The collimation region in extragalactic jets

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Intro & Outline

High collimation degree is among the most remarkable features of relativistic jets!

- Probing the jet collimation region is important

1) to test theoretical models of jet formation;
2) in relation to the feedback the jet will have on the environment.

<u>In this talk I will</u>

- Summarise the theoretical predictions and the main observational tests performed so far.

- Present new results from the investigation of unexplored sources (mainly NGC315).

- Present a first comparison between the properties of the jet collimation region in different AGN classes. Spoiler: some young/compact sources in our sample may present peculiarities…

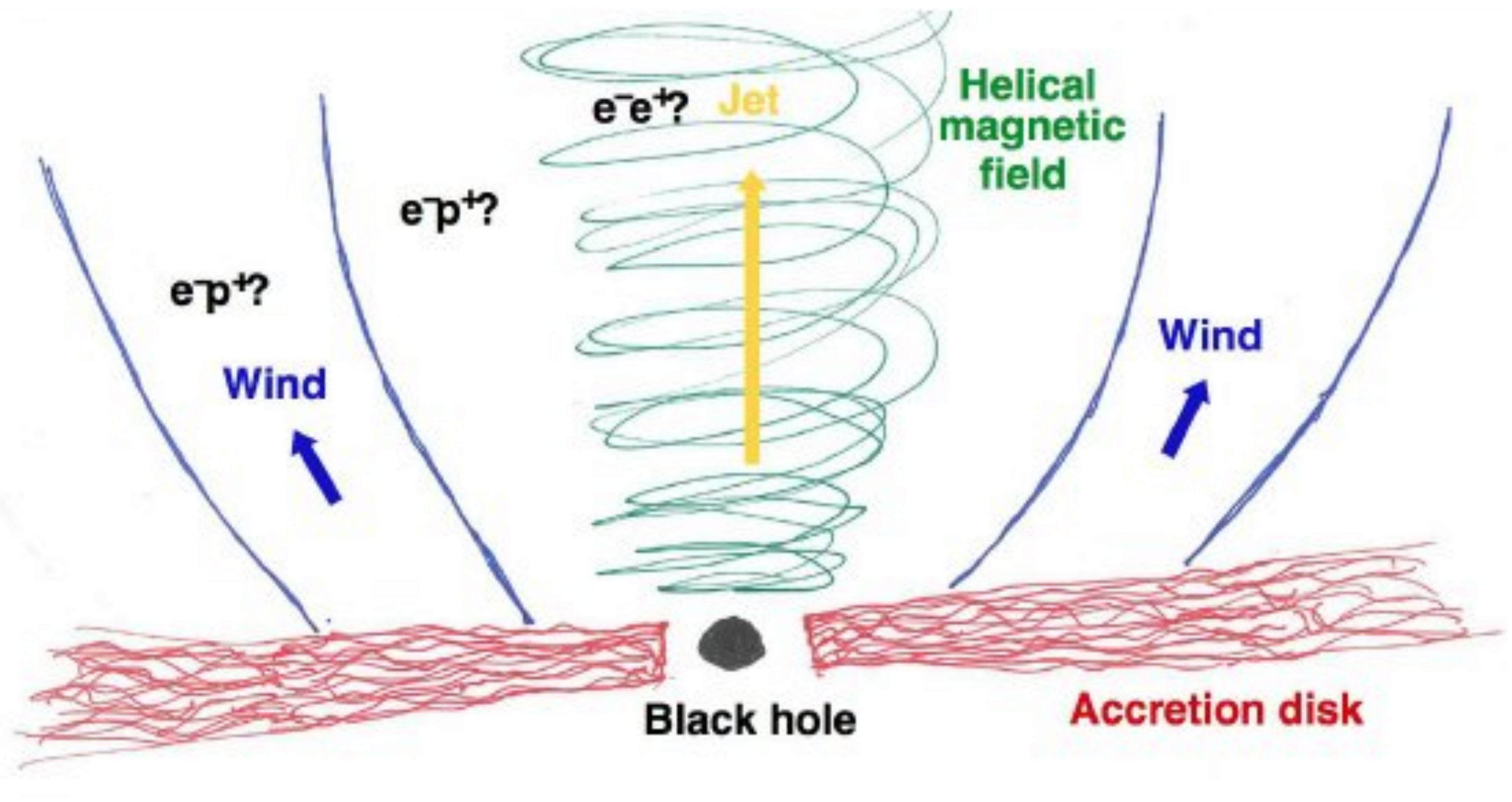
Jet formation

Blandford & Znajeck 1977 (BZ)
Blandford & Payne 1982 (BP)

- Strong magnetic fields channel the outflow by extracting the rotational energy of the accretion disk (BP) and/or of the black hole (BZ), if this is spinning.

- As the jet is accelerated and collimated, the magnetic energy at the jet base is converted into kinetic energy.

(in the following, ACZ= acceleration & collimation zone)



Credits: I. Agudo

- Fundamental scale unit in magnetohydrodynamic jet launching process is Schwarzschild radius $R_S = 2GM_{BH}/c^2$.

Collimation region

- <u>What does it mean:</u>

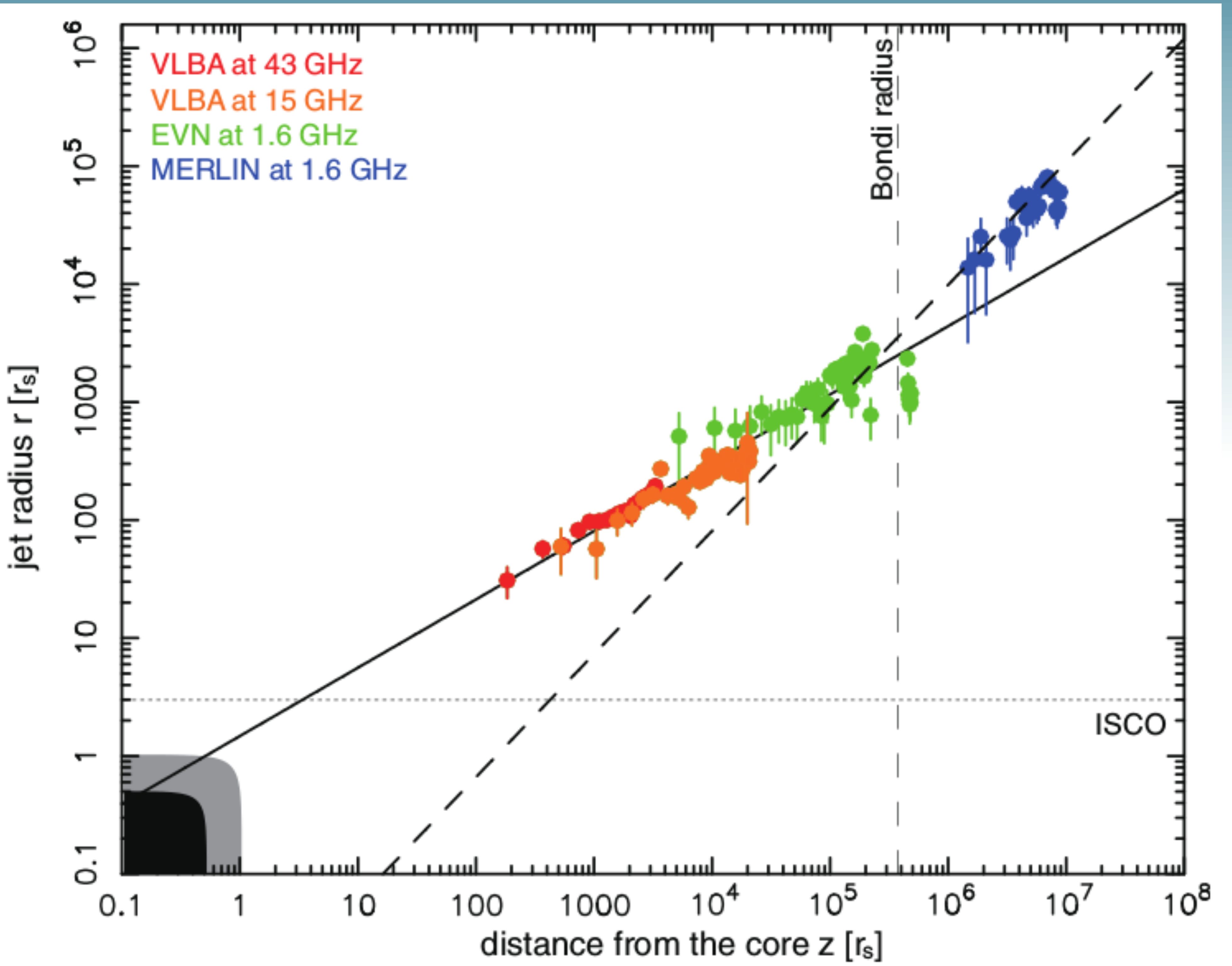
  - It is the region at the jet base along which the jet opening angle decreases, until a roughly constant, small opening angle is attained.

- <u>What have we learned from observations:</u>

- Jet shape in collimation region is usually parabolic ($d \propto z^{0.5}$).

- Acceleration and collimation are indeed co-spatial.

- ACZ may terminate in proximity of BH sphere of influence (?).



Jet expansion profile in M87 (Asada & Nakamura 2012).

See also Tseng 2016, Boccardi 2016, 2019, Pushkarev 2017, Nakahara 2018, 2020, Kovalev 2020, Casadio 2021

Collimation region

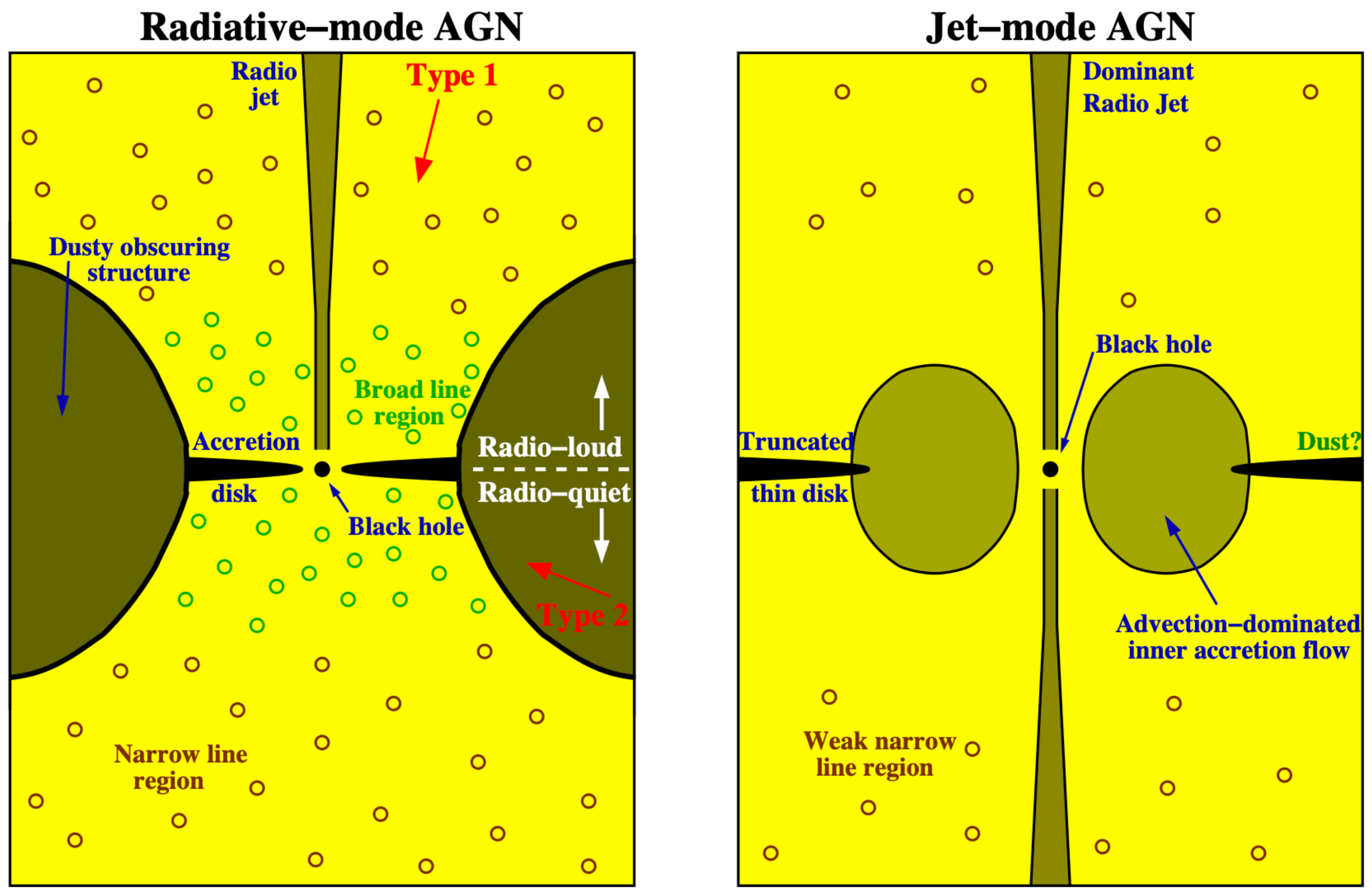
- What we do NOT know:

  - Is magnetic field sufficient to collimate jets, or is confinement from a medium also required? In the latter case, what is the nature of this medium?

  - Does collimation mechanism vary in different luminosity classes/accretion regimes? Few objects studied so far, mostly low-power.

Confinement by ambient medium: parabolic jet shape is expected for an external pressure profile $p \propto z^{-2}$, e.g., inside Bondi sphere.

