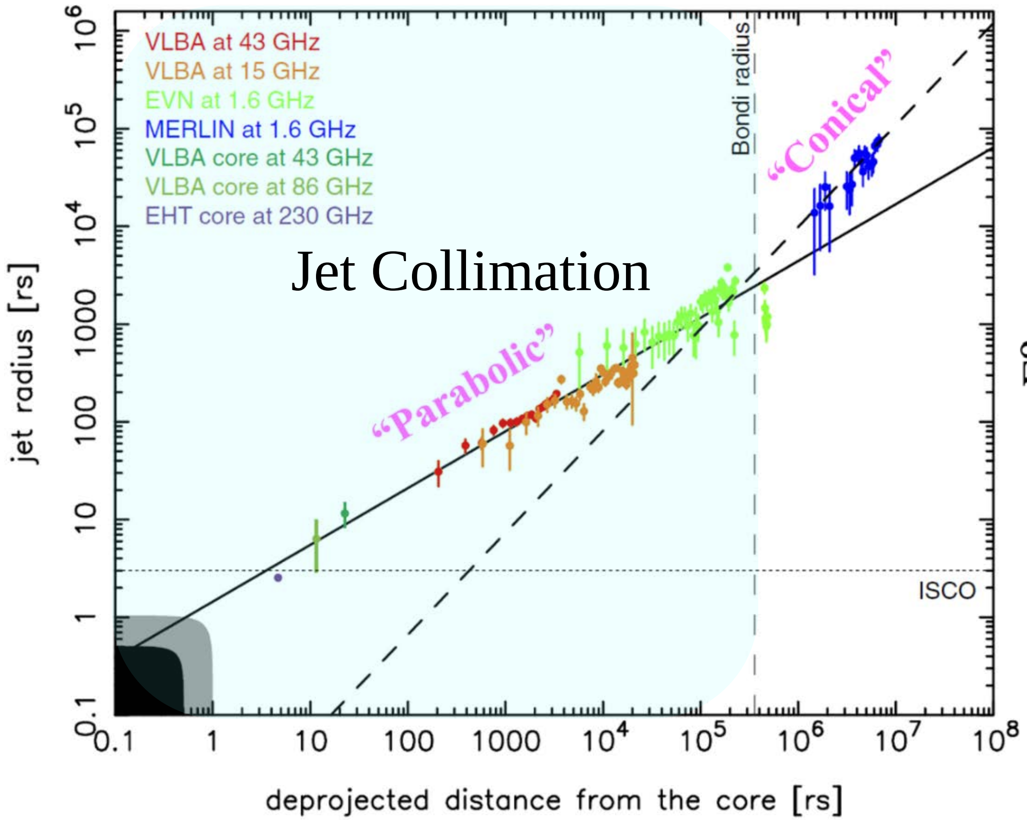
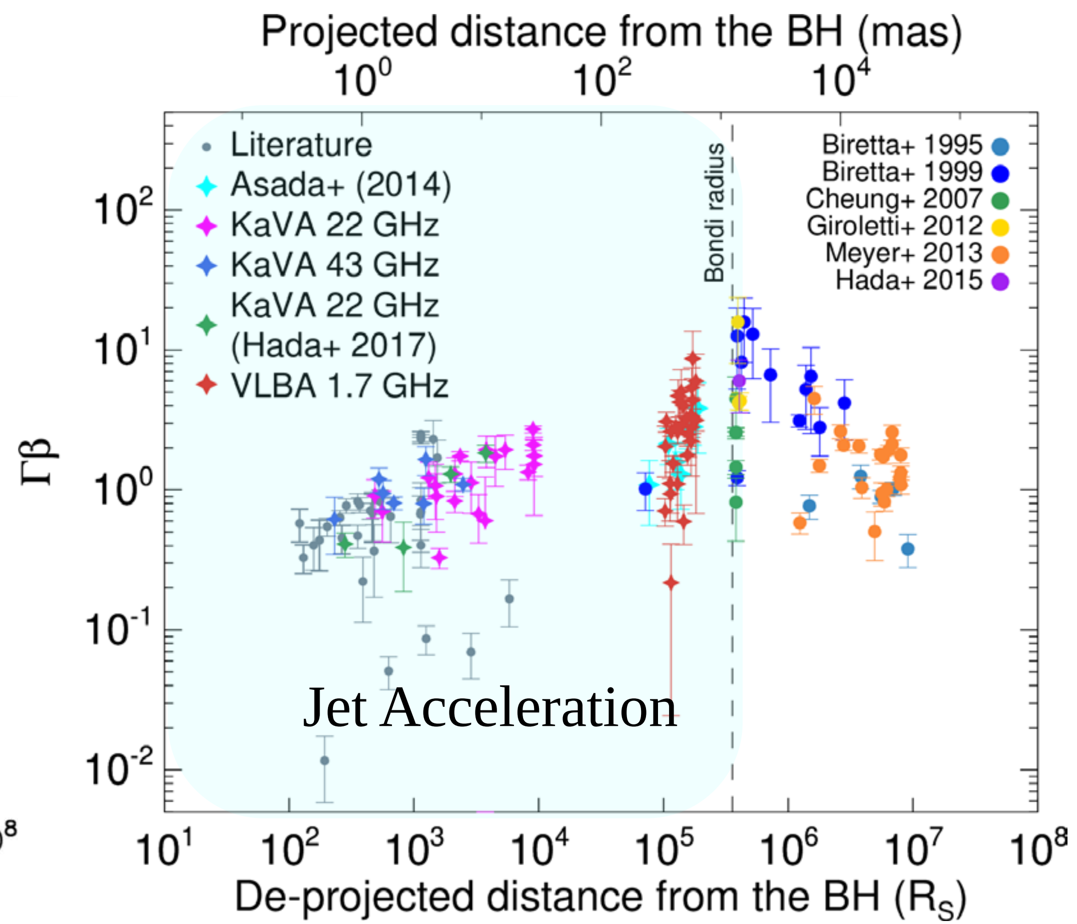
Kinematics of the M87 Jet in the Collimation Zone: Gradual Acceleration and Velocity Stratification



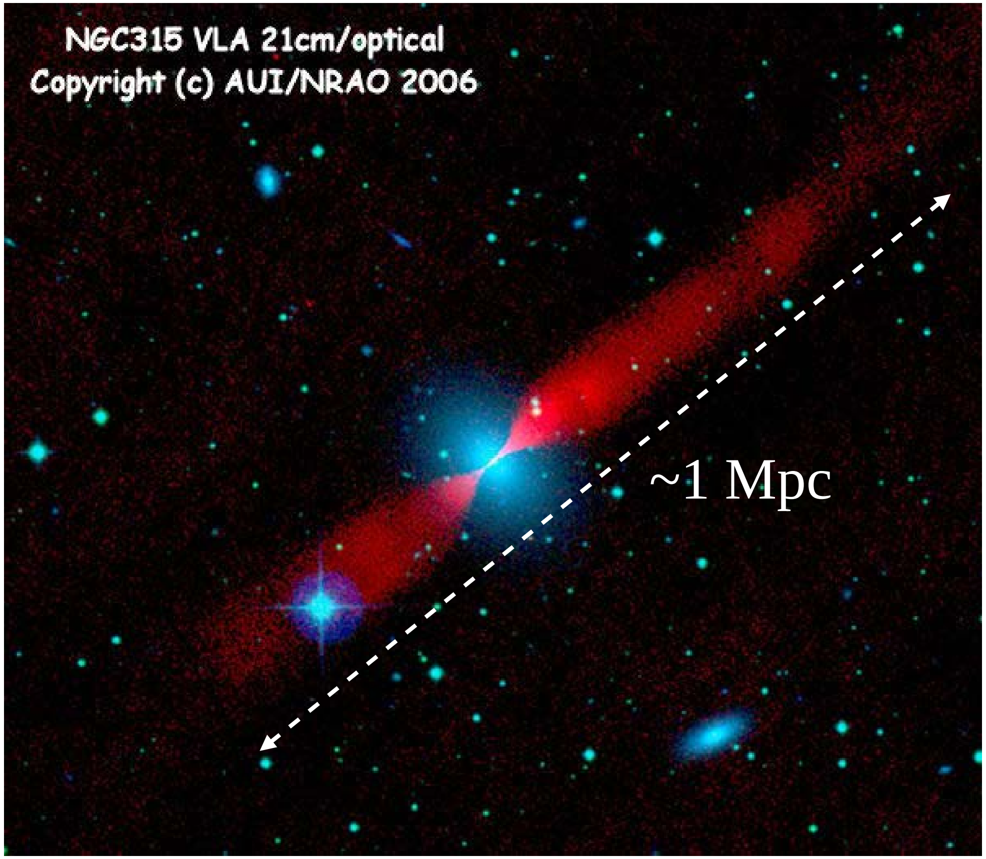
Nakamura & Asada (2013)



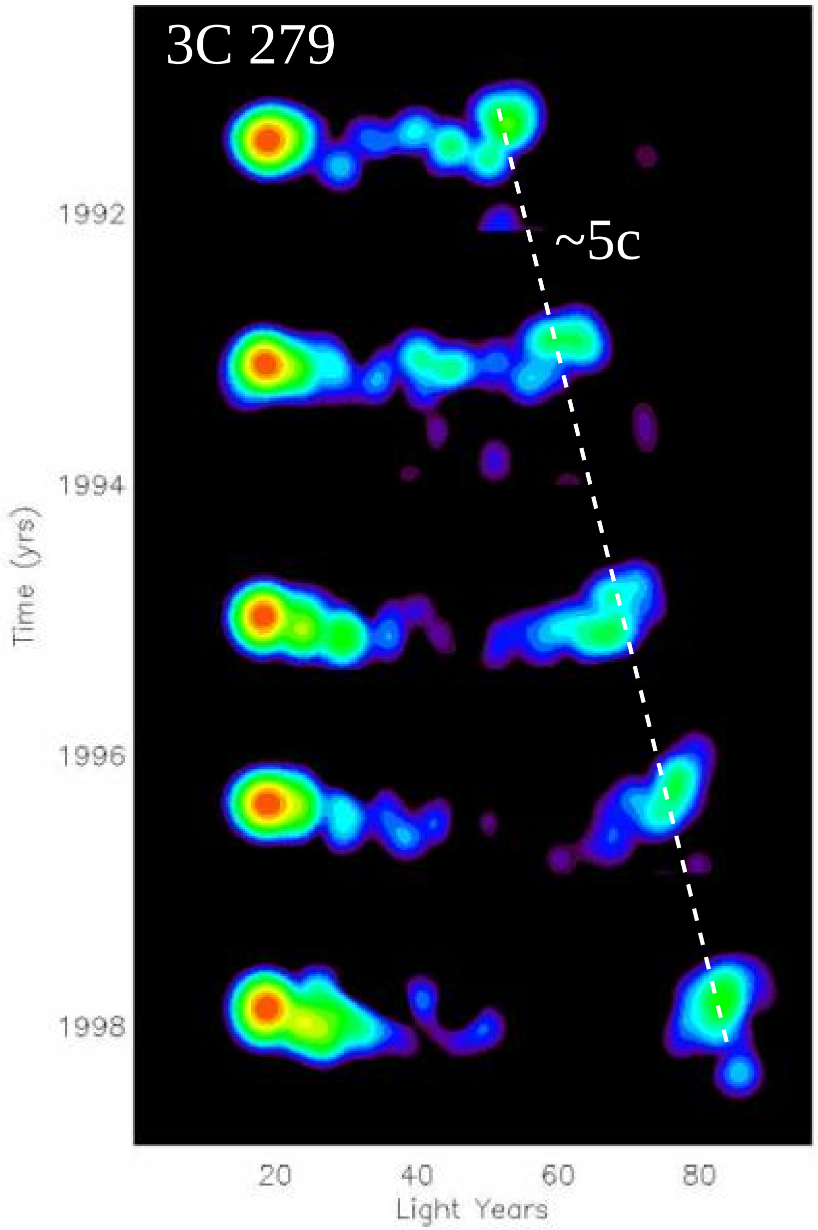
Park et al. 2019

Jongho Park (ASIAA) In collaboration with
Kazuhiro Hada, Motoki Kino, Masanori Nakamura, and EAVN AGN SWG

Highly Collimated and Relativistic Jets of AGNs

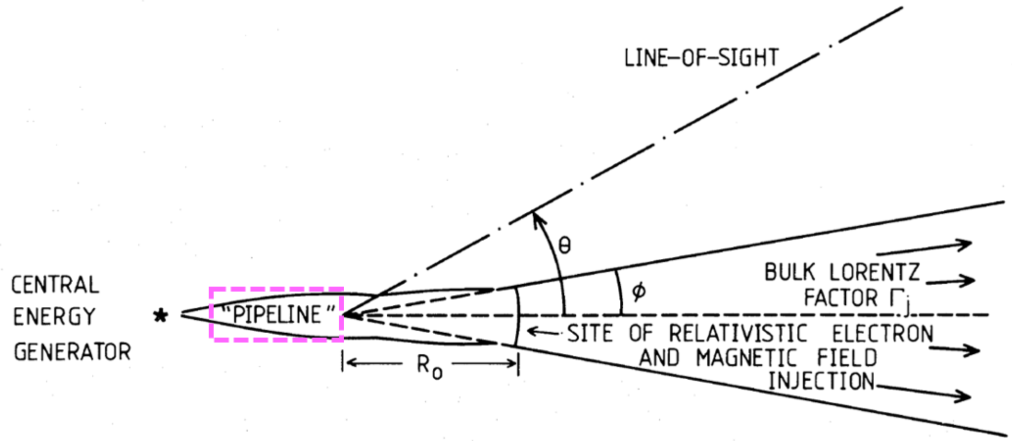


Highly collimated, very narrow jets

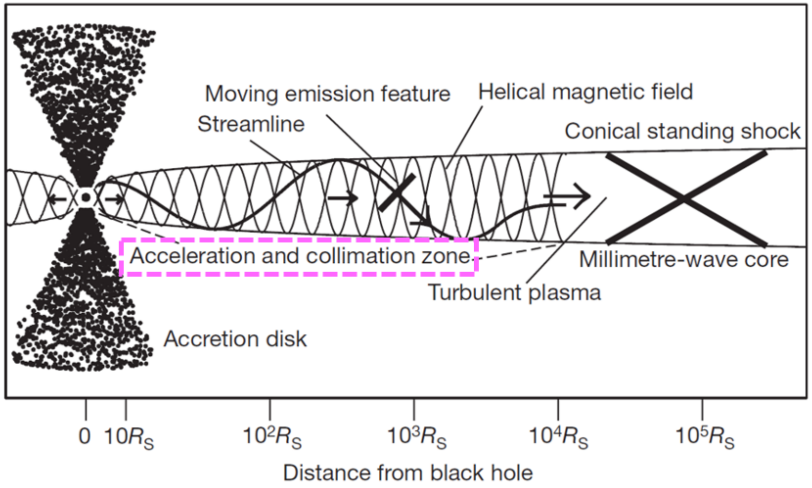


Superluminal motions

Acceleration and Collimation of AGN Jets



Understanding of AGN jets in 1985
(Marscher & Gear 1985)

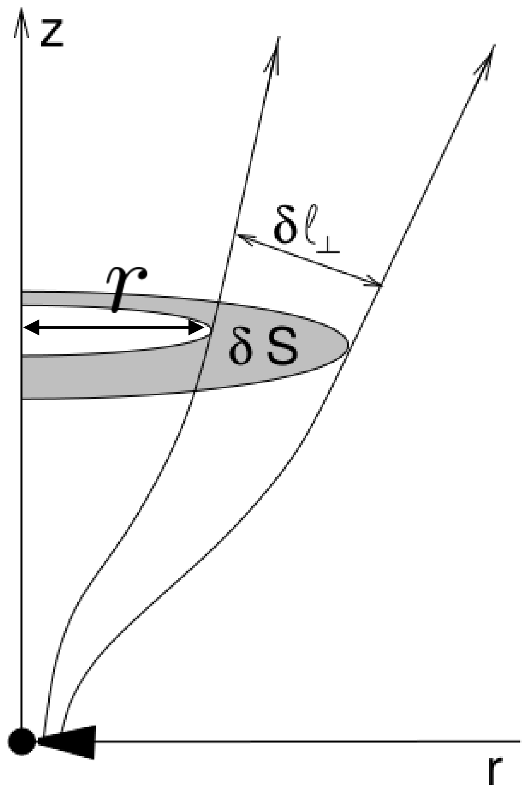


Understanding of AGN jets in 2008
(Marscher et al. 2008)

Jet Acceleration & Collimation

: a "pipeline" to produce highly collimated relativistic AGN jets

Magnetic Jet Acceleration Model



Vlahakis 2015

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

$$\frac{\text{Poynting flux}}{\text{Total energy flux}} \propto r^2 B_p$$

$$B_p \delta S = \text{const} \qquad \delta S = r\delta l_\perp$$

$$\frac{\text{Poynting flux}}{\text{Total energy flux}} \propto \frac{r}{\delta l_\perp}$$

'Differential Collimation' of Poloidal Field Lines

: Inner fields are more collimated than outer lines

→ Jet *Collimation* & *Acceleration* are intimately related to each other.

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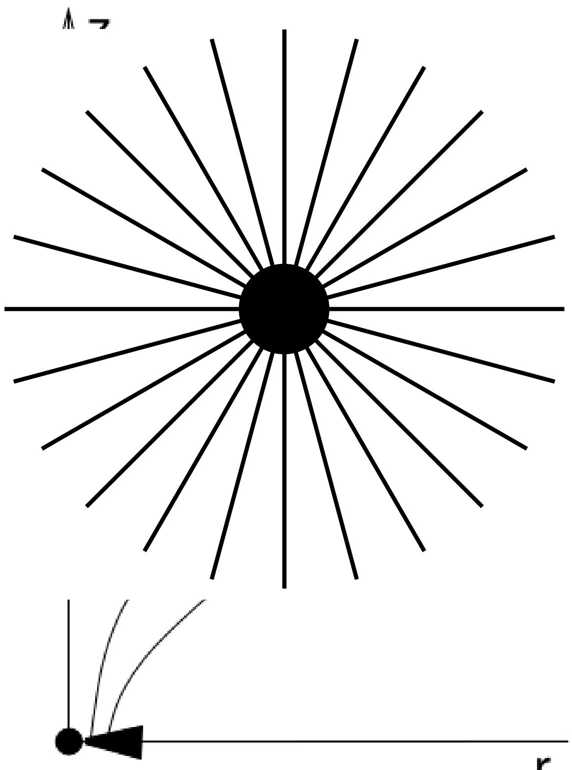

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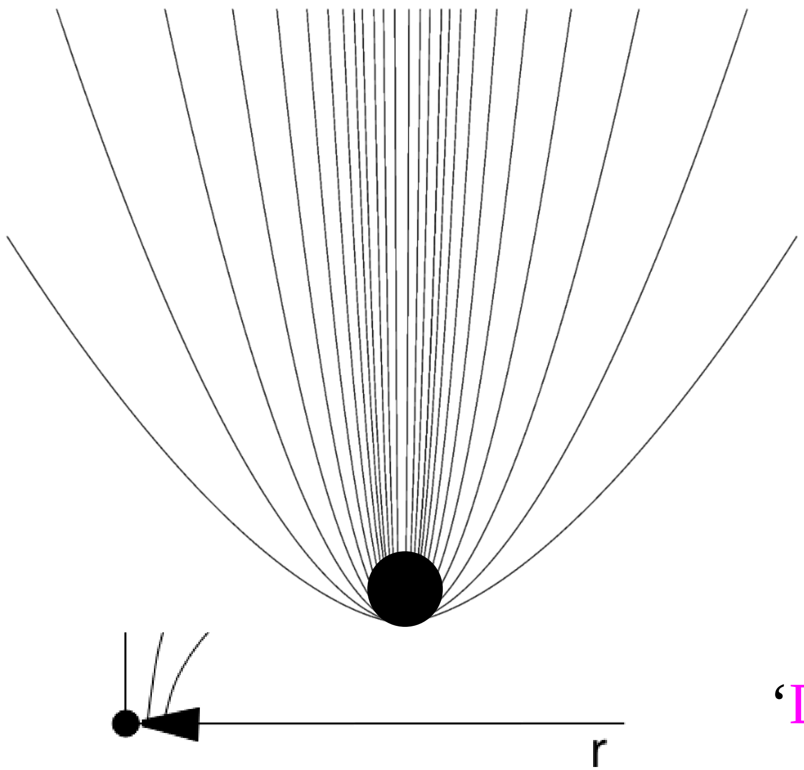

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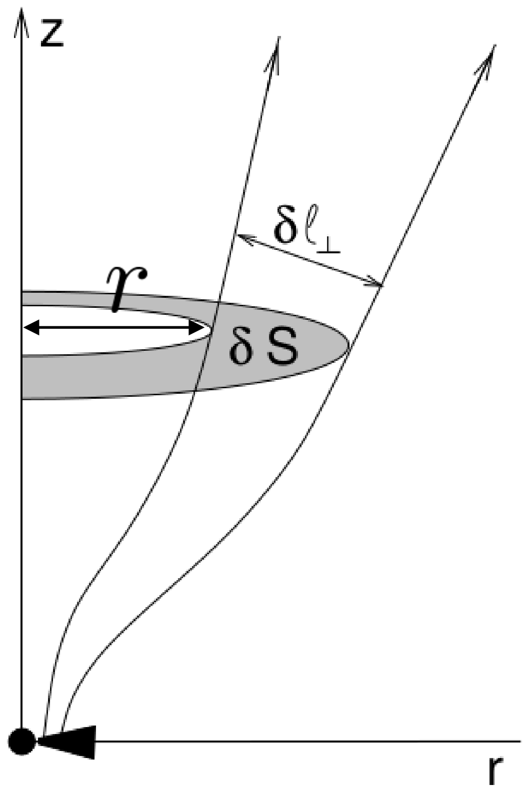

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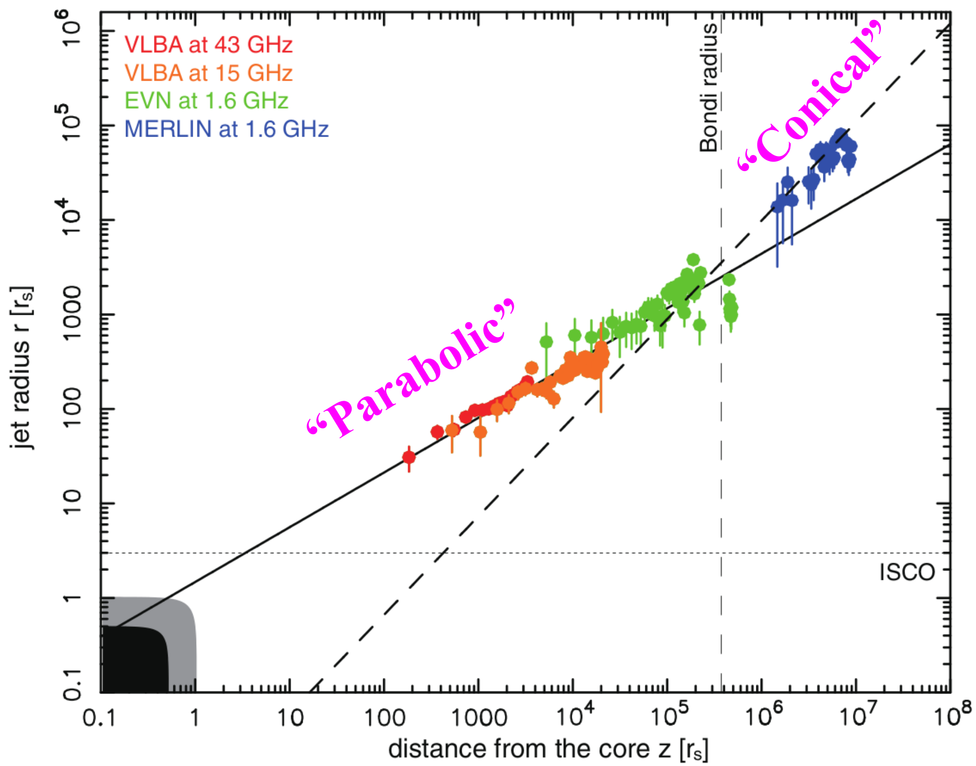
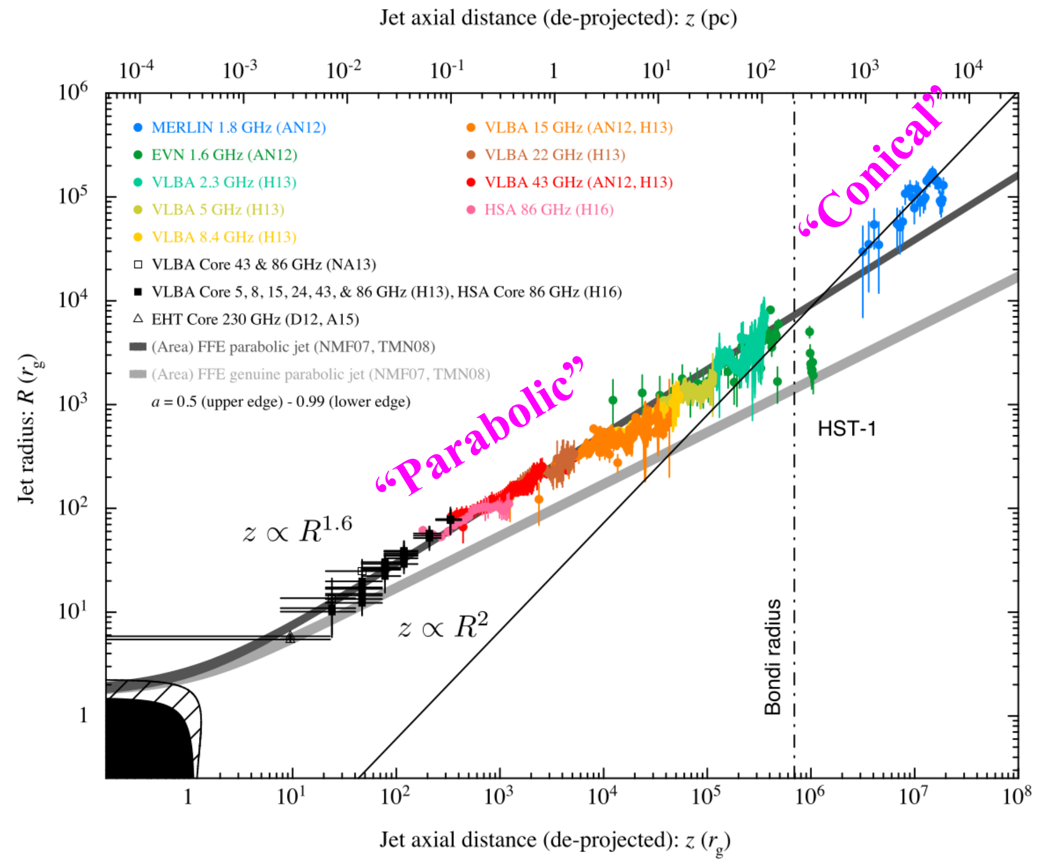
Jet Collimation in nearby AGN jets



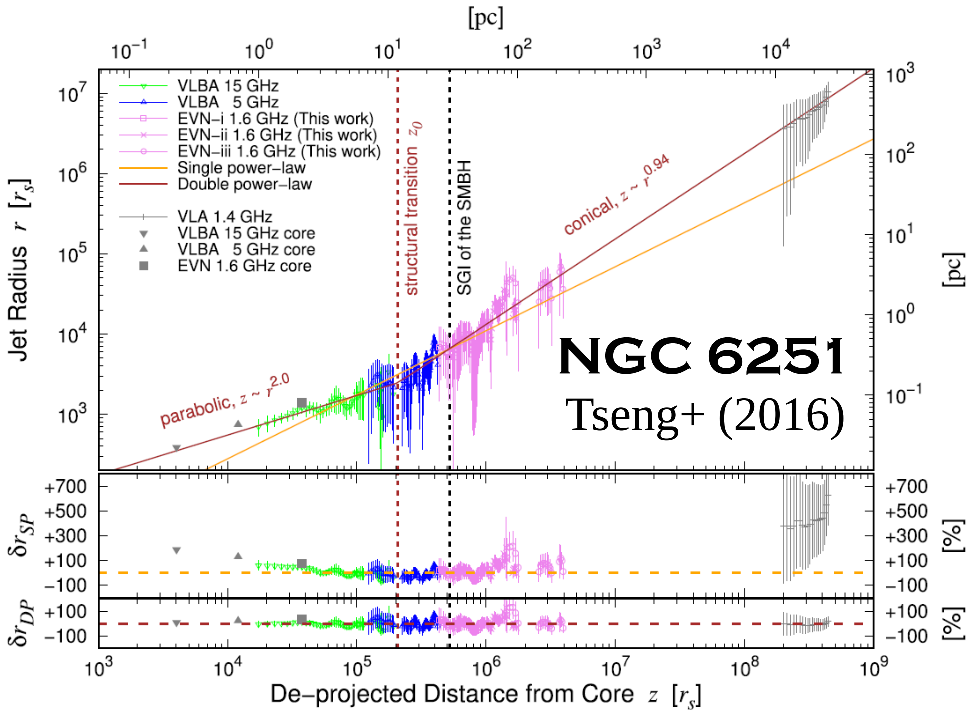
Asada & Nakamura (2012)

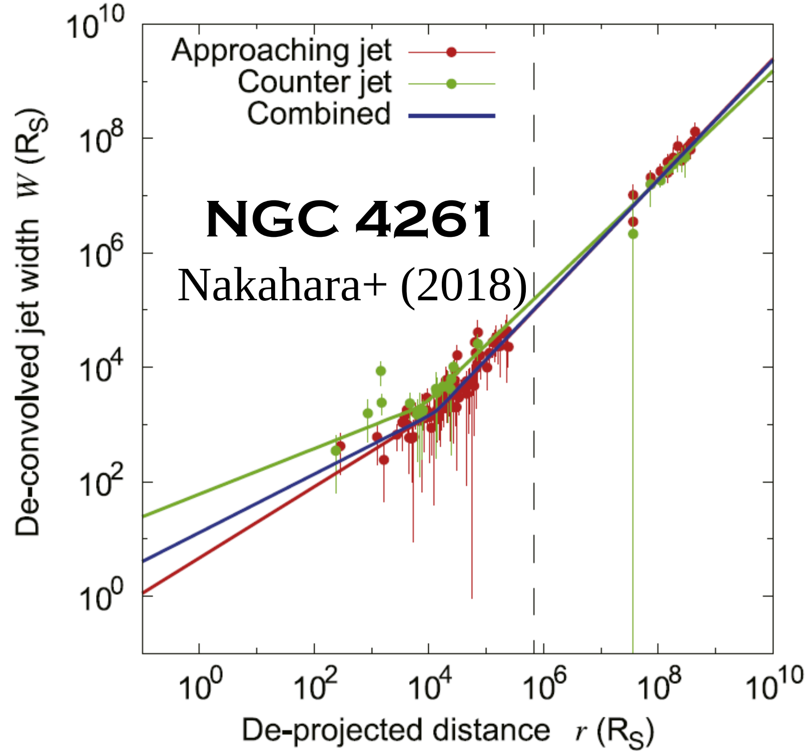


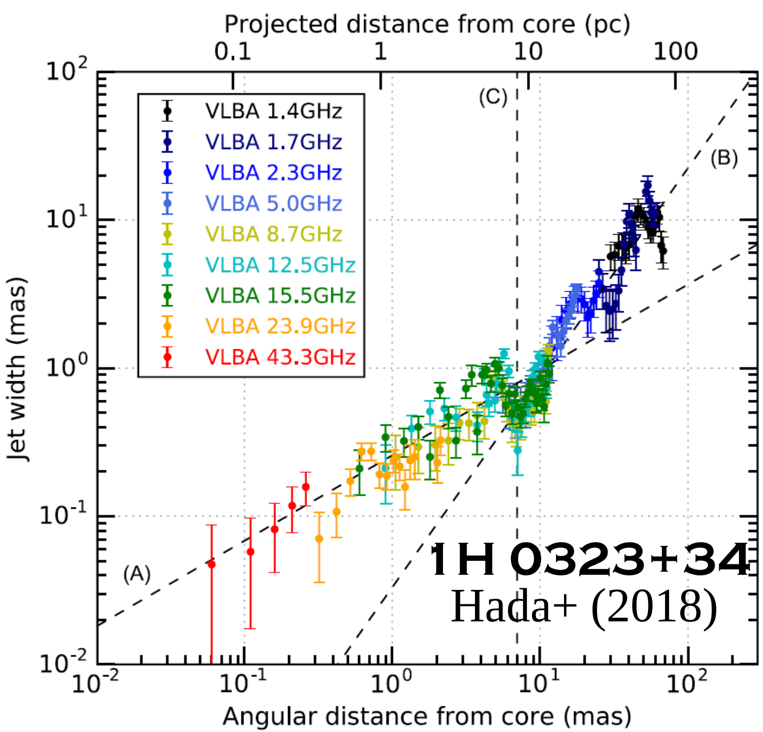
Hada et al. (2013)
Nakamura et al. (2018)

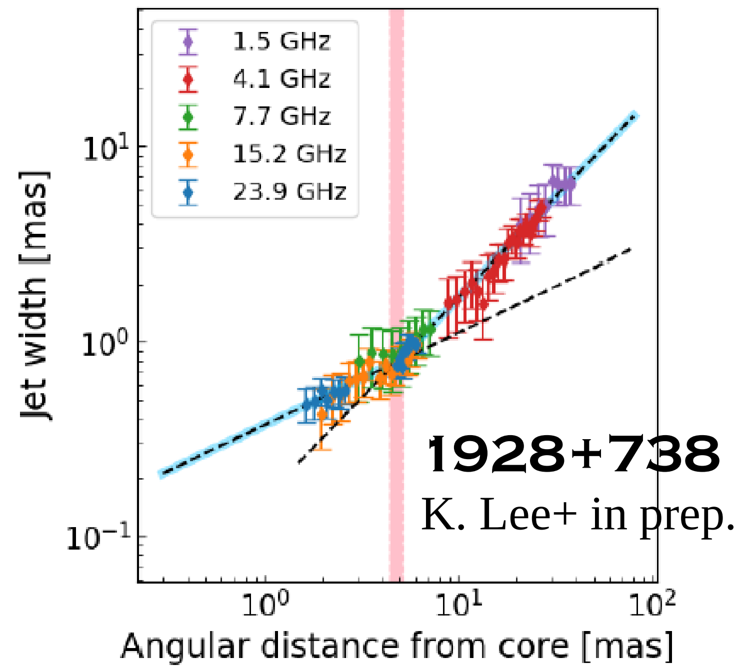
M87

Jet Collimation in nearby AGN jets

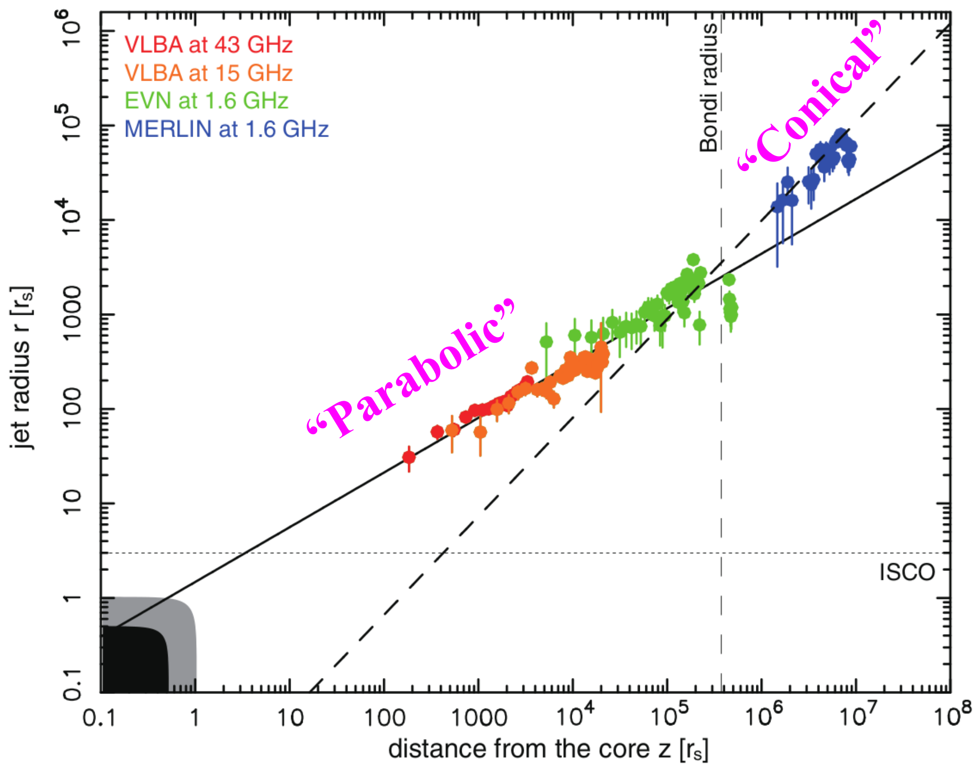




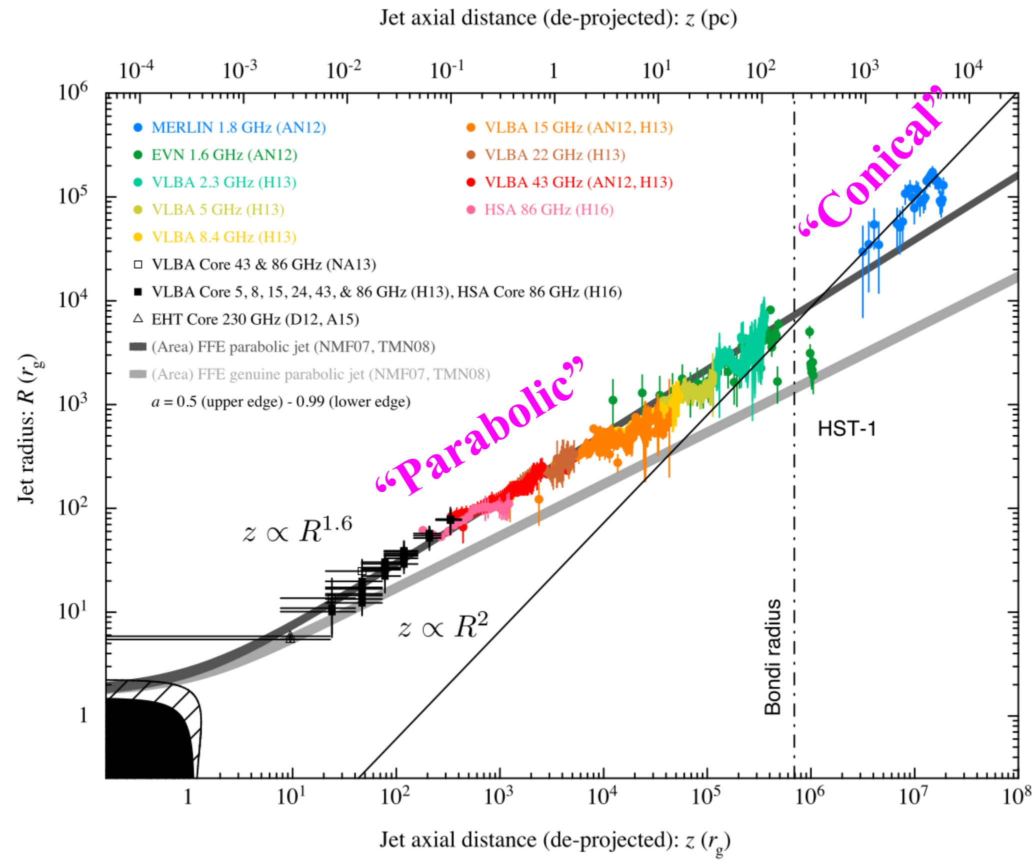




Jet Collimation in M87



Asada & Nakamura (2012)

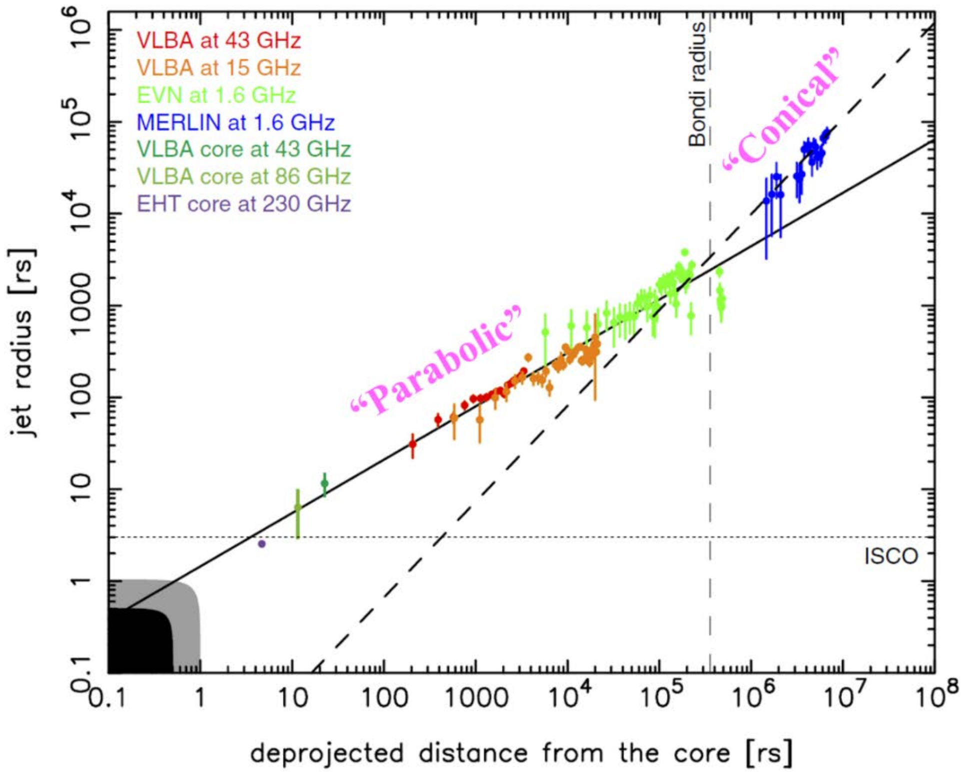


Nakamura et al. (2018)

Is the M87 jet accelerated to relativistic speeds in the collimation zone?

