AGN Outflows in Dynamic ICMs: Winds and Twists

Tom Jones
University of Minnesota

Pete Mendygral (UMN, Cray Computer)
David Porter (UMN)
Klaus Dolag (MPA, U Munich)

Outline

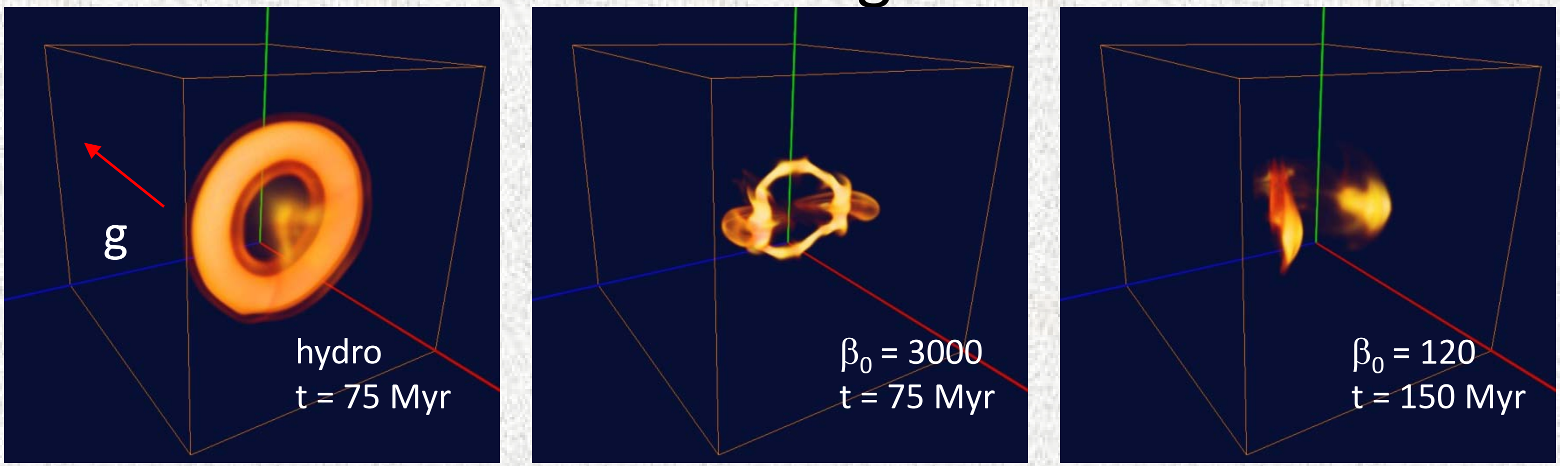
•AGN outflows (radio jets) are major dynamical & thermodynamical ICM components

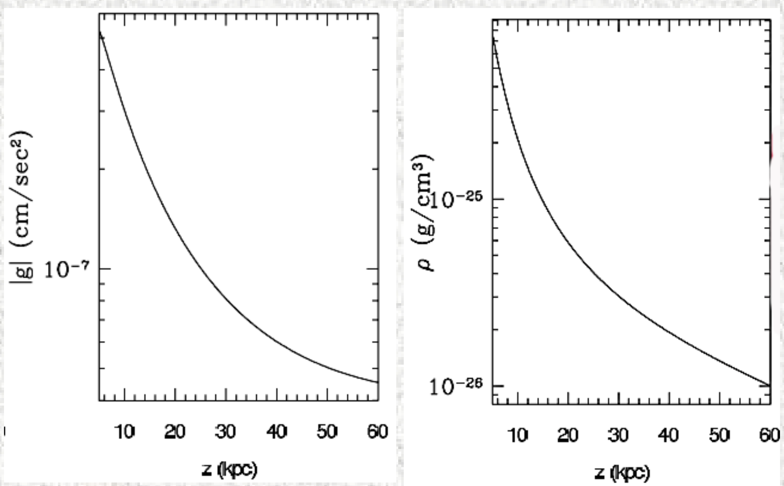
•AGN/ICM interactions may provide insights to AGN & ICM physics

•Is binarity in radio mode AGNs useful as a tool in these investigations?

Dave DeYoung was keenly interested in AGN/ICM interactions
(from 2007 Anchorage Workshop)

3D Buoyant Bubble – AGN-made ICM cavity: Role of the ICM magnetic field





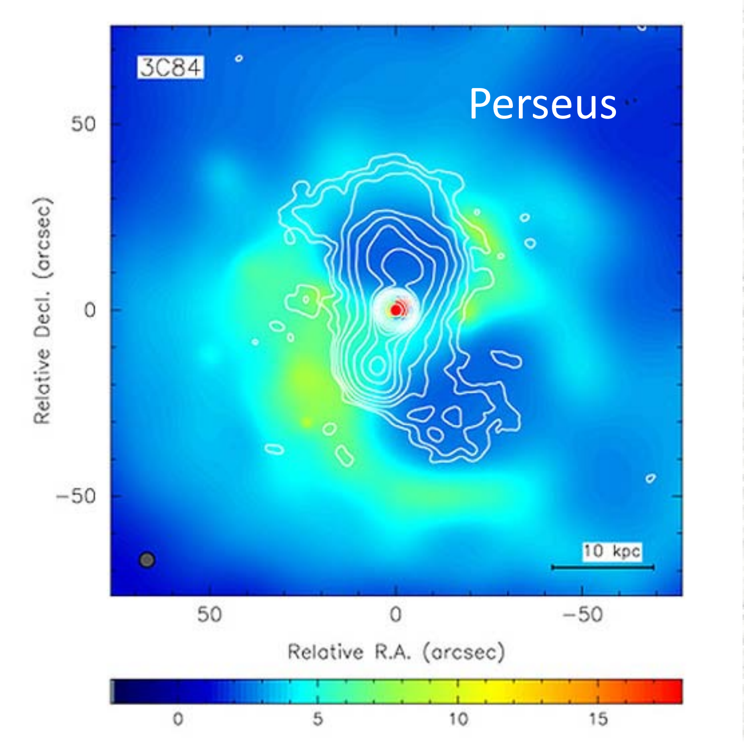
Bubble mass fraction

r_0 = 2 kpc
x_0 = 15 kpc
ρ_{bub}/ρ_{icm} = 0.01
40x34x34 kpc
Δx=0.13 kpc

DeYoung, O'Neill & Jones 2007

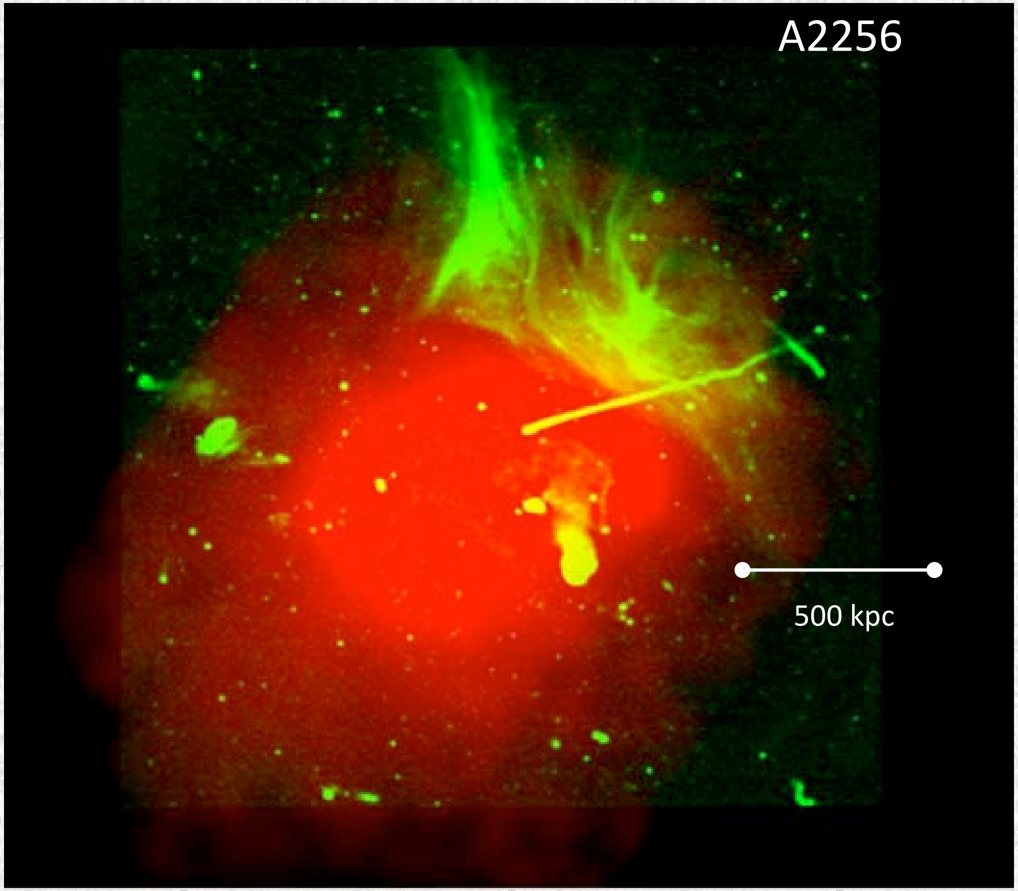
Radio AGNs are Common in Clusters

Cluster cores



Xray w/ radio contours
Croston +

Cluster outskirts



X-ray (red) & radio (green) Rudnick +

Importance:
Energy Input to ICM Can Be Large

Rafferty +

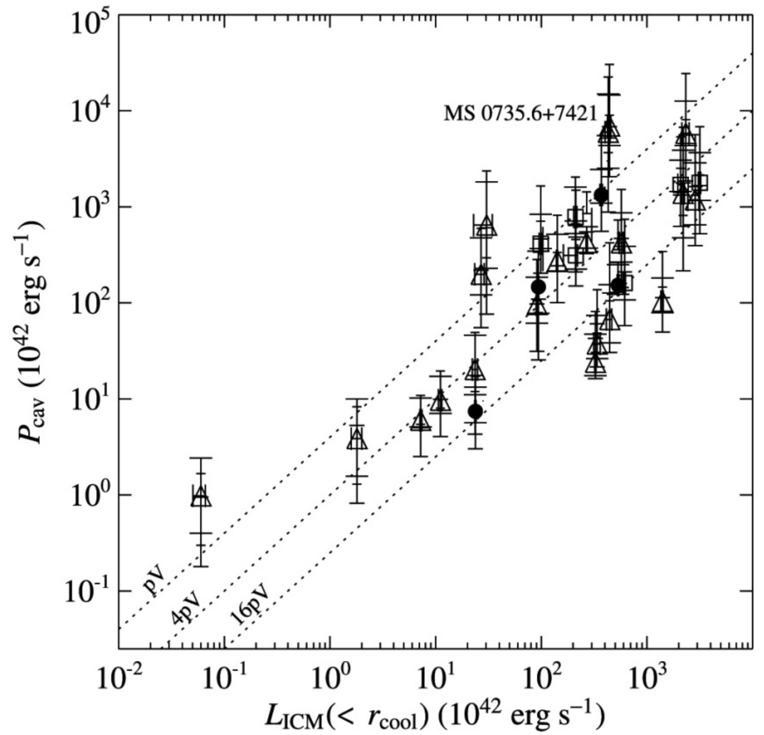
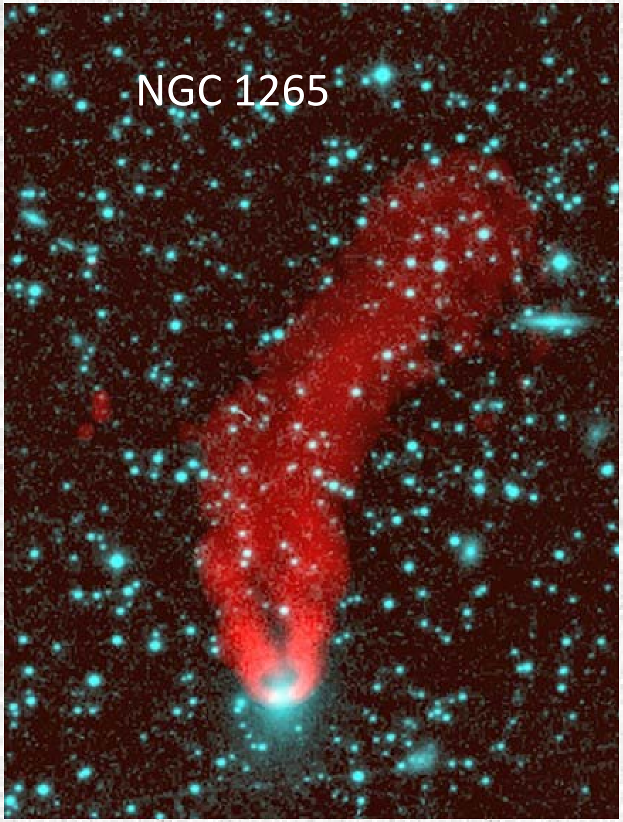


