Cosmic jets:

their dynamics and the role of the magnetic field

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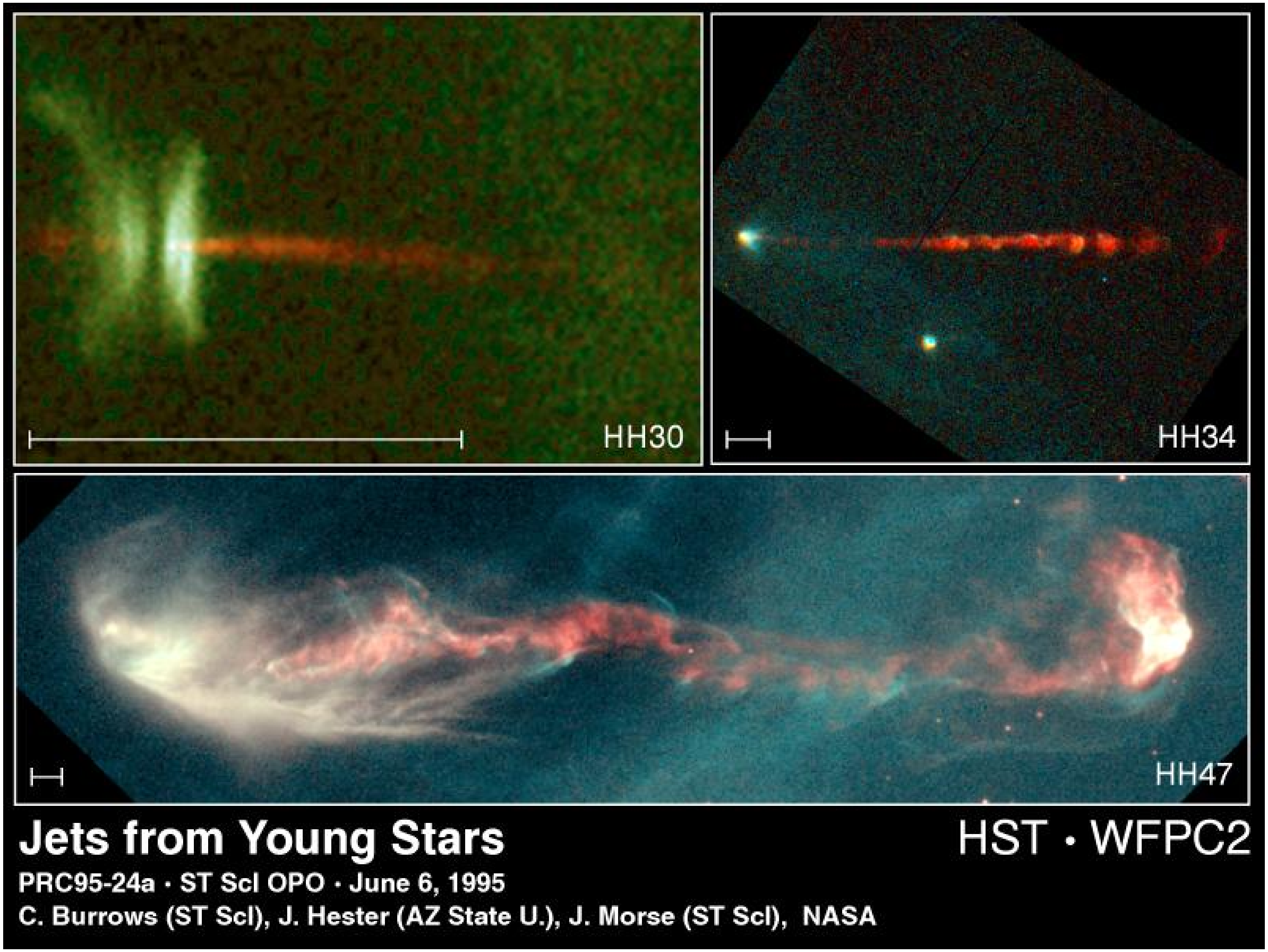
Outline

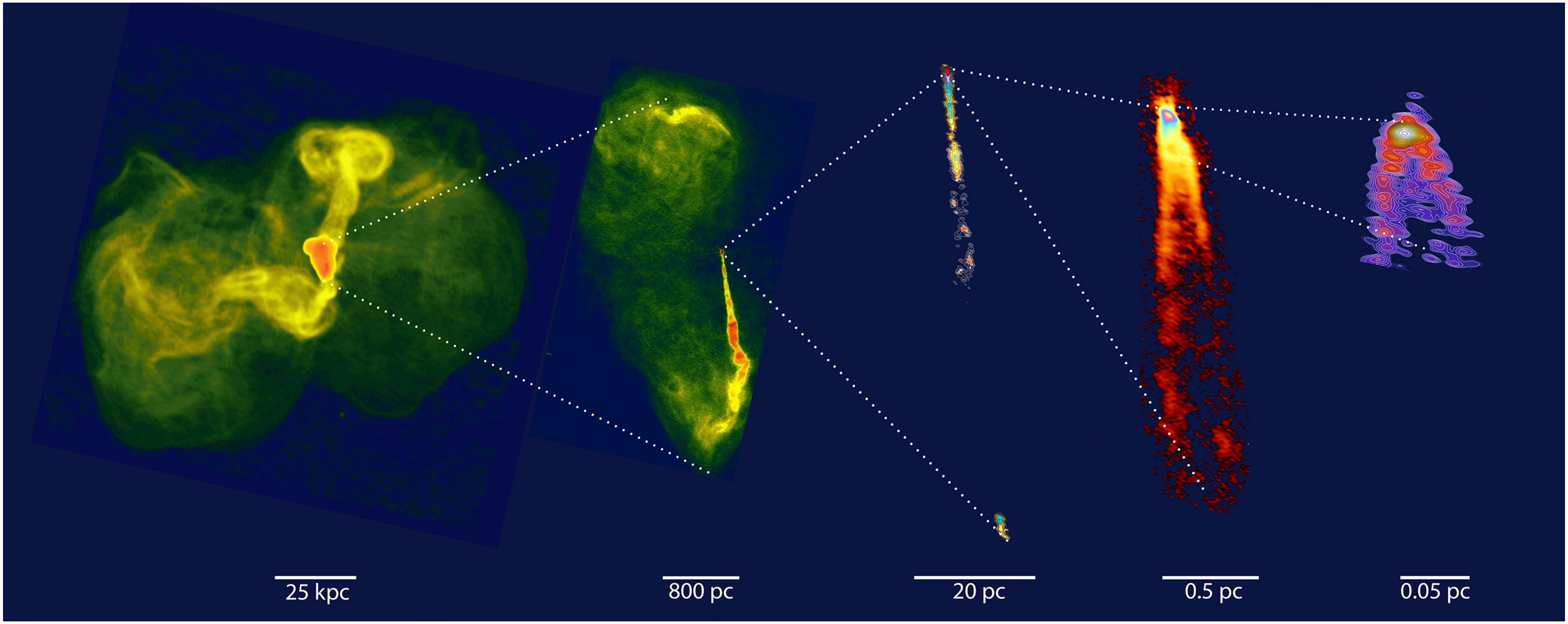
- introduction (observed jet characteristics)
- collimation-acceleration paradigm
- jet stability

Examples of astrophysical jets

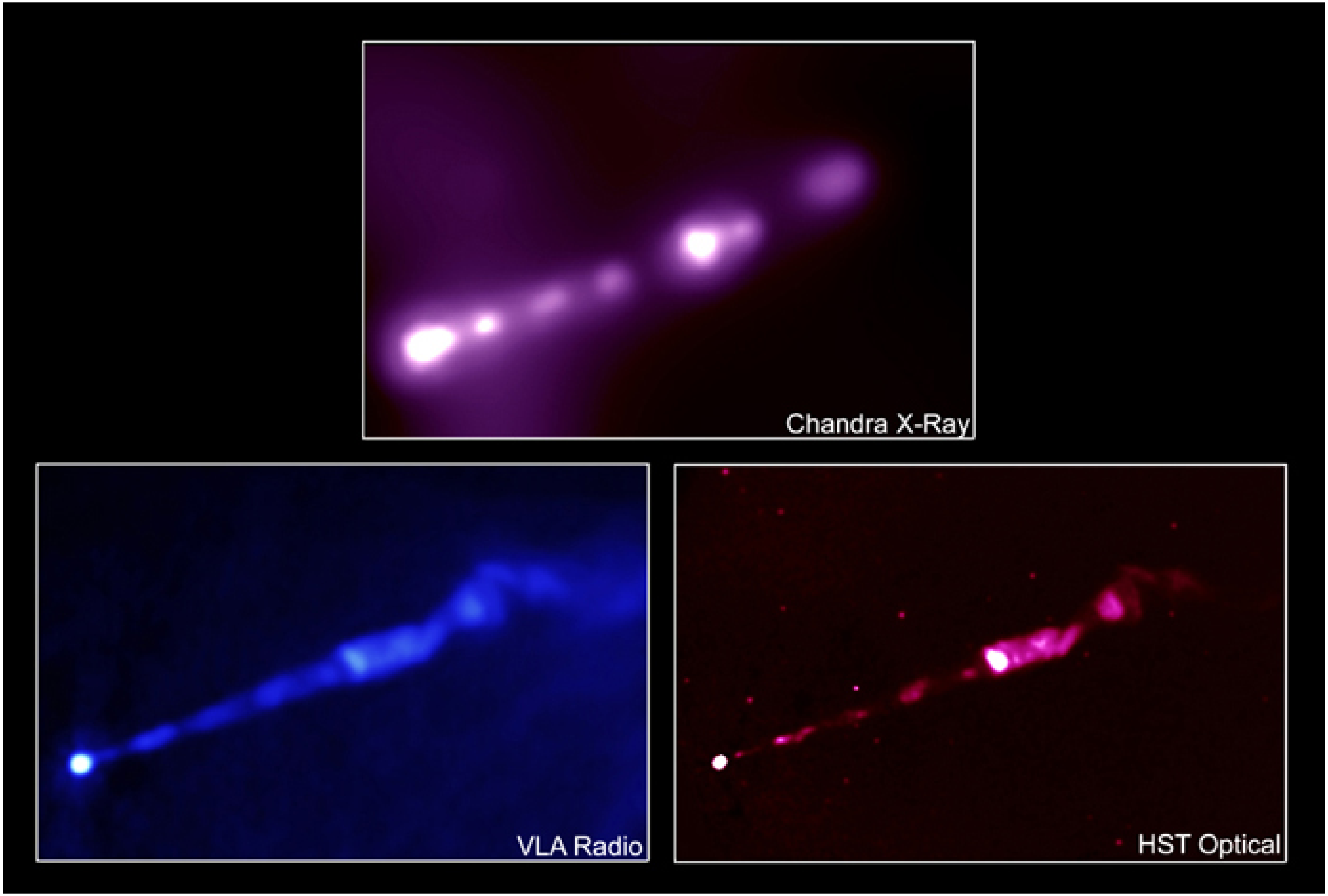


(scale =1000 AU, $V_\infty = afew100$km/s)

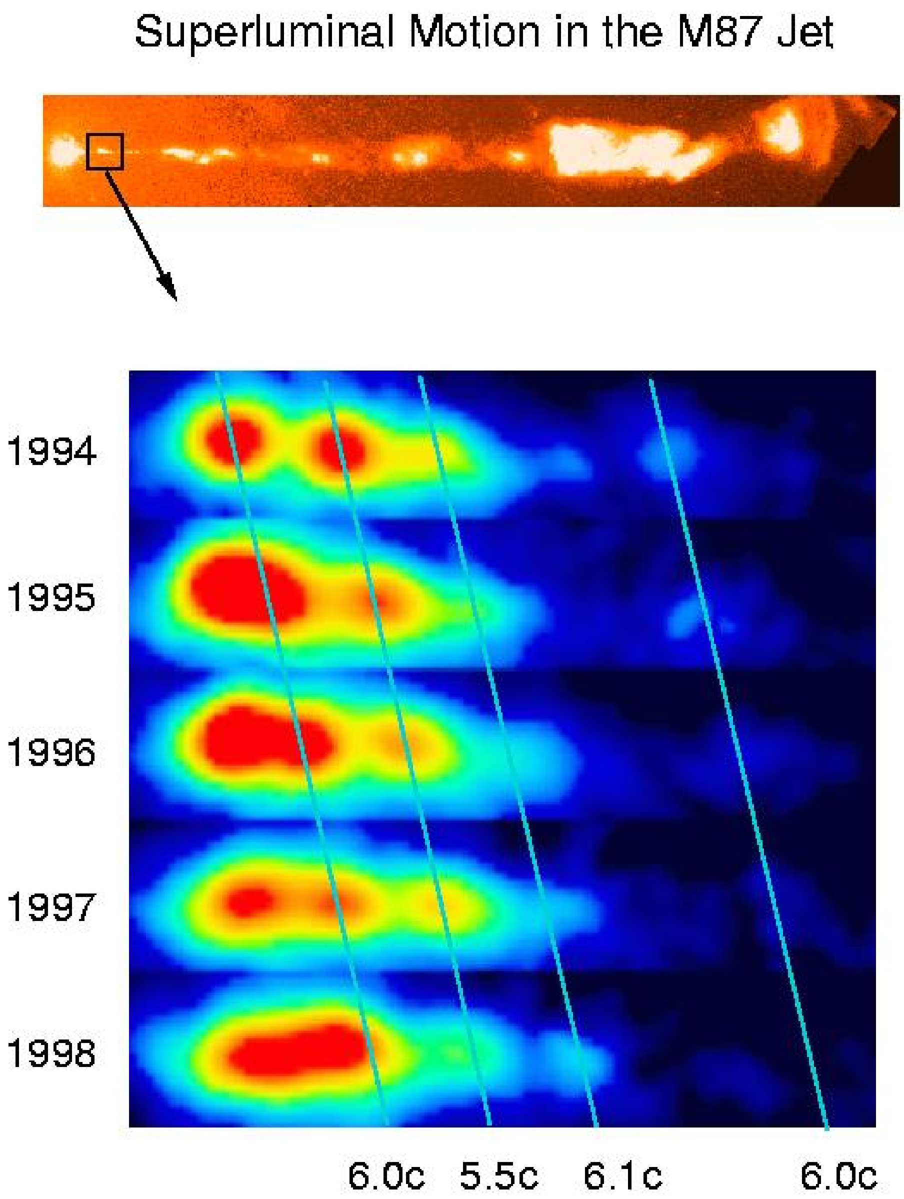
The jet from the M87 galaxy

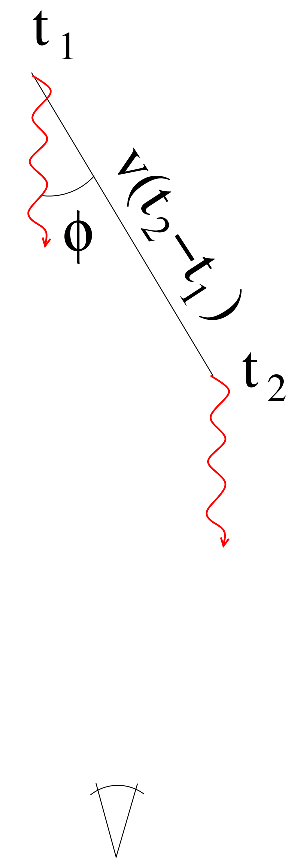


(from Blandford+2018)

