IMPRS astronomy & astrophysics
Bonn and Cologne

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for Radio Astronomy

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Exploring the disk-jet connection in NGC 315

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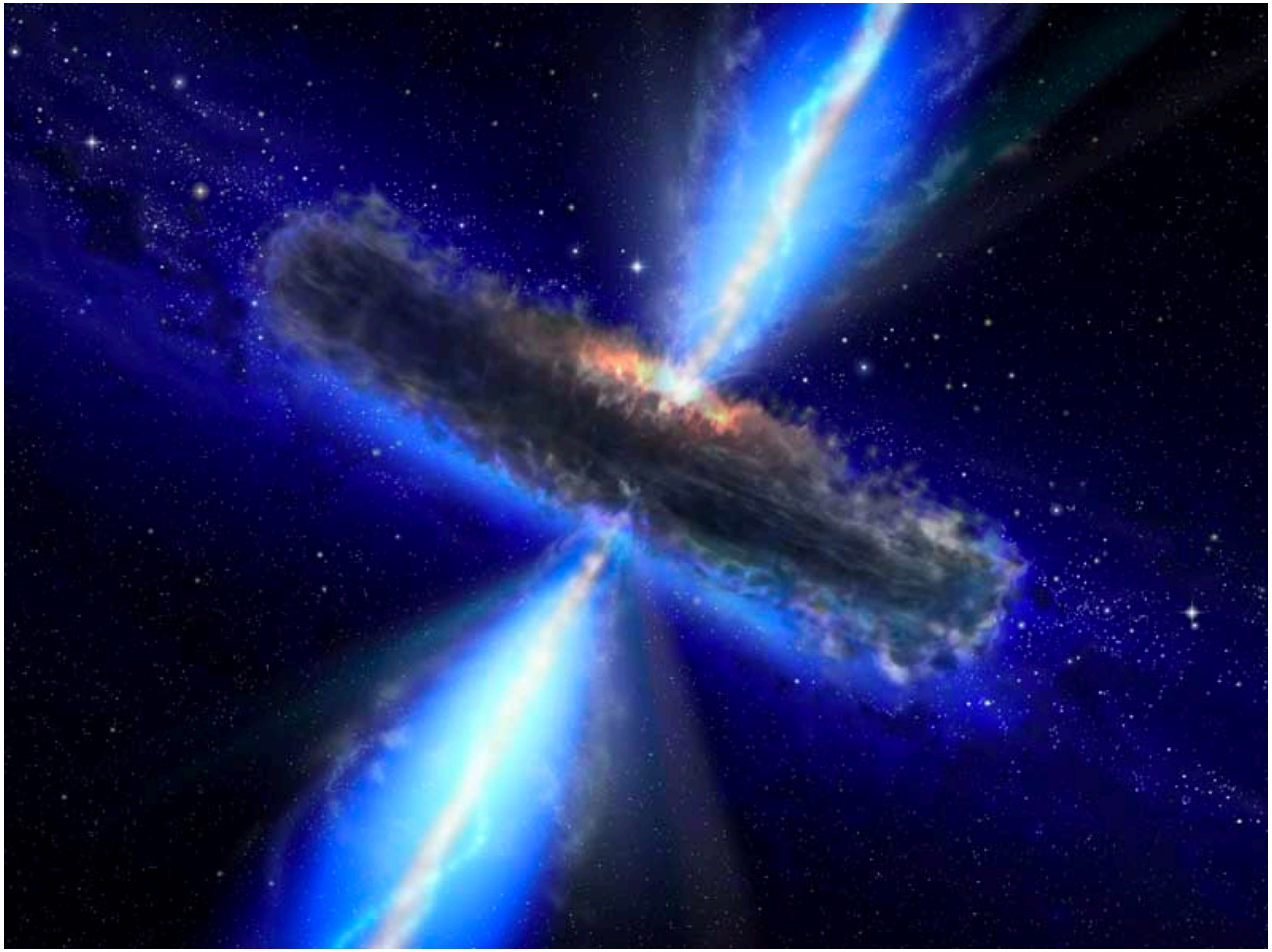
AGNs - disk-jet connection



Credits: ESA/NASA/AVO/Paolo Padovani

Virially hot and optically thin

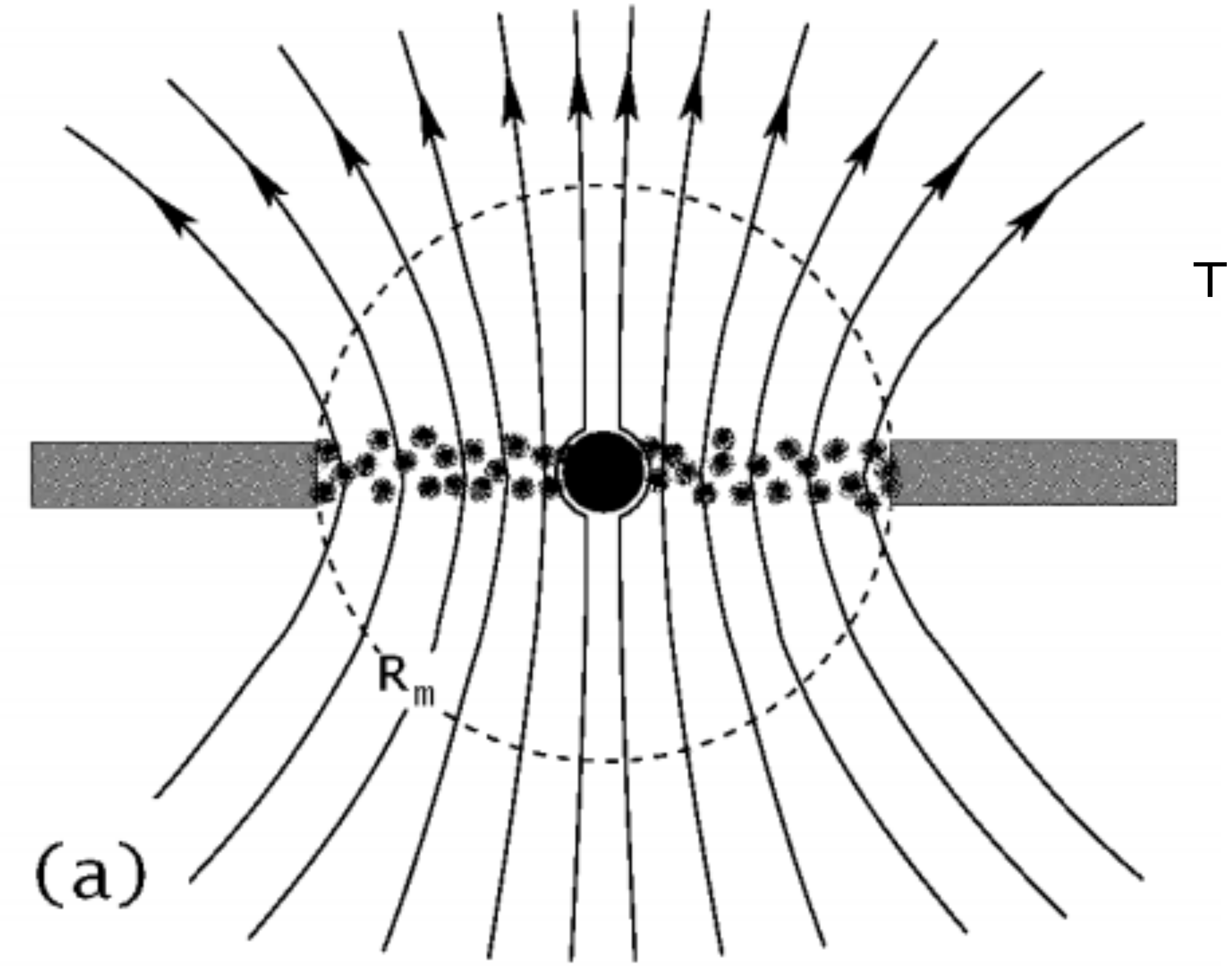
See the review Yuan+, 2014

Hot accretion flows are able to eject the powerful relativistic jets we see in AGNs.

SANE (Standard And Normal Evolution)

MAD (Magnetically Arrested Disks)

Magnetically arrested disks (MAD)



Narayan+, 2003

A significant amount of poloidal magnetic flux is collected in the vicinity of the black hole

↓

The accumulated magnetic poloidal field disrupts the accretion flow at the distance $R_m = r_m R_s$

