# Stirring and Heating the ICM with AGN Outflows: What are Simulations Telling Us ?

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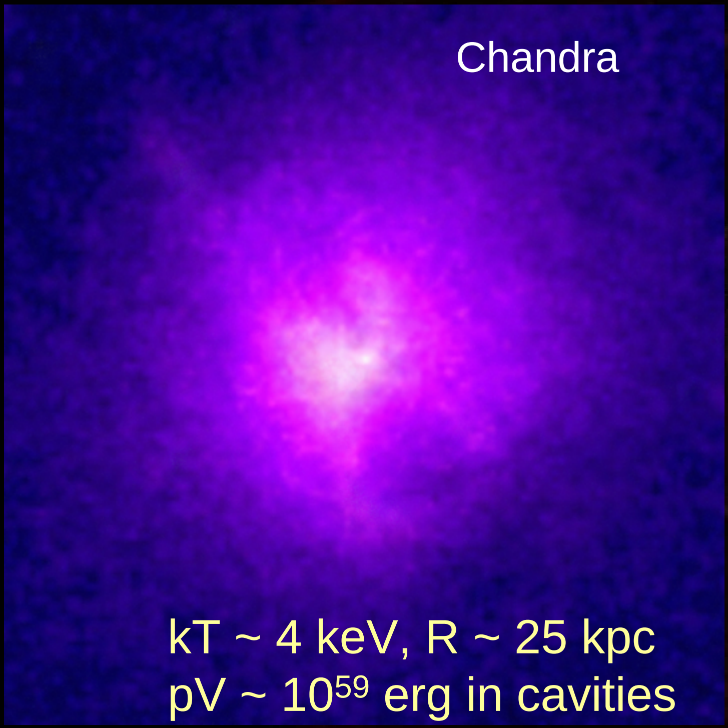
# Outline

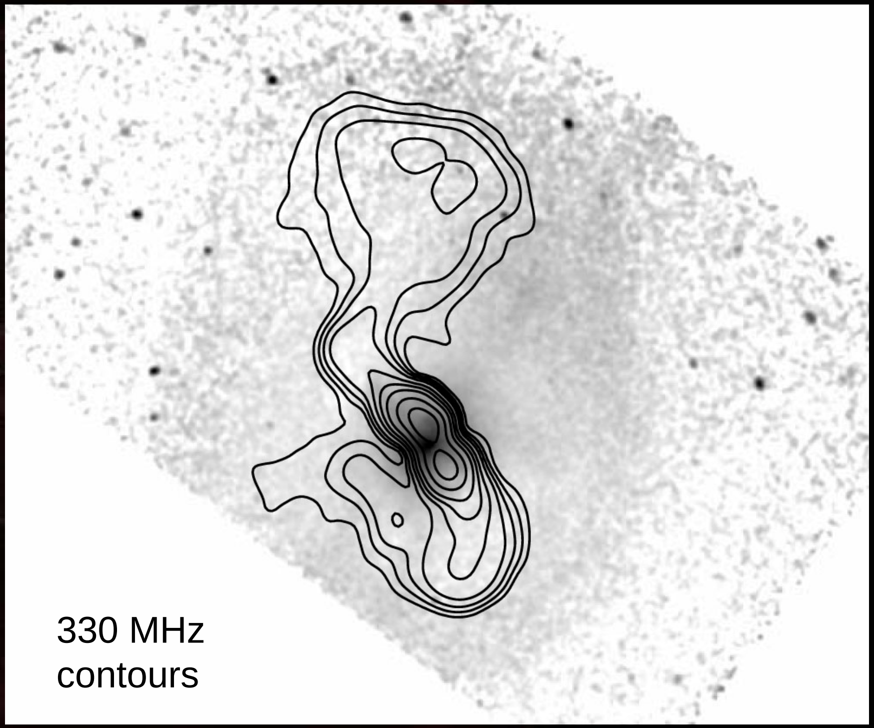
- Motivations
- Some Empirical Evidence
- Jets
- Bubbles
- Conclusions

# Motivations:

- "Cooling Flow Problem" (e.g., Tabor & Binney 1993, Fabian 1994, Peterson etal 2003)
- Entropy "Floor" (e.g., Ponman etal 1999)
- AGNs in cD galaxies in cooling clusters (e.g., Burns & Owen 1977, Best etal 2007, Magliocchetti & Brueggen 2007)
- Rough match of energetics ($L_x \sim L_{AGN} \sim 10^{45}$ erg/s)
- Key Questions:
  - How and how well are AGNs & ICM coupled?
  - Feedback? (Accretion feeds AGN, AGN outflow limits accretion)
  - Long-term balance? (e.g., Tabor & Binney 1993)

# Empirical Evidence of AGN Connection: Radio-filled X-ray cavities & shocks: Hydra

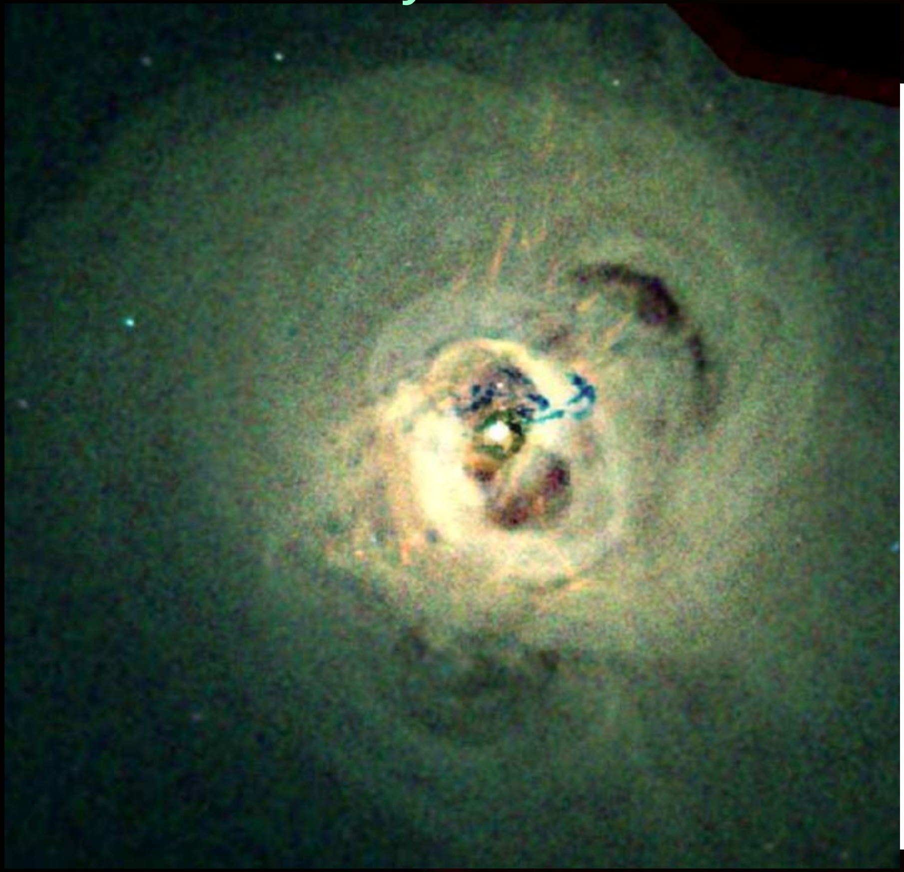


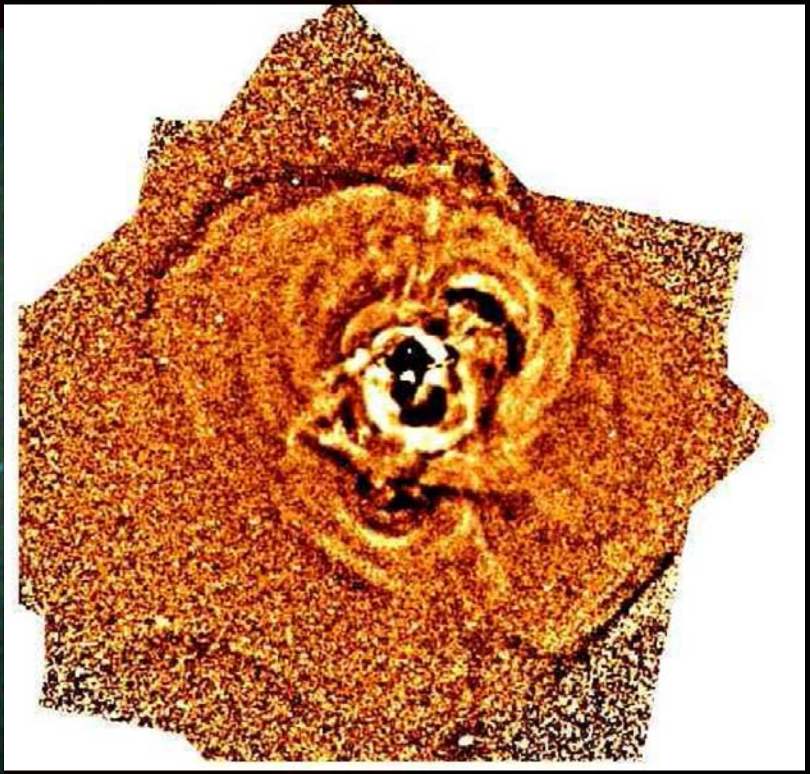




Nulsen etal 2005

Shock M ~ 1.2-1.4, R ~ 200 kpc
$t_{shock}$ ~ 140 Myr, E ~ $10^{61}$ erg,
$L_{AGN}$ ~ $2 \times 10^{45}$ erg/s

