Relativistic jets
from black holes and disks

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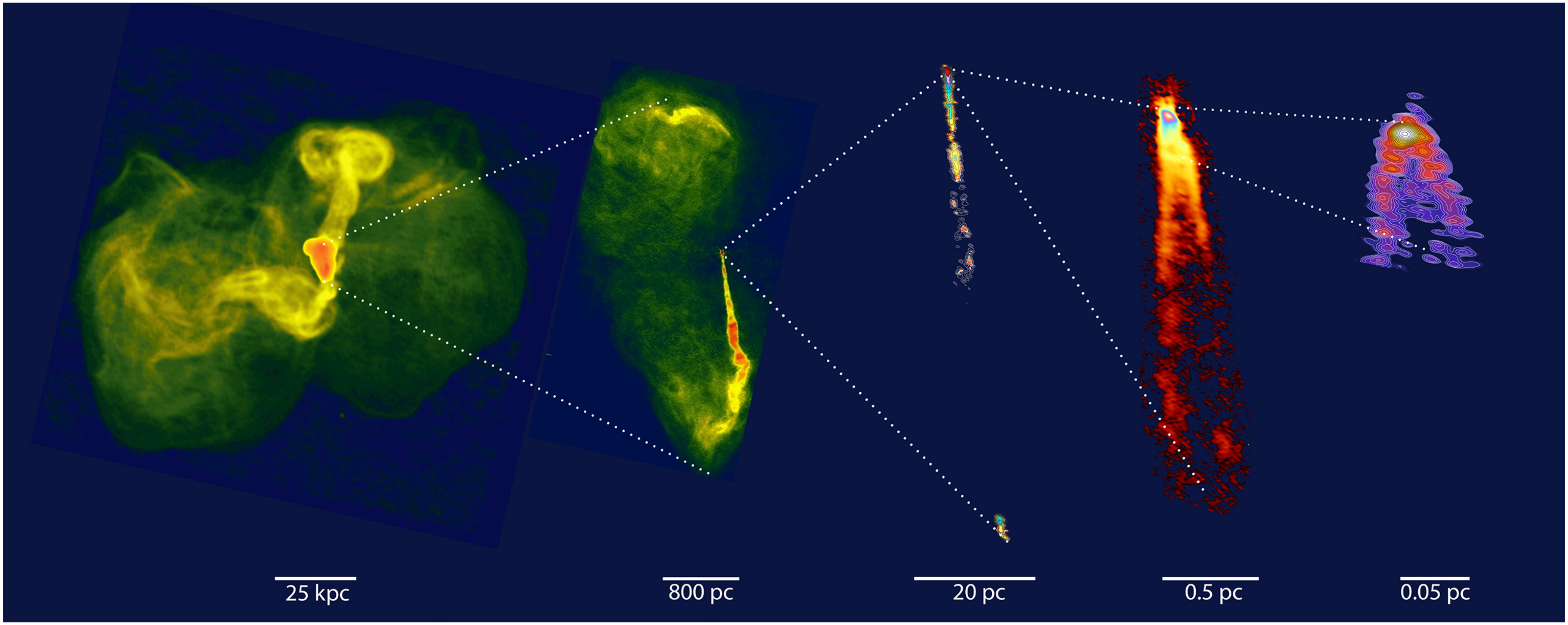
Outline

- observations (AGN jets)
- theoretical questions:
  what defines the asymptotic speed and the jet power
  role of environment
  GR effects (spine jets from black holes)