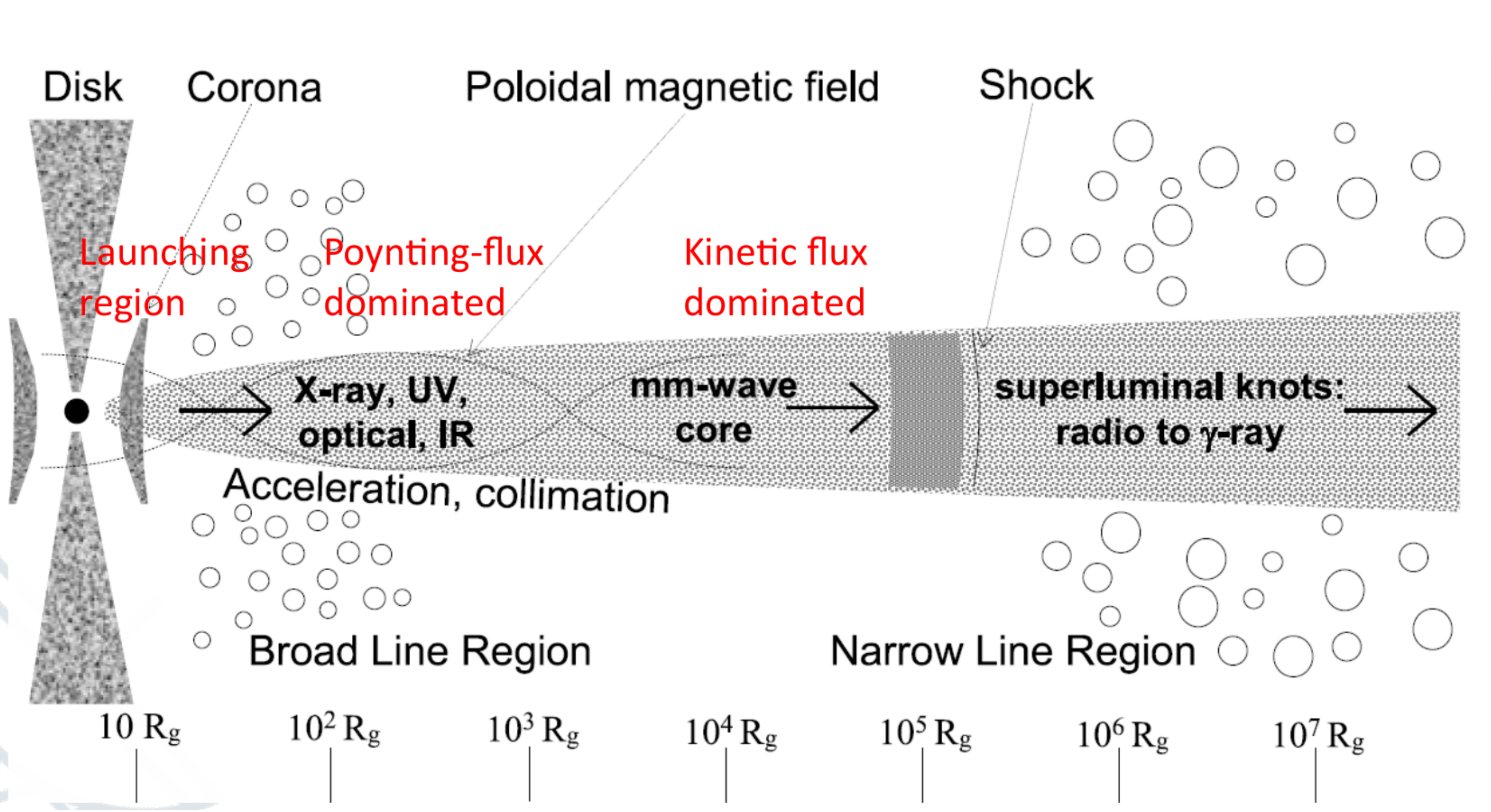
However, Bondi accretion is a simplification! (see e.g. Gaspari 2013).



Heckman & Best 2014

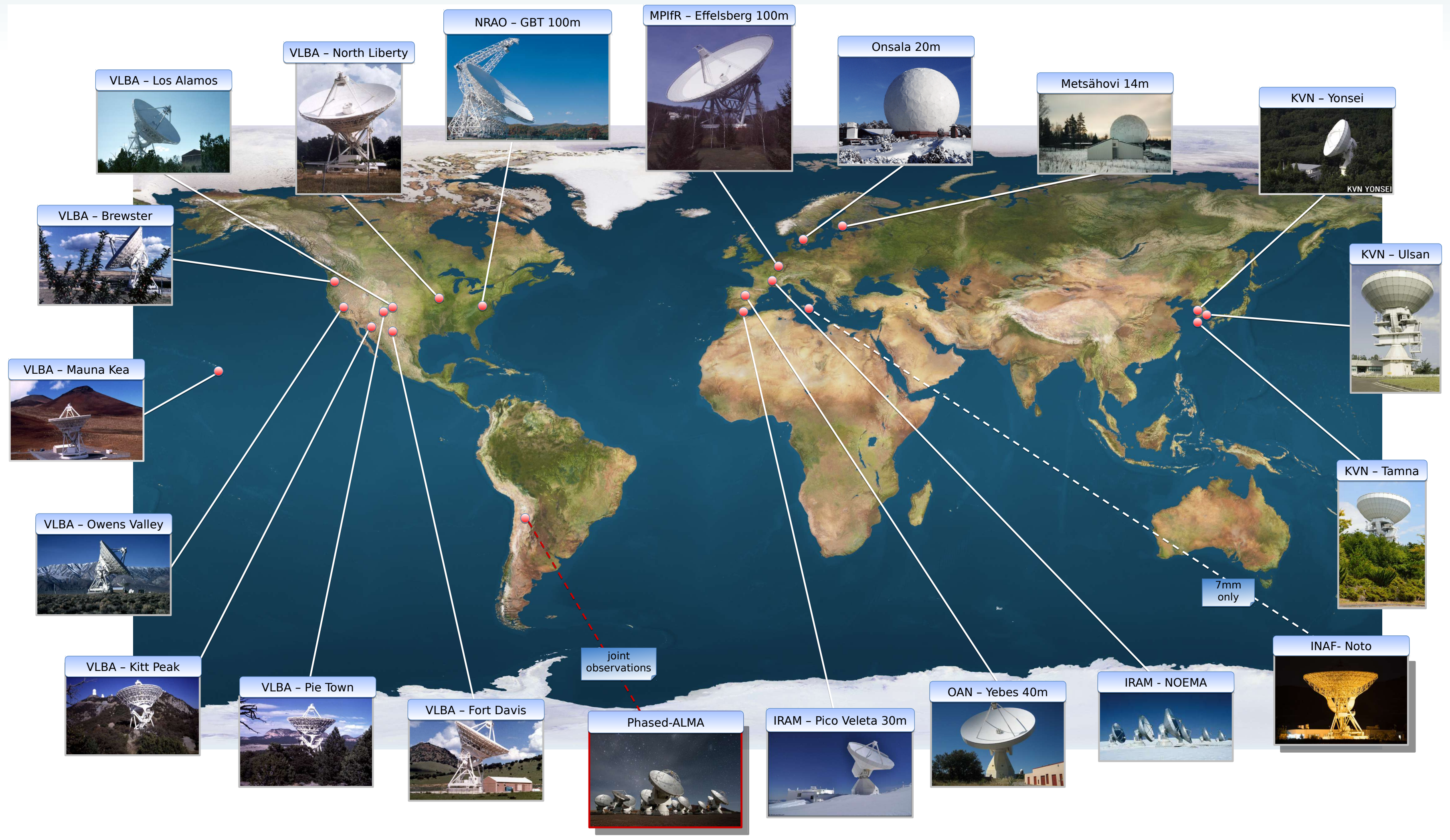
Zooming towards the jet base

VLBI observations generally DO NOT probe ACZ



Sketch of the blazar jet base. Credits A. Marscher, A. Lobanov

→ **Millimeter-VLBI**



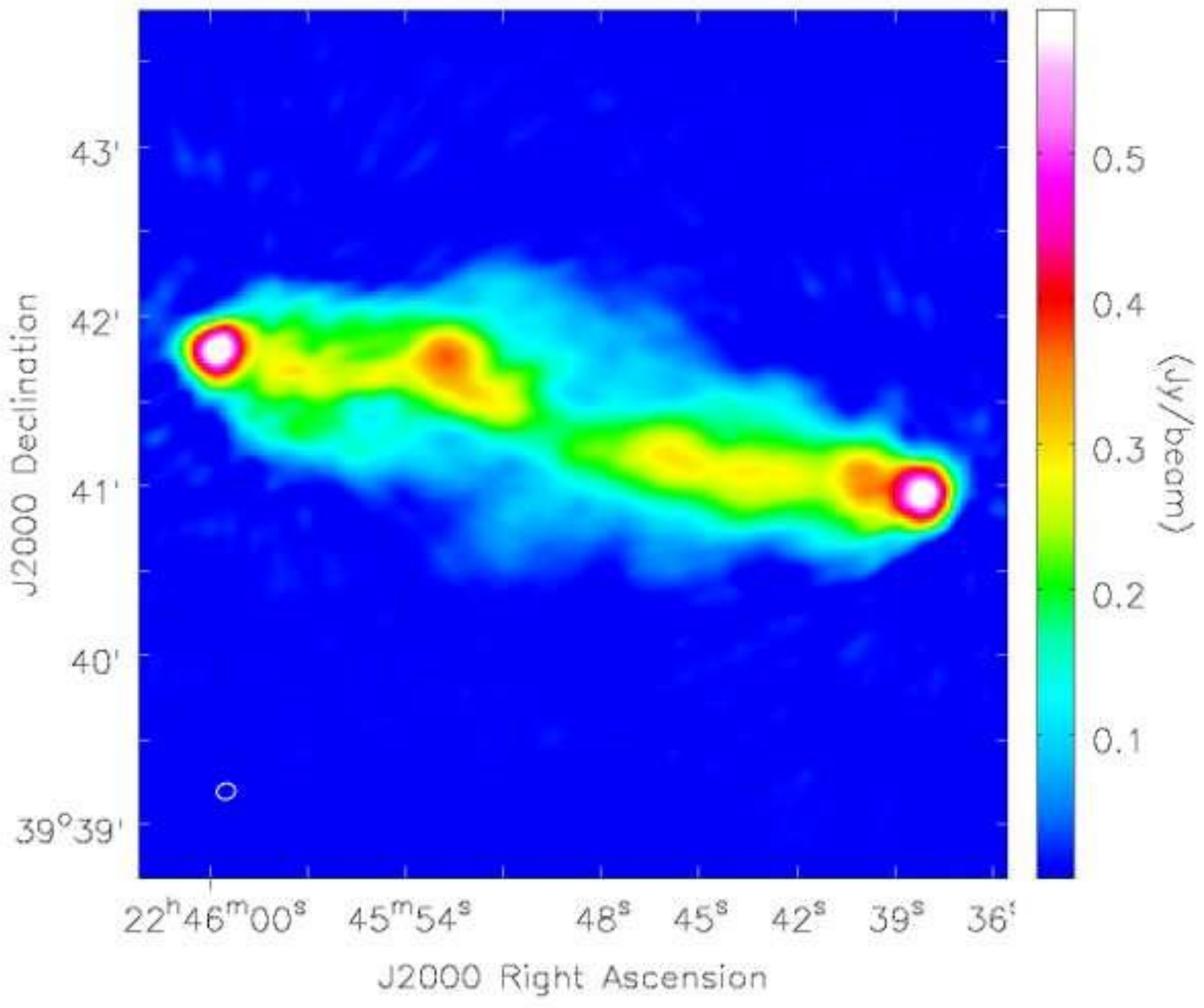
We need to penetrate synchrotron opacity barrier by observing at high frequencies, AND we need to pick the right targets!

Nearby radio galaxies with large $M_{\rm BH}$ are especially convenient targets: high spatial resolution in units of $R_{\rm S}$! (but faint)

HSA observations of unexplored sources

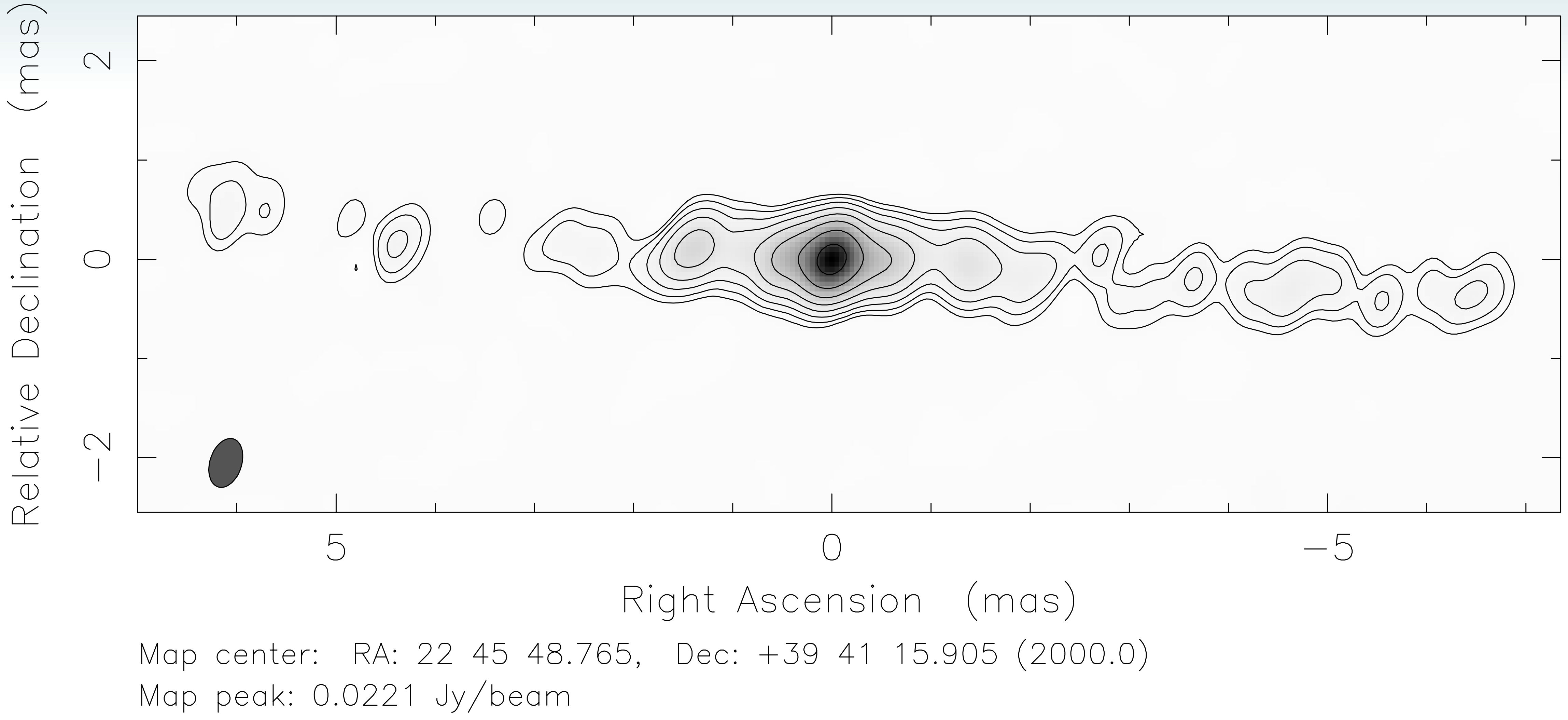
We obtained first mm-VLBI data (VLBA+VLA+Effelsberg) for a sample of 16 nearby (z<0.1) radio galaxies hosting very massive black holes $(\log M_{\rm BH} > 8.5)$.