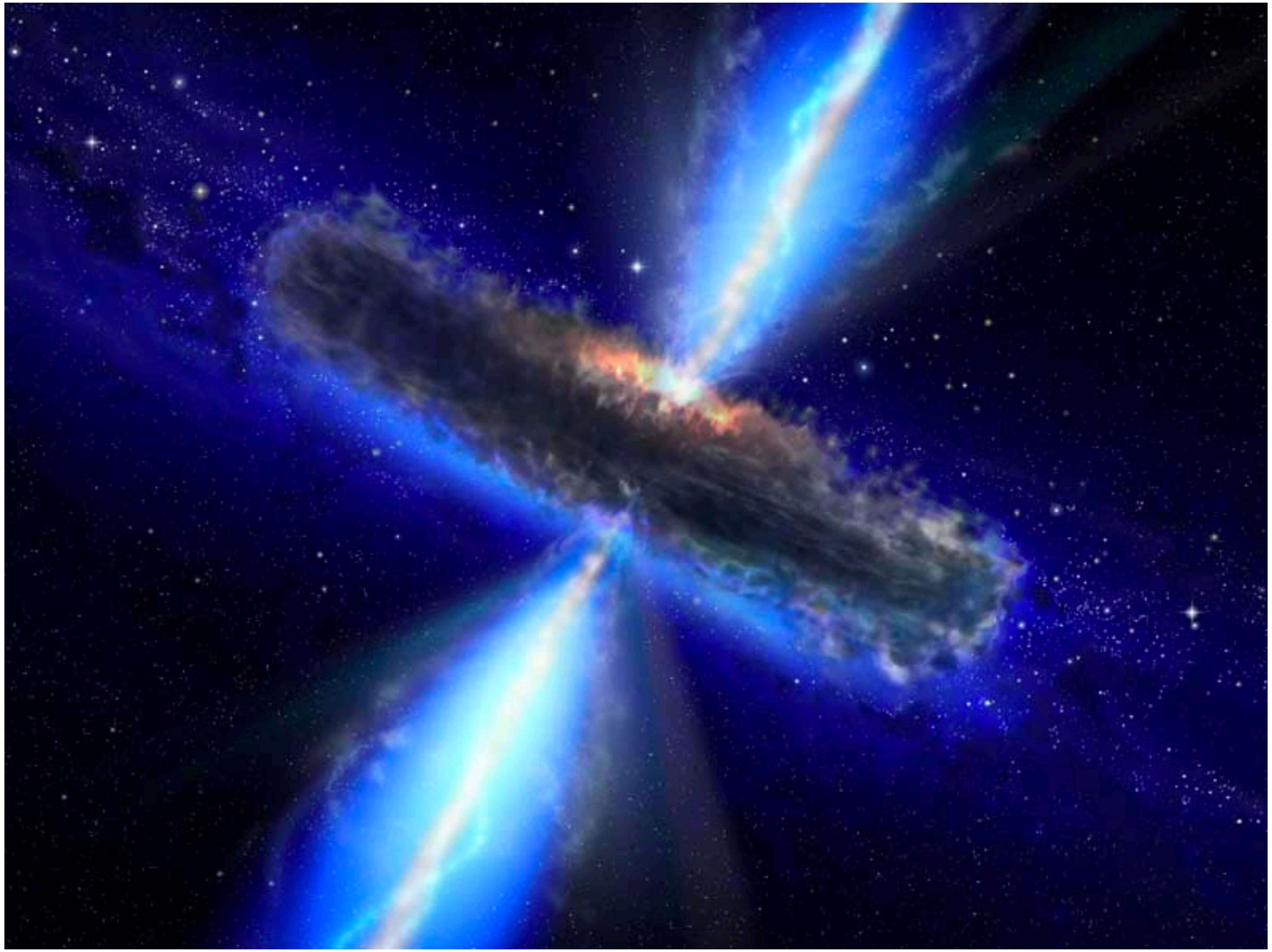
- R_s Schwarzschild radius
- R_m magnetosphere radius
- r_m magnetosphere in units of R_s

↓

The flow breaks into blobs or streams and the gas goes towards the black hole

→ Confirmed in numerous simulation works (e.g. McKinney+, 2012, White+, 2019, Narayan+, 2021)

AGNs - disk-jet connection



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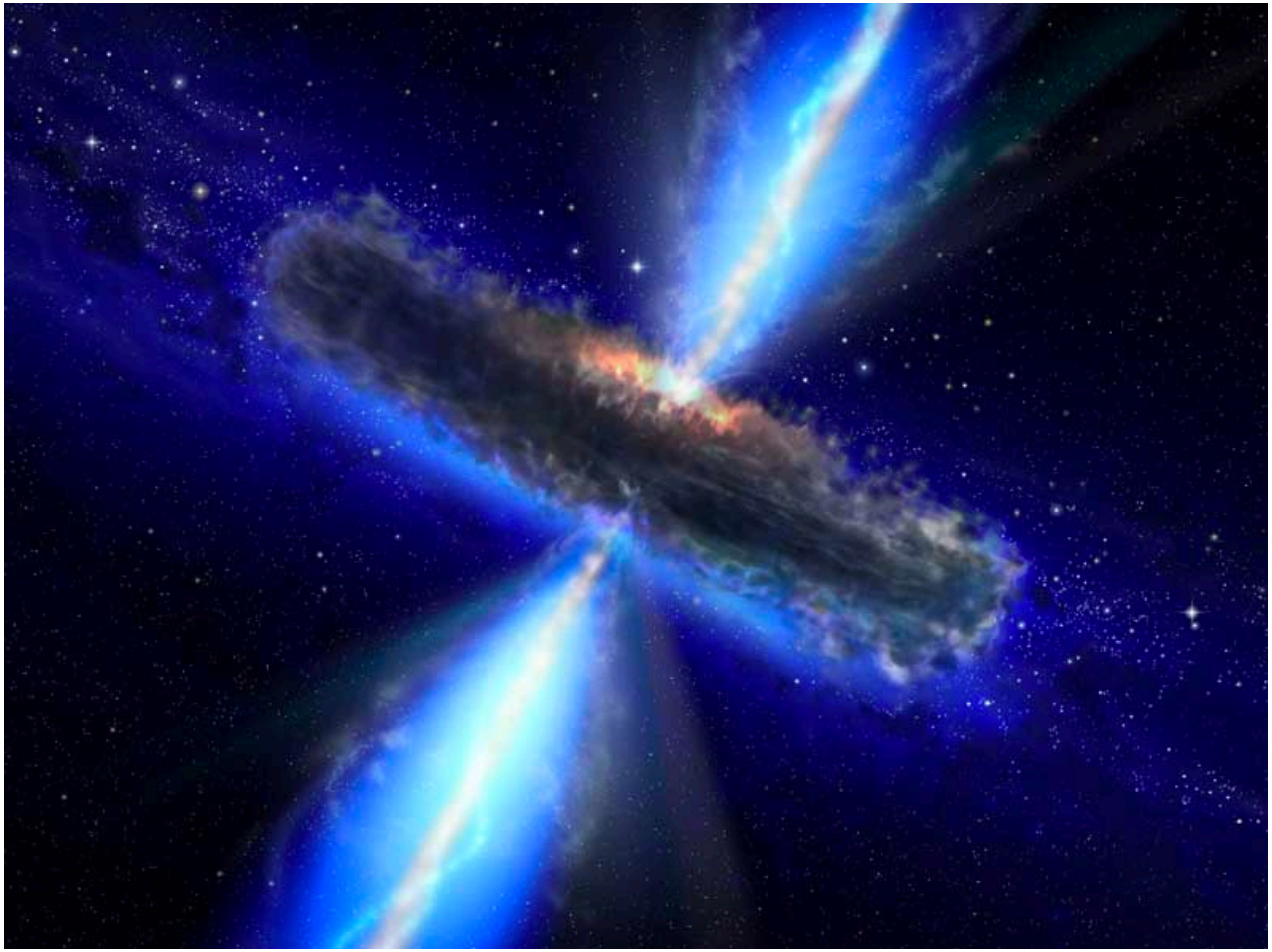

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Different magnetic field properties: in the accretion disk and...

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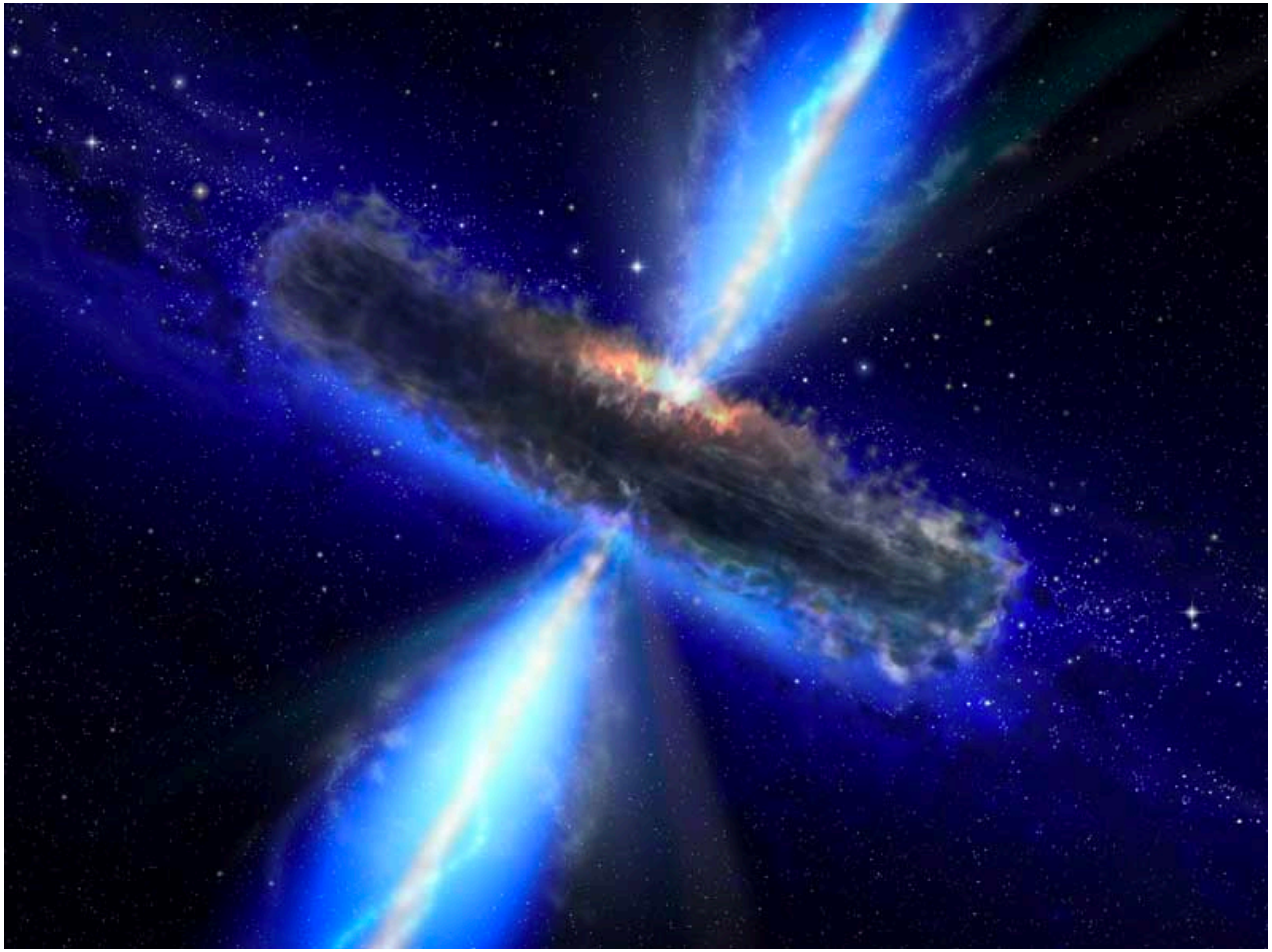

