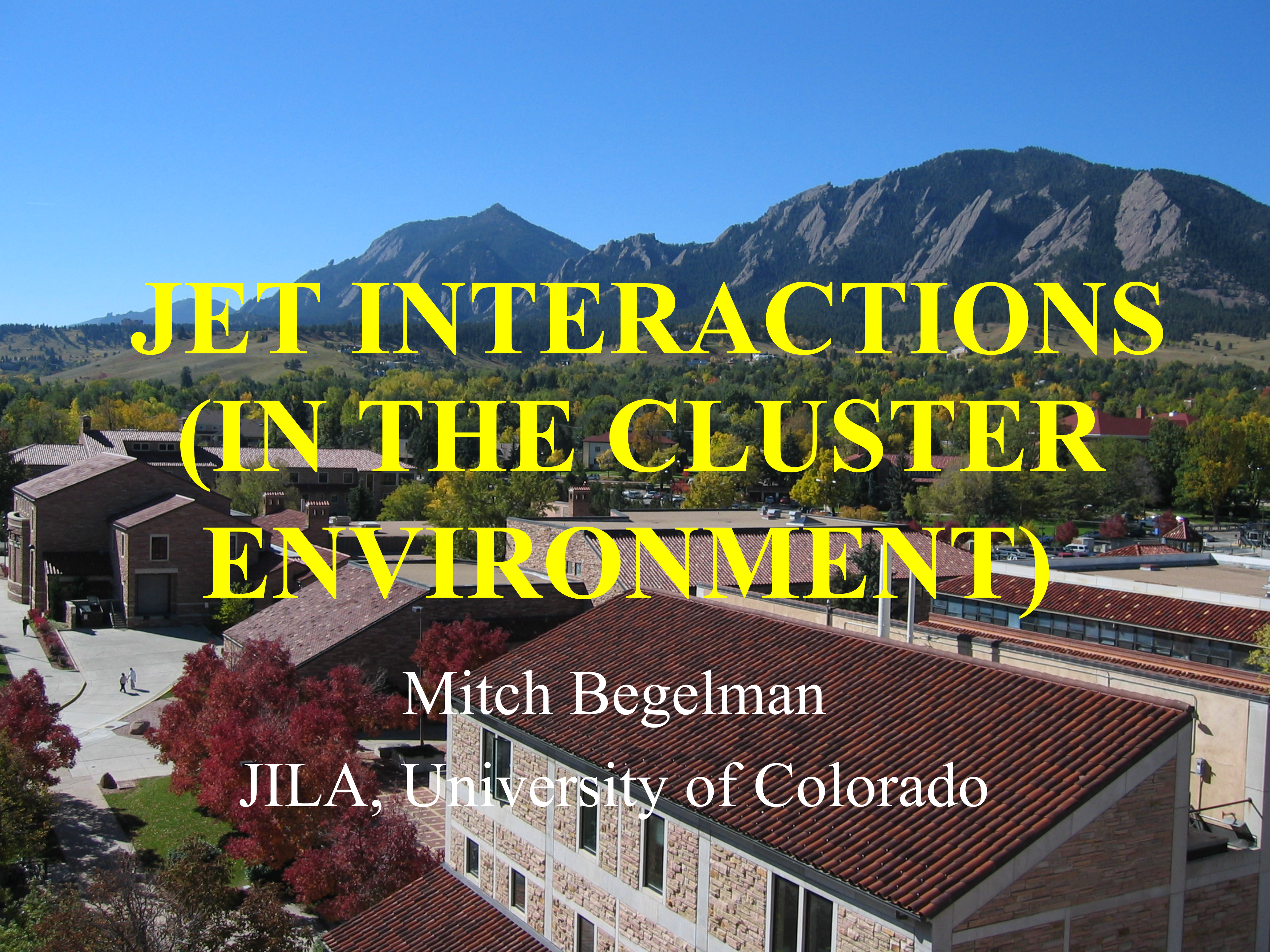


JET INTERACTIONS (IN THE CLUSTER ENVIRONMENT)

Mitch Begelman

JILA, University of Colorado

COLLABORATORS:

- **Mateusz Ruszkowski (JILA/MPA)**
- Davide Lazzati (JILA)
- Brian Morsony (JILA)
- Marcus Brüggen (IU Bremen)
- Eric Hallman (CASA, U. Colo.)
- Biman Nath (Raman Inst., Bangalore)
- Suparna Roychowdhury (Raman Inst., Bangalore)

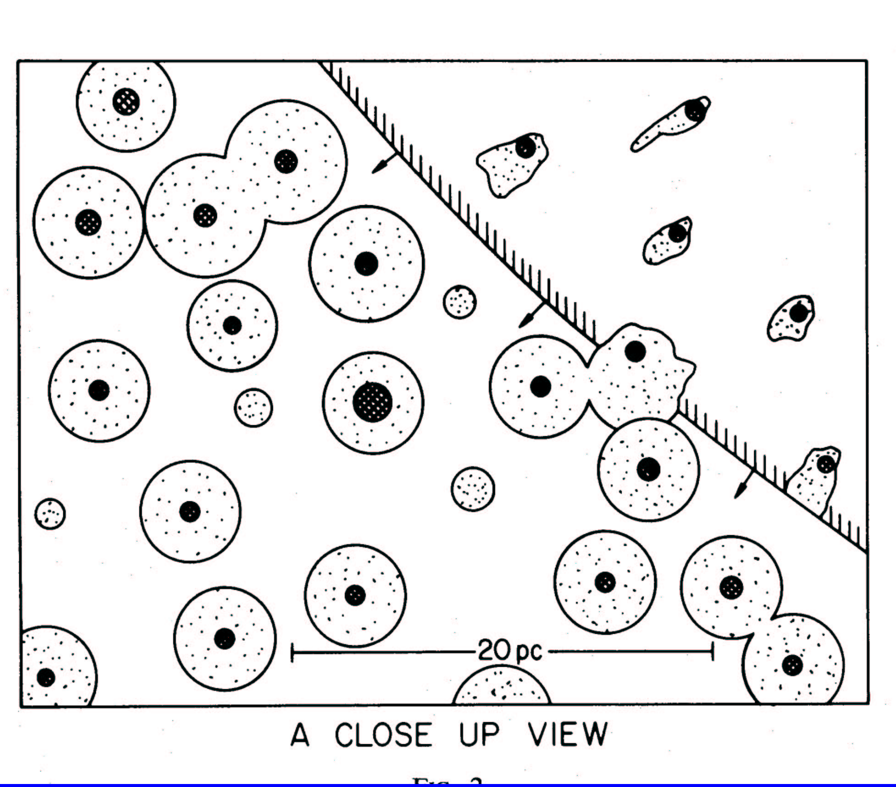
Jets inject kinetic energy into their surroundings, but…

…energy use depends on…

- **Rate of deposition**
  - power $\langle L \rangle$ vs. total output $\varepsilon_{KE} M c^2$
  - intermittency?
- **Importance of cooling**
- **Uniformity of gas**
  - Clumpy: energy "goes around" the clumps
  - Gas in a disk may be immune
- **Directionality of outflow**
  - Collimated jet vs. broad disk wind

Why is “porosity” important?

McKee & Ostriker 77 (ISM theory)



Outflow only interacts with diffuse medium

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

Directionality: analogous effect – how can a powerful jet source continue to accrete?

EVOLUTION – 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)

EVOLUTION – 3 STAGES:

- **MOMENTUM-DRIVEN**

$$v_{head} \sim \left(\frac{L}{\rho c}\right)^{1/2} \left(\frac{\Omega}{2\pi}\right)^{-1/2} R^{-1}$$

- **ENERGY-DRIVEN**

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

- **BUOYANCY-DRIVEN**

$$v_{bubble} \sim c_s$$

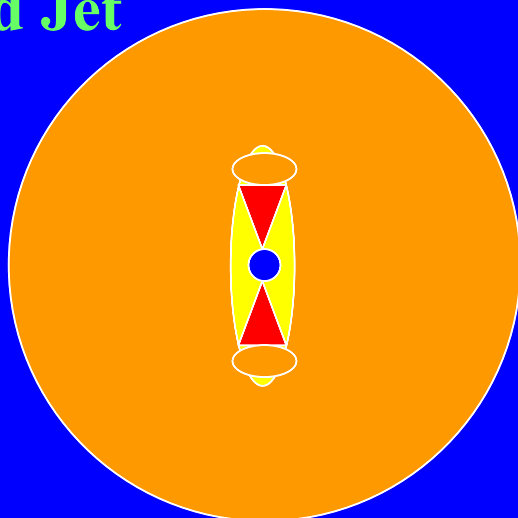
EVOLUTION – SCALING:

	$L\left(\frac{erg}{s}\right)$	$n(cm^{-3})$	$c_s\left(\frac{km}{s}\right)$	r_{blast} / t_{blast}	r_{bubble} / t_{bubble}
μQSO	10^{38}	1	10	$0.5\,pc / 100\,yr$	$2kpc / 10^8\,yr$
GRB	10^{50}	10^{24}	10^3	$0.1AU / 1hr$	$0.5\,AU / 1day$
RG	10^{44}	0.1	10^3	$2kpc / 1Myr$	$8kpc / 10Myr$

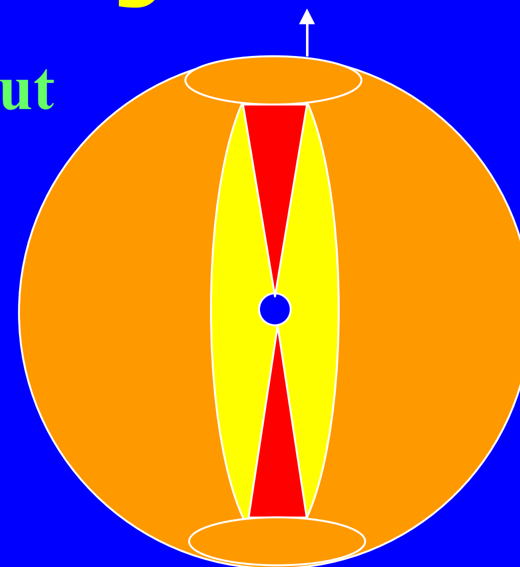
$$\left(\text{for } \frac{\Omega}{2\pi} = 0.01\right)$$

GRB collapsar jet

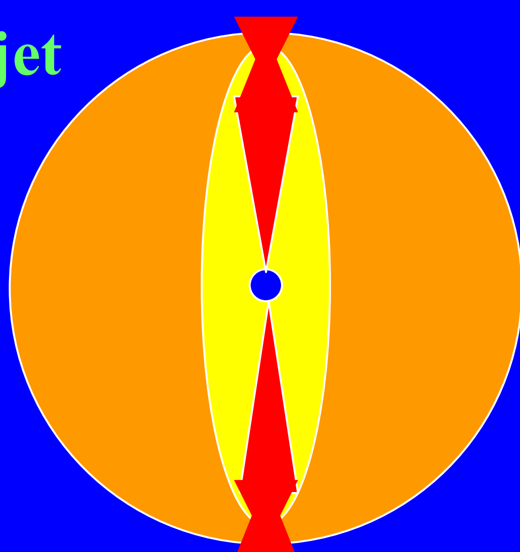
Confined Jet



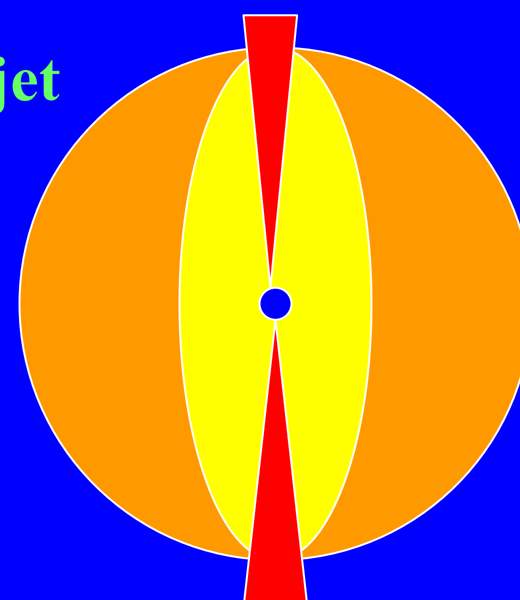
Shock breakout



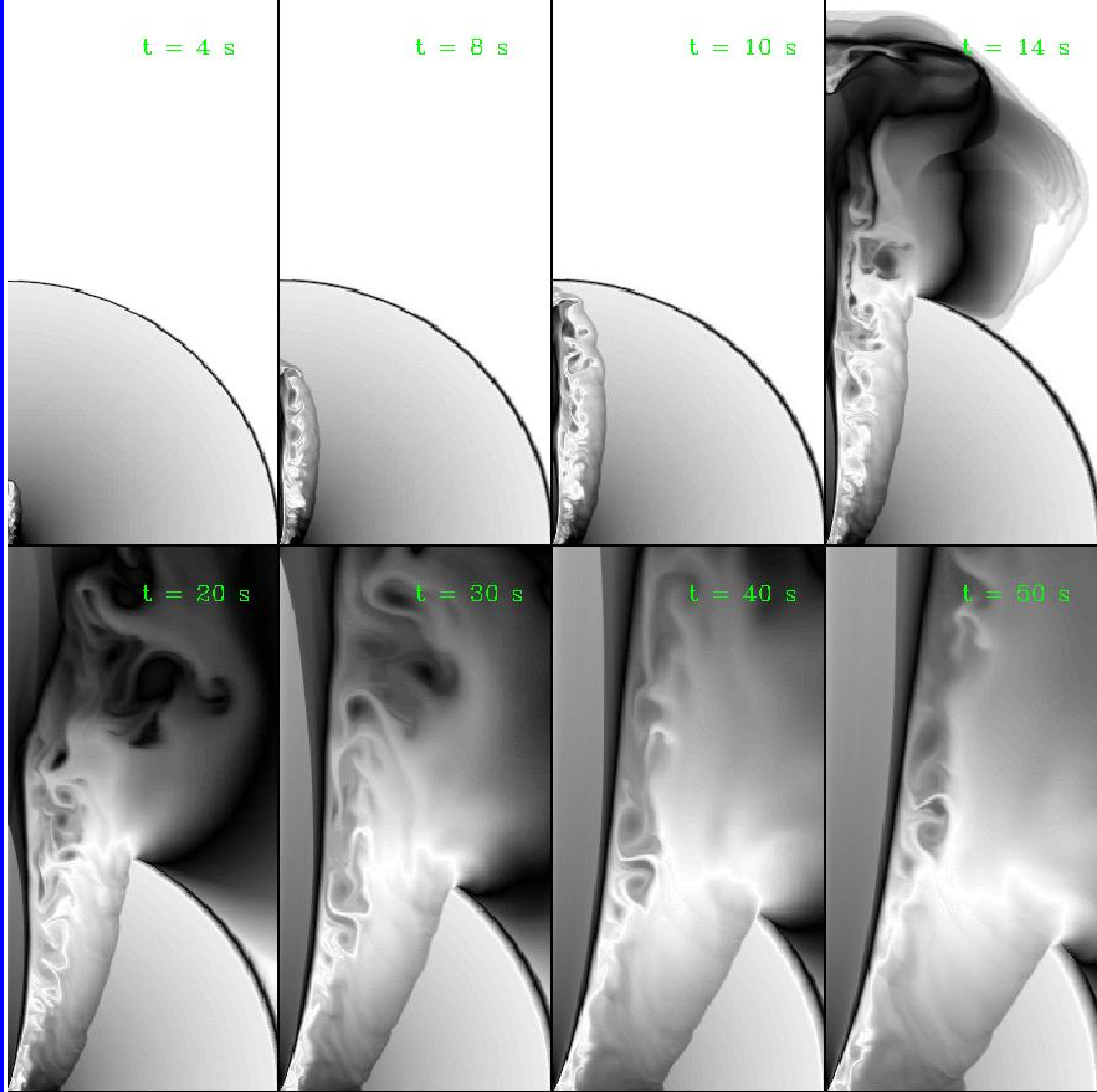
Shocked jet



Unshocked jet

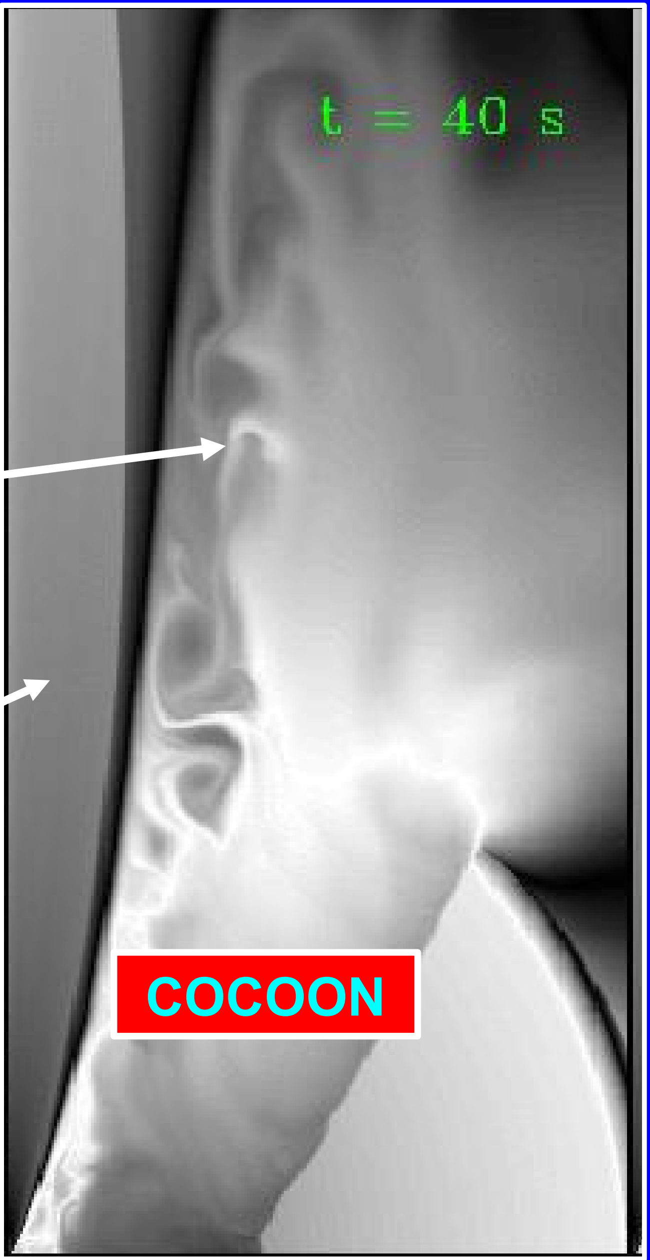


GRB JET LEAVES COLLAPSAR WHILE STILL IN MOMENTUM DOMINATED PHASE



SIMULATION:

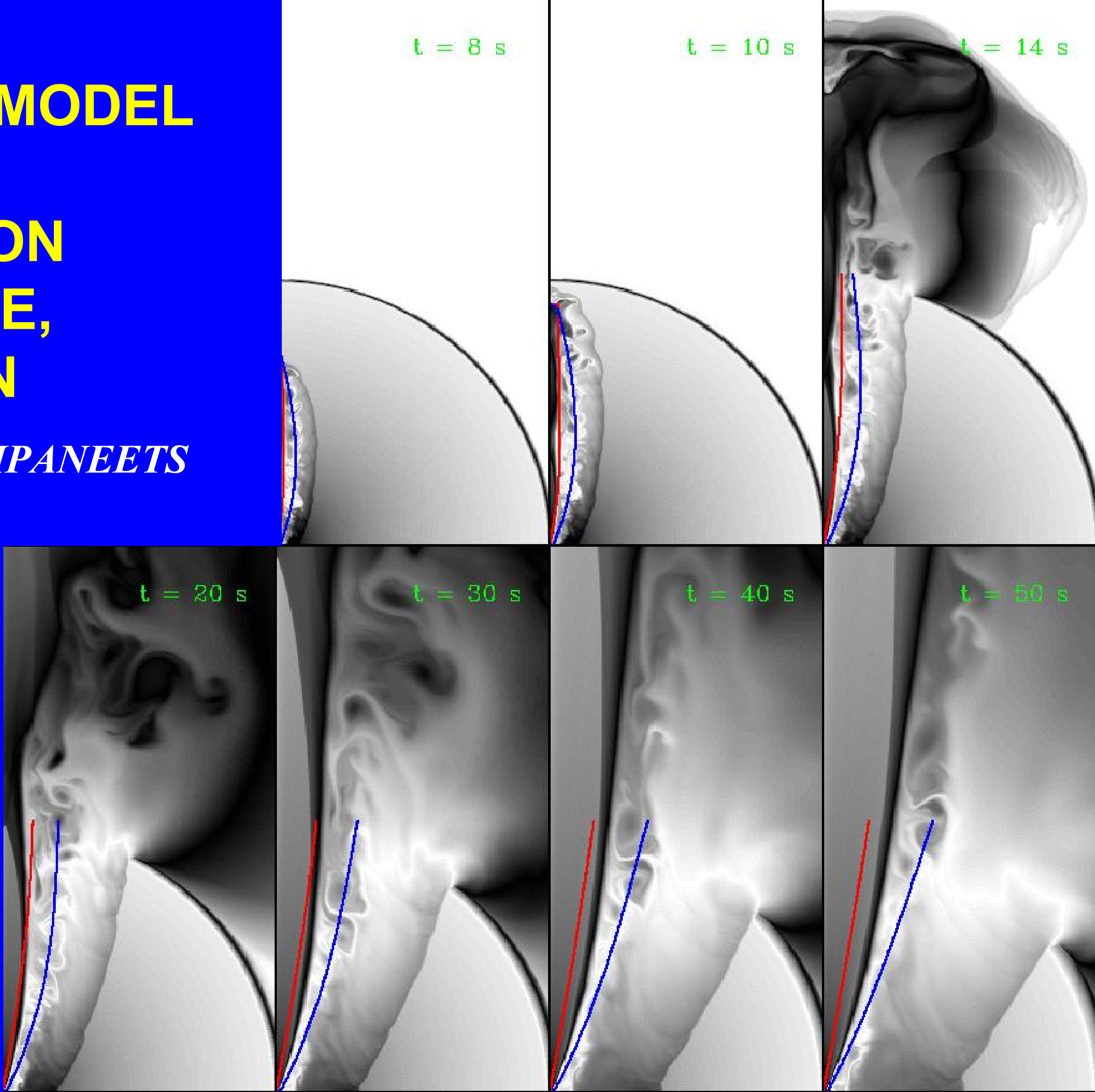
2D RELATIVISTIC FLASH CODE



Morsony, Lazzati & Begelman 2006, in prep.