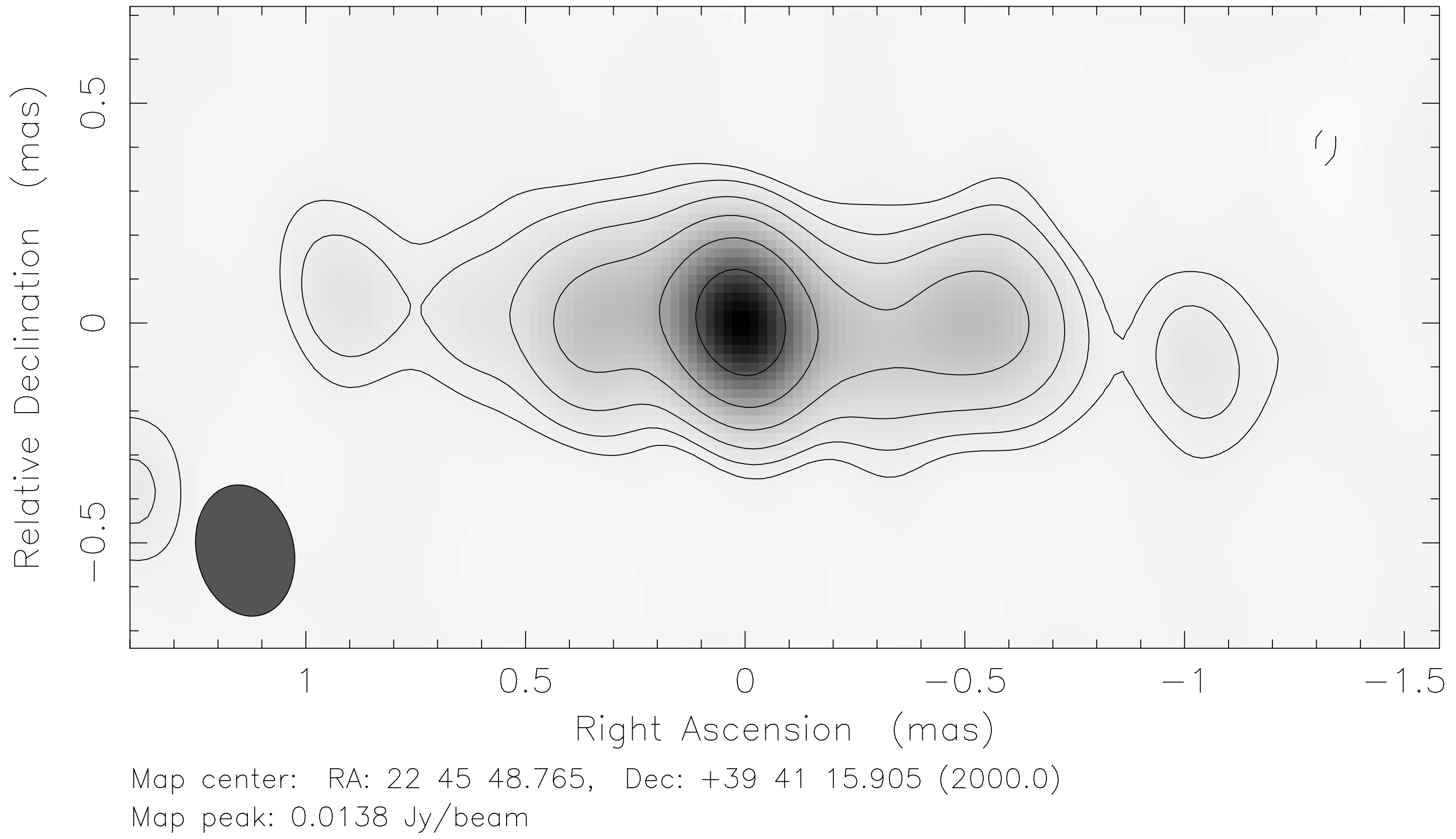
The FRII radio galaxy 3C452, one of the faintest in the sample.



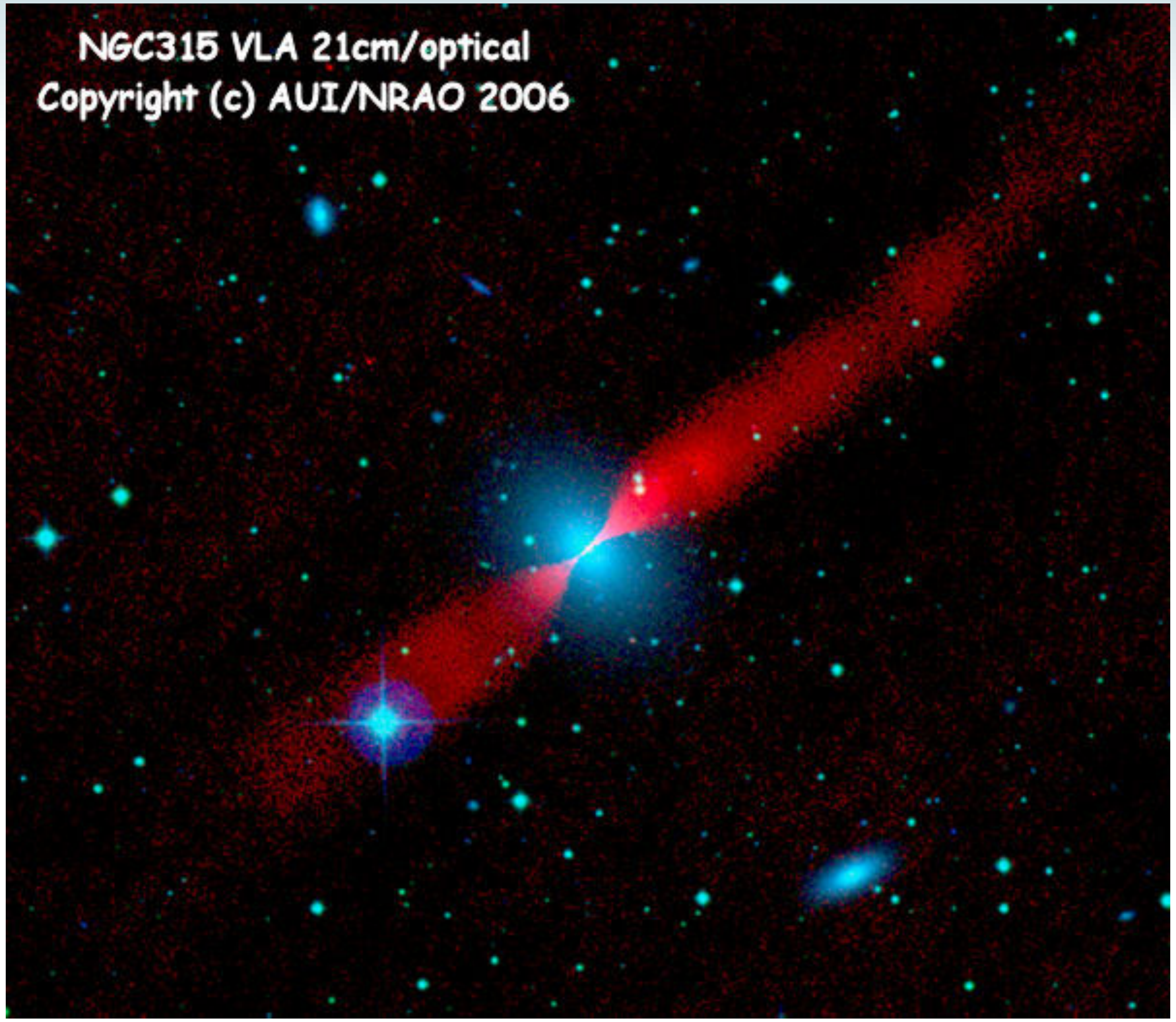
138 MHz LOFAR image of 3C452 (Hardwood et al. 2018)

First sub-pc scale view of 3C452 at 22 GHz (top) and 43 GHz (bottom)





The giant radio galaxy NGC315



- Brightest and best resolved in the sample
- z=0.0165
- Size > 1 Mpc
- FR I powered by hot accretion flow (e.g. Worrall 2007)
- $M_{\rm BH} \sim$ 1-2 $\times 10^9 M_{\odot}$ (Satyapal et al. 2005; Boizelle et al. 2020)
- $\theta \sim 38^{\circ}$ (Canvin et al. 2005)

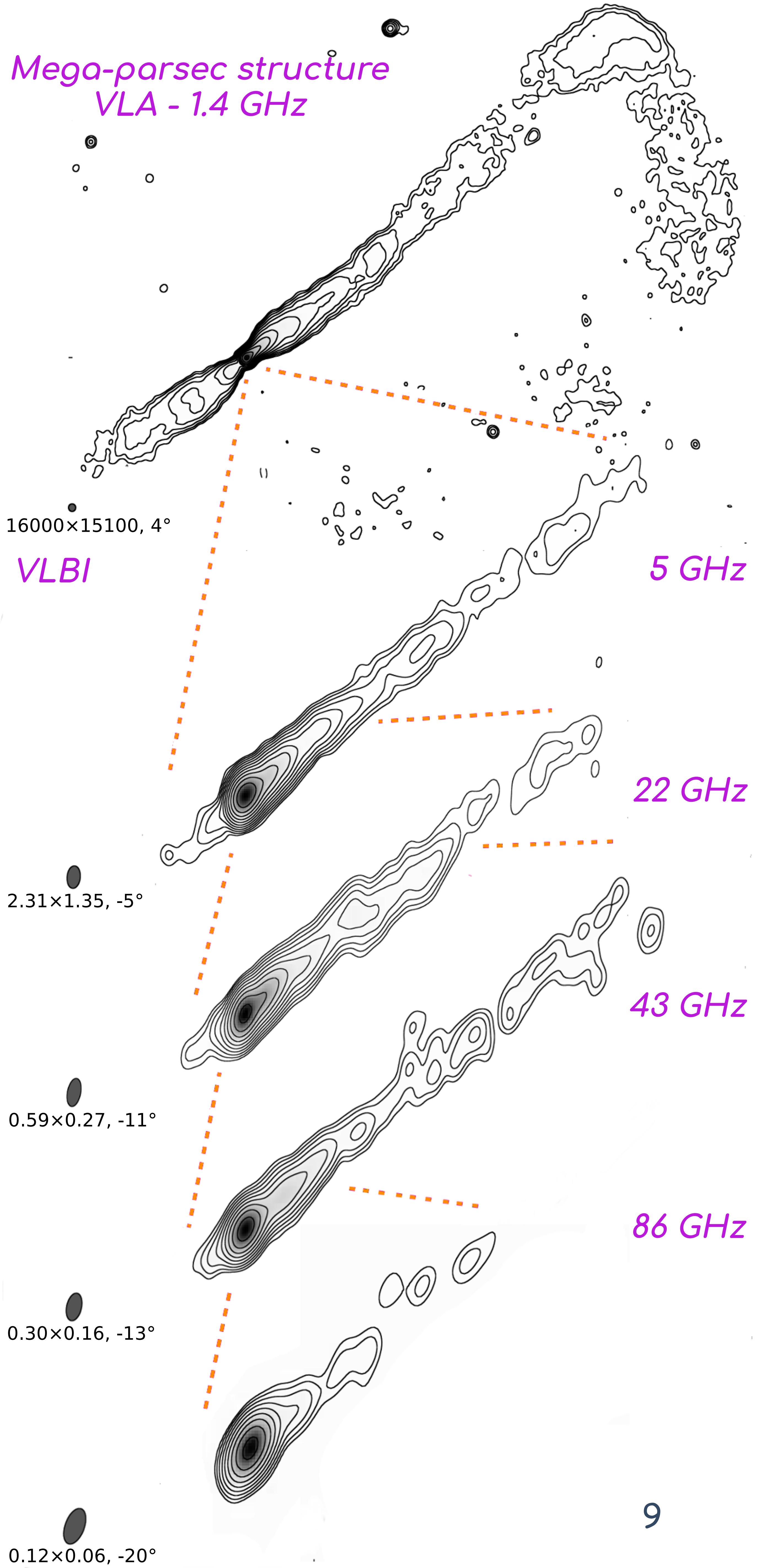
A multi-scale view of NGC315

- We also obtained GMVA data (86 GHz), and assembled a large multi-frequency VLBI data set (18 images at 1 - 86 GHz)

- Imaging on scales of 60 μas, or $\sim 10^2 R_S$ at 86 GHz.

- Faint counter-jet detected.

