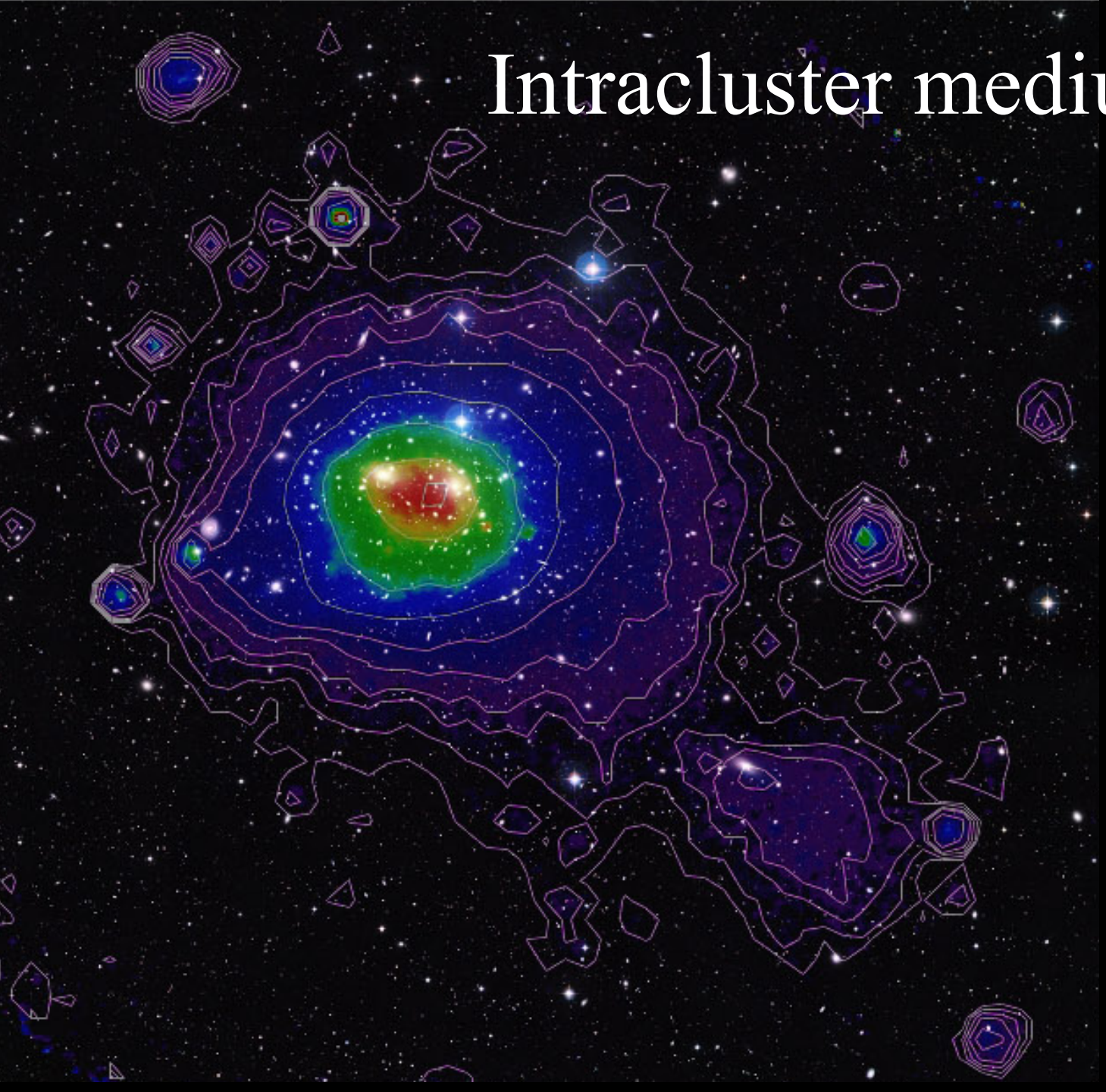
- Basic properties of galaxy clusters and groups
- Zero order model for the Intracluster Medium
- The failure of the cooling flow model and the need for an heating source
- Evidence of AGN Feedback: cavities, shocks, sound waves and turbulence
- Entropy structure and the gas-fraction – mass relation

# The intracluster medium (ICM)



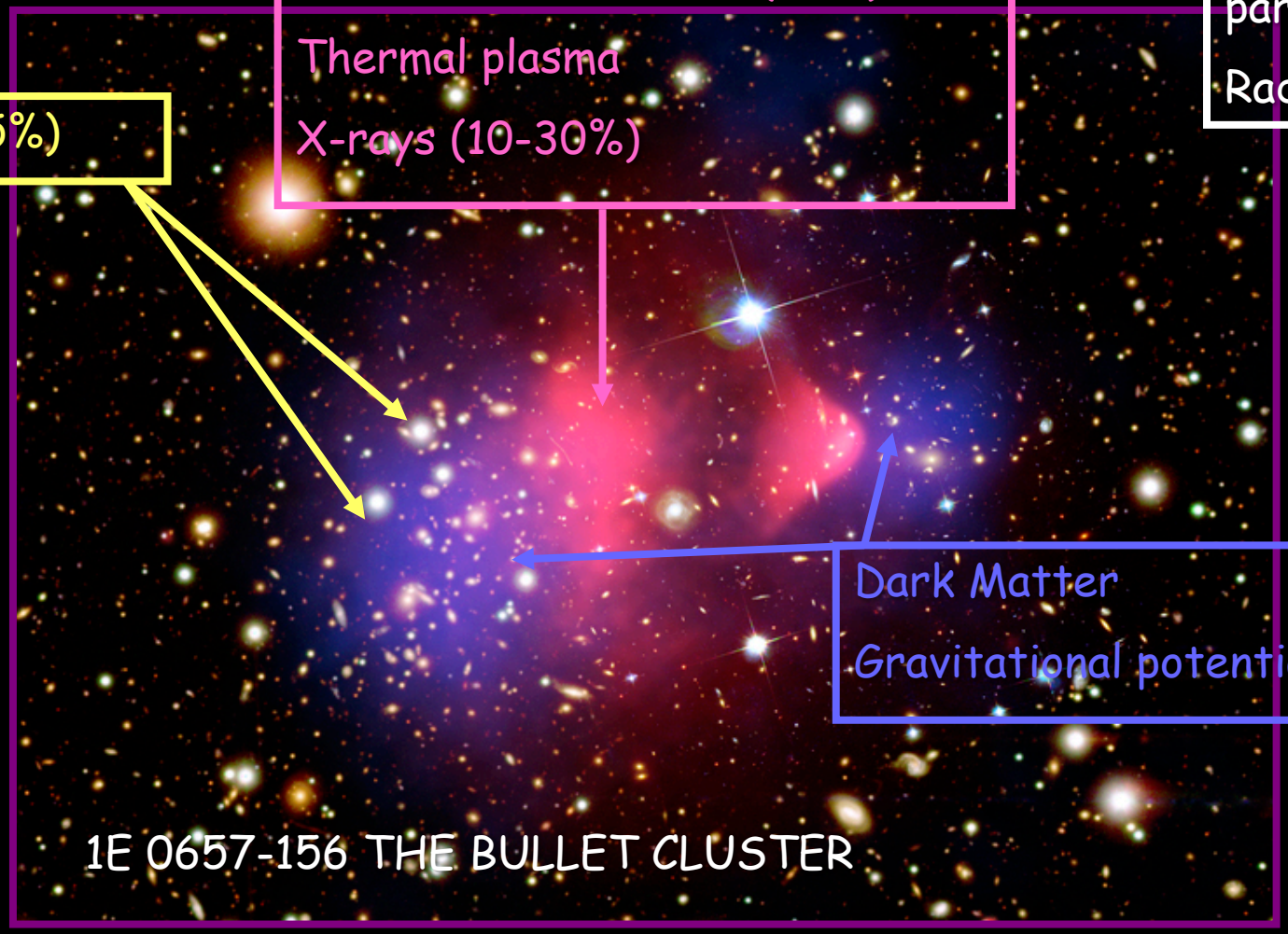
X-ray image of the Coma cluster

# Intracluster medium (ICM)



- Hot with temperatures $10^7$-$10^8$ K o 1-10 keV)
- Low density ($10^{-2}$-$10^{-4}$ particles/cm$^3$)
- Mainly H and He completely ionized. Chemically enriched with heavy elements (C, O, Si, Fe)
- Dominant baryonic component
- Bremsstrahlung: $n^2$ dependence

# The components of Galaxy Clusters




Clowe+04

Galaxy clusters are the most massive ($M \sim 10^{14}$-$10^{15}$ $M_{SUN}$) objects in the Universe

# Properties of Groups and Clusters

| | CLUSTERS | GROUPS/POOR CLUSTERS |
|---|---|---|
| $L_X$ (erg/s) | $10^{43}$ - $10^{45}$ | $10^{41.5}$ - $10^{43}$ |
| $kT_X$ (keV) | 2 – 15 | ≤ 2 |
| N gal | 100-1000 | 5 – 100 |
| $\sigma_v$ (km/s) | 500-1200 (median 750) | 200 – 500 |
| $M_{tot}$ (< 1.5 Mpc) | $10^{14}$ – 5 x $10^{15}$ | $10^{12.5}$ - 2 x $10^{14}$ |
| Number Density | $10^{-5}$ – $10^{-6}$ $Mpc^{-3}$ | $10^{-3}$ – $10^{-5}$ $Mpc^{-3}$ |

Groups and poor clusters provide a natural and continuous extension to lower mass, size, luminosity and richness of rich, massive and rare clusters

Bahcall 99

# Timescales and other fundamentals

## Cooling timescale

The ICM cools by emitting radiation

$$t_{cool} \approx \frac{u}{\varepsilon} \propto n_p^{-1} T_g^{1/2}$$

$$t_{cool} \approx 8.5 \times 10^{10}\, yr \left( \frac{n_p}{10^{-3}\, cm^{-3}} \right)^{-1} \left( \frac{T_g}{10^{8}\, K} \right)^{1/2}$$

Except for the innermost regions where $n_p$ is high, gas cools on timescales > Hubble time

In first approx. we may consider the ICM as a stationary ball of hot plasma

# Heating

- No major on-going heating of the gas is necessary (the cooling is very slow)
- The ultimate origin of the bulk of the thermal energy of the ICM is the gravitational energy lost by the gas as it falls into the cluster's potential well

$$T_g \approx \frac{GM}{r}$$

- The temperature of the ICM is related to the depth of the potential well and to the total mass of the cluster

# Fluid approximation

- The ICM is highly ionized
  $T_g \sim 10^7 - 10^8$ K ⇒ H, He completely ionized
- Coulomb interactions are the dominant mechanism for collisions, for $T_e = T_i$ the mean free path is:

$$\lambda_e = \lambda_i \approx 23 kpc \left(\frac{T_g}{10^8 K}\right)^2 \cdot \left(\frac{n_p}{10^{-3} cm^{-3}}\right)^{-1}$$

$$\lambda_e = \lambda_i << R_{cluster} \approx 1 Mpc$$

ICM can be treated as a fluid, satisfying hydro-dynamical equations

# Sound-crossing time

$$v_s \approx \left(\frac{p}{\rho}\right)^{1/2} \propto T_g^{1/2}$$

$$t_s \approx 6.6\times10^8\, yr \left(\frac{D}{Mpc}\right)\cdot\left(\frac{T_g}{10^8 K}\right)^{-1/2}$$

$$t_s << t_{cool}$$

$$t_s << t_{age}$$

The ICM is in (close to) hydrostatic equilibrium

# Radiation process

**Continuum emission is dominated by thermal bremsstrahlung**

$$\varepsilon_\nu \propto n_g^2 \cdot T_g^{-1/2} \cdot \exp\left(-\frac{h\nu}{kT_g}\right)$$

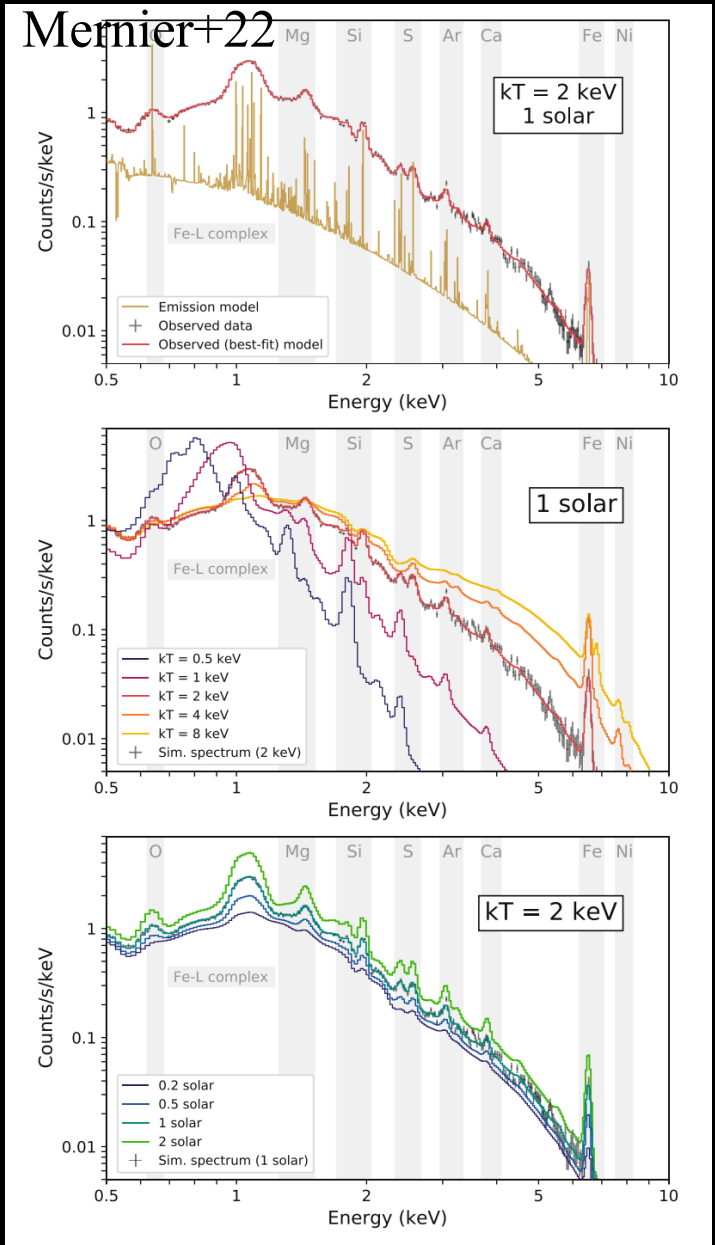
spectral shape $\rightarrow T_g$

spectrum normal. $\rightarrow n_g$

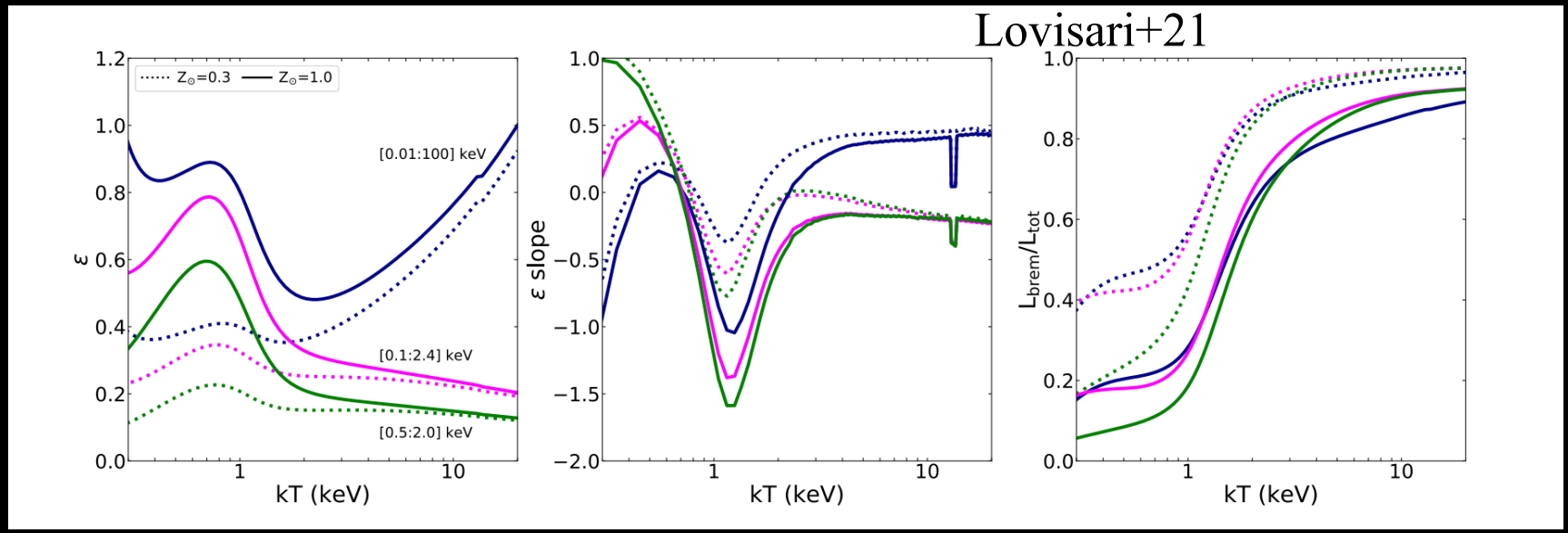
Optically thin: $n_g \sigma_T L \approx 10^{-2}\ 6.65\text{x}10^{-25}\ 3.18\text{x}10^{24} \ll 1$

