Interaction of AGN Outflows and Plasma Bubbles with the ICM

Tom Jones

UNIVERSITY OF MINNESOTA

Pete Mendygral (UMN), Sean O'Neill (CU), David Porter (UMN), Dongsu Ryu (PNU), Dave DeYoung (NOAO), Klaus Dolag (MPA), Christoph Pfrommer (CITA)

Outline

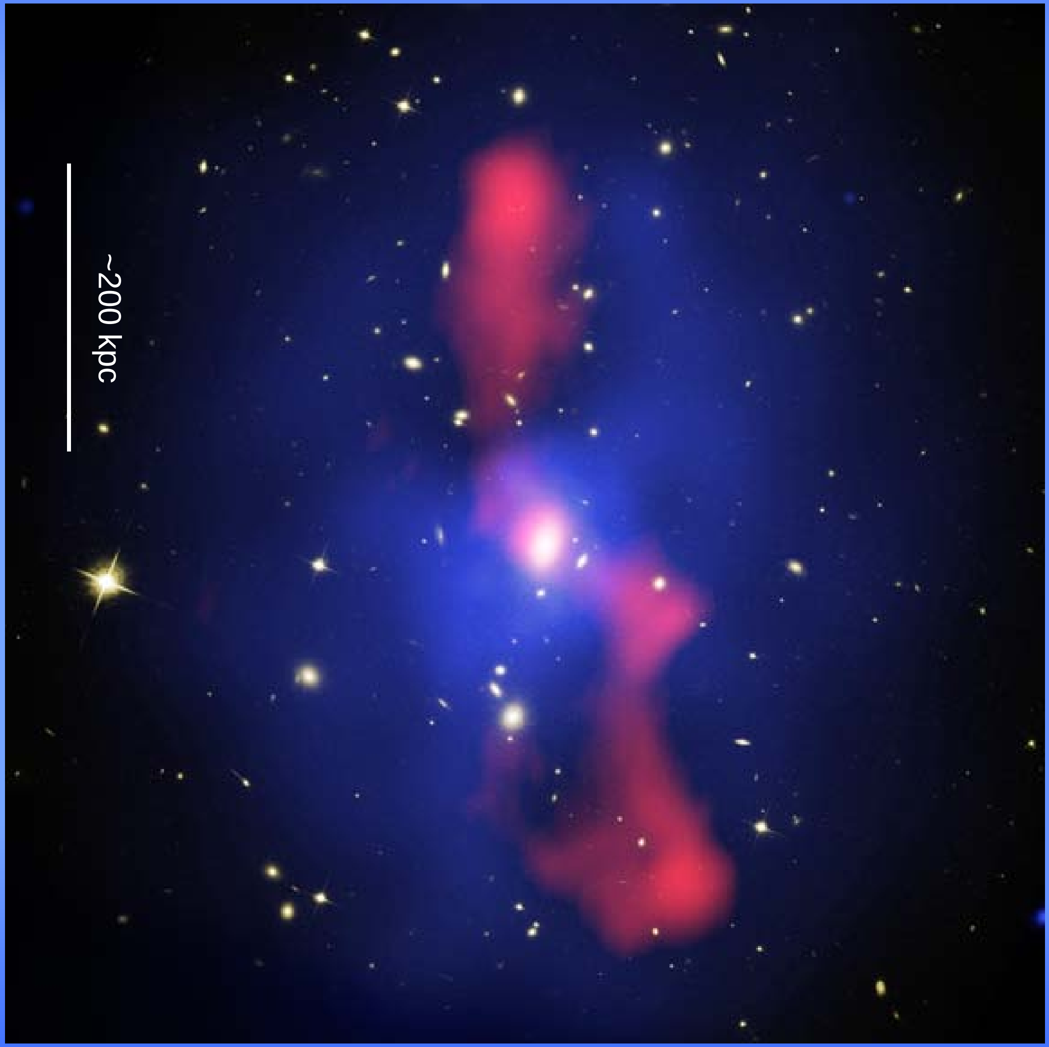
--AGN/ICM Interactions Provide a Rich Laboratory--

- A) X-ray Cavities (Bubbles) as AGN Calorimeters
- B) Stability of Cavities
- C) Dynamic ICMs
- D) NATs as Possible Probes of ICM Shocks

A) Giant AGN-related Cavities Commonly Seen in ICMs
Potential Calorimeters of AGN Energy Output

MS0735.6+7421

Red: radio
Blue: X-ray
White: visible



200 kpc Cavities

E> 10^{61} erg

t > 10^{8} yrs

McNamara etal

Cavity Enthalpy as an AGN Calorimeter: How Well Does it Measure?

Thermal X-rays from ICM provide local pressure estimates:

$E_{tot} \sim E_{cav} + PV = H$

$= \gamma/(\gamma-1)\ PV$ (assuming $E_{cav}=1/(\gamma-1)\ PV$)

$E_{tot} \sim H \sim (5/2)\ PV\ (\gamma = 5/3)$

$\sim 4\ PV\ (\gamma = 4/3)$

$L_{AGN} \sim E_{tot} / t_{age}$ (given some age estimate)

Cavity-ICM pressure balance assumed

$$\text{'PV'} = \int P_{ICM}\, dV_{cavity}$$

Test: 3D MHD Jet Simulations & Synthetic Observations

- **Bipolar, collimated jet outflows**

  L_{jet} = 1.2x10^{46} erg/s (combined jets at full power), Mach 30, v_j = 0.1c
  r_{jet} = 3 kpc
  ρ_{jet}/ρ_0 = 0.01

  Toroidal jet B field at source (β ~ 100; B ~ 10 μG)

- **Steady, <u>Intermittent</u> & Terminated @26 Myr Outflows**

- **AGN at center of ~ 4x10^{14} M_o relaxed cluster (NFW potential)**

  kT_{ICM} ~3 keV (~ Perseus)

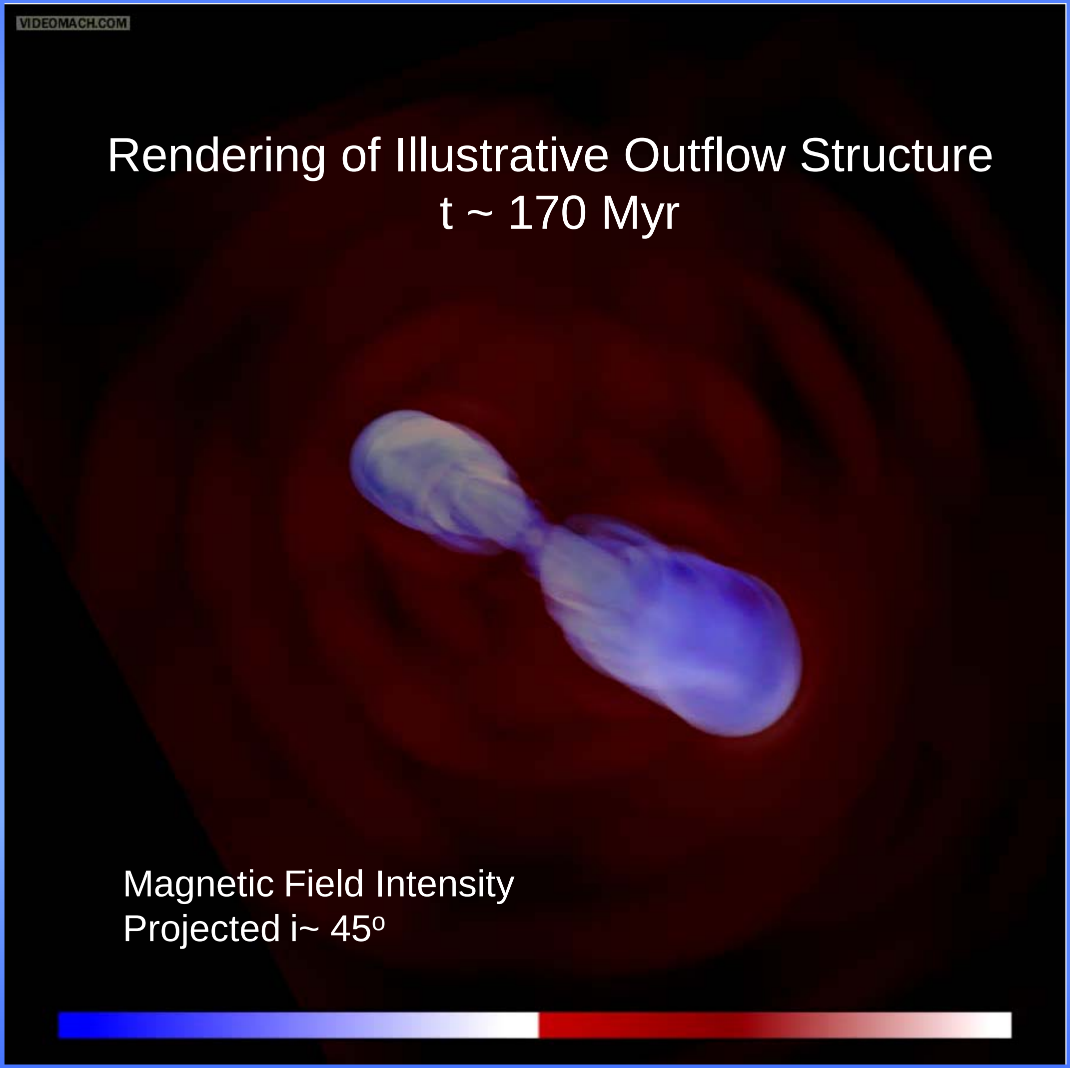
  Double β ICM density profile with random density fluctuations
  Tangled ICM magnetic field
  <β_{plasma}>~ 100 (range ~ 30:1000) (<B_{core}> ~ 7μG)
  No radiative cooling of ICM
  600x480x480 kpc box (1 kpc resolution) (O'Neill &Jones 2010)

