Simulations and Analytic Models of Magnetized Gamma-Ray Burst Jets: Beyond the Progenitor Star

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Tchekhovskoy et al. (2009, arXiv:0911.2228)

Gamma-ray bursts

Come in 2 flavors:

Short, $\lesssim 2$ s

Coalescence of a compact object binary

Long, $\gtrsim 2$ s

Death of a massive star (Woosley 1993)

Gamma-ray bursts (GRBs)

- Acceleration: ultra-relativistic velocity, Lorentz factor $\gamma \gtrsim 100$

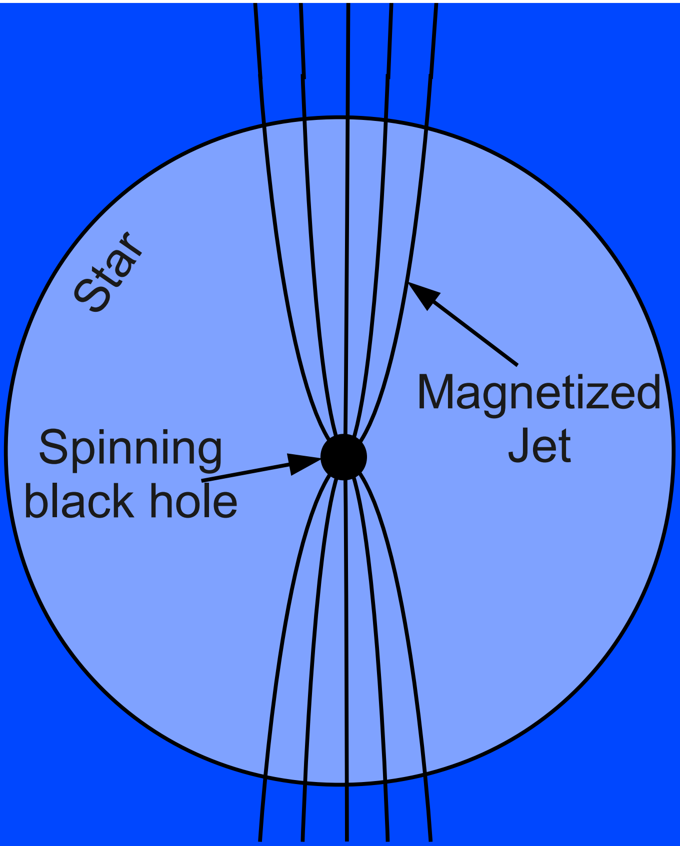
Non-thermal prompt spectrum

GRB jet quick facts:

1. Ultra-relativistic: $\gamma \gtrsim 100$
2. Collimated: $\theta = 0.04 - 0.2$
3. Product $\gamma\theta \simeq 20 \gg 1$

- Collimation: opening angle $\theta \lesssim 0.1$
- Relation between acceleration and collimation: $\gamma\theta \gtrsim 20$

