Prospect of Polarization Observations of M87 with the EHT

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Jet Collimation and Acceleration in the Giant Radio Galaxy NGC 315

Jongho Park (ASIAA, EACOA)

Prospect of Polarization Observations of M87 with the EHT

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Jet Collimation and Acceleration in the Giant Radio Galaxy NGC 315

Jongho Park on behalf of the EHT collaboration

Are AGN jets launched by strong, dynamically important magnetic fields?

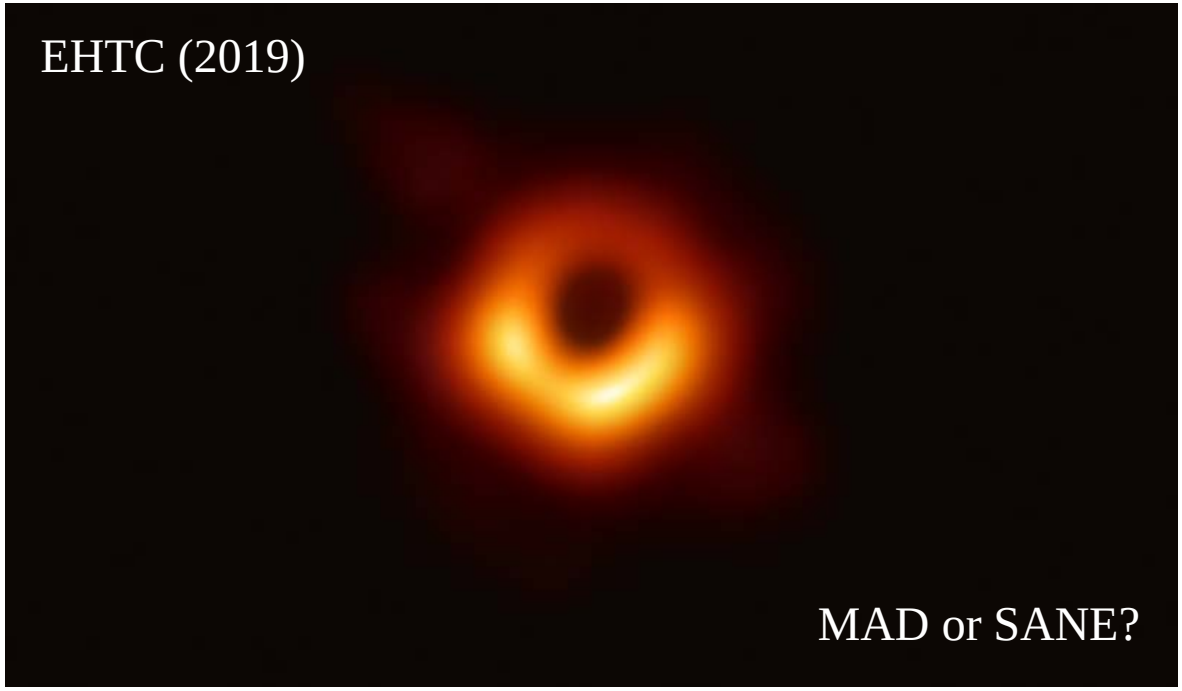

Table 2
Rejection Table

Flux[a]	a_*[b]	R_{high}[c]	AIS[d]	ϵ[e]	L_X[f]	P_{jet}[g]	
SANE	−0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	−0.94	10	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	20	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	40	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	80	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	−0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	−0.5	10	Pass	Pass	Fail	Fail	Fail
MAD	+0.5	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	160	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	80	Pass	Pass	Pass	Pass	Pass
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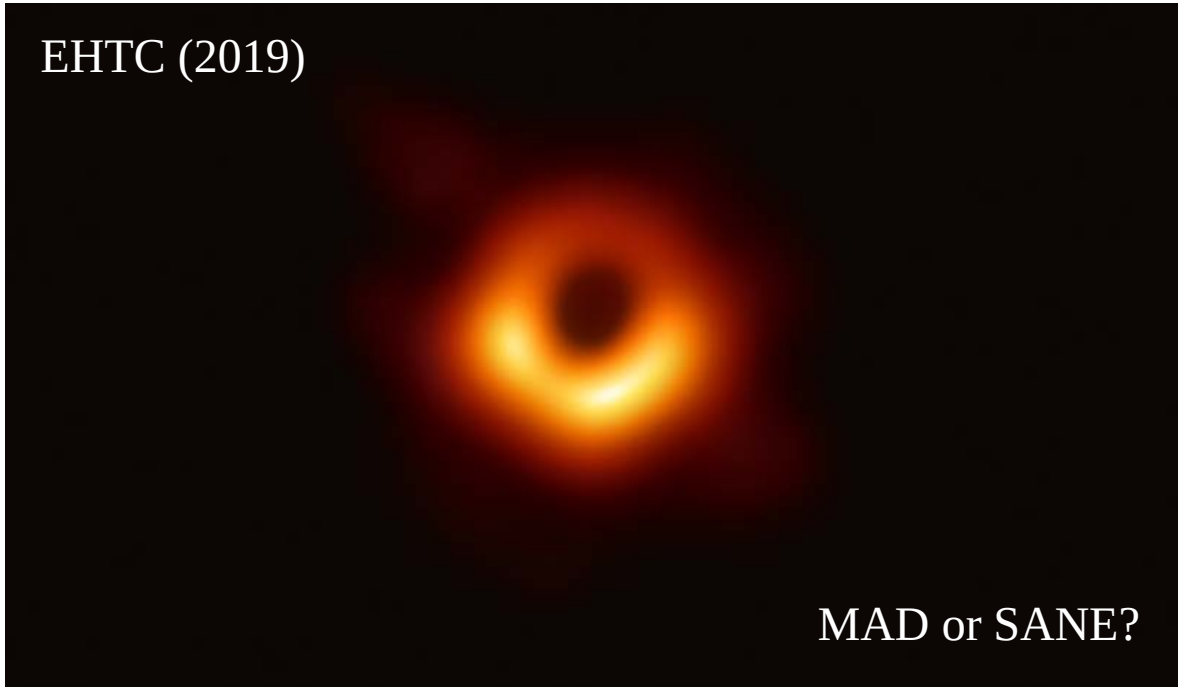
Are AGN jets launched by strong, dynamically important magnetic fields?



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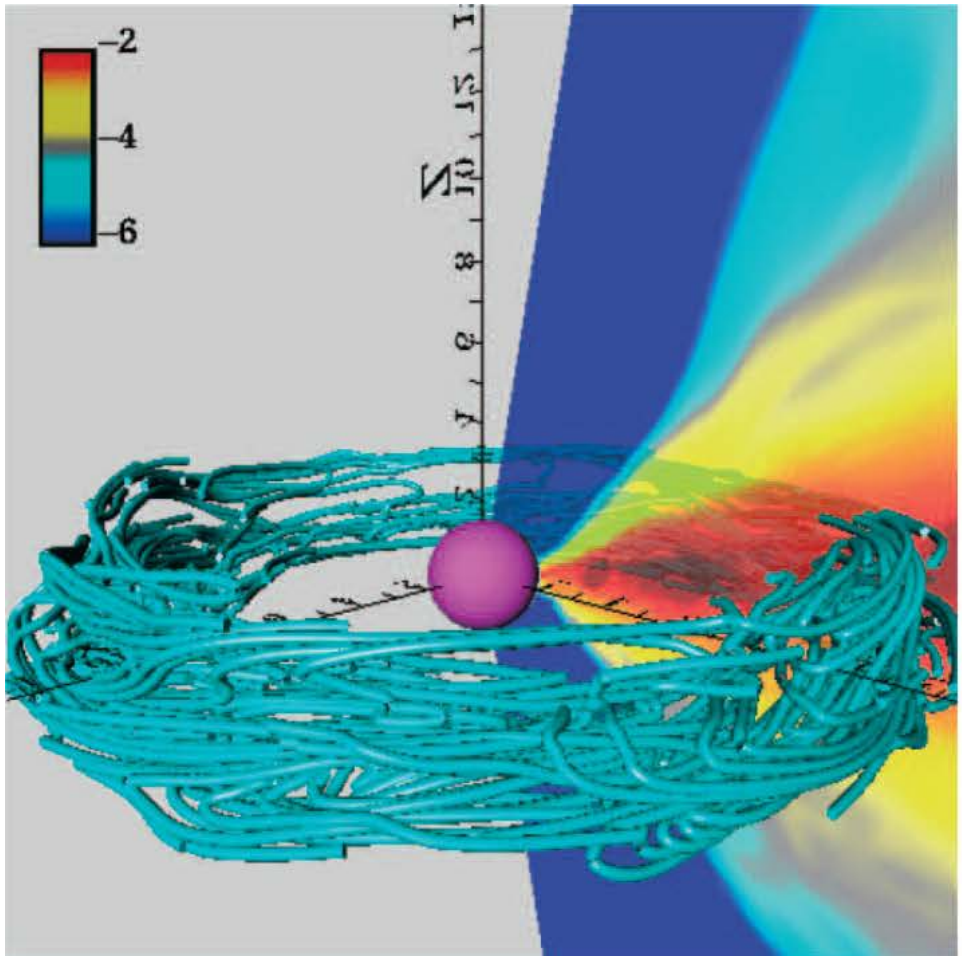
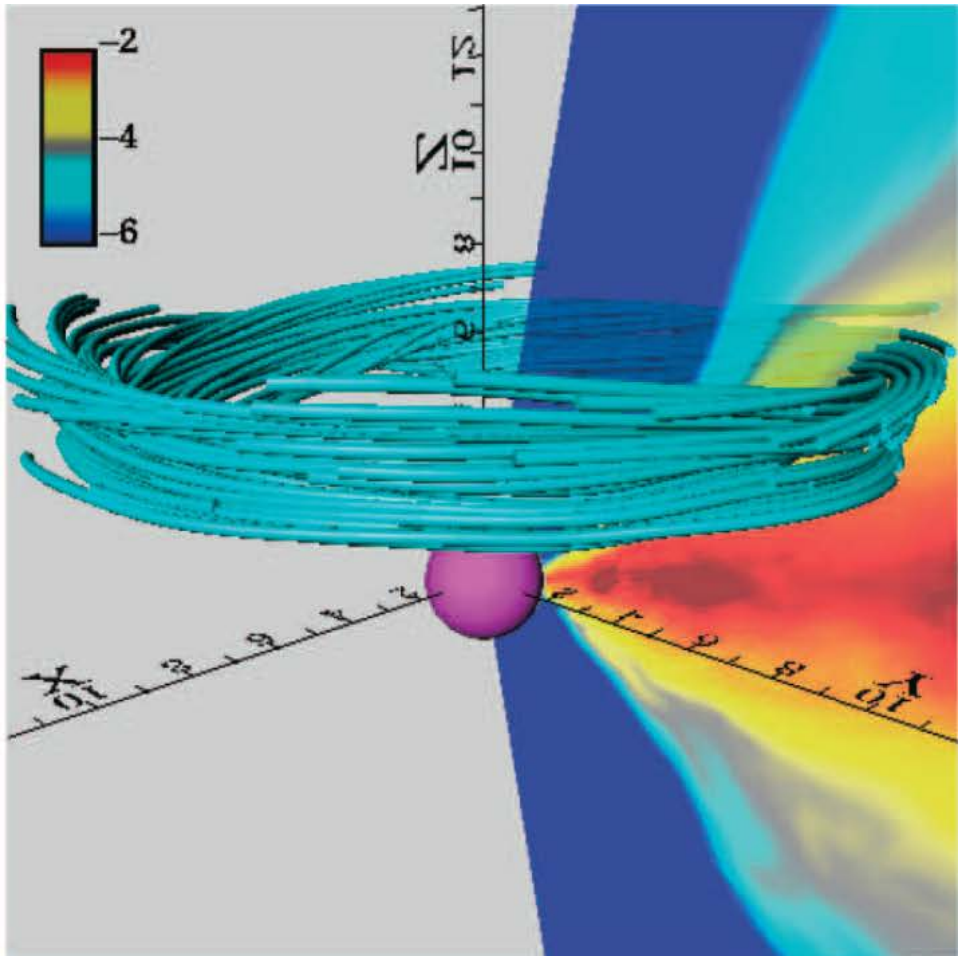
MAD	+0.94	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	160	Pass	Pass	Pass	Pass	Pass

Are AGN jets launched by strong, dynamically important magnetic fields?

Standard and Normal Evolution Disk (SANE)

Hirose+ (2004)



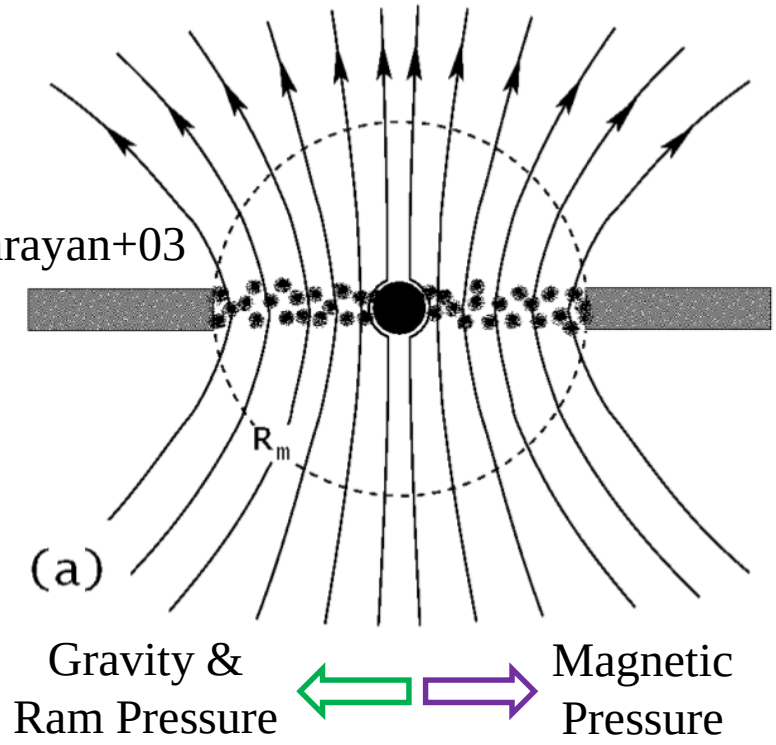


Accretion Flow Region

Corona/Wind Region

Are AGN jets launched by strong, dynamically important magnetic fields?

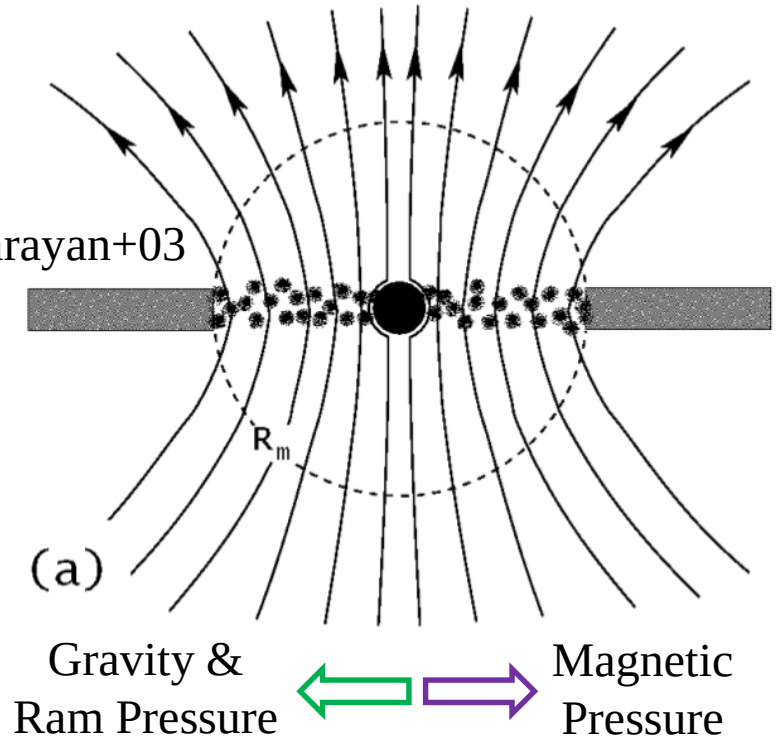
Magnetically Arrested Disk (MAD)



Gas Accretion → Poloidal B fields advected
→ Accretion Halted due to the strong B pressure
→ MAD!

Are AGN jets launched by strong, dynamically important magnetic fields?

Magnetically Arrested Disk (MAD)



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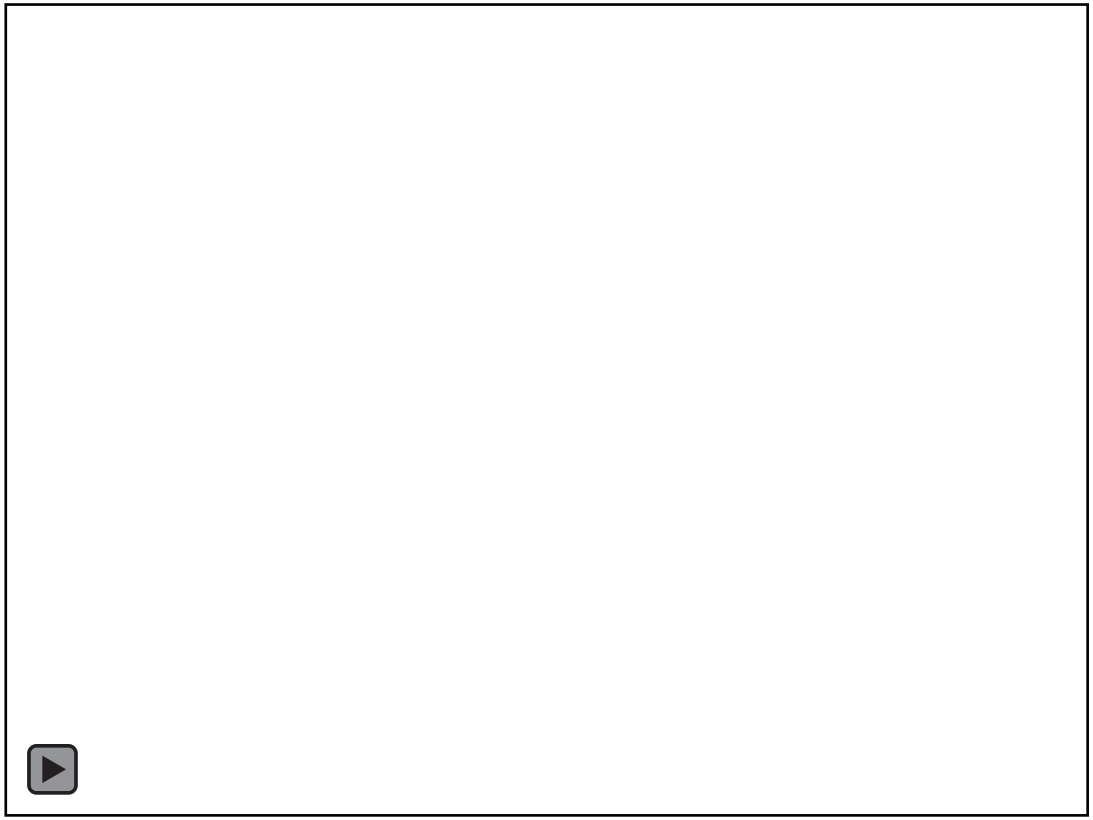
→ MAD!

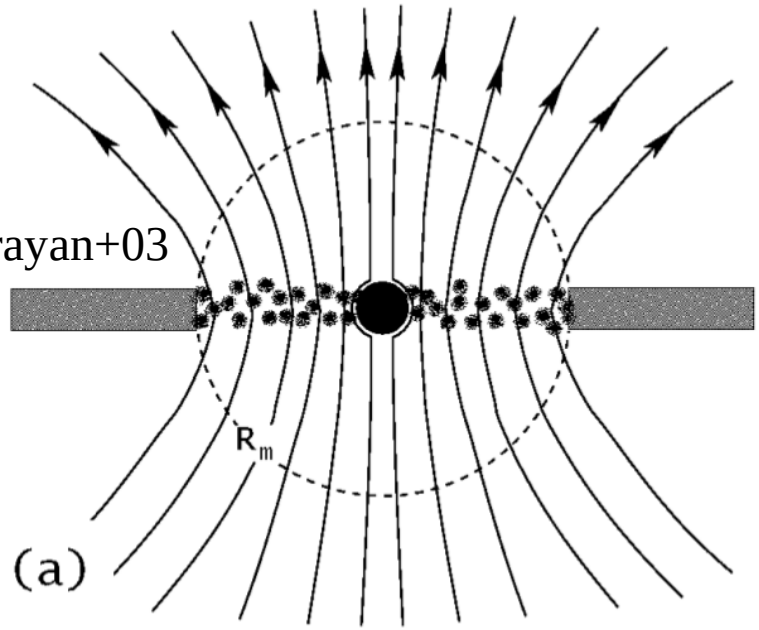
Tchekhovskoy et al. (2011)



MAD : strong jets easily launched

Are AGN jets launched by strong, dynamically important magnetic fields?

Magnetically Arrested Disk (MAD)



Gas Accretion → Poloidal B fields advected
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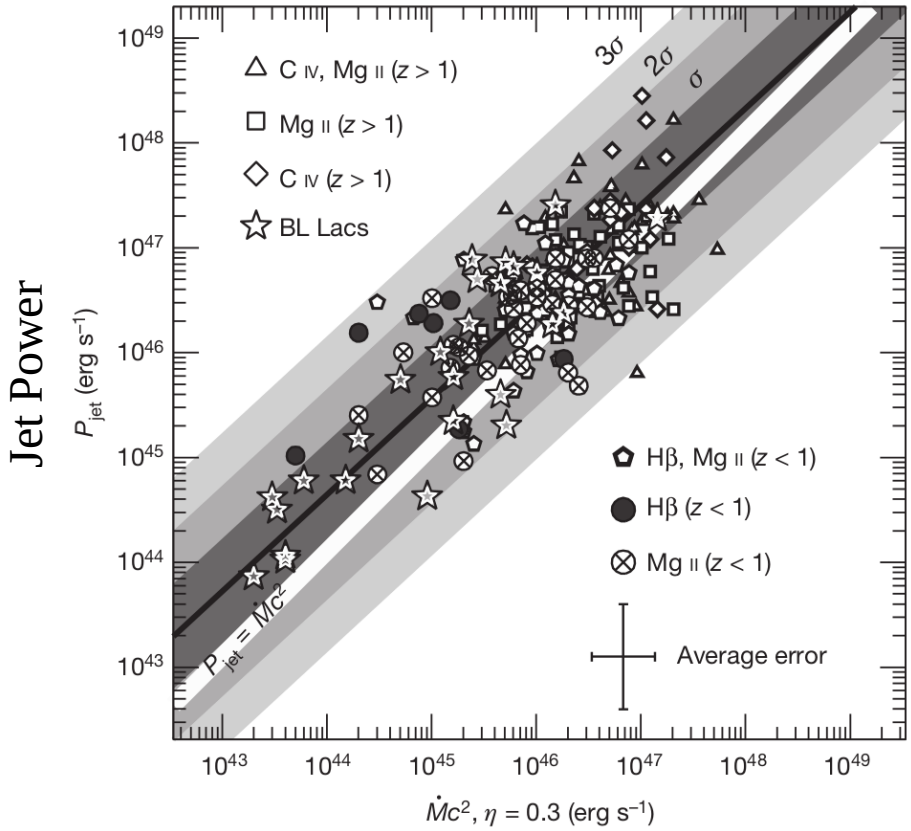
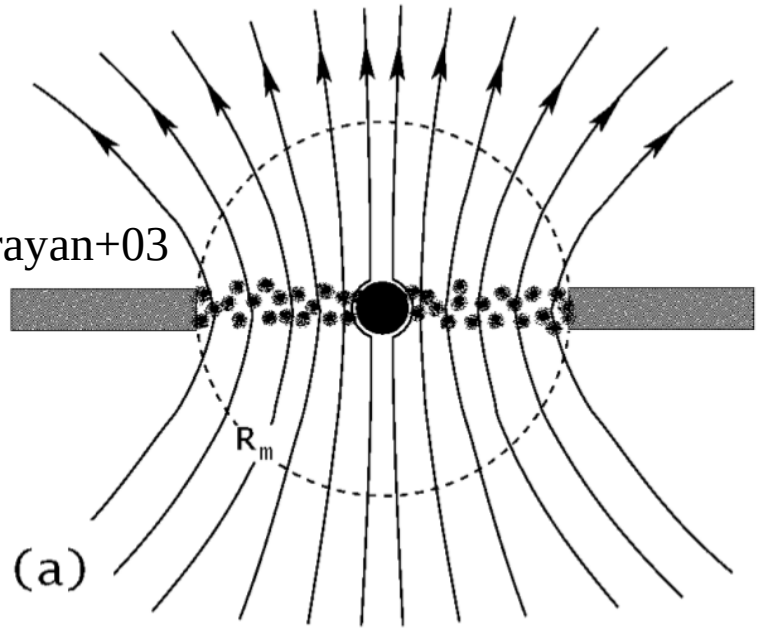
Ghisellini+ (2014)



Output Jet Power >~ Input Accretion Power
→ Only possible when MAD in action.
(But jet power is model-dependent,
e.g., conical jet, spherical geo., leptonic, ...)

