INTERACTION BETWEEN A CENTRAL RADIO GALAXY AND THE ICM

PAUL NULSEN, JOHN ZUHONE,

CENTER FOR ASTROPHYSICS | HARVARD & SMITHSONIAN

BRADFORD SNIOS (CFA), MICHAEL WISE (SRON),

MARTIJN DE VRIES (STANFORD)

ICM 2022

2022 Aug 17

CYGNUS A

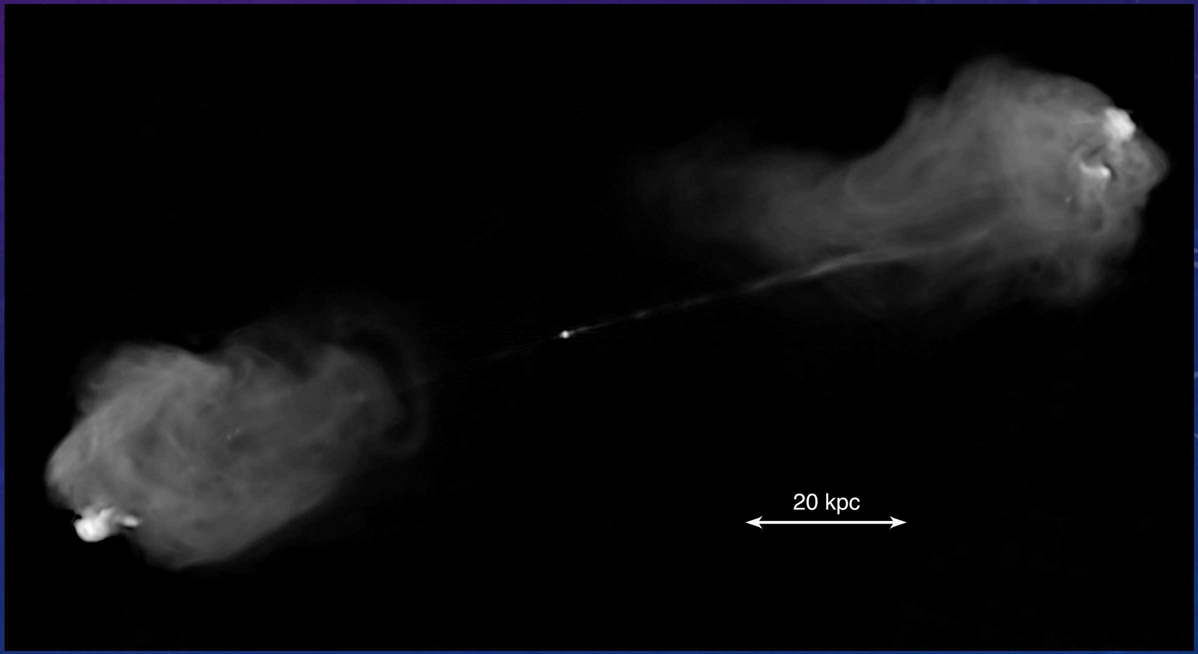
Archetype of powerful FR II radio sources (Carilli & Barthel 1994)

Radio luminosity ≈ 7×10^{44} erg s^{-1}; z = 0.056; scale = 1.1 kpc $arcsec^{-1}$

Hosted by the central galaxy of a cool-core cluster

Chandra X-ray image reveals AGN, radio hotspots, cocoon shock, X-ray cavities, shock compressed rim, nonthermal X-rays from the lobes, “X-ray jet”

C band radio map (4 – 8 GHz; Kokotanekov 2018)

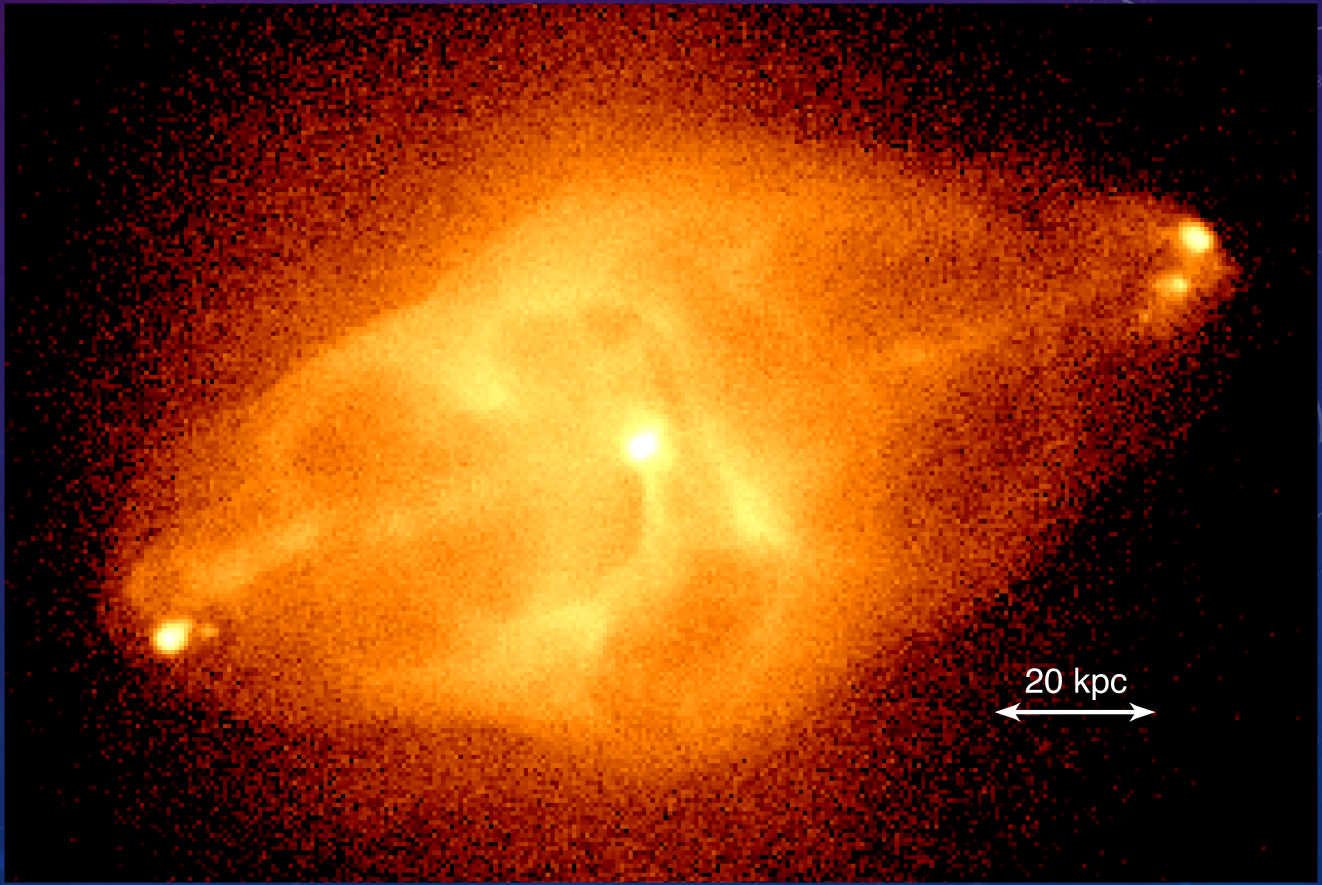


CYGNUS A

Archetype of powerful FR II radio sources (Carilli & Barthel 1994)

Radio luminosity ≈ 7×10^{44} erg s^{-1}; z = 0.056; scale = 1.1 kpc $arcsec^{-1}$

Chandra 0.5 – 5 keV (2 Msec)