# Line emission and metal abundances

Mernier+22




Lovisari+21

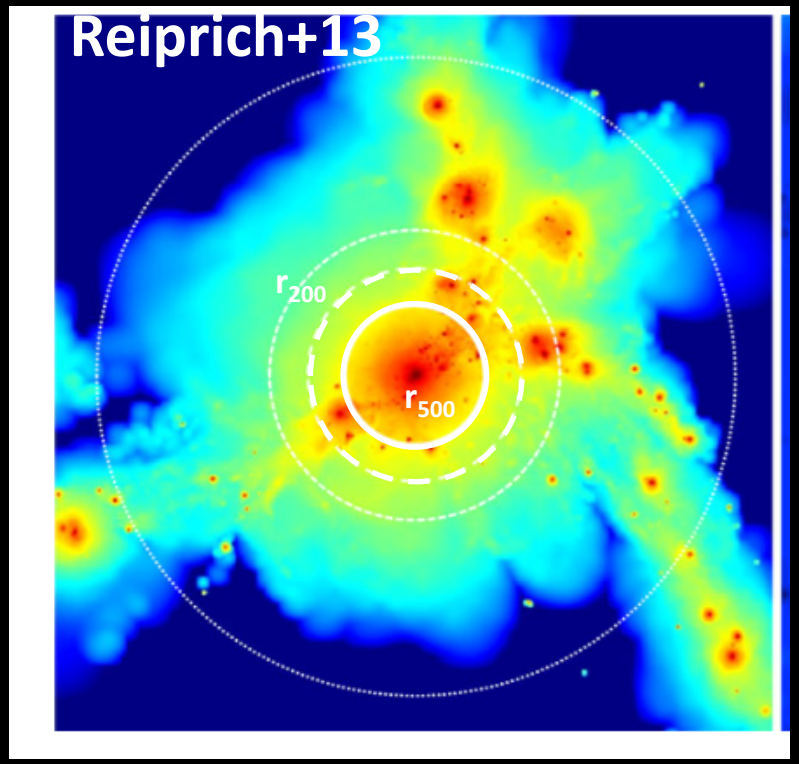



The ICM is metal enriched. The Fe-K complex is the strongest feature for clusters, with the He-like resonant line at 6.7 keV and H-like line at 6.9 keV. At the temperature of groups line emission become important and the Fe-L complex (hundreds of line from multi-electron ions) dominates the emission

# Summary of basic properties of the ICM

- A hot, tenuous and weakly magnetized plasma (ICM) rests in the potential well of galaxy clusters
- The temperature of the ICM is related to the total mass of the cluster
- The ICM is enriched and heavily ionized
- It dissipates energy at a very slow rate by emitting X-rays by thermal bremsstrahlung
- It can be treated as a fluid in hydro-static equilibrium
- At the scale of groups line emission is an important contribution to the emission

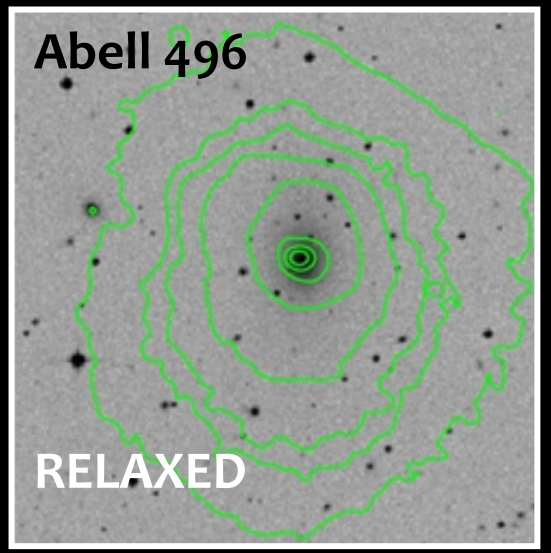
# Glossary

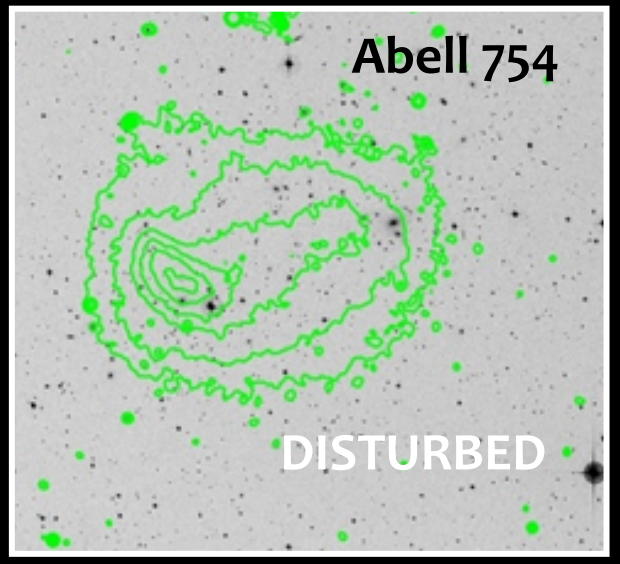





Credits:
B. Maughan

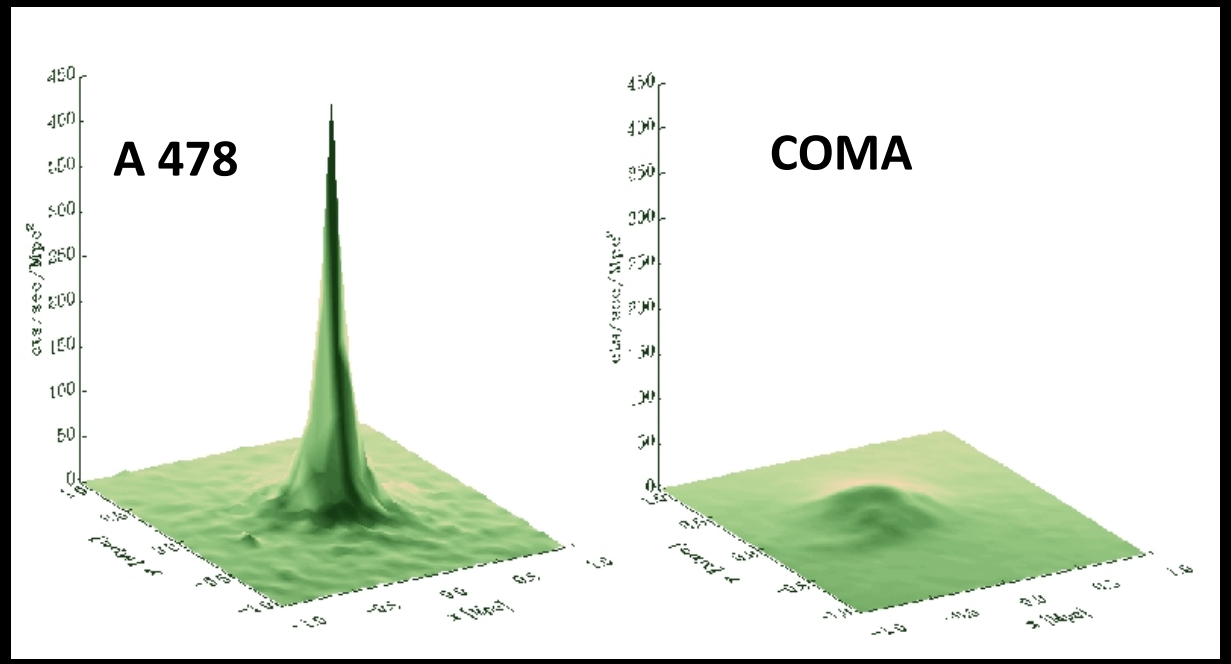
If only gravity works, clusters of different masses are scaled versions of each other and we expect power-laws relations between observables (L, T, etc.) and mass (Kaiser 86)

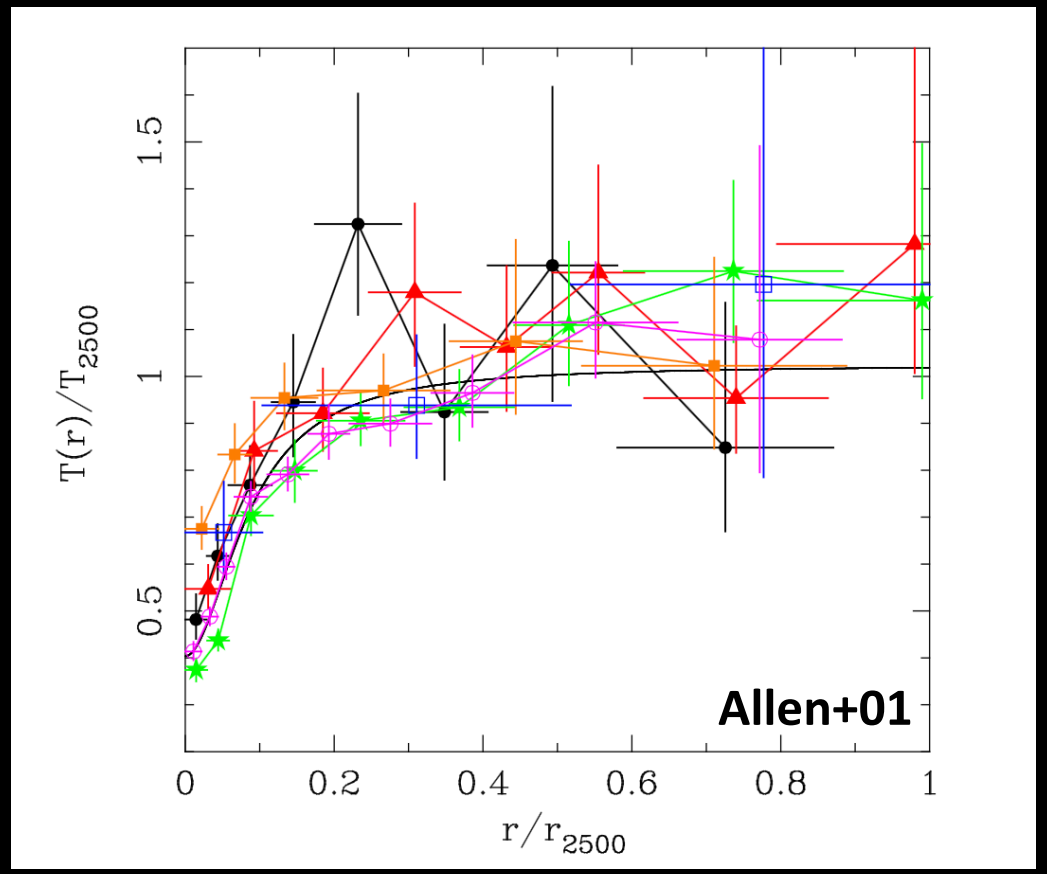


# Falsification of the steady cooling flow model

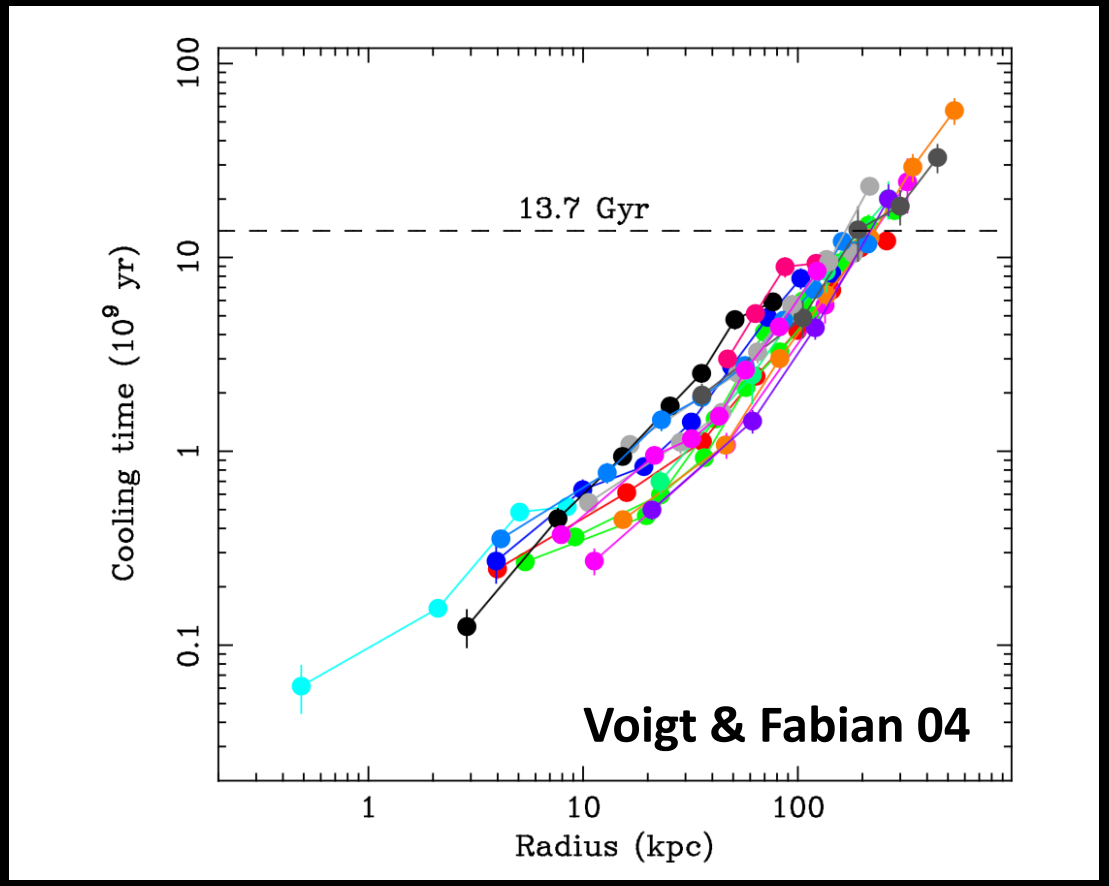
- Great debate untile the early 2000s: there was evidence of cool temperatures in the center of the peaked surface brightness clusters with cooling times smaller than the Hubble time

