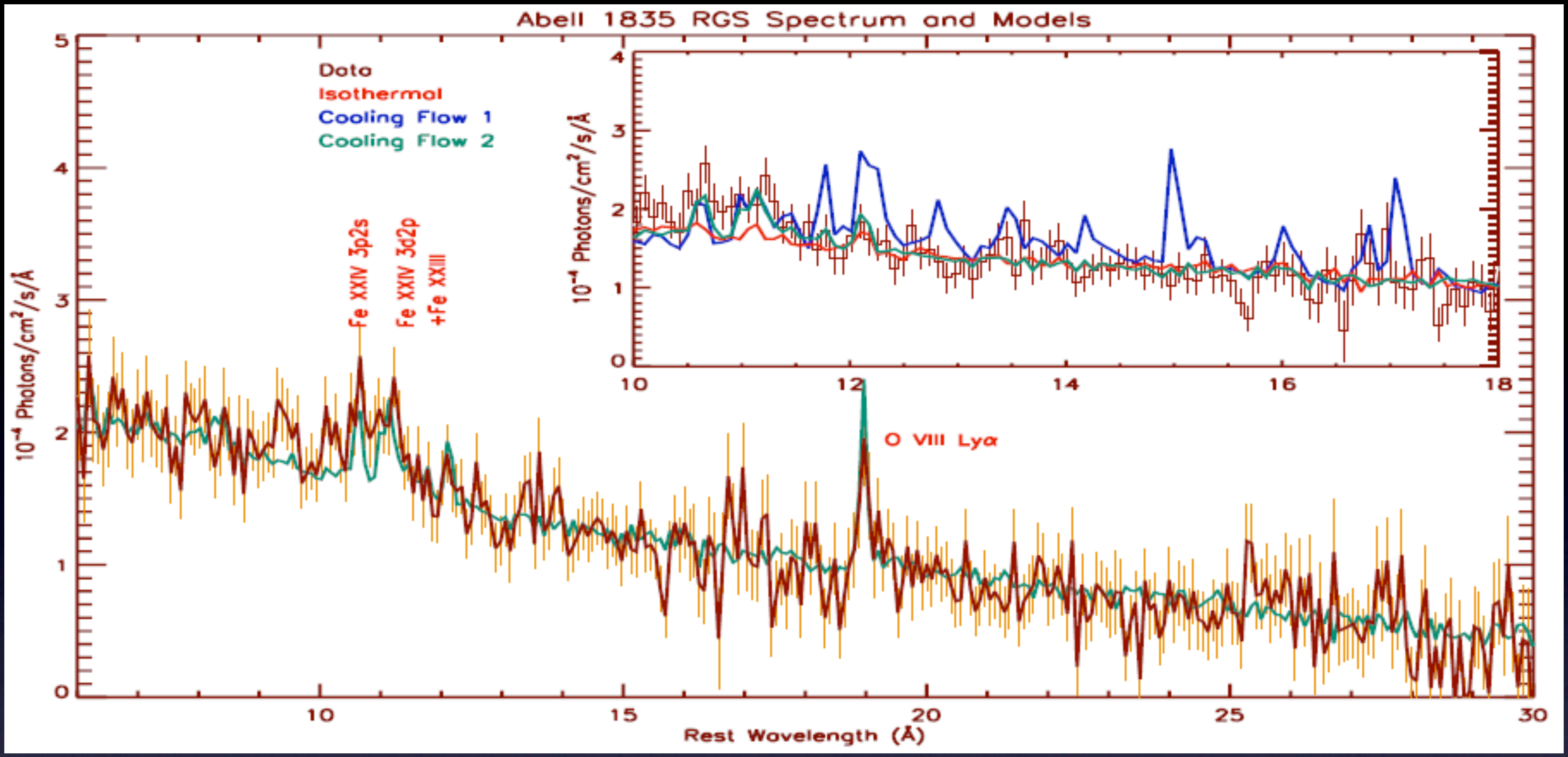
The Role of Shock Heating in AGN Feedback

S. W. Randall - CfA

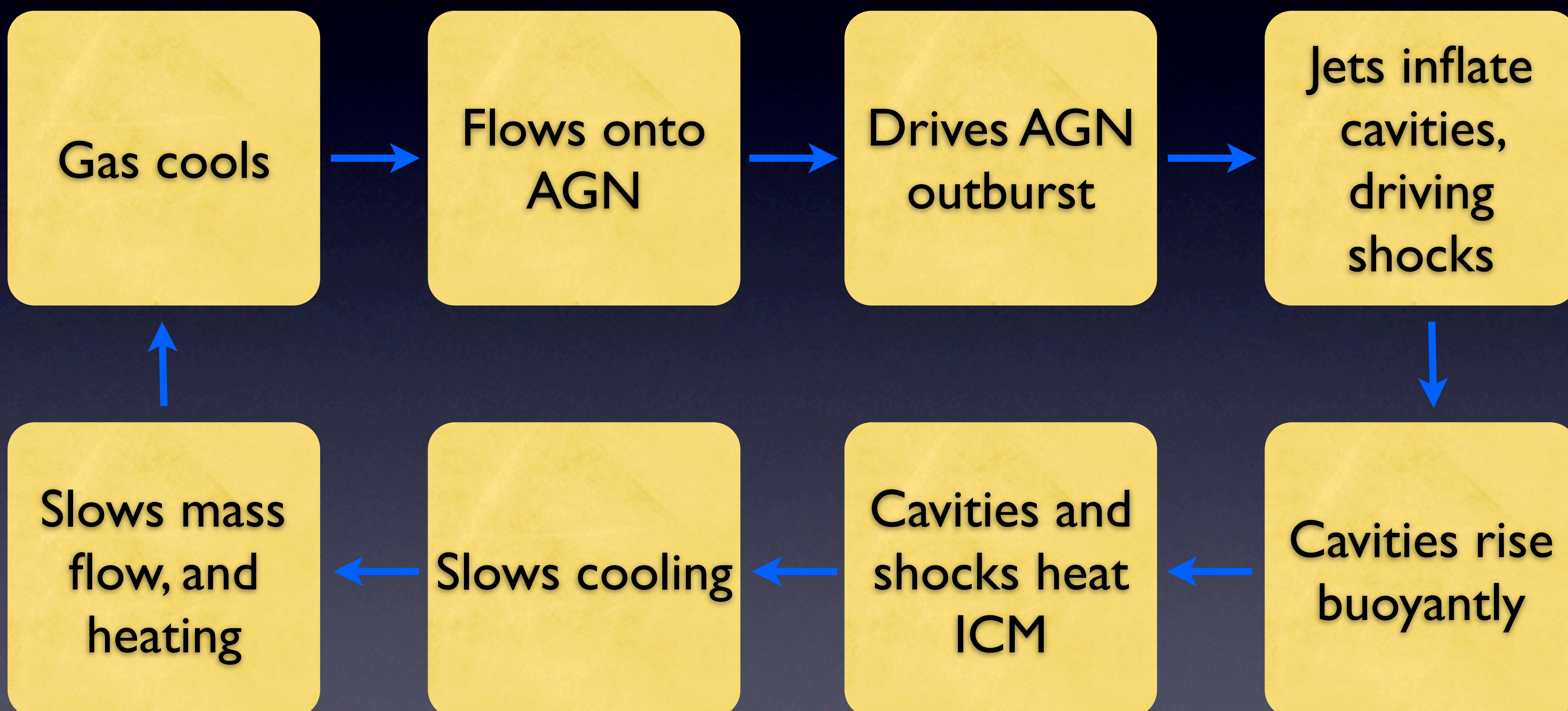
P. Nulsen, W. Forman, S. Giacintucci, M. Sun, C. Jones, E. Churazov, L. David, R. Kraft, M. Donahue, E. Blanton, A. Simionescu, & N. Werner



Peterson+ 2001

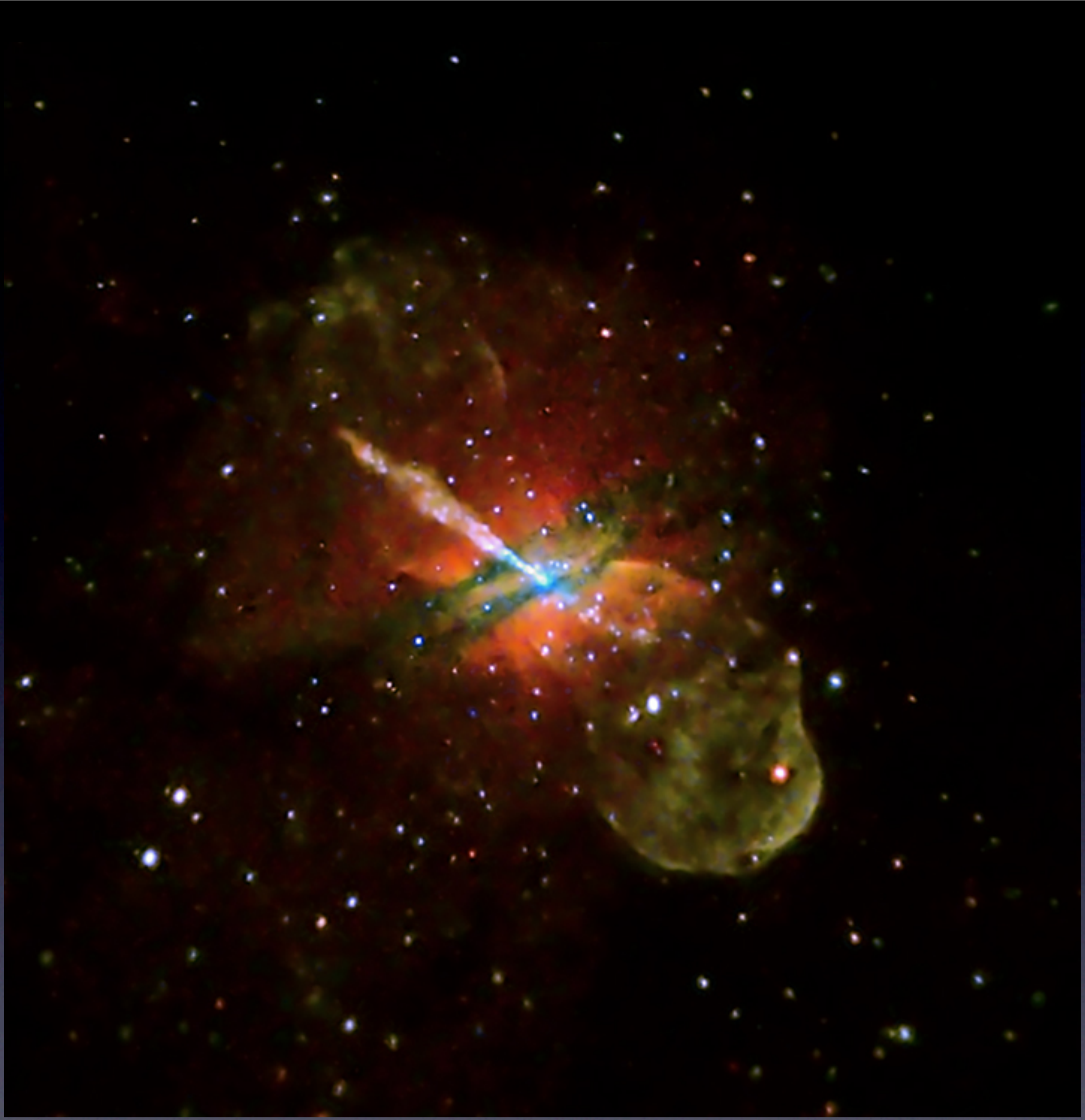
- Early XMM-Newton and Chandra observations showed that there is not as much gas cooling to low temperatures as predicted in "cool core" clusters
- Gas must be heated, most likely through feedback with the central AGN (McNamara & Nulsen 2007)

The AGN Feedback Cycle

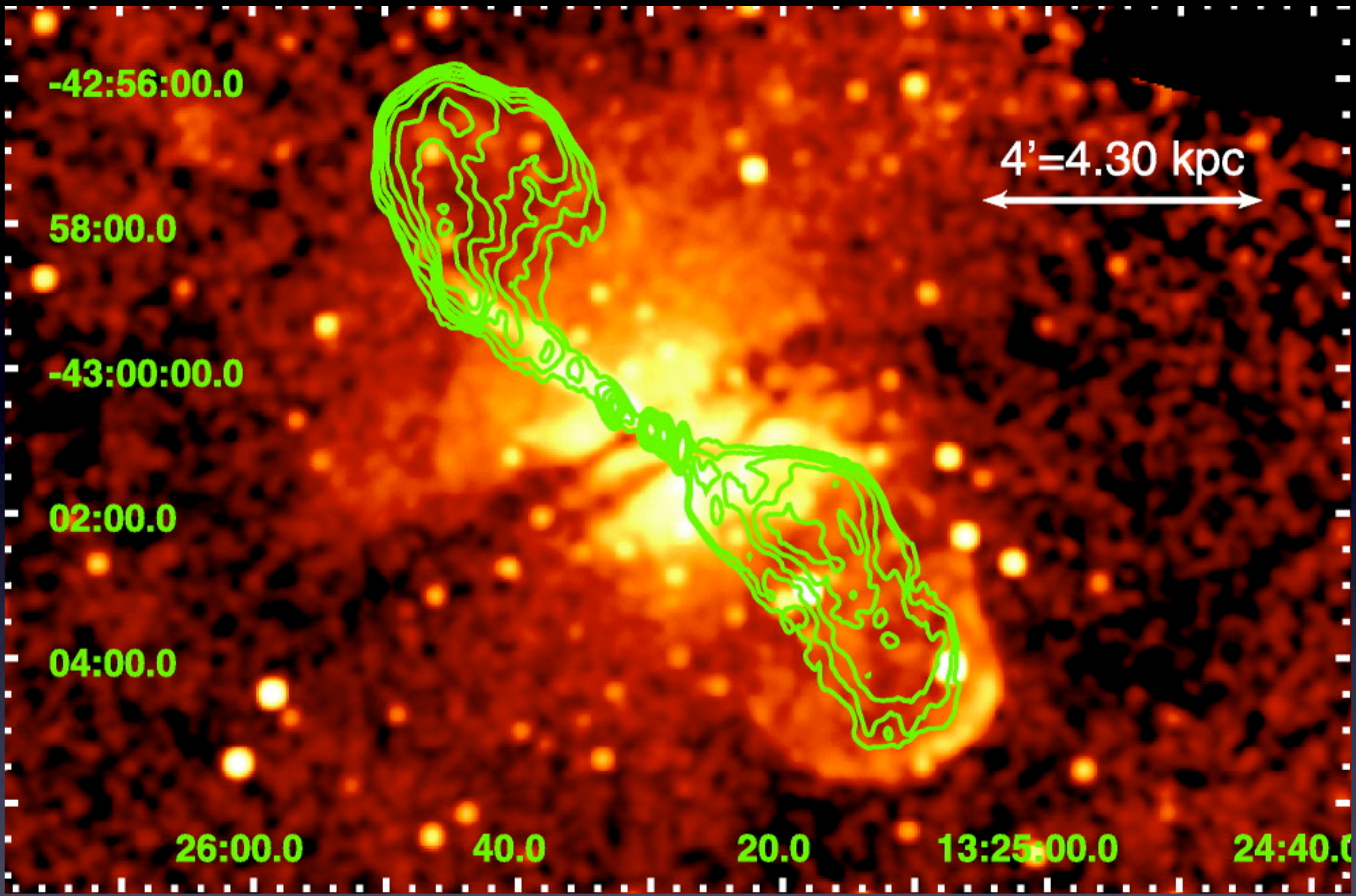


Centaurus A

X-ray false color image



Kraft+ 08, Croston+ 09


-42:56:00.0
58:00.0
-43:00:00.0
02:00.0
04:00.0
26:00.0
40.0
20.0
13:25:00.0
24:40.0
4’=4.30 kpc

Why Do We Care About Feedback?