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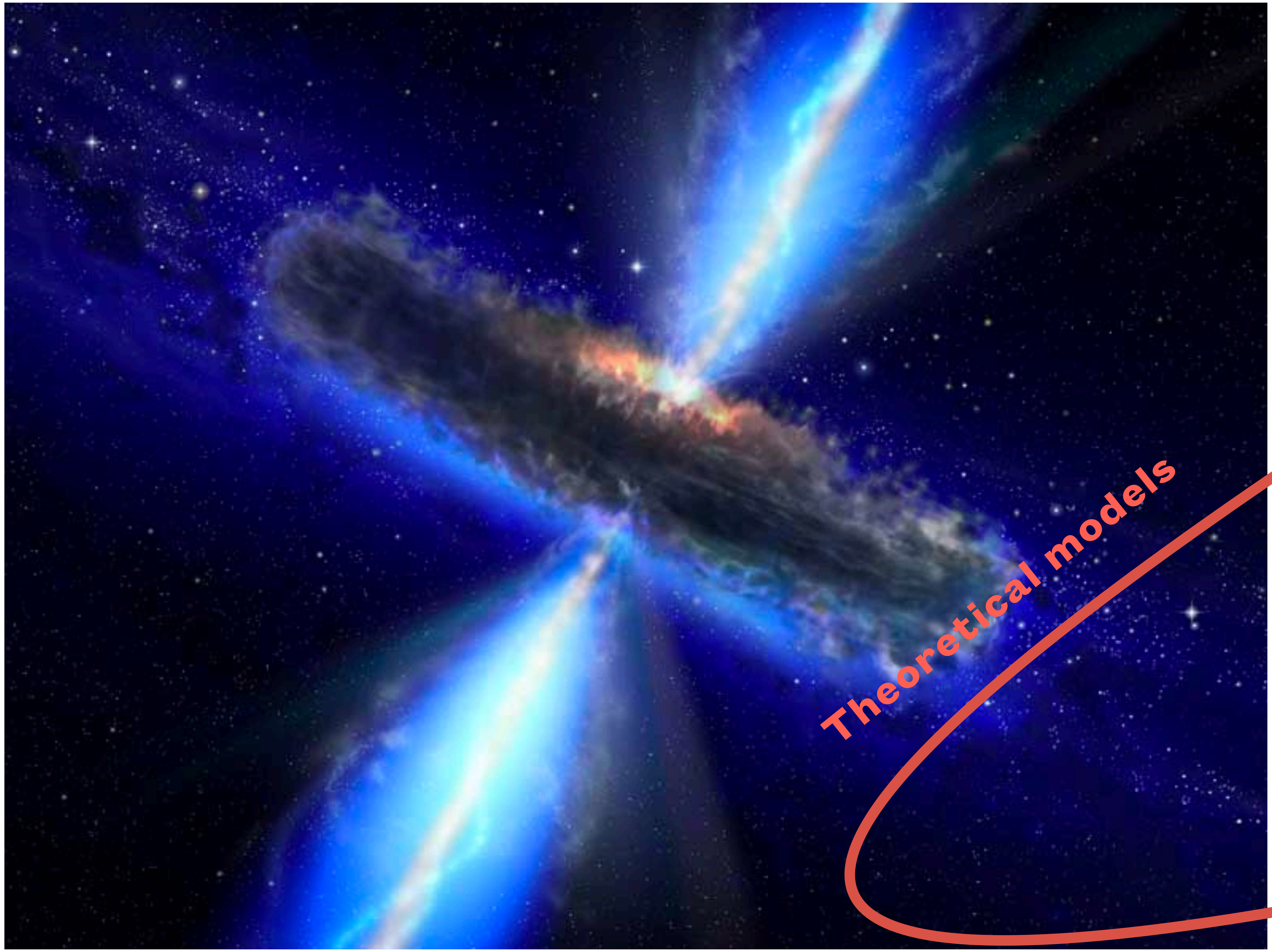

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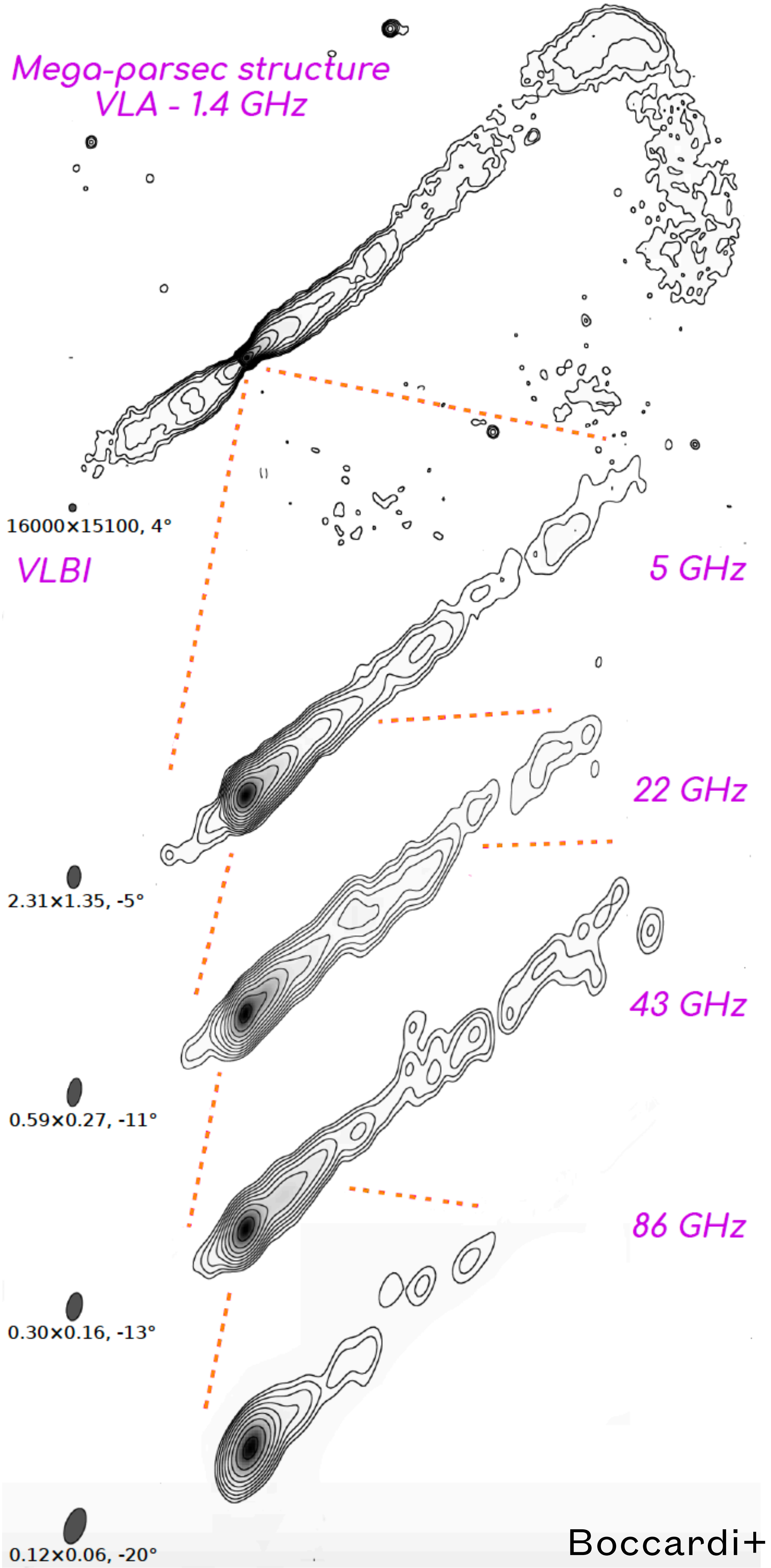
NGC 315

- FRI giant radio galaxy with linear size > 1 Mpc
- Low luminosity object with a radiatively inefficient accretion (LEG)
- z = 0.0165 (Trager+, 2000)
- Angle to the line of sight $\theta \sim 38°$ (debated)
- $M_{\rm BH} = 2.08 \times 10^9 M_\odot$ (Boizelle+,2021)
—> $\sim\ 100\, R_s$

