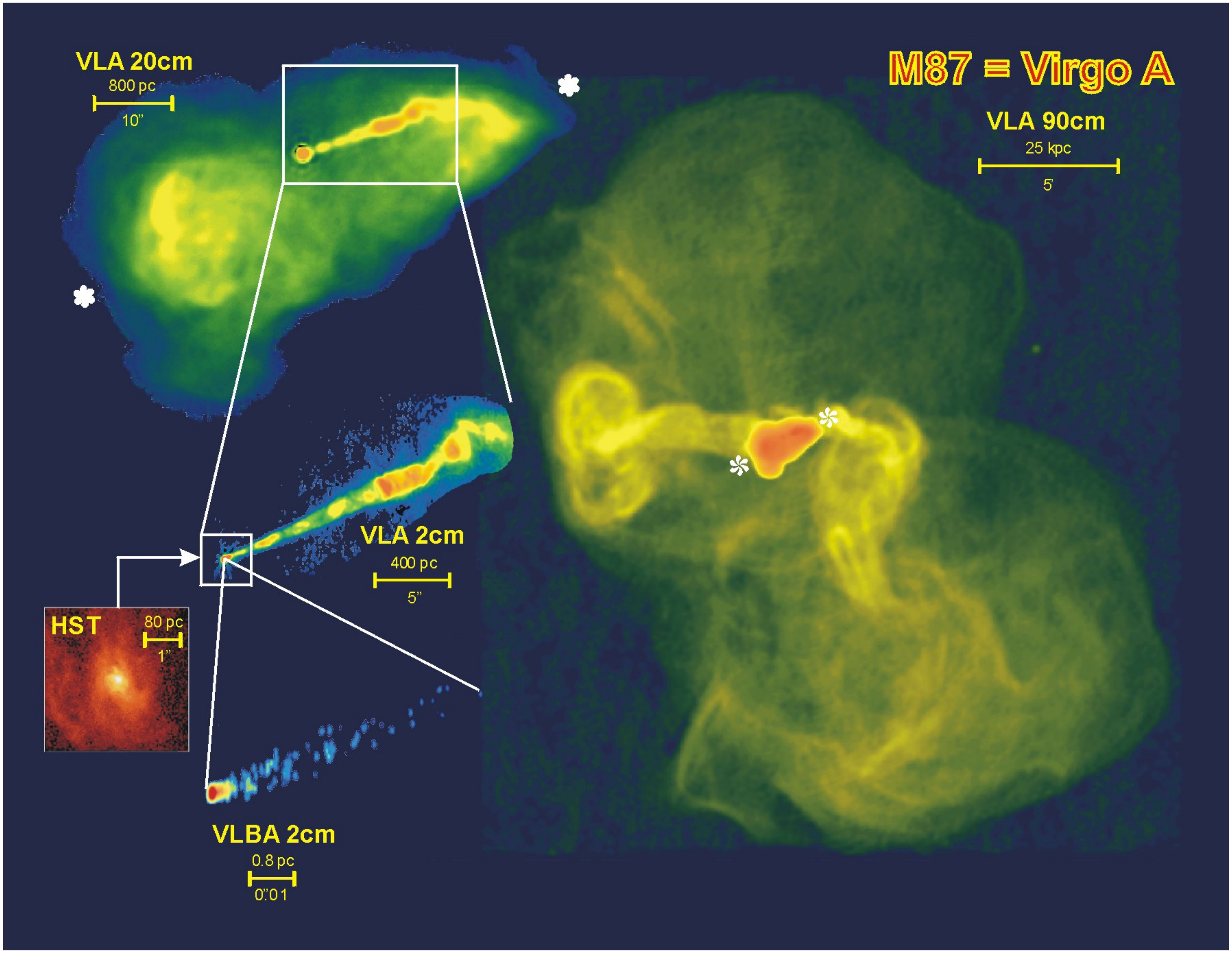
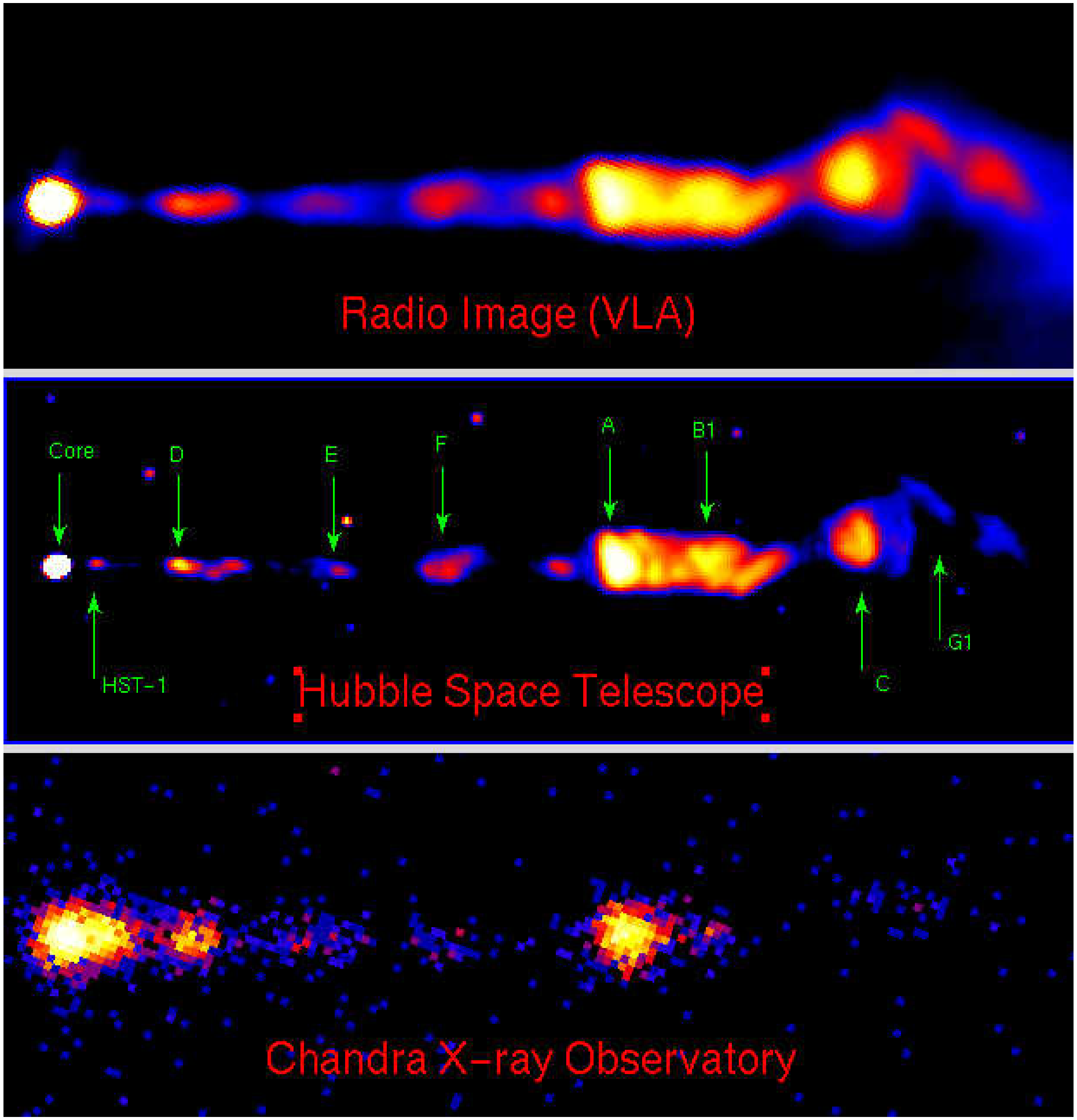
Formation of AGN Jets

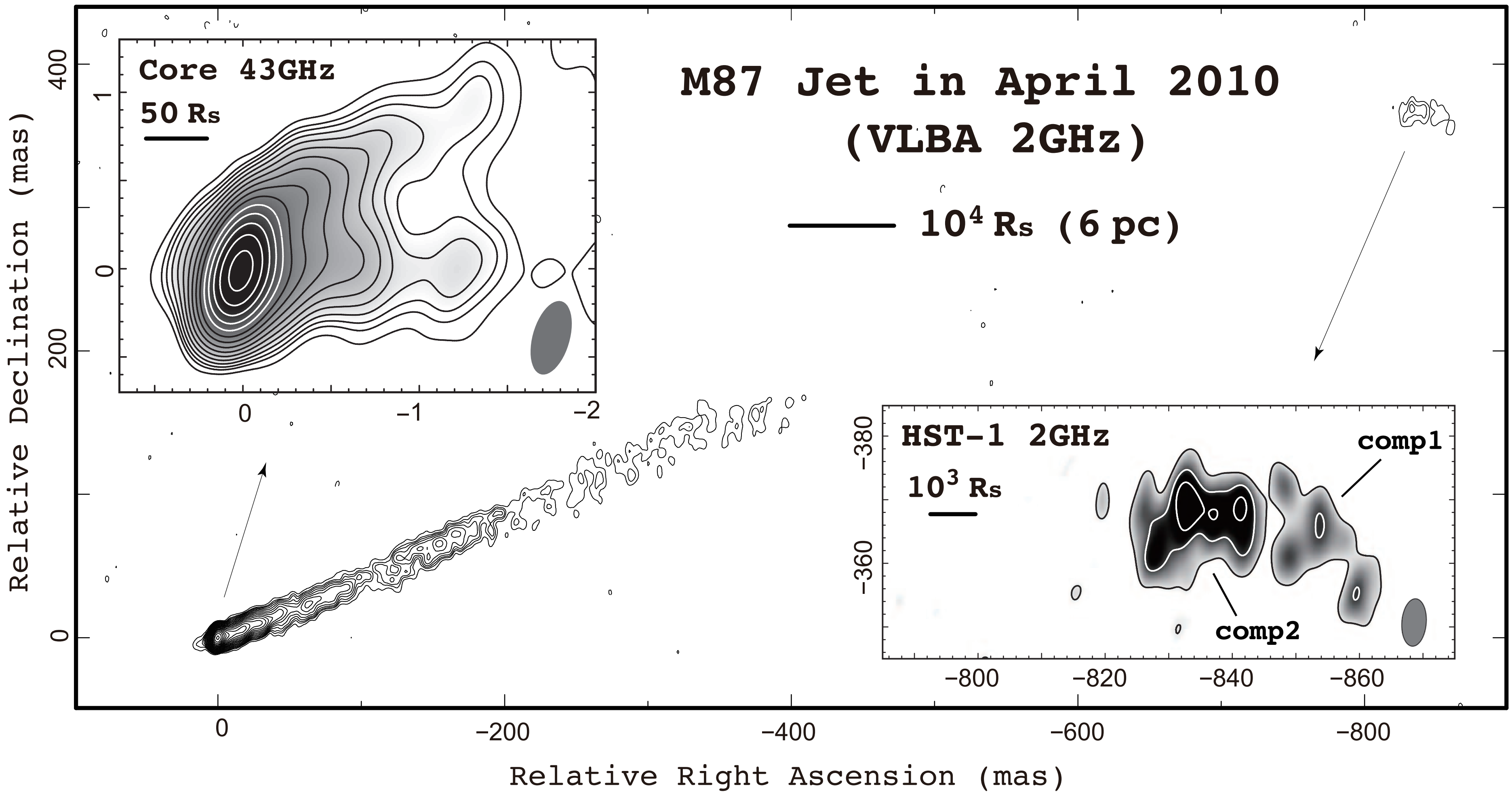
Nektarios Vlahakis
University of Athens

Outline

- observations
- why magnetic driving
- jet dynamics


M87 = Virgo A
VLA 20cm
800 pc
10"
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0."01

