Rarefaction acceleration in magnetized gamma-ray burst jets

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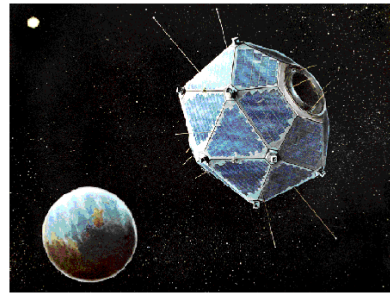
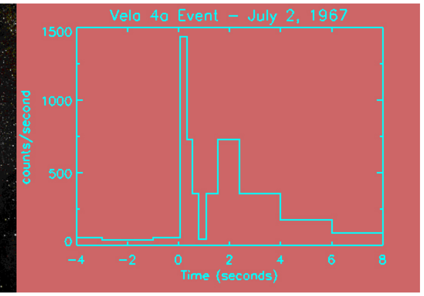
Outline

- introduction on GRBs
- “standard” magnetic acceleration – caveat $\gamma\vartheta \sim 1$
- rarefaction wave – application to GRBs

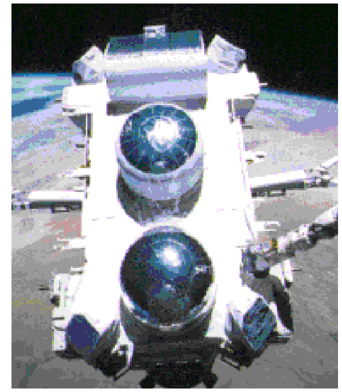
Observations

- 1967: the first GRB
  Vela satellites
  (first publication on 1973)



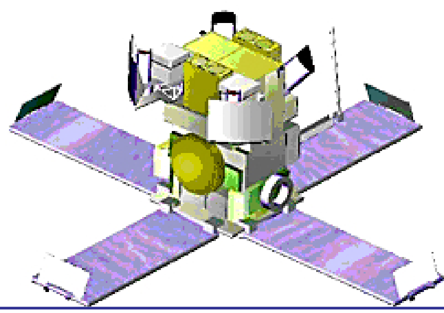


- 1991: launch of ComptonGammaRayObservatory
  Burst and Transient Experiment (BATSE)
  2704 GRBs (until May 2000)
  isotropic distribution (cosmological origin)



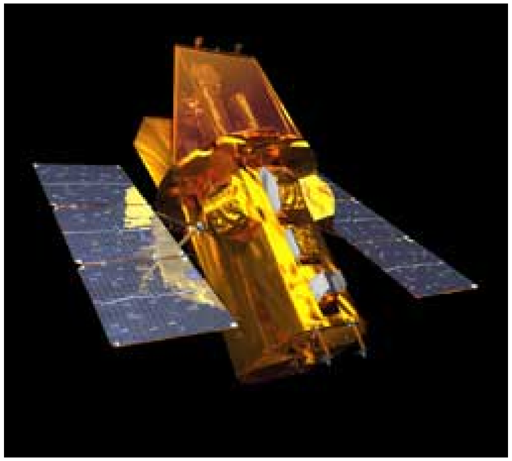
- 1997: Beppo(in honor of Giuseppe Occhialini) Satellite per Astronomia X
  X-ray afterglow
  arc-min accuracy positions
  optical detection
  GRB afterglow at longer wavelengths
  identification of the host galaxy
  measurement of redshift distances

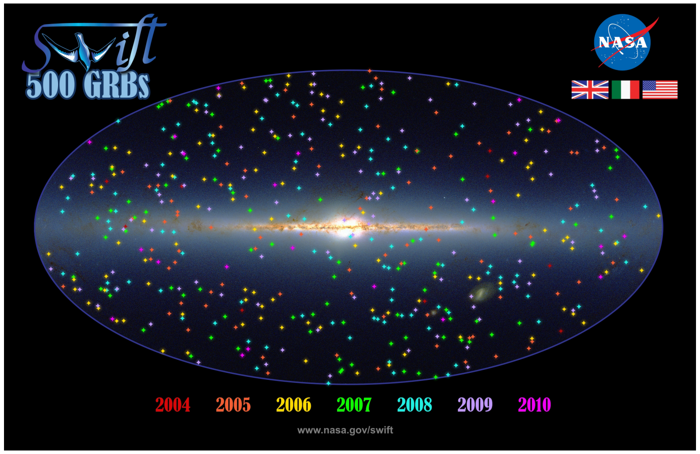
- HighEnergyTransientExplorer-2



- INTErnationalGamma-RayAstrophysicsLaboratory

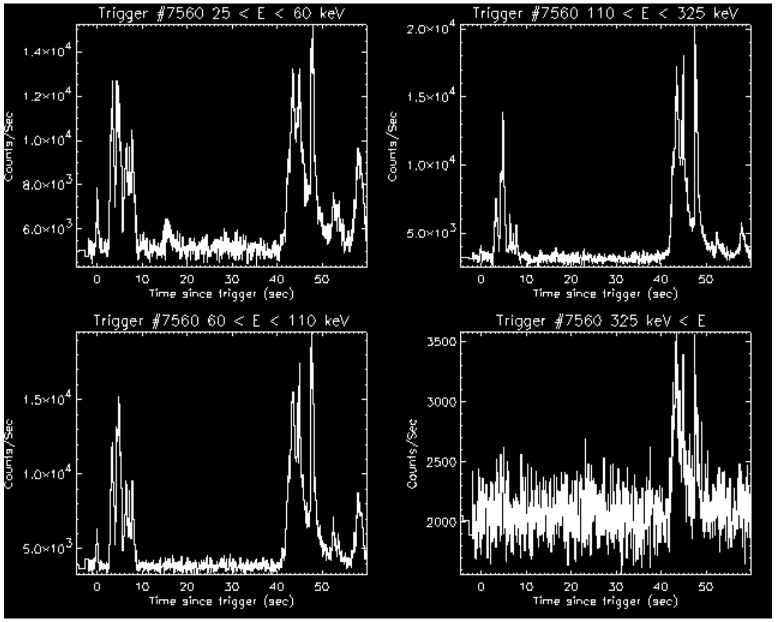
SWIFT

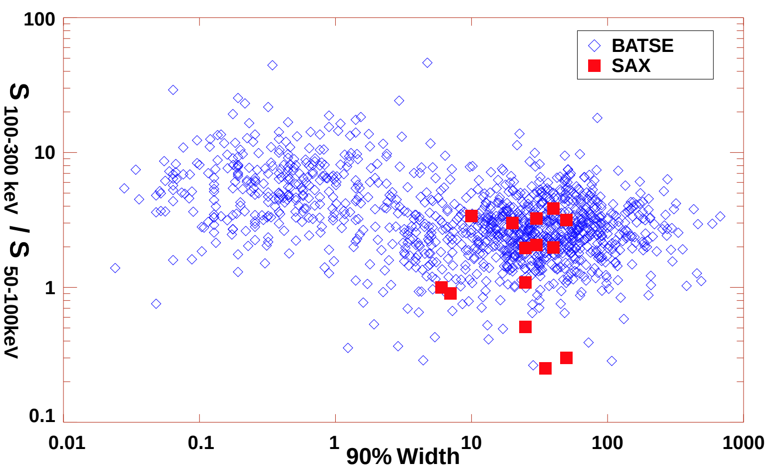



Swift
500 GRBs
NASA
2004 2005 2006 2007 2008 2009 2010
www.nasa.gov/swift

FERMI

GRB prompt emission





(Djorgovski et al.)

- Fluence $F_\gamma = 10^{-8} - 10^{-3}$ergs/cm^2

  energy

  $$E_\gamma = 10^{53} \left(\frac{D}{3\ \mathrm{Gpc}}\right)^2 \left(\frac{F_\gamma}{10^{-4}\ \frac{\mathrm{ergs}}{\mathrm{cm}^2}}\right) \left(\frac{\Delta\Omega}{4\pi}\right) \text{ergs}$$

  collimation { reduces E_γ ; increases the rate of events }
- non-thermal spectrum
- Duration $\Delta t = 10^{-3} - 10^3$s

  long bursts > 2 s, short bursts < 2 s
- Variability $\delta t = \Delta t / N\,, N = 1 - 1000$

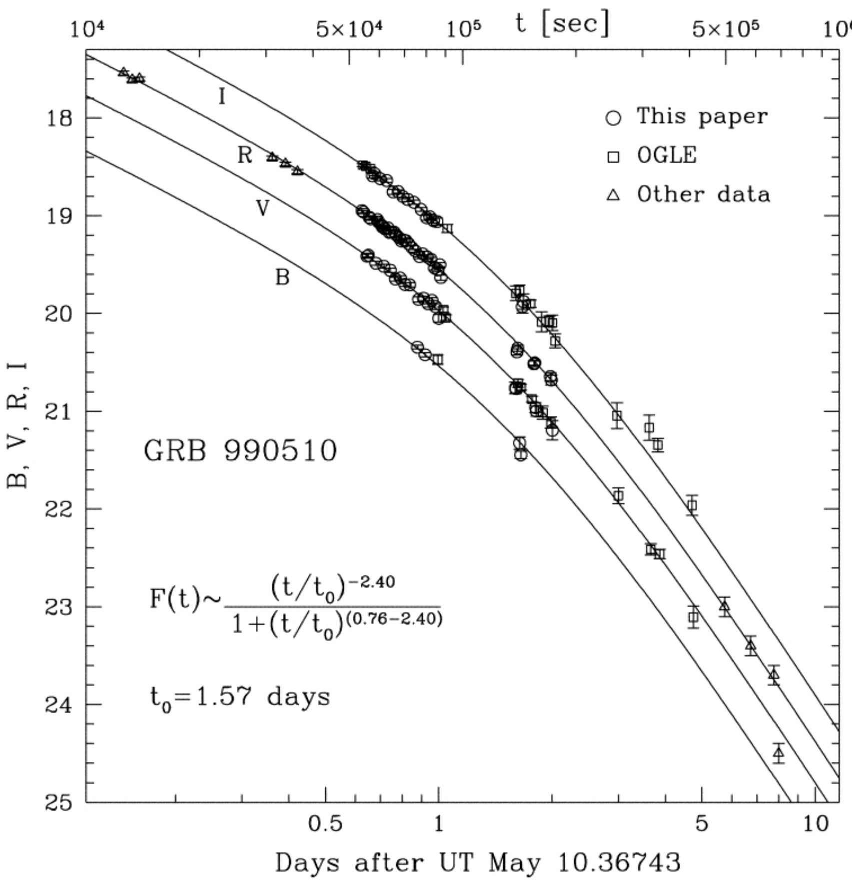
  compact source $R < c\,\delta t \sim 1000$ km

  huge optical depth for $\gamma\gamma \to e^+ e^-$

  compactness problem: how the photons escape?

  relativistic motion $\gamma \gtrsim 100$ { $R < \gamma^2 c\,\delta t$; blueshifted photon energy ; beaming ; optically thin }

Afterglow



(Stanek et al.)