Jet breaks in afterglow emission

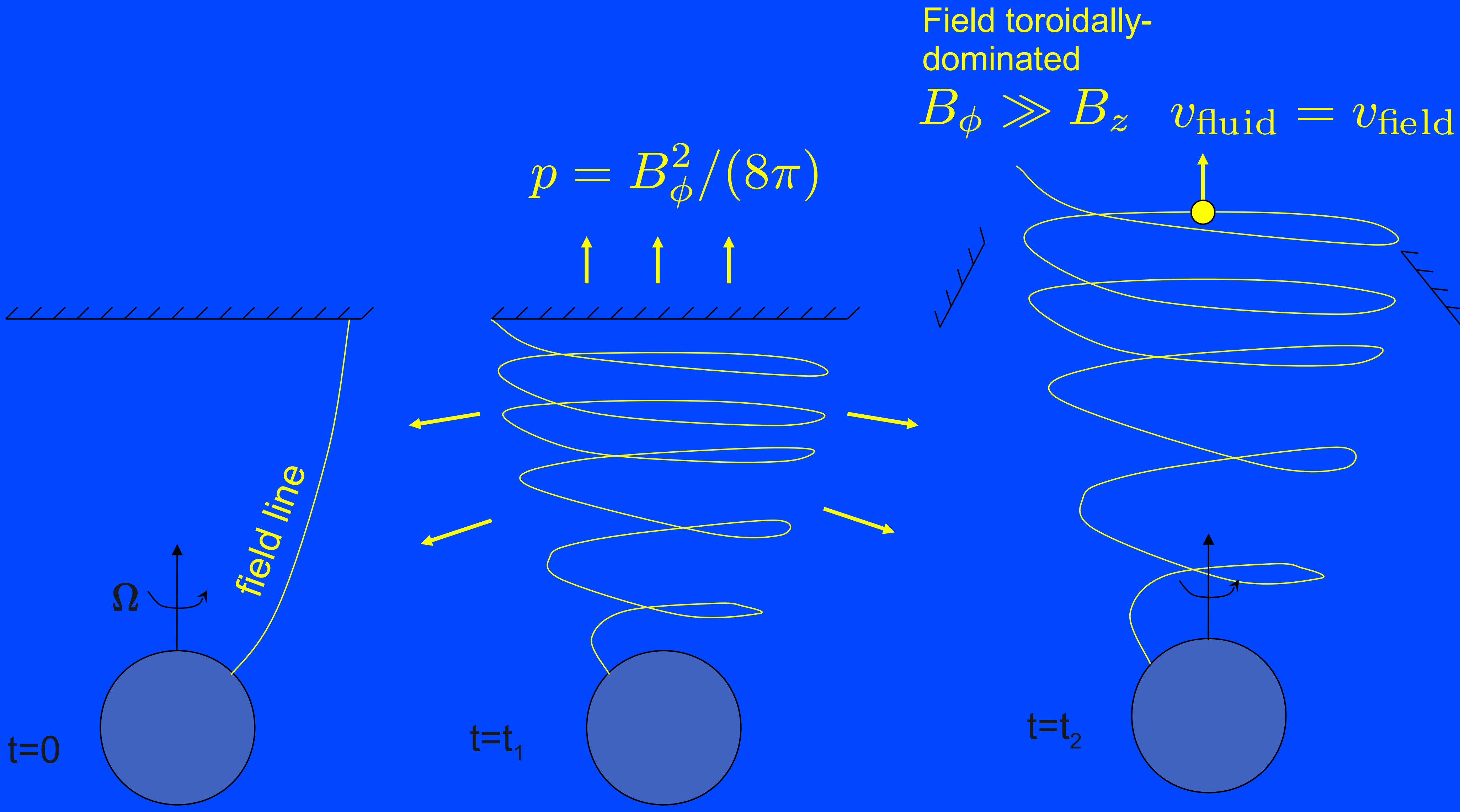


✗ Recent simulations of magnetized (MHD) continuously collimated jets (Komissarov et al. 2009):

$$\gamma\theta \lesssim 1$$

I will now present the first model of a magnetized GRB jet that correctly reproduces ***both*** collimation and acceleration

How do magnetic jets work?



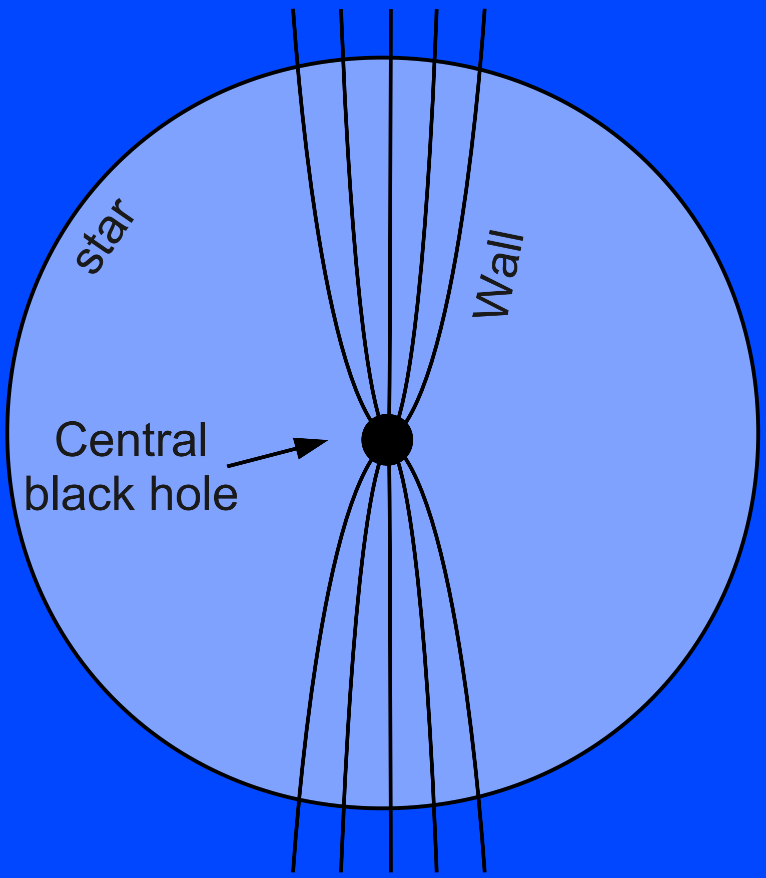
Simulation setup

GRB jet quick facts:

1. Ultra-relativistic: $\gamma \gtrsim 100$
2. Collimated: $\theta = 0.04 - 0.2$
3. Product $\gamma\theta \simeq 20 \gg 1$

