Decoding AGN/ICM Structures and Emissions: Probes of Cluster Dynamics and History

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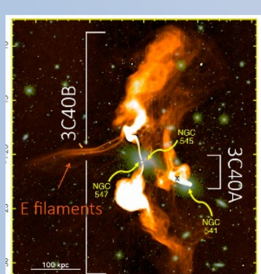
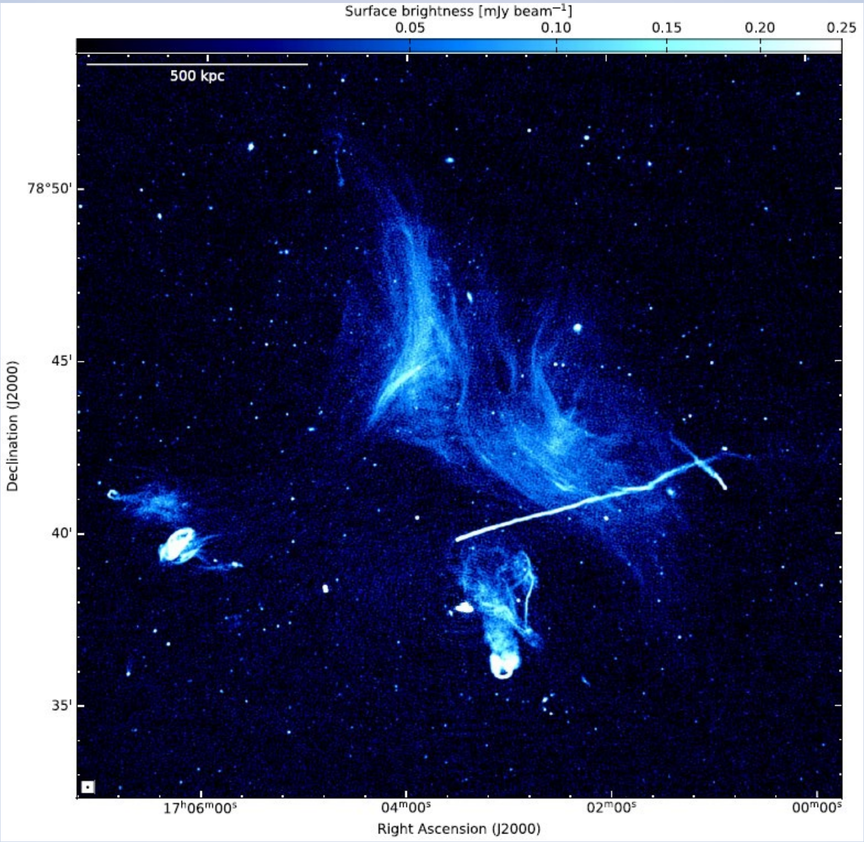


Outline

- **AGN jet and backflow structures often reflect interaction with ICM structures**
- **AGN-ICM structure encounters can “highlight” ICM physics**
- **Such encounters offer key insights into AGN and ICM dynamics and histories**
- **We report on “MHD+CR” simulation studies targeting such issues**

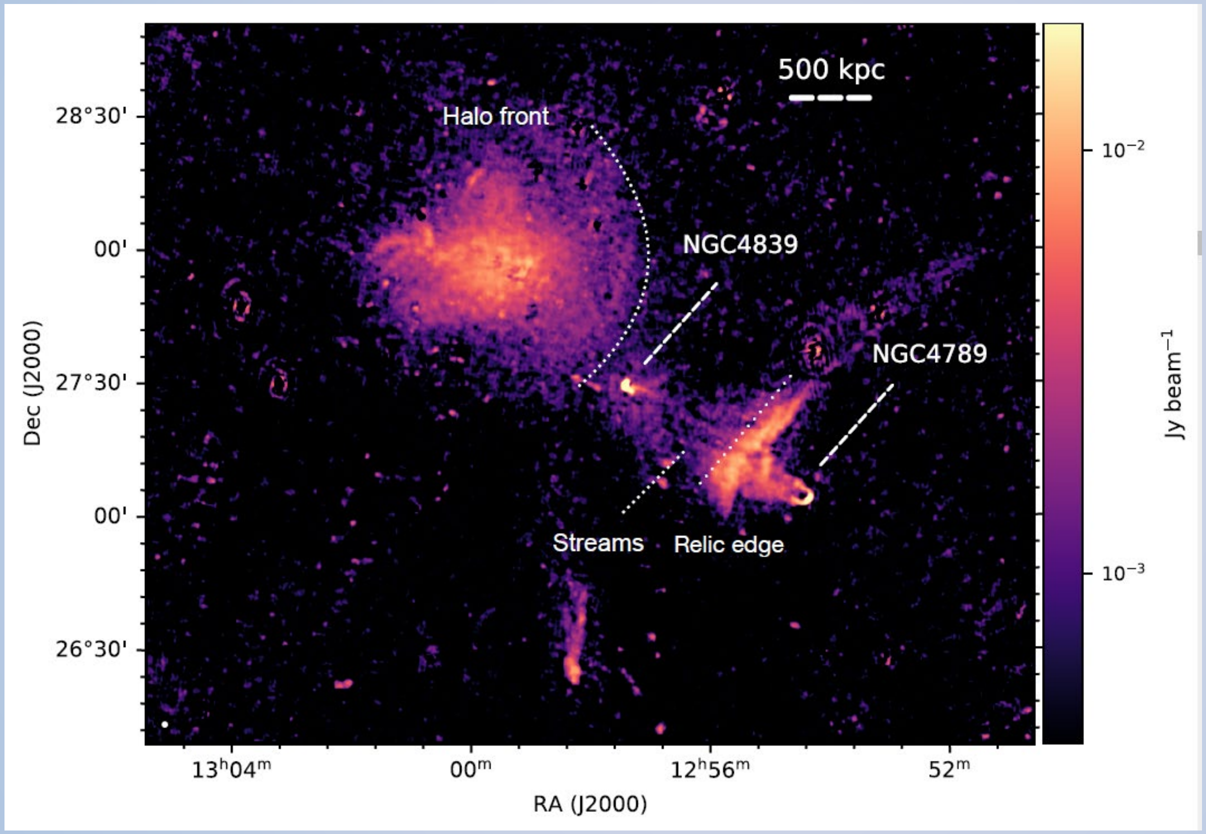
Familiar Observational Motivation Example:
Abell 2256: Classic Illustration of Complex ICM Structures with Distinctive AGN Interaction-driven Highlights



K. Rajpurohit, 2022
ApJ, 927, 80

Abell 2256: uGMRT, LOFAR, VLA

Familiar Observational Motivation Example:
Coma: Impressive Illustration of Complex ICM Structures Showing AGN Interaction Highlights



Bonafede et al 2021
ApJ, 907, 32

Coma: LOFAR

3D MHD+CR Exploratory Simulations:

* WOMBAT MHD “in house” code; multiple solvers
  - Up to 5th order spatial, ideal, non-ideal
  - Reported here: 2nd order, ideal MHD

* CRe (f(E) --adiabatic, radiative, Fermi—)

* Sub kpc resolution; still need better, with non-ideal micro-scale physics

* Cartesian Grids

Some "Prototypical" AGN/ICM Dynamic Scenarios Being Modeled:
(Isolated interactions-- for simplicity; Complementary to Cluster-Scale/Cosmological)