Hosted by the central galaxy of a cool-core cluster

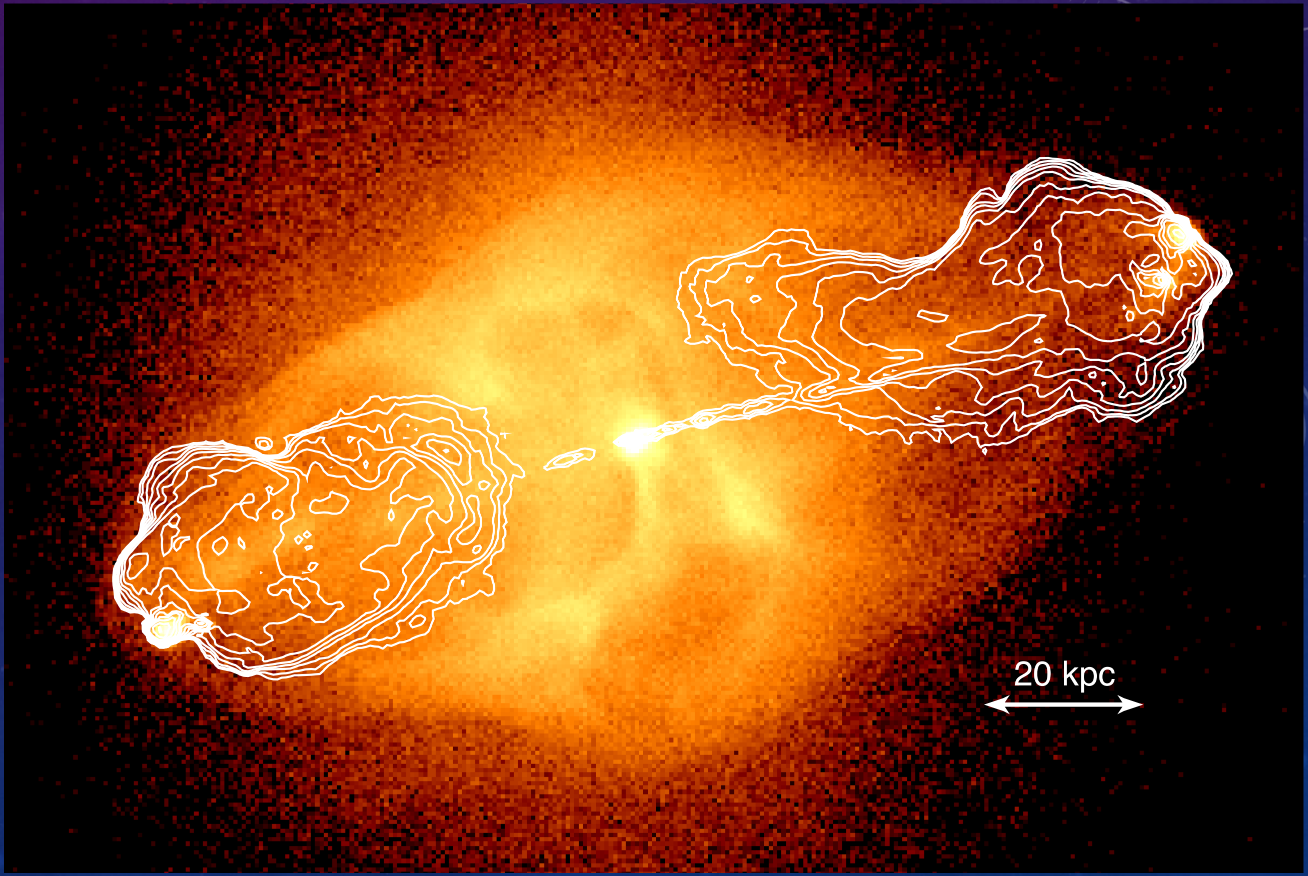
Chandra X-ray image reveals AGN, radio hotspots, cocoon shock, X-ray cavities, shock compressed rim, nonthermal X-rays from the lobes, "X-ray jet"

CYGNUS A

Archetype of powerful FR II radio sources (Carilli & Barthel 1994)

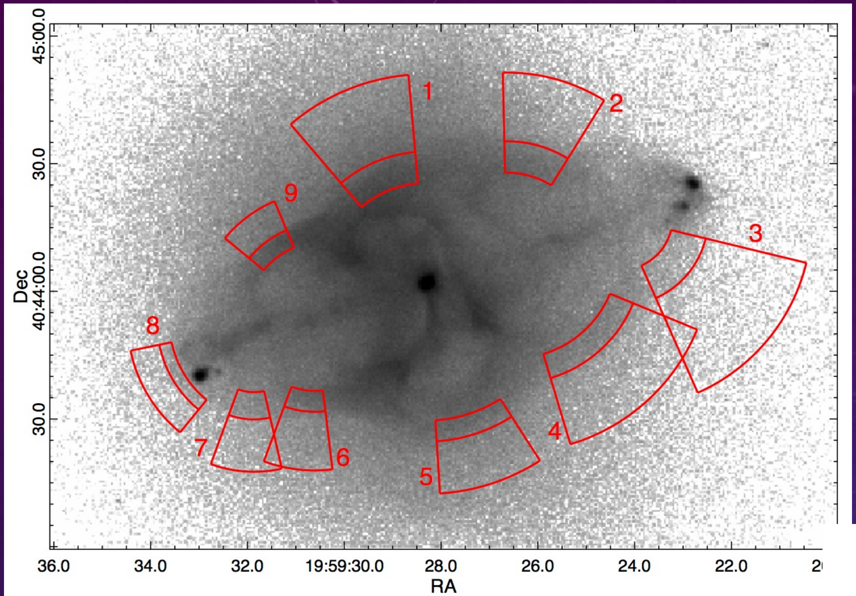
Radio luminosity ≈ 7×10^{44} erg s^{-1}; z = 0.056; scale = 1.1 kpc $arcsec^{-1}$

Chandra + C band radio contours



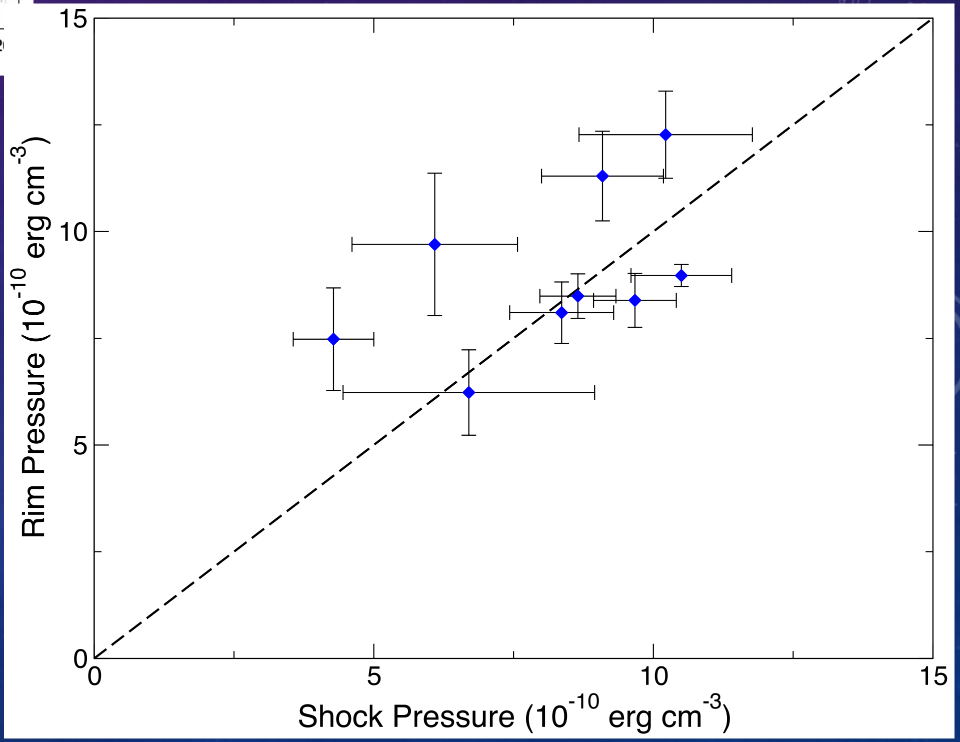
Hosted by the central galaxy of a cool-core cluster

Chandra X-ray image reveals AGN, radio hotspots, cocoon shock, X-ray cavities, shock compressed rim, nonthermal X-rays from the lobes, “X-ray jet”



COCOON PRESSURE IS WELL DETERMINED

Snios+ (2018) use deprojected pressures plus shock strengths to determine postshock pressures at 8 positions



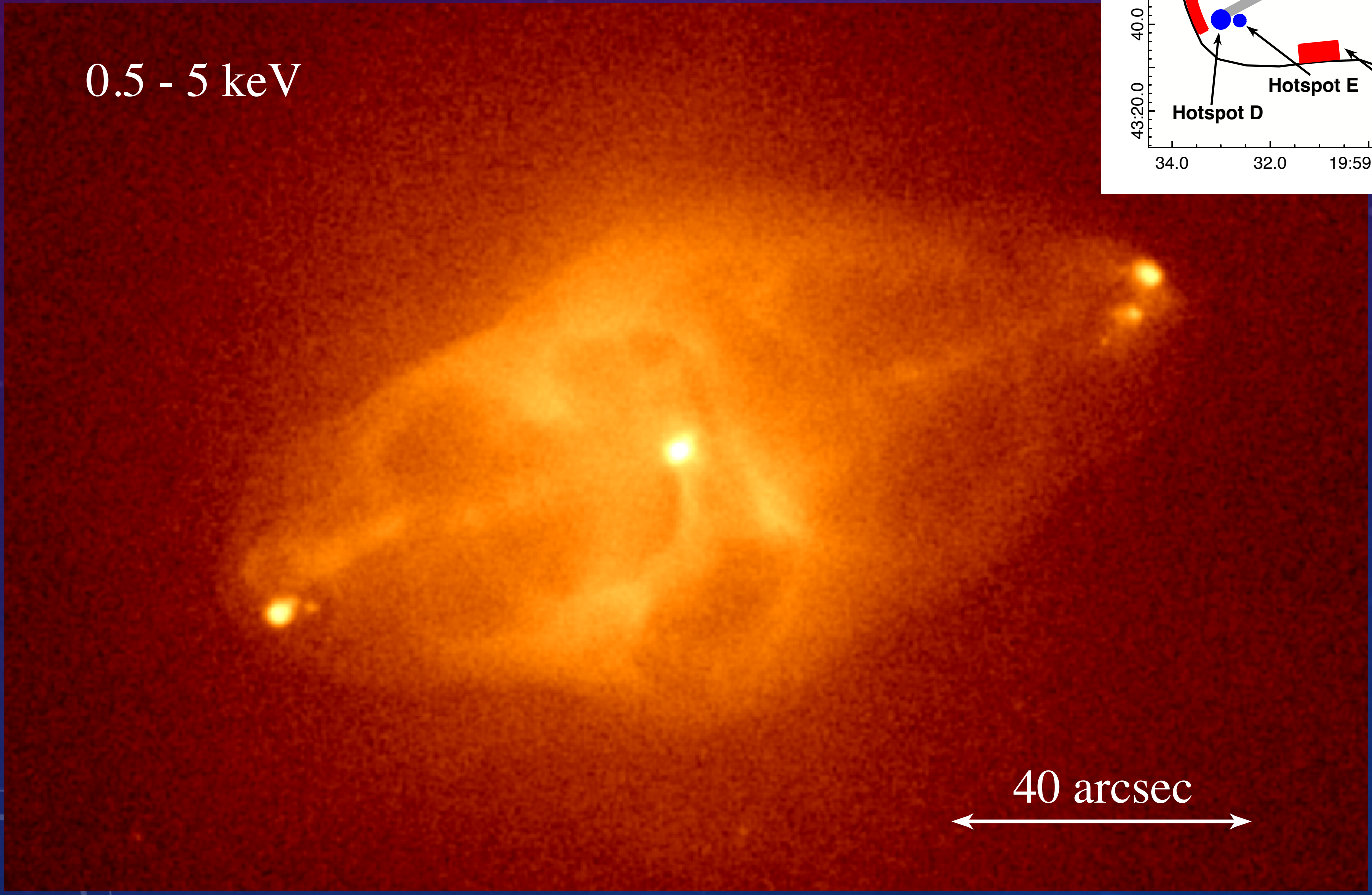
They also made largely independent measures of pressure in the bright rim

