Magnetized Outflows

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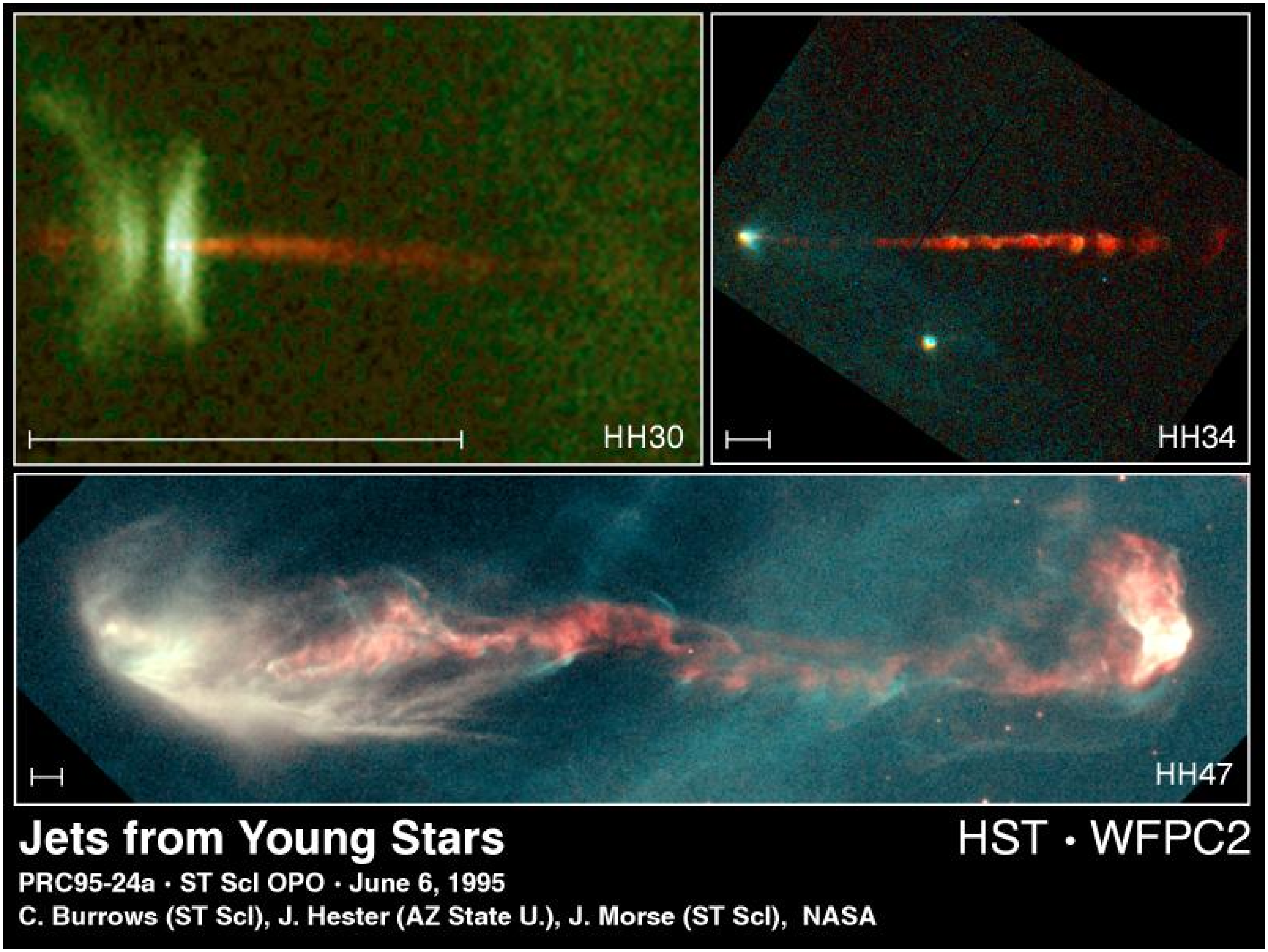
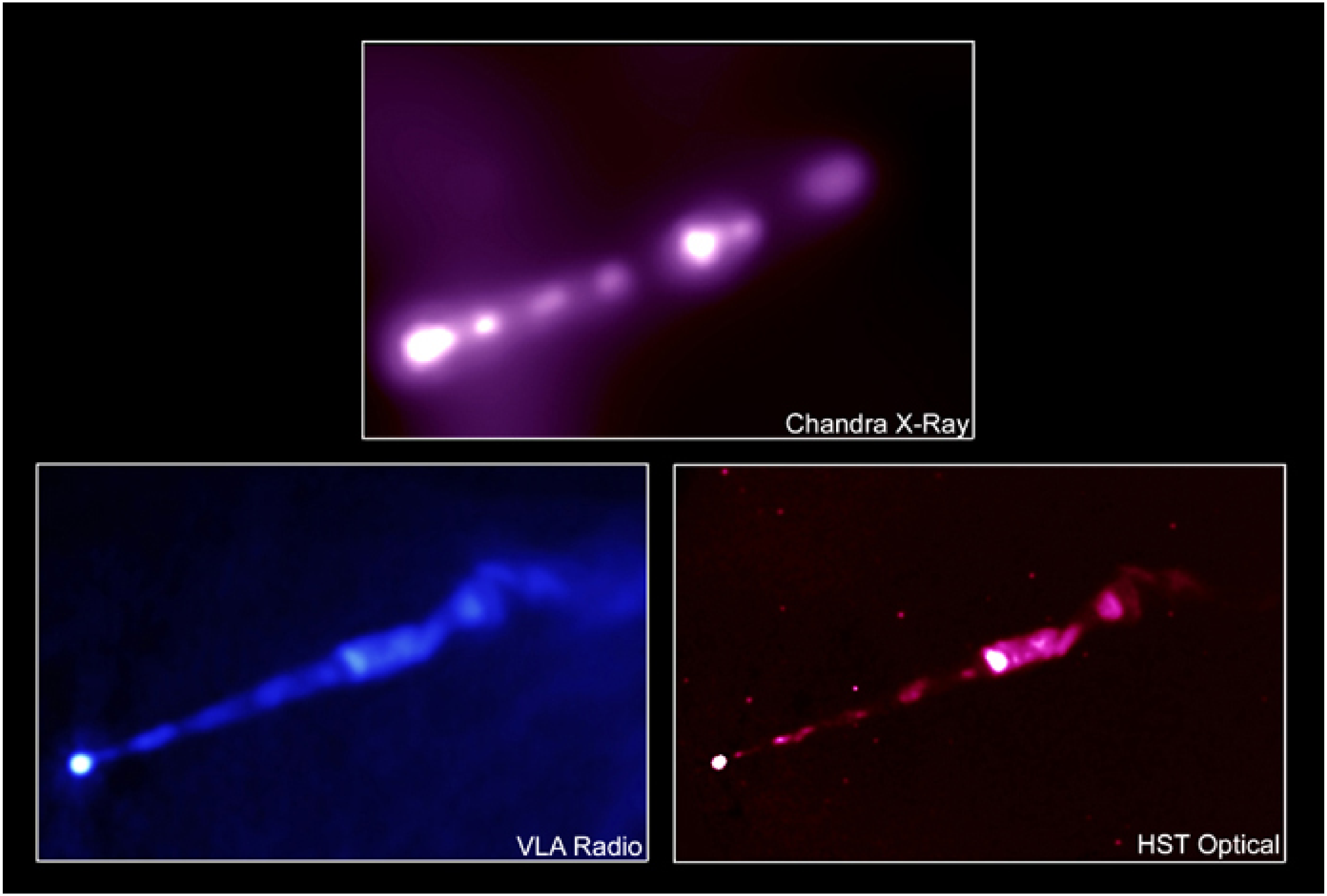
outline

- introduction: astrophysical jets
- the MHD description
  - structure of flows
  - acceleration-collimation mechanisms
- related issues in GRB outflows
- alternatives

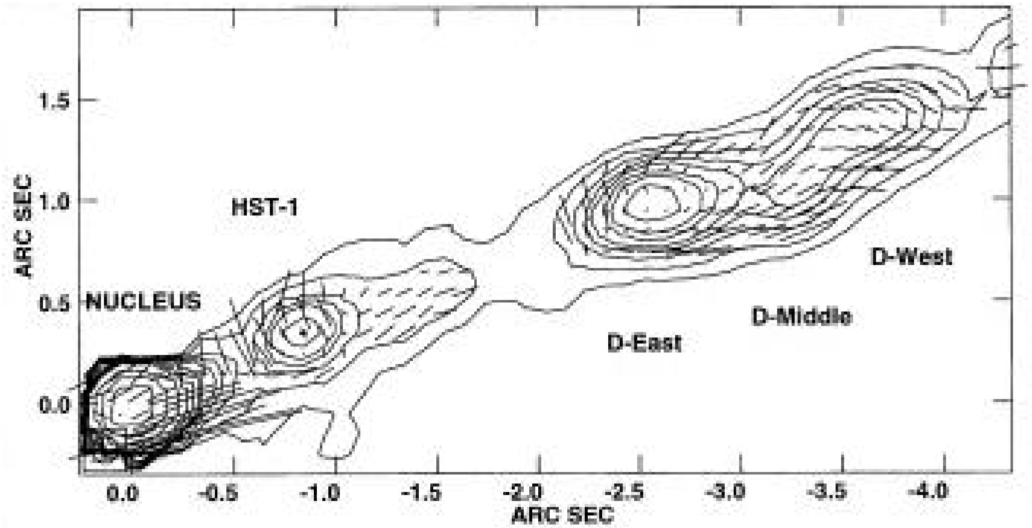


(scale =1000 AU, $V_\infty = afew100$km/s)