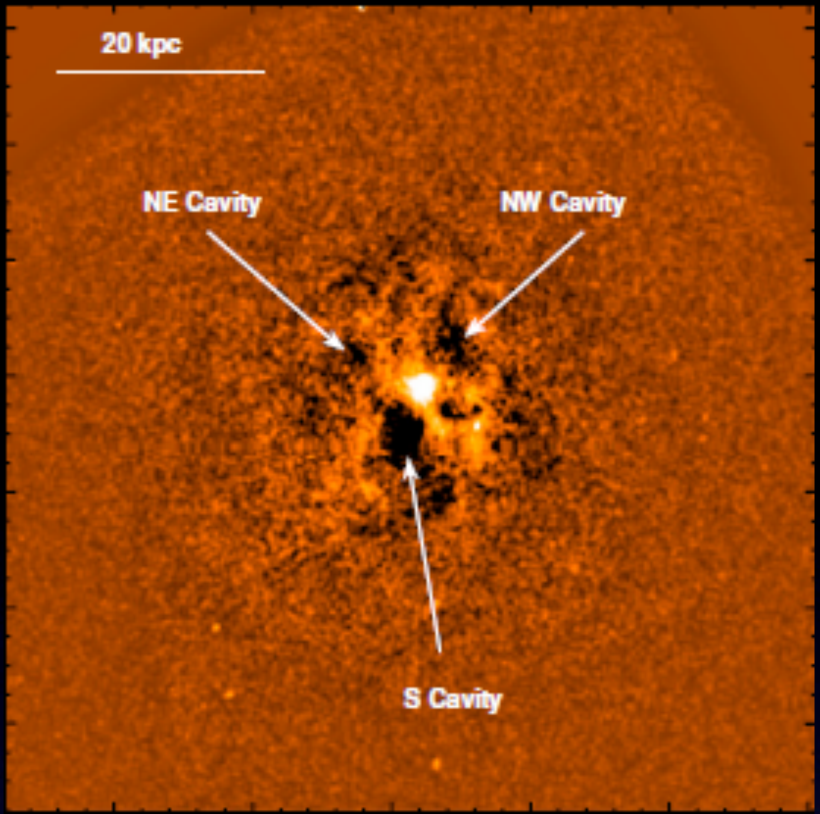
- Solution to the "cooling flow problem"
- Affects the structure and evolution of clusters and groups
- Buoyant bubbles redistribute gas and metals
- Need to understand to use clusters as cosmological probes
- Regulates black hole growth rate
- Regulates star formation rate => galaxy evolution theory

Does It Work?

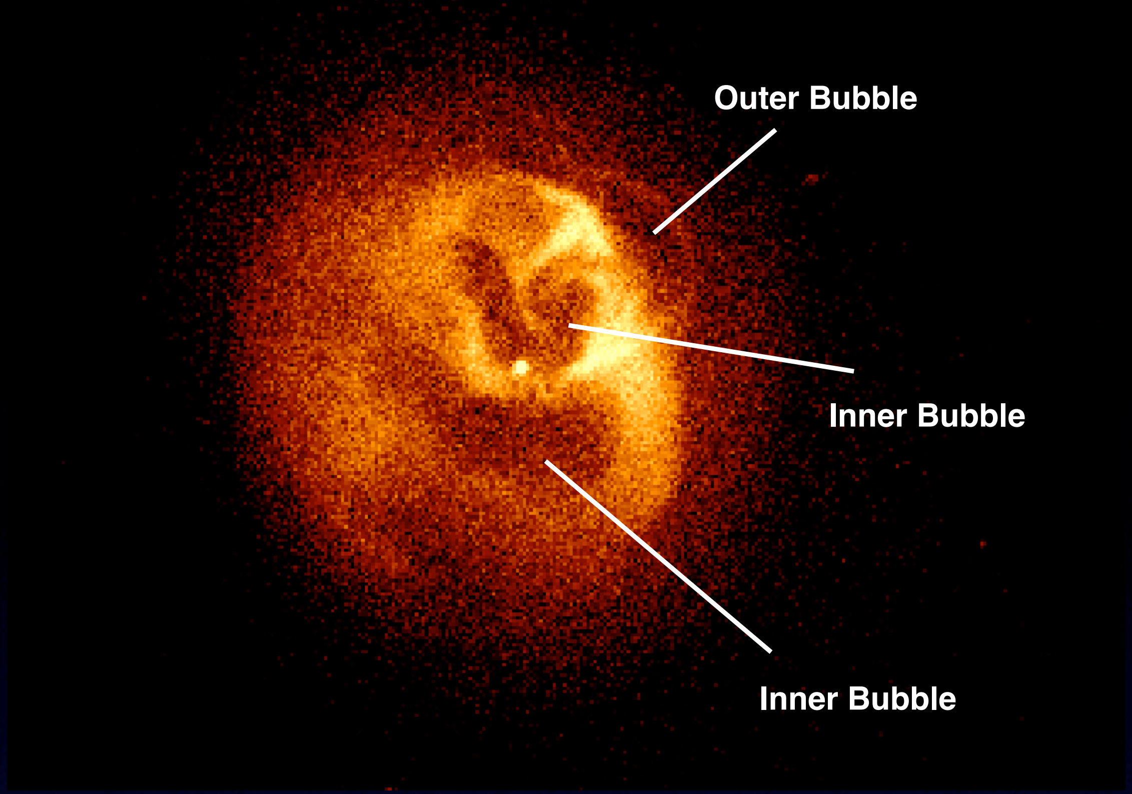
Cavities are easy to detect, and are seen in many systems (clusters, groups, and galaxies)

- Generally, the total energy of the cavities (estimated from PV work) is sufficient to offset cooling (Birzan+04, Dunn & Fabian 04, Rafferty+06)

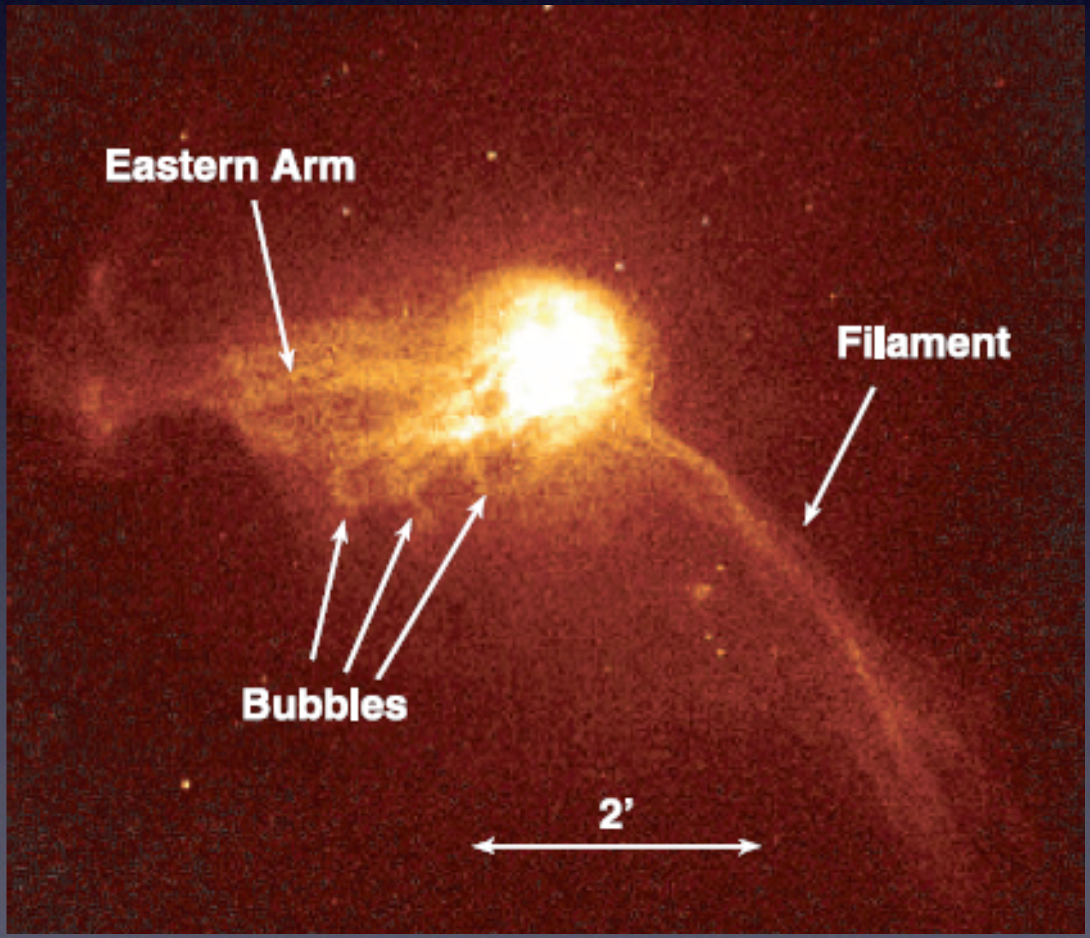
- However, the details of how and where the cavities release their energy to heat the ICM are poorly understood



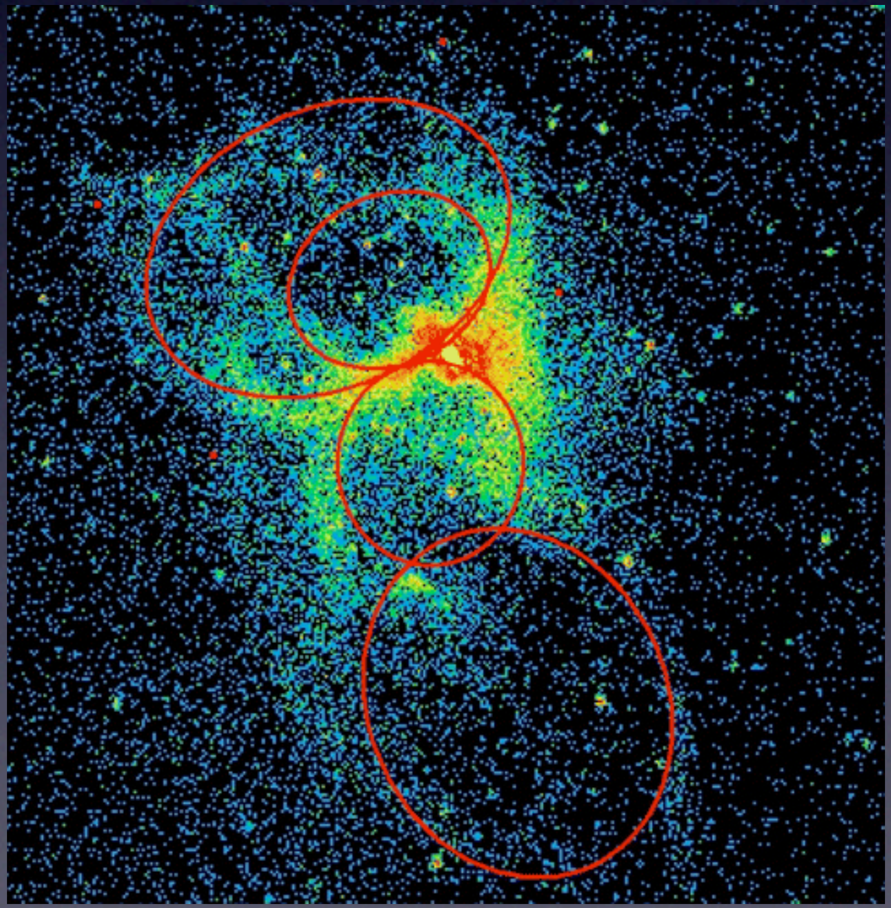
David+09



Blanton+09,10,11



Forman+07

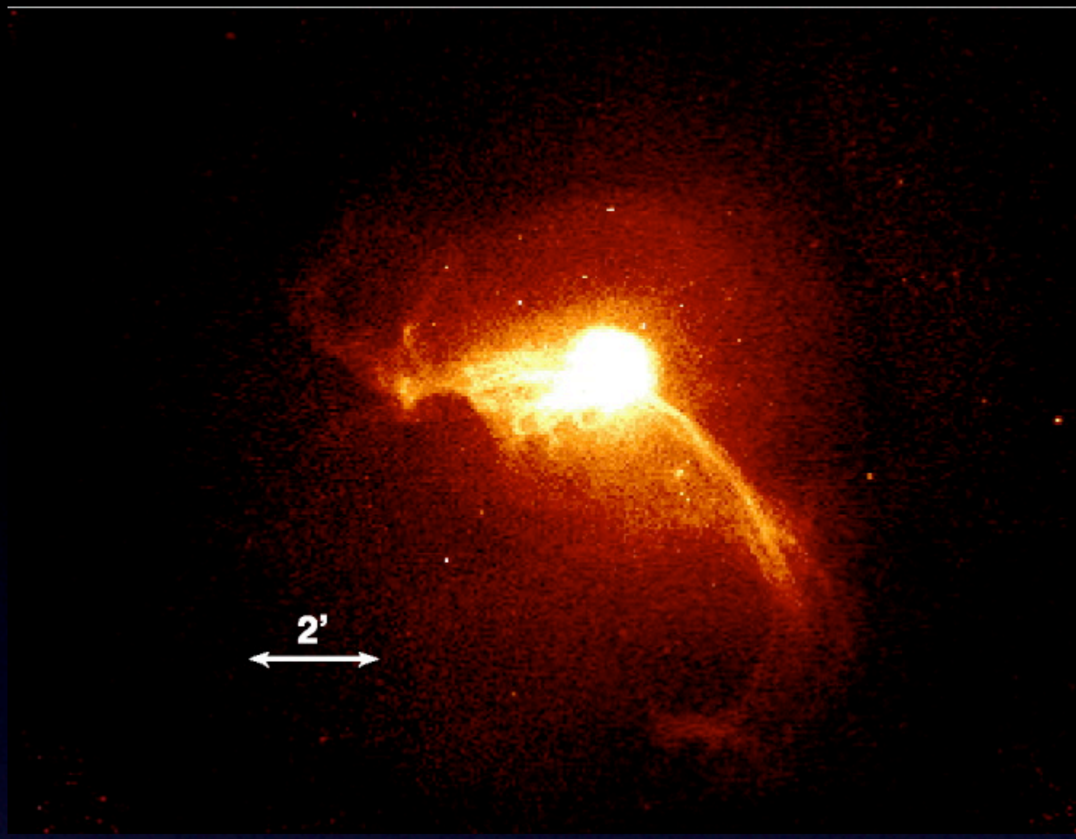


Finoguenov+08

What About Shocks?

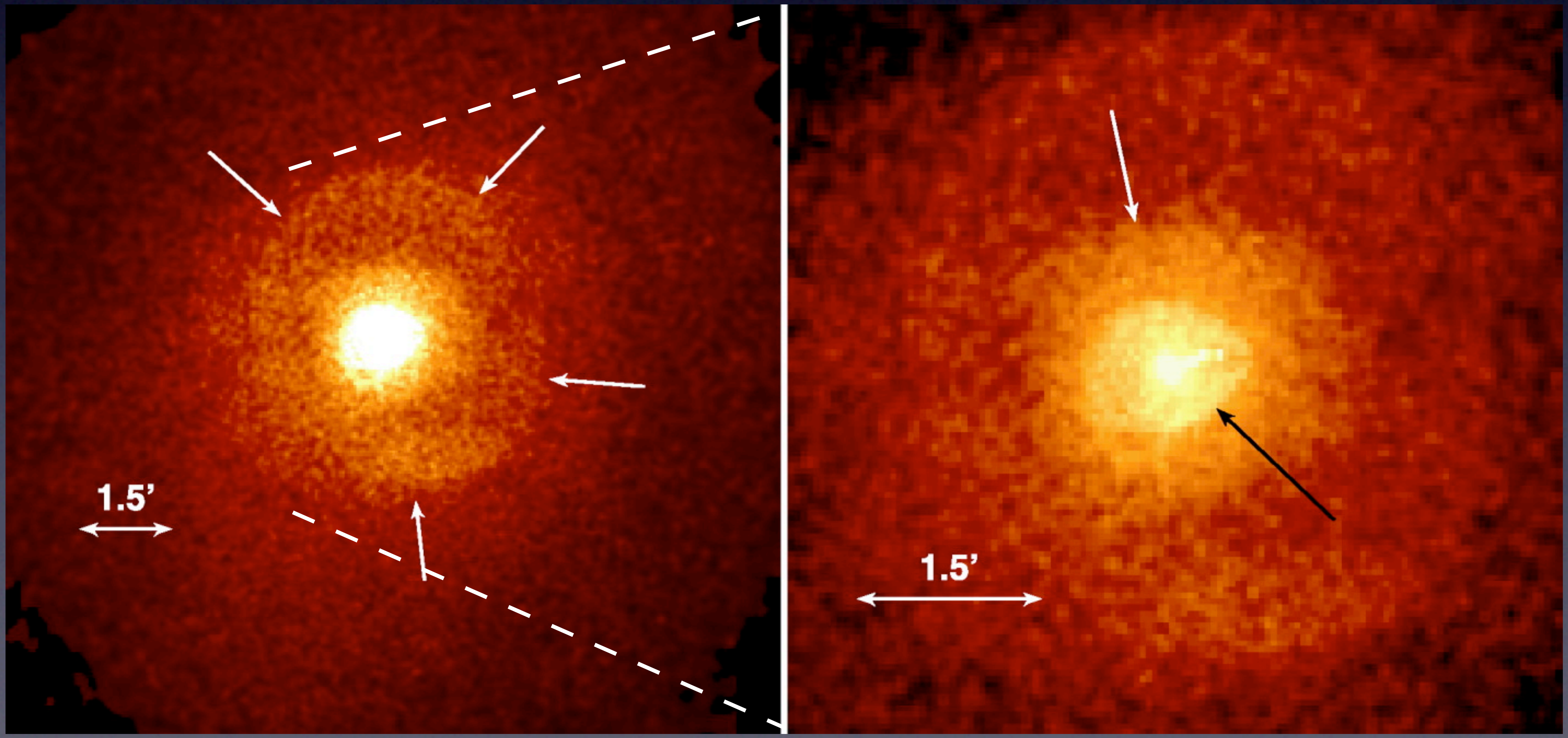
- Expect a total shock energy similar to cavities, especially soon after the outburst
- Basic shock physics is well understood
- Shocks will naturally heat the ICM isotropically, and more strongly near the AGN, as required for feedback