Are AGN jets launched by strong, dynamically important magnetic fields?

Magnetically Arrested Disk (MAD)



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→ Accretion Halted due to the strong B pressure
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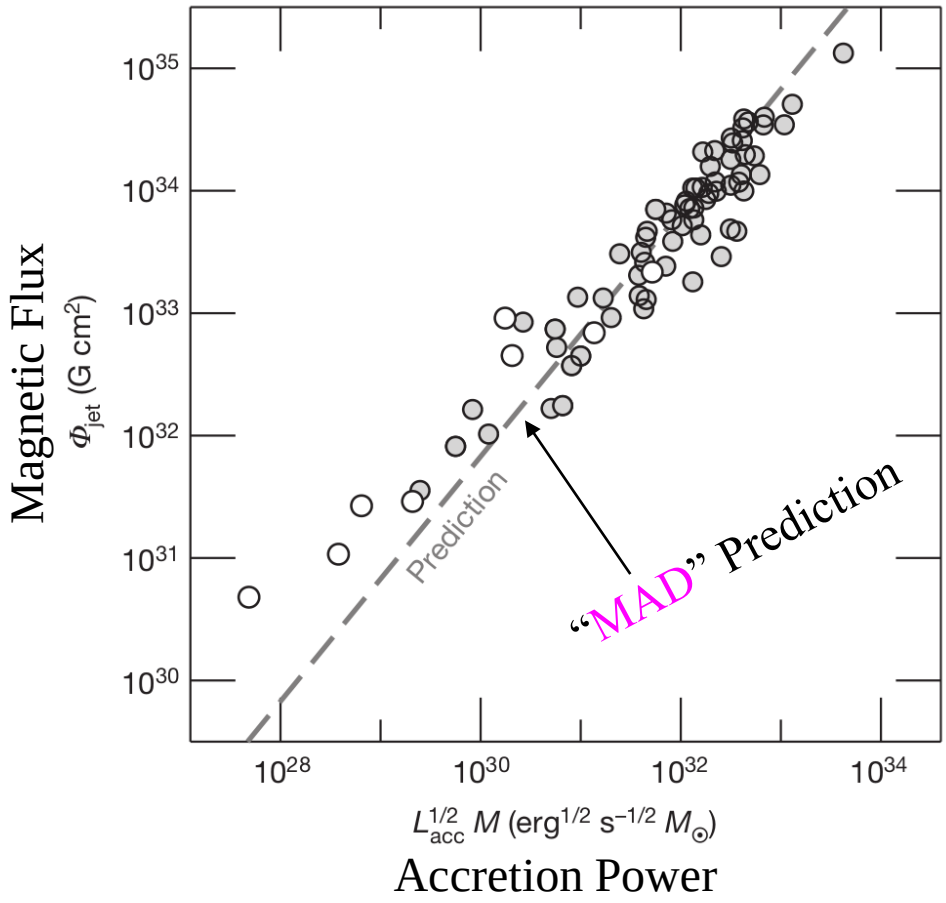
Zamaninasab+ (2014)



Observed B field strength is consistent with the MAD prediction

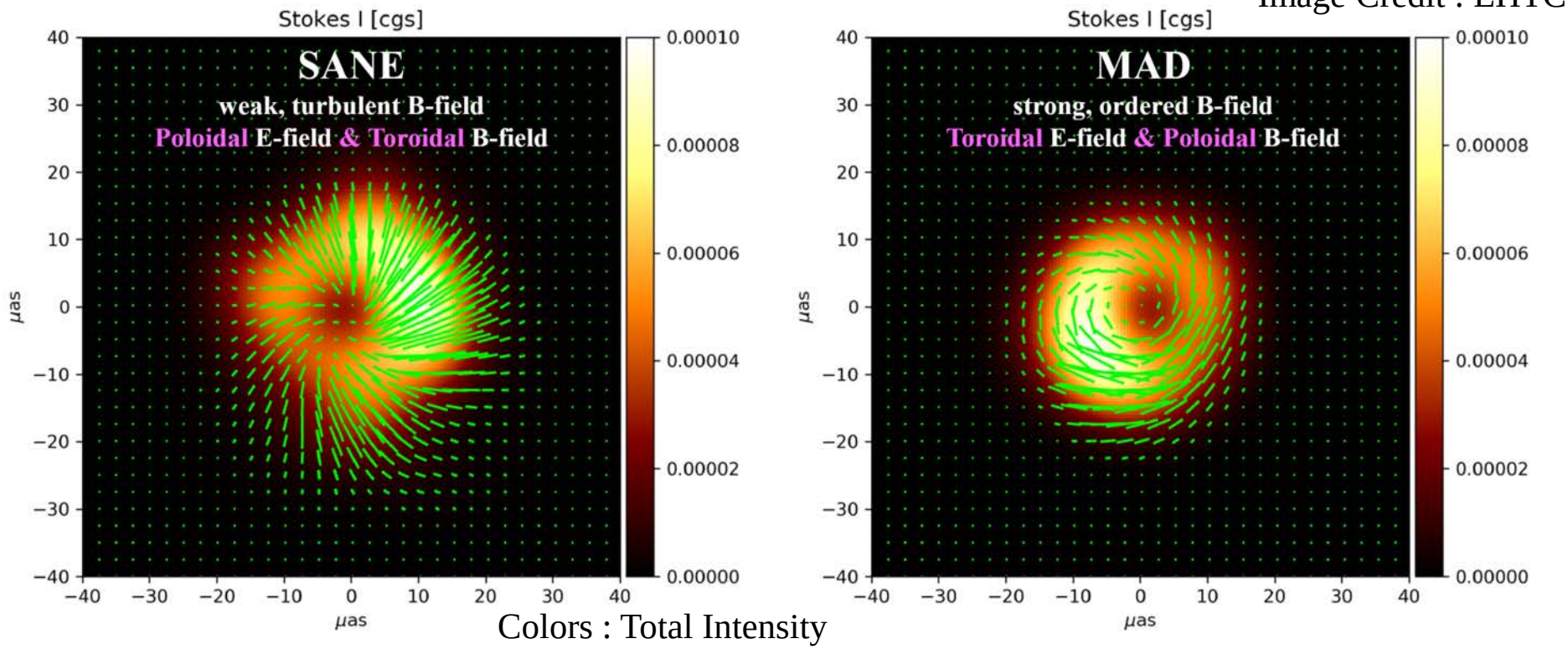
(But the B field flux is model-dependent, e.g., conical jet, constant speed, ...)

Prospect of Polarization Observations of M87 with the EHT

Are AGN jets launched by strong, dynamically important magnetic fields?

GRMHD Simulations

Image Credit : EHTC



Colors : Total Intensity

Green sticks : Polarization Angle

EHT Polarization results of M87 will be very powerful for constraining models (will be coming out soon).

Prospect of Polarization Observations of M87 with the EHT

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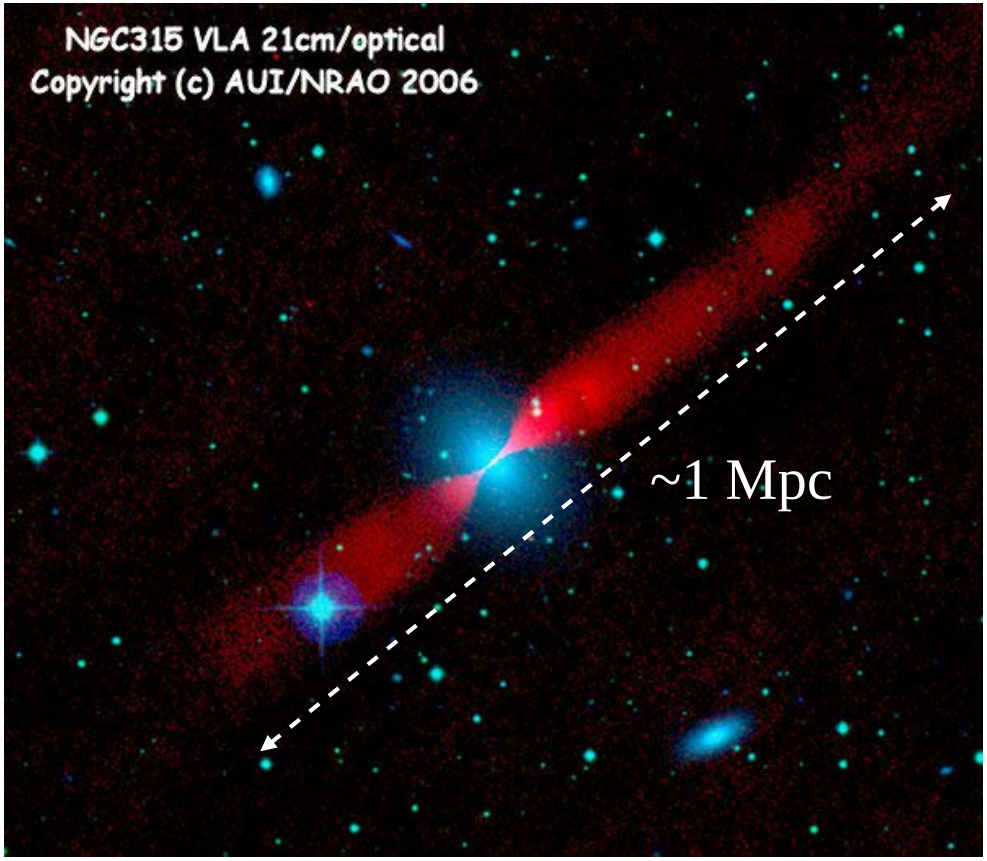
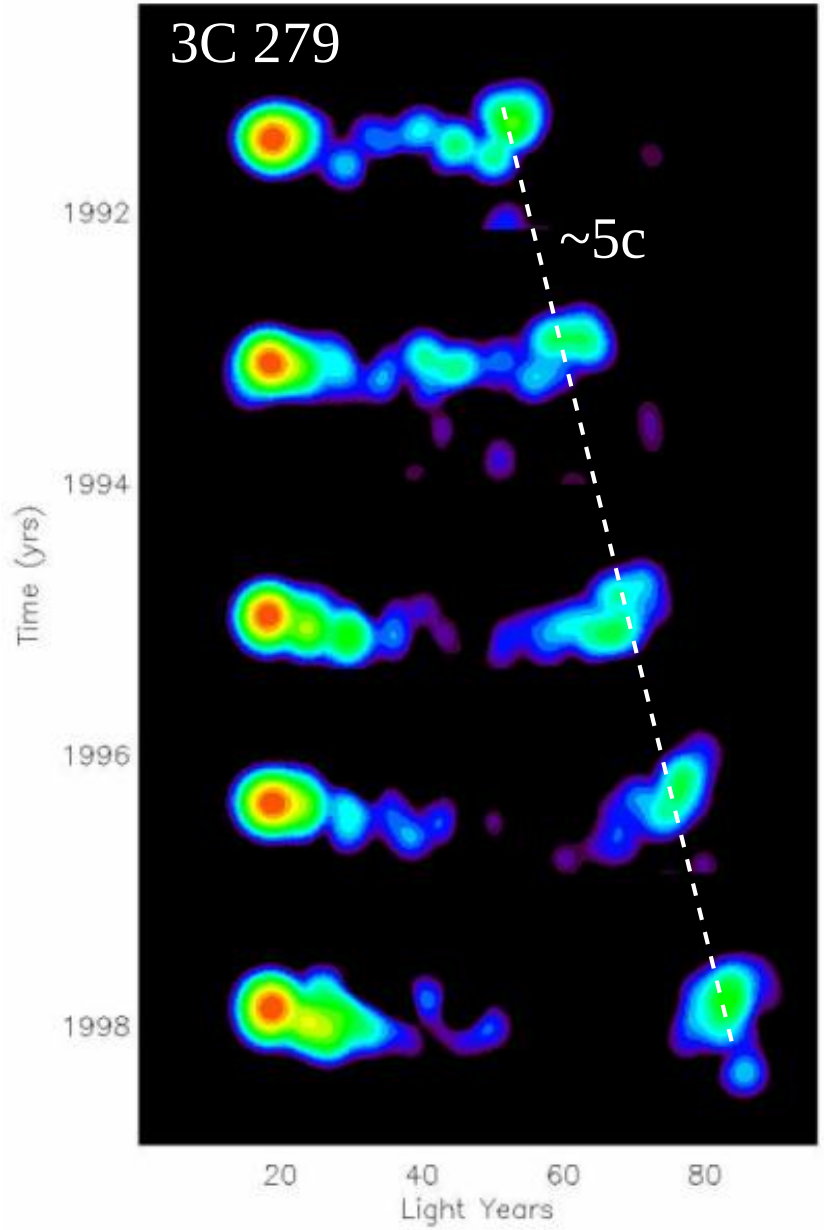
Jet Collimation and Acceleration in the Giant Radio Galaxy NGC 315

Jongho Park, Kazuhiro Hada, Masanori Nakamura, Keiichi Asada, Guang-Yao Zhao, & Motoki Kino

Highly Collimated and Relativistic Jets of AGNs



Highly collimated, very narrow jets

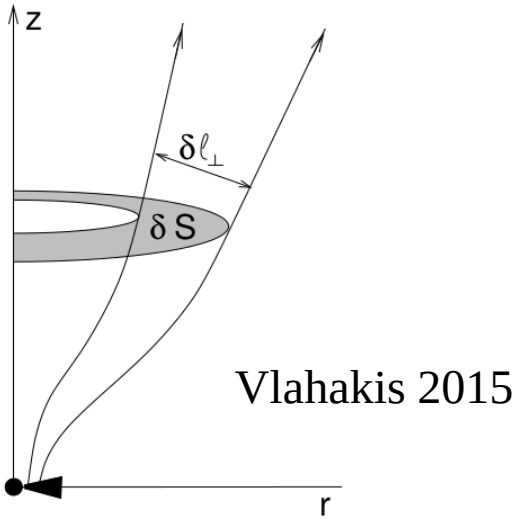


Superluminal motions

Magnetic Jet Acceleration Model

$$\text{Total Energy Flux} \approx \text{Poynting Flux} + \text{Kinetic Energy Flux}$$

(Conserved) ↓ (when decrease) ↑ (increase)



Vlahakis 2015

"Poynting Flux Conversion"

(Jet acceleration through the magneto-centrifugal force or magnetic pressure gradients)

A critical condition for efficient Poynting flux conversion (jet acceleration)

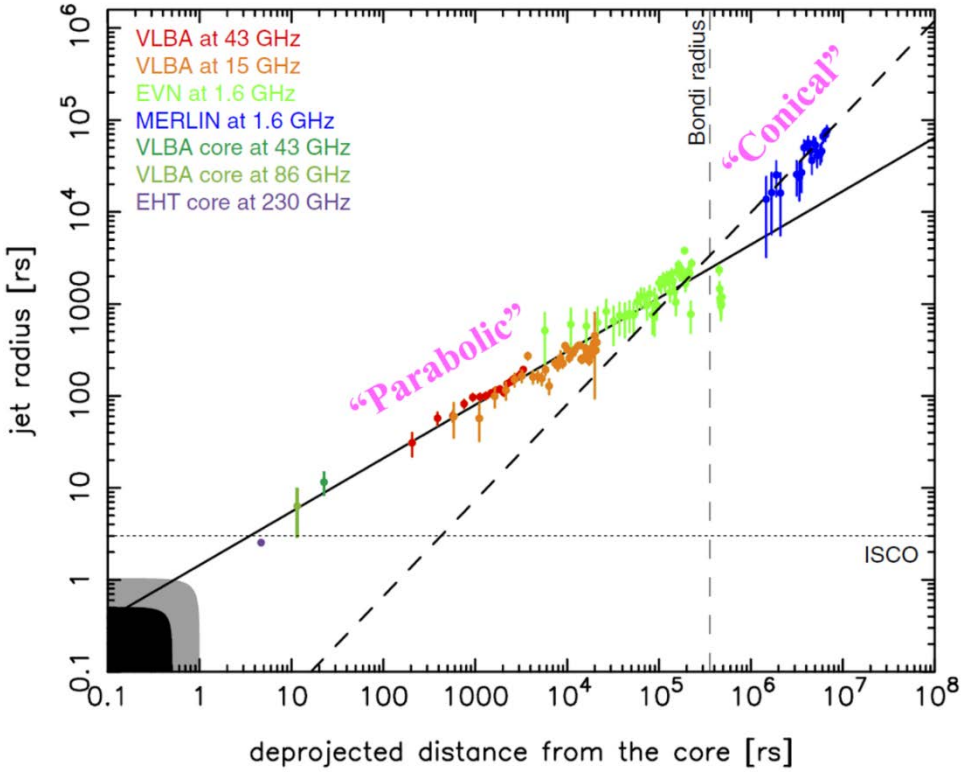
→ **Jet must be gradually collimated*** (opening angle becoming smaller at larger distances).

→ Jet collimation & acceleration occur simultaneously.

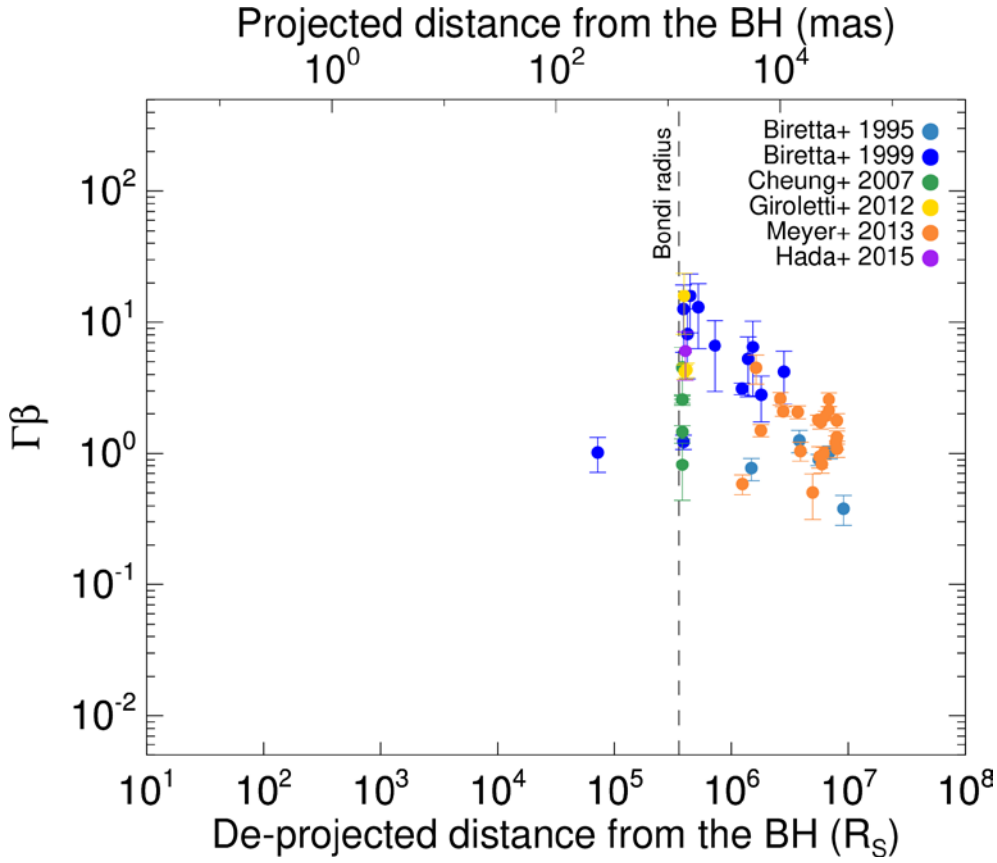
(*More specifically, *differential collimation of poloidal field lines*)

Jet Collimation and Acceleration in M87

Jet Collimation ⟷ Jet Acceleration



Asada & Nakamura (2012)



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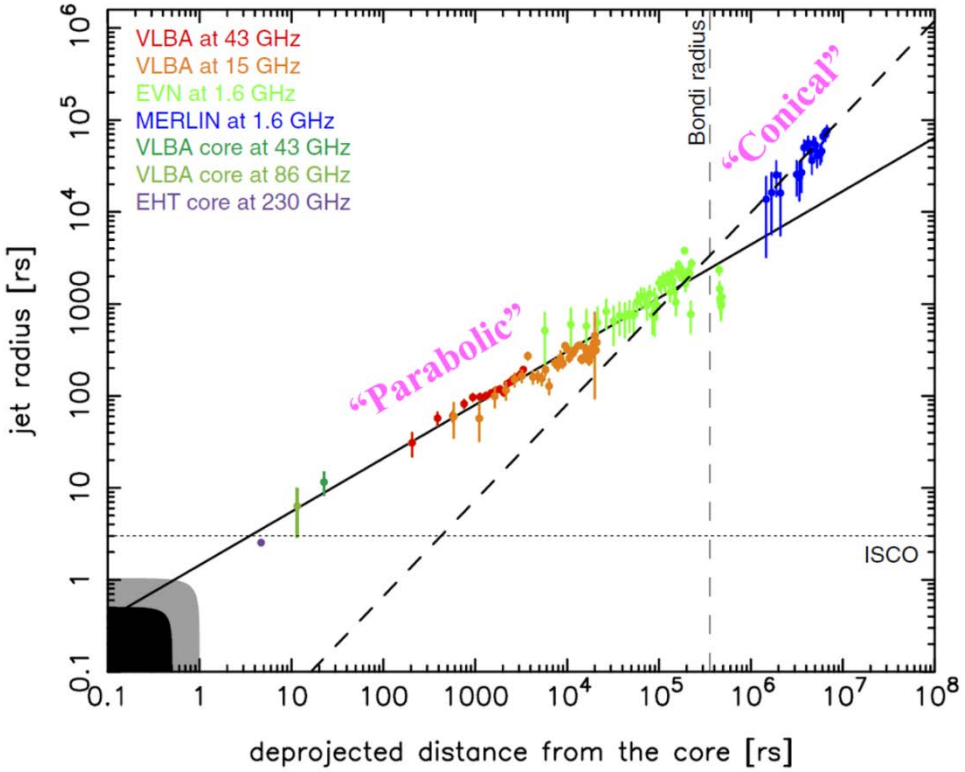