# Empirical Evidence of AGN Connection: X-ray cavities & ICM Ripples: Perseus





Ripples out to ~ 50 kpc
pV ~ $10^{59}$ erg in cavities

Fabian etal 2006

# Empirical Connection:
# Correlation of Implied Jet Power and Bondi Accretion Power

9 nearby ellipticals with cavities & good BH mass estimates

$$P_{jet} = 4pV_{cav}R / c_s$$

$$P_{Bondi} = \eta \dot{M}_B c^2$$

$$\dot{M}_B \sim 4\pi\rho r_B^2 c_s$$

$$r_B = 2GM_{BH}/c_s^2$$

$$\eta = 0.1$$

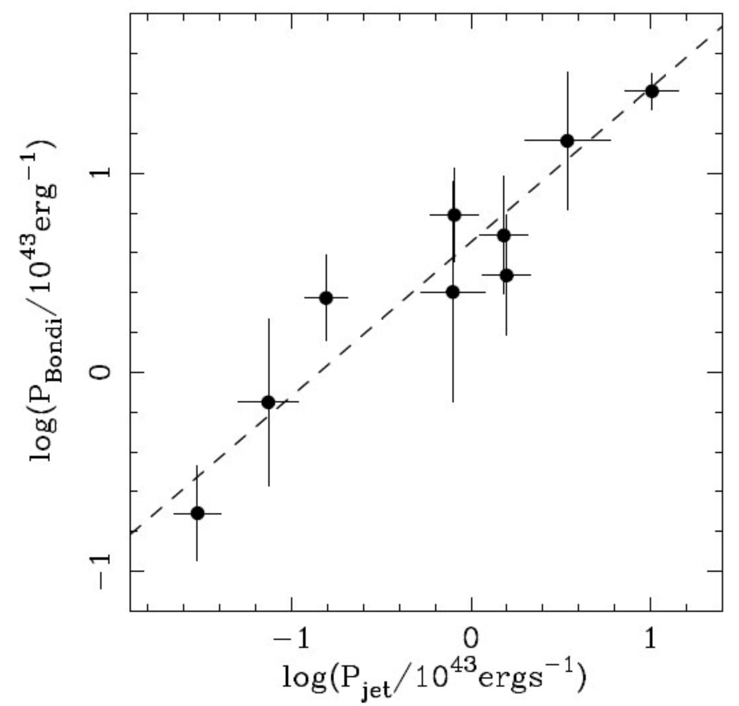



**Figure 4.** The logarithm of the Bondi accretion power (in units of $10^{43}$ erg s$^{-1}$) determined from the Chandra X-ray data, assuming an efficiency $\eta = 0.1$ for the conversion of rest mass into energy, versus the logarithm of the jet power (also in units of $10^{43}$ erg s$^{-1}$). The dashed line shows the best-fitting linear-plus-constant model, determined using the BCES estimator. (See text for details.)

Allen etal 2006

See also Birzan etal 2008

# Some issues simulations can help address:

(> 30 yr theory/simulation history)

- Efficiency of ICM heating, entropy generation

- Relative roles of active outflow vs buoyant bubbles
  - Dynamical feedback mechanisms
  - Stability

- AGN driven convection?

- Sustained feedback?

# Focus Here on 3D Simulations

Incomplete list of published 3D simulations addressing some of these issues:

Clarke etal 1997
Churazov etal 2001
Quilis etal 2001
Brueggen etal 2002
Basson & Alexander 2003
Omma etal 2004
Dalla Vecchia etal 2004
Ruszkowski etal 2004
O'Neill etal 2005
Vernaleo & Reynolds 2006
Heinz etal 2006
Ruszkowski etal 2006
Nakamura etal 2007
Ruszkowski etal 2008
Xu etal 2008

# A Set of 3D MHD Jet Simulations (+ Relativistic Electrons)

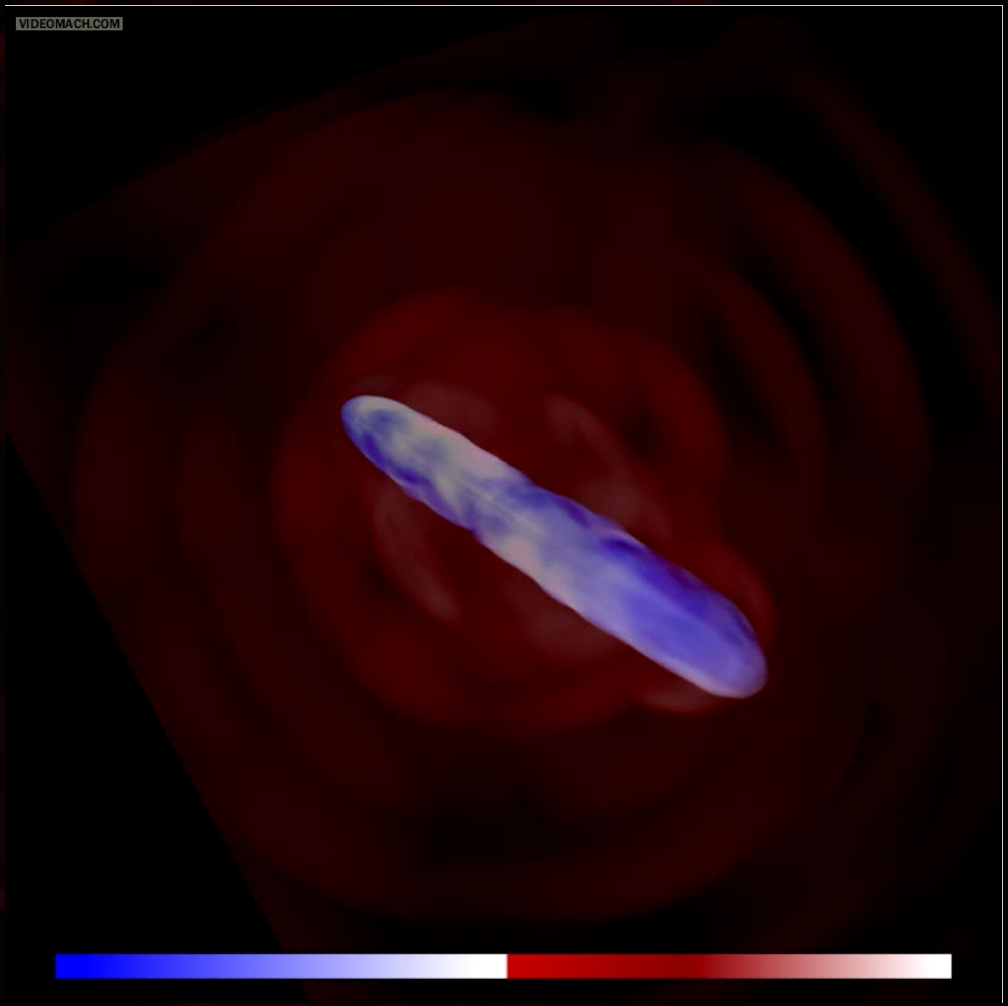
O'Neill & Jones 2008

- Bipolar, collimated Mach 30 outflows
  - 600x480x480 kpc box (1 kpc resolution)
  - $P_{jet} \sim 10^{45}$ erg/s
  - $r_{jet} = 3$ kpc
  - $\rho_{jet}/\rho_{I} = 0.01$
  - Toroidal B field

- AGN at center of ~ $10^{15}$ $M_o$ cluster (NFW potential)
  - $kT_{ICM}$ ~3keV
  - Double $\beta$ profile with random density fluctuations
  - Tangled ICM magnetic field
  - $\beta_{plasma} \sim 100$ ($B_{core} \sim 7\mu G$)
  - No radiative cooling of ICM

- Passive `CR' electrons, shock injection & DSA
  - Adiabatic & radiative (synch, IC) losses

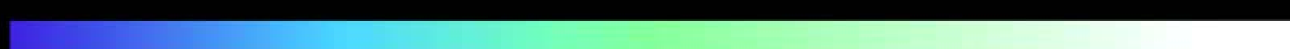
# Steady Jets ($t_{end}$ ~ 60 Myr)




Magnetic Field Intensity

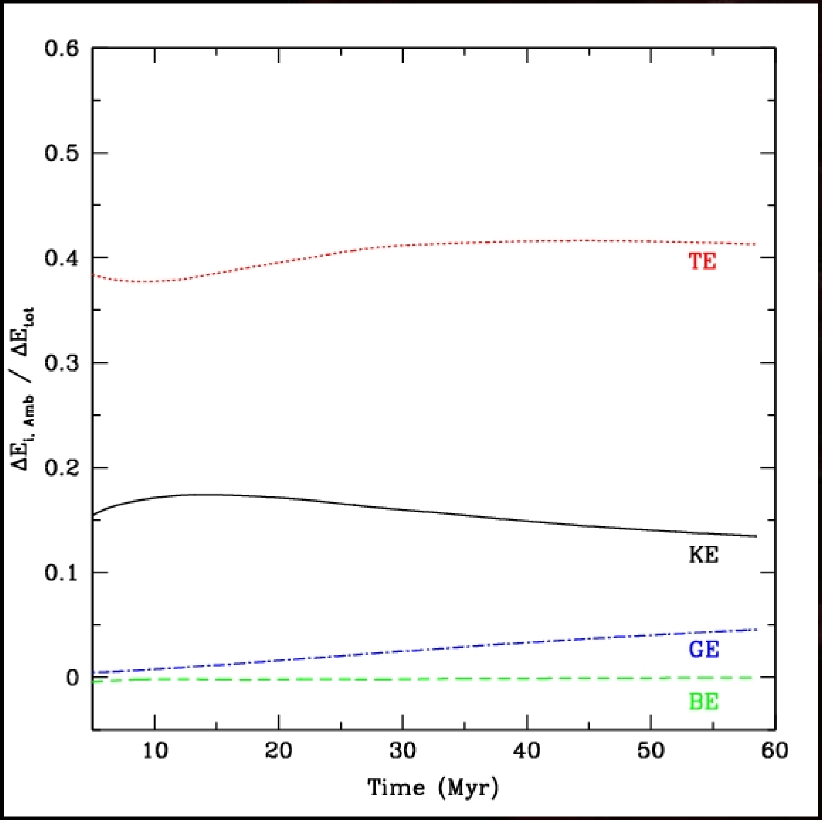
Blue (AGN plasma)
Red (ICM plasma)

