

Relativistic HD and MHD modeling for AGN jets

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1 MPI-AMRVAC

2 AGN jet applications

MPI-AMRVAC Philosophy

- HTML documentation info at
`http://homes.esat.kuleuven.be/~keppens`

- **any set of equations of generic type**

$$\partial_t \mathbf{U} + \nabla \cdot \mathbf{F}(\mathbf{U}) = \mathbf{S}(\mathbf{U}, \partial_i \mathbf{U}, \partial_i \partial_j \mathbf{U}, \mathbf{x}, t)$$

⇒ conserved variables $\mathbf{U}$, fluxes $\mathbf{F}$, sources $\mathbf{S}$

⇒ (near-) conservation laws: hyperbolic PDEs

- Adaptive Mesh, emphasis on **shock-governed dynamics**

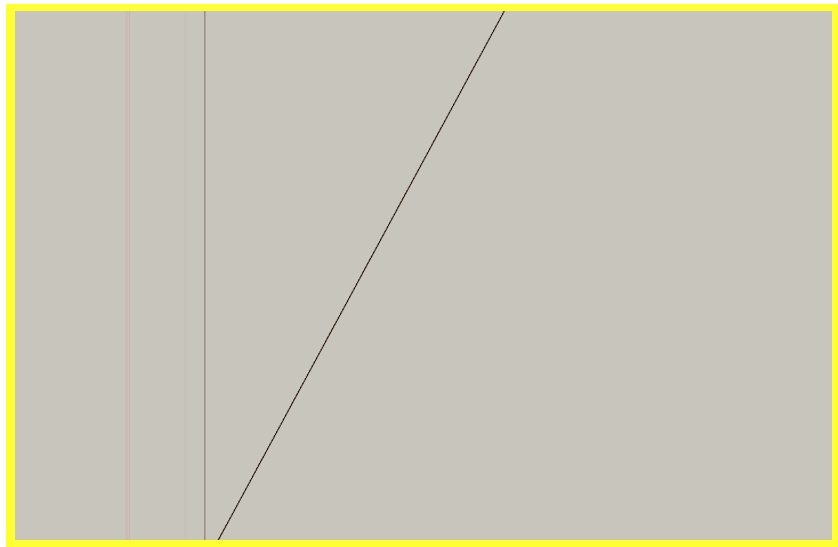
⇒ shock-capturing schemes (TVDLF, HLL[C], Roe)

- **any-dimensionality**: Perl preprocessor to Fortran 90

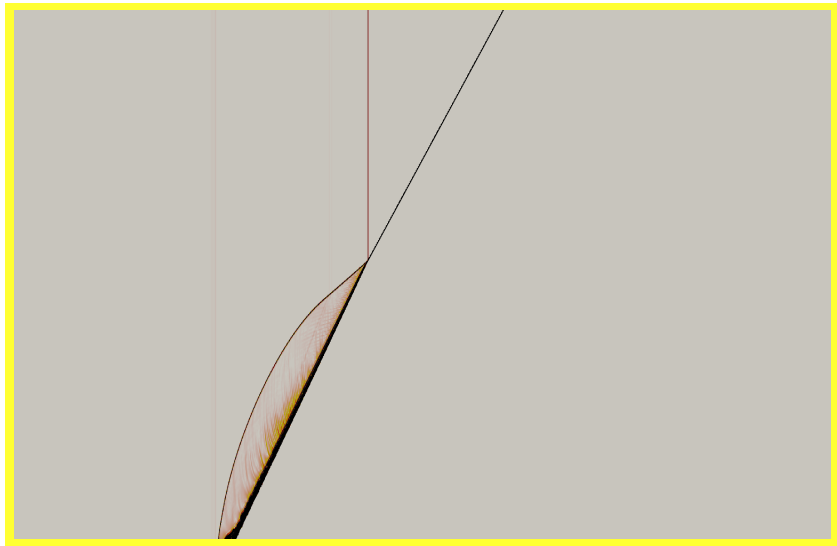
⇒ can handle Cartesian, cylindrical, spherical geometries

- **Special relativistic HD and MHD** with AMR
 - ⇒ See *Journal Computational Physics*, 2012, **231**, 718-744
- extreme contrasts, positive $p, \rho, \tau, v < 1, \Gamma \geq 1$, solenoidal $\mathbf{B}$
 - ⇒ stringent demands on numerics and accuracy: **AMR vital**
 - ⇒ **different EOS implemented for relativistic modules**
- Relativistic hydro refraction
 - ⇒ 7 levels, effective 1536×7680 in day(s) on local desktop!

