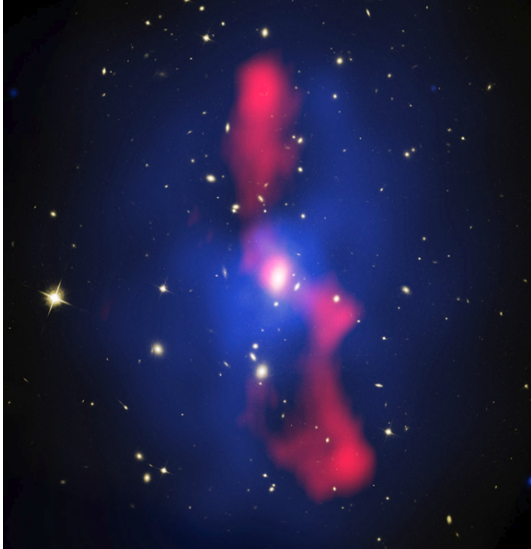


# The balance of cooling + AGN heating in galaxy cluster cores



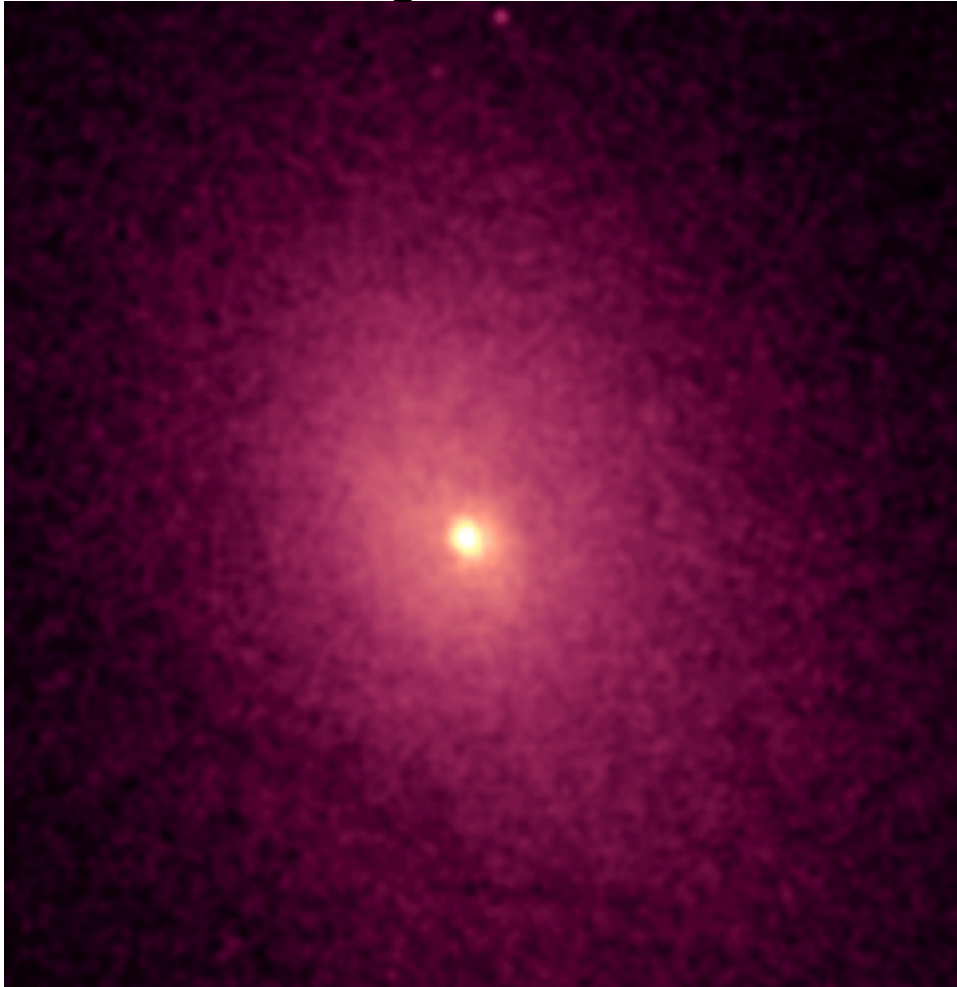
Helen Russell  
Brian McNamara  
Alastair Edge  
Rupal Mittal  
Clif Kirkpatrick  
Andy Fabian  
Jeremy Sanders  
Chris O'Dea

# Outline

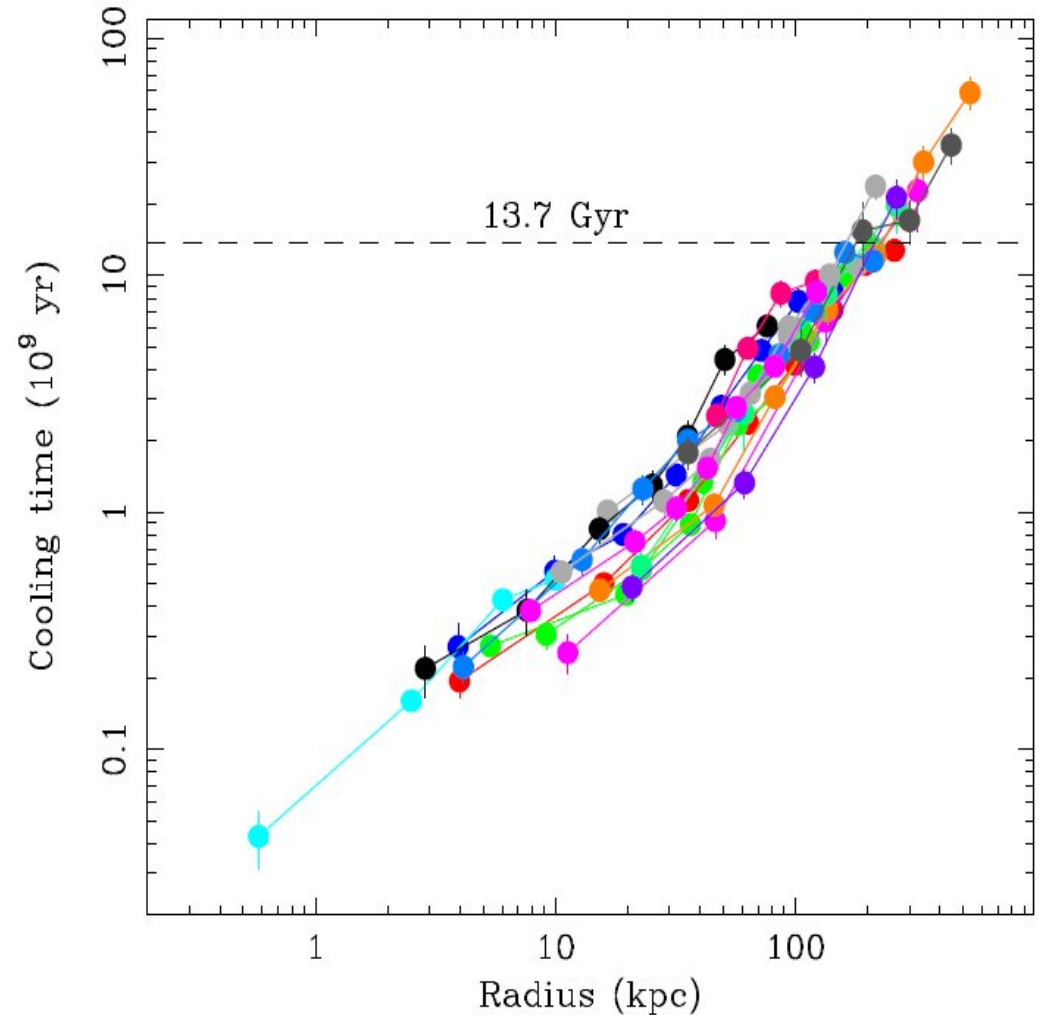
- Radiative cooling in clusters
- AGN cavity heating and metal outflows
- Tracing residual cool gas with Spitzer and Herschel
- Future observations with Alma

# Radiative cooling in cluster cores

Chandra image of Abell 2029



Lewis et al. 2003, Allen et al. 2004

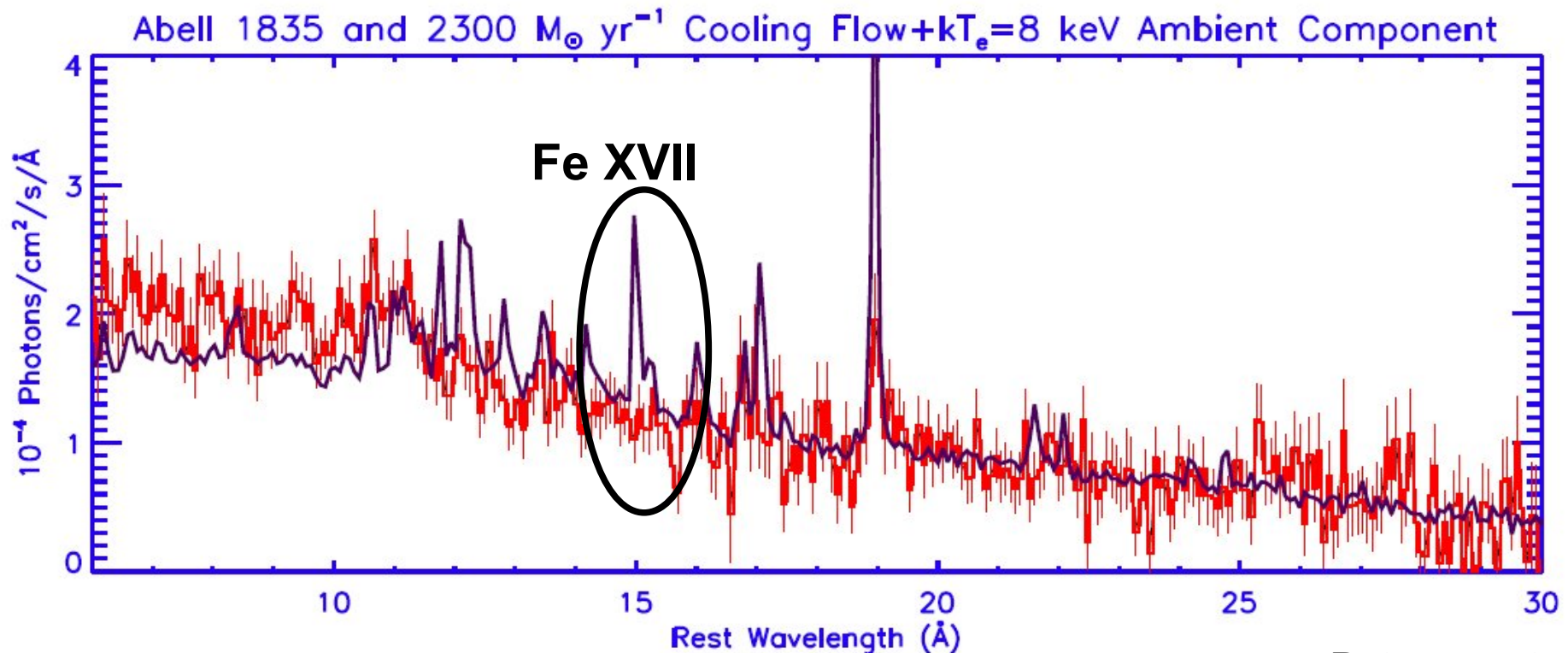


Voigt & Fabian 2004

- 100 – 1000 solar masses per year cooling?

