Deciphering Interplay Between ICM Weather and Radio AGN

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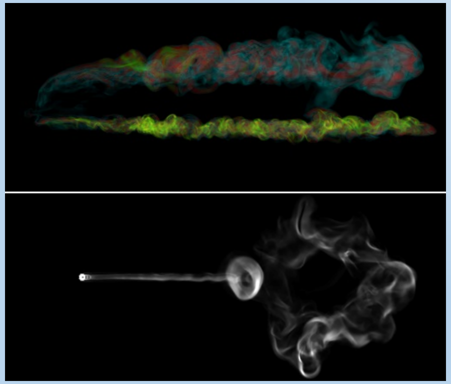
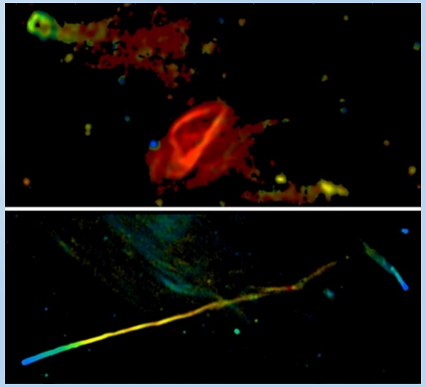
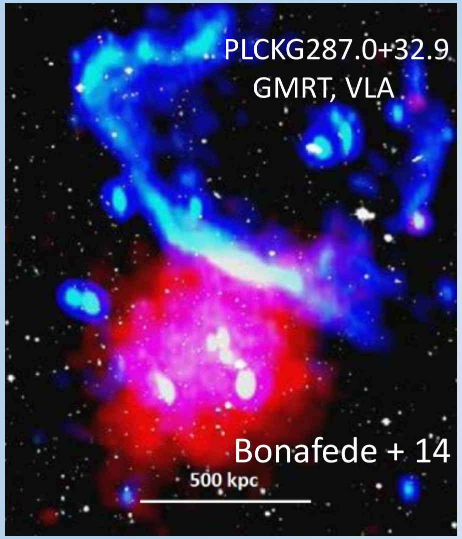




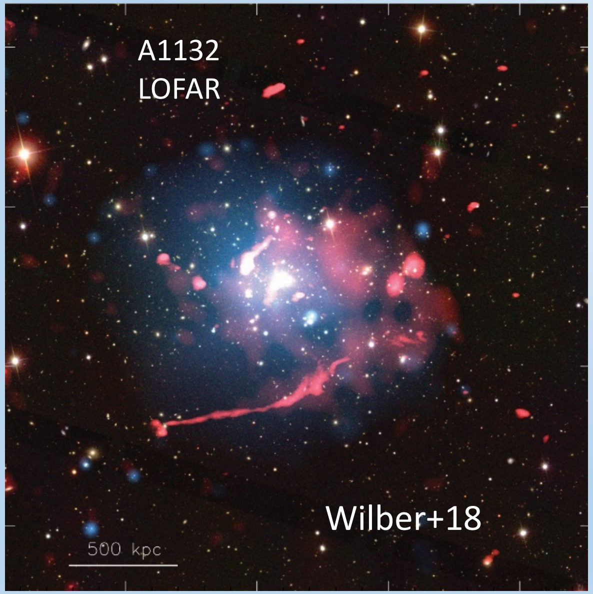
Outline

- Motivation: ICM-RG encounters reveal ICM structures on multiple scales
- Introduction to our simulation study approach
- Brief outline of initial tests and findings

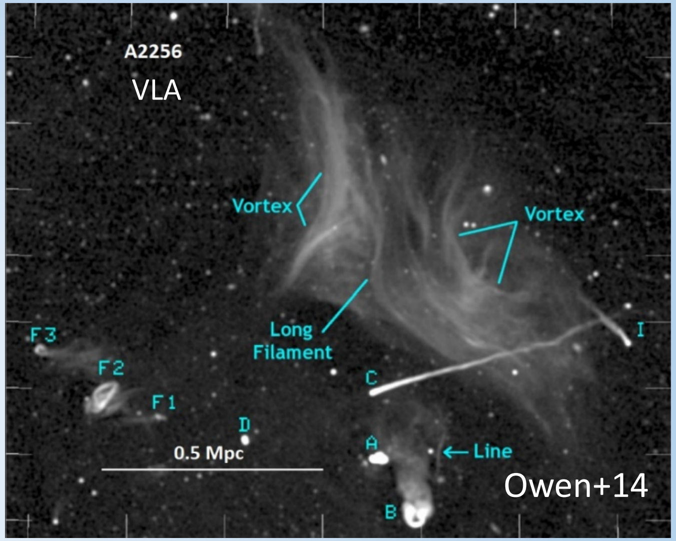
Small Sample of Cluster-Scale Deformed Radio Galaxy (RG) Structures