Intermittent Jets

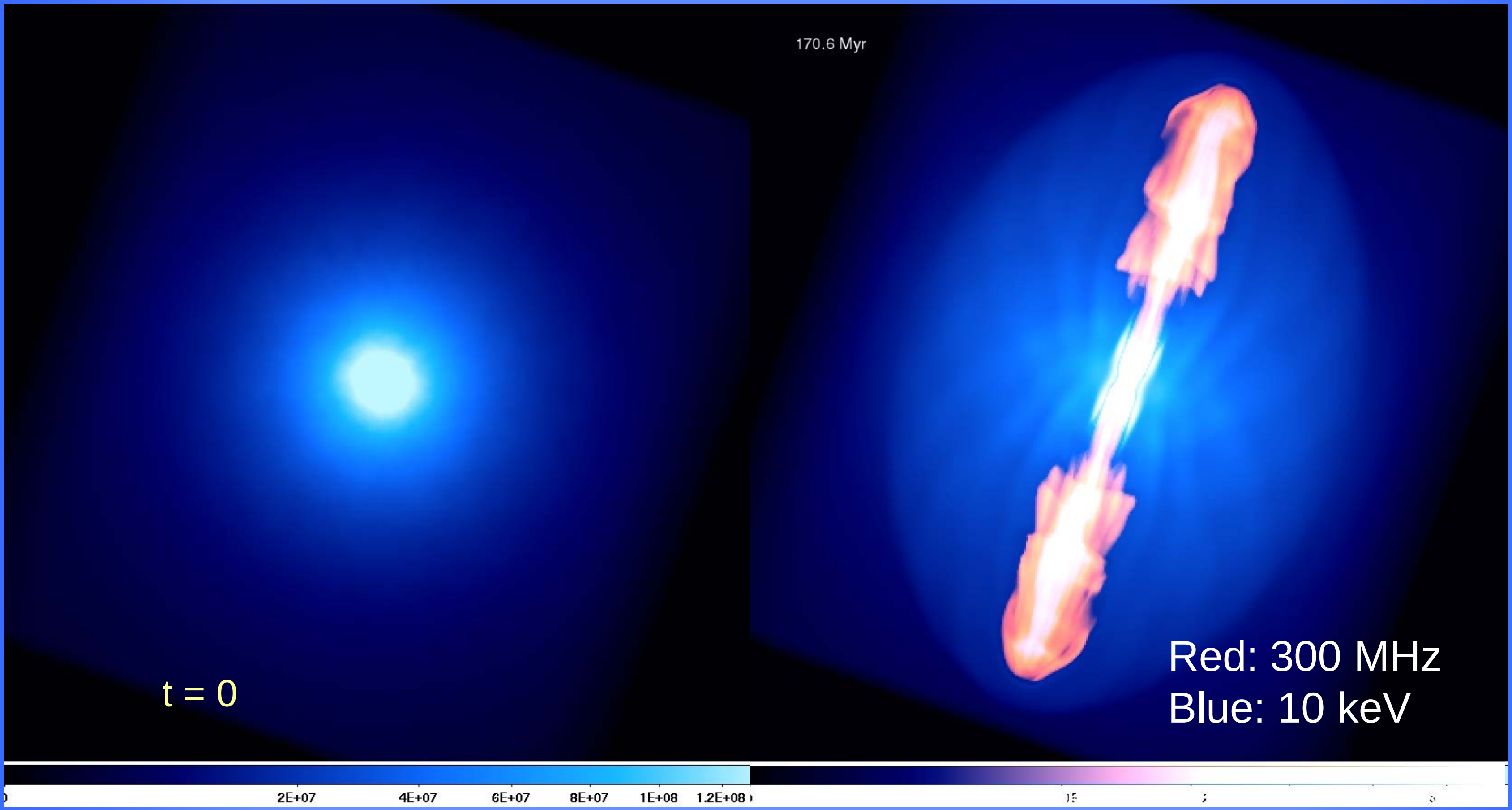
t_{on} = 13 Myr
t_{off} = 13 Myr

Six cycles

Blue (AGN plasma)
Red (ICM plasma)



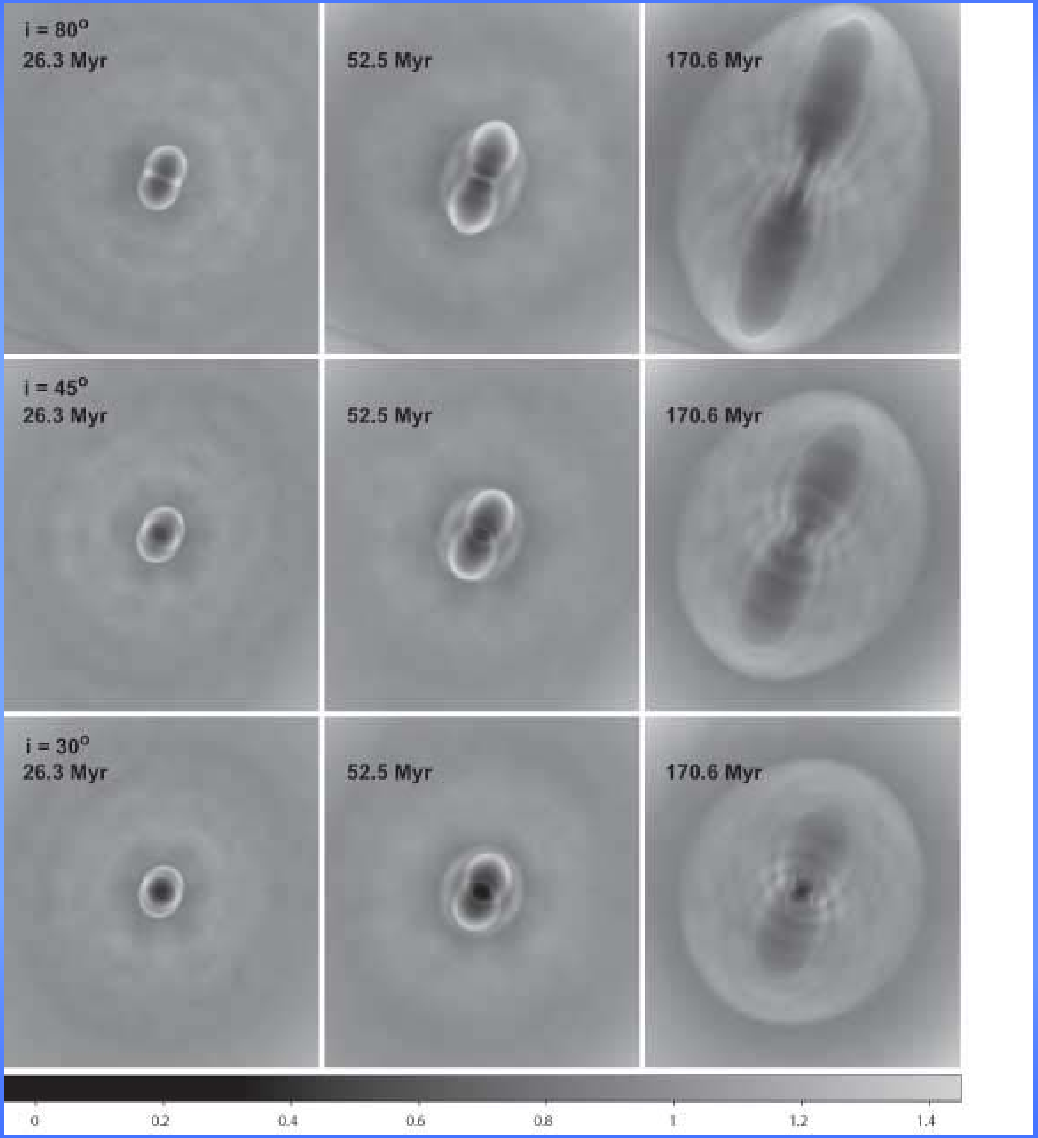
Synthetic 2 keV X-ray Observations: Thermal + Inverse Compton (CMB) Radio Synchrotron



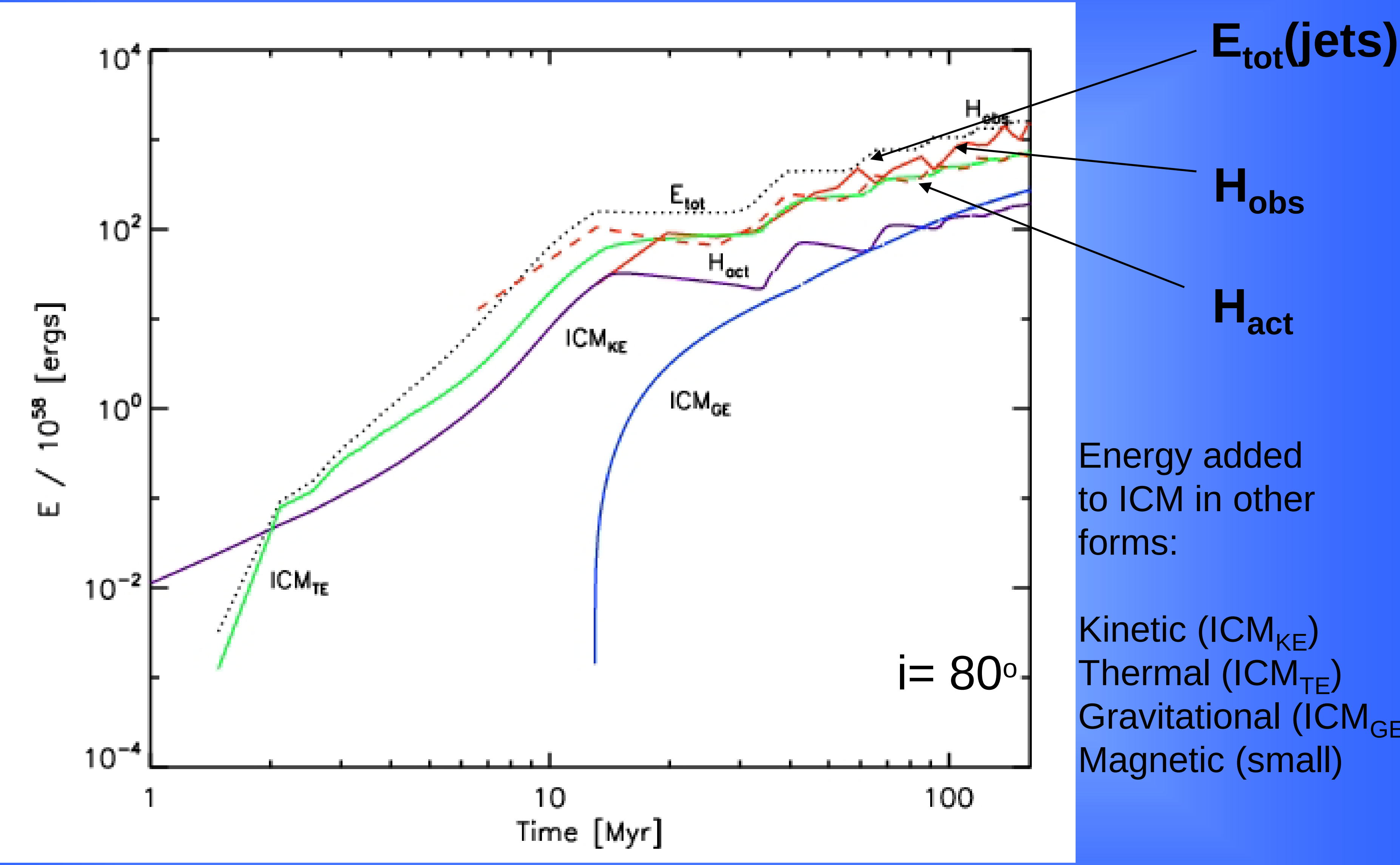
Intermittent Jets, projected i=80°

2 keV intensity divided by double β fitted profile

Intermittent Jets



Intermittent Jet 'Observed' & Actual Energetics



Energy added to ICM in other forms:

Kinetic (ICM_{KE})
Thermal (ICM_{TE})
Gravitational (ICM_{GE})
Magnetic (small)

Cavity Ages Not Really Known-- Common Estimates:

$t_{buoy} \sim R \sqrt{(A/(2gV))}$, $t_s \sim R/c_s$

R, A & V are size, cross-section and volume estimates*

Model (i=80^o)	Age in sim. (Myr)	t_{buoy} (Myr)	t_s (Myr)
Intermittent	170	154	155
Terminated	157	110	155

*All 'derived from observation'

Resultant Jet Power ‘Observations’

Model (i=80^o)	E_{tot}(sim.) 10^{60}erg	E_{obs}= 2.5H_{obs} 10^{60}erg	$\langle P_{jet}\rangle$(sim.) 10^{45}erg/s	P_{obs} = E_{obs}/t_{buoy} 10^{45}erg/s
Intermittent	15	25	2.8	3.0
Terminated	9	15	1.8	4.3

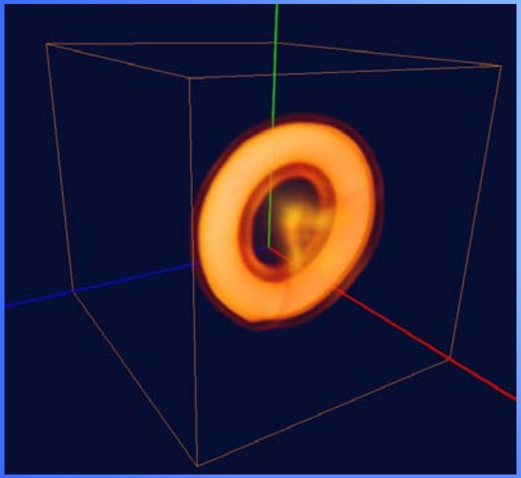
B) Should the cavities survive ~ 10^8 yr?

