Astrophysical jet dynamics

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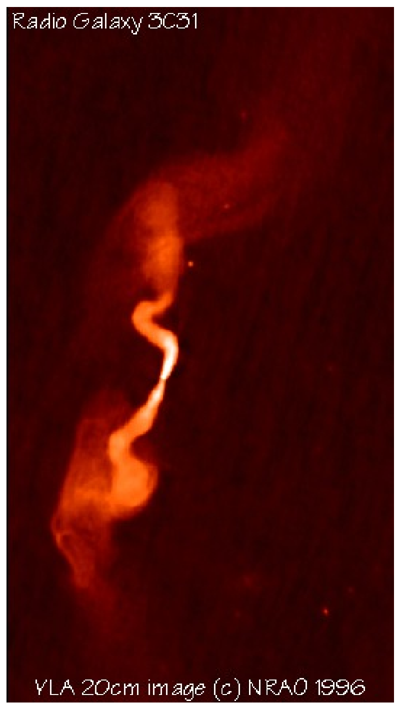
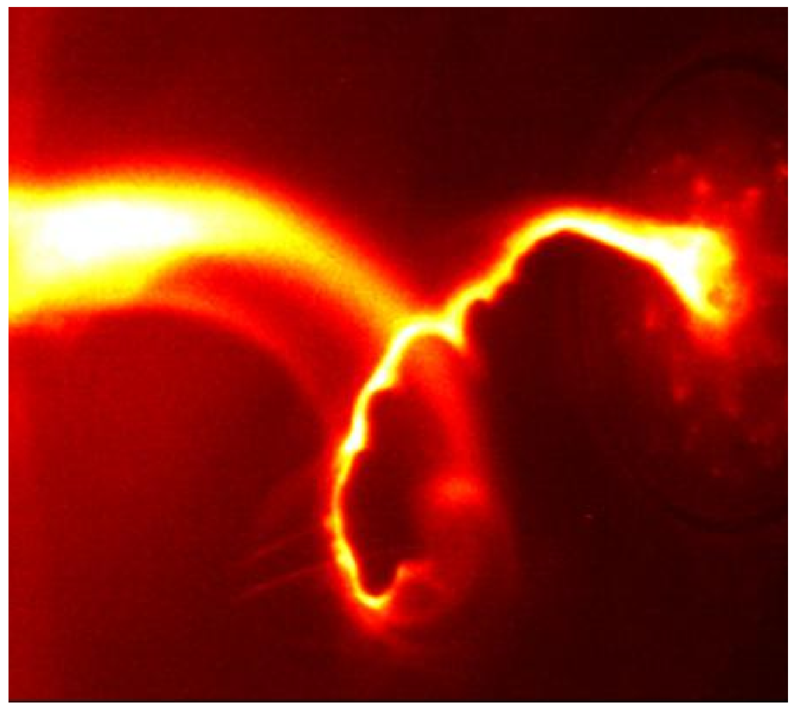
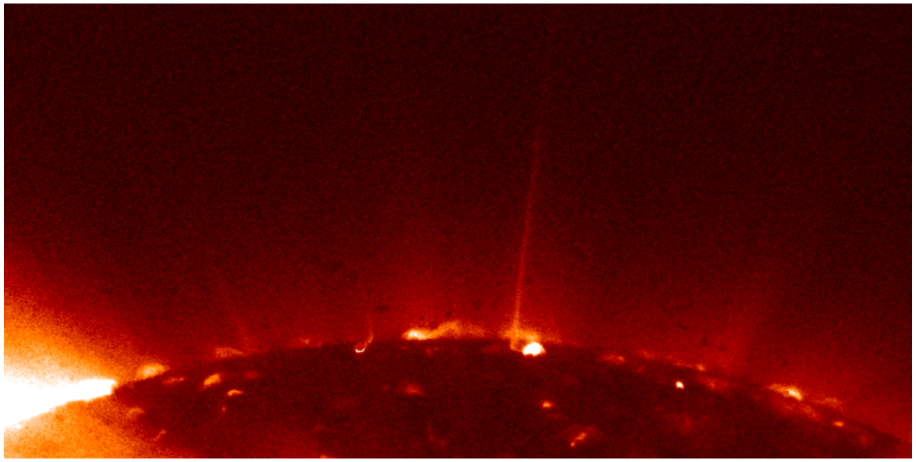
Outline

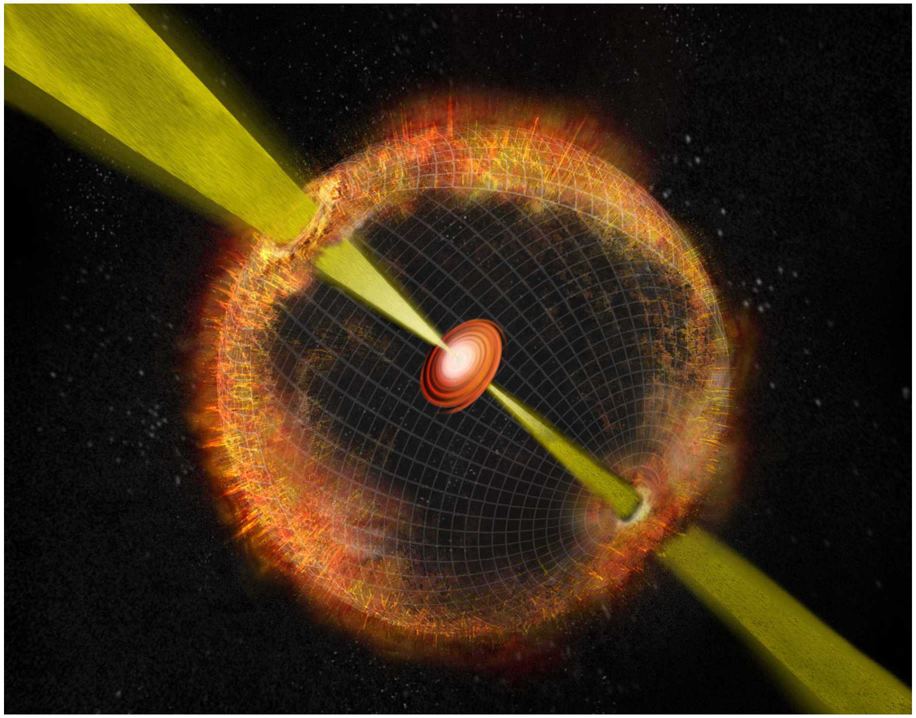
- observed jet characteristics
- basic questions:
  bulk acceleration, stability

Astrophysical jet examples









Relativistic jet models: Why magnetic fields

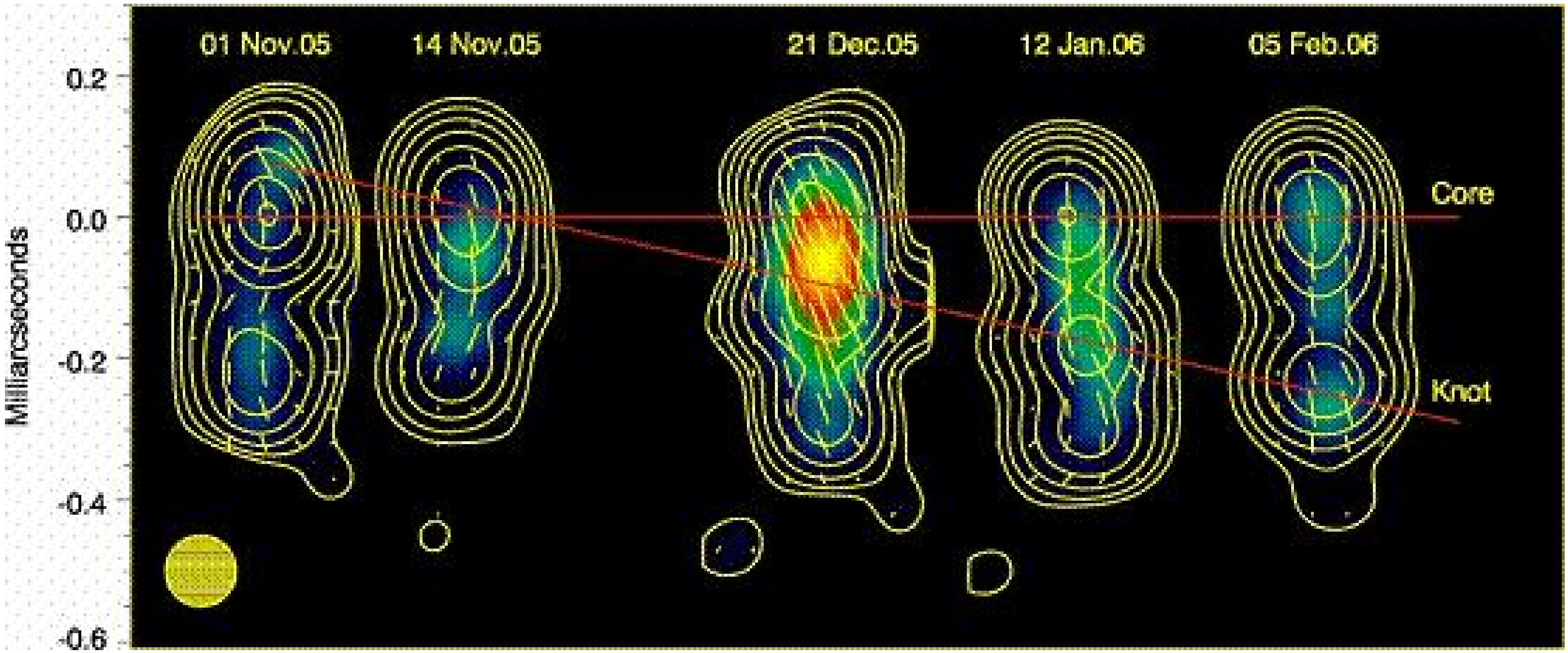
- Hydrodynamic acceleration $\rightarrow$ Lorentz factors $\gamma \sim k_{\rm B}T_i/m_pc^2$ need very high initial temperatures T_i to explain the observed motions ($u =$ few 100 km/s in YSO jets, $\gamma =$ few 10 in AGN jets, $\gamma =$ few 100 in GRB jets)

- Hydrodynamic acceleration is a fast process (saturates at distances where gravity is still important) while observations imply pc-scale acceleration (in AGN jets)

- "Clean" energy extraction – makes high $\gamma = \dot{\mathcal{E}}/\dot{M}c^2$ possible

- Radiation through shocks (particle acceleration and synchrotron/inverse Compton mechanisms) or magnetic reconnection

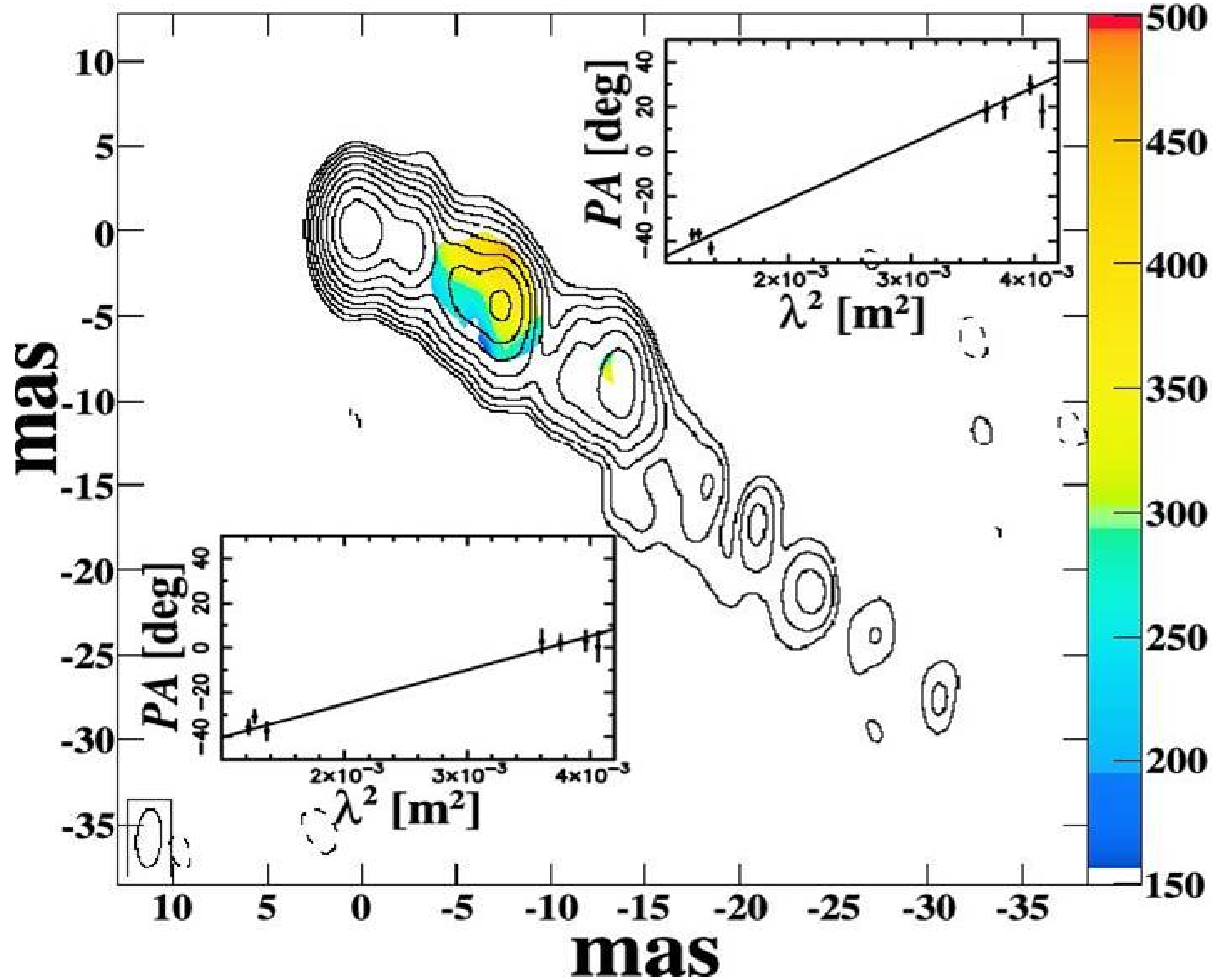
Polarization

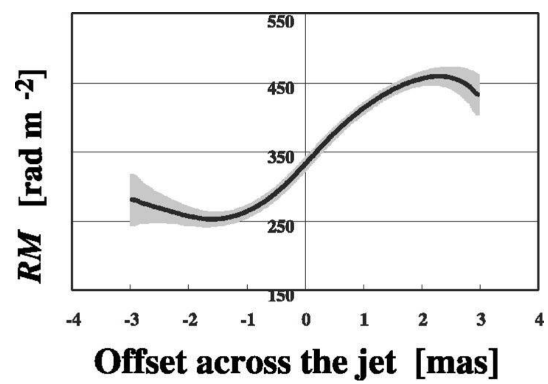


(Marscher et al 2008, Nature)