Jet Acceleration in M87

Jet Collimation ⟷ Jet Acceleration

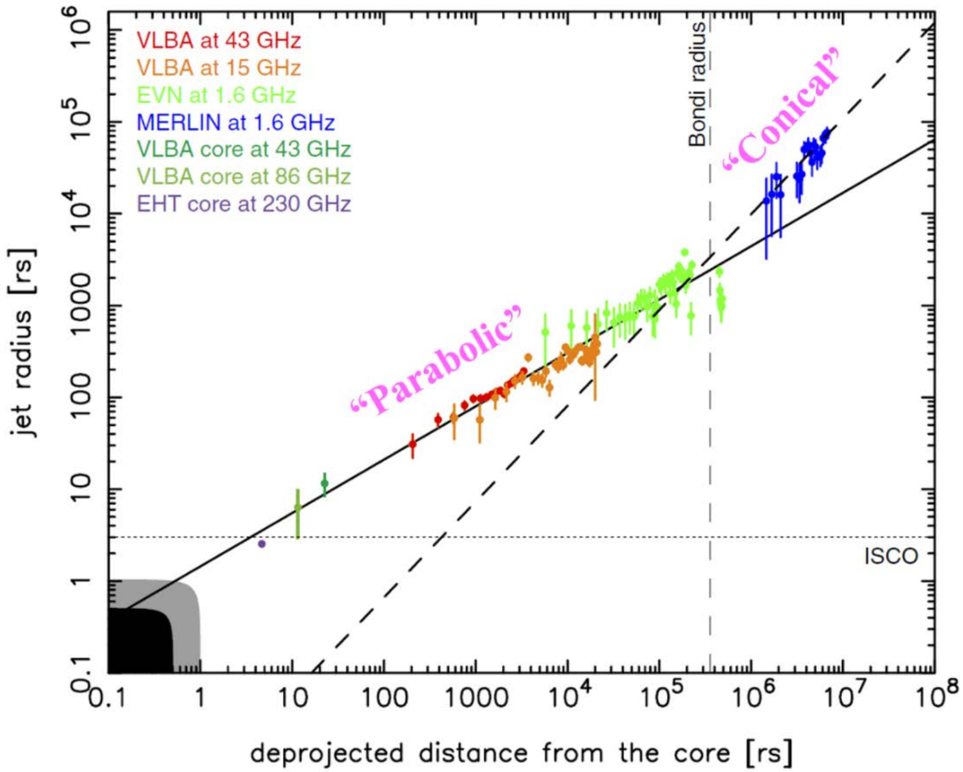


Asada & Nakamura (2012)
Nakamura & Asada (2013)

?

Jet Acceleration in M87

Jet Collimation ⟷ Jet Acceleration



Asada & Nakamura (2012)
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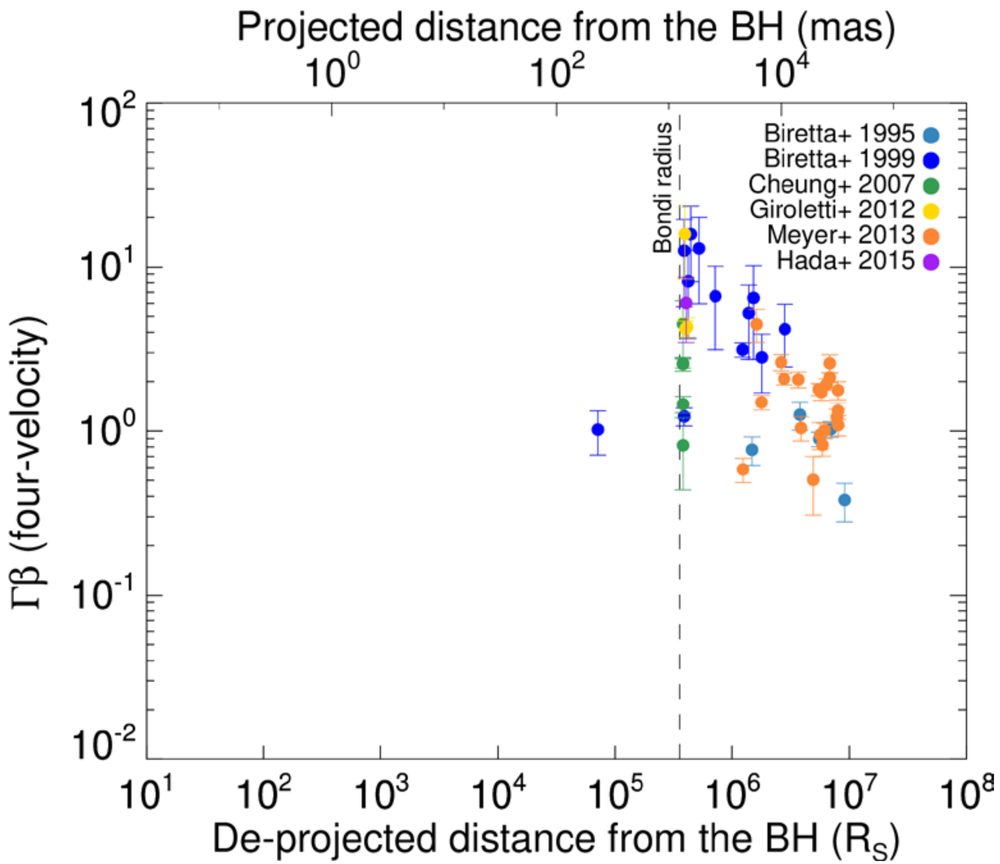

Jet Acceleration in M87

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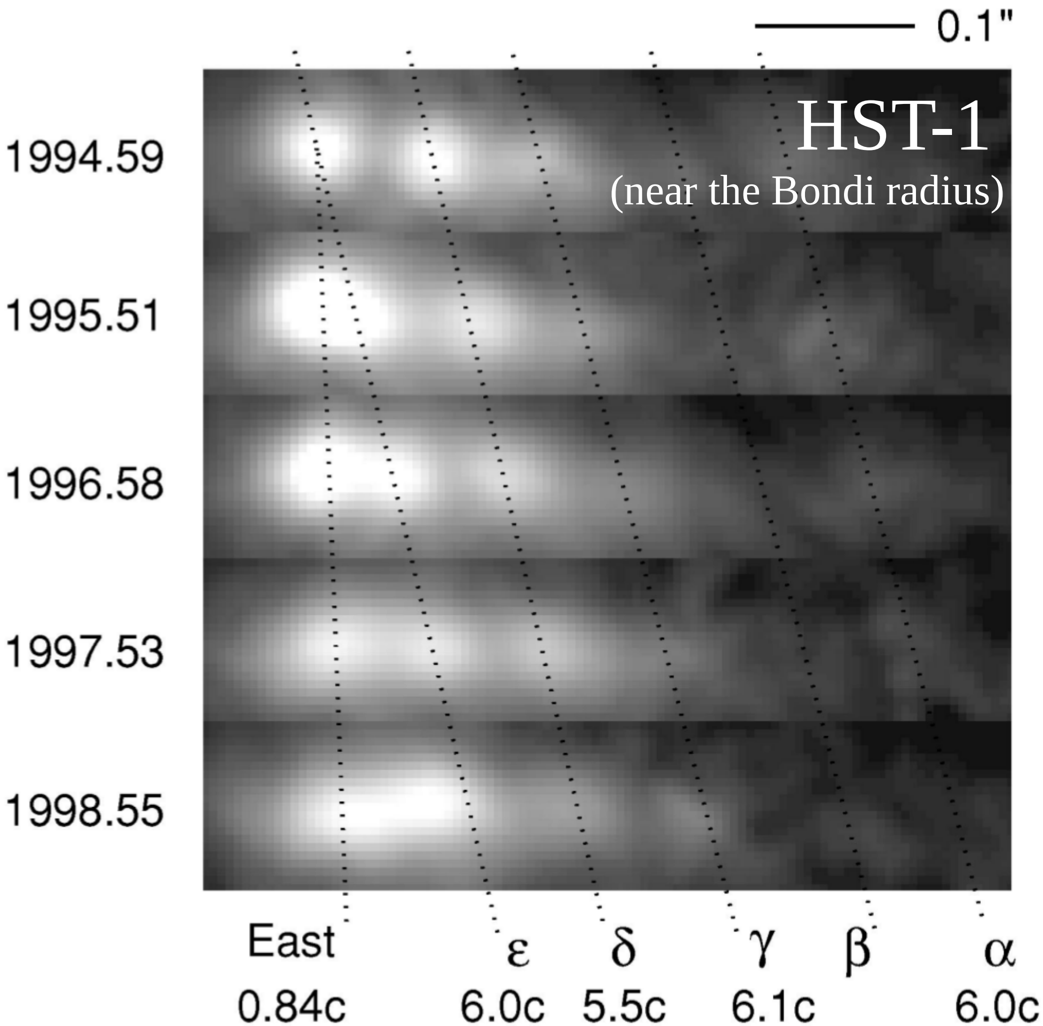
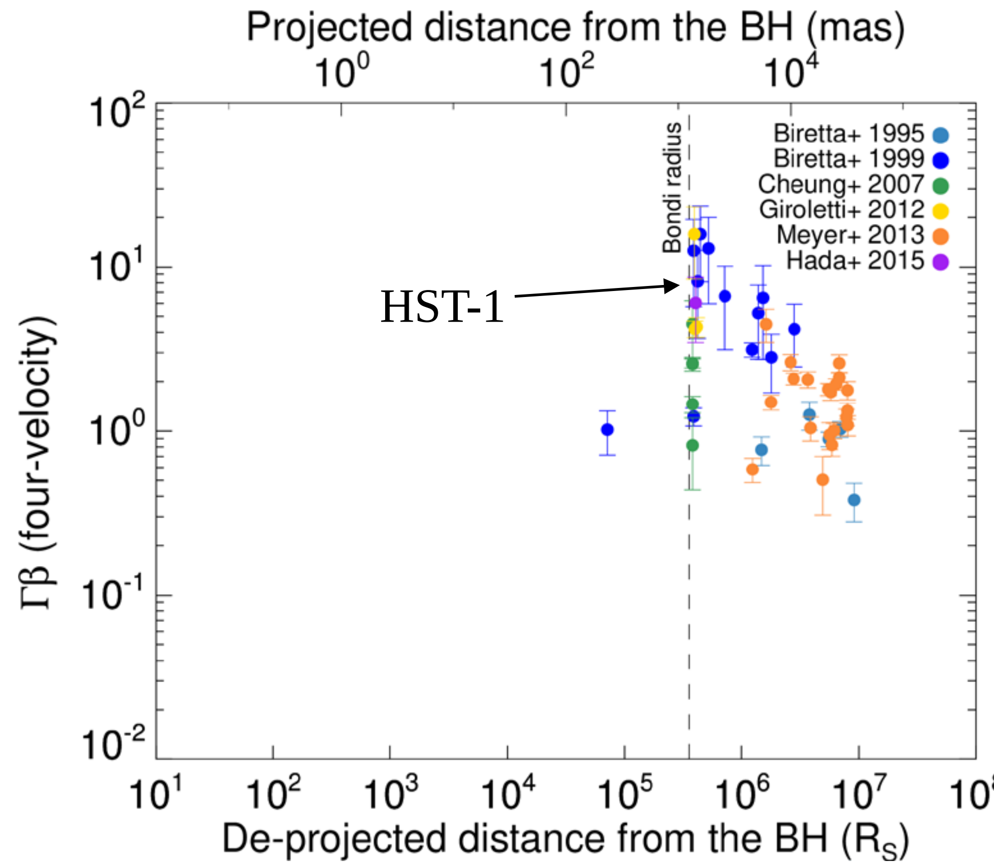
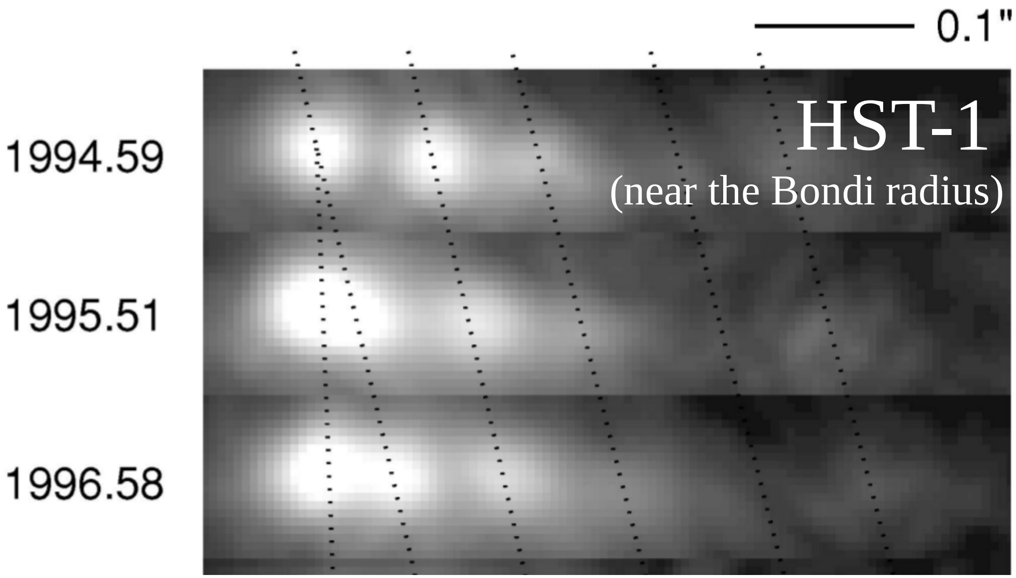


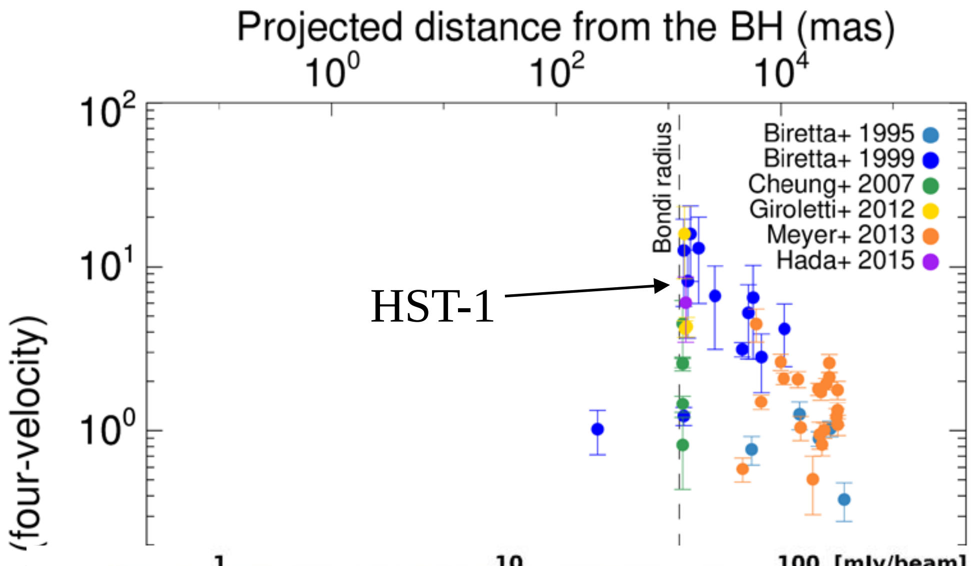
Biretta+ (1999), HST optical

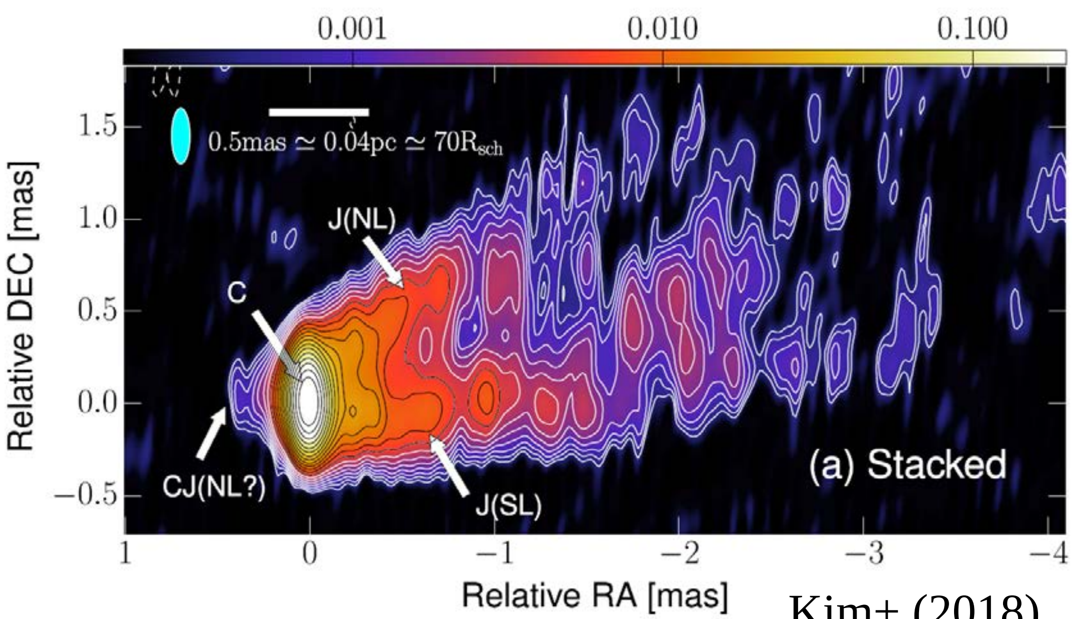


Jet Acceleration in M87

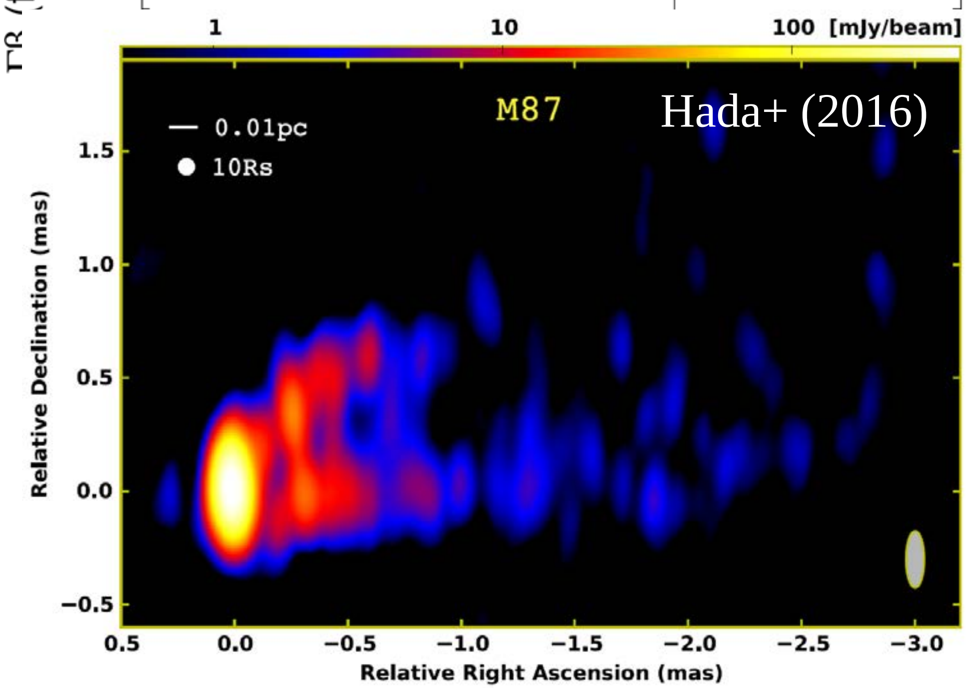
Jet Collimation ⟷ Jet Acceleration







Kim+ (2018)

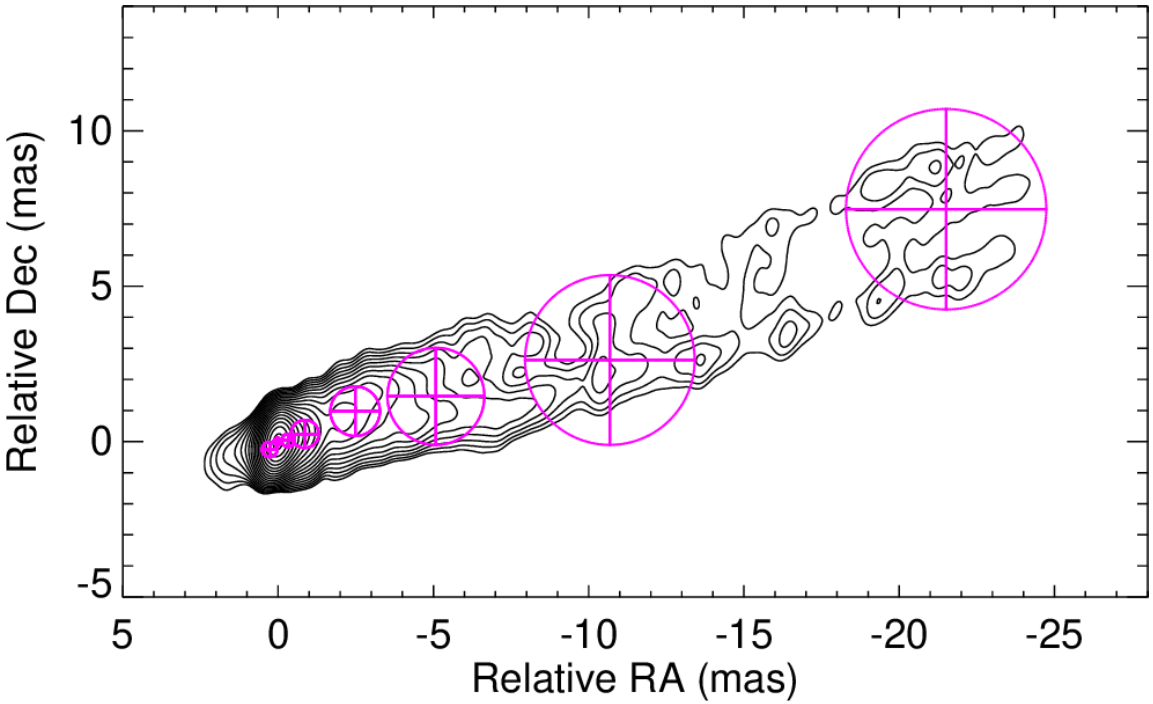


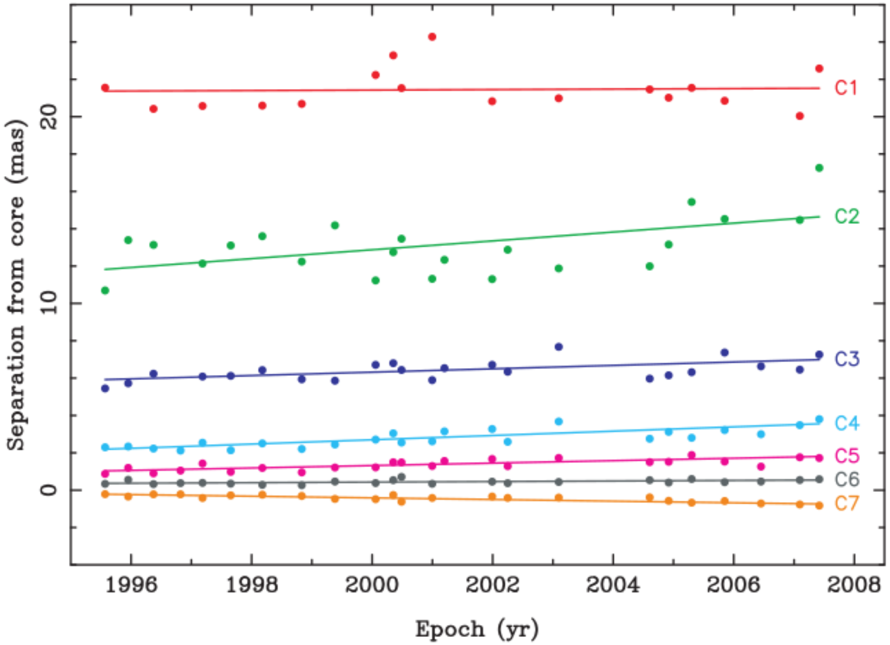
THE MOJAVE MONITORING PROGRAM

VLBA 15 GHz over ~10 years
Sampling Interval : ~6 months

'modelfit' components with
circular Gaussian brightness distributions

Kovalev et al. (2007)



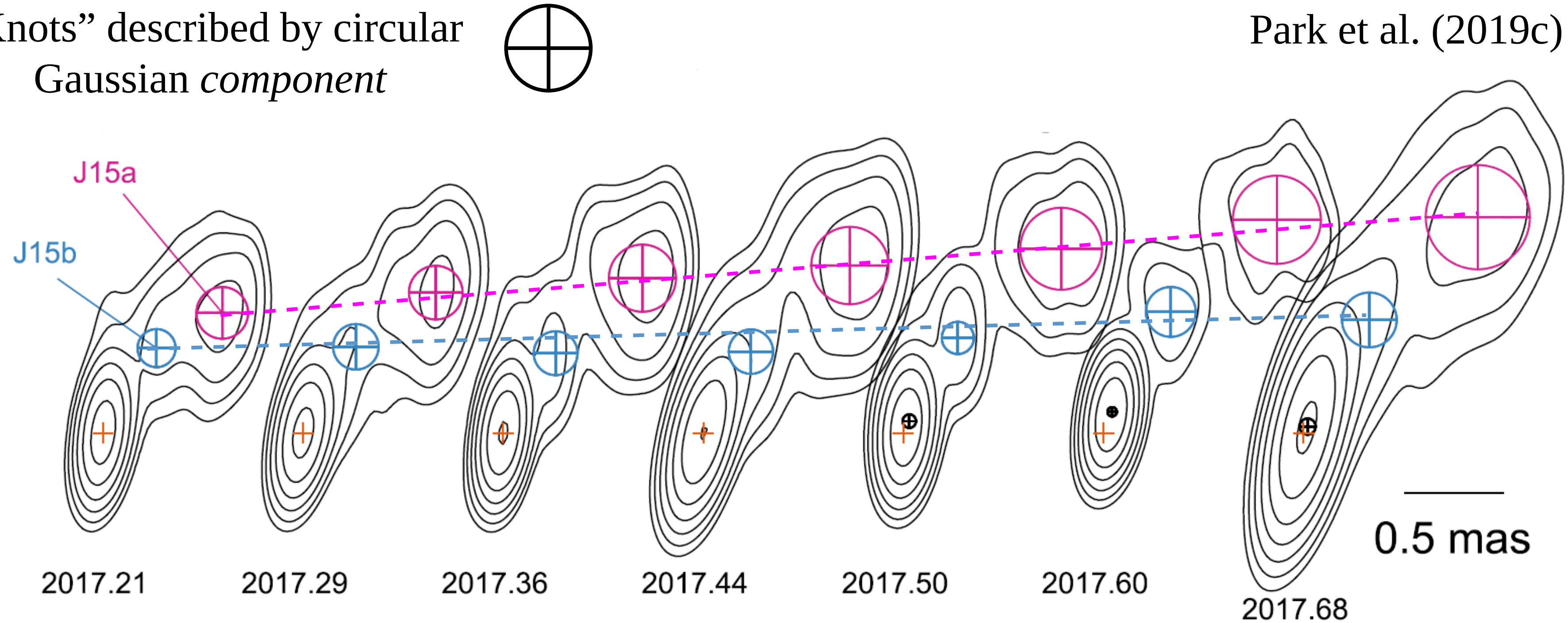


$$\beta_{\rm app} \lesssim 0.05c$$ at <~ 20 mas

Kinematics of the M87 jet : 1. modelfit

“Knots” described by circular Gaussian *component*

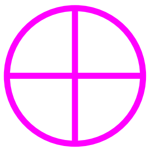
Park et al. (2019c)



Modelfit works very well for most blazars whose jets consist of several “knots”

The MOJAVE monitoring program

VLBA 15 GHz over ~10 years
Sampling Interval : ~6 months



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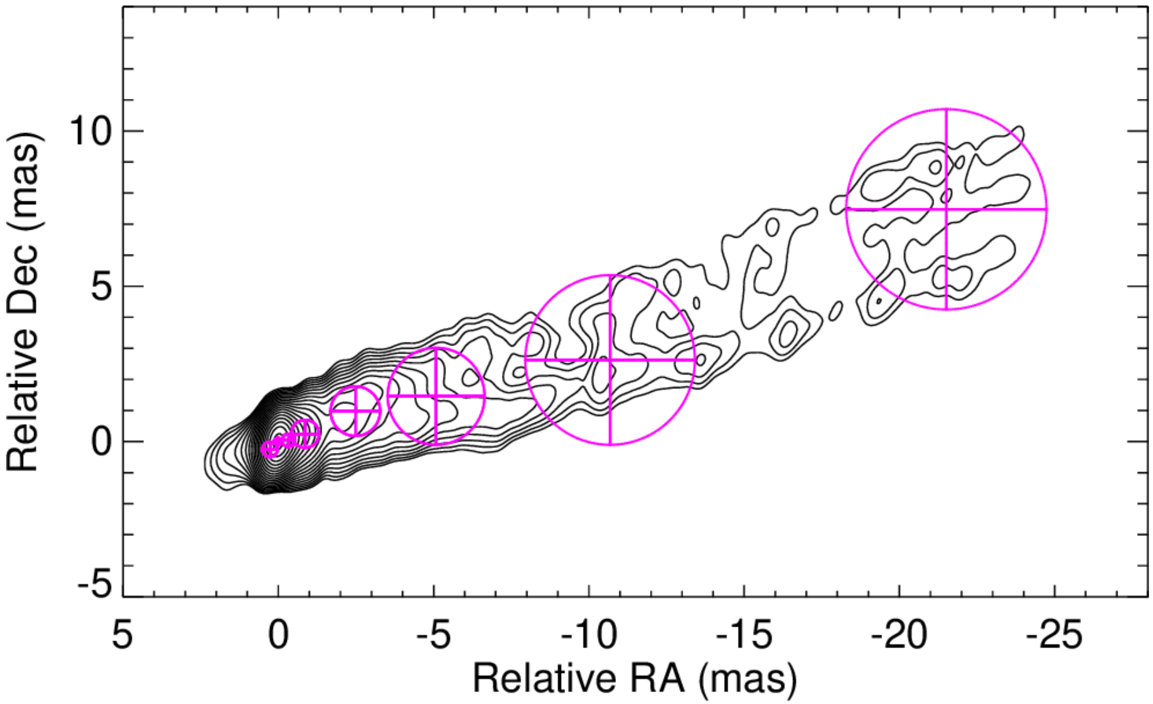
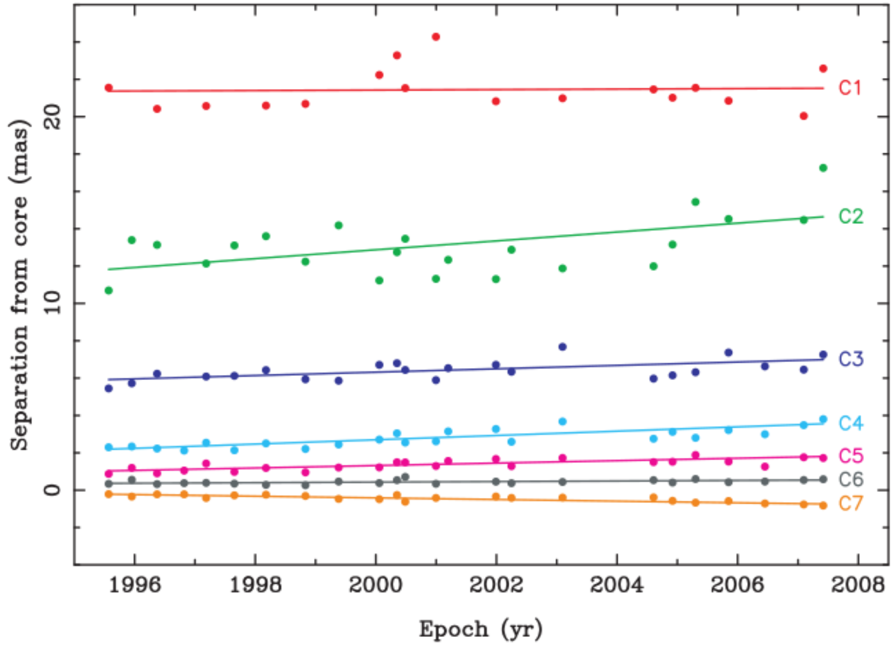
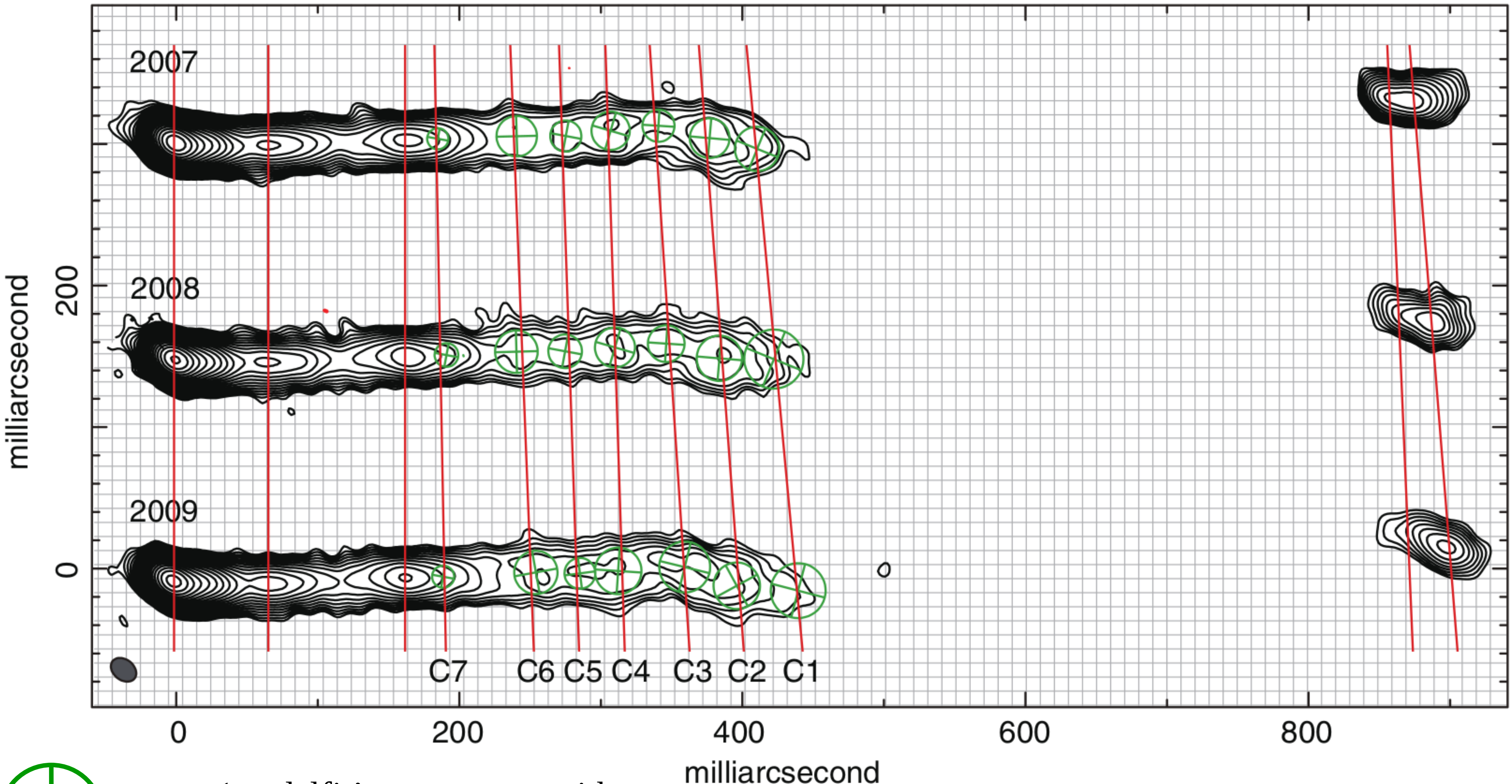


