Heating the Intracluster Medium Through AGN Feedback

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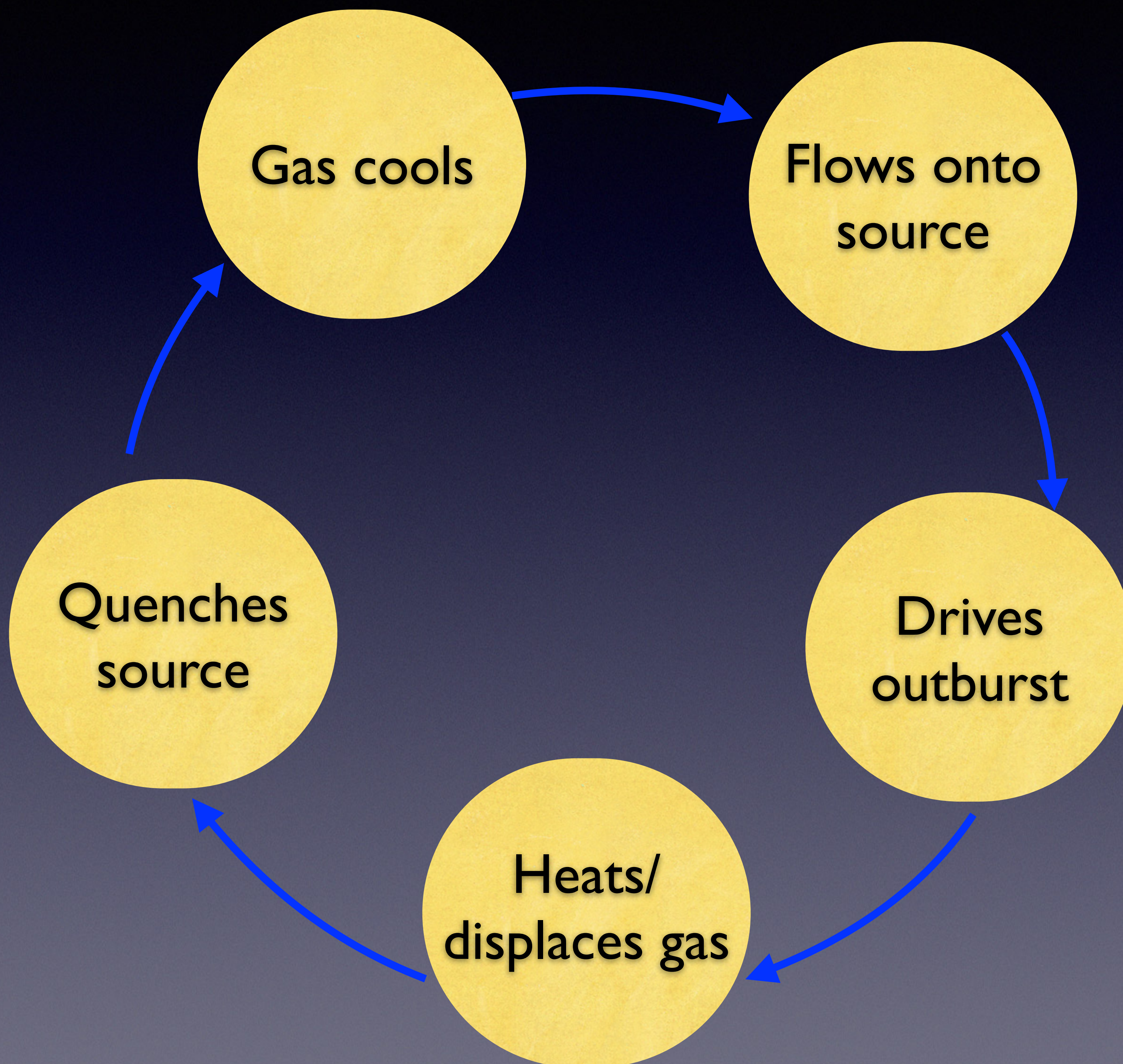
What is Feedback?

- Output from AGNs/stars regulates the cooling rate and distribution of the diffuse gas that forms/fuels them
- Has implications for star formation rates; the evolution of galaxies, groups, and clusters; black hole growth; and the growth of large scale structure
- Must be included in cosmological simulations to reproduce the observed universe (e.g., Illustris; Nelson+15)
- Solution to the "cooling flow problem"

The Feedback Cycle



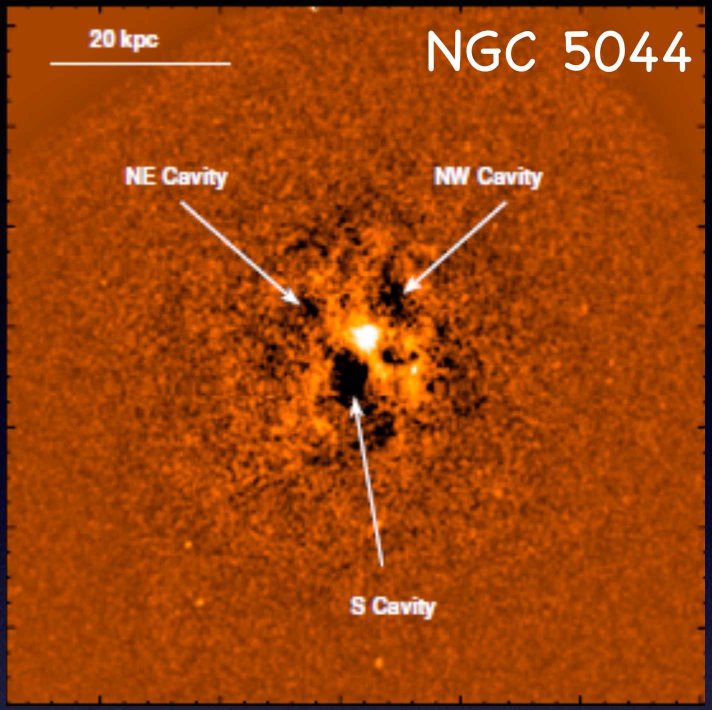
AGN Kinetic Feedback

- There is feedback from stars (galactic winds) and AGN (both kinetic and radiative mode)

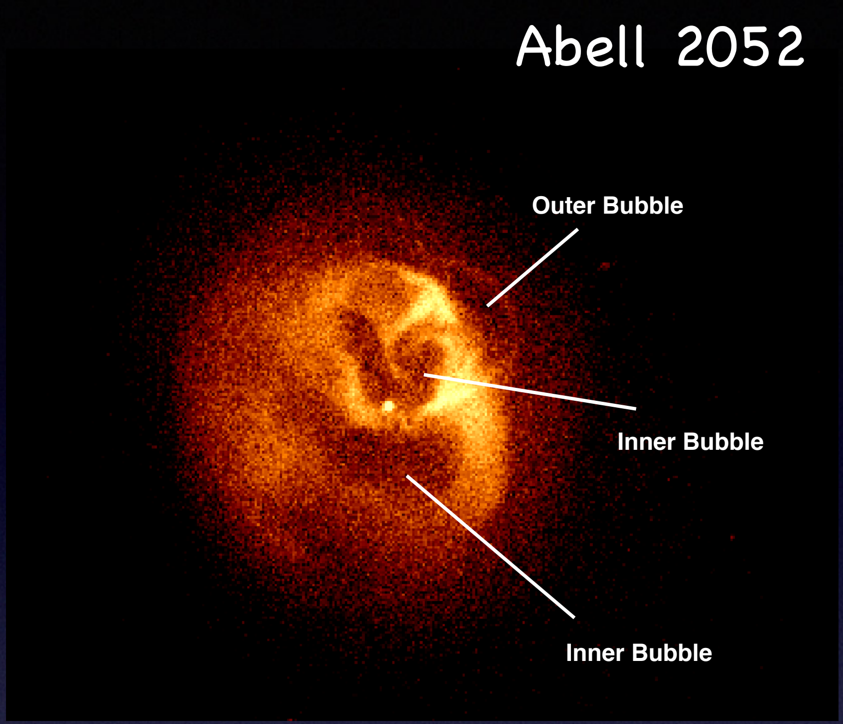
- Here we focus on kinetic mode AGN feedback in central SMBHs (local universe, radiative power negligible, accreting at 1-10% Eddington)

- AGN jets inflate cavities in the ICM filled with radio plasma, cavity inflation drives shocks, cavities rise buoyantly