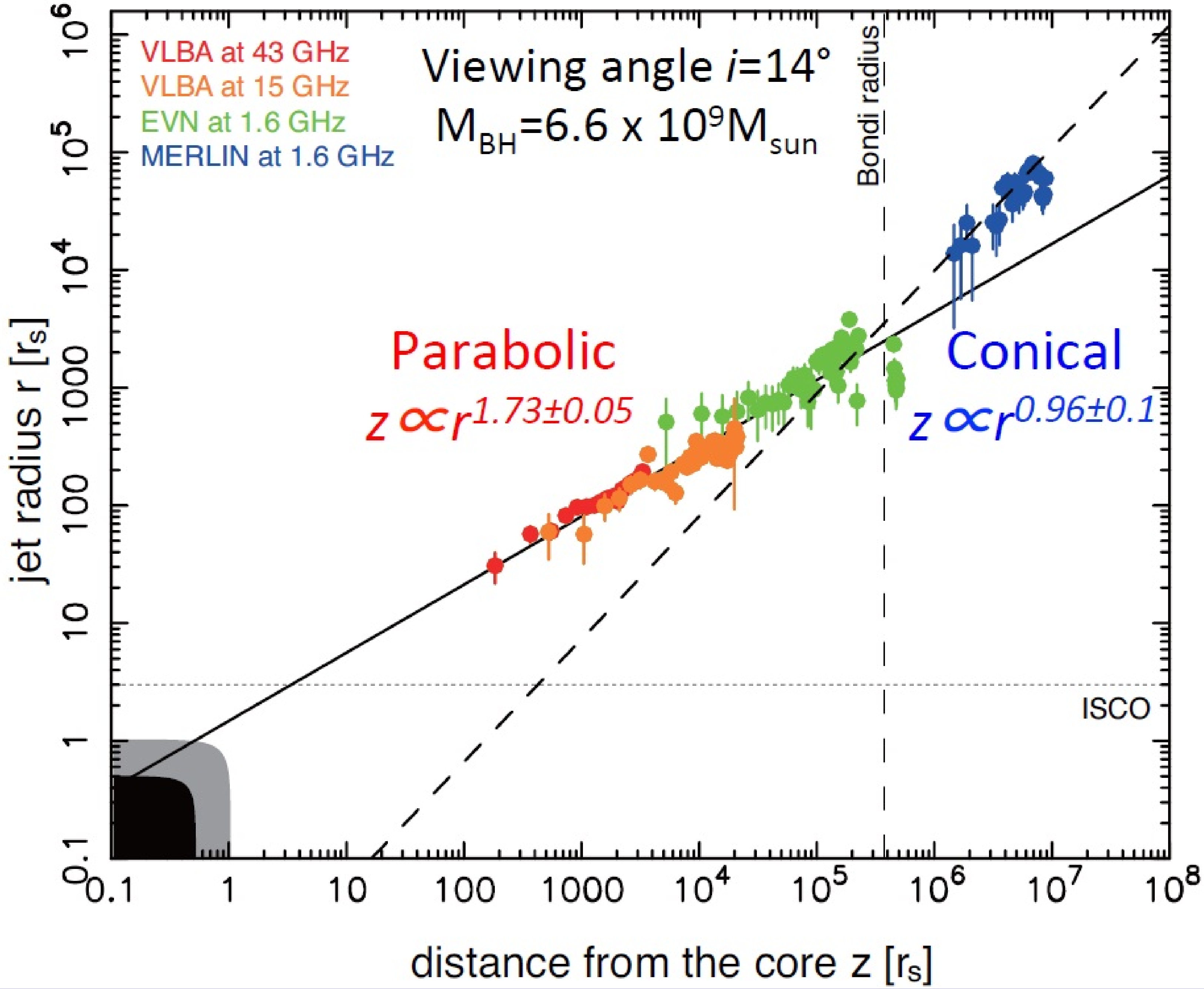

Radio Image (VLA)
Core
D
E
F
A
B1
HST-1
Hubble Space Telescope
C
G1
Chandra X-ray Observatory

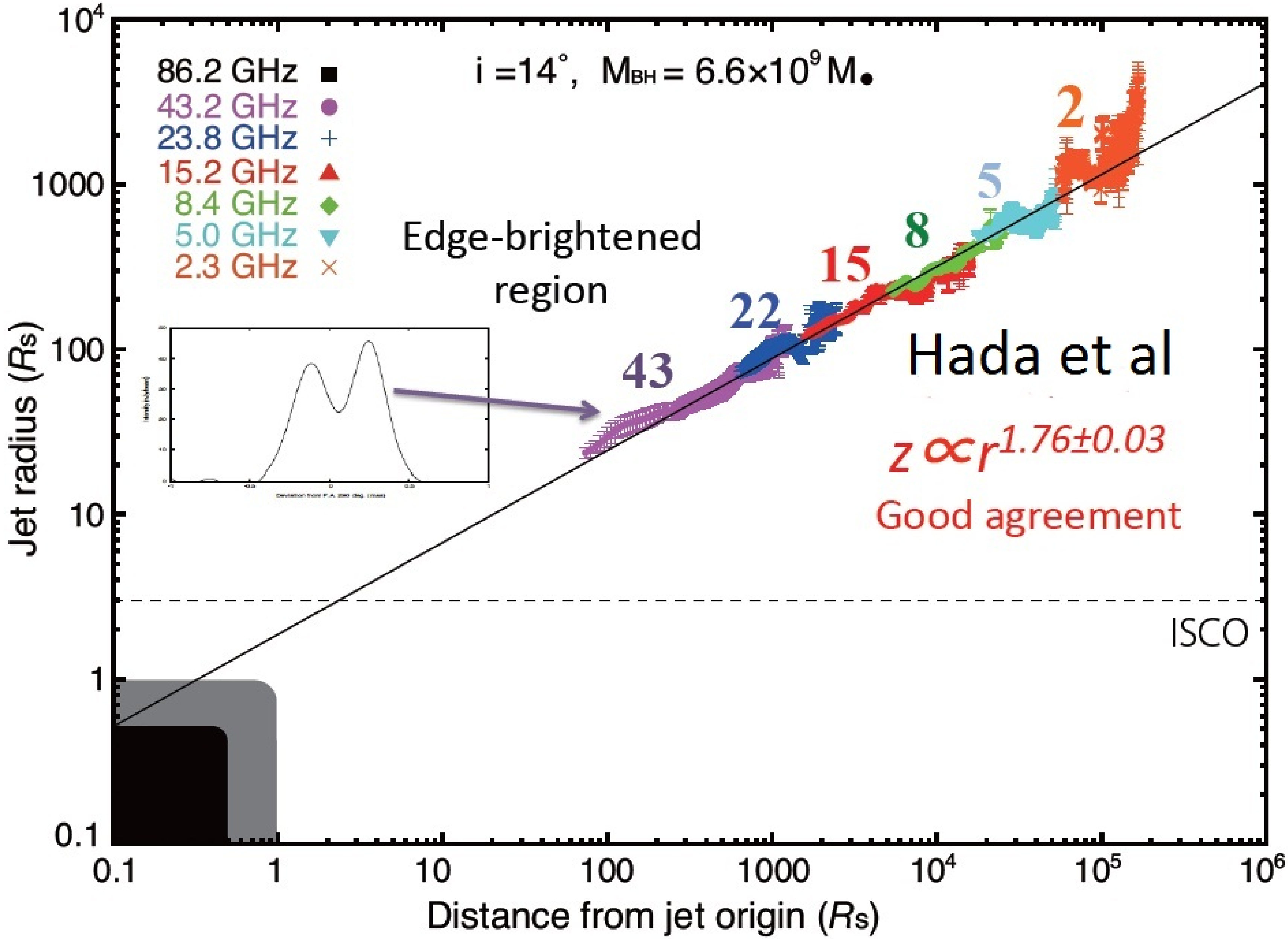


M87 Jet in April 2010
(VLBA 2GHz)
10^4 Rs (6 pc)
Core 43GHz
50 Rs
HST-1 2GHz
10^3 Rs
comp1
comp2
Relative Declination (mas)
Relative Right Ascension (mas)

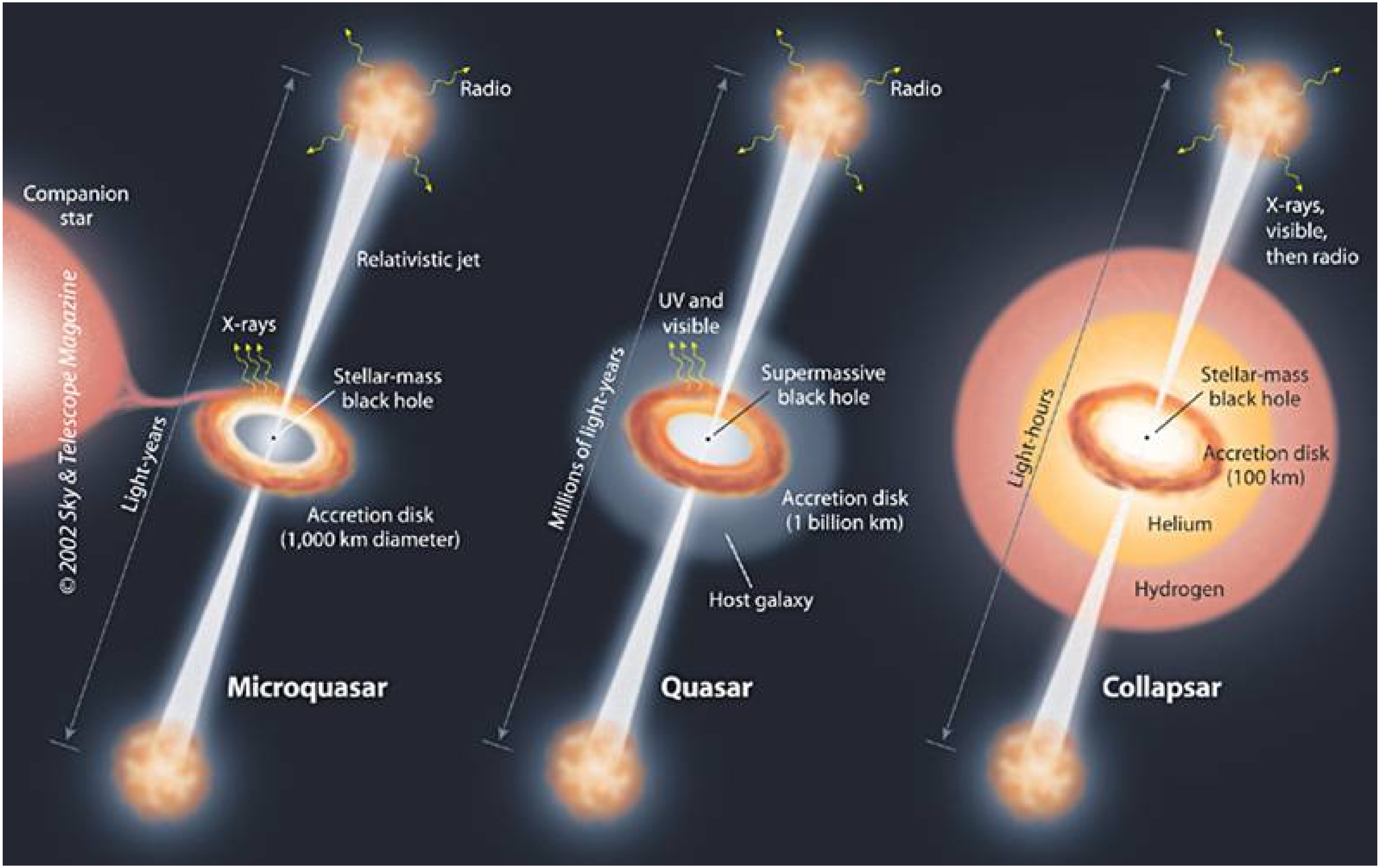
(Hada et al)

(Asada & Nakamura 2011)