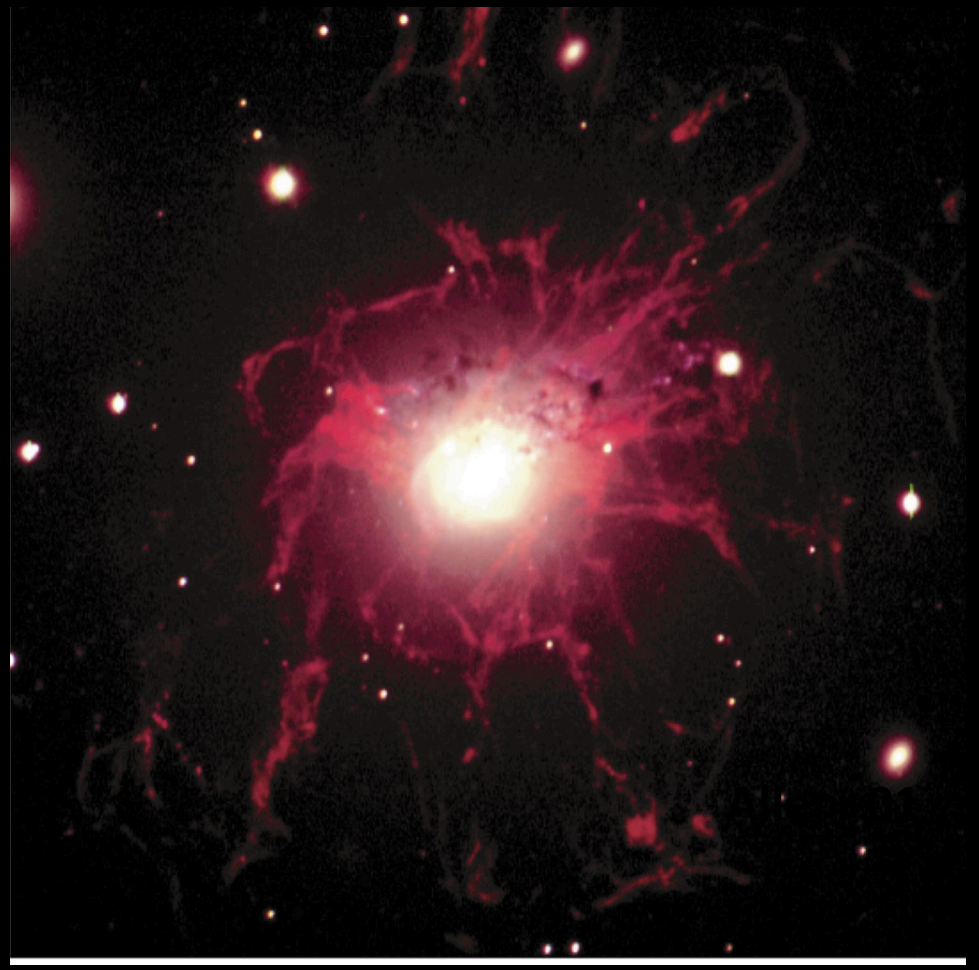


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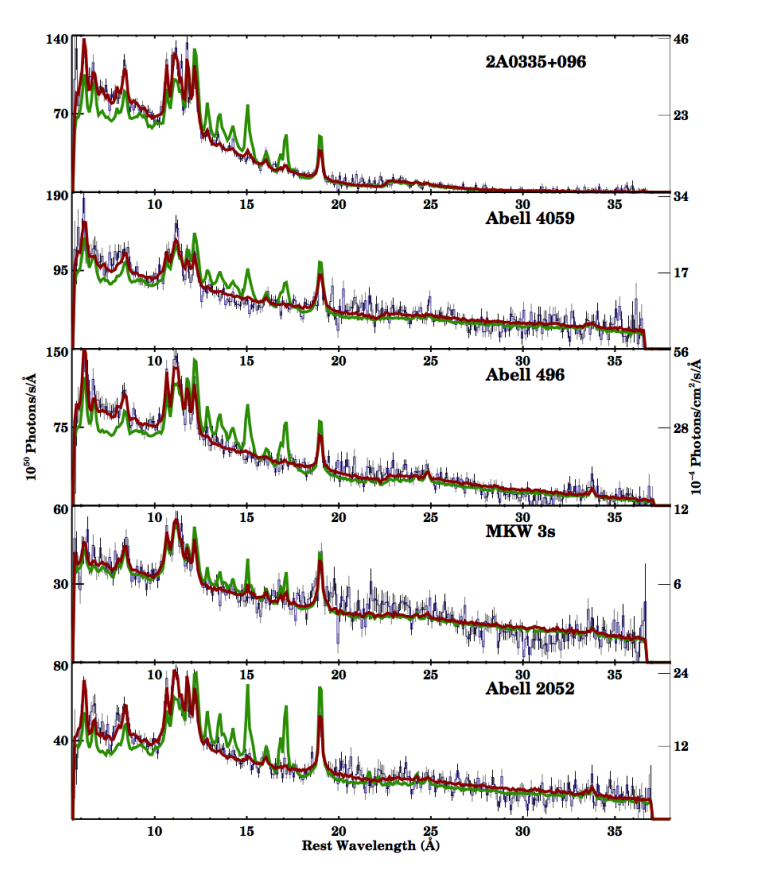
- "In the absence of heating a cooling flow must occur". Cooling flow rates could be $10^2$-$10^3$ M/yr. Only smaller fraction (few %) of all this gas was found at various wavelengths

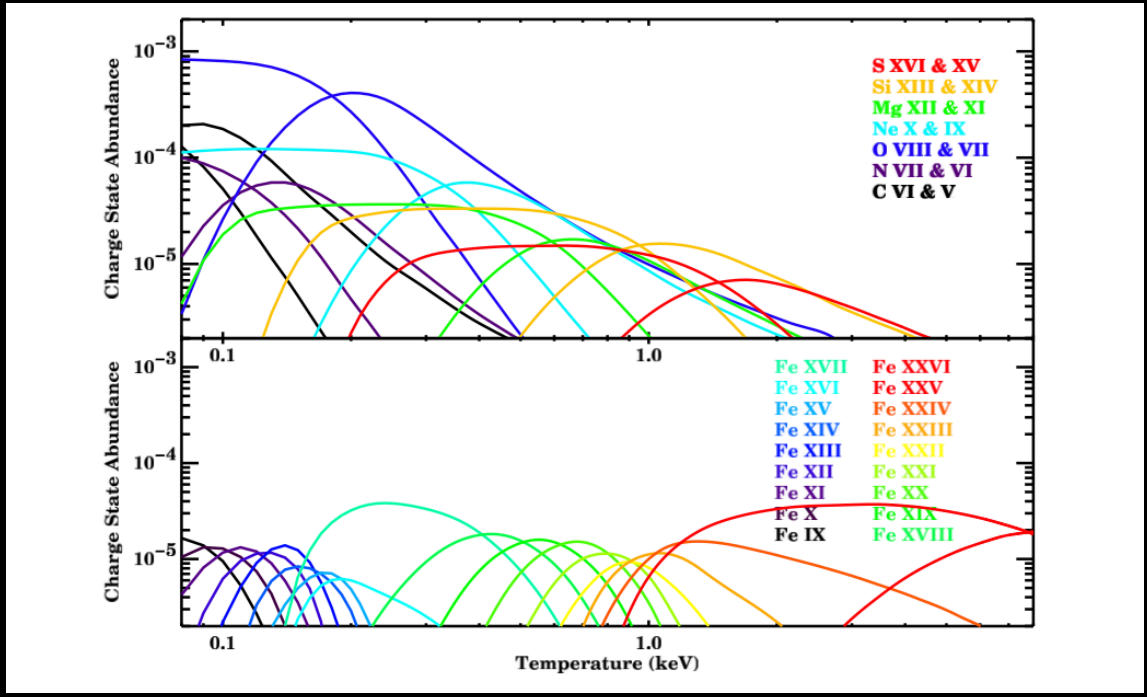


# Falsification of the steady cooling flow model

- RGS and EPIC spectra of the core of the clusters found no evidence for gas cooling at low temperatures below $T_{vir}/3$. There must be a heating source !

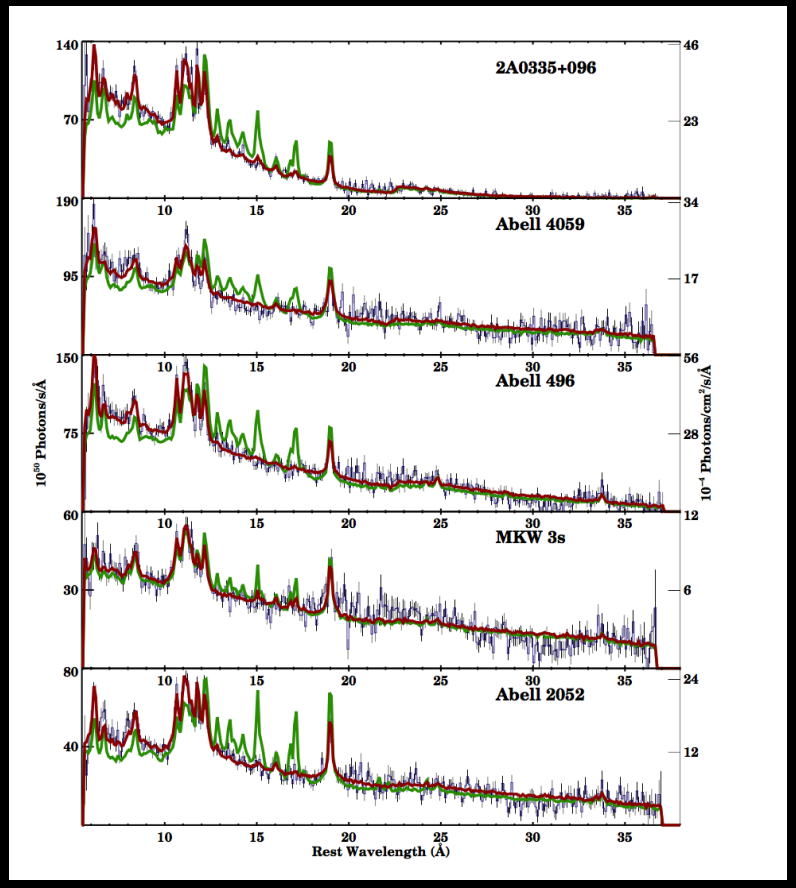


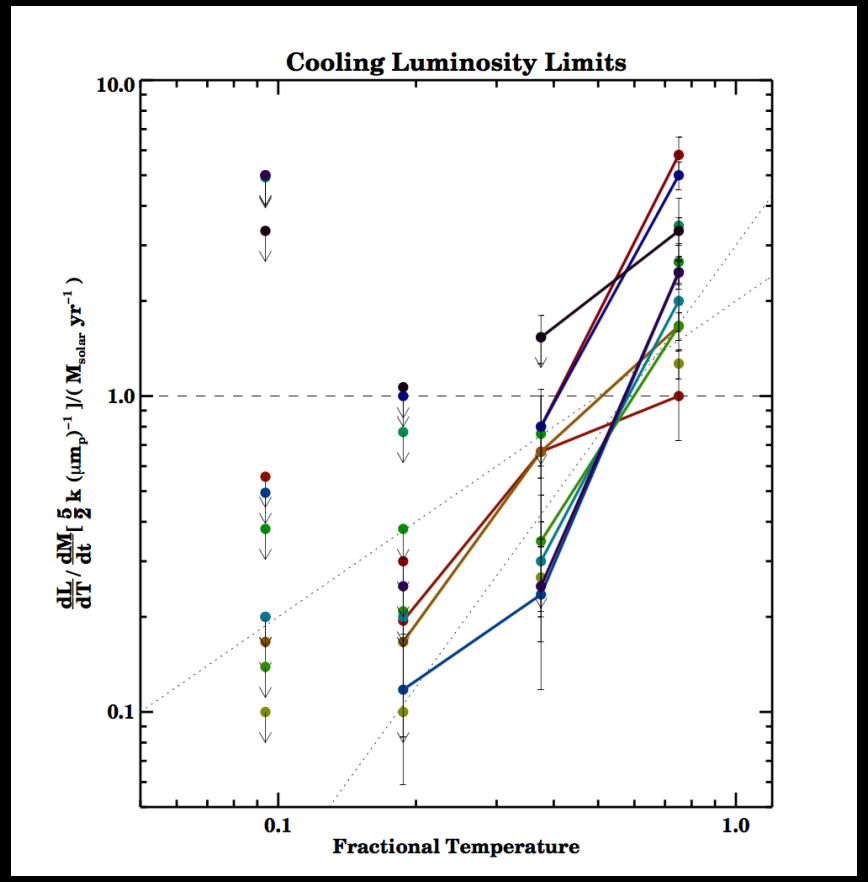

**Peterson+03**

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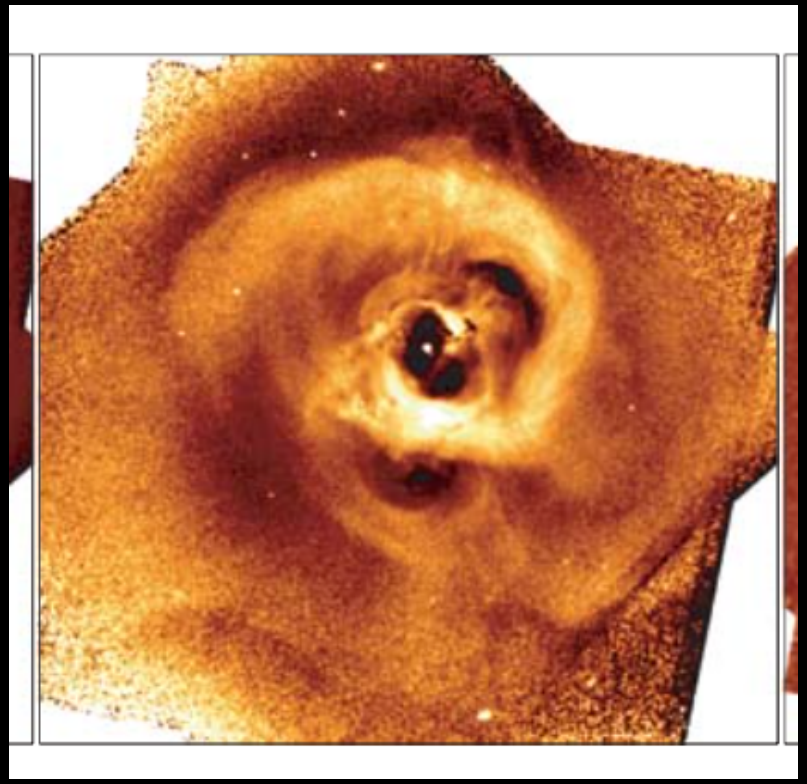