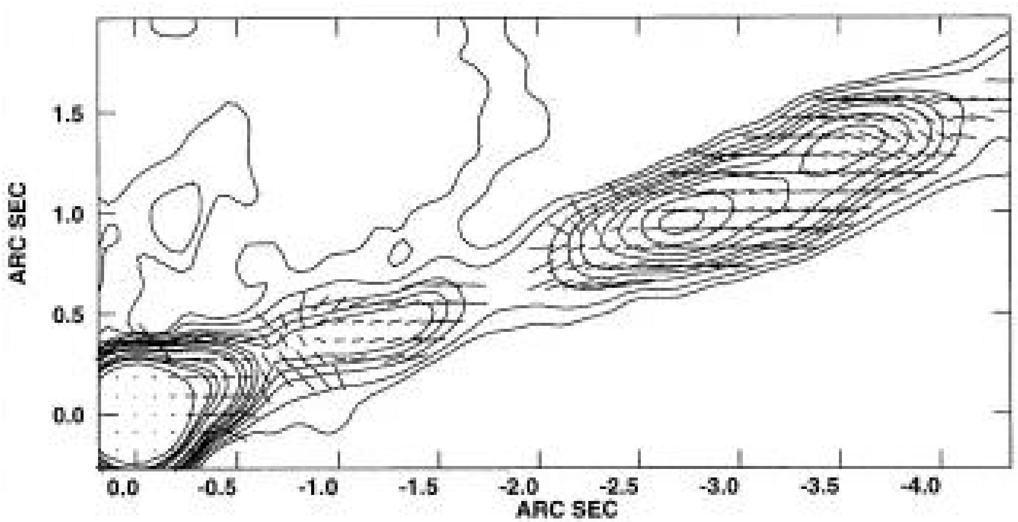

Herbig-Haro 49/50
NASA / JPL-Caltech / J. Bally (Univ. of Colo.)
Spitzer Space Telescope • IRAC
sig06-002



collimation at $\sim$100 Schwarzschild radii, $\gamma_\infty \sim 10$



M87 - OPTICAL POLARIZATION



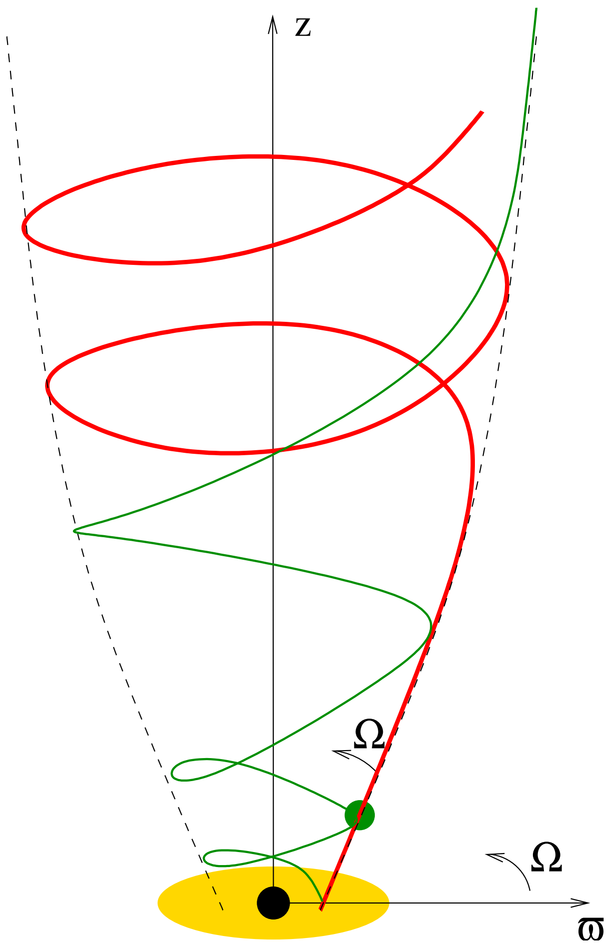
M87 - RADIO POLARIZATION

We need magnetic fields

- to extract energy (Poynting flux)
- to extract angular momentum
- to transfer energy and angular momentum to matter
- to collimate outflows and produce jets
- for synchrotron emission
- to explain polarization maps

The structure of a magnetized outflow

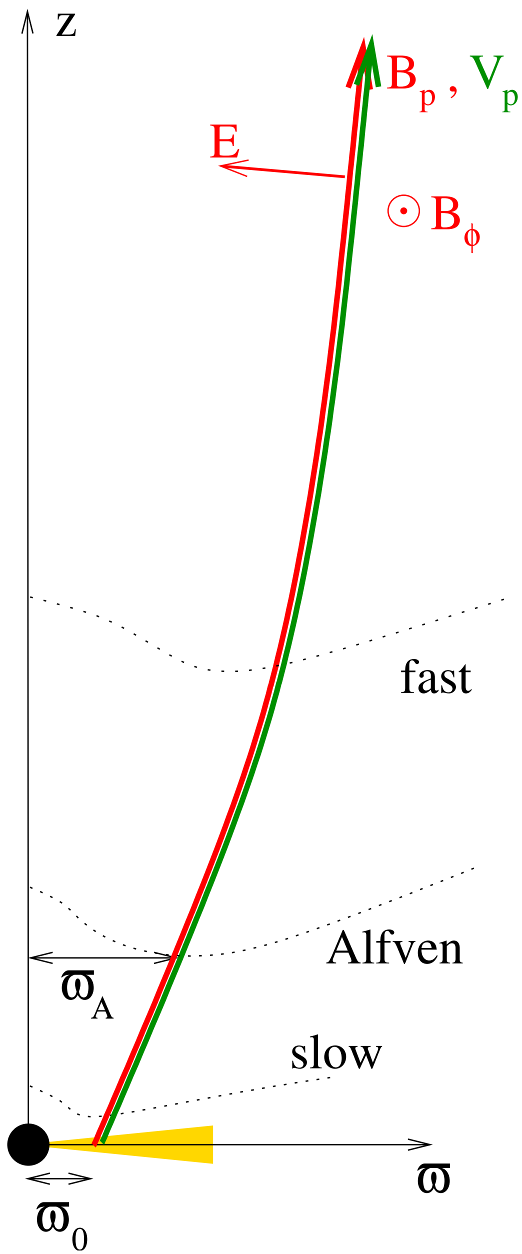
A rotating source (disk or star) creates an axisymmetric outflow



Assume steady-state and ideal magnetohydrodynamics (MHD):

- Initially $V_\phi = \varpi\Omega \gg V_p$, $B_p \gtrsim B_\phi$
- Flux freezing: velocity $\parallel \boldsymbol{B}$ plus $\boldsymbol{E} \times \boldsymbol{B}$ drift $\rightarrow \boldsymbol{V}_p \parallel \boldsymbol{B}_p$.
- $\boldsymbol{B}_p \propto 1/\varpi^2$, $\boldsymbol{B}_\phi \propto 1/\varpi$

Critical surfaces



Regularity conditions:

- slow $\rightarrow$ mass-loss rate $\dot{M}_j = \dfrac{dM}{dt}$
- Alfvén $\rightarrow$ angular momentum rate $L\dot{M}_j$ (for relativistic flows, Alfvén = light surface $\varpi_{\rm A} = c/\Omega$)
- fast $\rightarrow$ acceleration (nontrivial)

Angular momentum extraction

$L = \mu\Omega{\varpi_{\rm A}}^2$ where $\mu = \dfrac{\dfrac{dE}{dSdt}}{\dfrac{dM}{dSdt}c^2}$ = maximum Lorentz factor

So rate of angular momentum $= \mu\Omega\varpi_{\rm A}^2\dot{M}_j$ (initially carried by the field and later by the matter).

In the disk, rate $= \Omega\varpi_0^2\dot{M}_a$. If these are equal, $\dfrac{\dot{M}_j}{\dot{M}_a} = \dfrac{\varpi_0^2}{\mu\varpi_{\rm A}^2}$.

- in YSO confirmed by HST observations! (Woitas et al 2005)
- in GRBs $\dot{M}_a = 0.01 M_\odot s^{-1}\left(\dfrac{\dot{M}_j}{10^{-6}M_\odot s^{-1}}\right)\left(\dfrac{\mu}{400}\right)\left(\dfrac{\varpi_{\rm A}/\varpi_0}{5}\right)^2$

  (cf Popham et al 1999)

  (This is equivalent to $\dfrac{dE}{dt} \equiv \mu\dot{M}_j c^2 = \dfrac{GM\dot{M}_a}{\varpi_0}$.)

Acceleration mechanisms

- thermal (due to ∇P) $\rightarrow$ velocities up to C_s
- magnetocentrifugal (beads on wire - Blandford & Payne)
  - in reality due to magnetic pressure
  - initial half-opening angle $\vartheta > 30^o$
  - the $\vartheta > 30^o$ not necessary for nonnegligible P
  - velocities up to $\varpi_0 \Omega$
- relativistic thermal (thermal fireball) gives $\gamma \sim \xi_i$, where $\xi = \dfrac{\text{enthalpy}}{\text{mass} \times c^2}$.
- magnetic – up to $\gamma_\infty = \mu$? Not always possible.

All acceleration mechanisms can be seen in the energry conservation equation

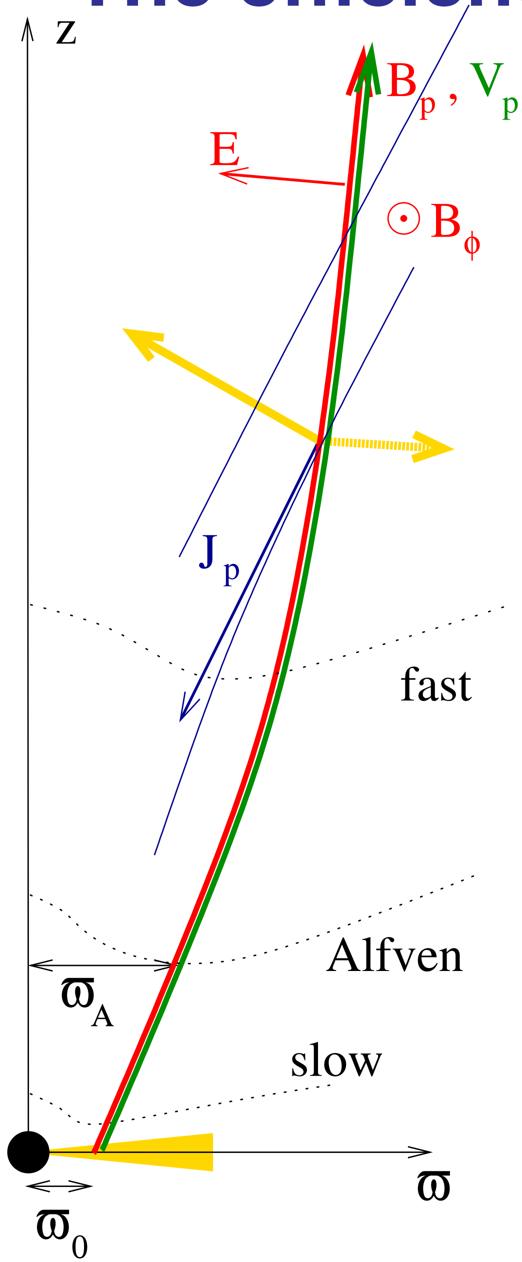
$$\mu = \xi\gamma + \frac{\Omega}{\Psi_A c^2}\varpi B_\phi$$

where μ, Ω, Ψ_A(=mass-to-magnetic flux ratio) are constants of motion.