ANALYTIC MODEL PREDICTS JET-COCOON STRUCTURE, EVOLUTION

BASED ON KOMPANEETS APPROX.

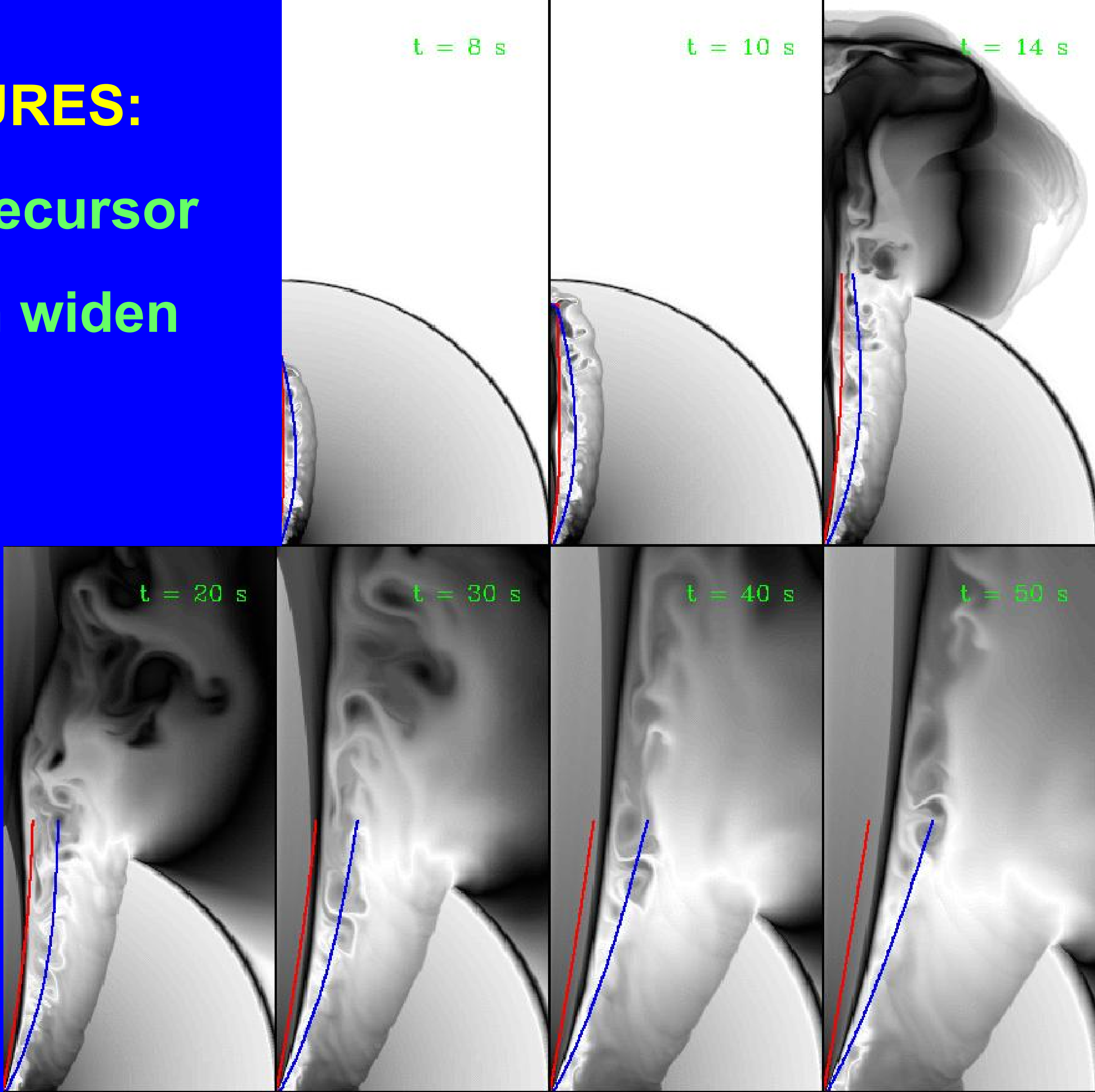


Morsony et al. 2006, in prep.

KEY FEATURES:

X-ray (?) precursor

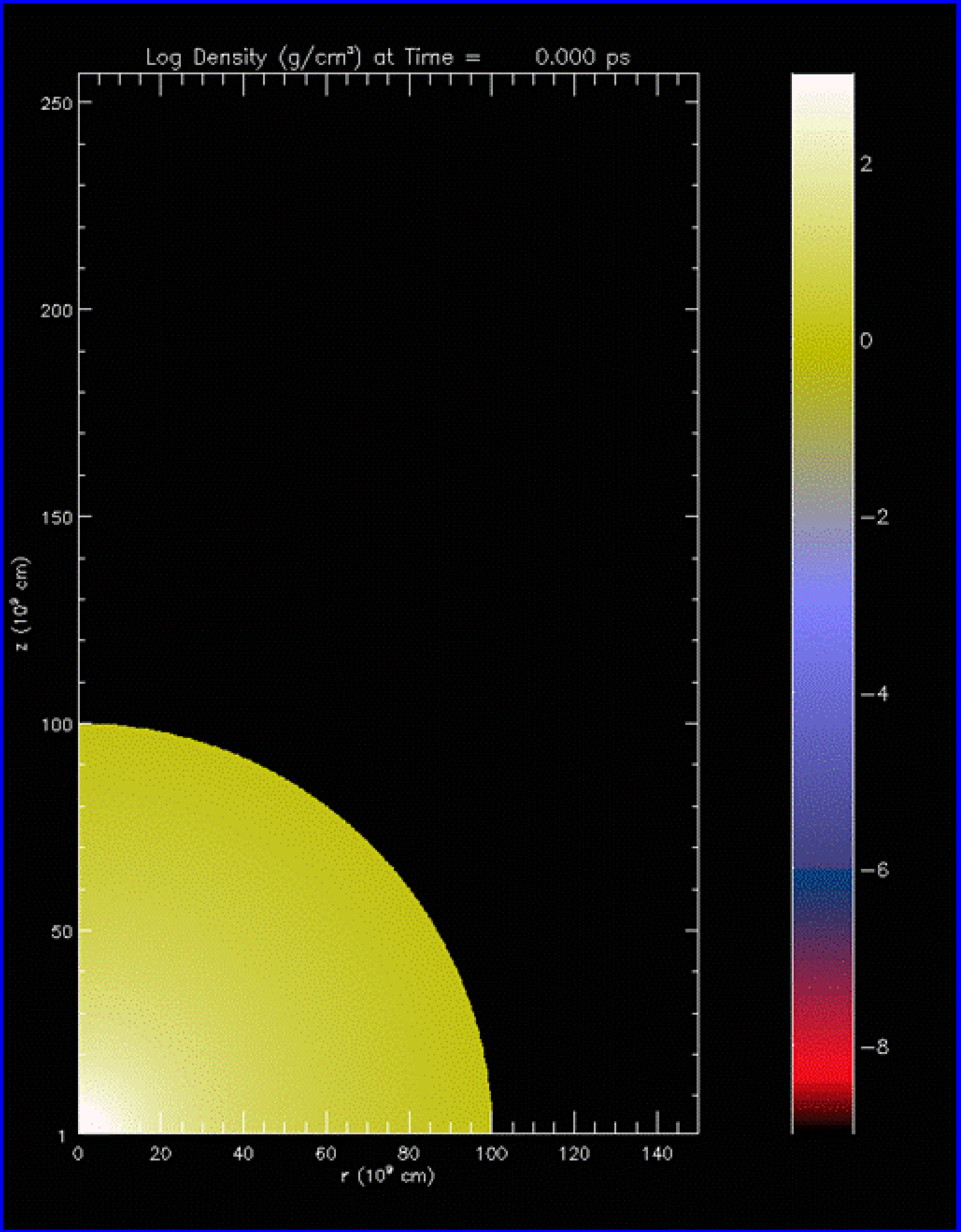
Jet, cocoon widen with time



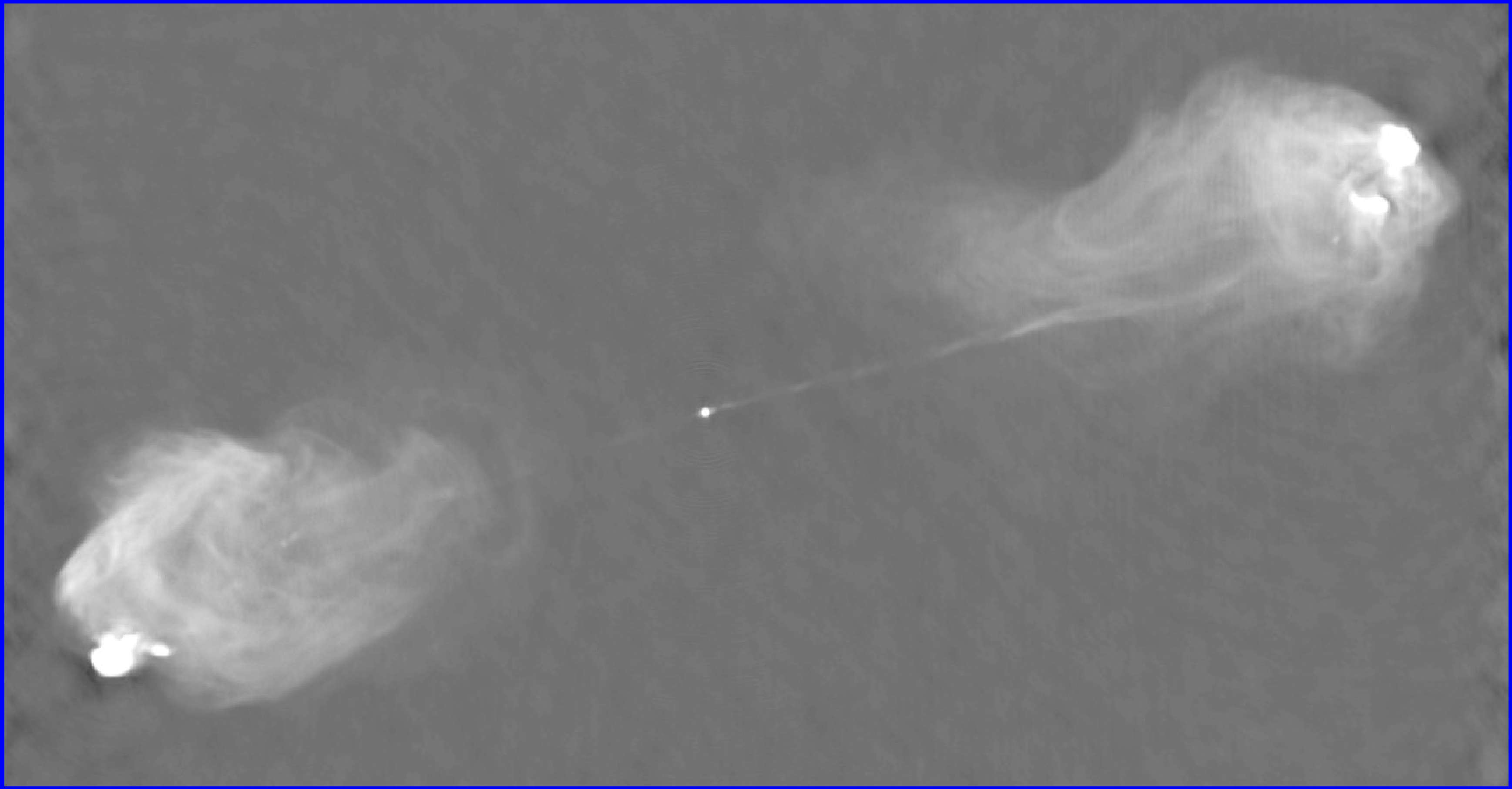
Morsony et al. 2006, in prep.

SIMULATION:
2D RELATIVISTIC FLASH CODE

Morsony, Lazzati & Begelman 2006, in prep.



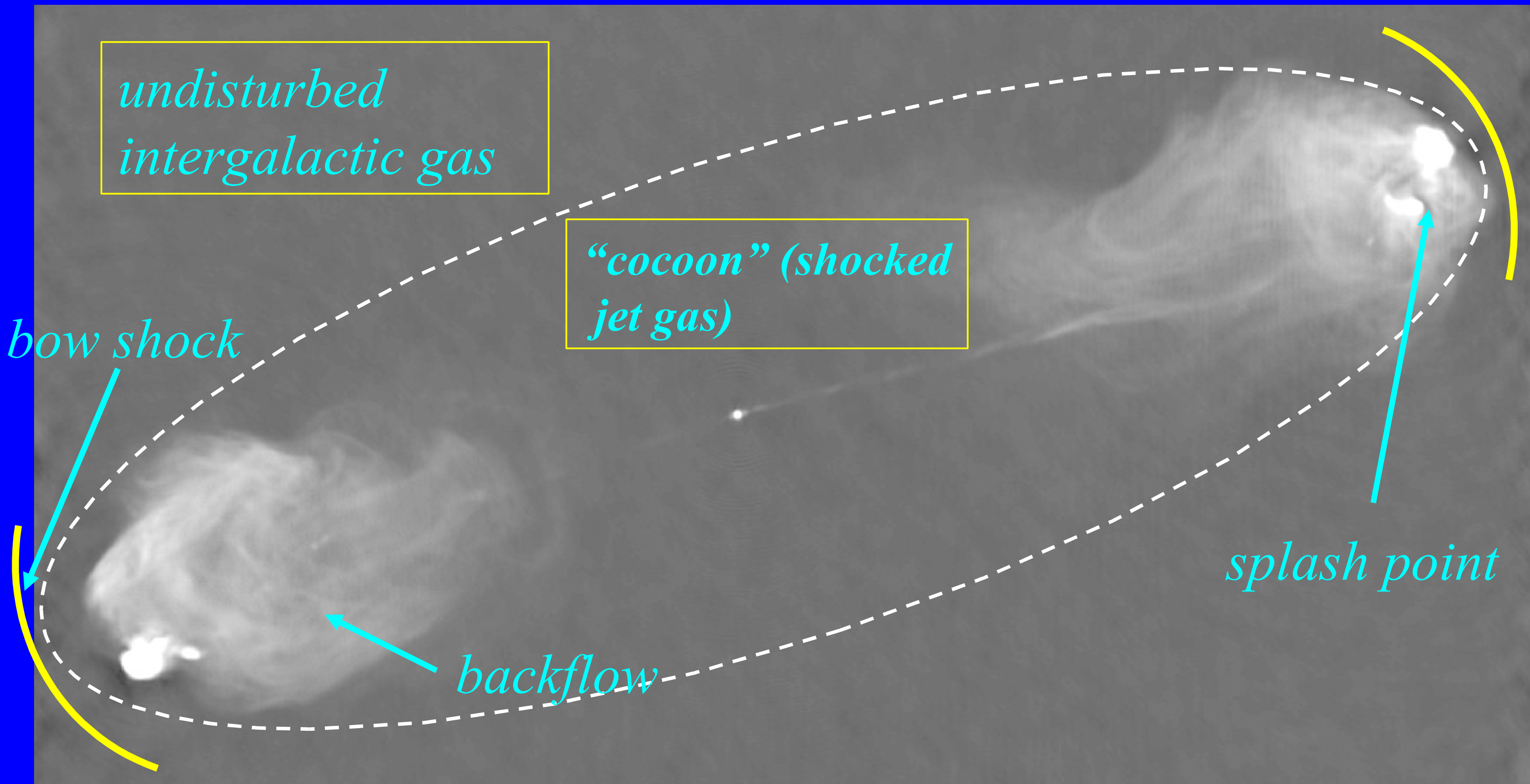
CYGNUS A in radio (VLA, 6cm)



Energy injection concentrated into “hotspots”

Elongated structure (momentum-dominated)

CYGNUS A – Exception rather than rule?

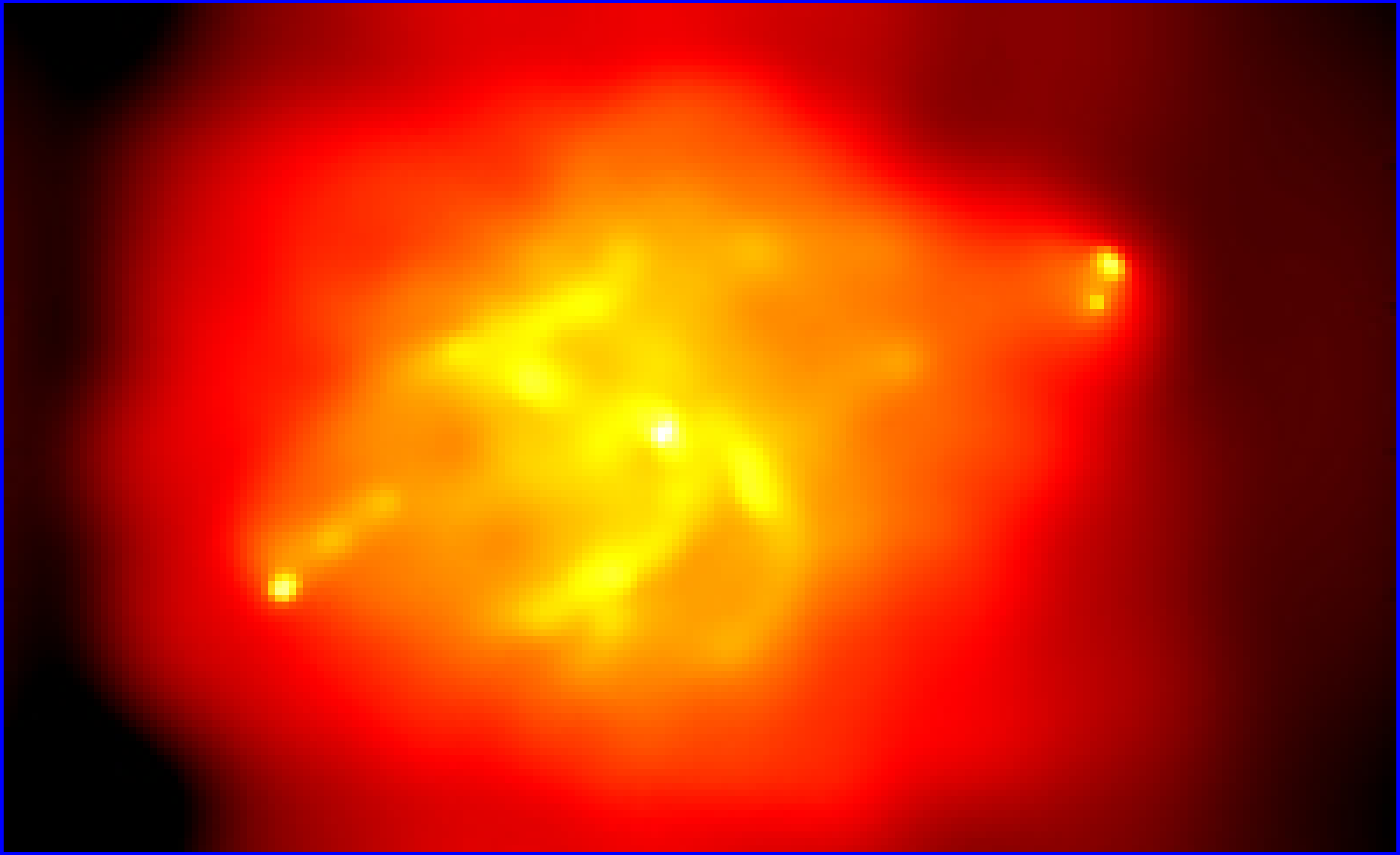


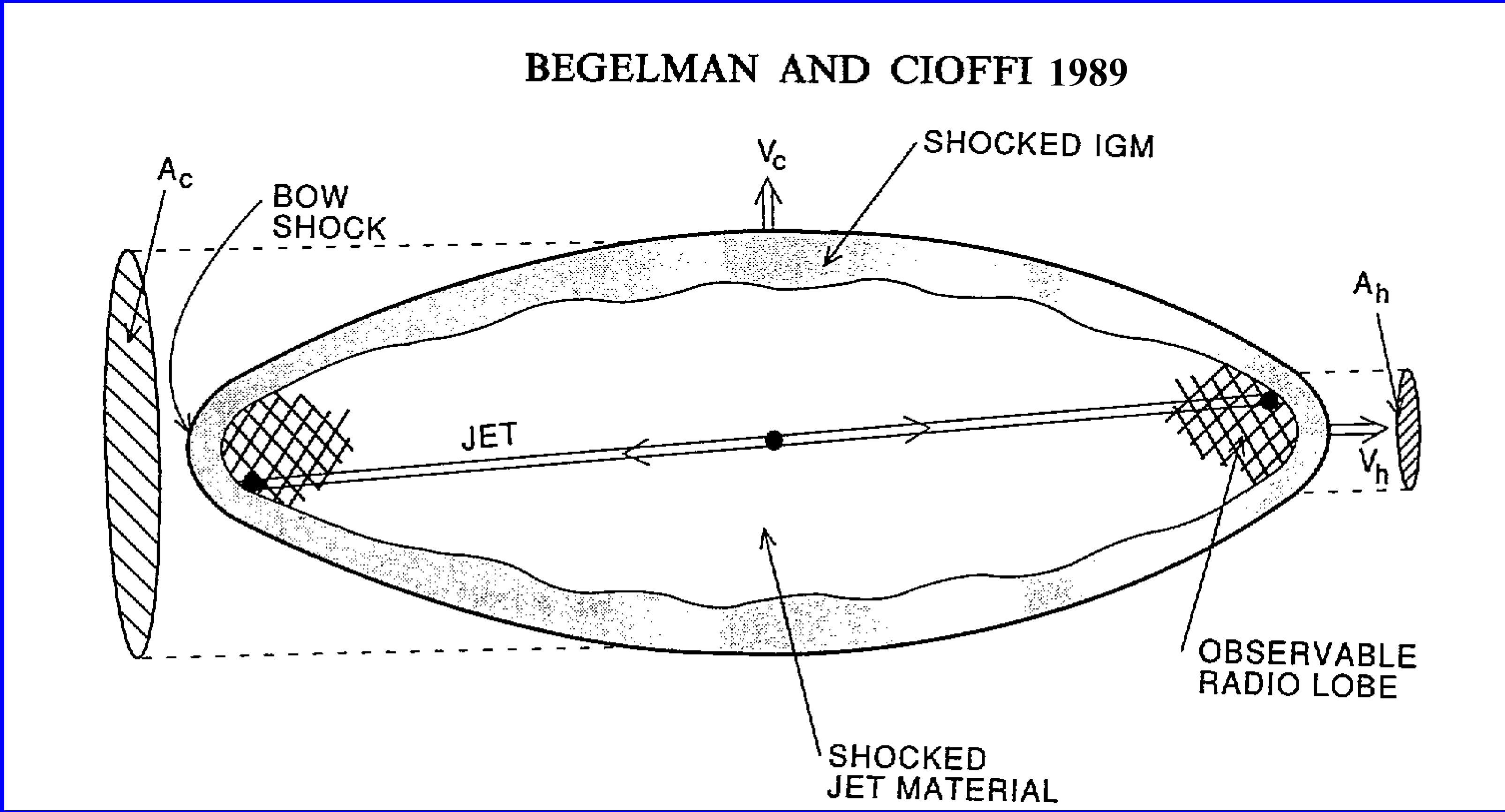
Very powerful source in relatively tenuous ICM