- from X-rays to radio
- fading – broken power law

  “panchromatic” break $F_\nu \propto \begin{cases} t^{-a_1}, t < t_o \\ t^{-a_2}, t > t_o \end{cases}$

  not really panchromatic
- non-thermal spectrum

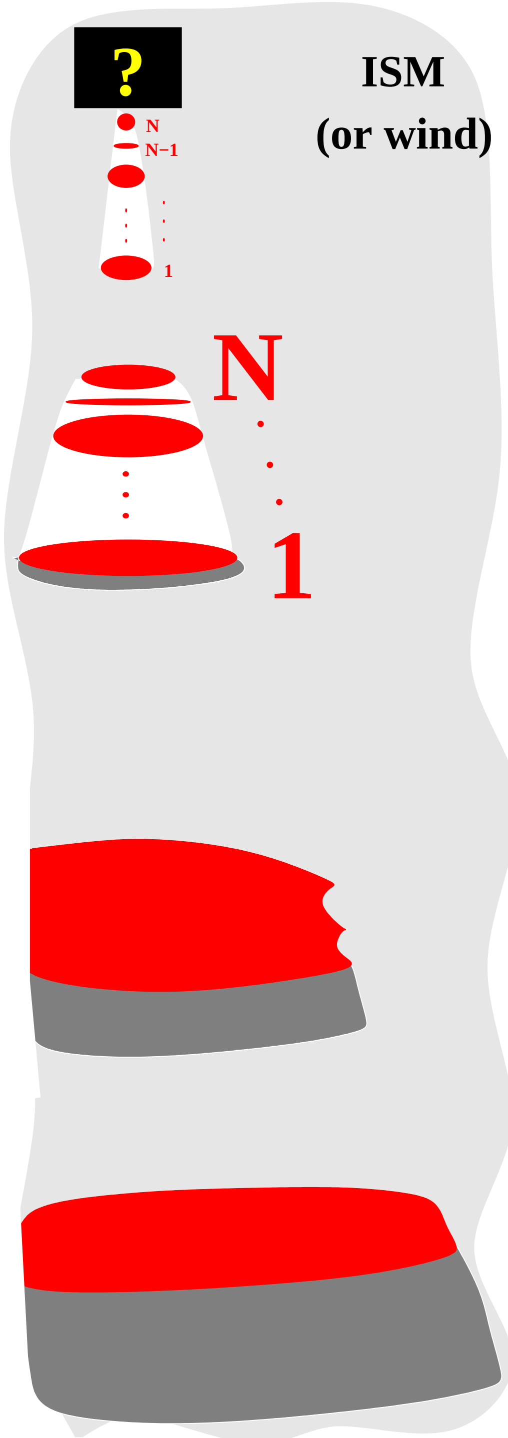
  (synchrotron + inverse Compton)

The internal–external shocks model

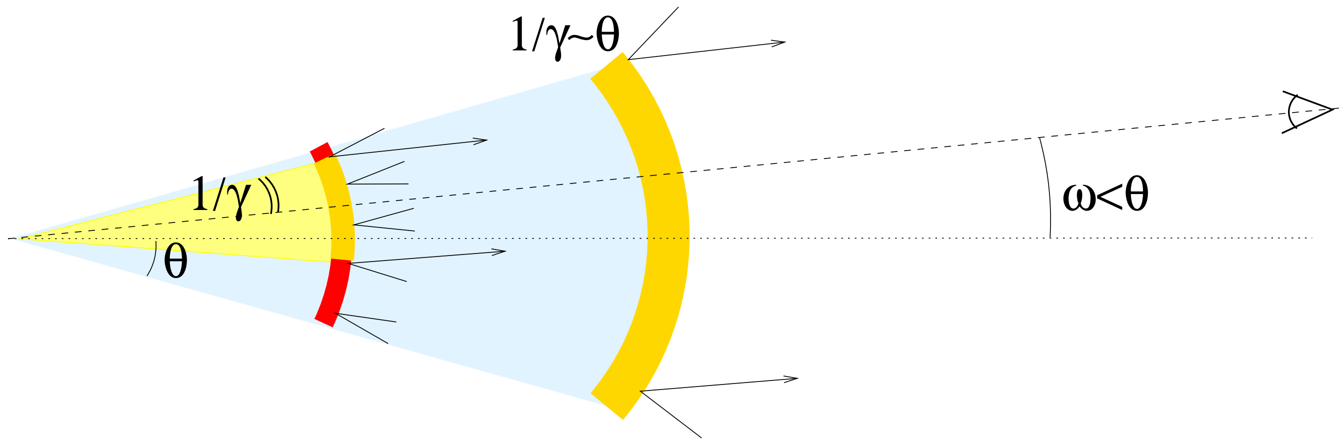
mass outflow (pancake)
N shells (moving with different $\gamma \gg 1$)

internal shocks
(a few tens of kinetic energy $\rightarrow$ **GRB**)

external shock
interaction with ISM (or wind)
(when the flow accumulates $M_{ISM} = M/\gamma$)
As γ decreases with time, kinetic energy $\rightarrow$ X-rays . . . radio
$\rightarrow$ **Afterglow**