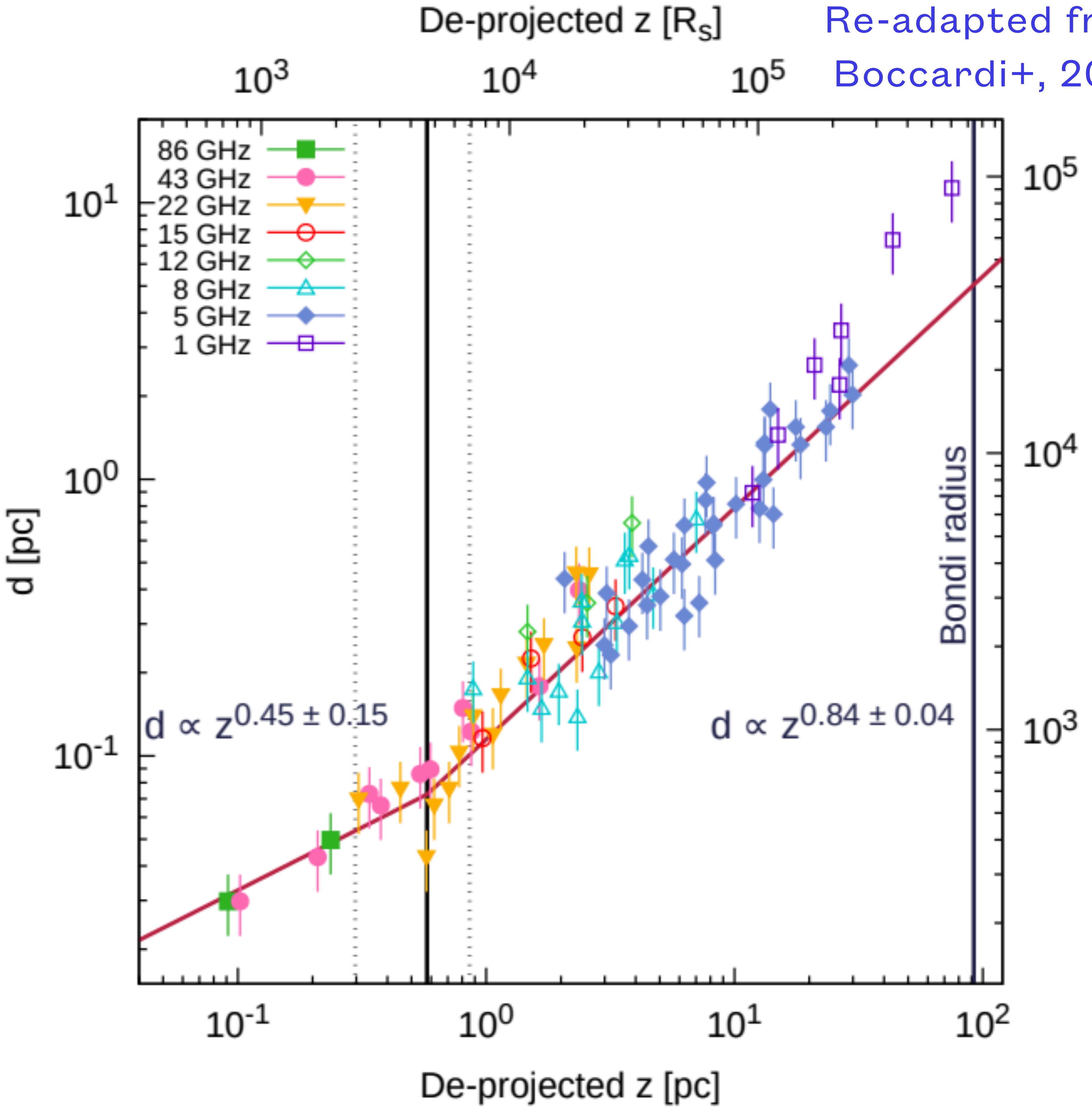


Boccardi+, 2021

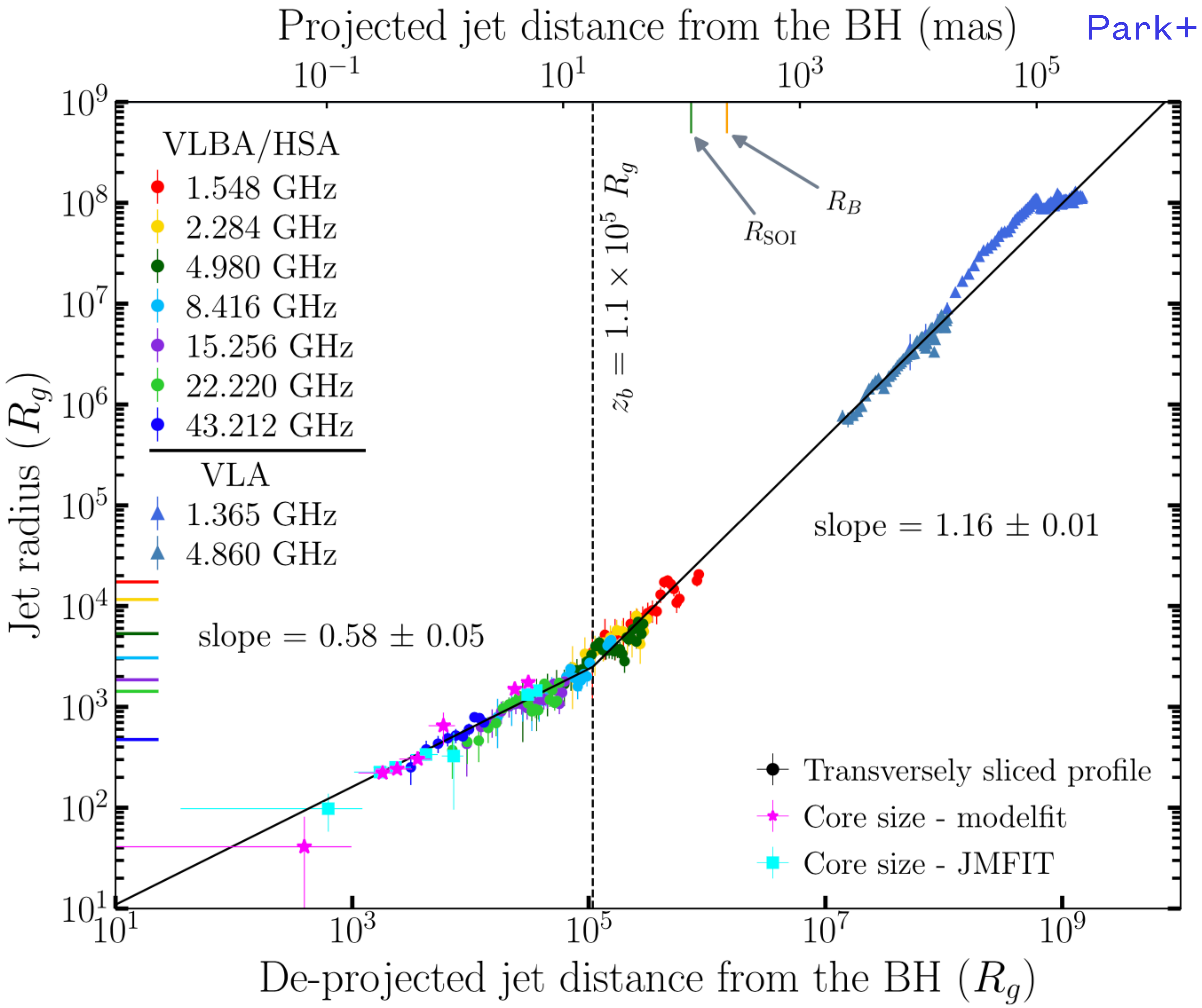
Why NGC 315?

