Magnetically driven astrophysical relativistic jets and their stability

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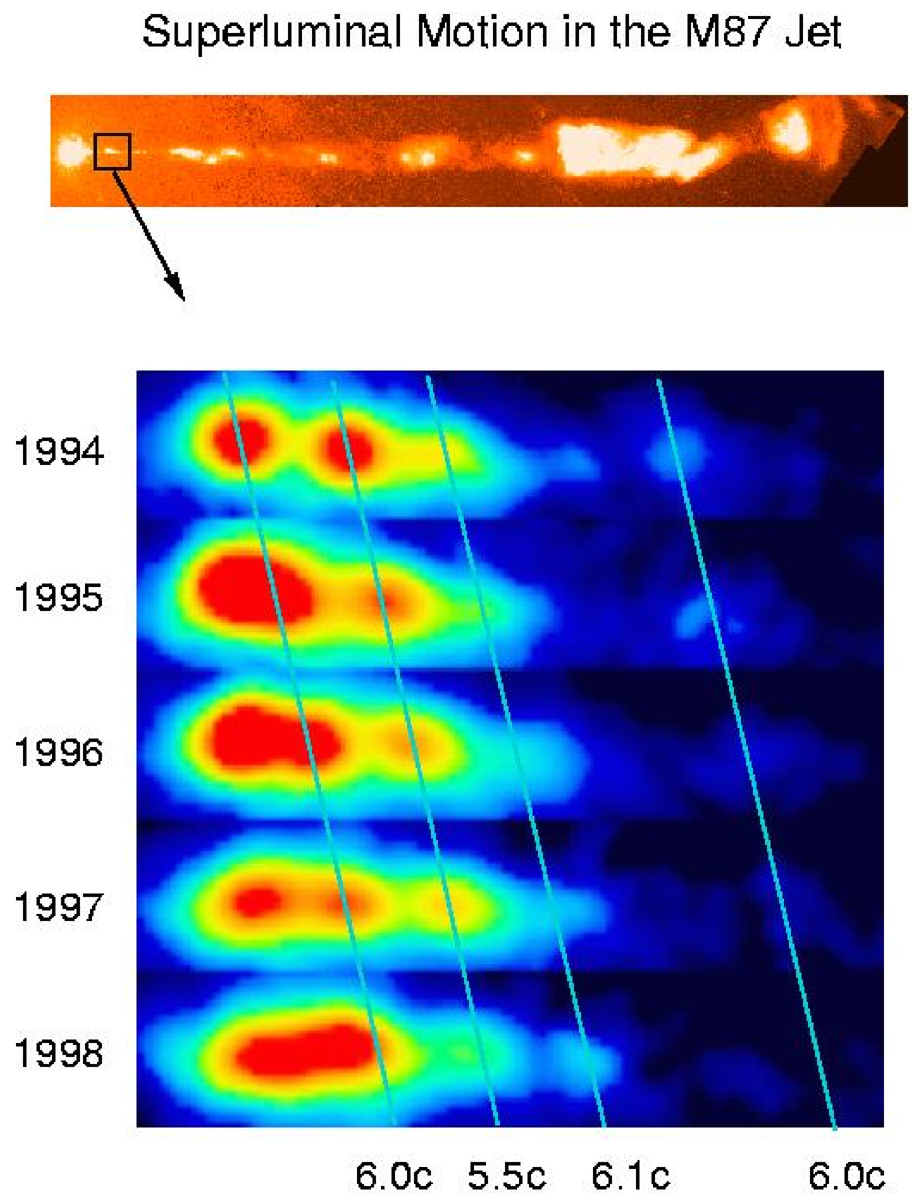
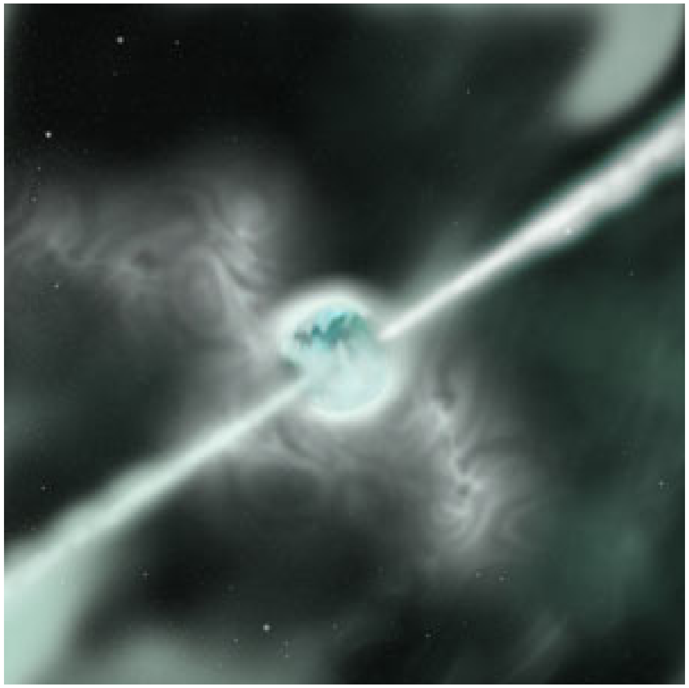
Outline