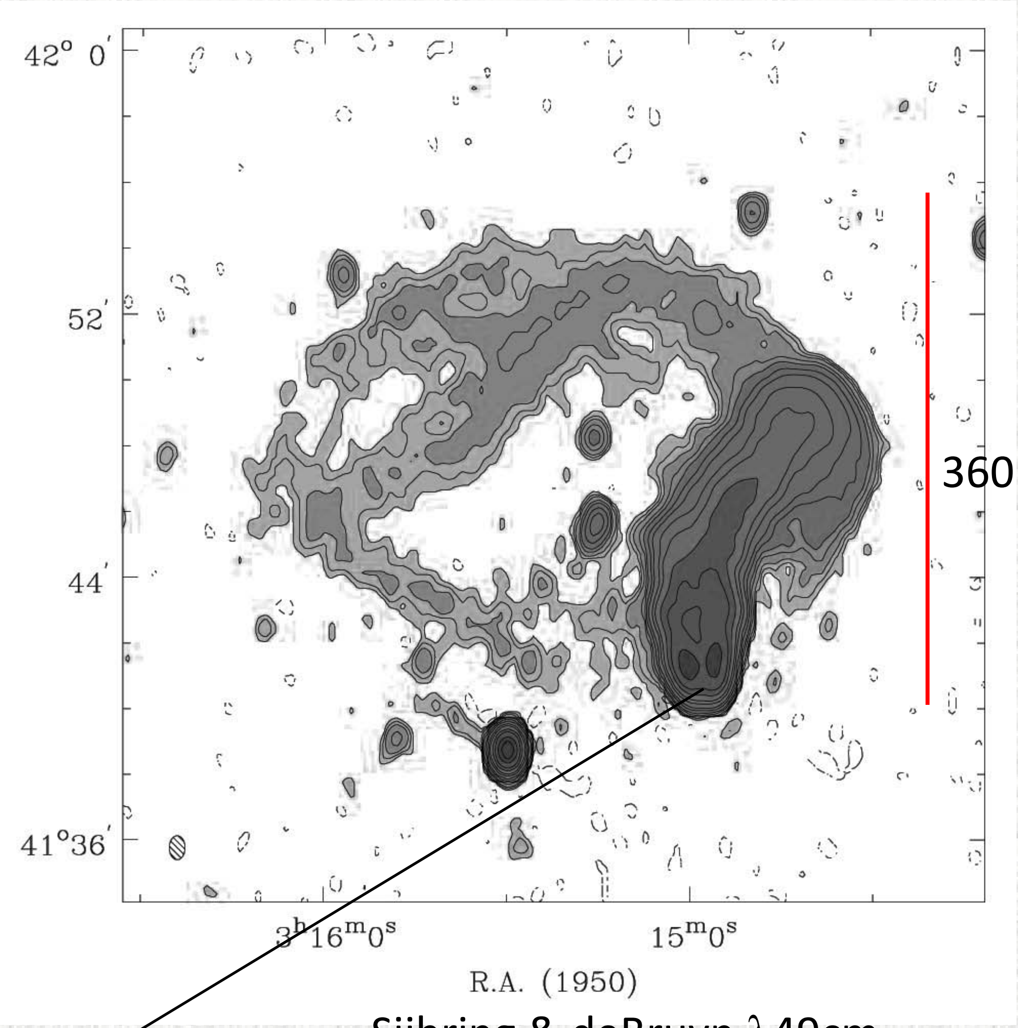
FIG. 6.—Cavity power of the central AGN vs. the X-ray luminosity of the ICM inside the cooling radius that must be offset to be consistent with the spectra ($L_{ICM} = L_X - L_{cool}$). The symbols and wide error bars denote the values of cavity power calculated using the buoyancy timescale. The short- and medium-width error bars denote the upper and lower limits of the cavity power calculated using the sound speed and refill timescales, respectively. Different symbols denote different figures of merit: *circle:* well-defined cavity with bright rims; *triangle:* well-defined cavity without bright rims; *square:* poorly defined cavity. The diagonal lines denote $P_{cav} = L_{ICM}$ assuming pV, $4pV$, or $16pV$ as the total enthalpy of the cavities.

Importance:
Dynamics Reflect ICM Motions/Structure



O'Dea & Owen λ21cm

U_{gal} ~ 2000 km/s
$\tau_{AGN} > 2x10^8$ yr

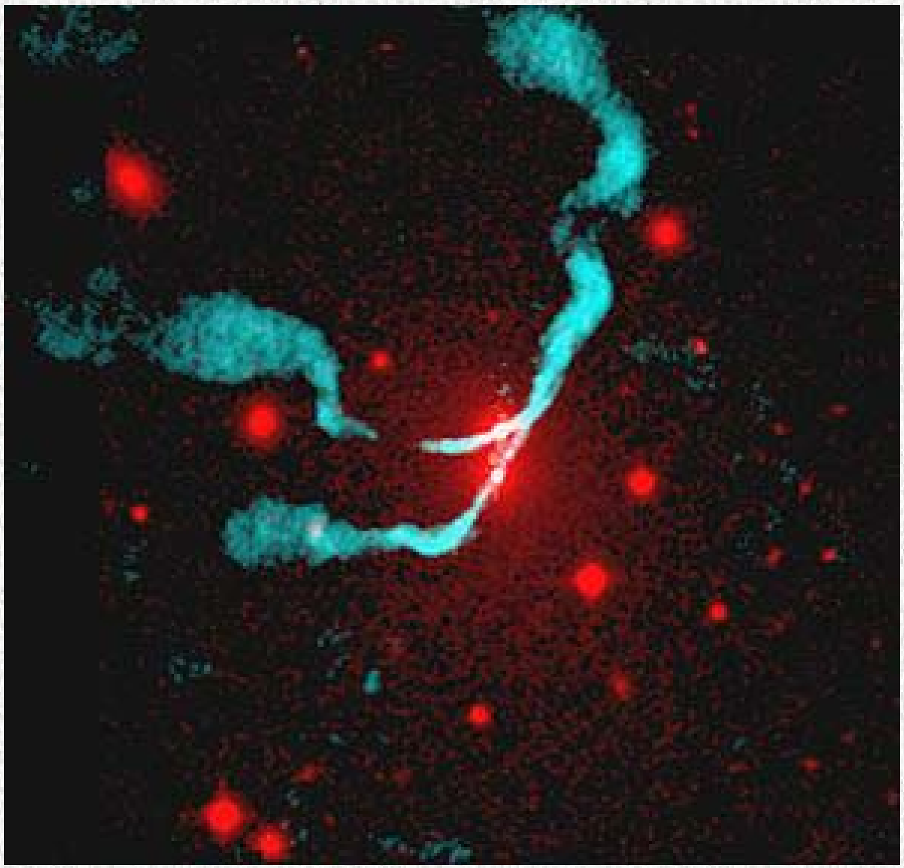


Sijbring & deBruyn λ49cm

3C 84
~540 kpc

Some Known to be Binary
(Many Might Be)

Binary Example: 3C 75



A400
NGC 1128
~ 8kpc separation

Red (visible)
Blue (radio)

Binary Example: AS345

102   *I. Klamer, R. Subrahmanyan and R. W. Hunstead*

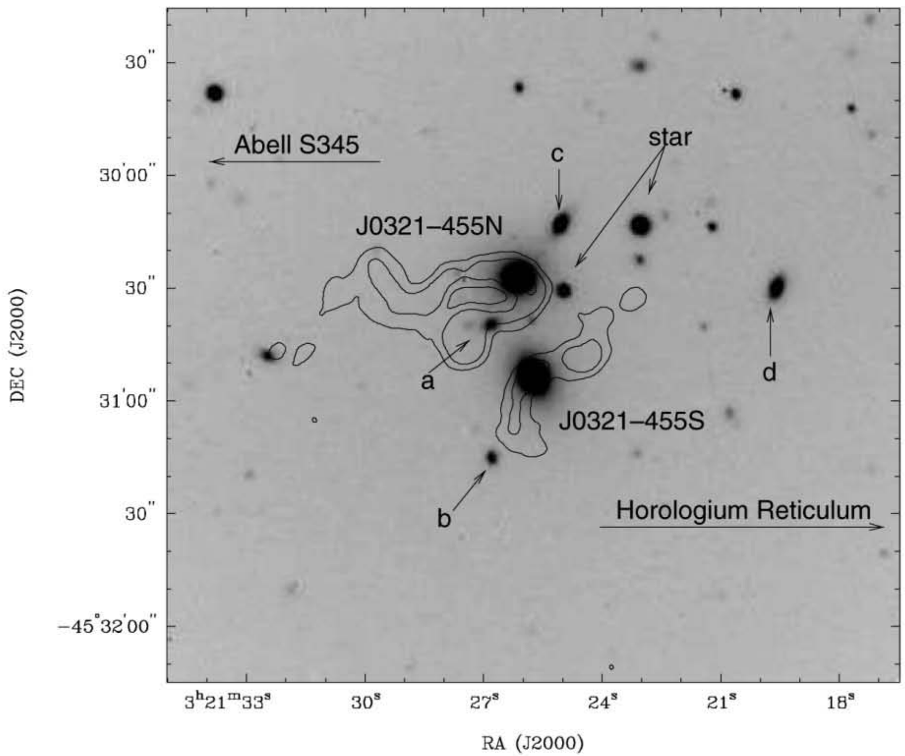


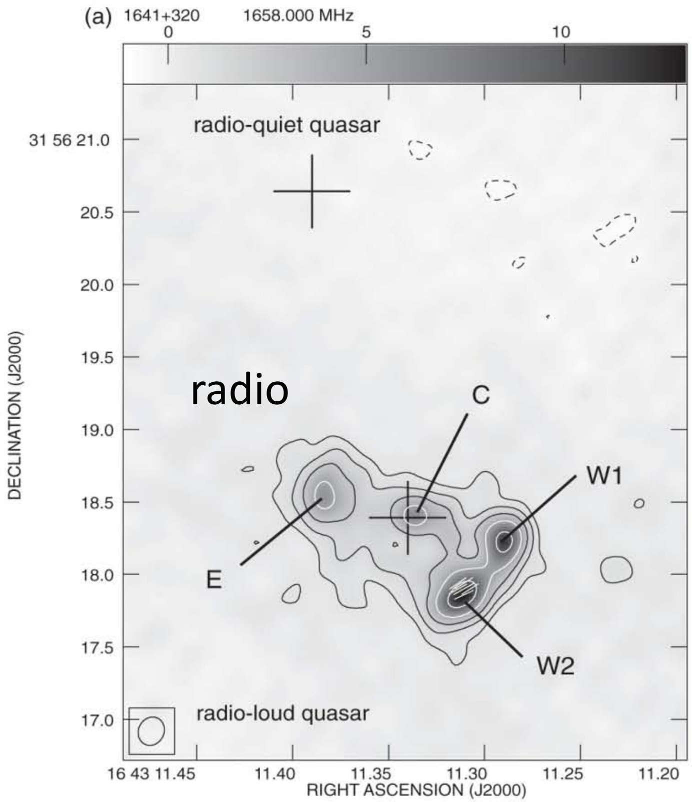
Figure 1. The binary radio galaxies J0321−455N and J0321−455S. 2.4-GHz radio contours are overlaid on a combined *R*- and *V*-band optical image of the field made using the ANU 2.3-m telescope. The contours correspond to 4, 16, 64 and 128 times the rms image noise of 60 μJy beam^{-1}. Spectroscopy (see Table 2) reveals that the objects labelled c and d and the radio galaxies are at about the same redshift.