Peterson+03

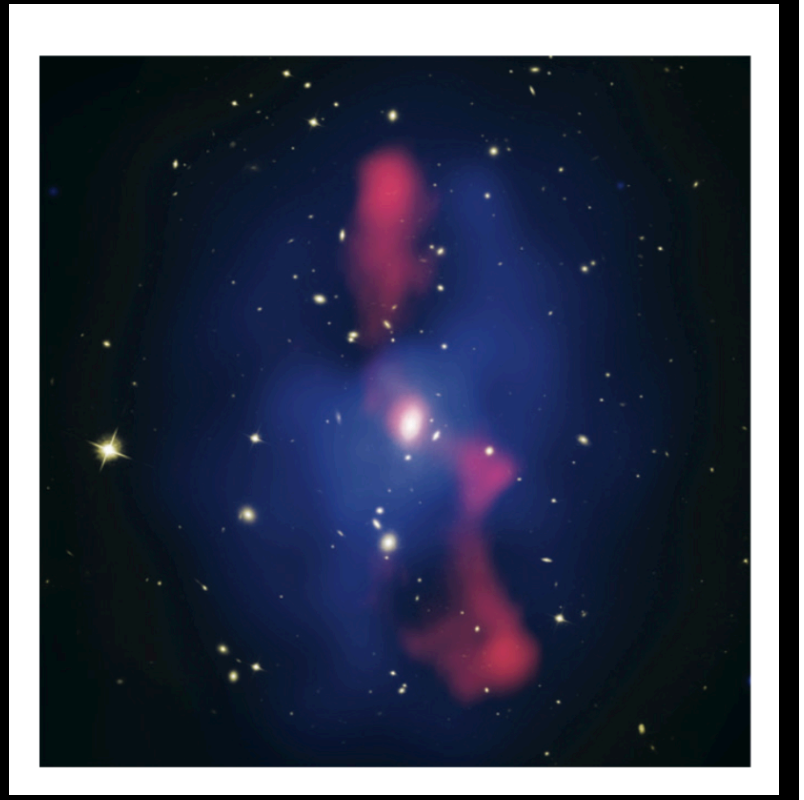


# Spoiler - AGN feedback in the ICM

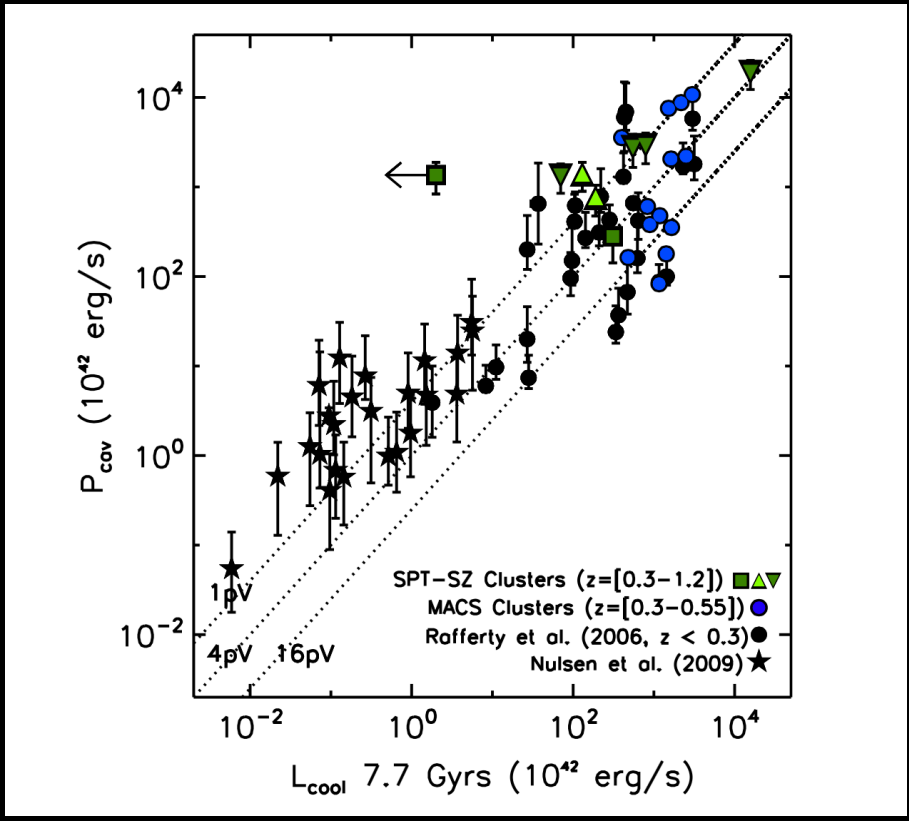
- Feedback from the central supermassive BH by means of cavities mechanically inflated by its radio jets, weak shocks and possibly turbulence is the way to balance cooling and heating



Perseus Sanders+07

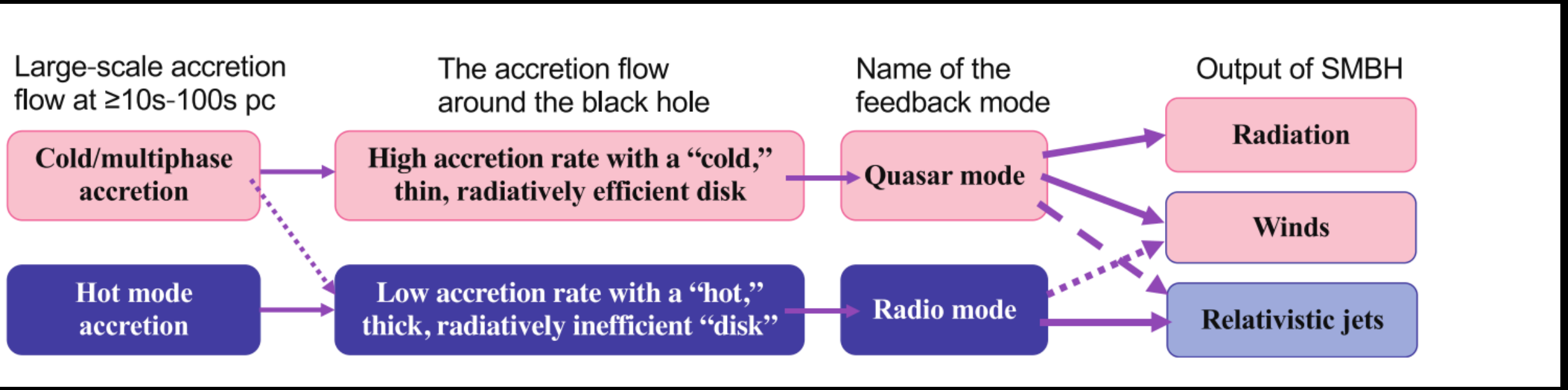


MS 0735+7241 McNamara+05



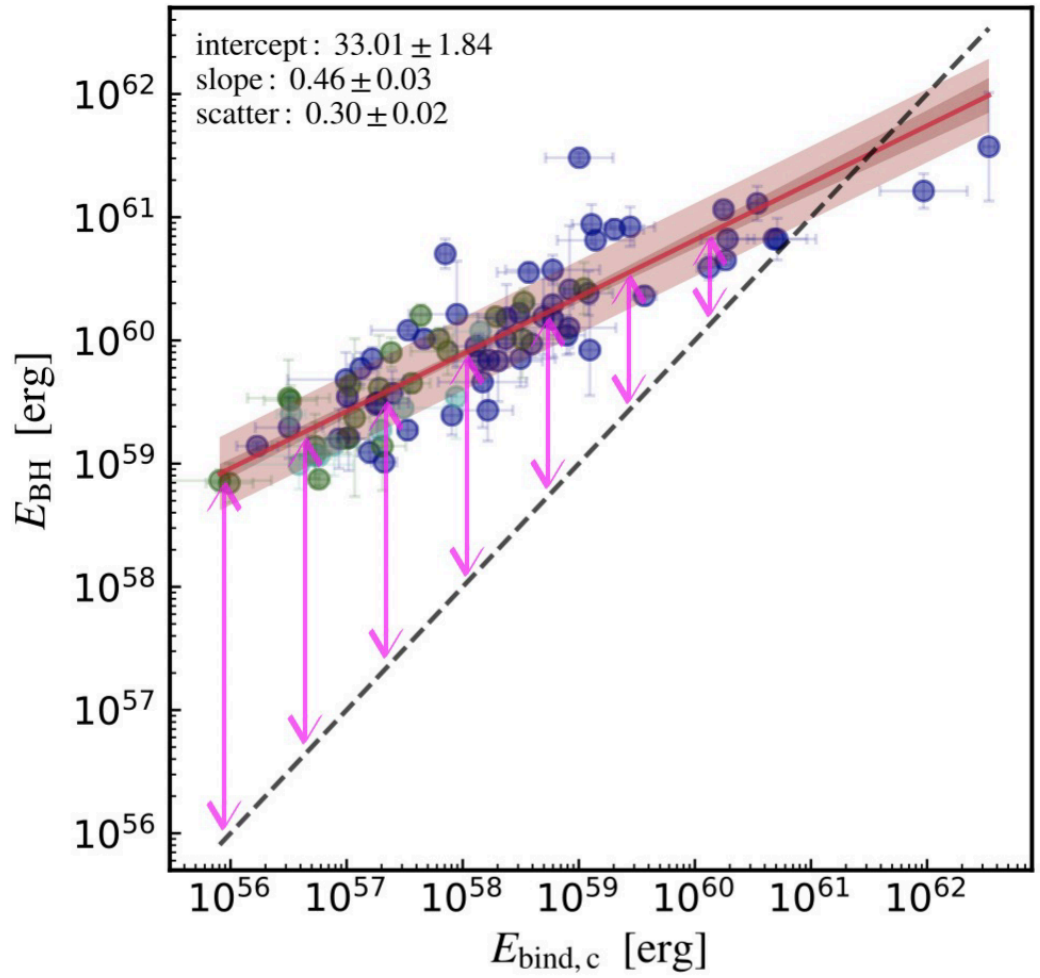

Hlavacek-Larrondo+15

# The different modes of AGN feedback




Hlavacek-Larrondo+22 Review

# BHs have enough energy




$$E_{\rm BH} = \eta M_{\rm BH} c^2 \sim 2 \times 10^{63} \left(\frac{\eta}{0.1}\right) \left(\frac{M_{\rm BH}}{10^{10}\,M_\odot}\right) \,{\rm erg}$$

$$E_{\rm th} = \left(\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right) \left(\frac{M_{\rm CL}}{\mu m_{\rm p}}\right) \frac{1}{\gamma - 1} kT \sim 7 \times 10^{63} \left(\frac{10^{15}}{M_\odot}\right) \left(\frac{kT}{10\,{\rm keV}}\right) \,{\rm erg},$$

At the scale of galaxies and groups to totally unbind the gas from the DM halo

Eckert+21 Review

# BHs have enough energy

$$L_{\rm cool} \sim 10^{45}\,{\rm erg\,s^{-1}}$$

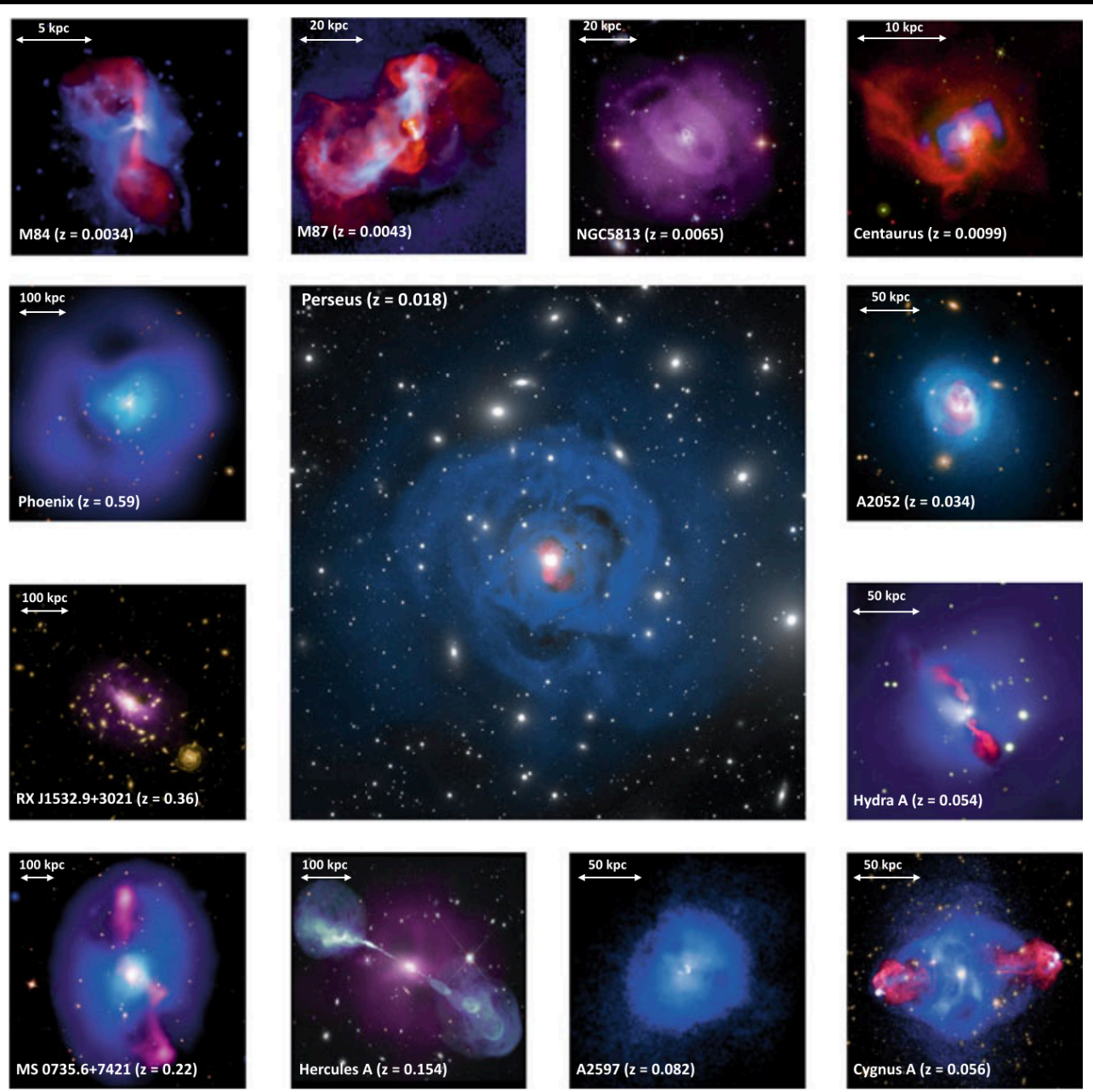
$$L_{\rm BH} = E_{\rm BH}/t_{\rm H} \sim 4 \times 10^{45} \left(\frac{\eta}{0.1}\right)\left(\frac{M_{\rm BH}}{10^{10}\,M_\odot}\right)\,{\rm erg\,s^{-1}}.$$

$$R_{\rm Edd} = \frac{L_{\rm cool}}{L_{\rm Edd}} \sim 10^{-3}\left(\frac{L_{\rm cool}}{10^{45}\,{\rm erg\,s^{-1}}}\right)\left(\frac{M_{\rm BH}}{10^{10}M_\odot}\right)^{-1}$$

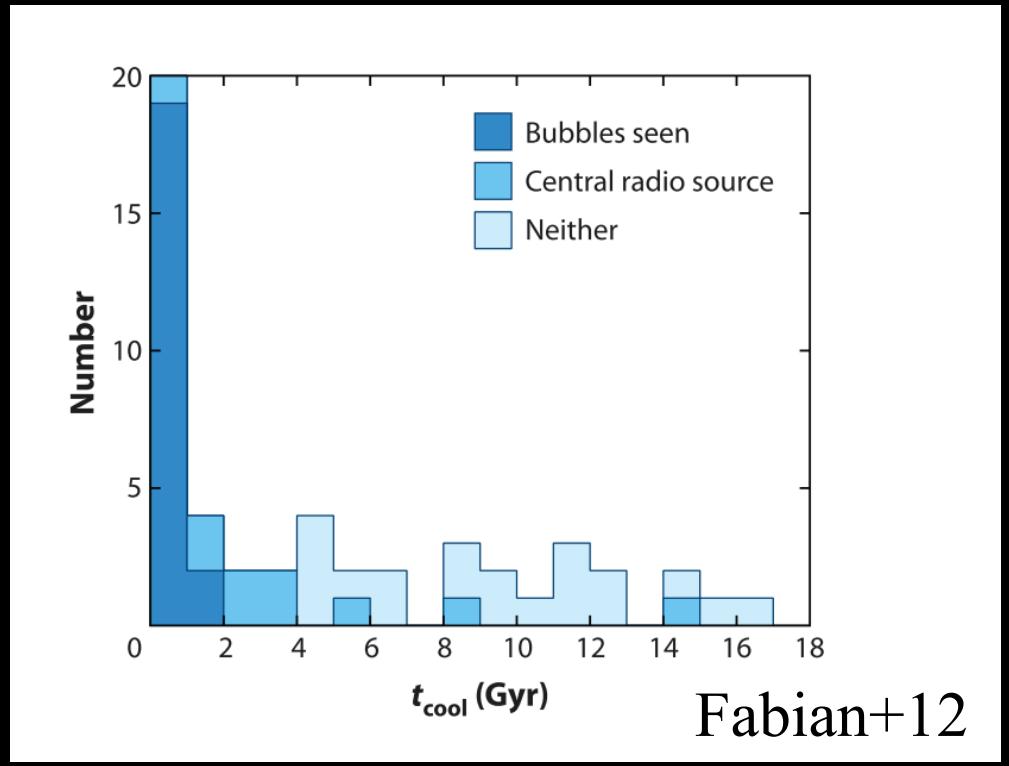
$$L_{\rm Edd} = \frac{4\pi c G m_{\rm p}}{\sigma_{\rm T}} M_{\rm BH}$$