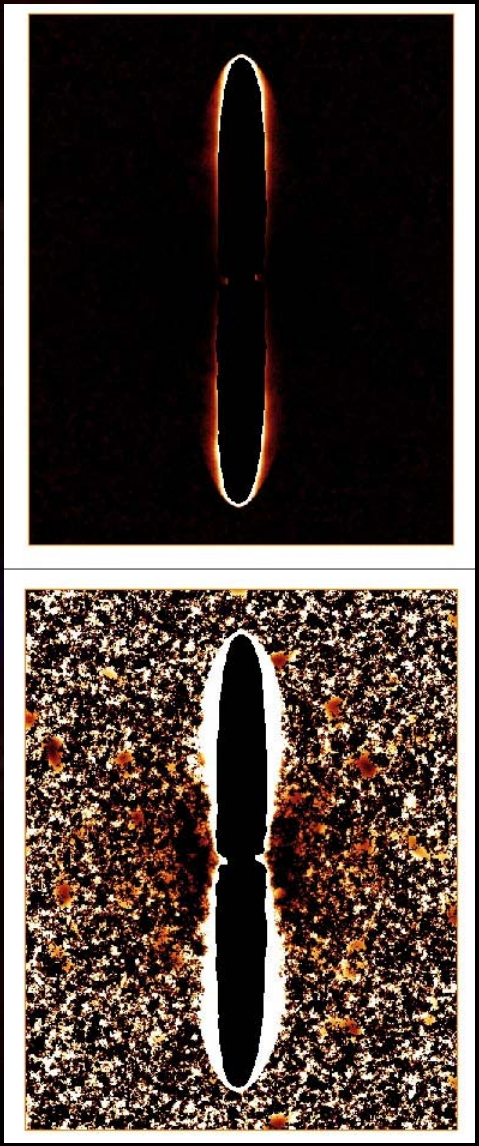
# Shocks in Steady M=30 Jets



# Net Energy Fraction Deposited in ICM by Steady Jets

TE(Thermal), KE(Kinetic), GE(Gravitational), BE(Magnetic)



Specific Entropy

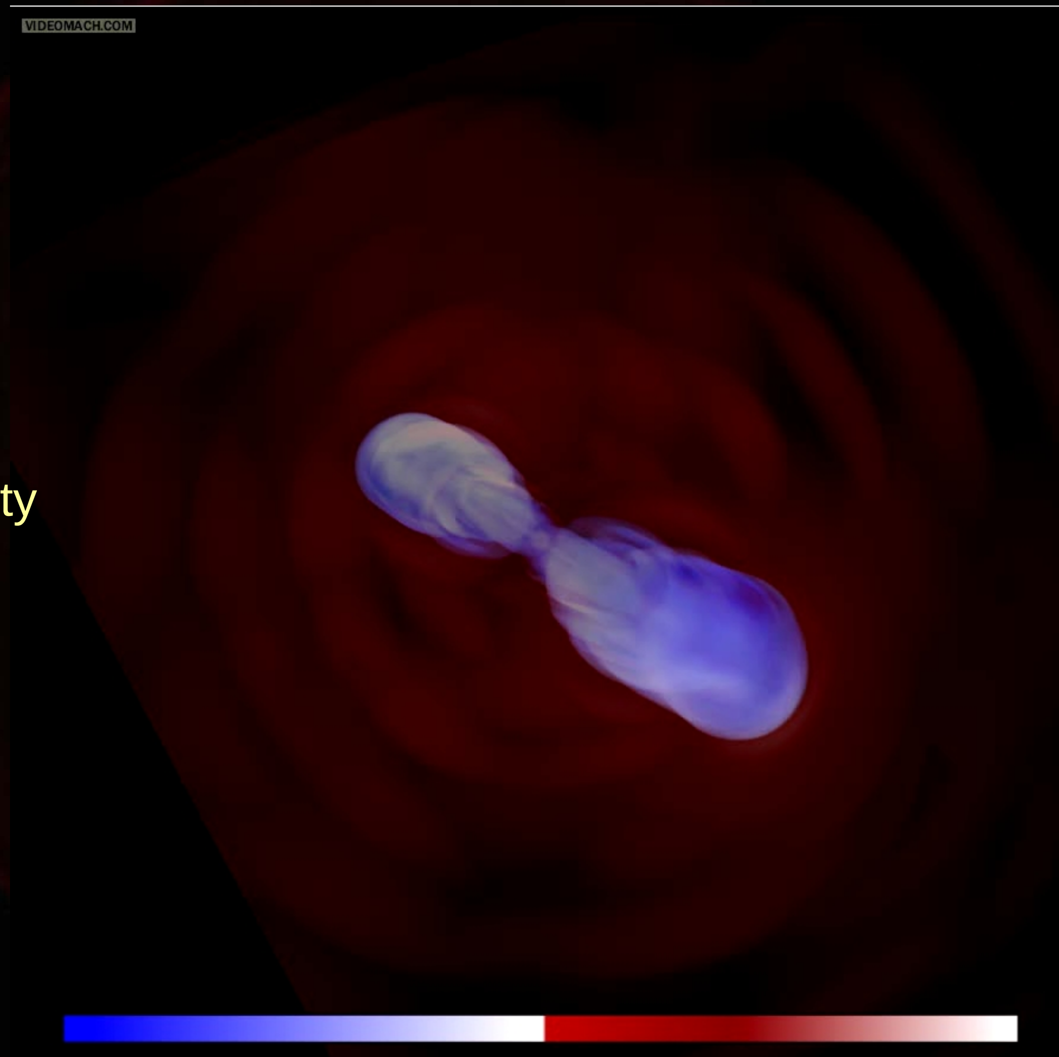
# Intermittent Jets ($t_{end}$ ~ 173 Myr)

$t_{on}$ = 13 Myr
$t_{off}$ = 13 Myr

Six cycles

Magnetic Field Intensity

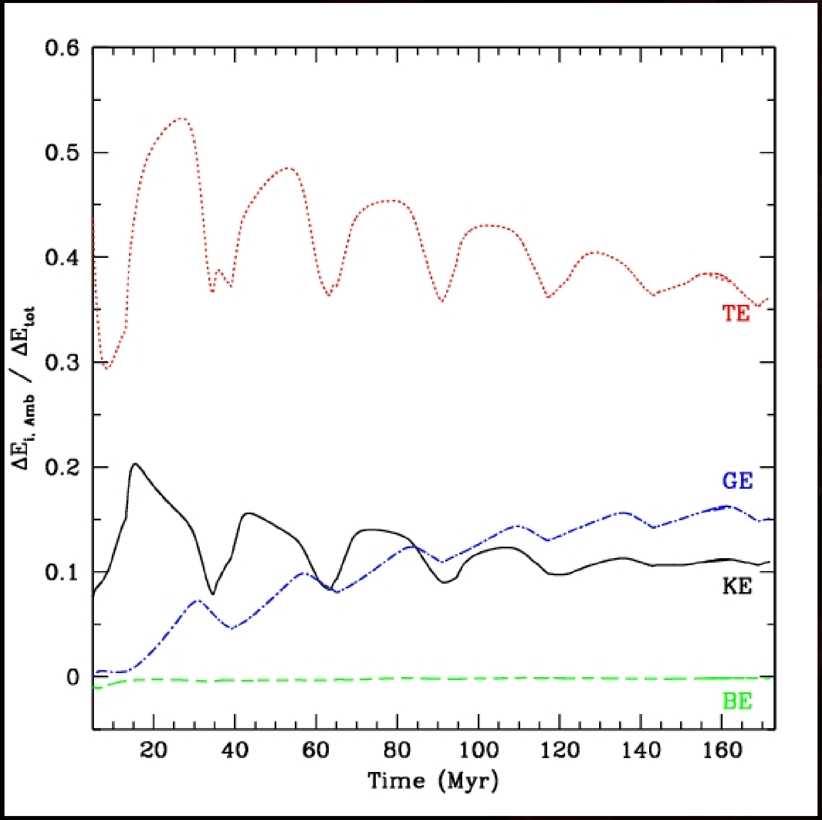
Blue (AGN plasma)
Red (ICM plasma)

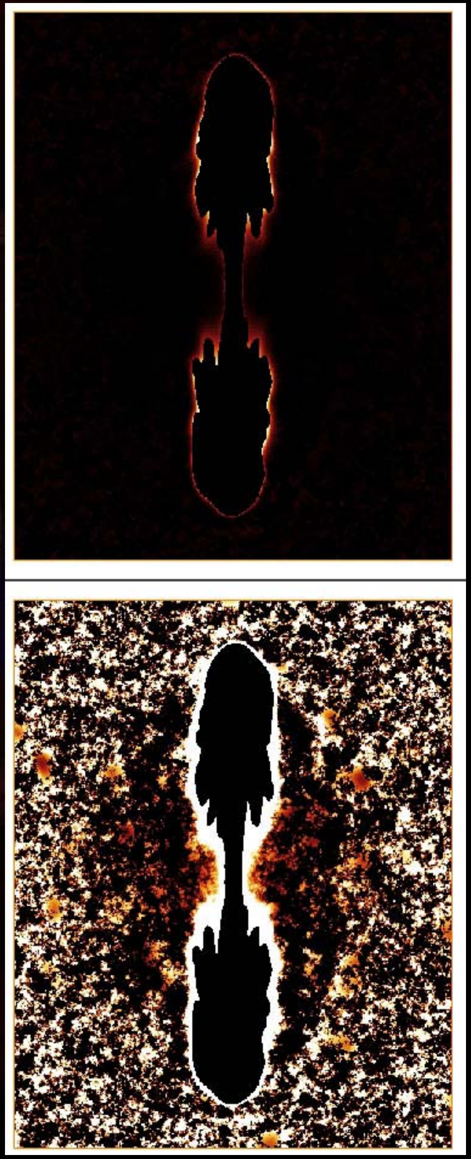


# Shocks in intermittent jet

# Net Energy Fraction Deposited in ICM by Intermittent Jets

TE(Thermal), KE(Kinetic), GE(Gravitational), BE(Magnetic)