Most powerful RGs this age have: ~spherical cocoons

subsonic expansion

Cygnus A in X-rays (Chandra) – a round bubble





Scheuer (1982) "DENTIST'S DRILL" EFFECT: location of jet impact fluctuates → quicker transition to bubble/buoyancy phase

RADIO GALAXY EVOLUTION:

- MOMENTUM-DRIVEN
- ENERGY-DRIVEN

SUPERSONIC, OVERPRESSURED

- BUOYANCY-DRIVEN

SUBSONIC

LONGEST-LASTING PHASE

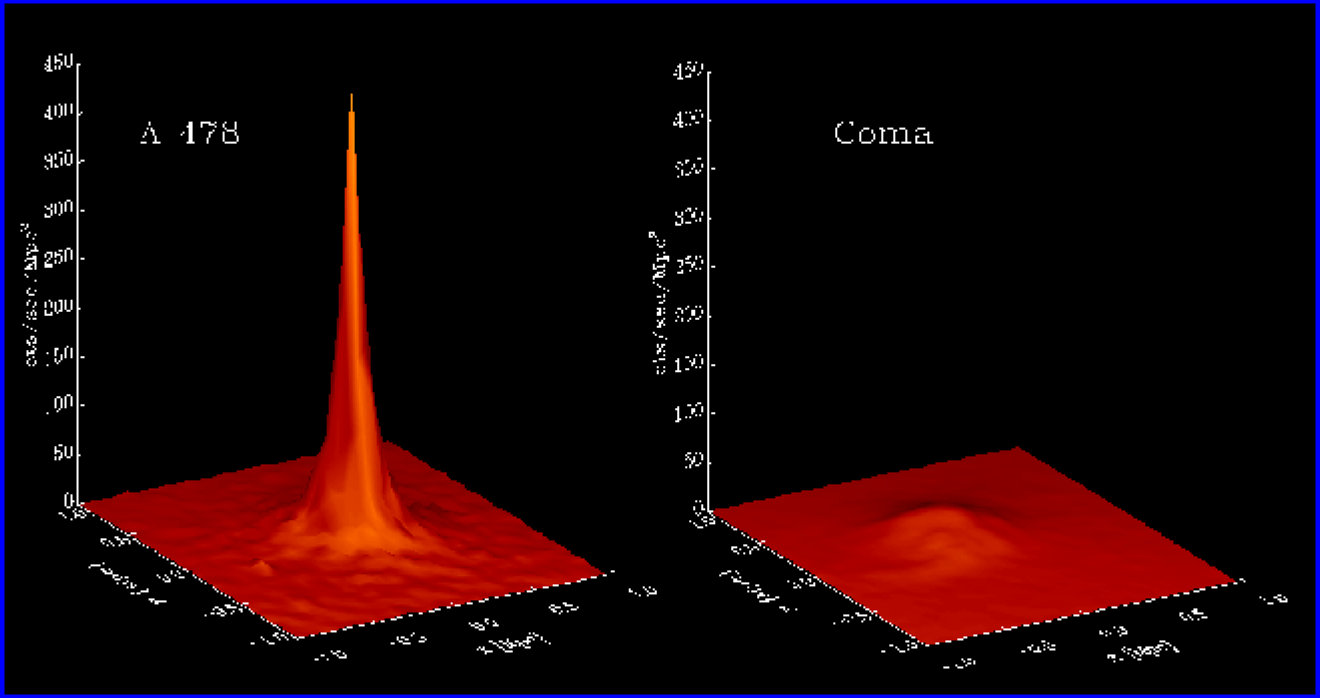
MOST ENERGY

EVIDENCE FOR GENTLE HEATING BY AGN JETS

- “COOLING FLOWS”
- CLUSTER/GROUP ENTROPY EXCESS

“COOLING FLOWS”

Cooling flow cluster   Non-cooling flow cluster



PREDICT: GAS COOLS IN LESS THAN HUBBLE TIME AND FLOWS IN

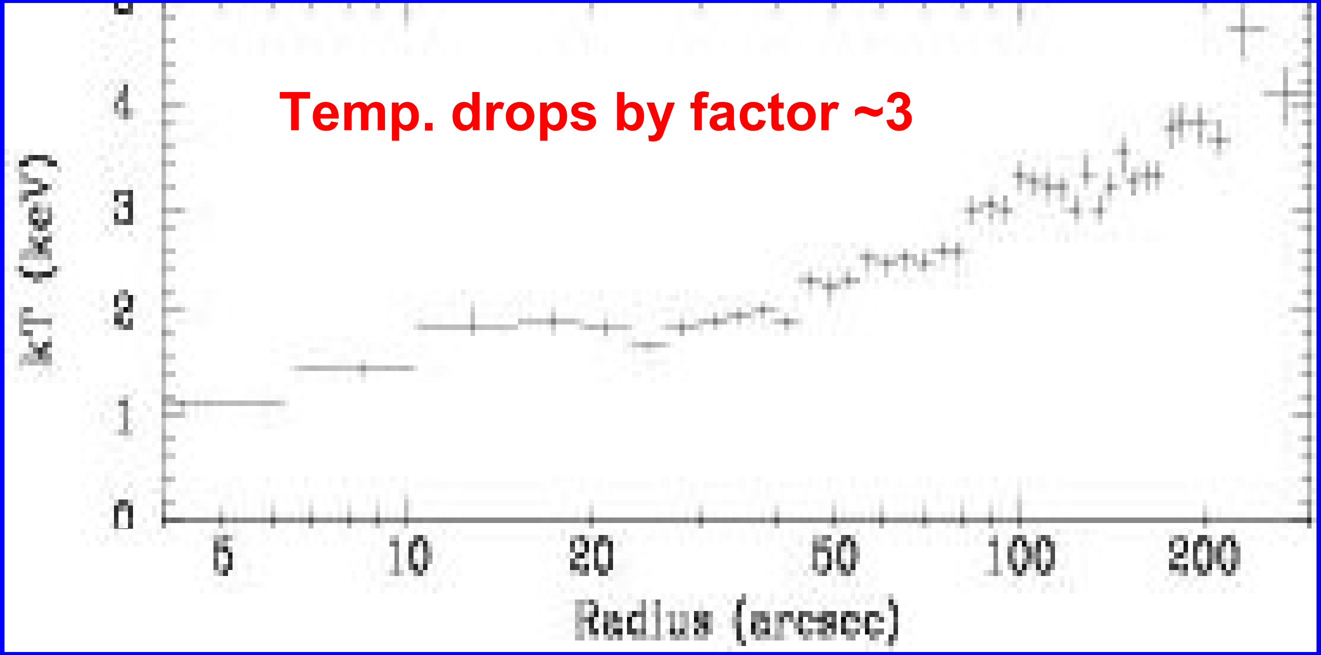
COOLING FLOW PREDICTIONS

- Mass inflow rates up to 1000 $M_{Solar}\ yr^{-1}$
- Mass "dropout" $\dot{M} \propto r$
- "Cooling catastrophe" near center

"COOLING FLOWS": REALITY

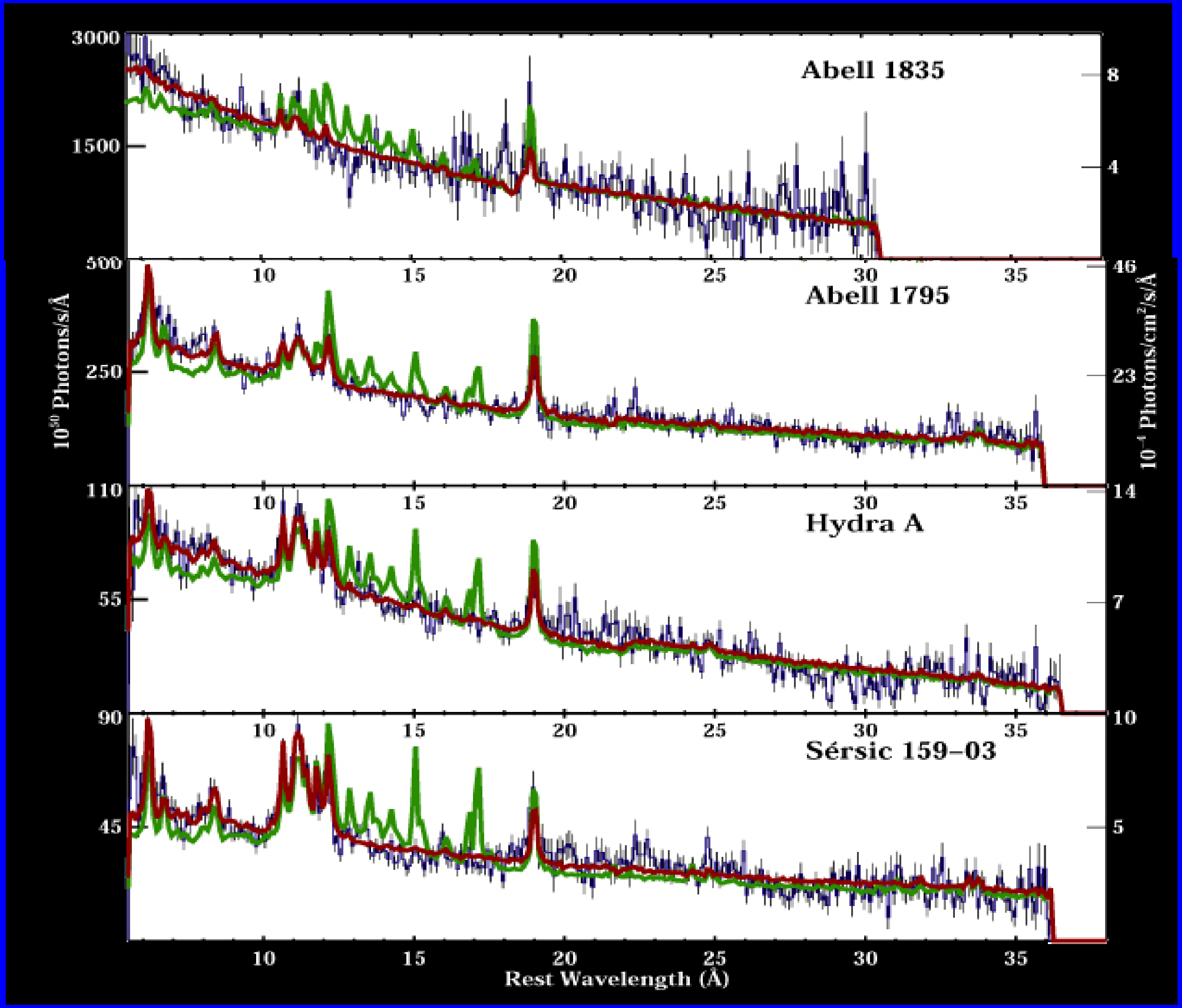
- No evidence for large mass dropout
  - Stars, absorbing gas missing
- Temperature "floor"

Sanders & Fabian 2002



Centaurus cluster

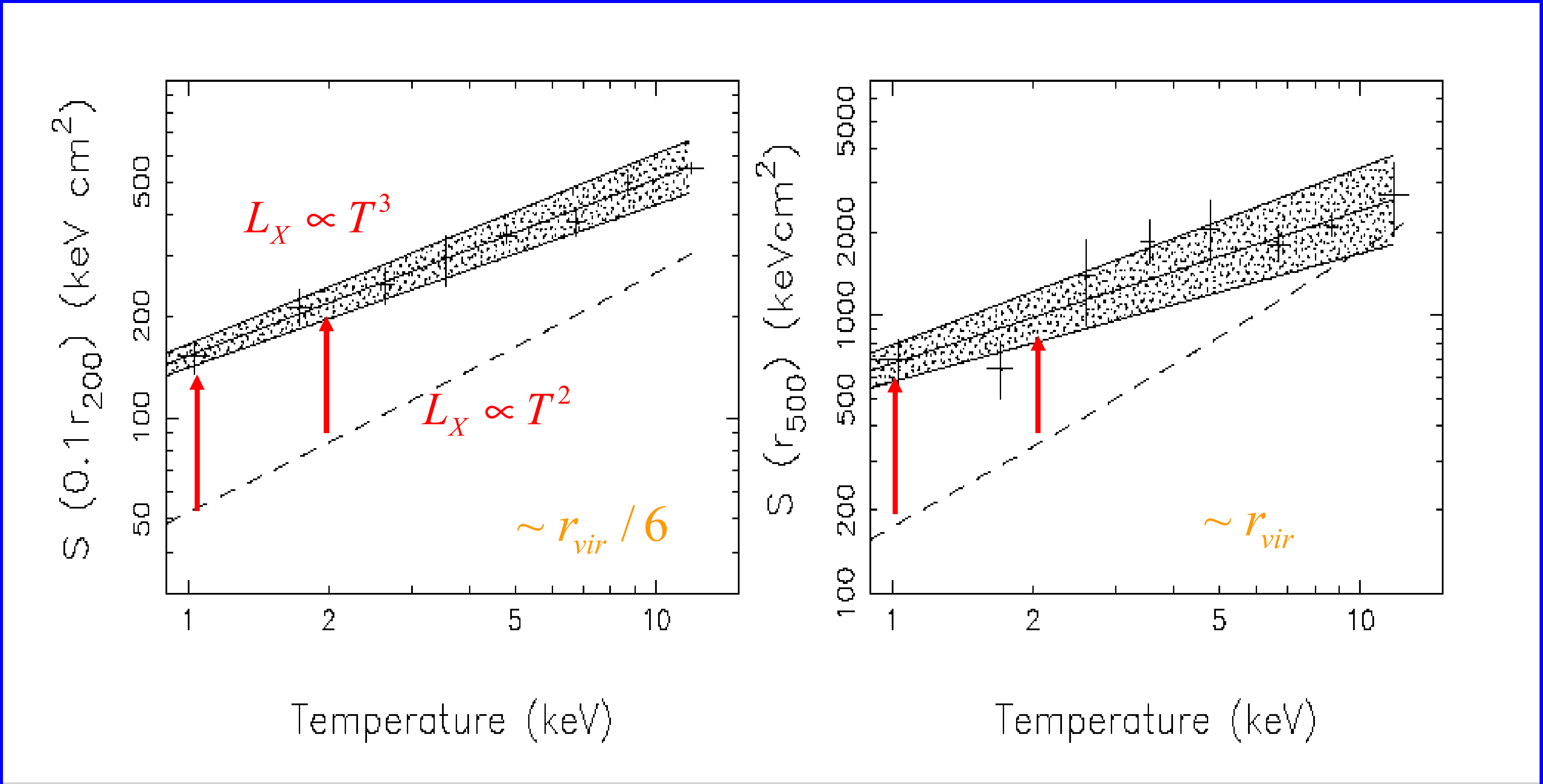
Lines from cooling gas missing:



IMPLIES…

- …just the right amount of heating to balance radiative losses
- …heating spread radially throughout cluster
- …heating continues for cluster lifetime

ENTROPY “FLOOR”



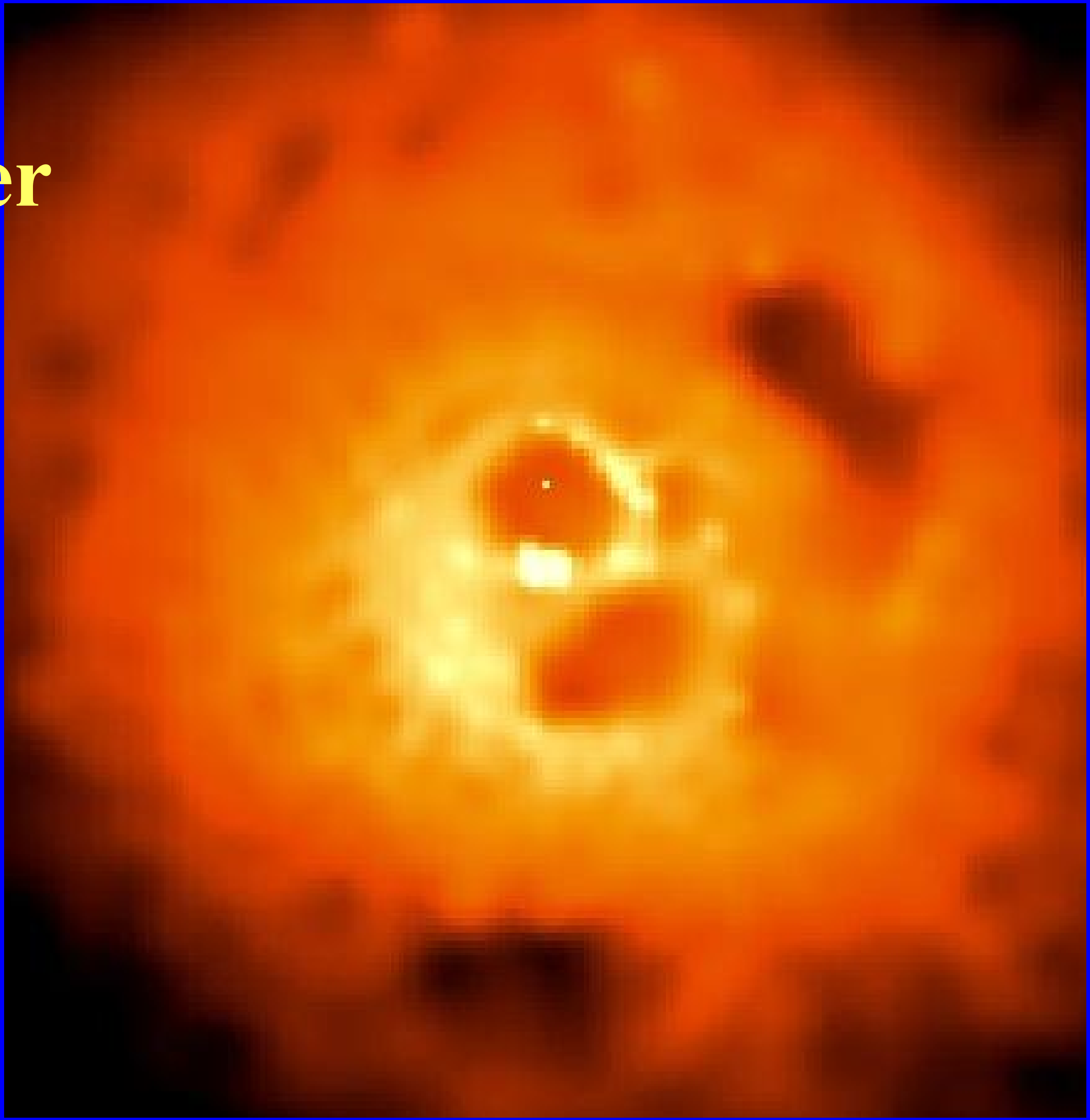
- One-time heating event OK
- BUT…extra entropy distributed evenly throughout cluster

MORPHOLOGICAL EVIDENCE OF AGN HEATING

- Radio-filled bubbles and “ghost cavities”
- Shocks
- Ripples
- Plumes, eddies - connected to AGN