So $\gamma \uparrow$ when $\xi \downarrow$ (thermal, relativistic thermal), or, $\varpi B_\phi \downarrow \Leftrightarrow I_p \downarrow$ (magnetocentrifugal, magnetic).

At fast $\gamma \approx \mu^{1/3} \ll \mu$. Can we reach $\gamma_\infty \sim \mu$ in the superfast regime?

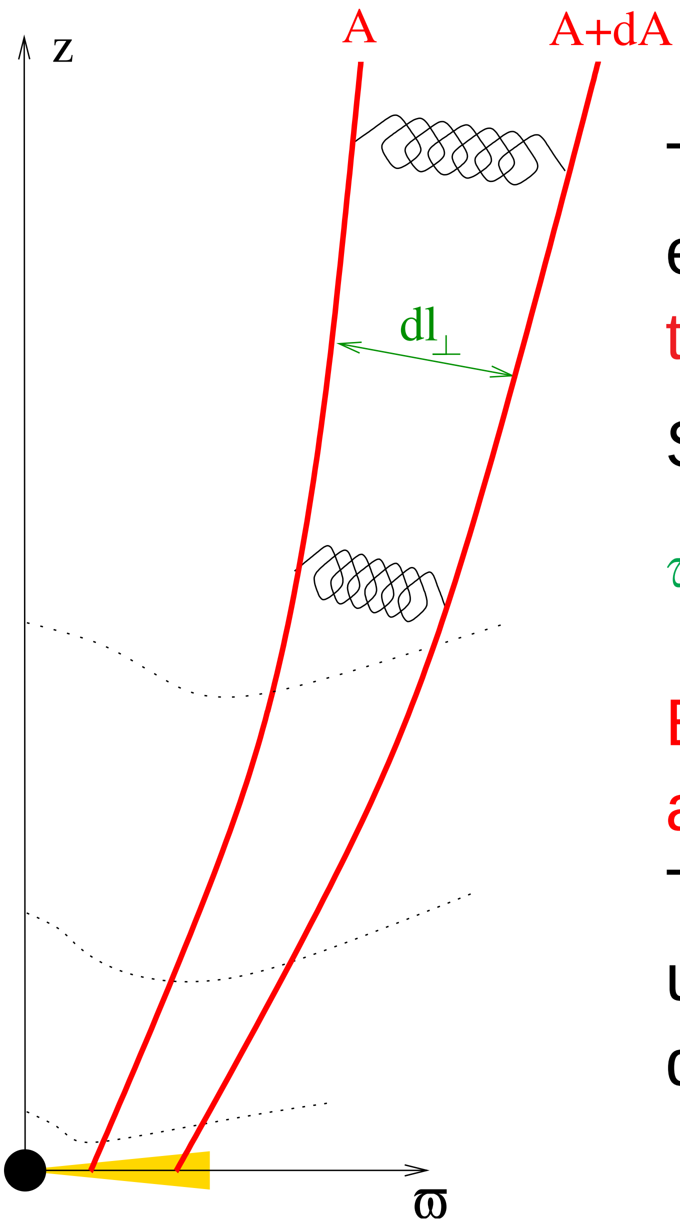
The efficiency of the magnetic acceleration



The $\boldsymbol{J}_p \times \boldsymbol{B}_\phi$ force strongly depends on the angle between field-lines and current-lines.

Are we free to choose these two lines? NO! All MHD quantities are related to each other and should be found by solving the full system of equations.

From Ferraro's law, $\varpi B_\phi \approx \varpi^2 B_p \Omega / V_p$. So, the transfield force-balance determines the acceleration.



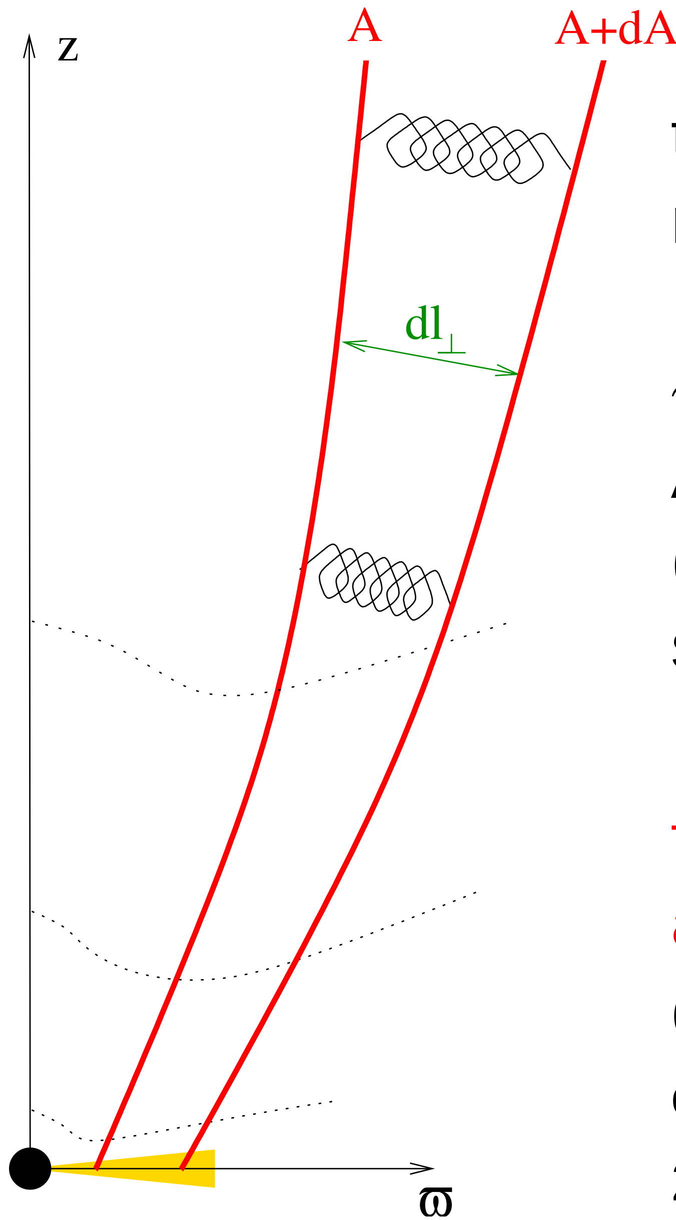
The magnetic field minimizes its energy under the condition of keeping the magentic flux constant.

So, $\varpi B_\phi \downarrow$ for decreasing

$$\varpi^2 B_p = \frac{\varpi^2}{2\pi\varpi dl_\perp}(\underbrace{B_p dS}_{dA}) \propto \frac{\varpi}{dl_\perp}.$$

Expansion with $dl_\perp/\varpi$ leads to acceleration (Vlahakis 2004).
The expansion ends in a more-or-less uniform distribution $\varpi^2 B_p \approx A$ (in a quasi-monopolar shape).

Conclusions on the magnetic acceleration



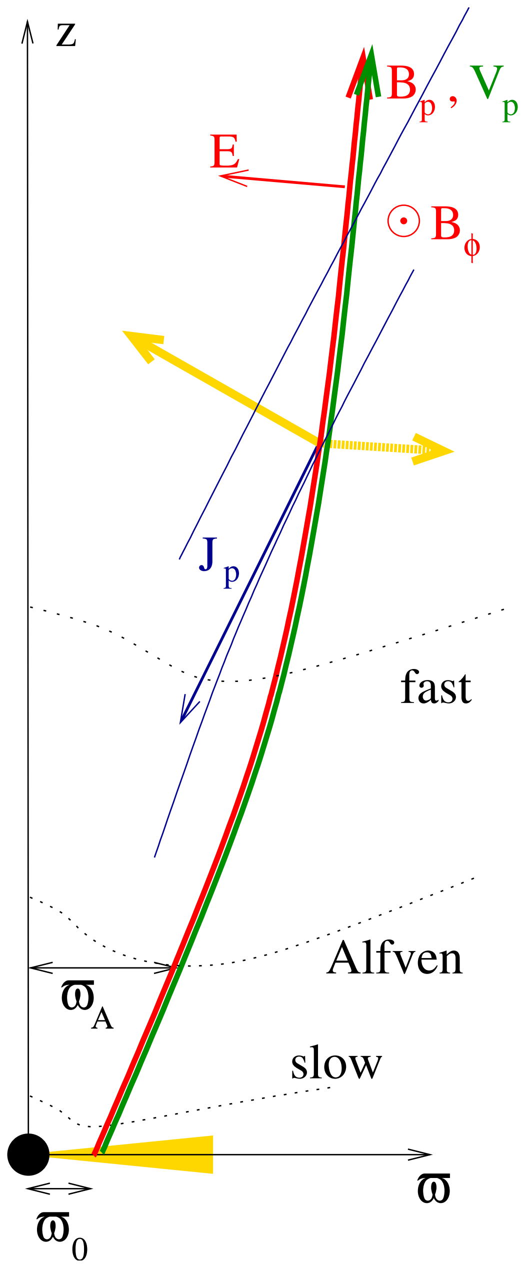
If we start with a uniform distribution the magnetic energy is already minimum → no acceleration. Example: Michel's (1969) solution which gives $\gamma_\infty \approx \mu^{1/3} \ll \mu$.

Also Beskin et al (1998); Bogovalov (2001) who found quasi-monopolar solutions.

For any other (more realistic) initial field distribution we have efficient acceleration!

(For more details and an analytical estimation of the efficiency, see Vlahakis 2004, ApSS 293, 67).

On the collimation



The $\boldsymbol{J}_p \times \boldsymbol{B}_\phi$ force contributes to the collimation (hoop-stress paradigm). In relativistic flows the electric force plays an opposite role (a manifestation of the high inertia of the flow).