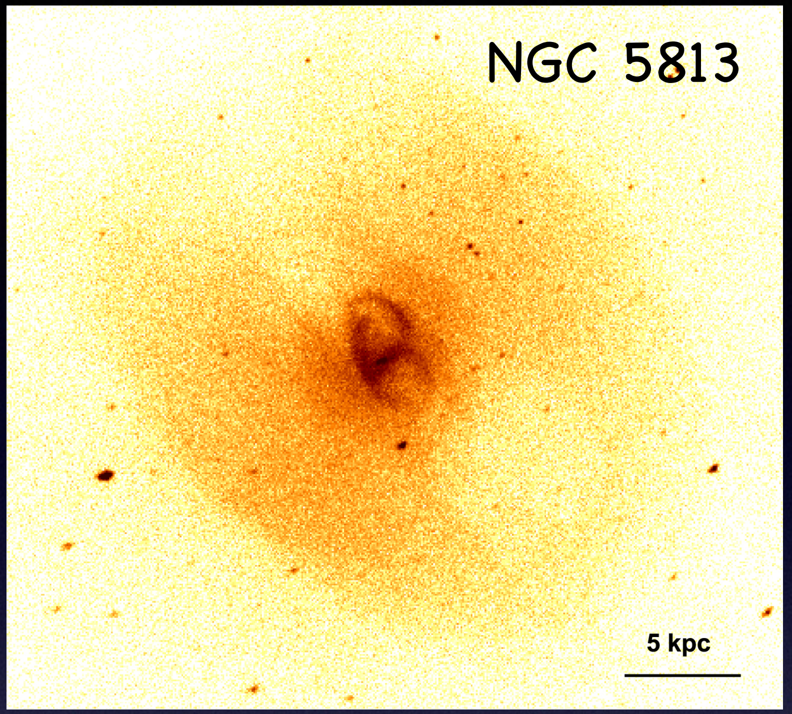
Cavities and Shocks



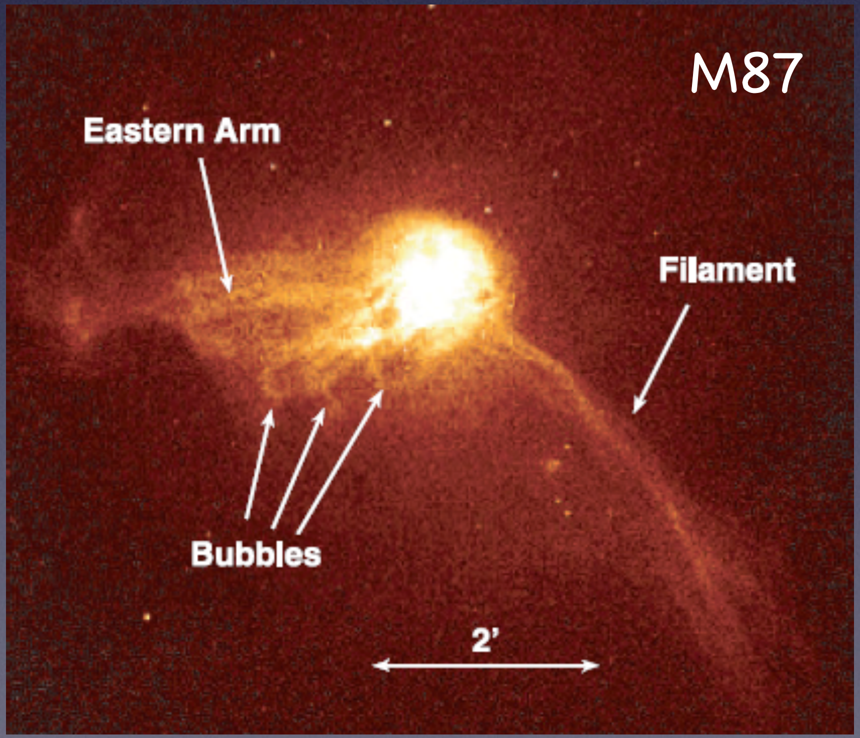
David+09



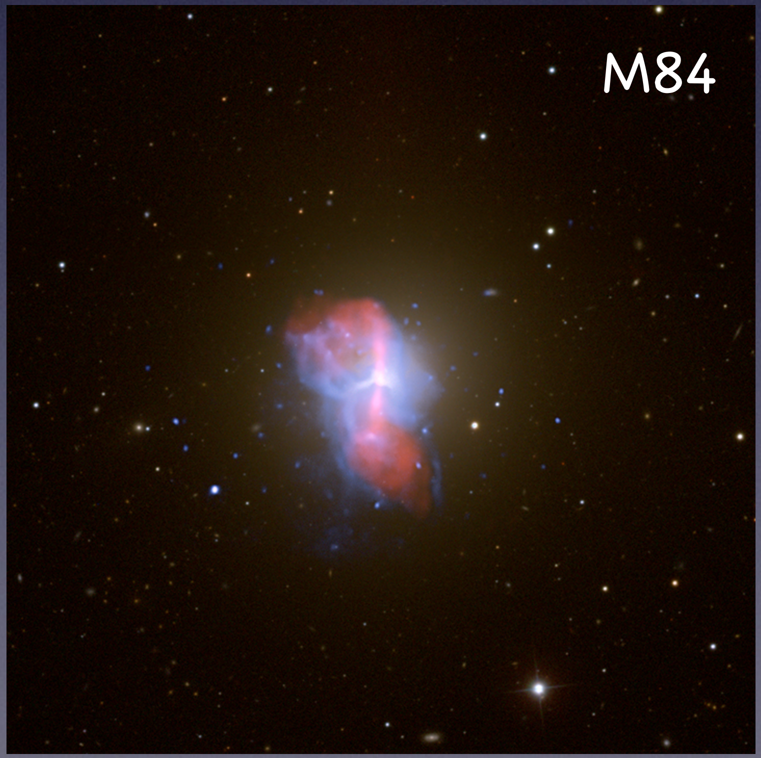
Blanton+09,10,11



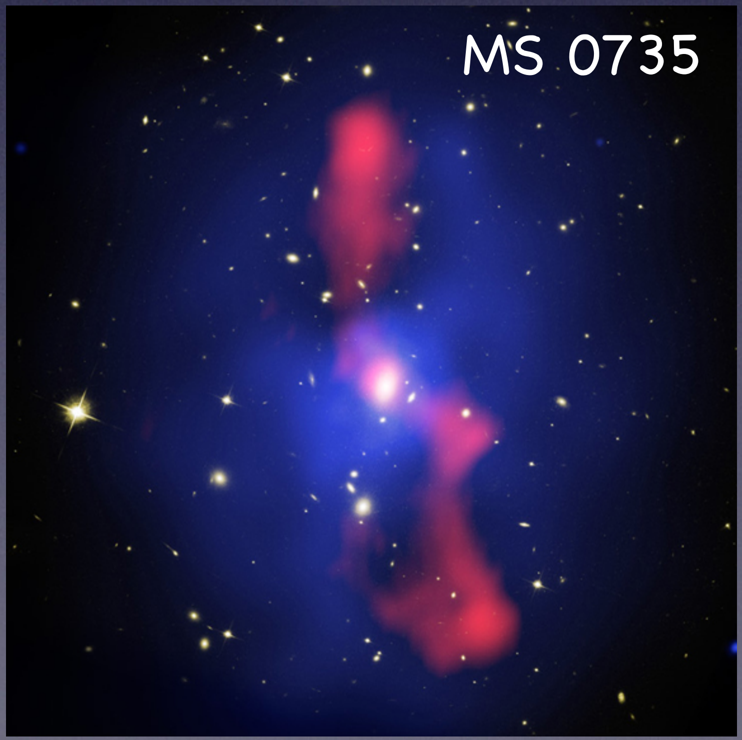
Randall+11,15



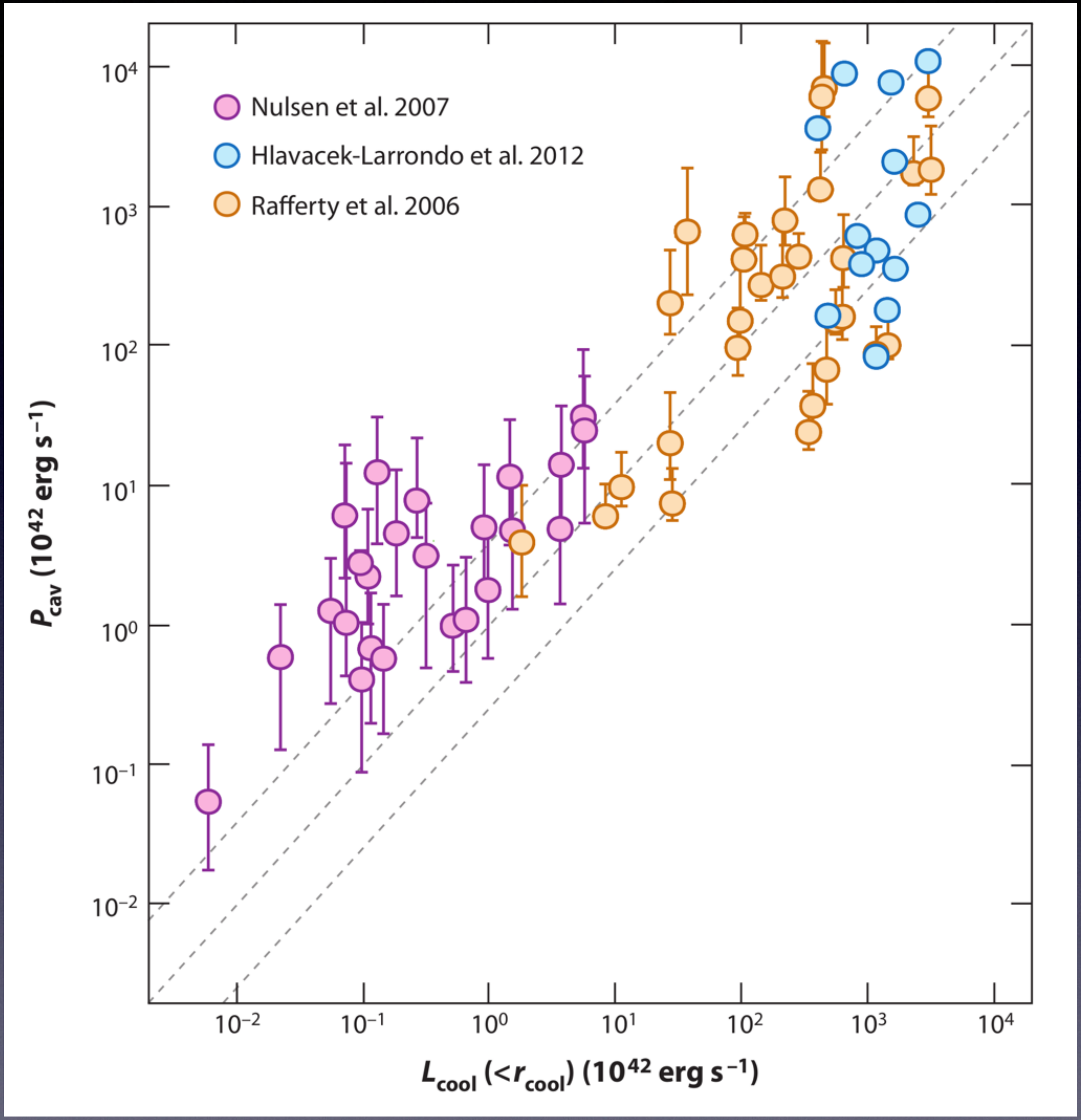
Forman+07



Finoguenov+08



McNamara+05



Fabian 12

Estimate P_{cav} as cavity enthalpy divided by cavity lifetime

Correlation with cavity power and cooling luminosity over six orders of magnitude, and out to Z~0.7 (Birzan+04; Rafferty+06; Nulsen+07; Hlavacek-Larrondo+12)

How Does the AGN Heat the ICM?

