Open questions in Astrophysical Jets

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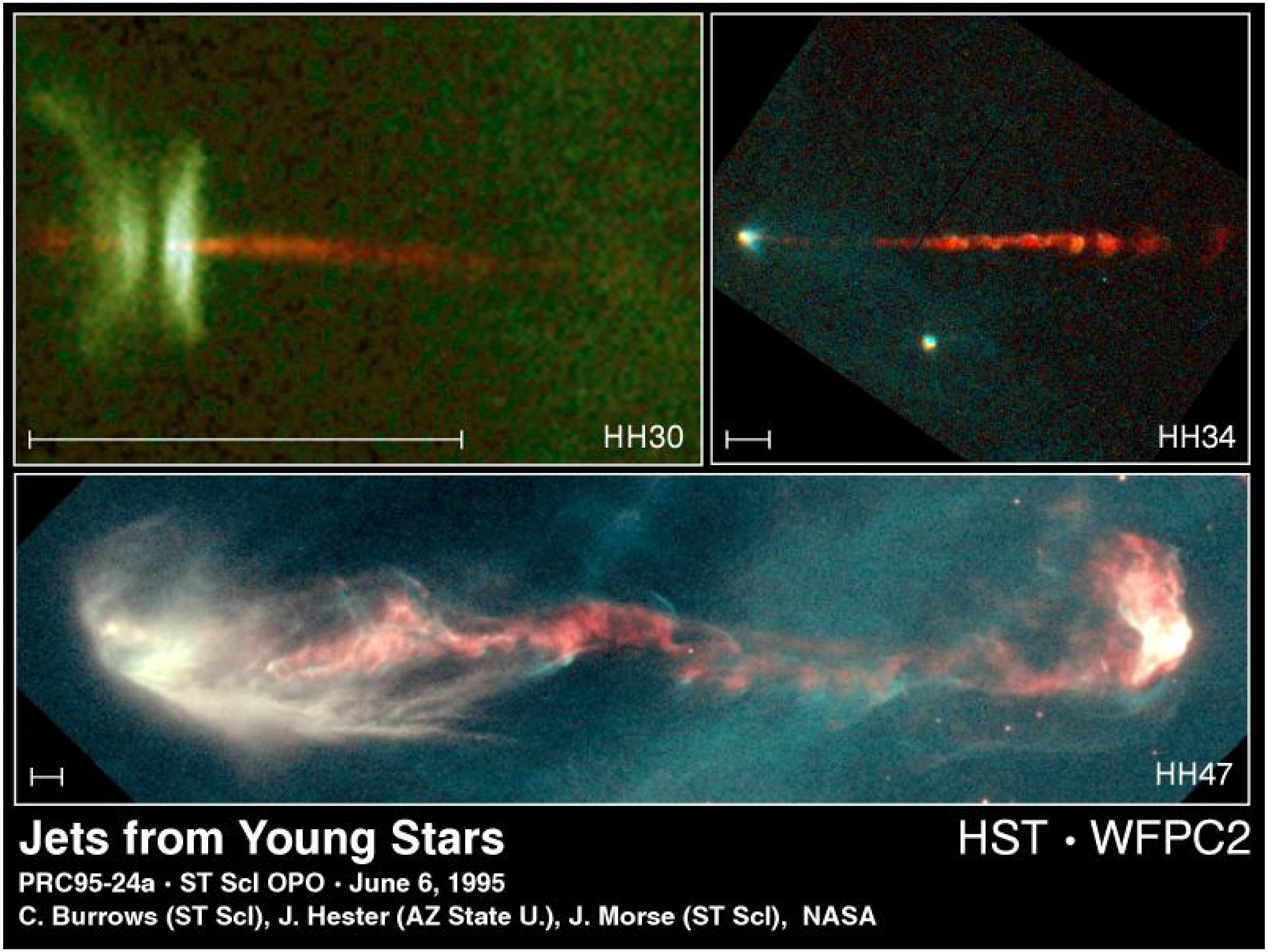
Outline

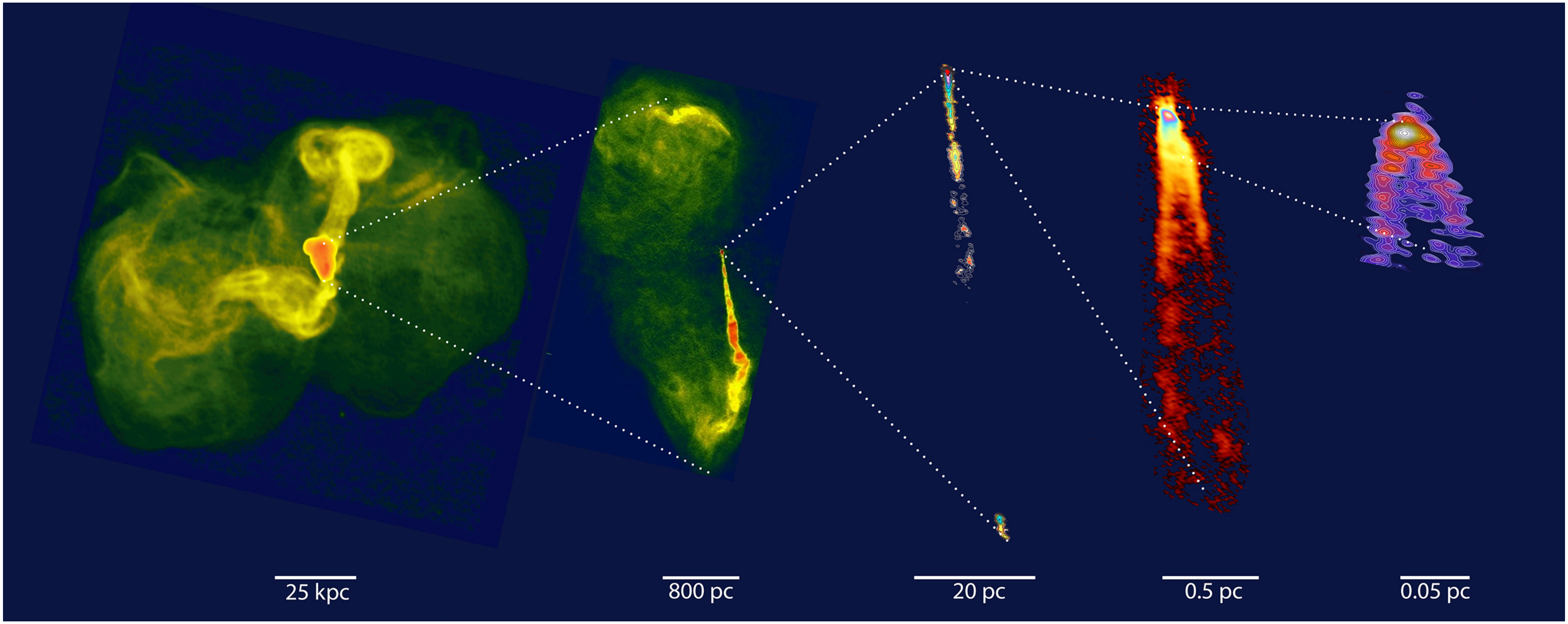
- introduction (observed jet characteristics)
- 1st level (magnetohydrodynamic collimation-acceleration)
- 2nd level (stability, resistivity, GR effects)

Examples of astrophysical jets

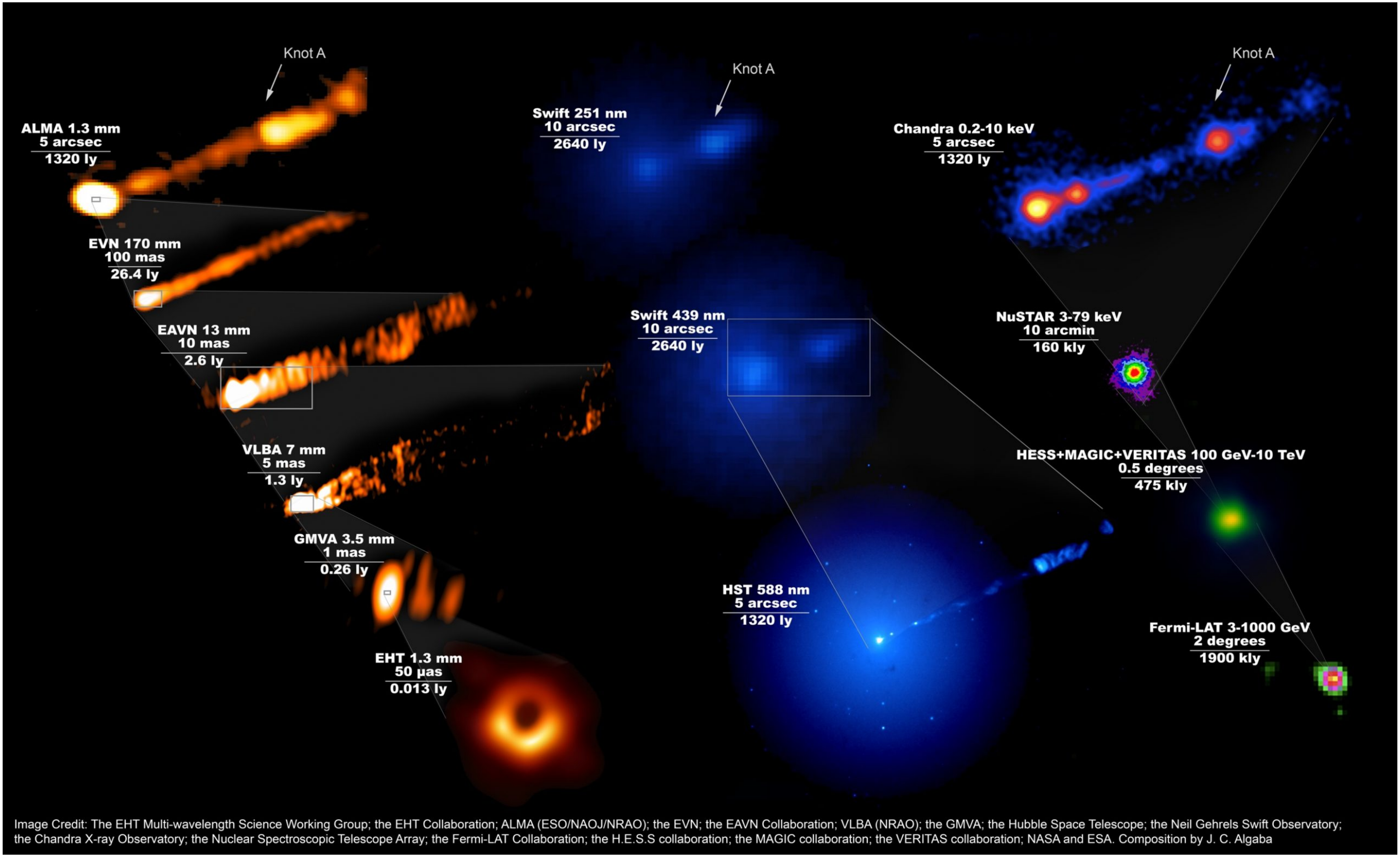


(scale =1000 AU, $V_\infty = afew100$km/s)

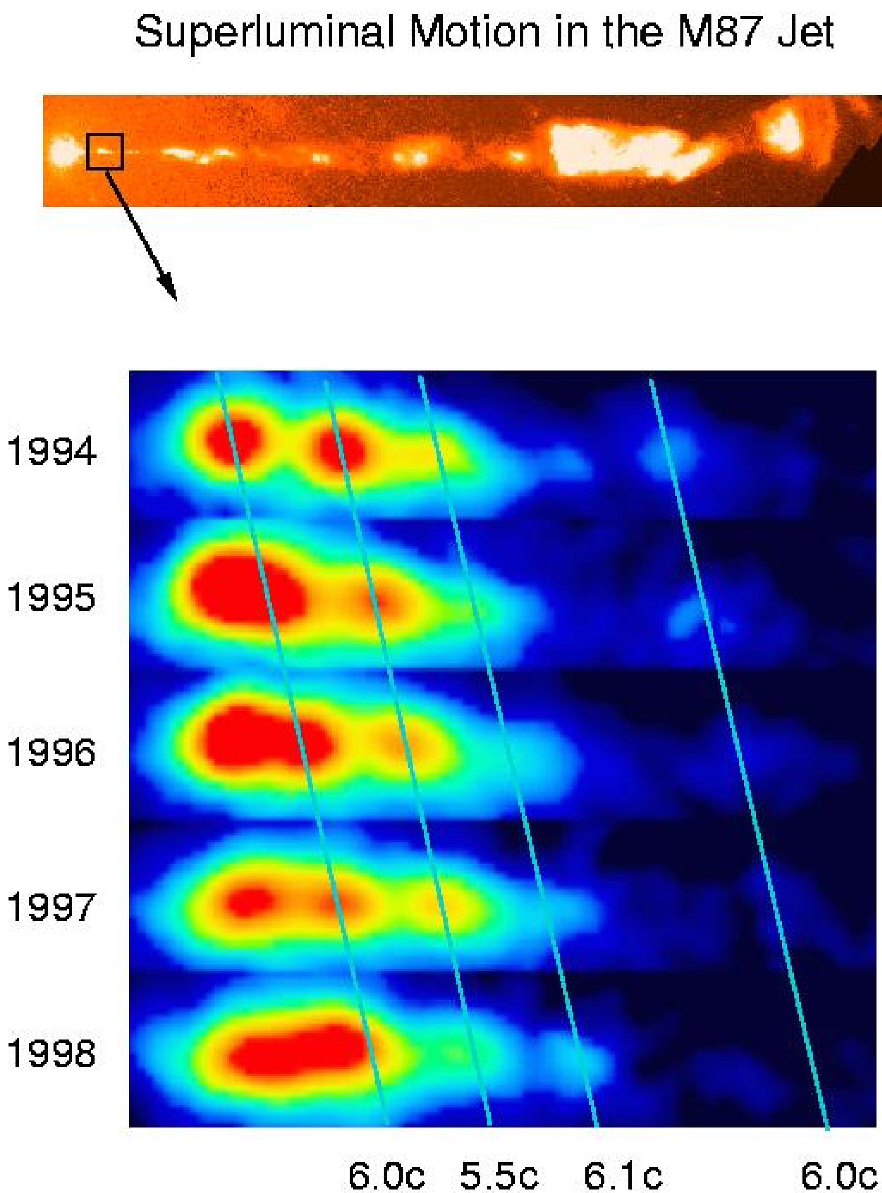
The jet from the M87 galaxy

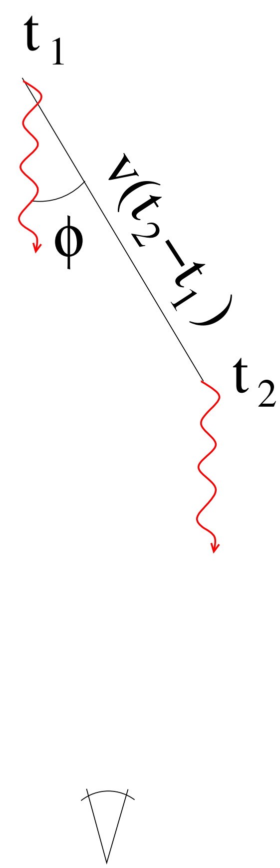


(from Blandford+2018)

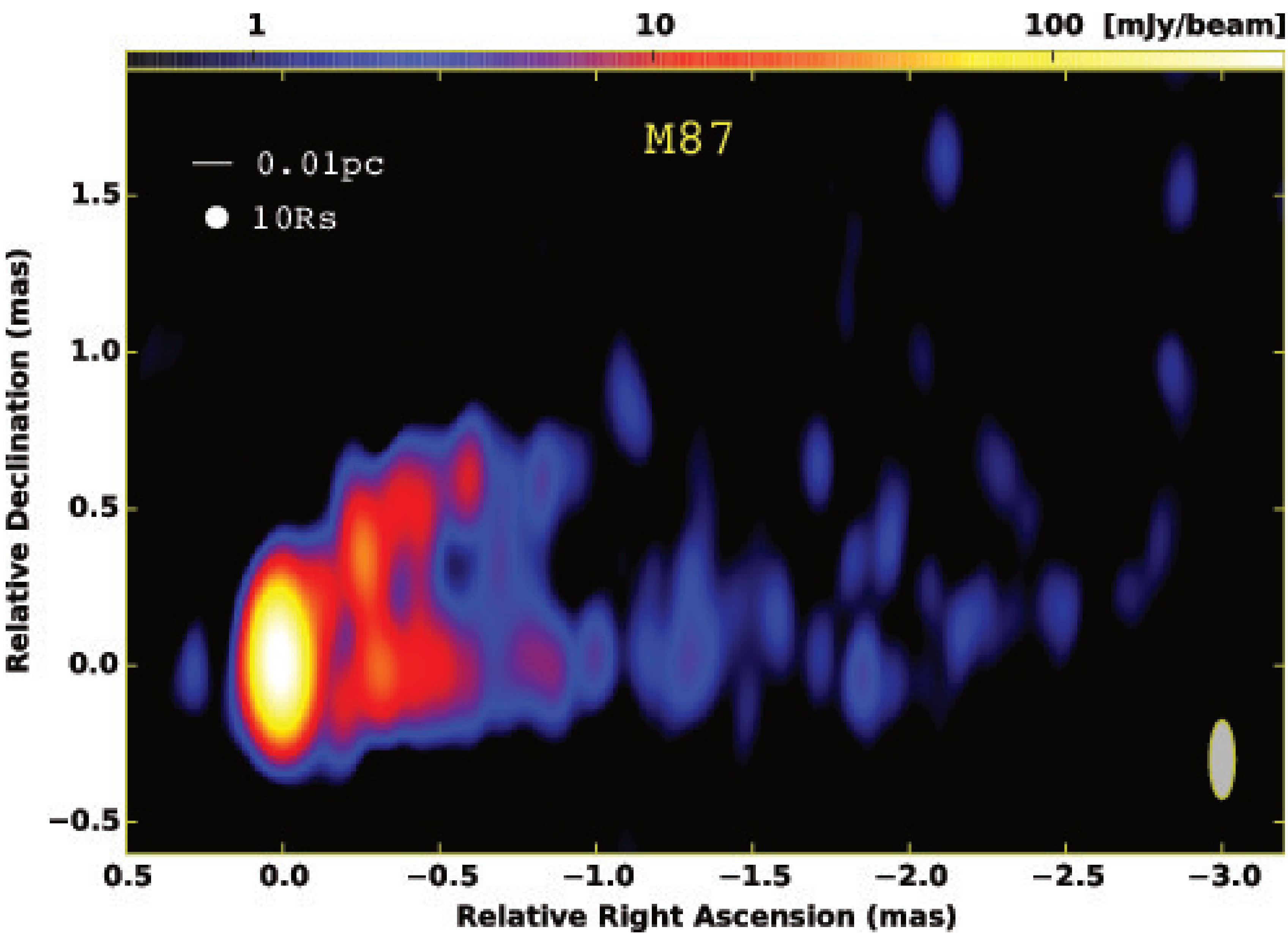

Knot A
ALMA 1.3 mm
5 arcsec
1320 ly
EVN 170 mm
100 mas
26.4 ly
EAVN 13 mm
10 mas
2.6 ly
VLBA 7 mm
5 mas
1.3 ly
GMVA 3.5 mm
1 mas
0.26 ly
EHT 1.3 mm
50 µas
0.013 ly
Knot A
Swift 251 nm
10 arcsec
2640 ly
Swift 439 nm
10 arcsec
2640 ly
HST 588 nm
5 arcsec
1320 ly
Knot A
Chandra 0.2-10 keV
5 arcsec
1320 ly
NuSTAR 3-79 keV
10 arcmin
160 kly
HESS+MAGIC+VERITAS 100 GeV-10 TeV
0.5 degrees
475 kly
Fermi-LAT 3-1000 GeV
2 degrees
1900 kly
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

Jet speed





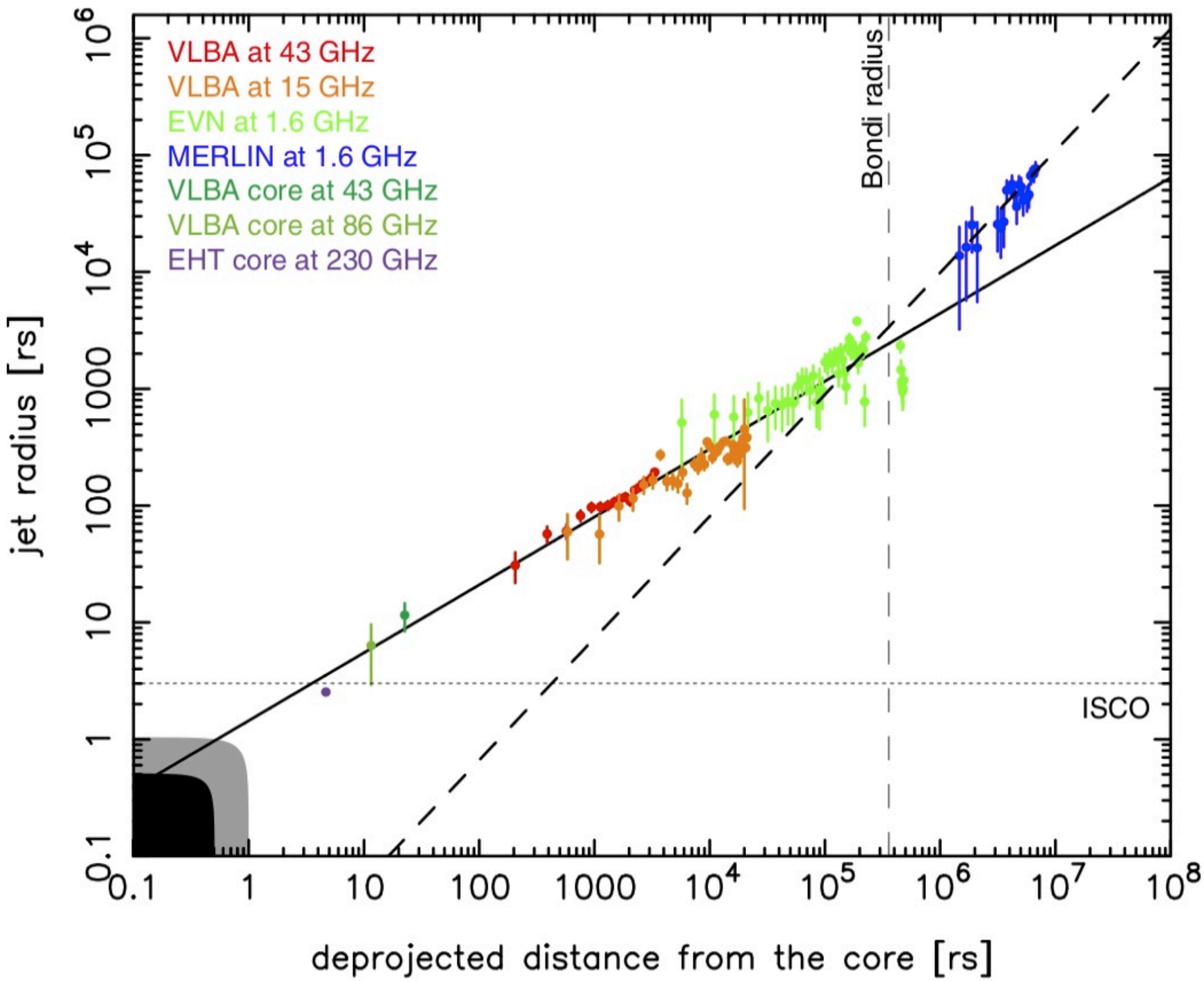
$$\gamma_\infty \sim 10$$



(Hada et al 2016)