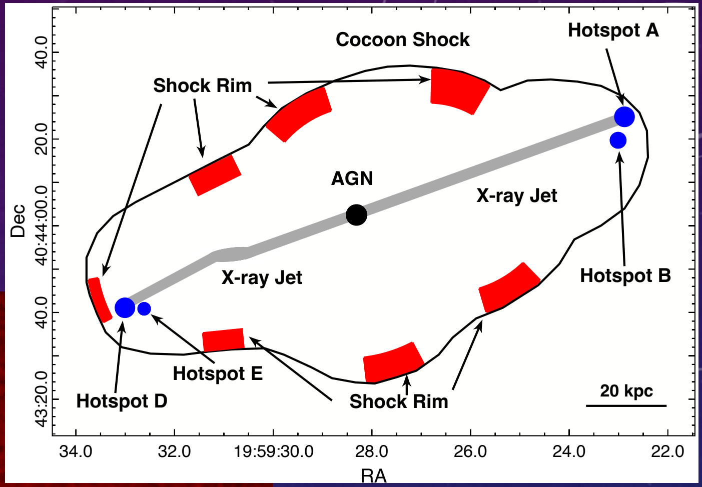
Rim pressures and postshock pressures are approximately consistent with one another

Combine to give the cocoon pressure estimate $8.6 \pm 0.3 \times 10^{-10}$ erg cm^{-3}

THE X-RAY JET

Steenbrugge+ (2008) argue it is inverse Compton emission from a “relic” jet.





De Vries+ (2018) show the emission is nonthermal

Minimum pressures for IC (SSC) model

East

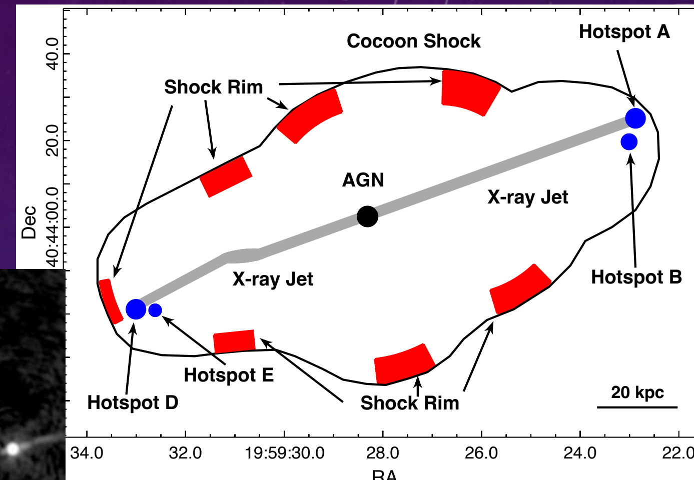
$4 - 8 \times 10^{-10}$ erg cm^{-3}

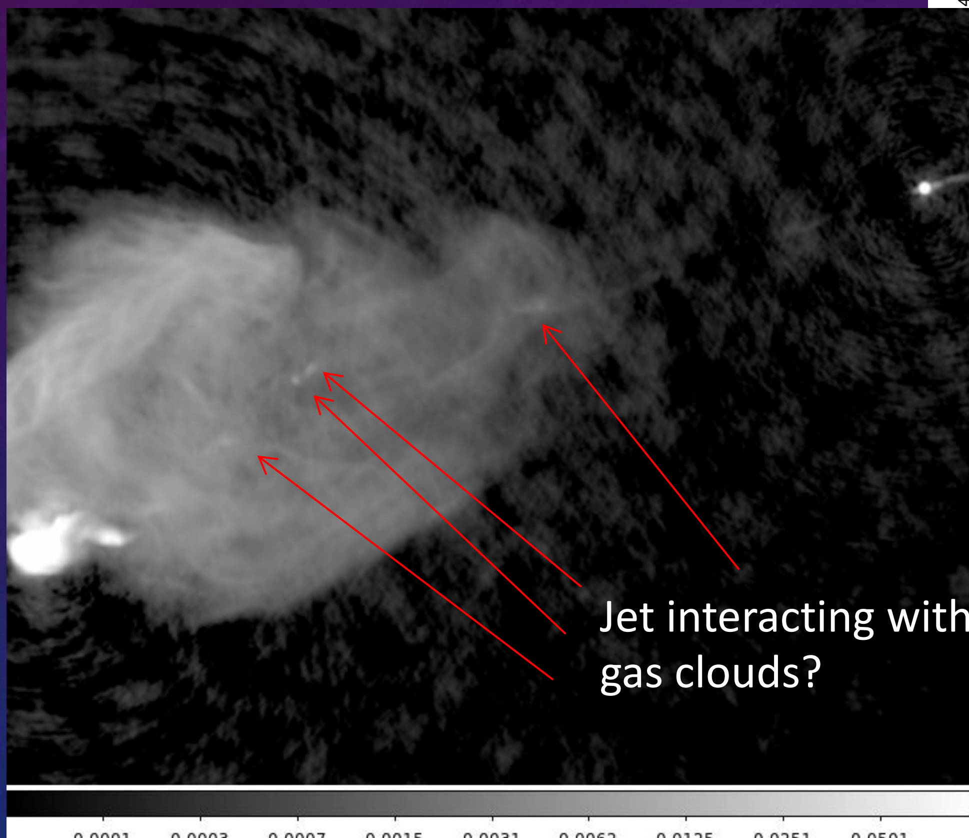
West

$2 – 10 \times 10^{-9}$ erg cm^{-3}

THE X-RAY JET

Steenbrugge+ (2008) argue it is inverse Compton emission from a “relic” jet.





Cygnus A, X band (Sebokolodi p. comm.)