M87 (Virgo Cluster)



Broad energy band

Forman+07



Hard band only

Hydra A

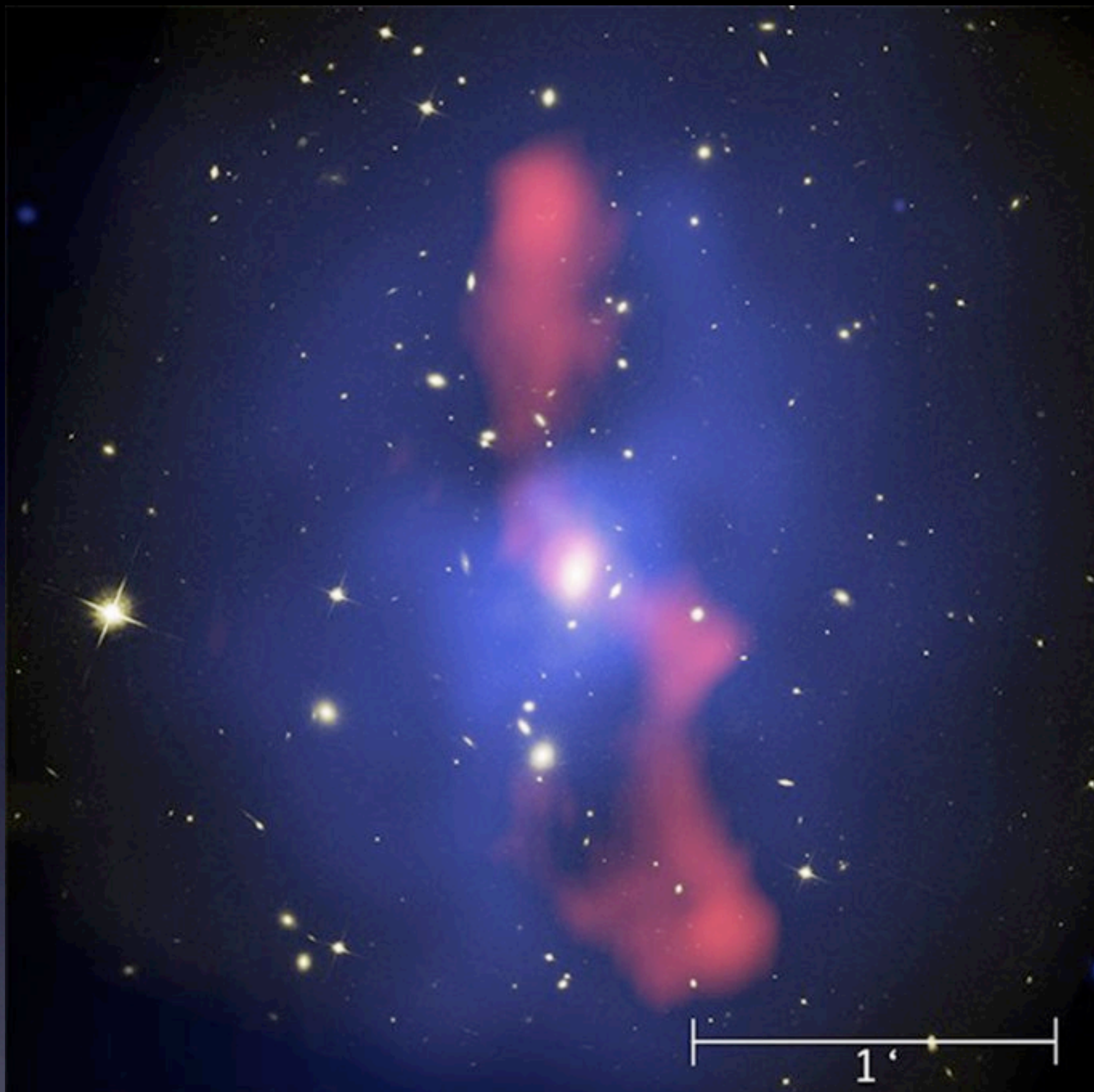
Gitti+11

Hercules A

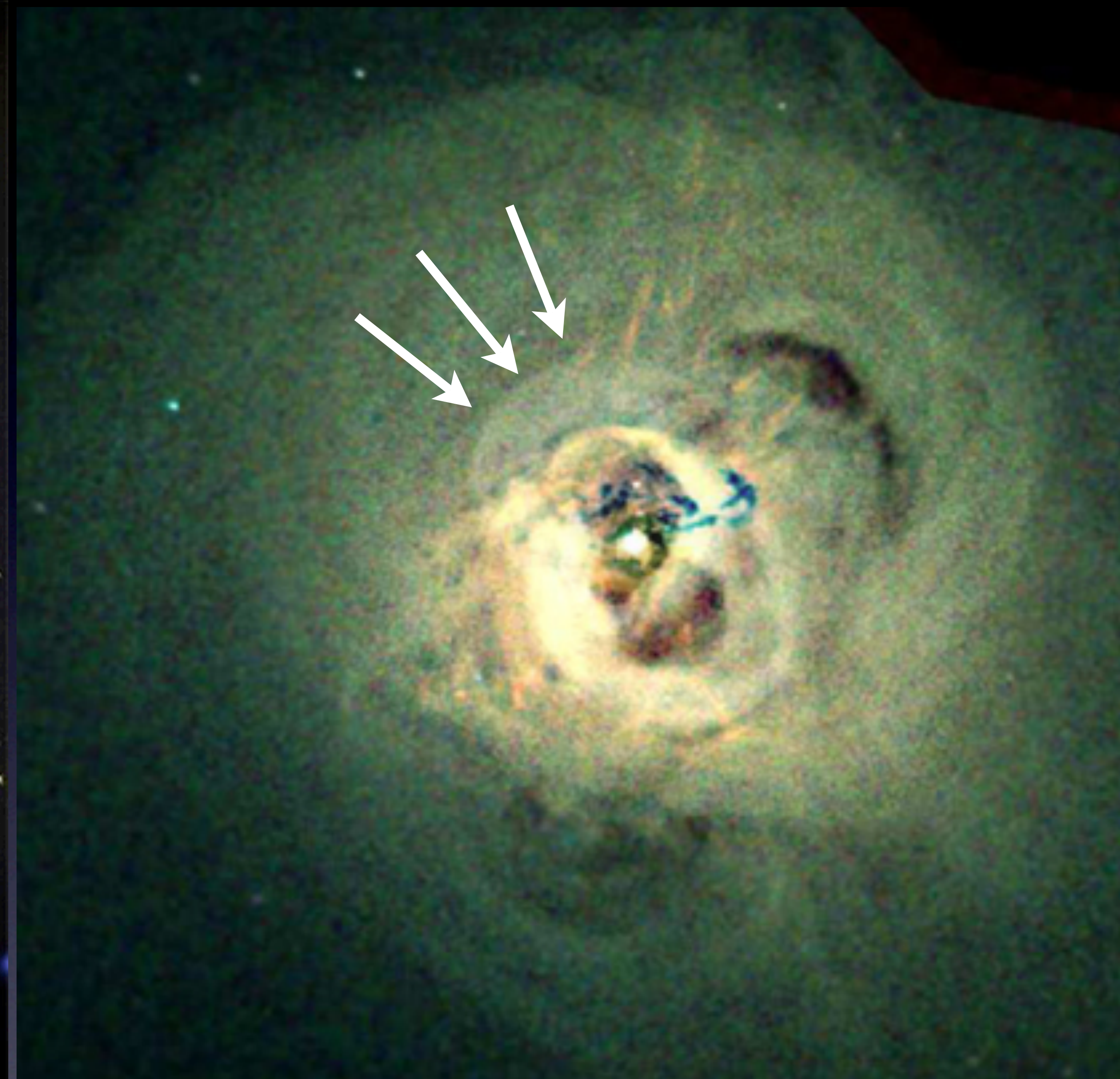
Nulsen+05

MS0735.6+7421

Perseus

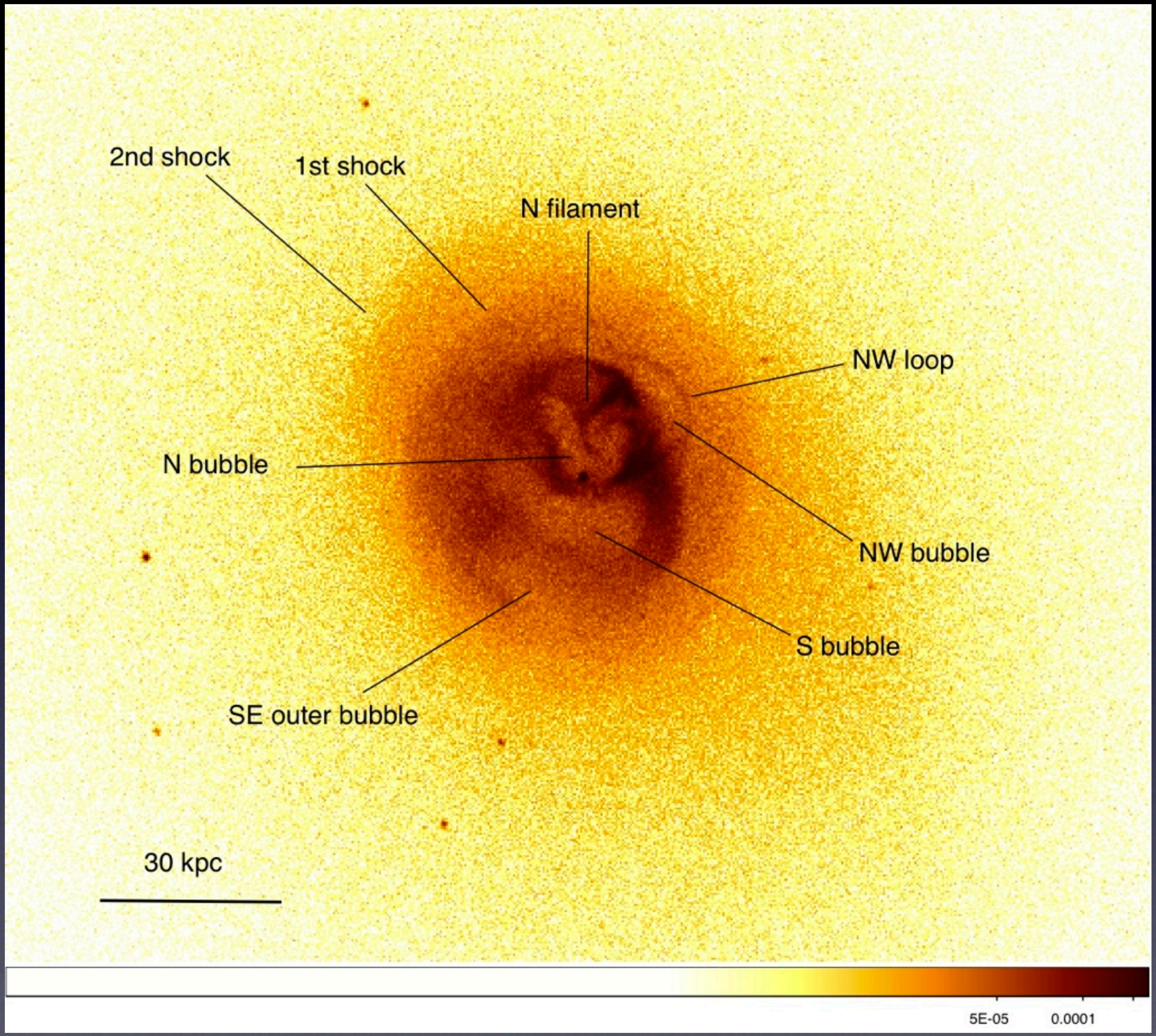


McNamara+05



Fabian+06

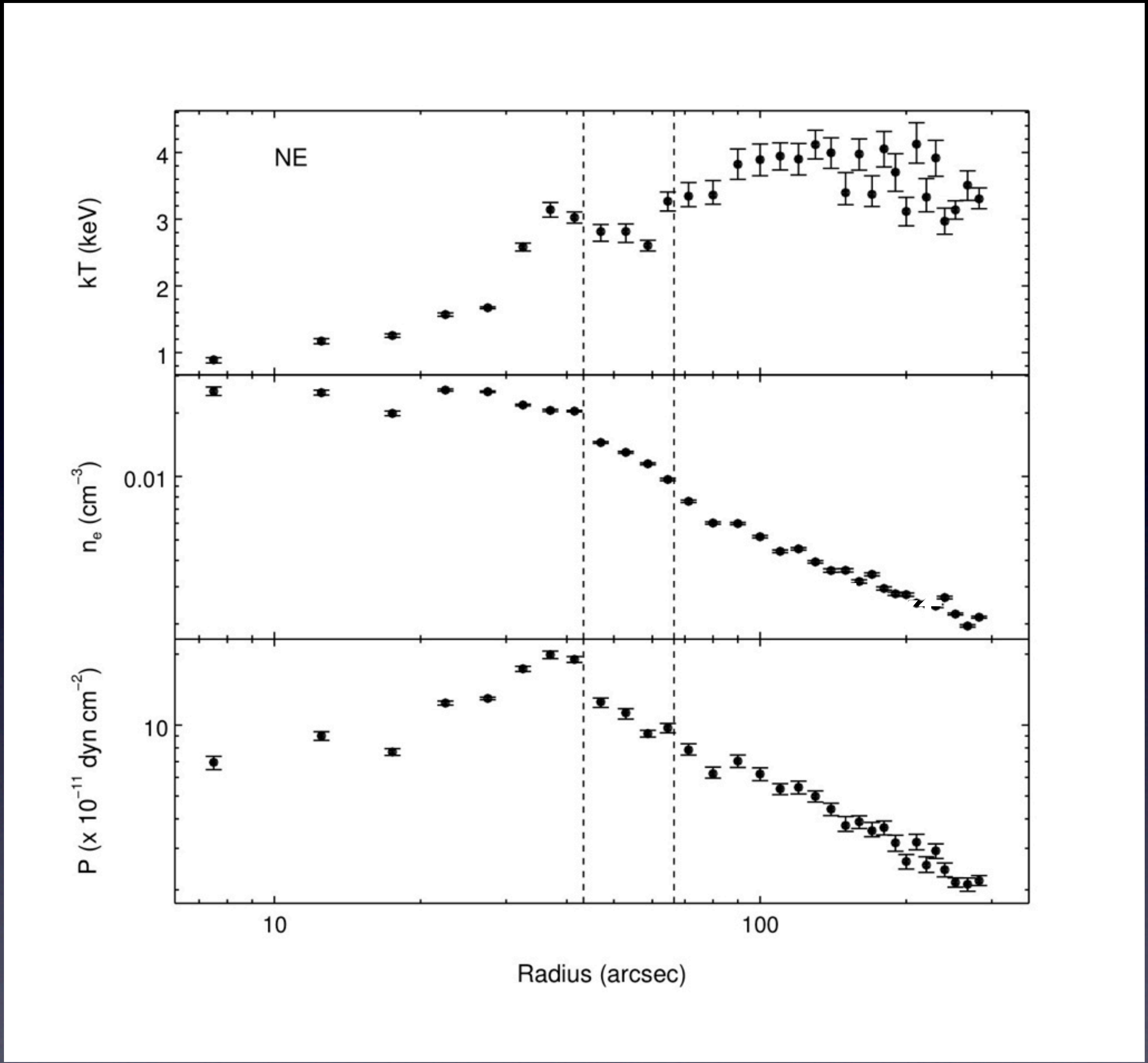
Abell 2052



Blanton+11

Observations of Outburst Shocks

- There are a handful of AGN outburst shocks detected, many fewer than X-ray cavities
- Outburst shocks tend to be weak, with M~ 1.1-1.8
- Need to measure temperature rise across edge to confirm as a shock (and not a "cold front" from gas sloshing)
- Detecting temperature rise is generally very difficult