Confined Jet

$\gamma\theta = 2$ ✗



Numerical Approach

Time-dependent ultrarelativistic MHD equations

Axisymmetry, perfect conductivity, and zero T

Problem setup

Perfectly conducting spinning compact object

Collimating wall of shape $z \propto R^{\alpha}$

Model parameters

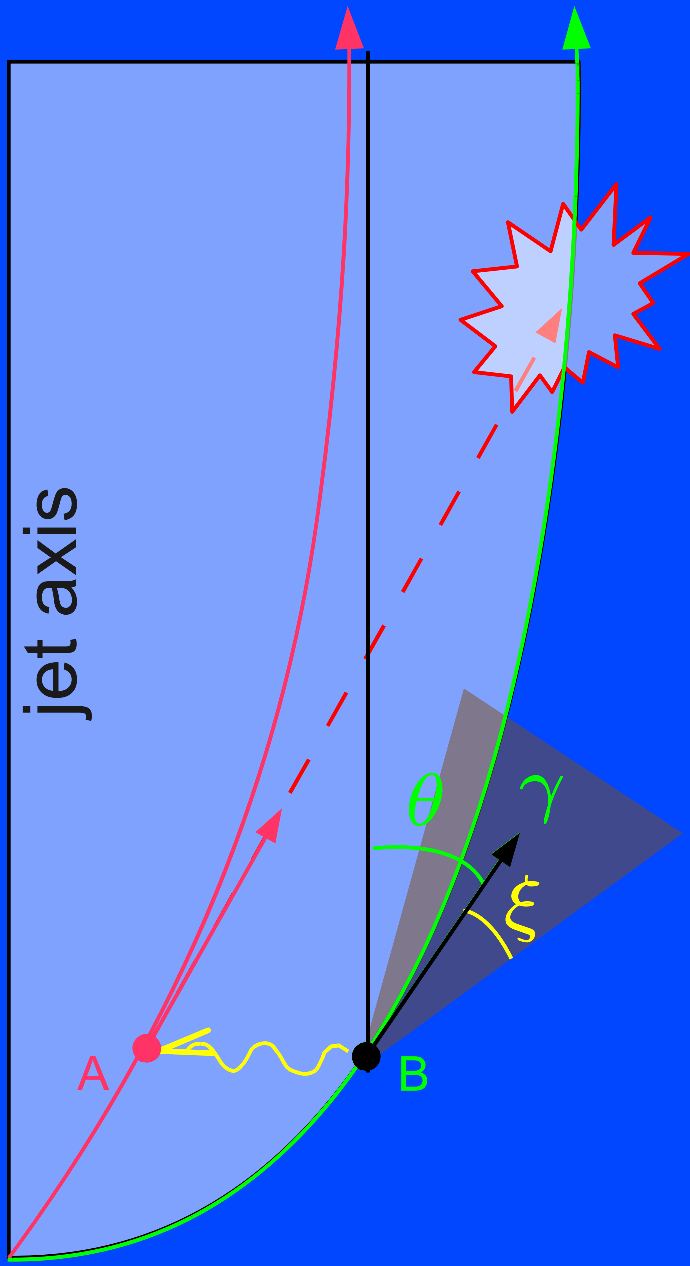
Jet wall shape

Spin of compact object

Magnetic field strength

Surface mass loss rate

Why is $\gamma\theta \lesssim 1$ in confined jets?



- Communication is essential
- Jet boundary B needs to keep announcing its trajectory to the rest of the jet to avoid collisions

GRB jet quick facts:
1. Ultra-relativistic: $\gamma \gtrsim 100$
2. Collimated: $\theta = 0.04 - 0.2$
3. Product $\gamma\theta \simeq 10 \gg 1$

- All signals travel inside Mach cone ξ:

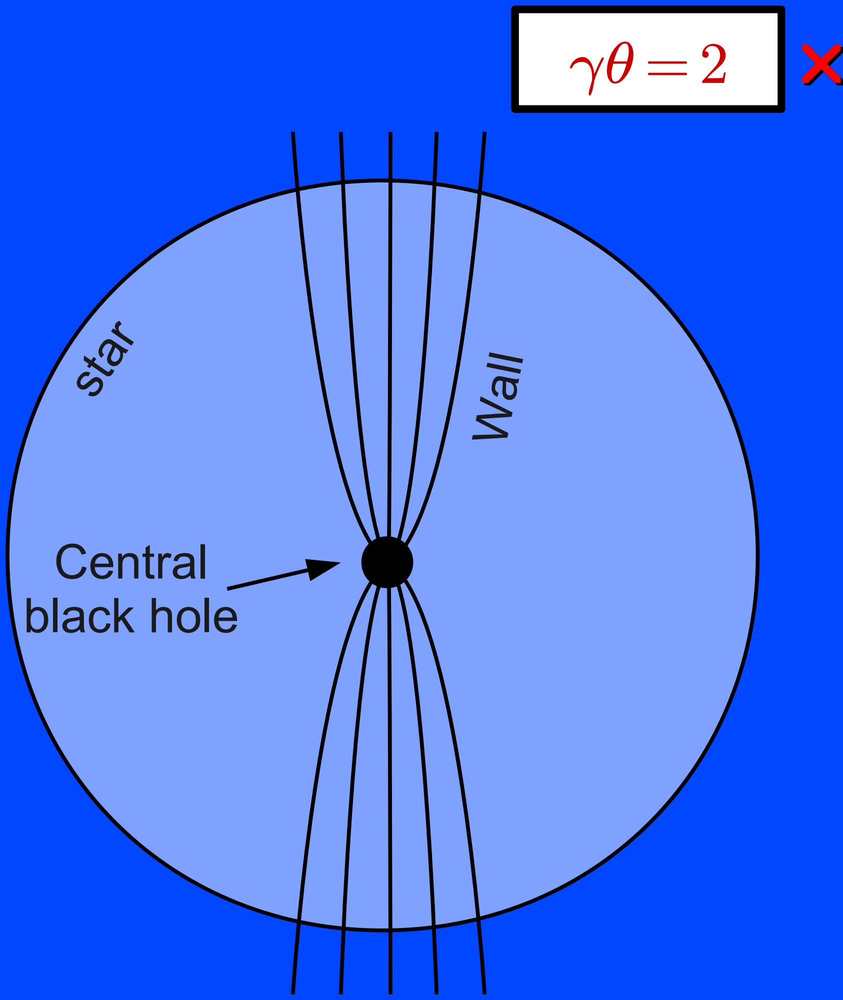
$$\theta < \xi \approx \frac{1}{\gamma}$$