- collimation by an external wind (Bogovalov & Tsinganos 2005, for AGN jets)
- surrounding medium may play a role (in the collapsar model)
- self-collimation mainly works at small distances where the velocities are mildly relativistic (Vlahakis & Königl 2003)

Application to GRB outflows

- is steady-state reasonable?
  - $\Omega \sim 10^4$rad s^{-1} $\Rightarrow$ many rotations during the engine's activity (~ 10s)
  - the outflow is faster than the fastest signals propagating inside the flow $\Rightarrow$ different shells are causally disconnected (frozen pulse)
    (proof can be found in Vlahakis & Königl 2003, ApJ, 596, 1080)

- $\mathcal{E} = \frac{c}{4\pi} \underbrace{\frac{\varpi\Omega}{c} B_p}_{E} B_\phi \times$ area $\times$ duration $\Rightarrow$

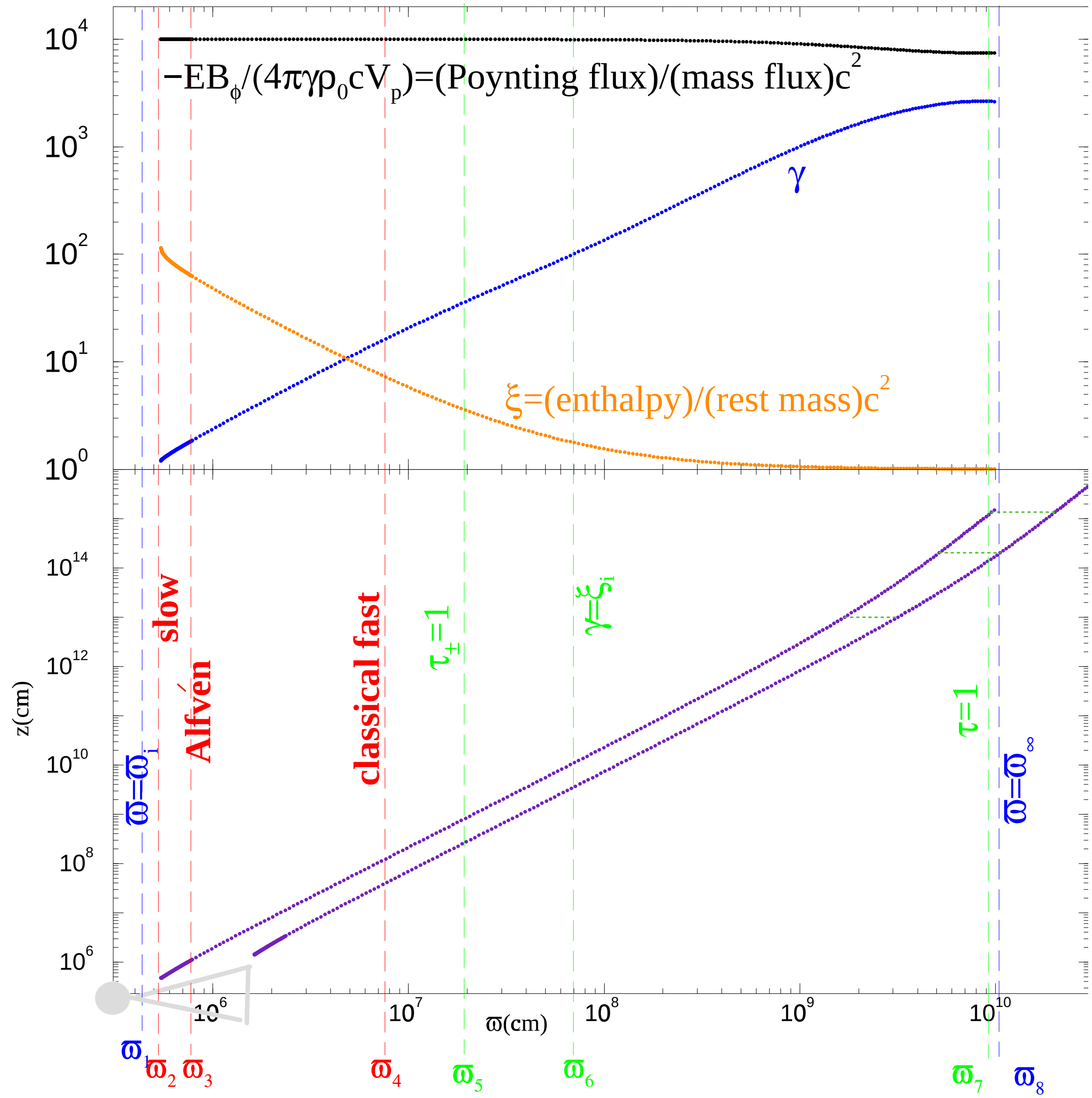
$$\frac{B_p B_\phi}{(2 \times 10^{14}\text{G})^2} = \left[\frac{\mathcal{E}}{5 \times 10^{51}\text{erg}}\right] \left[\frac{\text{area}}{4\pi \times 10^{12}\text{cm}^2}\right]^{-1} \left[\frac{\varpi\Omega}{10^{10}\text{cm s}^{-1}}\right]^{-1} \left[\frac{\text{duration}}{10\text{s}}\right]^{-1}$$

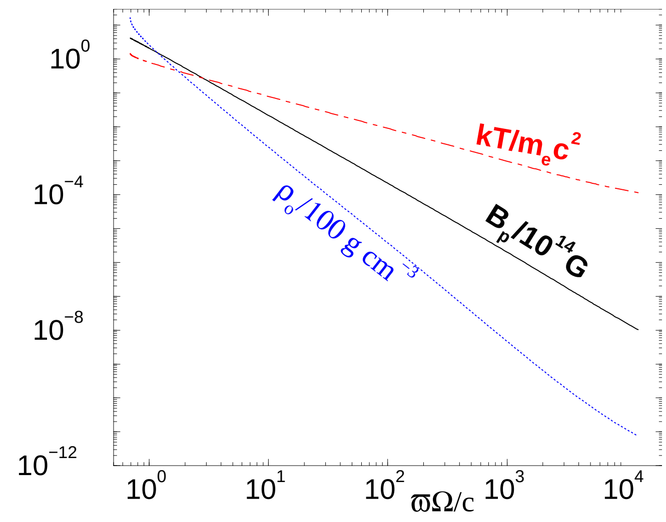
  - from the BH: $B_p \gtrsim 10^{15}$G (small B_ϕ, small area)
  - from the disk: smaller magnetic field required $\sim 10^{14}$G

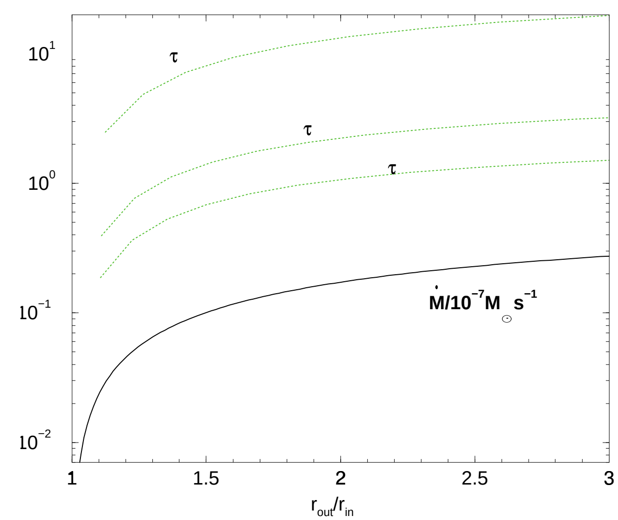
  - If initially $B_p/B_\phi > 1$, a **trans-Alfvénic** outflow is produced.

  - If initially $B_p/B_\phi < 1$, the outflow is **super-Alfvénic** from the start.

Trans-Alfvénic Jets (NV & Königl 2001, 2003a)