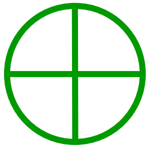


$$\beta_{\mathrm{app}} \lesssim 0.05c$$ at <~ 20 mas

EVN observations

EVN 1.6 GHz in three epochs
Sampling Interval : ~1 year

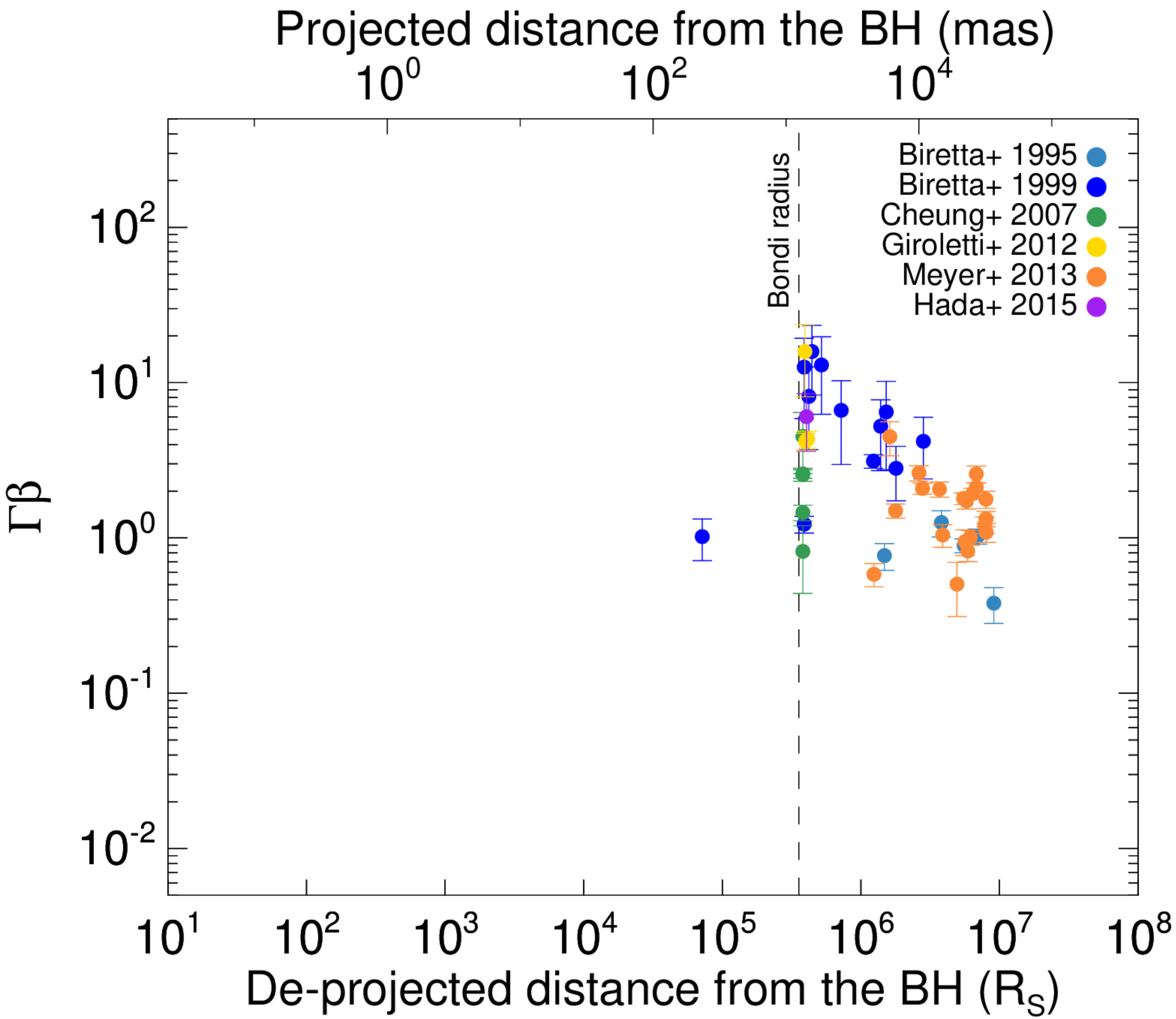




‘modelfit’ components with
circular Gaussian brightness distributions

Asada et al. (2014)

Kinematics of the M87 jet : 1. modelfit



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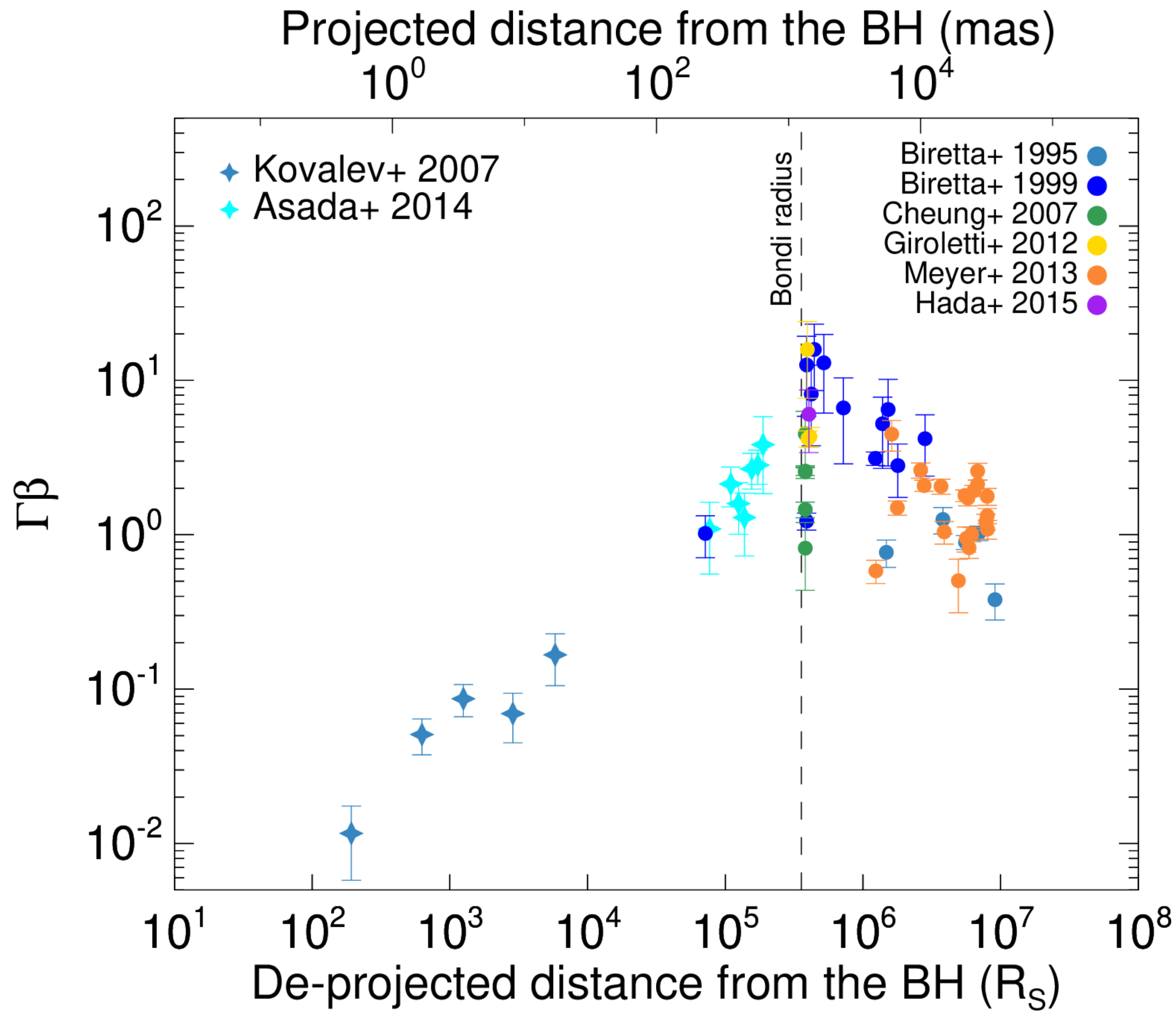

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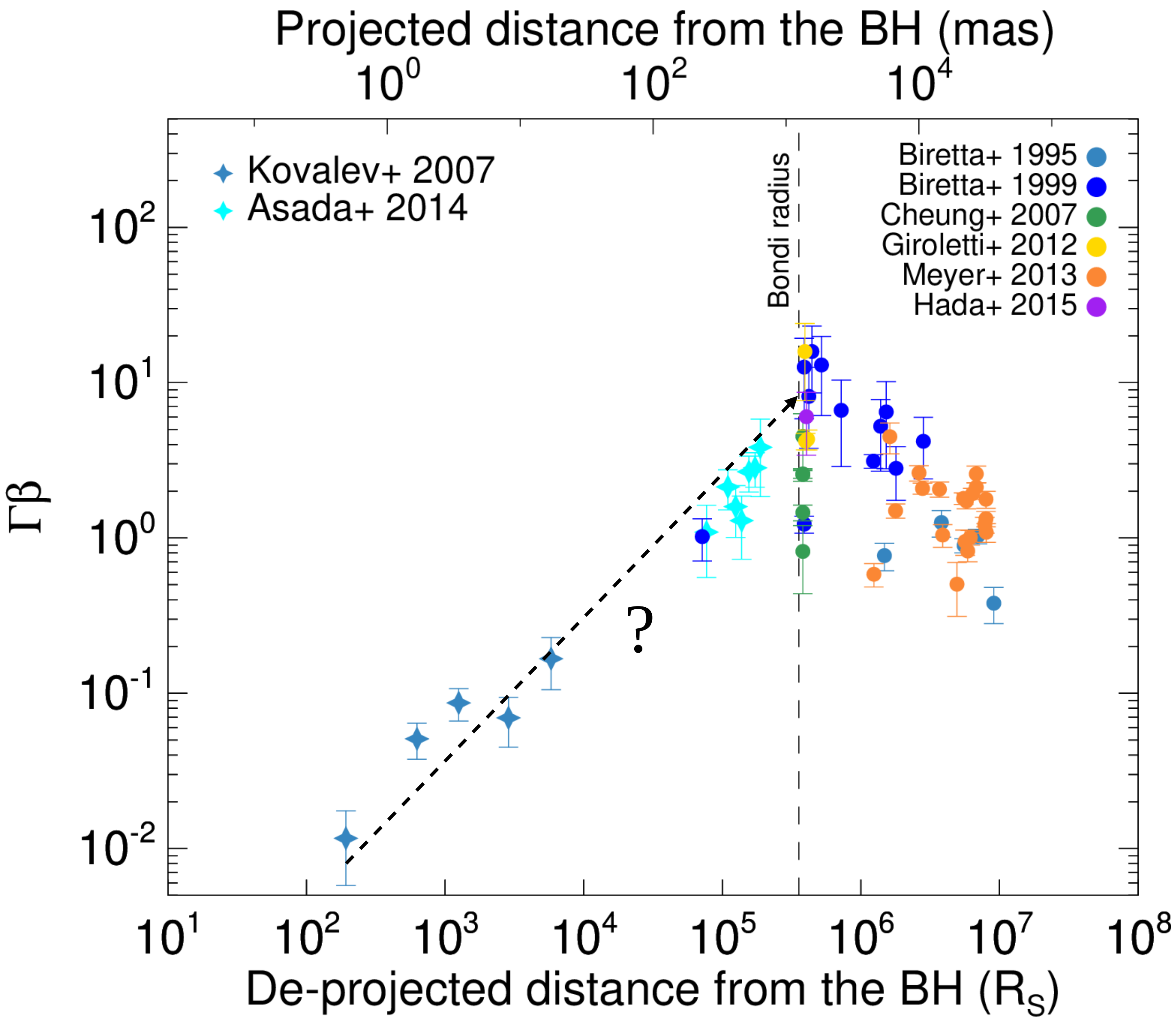
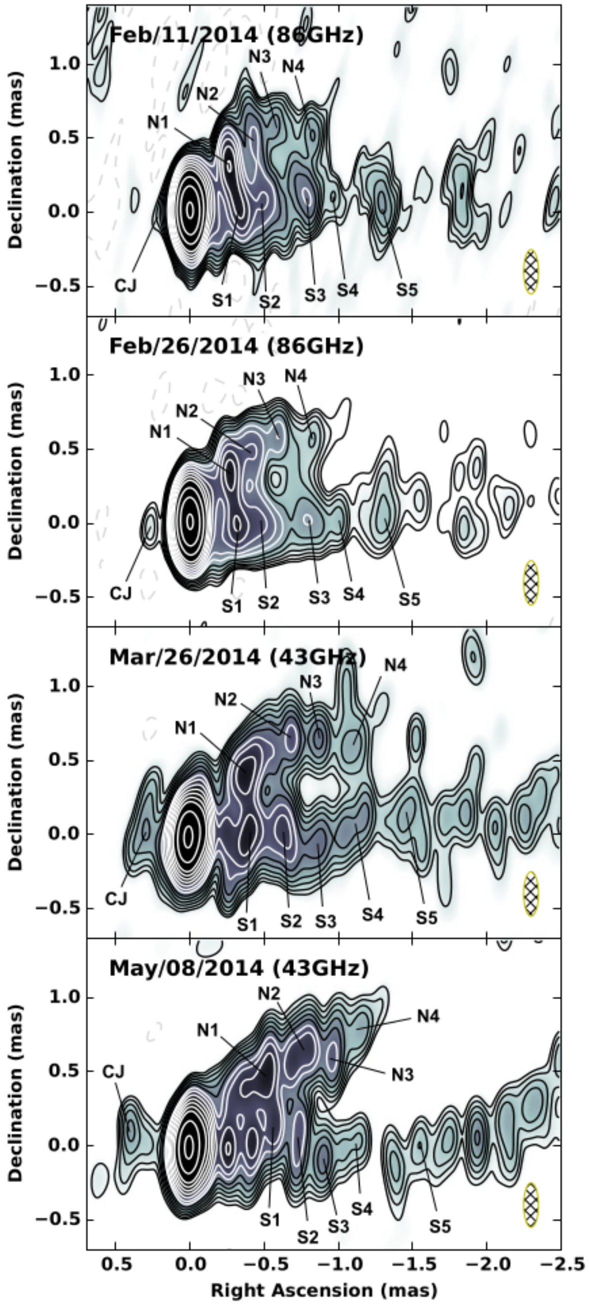


Kinematics of the M87 jet : 2. Visual Inspection

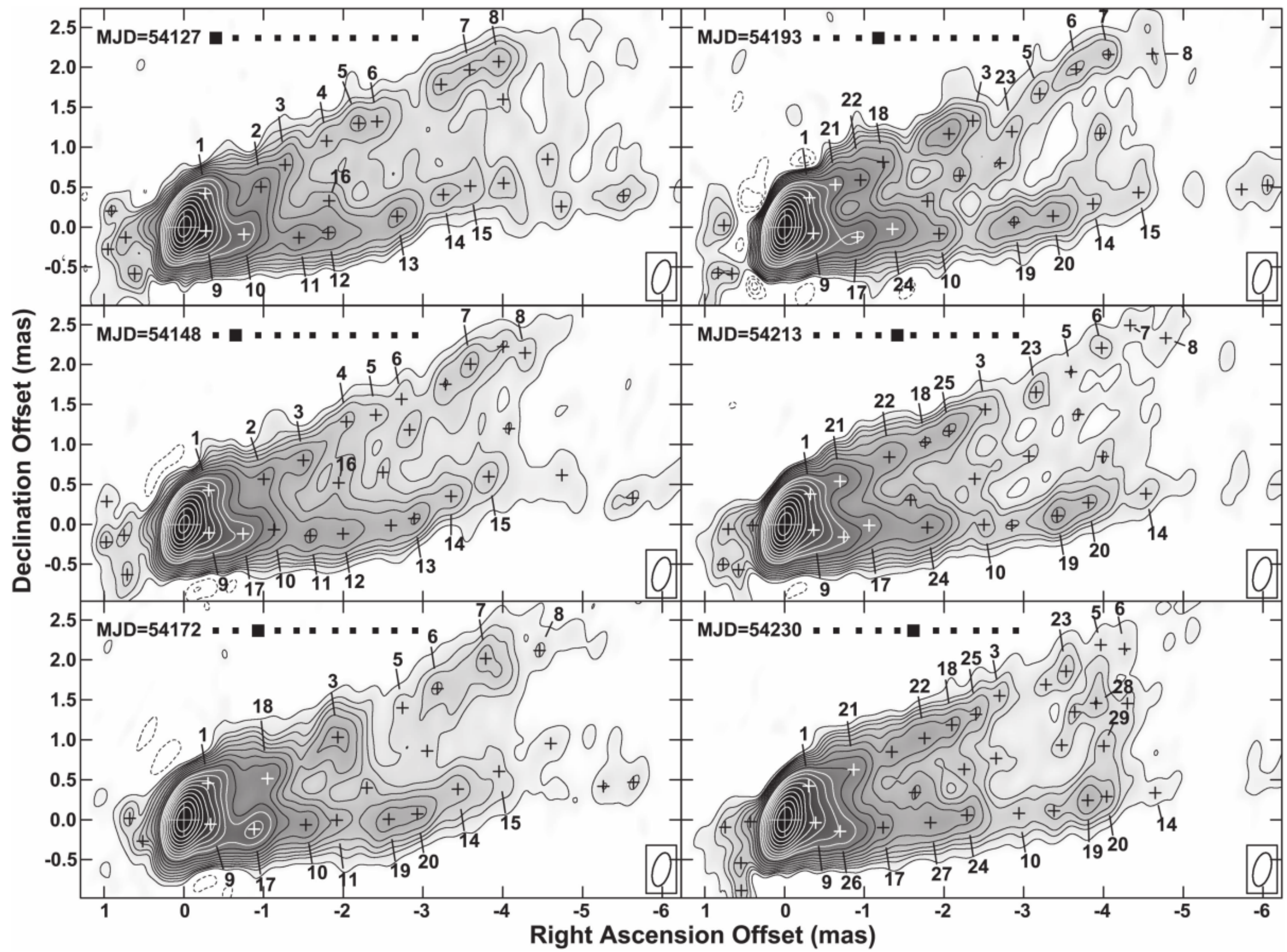
VLBA 43/86 GHz (~2 weeks)



Hada et al. (2016)

VLBA 43 GHz (~3 weeks)

Walker et al. (2018)



Identify each locally brightened jet region in different epochs by 'Visual Inspection'

Kinematics of the M87 jet : 2. Visual Inspection

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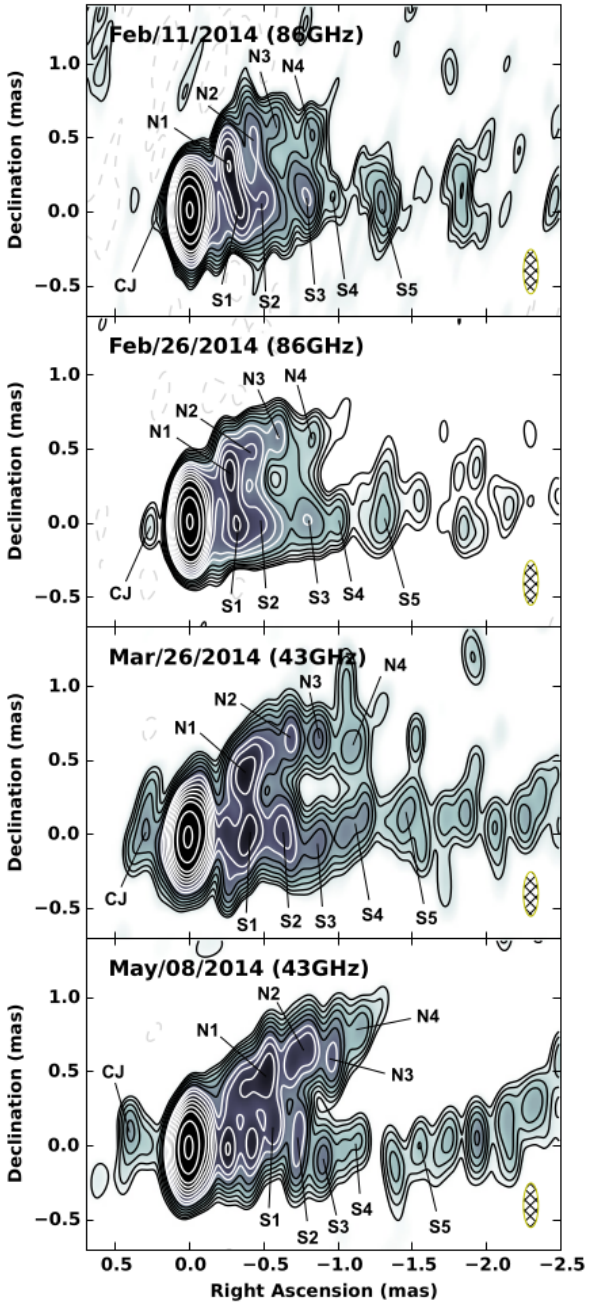

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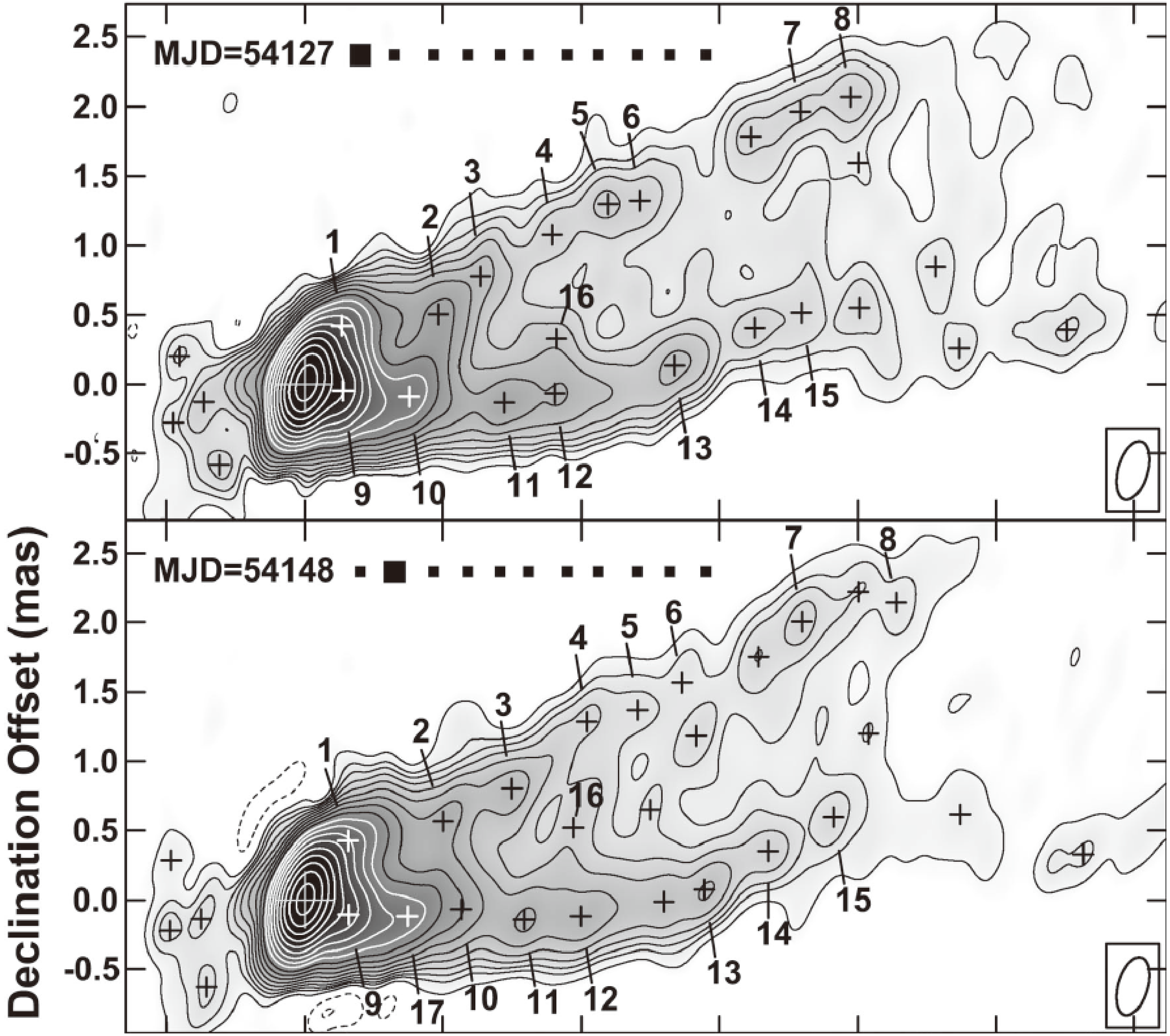

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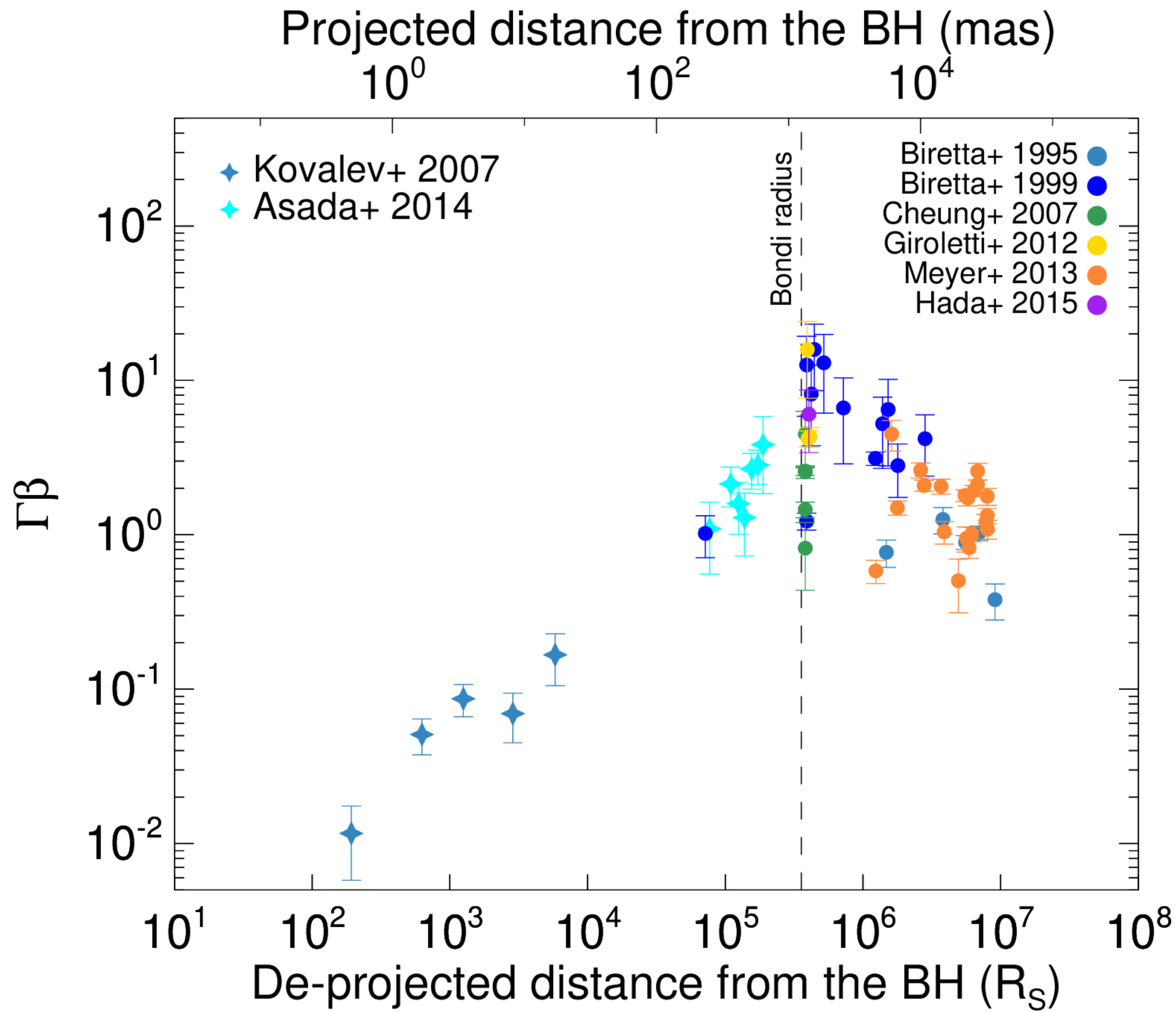
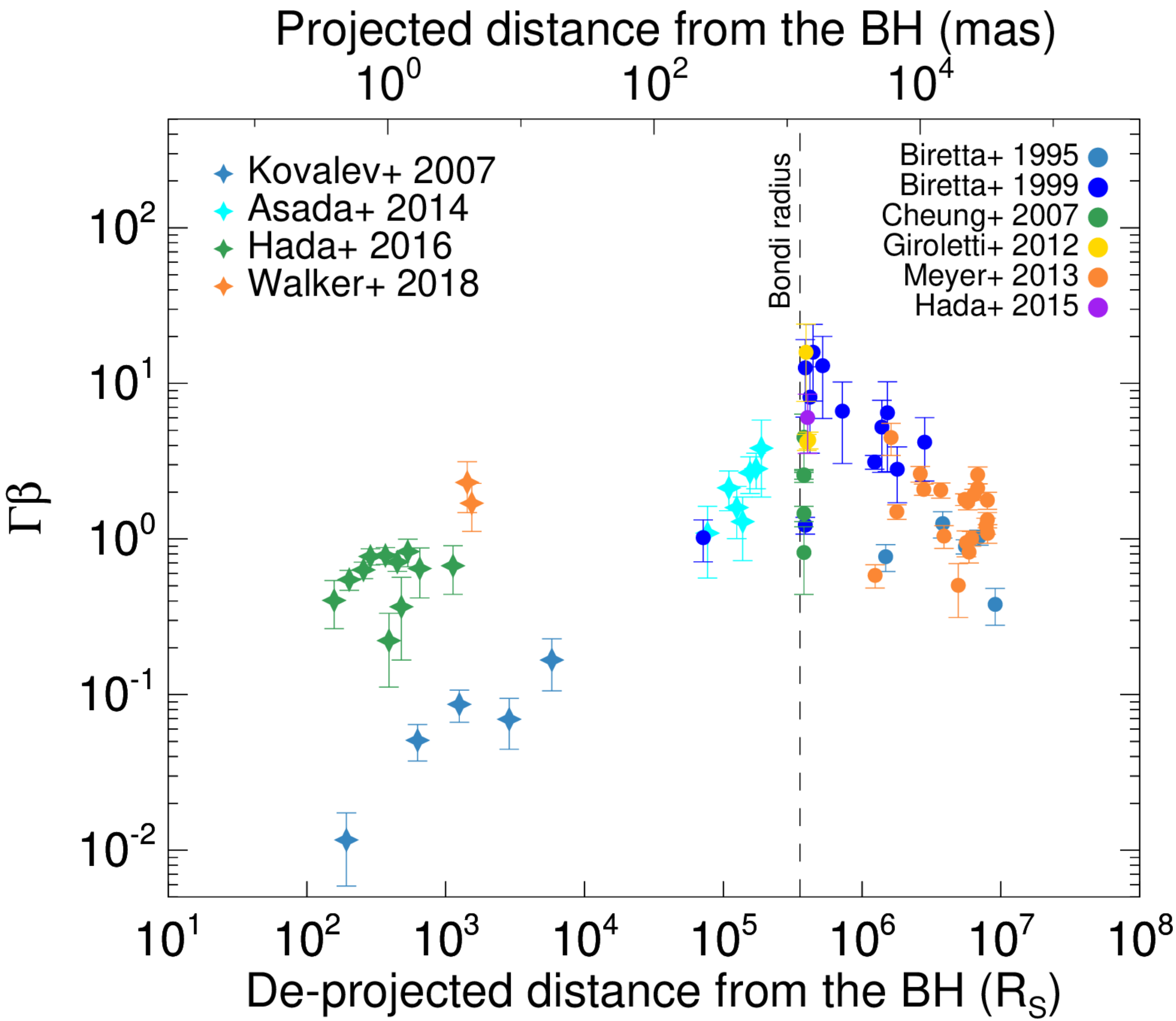
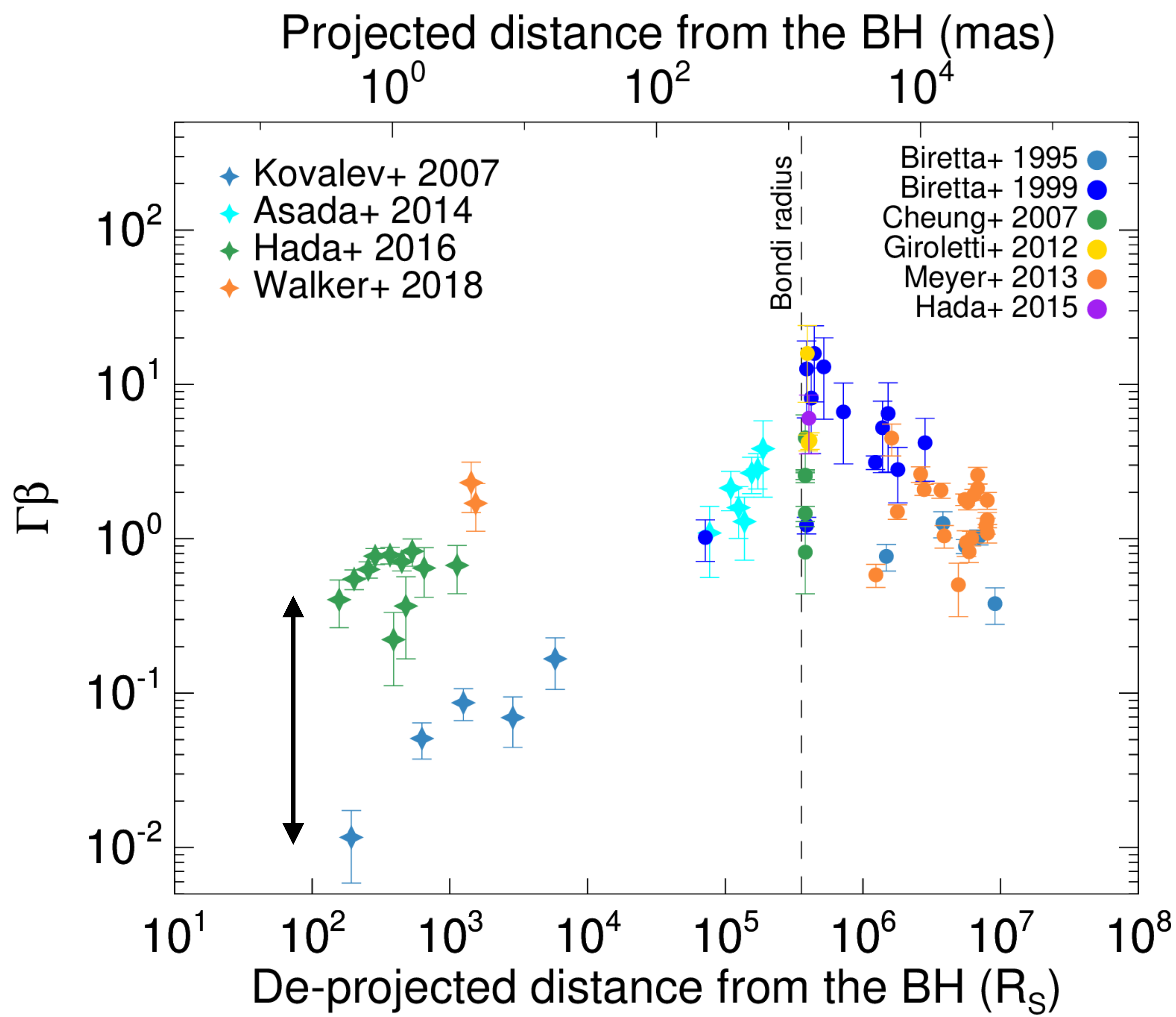




Projected distance from the BH (mas)
10^0
10^2
10^4
Kovalev+ 2007
Asada+ 2014
Hada+ 2016
Walker+ 2018
Bondi radius
Biretta+ 1995
Biretta+ 1999
Cheung+ 2007
Giroletti+ 2012
Meyer+ 2013
Hada+ 2015
Γβ
10^2
10^1
10^0
10^-1
10^-2
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
De-projected distance from the BH (R_S)



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Hada+ 2015
$\Gamma\beta$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^1
10^2
10^3
10^4
10^5
10^6
10^7
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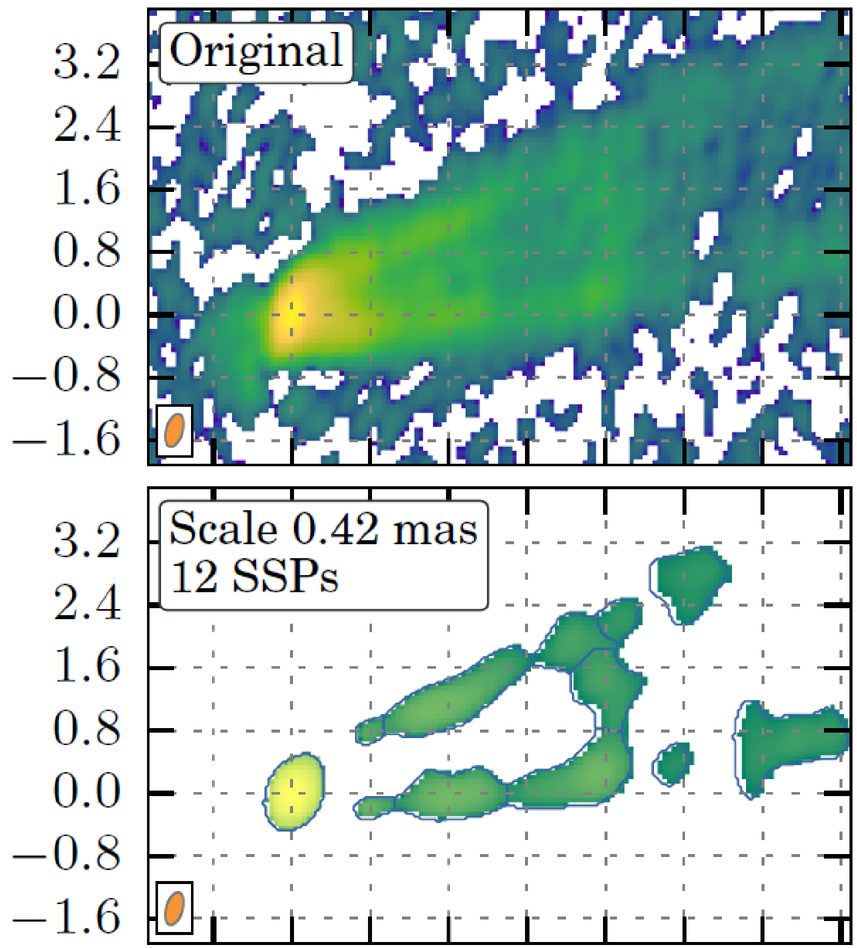
De-projected distance from the BH (R_S)

VLBA 43 GHz (~3 weeks)

Mertens et al. (2016)



WISE (Wavelet-based Image Segmentation and Evaluation)

Wavelet Transformation
(Detect brightness patterns)