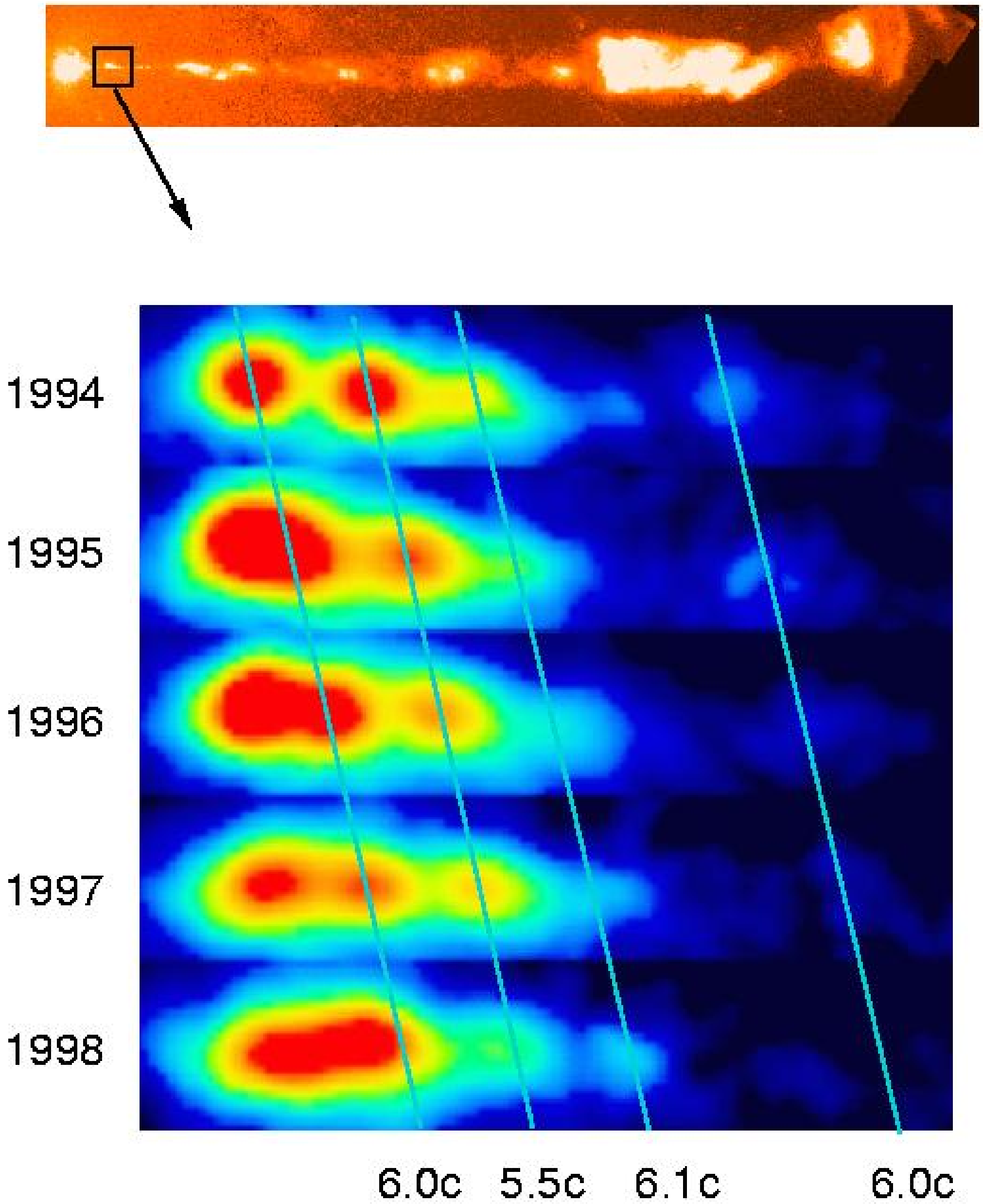
The jet from the M87 galaxy

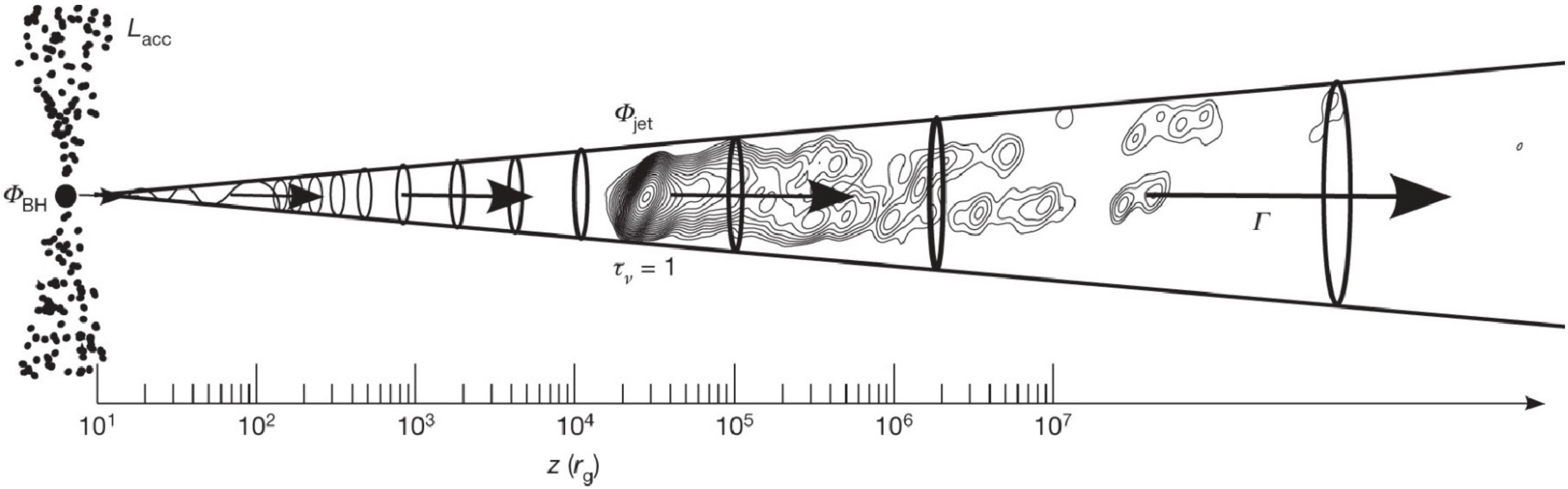


(from Blandford+2018)

The 3rd image shows the HST-I knot, located at the Bondi radius

Superluminal Motion in the M87 Jet

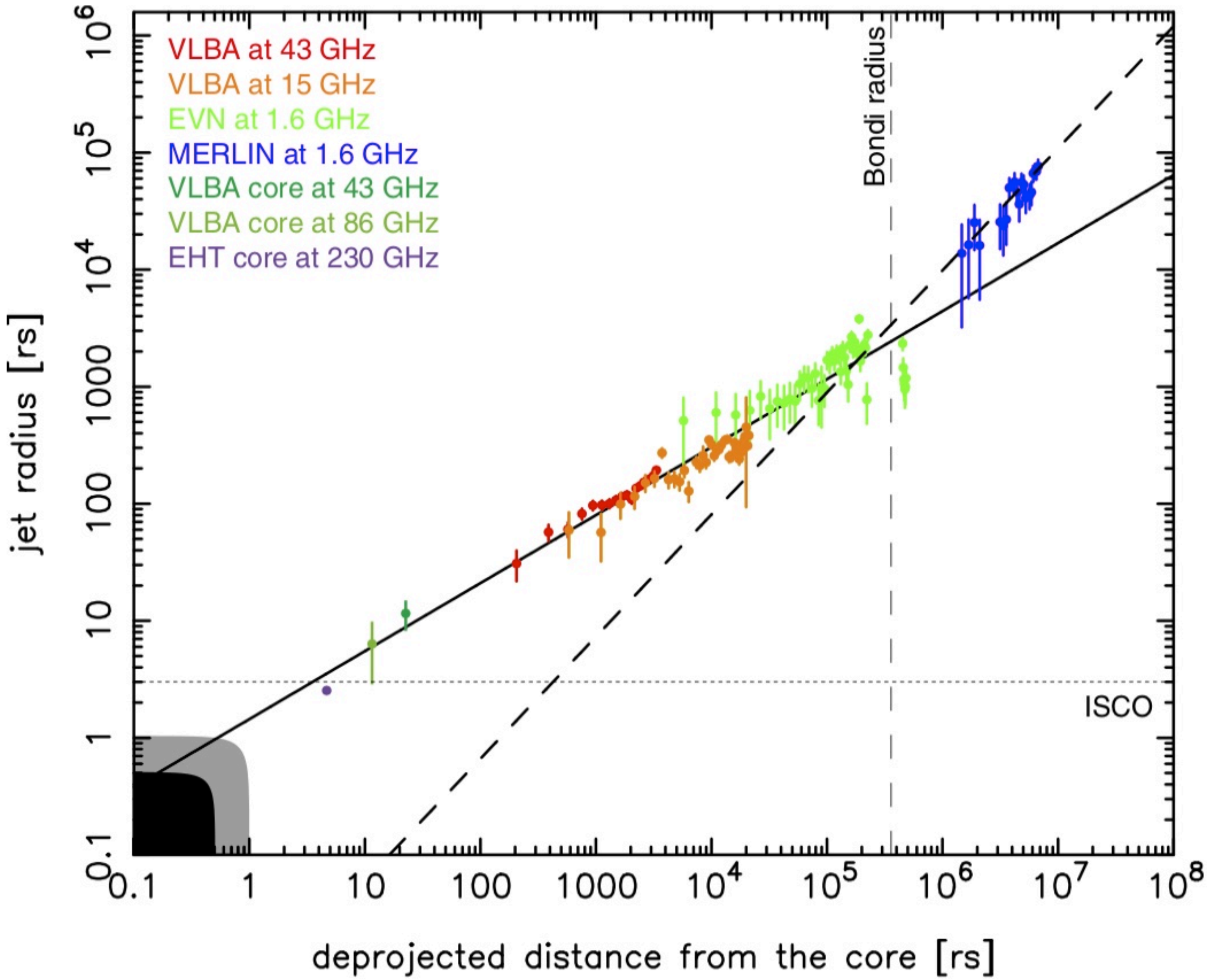




(a sketch of an AGN jet from Zamaninasab+2014)