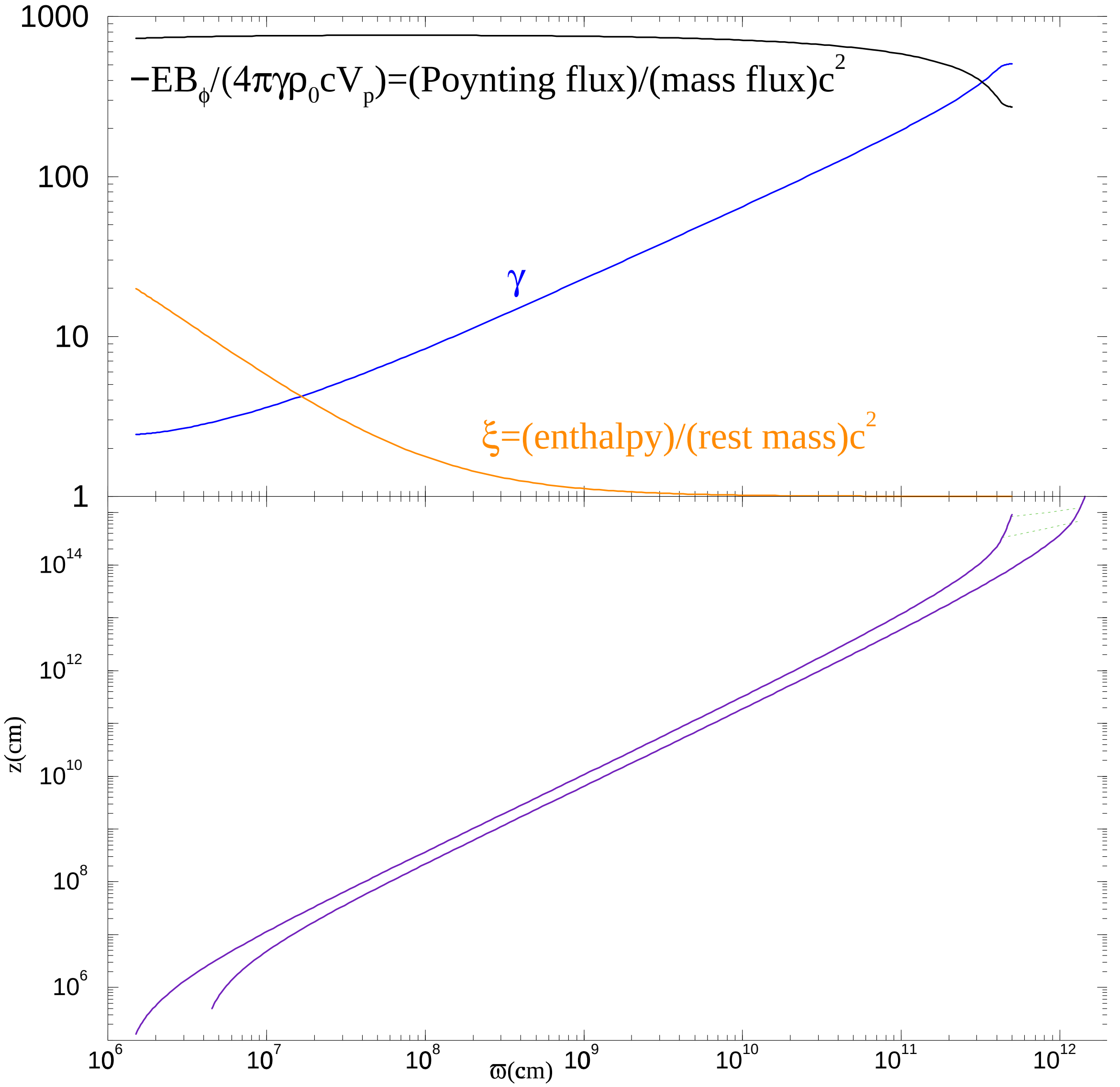


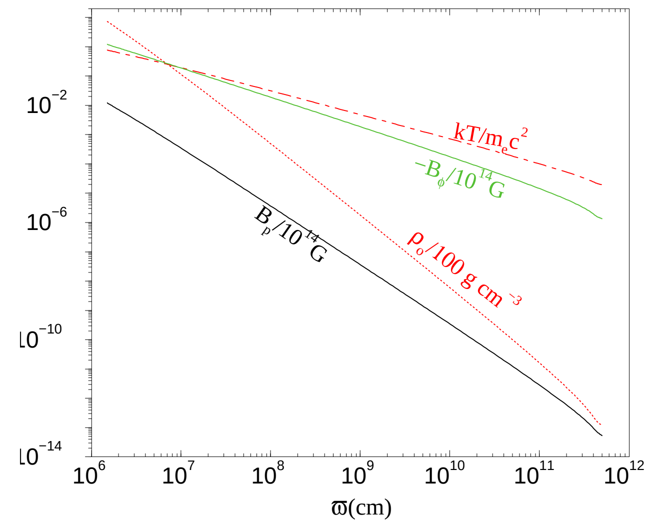


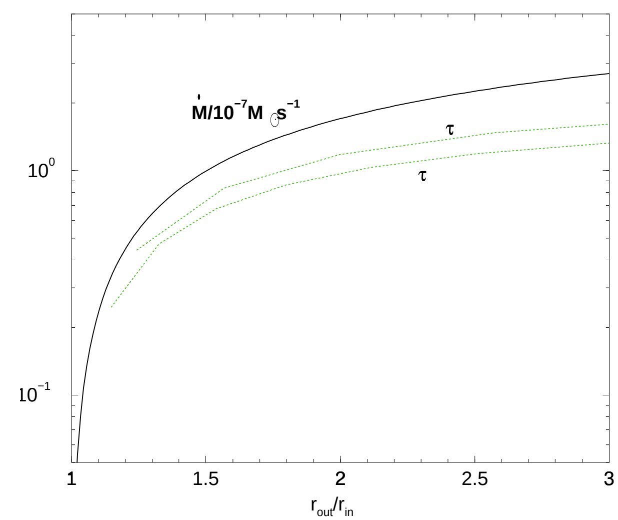


- $\varpi_1 < \varpi < \varpi_6$: Thermal acceleration - force free magnetic field ($\gamma \propto \varpi$, $\rho_0 \propto \varpi^{-3}$, $T \propto \varpi^{-1}$, $\varpi B_\phi = const$, parabolic shape of fieldlines: $z \propto \varpi^2$)
- $\varpi_6 < \varpi < \varpi_8$: Magnetic acceleration ($\gamma \propto \varpi$, $\rho_0 \propto \varpi^{-3}$)
- $\varpi = \varpi_8$: cylindrical regime - equipartition $\gamma_\infty \approx (-EB_\phi/4\pi\gamma\rho_0 V_p)_\infty$

Super-Alfvénic Jets (NV & Königl 2003b)

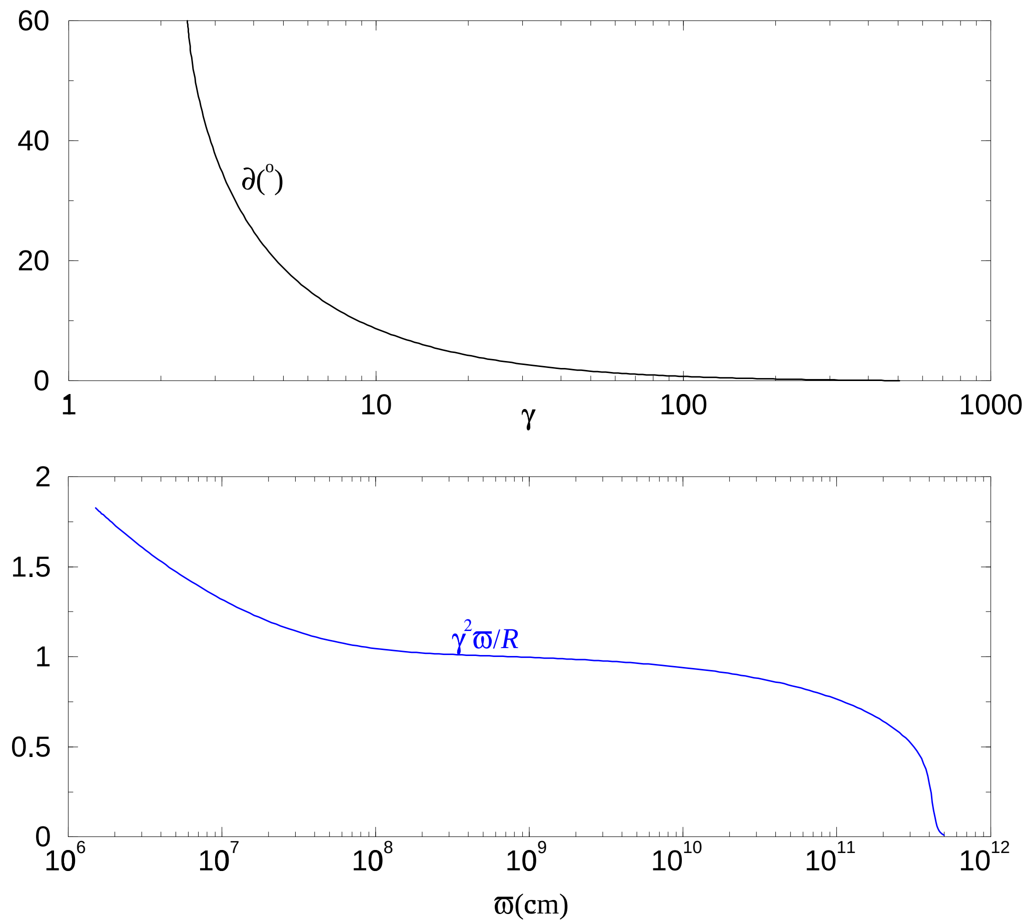






- Thermal acceleration ($\gamma \propto \varpi^{0.44}$, $\rho_0 \propto \varpi^{-2.4}$, $T \propto \varpi^{-0.8}$, $B_\phi \propto \varpi^{-1}$, $z \propto \varpi^{1.5}$)
- Magnetic acceleration ($\gamma \propto \varpi^{0.44}$, $\rho_0 \propto \varpi^{-2.4}$)
- cylindrical regime - equipartition $\gamma_\infty \approx (-EB_\phi/4\pi\gamma\rho_0 V_p)_\infty$

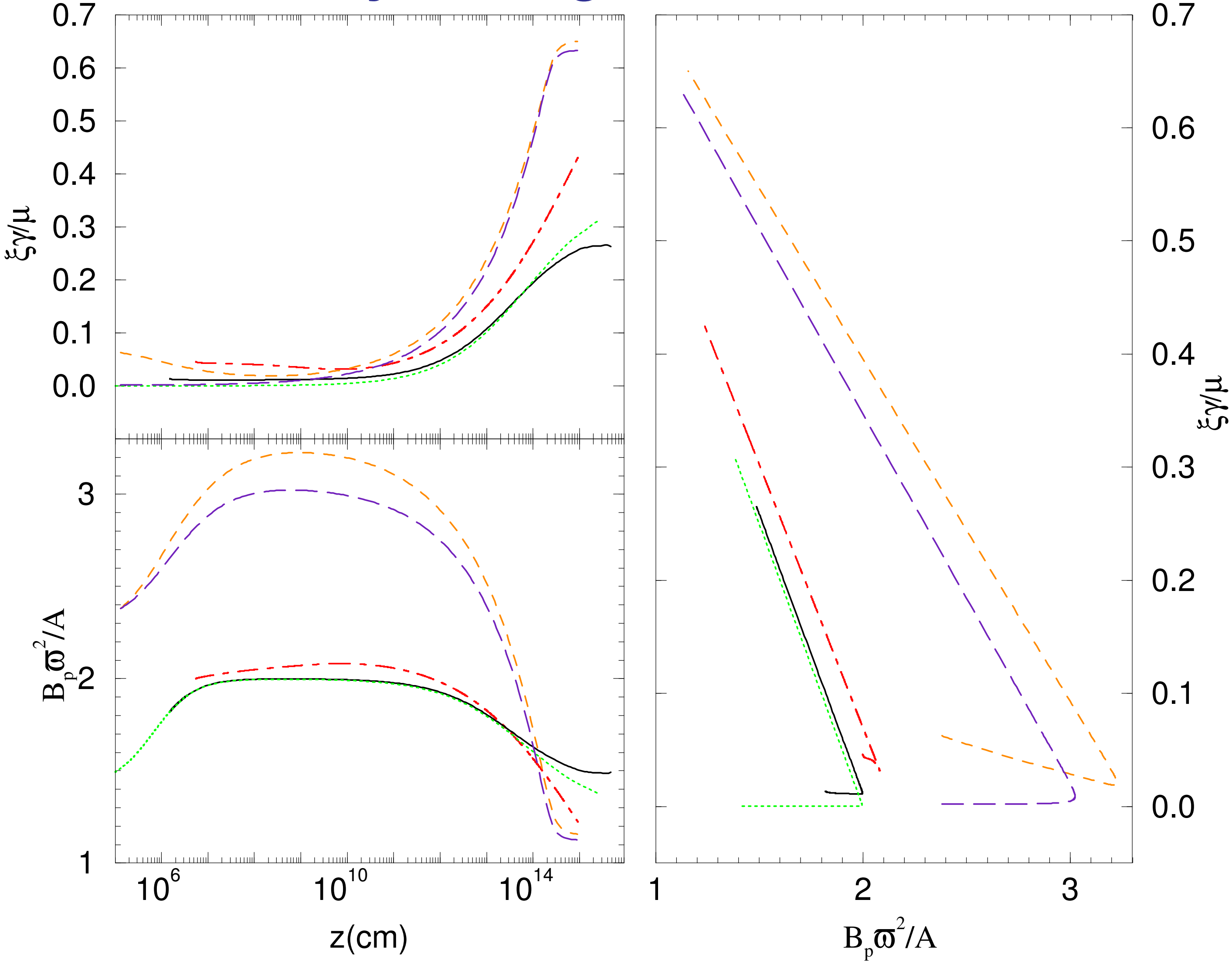
Collimation



⋆ At $\varpi = 10^8$cm – where $\gamma = 10$ – the opening half-angle is already $\vartheta = 10^o$