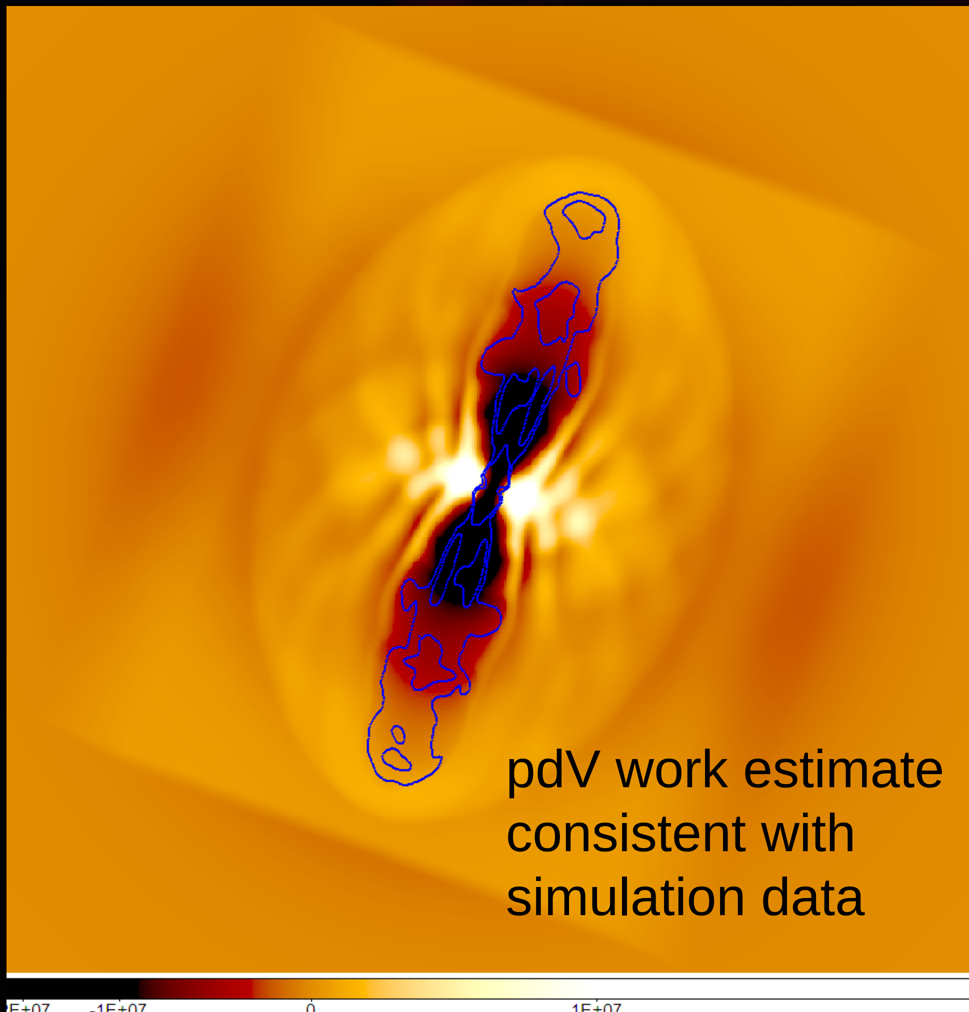


Specific Entropy

# Intermittent Jets:

## Synthetic X-ray & Radio Observations, t ~ 170 Myr




pdV work estimate consistent with simulation data

Color: 2 keV intensity
Contour: 300 MHz
~ 2 arc sec resolution
for D = 240 Mpc

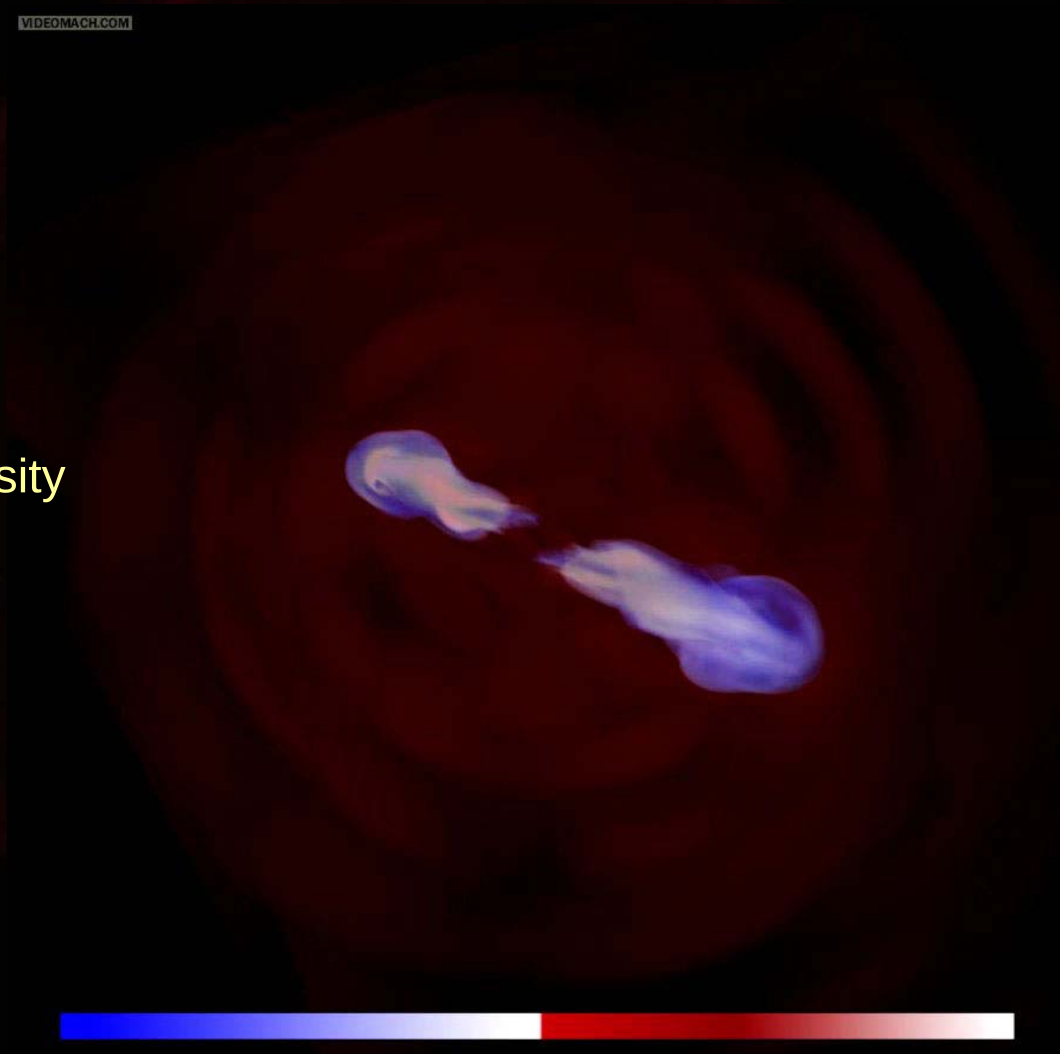
See Pete Mendygral's poster for details

# Terminated Jets (Relic) ($t_{end}$ = 144 Myr)

$t_{on}$ = 26 Myr

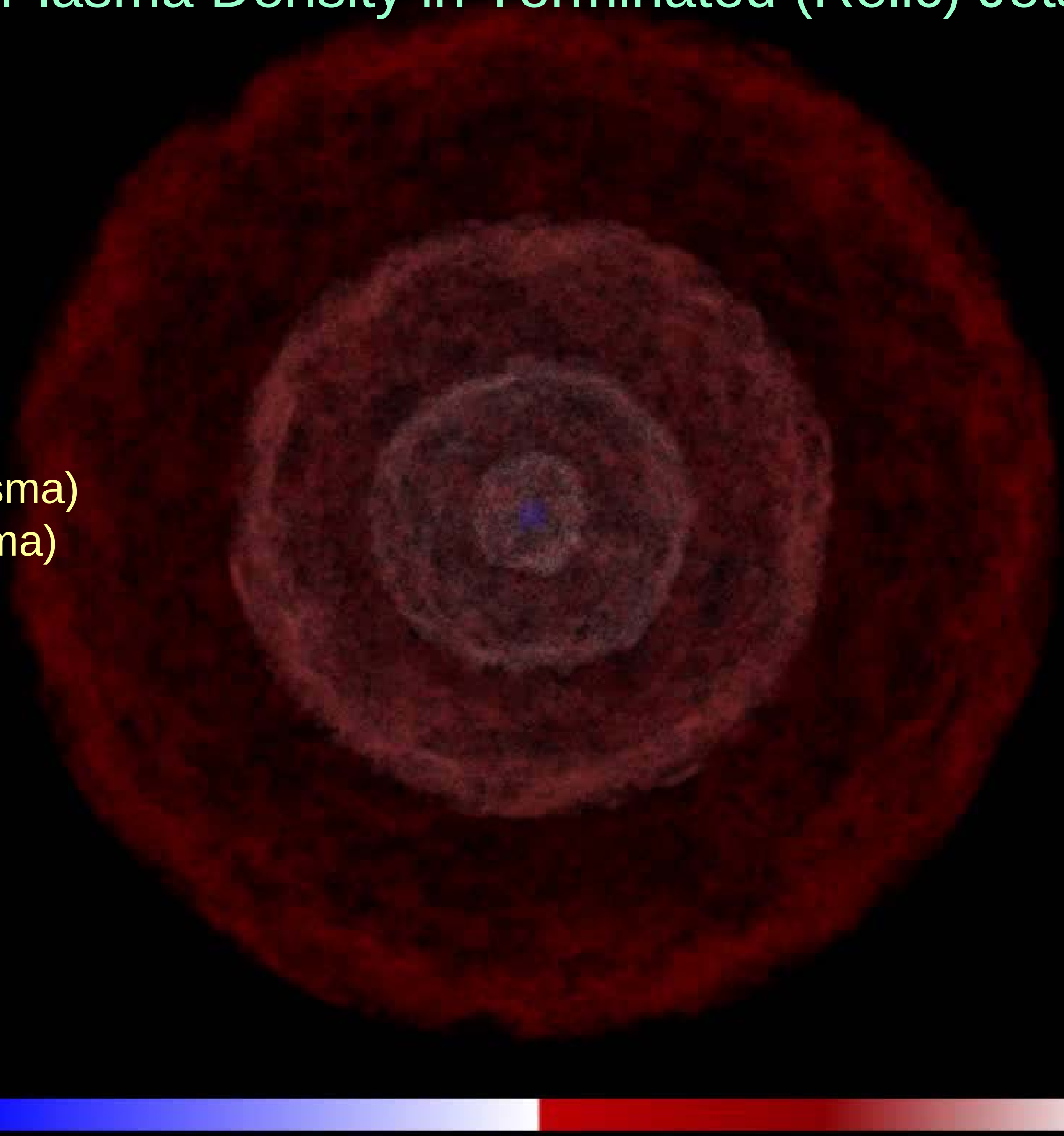
Magnetic Field Intensity