De Vries+ (2018) show the emission is nonthermal

Minimum pressures for IC (SSC) model

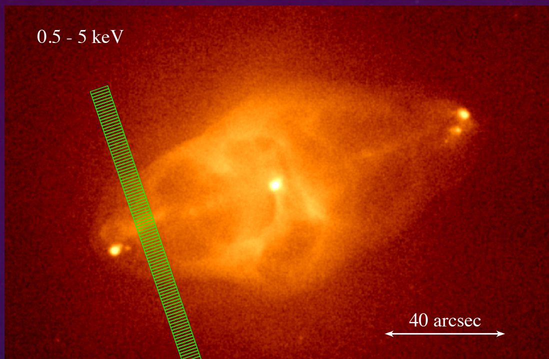
east

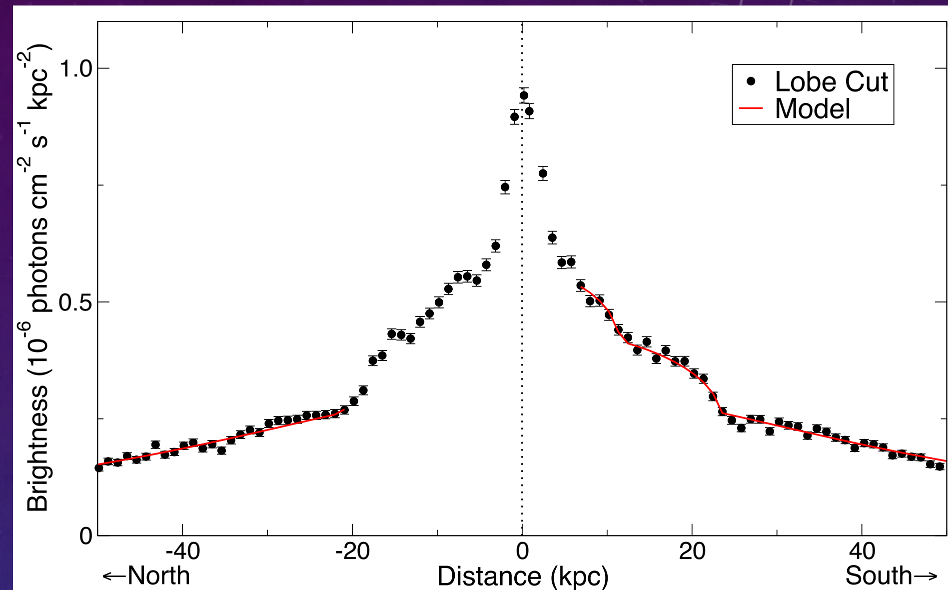
$4 - 8 \times 10^{-10}$ erg cm^{-3}

West

$2 - 10 \times 10^{-9}$ erg cm^{-3}

NONTHERMAL X-RAYS FROM EASTERN LOBE





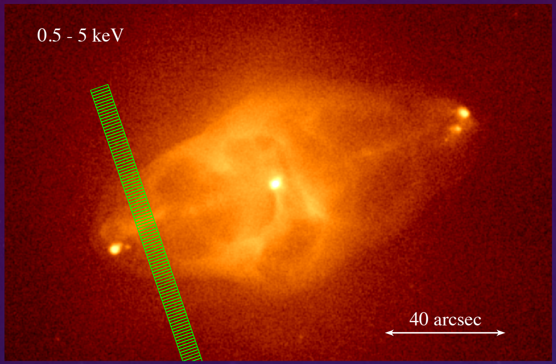
SB profile shows: ICM; shocked ICM; lobe (SSC+ICCMB); X-ray jet.

Strong X-ray emission is detected from within the radio lobes

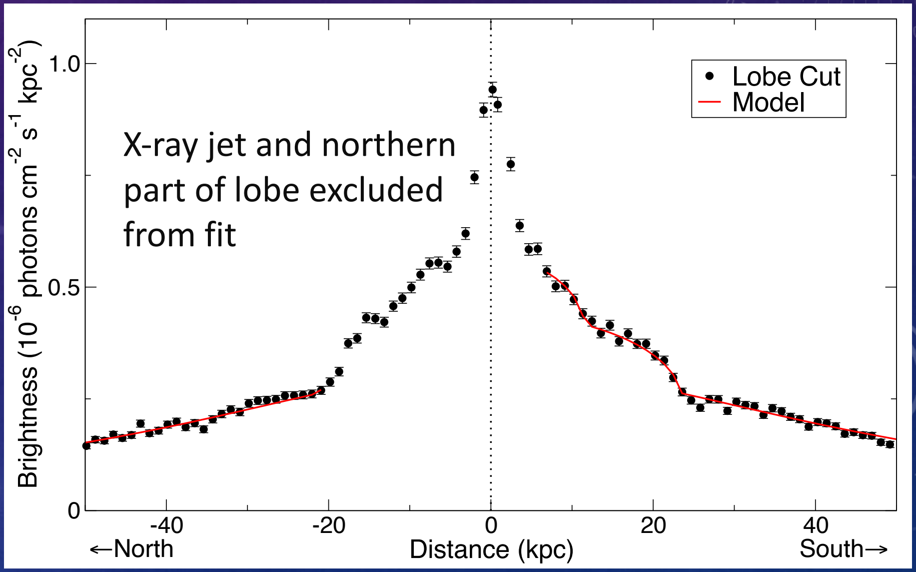
de Vries+ (2019): Eastern lobe power law flux ≈ 70 nJy at 1 keV, photon index ≈ 1.72; western lobe, 50 nJy and photon index 1.97

Predominantly synchrotron-self Compton emission (SSC), with ≈ 30% ICCMB X-rays

LOBE EMISSION



SB profile model: two nested shells, each with constant emission per unit volume (shocked ICM and lobe), embedded in a beta model (ICM). Disregard X-ray jet (Snios+ 2020)



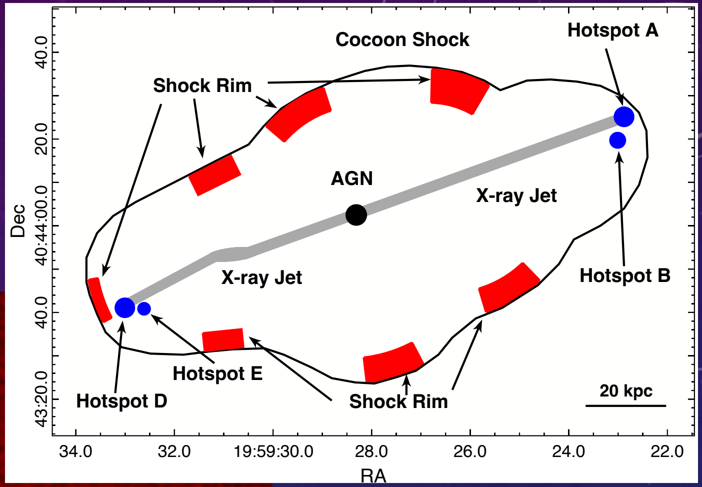
Emission per unit volume

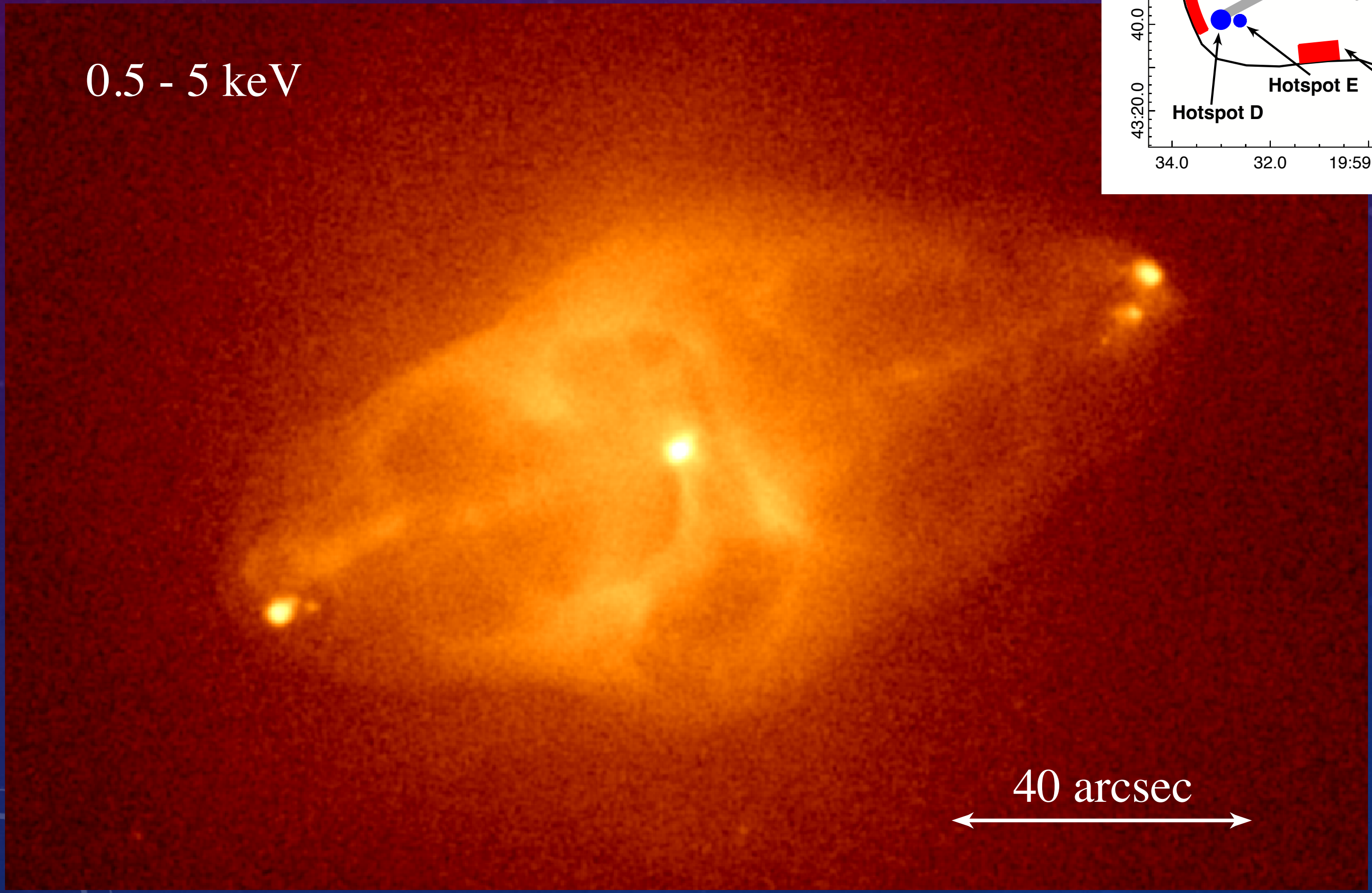
Shocked ICM: $0.68 \pm 0.03 \times 10^{-8}$ ct cm^{-2} $arcsec^{-3}$