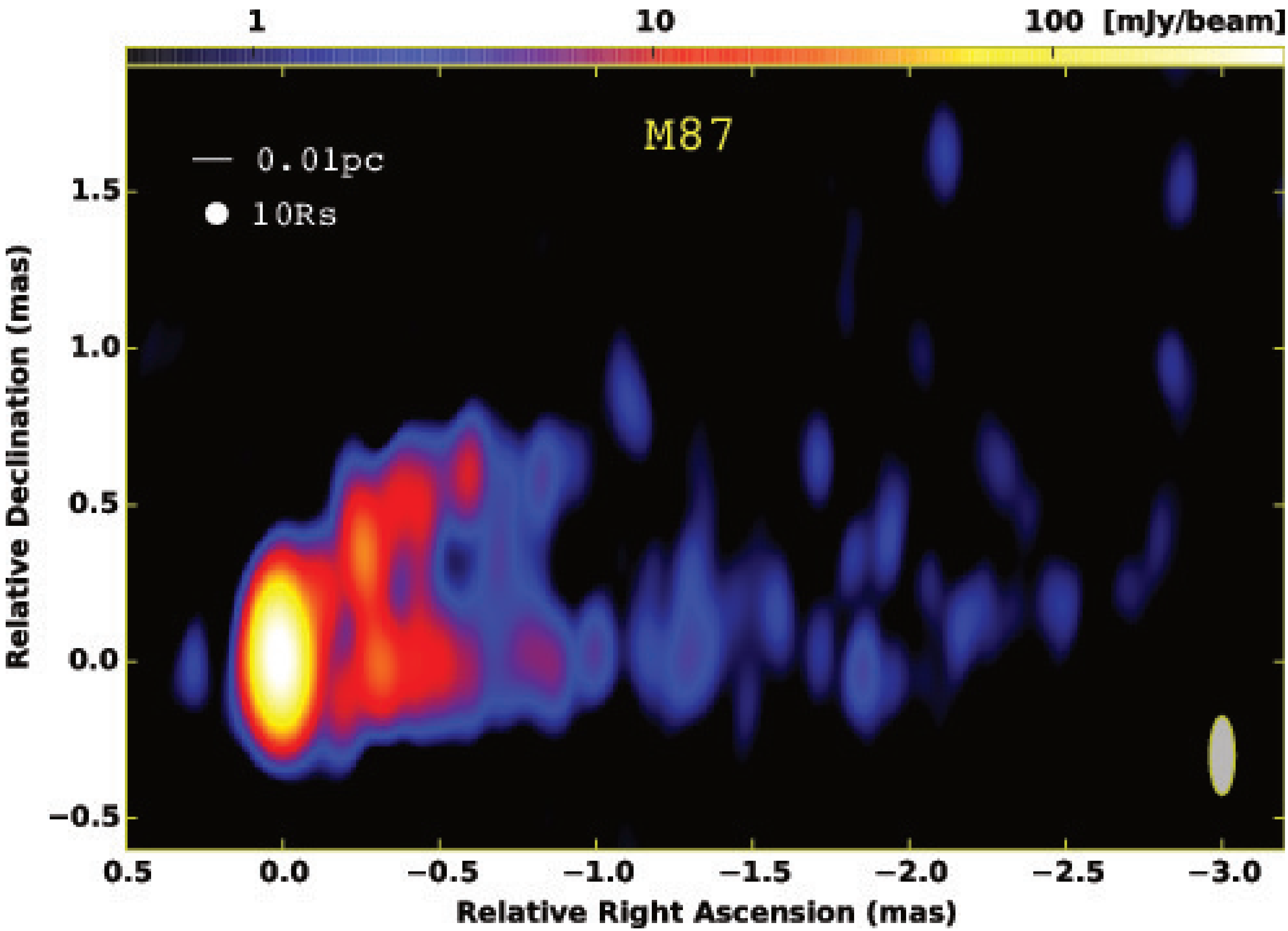

Chandra X-Ray
VLA Radio
HST Optical

Jet speed





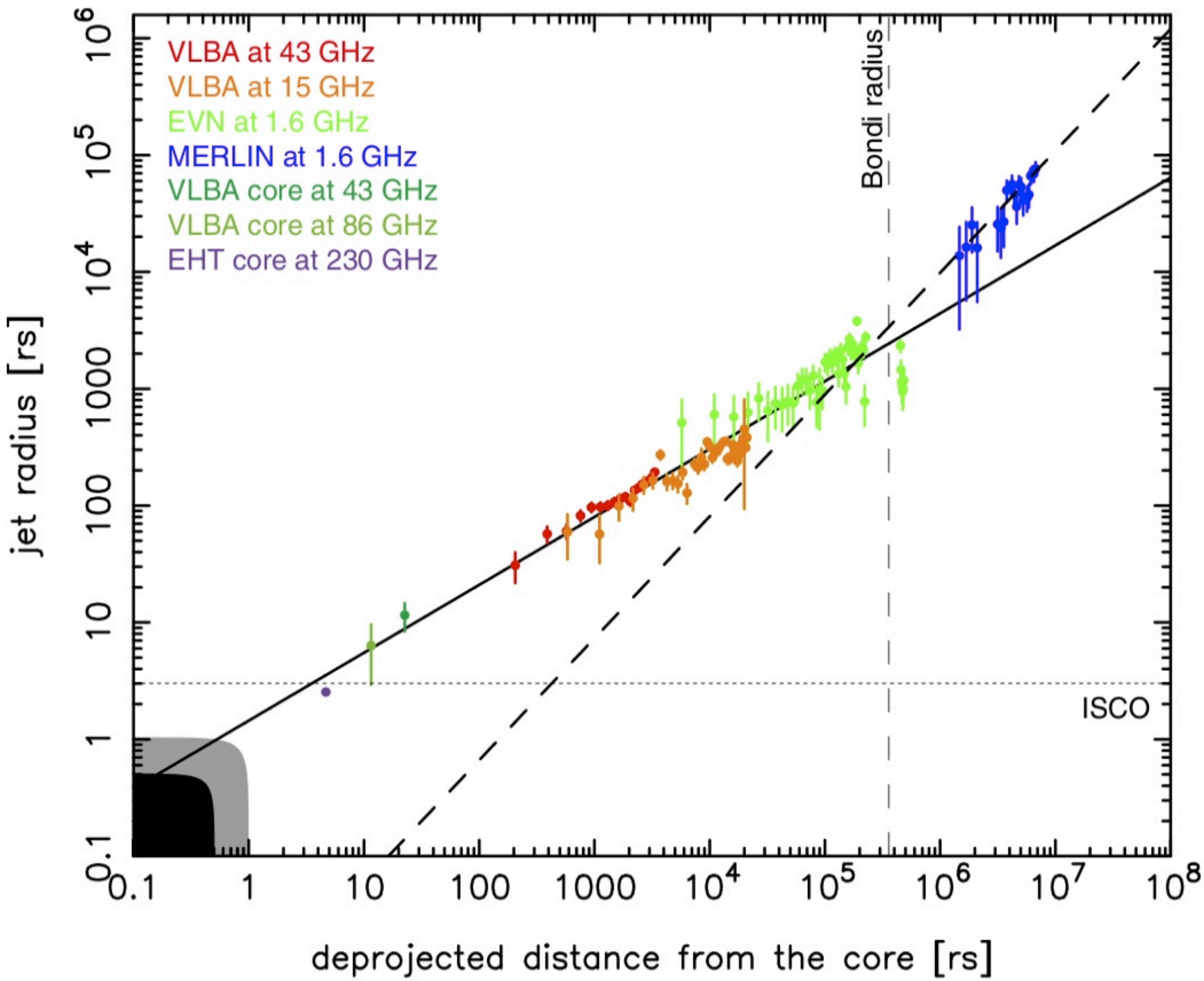
$$\gamma_\infty \sim 10$$



(Hada et al 2016)

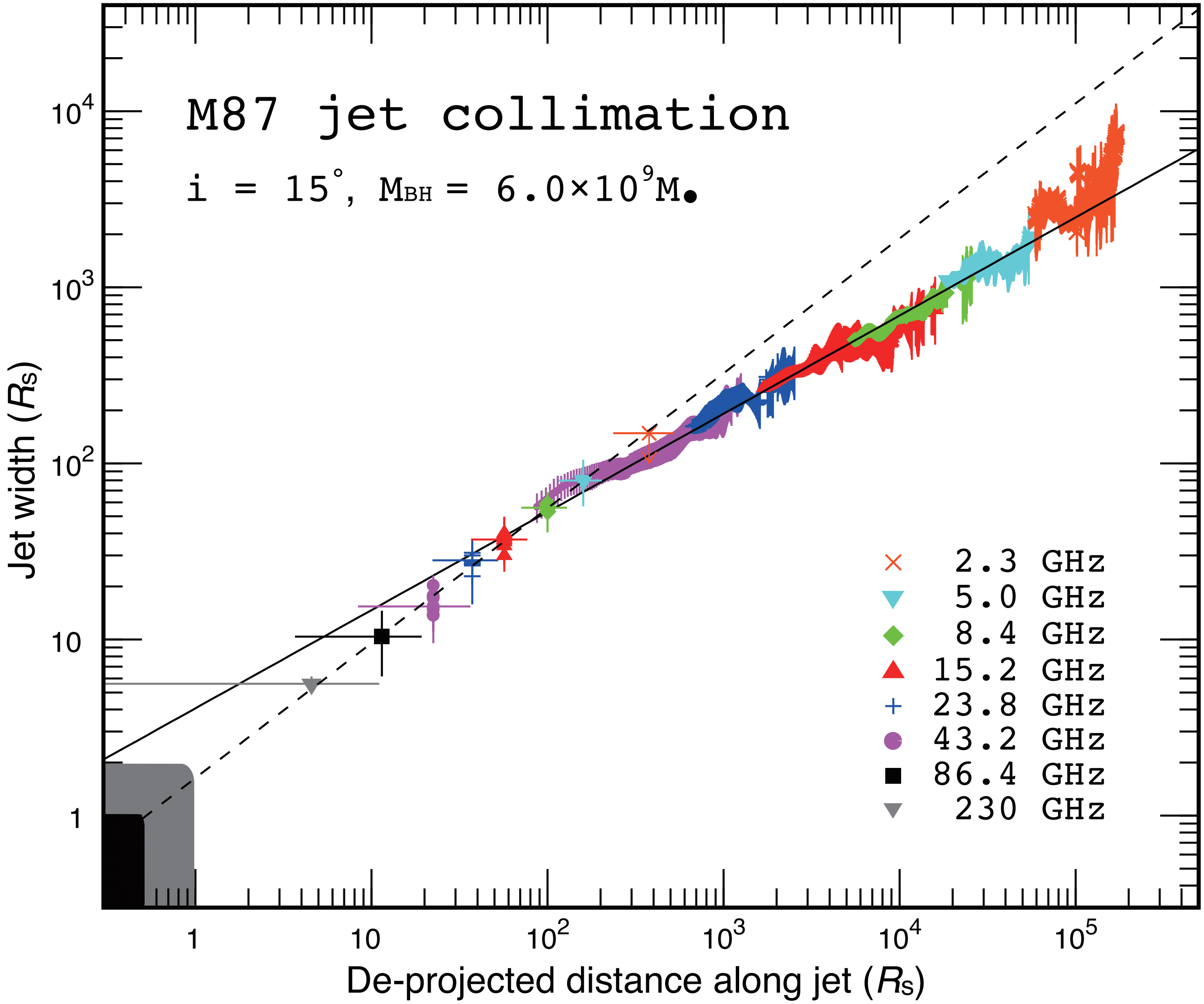
collimation at $\sim$100 Schwarzschild radii

The jet shape (Nakamura & Asada 2013)



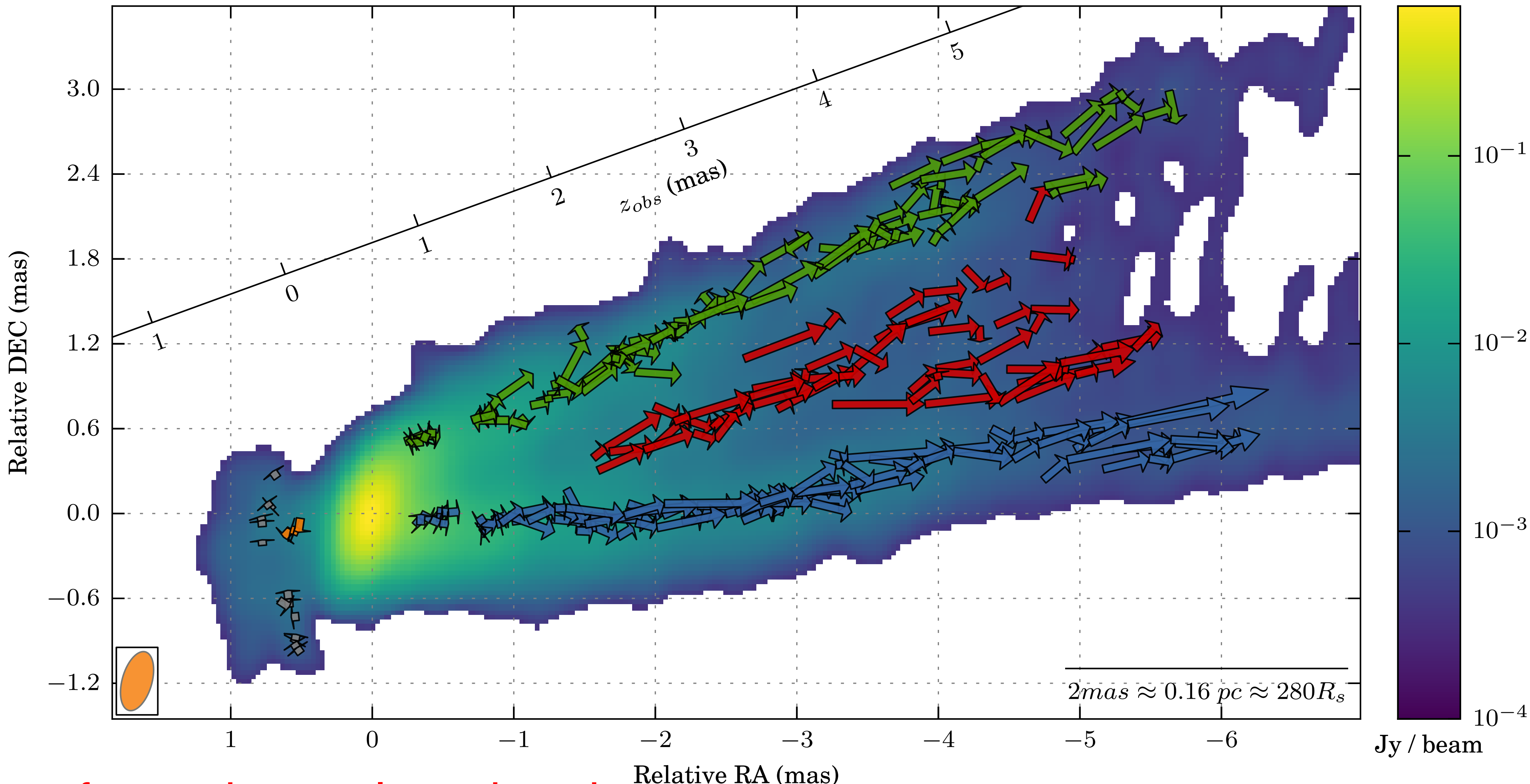
Parabolic up to the Bondi radius, then radial

(Hada+2013)



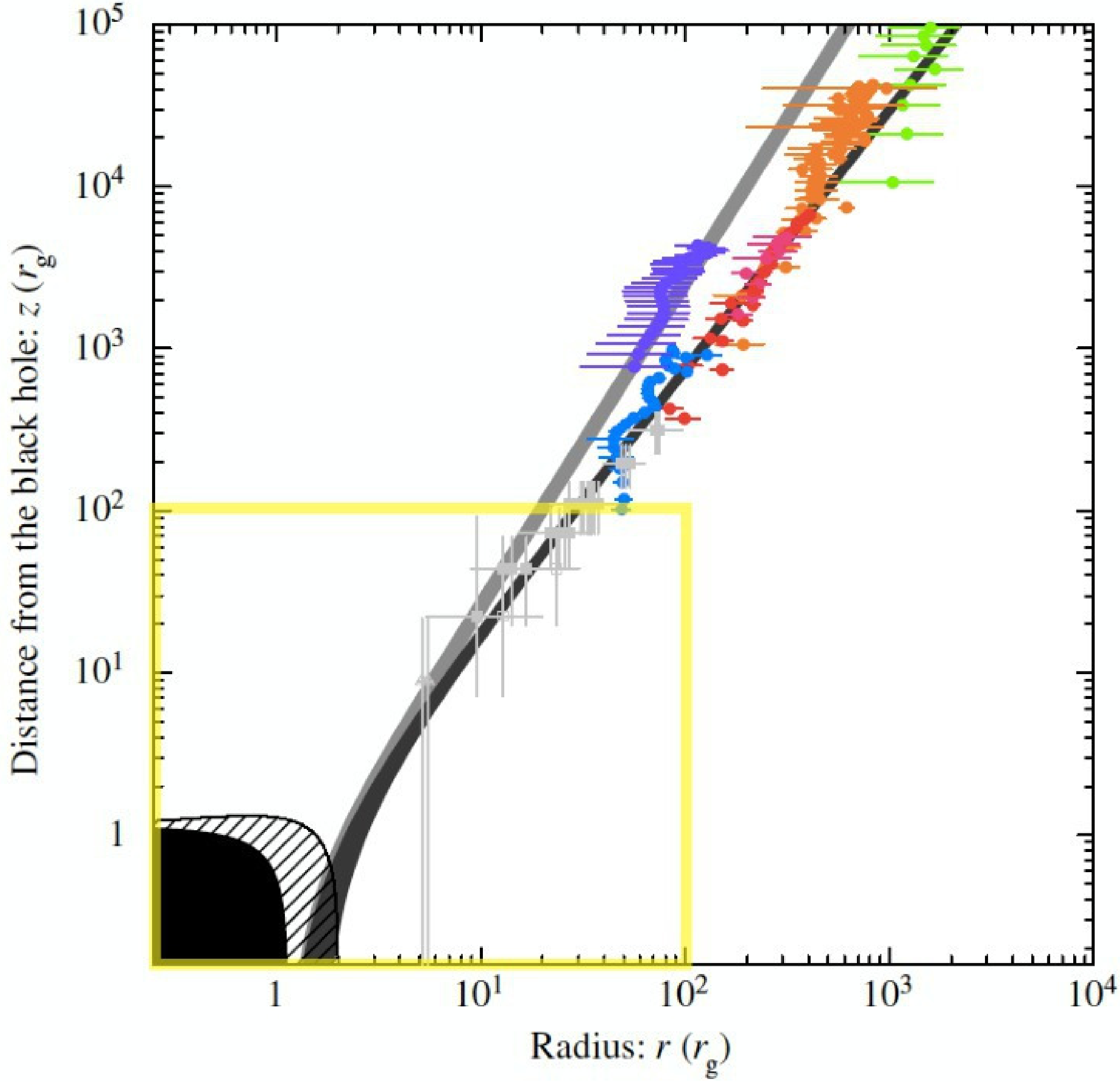
jet from the disk or the black hole?