Blue (AGN plasma)
Red (ICM plasma)



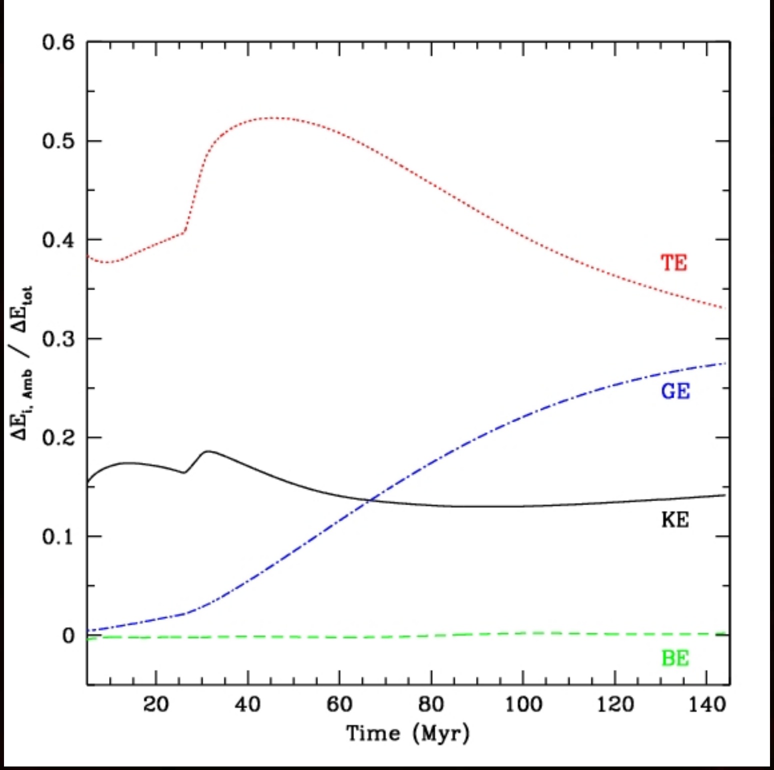
# Plasma Density in Terminated (Relic) Jets

Blue (AGN plasma)
Red (ICM plasma)

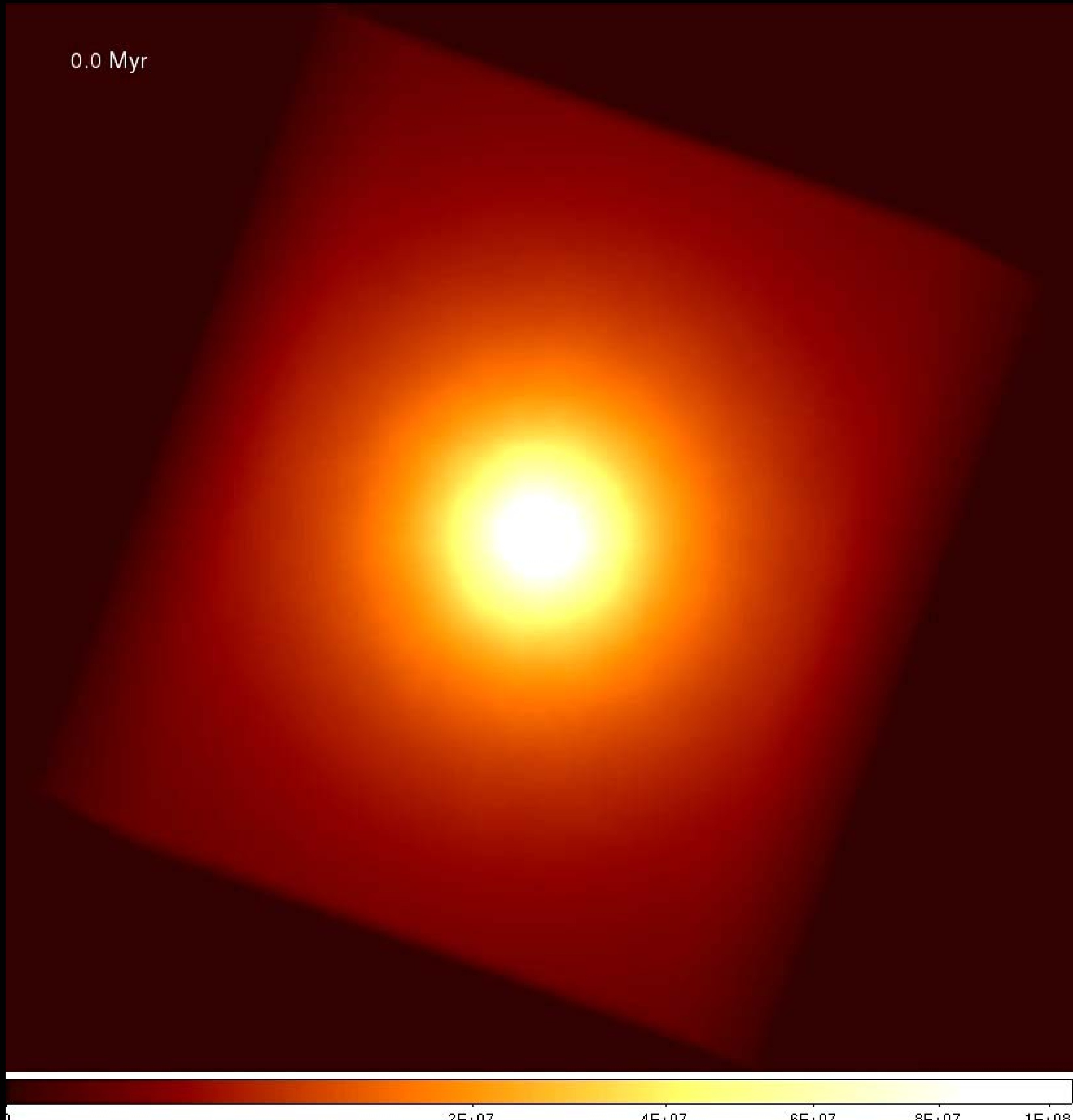


# Net Energy Fraction Deposited in ICM by Terminated Jets

TE(Thermal), KE(Kinetic), GE(Gravitational), BE(Magnetic)



2 keV
animation




tensity
MHz
solution
pc

ygral’s poster

# Sustaining Feedback

- Can energy & momentum deposition limit accretion?
- Is there an equilibrium or Limit cycle?

