FEEDBACK FROM GROWTH OF SUPERMASSIVE BLACK HOLES

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ACCRETING BHs PRODUCE OUTFLOWS

- Observational
  - Jets (radio galaxies)
  - BAL outflows
- Theoretical
  - Inefficient accretion (ADIOS)
  - Radiative accretion
    - Magnetized coronae and winds

KINETIC OUTPUT > 0.01 $M_{BH}c^2$

AVAILABLE ENERGY

- 1 g mass accreted liberates

$$10^{19}\left(\frac{\varepsilon_{KE}}{0.01}\right) erg$$

- Could accelerate $20{,}000\left(\frac{\varepsilon_{KE}}{0.01}\right)\sigma_{200}^{-2}\, g$ to escape speed of galaxy
- Feedback from forming SBHs *could* unbind protogalaxies, or limit BH growth
  - but how efficiently is energy used?

ENERGY USE DEPENDS ON…

- How fast it's deposited – power more important than total output
  - SBHs grow at close to Eddington rate
- Whether cooling is important
- How uniform the gas is
  - Clumpy: energy "goes around" the clumps
  - Gas that has collected into disk may be immune
- Directionality of the outflow
  - Collimated jet vs. broad disk wind

FEEDBACK + COOLING

- **ENERGY CRITERION (Silk & Rees, Blandford)**

Unbind gas if: $$L_{feedback} \sim \frac{\sigma^5}{G} = 5\times10^{43}\,\sigma_{200}^5\, erg\, s^{-1}$$

$$M \sim 10^8 \left(\frac{L_{feedback}}{0.004 L_E}\right)^{-1} \sigma_{200}^5\; M_{Sun}$$

- **MOMENTUM CRITERION (Fabian)**

Appropriate for strong cooling - "mechanical L_{Edd}"

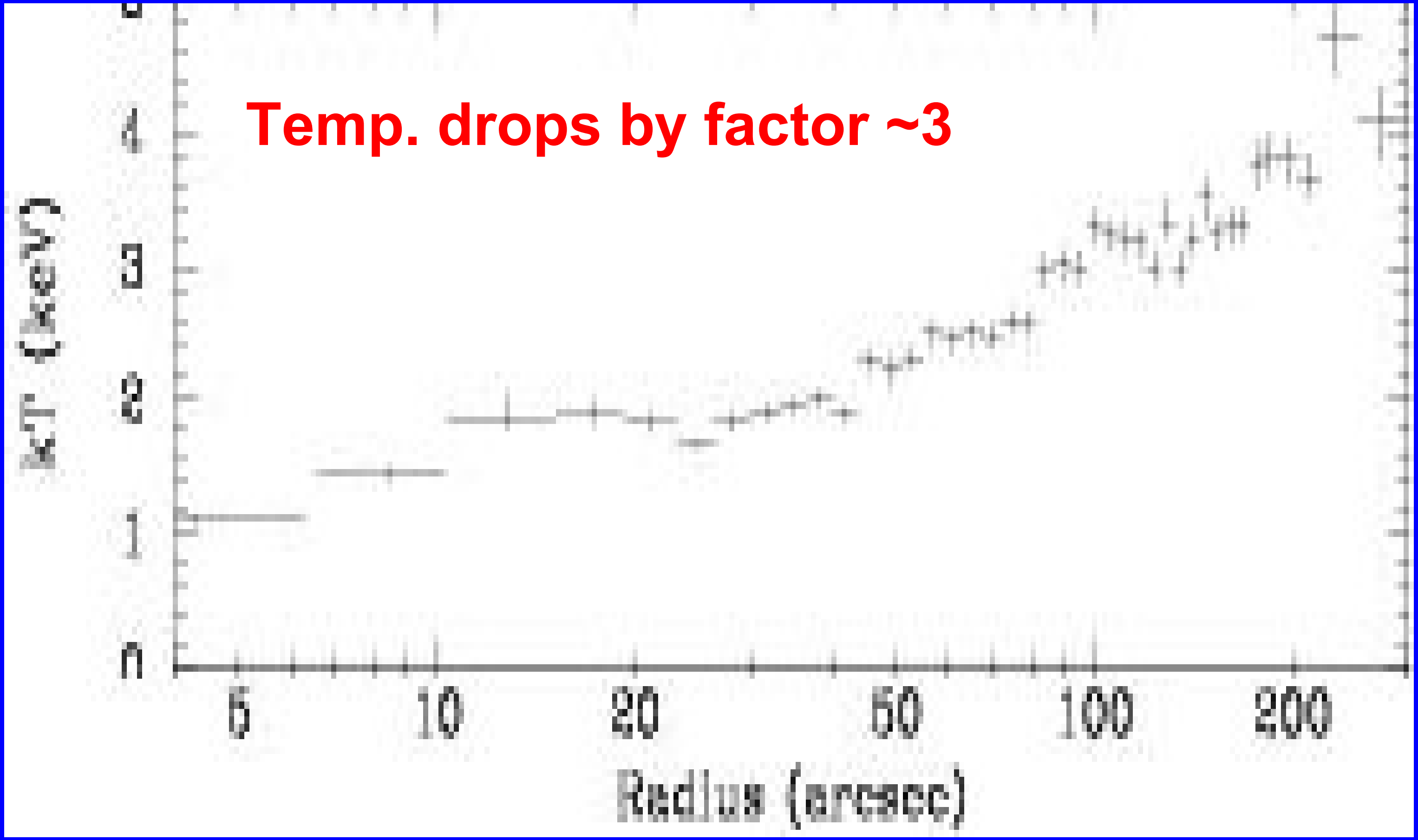
$$L_{feedback} \sim \frac{\sigma^5}{G}\frac{c}{\sigma} = 8\times10^{46}\,\sigma_{200}^4\, erg\, s^{-1}$$

$$M \sim 6\times10^8 \left(\frac{L_{feedback}}{L_E}\right)^{-1} \sigma_{200}^4\; M_{Sun}$$

GALAXY CLUSTERS: A LAB FOR SBH FEEDBACK?

- **"COOLING FLOWS"**
  - No evidence for mass dropout
    - New stars, absorbing gas missing
  - Temperature "floor"
  - Candidates for heat source
    - Conduction from outside
    - AGN heating from center
- **INTRACLUSTER MEDIUM**
  - $L_X \propto T^3$ → entropy "floor"
  - Need ~ 1 eV/baryon during cluster assembly
  - Supernova heating may be inadequate

CENTAURUS CLUSTER



Sanders and Fabian 2002

CLUSTER HEATING APPEARS TO BE:

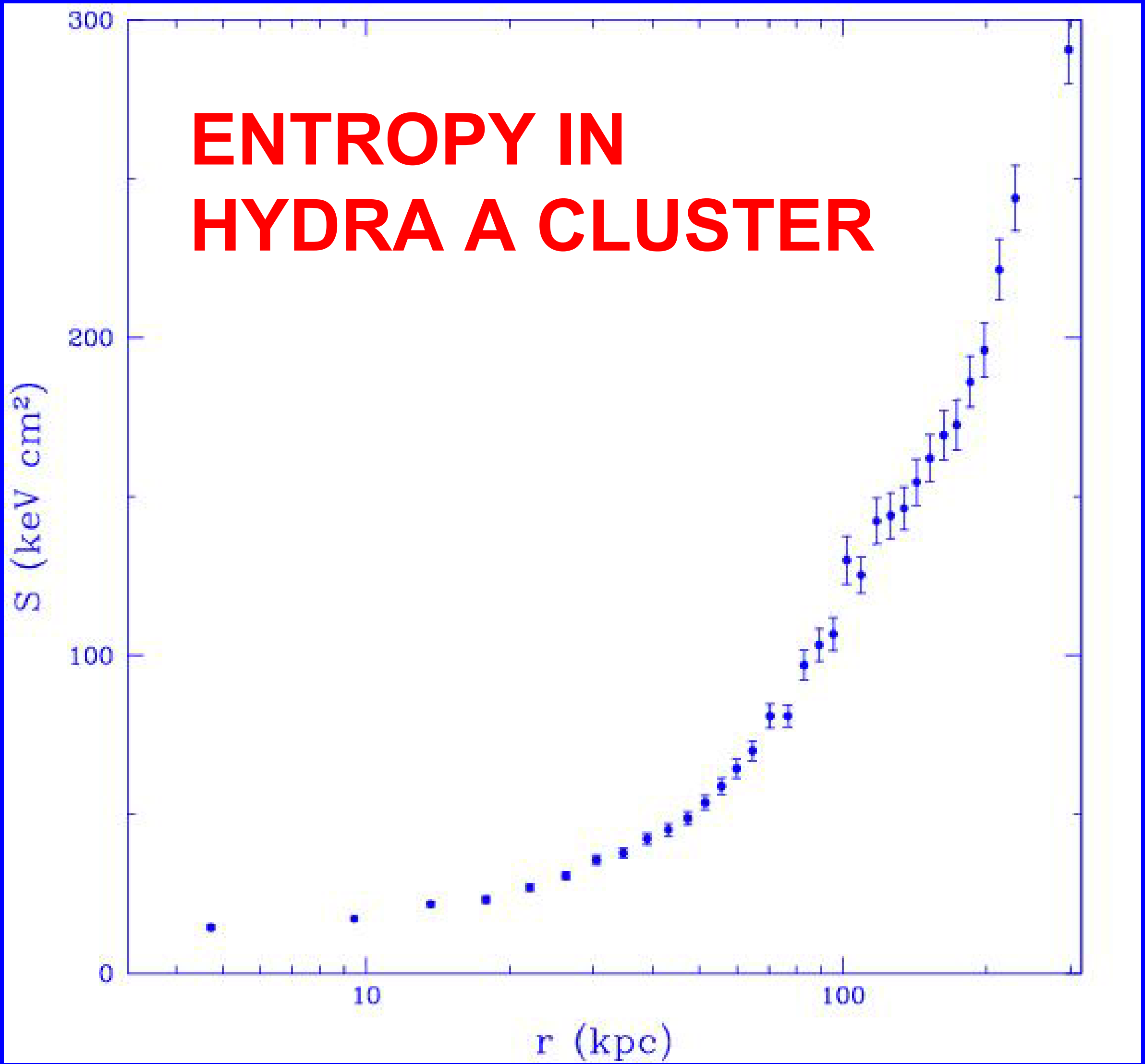
- RELATIVELY GENTLE
  - Not shock heating
  - Not convection: cluster gas is convectively stable