⋆ For $\varpi > 10^8$cm, collimation continues slowly ($\mathcal{R} \sim \gamma^2 \varpi$)

Efficieny of magnetic acceleration

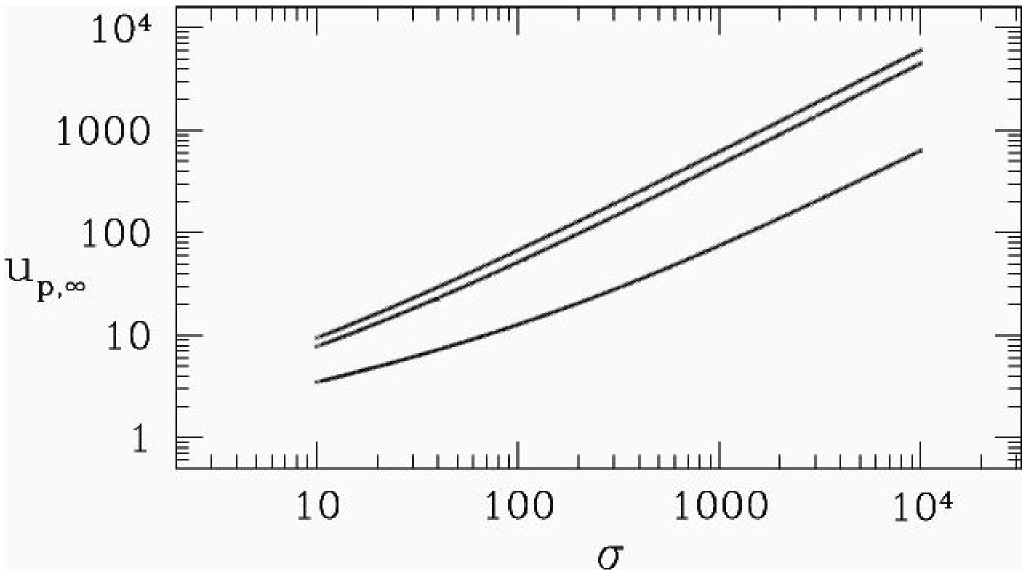


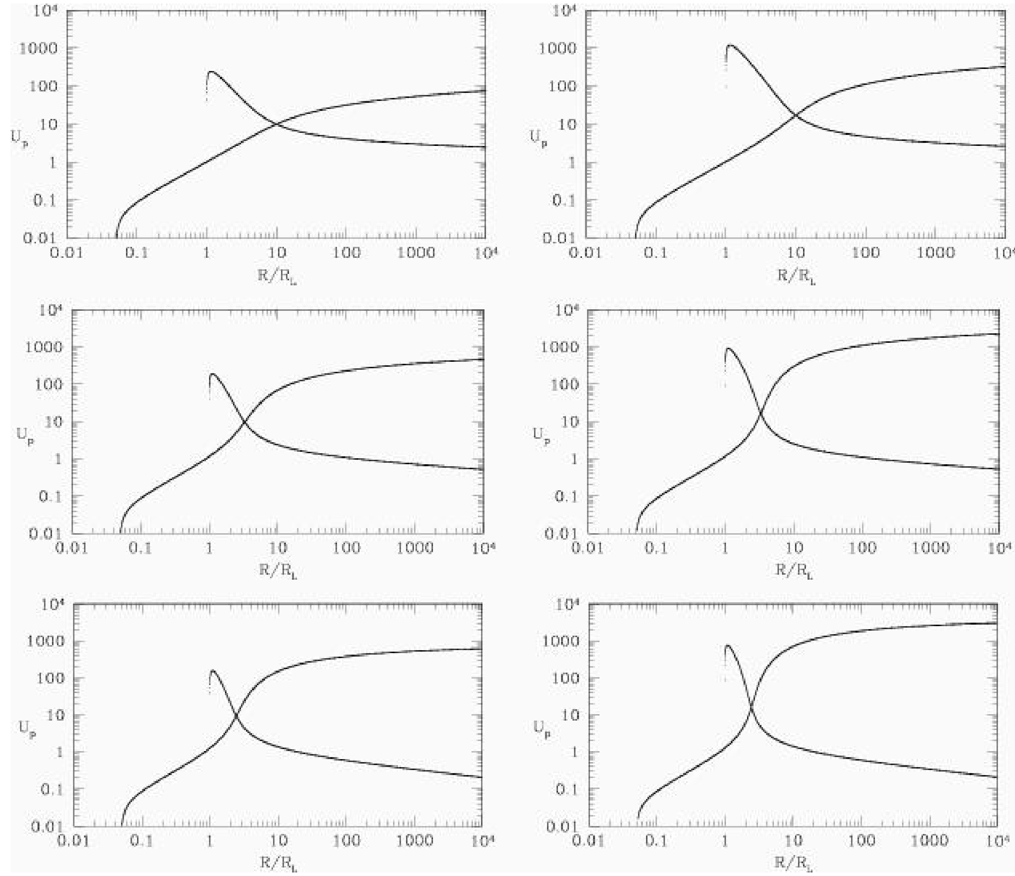
⋆ Linear relation γ/μ–$\varpi^2 B_p/A$ in the superfast regime

⋆ Asymptotically $\varpi^2 B_p/A \sim 1$

Other solutions

- Fendt & Ouyed (2004):

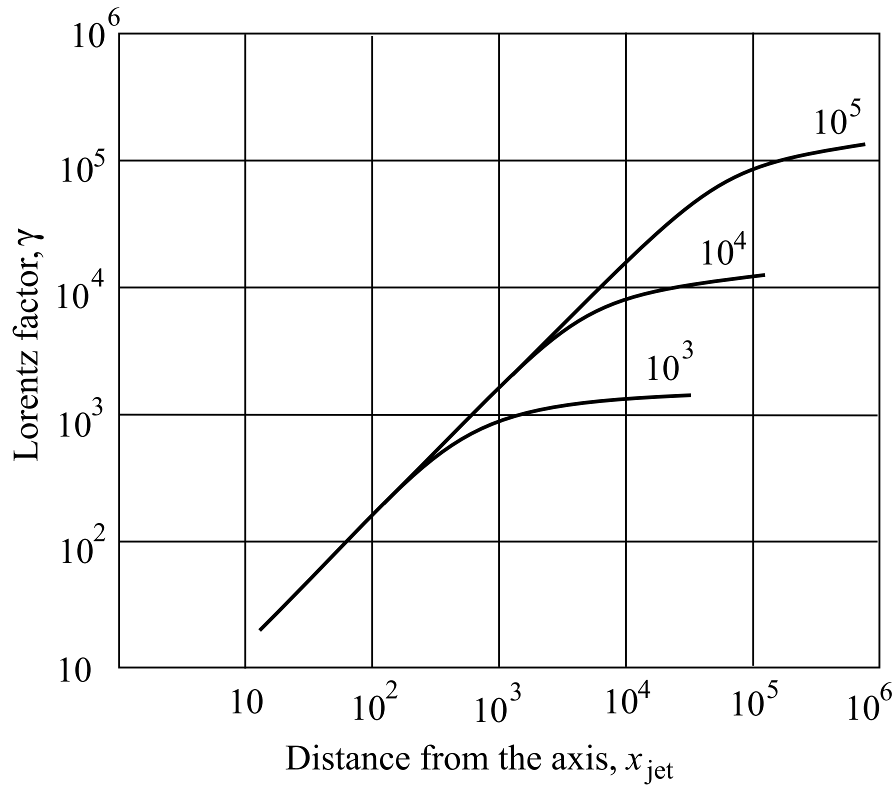




They used prescribed fieldlines (with $\varpi^2 B_p / A \propto \varpi^{-q}$) and found efficient acceleration with γ_∞ (their $u_{p,\infty}$) $\sim \mu$ (their σ).

Although the analysis is not complete (the transfield is not solved), the results show the relation between line-shape and efficiency.

- Beskin & Nokhrina (2006):



By expanding the equations wrt $2/\mu$ (their $1/\sigma$) they found a parabolic solution. The acceleration in the superfast regime is efficient, reaching $\gamma_\infty \approx \mu$.

The scaling $\gamma \propto \varpi$ is the same as in Vlahakis & Königl (2003a).

- simulations:
  many nice works (e.g., by De Villiers; Proga; McKinney), but still there are numerical problems to cover all the outflow and high Lorentz factors.