~ 40 kpc separation

Grey (visible)
Contours (radio)

Binary Example: FIRST J1643+3156

Kunert-Bajraszewska & Janiuk



grey scale flux range= -1.06 13.03 mJy/beam
peak flux density=13.03 mJy/beam, beam size=198x169 mas
first contour level=0.6 mJy/beam
Pol line 1 arcsec=5 mJy/beam

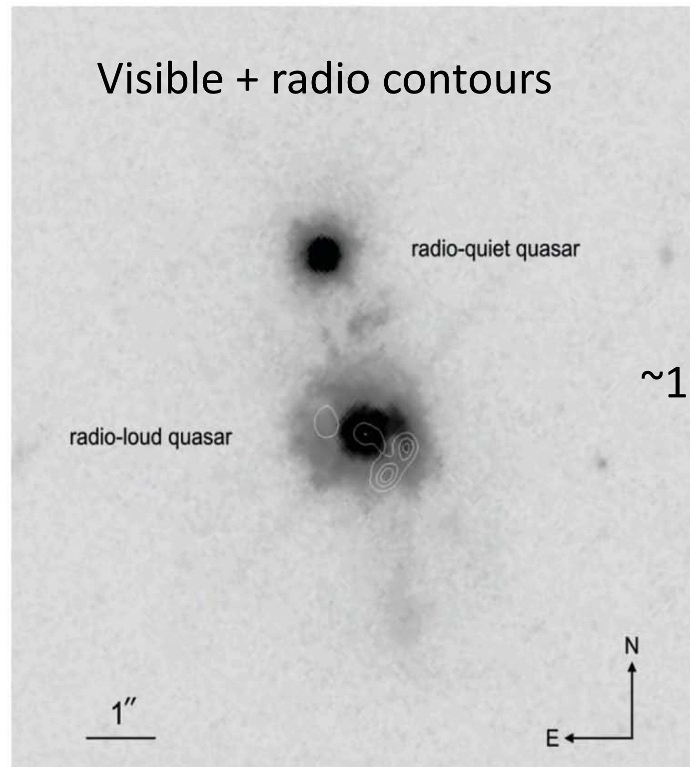


Figure 2. *HST*/ACS image of FIRST J1643+3156 in the F814W filter with an overlay of contours of the radio emission at 1.66 GHz. The two bright quasar nuclei are visible. The host galaxy of the radio-loud quasar is perturbed.

~15 kpc separation

Given the commonality of AGNs in ICMs
The Challenge:

Decipher complex morphological (& other) clues to establish useful dynamical diagnostics:

E.G.,
ICM flow properties
ICM magnetic field properties
Jet physical properties
Define key Jet/ICM interaction parameters

We've mostly explored through simulations

Previous Generation Jet Simulations in Static ICMs (3D MHD)

e.g., O'Neill, Mendygral & Jones 2009

- Bipolar, collimated Mach 30 (internal) jet outflows
  $L_{jet} = 1.2\text{x}10^{46}$ erg/s (combined jets at full power)
  Steady or intermittent (50%, 26 Myr cycle)
  $r_{jet} = 3$ kpc
  $\rho_{jet}/\rho_0 = 0.01$
  Toroidal jet B field at source ($\beta = P_g/P_M \sim 100$; $B_j \sim 10\ \mu$G)

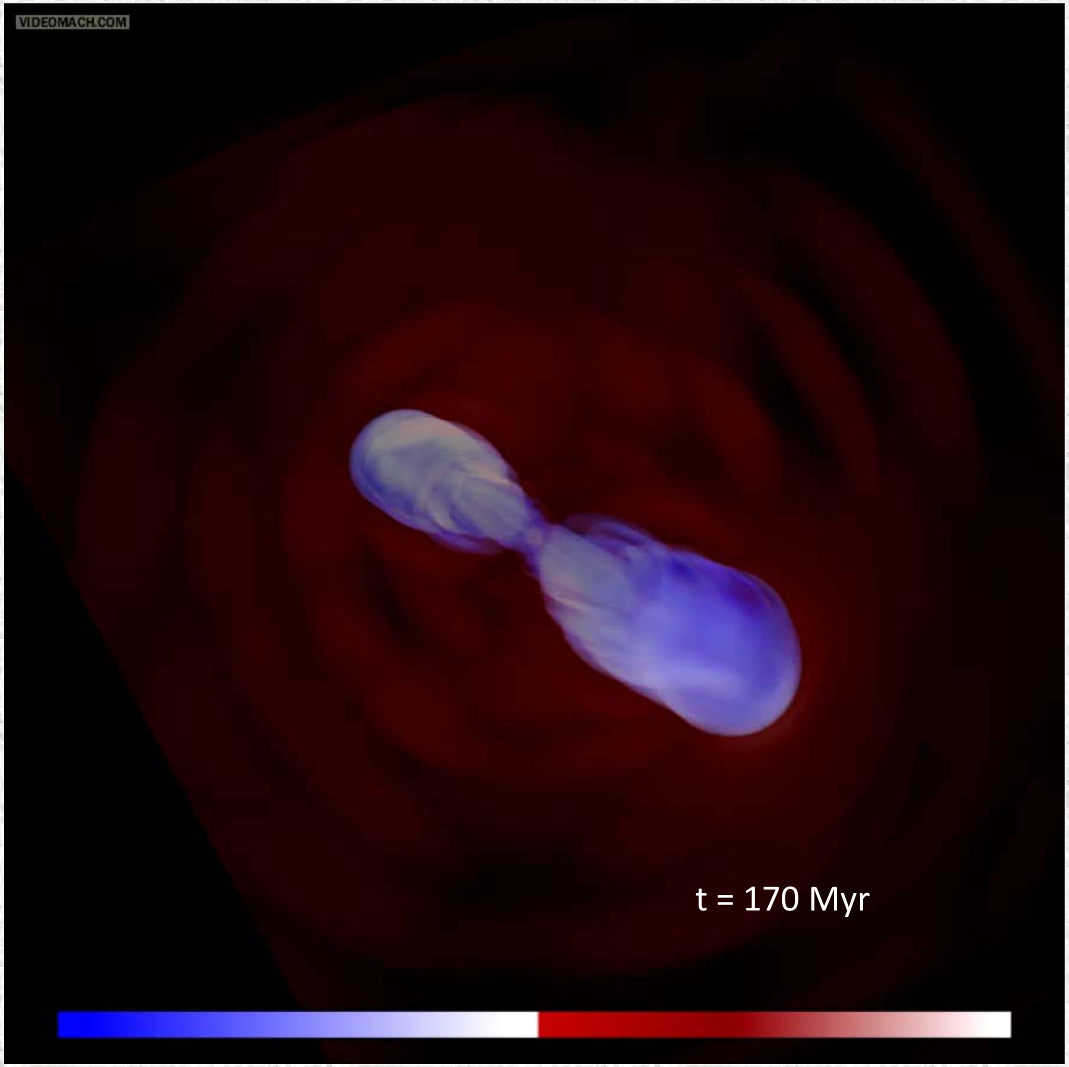
- Passive `CR' electrons, shock injection & DSA
  Adiabatic & radiative (synch, IC) losses

- AGN at center of ~ $4\text{x}10^{14}\ M_o$ cluster (NFW potential)
  Static ICM, kT_{ICM} ~3keV (~ Perseus)
  Double β profile with random density fluctuations
  Tangled ICM magnetic field
  $<\beta_{plasma}>\sim 100$ (range ~ 30:1000) ($<B_{core}> \sim 7\mu$G)
  No radiative cooling of ICM

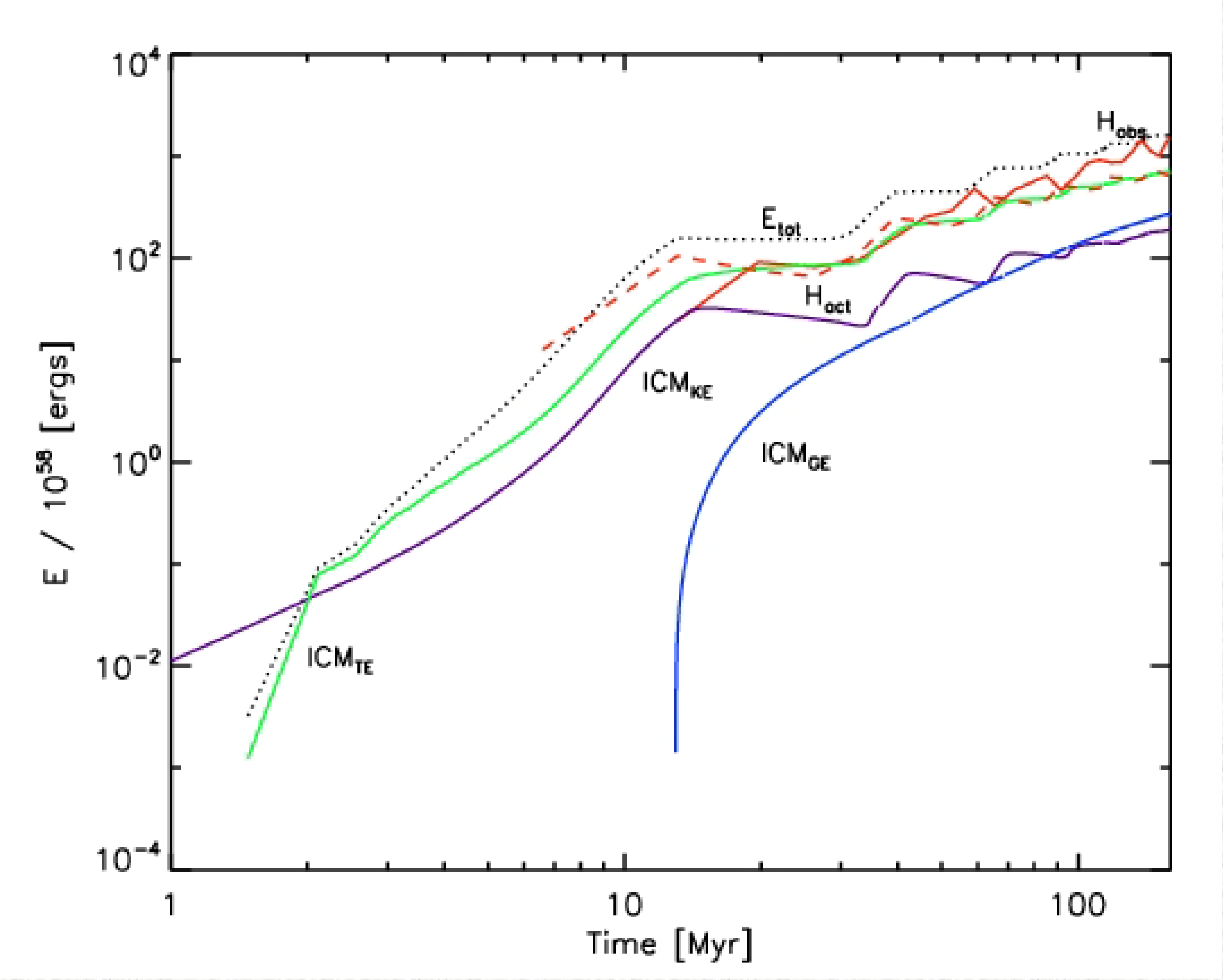
Illustration: Intermittent Jets

Magnetic Field Intensity

Blue (AGN plasma)
Red (ICM plasma)