Boccardi et al. 2021



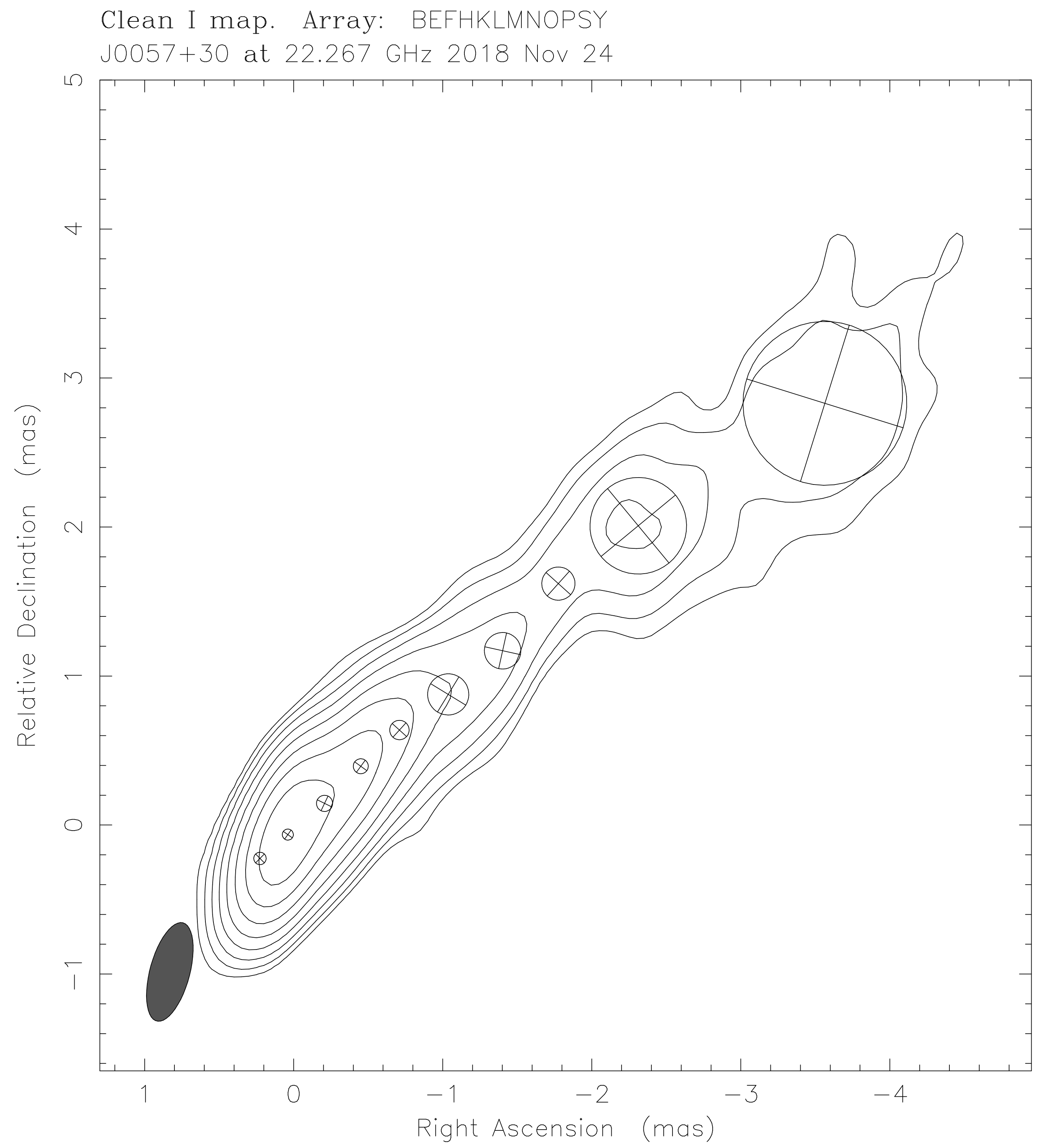
Modelling and maps alignment

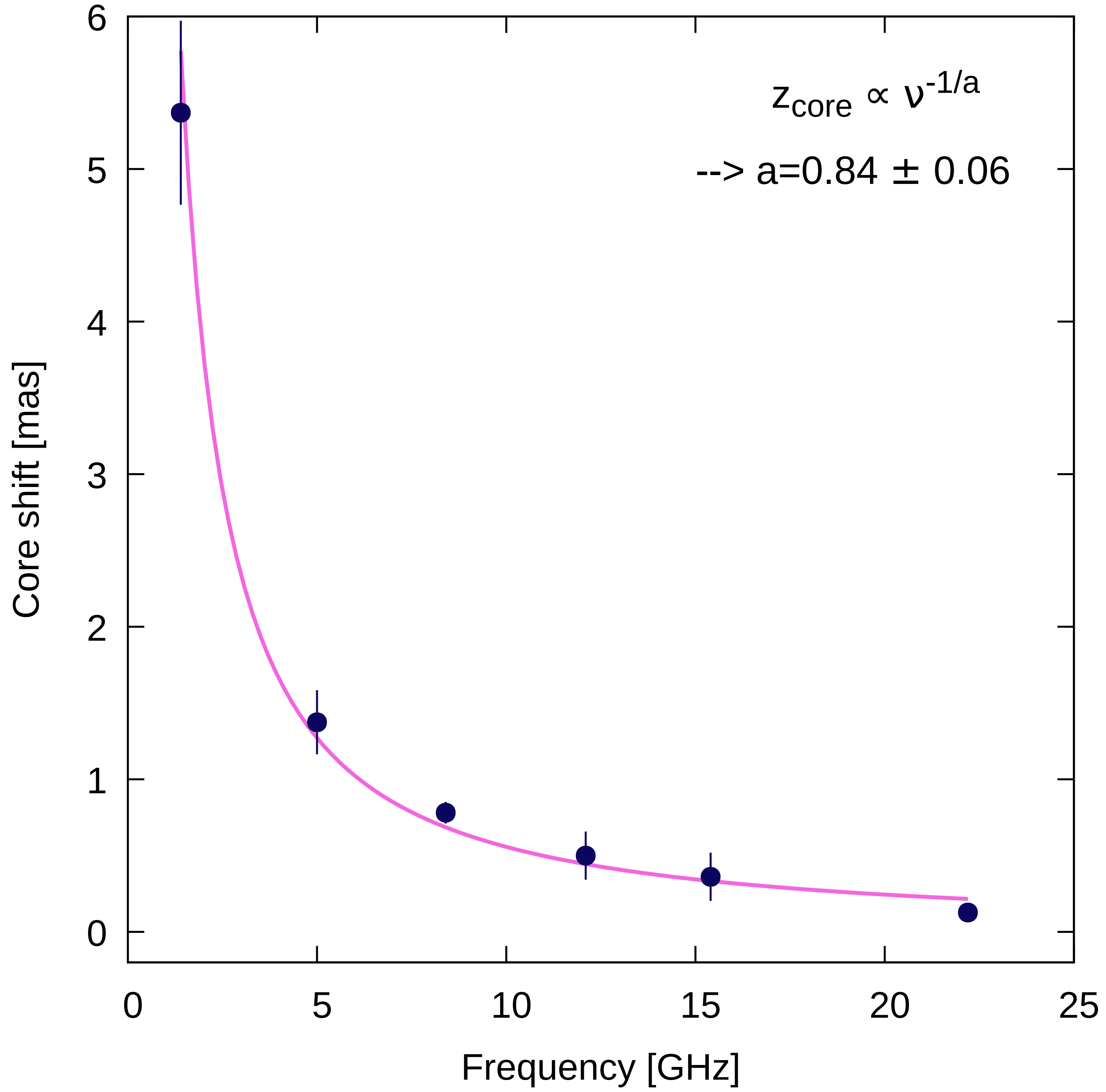
- Modelfit

To determine the jet width at different locations, we have modelled the emission by fitting a series of circular Gaussian components to the visibilities.

- Core-shift

To reconstruct the jet expansion profile, we aligned the images after determining the synchrotron opacity shift of the cores through a 2D cross correlation analysis.



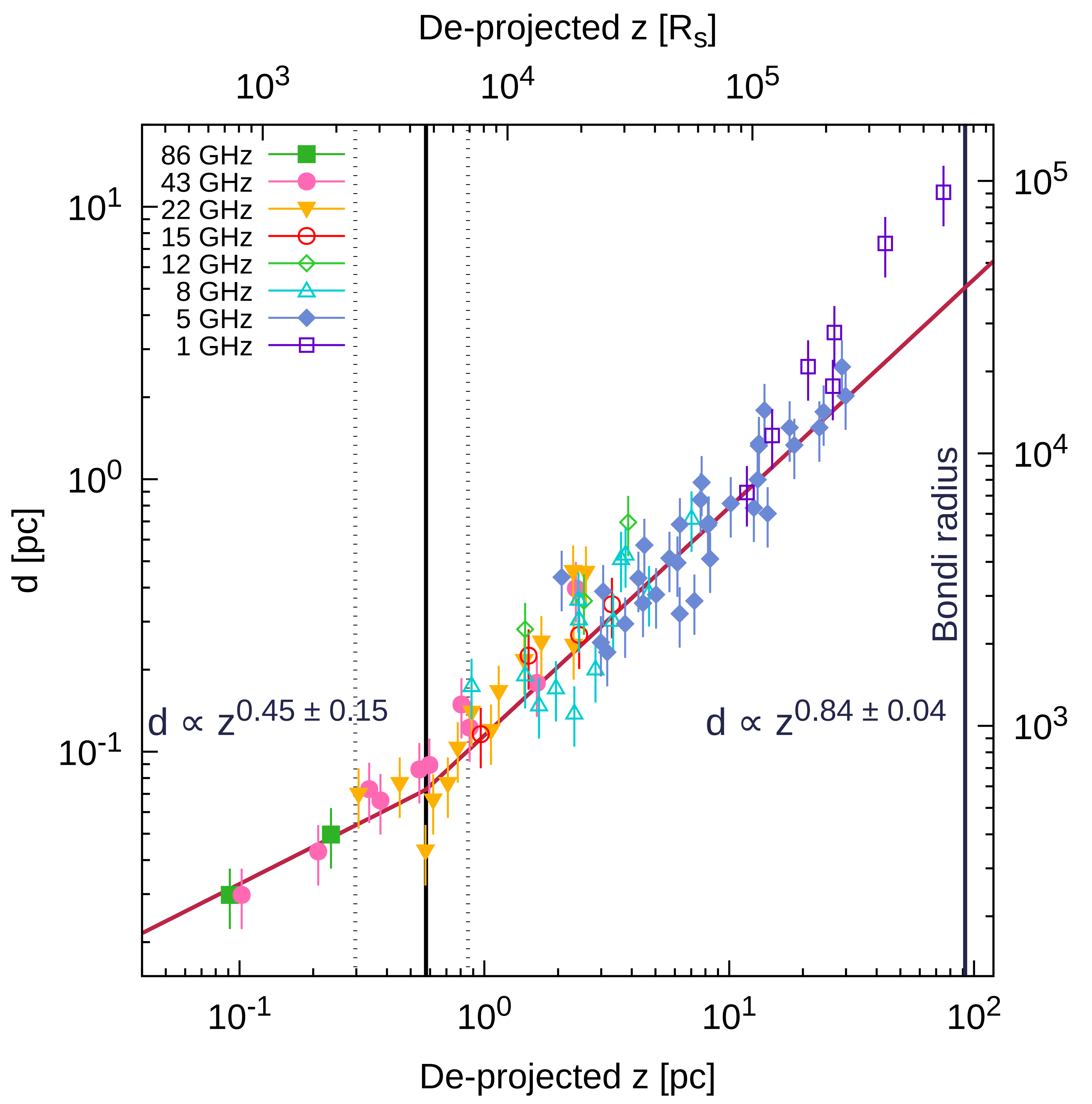


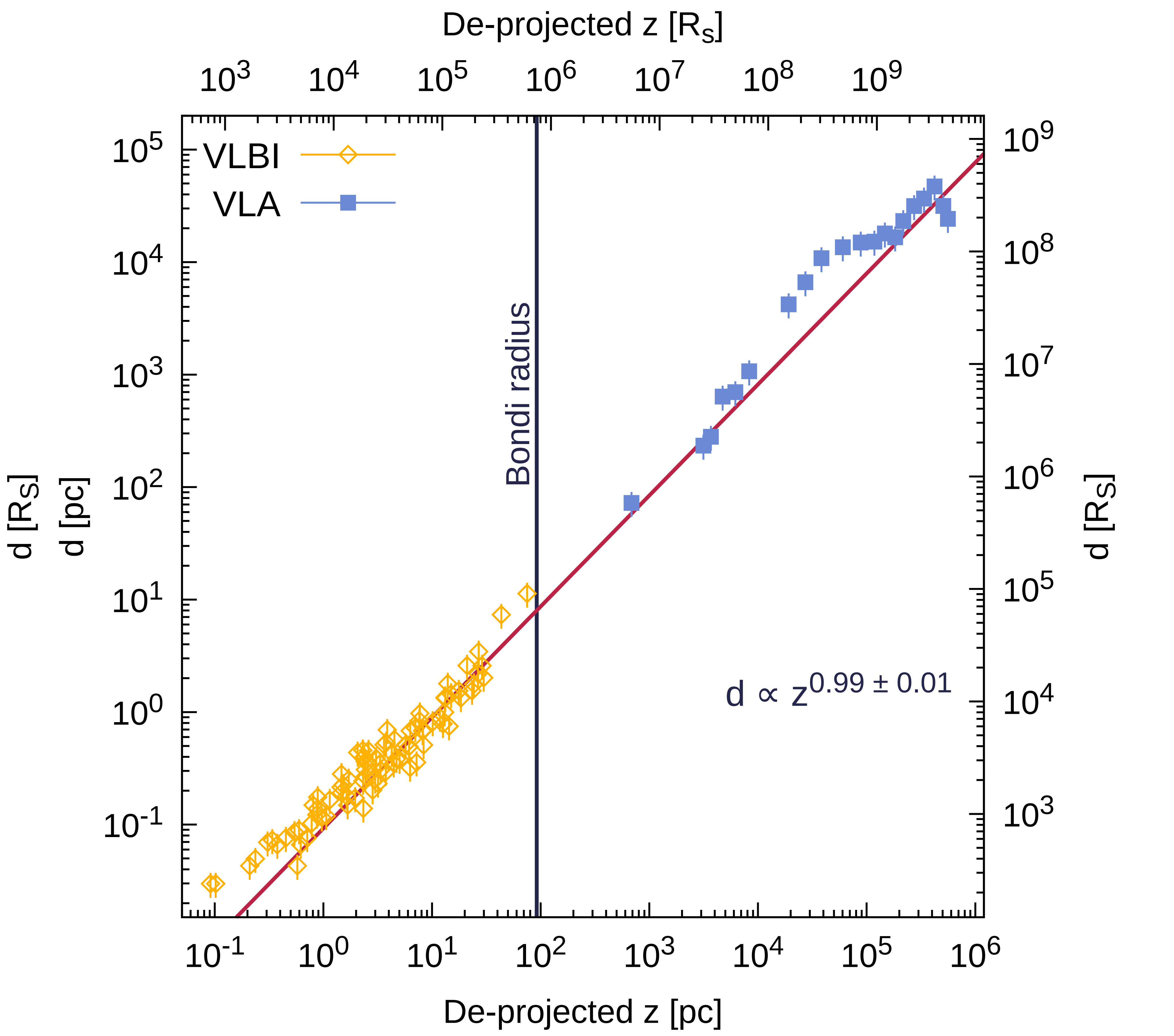
Jet expansion profile

See also Park et al. 2021

Transition from parabolic to conical expansion on sub-pc scales $z_t = 0.58 \pm 0.28$ pc << Bondi radius $R_B \sim 92$ pc