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

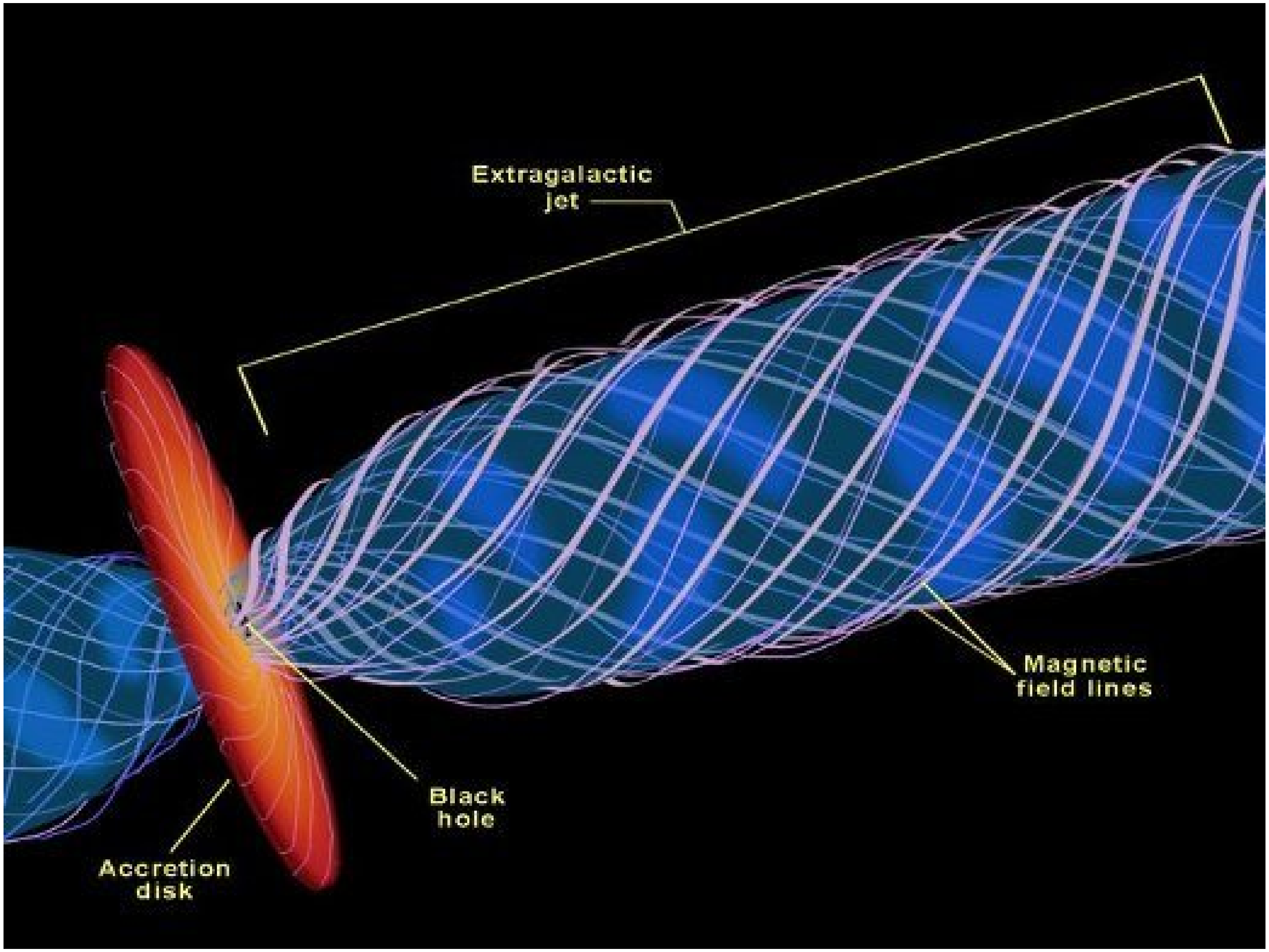
Faraday RM gradients across the jet



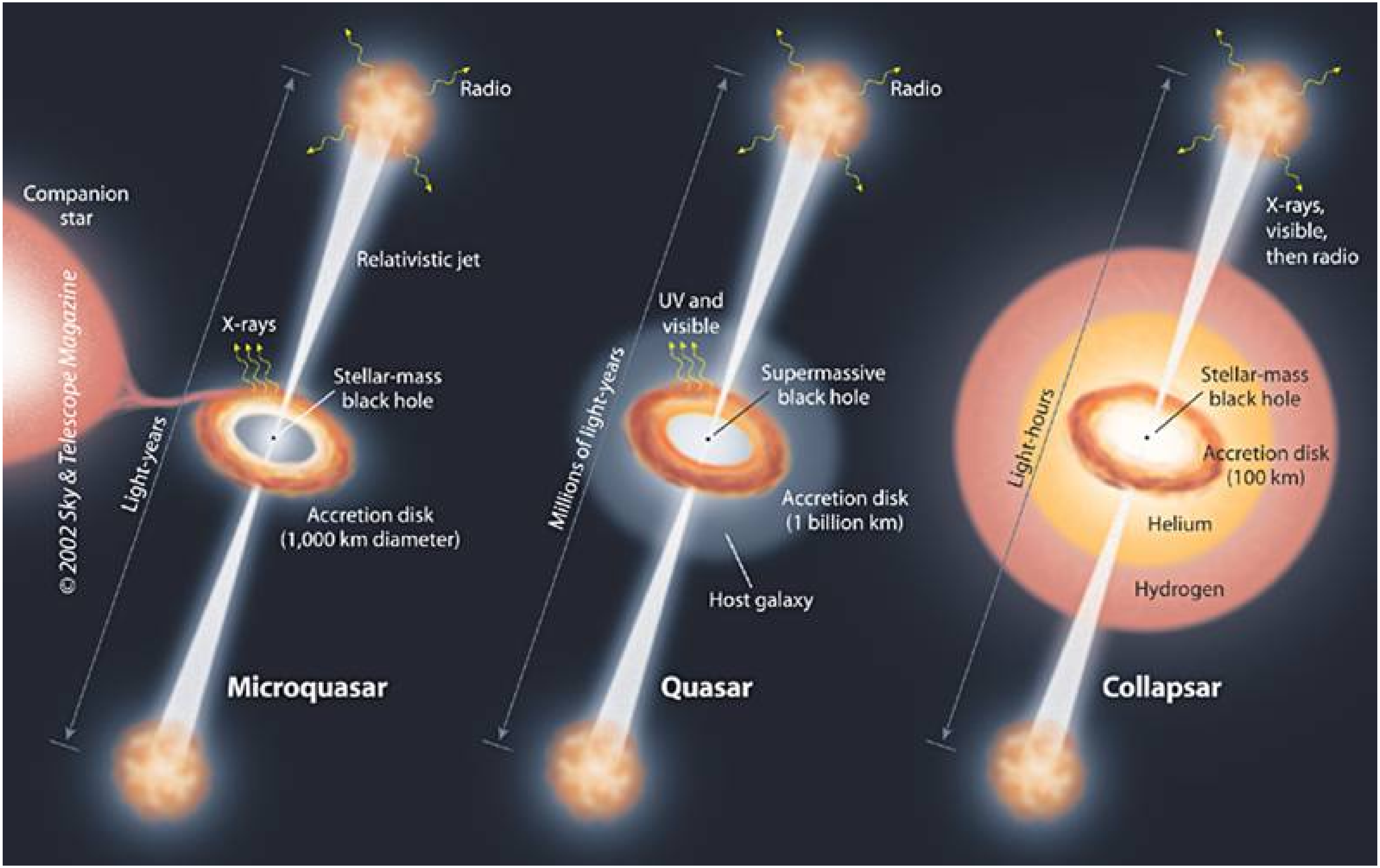


(Asada et al)

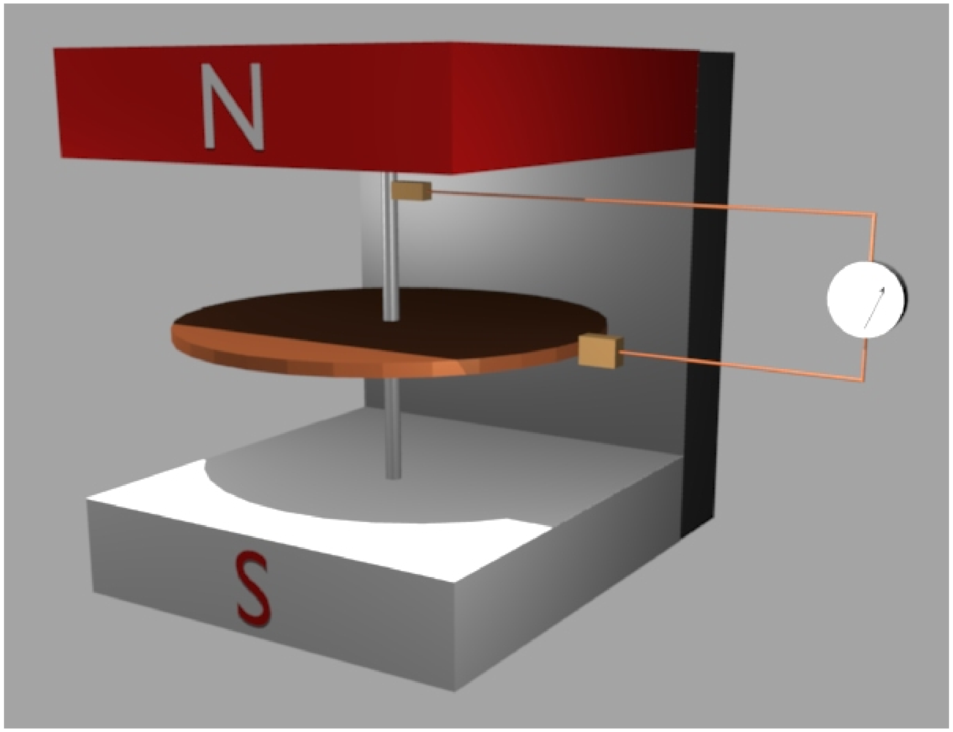
helical field surrounding the emitting region (Gabuzda)



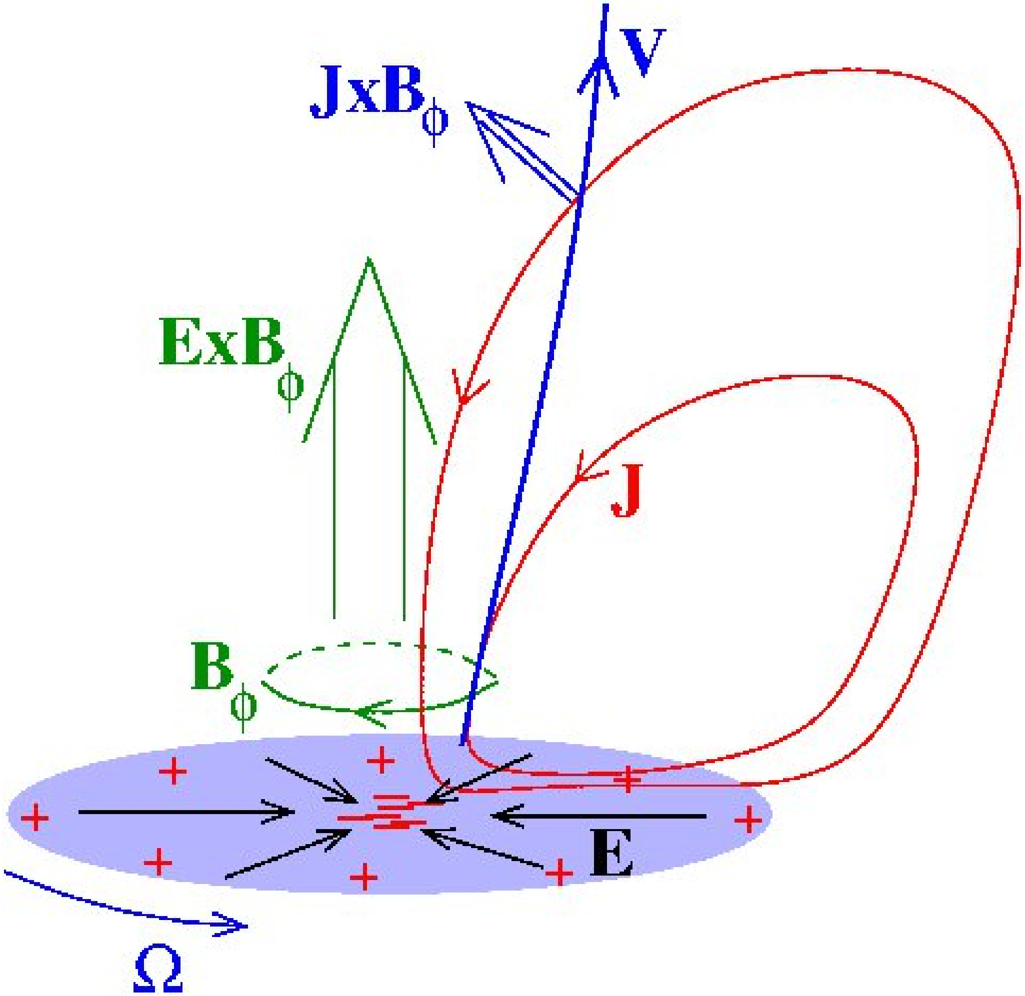
B field from advection, or dynamo, or cosmic battery


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

Energy extraction: A unipolar inductor



magnetic field + rotation



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

gravity feeds the system with energy (through rotation)

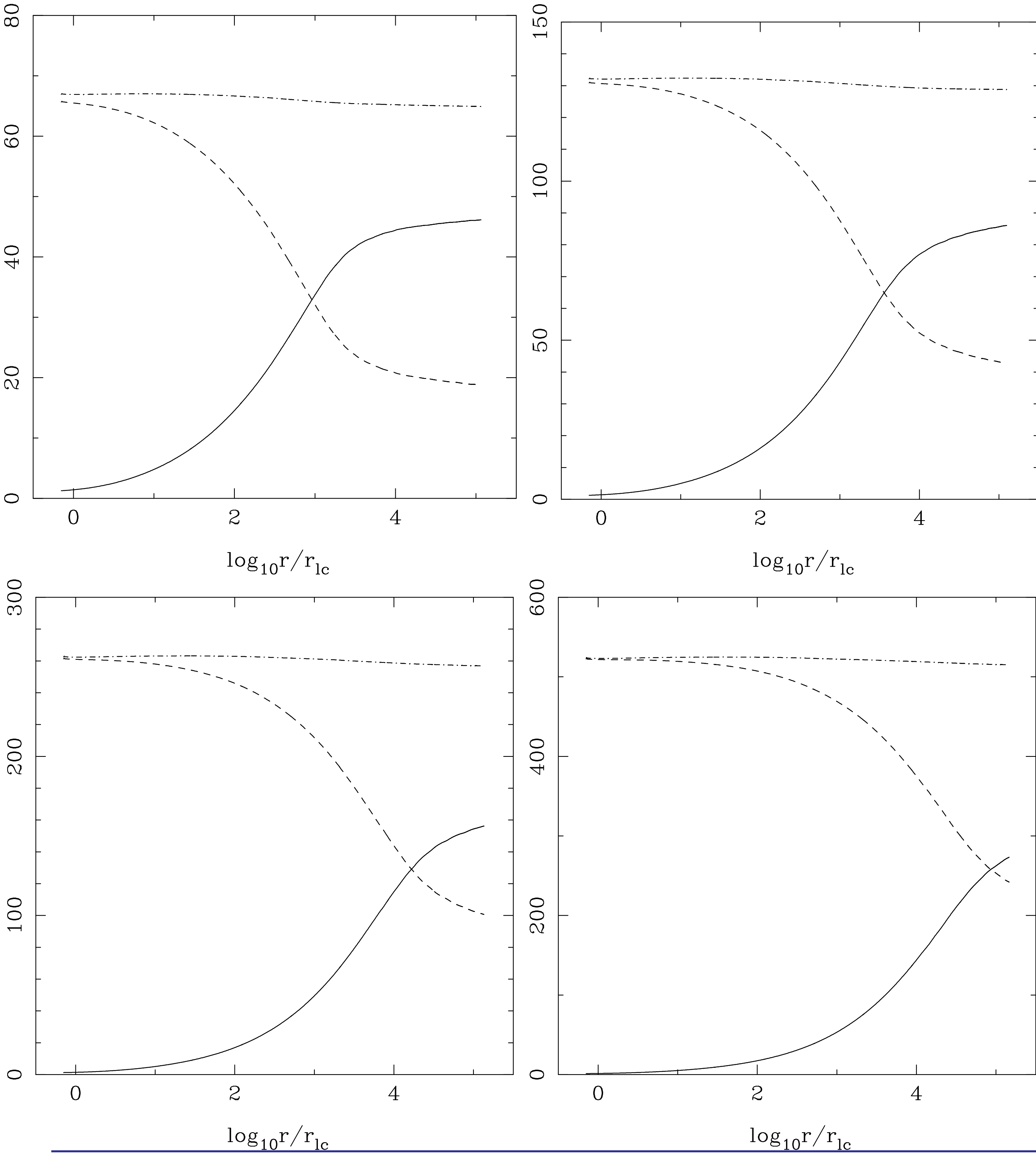
The Faraday disk could be the rotating accretion disk, or the frame dragging if energy is extracted from the ergosphere of a rotating black hole (Blandford & Znajek mechanism)

Acceleration efficiency

- Analytical steady-state self-similar models
(radial self-similar Blandford & Payne, Li, Chiueh & Begelman, Contopoulos & Lovelace, Vlahakis & Königl, and meridionally self-similar Sauty & Tsinganos, Vlahakis & Tsinganos)
$\rightarrow$ efficient conversion of Poynting to kinetic energy flux

- Verified and extended by axisymmetric numerical simulations (Komissarov, Vlahakis & Königl, Tchekhovskoy, McKinney & Narayan)

- role of environment: $\gamma \gtrsim 100$ achievable only for confined outflows (unconfined remain Poynting dominated)



energy flux ratios:

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

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

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

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

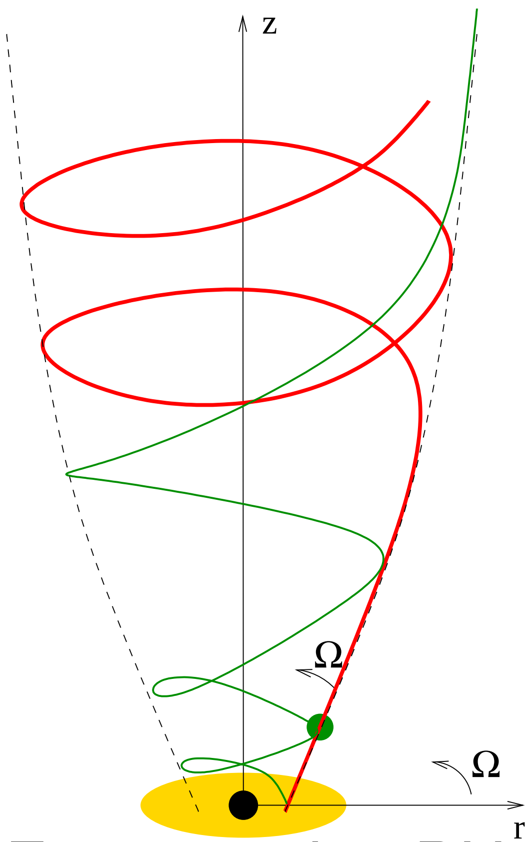
γ (increasing),

$\gamma\sigma$ (decreasing),

and μ (constant)

efficiency $> 50\%$

Magnetohydrodynamics



- successfully explain the main characteristics

- At small distances $|B_\phi| \ll B_p$, $V_\phi \gg V_p$.
At large distances $|B_\phi| \gg B_p$, $V_\phi \ll V_p$.

