# The X-Ray View of AGN Feedback in Early Type Galaxies

S. W. Randall - CfA

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

# X-ray Emission from Early Type Galaxies

- X-rays from BCG's from early rocket experiments (e.g., Bryam+66)
- First detected in "normal" elliptical galaxies with Einstein satellite (e.g., Forman+79)
- Emission a combination of that from diffuse thermal and point sources, with a wide range of relative contributions
- Focus here is on diffuse emission and AGN feedback

# What is Feedback and Why Do We Care?

- Output from compact objects (stars, black holes) affects their formation and/or growth rates
- Affects the structure (self-similarity) and evolution of clusters and groups
- Buoyant bubbles redistribute gas and metals
- Implications for cosmology (clusters as cosmological probes, growth of structure)
- Regulates black hole growth rate
- Regulates star formation rate => galaxy evolution theory
- ICM microphysics (viscosity, turbulence, transport...)
- Solution to the "cooling flow problem"

# AGN Feedback Modes

| Radiative (Quasar) Mode | Kinetic (Radio) Mode |
|---|---|
| Kinetic power is negligible | Radiative power is negligible |
| Black hole accreting close to Eddington limit | Black hole accreting at a few to ten percent of Eddington limit |
| Radiation couples BH energy output to the gas | BH energy output couples to gas through jets, via bubbles and shocks |
| Dominant at higher z (2-3) | Dominant in the local Universe |

Reviews: Peterson & Fabian 06; McNamara & Nulsen 07; Cattaneo+09; Fabian 12; Gitti+12

Transition from radiative to kinetic mode, see Churazov+05

Also stellar feedback, important when $\sigma_v \lesssim 200$ km/s

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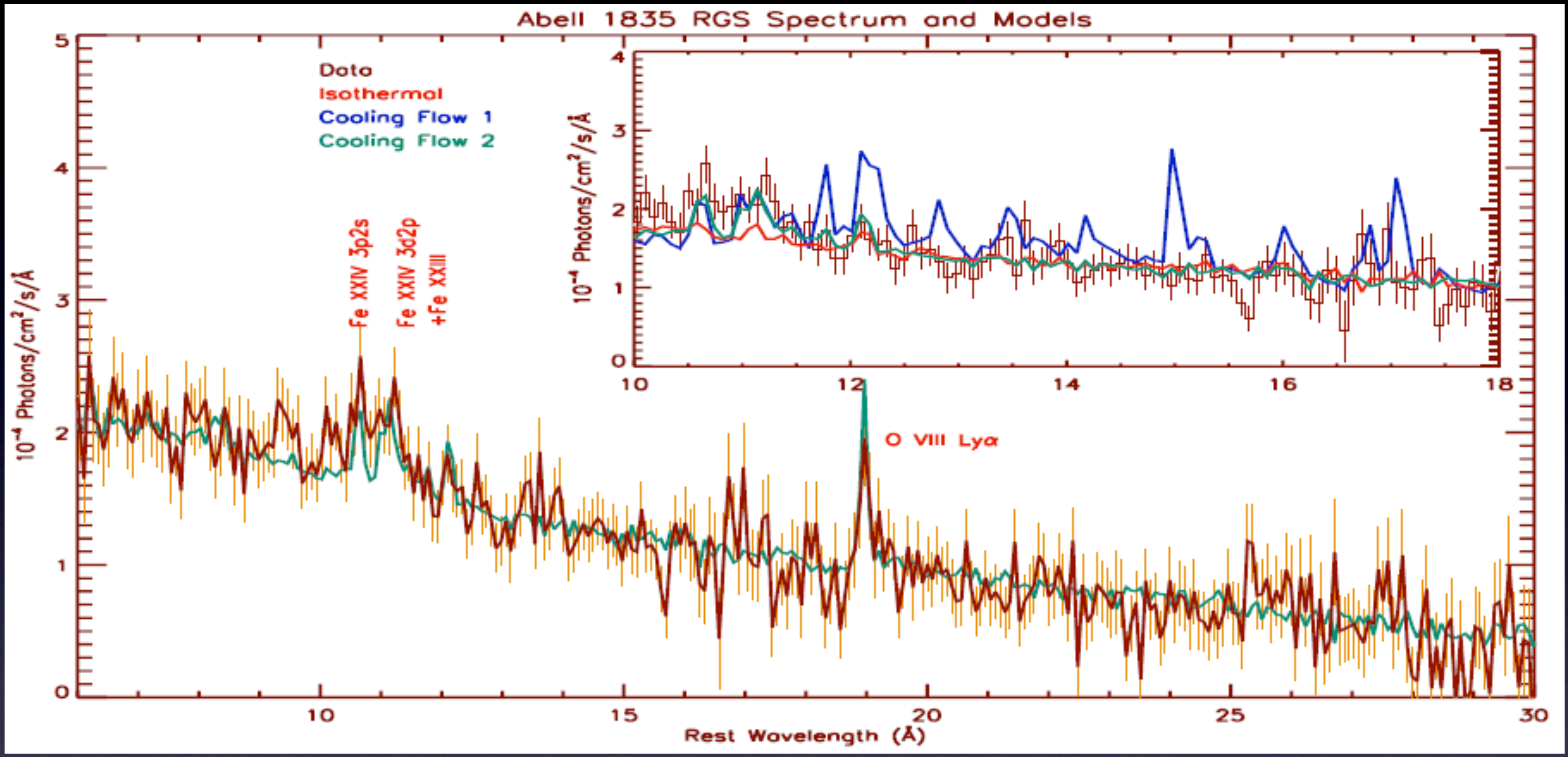
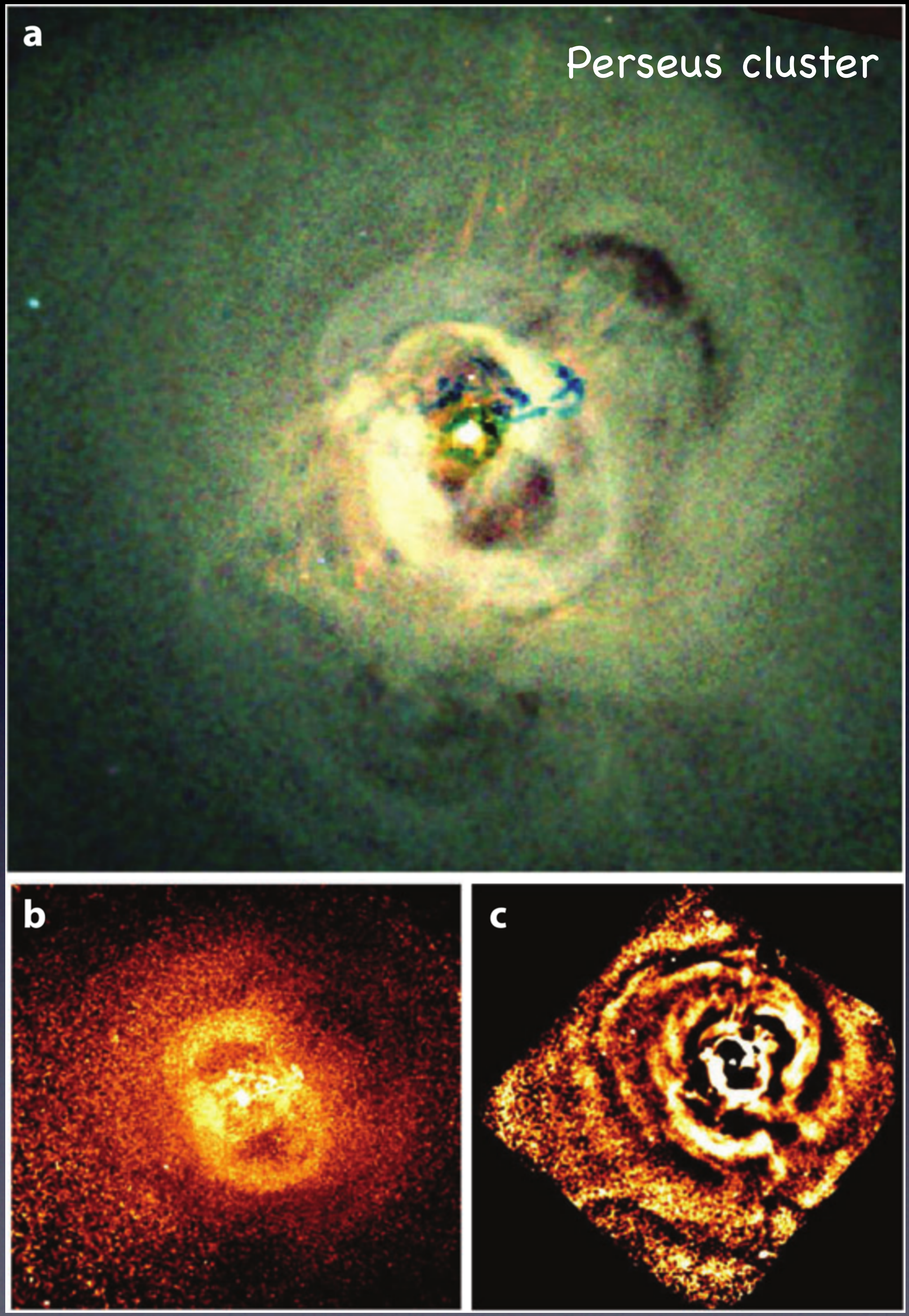
# Evidence for Feedback



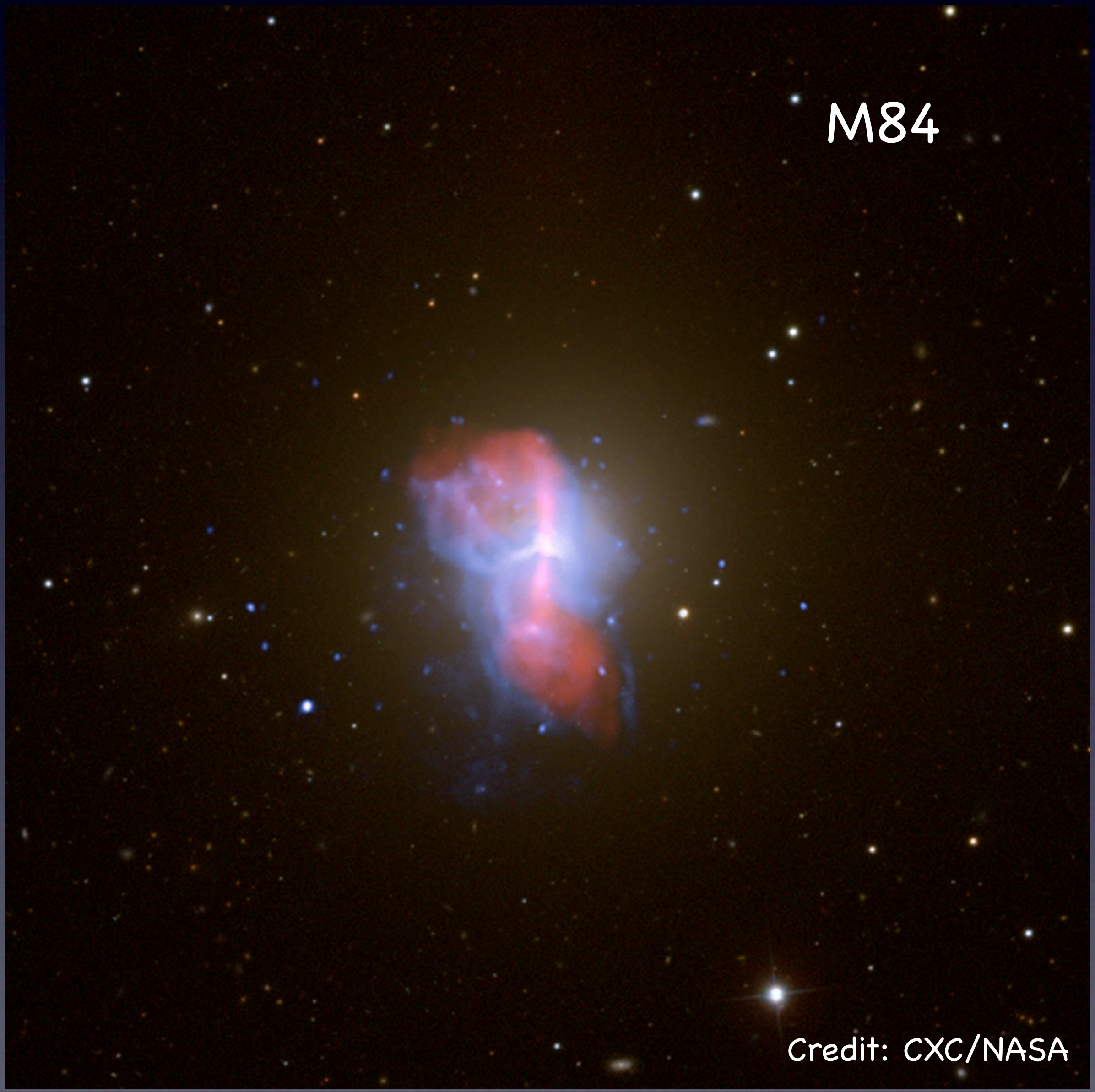

Peterson+01

- Early XMM-Newton and Chandra observations showed that there is not as much gas cooling to low temperatures as predicted in "cool core" clusters (the "cooling flow problem")
- Implies balance of heating and cooling rates (McNamara & Nulsen 2007)

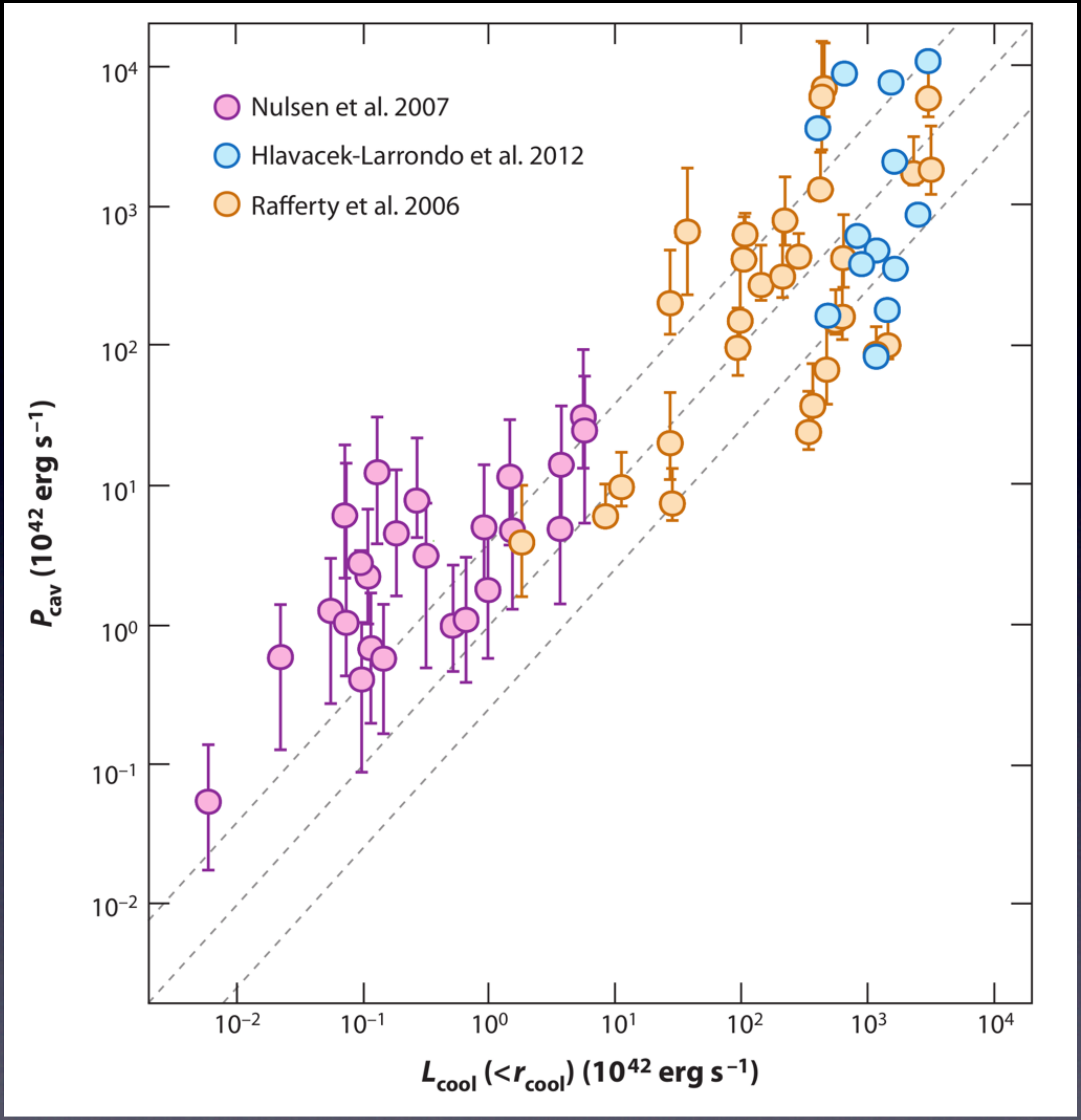



Fabian 12

Cavities, shocks, and sound waves observed in clusters, groups, and individual galaxies