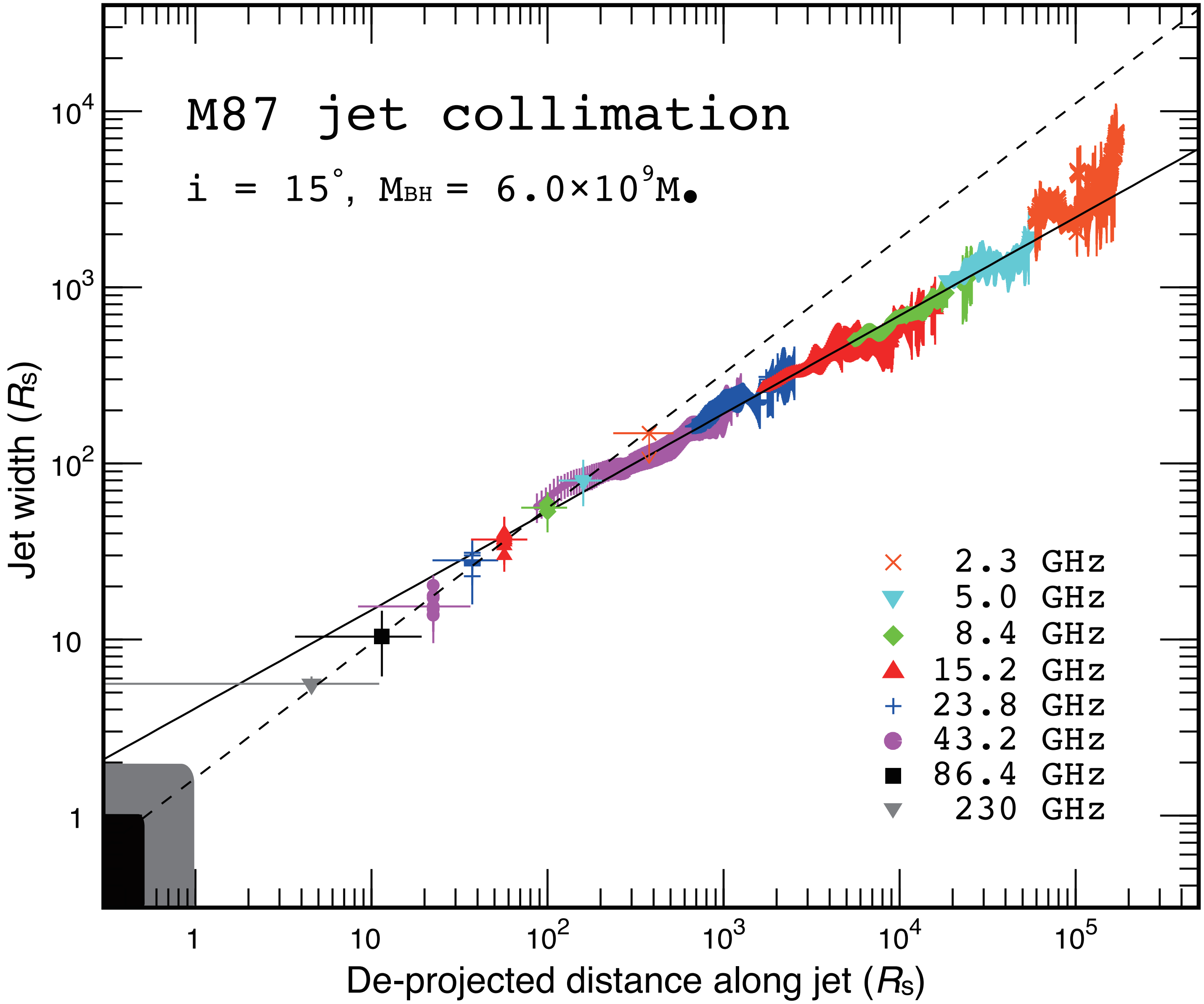
collimation at ∼100 Schwarzschild radii

The jet shape (Nakamura & Asada 2013)



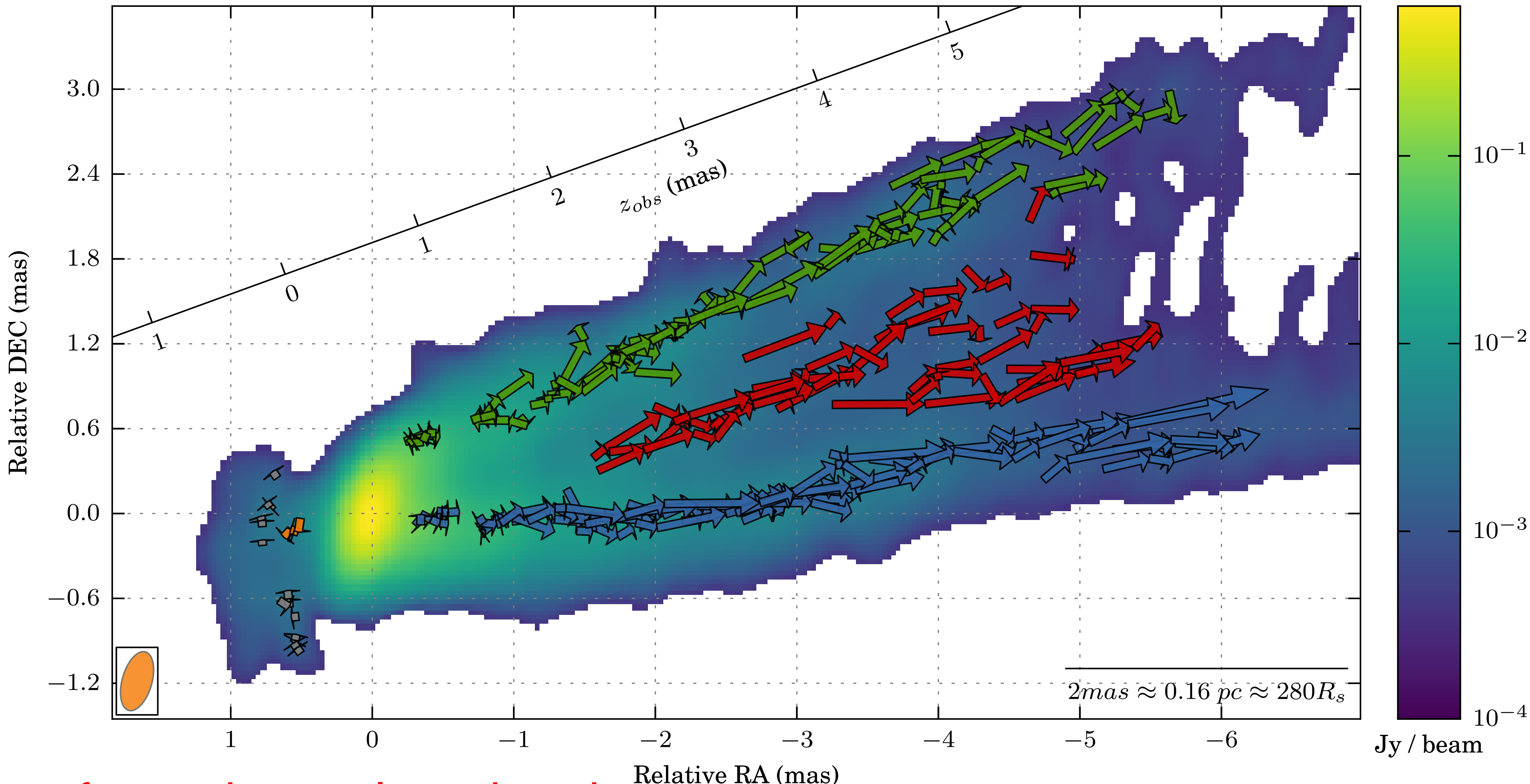
Parabolic up to the Bondi radius, then radial

(Hada+2013)



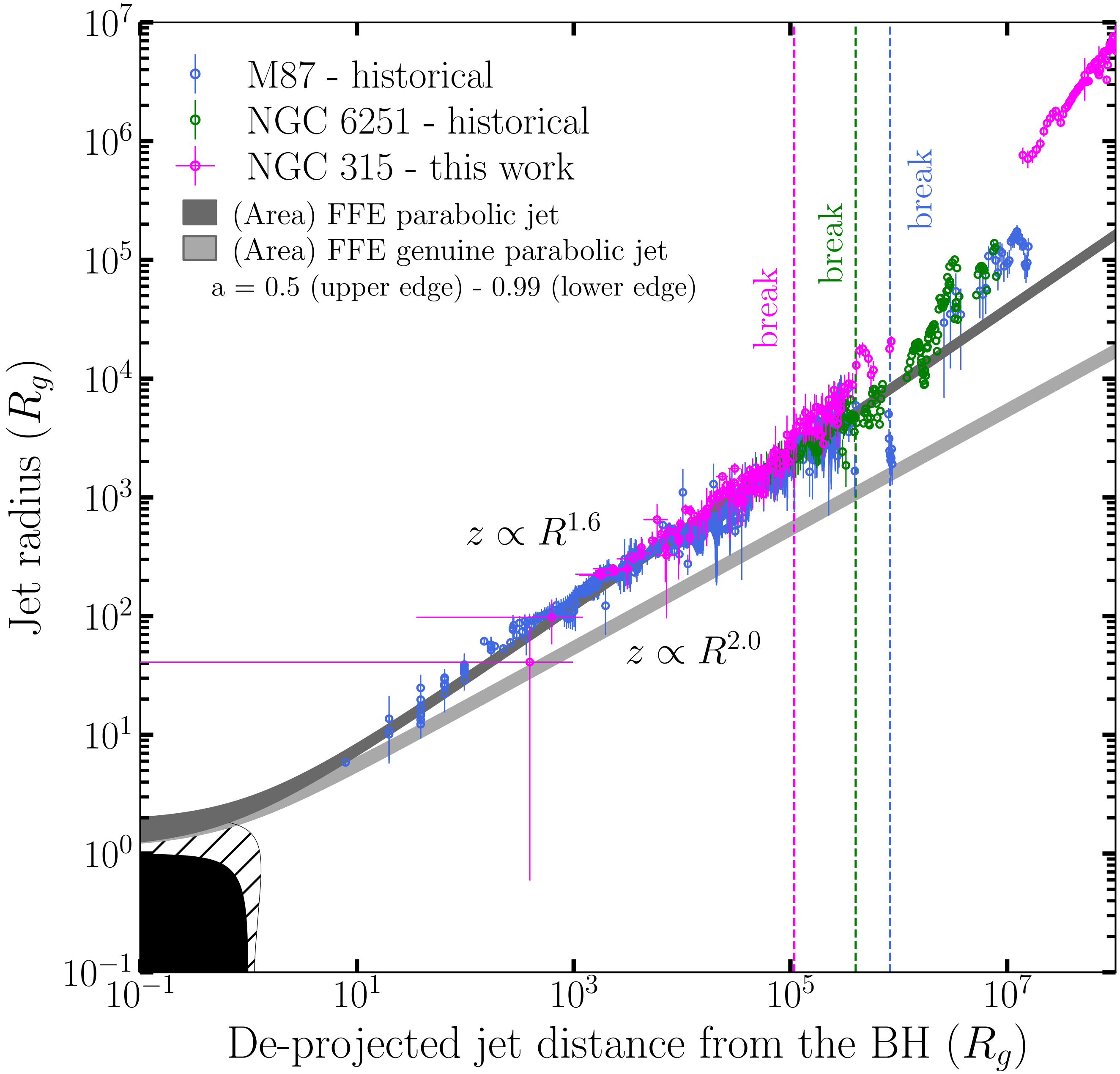
jet from the disk or the black hole?

Transverse profile (Mertens+2016)

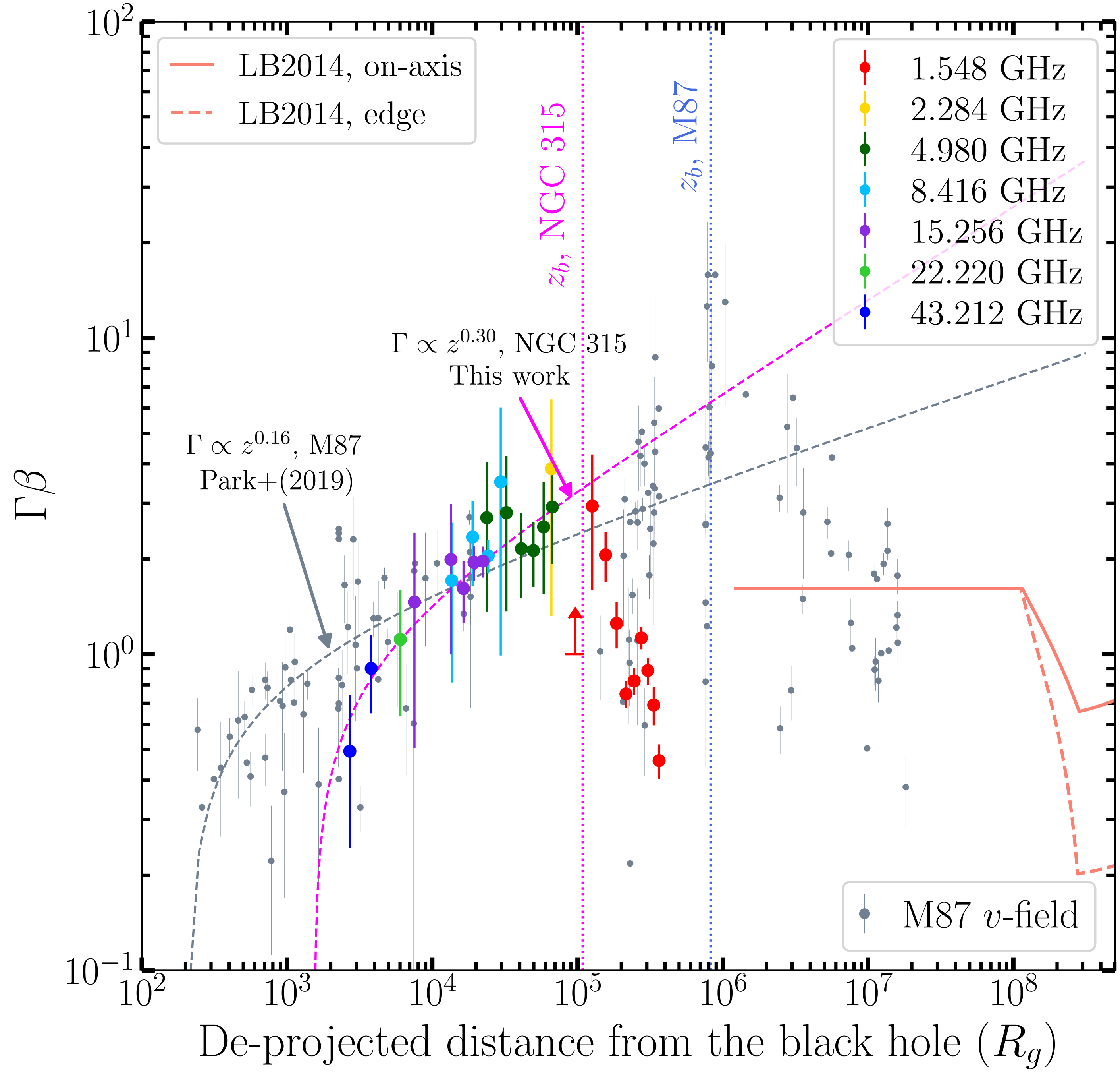


- fast spine – slow sheath
- they manage to observe sheath rotation: the value favors disk-driven (and not BH-driven) jet
- the spine?

(Park+2021)



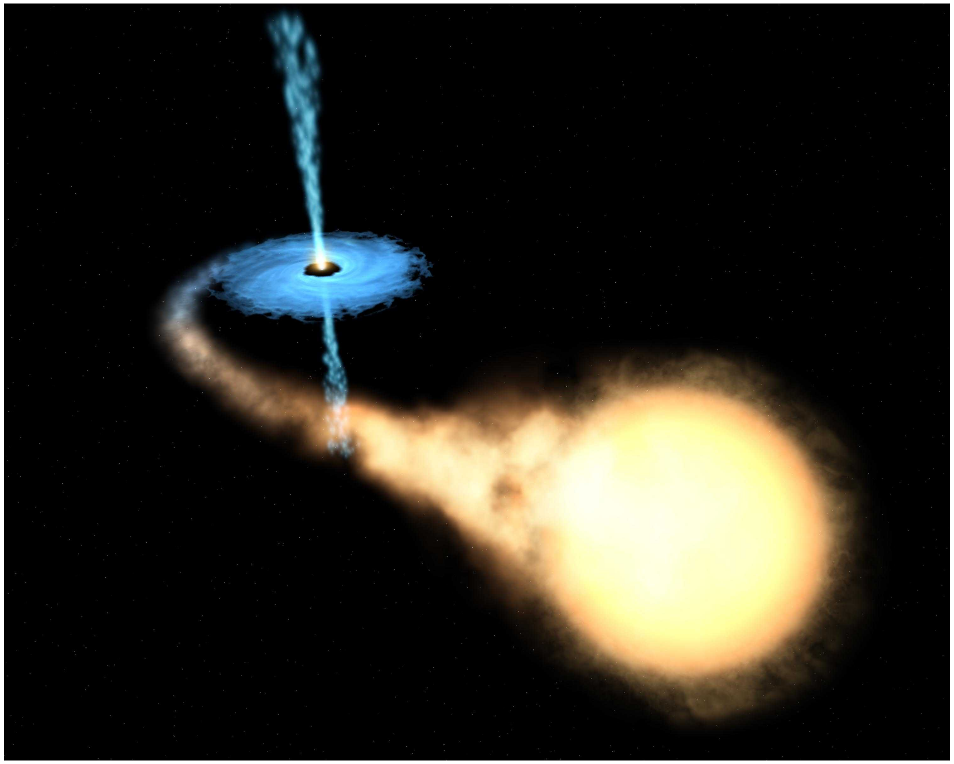
M87 - historical
NGC 6251 - historical
NGC 315 - this work
(Area) FFE parabolic jet
(Area) FFE genuine parabolic jet
a = 0.5 (upper edge) - 0.99 (lower edge)
break
break
break
$z \propto R^{1.6}$
$z \propto R^{2.0}$
Jet radius (R_g)
De-projected jet distance from the BH (R_g)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}

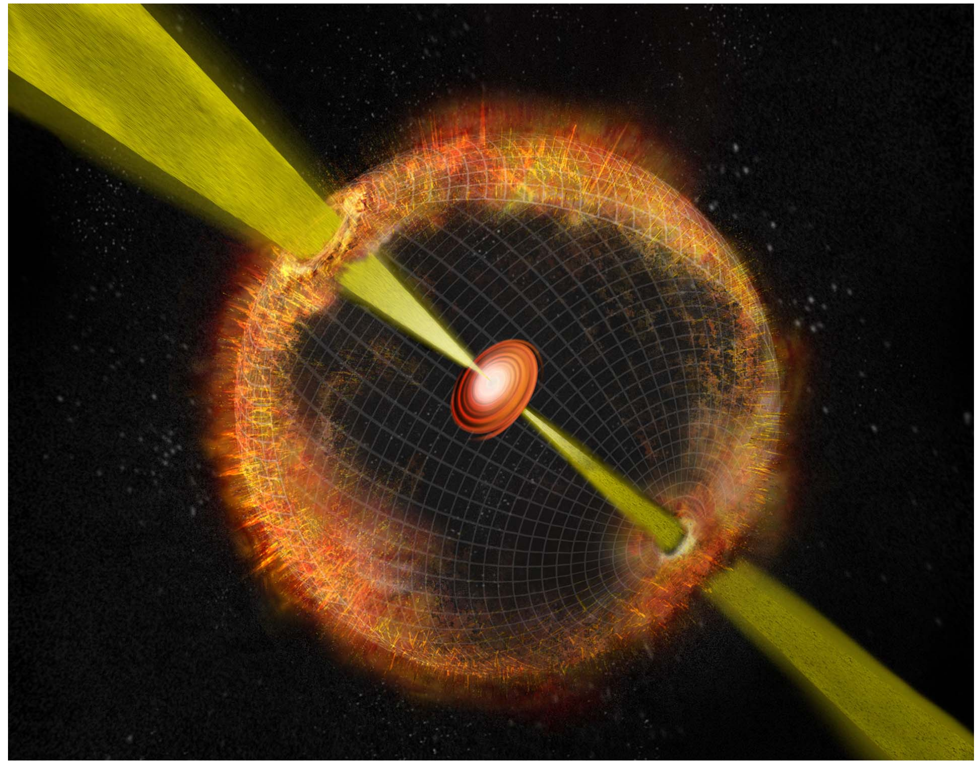


LB2014, on-axis
LB2014, edge
1.548 GHz
2.284 GHz
4.980 GHz
8.416 GHz
15.256 GHz
22.220 GHz
43.212 GHz
z_b, NGC 315
z_b, M87
$\Gamma \propto z^{0.30}$, NGC 315
This work
$\Gamma \propto z^{0.16}$, M87
Park+(2019)
M87 v-field
$\Gamma\beta$
De-projected distance from the black hole (R_g)

X-ray binaries

γ-ray bursts

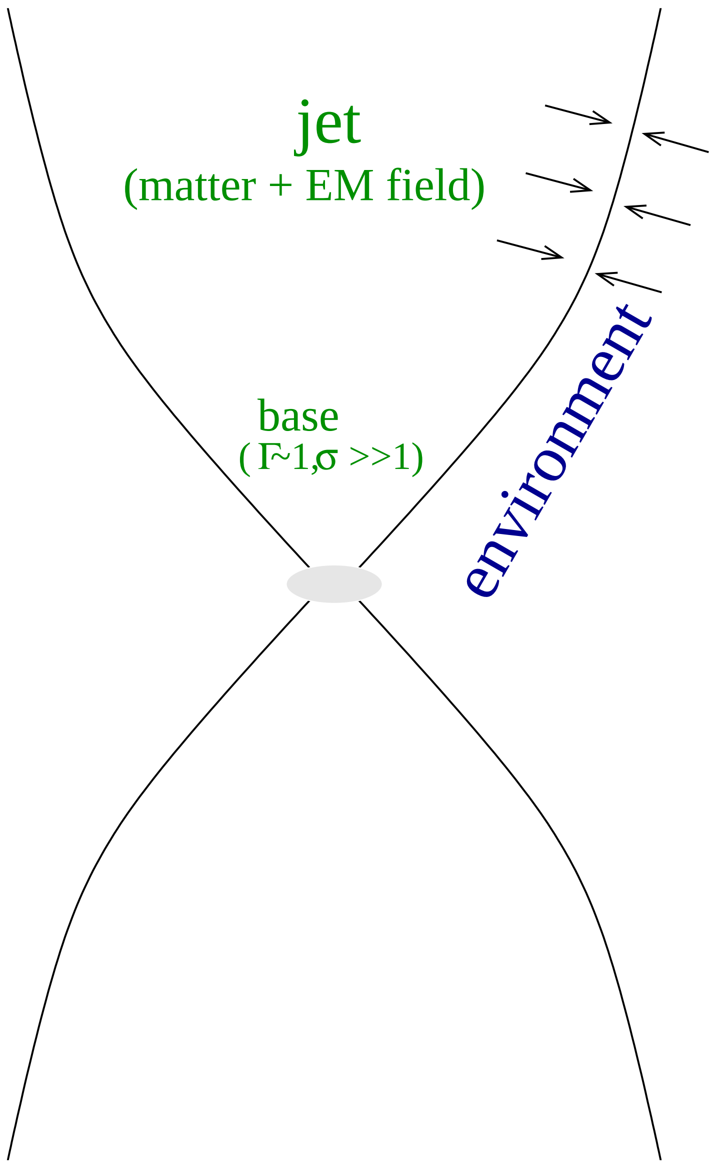




mildly relativistic

γ = a few 100

Basic questions



- source of matter/energy?
- bulk acceleration?
- collimation?
- role of environment?