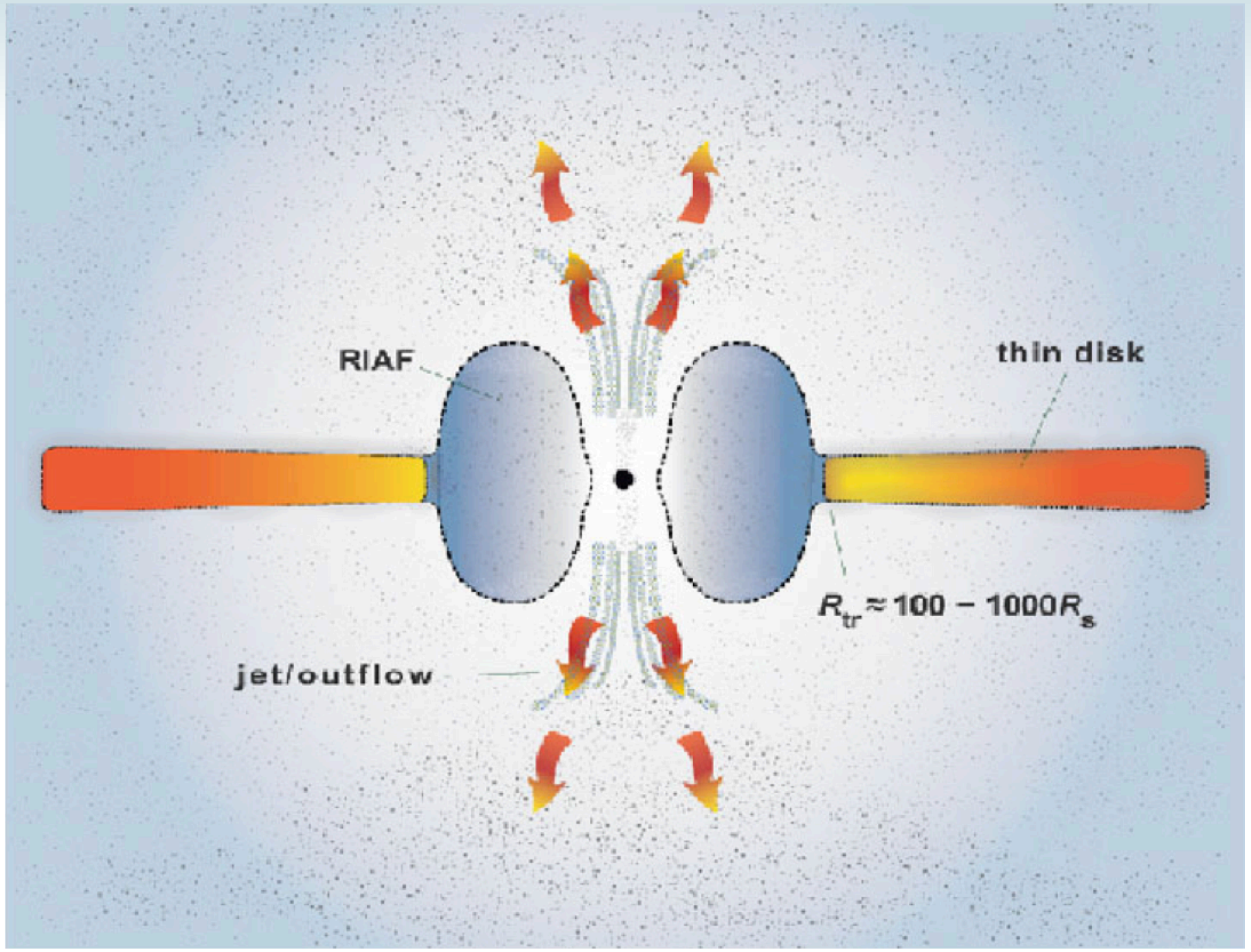
VLBI





VLBI+ VLA

Nature of confining medium?



Sketch of a hybrid accretion disk. Credits: F. Panessa

The extent of the collimation region in NGC315 may be comparable with expected extent of a hot thick disk, $\sim 10^3 - 10^4\, R_S$ (e.g., , Mahadevan 1997, Nemmen et al. 2014).

In the following, we show that this applies to other low-luminosity jets as well.

Accretion regime and jet collimation

We have considered 27 sources at z<0.15 with known jet shape* and black hole mass.

We have classified them as low-excitation galaxies (LEG) or high-excitation galaxies (HEG).

*Boccardi 2016, 2019, Pushkarev 2017, Nakahara 2018, Kovalev 2020

13 radio galaxies
1 NLSy1
} → Classified as LEG or HEG based on L_X/L_{Edd} ratio, assuming a dividing value of $\sim 10^{-3}$ (see Macconi et al. 2020).

13 BL Lacs → Directly classified as LEG.

Most of the sources belong to the MOJAVE sample, 15 GHz data were considered.

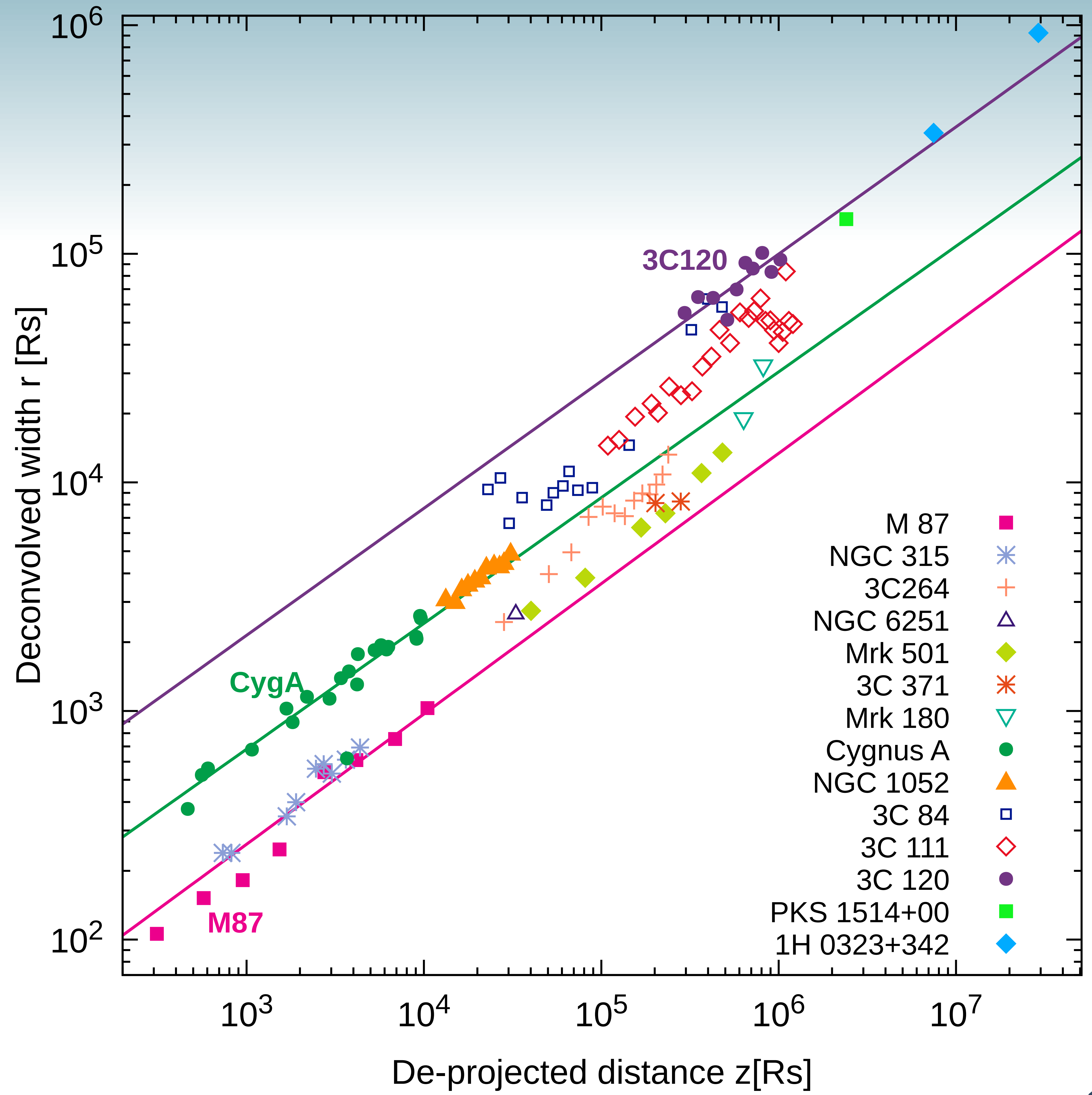
Parabolic profiles

NGC315 follows a profile similar to M87, other sources like Cygnus A, 3C120, or the NLSy1, show wider jet width at the same distance from the black hole.

Assuming a single parabolic profile down to BH (as observed in M87), this may suggest that some jets are anchored at larger disk radii.