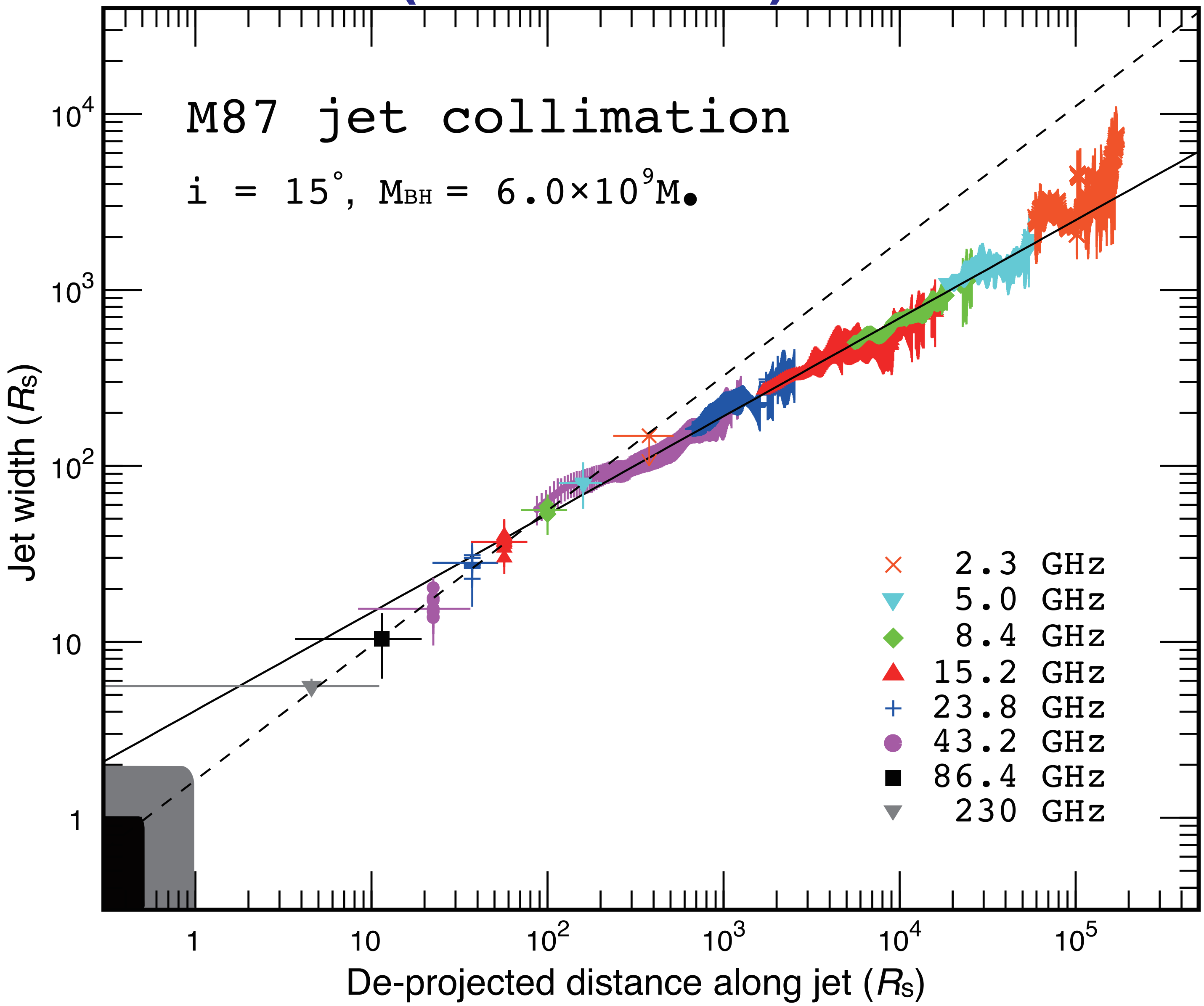
- the position of the radio core (synchrotron self-absorption) depends on frequency
- the core-shift gives the position of the BH
- (also an estimation of the magnetic field, Lobanov 1998)

The jet shape (Nakamura & Asada 2013)



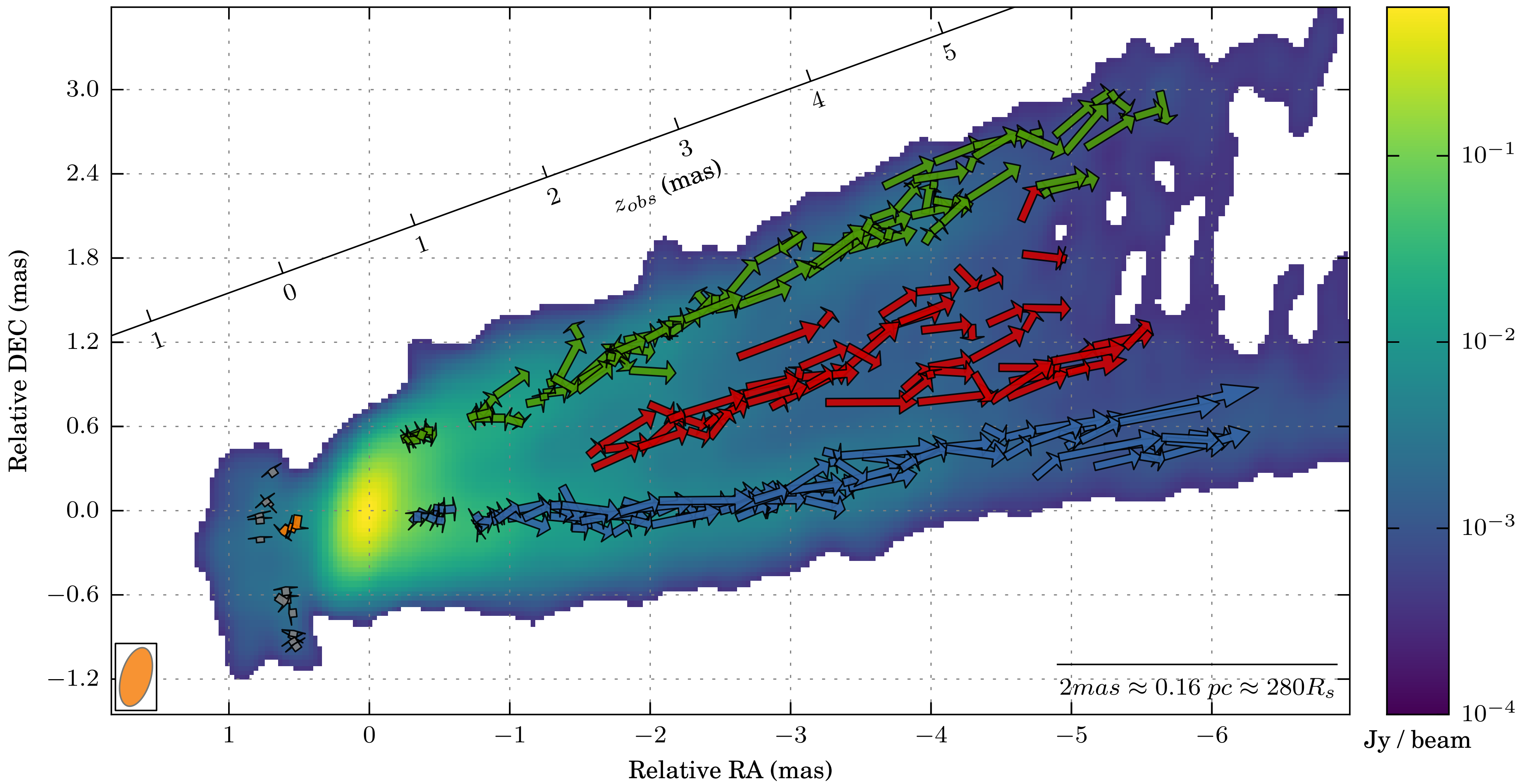
Parabolic (accelerating) up to HST-I, then radial (decelerating)

(Hada+2013)