- There is generally enough energy output by central AGN to heat the ICM and balance radiative cooling, but how is this energy deposited in the ICM?
- Suggestions include turbulence, mixing with cavities, and weak shocks (Churazov+02; Soker+05; Fabian+06; Nulsen+07; Randall+11; Zuravleva+14; Hillel+16;...)
- Likely many or all of these mechanisms play a role

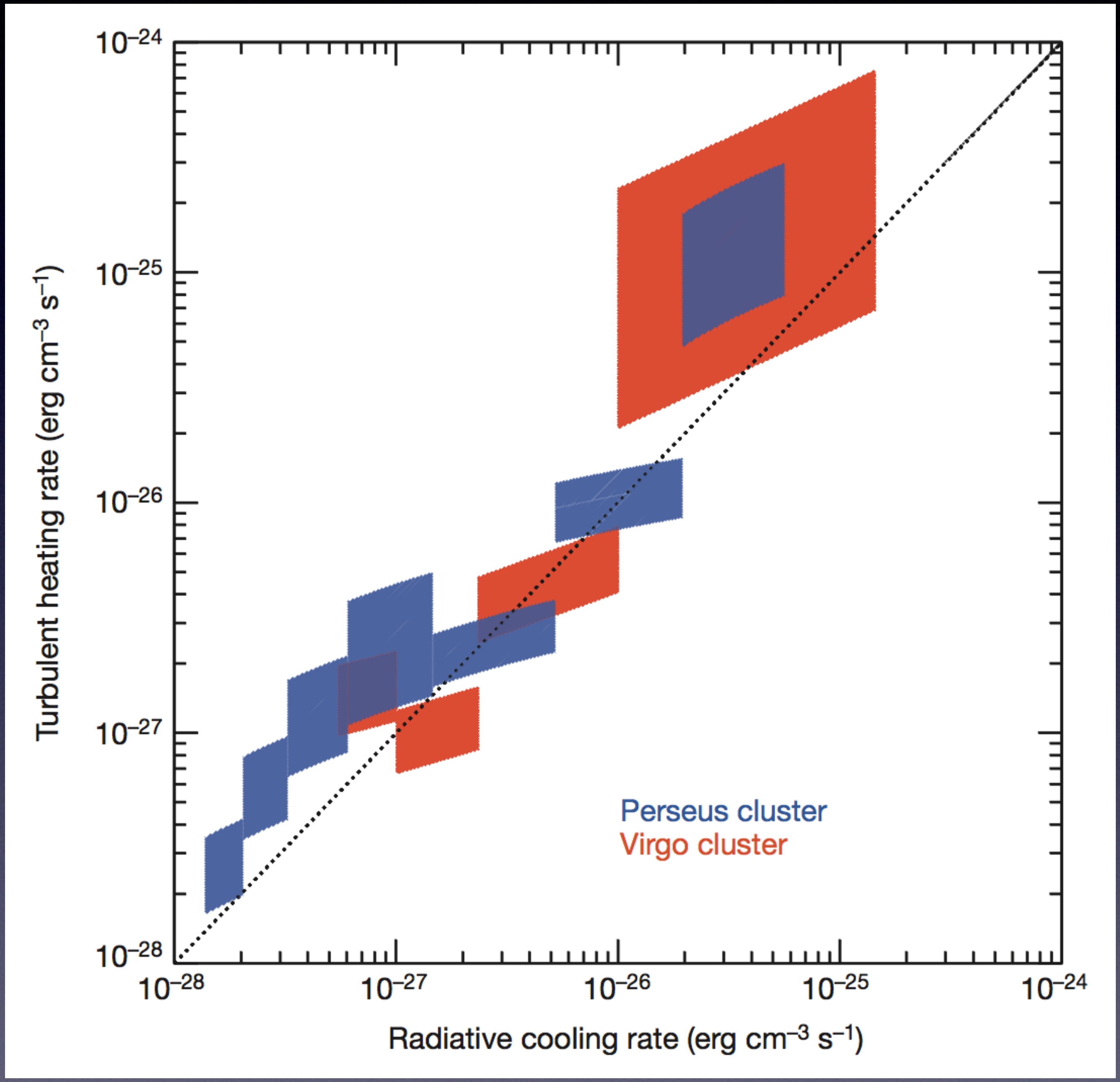
Turbulent Heating

- Assume density (surface brightness) fluctuations scale linearly with turbulent velocity

$$\left(\frac{\delta\varrho_k}{\varrho}\right)^2 \sim \left(\frac{V_k}{c_s}\right)^2$$

- Balances well with cooling rate in the few objects looked at (Zuravleva+14)

- All fluctuations over some range of scales are attributed to turbulence

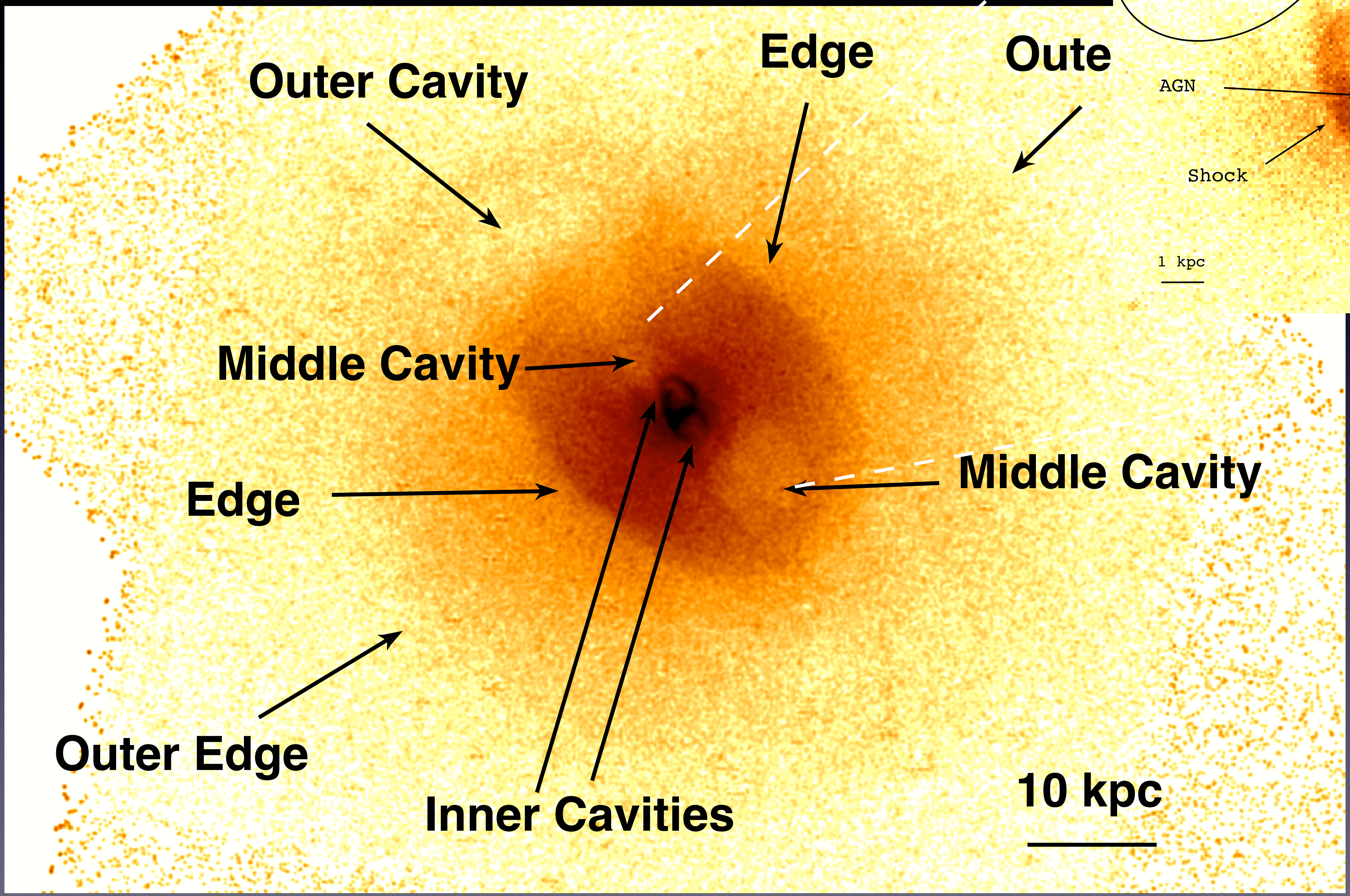


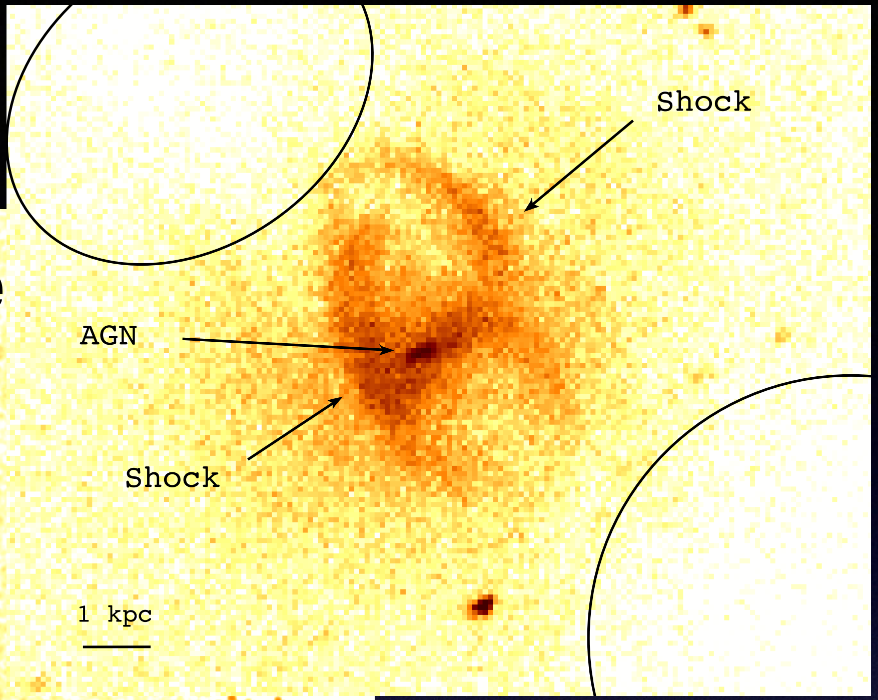
Zhuravleva+14

Shock Heating

- Shocks should be there from cavity inflation
- Expect a total shock energy similar to cavities
- Basic shock physics is well understood
- Shocks will naturally heat the ICM isotropically, and more strongly near the AGN, as required for feedback
- Shocks are directly observable