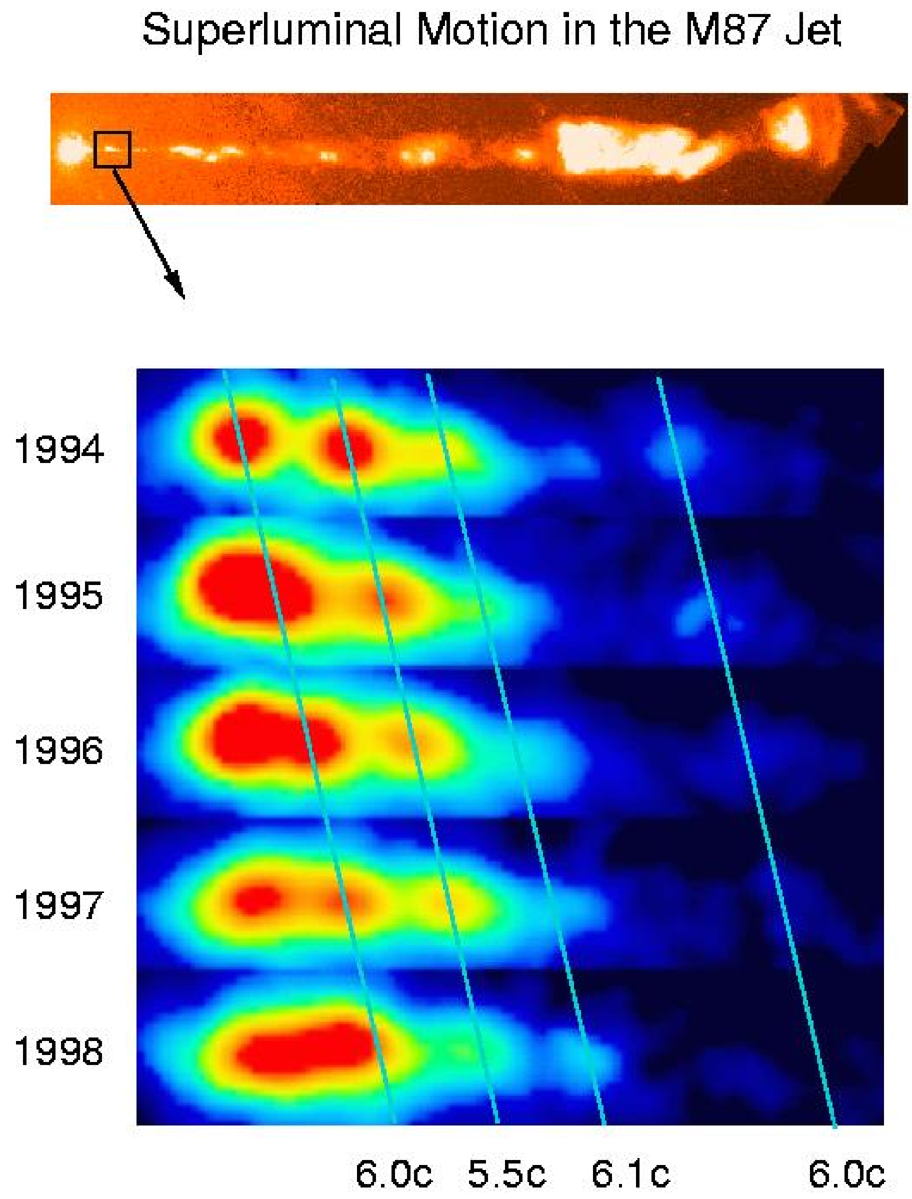


i =14°, M_{BH} = 6.6×10^9 $M_\odot$
86.2 GHz
43.2 GHz
23.8 GHz
15.2 GHz
8.4 GHz
5.0 GHz
2.3 GHz
Edge-brightened region
43
22
15
8
5
2
Hada et al
$z \propto r^{1.76\pm0.03}$
Good agreement
ISCO
Jet radius (Rs)
Distance from jet origin (Rs)



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

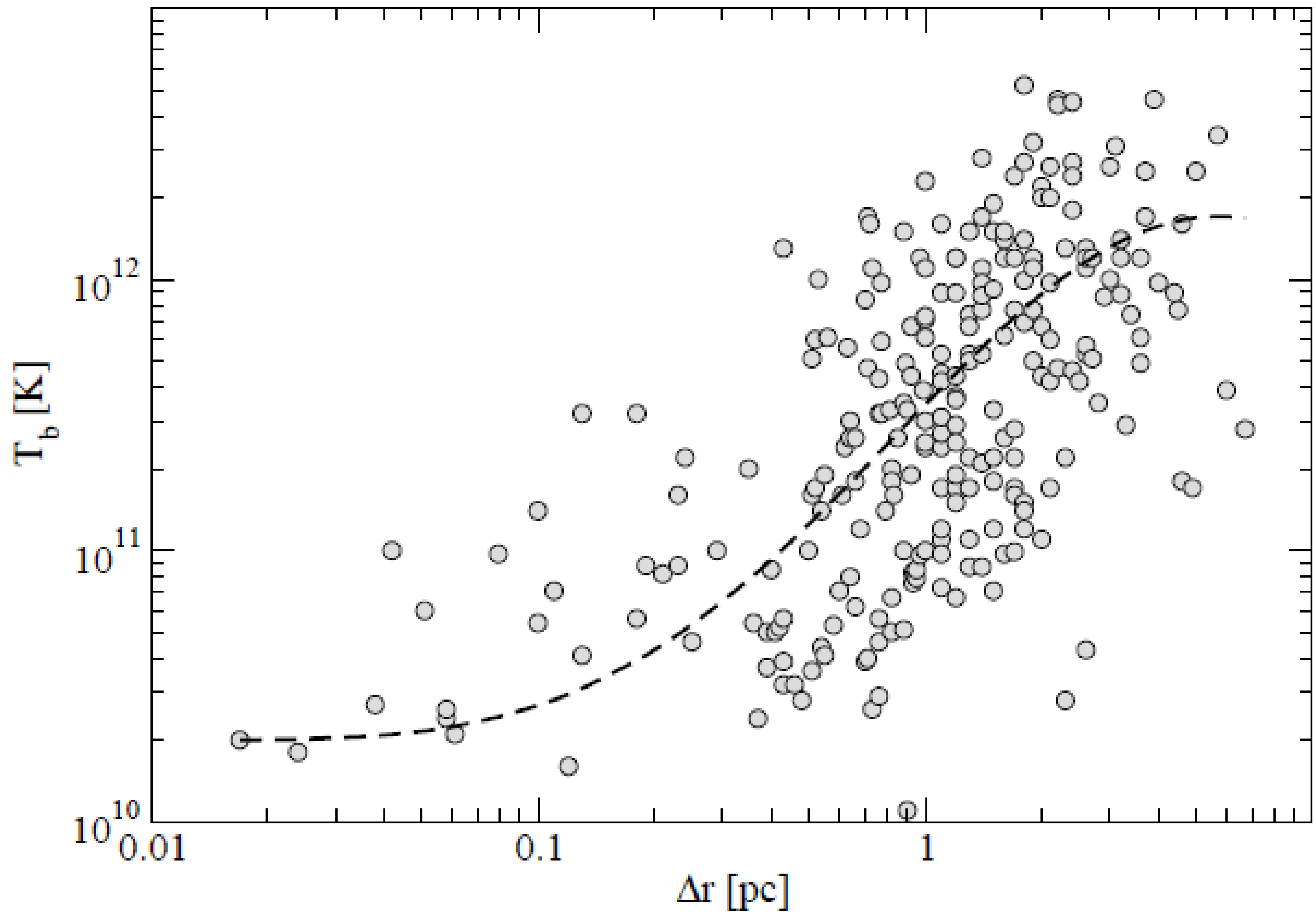
Jet speed



Superluminal Motion in the M87 Jet
1994
1995
1996
1997
1998
6.0c
5.5c
6.1c
6.0c

On the bulk acceleration

- More distant components have higher apparent speeds
- Brightness temperature increases with distance

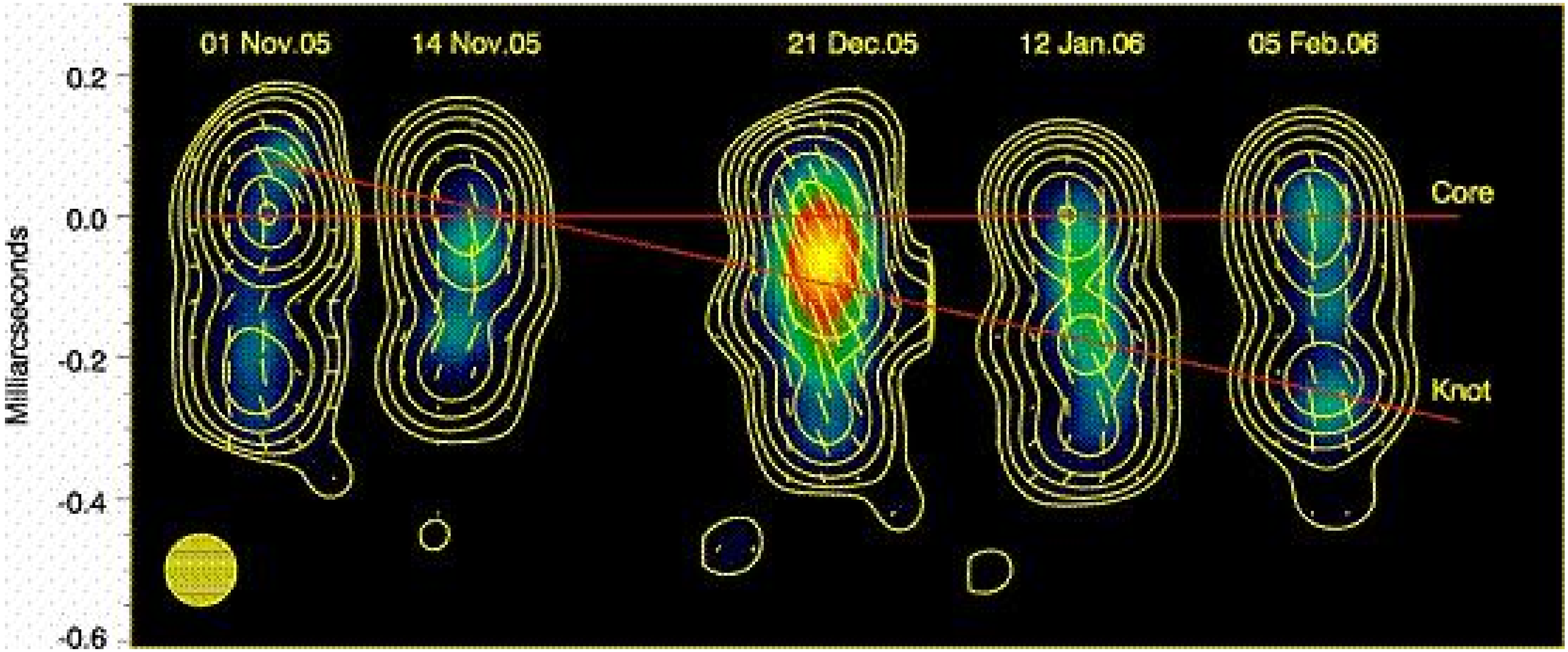


- A more general argument on the acceleration (Sikora et al):
  - ⋆ lack of bulk-Compton features $\rightarrow$ small ($\gamma < 5$) bulk Lorentz factor at $\lesssim 10^3 r_g$
  - ⋆ the γ saturates at values $\sim$ a few 10 around the blazar zone $(10^3 - 10^4 r_g)$

  So, relativistic AGN jets undergo the bulk of their acceleration on parsec scales ($\gg$ size of the central black hole)

- Sikora et al also argue that the protons are the dynamically important component in the outflow.

Polarization



(Marscher et al 2008, Nature)

helical motion and field rotate the EVPA as the blob moves

observed $\boldsymbol{E}_{rad} \perp \boldsymbol{B}_{rad}$ and $\boldsymbol{B}_{rad}$ is $\parallel$ $\boldsymbol{B}_{\perp los}$
(modified if the jet is relativistic)

Faraday rotation

Faraday rotation – the plane of LP rotates when polarized EM wave passes through a magnetized plasma, due to different propagation velocities of the RCP and LCP components of the EM wave in the plasma.