# Reduced cooling

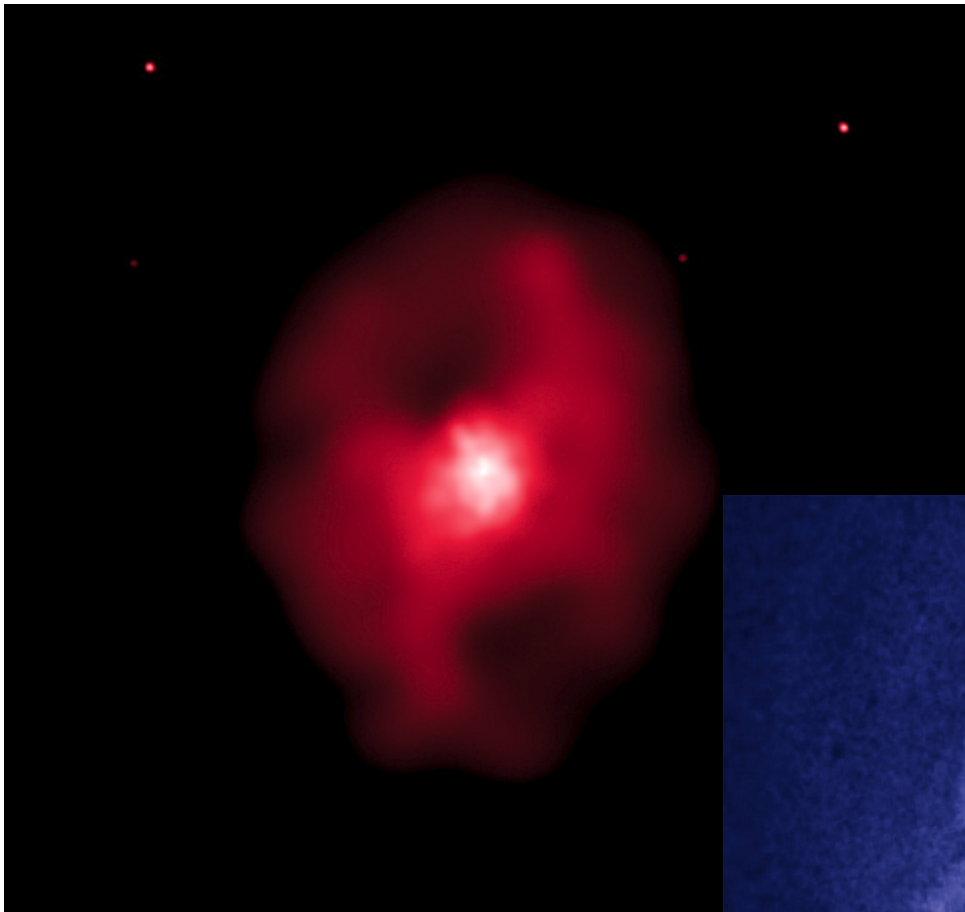
- Searches for vast reservoir of molecular gas and star formation find less than 10% of that expected
- High resolution X-ray spectra find reduced cooling



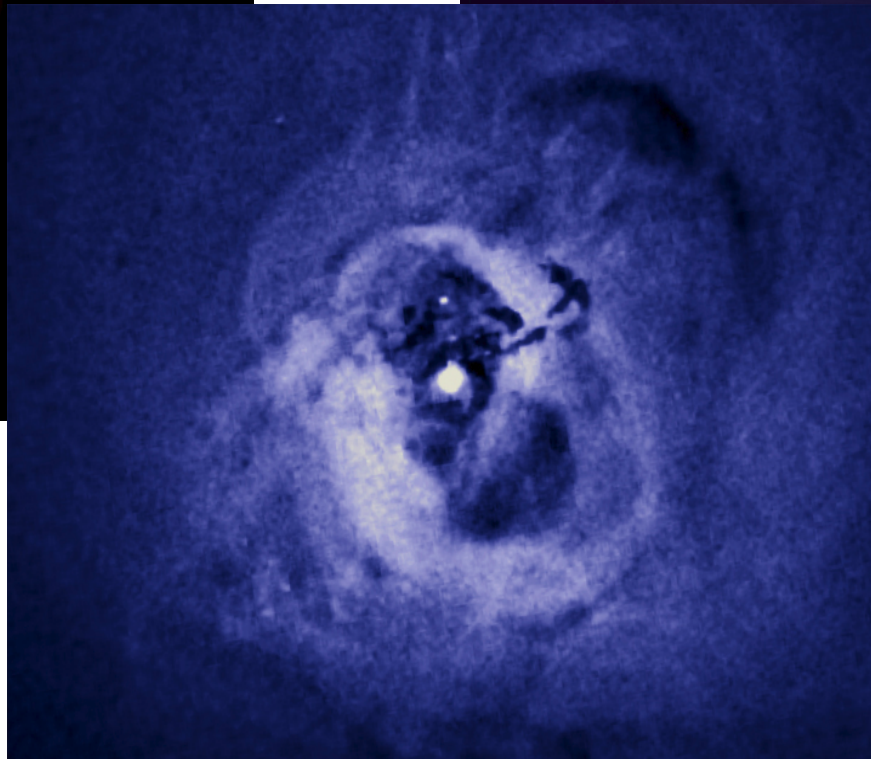
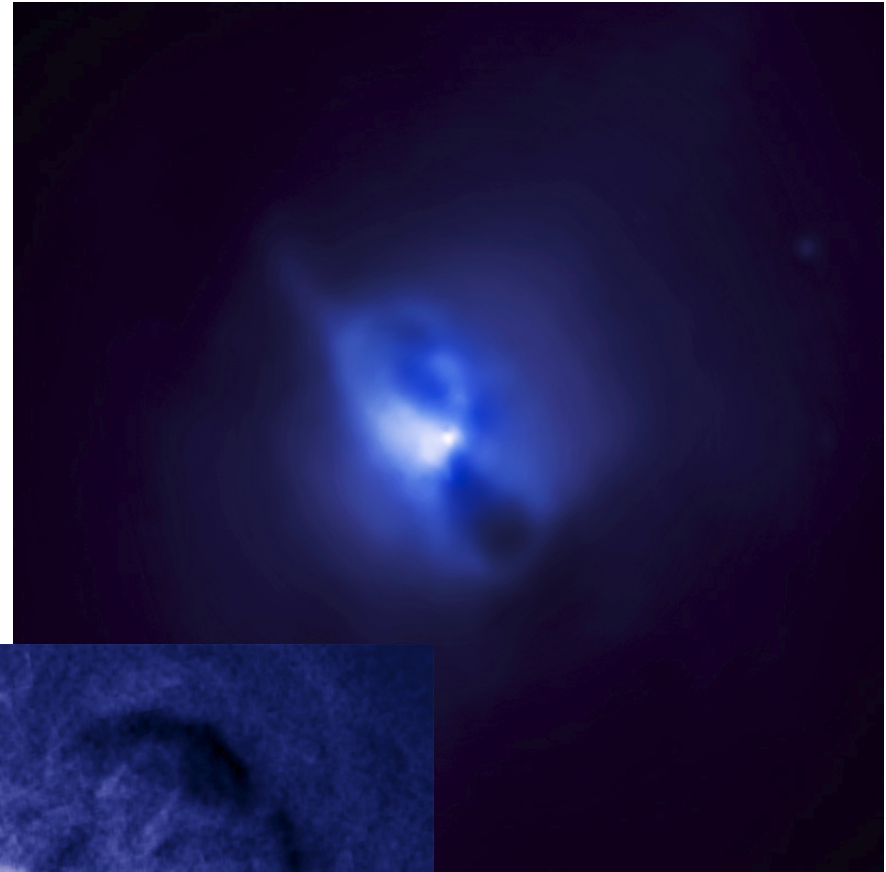