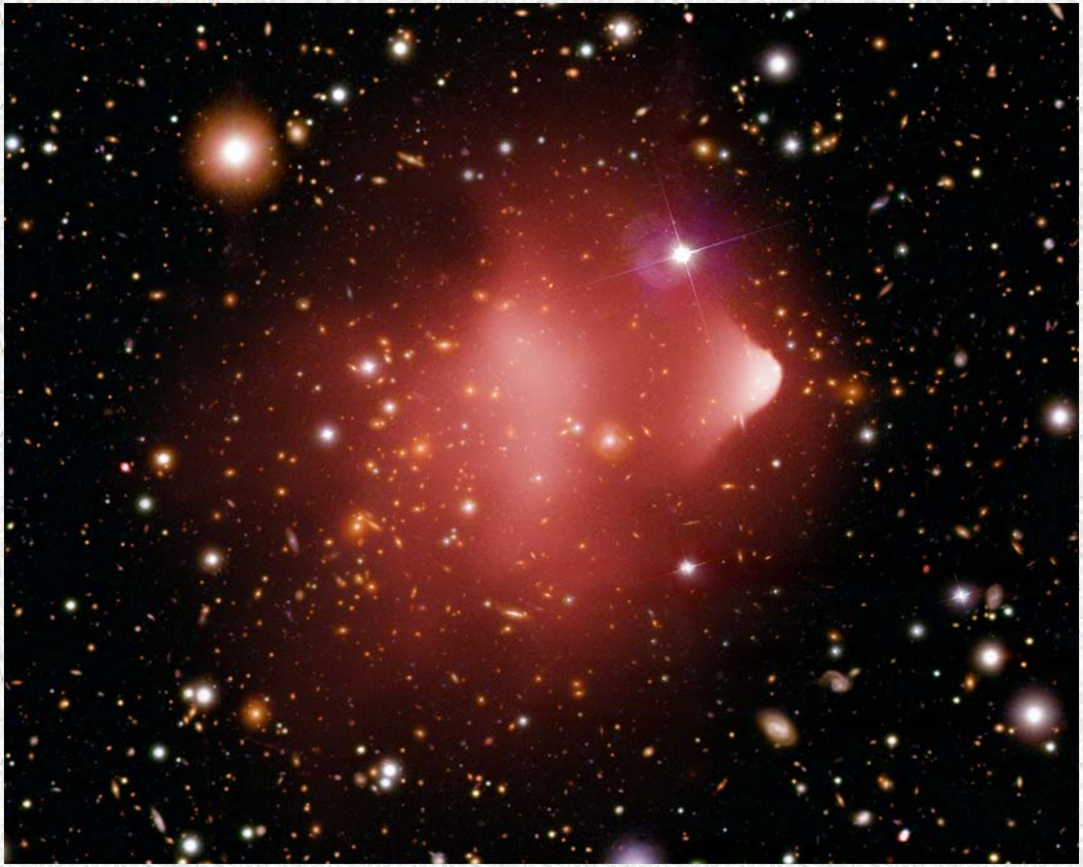


Synthetically Observed' & Actual Energetics Comparisons Good to ~ 50%



On the Other Hand: Real ICMs are Dynamic:

"Bullet Cluster" 1E 0657-56



Chandra
+ HST

Two Classes of More Realistic Simulations:

- AGN Jets in simple, but dynamic media

- AGN Jets in self-consistent ICMs

Example: Bipolar AGN Jets in a Turbulent ICM Wind:

Narrow Angle Tail (NAT) FRI Source
(Porter + 2009)

- Code: MHD TVD with passive CR electrons (CGMV)

- Box: 1 Mpc x 1 Mpc x 200 kpc
  2000x2000x400 =1.6×10^9 zones
  $\Delta x = 0.5$ kpc

- Jet Power: 5×10^{44} erg/s
- Jet Radius: 5 kpc
- Bending Radius: ~ 20 kpc (M_j/M_{ICM} ~ 2)
- Simulation Duration: 215 Myr
- Tail Length: ~ 600 kpc

NAT Simulation Setup:

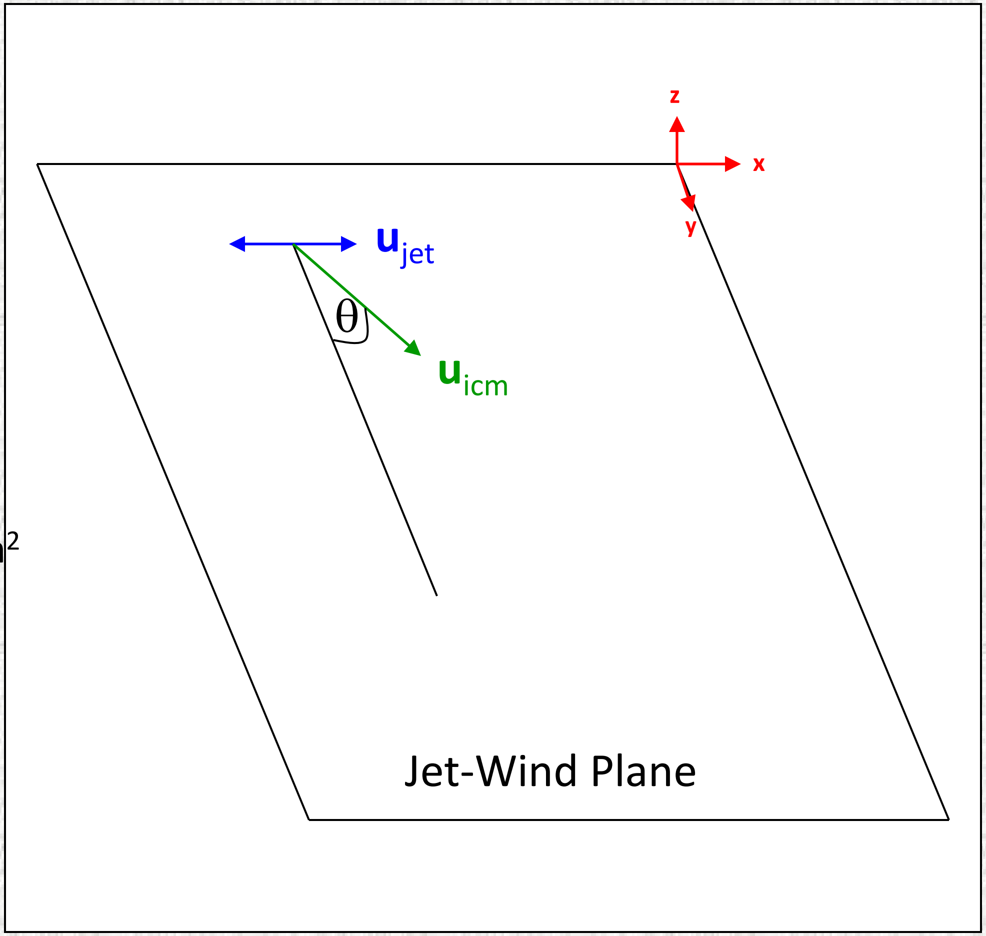
Emergent Jets:

$U_{jet} = 0.044c$
$R_{jet} = 5$ kpc
$\rho_{jet} = 0.1 \langle\rho_{icm}\rangle$
$M_{jet} = u_{jet}/s_{jet} = 3$
$\beta_{jet} = P_{mag}/P_{gas} \sim 10$
(toroidal field)

ICM:

$U_{icm} = 2000$ km/s
$\theta = 30$ degrees
$M_w = u_{icm}/s_{icm} = 1.5$
$P_{icm}=P_{jet}=1.8\times10^{-11}$ dy/cm^2
$\langle n_{icm}\rangle=.001$ cm^{-3}
$B_{rms} = 2.2\ \mu G$
$\langle\beta_{icm}\rangle = 100$

Turbulent ICM:
Outer scale 20 kpc
Kolmogorov



Bending Radius:

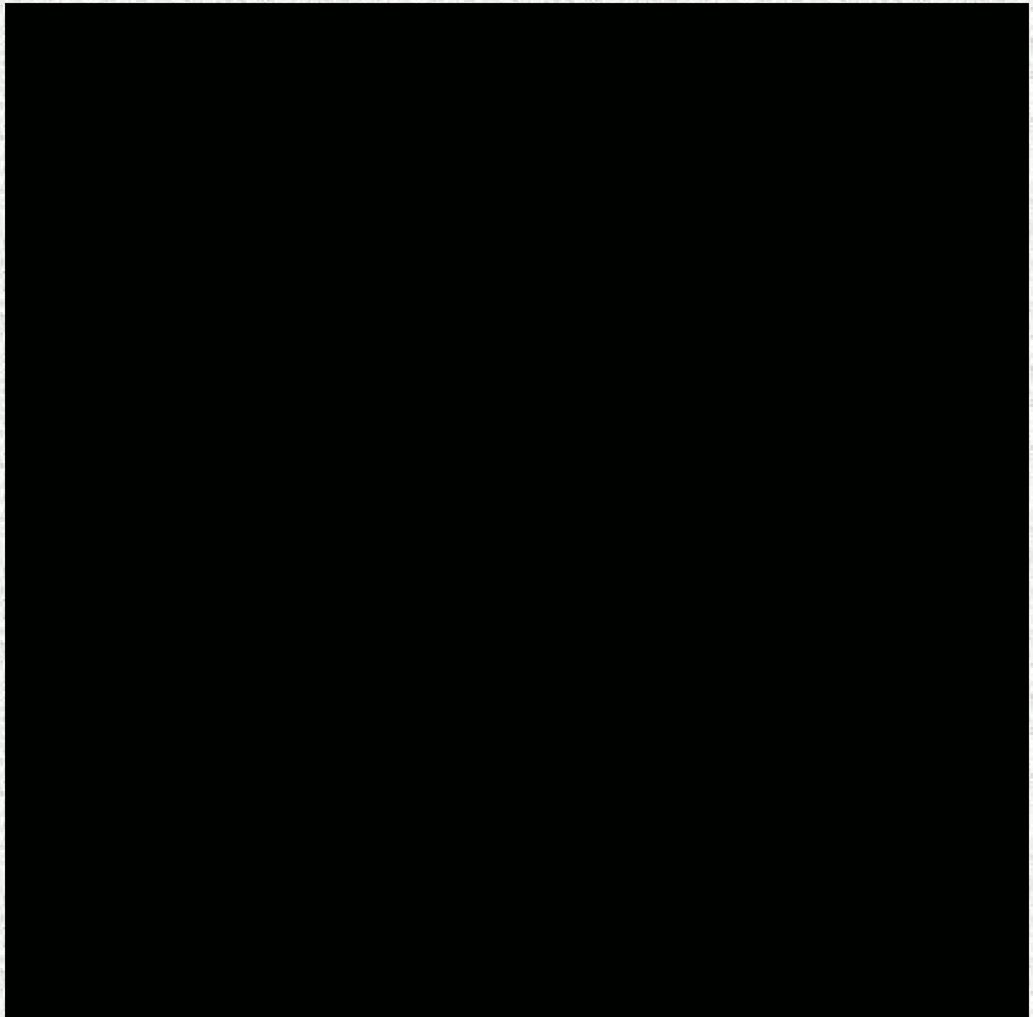
$R_b/R_j \sim (M_j/M_w)^2(P_j/P_i)$

for $(P_j/P_i) = 1$

$R_b/R_j \sim (M_j/M_i)^2 = 4$

So $R_b \sim 20$ kpc

Kinetic Energy Deposition



KE in ICM
Rest Frame

Jet-wind plane

Vorticity (Shear, turbulence)