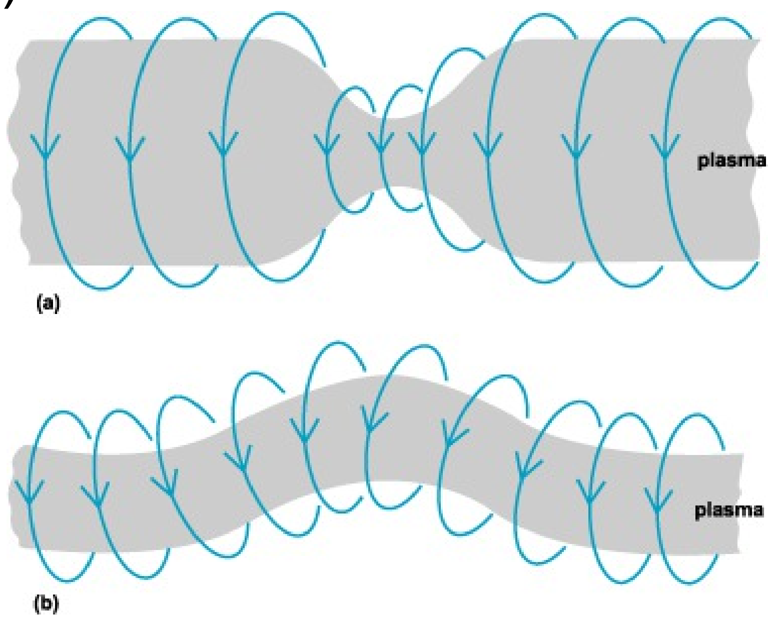
- From Ferraro's law $V_\phi = r\Omega + V_p B_\phi / B_p$, where Ω integral of motion = rotation at base, we get $-B_\phi/B_p \approx r\Omega/V_p$, or, $-B_\phi/B_p \approx r/r_{\rm LC}$.

For a rotating BH-jet

$$\frac{|B_\phi|}{B_z} \approx 150 \left(\frac{r_j}{10^{16}\rm cm}\right) \left(\frac{r_{\rm LC}}{4GM/c^2}\right) \left(\frac{M}{10^8 M_\odot}\right)^{-1}$$

For a disk-jet $\frac{|B_\phi|}{B_z} \approx 20 \left(\frac{r_j}{10^{16}\rm cm}\right) \left(\frac{r_{base}}{10GM/c^2}\right)^{-3/2} \left(\frac{M}{10^8 M_\odot}\right)^{-1}$

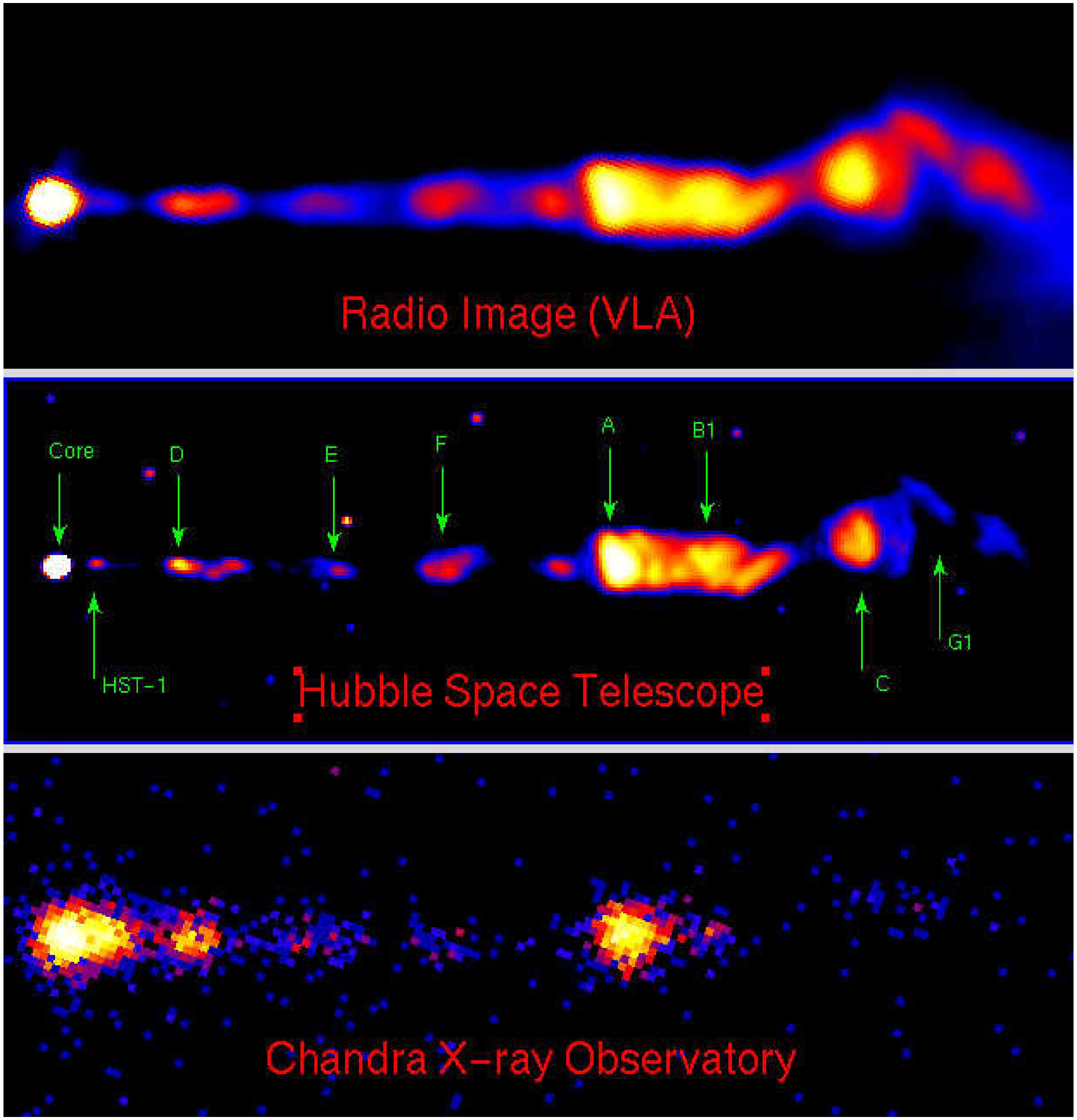
Strong B_ϕ induces current-driven instabilities (Kruskal-Shafranov)

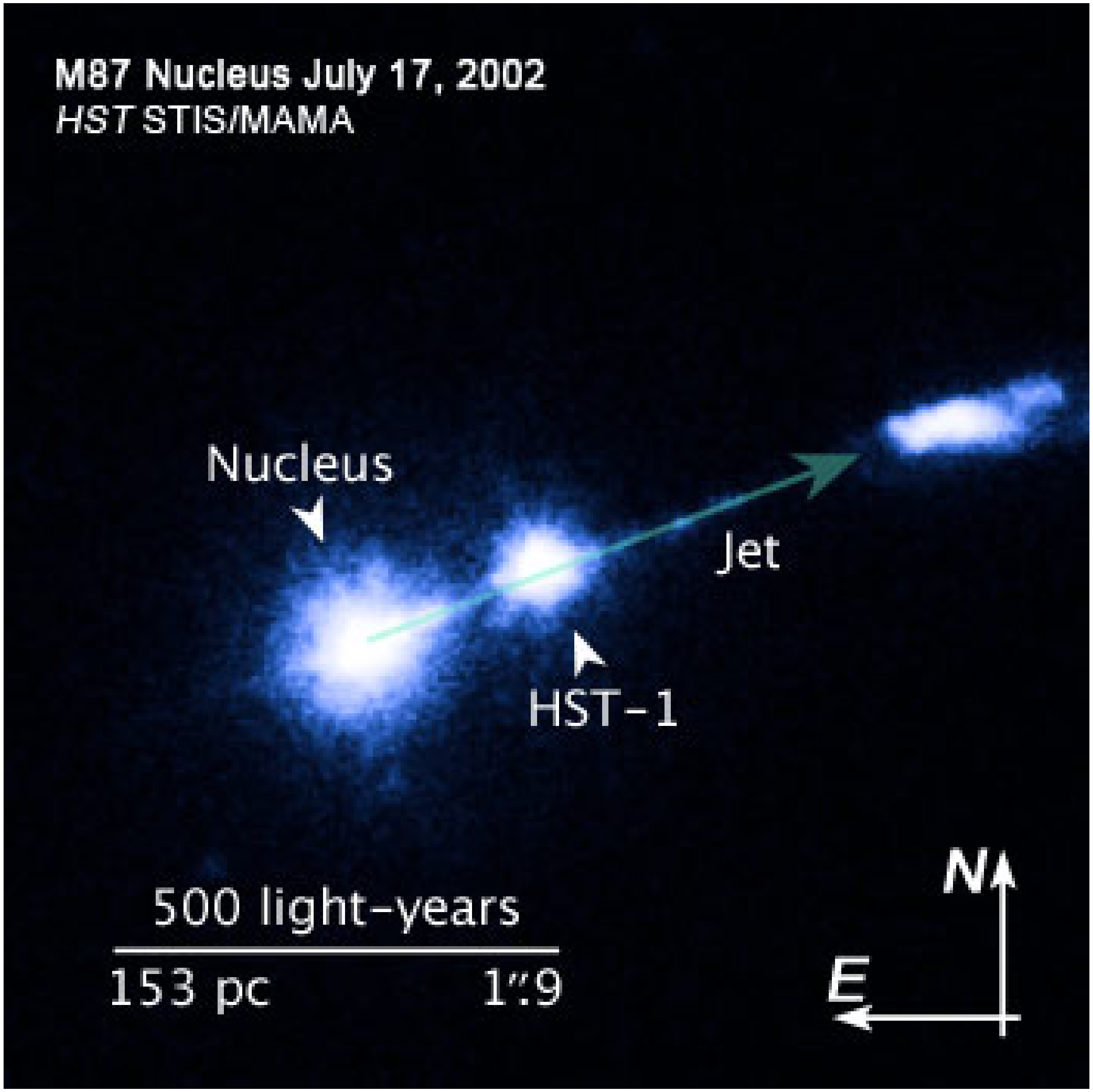


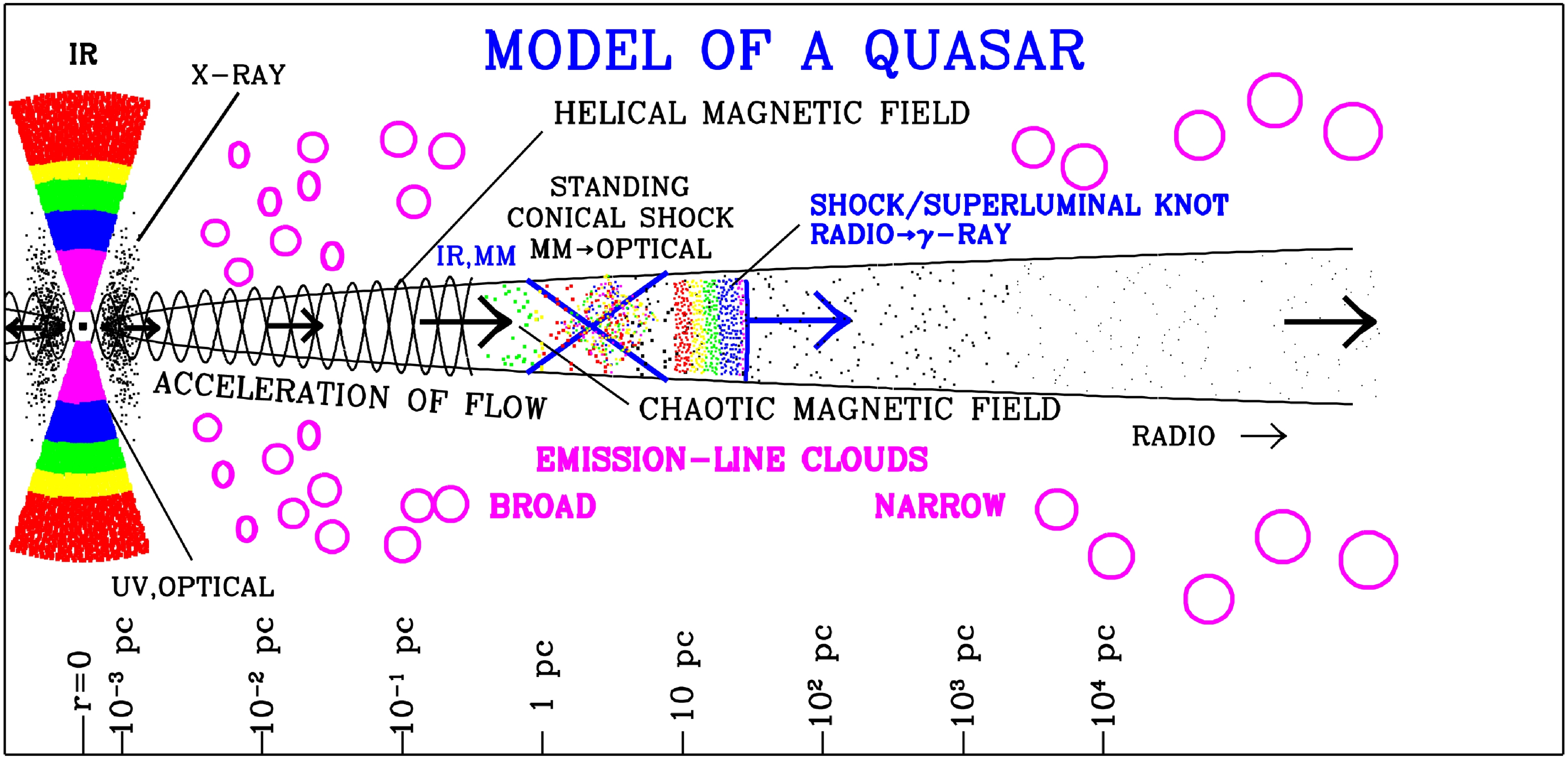
Interaction with the environment $\rightarrow$ Kelvin-Helmholtz instabilities

Stability of axisymmetric solutions (analytical or numerical)? Role of B_z? of inertia?

Relation with observations? (knot structure, jet bending, shocks, polarization degree, reconnection)


Radio Image (VLA)
Core
D
E
F
A
B1
HST-1
G1
C
Hubble Space Telescope
Chandra X-ray Observatory


M87 Nucleus July 17, 2002
HST STIS/MAMA
Nucleus
Jet
HST-1
500 light-years
153 pc
1."9
N
E



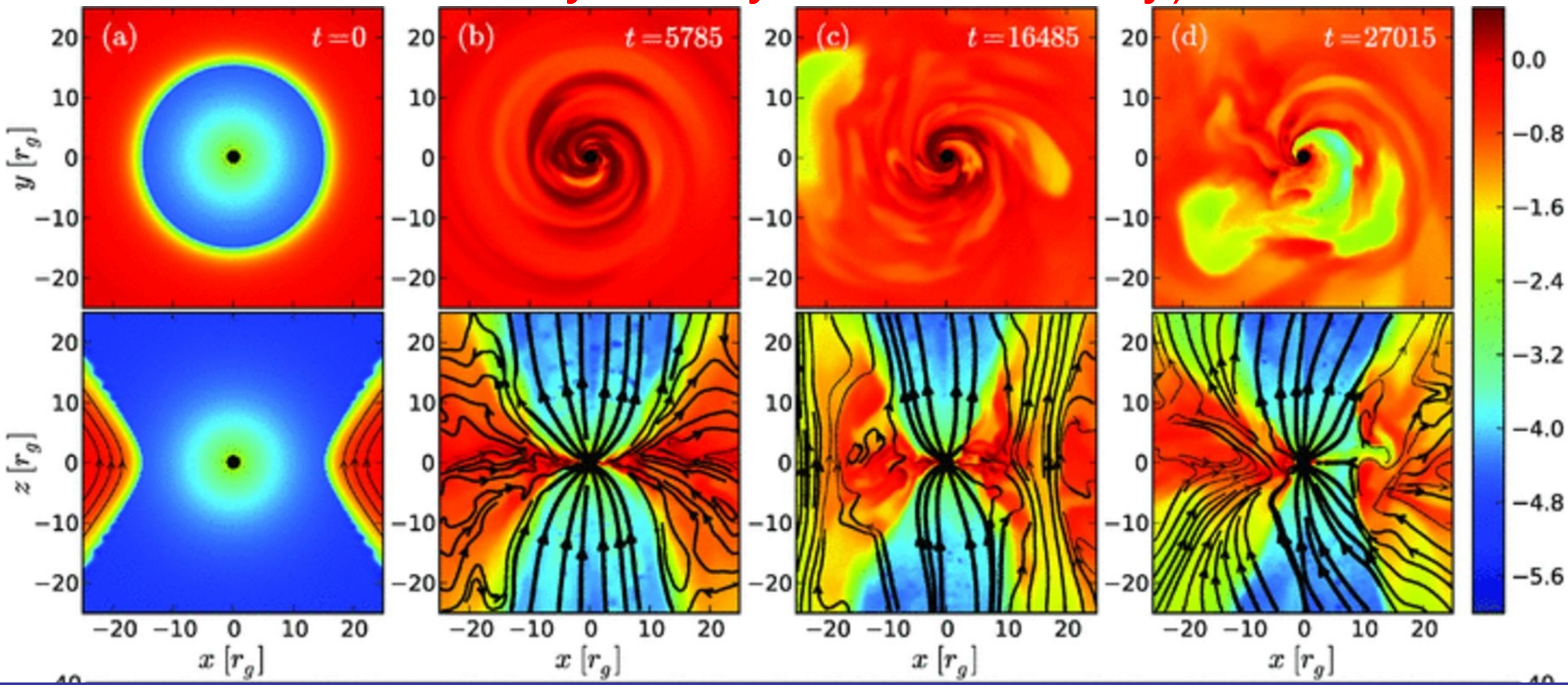
credit: Boston University Blazar Group

Stability analysis

- Why astrophysical jets are stable? (contrary to lab jets)