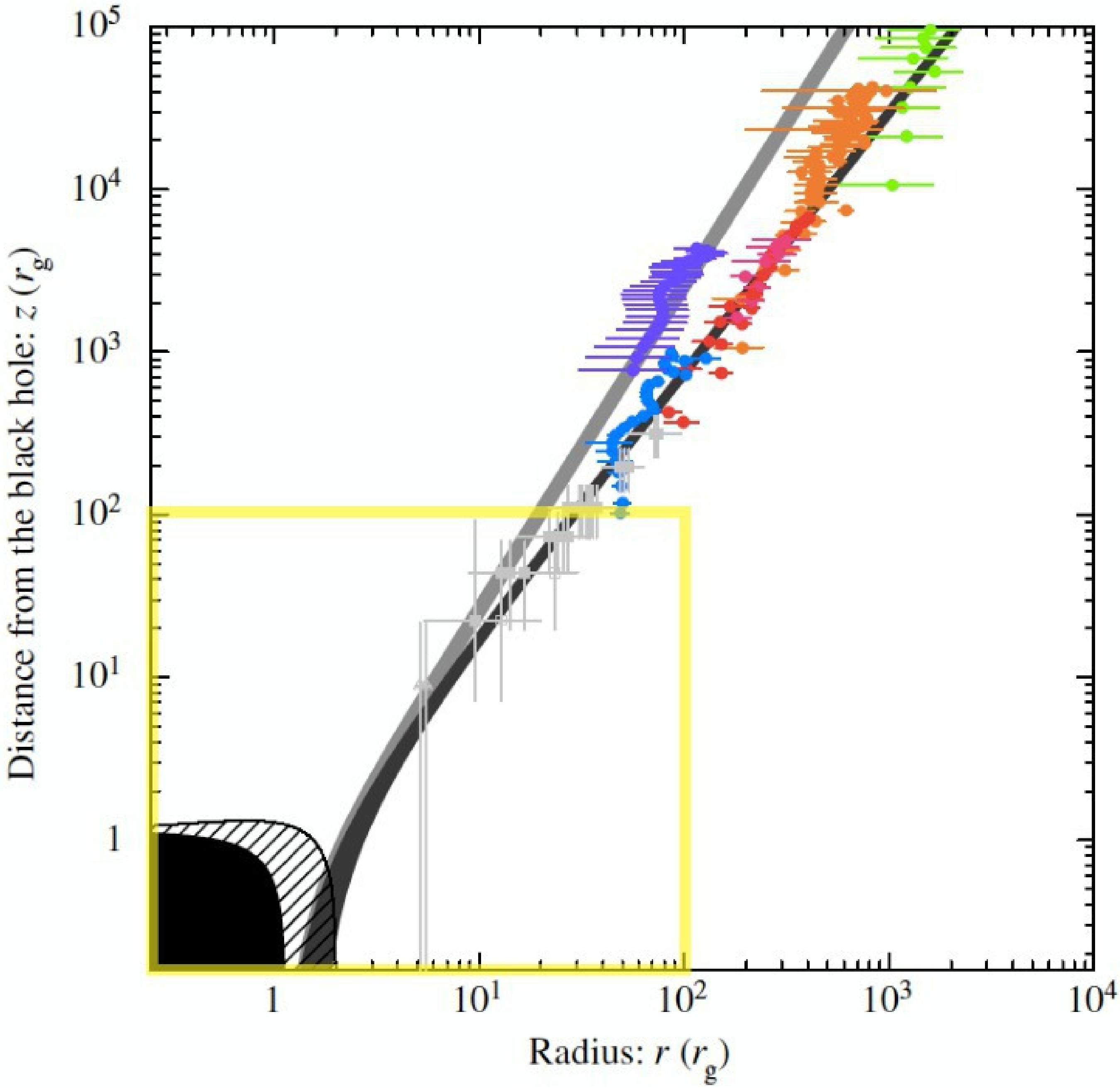
jet from the disk or the black hole?

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)



10^5
10^4
10^3
10^2
10^1
1
Distance from the black hole: z (r_g)
1
10^1
10^2
10^3
10^4
Radius: r (r_g)

Theoretical modeling

- For disk-driven jets:

☞ mass loading from accretion (baryonic)

☞ if energy source = thermal energy then

$$\dot{\mathcal{E}} = cT^{0z} \times \pi \varpi^2 = \gamma^2 V \left(\rho_0 c^2 + \frac{\Gamma}{\Gamma - 1} P \right) \pi \varpi^2$$

$$\dot{M}_{jet} = \gamma \rho_0 V \times \pi \varpi^2$$

$\mu = \dfrac{\dot{\mathcal{E}}}{\dot{M}_{jet} c^2} =$ maximum possible asymptotic Lorentz factor

thermal acceleration is an efficient mechanism
gives Lorentz factors $\gamma \sim \mu \sim k_{\rm B} T_i / m_p c^2$
need very high initial temperatures T_i to explain the observed motions ($\gamma =$ few 10 in AGN jets)

☞ magnetic acceleration more likely

if energy source = magnetic:

- ☞ B_z field threads the disk
  (magnetic field from advection, or MRI, or cosmic battery)

- ☞ disk rotation creates $B_\phi \sim \frac{\varpi\Omega}{c} B_z$ and electric field $E \sim B_\phi$

- ☞ magnetic field + disk rotation $\rightarrow$ extraction of Poynting flux

  $$\dot{\mathcal{E}} = cT^{0z} \times \pi\varpi^2 = \frac{c}{4\pi} E B_\phi \times \pi\varpi^2 \sim \frac{c}{4\pi}\left(\frac{\varpi\Omega}{c}\right)^2 B_z^2 \times \pi\varpi^2,$$

  or in terms of magnetic flux $\dot{\mathcal{E}} = \frac{\Omega^2\Phi^2}{4\pi^2 c}$

  $$\dot{M}_{jet} = \gamma\rho_0 V \times \pi\varpi^2$$

  $\mu = \frac{\dot{\mathcal{E}}}{\dot{M}_{jet} c^2} =$ maximum possible asymptotic Lorentz factor