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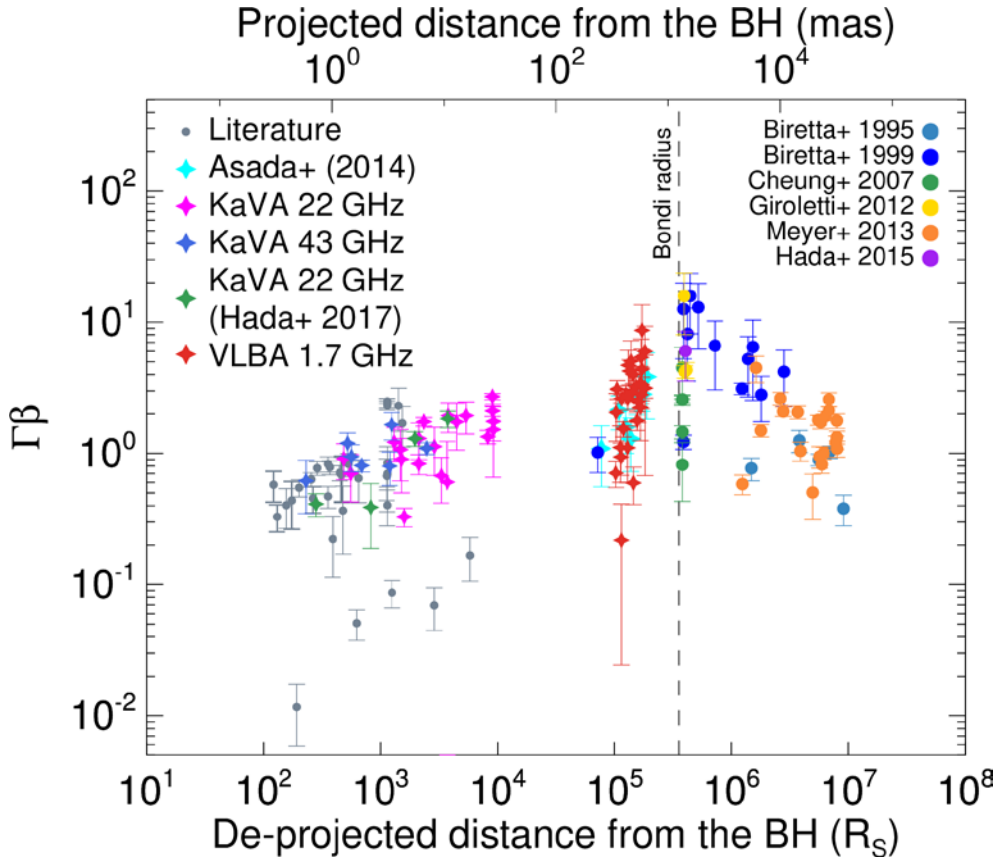

Park, Hada, Kino, Nakamura+ (2019)

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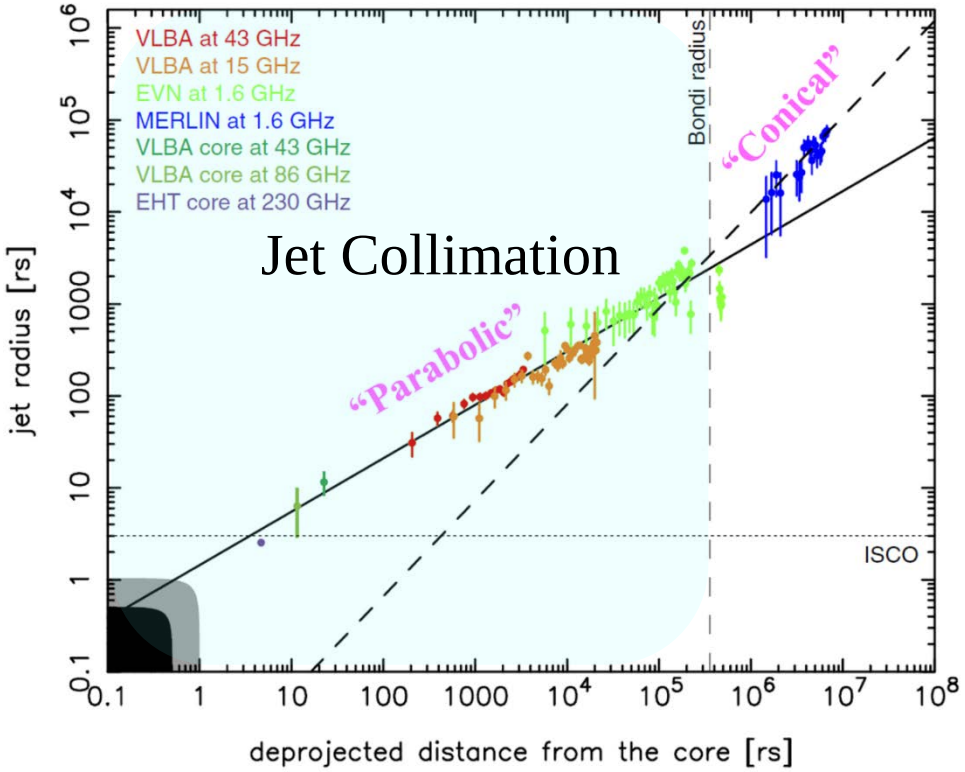

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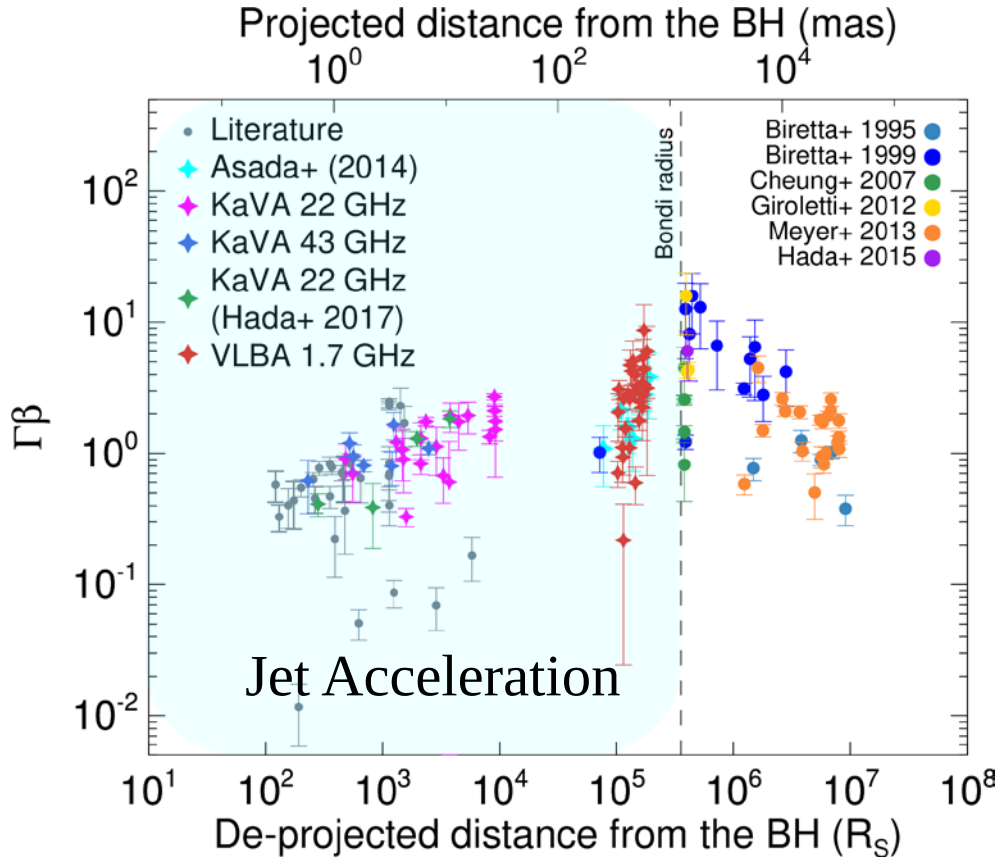

Park, Hada, Kino, Nakamura+ (2019)

We studied jet acceleration of M87 with KaVA and VLBA data and our results suggest a **GRADUAL JET ACCELERATION IN THE SAME REGION AS THE COLLIMATION ZONE.**
→ **SUPPORTS THE MAGNETIC JET ACCELERATION MODEL.**

Jet Collimation and Acceleration in M87

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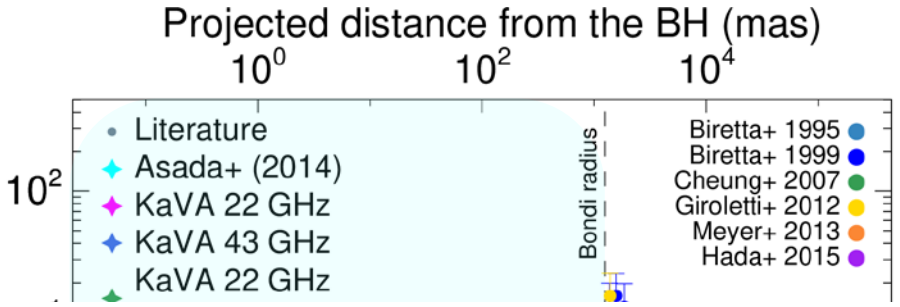
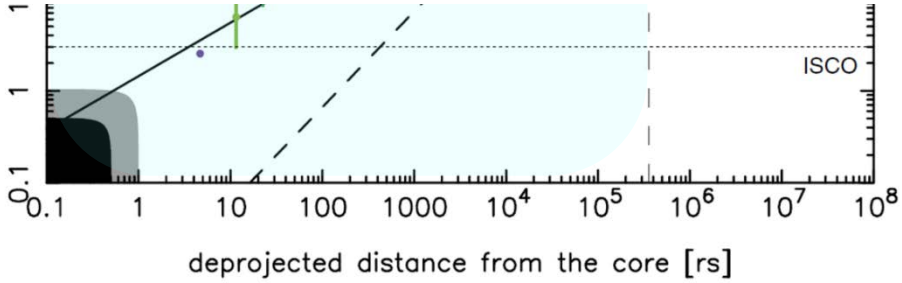


Are there **"the jet acceleration and collimation zones (ACZs)"** in all AGN Jets?



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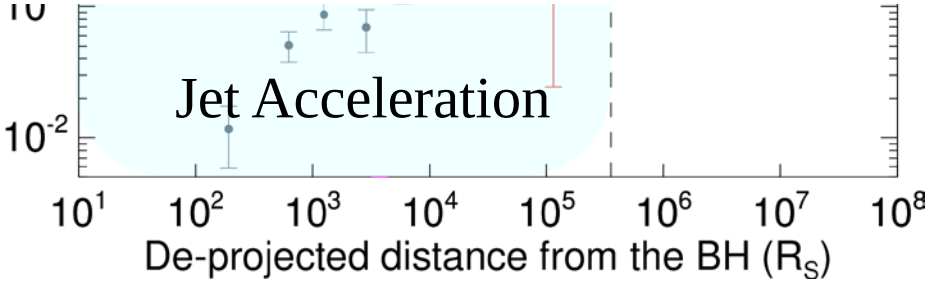

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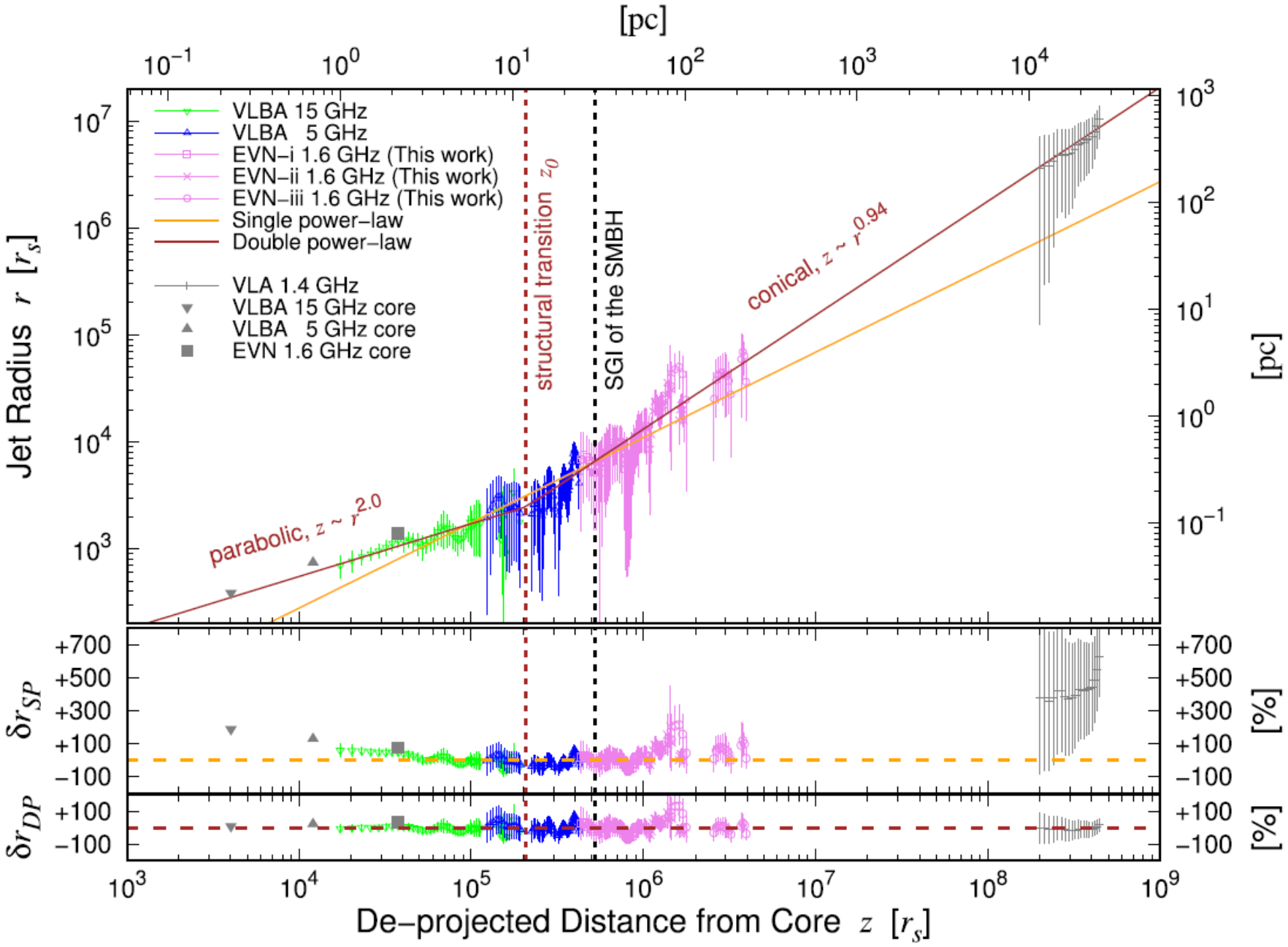
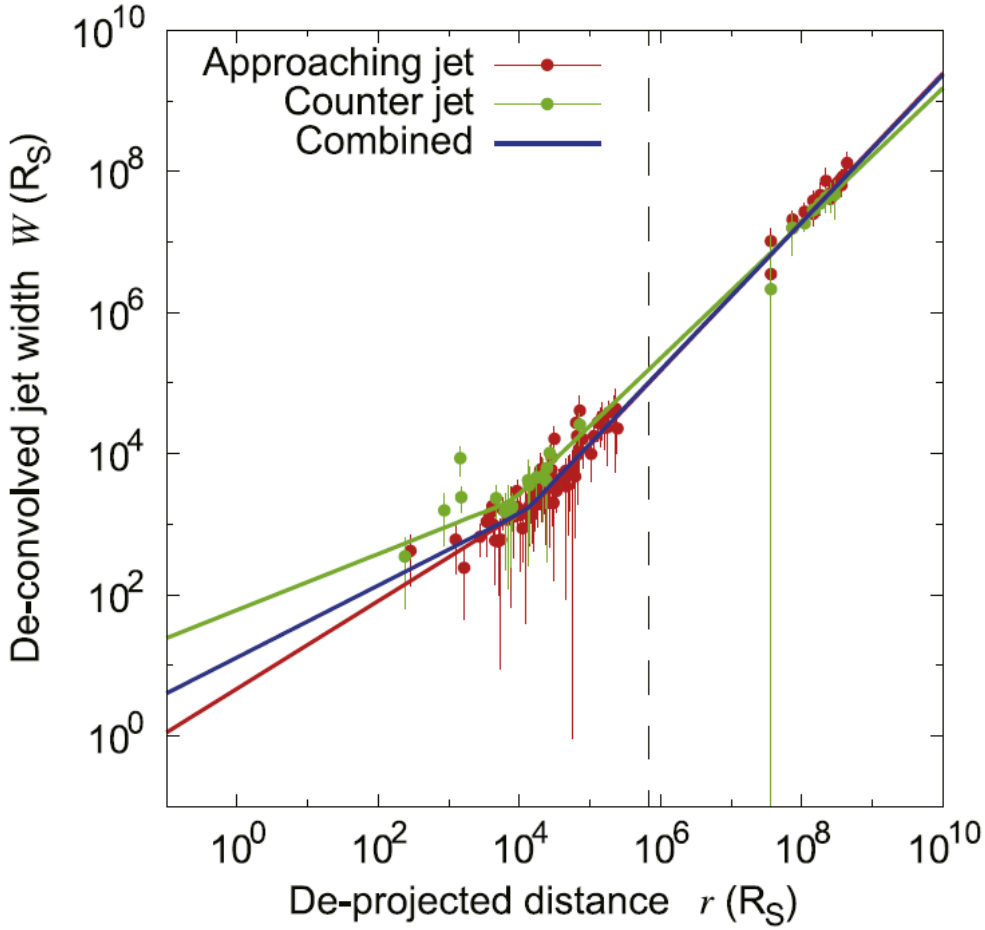
“Jet Collimation Break” in AGNs