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

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



- our approach:

- focus on the propagation phase

- assume cylindrical unperturbed jet

- linear (normal mode) analysis

try to understand how a jet is transformed to stable configuration

first step to find the dependence of the growth rate on various jet parameters

Unperturbed flow

Unperturbed relativistic cylindrical jet

helical, axisymmetric, cylindrically symmetric and steady flow

$$\boldsymbol{V}_0 = V_{0z}(r)\hat{z} + V_{0\phi}(r)\hat{\phi}\,, \quad \gamma_0 = \gamma_0(r) = (1 - V_{0z}^2 - V_{0\phi}^2)^{-1/2}\,,$$

$$\boldsymbol{B}_0 = B_{0z}(r)\hat{z} + B_{0\phi}(r)\hat{\phi}\,, \quad \boldsymbol{E}_0 = (V_{0z}B_{0\phi} - V_{0\phi}B_{0z})\hat{r}\,,$$

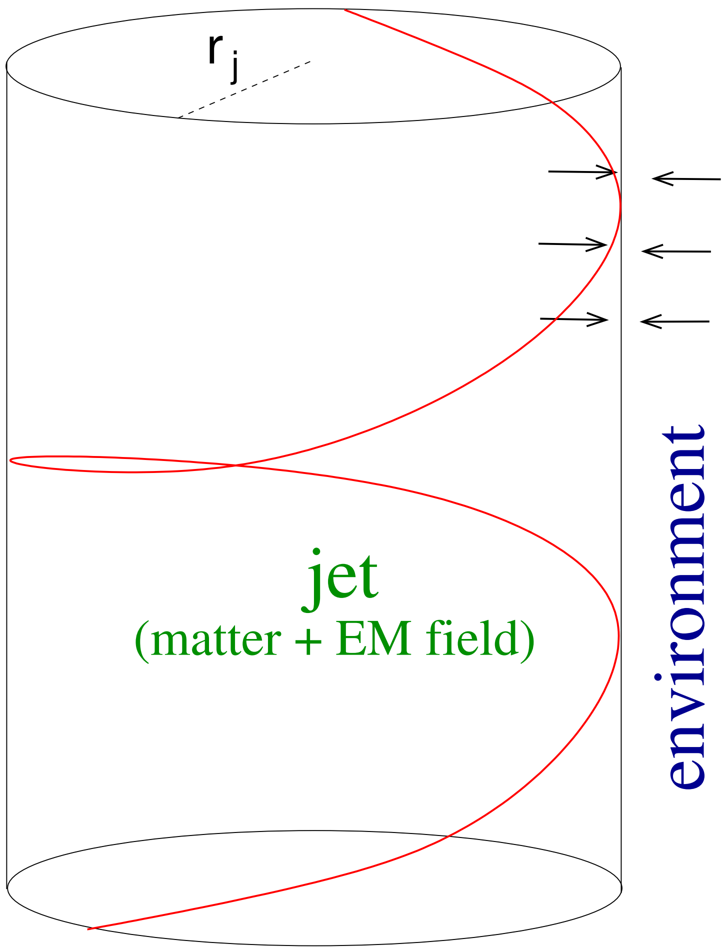
$$\rho_{00} = \rho_{00}(r)\,, \quad \xi_0 = \xi_0(r)\,, \quad \Pi_0 = \frac{\Gamma - 1}{\Gamma}(\xi_0 - 1)\,\rho_{00} + \frac{B_0^2 - E_0^2}{2}\,.$$

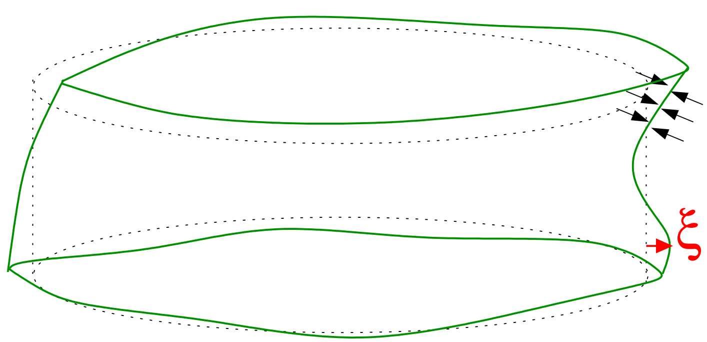
Equilibrium condition $$\frac{B_{0\phi}^2 - E_0^2}{r} - \xi_0\rho_{00}\frac{\gamma_0^2 V_{0\phi}^2}{r} + \frac{d\Pi_0}{dr} = 0\,.$$

Linearized equations

$$Q(r\,,z\,,\phi\,,t) = Q_0(r) + Q_1(r)\exp\left[i(m\phi + kz - \omega t)\right]$$

$$\begin{pmatrix} \\ \\ \\ \text{10×12 array} \\ \text{function of } r\,,\omega\,,k \\ \\ \\ \end{pmatrix} \begin{pmatrix} \gamma_1 \\ \rho_{01} \\ B_{1z} \\ B_{1\phi} \\ iB_{1r} \\ \xi_1 \\ V_{1z} \\ V_{1\phi} \\ d\left(irV_{1r}\right)/dr \\ d\Pi_1/dr \\ irV_{1r} \\ \Pi_1 \end{pmatrix} = 0$$





Eigenvalue problem

- solve the problem inside the jet (attention to regularity condition on the axis)
- similarly in the environment (solution vanishes at ∞)
- Match the solutions at r_j: $[\![y_1]\!] = 0\,, [\![y_2]\!] = 0 \longrightarrow$ dispersion relation

⋆ spatial approach: $\omega = \Re\omega$ and $\Re k = \Re k(\omega), \Im k = \Im k(\omega)$

$$Q = Q_0(r) + Q_1(r) e^{-\Im k z} e^{i(m\phi + \Re k z - \omega t)}$$

⋆ temporal approach: $k = \Re k$ and $\Re\omega = \Re\omega(k), \Im\omega = \Im\omega(k)$

$$Q = Q_0(r) + Q_1(r) e^{\Im\omega t} e^{i(m\phi + kz - \Re\omega t)}$$

Unperturbed jet solutions

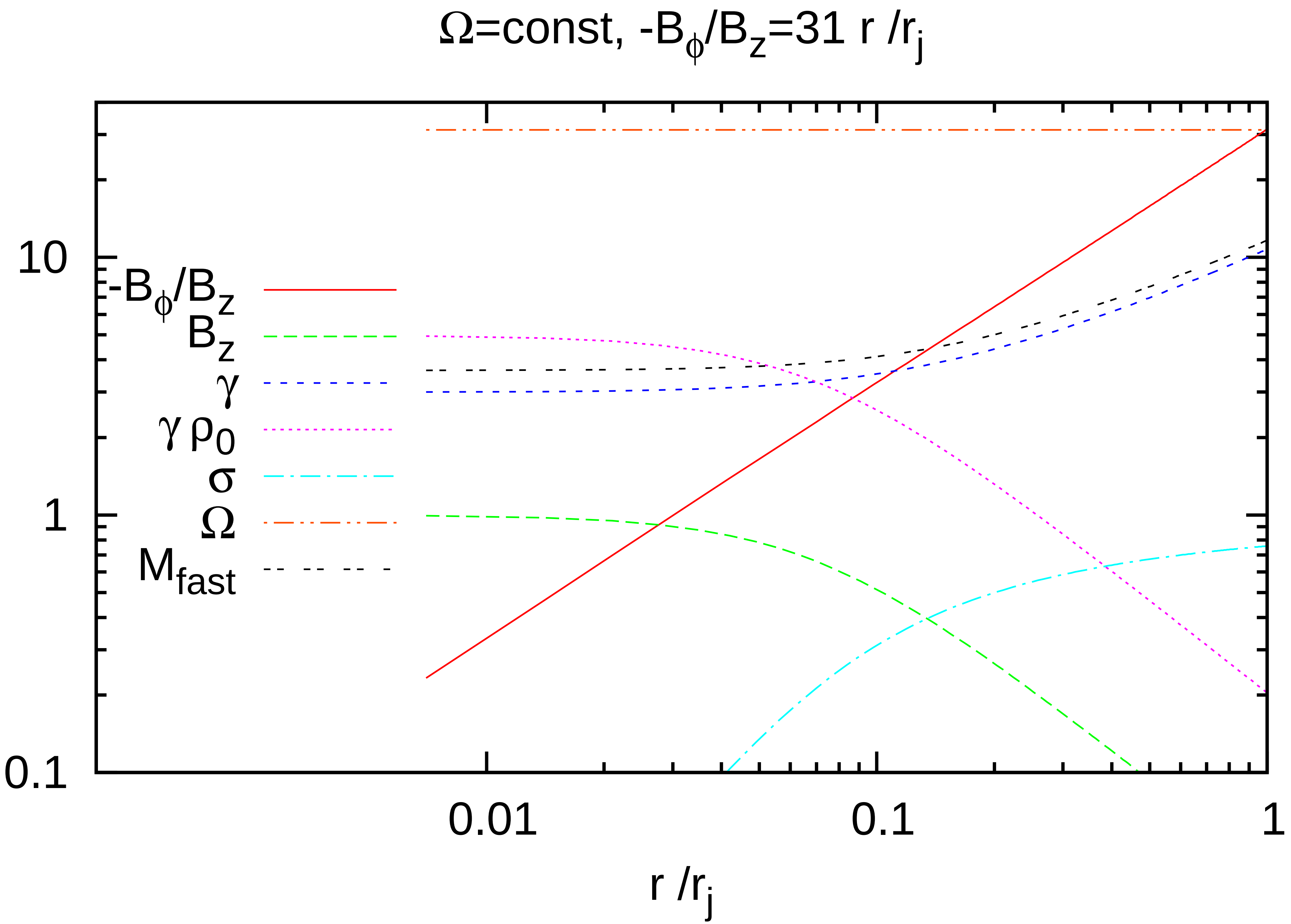
Try to mimic the Komissarov et al simulation results
(for AGN and GRB jets)

- cold, nonrotating jet
- Equilibrium field ("force-free")

$$B_{0z} = \frac{B_j}{\left[1+(r/r_0)^2\right]^{\zeta}}\,, \quad B_{0\phi} = -\gamma_0 B_{0z}\sqrt{\frac{\left[1+(r/r_0)^2\right]^{2\zeta}-1-2\zeta(r/r_0)^2}{(2\zeta-1)(r/r_0)^2}}\,.$$

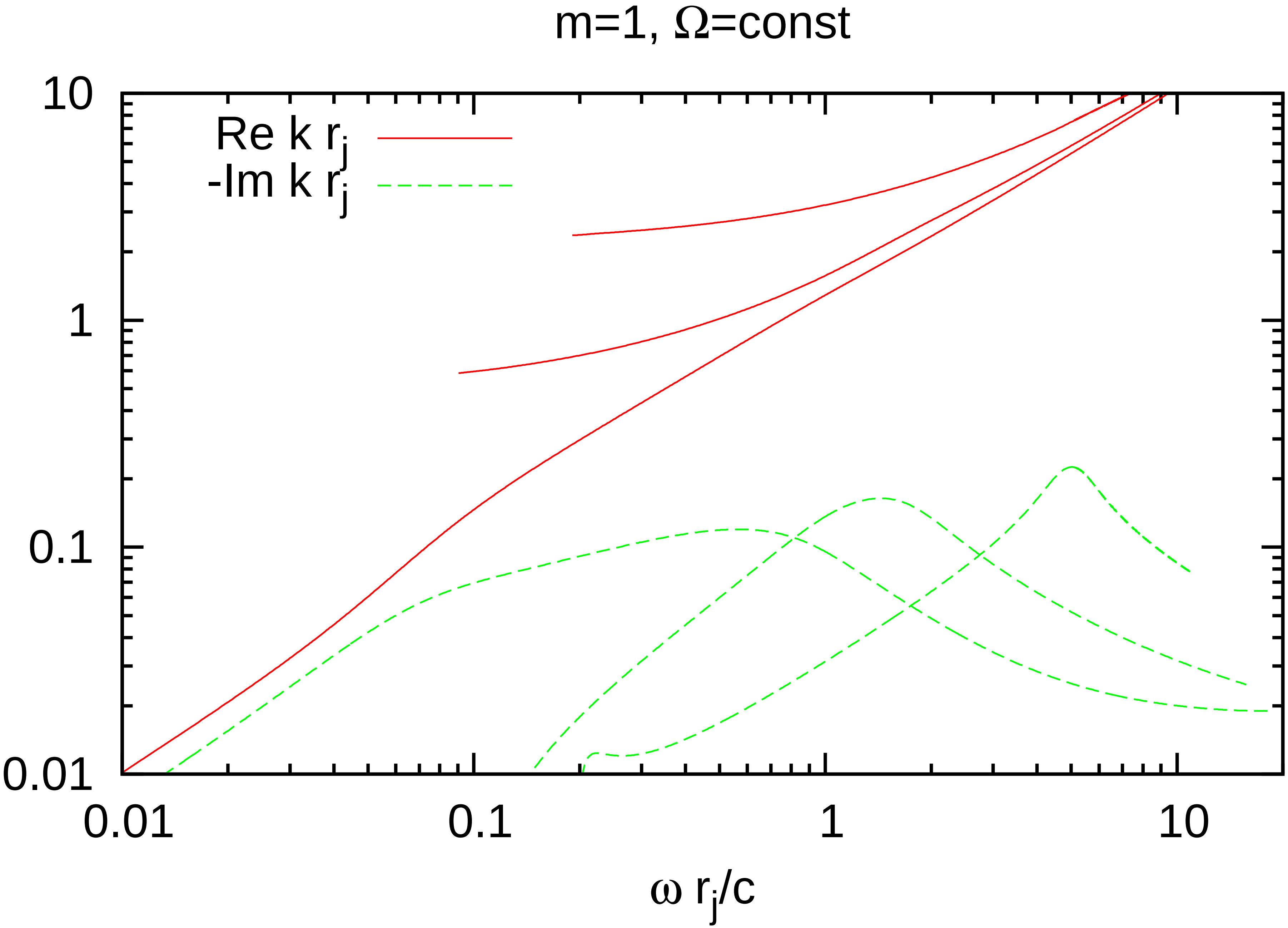
$r_0\,,\zeta$ free parameters, $\gamma_0\,,\rho_{00}$ free functions.

- $\zeta = 0.6$, $\rho_{00} \propto B_{0z}/\gamma_0$
- external medium: uniform, static, with zero $B_{0\phi}$ and $V_{0\phi}$.



Ω=const, -B_φ/B_z=31 r /r_j
10
1
0.1
0.01
0.1
1
r /r_j
-B_φ/B_z
B_z
γ
γ ρ_0
σ
Ω
M_fast

A “fundamental” and multiple ”reflective” modes



$Q = Q_0(r) + Q_1(r) e^{-\Im k z} e^{i(m\phi + \Re k z - \omega t)}$

growth length $= 1/(-\Im k) \sim r_j/0.2 = 5 r_j$

growth time $\approx$ growth length ($c = 1$)

growth rate $\approx -\Im k \sim 0.2/r_j$

in rough agreement with nonrelativistic linear studies which predict growth rates in comoving frame $\Gamma_{\rm co} \sim \dfrac{v_A}{10 r_0}$ (Appl et al)

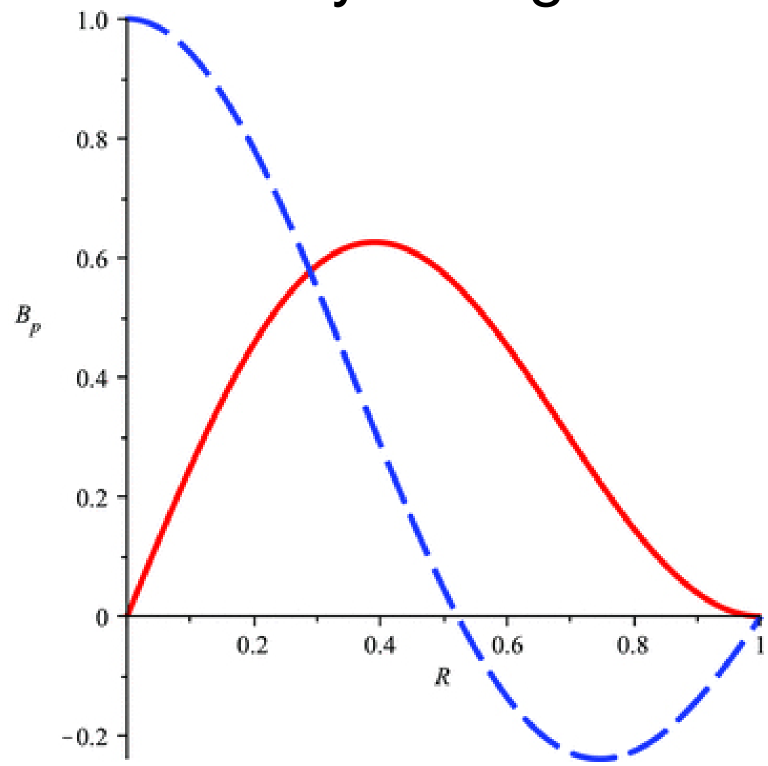
in the lab frame $\Gamma = \dfrac{\Gamma_{\rm co}}{<\gamma>} \approx 0.2/r_j$

$(v_A = \sqrt{\frac{\sigma}{\sigma+1}} \sim \frac{2}{3}, \quad r_0 = 0.1 r_j, \quad <\gamma> \sim 5)$

Similar results by Sobacchi, Lyubarsky & Sormani 2017.