- **Static bubble top Rayleigh-Taylor unstable:**
  ($\eta = \rho_{bub} / \rho_{ICM} << 1$; disruption for λ~R)

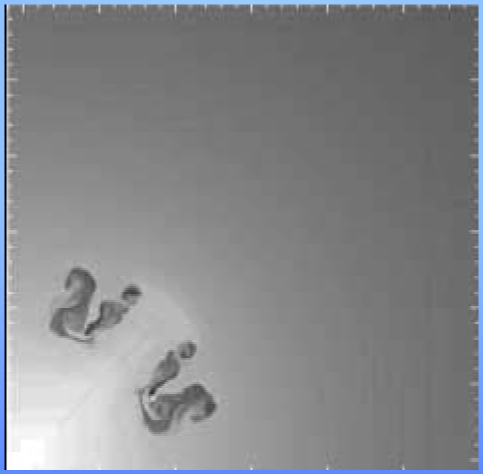
$$t_{R-T} \sim \sqrt{\frac{1}{kg}} \sim \sqrt{\frac{h\lambda}{c_s^2}} \sim_{\lambda \to R} t_s \sqrt{\frac{h}{R}} <_{R>h} t_s$$

- **Static bubble unstable to vortex ring formation (faster than R-T):**
  (lower boundary not in HSE)

$$t_{vort} \sim \sqrt{\frac{\eta^{1/2} R}{g}} \sim t_{R-T}\eta^{1/4} < t_{R-T}$$

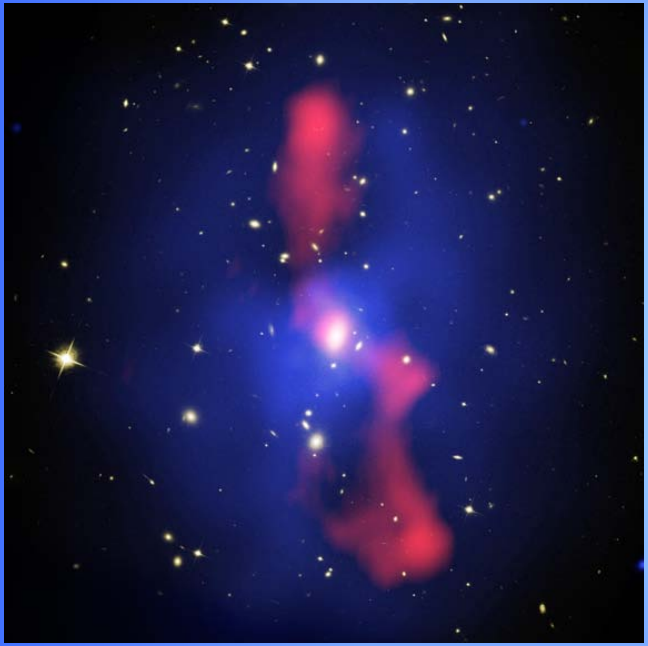


ONeill etal 2009



Scannapieco & Bruggen 2008

Real Cavities & Simulated 'Dynamical' Cavities Do Survive



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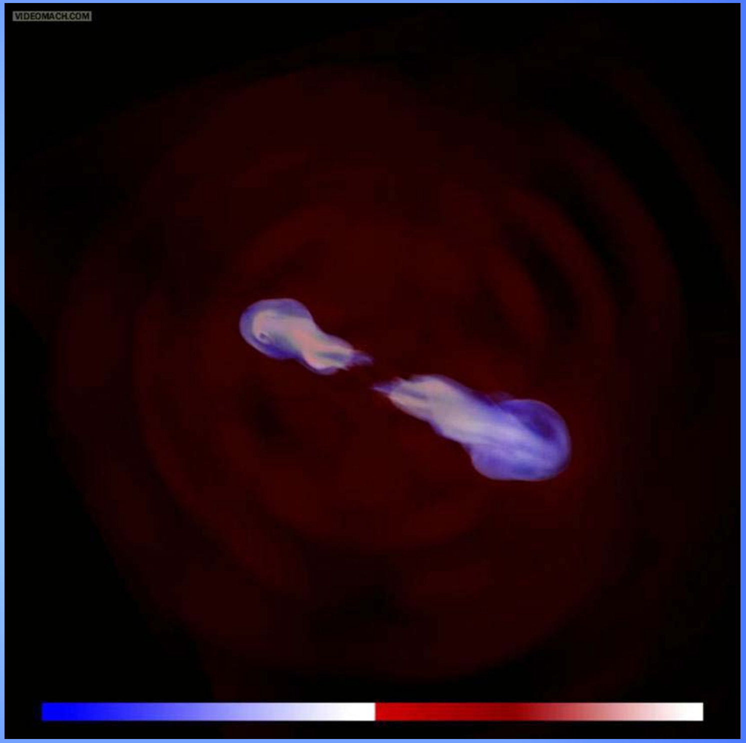
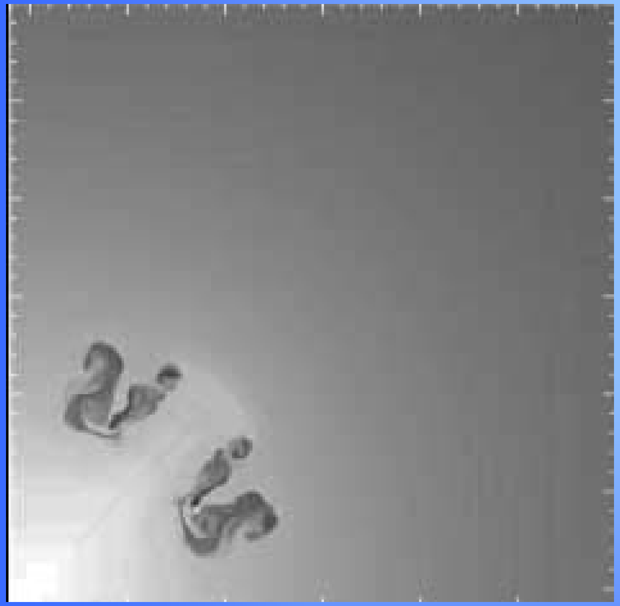


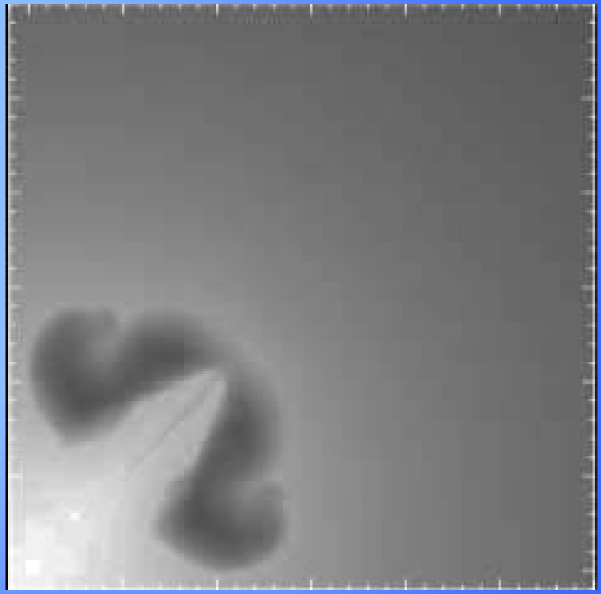
Simulation: relic plasma
125 Myr after jet termination
in cluster-like environment

Some Possible Stabilizing Factors

- R-T instabilities could lead to small-scale turbulence, entrainment, enhanced effective viscosity



High Reynolds number simulation with subgrid turbulence model

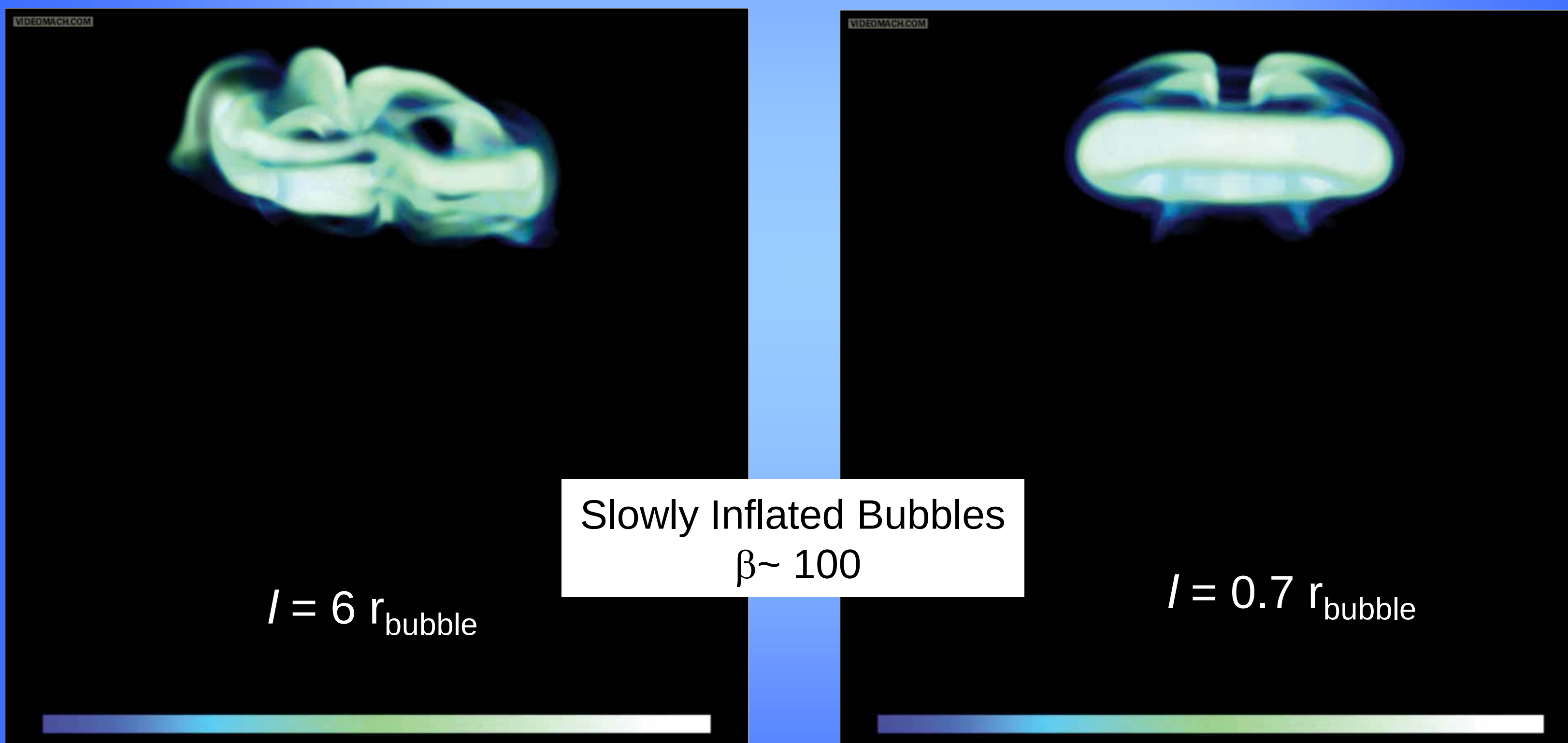


Scannapieco & Bruggen 2008

•“Large Scale” Magnetic Fields

Field Tension can stabilize R-T & K-H instabilities in field plane;
Note, however, tension also can ‘cut’ bubble, disrupting it.
Field tangling on scales $l < r_{bubble}$ limits disruption, maximizes stabilizing role