Lobe: $1.42 \pm 0.07 \times 10^{-8}$ ct cm^{-2} $arcsec^{-3}$

X-RAY HOLE AROUND HOTSPOT E

X-ray emission around hotspot E, "primary" hotspot in east, is depressed within r ≈ 4 arcsec

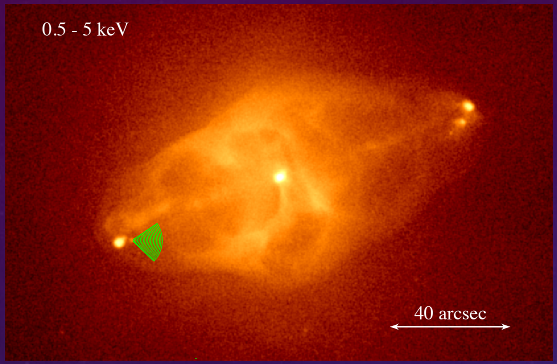




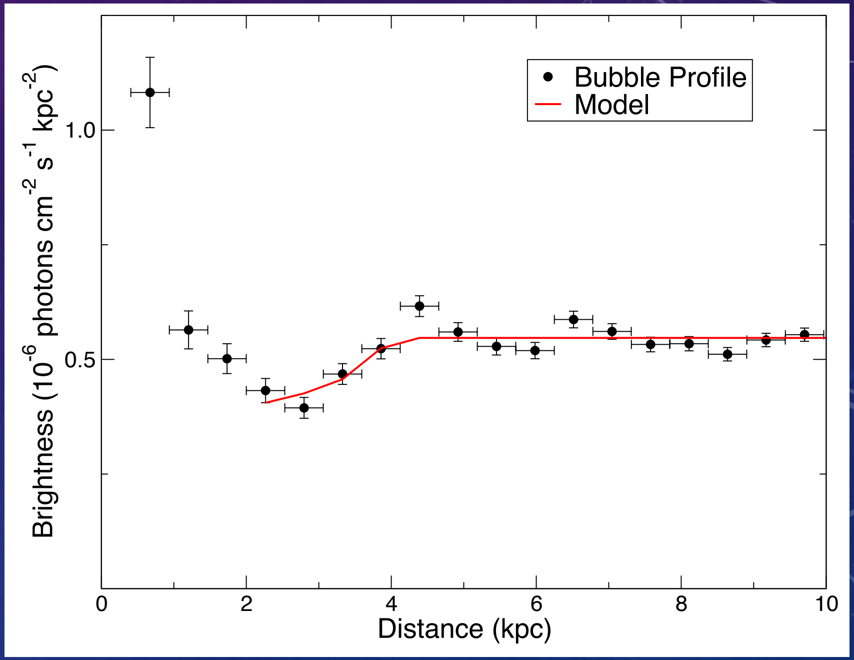
No similar hole around hotspot B (western primary hotspot)

2022 Aug 17

CAVITY PROFILE



Model the SB profile as a spherical hole in a region with constant emission per unit volume



Missing emission per unit volume:

$2.5 \pm 0.3 \times 10^{-8}$ ct cm^{-2} $arcsec^{-3}$

At least 70% greater than emission being displaced

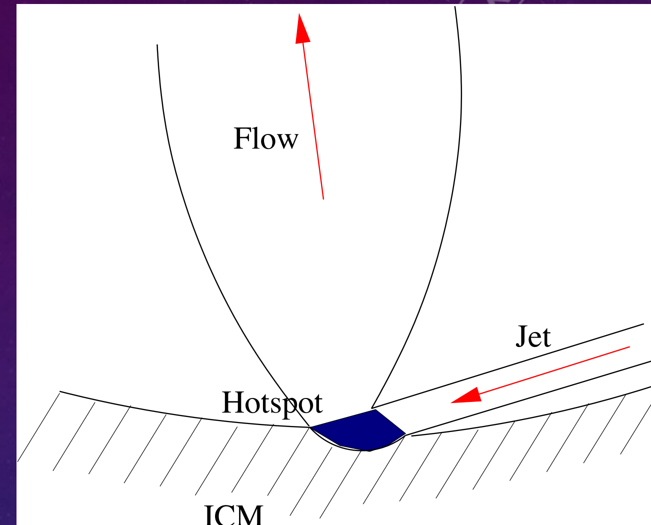
=> Hole must be deeper along our line of sight than its diameter (Snios+ 2020)

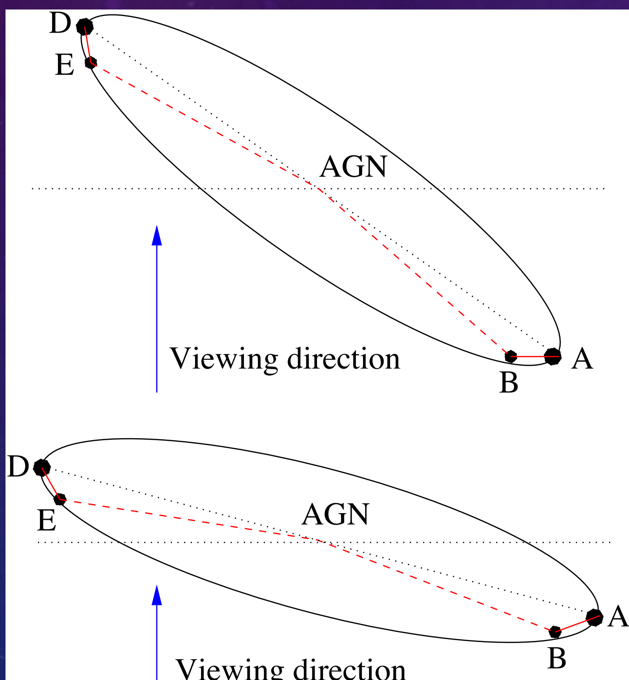
JET CAVITY FORMATION

Jet is deflected off the shock compressed ICM at hotspot E

Shock(s) convert jet kinetic to thermal energy

Outgoing jet expands to match the lobe pressure





Jets deflects off the ICM at primary hotspot

=> outflow is Doppler dimmed

Dimming depends on viewing direction, or axis inclination, which is poorly determined: 55° (Vestergaard & Barthel 1993) or 75° (Boccardi+ 2016)

Hotspot B is on side inclined towards us (Carilli+ 1988), so its outflow may experience less dimming

HOTSPOT SIMULATIONS

GAMER: GPU accelerated, AMR, relativistic, 3d hydrodynamic code using Taub-Mathews equation of state – approximate Synge model for a single particle species (Tseng, Schive & Chiueh 2020)

Light jet – minimizes ram pressure for fixed jet power; “thermal” power dominates kinetic power and momentum flux is close to P/c

$$P = (\gamma - 1)\dot{M}c^2 + hAc\beta\gamma^2$$

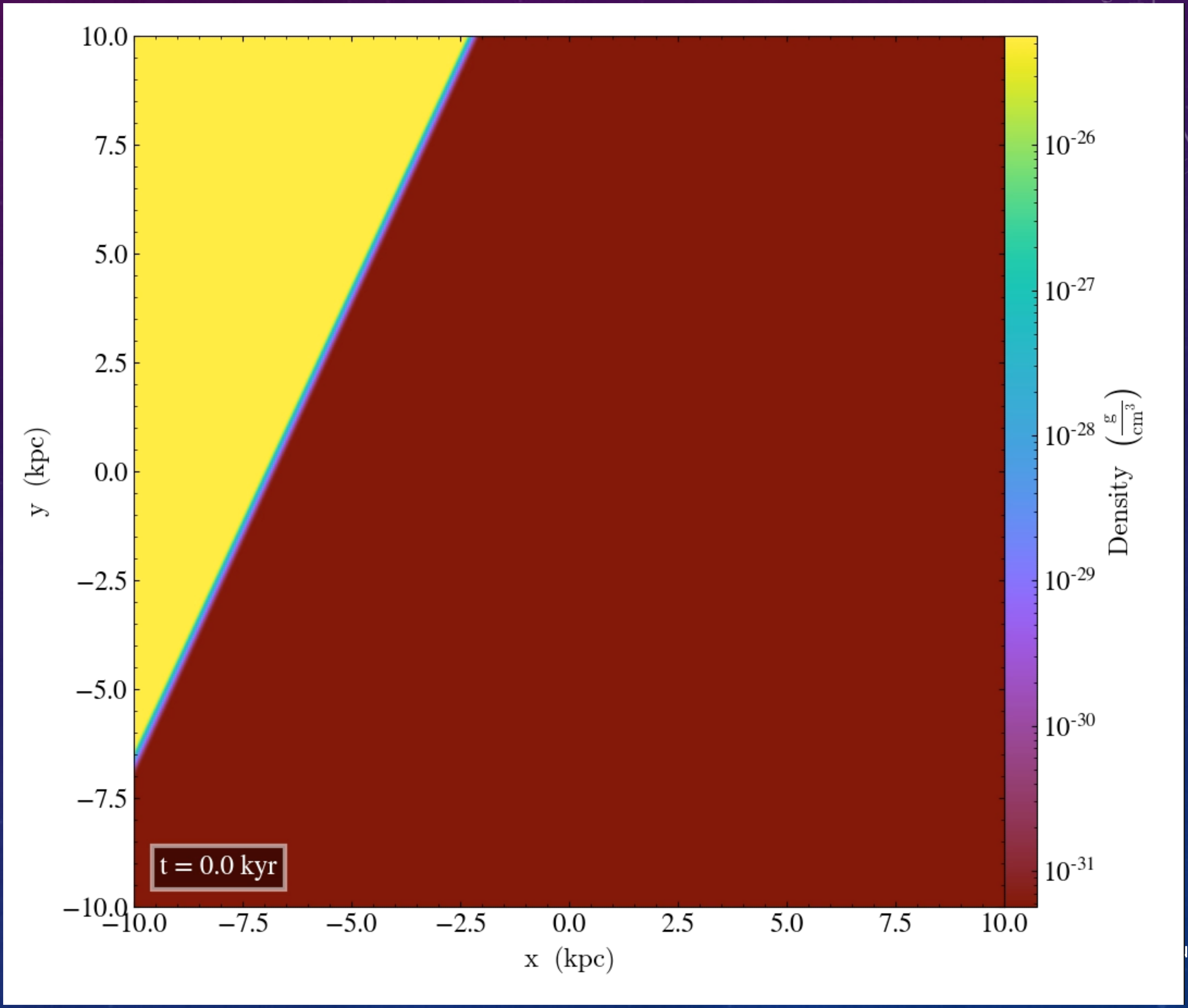
Initial pressure is uniform, with inclined interface between ICM and lobe.