Relativistic hydro refraction $t = 0.5$



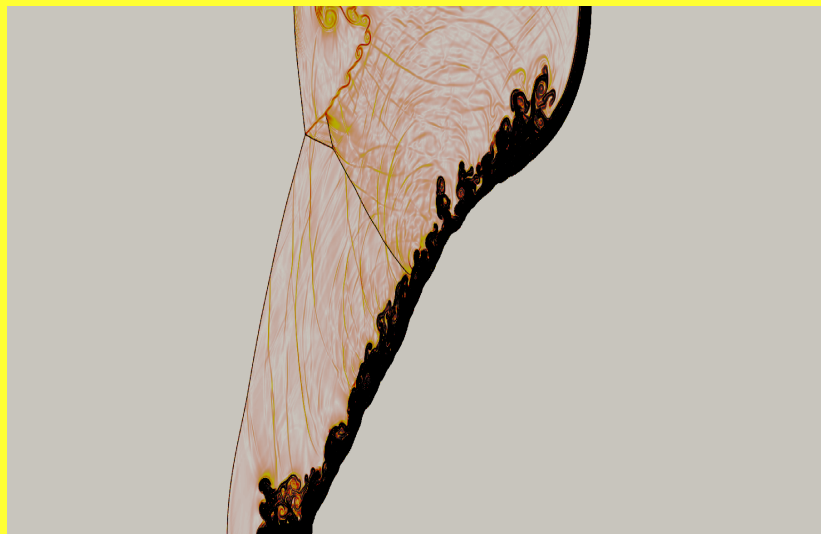
Relativistic hydro refraction $t = 1$



Relativistic hydro refraction $t = 2$



Relativistic hydro refraction $t = 3$



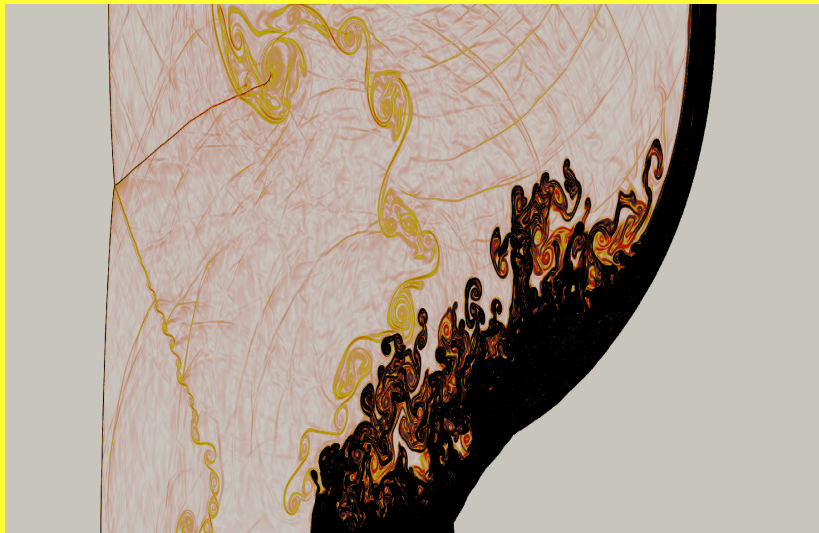
Relativistic hydro refraction $t = 4$



Relativistic hydro refraction $t = 5$



Relativistic hydro refraction $t = 6$



1 MPI-AMRVAC

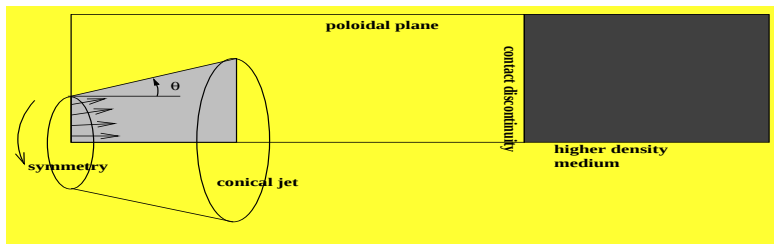
2 AGN jet applications

AGN jet challenges

- How to decelerate highly energetic (especially FR II) flows?
⇒ investigate **external medium influence**
- How does **finite opening angle** modify the jet dynamics?
⇒ energy transfer to ISM/IGM quantification