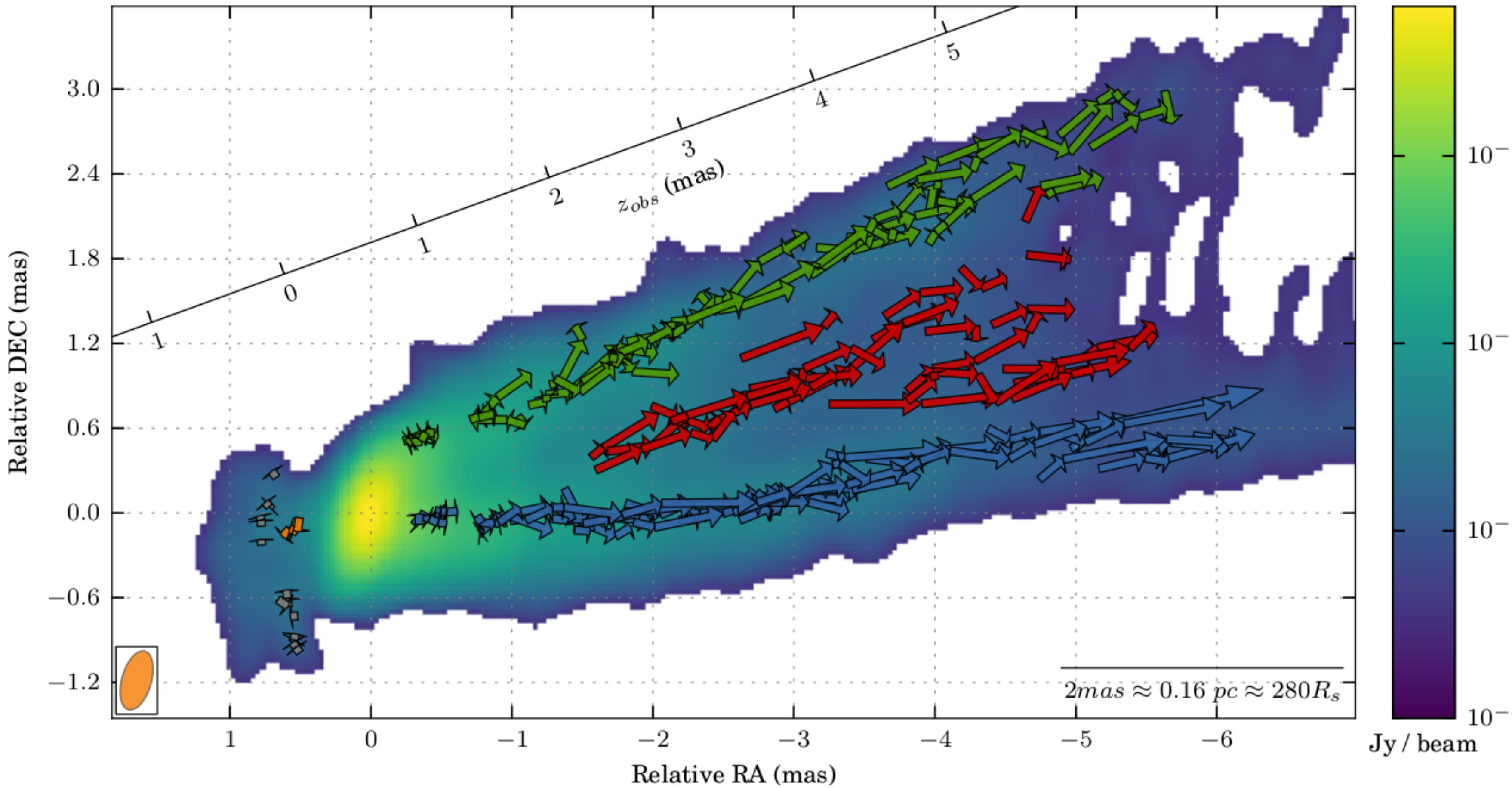
+

2D Cross-Correlation
(Kinematics)

Kinematics of the M87 jet : 3. WISE

VLBA 43 GHz (~3 weeks)

Mertens et al. (2016)



WISE (Wavelet-based Image Segmentation and Evaluation)

Wavelet Transformation (Detect brightness patterns)	+	2D Cross-Correlation (Kinematics)

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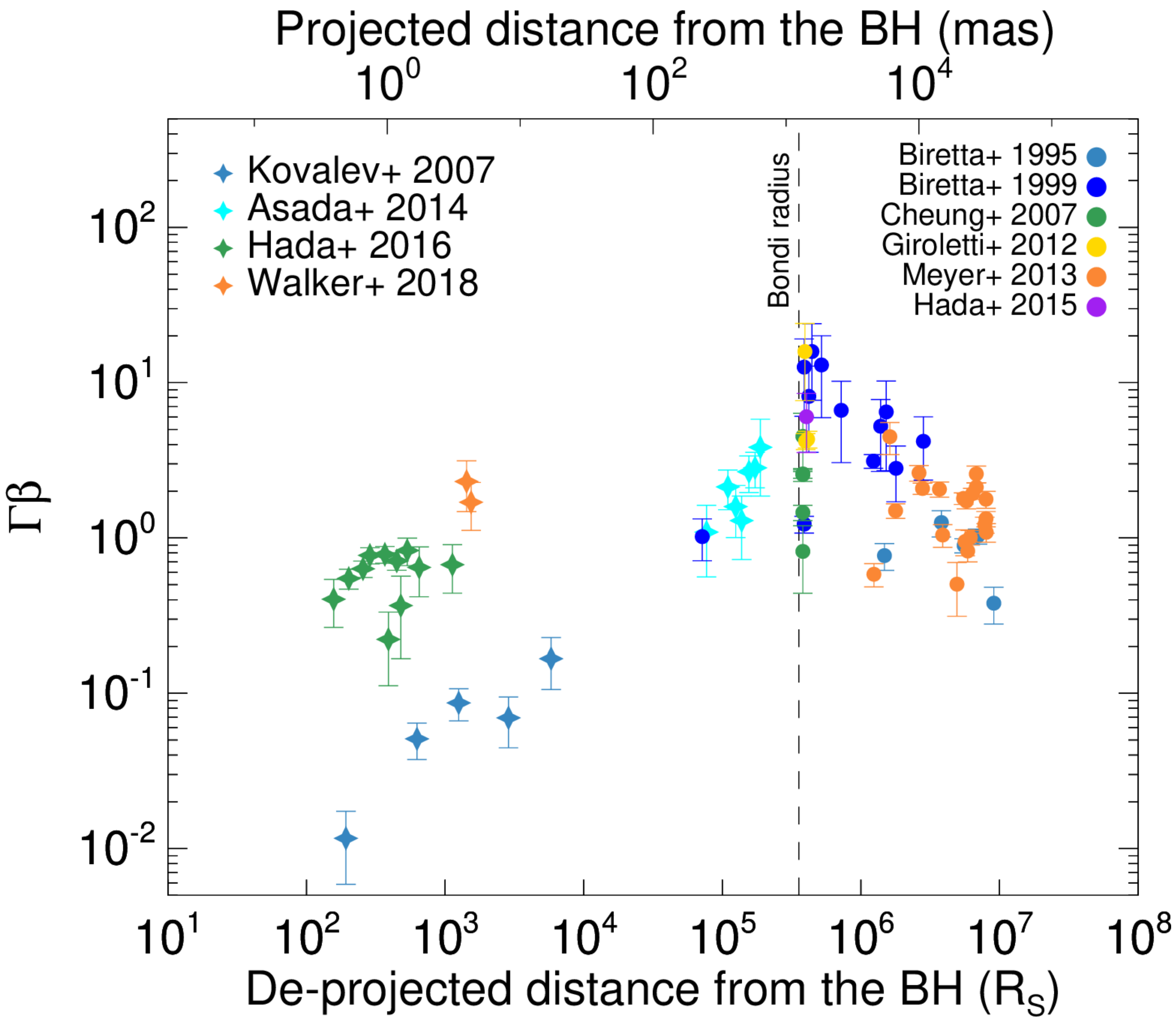
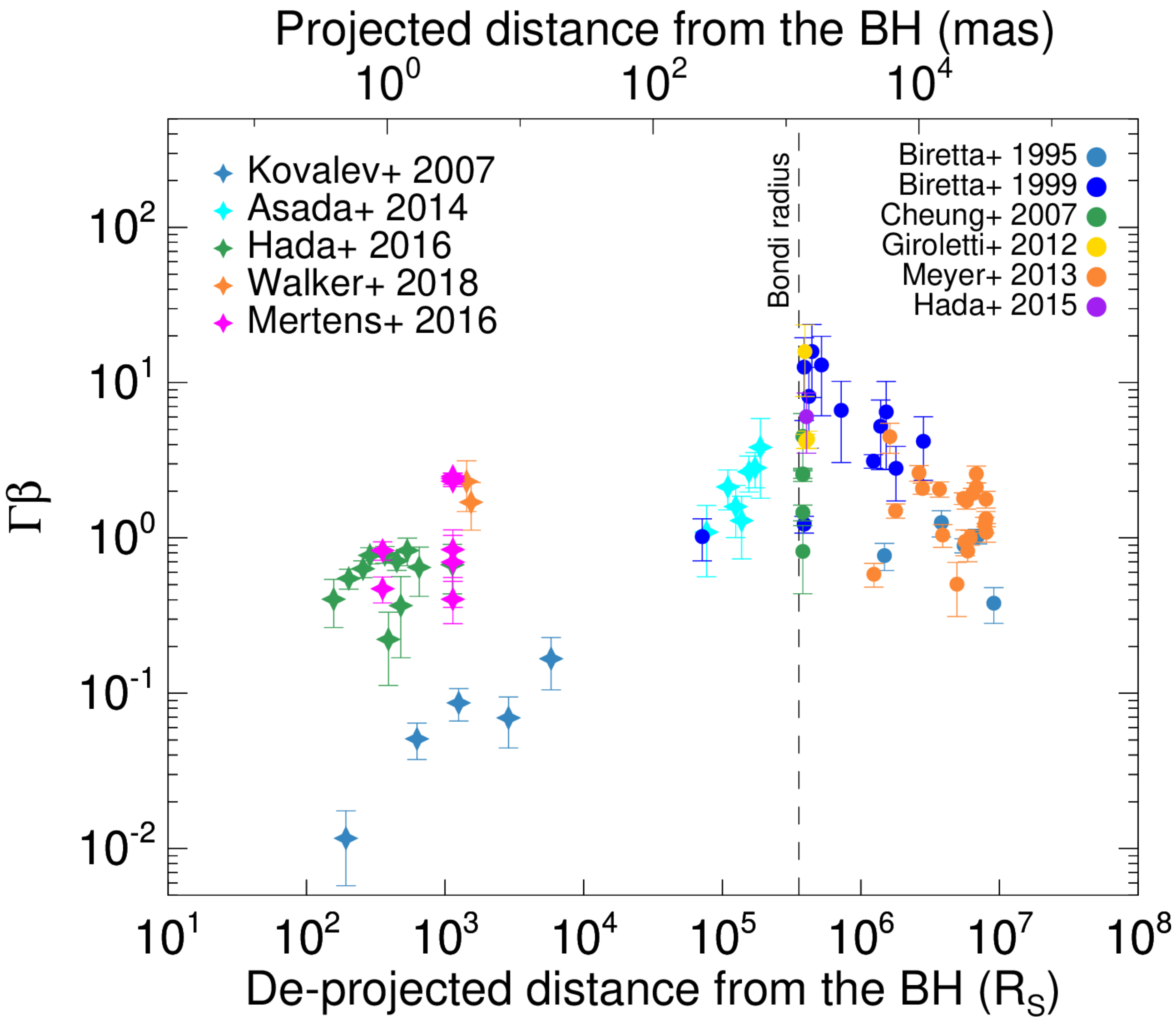
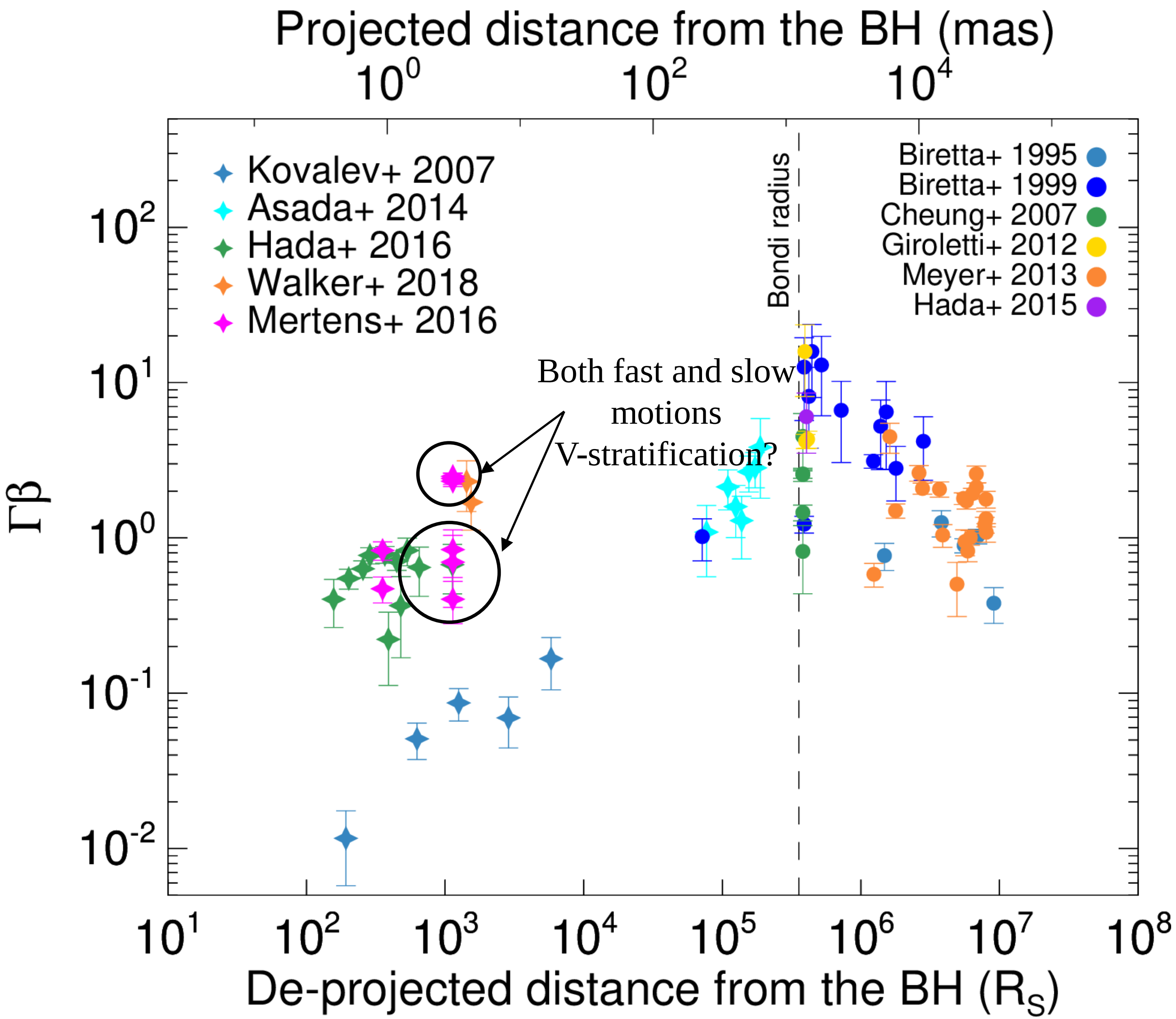


Kinematics of the M87 jet : 3. WISE

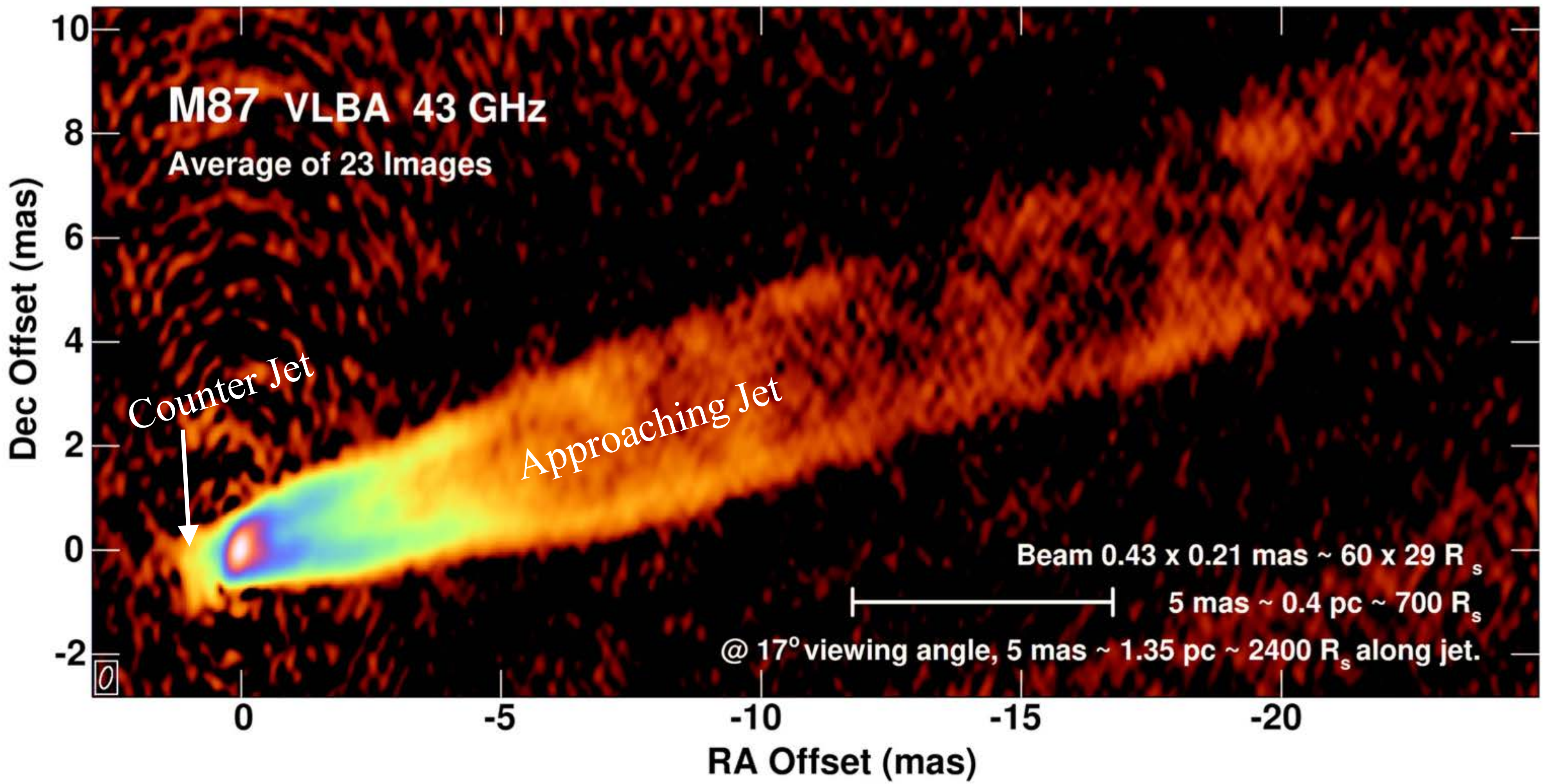


Kinematics of the M87 jet : 3. WISE



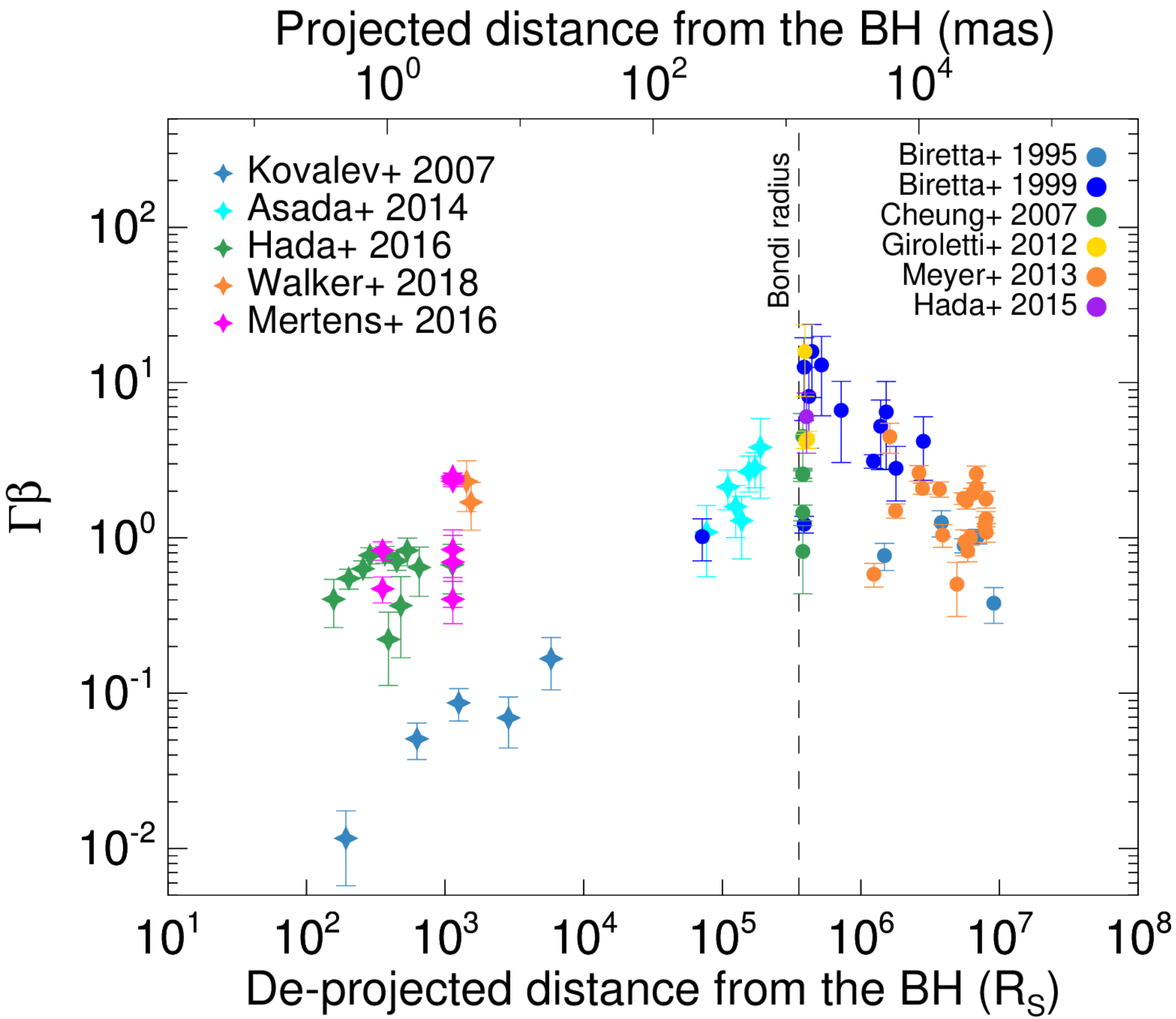
Kinematics of the M87 jet : 4. Jet-to-counterjet brightness ratio

VLBA 43 GHz   Walker et al. (2018)



The brightness difference : due to the Doppler boosting/deboosting

Kinematics of the M87 jet : 4. Jet-to-counterjet brightness ratio



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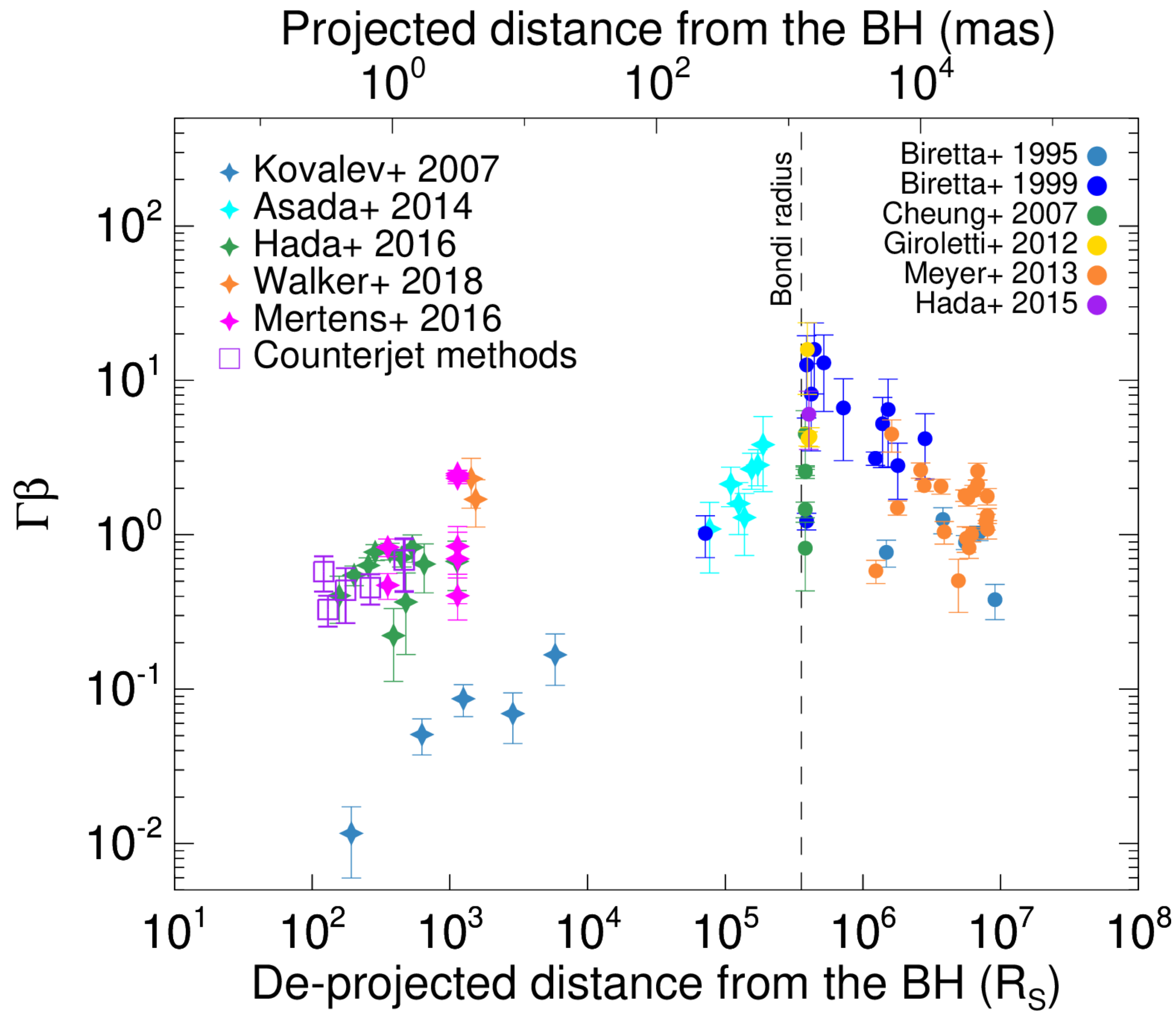
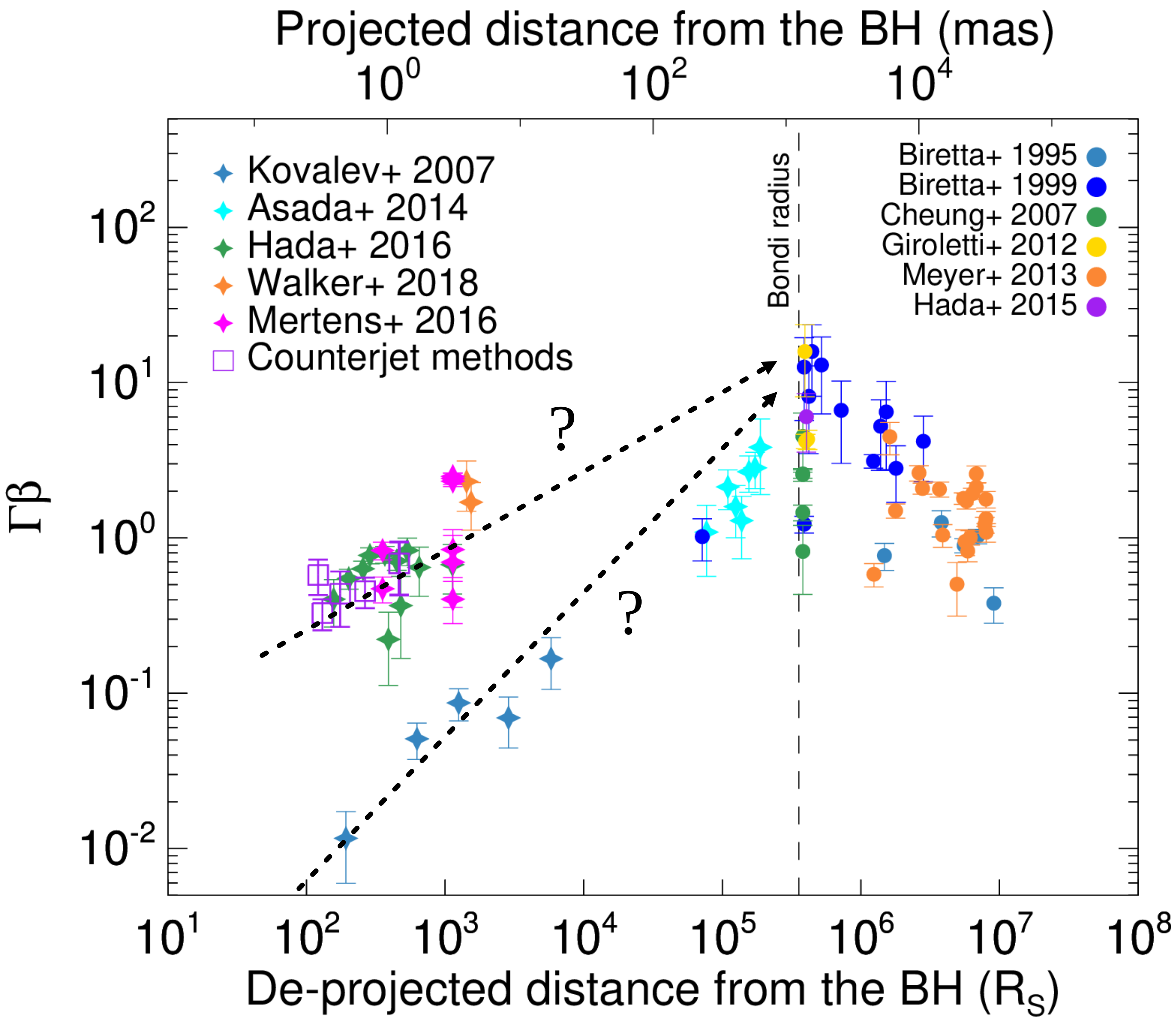
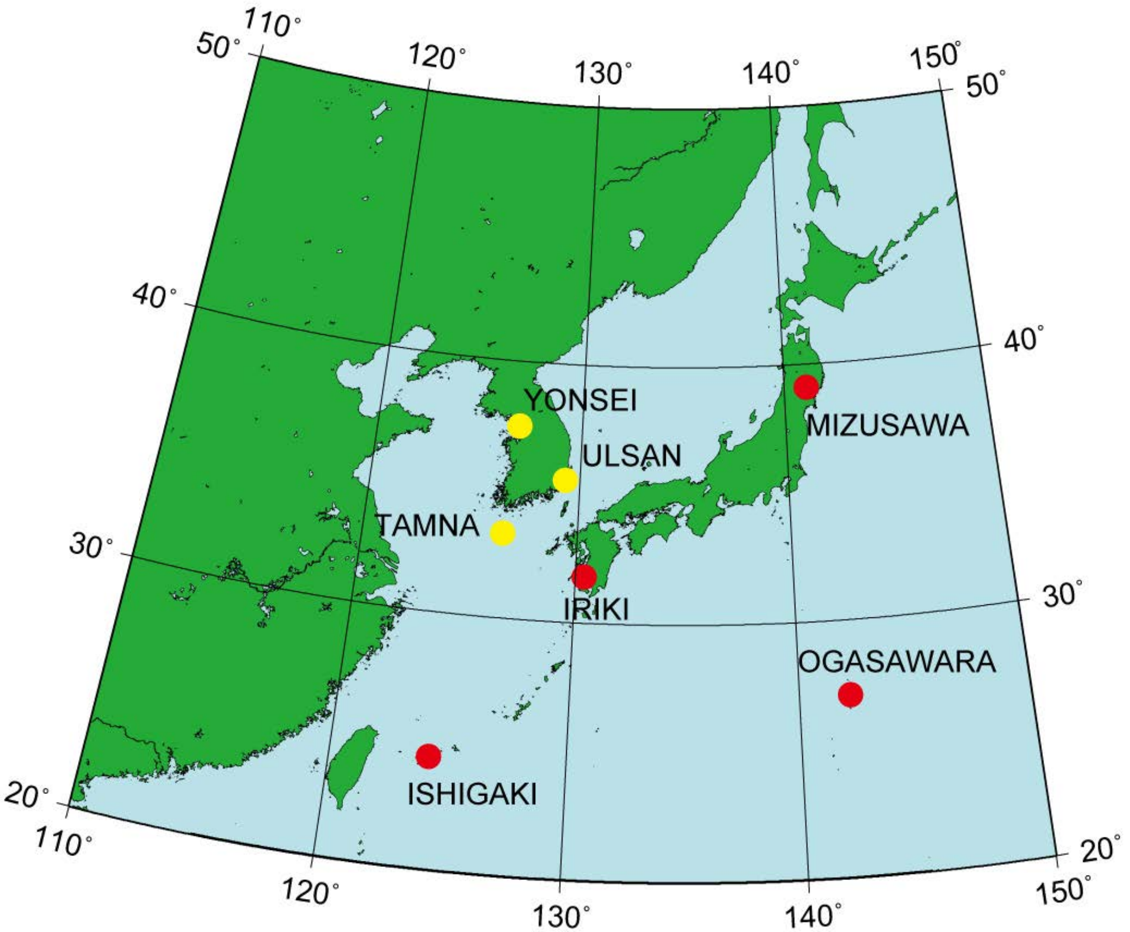


Kinematics of the M87 jet : 4. Jet-to-counterjet brightness ratio

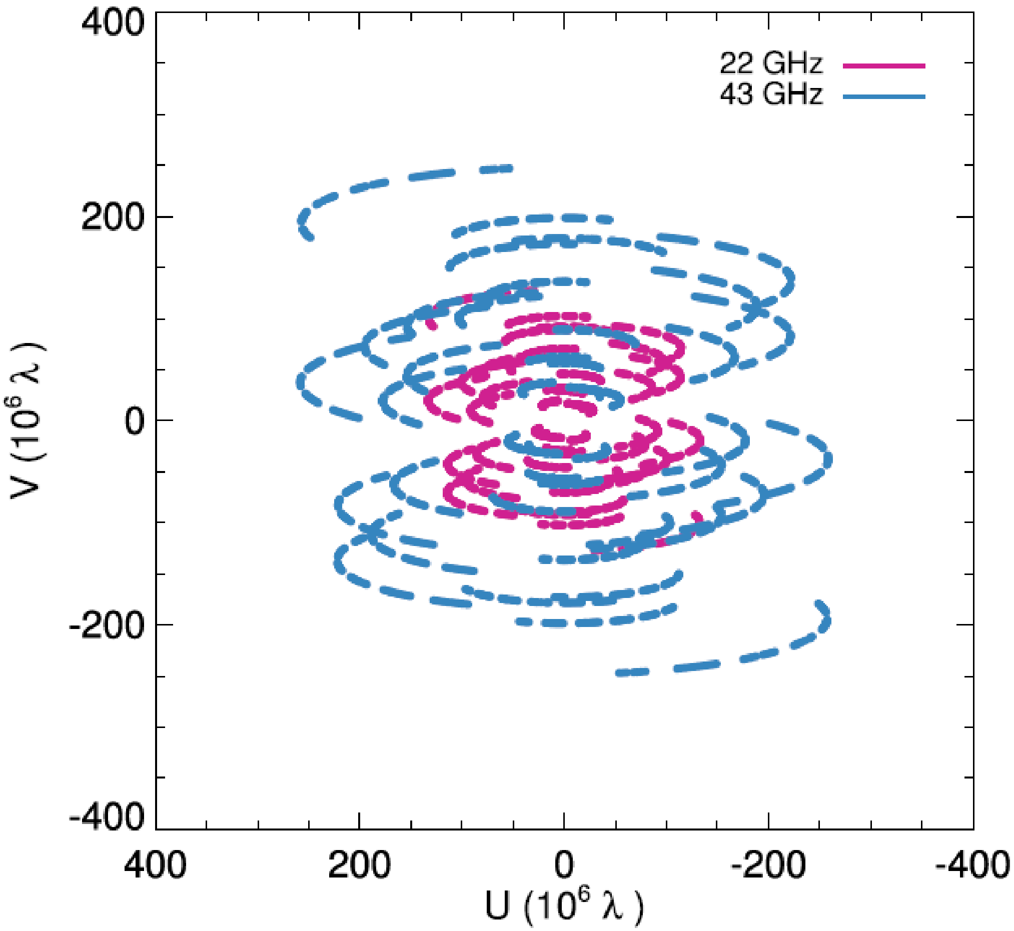


KVN and VERA Array (KaVA)



— Good Sensitivity.
— Reasonably good angular resolution.
— Good uv-coverage.
→ KaVA Large Program : Observations of M87 ‘biweekly’ at 22 & 43 GHz (~10 epochs per year).