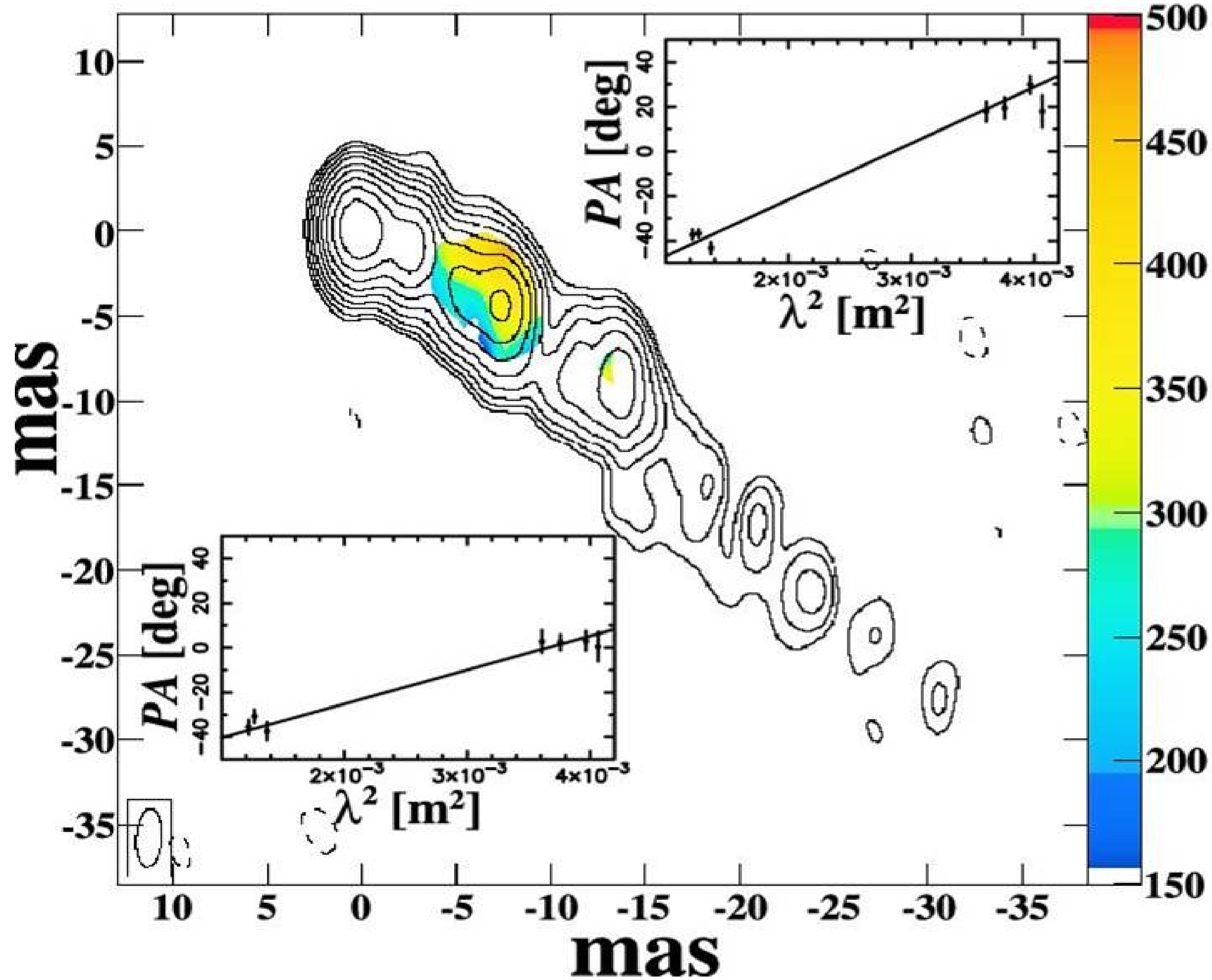
If internal, there is also depolarization (fractional polarization depends on λ).

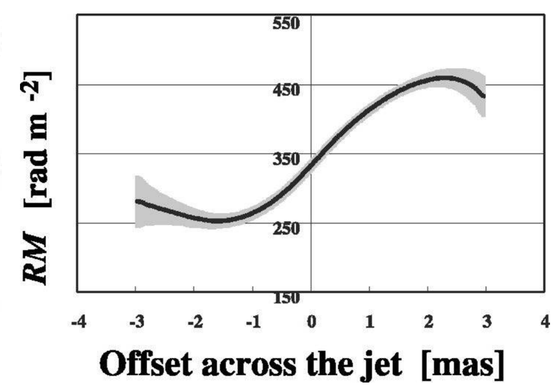
If external, the amount of rotation is proportional to the square of the observing wavelength, and the sign of the rotation is determined by the direction of the line of sight B field:

$$\chi = \chi_0 + (RM)\lambda^2$$

$$(RM) \propto \int n_e B_{\| los} d\ell$$

Faraday RM gradients across the jet





(from Asada et al)

helical field surrounding the emitting region

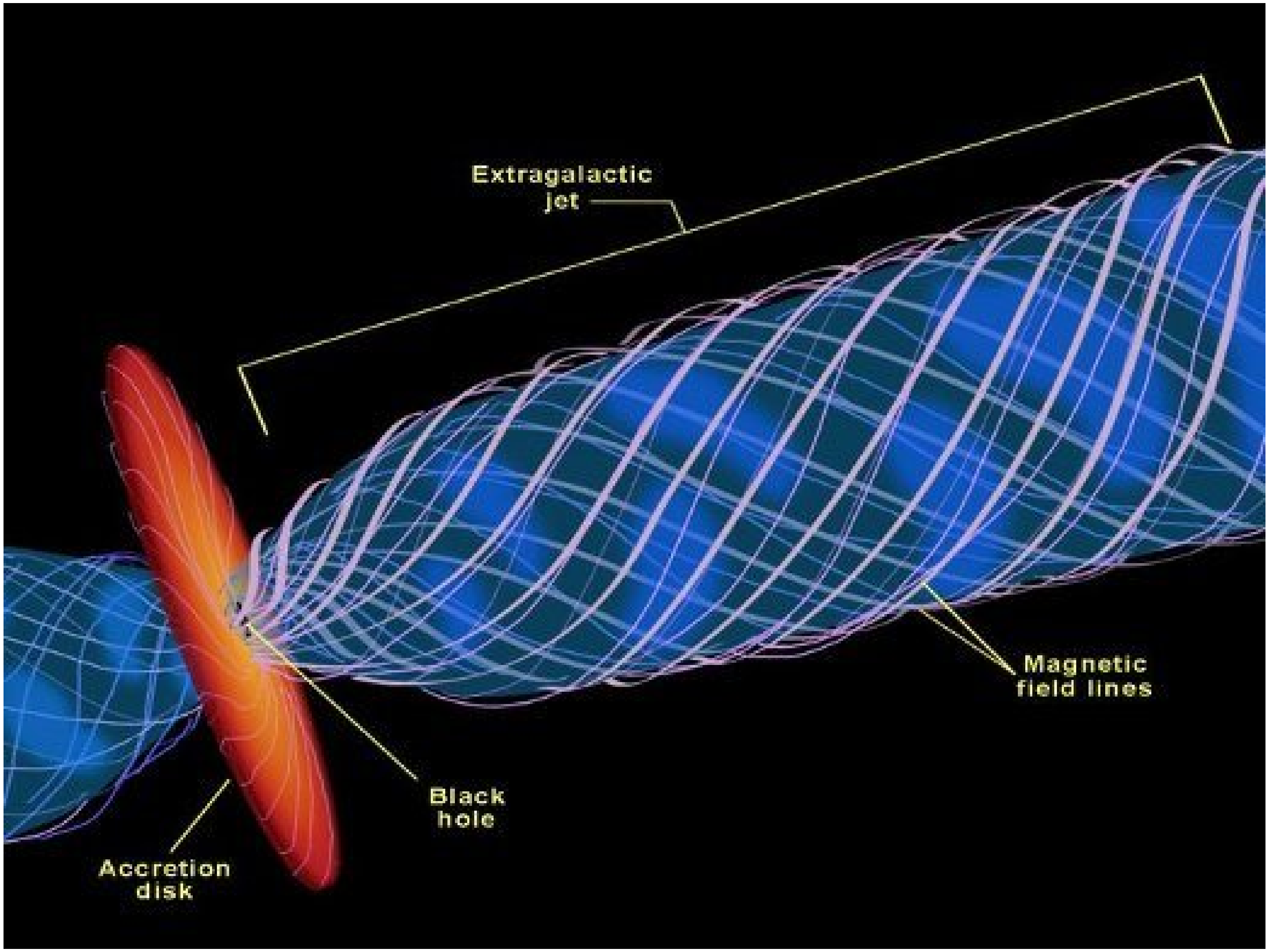
Theory: Hydro-Dynamics

- In case $n_e \sim n_p$, $\gamma_{\max} \sim kT_i/m_pc^2 \sim 1$ even with $T_i \sim 10^{12}K$
- If $n_e \neq n_p$, $\gamma_{\max} \sim (n_e/n_p) \times (kT_i/m_pc^2)$ could be $\gg 1$
- With some heating source, $\gamma_{\max} \gg 1$ is in principle possible

However, even in the last two cases, HD is unlikely to work because the HD acceleration saturates at distances comparable to the sonic surface where gravity is still important, i.e., very close to the disk surface (certainly at $\ll 10^3 r_g$)

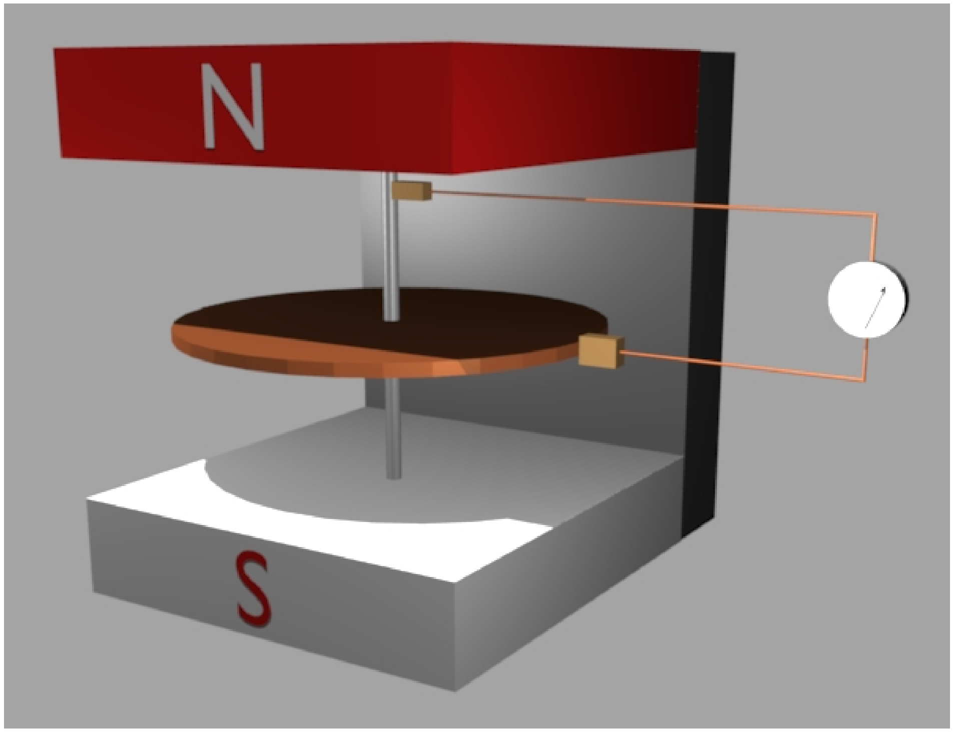
We need magnetic fields

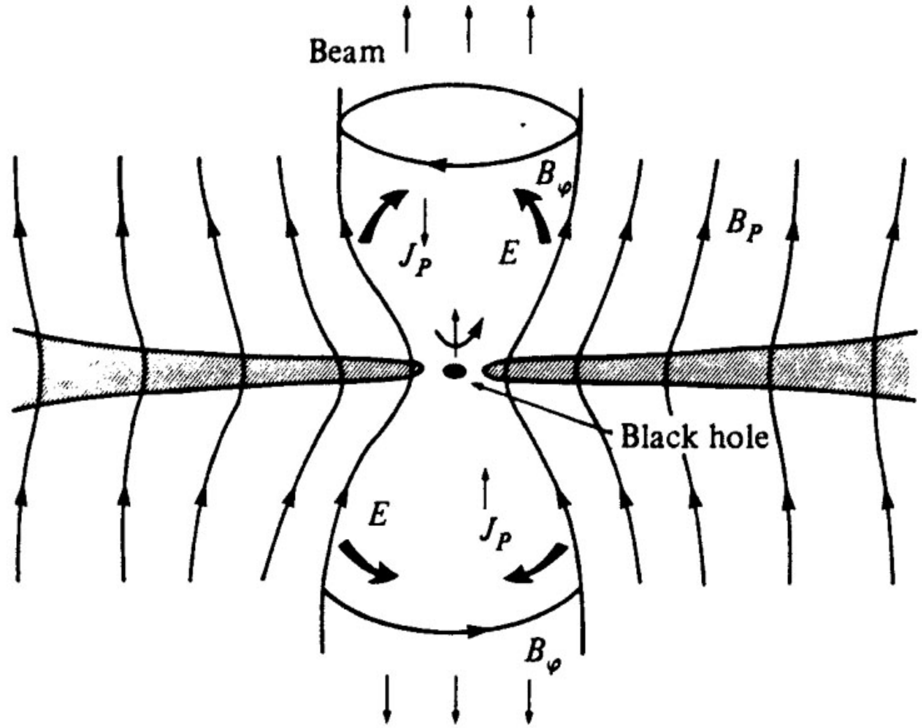
- ⋆ They extract energy (Poynting flux)
- ⋆ extract angular momentum
- ⋆ transfer energy and angular momentum to matter
- ⋆ explain relatively large-scale acceleration
- ⋆ collimate outflows and produce jets
- ⋆ needed for synchrotron emission
- ⋆ explain polarization and RM maps



B field from advection, or dynamo, or cosmic battery (Poynting-Robertson drag).