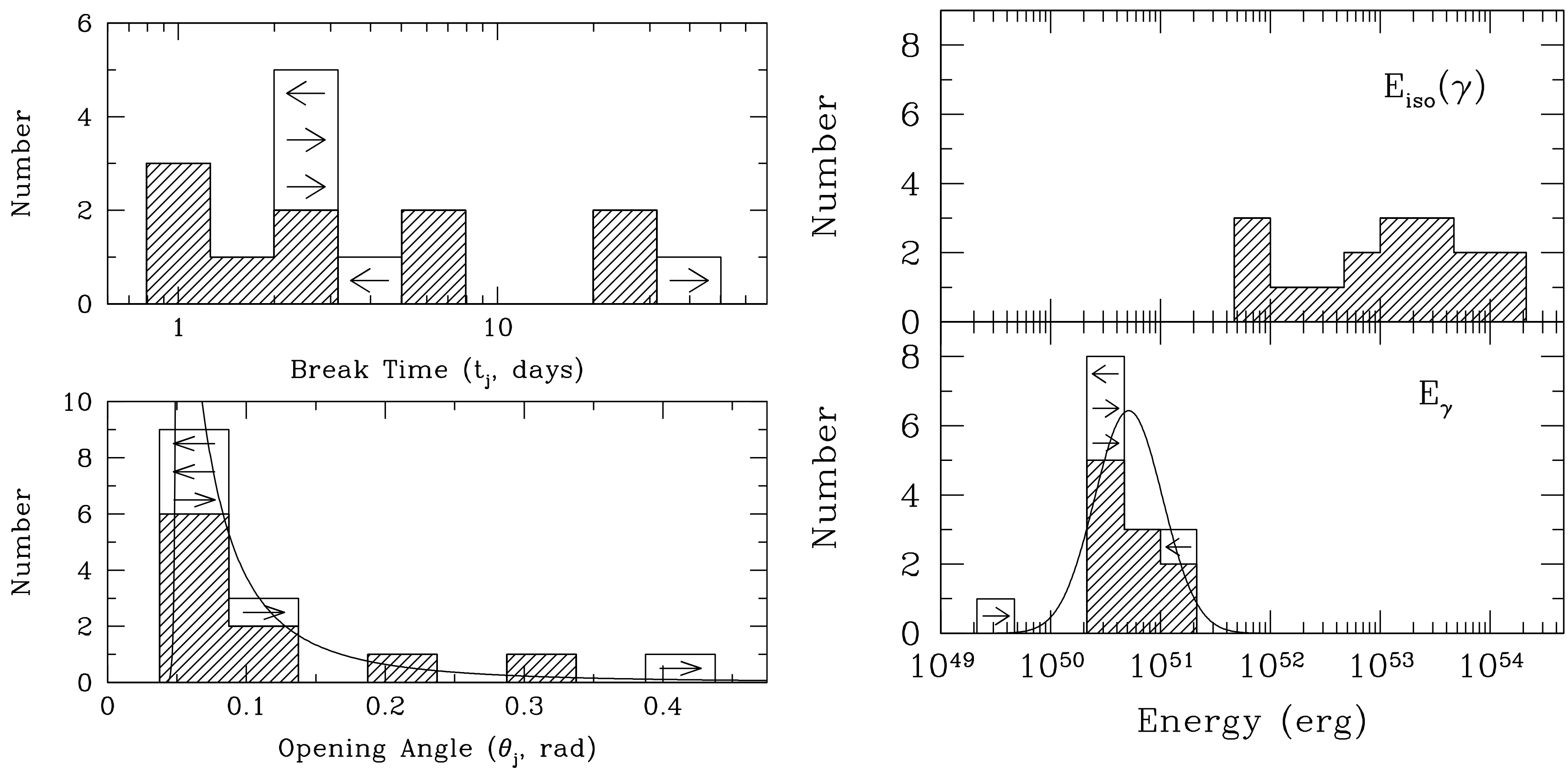


Beaming – Collimation



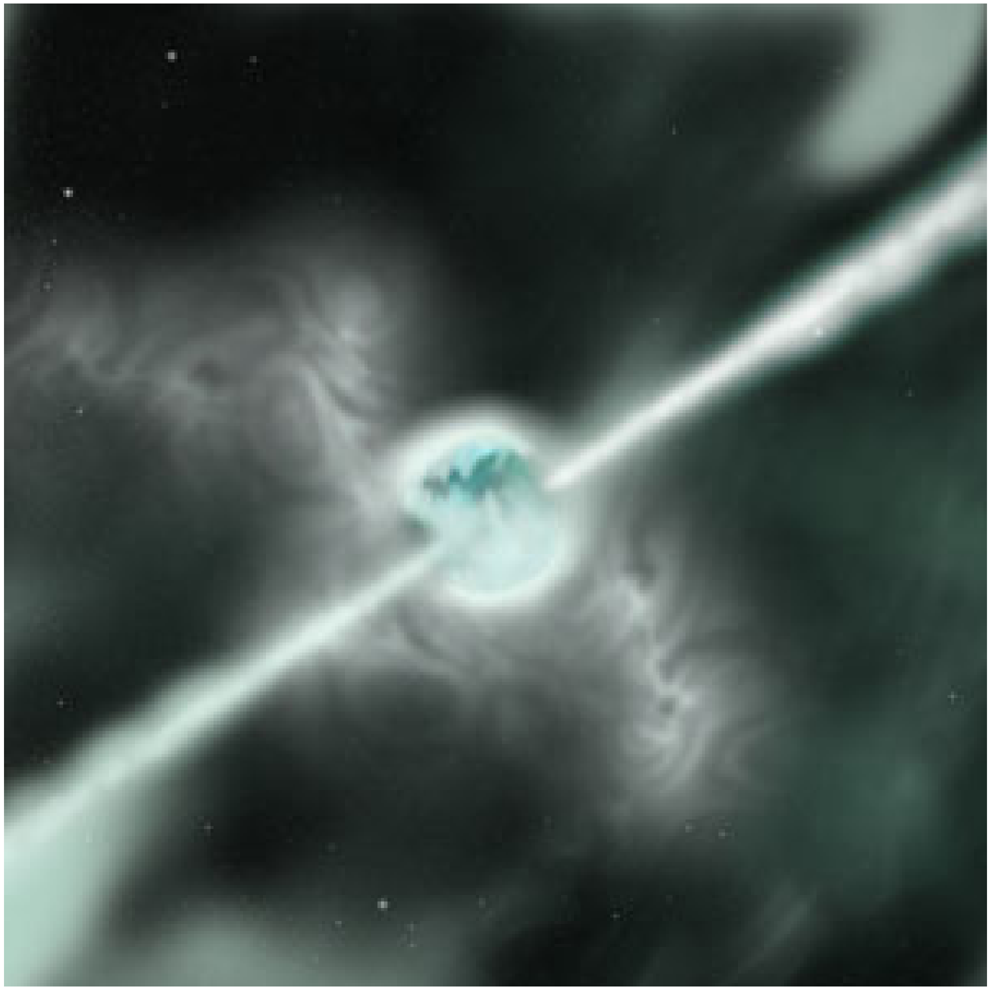
- During the afterglow γ decreases
  When $1/\gamma > \vartheta$ the $F(t)$ decreases faster
  The broken power-law justifies collimation

- at the start of the afterglow phase, $\gamma\vartheta \gg 1$

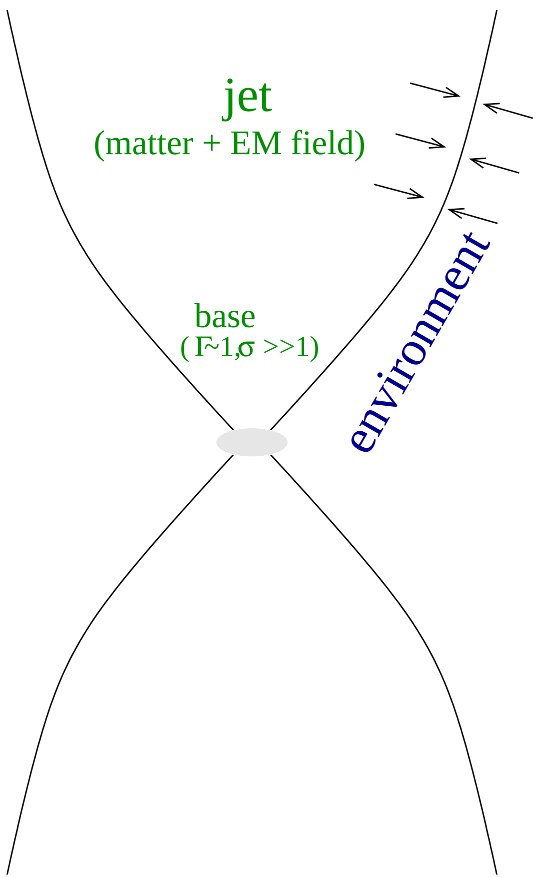


- afterglow fits $\rightarrow \left\{ \begin{array}{l} \text{opening half-angle } \vartheta = 1^o - 10^o \\ \text{energy } E_\gamma = 10^{50} - 10^{51}\text{ergs} \\ E_{\rm afterglow} = 10^{50} - 10^{51}\text{ergs} \end{array} \right.$

Progenitors of long GRBs: collapsar model



Magnetized outflows



- Extracted energy per time $\dot{\mathcal{E}}$ mainly in the form of Poynting flux (magnetic fields tap the rotational energy of the compact object or disk)

$$\dot{\mathcal{E}} = \frac{c}{4\pi} \underbrace{\frac{r}{r_{\rm lc}} B_p}_{E} \; B_\phi \times (\text{ area }) \approx \frac{c}{2} B^2 r^2$$

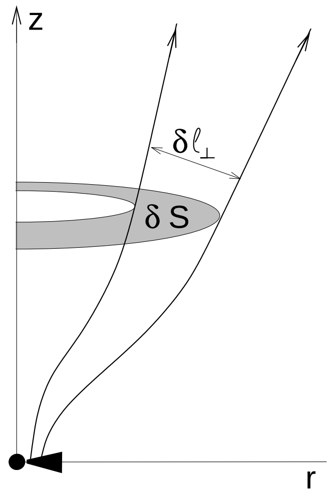
- Ejected mass per time $\dot{M}$

- The $\mu \equiv \dot{\mathcal{E}} / \dot{M} c^2$ gives the maximum possible bulk Lorentz factor of the flow

- Magnetohydrodynamics:
matter (velocity, density, pressure)
\+ large scale electromagnetic field

"Standard" model for magnetic acceleration

☞ component of the momentum equation



$$\gamma n(\boldsymbol{V}\cdot\nabla)\,(\gamma w\boldsymbol{V}) = -\nabla p + J^0\boldsymbol{E} + \boldsymbol{J}\times\boldsymbol{B}$$

along the flow (wind equation): $\gamma \approx \mu - \mathcal{F}$

where $\mathcal{F} \propto r^2 n\gamma V_p = r^2\times$ mass flux

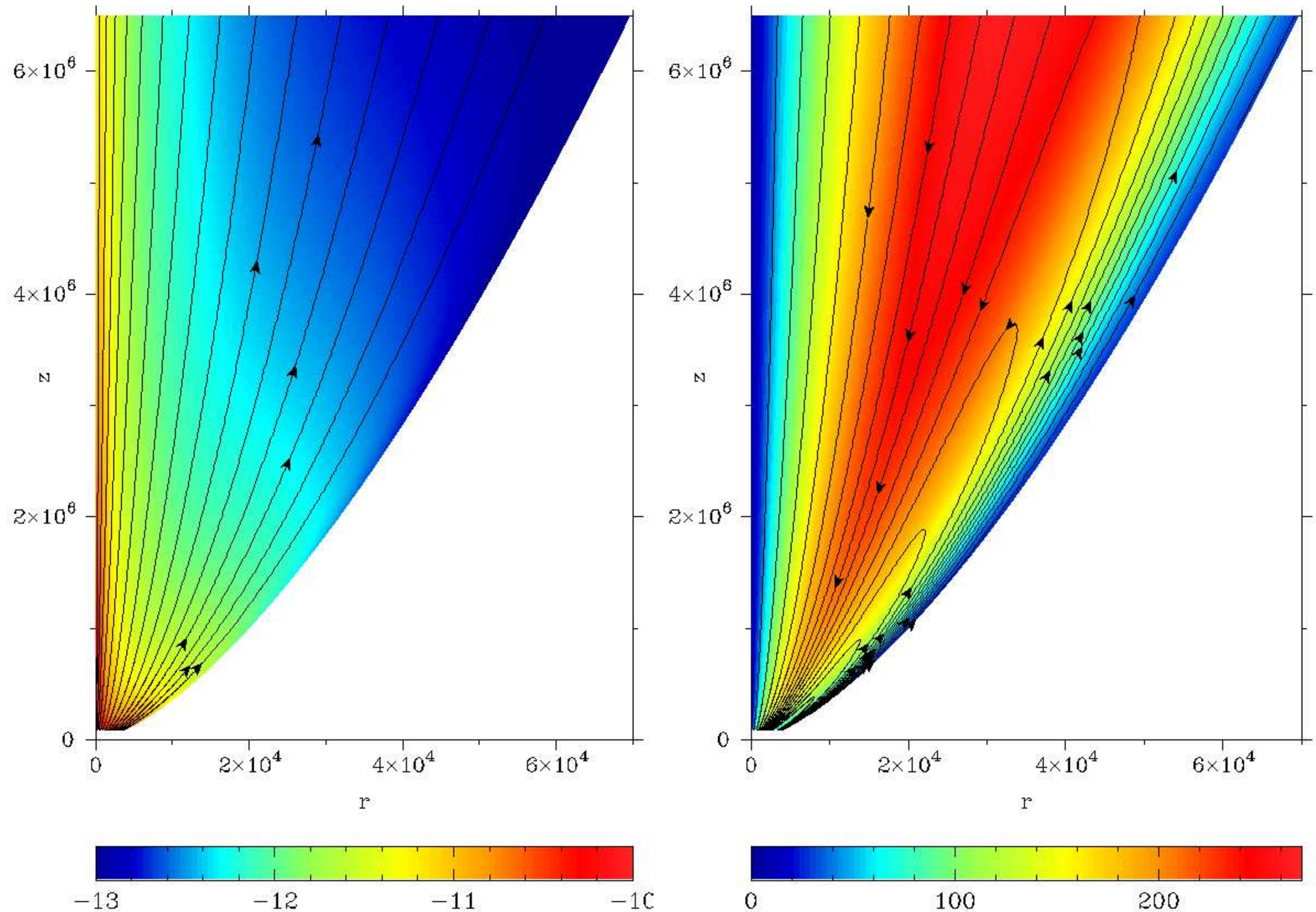
since mass flux $\times\delta S =$ const,