PLCKG287.0+32.9
GMRT, VLA

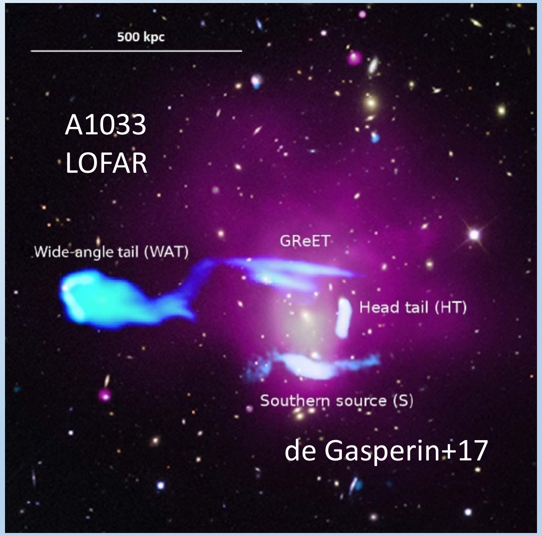
Bonafede + 14


A1132
LOFAR

Wilber+18

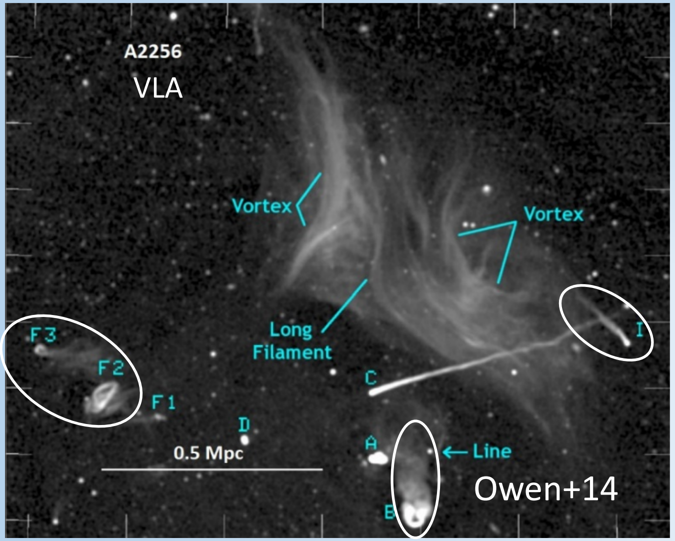

A2256
VLA

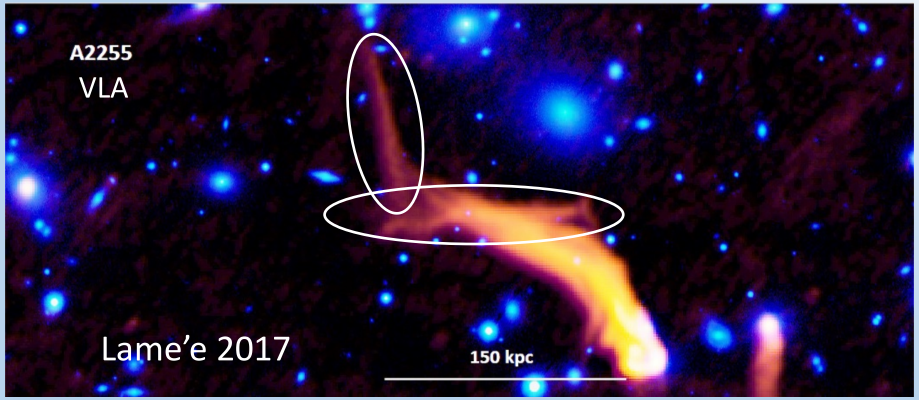
Owen+14

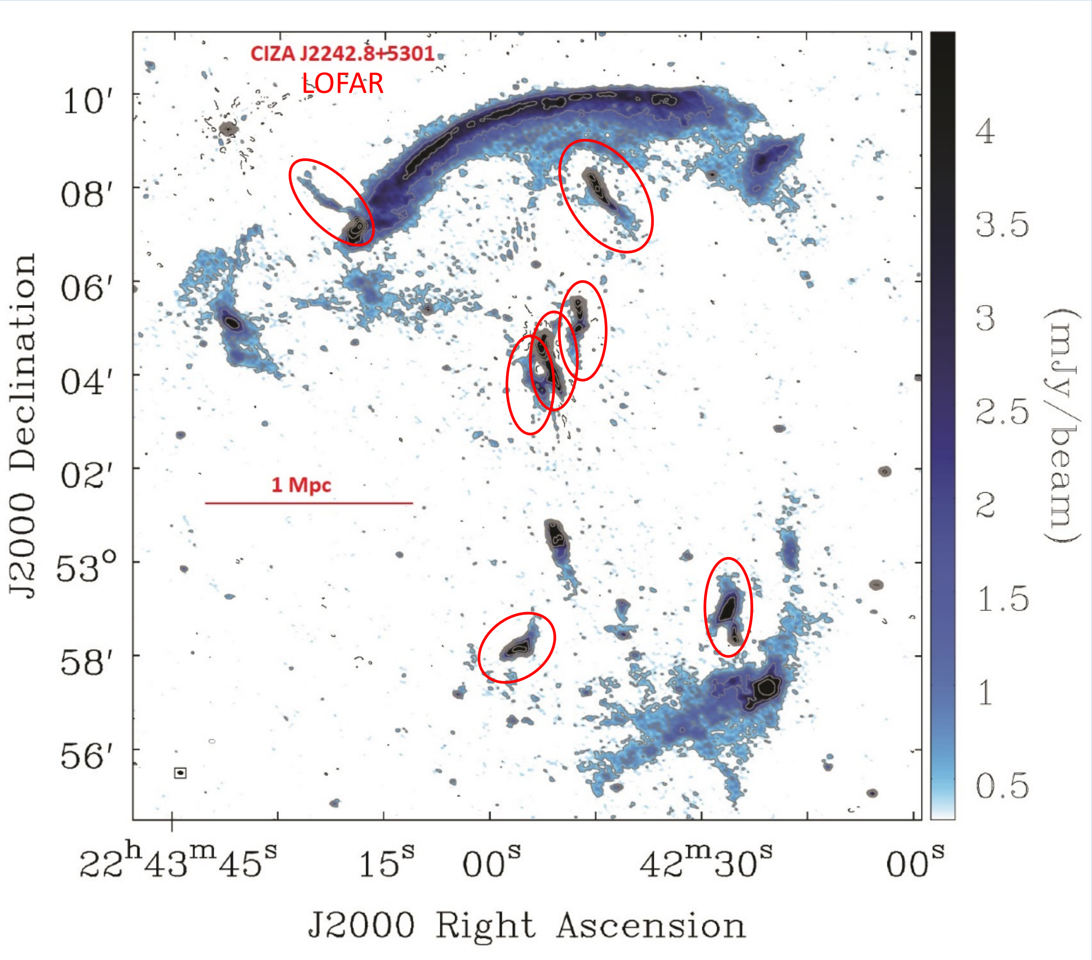

A1033
LOFAR

de Gasperin+17

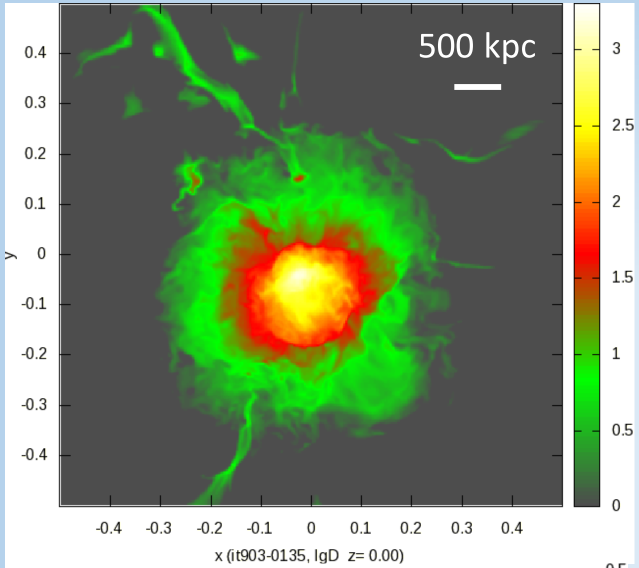
Small Sample of ~100 kpc-scale RG "Features" Implying Dynamical ICM Encounters



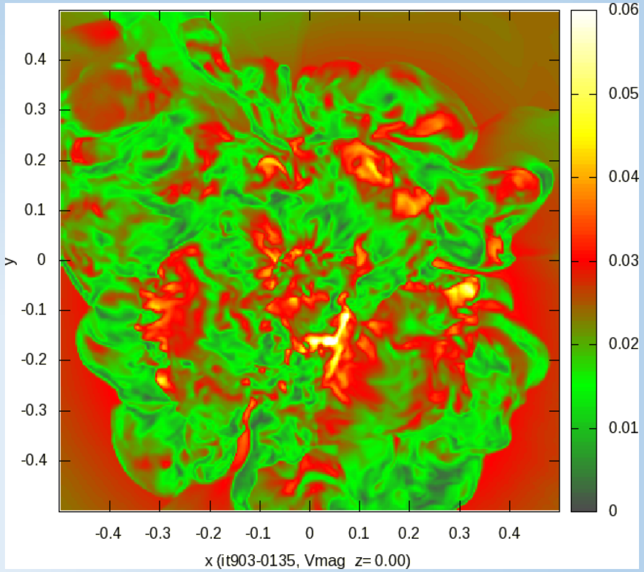




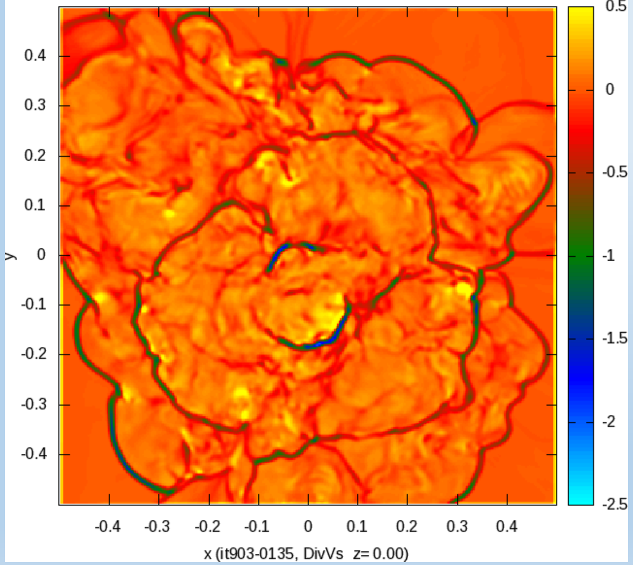
ICMs ARE Dynamic & Complex:
Slices through Merging Cluster Simulation



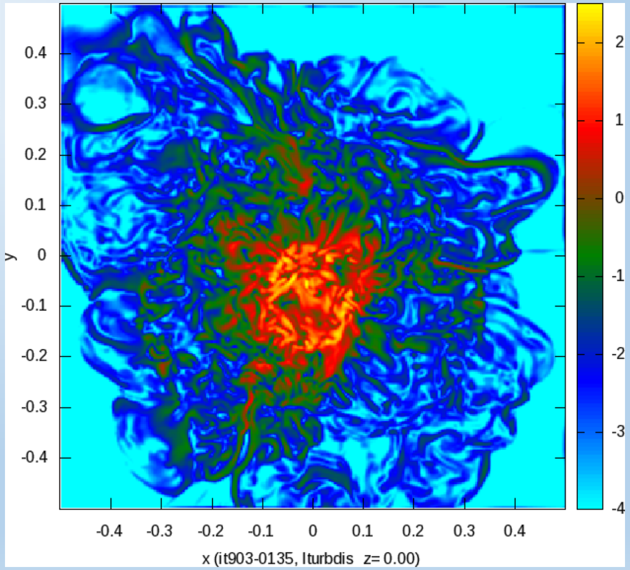
ICM density



ICM velocity



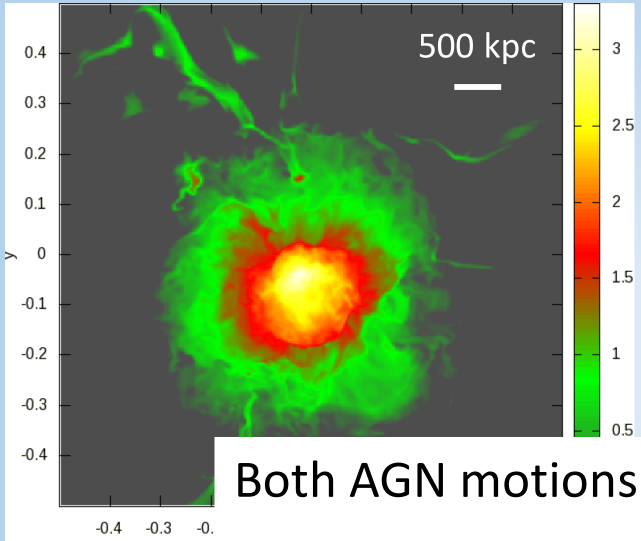
ICM shocks



ICM turbulence

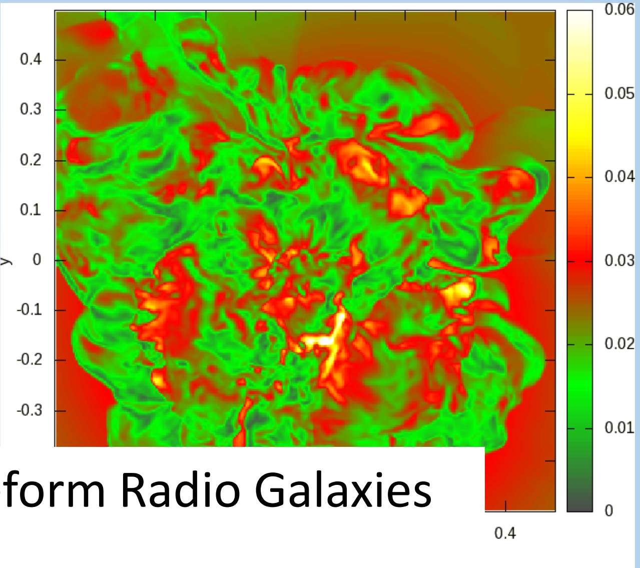
Vazza + (TJ) 17

ICMs ARE Dynamic & Complex:
Slices through Merging Cluster Simulation



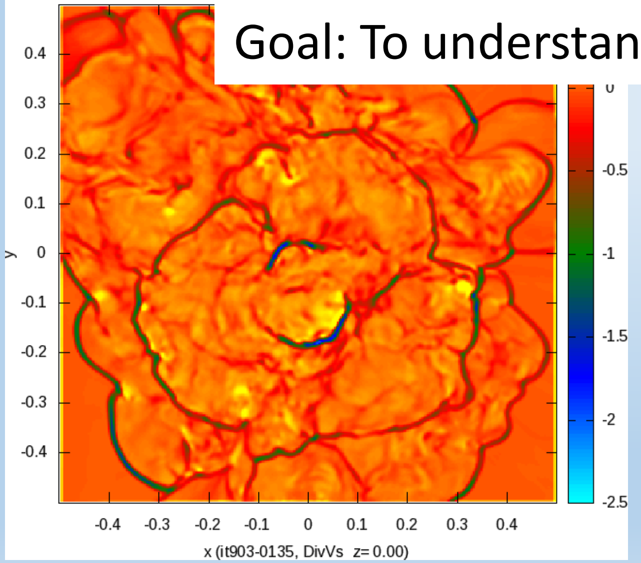
ICM density

ICM velocity



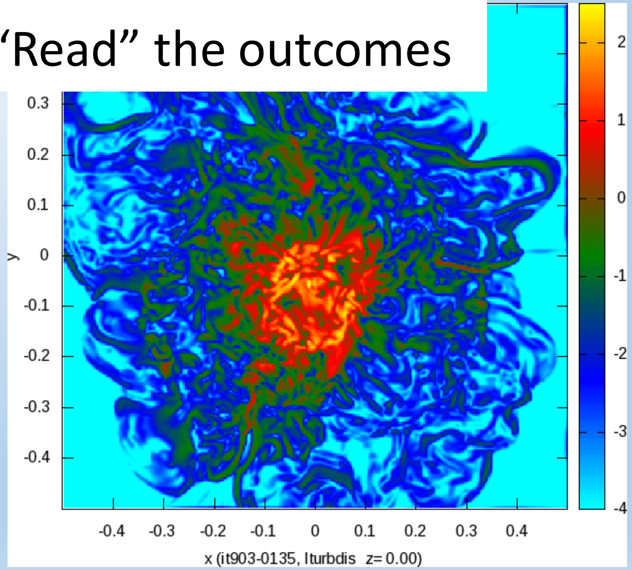
Both AGN motions and ICM dynamical structures deform Radio Galaxies

Goal: To understand ICM-RG interactions & How to “Read” the outcomes



ICM shocks

ICM turbulence



Vazza + (TJ) 17

RG ICM-Driven Deformations Are Largely Pressure (Gradient) Driven

  - “Winds” (simplest are just relative motions, but structure matters)
    - turbulent motions
  - Shocks (Discontinuity followed by “dense”, “high pressure” wind)
  - Hydrostatic (less dramatic, but still can be factor on large scales)
- ICM Magnetic Fields (B) certainly influence emissions associated with RG
  -Influence on RG dynamics maybe (?)