Stability of jets with zero current at the boundary

Such equilibrium were found by Gourgouliatos+2012



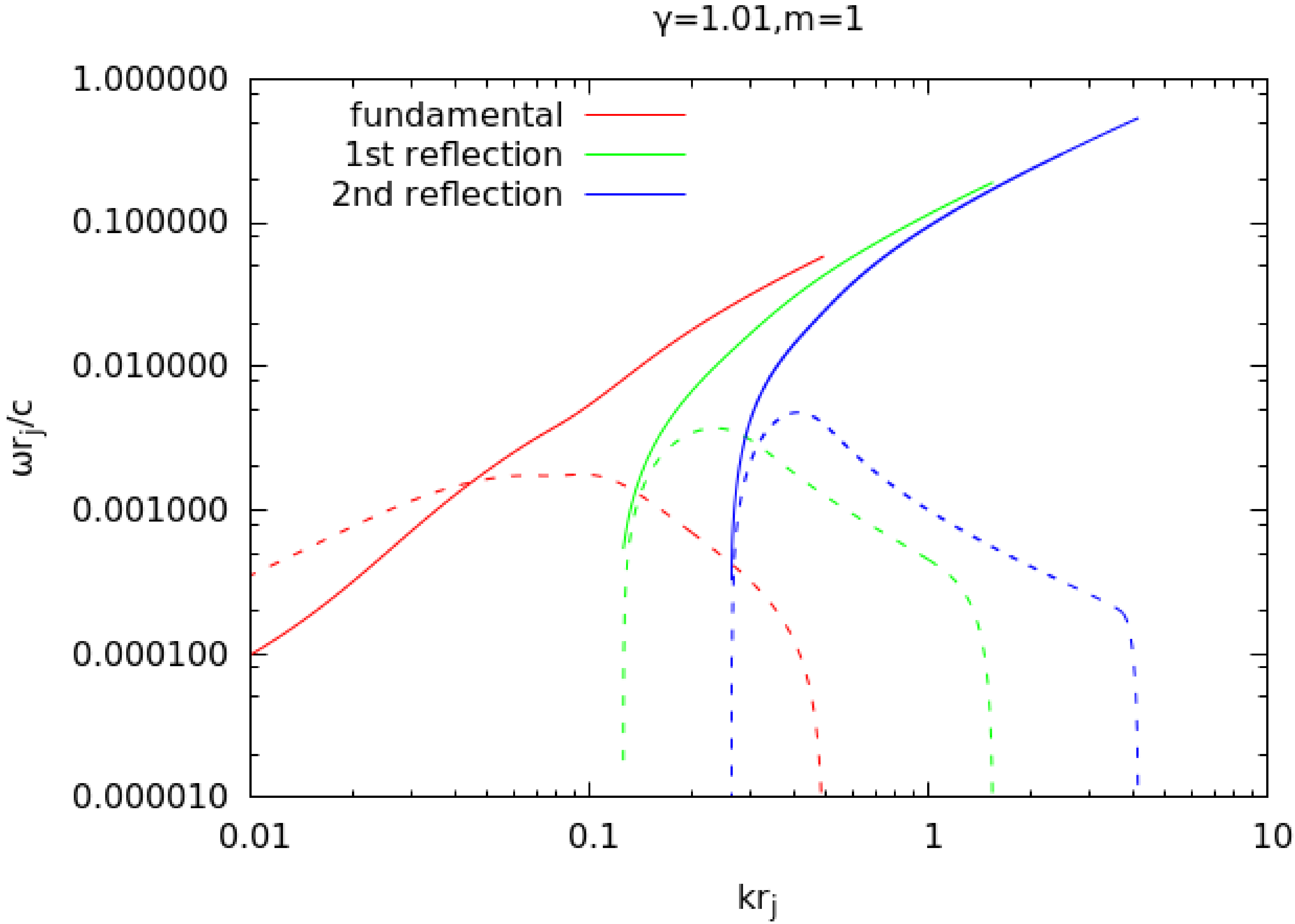
Charis Sinnis 2016 (master thesis) studied the linear regime

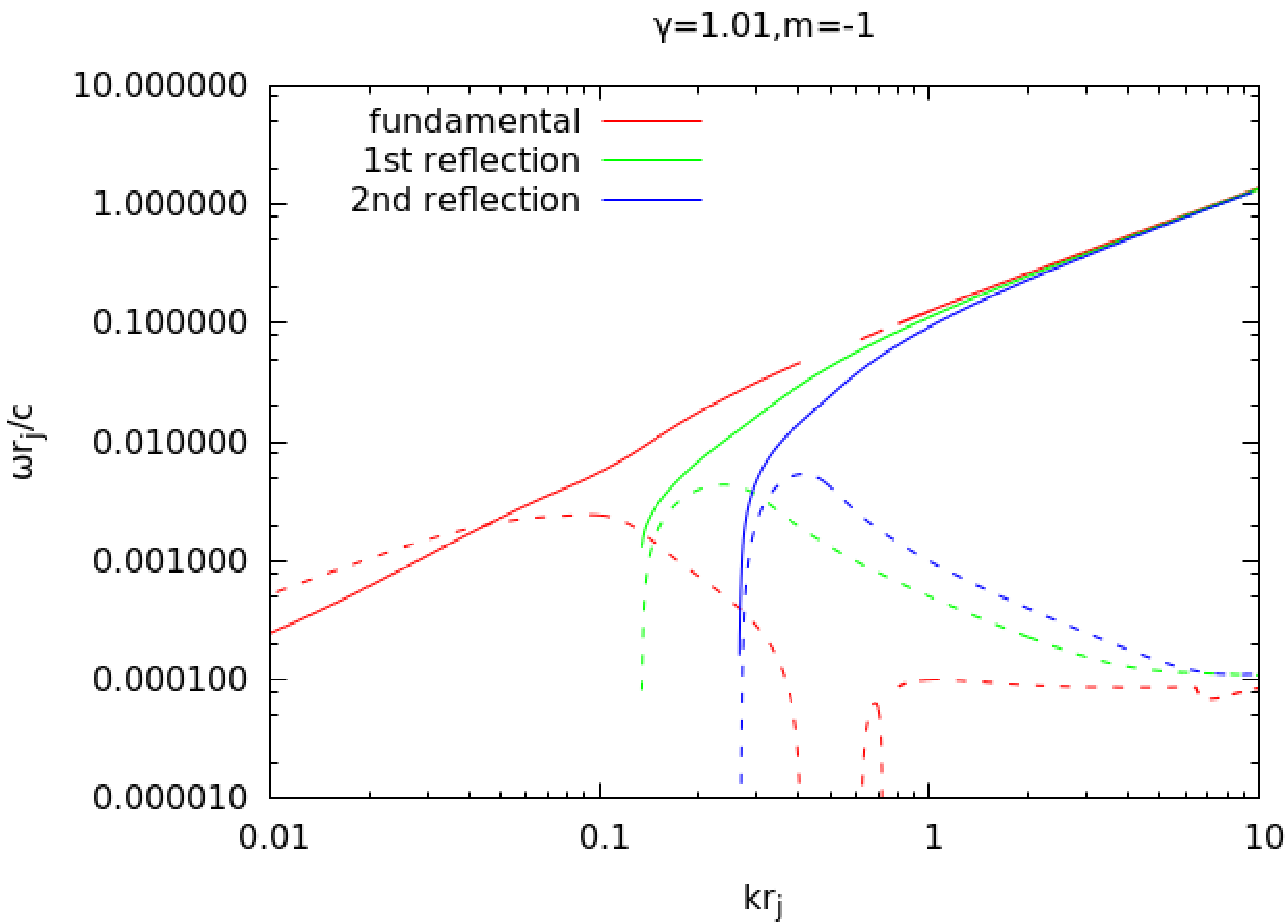
Similar results in Kim+2017

growth rates ~ 100 times smaller!

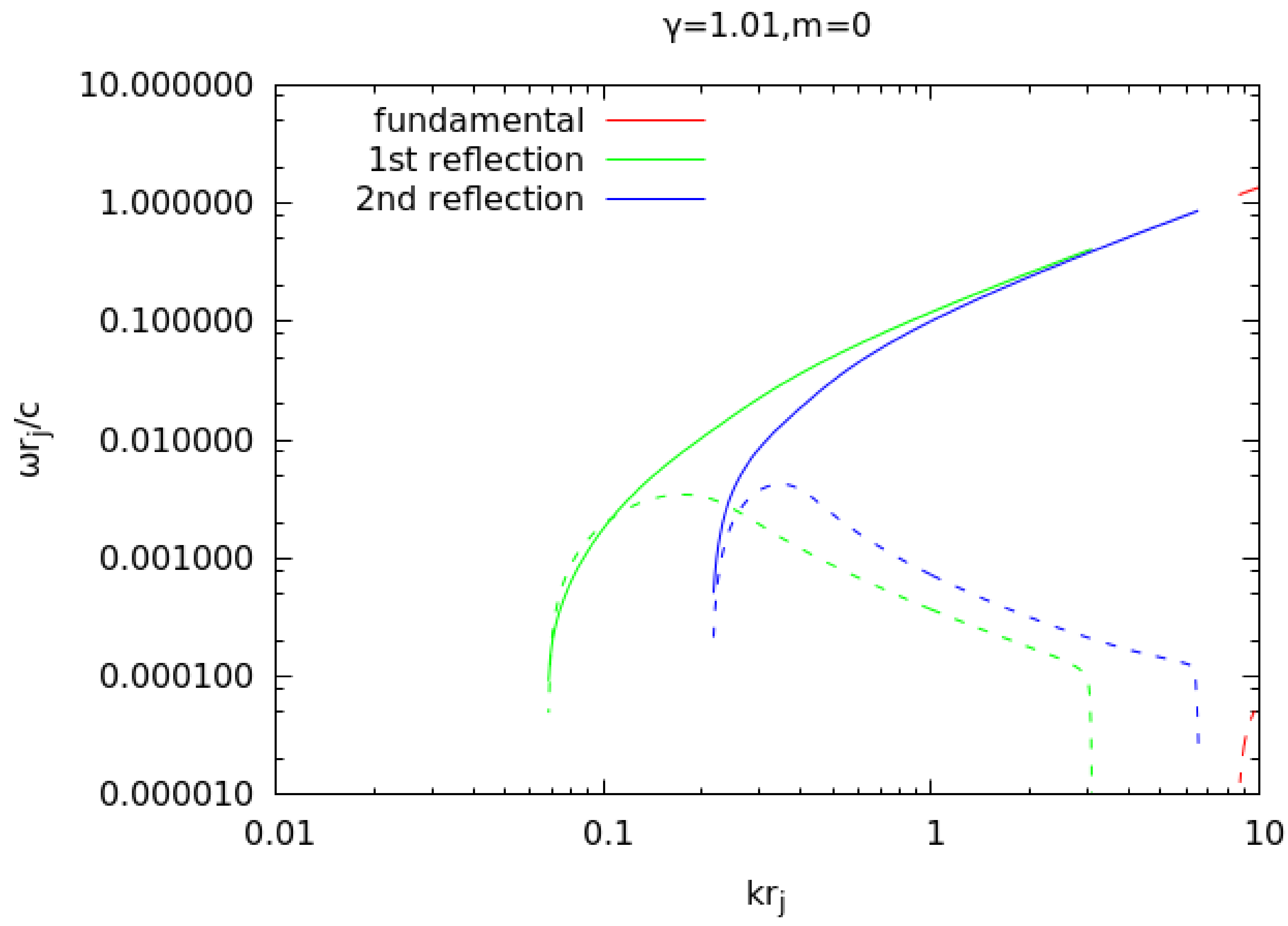
(because B_ϕ / B_z is also smaller)

$$Q = Q_0(r) + Q_1(r) e^{\Im \omega t} e^{i(m\phi + kz - \Re \omega t)}$$

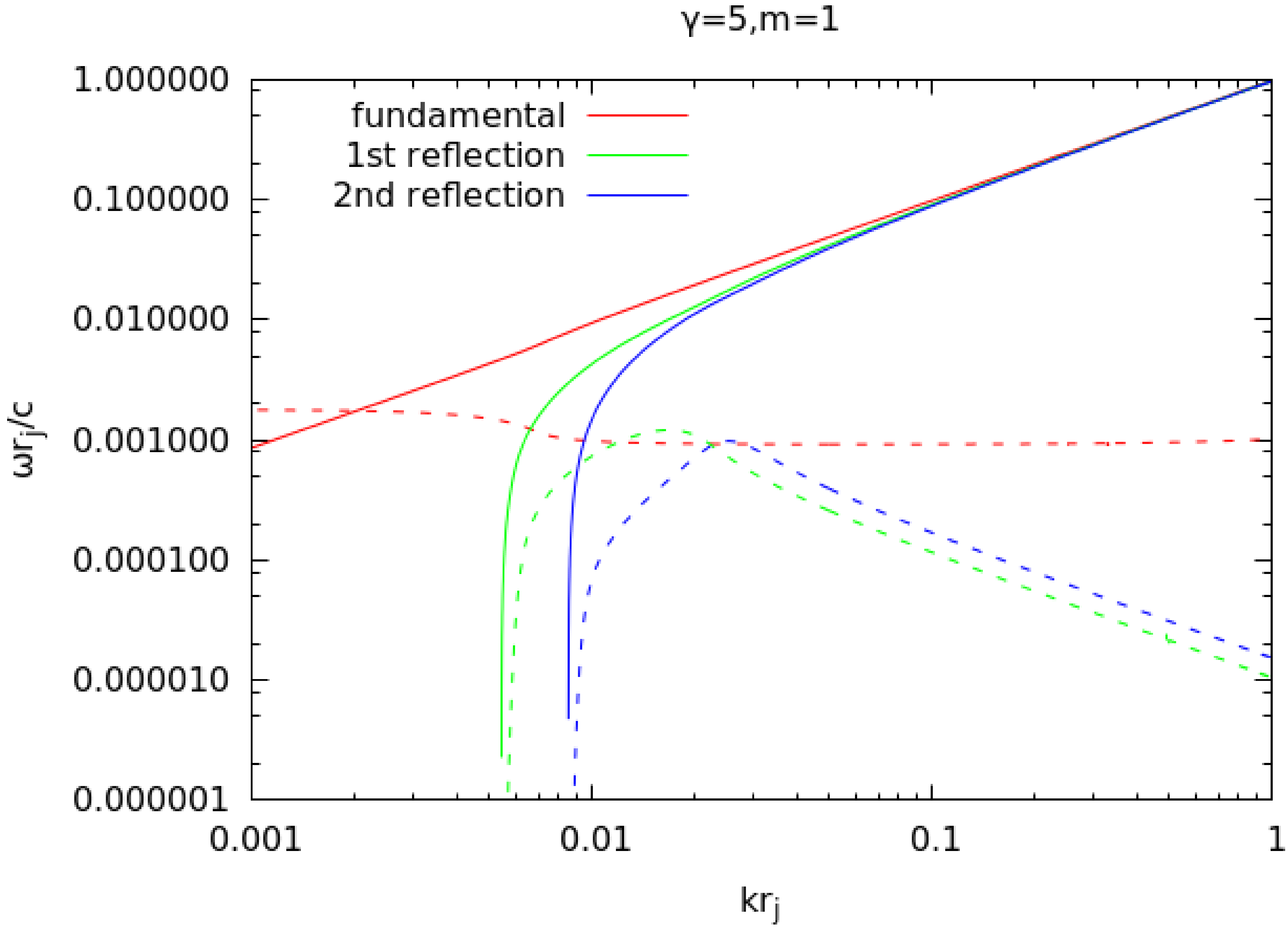




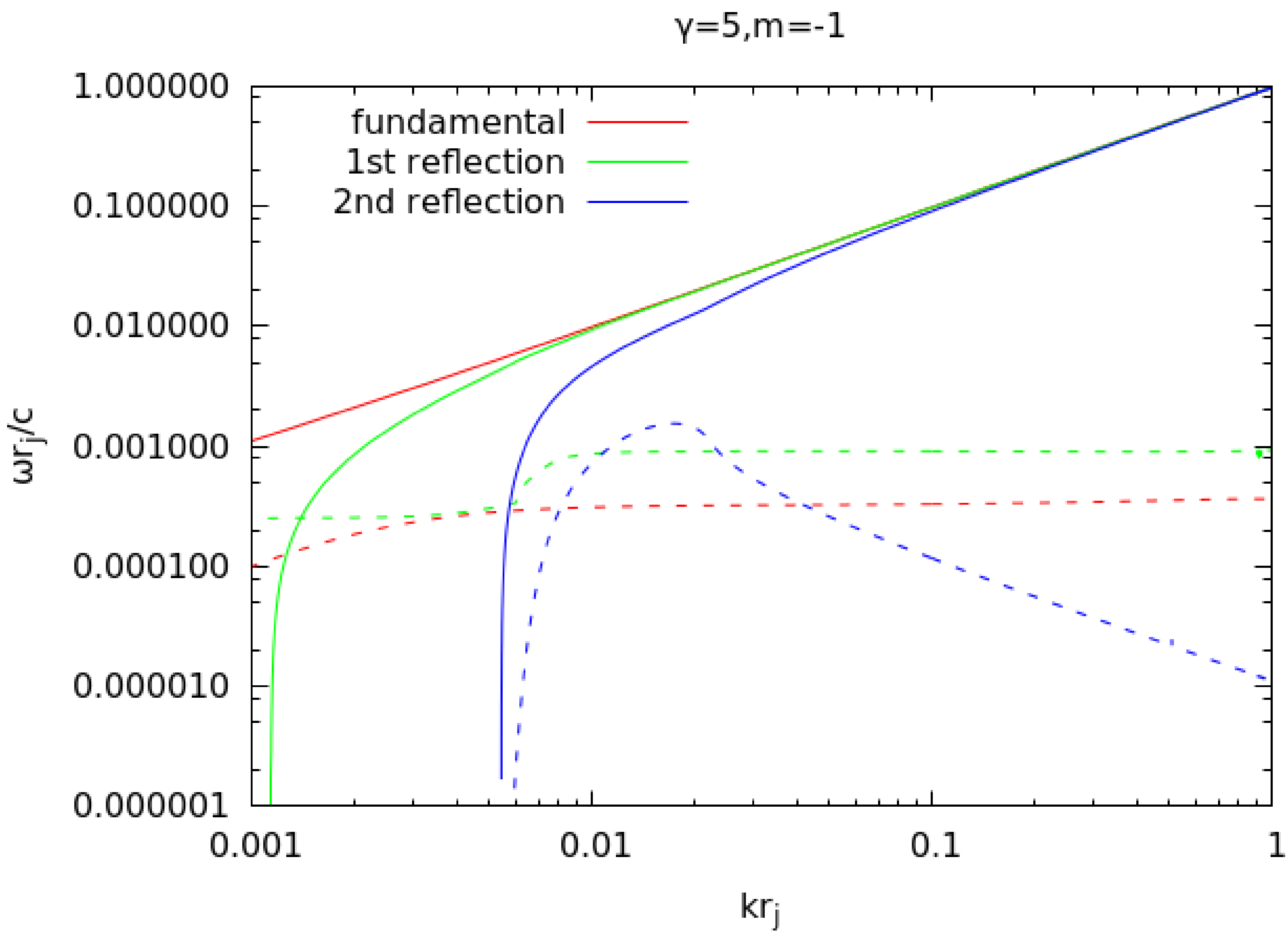
γ=1.01,m=-1
fundamental
1st reflection
2nd reflection
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.01
0.1
1
10
ωr_j/c
kr_j