Even “weak” fields ($\beta \gg 1$) have influence



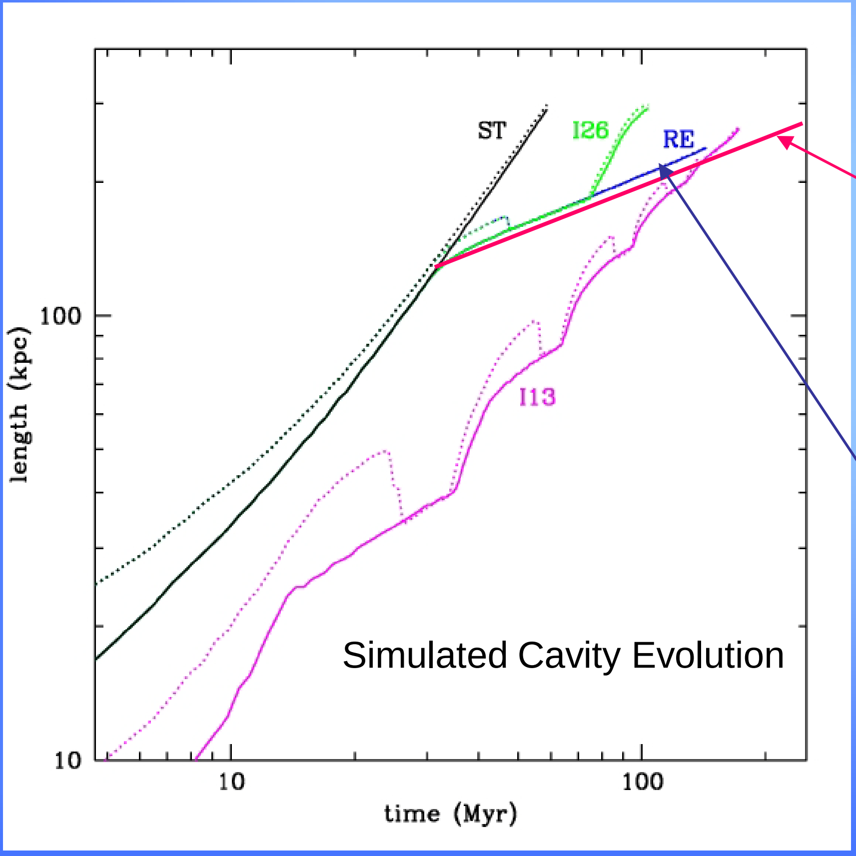
O’Neill, DeYoung & Jones 2009

Also e.g., Ruszkowski etal 2006, Dursi & Pfrommer 2008

•Real Cavities Form 'Dynamically'

Dynamical Formation & Entrainment => stabilizing

• Jet momentum transferred to adjacent ICM, continues to drive out (ONeill & Jones 2010)



Simple dynamical model

$$v_{head}(t > t_{off}) \approx \frac{1}{M_e}\left[\frac{P_{jet} t_{off}}{v_{jet}} - \int_{t_{off}}^{t} F_{drag}\, dt\right],$$

$$M_e \sim \int_0^t \rho_{ICM}(r) A_{head} v_{head}\, dt$$

V_{head} is propagation speed of head; M_e is entrained mass being "carried along"

Evolution of terminated 'relic' jet cavity length

Underlying Issue: Small Scale Flows, Turbulence, Viscosity:

Key question: effective viscosity, Reynolds number difficult to estimate
ICM is a collisionless plasma (Coulomb scattering, $\tau_{col} >> 1/\omega_g$)

$$\nu_{Brag} \sim \mathrm{v}_p l_{col,p} \sim 10 \frac{T_{keV}^{5/2}}{n_{-2}} kpc - km/\sec$$

$$l_{col} \sim 20 \frac{T_{keV}^{2}}{n_{-2}} pc;$$

$$\tau_{col,p} = \frac{l_{col}}{\mathrm{v_p}} \sim 3.8x10^4 \frac{T_{keV}^{3/2}}{n_{-2}} yrs$$

$$n_{-2} = \frac{n}{10^{-2} cm^{-3}};$$

$$u_{100} = \frac{u}{100 km/\sec}$$

For typical ICMs (T_{kev} ~ several, $n_{-2} < 1$)
Can be that $l_{col} \sim$ kpc, $\tau_{col} \sim$ Myr

Underlying Issue:
Small Scale Flows, Turbulence, Viscosity:

- For turbulence need $R_e > 10^3$ on driving scales, $l \sim L$

$$R_e \sim \frac{ul}{\nu_{Brag}} \sim 20\,\frac{u_{100}\,l_{kpc}\,n_{-2}}{T_{keV}^{5/2}}$$

$$\mathrm{M(L)} = \left(u(L)/c_s\right) >> 1/2\left(\mathrm{T}_{keV}^{2}/\mathrm{L}_{100}\mathrm{n}_{-2}\right)$$

$$L_{100} = \frac{L}{100kpc}$$

Small Scale Flows, Turbulence: Magnetic Fields

Particle streaming along fields;

mfp limited by field line bends:

Field lines bend only on scales where $M_A = u(l)/v_A > 1$

turbulent velocity $u(l_A) \sim u(L)(l_A/L)^{1/3}$

$\Rightarrow$ mpf ~min(l_c, l_A),

$$\mathrm{v}_A \approx 20 \frac{B_{\mu G}}{n_{-2}^{1/2}} km/\sec$$

$$\frac{l_A}{L} \sim \left(\frac{\mathrm{v}_A}{u_L}\right)^3 \sim 10^{-2} \frac{B_{\mu G}^3}{u_{L,100}^3 n_{-2}^{3/2}}$$

So for example, with $L_{100} \sim 1$, $u_{L,100} \sim 1$, $B_{\mu G} \sim 3$,

Micro instabilities may be
critical players: e.g., firehose, mirror

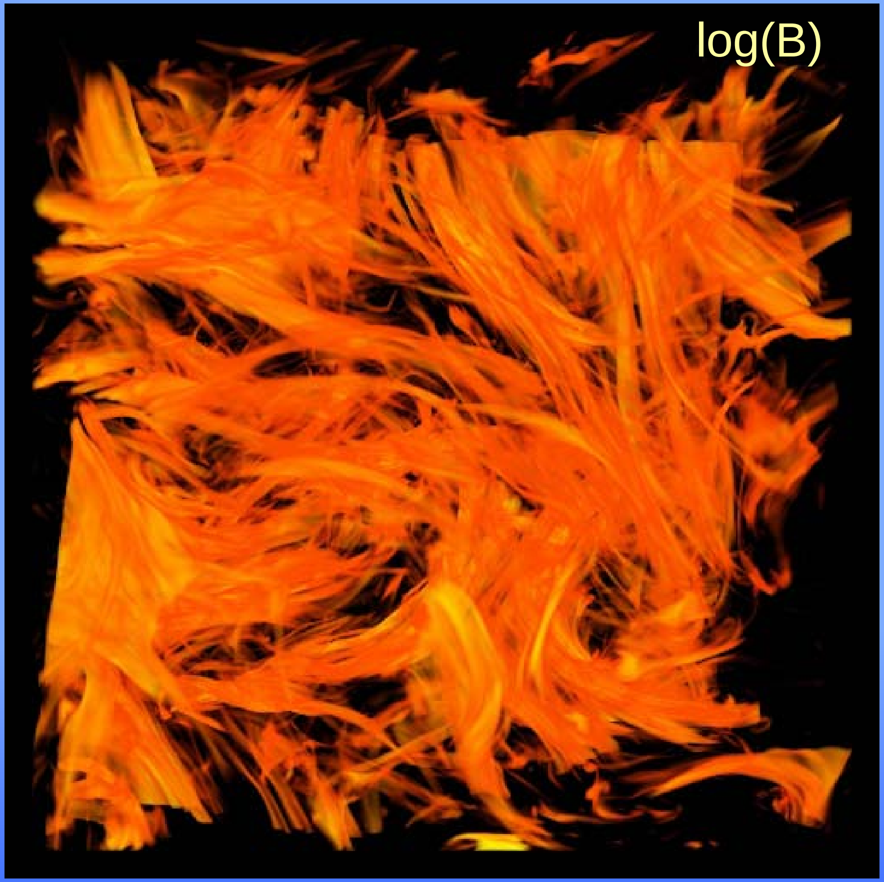
Magnetic Field Structure in Turbulent Flow:

•u & B fields intermittent on MHD scales, $l_{A,}$,
•small-scale power ⊥ **B**(l_A), *laminated ribbons spanning large eddies*

Driven, isothermal turbulence, *evolved from very weak field,* $\beta=E_t/E_B=10^6$;