  - AGN variations Do influence RG morphologies/symmetries
    -e.g., Jet Precession, Intermittency…

- AGN outflows will influence nearby ICM structures & emissions
  -e.g., A2255 “cross bars”? And, of course, may supply CRe & B for “Later Activity”

Our Simulation Study to Date:

- **AGNs in Winds and Encountering Merger-like Shocks-- Cases include:**
  -Active AGNs initially stationary in quiet ICM then impacted by shocks-
  -AGNs in motion @various orientations ($\Rightarrow$ Narrow Angle Tails) followed by Shock Impact-

- **3D MHD + CR electrons $\Rightarrow$ Synchrotron Emissions, incl. spectra &polarization**
  -$\Delta x = 0.5$ kpc ; boxes vary, but typically ~ 250 kpc x 250 kpc x 1 Mpc volumes
  -in-house "WOMBAT" Eulerian non=relativistic MHD Code (Mendygral+ 17 (TJ, CN, BO'N))

- **ICMs (initially uniform for now):** $z = 0.2$ (relevant mostly to CRe losses)
- kT ~ 2-4 keV (sound speeds: $a_i \sim 700 - 1000$ km/sec)
- $P_i = P_j \sim 10^{-12} - 10^{-11}$ dyne/cm^2, $\rho_i = 2\mathrm{x}10^{-28} - 5\mathrm{x}10^{-27}$ g/cm^3 , $\gamma_i = 5/3$
- ICM magnetic field, $B_i = 0$, but jets magnetized as below
- **Shock Mach numbers: $M_s \sim 2 - 4$ (plane shocks)**

- **AGN Jets (steady for now):**
- Jet/ICM density, pressure, sound speed:$\boldsymbol{\rho_i/\rho_j = \chi = 10^2\ 10^3}$**,** $\boldsymbol{P_j/P_i = 1}$, $\gamma_j = 5/3$, $\boldsymbol{a_j \approx 10 - 30\ a_i}$
- **Jet velocities: $v_j \sim 0.1$ c; $M_j = v_j/a_j \sim 3 - 10$ (internal) (Mach ~ 30-300 external)**
- Jet radius at source: $r_j = 3$-4 kpc ($L_j \sim 10^{44}$ erg/sec)
- Jet magnetic field: $\beta_j = 10 - 10^3$ (mostly $B_j \sim 1$ -2 μG) toroidal field (net current is zero)
- $\Rightarrow$ Radio lobe, tails, etc -- B ~ 0.1—10+ μG

CR Electrons (CRe) Injected in AGN Jets:

Passive with $f(p) \propto p^{-q}$, $j_{sync} \propto \nu^{-(q-3)/2}$, q = 4-4.5

- Transported with convection-diffusion equation using Eulerian "CGMV" algorithm (Jones & Kang 05)

$$\boxed{\frac{\partial f}{\partial t} = -\vec{v}\cdot\nabla f + \frac{1}{3}(\nabla\cdot\vec{v})p\frac{\partial f}{\partial p} + \nabla\cdot(\kappa\nabla f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p} - \frac{p^3 f}{\tau_{rad}}\right) + S}$$

In these simulations $\kappa = D_p = S = 0$;
i.e., spatial & momentum diffusion neglected (no streaming or 2nd order Fermi) so far,
No CRe injection outside of AGN so to focus on AGN contributions

- inverse Compton and synchrotron losses included:
  (Compton losses mostly dominate in these sims)
  adiabatic effects included

$$\boxed{\tau_{rad} \approx 1.2\ \mathrm{Gyr}\ \frac{1}{[(1+z)^2 + \langle B^2_{3.25\mu G}\rangle]}\ \frac{1}{E_{GeV}}}$$

$$\boxed{E_{GeV} = 7.89\sqrt{\frac{\nu_{GHz}}{B_{\mu G}}}}$$

At z = 0.2 used here:

$$\boxed{\tau_{rad} \approx 93\ \mathrm{Myr}\ \frac{1}{1 + \langle B^2_{4.7\mu G}\rangle}\ \sqrt{\frac{B_{\mu G}}{\nu_{GHz}}}}$$

- Diffusive Shock Acceleration at shocks:
Test particle ⇒ $f(p)_{postshock} \propto p^{-q}$ with

$$q = \frac{4M_s^2}{M_s^2 - 1}$$

Note: DSA "instantaneous" for energies of interest

$$t_{acc} \sim \frac{E_{GeV}}{B_{\mu G}}\left(\frac{u_s}{10^3\ \mathrm{km/sec}}\right)^2\ \mathrm{yrs}$$

I. Shocks Impacting “Normal”, Lobed RGs

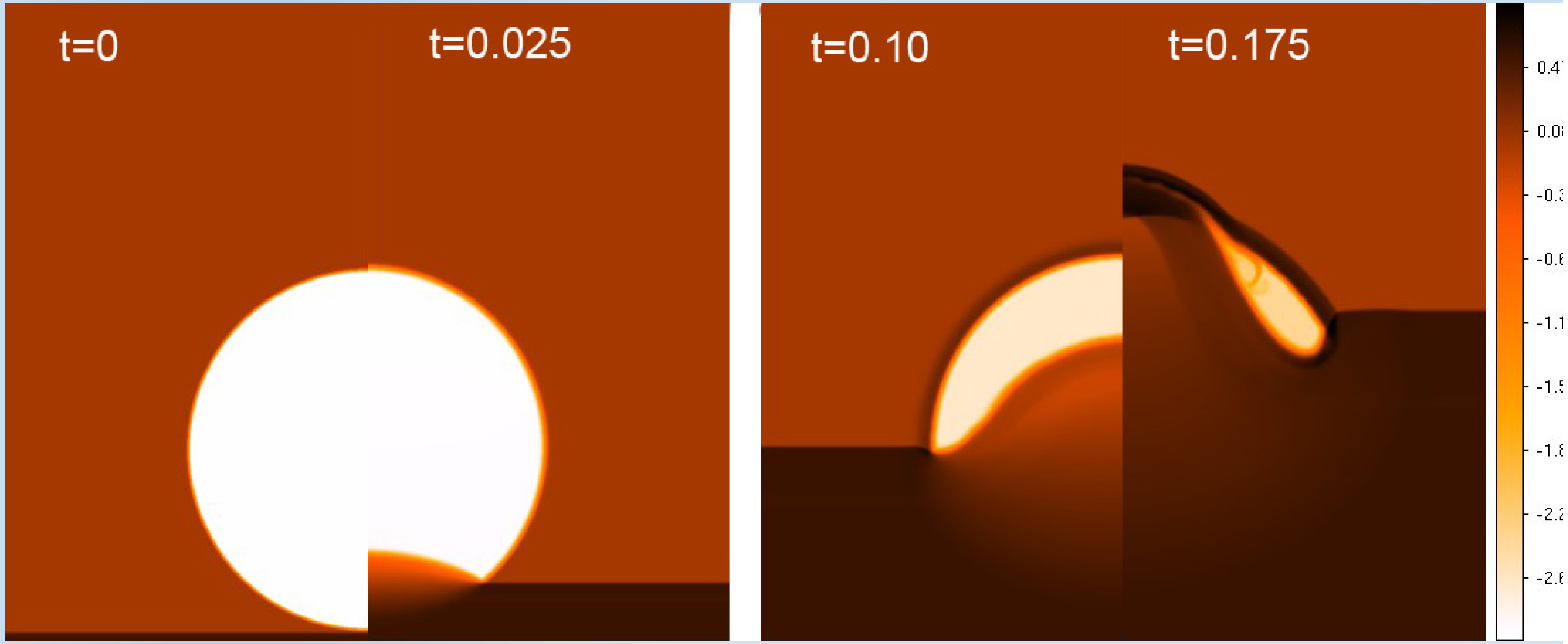
Summary:

- Shock Impact Crushes & Maybe Disrupts Radio Lobes into Vortex Rings (if Shock is Strong Enough)

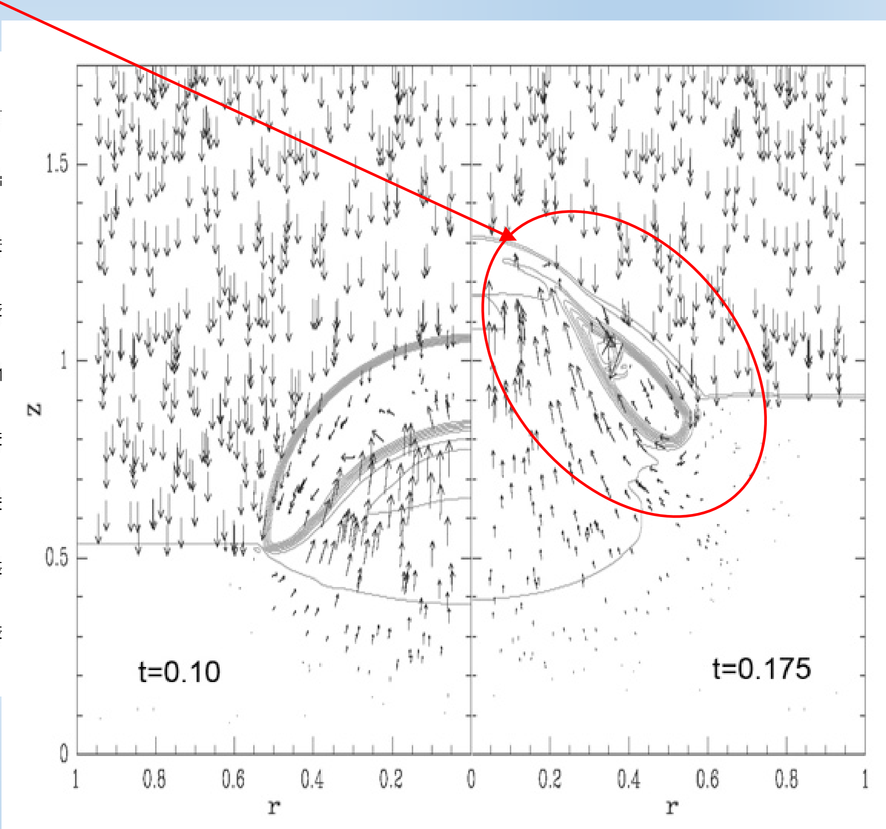
- Post Shock “Wind” Advects Away Lobe Remnants
  -& Modifies Propagation of Stripped AGN Jets