Transverse profile (Mertens+2016)



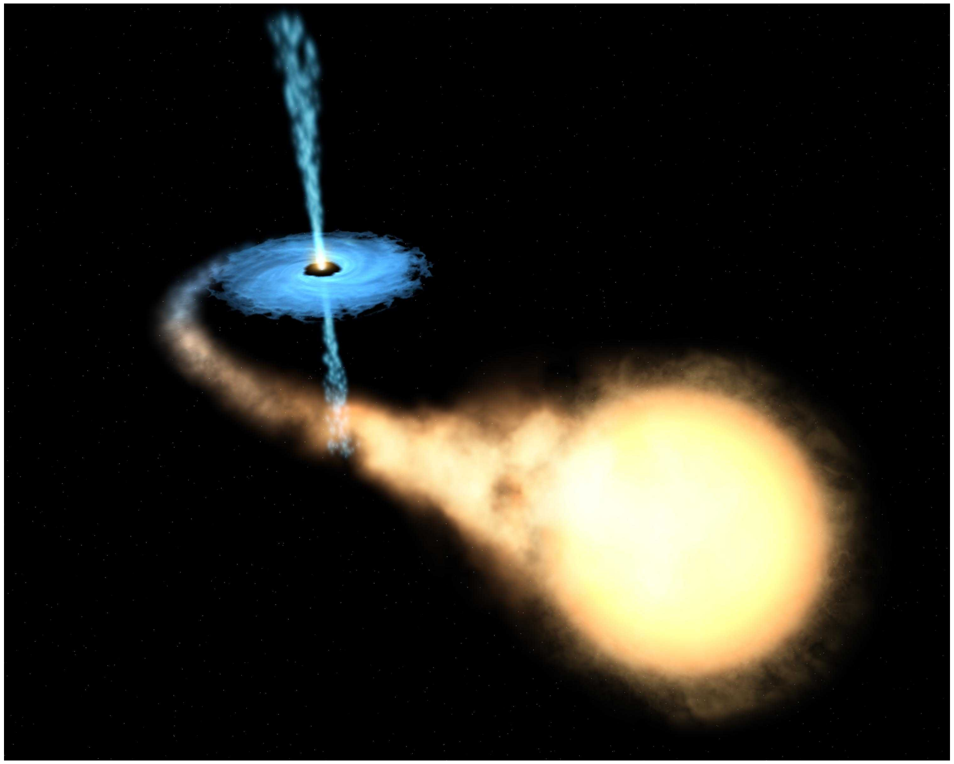
- fast spine – slow sheath
- they manage to observe sheath rotation:
  the value favors disk-driven (and not BH-driven) jet
- the spine?

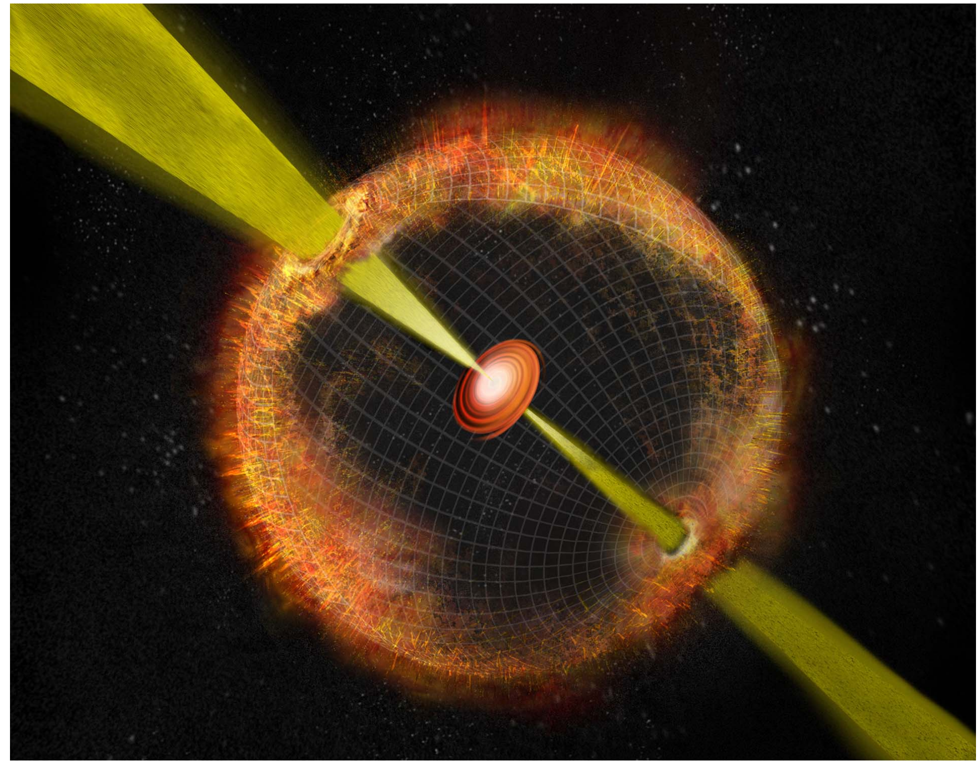
(Asada+2017)



X-ray binaries

γ-ray bursts

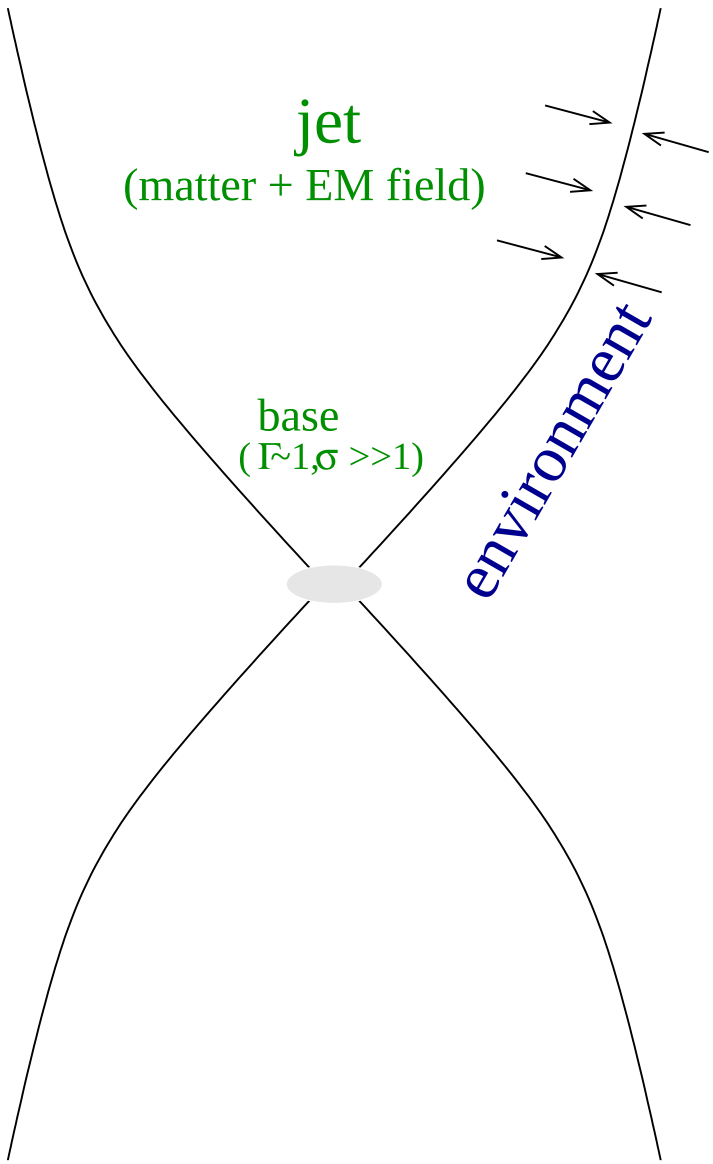




mildly relativistic

$\gamma =$ a few 100

Basic questions



- source of matter/energy?
- bulk acceleration?
- collimation?
- interaction with environment?

Theoretical modeling

☞ if energy source = thermal energy:

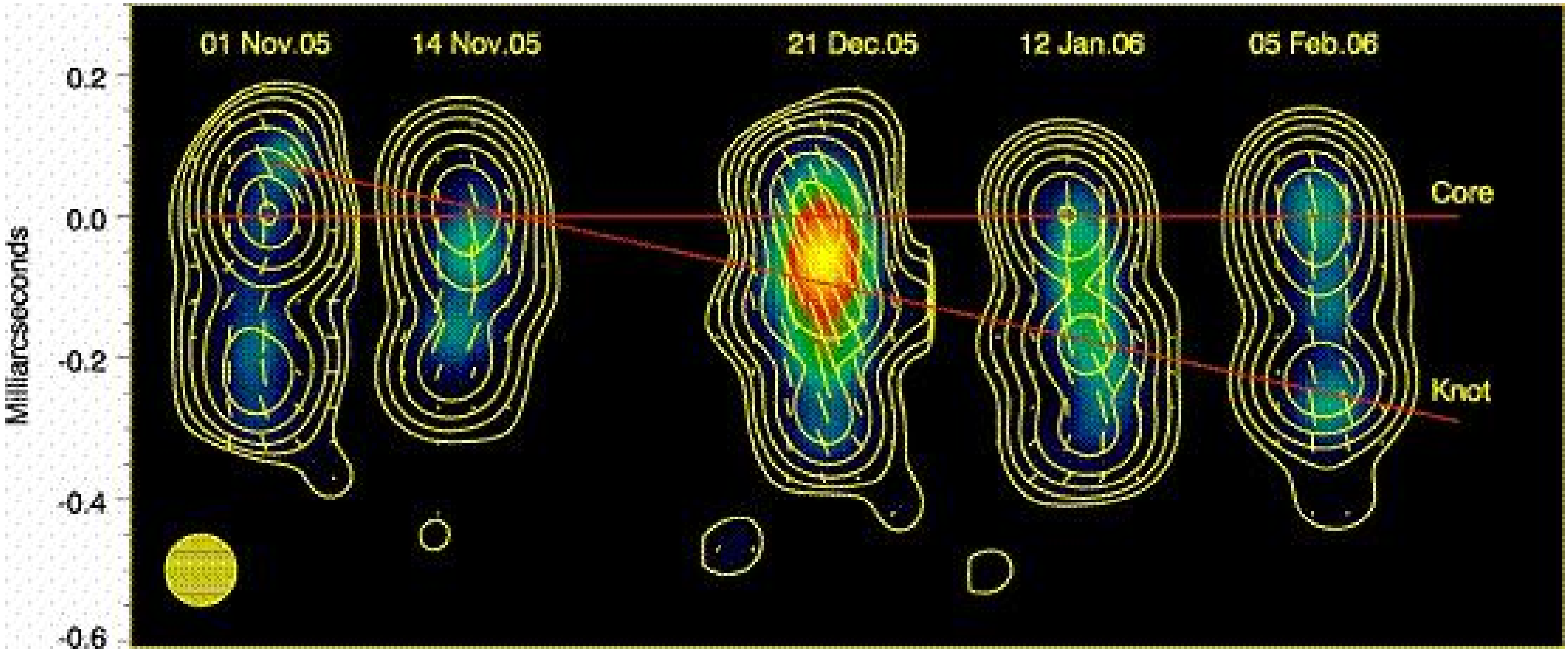
thermal acceleration is an efficient mechanism

gives terminal speed $\frac{m_p V_\infty^2}{2} \sim k_{\rm B} T_i$ for YSO jets
or terminal Lorentz factors $\gamma_\infty m_p c^2 \sim k_{\rm B} T_i$ for relativistic jets

in both cases needs high initial temperatures T_i to explain the observed motions

☞ magnetic acceleration more likely

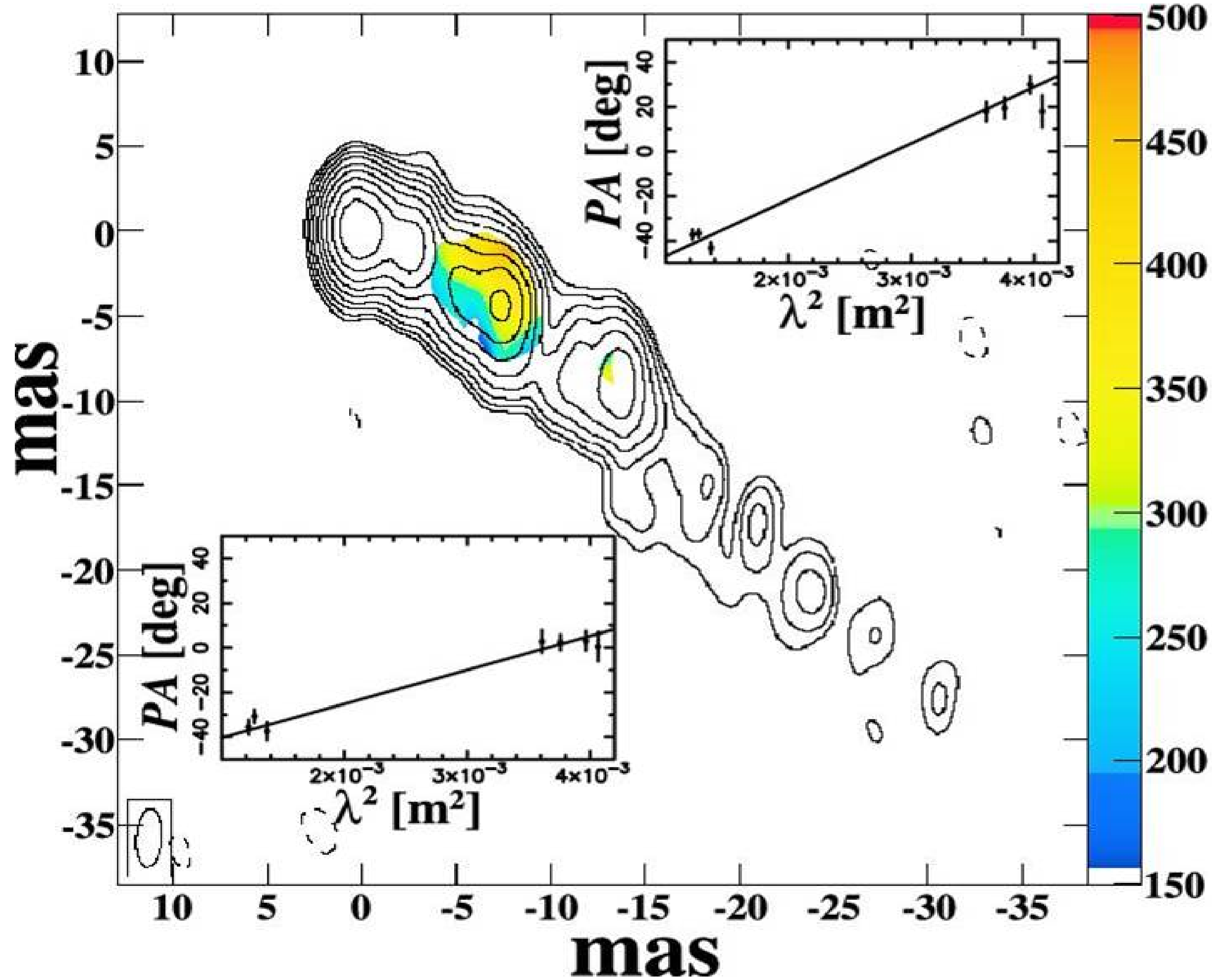
Polarization

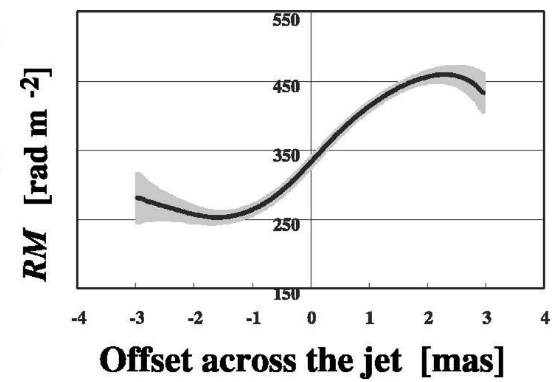


(Marscher et al 2008, Nature)

observed $\boldsymbol{E}_{\rm rad} \perp \boldsymbol{B}_{\perp \rm los}$
(modified by Faraday rotation and relativistic effects)

Faraday RM gradients across the jet





(Asada et al)