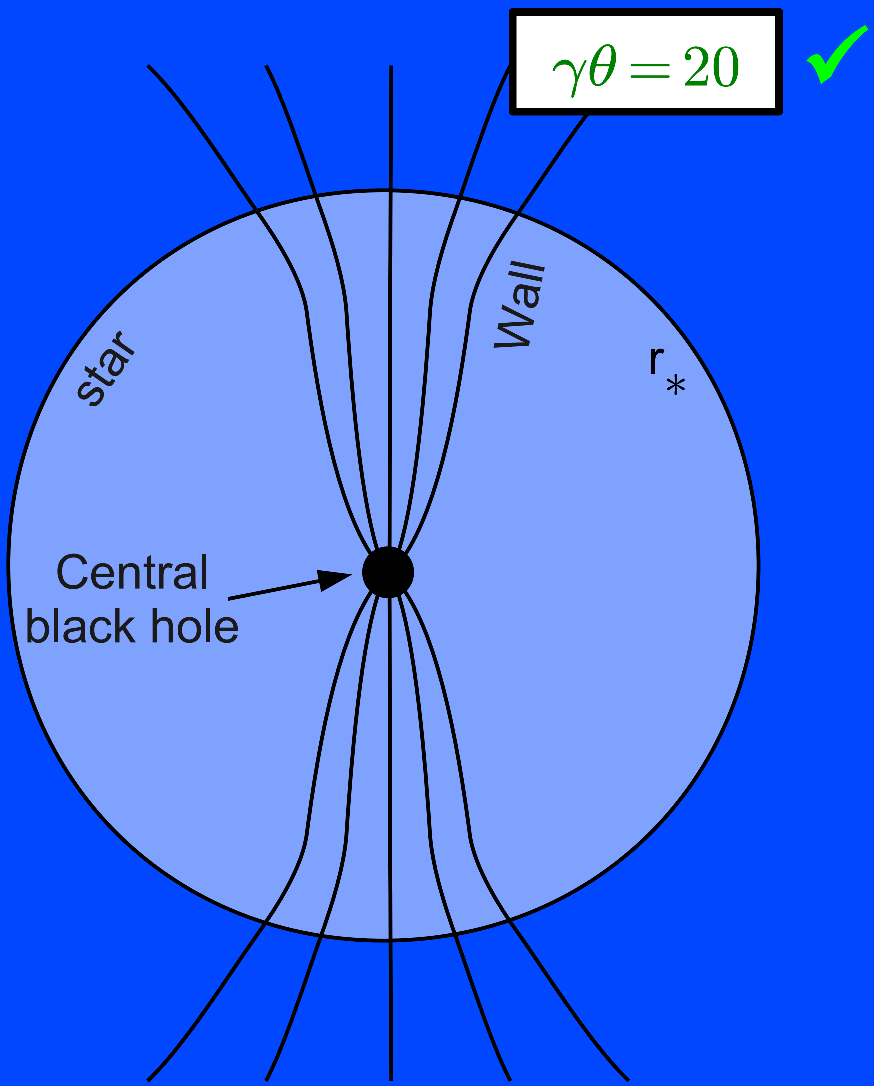
- Communication across jet → $\theta < \xi$
- Robust conclusion: $\gamma\theta \lesssim 1$ in confined jets