- Details Depend on Alignments & Shock Strength
  -Shock Mach Number vs Jet Mach Number

Familiar Aspect of Shock/Lobe Impact:
Low Density Cavity Crushed ⇒ Strong Boundary Shear ⇒ Vortex Ring
(Shock is faster inside Cavity)



Pfrommer & Jones 2011

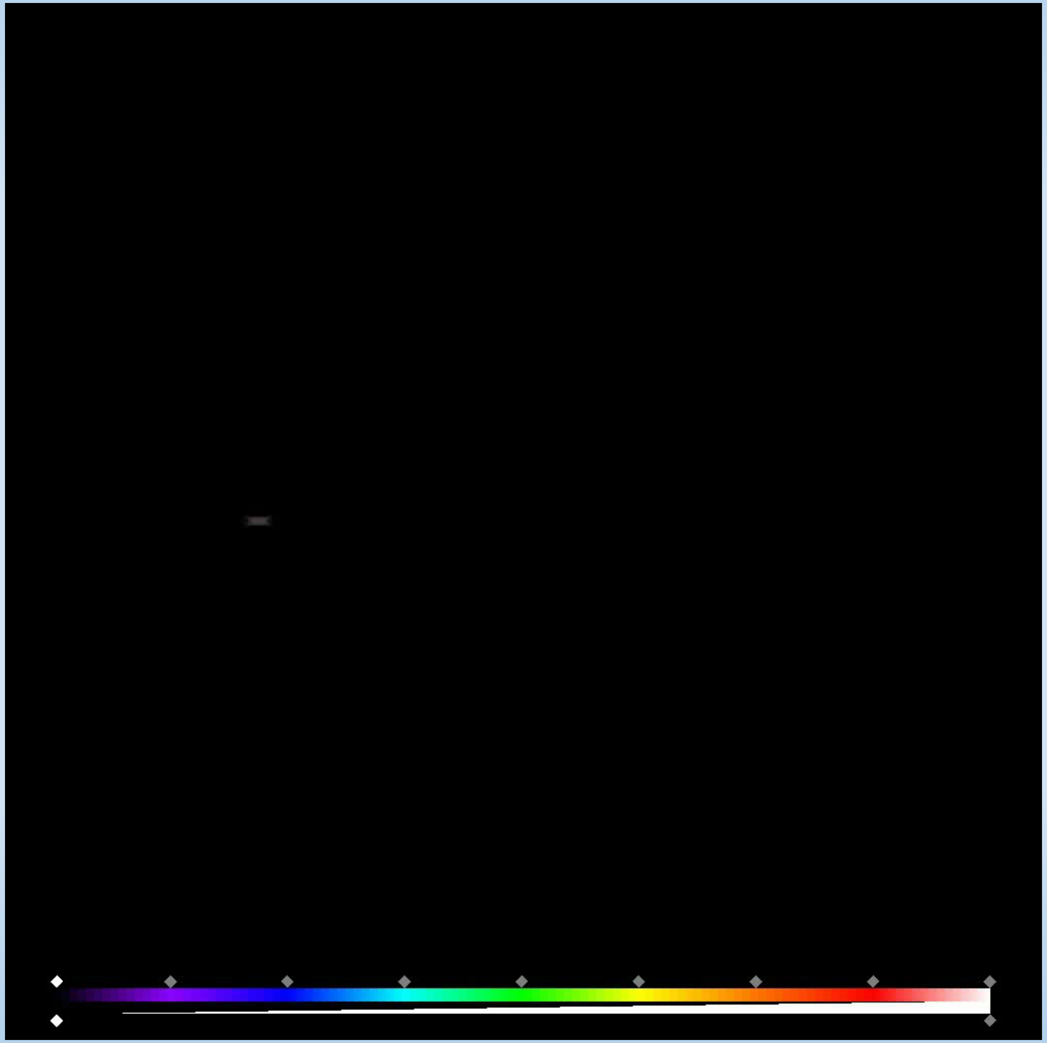


(Density Contours w/ Velocity Vectors

See also, for example, Ensslin & Bruggen 2002

Simulation of Mach 4 Shock Interaction with Normal Aligned to RG Jet Axis (Volume Rendering of Passive Jet Mass Fraction Tracer)

Viewed with jet axis
and shock normal 60
degrees from LoS
to reveal vortex structure



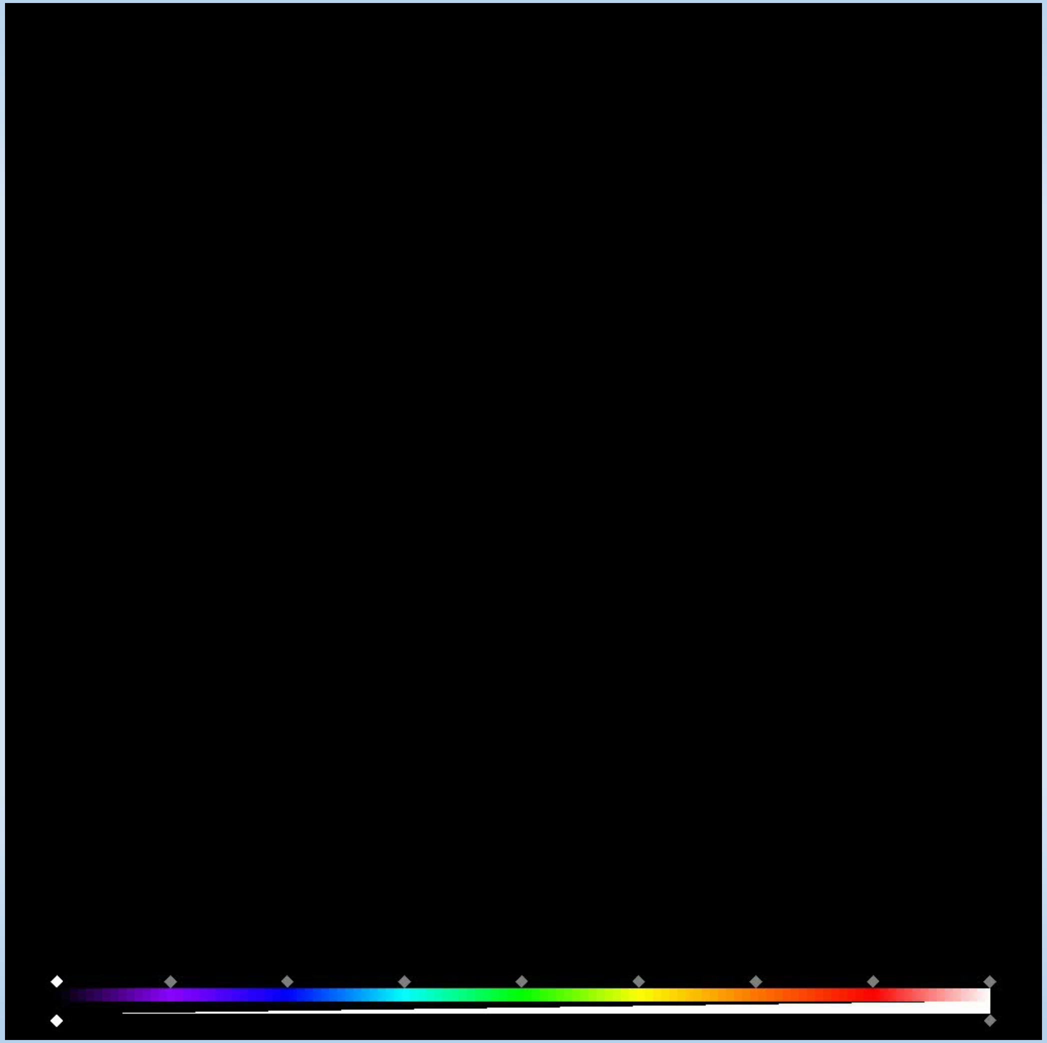
RG Evolved ~ 50 Myr Before
Shock Content

$M_j = 3.5$

Simulation of Mach 4 Shock Interaction with Normal Orthogonal to RG Jet Axis (Volume Rendering of Passive Jet Mass Tracer)

Viewed with shock normal
60 degrees from LoS
to reveal vortex structure

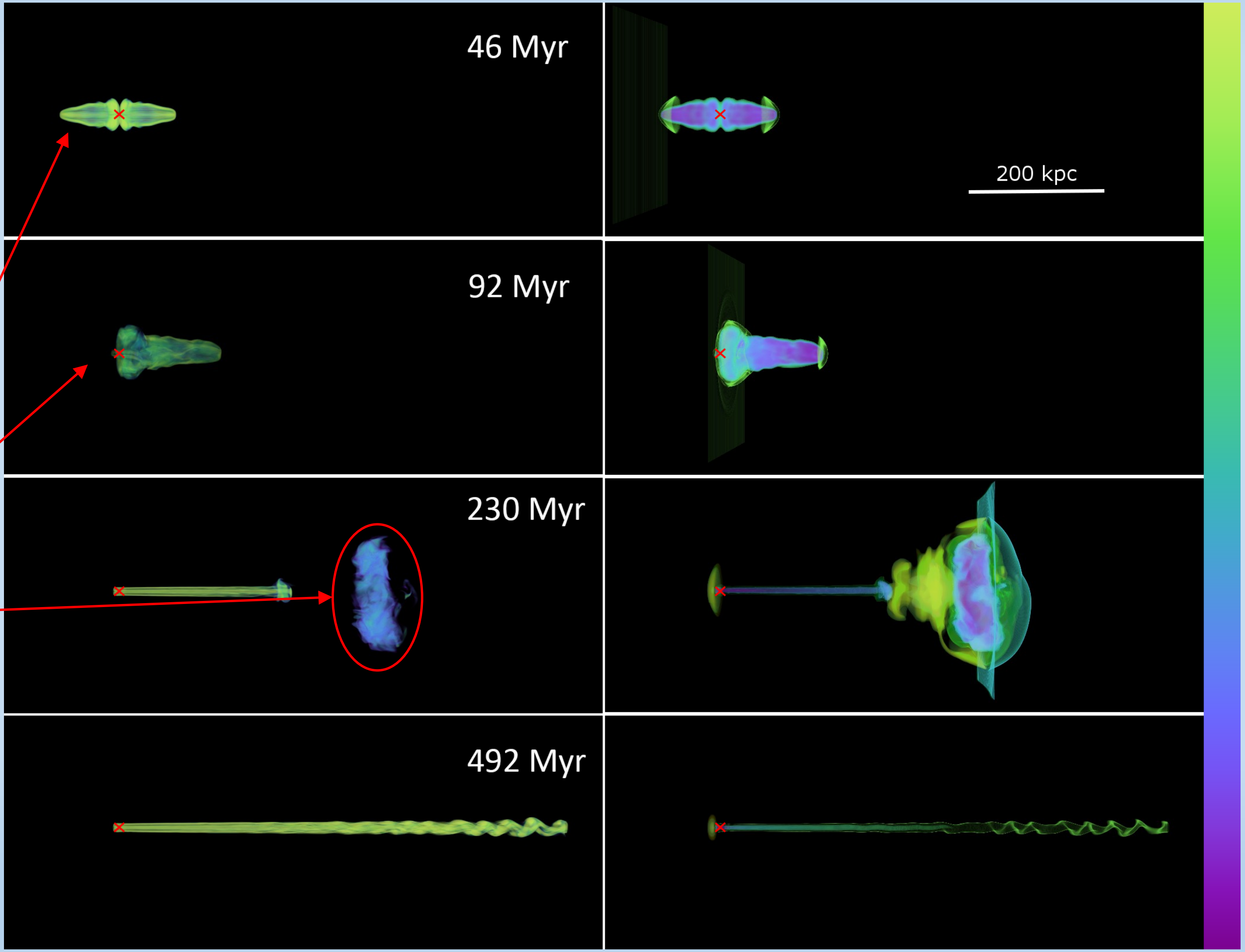
Note formation of vortex
and reversal of “upwind” jet