# Vernaleo & Reynolds 2006

AGN outflow "fed" by accretion through Inner radius (10 kpc)

$P_{jet} = 10^{-5}$ (dM/dt) $c^2$, opening angle $15^o$

Initially spherical $\beta$-law ICM density

Radiative cooling

# Resultant Mass Accretion Rates

Vernaleo & Reynolds 2006

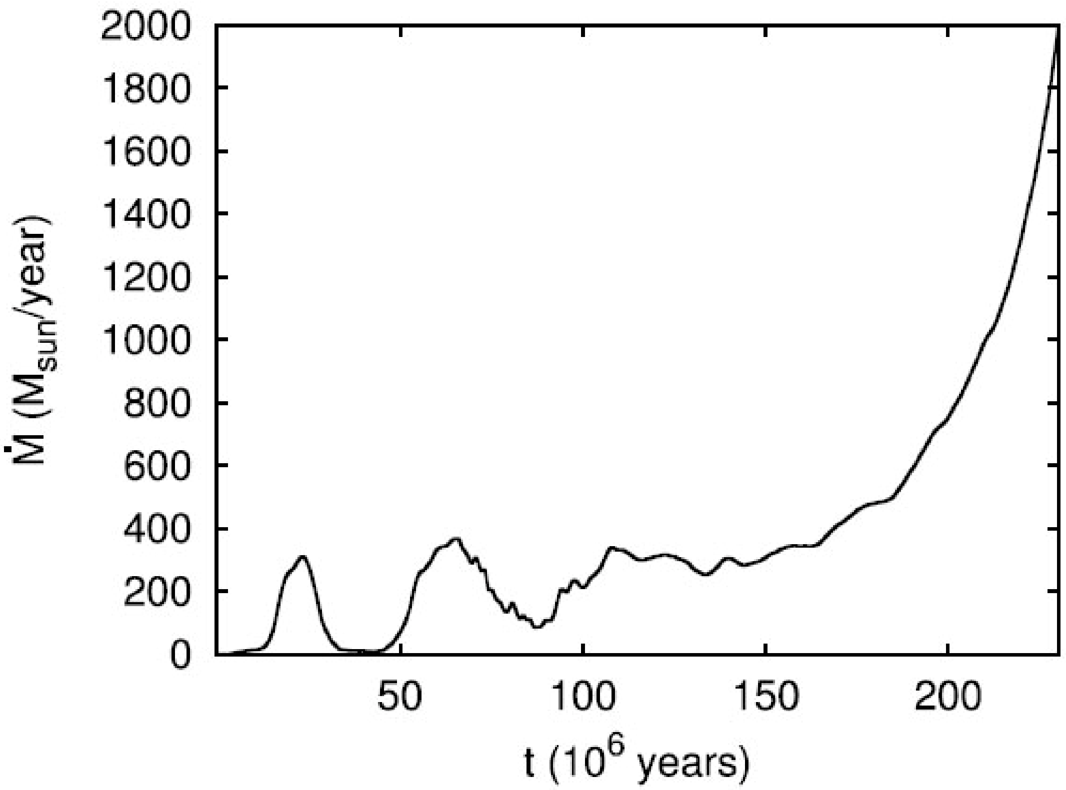



FIG. 5.—Mass accretion rate for feedback model (run E). [*See the electronic edition of the Journal for a color version of this figure.*]

# AGN Energy Is Channeled

Vernaleo & Reynolds 2006

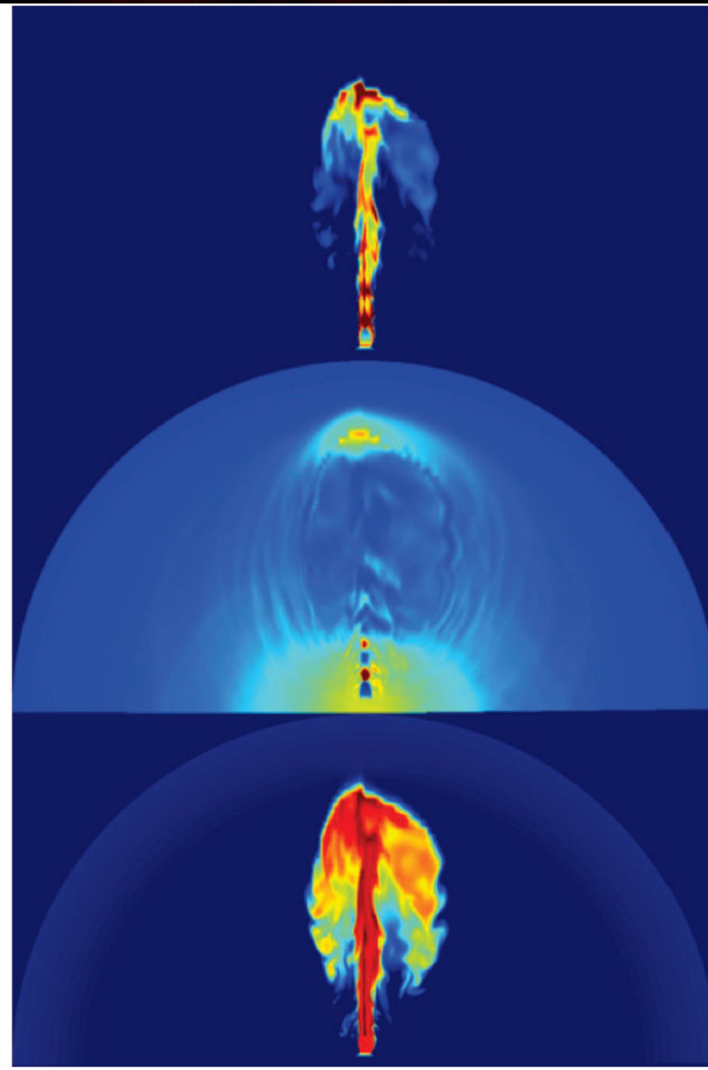


Fig. 6.—Temperature map (*top*), pressure map (*middle*), and entropy map (*bottom*) for immediate feedback jet. The temperature map only shows the highest temperatures to pick out primarily jet material. The thin, low-density channel can be easily seen in temperature and pressure (and, to a lesser extent, entropy). Only the inner 254 kpc of the simulation is shown.

T

P

$P/\rho^{5/3}$

# Channel effect can be reduced

- Poor collimation of AGN outflow
  (e.g., Sternberg & Soker 2008)

- ICM Inhomogeneities & dynamics
  (e.g., Heinz etal 2006)

--Of course many (most) real objects show clear breaks in simple, axial symmetry

# AGN Outflow into a Dynamic ICM

~$10^{15}$ $M_o$ cluster from SPH simulation

Disturbed, with large-scale shear & rotation

AGN jet on 33 Myr
$P_{jet}$ = $10^{46}$ erg/s, M = 32
Directional "jitter" 20$^o$

Net entropy increase
In inner ~100 kpc ~ 25%

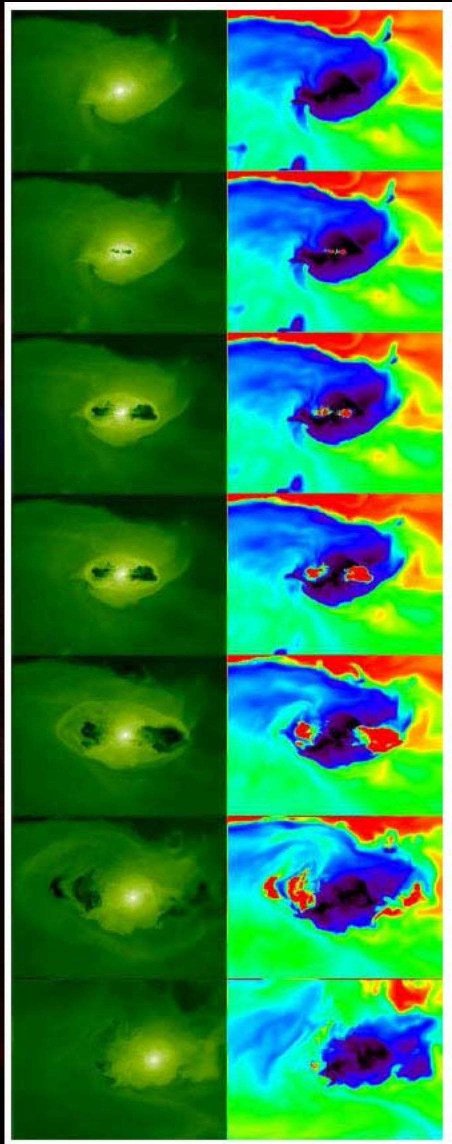


Figure 1. Top-to-bottom: Time series of snapshots at 0Myrs, 5Myrs, 10Myrs, 20Myrs, 40Myrs, 80Myrs, and 160Myrs after jet onset. Left-to-right: (a) density cut through cluster centre, (b) entropy cut through cluster centre. The images are 450 kpc in width and 335 kpc in height.

Left (density)
Right (entropy)

t = 0, 10, 20, 40, 80, 160 Myr

(top to bottom)

Heinz etal 2006

# ICM/ AGN Feedback

Mass Distribution --- channel is disrupted by ICM

Deposited energy becomes broadly distributed

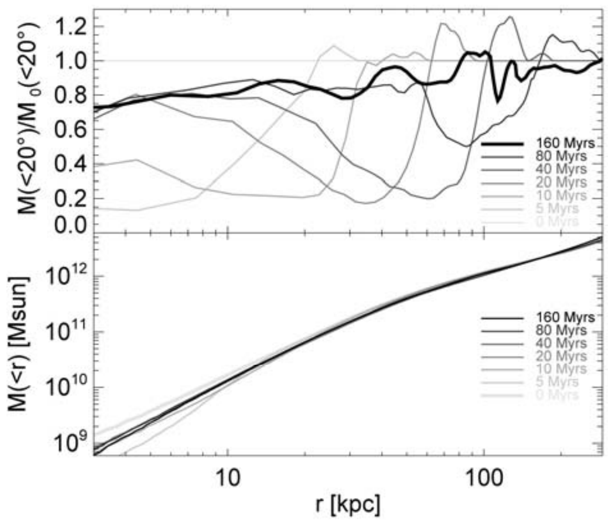



**Figure 3.** *bottom panel:* cumulative mass $M_{\rm R}$ within radius $r$ as a function of $r$ at different times (grey scales); note the general inflation of the cluster atmosphere by the energy injection into the centre; *top panel:* ratio of target mass $M_{20}$ (mass contained within 20° of jet axis) over $M_{20}$ for the control simulation, indicating the relative gas depletion around the jet axis. The residual $\sim$ 20% reduction after 160 Myrs is consistent with the general reduction in density seen in the $M_{\rm R}$.

