Stability of relativistic two-component jets

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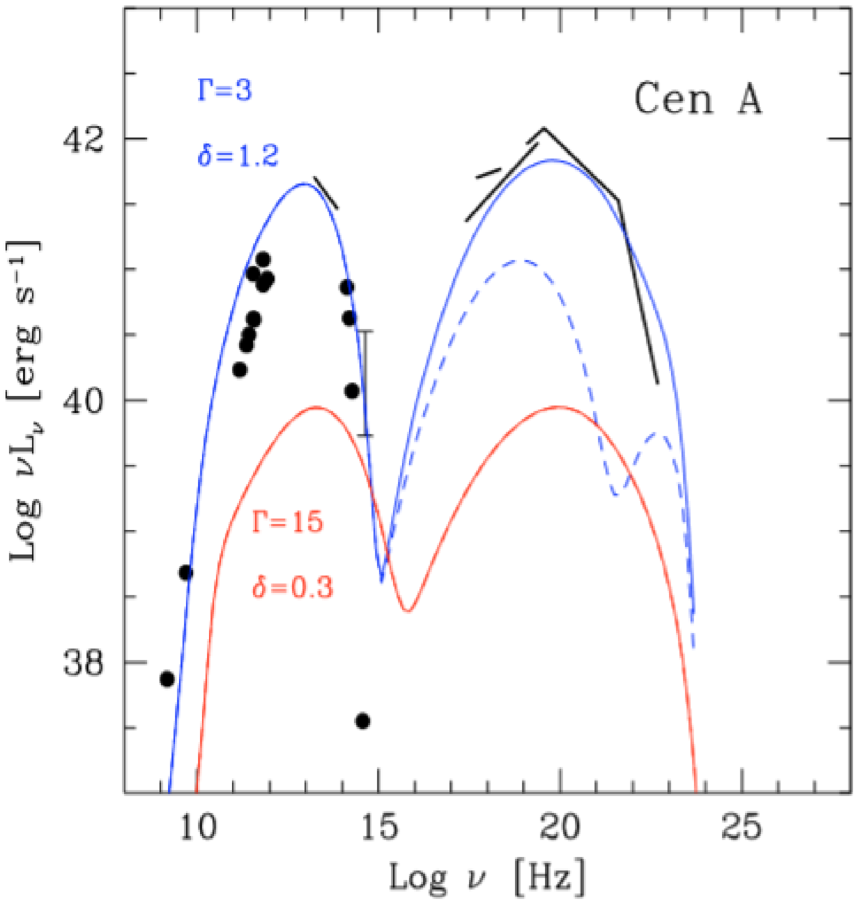
Outline

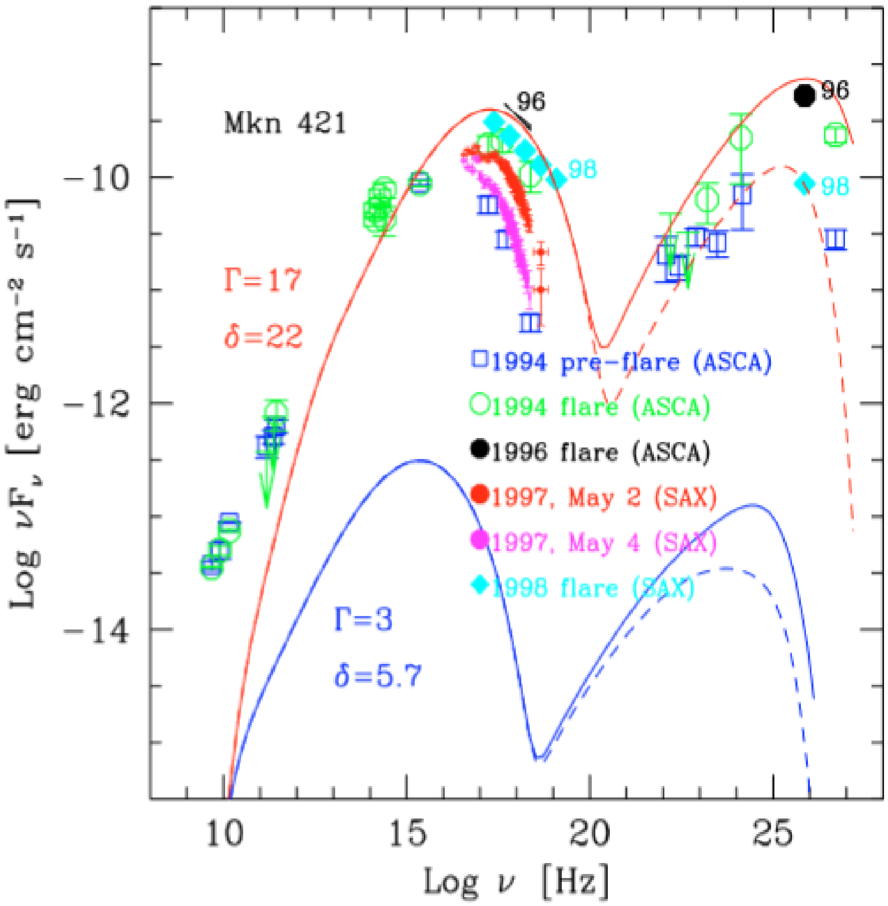
- Why two-component jets?
- Previous work
- Jets with poloidal & toroidal magnetic field
- Summary
- Future work

Why two components ? Observations !