NGC 6251, Tseng, Asada, Nakamura+ 2016

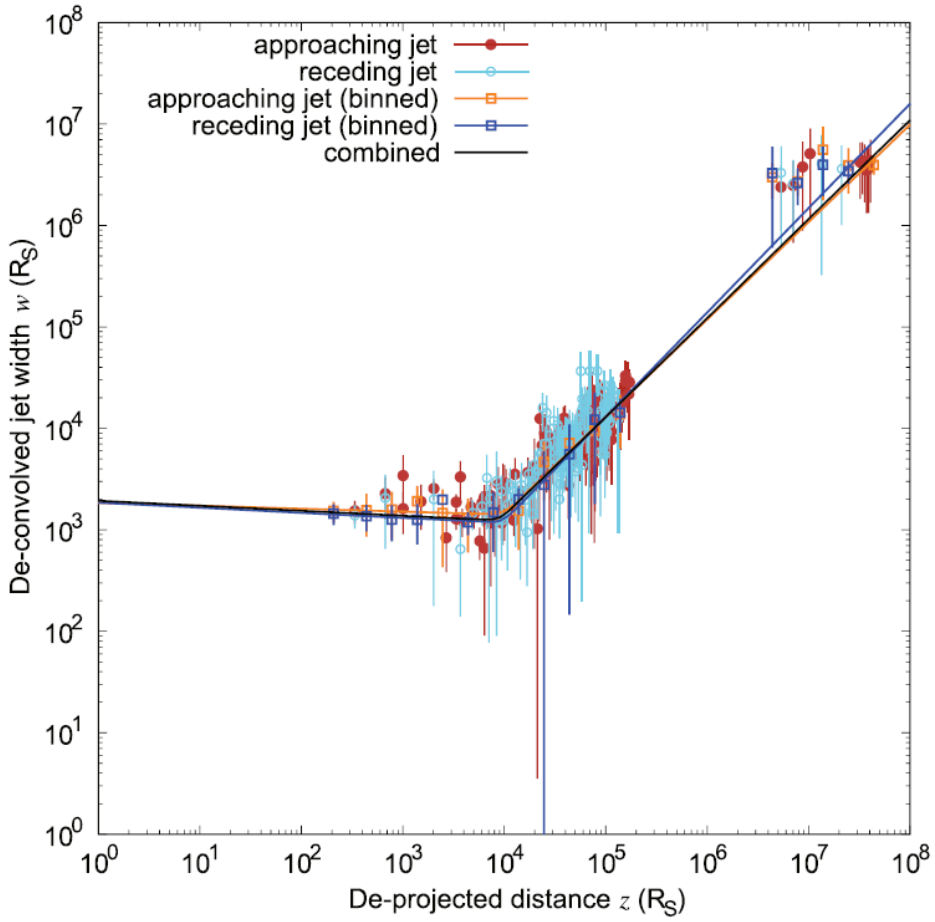


“Jet Collimation Break” in AGNs

NGC 4261, Nakahara, Doi+ 2018



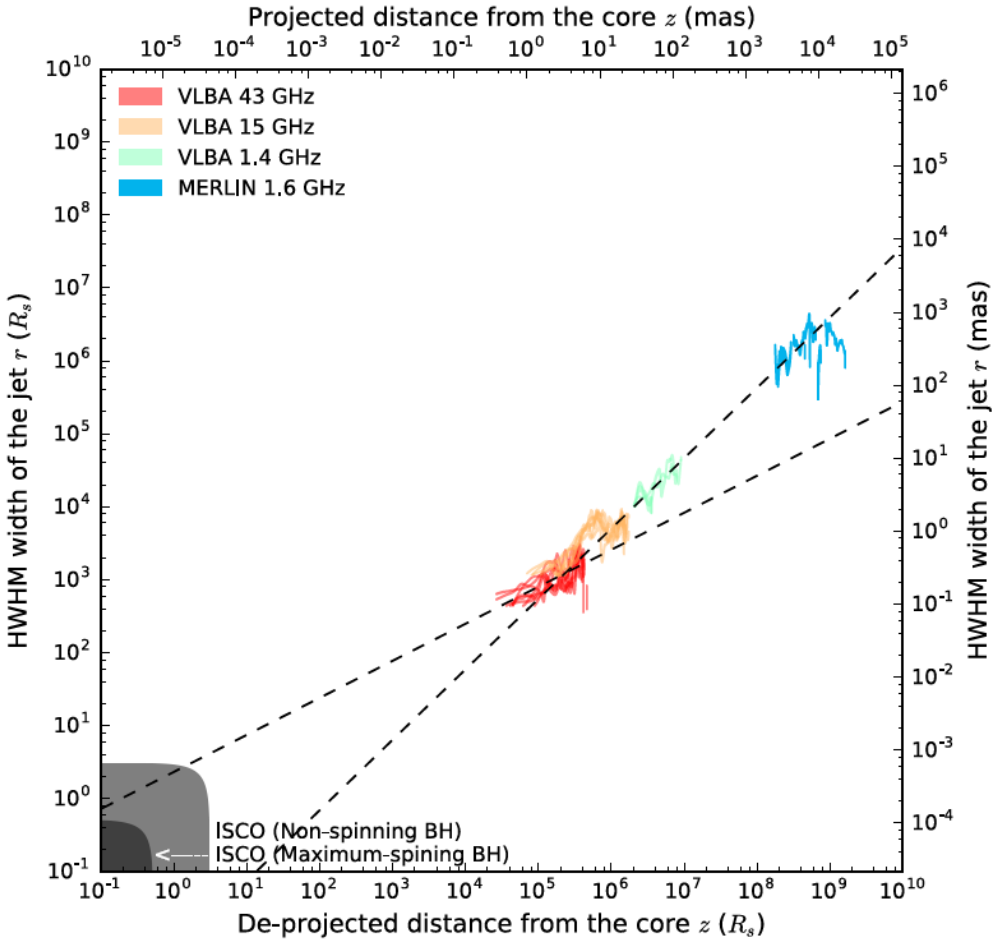
NGC 1052, Nakahara, Doi+ 2020



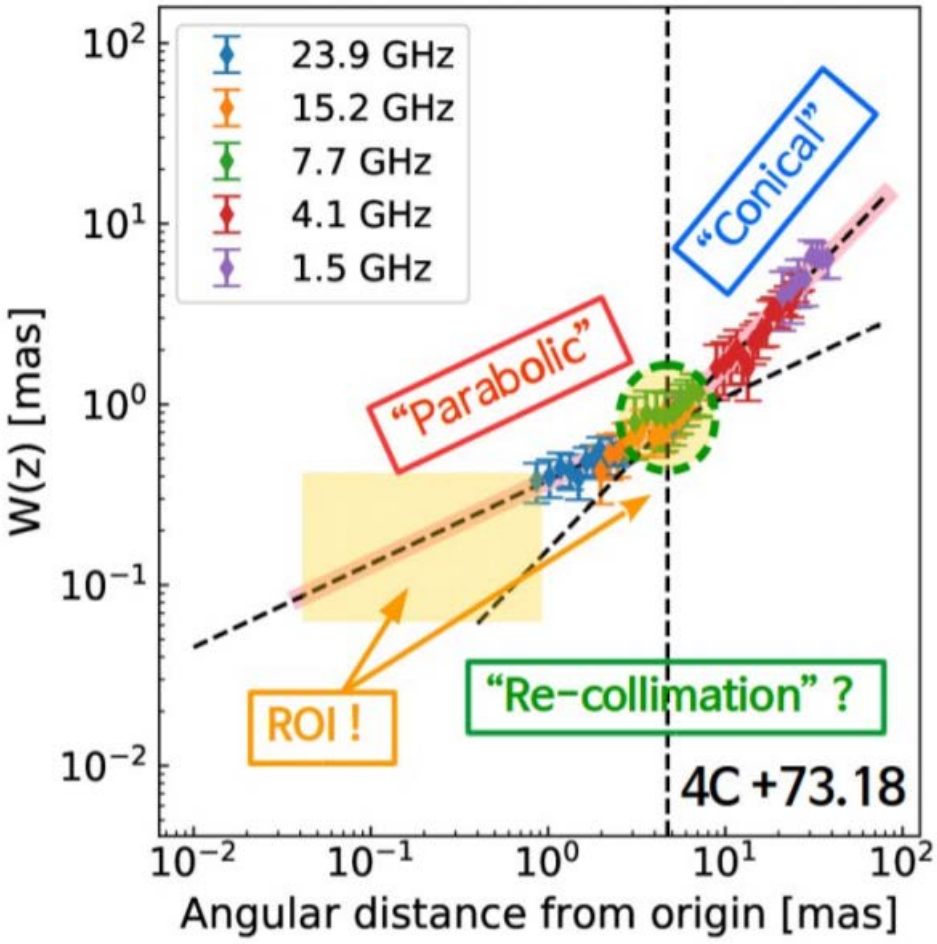
The jet shape before the jet collimation break can be different depending on source’s environments.

“Jet Collimation Break” in AGNs

3C 273, Akiyama, Asada+ 2018



1928+738, Lee+ (in prep)

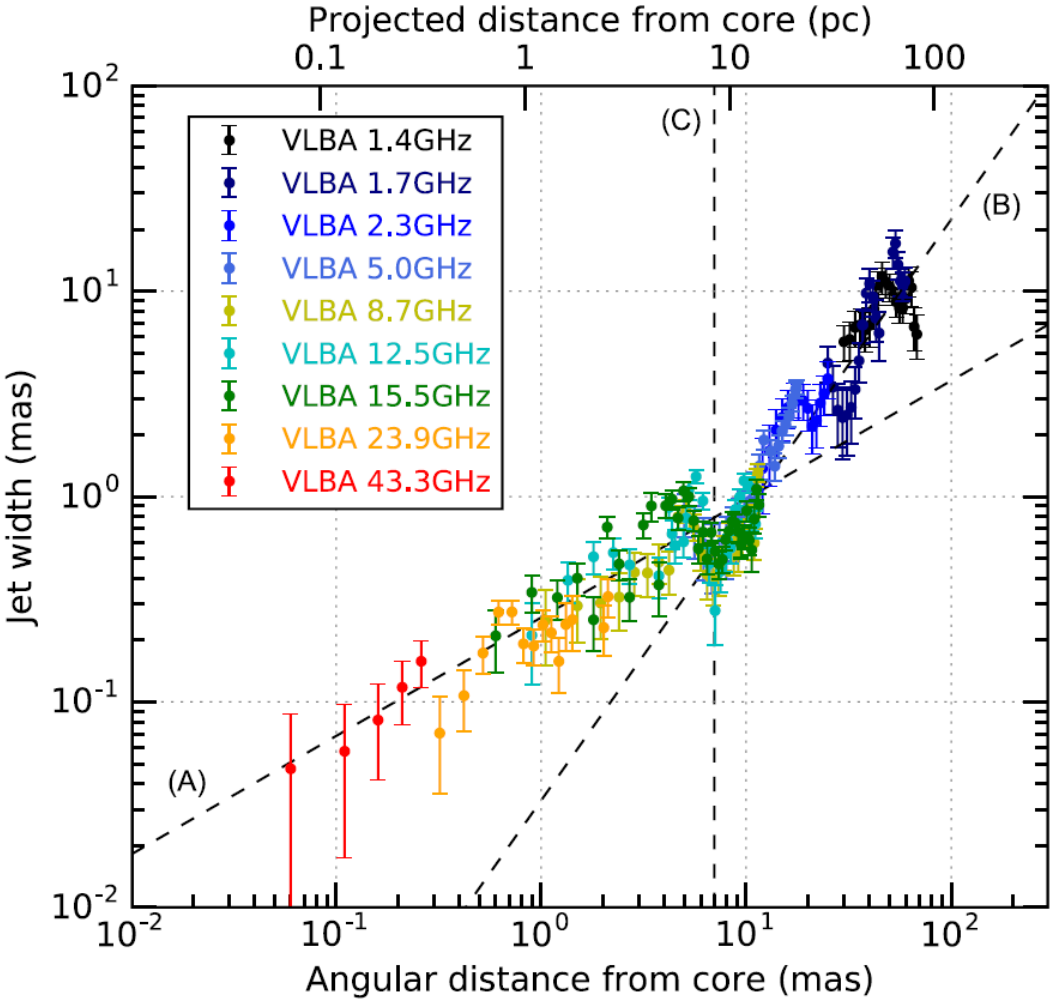


The jet collimation breaks are seen even in distant quasars!

However, their jet acceleration profiles are not well known (it requires high-resolution & high-cadence monitoring data or an accurate jet viewing angle constraint).

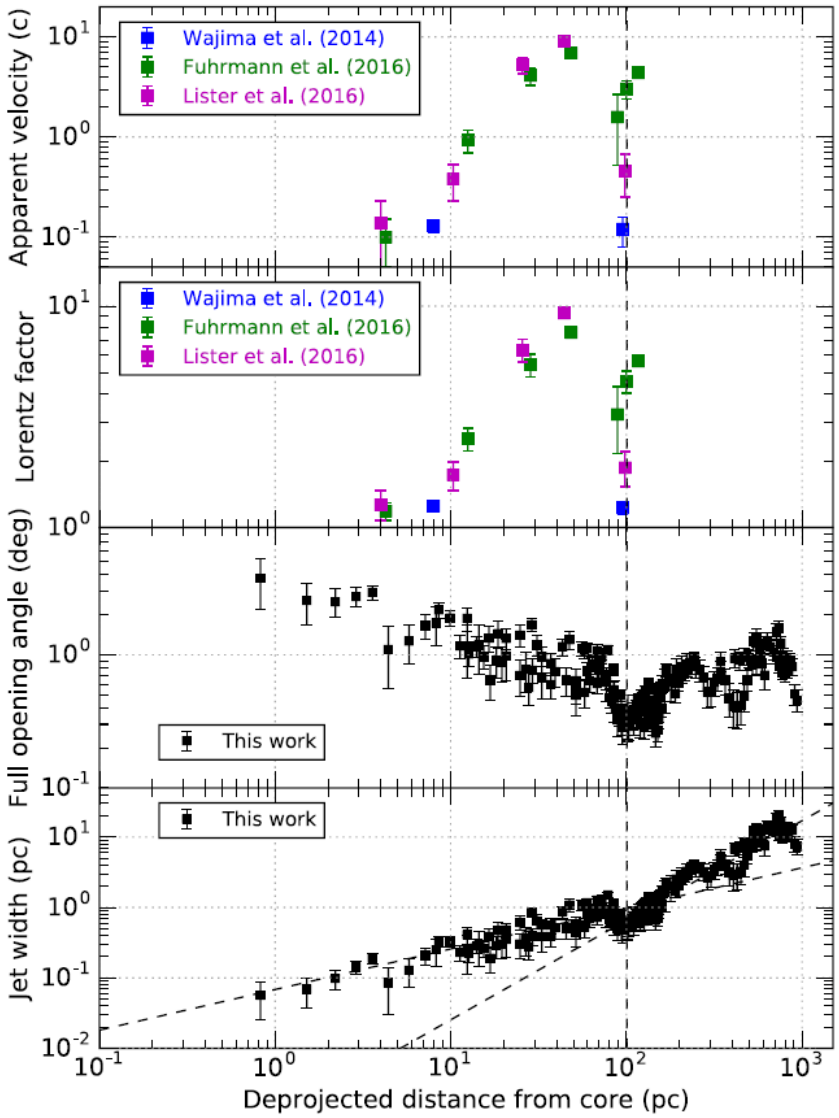
Are the jets accelerated in the collimation zones?

Jet Collimation in 1H 0323+342



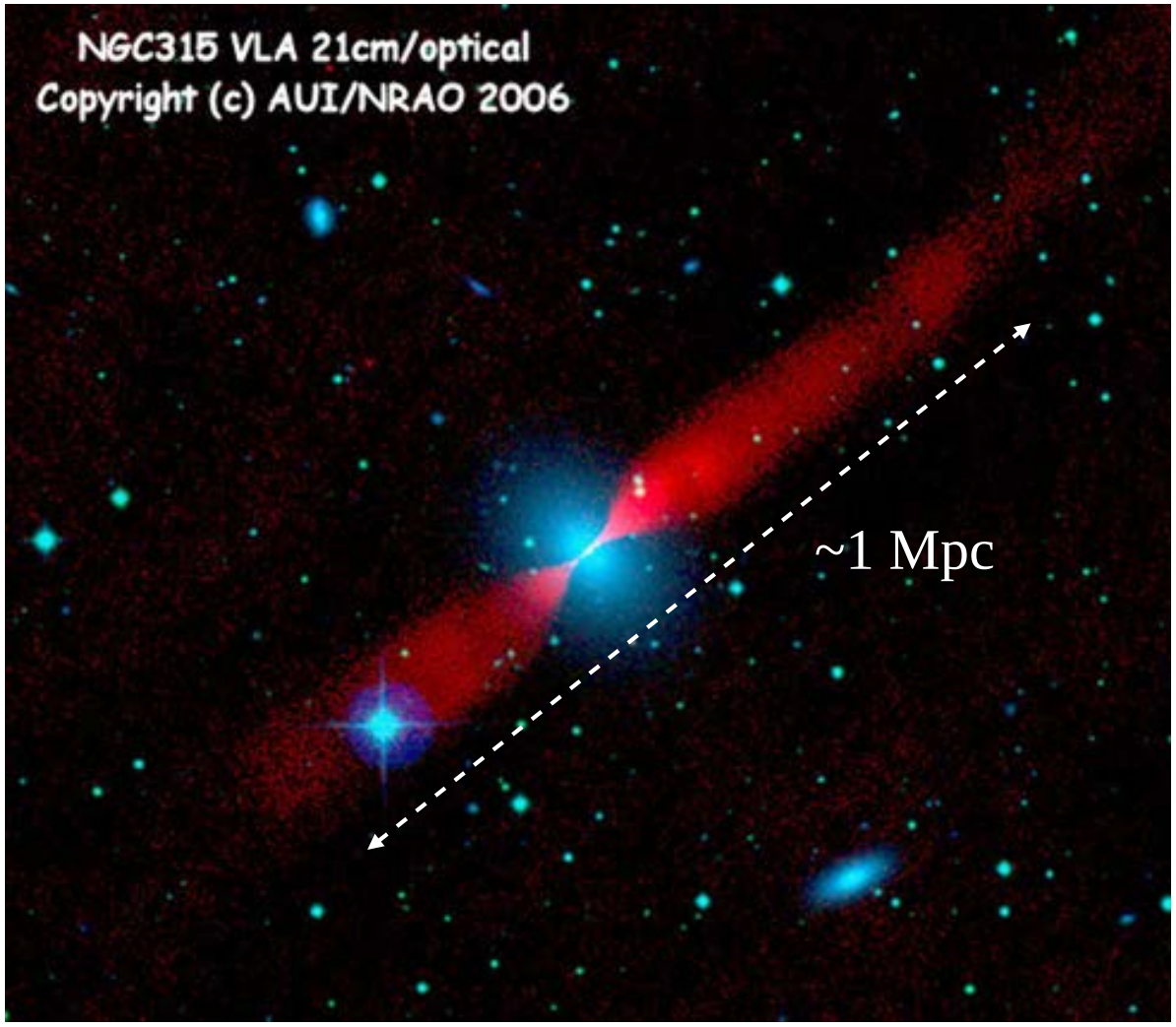
Hada, Doi, Wajima+ (2018)

Jet Acceleration in 1H 0323+342



The jet acceleration and collimation occur in the same region in the narrow-line Seyfert 1 galaxy 1H 0323+342, similar to M87.

NGC 315: a giant nearby radio galaxy

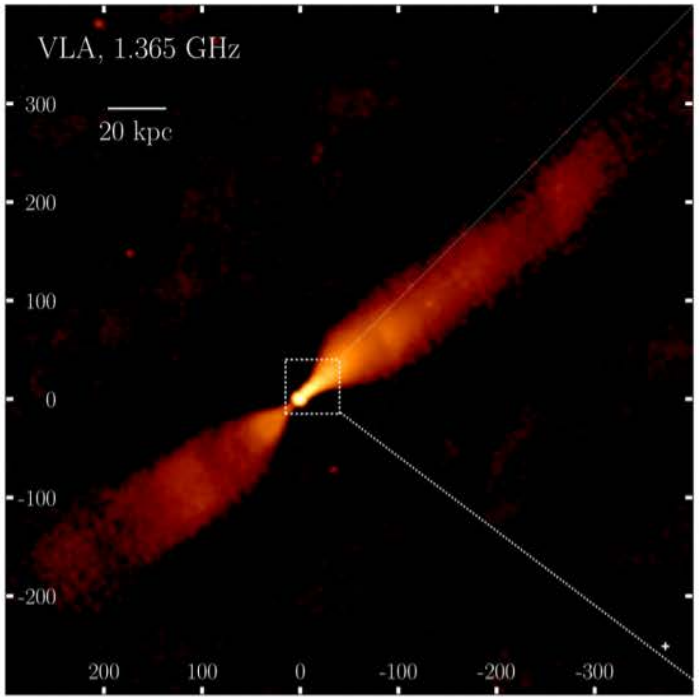


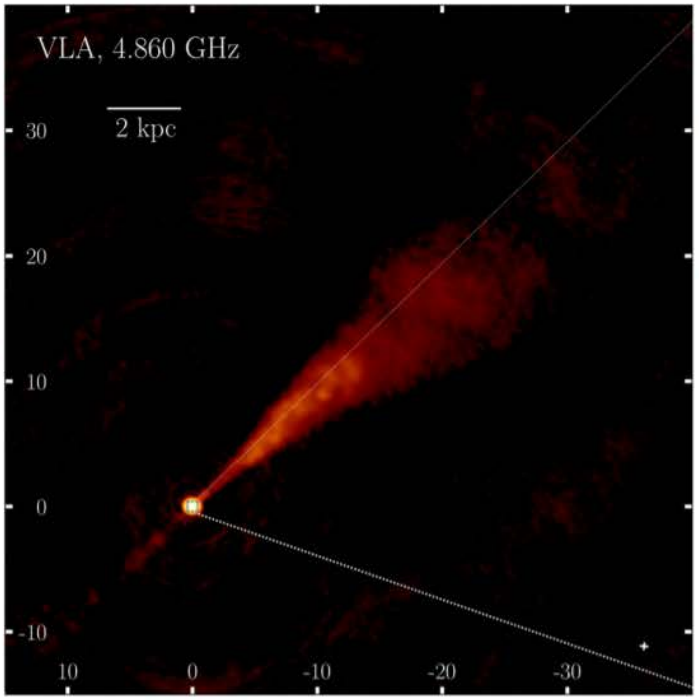
Distance: 71.4 Mpc
Black Hole Mass: 1.6e9 Msun
Jet Viewing Angle: 49.8 deg

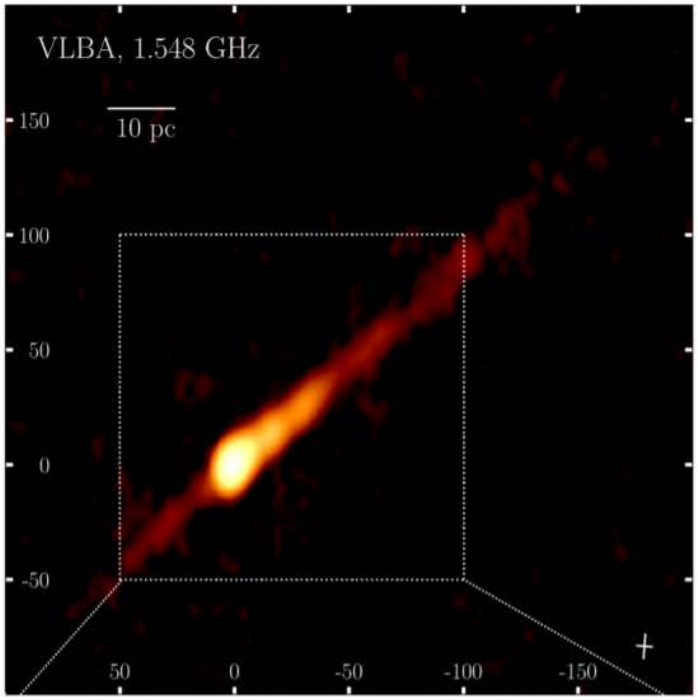
Jet Collimation and Acceleration in NGC 315

VLA, kpc-scale

VLBA, pc-scale

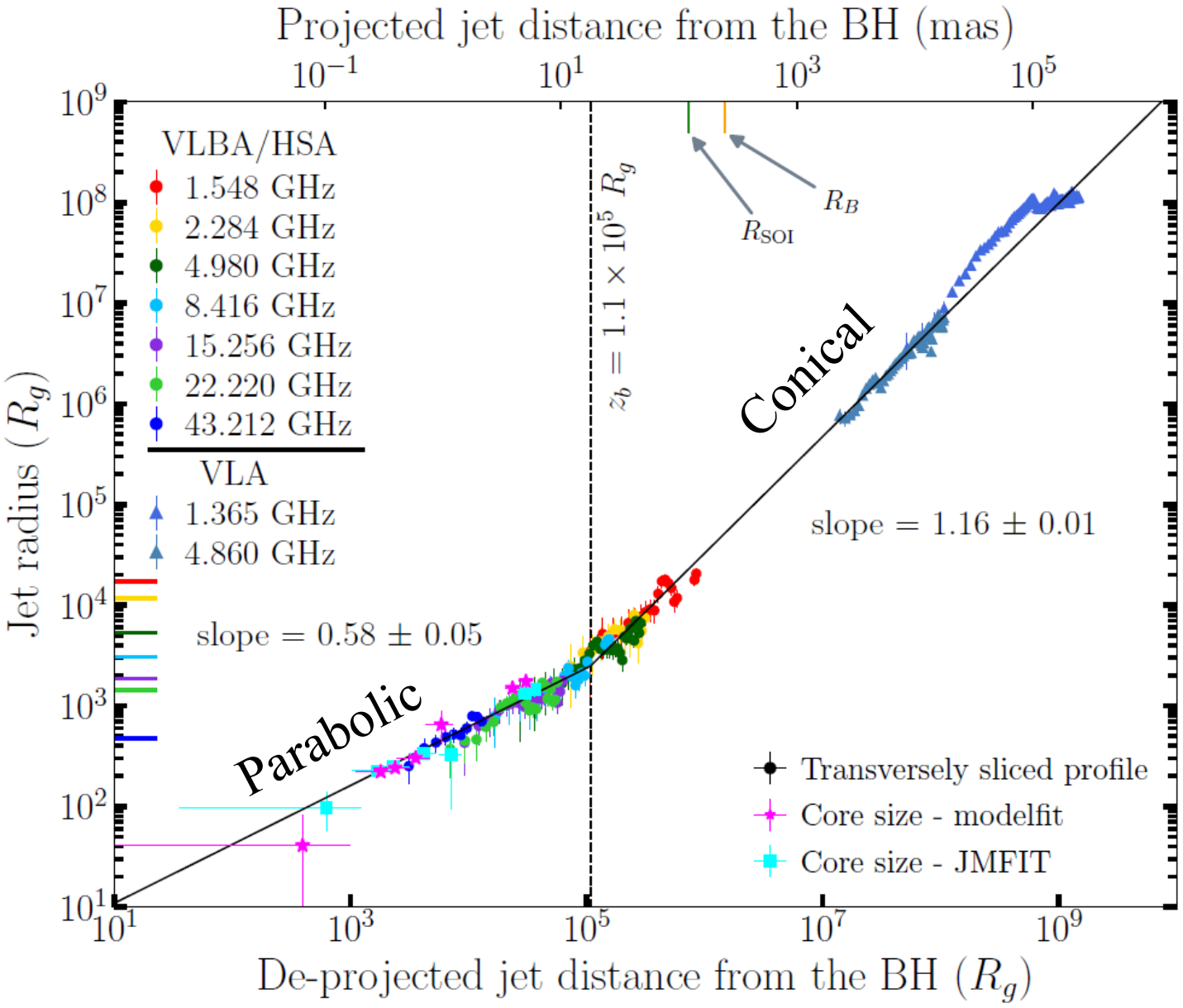






VLBA observations at 21 – 0.7 cm.
+ archival VLA data analysis.