- why magnetic driving
- numerical simulations
- bulk acceleration, jet shape, stability

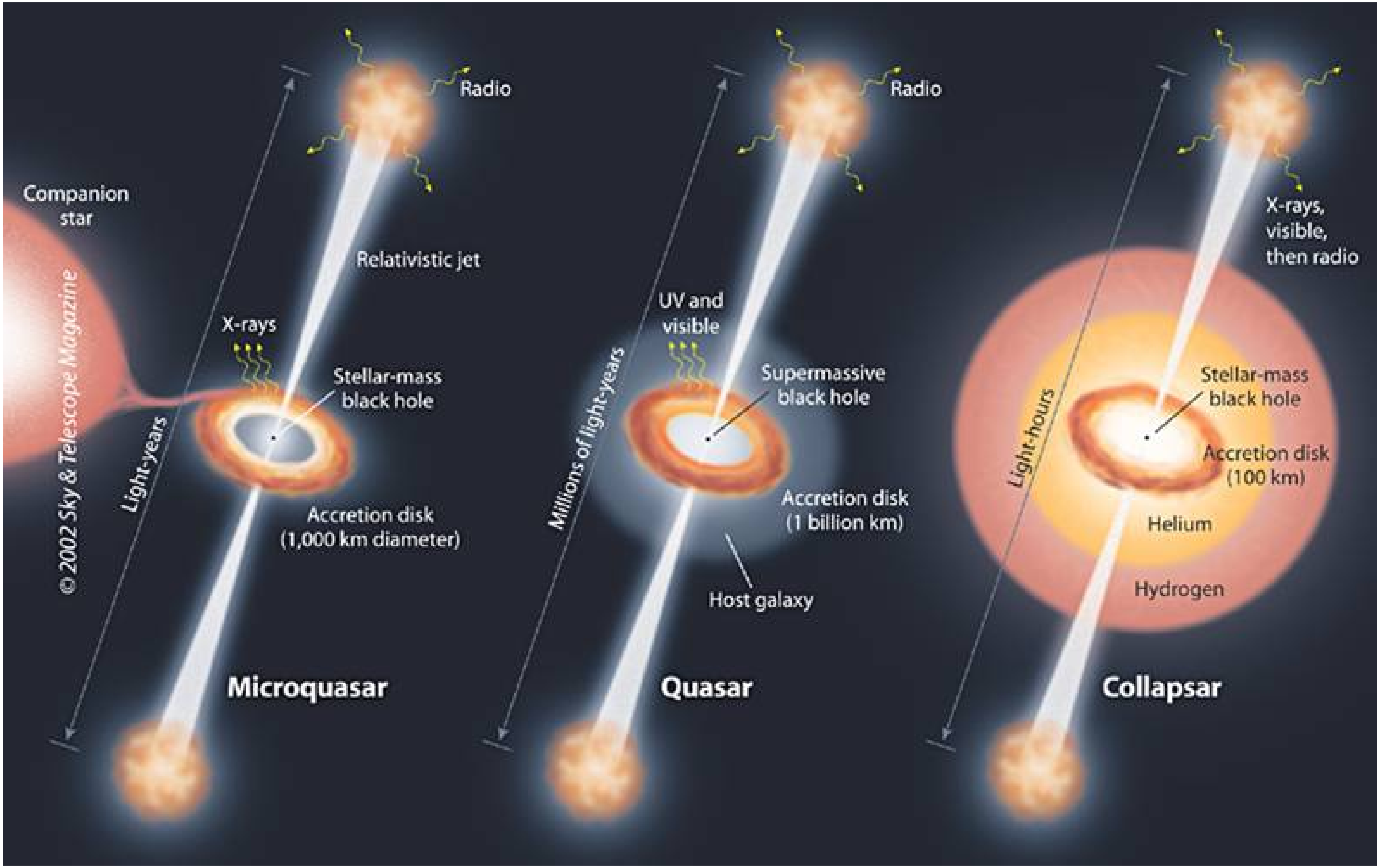
Relativistic motion in AGN jets



Relativistic motion in GRB jets



the only solution to the “compactness problem”


Radio
Radio
Companion star
Relativistic jet
X-rays,
visible,
then radio
© 2002 Sky & Telescope Magazine
UV and visible
X-rays
Stellar-mass black hole
Supermassive black hole
Stellar-mass black hole
Light-years
Millions of light-years
Light-hours
Accretion disk (100 km)
Accretion disk (1 billion km)
Accretion disk (1,000 km diameter)