Finoguenov+08



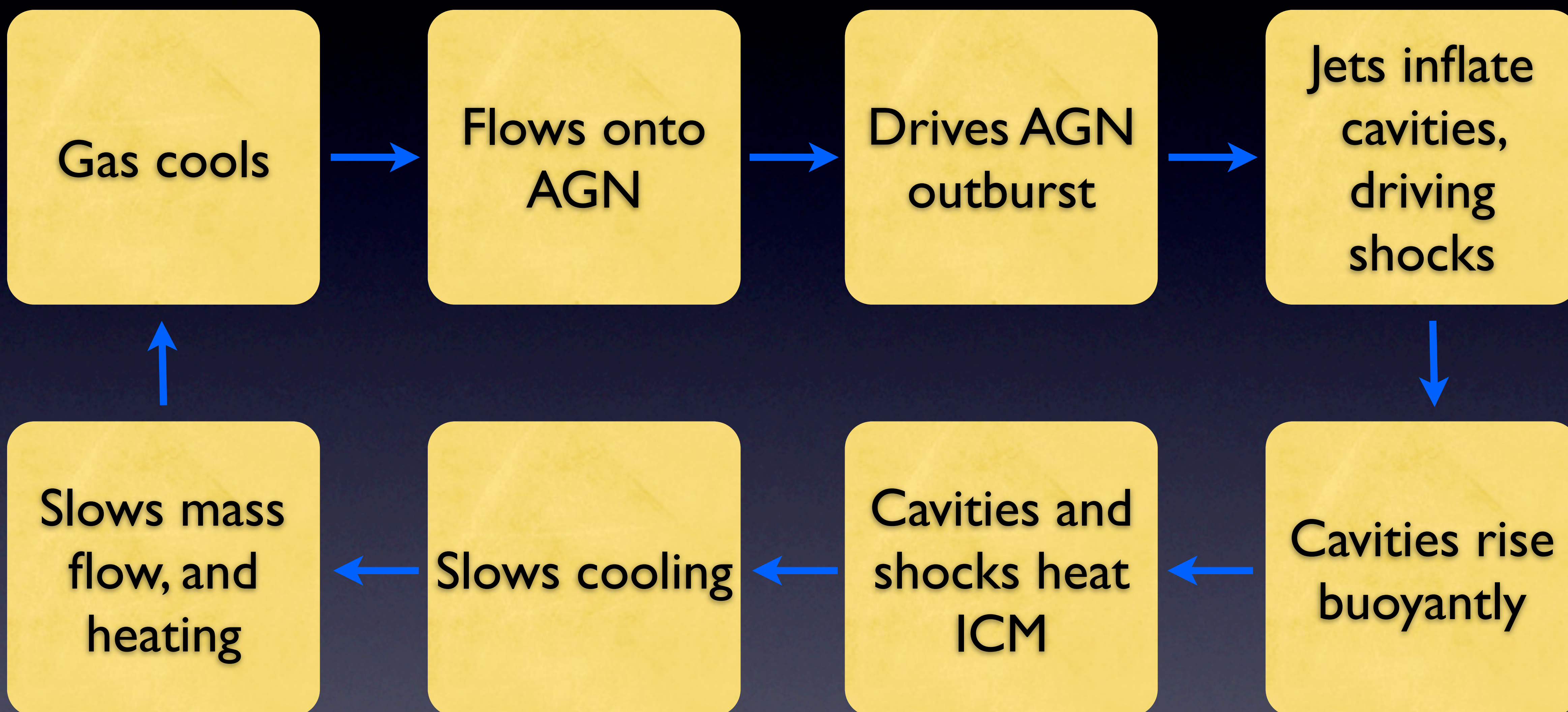

Fabian 12

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)

# Evidence for Feedback

- Central cooling times < $t_{Hubble}$ without prodigious star formation (implies balance of heating and cooling rates)
- Cavities, shocks, and sound waves in X-ray observations of clusters, groups, and galaxies
- Correlation between cavity power and cooling luminosity
- Central entropy floor (~10 keV $cm^2$) in cluster BCG's
- High-velocity galactic outflows (e.g., Rupke & Veilleux 11)
- $M_{BH}$ - $\sigma_v$ relation? Cosmic Downsizing?

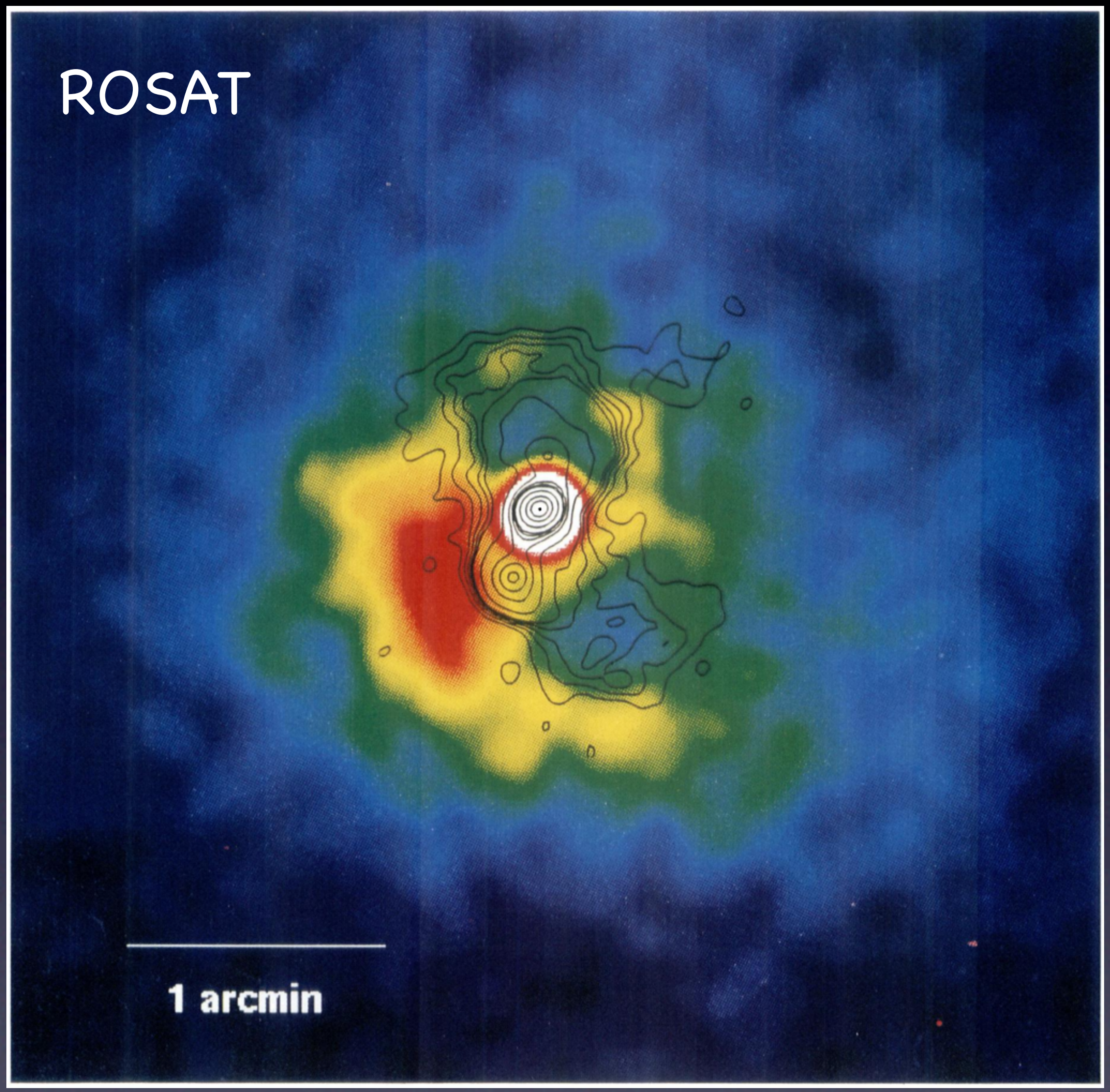
# The (Kinetic) AGN Feedback Cycle

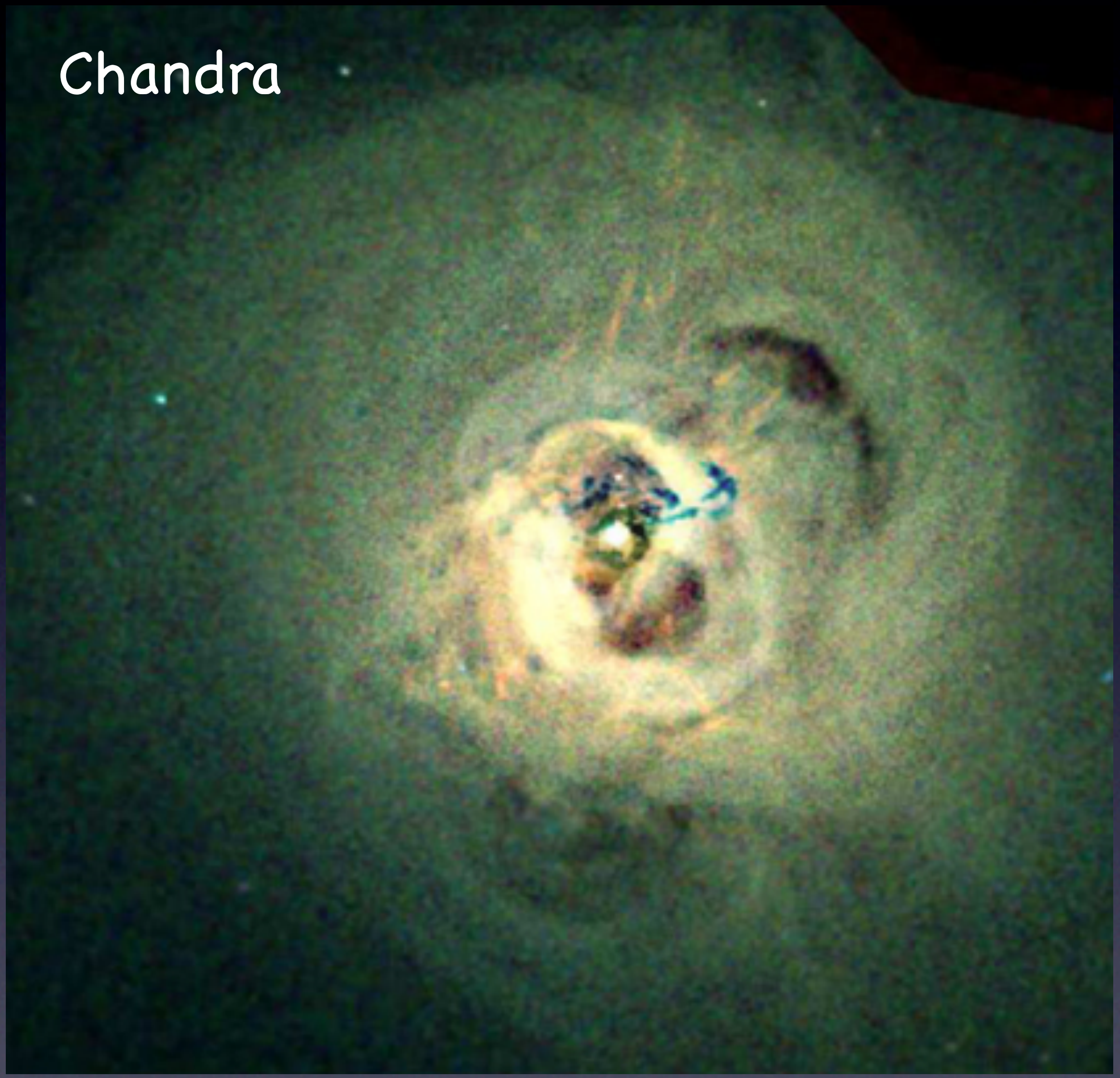



Mechanical energy available to heat the ICM and balance radiative cooling is in cavities and shocks

# X-ray Cavities

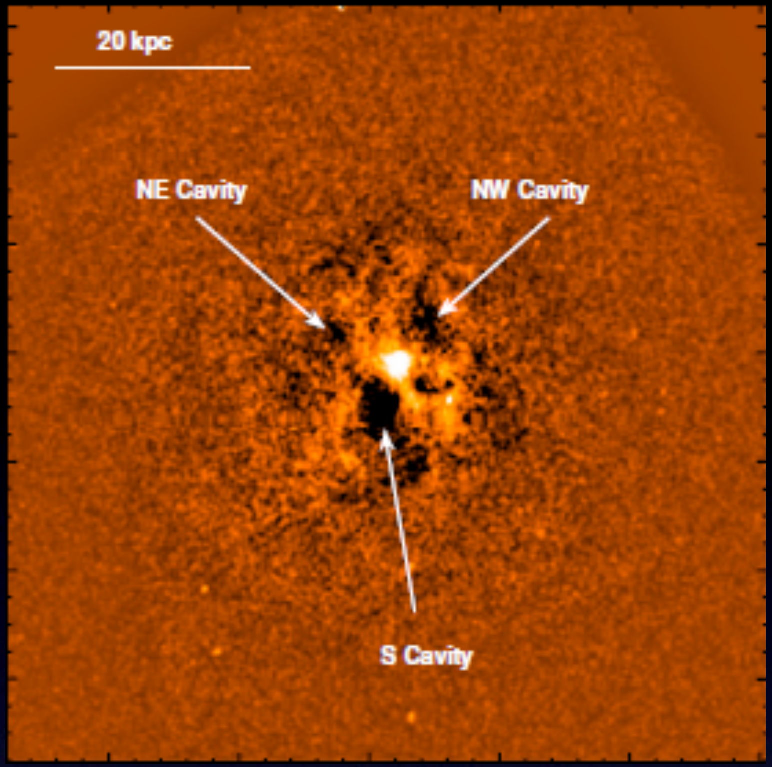
## Perseus (NGC 1275)