3C 84 and Perseus Cluster

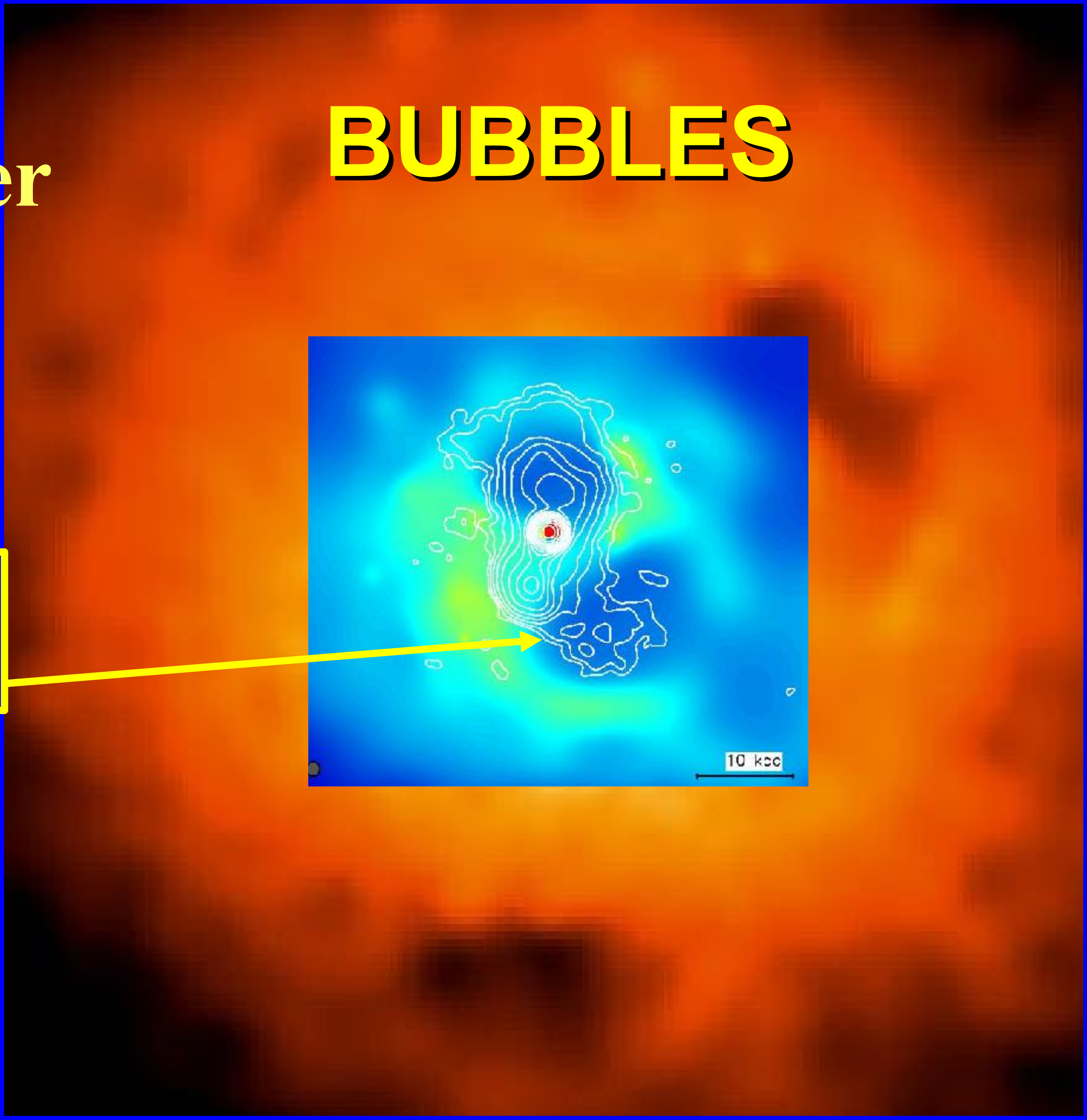
Fabian et al. 2000



3C 84 and Perseus Cluster

Fabian et al. 2000

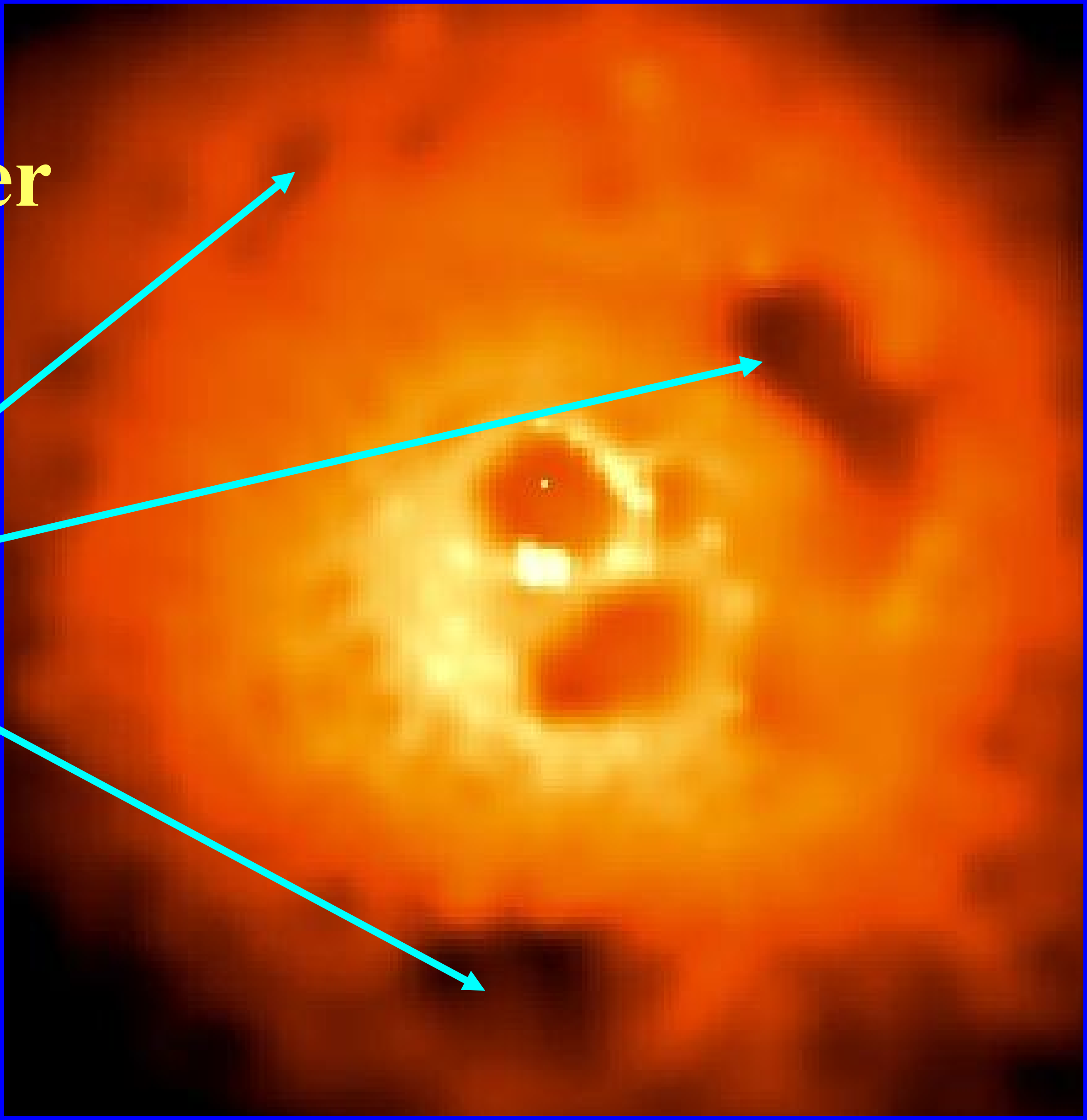
Radio emitting plasma fills holes



Chandra image + radio

3C 84 and Perseus Cluster

Fabian et al. 2000



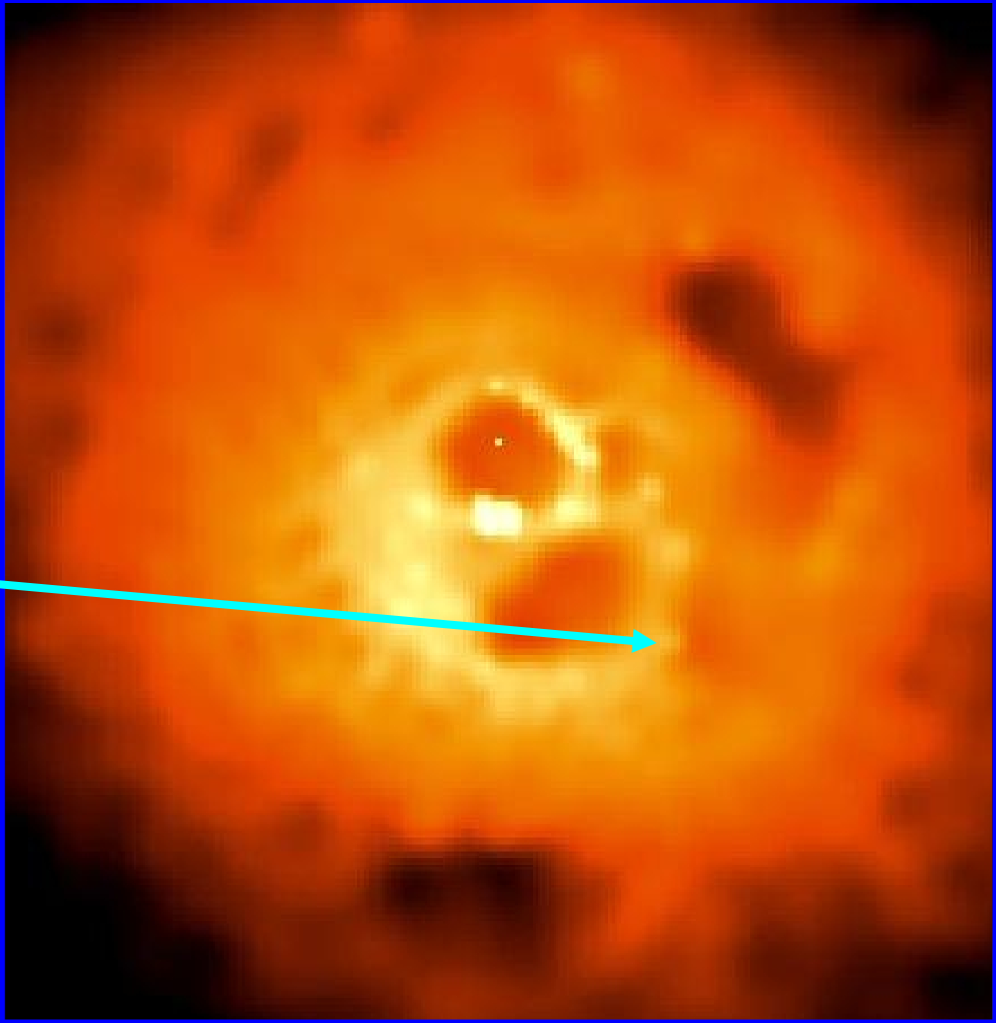
Multiple "fossil" bubbles(?), not aligned with current radio jets

Chandra image

3C 84 and Perseus Cluster

Fabian et al. 2000

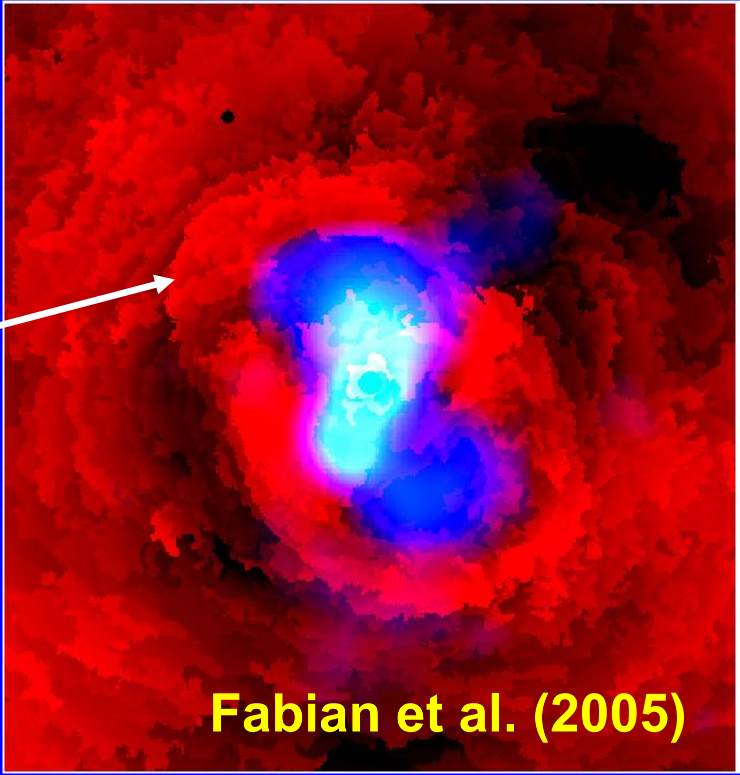
Cool rims



Chandra image

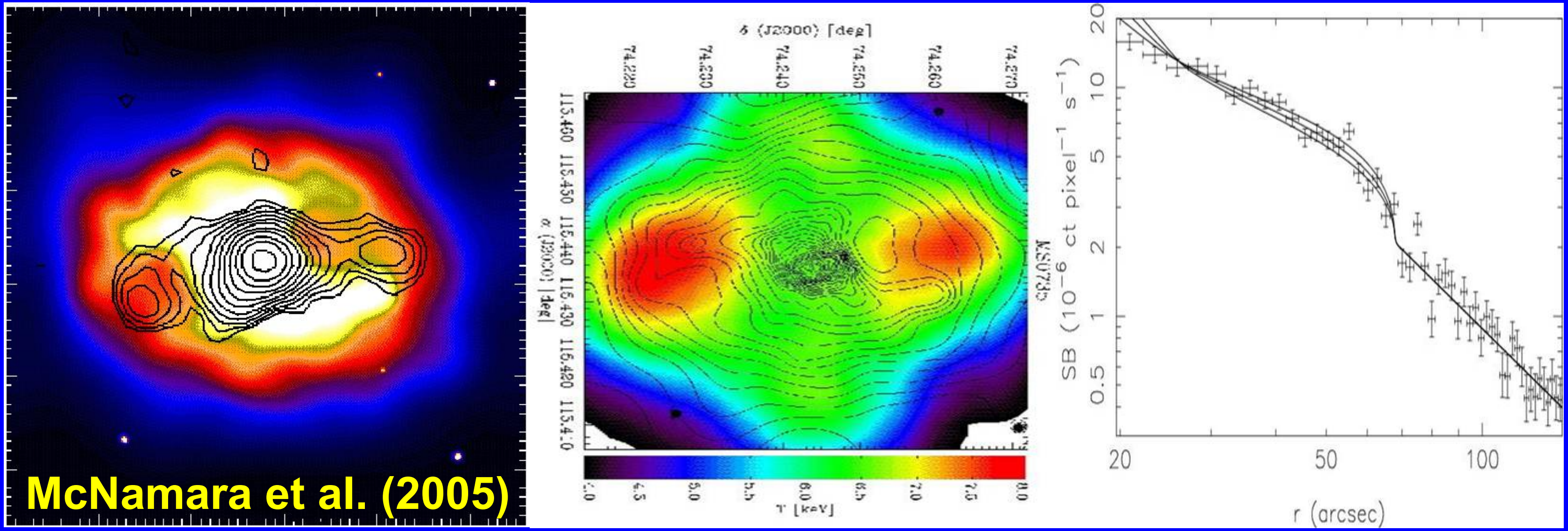
WEAK SHOCKS

PERSEUS – isothermal shock?



Fabian et al. (2005)

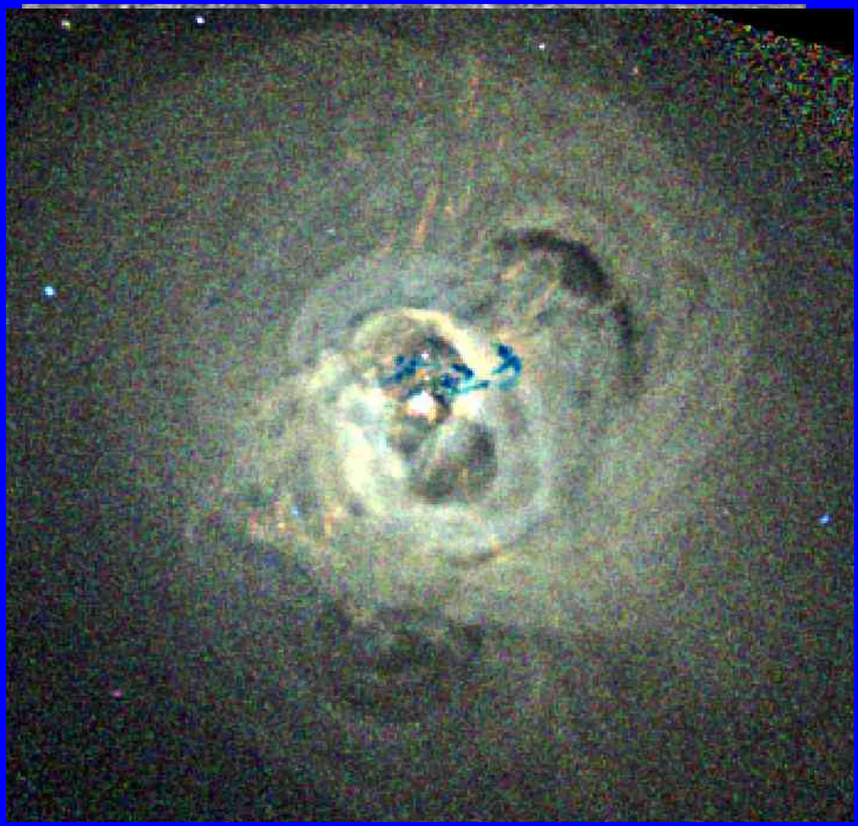
Mach nos. ~ 1.3



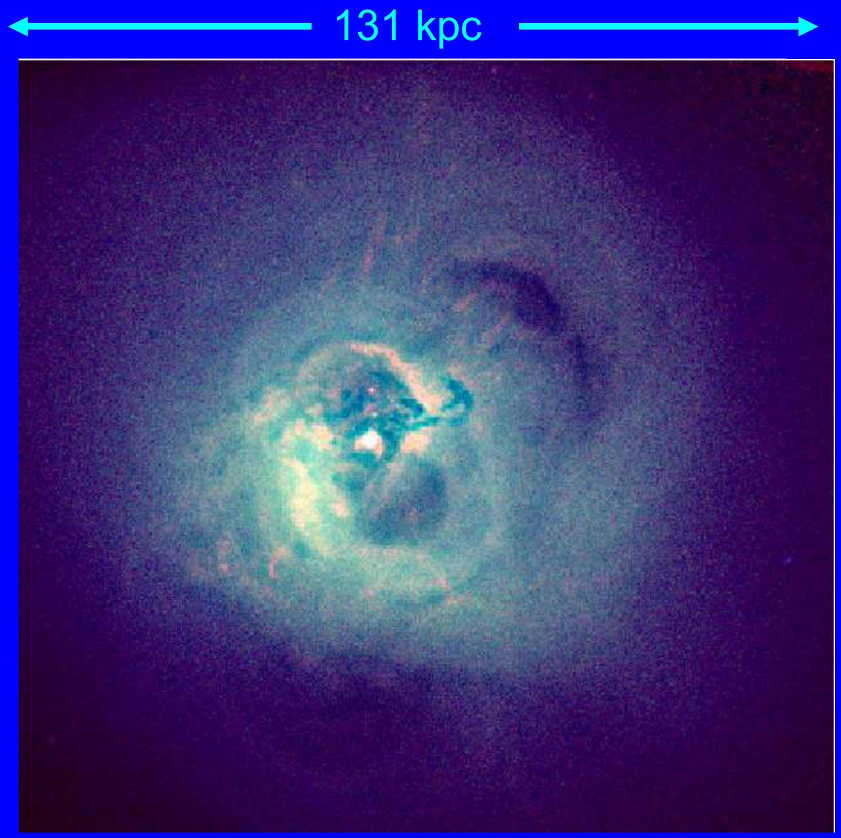
McNamara et al. (2005)