Helium
Host galaxy
Hydrogen
Microquasar
Quasar
Collapsar

Thermal driving is problematic

- requires high temperatures – the corresponding thermal component of the emission is not observed in GRBs (Zhang & Pe'er 2009)

- cannot explain the pc-scale acceleration in AGN jets (lack of Compton features implies a lower limit on γ at $10^3 r_g$, Sikora et al 2005)

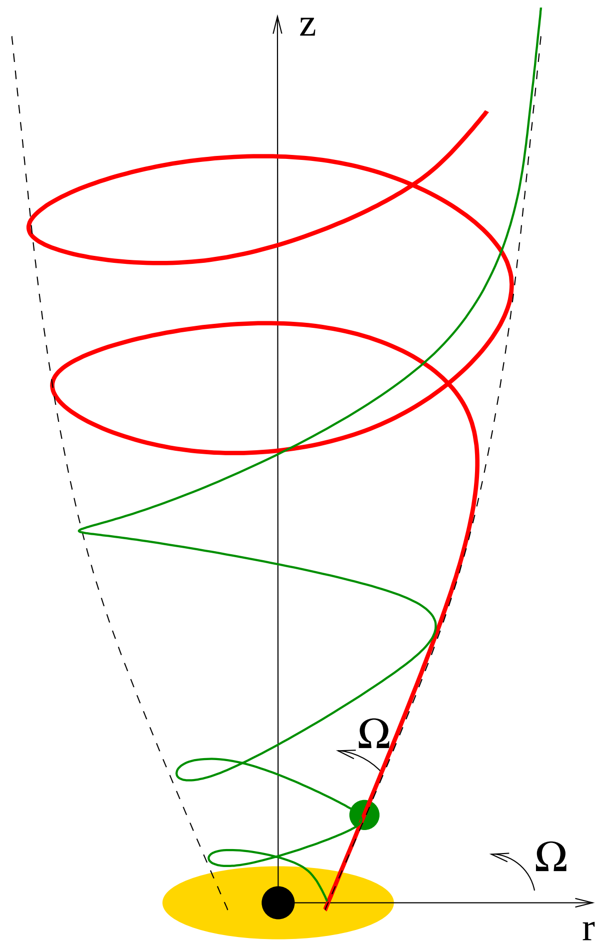
Viable alternative: magnetic driving

Two additional features:

- Extraction of "clean" energy (high energy-to-mass ratio leads to relativistic flows)