***Jets Deflected by ICM "Winds" (Relative Motion)(NATs)**
(Or by Density/Pressure Gradients)

***Jets Impacted by ICM Shocks**

***Jets Encountering Existing ICM Magnetic Filaments**

Aiming Especially to Identify Diagnostic Interactions

Simulated Jets at Injection onto Grid:

*Bipolar, Cylindrical, r_j ~ 2-3 kpc

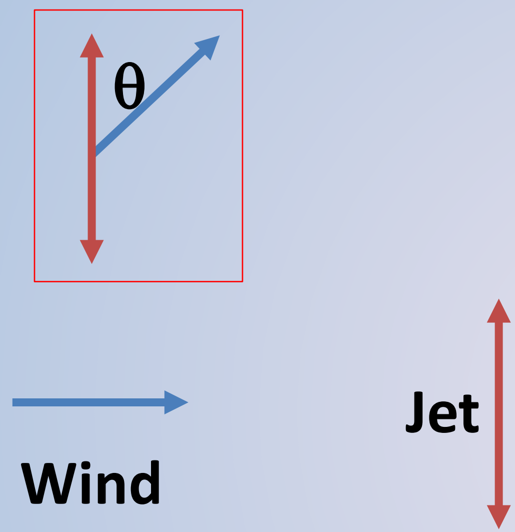
*Low density, typically, $\rho_j \sim 0.01\rho_a$

*Pressure balanced with total $P_j \sim P_a$

*Kinetically dominated, typically M_j ~ 6-10

*Toroidal magnetic field, typically β_j ~ 10
(Uniform axial current with boundary return current)

Scenario 1: Jets in a "Wind" (Relative Motion)*



Following results from O'Neill et al (TJ) 2019 ApJ, 884, 120

***Simulations done in AGN rest frame**

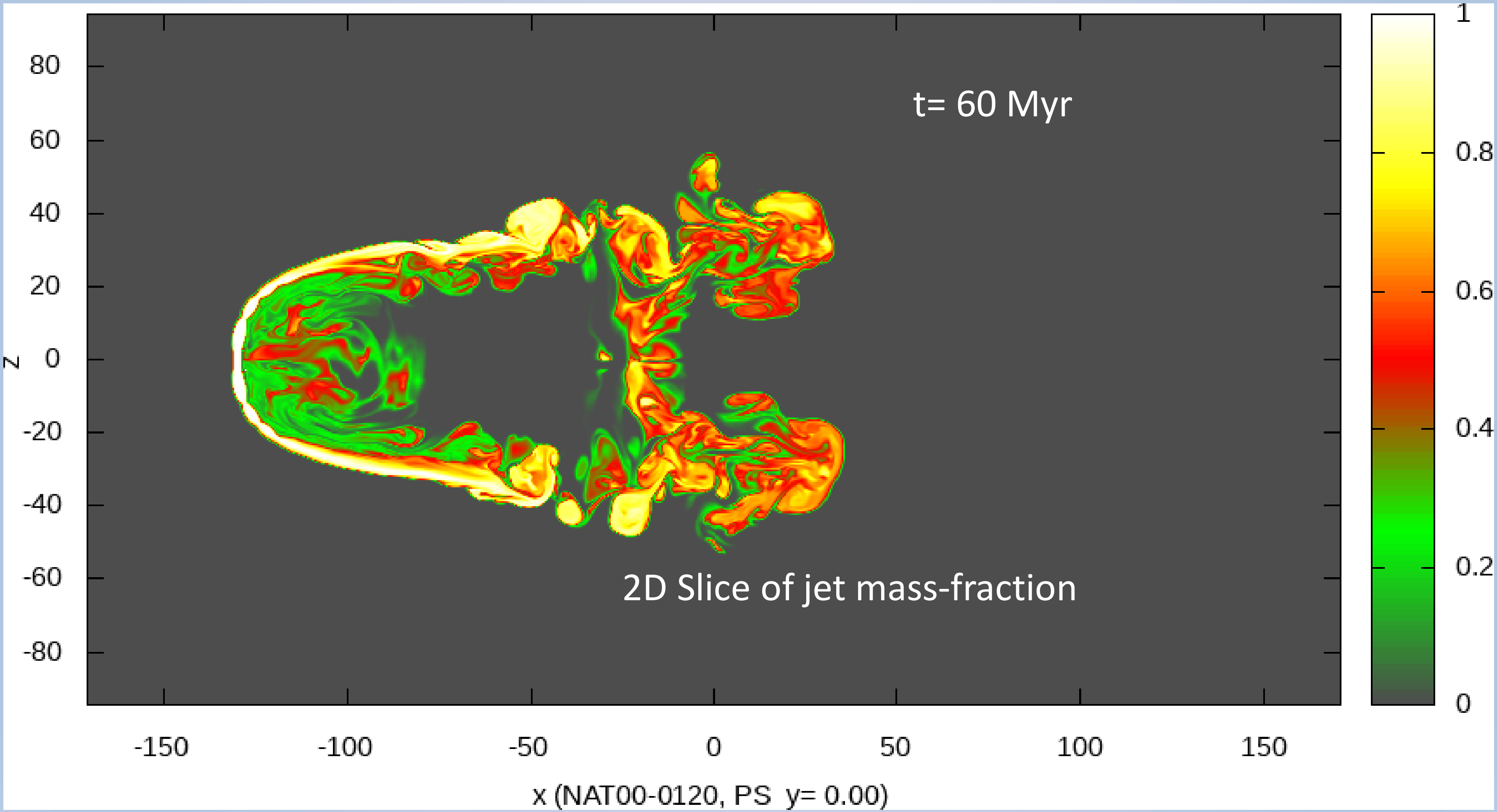
Bending Radius, r_b, of a jet with radius, r_j, in a cross flow:

$$r_b \cong r_j\ (\rho_j {v_j}^2)/(\rho_w v_w^2)$$

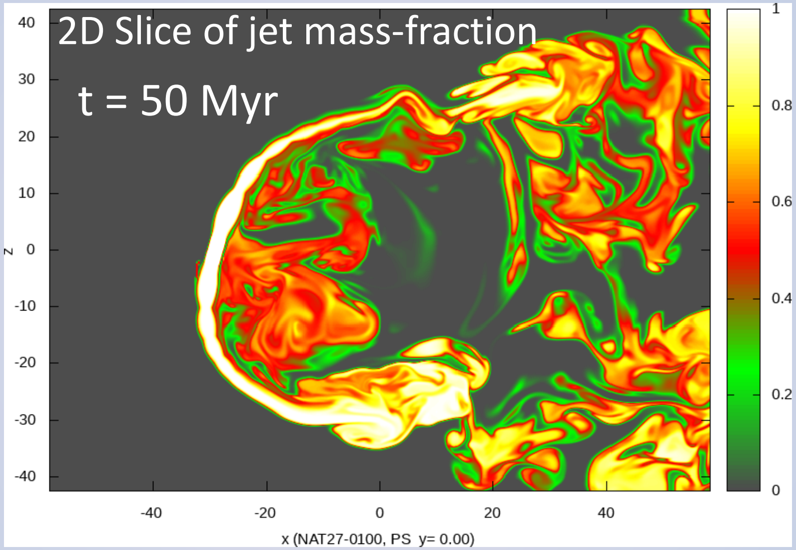
With v_w the local transverse wind velocity.