$\mathcal{F} \propto r^2/\delta S \propto r/\delta\ell_\perp$

acceleration requires the separation between streamlines to increase faster than the cylindrical radius

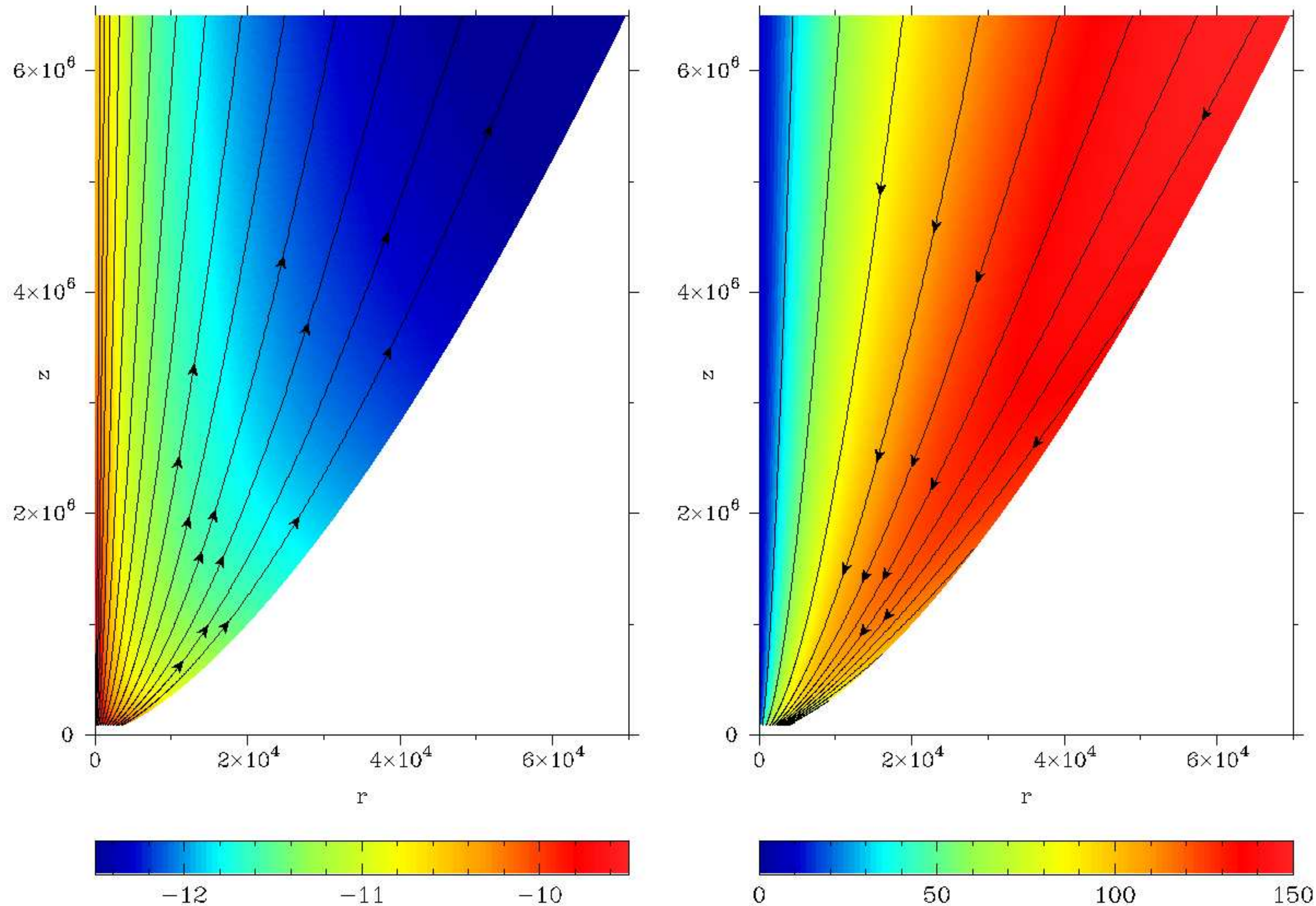
the collimation-acceleration paradigm:

$\mathcal{F}\downarrow$ through stronger collimation of the inner streamlines relative to the outer ones (differential collimation)

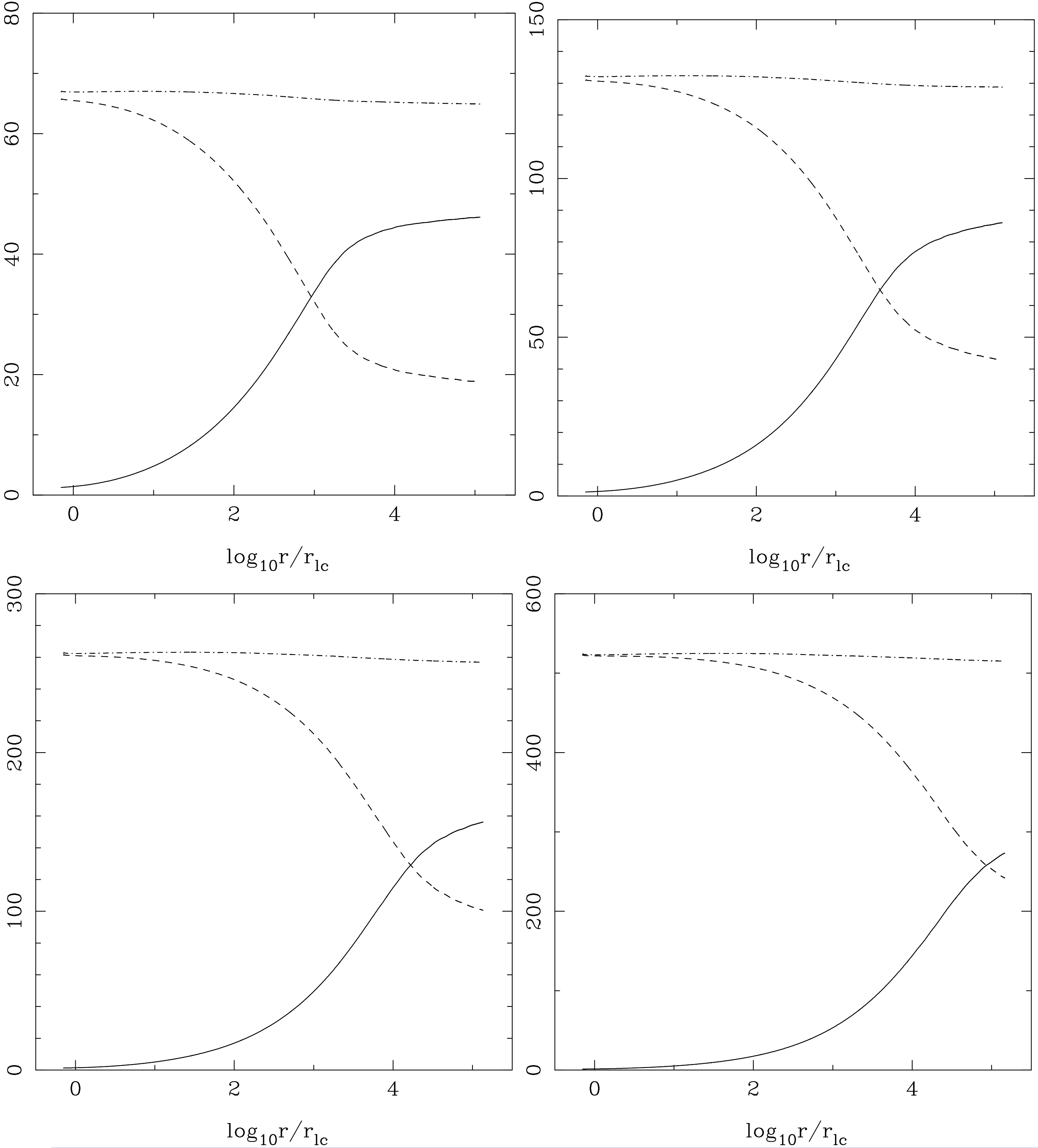


left: density/field lines, right: Lorentz factor/current lines (wall shape $z \propto r^{1.5}$)

Differential rotation $\rightarrow$ slow envelope



Uniform rotation $\rightarrow \gamma$ increases with r



γ (increasing),

$\gamma\sigma$ (decreasing),

and μ (constant)