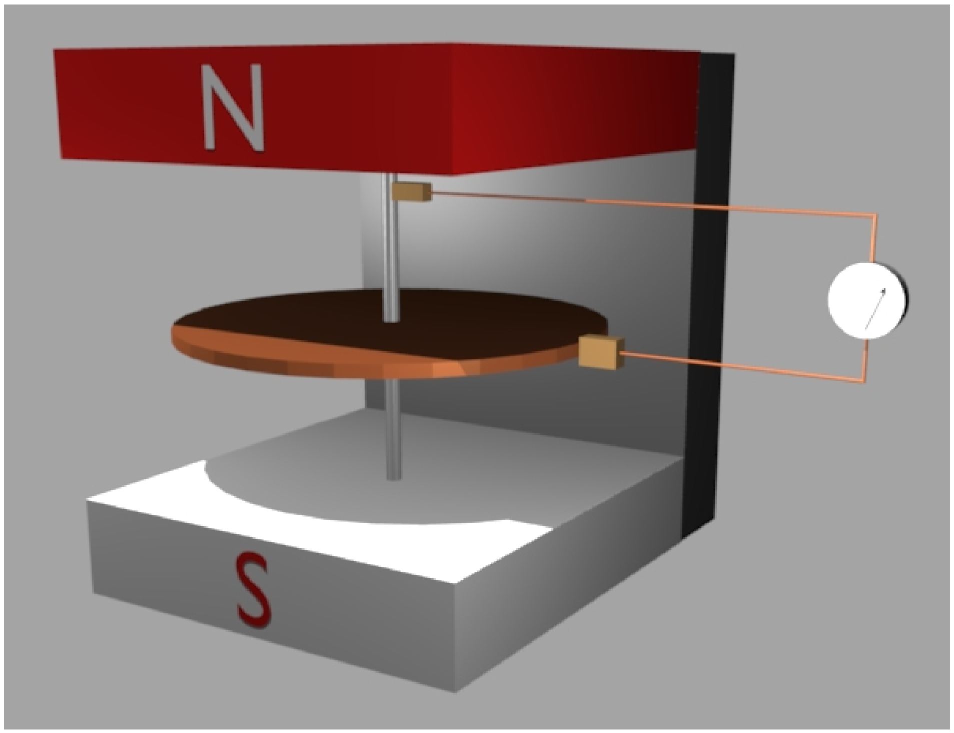
helical field surrounding the emitting region (Gabuzda)

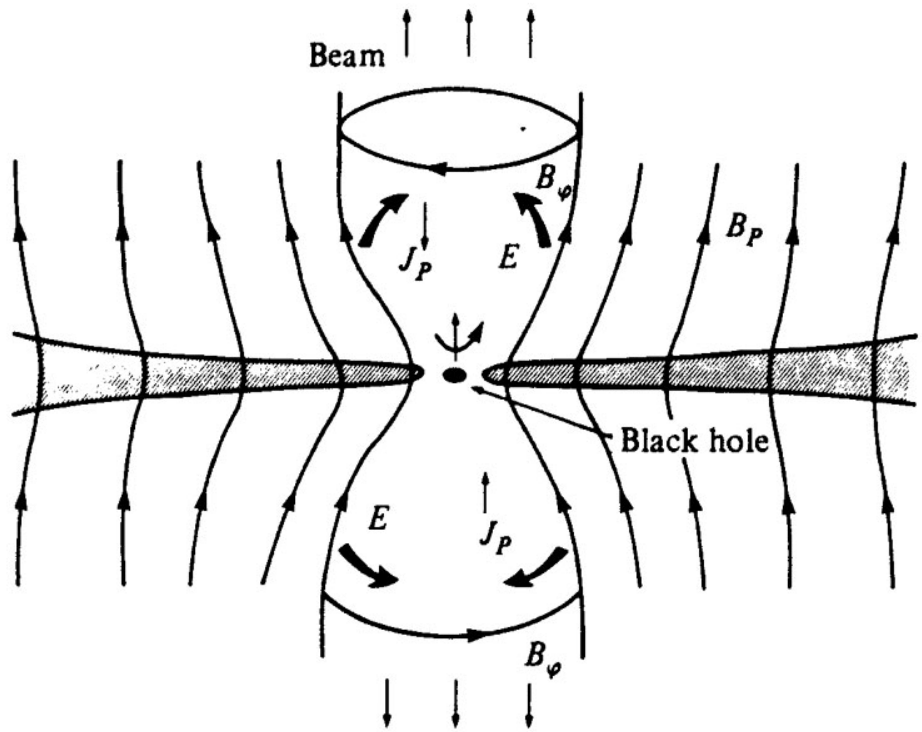
What magnetic fields can do

- ⋆ extract energy (Poynting flux)
- ⋆ extract angular momentum
- ⋆ transfer energy and angular momentum to matter
- ⋆ explain relatively large-scale acceleration
- ⋆ self-collimation
- ⋆ synchrotron emission
- ⋆ polarization and Faraday RM maps

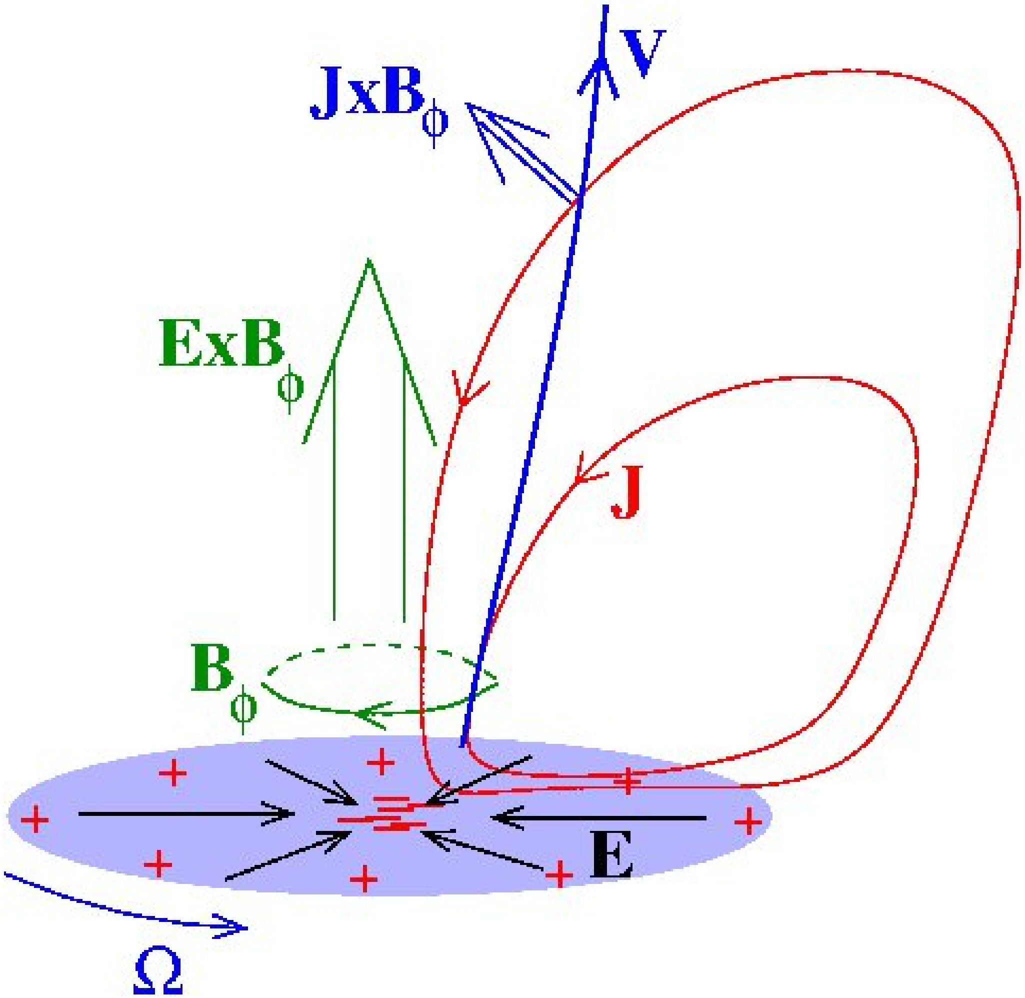
How MHD acceleration works

A unipolar inductor (Faraday disk)





magnetic field + rotation



current $\leftrightarrow B_\phi$
Poynting flux $\frac{c}{4\pi}EB_\phi$ is extracted (angular momentum as well)

The Faraday disk could be the rotating accretion disk, or the frame dragging if energy is extracted from the ergosphere of a rotating black hole (Blandford & Znajek mechanism)

magnetic acceleration

- simplified nonrelativistic momentum equation along the flow

$$\rho \frac{dV}{dt} = -\frac{B_\phi}{4\pi\varpi}\frac{\partial}{\partial \ell}(\varpi B_\phi) \quad = \boldsymbol{J} \times \boldsymbol{B} \text{ force}$$

(ϖ= cylindrical distance, ℓ= arclength along flow)

- simplified Ferraro's law (ignore V_ϕ – small compared to $\varpi\Omega$)

$$V_\phi = \varpi\Omega + V B_\phi / B_p \quad \Leftrightarrow \quad B_\phi \approx -\frac{\varpi\Omega B_p}{V} \quad \text{“Parker spiral”}$$

- combine the two, use the mass-to-magnetic flux $\Psi_A = \frac{4\pi\rho V}{B_p}$

(constant due to flux-freezing)

$$m\frac{dV}{dt} = -\frac{\partial}{\partial \ell}\left(\frac{S}{V}\right), \quad m = \frac{\Psi_A}{A\Omega^2}, \quad S = \frac{\varpi^2 B_p}{A}$$

(A is the magnetic flux – integral)

bunching function $S = \varpi^2 B_p / A$

using the definition of A, $S = \dfrac{2\pi\varpi^2 B_p}{\int \boldsymbol{B}_p \cdot d\boldsymbol{a}}$

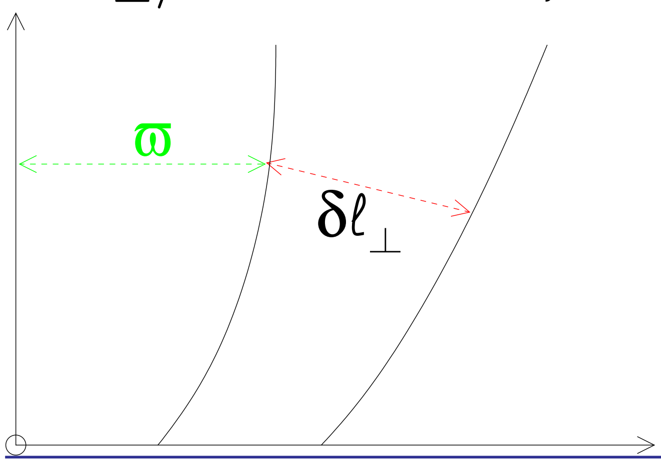
thus S measures the ratio of the local over the mean poloidal magnetic field

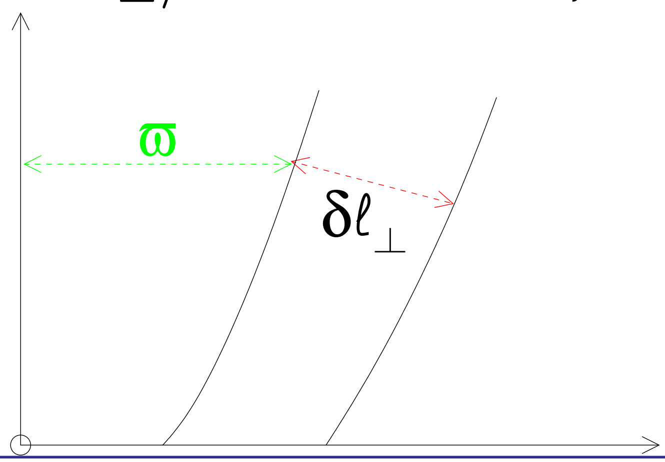
it measures how bunched are the fieldlines at a given point

its variation along the flow measures the expansion of the flow,

$$S = \frac{2\pi\varpi\delta\ell_\perp B_p}{A}\frac{\varpi}{\delta\ell_\perp} \propto \frac{\varpi}{\delta\ell_\perp}$$

if $\delta\ell_\perp/\varpi$ increases, S decreases if $\delta\ell_\perp/\varpi$ decreases, S increases





toy model

$$m\frac{dV}{dt} = -\frac{\partial}{\partial \ell}\left(\frac{S}{V}\right)$$

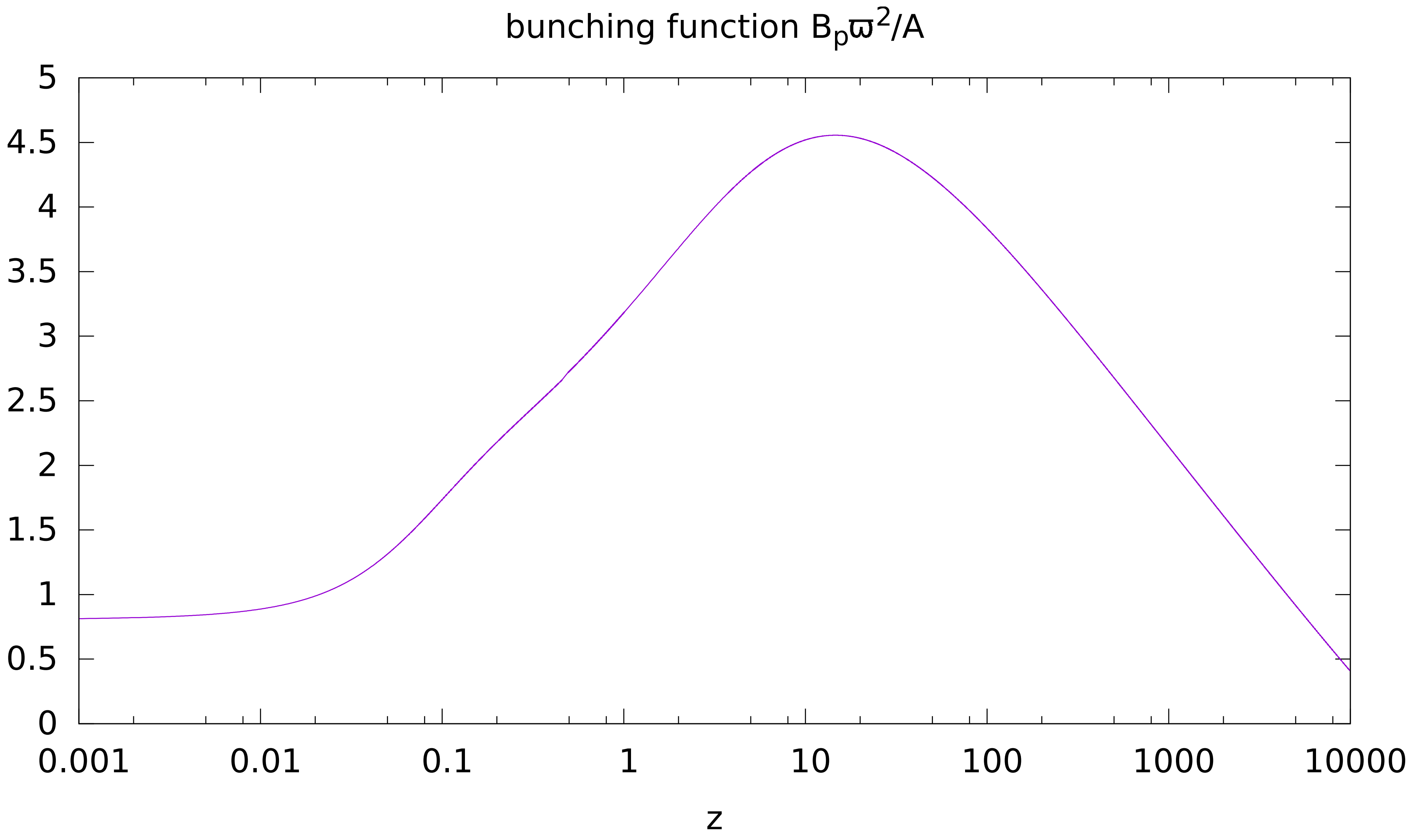
motion of a mass $m = \dfrac{\Psi_A}{A\Omega^2}$ in a velocity-dependent potential $\dfrac{S}{mV}$