- DISTRIBUTED WIDELY – not too centrally concentrated
  - Entropy “floor” manifest on large scales
  - Needed to avoid cooling “catastrophe”

HEATING NOT BY CONVECTION

Entropy increases with *r*

Convectively stable



David et al. 2001

WHY GENTLE HEATING?

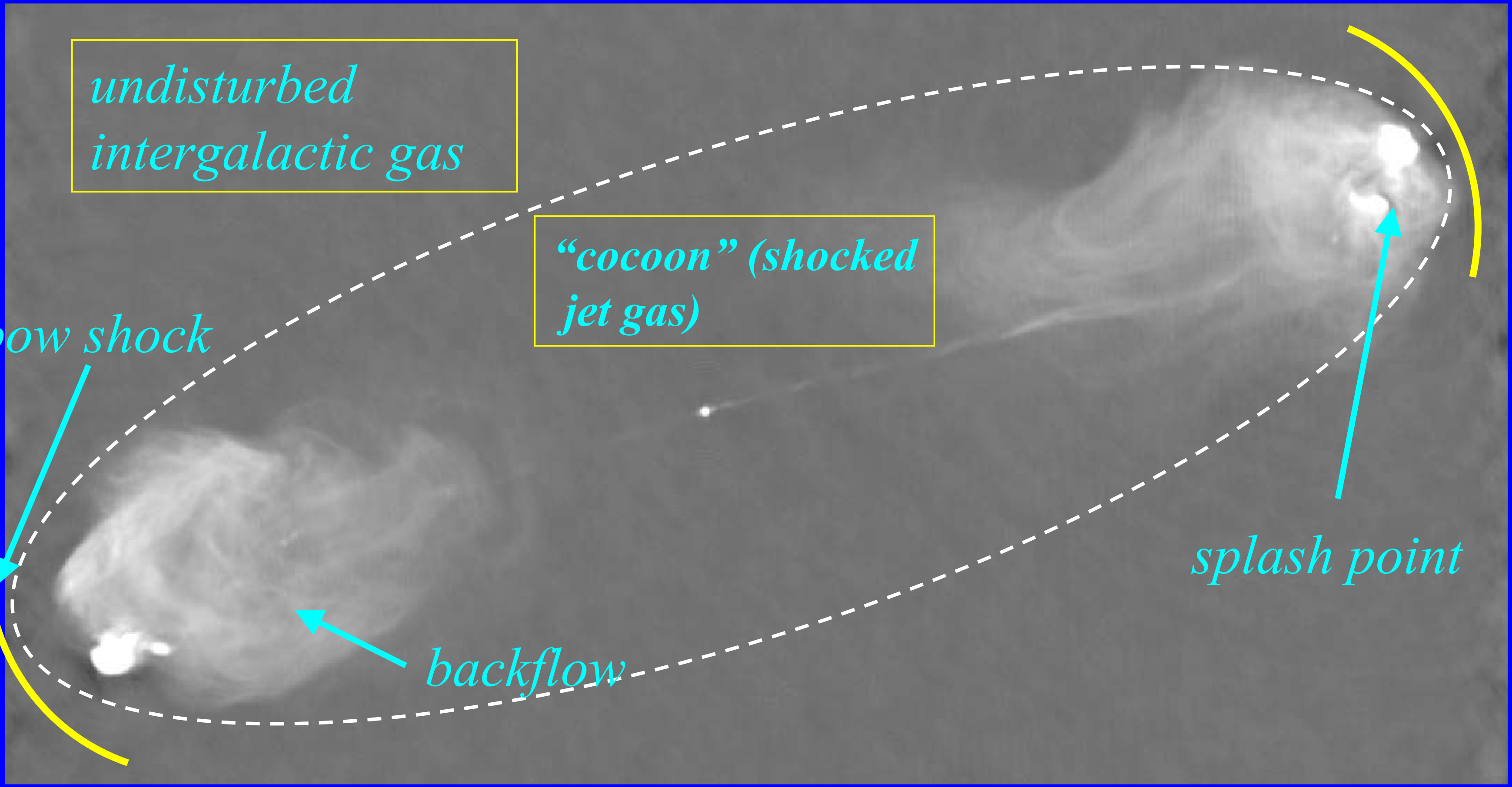
RADIO GALAXY EVOLVE IN 3 STAGES:

- **MOMENTUM-DRIVEN**
  - Jet momentum dominates
  - Elongated cocoon
- **ENERGY-DRIVEN**
  - Cocoon pressure dominates
  - Like stellar wind bubble or supernova blast wave
  - ~ spherical cocoon
- **BUOYANCY-DRIVEN**
  - Rising bubbles of hot fluid

} SUPERSONIC, OVERPRESSURED (momentum-driven and energy-driven stages)

SUBSONIC (buoyancy-driven stage)

CYGNUS A – Exception rather than rule?



Very powerful source in relatively tenuous ICM

Most powerful RGs this age have: ~spherical cocoons
subsonic expansion

WHEN DO SHOCKS BECOME BUBBLES?