Jet flows parallel to the y axis; core is faster than the sheath

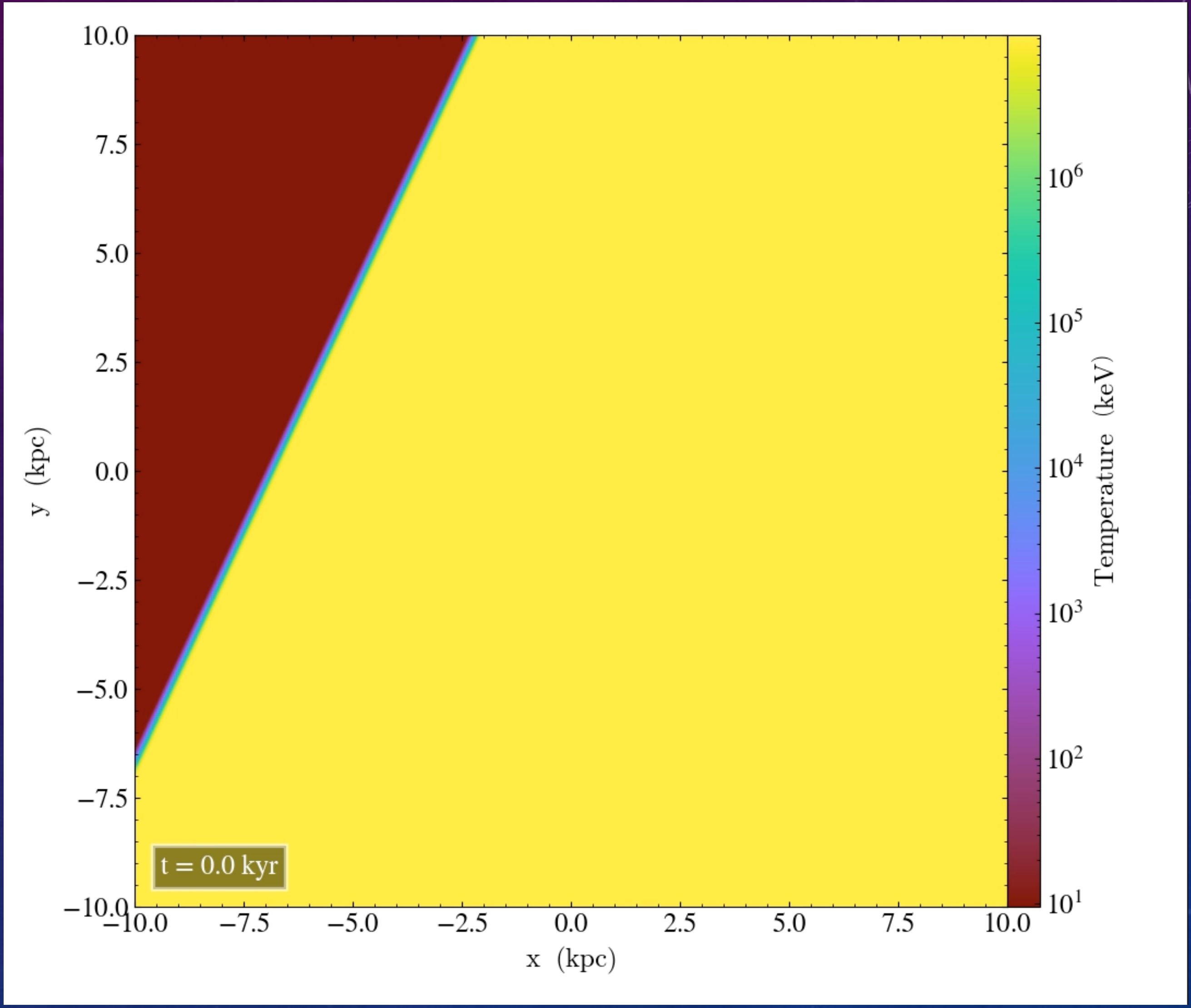
Jet diameter 0.5 kpc to match hotspot E width