- Self-collimation

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)

- 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

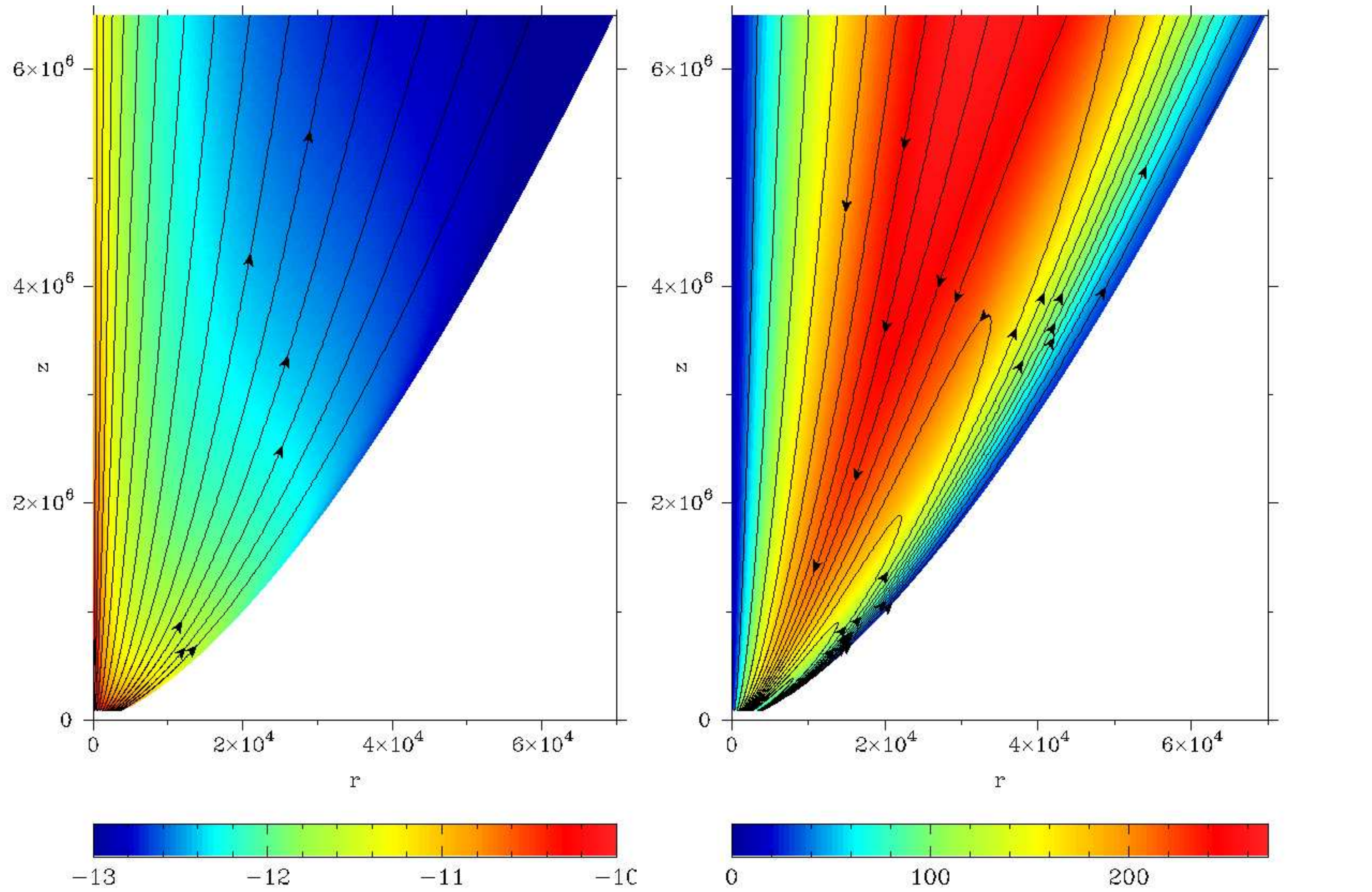
Numerical simulations