we will see it in a bit

In NGC 315 we can observe the acceleration and collimation region

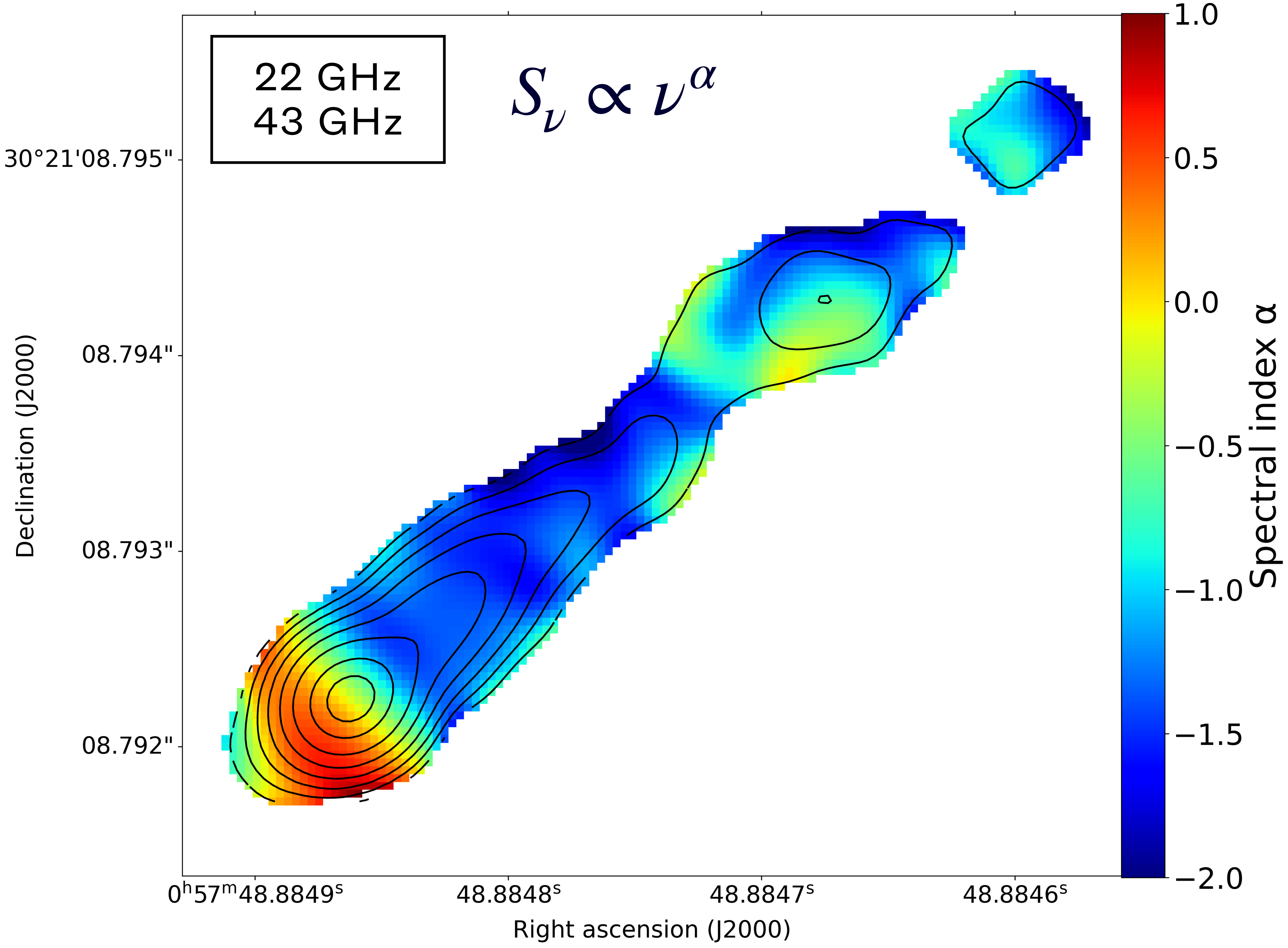


Re-adapted from Boccardi+, 2021



Park+, 2021

Spectral analysis



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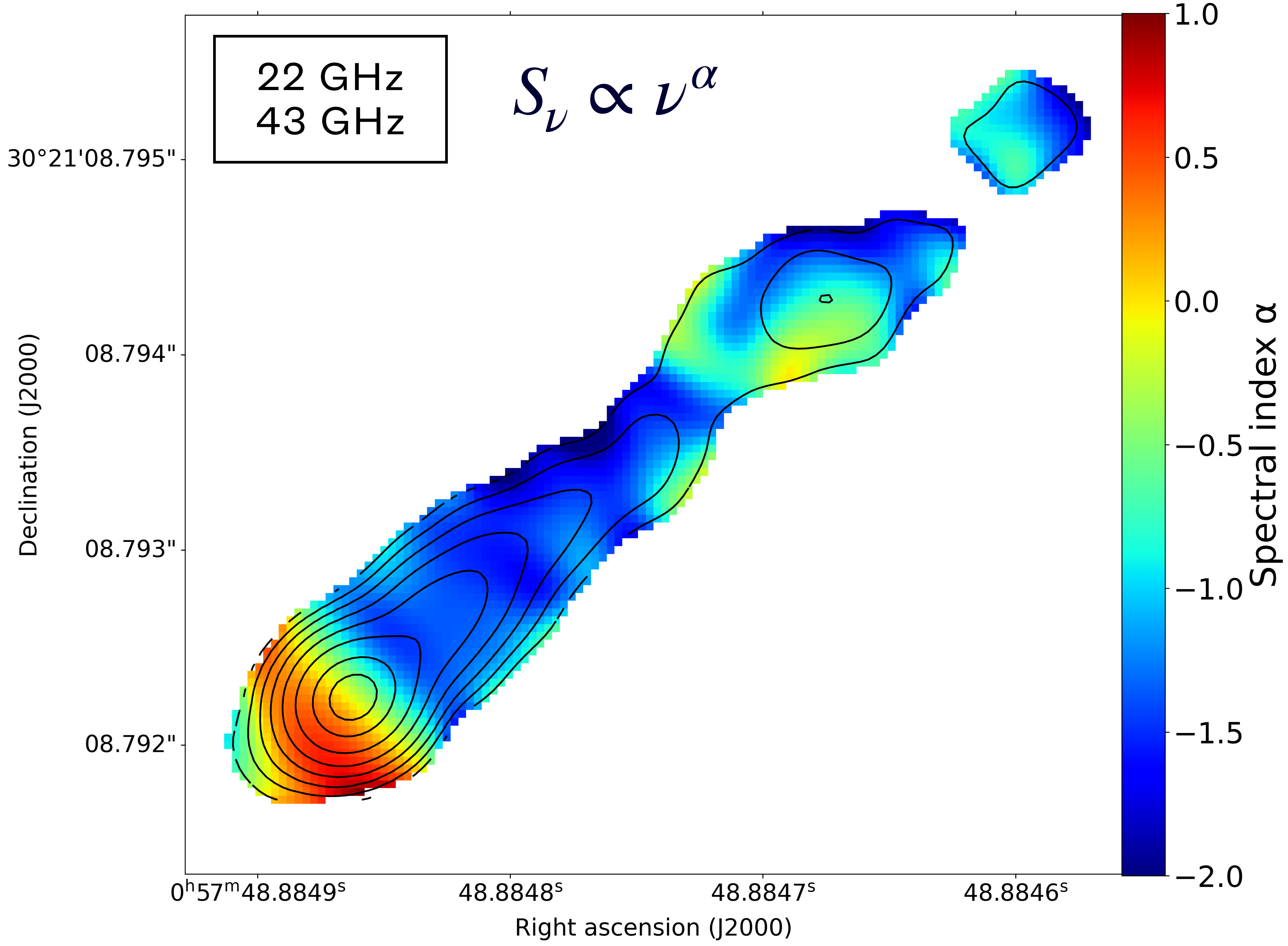
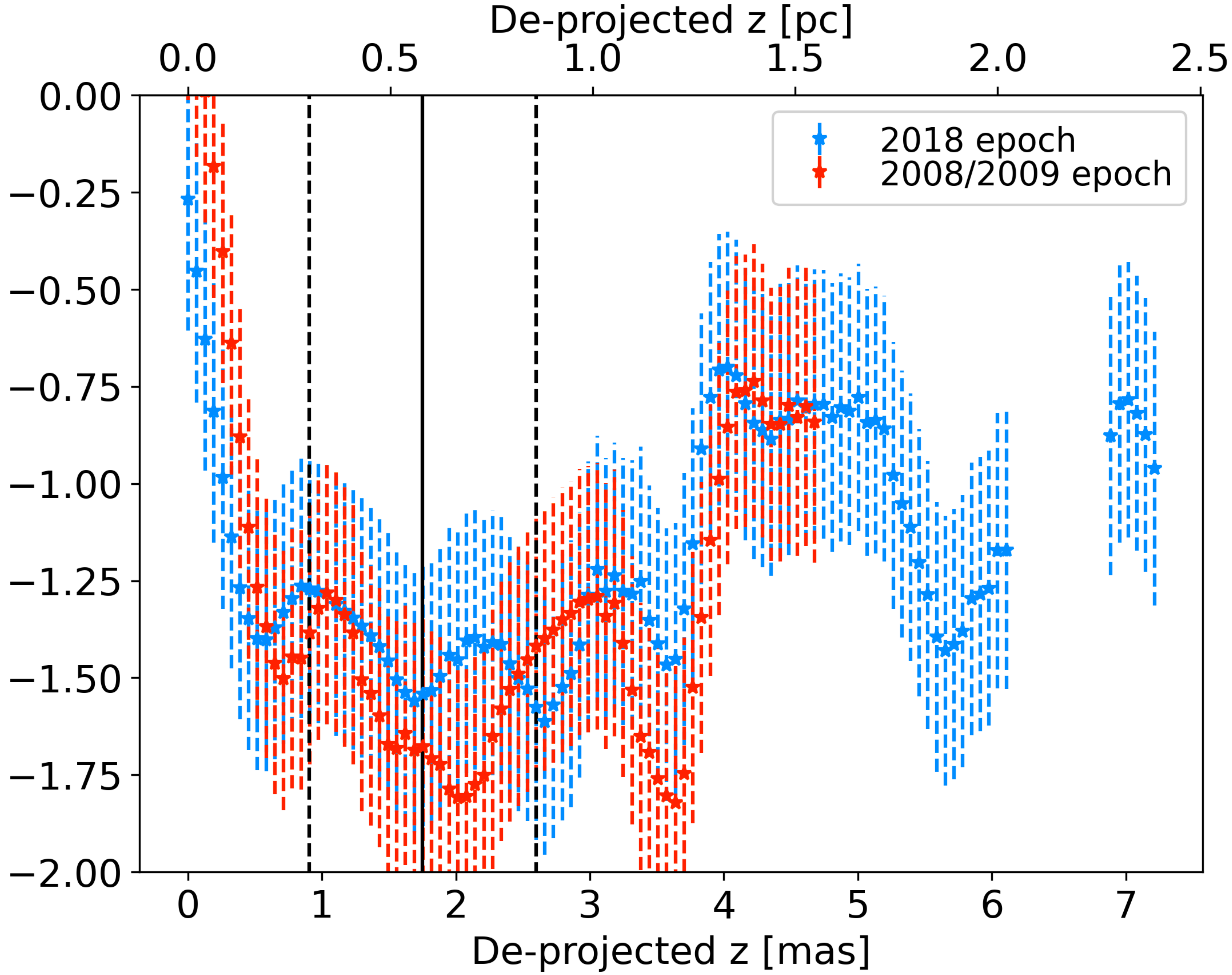




In a distance range similar to the collimation region the spectral index shows very steep values —> synchrotron losses due to strong magnetic fields?

Jet speed

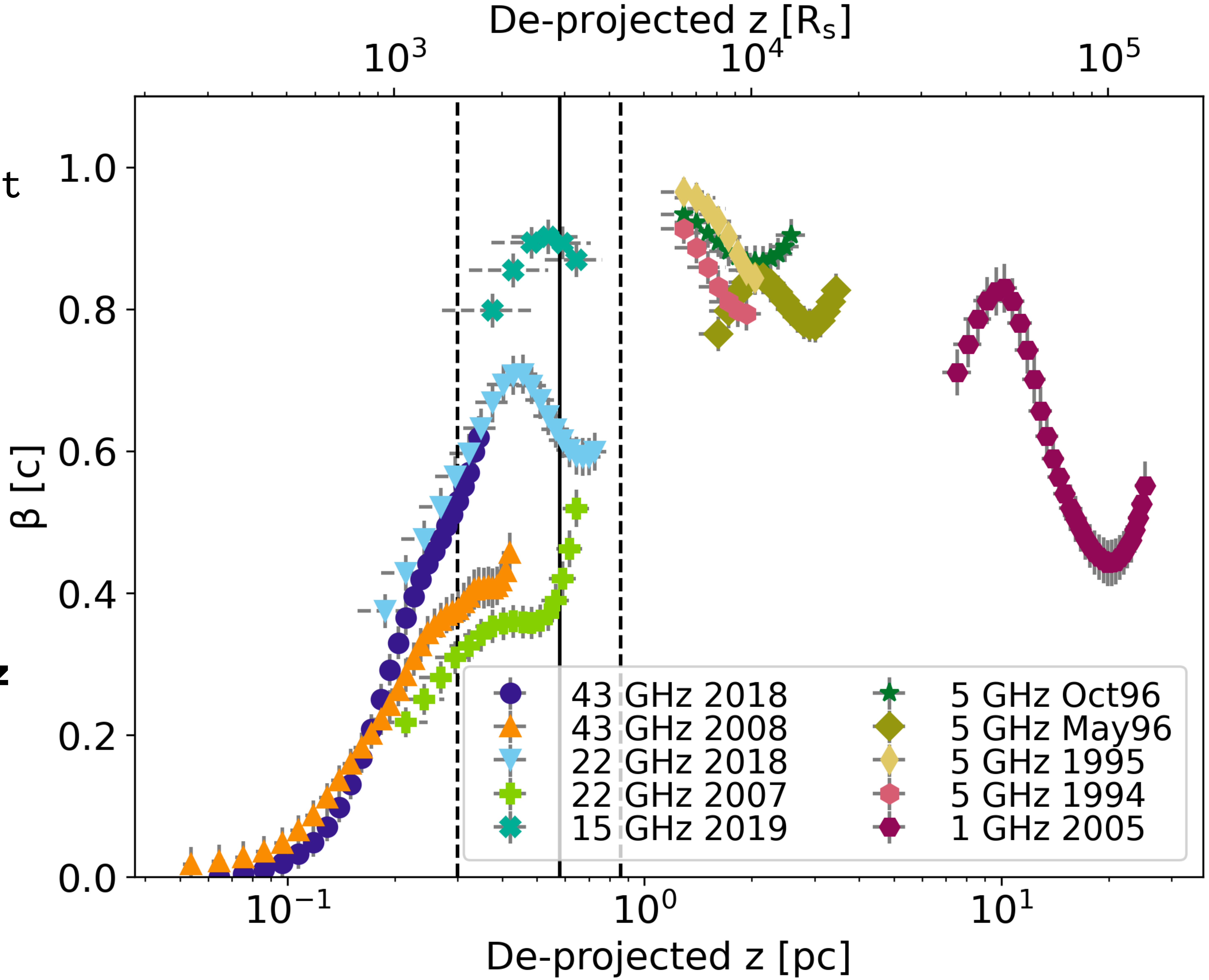
Jet to counter-jet intensity ratio

Hp: intrinsic symmetry between the jet and the counter-jet

$$\beta = \frac{1}{\cos(\theta)} \cdot \frac{R^{1/p} - 1}{R^{1/p} + 1}$$

$$p = 2 - \alpha \qquad (S_\nu \propto \nu^\alpha)$$

The maps are aligned on the 43 GHz core (Boccardi+, 2021)