$\Rightarrow E_B/E_k \sim 1/2$
$\Rightarrow E_k/E_t \sim 1/5$

Porter, Ryu, Cho & Jones



Volume containing one large eddy on ~driving scale

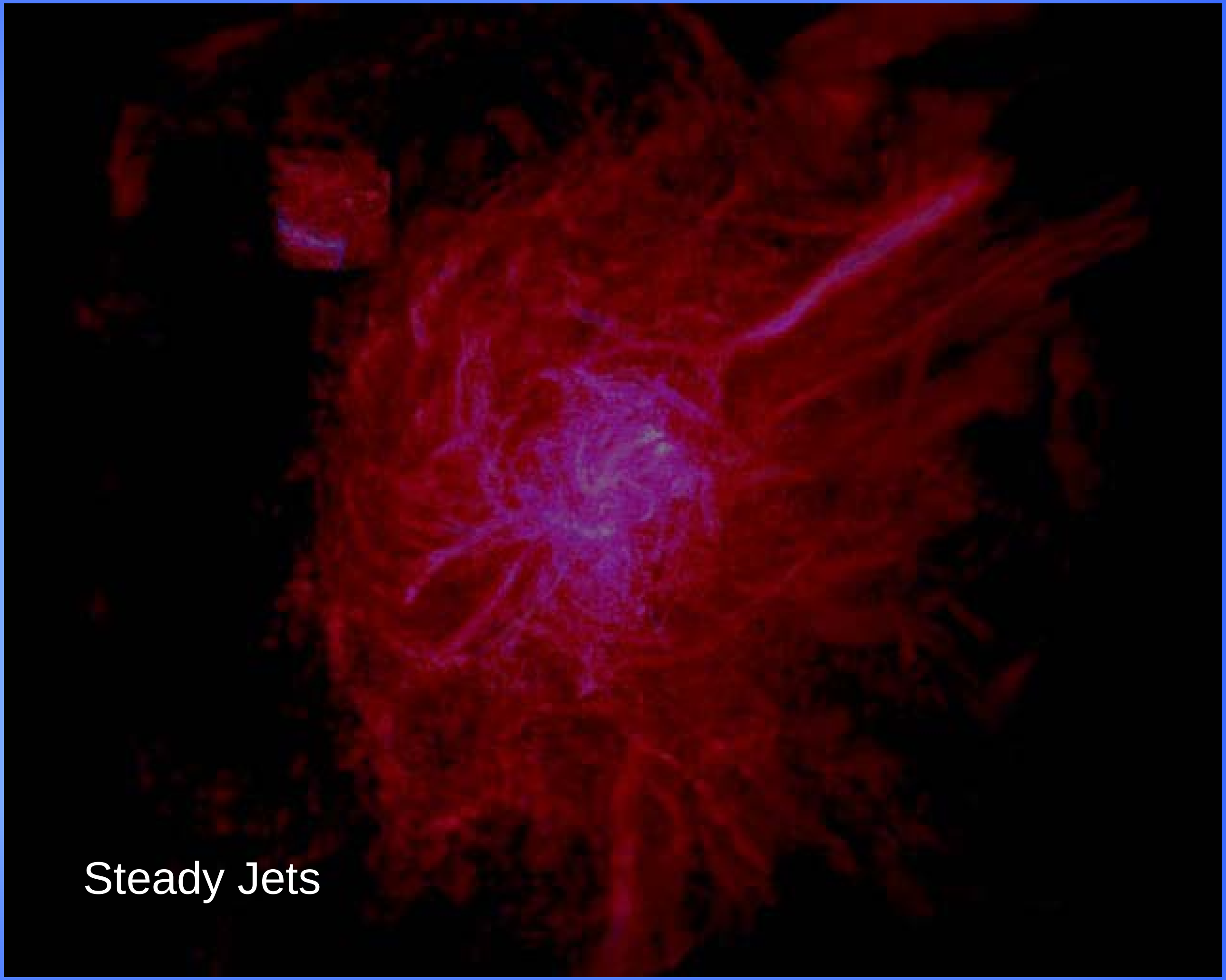
From 2048^3 compressible MHD simulation

C) Dynamical ICM Interactions with AGN

‘Relaxed’,dynamical cluster from SPH MHD cosmological simulation

This box (588 kpc^3)
$\Delta x = 1$ kpc

Mendygral,
Dolag & Jones



Magnetic Field Strength

Influence Enhanced on Unsteady Outflows

‘Relaxed’,dynamical cluster from SPH MHD cosmological simulation

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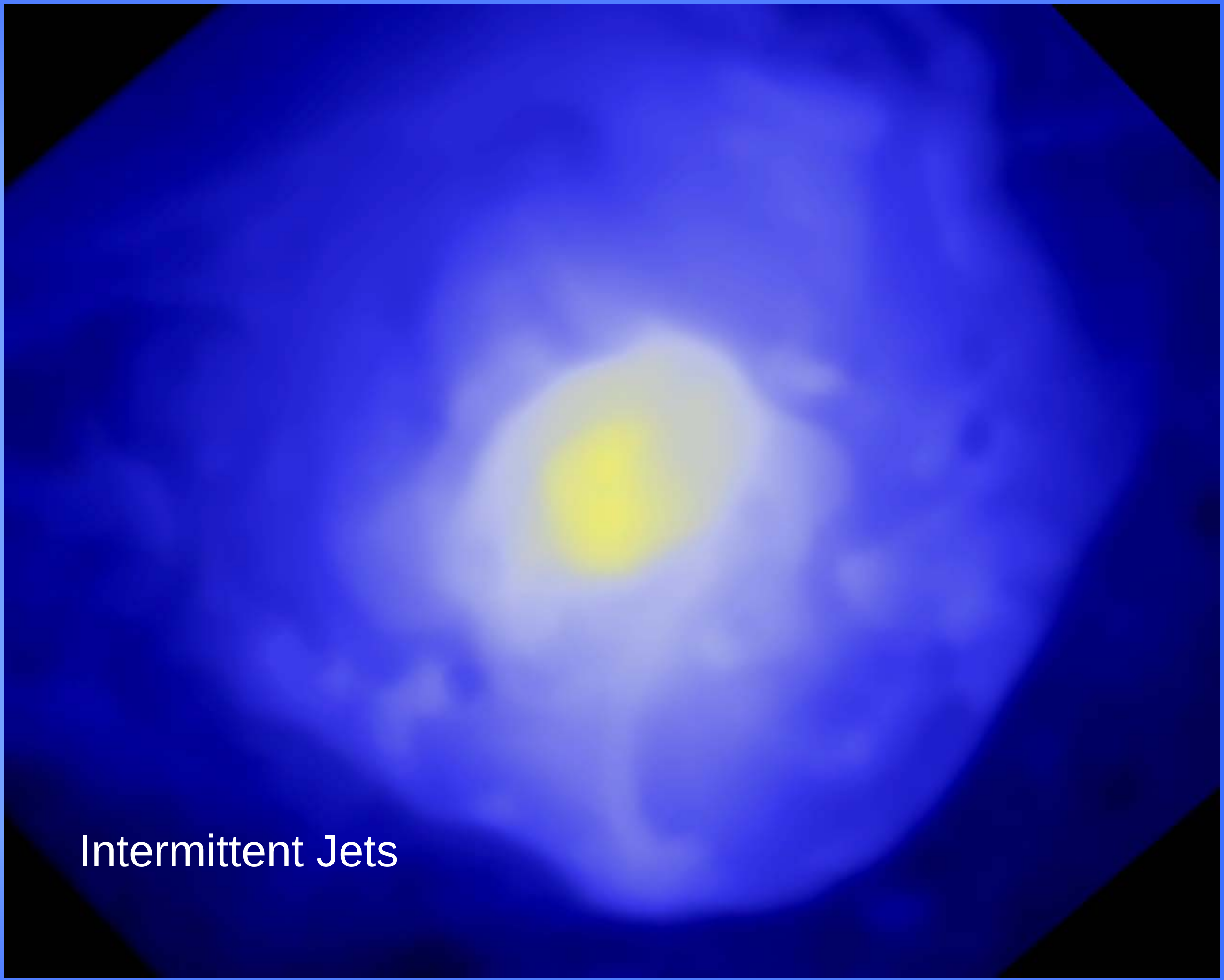


Gas Density

Mendygral, Dolag & Jones

Flows in Disturbed Clusters May Also Disrupt Outflows & Broadly Extend Interactions

AGN in disturbed cluster extracted from SPH cosmological simulation

High R_e gasdynamics, so outflows unstable

Morsony etal 2010

14 *B. J. Morsony et al.*

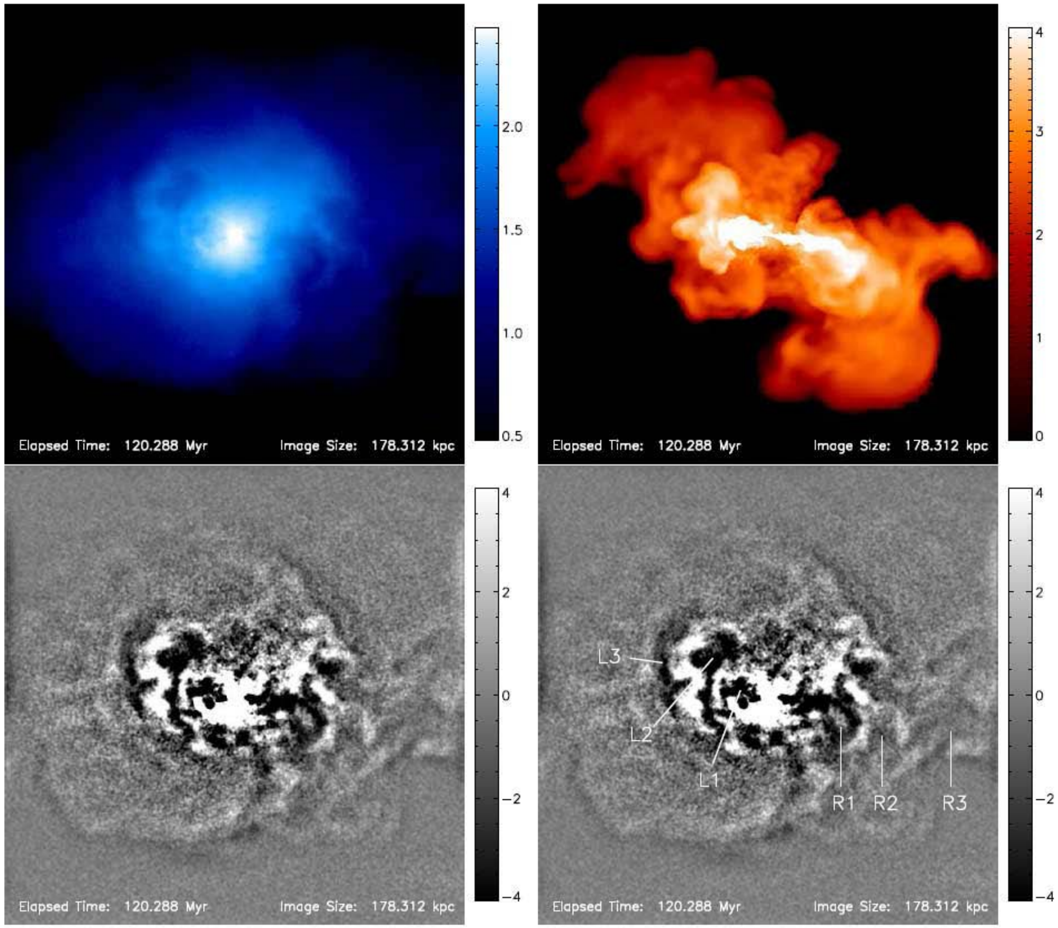
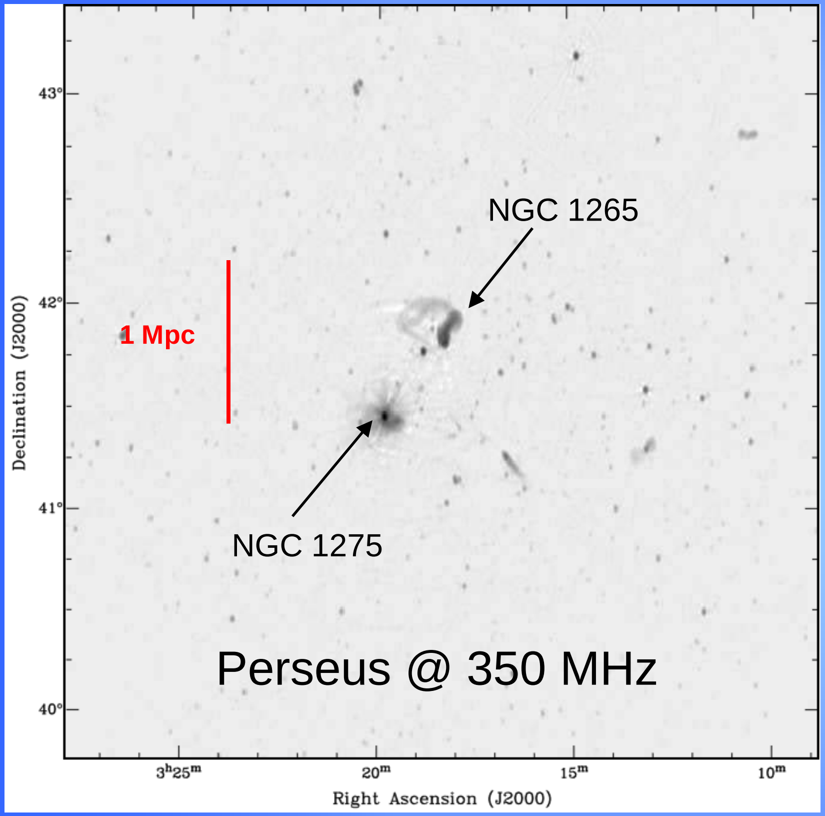
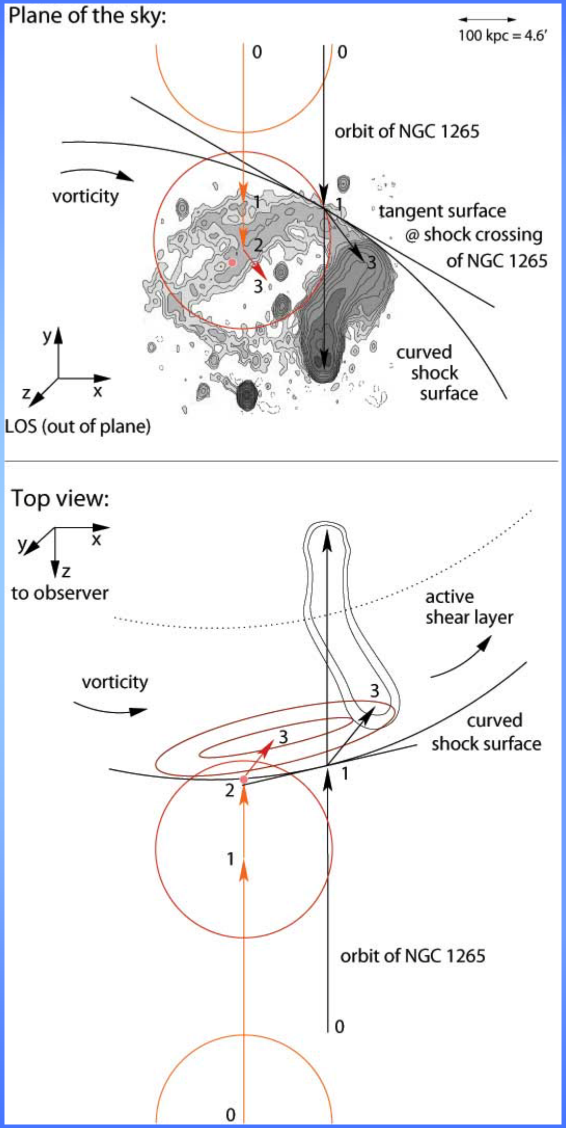


Figure 8. Synthetic Chandra X-ray data (upper left, log scale, counts/pixel) and radio data (upper right, log scale, arbitrary units) for simulation with continuous AGN of 10^{45} erg/s (45C) after 120 Myr, at the distance of the Perseus cluster. Lower left and lower right panels are an unsharp-masked image (with and without labels) of the X-ray data produced by the same procedure as in Fabian et al. 2003. A series of bubbles detached from the AGN are visible to the upper left and lower right of the cluster centre, and are labelled L1 - L3 and R1 - R3 in the lower right image. Low level radio emission extends beyond the distinct bubbles visible in the X-ray images, although there are small ripples in the unsharp-masked image throughout the radio region.