Deprojected temperature, density, and pressure for A2052. Positions of the shocks are indicated. Blanton+11

A2052: 660 ksec

kT jump only across inner shock, after deprojection

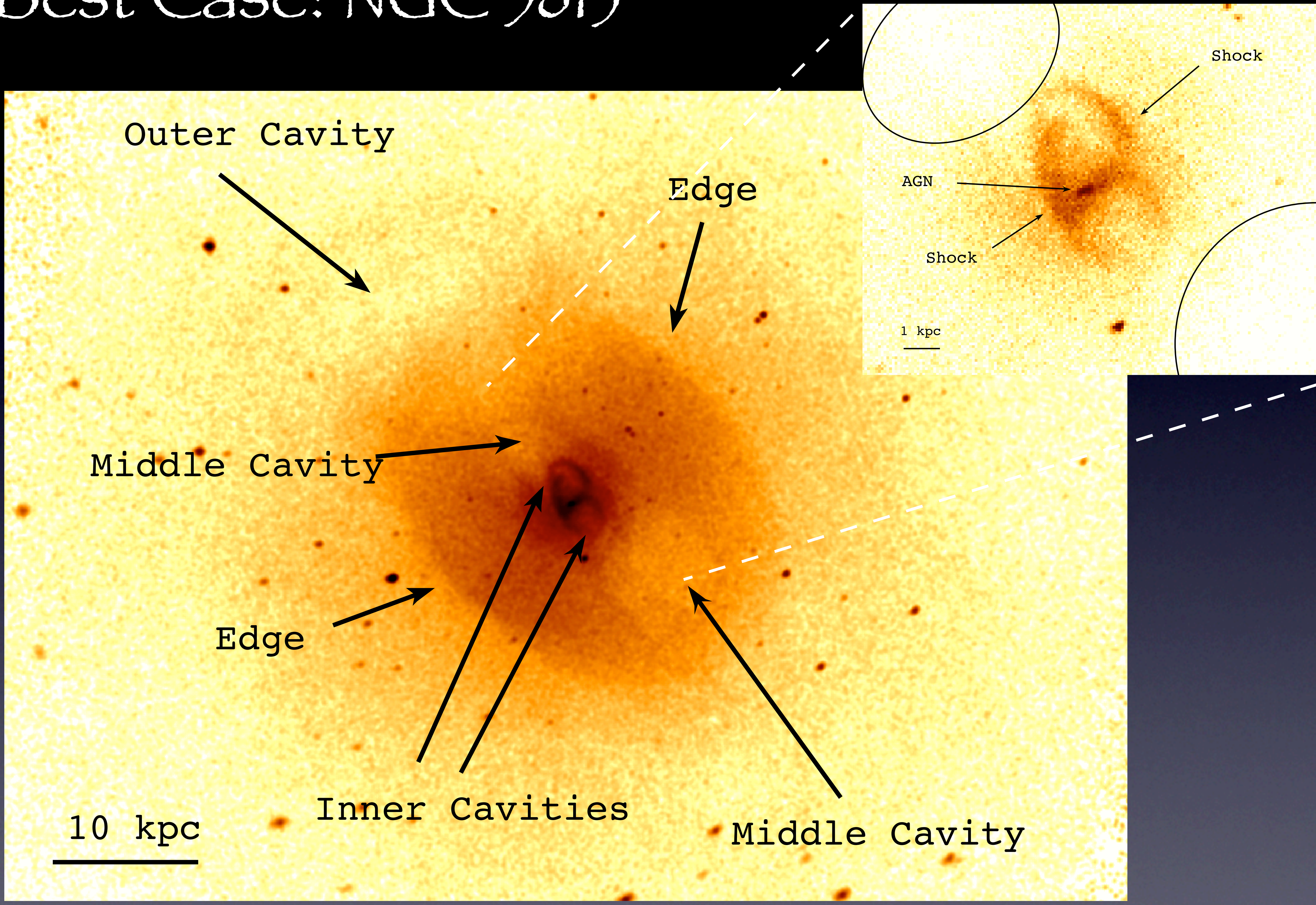
Perseus: 900 ksec

Originally isothermal shock claimed. kT rise detected behind shock with deprojection (Graham+08)

Moral: Outburst Shocks with kT Jumps are VERY Difficult to Detect

- Shocks are weak, and shock fronts are thin
- Obscured by complicated central structure
- Projection effects (from the ICM and post-shock adiabatic expansion) mask kT jumps

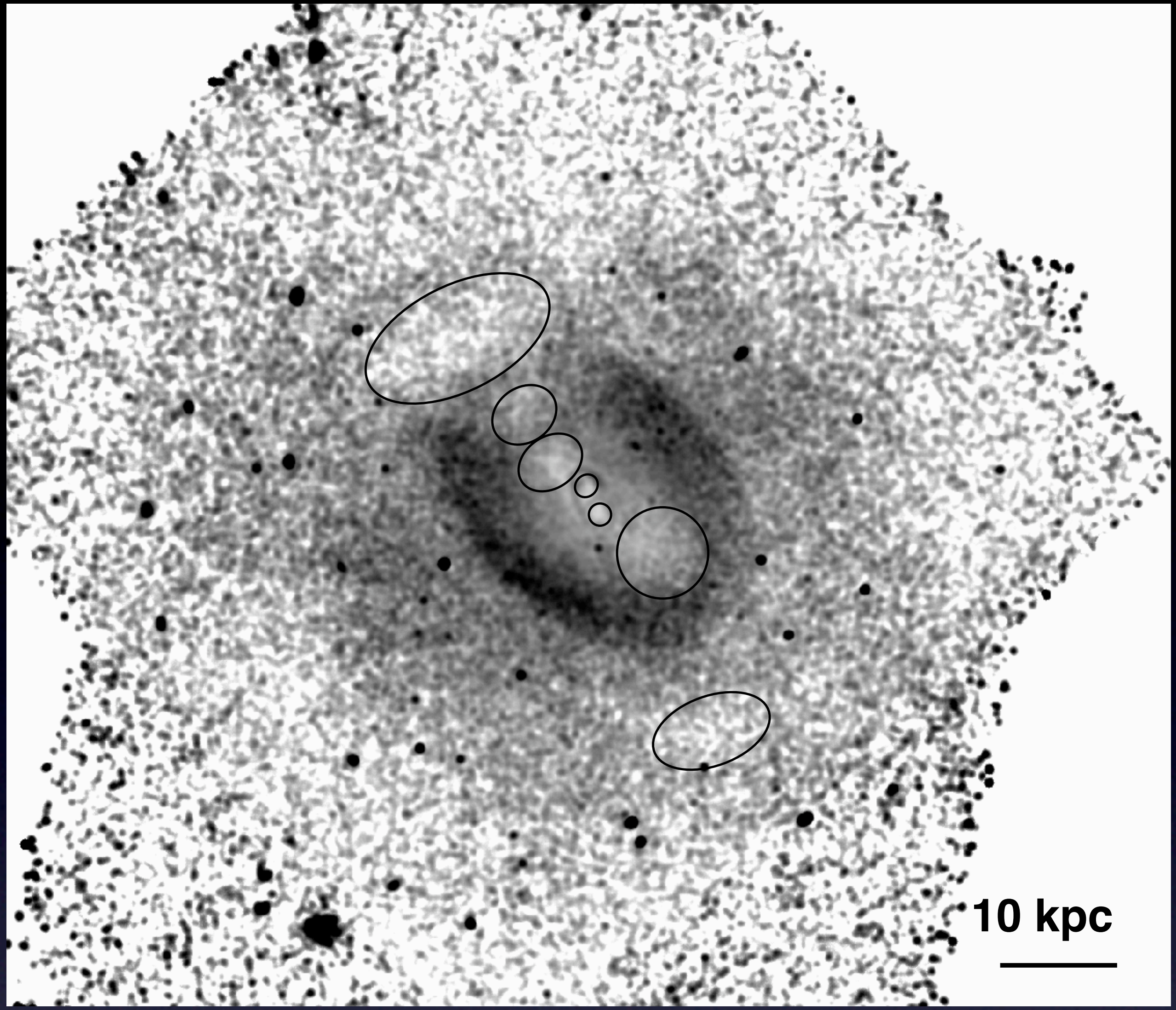
Best Case: NGC 5813



Randall+11, NEW 650 ksec image here

Ideal for the Study of Feedback

- Three pairs of collinear, regular cavities
- Sharp surface brightness edges associated with inner and middle pairs
- Radio spectral index steepens rapidly with cavity radius

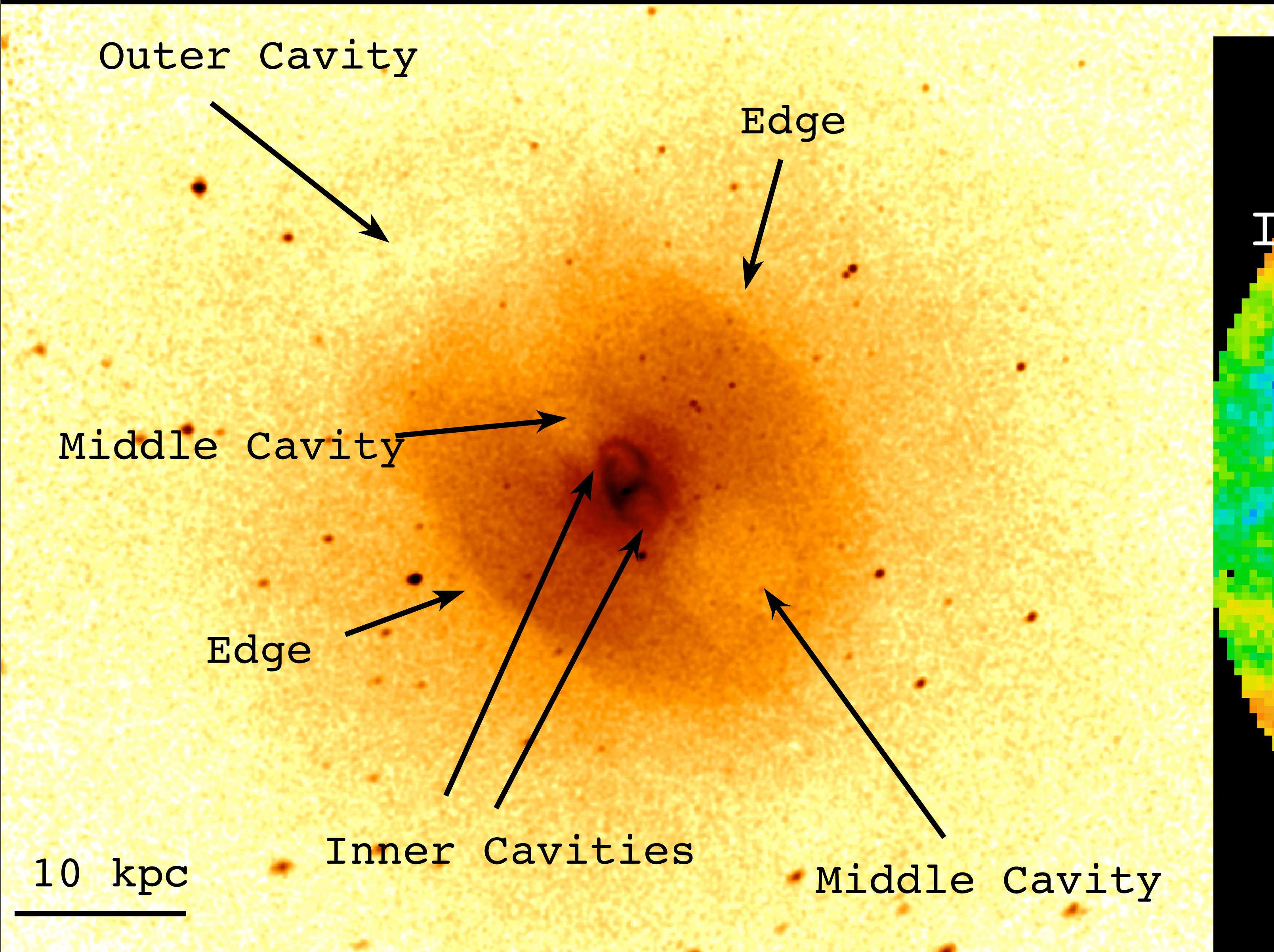


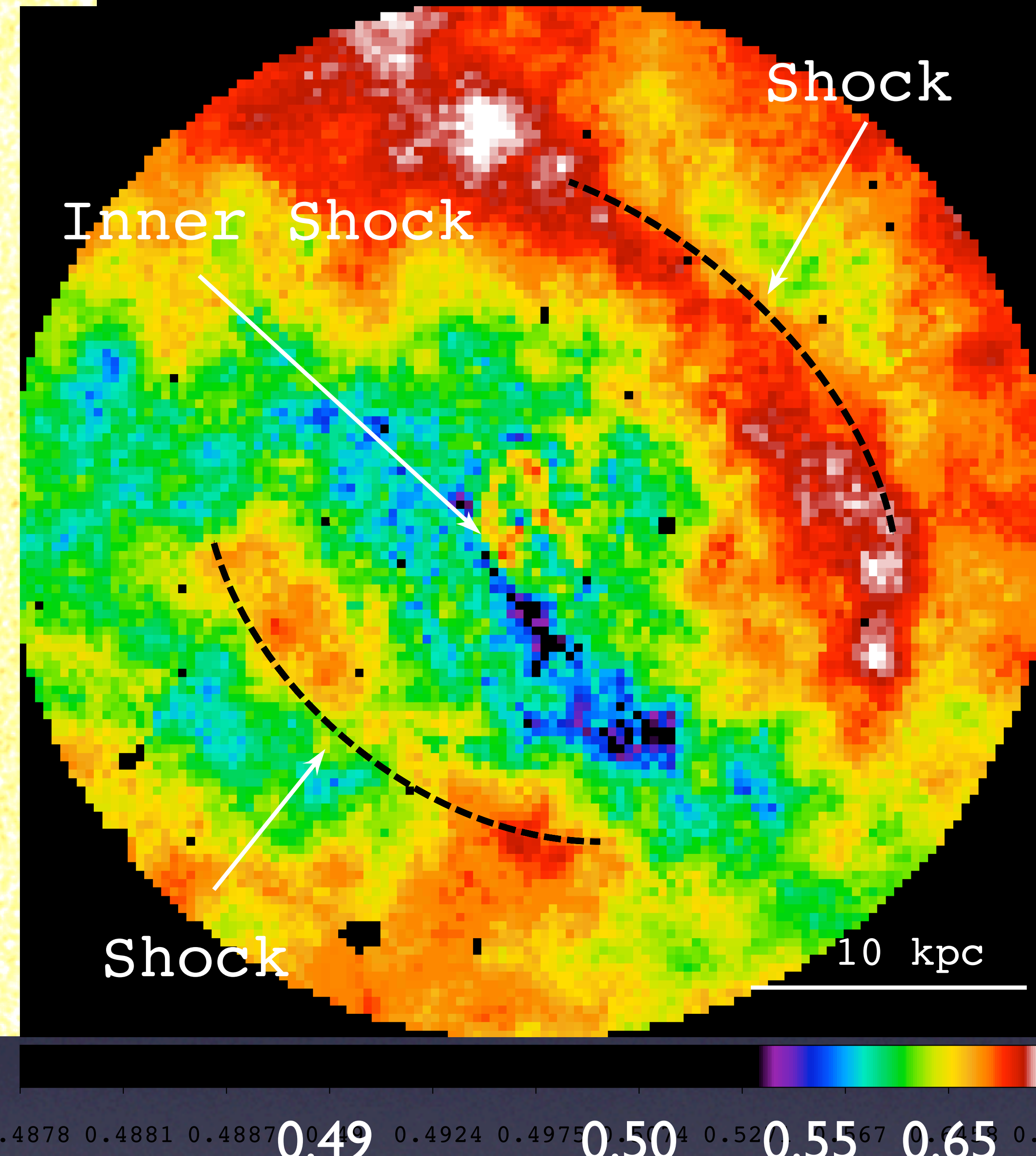
Residual map (original 150 ks only)