Komissarov, Vlahakis, Königl & Barkov 2009

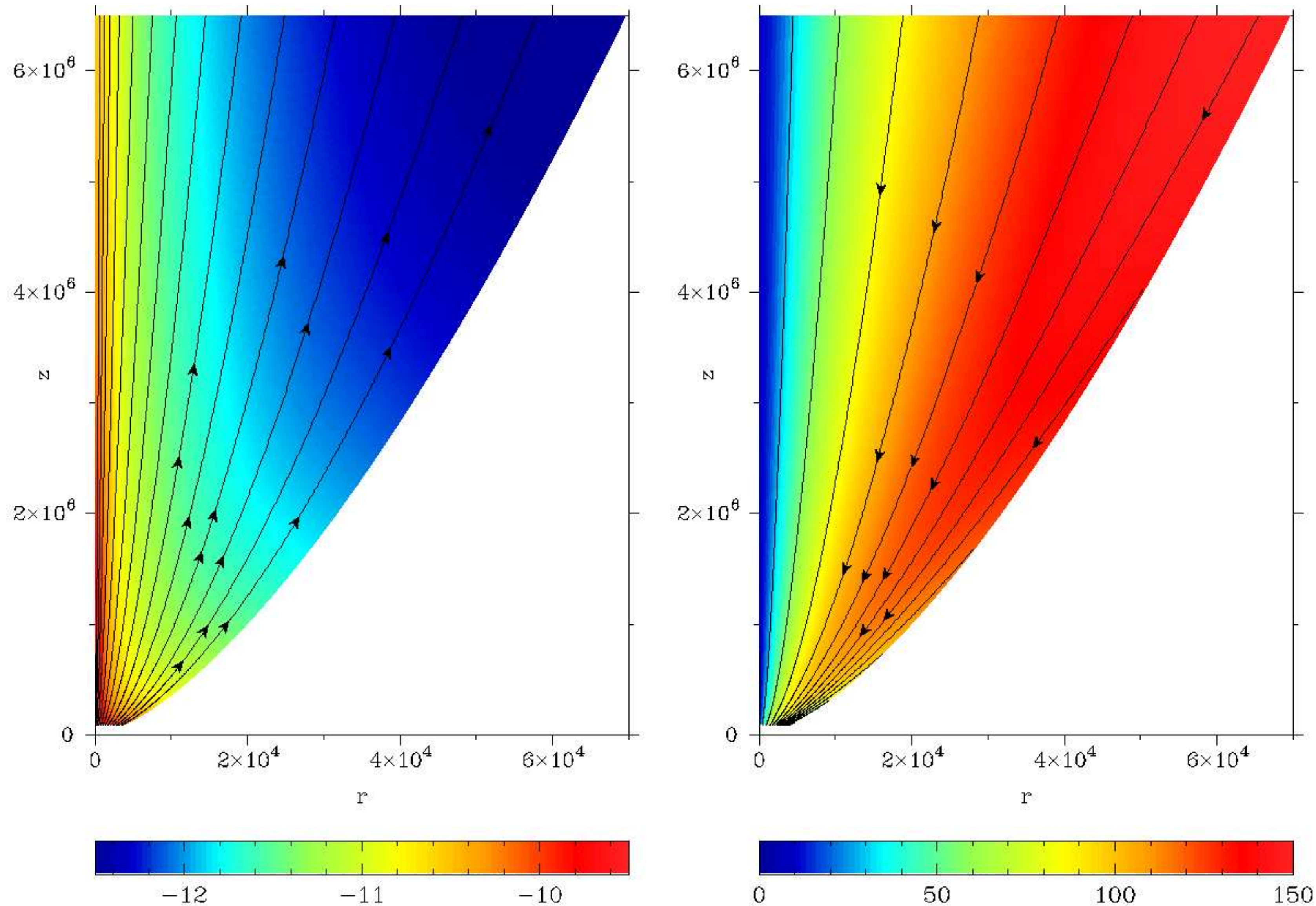
magnetized plasma of a given magnetization (given μ) is ejected into a funnel of a given shape

Basic questions:

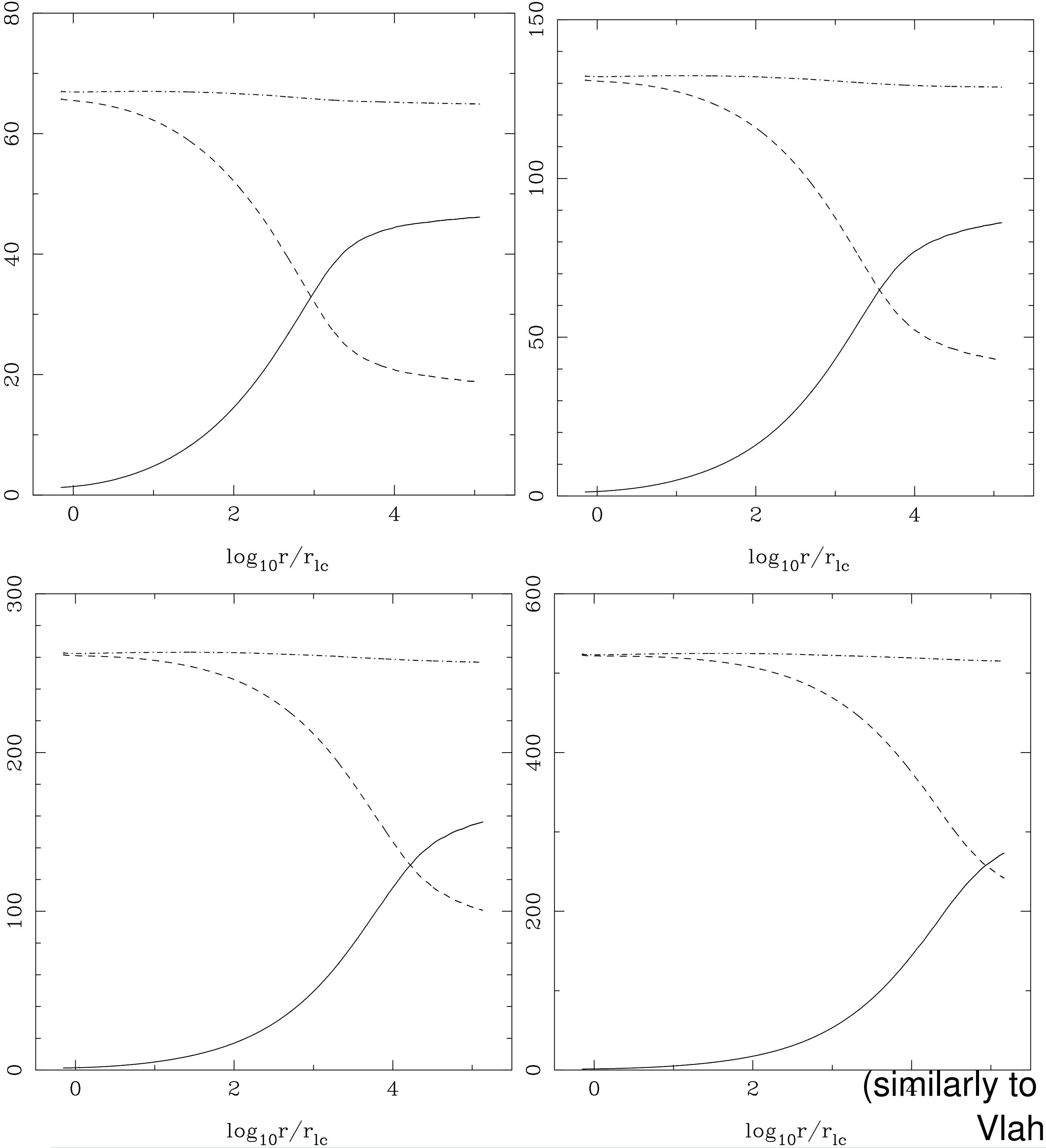
- ☞ γ *vs* distance ?
- ☞ γ_∞ and the acceleration efficiency $\dfrac{\gamma_\infty}{\mu} = \dfrac{\gamma_\infty \dot{M} c^2}{\dot{\mathcal{E}}} =$?
- ☞ self-collimation (formation of a cylindrical core) ?
- ☞ pressure on the wall ?
  (pressure of the jet environment)



