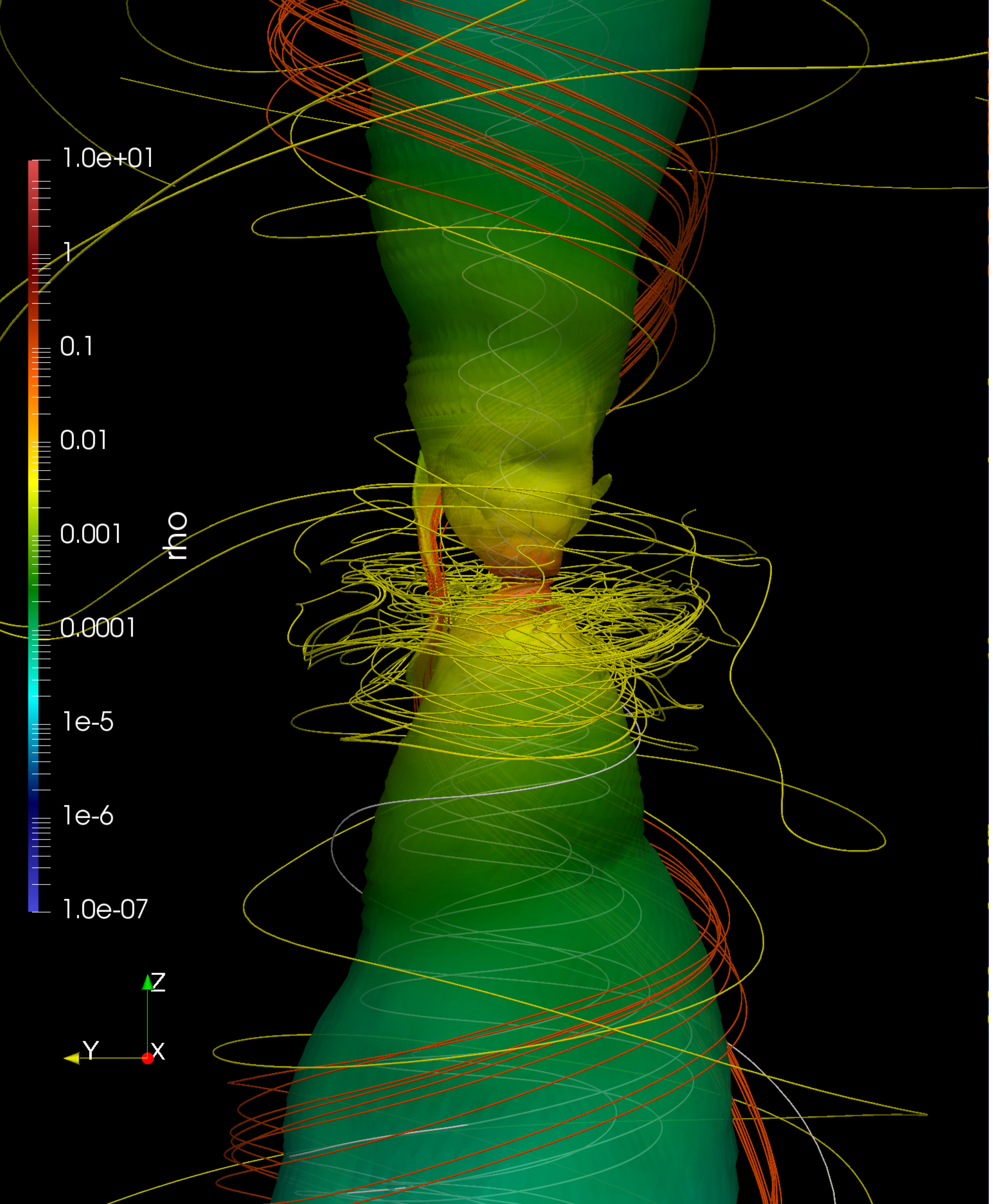


Jet collimation and acceleration

Oliver Porth
Anton Pannekoek Institute, Amsterdam

European Research Council

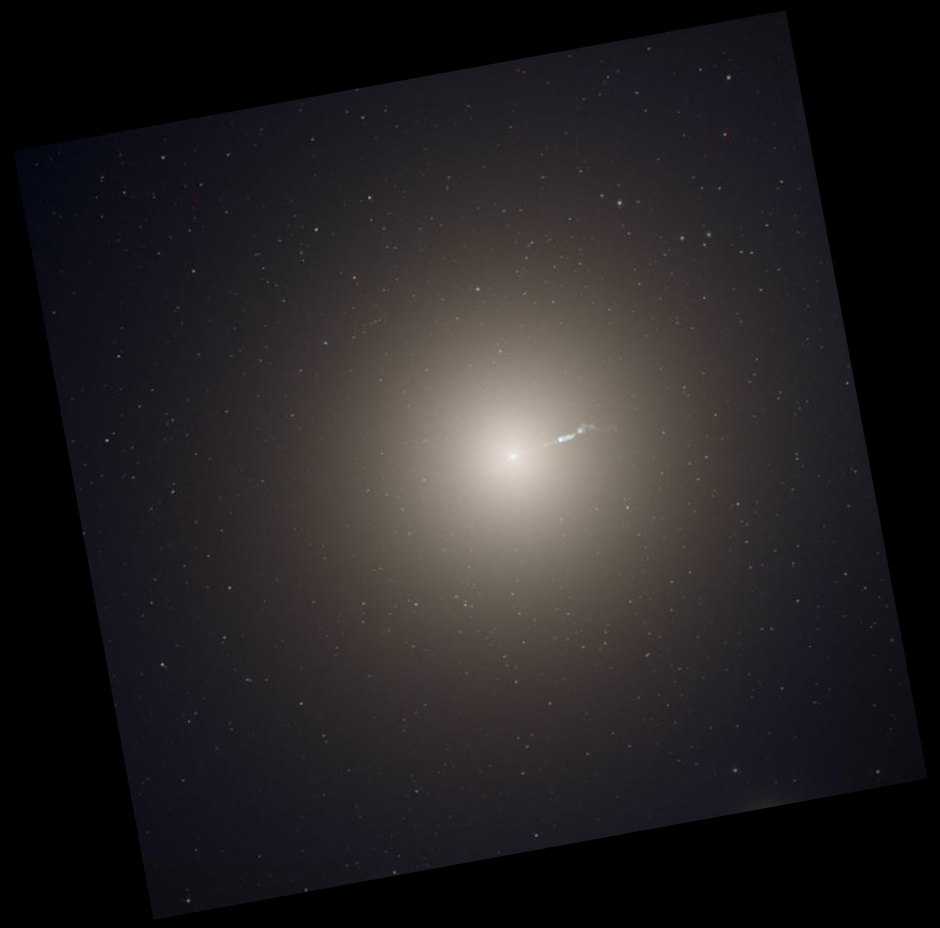
ANTON PANNEKOEK INSTITUTE

Event Horizon Telescope

The radio jet in M87 (Virgo A)

Elliptical galaxy in center of Virgo cluster 50 Million lightyears away

There is evidence for a central dark mass of $3\text{-}6\times10^9\ M_{sun}$



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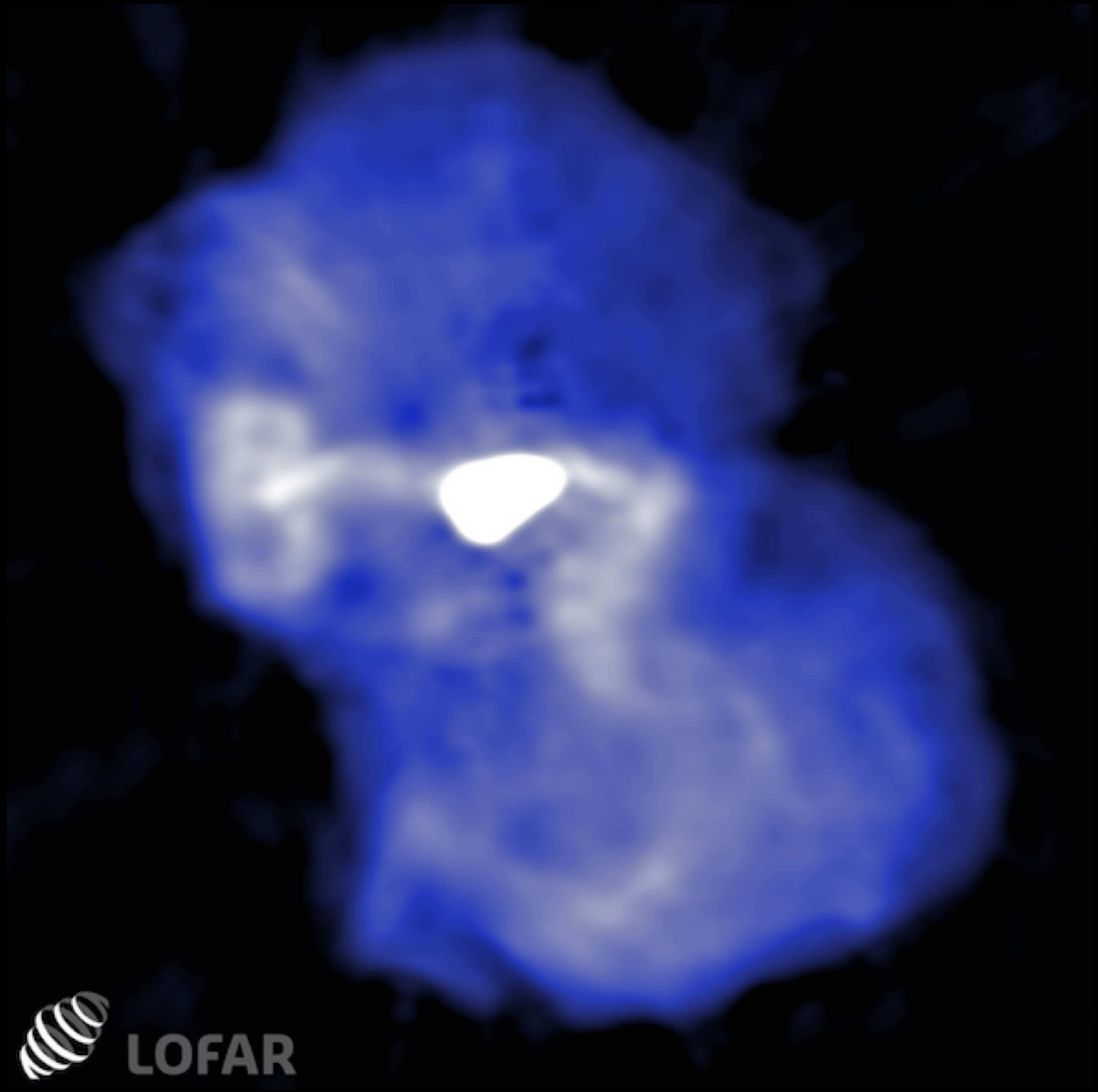

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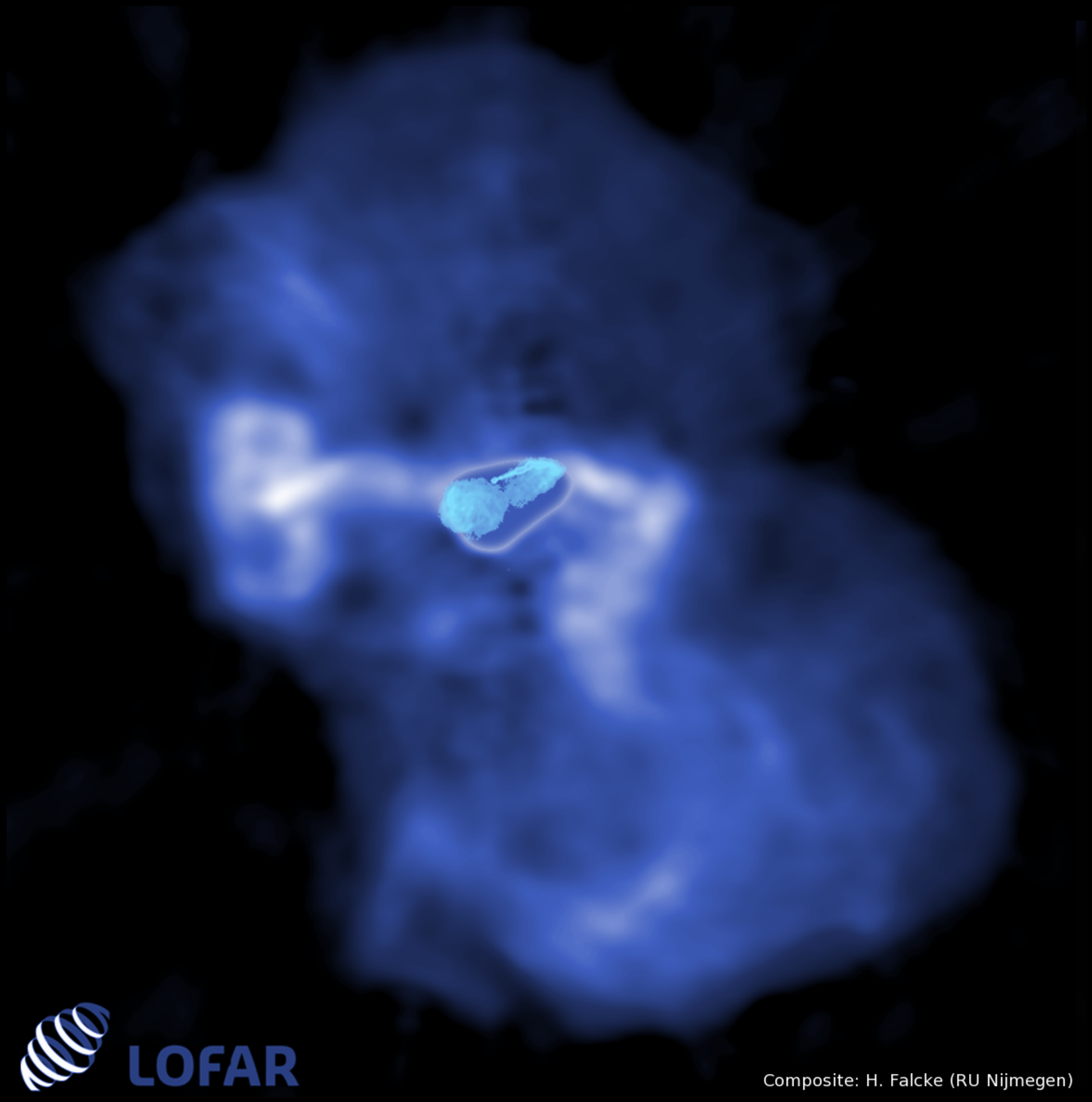

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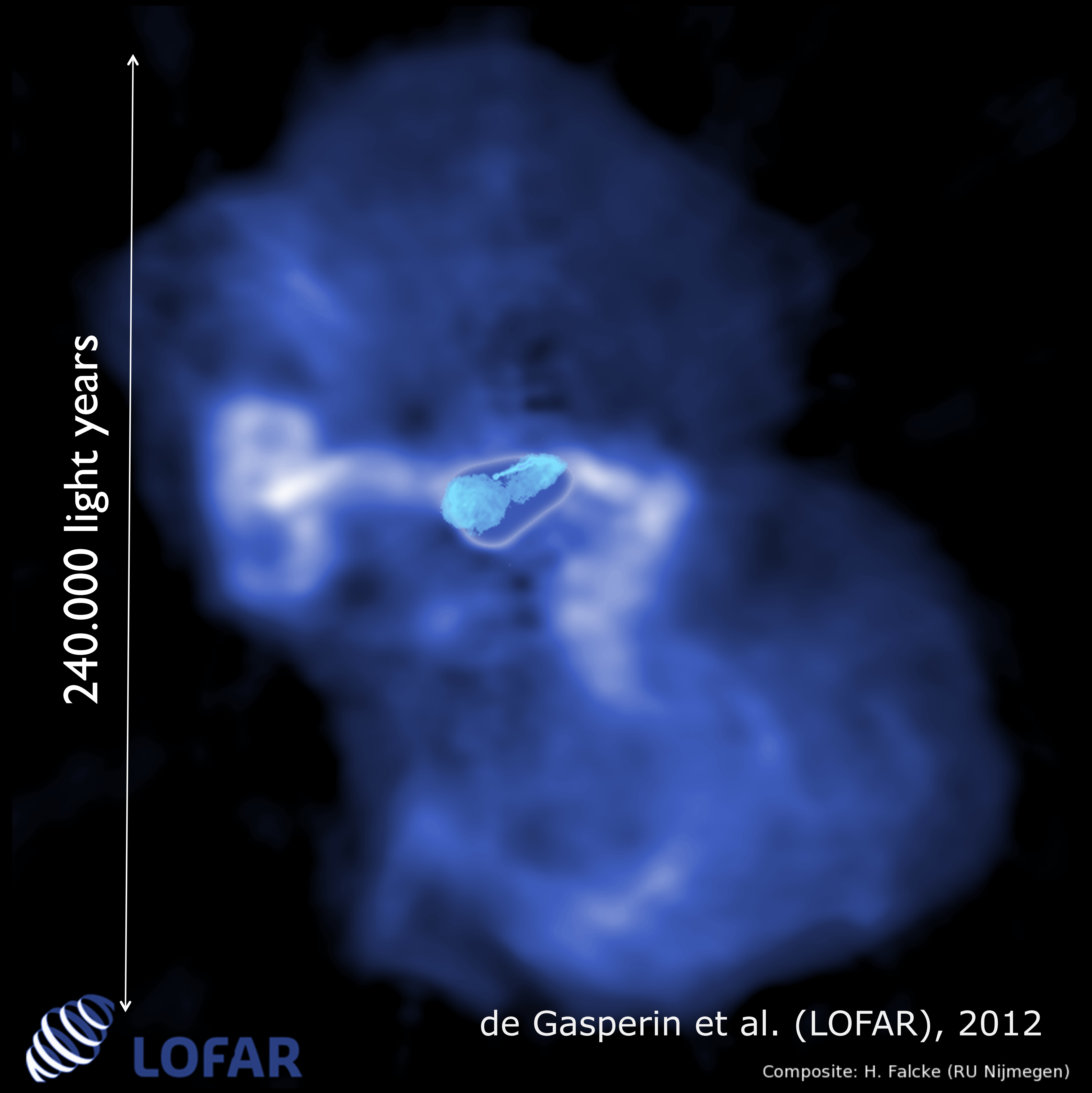

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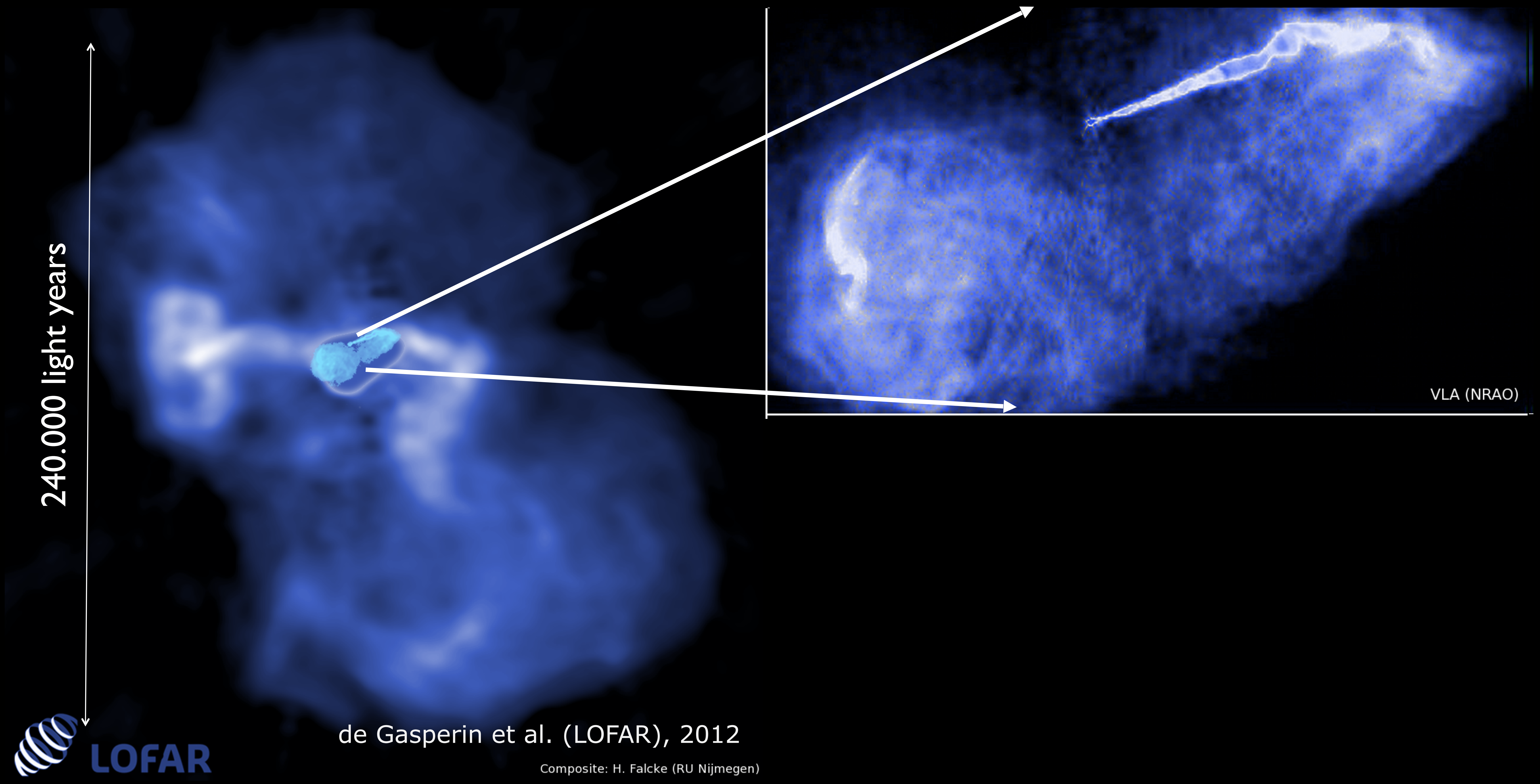

de Gasperin et al. (LOFAR), 2012

Composite: H. Falcke (RU Nijmegen)

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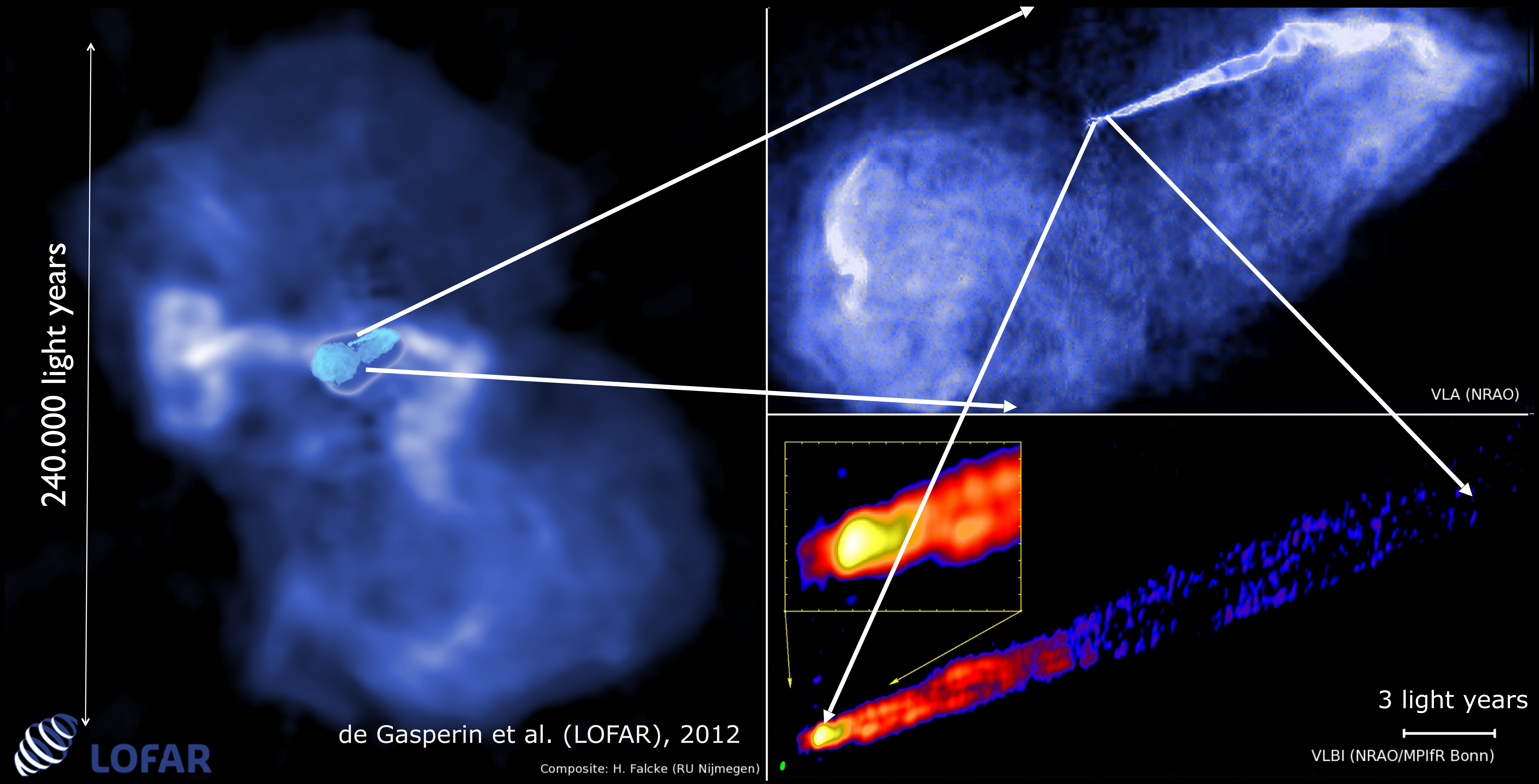

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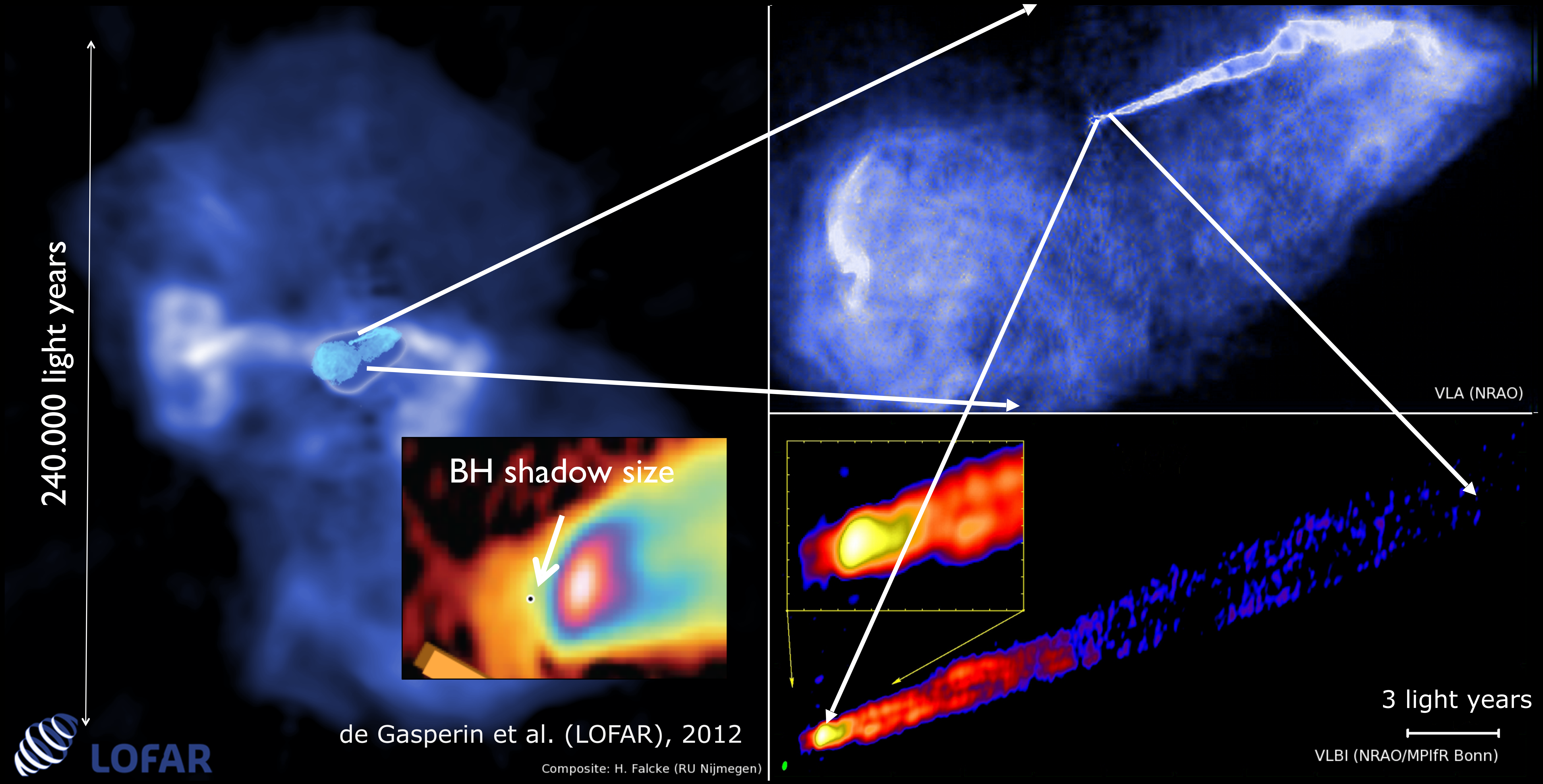

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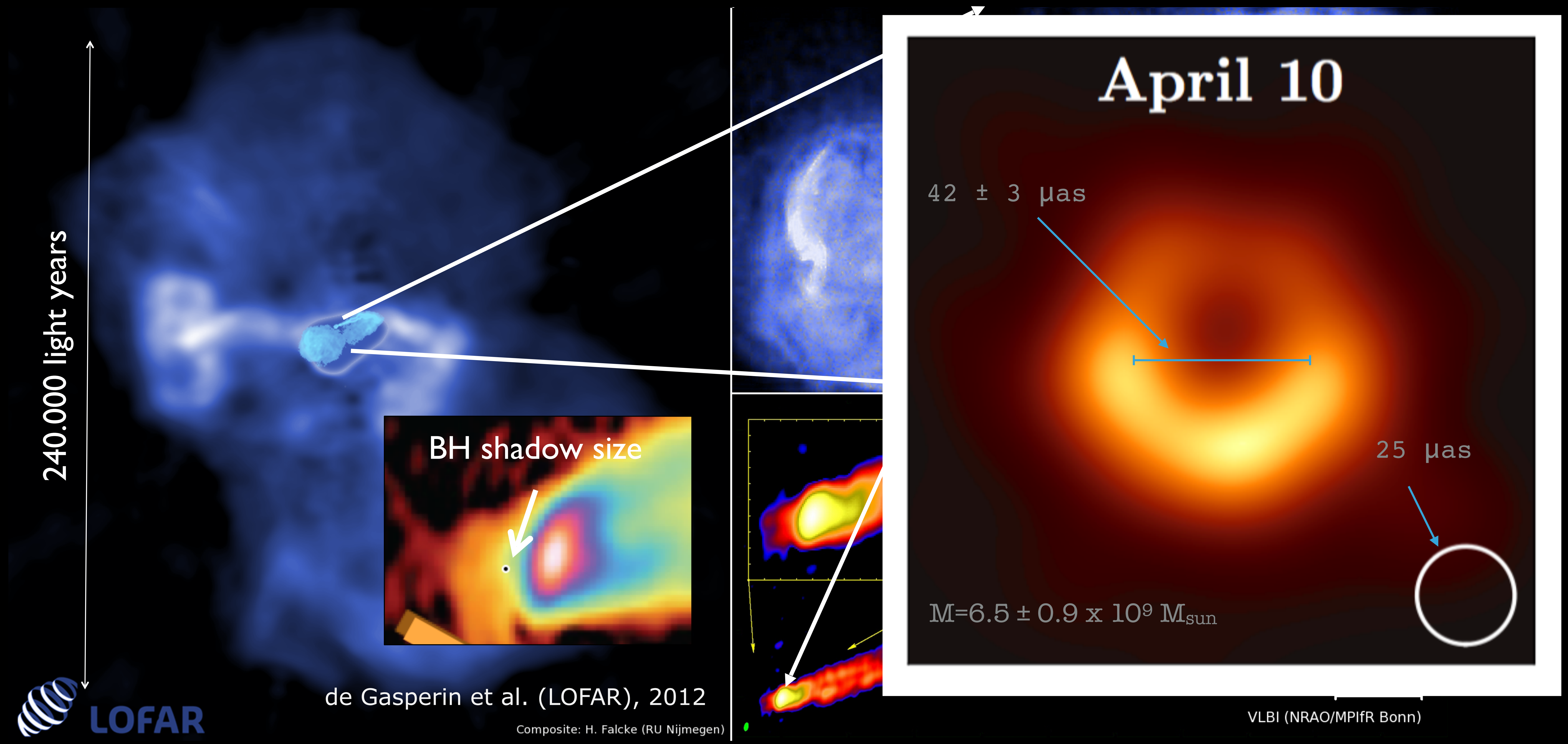
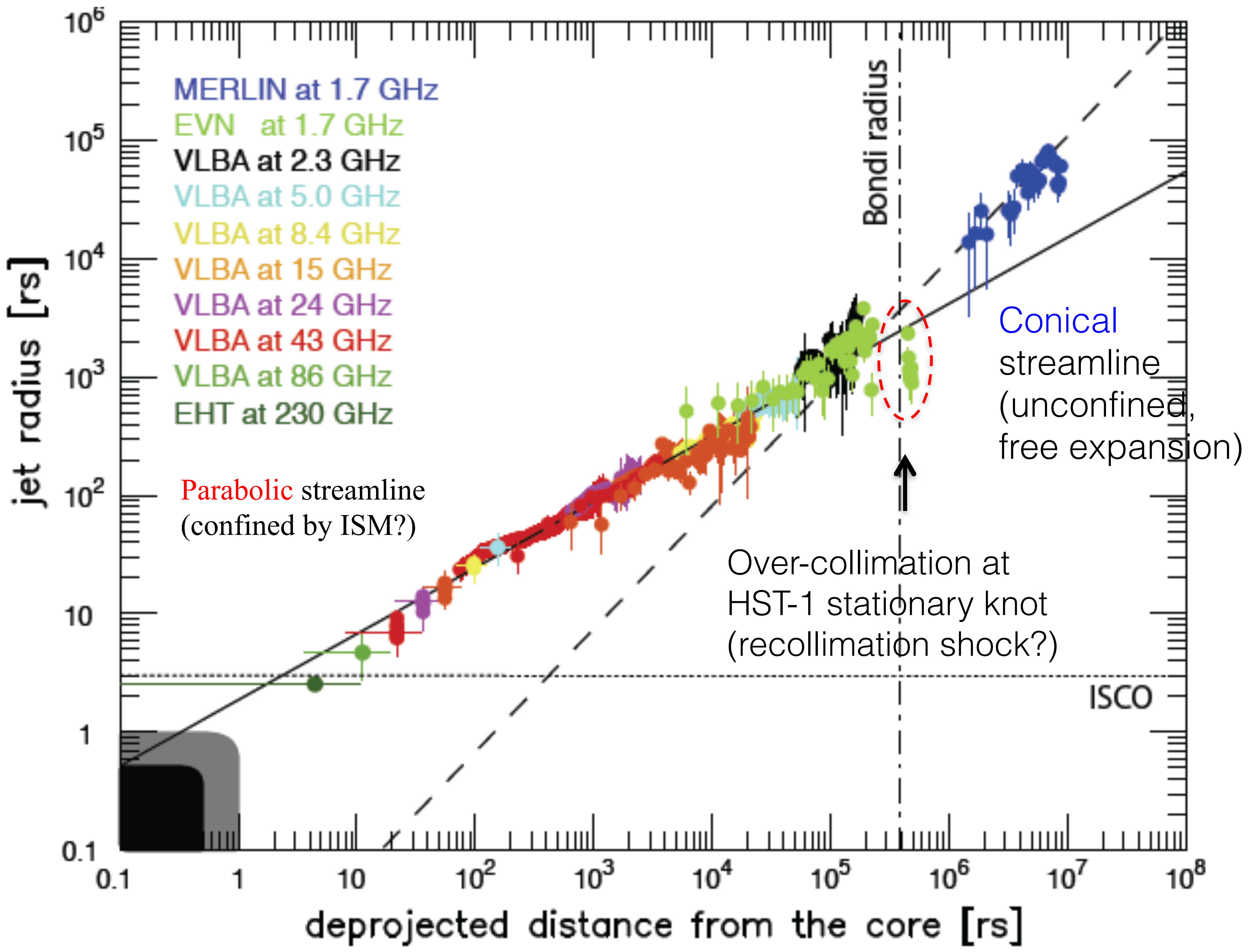


Global Structure of M87

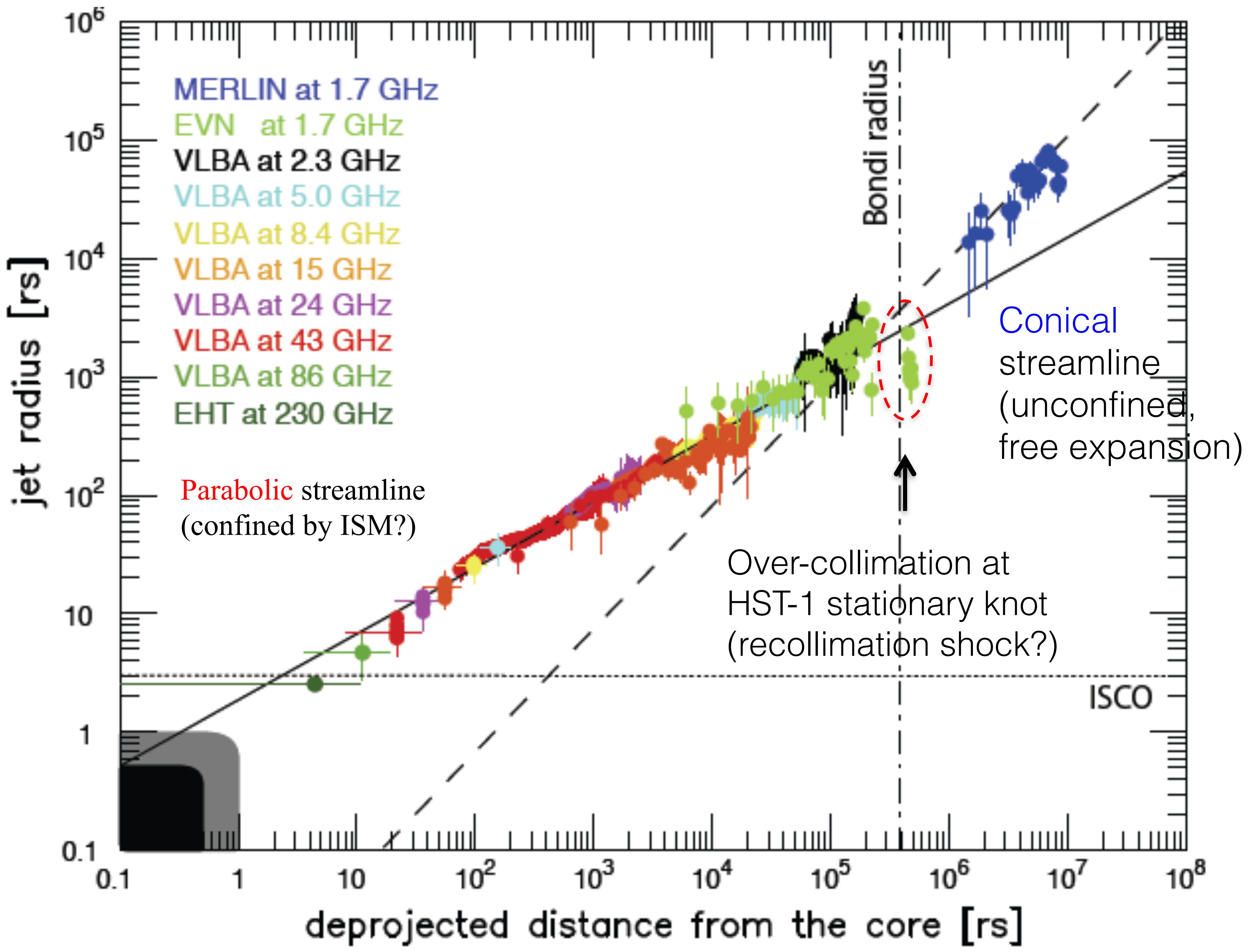


Asada & Nakamura (2012), Hada et al. (2013)