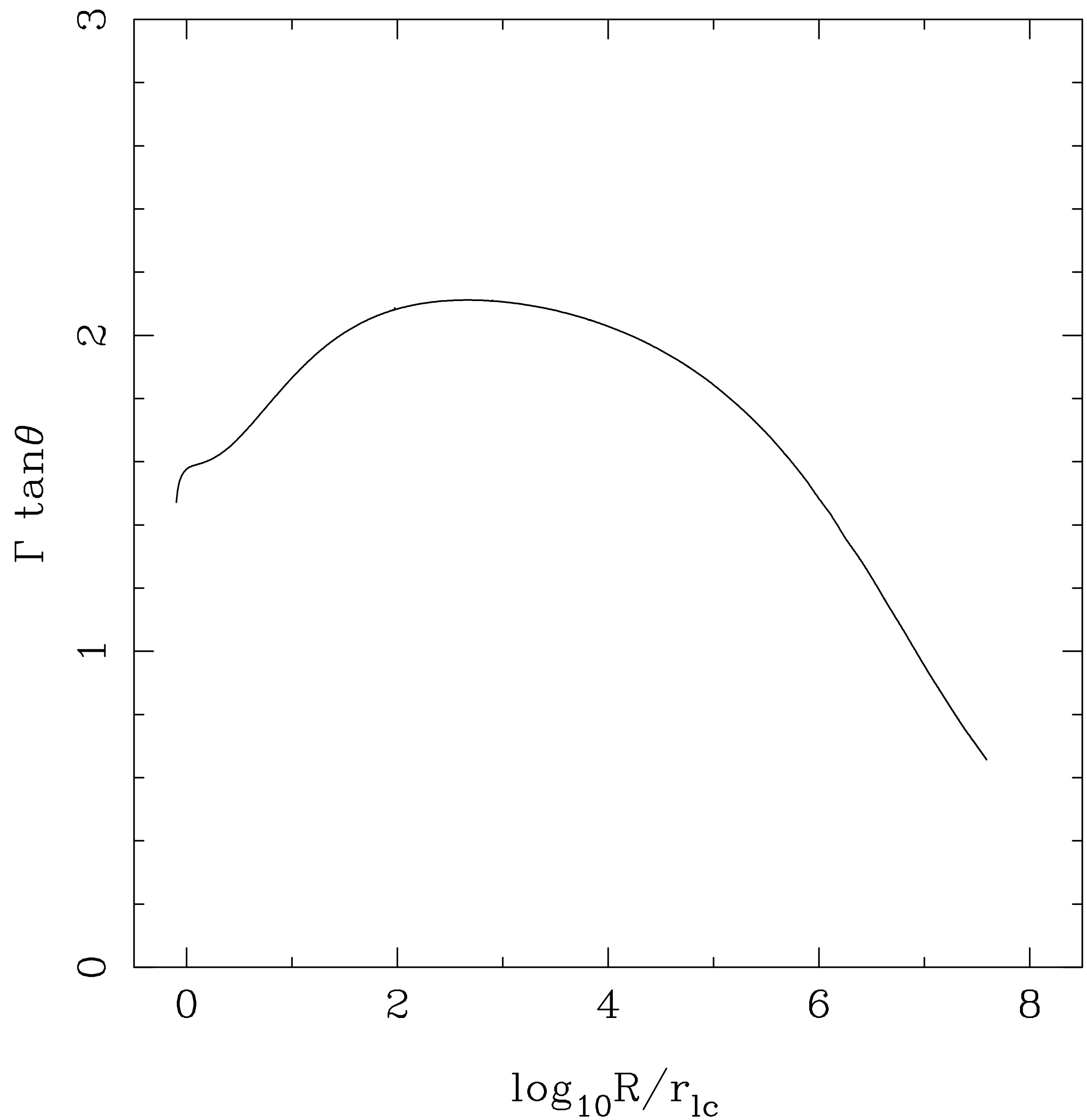
efficiency $> 50\%$

Caveat $\gamma\vartheta \sim 1$ of the "standard" model

- very narrow jets ($\vartheta < 1^\circ$ for $\gamma > 100$) $\longrightarrow$ early breaks or no breaks at all

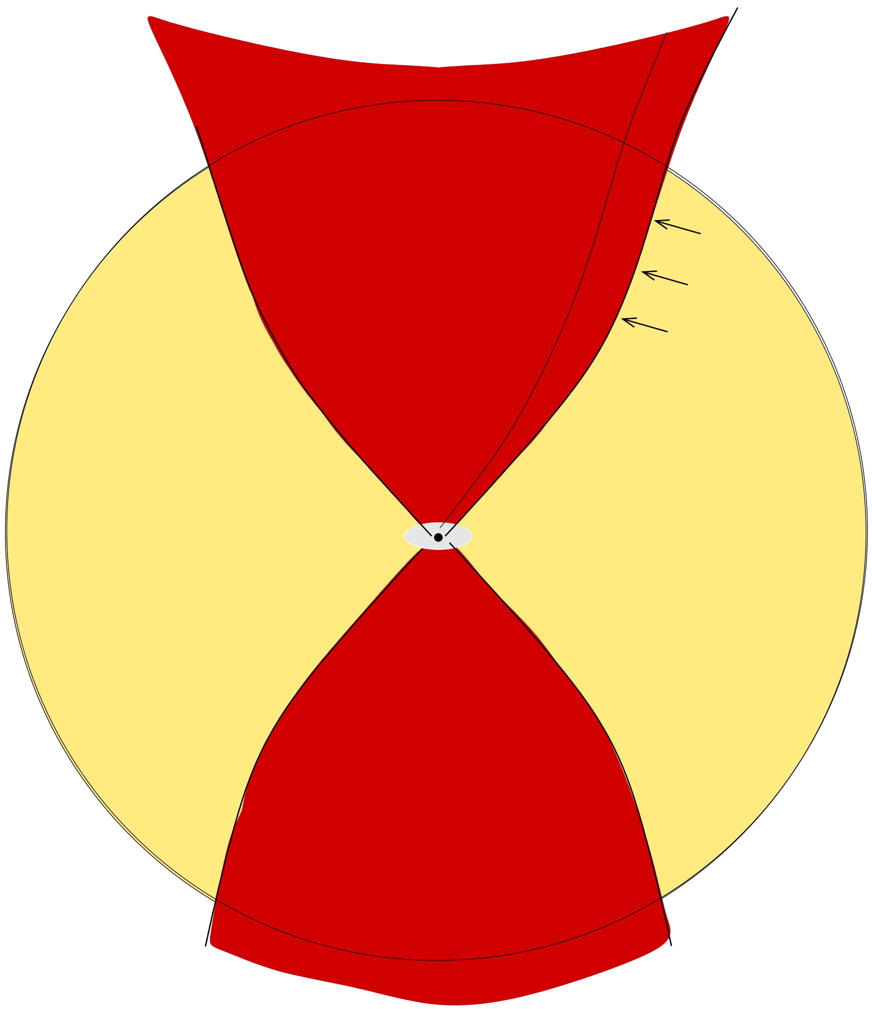
- this is a result of causality (across jet): outer lines need to know that there is space to expand

- Mach cone half-opening $\theta_m > \vartheta$
  With $\sin\theta_m = \dfrac{\gamma_f c_f}{\gamma V_p} \approx \dfrac{\sigma^{1/2}}{\gamma}$ (where $\sigma =$ Poynting-to-kinetic energy flux ratio) the requirement for causality yields $\gamma\vartheta < \sigma^{1/2}$.
  For efficient acceleration ($\sigma \sim 1$ or larger) we always get $\gamma\vartheta \sim 1$