Theoretical modeling

- ☞ if energy source = thermal energy:

thermal acceleration is an efficient mechanism

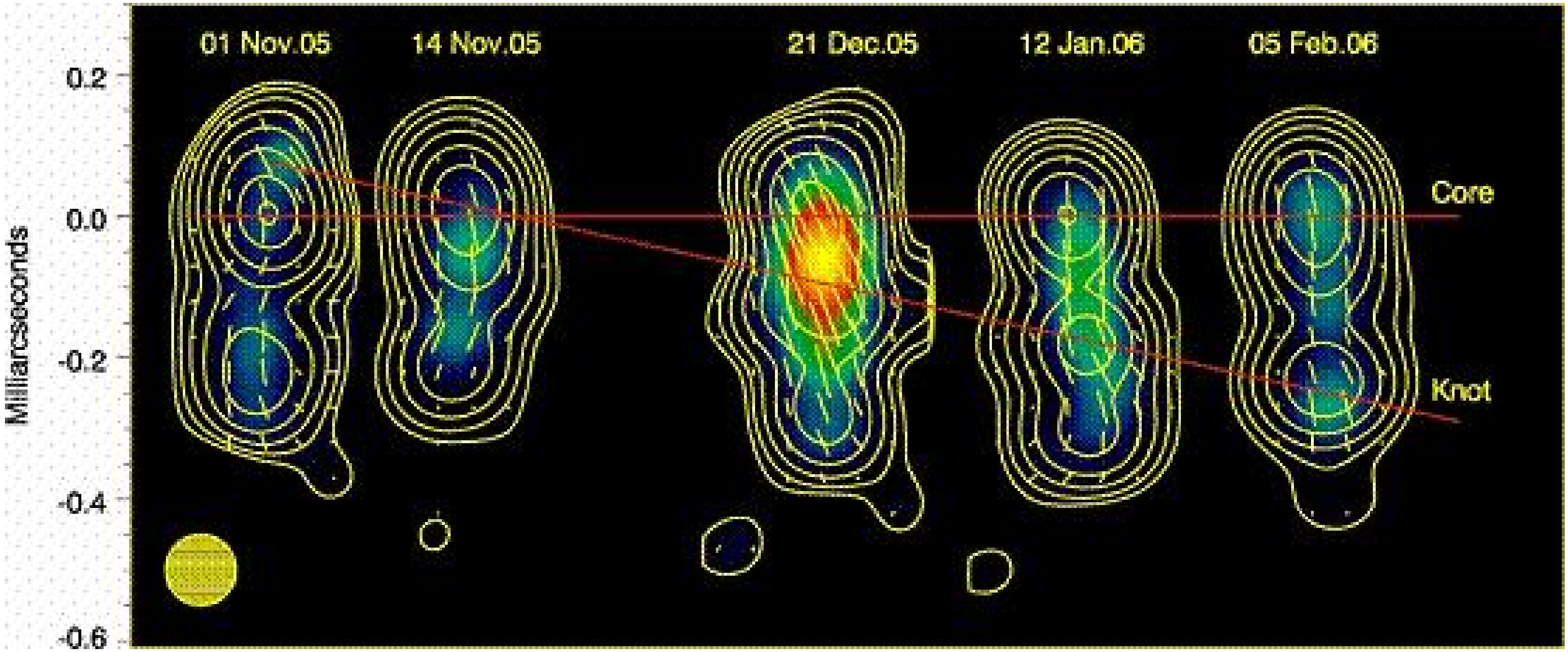
gives terminal speed $\frac{m_p V_\infty^2}{2} \sim k_{\rm B} T_i$ for YSO jets
or terminal Lorentz factors $\gamma_\infty m_p c^2 \sim k_{\rm B} T_i$ for relativistic jets

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

- ☞ leptonic jets? (require m_p/m_e smaller temperatures)

- ☞ magnetic acceleration more likely

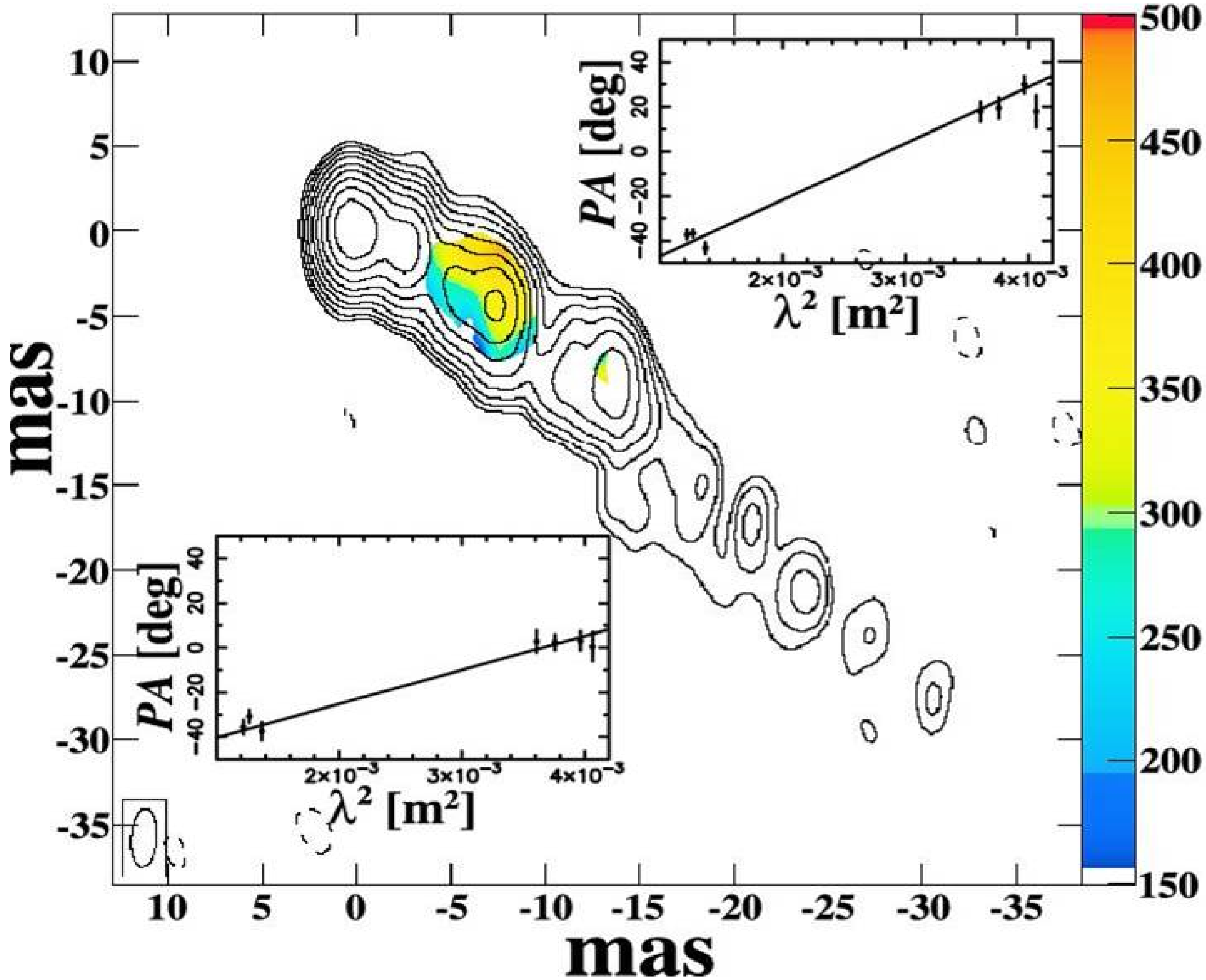
Polarization

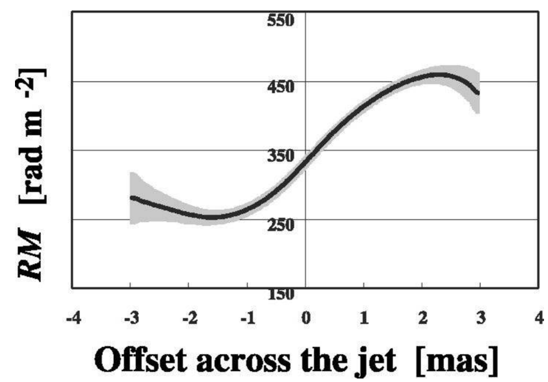


(Marscher et al 2008, Nature)

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

Faraday RM gradients across the jet





(Asada et al)

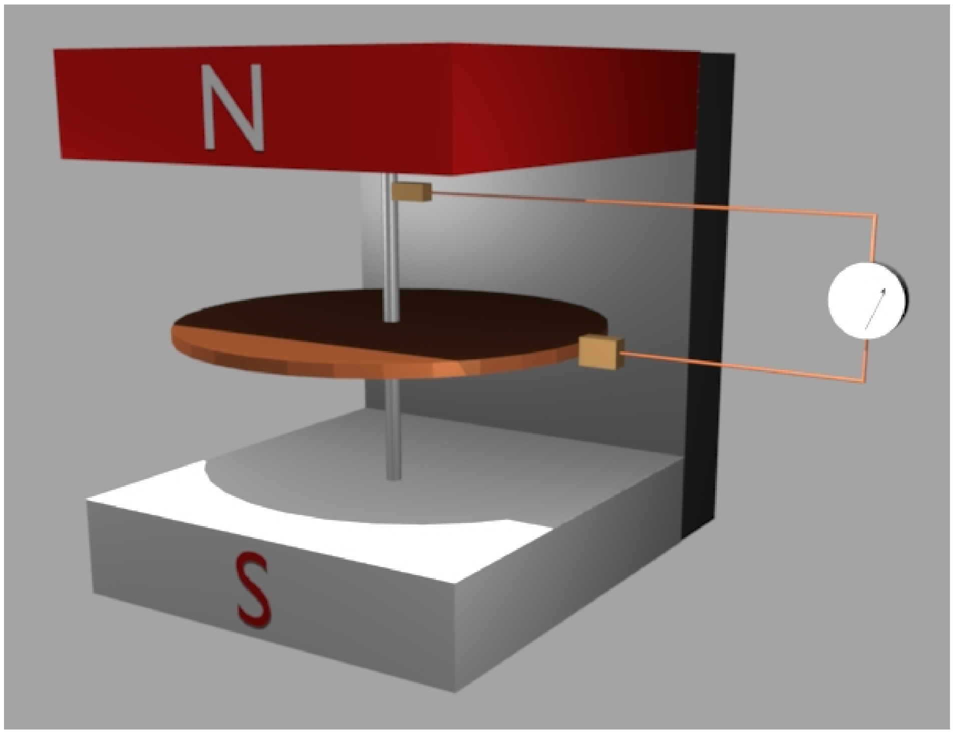
helical field surrounding the emitting region (Gabuzda)

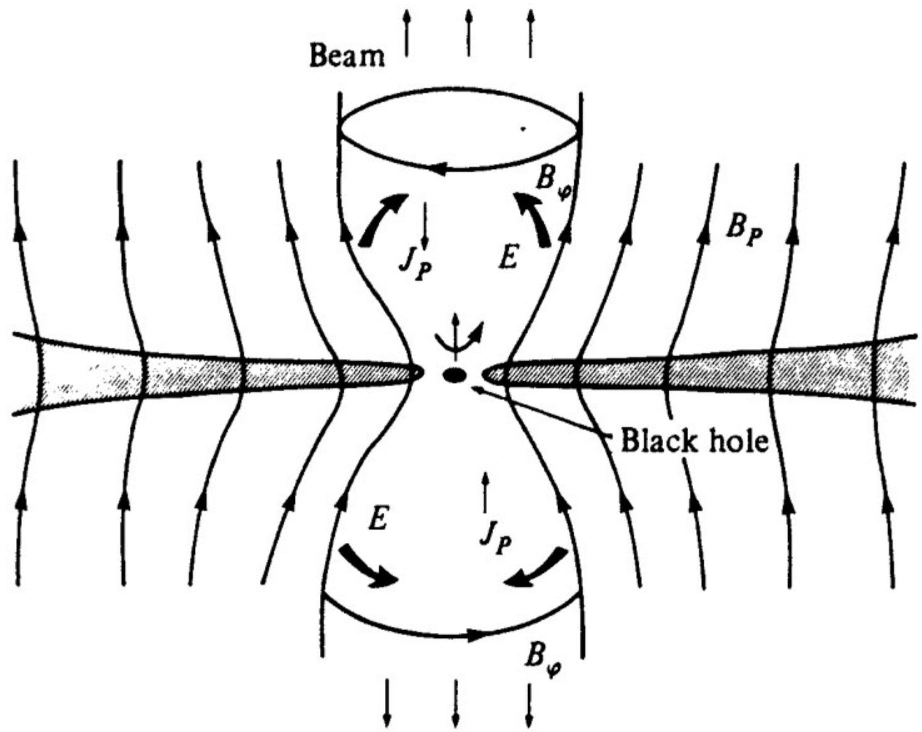
Role of magnetic field

- ⋆ 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

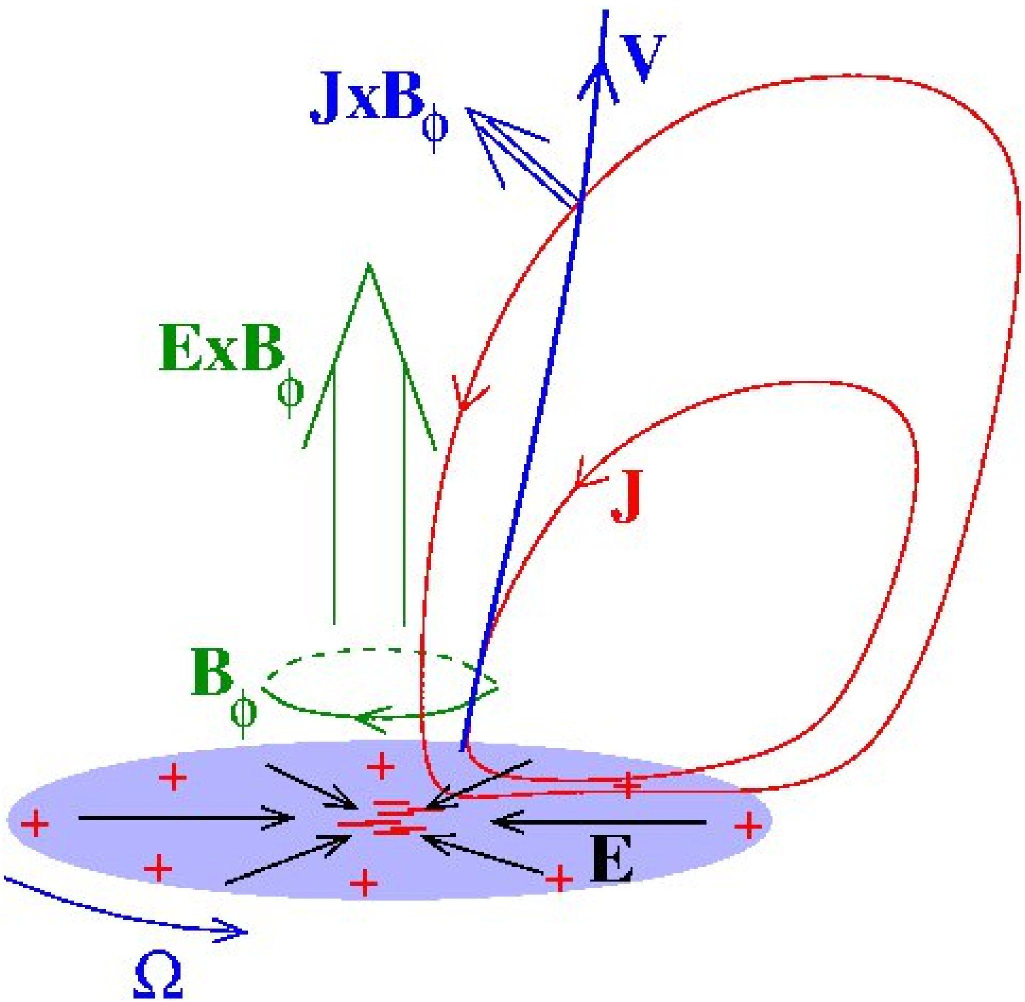
How MHD acceleration works

A unipolar inductor (Faraday disk)





magnetic field + rotation

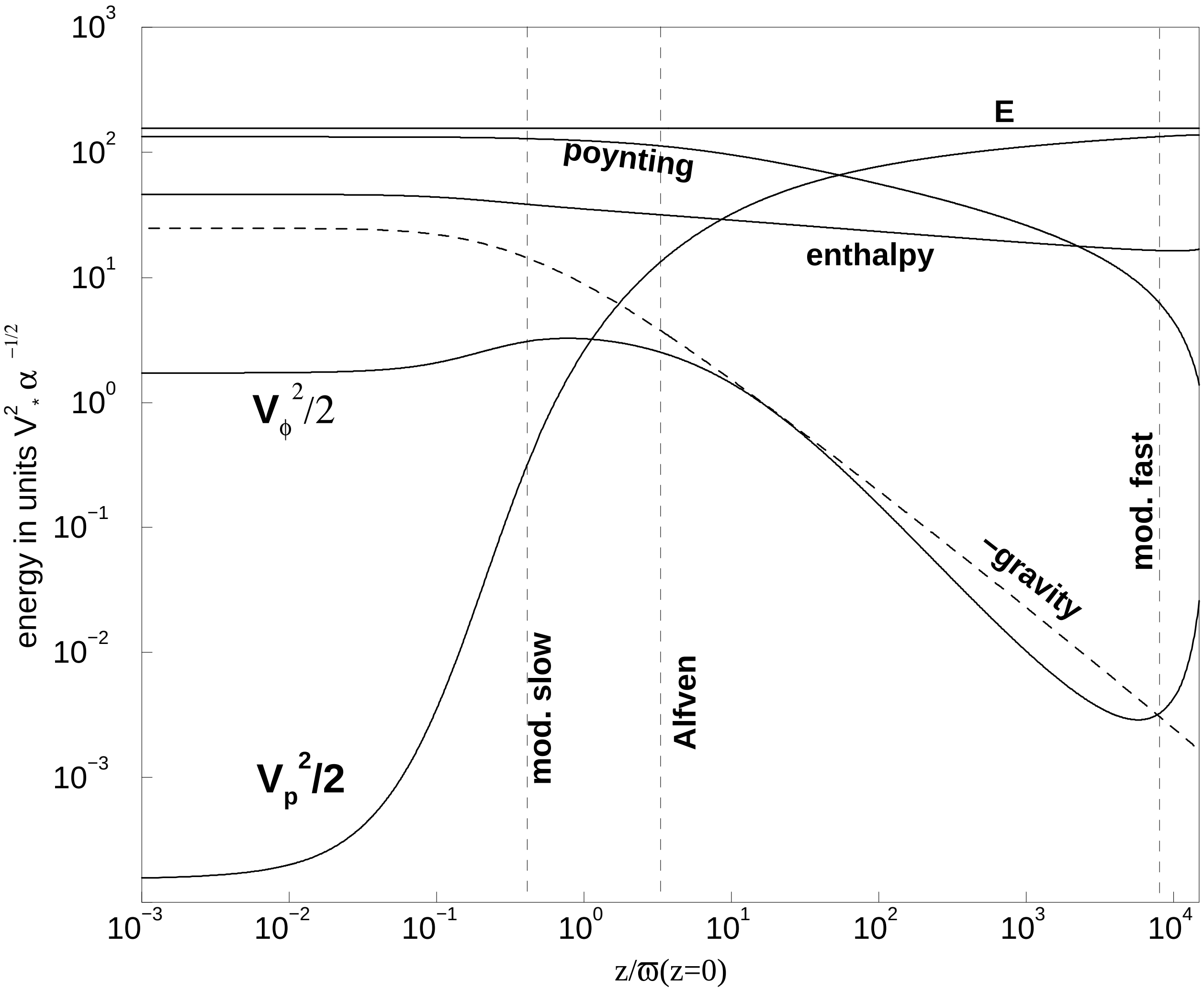


current $\leftrightarrow B_\phi$
Poynting flux $\frac{c}{4\pi}EB_\phi$ is extracted (angular momentum as well)