[1]Reynolds et al. (1996), Li et al. (2009), de Gasperin et al. (2012), Broderick et al. (2015), Prieto et al. (2016)

Global Structure of M87

- **Parabolic ($z \propto r^{1.7}$)** over 10^5 r_s
- Above bondi sale: **conical** streamlines **$z \propto r$**



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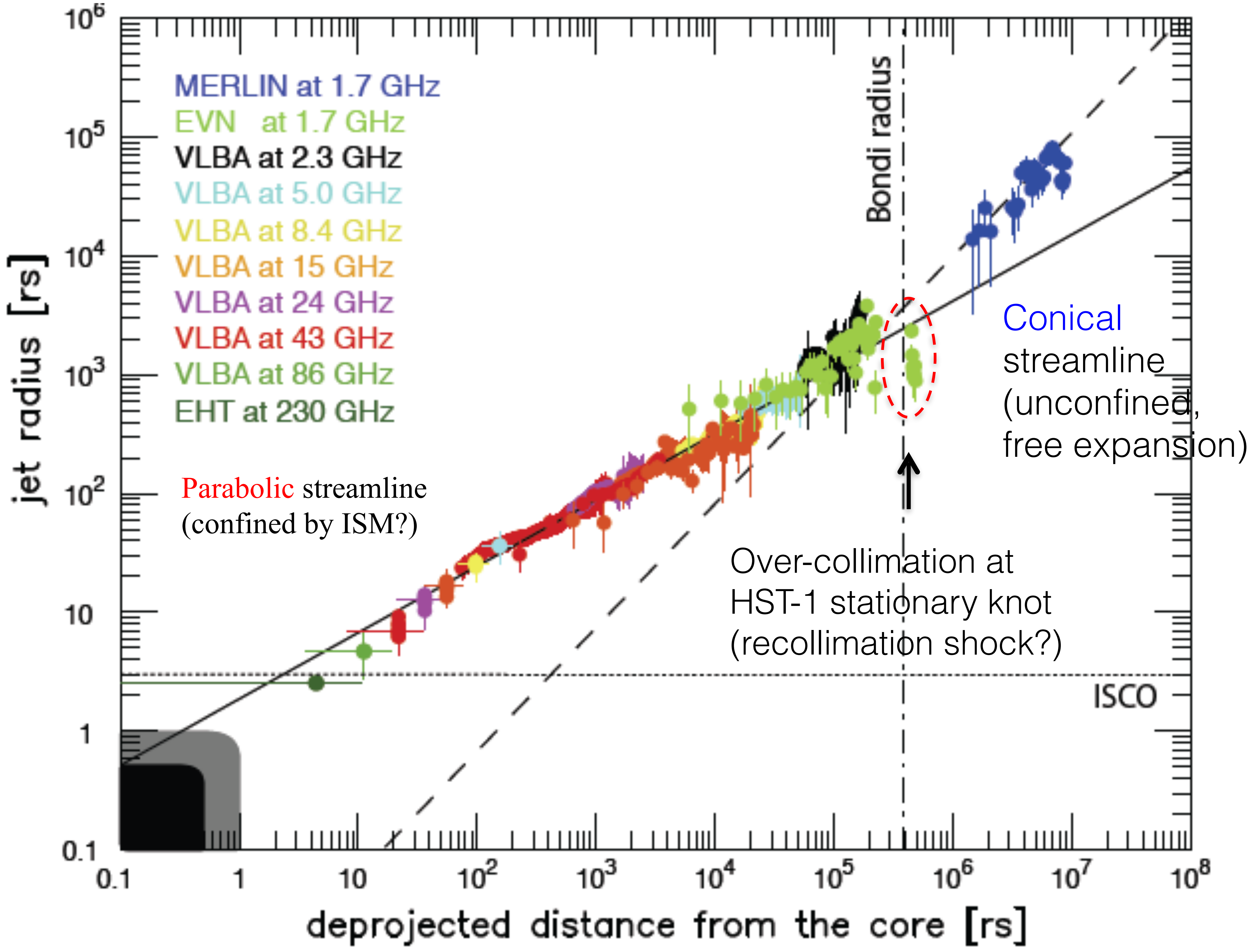


Asada & Nakamura (2012),
Hada et al. (2013)

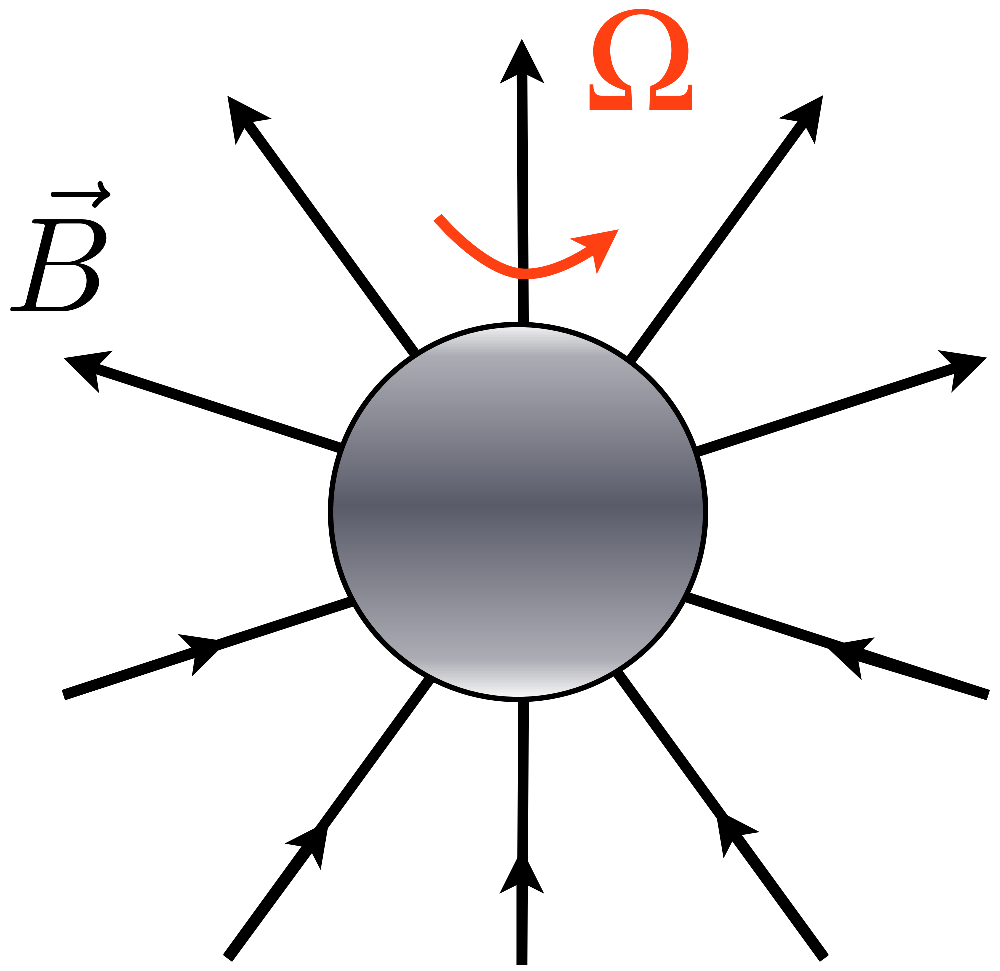
```
Jet power¹:
 10⁴² erg/s - 10⁴⁵ erg/s
BH-mass:
 3.45 10⁹ Msun (Walsh et al., 2013)
 6.14 10⁹ Msun (Gebhard et al. 2011)
Distance:
 16.8 Mpc (Bird+, 2010, Blakeslee+ 2009, Cantiello 2018)
```

[1]Reynolds et al. (1996), Li et al. (2009), de Gasperin et al. (2012), Broderick et al. (2015), Prieto et al. (2016)

some theory…

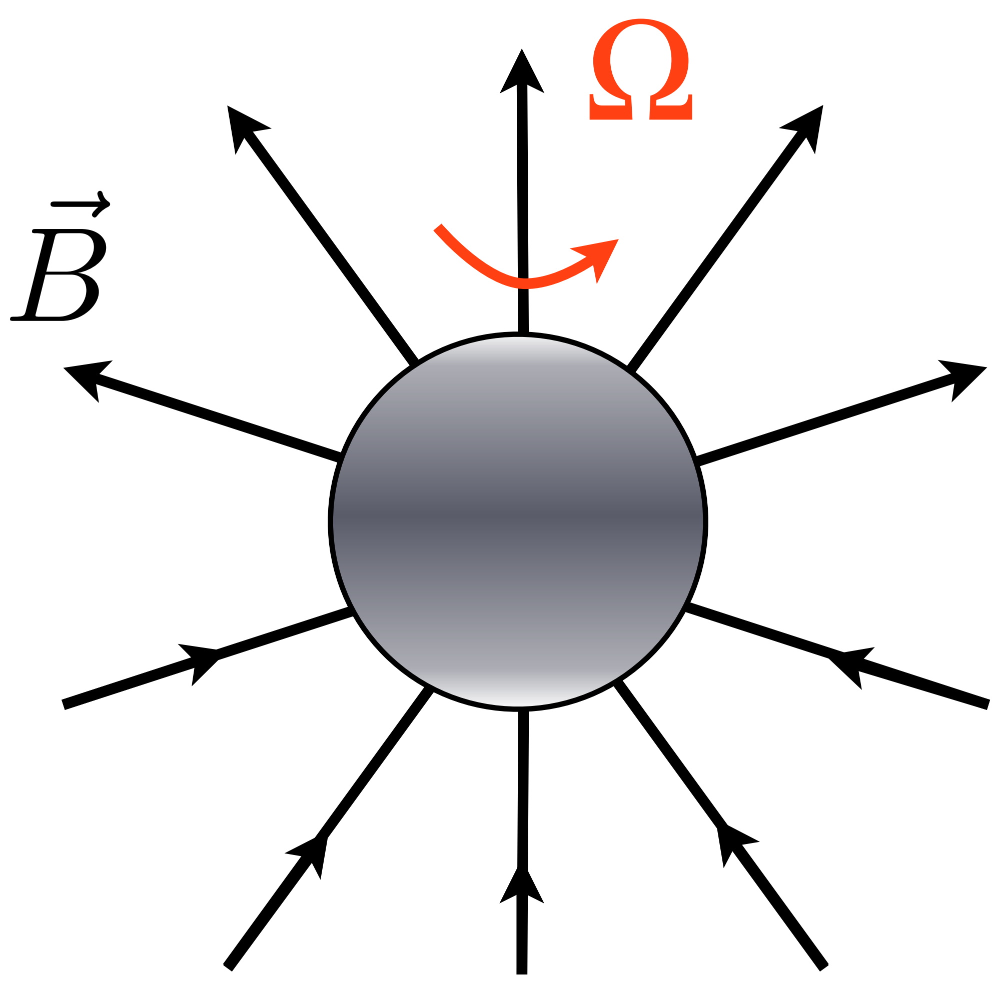
…ok, a lot of theory

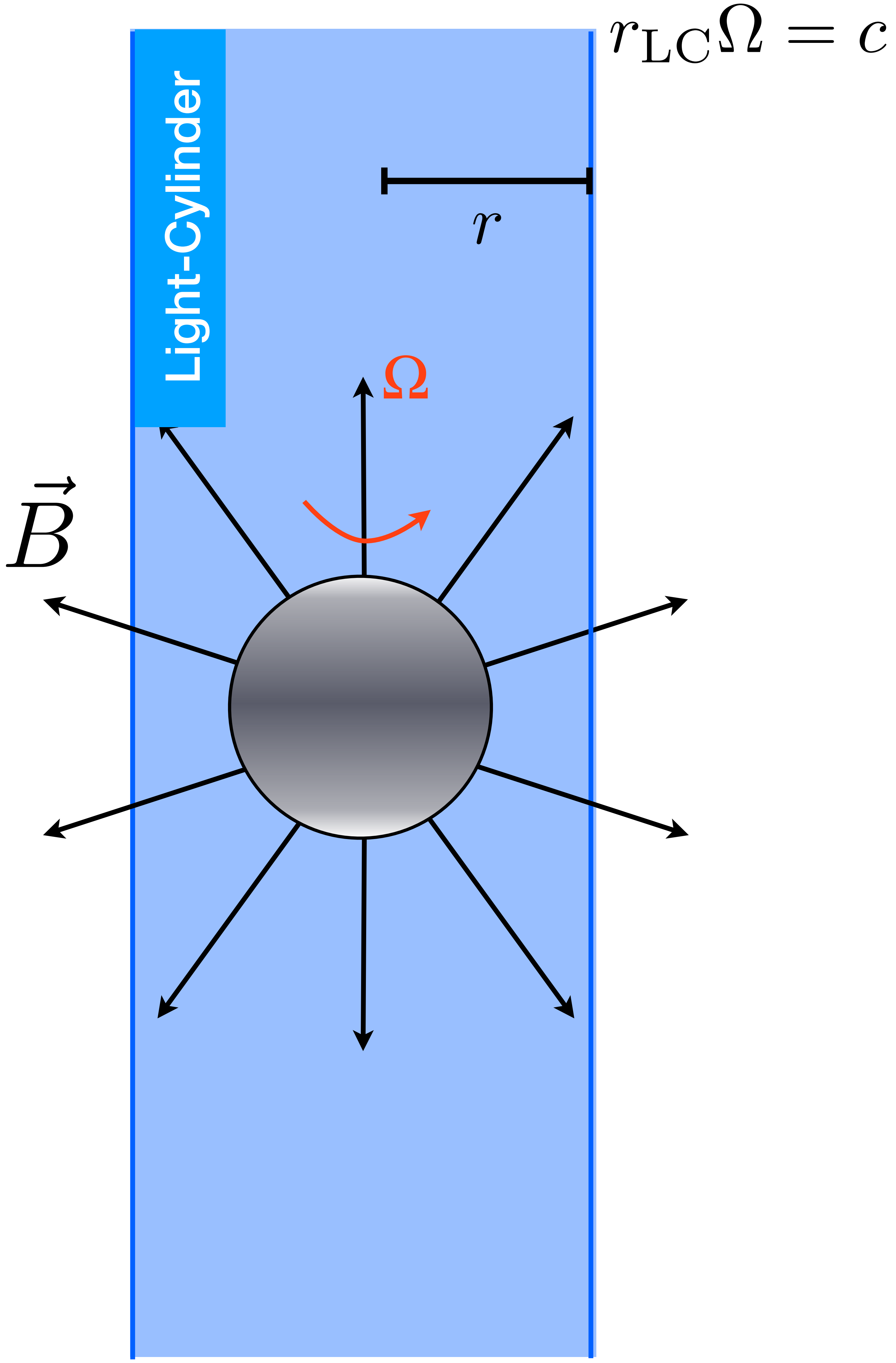
How do Jets Accelerate: The magnetic paradigm



Adopted from Alexander (Sasha) Tchekhovskoy

How do Jets Accelerate: The magnetic paradigm





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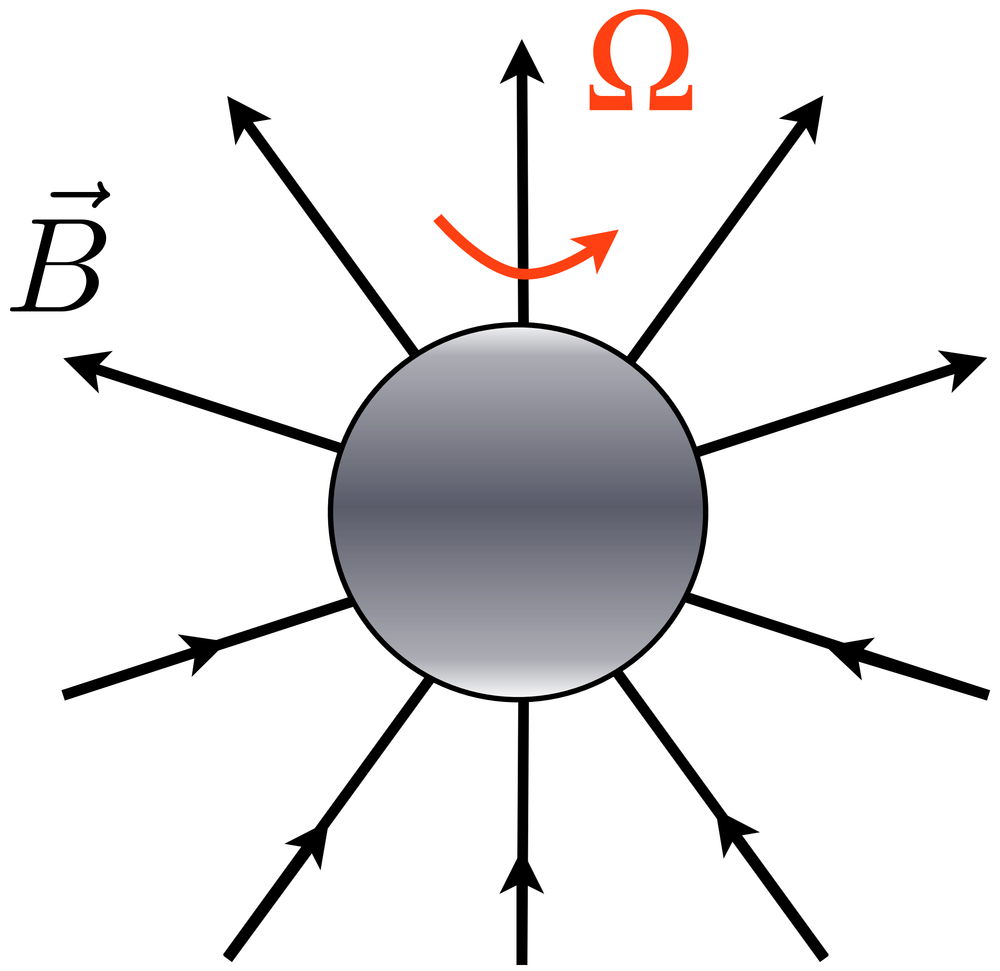
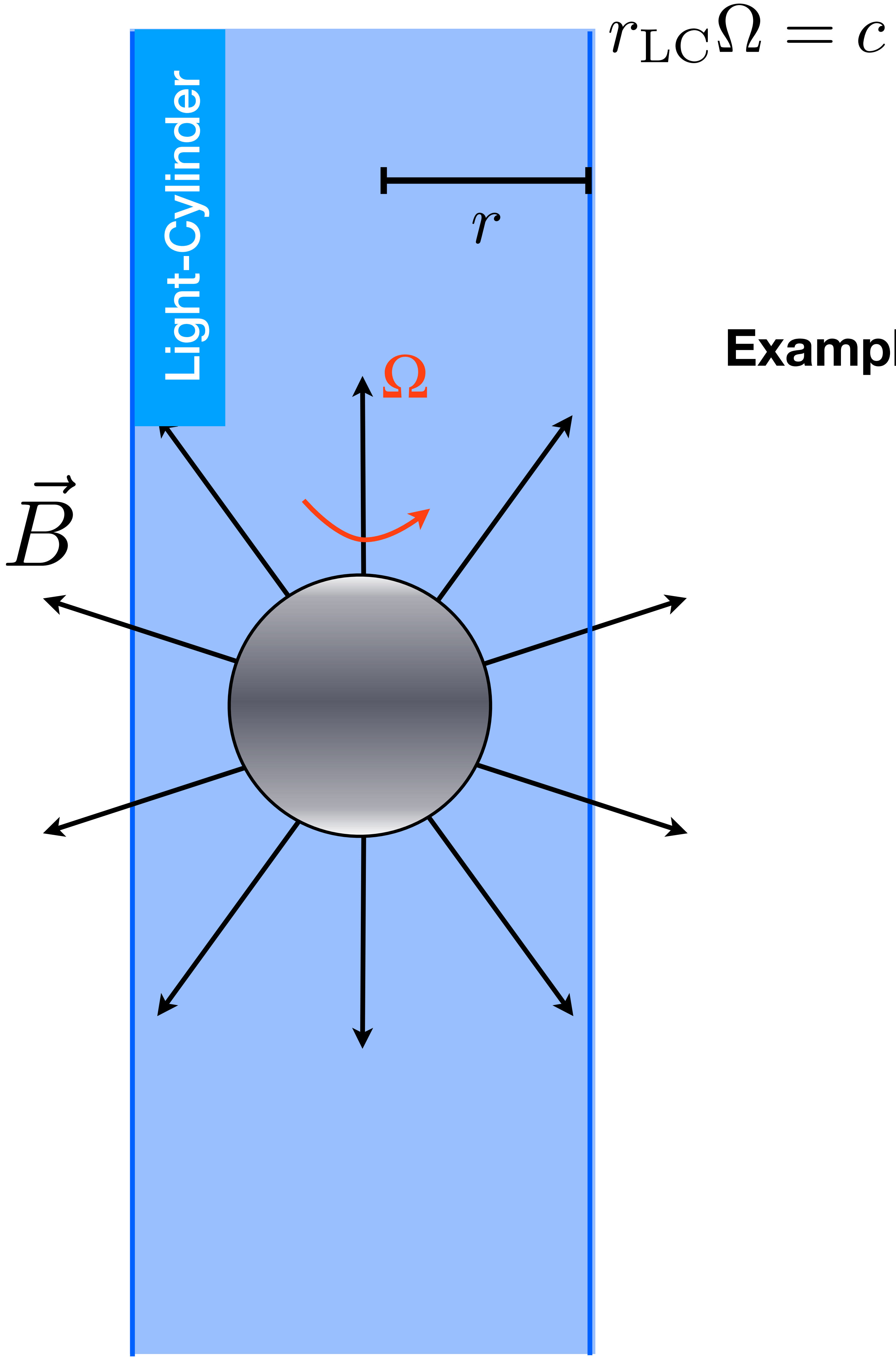




Example: light cylinder for sun

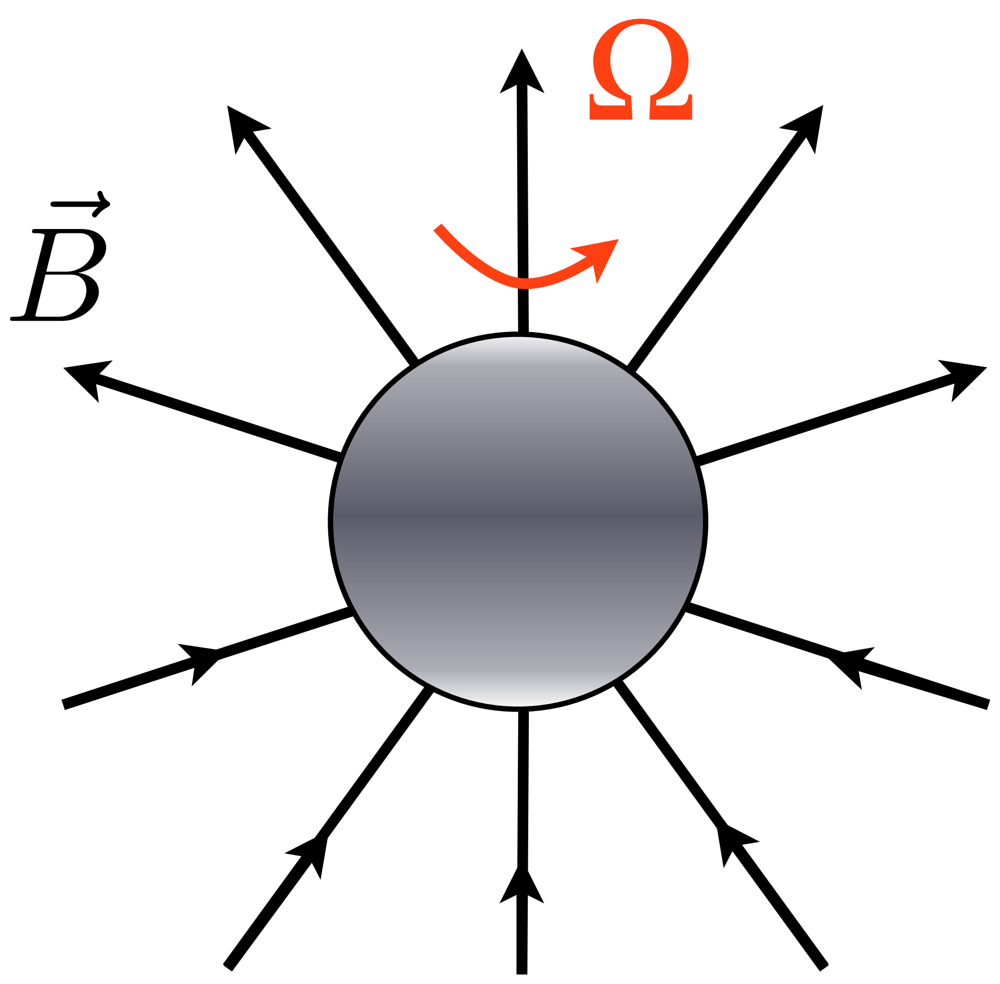
$$\Omega = \frac{2\pi}{24\mathrm{d}} = 3 \times 10^{-6}\,\mathrm{s}^{-1}$$

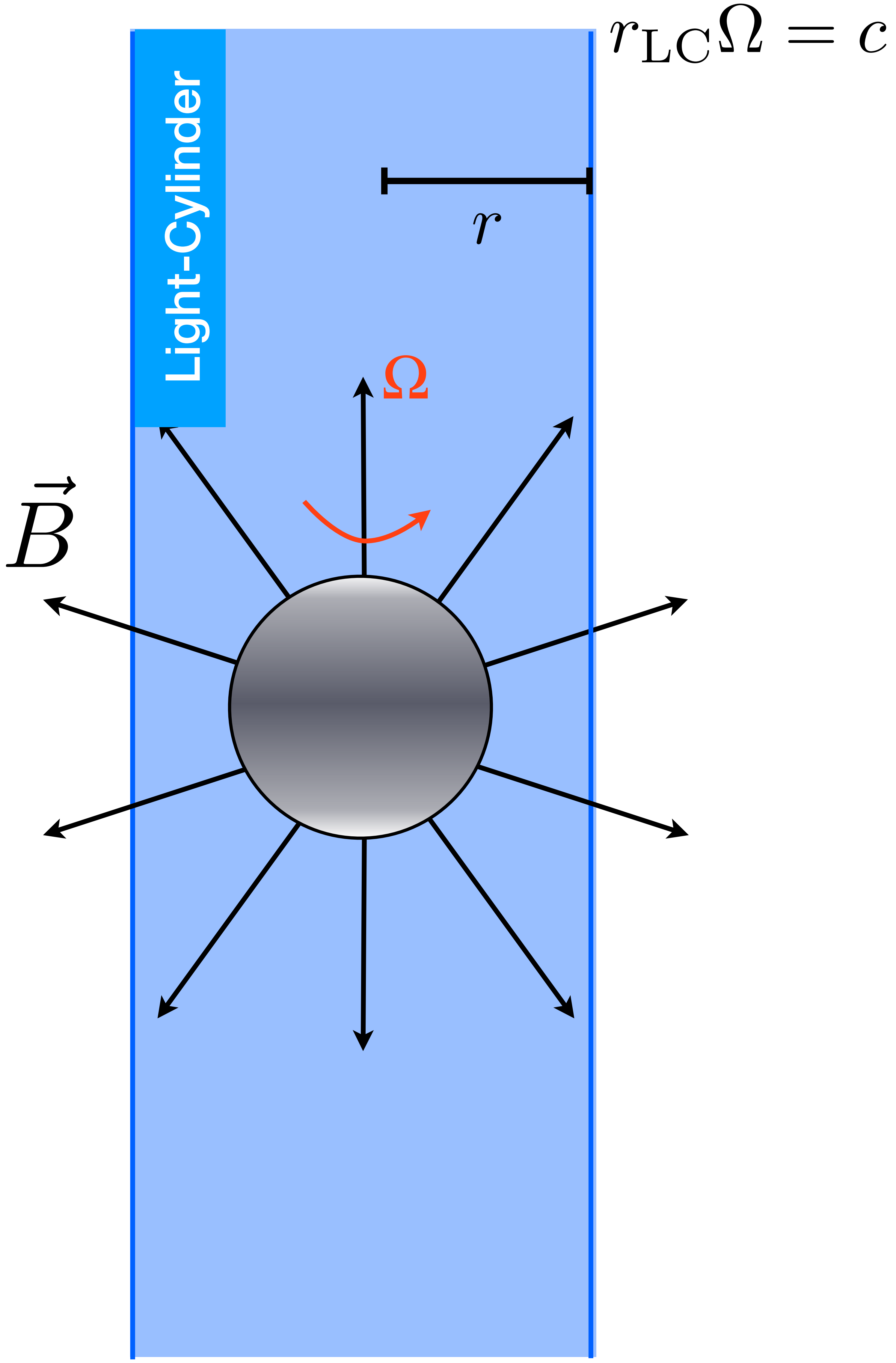
$$c = 3 \times 10^{10}\ \mathrm{cm/s}$$

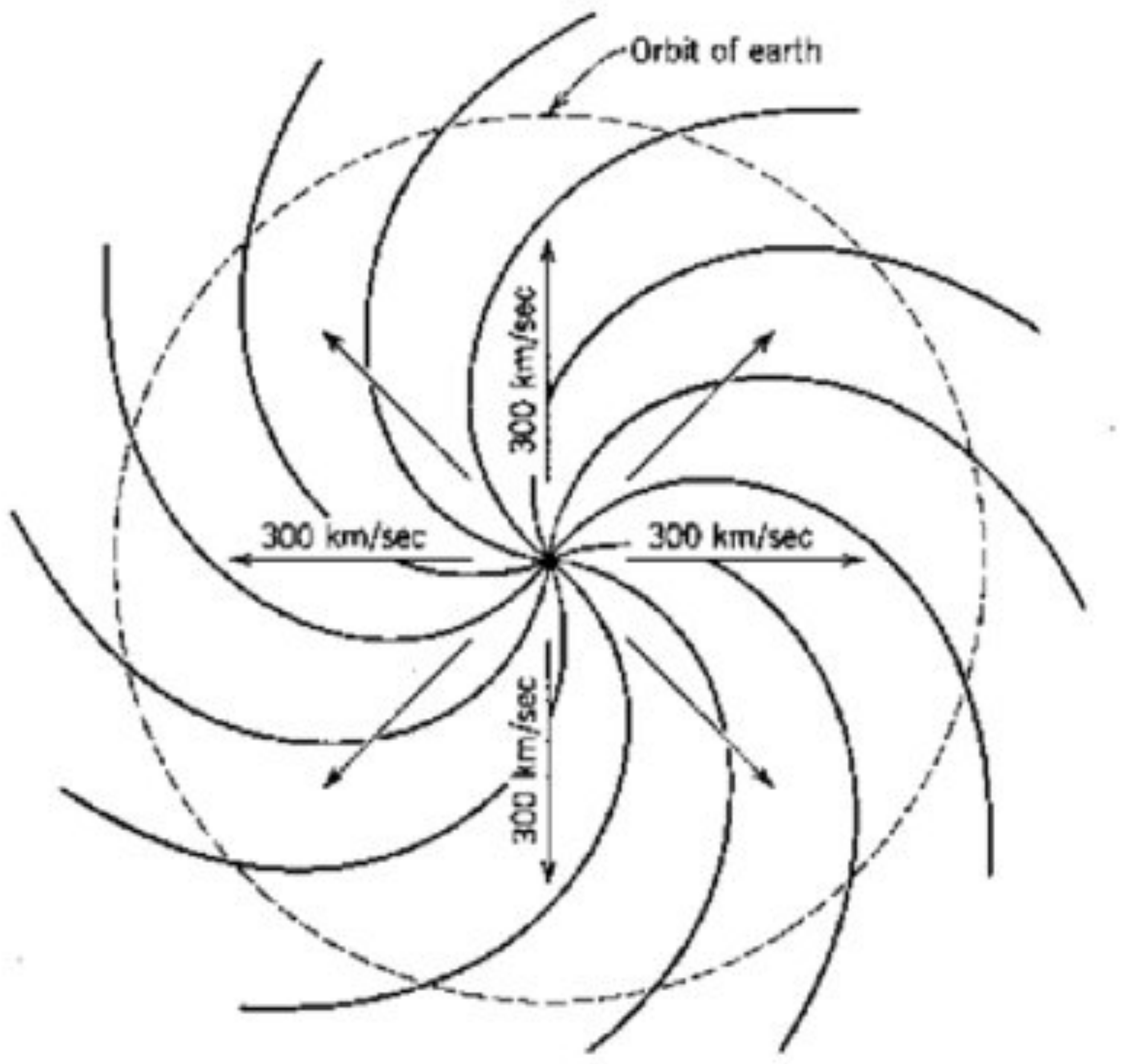
$$\Rightarrow r_{\mathrm{LC}} = c/\Omega = 10^{16}\mathrm{cm} = 660\mathrm{AU}$$

Adopted from Alexander (Sasha) Tchekhovskoy

How do Jets Accelerate: The magnetic paradigm







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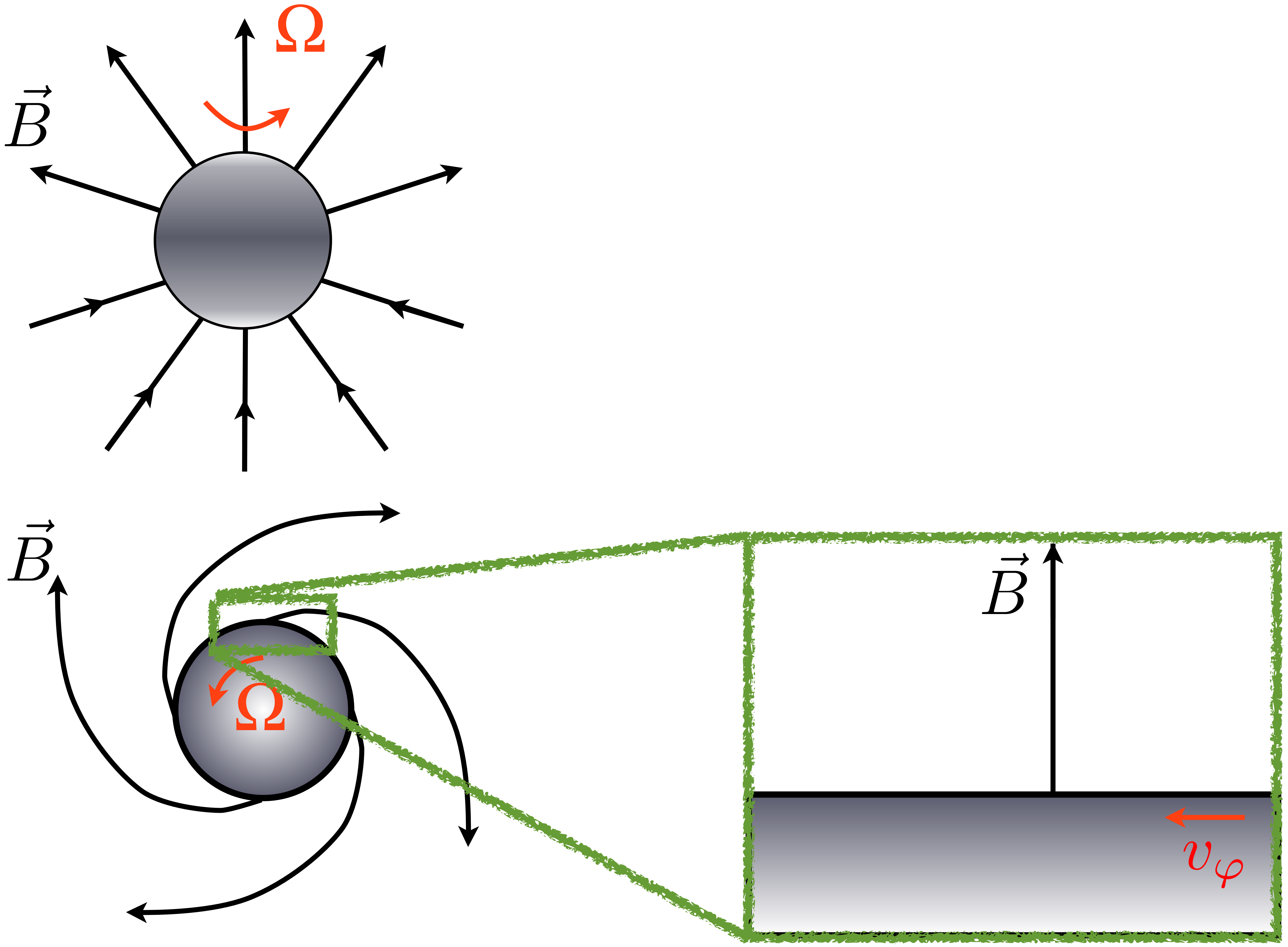

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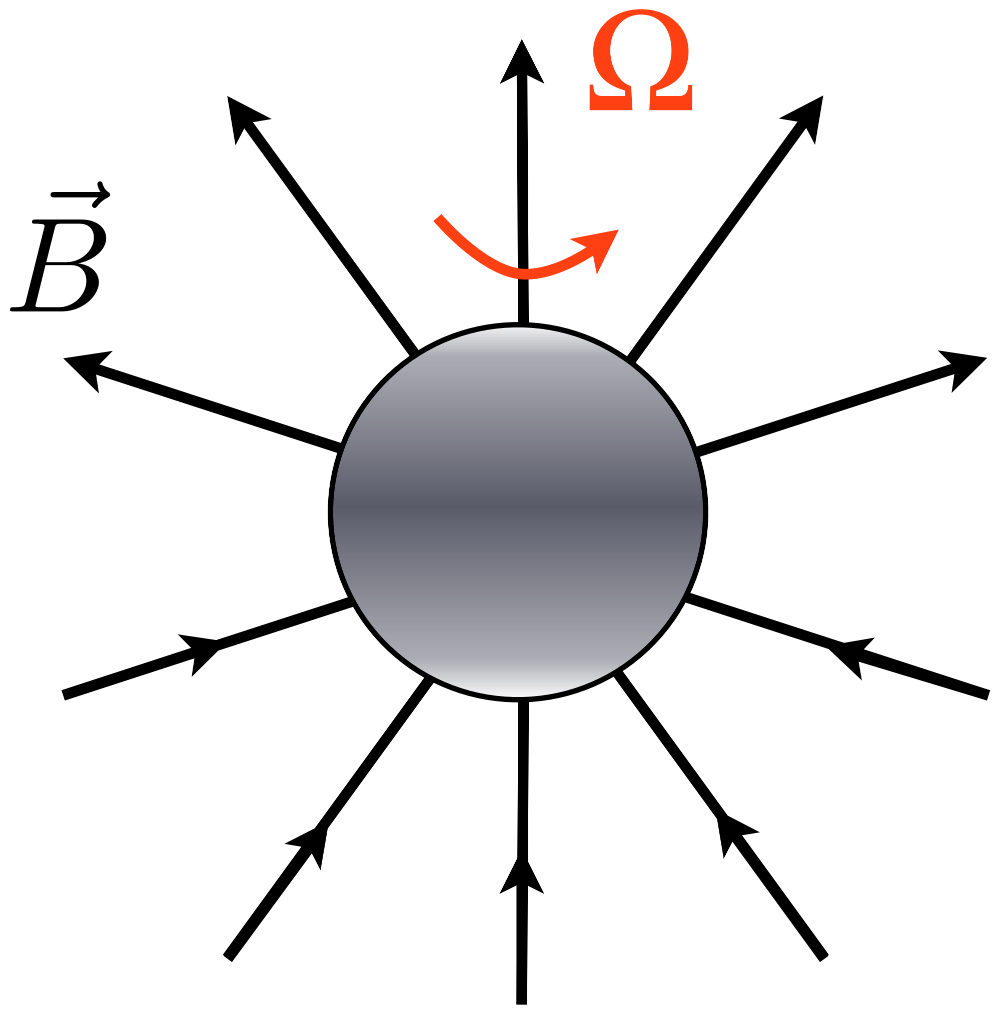