Jet power $4\mathrm{x}10^{45}$ erg s^{-1}

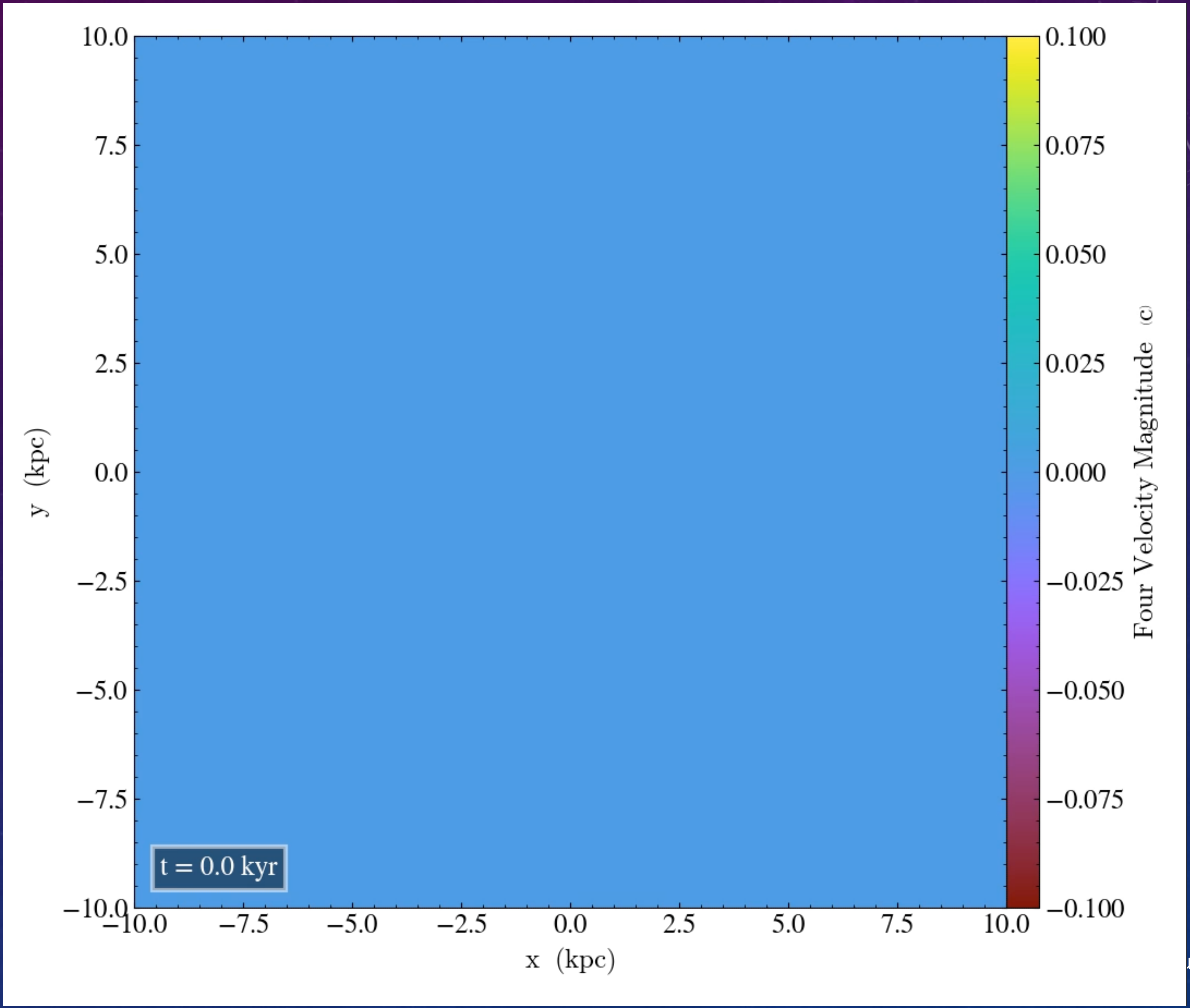
PROPER DENSITY



TEMPERATURE

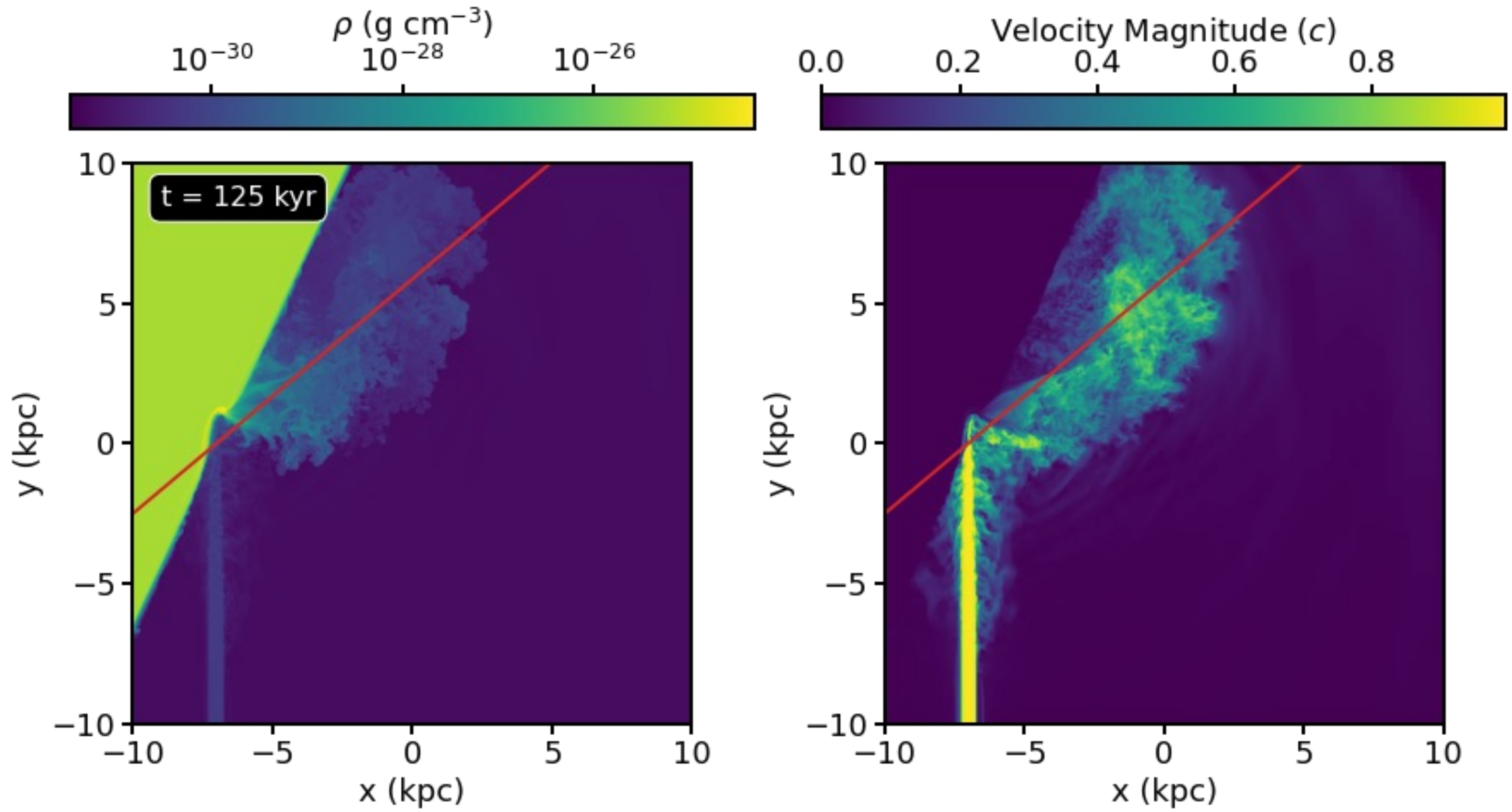


MOMENTUM MAGNITUDE

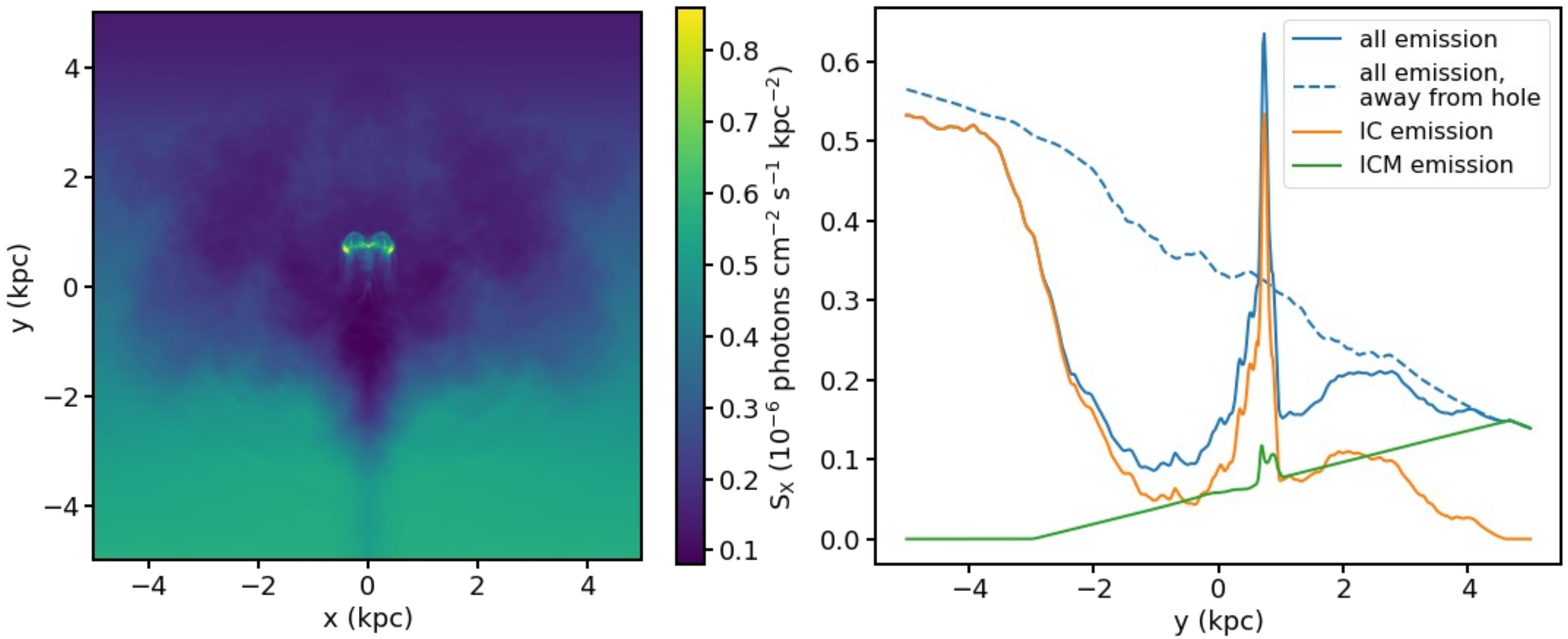


HOLE DUE TO DOPPLER BEAMING

Line of sight in red



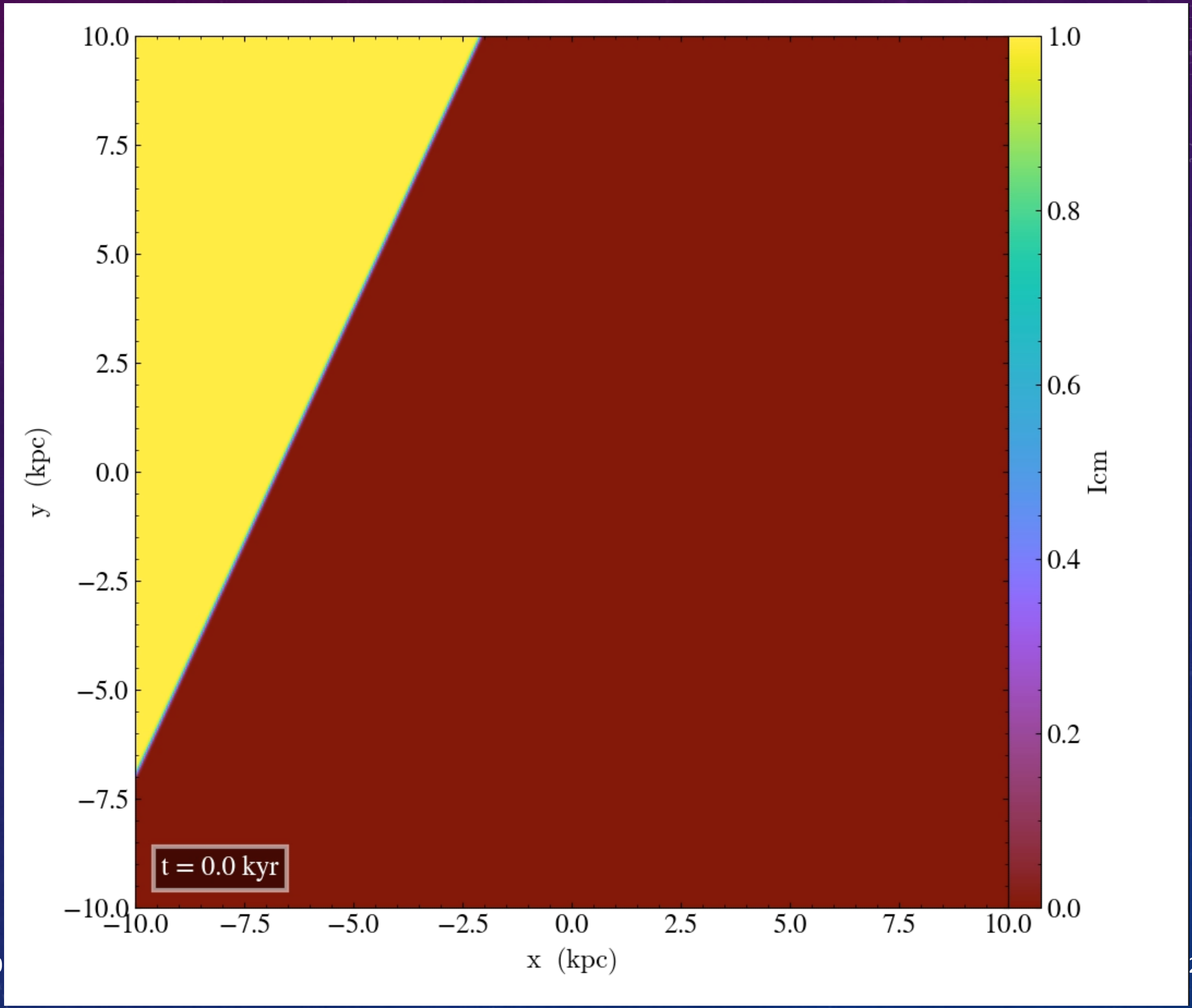
HOLE DUE TO DOPPLER BEAMING



Radiation isotropic in rest frame; power per unit volume proportional to pressure

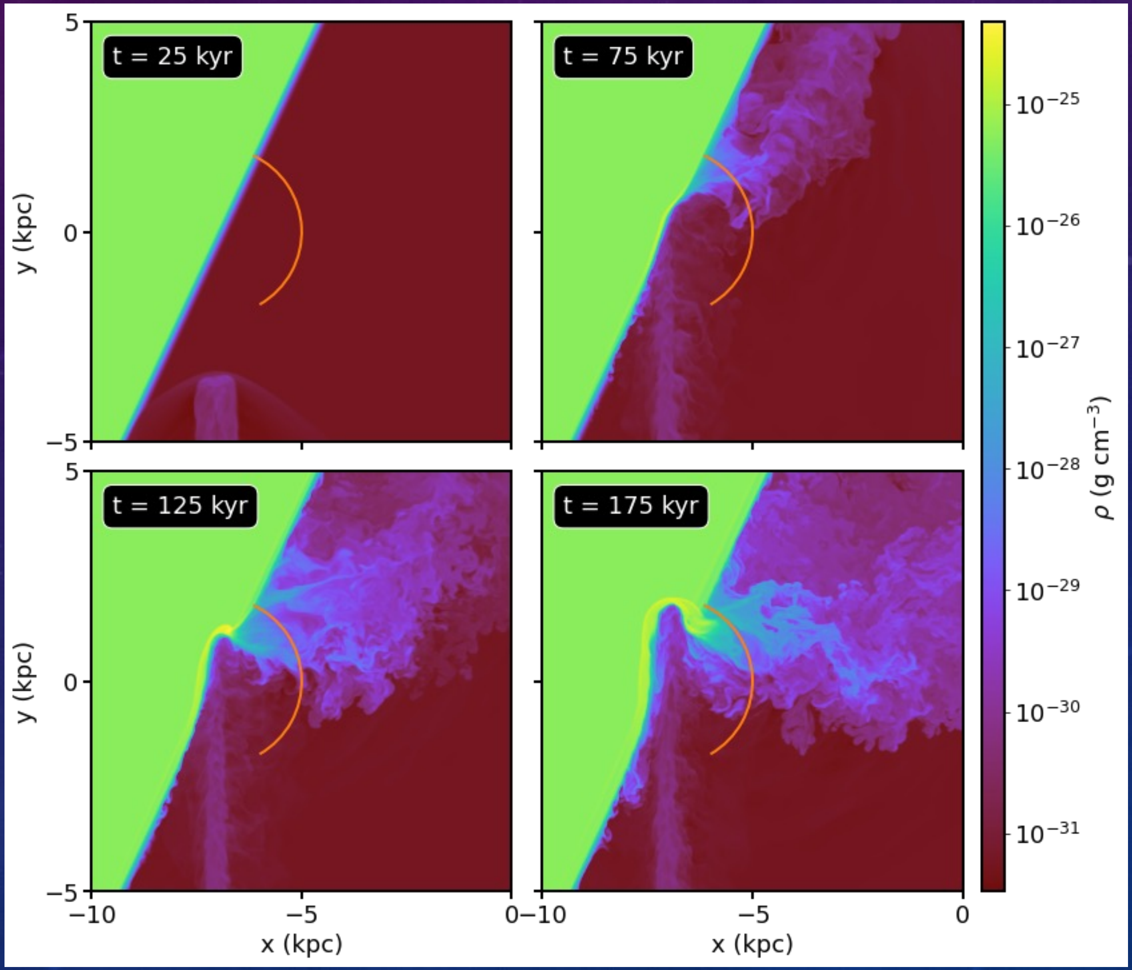
Apply Doppler factor for spectral index of -1 in each fluid element

ICM FRACTION

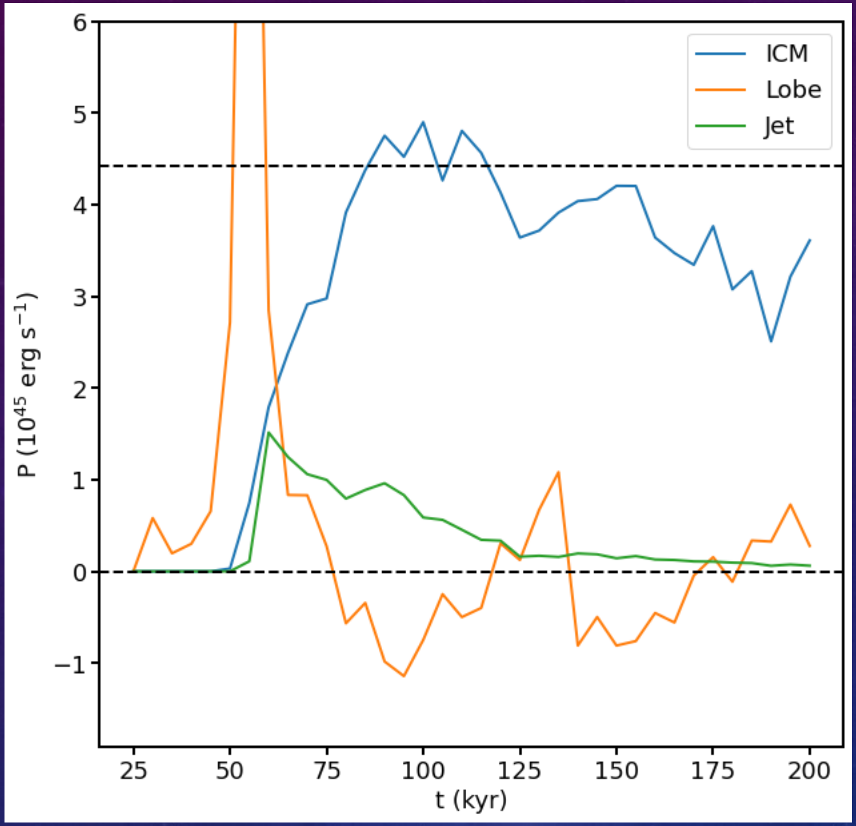


ESTIMATE "ICM" FRACTION OF LOBE VOLUME

Pressure approx. uniform away from hotspot – assume fraction of volume proportional to kinetic + thermal power crossing enclosing surface



ESTIMATE "ICM" FRACTION OF LOBE VOLUME



A lobe inflated by such a jet is dominated by shocked ICM – depending on particle acceleration efficiency, a significant fraction of lobe energy may thermalize quickly when mixed into the ICM

CONCLUSIONS

- Pressure in the lobes of Cygnus A is well constrained
- Relic emission in the X-ray jet is created by ”cold” gas clouds intercepting the jet
- The hole around hotspot E is due to Doppler beaming in the outflow from the hotspot
- The lobe plasma is dominated by shocked ICM