In clusters it has enough energy to offset cooling within the cooling radius. Clusters also experience mergers so only a fraction of the Hubble time AGN is needed, between mergers. Efficiences must be relatively high, otherwise very massive BHs at he center of BCGs. Low Eddington ratio needed if AGN operates almost continuously (and efficiently energy is coupled to the gas)

# Cavities in Clusters, Groups and Galaxies



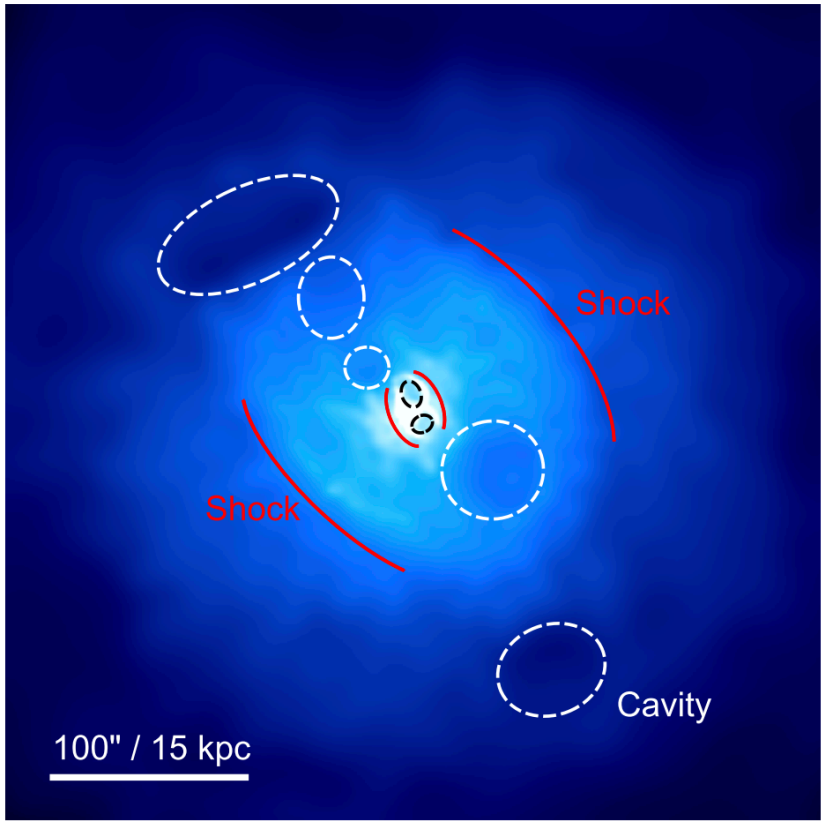

Cavities are ubiquitously present across the mass scales with cavity sizes ranging from few kpc up tp 200 kpc (MS 0735.6+7421)

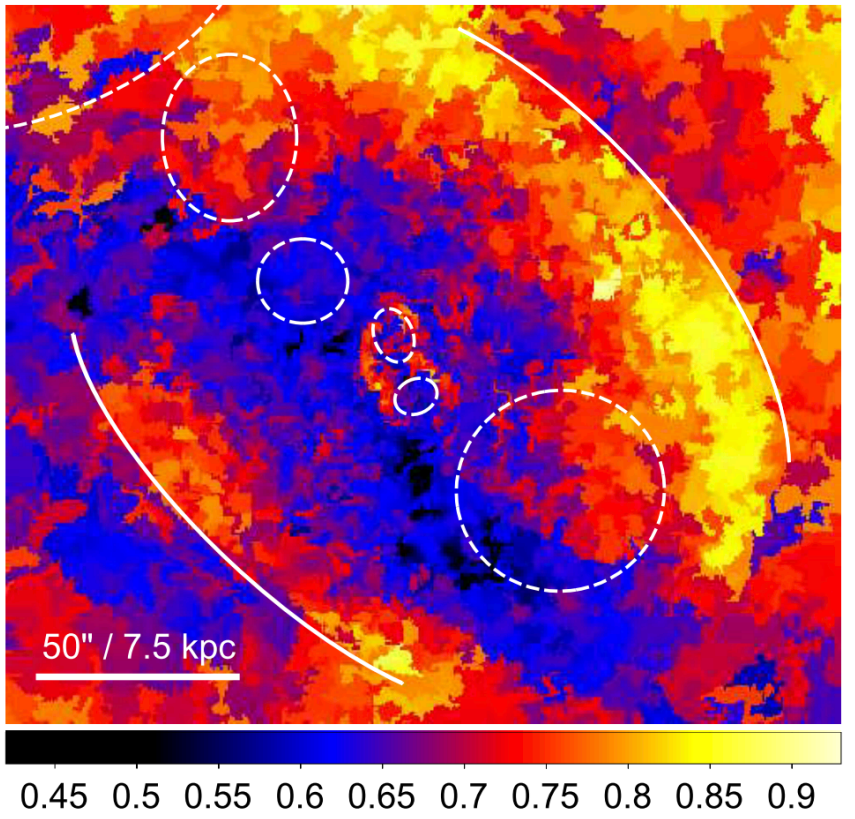



Fabian+12

Hlavacek-Larrondo+22

# Multiple generation of cavities



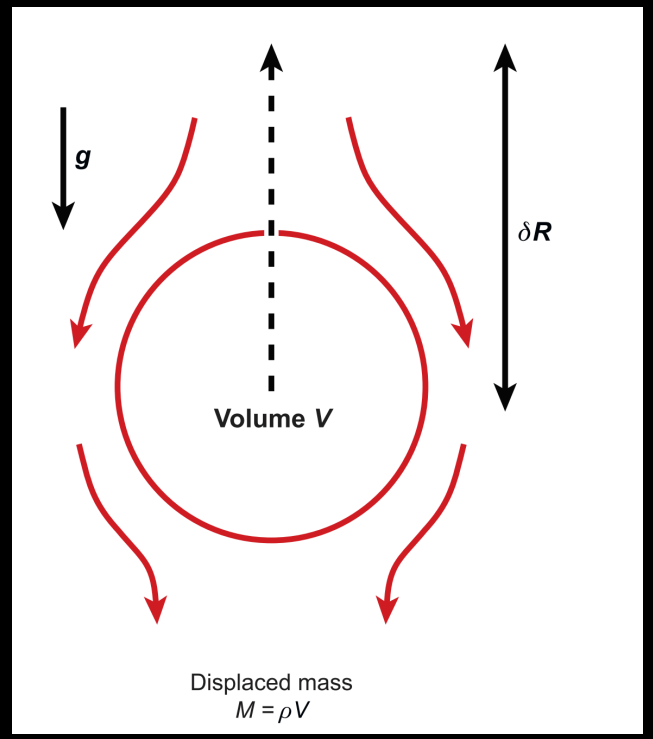

NGC 5813
Randall+15

Many systems presents multiple generation of cavities showing several episodes of past AGN outbursts, filled with aged radio emitting plasma at low frequency

# Cavities as calorimeters

$$E_{\text{cav}} = E_{\text{thermal}} + PV = \frac{\gamma PV}{\gamma - 1}$$

$$H = \frac{\gamma}{\gamma - 1} pV = \begin{cases} 2.5\, pV, & \text{for } \gamma = 5/3, \\ 4\, pV, & \text{for } \gamma = 4/3, \end{cases}$$



# Cavity timescales

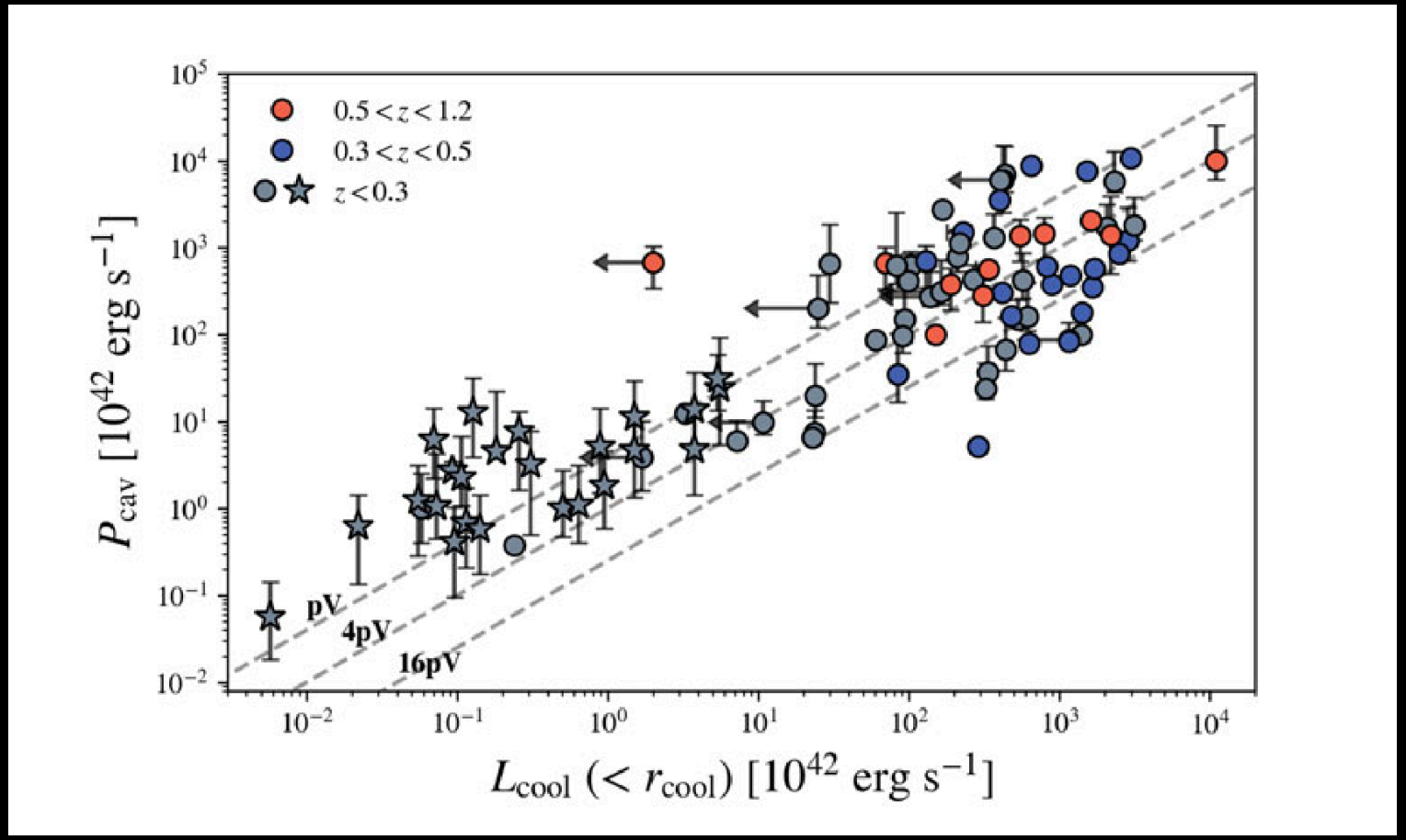
$$t_{\text{buoyant}} = \frac{R}{v_{\text{terminal}}} = R\sqrt{\frac{SC_{\text{D}}}{2gV}} \approx 0.5\frac{R}{r}\sqrt{\frac{r}{g}}$$

$$t_{\text{refill}} = 2\sqrt{\frac{r}{g}}$$

$$t_{\text{cross}} = \frac{R}{c_{\text{s}}}$$

The various age estimates agree within a factor of 2 and they are tipically of the order of $10^7$ yrs

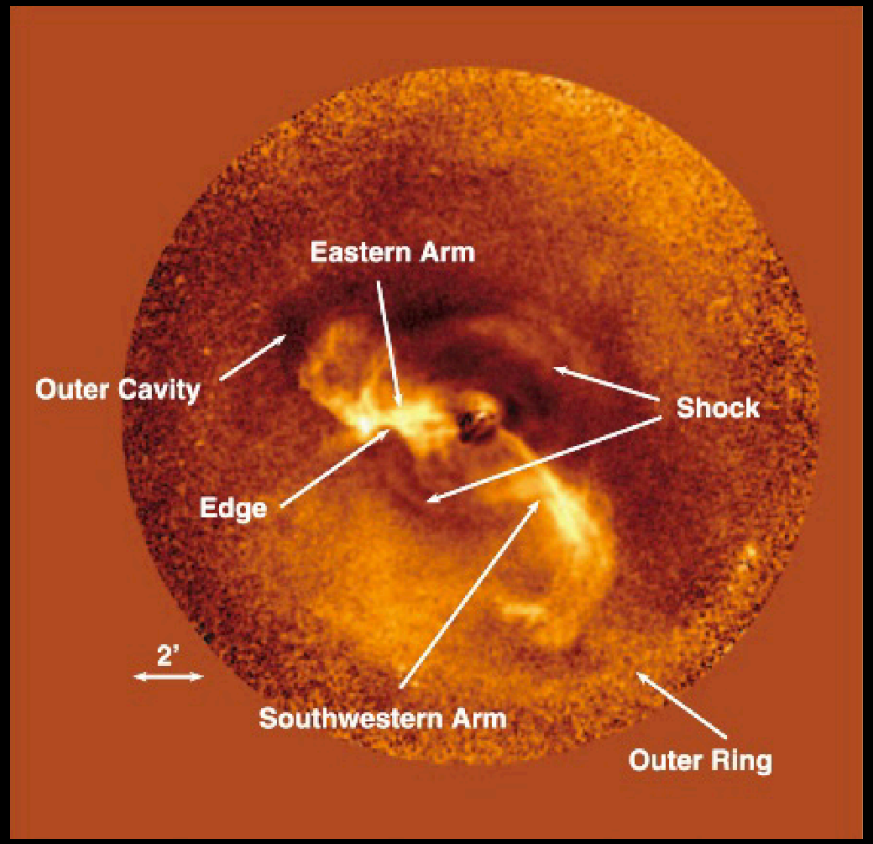
# Cavity power offsets cooling



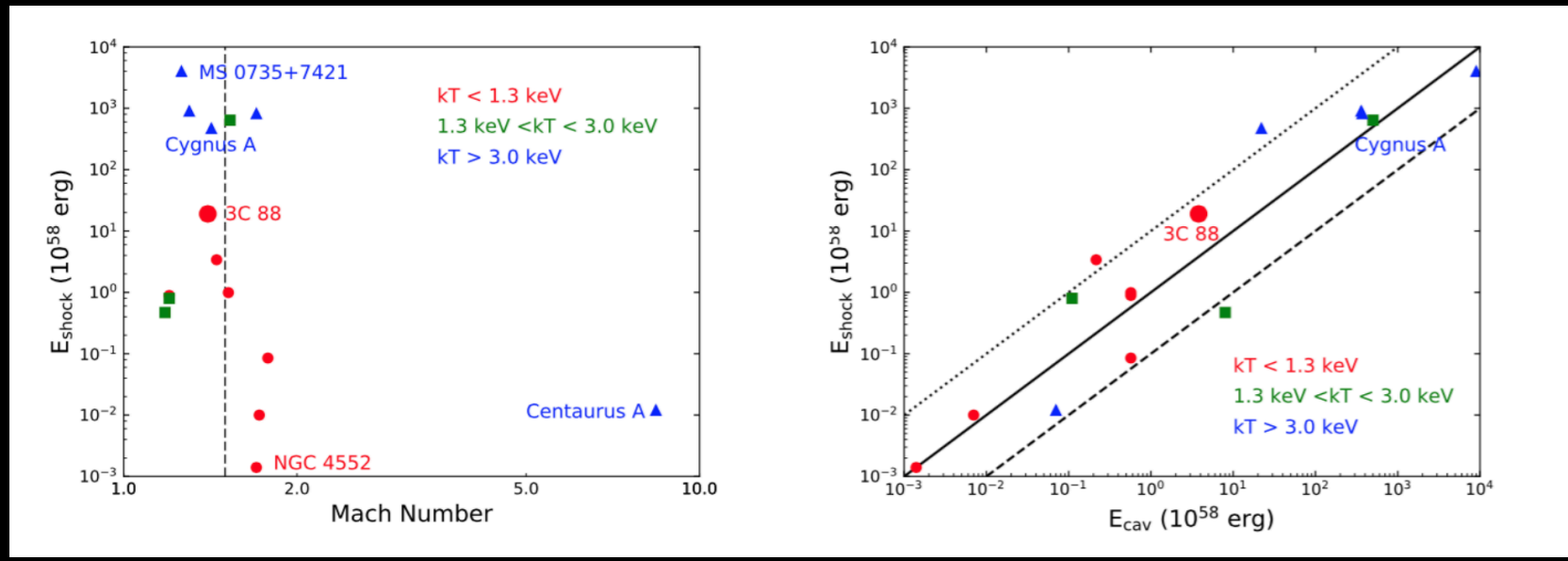

H-L+22

One of the most important results is that the cavity mechanical power can offset cooling, also in high redshift clusters