- Cooler group temperatures easier to measure with Chandra

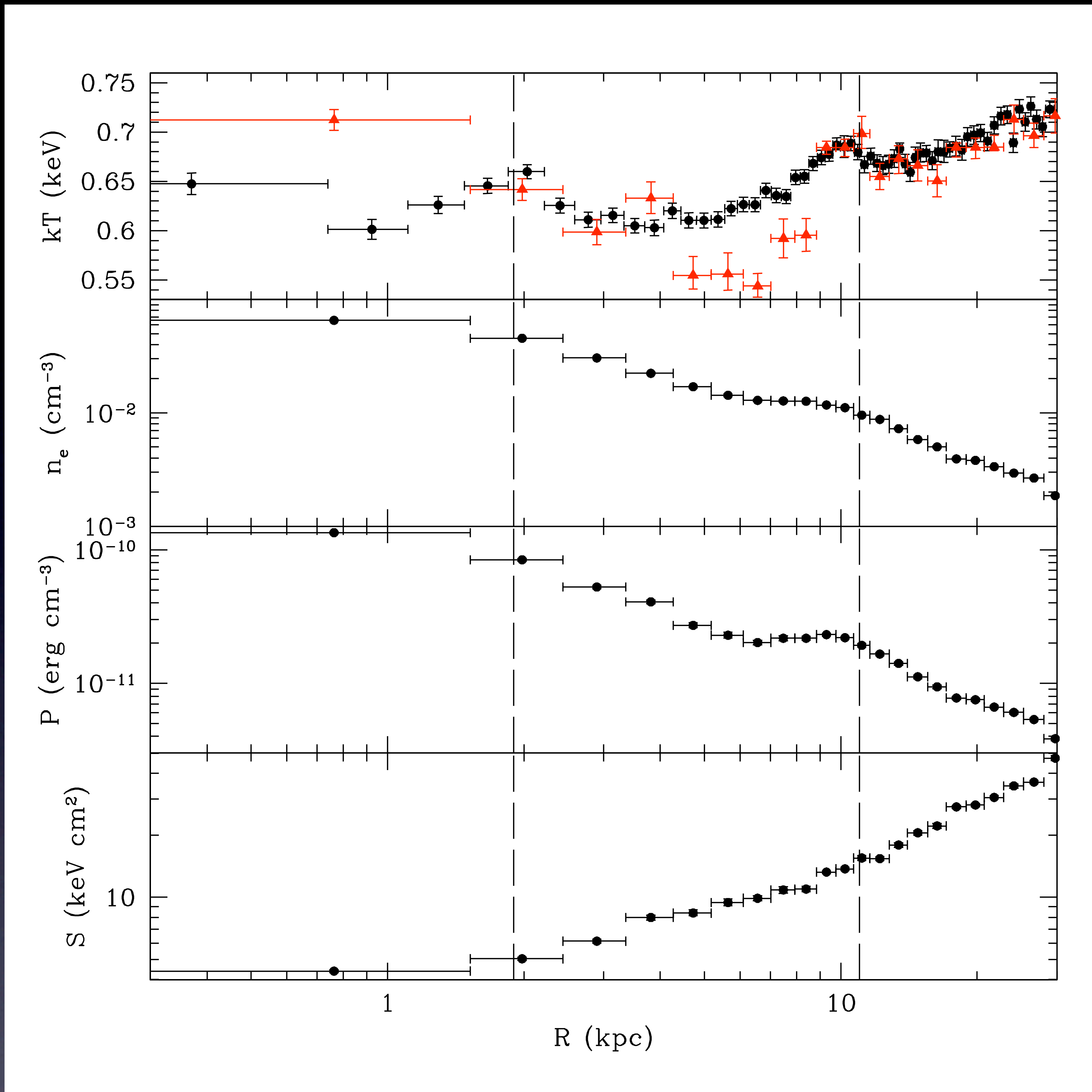
New Long Observation

- An additional 500 ksec, 650 ksec total
- Longest Chandra observation to date of any galaxy group core
- Initial results: can measure the surface brightness profile out to ~190 kpc (~60% r_{500}) in one direction, and the projected temperature on a scale of ~0.3 kpc in the brightest regions

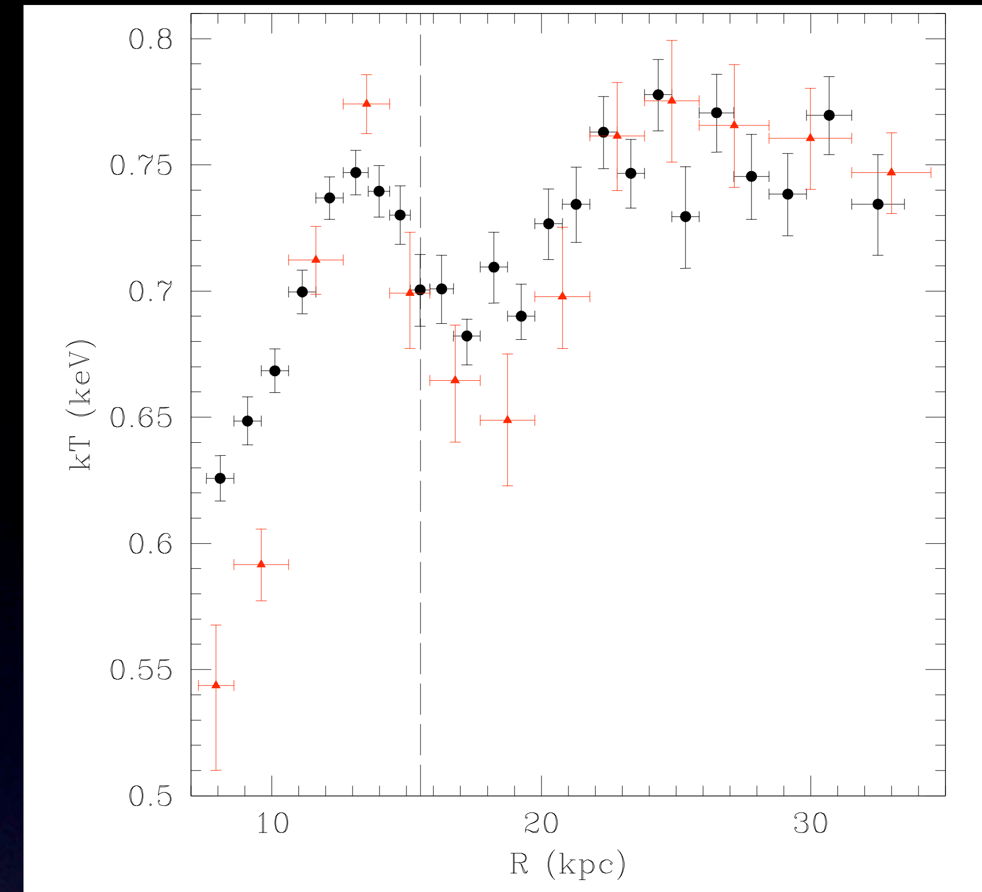




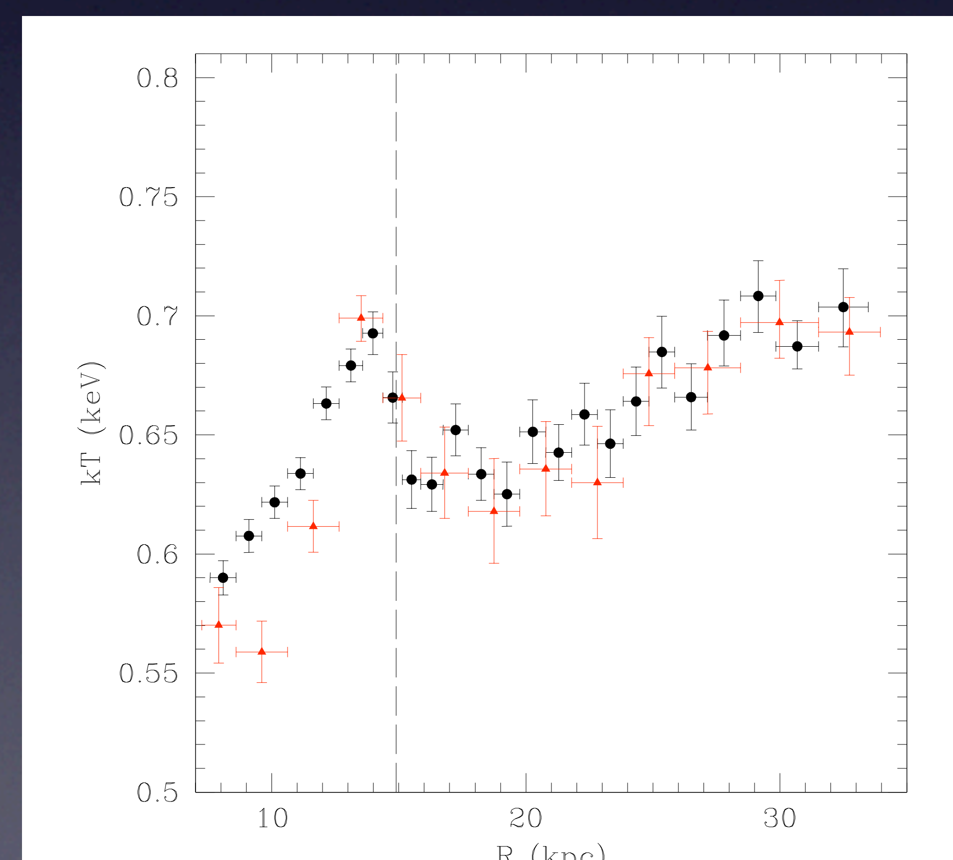
- Shocks are clearly visible, even in the temperature map
- Cool gas filament, lifted by buoyant bubbles
- Higher resolution temperature map coming soon!



Azimuthally averaged profiles
(from original 150 ks observation, SR+11)



NW shock



SE shock

Shock Structure

Back to original 150 ksec observation:

- All edges are well-modeled by a discontinuous power law density model

- Outer shocks: $\rho_1/\rho_2 = 1.74$, M = 1.52
- Core shock: $\rho_1/\rho_2 = 1.97$, M = 1.71

- Mach numbers correspond to similar jumps in temperature (by factors of 1.5 and 1.7)

- Simple 1D hydro simulations reproduce measured density, Mach number, and projected temperature jumps (SR+11)

What About Heating?

- Within 170″ (26.3 kpc) U_{gas} = 1.7 x 10^{58} erg, t_{cool} = 1.0 Gyr
- Outburst repetition rate (from bubble rise times and shocks) is ~10^7 yr
- Gives 100 shocks per cooling time, with E_{shock} = 2 x 10^{57} erg per shock (from observations and hydro simulations), gives more than 10 x's total energy needed to offset cooling

- BUT, only some fraction of this energy goes into heating (and this fraction is small for weak shocks)

- Transient temperature rise as shock passes, but lasting heating comes from change in entropy, so the heating done by the shock expressed as a fraction of the thermal energy in the gas E is:
$\triangle Q \sim T \triangle S \Rightarrow T\triangle S/E \sim \triangle \ln[P / \rho^{\gamma}]$

Shocks Alone Can Do the Job!

- Shock heat input is 10% and 5% of the local thermal energy of the gas for the inner and outer shocks respectively. Therefore, to completely replace the thermal energy of the gas per *local* cooling time requires 10 and 20 shocks

- $t_{cool,inner}$ ~ 2 x 10^8 yr (20 shocks per cooling time)
- $t_{cool,outer}$ ~ 9 x 10^8 yr (90 shocks per cooling time)

- This heating takes place near the core, close to the central AGN where the Mach numbers are large, as is required for AGN feedback (in contrast to the internal energy in bubbles)

What to Take Away

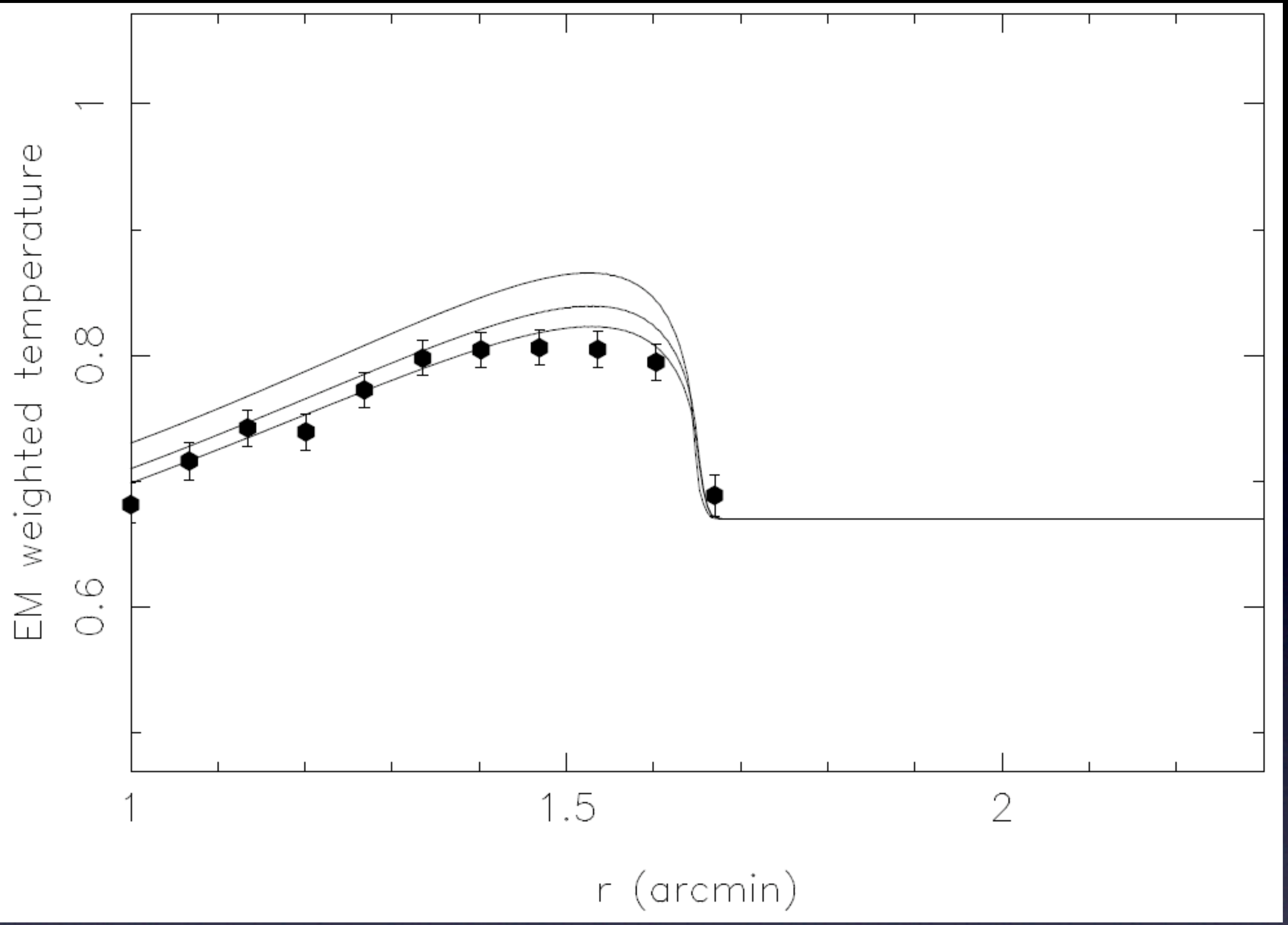
- Although the energetics of X-ray cavities are sufficient to offset radiative cooling, the details of the heating process are not well understood
- Shocks also heat the gas, isotropically and in the core, in an understood way
- Detecting outburst shocks (especially with measured temperature jumps) is difficult

NGC 5813 (now with 650 ksec total Chandra exposure, more than any other group) uniquely shows collinear cavities and shocks with temperature jumps from multiple outbursts, and is ideal for studying AGN feedback, shock heating, outburst history, and buoyant bubble evolution

- In this case, shocks alone offset cooling within the central 15+ kpc (can expect that shocks do the job at small radii in other systems)