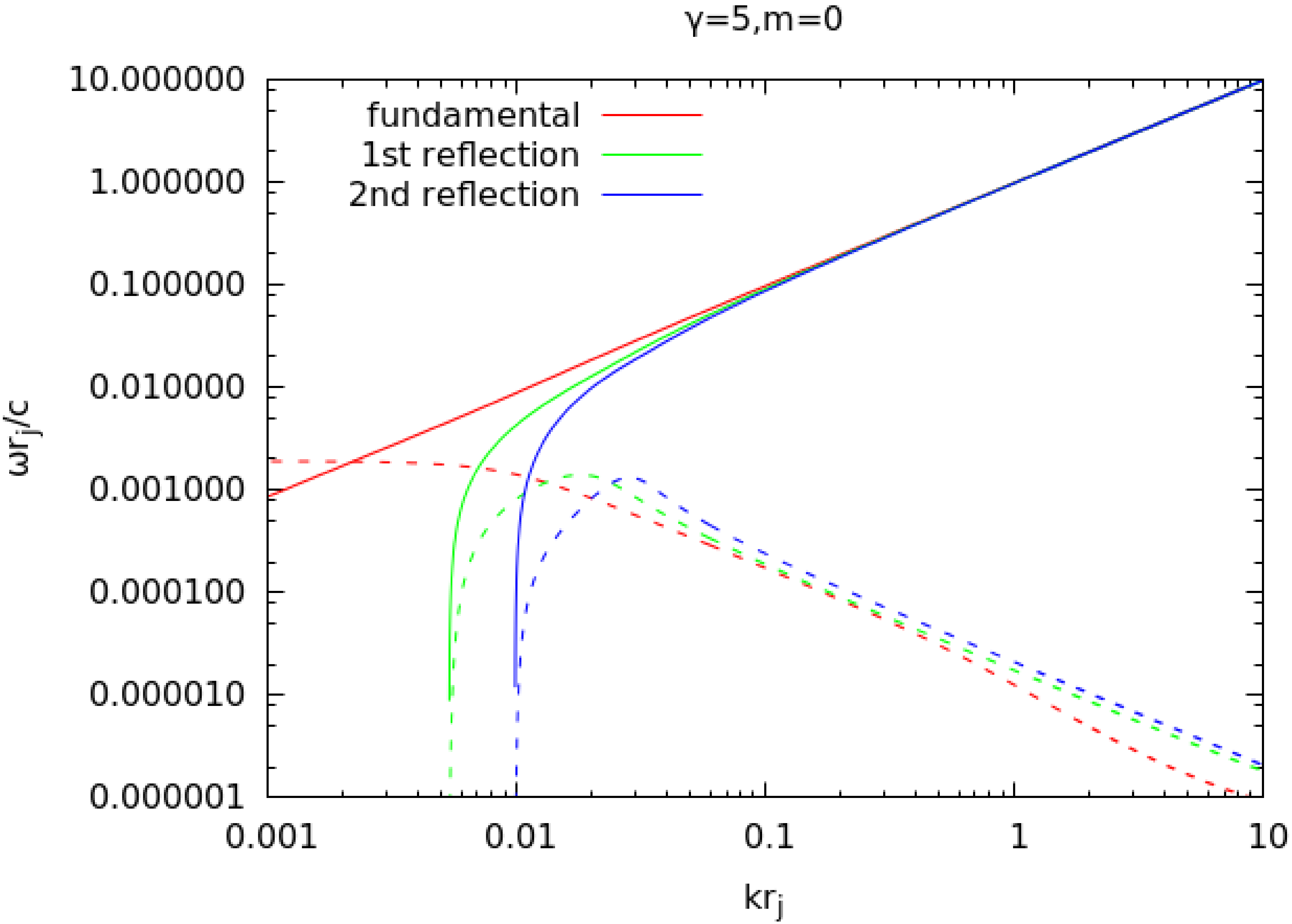


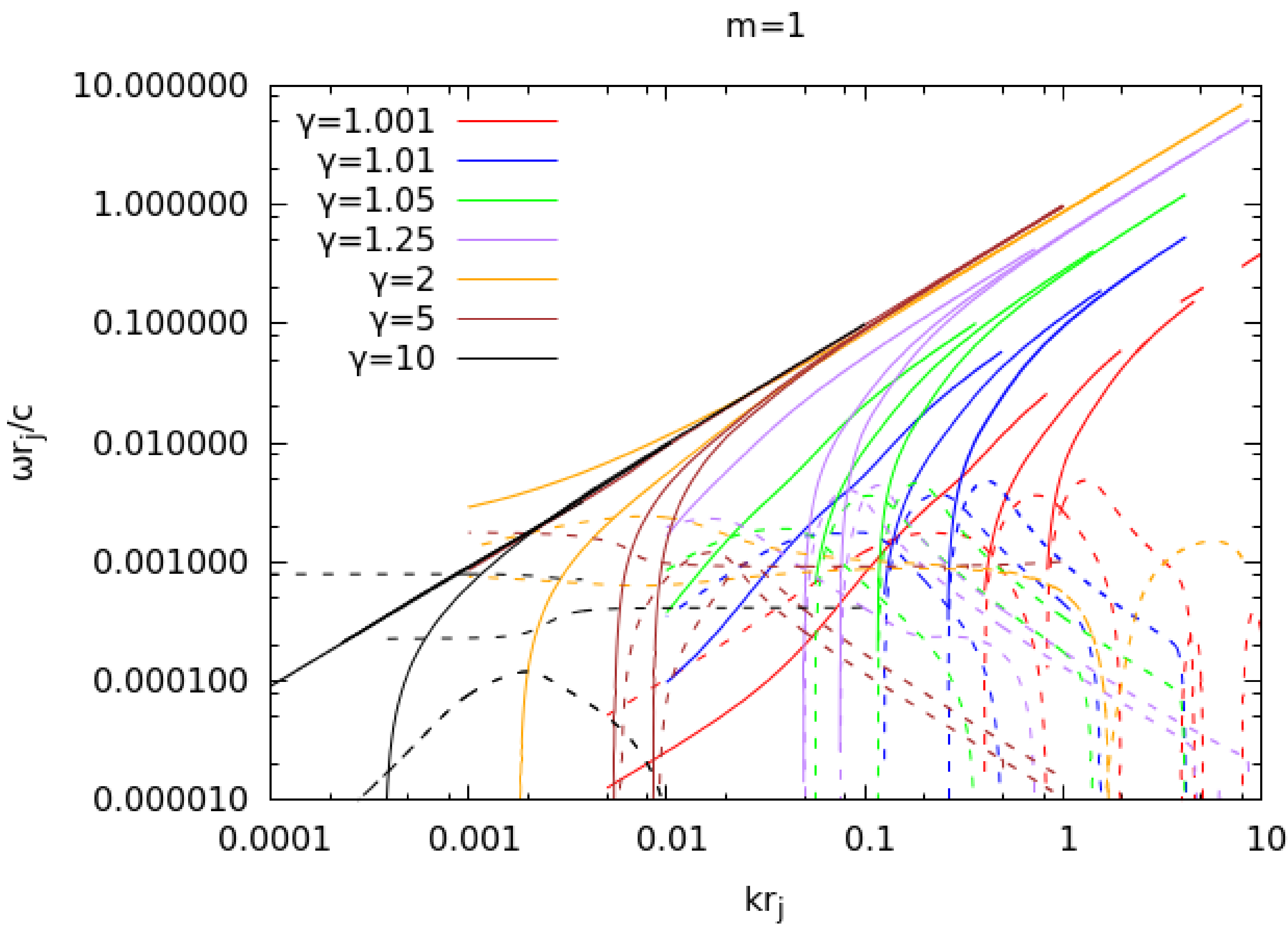
γ=1.01,m=0
fundamental
1st reflection
2nd reflection
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
ωrj/c
0.01
0.1
1
10
krj

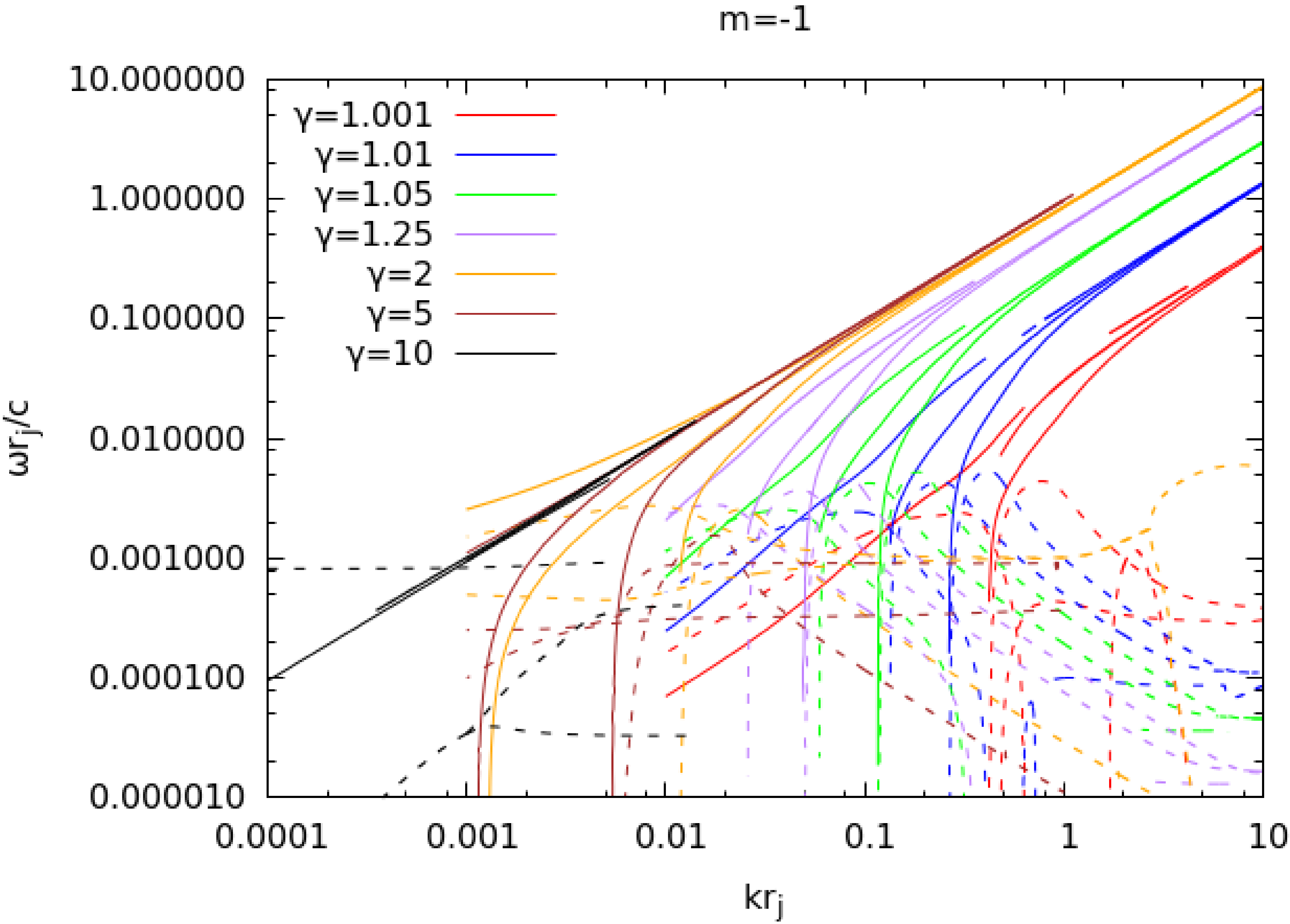


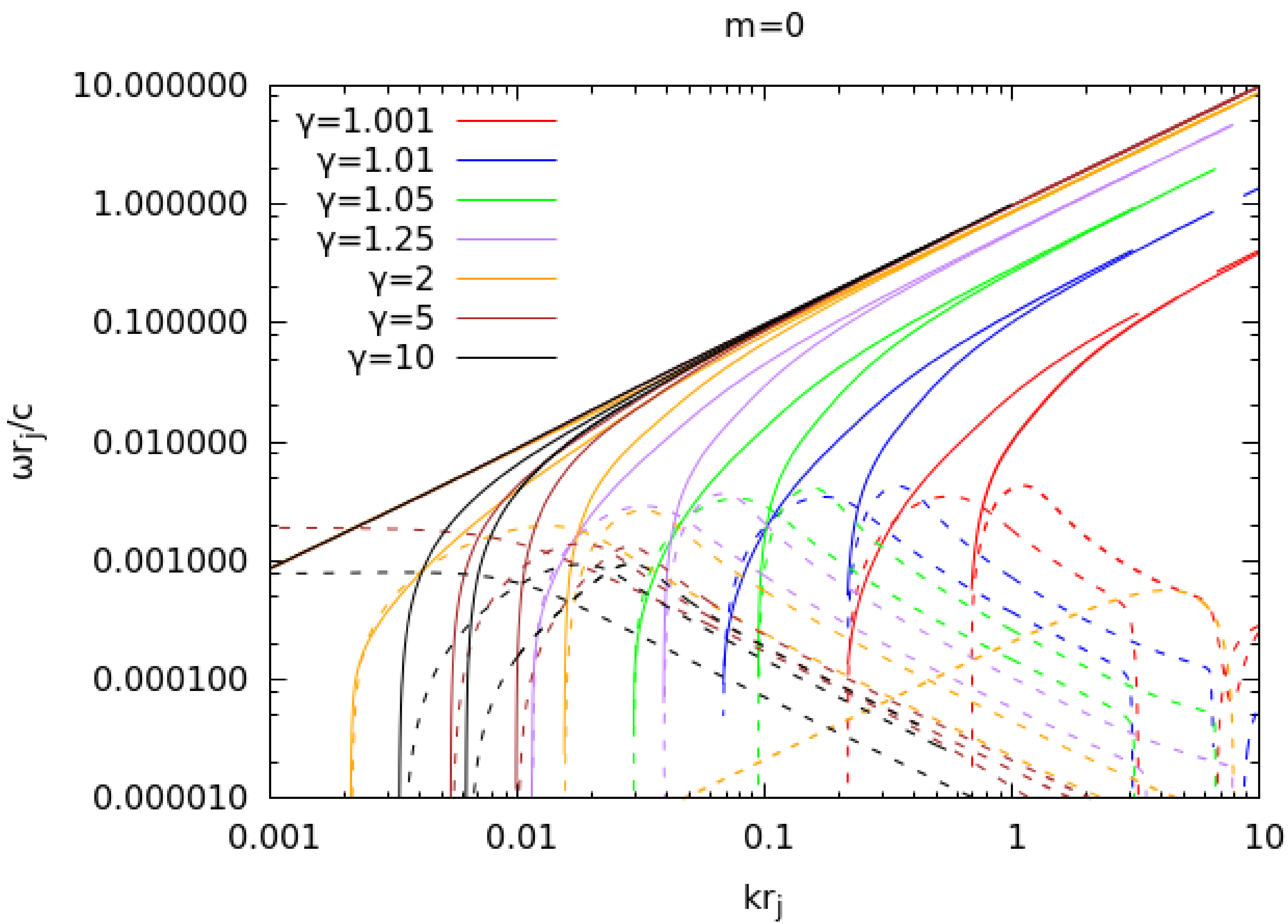
γ=5,m=1
fundamental
1st reflection
2nd reflection
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.000001
0.001
0.01
0.1
1
$\omega r_j/c$
kr_j