# Cavity heating

MS0735, McNamara et al. 2005



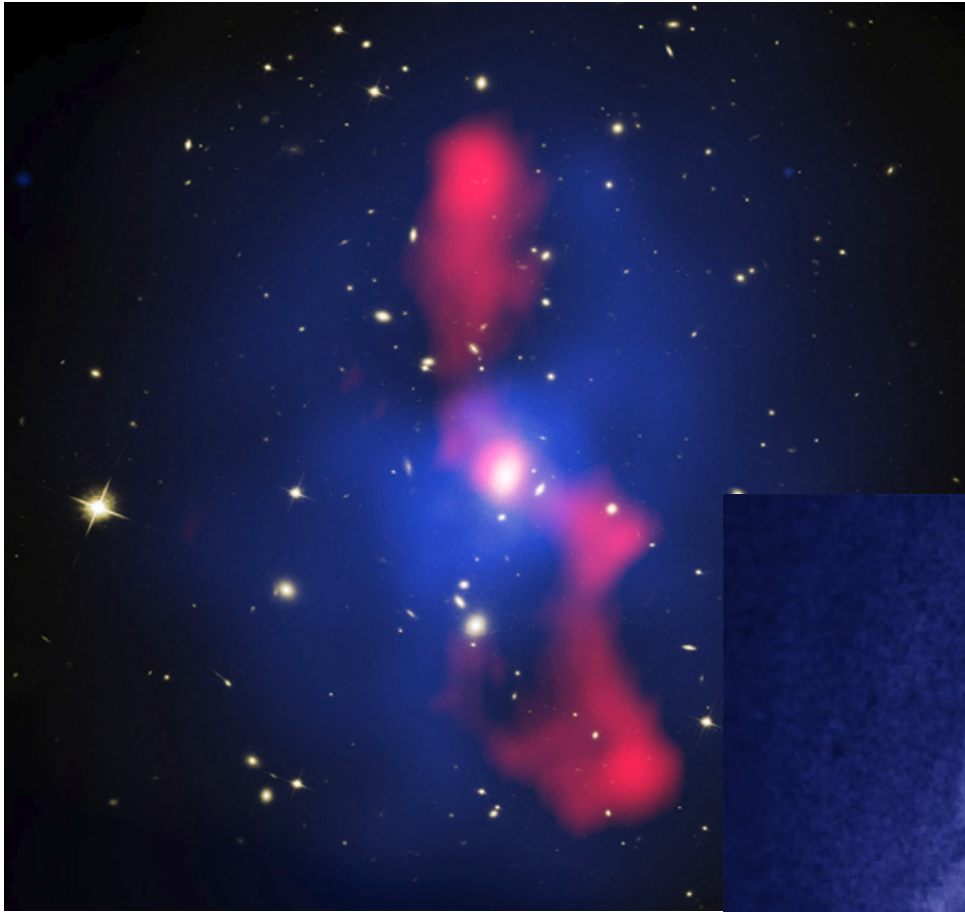
Hydra A, Kirkpatrick et al. 2009



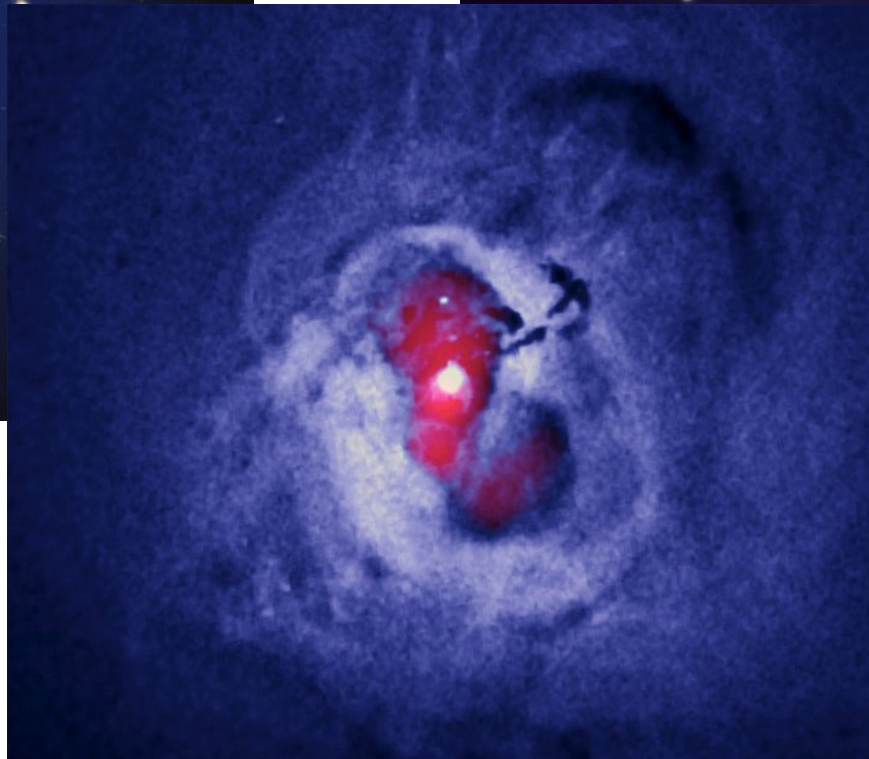
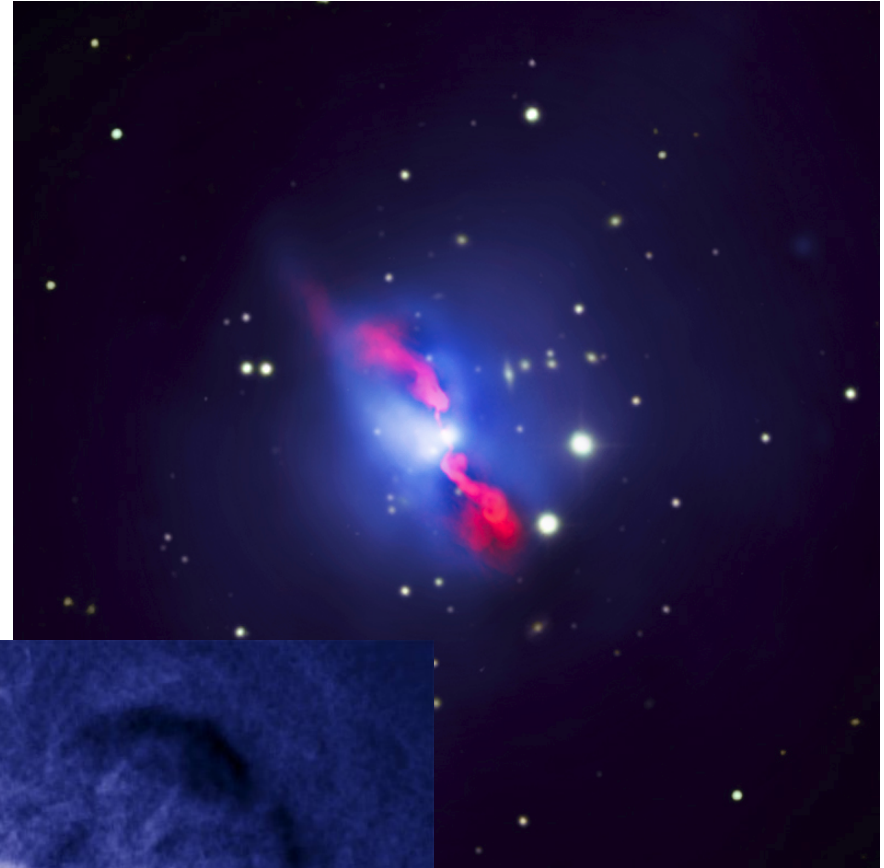
Perseus  
Fabian et al. 2008

# Cavity heating

MS0735, McNamara et al. 2005



Hydra A, Kirkpatrick et al. 2009

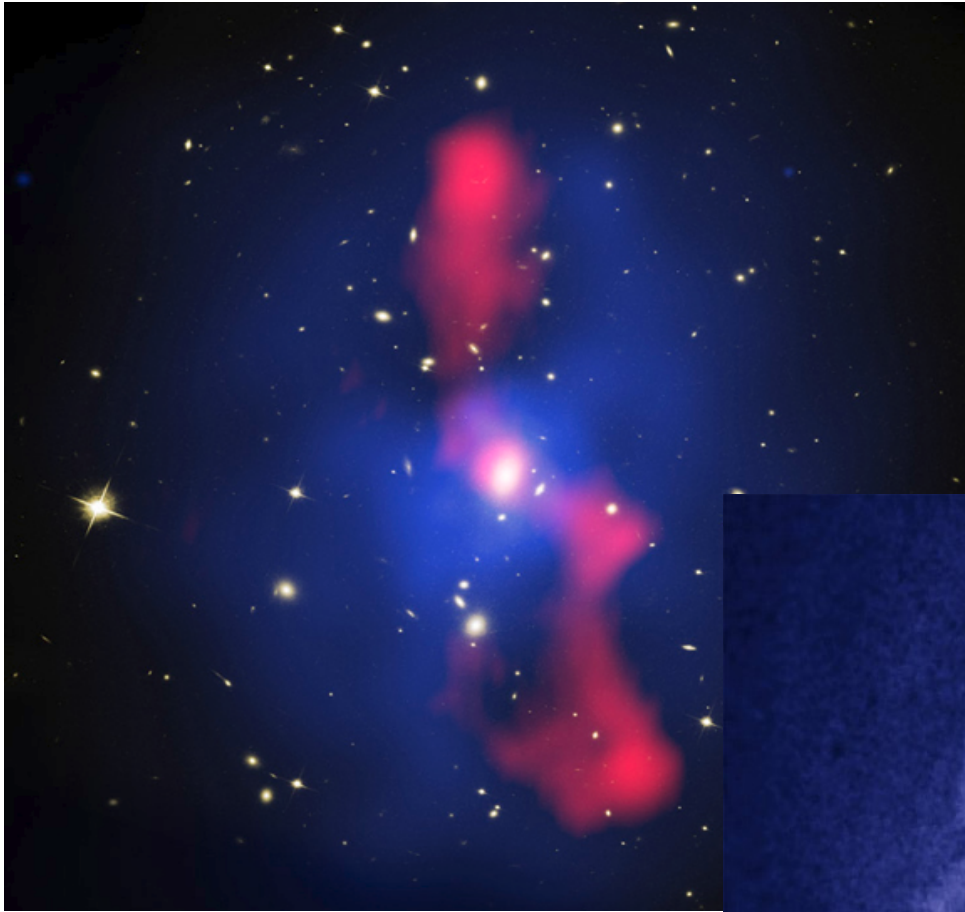


Perseus  
Fabian et al. 2008



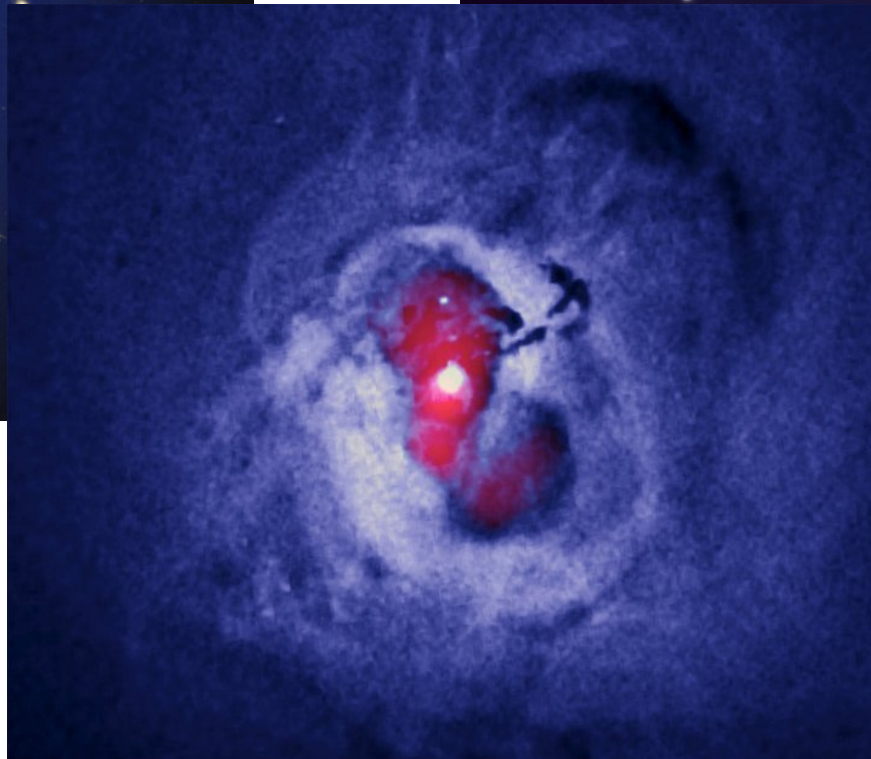
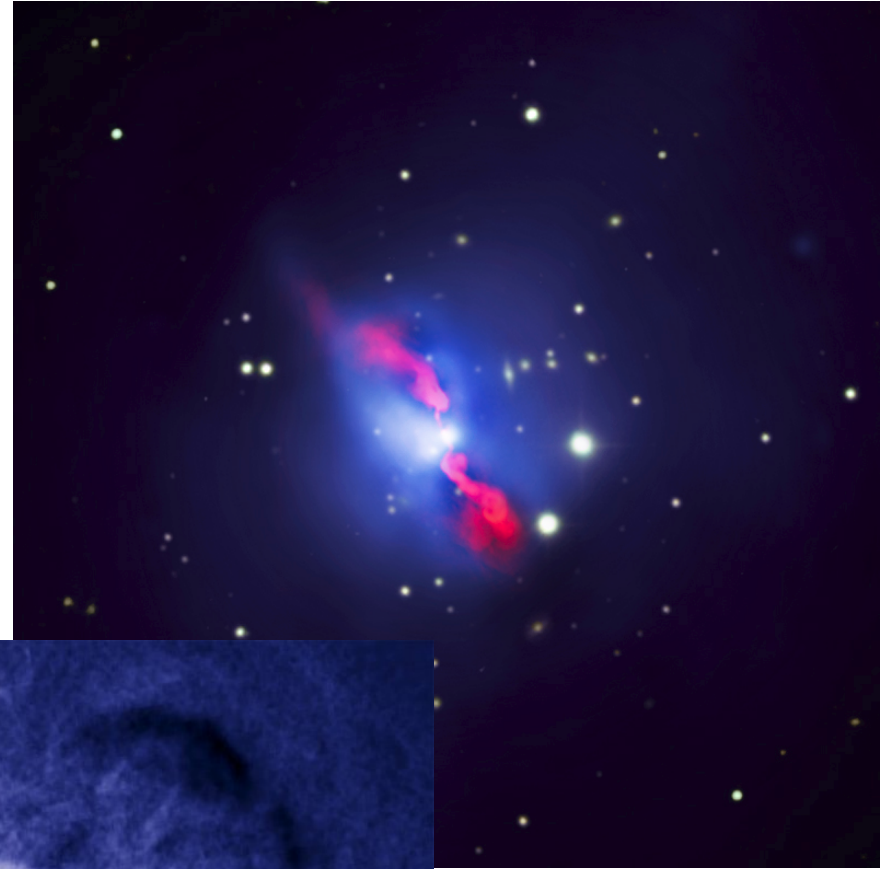
# Cavity heating