- ☞ often called “Blandford & Payne” modeling

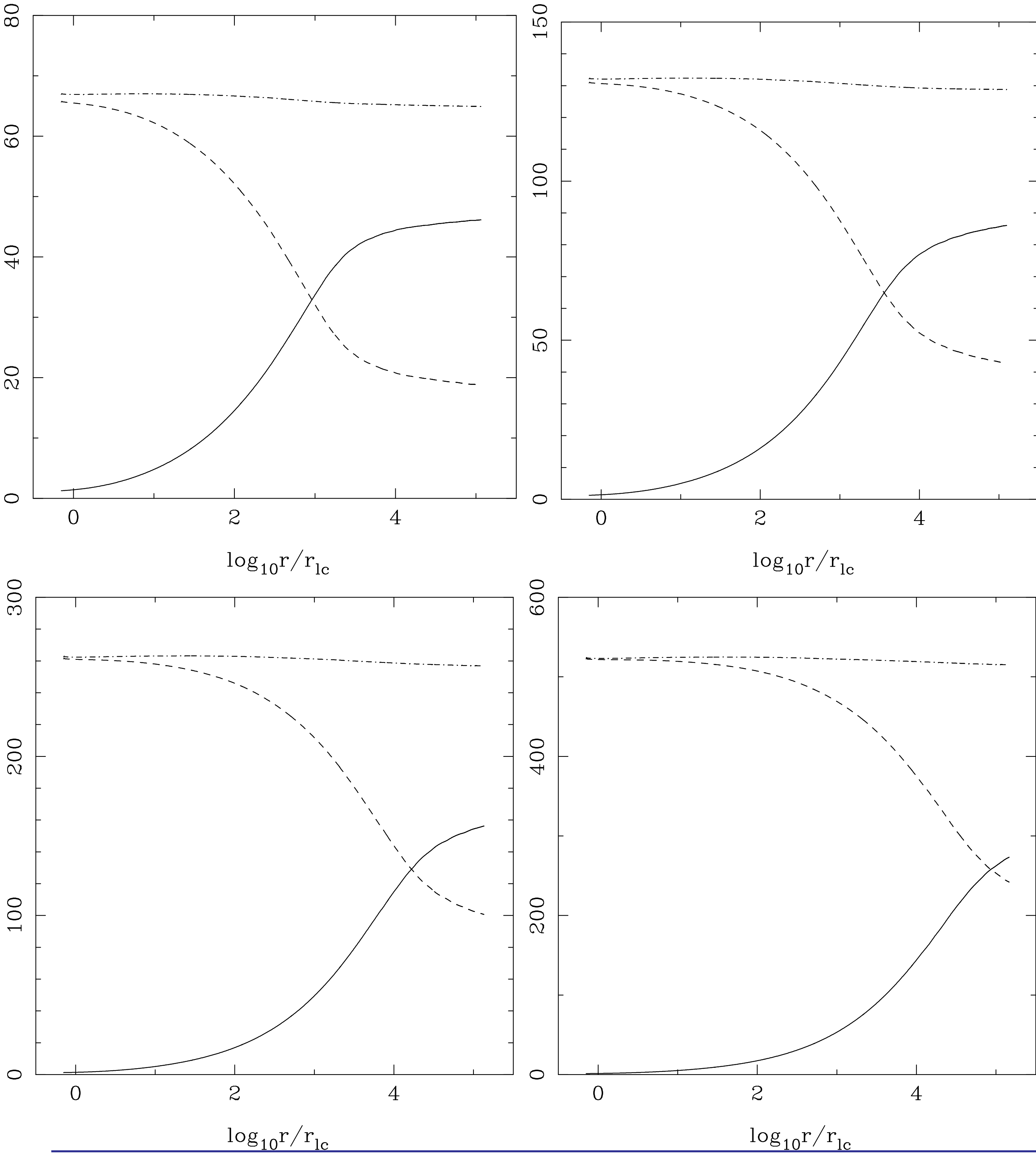
Disk-driven relativistic MHD jets

bulk acceleration ✓

• Analytical steady-state special-relativistic self-similar MHD models (Li, Chiueh & Begelman 1992, Contopoulos 1994, Vlahakis & Königl 2004)
$\rightarrow$ efficient conversion of Poynting to kinetic energy flux

• Verified and extended by axisymmetric special-relativistic MHD simulations of jets confined by rigid walls (Komissarov, Vlahakis & Königl 2007 & 2009, Tchekhovskoy, McKinney & Narayan 2009)

• role of confinement by the wall (by the environment):
For GRB jets with $\gamma \gtrsim 100$ achievable only for confined outflows (unconfined remain Poynting dominated)
However for AGN jets even unconfined flows are efficiently accelerated



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 $> 50\%$

Parabolic jet shape ✓

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

BH-driven jets

- If the spine comes from the B-H:

☞ mass loading from pair creation at the “stagnation surface”

☞ (also possible through diffusion of disk material)

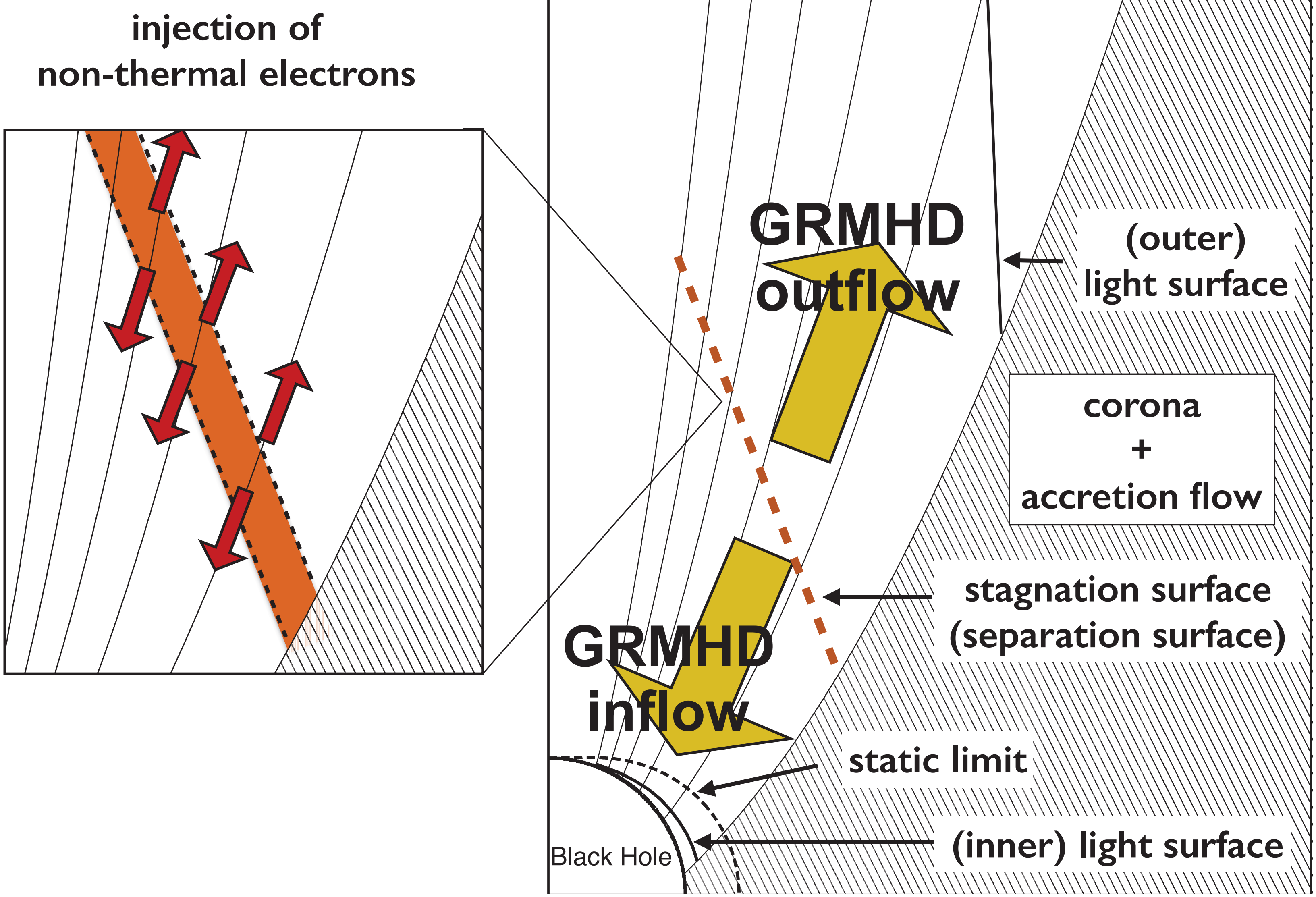
☞ Hydrodynamic acceleration $\rightarrow$ Lorentz factors $\gamma \sim k_{\rm B} T_i / m_e c^2$ cannot be ruled out

☞ magnetic acceleration still more likely

☞ $\boldsymbol{B}$ field through advection from the disk

☞ energy source = B-H spin

☞ often called “Blandford & Znajek” modeling



injection of
non-thermal electrons
GRMHD
outflow
(outer)
light surface
corona
+
accretion flow
stagnation surface
(separation surface)
GRMHD
inflow
static limit
(inner) light surface
Black Hole

(from Pu+2017)

similarly to disk-driven MHD jets:

☞ B_z field threads the BH

☞ BH rotation creates $B_\phi \sim \dfrac{\varpi\Omega}{c} B_z$ and electric field $E \sim B_\phi$

with Ω a fraction of $\Omega_H = \dfrac{a}{1+\sqrt{1-a^2}} \dfrac{c^3}{2GM}$ ($a =$ BH spin)

☞ magnetic field + BH rotation $\rightarrow$ extraction of Poynting flux

$$\dot{\mathcal{E}} = cT^{0r} \times \text{ area } \sim \frac{\Omega^2\Phi^2}{4\pi^2 c}$$

$$\dot{M}_{jet} = \gamma\rho_0 V \times \pi\varpi^2$$

$\mu = \dfrac{\dot{\mathcal{E}}}{\dot{M}_{jet}c^2}$ = maximum possible asymptotic Lorentz factor

☞ values of Ω/Ω_H, Φ, $\dot{M}_{jet}$?