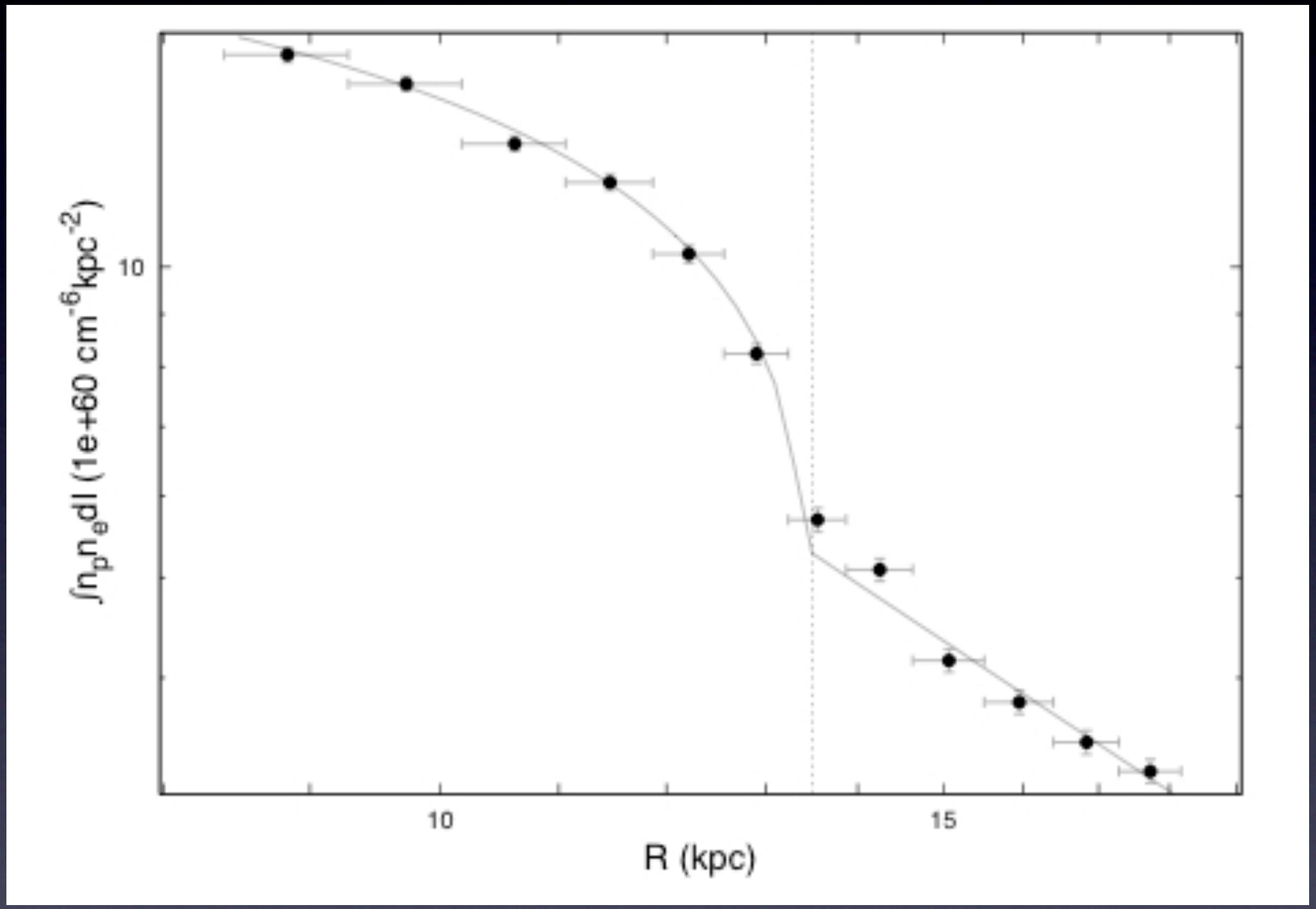
- This not only solves the cooling flow problem, but also has important implications for galaxy evolution theory (e.g., Kormendy+09)

Thank You!

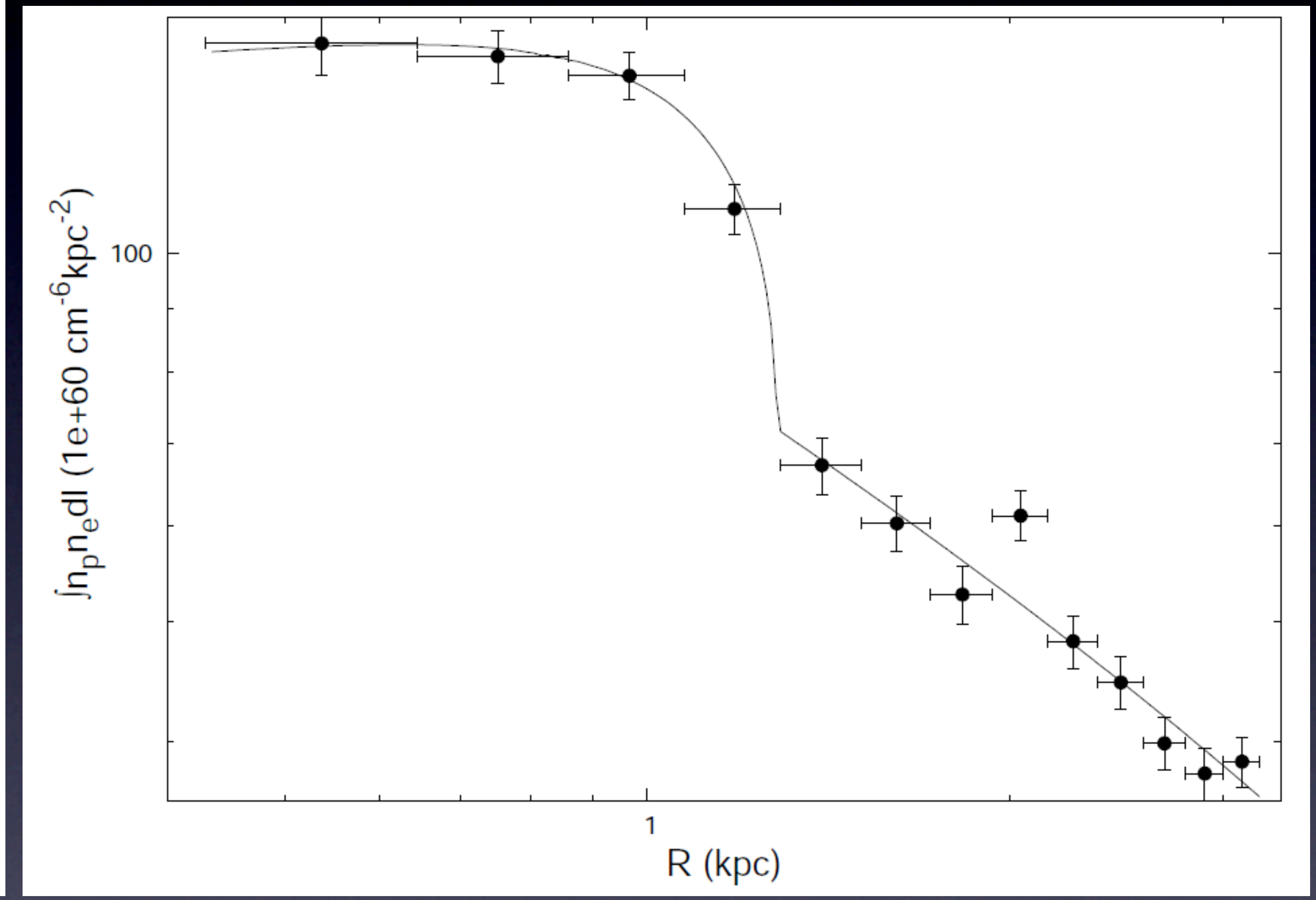


- Model shock with hydro-code as a point explosion in an isothermal, power law density gas sphere
- Predicted projected temperature jump of ~ 0.1 keV is consistent with observations (and Mach number exactly matches above estimate)

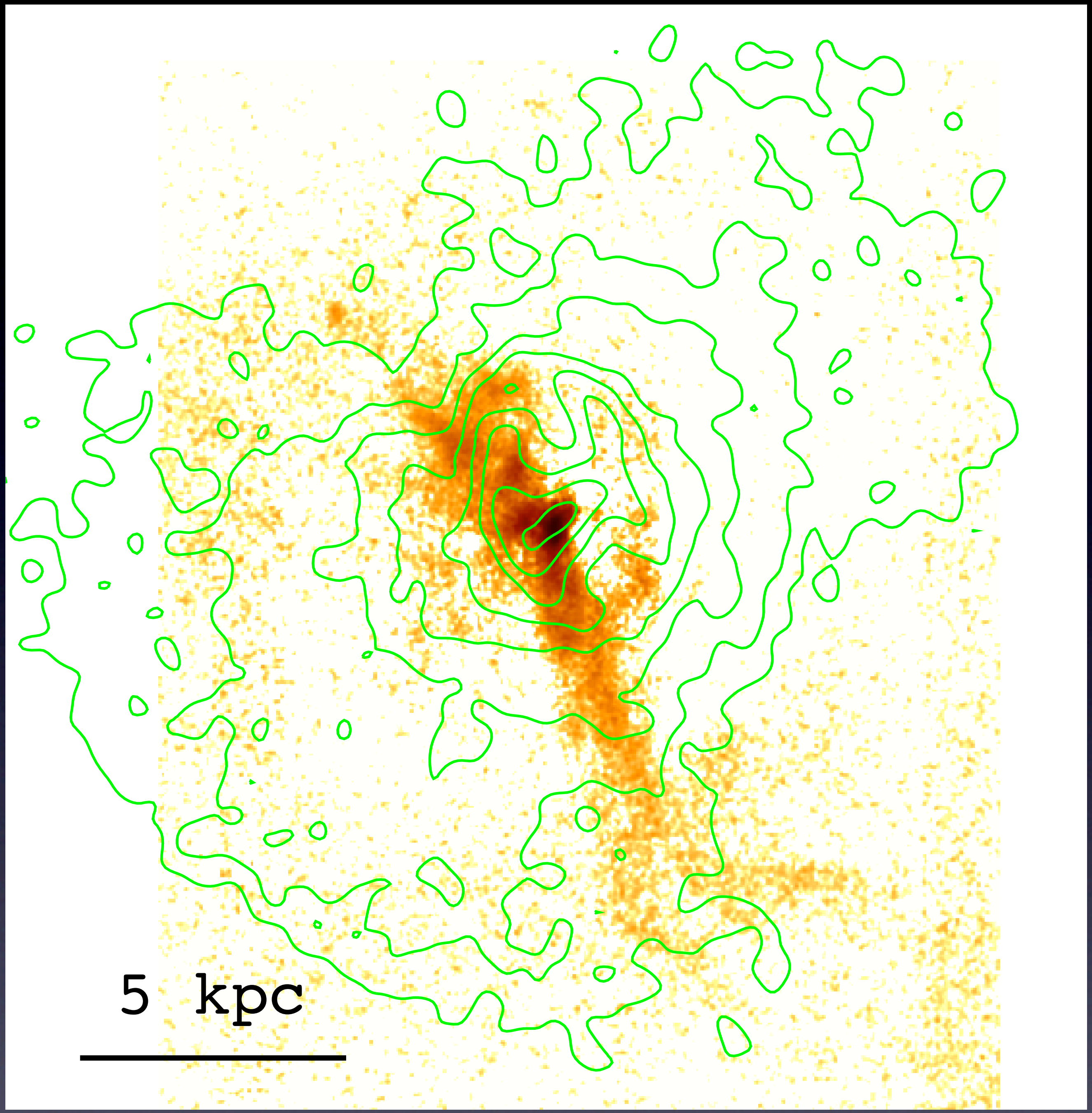
To measure shock properties, fit the integrated emission measure profile with a discontinuous power law density model