- **Self-similar, adiabatic expansion**

$$v \sim \left(\frac{L}{\rho}\right)^{1/3} R^{-2/3}$$

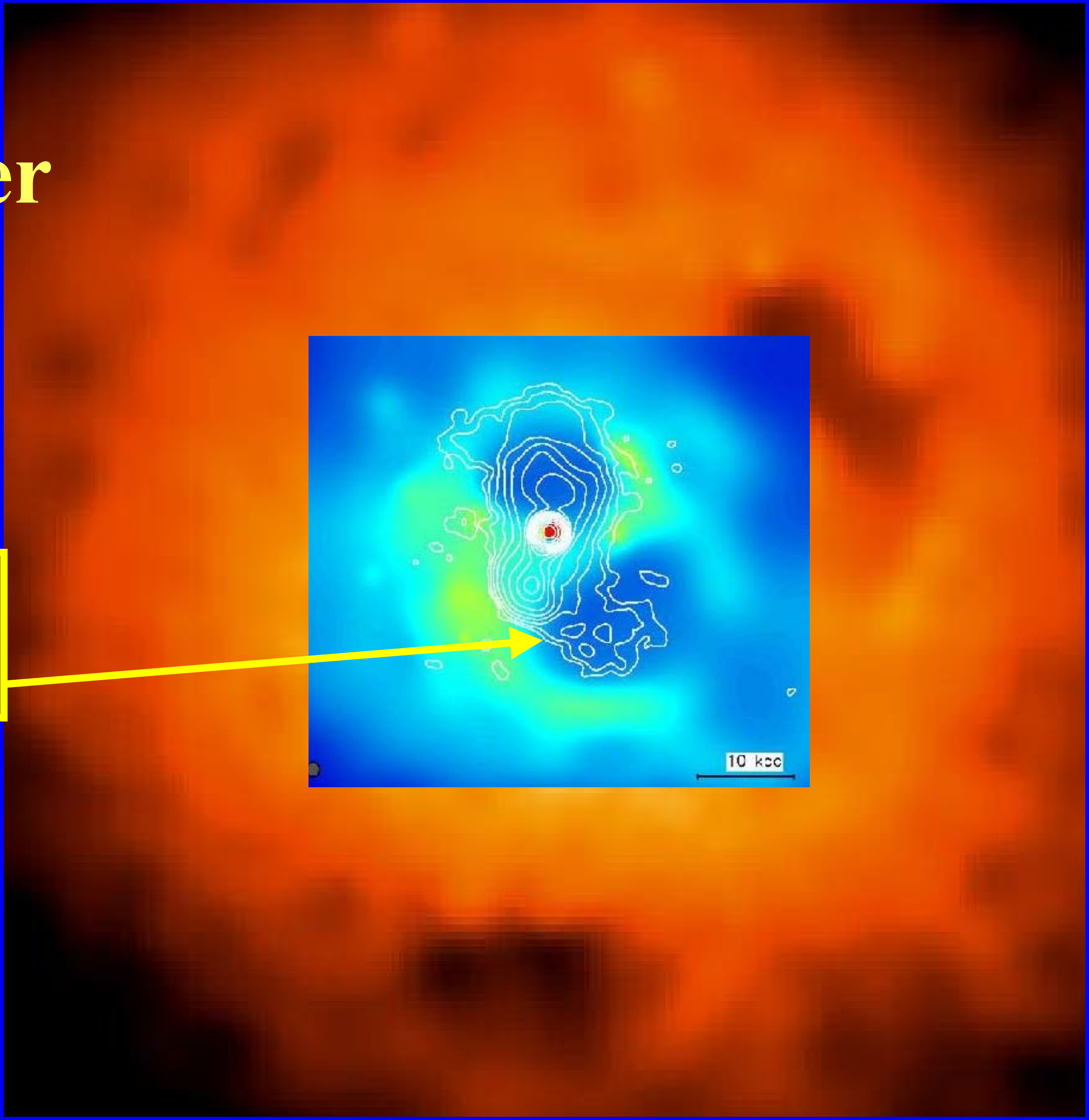
- **Goes subsonic when** $v \leq c_s$

$$\Rightarrow \quad r_{bubble} \sim 5\left(\frac{\langle L_{43} \rangle}{n}\right)^{1/2} T_{keV}^{-3/4}\ kpc$$