NGC 5813



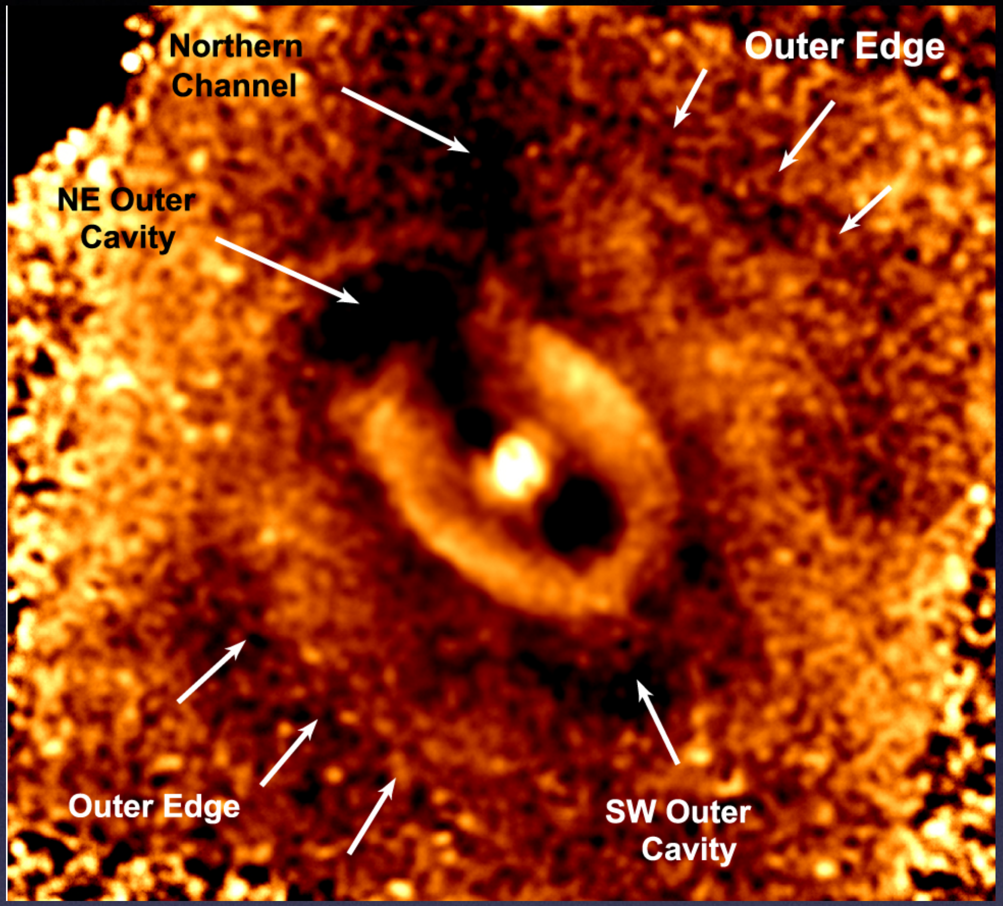


kT~0.65
z~0.0066

650 ksec image, Randall+15

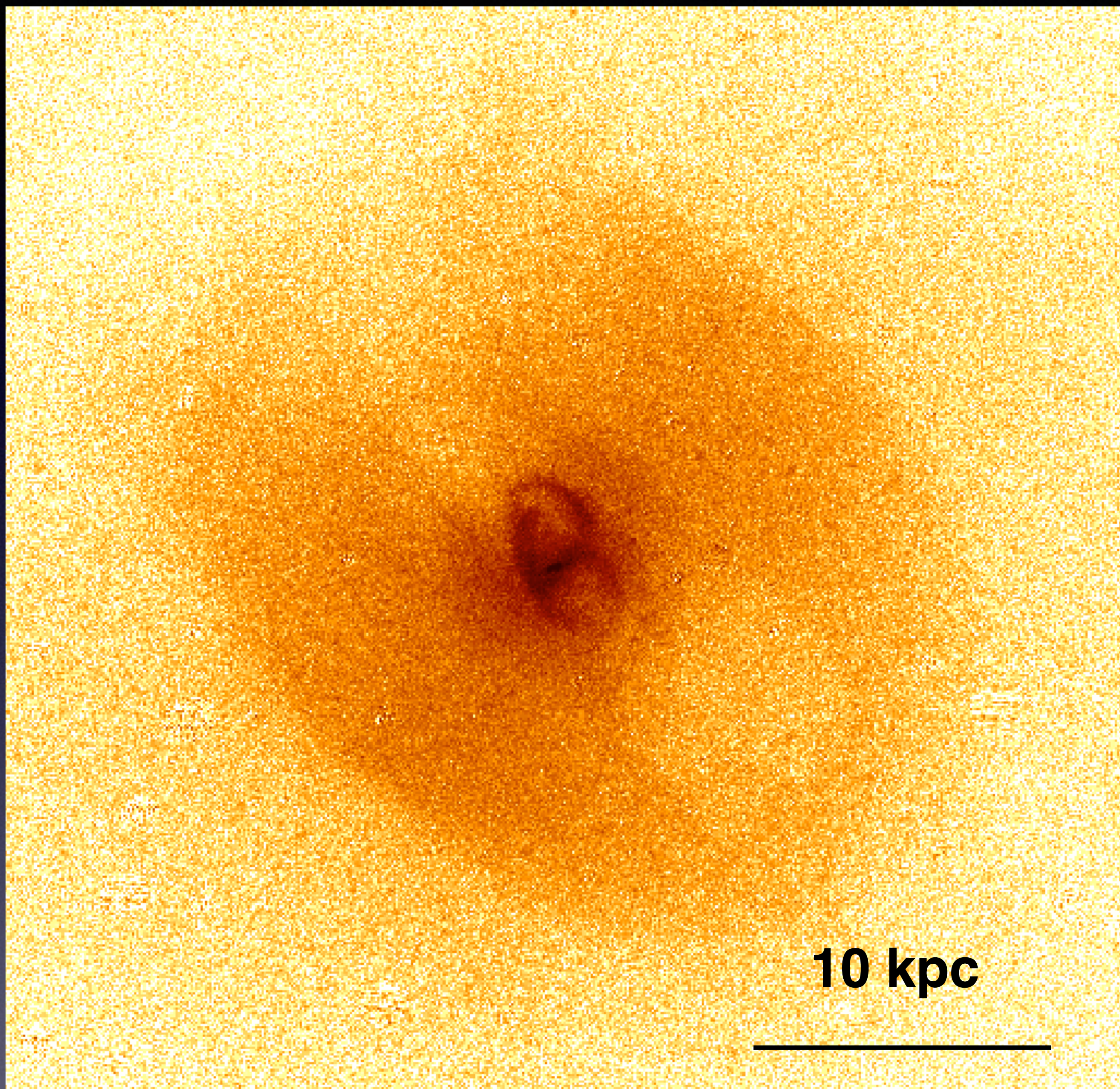
NGC 5813

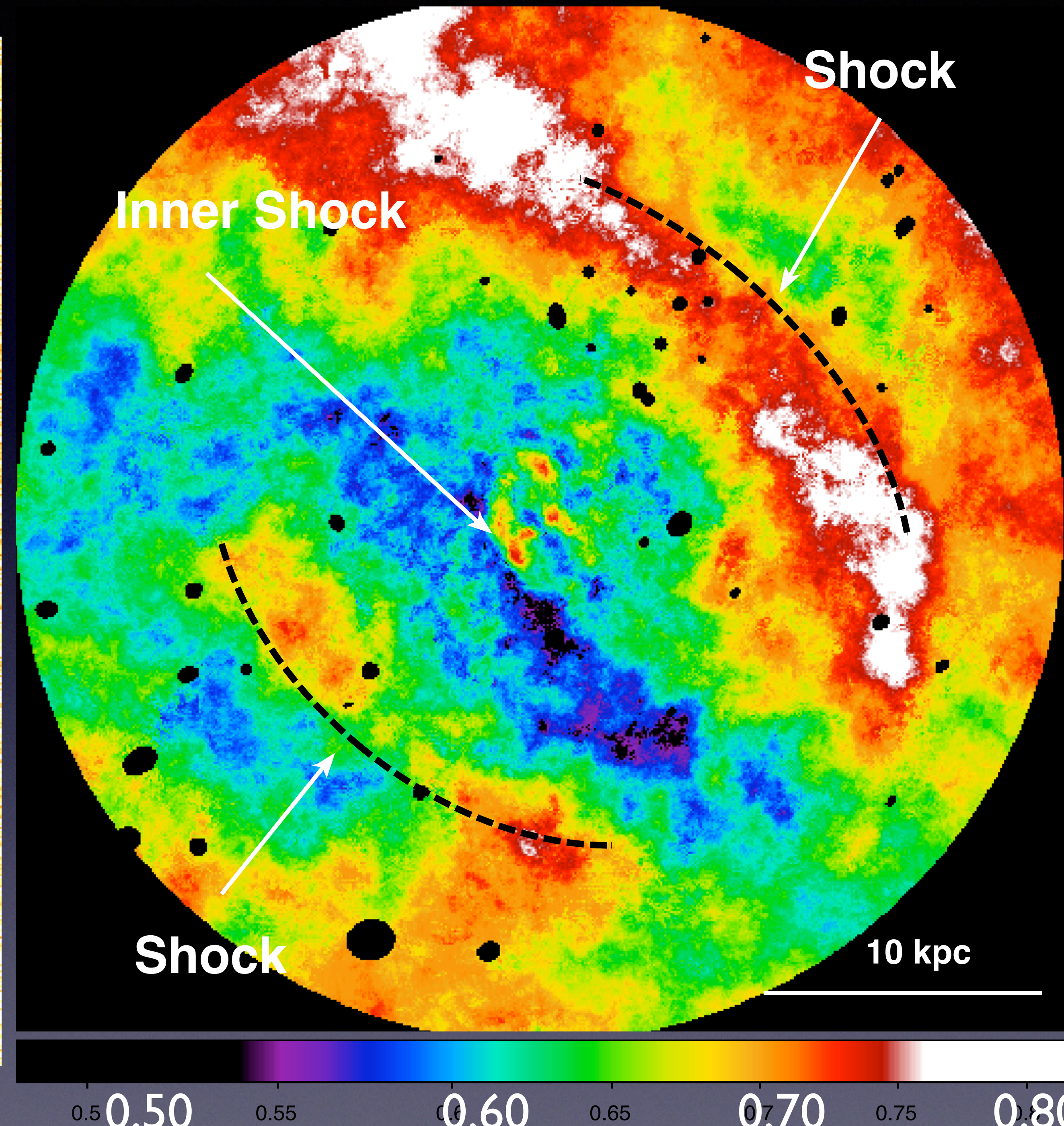
- Three pairs of collinear cavities and associated concentric surface brightness edges from three *distinct* outbursts of the central AGN