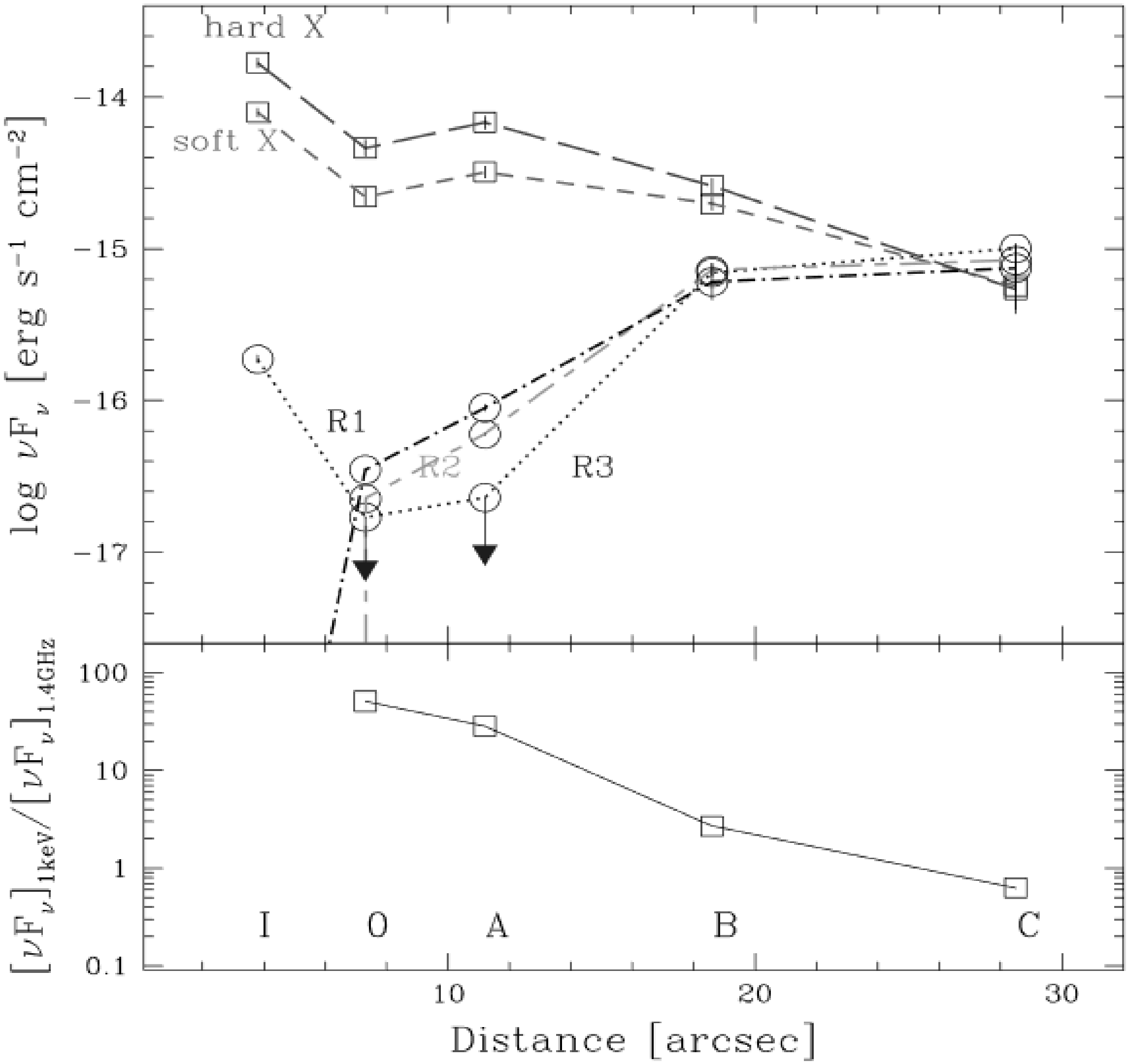
- Indications: brightening, variability in TeV,…
- Variability in TeV:
  - high γ
  - ultra relativistic bulk motion of the jet
- Radio observations of pc-scale structure:
  - broad, slow (but relativistic) motion
- **Two different (at least in terms of velocity) regions !**
- Sometimes (?) :
  - Fast, light inner jet
  - Slow, heavier outer jet

Examples





SEDs comparison for Cen A and Mkn 421 (Ghisellini et al. 2005)



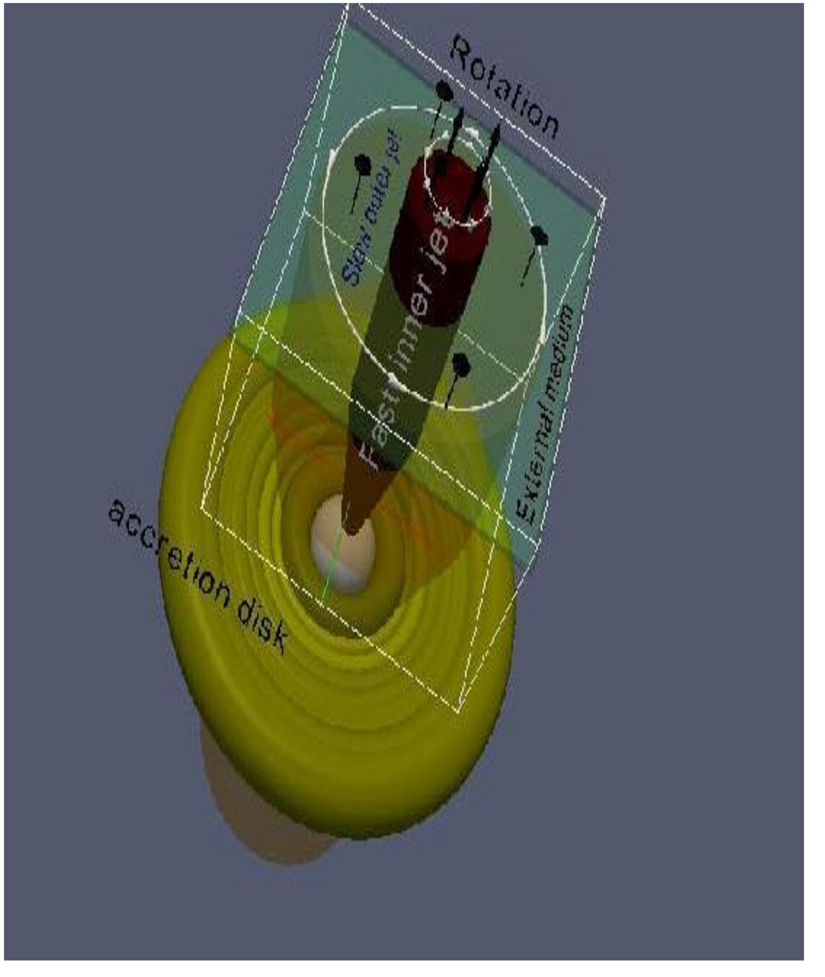
Radio and x-ray observations of radio loud quasar PKS 1127-145 (Siemiginowska et al. 2007)

Previous work

MHD 2.5D simulations with MPI-AMRVAC

- Meliani & Keppens 2007: Relativistic HD
- Meliani & Keppens 2009: Relativistic MHD, poloidal magnetic field only

Aim:
Investigate non-axisymmetric instabilities, induced by differential rotation



Meliani & Keppens, 2009, ApJ, 705, 1594

Rayleigh criterion for rotational stability

- Rotation leads to centrifugal effects

- How to determine (in)stability?

  i. $\frac{\mathrm{d}(r^4\Omega^2)}{\mathrm{d}r} > 0$ stable

  ii. $\frac{\mathrm{d}(r^4\Omega^2)}{\mathrm{d}r} < 0$ unstable

  iii. $\frac{\mathrm{d}(r^4\Omega^2)}{\mathrm{d}r} = 0$ marginally stable

- Relativistic equivalent: angular momentum flux must increase with r

$$I = \gamma \frac{\rho + \frac{\Gamma}{\Gamma - 1} P}{\rho} v_\varphi r - \frac{B_p}{\gamma \rho v_p} r B_\varphi$$