RIPPLES: PERSEUS CLUSTER

Unsharp masked Chandra image

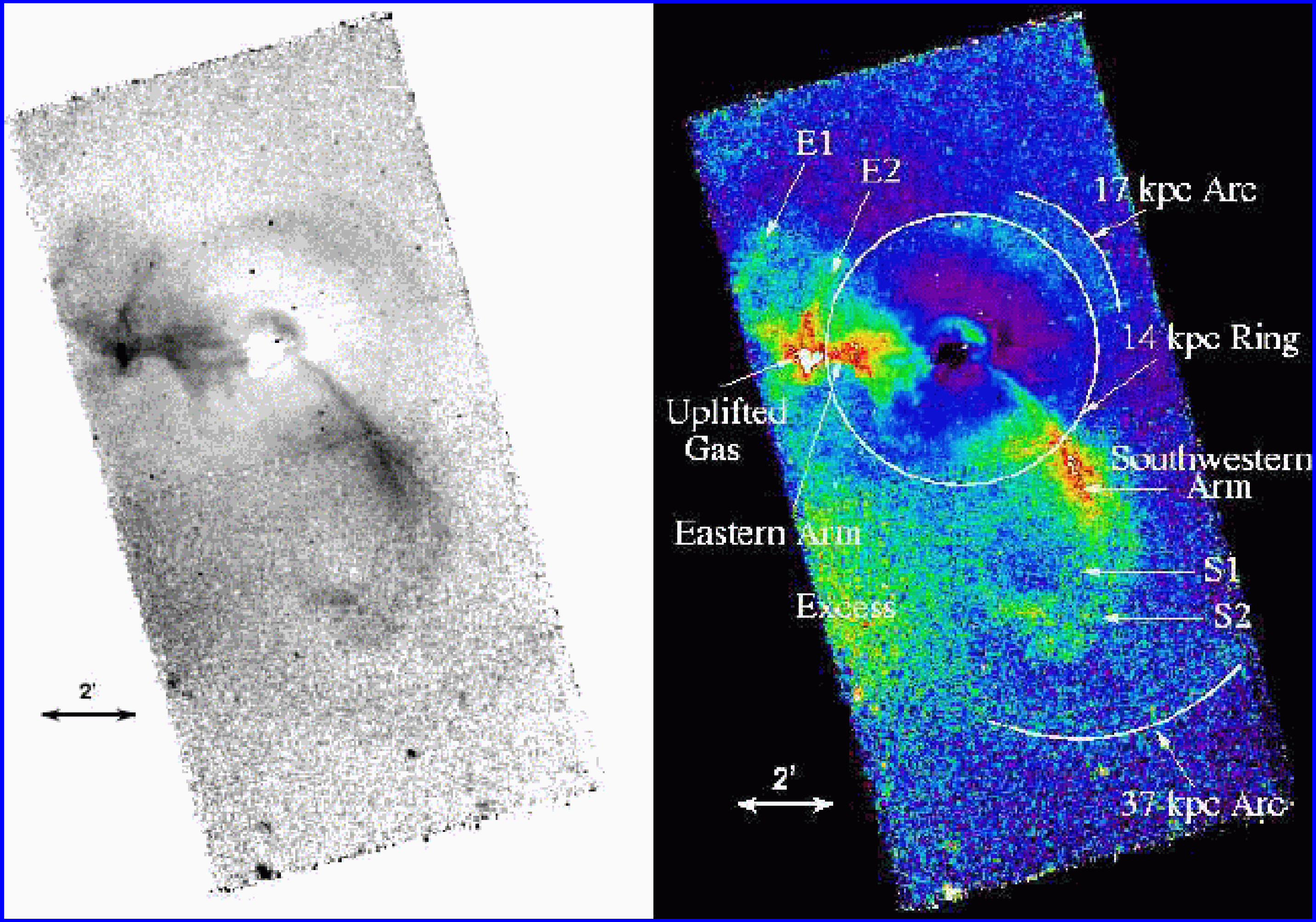


X-ray temperatures



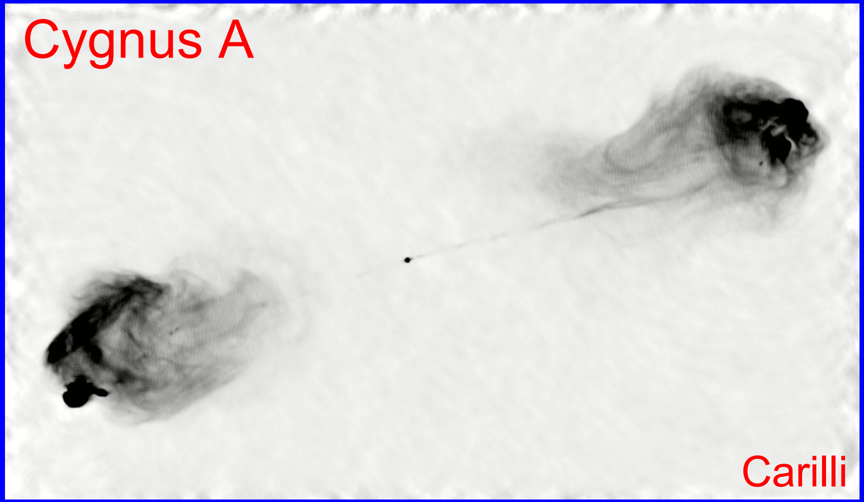
Fabian et al. 2006

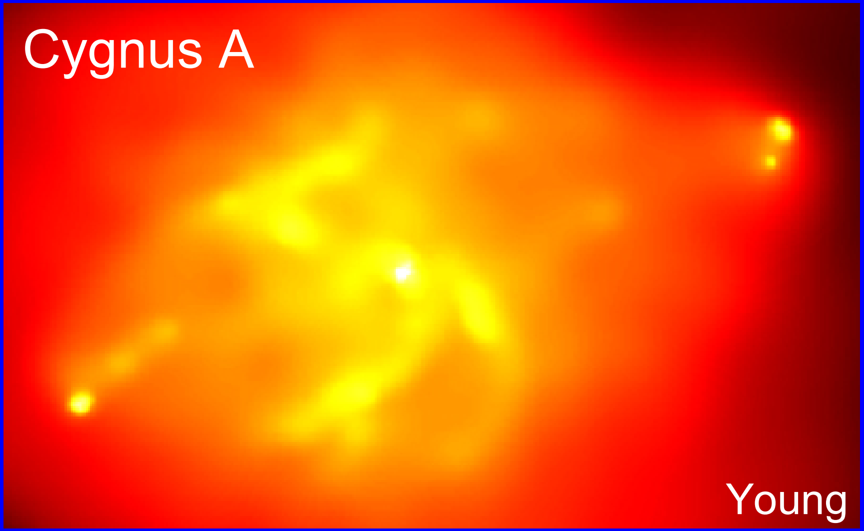
RIPPLES: VIRGO CLUSTER

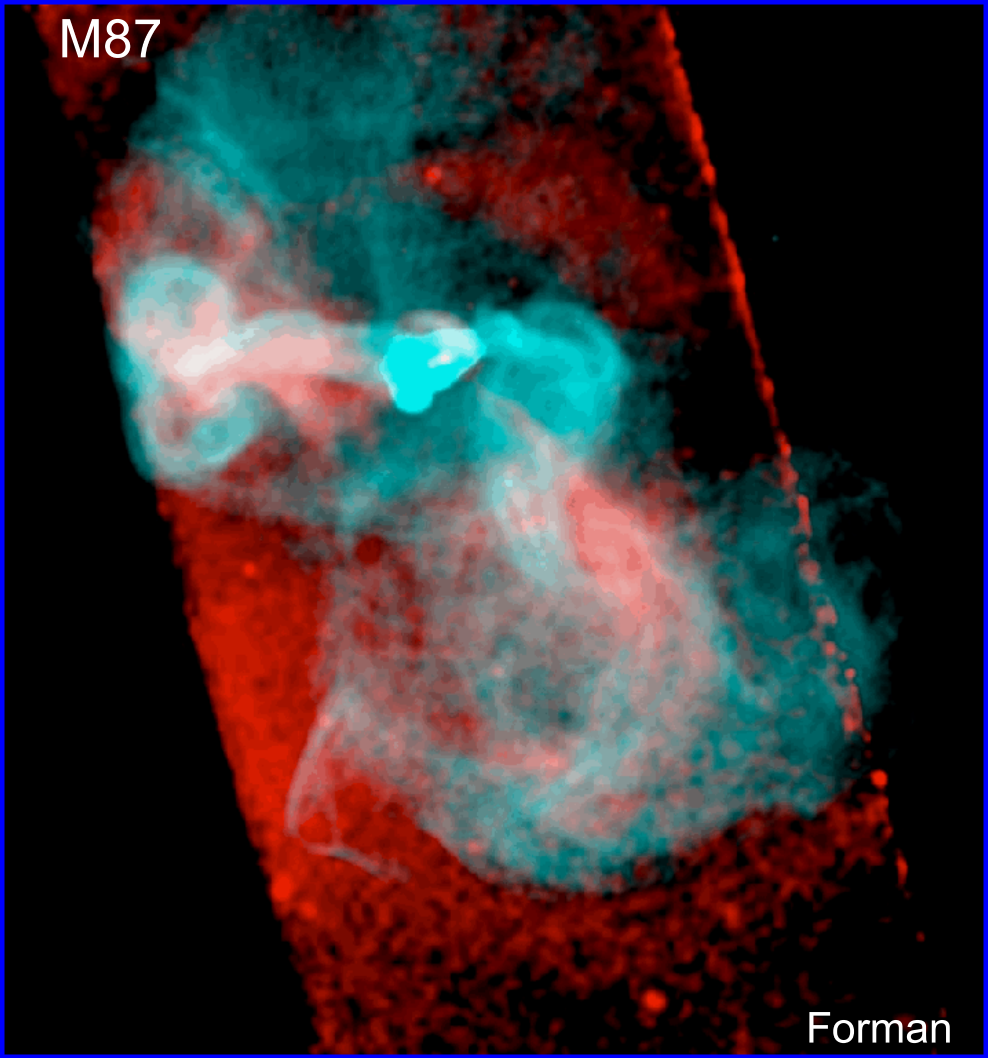


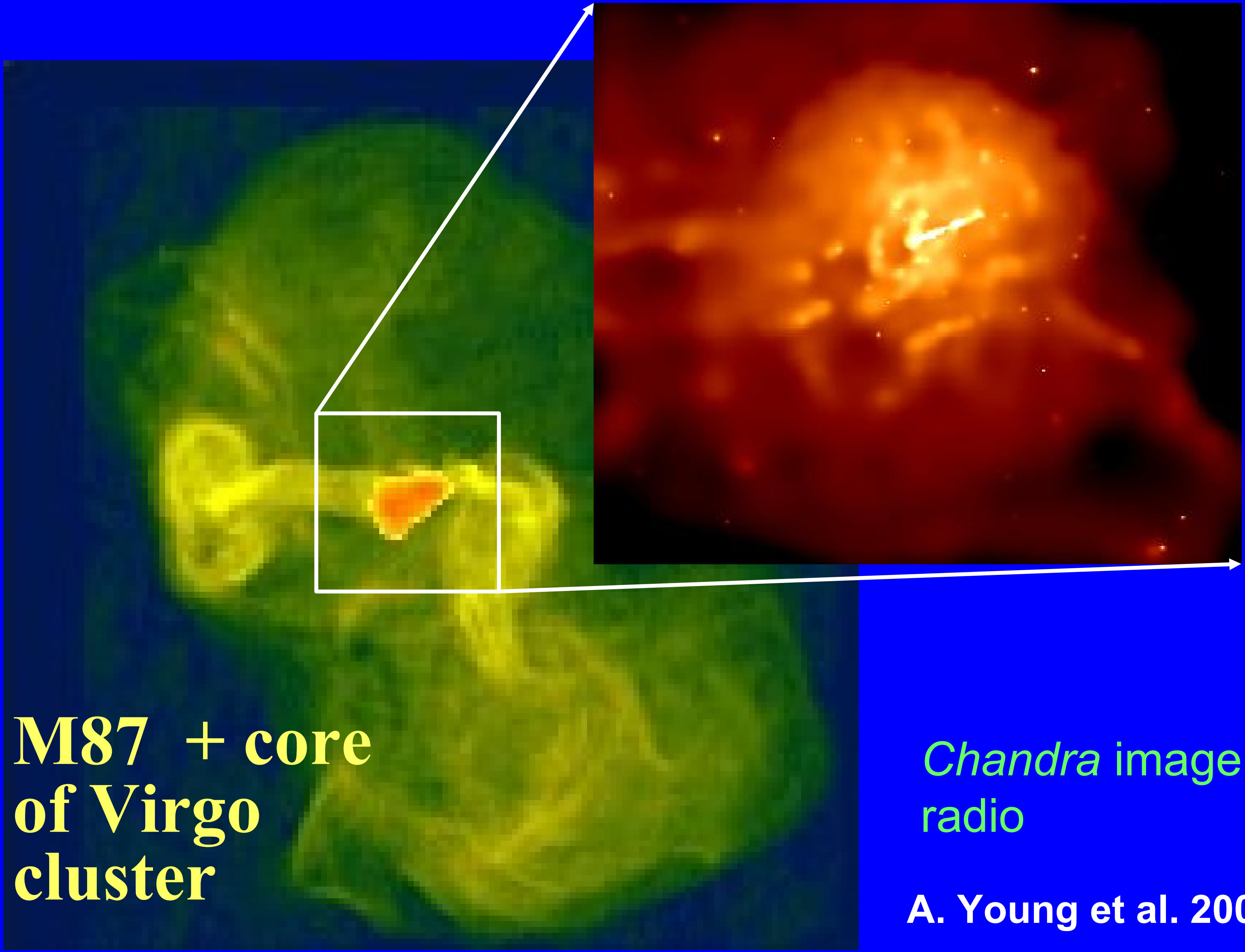
Forman et al. 2004

PLUMES AND EDDIES









Chandra image + radio

A. Young et al. 2002

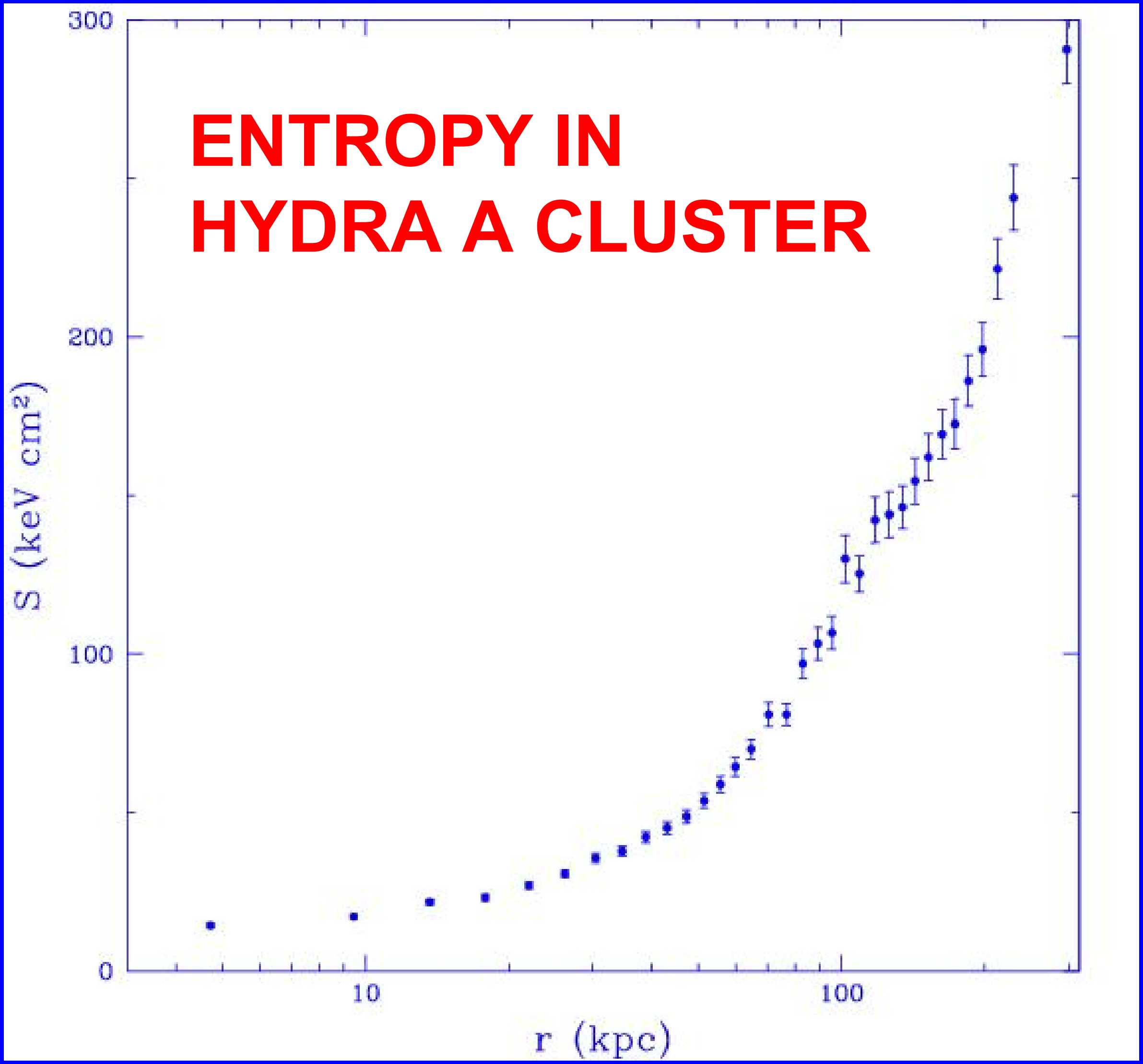
THE THEORETICAL CHALLENGE:

- WIDESPREAD, EVEN HEATING FROM CENTRALLY CONCENTRATED SOURCE
  - Entropy “floor” manifest on large scales
  - Cooling “catastrophe” avoided

- HEATING IS RELATIVELY GENTLE
  - Not convection: cluster gas is convectively stable beyond 10s of kpc
  - Not strong shock heating – cool rims
  - Metallicity gradients not washed out

Entropy increases with *r*

Convectively stable



David et al. 2001

Analytic model: "EFFERVESCENT HEATING"

- Very buoyant gas rises subsonically through pressure gradient
- Does *pdV* work as it expands
  - Does not mix with cluster gas; X-ray "holes"
  - Acoustic & potential energy converted to heat by damping and/or mixing

LIKE BUBBLES IN A (VERY TALL) GLASS OF BEER

HEATING MODEL

TARGETS PRESSURE GRADIENT → STABILIZES COOLING

- **Volume heating rate:**

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

- **Compare to cooling rate:**

$$C = n^2 \Lambda(T) \propto \rho^2 T^\alpha$$

1D ZEUS SIMULATIONS

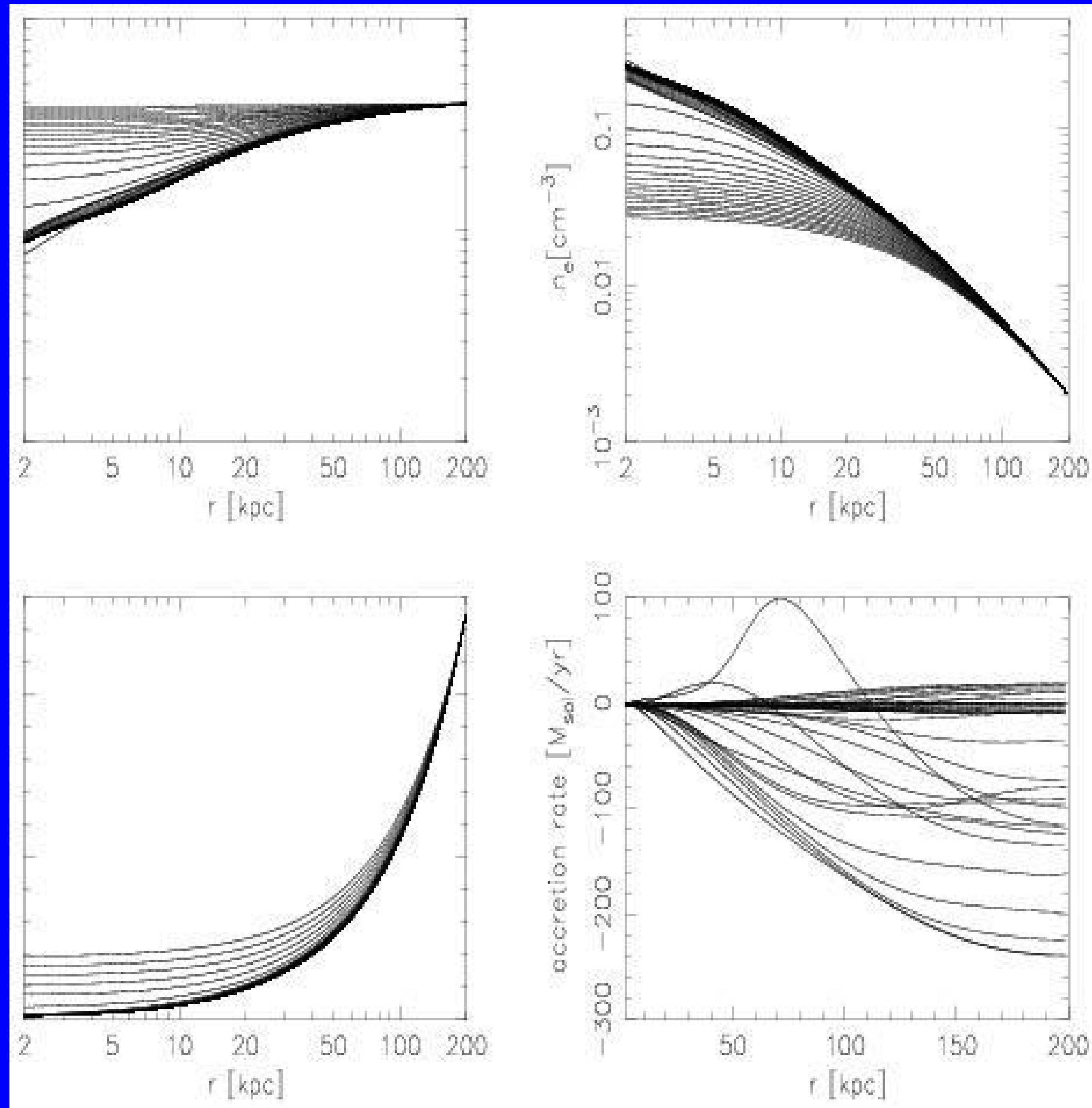
Ruszkowski & Begelman 2002

Includes:

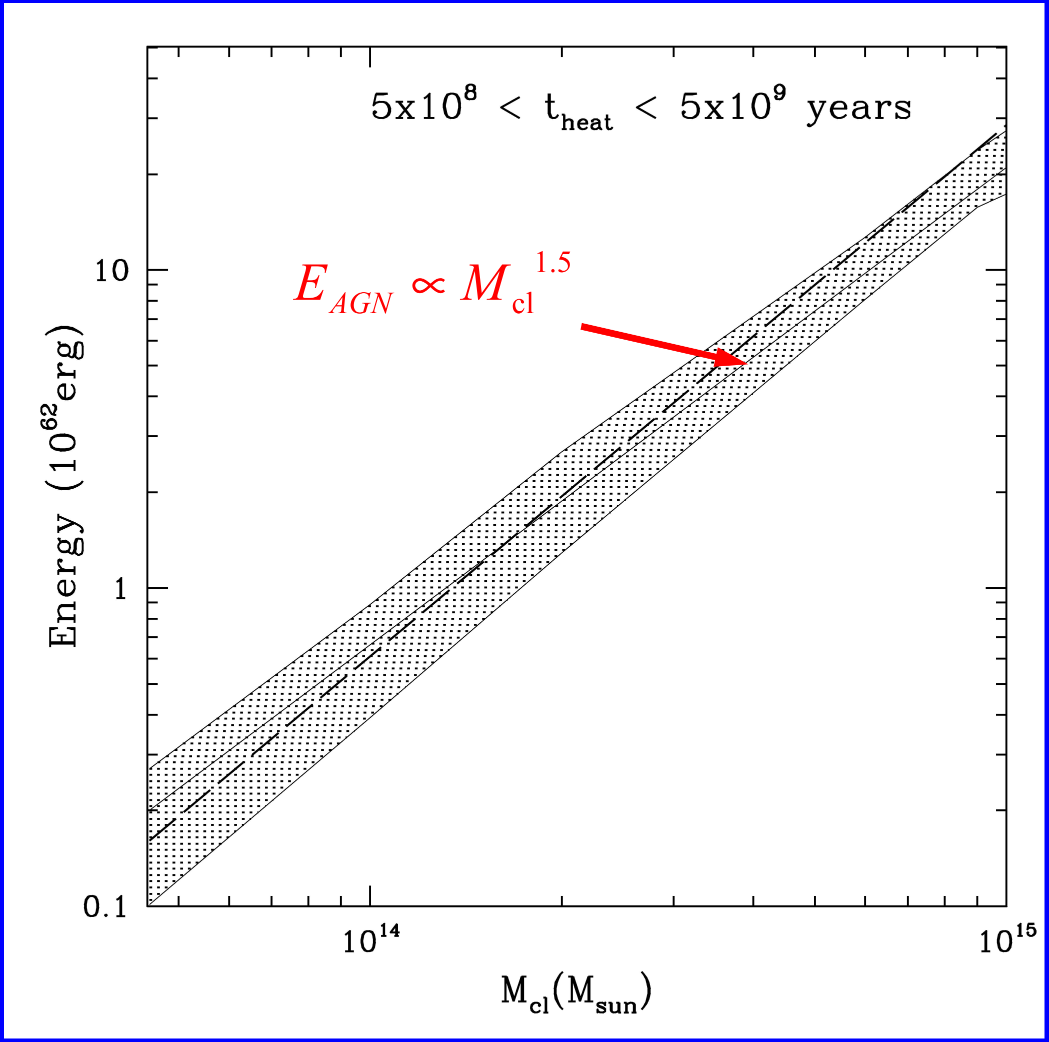
Conductivity @

Spitzer/4; $\dot{M}$

Simple feedback in center

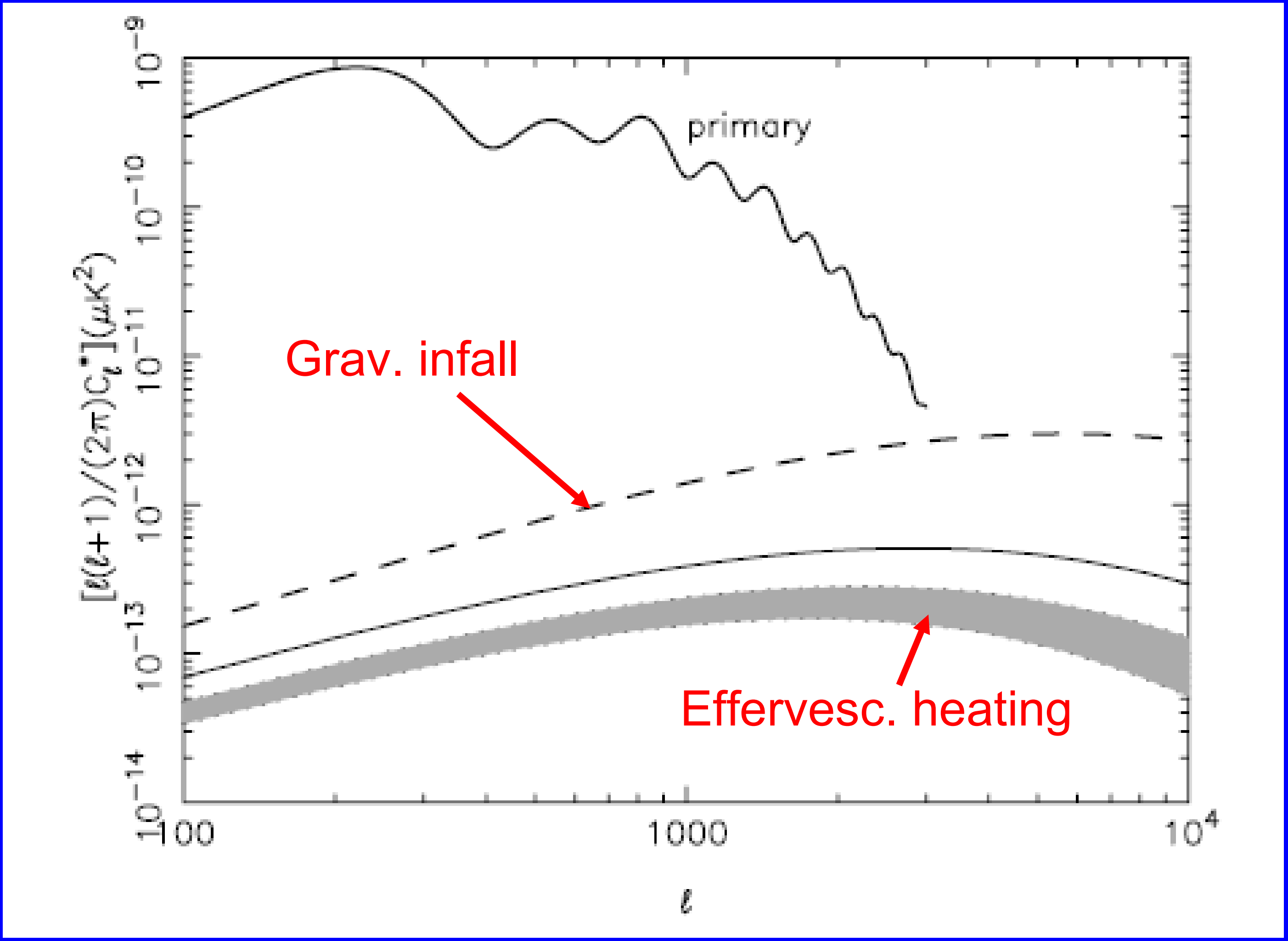


EFFERVESCENT HEATING CAN EXPLAIN CLUSTER ENTROPY EXCESS IF $E_{\rm AGN} \propto M_{\rm cluster}^{1.5}$



Roychowdhury et al. 2004, 2005

Depression of SZ Signal



Roychowdhury, Ruszkowski & Nath 2005

NUMERICAL MODELING

Energetic constraints

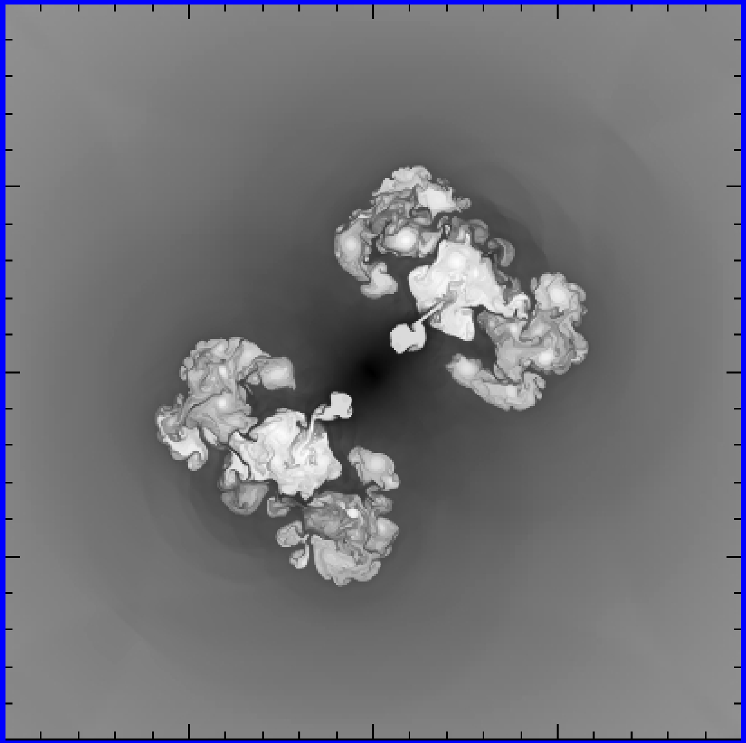
- Energy spread broadly in radius and solid angle
- Total energy supply must be adequate (entropy floor)
- Duty cycle shorter than cooling time; feedback to regulate rate of injection (cooling flows)
- Spreading and dissipation faster than cooling

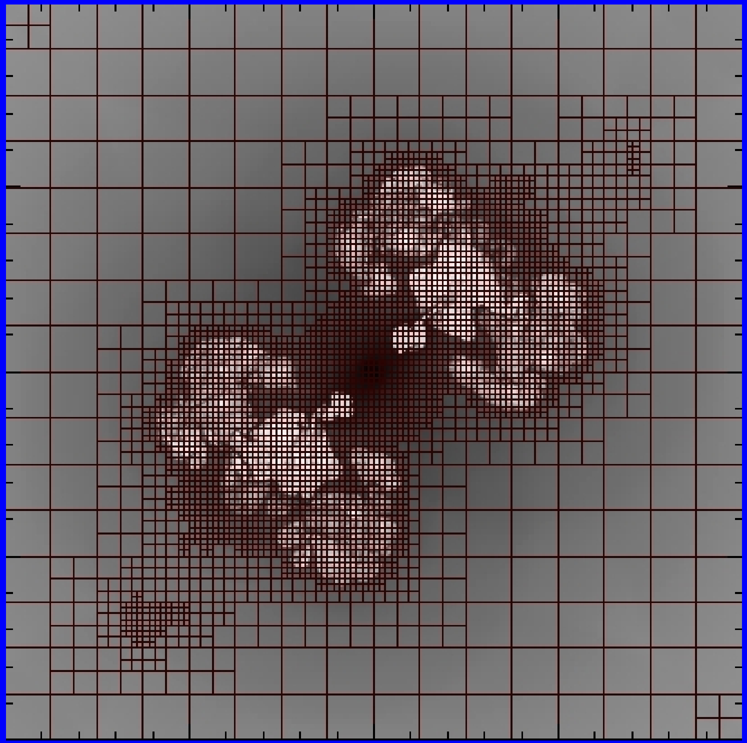
Morphological constraints

- No convection
- Preserved abundance gradients
- Cool rims around rising bubbles - entrainment
- Radio emission less extended spatially than X-rays
- “Streamlines” of Hα filaments
- Sound waves

SIMULATIONS:

- **Crucial to model mixing and weak shocks accurately**
  - **Use PPM code with Adaptive Mesh Refinement, e.g., FLASH**



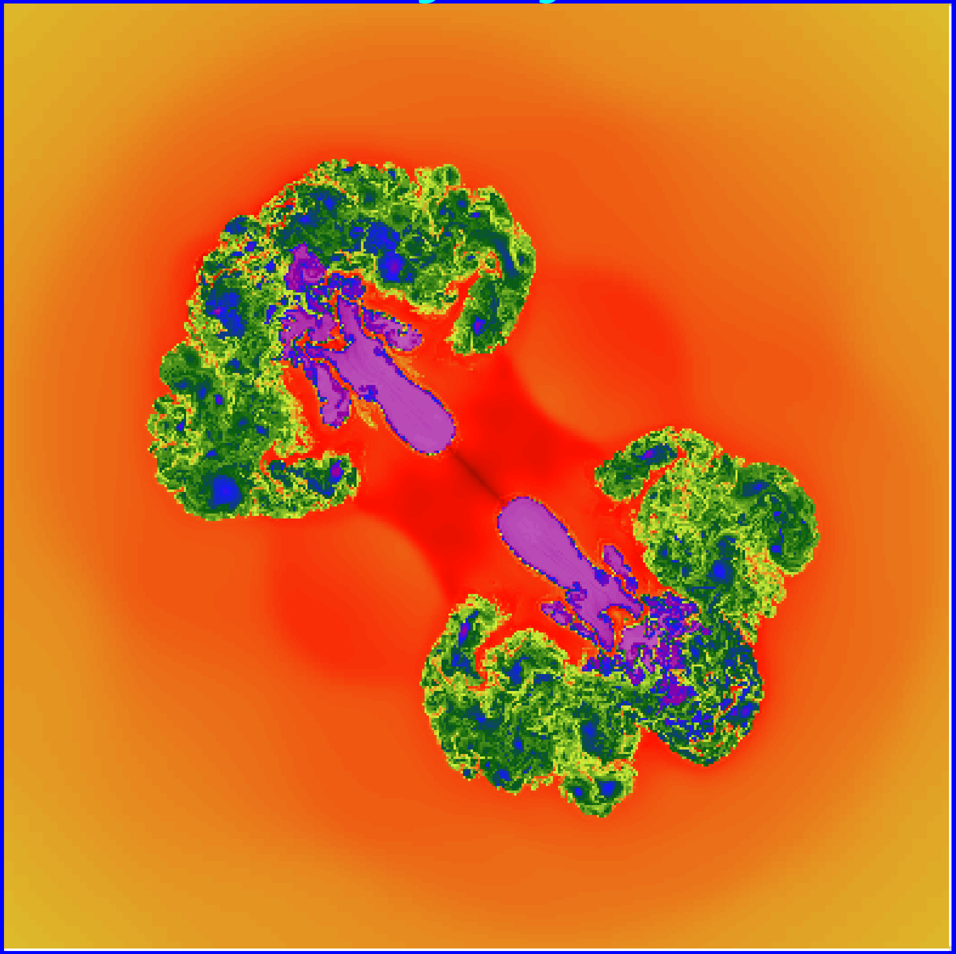


FLASH 2D, 8 levels of mesh refinement

Current 3D dynamic range: 1000:1 (FLASH), 33,000:1 (ENZO)

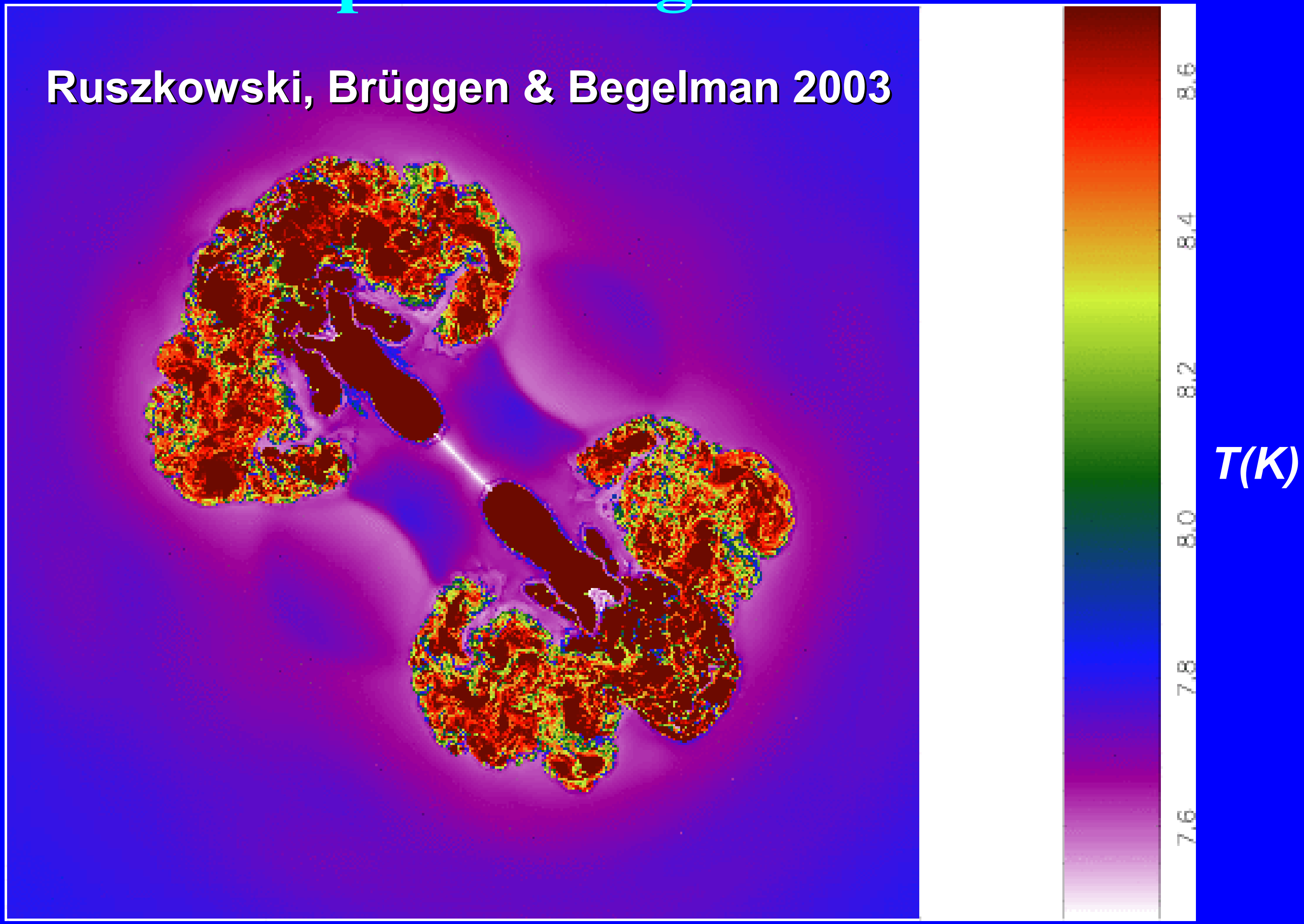
ISOTROPIZATION?

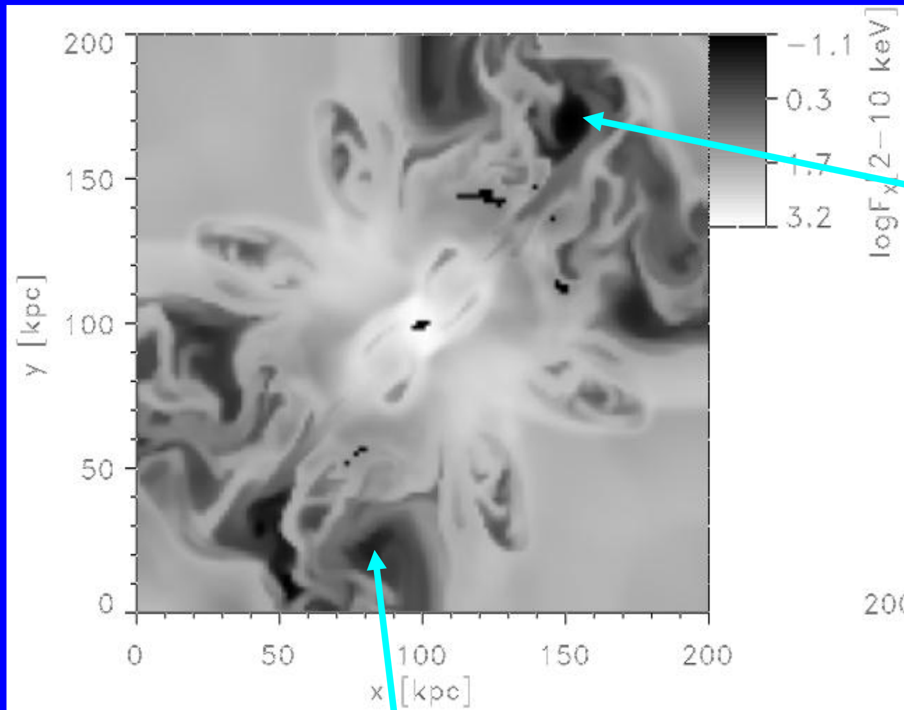
- mushroom cloud effect
- unsteady injection