MS0735, McNamara et al. 2005



$$E = 4PV$$

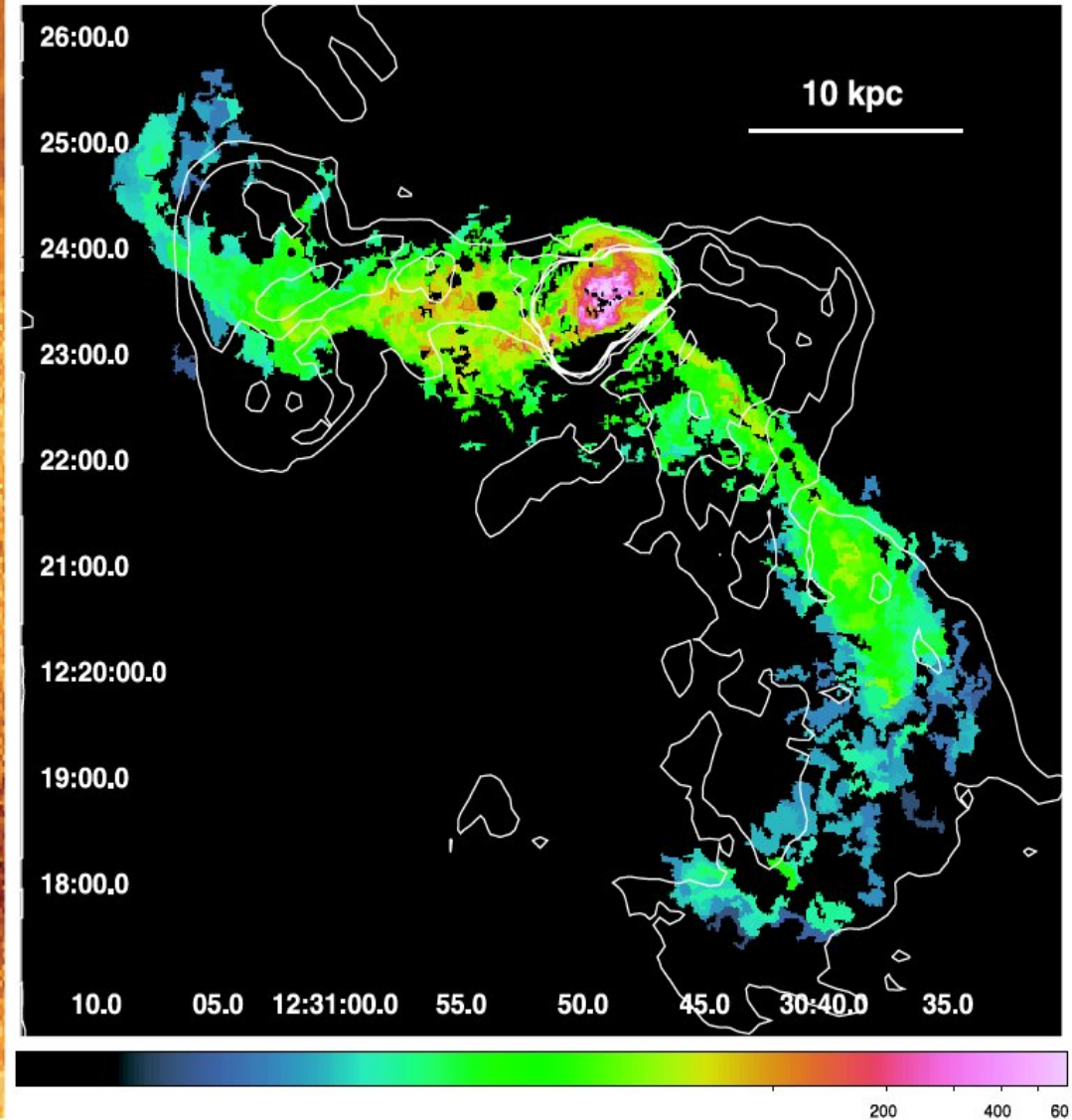
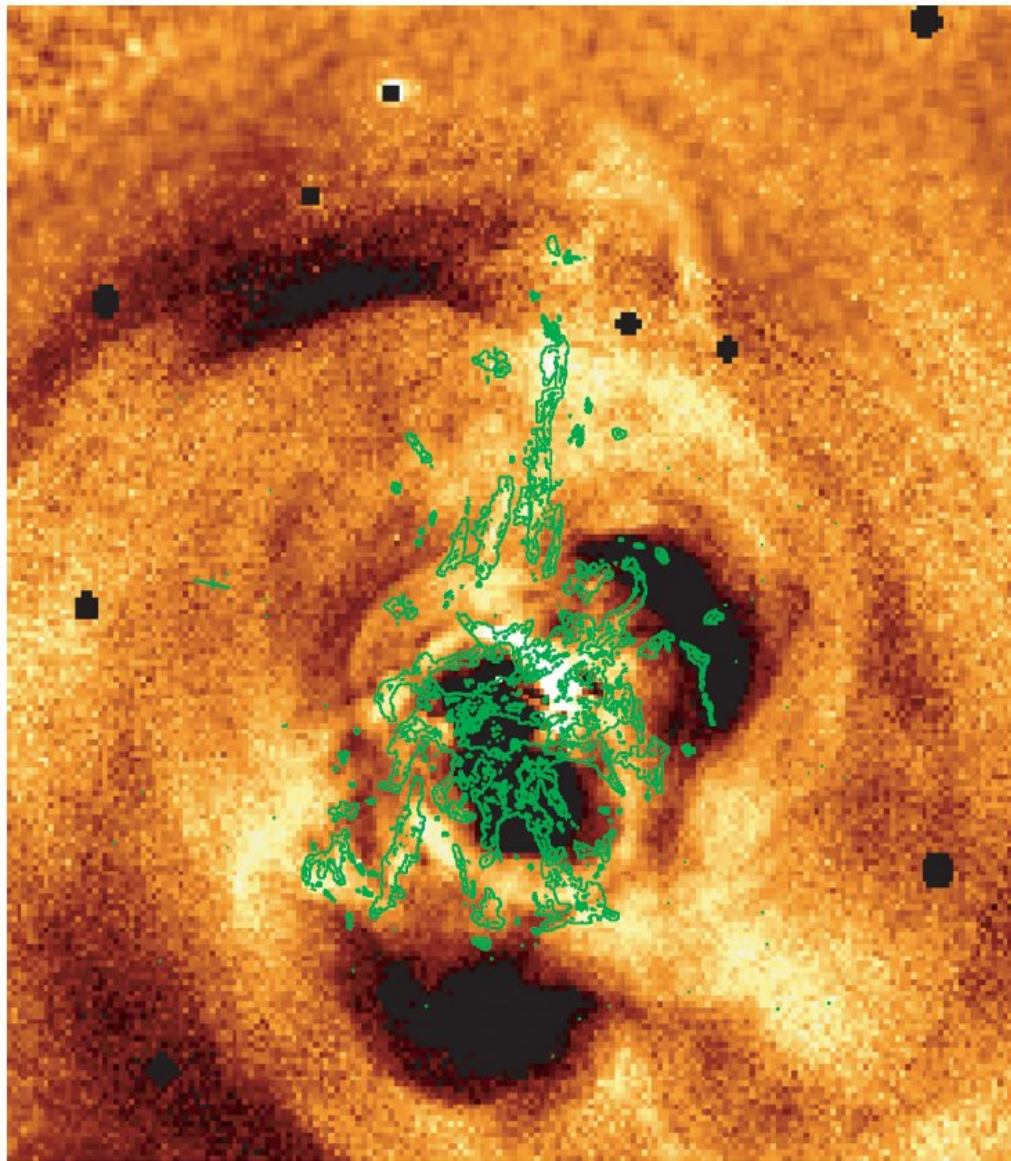
Hydra A, Kirkpatrick et al. 2009