Stability:

- Momentum equation near equilibrium

$$(\boldsymbol{\gamma^2 \rho h} + \boldsymbol{B_z^2})(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla)\vec{v} + \nabla P_{tot} + \vec{v}\frac{\partial Ptot}{\partial t} + \cdots = 0$$

- Ignore lab frame contribution to charge separation (valid far inside the light cylinder)

- Assume perturbation is potential, plane wave

$$\lambda^2 \sim k[(\gamma^2 \rho h + B_z^2)_{in} - (\gamma^2 \rho h + B_z^2)_{out}]$$

Stability: $\lambda^2 < 0$ thus $(\gamma^2 \rho h + B_z^2)_{in} < (\gamma^2 \rho h + B_z^2)_{out}$

Initial velocity profile

- $V_z(r) = \begin{cases} \gamma_{z,in} \approx 30\,, & r \leq r_{in} \\ \gamma_{z,out} \approx 3\,, & r > r_{in} \end{cases}$

- $V_\varphi(r) = \begin{cases} v_{\varphi,in} \left(\frac{r}{\mathrm{r}_{in}}\right)^{a_{in}/2}, & \mathrm{r} \leq \mathrm{r}_{in} \\ v_{\varphi,out} \left(\frac{\mathrm{r}}{\mathrm{r}_{in}}\right)^{a_{out}/2}, & \mathrm{r} > \mathrm{r}_{in} \end{cases}$

$\frac{\mathbf{d}(\boldsymbol{r}^4\boldsymbol{\Omega}^2)}{\mathbf{d}\boldsymbol{r}}$ **> 0 stable**

$\frac{\mathbf{d}(\boldsymbol{r}^4\boldsymbol{\Omega}^2)}{\mathbf{d}\boldsymbol{r}}$ **= 0 marginally stable**

$$\frac{\boldsymbol{d|I|}}{\boldsymbol{dr}} \propto (\mathbf{1} + {}^{\boldsymbol{a}}/_{\mathbf{2}})$$

$v_{\varphi in} = 0.01, v_{\varphi out} = 0.001$

$\boldsymbol{\alpha_{in} = 0.5, a_{out} = -2}$

- **Interface is unstable!**

Constraints from observations:

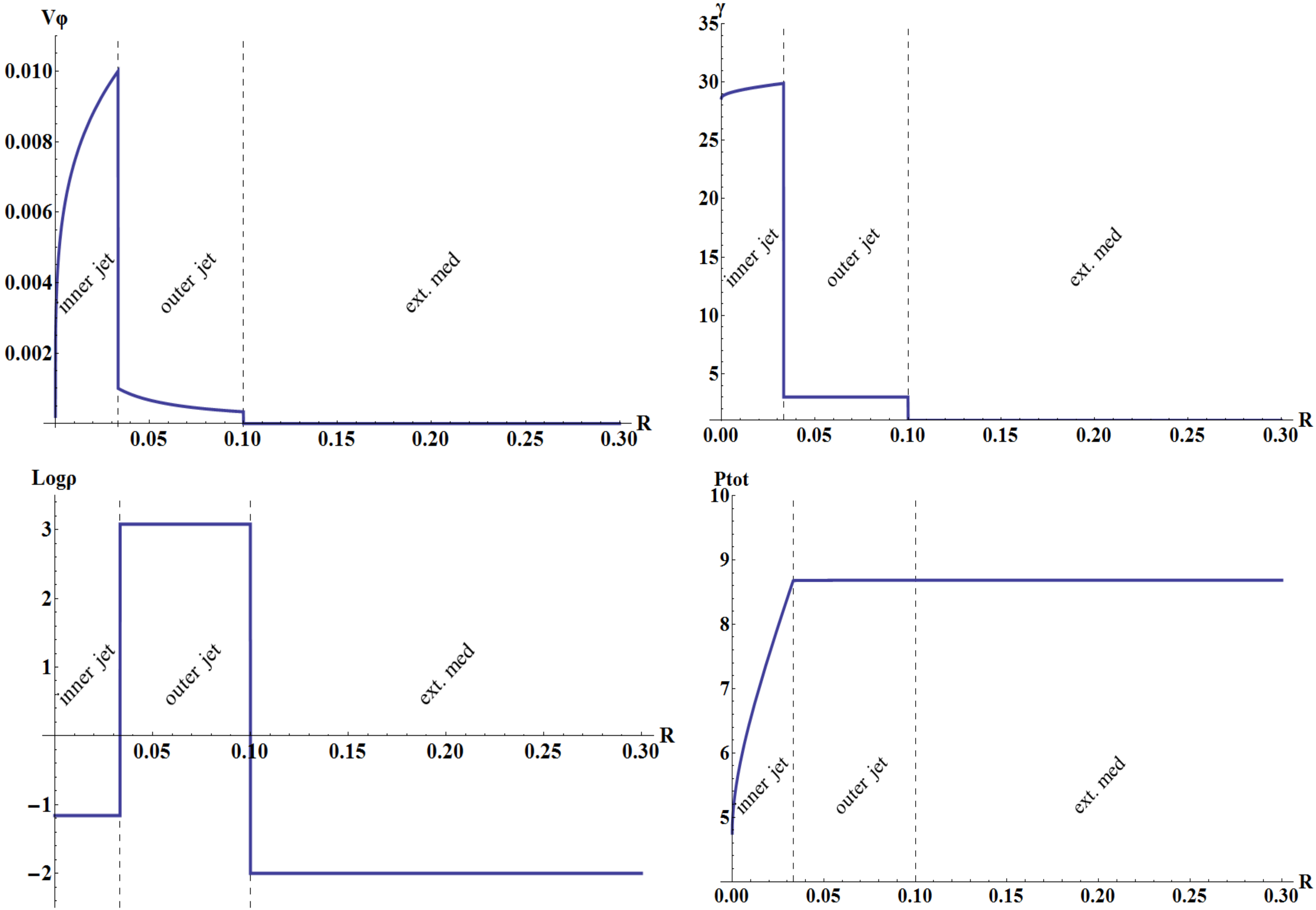
- Radius of outer jet: R_{out} = 0.1 pc
  - Radio observations of M87, Biretta et al. 2002
- Inner radius less constrained: $R_{in} = R_{out}/3$
- Kinetic luminosity flux: L = 10^{46} erg/s
  - typical for radio loud galaxy
- Initial density profile: constrained by kinetic energy flux
  - Assume that inner jet carries <1% of total kinetic energy flux