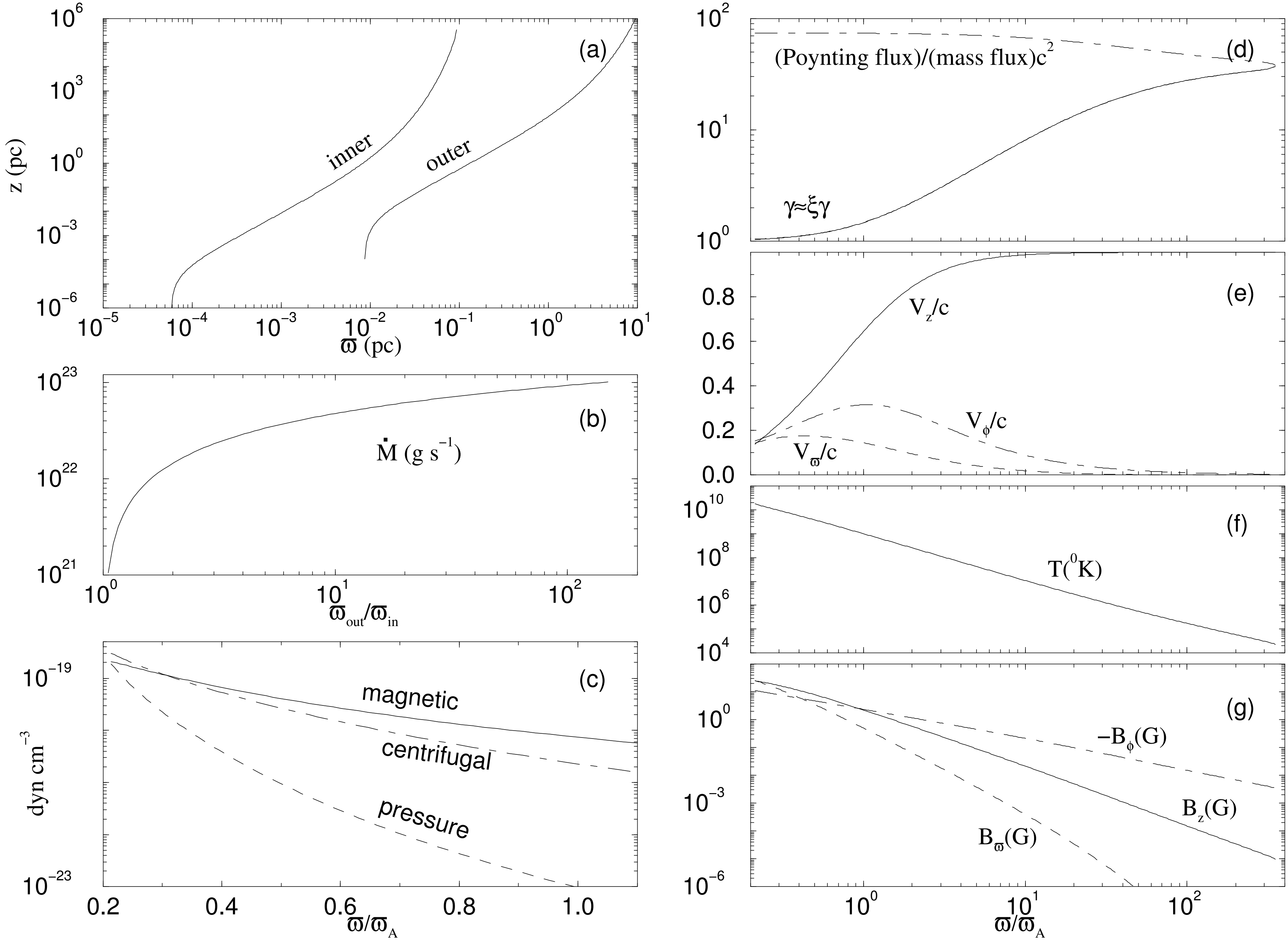
The Faraday disk could be the rotating accretion disk, or the frame dragging if energy is extracted from the ergosphere of a rotating black hole (Blandford & Znajek mechanism)

magnetic acceleration

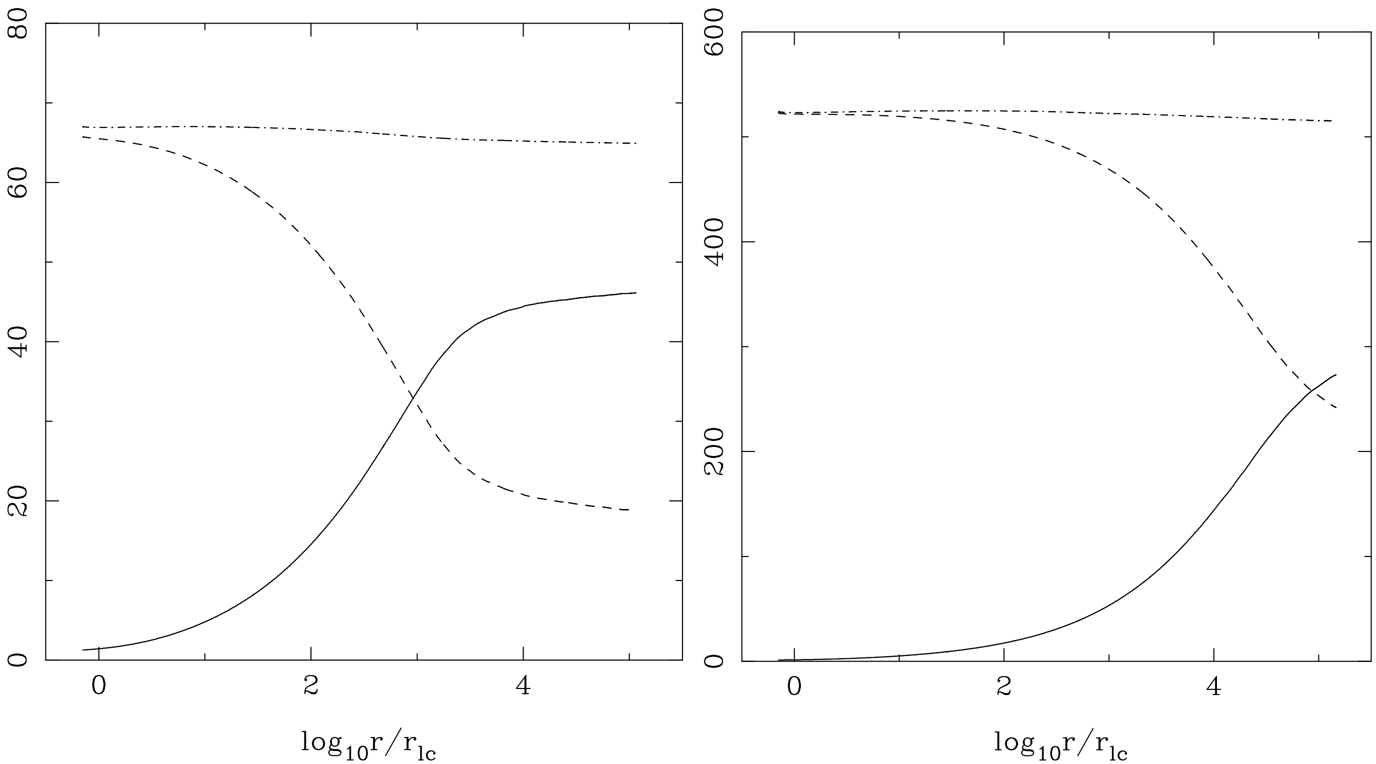
Vlahakis+2000 nonrelativistic solution



Vlahakis & Königl 2003, 2004 relativistic solutions



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



energy flux ratios:

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

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

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

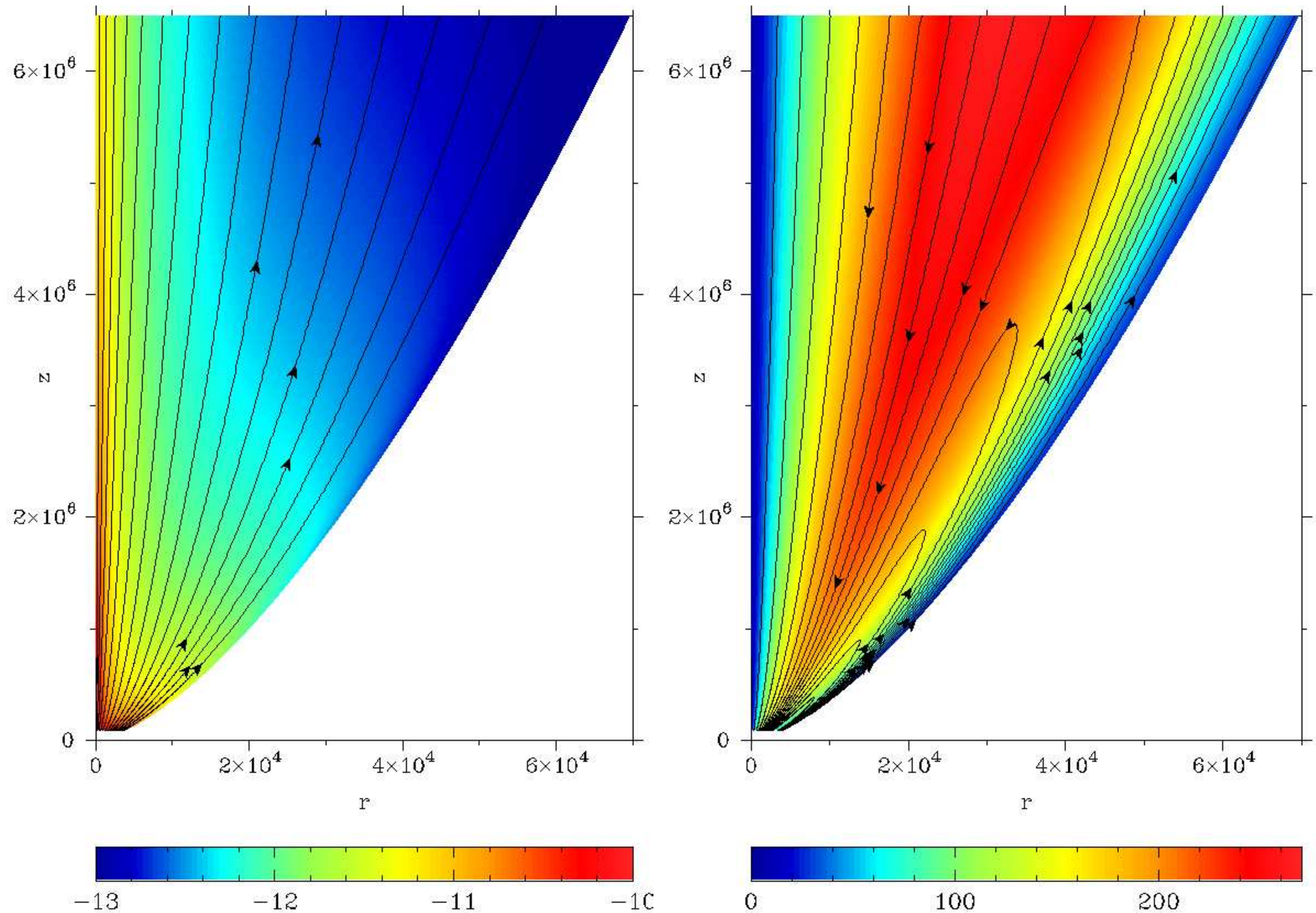
$$\mu = \gamma + \gamma\sigma$$

γ (increasing),

$\gamma\sigma$ (decreasing),

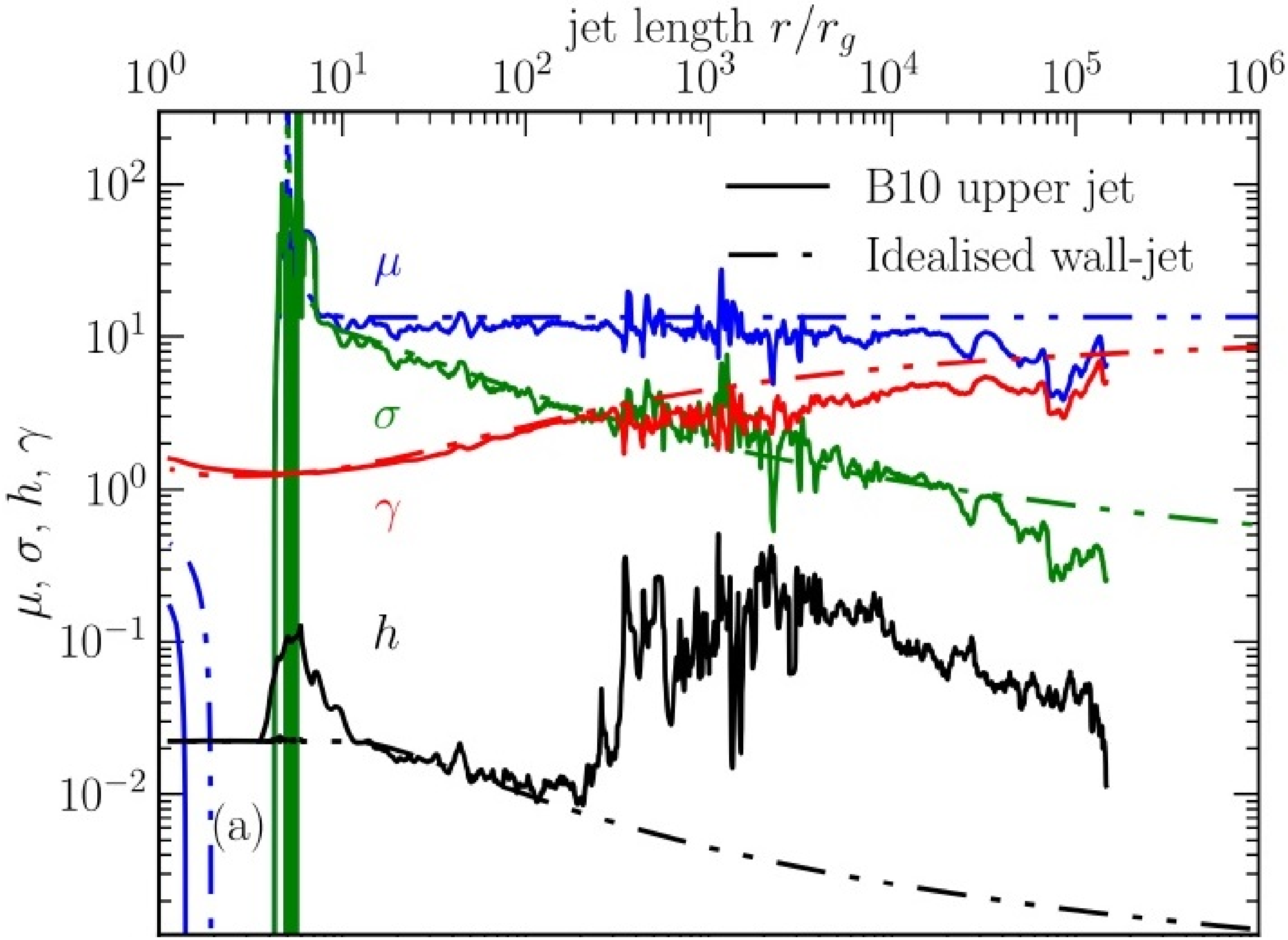
and μ (constant)

efficiency $> 50\%$



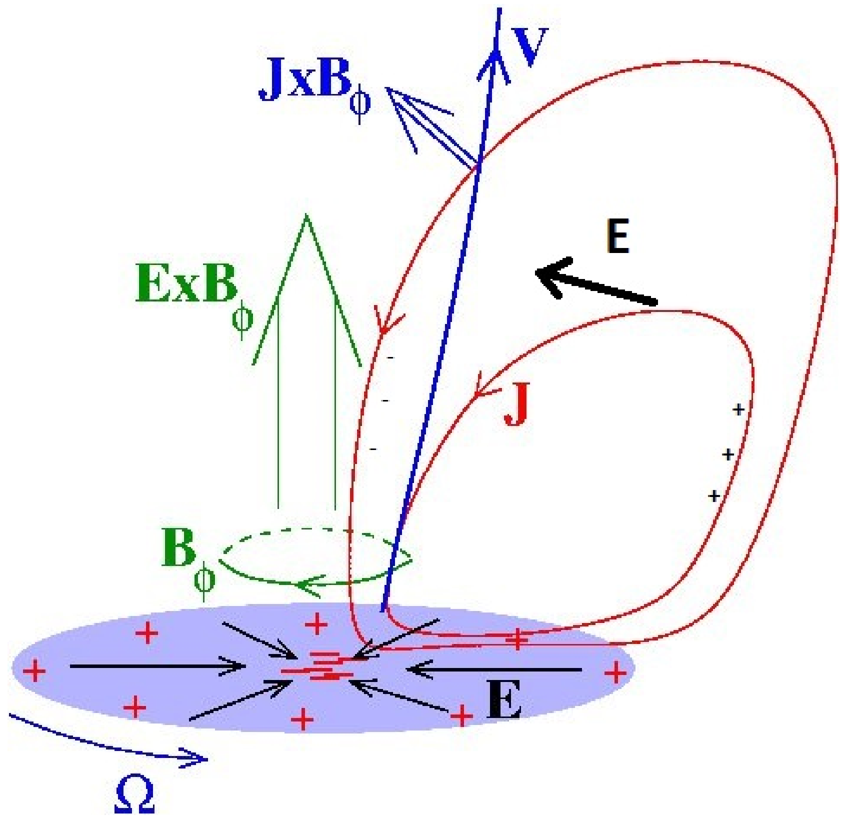
left: density/field lines, right: Lorentz factor/current lines (jet shape $z \propto r^{1.5}$)

Even in general relativistic MHD jet simulations (Chatterjee+2019 - review Mizuno 2022)



Basic questions: collimation

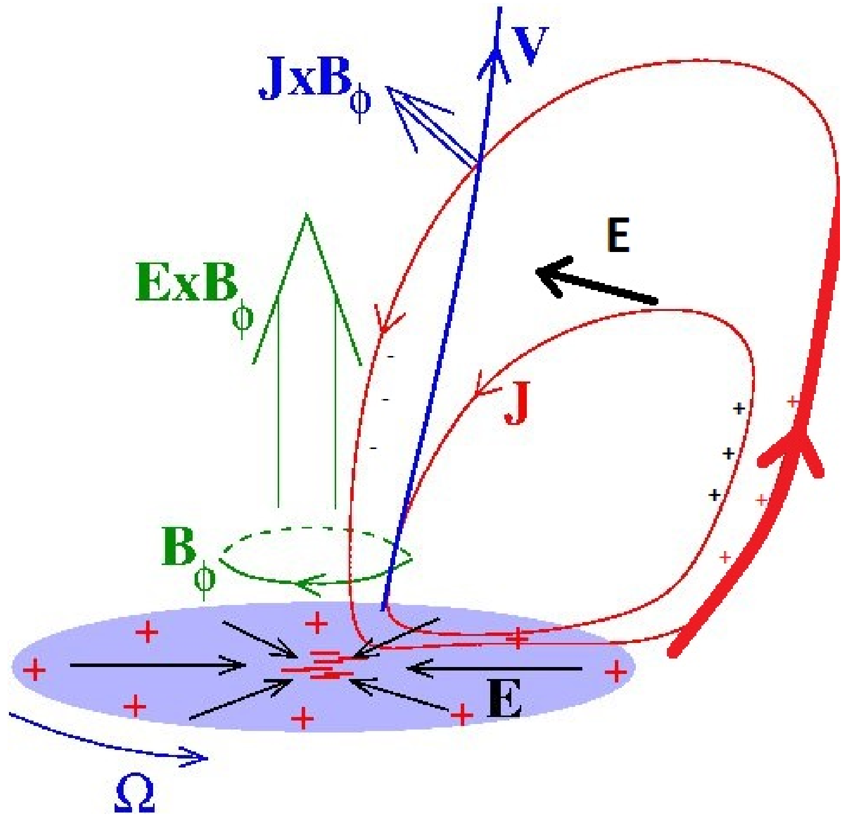
hoop-stress:



+ electric force (acts in the opposite way in the core of the jet)

degree of collimation ?   Role of environment?