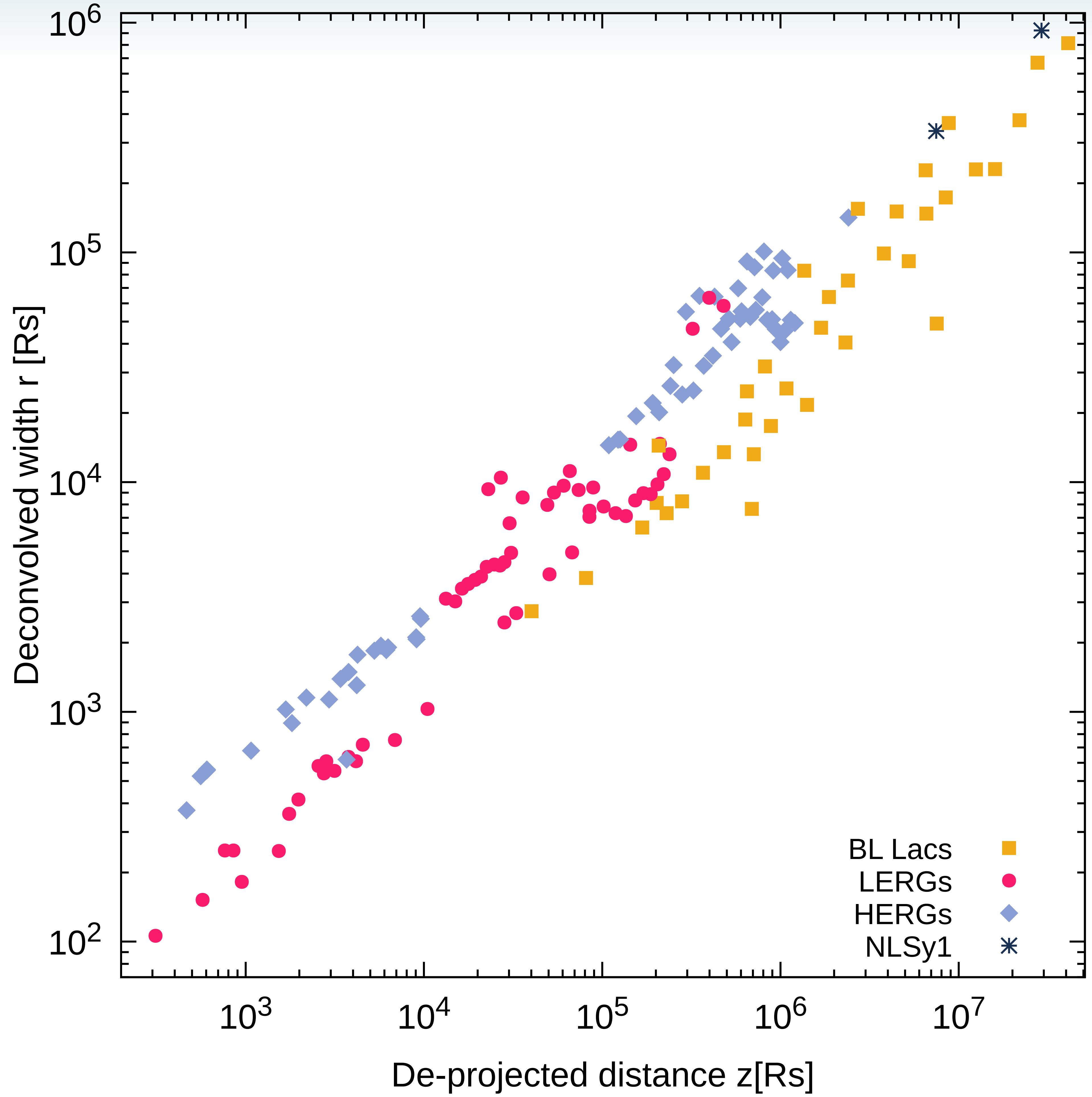
Boccardi et al. 2021

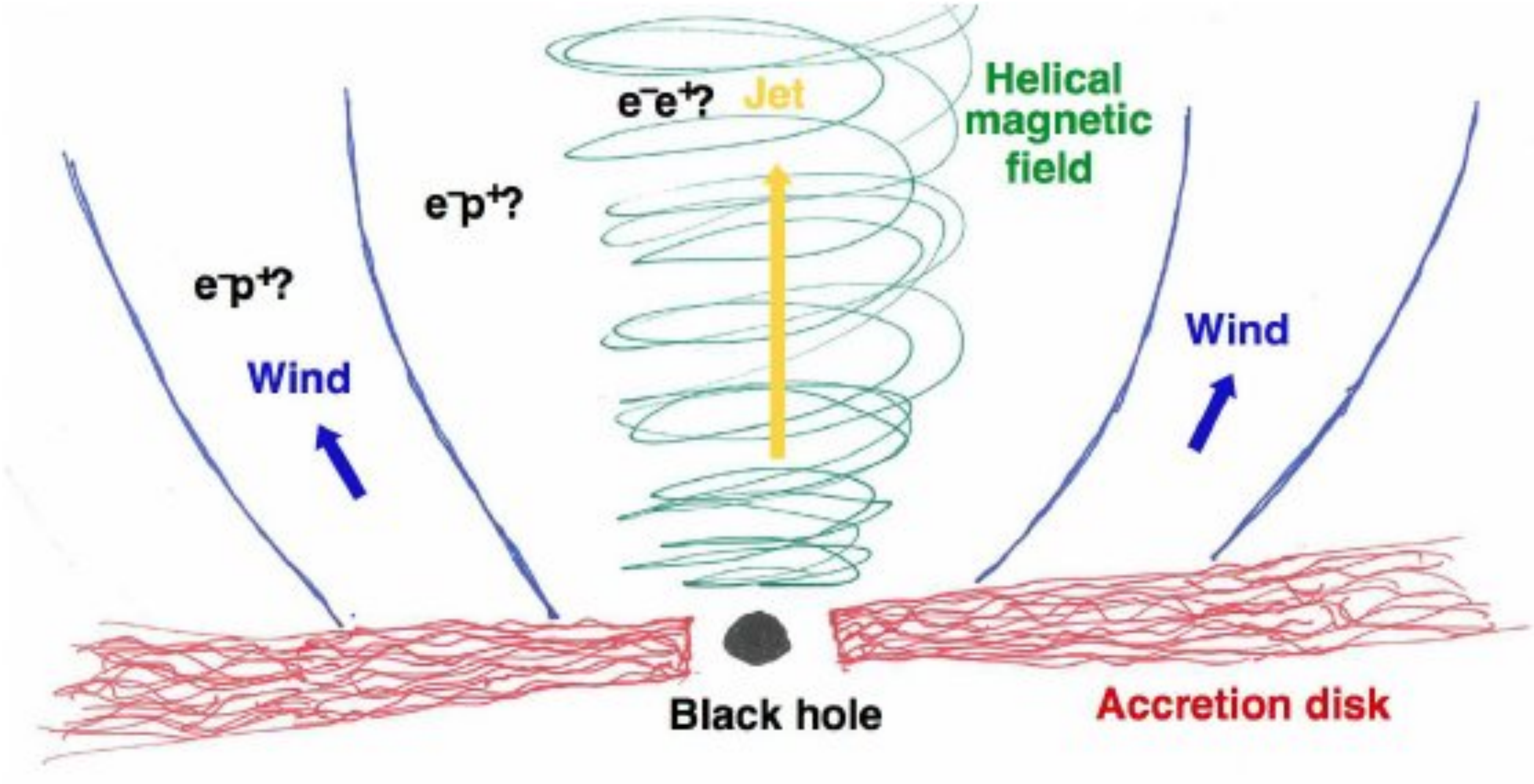
14 Sources with parabolic jet shape



Class-based comparison

We have then compared the profiles of all the 27 jets divided per classes, including those with conical shape (mostly BL Lacs).





Credits: I.Agudo

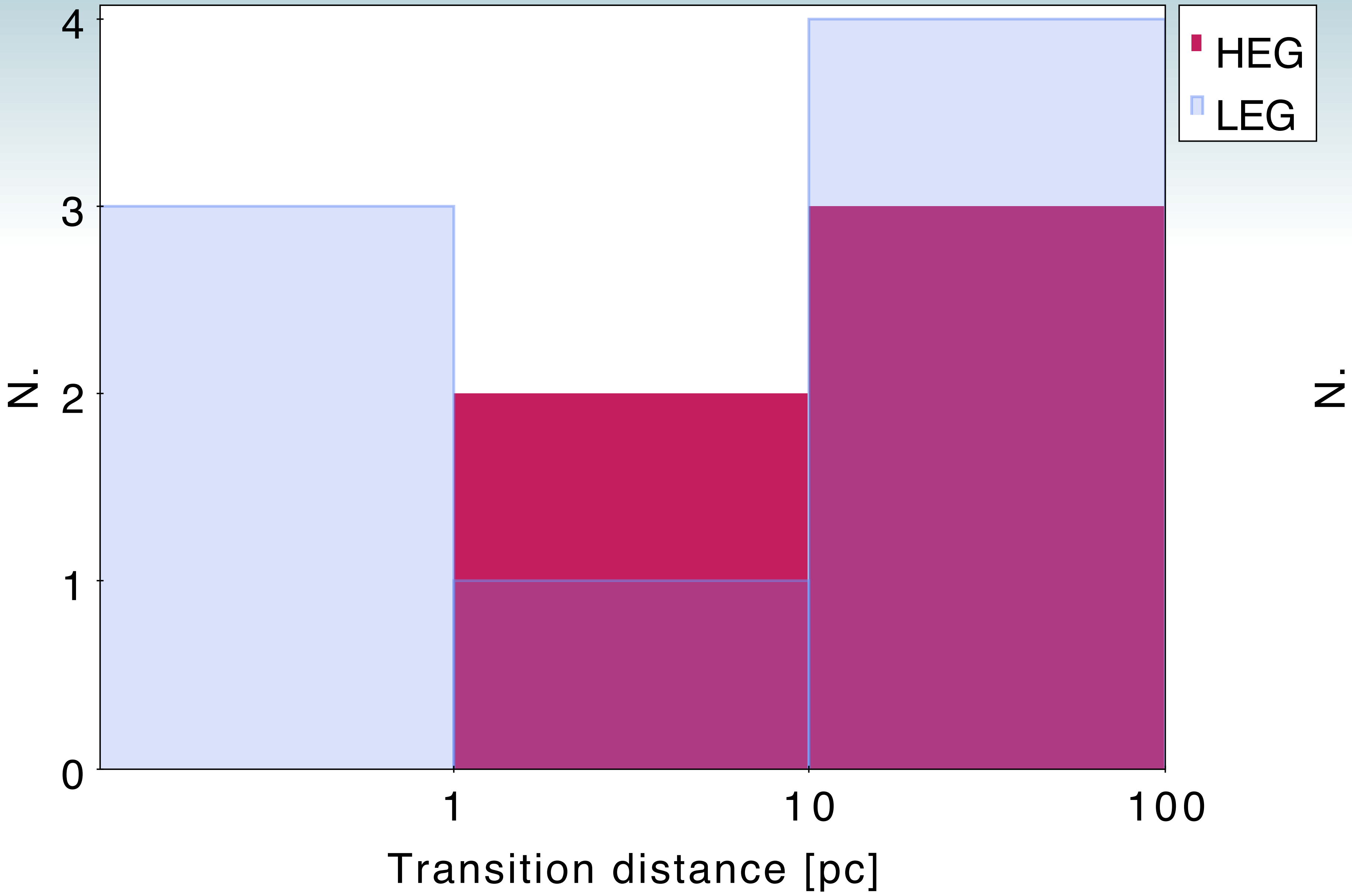
Jets in HERG are wider than jets in most LERG and in BLLacs, at the same distance from the black hole.
More extended jet sheath/disk wind?

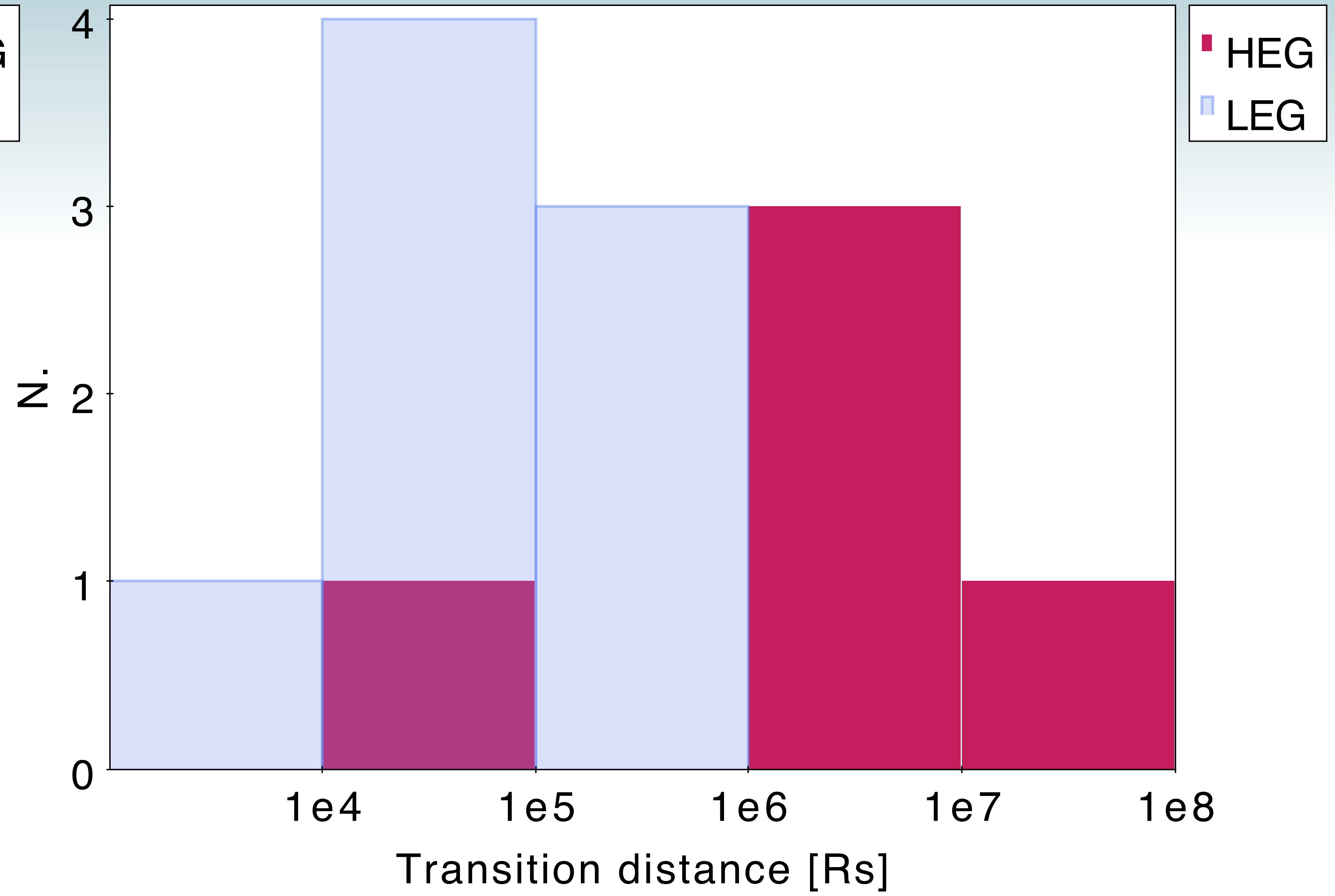
$$R_{out} > 100\, R_S$$

Extent of the jet collimation region

- Collimation distance spans a broader range than expected ($10^3 - 10^7\ R_S$).

- Collimation is completed on sub-pc scales in 3 LEG.





- Jets in HEG collimate on larger scales than jets in LEG. Separation is stronger when distance is expressed in units of R_S (KS test p-value=0.02).