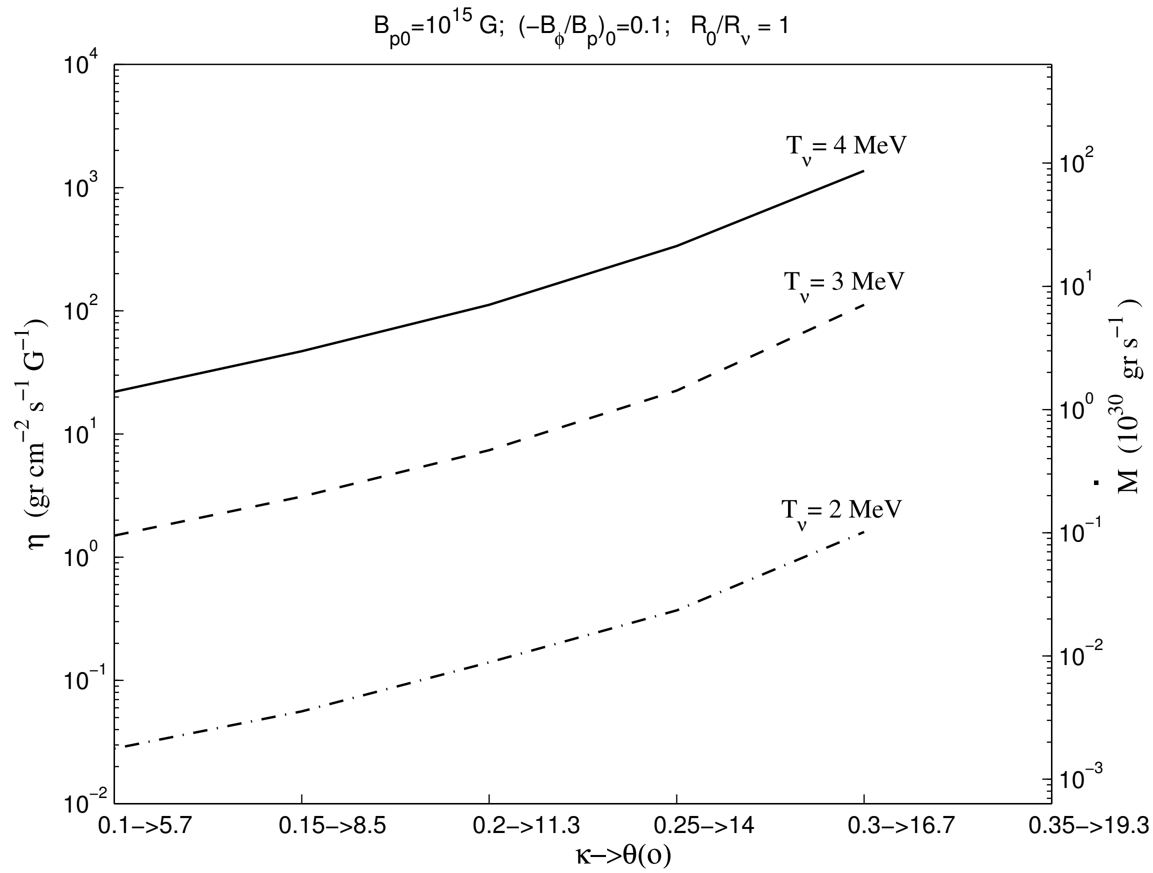
  Probably enough to solve up to the fast point?

  (work in progress to solve the superfast part in a non-self-similar way, Sapountzis & Vlahakis).

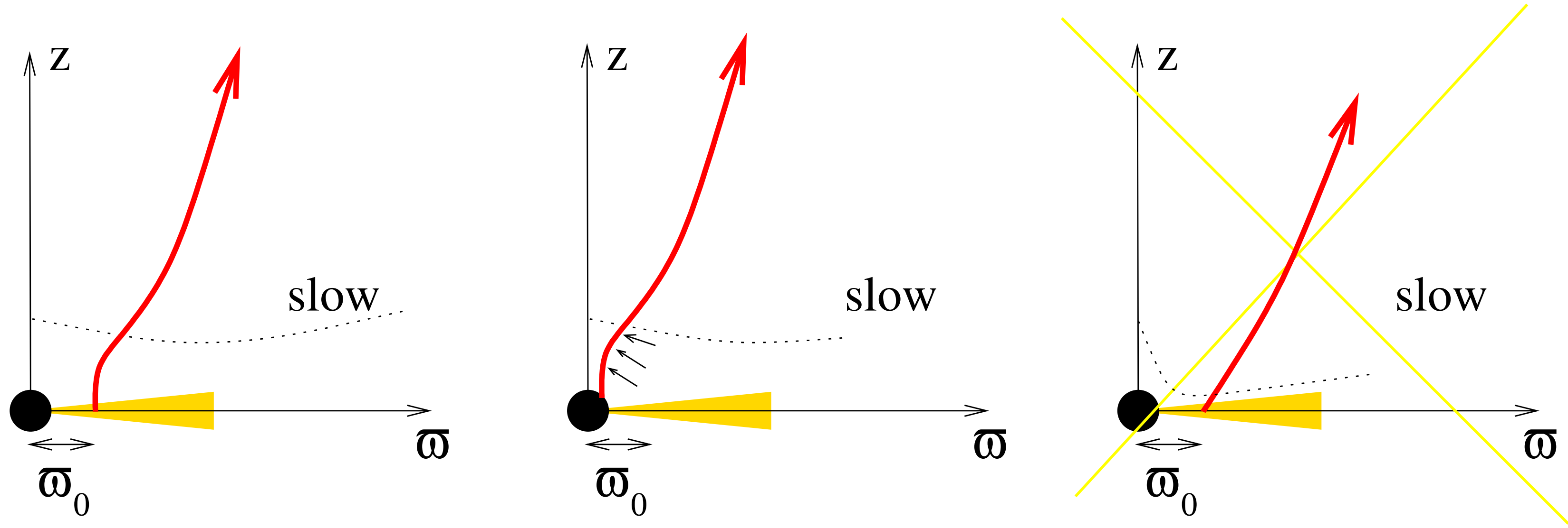
On the mass loading

In all previous solutions gravity was ignored, so no slow point → the issue of the mass-loading was not directly addressed.

Levinson (ApJ in press, astro-ph/0602358), analysed the trans-slow regime for various prescribed line-shapes in Schwarzschild geometry (with neutrino heating included).

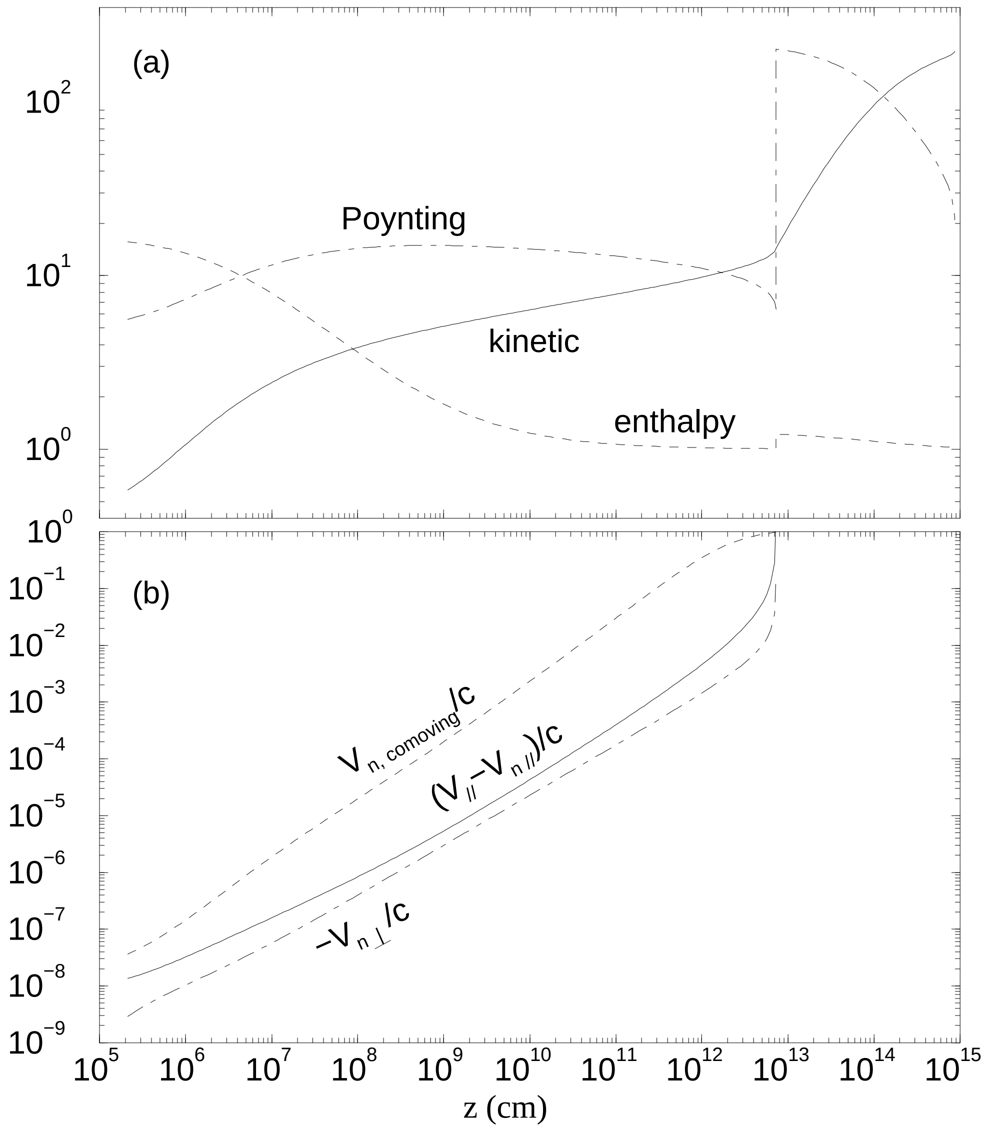


Too high $\dot{M}_j$ for centrifugally-driven winds ($z_s \ll \varpi$). Thermal effects play some role near the origin leading to $z_s \sim \varpi$.



Neutron rich outflows

- Disk-fed GRB outflows are expected to be neutron-rich (Pruet et al. 2003; Beloborodov 2003; Vlahakis et al. 2003).
- The neutrons decouple, leaving the protons to accelerate to high γ.
- The decoupling Lorentz factor $\gamma_{\rm d}$ in a purely hydrodynamic outflow is a few 100 (e.g., Derishev et al. 1999; Beloborodov 2003; Rossi et al astro-ph/0512495), i.e., of the order of the inferred value of γ_∞. The reason is the scaling $\gamma \propto \varpi$ which always holds in HD.
- In a magnetized flow decoupling happens in much smaller γ ($\gamma_d = 15$, see Vlahakis, Peng, & Königl 2003).
- Iplications for a two-component jet: Peng, Königl, & Granot (2005); Granot, Königl, & Piran (astro-ph/0601056).