Simulation setup

Confined Jet

Deconfined Jet

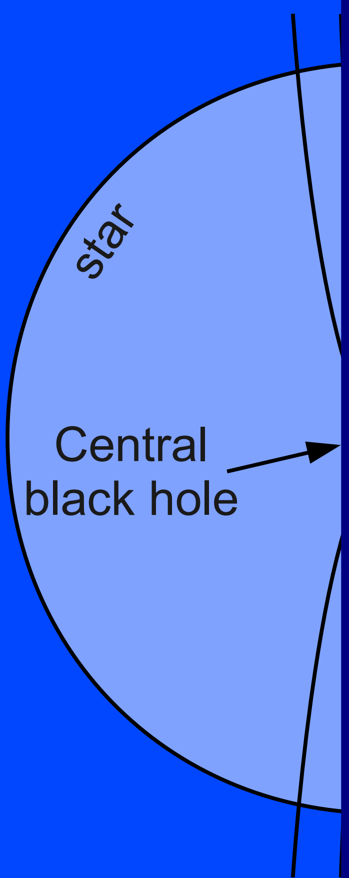


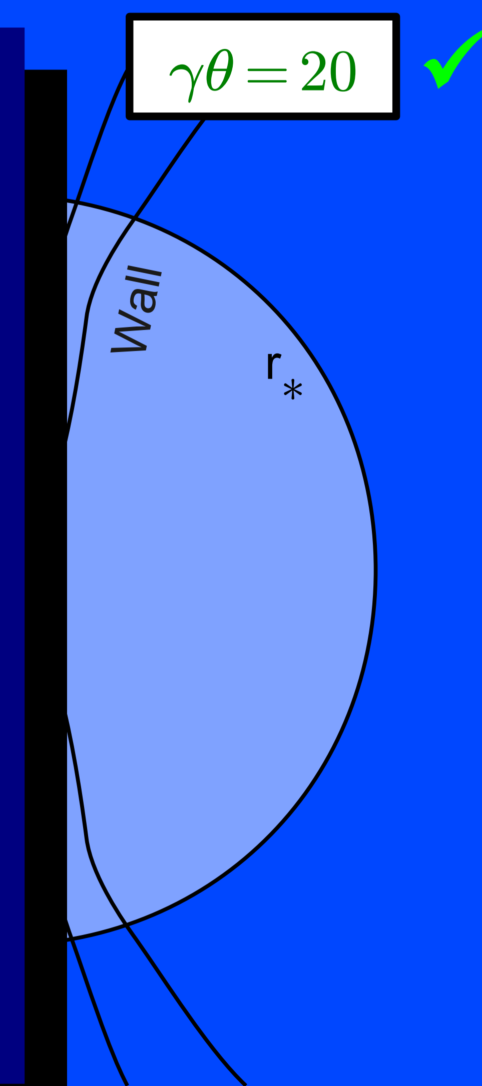


Simulation setup

Confined Jet

Deconfined Jet





Numerically-challenging problem

High magnetization and Lorentz factor (~ 1000): very stiff regime

Evolution over 10 orders of magnitude in distance

Our numerical method uses

Collimating grid that follows field lines at high resolution 1536x256

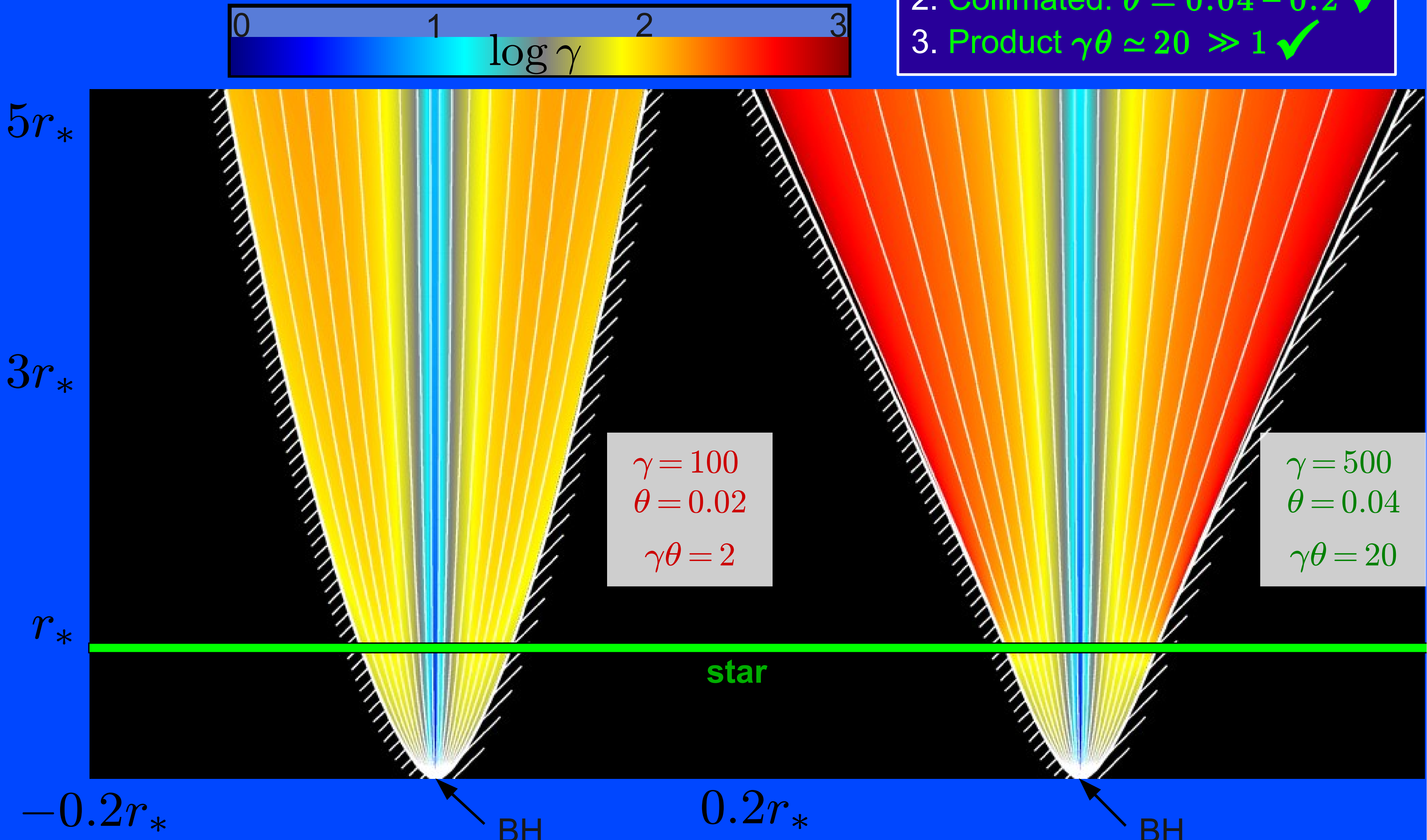
Equivalent resolution using non-collimating grid: 1536x100,000