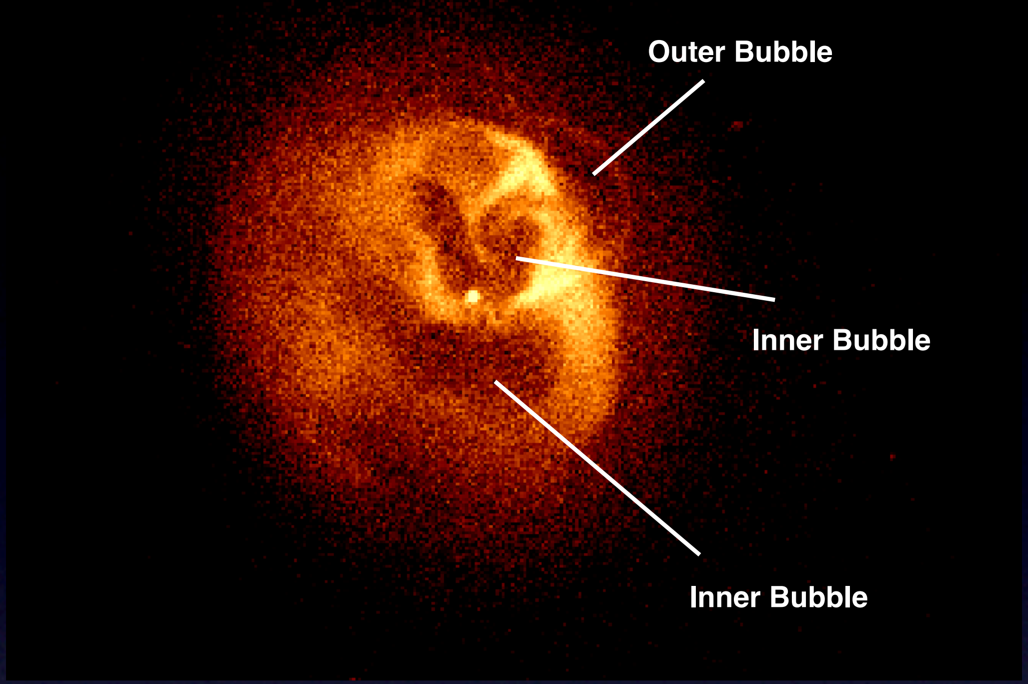




Cavities first seen (but not identified) in Perseus with Einstein (Branduardi-Raymont+81; Fabian+81); later clearly identified with ROSAT (Boehringer+93)

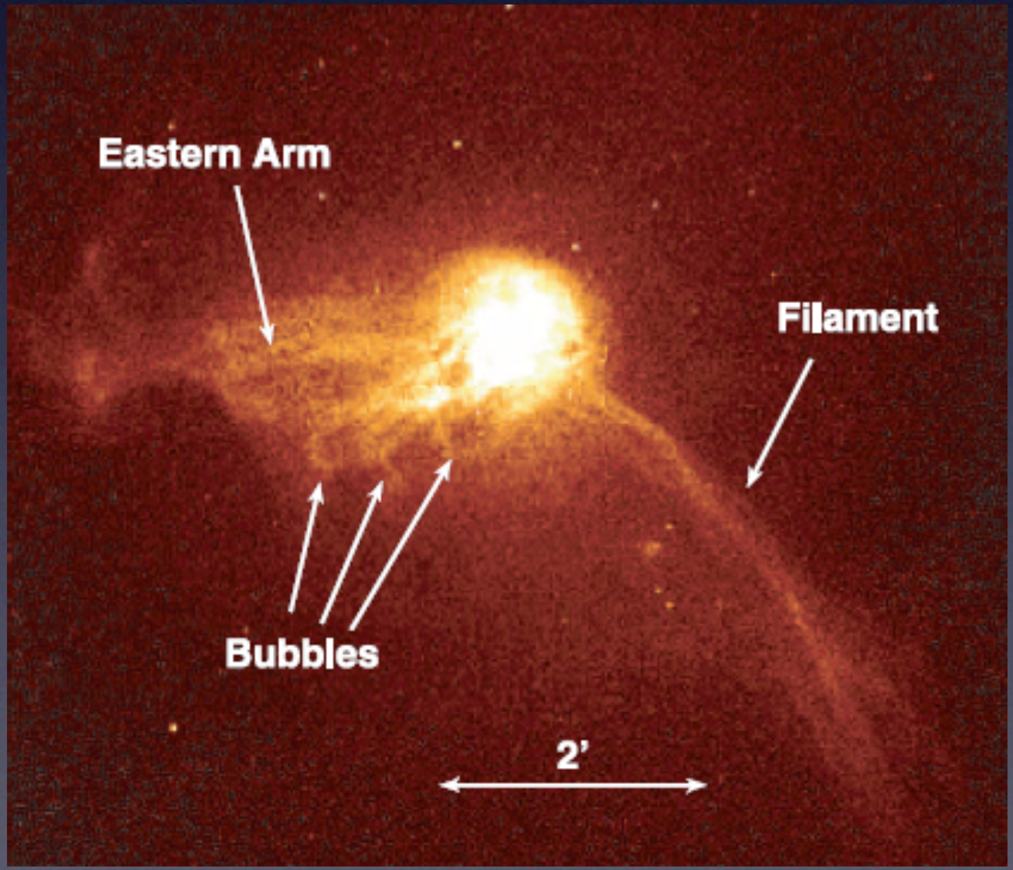
# Many Cavity Examples...



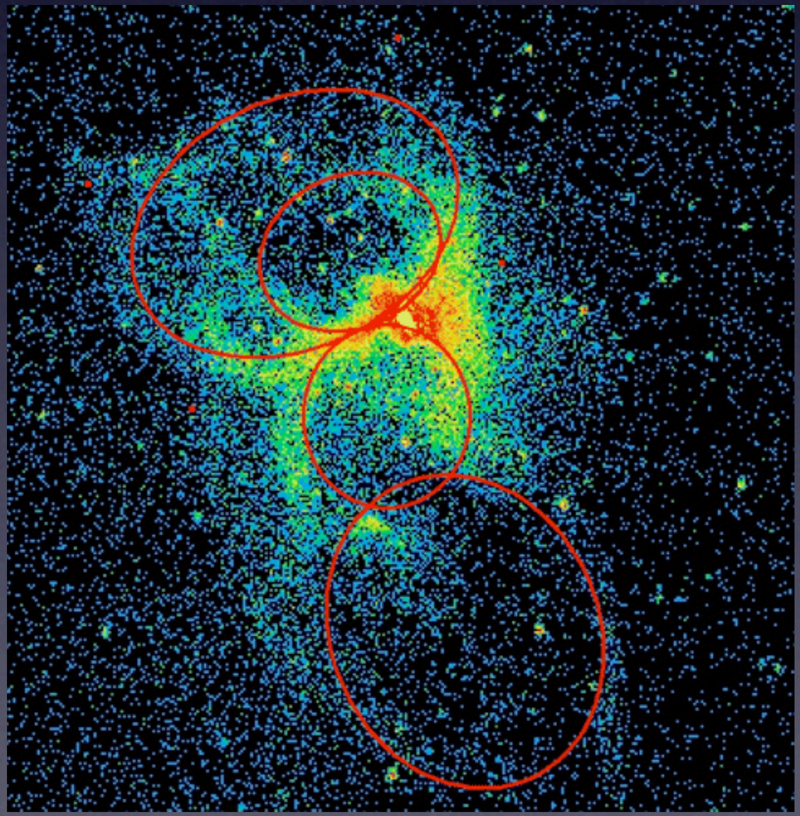

NGC 5044: David+09




Abell 2052: Blanton+09,10,11




M87: Forman+07



M84: Finoguenov+08

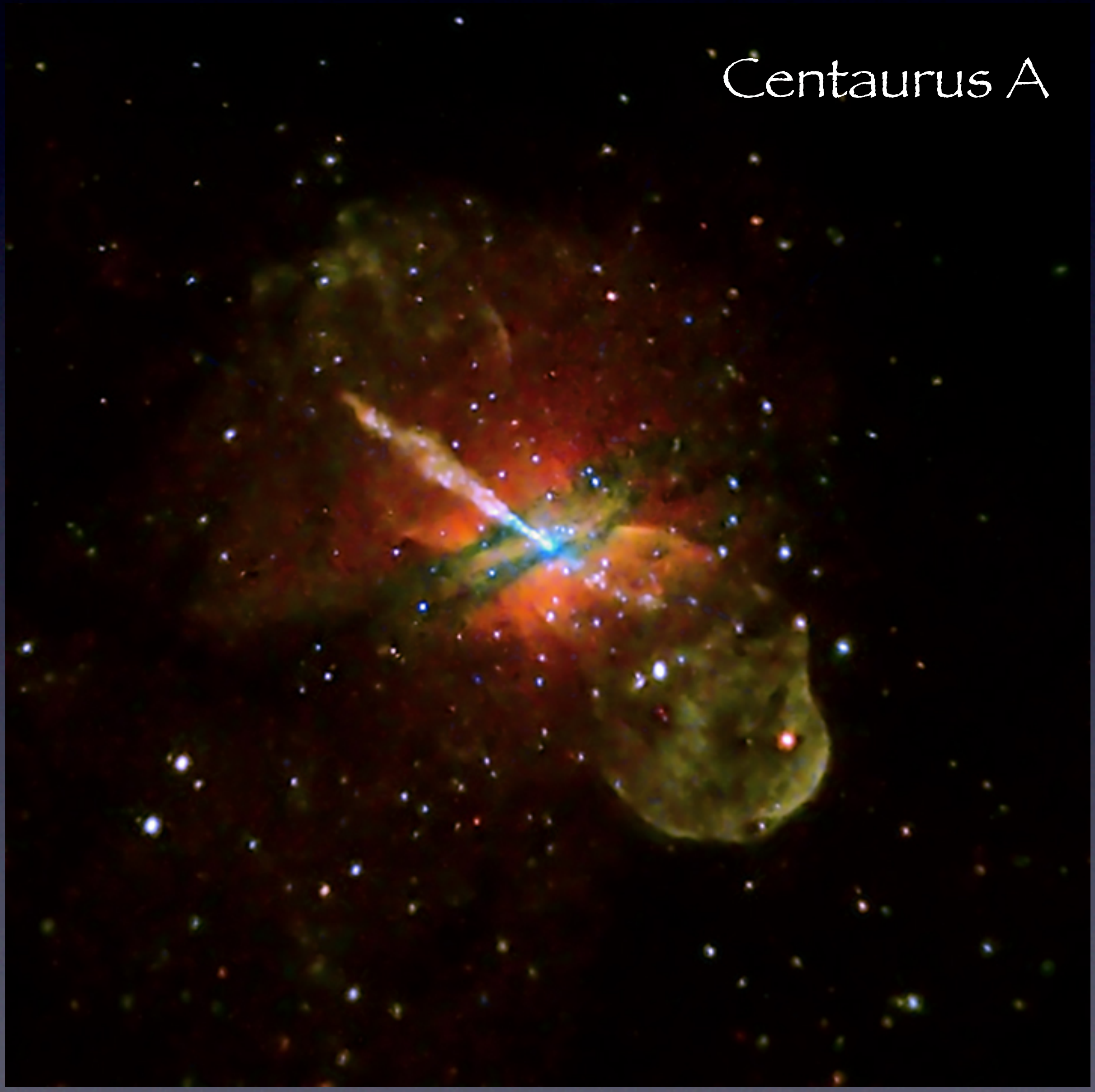
# Heating with Cavities

- AGN jets inflate cavities in the diffuse gas, filled with radio-emitting plasma

- Total enthalpy of cavities is PV work to inflate cavities plus the internal energy: $H = E + PV = PV \gamma/(\gamma-1)$

- H is 2-4 PV, depending on cavity contents

- Cavities detach from jets and rise buoyantly; radio power drops, resulting in "ghost cavities"



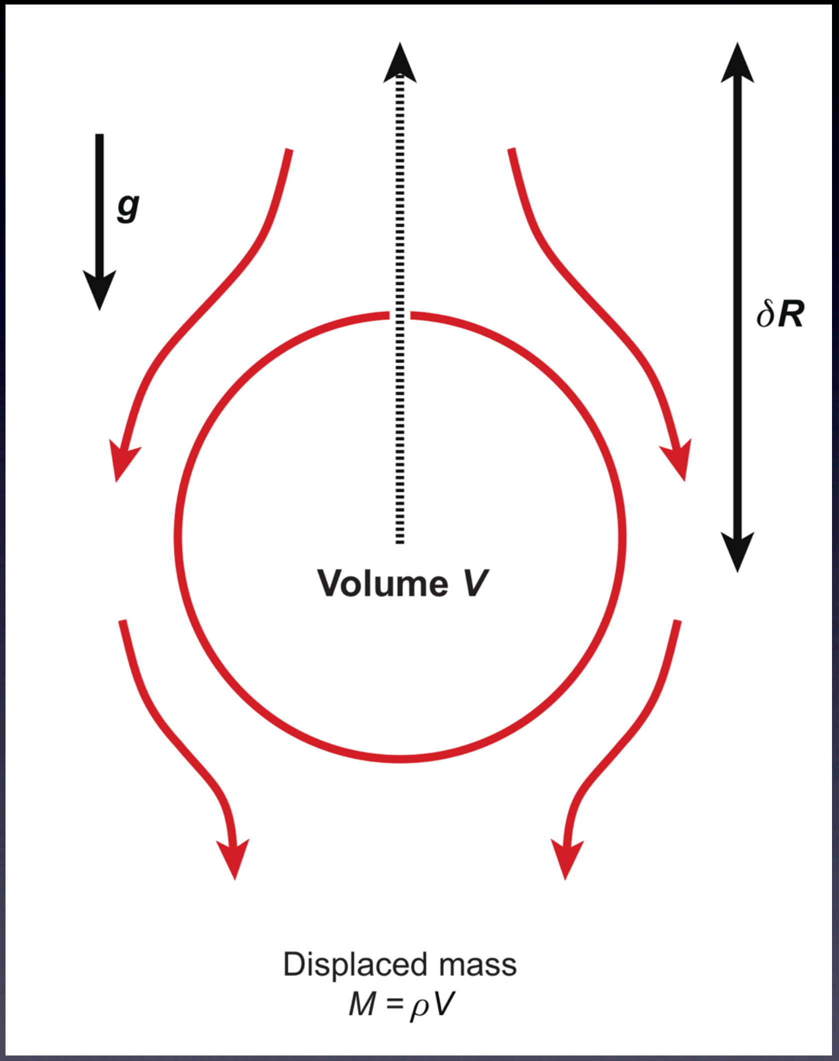

Kraft+08, Croston+09

# Heating with Cavities

- Heating is expected in the wake of rising cavities due to the release of gravitational potential energy (Churazov +02; McNamara & Nulsen 07)

$$\delta U = Mg\delta R = V\rho g\delta R = -V\frac{dp}{dR}\delta R = -V\delta p,$$

- Cavity power is defined as enthalpy divided by age, where the age is estimated by the buoyant rise time, the sound crossing time, or the refill time (typical spread is a factor of 3; Birzan+04)