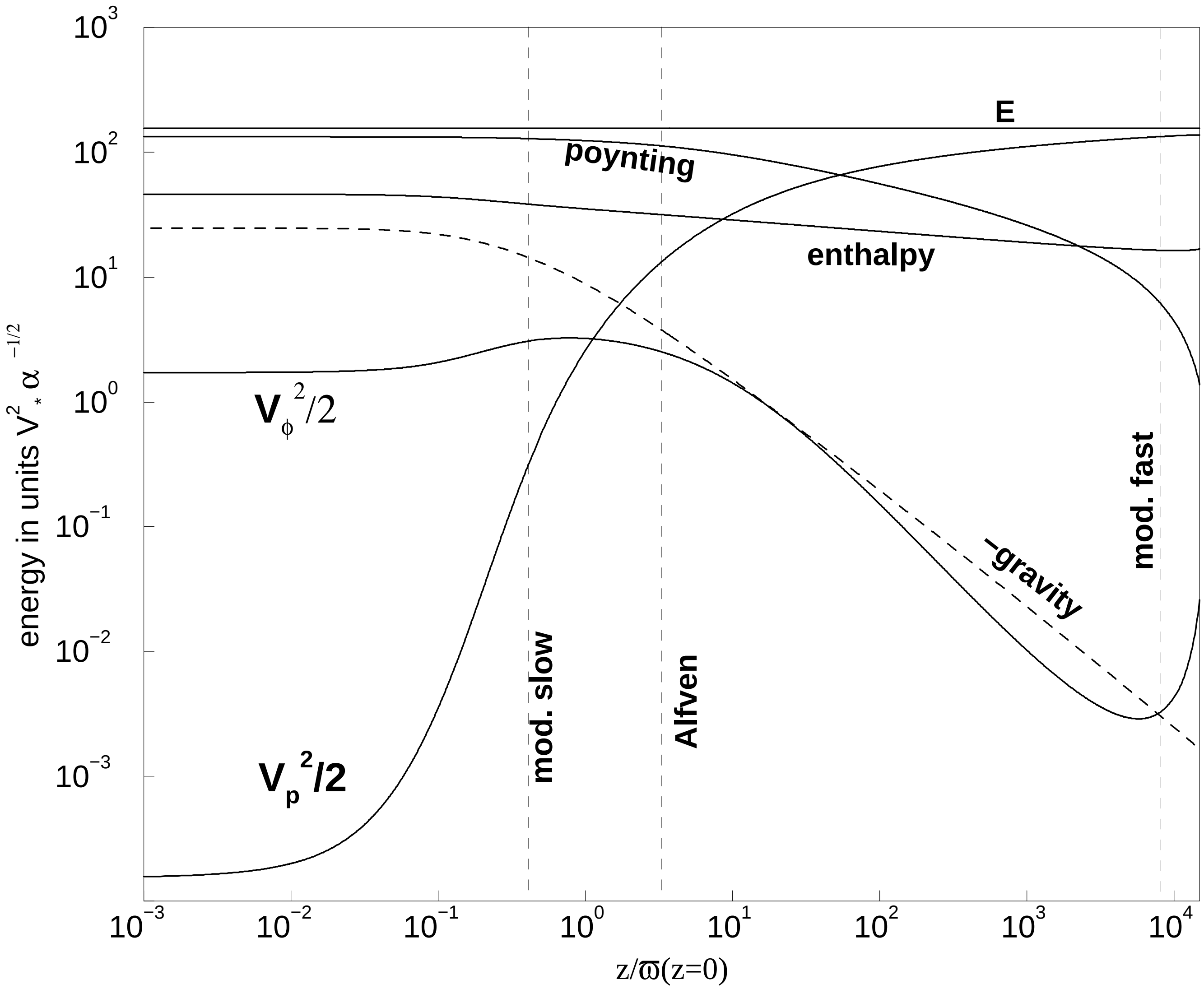
corresponding energy integral = Bernoulli $\quad \dfrac{V^2}{2} + \dfrac{S}{mV} = E$

The equation of particle motion can be written as a de-Laval nozzle equation

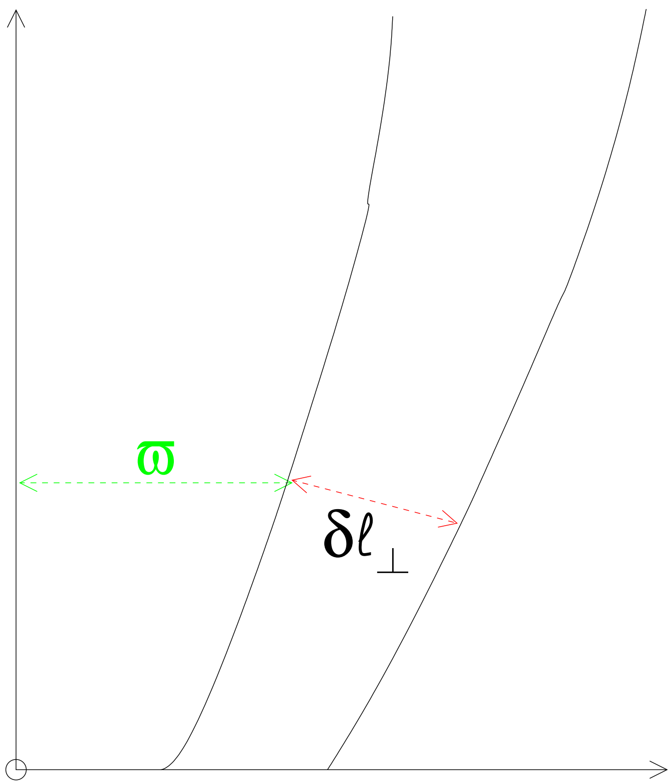
$$\frac{dV}{d\ell} = \frac{V\dfrac{dS}{d\ell}}{S - mV^3}, \qquad \frac{1}{S} \propto \frac{\delta\ell_\perp}{\varpi}$$

Vlahakis+2000 nonrelativistic solution





E
poynting
enthalpy
$V_\phi{}^2/2$
$V_p{}^2/2$
mod. slow
Alfven
-gravity
mod. fast
energy in units $V_*^2\,\alpha^{-1/2}$
$z/\varpi(z=0)$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



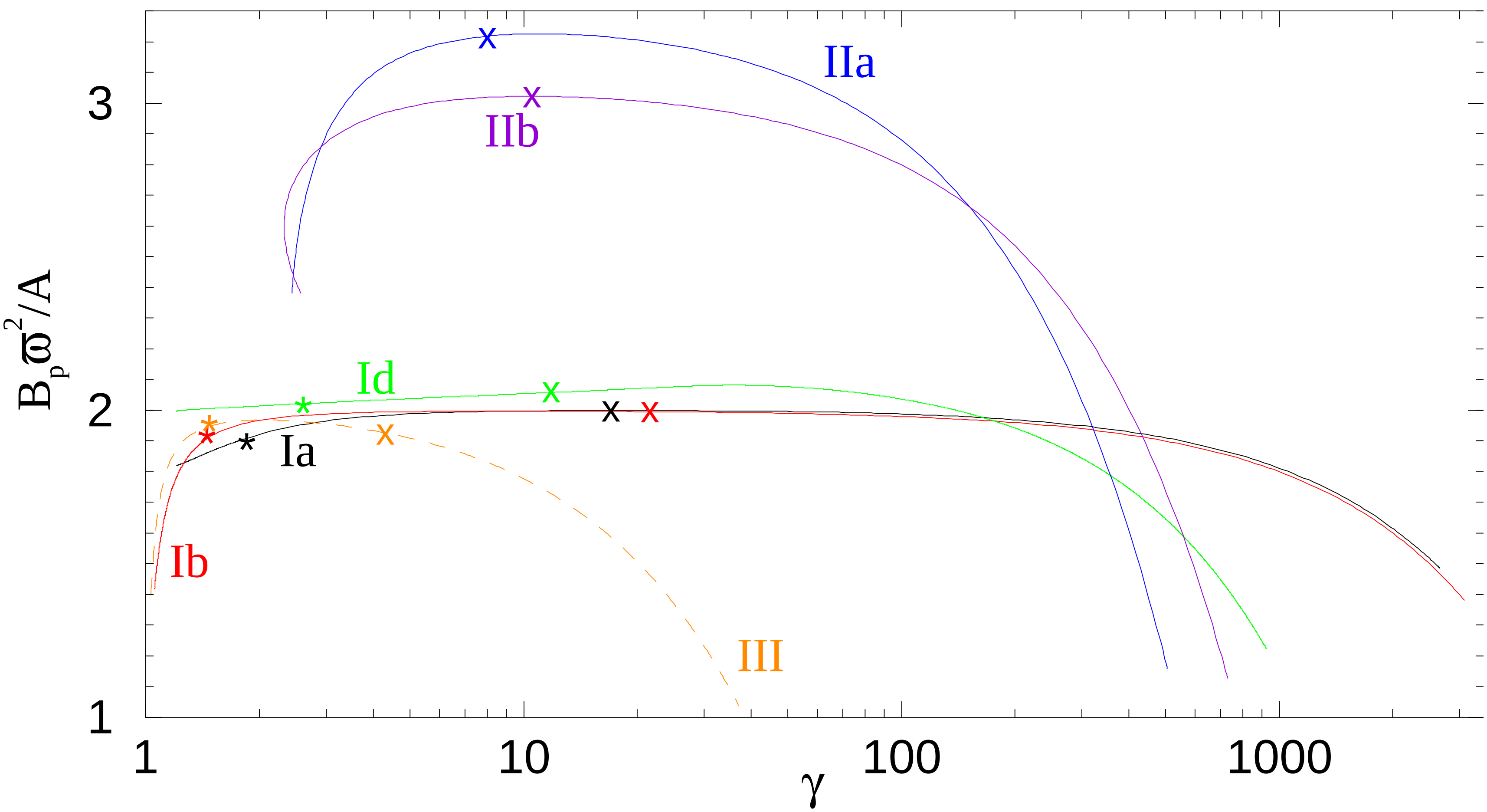
first S increases then decreases (differential collimation)

$S_\infty \sim 1$ so the Bernoulli integral gives the value of V_∞

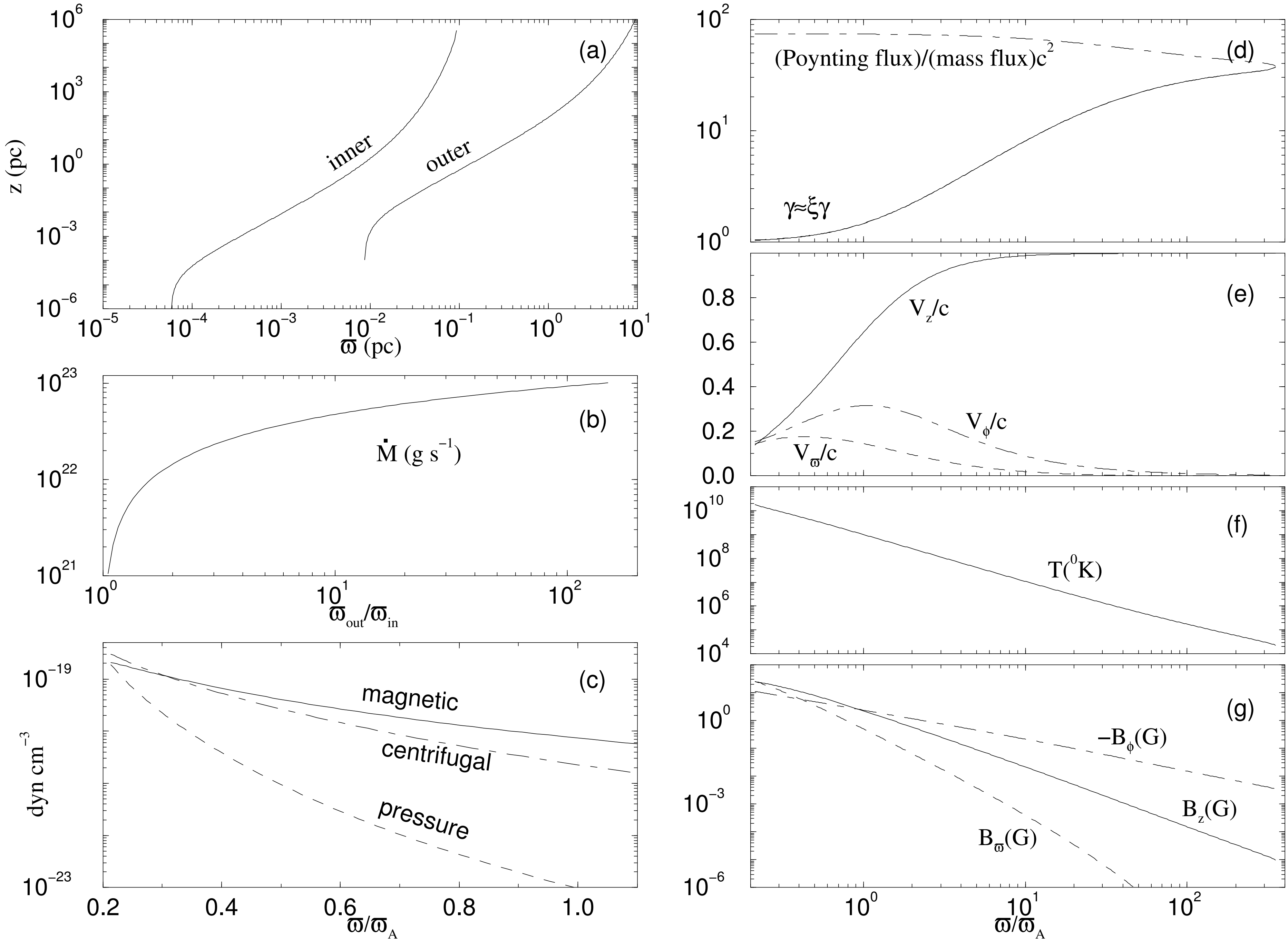
higher $S_{\rm max}$ $\rightarrow$ higher acceleration efficiency

in V00 $S_{\rm max} \approx 4.5$ and acceleration efficiency $\gtrsim 90\%$

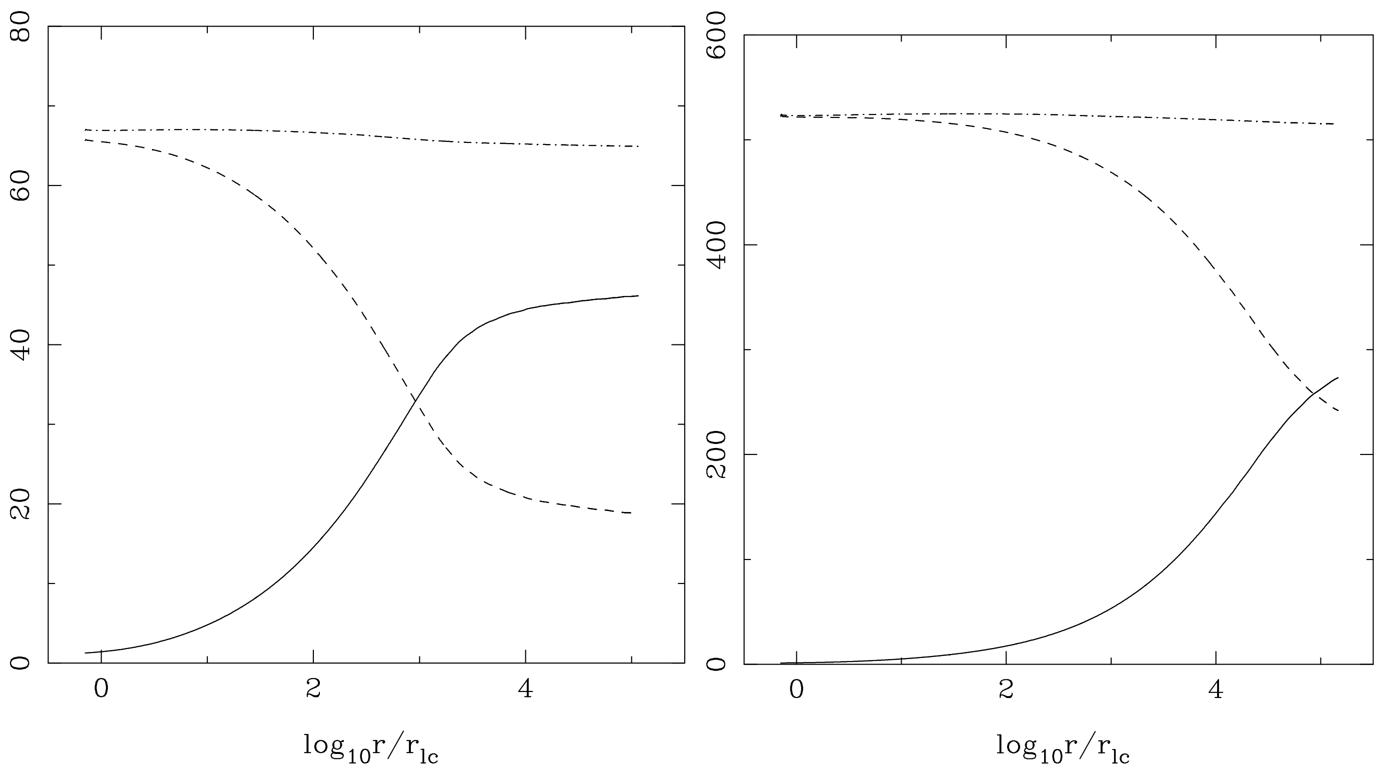
Vlahakis & Königl 2003, 2004 relativistic solutions



acceleration efficiency $\gtrsim 50\%$


(a)
z (pc)
ϖ (pc)
inner
outer
(b)
Ṁ (g s^-1)
ϖ_out/ϖ_in
(c)
dyn cm^-3
magnetic
centrifugal
pressure
ϖ/ϖ_A
(d)
(Poynting flux)/(mass flux)c^2
γ≈ξγ
(e)
V_z/c
V_φ/c
V_ϖ/c
(f)
T(^0K)
(g)
−B_φ(G)
B_z(G)
B_ϖ(G)
ϖ/ϖ_A