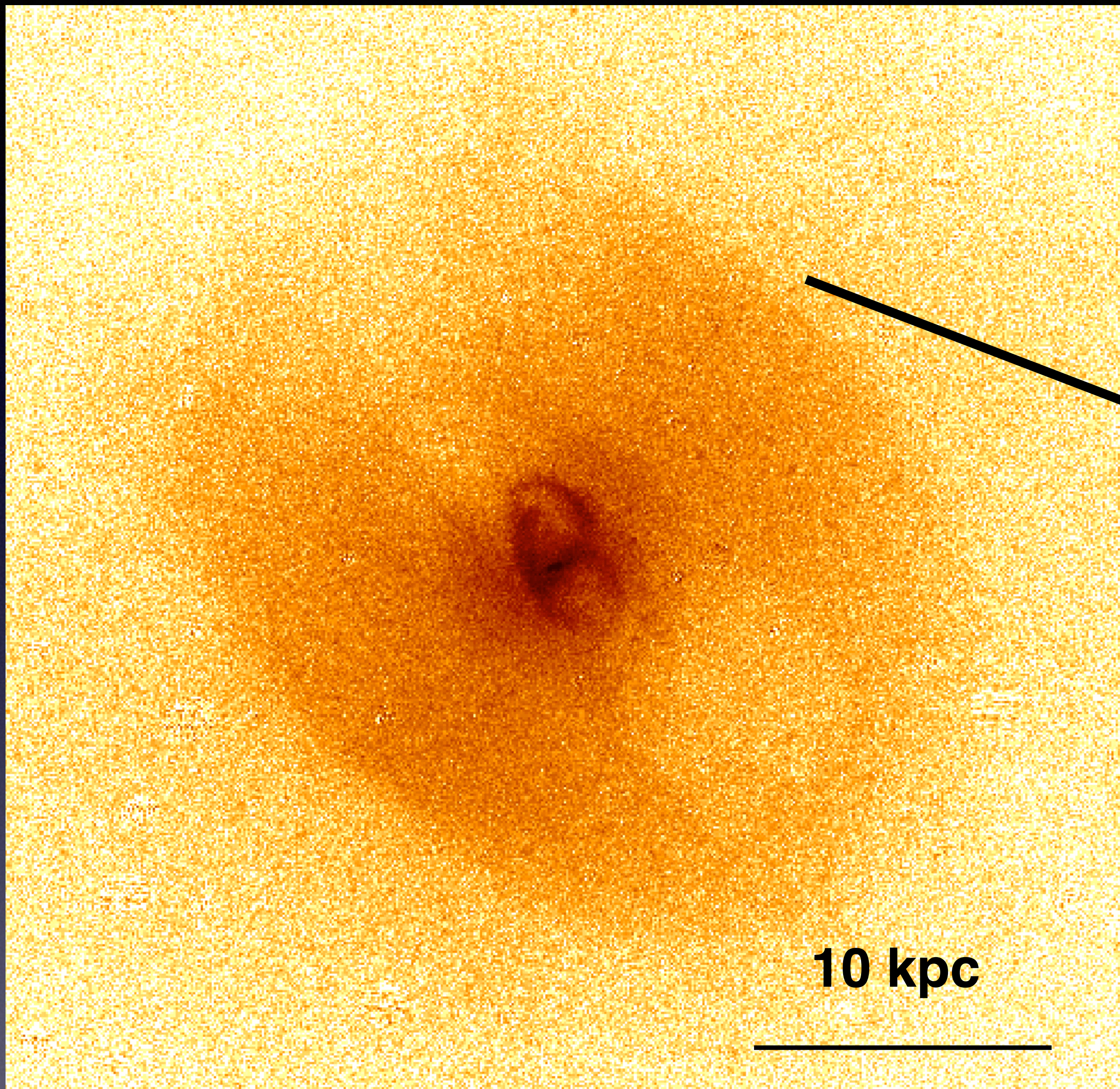
- Regular morphology, apparently in a "steady state" feedback mode, with relatively little IGM "weather"
- Nearby, good for resolving shock edges
- Particularly well suited to the study of AGN feedback

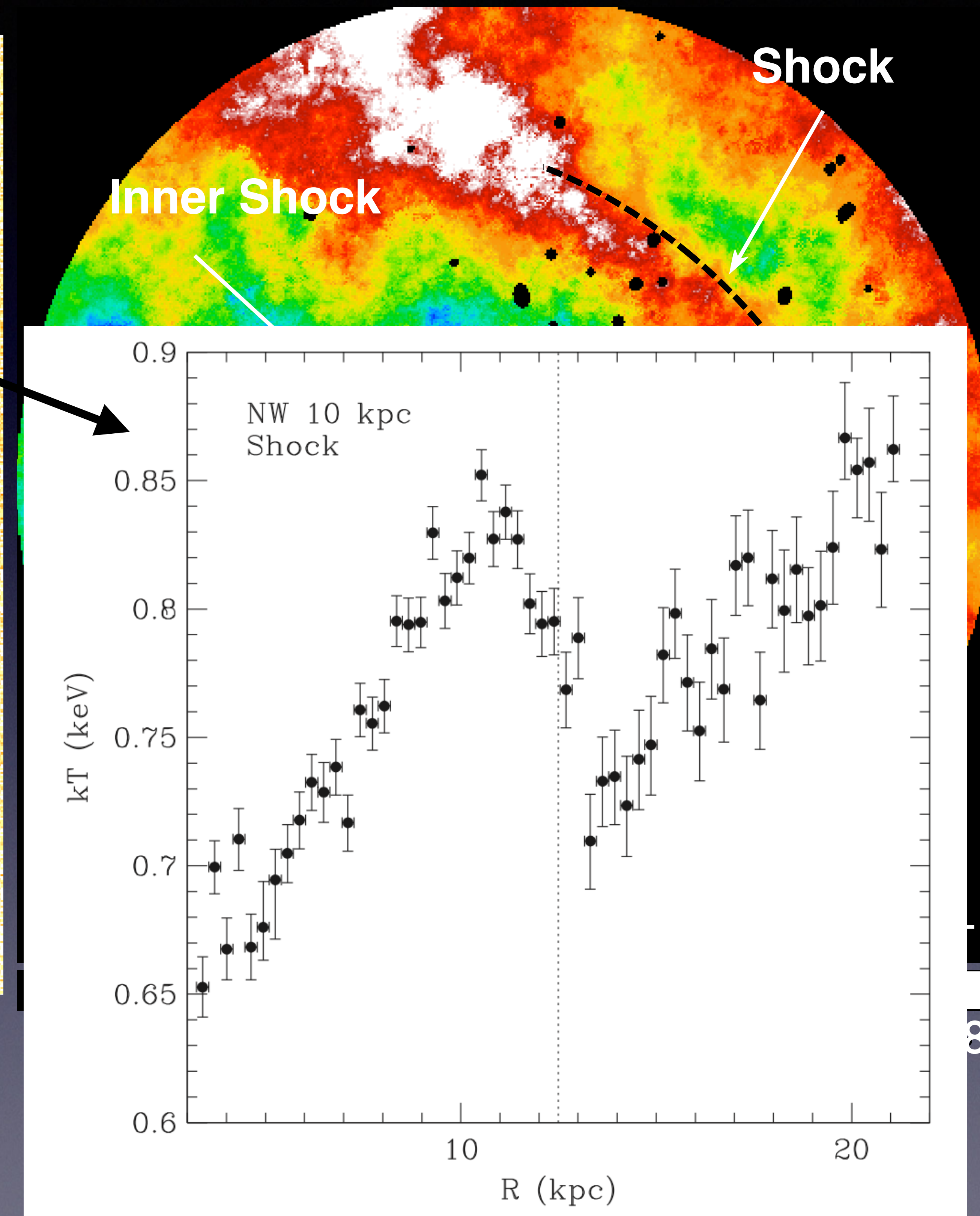
Central and intermediate shocks





Central and intermediate shocks





Shock Structure

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

  - Core shocks (1 kpc): $\rho_1 / \rho_2 = 1.97$, $M = 1.71$
  - Middle shocks (10 kpc): $\rho_1 / \rho_2 = 1.74$, $M = 1.52$
  - Outer shocks (30 kpc): $\rho_1 / \rho_2 = 1.44$, $M = 1.30$