Transverse ambient density/pressure Gradients can similarly bend jets

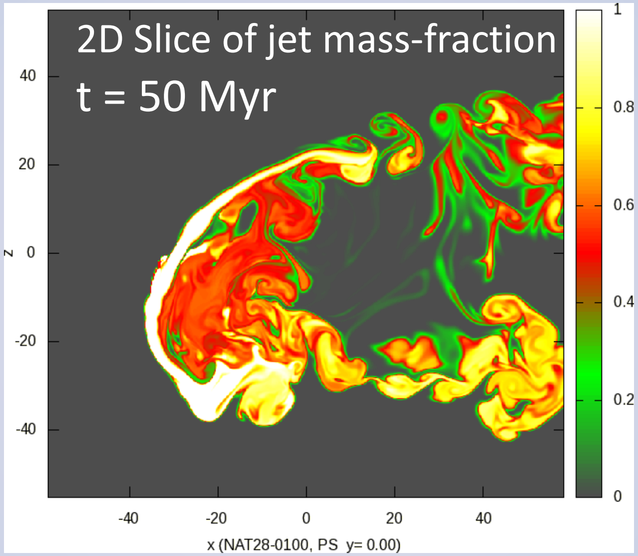
Uniform Cross "Wind" (Mach ratio: $M_j/M_w = 3$): Orthogonal Incidence: $\theta = 90$ deg $\rightarrow$ Classic, "Symmetric" NAT (Jets "Flap" & Perturb the Other, But Continue Far into Tails)



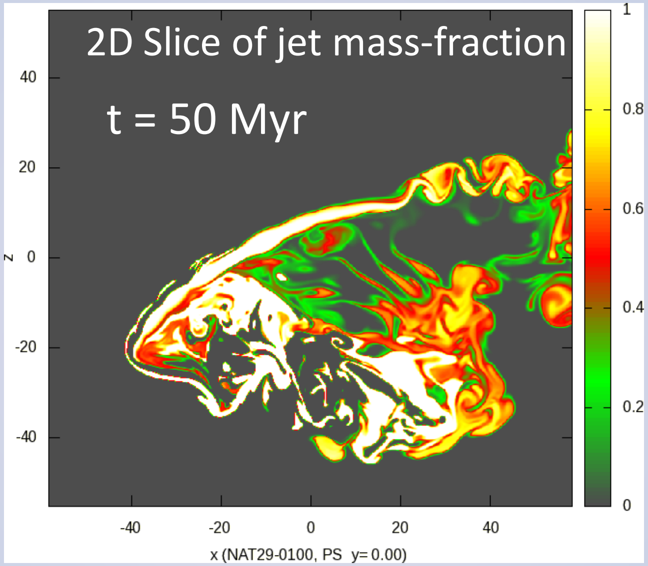
Oblique “Wind”
$\theta = 75$ deg $\rightarrow$ Asymmetric NAT



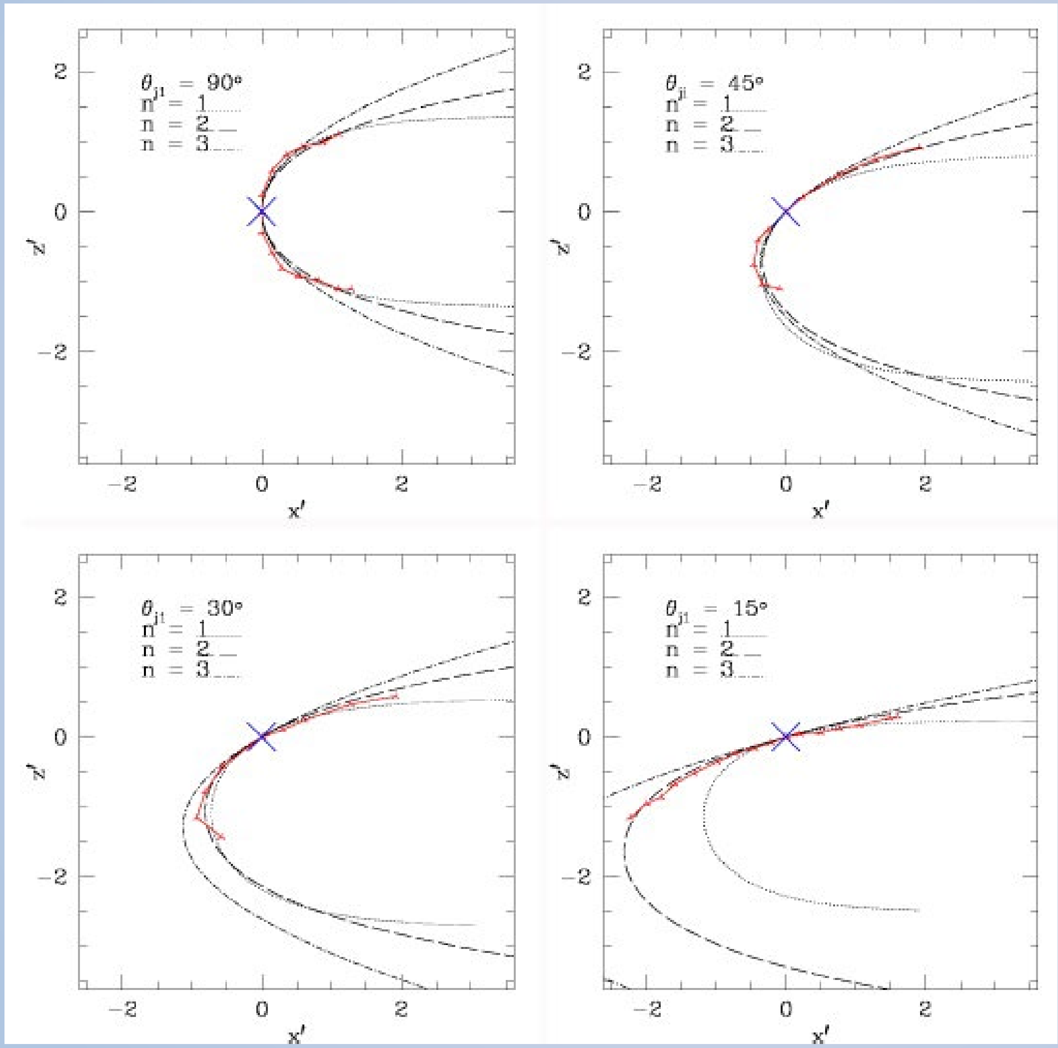
Oblique "Wind"
$\theta = 45$ deg $\rightarrow$ Asymmetric NAT