- Initial Lorentz factor: typical values for AGN jets
  - $\gamma_{z,in} \approx 30$
  - $\gamma_{z,out} \approx 3$

- $$\rho(r) = \begin{cases} 6.92\rho_{ext}, & r \leq r_{in} \\ 119.94 \cdot 10^3 \rho_{ext}, & r_{in} < r < r_{out} \\ \rho_{ext}, & r > r_{out} \end{cases}$$

- Total pressure balanced at each interface

- External medium density: used for scaling only

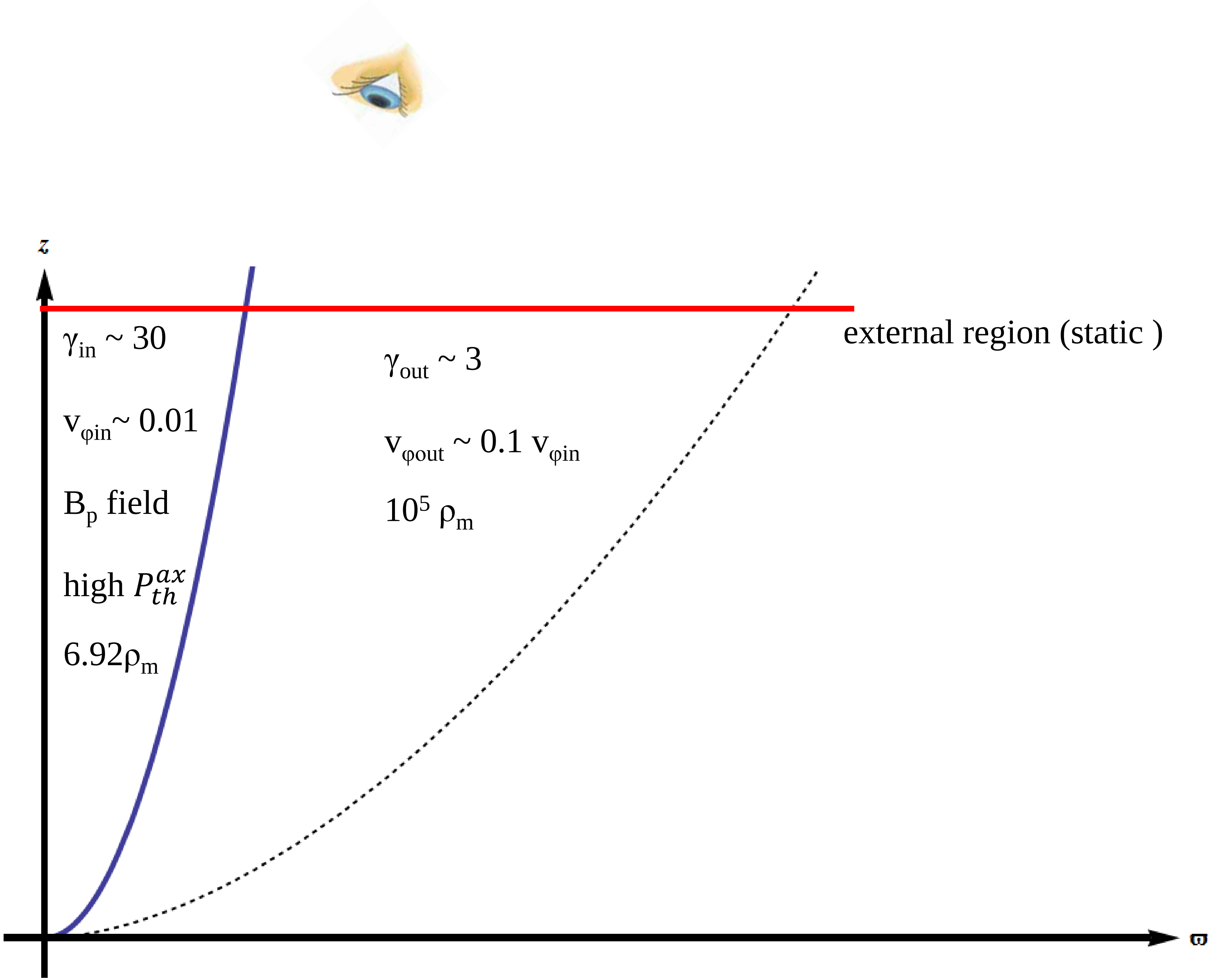

Vφ
0.010
0.008
0.006
0.004
0.002
0.05
0.10
0.15
0.20
0.25
0.30
R
inner jet
outer jet
ext. med
γ
35
30
25
20
15
10
5
0.00
0.05
0.10
0.15
0.20
0.25
0.30
R
inner jet
outer jet
ext. med
Logρ
3
2
1
−1
−2
0.05
0.10
0.15
0.20
0.25
0.30
R
inner jet
outer jet
ext. med
Ptot
10
9
8
7
6
5
0.00
0.05
0.10
0.15
0.20
0.25
0.30
R
inner jet
outer jet
ext. med