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



Uniform rotation $\rightarrow \gamma$ increases with r



γ (increasing),

$\gamma\sigma$ (decreasing),

and μ

efficiency $> 50\%$

(similarly to the semi-analytical results of Vlahakis & Königl 2003, 2004)

The role of the external pressure

The wall-shape $z \propto r^a$ and the acceleration law is controlled by the external pressure $p_{\rm ext} \propto z^{-\alpha_p}$:

- if $\alpha_p < 2$ (the pressure drops slower than z^{-2}) then
  - ⋆ $a > 2$ (shape more collimated than $z \propto r^2$)
  - ⋆ linear acceleration $\gamma \propto r$
- if $\alpha_p = 2$ then
  - ⋆ $1 < a \leq 2$ (parabolic shape)
  - ⋆ first $\gamma \propto r$ and then power-law acceleration $\gamma \sim z/r \propto r^{a-1}$
- if $\alpha_p > 2$ (pressure drops faster than z^{-2}) then
  - ⋆ $a = 1$ (conical shape)
  - ⋆ linear acceleration $\gamma \propto r$ (small efficiency)

The above scalings result from the transfield component of the momentum equation – verified by the numerical results

On current-driven instabilities

The jet is expected to be unstable if the azimuthal magnetic field dominates the poloidal magnetic field (Kruskal-Shafranov).

In source's frame $\dfrac{|B_\phi|}{B_p} \approx x \equiv \dfrac{r\Omega}{c} \gg 1$ — role of inertia?

In the comoving frame $\left(\dfrac{|B_\phi|}{B_p}\right)_{\rm co} \approx \dfrac{|B_\phi|/\gamma}{B_p} \approx \dfrac{x}{\gamma}$

In the power-law regime ($\gamma \ll x$) the azimuthal component dominates (unstable)

In the linear acceleration regime ($\gamma \approx x$) azimuthal and poloidal components of the magnetic field are comparable

Linear stability analysis

Equilibrium: For $0 < r < r_j$ (jet), $V = 0$ (comoving frame),

$$B_z = \frac{B_j}{1 + (r/r_0)^2},\ B_\phi = \frac{r}{r_0} B_z,\ \rho = \frac{\rho_j}{\left[1 + (r/r_0)^2\right]^2},\ P = 0 \text{ (cold).}$$