# Heating by weak shocks



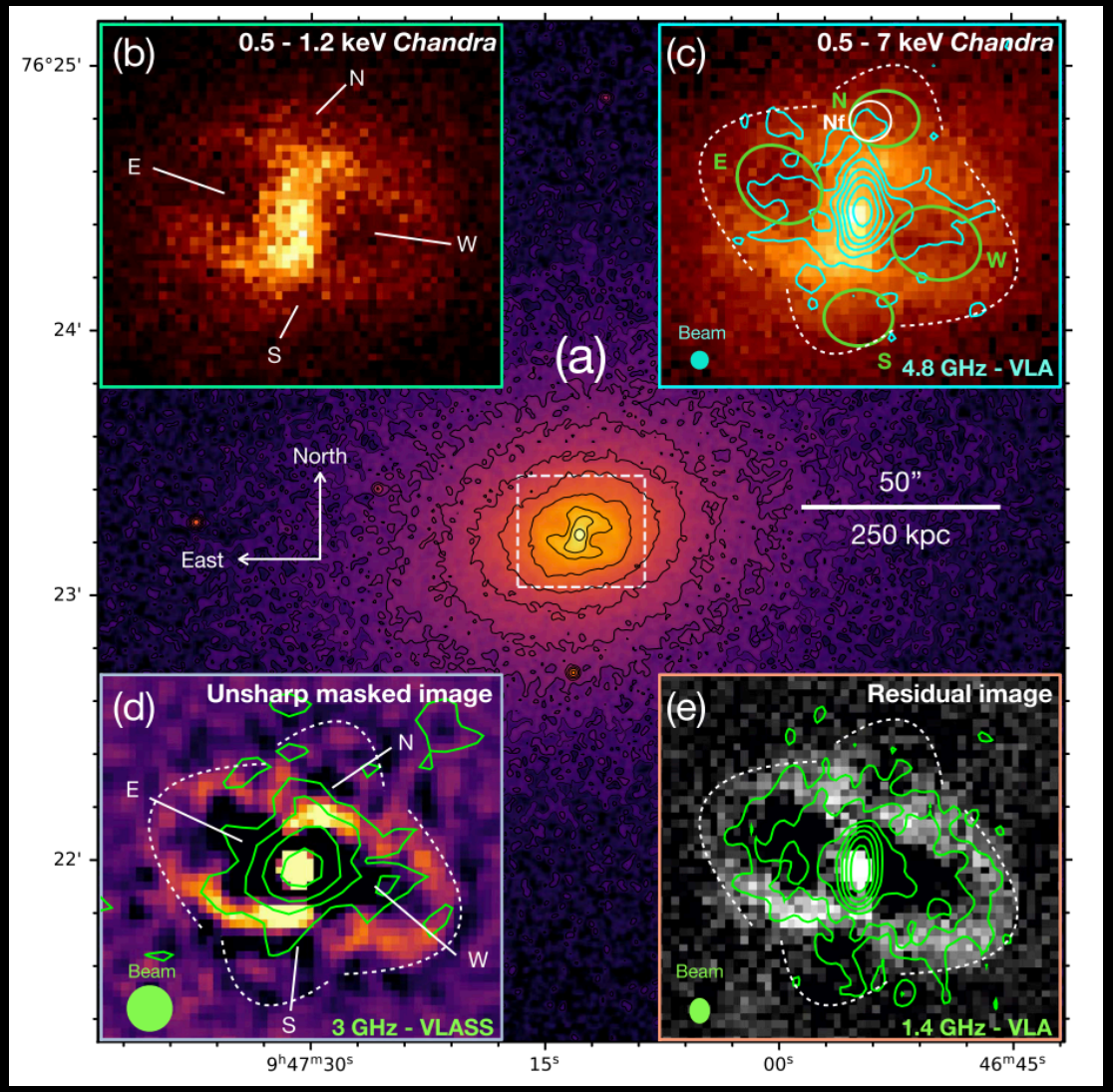

Forman+07

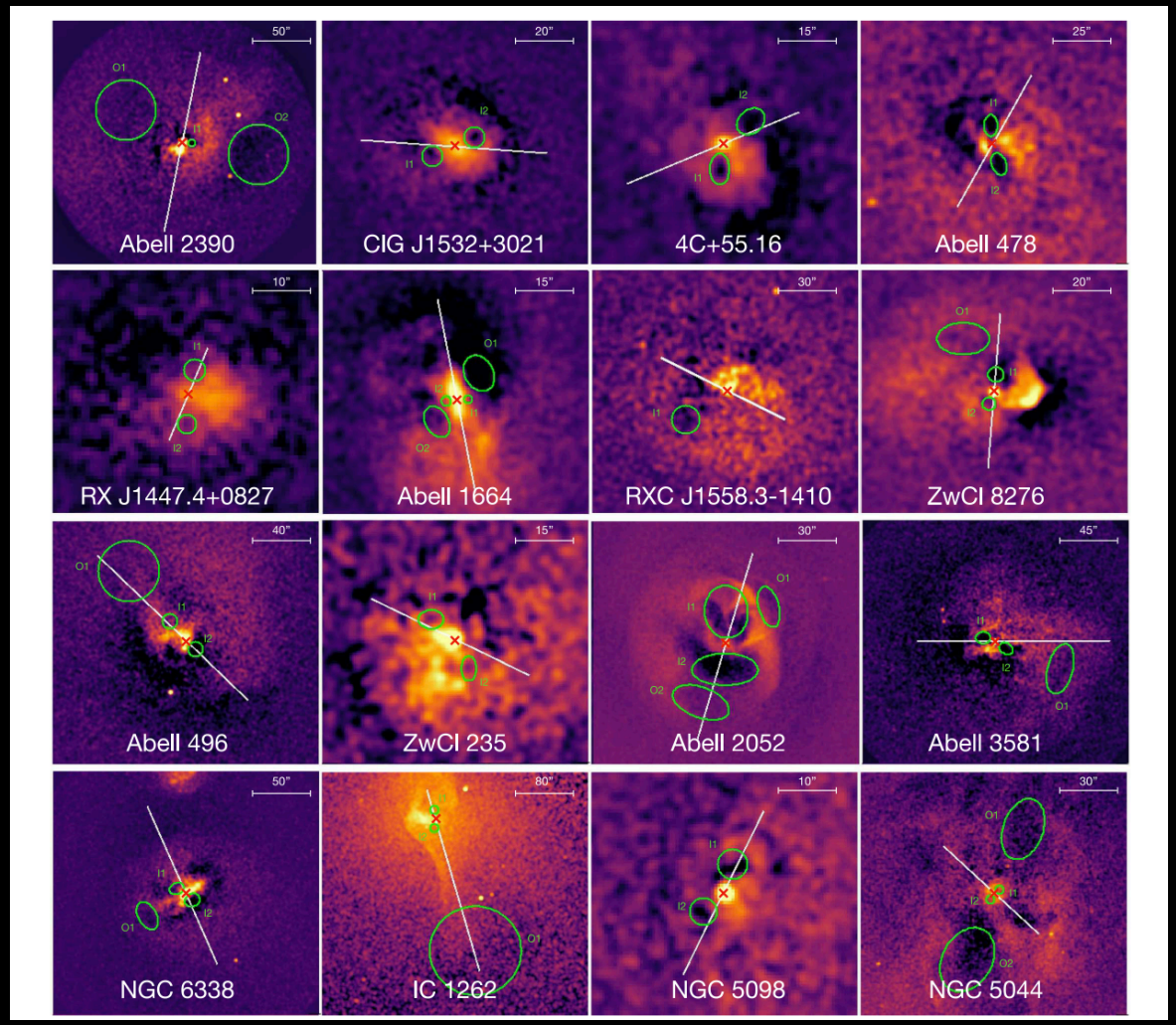



Liu+19

Detective shocks are weak and a single shock can not heat the gas entirely. But multiple genrations may play a role in the inner 30 kpc with shock energy comparable to cavity energy

# Jet Reorientation

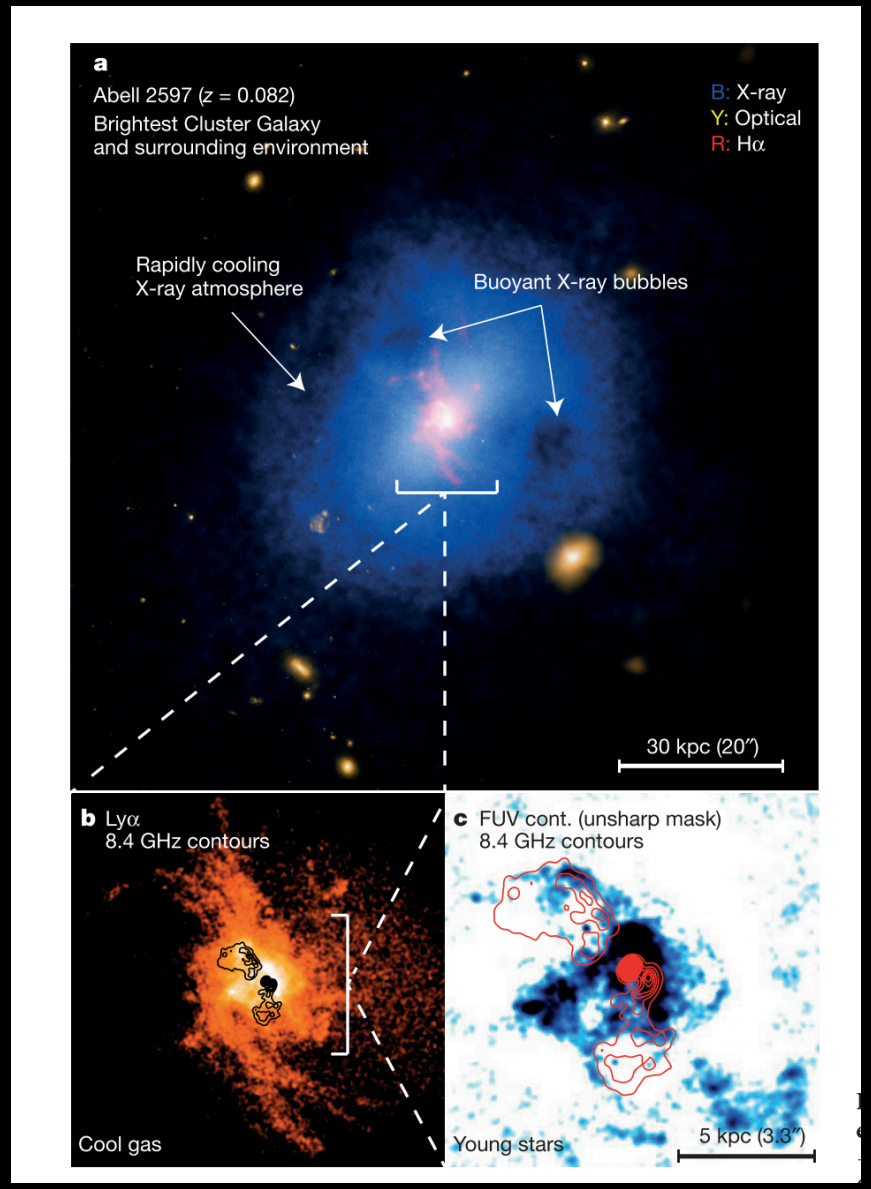


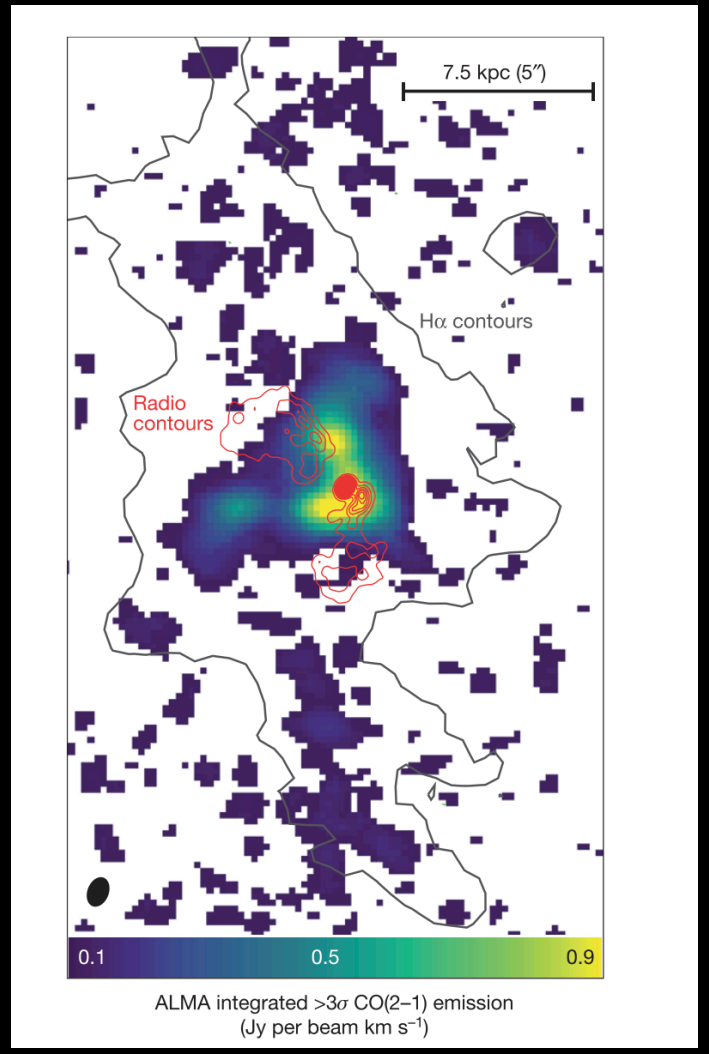




Ubertosi+21, 24

Reorientation of the jest in RBS 797 on a 10 Myr timescale. Found for a 38% fraction of jet-cavity misalignment in a sample of 16 pair of cavities-jet systems