- Magnetization of jet flows
⇒ **role of helical B in collimation/propagation**

Model parameters

- jet kinetic energy & Lorentz factor Γ (order 10-20)
- ratio between jet/IGM inertia (density contrast)
- opening angle: cylindrical/conical models



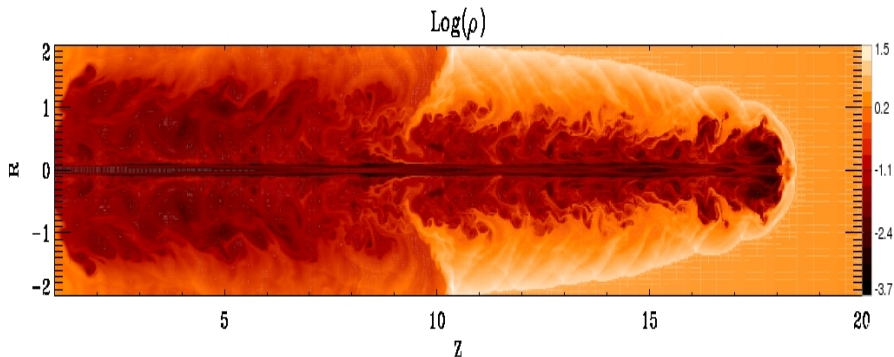
- external medium stratification: **density discontinuities**
 $\Rightarrow$ separating differing regions of influence

- differences between **low-high energy jets**: 10^{43} or 10^{46} ergs/s
 $\Rightarrow$ jet beam kinetic luminosity

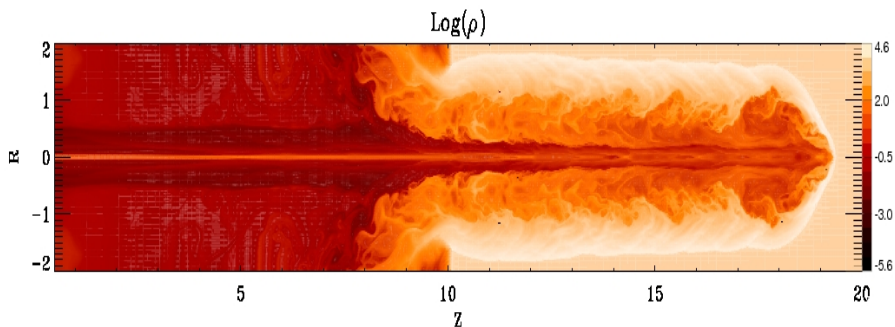
$$L_{\text{jet,Kin}} = (\Gamma_b h_b - 1) \rho_b \Gamma_b \pi R_b^2 v_b$$