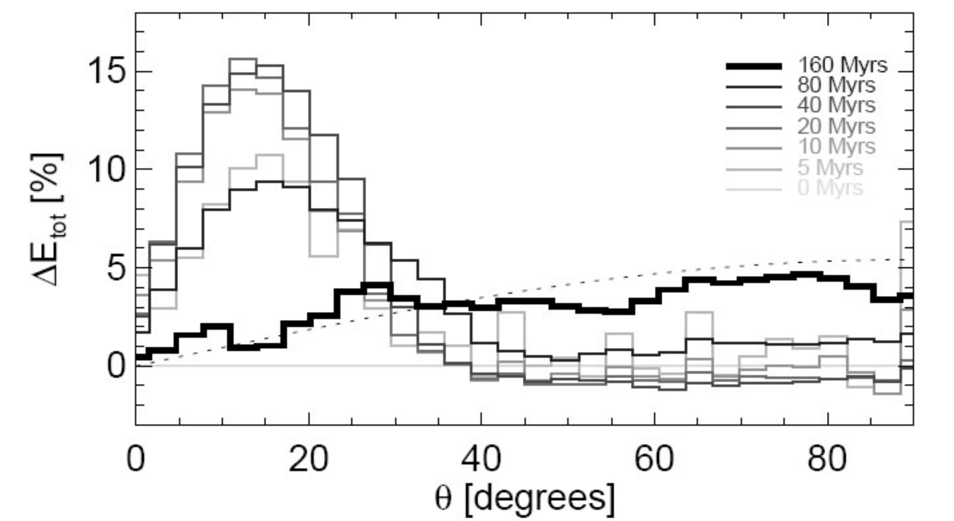



**Figure 5.** Angular distribution (relative to mean jet axis) of excess energy $\Delta E$ injected by jet into thermal gas phase as percentage relative to total injected energy. For comparison, the dotted line shows the isotropic case.

Heinz etal 2006

# Bubble Models:
## Depositing Energy Only

- Study buoyant transport
- Explore stability issues

# Preformed Bubbles tend to evolve into rings

Bubble animation

Hot Bubble:
Inflated in stratified atmosphere
MHD with weak field
$t_{inf}$ = 10 Myr; $h/c_s$ = 25 Myr

O'Neill etal 2008



# Long inflation leads to “jets”

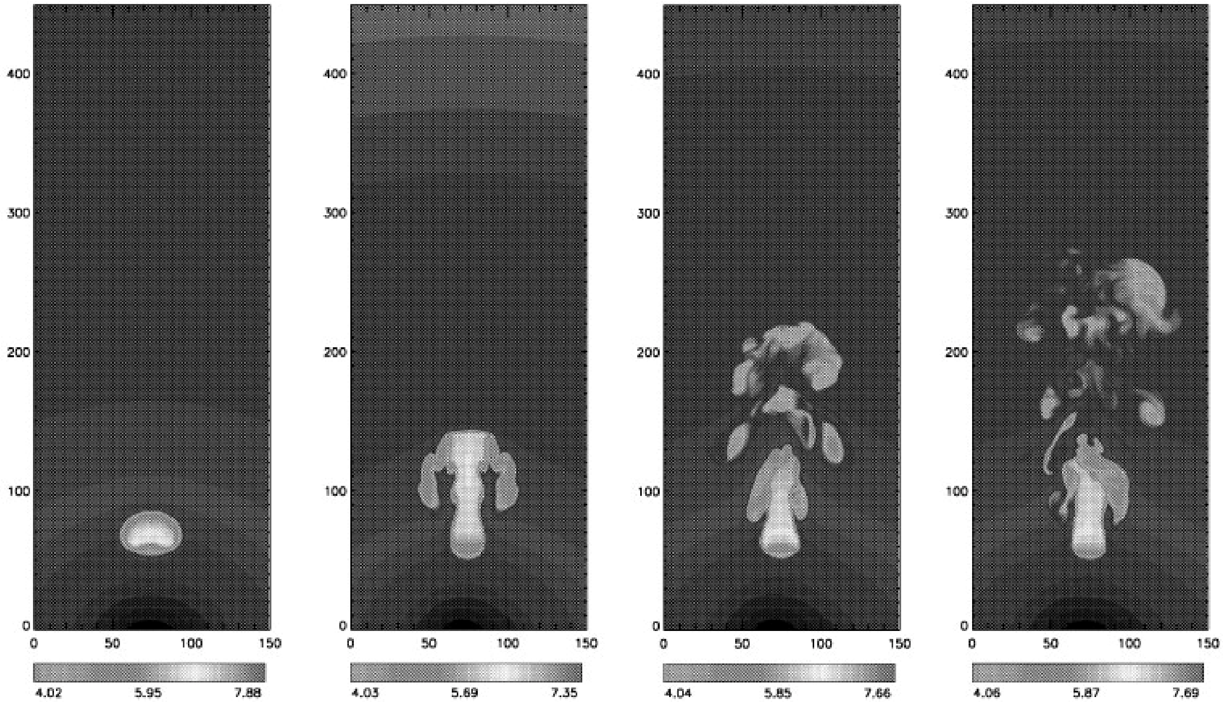



**Figure 3.** Snapshots of specific entropy in a vertical slice through the computational domain for $L = 4.4 \times 10^{41}$ erg s$^{-1}$ at the same times as in the previous plot (run 1). This figure is available in colour in the on-line version of the journal in *Synergy*.

Brueggen etal 2002

# Magnetic Fields Can Be Some Help to Stabilize Against Fragmentation (Details Matter)

t = 50, 80, 115 Myr

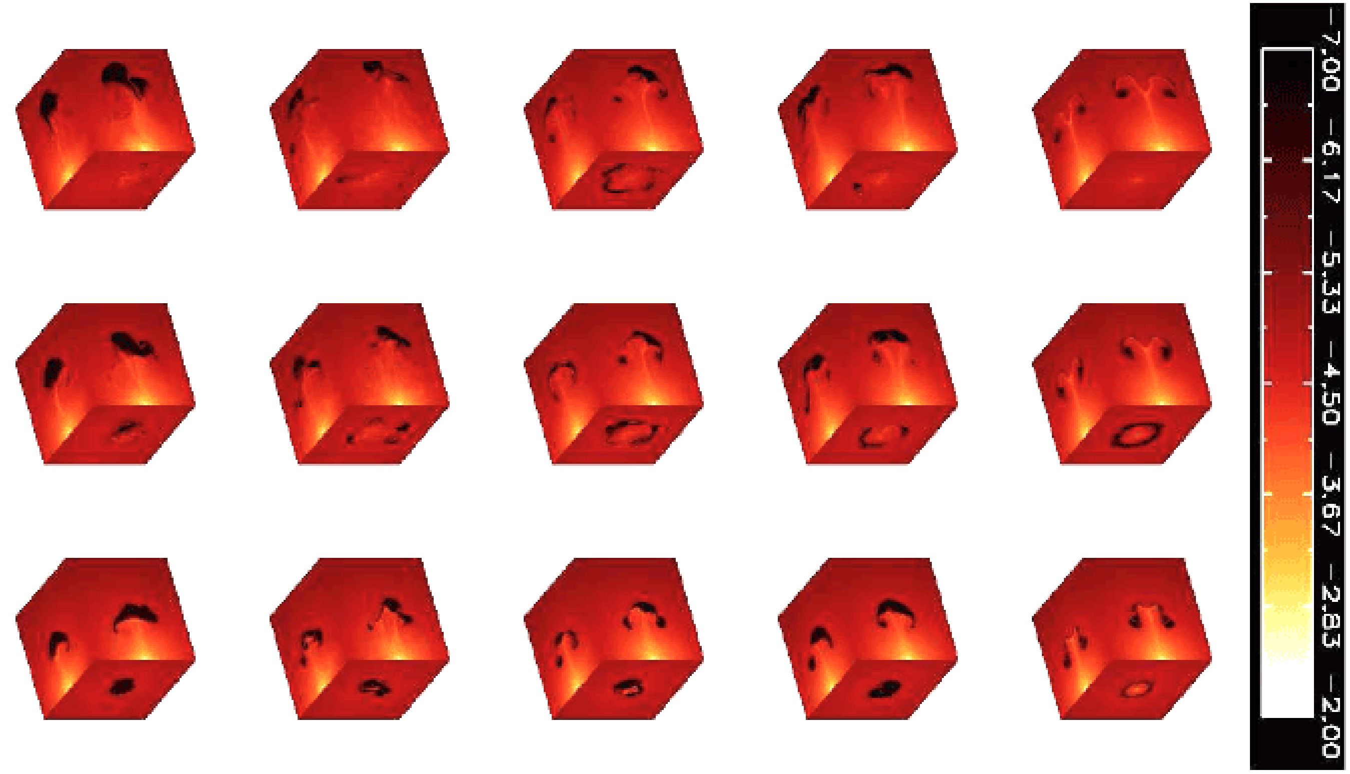



**Figure 4.** Natural logarithm of density in the cluster. Columns show time sequences of density for draping, random (i), random (ii), helical and non-magnetic cases from left column to the right, respectively. Rows correspond to time of 15.0, 25.0, 35.0 code time units from bottom to top. Sides of all boxes show densities in the planes intersecting the box and containing its center.