Oblique "Wind"
$\theta = 30$ deg $\rightarrow$ Asymmetric NAT



NAT Formation: Mean Jet Trajectory vs "Wind" Incidence Angle, θ

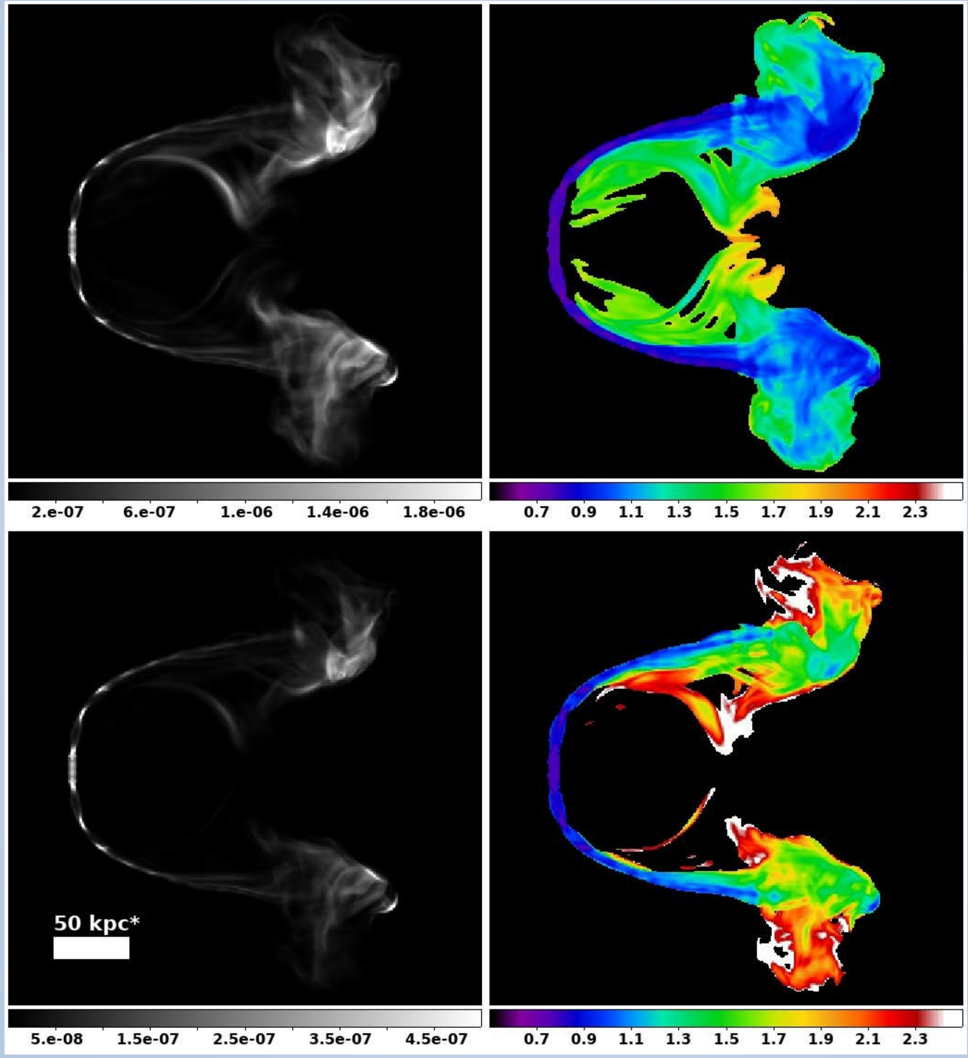


Rate of jet bending
$d\psi/dl \propto (1/r_b)\sin(\psi)^n$
with ψ the jet deflection angle and l displacement along the Jet.
Intuitively, n ~ 2.

Synthetic Synchrotron Emissions from "Symmetric" NAT @45 Myr

150 MHz

950 MHz

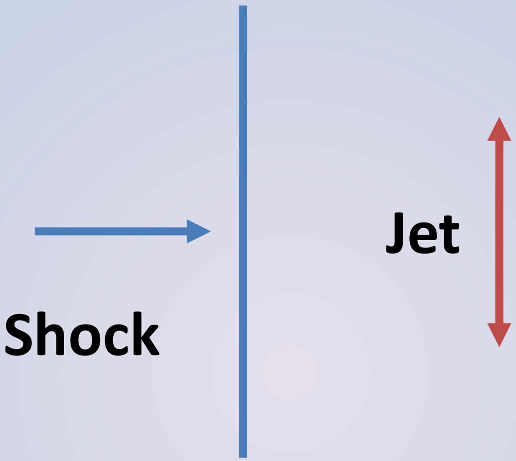


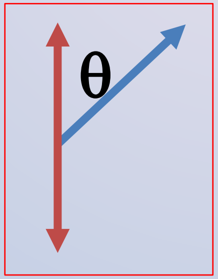
Intensity (Left)

Spectral Index (Right)

All CRe Originate In AGN- Injected With Power-law Energy Distribution, d ln N/d ln E = -2.4

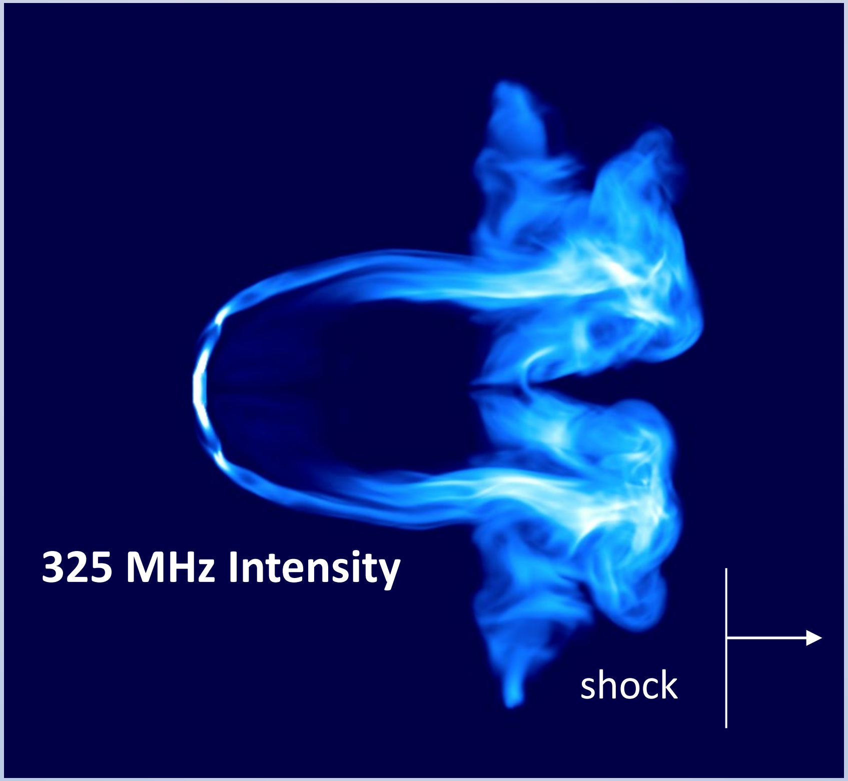
Scenario 2: AGN Jets Overrun by an ICM Shock





Shocked AGN Jet Emissions:
~30 Myr After Orthogonal ($\theta = 90$ deg) Mach 4 ICM shock impact on Mach 10 Jets;
<u>2 μGauss ambient B field aligned with shock face along LoS</u>