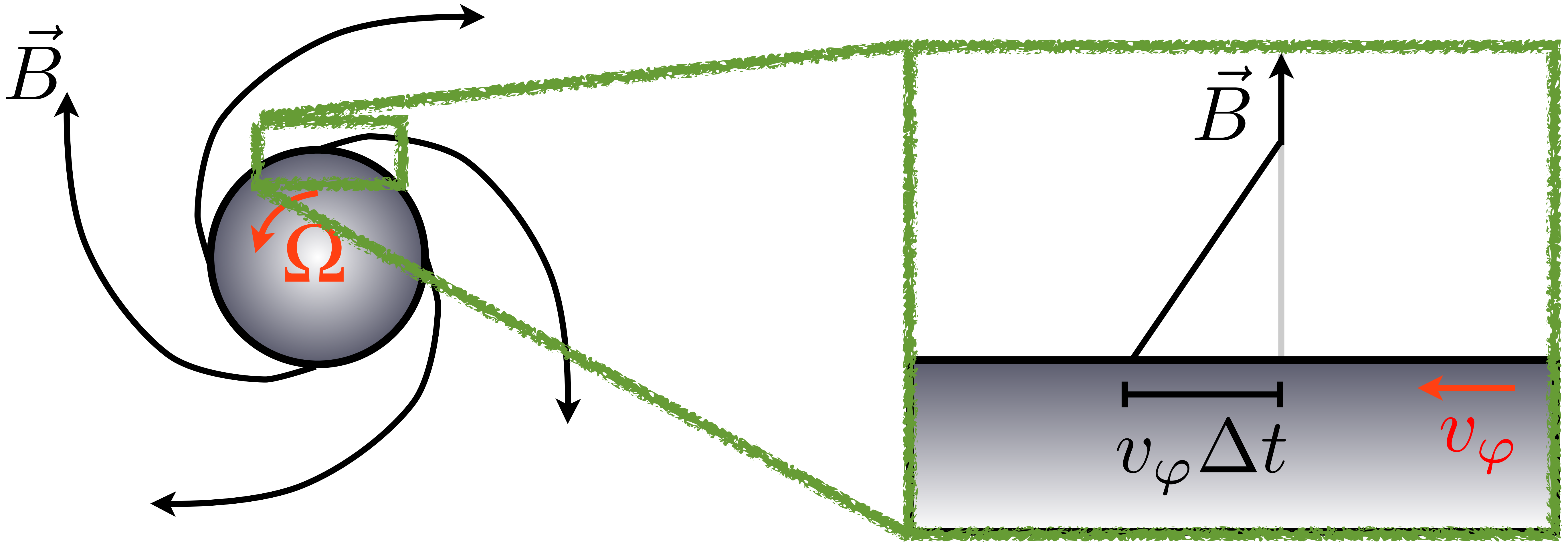

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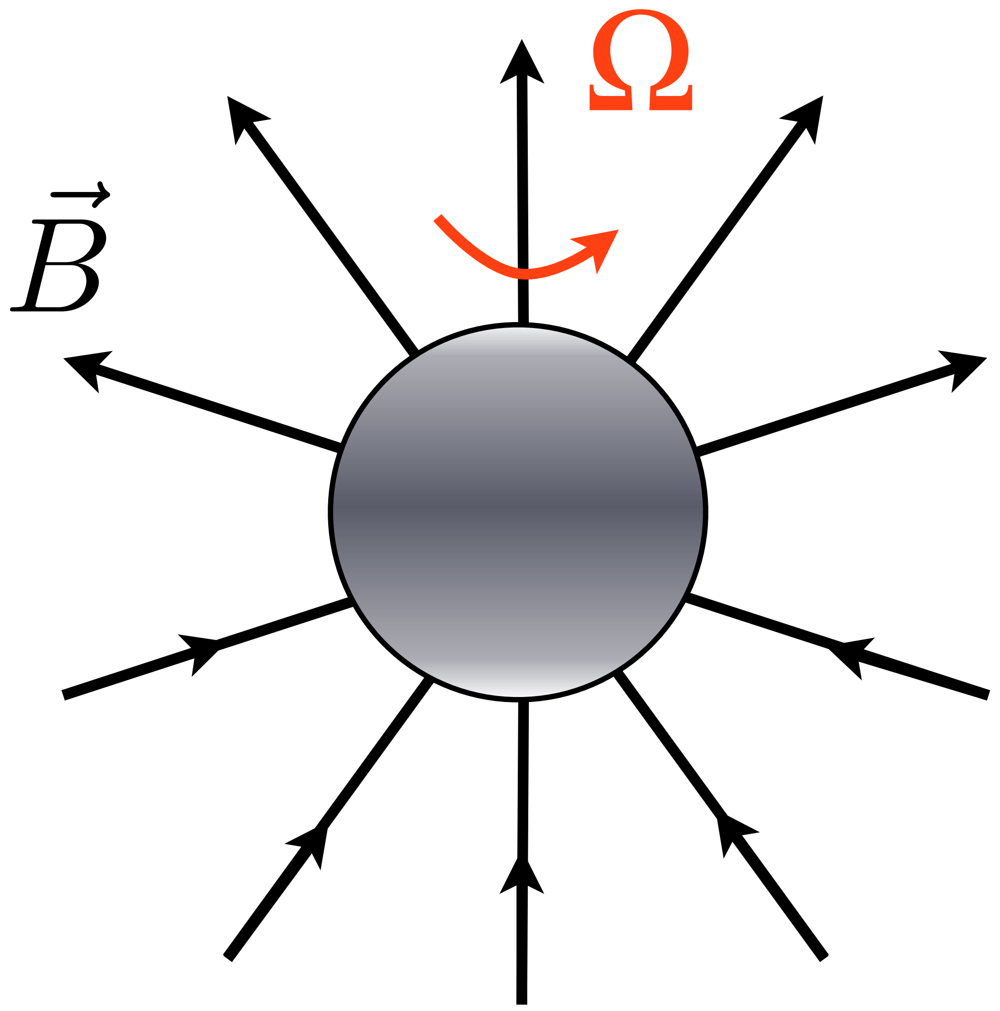
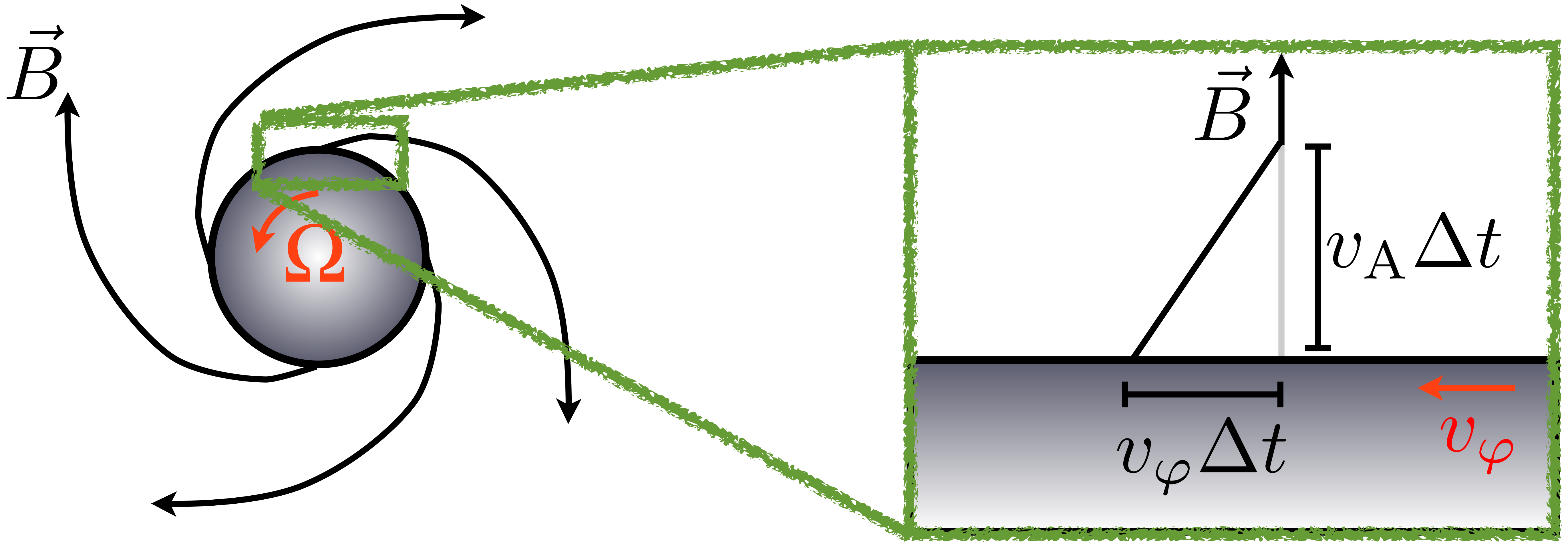
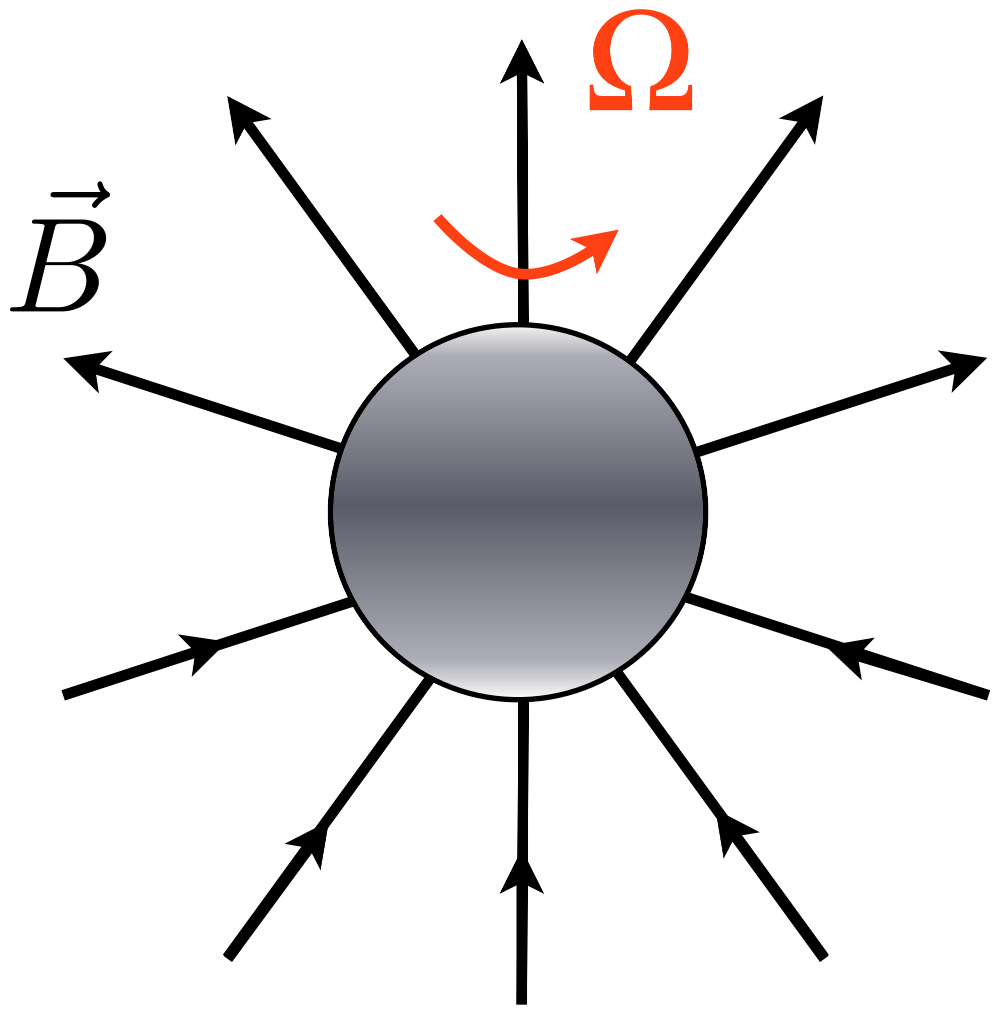
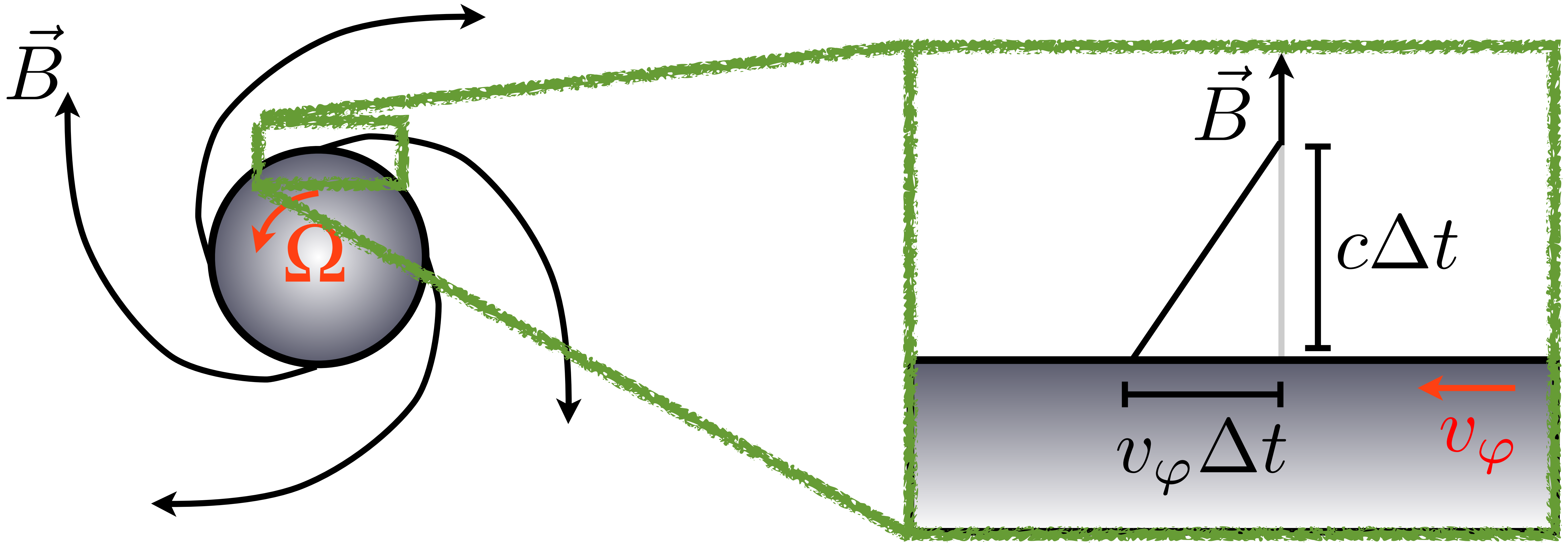




Adopted from Alexander (Sasha) Tchekhovskoy

How do force-free Jets Accelerate: The magnetic paradigm

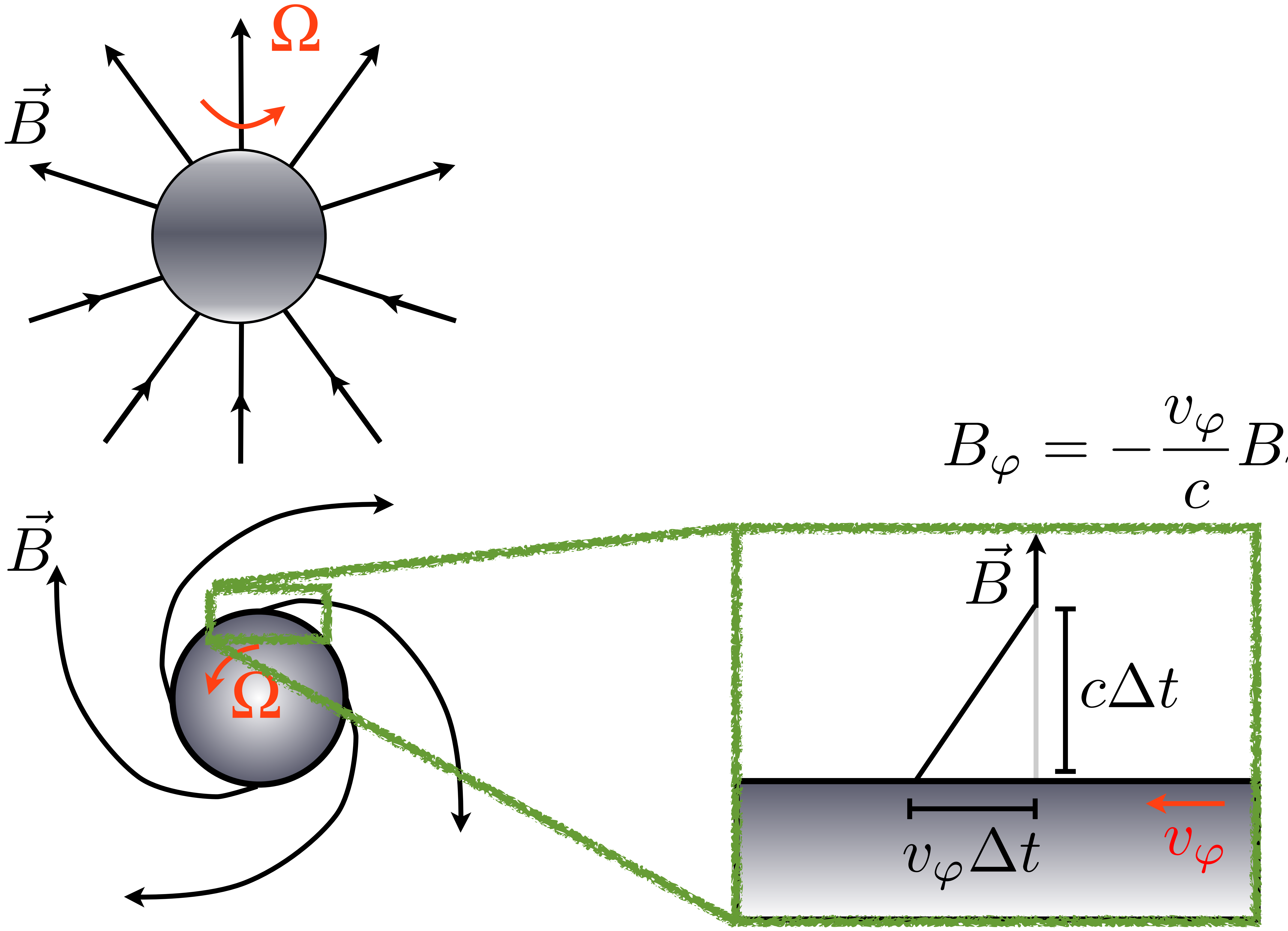




Assume the jets
are ***massless (force-free)***
for simplicity

Adopted from Alexander (Sasha) Tchekhovskoy

How do force-free Jets Accelerate: The magnetic paradigm



$$B_\varphi = -\frac{v_\varphi}{c} B_r = -\frac{\Omega R}{c} B_r$$

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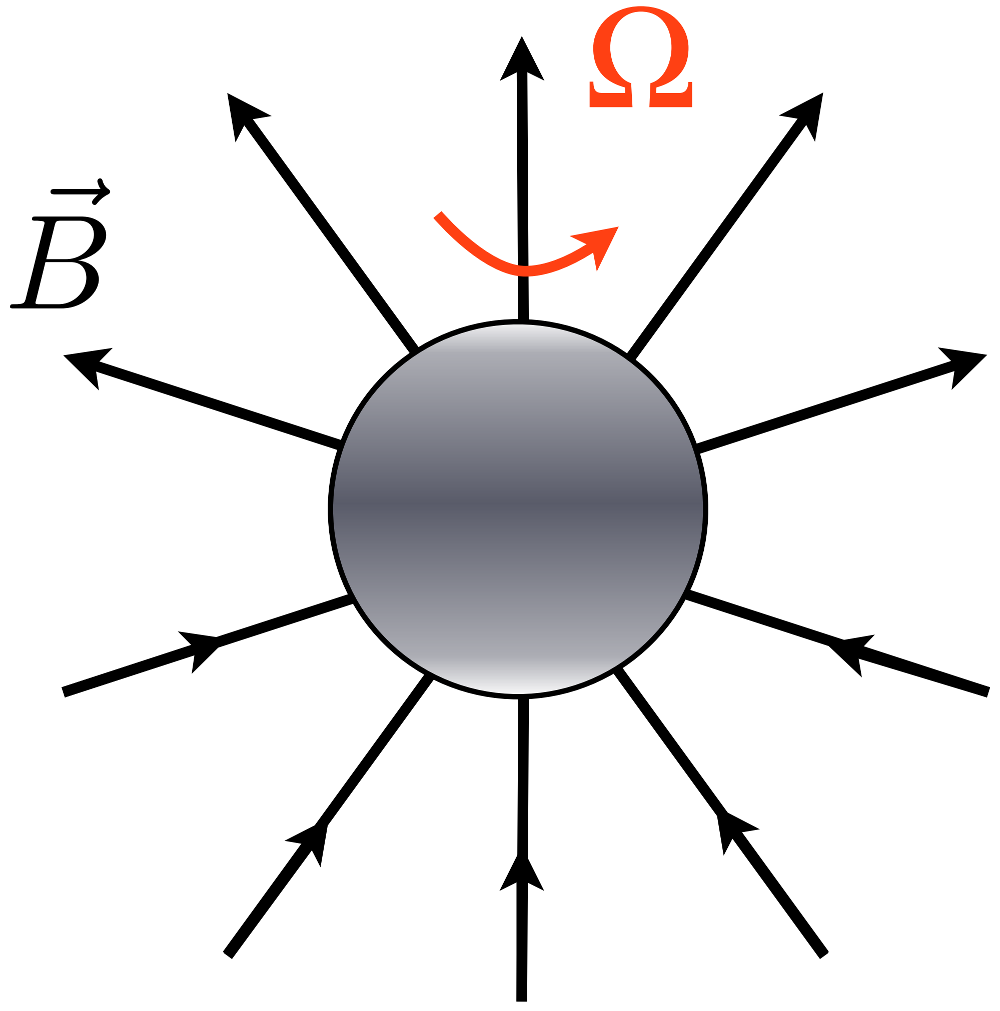
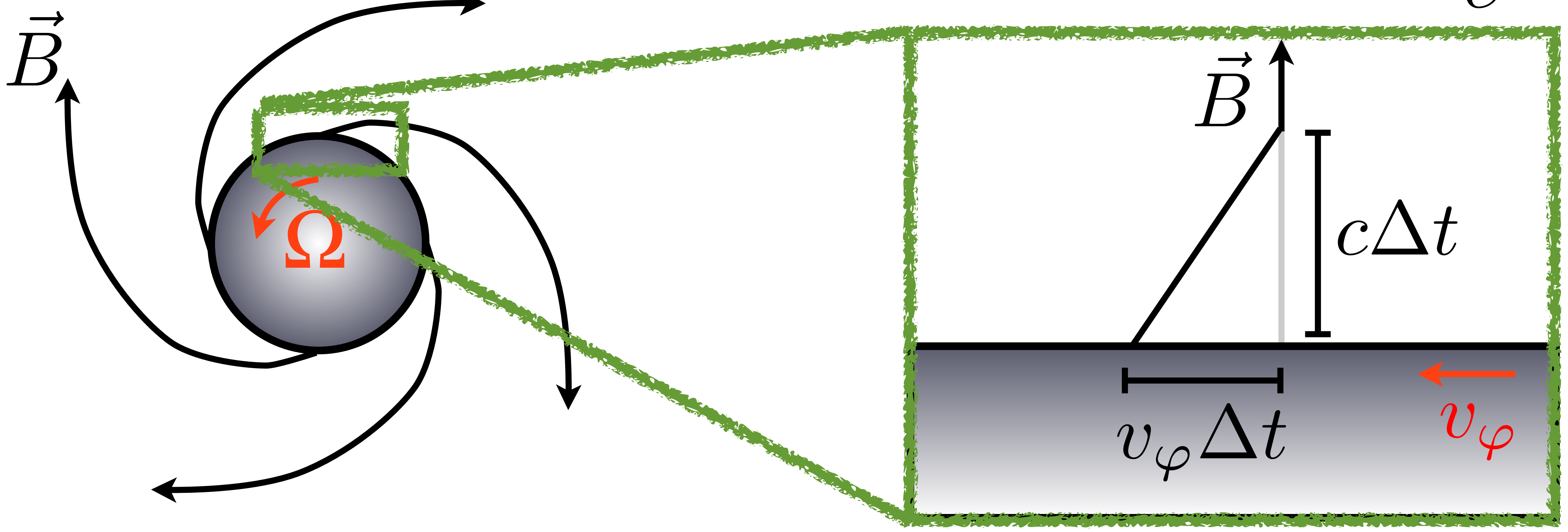
How do force-free Jets Accelerate: The magnetic paradigm



$$E = \left| -\frac{\vec{v}}{c} \times \vec{B} \right| = +\frac{\Omega R}{c} B_r$$

$$B_\varphi = -\frac{v_\varphi}{c} B_r = -\frac{\Omega R}{c} B_r$$



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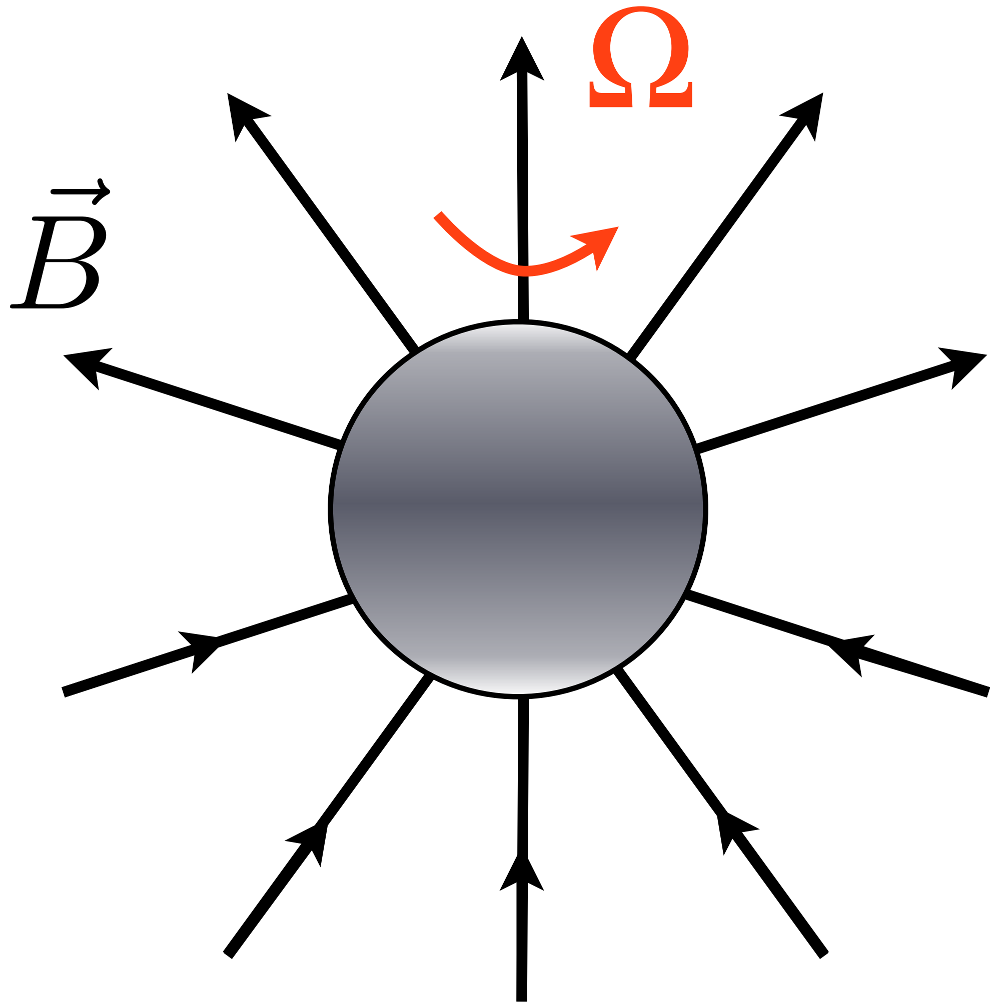
How do *force-free* Jets Accelerate: The magnetic paradigm



$$\frac{v}{c} = \left|\frac{\vec{E}\times\vec{B}}{B^2}\right| = \frac{E}{B}$$

$$E = \left|-\frac{\vec{v}}{c}\times\vec{B}\right| = +\frac{\Omega R}{c}B_r$$

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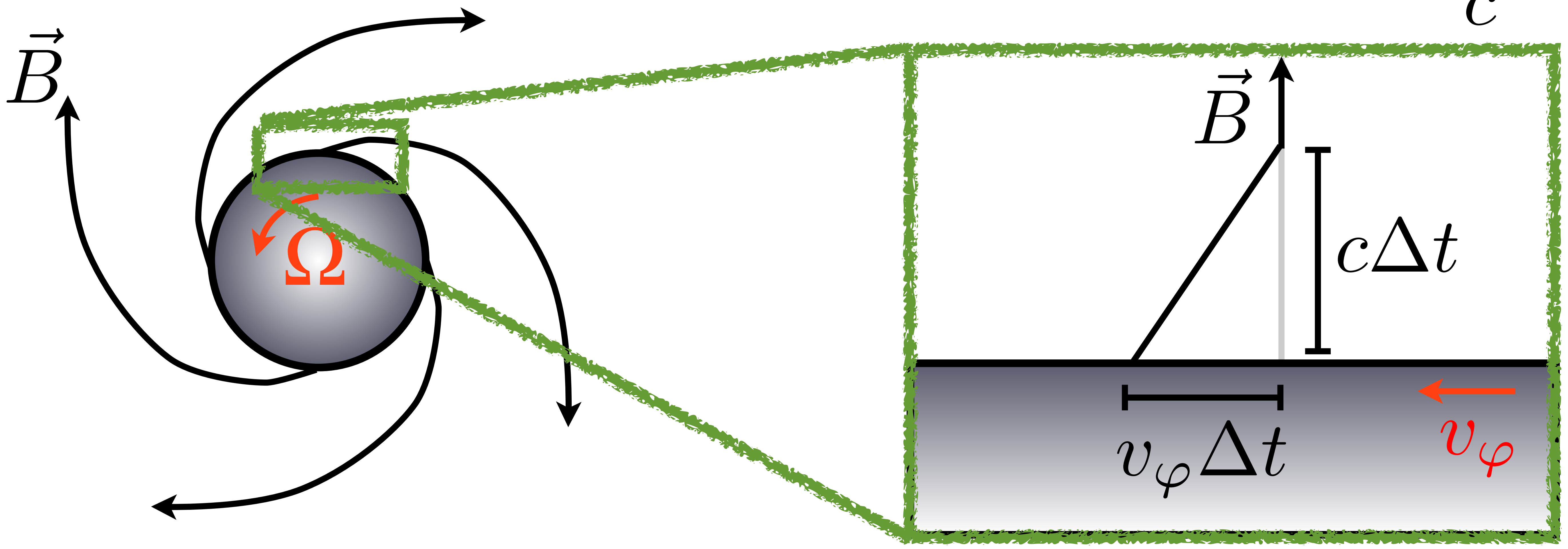

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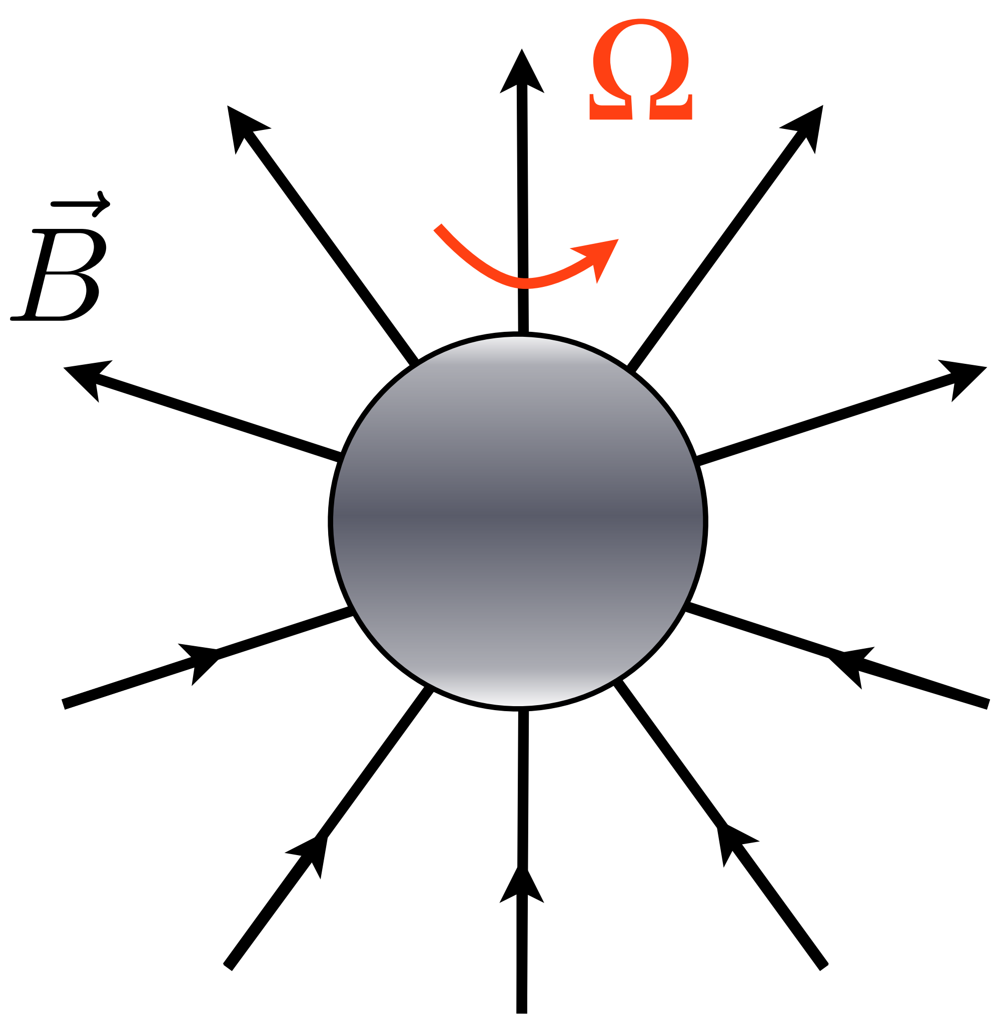
How do Jets Accelerate: The magnetic paradigm

force-free



$$\frac{v}{c} = \left|\frac{\vec{E}\times\vec{B}}{B^2}\right| = \frac{E}{B} \Rightarrow \; 1 - \frac{v^2}{c^2} = \frac{B^2 - E^2}{B^2}$$

$$E = \left| -\frac{\vec{v}}{c} \times \vec{B} \right| = +\frac{\Omega R}{c} B_r$$

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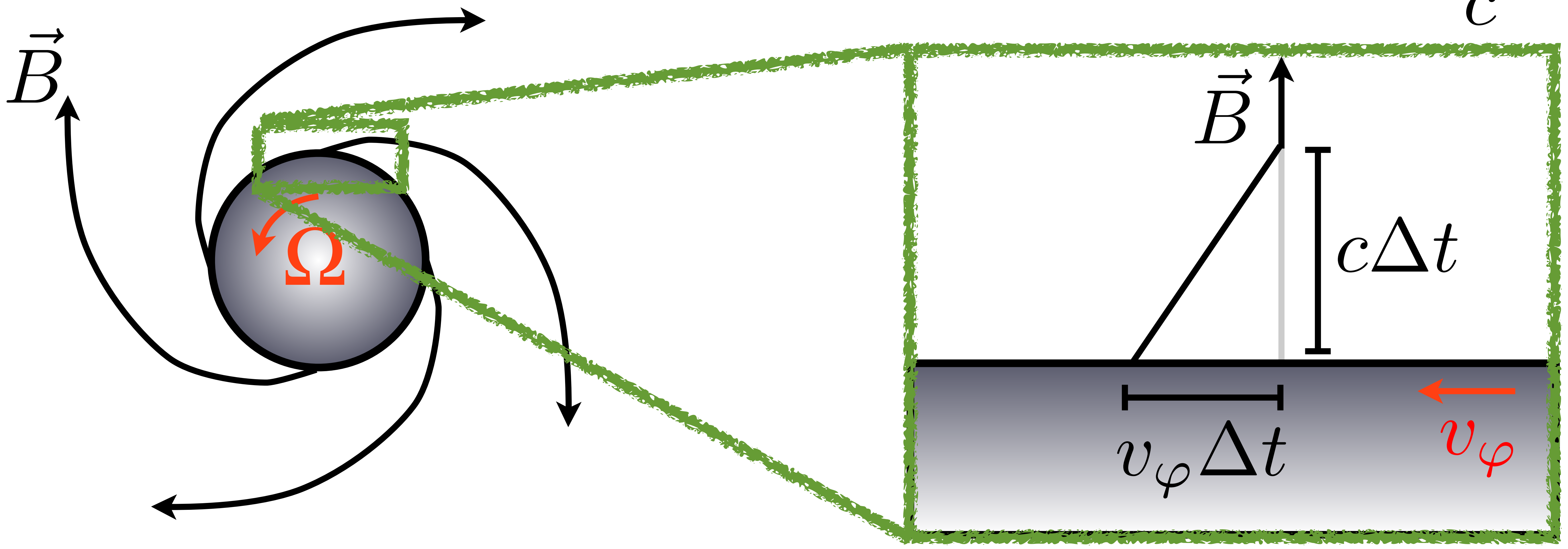

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How do force-free Jets Accelerate: The magnetic paradigm

$$\gamma^2 = \frac{1}{1 - v^2/c^2} = \frac{B_r^2 + B_\varphi^2}{B_r^2 + \cancel{B_\varphi^2 - E^2}} = 1 + \frac{B_\varphi^2}{B_r^2} = 1 + (\Omega R/c)^2$$

$$\frac{v}{c} = \left|\frac{\vec{E}\times\vec{B}}{B^2}\right| = \frac{E}{B} \Rightarrow \; 1 - \frac{v^2}{c^2} = \frac{B^2 - E^2}{B^2}$$

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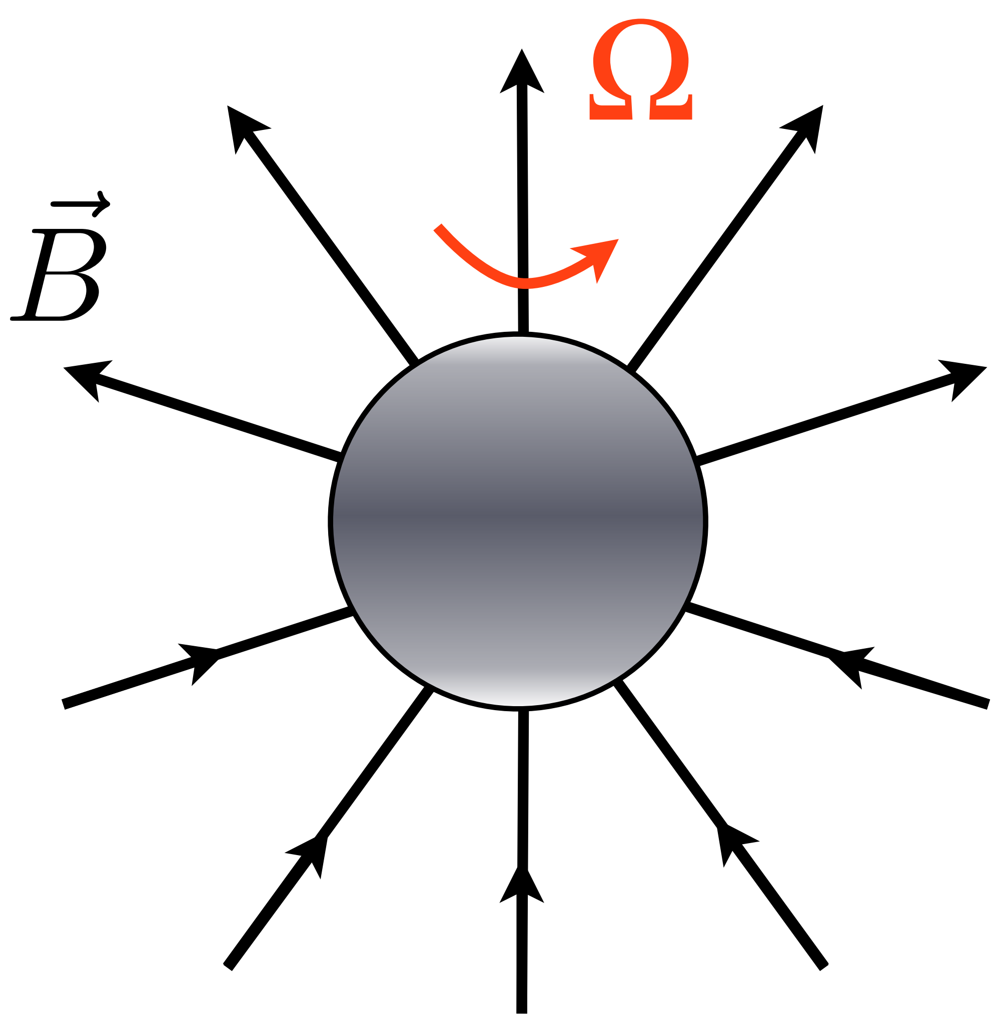