A unipolar inductor





current $\leftrightarrow B_\phi$

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

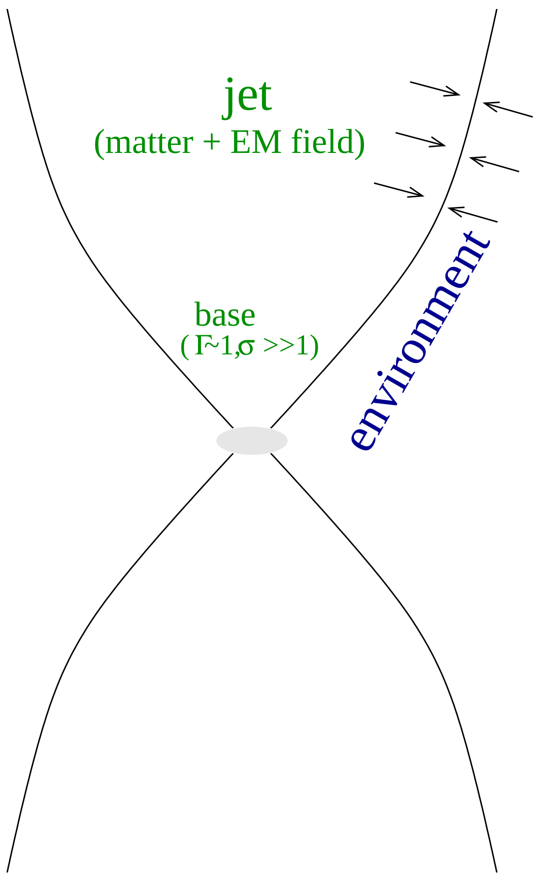
The Faraday disk could be the rotating accretion disk, or the frame dragging if energy is extracted from the ergosphere of a rotating black hole (Blandford & Znajek mechanism - the electromagnetic analogue of the Penrose mechanism)

How to model magnetized outflows?

- ⋆ as pure electromagnetic energy (force-free, magnetodynamics, electromagnetic outflows):
  – ignore matter inertia (reasonable near the origin)
  – this by assumption does not allow to study the transfer of energy form Poynting to kinetic
  – wave speed $= c \rightarrow$ no shocks
  – there may be some dissipation (e.g. reconnection) $\rightarrow$ radiation

- ⋆ as magneto-hydro-dynamic flow
  – the force-free case is included as the low inertia limit
  – MHD can also describe the back reaction from the matter to the field (this is important even in the superfast part of the regime where $\sigma \gg 1$)

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)

$$\dot{\mathcal{E}} = \frac{c}{4\pi} \underbrace{\frac{r\Omega}{c} B_p}_{E} B_\phi \times (\text{ area }) \approx \frac{c}{2} B^2 r^2$$

- 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

Relativistic Magneto-Hydro-Dynamics

- Outflowing matter
- large scale electromagnetic field
- thermal pressure

We need to solve:

- Maxwell + Ohm equations
- mass + entropy conservation
- momentum equation

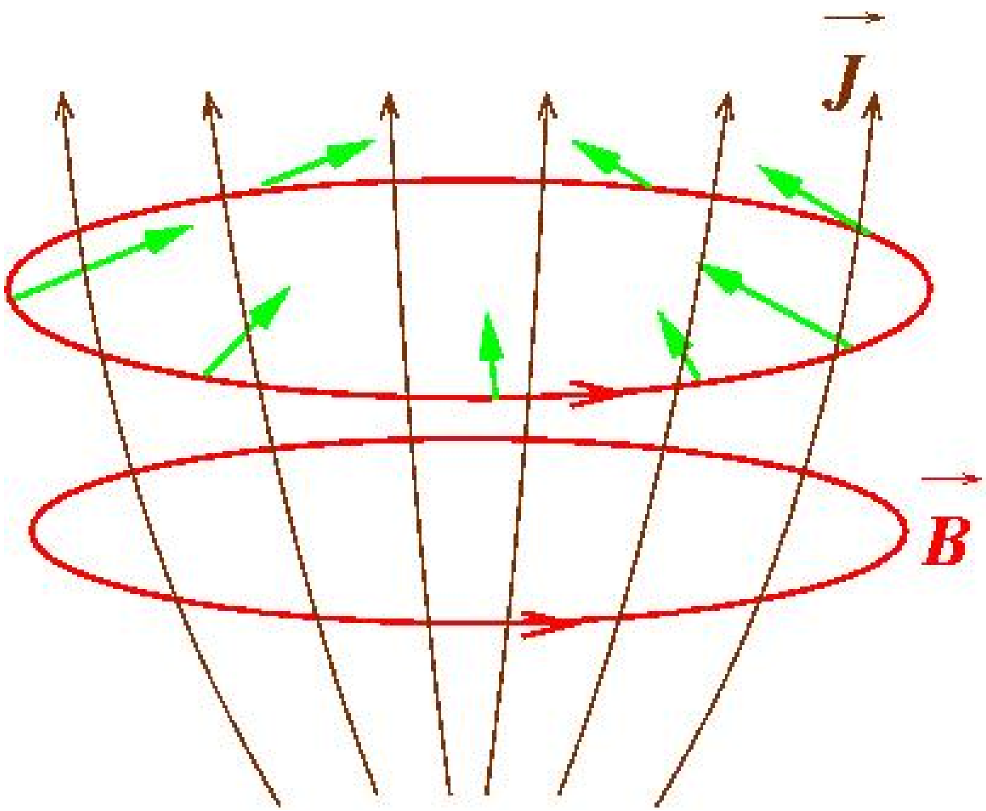
Basic questions: bulk acceleration

- thermal (due to ∇P) $\rightarrow$ velocities up to C_s
- magnetocentrifugal (beads on wire - Blandford & Payne)
  - initial half-opening angle $\vartheta > 30^o$
  - the $\vartheta > 30^o$ not necessary for nonnegligible P
  - velocities up to $r_0\Omega$
- relativistic thermal (thermal fireball) gives $\gamma \sim \xi_i$, where $\xi = \dfrac{\text{enthalpy}}{\text{mass} \times c^2}$.
- magnetic

acceleration efficiency $\gamma_\infty/\mu =$?

Basic questions: collimation

hoop-stress:



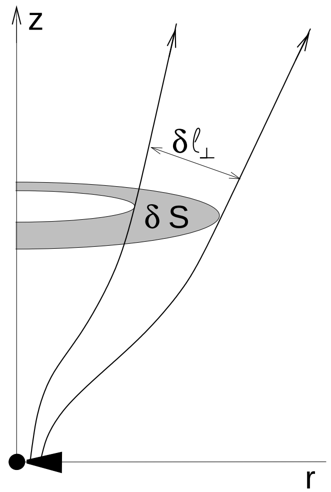
+ electric force

degree of collimation ?

Role of environment?

“Standard” model for magnetic acceleration

☞ component of the momentum equation



$$\gamma n(\boldsymbol{V}\cdot\nabla)\,(\gamma w \boldsymbol{V}) = -\nabla p + J^0 \boldsymbol{E} + \boldsymbol{J}\times\boldsymbol{B}$$

along the flow (wind equation): $\gamma \approx \mu - \mathcal{F}$

where $\mathcal{F} \propto r^2 n\gamma V_p = r^2\times$ mass flux

since mass flux $\times\delta S =$ const,

$\mathcal{F} \propto r^2/\delta S \propto r/\delta\ell_\perp$

acceleration requires the separation between streamlines to increase faster than the cylindrical radius

the collimation-acceleration paradigm:

$\mathcal{F}\downarrow$ **through stronger collimation of the inner streamlines relative to the outer ones (differential collimation)**

☞ transfield component of the momentum equation

$$\frac{\gamma^2 r}{\mathcal{R}} \approx \frac{\left(\frac{2I}{\Omega B_p r^2}\right)^2 r\nabla_\perp \ln\left|\frac{I}{\gamma}\right|}{1+\frac{w}{\rho c^2}\frac{4\pi\rho u_p^2}{B_p^2}\frac{r_{\rm lc}^2}{r^2}} - \gamma^2\frac{r_{\rm lc}^2}{r^2}\nabla_\perp r, \text{ with } \nabla_\perp \sim \frac{1}{r},\ r_{\rm lc}=\frac{c}{\Omega},$$

simplifies to $\underbrace{\frac{\gamma^2 r}{\mathcal{R}}}_{inertia} \approx \underbrace{1}_{EM} - \underbrace{\gamma^2\frac{r_{\rm lc}^2}{r^2}}_{centrifugal}$

• if centrifugal negligible then $\gamma \approx z/r$ (since $\mathcal{R}^{-1} \approx -\frac{d^2 r}{dz^2} \approx \frac{r}{z^2}$)
power-law acceleration regime
(for parabolic shapes $z \propto r^a$, γ is a power of r)

• if inetria negligible then $\gamma \approx r/r_{\rm lc}$ linear acceleration regime

• if electromagnetic negligible then ballistic regime

☞ role of external pressure

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

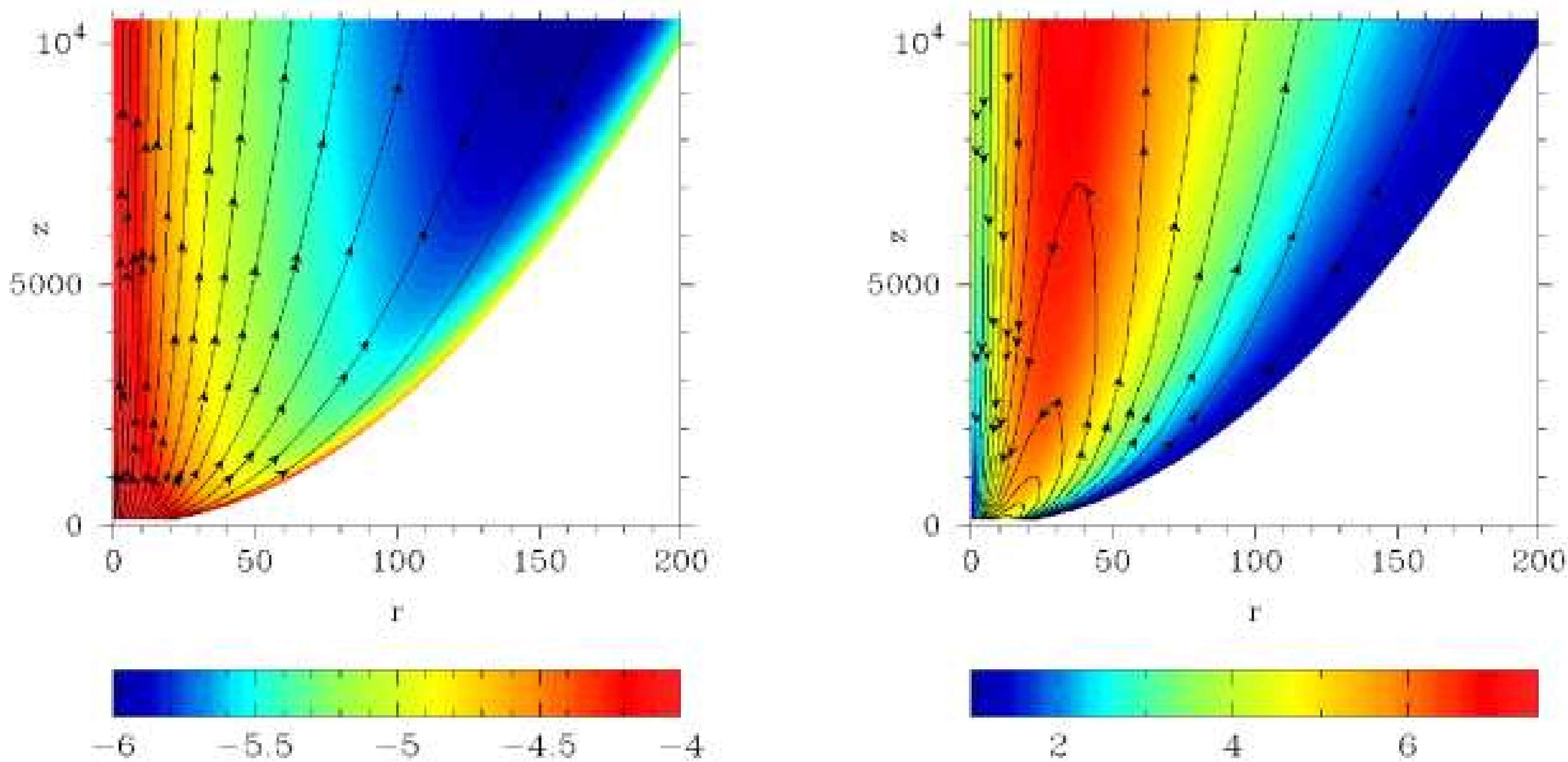
Assuming $p_{\rm ext} \propto z^{-\alpha_p}$ we find $\gamma^2 \propto z^{\alpha_p}/r^2$.