KVN and VERA Array (KaVA)



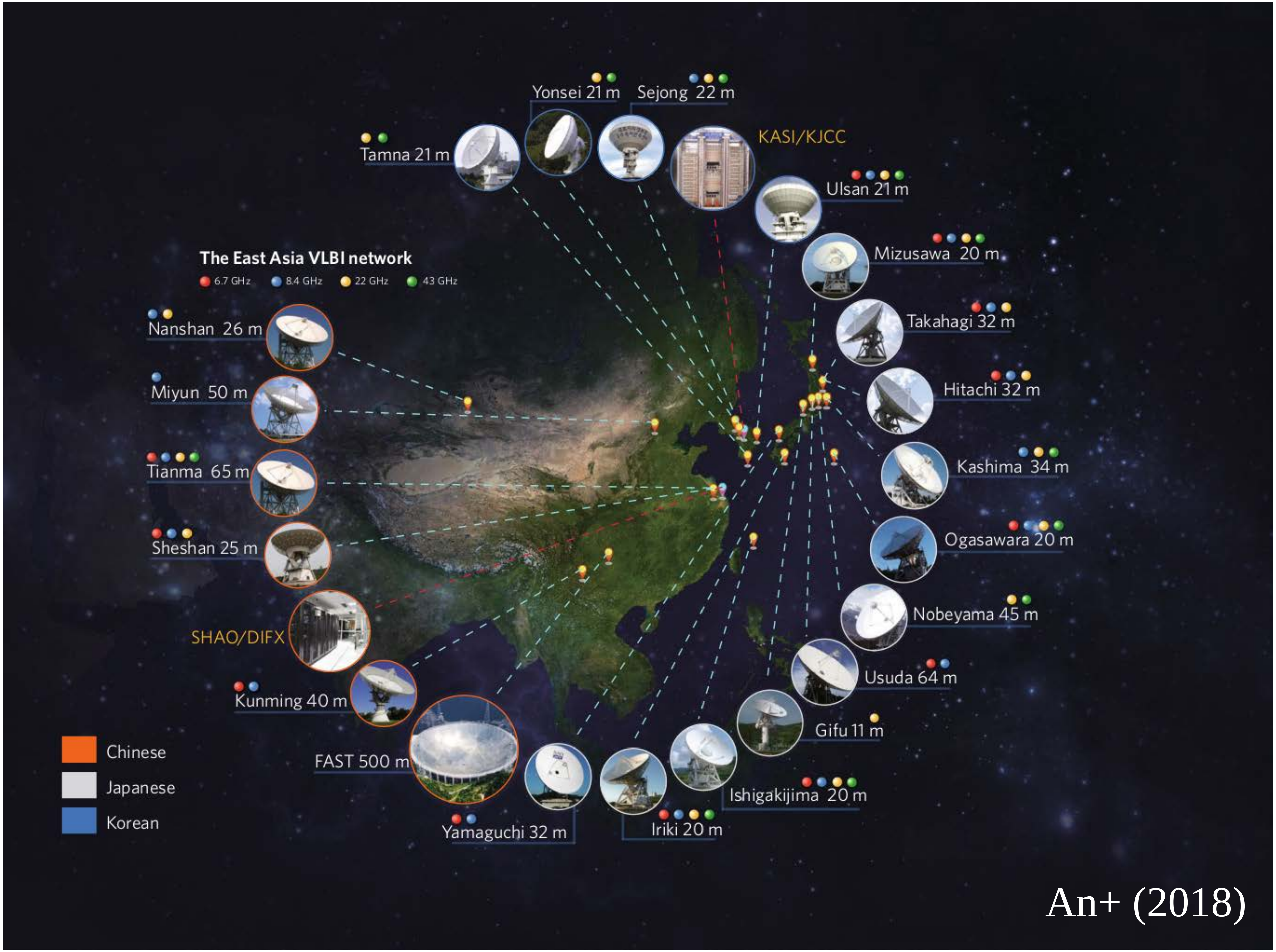
— Good Sensitivity.

— Reasonably good angular resolution.

— Good uv-coverage.

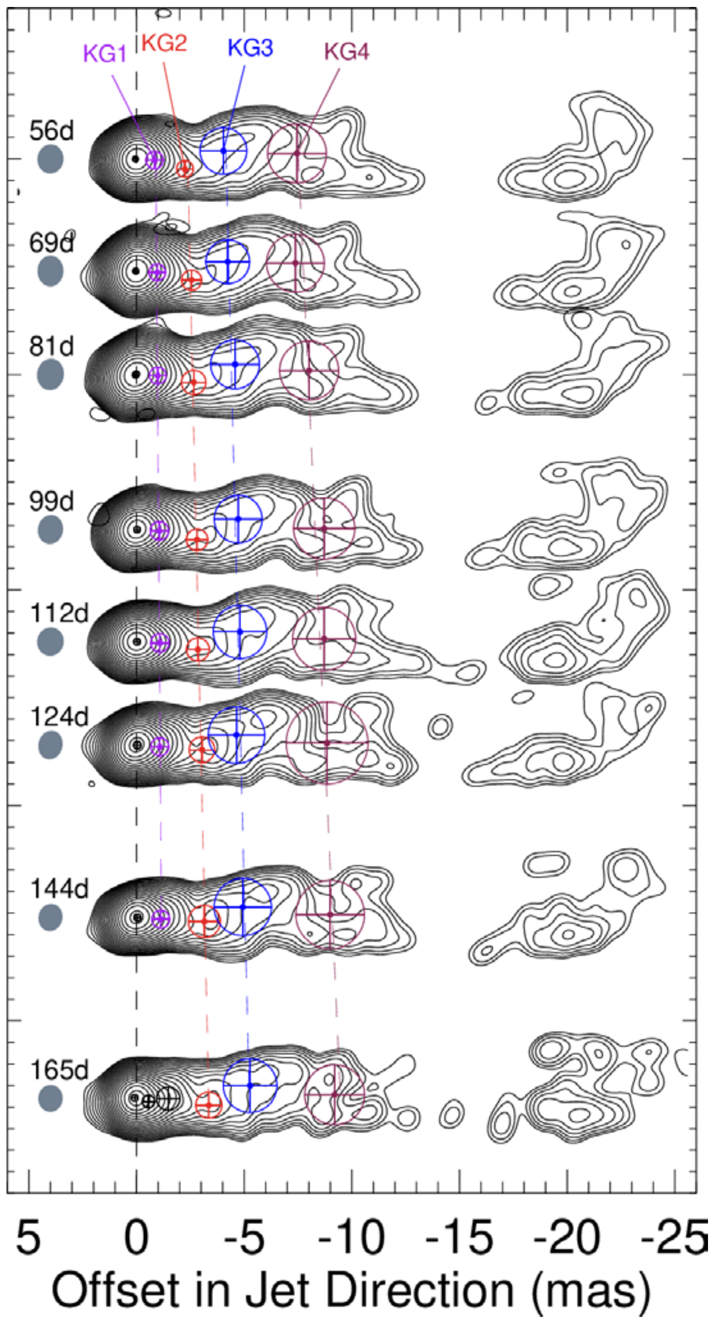
→ KaVA Large Program : Observations of M87 ‘biweekly’ at 22 & 43 GHz (~10 epochs per year).

KVN and VERA Array (KaVA) → The East Asian VLBI Network (EAVN)

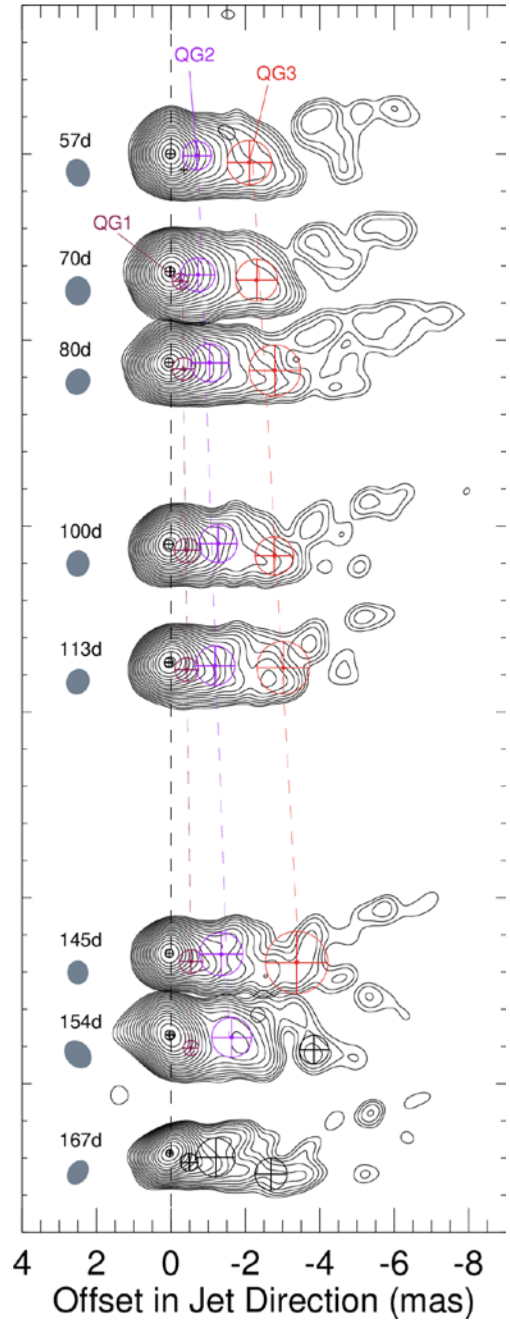


KaVA observations in 2016 : 1. modelfit

THE KAVA LARGE PROGRAM (~2 WEEKS)



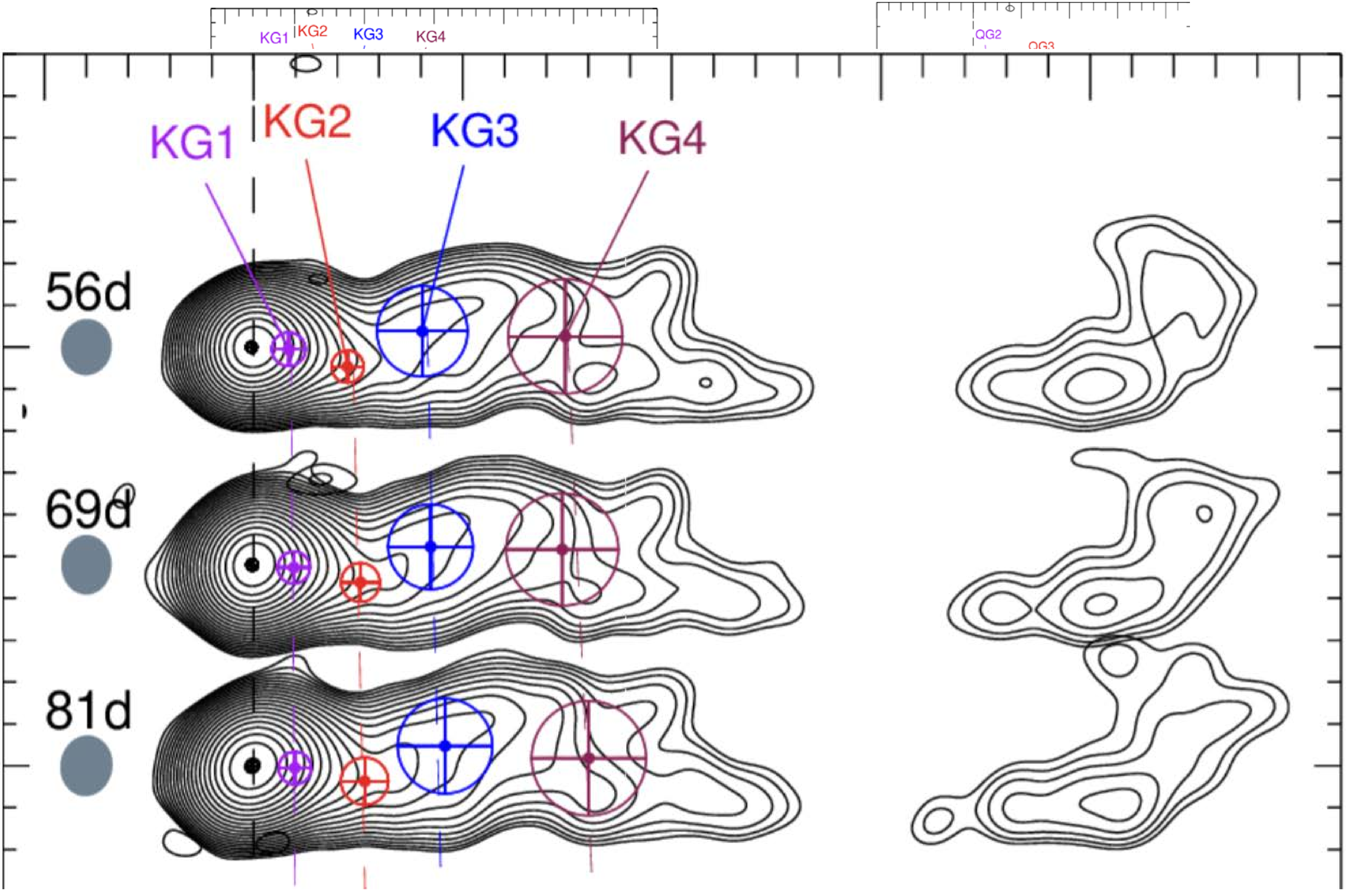
22 GHz



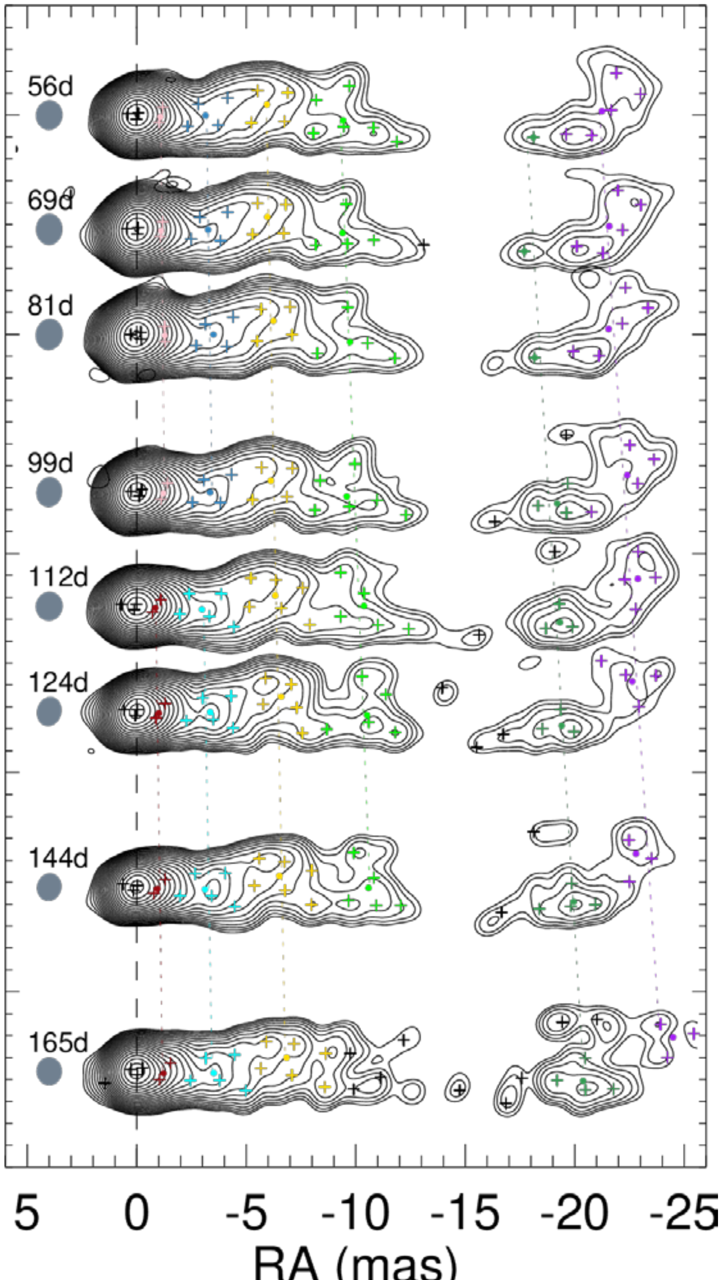
43 GHz

KaVA observations in 2016 : 1. modelfit

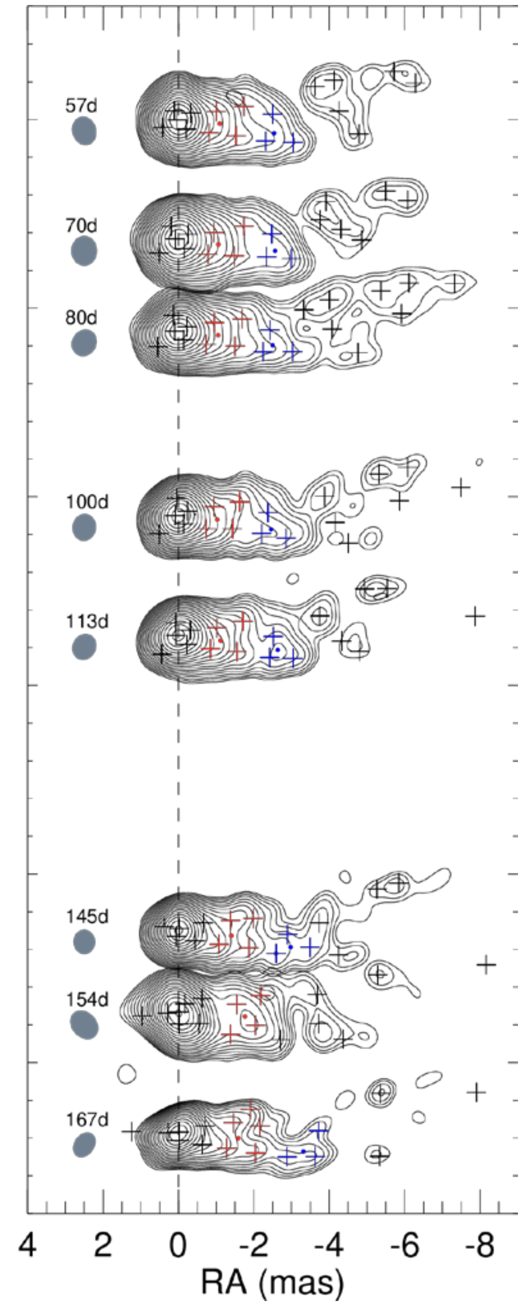
THE KAVA LARGE PROGRAM (~2 WEEKS)



THE KAVA LARGE PROGRAM (~2 WEEKS)



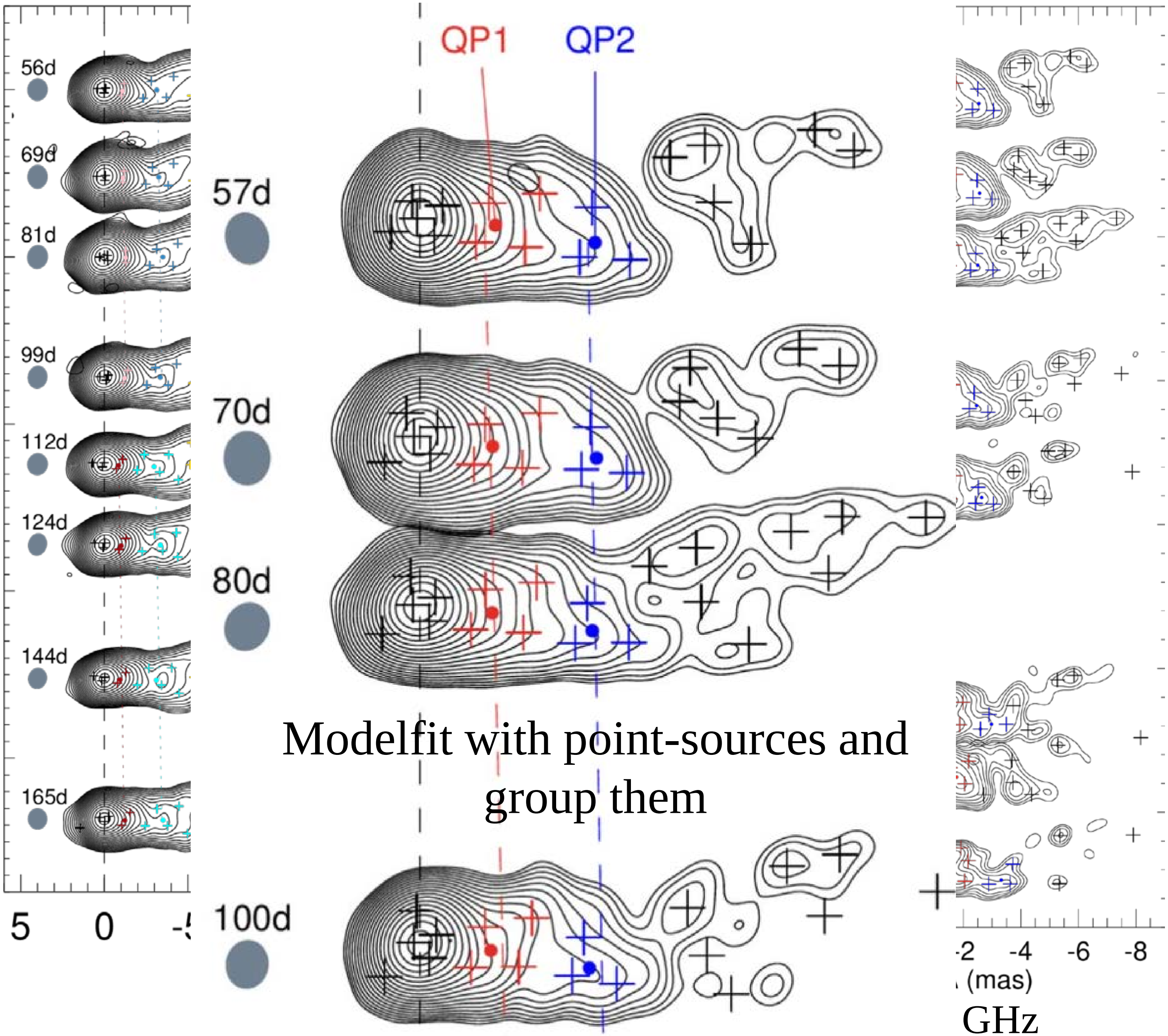
22 GHz



43 GHz

KaVA observations in 2016 : 2. Visual Inspection

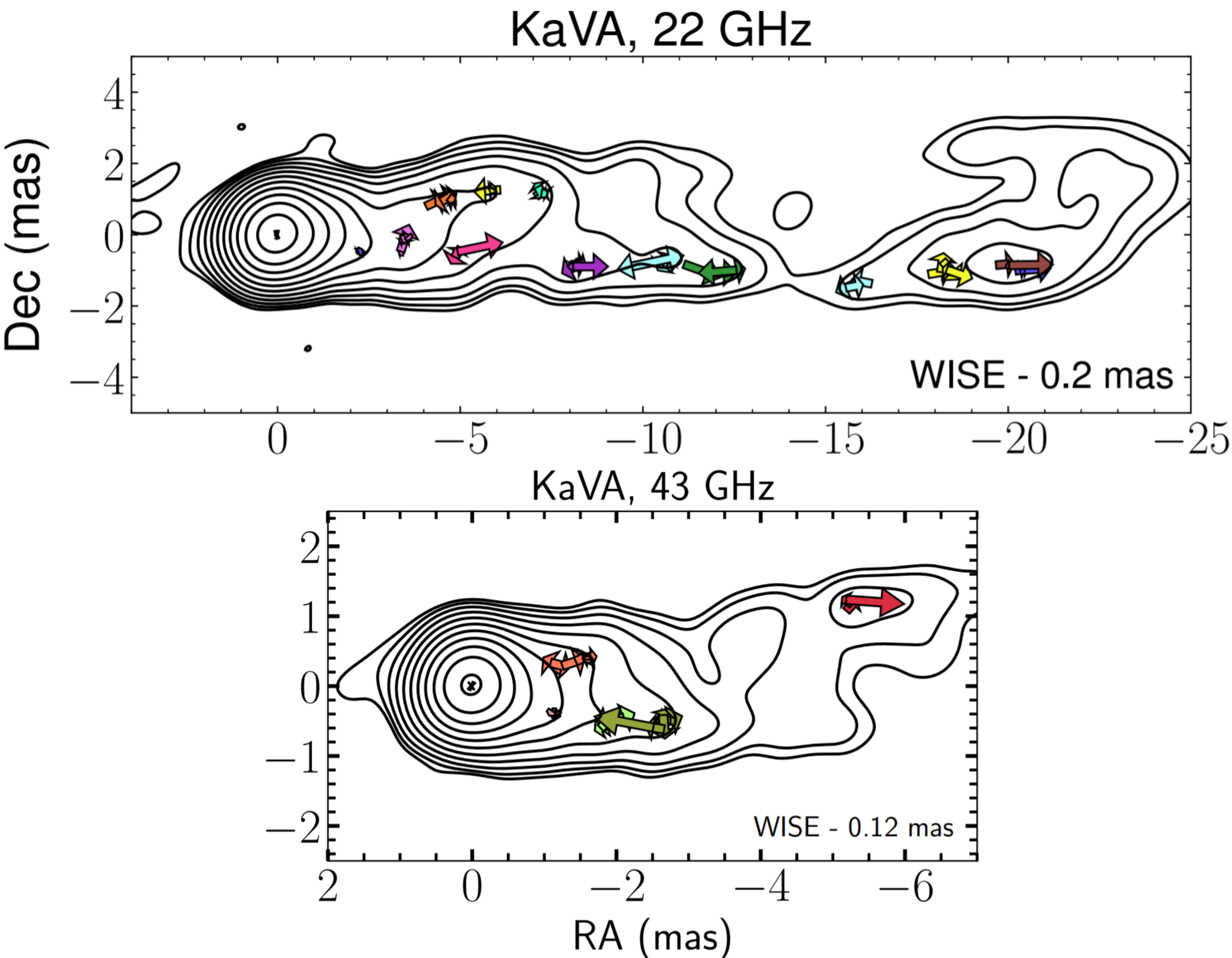
THE KAVA LARGE PROGRAM (~2 WEEKS)



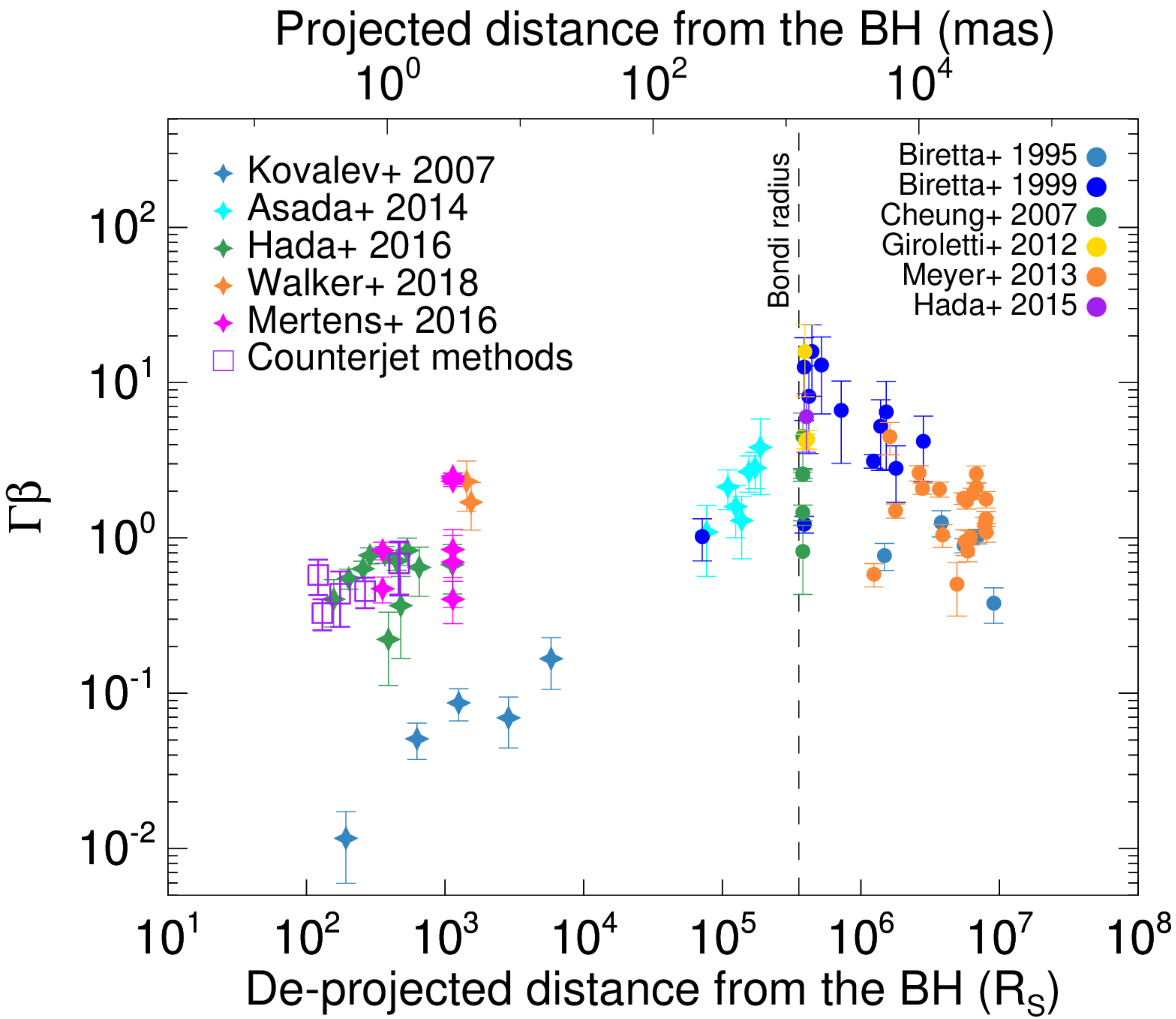
Modelfit with point-sources and group them

KaVA observations in 2016 : 3. WISE

THE KAVA LARGE PROGRAM (~2 WEEKS)



Kinematics of the M87 jet : Results



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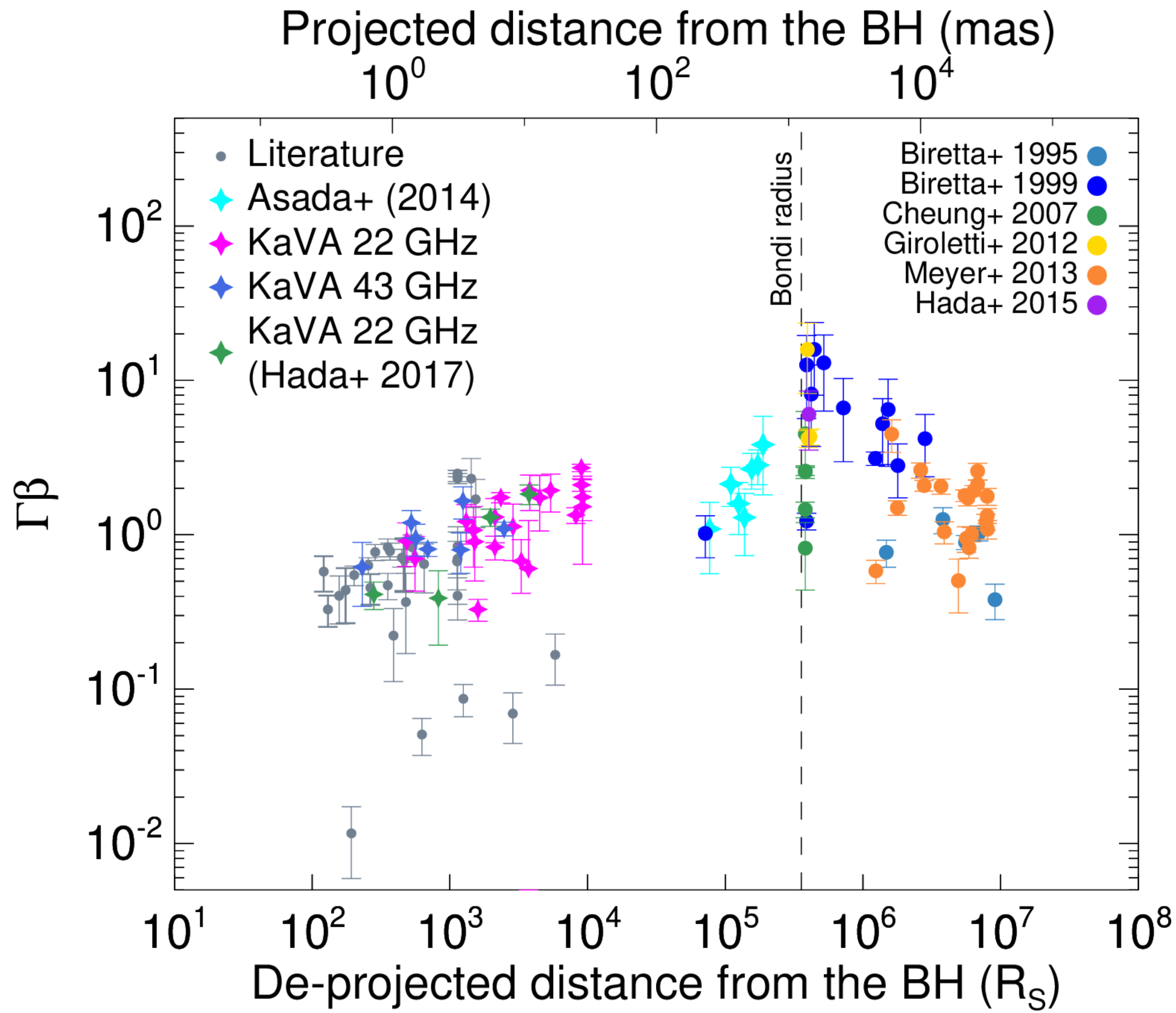

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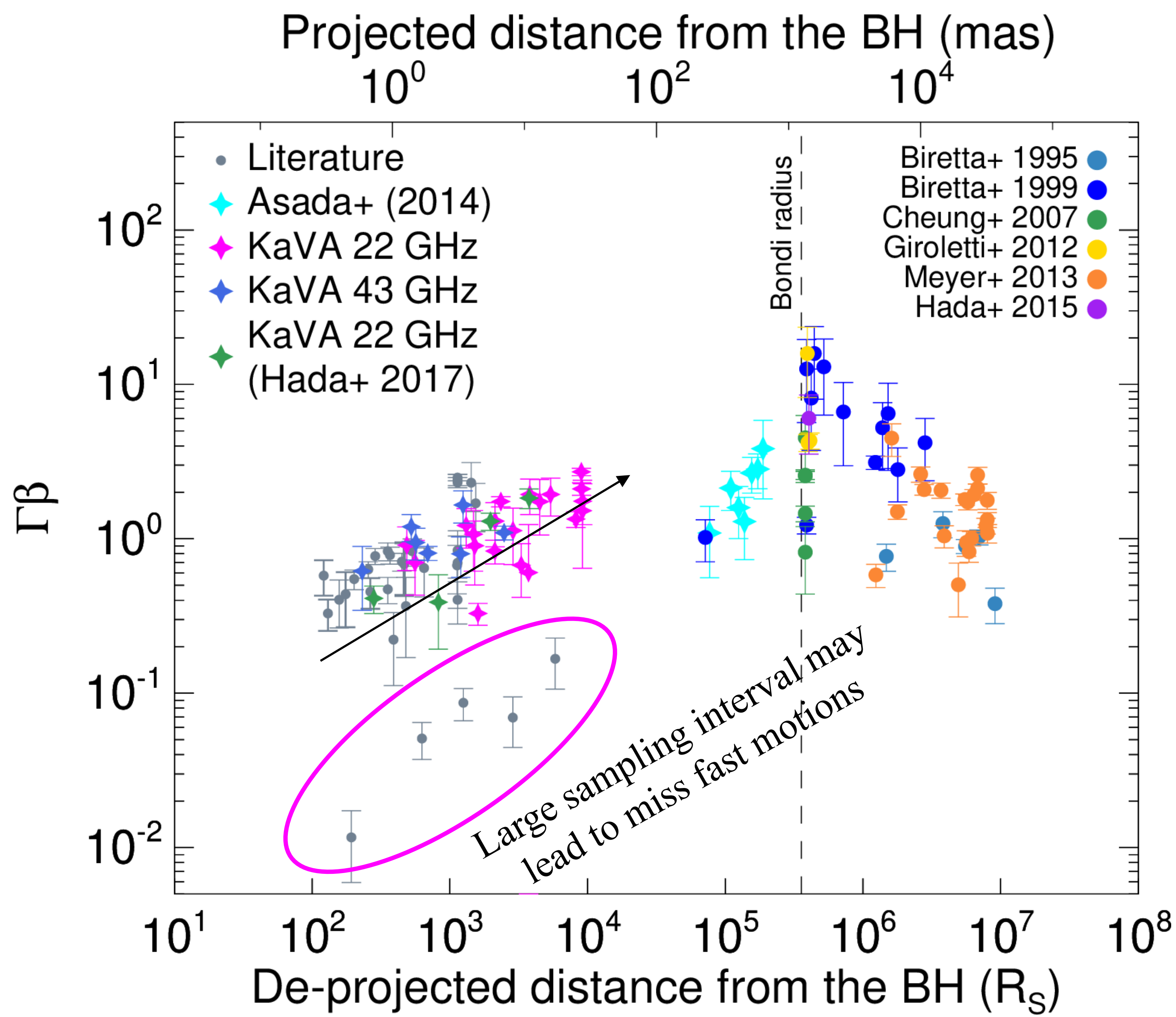

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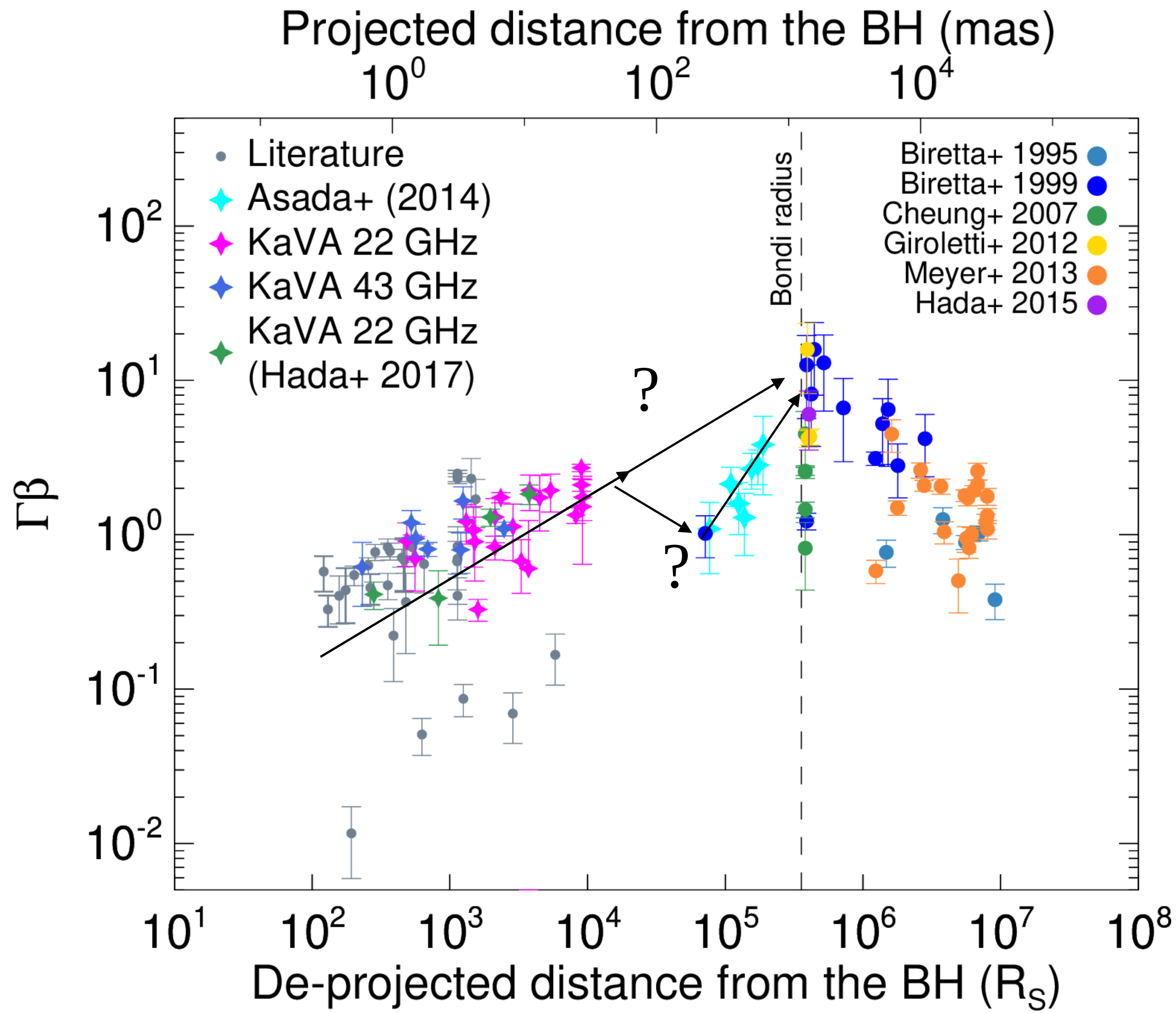
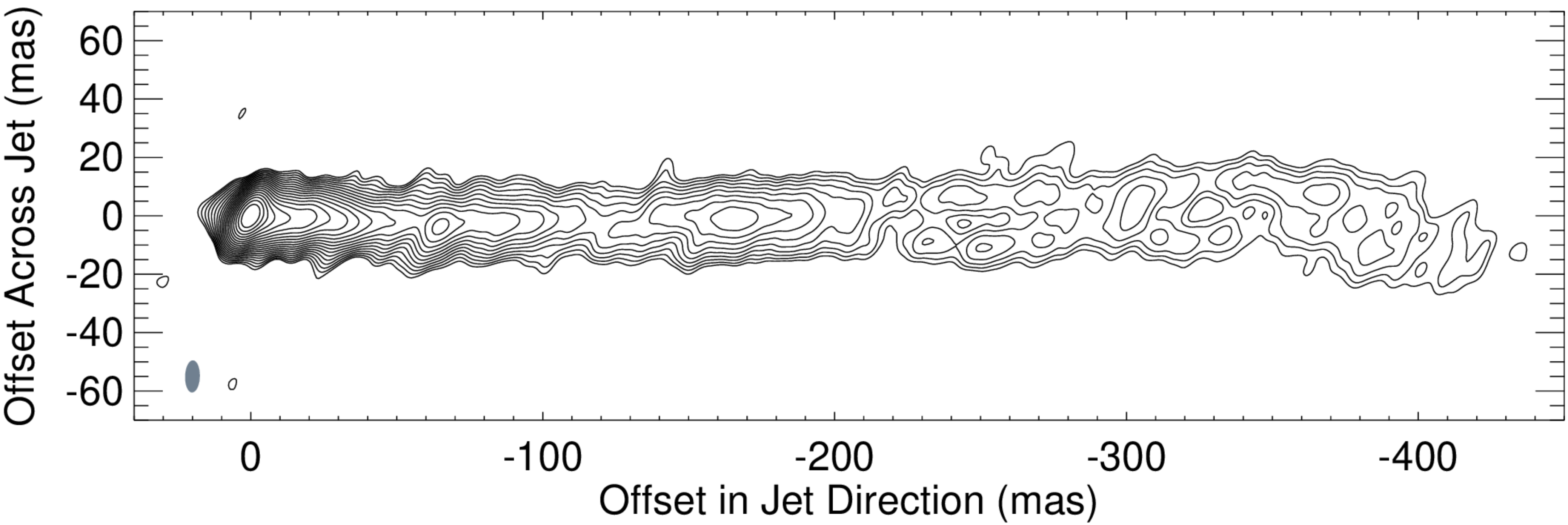