$\Rightarrow$ 10 models, **varying** $\Gamma_b = 10 - 20$ and $\theta = 0 - 1$

- FR I low energy jets: **Richtmeyer-Meshkov instability** as shock passes CD

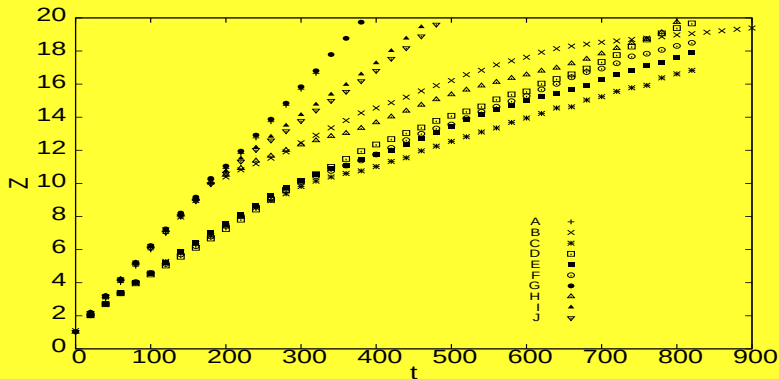


- **FR II jet at first, then dramatic slowdown to FR I**
 $\Rightarrow$ high energy 10^{46} ergs/s at $t = 900$



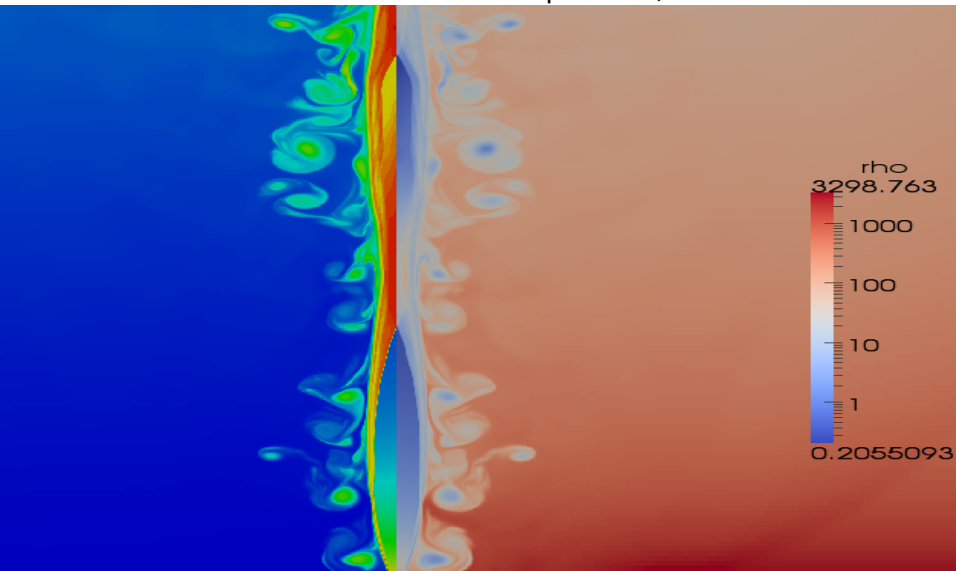
A&A 491, 321-337 (2008)

- overall findings on jet deceleration
 - ⇒ **FR II-FR I transition feasible at large density contrast**
 - ⇒ FR I changeover: relativistic at pc to subrelativistic at kpc



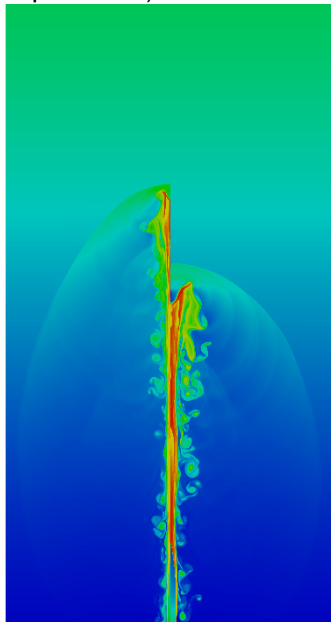
- previous models: IGM has discontinuous 2-layer structure
 - ⇒ jet is (nearly) cylindrical
 - ⇒ from overdense jet to light jet conditions
 - ⇒ upper medium either uniform or decreasing with distance
- Recent work: *Monceau-Baroux et al., A&A 545, A62, 2012*
 - ⇒ explore FR II jets, at large opening angle ($5 - 10^\circ$)
 - ⇒ enter a decreasing density (King atmosphere) ISM/IGM