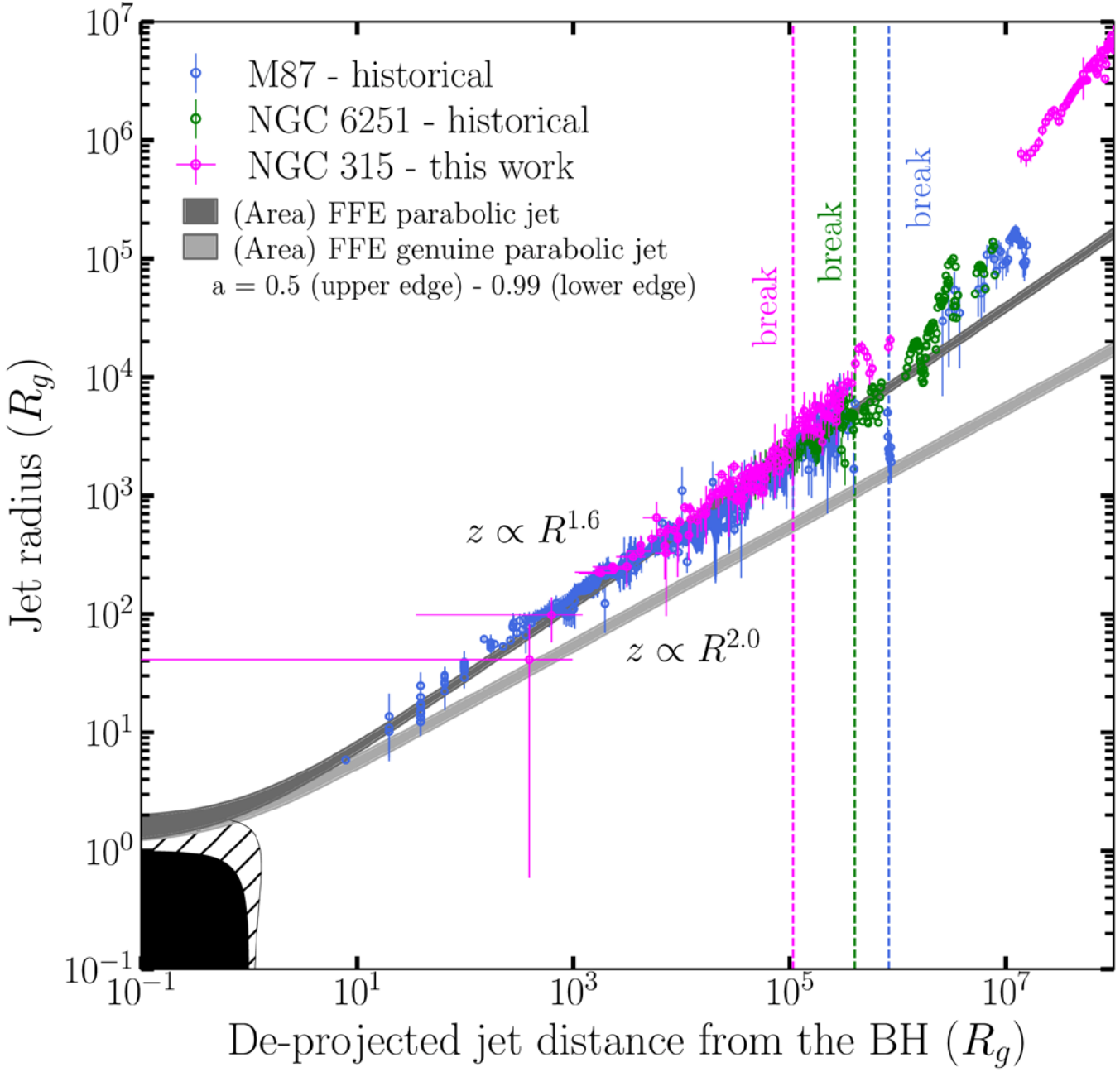
Jet Collimation and Acceleration in NGC 315



We have discovered a "jet collimation break" at $10^5 R_g$.

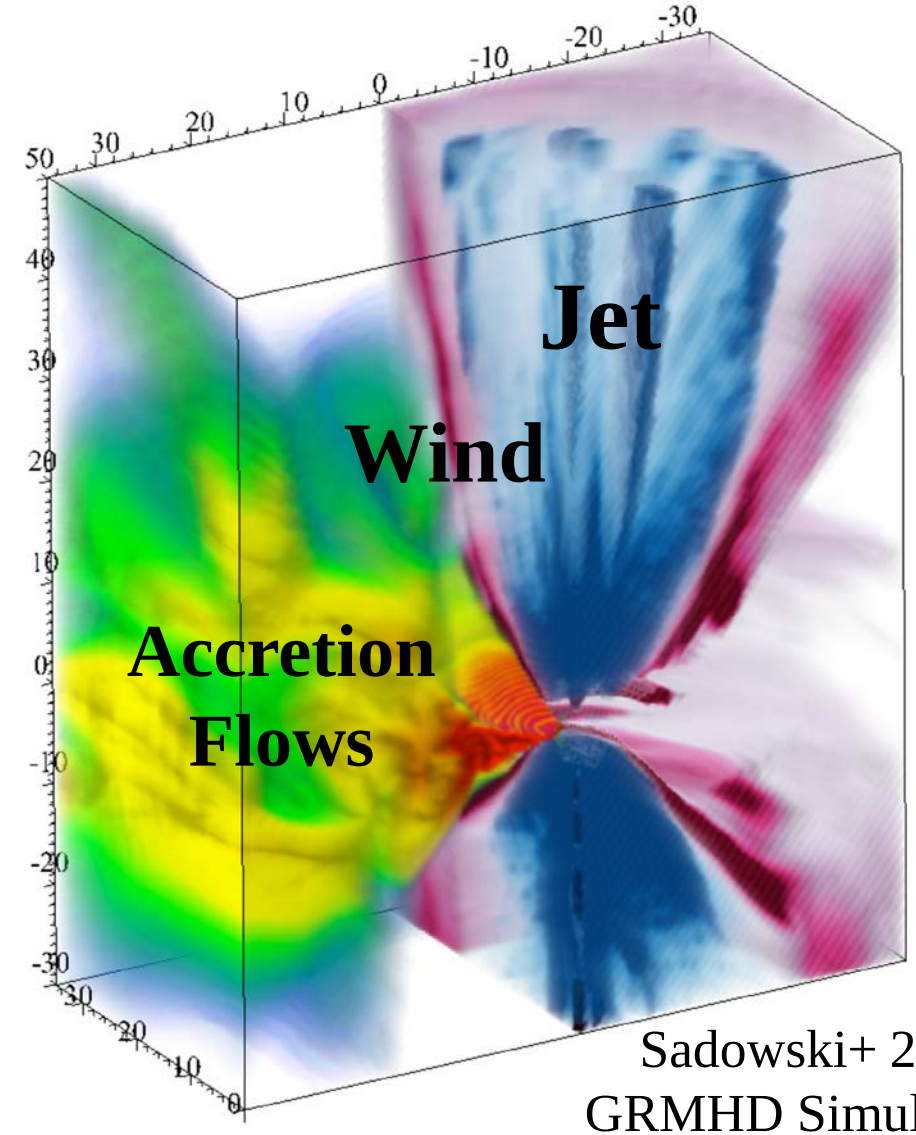
→ This is shorter than the Bondi radius and the black hole sphere of influence radius.

Jet Collimation and Acceleration in NGC 315

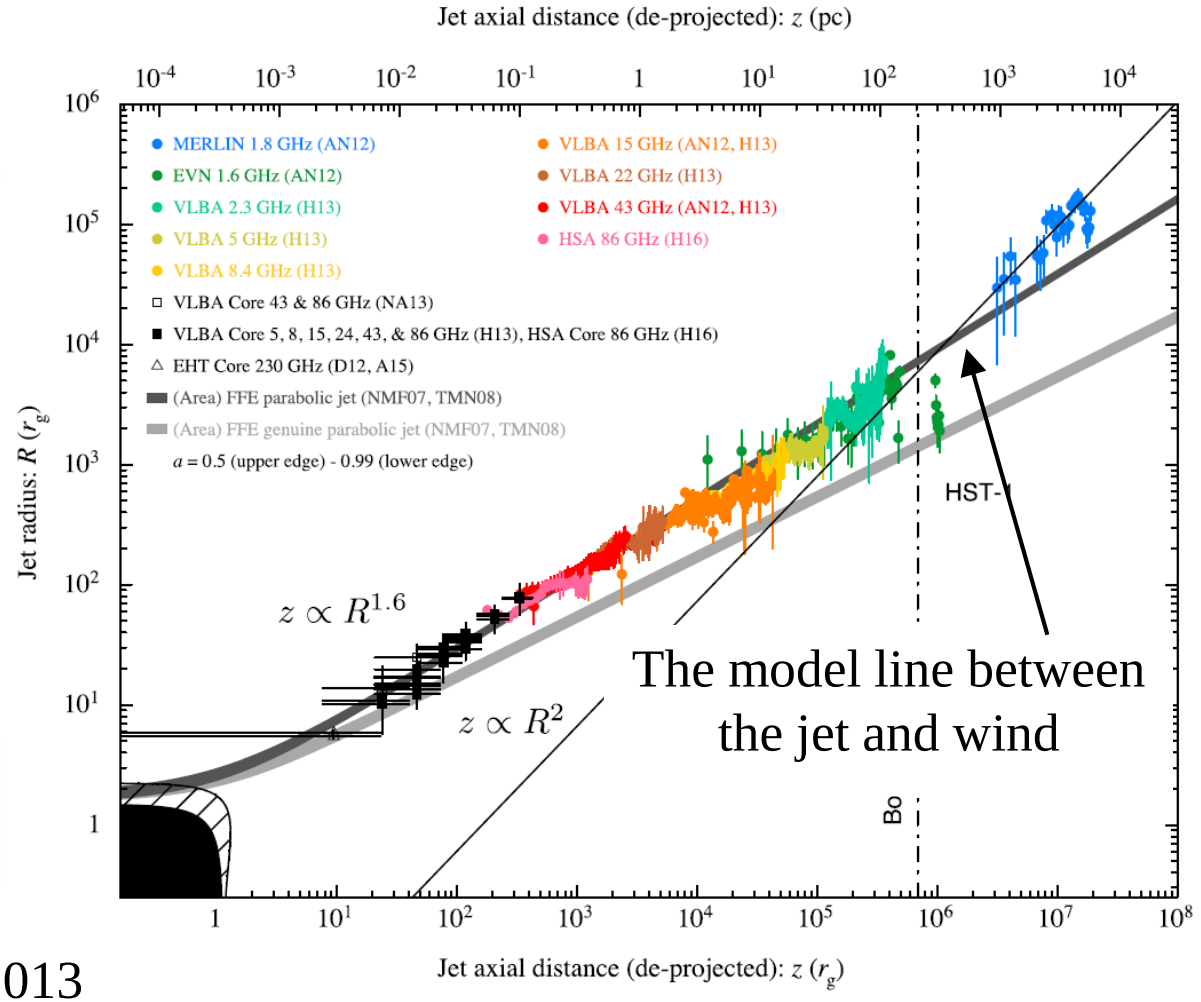


The jet collimation profile of NGC 315 is very similar to those of M87 and NGC 6251.

Jet Collimation and Acceleration in NGC 315



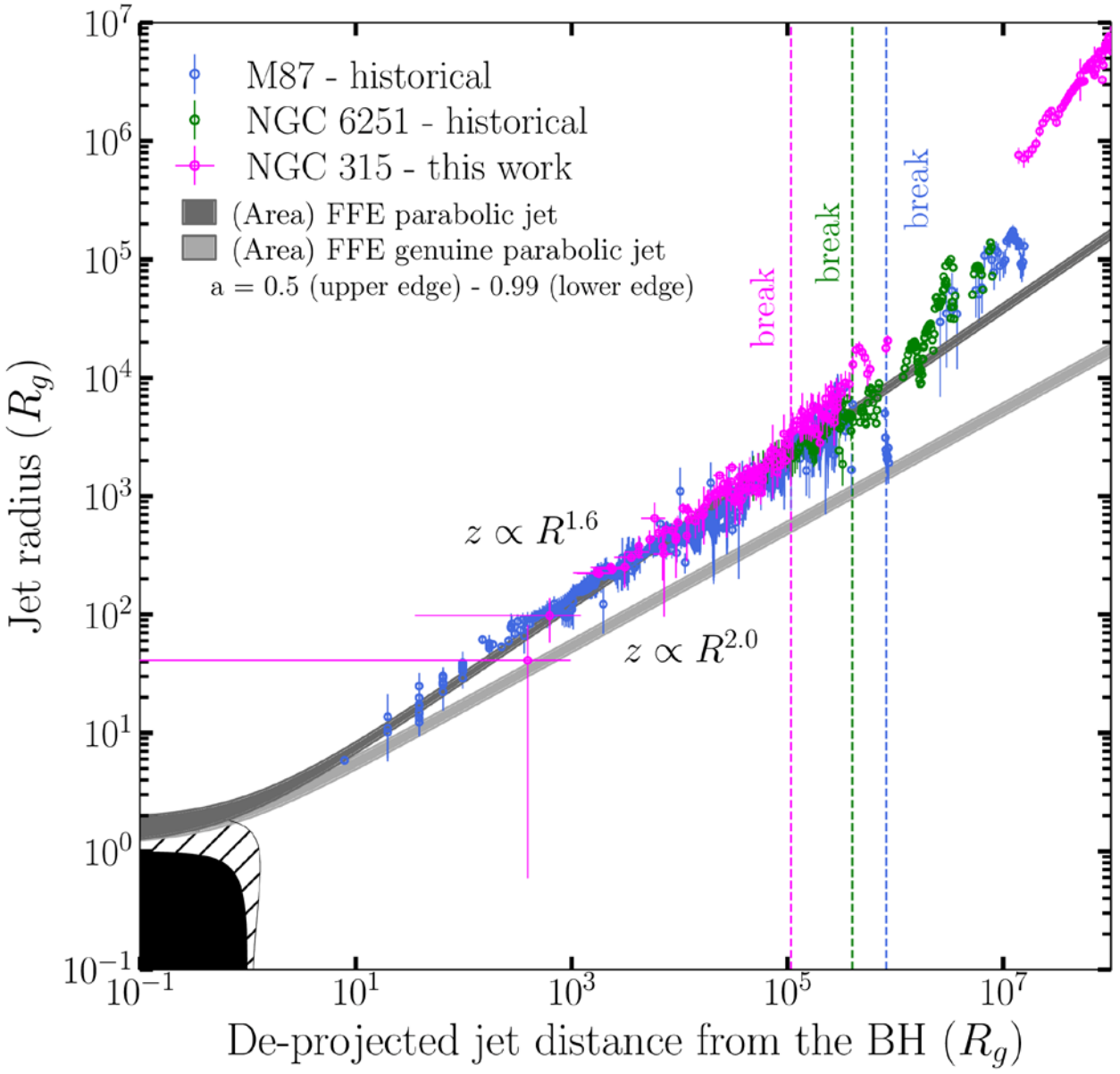
Sadowski+ 2013
GRMHD Simulations



Nakamura+ 2018

The current understanding of the M87 jet collimation mechanism is that the jet is collimated by the pressure of “winds”, non-relativistic gas outflows launched from accretion flows.

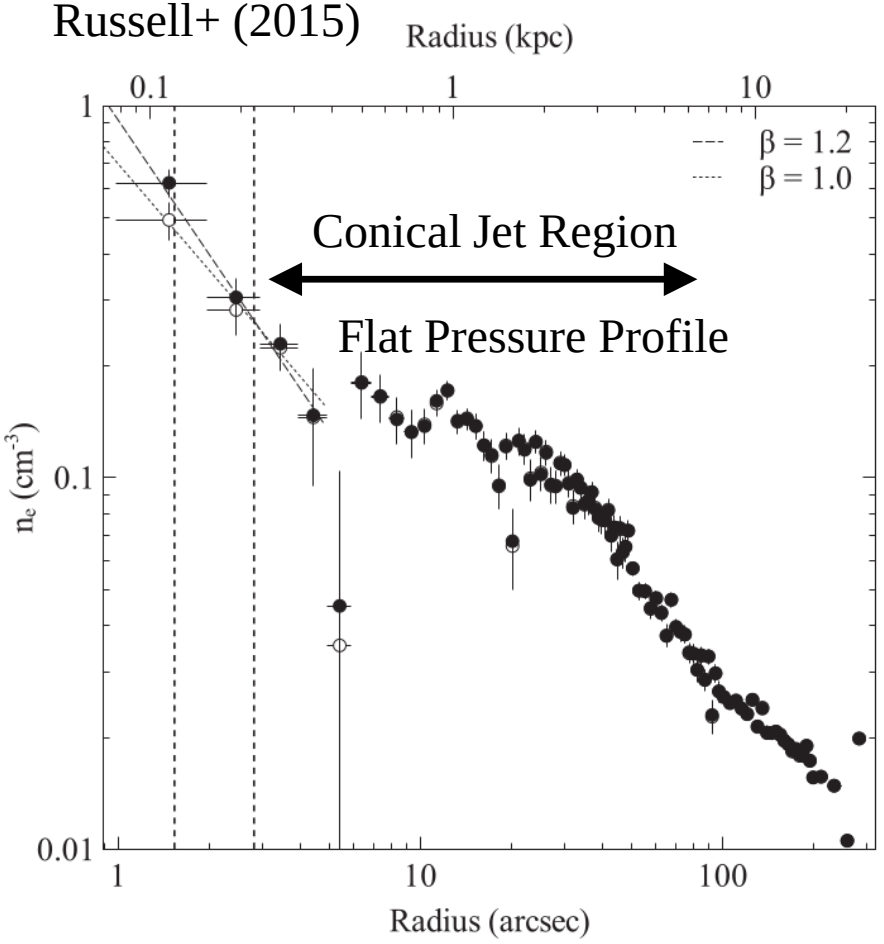
Jet Collimation and Acceleration in NGC 315

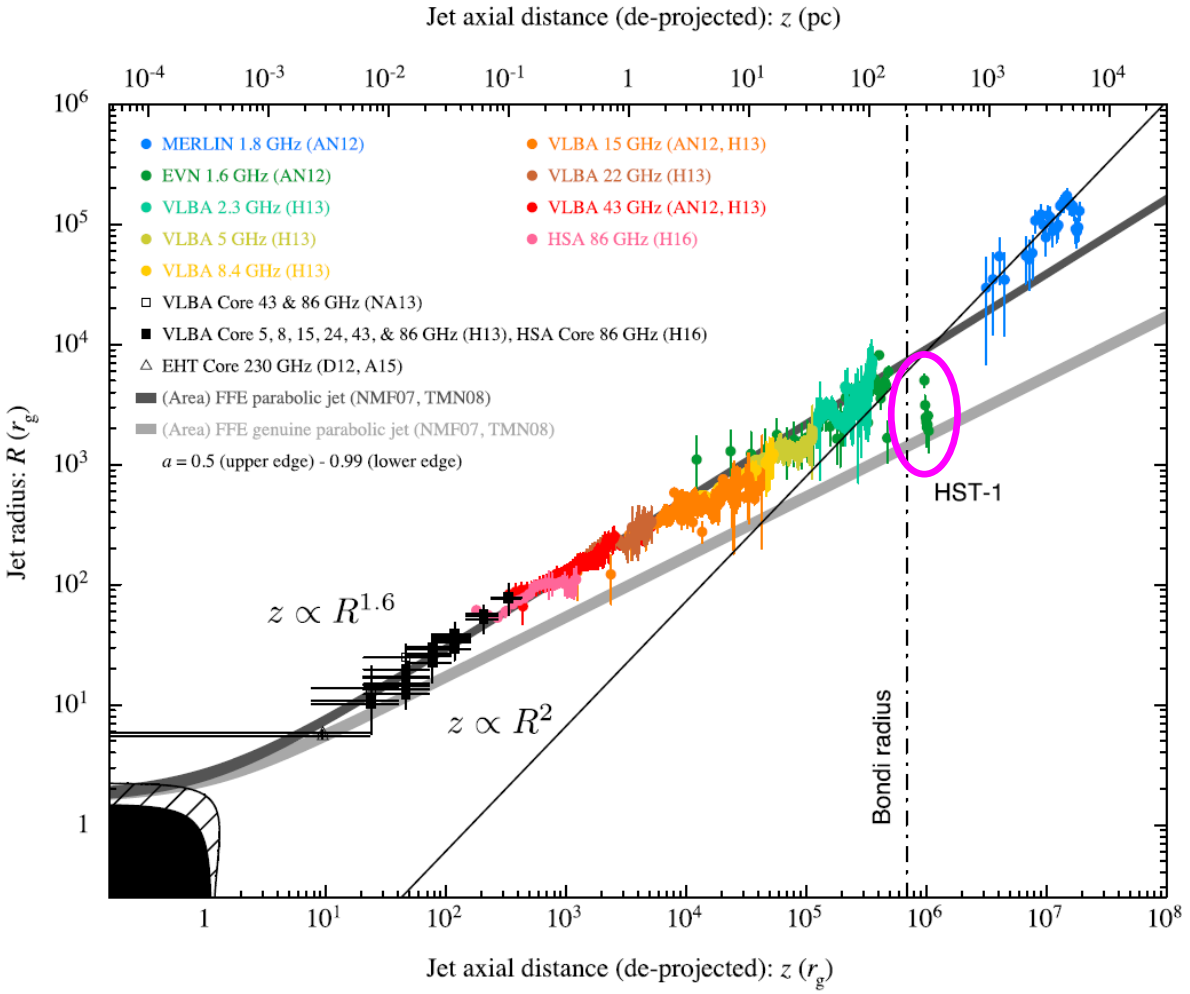


If this scenario applies to these sources, the distance that the “winds” can reach may depend on sources.