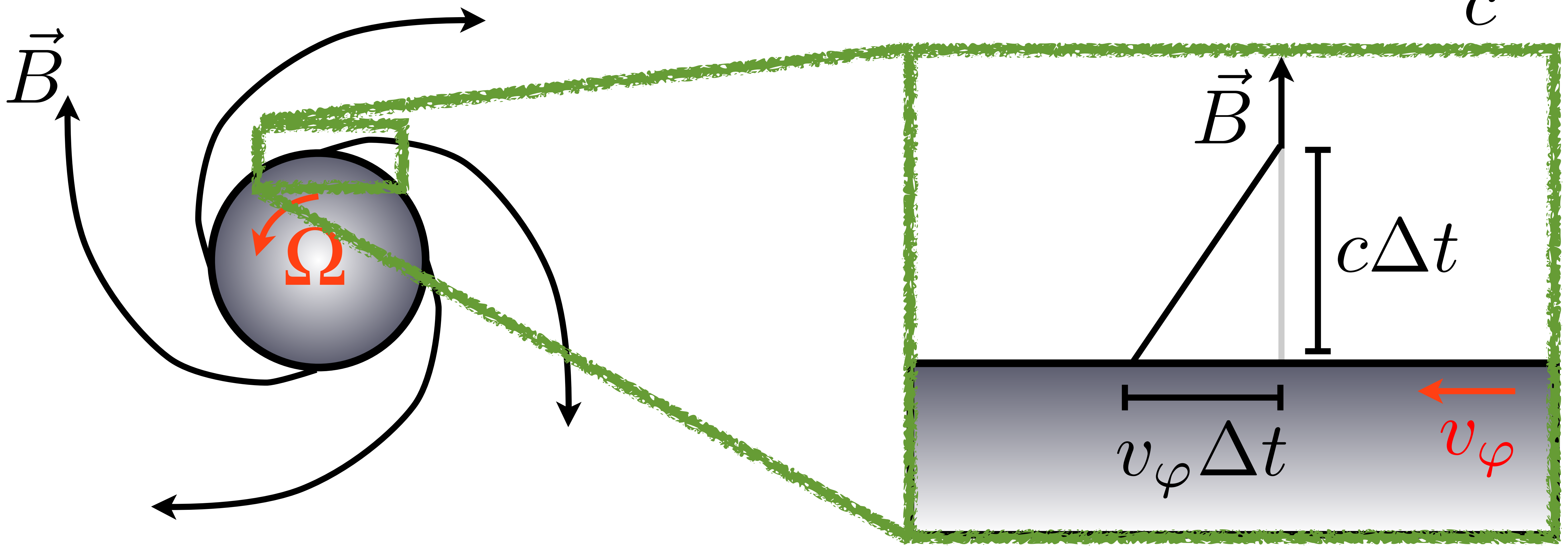

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How do force-free Jets Accelerate: The magnetic paradigm

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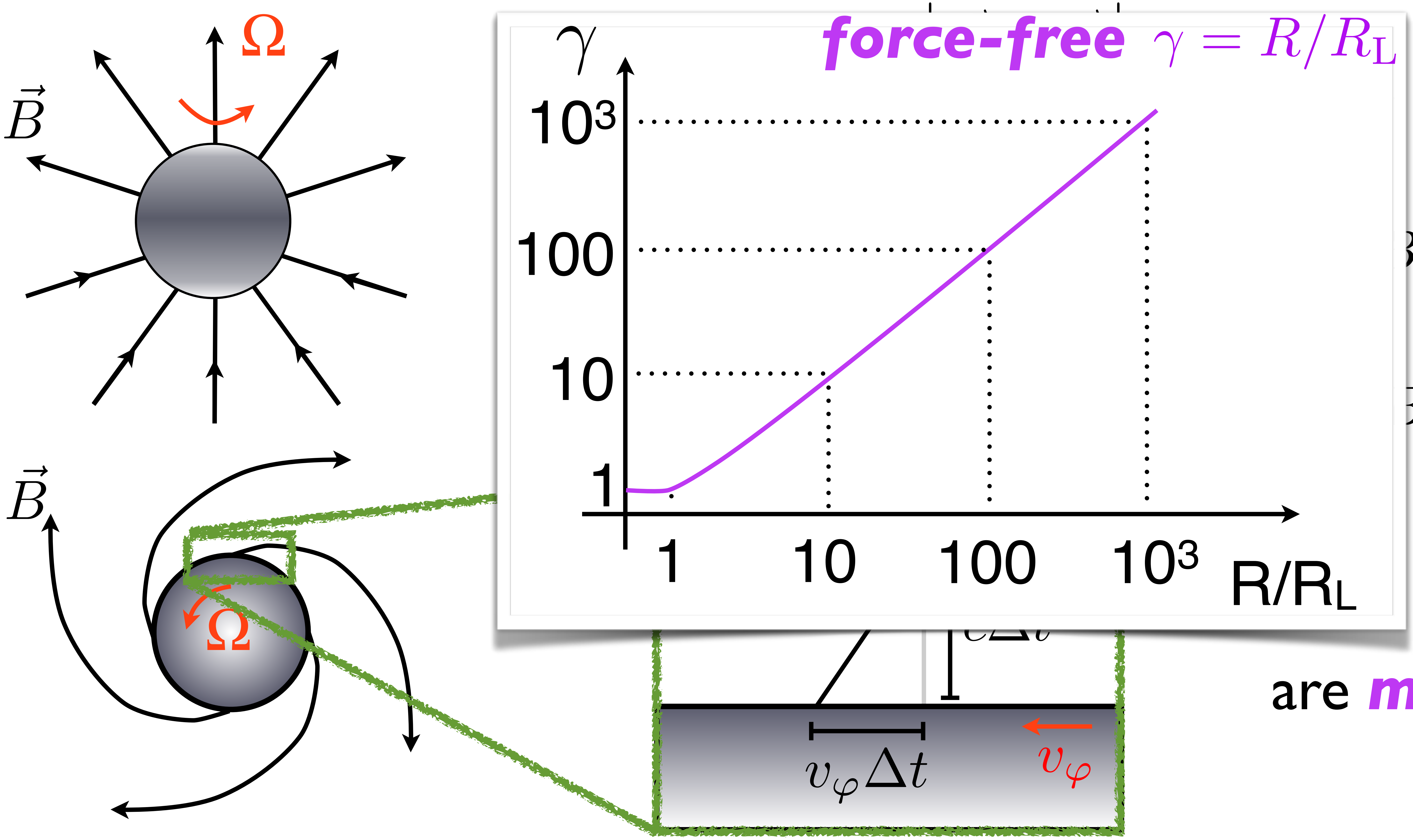

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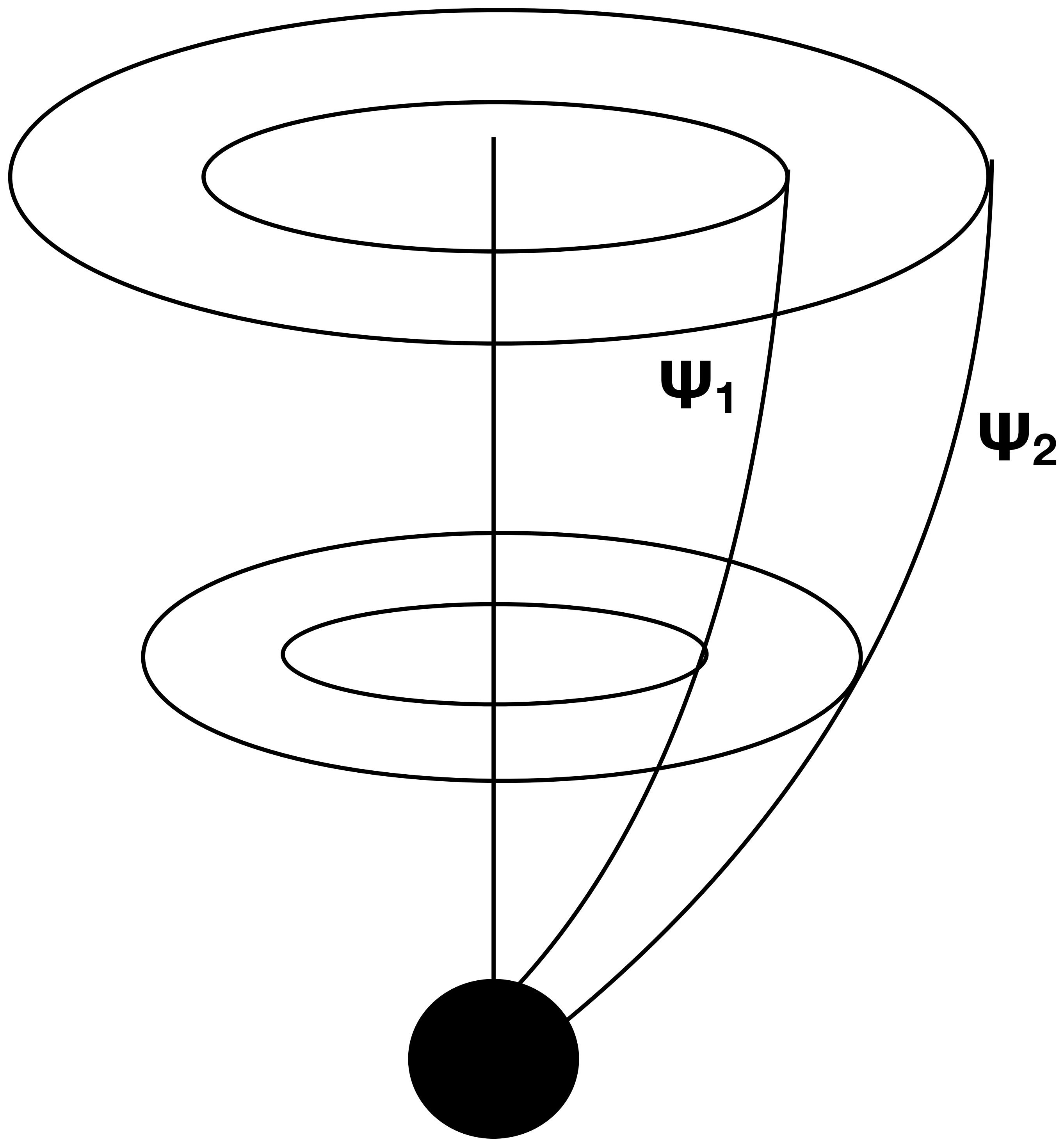
mass loaded - Poynting dominated flows



mass loaded - Poynting dominated flows

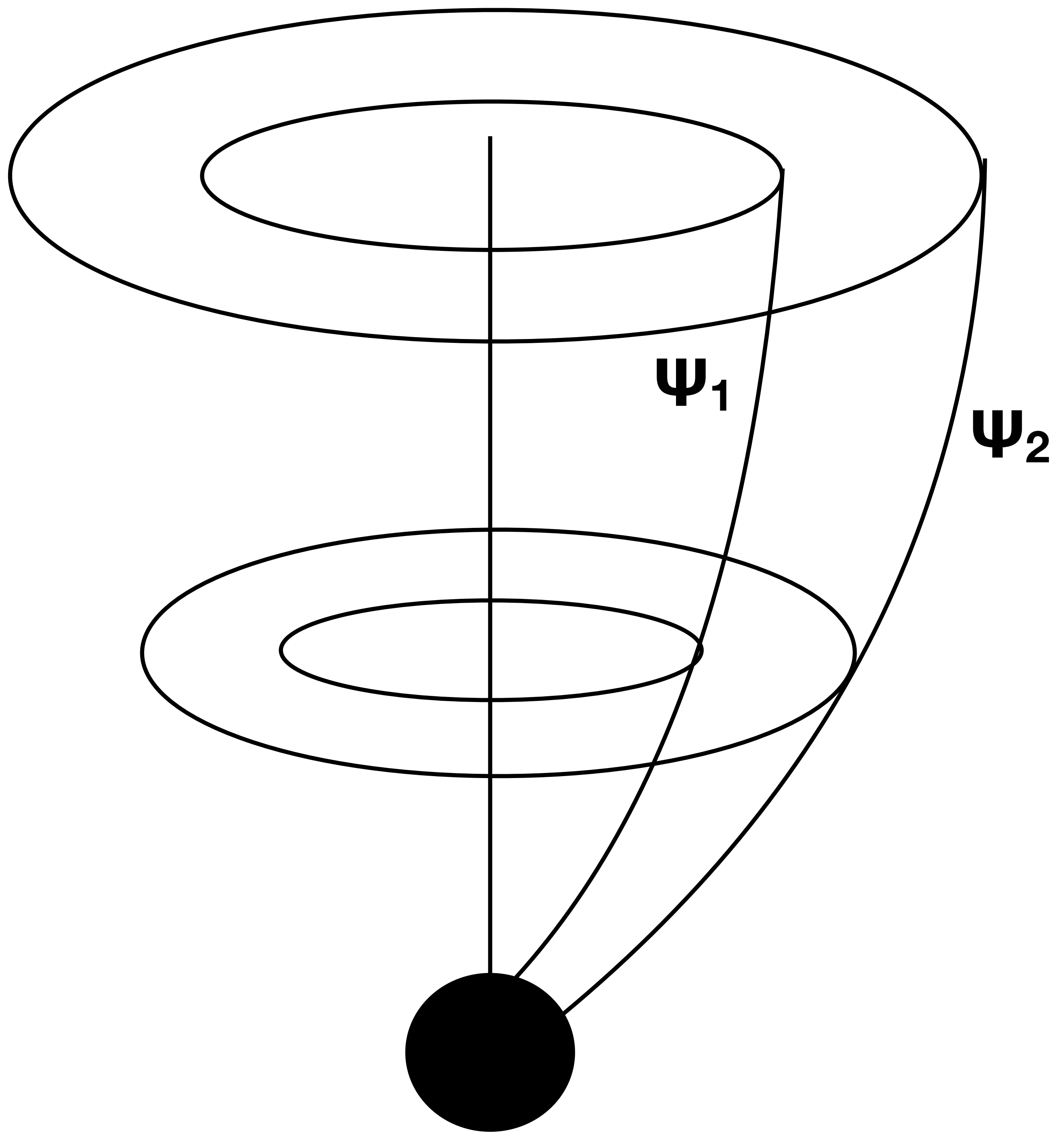
Fluxes between streamlines:

$$F_M = \Gamma \rho v_p$$

$$F_E = \Gamma F_M + F_{Poynting}$$

$$F_B = B_p$$

$$F_L = -rB_pB_\phi + r\Gamma v_\phi \Gamma \rho v_p$$



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Ratios of fluxes: conserved along the stream line Ψ!

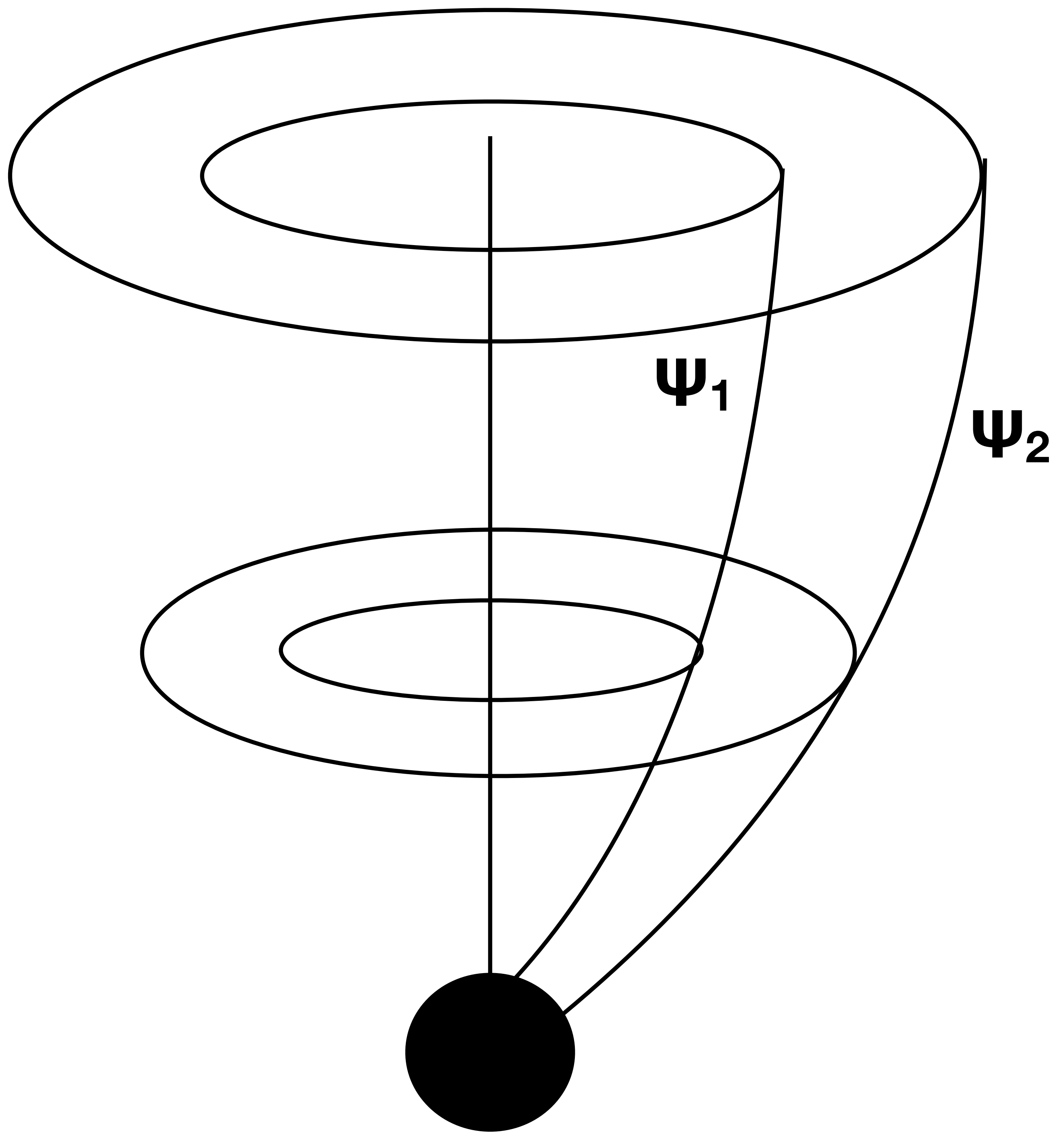
Conserved quantities:

$$\mu(\Psi) \equiv \frac{F_{\rm kin} + F_{\rm Poynting}}{\rho \Gamma v_p}$$

$$r\Omega(\Psi) \equiv v_\phi - v_p \frac{B_\phi}{B_p}$$

$$k(\Psi) \equiv \frac{\rho \Gamma v_p}{B_p}$$

$$l(\Psi) \equiv -\frac{I}{2\pi k} + r \Gamma v_\phi$$



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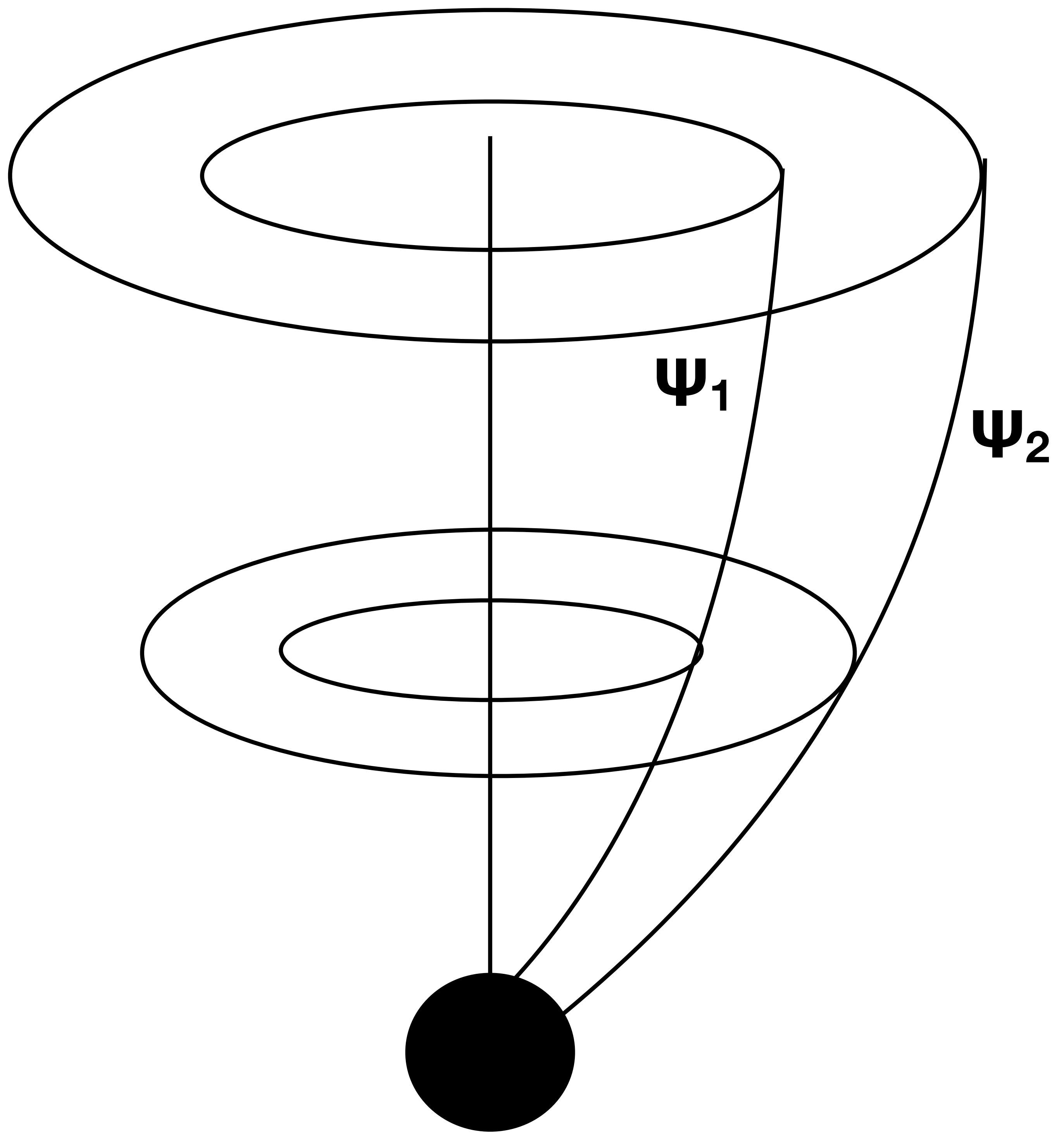

$$\mu = \frac{F_E}{F_M} = \Gamma + \frac{|\mathbf{E} \times \mathbf{B}|}{\rho v_p \Gamma} = \Gamma \left(1 + \frac{F_{Poynting}}{F_{Kinetic}}\right)$$

mass loaded - Poynting dominated flows

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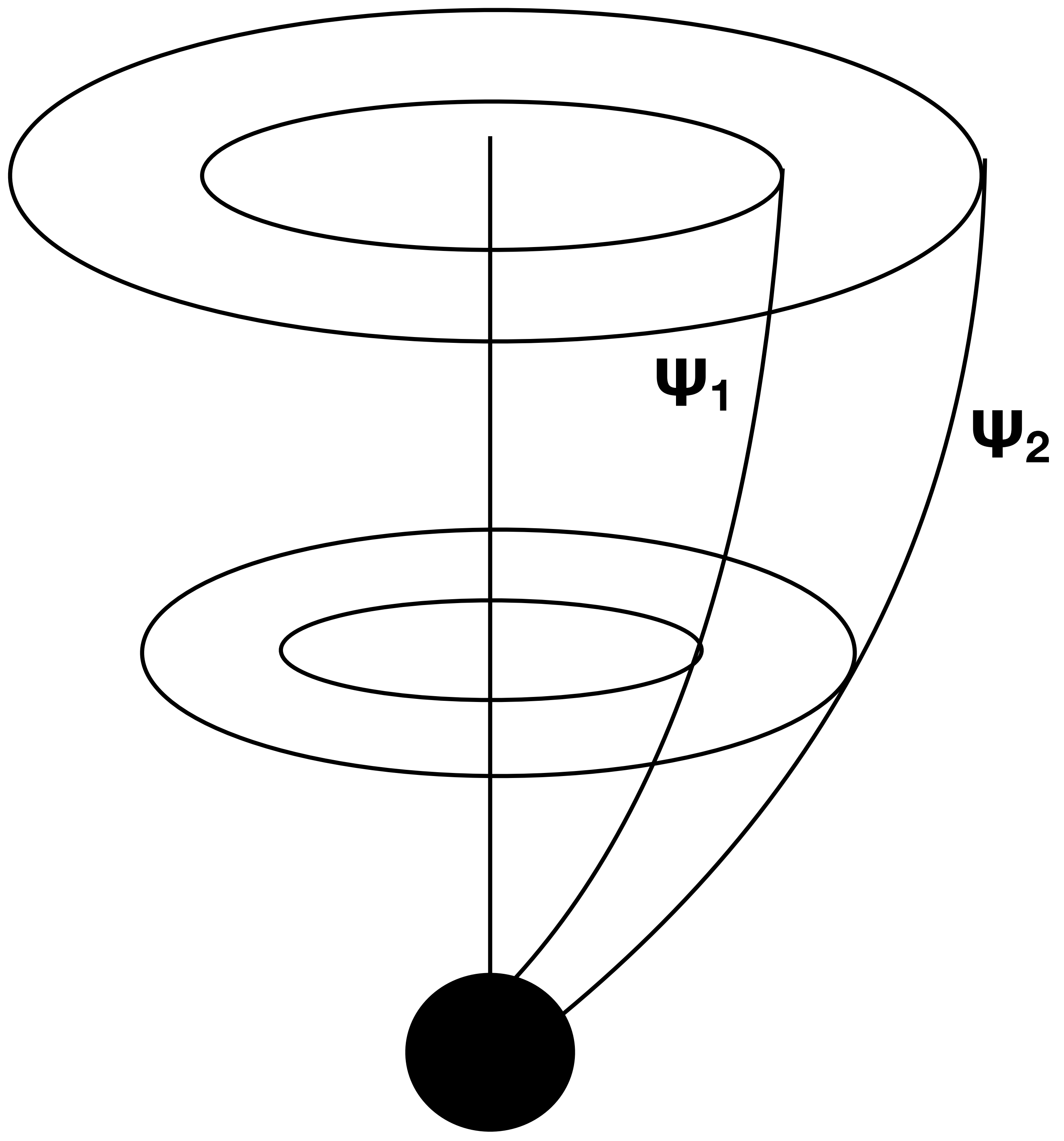

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mass loaded - Poynting dominated flows

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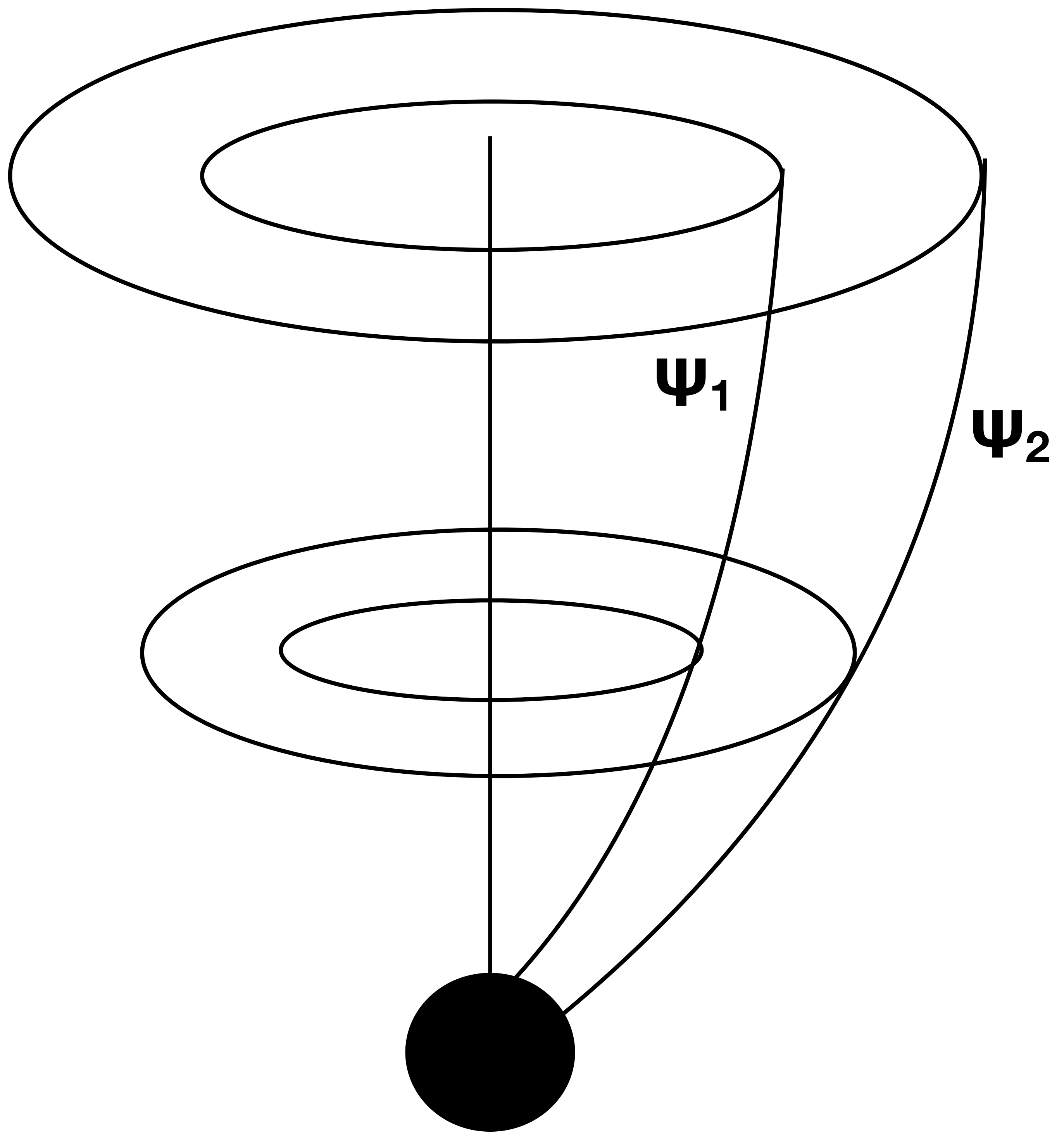

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$$\mu = \Gamma(1+\sigma); \;\; \Gamma \to \mu(\sigma \to 0)$$

mass loaded - Poynting dominated flows

Fluxes between streamlines:

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Ratios of fluxes: conserved along the stream line Ψ!

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$$\mu(\Psi) \equiv \frac{F_{\rm kin} + F_{\rm Poynting}}{\rho \Gamma v_p}$$

$$r\Omega(\Psi) \equiv v_\phi - v_p \frac{B_\phi}{B_p}$$

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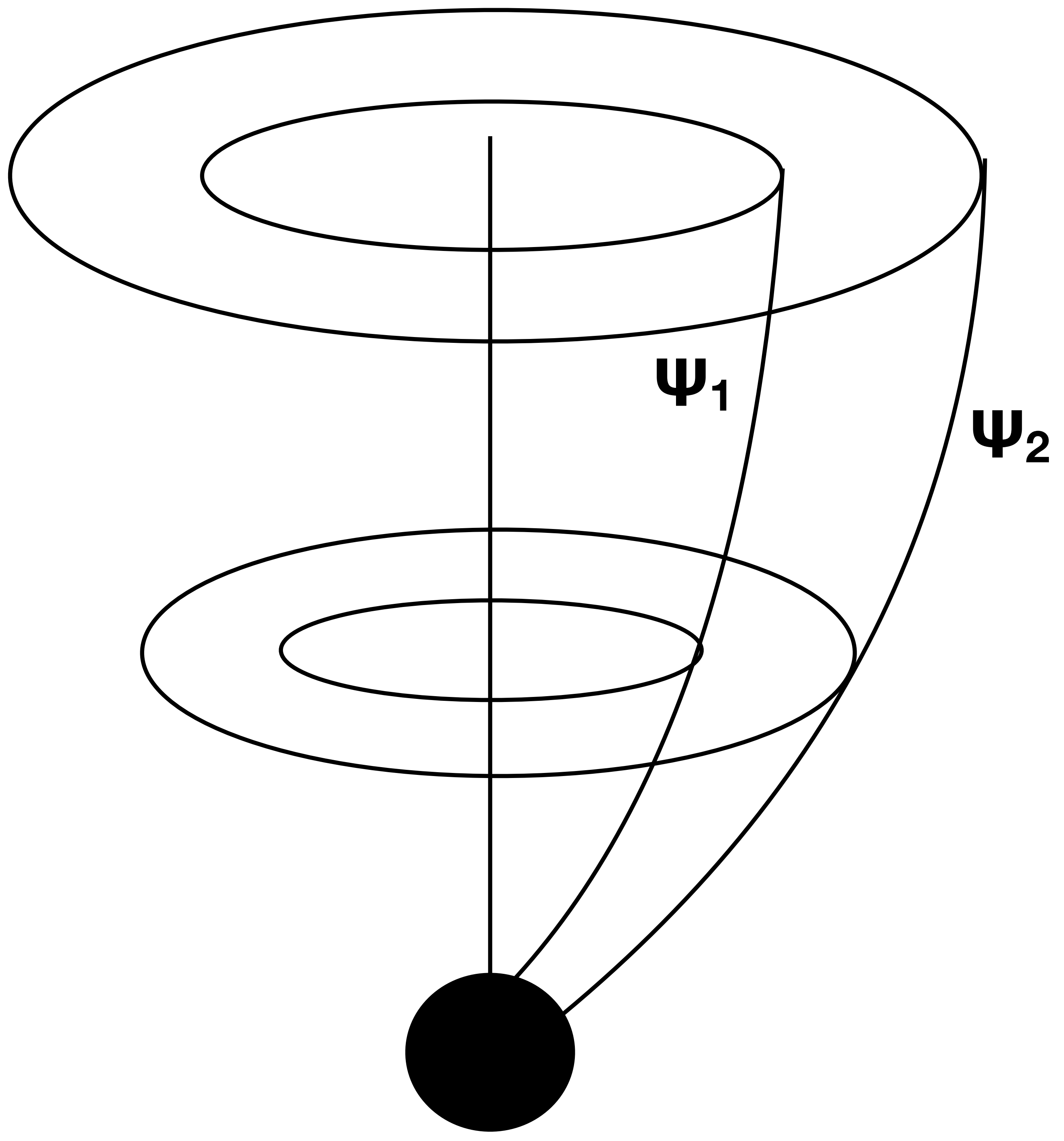


$$\mu = \frac{F_E}{F_M} = \Gamma + \frac{|\mathbf{E} \times \mathbf{B}|}{\rho v_p \Gamma} = \Gamma \left(1 + \boxed{\underbrace{\frac{F_{Poynting}}{F_{Kinetic}}}_{\equiv\, \sigma}}\right)$$

$$\mu = \Gamma(1+\sigma);\ \Gamma \to \mu(\sigma \to 0)$$

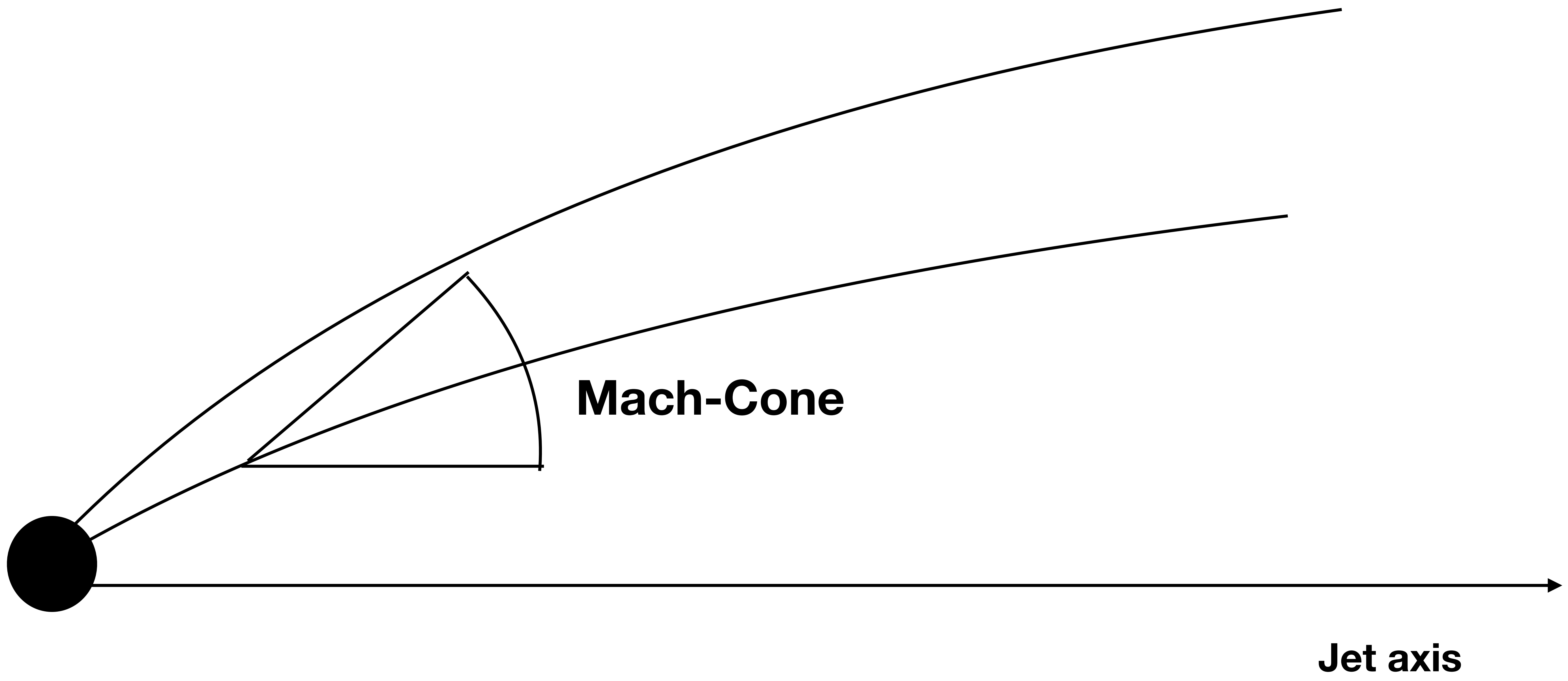
Maximum achievable Lorentz-factor: **μ**

Jet accelerates by decreasing its magnetization **σ**

Force-free breaks at the fast point!

speed of fast waves?

$$v_{FMS}^2 = \frac{B'^2}{\rho + B'^2} = \frac{\sigma}{1+\sigma}$$



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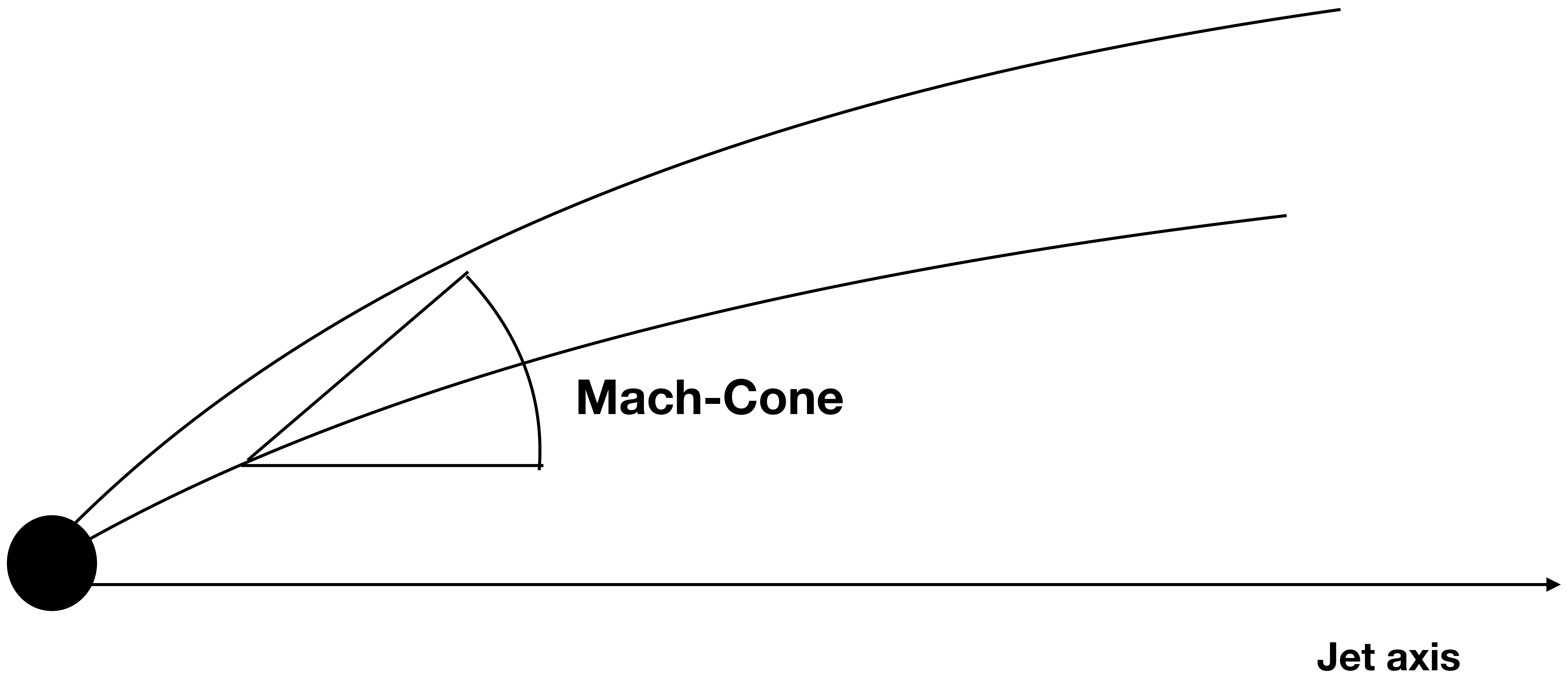
$$v_{FMS}^2 = \frac{B'^2}{\rho + B'^2} = \frac{\sigma}{1+\sigma} \qquad 1 - v_{FMS}^2 = \frac{1}{1+\sigma}$$