Spatial scale of γ



pressure equilibrium at the boundary $\dfrac{B^2 - E^2}{8\pi} = P_{\rm ext}$

ideal conductor $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}/c \Rightarrow E \approx V B_\phi / c$
$B \approx B_\phi \propto 1/\varpi$ (from Ampére with approximately constant I)
knowing $P_{\rm ext}(z)$ we find $\gamma = \sqrt{B^2/8\pi P_{\rm ext}}$

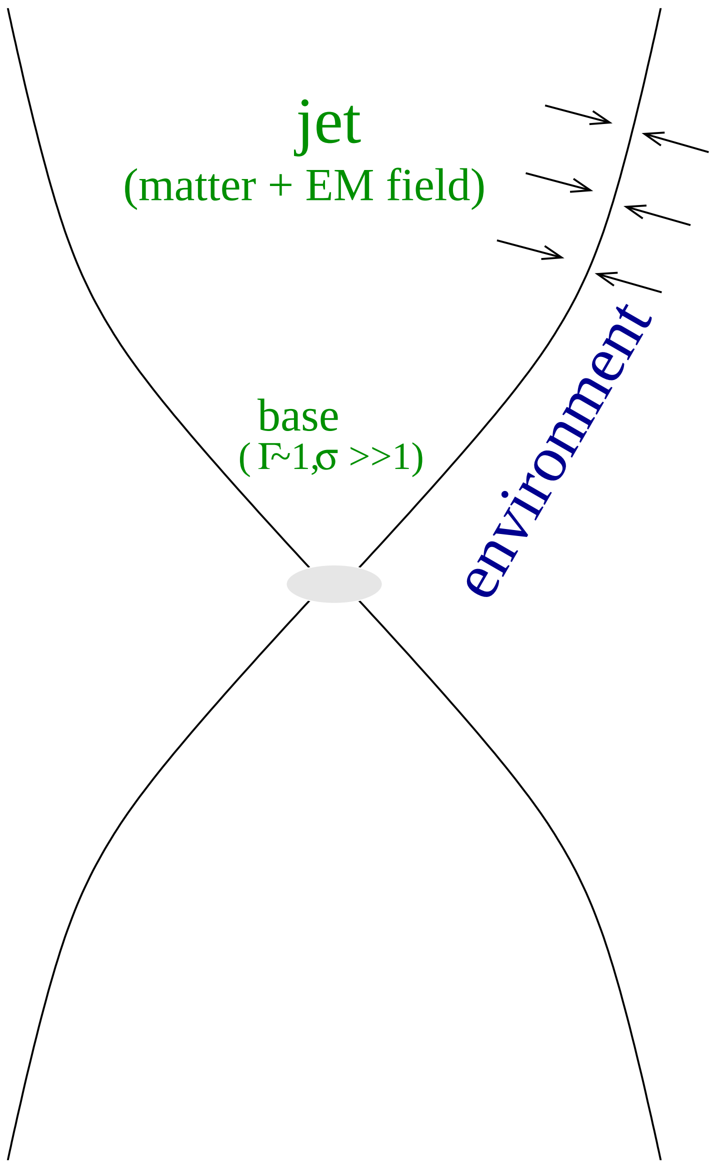
☞ transfield component of the momentum equation for relativistic jets simplifies to $\mathcal{R} \approx \gamma^2 \varpi$

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
combining $\mathcal{R} \approx \gamma^2 \varpi$ with $\gamma = \sqrt{B^2/8\pi P_{\rm ext}}$:

- 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 $1 < a \le 2$
  - ⋆ 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)

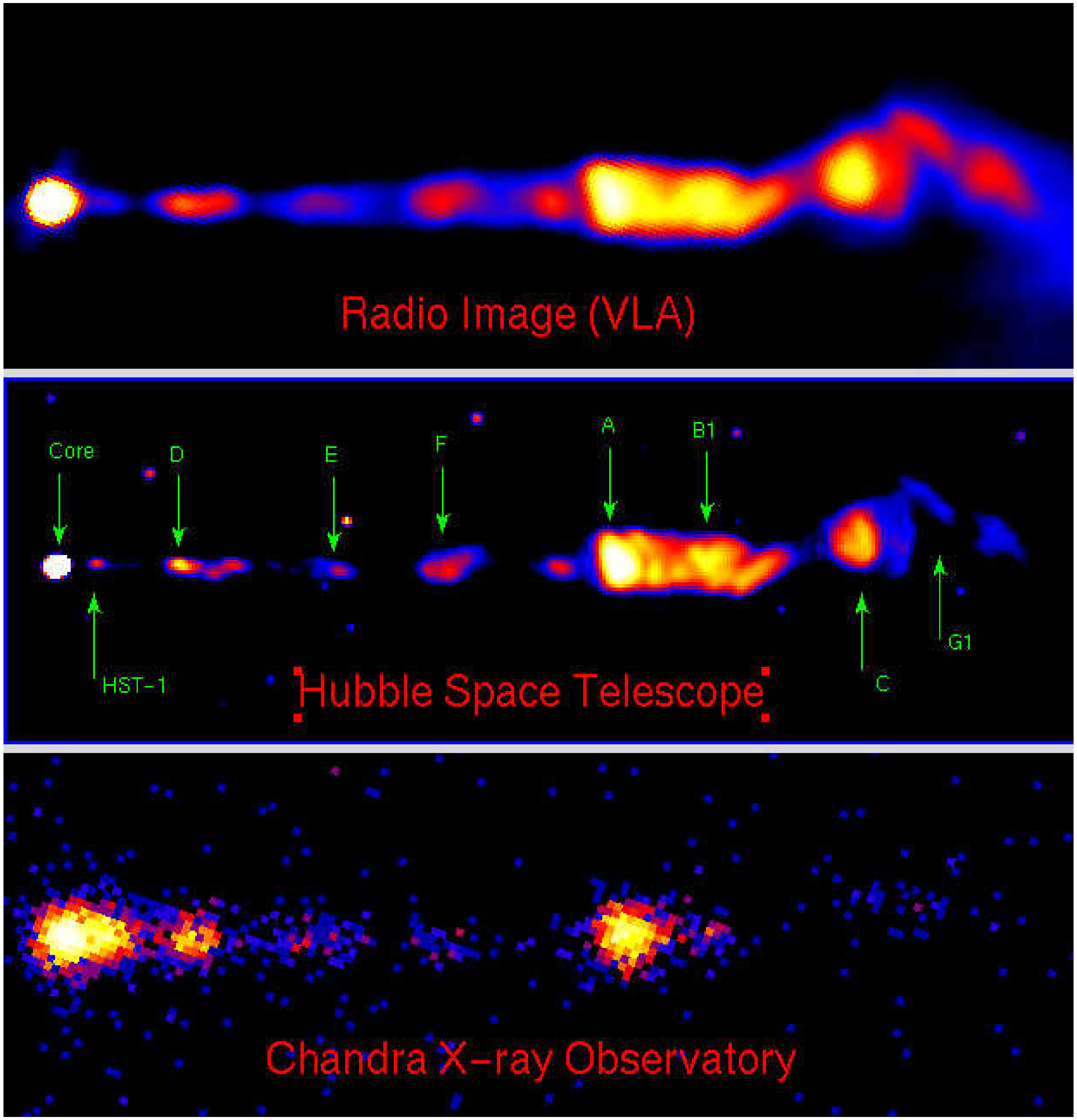
Basic questions

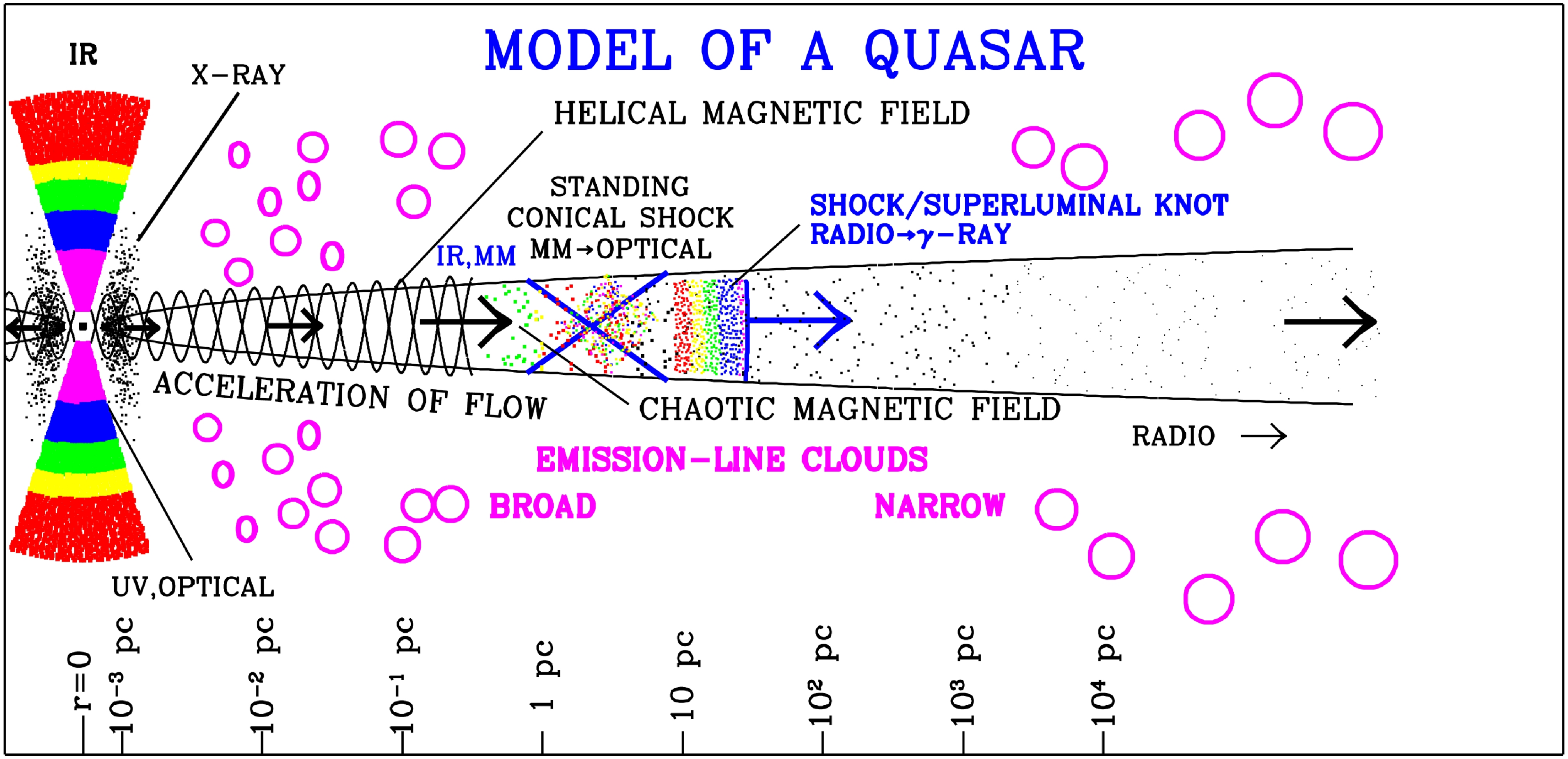


- source of matter/energy?
  disk or central object,
  rotation+magnetic field
- bulk acceleration ✓
- collimation ✓
- role of environment? ✓

2nd level of understanding

- ☞ distribution of B in the source? (advection vs diffusion, disk instabilities?)
- ☞ details of jet physics near rotating black holes (pair creation in stagnation surface or by $\gamma\gamma$ collisions) – energy extraction from the black hole?
- ☞ environment: pressure distribution? disk wind? detailed study of the interaction with environment (Riemann problem – shock and rarefaction waves)


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



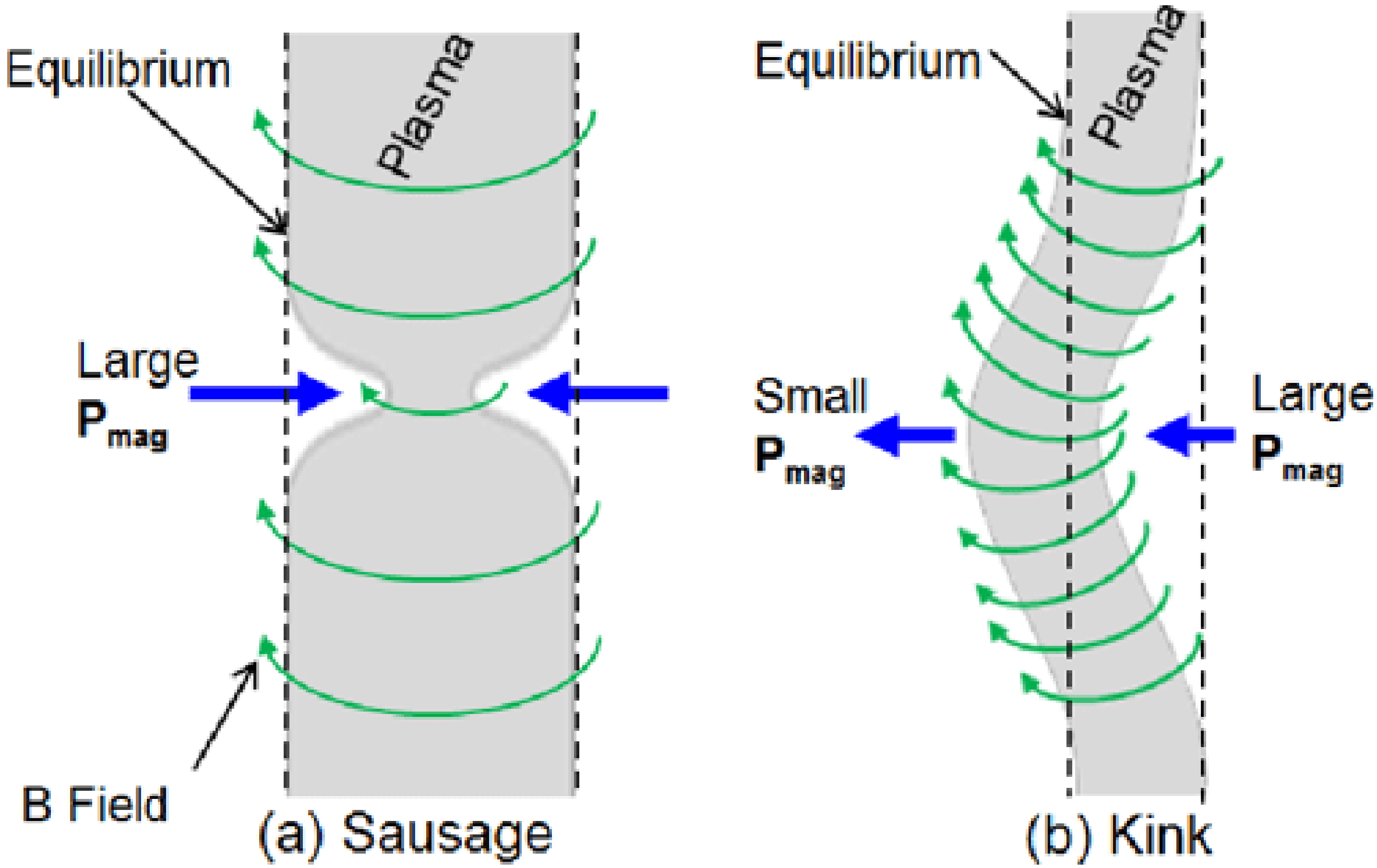
credit: Boston University Blazar Group

- ☞ jet stability (Kelvin-Helmholtz? current driven? centrifugal?)
- ☞ nonthermal radiation – particle acceleration

  shocks or reconnection ? connection with instabilities ?
- ☞ polarization maps and comparison with observations
- ☞ role of resistivity?
- ☞ kinetic description ?

  (combination with magnetohydrodynamics)

Current-driven instabilities



(sketch from Yager-Elorriaga 2017)

Role of B_z? of inertia?

- At large distances distances the field is mainly toroidal (since $B_p \propto 1/\varpi^2$, $B_\phi \propto 1/\varpi$)

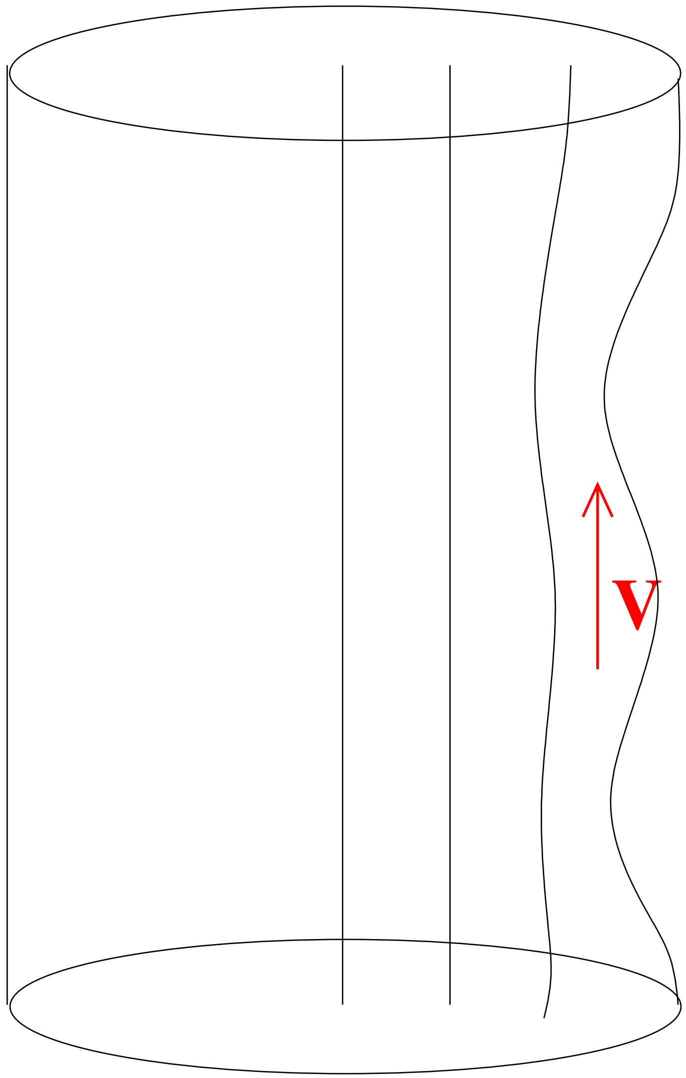
- From Ferraro's law $-B_\phi/B_p \approx \varpi\Omega/V_p \approx \varpi/\varpi_{\rm LC}$.

For a rotating BH-jet

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

For a disk-jet $\dfrac{|B_\phi|}{B_z} \approx 20 \left(\dfrac{\varpi_j}{10^{16}{\rm cm}}\right) \left(\dfrac{\varpi_0}{10GM/c^2}\right)^{-3/2} \left(\dfrac{M}{10^8 M_\odot}\right)^{-1}$

Kinetic instabilities



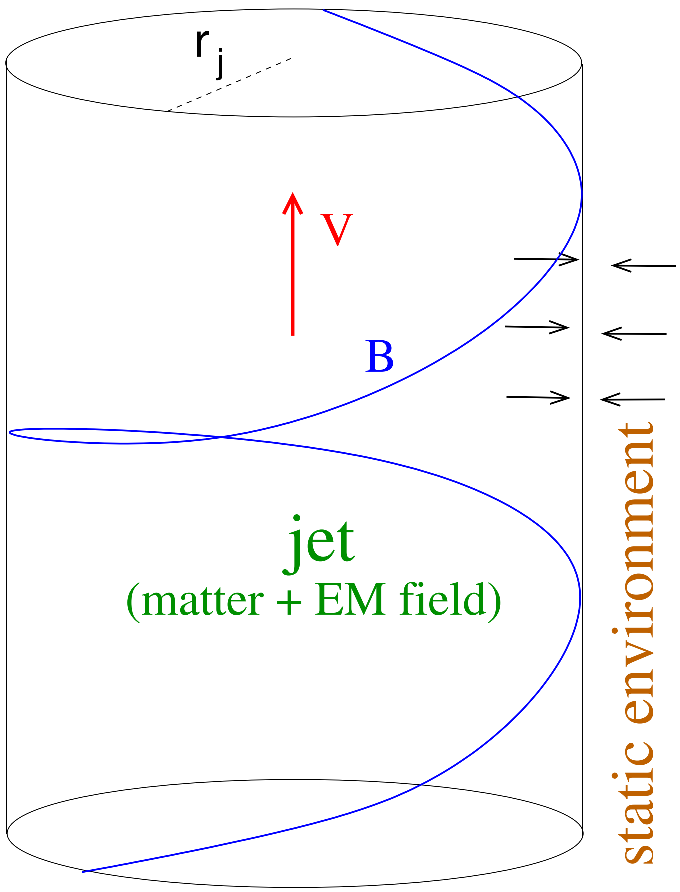
Relative motion drives
Kelvin-Helmholtz instability

For astrophysical jets we need to combine

- magnetic field
- compressibility
- relativity (in bulk speed, sound speed, Alfvén speed)
- cylindrical geometry

Linear stability analysis

Charis Sinnis' PhD work



Unperturbed state:

- Cylindrical jet, cold, with constant speed $V_0\hat{z}$, constant density ρ_0, and helical magnetic field

$$B_{0z} = \frac{B_0}{1+(\varpi/\varpi_0)^2}\,, \quad B_{0\phi} = B_{0z}\gamma\frac{\varpi}{\varpi_0}$$

(satisfying the force balance equation).
B_0 controls the magnetization
$\sigma = \dfrac{B_{\rm co}^2}{4\pi\rho_0 c^2}$, ϖ_0 controls the $\dfrac{B_\phi}{B_z}$

- Environment: uniform, static, with density $\eta\rho_{0\,jet}$, either hydrodynamic or cold with uniform B_{0z}

- Add perturbations in all quantities

$Q(\varpi\,, z\,, \phi\,, t) = Q_0(\varpi) + Q_1(\varpi)e^{i(kz+m\phi-\omega t)}$

with integer m, real k, and complex ω (temporal approach),

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

(instability corresponds to $\Im\omega > 0$)

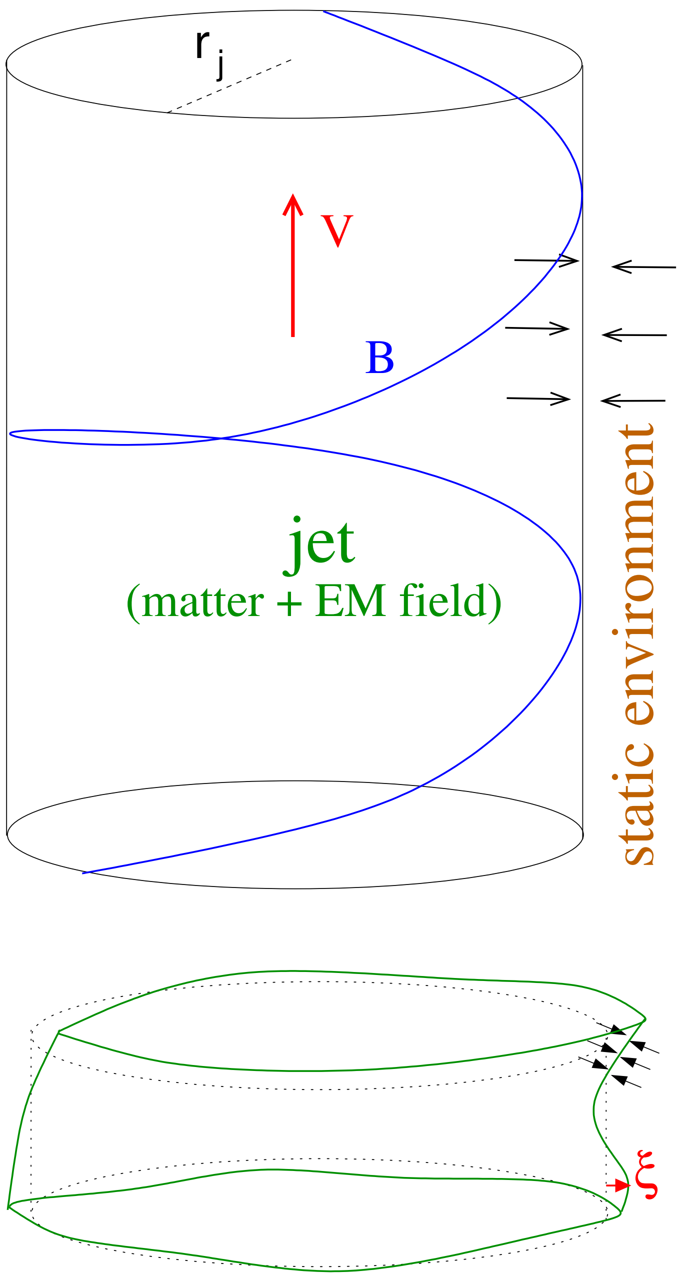
Linearization of the ideal relativistic magnetohydrodynamic equations reduces to two equations with (complex) unknowns:

- the Lagrangian displacement of each fluid element in the radial direction y_1

- the perturbation of the total pressure at the displaced position y_2

These should be continuous everywhere (at the interface as well)

Eigenvalue problem



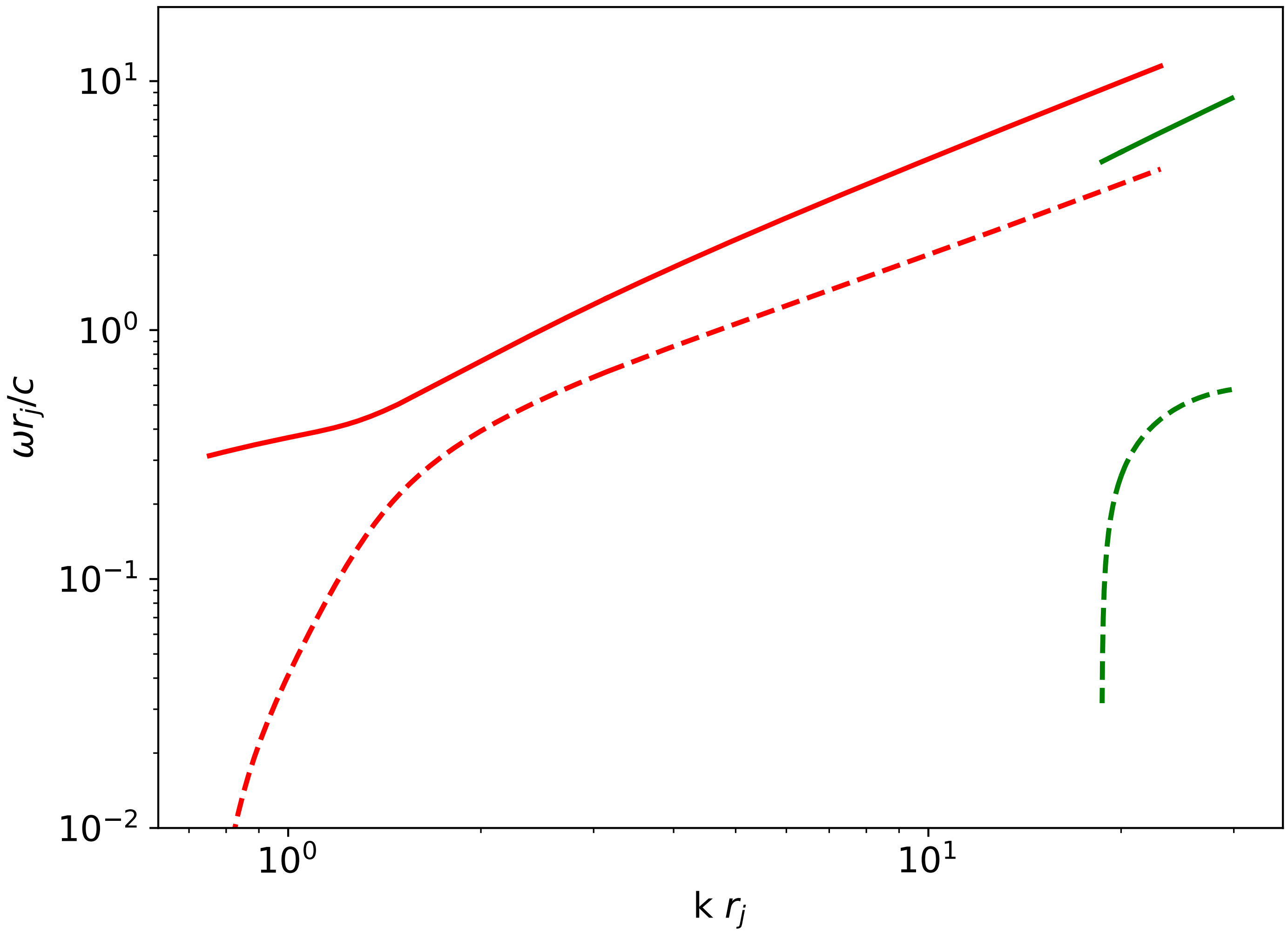
- integrate the equations inside the jet (attention to regularity condition on the axis)

- integrate the equations in the environment (solution vanishes at $\varpi \gg \varpi_j$)

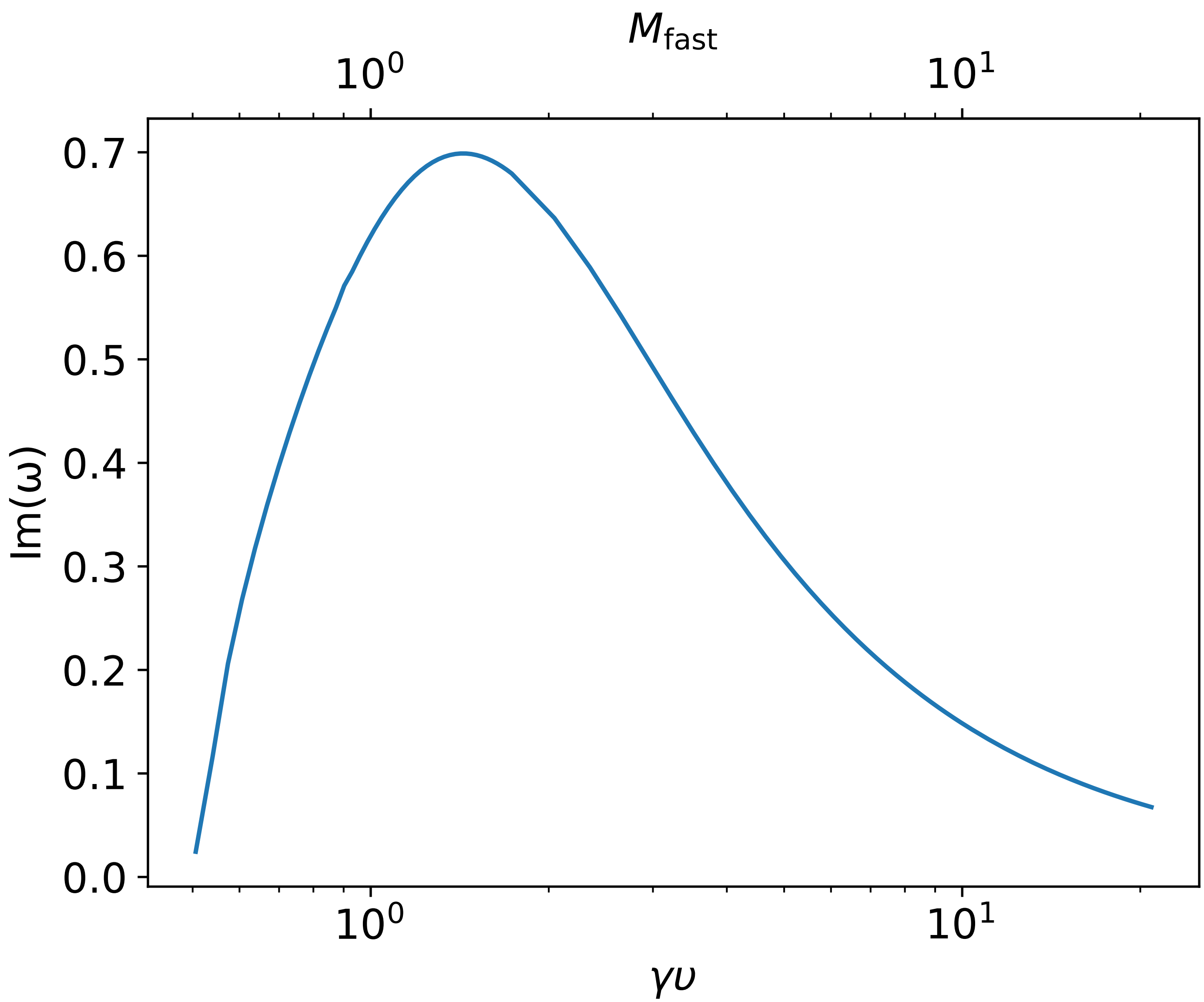
- Match the solutions at ϖ_j:
find ω for which y_1 and y_2 are continuous $\longrightarrow$ dispersion relation

- The solution depends on γ, σ, ϖ_0, η, and the wavenumbers k, m

Result for the dispersion relation (Re=solid, Im=dashed), for $\gamma = 2$, $\sigma = 1$ (at ϖ_j), $\varpi_0 = 0.1$, $\eta = 10$, and $m = 0$.
K-H is the most unstable mode.

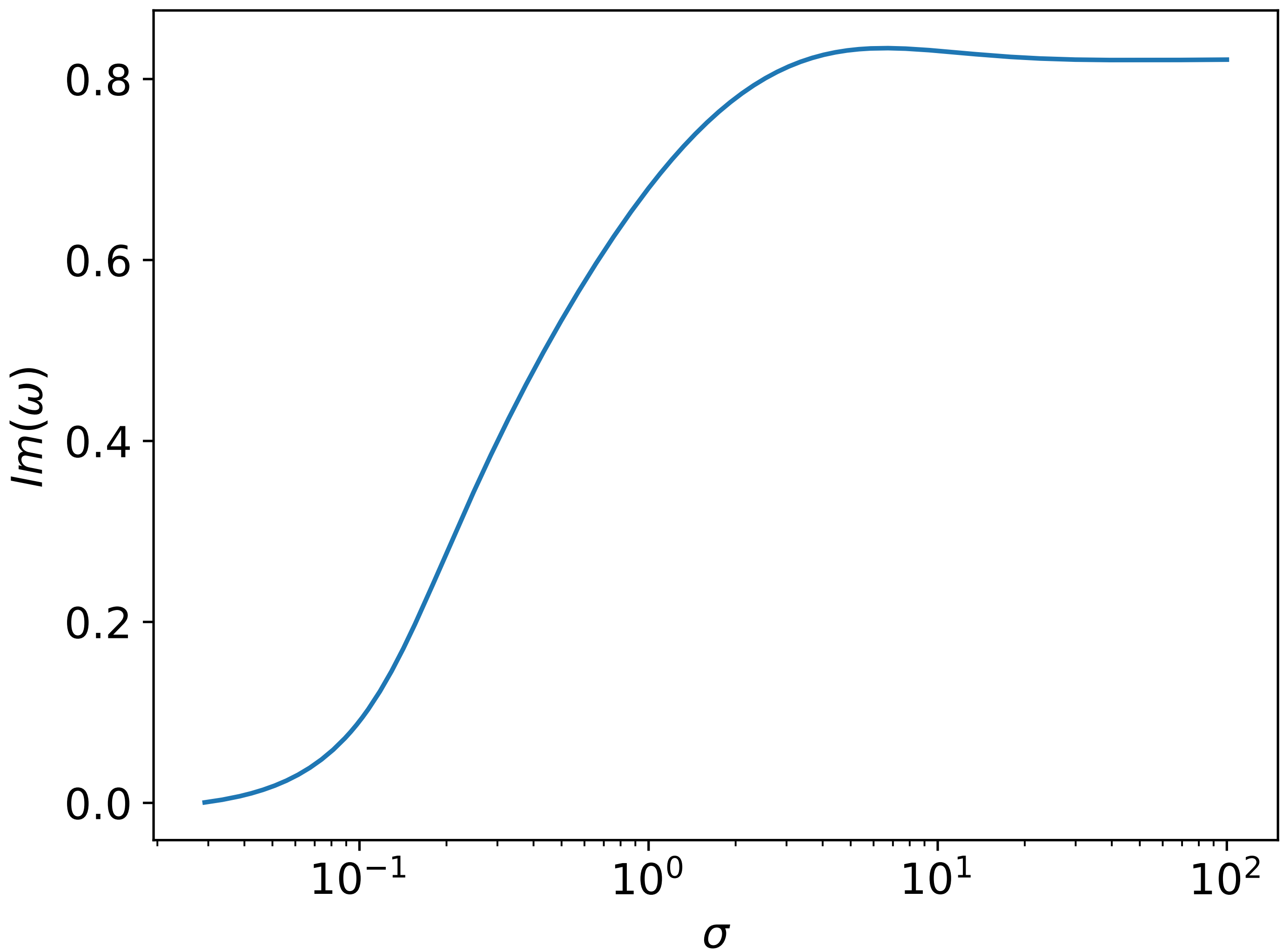


We explore in the following a fiducial case with $k = \pi$

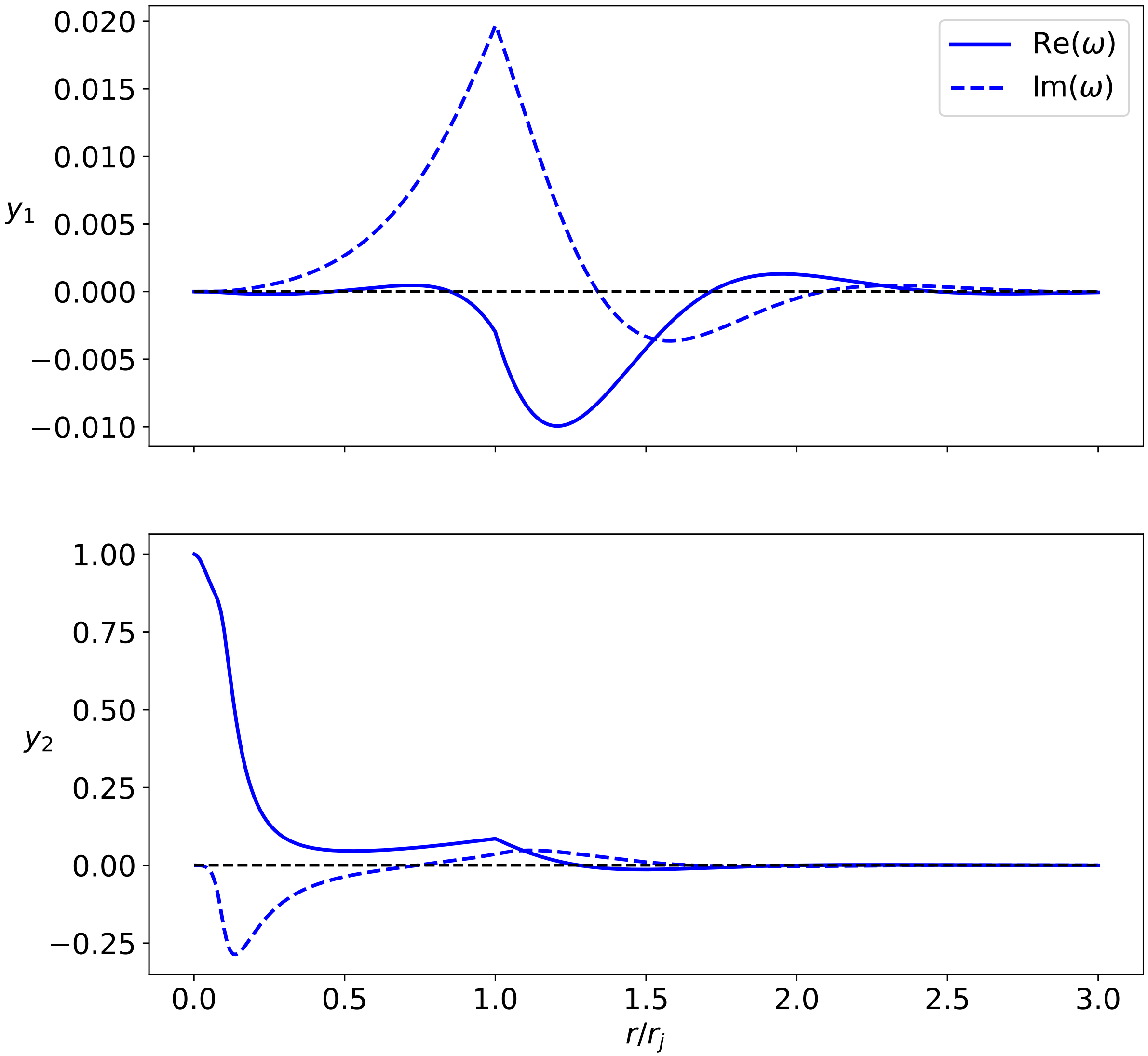


For small speeds $\Im\omega \propto V$ while sufficiently large M_{fast} stabilizes

Dependence on the jet magnetization (at ϖ_j)



Locality of the eigenfunction y_1 (Lagrangian displacement)