Jet Collimation and Acceleration in NGC 315

Russell+ (2015)



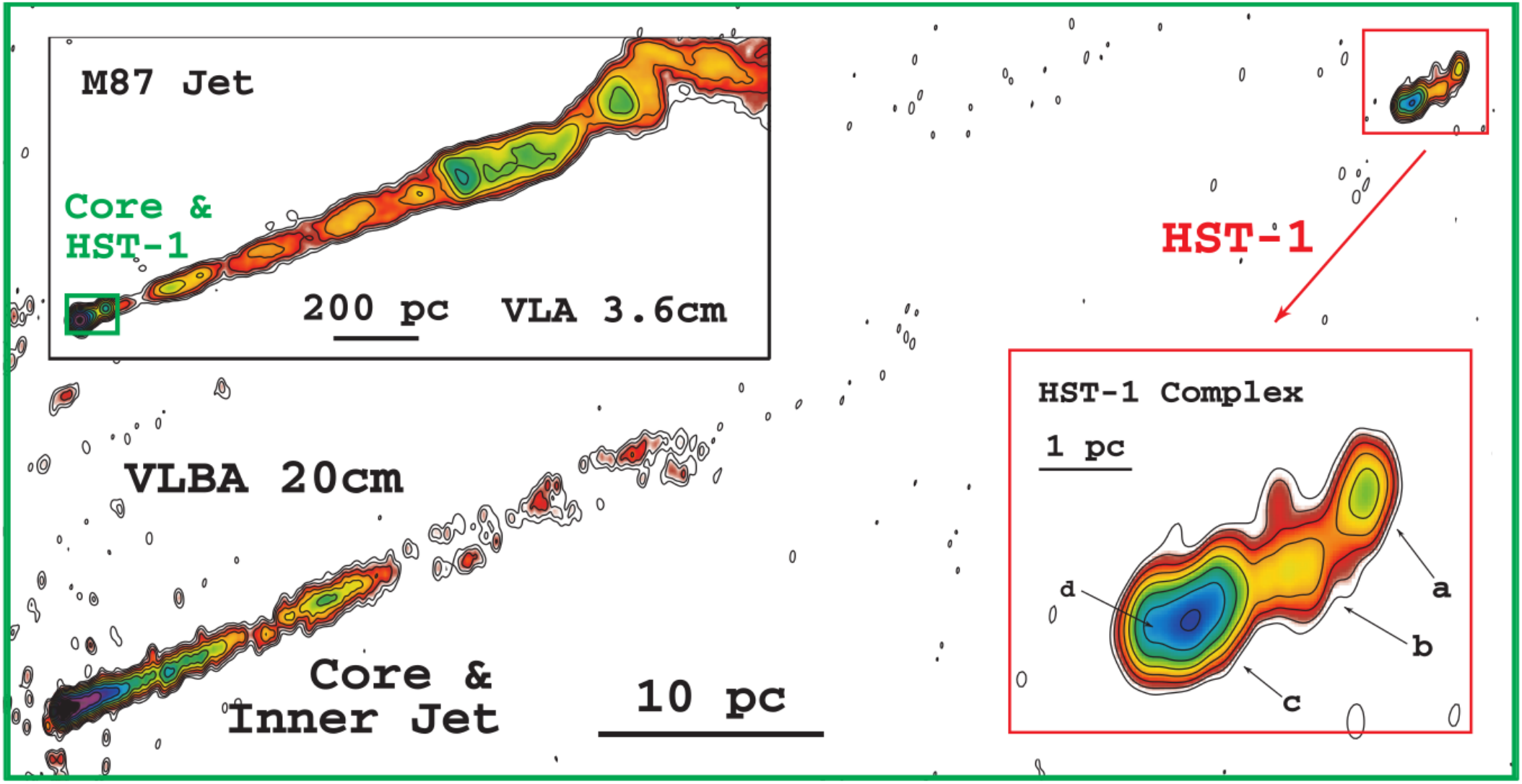


Nakamura+ 2018

How can the jet expand conically through the ambient medium having a nearly flat pressure profile?

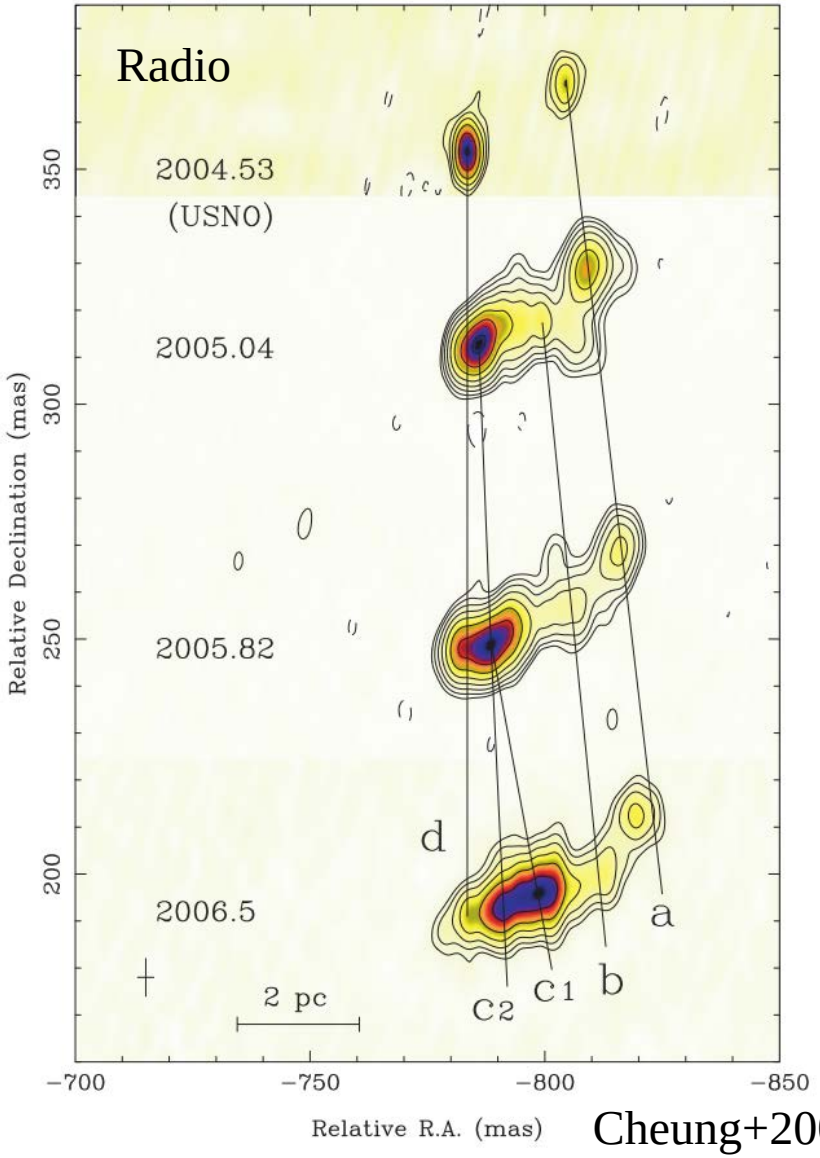
HST - 1 : a recollimation shock?

Cheung+2007



— A peculiar structure consisting of ‘stationary’ and ‘moving’ **knots** (c.f. inner jet : smooth and continuous).

HST - 1 : a recollimation shock?



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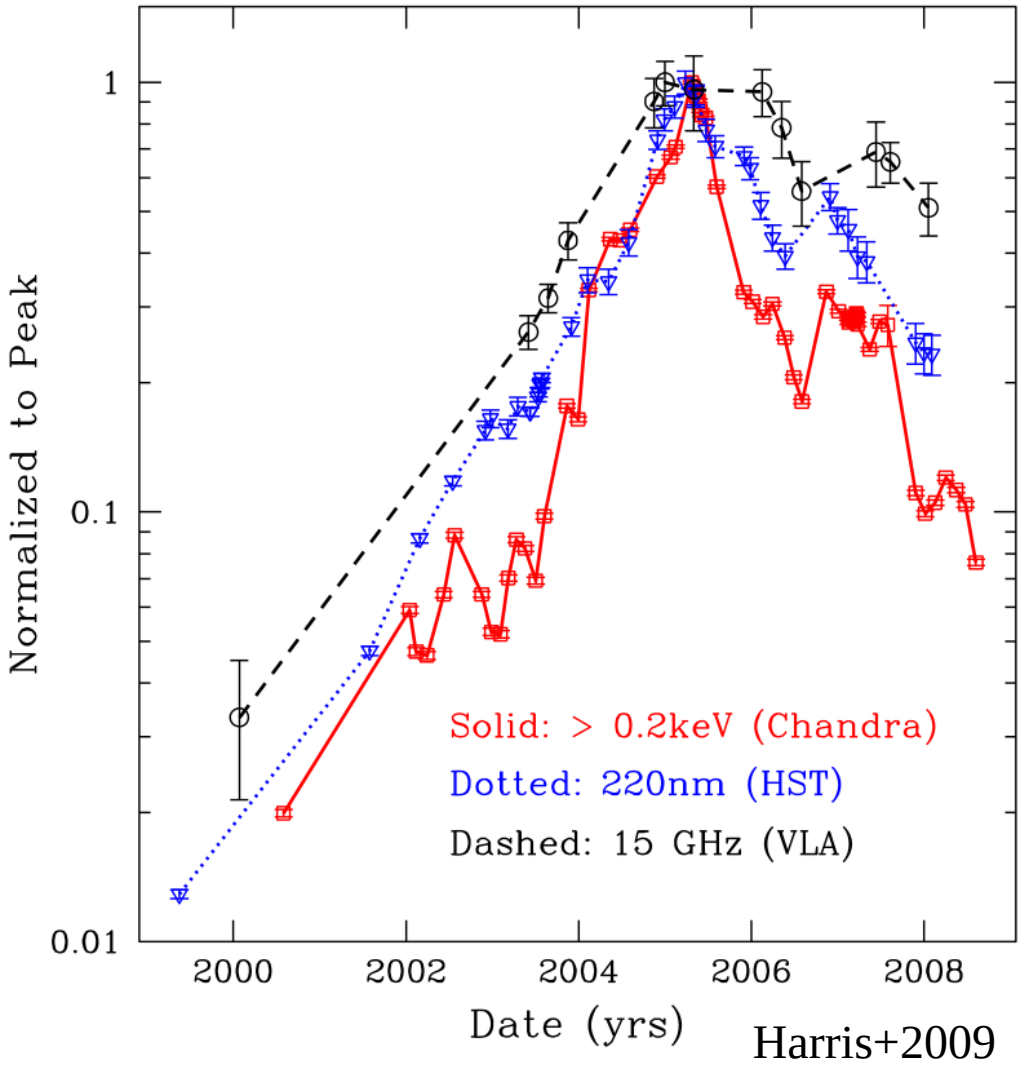
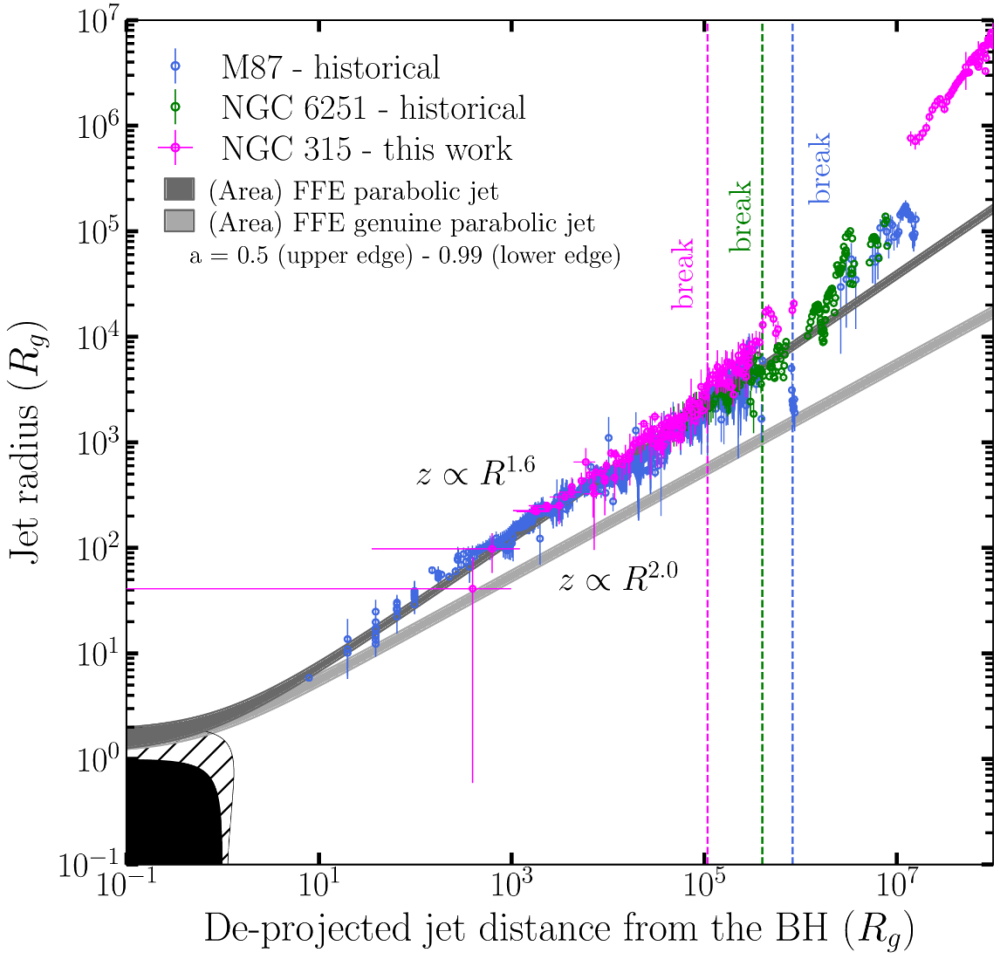


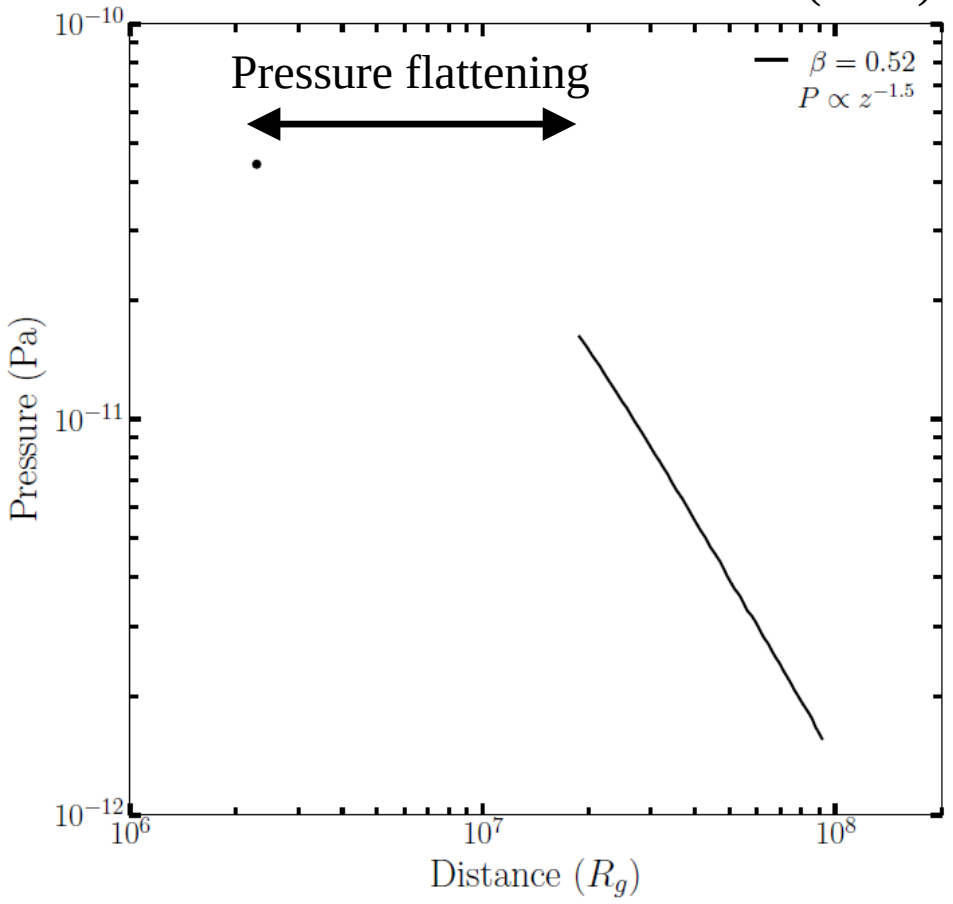
Harris+2009

— The recollimation feature and superluminal/stationary knots.
— There was a huge multi-wavelength flare in 2005 (*blazar*-like feature).
→ efficient particle acceleration to high energies → enhance the internal jet pressure → the conical jet expansion.

Jet Collimation and Acceleration in NGC 315



Worrall+ (2007)

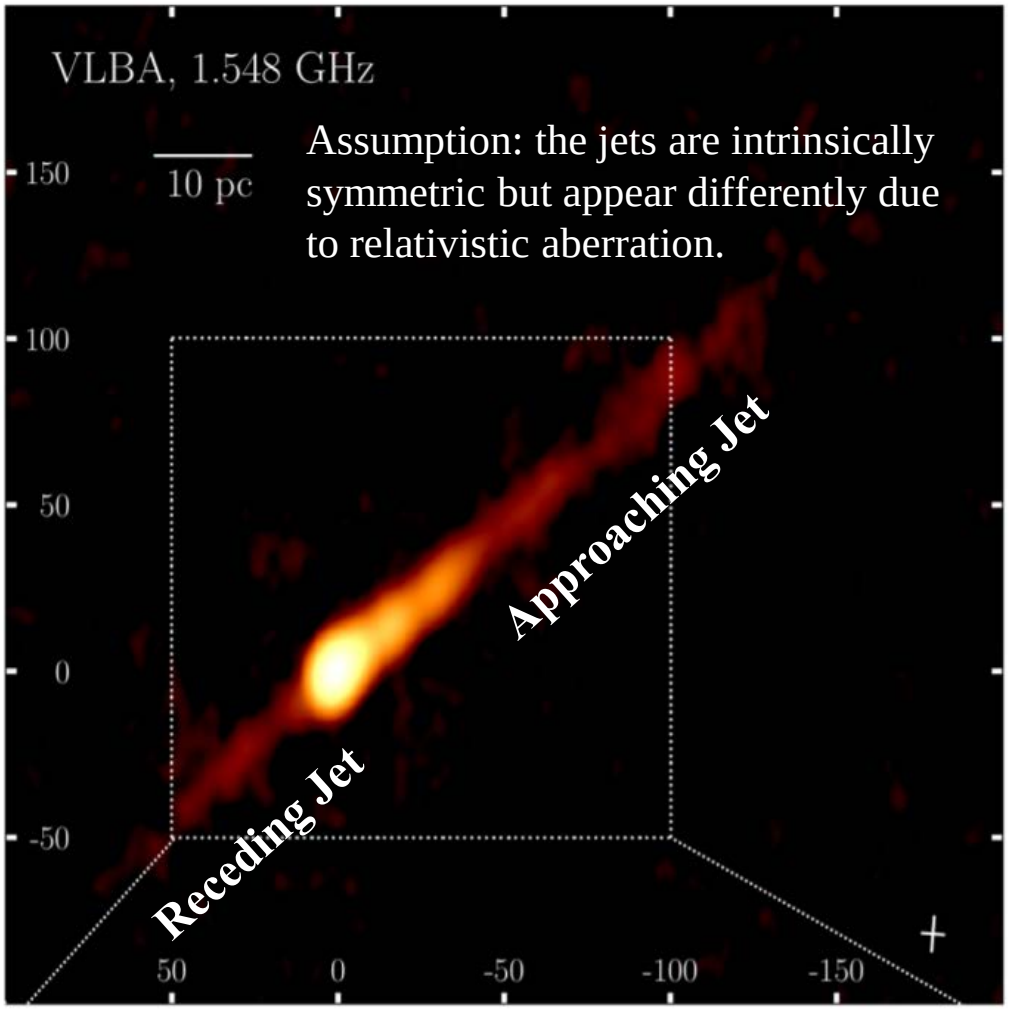


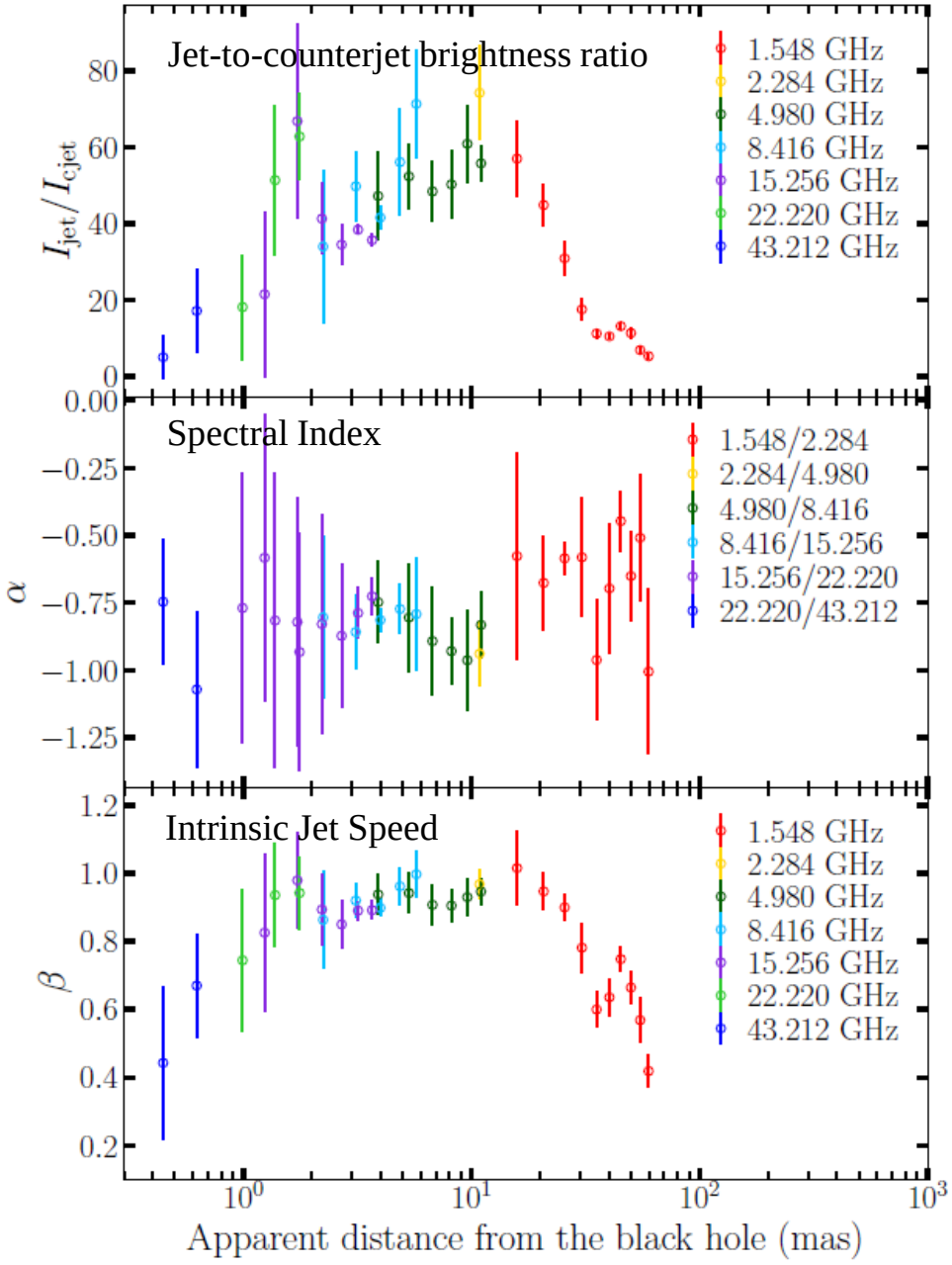
— There is no indication of a recollimation shock at the break location in NGC 315.

— The jet is conically expanding in the region where the ambient gas has a flat pressure profile.

→ Another mechanism is necessary to enhance the internal jet pressure.