# Feeding of the BH

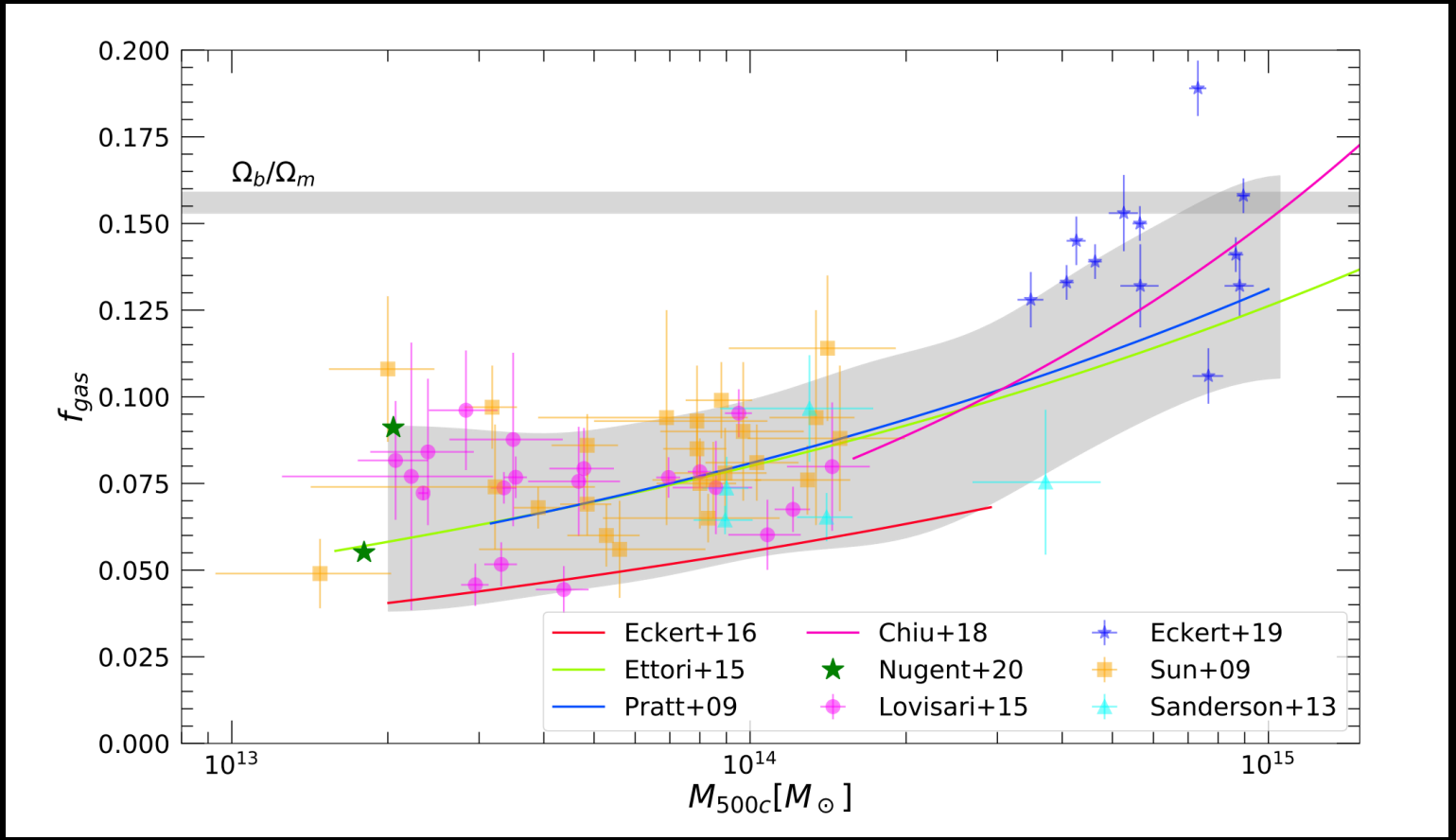



Tremblay+16

Critical problem. Hot Bondi accretion does not seem to work, cahotic cold (and clumpy) accretion (CCA, e.g Gaspari+13) is supported by clear observational evidence of multi-phase gas down to the cold molecular phase traced by CO emission

# Gas fraction – mass relation

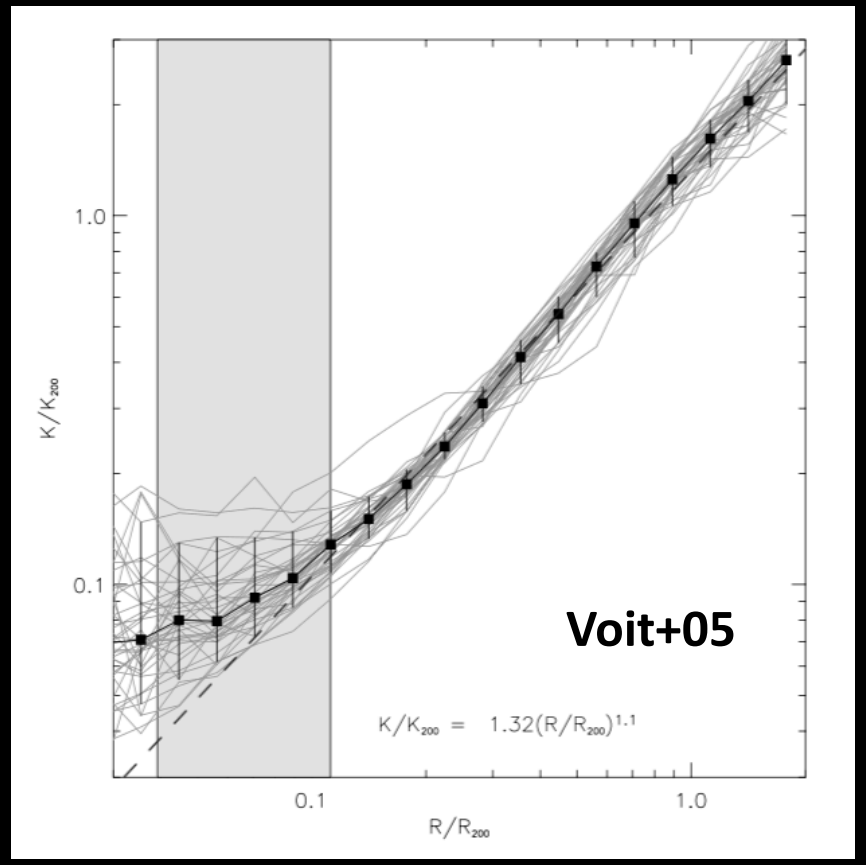


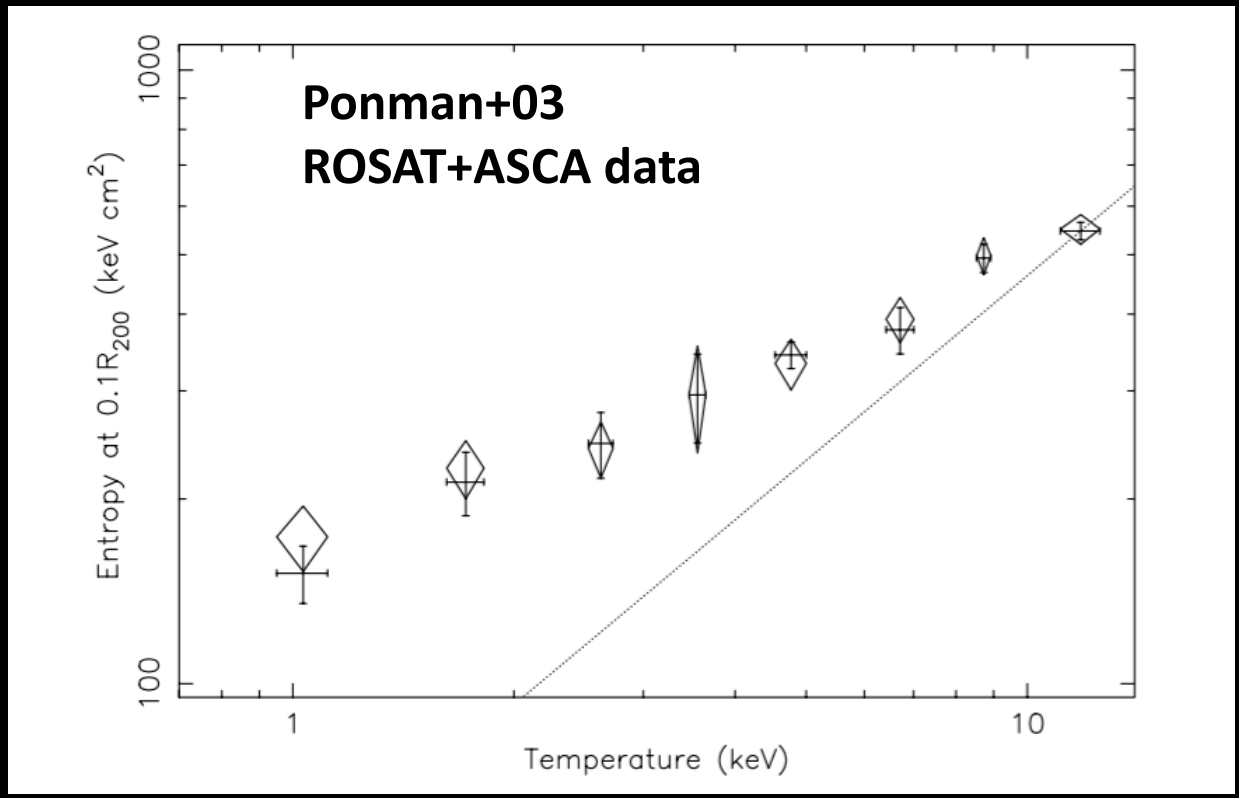

Eckert+21

Depletion of baryons at the group scale, the strongest deviation from a pure gravitational self-similar model for structure formation and the manifestation of non-gravitational AGN feedback. key observational constrain for modeling AGN feedback in cosmological simulations.

# Entropy profiles

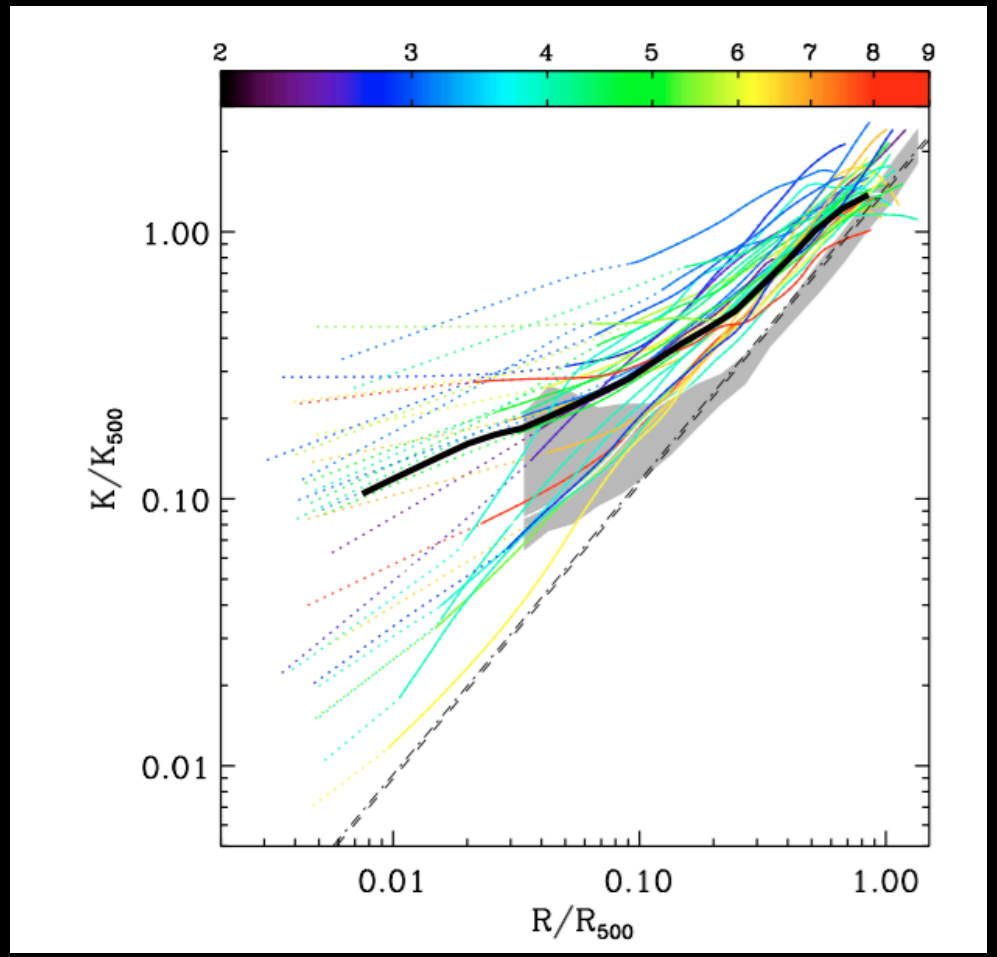
- Entropy, $S=kT/n_e^{2/3}$, is a key quantity related to non-gravitational feedback. Its radial profiles in objects of different masses reveals the details of the various astrophysical processes



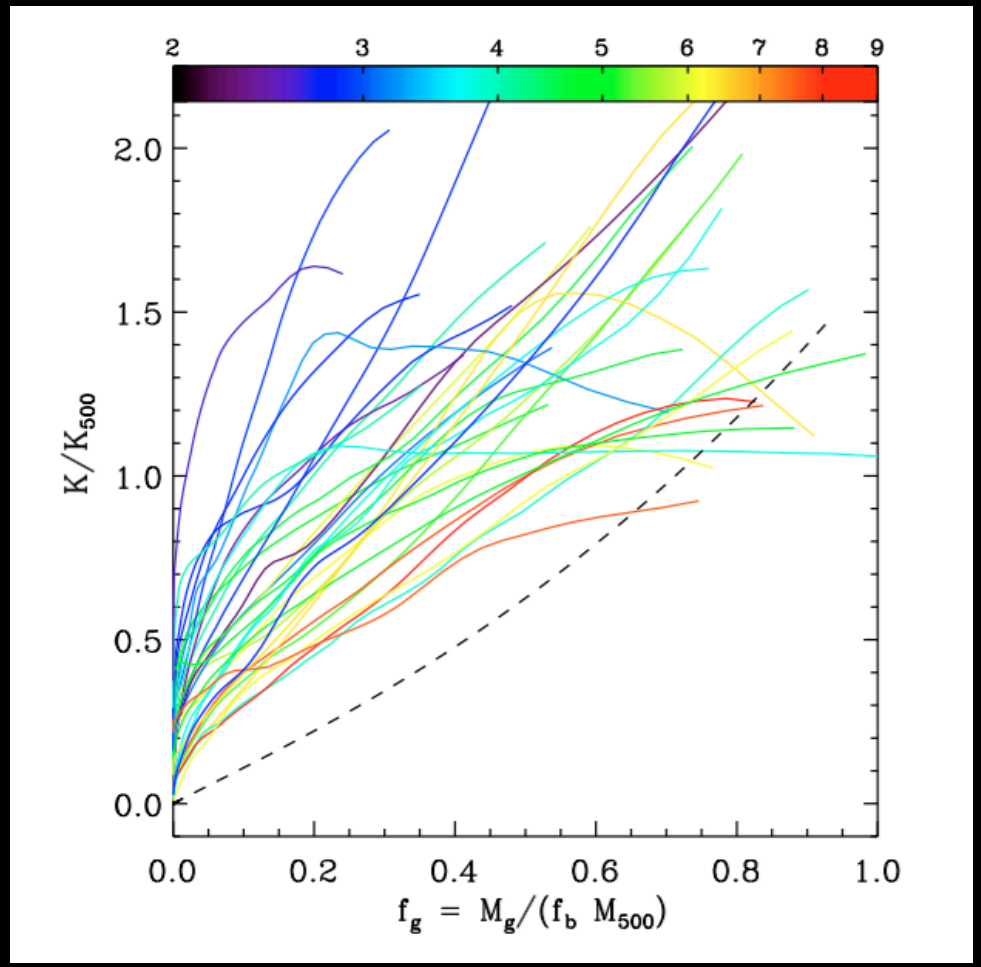



# Entropy profiles

- In the REXCESS sample of 31 objects, XMM measurements allowed to show a radial and mass dependent excess entropy.