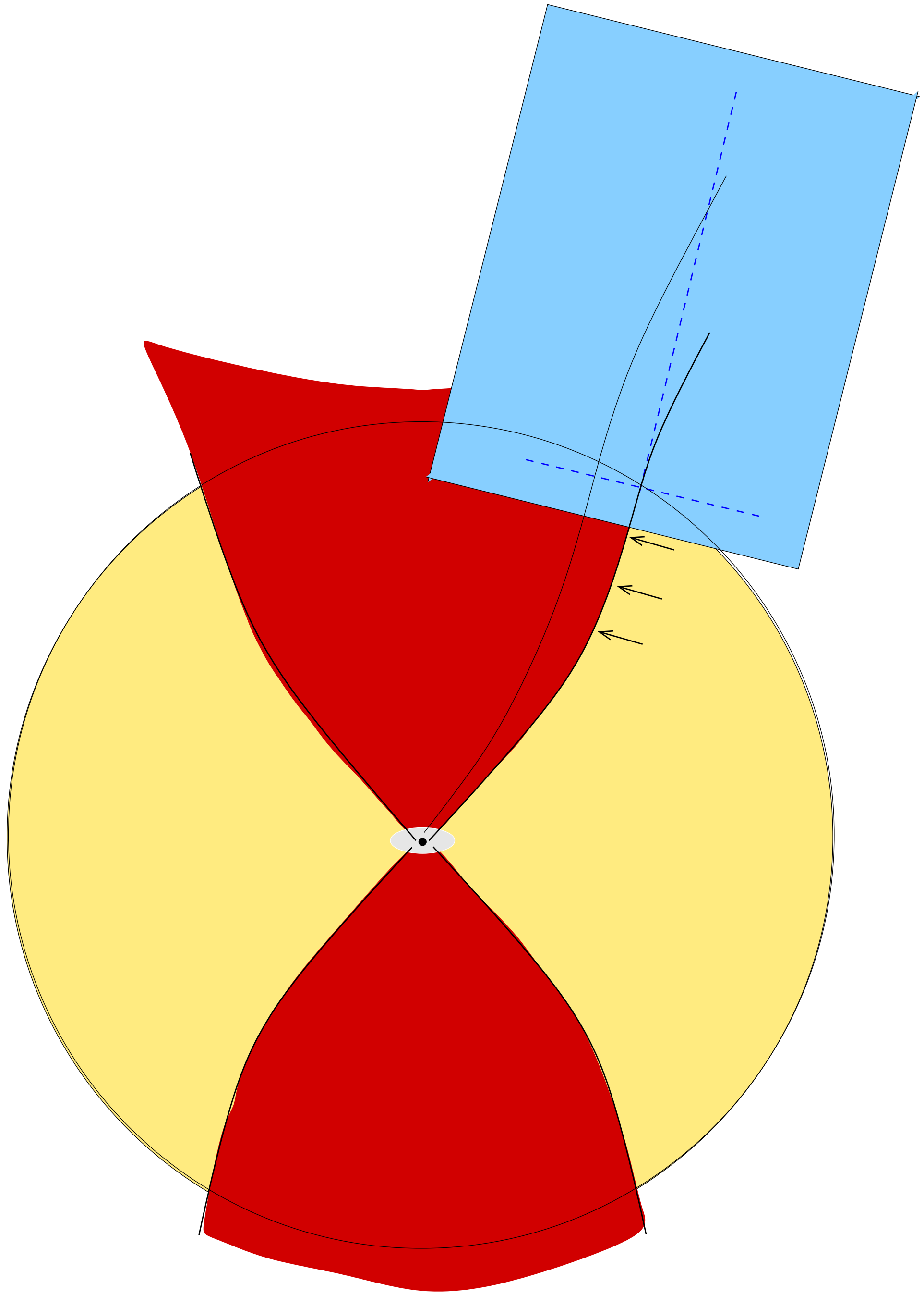


$\Gamma\ \tan\theta$
0
1
2
3
0
2
4
6
8
$\log_{10} R/r_{lc}$

Rarefaction acceleration

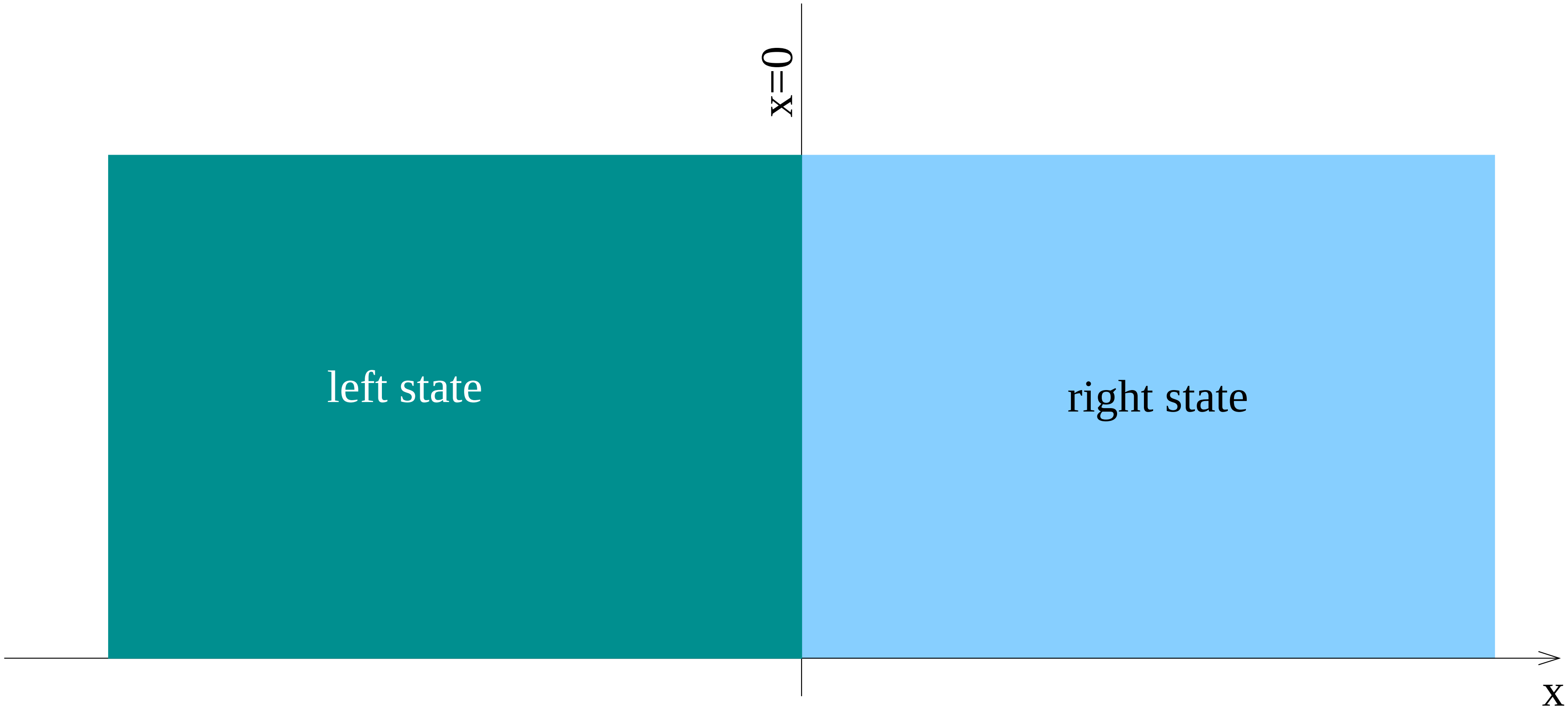


Rarefaction acceleration



Rarefaction simple waves

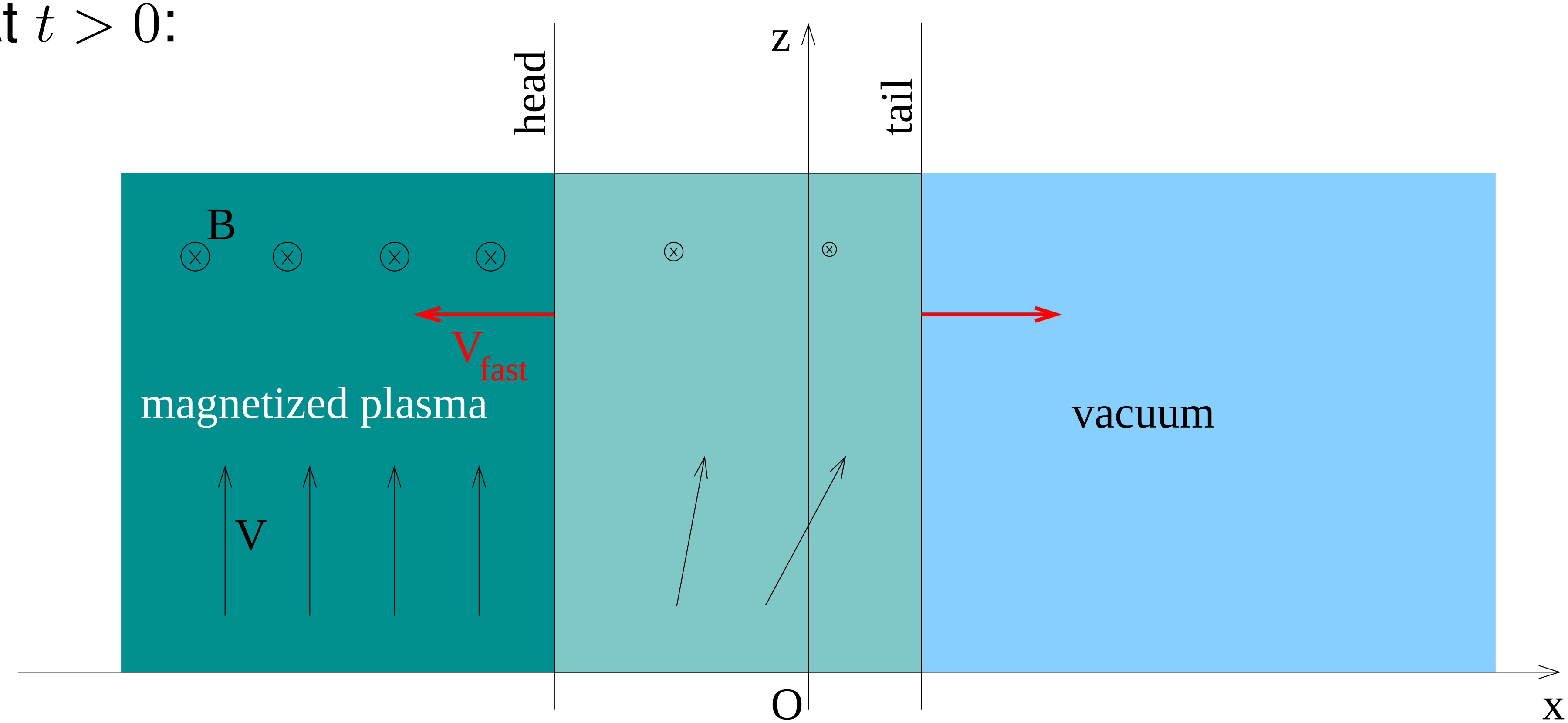
At $t = 0$ two uniform states are in contact:



This Riemann problem allows self-similar solutions that depend only on $\xi = x/t$.