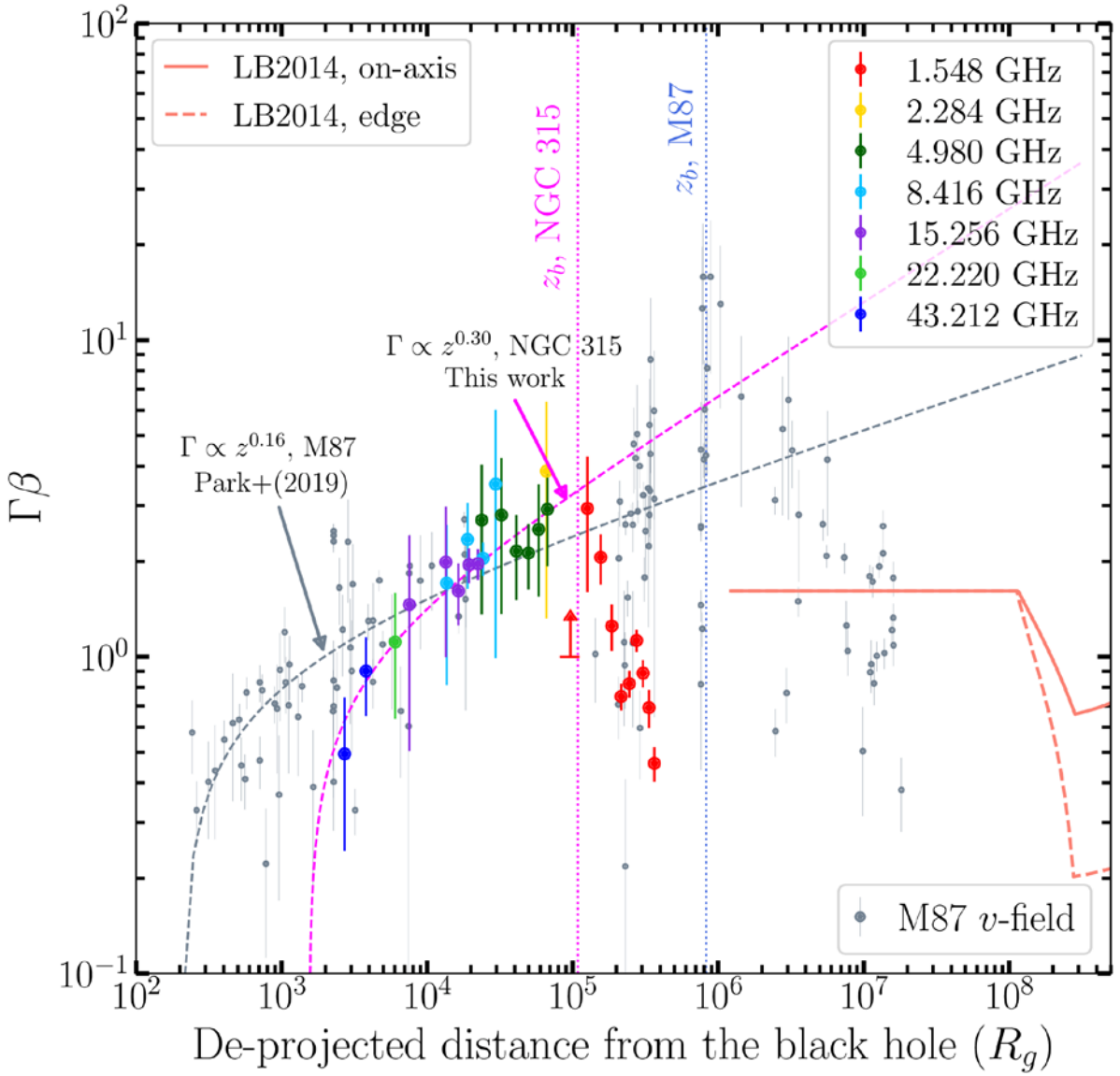
Jet Collimation and Acceleration in NGC 315





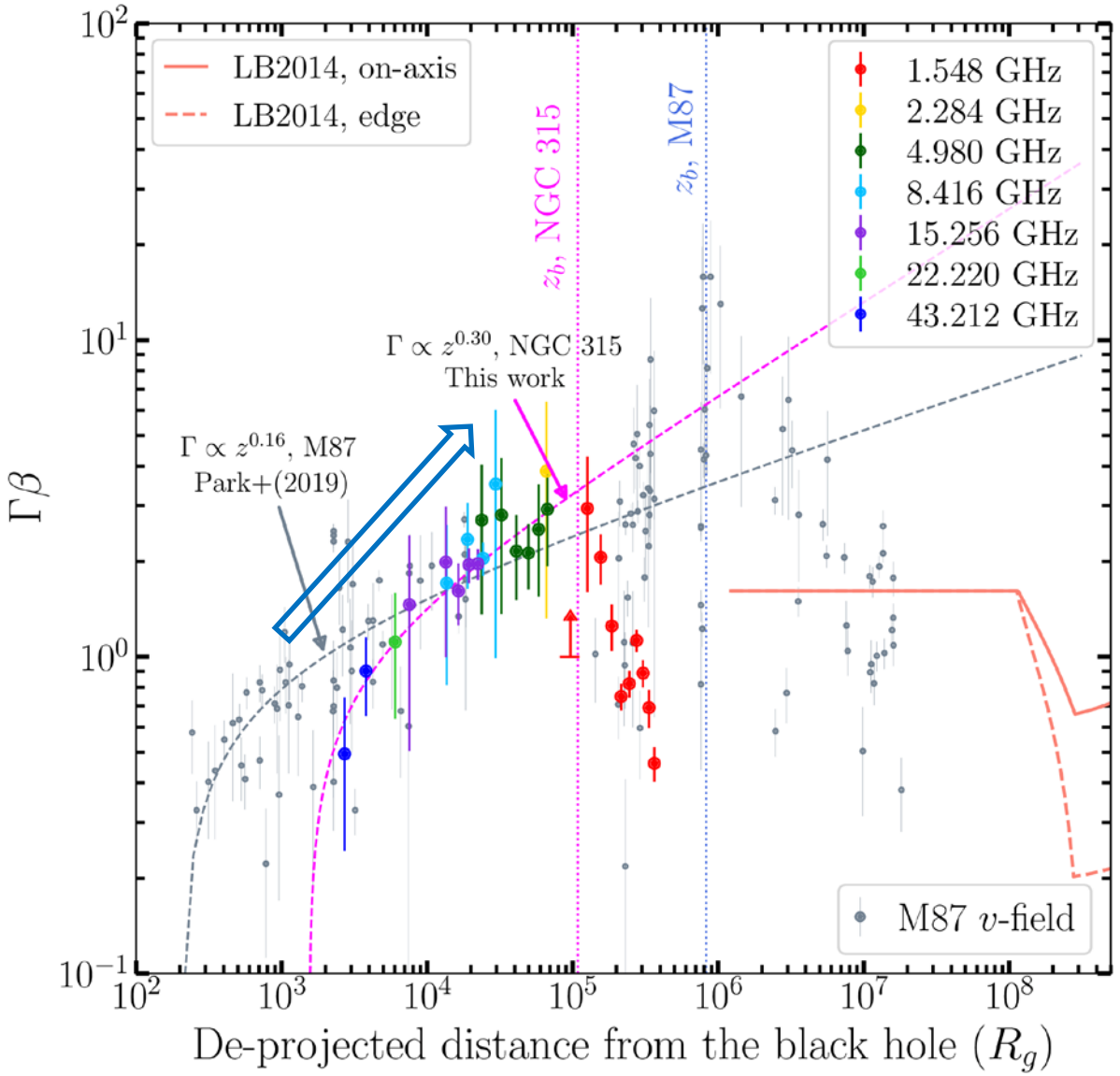
The jets are gradually accelerated to relativistic speeds and then gradually decelerated.

Jet Collimation and Acceleration in NGC 315



1. The jet is gradually accelerated to relativistic speeds in the collimation zone.
→ The existence of the “jet acceleration and collimation zone” in NGC 315 is confirmed.
→ This is consistent with the prediction of the magnetic jet acceleration model.

Jet Collimation and Acceleration in NGC 315



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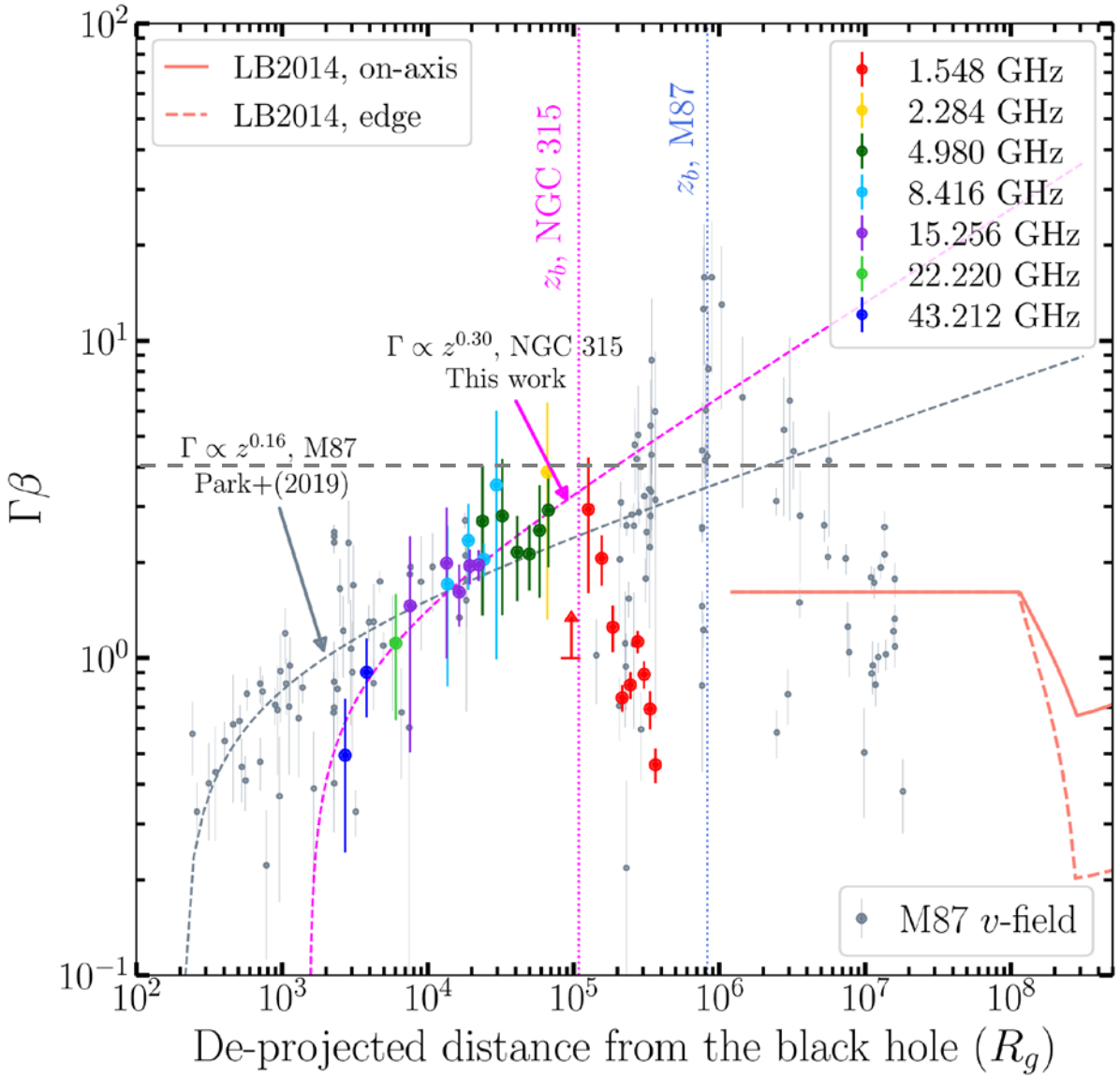
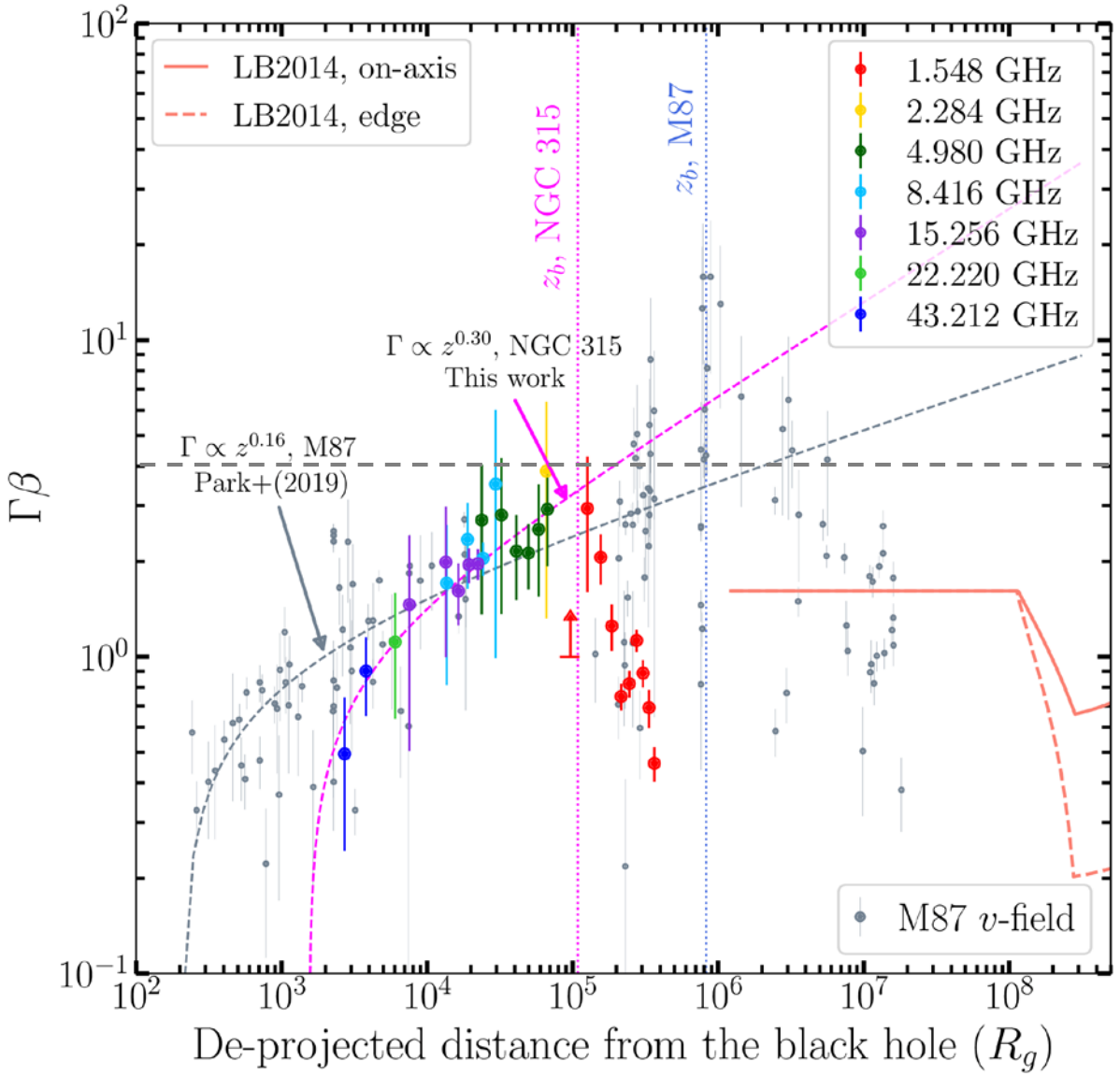


2. The jet becomes relativistic at a large distance ($\approx 10^4 R_g$). The jet acceleration is slow (the maximum $\Gamma \sim 3$).

→ (i) the jet base may not be highly magnetized. (ii) the Poynting flux conversion is not efficient. (iii) the interaction between the jet and wind is significant.

Jet Collimation and Acceleration in NGC 315



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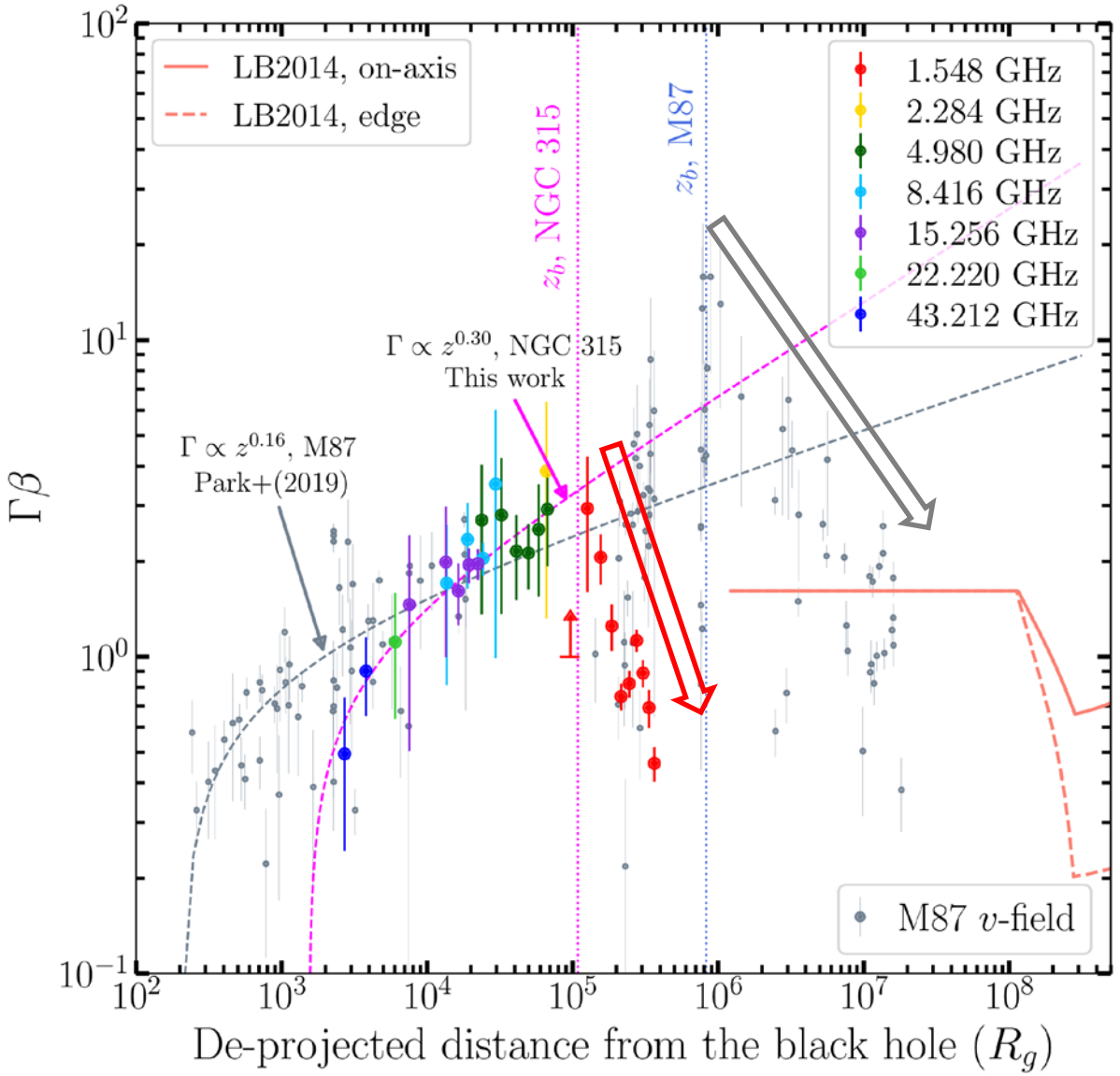


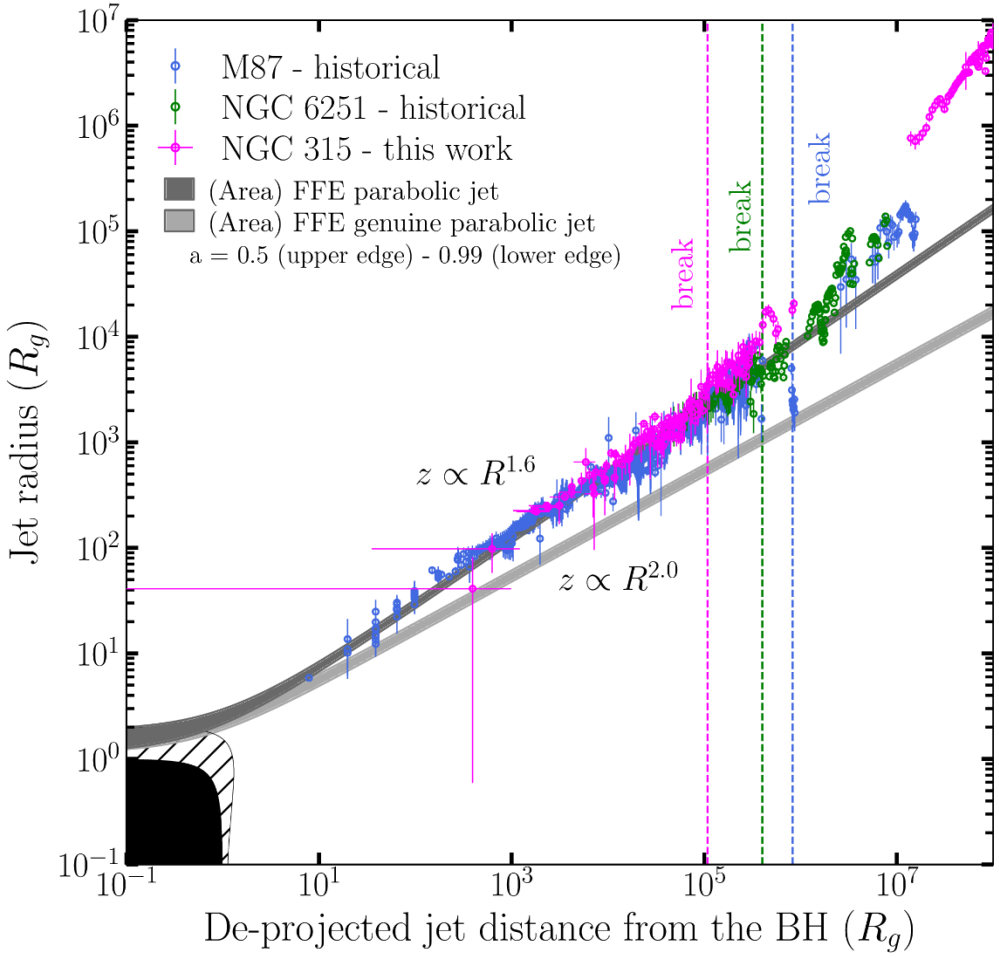
3. The jet decelerates right after the jet collimation break.

→ Due to the interaction of the jet with the ambient medium?

→ In that case, the jet internal pressure may be enhanced due to the interaction.

→ This is the origin of the conical jet expansion despite that there is no recollimation shock?