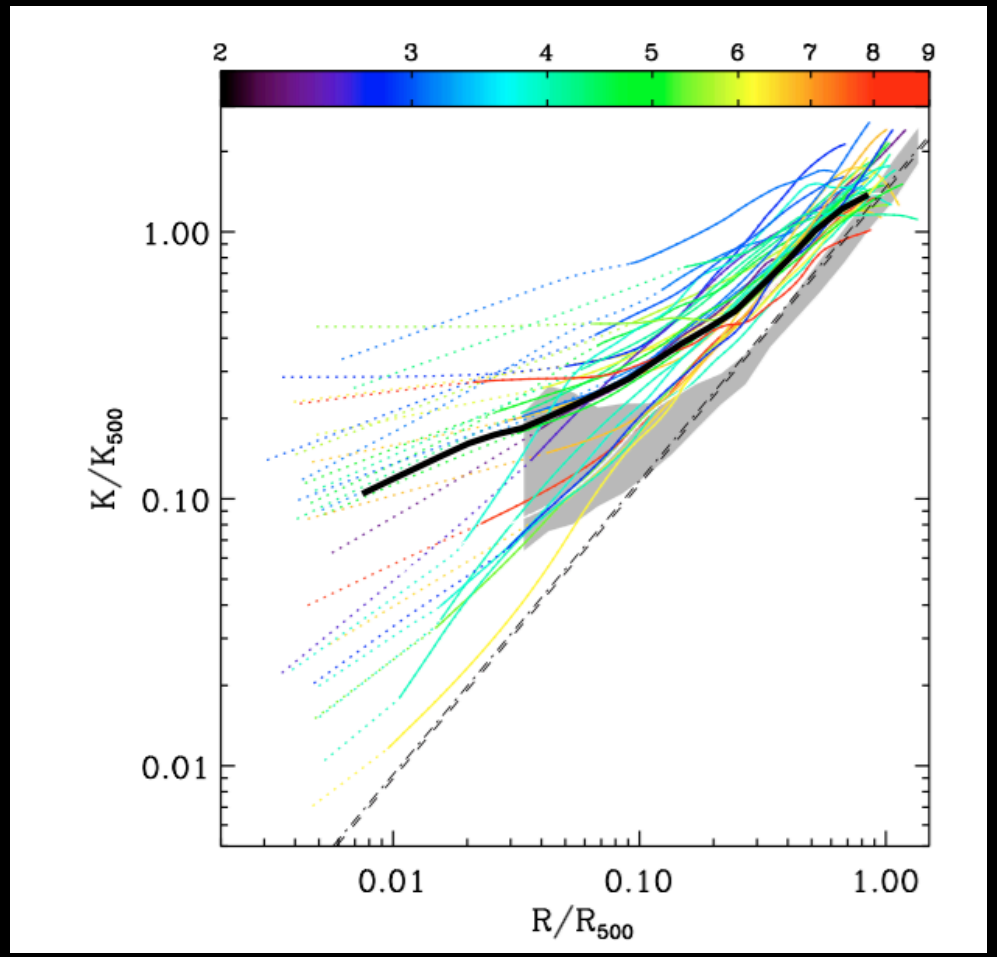



Pratt+10

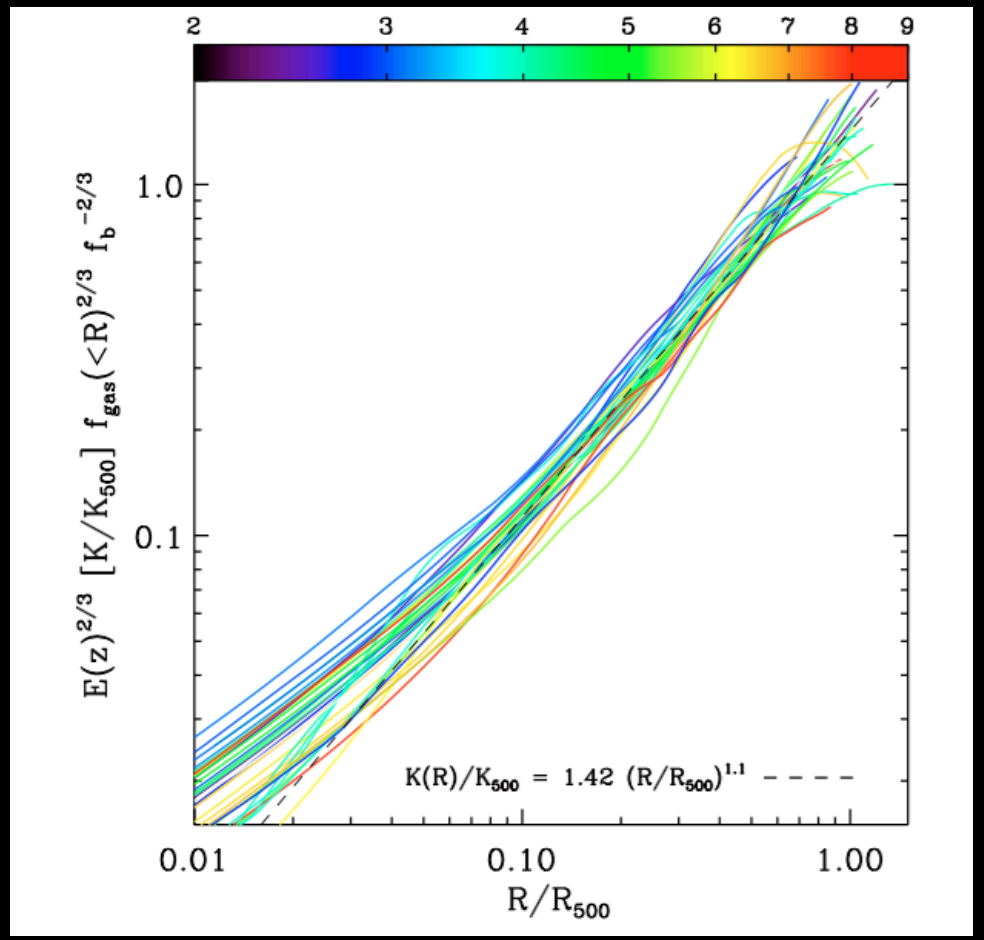


# Entropy profiles

- When rescaled by the $f_{gas}$ entropy profiles have a much reduced scatter in close agreement with gravity-only prediction.

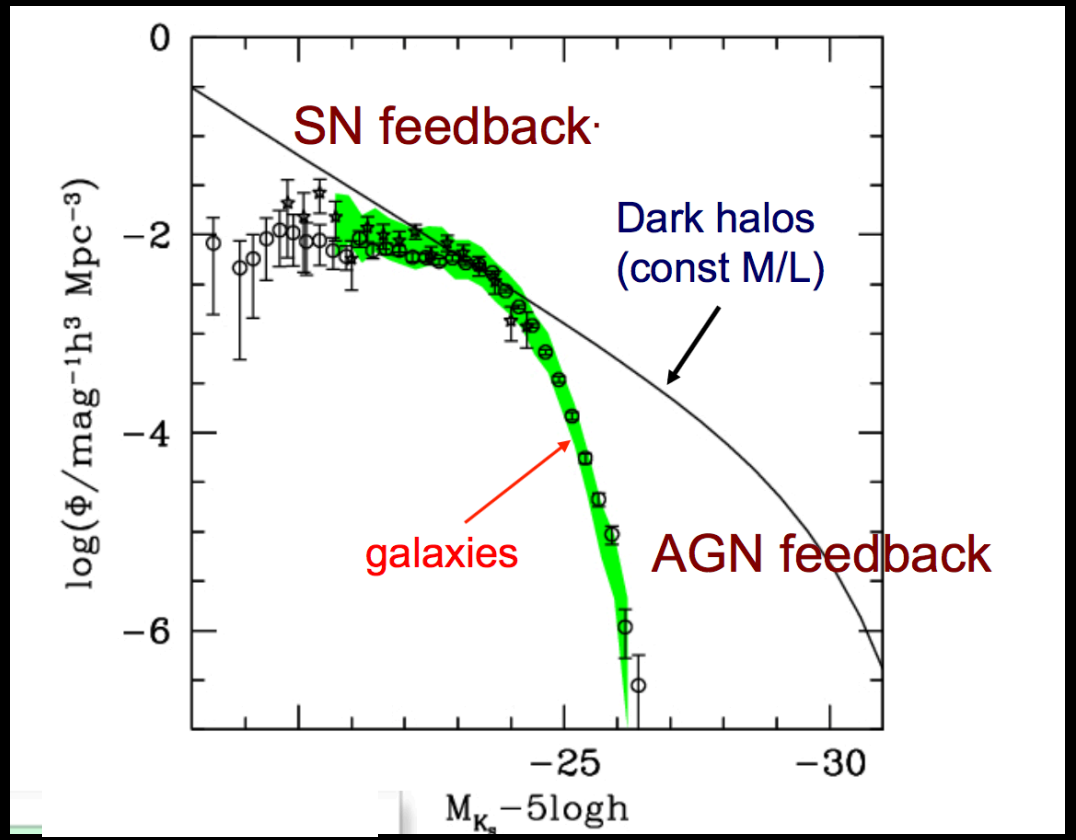



Pratt+10

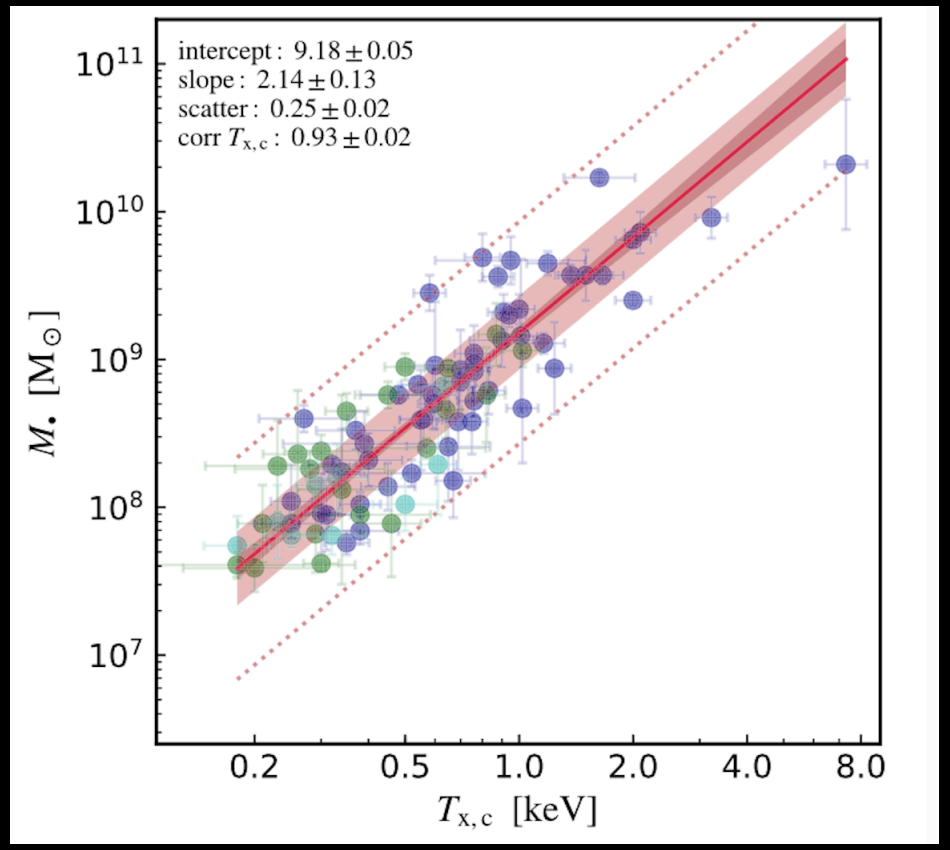


# Important implications of AGN feedback

- AGN feedback has broad astrophysical implications for galaxy formation, explaining the truncation of the high end of the luminosity function, the symbiosis of BHs and stellar and gaseous halos




Benson+03

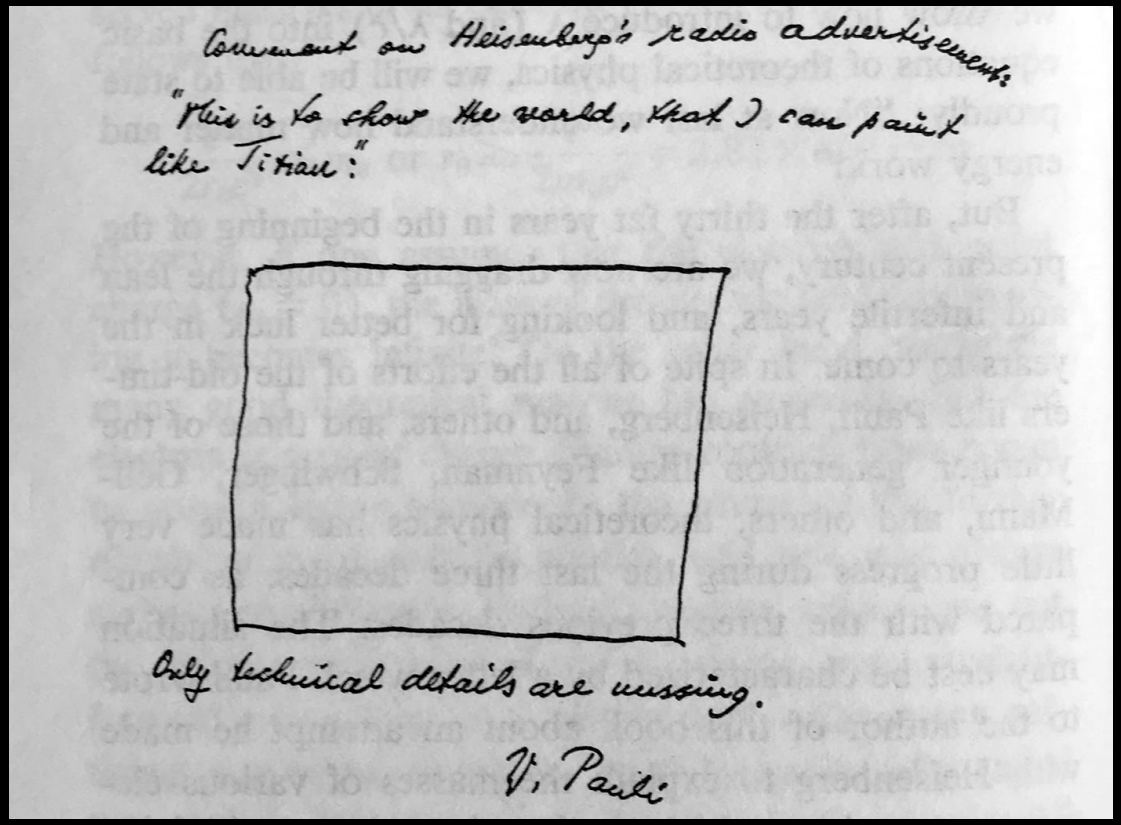



Gaspari+19

# Summary and open questions

The editors of *Discover Magazine*'s Winter 2007 special issue "Unseen Universe" posed the following question to Martin Rees: "Is there any particular image that you saw recently that reminded you anew of just how much progress we've made?" Rees's response provides a succinct history of this field. "I've been especially impressed by the X-ray images of galaxy clusters which are now becoming available from the *Chandra* satellite and other instruments. We see gas being churned up by explosions and huge black holes in the center of the cluster. We see how it's cooling down and how the cooling is being balanced by tremendous outbursts of jets and bubbles of hot gas. This is something that most people didn't suspect was happening until these images revealed it."

# Summary and open questions




- What is the nature of the plasma inside the cavities ?
- How really is the energy spread out isotropically through the core ?
- What is the feeding mechanism(s) of the BH ?
- When did the feedback loop started (protoclusters at z>2) ?