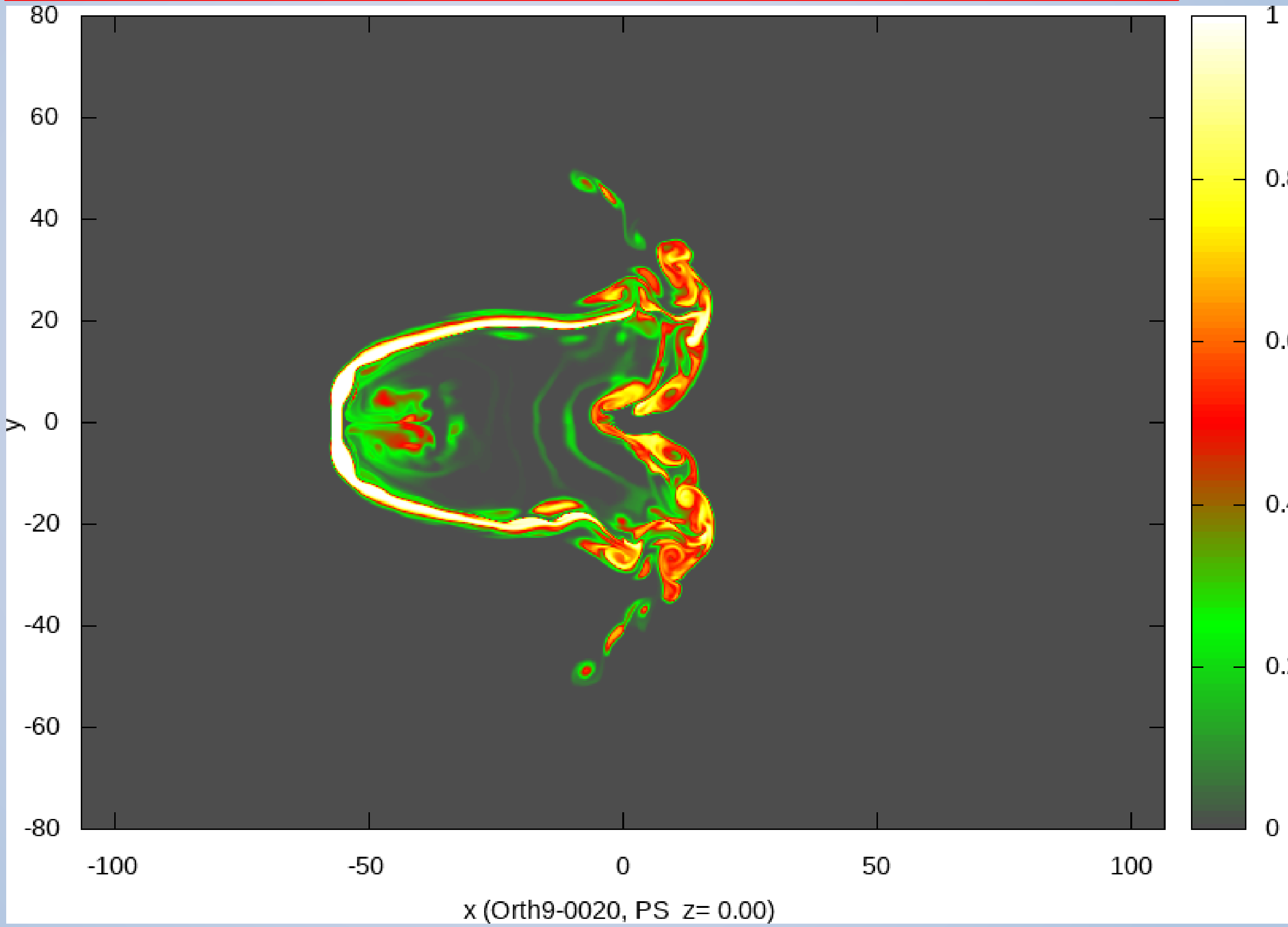
Note: All CRe initially Injected from AGN



Note:
Shock/Jet Interaction Generates Turbulence, Tangles and Amplifies Postshock ICM B Field along with Jet Injected Field

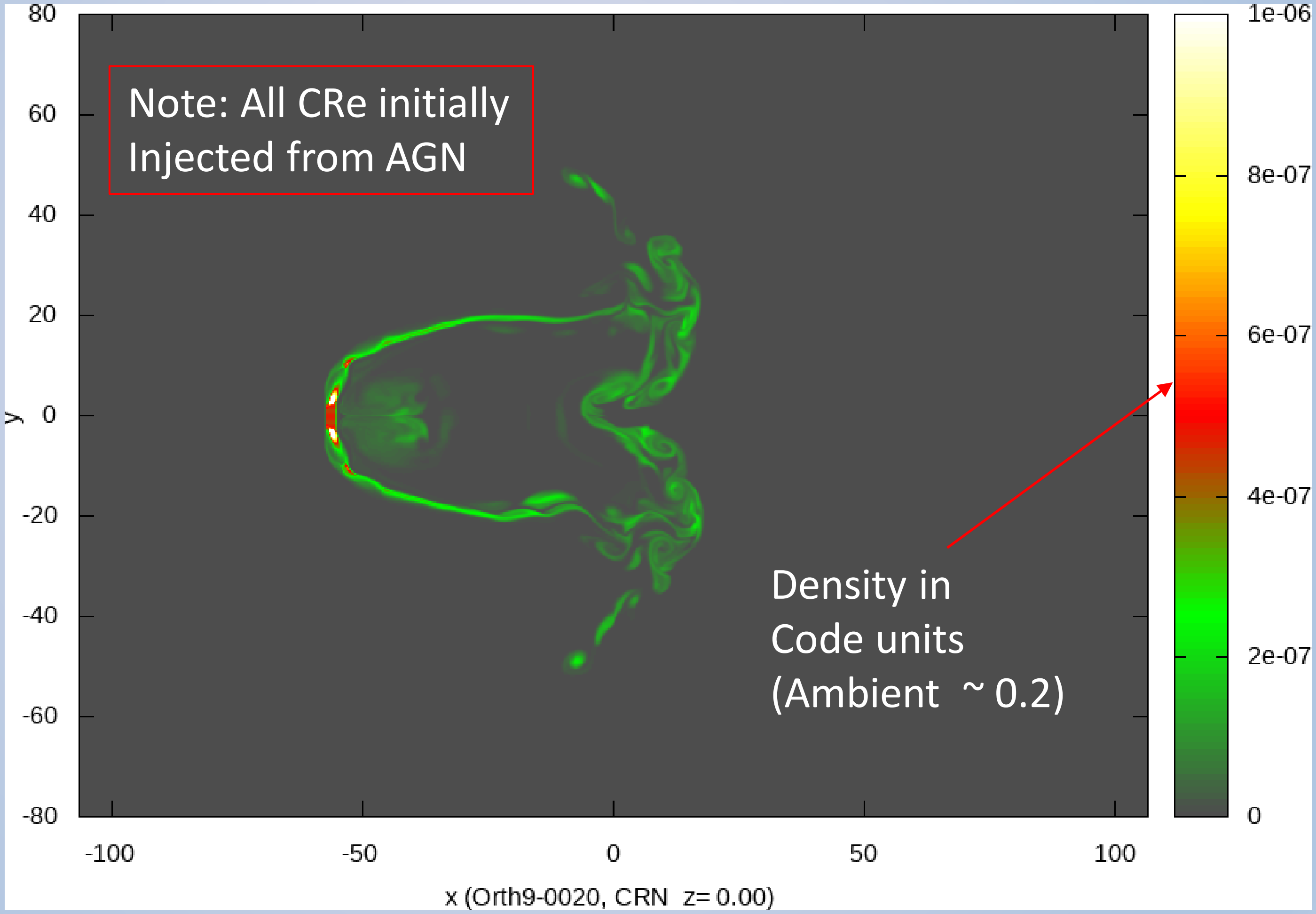
Above Shocked Jets:

Jet Mass Fraction in Jet/Shock-Normal Plane

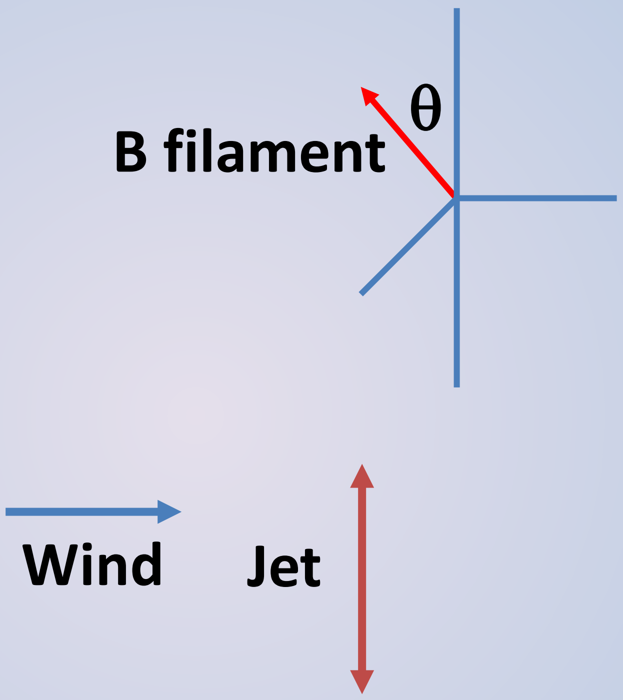


Above Shocked Jets:

CRe Density in Jet/Shock-Normal Plane

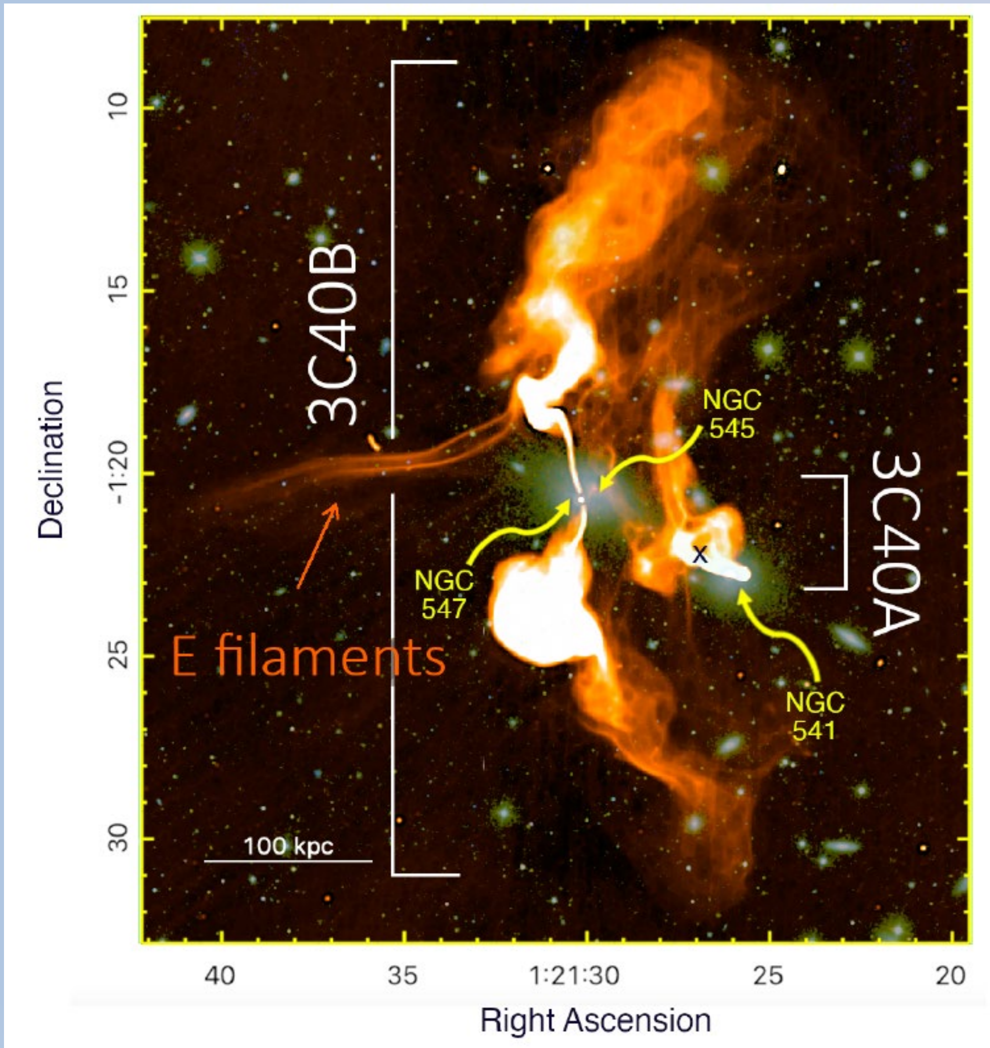


Scenario 3: Interaction of ICM Magnetic Filaments with AGN Jets



Radio filaments may be ubiquitous

Motivation Example: Abell 194 (3C40B)



Note:

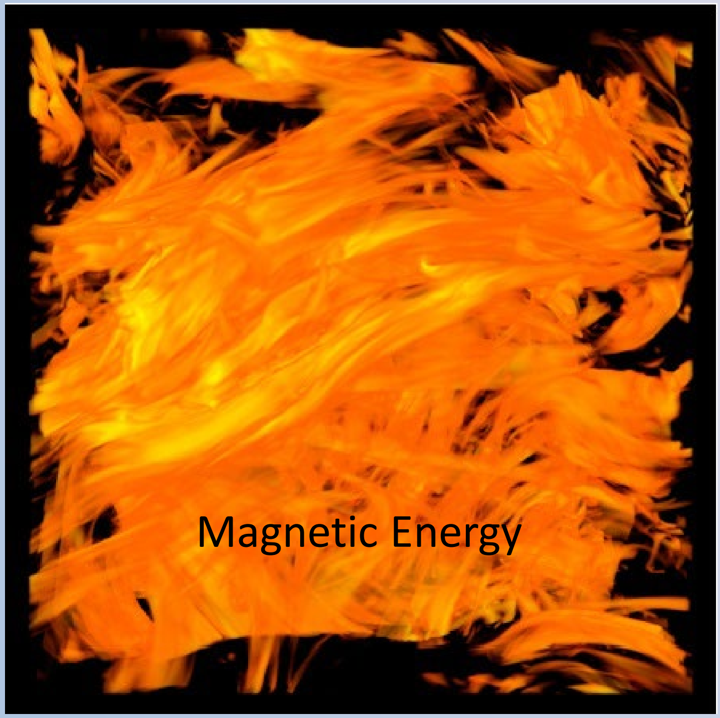
*Such ICM radio filaments common and not "cold":
*Magnetic fields align
*Diverse patterns (some >> 100 kpc lengths)
*Filament/RG associations common, but not universal

*Multiple origins possible
*Origins of CRe?