- finite angle jets: recollimation leading to 'static' shock patterns
⇒ Fermi acceleration sites for particles, nodes

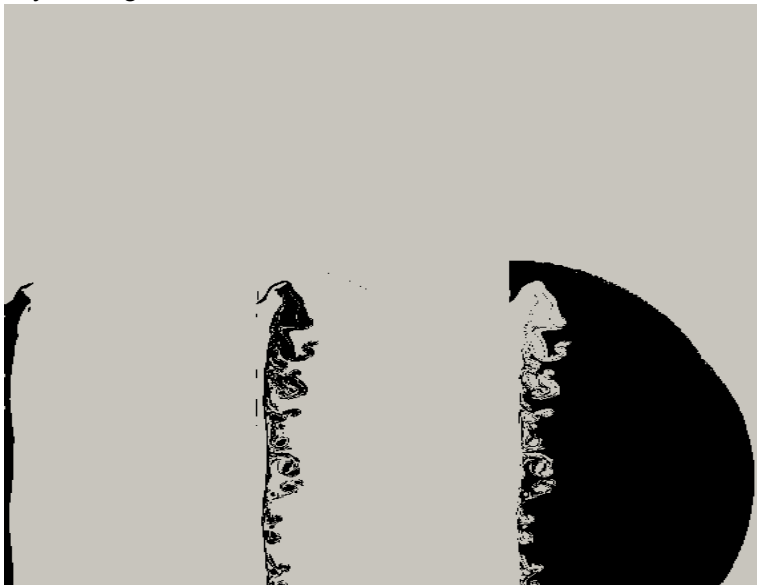


- compare (effective polytropic index) view for 5° to 10°

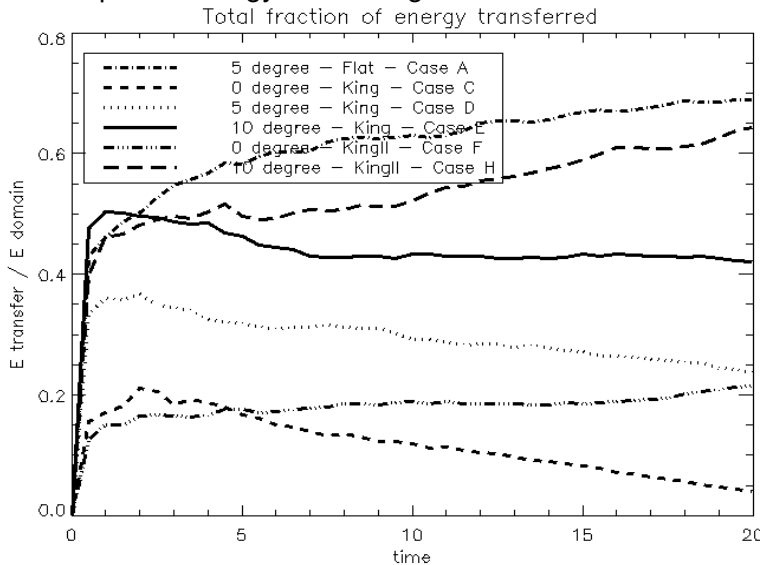
Gef
1.665133
1.335843



- quantitative comparisons: identify shocked ISM, jet beam, instability mixing zone with instantaneous masks



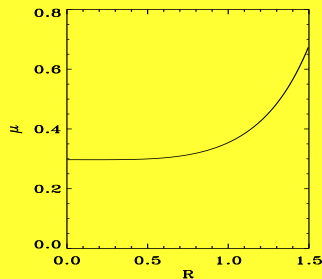
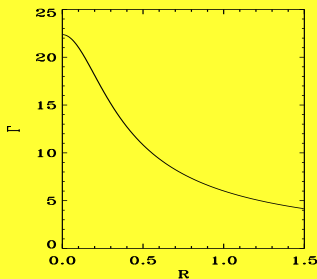
- use masks to quantify volumes, energy content, energy transfer
 $\Rightarrow$ example for energy into mixing/shocked ISM