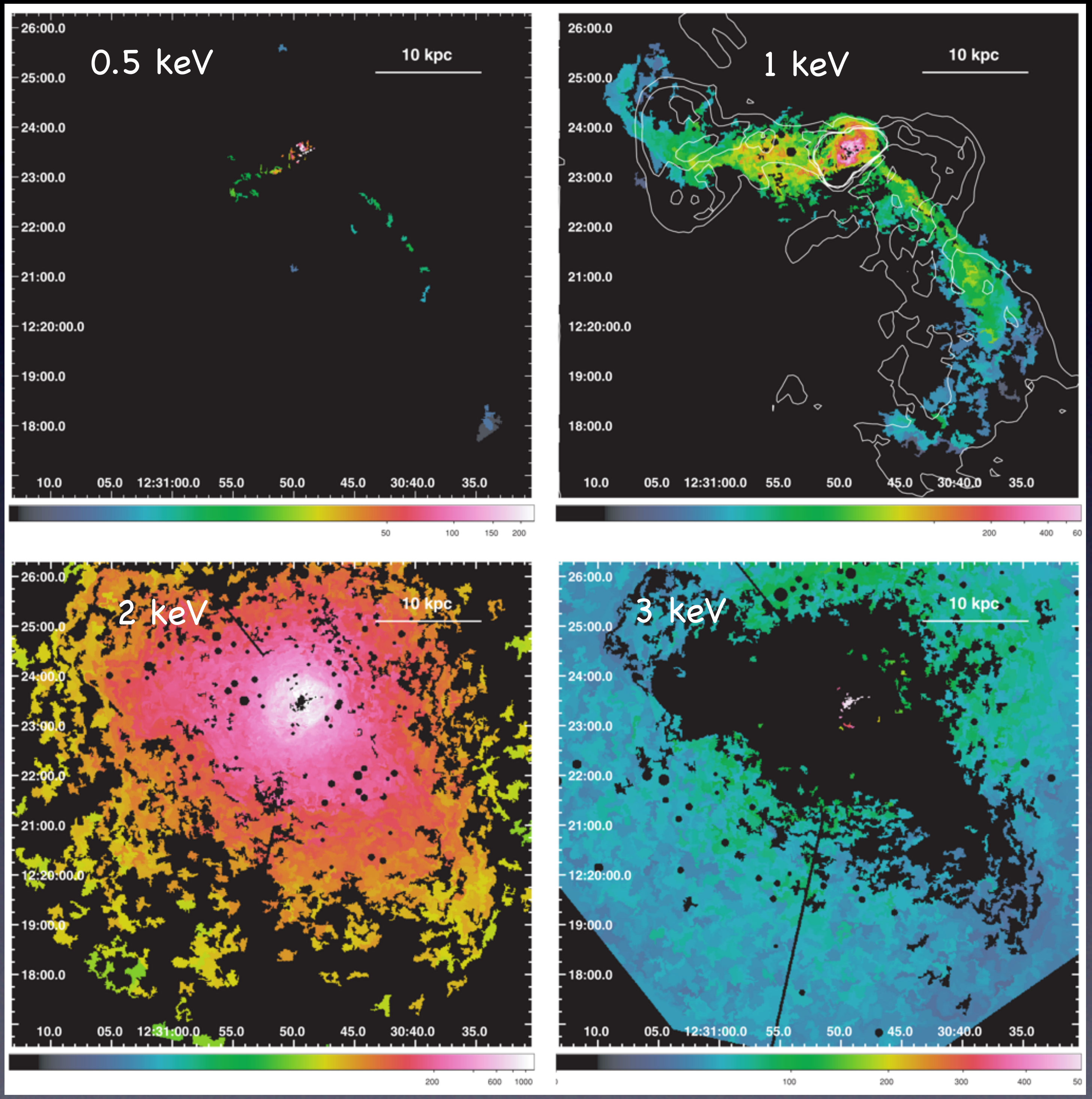

McNamara & Nulsen 07

# Heating with Cavities

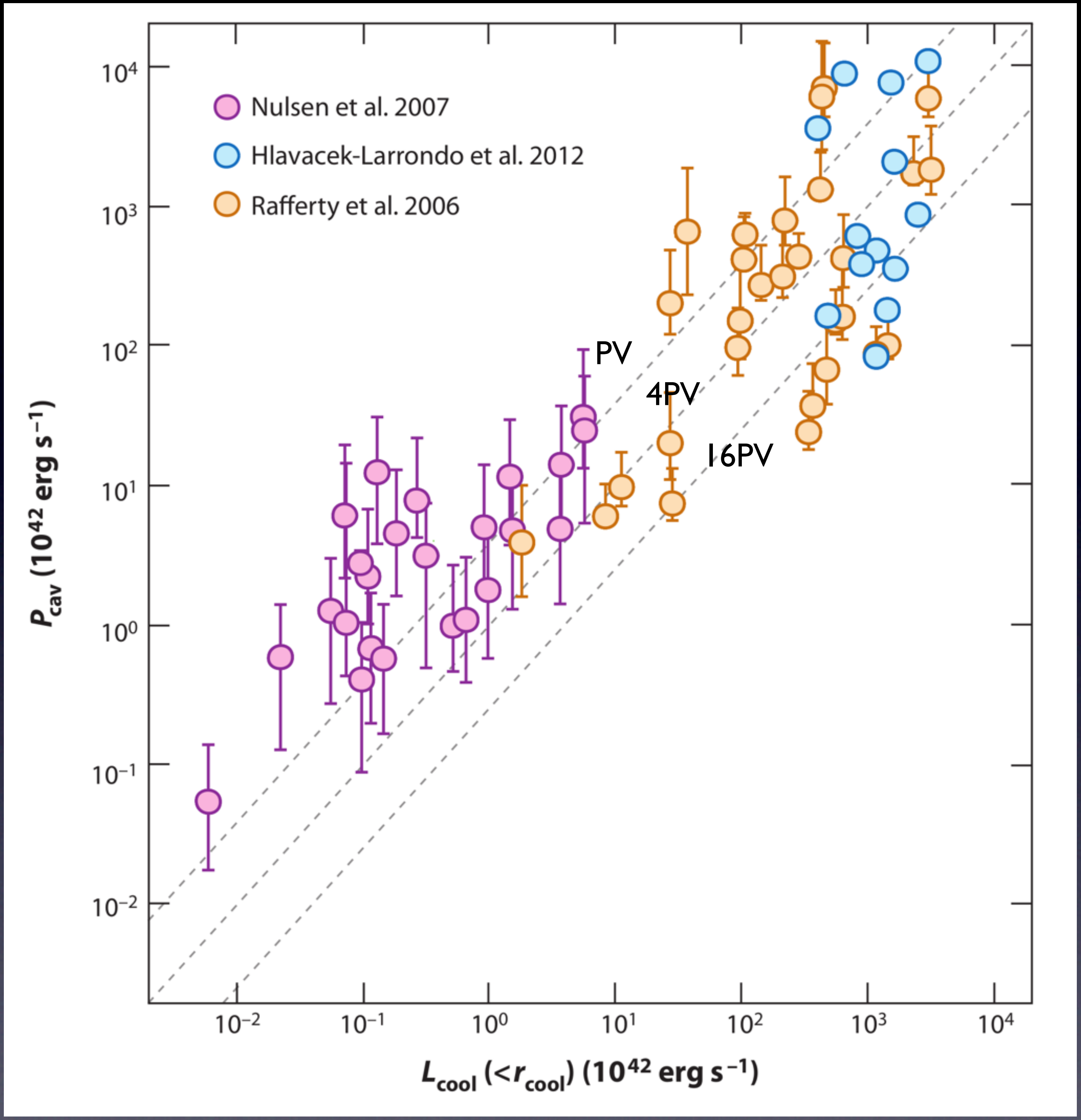
- Outburst repetition rates inferred from cavity ages (and from outburst shocks) are on the order of one every $10^7$–$10^8$ yr

- Cavities lift cooler, higher metallicity gas from the core as they rise buoyantly (e.g., M87 Werner +10; A133 Randall+10)

**M87**




Werner+10




Fabian 12

Generally, cavity power is sufficient to offset radiative cooling over a large mass range

# Evolution of Feedback

- An analysis of MACS clusters between $0.3 \leq Z \leq 0.7$ shows cavity power balances cooling luminosity in clusters with cavities (13/76), Hlavacek-Larrondo+12

- From X-ray observations of an SZ selected (SPT) cluster sample, McDonald+13 find no evolution in cluster entropy profiles (including the presence of an entropy floor) out to $z \sim 1$

- Radiative mode likely dominates around $z \sim 2$-3, and may be the main driver behind the observed $M_{BH} - \sigma_v$ relation (Fabian 12)

# Feedback in Galaxies

- Clearest evidence for feedback is in BCG's, however, many individual galaxies also show clear X-ray cavities (e.g., Cen A Kraft+03; N4636 Jones+02; N507 Kraft+04; N4552 Machacek+06)
- In a Chandra sample of 160 early-type galaxies, 109 have diffuse emission, 27 of which contain cavities (Jones+07)
- Fraction of normal galaxies with cavities (~25%) is lower than in BGC's in cool core clusters (70-100%) (Fabian+05;+12)
- Lower duty cycle of cavities in galaxies (due to lower cooling rates), or selection effect (smaller cavities, lower surface brightness, LMXB contamination)?

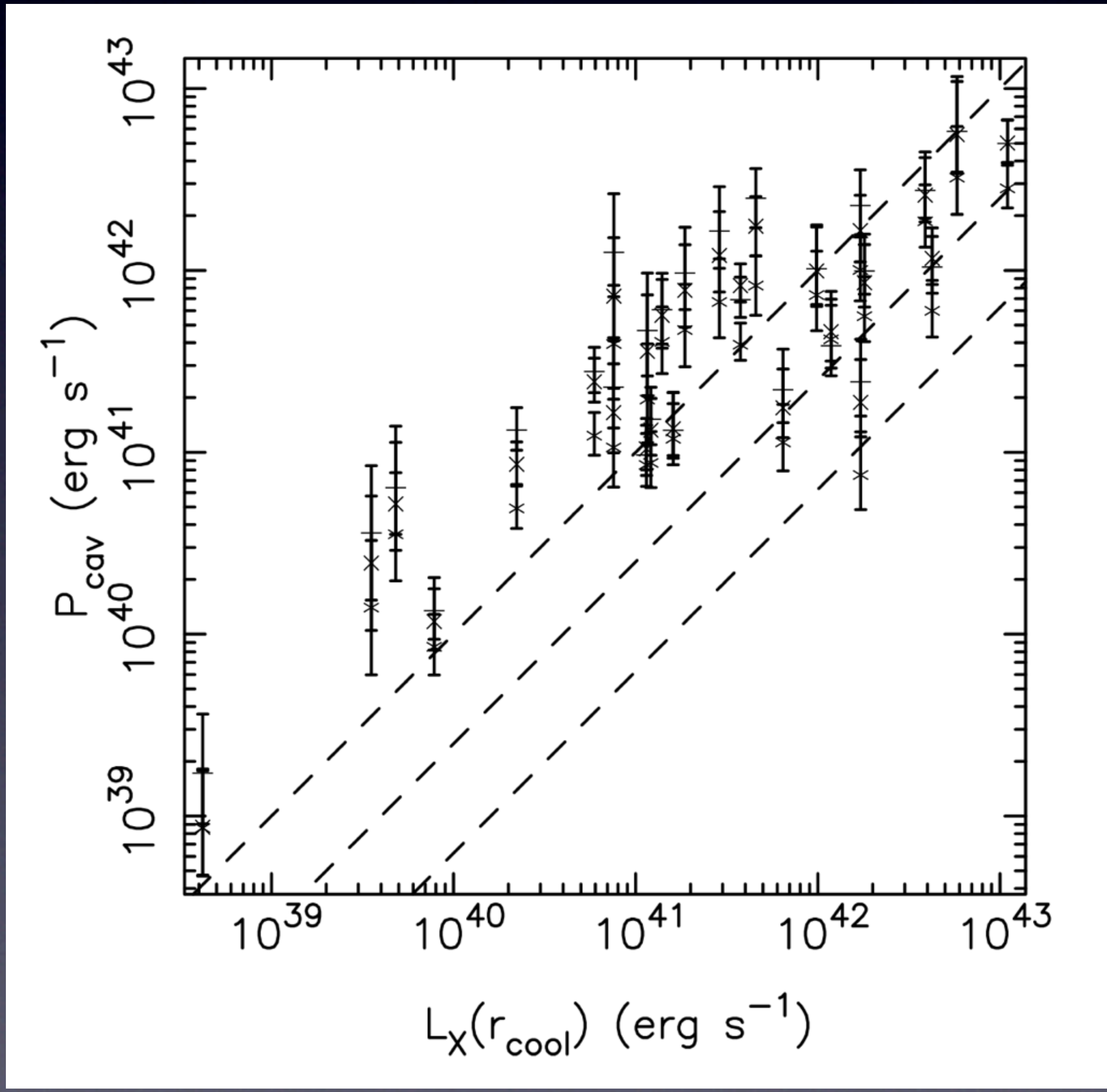
# Feedback in Galaxies

- Total heating power of the cavities in 27 galaxies is roughly enough to balance total cooling power of *all* 109 gals with diffuse emission (Nulsen+07)

$P_{cav} = 1.5\text{–}3 \times 10^{43}$ erg/s (1PV)

$L_{cool} = 1 \times 10^{44}$ erg/s

3.5-7 PV work needed to offset cooling




Nulsen+07

# Caveats to Cavity Heating

- Heating is not directly observed in cavity wakes (instead, buoyantly uplifted cool gas filaments are observed)
- Heating is not symmetric (although turbulence and bulk gas motions will help)
- Heating takes place at cavity locations (at larger radii), need to heat gas close to central AGN to enable feedback
- Observed cavities, by definition, have not yet released their enthalpy to heat the diffuse gas

# What About Shock Heating?

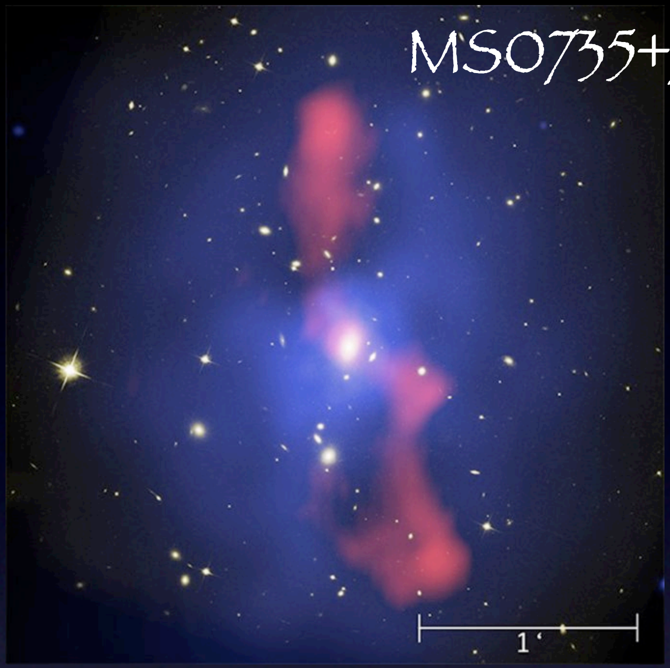
- Expect a total shock energy similar to cavities, especially soon after the outburst
- Basic shock physics is well understood
- Shocks will naturally heat the ICM isotropically, and more strongly near the AGN, as required for feedback
- However, outburst shock detections are rare...