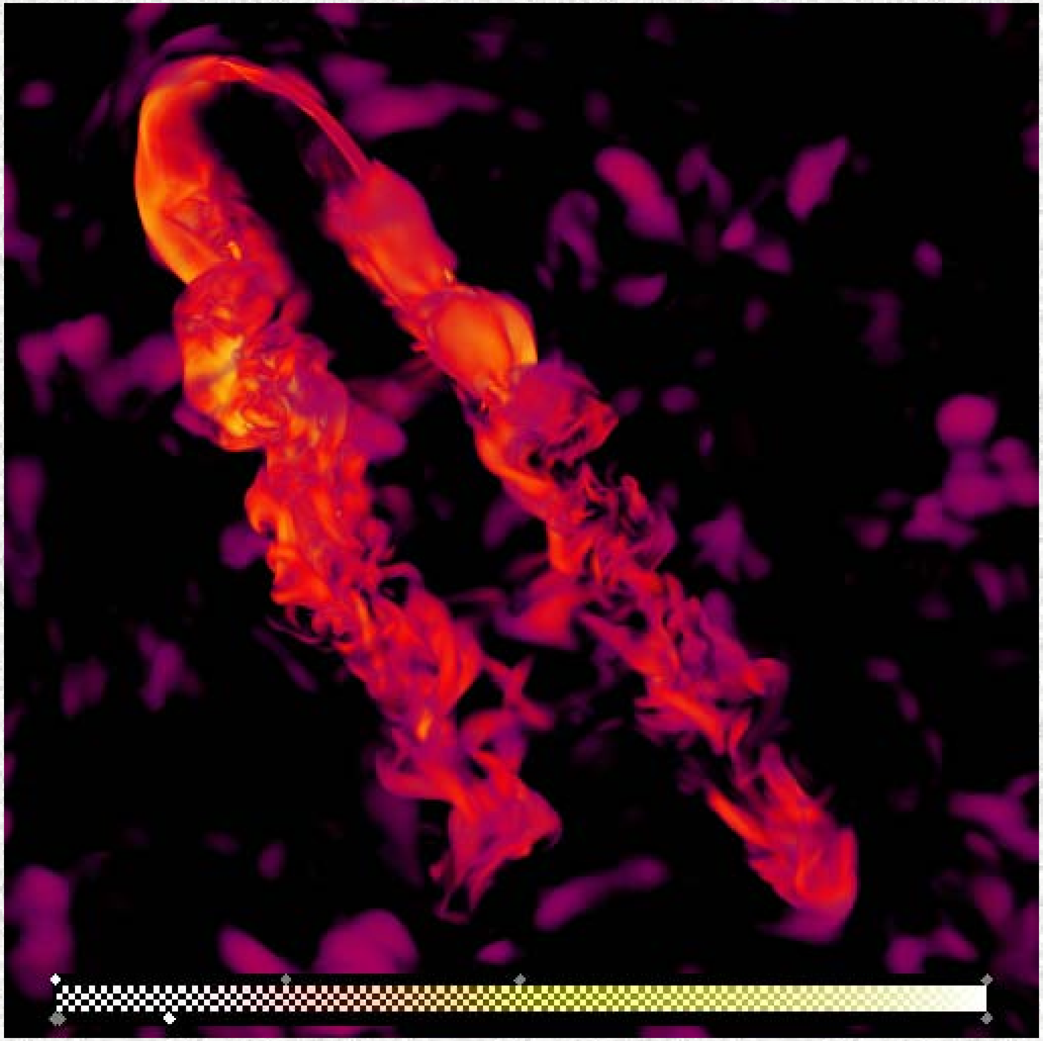
Volume Rendered

t = 215 Myr

Magnetic Field Injection/Amplification

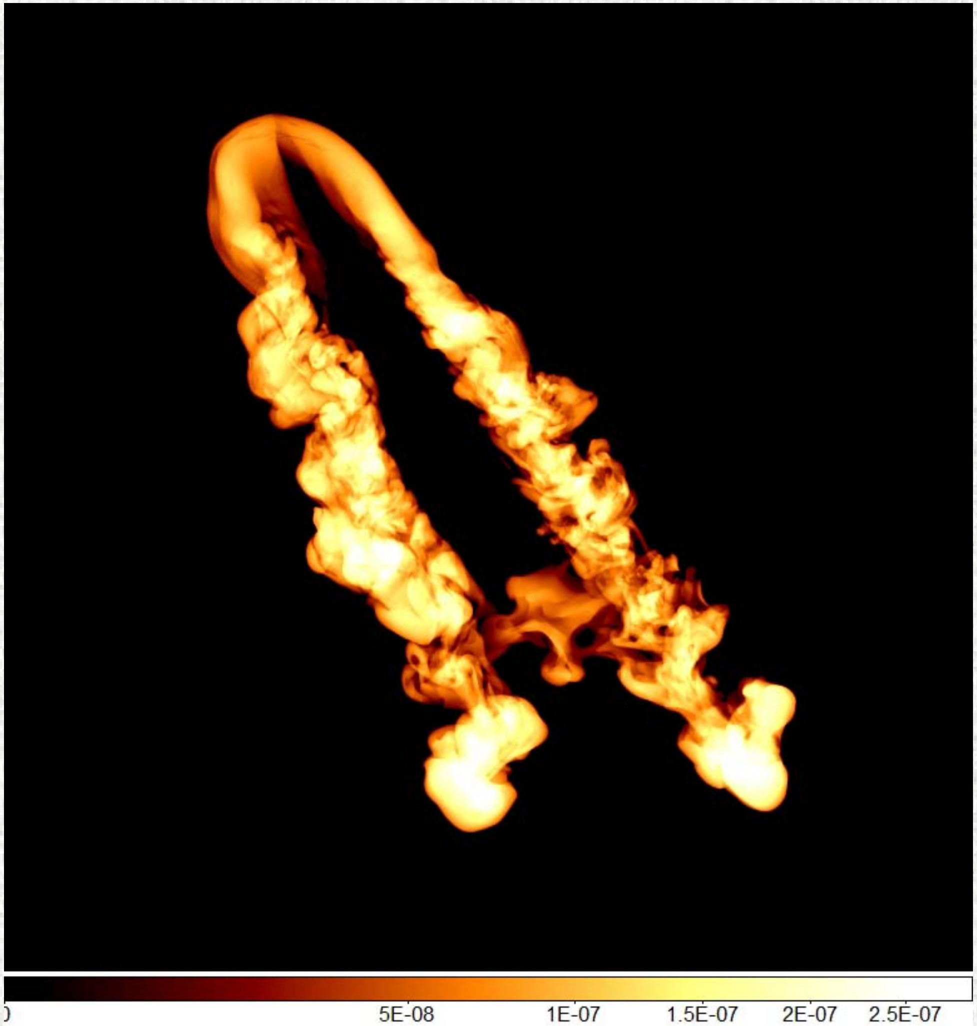
Volume Rendered

t = 215 Myr



Synthetic Synchrotron Emission

178 MHz
215 Myr



(Using included Cre population)

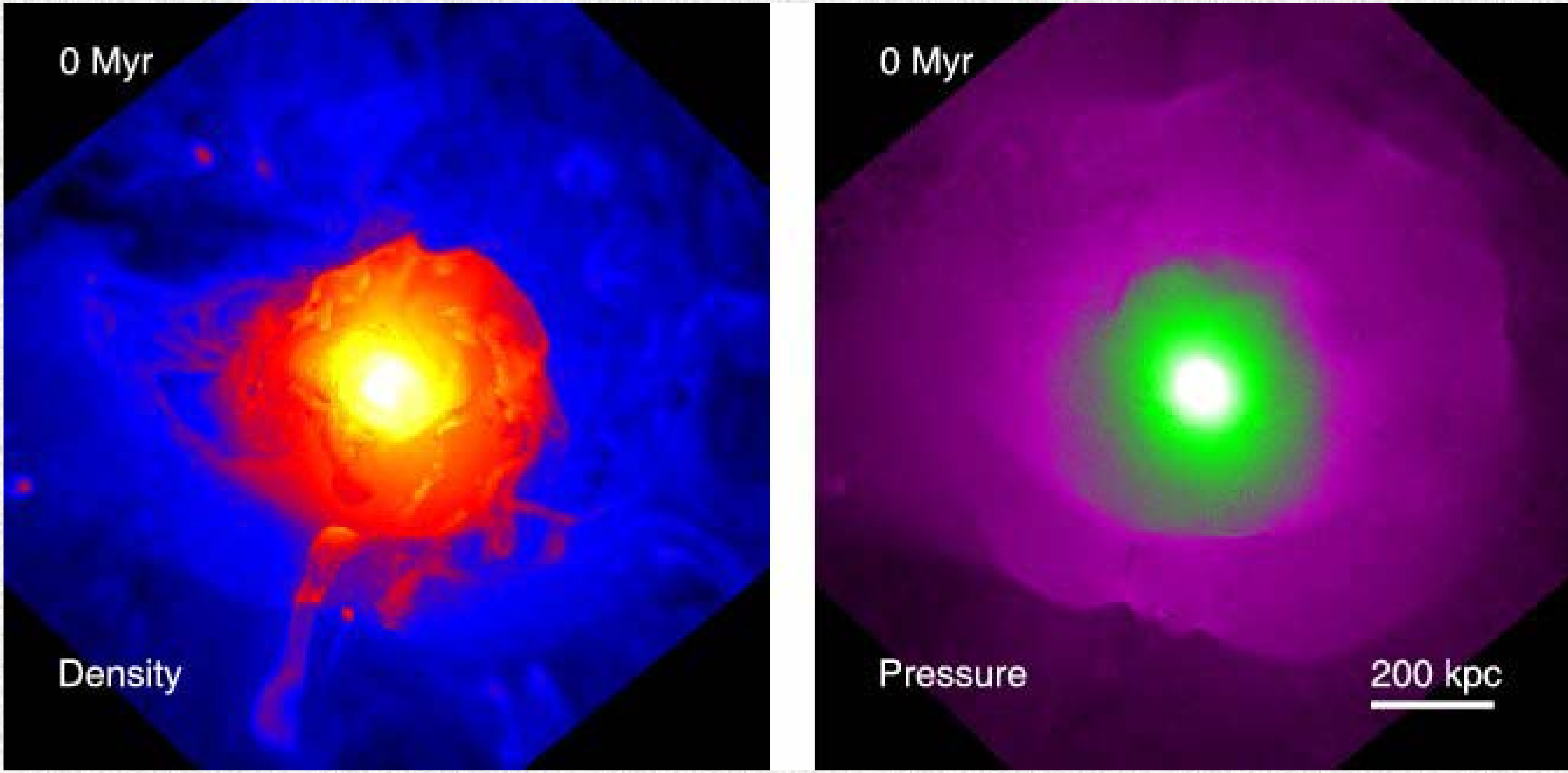
Self-Consistent ICM Example:

Intermittent Bipolar AGN Jets in a Nominally Relaxed ICM
Extracted from Cosmological Simulation (SPH MHD):
Wide Angle Tail (WAT) FR II Source
Mendrygral + 2012

- Code: MHD TVD (grid-based) with passive CR electrons (CGMV)
- Box: 1 Mpc^3; 1008^3 zones
  $\Delta x = 1$ kpc
- Jet Power: 6×10^{44} erg/s
- Jet Radius: 3 kpc
- Jet Velocity: $v_j = 10^4$ km/s
- Jet Density: $\rho_j = 4 \times 10^{-28}$ g/cm^3
- Toroidal Magnetic Field (β = 1, 10, 100)
- Cluster (7 Gyr since major merger):
  Mass = 1.5 x 10^{14} M_o ; kT ~ 1.5 keV; c_s ~ 650 km/s
  B_{core} ~ 5 μ G