Combining with the transfield $\frac{\gamma^2 r}{\mathcal{R}} \approx 1 - \gamma^2 \frac{r_{\rm lc}^2}{r^2}$ we find the funnel shape (we find the exponent a in $z \propto r^a$).

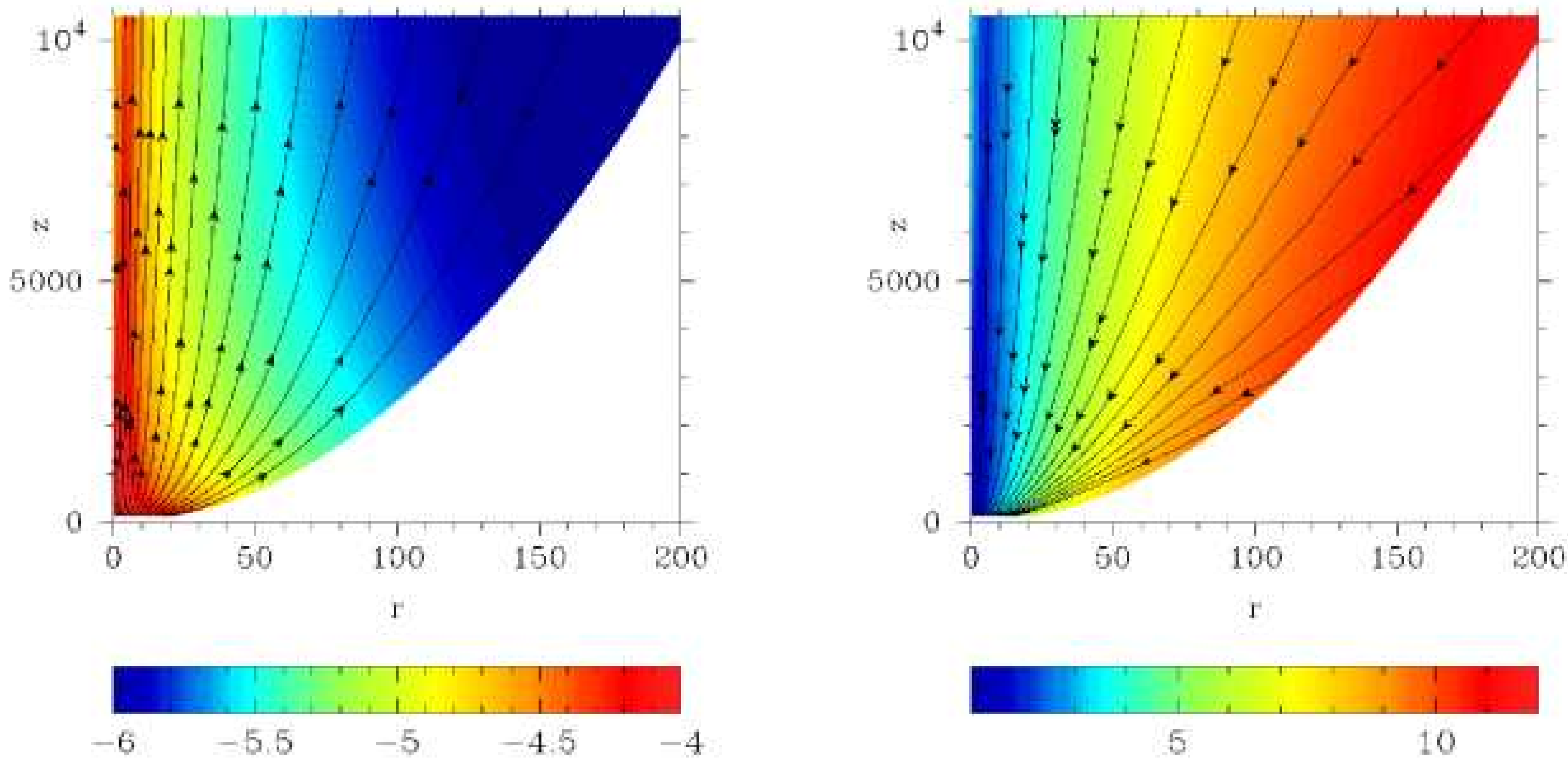
- if the pressure drops slower than z^{-2} then
  - ⋆ shape more collimated than $z \propto r^2$
  - ⋆ linear acceleration $\gamma \propto r$
- if the pressure drops as z^{-2} then
  - ⋆ parabolic shape $z \propto r^a$ with $1 < a \leq 2$
  - ⋆ first $\gamma \propto r$ and then power-law acceleration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

Simulations of relativistic jets

Komissarov, Barkov, Vlahakis, & Königl (2007)

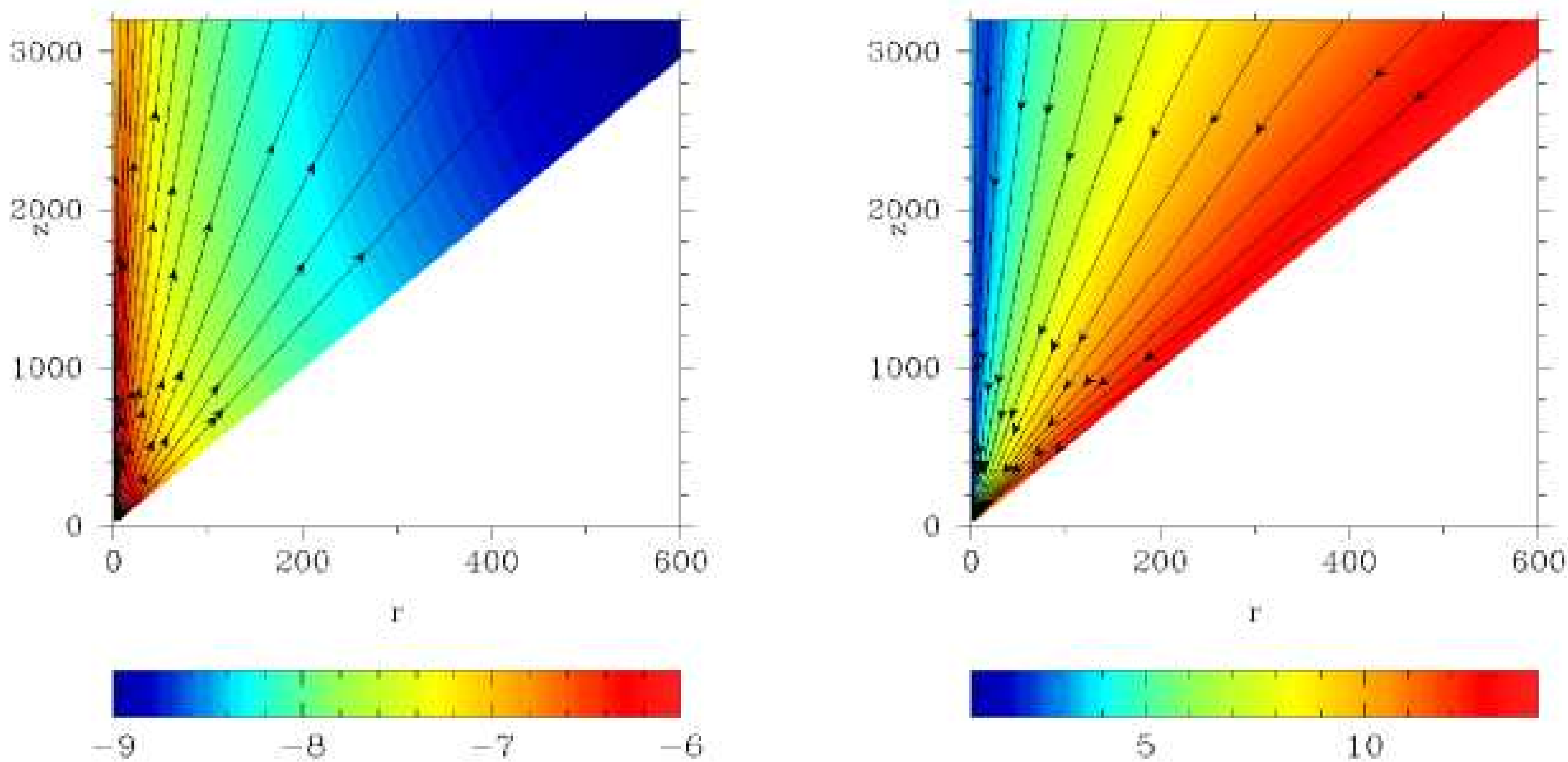


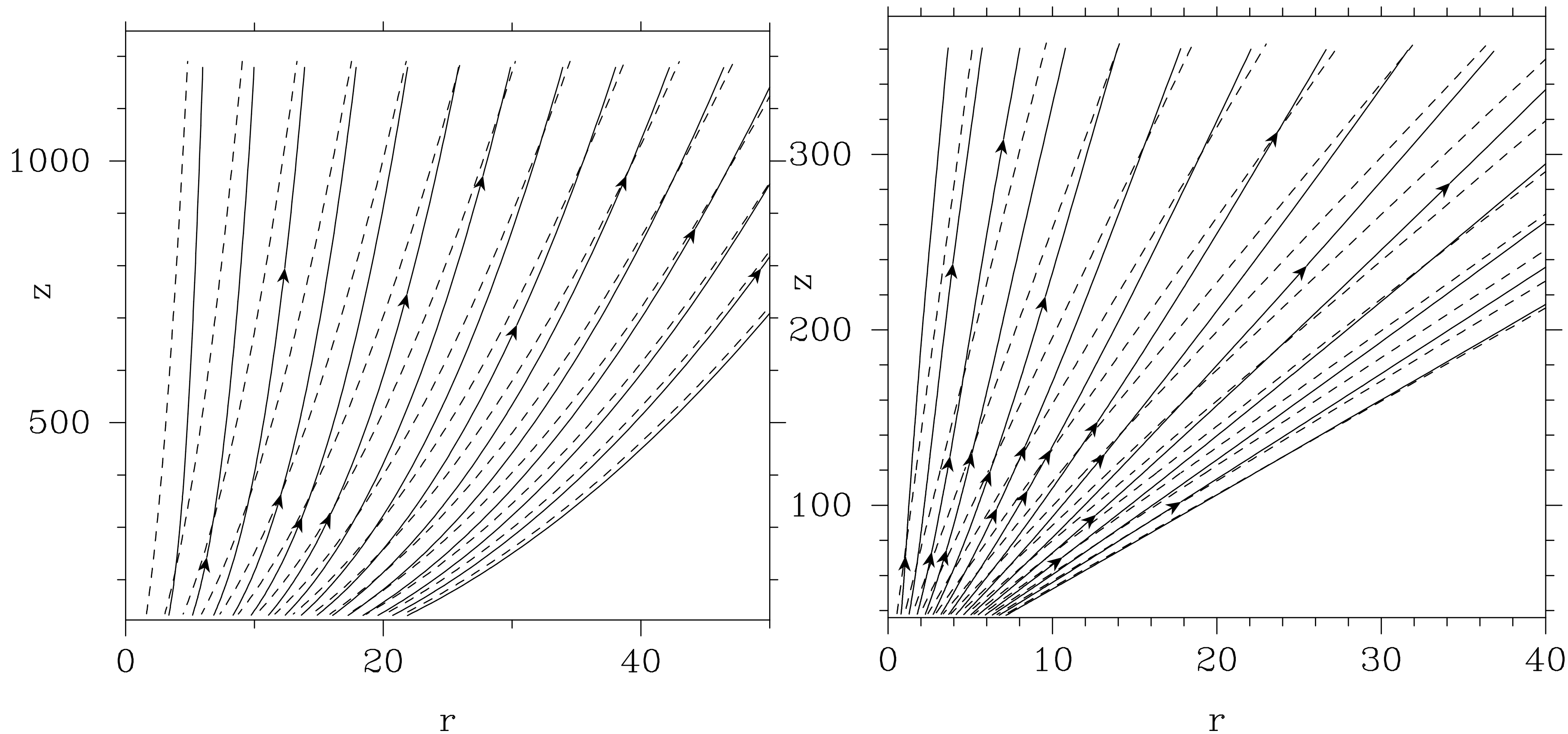
Left panel shows density (colour) and magnetic field lines. Right panel shows the Lorentz factor (colour) and the current lines.