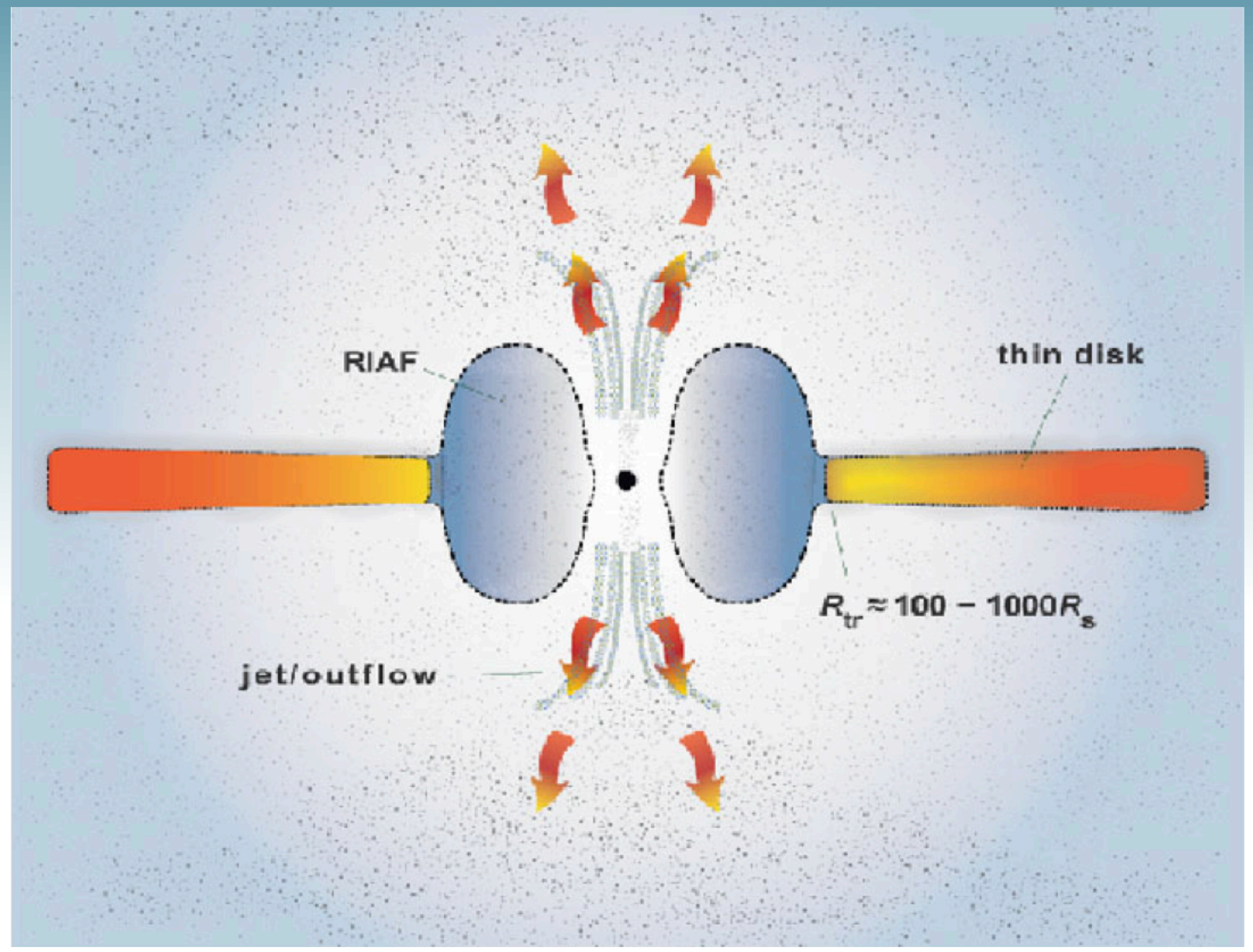
- This matches results by Potter & Cotter (2015), who suggested that FSRQs accelerate over larger scales ($> 10^5\ R_S$) w.r.t. BL Lacs.

So, what collimates jets?

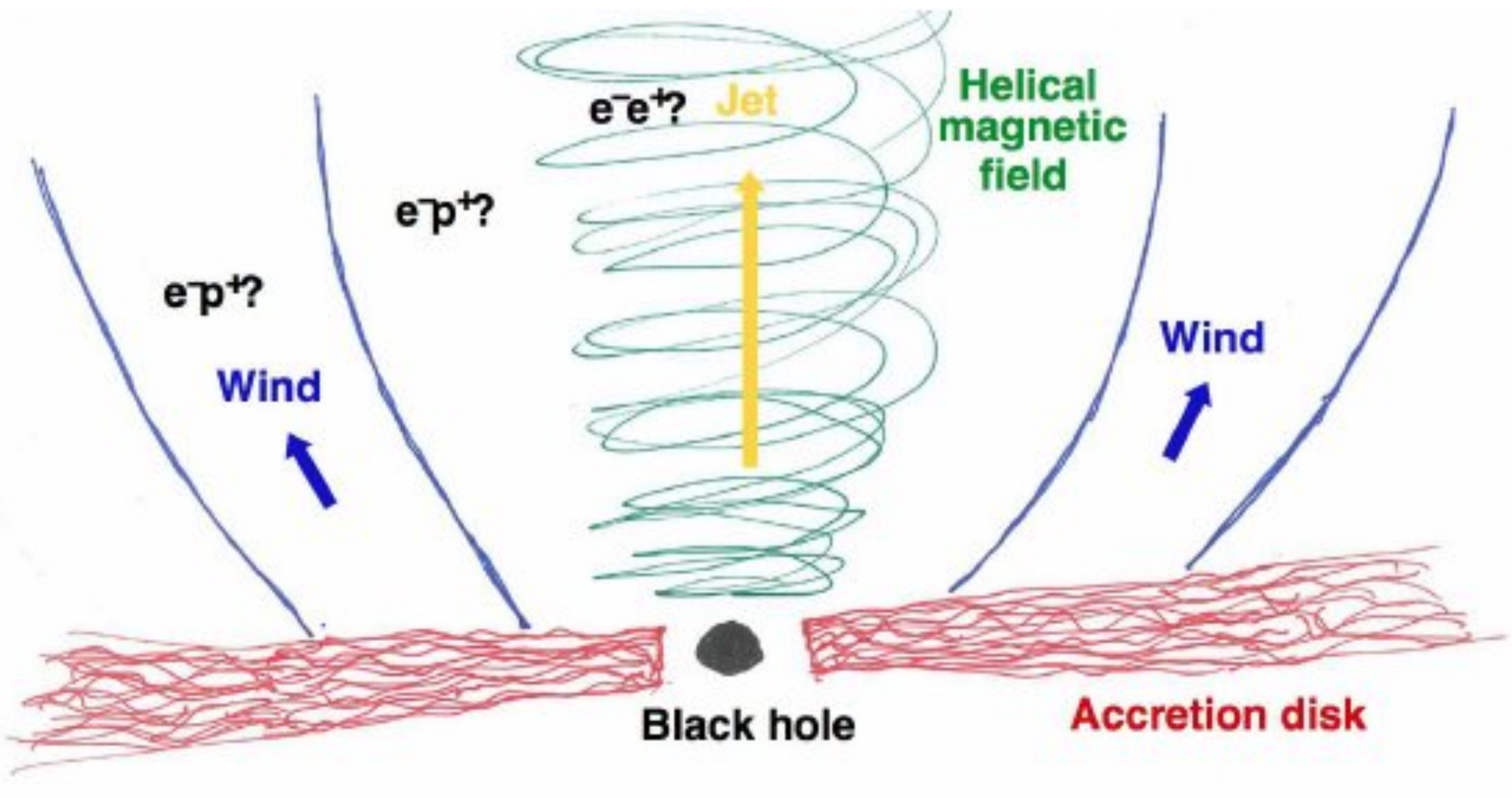
In NGC315 and other LEG in the sample where the collimation is completed on sub-parsec scales, the jet may be initially confined by a thick disk, extending to $\sim 10^3 - 10^4\, R_S$.

HEG, likely powered by classic thin disks, are suggested to collimate on larger scales, and to present more extended jet sheaths.

Collimation by disk winds?



Sketch of a hybrid accretion flow.
Credits: F. Panessa



Thin disk. Credits: I.Agudo

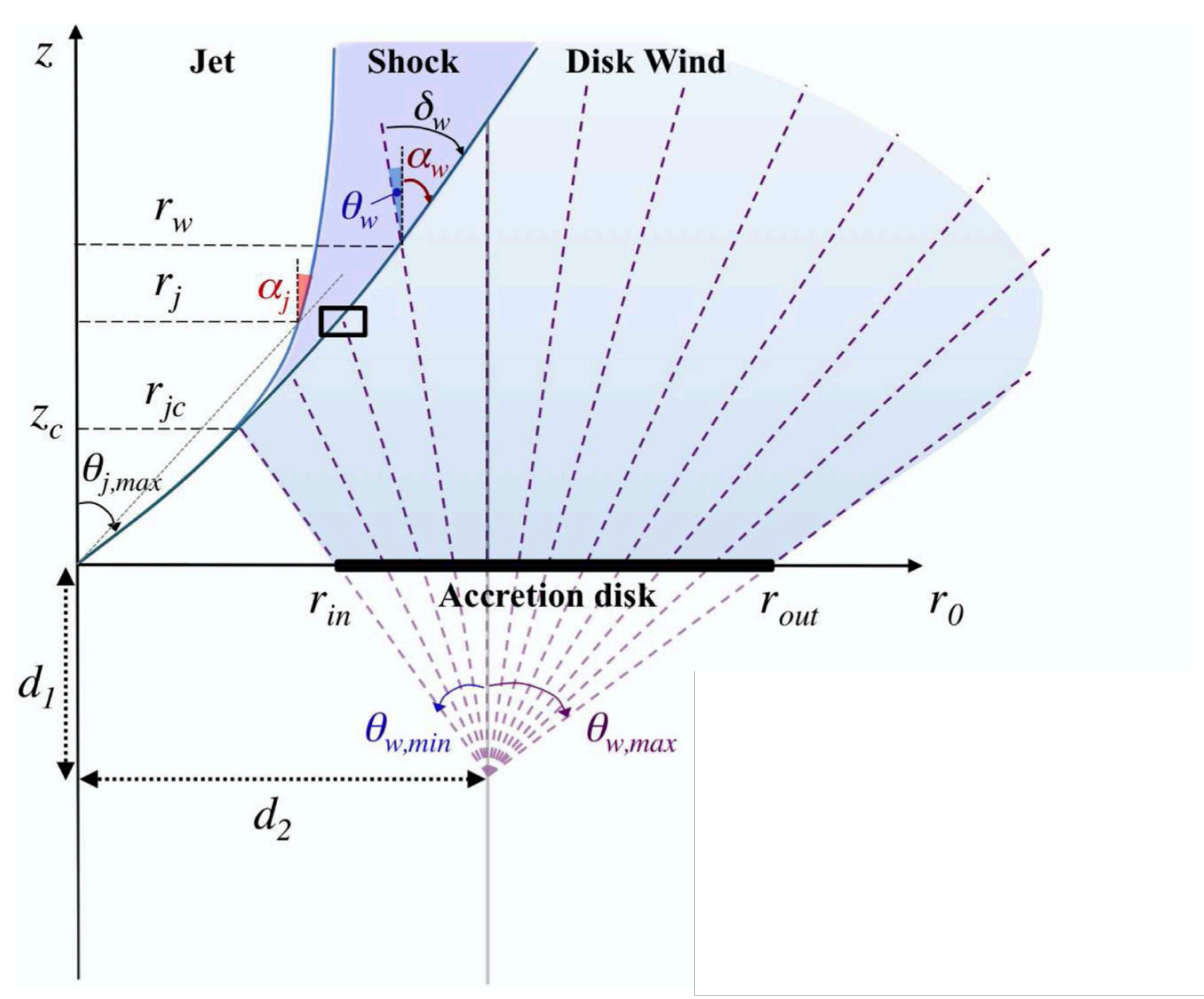
Collimation by disk winds?

Also disk winds can be characterised by a pressure gradient $p \propto z^{-2}$ (see Globus & Levinson 2016).

Collimation by disk winds is effective when $P_{\rm wind}/P_{\rm jet} > 0.1$.

For a given $P_{\rm wind}/P_{\rm jet}$, larger wind radii correspond to more extended collimation zones —> May explain what we observe in HEG.

Ultra-fast outflows, with mildly relativistic speeds and origin at $10^2 - 10^4\,R_{\rm S}$, have been detected in most of our HEG (Tombesi 2010, 2014, Reynolds 2014).