RG Evolved ~ 50 Myr Before
Shock Content

$M_j = 3.5$

Snapshots of Aligned Mach 4 Shock Impact
Volume Renderings with Jet Axis in Sky Plane



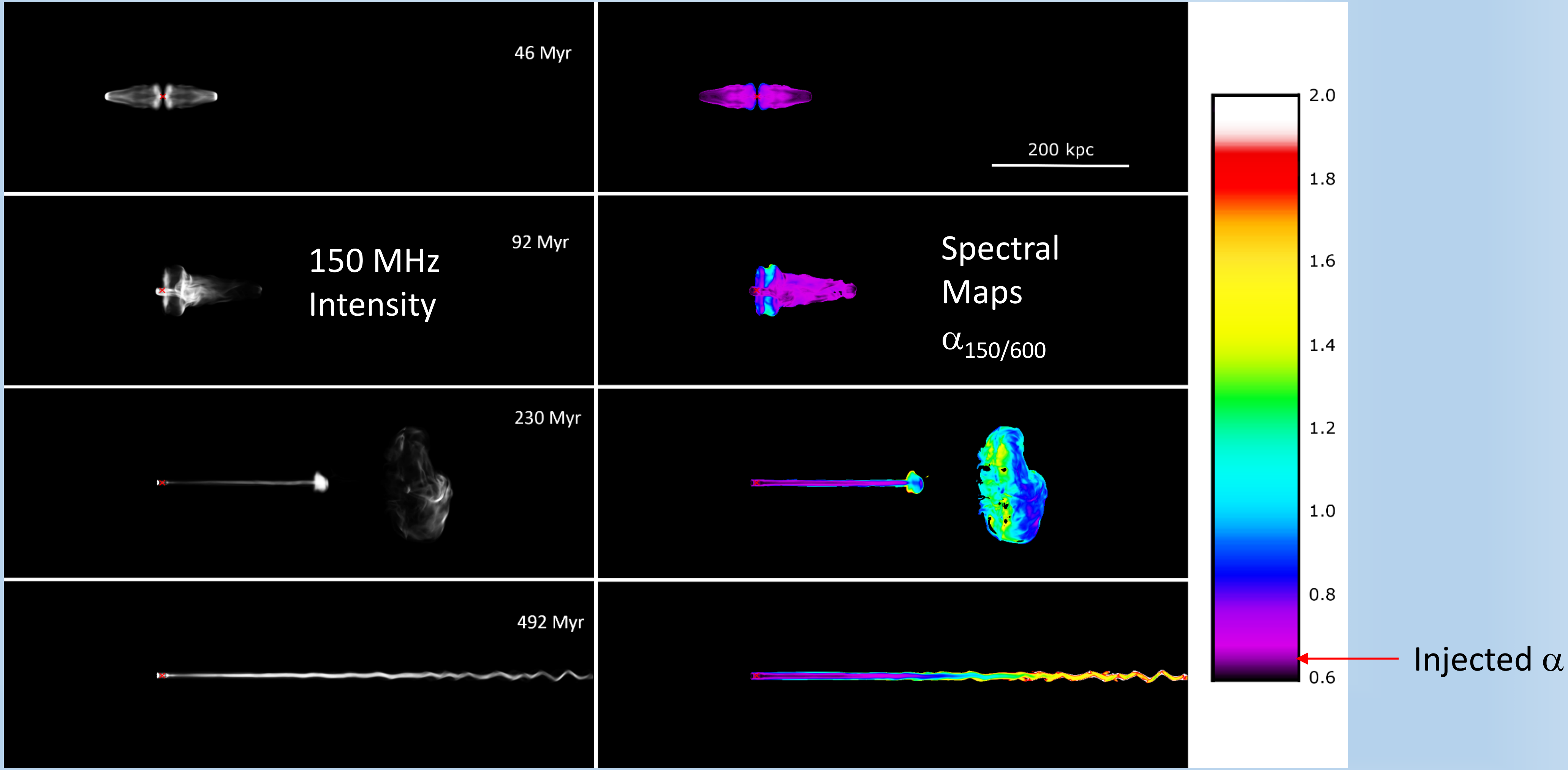
Jet Mass Tracer

Mass Density

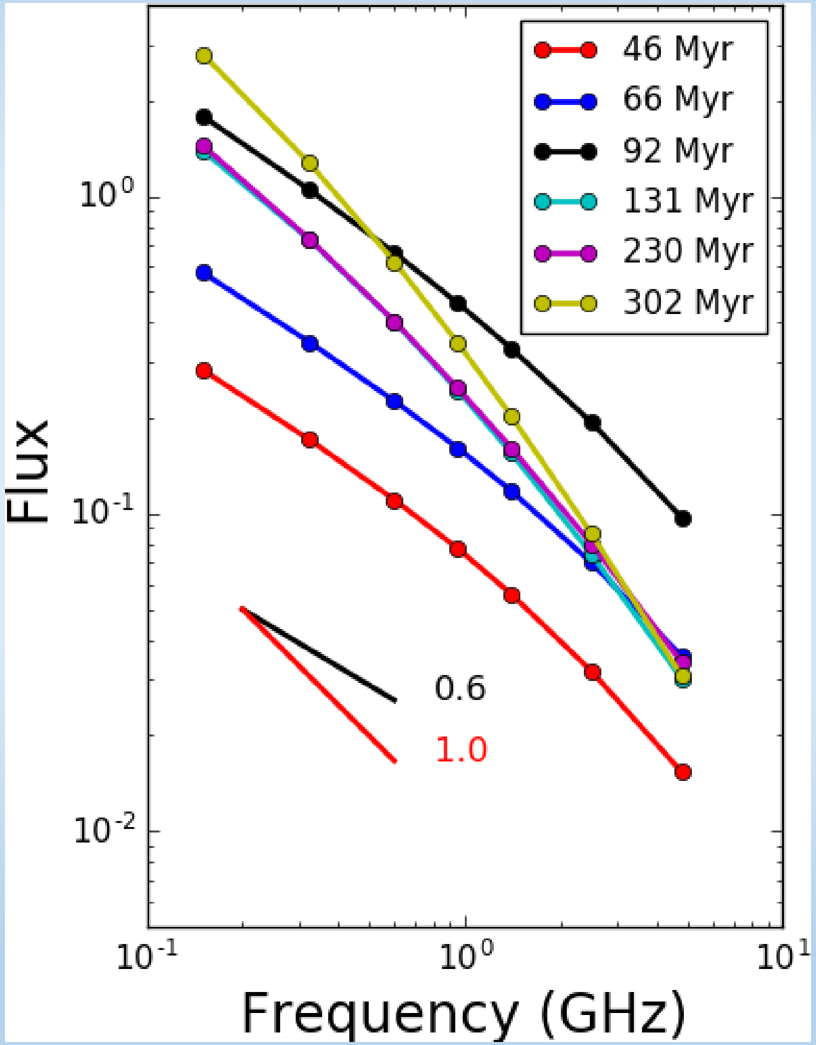
reversed jet

vortex ring

Snapshots of Aligned Mach 4 Shock Impact Synchrotron Images with Jet Axis in Sky Plane



Integrated Fluxes (Arbitrary Units)
Mach 4 Shock Impact Aligned Case



Note: After ~ 100 Myr
Total Fluxes Dominated by
Shed Vortex Ring

(Strong Magnetic Field Amplification)

II. Propagation of Aligned “Upwind” Jet Head in Postshock Wind: Simple Estimate Assuming Local Pressure Balance ($P_j = P_{ambient}$) Shock Mach Number M_{si}

Postshock “wind” properties
(jumps from “ICM” (i) conditions)

$$\rho_w = \frac{4\mathcal{M}_{si}^2}{\mathcal{M}_{si}^2 + 3}\rho_i,$$

$$P_w = \frac{5M_{si}^2 - 1}{4}P_i,$$

$$|v_w| = \frac{3}{4}\frac{M_{si}^2 - 1}{M_{si}}a_i,$$

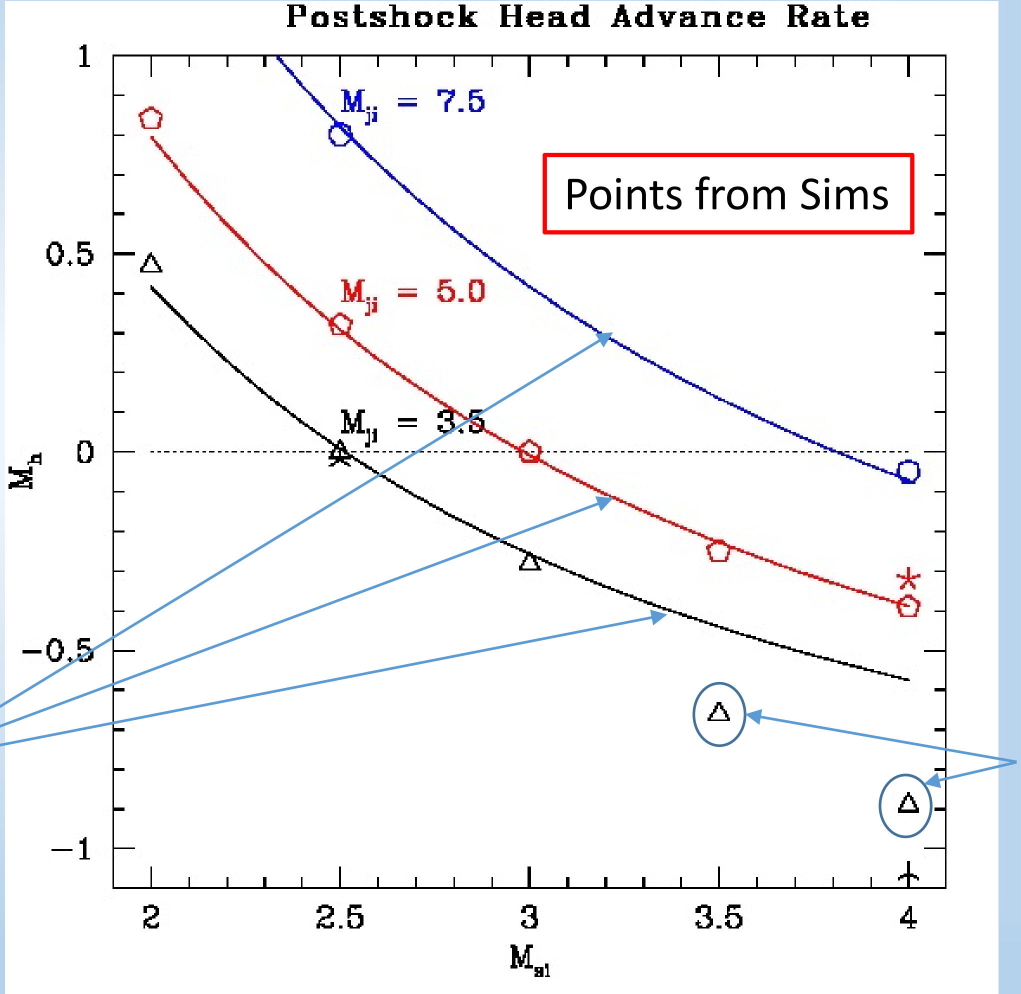
$$a_w = \frac{\sqrt{(M_{si}^2 + 3)(5M_{si}^2 - 1)}}{4M_{si}}a_i,$$