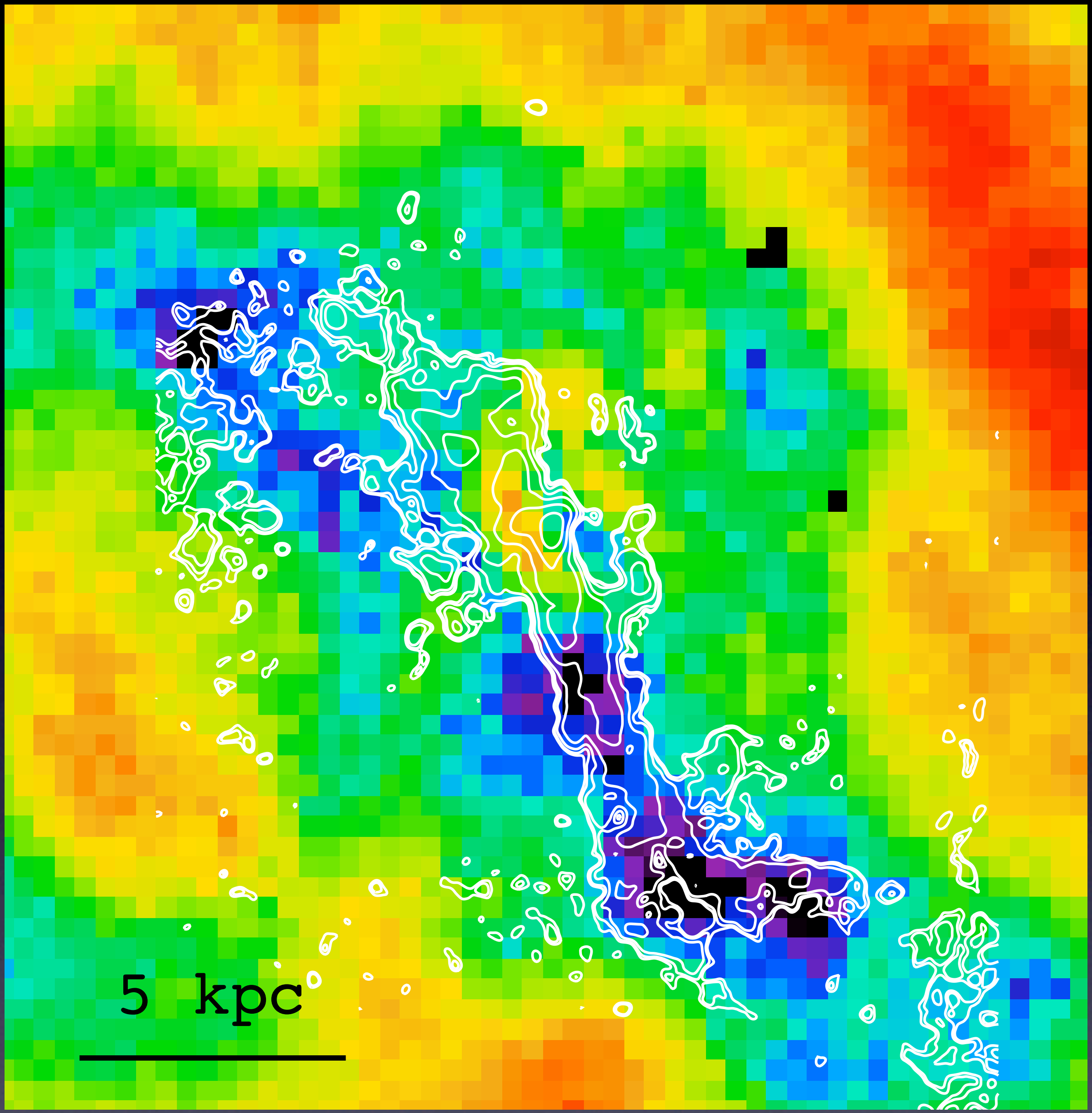


SE outer shock

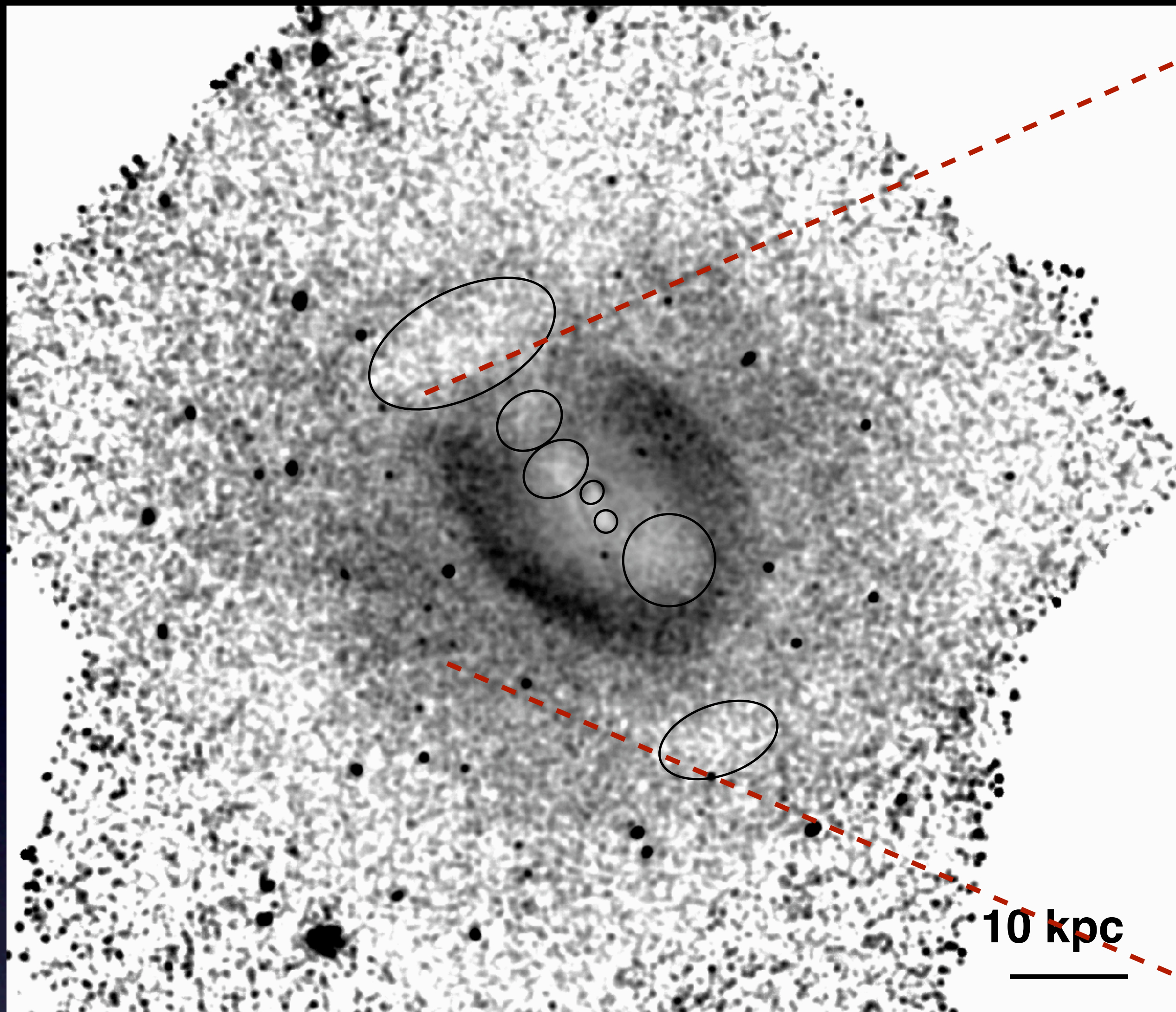


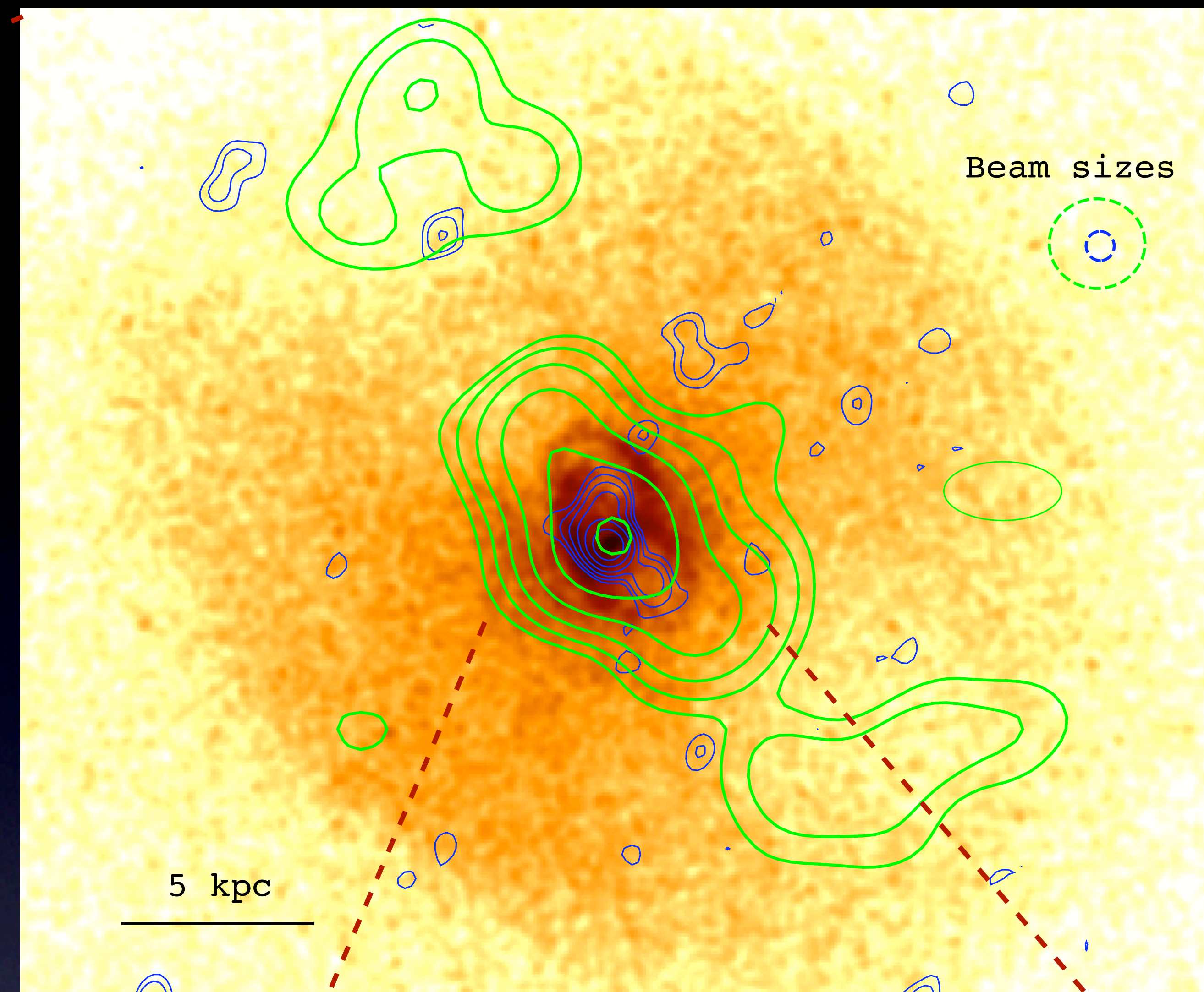
Core shock



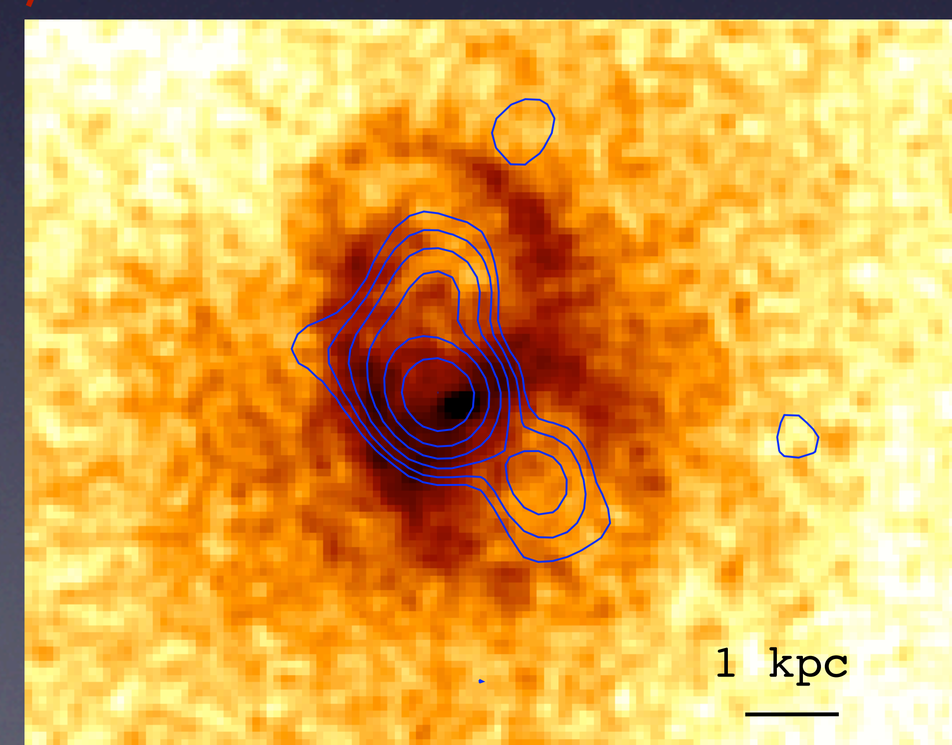


Hα image from SOAR





Residual map



- Three pairs of collinear, regular cavities
- Sharp surface brightness edges associated with inner and middle pairs
- Radio spectral index steepens rapidly with cavity radius

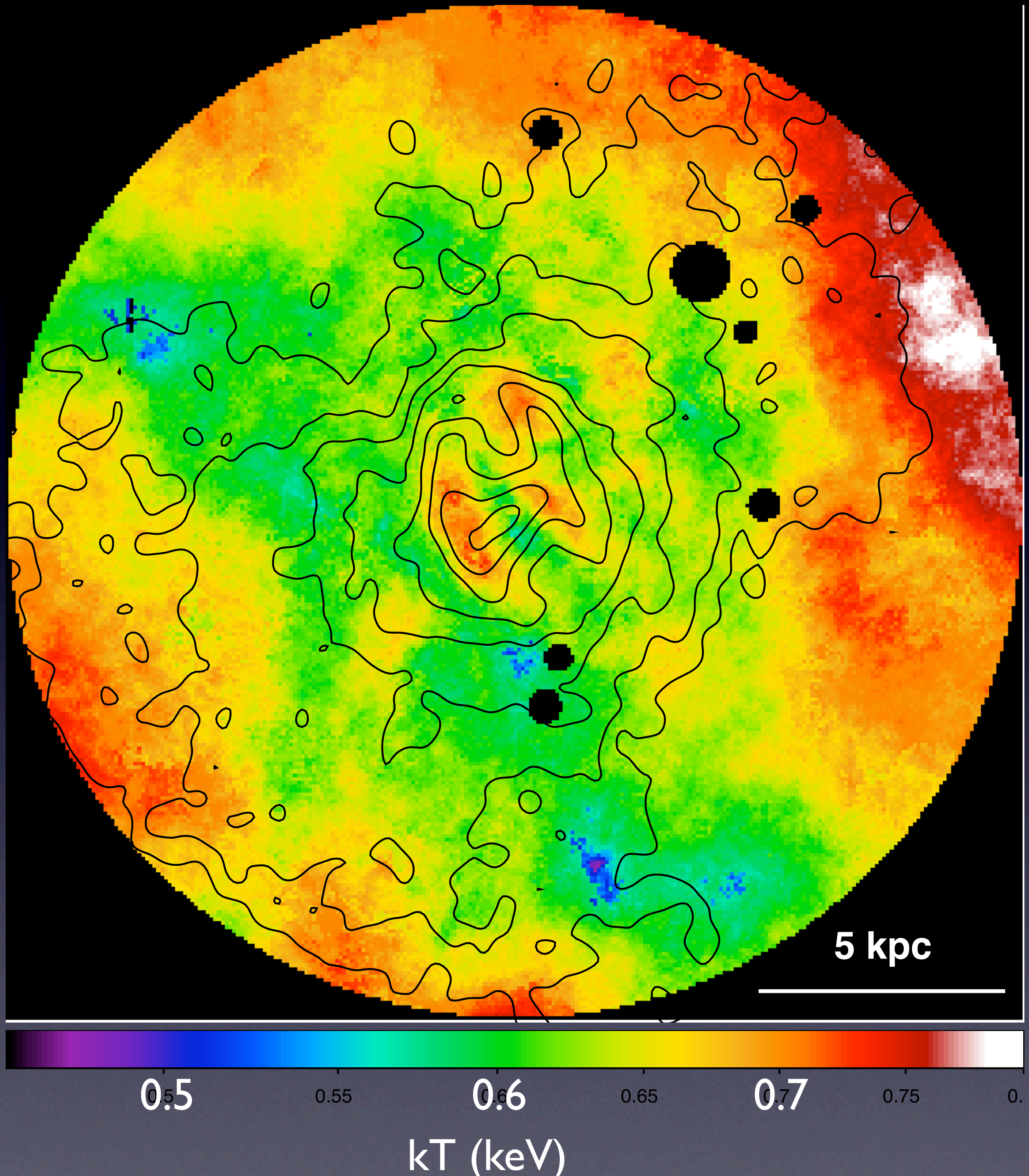
Blue: 1.4 GHz VLA, Green: 235 MHz GMRT

Outburst Energy

- The total shock energy is roughly $E_{shock} \sim PV\,(f_p - 1)$
  [Also estimated shock energy from hydro simulations]
- Cavity internal energy is ~ 3 PV
- Total outburst energy ~ shock energy + cavity internal energy
- Outburst repetition rate is ~ 10^7 yr (from cavities *and* shocks), so we can calculate the mean outburst power

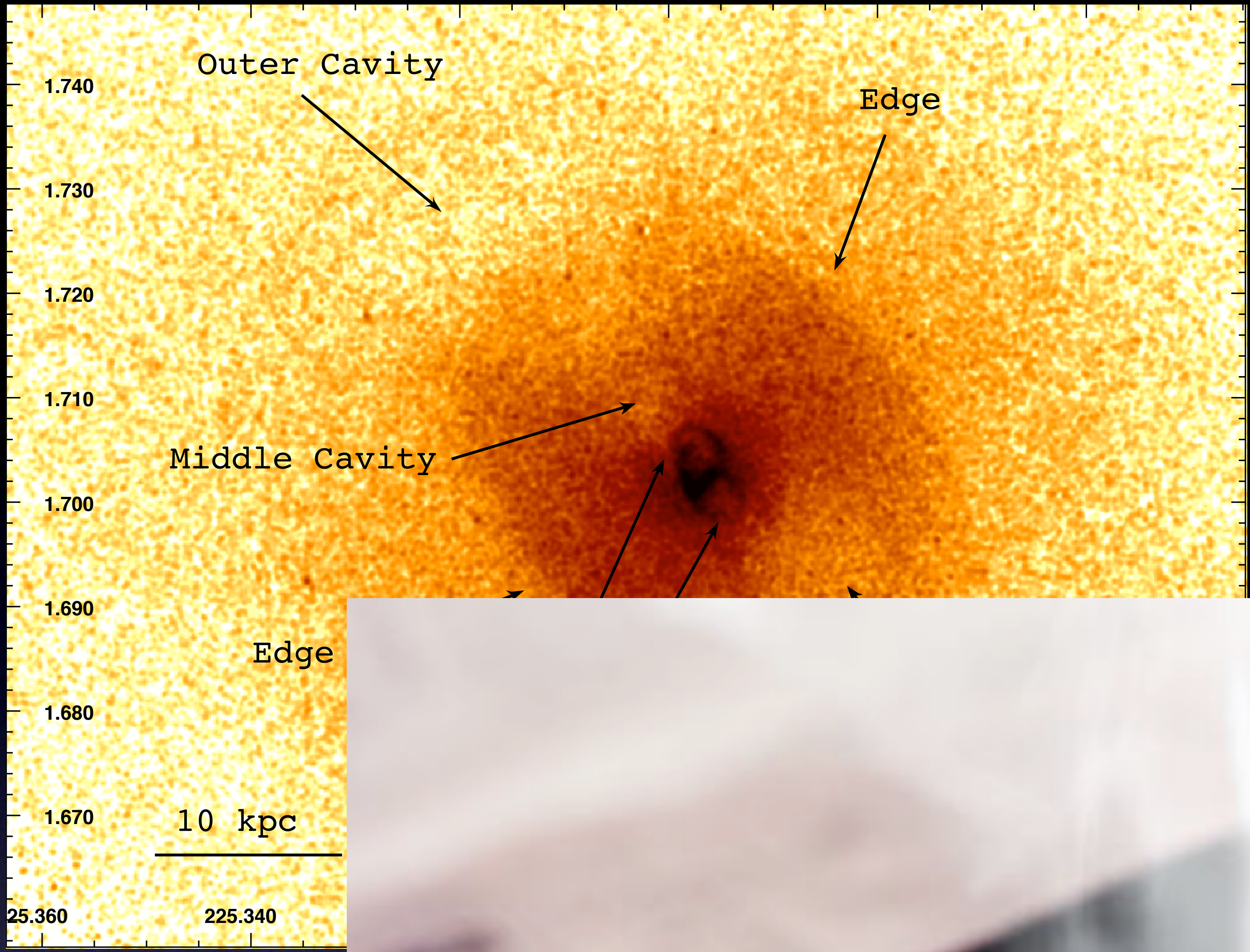
Results

- Total previous outburst energy more than 10 x's that of the current outburst (1.5 x 10^{56} erg vs. 4 x 10^{57} erg)
- Mean power of the current outburst is also less (1.5 x 10^{42} erg/s vs. 1 x 10^{43} erg/s)
- Conclusion: Mean outburst power can vary significantly over long (~10^7 yr) timescales, even in an otherwise relaxed system