- when right=vacuum, simple rarefaction wave

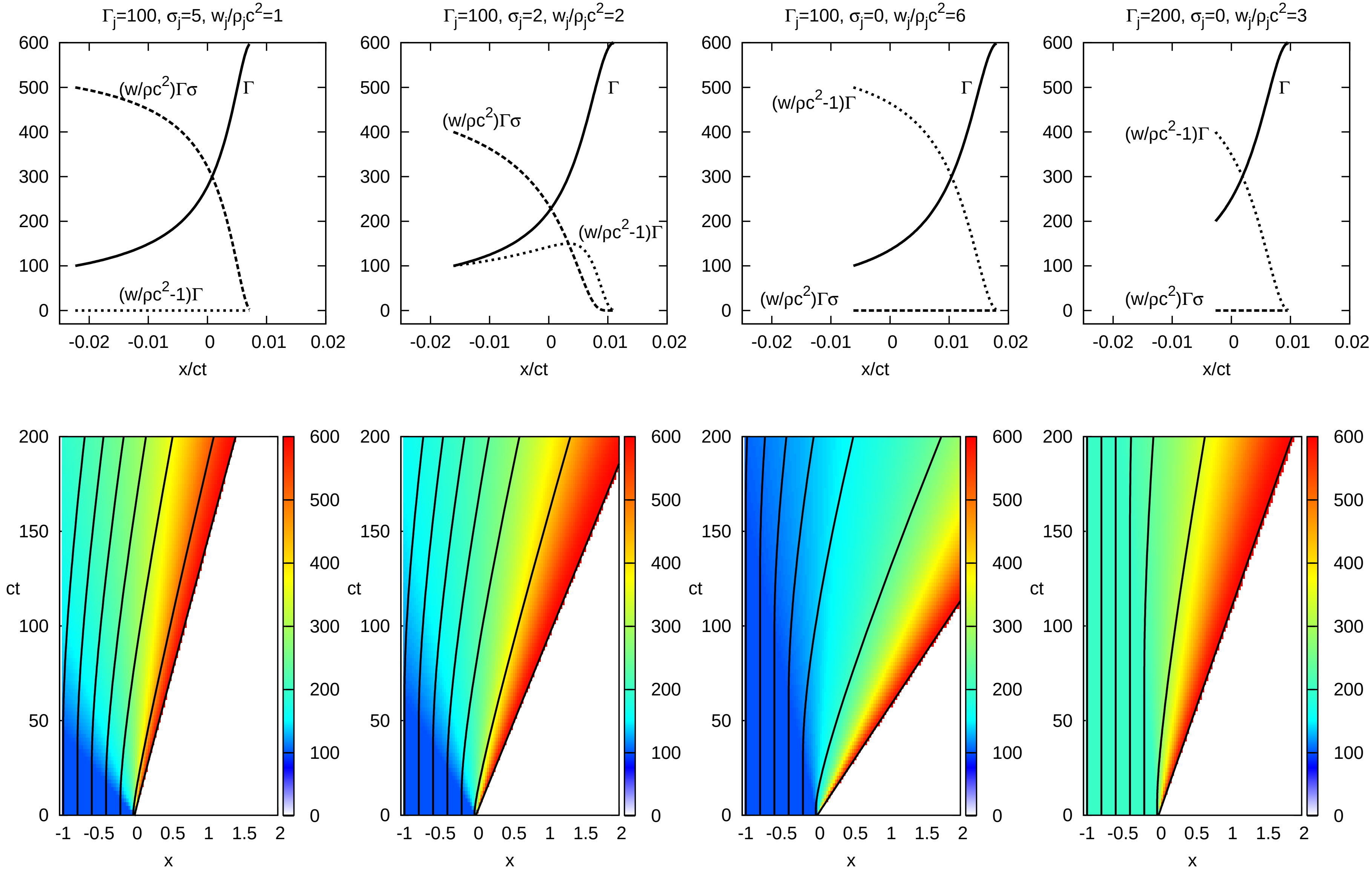
At $t > 0$:



for the cold case the Riemann invariants imply

$$v_x = \frac{1}{\gamma_j}\frac{2\sigma_j^{1/2}}{1+\sigma_j}\left[1-\left(\frac{\rho}{\rho_j}\right)^{1/2}\right],\ \gamma = \frac{\gamma_j\,(1+\sigma_j)}{1+\sigma_j\rho/\rho_j},\ \rho = \frac{4\rho_j}{\sigma_j}\sinh^2\left[\frac{1}{3}\mathrm{arcsinh}\left(\sigma_j^{1/2}-\frac{\mu_j}{2}\frac{x}{t}\right)\right]$$

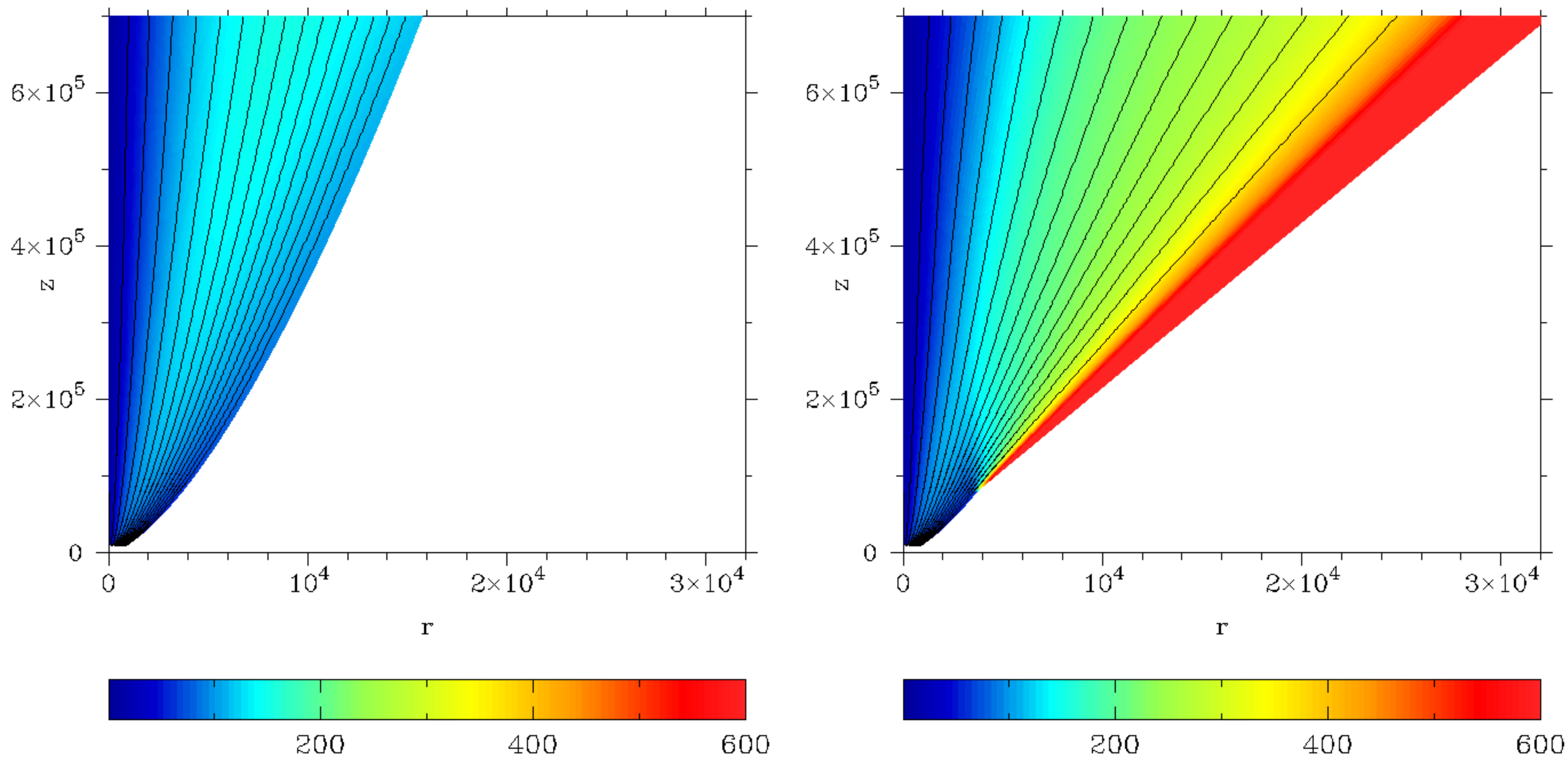
$$V_{head} = -\frac{\sigma_j^{1/2}}{\gamma_j}, \qquad V_{tail} = \frac{1}{\gamma_j}\frac{2\sigma_j^{1/2}}{1+\sigma_j}, \qquad \Delta\vartheta = V_{tail} < 1/\gamma_i$$

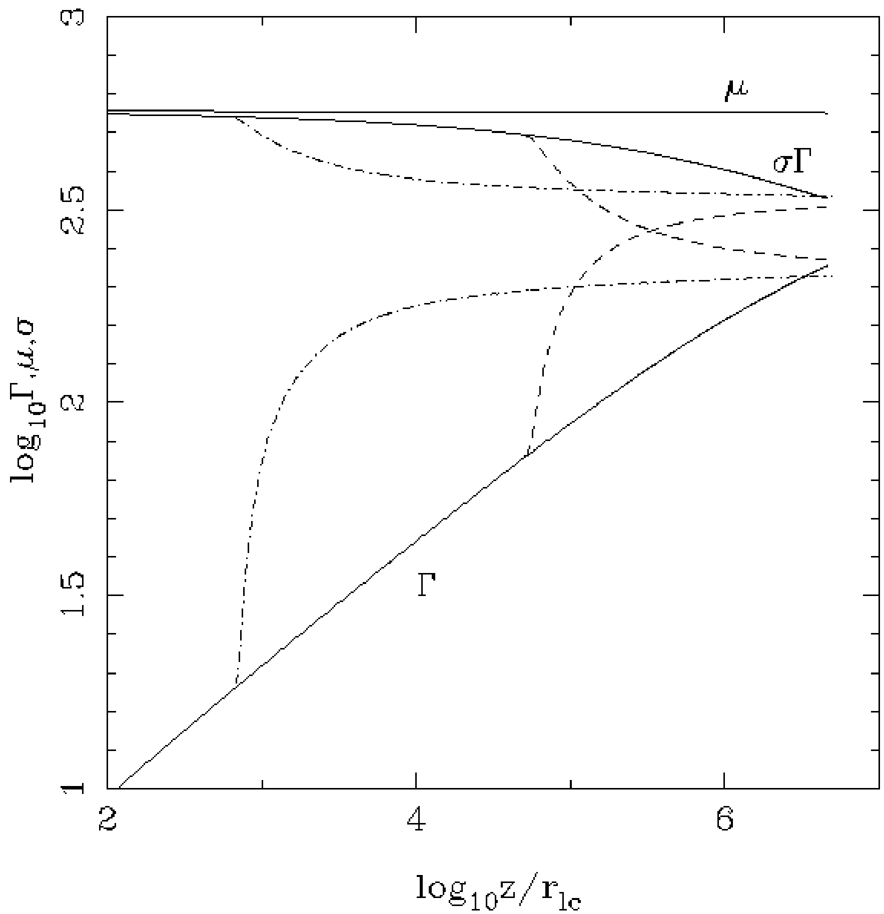


The colour image in the Minkowski diagrams represents the distribution of the Lorentz factor and the contours show the worldlines of fluid parcels initially located at $x_i = -1, -0.8, -0.6, -0.4, -0.2, -0.02, 0$.