$$|M_w| = \frac{|v_w|}{a_w} = 3\frac{M_{si}^2 - 1}{\sqrt{(M_{si}^2 + 3)(5M_{si}^2 - 1)}}.$$

If jet remains supersonic

$$M_{hw} \approx \; - M_w + M_{ji}\sqrt{\frac{P_i A_j}{P_w A_h}}$$

Initial Jet Mach number, M_{ji}



Reversed Jet

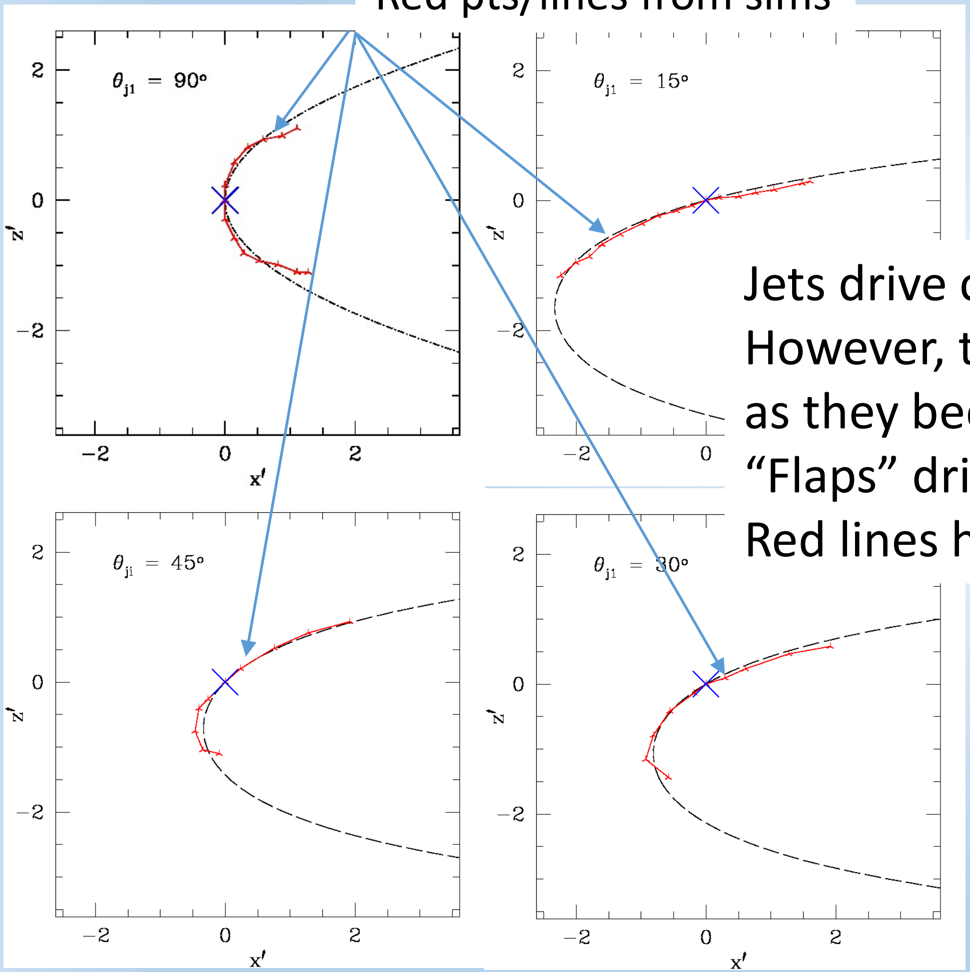
Subsonic Postshock Jets

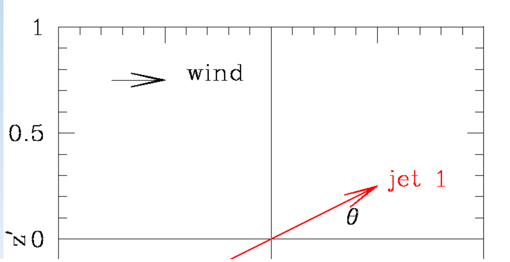
Bending Jets in a Cross Wind: Simple Model & Sims

Model
Normal Accel. $a_\perp \approx \alpha \rho_w v_w^2 \sin^2\theta/(r_j \rho_j) \approx \alpha v_j^2/\ell_b \quad \alpha \sim 1$

$$\ell_b = r_j(\rho_j v_j^2)/(\rho_w v_w^2)$$

Red pts/lines from sims



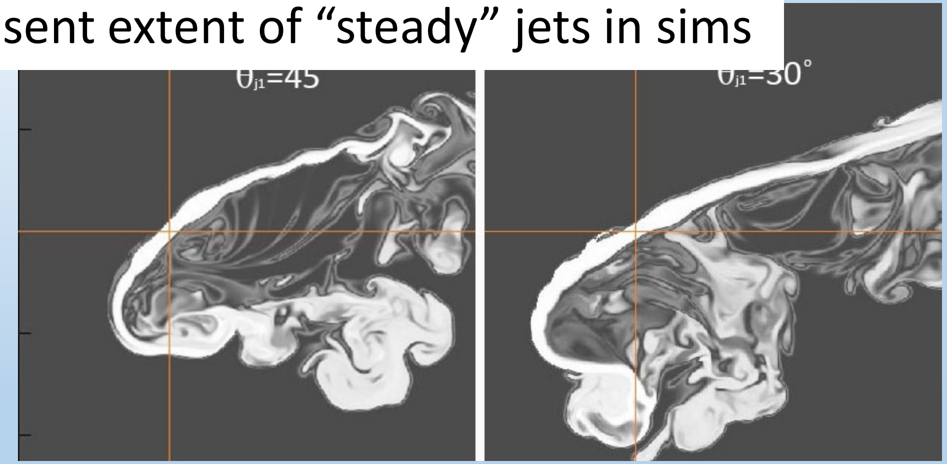


Black curves:

$$x' = x/\ell_b = (1/\alpha)(1/\sin\theta - 1/\sin\theta_i)$$

$$z' = z/\ell_b = (1/\alpha)\ln\left[\tan(\theta/2)/\tan(\theta_i/2)\right]$$

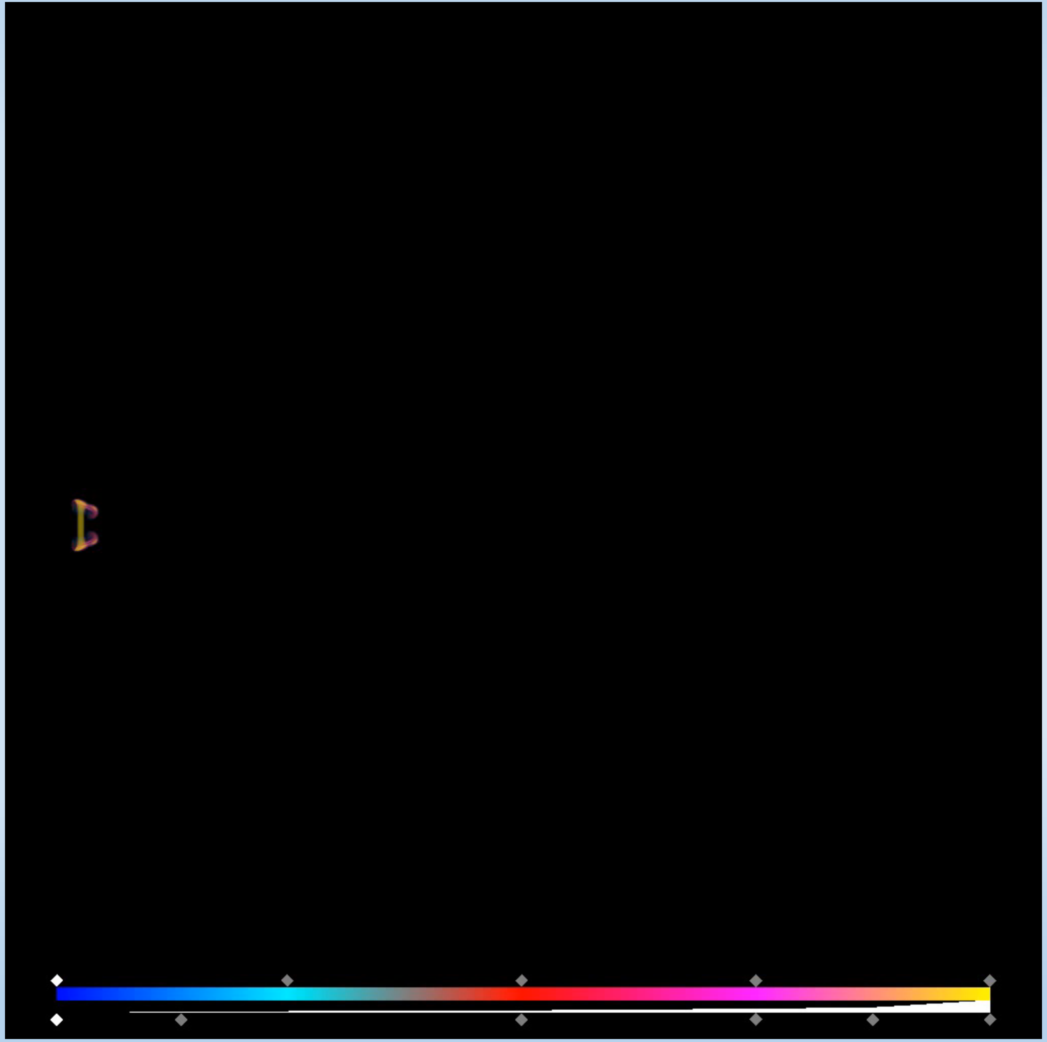
Jets drive coherently quite far down tails!
However, they “flap”, pinch off and reform
as they become sharply bent.
“Flaps” driven by downstream, “turbulent” flows
Red lines here represent extent of “steady” jets in sims



slices of
jet mass fraction
sample sims

Evolution of Jet Mass Tracer in Orthogonal Wind
(Shocked at end↑)