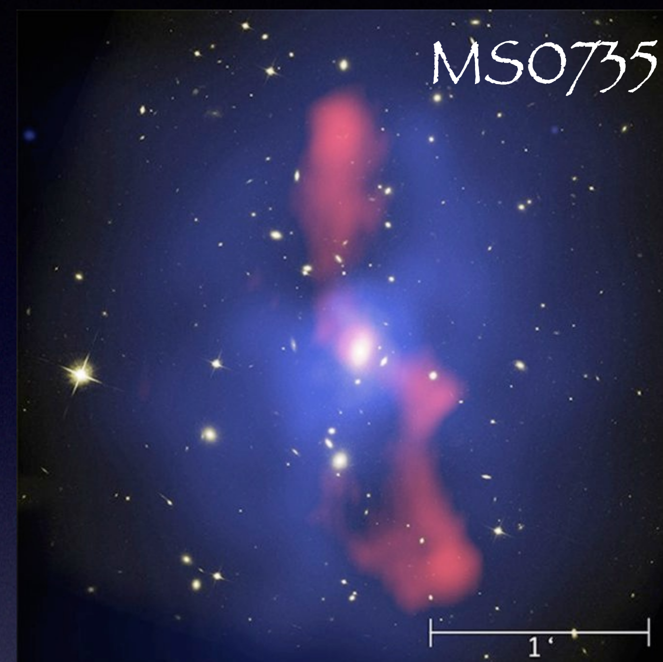
- Heating occurs due to entropy jump across shock fronts. "Replaces" only 1-9% of the total thermal energy, but shocks are repeated, and there are several per local cooling time (repetition time is roughly 20 Myr from shock separations)

Shocks Alone Balance Cooling

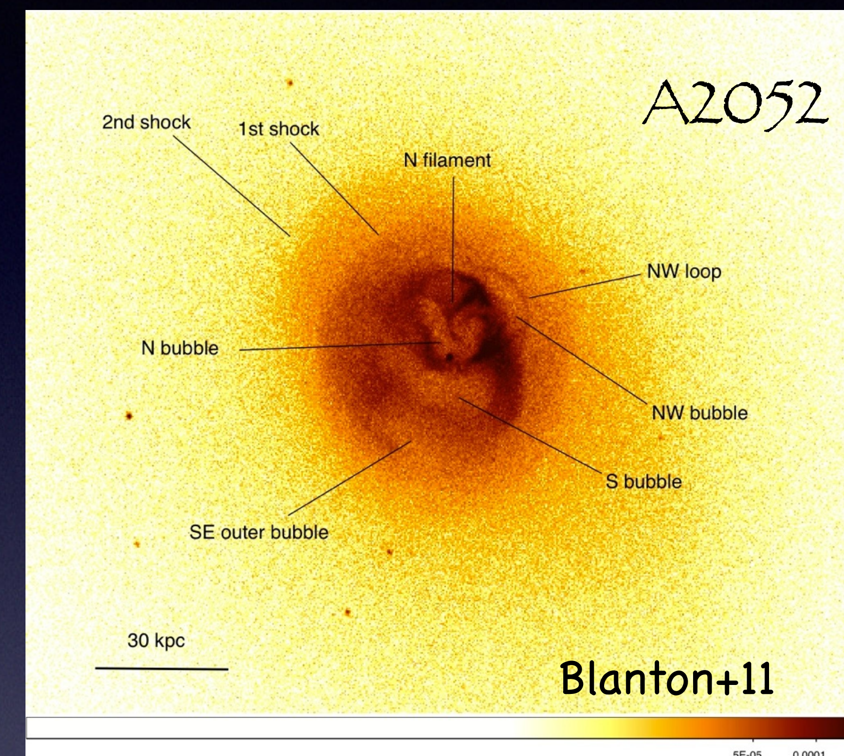
	t_{cool} [yr]	shocks/t_{cool}	shocks required
~1 kpc shock	2 x 10	10	10
~10 kpc shock	9 x 10	45	20
~30 kpc shock	2 x 10	100	77

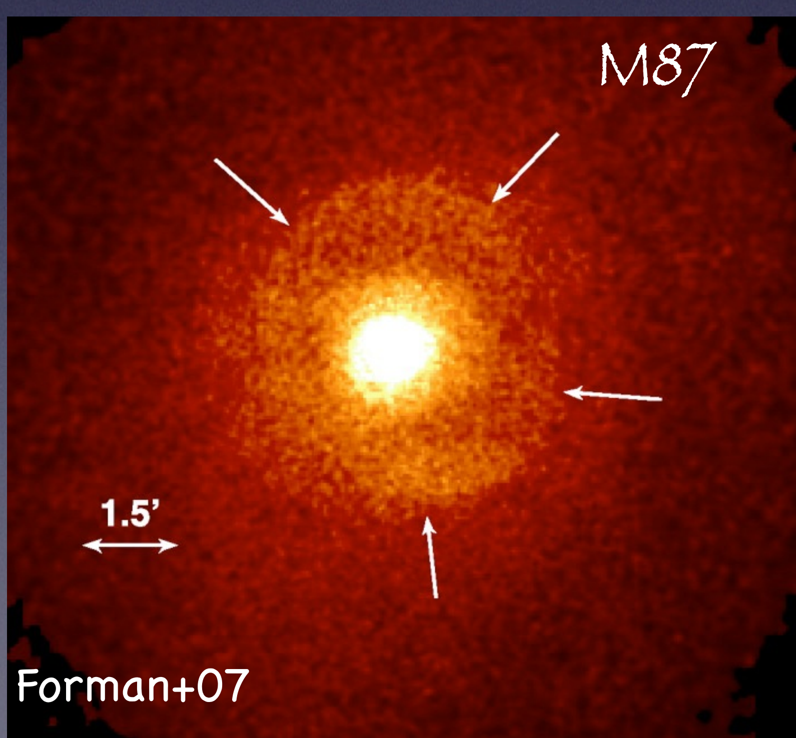
- How many shocks are needed per local cooling time to offset radiative cooling?
- Agreement is remarkably good for rough estimates
- Even though shocks are weak, repetition rate is much shorter than the cooling time

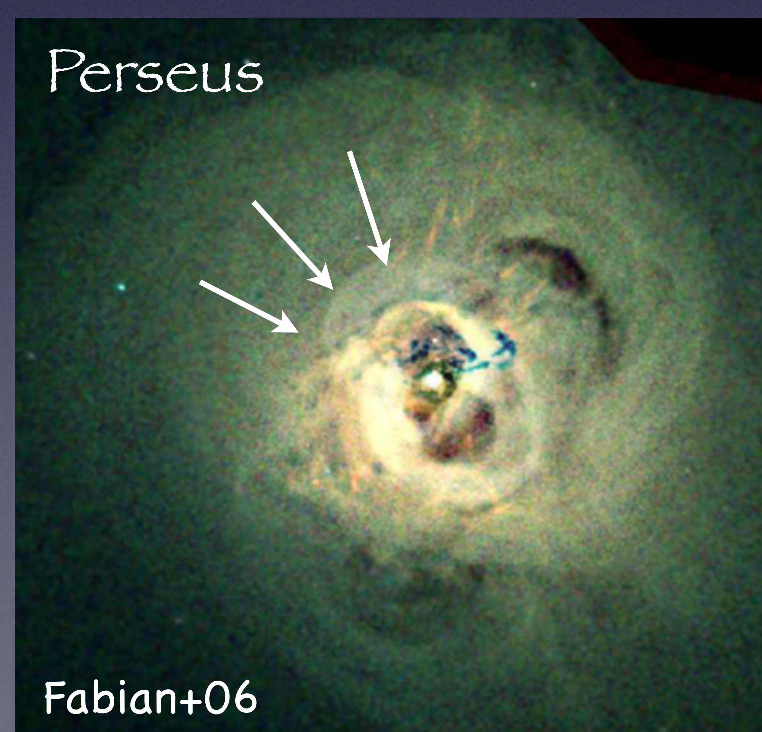
Outburst shock detections are rare...