Simulations of special relativistic jets (e.g. Komissarov+2009)



energy flux ratios:

$$\gamma = \frac{\text{kinetic}}{\text{rest mass}}$$

$$\gamma\sigma = \frac{\text{Poynting}}{\text{rest mass}}$$

$$(\sigma = \frac{\text{Poynting}}{\text{kinetic}})$$

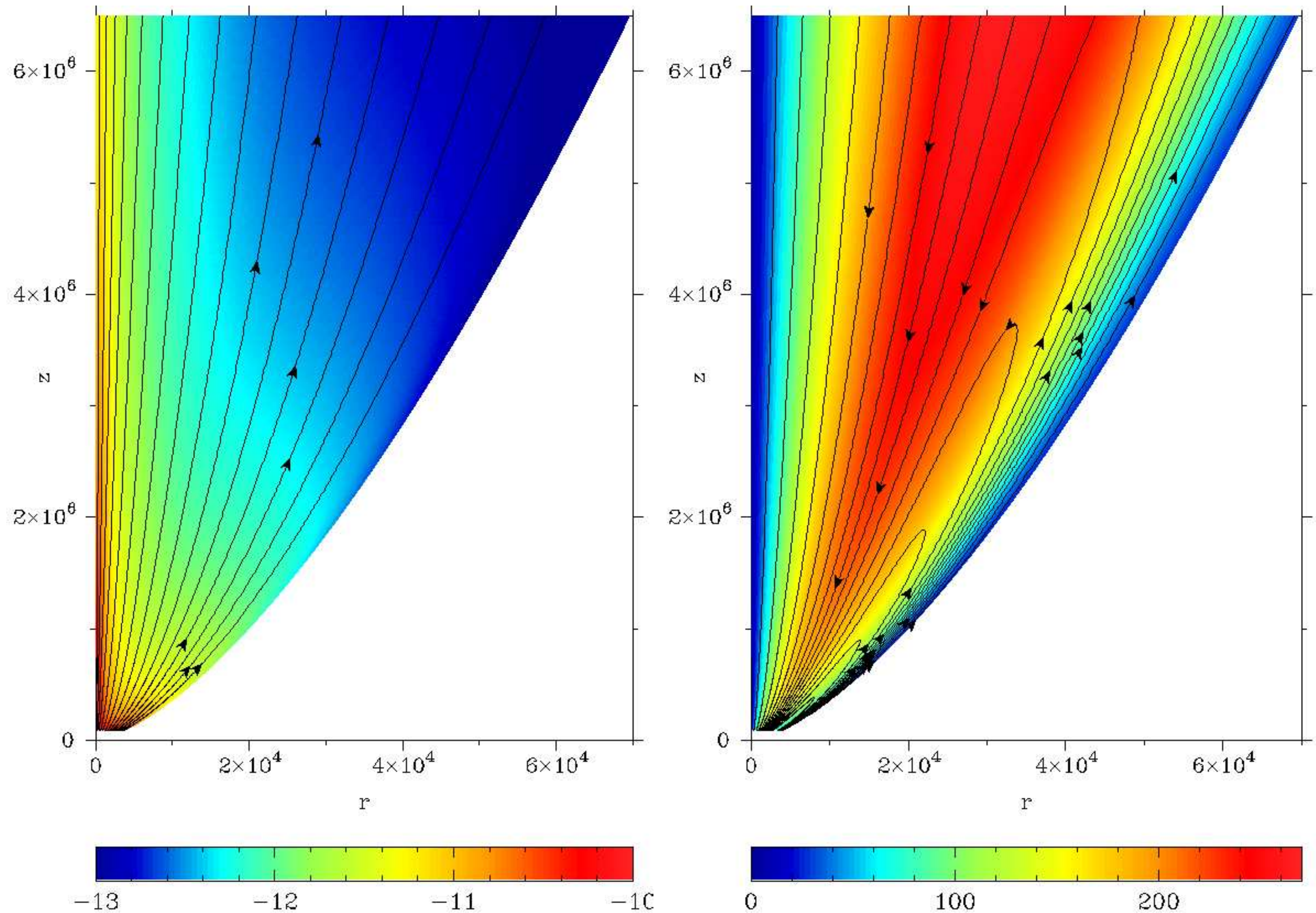
$$\mu = \gamma + \gamma\sigma$$

γ (increasing),

$\gamma\sigma$ (decreasing),

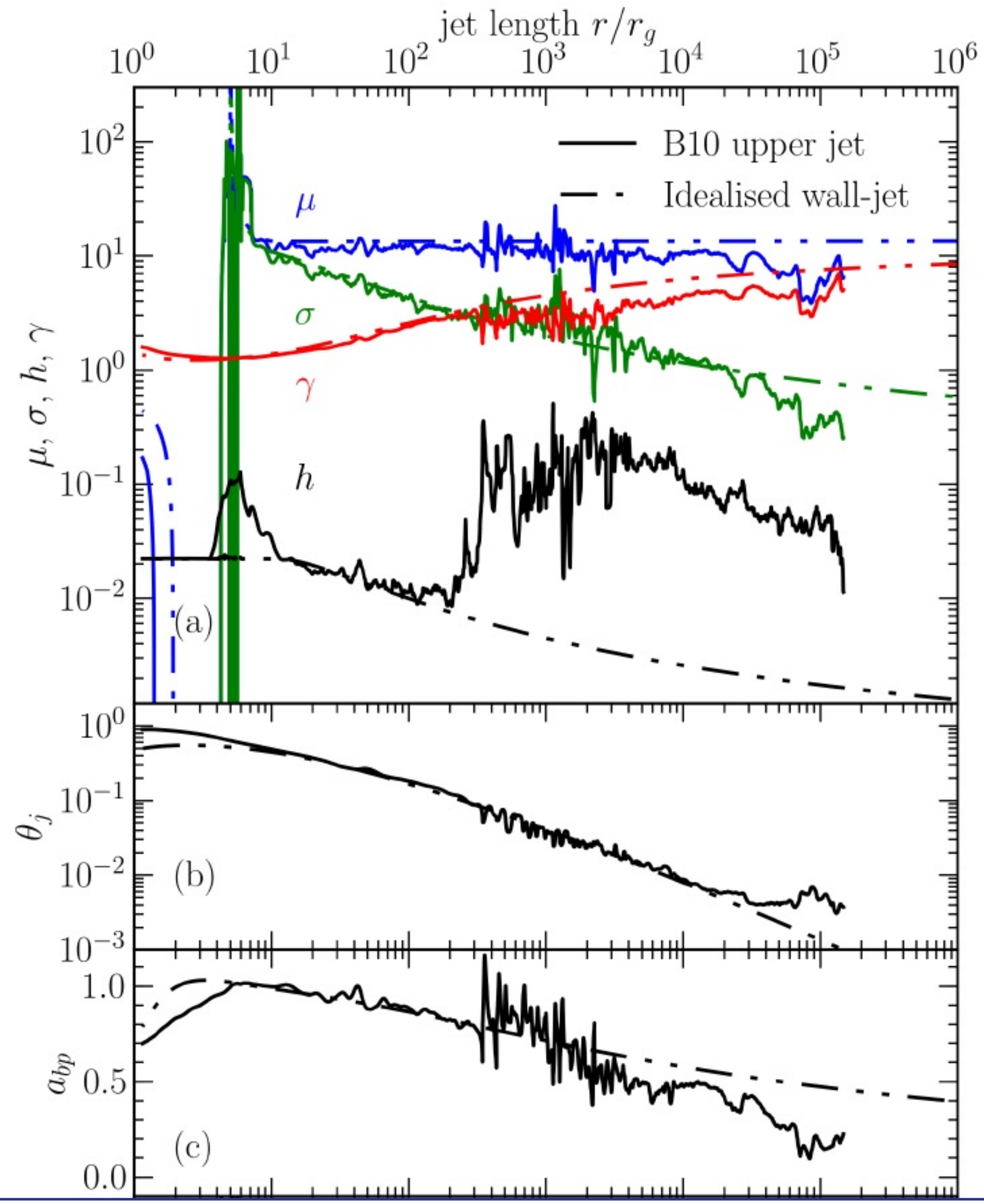
and μ (constant)

efficiency $> 50\%$



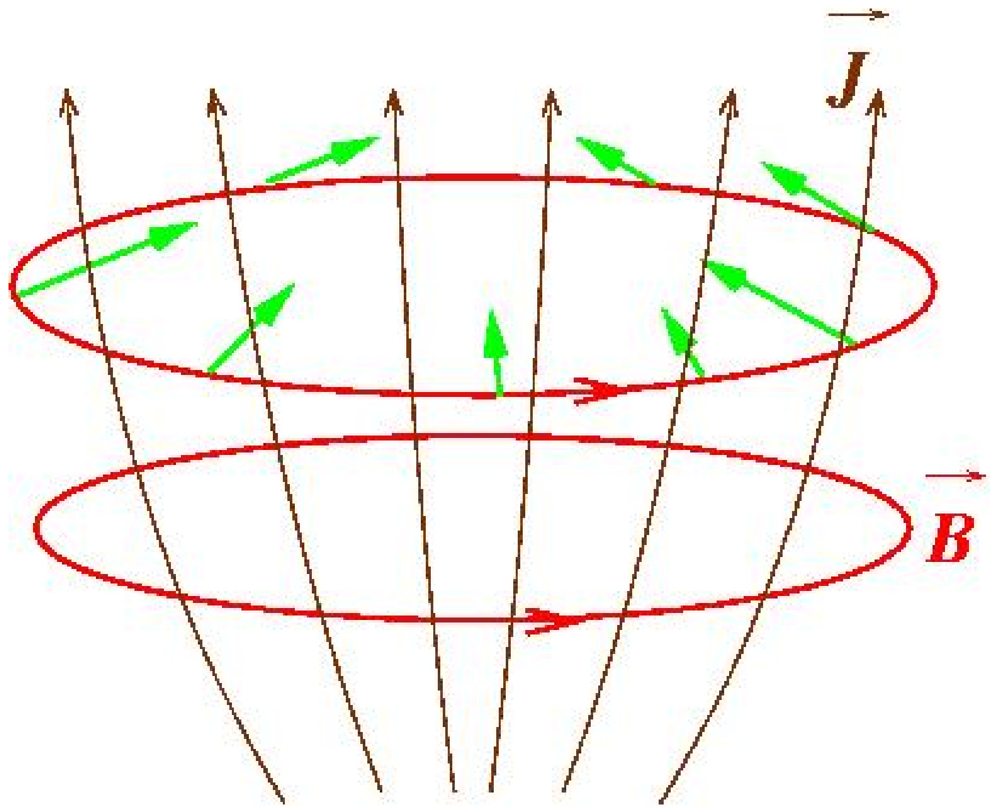
left: density/field lines, right: Lorentz factor/current lines (jet shape $z \propto r^{1.5}$)

Even in general relativistic magnetohydrodynamic jet simulations (the latest Chatterjee+2019)



Basic questions: collimation

hoop-stress:



+ electric force

degree of collimation ?   Role of environment?

☞ transfield component of the momentum equation for relativistic jets simplifies to $\mathcal{R} \approx \gamma^2 \varpi$

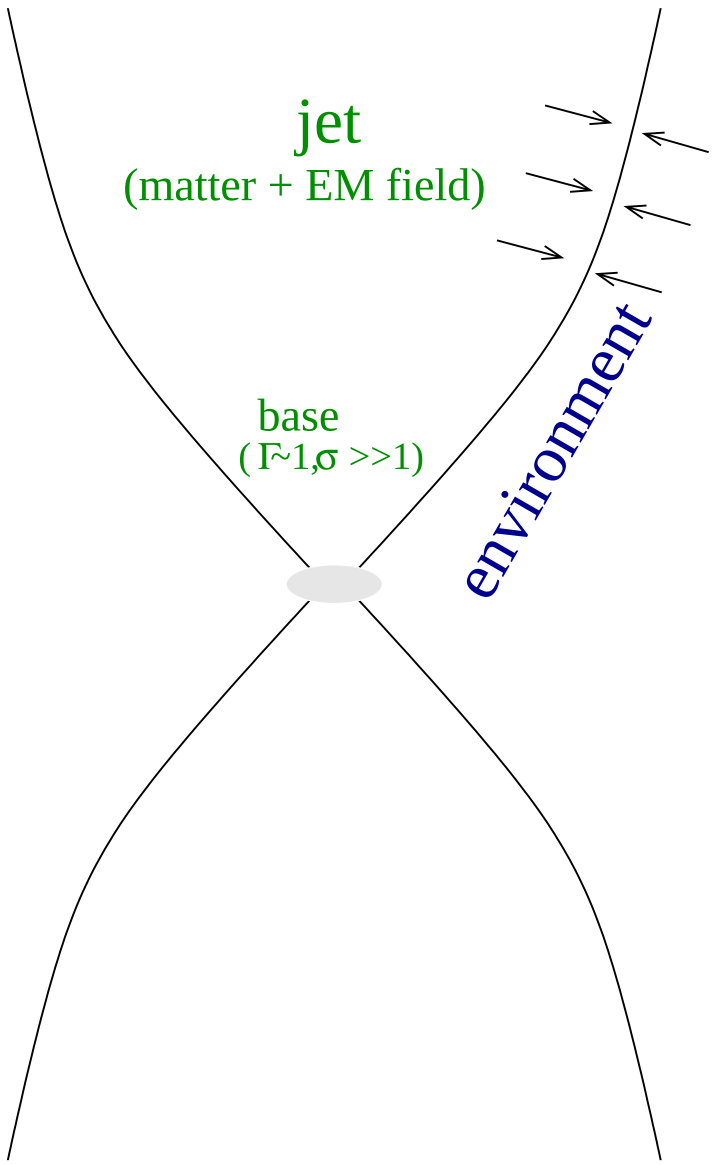
since $\mathcal{R}^{-1} \approx -\frac{d^2\varpi}{dz^2} \approx \frac{\varpi}{z^2}$ it gives power-law $\gamma \approx z/\varpi$
(for parabolic shapes $z \propto \varpi^a$, γ is a power of ϖ)

☞ role of external pressure

$p_{\rm ext} = B_{\rm co}^2/8\pi \simeq (B^{\hat{\phi}})^2/8\pi\gamma^2 \propto 1/\varpi^2\gamma^2$

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

Basic questions



- source of matter/energy?
  disk or central object, rotation+magnetic field

- bulk acceleration ✓

- collimation ✓

- interaction with environment?
  $P_{\rm ext}$ is important especially in relativistic jets

2nd level of understanding

- ☞ distribution of B in the source? (advection vs diffusion, instabilities in disks?)

- ☞ details of jet physics near rotating black holes (pair creation in stagnation surface) – energy extraction from the black hole?

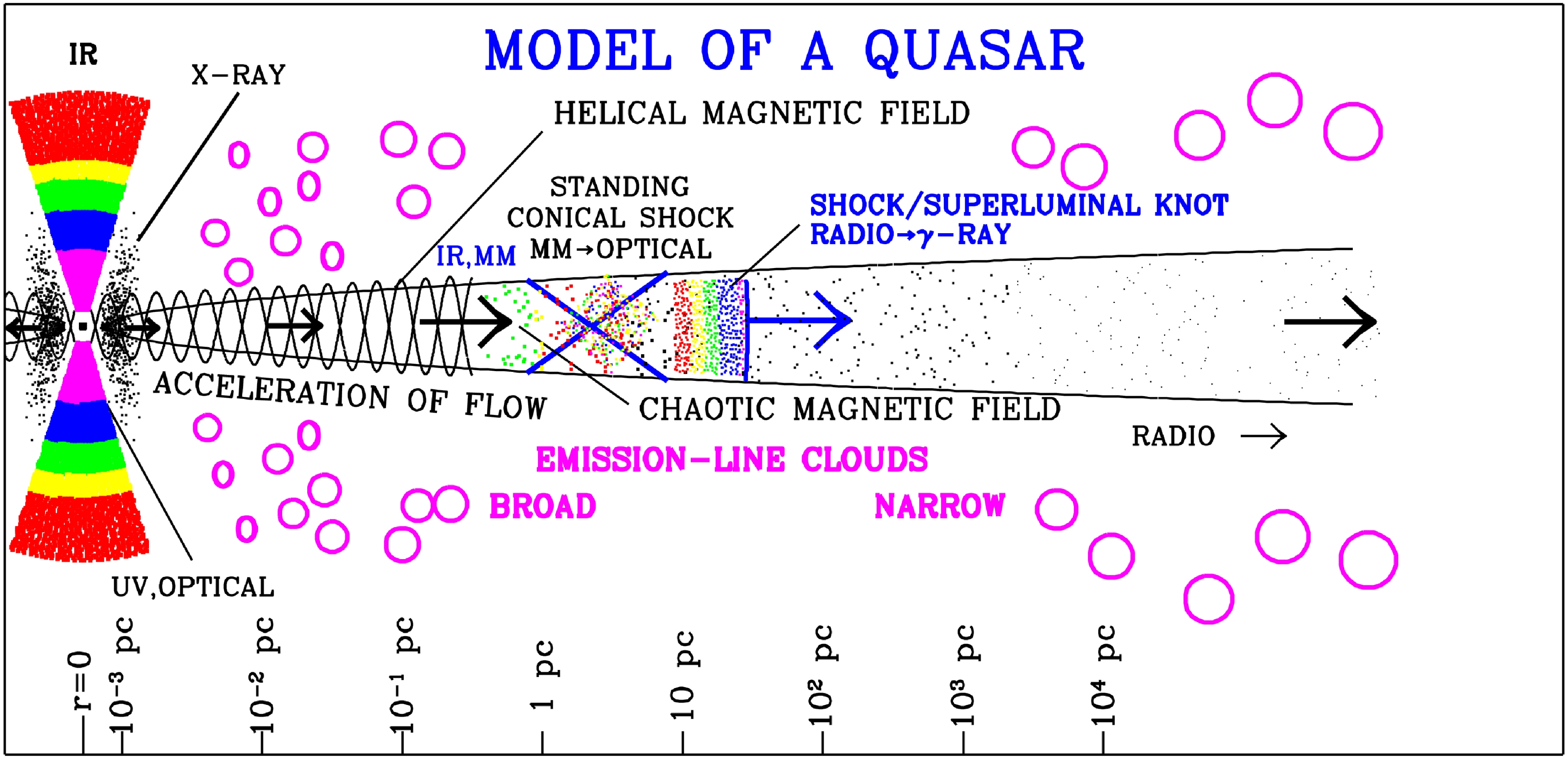
- ☞ detailed study of the interaction with environment (Riemann problem – shock and rarefaction waves)

- ☞ jet stability (Kelvin-Helmholtz? current driven?)