γ=5,m=-1
fundamental
1st reflection
2nd reflection
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.000001
0.001
0.01
0.1
1
ωr_j/c
kr_j


γ=5,m=0
fundamental
1st reflection
2nd reflection
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.000001
0.001
0.01
0.1
1
10
kr_j
ωr_j/c

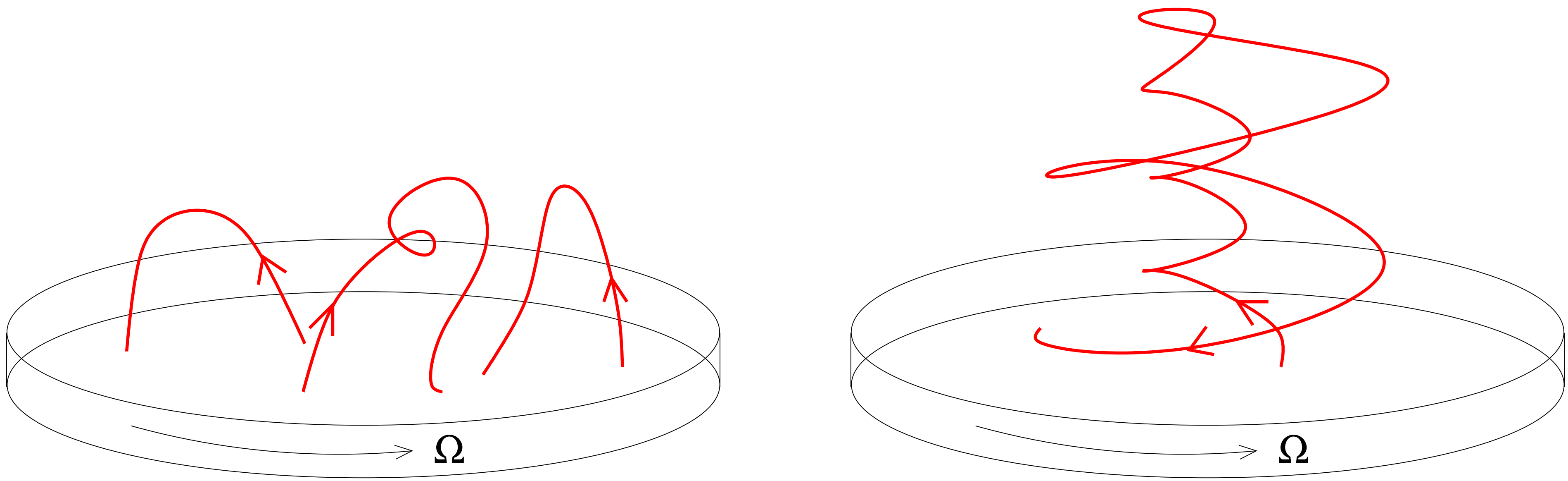

m=1
γ=1.001
γ=1.01
γ=1.05
γ=1.25
γ=2
γ=5
γ=10
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.0001
0.001
0.01
0.1
1
10
ωr_j/c
kr_j


m=-1
γ=1.001
γ=1.01
γ=1.05
γ=1.25
γ=2
γ=5
γ=10
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
0.0001
0.001
0.01
0.1
1
10
ωr_j/c
kr_j



m=0
γ=1.001
γ=1.01
γ=1.05
γ=1.25
γ=2
γ=5
γ=10
10.000000
1.000000
0.100000
0.010000
0.001000
0.000100
0.000010
ωrj/c
0.001
0.01
0.1
1
10
krj

How to create jets with $J_{\mathrm{surface}} = 0$?

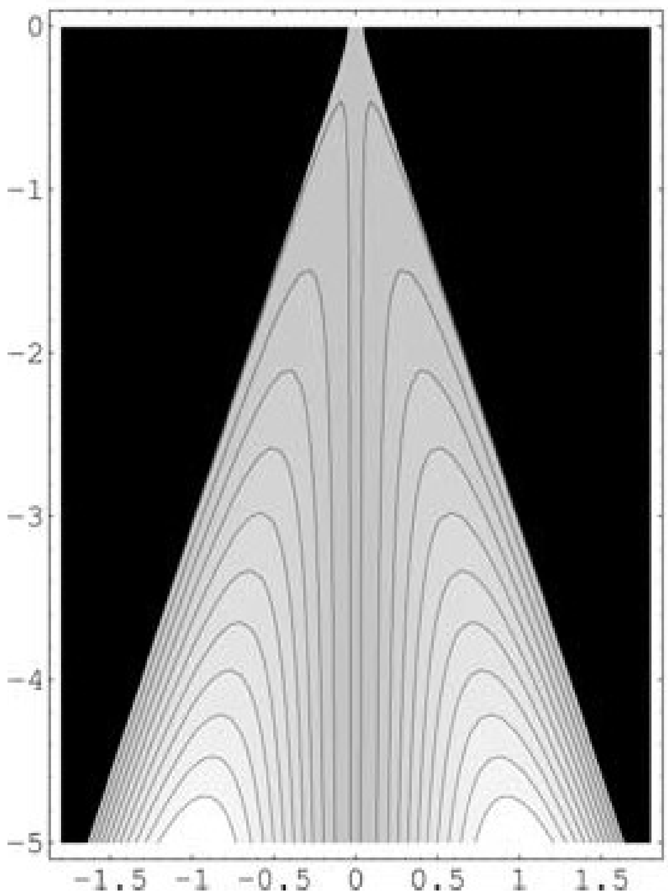


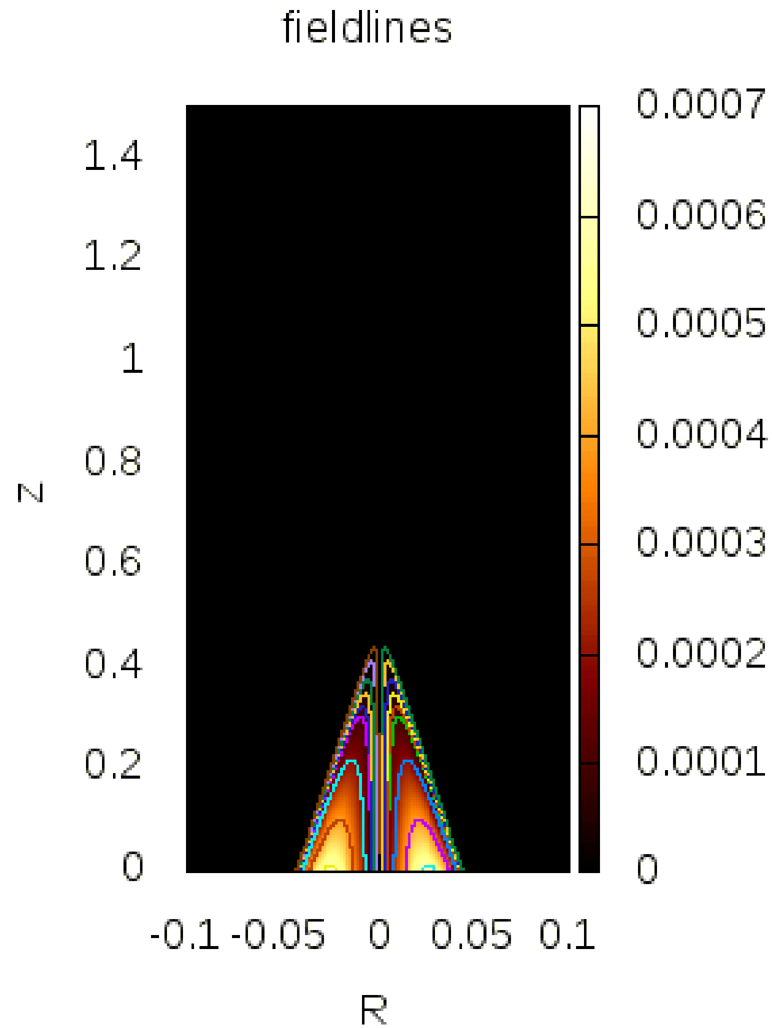
magnetic tower (Lynden-Bell)
loops of magnetic field + differential rotation

magnetic field not advected, but amplified locally
(dynamo or cosmic battery)

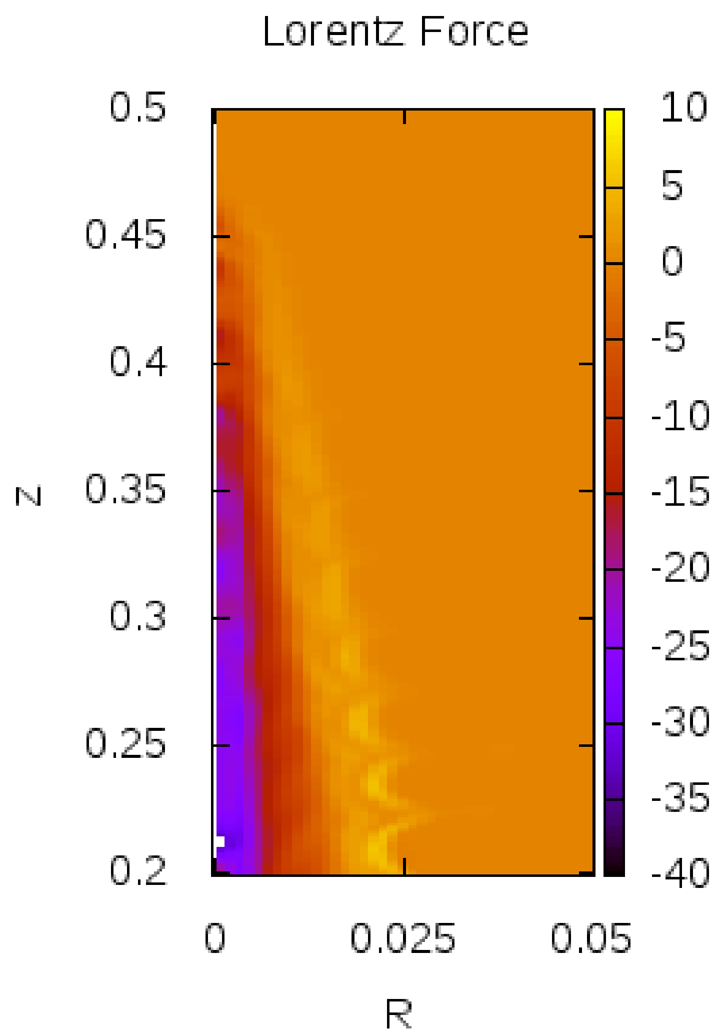
simulations using PLUTO code (Mignone et al) starting with the
"Dunce's cap" model of Lynden-Bell
Eugene Zhuleku 2016 (master thesis)

initial condition
pressure equilibrium
B_z and B_ϕ (and current)
change polarity

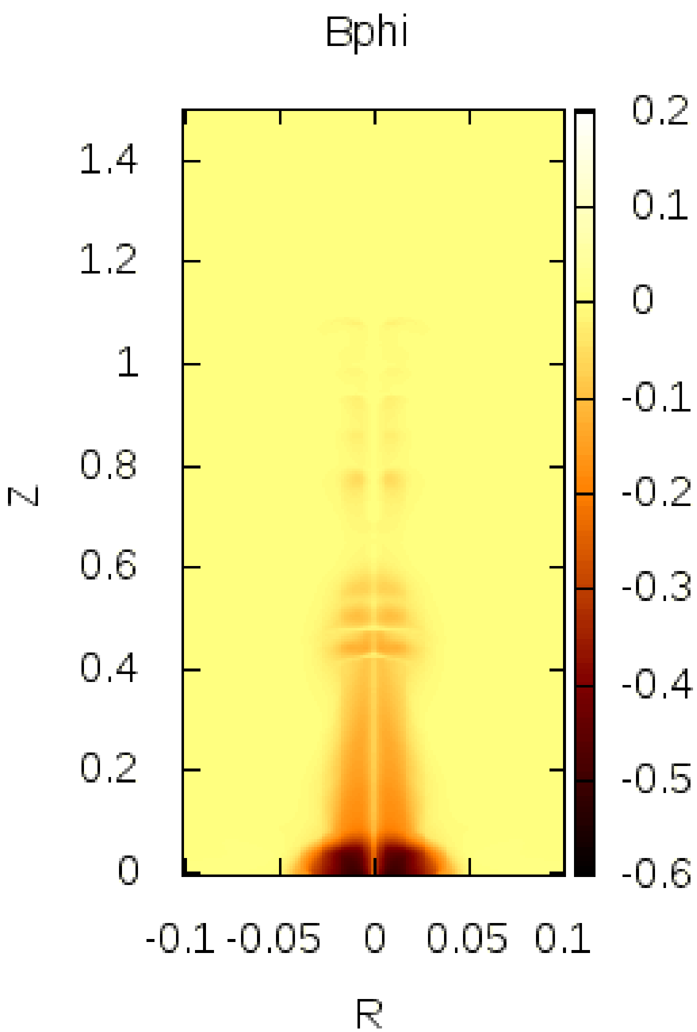


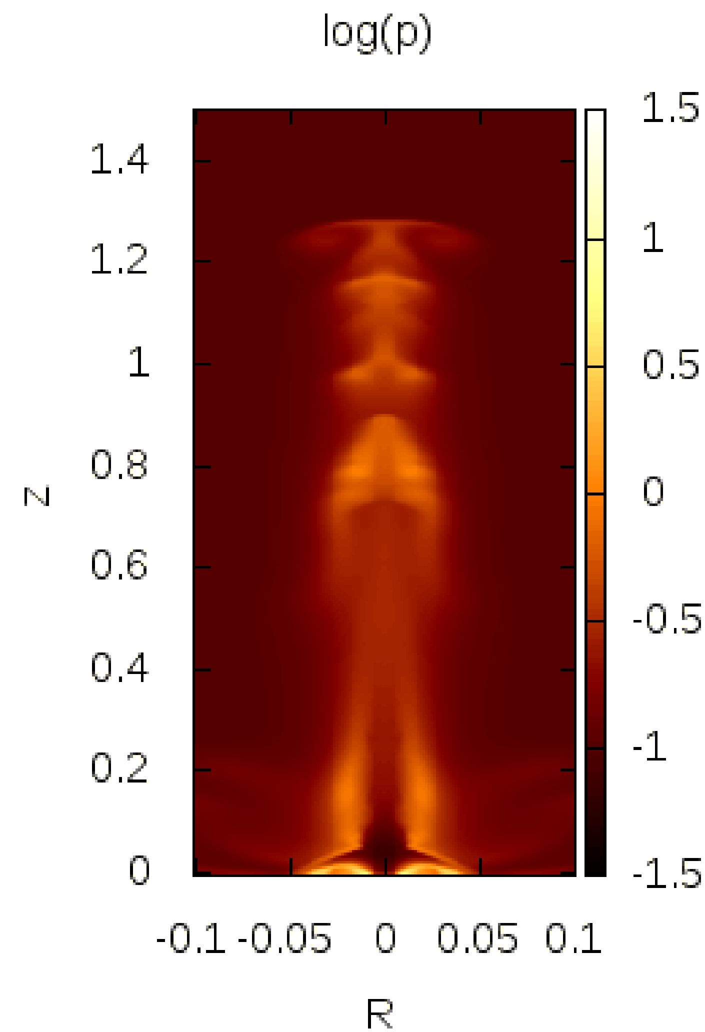


the two currents repel each other

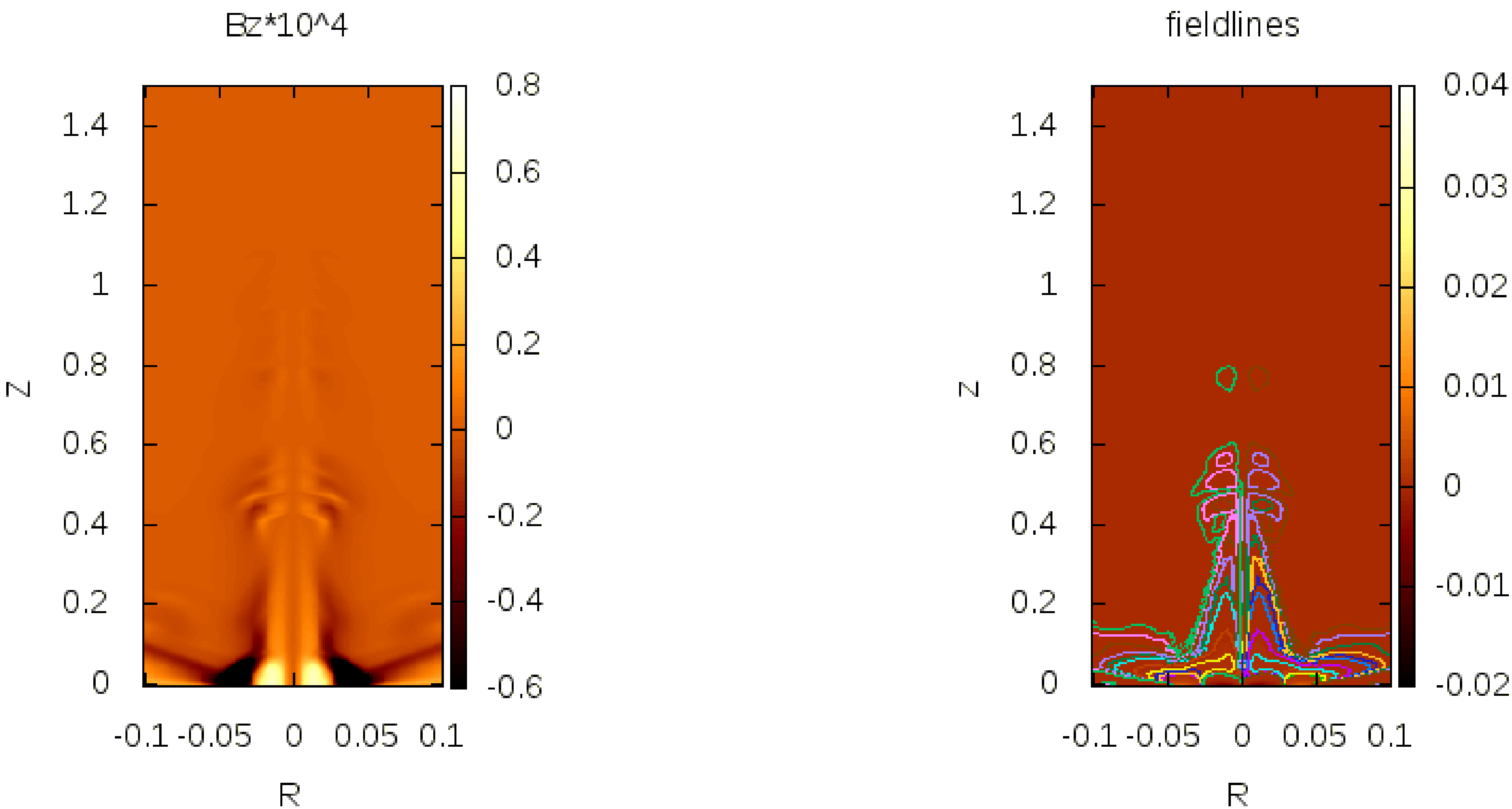


B_ϕ (left) and density (right)