Perseus  
Fabian et al. 2008

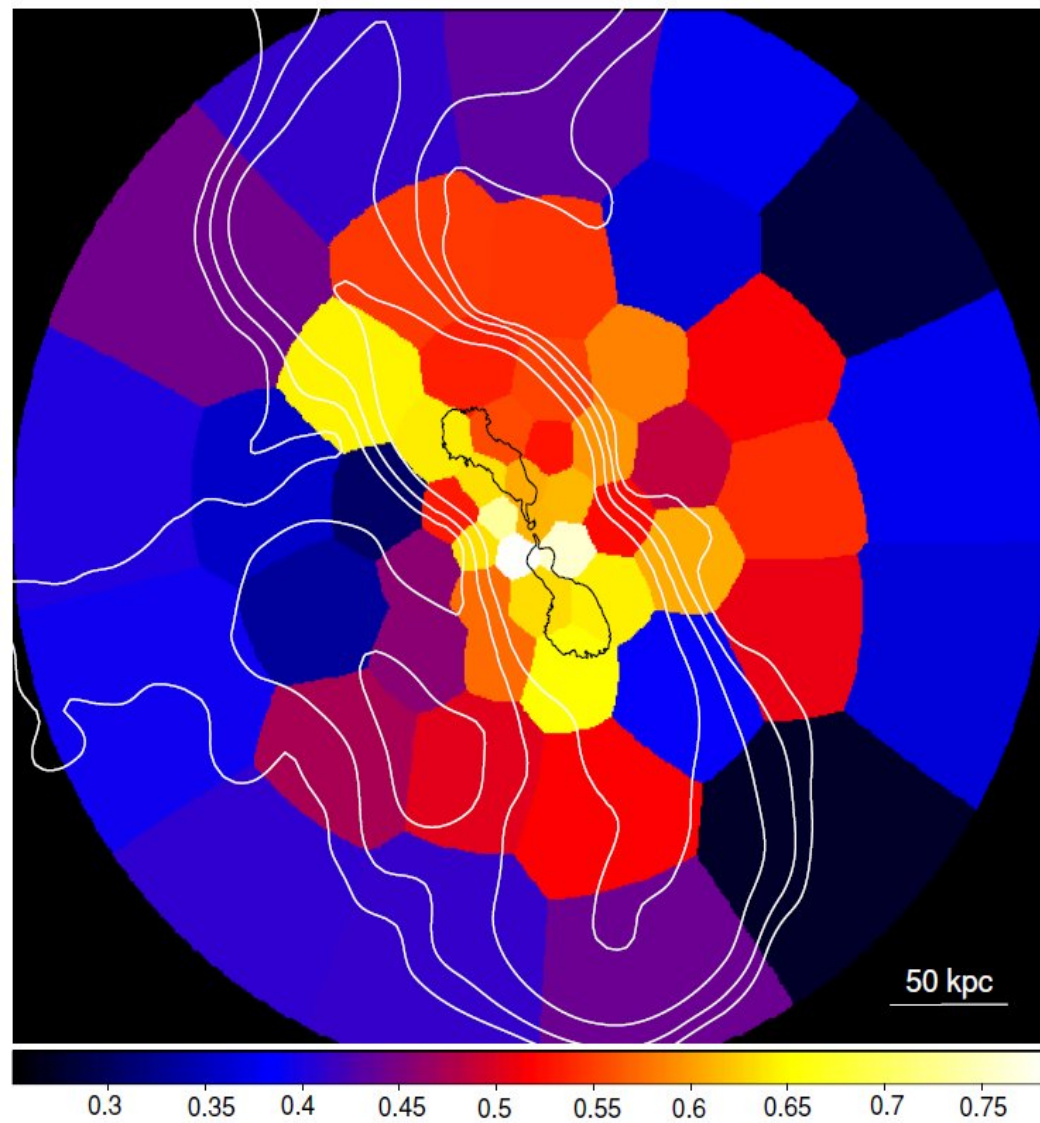
# Gas dynamics

H $\alpha$

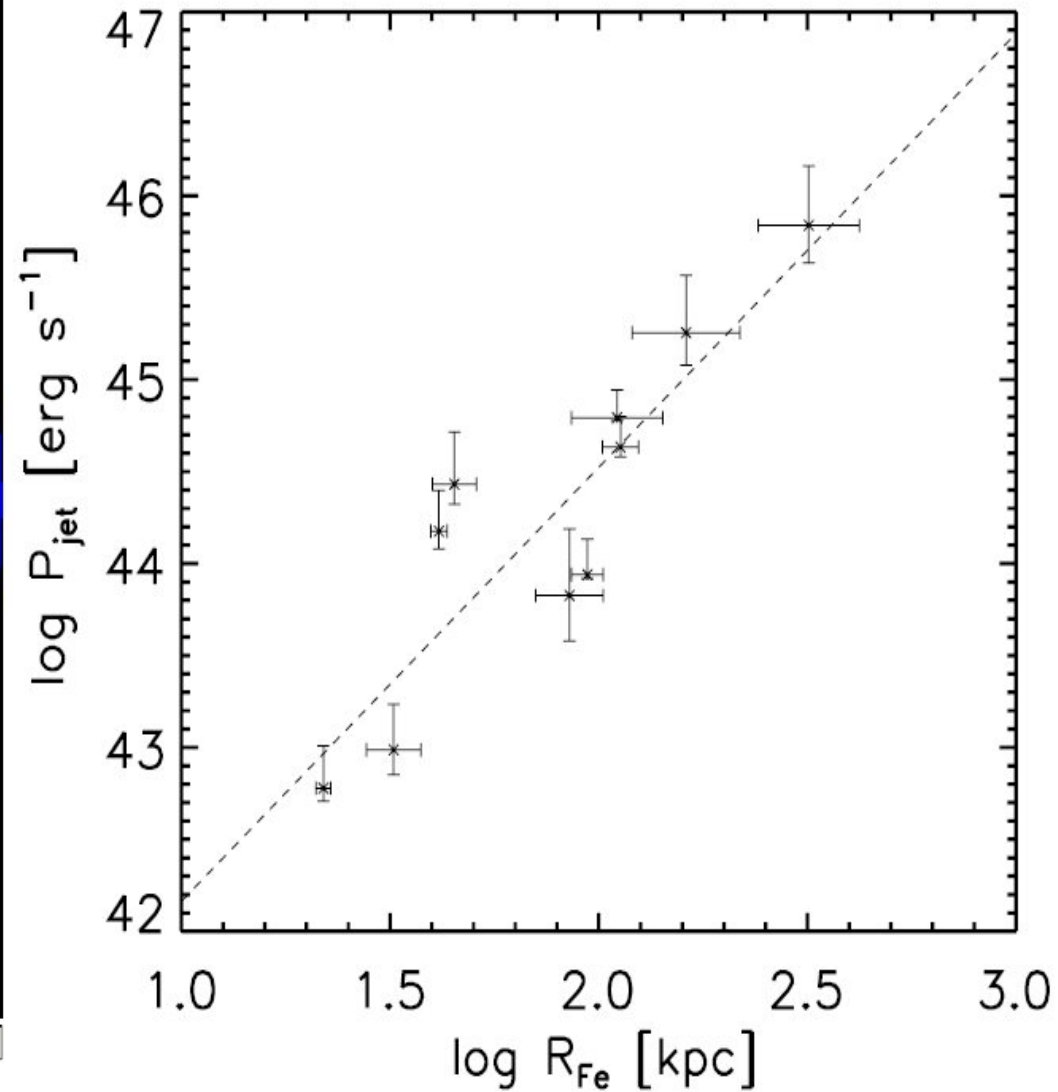




# Metal outflows

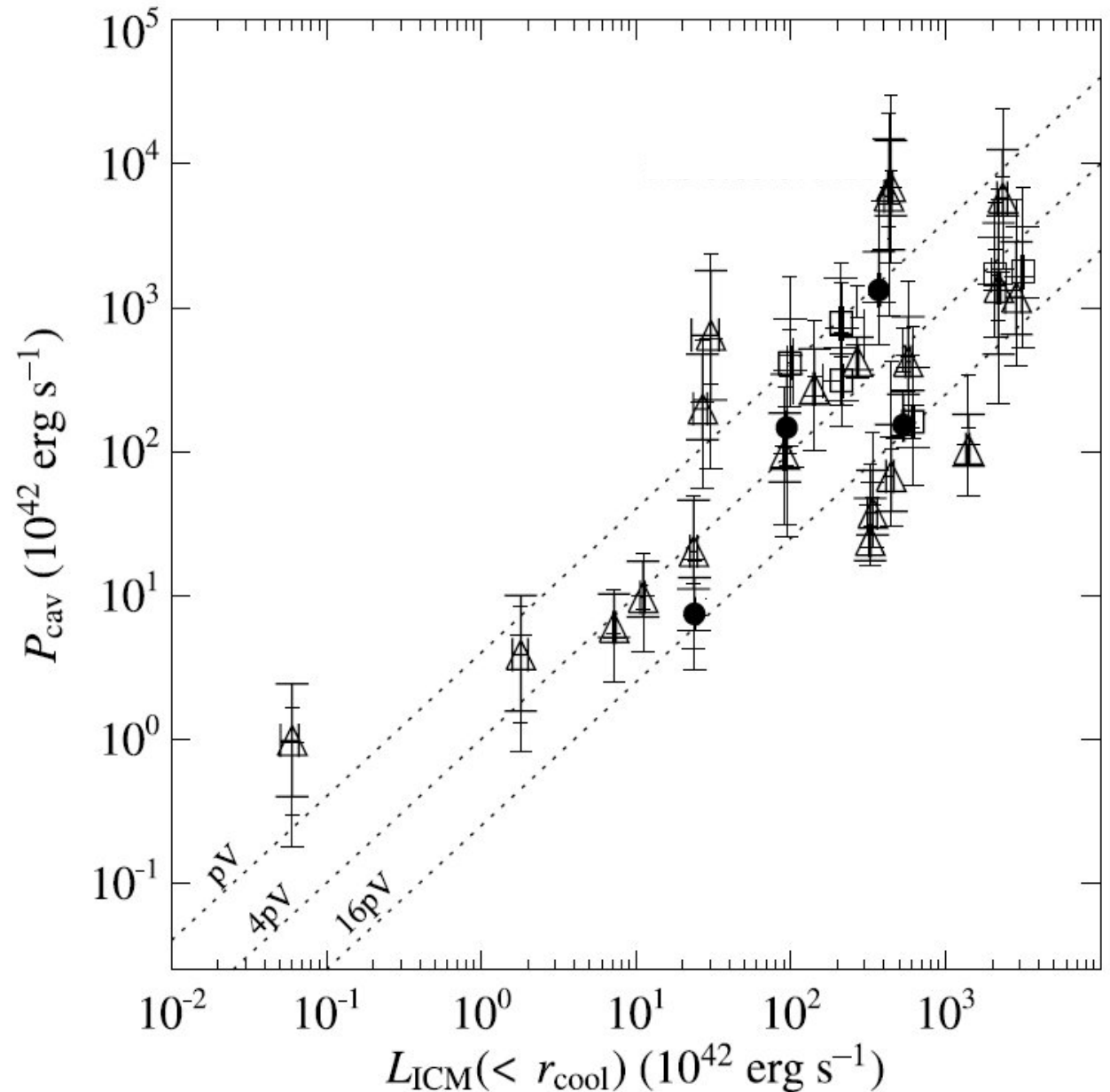


→ 100 solar masses per year outflow



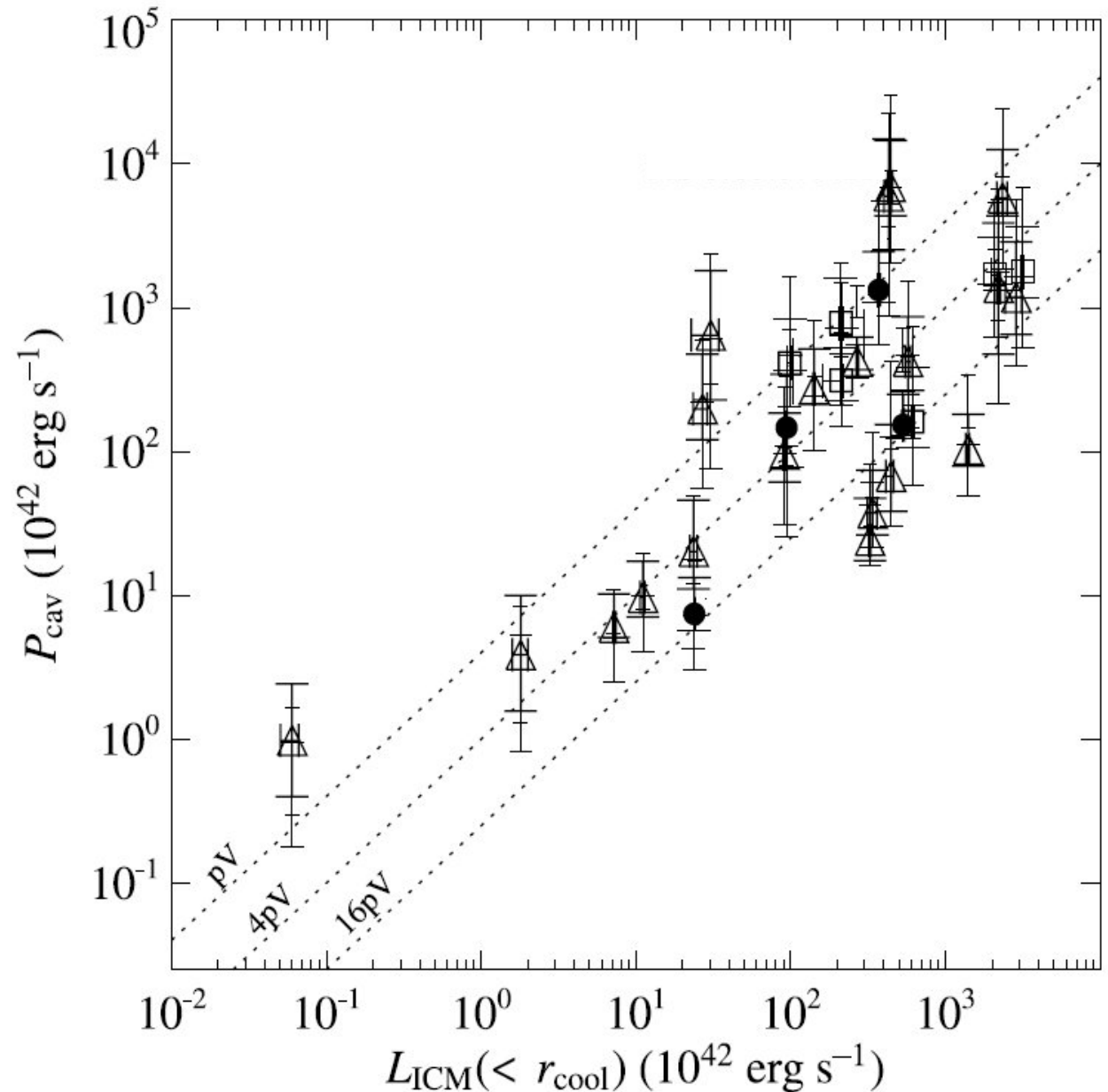
# Heating + cooling balance

- AGN heating is energetically sufficient to offset radiative cooling.