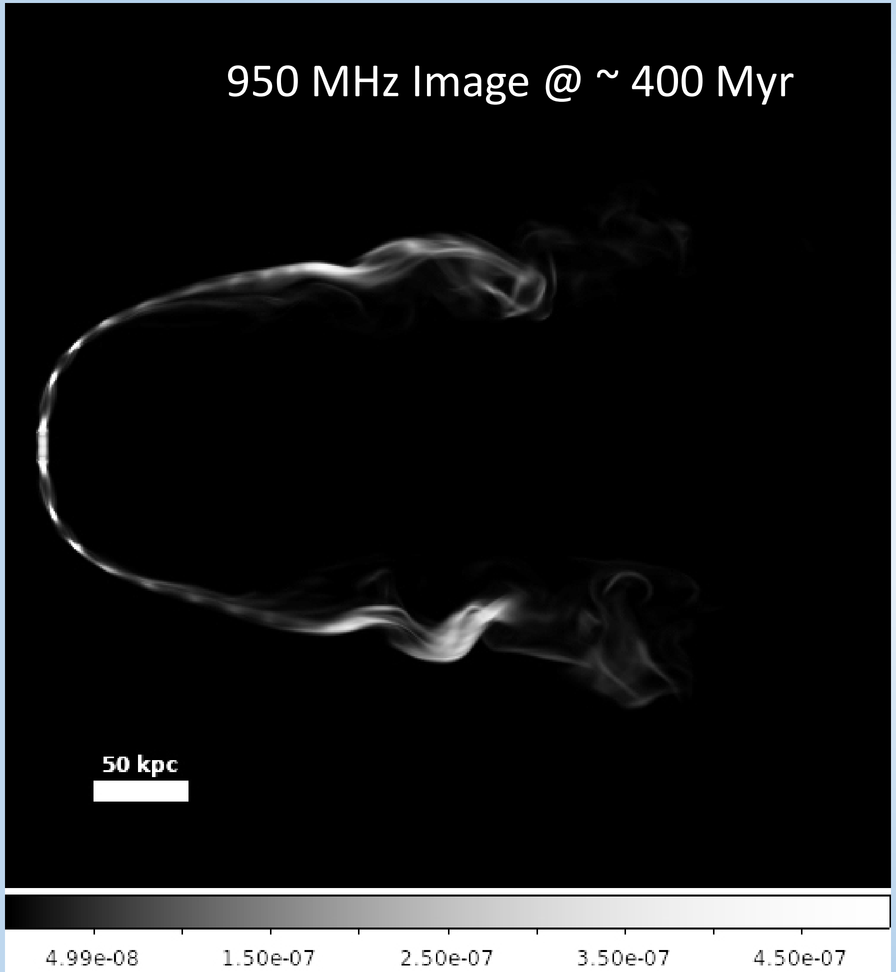
Volume rendered jet mass fraction tracer

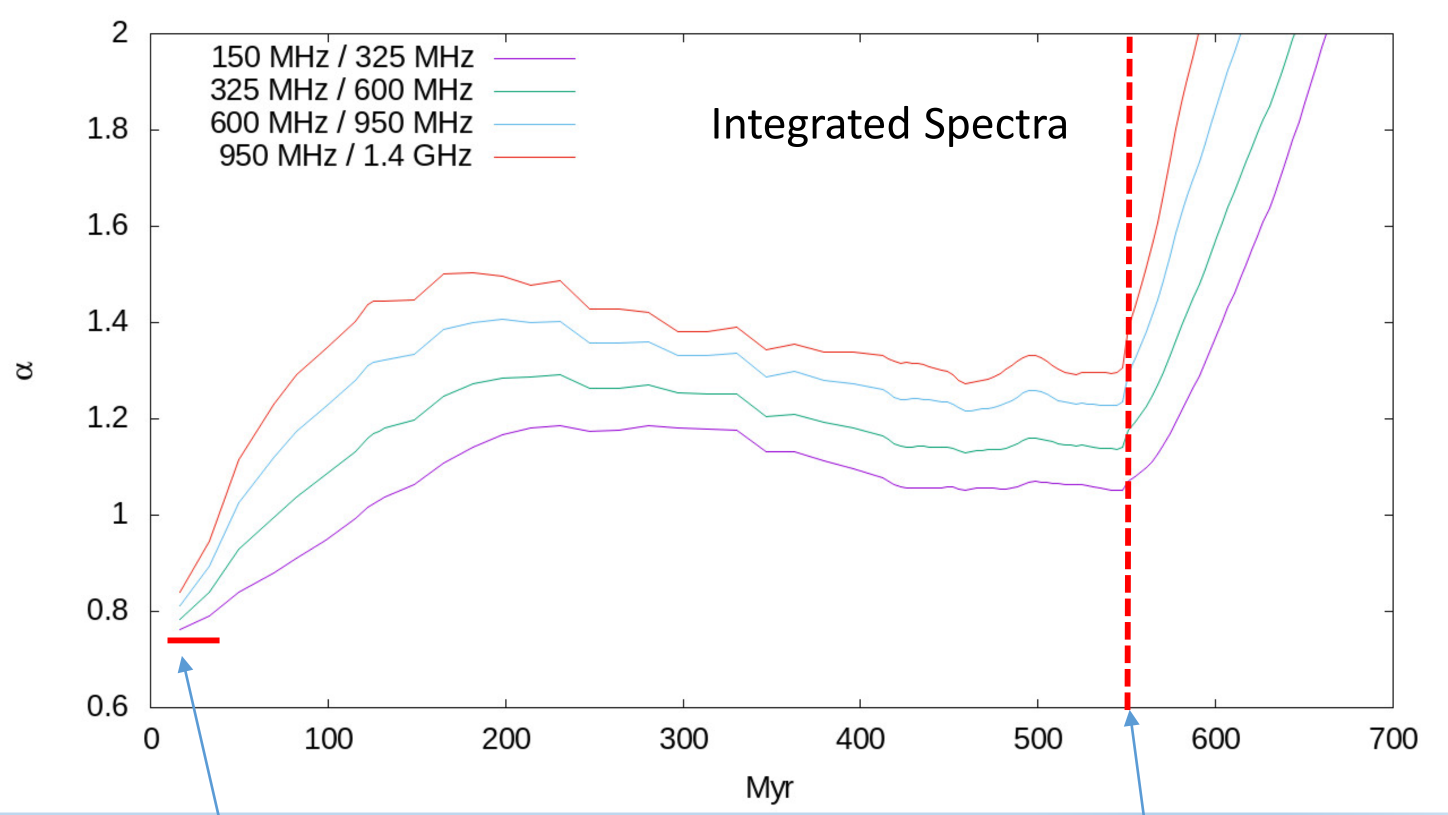


Shock Impacts After ~550 Myr
(I'll Get to That)

Synchrotron Emissions

Note ~ 200 - 550 Myr spectral form almost “Constant”
(Rough balance between aging and replenishment)