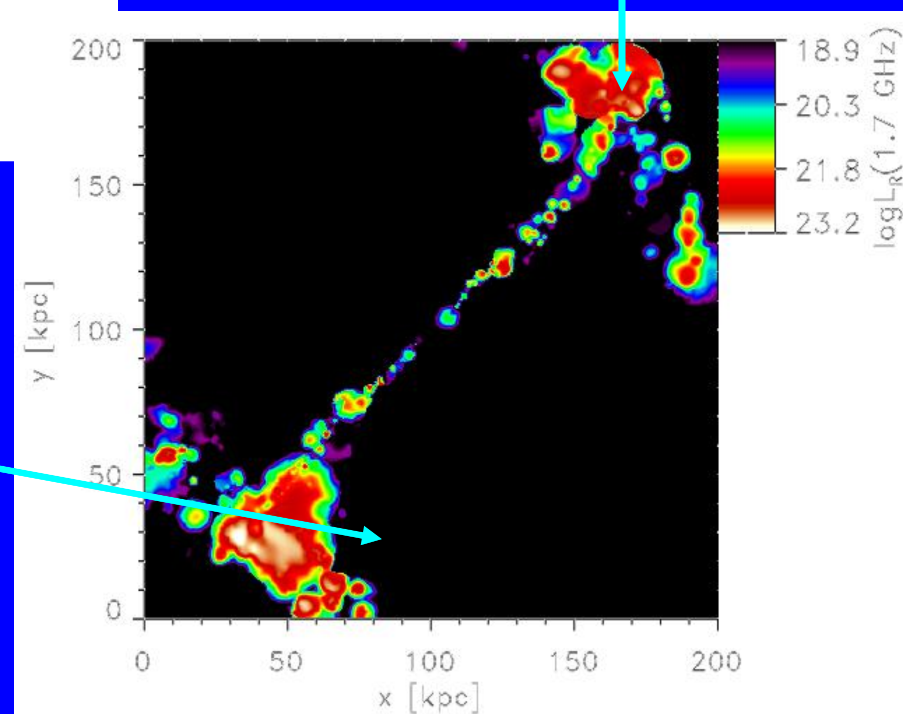
Ruszkowski, Brüggen & Begelman 2003

COOL RIMS – entrainment of lower temperature gas



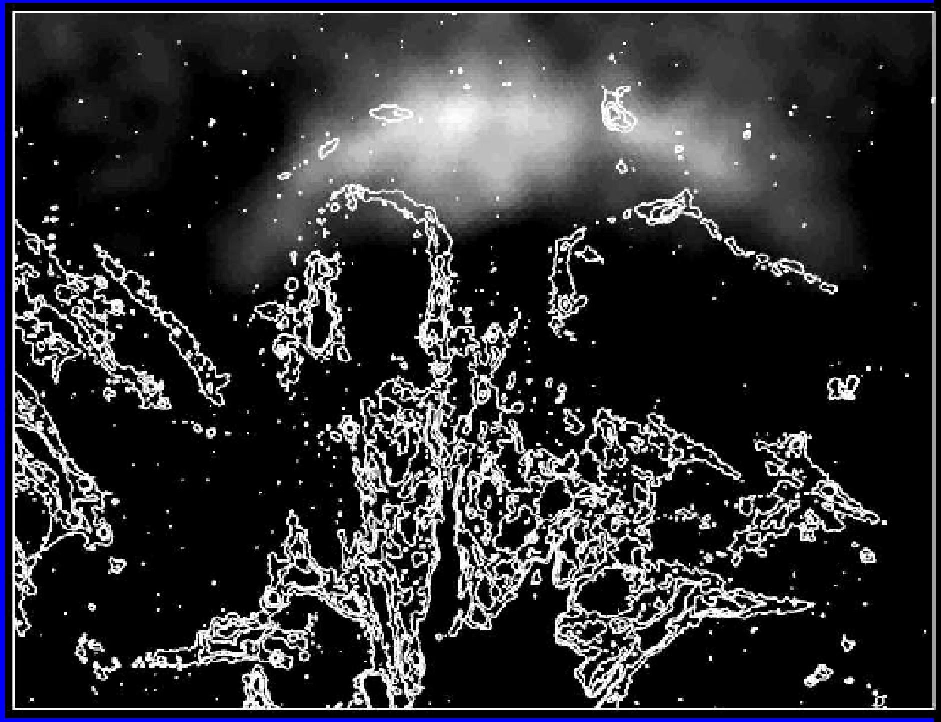


X-ray "holes" filled with radio emission…

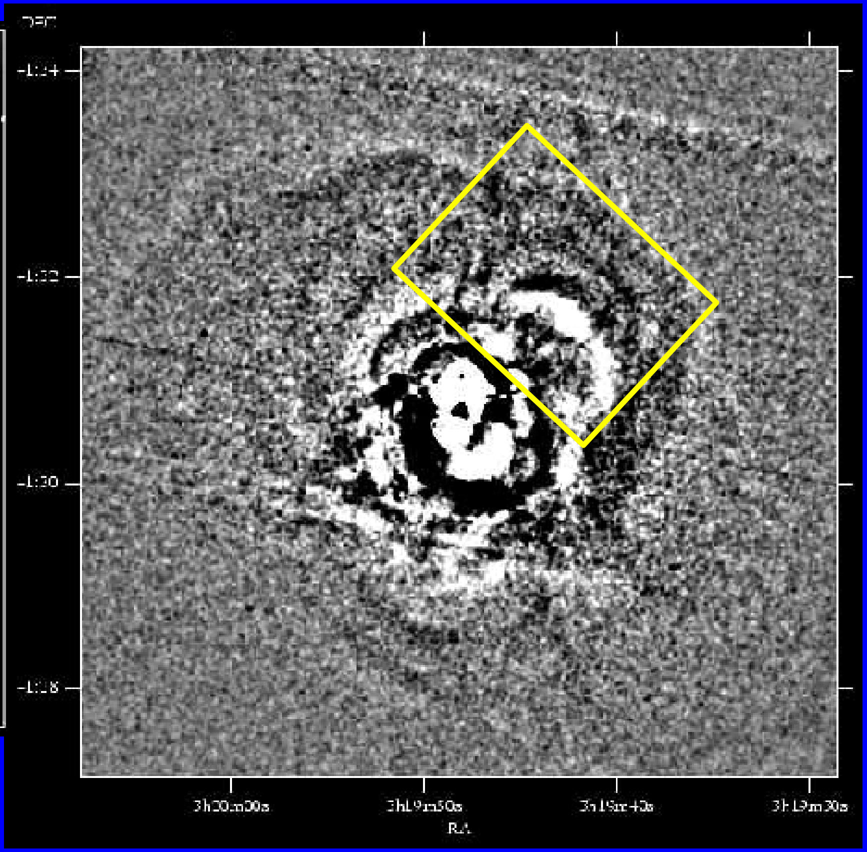


…or not

Do Hα filaments trace streamlines…

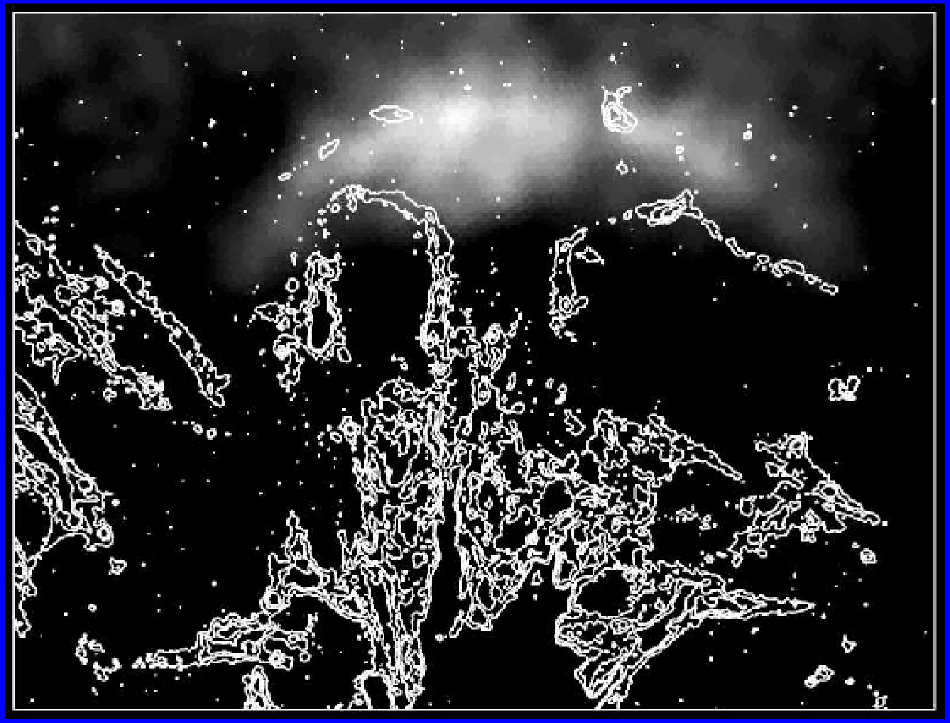


Fabian et al. 2003, Conselice et al. 1998

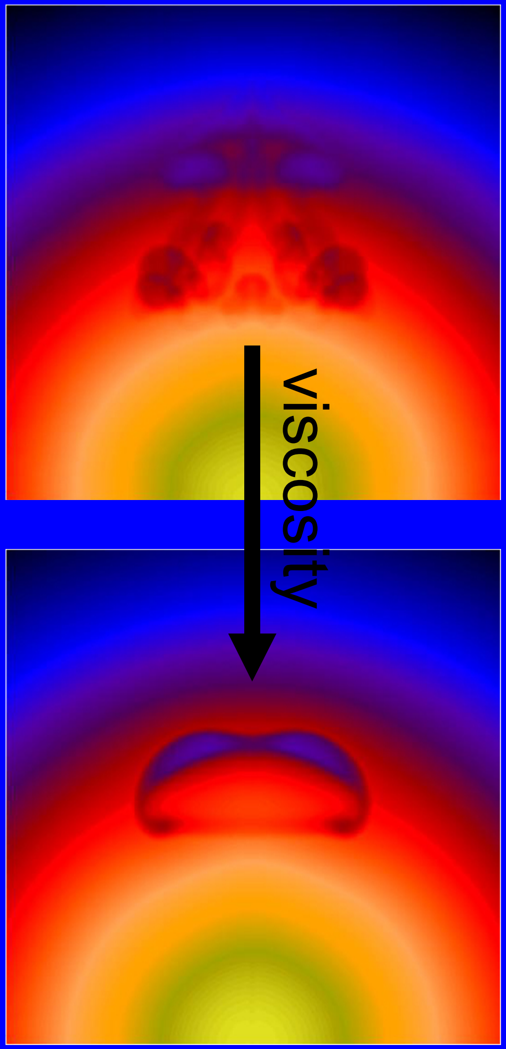


Fabian et al. 2003

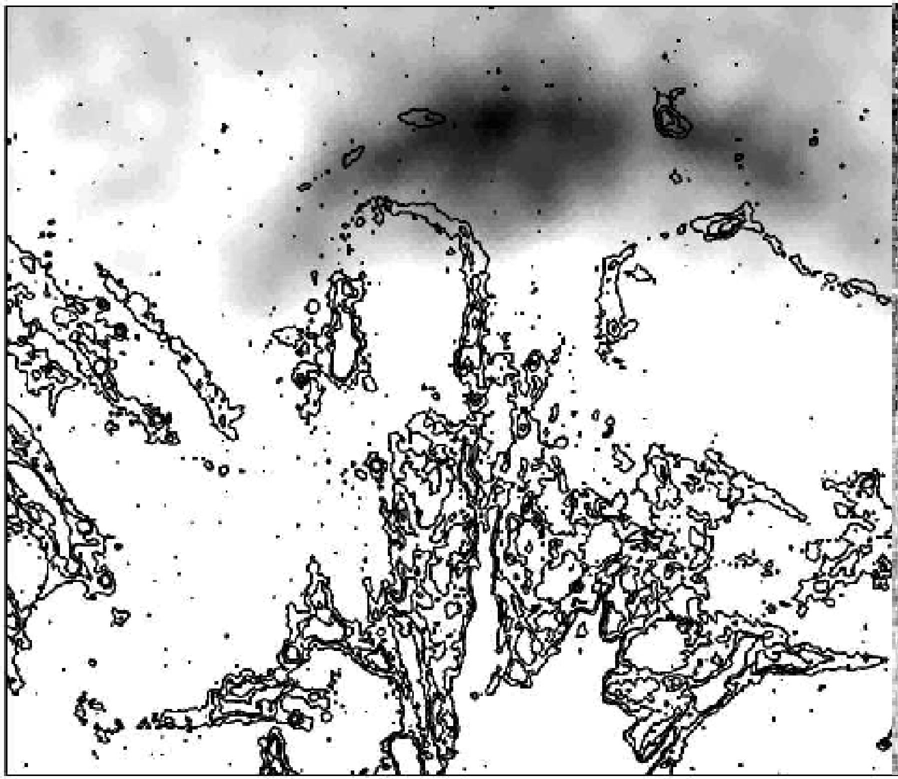
…behind a rising of spherical bubble cap?

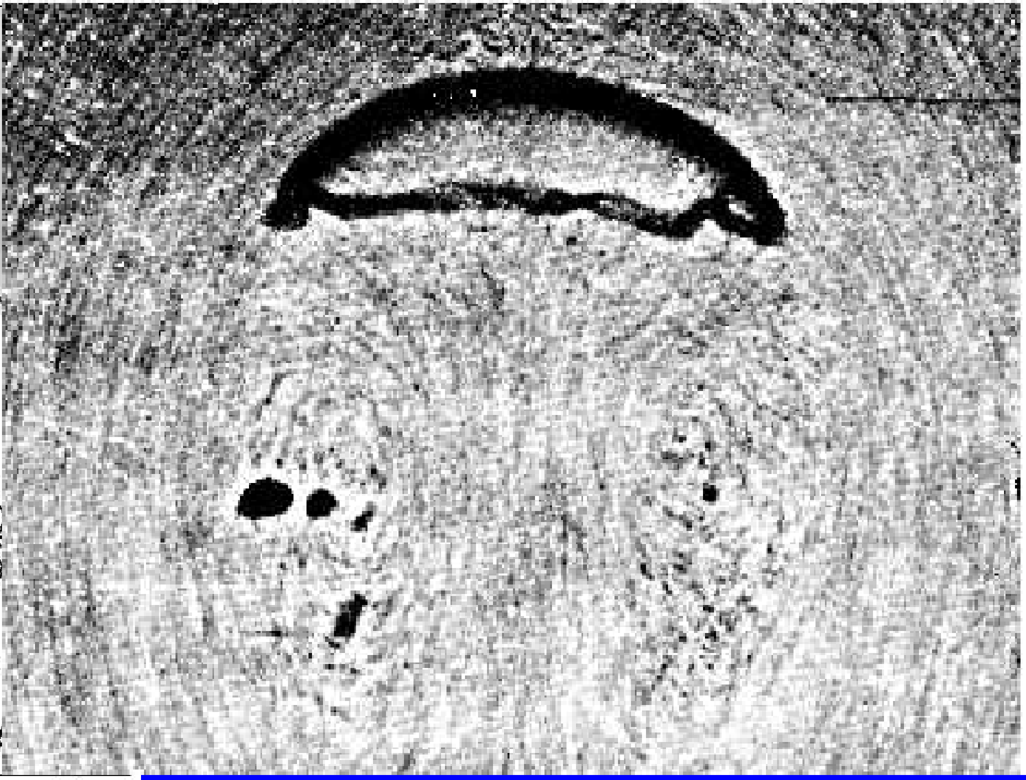


Fabian et al. 2003, Conselice et al. 1998



Reynolds et al. 2004





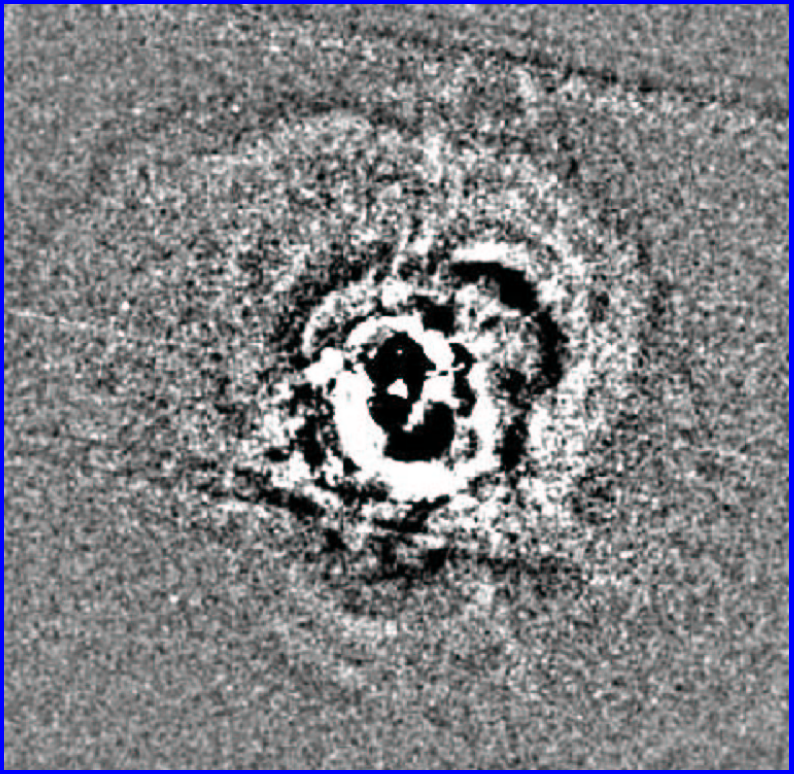
Contours of H-alpha image overlaid on X-ray bubble