- main findings:
 - ⇒ wider opening angle jets decelerate faster, and are accompanied by a larger mixing zone
 - ⇒ energy transfer mainly happens in shocked ISM region, by cocoon traversing waves and at frontal bow shock
 - ⇒ finite opening angle jets can get up to 70% of their energy fed into shocked ISM regions

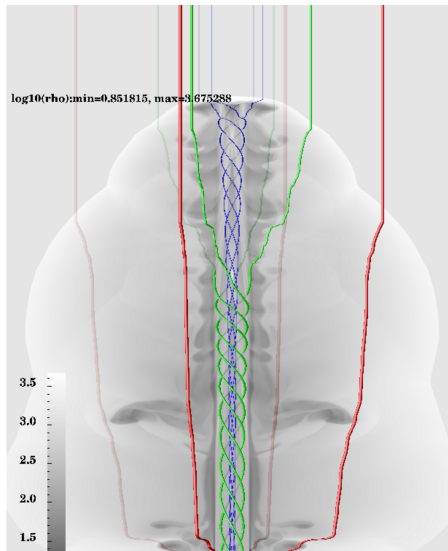
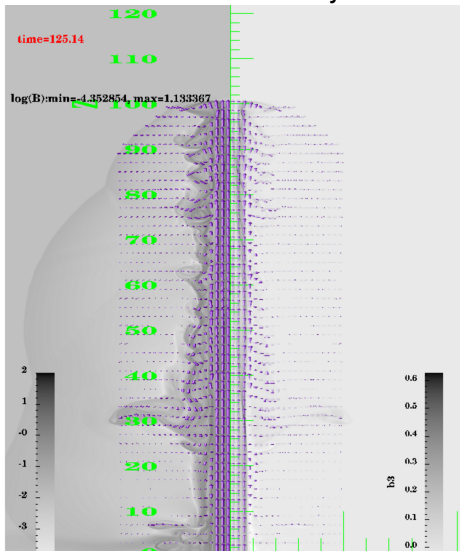
Helically magnetized jets

- Axisymmetric **helical field configurations**
 - $\Rightarrow$ again 2.5D, density contrast 1/10: light jet
 - $\Rightarrow$ inlet profile of Γ and $\mu = \frac{R_l B_\varphi}{R B_z}$

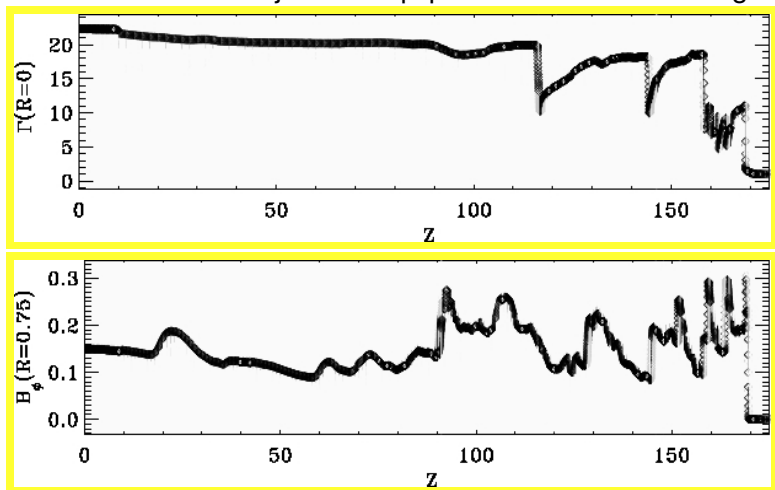


- average $\bar{\Gamma} \simeq 7$, $\beta_l = 0.3$ and $\sigma = 0.006$
 - $\Rightarrow$ **kinetic energy dominated, near equipartition**
- both helical field and rotation within jet!