D) NATs as Possible Probes of ICM Shocks



Brentjens & deBruyn



Pfrommer & Jones
2010arXiv1004.3540

Summary

•X-ray cavities provide approximate calorimeters of AGN activity

•Cavities are dynamically formed & stabilized by entrainment,
potentially by magnetic fields &
perhaps locally generated turbulent viscosity.

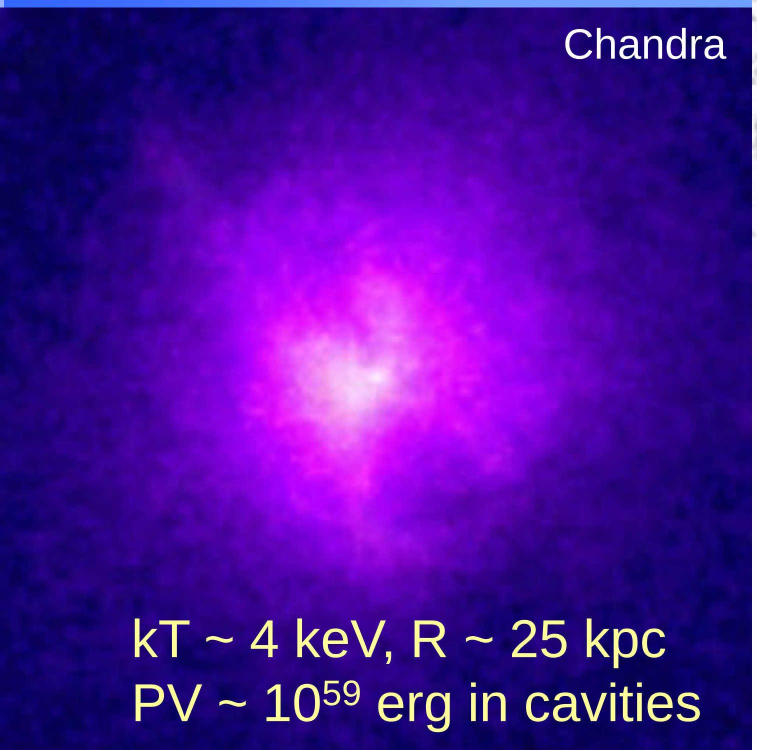
•ICM strength magnetic fields have structure-dependent roles

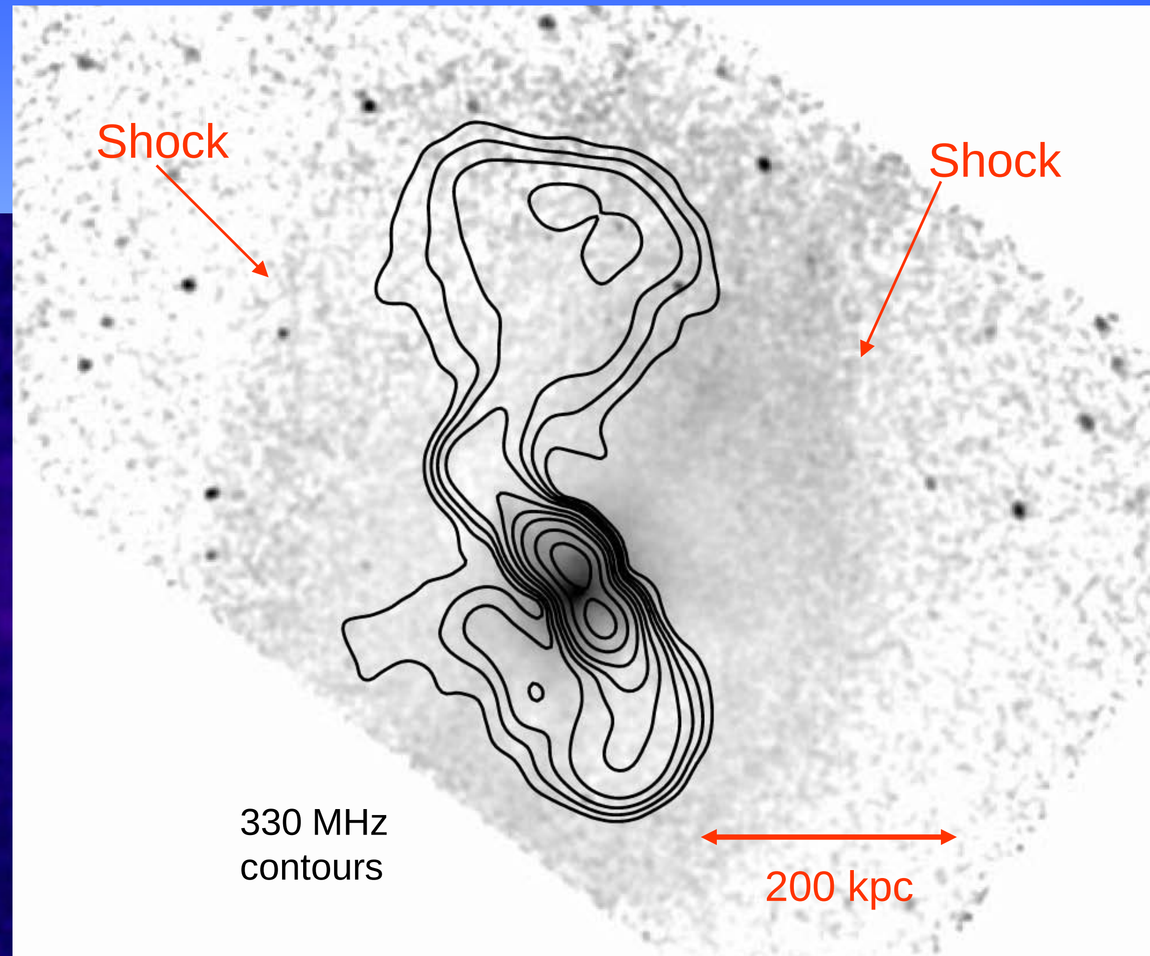
•Large scale ICM flows & turbulence can control long term
AGN outflow evolution, disruption & impact on the ICM

•AGN outflows provide unique probes of ICM environments &
dynamics

Thanks!

Example: Hydra (cavities & shocks)



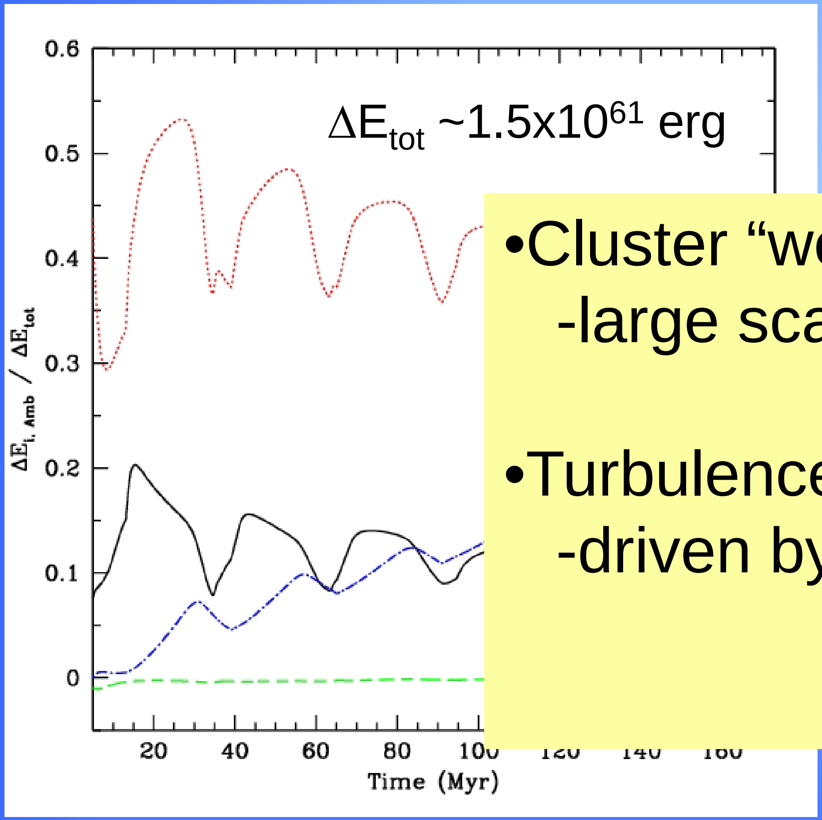


Nulsen etal 2005

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

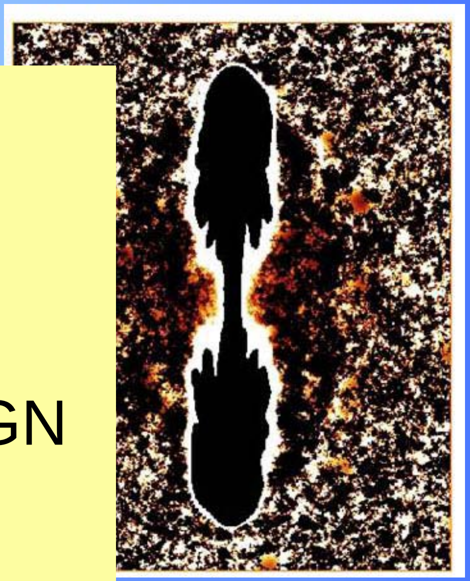
Deposition of Outflow Contents in the ICM:

~ ½ of outflow energy deposited *locally* in ICM
How to get it distributed more broadly?



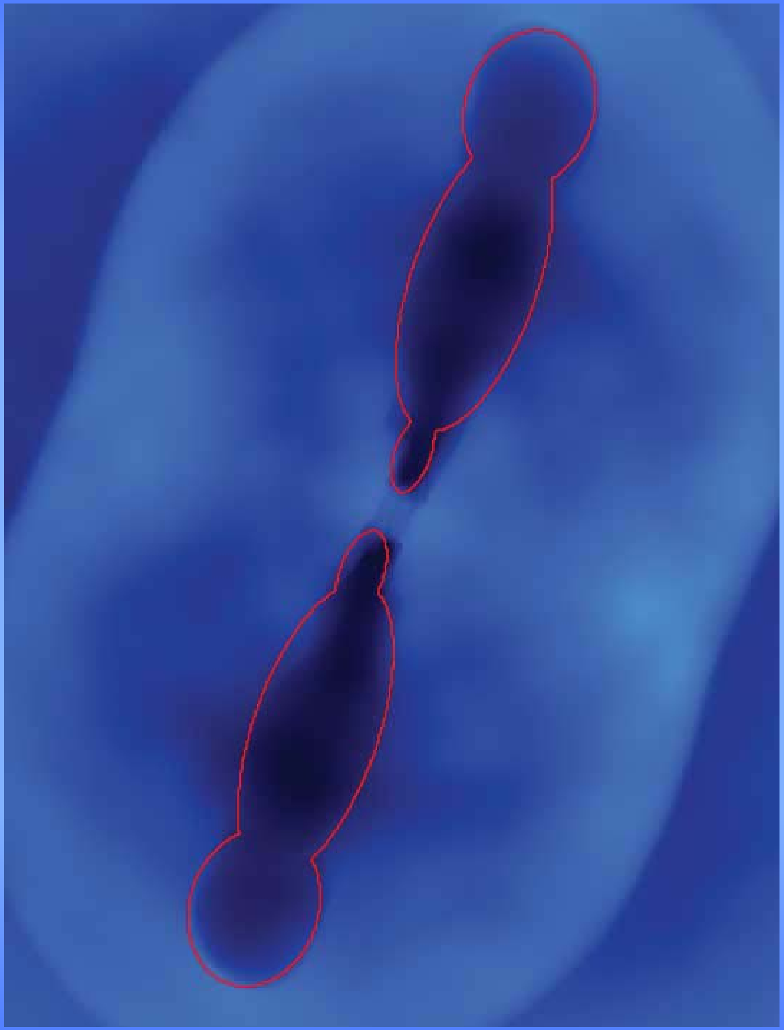
- Cluster "weather"
  - -large scale flows
- Turbulence
  - -driven by flows, AGN