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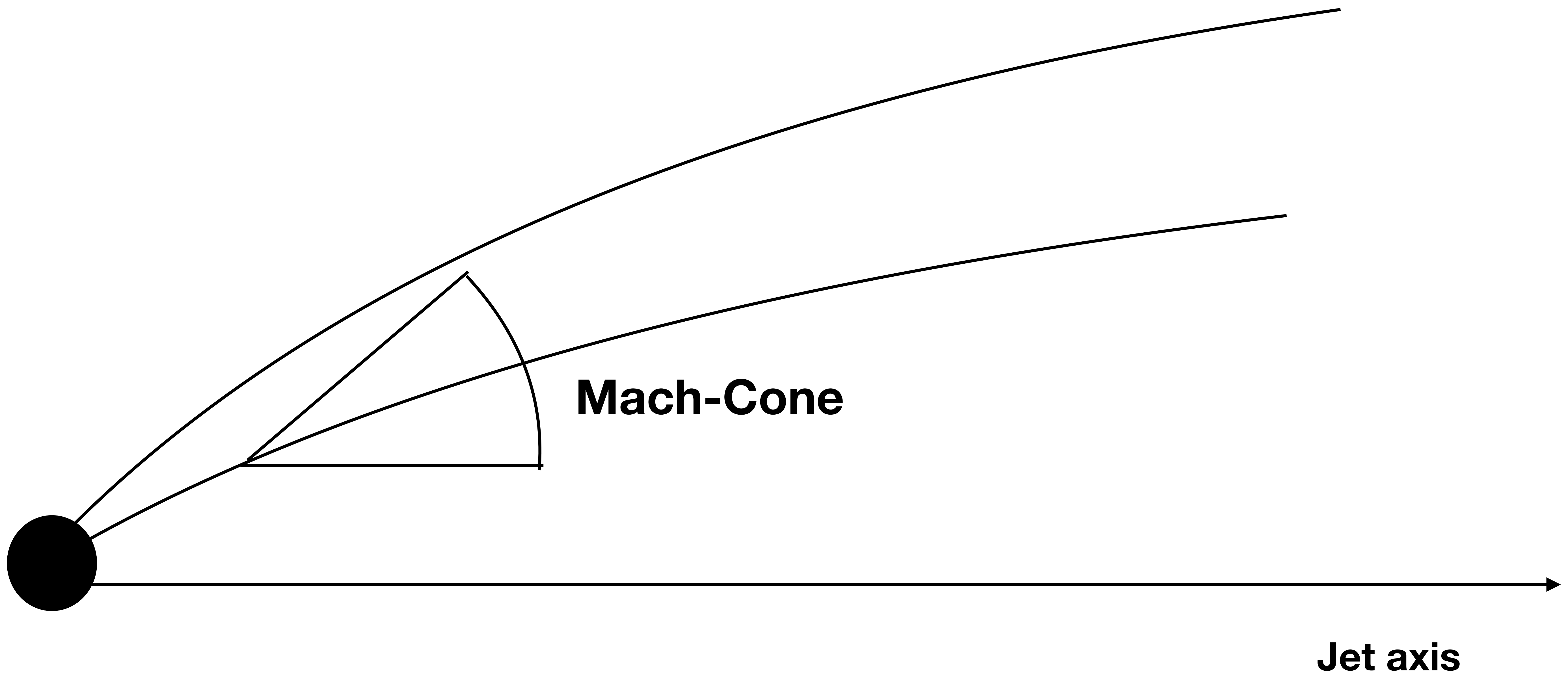

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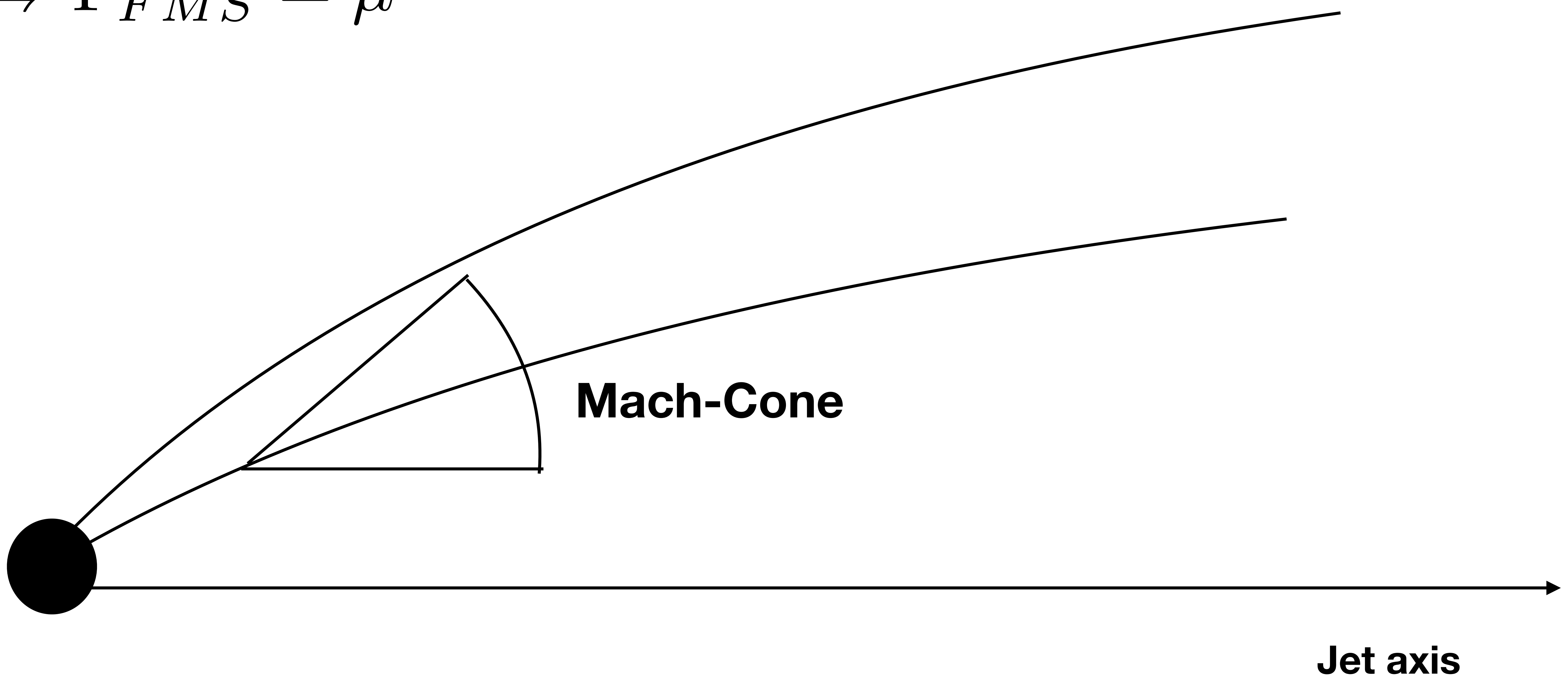

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force-free: $\sigma = \infty$ fast waves travel at c

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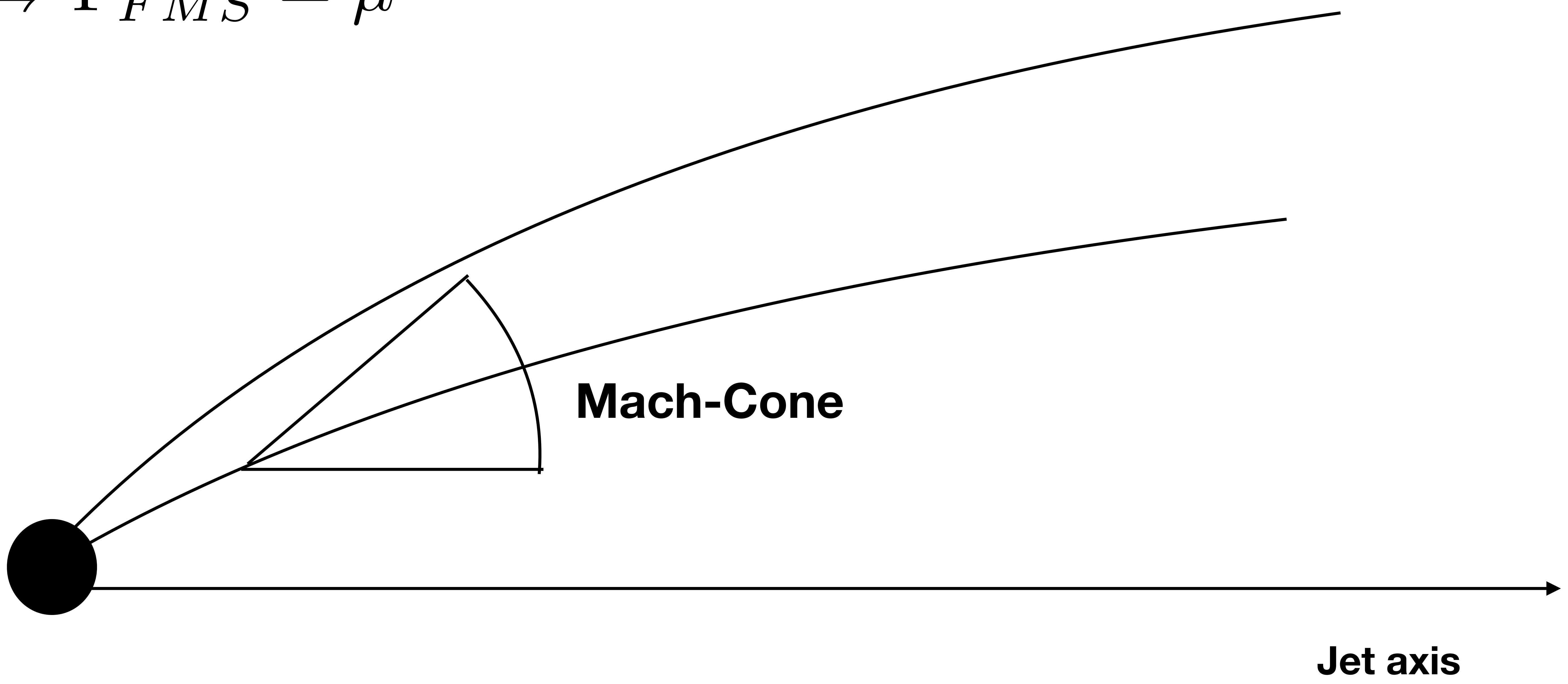

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$$\Gamma = \mu^{1/3} \ll \mu$$

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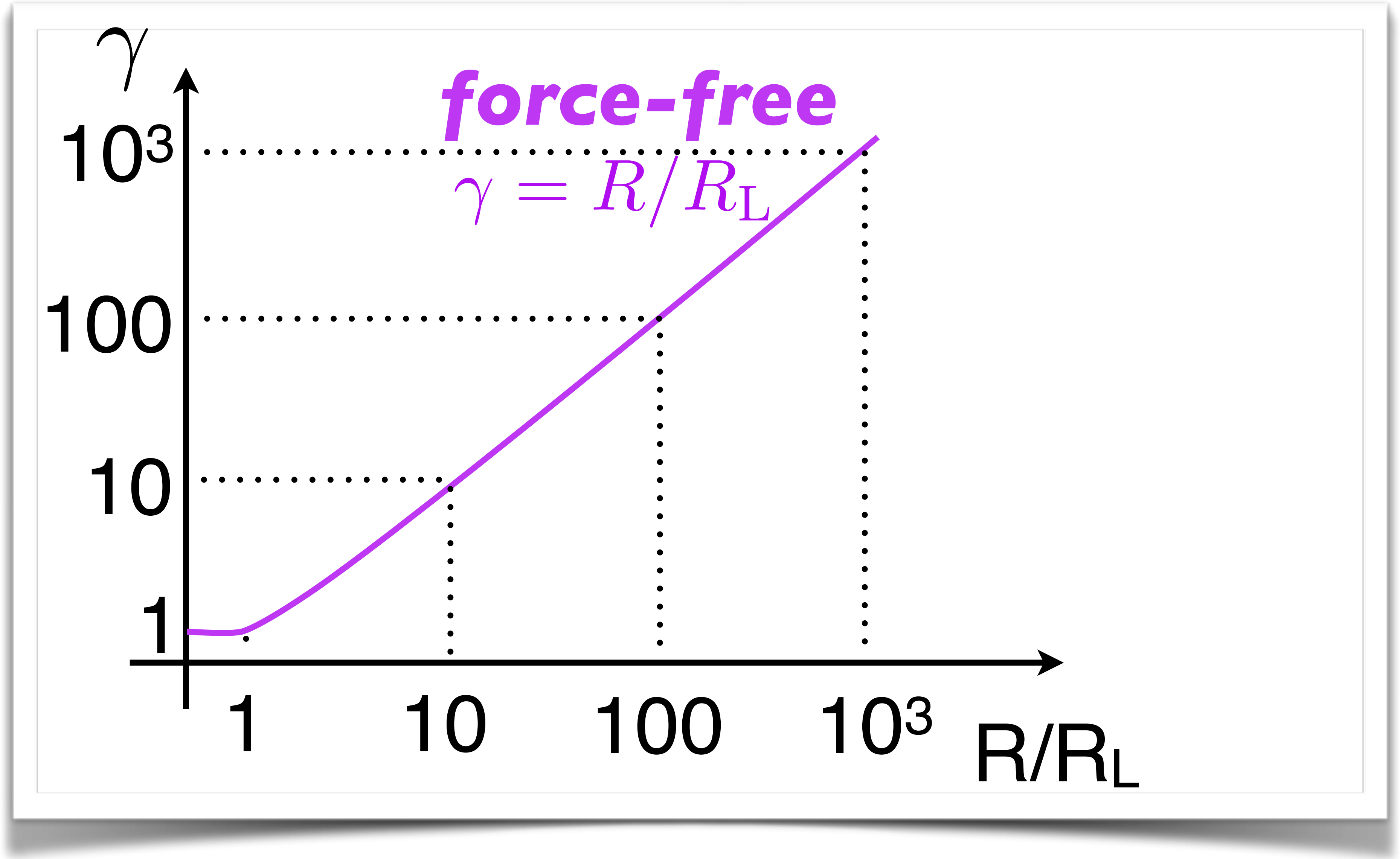

Adopted from Sasha

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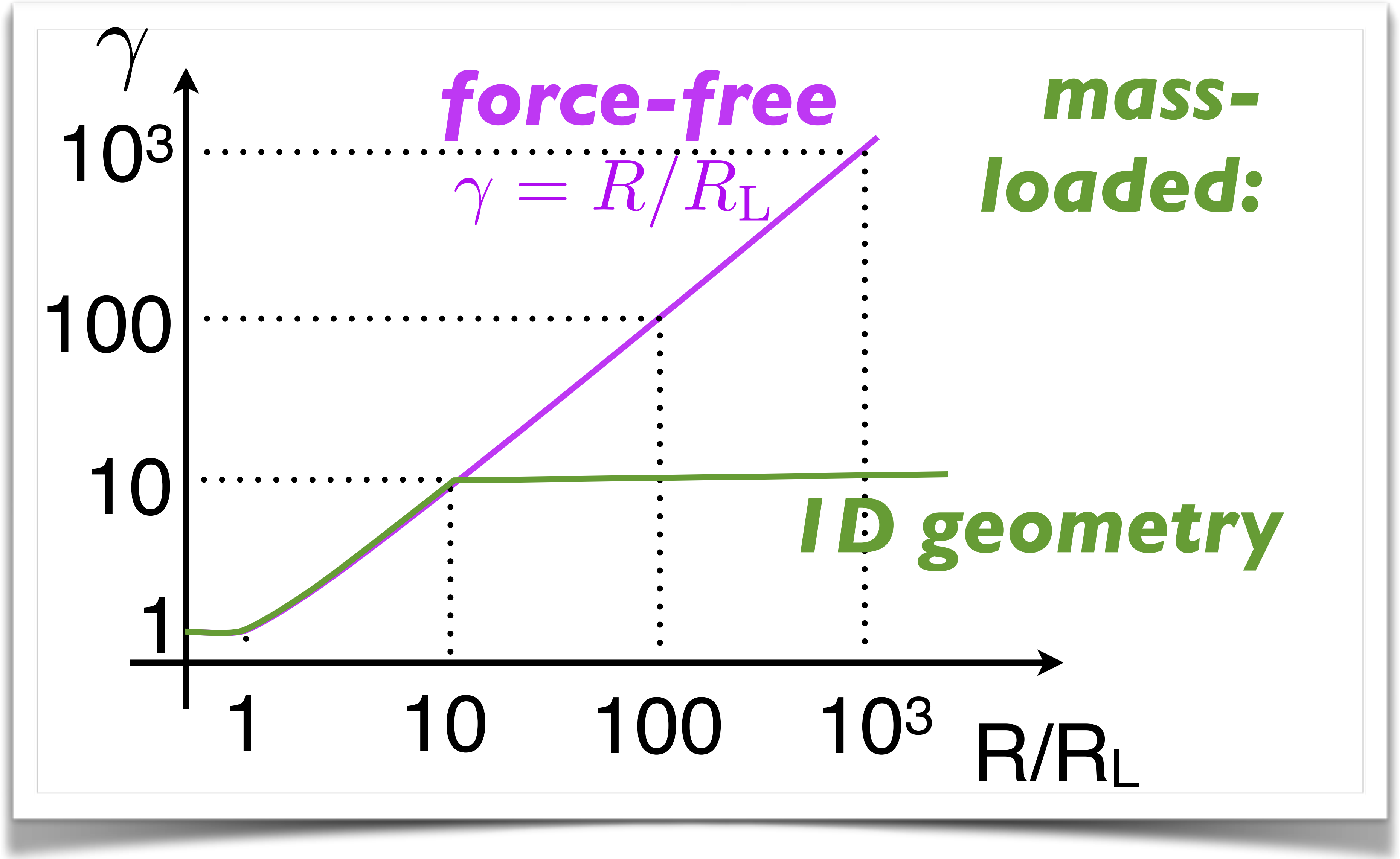

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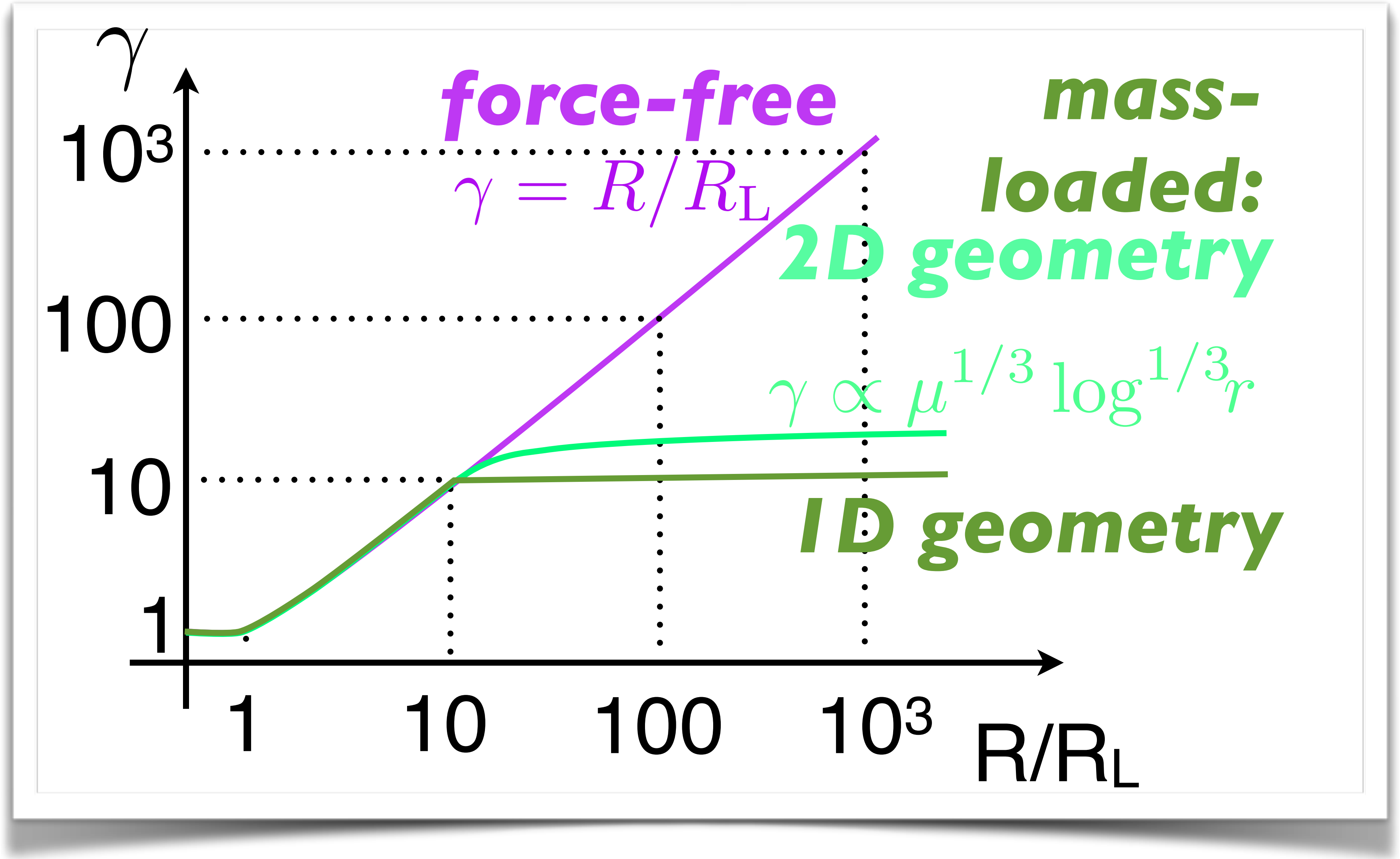

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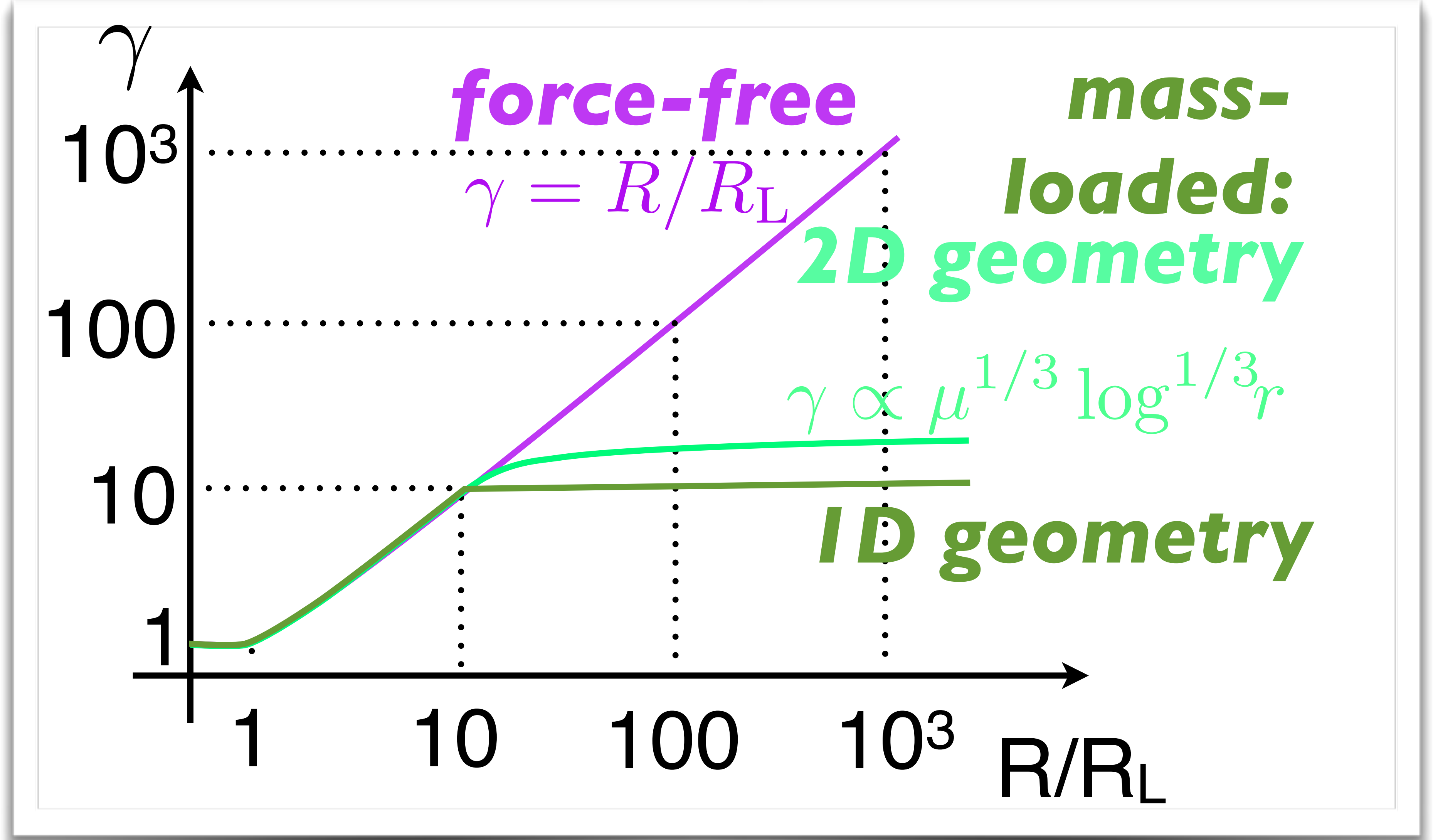

Adopted from Sasha

(unconfined) relativistic jets accelerate inefficiently
=> σ-Problem

Poynting dominated flows - in axisymetry

Beyond the light cylinder $(r\Omega \equiv c)$:

$$v_\phi \ll r\Omega; \quad v_p \to 1: \qquad E = |B_\phi|; \quad |B_\phi| = r\Omega B_p$$

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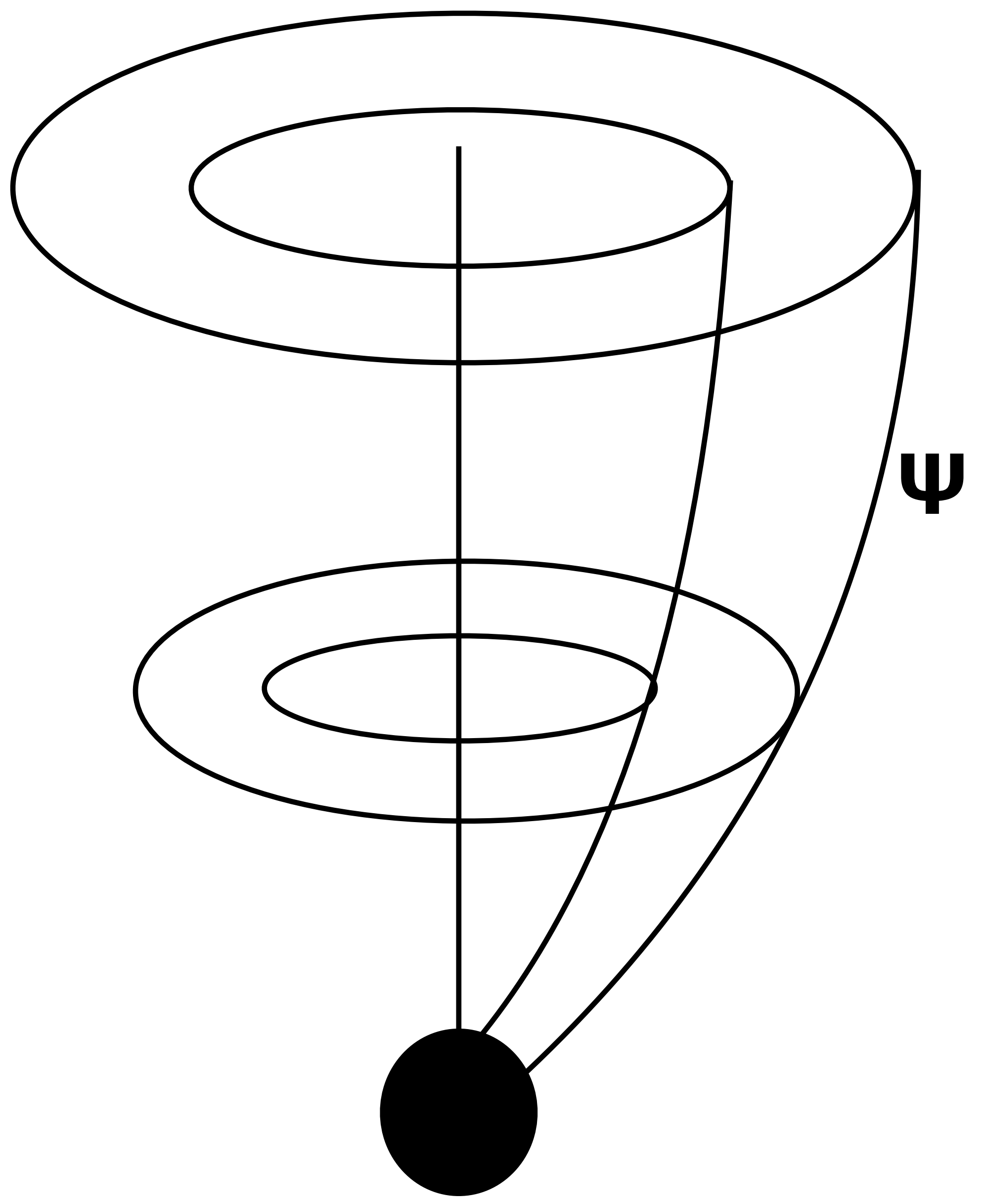

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$$\phi = r^2 B_p$$

$$\Rightarrow \mu = \Gamma + \frac{\Omega(\Psi)^2 r^2 B_p}{k(\Psi)}$$

Michel (1969)

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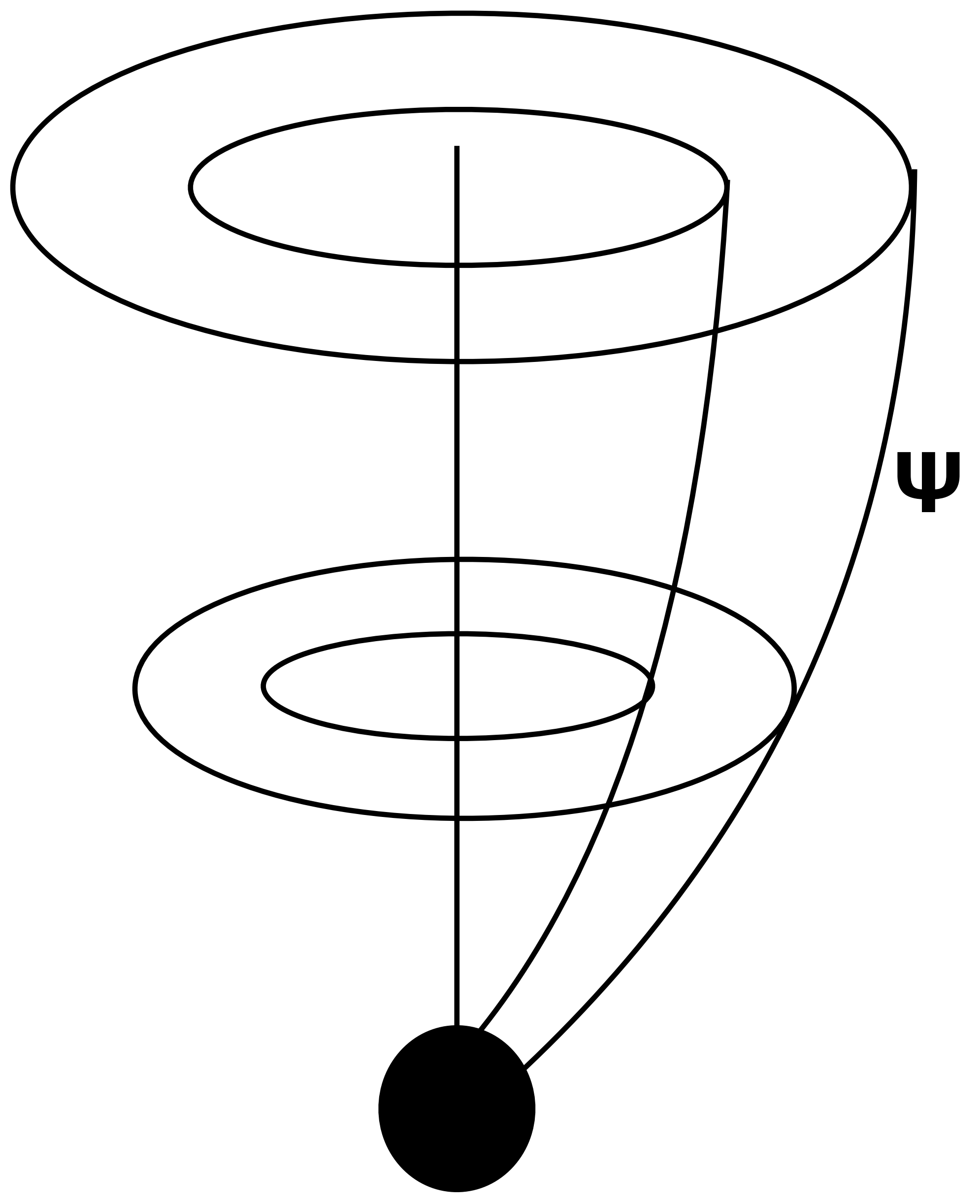

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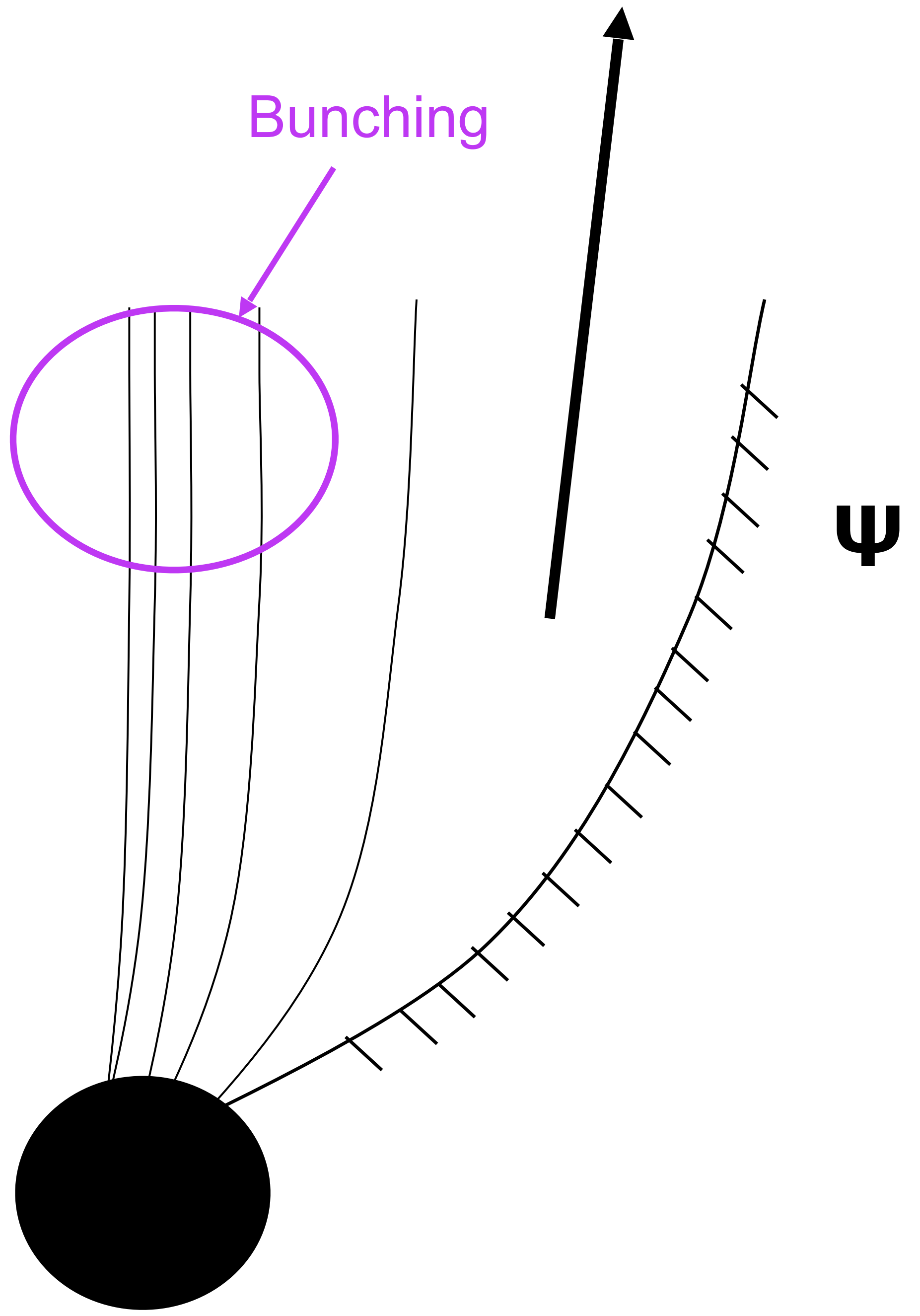

Acceleration proceeds via differential „bunching“ of field lines $\phi \to 0$
=> No acceleration without collimation!