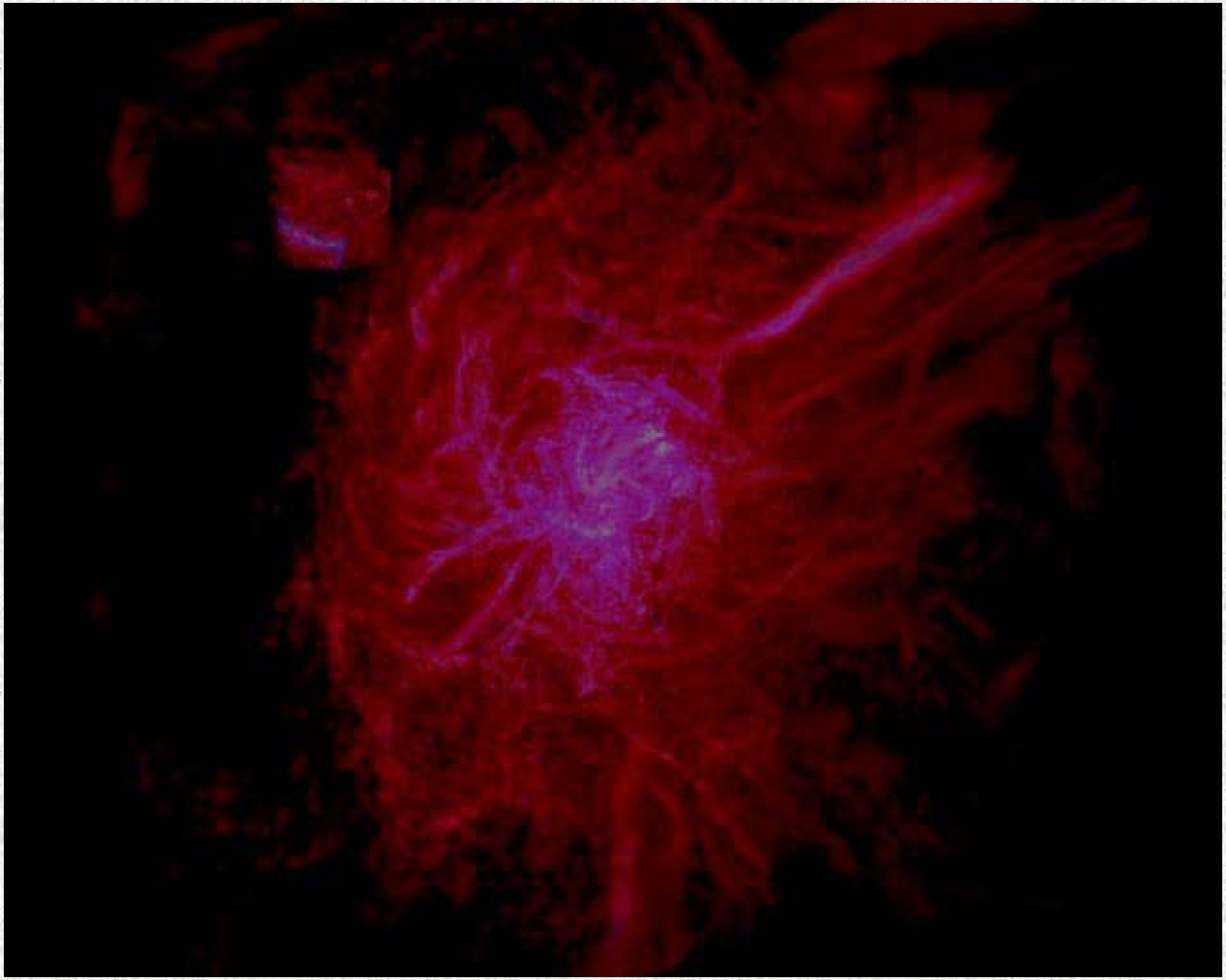
Overview of Selected Cluster

z = 0



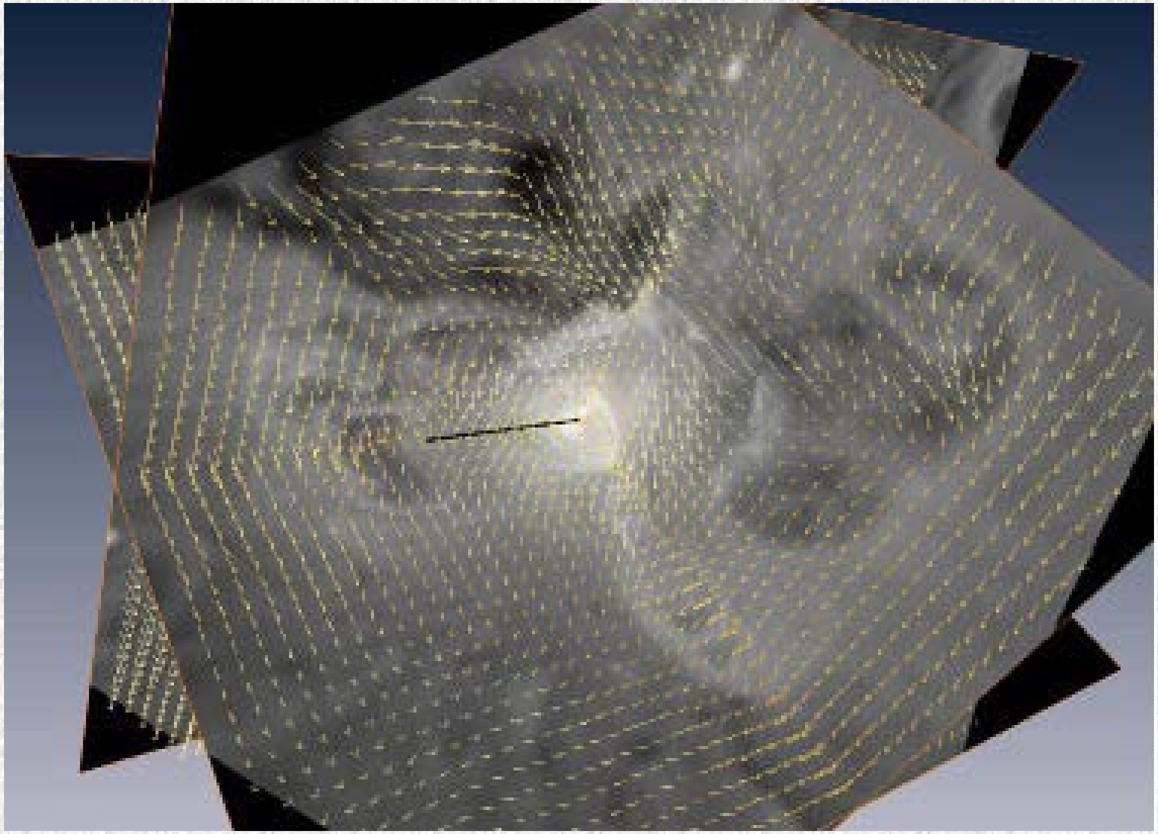
1 Mpc

Cluster Magnetic Field



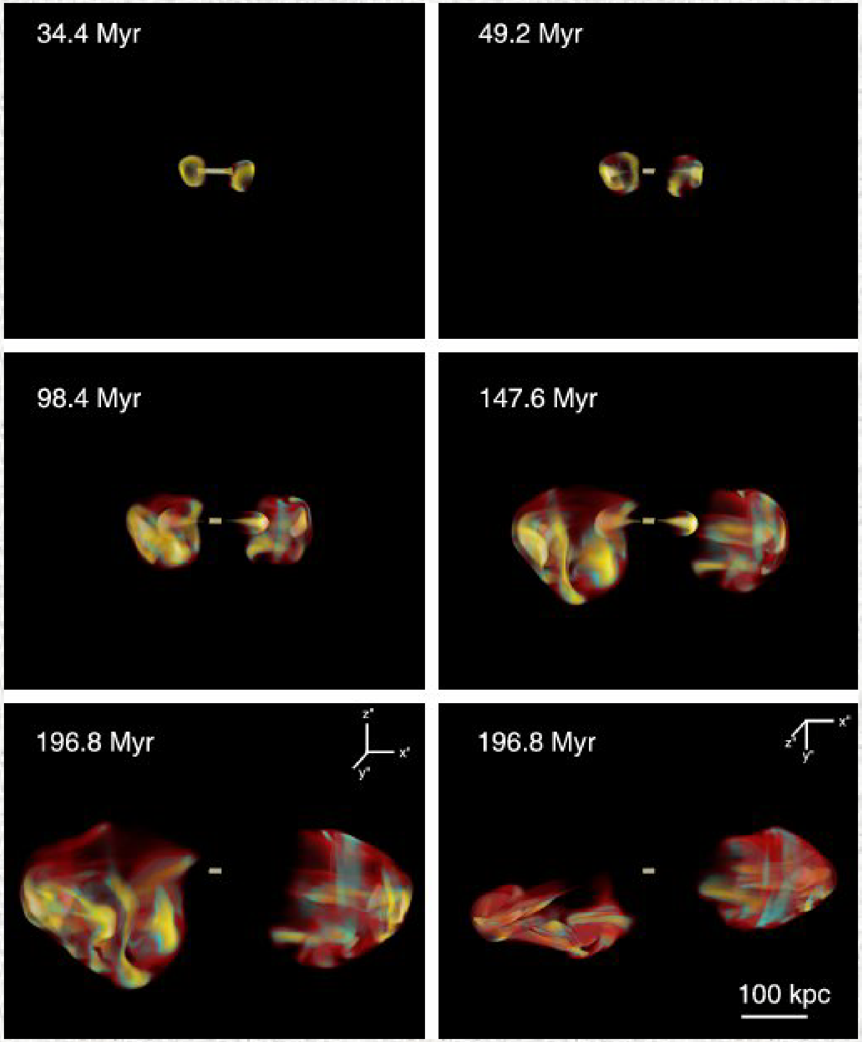
Initial ICM Gas Entropy Slices with Velocity Vectors