(a) The three components of the total energy flux, normalized by the mass flux $\times\ c^2$.
(b) Proton–neutron drift velocity.

$n/p = 30$
decoupling at $\gamma_d = 15$

$\gamma_\infty = 200$
$\mathcal{E}_{\rm proton} \approx 10^{51}$ergs $\approx 0.5\ \mathcal{E}_{\rm neutron}$

Because of the magnetic collimation, the neutrons

also acquire a transverse drift relative to the protons:

$V_{\rm neutron,\perp} \sim 0.1c$ at decoupling.

Dissipation processes

- reconnection if there exist a small-scale field component (e.g., Drenkahn & Spruit 2002 modified the induction equation by adding a term B/τ). The resulting gradient of $B^2/8\pi$ accelerates the flow, $\gamma \propto r^{1/3}$. The dissipated energy is radiated (above the photosphere). Interesting to combine with MHD (they considered monopolar flow), and to describe the reconnection with a more exact way if possible.

- kink instability operates when $(B_\phi/B_p)_{co} \gg 1$, or, $B_\phi/\gamma \gg B_p$. In the Vlahakis & Königl trans-Alfvénic solutions this never happens, but in the super-Alfvénic solutions it does.
  Giannios & Spruit (2006) modeled the instability by adding a term $\sim B/\tau$ in the induction equation, with $\tau \approx \gamma\varpi/c$. Results similar to Drenkahn & Spruit (2002).
  3D relativistic MHD simulations needed.

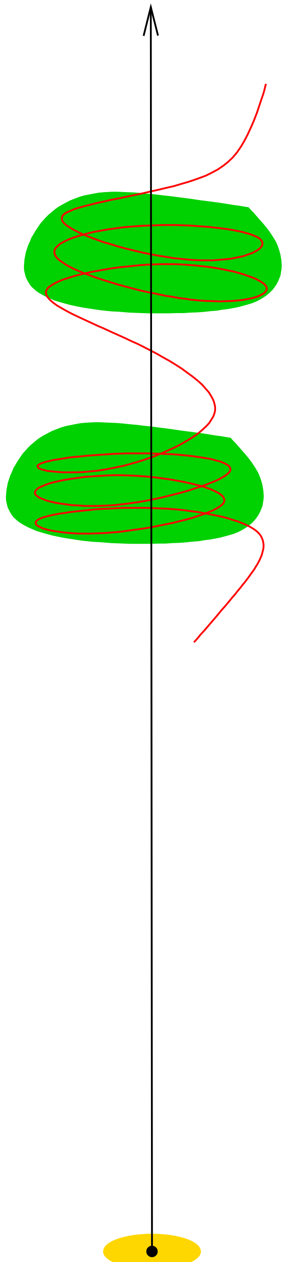
- minimum energy solutions by conserving helicity (Königl & Choudhouri 1985)

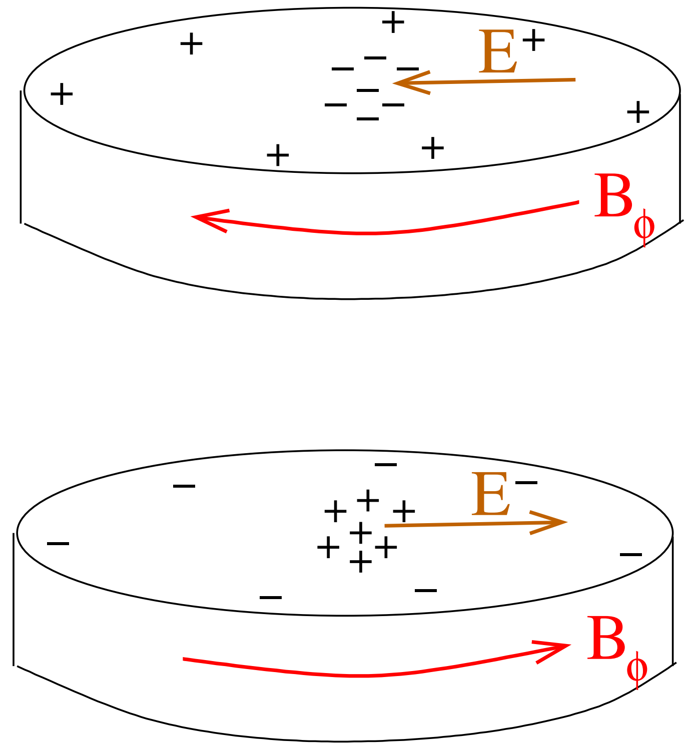
Internal shocks

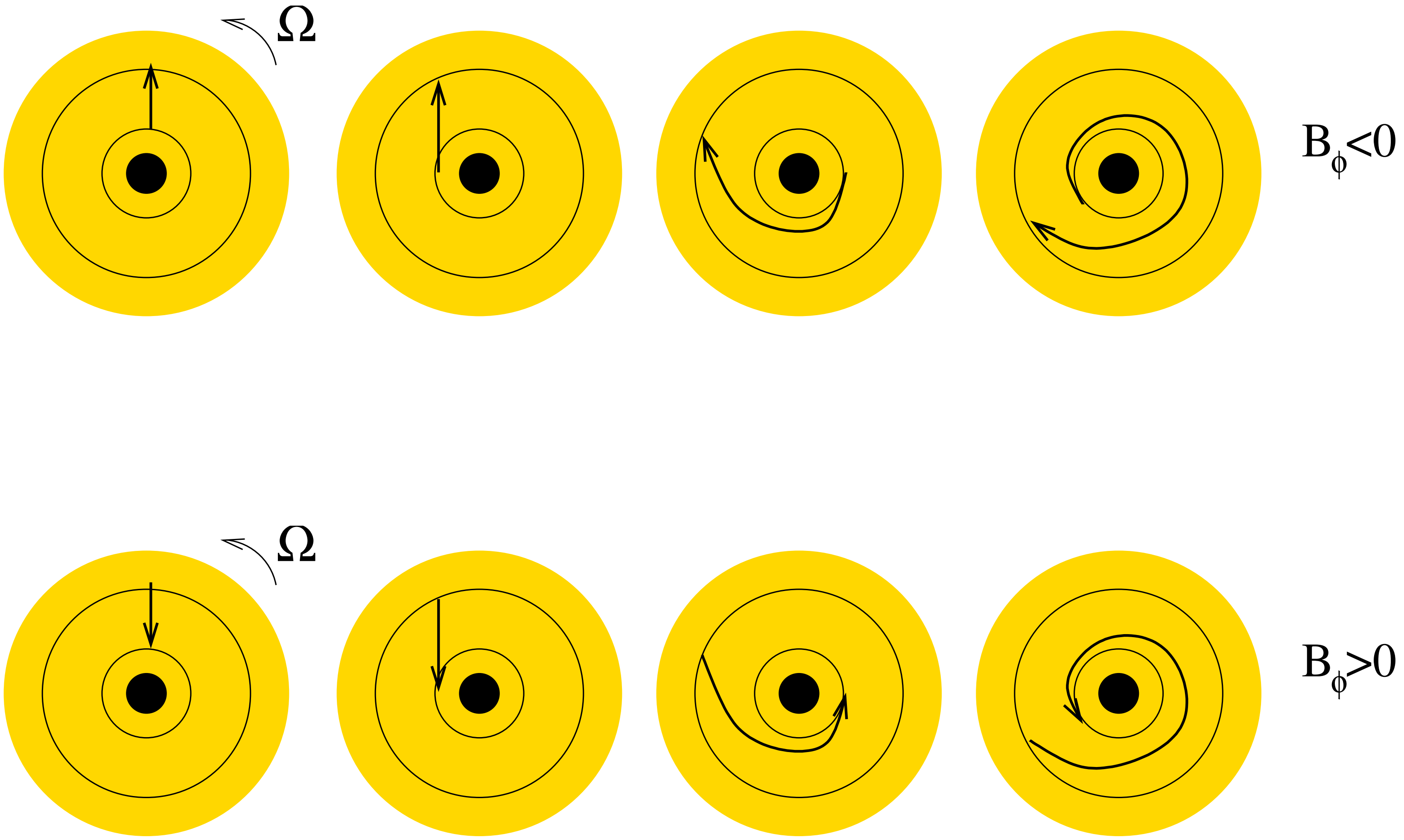
Can the magnetic field enhance the efficiency? Fan, Wei, & Zhang (2004) modeled the dissipation of magnetic field using a parameter $k =$ ratio of electric fields downstream and upstream.

See also the poster no 138 “Radiation from internal shocks in magnetized Supercritical flows” by Magkanari, Sapountzis, Mastichiadis, & Vlahakis, where a possible explanation for the emitting spectrum is also given.

The physics of the parameter k?




E
B_ϕ
E
B_ϕ


Ω
$B_\phi<0$
Ω
$B_\phi>0$

Alternatives

- thermal driving
  - cannot explain the observed angular momentum in YSO jets
  - cannot explain pc-scale accelerations in AGN
  - photospheric emission would have been detectable (Daigne & Mochkovitch 2002)

- outflow from black-hole *vs* disk
  - no difference if the result is baryonic flow (disk outflow, or, Fick difussion across fieldlines above a BH – Levinson & Eichler 2003). In both cases we have MHD (although the mechanism that transfers energy to the field is different: Blandford & Znajek *vs* accretion).
  - the field is higher in the BH-case (smaller ejection surface)

- electromagnetic outflows:
  - This corresponds to the case (subcase of MHD) where the field distribution is force-free – already at the minimum-energy (the spring doesnot release energy)
  - extraction of pure electromagnetic energy (without adding baryons) – Lyutikov & Blandford astro-ph/0312347
  - the flow never becomes superfast
  - current-driven instabilities lead to dissipation of magnetic field and subsequent emission

Conclusions

⋆ MHD could explain the dynamics of GRB jets:

- acceleration (the flow is initially thermally, and subsequently magnetically accelerated up to Lorentz factors corresponding to rough equipartition between kinetic and Poynting fluxes) – $\gamma \propto \varpi^{\beta}$ with $\beta \approx 1$ in trans-Alfvénic flows and $\beta < 1$ in super-Alfvénic from the start
- collimation (parabolic shape $z \propto \varpi^{\beta+1}$)

⋆ trans-Alfvénic flows are probably kink-stable, while kink-instability could operate in flows that are super-Alfvénic from the start

⋆ The paradigm of MHD jets works in a similar way in YSOs, AGN, GRBs!