Evolve only non-stationary region to speed up computation

Confined vs. Deconfined

GRB jet quick facts:

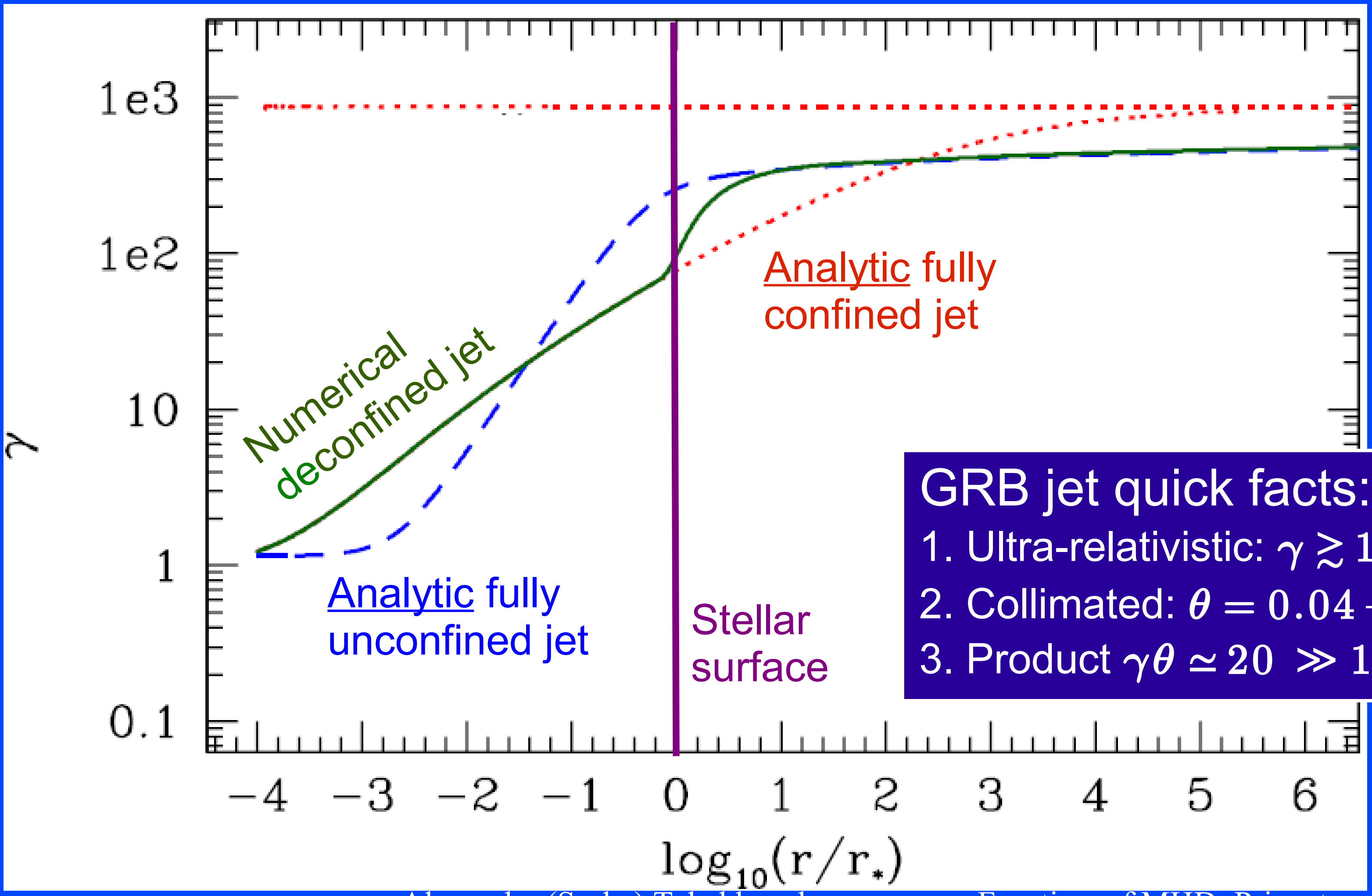
1. Ultra-relativistic: $\gamma \gtrsim 100$ ✓
2. Collimated: $\theta = 0.04 - 0.2$ ✓
3. Product $\gamma\theta \simeq 20 \gg 1$ ✓



MHD models can produce jet breaks ✓

Understand this analytically

After jet loses ambient pressure support, it switches from the fully confined solution to the fully unconfined solution (AT+ 2009).