# ...Only a Few Shocks

Hydra A

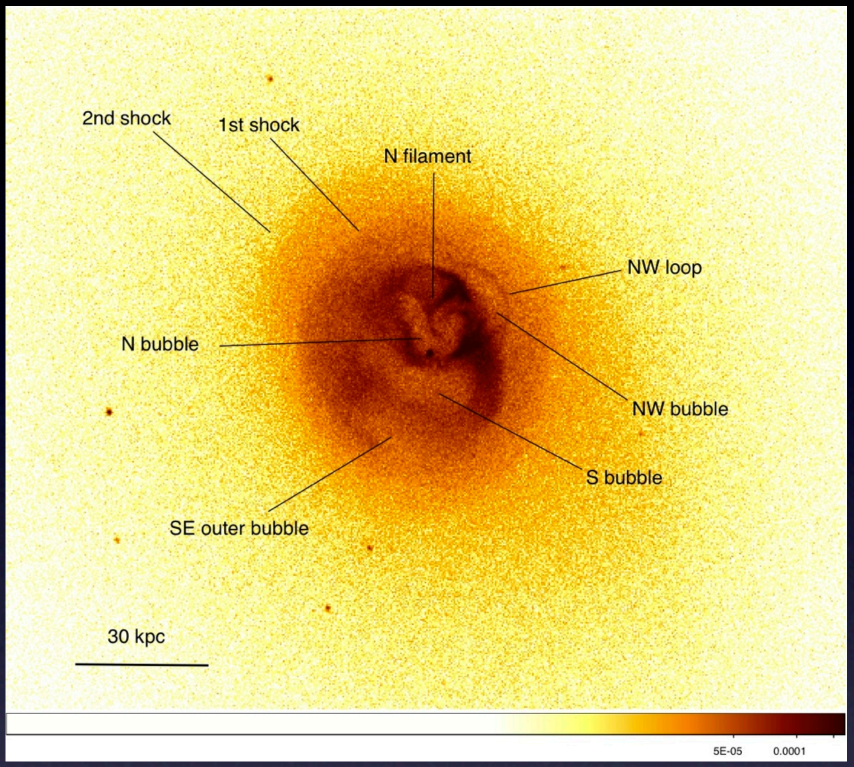
Nulsen+05, Simionescu+09

MS0735+7421

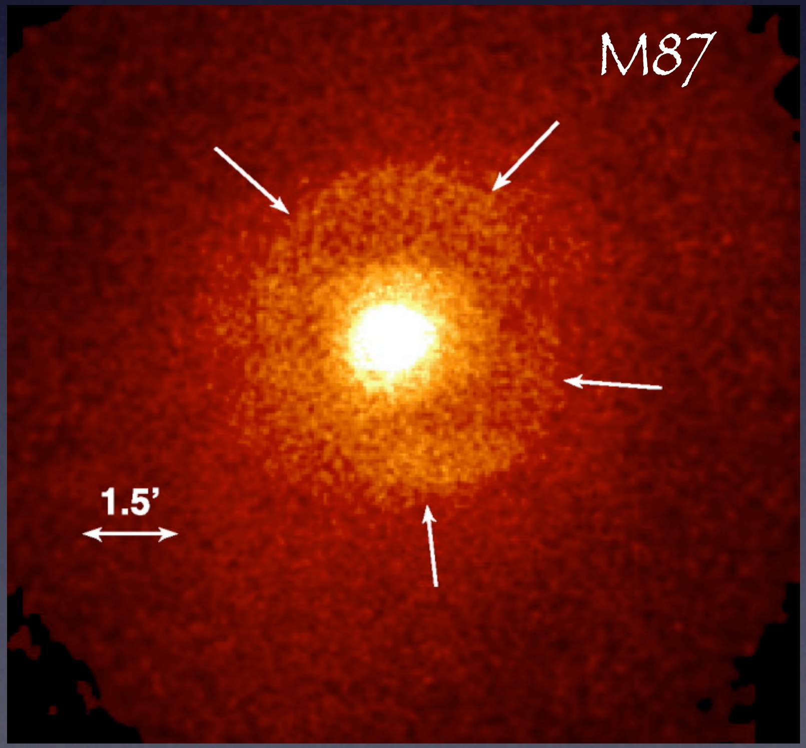



McNamara+05

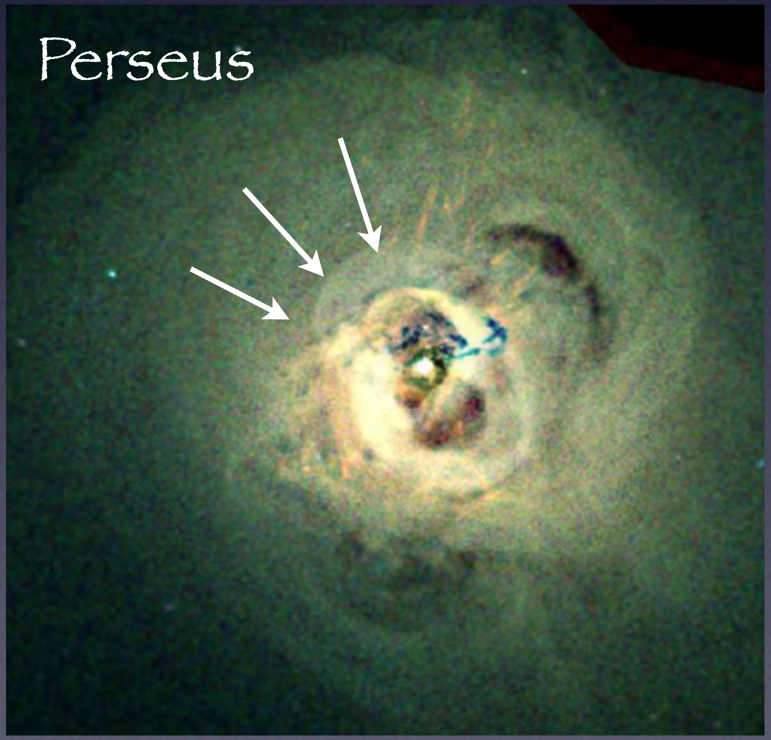
A2052




Blanton, SWR+11



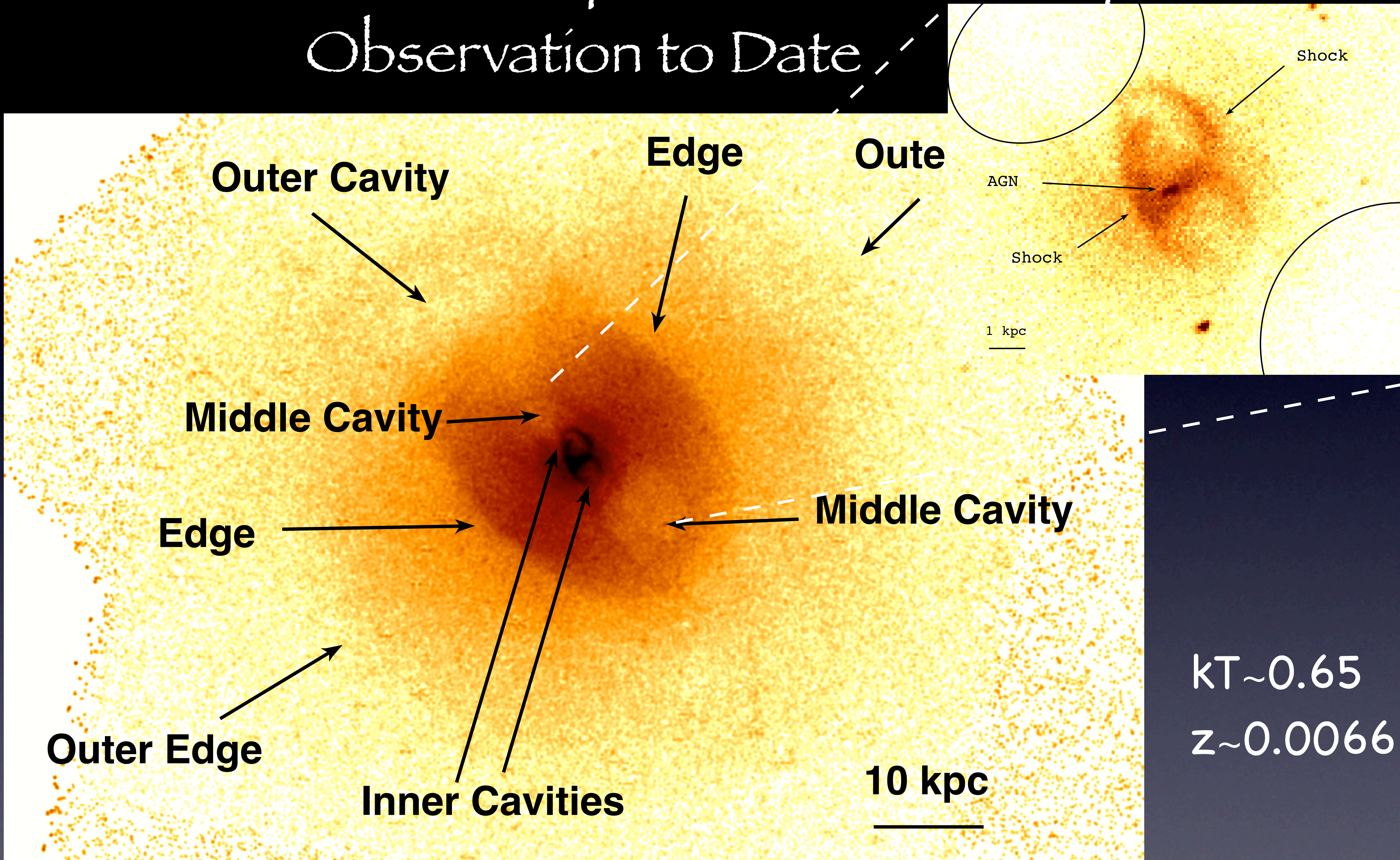

Forman+07




Fabian+06

Need to measure temperatures to discriminate shocks from cold fronts!

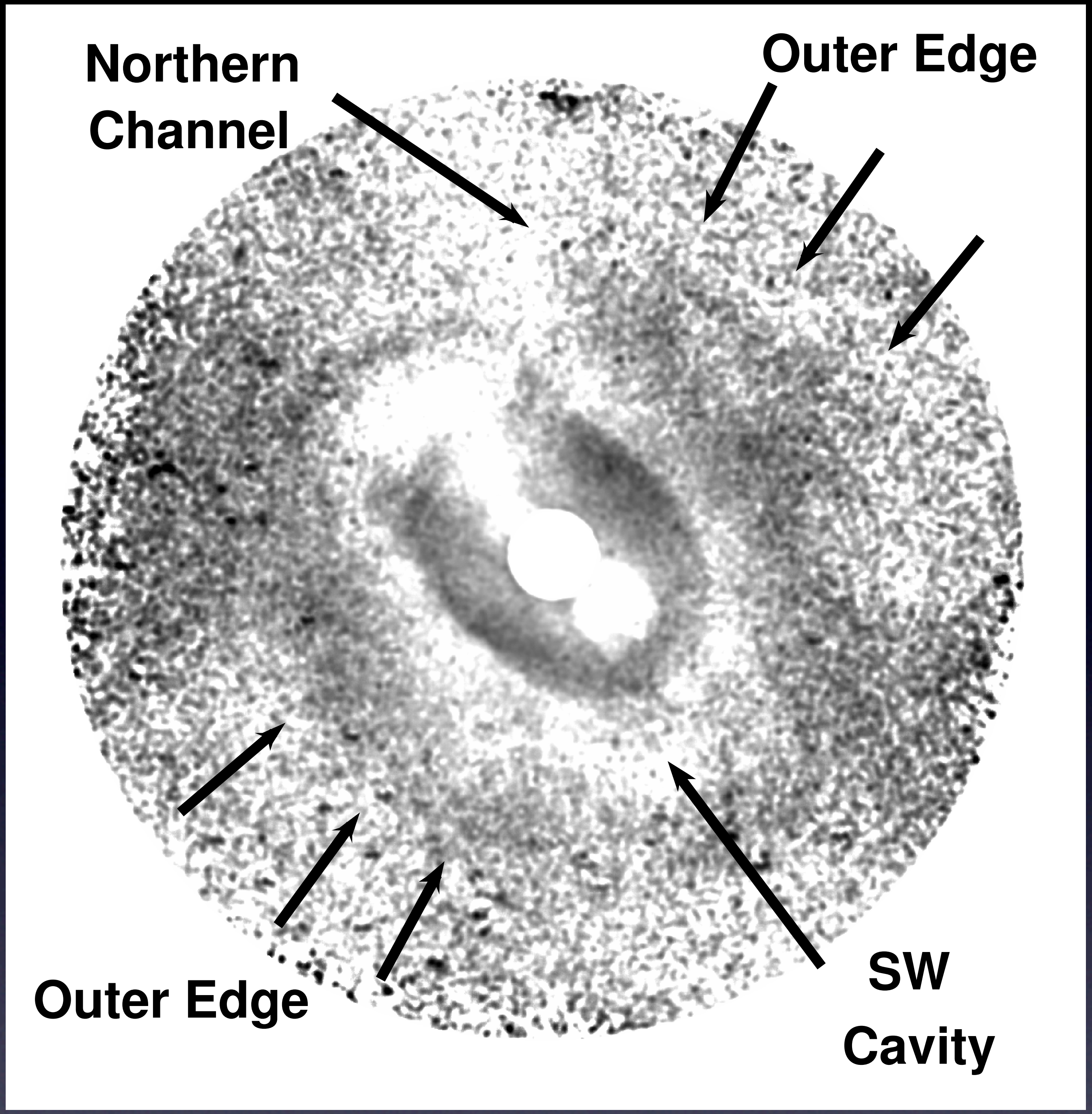
# Enter NGC 5813, Deepest Chandra Group Observation to Date