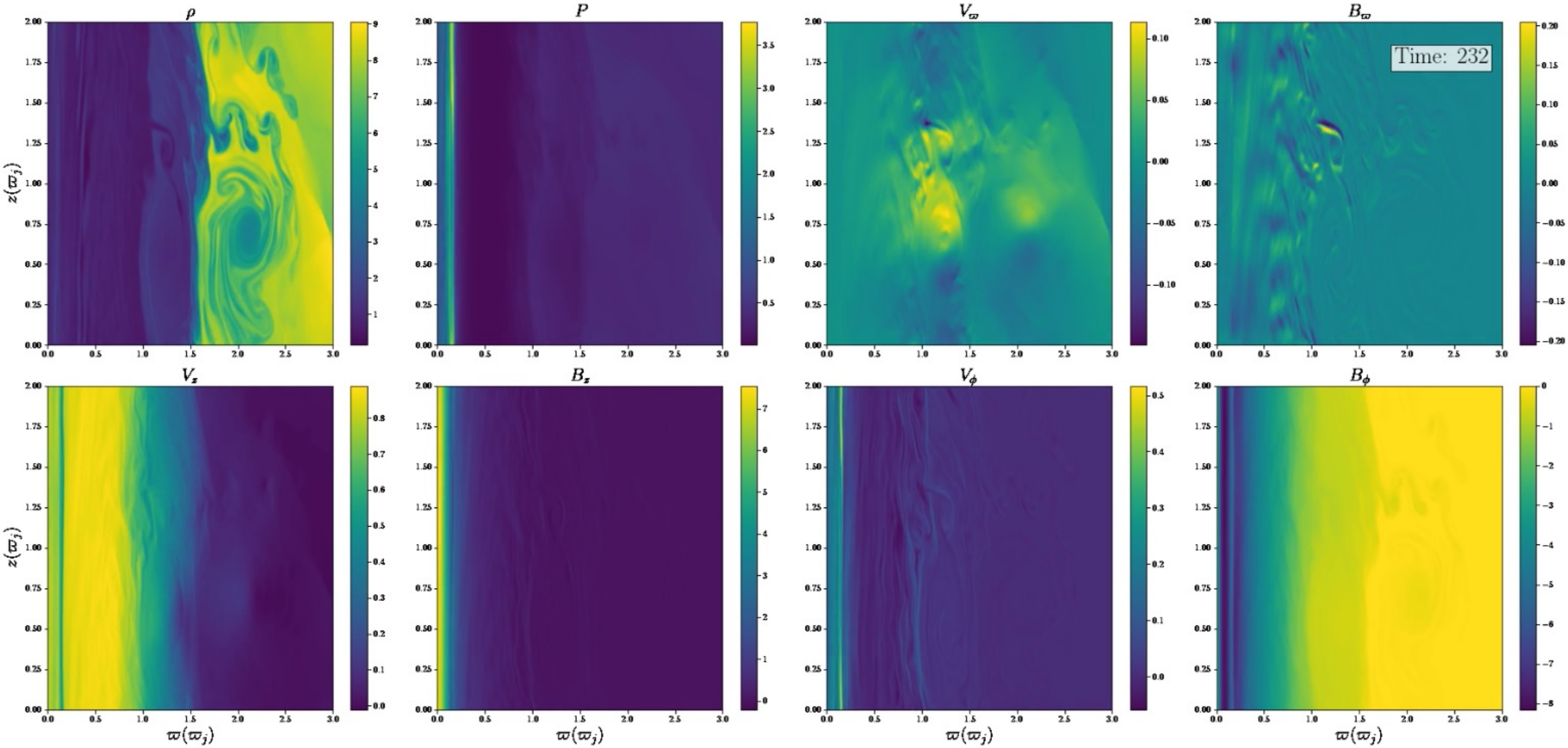


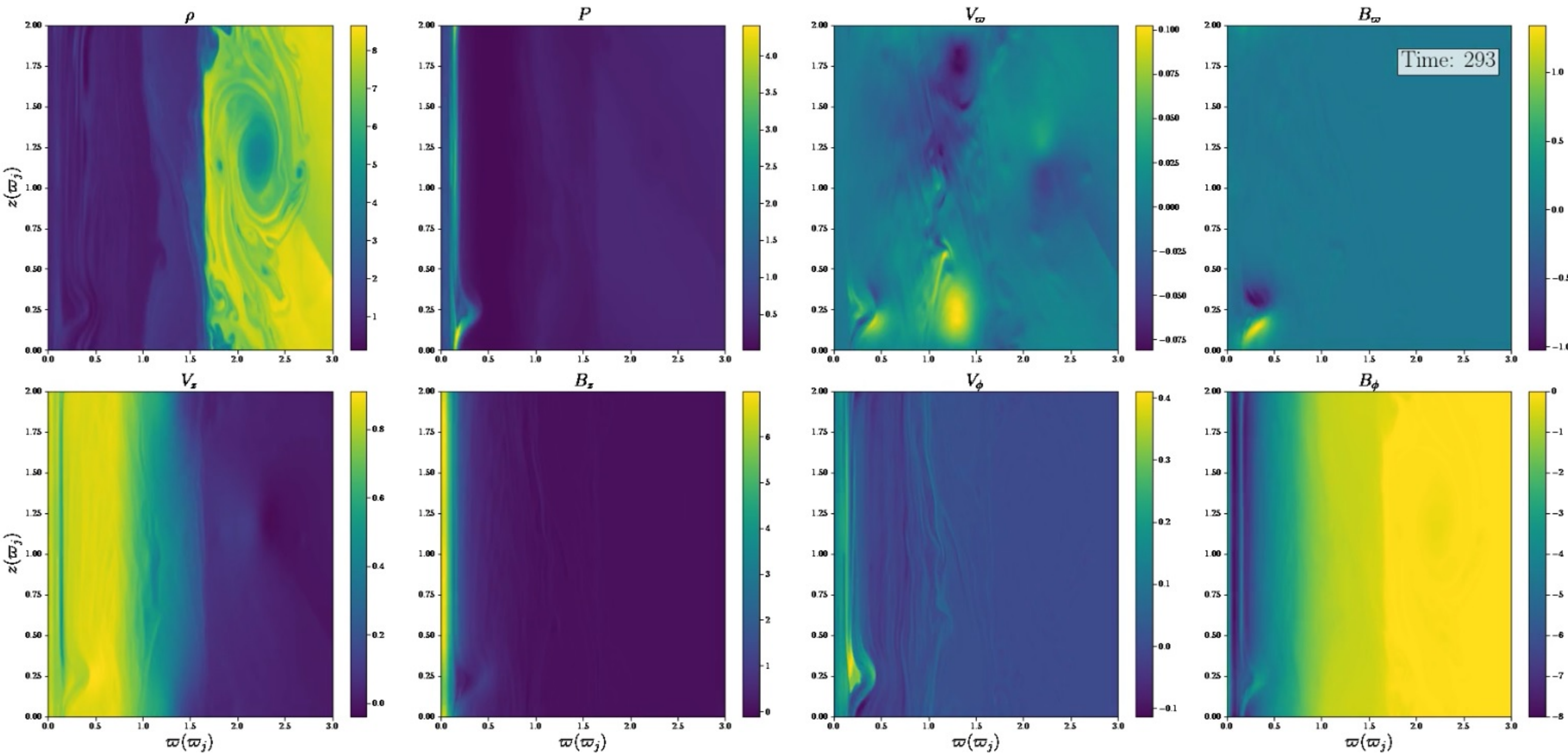
Nonlinear evolution

Thodoris Nousias' master thesis

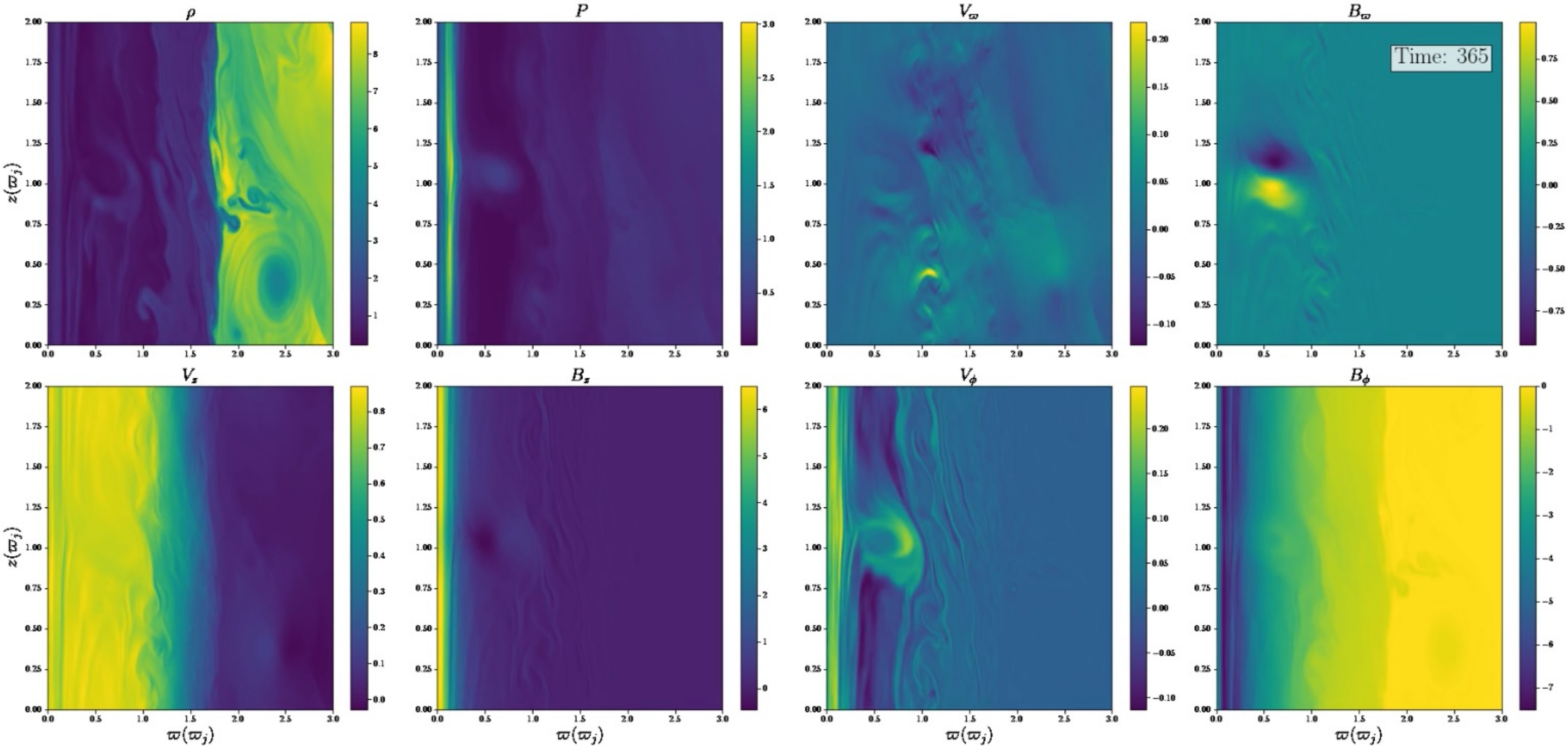
Simulation using the PLUTO code, with initial condition eigenfunction of the linear analysis (fiducial case).

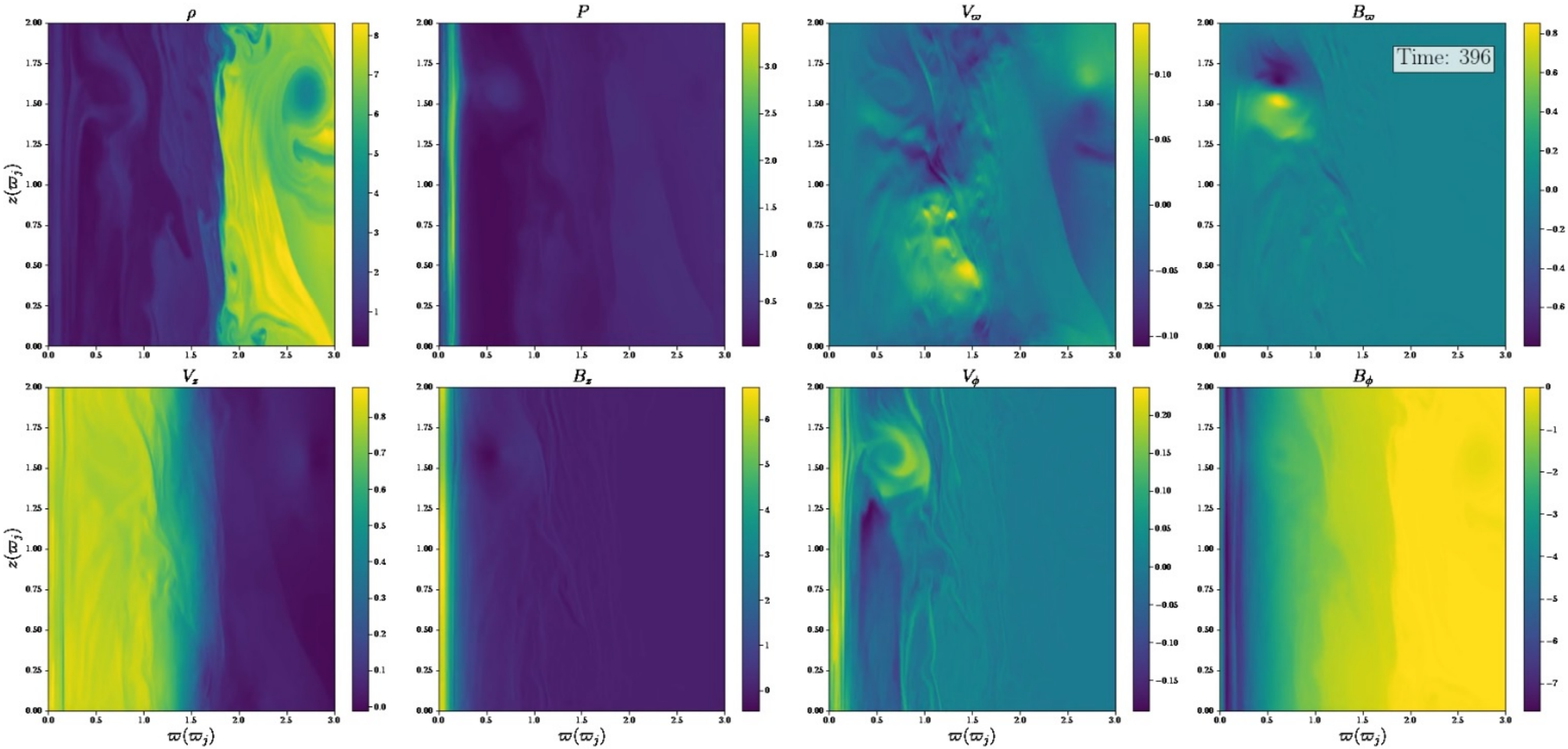
$\langle$ movie $\rangle$


ρ
P
V_ϖ
B_ϖ
Time: 232
V_z
B_z
V_ϕ
B_ϕ
$z(\varpi_j)$
$\varpi(\varpi_j)$



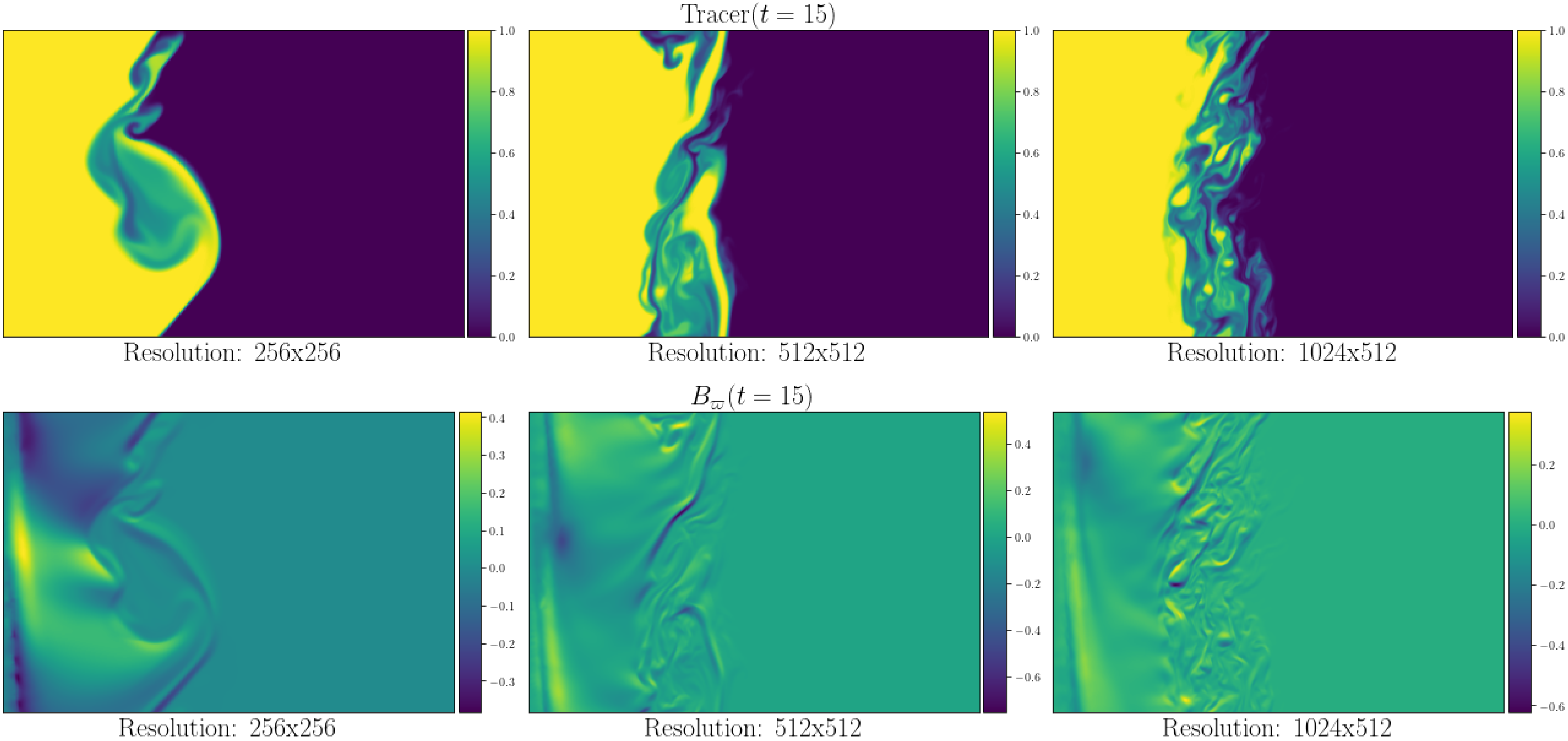
ρ
P
V_ϖ
B_ϖ
Time: 293
V_z
B_z
V_ϕ
B_ϕ
$z(\varpi_j)$
$\varpi(\varpi_j)$


ρ
P
V_ϖ
B_ϖ
Time: 365
V_z
B_z
V_ϕ
B_ϕ
$z(\varpi_j)$
$\varpi(\varpi_j)$

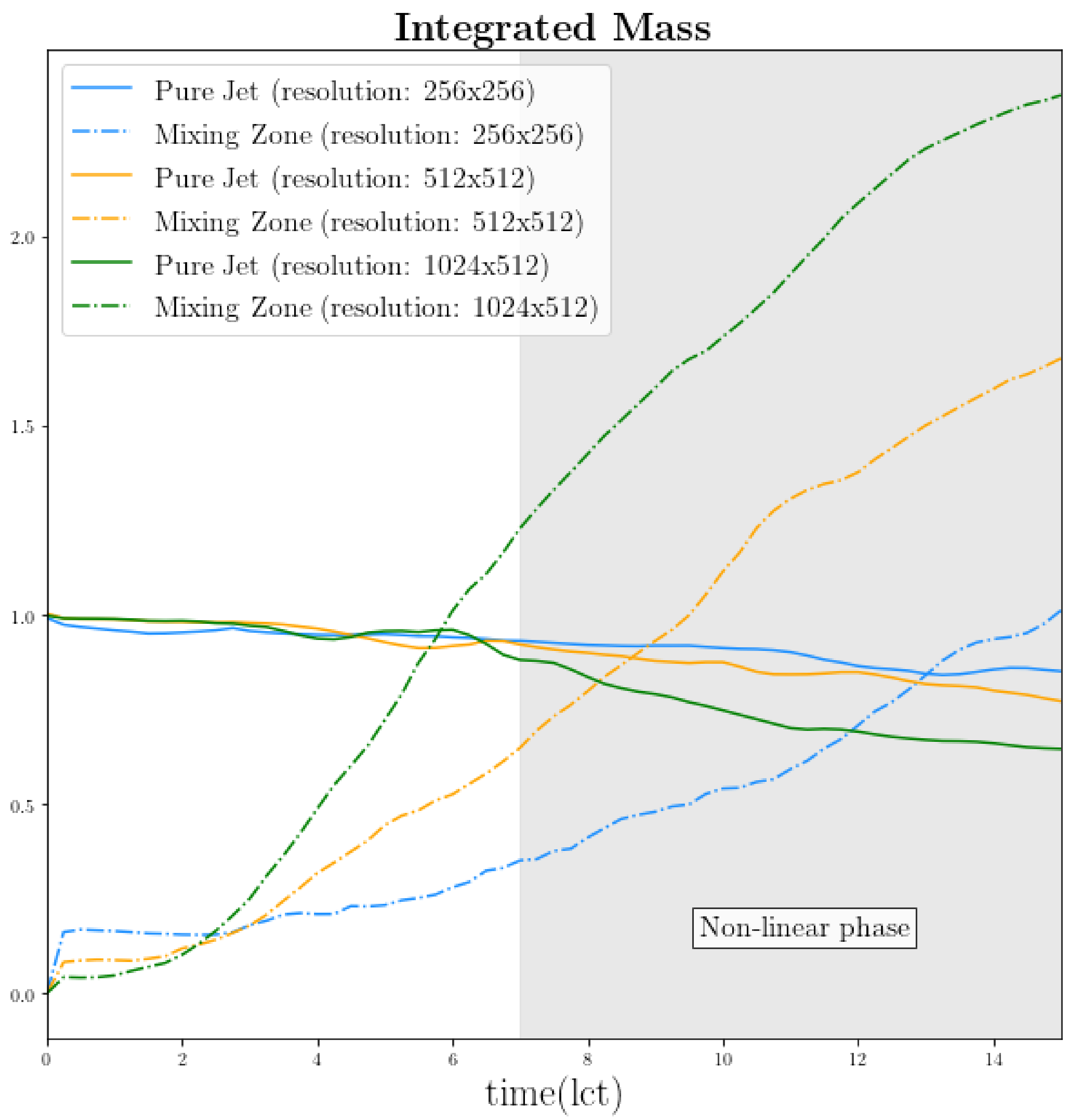


ρ
P
V_ϖ
B_ϖ
Time: 396
V_z
B_z
V_ϕ
B_ϕ
$z(\varpi_j)$
$\varpi(\varpi_j)$

Resolution effects



- for kinetic instabilities growth time increases with k
- cannot be fully resolved
- numerical errors mimic physical diffusion effects

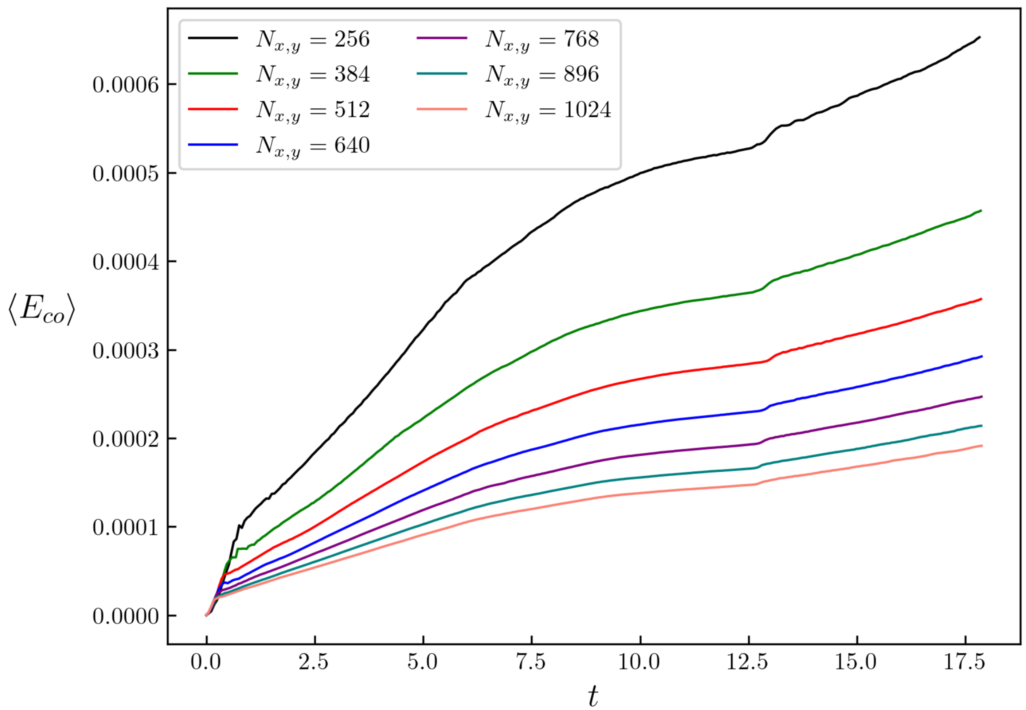

Integrated Mass
Pure Jet (resolution: 256x256)
Mixing Zone (resolution: 256x256)
Pure Jet (resolution: 512x512)
Mixing Zone (resolution: 512x512)
Pure Jet (resolution: 1024x512)
Mixing Zone (resolution: 1024x512)
Non-linear phase
0.0
0.5
1.0
1.5
2.0
0
2
4
6
8
10
12
14
time(lct)