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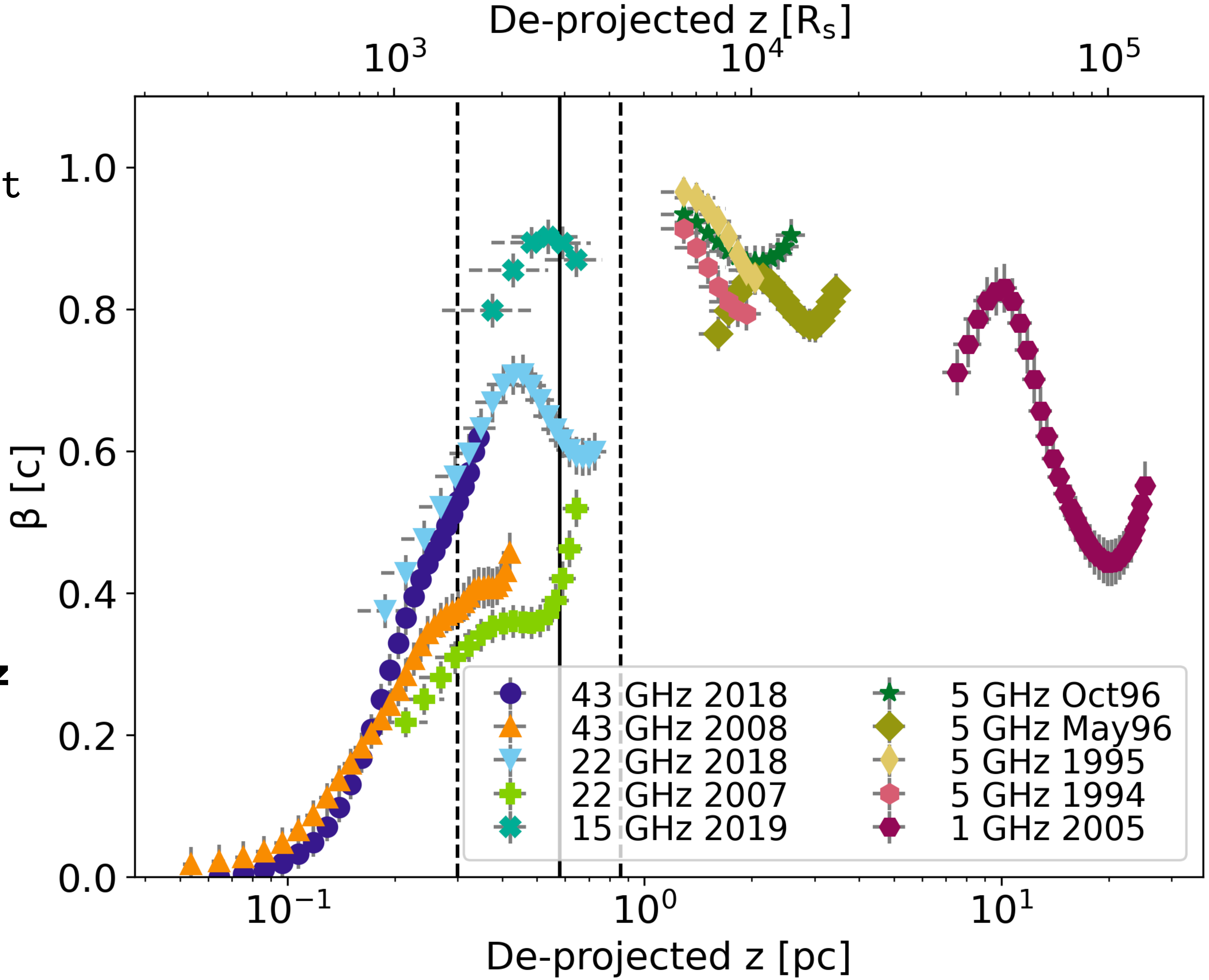
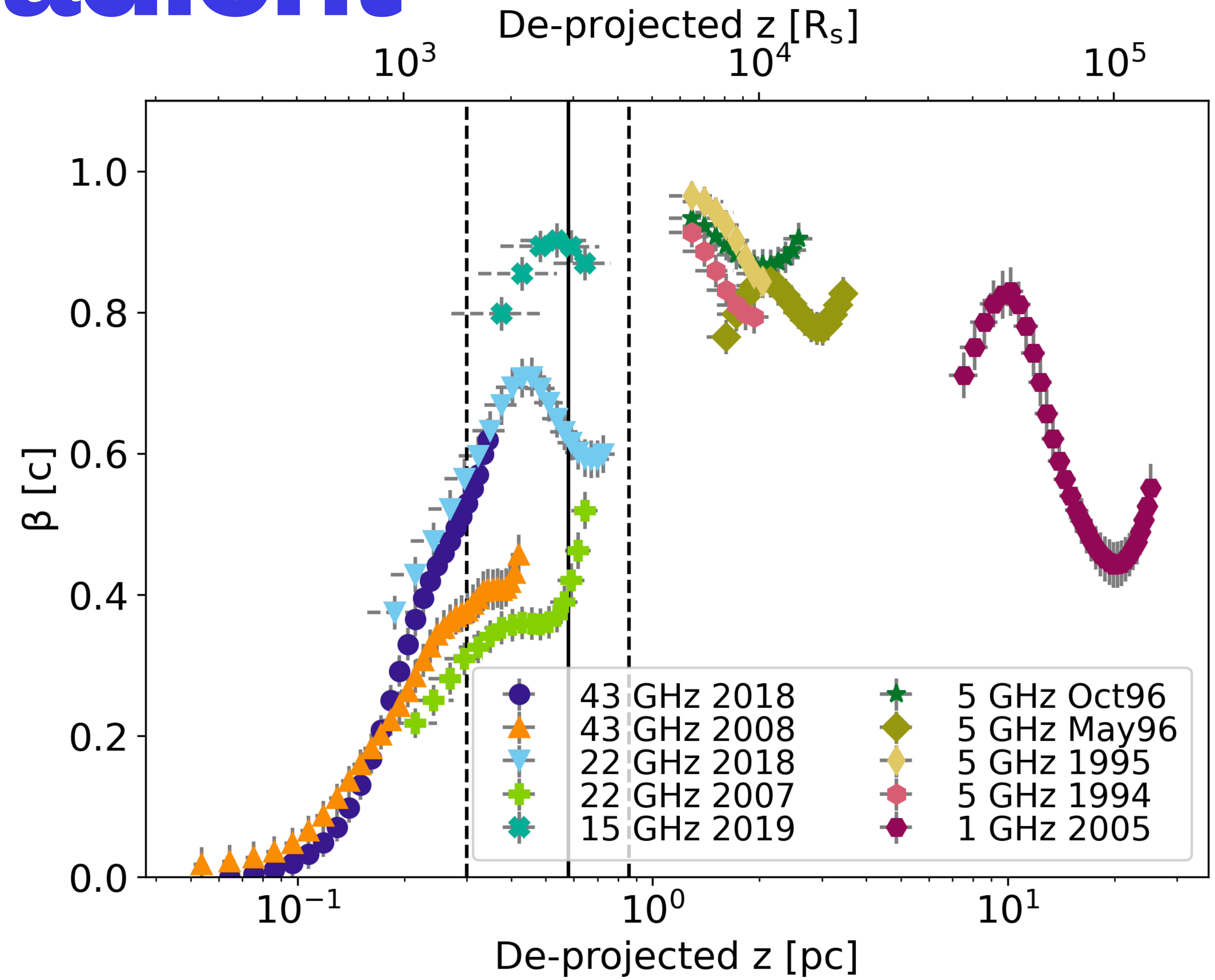
magnetically driven acceleration