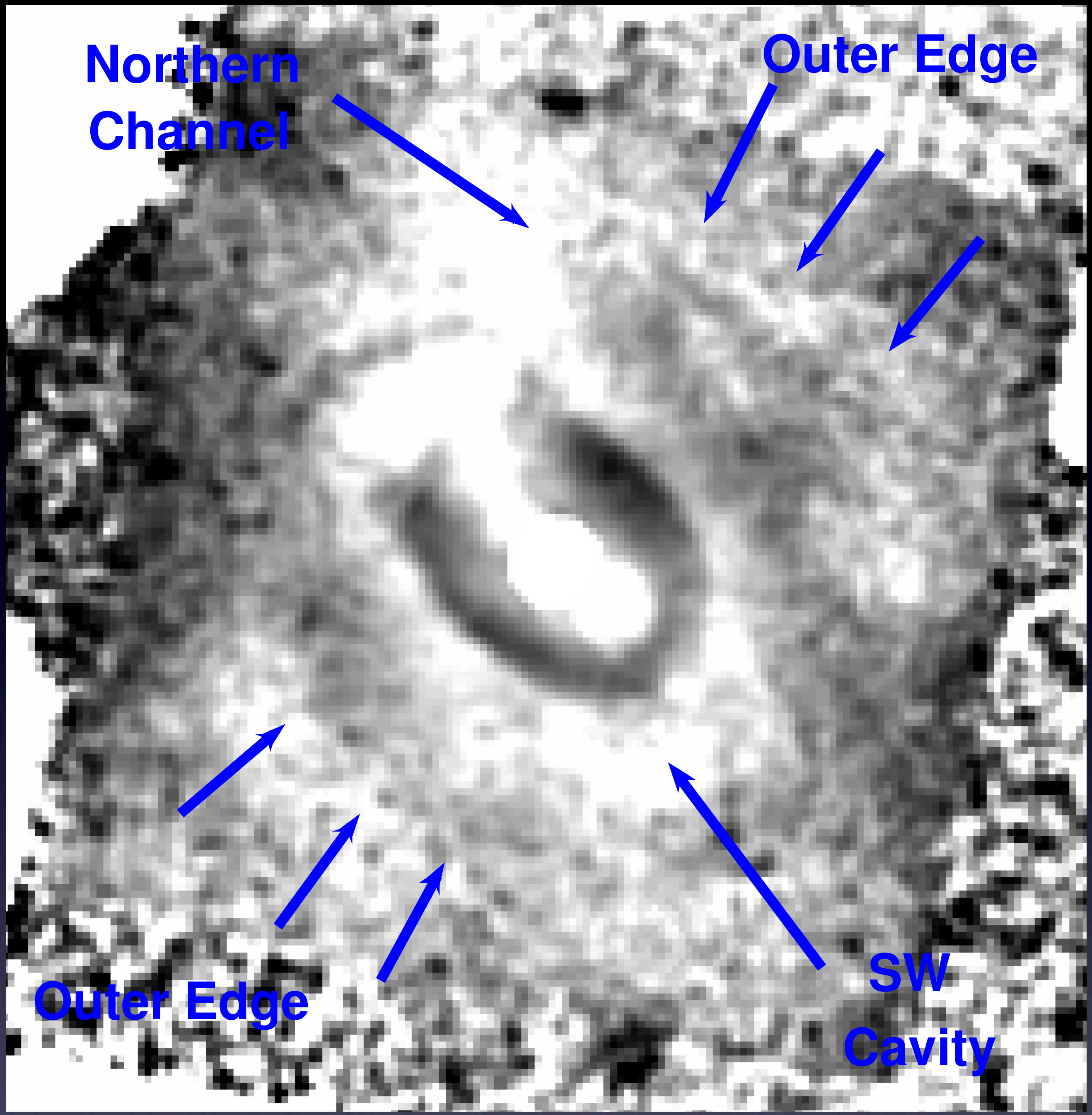



kT~0.65

z~0.0066

650 ksec image, Randall+14 (in prep.), also Randall+11



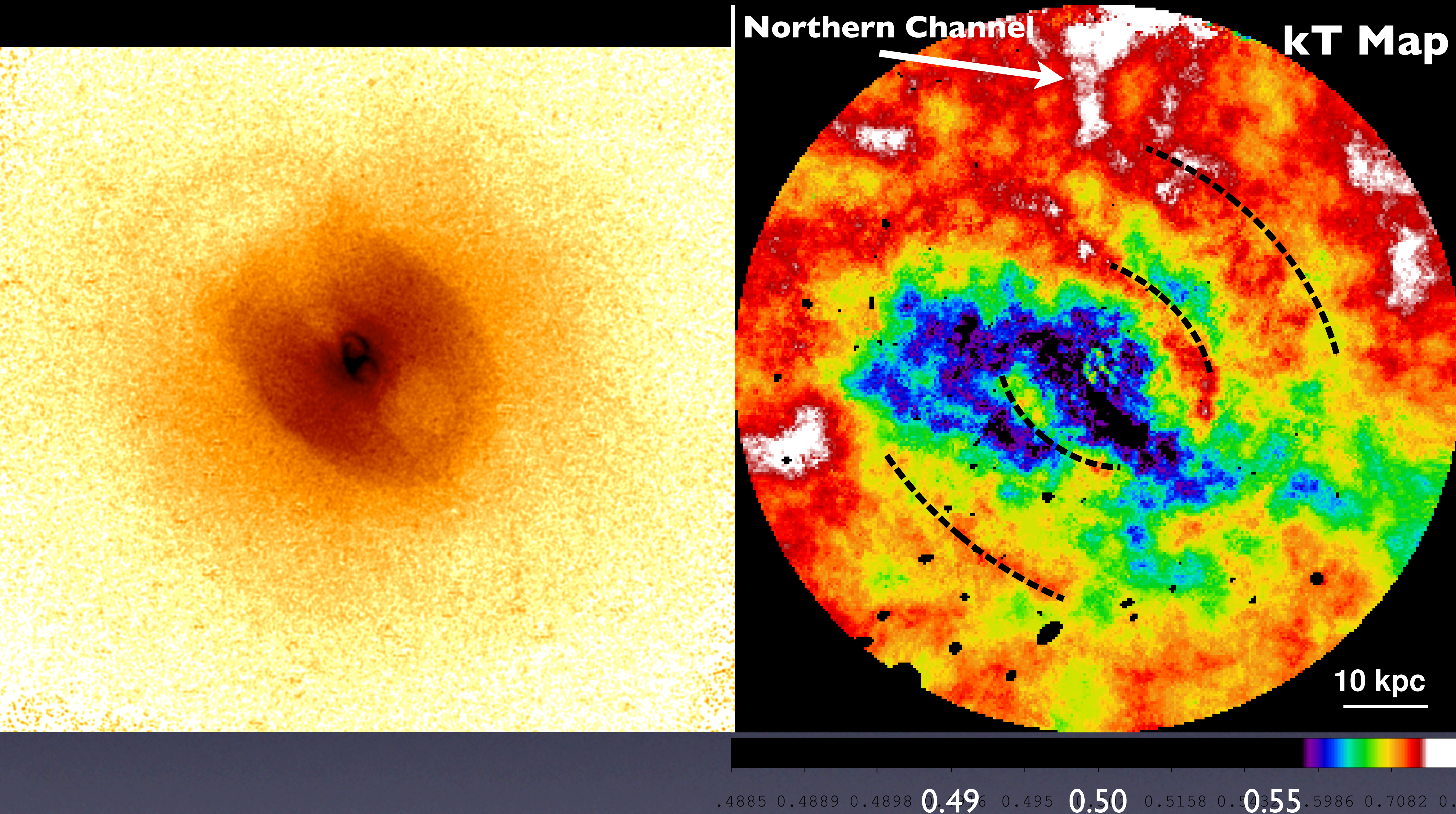




Beta-model divided residual images

Is the "northern channel" a leaking bubble?

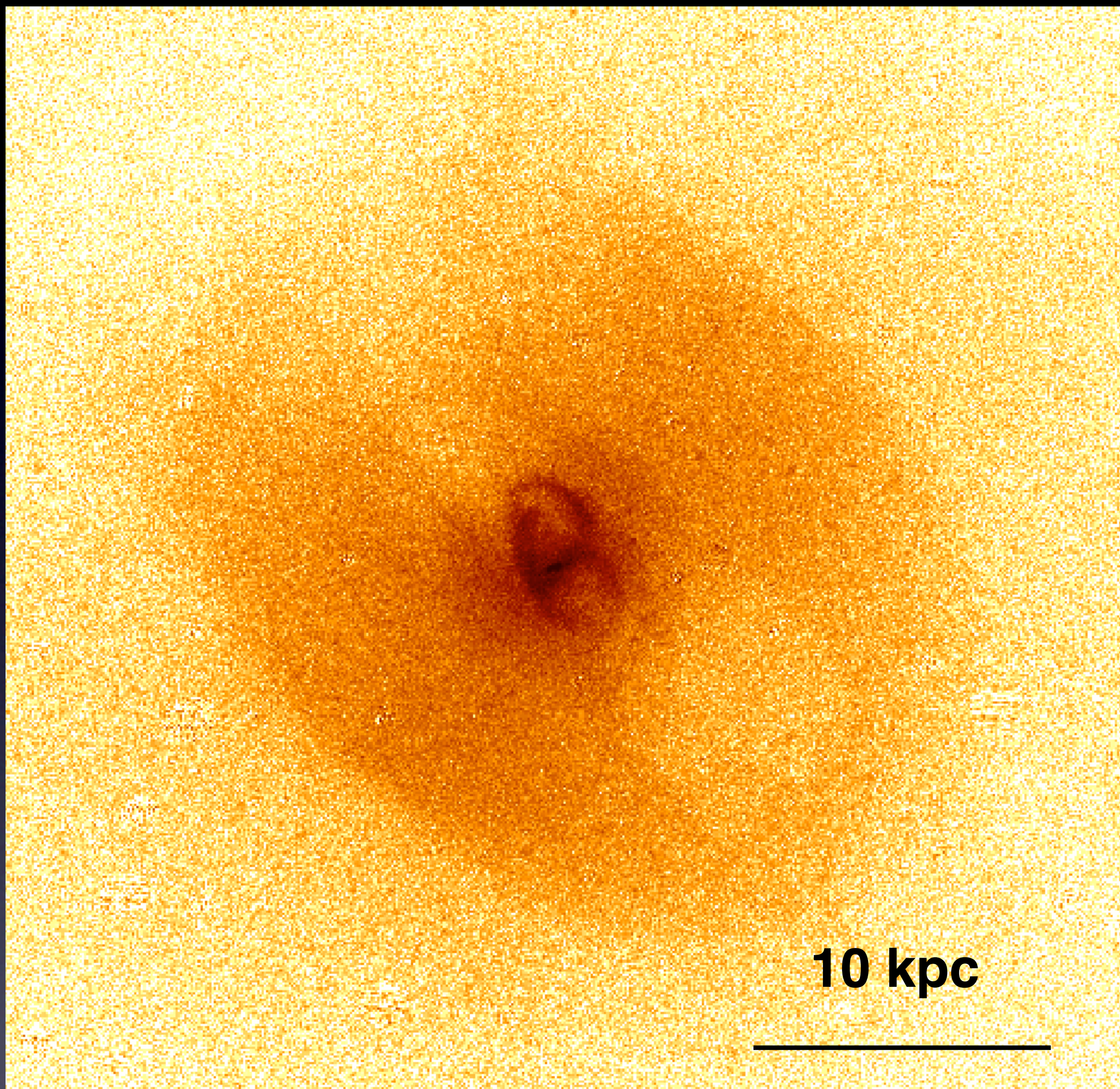
# Why NGC 5813?

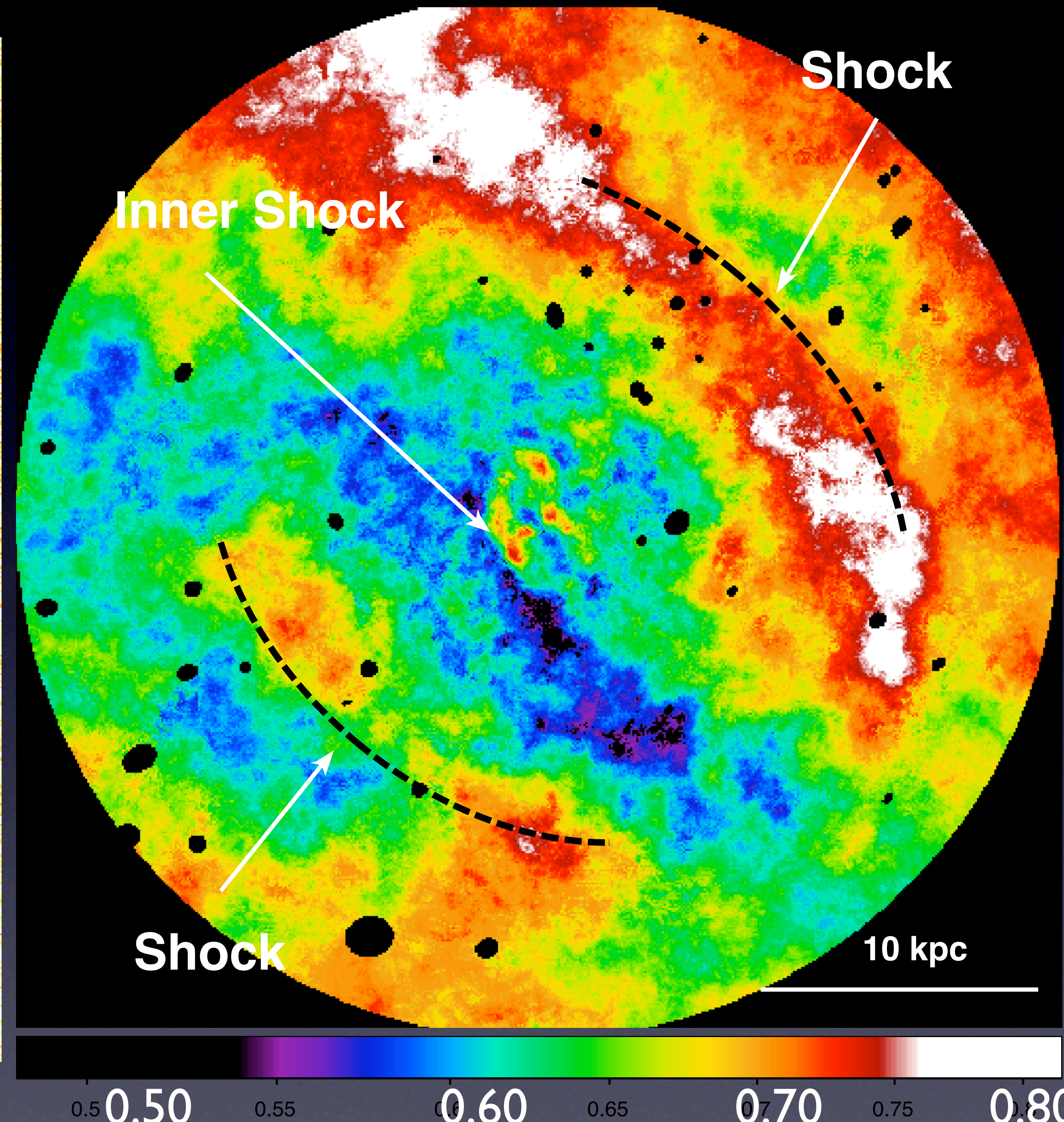
- NGC 5813 shows three pairs of collinear cavities and associated concentric surface brightness edges from three *distinct* outbursts of the central AGN
- Regular morphology, apparently in a “steady state” feedback mode, with relatively little IGM “weather”
- Cool temperatures ($\lesssim$ 1 keV) allow very accurate Chandra temperature measurements (for shock detection)
- It is therefore *uniquely* well suited to the study of AGN feedback (the balance of heating and cooling in the IGM, evolution of buoyantly rising cavities or “bubbles”, outburst history of the central AGN, etc.).