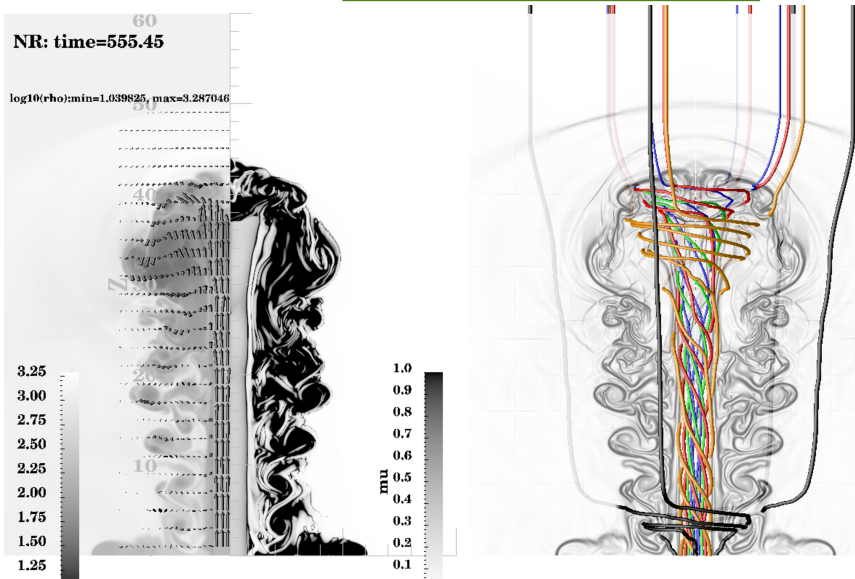
- magnetic field: helicity throughout the jet beam
 - ⇒ changes at internal cross-shocks
 - ⇒ localized mainly toroidal field within vortical backflows



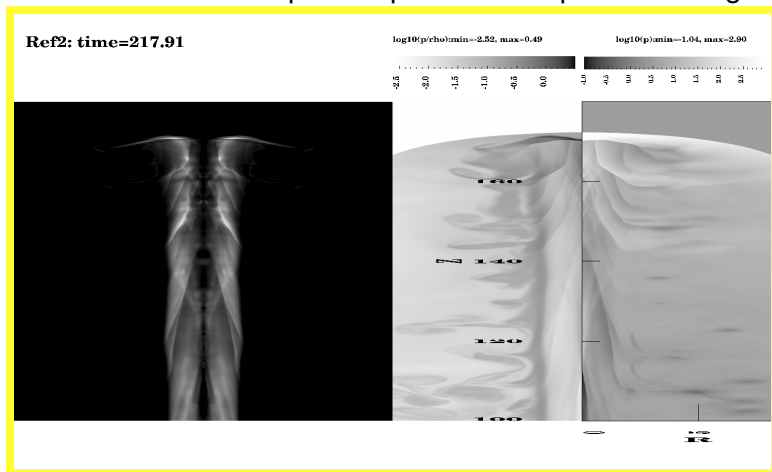
- beam cross-shocks: **helical field pinches flow**
 - $\Rightarrow$ matter reaccelerates up to next cross-shock
 - $\Rightarrow$ deceleration jet with equipartition **B**: extreme lengths



- explored transition $\bar{\Gamma} = 1.15 \rightarrow 7$
 $\Rightarrow$ non-relativistic: **strong toroidal field in cocoon**



- power maps give **indication of sites of synchrotron emission**
 - $\Rightarrow$ total radiation emitted is $\propto v^2 \Gamma^2 B^2 \sin^2 \psi$
 - $\Rightarrow$ varies significantly from toroidal to poloidal field cases
 - $\Rightarrow$ simultaneous plots of pressure/temperature at right



Outlook

- from 2.5D axisymmetric (M)HD to 3D scenarios
 - ⇒ can investigate full morphology, stability aspects
- ongoing studies explore 3D precessing jet scenarios
 - ⇒ will make synthetic radio views, target SS433 conditions
- relativistic MHD runs provide all info for future synthetic polarization views
 - ⇒ examples given in next talk (Oliver Porth)