Jet Collimation and Acceleration in NGC 315



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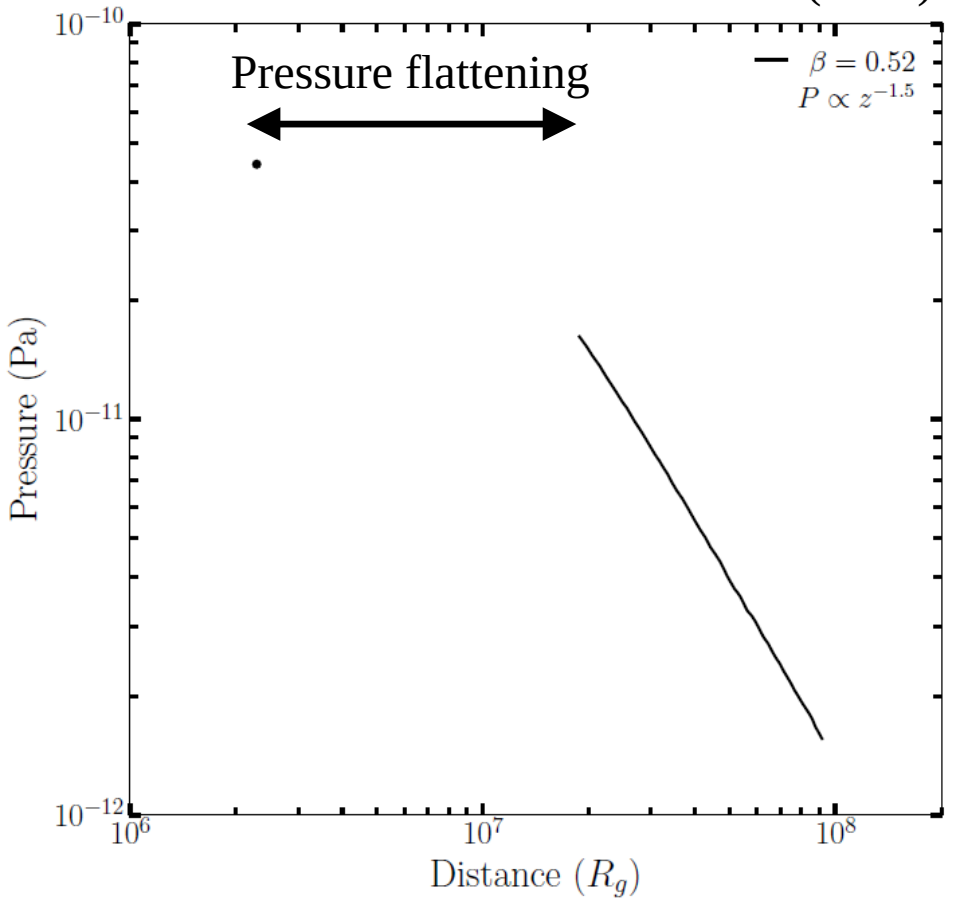

— There is no indication of a recollimation shock at the break location in NGC 315.

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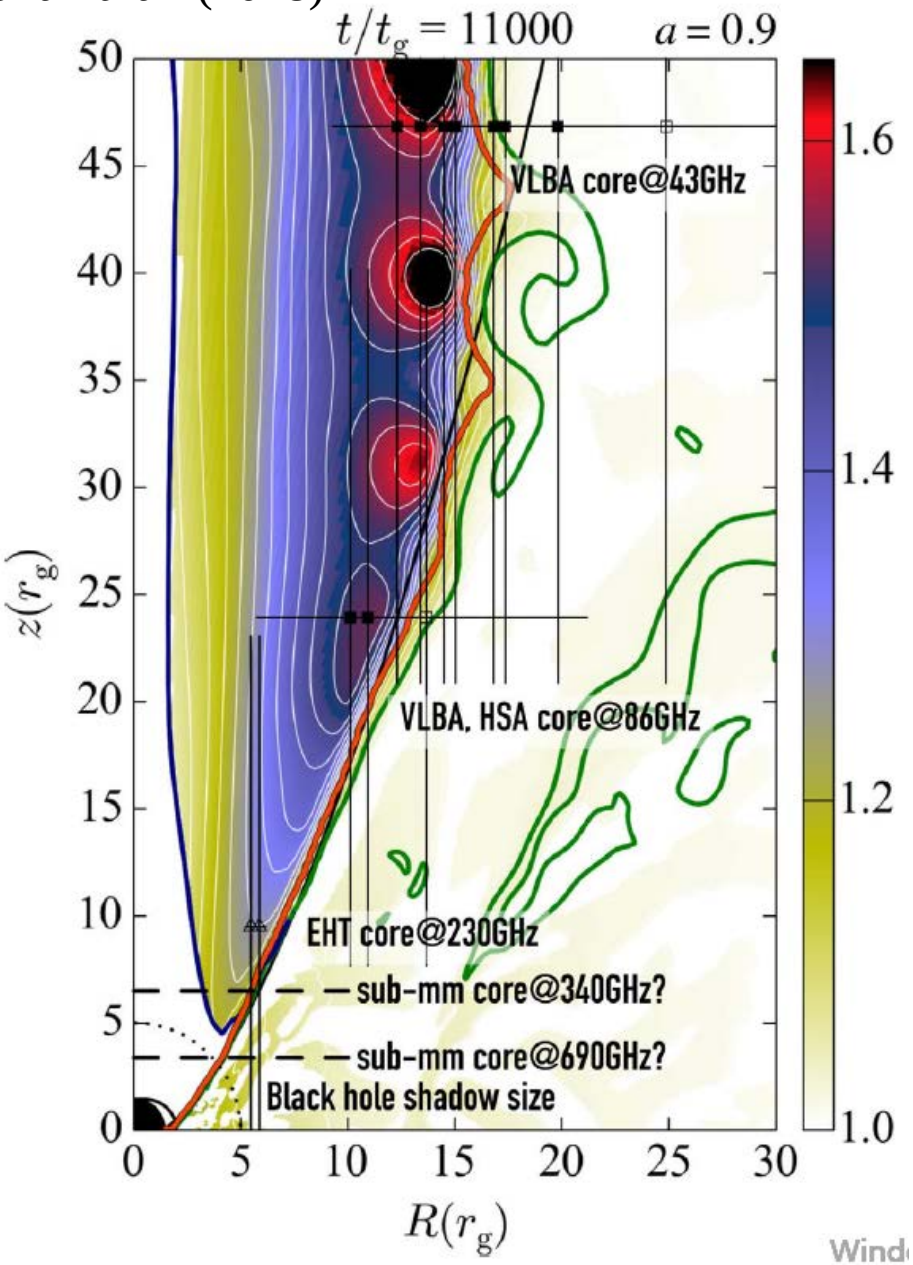
Nakamura+ (2018)

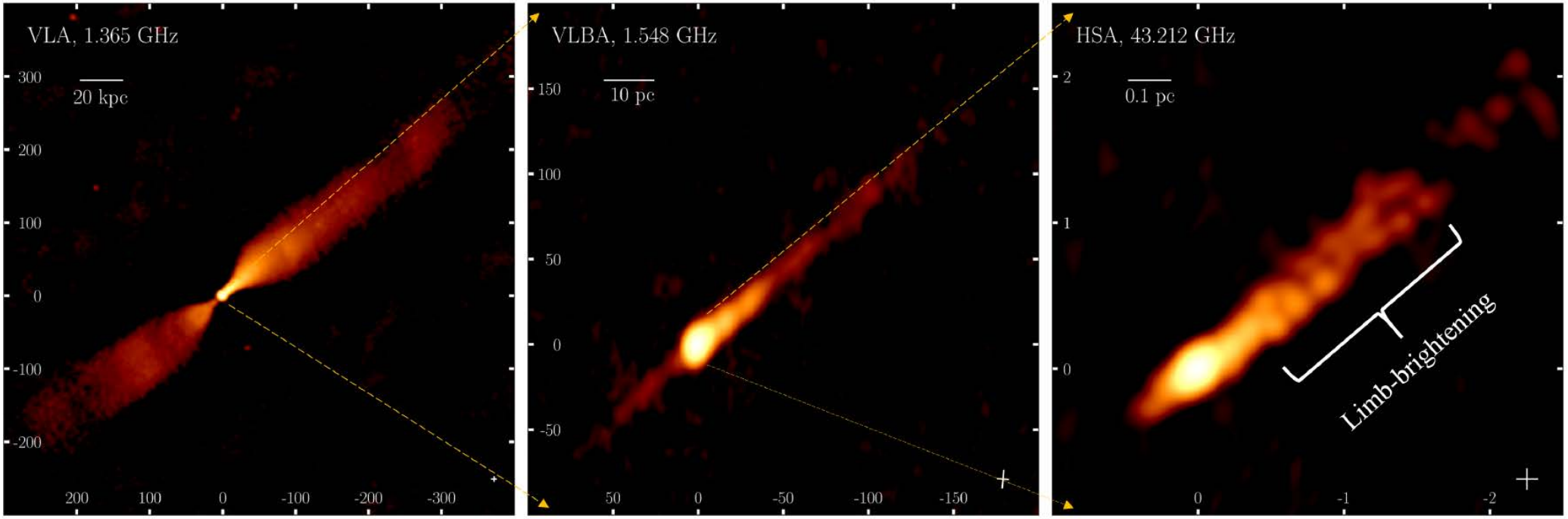


Chatte

— Interaction between the jet and the wind → Mas

Development of pinch instabilities → Deceleration of the jet & Radiating superluminal hotspots or magnetic reconnection

Limb-brightening of the jet in NGC 315

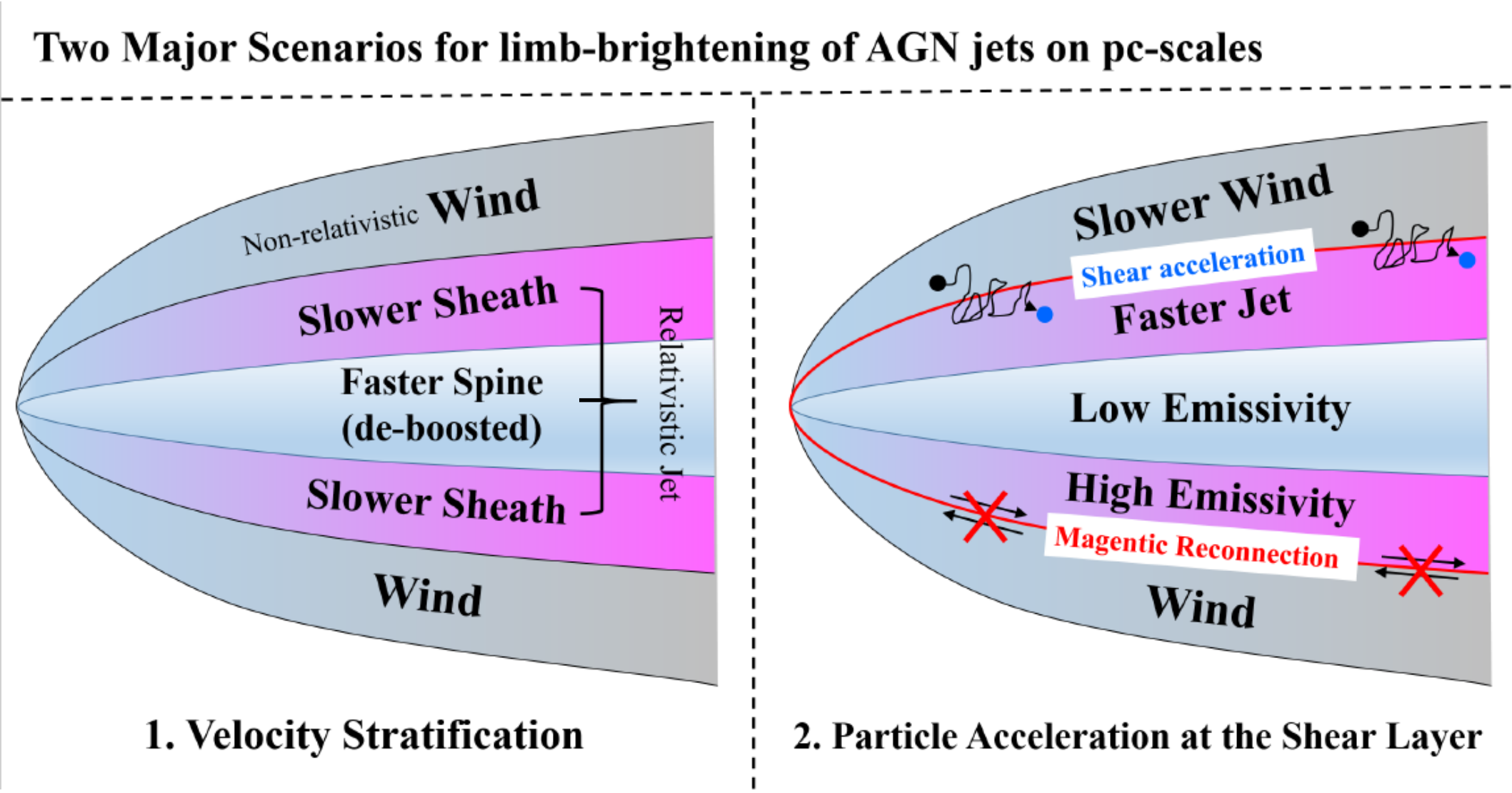


The only data having good enough resolution

— A limb-brightening of the jet is detected only at 43 GHz where the angular resolution is higher than the observed jet width.

→ There is a possibility that the jet is intrinsically limb-brightened but this has not been observed in previous studies using low angular resolution.

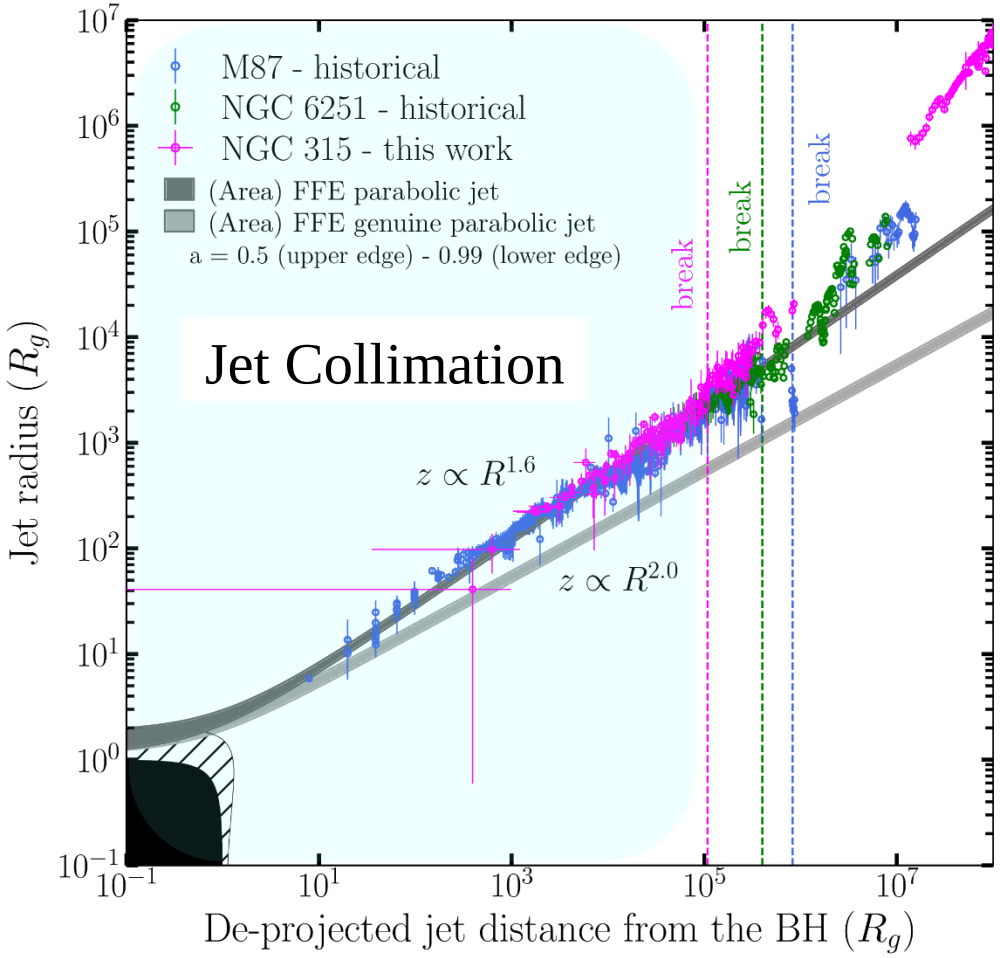
Limb-brightening of the jet in NGC 315

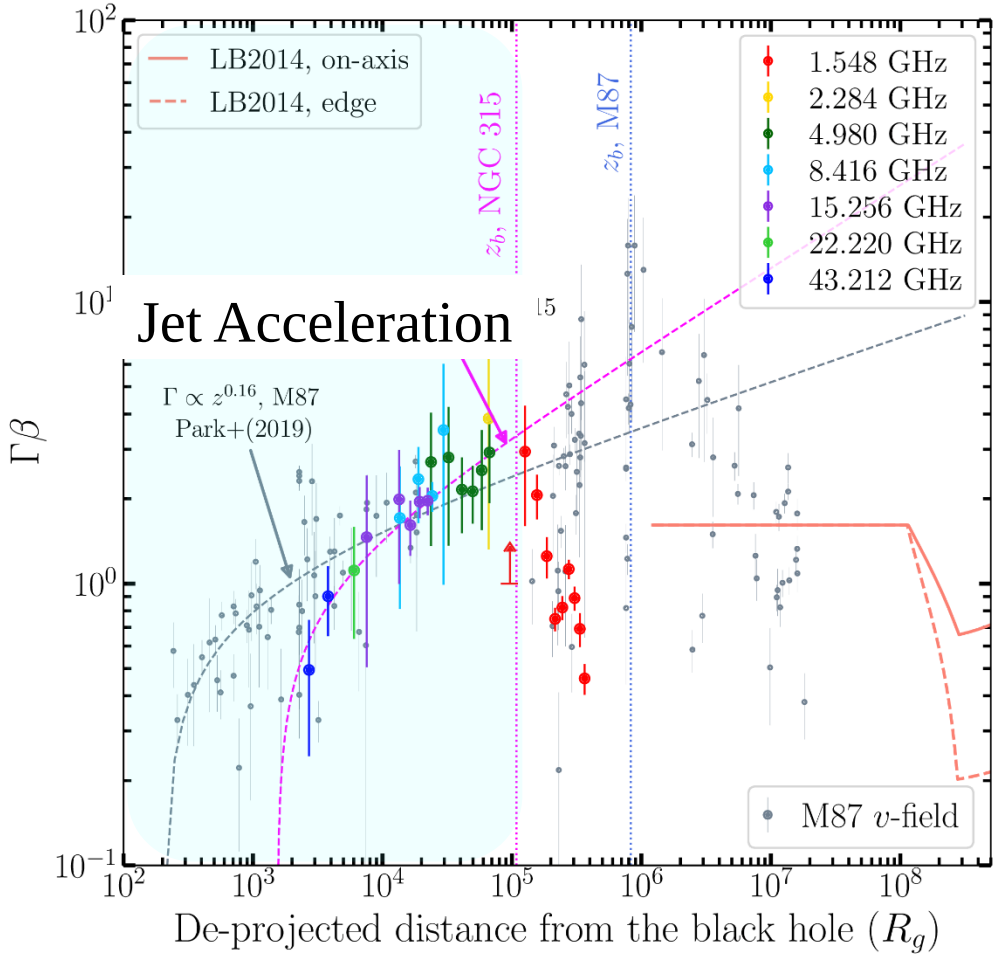


— The faster-spine and slower-sheath velocity structure has been considered in many previous studies. However, the MHD jet acceleration models have shown that it is difficult to accelerate the spine to relativistic speeds (weak magneto-centrifugal force).

Conclusions (Park et al. 2021, ApJ, in press, arXiv:2012.14154)

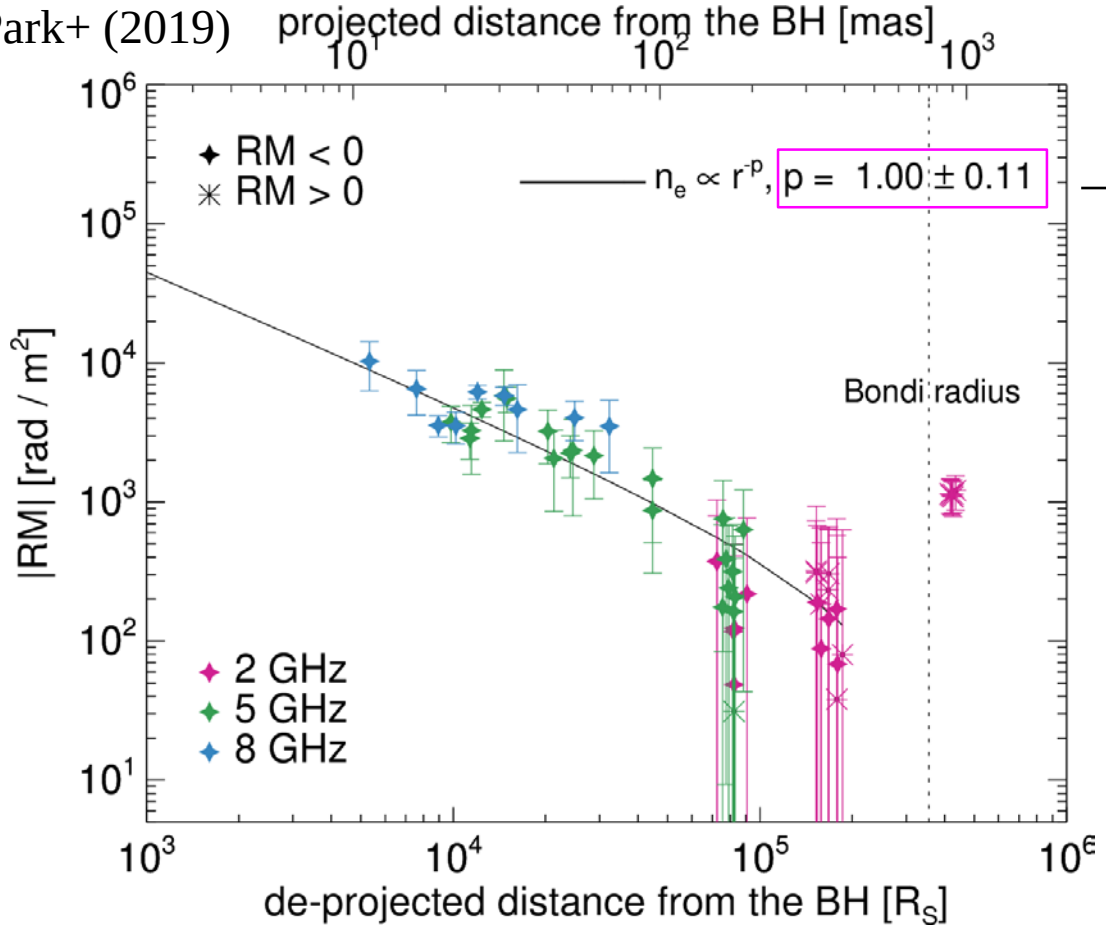
— We have discovered that systematic jet collimation and acceleration occur in the same region over a broad distance range, very similar to M87.
→ Consistent with the key prediction of the MHD jet acceleration model.
— Some of our findings indicate that the jet is already actively interacting with the ambient medium on pc-scales.





Applying the model of hot accretion flows to the RM data

Park+ (2019)



$\rho \propto r^{-1}$

Observations of Faraday Rotation Measures in the M87 Jet (Park+ 2019)

$P_{\rm gas} \propto \rho^{\gamma} \propto r^{-1.67}$

$\gamma = 5/3$

$\alpha \sim 1.67$

$P_{\rm ext} \propto r^{-\alpha}$

Komissarov+ (2009)

(Cold, axisymmetric MHD models)

The external pressure

distance

– To have a parabolic jet shape, $\alpha \leq 2$ is needed (external-confinement).