Cross winds up to 450 km/sec



Bar shows jet axis

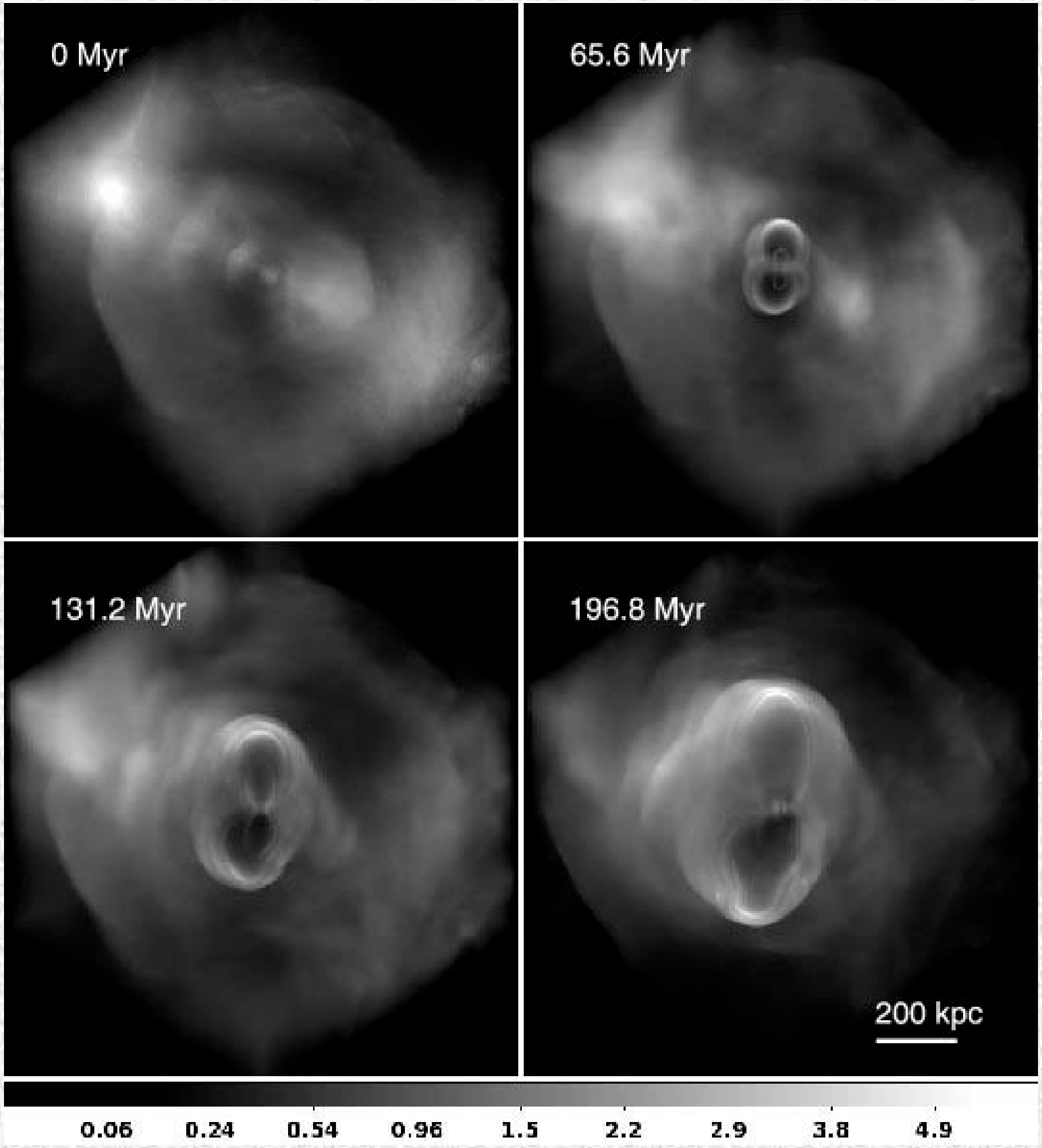
Evolution of AGN Cavity



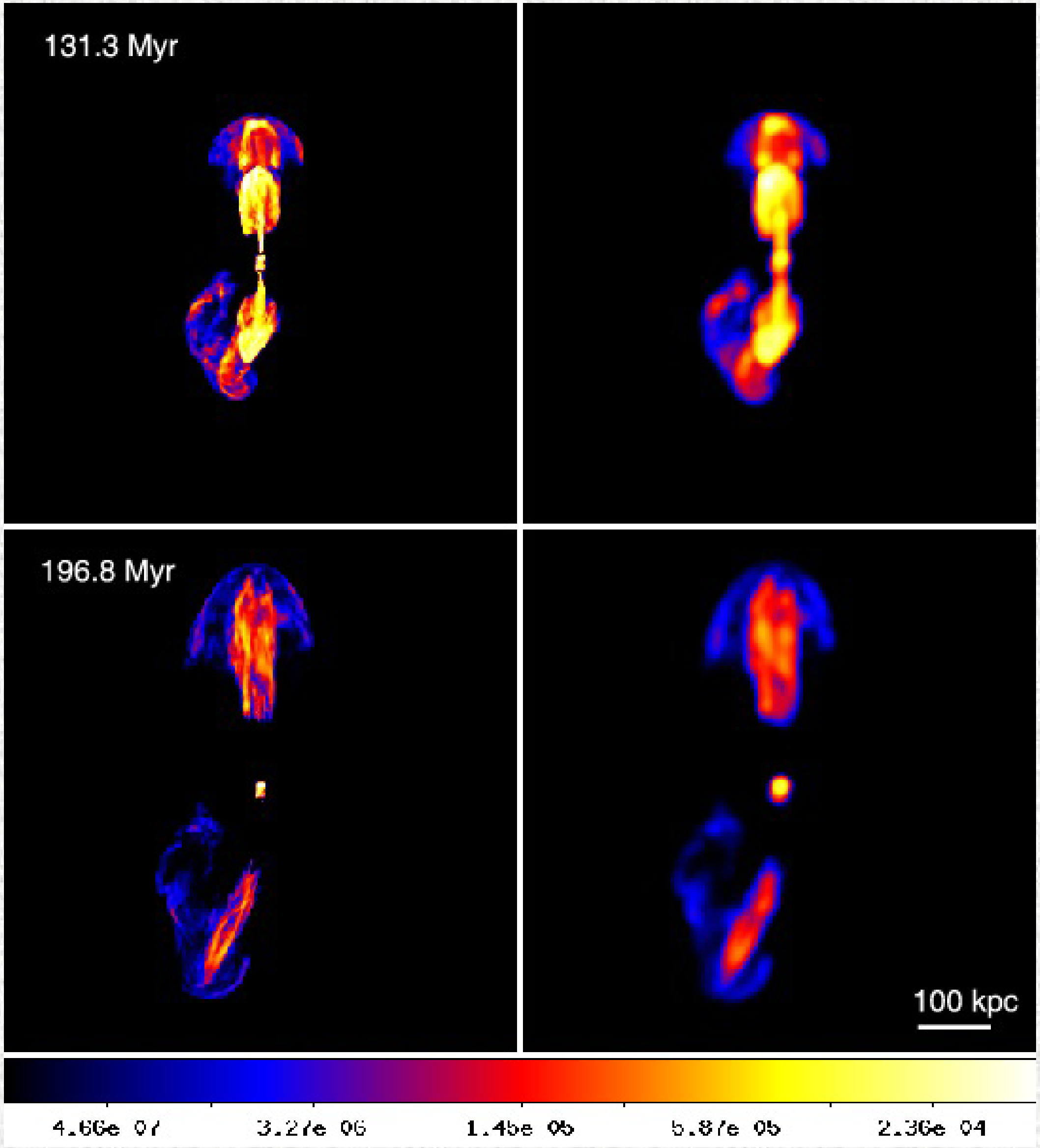
Note distortions
From axial symmetry

('Launch cylinder' visible)

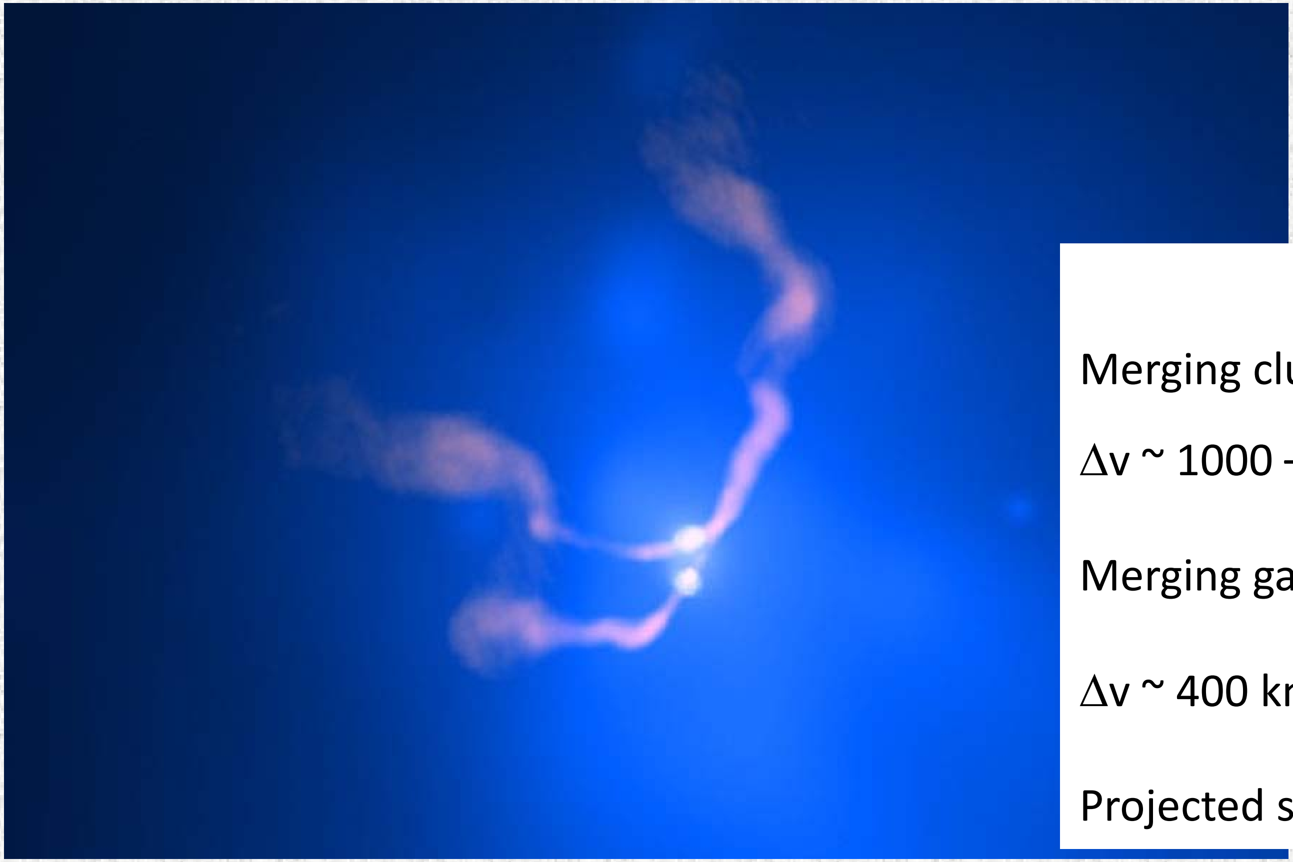
Synthetic X-Ray Image (divided by β-law)



Synthetic Radio Images



Back to Binary AGNs: 3C 75



A400

Merging clusters

Δv ~ 1000 – 2000 km/s

Merging galaxies

Δv ~ 400 km/s

Projected separation ~ 7 kpc

Blue (X-ray) Pink (radio)

Model 3C 75 as Pair of Orbiting BHs in Cross Wind

658 M. Yokosawa and M. Inoue [Vol. 37,

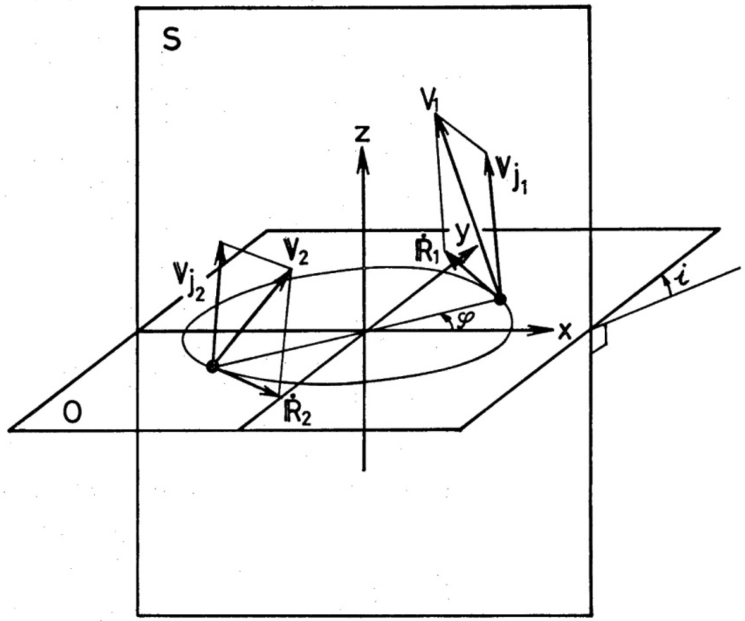


Fig. 1. The coordinate system; x–y plane is the orbital plane of the binary galaxy and x-axis is the major axis of the orbit. The plane of the sky is S and i is the inclination of the orbital plane O from the line of sight.