3C 84 and Perseus Cluster

Fabian et al. 2000

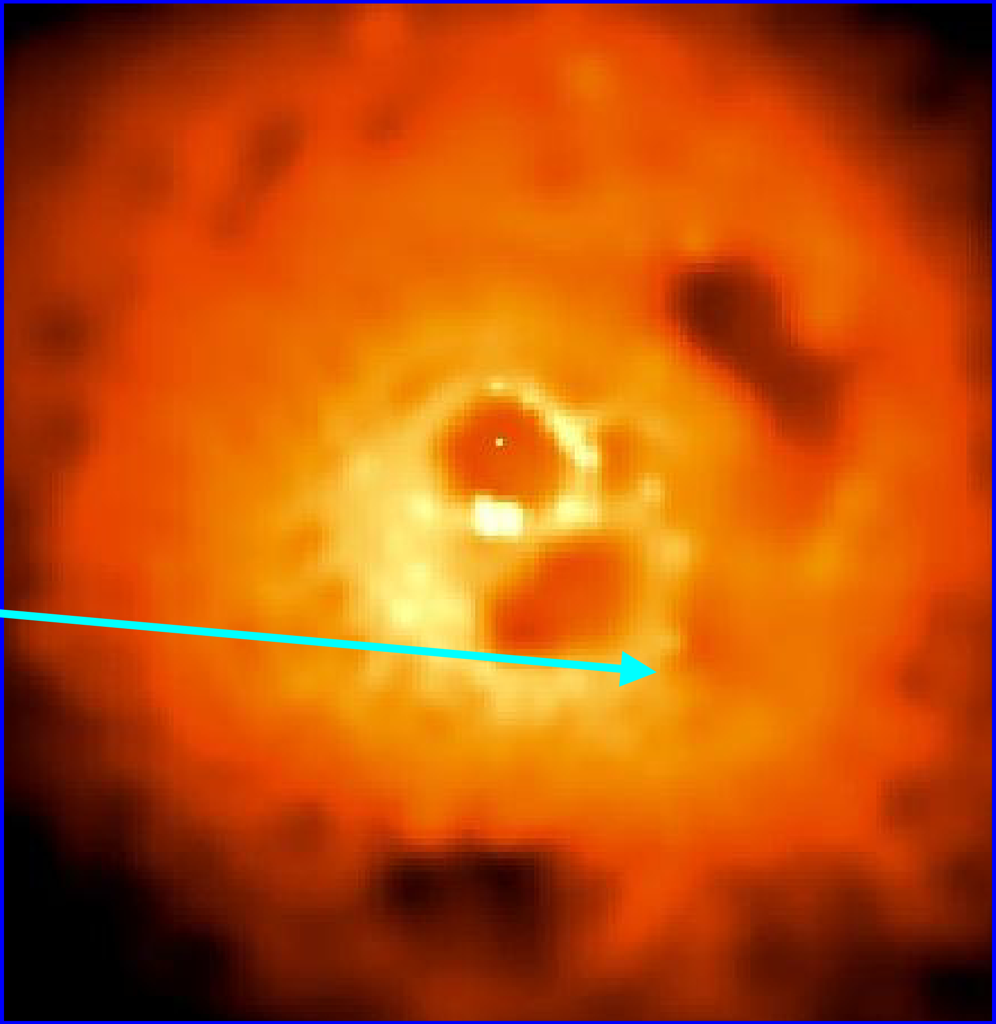
Radio emitting plasma fills holes



Chandra image + radio

3C 84 and Perseus Cluster

Fabian et al. 2000

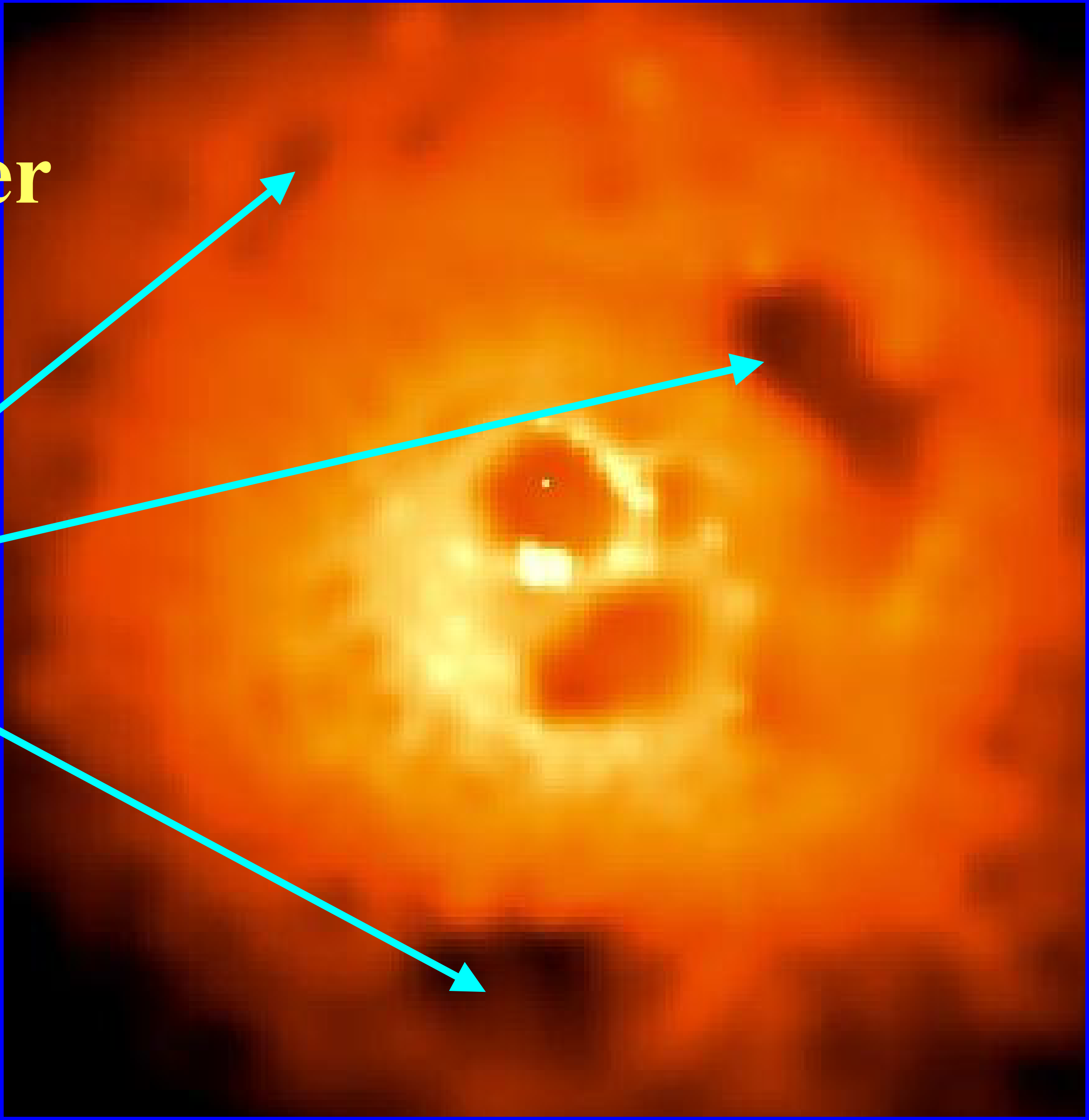


Cold rims, not strong shocks

Chandra image

3C 84 and Perseus Cluster

Fabian et al. 2000

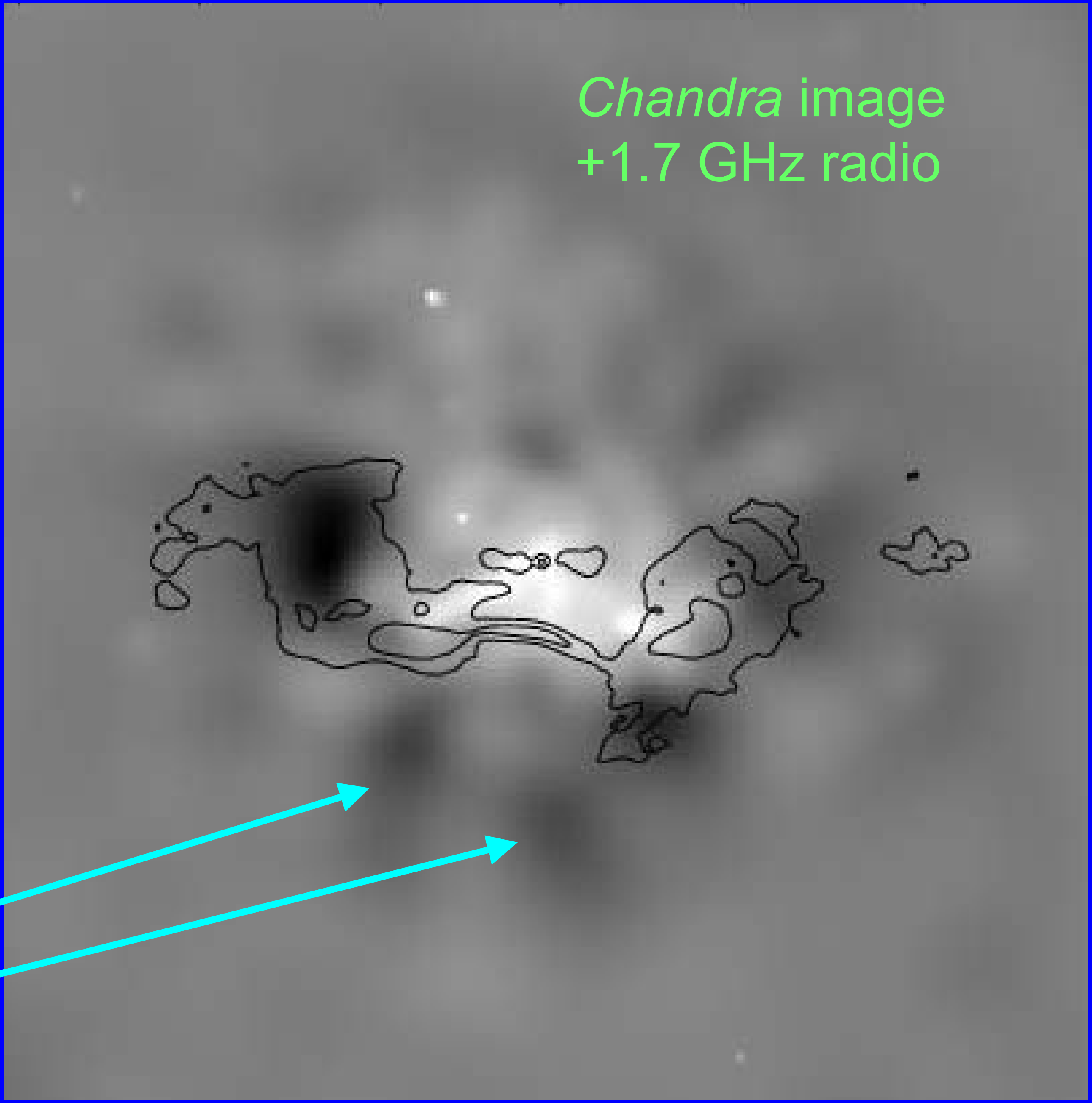


Note multiple "fossil" bubbles, not aligned with current radio jets

Chandra image

3C 338 and Abell 2199

Johnstone et al. 2002



More "fossil" bubbles

- Cluster gas heated by pockets of very buoyant (relativistic?) gas rising subsonically through ICM pressure gradient
  - Expanding bubbles do *pdV* work
- Dependent on two conditions:
  - Buoyant fluid does not mix (much) with cluster gas persistent X-ray “holes”
  - Acoustic & potential energy is converted to heat by damping and/or mixing

WE CALL THIS “EFFERVESCENT HEATING”

EFFERVESCENT HEATING: 1D MODEL

- "Bubbles" rise on ~ free-fall time $<< t_{cool}$
- Assume
  - <u>Number flux</u> of CR conserved
  - <u>Energy flux</u> decreases due to adiabatic losses

→ Size, filling factor, rise speed of bubbles cancels out

  - Dissipation converts motion to heat ~locally
- Power available for heating out to radius r (in steady state):

$$\dot{E} \propto p_{CR}(r)^{(\gamma-1)/\gamma} \propto p_{CR}{}^{1/4} \text{ for } \gamma = 4/3$$

STEADY HEATING MODEL

TARGETS PRESSURE GRADIENT → STABILIZES COOLING

- **Volume heating rate:**

$$\square \sim -\nabla \cdot \frac{\dot{E}_{CR}}{4\pi r^2} \propto \frac{p^{1/4}}{r^3} \frac{d \ln p}{d \ln r}$$