Jet acceleration gradient

$$f(z) = A + B\tanh(ar - b)$$

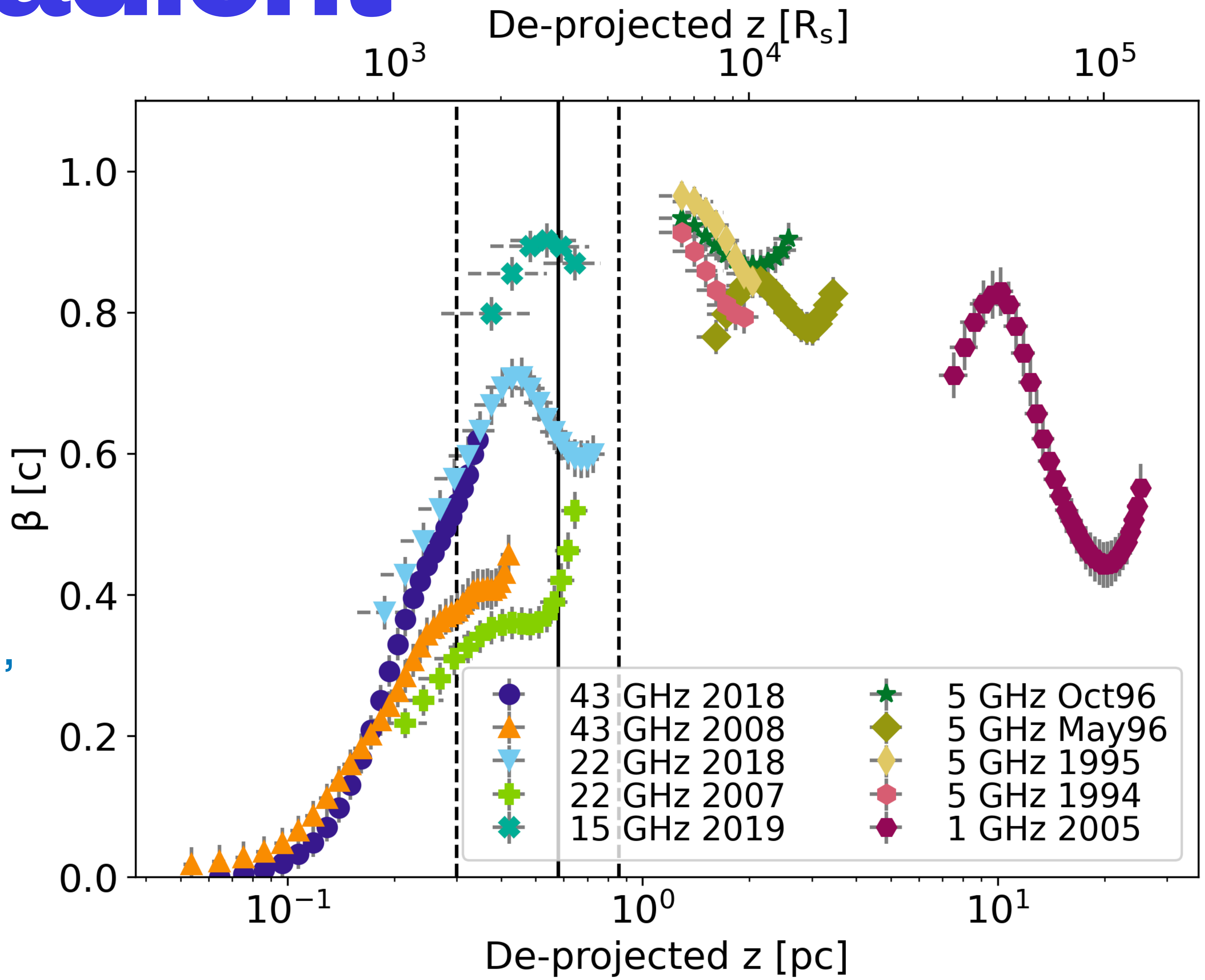


Jet acceleration gradient

$$f(z) = A + B\tanh(ar - b)$$

- $f(0) = 1$
- $f(\infty) = \Gamma_{\max}$
- $\delta\Gamma/\delta r < R_L^{-1}$
- $\Gamma = \Gamma_{\max}/2 \;\; @ \;\; r \sim R_L\Gamma_{\max}/2\rho$

MHD conditions (Beskin+, 2006, Tchekhovskoy+, 2009, Lyubarsky+, 2009; Nakamura+, 2018)



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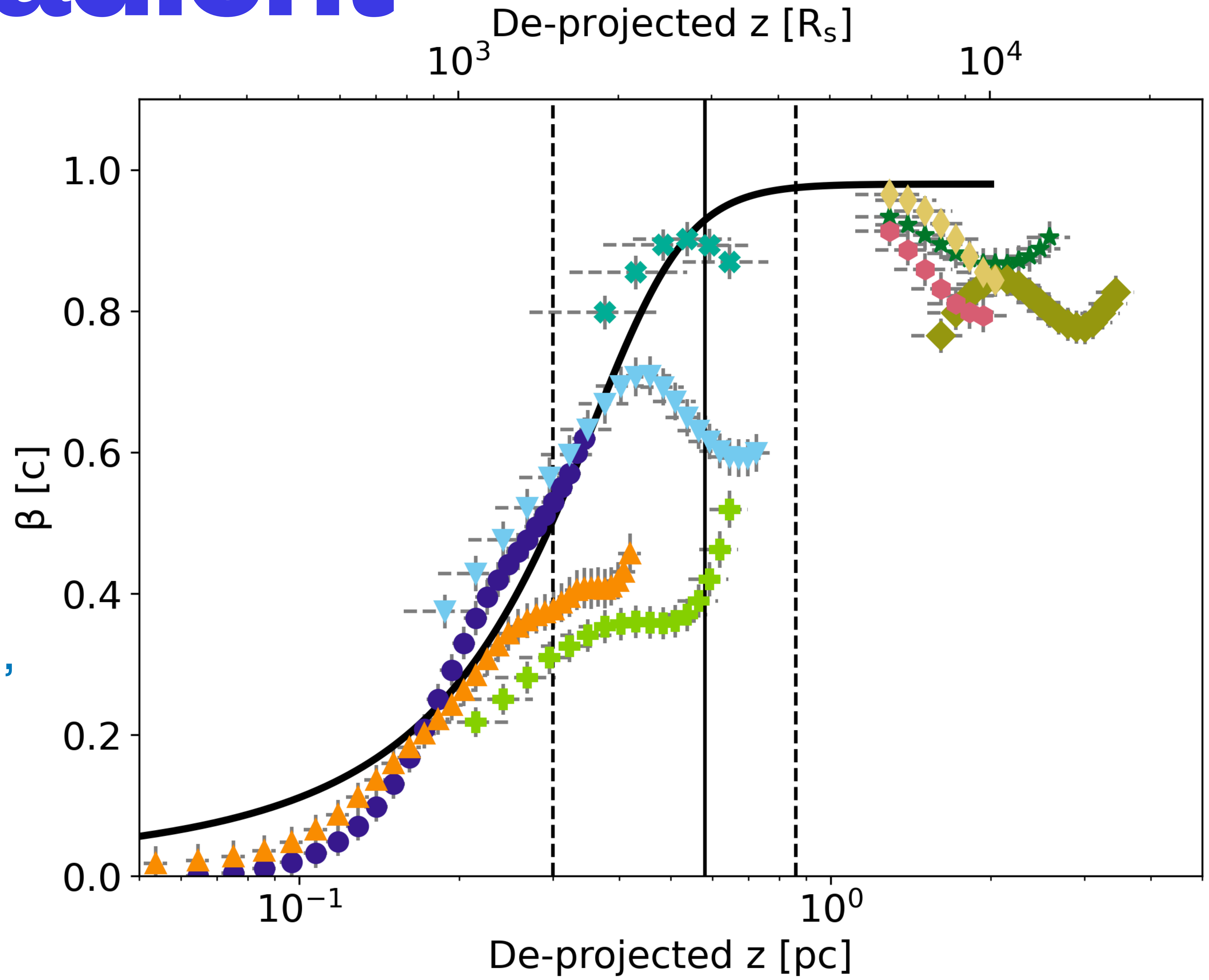

$$\Gamma(z) = \frac{\Gamma_{\mathrm{max}}+1}{2} + \frac{\Gamma_{\mathrm{max}}-1}{2}\tanh\left(\frac{z}{R_L}\frac{2}{\Gamma_{\mathrm{max}}-1} - \frac{\Gamma_{\mathrm{max}}}{\rho(\Gamma_{\mathrm{max}}-1)}\right)$$

Theoretically reconciled with a magnetically driven acceleration

Nuclear properties

- Black hole spin (Nokhrina+ (2019,2020))

$$a_* = \frac{8(r_g/R_L)}{1 + 16(r_g/R_L)^2} \gtrsim 0.72$$

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$$\Phi_\mathrm{N} = (1.1 \pm 0.8) \times 10^{33}\,\mathrm{G\,cm^2}$$

obs + model

Nuclear properties

- Black hole spin (Nokhrina+ (2019,2020))

$$a_* = \frac{8(r_g/R_L)}{1 + 16(r_g/R_L)^2} \gtrsim 0.72$$

- Magnetic flux threading the accretion disk (Nokhrina+ (2019,2020) and Zamaninasab+, 2014)

$$\underset{\text{obs + model}}{\Phi_{\mathrm{N}} = (1.1 \pm 0.8) \times 10^{33}\,\mathrm{G\,cm^2}} \quad \sim \quad \underset{\text{expected}}{\Phi^{\mathrm{exp}} = (1.4 \pm 0.3) \times 10^{33}\,\mathrm{G\,cm^2}}$$

obs + model

expected

→ **First hint for an established MAD**

Magnetic field based on the core shift

- Conical geometry (Lobanov, 1998 and Hirotani, 2005)

- Case 0)

$$B_1 = 0.025\left(\frac{\Omega_{r\nu}^3(1+Z)^2}{\delta^2\phi\sin^2\theta}\right)^{1/4}\,\mathrm{G}$$

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where:

$$\Omega_{r\nu} = 4.85\times10^{-9}\,\frac{\Delta r_{\mathrm{mas}}D_{\mathrm{L}}}{(1+z)^2}\left(\frac{\nu_1^{1/k_r}\nu_2^{1/k_r}}{\nu_2^{1/k_r}-\nu_1^{1/k_r}}\right)\mathrm{pc\,GHz}$$

Core shift

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- Quasi-parabolic geometry and accelerating jet (Ricci+, 2022arXiv220612193R, A&A in press)

- Case A) $\theta \sim \Gamma^{-1}$

$$B_z = 0.025\left(\frac{\Omega_{r\nu}^{6\psi}(1+Z)^2}{z^{6\psi}r_z\delta^2\sin^{6\psi-1}\theta}\right)^{1/4}\,\mathrm{G}$$

- Case B) $\theta \lesssim \Gamma^{-1}$

$$B_z = 0.018\left(\frac{\Omega_{r\nu}^{4\psi}(1+Z)^2}{z^{4\psi}r_z\sin^{4\psi-1}\theta}\left(\frac{R_L}{r_z}\right)^2\right)^{1/4}\,\mathrm{G}$$

$$z \propto r^{\psi}$$

- Case C) $\theta \gtrsim \Gamma^{-1}$

$$B_z = 0.025\left(\frac{\Omega_{r\nu}^{8\psi}(1+Z)^2(1-\cos\theta)^2}{z^{8\psi}r_z\sin^{8\psi-1}\theta}\left(\frac{R_L}{r_z}\right)^2\right)\,\mathrm{G}$$

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$$B_1 = 0.13 \pm 0.02\,\mathrm{G}$$

- Quasi-parabolic geometry and accelerating jet (Ricci+, 2022arXiv220612193R, A&A in press)

$$z_{\rm br} = 0.58\,\mathrm{pc}$$

- Case A) $\theta \sim \Gamma^{-1}$ $$B_z = 0.025\left(\frac{\Omega_{r\nu}^{6\psi}(1+Z)^2}{z^{6\psi}r_z\delta^2\sin^{6\psi-1}\theta}\right)^{1/4}\,\mathrm{G}$$

$$B_{z_{\rm br}} = 0.18 \pm 0.06\,\mathrm{G}$$

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$$B_{z_{\rm br}} = 0.013 \pm 0.003\,\mathrm{G}$$