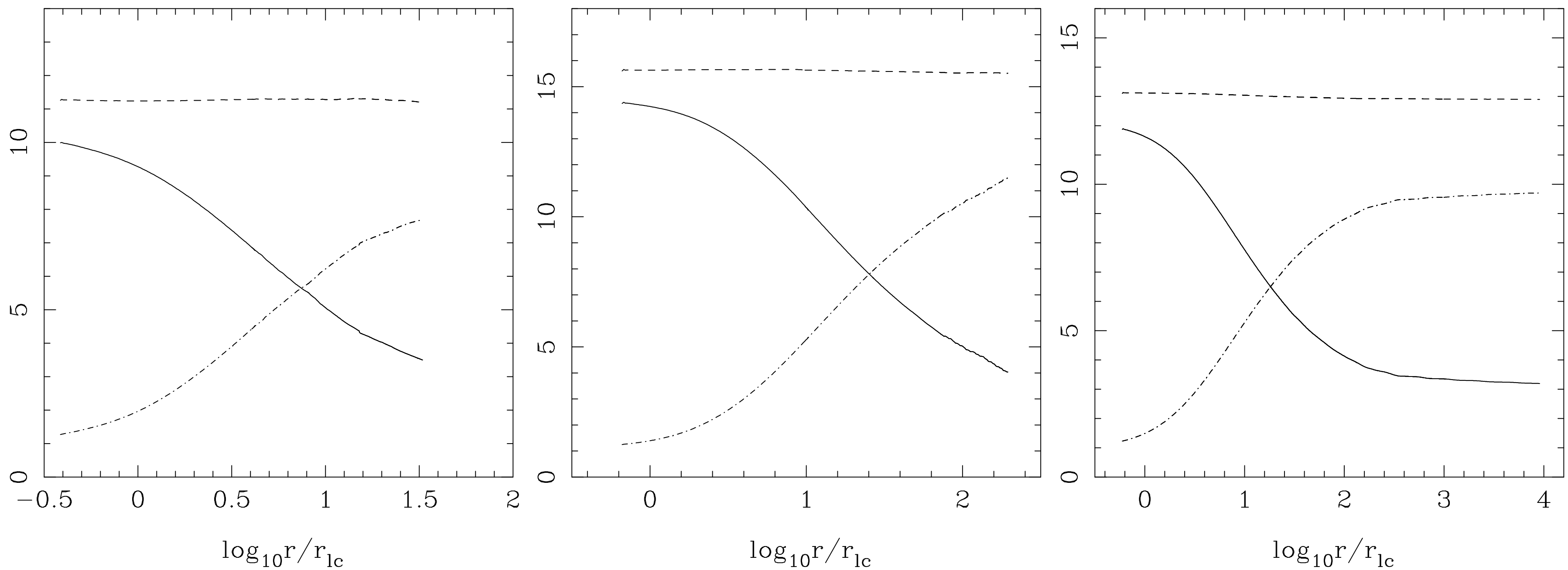


Note the difference in $\gamma(r)$ for constant z.

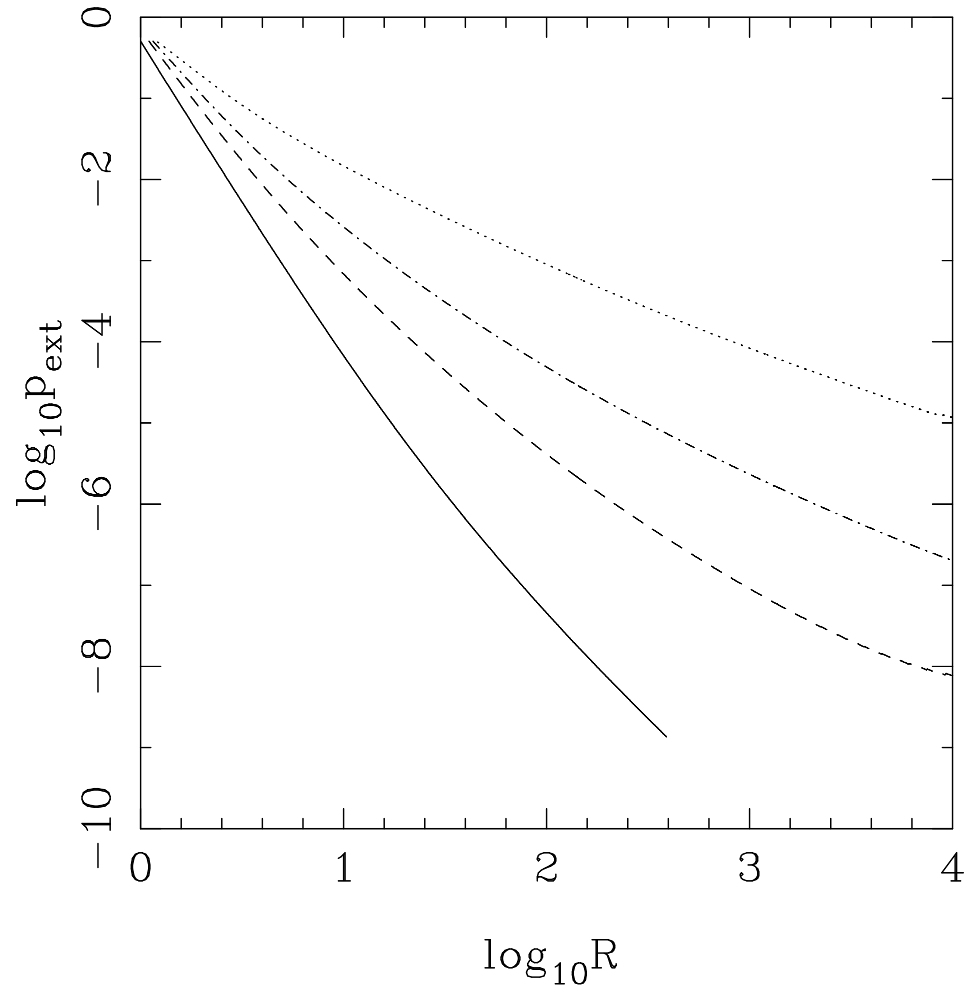
It depends on the current I, which is related to Ω:
$I \approx r^2 B_p \Omega / 2$


3000
2000
1000
0
z
0
200
400
600
r
−9
−8
−7
−6
3000
2000
1000
0
z
0
200
400
600
r
5
10


1000
500
z
0
20
40
r
300
200
100
z
0
10
20
30
40
r



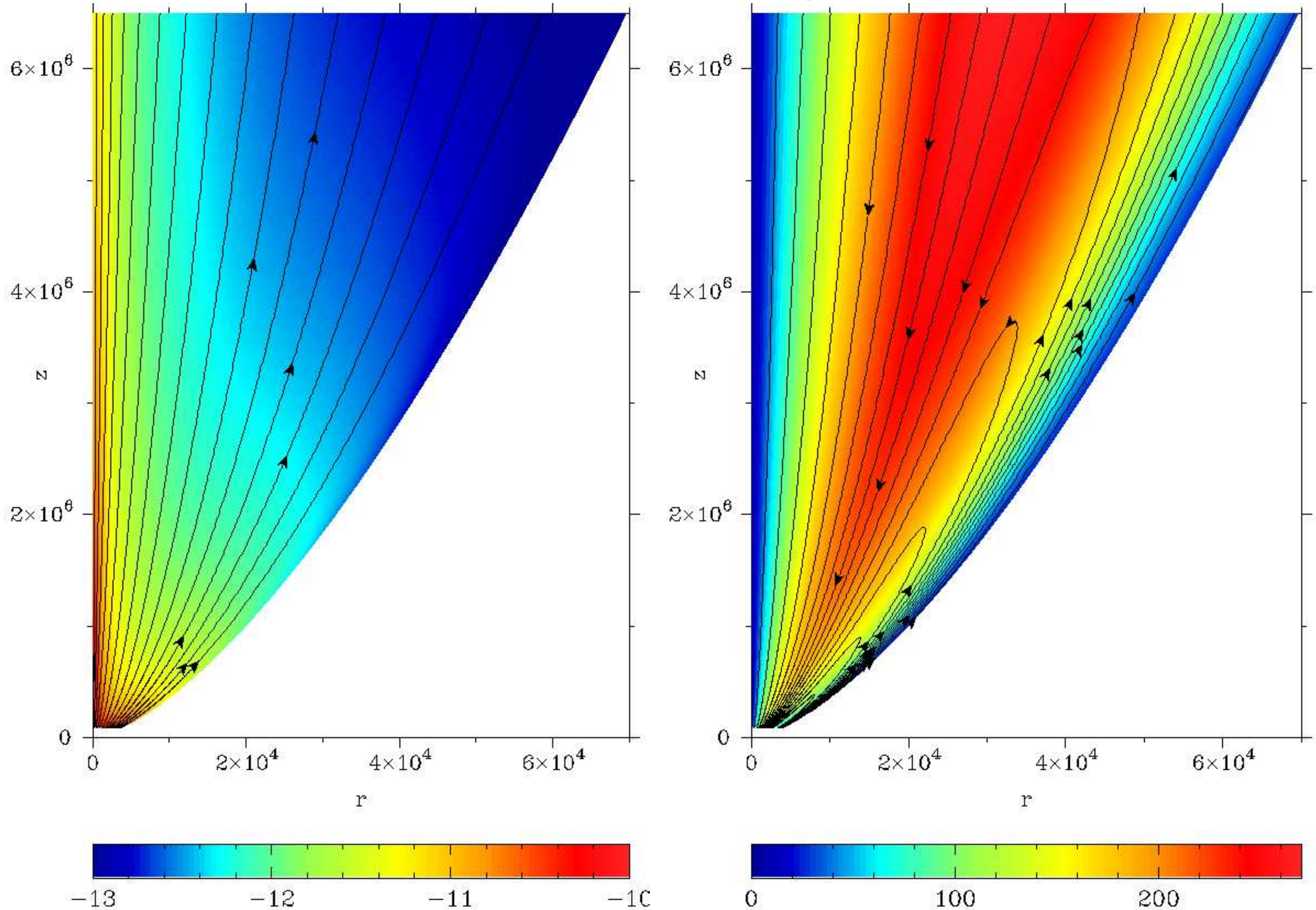
$\gamma\sigma$ (solid line), μ (dashed line) and γ (dash-dotted line) along a magnetic field line as a function of cylindrical radius for models C1 (left panel), C2 (middle panel) and A2 (right panel).



external pressure $P_{ext} = (B^2 - E^2)/8\pi$

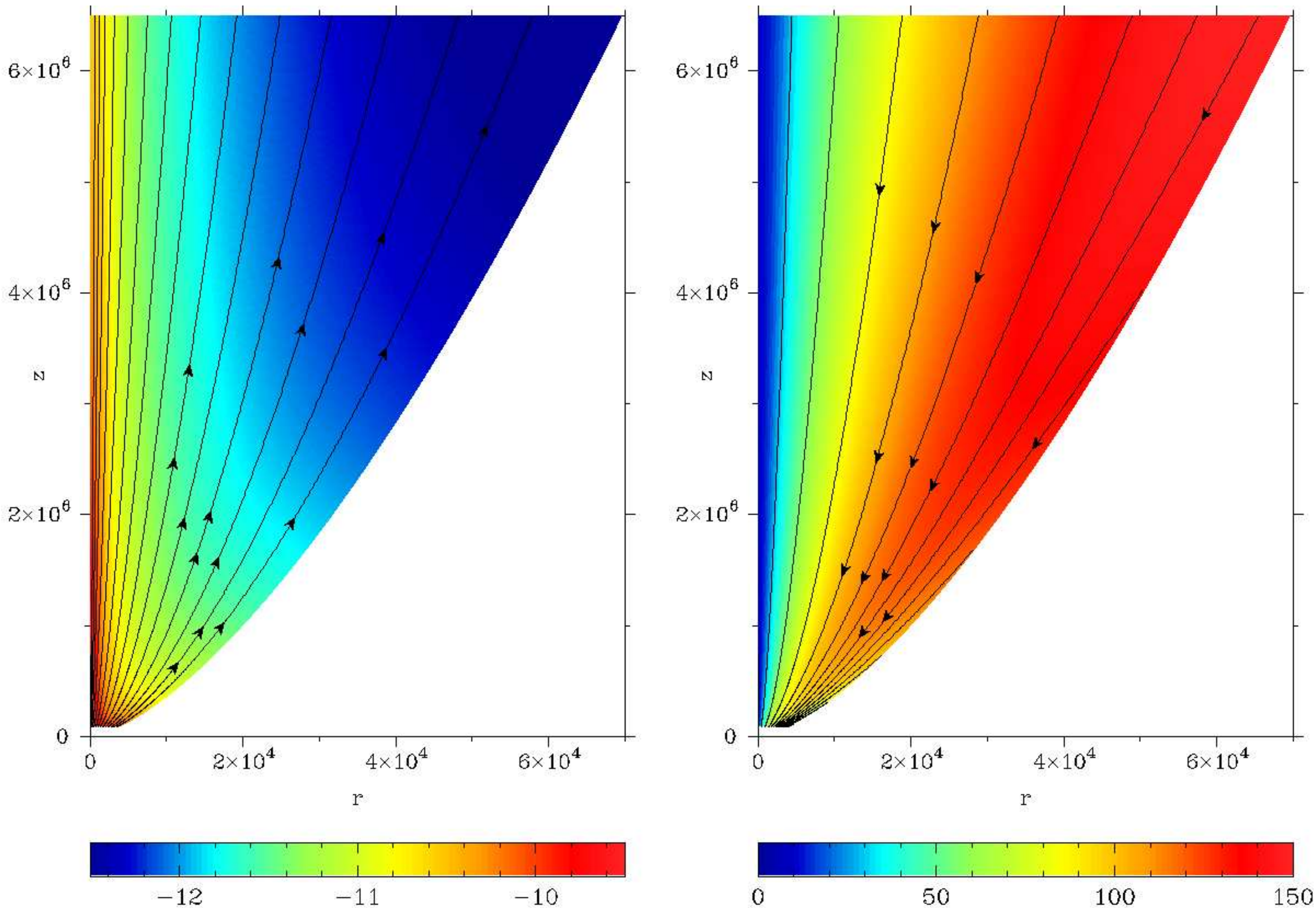
solid line: $p_{\rm ext} \propto R^{-3.5}$ for $z \propto r$, dashed line: $p_{\rm ext} \propto R^{-2}$ for $z \propto r^{3/2}$, dash-dotted line: $p_{\rm ext} \propto R^{-1.6}$ for $z \propto r^2$, dotted line: $p_{\rm ext} \propto R^{-1.1}$ for $z \propto r^3$