E.g. straight (monopolar) field lines: $B_p(r) \propto r^{-2} \Rightarrow \phi = const.$

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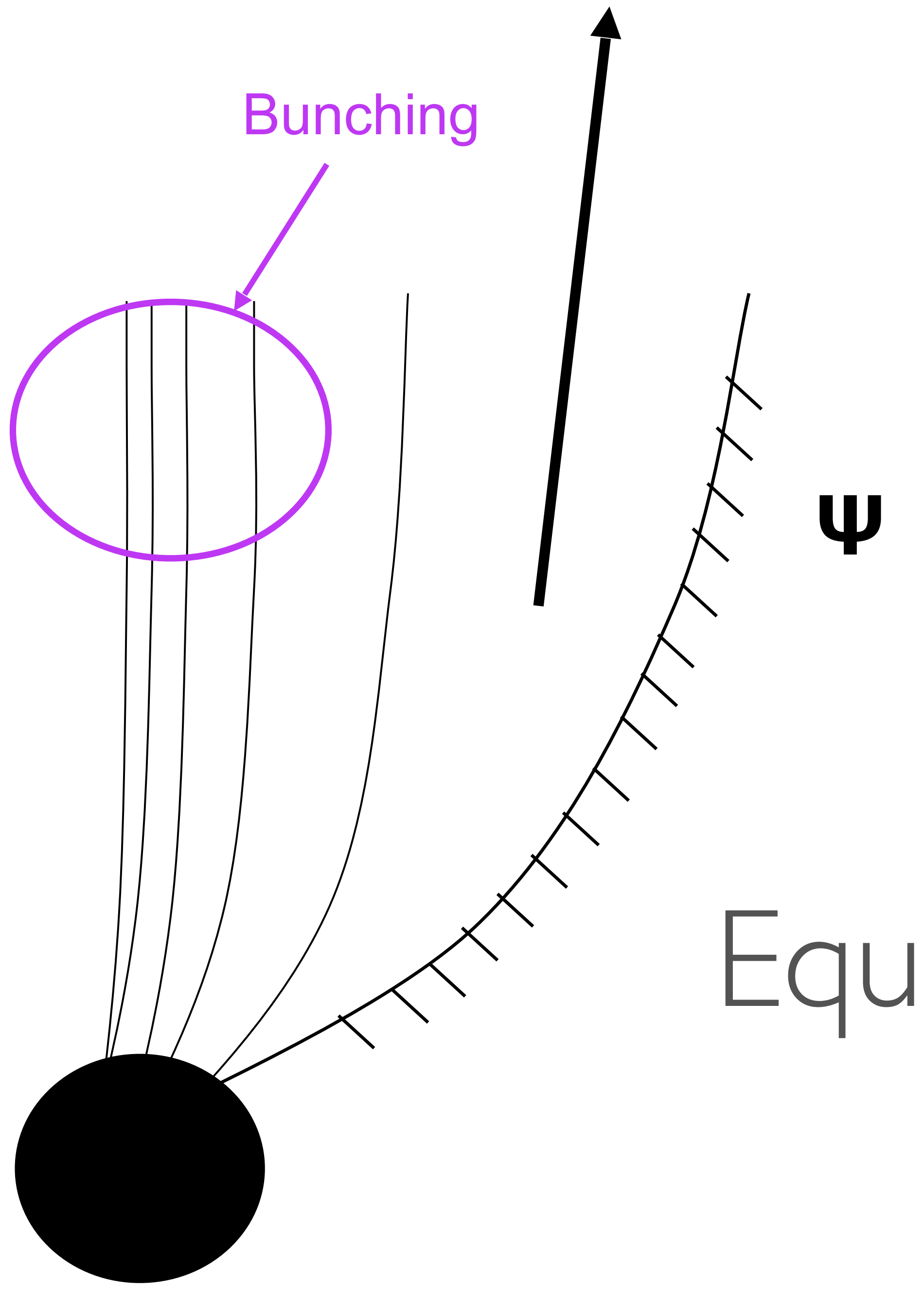

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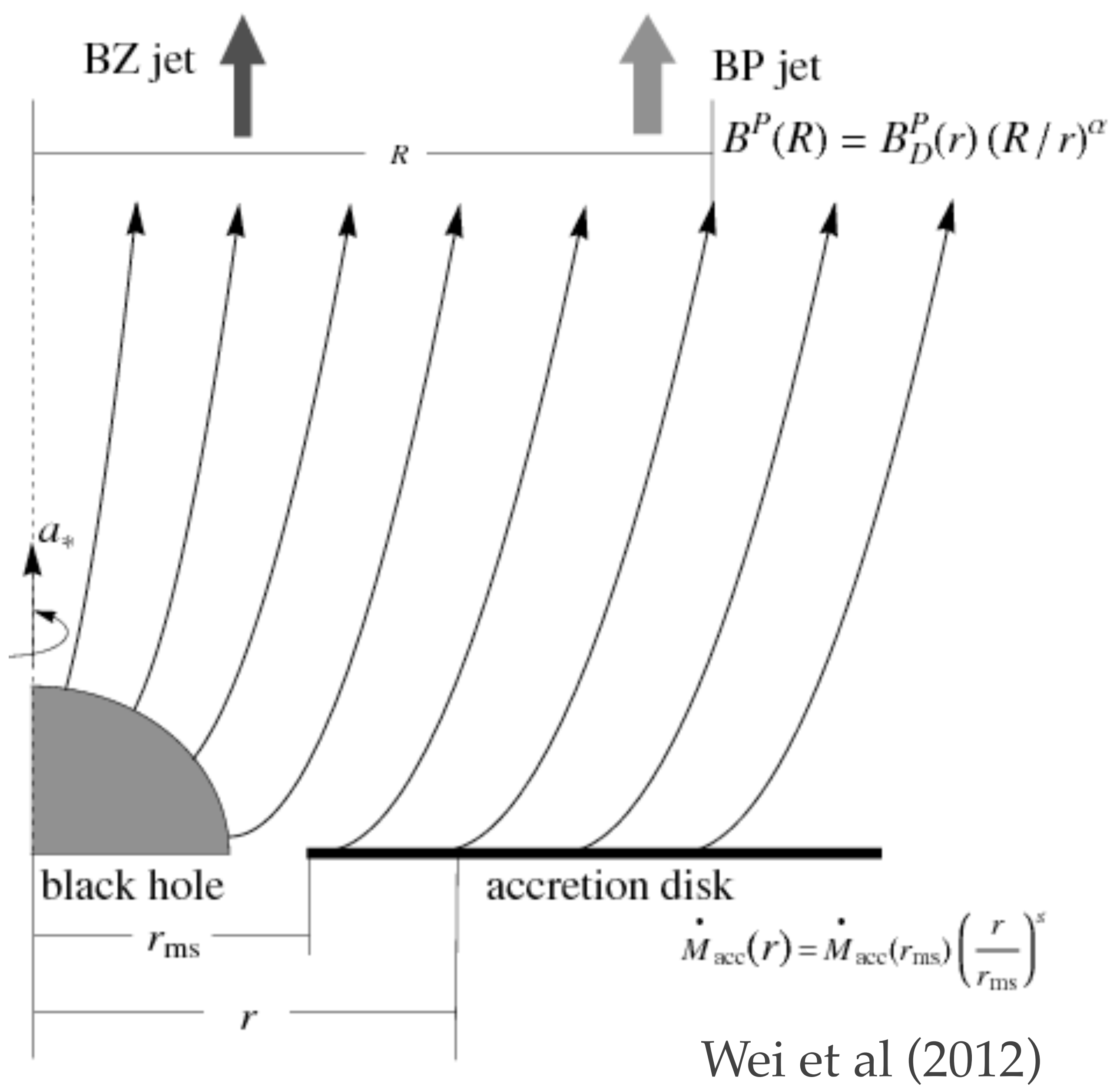
Equipartition scale for collimating $(z \propto r^{1.5})$ jet :

$$z_{\rm eq} = 2.7 \times 10^4 r_{\rm S} \left(\frac{\mu}{30}\right)^3 = 2 \left(\frac{\mu}{30}\right)^3 \frac{M_\bullet}{10^9 M_\odot} {\rm pc}$$

Barkov & Komissarov (2008)
Beskin & Nokhrina (2009)
Porth et al. (2011)

Conditions for relativistic jet formation

- Rotating magnetosphere with open magnetic fields (need Blandford)
- High magnetisation: Need to extract energy
- Collimating agent: disk wind, stellar remnant, shocked gas



Wei et al (2012)

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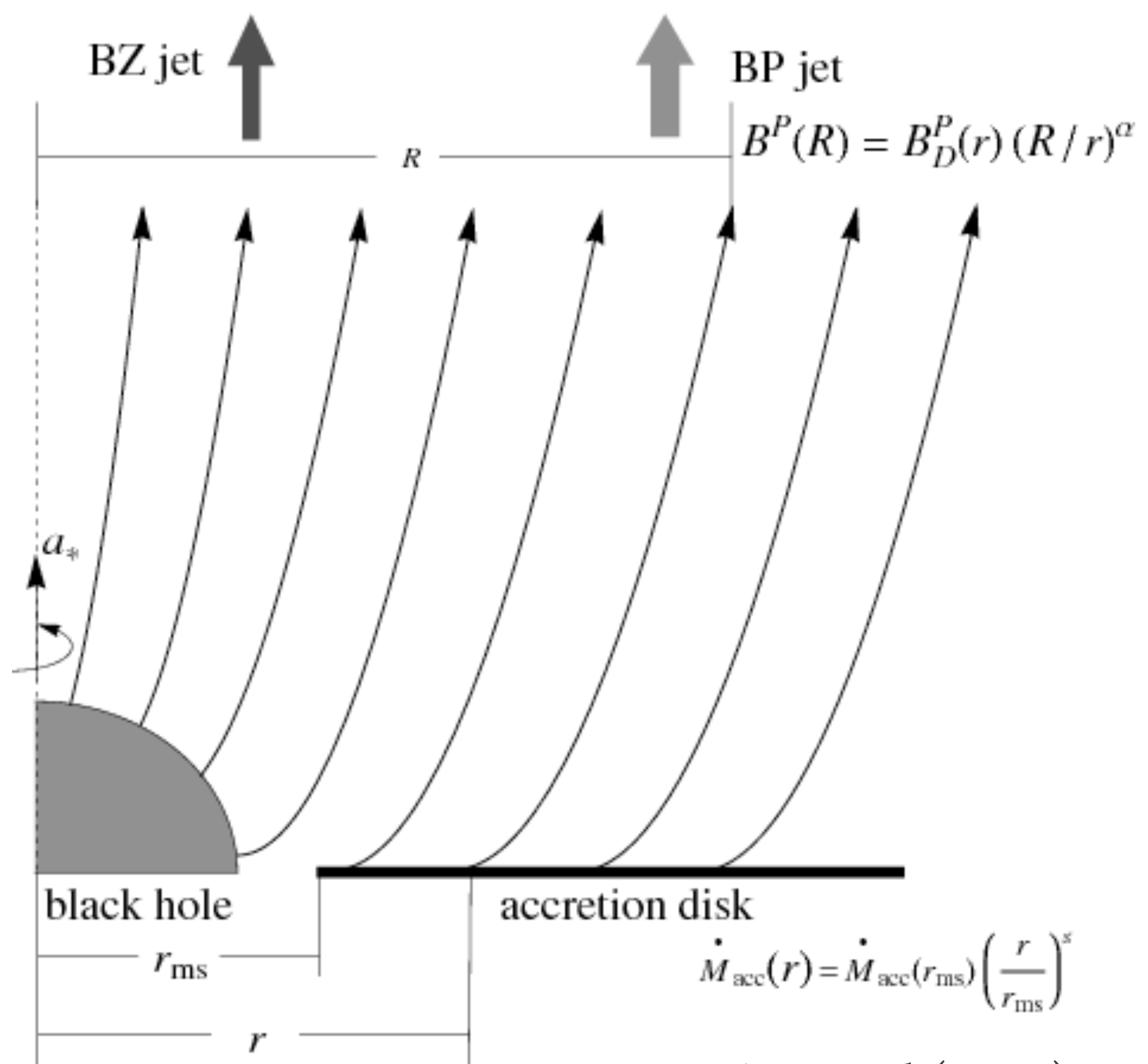

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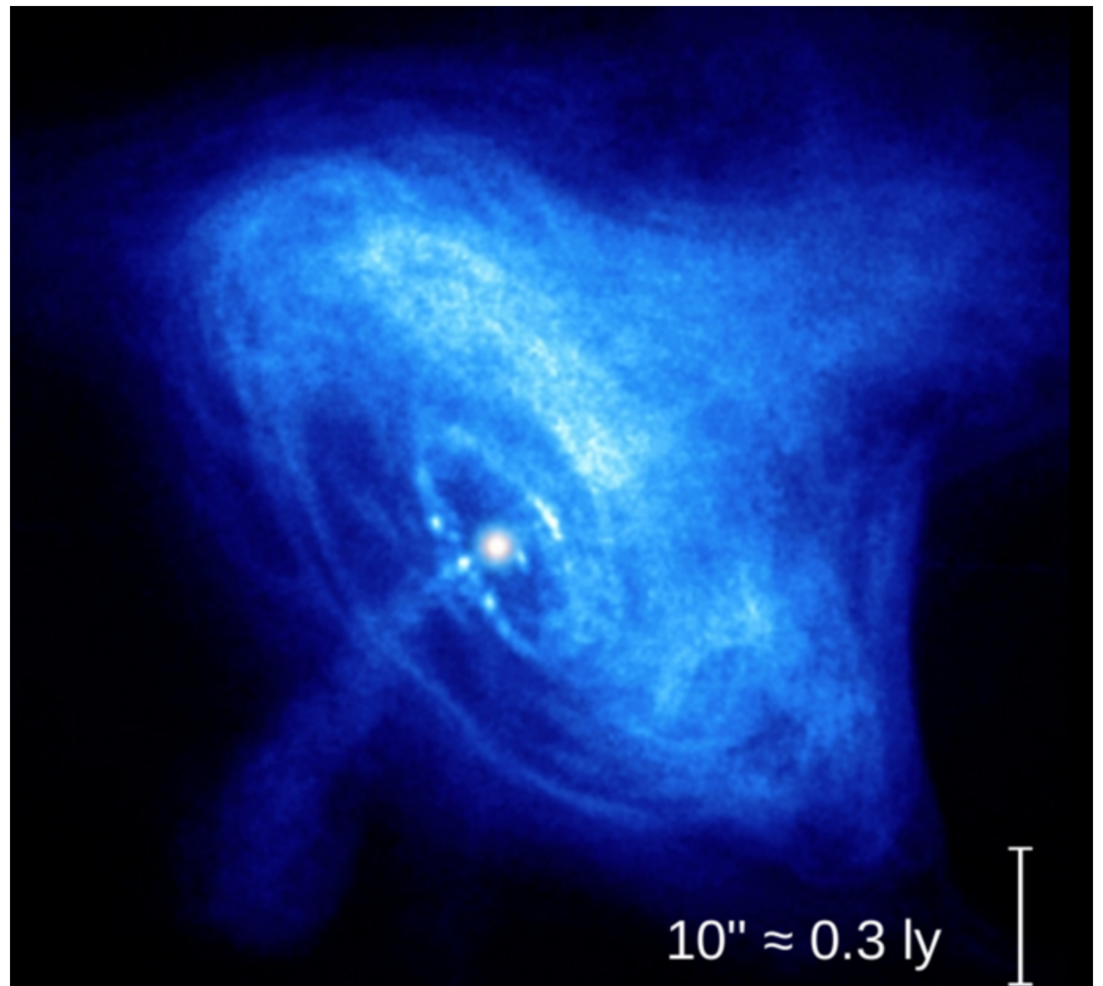

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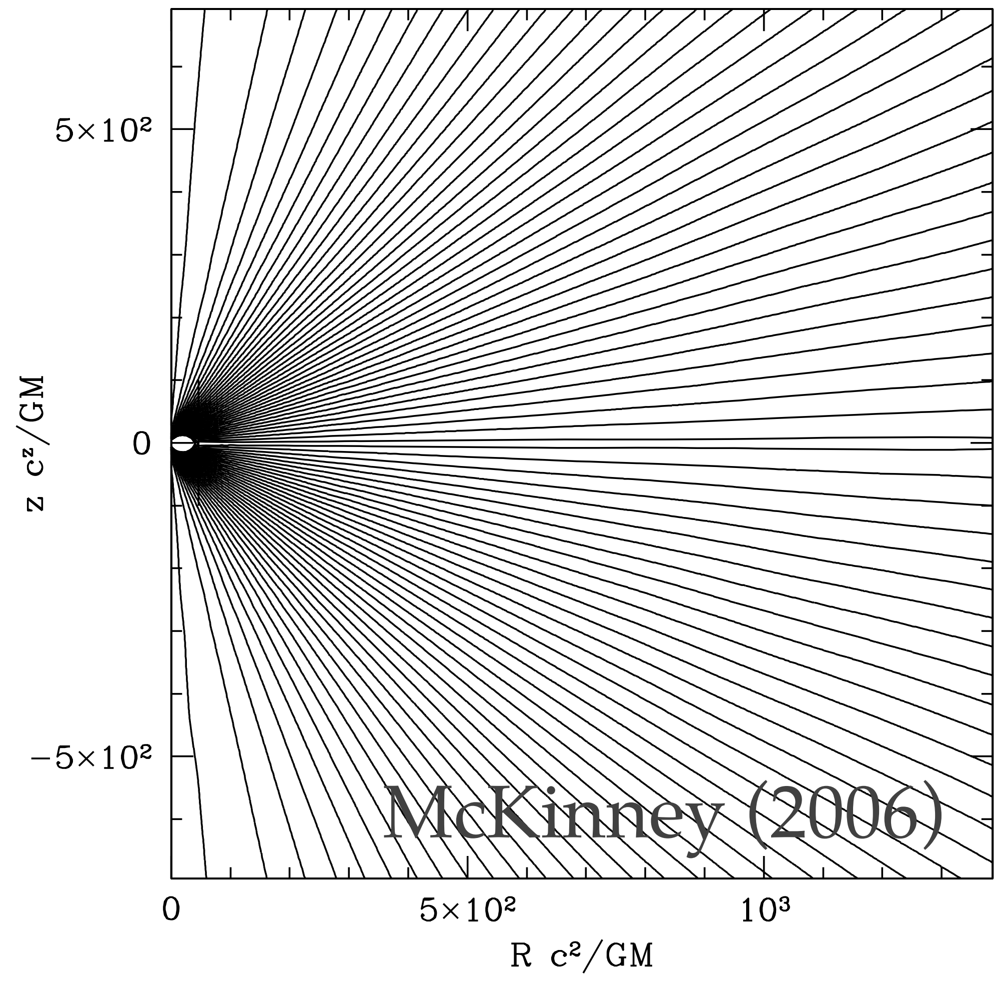

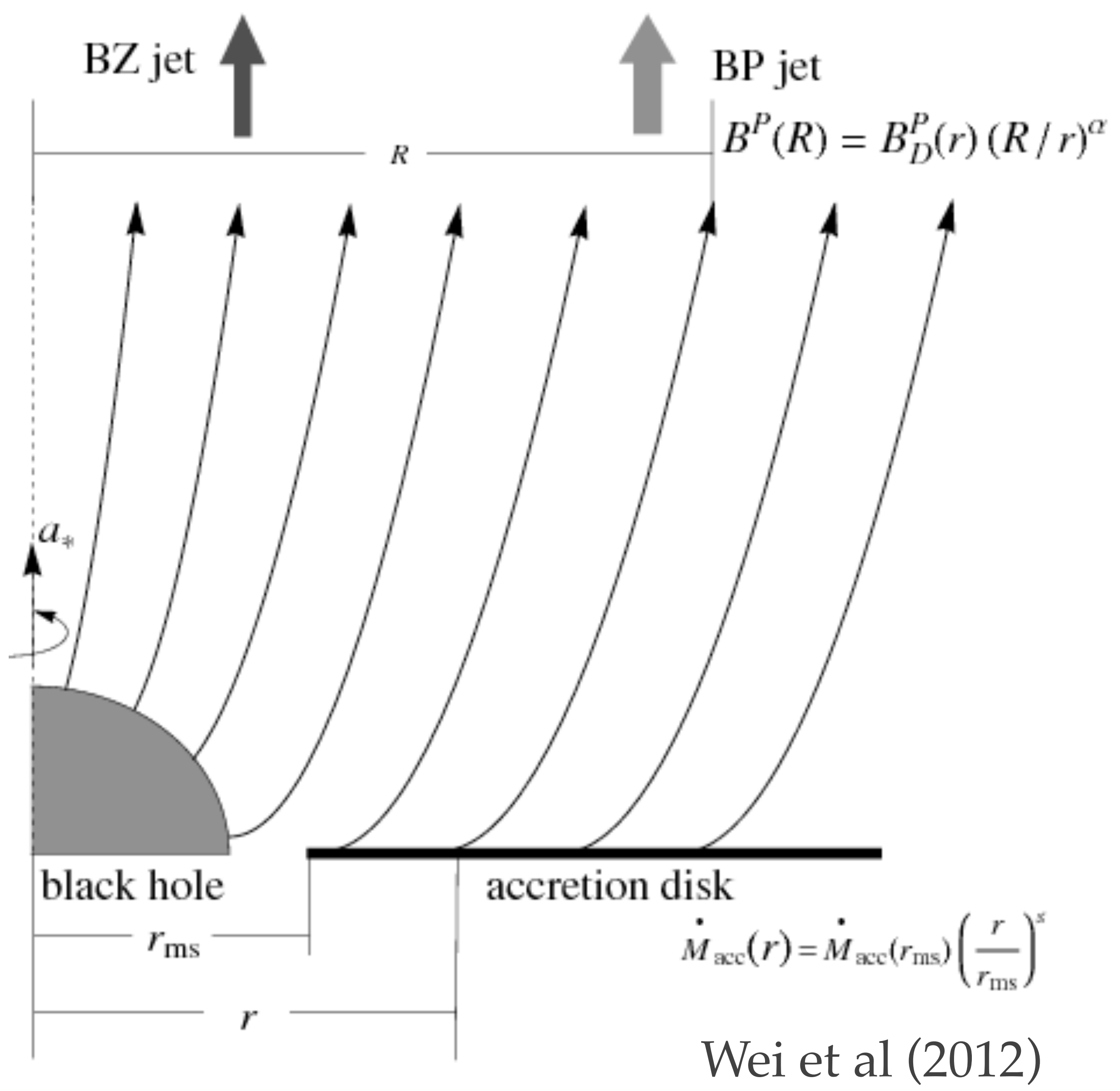

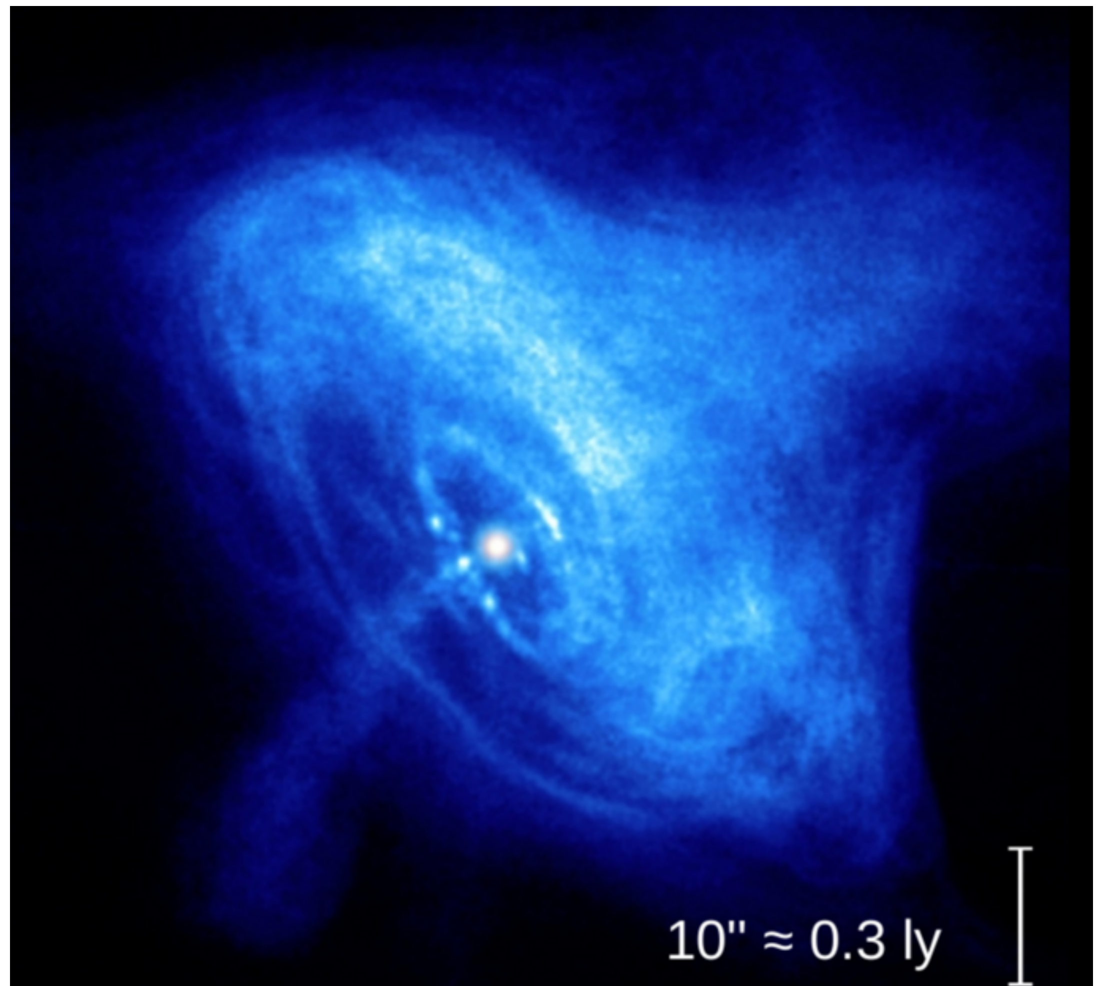

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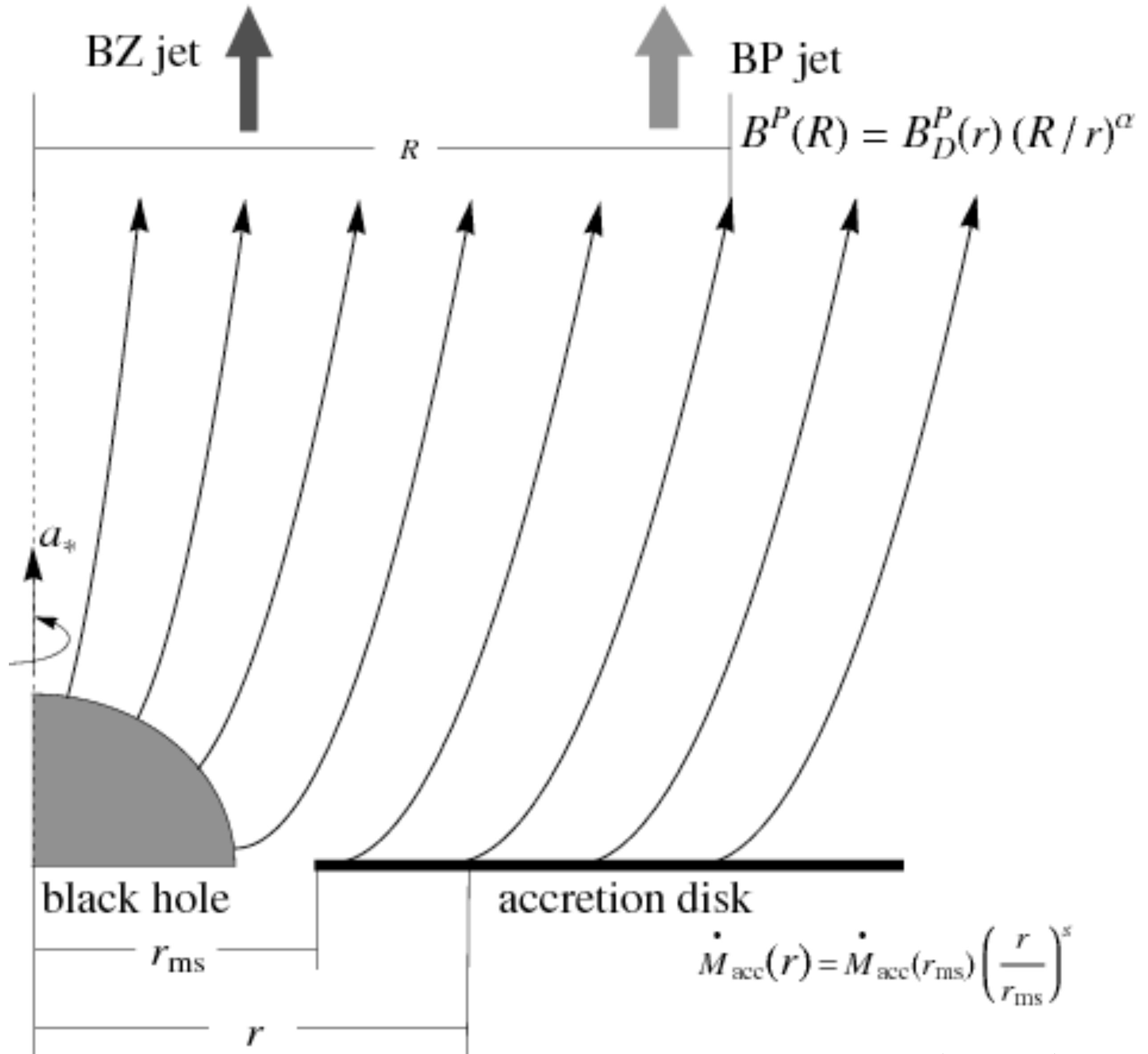

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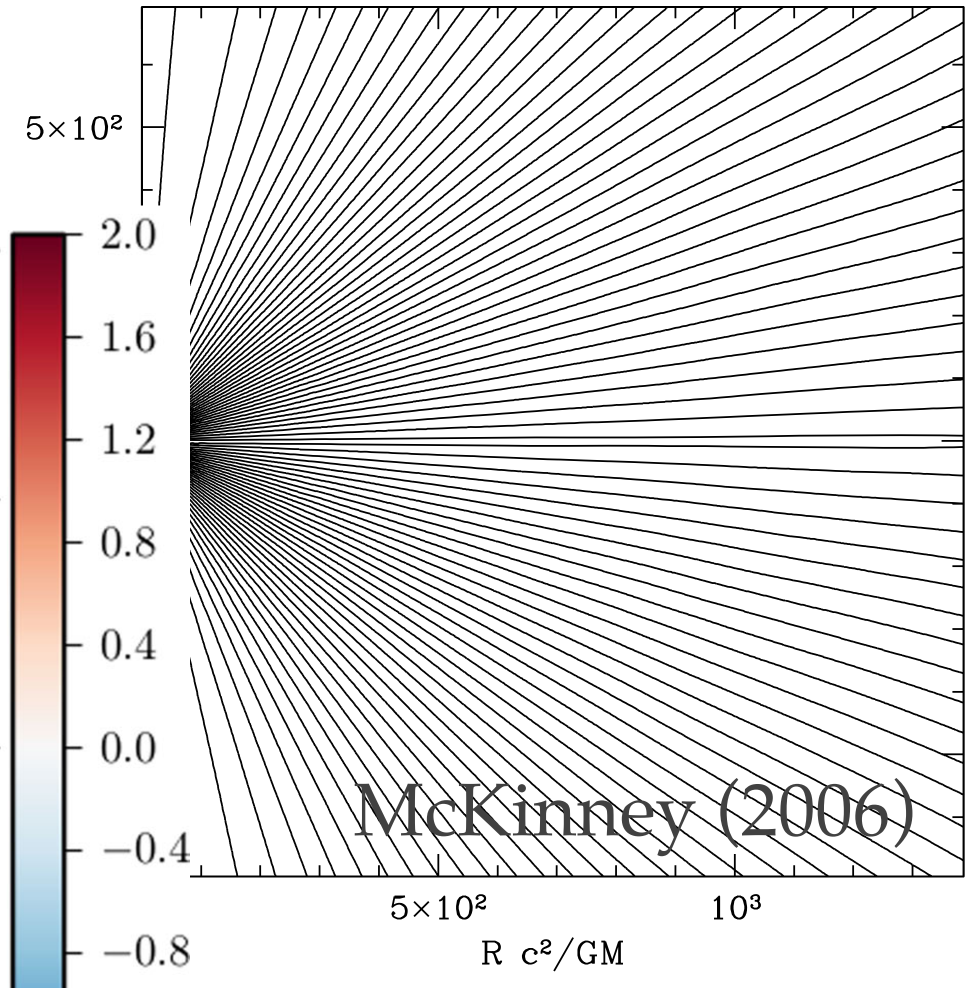
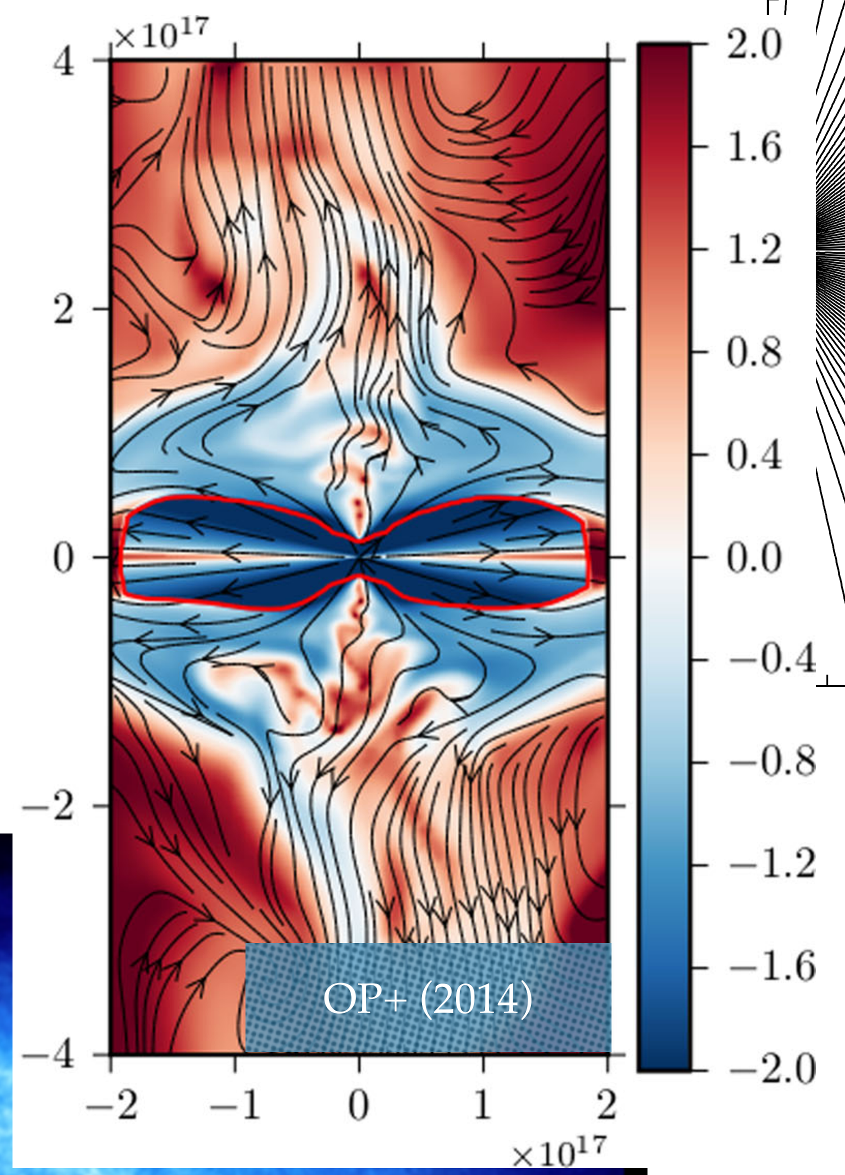
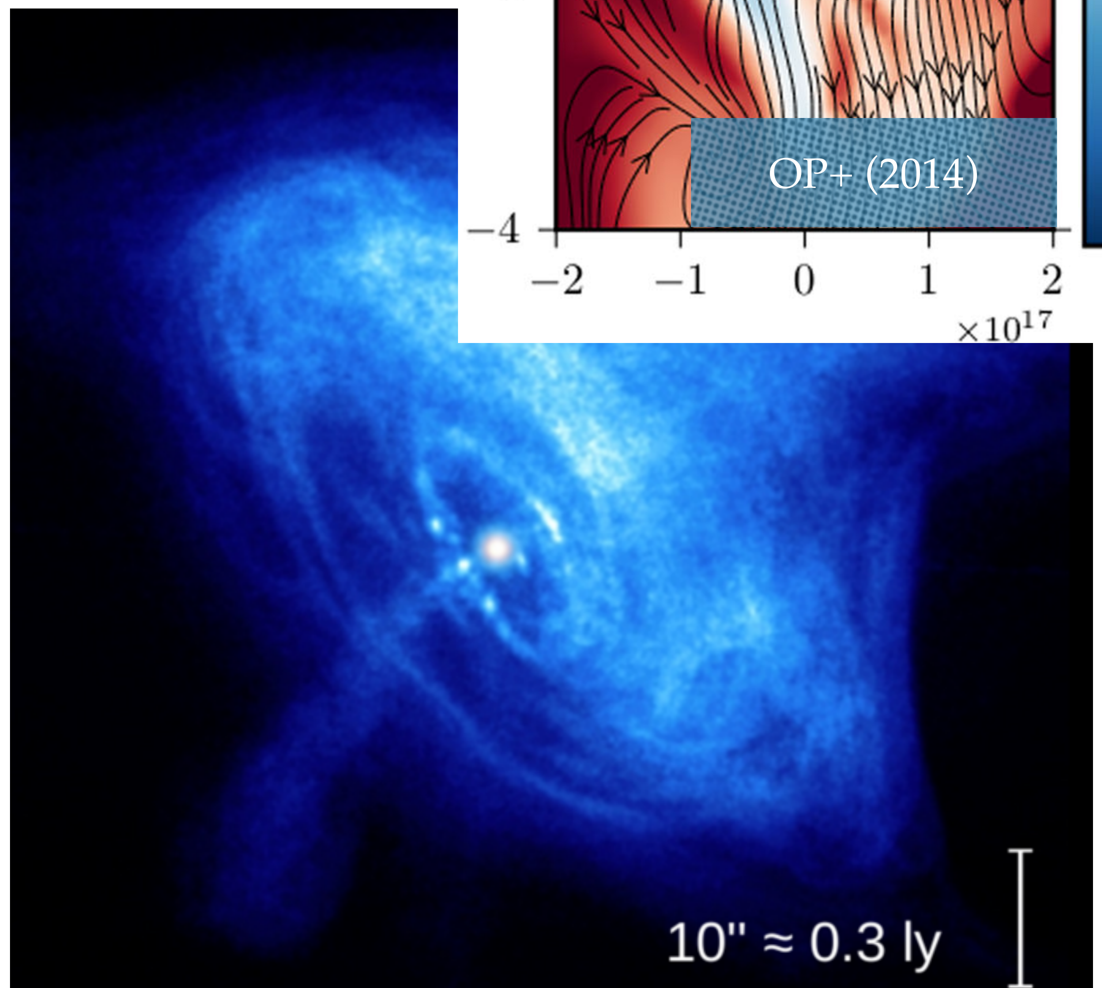


McKinney (2006)

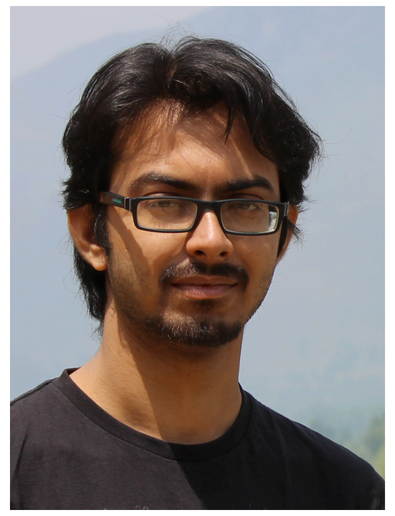


OP+ (2014)

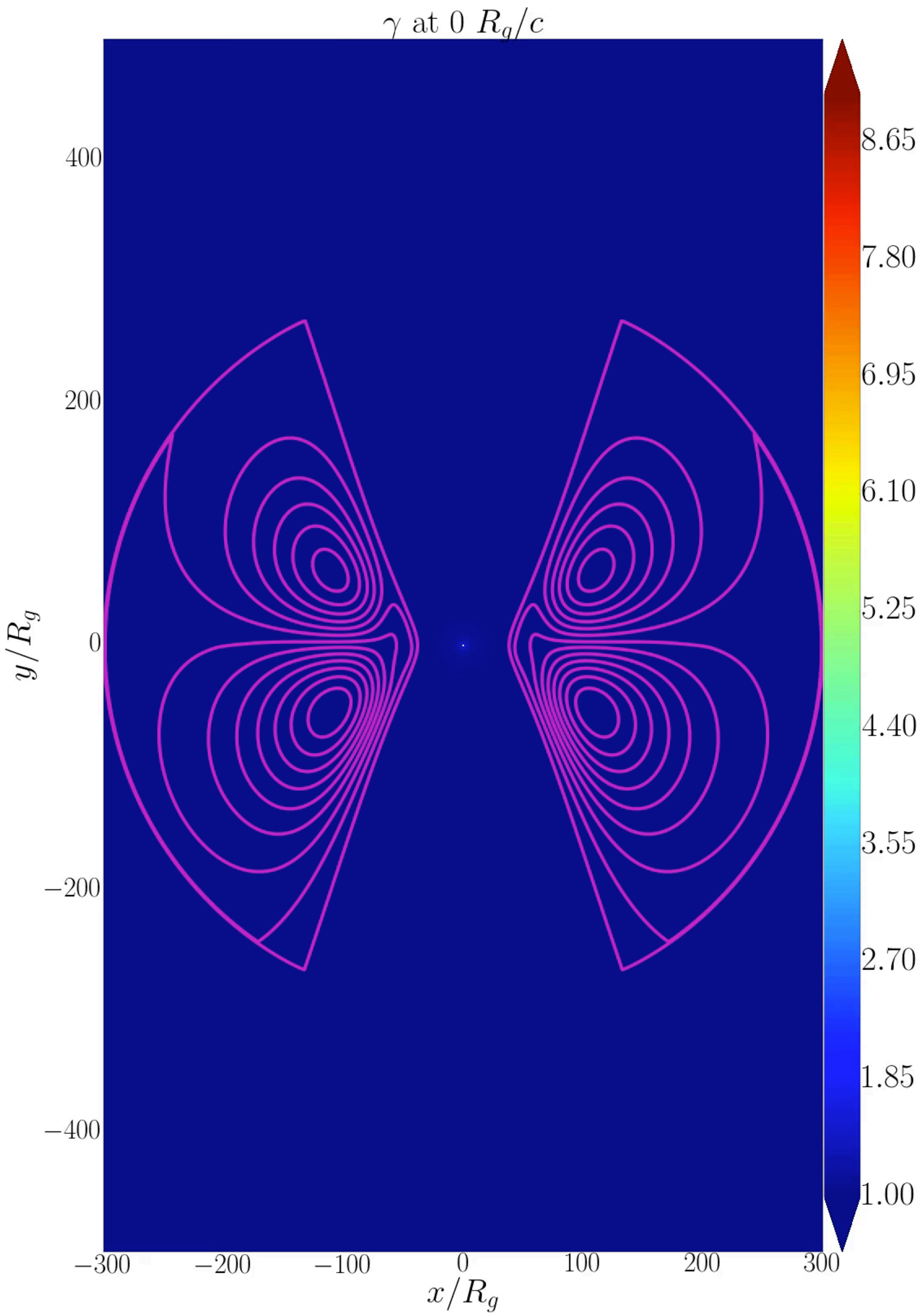


2D numerical simulations

- 5 orders of magnitude: can be directly compared to observations
- Jets gradually accelerate
  - as a power-law in distance
  - to relativistic Lorentz factors
- Jets efficiently convert magnetic to kinetic energy (to equipartition)
- Pinching and shear instabilities!
  - Mass-loading and jet deceleration