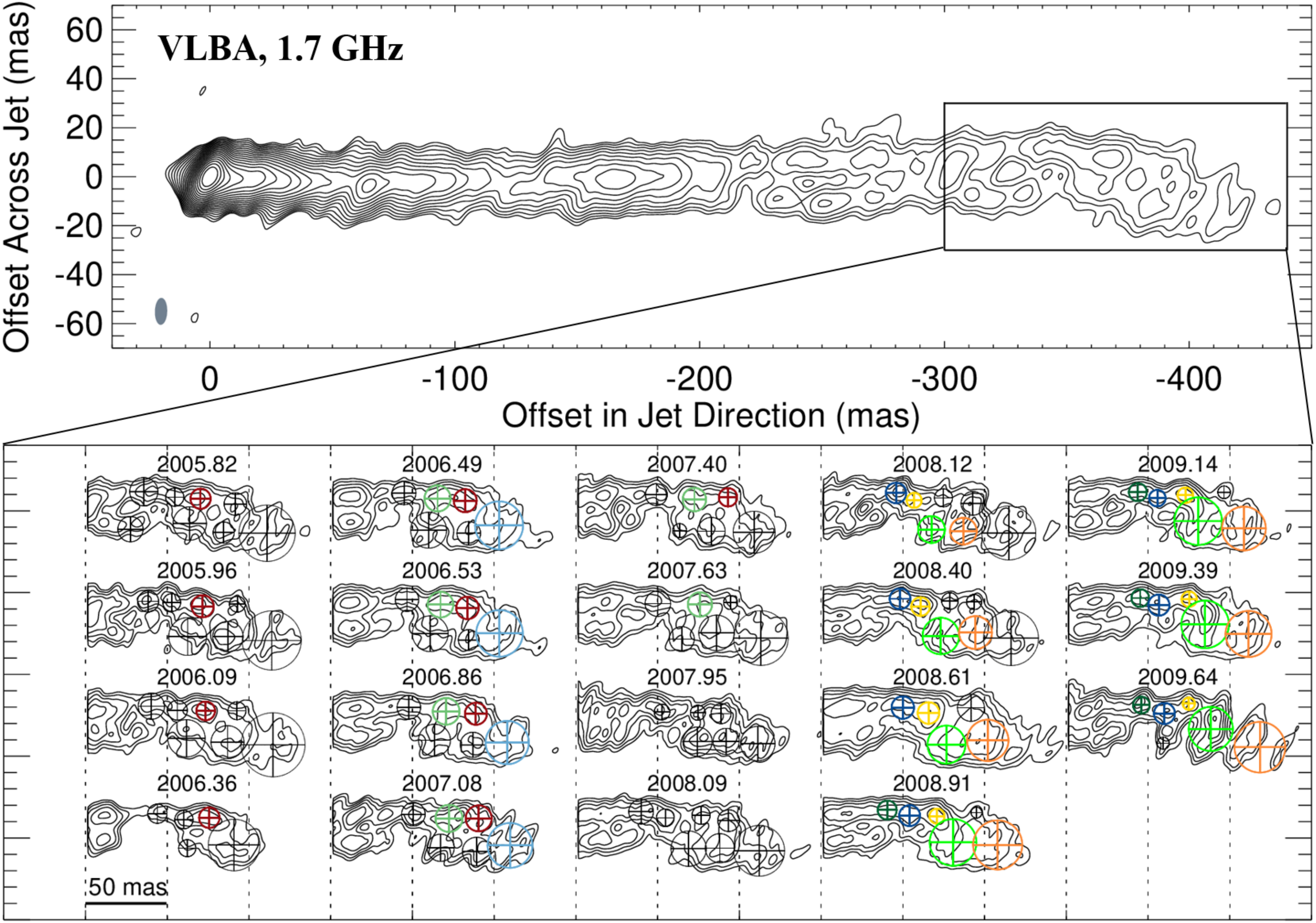
VLBA Archival data analysis

VLBA 1.7 GHz over ~4 years
Sampling Interval : ~2 months

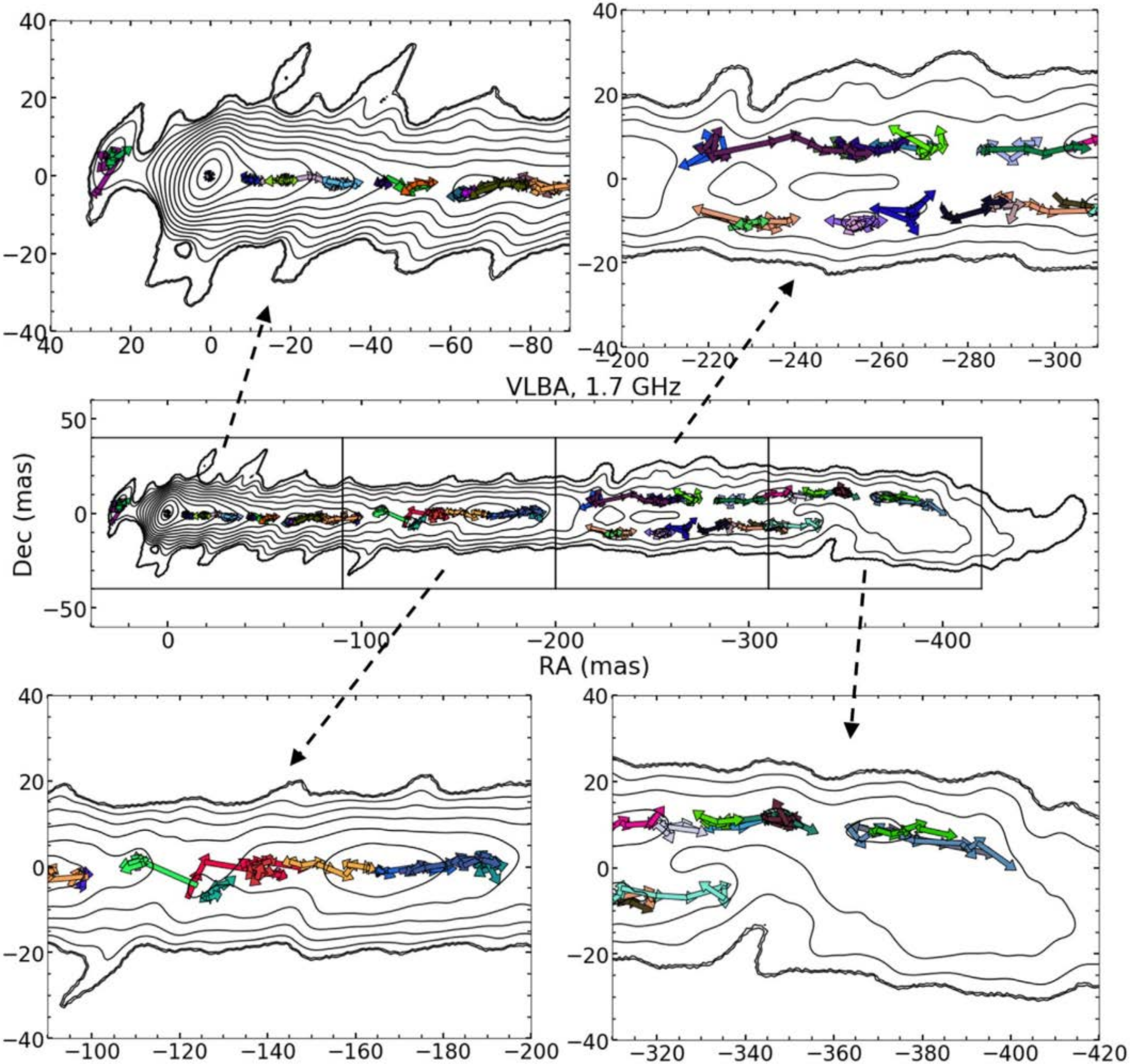


Compared to the EVN observations by Asada et al...
— Improved Sensitivity (by a factor of > a few).
— Improved Angular Resolution (by a factor of >2).
— Denser Monitoring (Interval : ~2 months).

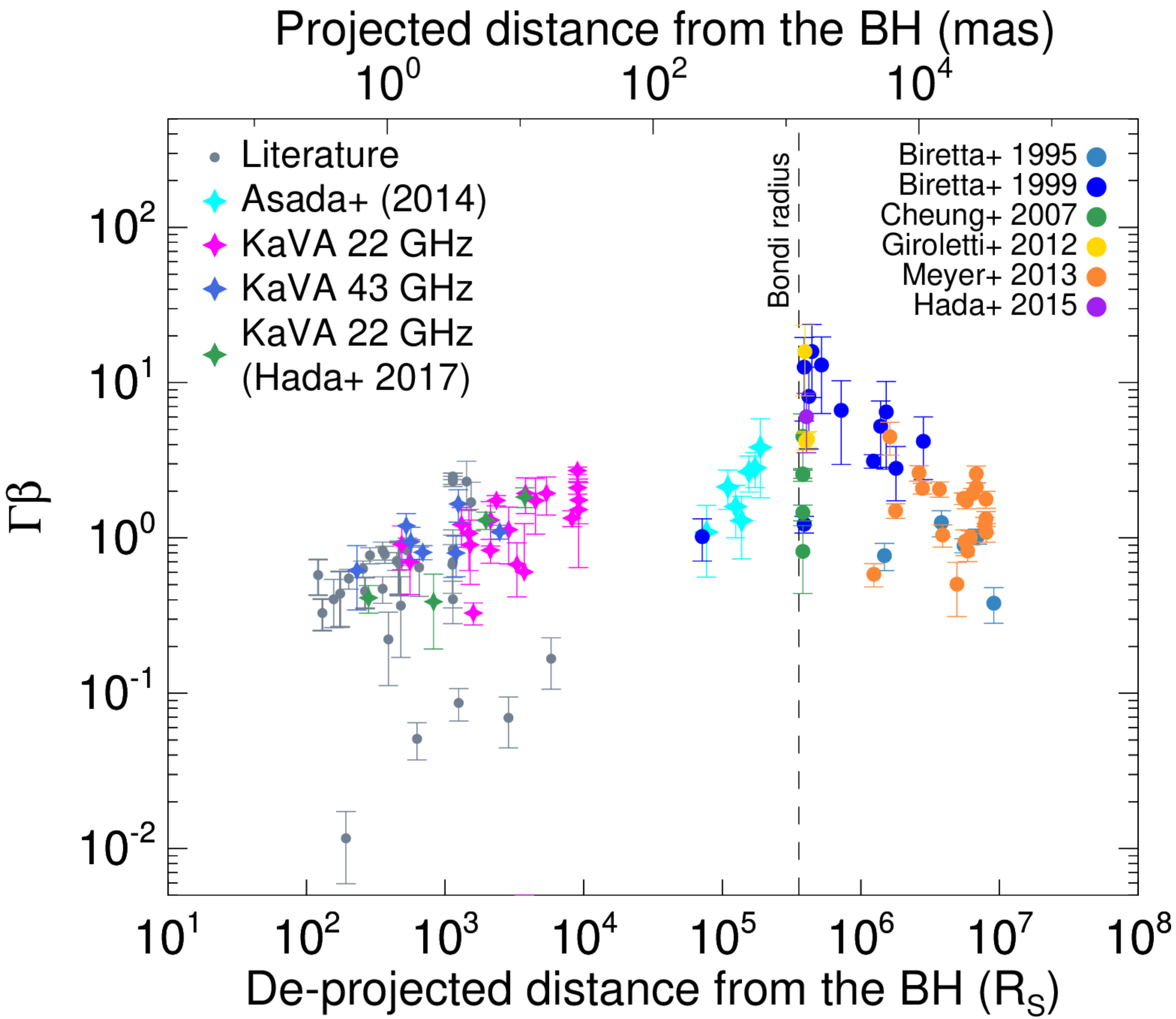
VLBA archival data analysis : 1. modelfit



VLBA archival data analysis : 2. WISE



Kinematics of the M87 jet : Results



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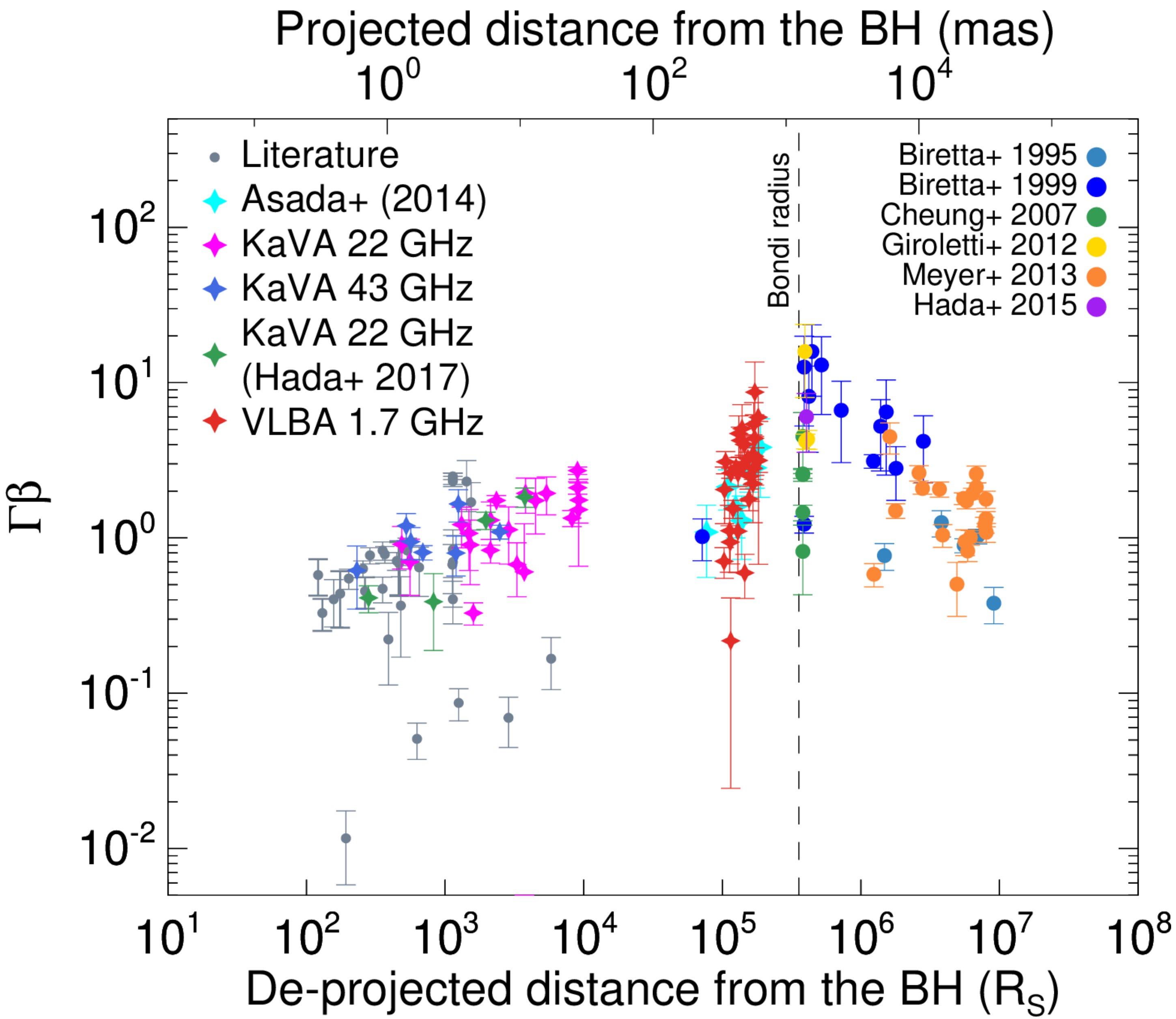
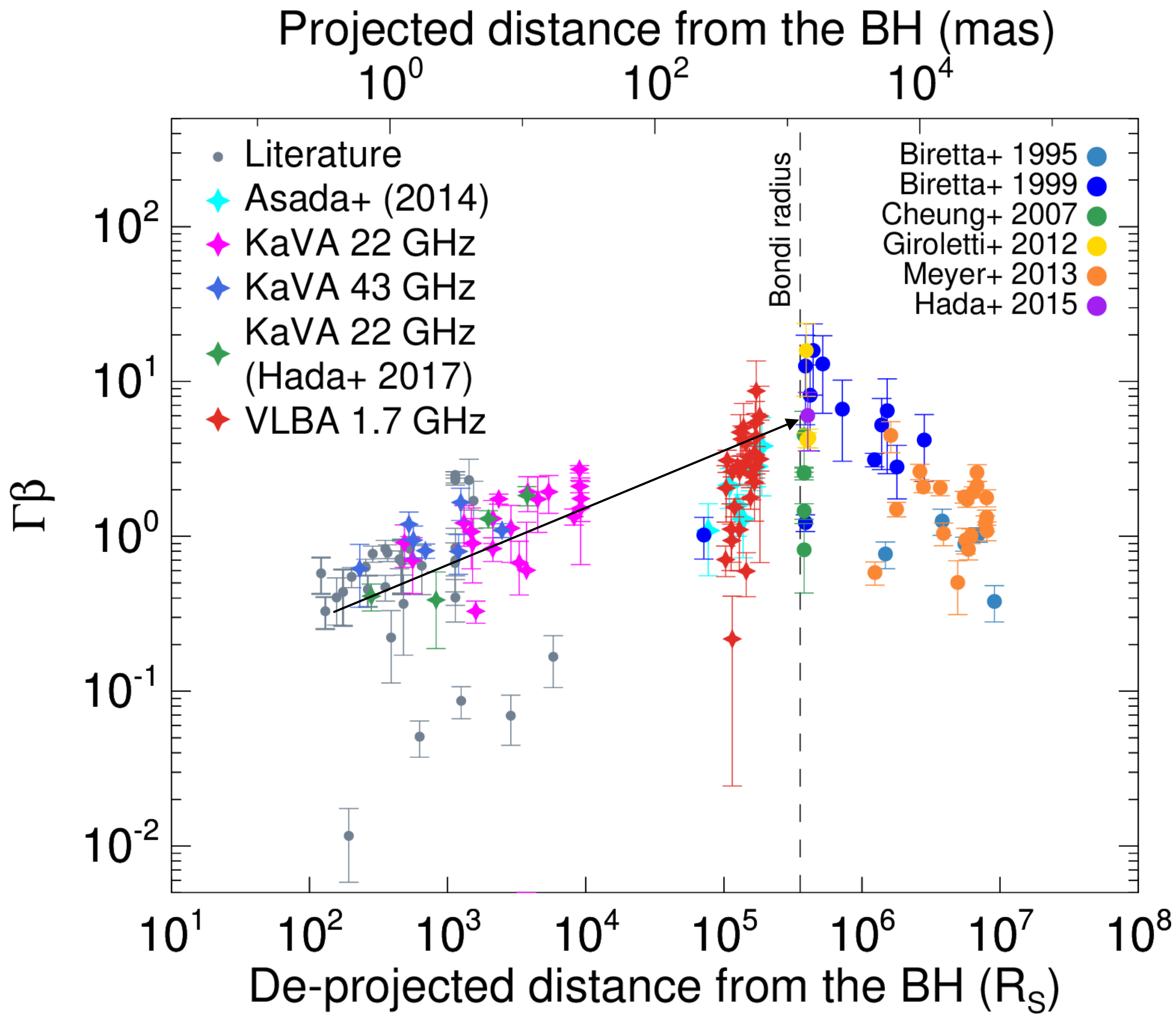
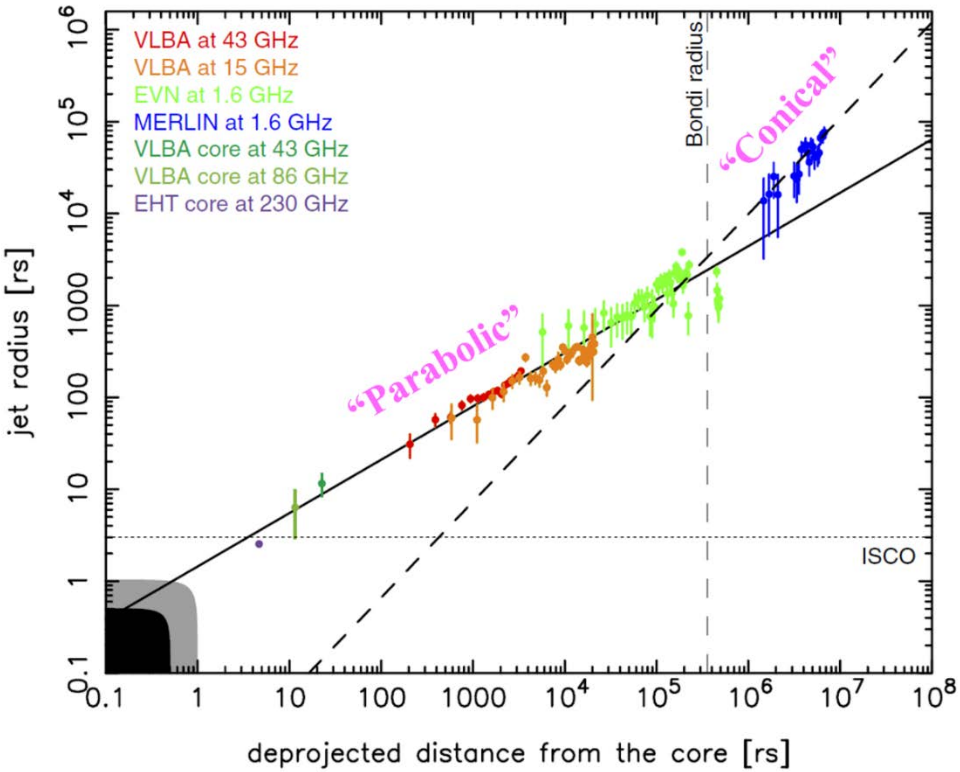


Kinematics of the M87 jet : Results

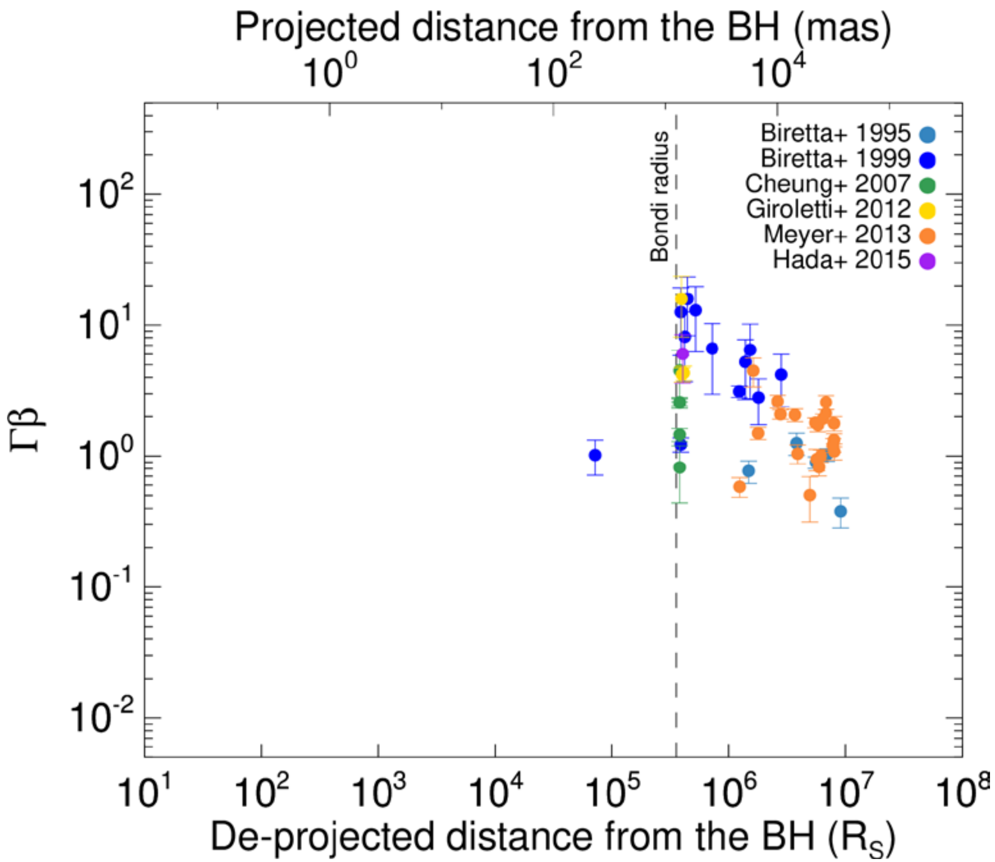


Jet Acceleration in M87

Jet Collimation ⟷ Jet Acceleration



Nakamura & Asada (2013)



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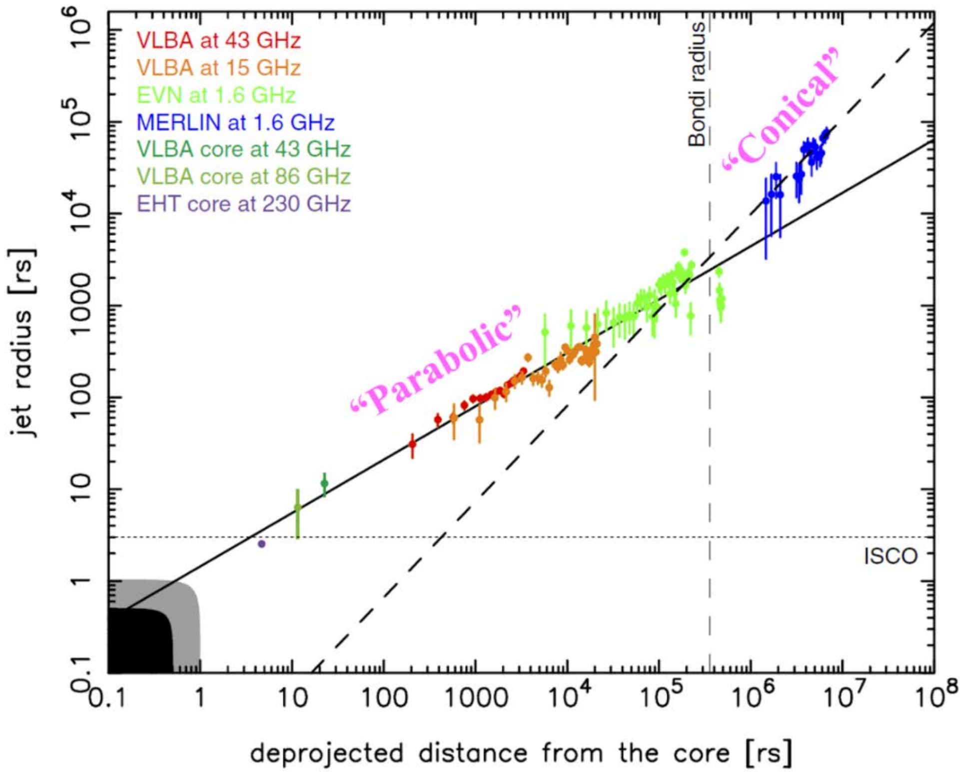
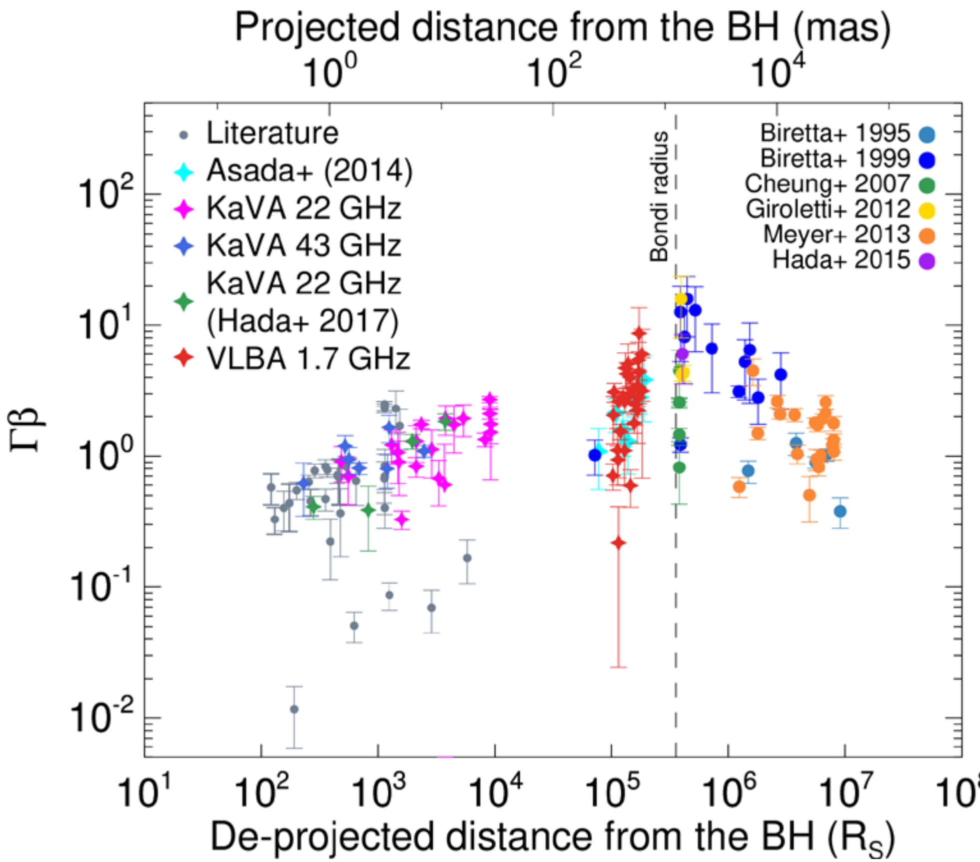


Nakamura & Asada (2013)



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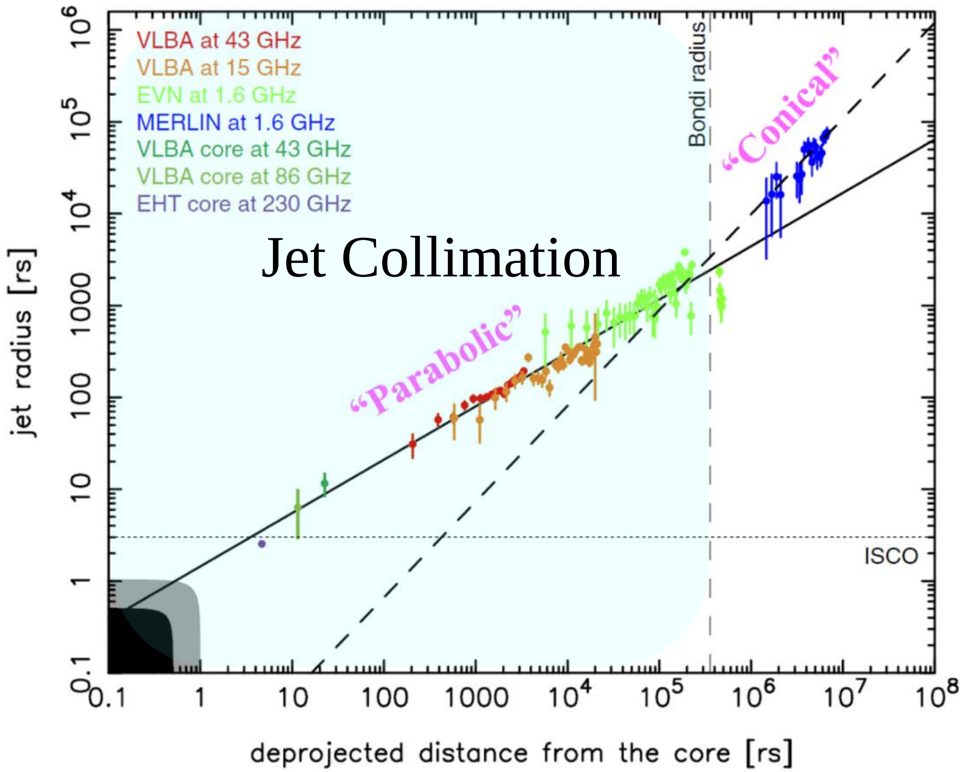

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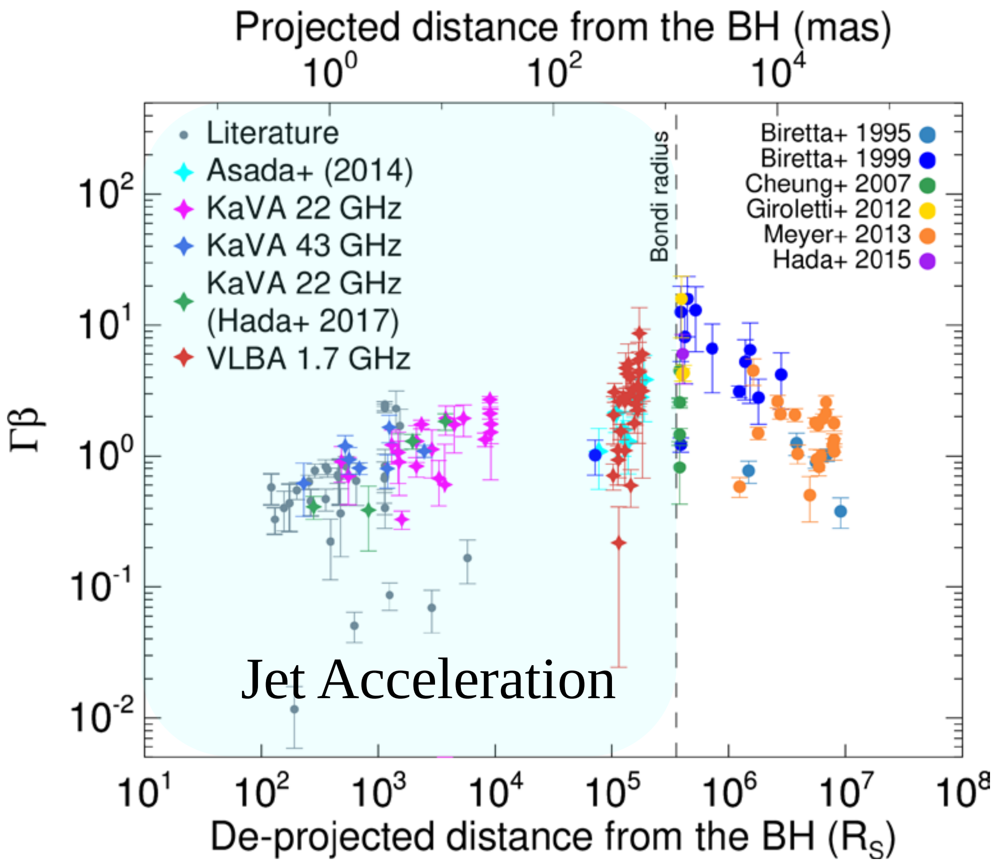
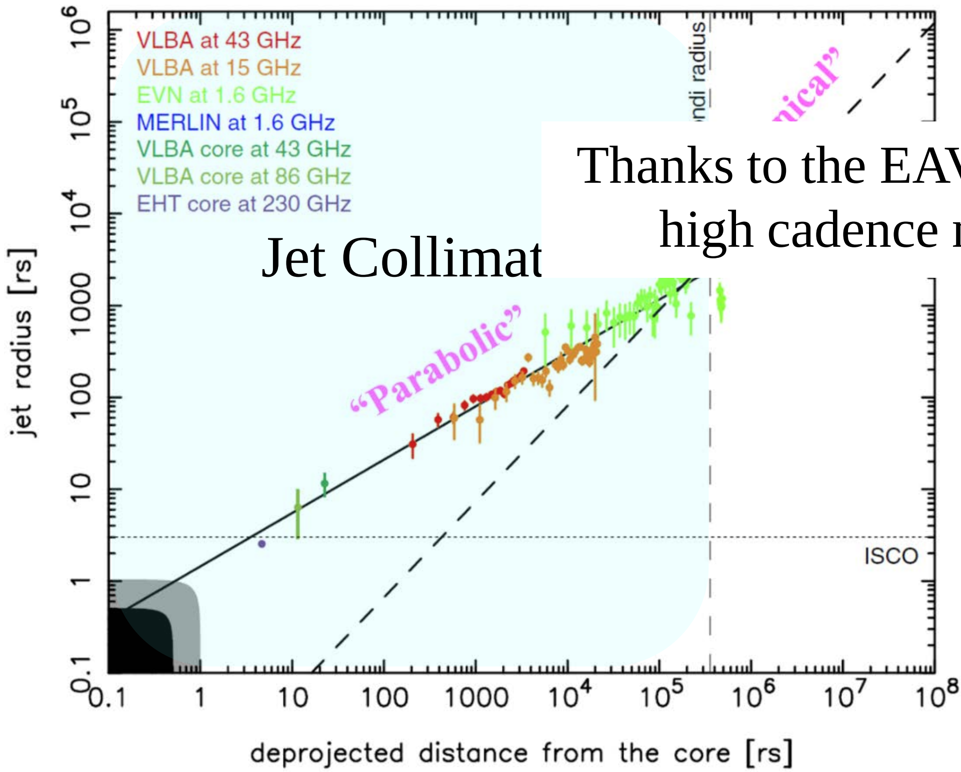