# Heating + cooling balance

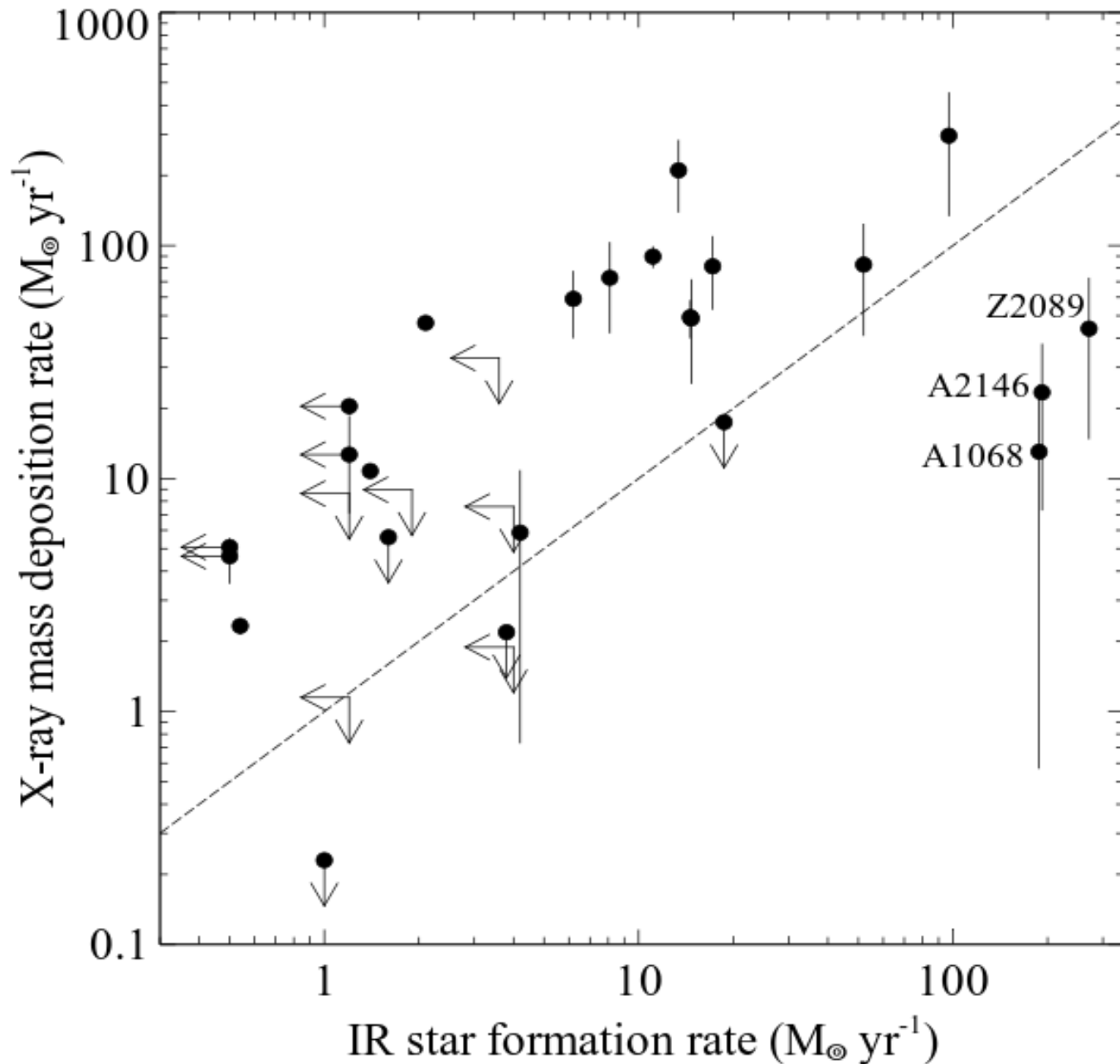
- AGN heating is energetically sufficient to offset radiative cooling.
- AGN heating can be coupled to the cooling gas  
→ feedback





# Tracing the residual cooling gas

- Spitzer IR survey of star formation in cluster cores



# Herschel observations

X-ray 0.5-1keV

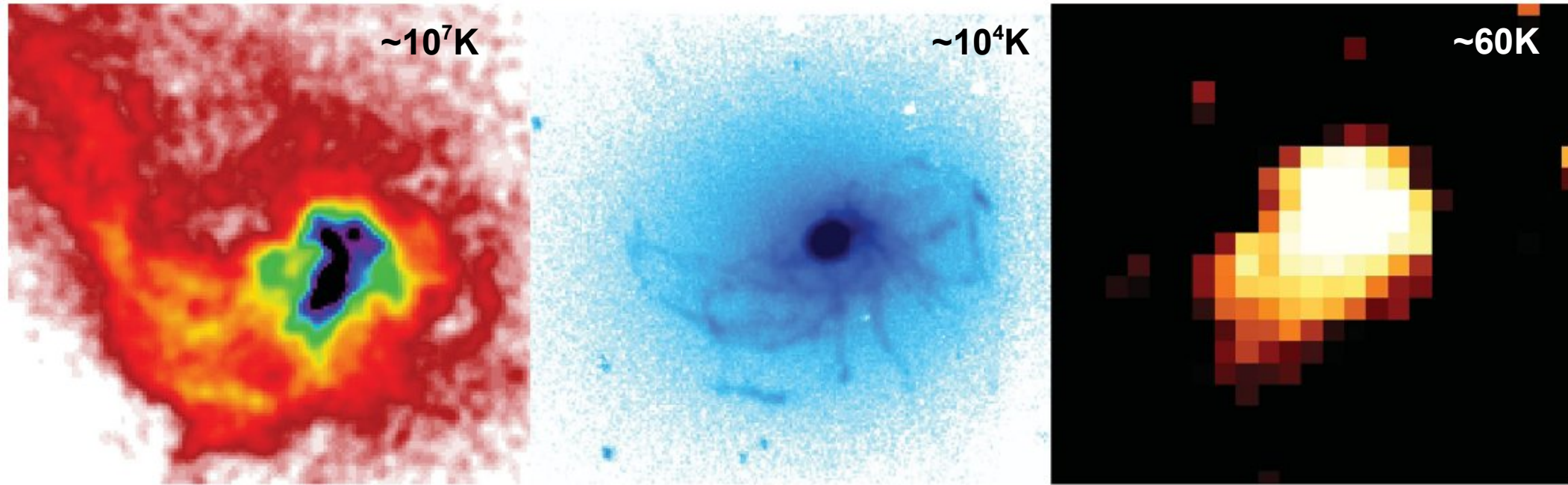
H $\alpha$

[CII]