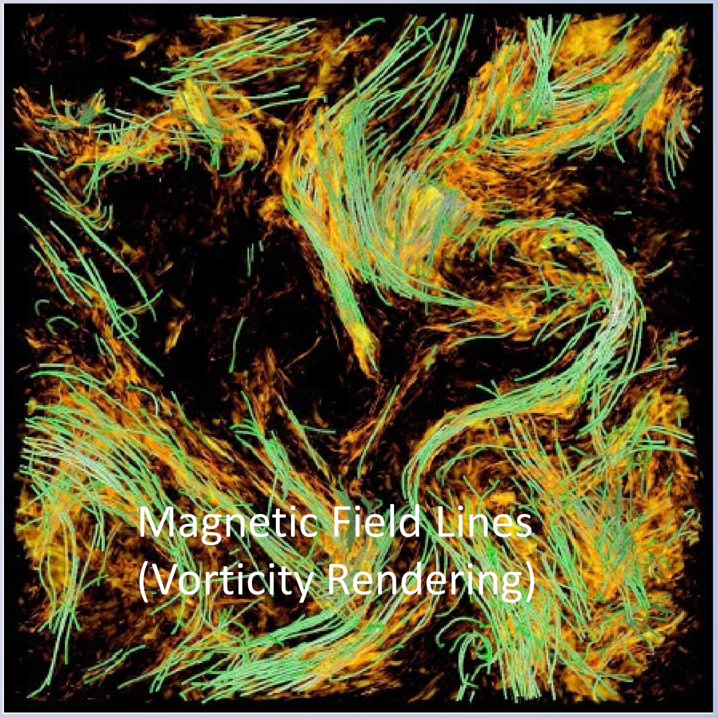
Rudnick et al (TJ) 2022
LOFAR/VLA

Sheared ICM Flows Likely to Generate Magnetic Filaments:
--Stretched Fields Tend to Filament--

Example: Turbulent Motions (... local infall, sloshing,...):
(Rendering ~ One Turbulence Driving Scale "in a Box")



Transverse scale ~ dissipation scale



Porter et al (TJ) 2015
ApJ, 810, 93

Simulations of Idealized ICM Filament/RG Encounters: (Individual, cylindrical filaments)

*Multiple Initial Jet/Filament Orientations

*Multiple Initial Jet/Filament Relative Initial Locations

*Multiple Relative Magnetic Field Intensities

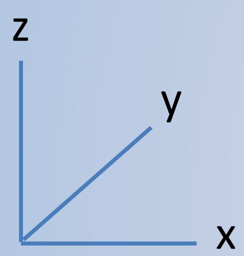
*Filament B “Aligned” and “Anti-aligned” with Near Jet B

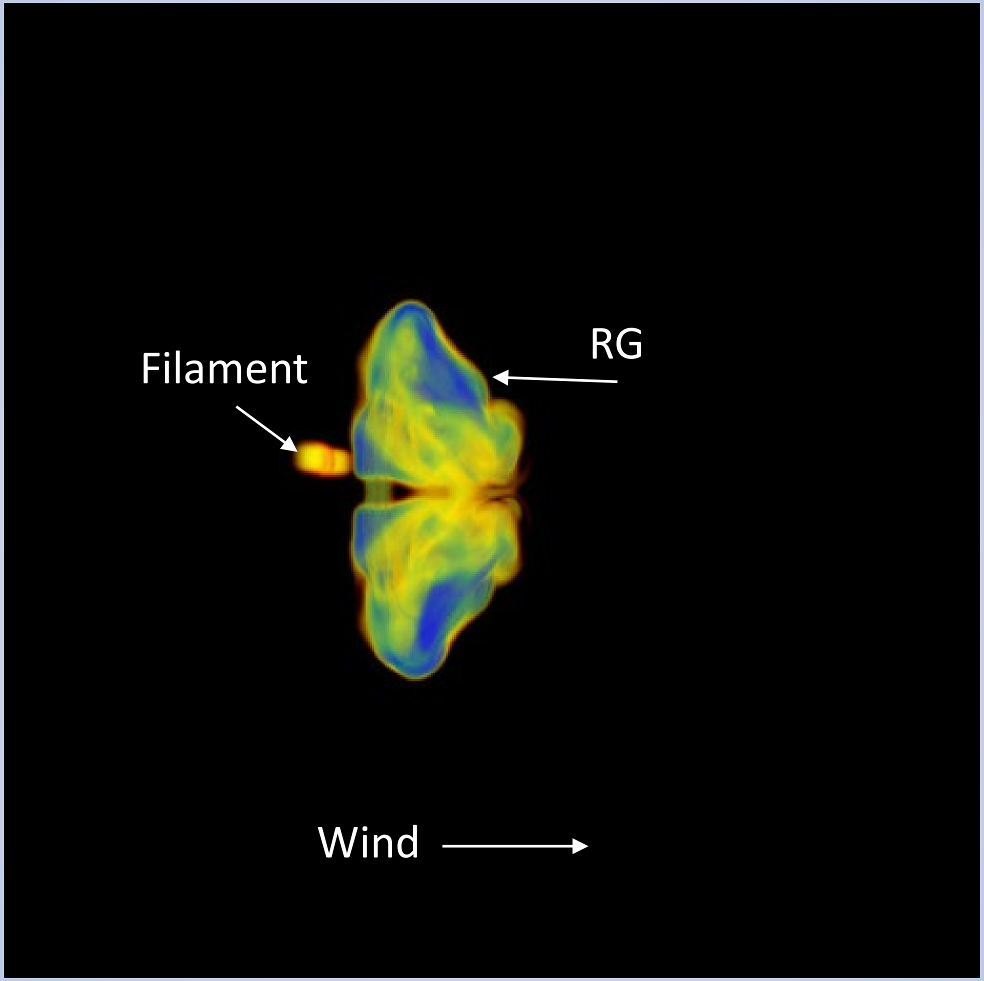
*Initial Tests Do Not Have CRe (“workstation jobs”)

Simulation Example: Orthogonal ICM Magnetic Filament Head On

AGN Jets along z:

Wind along x

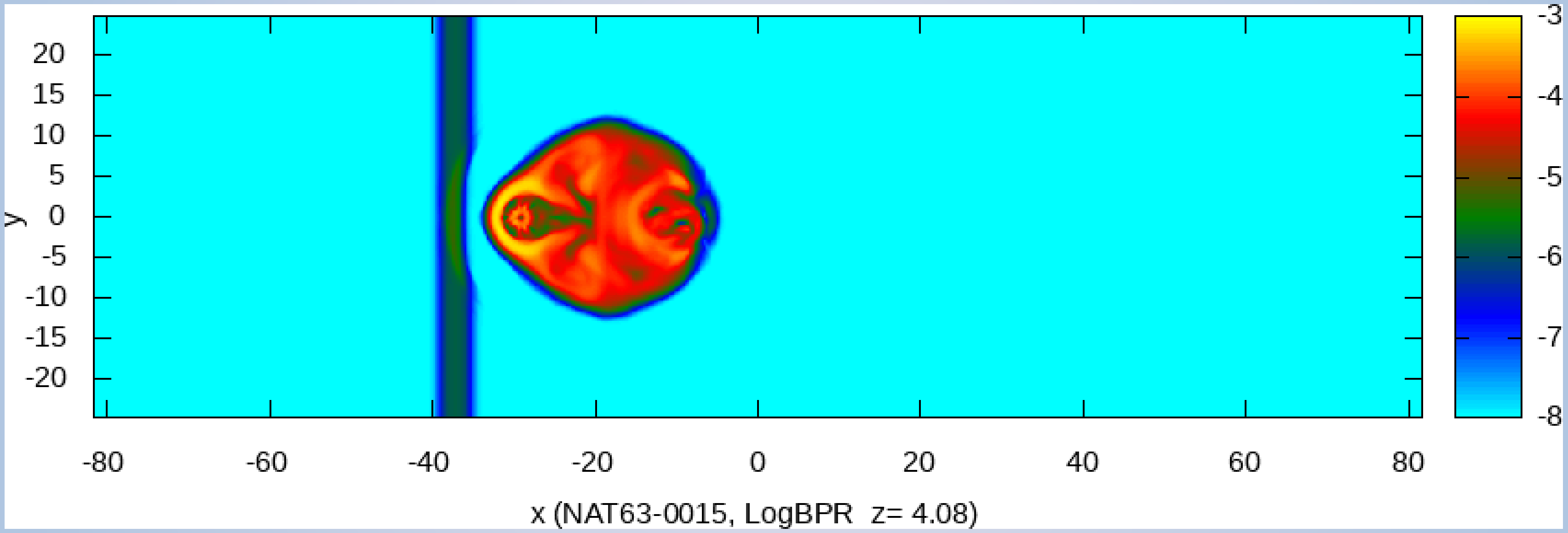




3D Rendering of
B (magnitude)
Before impact
Seen Normal
To Jets & Wind
(So along y)
Before Impact