High resolution temperature map of the core

- Rims around central cavities are hot and over-pressured, also consistent with shocks



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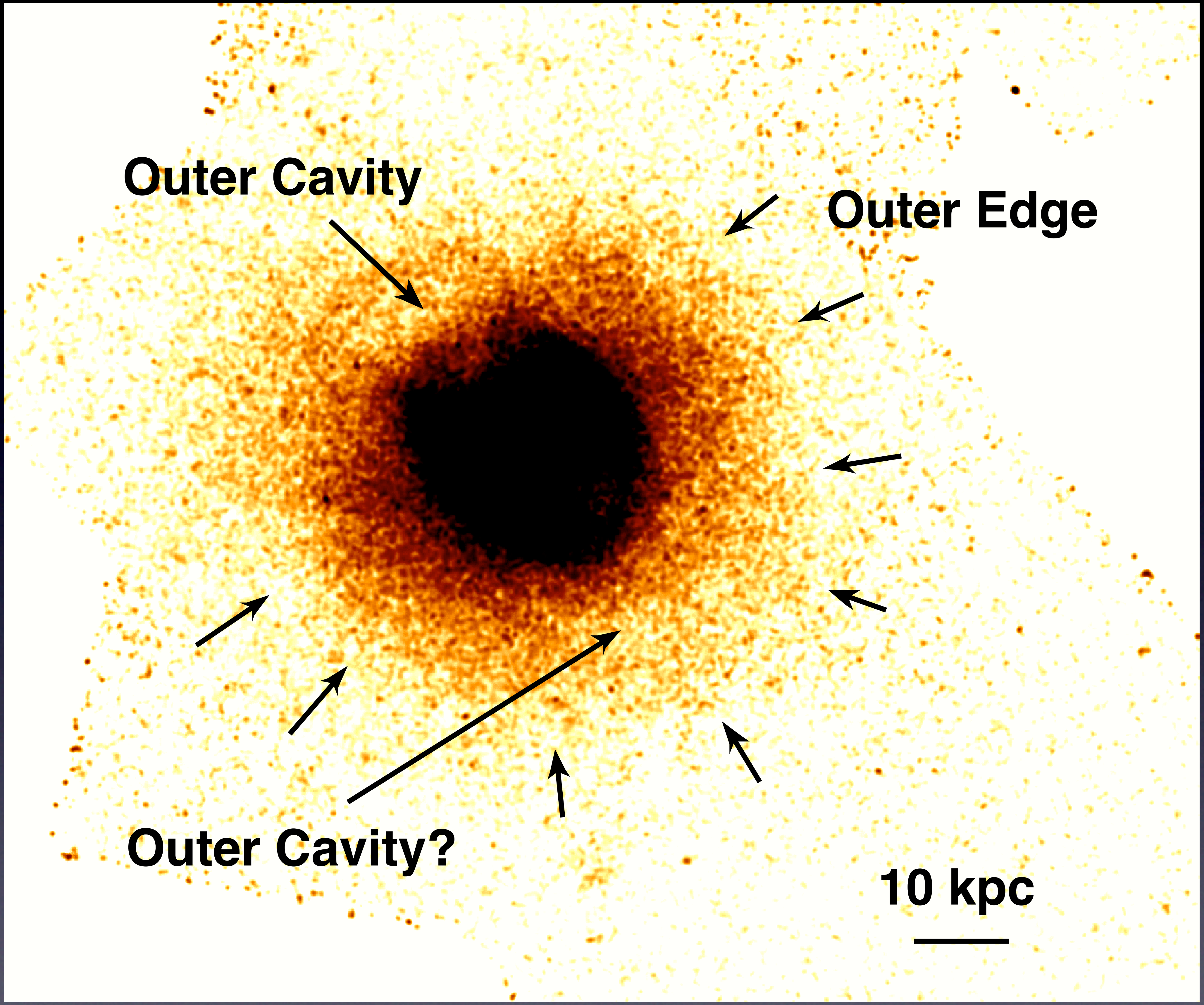
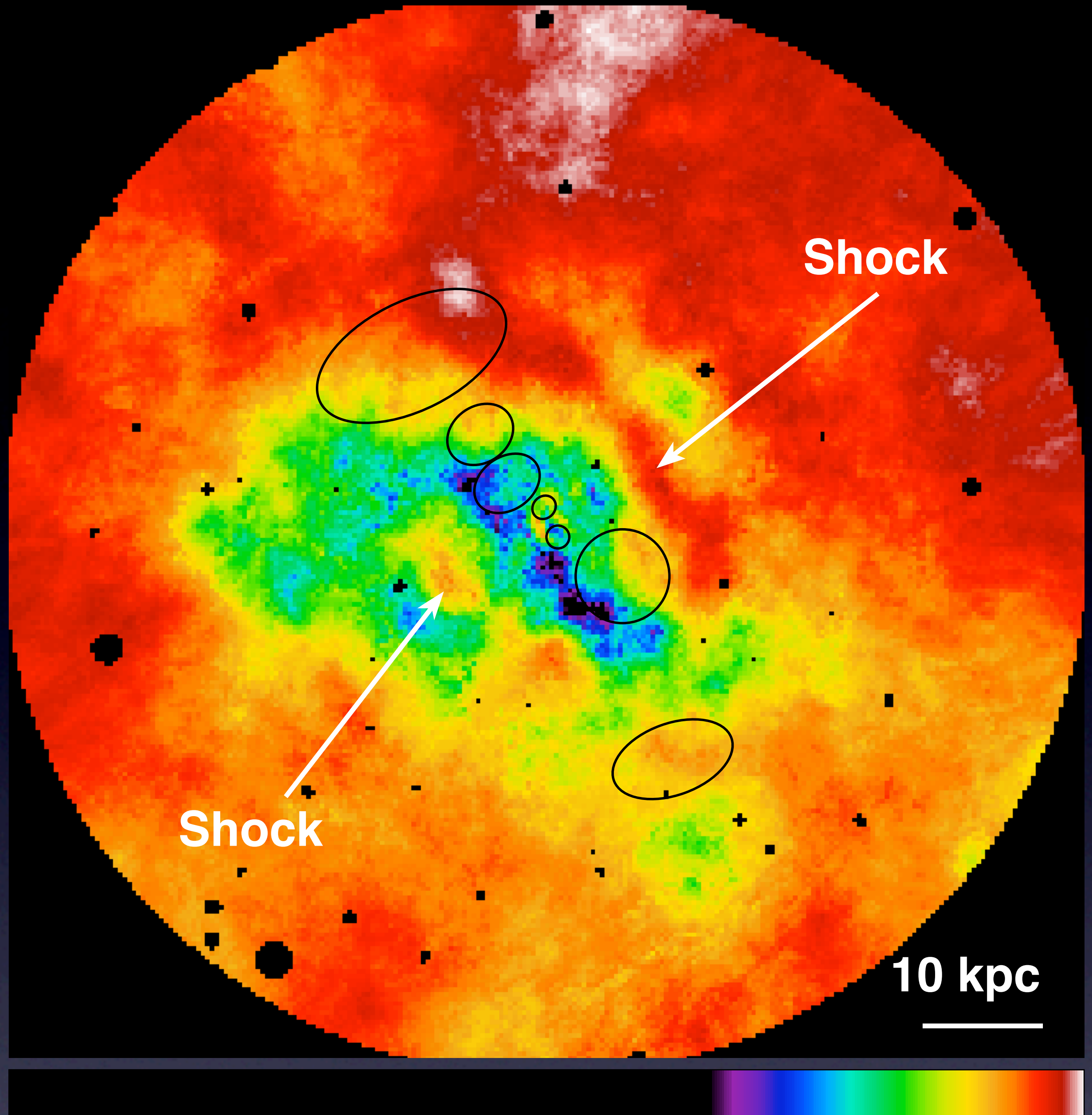
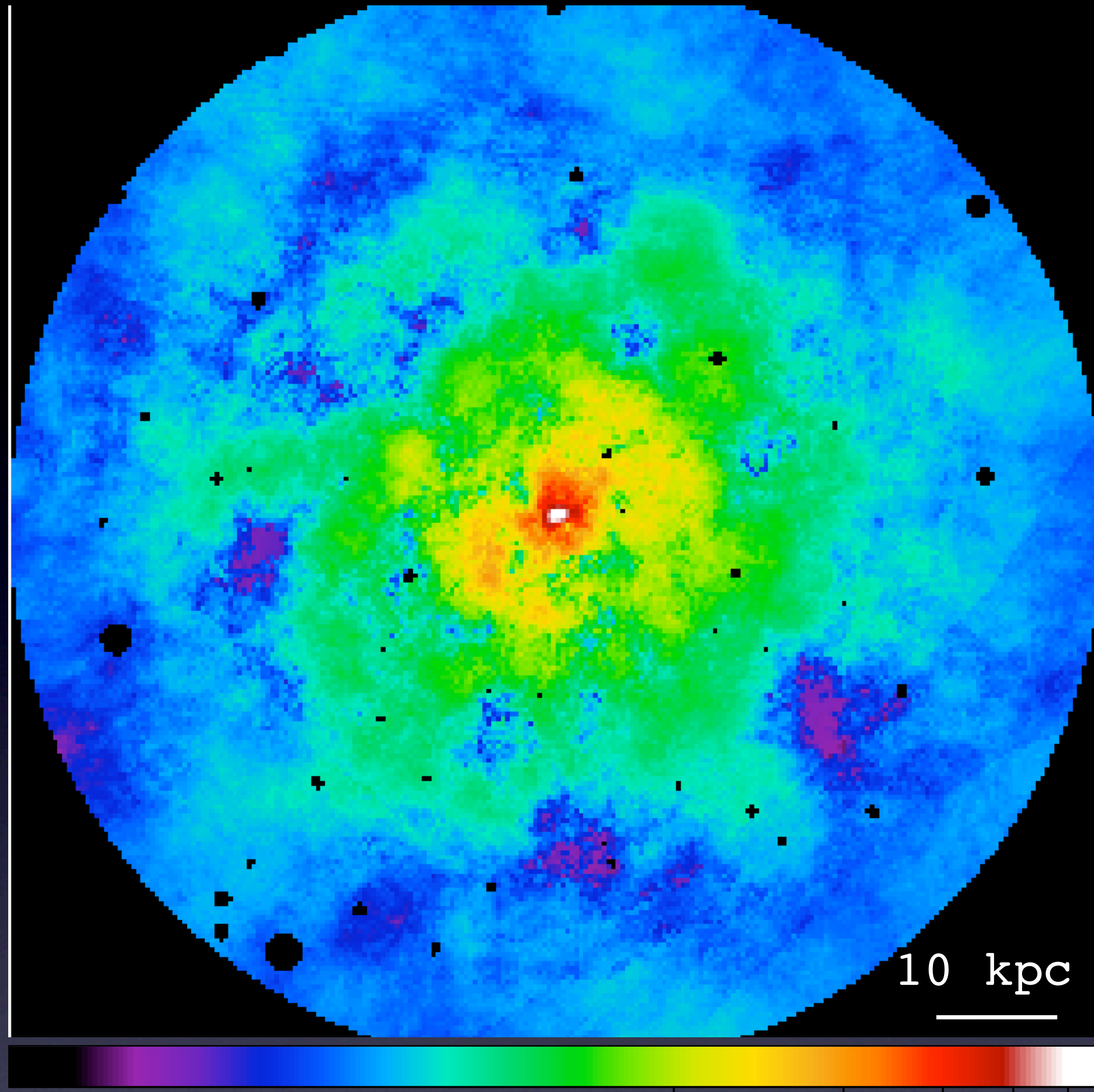
CXC Clusters, Boston 2011

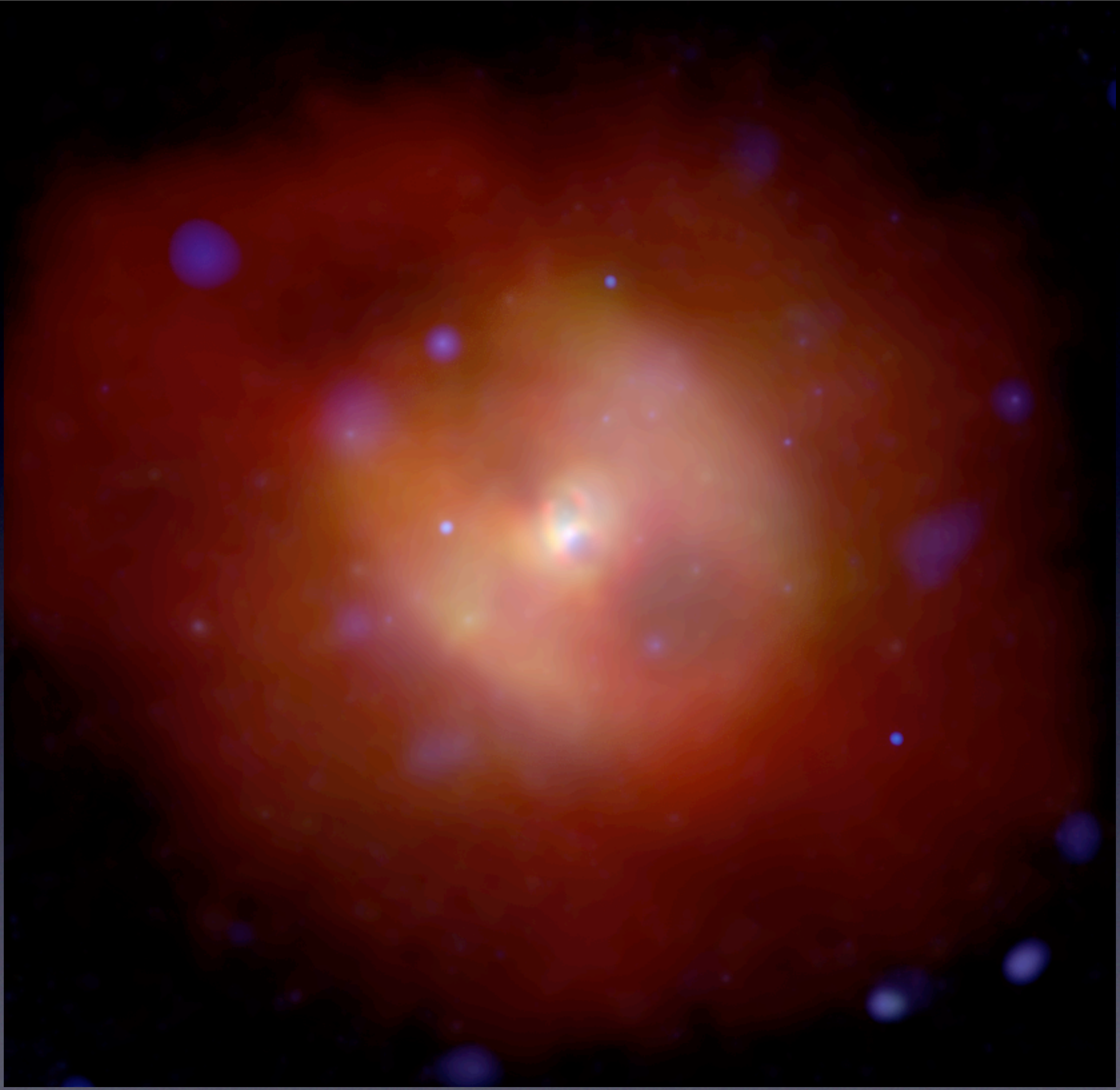


- Hint of an outer edge associated with the outer cavities (?)





- Jumps in the projected temperature (left) and pseudo-pressure (right) maps identify edges as shock fronts
- Cool trail corresponds to Hα emission, presumably buoyantly uplifted gas



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Red: 0.3 - 1.2 keV; Green: 1.2 - 2.0 keV; Blue: 2.0 - 7.0 keV

CXC Clusters, Boston 2011