$\sim 10^7$  K

$\sim 10^4$  K

$\sim 60$  K



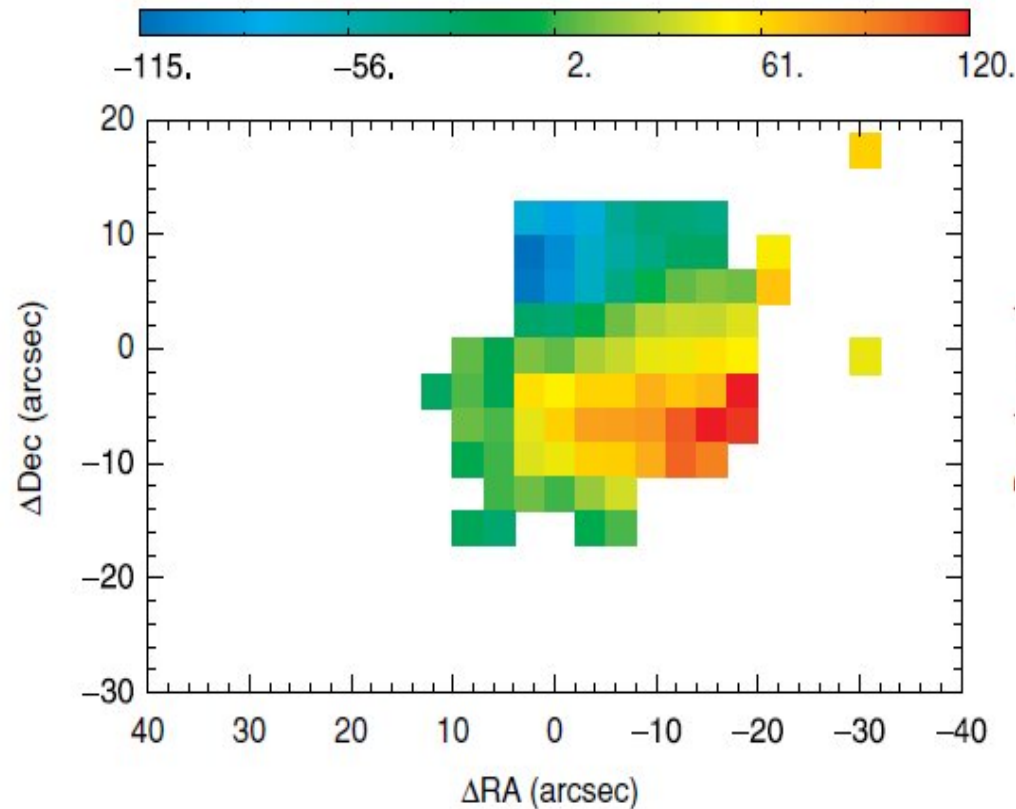
**Centaurus cluster**

Mittal et al. 2011

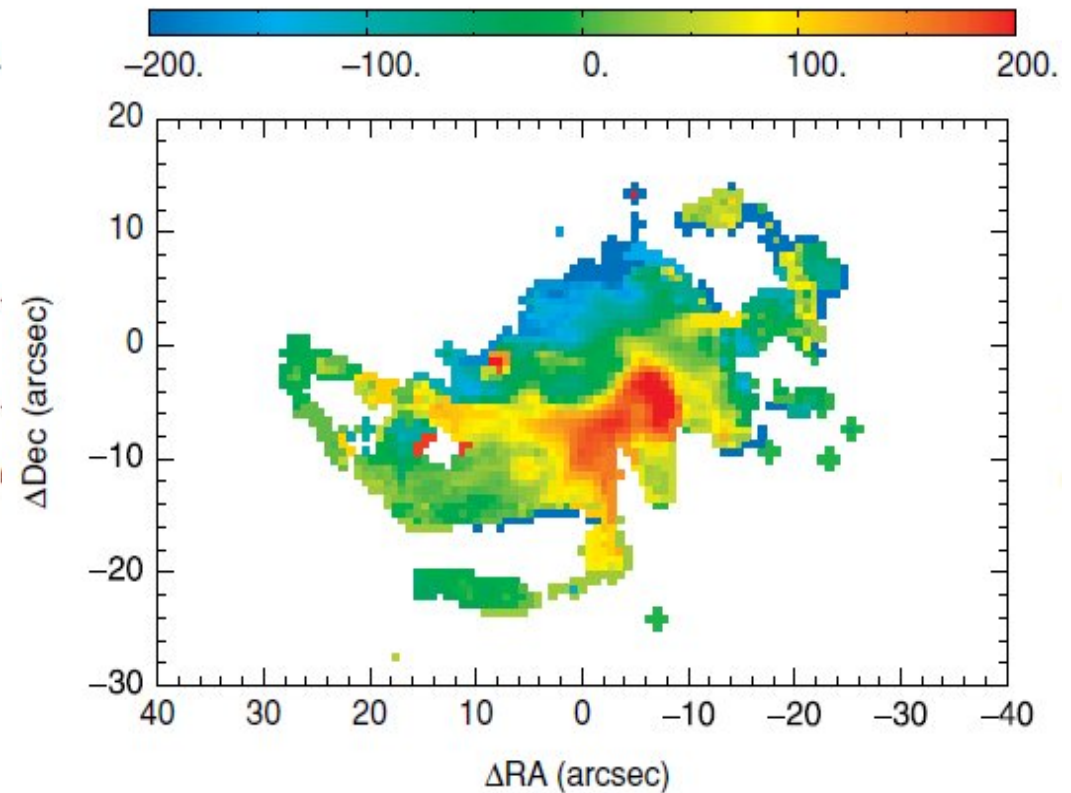
- Herschel-PACS first detections of the strongest atomic cooling lines [CII], [OI],... in cool core clusters

# Herschel observations

[CII]



H $\alpha$  + [NII]

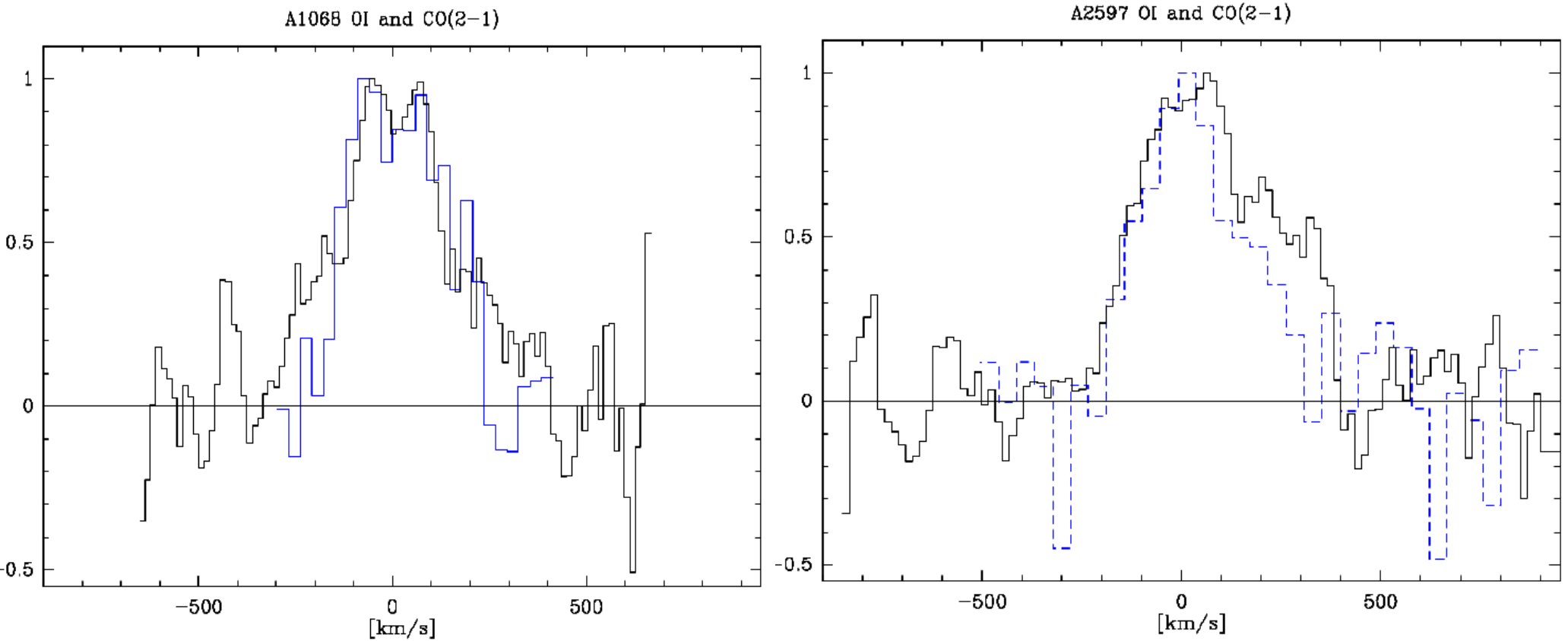


- FIR lines have kinematics similar to the ionised gas ...



# Herschel observations

- ... and the molecular gas.



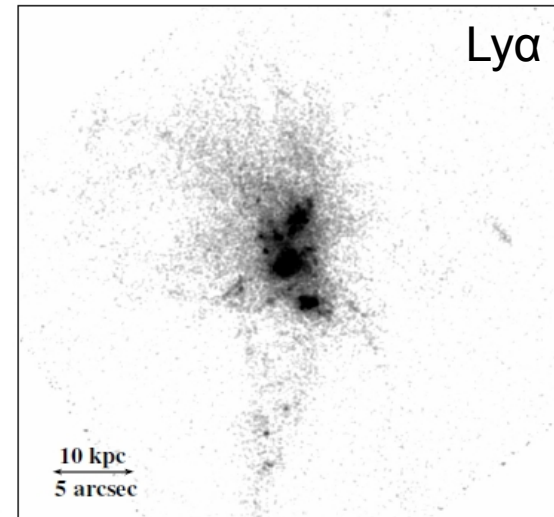
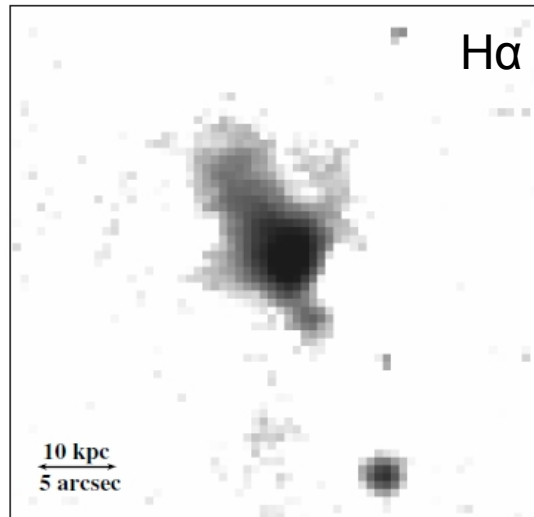
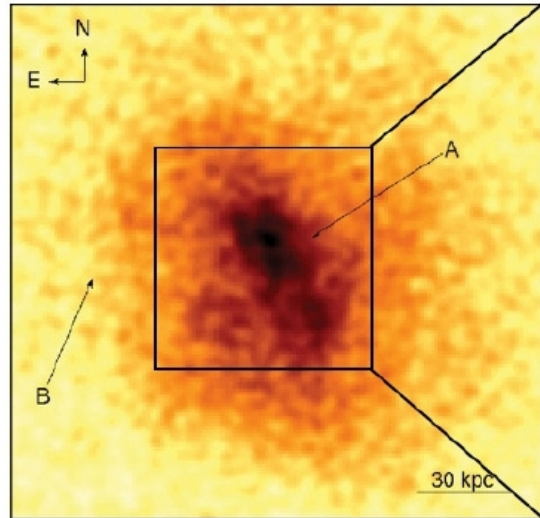
# Alma – a feedback loop?

- Spatial and velocity structure of the molecular gas
- Determine if AGN are fuelled by accretion from cold circumnuclear disks
- True feedback?