Koushik Chatterjee



Chatterjee+ 19

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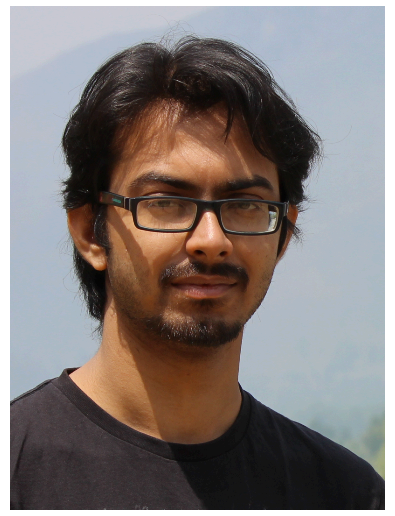

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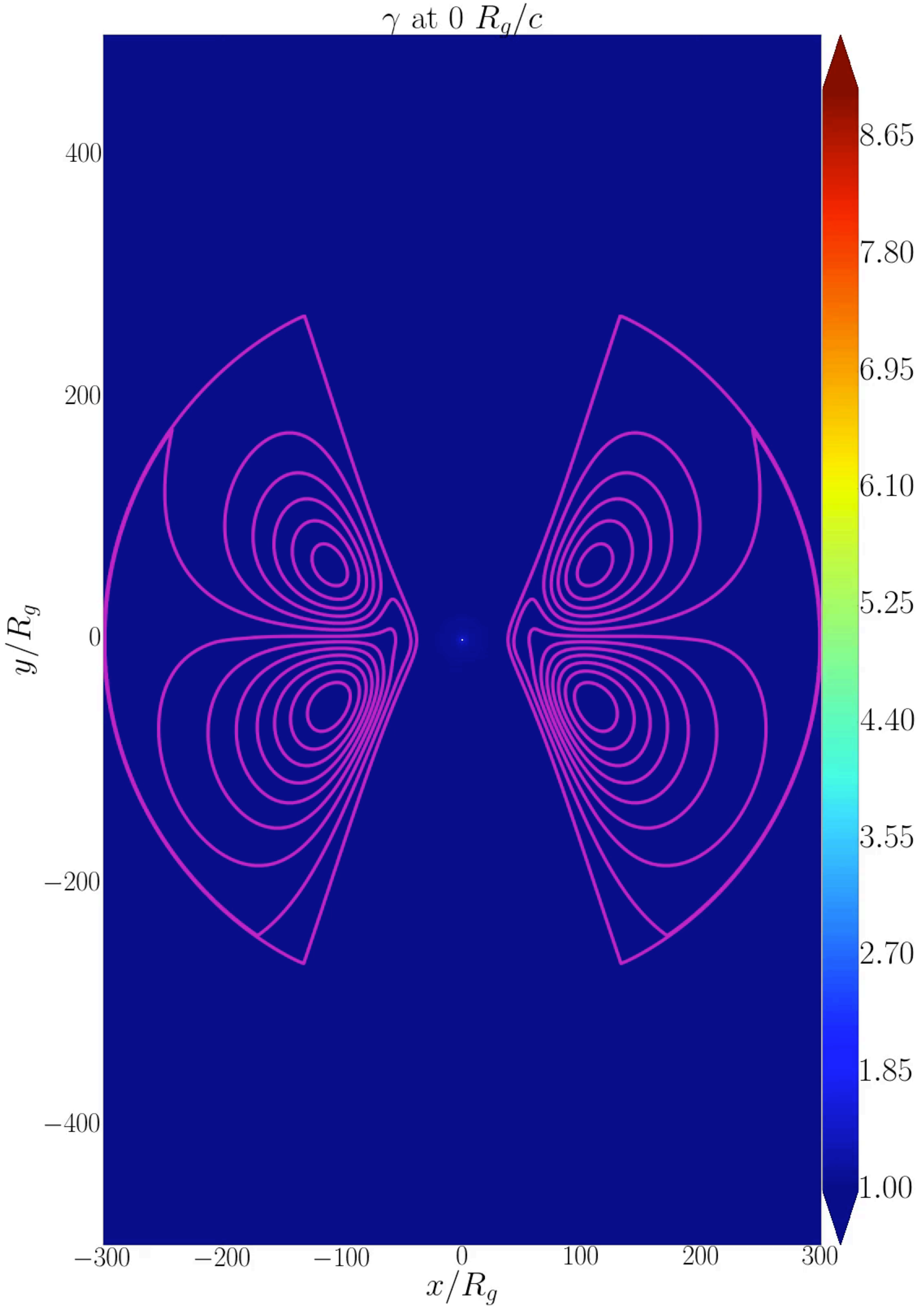
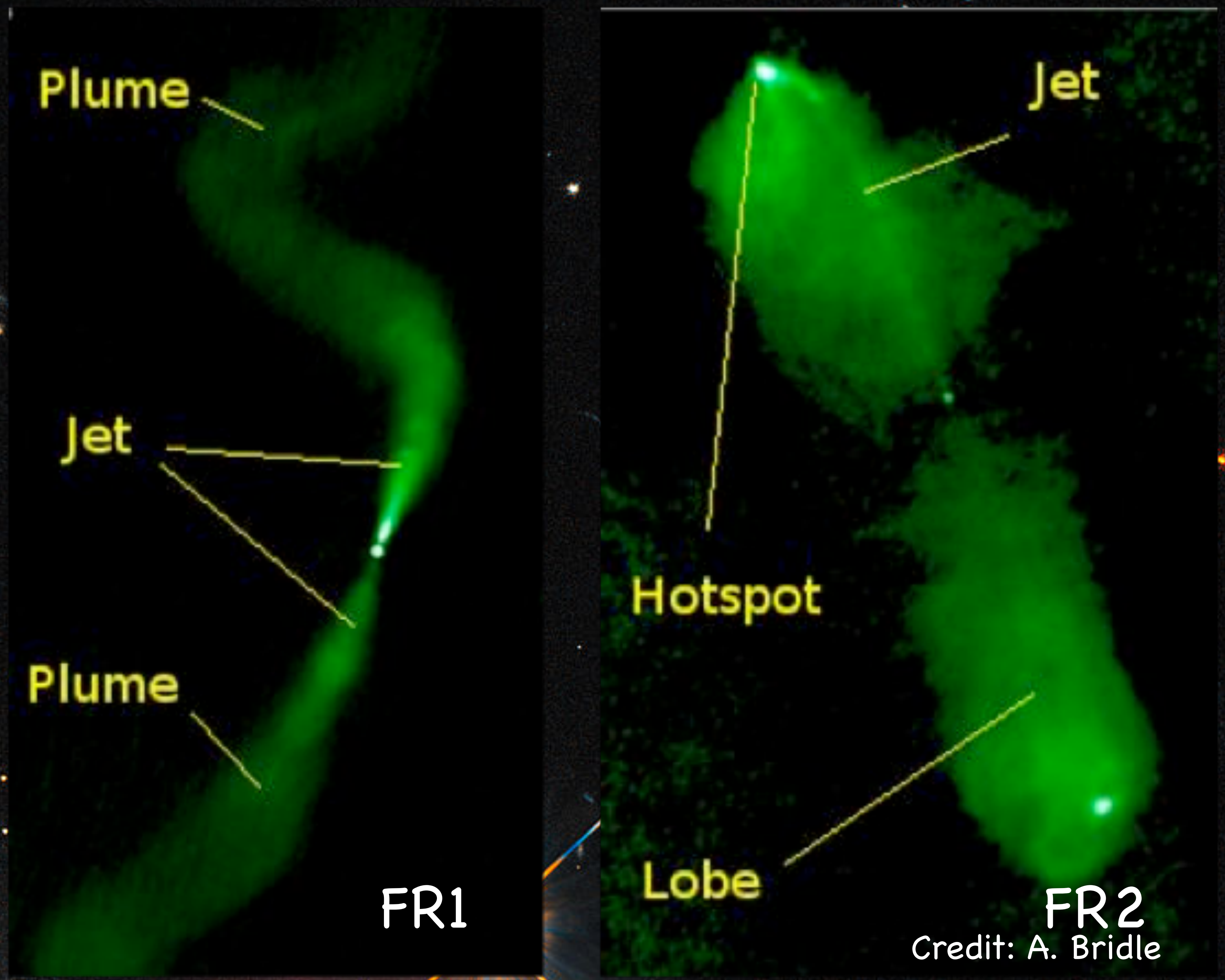


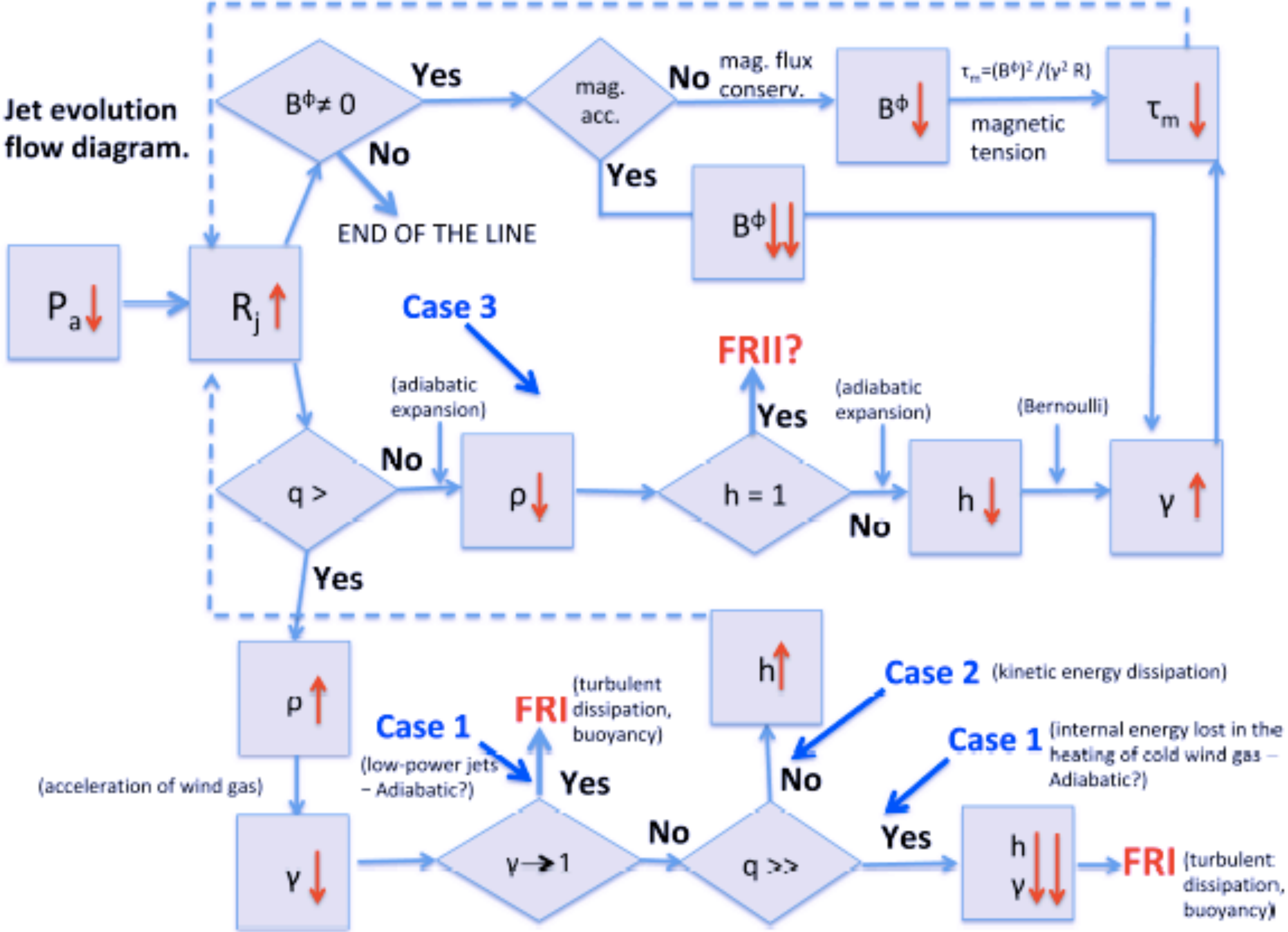
Chatterjee+ 19

Jet instabilities

- (AGN) Jets *can* cover 10^5-10^7 of initial radii without disruption

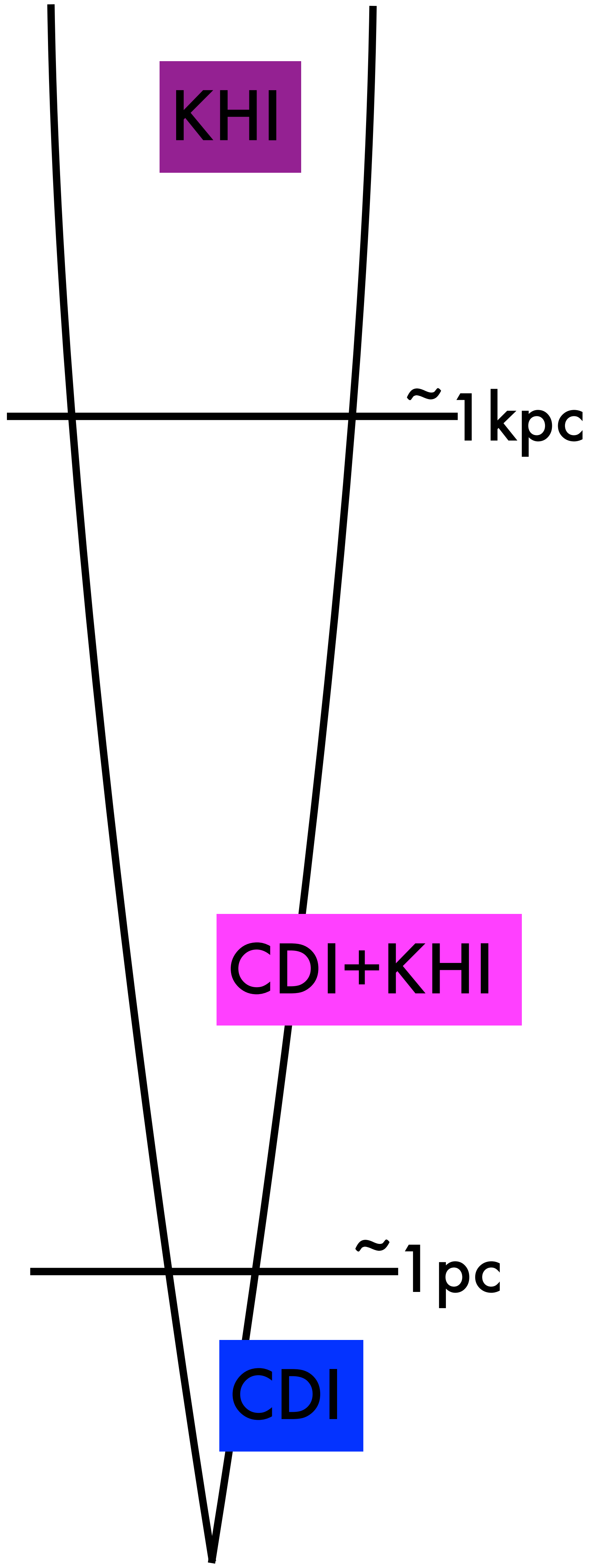


- Optical synchroton needs continuous particle re-acceleration
  thus dissipation (e.g. Meisenheimer 2003)
- How can we avoid disrupting fluid instabilities?
- What is the deciding factor between the FR1 and FR2 division?
- How can we have dissipation without disruption?

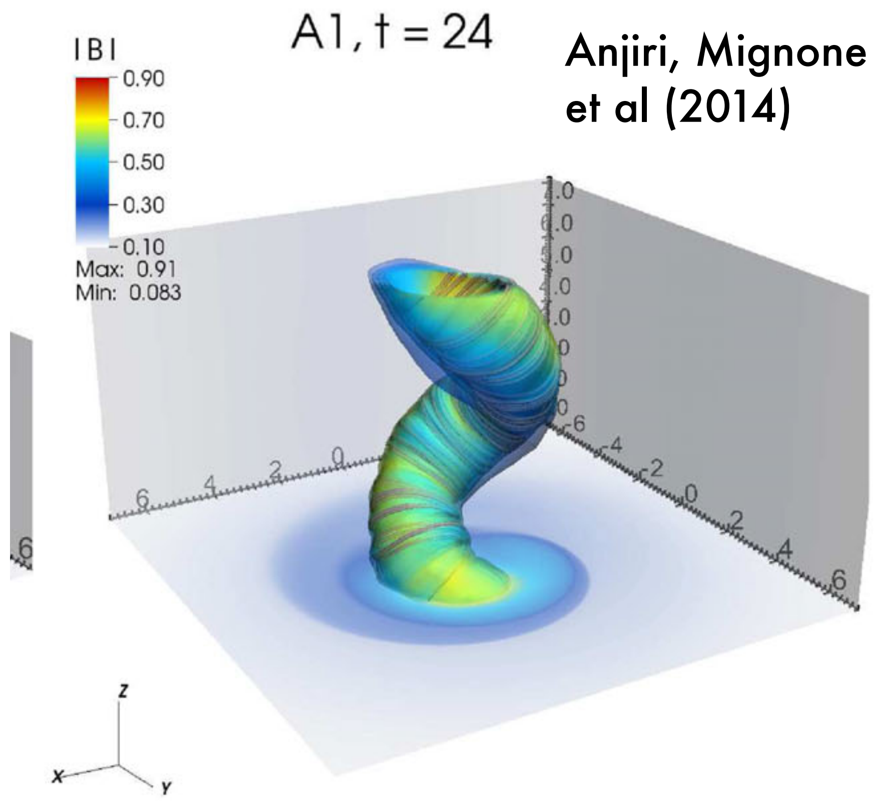


Many thanks to Manel Perucho for the diagram (in press)!

Dangerous jet instabilities



Current driven instabilities (CDI): Pinch, Kink and higher orders
(Bateman (1978), Begelman (1998), Appl et al. (2000), Baty (2005), Lery et al. (2000); Narayan et al. (2009); Moll et al (2011); Mizuno et al (2011,12,14); O'Neill et al (2012); Mignone et al. (2013); Anjiri+ (2014); ...)

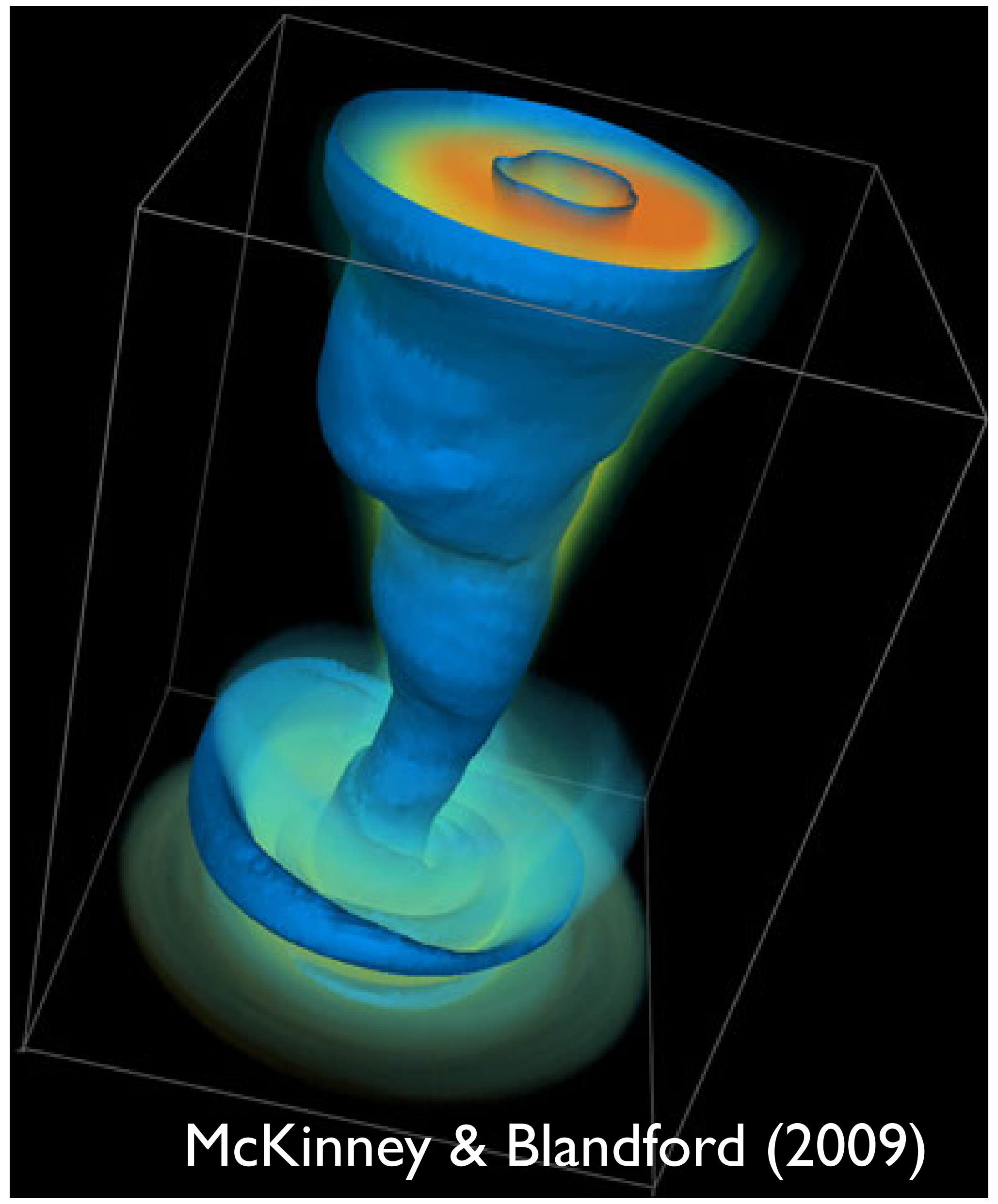


Anjiri, Mignone et al (2014)

Can be stabilized with:
Relativistic bulk motion, shear, being force-free, electric fields, poloidal fields, jet expansion

Kelvin Helmholtz type instabilities (KHI):
(Turland & Scheuer (1976); Ferrari+ (1978); Hardee (2004); Perucho et al (2004,07); Bodo et al (2006); Rossi et al (2008); ...)

Can be stabilized with:
Relativistic bulk motion,
Thick shear layer, poloidal fields,
jet expansion


McKinney & Blandford (2009)

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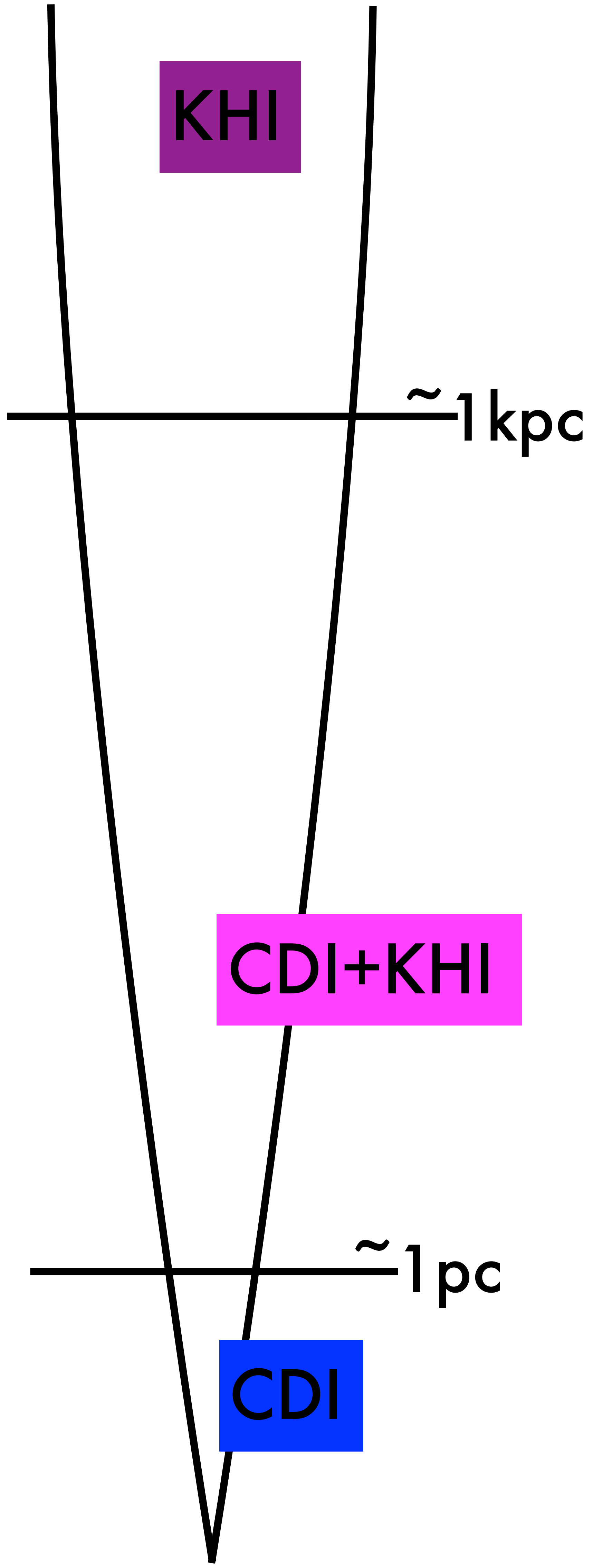

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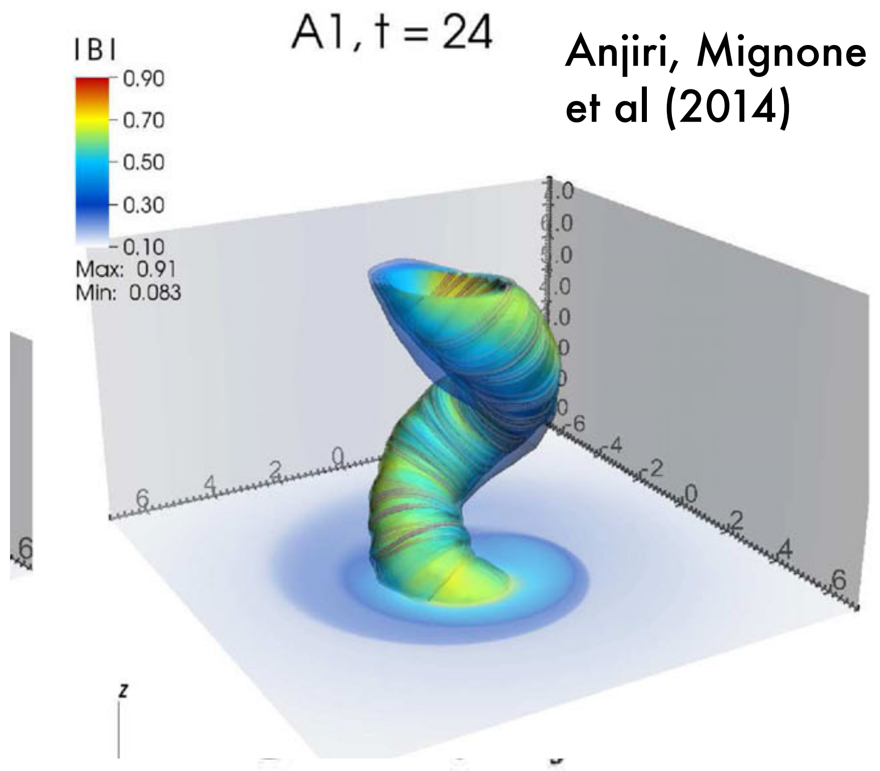

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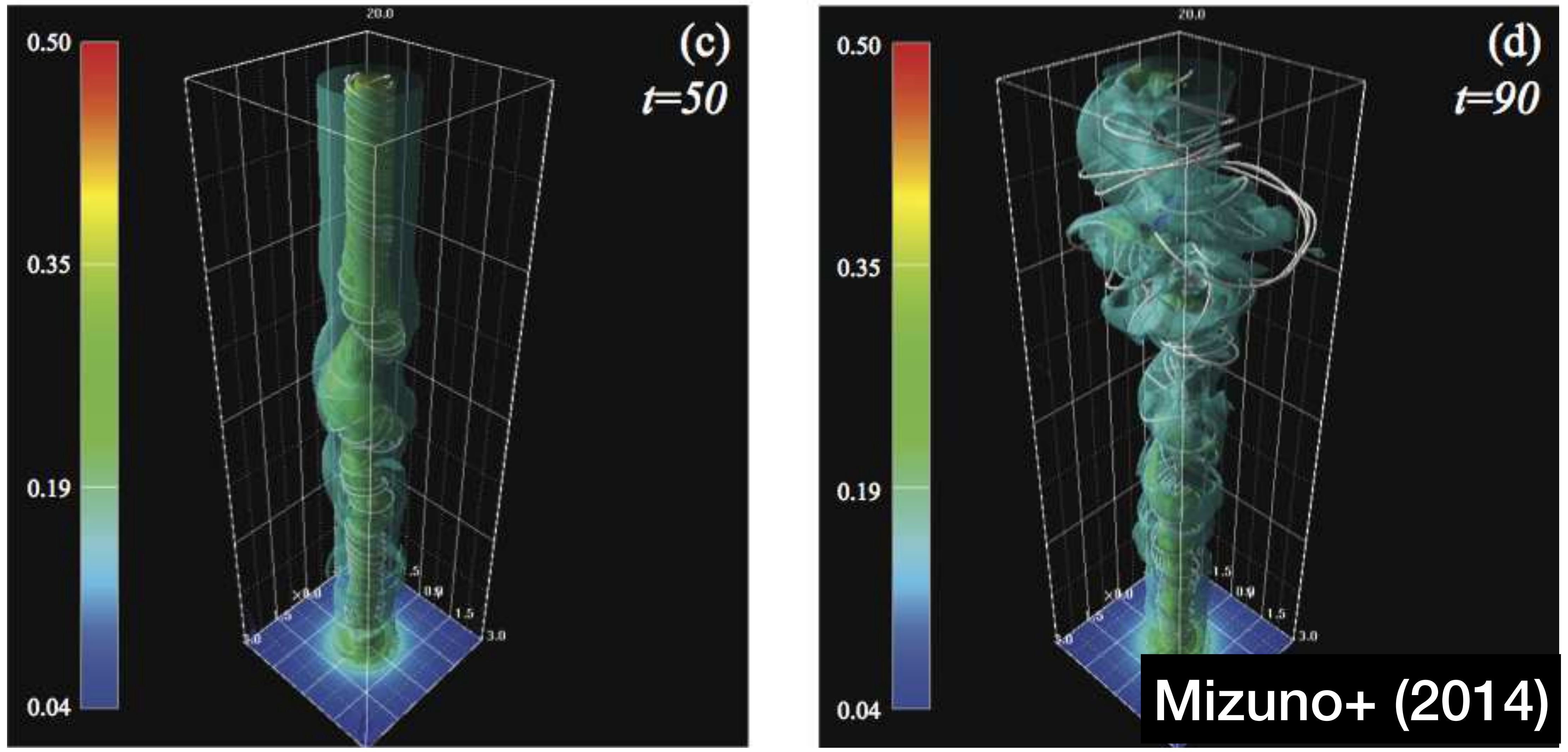
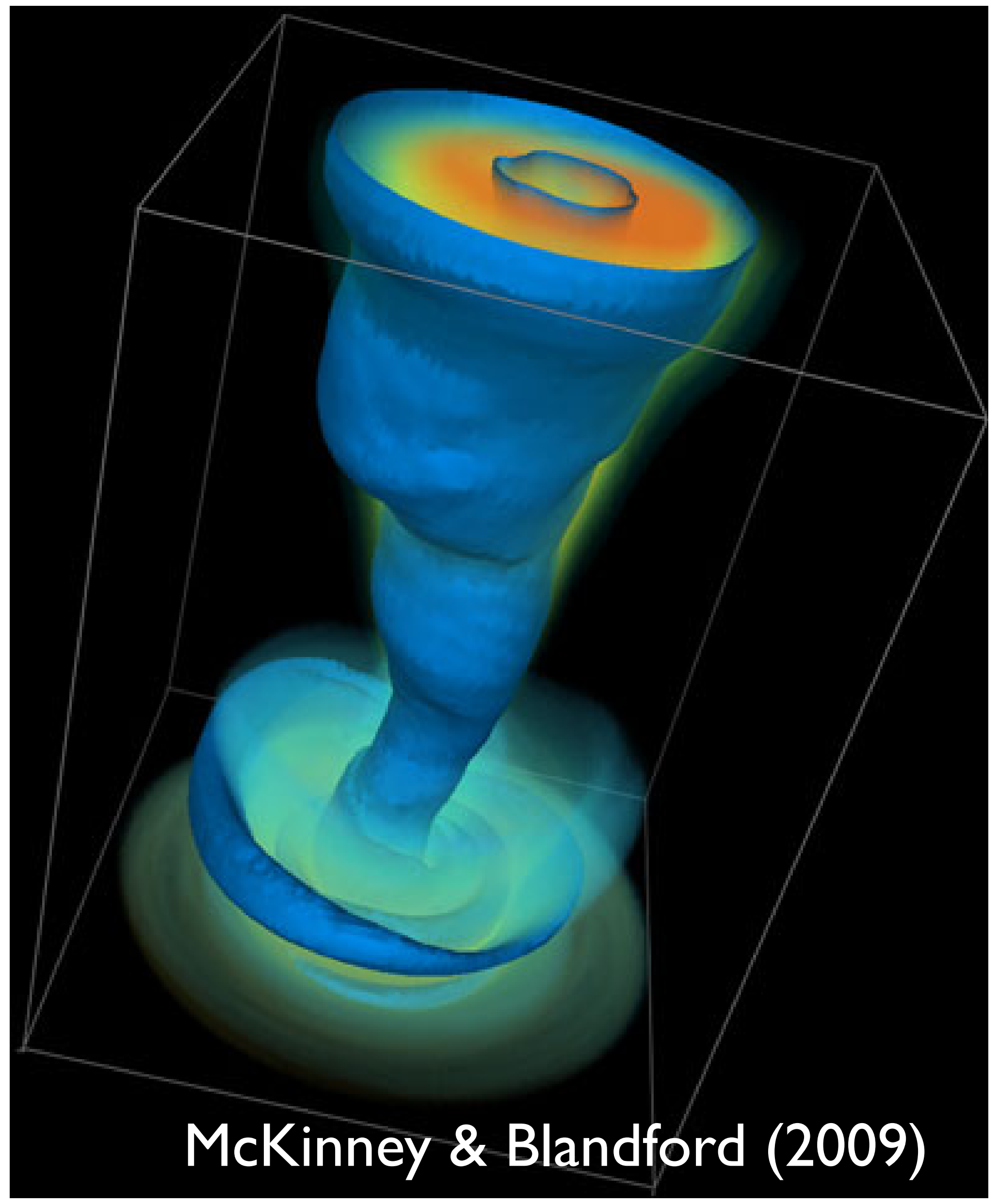