Entropy in ICM
Intermittent Jets



ONeill & Jones 2010

Volume Estimation: Ellipsoids (by Eye)

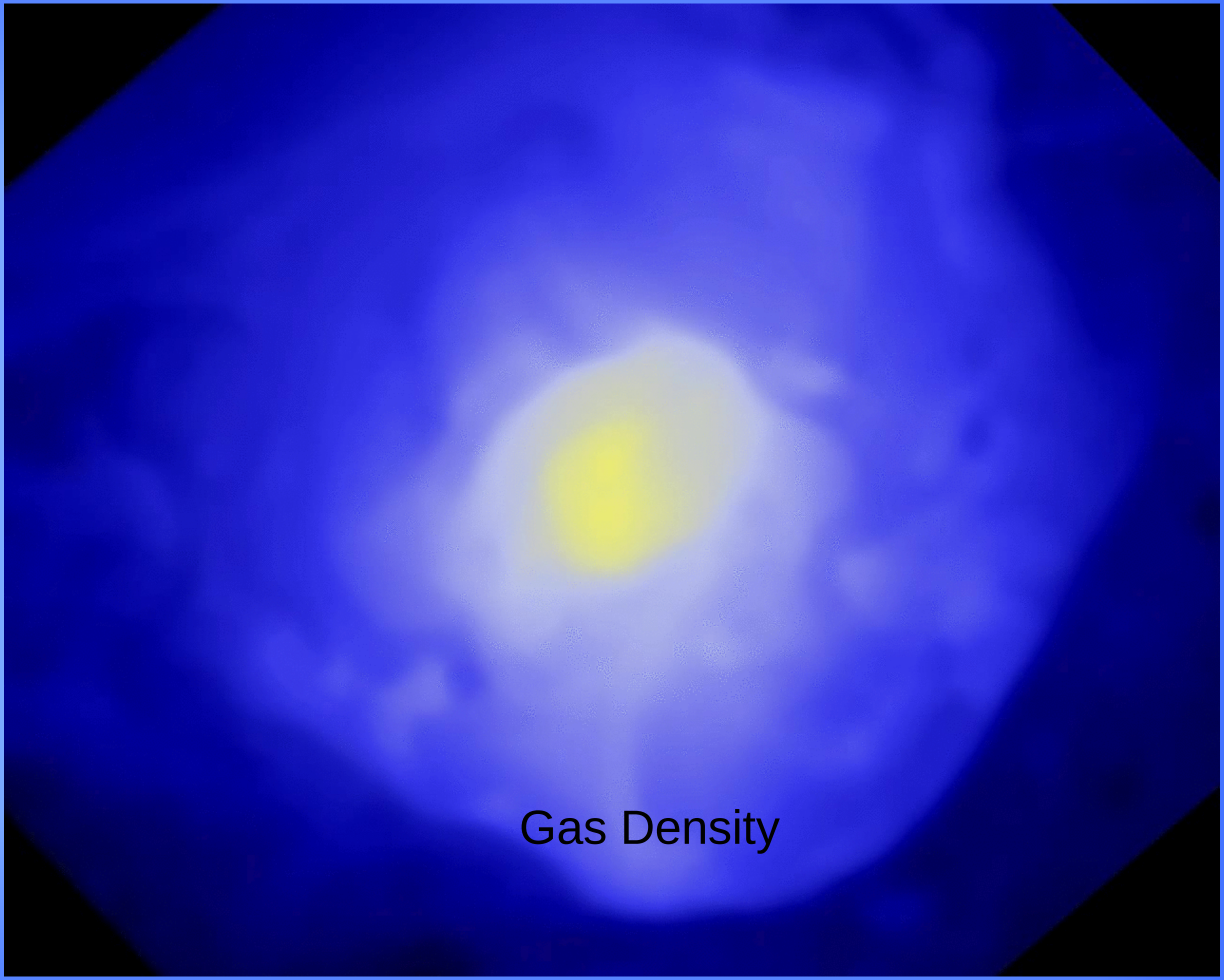


Dynamical ICMs Broaden & Complicate Interactions

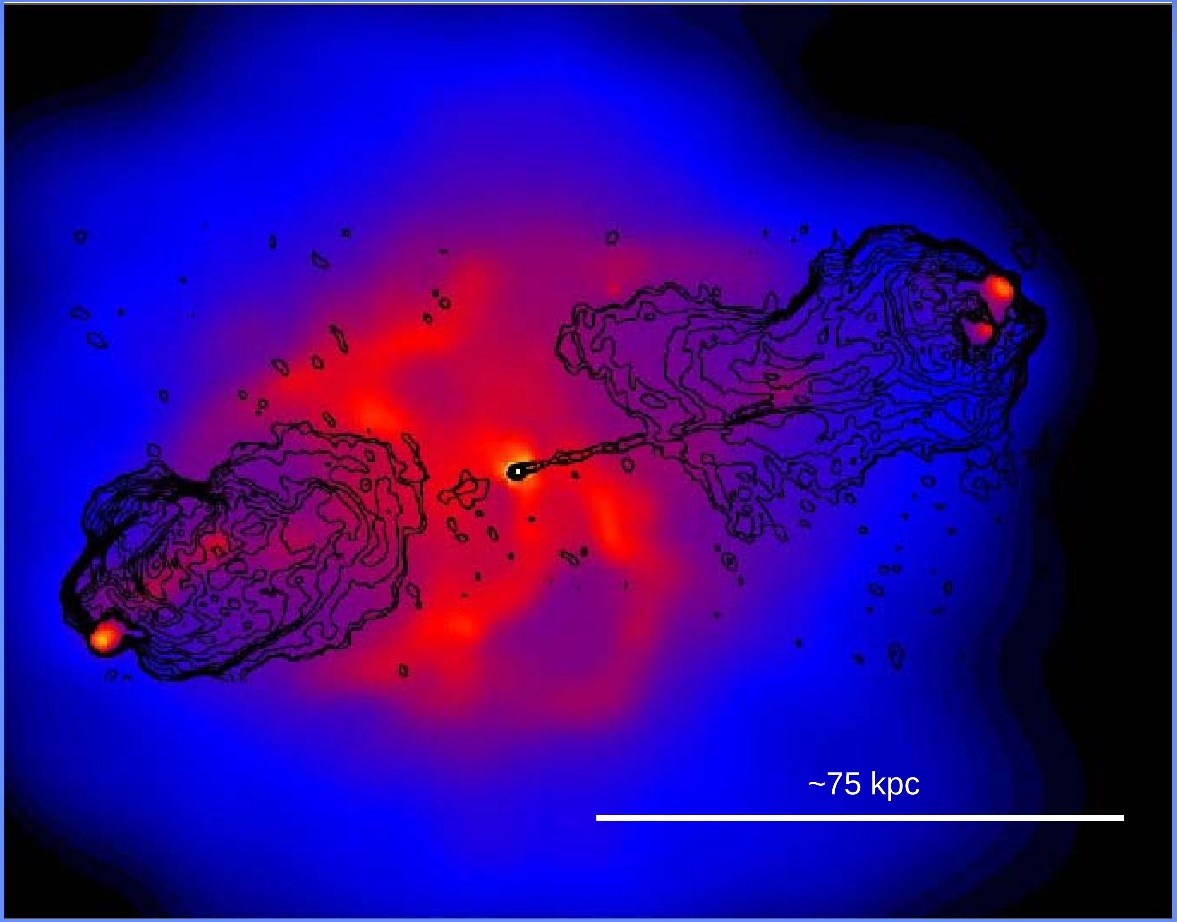
Intermittent AGN flow in 'relaxed', but dynamical cluster extracted from SPH MHD cosmological simulation

This box (588 kpc^3)
$\Delta x = 1$ kpc
$T_{end} \sim 130$ Myr

Mendygral, Dolag & Jones



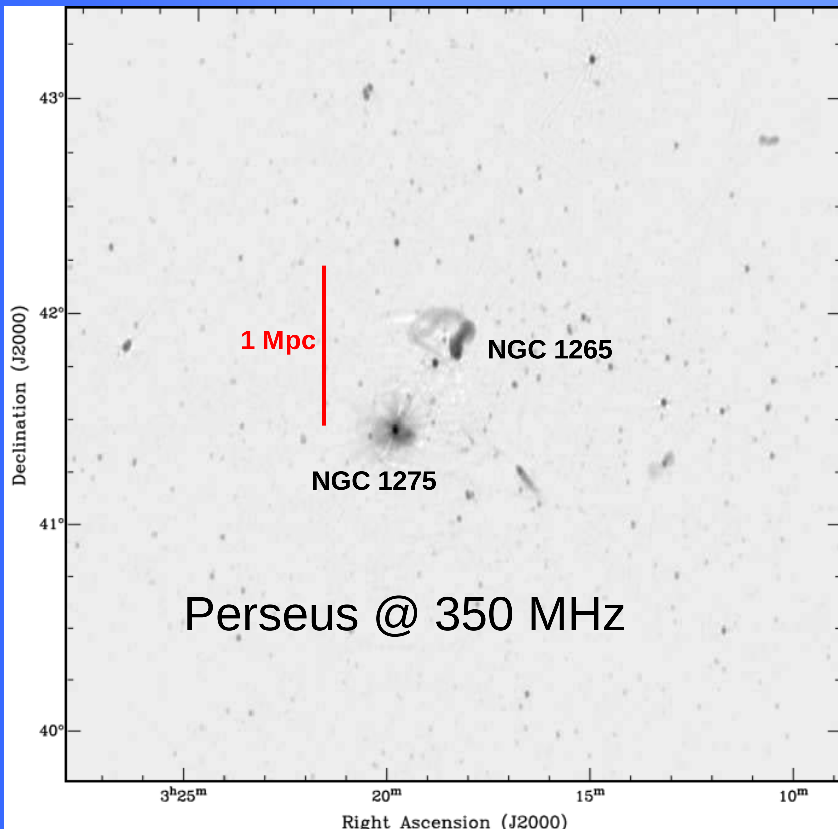
AGN Outflows Clearly Impact Environments