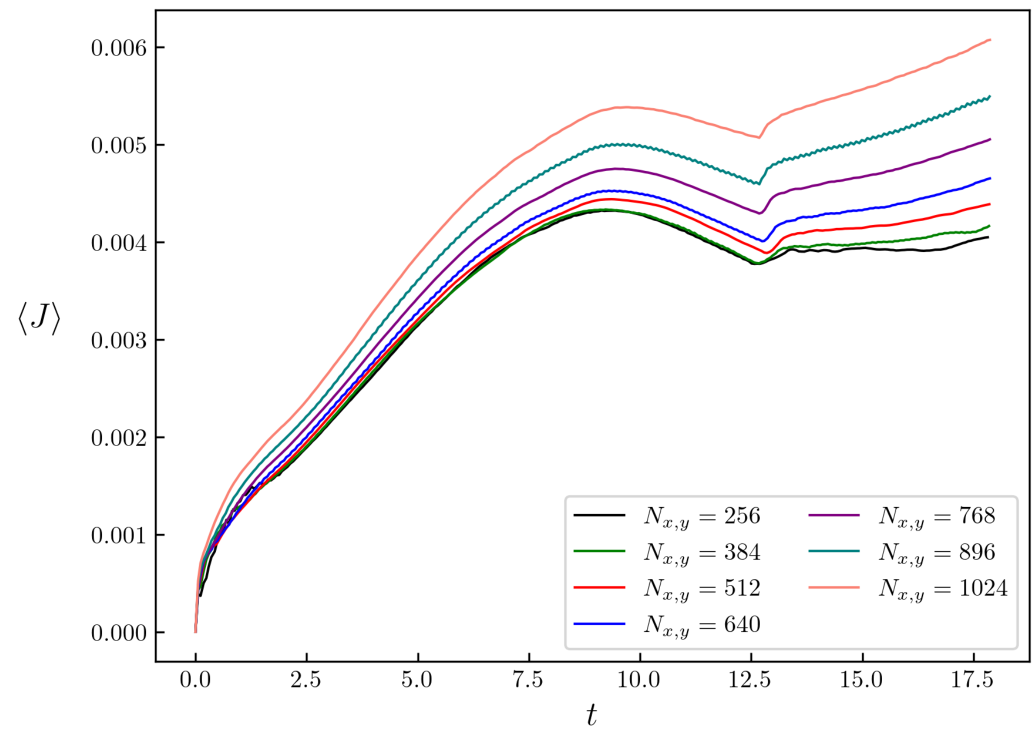
Numerical magnetic diffusivity

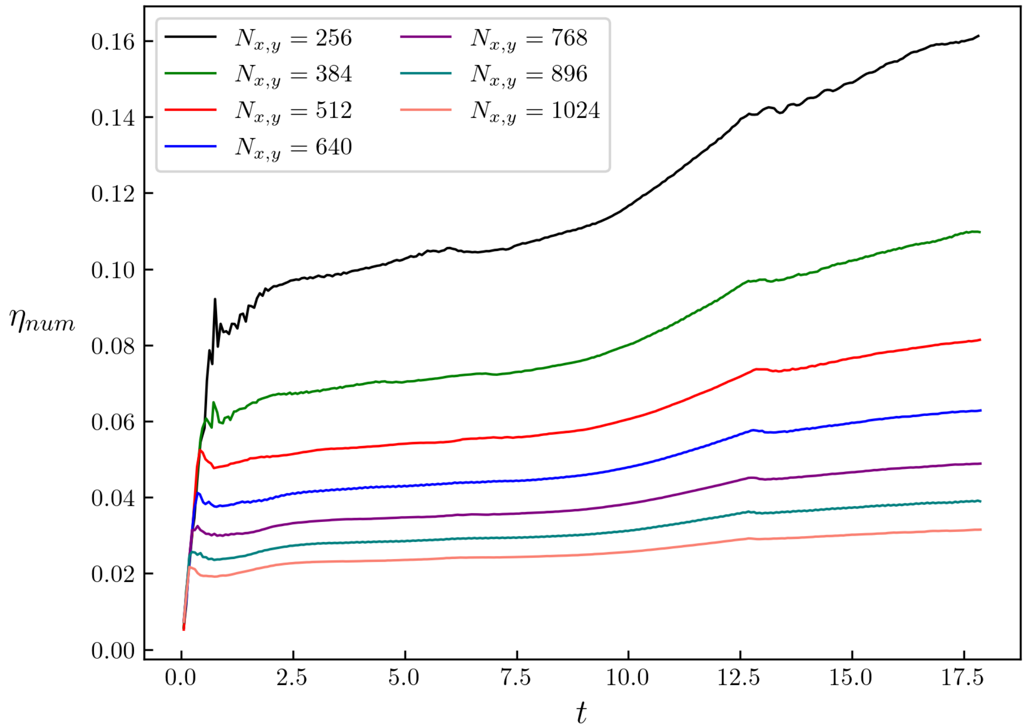
Argyris Loules' PhD thesis

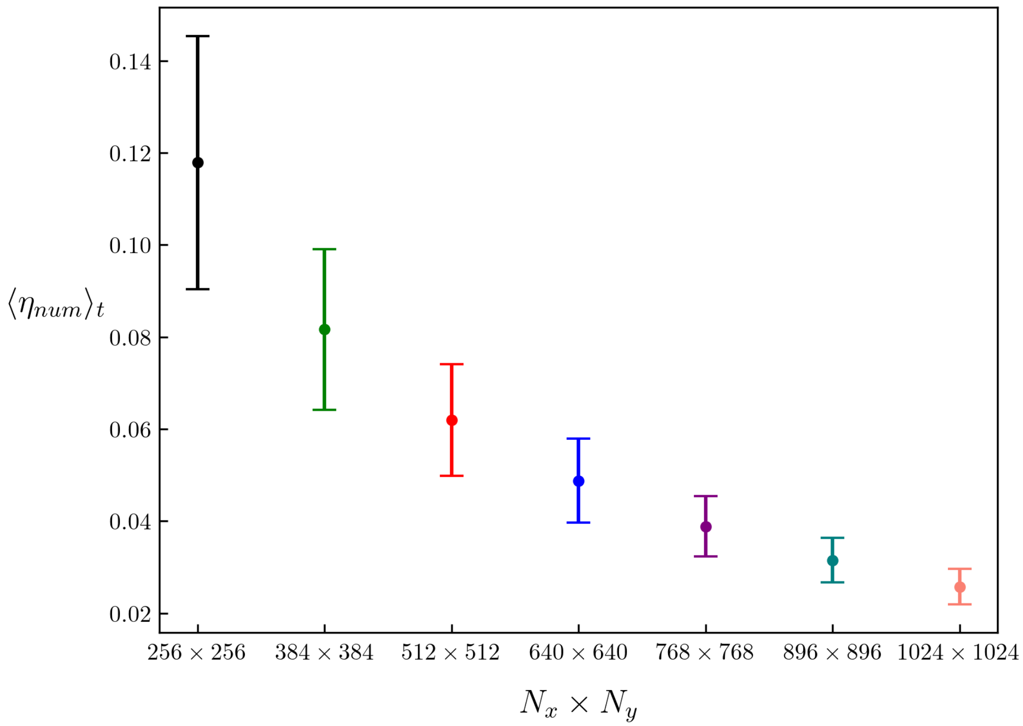
Estimation from "Ohm's law" $\langle J \rangle = \frac{c^2}{4\pi\eta}\langle E \rangle$

(using a numerical experiment of a blast wave in a homogeneous magnetic field)









The cell size defines the magnetic diffusivity ($\eta_{\mathrm{num}} \propto 1/N$).

Effects of physical resistivity cannot be seen if $\eta < \eta_{\mathrm{num}}$

Physical magnetic diffusivity
Argyris Loules' PhD thesis

Magnetic diffusivity affects magnetic field through

the diffusion equation $\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B} - \eta \nabla \times \boldsymbol{B})$

corresponding Reynolds number $\mathcal{R}_m = \frac{UL}{\eta}$

but also through the Joule heating in the energy equation

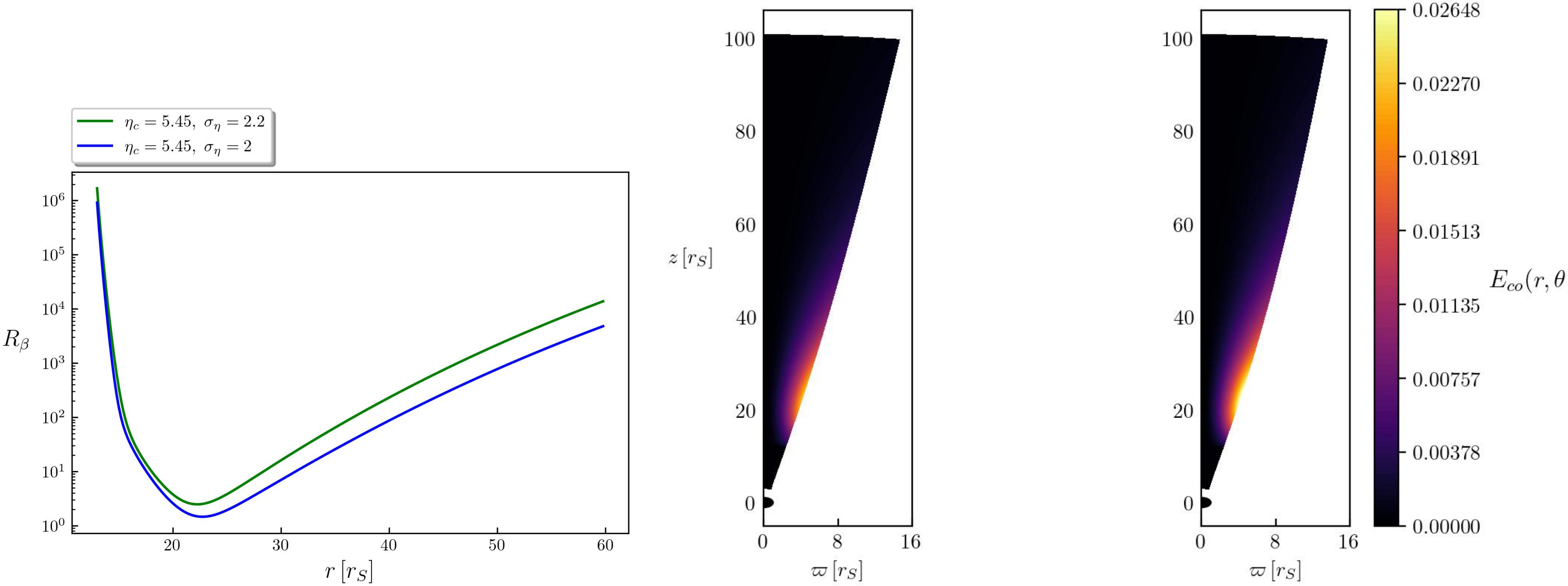
$$\frac{de}{dt} + P\frac{d(1/\rho)}{dt} = \frac{\eta}{4\pi\rho}(\nabla \times \boldsymbol{B})^2$$

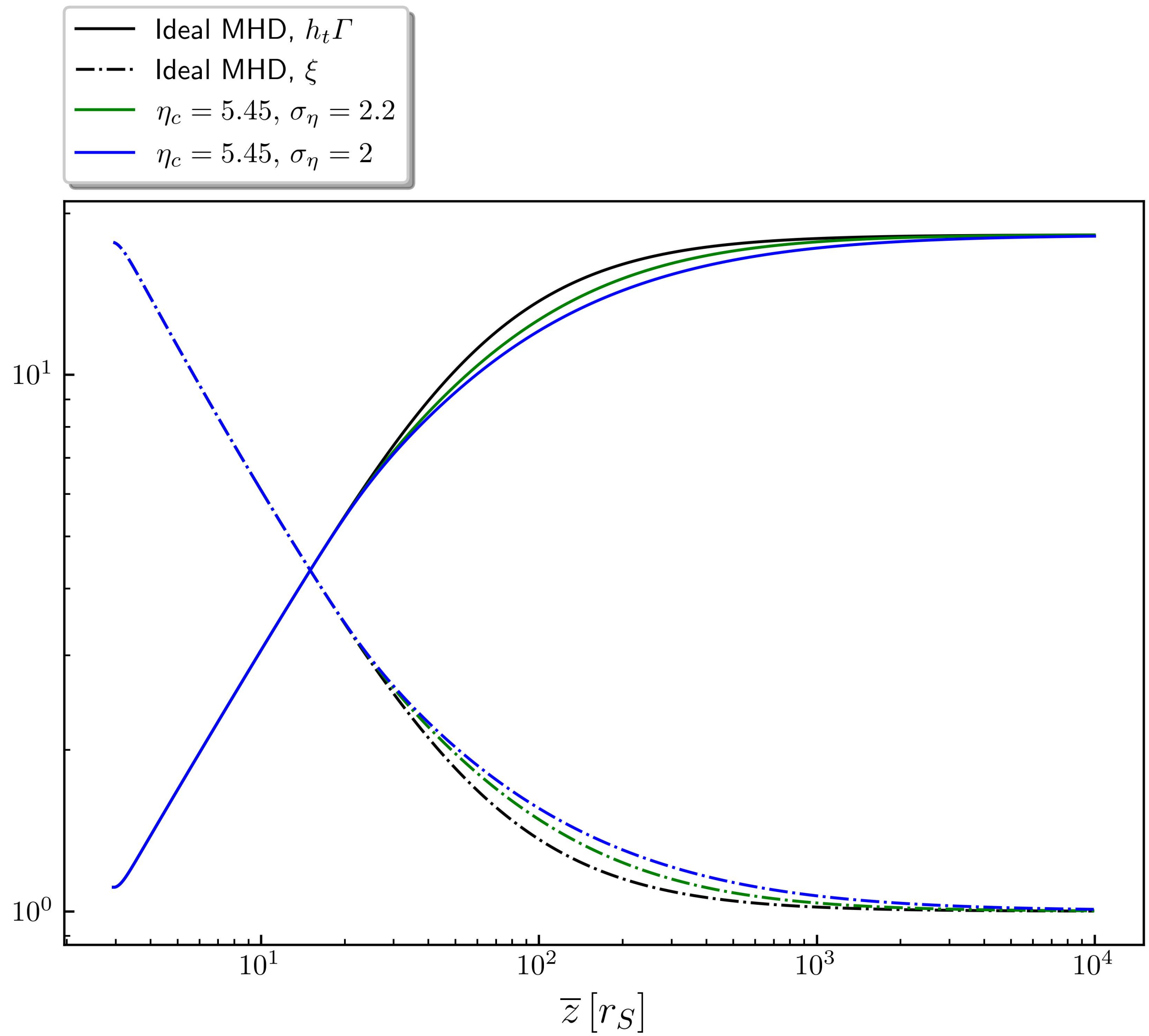
corresponding Reynolds number $\mathcal{R}_\beta = \frac{\beta}{2}\mathcal{R}_m$ (Čemeljić+2008)

Similarly in RMHD.

Analytical results

(based on expansion wrt polar angle θ near the symmetry axis of the jet)





the Joule heating temporarily compensates adiabatic cooling

Density floor in GRMHD simulations

Vasilis Mpisketzis' PhD thesis

Another case where a numerical problem is used to mimic a physical mechanism

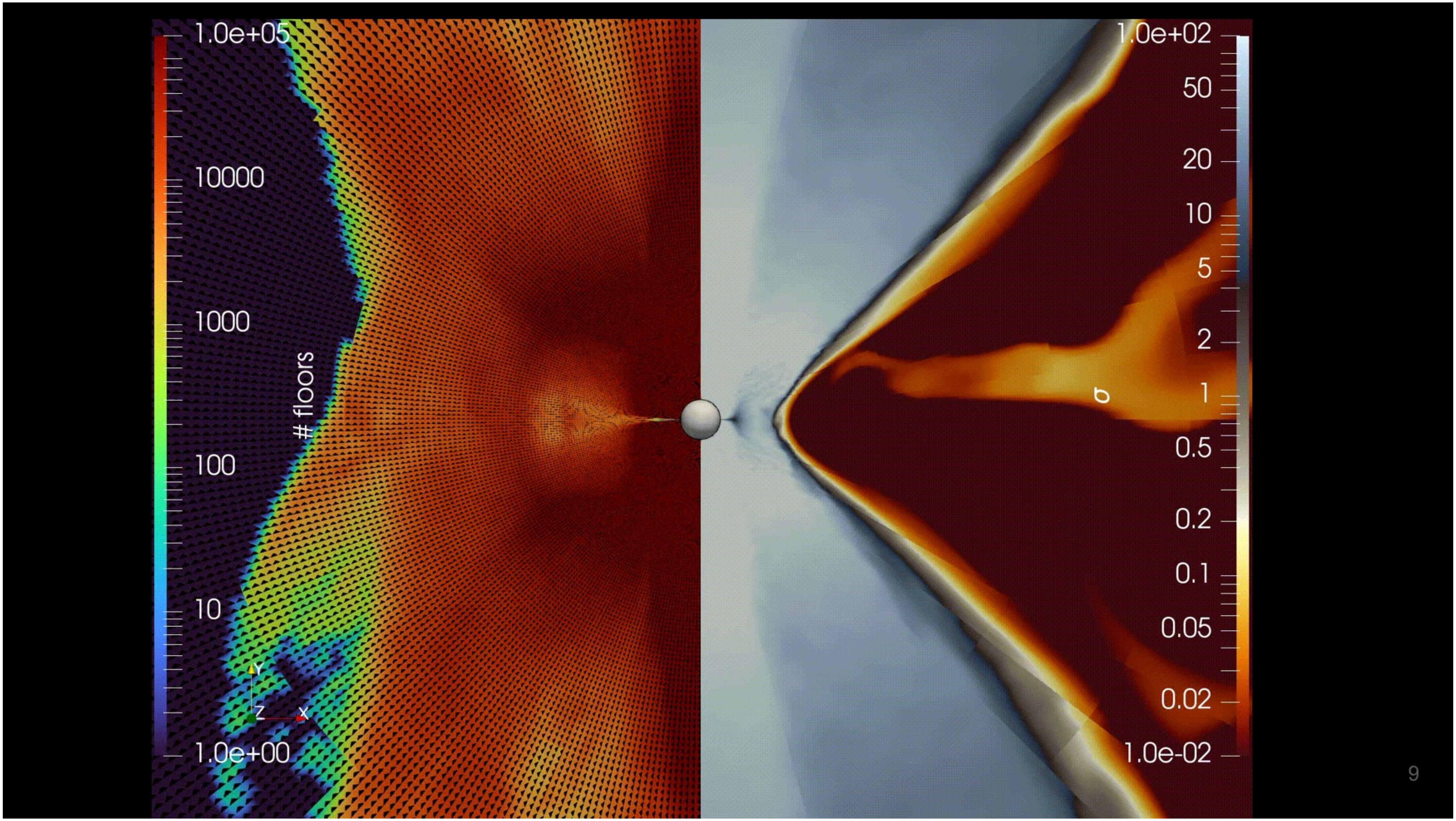
simulations cannot handle high σ, above some $\sigma_{\rm max}$

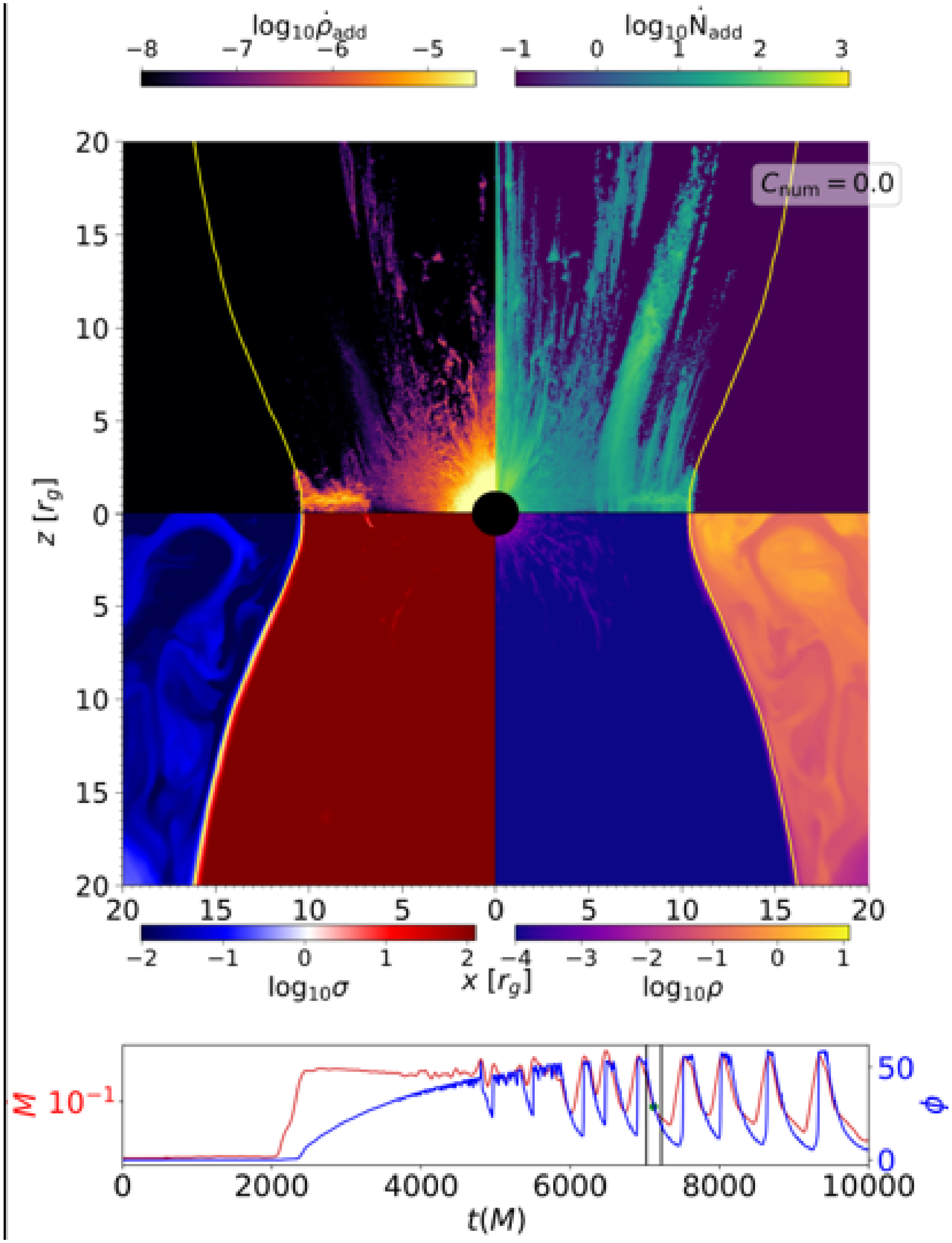
from the definition of σ, $\rho_{\rm min} = \dfrac{B_{\rm co}^2}{4\pi\sigma_{\rm max}}$

If $\rho < \rho_{\rm min}$ at some point in the simulation box, the density is replaced with $\rho_{\rm min}$

mass is added, mimicking the loading of the magnetosphere with $e^{\pm}$ pairs

$\langle$ movie $\rangle$


1.0e+05
10000
1000
100
10
1.0e+00
floors
1.0e+02
50
20
10
5
2
1
σ
0.5
0.2
0.1
0.05
0.02
1.0e-02



$\log_{10}\dot{\rho}_{add}$
$\log_{10}\dot{N}_{add}$
$C_{num} = 0.0$
$z\ [r_g]$
$x\ [r_g]$
$\log_{10}\sigma$
$\log_{10}\rho$
$\dot{M}$
ϕ
$t(M)$

Summary

- ⋆ magnetic field + rotation $\rightarrow$ Poynting flux extraction

- ⋆ the collimation-acceleration mechanism is very efficient – provides a viable explanation for the bulk acceleration in all jets (relativistic or not)

- ⋆ dissipative effects very important, not well understood, difficult to be simulated – numerical effects sometimes mimic physics but cannot be fully trusted

- ⋆ simulations could be inspiring to isolate physical mechanisms and examine them analytically

- ⋆ analytical thinking/connection with basic physics should go hand by hand with numerical experiments

Thank you for your attention