Mizuno+ (2014)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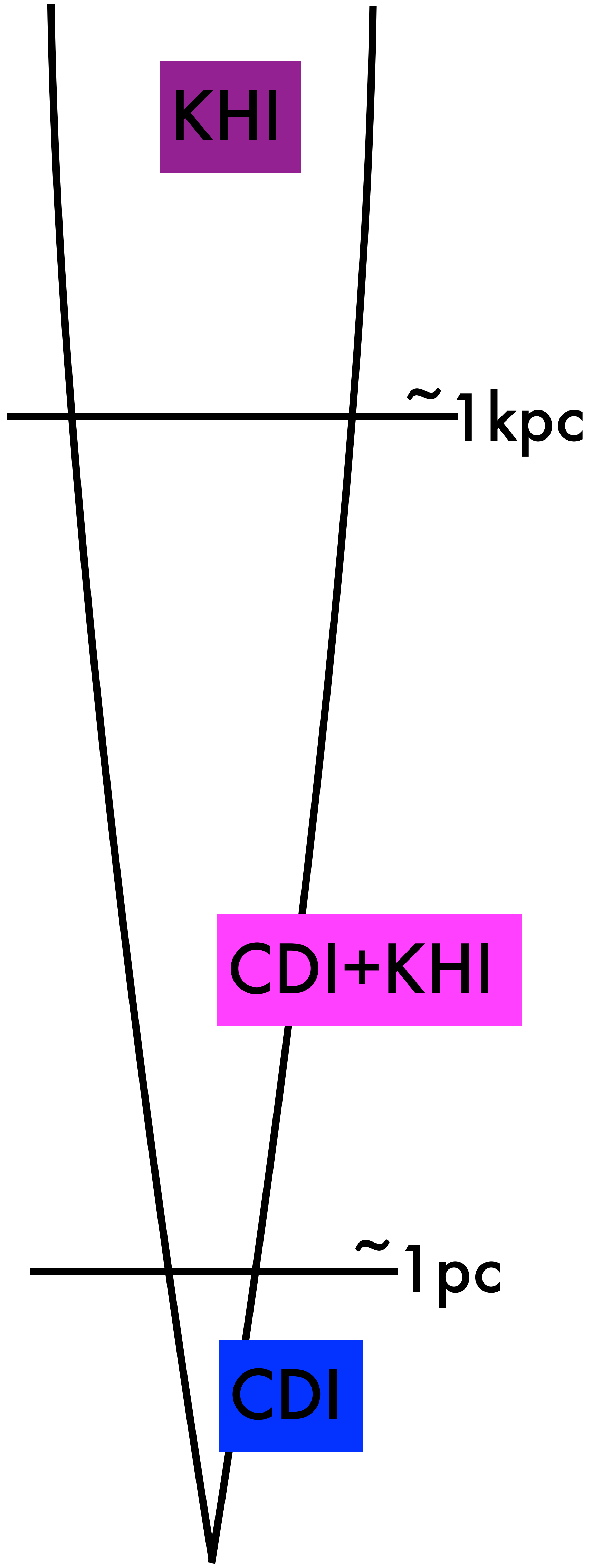
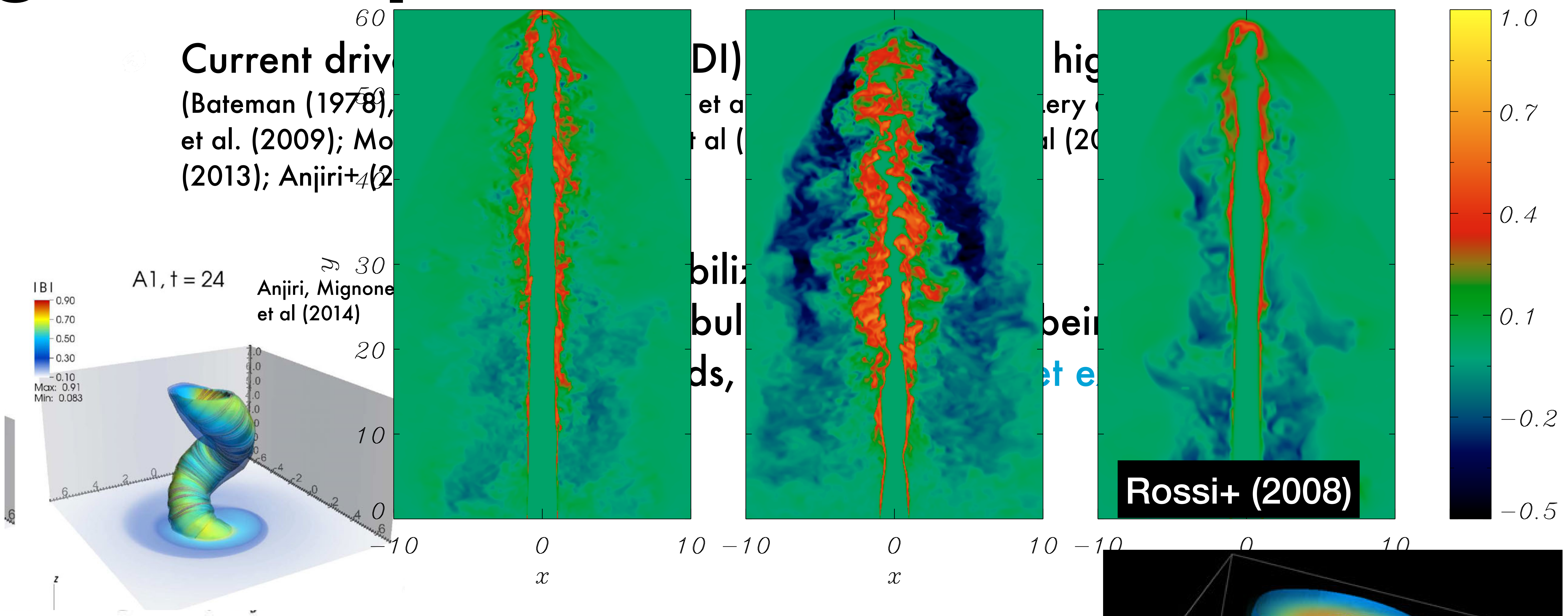
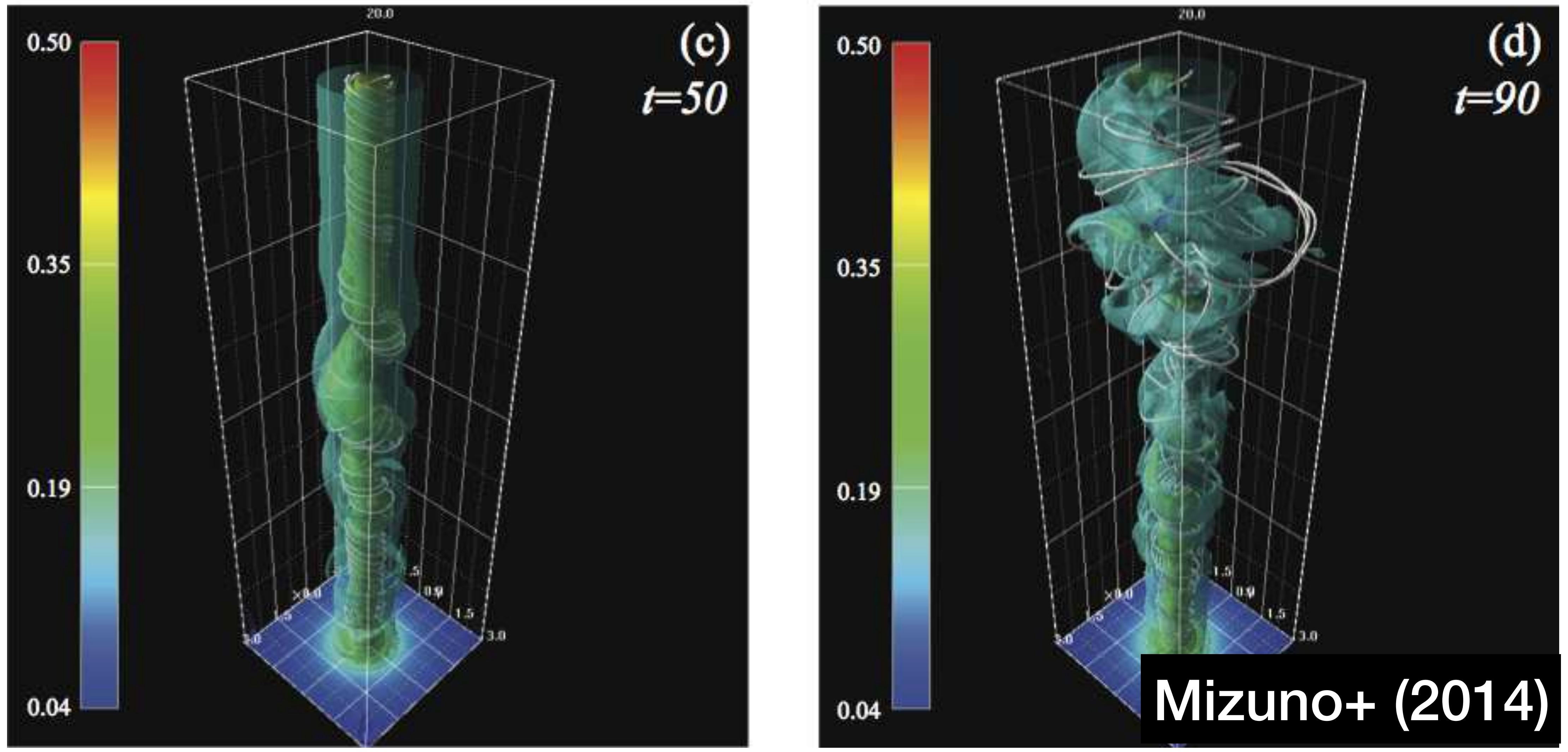
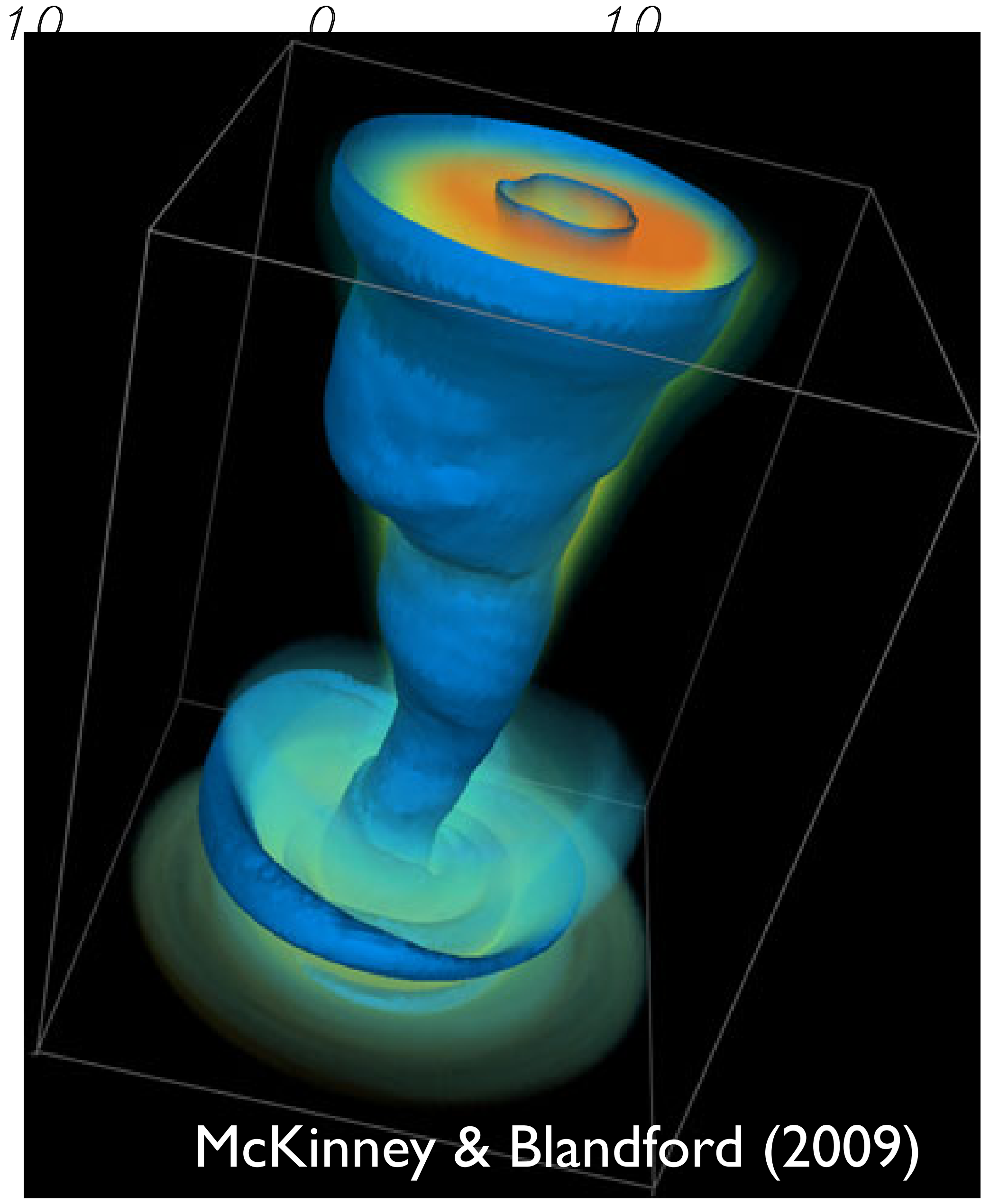


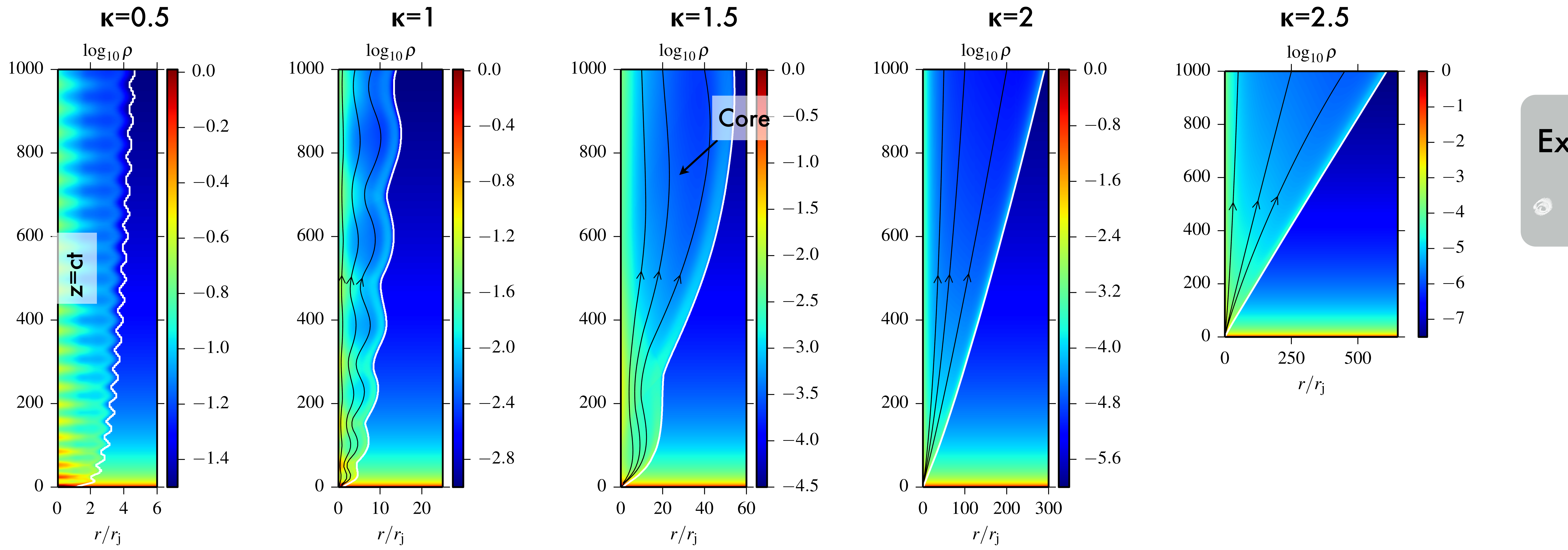






Komissarov, OP, Lyutikov (2015)

MHD jet in powerlaw atmosphere

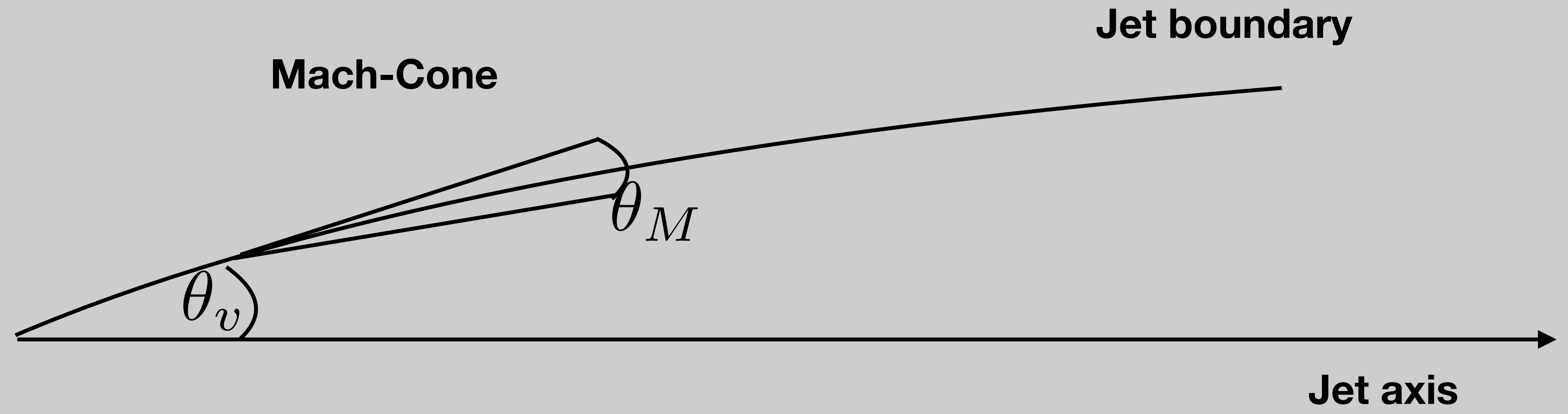


External gas:

- $p_{ext}=p_0\, z^{-\kappa}$

Sufficient criterion for jet stability:

Causally disconnected flows are globally stable!



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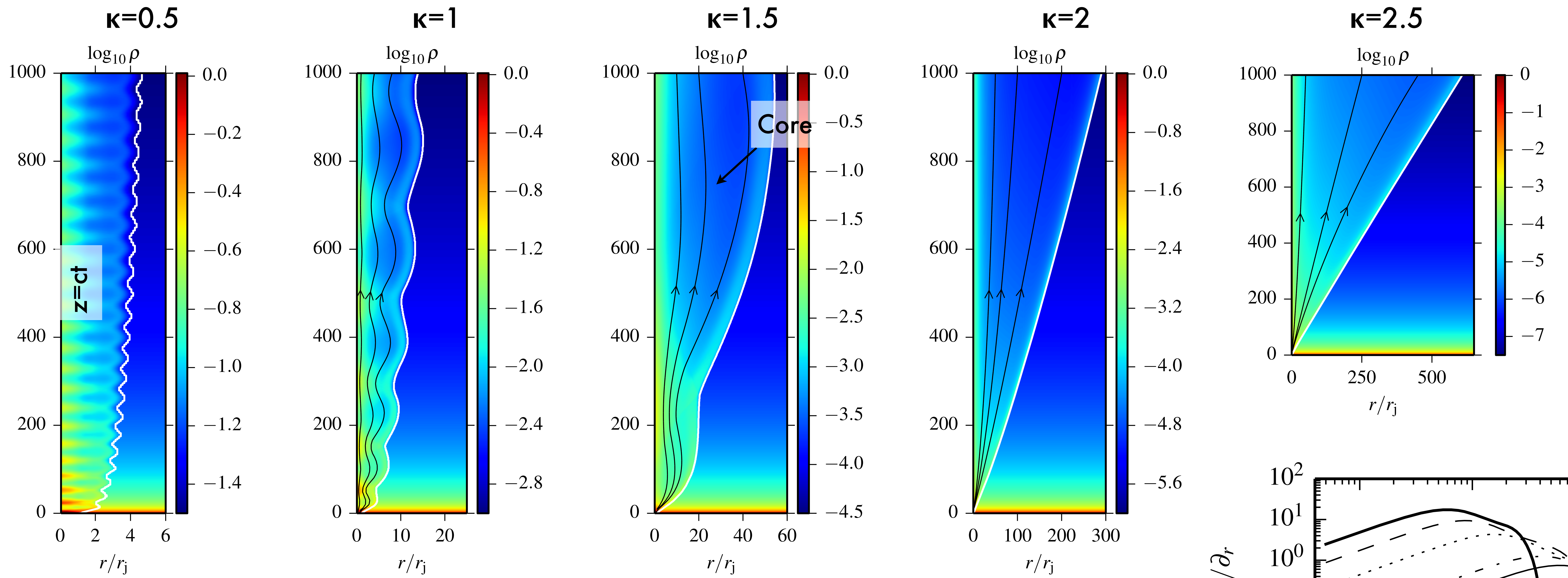

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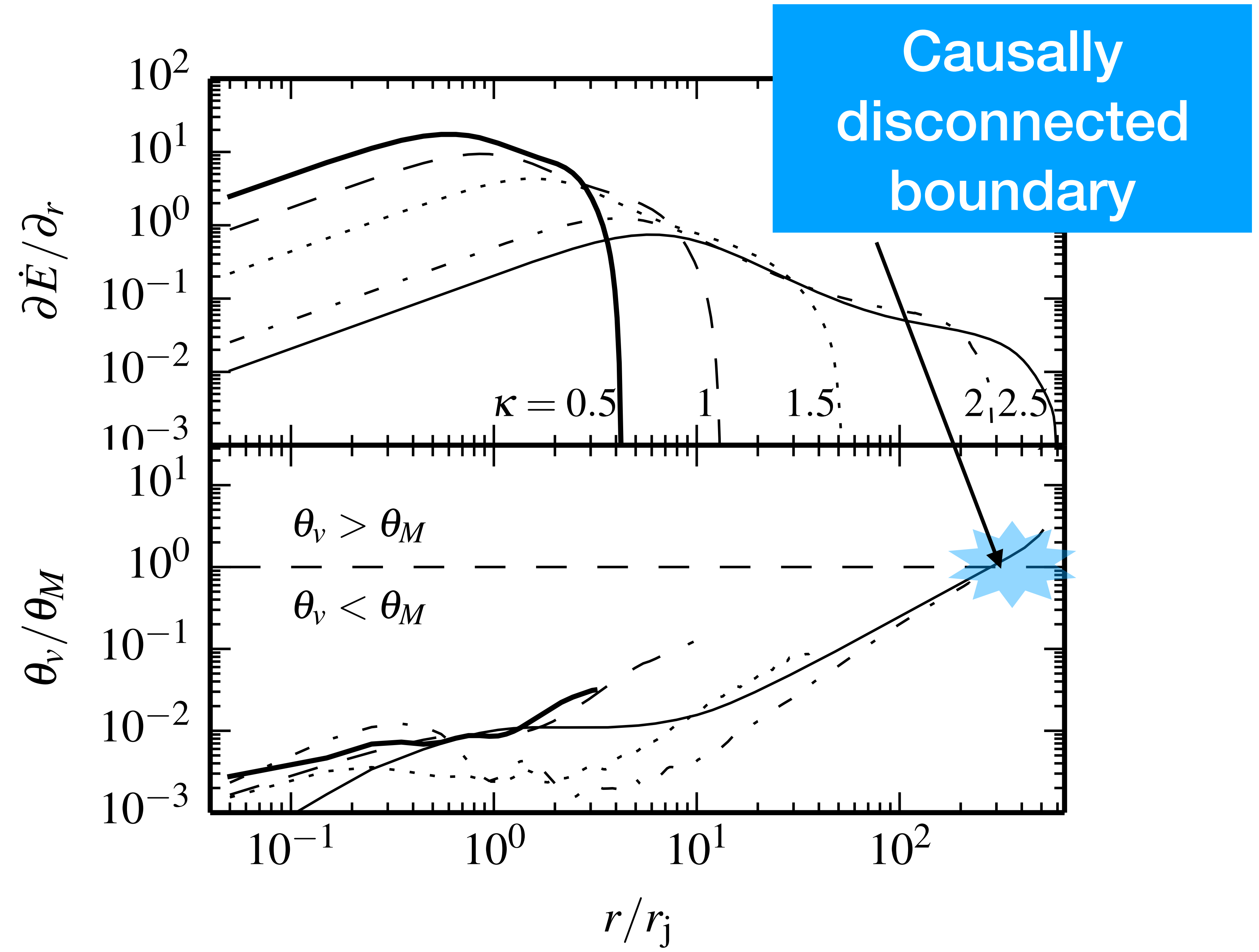

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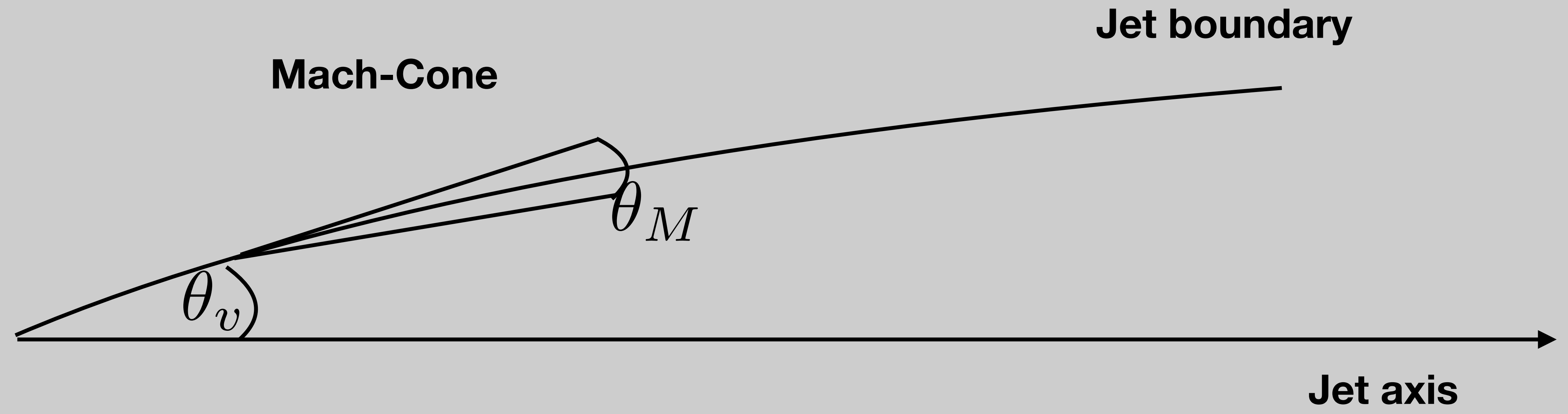

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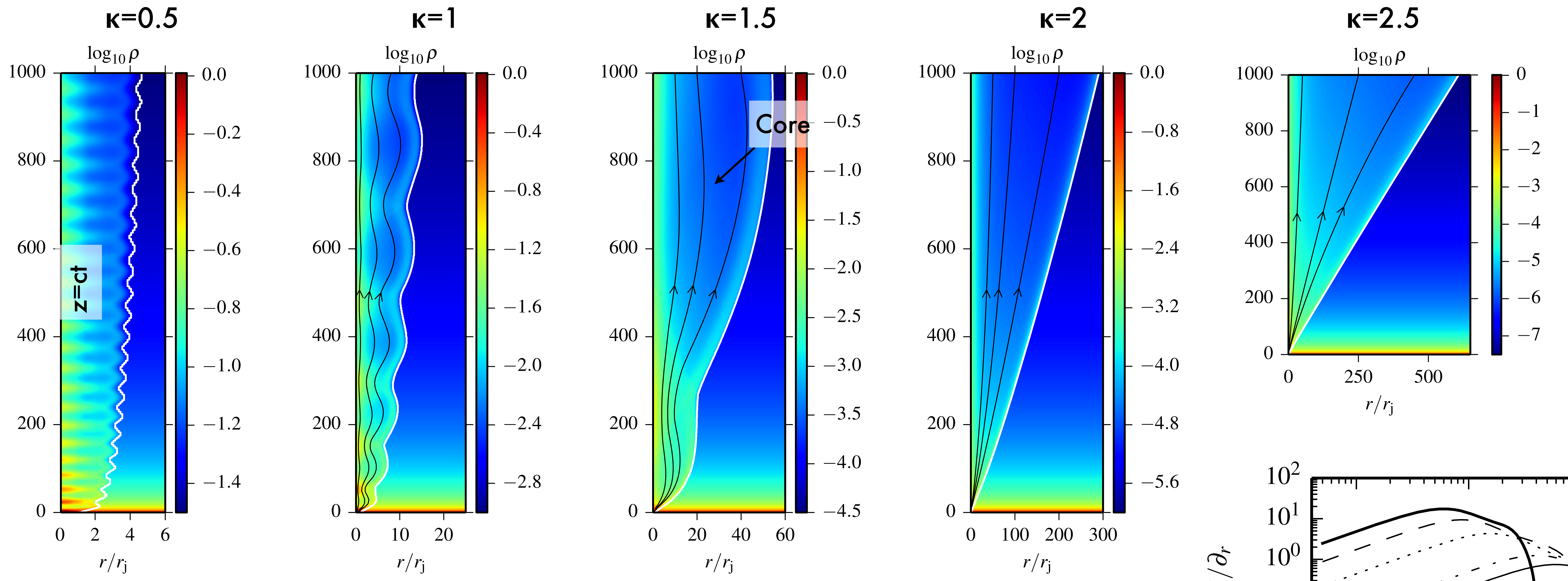

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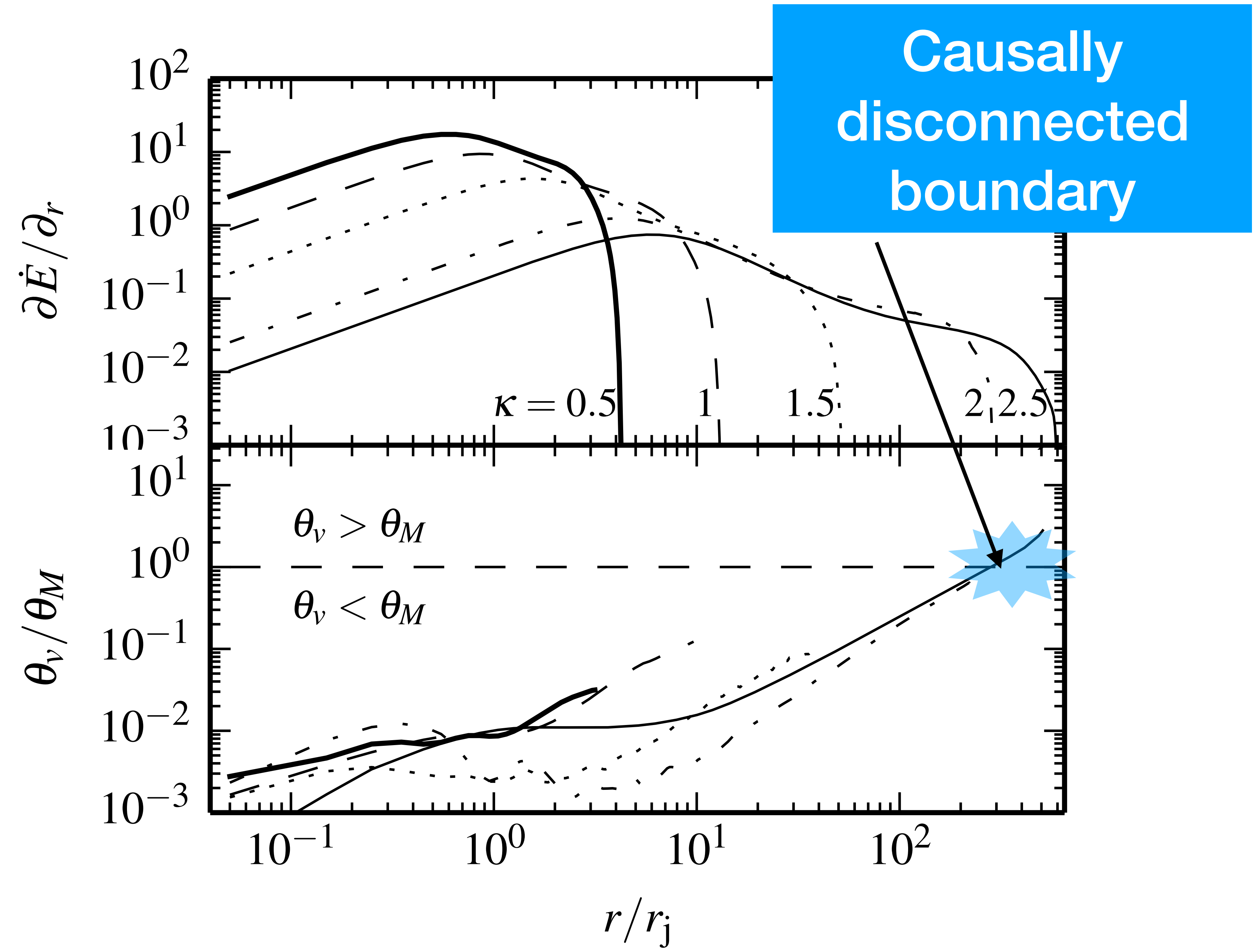
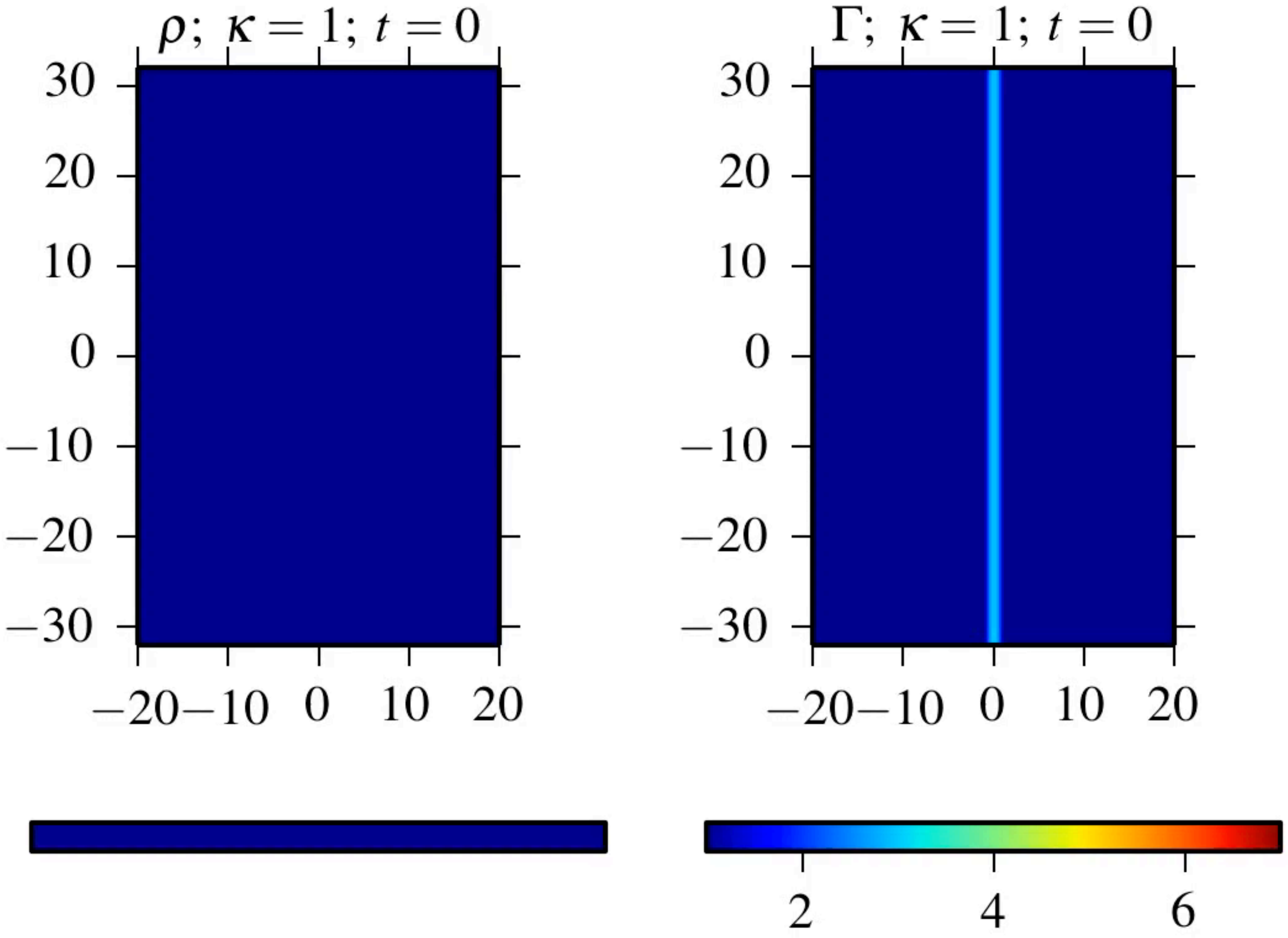


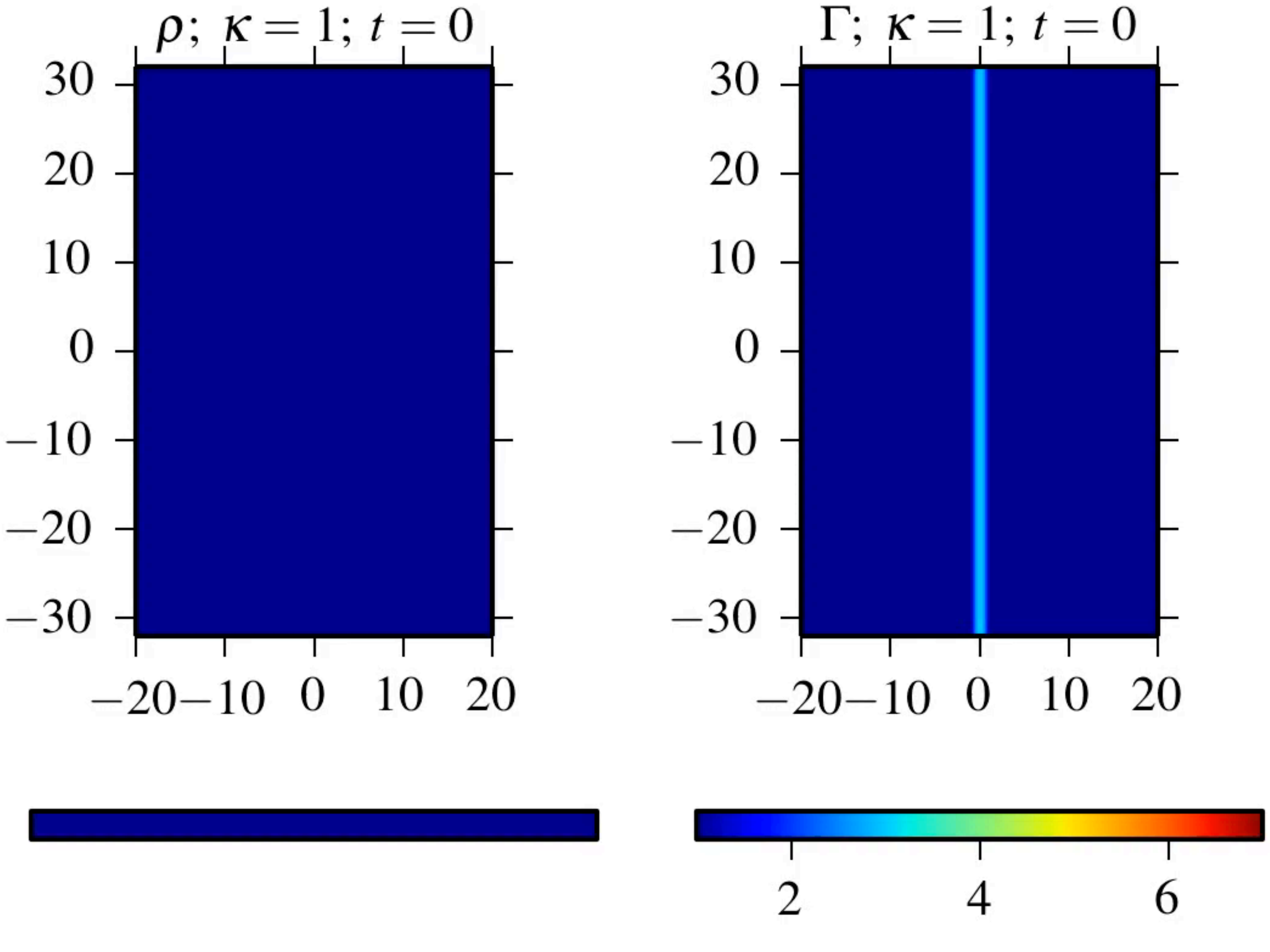
- Waves traveling back and forth the jet giving rise to oscillations of jet boundary
- For κ≥2 flow is conical and no waves traverse across the jet
- Jet boundary becomes disconnected for κ≥2

looking inside an expanding jet



- letting jets expand increases their stability
- Formation of sub-structure inside the jet
- shocks and magnetic reconnection => particle acceleration

looking inside an expanding jet



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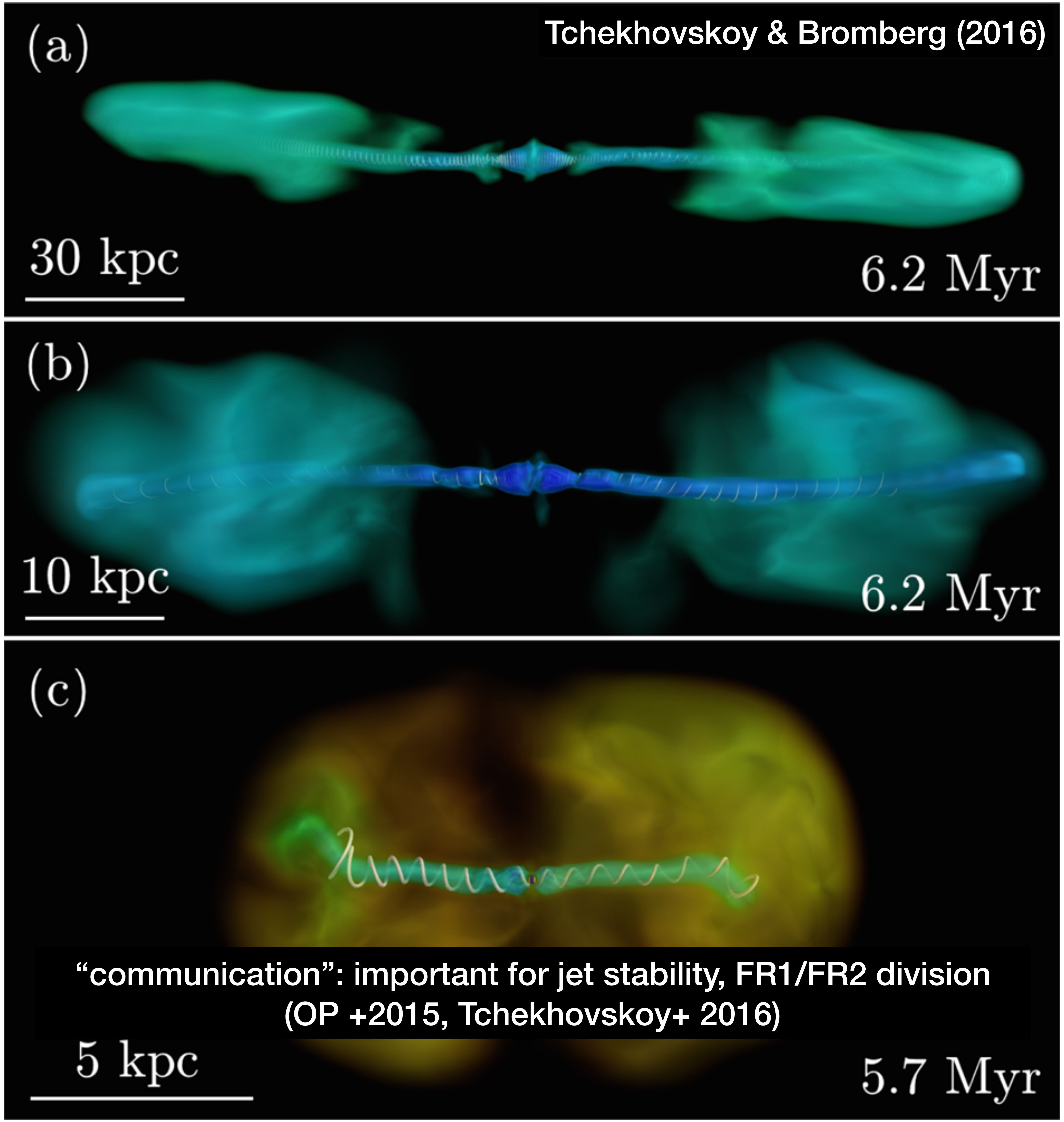

- Stabilization due to inhibited causal contact across the jet
  - Higher jet power: narrower Mach cones => more stable
  - Less collimated jet: Mach cone points away from axis => more stable
- Steep ambient pressure gradient enhances jet stability: necessarily globally stable for $\kappa \geq 2$
- Formation of unstable jet core:
  - can seed jet internal turbulence
  - dissipates energy and thus aids in jet acceleration

quick summary

- Rotating magnetospheres: jets!
- Magnetic acceleration: gradual, depends on (external) collimation
- Plethora of instabilities threatening jets, some good (dissipation), some bad (disruption)
- Communication and causality is key in jet acceleration and stability