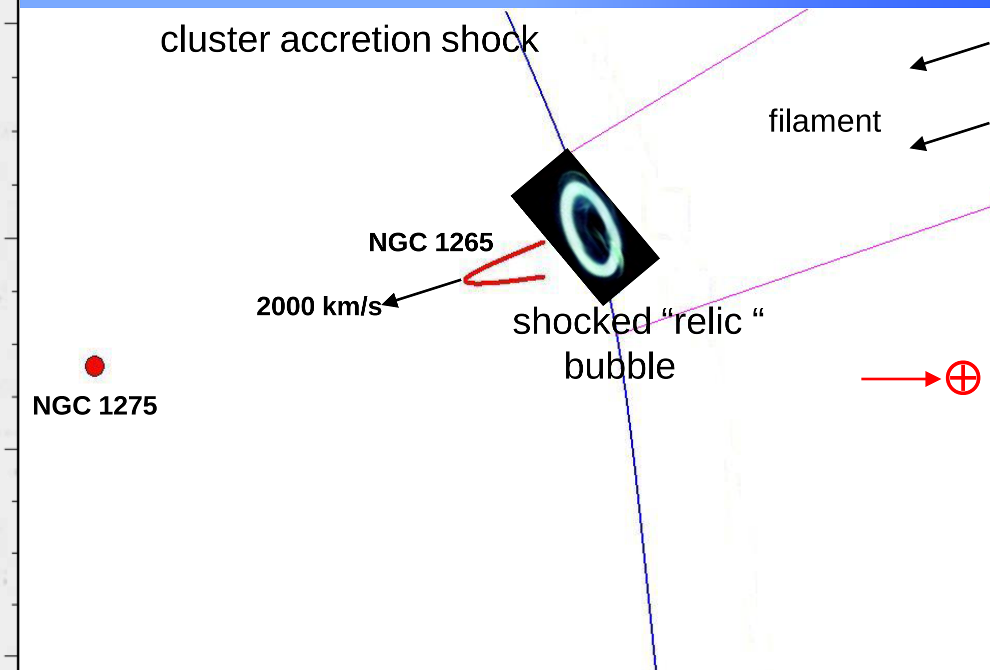


Cygnus A

Radio contours over Chandra X-ray

NGC 1265 “complex” probes Perseus’ periphery





Pfrommer & Jones

Brentjens & deBruyn

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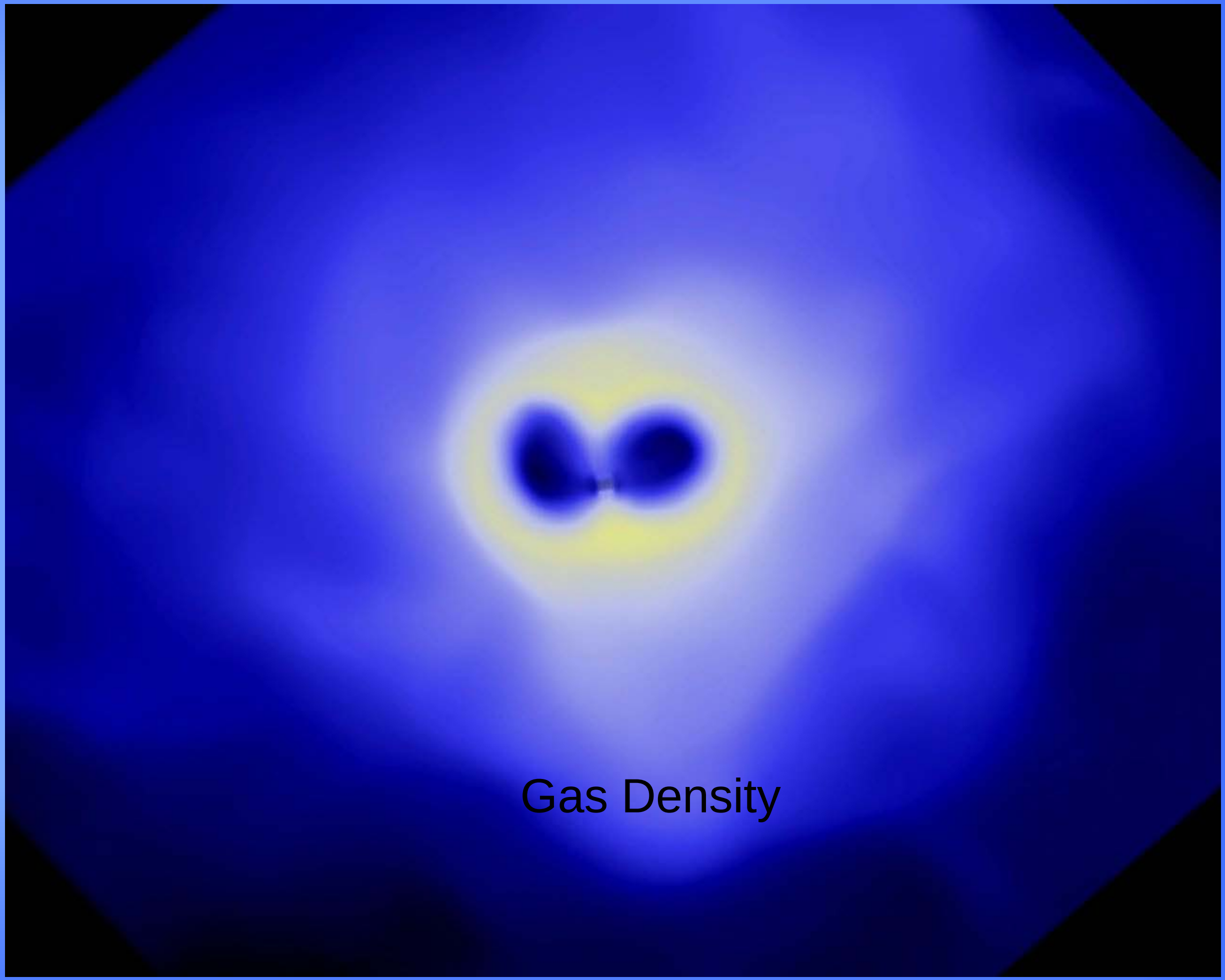

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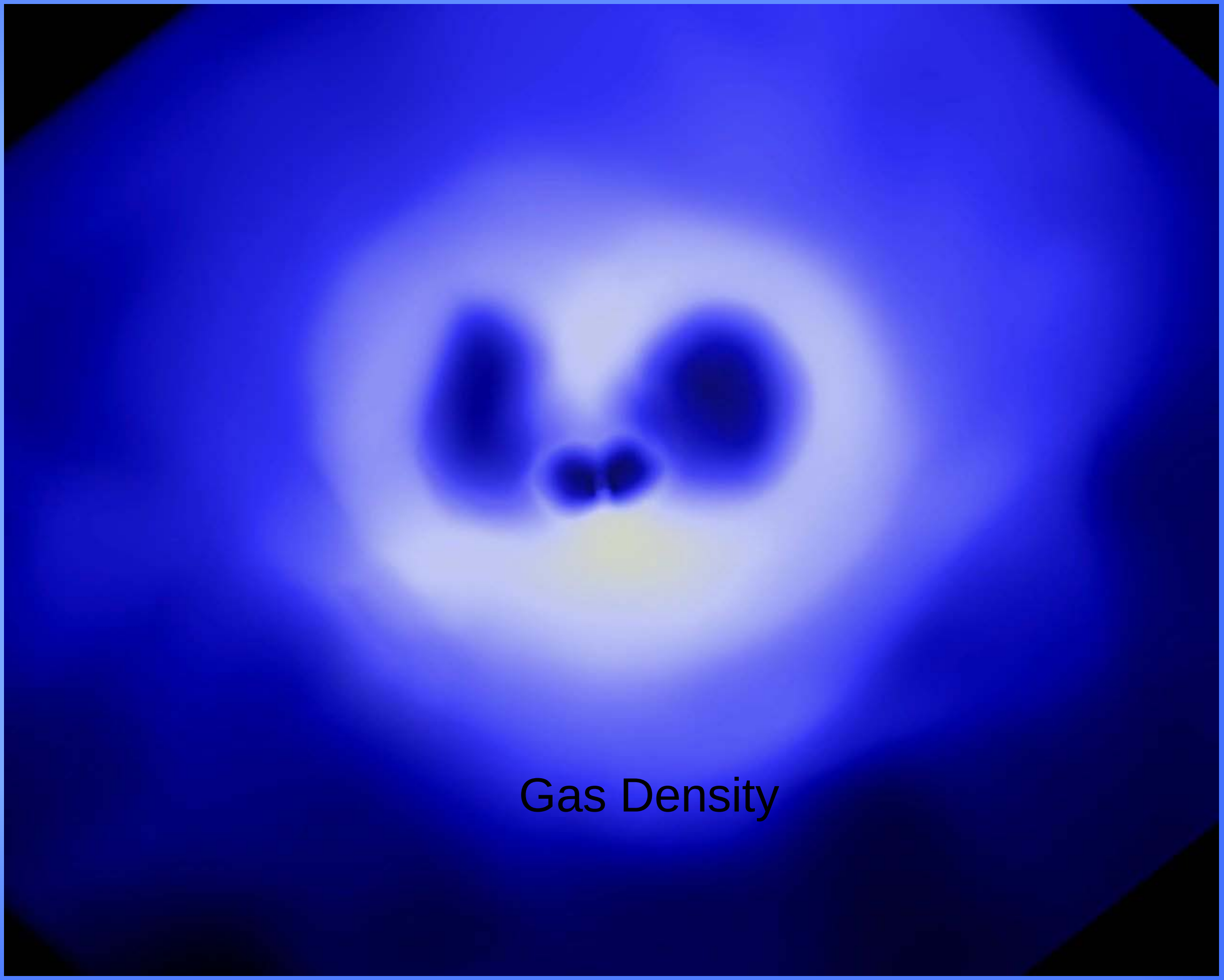
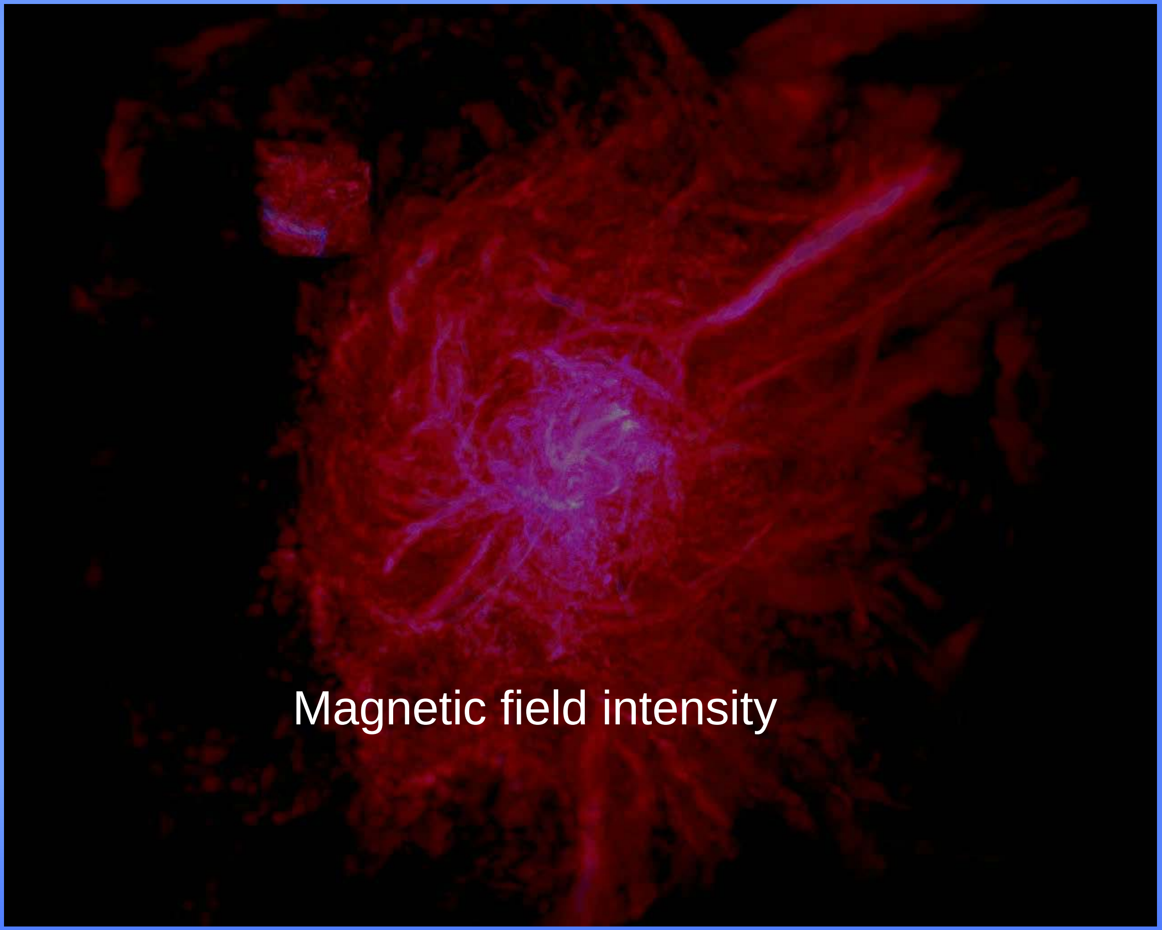


Mendygral,
Dolag & Jones

Dynamical ICMs Extend Outflow Interaction Even in Relatively 'Relaxed' Clusters

Steady AGN flow in 'relaxed', but dynamical cluster extracted From SPH MHD cosmological simulation



Mendygral, Dolag & Jones