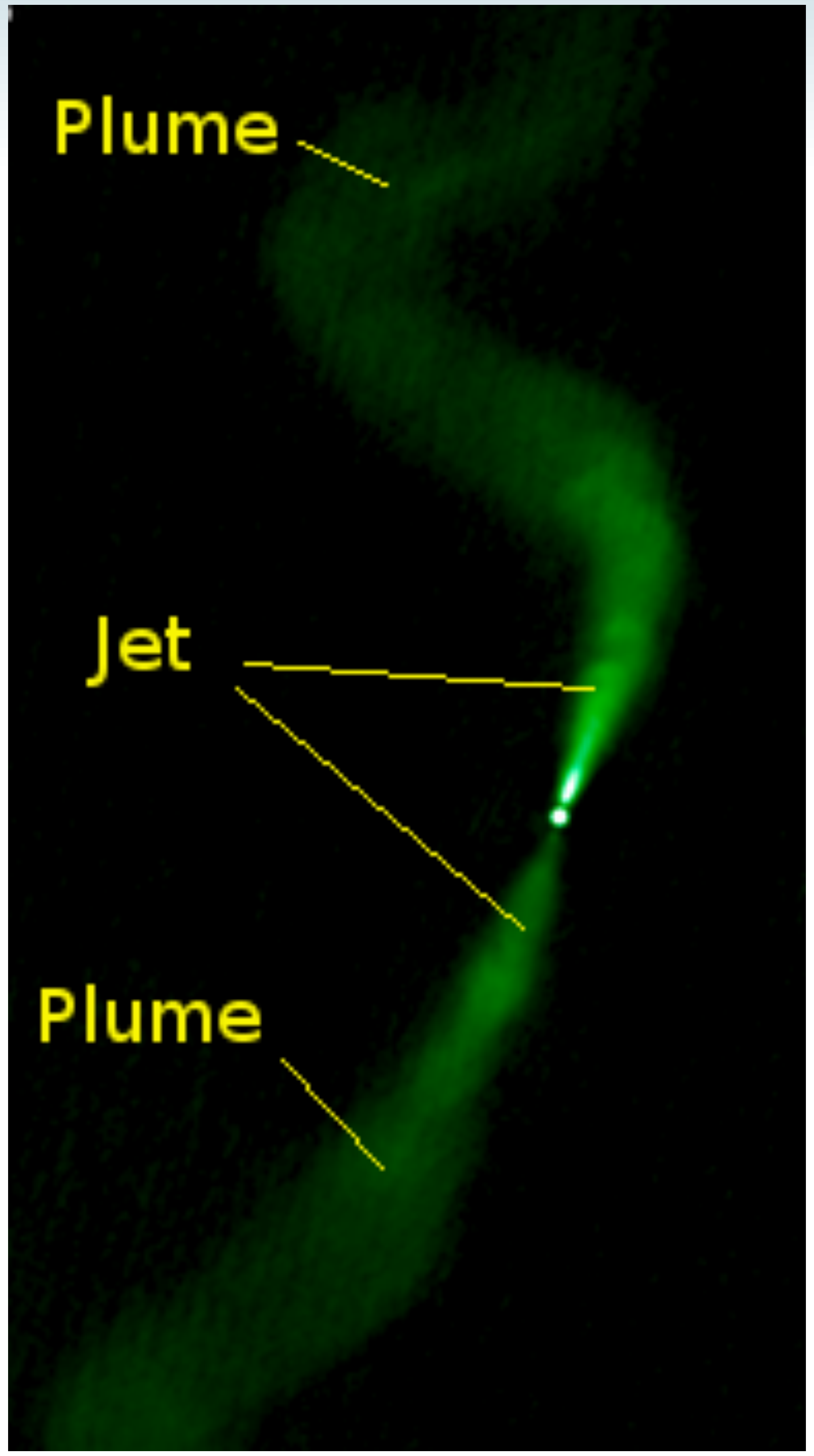


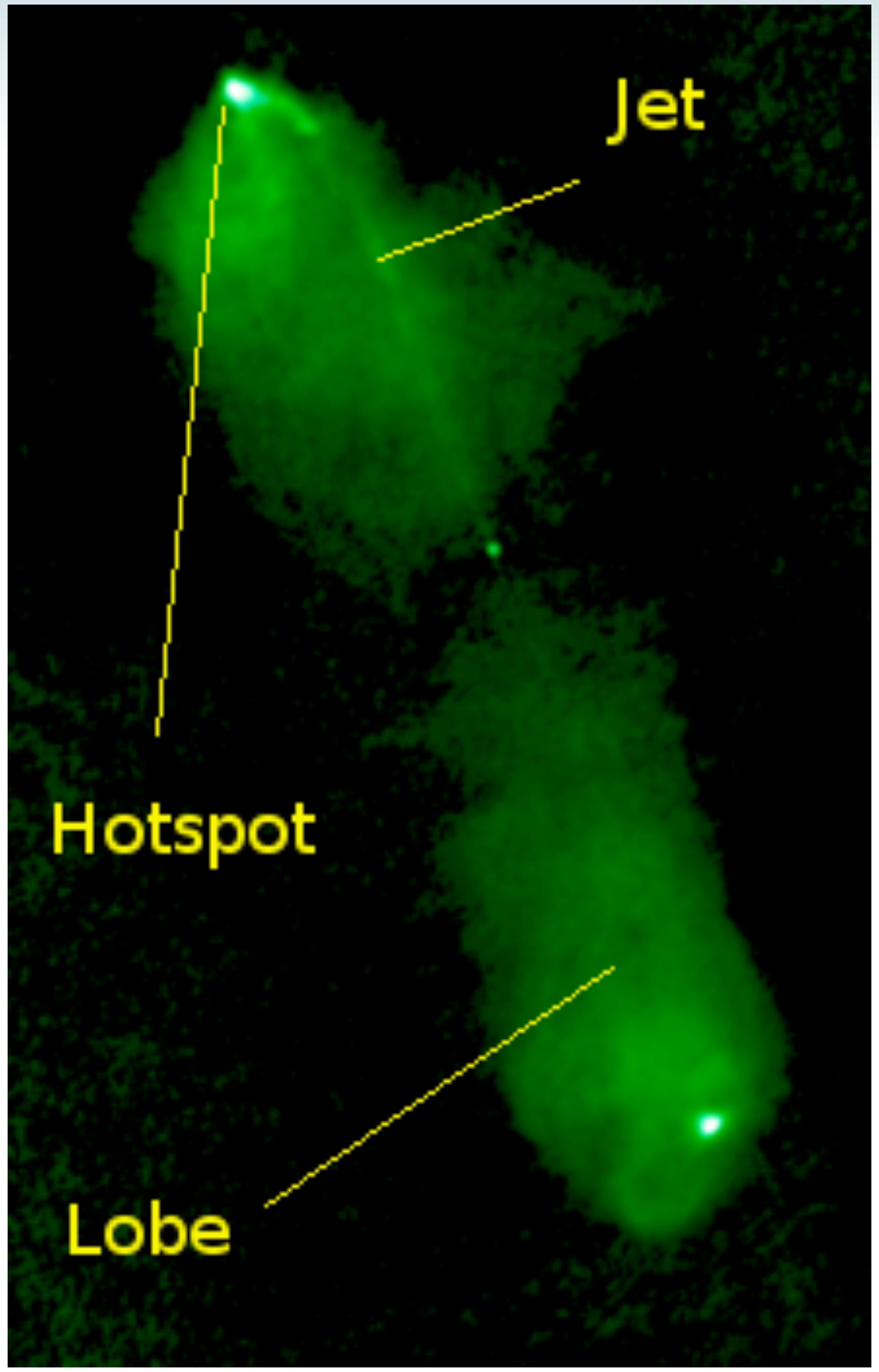
Modelling of a jet confined by a hydrodynamic wind layer (Globus & Levinson 2016).

Implications for the FRI/FRII dichotomy

A prominent wind can shield the inner spine against entrainment from the interstellar medium, enabling the jet to reach the intergalactic medium without being decelerated (e.g., Perucho 2012, 2016).

This may contribute to remarkable stability of FRII jets.

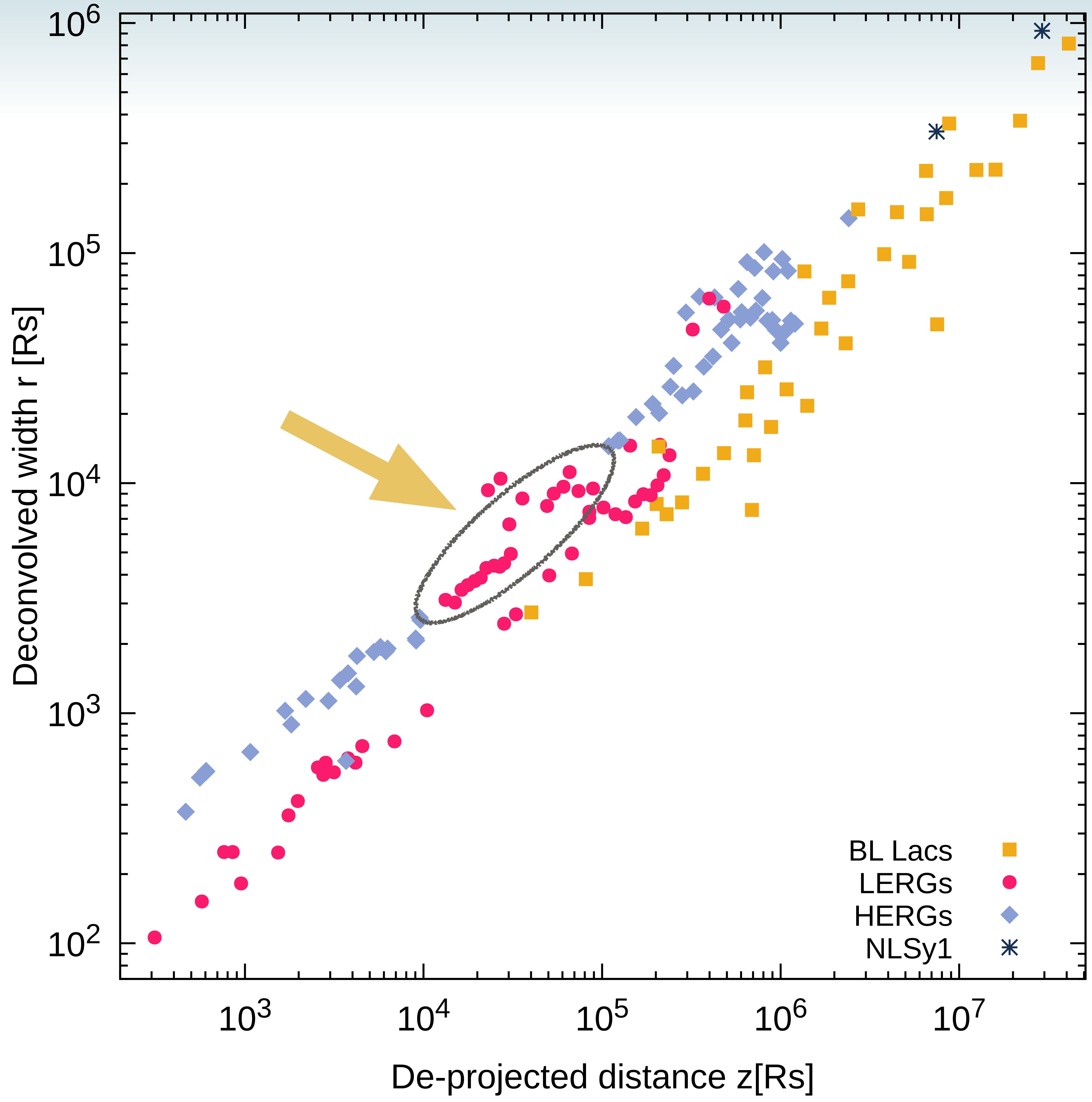




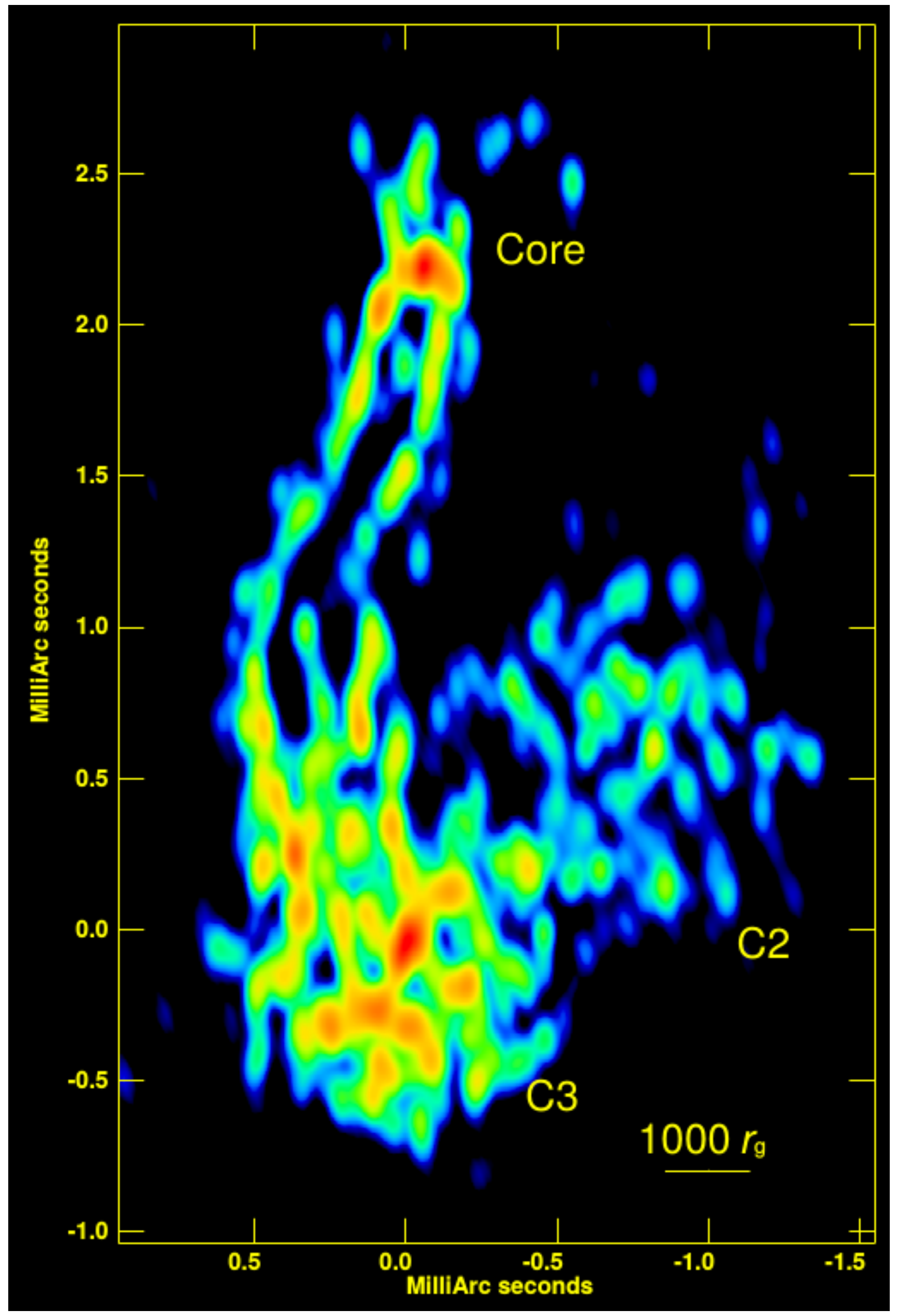
Credits: M. Hardcastle

Two outliers…

Two sources classified as low-excitation lie on the high-excitation track. These are the GPS **NGC1052** and the recently re-activated **3C84**!



Both powered by atypical low-luminosity nuclei, possible evidence for jet over-collimation (~cylindrical jet base, Nakahara et al. 2020, Giovannini et al. 2018).



RadioAstron image of 3C84

Summary

First results from HSA data reveal new sources suitable for jet formation studies.

In NGC315 we observe a transition from parabolic to conical shape on sub-parsec scales.
This jet may be confined by a thick disk extending to $10^3 - 10^4 R_S$.

Low-excitation sources like NGC315 typically have narrow jets whose expansion profiles are well aligned with those observed in BL Lacs. Jet origin in the innermost accretion disk/ergosphere?

High-excitation sources have wider jets at the same distance from the black hole, suggesting that the jet sheath is more extended. Outer regions of the disk contributing to jet launching?

The extent of the collimation region spans a broader range than previously thought ($10^3 - 10^7 R_S$).

The jet collimation region is more extended in jets from high-excitation sources. This may match expectations for jets confined by disk winds.