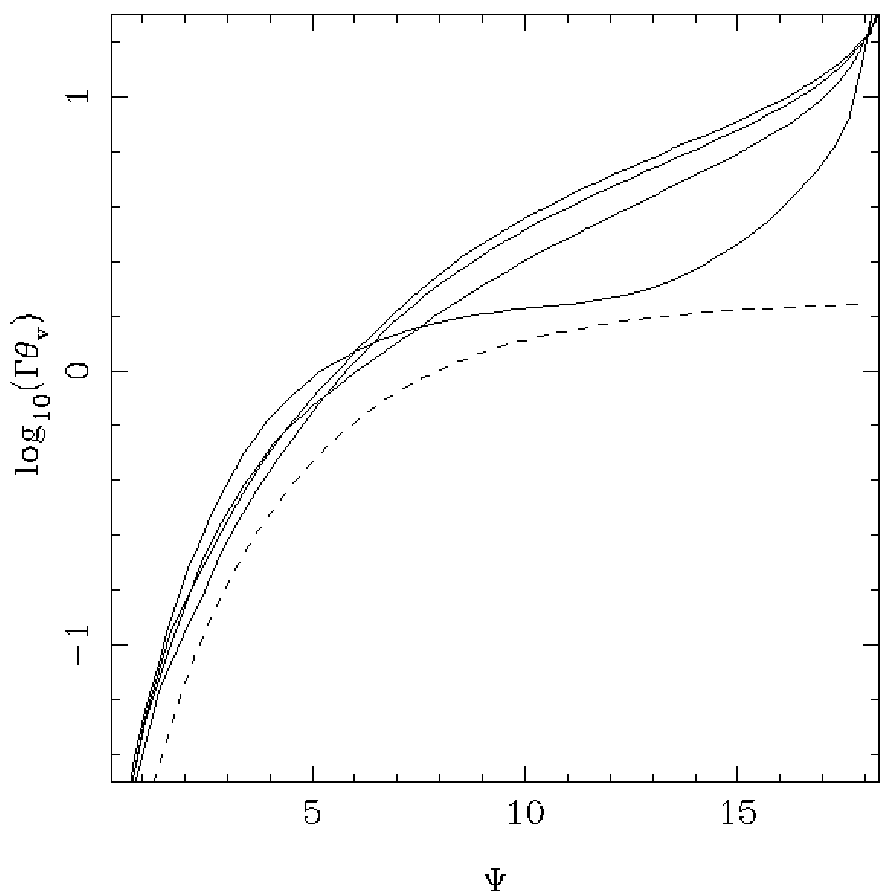
Simulation results

Komissarov, Vlahakis & Königl 2010





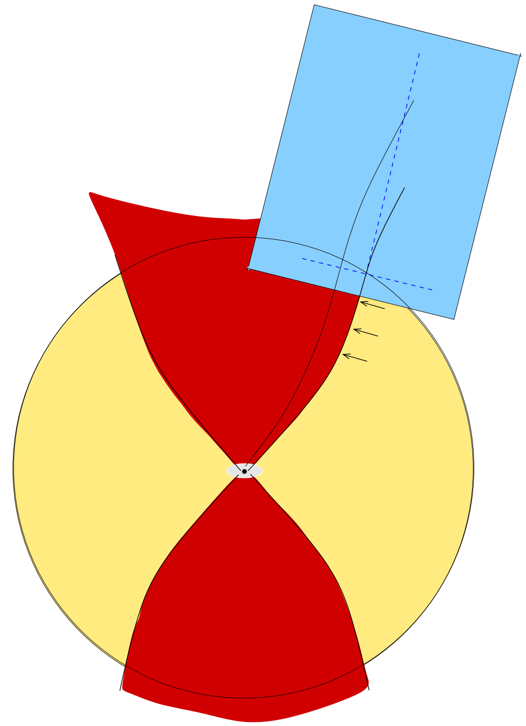
μ
$\sigma\Gamma$
Γ
$\log_{10}\Gamma,\mu,\sigma$
$\log_{10} z/r_{lc}$
1
1.5
2
2.5
3
2
4
6



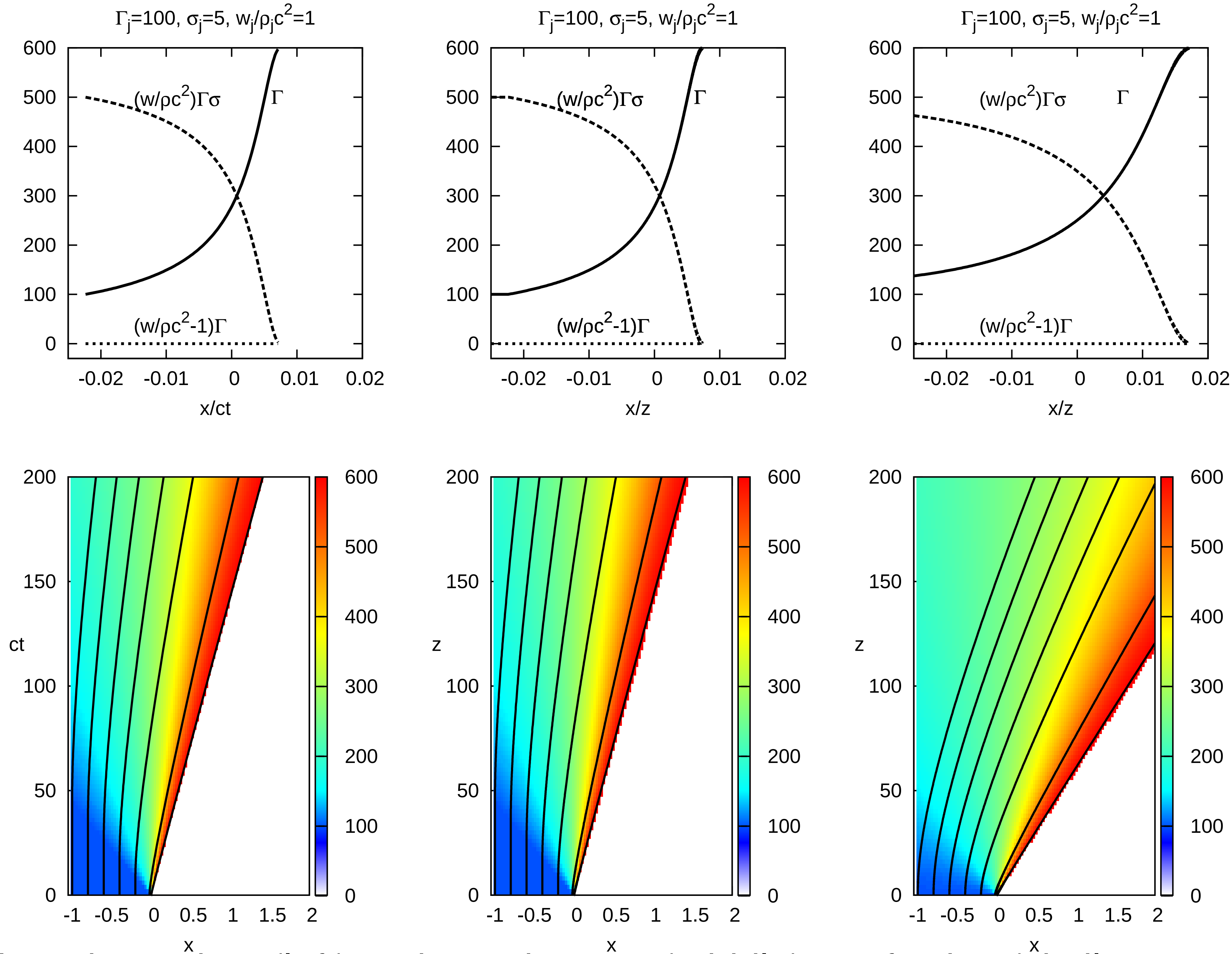
$\log_{10}(\Gamma\theta_v)$
Ψ
−1
0
1
5
10
15

Steady-state rarefaction wave

Sapountzis & Vlahakis (in preparation)



- "flow around a corner"
- planar geometry
- ignoring B_p (nonzero B_y)
- similarity variable x/z (angle θ)
- generalization of the nonrelativistic, hydrodynamic rarefaction (e.g. Landau & Lifshitz)
- in addition, allow for inhomogeneity in the "left" state



time-dependent (left) and steady-state (middle) rarefaction (similar; $ct \to z$)

right: combination of rarefaction and nonuniform initial flow

Summary

⋆ The collimation-acceleration paradigm provides a viable explanation of the dynamics of relativistic jets
(similarly to non-relativistic ones)

- bulk acceleration up to Lorentz factors $\gamma_\infty \gtrsim 0.5\frac{\mathcal{E}}{Mc^2}$
- however, $\gamma\vartheta \sim 1$ making the breaks problematic

⋆ Rarefaction acceleration

- further increases γ
- makes GRB jets with $\gamma\vartheta \gg 1$

⋆ Future work

- rarefaction in 3 dimensions?
- use pressure distributions inside the star from stellar-evolution models;
  also finite density of the exterior limits the terminal γ (?)