McNamara+05



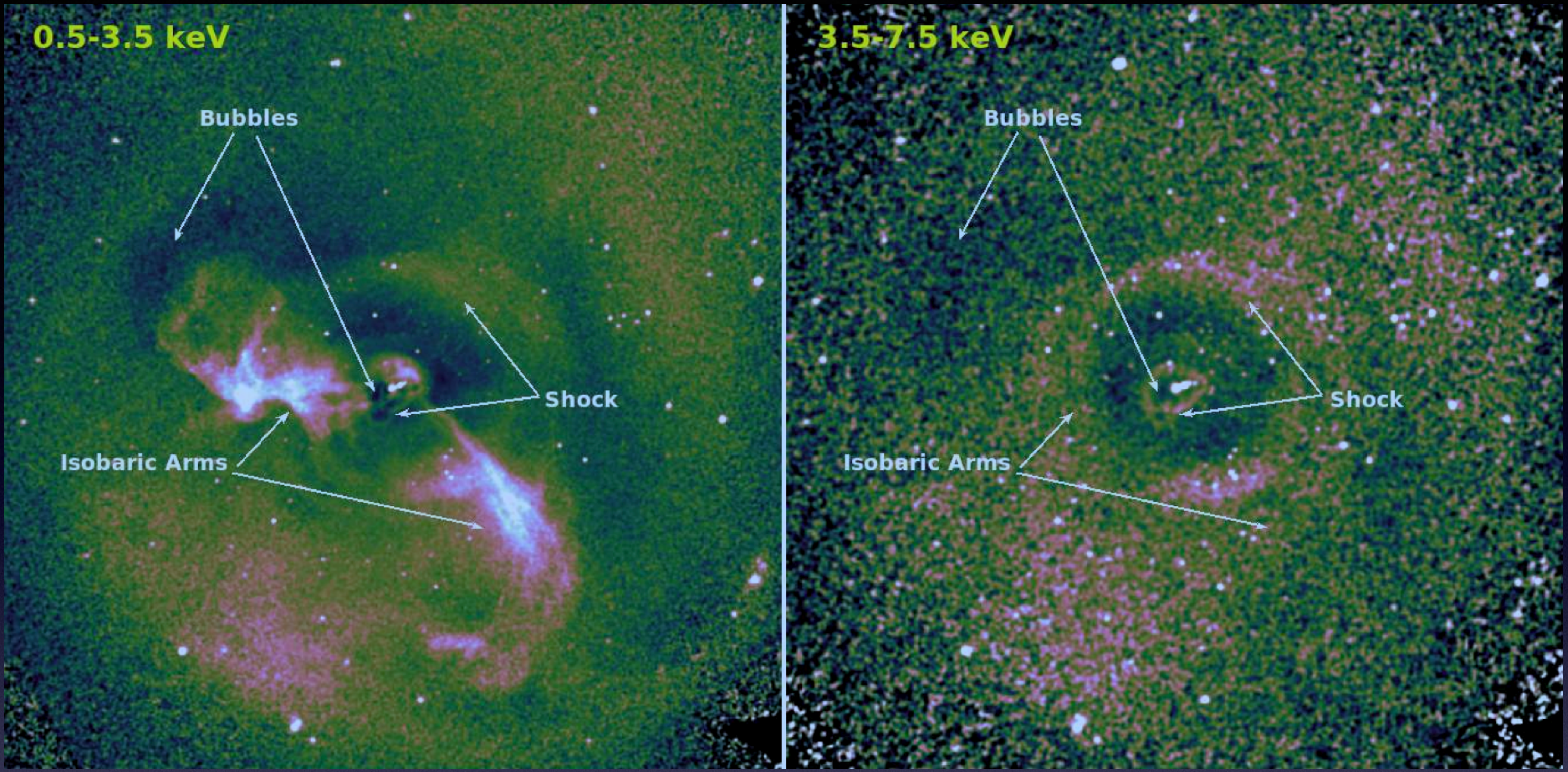




Need to measure temperatures to discriminate shocks from cold fronts

M87

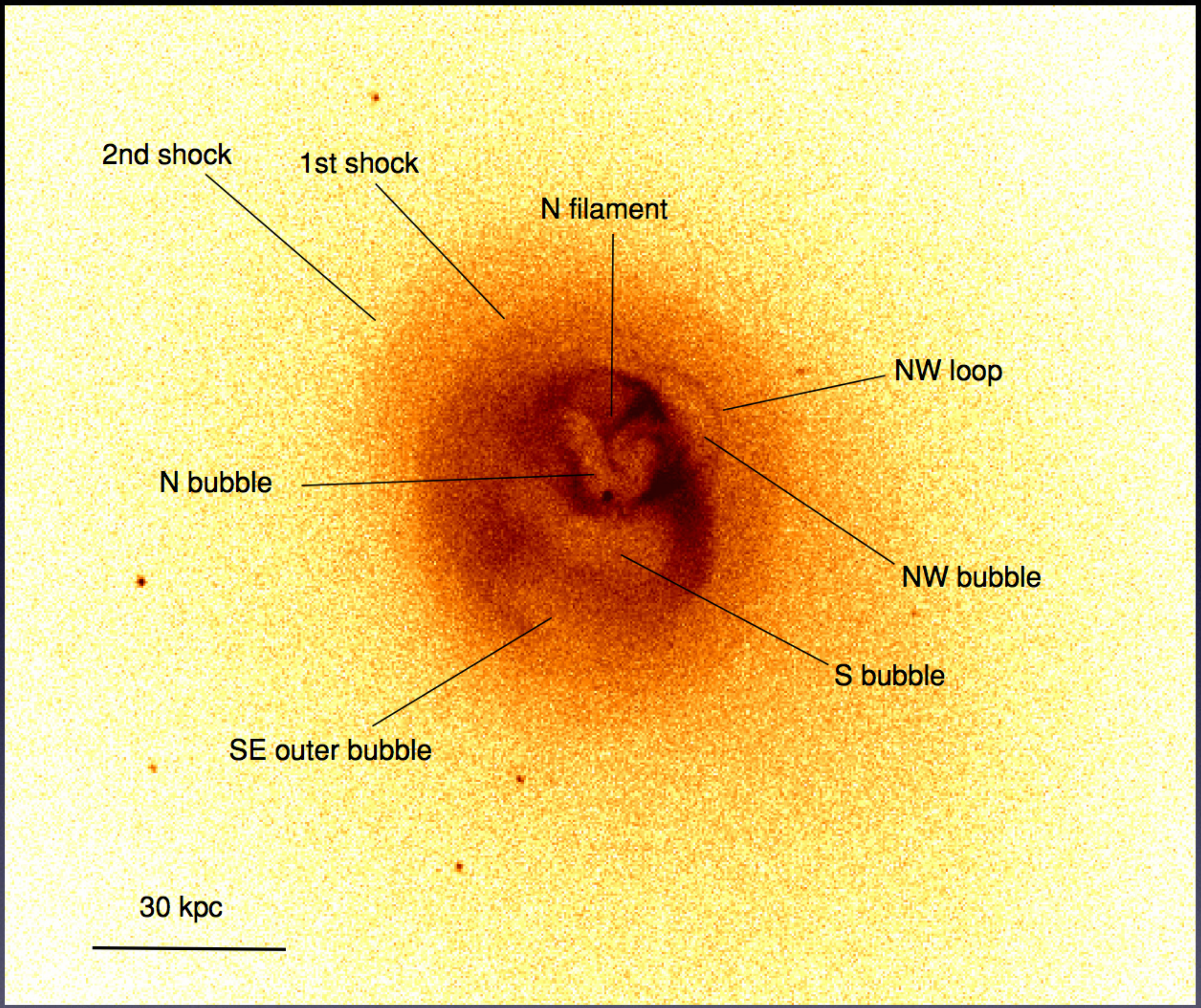
Forman+05,07; Nulsen+07; Million+10; Arevalo+16

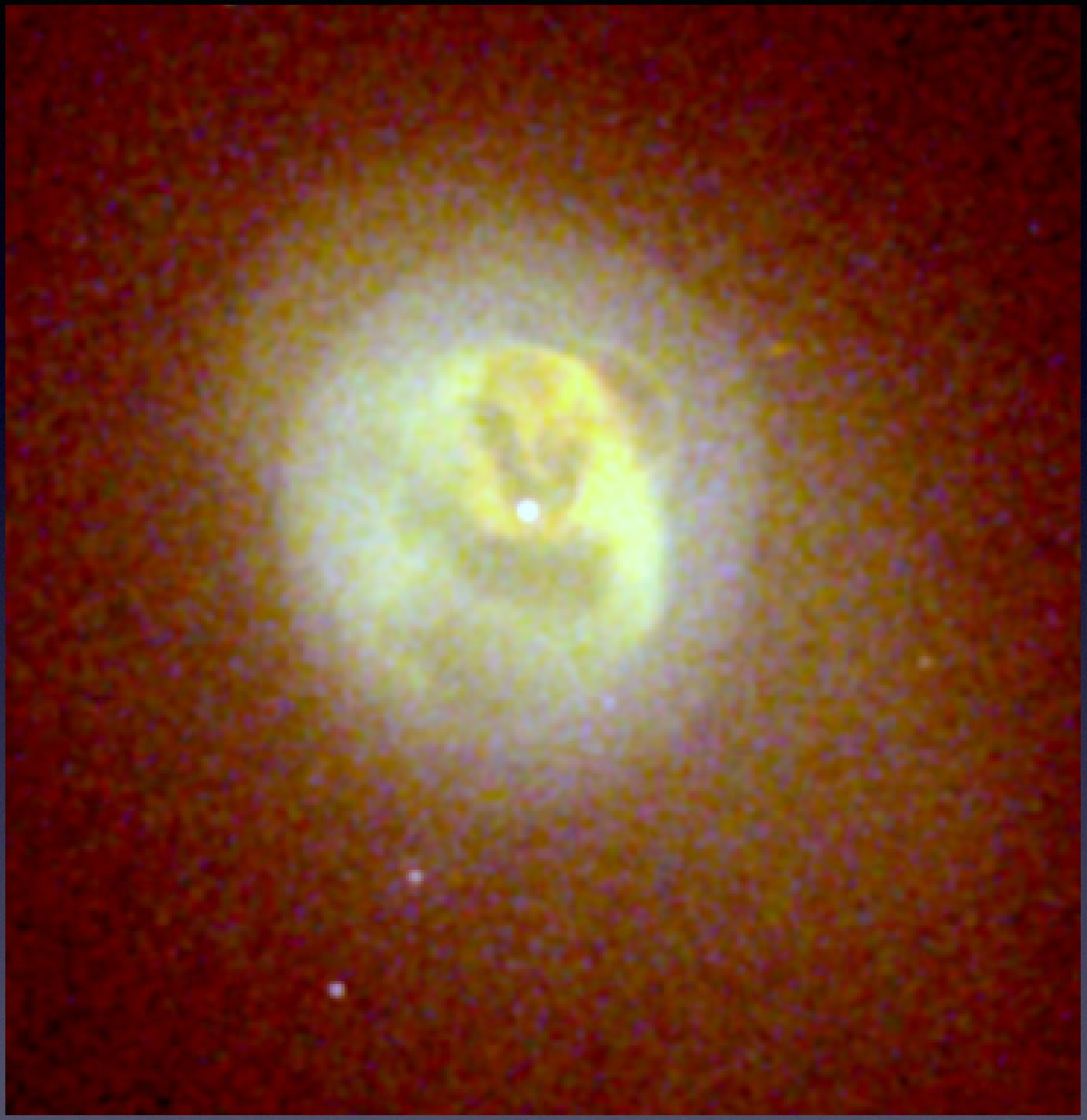


Arevalo+16

- Inner shock is difficult to disentangle, easier for outer shock at 14 kpc
- M≈1.3 (Million+10), which requires 77 shocks per cooling time, or a repetition time of 12 Myr
- Million+10 find t_{rep}≈10 Myr, consistent with shock heating balancing cooling, as found previously (Nulsen+07, Million+10)