- **Compare to cooling rate:**

$$\square = n^2 \Lambda(T) \propto \rho^2 T^{\alpha}$$

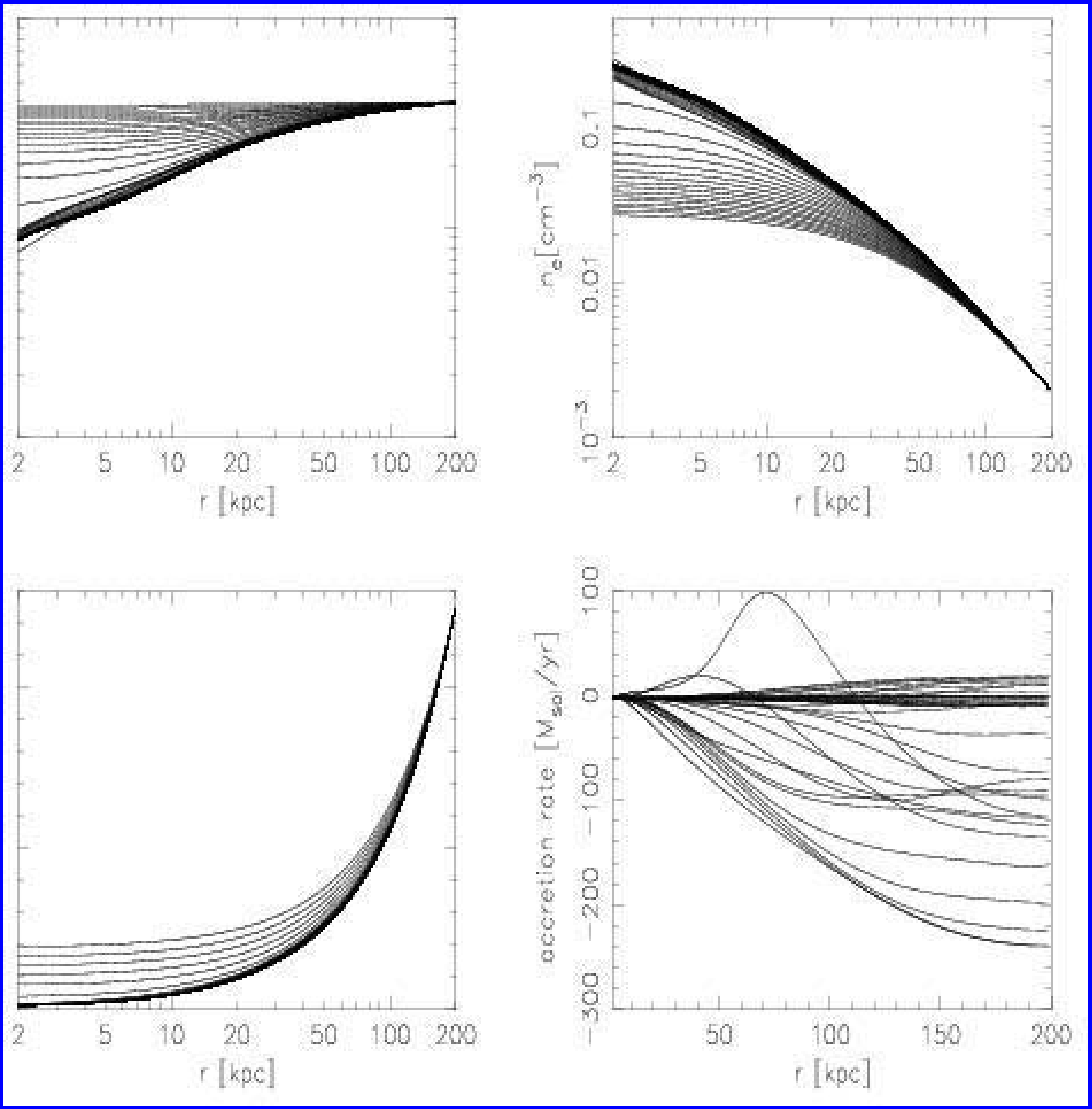
1D ZEUS SIMULATIONS

Ruszkowski & Begelman 2002

Includes:

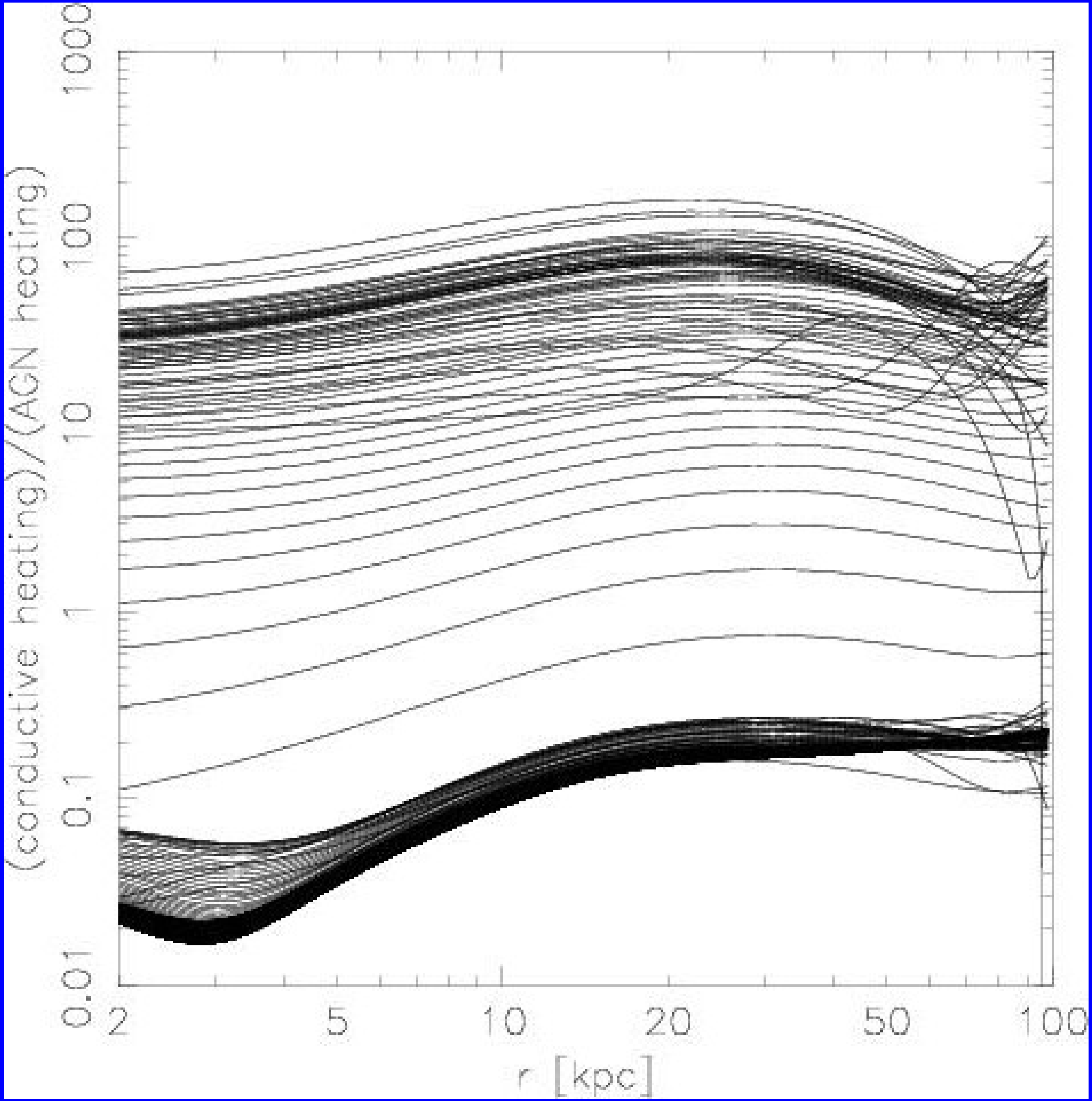
Conductivity @ Spitzer/4

Simple $\dot{M}$ feedback in center



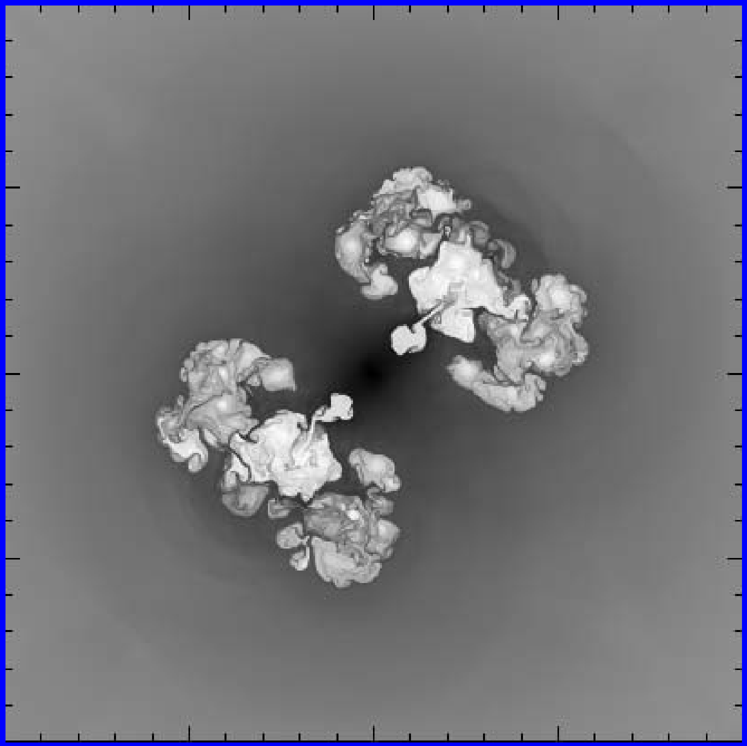
Ruszkowski & Begelman 2002

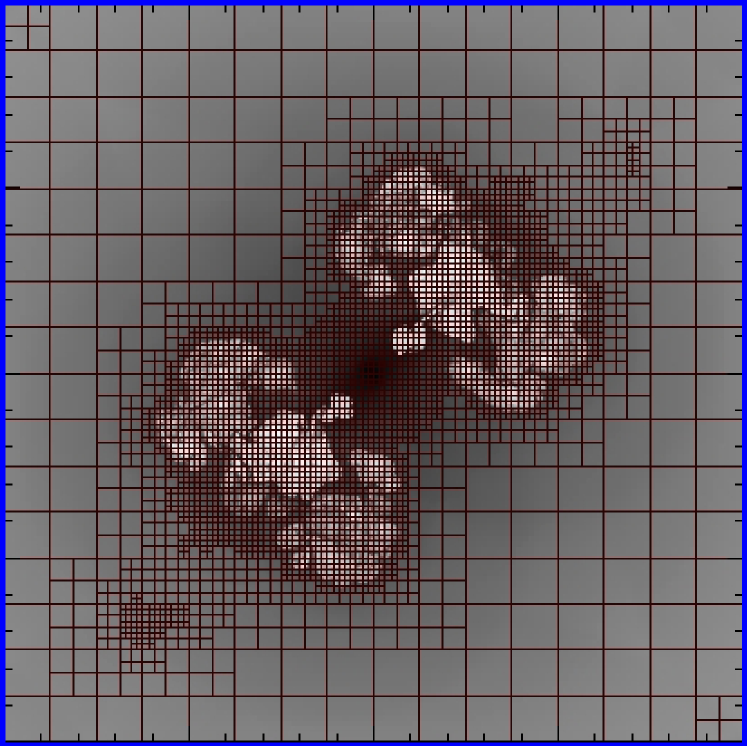
AGN, not conduction, dominates heating



SIMULATIONS:

- **Crucial to model mixing and weak shocks accurately**
  - **PPM code with Adaptive Mesh Refinement, e.g., FLASH, better than lower-order, diffusive code, e.g., ZEUS**



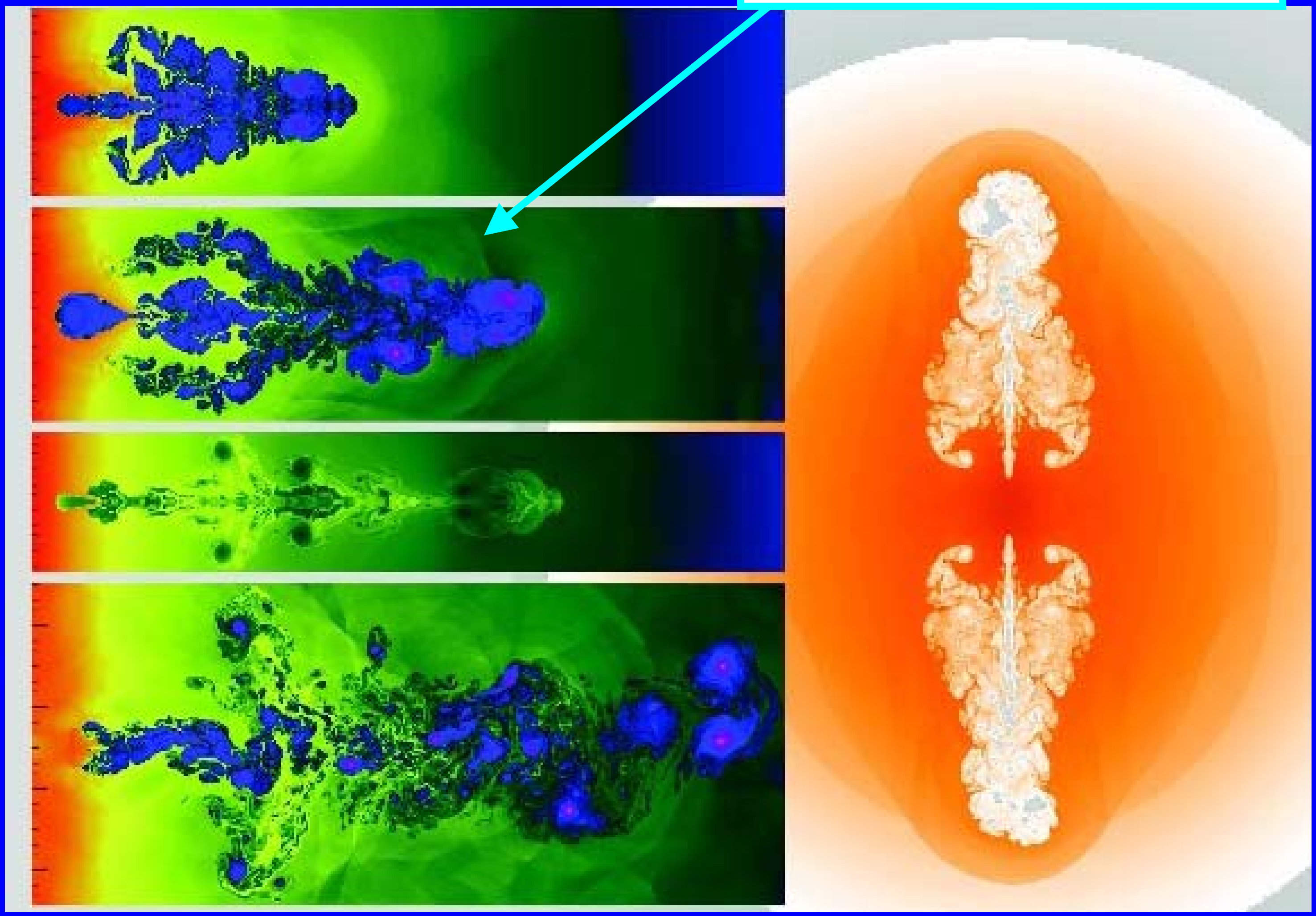


FLASH 2D, 8 levels of mesh refinement

2D FLASH SIMULATIONS

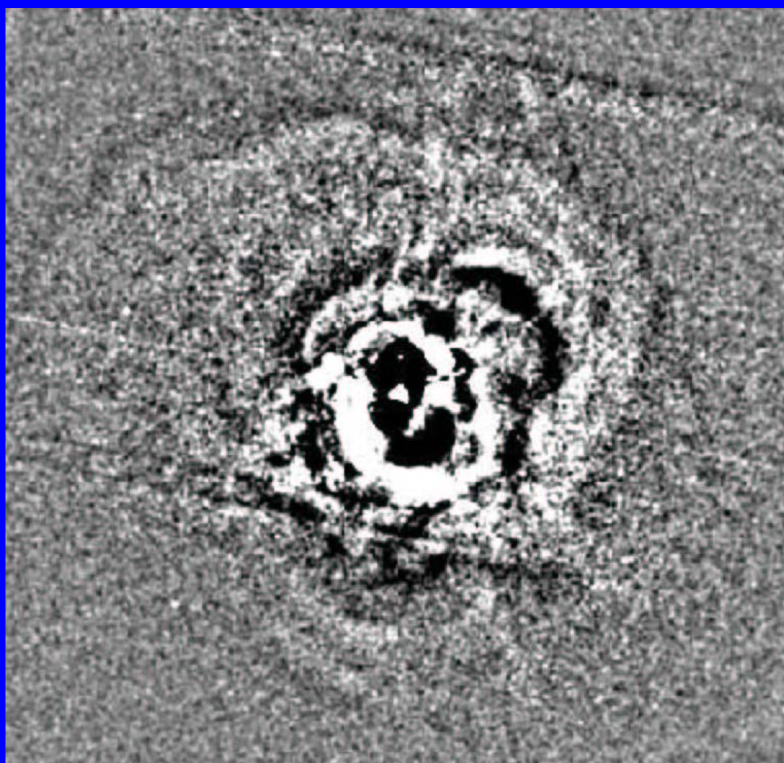
Brüggen & Kaiser, *Nature*, 2002

Note acoustic waves generated by bubble expansion