- ☞ nonthermal radiation – particle acceleration

  shocks or reconnection ? connection with instabilities ?

- ☞ polarization maps and comparison with observations



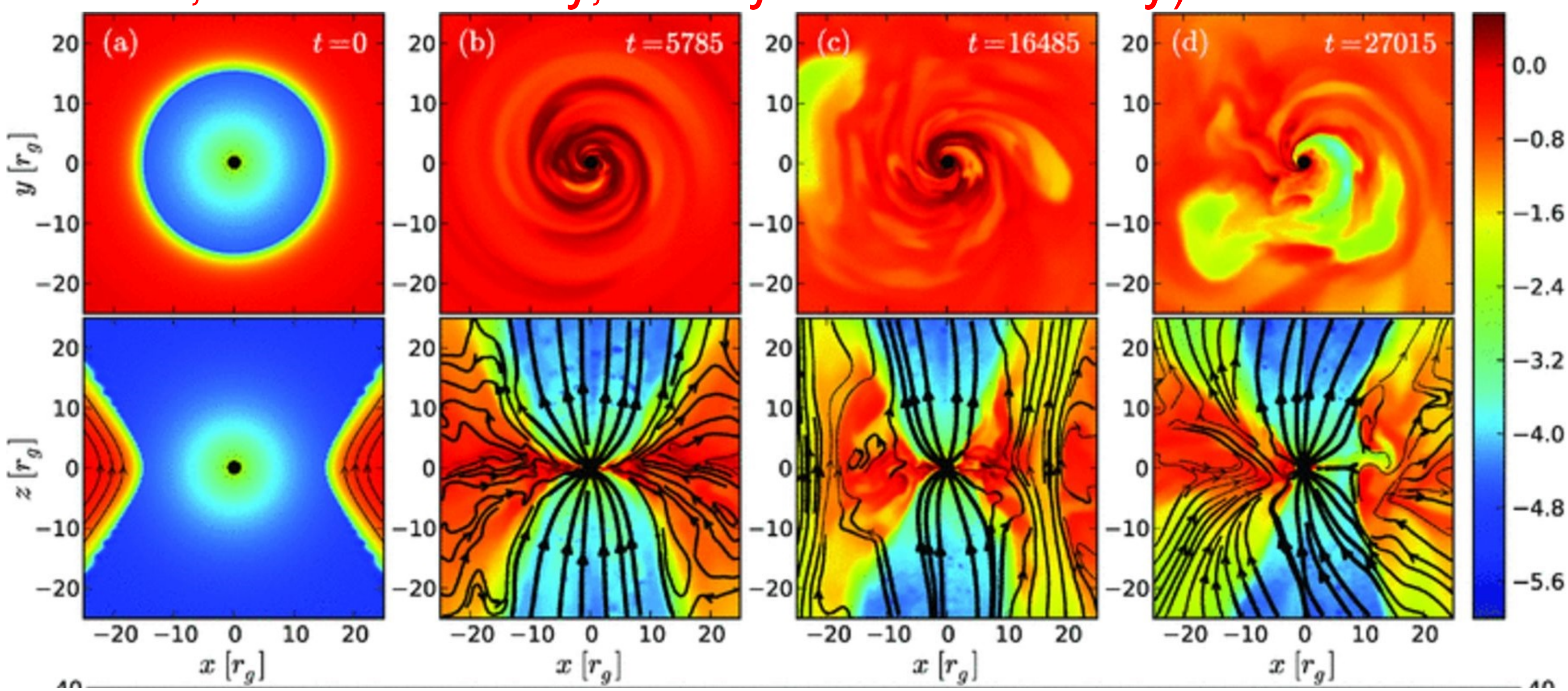
credit: Boston University Blazar Group

Stability analysis

- are astrophysical jets stable?

- 3D relativistic MHD simulations hard to cover the full jet range (formation and propagation zone + environment)

interesting results for the jet-formation region (McKinney & Blandford, Tchekhovskoy, Narayan & McKinney)



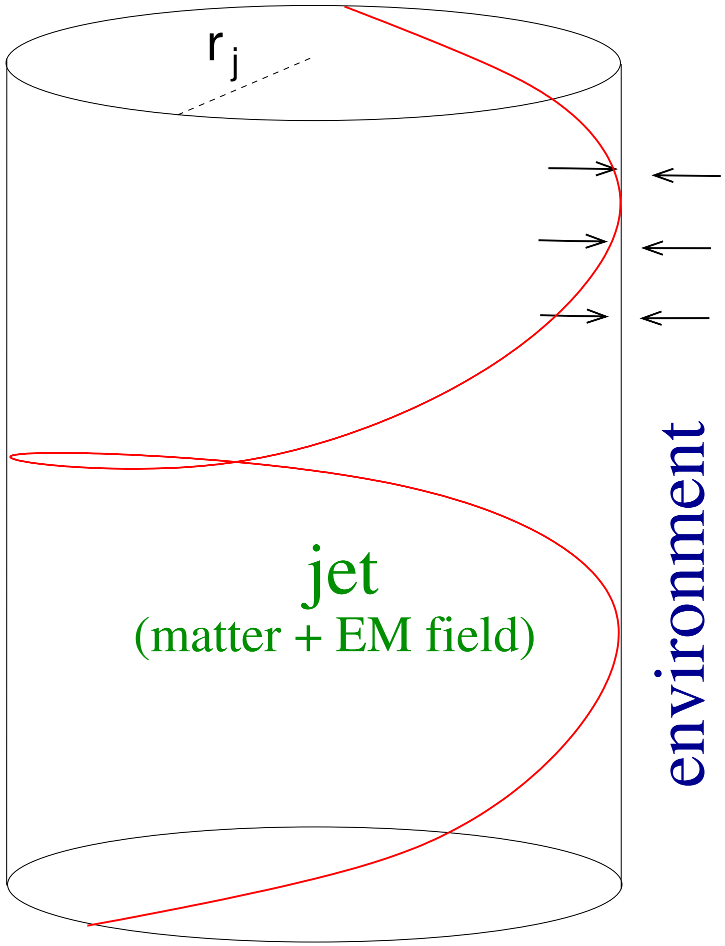
- our approach (Charis Sinnis & Vlahakis in preparation):

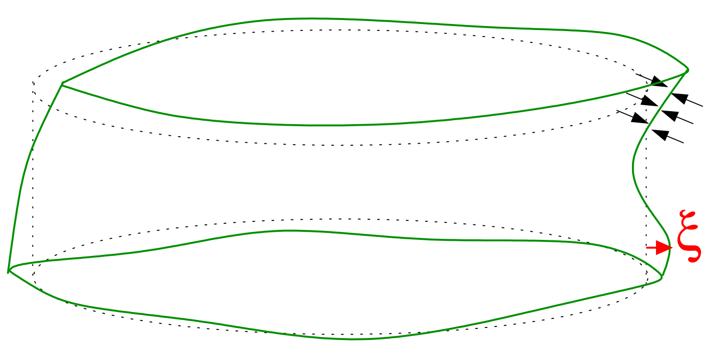
- focus on the propagation phase

- assume cylindrical unperturbed jet

- add perturbation
  $Q(\varpi\,, z\,, \phi\,, t) = Q_0(\varpi) + Q_1(\varpi)\exp\left[i(m\phi + kz - \omega t)\right]$ (with complex ω) and linearize

Eigenvalue problem



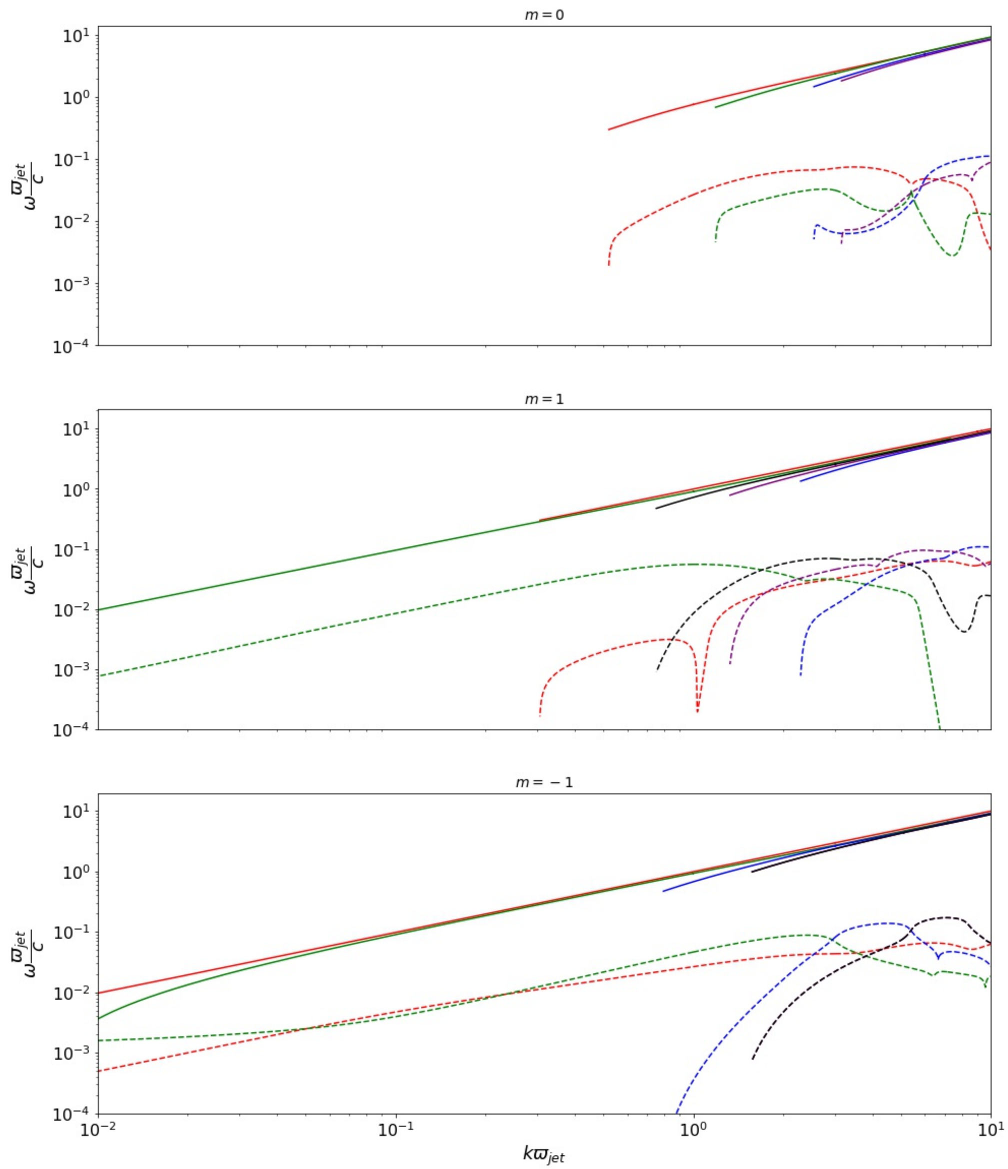


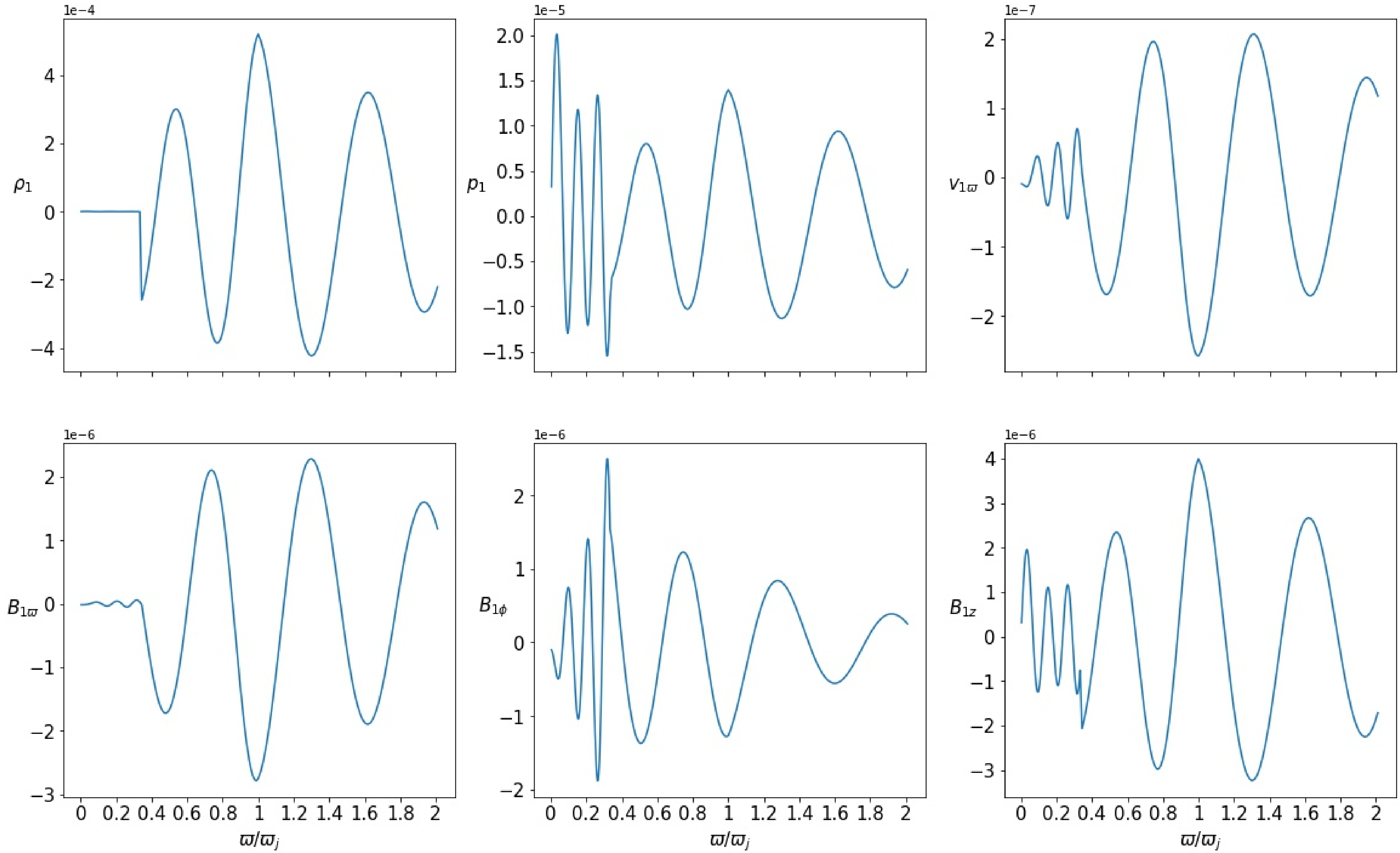
- solve the problem inside the jet
(attention to regularity condition on the axis)
- similarly in the environment
(solution vanishes at ∞)

- The matching of the solutions at ϖ_j gives the dispersion relation $\omega = \omega(k, m)$