Abell 2052

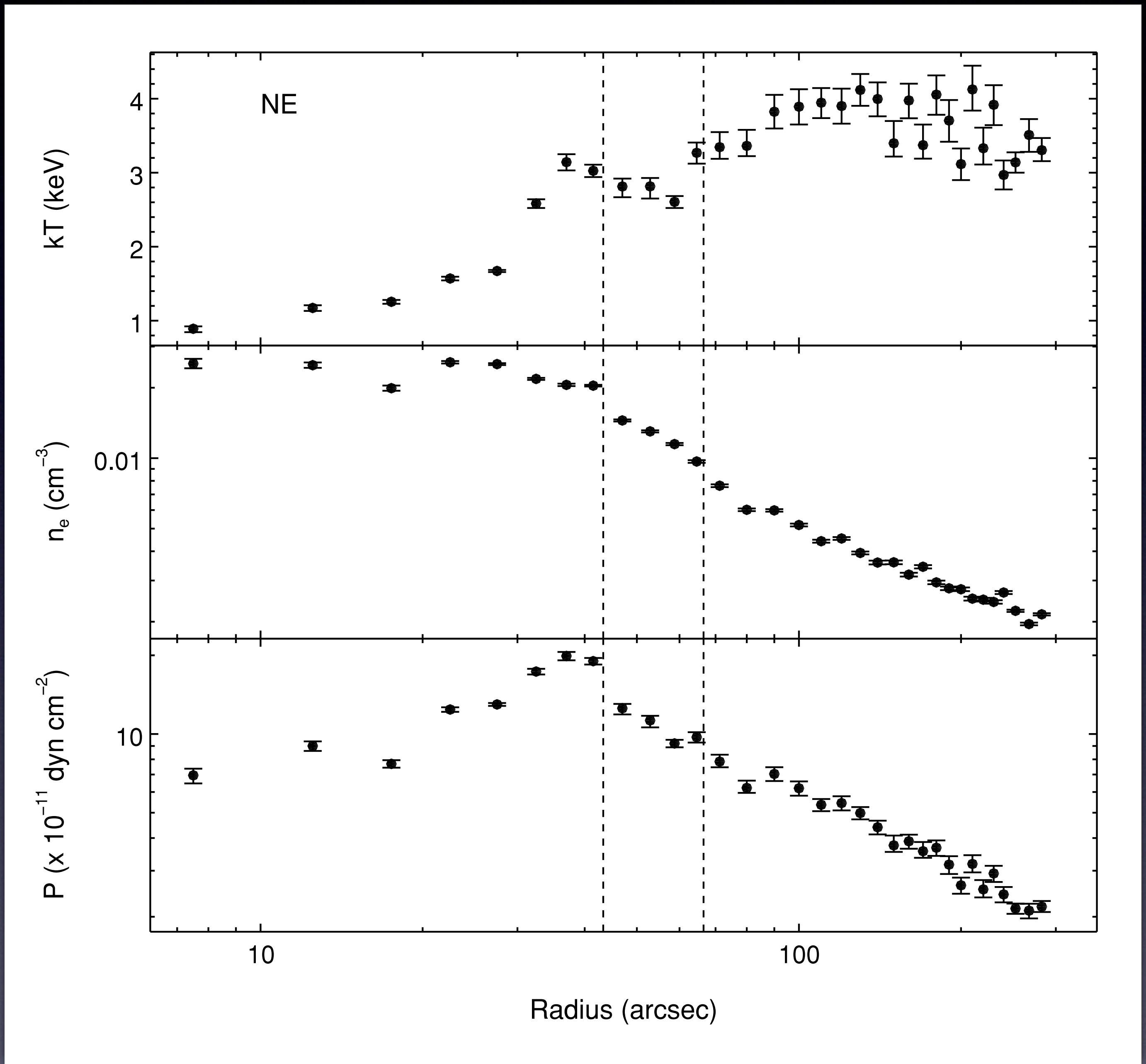




Blanton+11,+09

Abell 2052

- Temperature jump at 30 kpc edge is only evident after deprojection (note that outer edge is likely a cold front!)
- M≈1.2, requiring a repetition time of ~2 Myr



Blanton+11

Conclusion

- Heating from repeated weak outburst shocks is sufficient to offset radiative cooling in at least a few cases where current data allow measurements, within a few tens of kpc
- Shock heating is likely to generally play an important role in AGN feedback, particularly at smaller radii
- Unfortunately, weak outburst shocks are difficult to detect

The Next 10 Years...

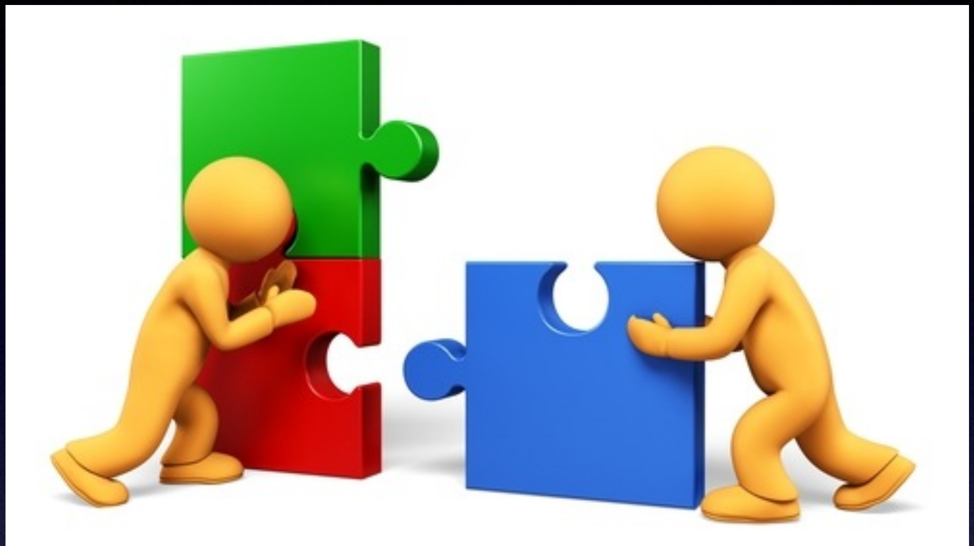
1) More data

- Need more detections. How does the heating rate and mechanism vary with cluster mass, black hole mass, AGN kinetic luminosity, radius, even redshift?
- Chandra's angular resolution is required to resolve shocks

- Observations are expensive. Note that each of the above detections (N5813, M87, A2052) is from >0.5 Msec observations

The Next 10 Years...

2) Synergy

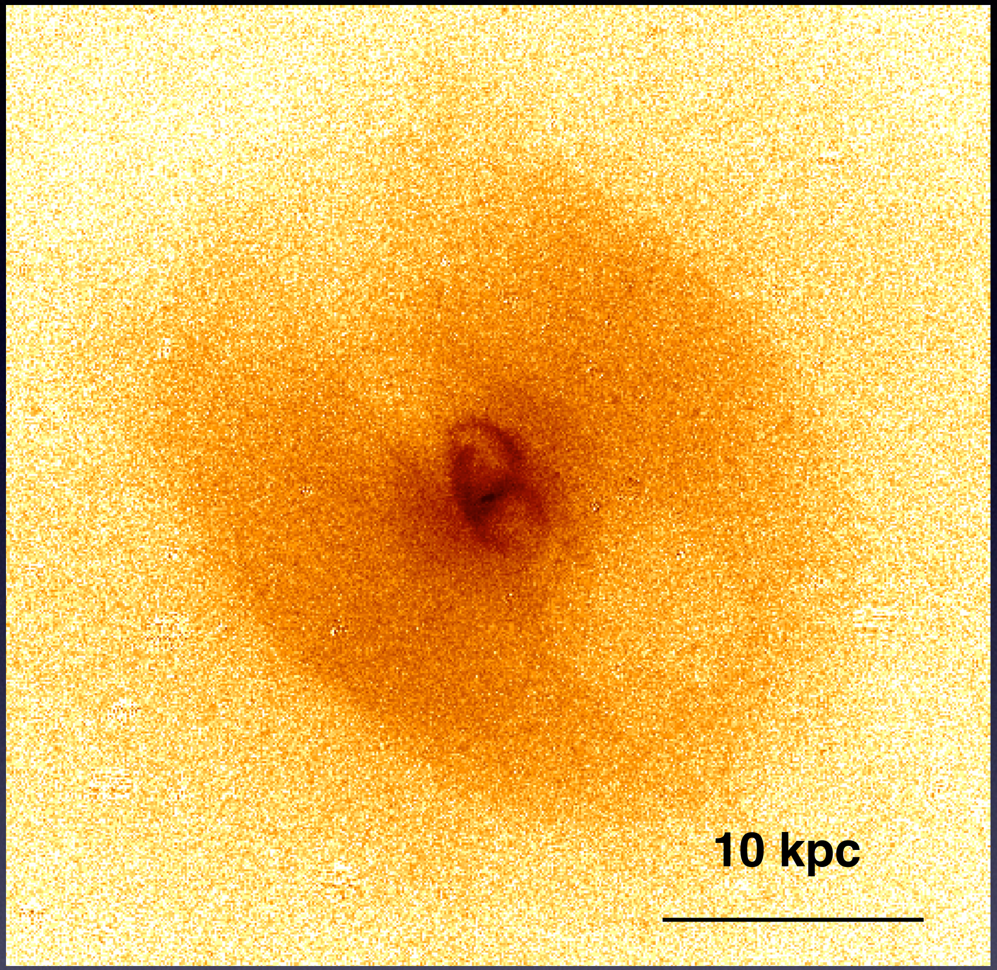


- Multi-wavelength observations to track star formation rates and trace the cooling gas over many orders of magnitude in temperature
- Low frequency radio to follow the evolution of cavities and non-thermal particles
- Surveys to identify new targets
- HST, LOFAR, JWST, eROSITA, Planck, SPT, ALMA...
- See work by M. McDonald, H. Russell, G. Tremblay, L. David, and others...

The Next 10 Years…

- Chandra's next decade will likely require very long observations to achieve some key science goals. How can we fairly accommodate such requests?
    - Combine observations with similar science?
    - Community chosen targets?
    - Bring back XVPs?
    - Expand the scope of multi-cycle projects?

Beyond the Next 10 Years…



- X-ray Surveyor will be very good at this kind of science
- Each of these observations represents ~650 ks with Chandra
- XRS will achieve this with 10-20 ks exposures, with subarcsecond resolution across a much wider FOV