950 MHz Image @ ~ 400 Myr

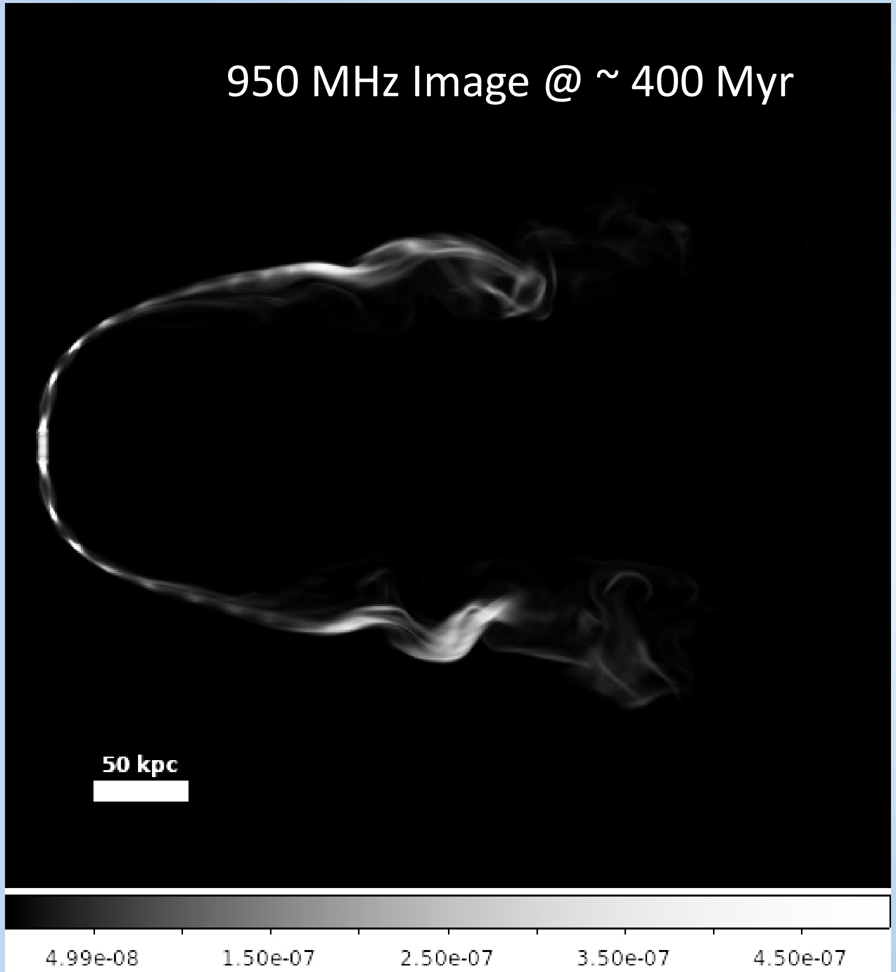

Integrated Spectra

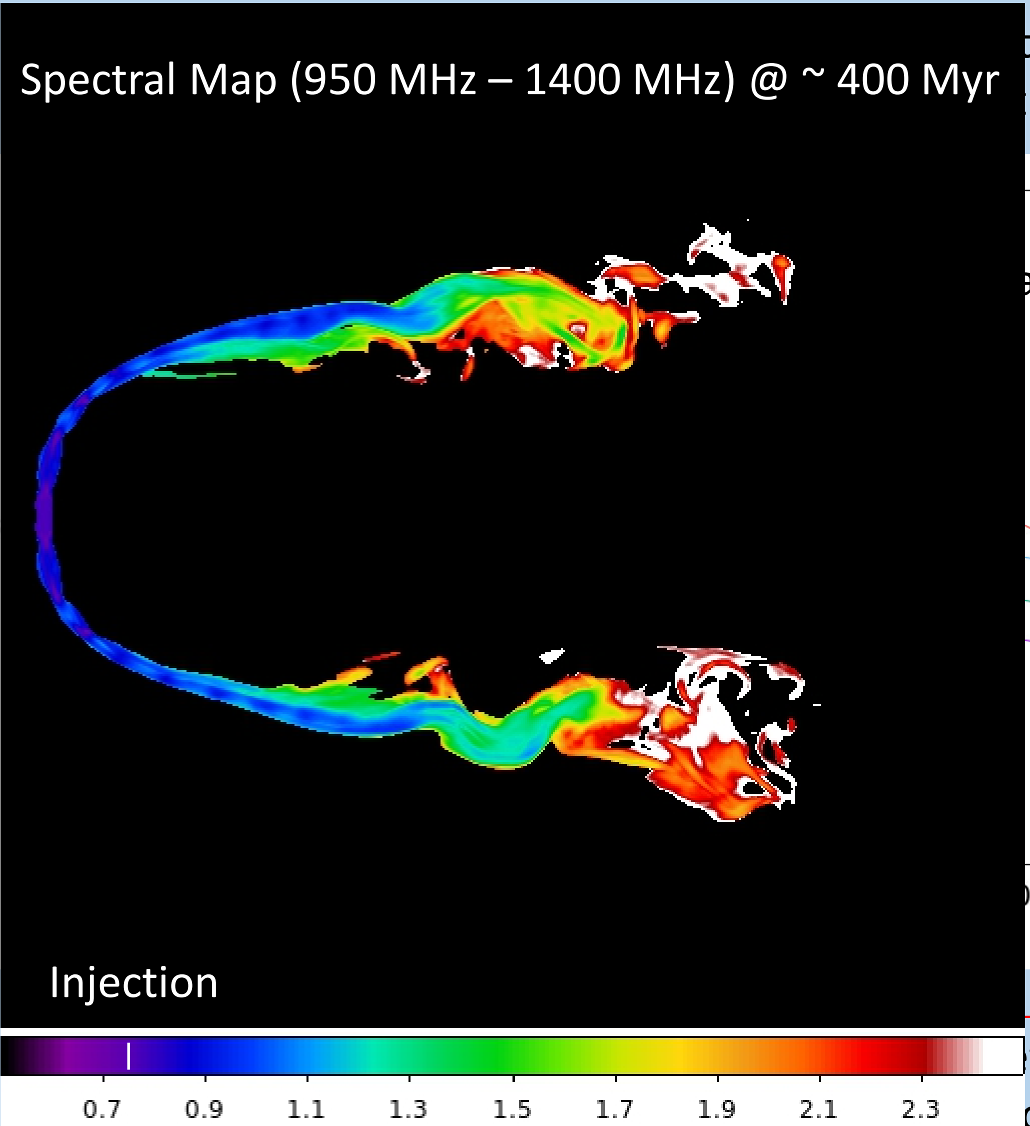
Injected α = 0.75

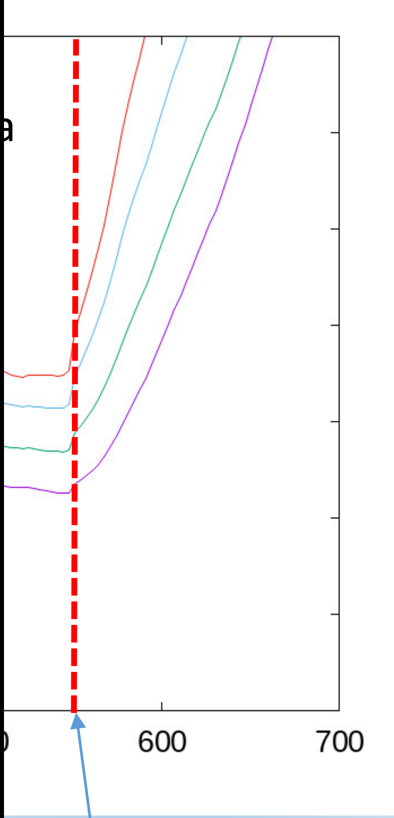
Jets Shut off:
No Shock

Synchrotron Emissions

tant”



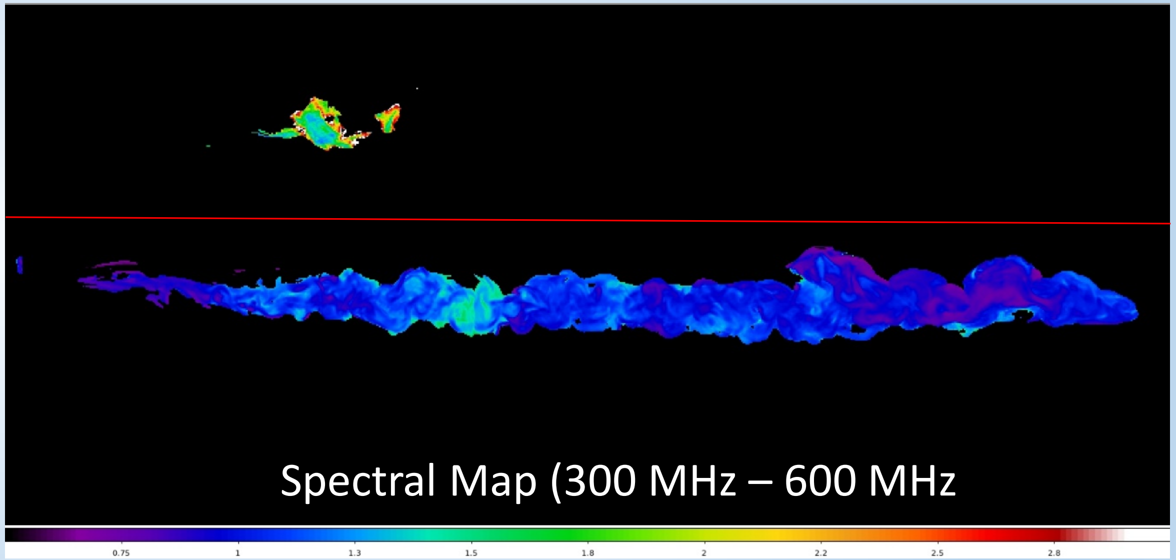




ts Shut off:
o Shock

Shock Impact Reinvigorates the Tails: $M_{si} = 4$ Leads to Obvious DSA
$\Rightarrow$Tails Are Not Cavities: Tail Densities Vary Widely; Can Exceed Ambient

Synchrotron Image @ 630 Myr
(Shock Between Tails)

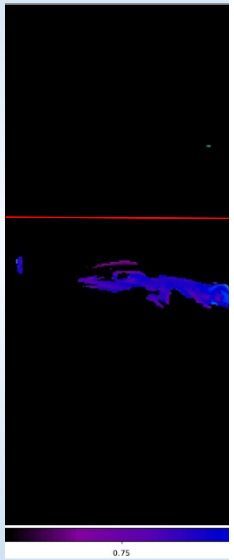


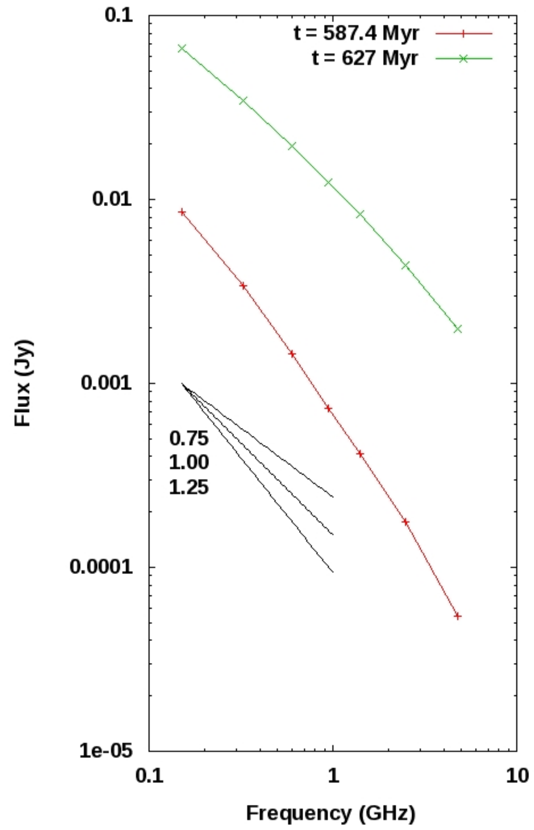
Spectral Map (300 MHz – 600 MHz

Shock Transit Time Across Tails ~ 20 Myr

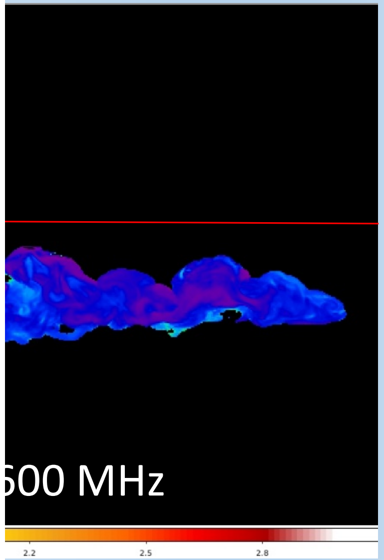
Shock Impact Reinvigorates the Tails: $M_{si} = 4$ Leads to Obvious DSA
$\Rightarrow$Tails Are <u>Not</u> Cavities: Tail Densities Vary Widely; Can Exceed Ambient

Synchrotron Image @ 630 Myr
(Shock Between Tails)





Integrated Spectral Changes



00 MHz

Shock Transit Time Across Tai

Conclusions

- ICMs can be highly dynamic and embedded with multiple Radio Galaxies

  -Understanding the Radio Galaxy/ICM interaction signatures may reveal ICM dynamics signatures

- Our initial efforts focus on simple scenarios in order to isolate key physical processes:

  -Simple Shock-RG encounters
  -Simple Wind-RG dynamics that forms tails and bent jets [basic Head-Tail (H-T) dynamics]
  -Simple Shock-Tail encounters

- Disrupted & separated radio lobes can remain bright for long periods

- Jets can continue coherent propagation well into NAT tails

- Simple analytic models of Jet-Wind interactions work reasonably well

- Shock-Tail encounters are quite different from shock-lobe encounters (shocks remain relatively strong)

Thanks!