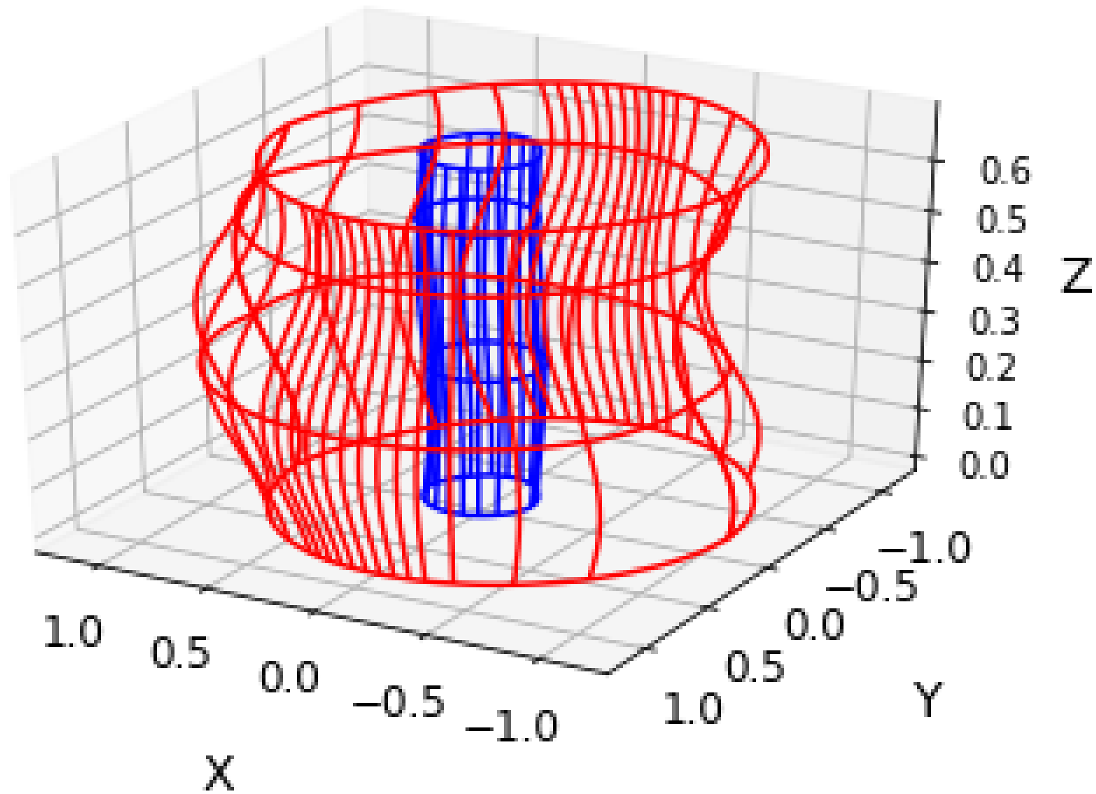
- find the growth rate $\Im\omega$ and the eigenfunctions

$\sigma = 0.01$





1e−4
ρ_1
1e−5
p_1
1e−7
$v_{1\varpi}$
1e−6
$B_{1\varpi}$
1e−6
$B_{1\phi}$
1e−6
B_{1z}
ϖ/ϖ_j
ϖ/ϖ_j
ϖ/ϖ_j


0.6
0.5
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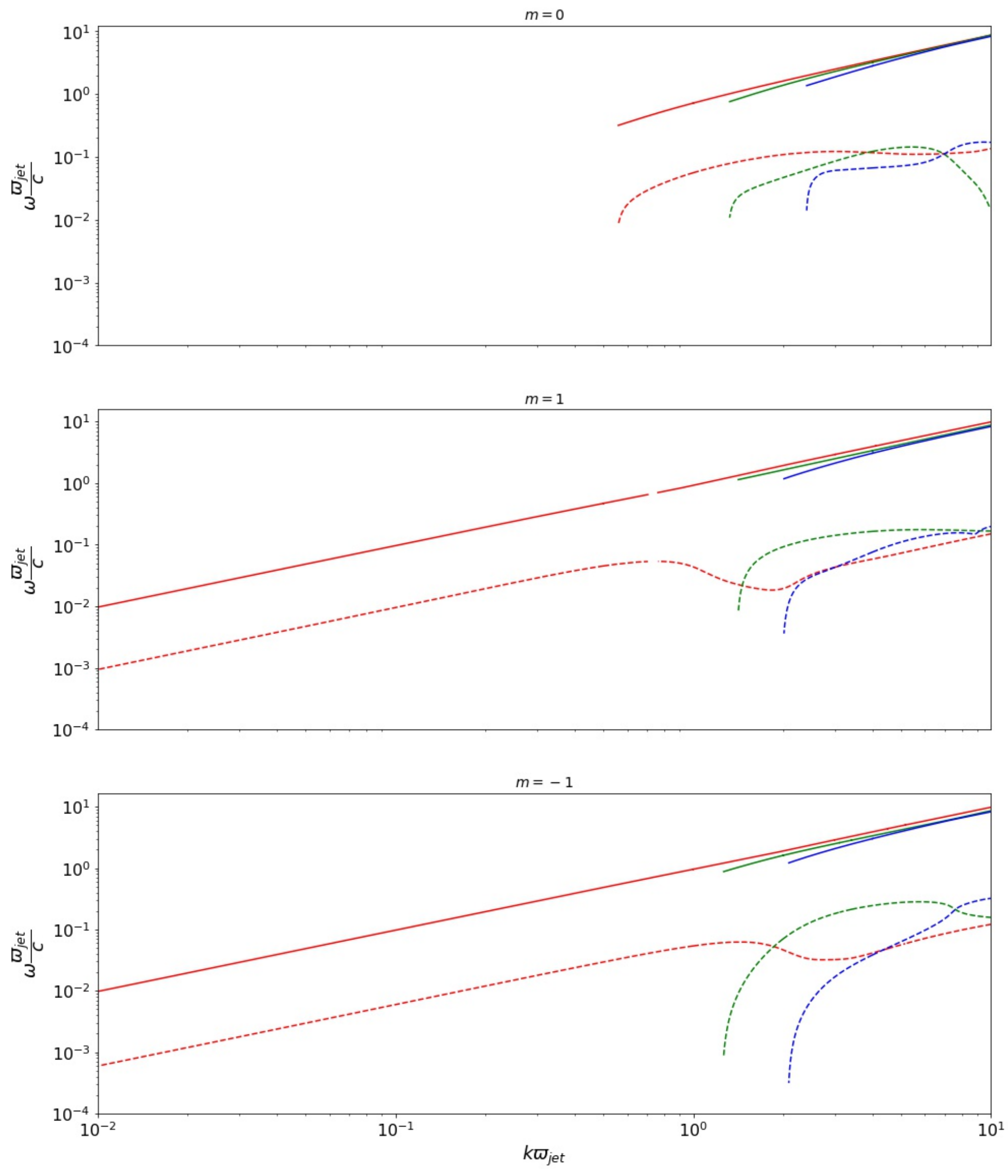
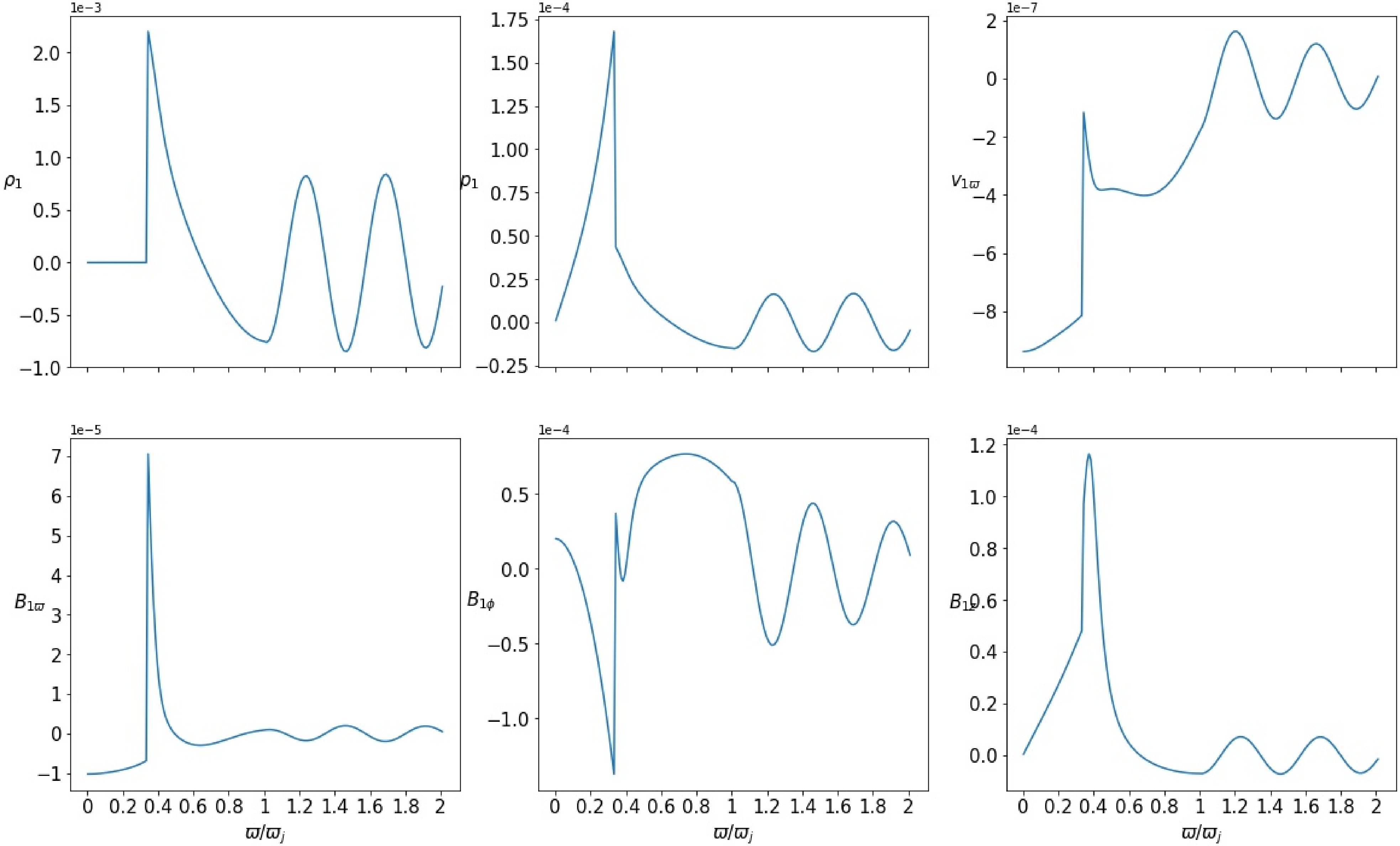
0.3
0.2
0.1
0.0
Z
1.0
0.5
0.0
−0.5
−1.0
X
−1.0
−0.5
0.0
0.5
1.0
Y

$\sigma = 10$




1e−3
ρ_1
1e−4
p_1
1e−7
$V_{1\varpi}$
1e−5
$B_{1\varpi}$
1e−4
$B_{1\phi}$
1e−4
B_{1z}
ϖ/ϖ_j
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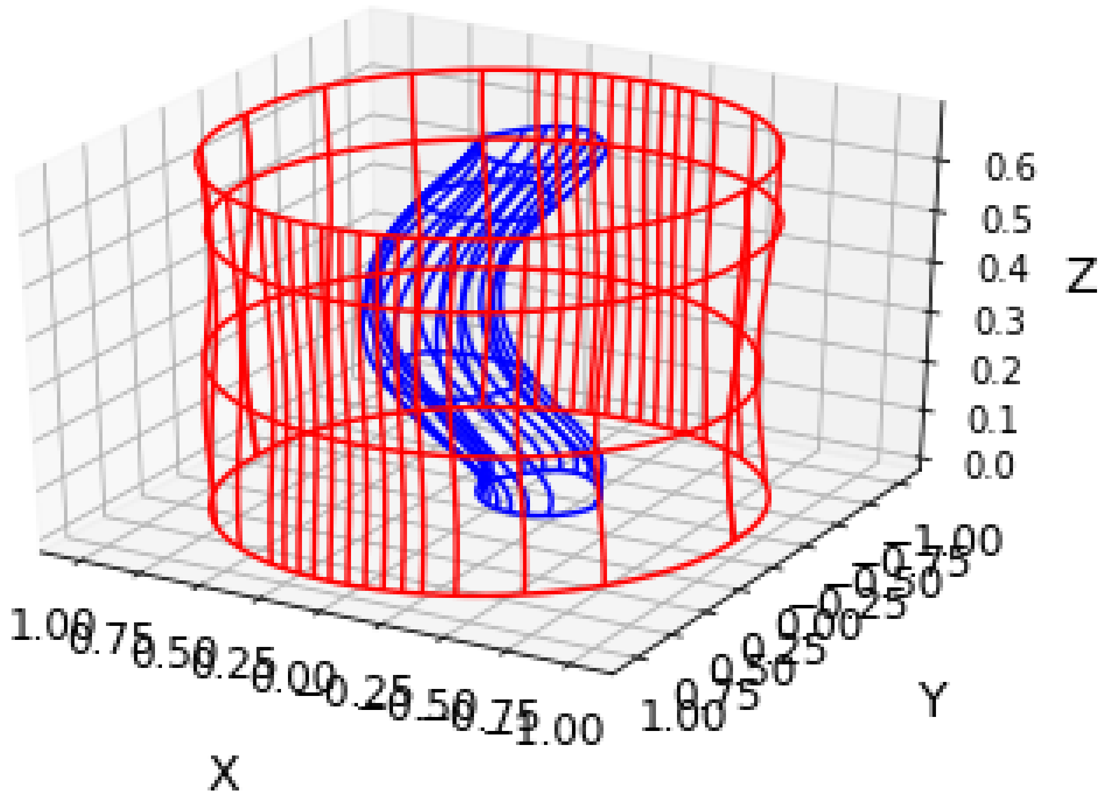
ϖ/ϖ_j


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Z
X
Y

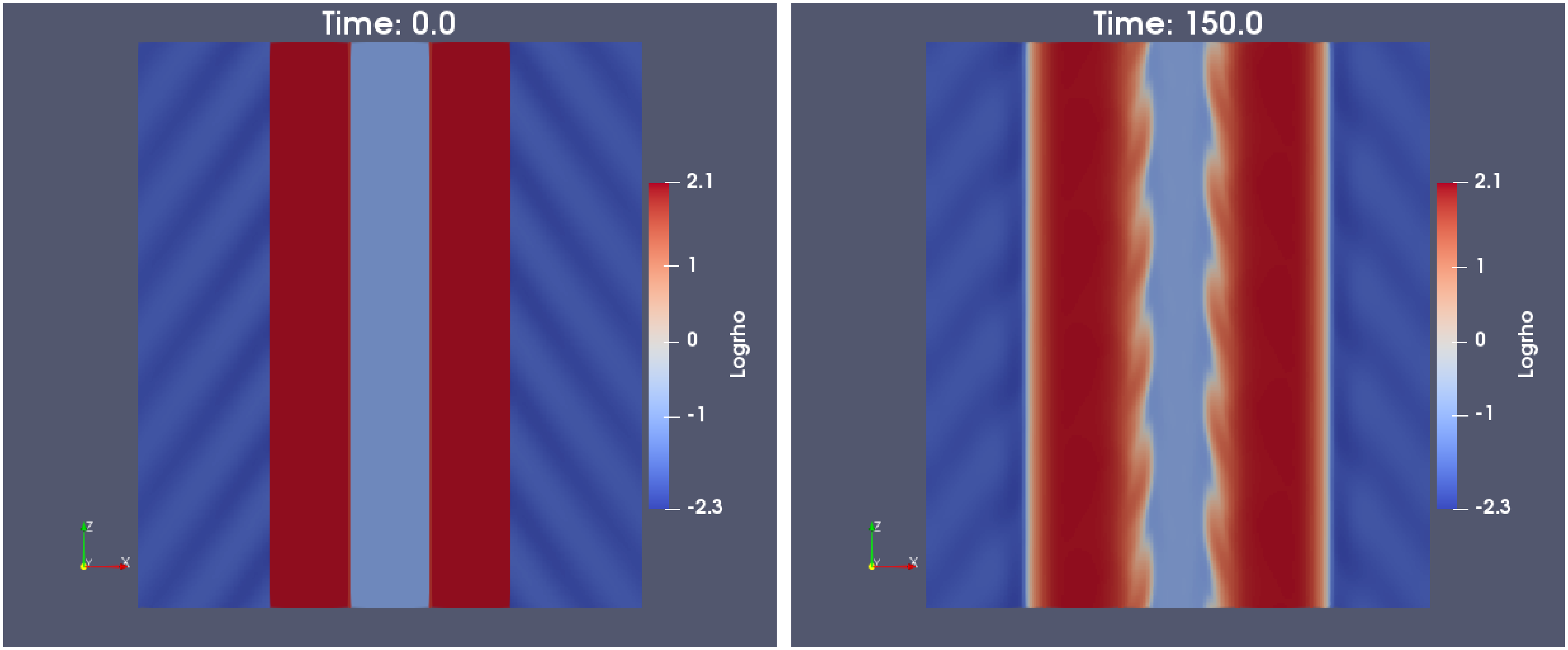
- $\star$ typical growth rate $= \Im\omega \sim 0.1c/\varpi_j$

- $\star$ growth length $\approx$ growth time ($c = 1$)
  a few tens of jet radii

- $\star$ for highly magnetized jet the instability is more important inside the volume of the jet

- $\star$ for low magnetized jet it is Kelvin-Helmholtz-type

Simulations of two-component jets (Millas & Vlahakis in preparation)



Summary

- $\star$ magnetic field + rotation $\rightarrow$ Poynting flux extraction
- $\star$ the collimation-acceleration mechanism is very efficient – provides a viable explanation for the bulk acceleration in all jets (relativistic or not)
- $\star$ acceleration efficiency $\gtrsim 50\%$
- $\star$ environment significantly affects jet dynamics (jet-shape, spatial scale of γ)
- $\star$ typical instability growth length = a few tens ϖ_j
  volume or surface instabilities depending on the magnetization