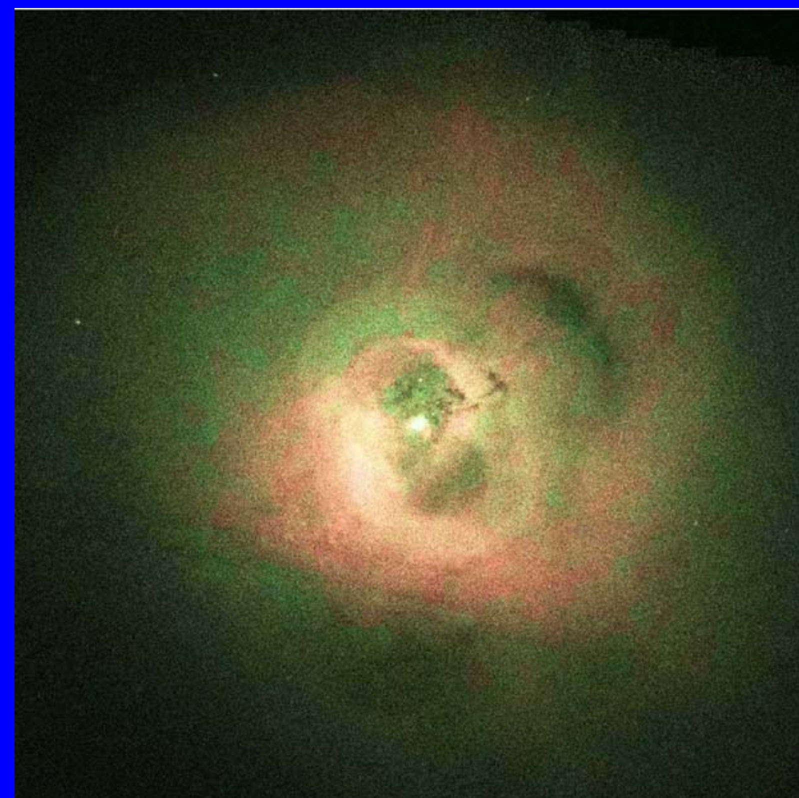
Ripples in the Perseus Cluster

Unsharp masked Chandra image



X-ray temperatures

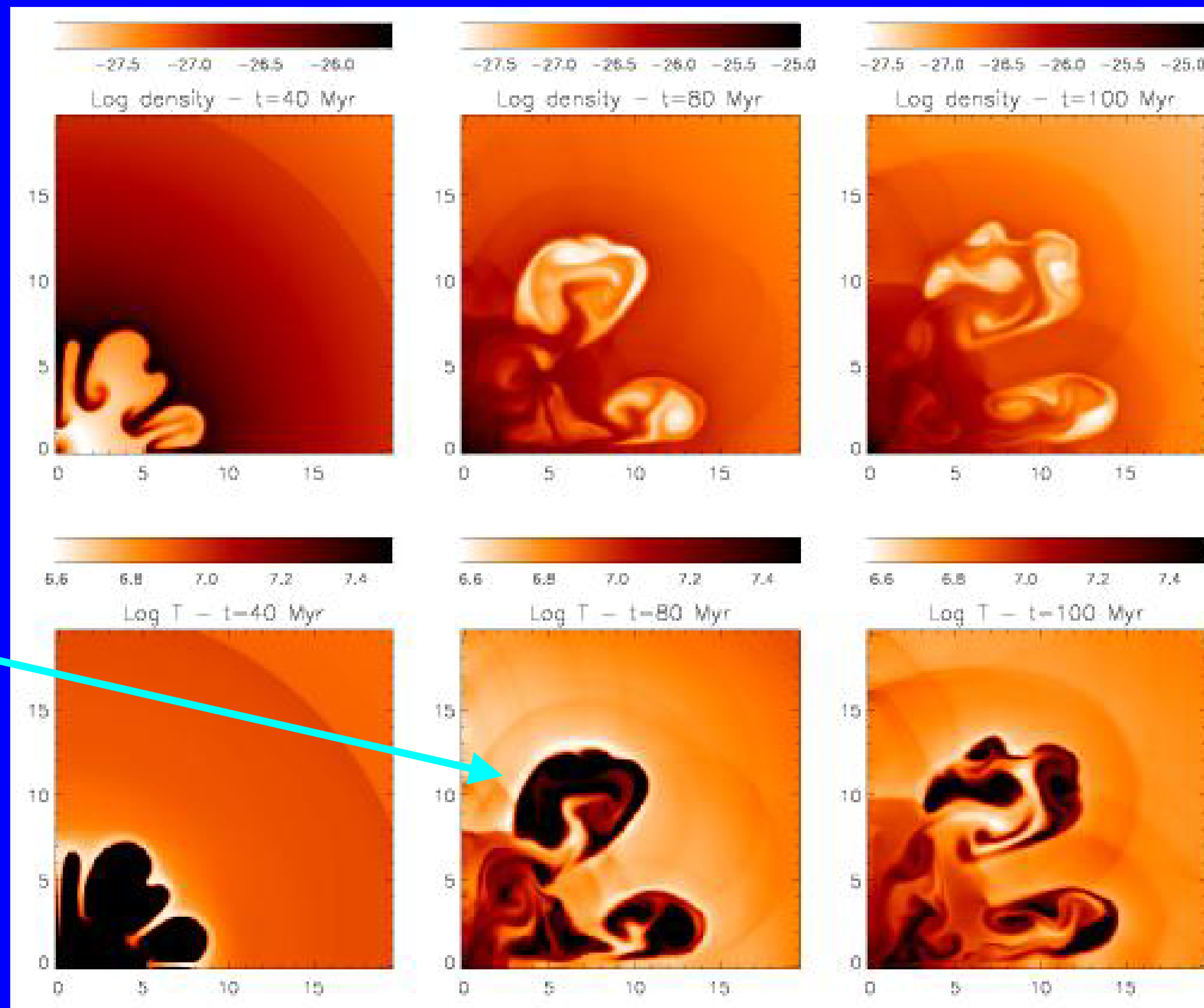
131 kpc



Fabian et al. 2003

ENTRAINMENT in 2D

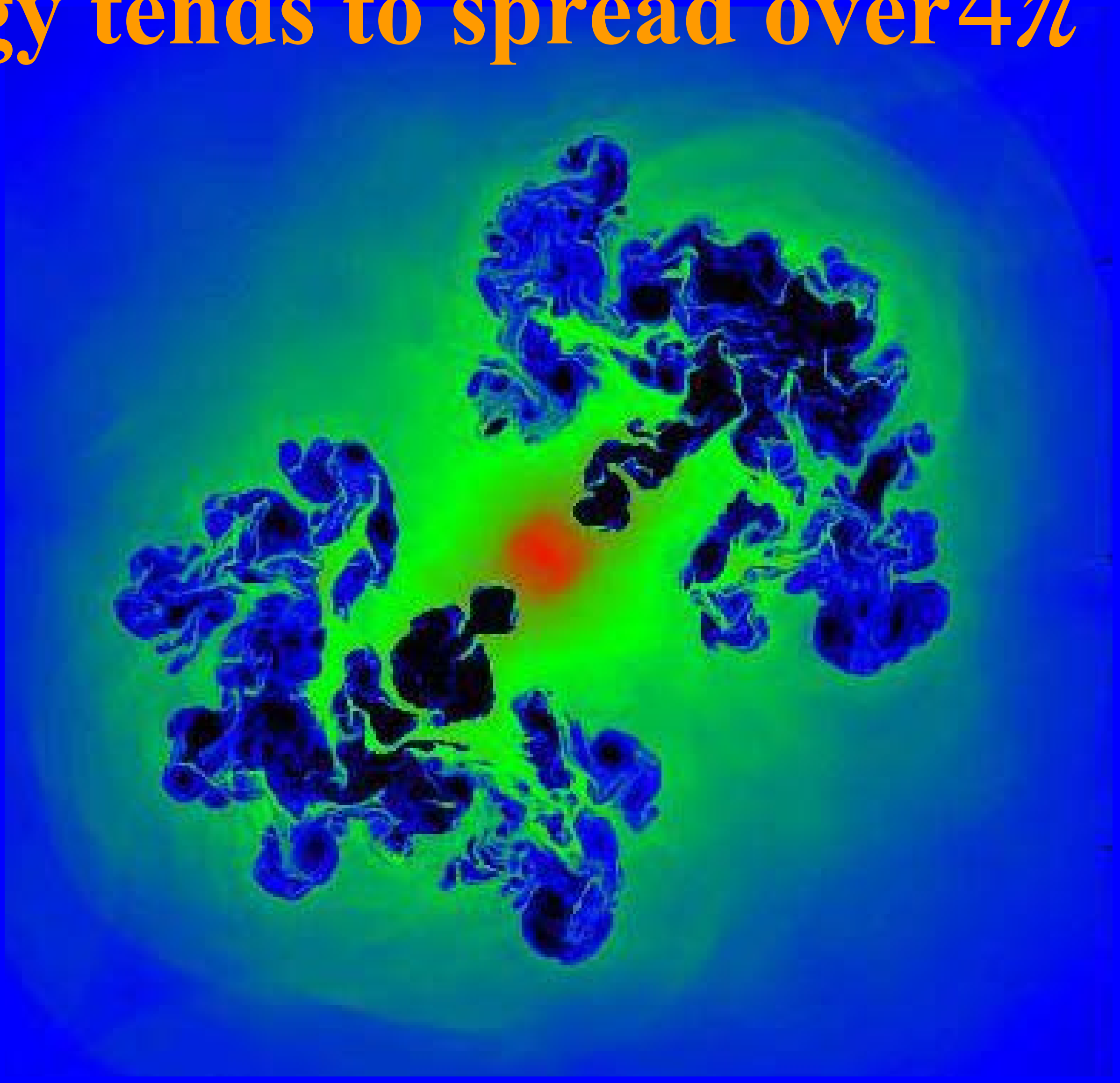
Brighenti & Mathews 2002



Cool rims from adiabatic expansion of lower entropy gas

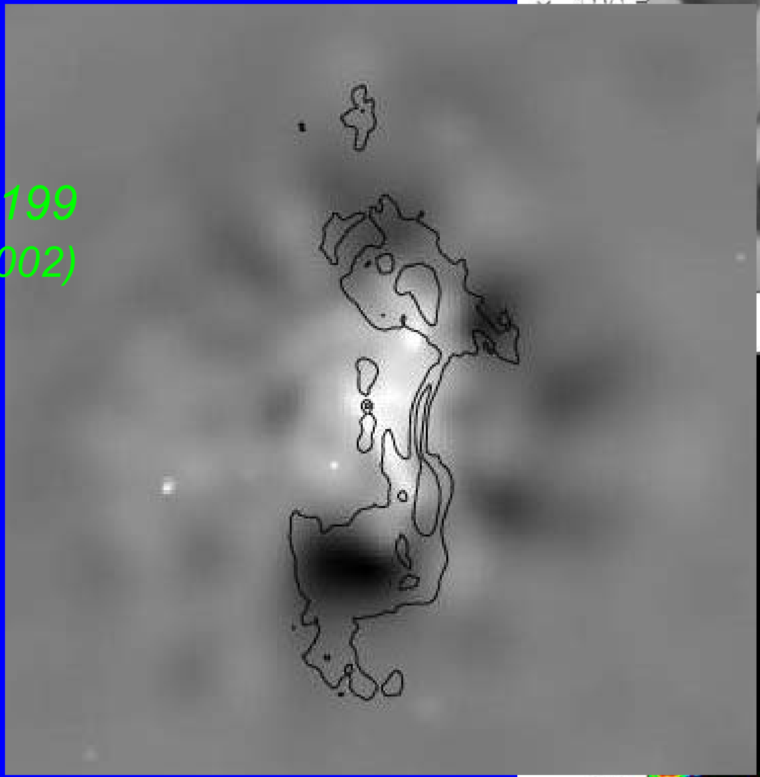
“Mushroom cloud” effect:

Energy tends to spread over 4π sr

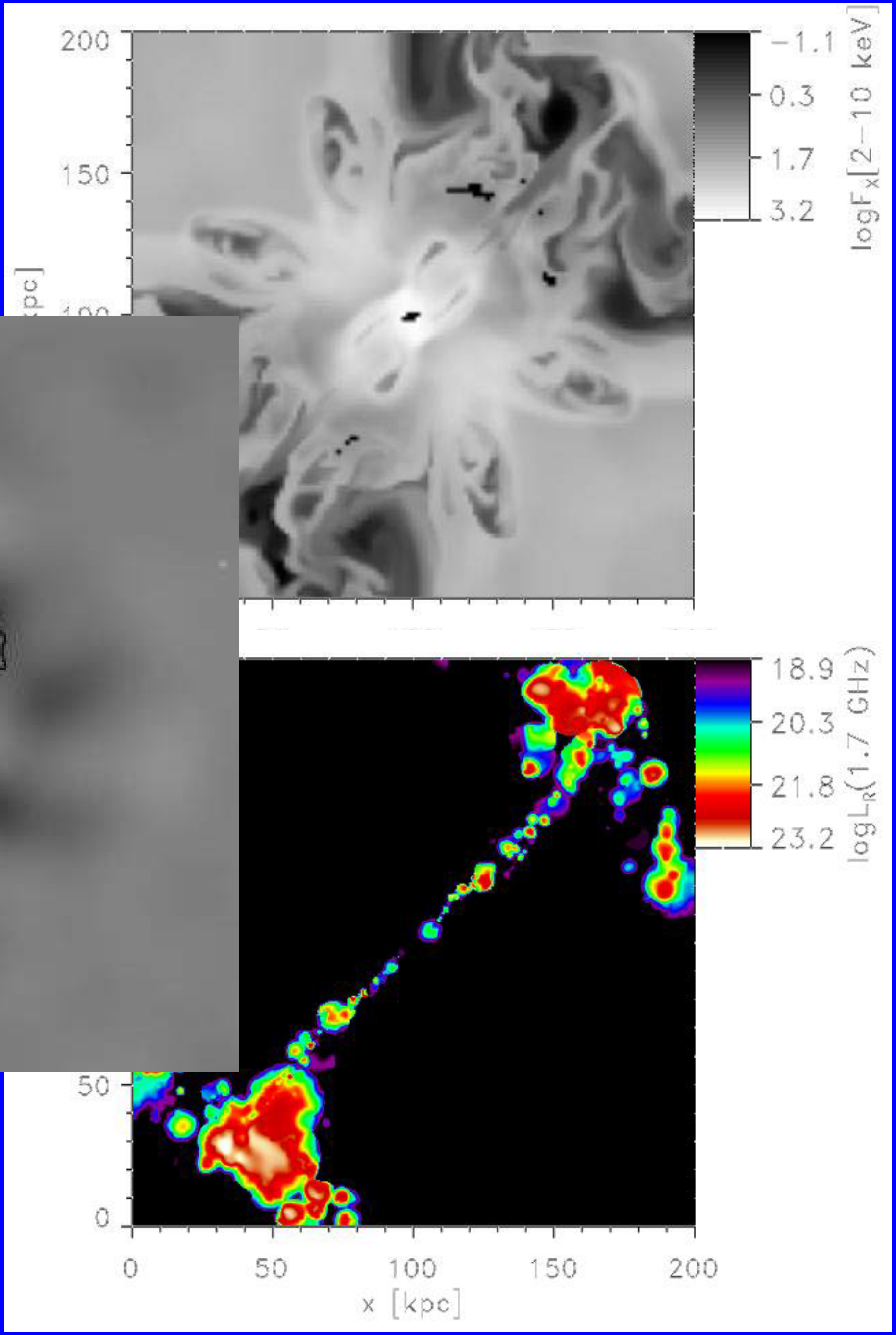


Radio: Higher contrasts, detectable only close to jet axis

X-rays: spread out laterally



3C 338 + Abell 2199
(Johnstone et al. 2002)



“Ghost cavities” do not trace previous jet axis

IS ANY OF THIS RELEVANT FOR FEEDBACK IN PROTOGALAXIES?

Different settings…

CLUSTERS

- $z \sim 1$
- $10^{15} M_{Sun}$ **CDM halo**
- $t_{cool} > t_{dyn}$

  $\Rightarrow$ **hydrostatic**
- **Smooth**
- **Conduction important?**
- **Intermittent or low BH power**

PROTOGALAXIES

- $z \sim 4$
- $10^{13} M_{Sun}$ **CDM halo**
- $t_{cool} < t_{dyn}$

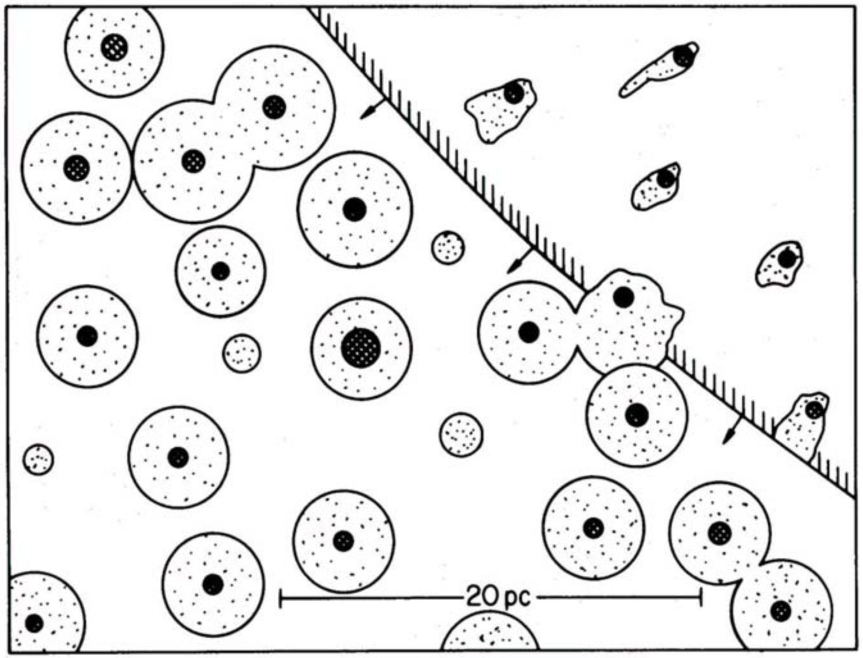
  $\Rightarrow$ **dynamical**
- **Clumpy**
- **Conduction unimportant?**
- **BH growing at close to Eddington rate**

Feedback depends on "porosity" of the infalling gas

McKee & Ostriker 77 (ISM theory)

Outflow only interacts with diffuse medium $(t_{cool} \sim t_{dyn})$

→ blasts out supersonically but has little effect on most of the mass



A CLOSE UP VIEW

More likely …. (?)

- Outflow must push aside the bulk of the mass → may be mildly supersonic or subsonic (depends on mean power/how close to Eddington + efficiency of outflow)

Influence would be spread more evenly over larger region – more effect on final state of galaxy and/or final BH mass?

SUMMARY

- X-ray emitting cluster gas seems to be heated gently rather than violently by AGNs
- "Effervescent Heating" may be able to explain:
  - quenching of cooling flows
  - "entropy floor" leading to observed $L_X \propto T^3$ relation
- Can it also be relevant to feedback in protogalaxies? It depends…
  - Geometric factors
    - Clumpiness of protogalactic gas
    - Early disk formation
    - Collimation of outflow
  - What fraction of accretion power emerges in an outflow?
  - One burst of ~Eddington accretion or intermittent lower level activity?

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