Ruszkowski etal 2006

# Conclusions

•AGNs likely do significantly stir and heat ICMs

•Effect on accretion depends on mechanisms to broaden influence
& redistribute ICM (e.g., poor or varying collimation,
dynamic ICM

•Simulations can be an invaluable tool here

•Observational energy estimates of jet power are reasonable measures

•Preformed buoyant bubbles not a good model for relic AGN plasma

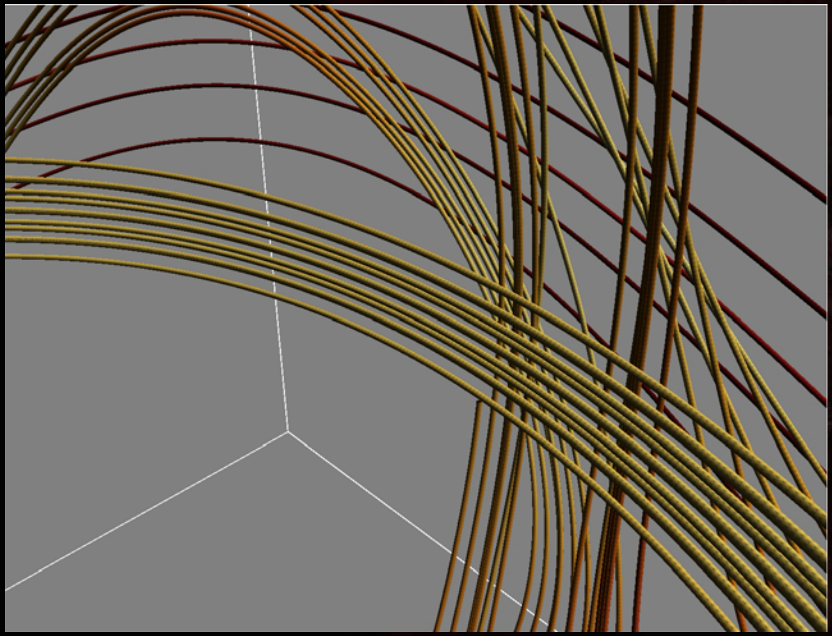
•Even weak magnetic fields can play important roles; topology dependent

•AGN & ICM magnetic fields likely to become interconnected

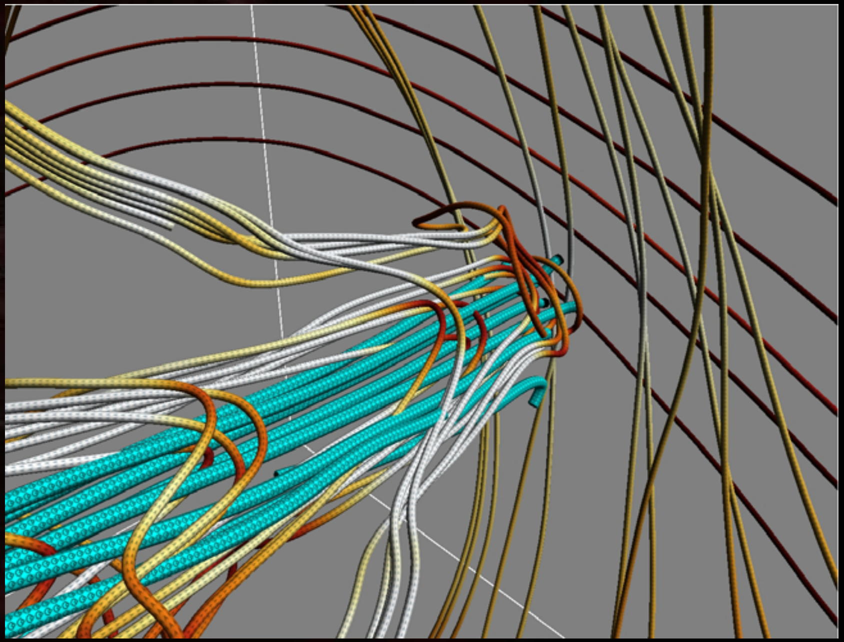
# The End

# Thanks!

# Relic Source Magnetic fields @ 120 Myr, R ~ 200 kpc



Before

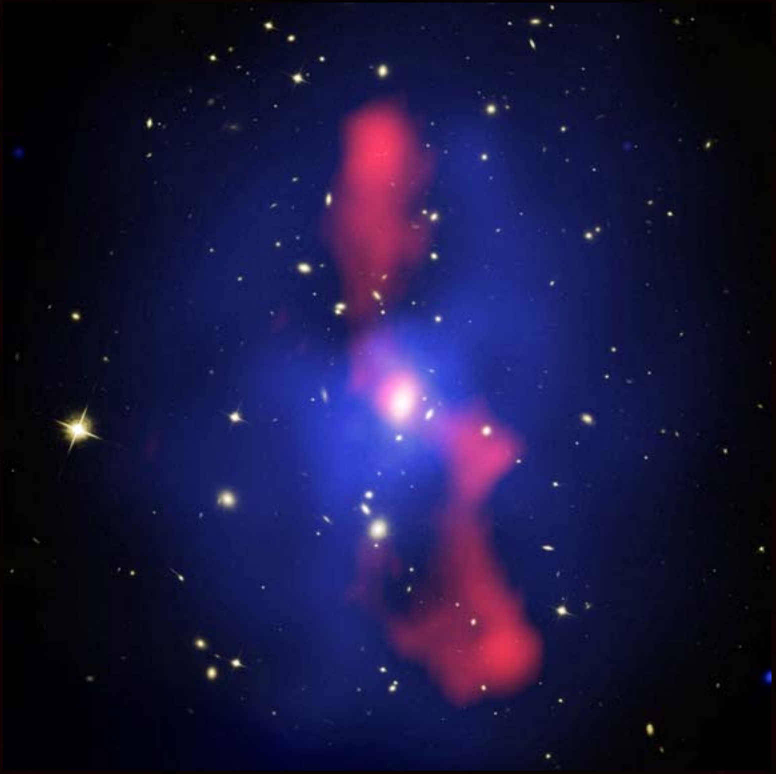


Bubble arrives

MS0735.6+7421

Composite:
Chandra, HST, VLA

McNamara etal 2005



Cavities ~ 200 kpc diam

pV ~ $6x10^{61}$ erg

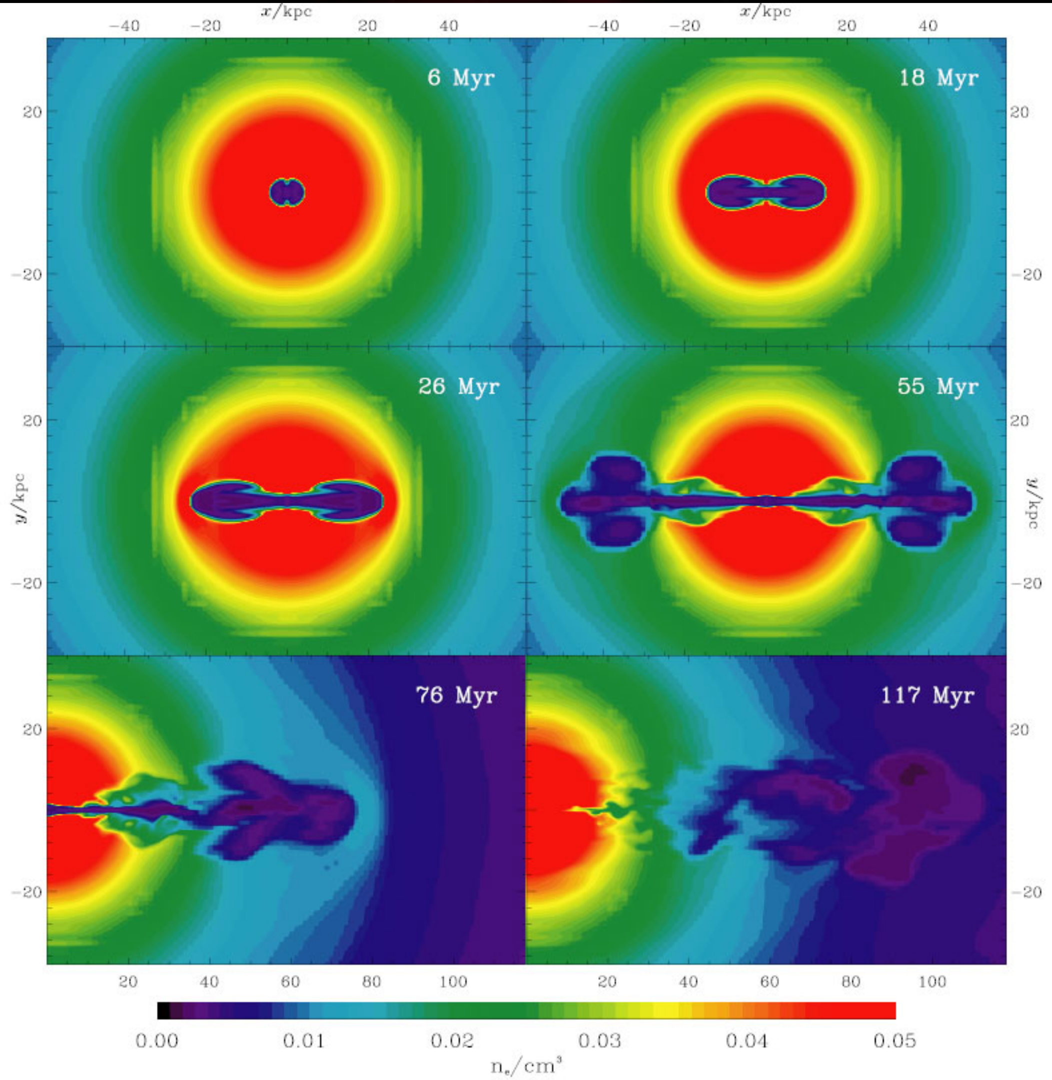



**Figure 4.** Density in the plane $z = 0$ at 6–117 Myr after the jets turn on, in the case of the 2-kpc jets. The intensity scaling and length-scale is the same for each image, but the last two panels show only the positive $x$-hemisphere.

Omma