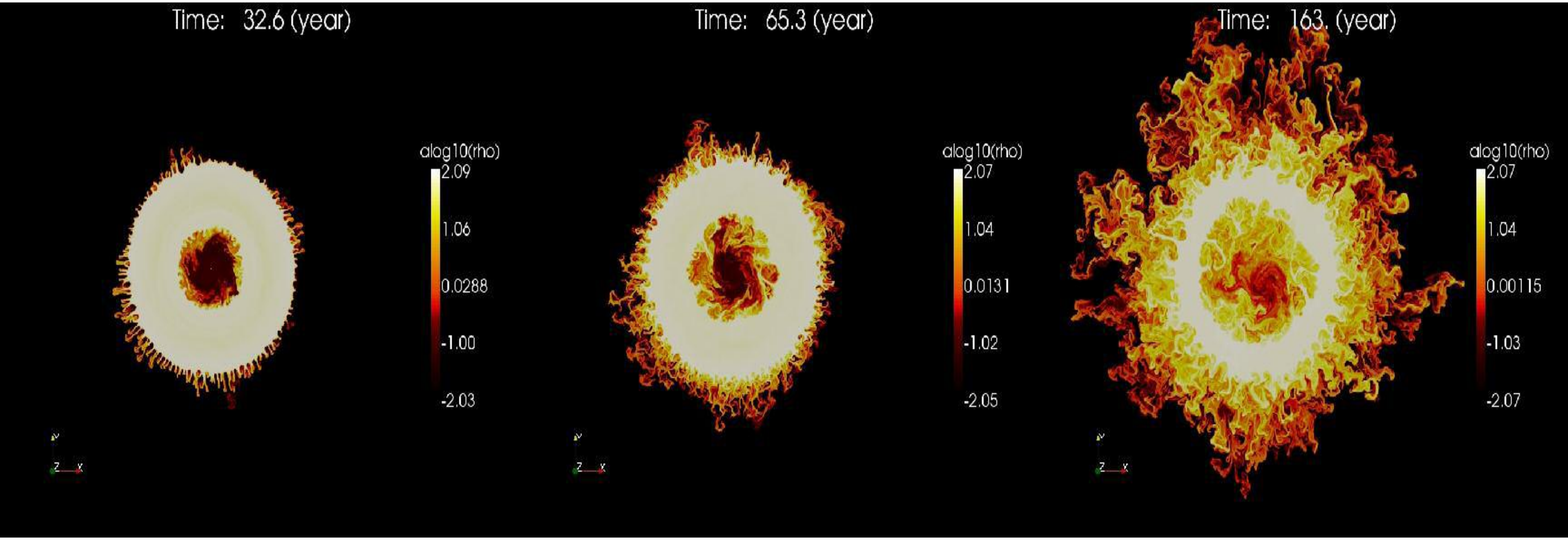
Initial magnetic field profiles

- $B_\varphi(r) = \begin{cases} B_{\varphi,in}\left(\frac{r}{r_{in}}\right)^{a_{in}/2} & , r \leq r_{in} \\ B_{\varphi,out}\left(\frac{r}{r_{in}}\right)^{a_{out}/2} & , r > r_{in} \end{cases}$

- $B_z(r) = \begin{cases} \sqrt{0.01\gamma_{in}^2\rho_{in}}\,, & r \leq r_{in} \\ 0\,, & r > r_{in} \end{cases}$

- σ = 0 → kinetically dominated jet
  (magnetization: σ ≡ poynting to mass flux ratio)


z
external region (static)
$\gamma_{in} \sim 30$
$v_{\varphi in} \sim 0.01$
B_p field
high P_{th}^{ax}
$6.92\rho_m$
$\gamma_{out} \sim 3$
$v_{\varphi out} \sim 0.1\, v_{\varphi in}$
$10^5\, \rho_m$
ϖ



Proper density at 0.5, 1 and 2.5 rotations of the inner jet
Meliani & Keppens, 2009, ApJ, 705, 1594

Output from the simulations

- Inner jet & shear region end up magnetized
- Inner jet decelerates a little ($\gamma \sim 20$)
- Components remain separable in inner and outer jet
- Inner jet displaced from on-axis due to non axisymmetric modes
- Stratification converges to:
  - Inner fast, magnetized spine with $\gamma \sim 20$
  - Shear shell 100 times denser, lower γ

- Effective inertia important for the evolution!

$$\boldsymbol{\gamma^2 \rho h + B_z^2}$$

- Why?
  - Dispersion relation depends on the difference between the eff. inertia of inner & outer jet !

- Purely poloidal field case: $\gamma^2 \rho h|_{out} \approx 3.2[\gamma^2 \rho h + B_z^2]_{in}$

- Different evolution for $\gamma^2 \rho h|_{out} \approx 18[\gamma^2 \rho h + B_z^2]_{in}$ (see Meliani & Keppens 2009)

Jets with toroidal magnetic field

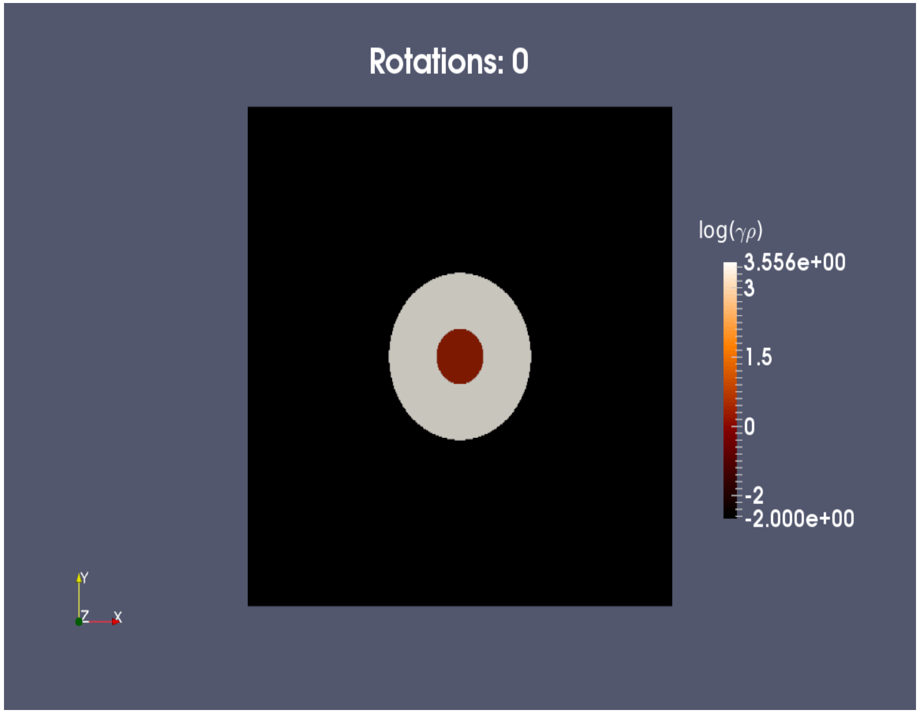
$$B_\varphi(r) = \begin{cases} \mathrm{B}_{\varphi,\mathrm{in}} \left(\frac{r}{r_{in}}\right)^{a_{in}/2} & , r \leq r_{in} \\ 0 & , r > r_{in} \end{cases}$$