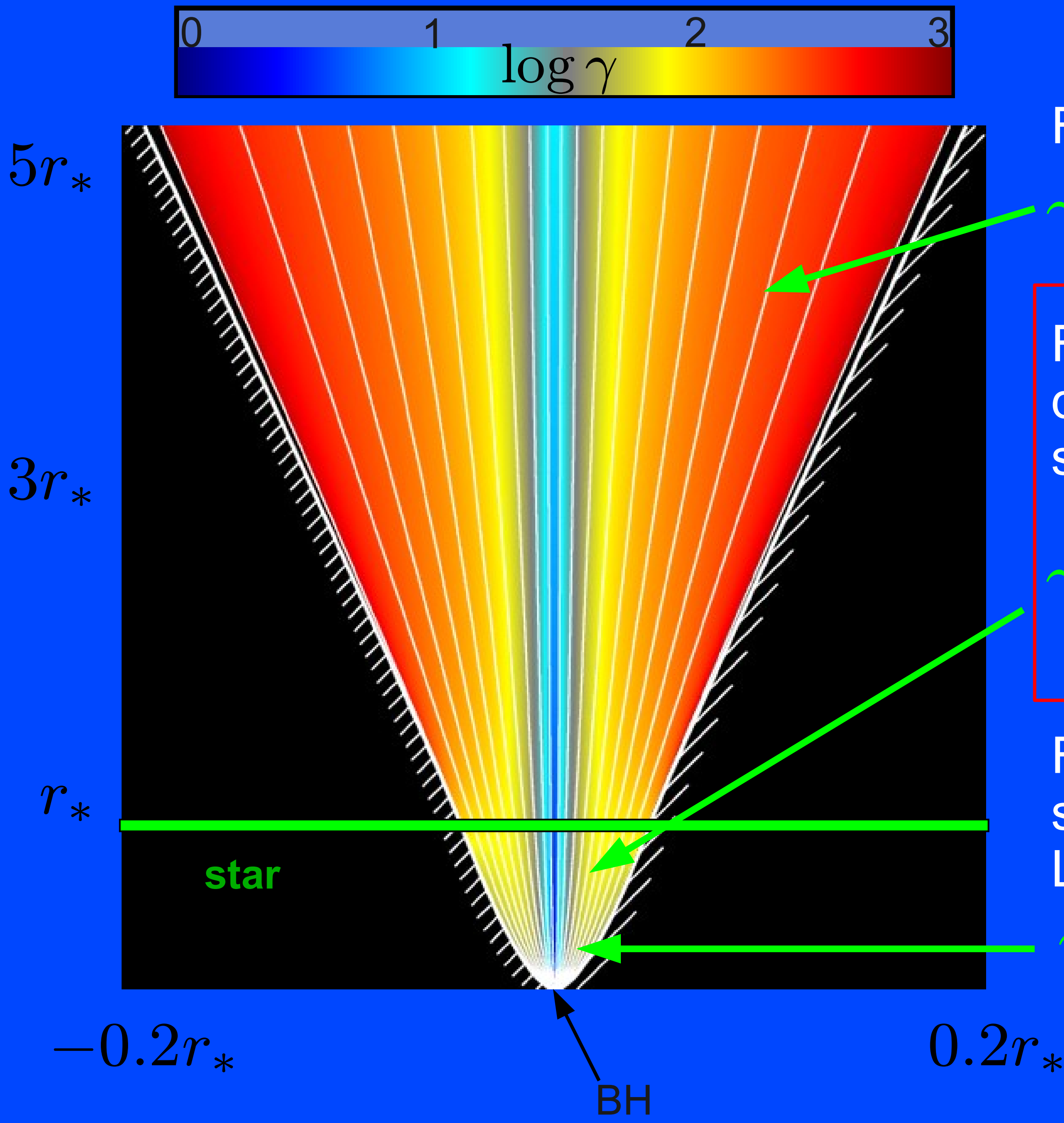


$\gamma = 500$
$\theta = 0.04$
$\gamma\theta = 20$

GRB jet quick facts:

1. Ultra-relativistic: $\gamma \gtrsim 100$ ✔
2. Collimated: $\theta = 0.04 - 0.2$ ✔
3. Product $\gamma\theta \simeq 20 \gg 1$ ✔

Understand this analytically (2/3)



Fully unconfined jet:

$\gamma_3 \propto \log^{1/3} r$ (Tomimatsu 94)

Fully confined jet, large distance. Centrifugal force slows jet down (AT+ 2008):