Rising air bubble in water

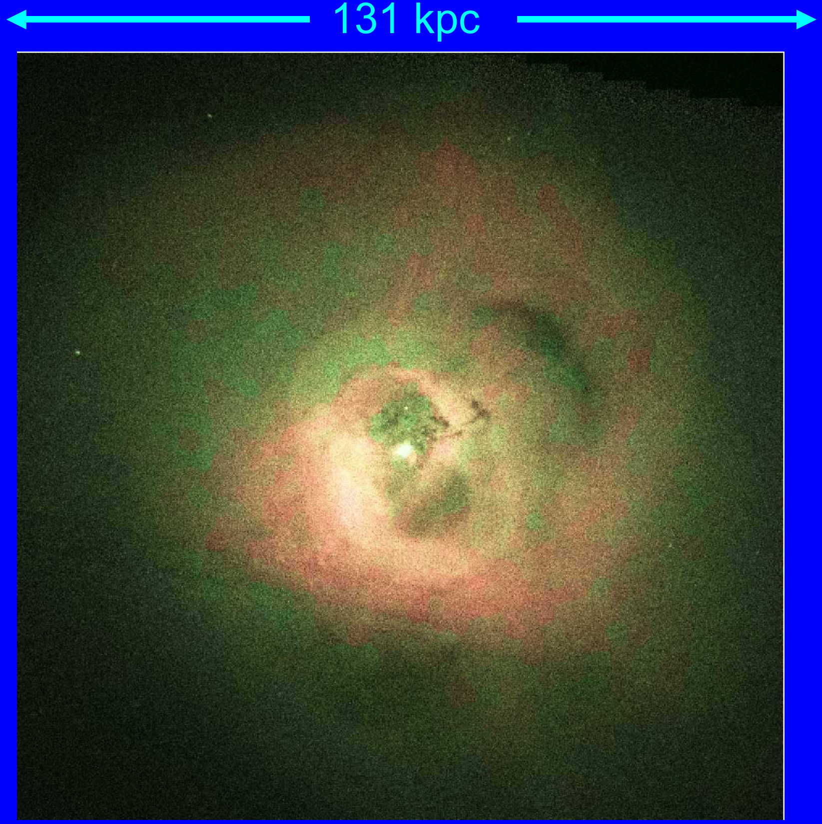
Fabian et al. 2003

RIPPLES IN THE PERSEUS CLUSTER

Unsharp masked Chandra image



X-ray temperatures



Fabian et al. 2003

DENSITY

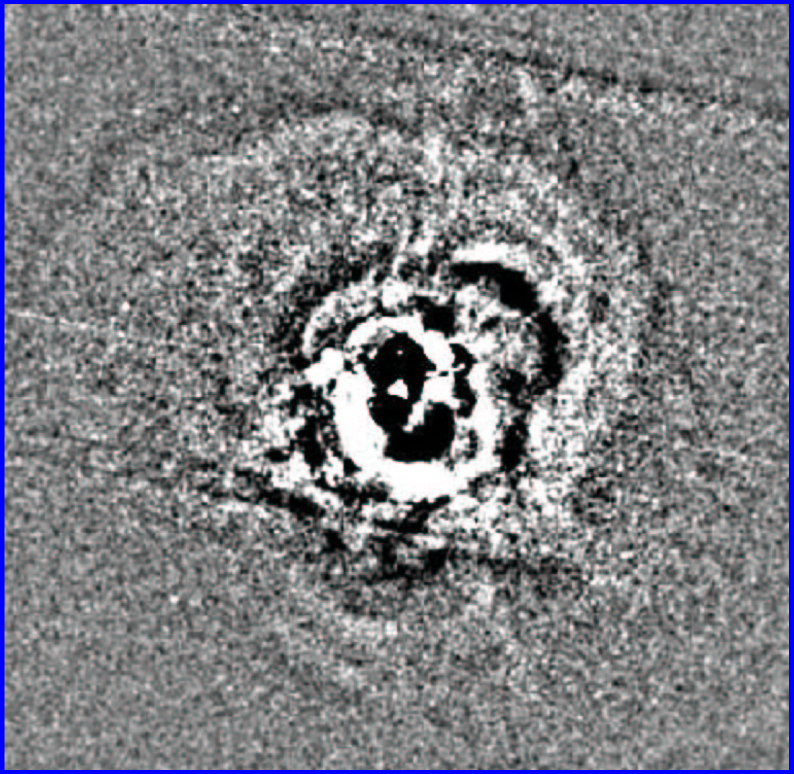
DISSIPATION RATE

Ruszkowski, Brüggen & Begelman 2004

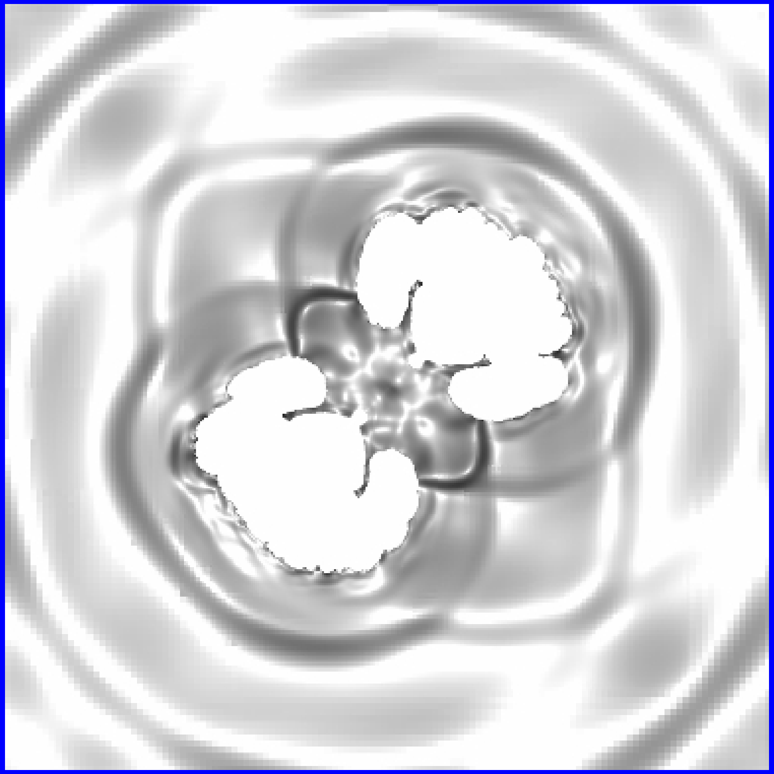
Ripples in the Perseus Cluster

Unsharp masked Chandra image

131 kpc



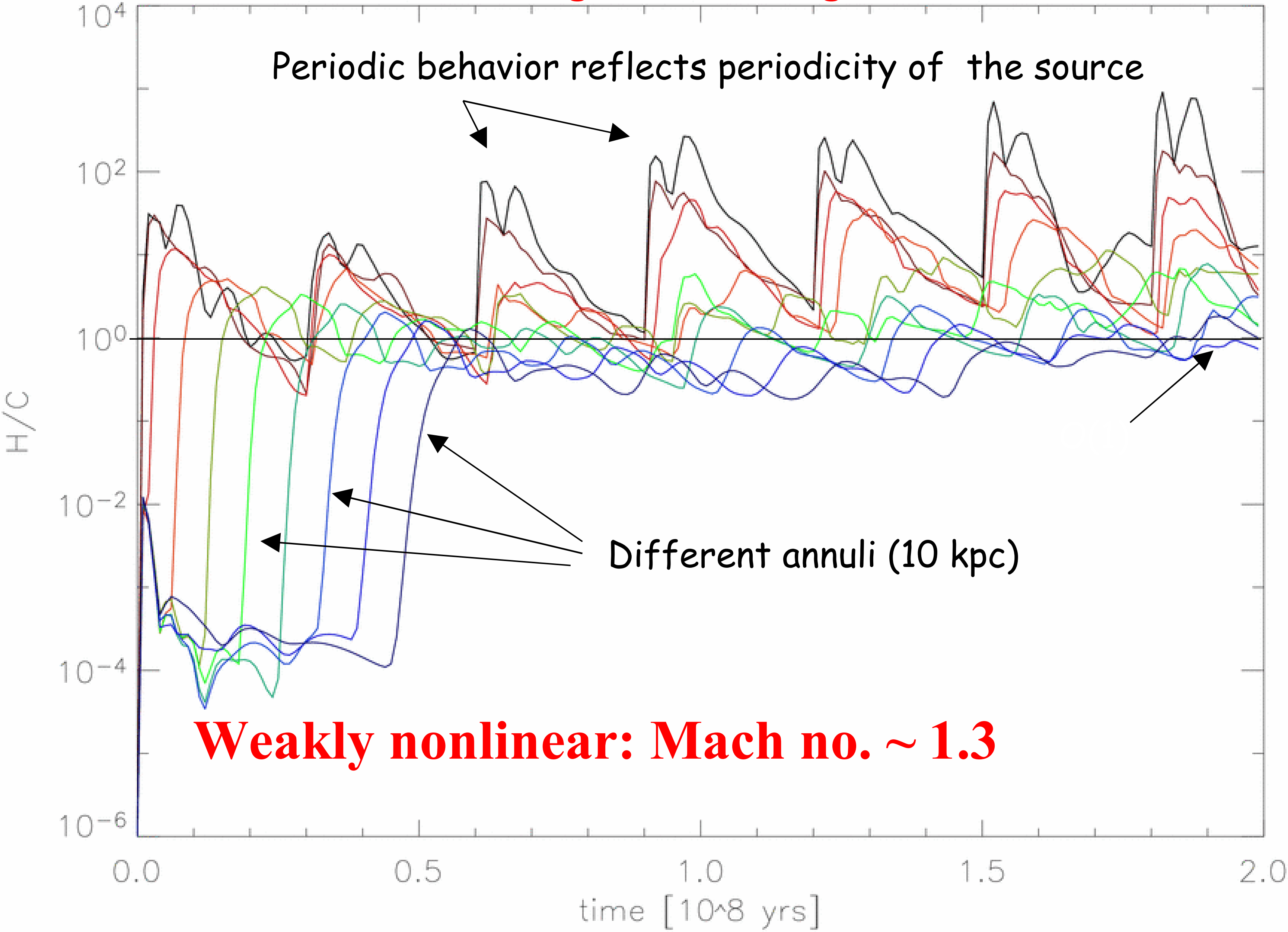
Viscous dissipation map: pulsed source



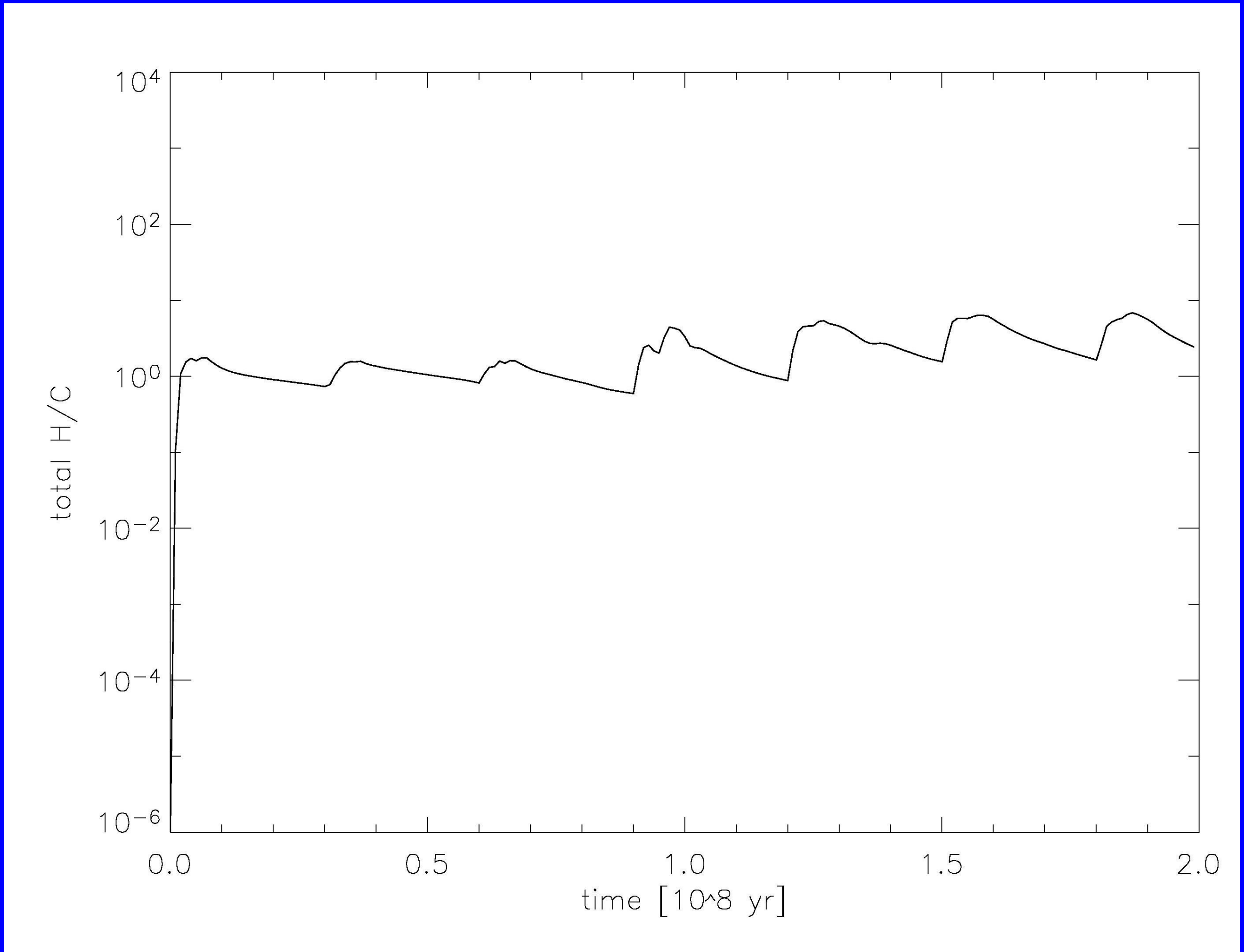
Fabian et al. 2003

Ruszkowski, Brüggen & Begelman 2004

3D Heating rate/ Cooling rate

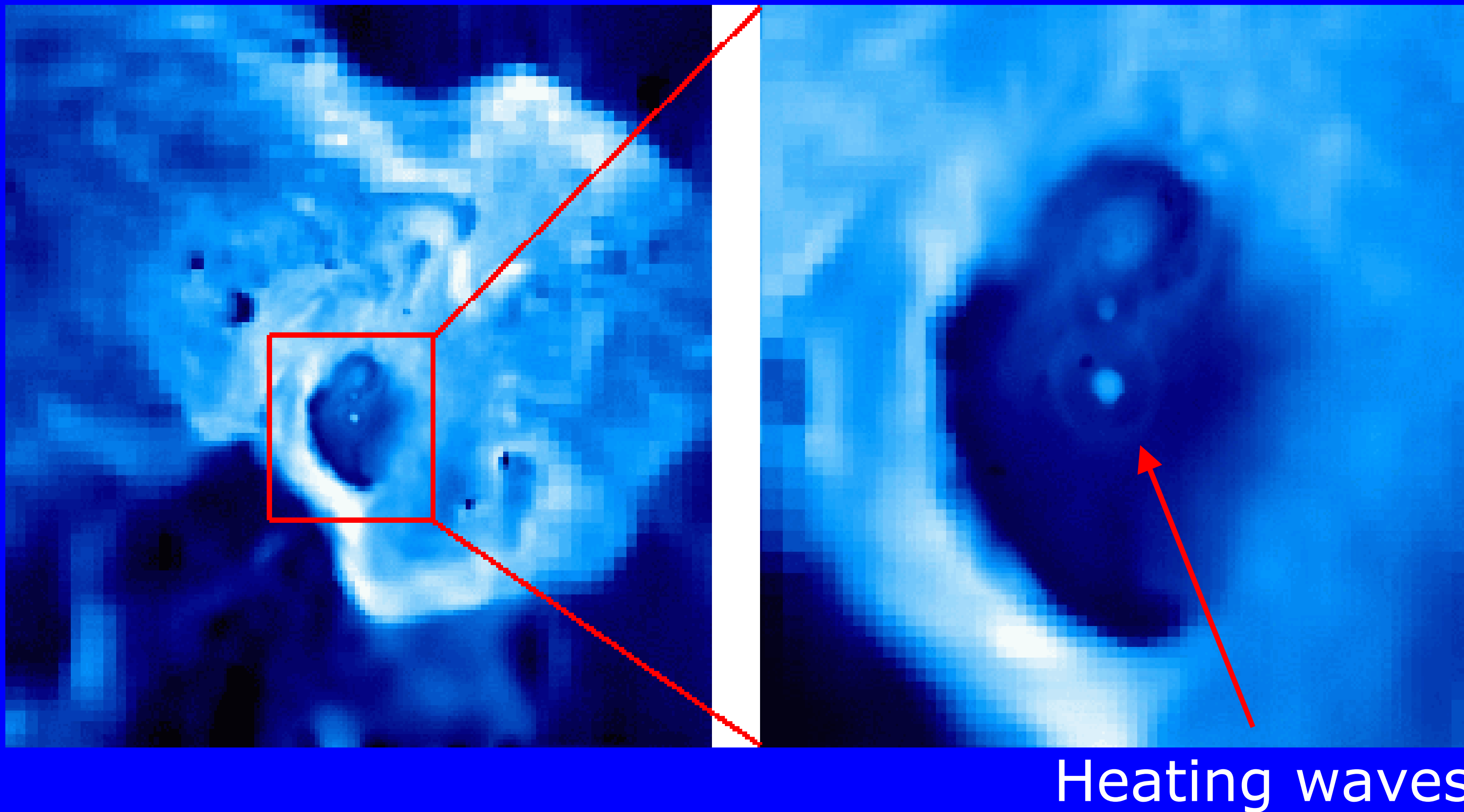


3D GLOBAL HEATING



Ruszkowski, Brüggen & Begelman 2004

AGN HEATING in the COSMOLOGICAL ENVIRONMENT

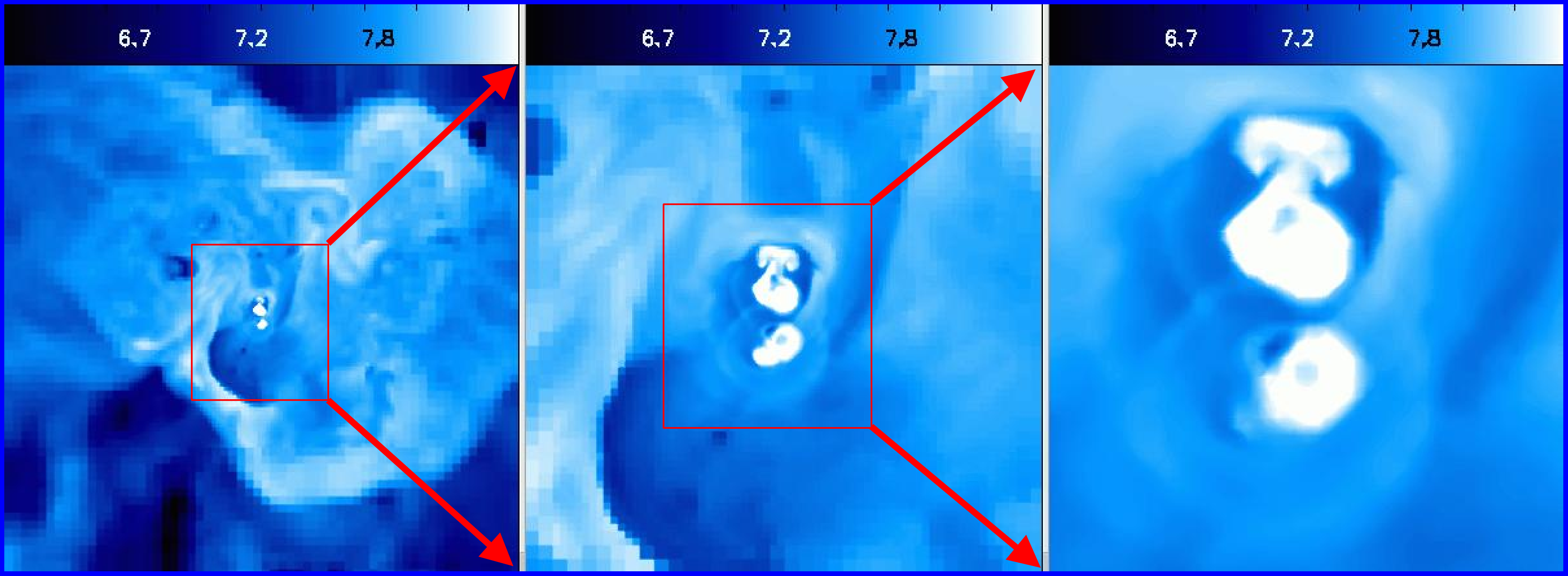


Physics : gas, DM, viscosity, conductivity, AGN heating

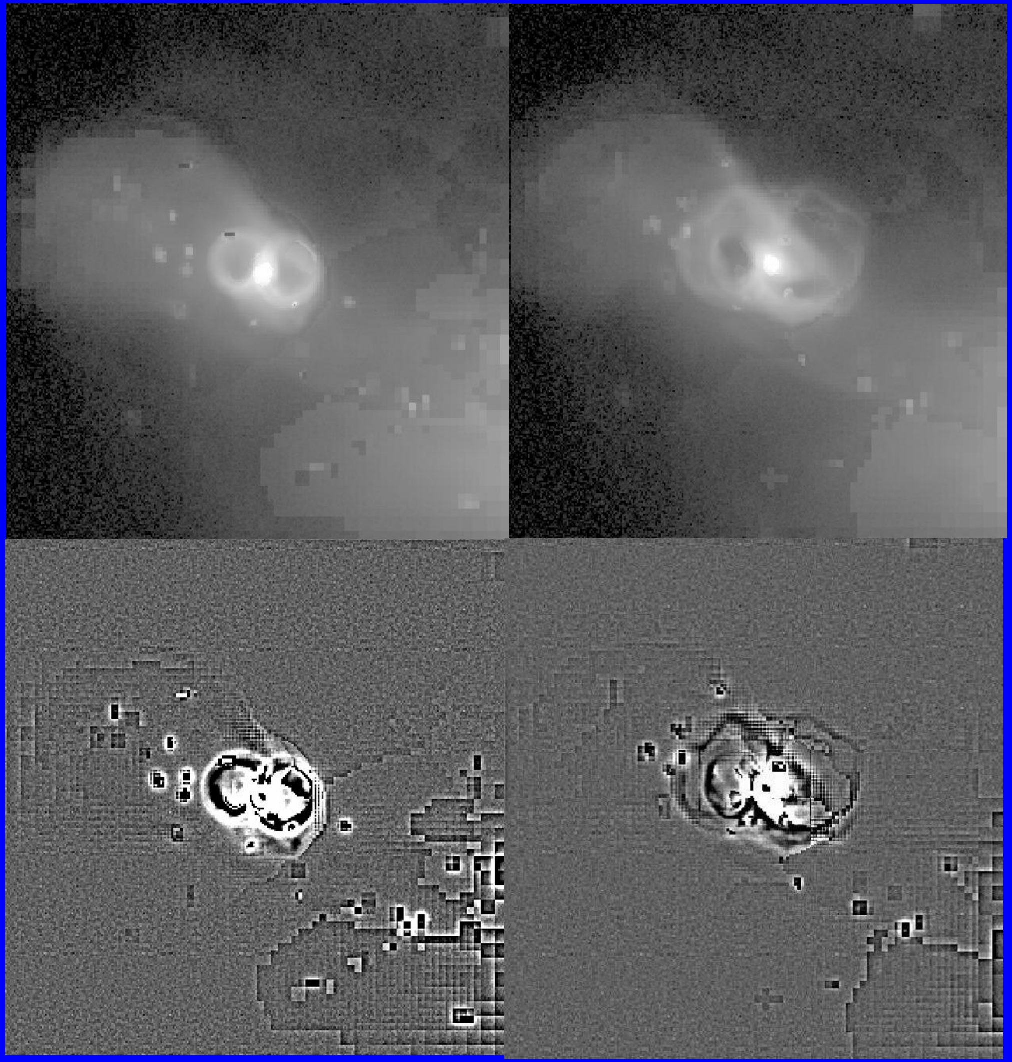
7 levels of AMR: initial conditions from Springel et al. 2001

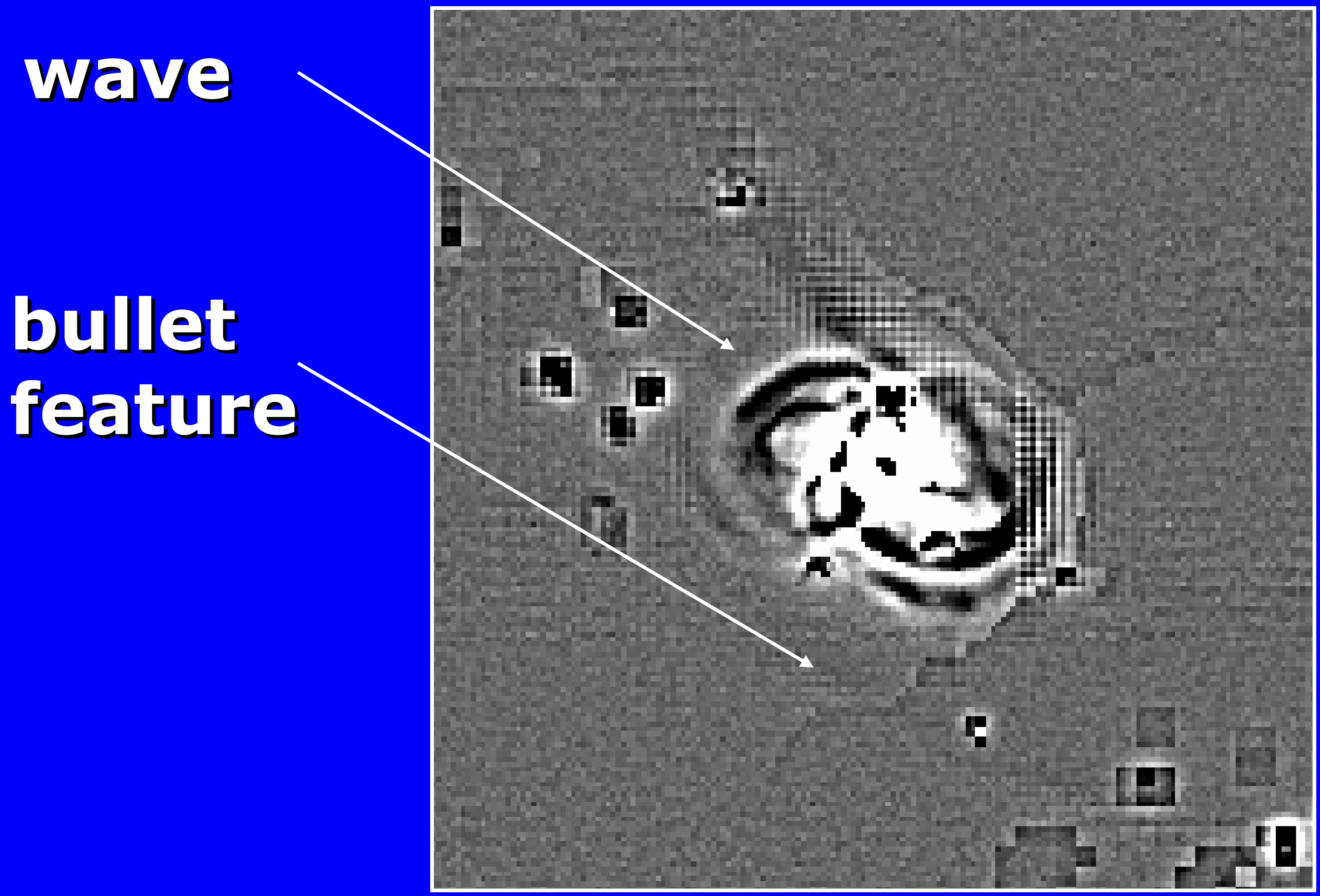
Brüggen, Ruszkowski & Hallman 2005

Buoyantly rising bubbles – temperature slice



SYNTHETIC *Chandra* OBSERVATIONS




wave
bullet
feature

cluster extracted from a full COSMOLOGICAL SIMULATION

~2.5Mpc **~400kpc**

Evolved for ~ 250 Myr

CONCLUSION

BUBBLES INFLATED BY AGN JETS CAN PROVIDE GENTLE, DISTRIBUTED HEATING OF CLUSTER GAS

Rough consistency with entropy floor, cooling flows, morphology ….

…BUT MANY UNCERTAINTIES REMAIN

- **ENERGY TRANSFER FROM BUBBLES TO ICM**
  - Sound waves (requires intermittency)
  - Conduction, "viscosity"
  - Role of "cosmic rays"
    - Why do bubbles persist for so long?
    - CR transport hindered by plasma instabilities, can lead to effective heating at interfaces?
- **FEEDBACK**
  - What regulates energy injection?
- **EFFICIENCY**
  - Are the black holes big enough?
    - Do they lie above M–σ?