Yokosawa & Inoue
v_w = 1100 km/s
(almost in plane)
Orbital diameter 8kpc
Orbital period 110 Myr

General idea of Expected Behavior (Yokosawa + Ballistic Model)

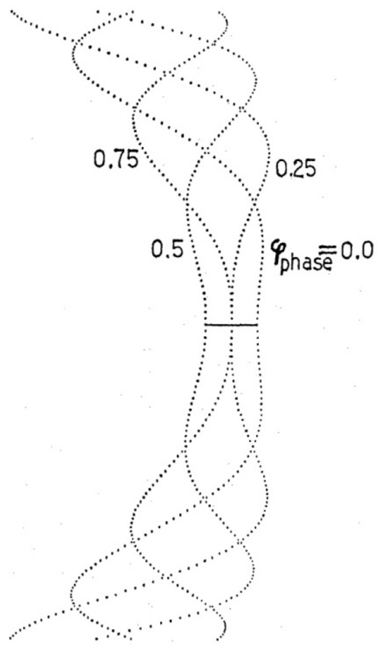


Fig. 2. Jet trajectories produced by the binary orbiting galaxy. $\varphi_{\rm phase}$ is the orbital phase of the galaxy. The intergalactic wind flows to the left direction.

Yokosawa + Ballistic Model

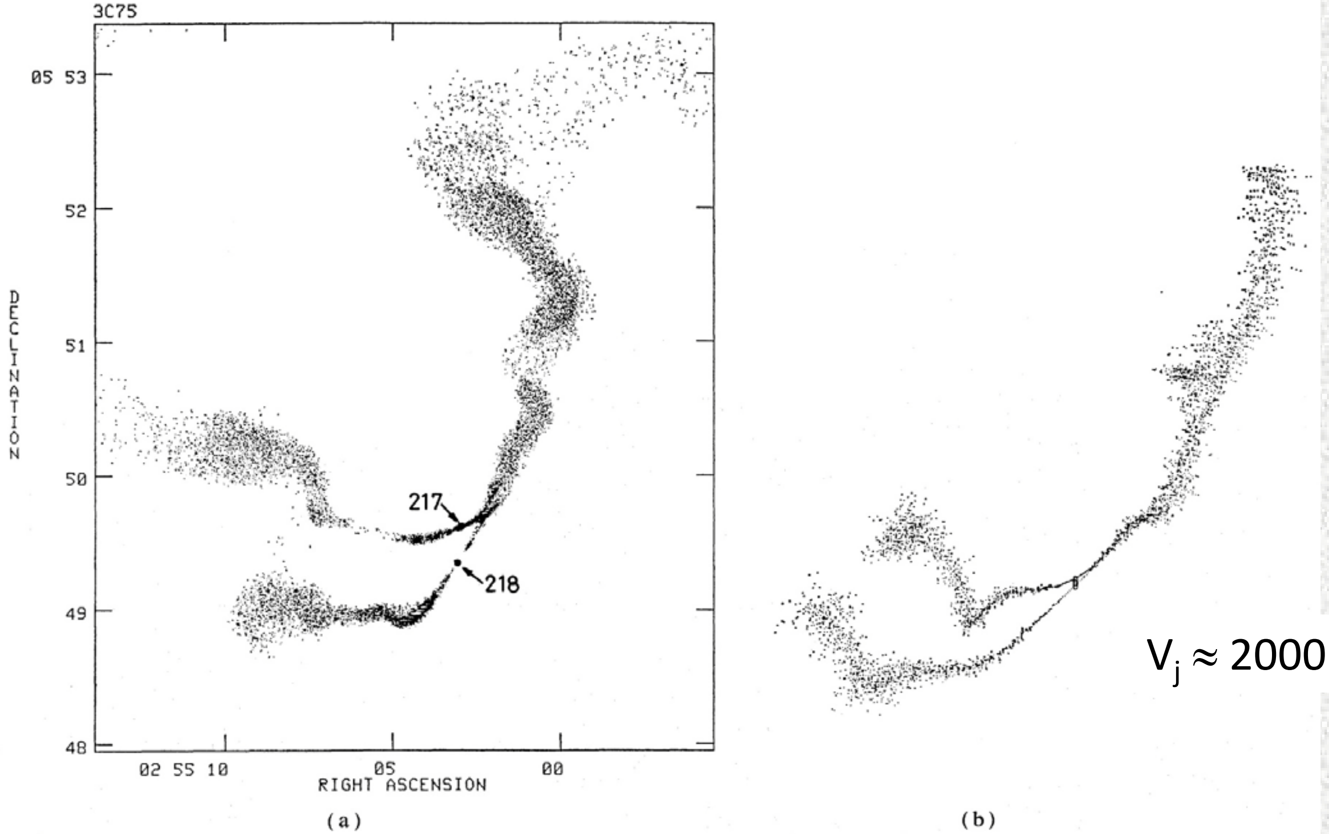


Fig. 4. (a) Radio map of 3C 75 at 5 GHz (Owen et al. 1985) obtained with the VLA.
(b) Halftone simulation of the best-fitted jets, in which each point has been replaced by a random dot pattern with Gaussian cross section. The half-width of the cross section increases linearly with time. Parameters of the jet velocities and the orbital elements are represented in table 1.

$V_j \approx 2000$ km/s

Our MHD Simulation Set Up:

Box: 500 kpc X 250 kpc X 500 kpc (1084 X 542 X 1084) grid
$\Delta x = 0.5$ kpc

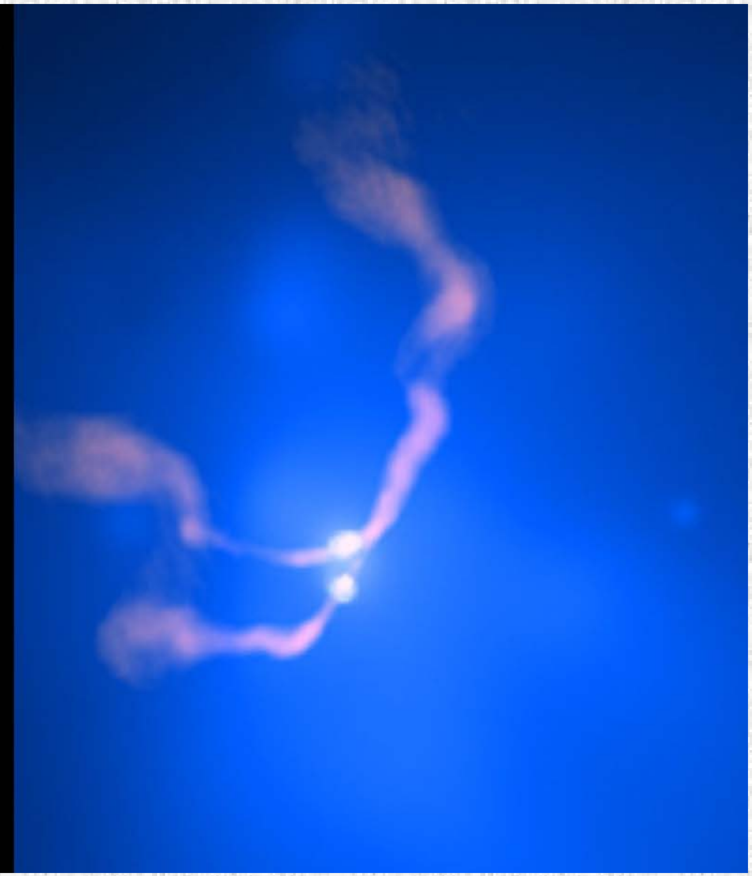
ICM:
$\rho_{ICM} = 5 \times 10^{-27}$ g/cm^3
$P_{ICM} = 1.3\times10^{-11}$ dyne/cm^2
$v_x = 1100$ km/s ($v_y = v_z = 0$)
$v_x/c_s = M_{ICM} = 1.67$
Turbulent ICM: $\langle v_{turb}\rangle_{RMS} = 150$ km/s, $\langle B_{turb}\rangle_{RMS} = 2\ \mu G$
outer scale 30 kpc

Jets: (paired & orthogonal to AGN orbit)
$r_j = 3$ kpc
$v_j = 1.5\times10^4$ km/s
$P_j = P_{ICM} = 1.3\times10^{-11}$ dyne/cm^2
$\rho_j = 5 \times 10^{-28}$ g/cm^3
$v_j/c_{sj} = M_j = 7.2$
$\beta = P_g/P_M = 10$
$L_j = 5 \times 10^{43}$ erg/s
orbital diameter = 12 kpc (x-y plane)
orbital period = 91 Myr

Crude Comparison

Simulation: Jet mass fraction

3C 75: radio in pink



Roughly similar scales

t = 215 Myr (~ 2 binary orbits)

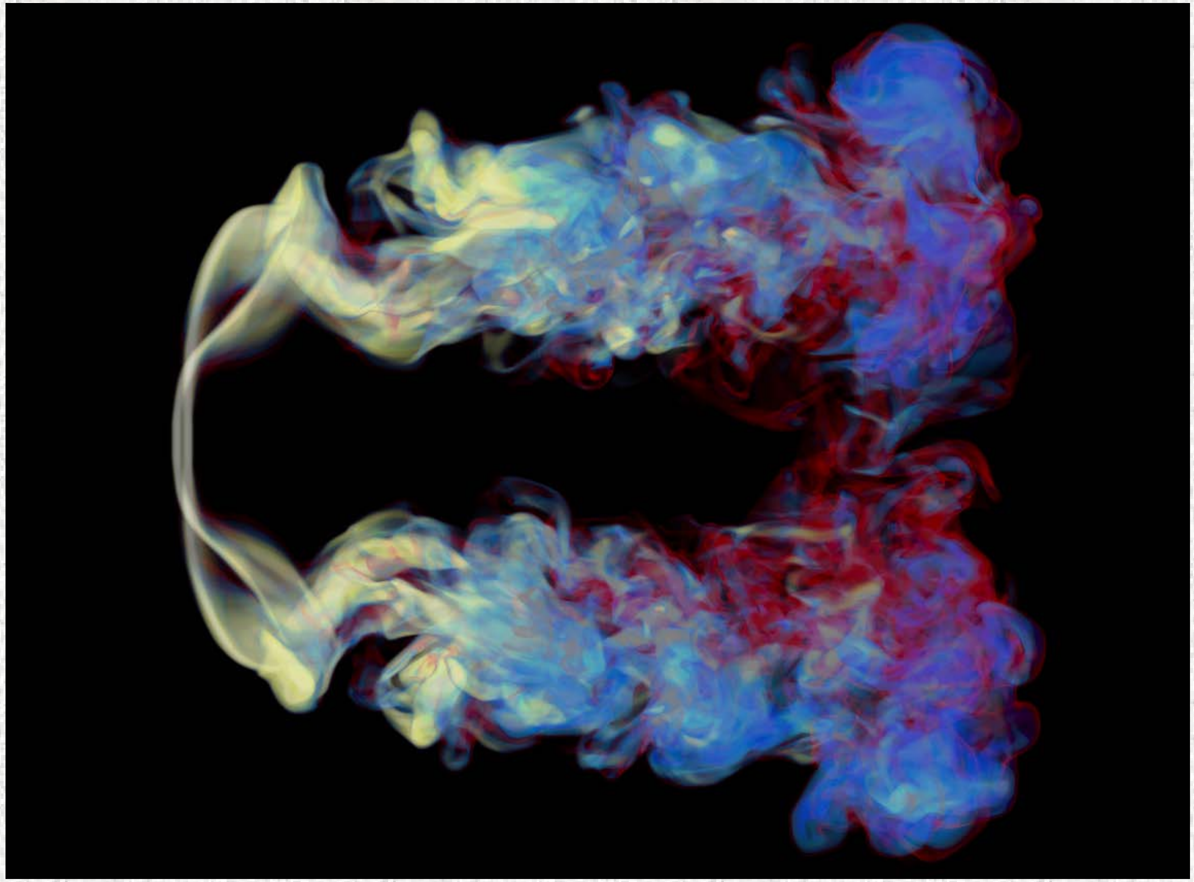
Jet mass fraction
'color'

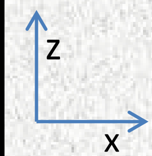
Jet break :

$l_b \sim (M_j/M_{ICM})^2 r_j$

Varies during
Orbit ($\mathbf{v}_w + \mathbf{v}_o$)

$< l_b > \sim 60$ kpc





Tail lengths ~ 300 kpc

Evolution of Mass Fraction

Thanks!