Simulation Example: Orthogonal Magnetic Filament (Jets Normal to Slice Plane)

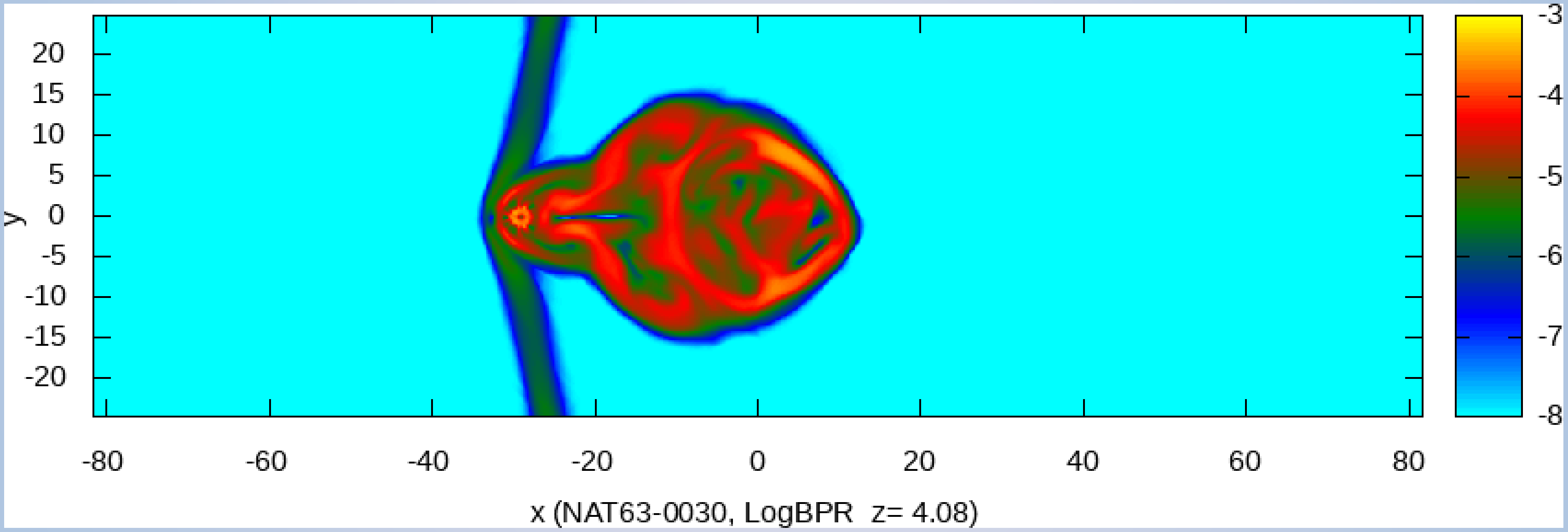
Before "impact"



Log Magnetic Energy in Plane of Incident Filament & Wind (<u>Filament $\vec{B}$ Opposite That of Near-Jet B</u>)

Simulation Example: Orthogonal Magnetic Filament (Jets Normal to Slice Plane)

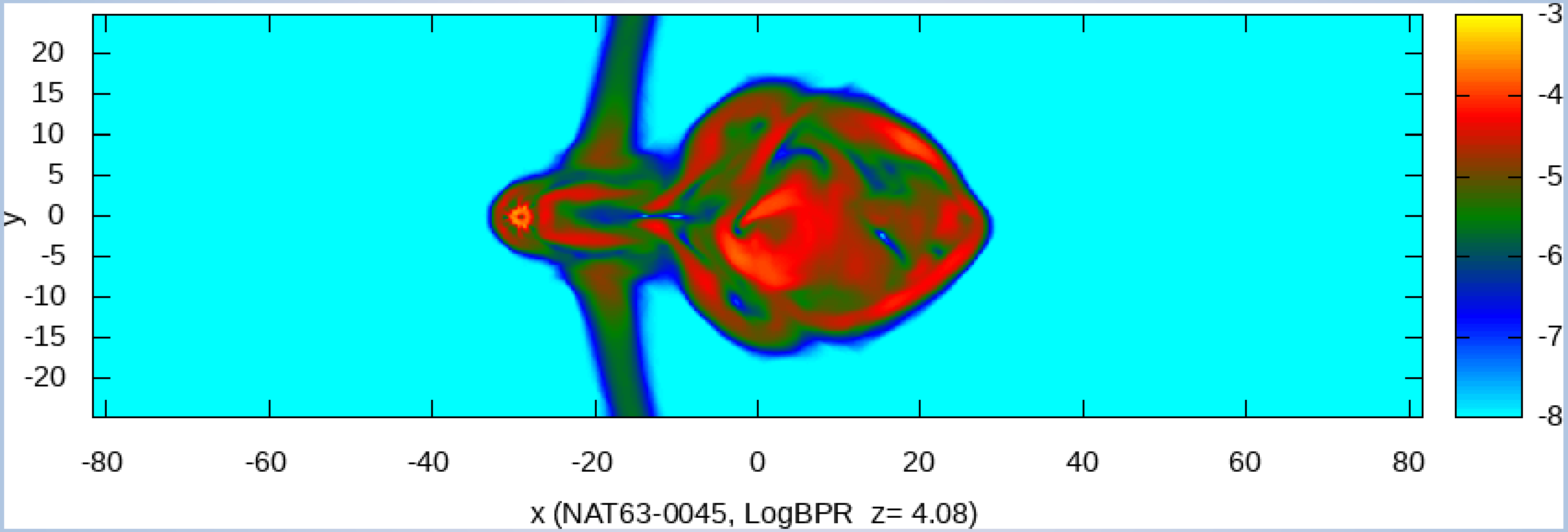
Early "impact"



Log Magnetic Energy in Plane of Incident Filament & Wind
(<u>Filament $\vec{B}$ Opposite That of Near-Jet B</u>)

Simulation Example: Orthogonal Magnetic Filament (Jets Normal to Slice Plane)

Late "impact"



Log Magnetic Energy in Plane of Incident Filament & Wind

(Filament $\vec{B}$ Opposite That of Near-Jet B)

Notable Filament Simulation Finding:

#

For All Test Encounters Simulated <u>So Far</u>

Some Field Lines Connect Between Filament &

RG Where Incident Filament B Misaligned

<u>But</u>, Incident Filaments Survive to Span the Box

Summary & Conclusion

New Observatory Generations Are Revealing Exciting, Previously Unknown, Rich and Multi-scale Structures in Clusters That Can Reveal Basic Cluster/AGN Dynamics & Physics

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Our MHD+CR Simulation Studies of RG Interactions in ICM Settings Can Help Reveal Links and Probe Cluster Formation, ICM Dynamics & Physics & AGN Dynamics and Physics

Thanks!