We studied jet acceleration of M87 with KaVA and VLBA data and our results suggest a **GRADUAL JET ACCELERATION IN THE SAME REGION AS THE COLLIMATION ZONE.**

→ **SUPPORTS THE MAGNETIC JET ACCELERATION MODEL.**

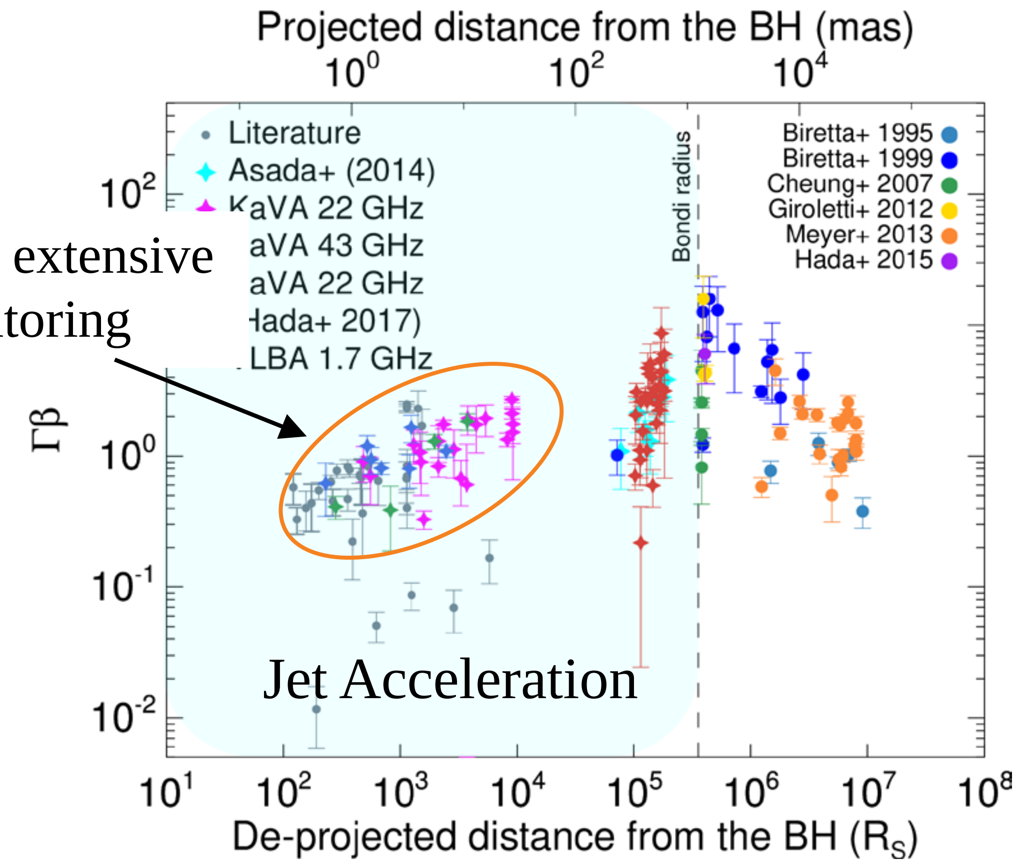
Jet Acceleration in M87

Jet Collimation ⟷ Jet Acceleration



Nakamura & Asada (2013)

Thanks to the EAVN's extensive high cadence monitoring



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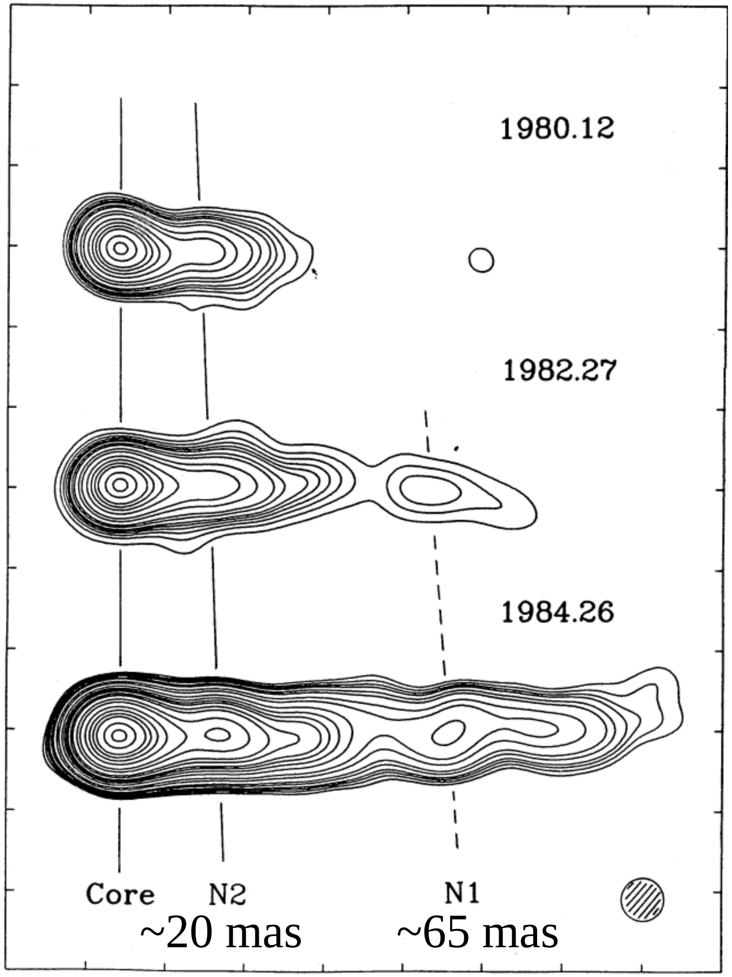
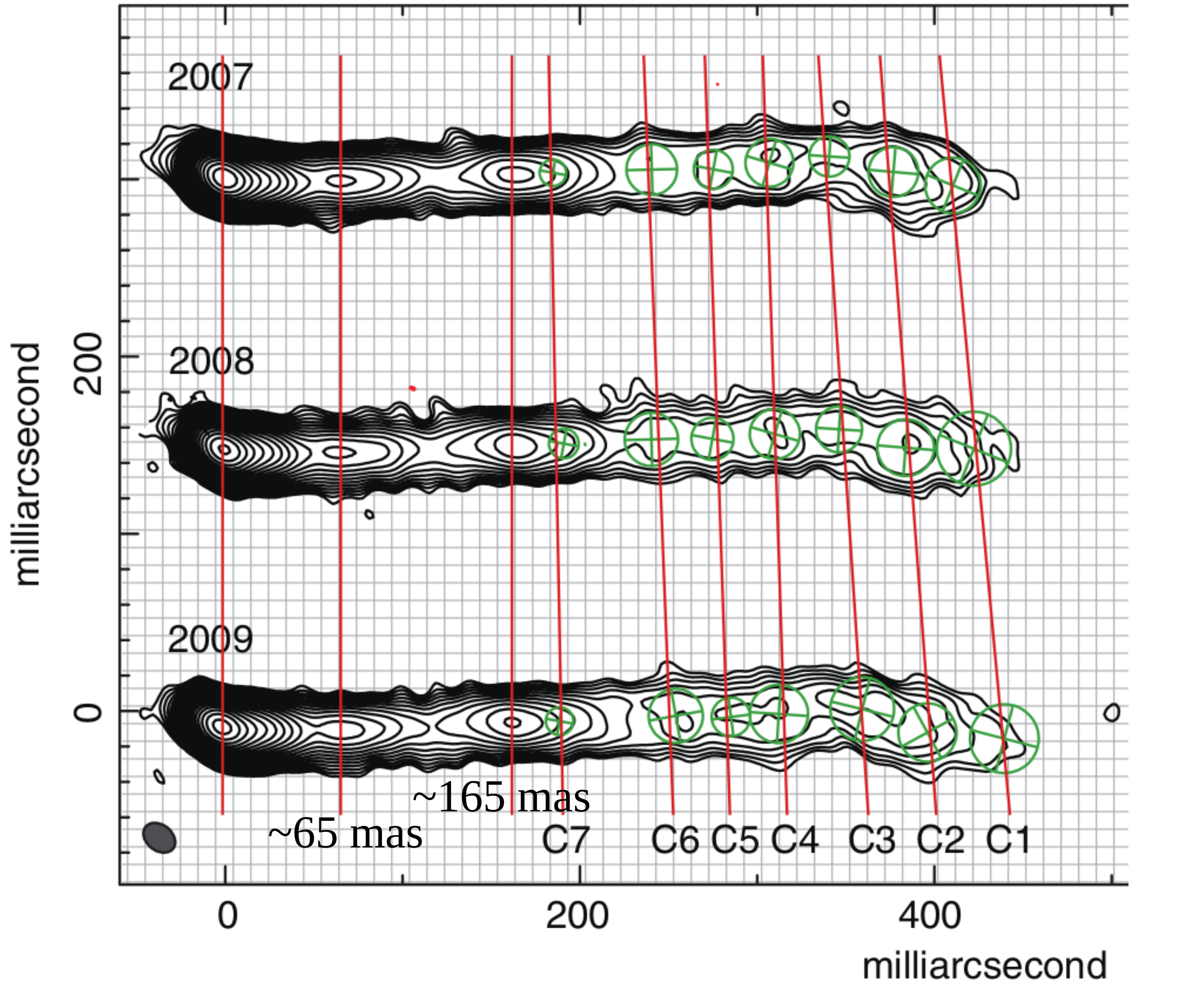
Discussion: Origin of the stationary features in the jet?

Reid+(1989)



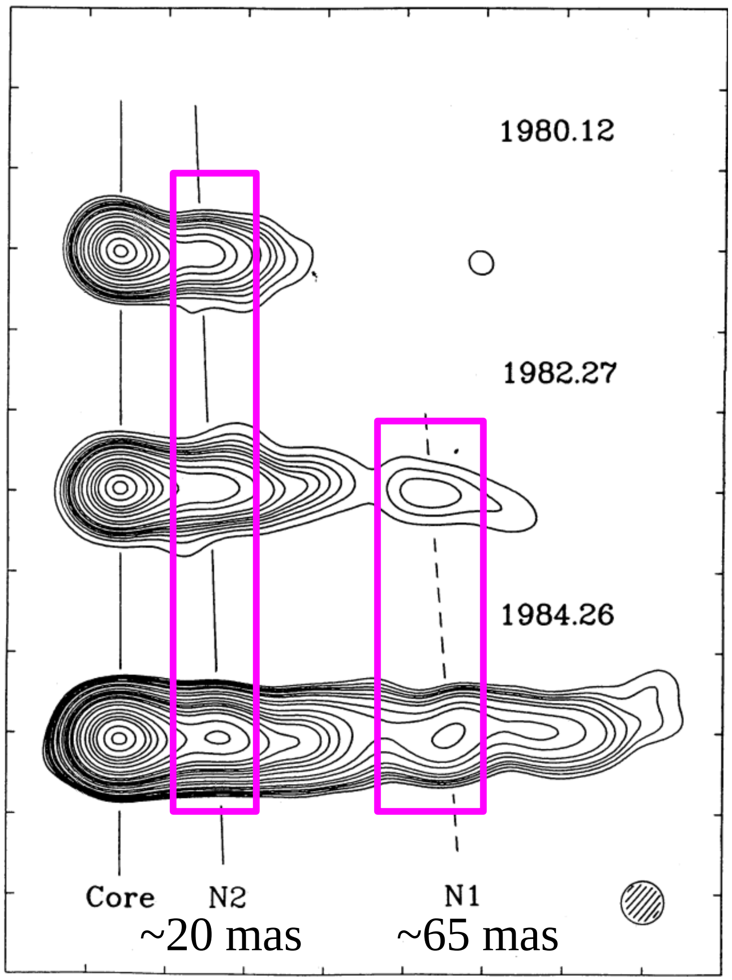
Asada+(2014)



Several ‘apparently stationary’ features exist in the jet at ~20, ~65, and ~165 mas.

Discussion: Origin of the stationary features in the jet?

Reid+(1989)



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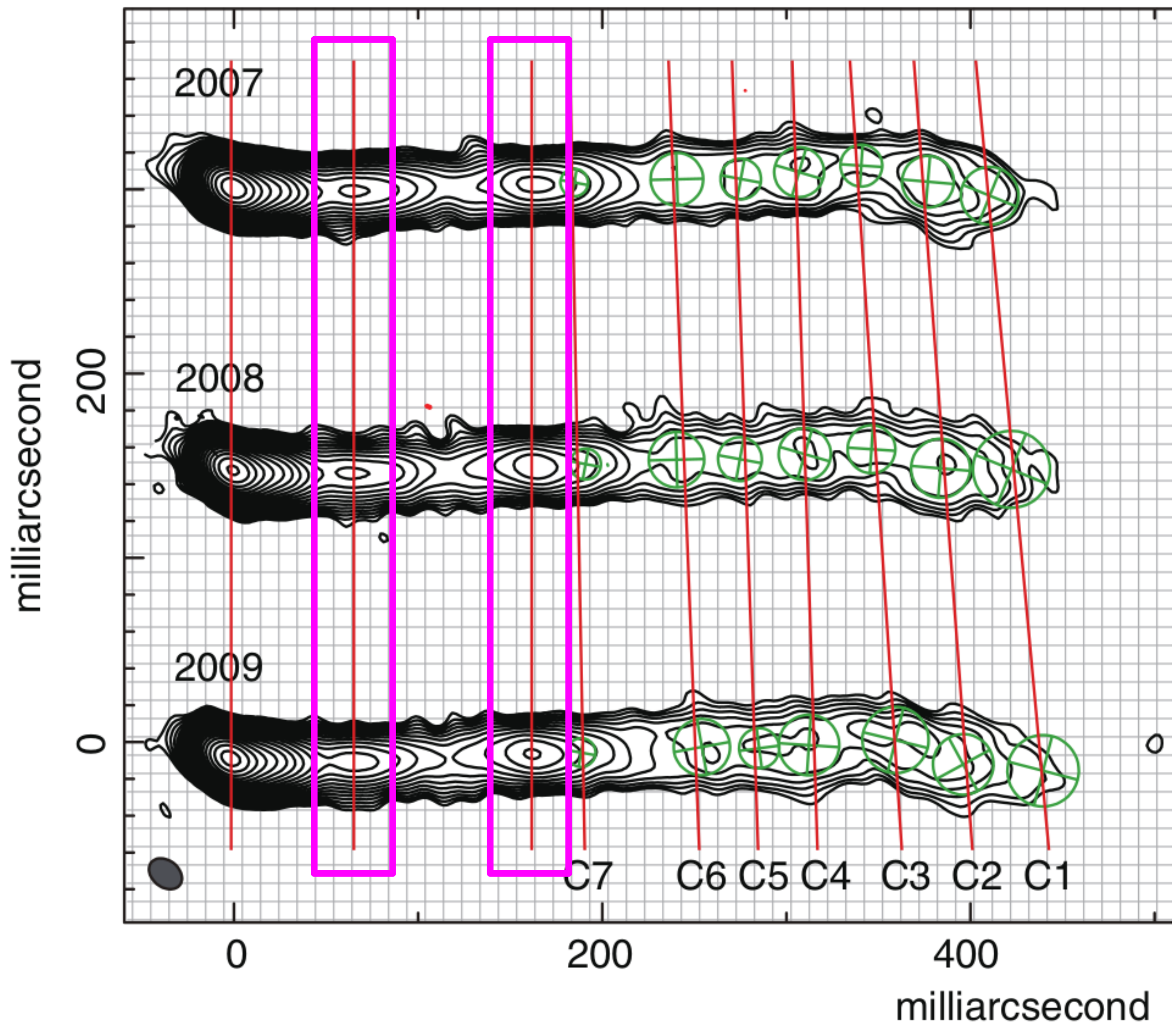

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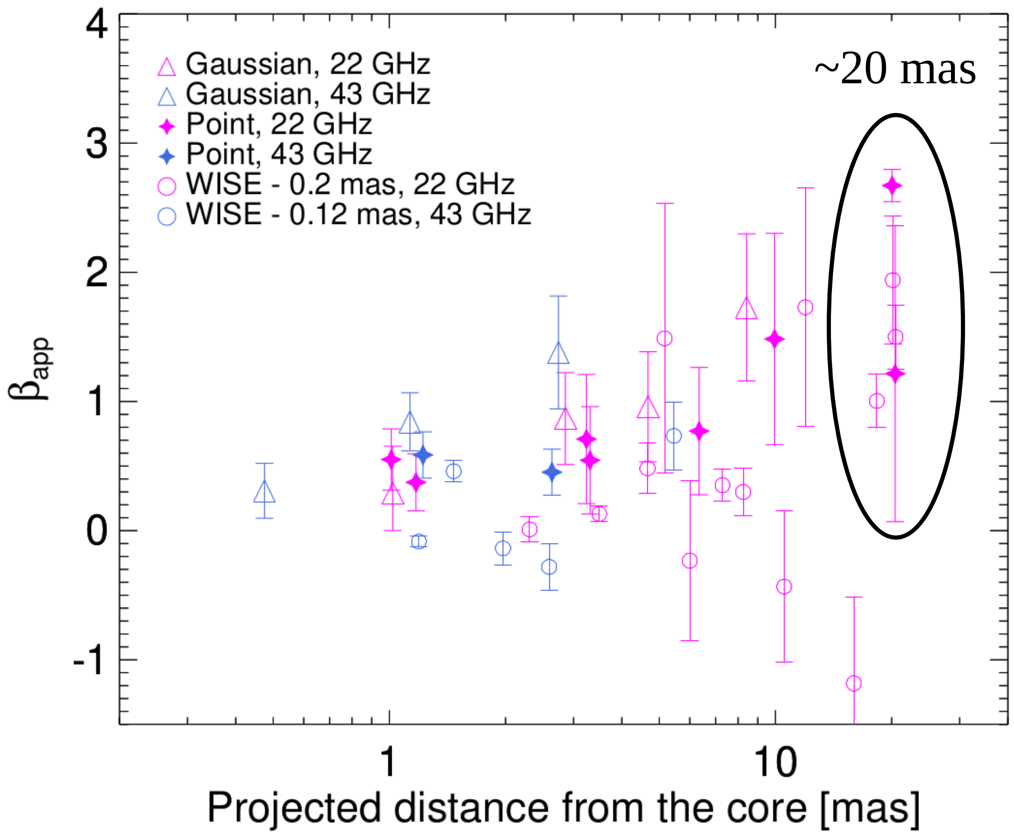
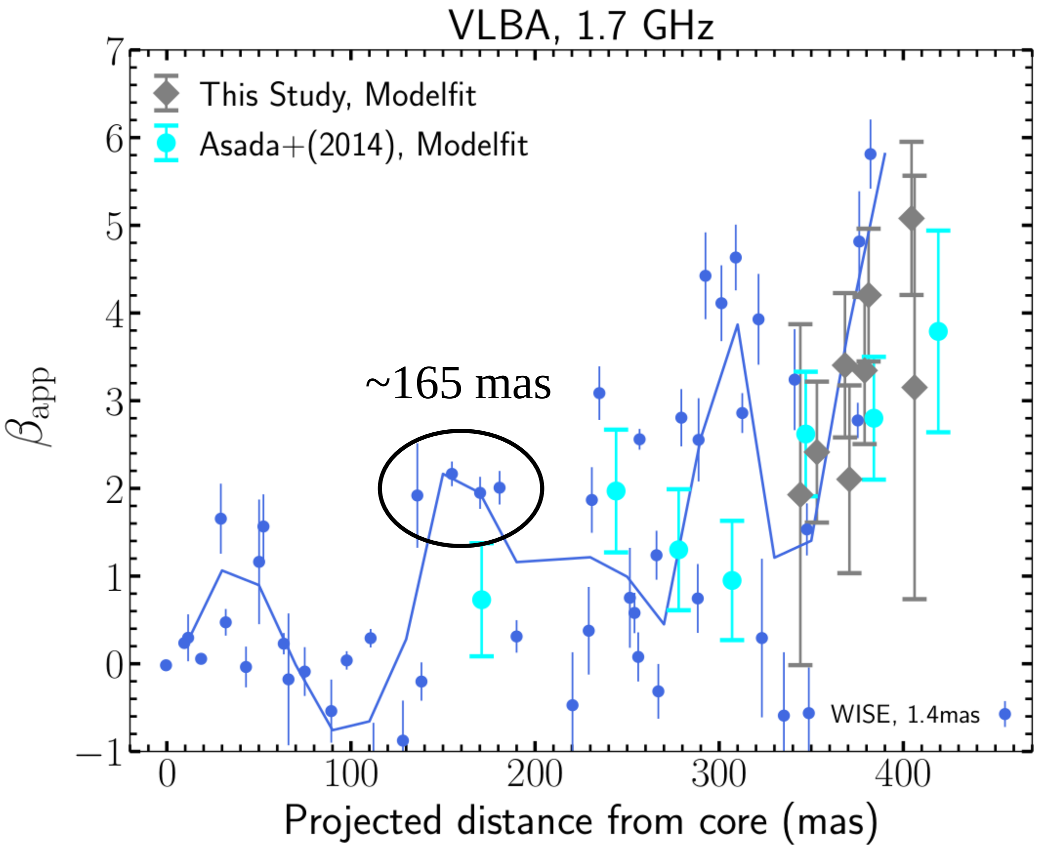
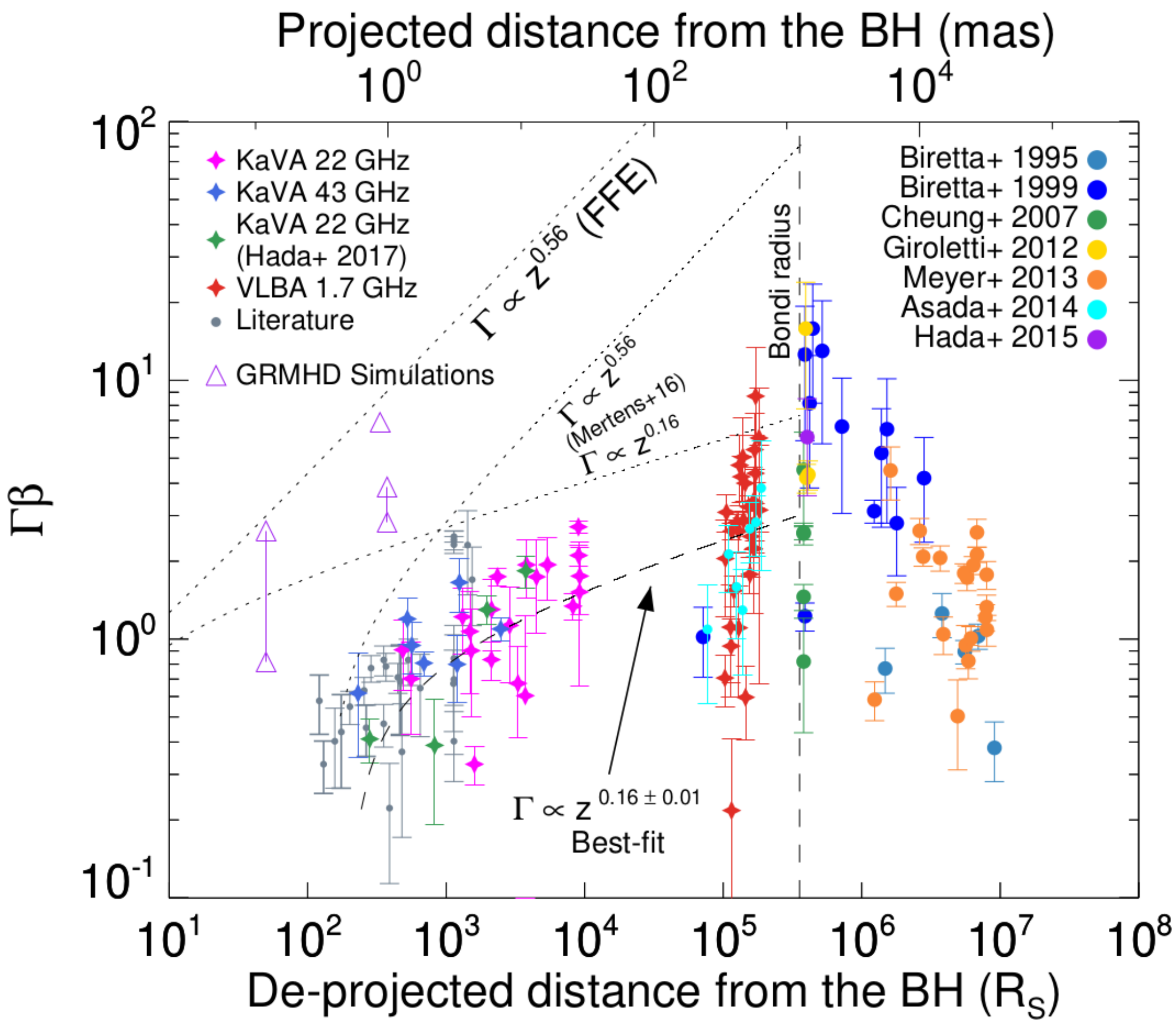




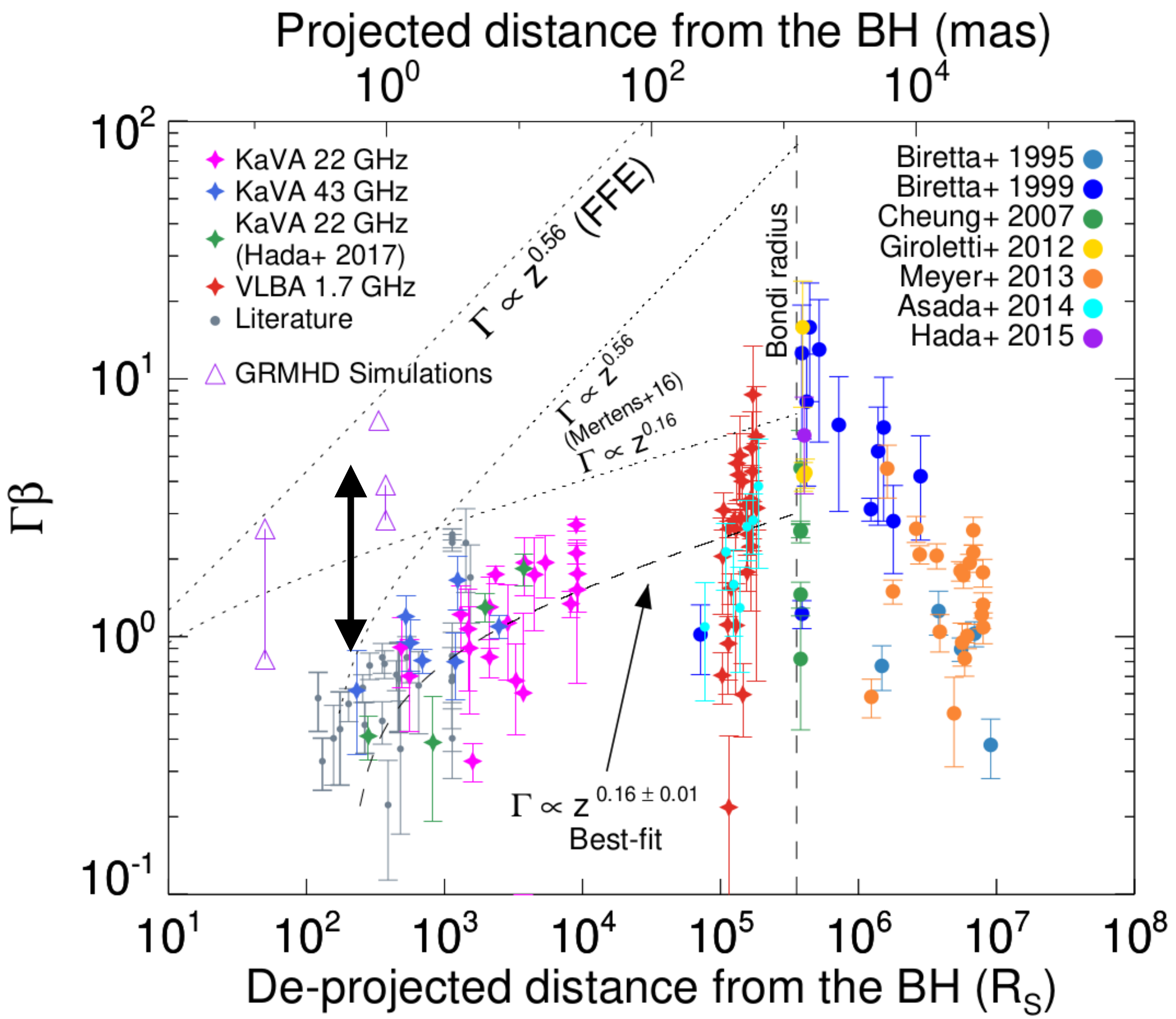
Several 'apparently stationary' features exist in the jet at ~20, ~65, and ~165 mas.
→ They may not be 'physically' stationary but result from the re-brightening of the jet (regions of particle acceleration? Or local Doppler boosting enhancement?).

Discussion: Slow Jet Acceleration



— The jet motion is not as fast as what GRMHD simulations showed on < a few hundreds Rs.

Discussion: Slow Jet Acceleration



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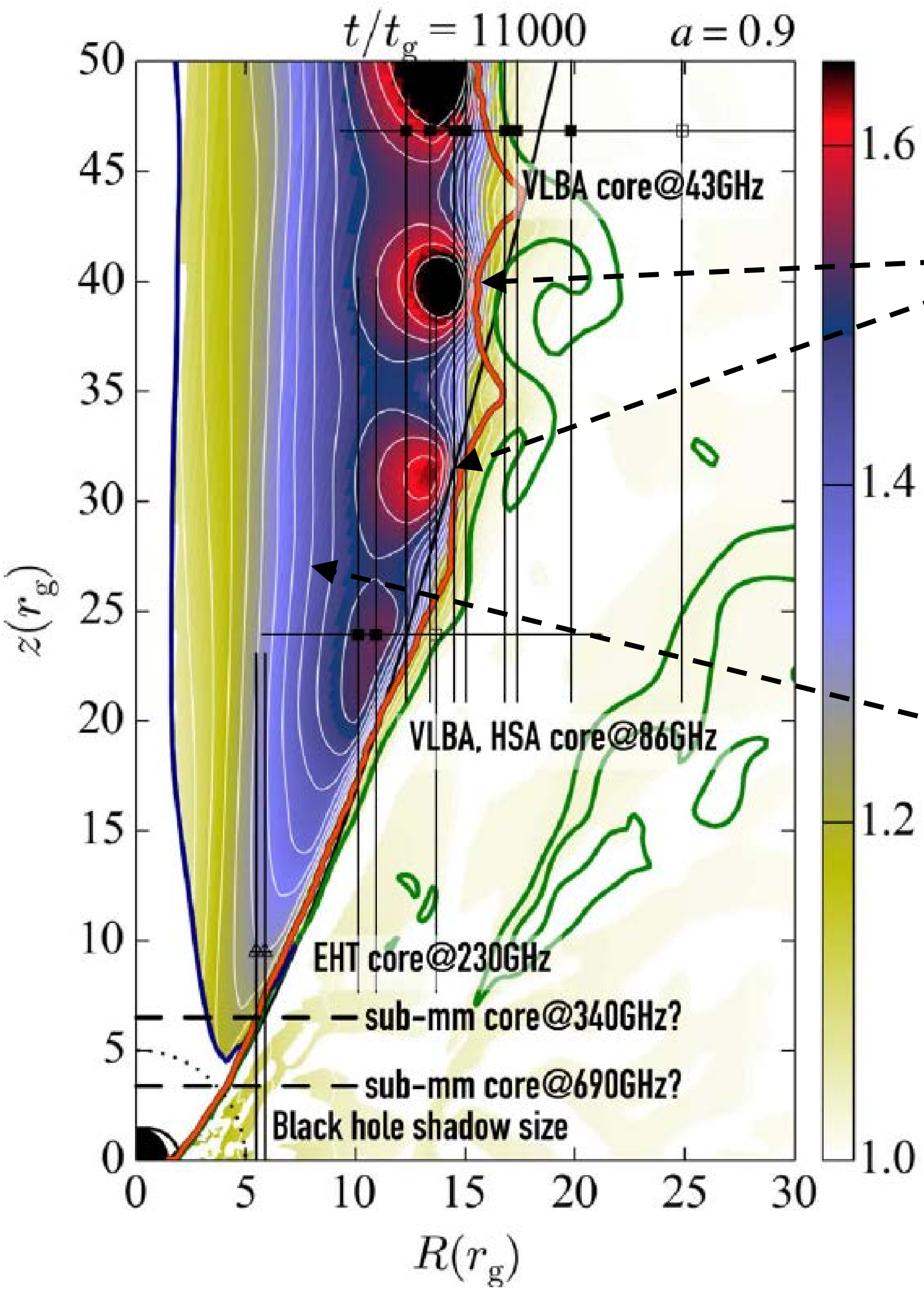


Local Hot spots
: VLBI speeds

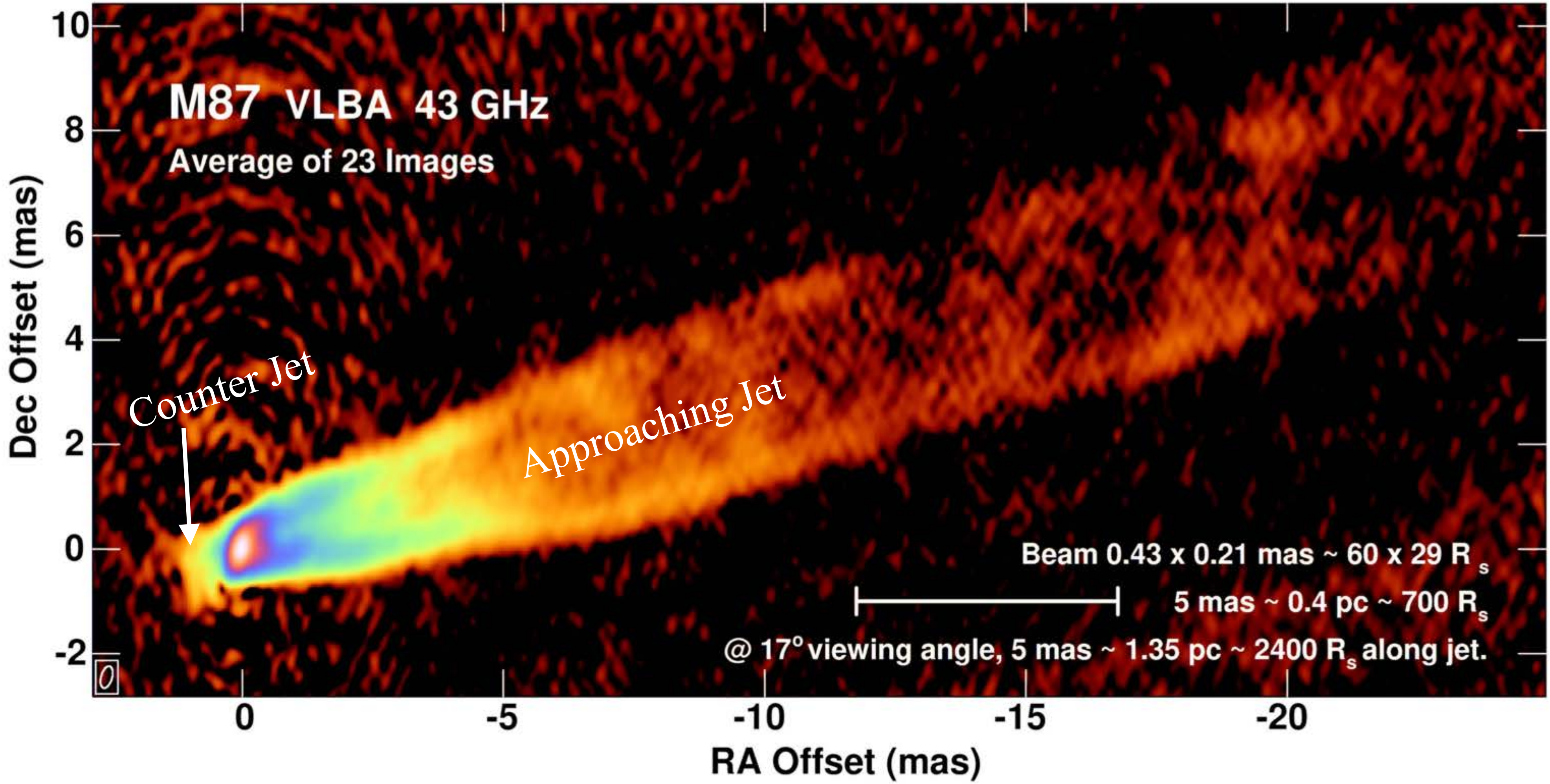
≠

Underlying Flows
: Jet Bulk Speeds

Kinematics of the M87 jet : 4. Jet-to-counterjet brightness ratio

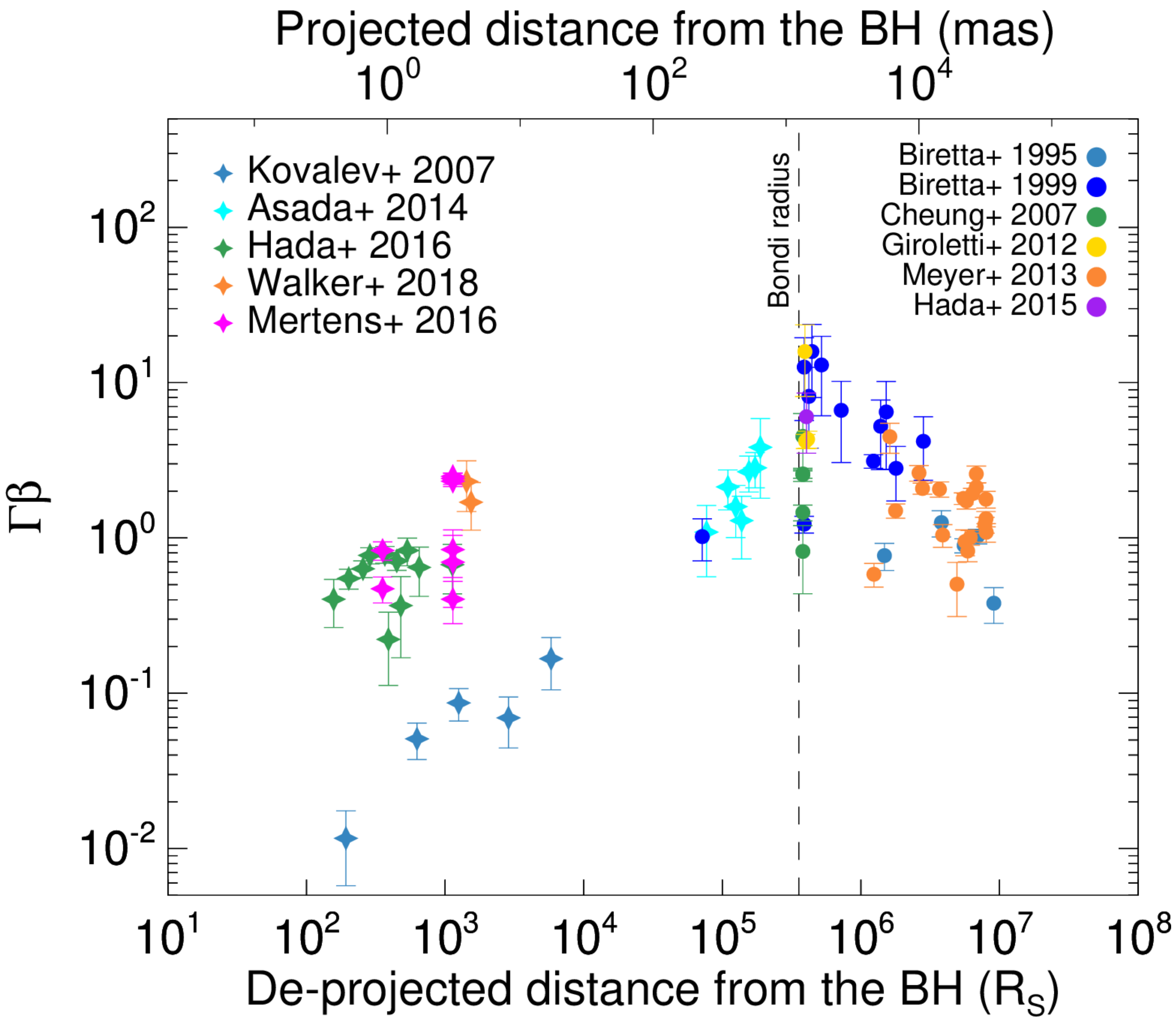
VLBA 43 GHz

Walker et al. (2018)