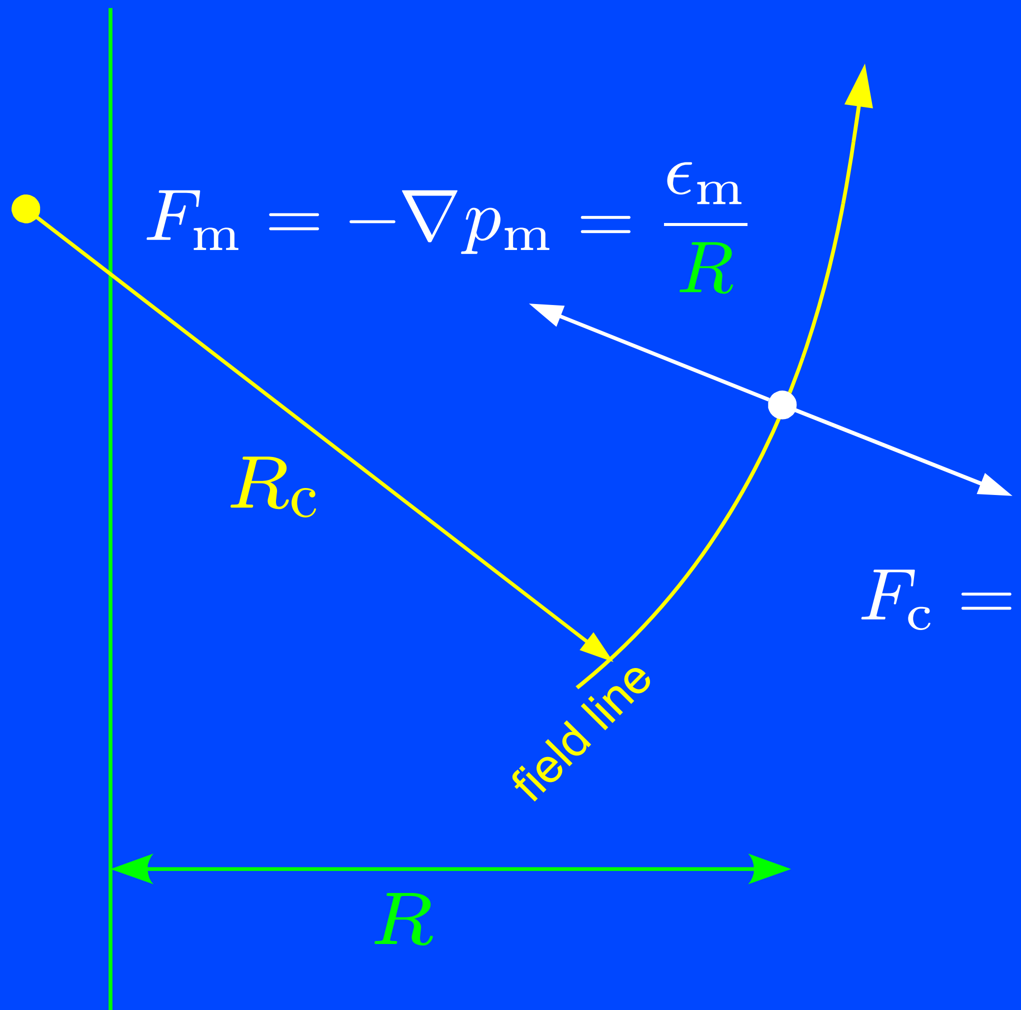
$$\gamma_2 \approx \left(\frac{3R_c}{R}\right)^{1/2}$$

Fully confined jet, short distance. Linear increase:

$\gamma_1 \approx \Omega R$ (Michel 1969)

Understand this analytically (3/3)

Centrifugal force slows jet down (approximate)



$$F_m = -\nabla p_m = \frac{\epsilon_m}{R}$$

$$F_c = \frac{\epsilon_m \gamma^2}{R_c}$$

$$F_m = F_c$$

$$\frac{\epsilon_m}{R} = \frac{\epsilon_m \gamma^2}{R_c}$$

$$\gamma = \left(\frac{R_c}{R}\right)^{1/2}$$

Required ingredients for GRB jets

Both propagation inside and outside the star are required for GRB jets:

1) Fully confined jets are too slow for their opening angles: $\gamma\theta \lesssim 1$

2) Fully deconfined jets have too large opening angles

Bottom line: need both
1) confinement to collimate the jet initially and
2) deconfinement to accelerate the jet

Conclusions

- Numerical & analytical models of magnetized deconfined ultra-relativistic jets, extending over 10 orders of magnitude in distance well into the afterglow region.
- Just outside the star, our jets undergo an abrupt period of acceleration during which γ increases but θ is constant
- Deconfinement is necessary to achieve ultrarelativistic γ and $\gamma\theta \gg 1$ required by jet breaks observations
- Confined jets with subequipartition magnetic fields always have $\gamma\theta \lesssim 1$
- Future work is the self-consistent simulation of magnetized jet propagation through realistic stellar envelope out to the afterglow region.