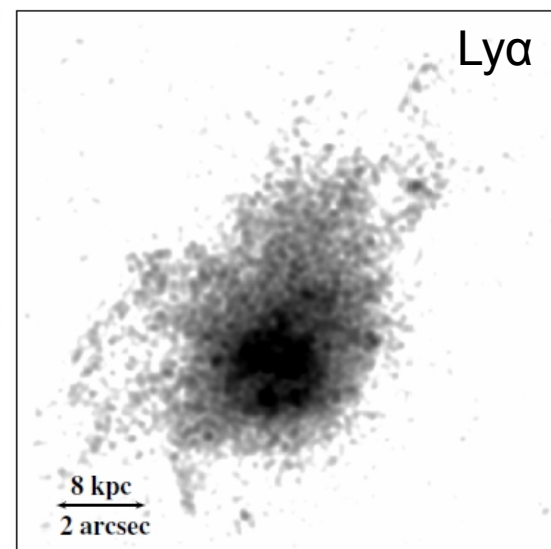
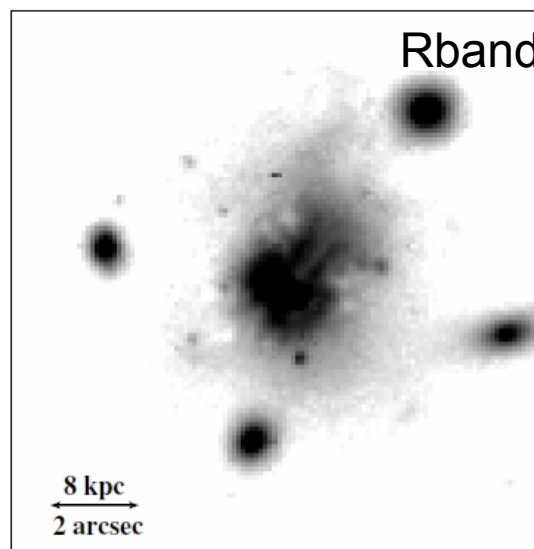
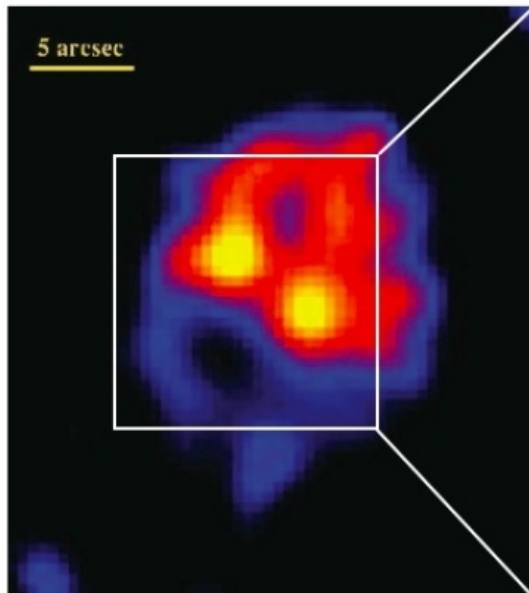


# Alma – a feedback loop?

**Abell 1664**



**Abell 1835**





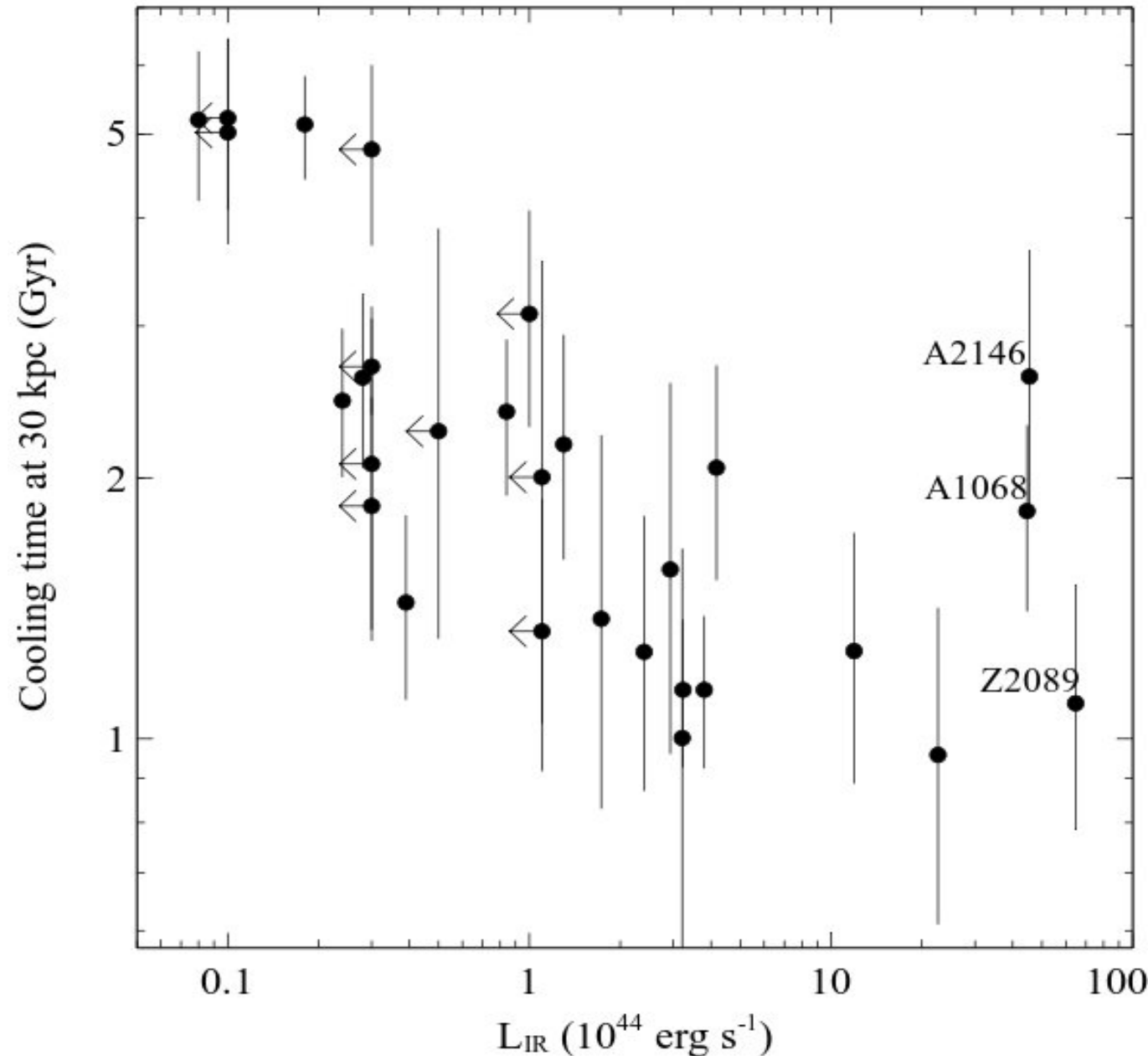
# Conclusions

- X-ray cavities provide a measure of the mechanical power injected by the SMBH
- AGN heating is energetically sufficient to offset radiative cooling in cluster cores
- Measures of reduced cooling from the X-ray are converging with star formation rates
- Herschel reveals similar morphology and dynamics of cooling gas
- Alma will uncover how AGN feedback is fuelled and regulated



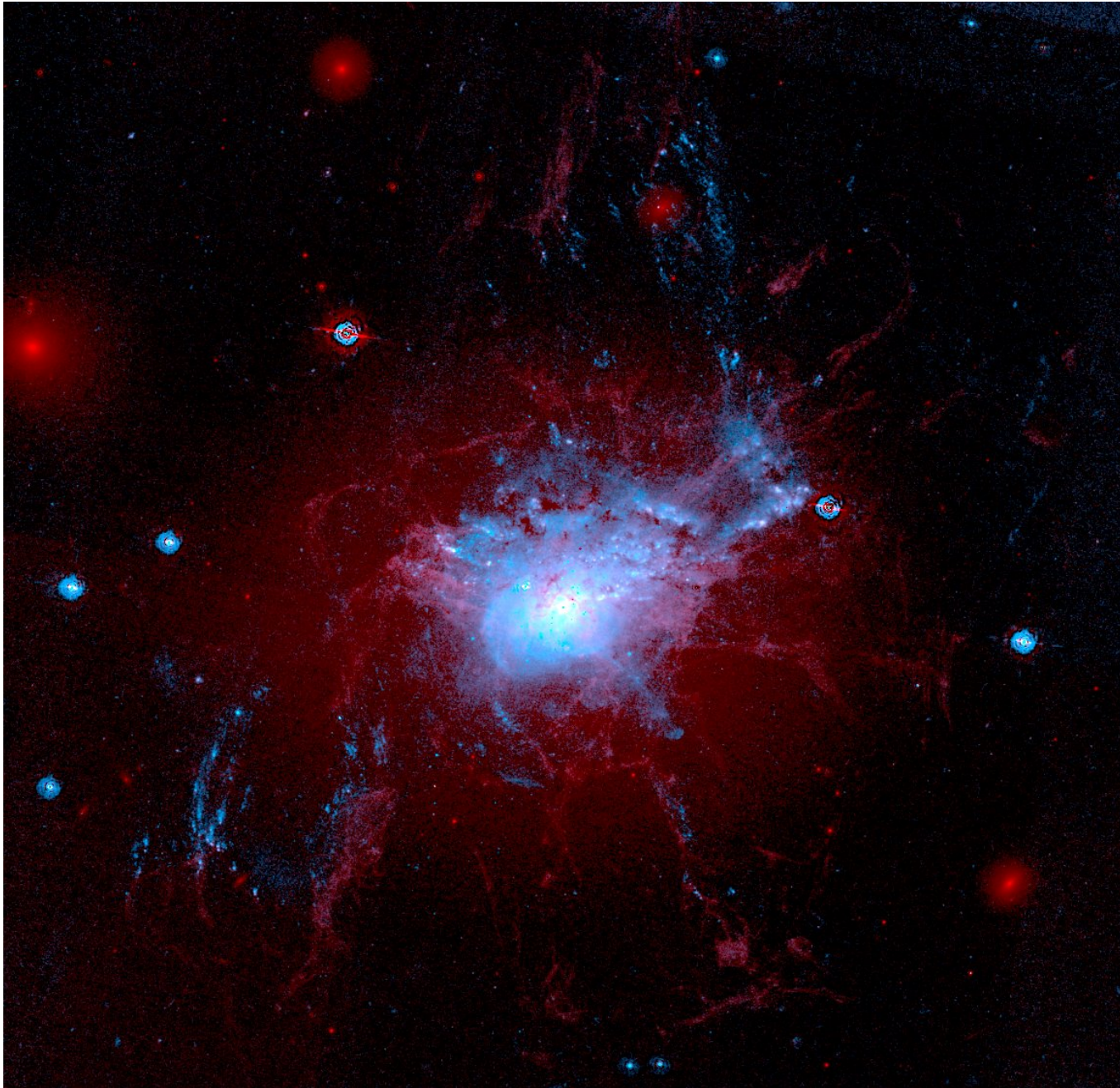
# Tracing the residual cooling gas

- Spitzer IR survey of star formation in cluster cores





# Perseus cluster



Canning et al. 2011