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Accretion disk magnetic field

Method 1: core shift

- Case 0) $B_1 = 0.13 \pm 0.02\,\mathrm{G}$
- Case A) $B_{z_{\mathrm{br}}} = 0.18 \pm 0.06\,\mathrm{G}$
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In an accelerating jet

$$\longrightarrow \quad B(z) = B_0 \left(\frac{z_0}{z}\right)^{2\psi}$$

$$\Big\downarrow \; \psi \sim 0.5$$

$$B(z) \propto z^{-1}$$

True for toroidal and poloidal dominated fields in an accelerating jet

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Method 2: poloidal field strength

$$B_p = \Phi_{\mathrm{N}}/(\pi r^2)$$

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$$F_{\rm B} = F_{\rm G}$$

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magnetosphere radius

$$r_m \in [0.6\,,5.3]\,R_{\mathrm{S}}$$

Accretion disk magnetic field

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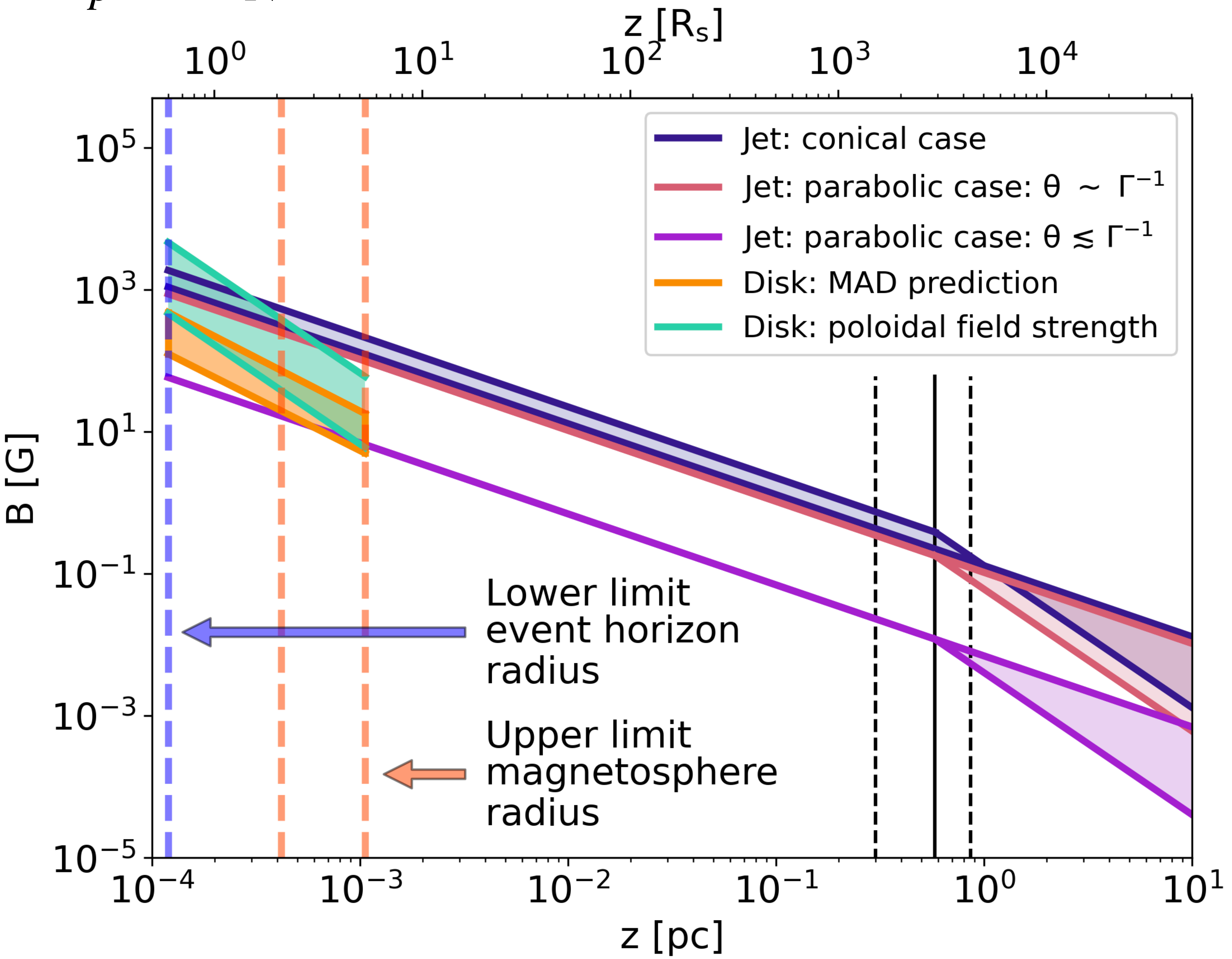

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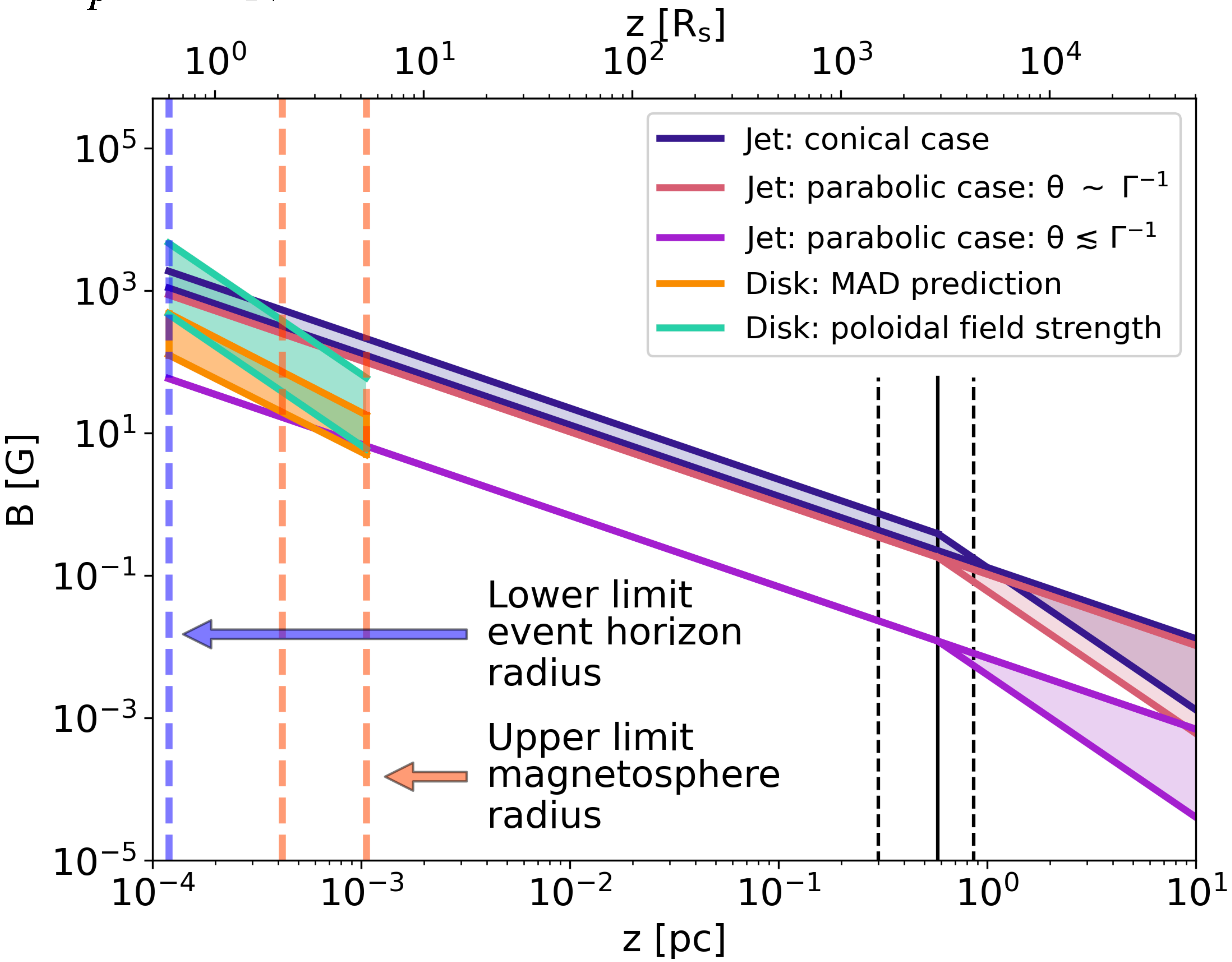

Second hint for an established MAD

Conclusions

- The collimation and acceleration scales are co-spatial —> it suggests the jet to consist of a cold outflow in which the acceleration is mainly driven by the conversion of magnetic energy into kinetic energy of the bulk (Komissarov+, 2007; Tchekhovskoy+, 2008; Lyubarsky+,2009). Following this, we modeled the jet acceleration in the context of MHD theories;

- We present a new formalism to compute the magnetic field from the core shift in a quasi-parabolic, accelerating jet. The extrapolated strengths are consistent with both the poloidal field values obtained from the magnetic disk flux and the needed saturation field strengths to form a MAD.

- Our analysis and modeling is compatible with a fast-rotating black hole surrounded by an accretion disk that has reached a magnetically arrested state.

Backup slide - Magnetic field extrapolation

$B_\varphi = B'_\varphi / \Gamma$ Toroidal field

B_z Estimated field

$B_p = B'_p$ Poloidal field

$B'_\varphi = B'_p r / R_L$ —> MHD relation for a relativistic flow

The toroidal component dominates in the core region

$$B_g = B'_p \left(\frac{r}{r_g}\right)^2 = B_\varphi \Gamma R_L / r \left(\frac{r}{r_g}\right)^2$$

—> effective acceleration region

$$\Gamma \frac{R_L}{r} \sim 1 \text{ and } r \propto z^\psi$$

—> $B_g = B_z \left(\frac{z}{z_g}\right)^{2\psi}$

The poloidal component dominates in the core region

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