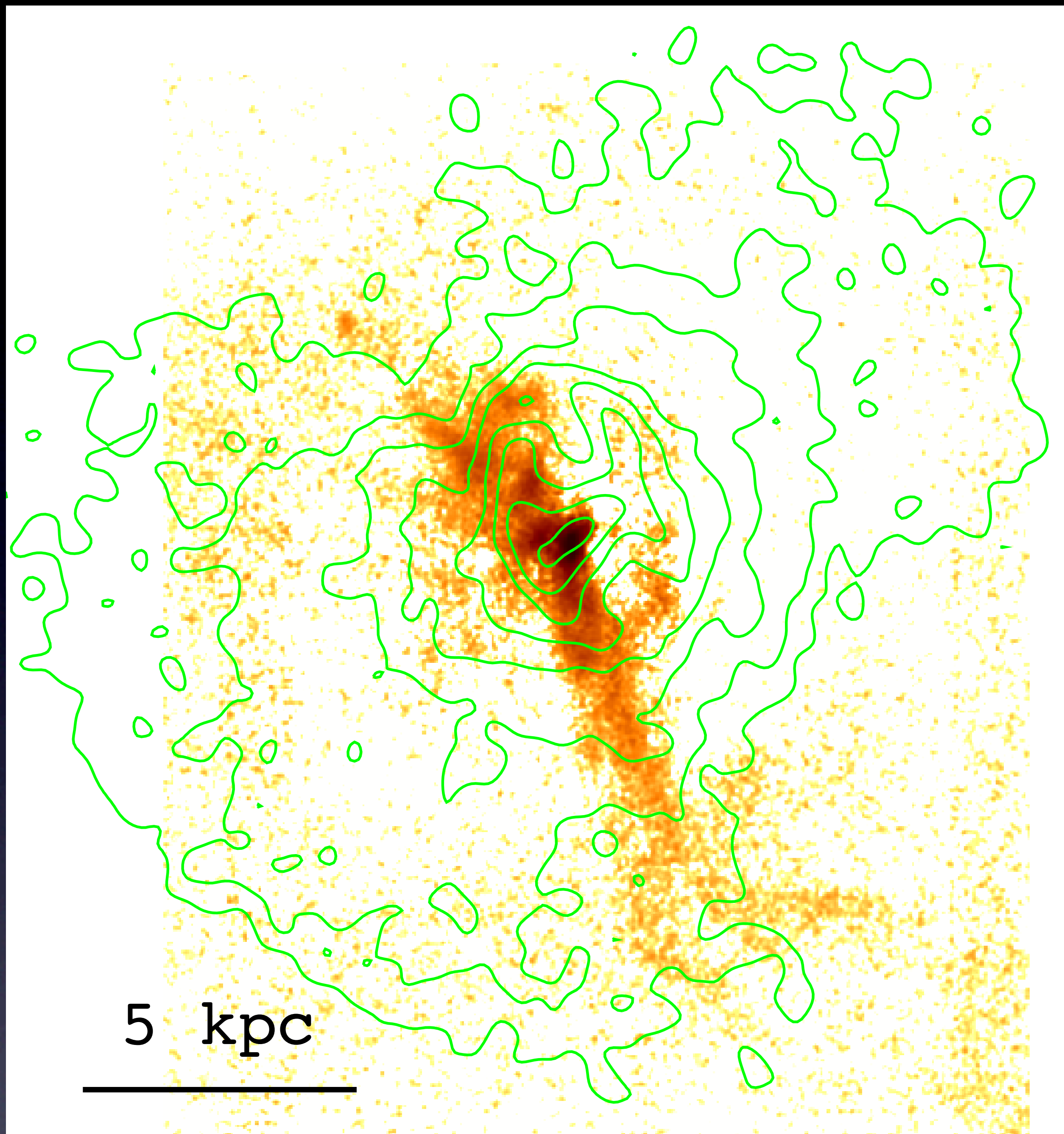



Shocks are clearly visible, even in the smoothed temperature map

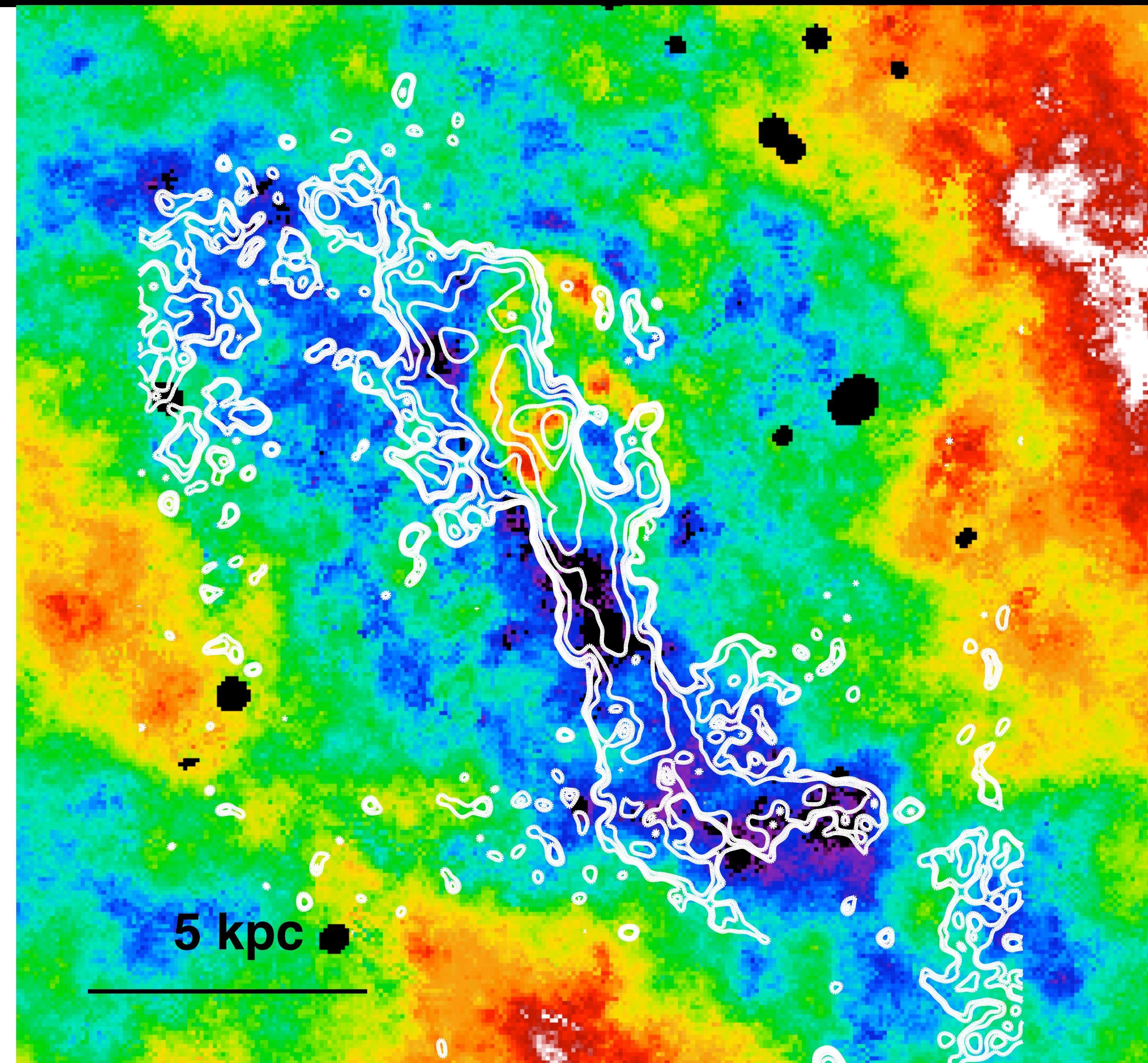
# Central and intermediate shocks





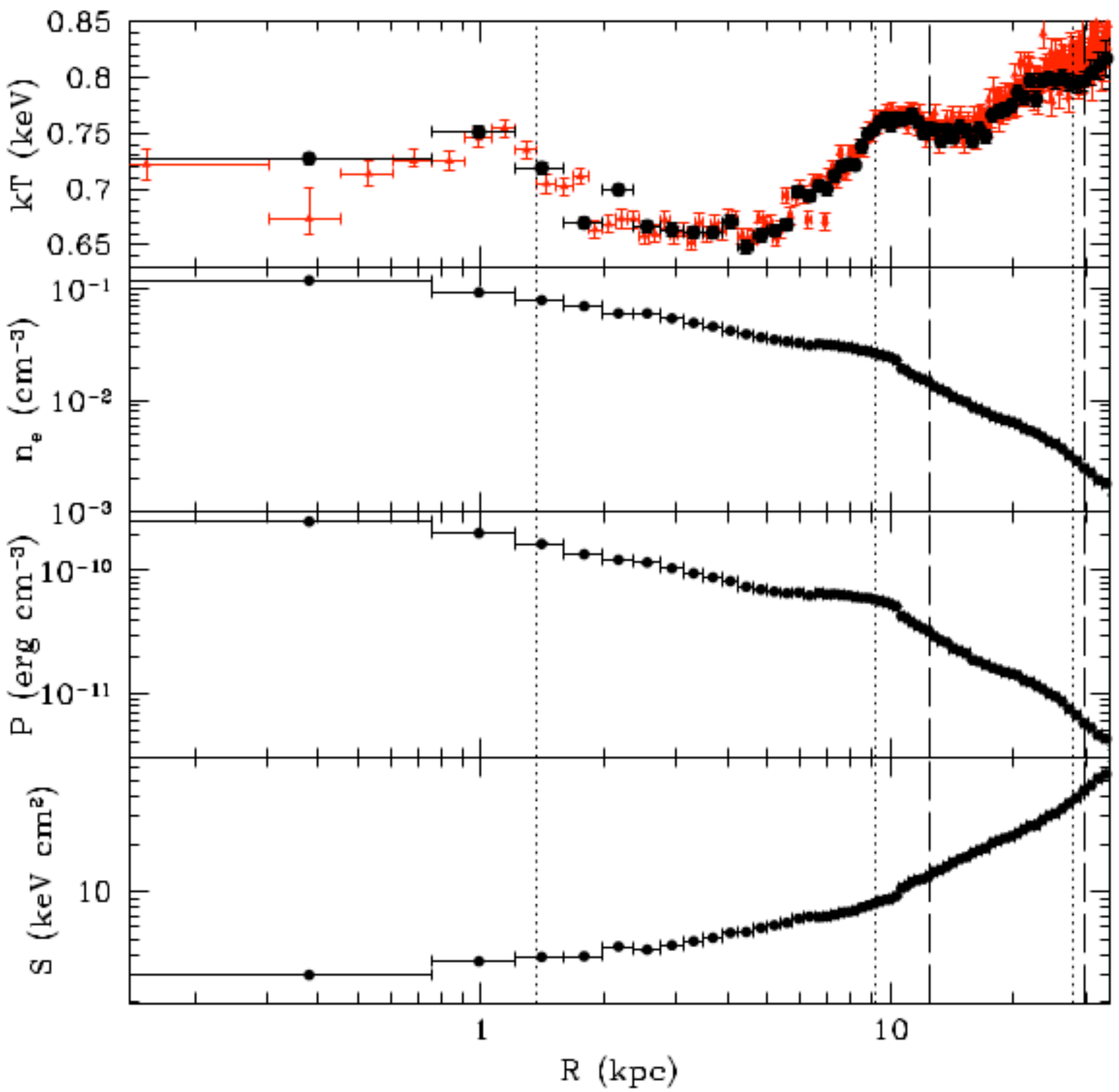

SOAR Hα image with X-ray contours

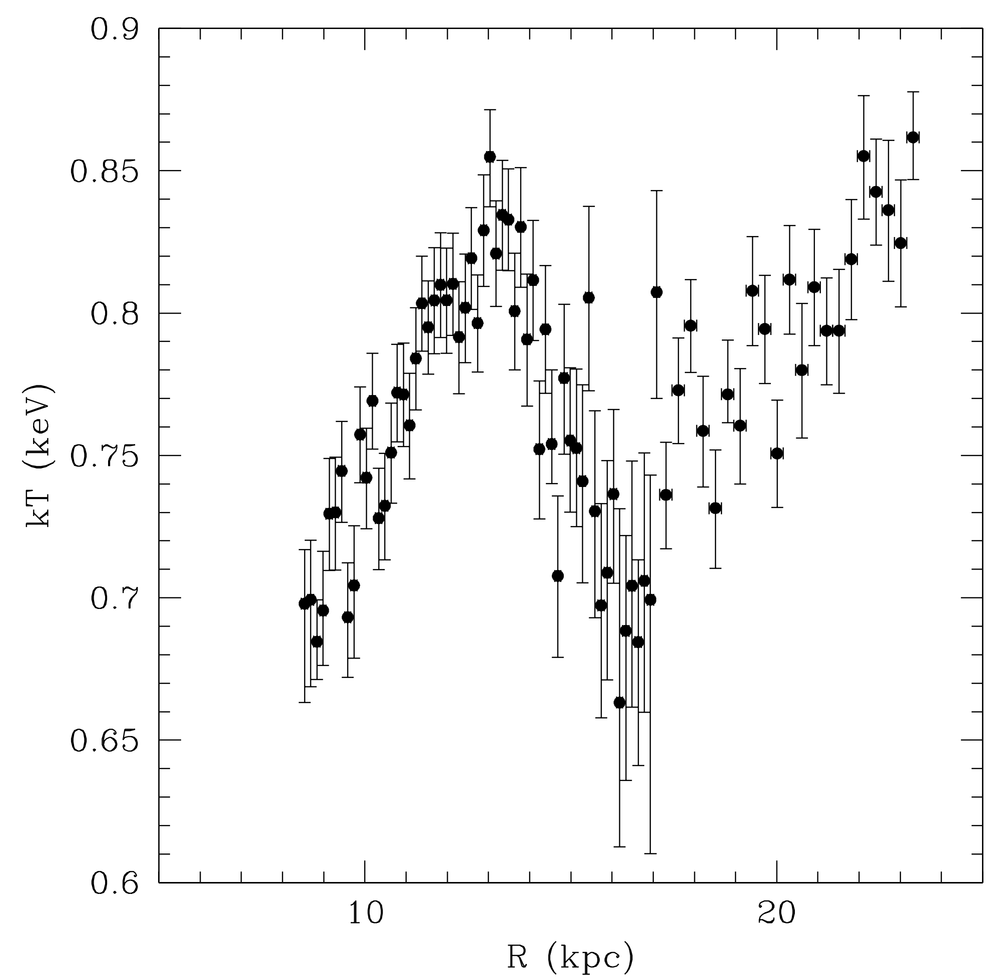



kT map with Hα contours

Cool central gas is uplifted by buoyantly rising bubbles
(see N. Werner's and L. David's talks on cool gas)

# NGC 5813




NW 10 kpc shock

Azimuthally averaged profiles

# Shock Structure

- All surface brightness edges are well-modeled by a discontinuous power law density model:
  - Core shocks: $\rho_1/\rho_2 = 1.97$, M = 1.71
  - Middle shocks: $\rho_1/\rho_2 = 1.74$, M = 1.52
  - Outer shocks: $\rho_1/\rho_2 = 1.44$, M = 1.30

# IGM Heating from Shocks

- Only some fraction of shock energy goes into heating (and this fraction is small for weak shocks, 1-9% for N5813 shocks)

- Lasting heating comes from change in entropy, $\Delta S$. Expressed as a fraction of the thermal energy in the gas: $\Delta Q \sim T \Delta S \Rightarrow T \Delta S / E_{\rm therm} \sim \Delta \ln[ P / \rho^{\gamma} ]$ (see Nulsen+07)

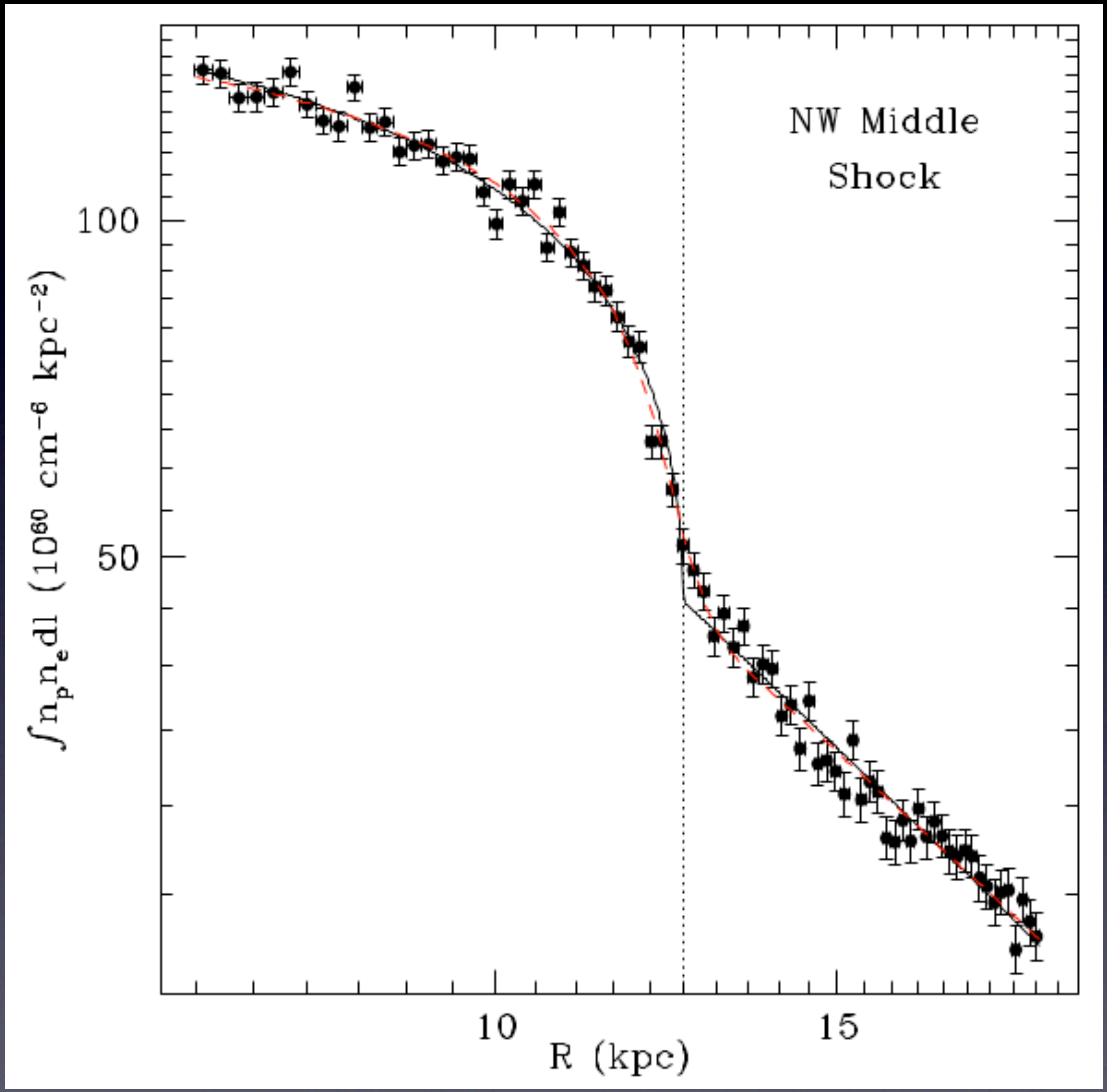
- Therefore, $(1/\Delta \ln[ P / \rho^{\gamma} ])$ shocks per *local* cooling time are needed to replenish $E_{\rm therm}$ and fully balance radiative cooling
- Repetition rate is ~ $2\times10^{7}$ yr (from shocks)

# Shocks Alone Can Do the Job!

| | $t_{cool}$ [yr] | shocks/$t_{cool}$ | shocks required |
|---|---|---|---|
| ~1 kpc shock | $2 \times 10^8$ | 10 | 10 |
| ~10 kpc shock | $9 \times 10^8$ | 45 | 20 |
| ~25 kpc shock | $2 \times 10^9$ | 100 | 77 |

- Agreement is remarkably good for rough estimates!
- Even though shocks are weak, repetition rate is much shorter than the cooling time
- Heating takes place near the AGN, as is required to establish feedback (in contrast to cavity enthalpy)

# ICM Physics with Shocks




10 kpc and 1 kpc shocks have finite widths, at a high level of significance

PSF? Clumpy and/or turbulent ICM? Particle diffusion?