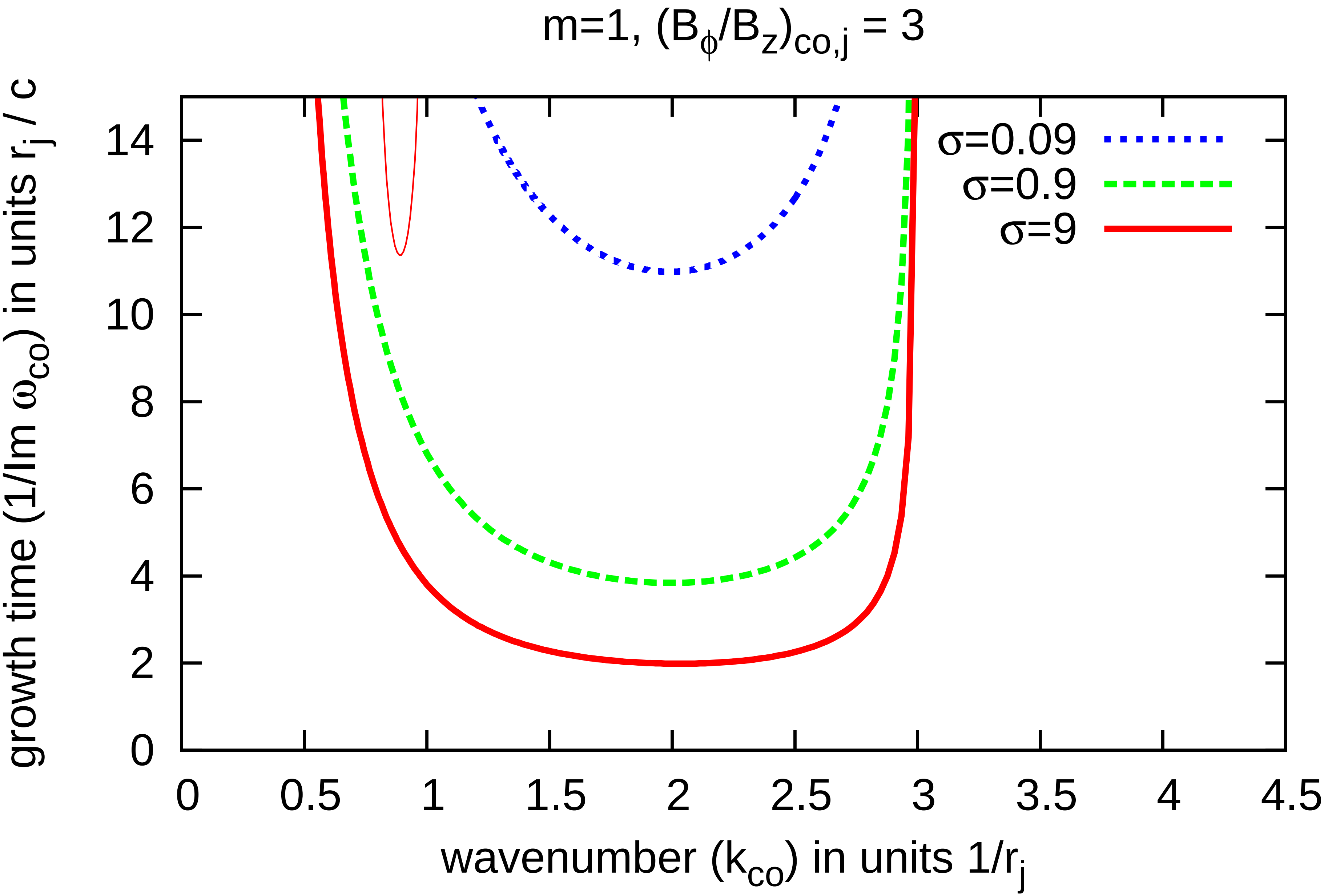
Magnetization $\sigma = \left(\frac{B_\phi^2}{4\pi\rho c^2}\right)_{r=r_j}$.

For $r > r_j$ (environment), pressure $p_{\rm ext}$.

Perturbations of the form $f(r) \exp\left[i\left(m\phi + kz - \omega t\right)\right]$.

We linearize the system of RMHD eqs and find $\omega = Re\omega + iIm\omega$ for given k and m.

$1/Im\omega$ is the growth time of the instability.



(thin red line for $(B_\phi/B_z)_{\rm co} = 1$)

In the source's frame growth time is γ times larger.

Summary

⋆ Magnetic driving provides a viable explanation of the dynamics of relativistic jets

- depending on the external pressure:
  collimation to parabolic shape $z \propto r^a, a > 2$ with $\gamma \propto r$,
  parabolic shape $z \propto r^a, 1 < a \leq 2$ with $\gamma \sim z/r \propto r^{a-1}$,
  or conical shape $z \propto r$ with $\gamma \propto r$
- bulk acceleration up to Lorentz factors $\gamma_\infty \gtrsim 0.5 \frac{\mathcal{E}}{Mc^2}$
  (in conical flows only near the axis)

⋆ current-driven instabilities depend on the spatial scale of the Lorentz factor (and thus, on the $p_{\rm ext}$)

- stable jet if acceleration is linear $\gamma \propto r$ ($p_{\rm ext}$ drops slower than z^{-2}, or initial phase of jets with $p_{\rm ext} \propto z^{-2}$)
  (becomes unstable when γ saturates)
- unstable in the power-law acceleration regime (end-phase of jets with $p_{\rm ext} \propto z^{-2}$)