Komissarov, Vlahakis, Königl, & Barkov 2009

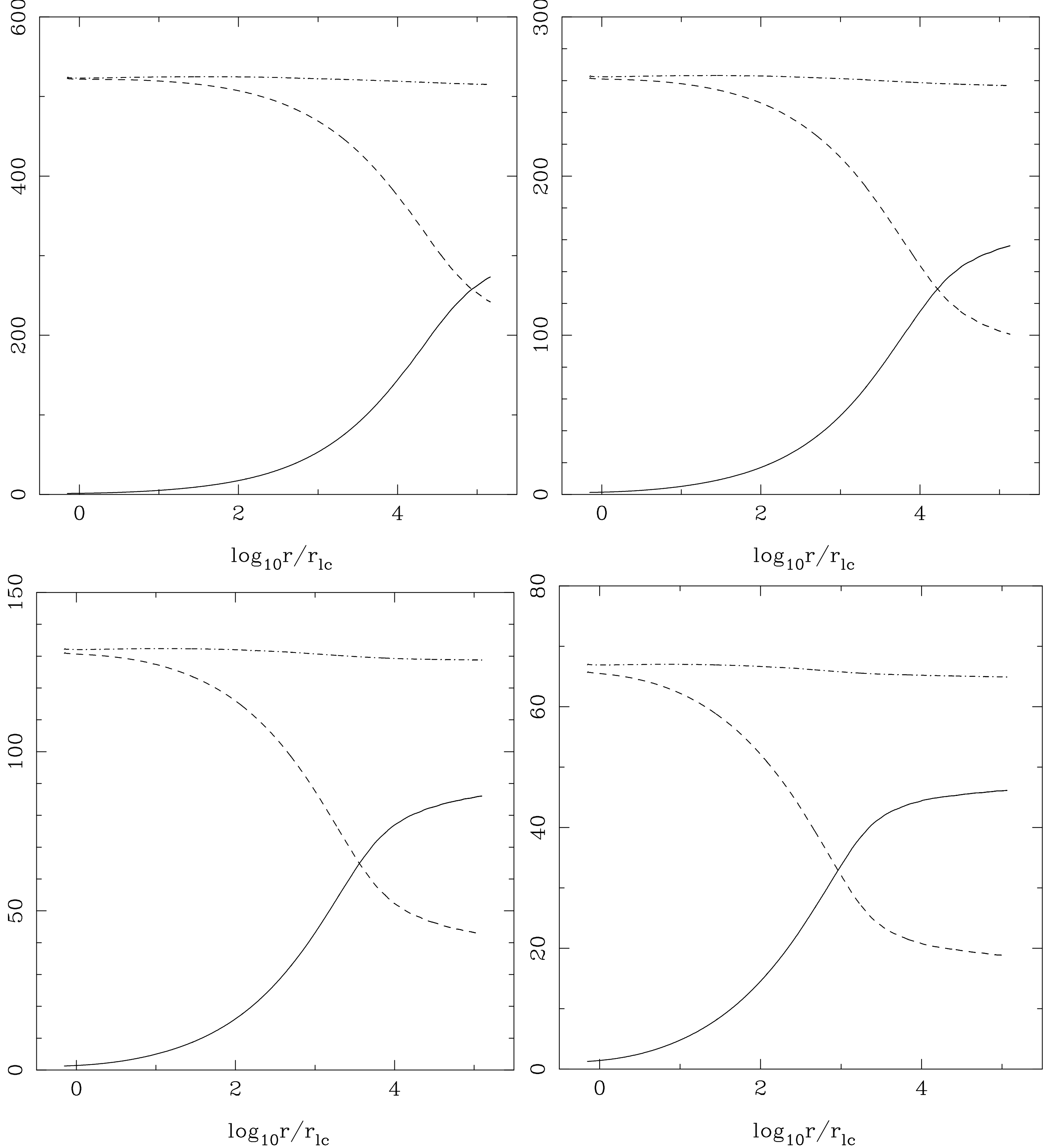


left: density/field lines, right: Lorentz factor/current lines (wall shape $z \propto r^{1.5}$)

Differential rotation $\rightarrow$ slow envelope



Uniform rotation $\rightarrow \gamma$ increases with r


600
400
200
0
0
2
4
log10r/rlc
300
200
100
0
0
2
4
log10r/rlc
150
100
50
0
0
2
4
log10r/rlc
80
60
40
20
0
0
2
4
log10r/rlc

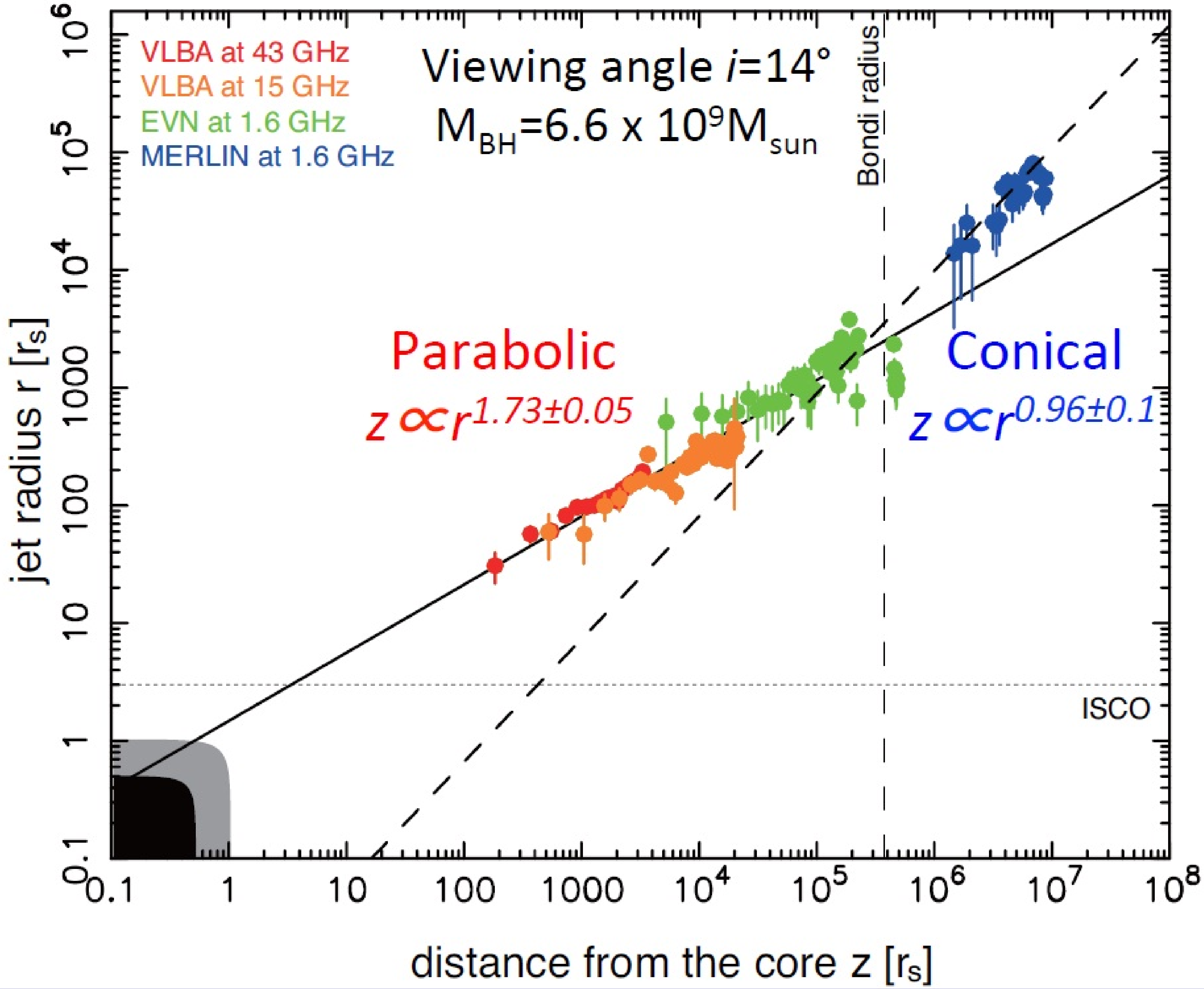
Summary

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

- bulk acceleration up to Lorentz factors corresponding to rough equipartition between kinetic and Poynting fluxes $\gamma_\infty \approx 0.5 \frac{\mathcal{E}}{Mc^2}$
- 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 $\Gamma \propto r$
- the intrinsic rotation of jets could be related to the observed kinematics and to the rotation of EVPA (Marscher et al 2008, Nature)

⋆ The paradigm of MHD jets works in a similar way in all astrophysical jets

(Asada & Nakamura 2011)



The ideal MHD equations

Maxwell:

$$\nabla \cdot \mathbf{B} = 0\,, \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{c\partial t}\,, \nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{\partial \mathbf{E}}{c\partial t}\,, \nabla \cdot \mathbf{E} = \frac{4\pi}{c}J^0$$

Ohm: $\mathbf{E} + \dfrac{\mathbf{V}}{c} \times \mathbf{B} = 0$

mass conservation: $\left(\dfrac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right)(\gamma\rho_0) + \gamma\rho_0 \nabla \cdot \mathbf{V} = 0\,,$

energy $U_\mu T^{\mu\nu}_{,\nu} = 0$: $\left(\dfrac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right)\left(\dfrac{P}{\rho_0^\Gamma}\right) dt = 0$

momentum $T^{\nu i}_{,\nu} = 0$:

$$\gamma\rho_0 \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right)(\xi\gamma\mathbf{V}) = -\nabla P + \frac{J^0\mathbf{E} + \mathbf{J} \times \mathbf{B}}{c}$$

The ideal, steady, GRMHD equations

Maxwell:

$$\nabla \cdot \boldsymbol{B} = 0\,, \nabla \times (h\boldsymbol{E}) = 0\,, \nabla \times (h\boldsymbol{B}) = \frac{4\pi h}{c}\boldsymbol{J}\,, \nabla \cdot \boldsymbol{E} = \frac{4\pi}{c}J^0$$

Ohm: $\boldsymbol{E} + \frac{\boldsymbol{V}}{c} \times \boldsymbol{B} = 0$

mass conservation: $\nabla \cdot (h\gamma n\boldsymbol{V}) = 0\,,$

energy $U_\mu T^{\mu\nu}_{;\nu} = 0$: $n\boldsymbol{V} \cdot \nabla w = \boldsymbol{V} \cdot \nabla P$

momentum $T^{\nu i}_{;\nu} = 0$:

$$\gamma n(\boldsymbol{V} \cdot \nabla)\left(\frac{\gamma w\boldsymbol{V}}{c^2}\right) = -\gamma^2 nw\nabla \ln h - \nabla P + \frac{J^0\boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B}}{c}$$