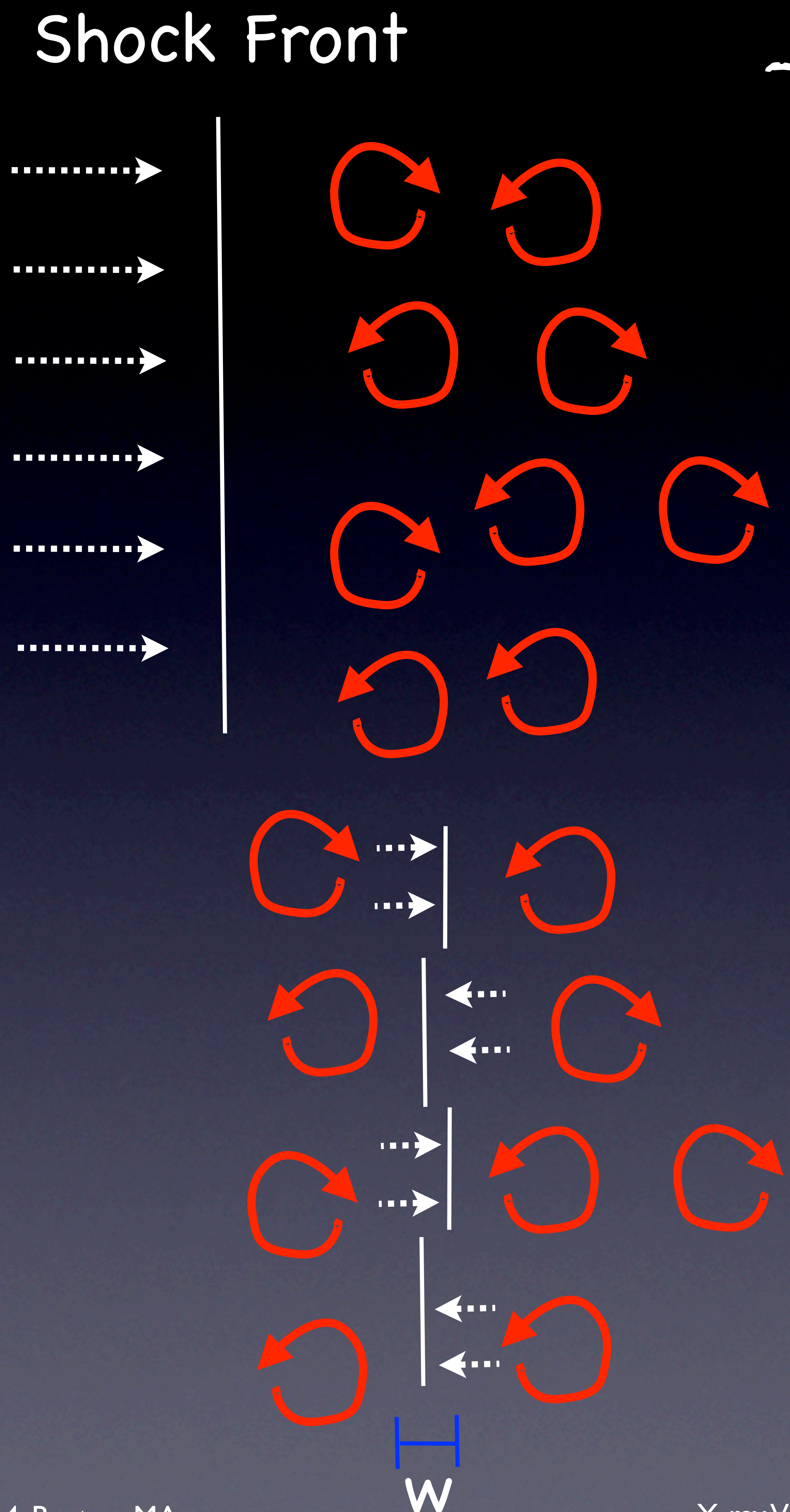
TABLE 2
PROPERTIES OF THE SHOCKS[a]

| ID | $r^b$ (kpc) | $\sigma^c$ (kpc) | PSF[d] (kpc) | $\lambda_{in\rightarrow out}{}^e$ (pc) | $\sigma_t{}^f$ (km/s) | $\Delta\rho^g$ | $M^h$ |
|---|---|---|---|---|---|---|---|
| Inner, SE | 1.37 | $0.08^{+0.04}_{-0.04}$ | 0.11 | 3.3 | $150 \pm 80$ | $2.06^{+0.08}_{-0.12}$ | $1.78^{+0.08}_{-0.11}$ |
| Middle, SE | 9.2 | $0.35^{+0.09}_{-0.08}$ | 0.15 | 25 | $80 \pm 20$ | $1.75^{+0.04}_{-0.03}$ | $1.52^{+0.03}_{-0.03}$ |
| Middle, NW | 12.5 | $0.42^{+0.12}_{-0.11}$ | 0.07 | 36 | $70 \pm 20$ | $1.74^{+0.03}_{-0.02}$ | $1.52^{+0.03}_{-0.01}$ |
| Outer, SE | 27.7 | $< 1.27$ | 0.31 | 88 | $< 76$ | $1.26^{+0.08}_{-0.06}$ | $1.17^{+0.05}_{-0.04}$ |
| Outer, NW | 29.9 | $< 1.03$ | 0.06 | 163 | $< 62$ | $1.41^{+0.12}_{-0.13}$ | $1.28^{+0.08}_{-0.09}$ |

[a]Error ranges are 90% confidence intervals.

- Widths larger than PSF (particularly for 10 kpc shocks)
- 10x's larger than the Spitzer particle mean free path: not particle diffusion
- What about turbulence?

# Turbulent Shock Broadening




$$\sigma_t \approx \frac{w\, v_s}{\sqrt{r\,\ell}}$$

see Nulsen+13 for details

# Results:

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[a]Error ranges are 90% confidence intervals.

- Each shock front consistent with an ICM turbulent speed of ~ 80 km/s
- Consistent with results from simulations and independent observations (Lau+09; de Plaa+12; Sanders+13)
- In principle, this is an upper limit (e.g., expect shock deformations due to clumpy ICM, broadening from modeling systematics)

# Conclusions

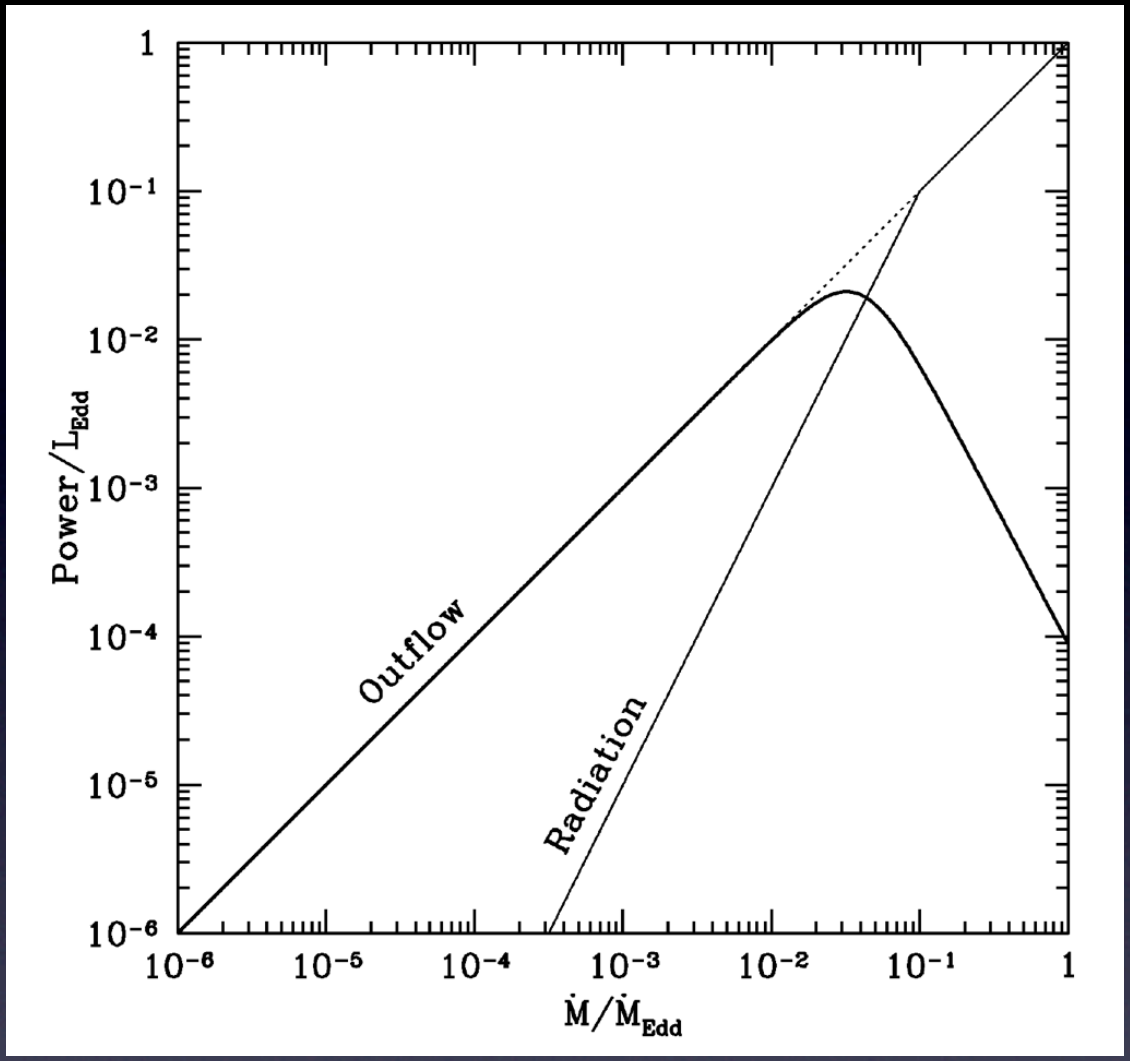
- Although the energetics of X-ray cavities are sufficient to offset radiative cooling, it is not clear how to distribute this energy isotropically and close to the central AGN
- Outburst shocks heat the ICM roughly isotropically and most strongly near the central AGN, as required to regulate feedback
- NGC 5813 provides a unique opportunity to study AGN feedback, due to tis regular morphology and cleanly separated features from 3 AGN outbursts (three pairs of cavities, each associated with an elliptical shock front)

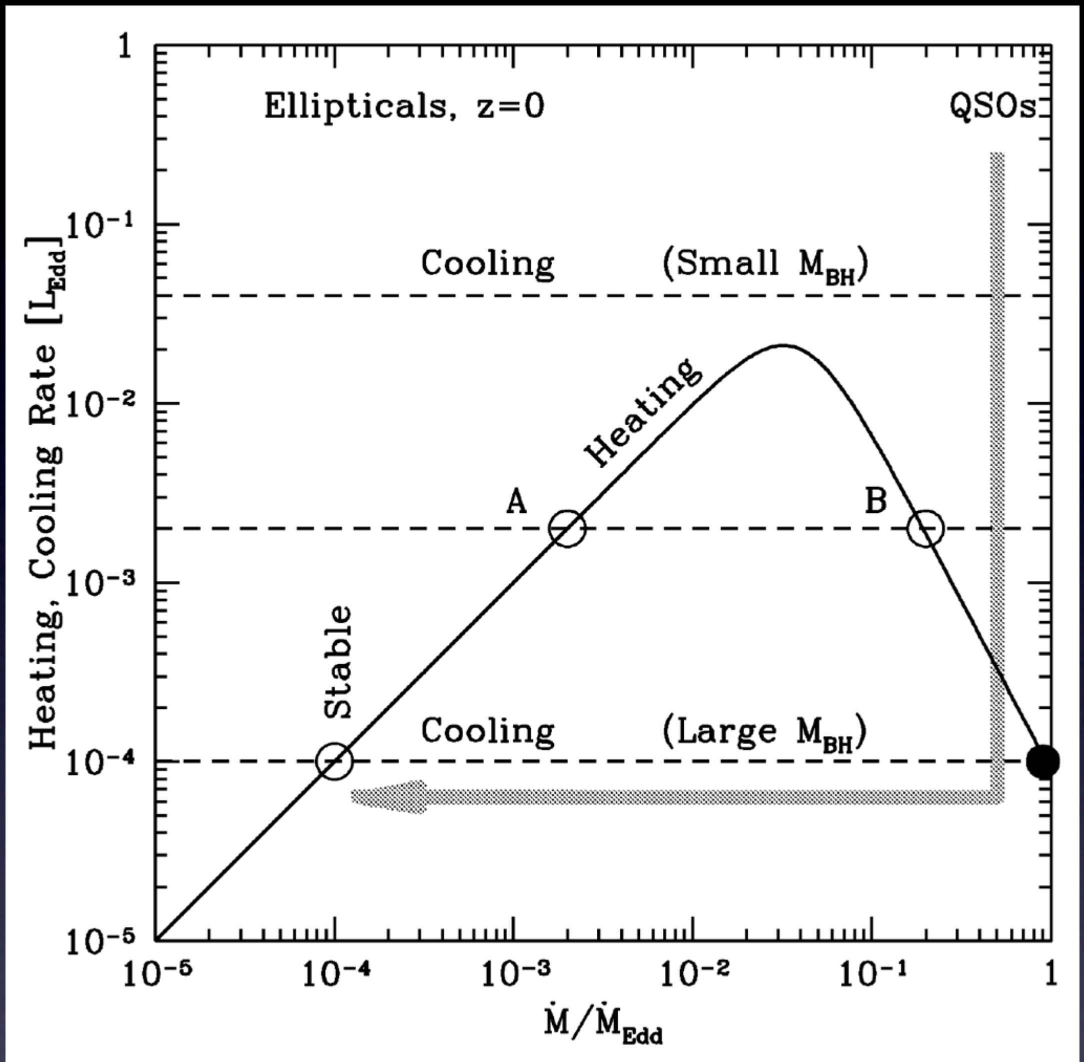
# Conclusions

- In NGC 5813, shocks alone balance radiative cooling (within 26 kpc, where cooling time is 2 Gyr, on order the group age). Shock heating is likely important in other systems, where shocks are more difficult to detect.
- Finite shock widths are >10x's larger than the particle mean free path, and imply reasonable ICM turbulent velocities on the order of 80 km/s. Thus, transport processes in the ICM are likely dominated by turbulence

# UNUSED SLIDES

# Evolution of Feedback




Transition from radiative to kinetic mode around 1-10% $\dot{M}_{Edd}$ (analogy with stellar mass BHs in binary systems, see Churazov+05)

$\dot{M}_{Edd} = 4\pi G m_p M_{BH}/c\sigma_T$