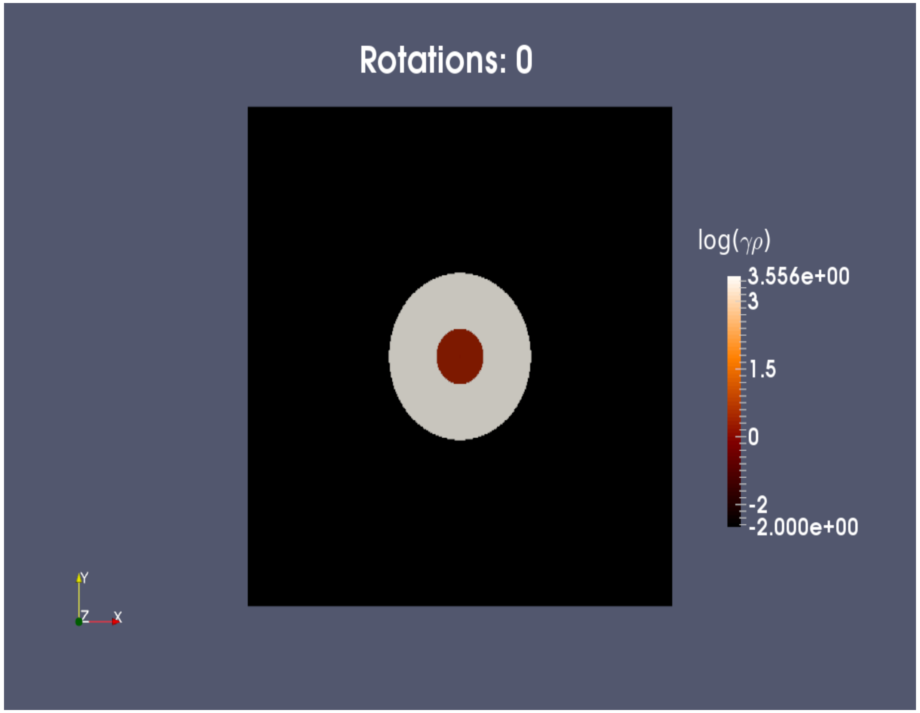
$$B_z(r) = \begin{cases} Bzin\,, & r \leq r_{in} \\ \sqrt{0.001\gamma_{out}^2 \rho_{out}}, & r > r_{in} \end{cases}$$

- Select B_φ that corresponds to $\sigma = 10^{-3}$
- Use I criterion to determine B_z of inner jet
- B_z of outer jet not explicitly constrained (~ $3B_{zin}$)
- Density contrast same as in previous cases