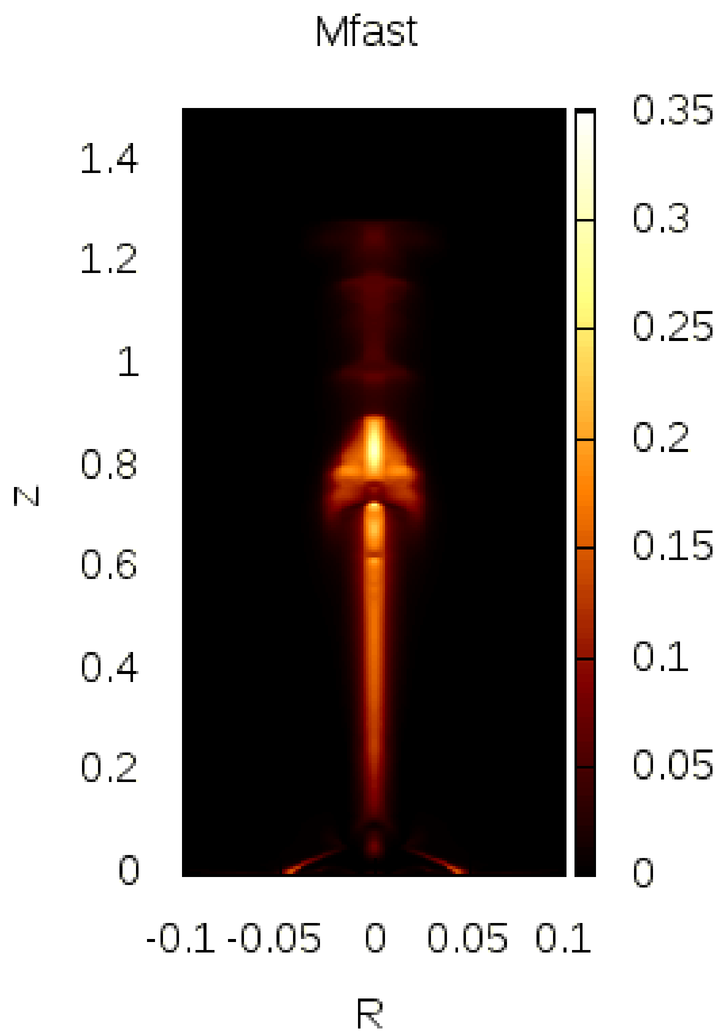




B_z (left) and poloidal fieldlines (right)

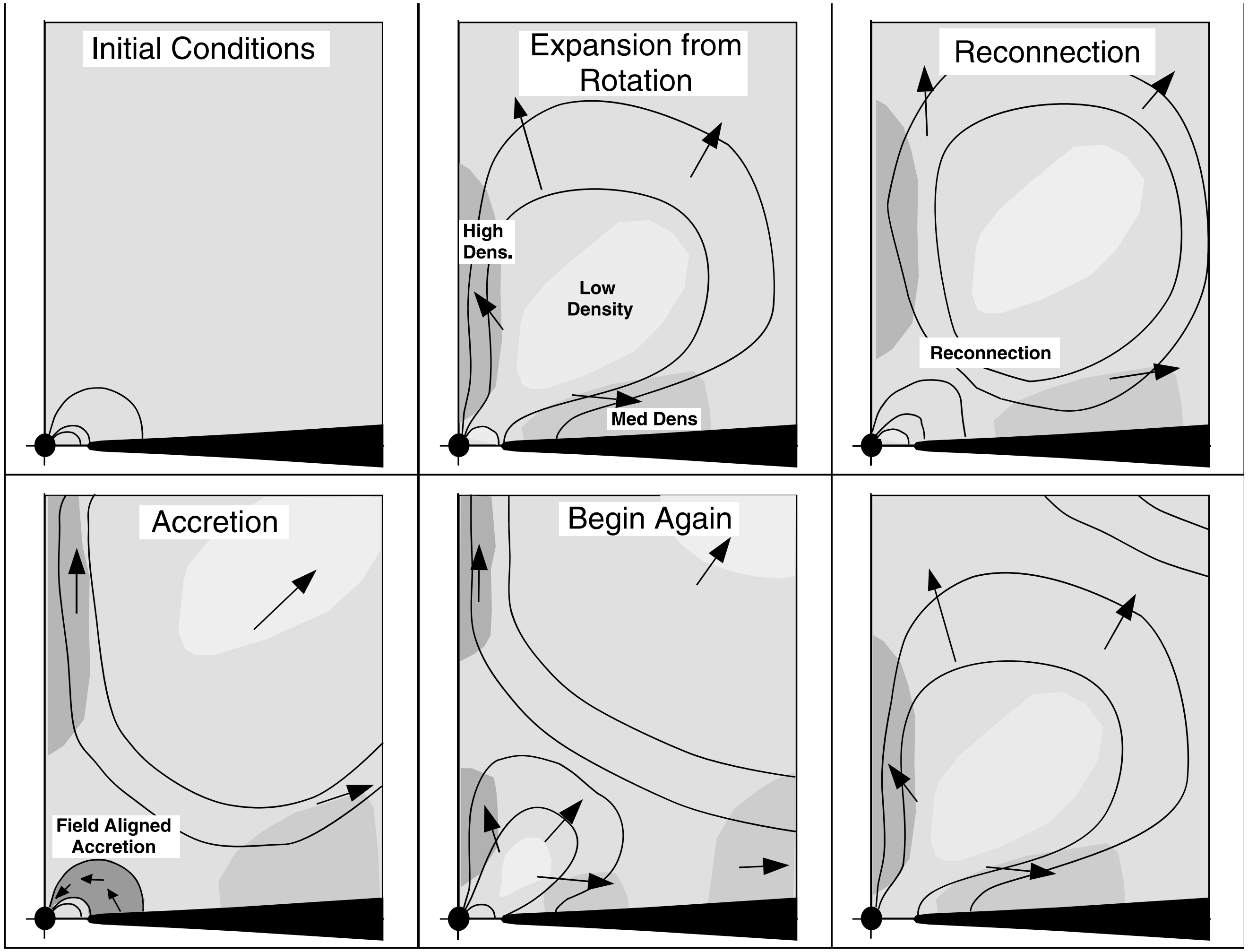


M^2_{fast} (remains subfast magnetosonic)



tendency to reconnect (although the simulations are ideal MHD)

similar to Goodson+1999



next step: include resistivity. Dissipation contributes to acceleration through B_ϕ gradients (Giannios & Spruit 2006)

Minimum energy solutions

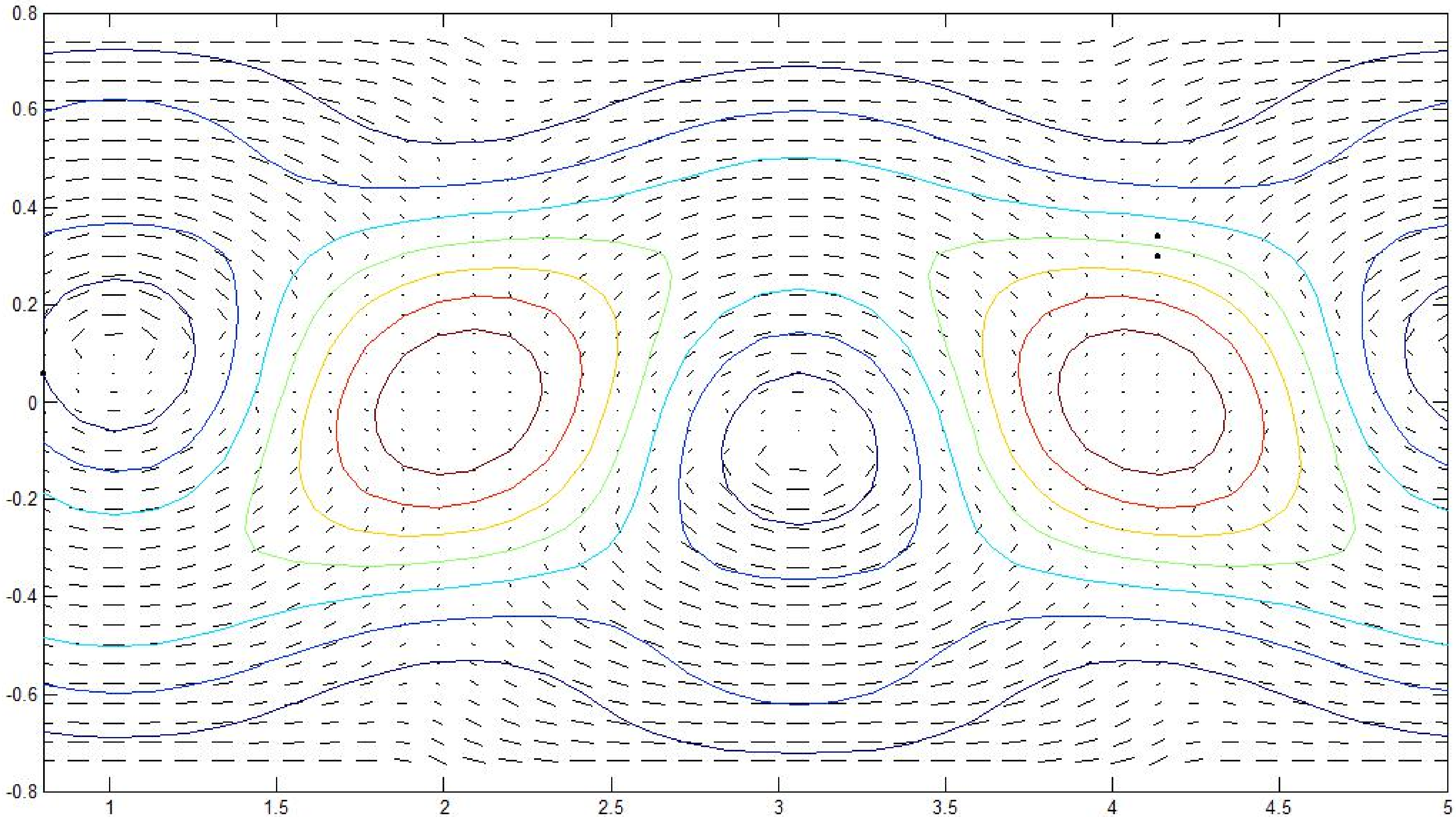
another way to atack the problem:

minimizing the energy $\int \frac{B^2}{8\pi}\, dV$ of a given plasma comoving volume, conserving helicity $\int \frac{\boldsymbol{A}\cdot\boldsymbol{B}}{8\pi}\, dV$, we end up with force-free fields (Woltjer 1958)

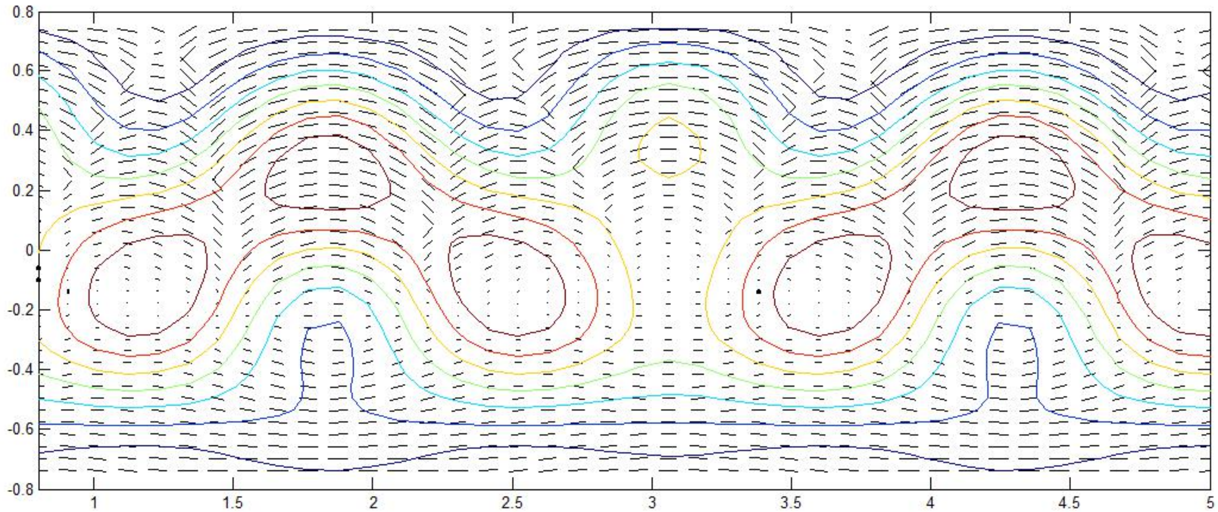
Using solutions found by Chandrasekhar and Kendall (1957), the minimum energy configurations are non-axisymmetric! (Choudhuri & Königl 1984).

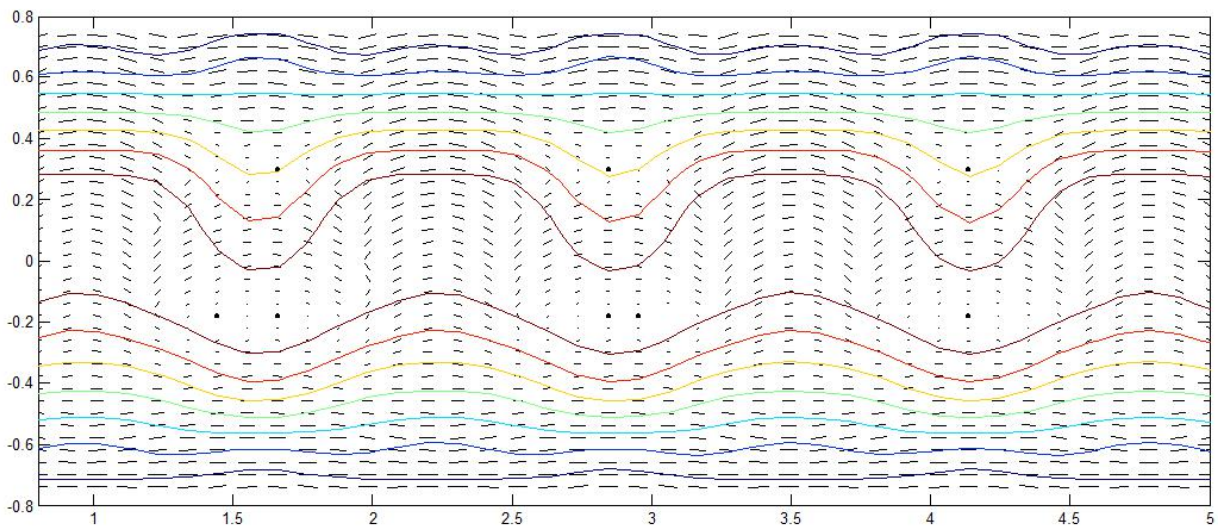
nontrivial to apply the method to non-uniformly moving flows

example of intensity + EVPA in the comoving frame



extended to relativistic motion (Lemesios master thesis)





Summary – Discussion – Next steps

⋆ bulk acceleration and jet morphology successfully explained by ideal magnetohydrodynamics

⋆ stability remains a puzzle

⋆ lower $|B_\phi|/B_z$, as in jets without surface currents, stabilize

⋆ still we have to connect accelerating jets with minimum energy asymptotic states (resistive MHD)