Magnetically Arrested Disks (Tchekhovskoy+2011)

- start with a donut disk around a Kerr BH
run ideal GRMHD simulation

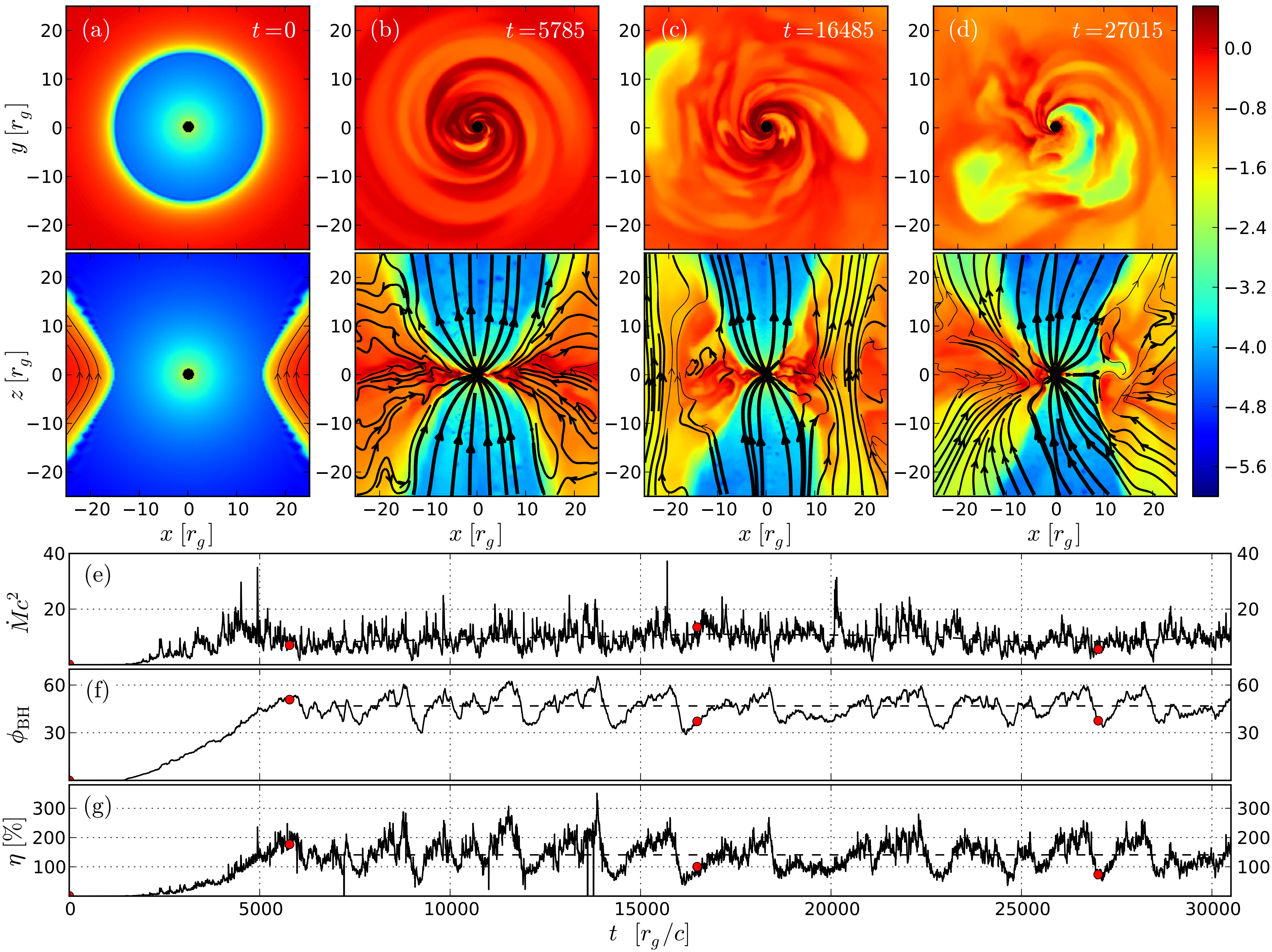
- MRI increases B

- B is advected through accretion $\rightarrow$ B threads the BH

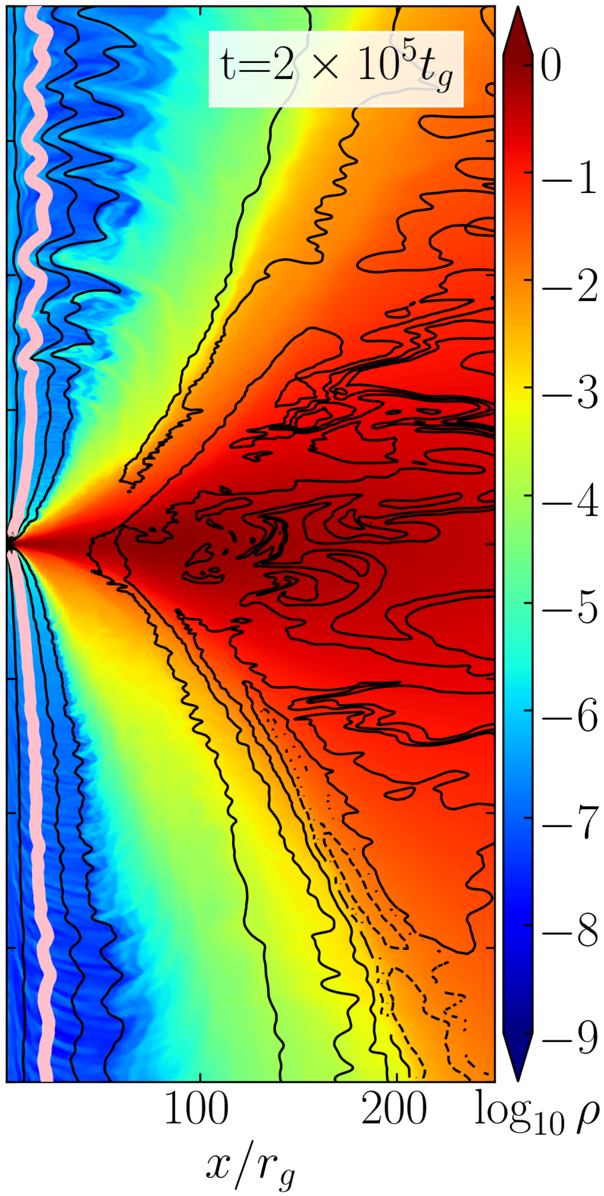
- Φ increases till magnetic pressure = accretion ram pressure
this sets Φ