Bφ = 0

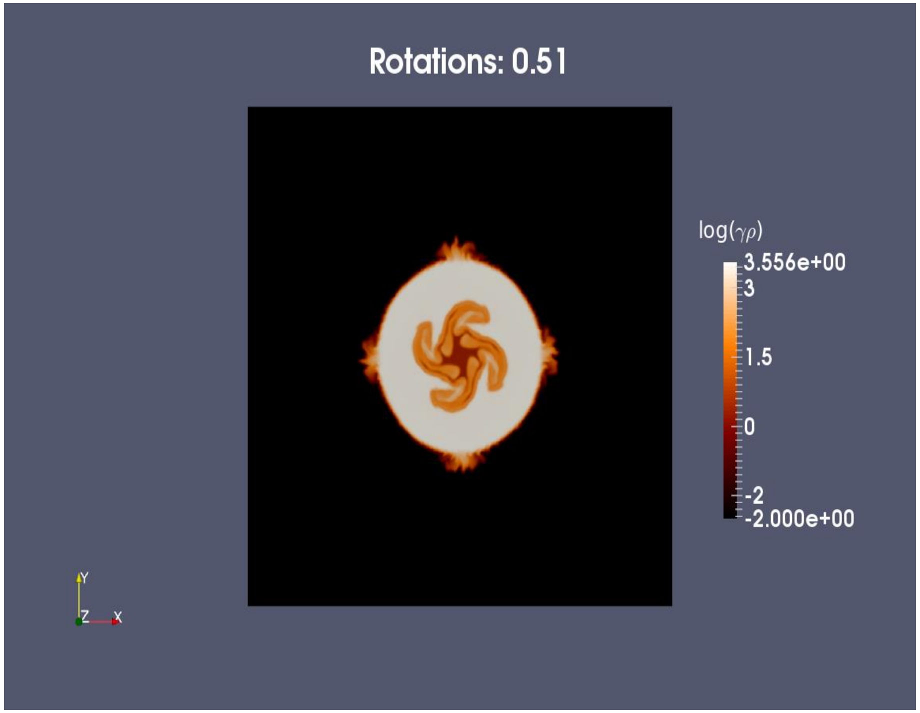
Bφ ≠ 0



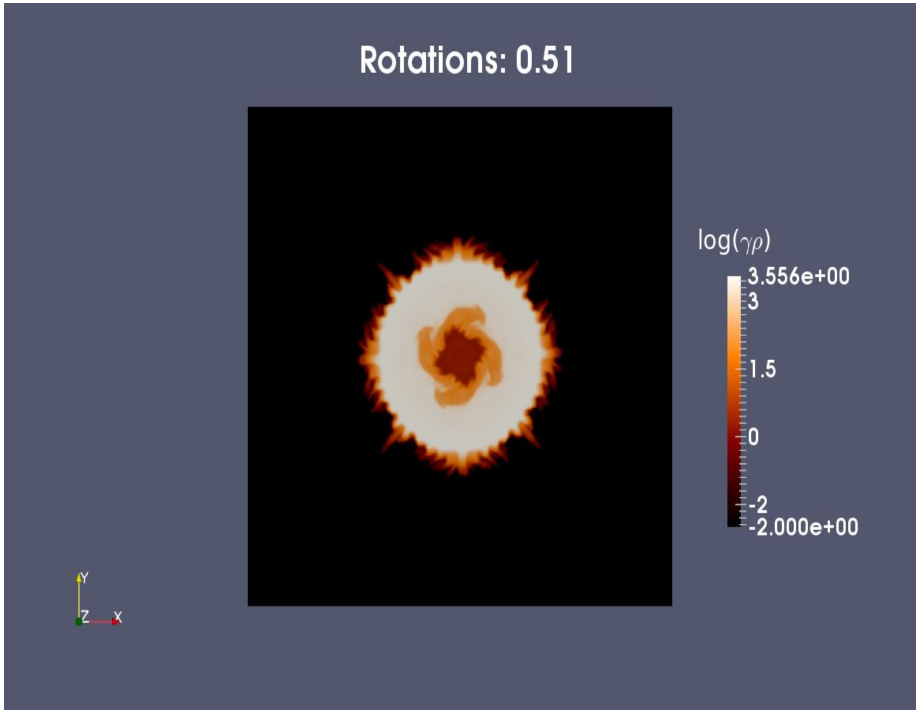


Proper density at t = 0

Bφ = 0

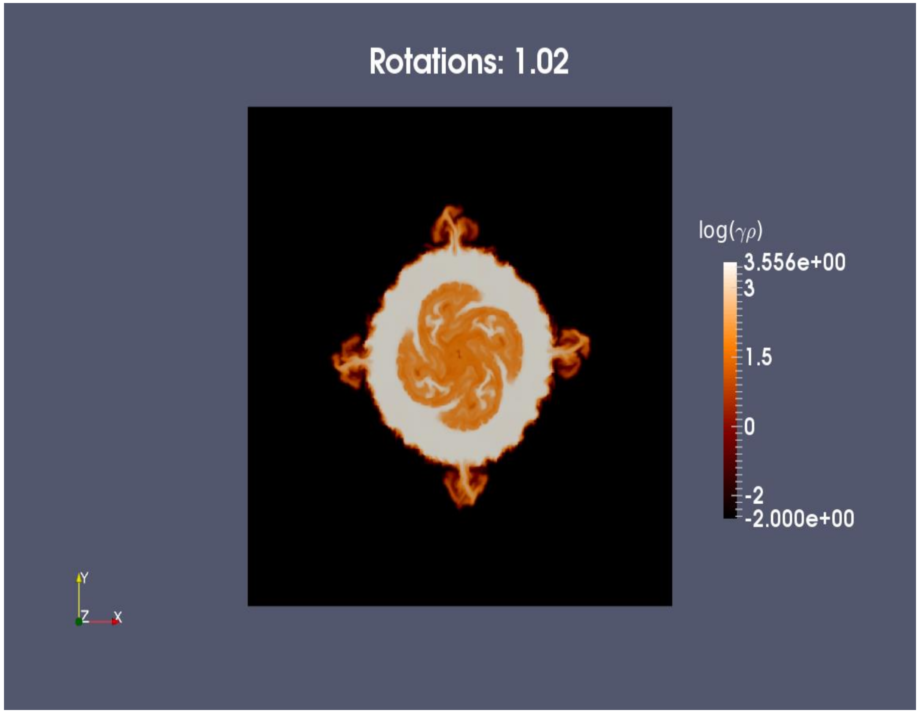


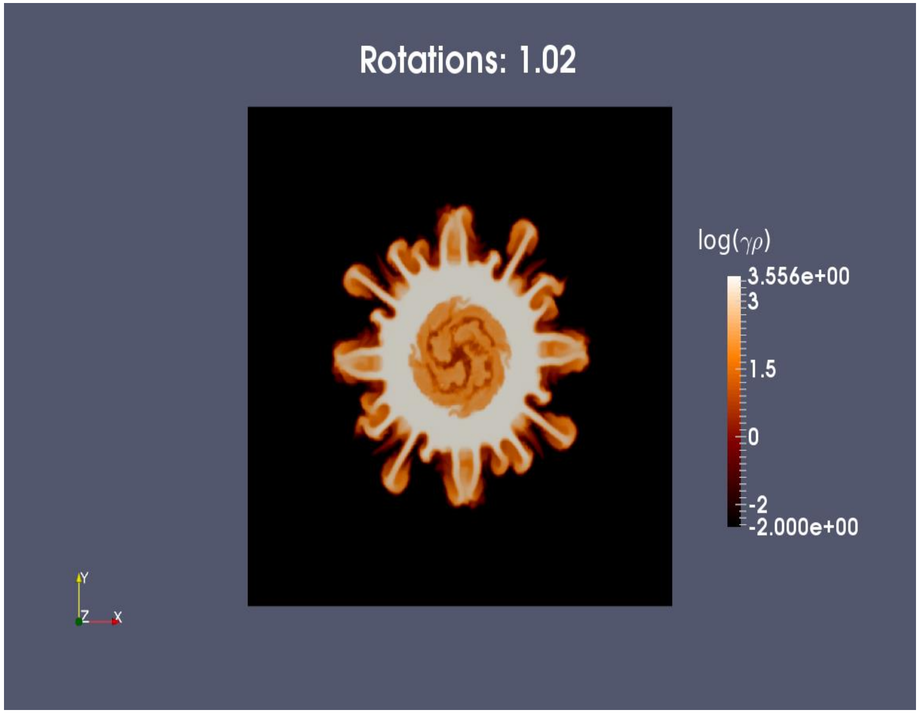
Bφ ≠ 0



Proper density after half rotation of the inner jet

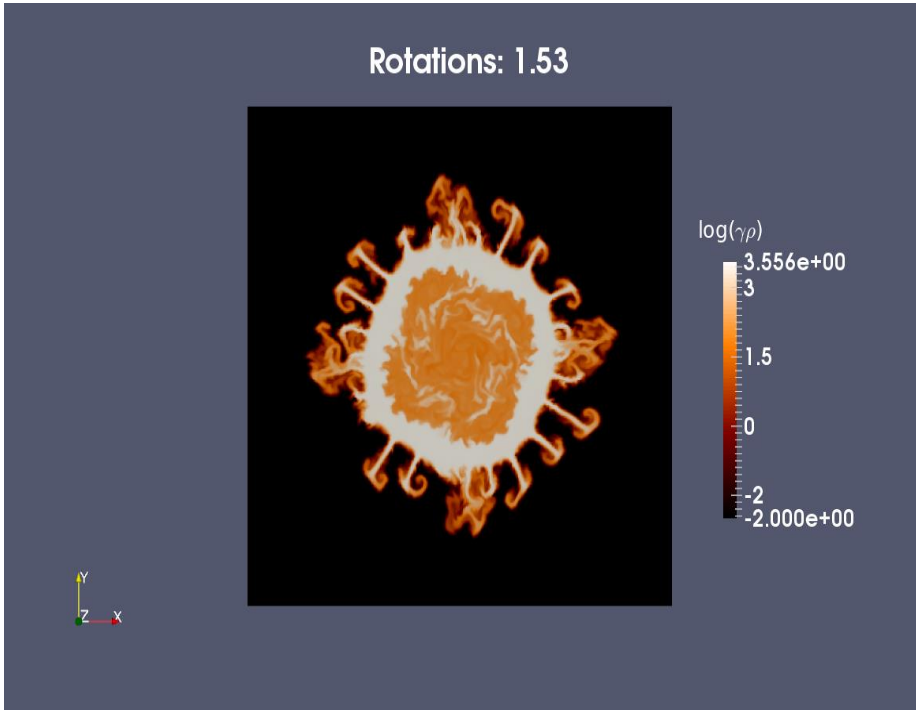
$B\varphi = 0$ $B\varphi \neq 0$



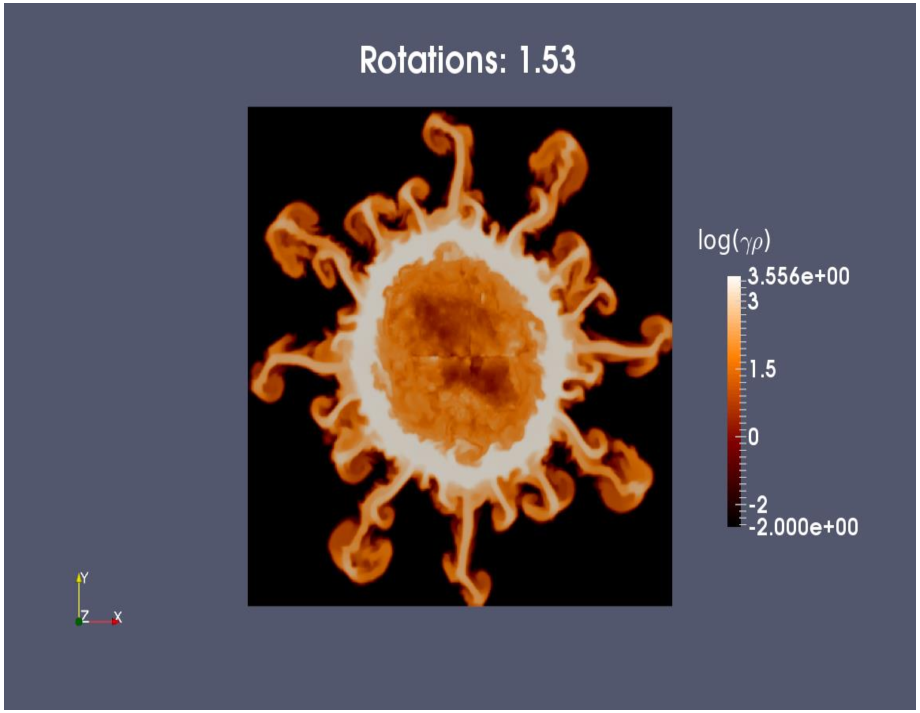


Proper density after one full rotation of the inner jet

$B\varphi = 0$

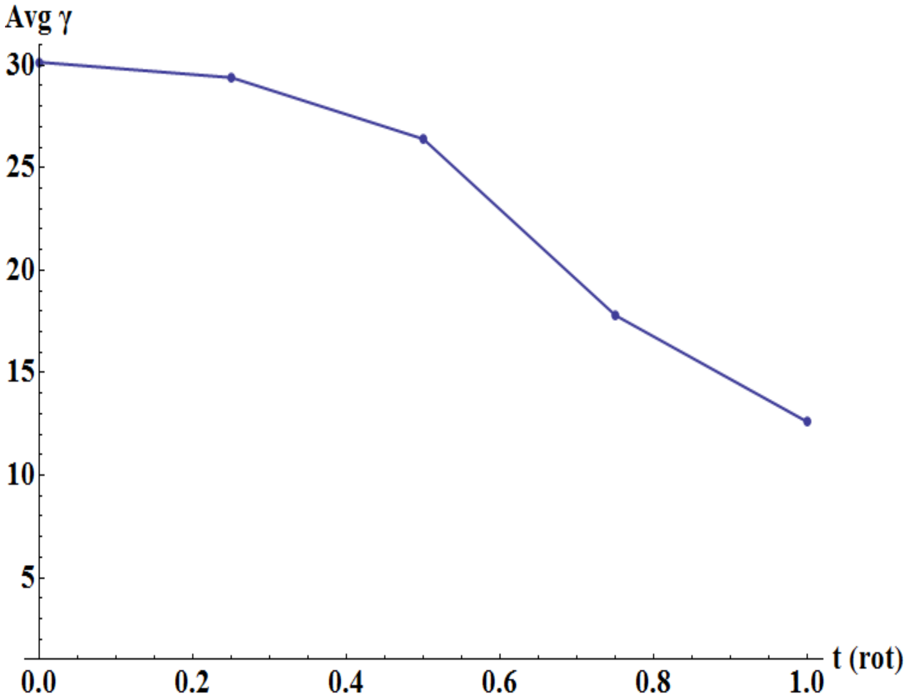


$B\varphi \neq 0$

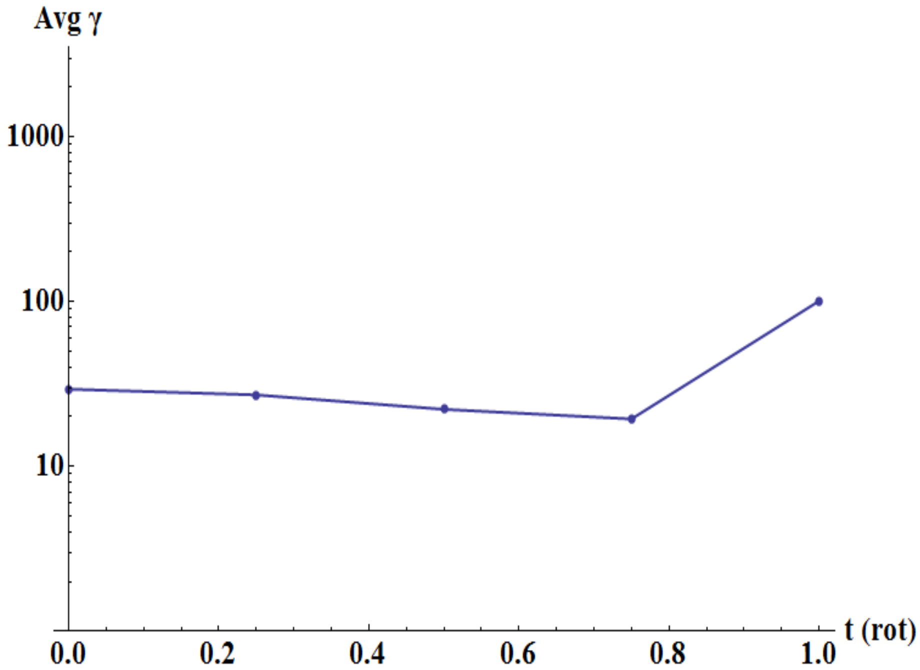


Proper density after 1.5 rotations of the inner jet

Bφ = 0



Bφ ≠ 0



Average Lorentz factor of the inner jet with time
(in rotations of inner jet)

(Preliminary) Results

- Case with zero toroidal field seems to agree with Meliani & Keppens, 2009
  - Rayleigh-Taylor type instabilities
- Including low σ toroidal field does not stabilize the system
- Eff.inertia ratio out/in ~ 0.1
- Formation of shear region, deceleration of the jet (up to ~1 rotation)
- Applications in FRI / FRII possible with proper adjustment

Future Work & Work in progress

- Examine B_φ connection with I criterion, new modes etc.
- High resolution runs (now 2 AMR levels, 200x200 base resolution)
- Analyze other jet parameters (e.g. radius with time)
- Examine different effective inertia ratios
  - ***Difference between FRI & FRII ?***
- More realistic configurations for B_φ and (mainly) v_φ
  - ***Avoid steep transition***
- Validate results:
  - ***create virtual radio maps & compare with observations***
- Later on: 3D simulations
  - ***Different magnetization regimes (Poynting / kinetically dominated jets)***
  - ***Other types of instabilities must be considered (e.g. Kink)***