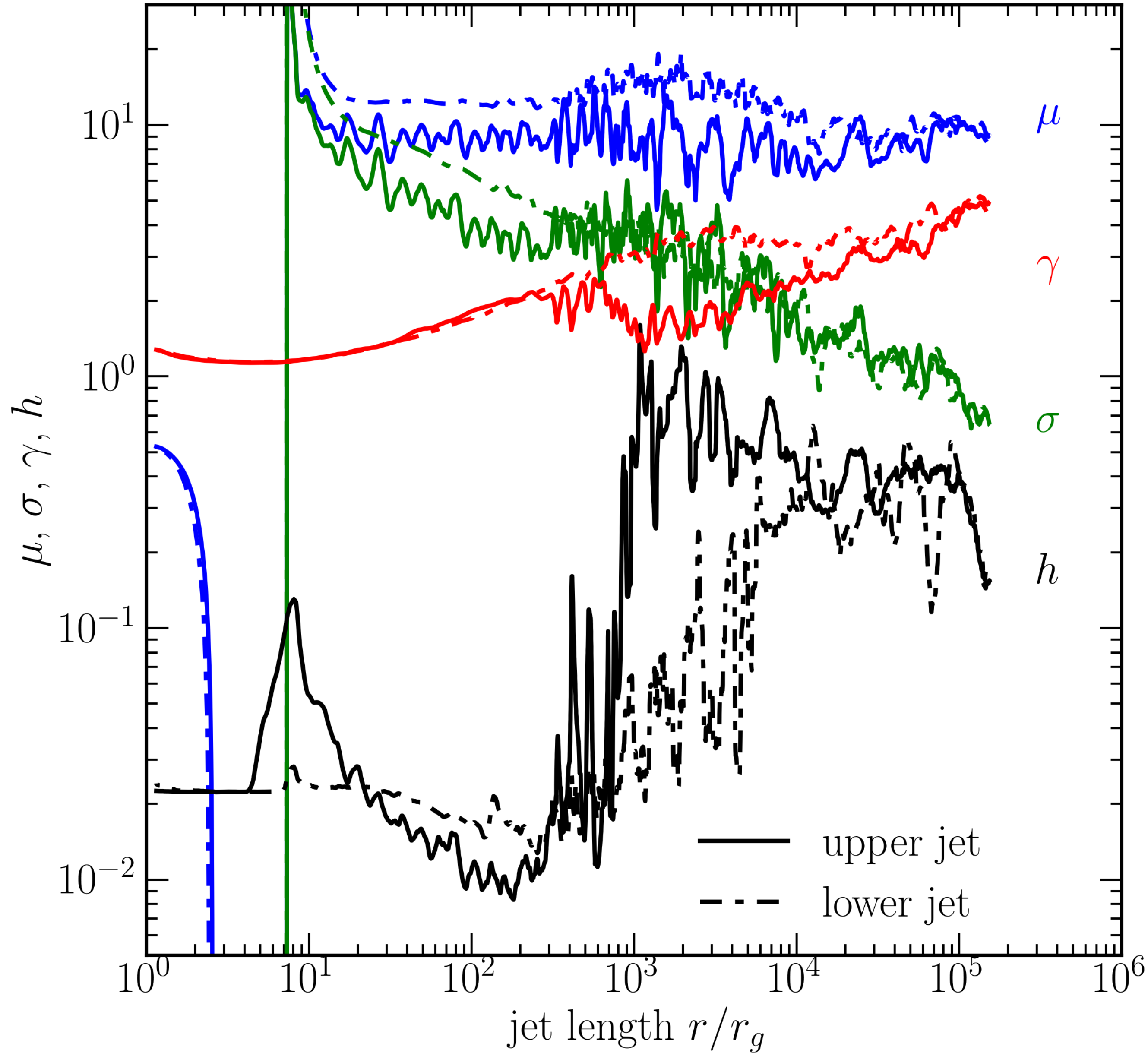
- Φ may be high enough to make $\dot{\mathcal{E}}$ higher than $\dot{M}_{acc}c^2$
the difference is interpreted as ejected BH spin energy

- $\dot{M}_{jet}$ is probably related to the floor density (minimum allowed value for numerical reasons)
this mimics the pair creation at the stagnation surface


(a)
t = 0
(b)
t = 5785
(c)
t = 16485
(d)
t = 27015
y [r_g]
z [r_g]
x [r_g]
(e)
$\dot{M}c^2$
(f)
ϕ_{BH}
(g)
η [%]
t [r_g/c]

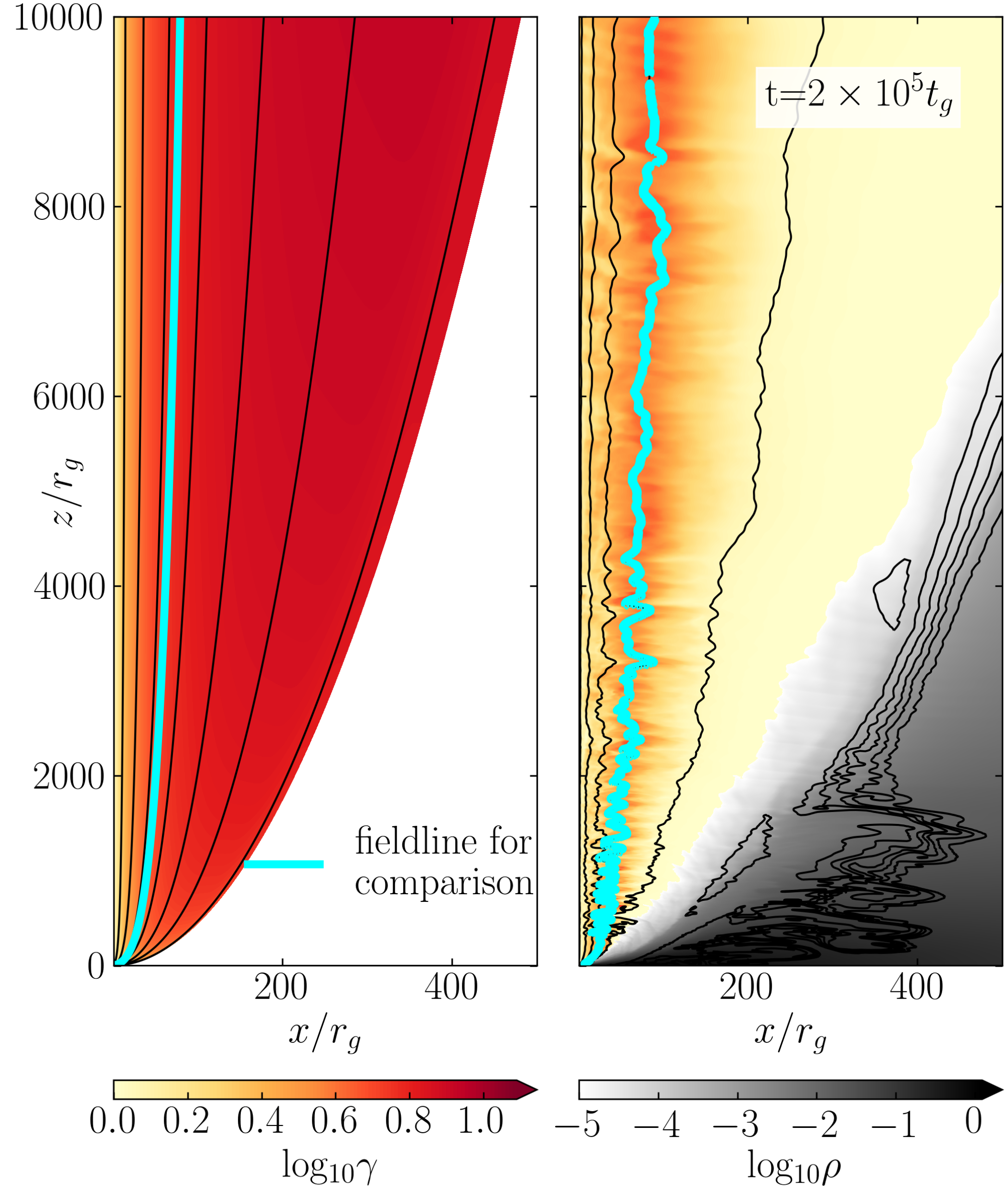
for given $\dot{\mathcal{E}}$ and $\dot{M}_{jet}$ bulk acceleration works as in disk-driven jets





(Chatterjee+2019)

GR effects and the absence of wall do not change drastically the results (besides the “pinch instabilities” whose origin is unclear)



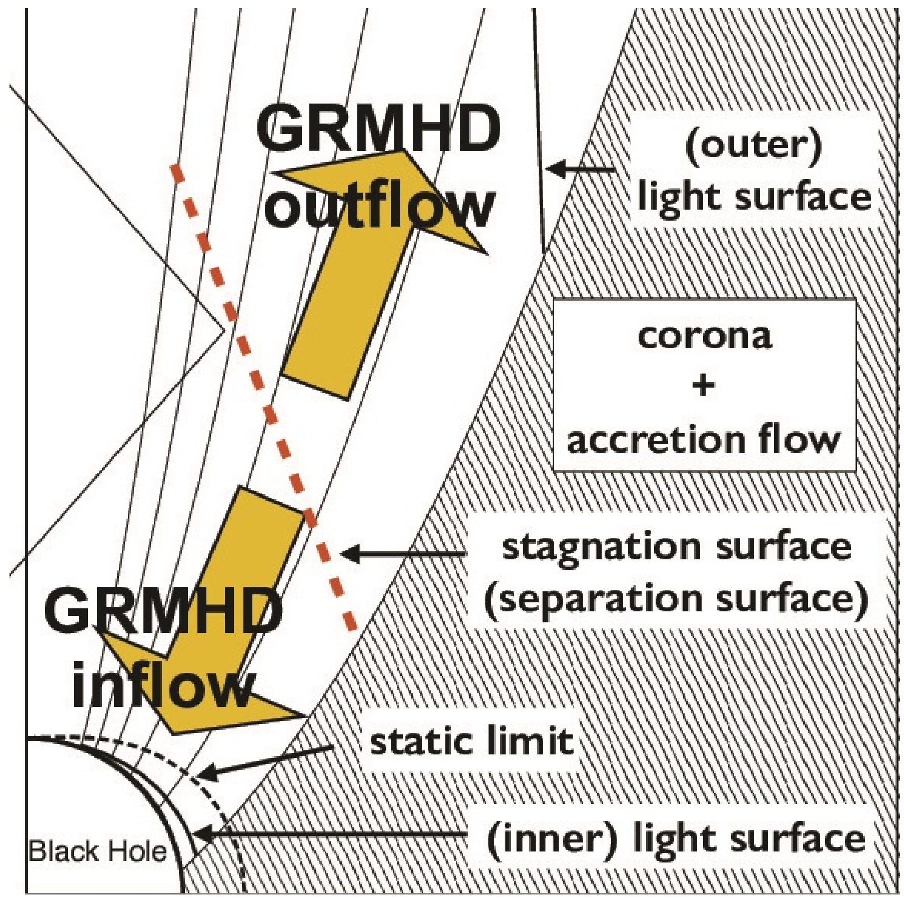
Other tries

besides numerical simulations (that can be improved wrt floor density and disk resistivity) other analytical tries include:

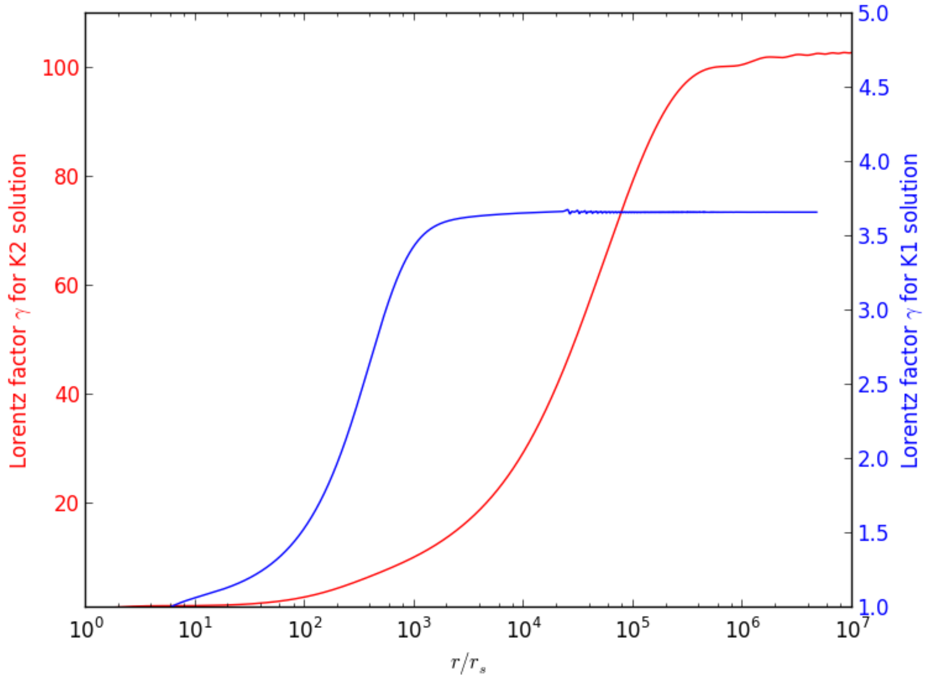
- Nathanail & Contopoulos (2014) assumed force-free magnetosphere and found the current and Ω distributions, i.e. the functions $B_\phi(\varpi)$ and $\Omega(\varpi)$, from the crossing of the two light surfaces (inner and outer)

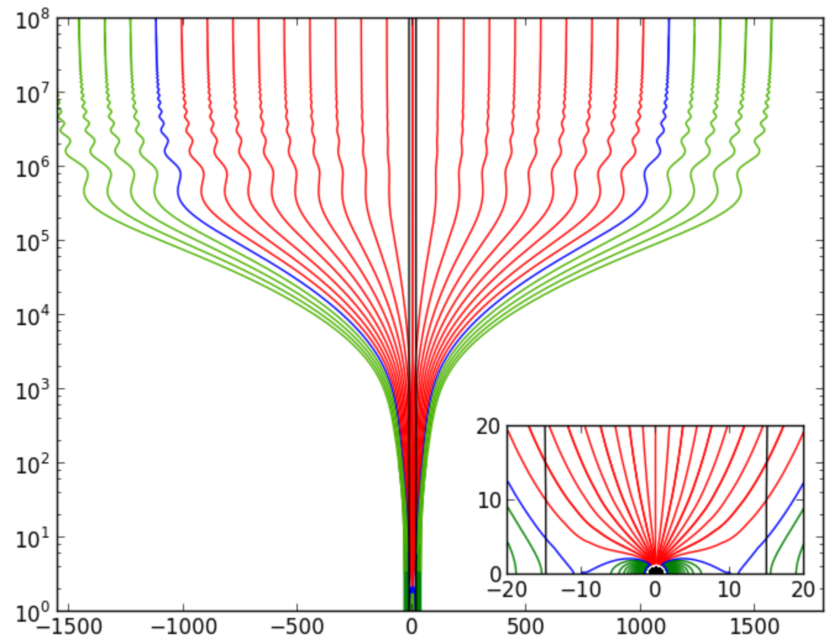
results consistent with

$$\frac{\Omega}{\Omega_H} \sim 0.5\,, \qquad B_\phi \approx \frac{\varpi\Omega}{c} B_z$$



- Chantry+2018 derived a meridionally self-similar model (nonpolytropic) based on expansions of all physical quantities near the symmetry axis.





The outflow solutions cross slow magnetosonic and Alfvén critical surfaces

- Another paper (Chantry+2019) is in preparation with inflow solutions and correct matching at the stagnation surface

Summary – Discussion – Next steps

- ⋆ bulk acceleration and jet morphology successfully explained by ideal magnetohydrodynamics
(GR effects and interaction with environment do not substantially change these results)

- ⋆ fluctuations due to interaction with environment ?
(stability analysis)

- ⋆ for BH-driven jets the mass loading and the advection of magnetic flux need to be better understood

- ⋆ analytical solutions may help even if they are based on expansions and do not hold everywhere (crossing of critical surfaces constrain the parameters and give important information)