The brightness difference : due to the Doppler boosting/deboosting

Kinematics of the M87 jet : 4. Jet-to-counterjet brightness ratio



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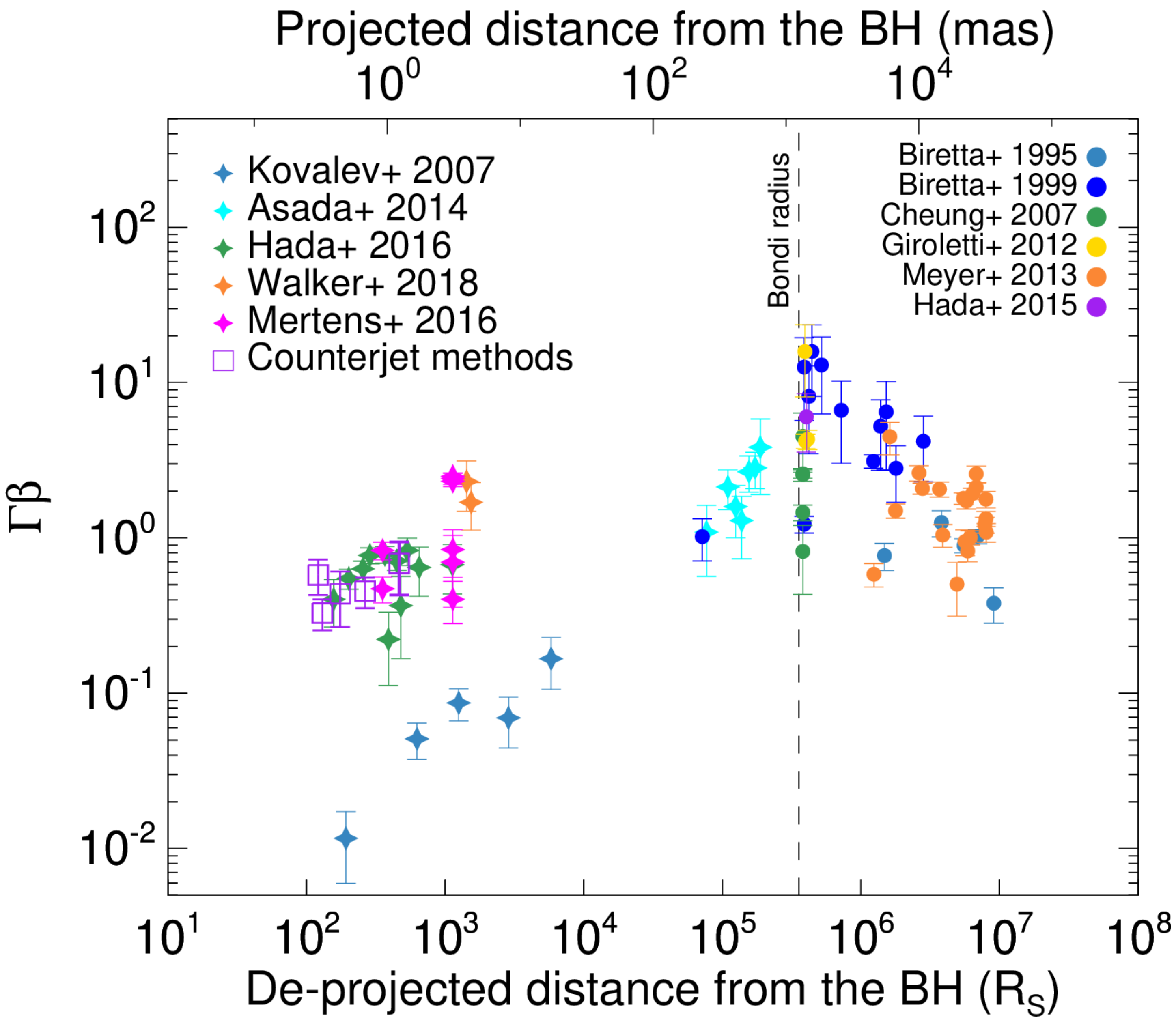
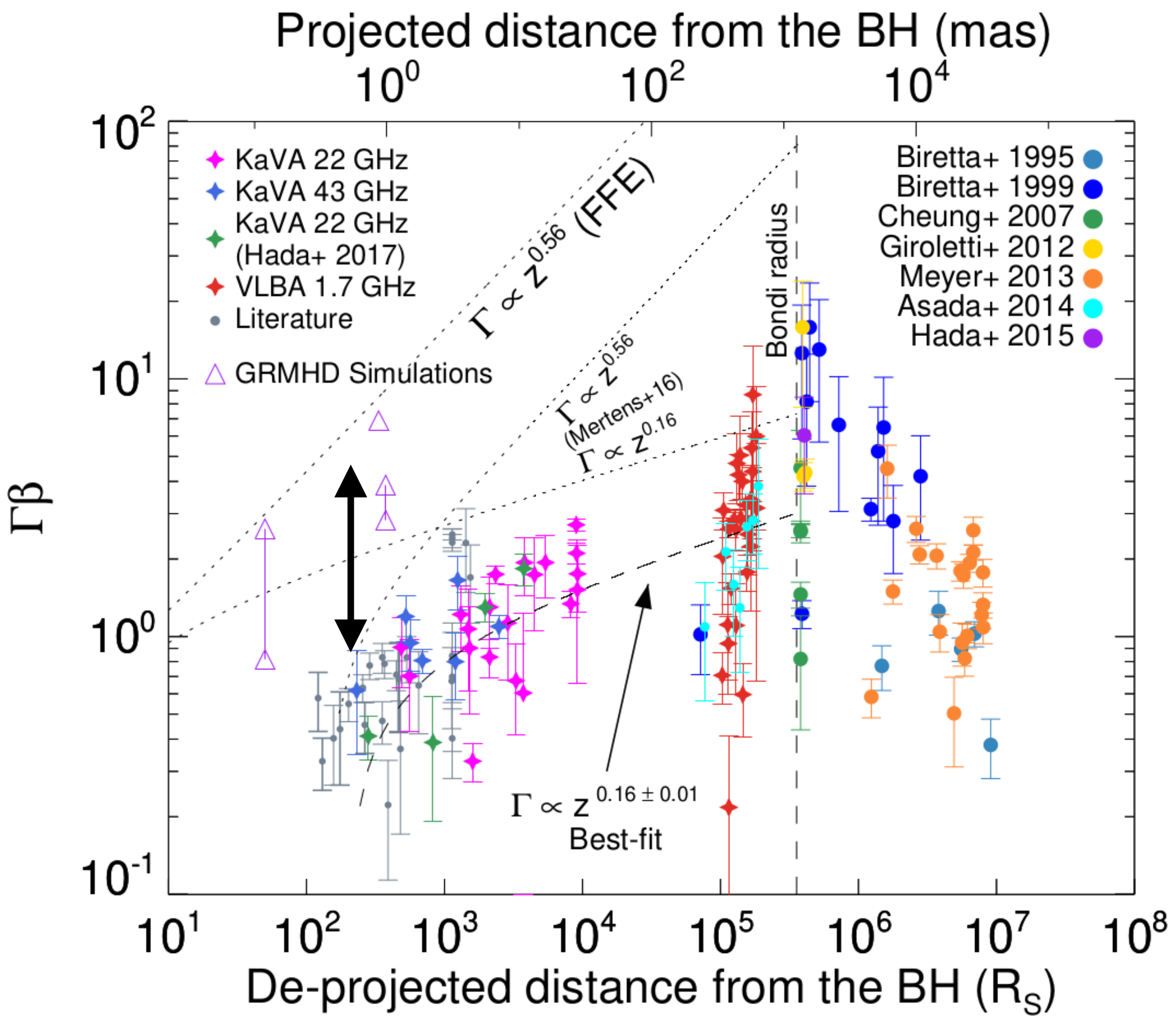


Discussion: Slow Jet Acceleration



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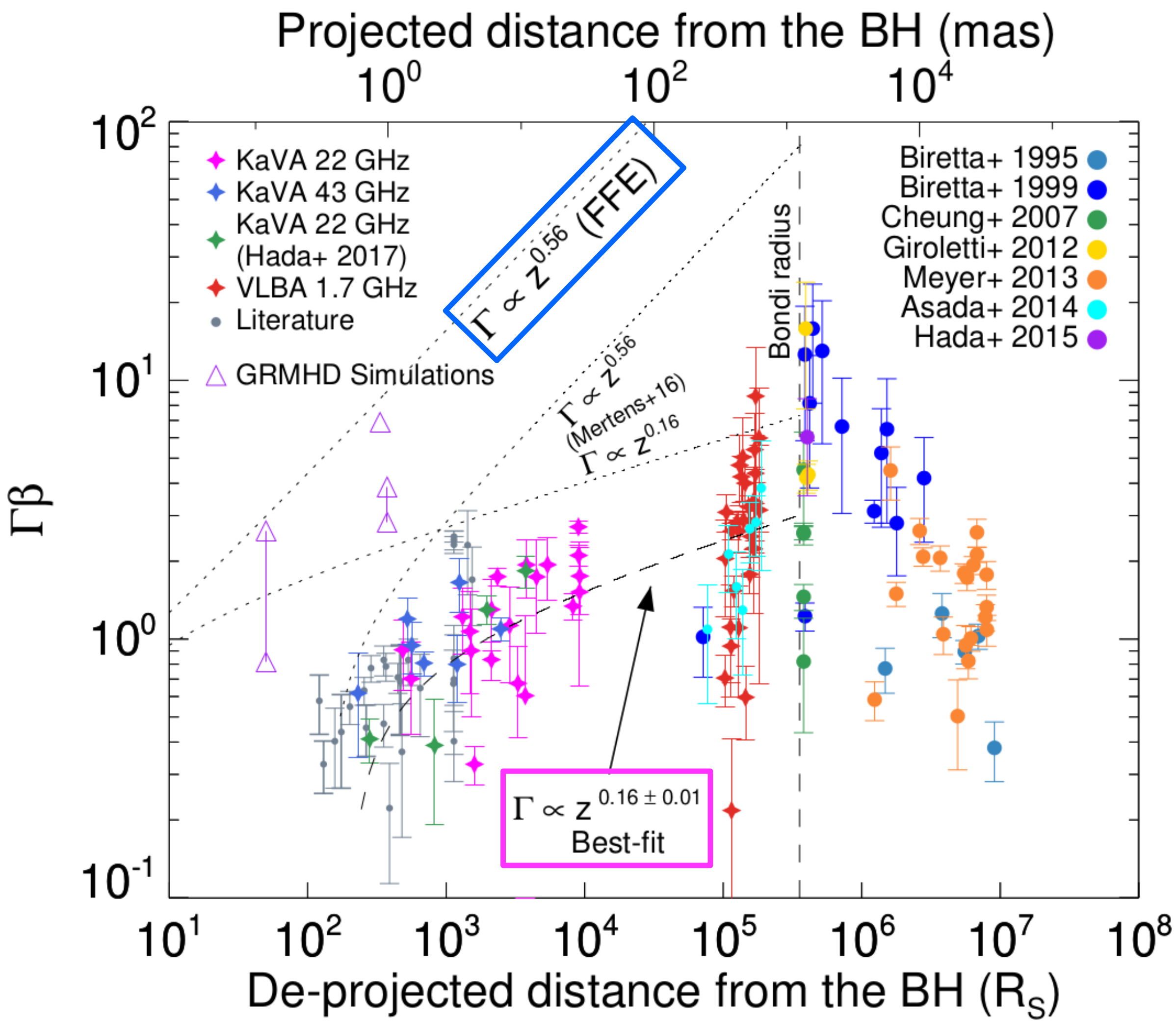

— The jet motion is not as fast as what the models of highly magnetized jet predict.

Discussion: Slow Jet Acceleration

Jet Magnetization + Differential Collimation of Poloidal Fields

⇨ Efficient Jet Acceleration

— The jet motion is not as fast as what the models of highly magnetized jet predict.

Discussion: Slow Jet Acceleration

Energy 'Budget'

↓

Jet Magnetization + Differential Collimation of Poloidal Fields

⇨ Efficient Jet Acceleration

— The jet motion is not as fast as what the models of highly magnetized jet predict.

Discussion: Slow Jet Acceleration

Energy 'Budget' → **Jet Magnetization**

\+

Acceleration Efficiency → **Differential Collimation of Poloidal Fields**

⇨ Efficient Jet Acceleration

— The jet motion is not as fast as what the models of highly magnetized jet predict.

Discussion: Slow Jet Acceleration

Acceleration Efficiency

Energy 'Budget'

Jet Magnetization

Differential Collimation of Poloidal Fields

Efficient Jet Acceleration

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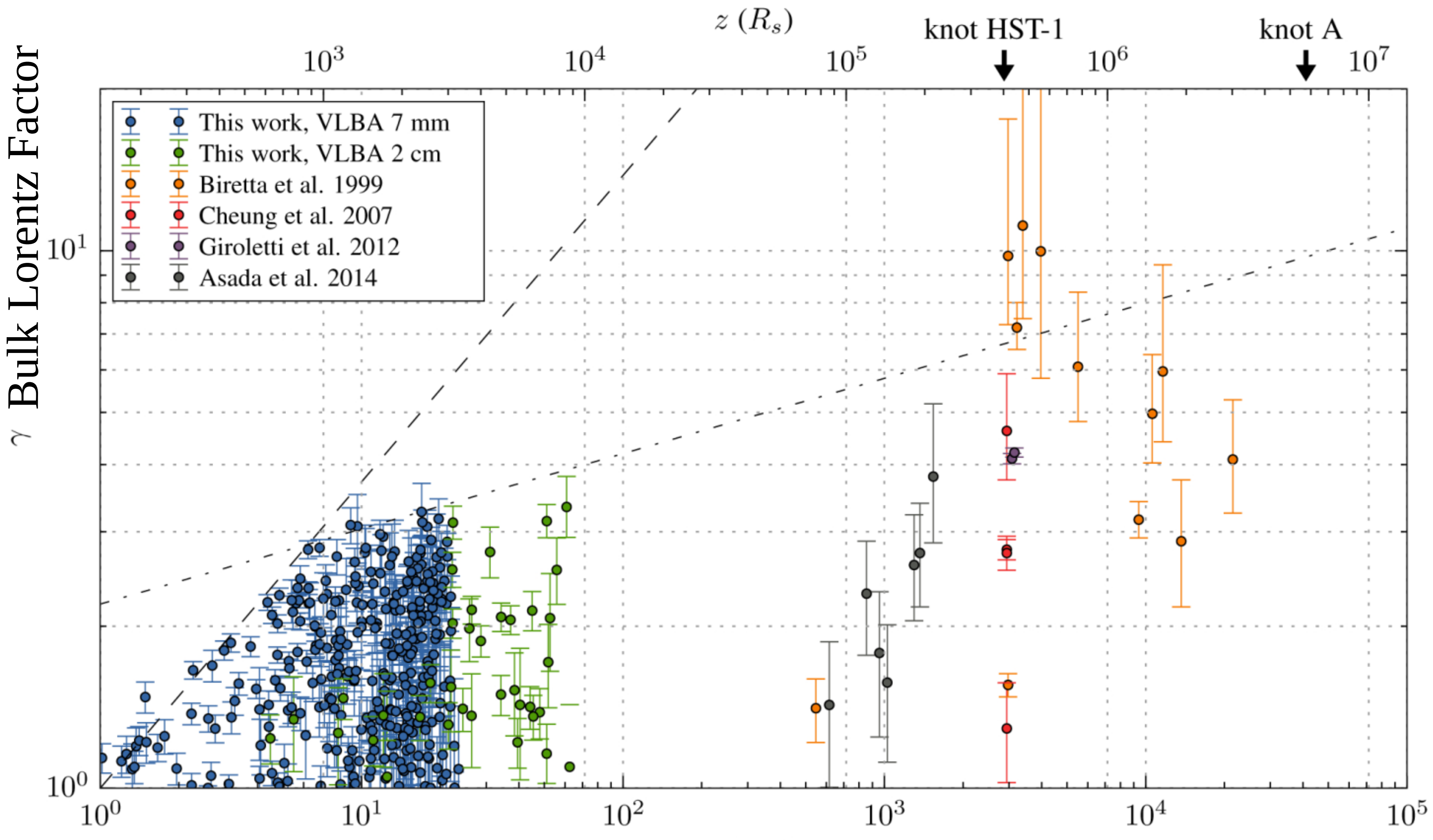
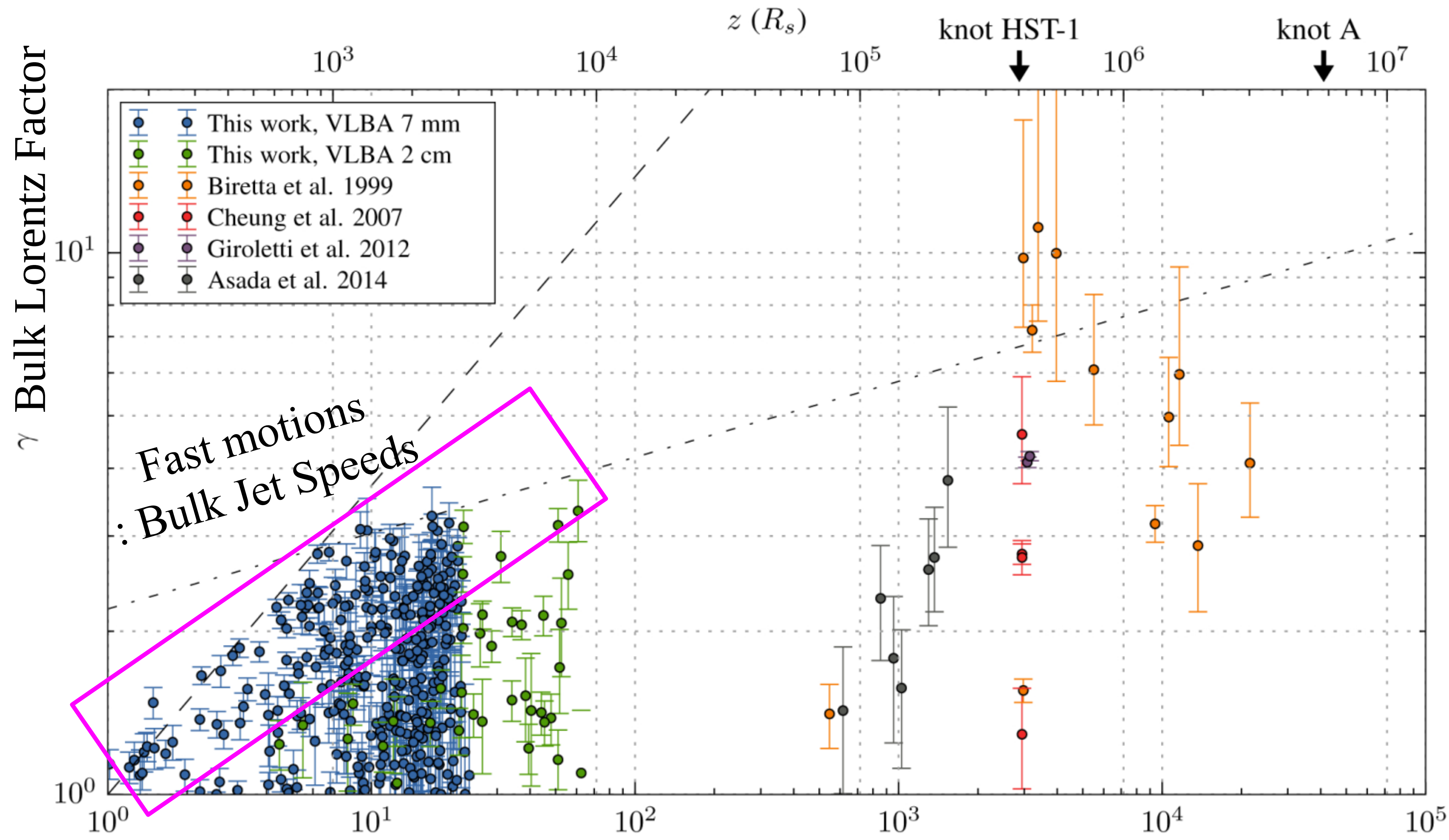
Discussion: Slow Jet Acceleration



Mertens+ (2016)

Discussion: Slow Jet Acceleration



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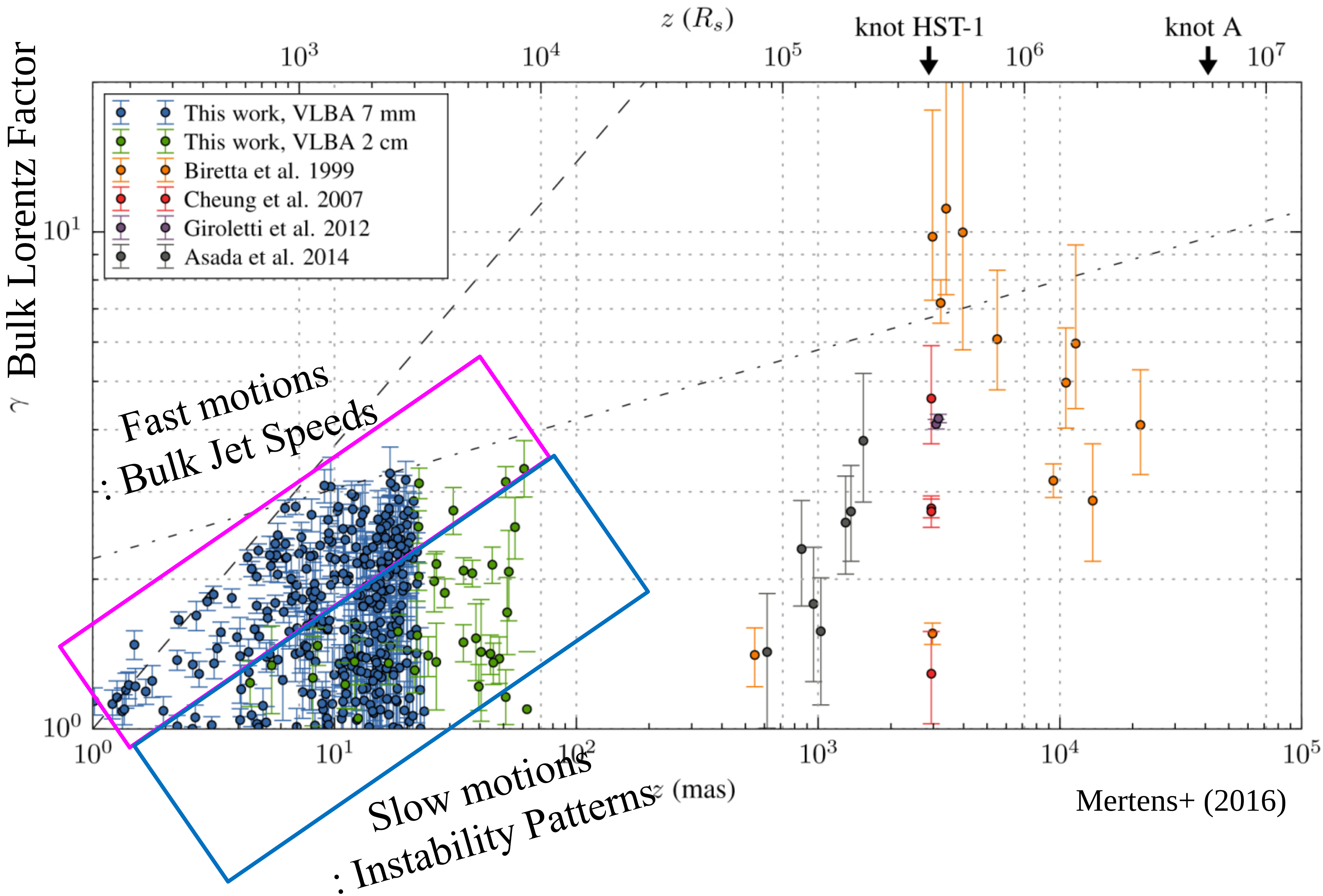

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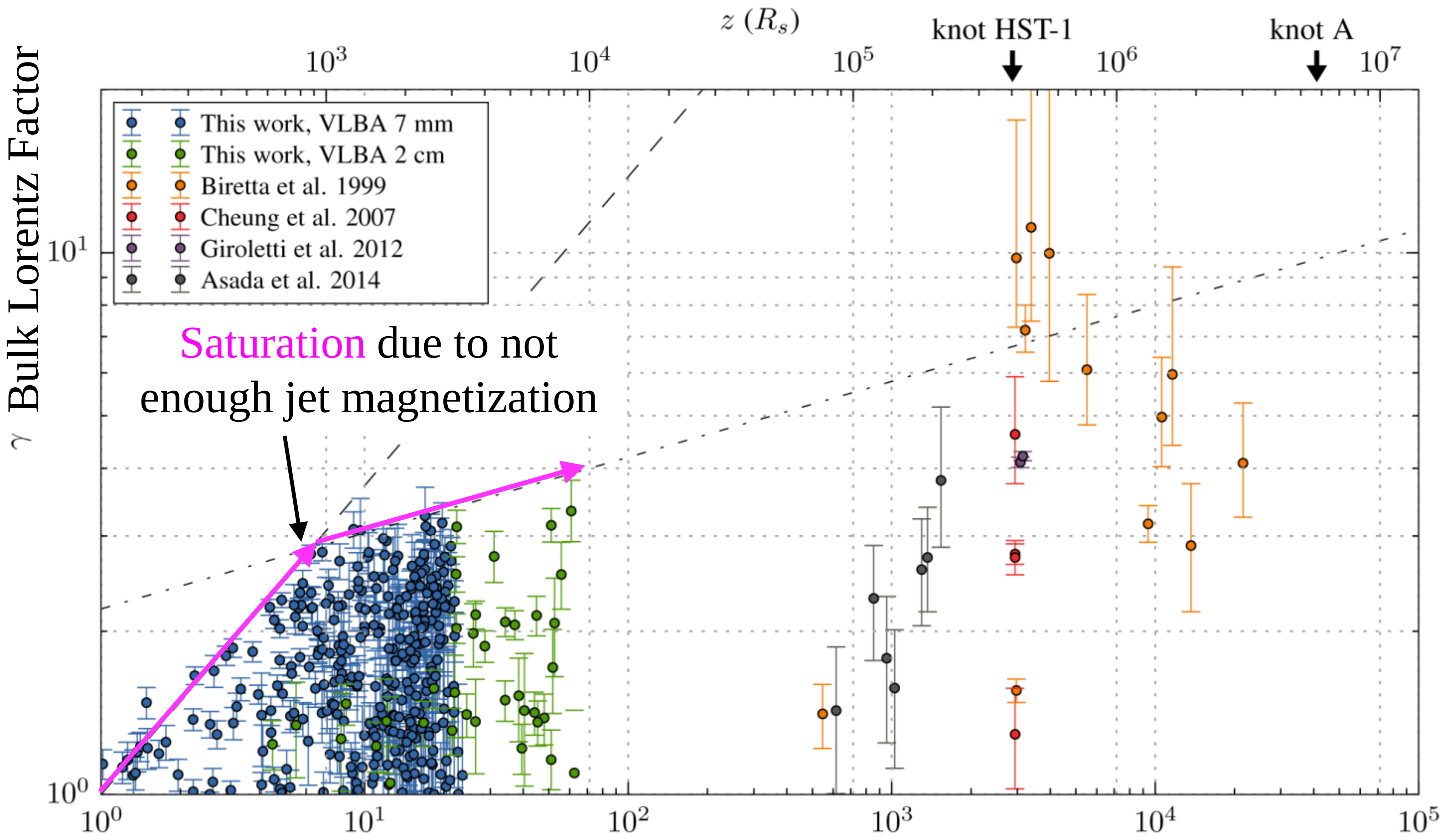
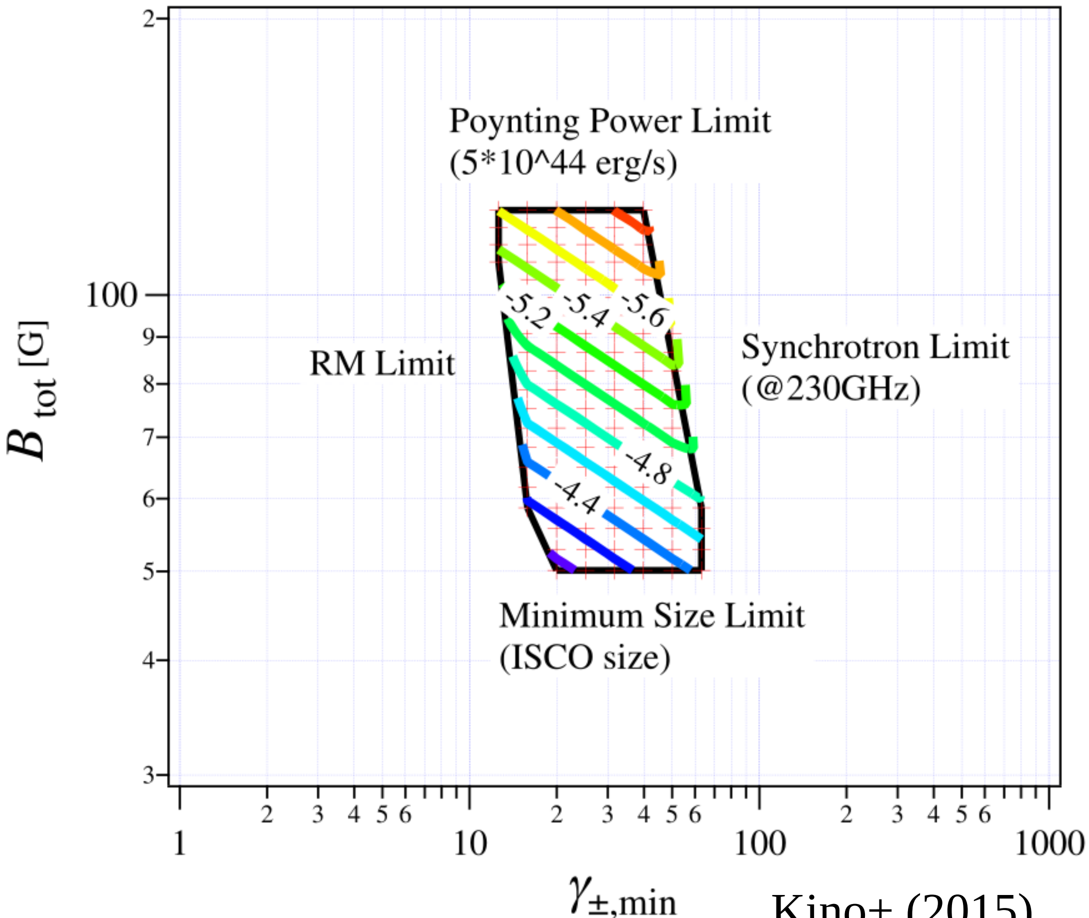


Mertens+ (2016)

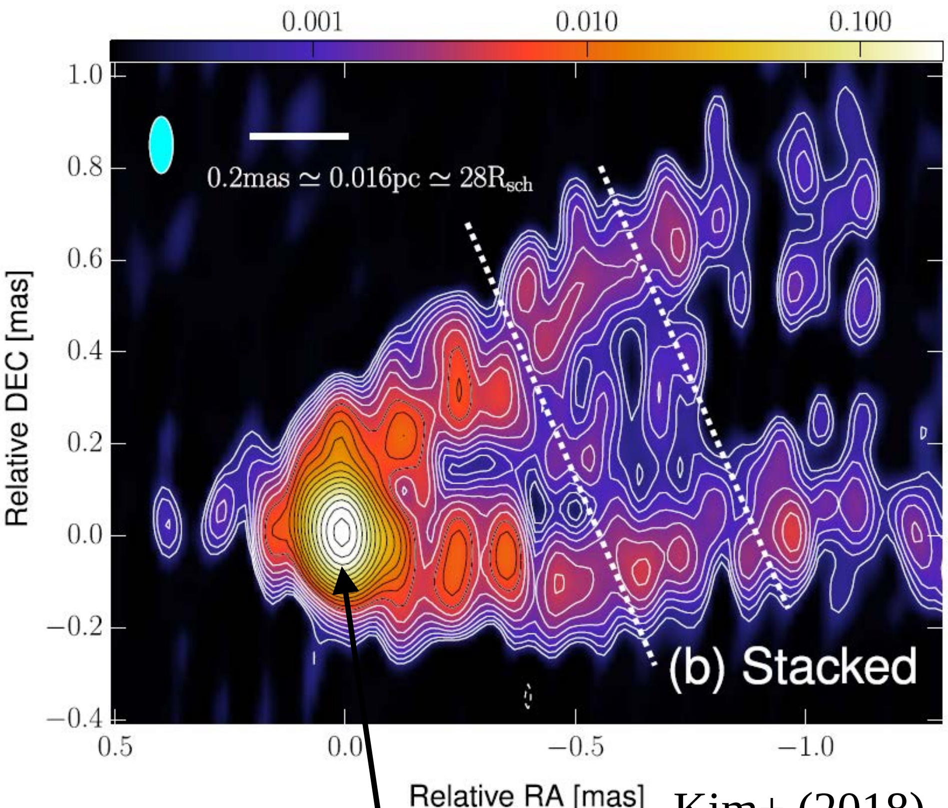
The highly magnetized jet base of M87

$$U_B \gg U_p$$



Kino+ (2015)

$$U_B \gg U_p$$



Kim+ (2018)

…from the observed
core brightness temperature

Discussion: Slow Jet Acceleration

Energy 'Budget' → **Jet Magnetization**

➕

Acceleration Efficiency → **Differential Collimation of Poloidal Fields**

⇨ Efficient Jet Acceleration

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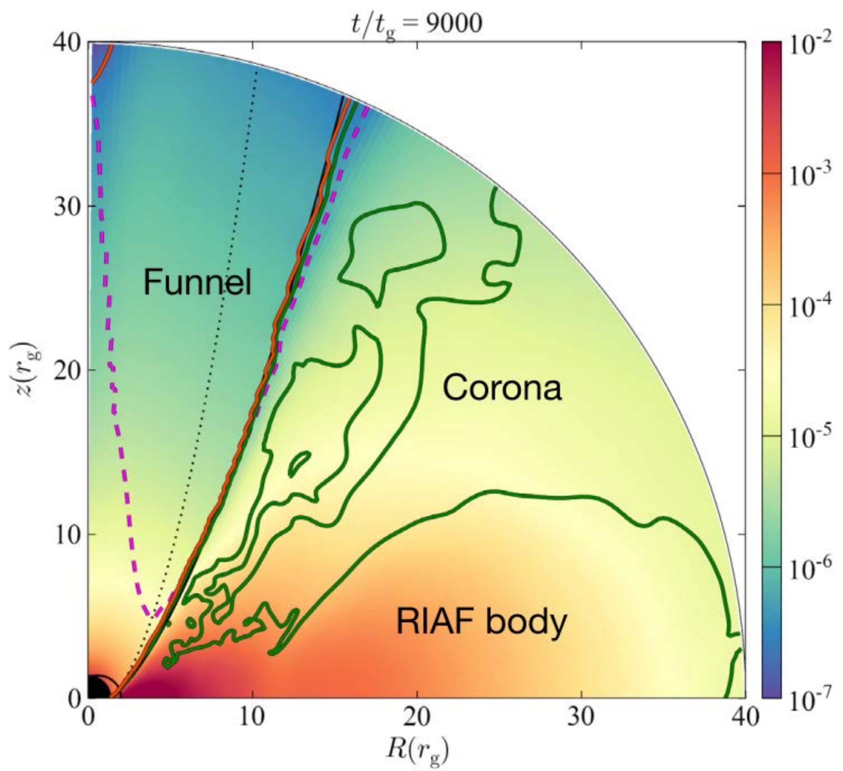
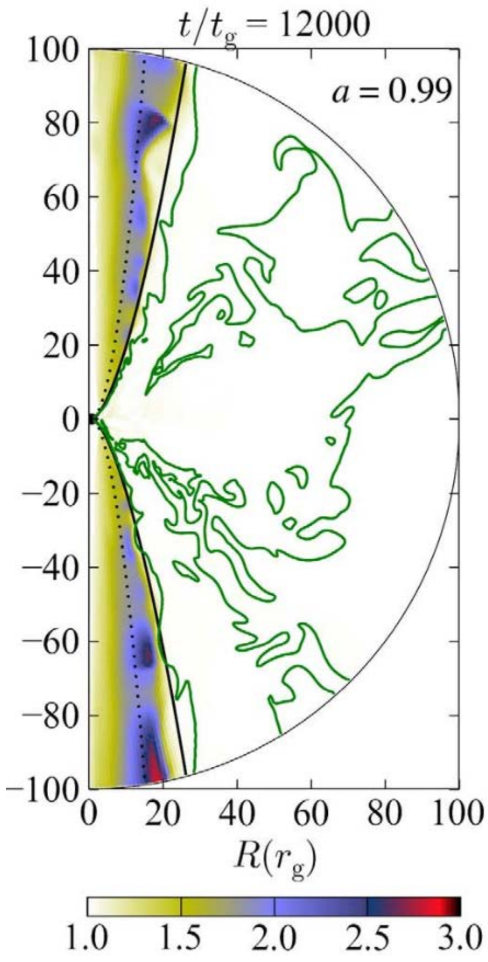
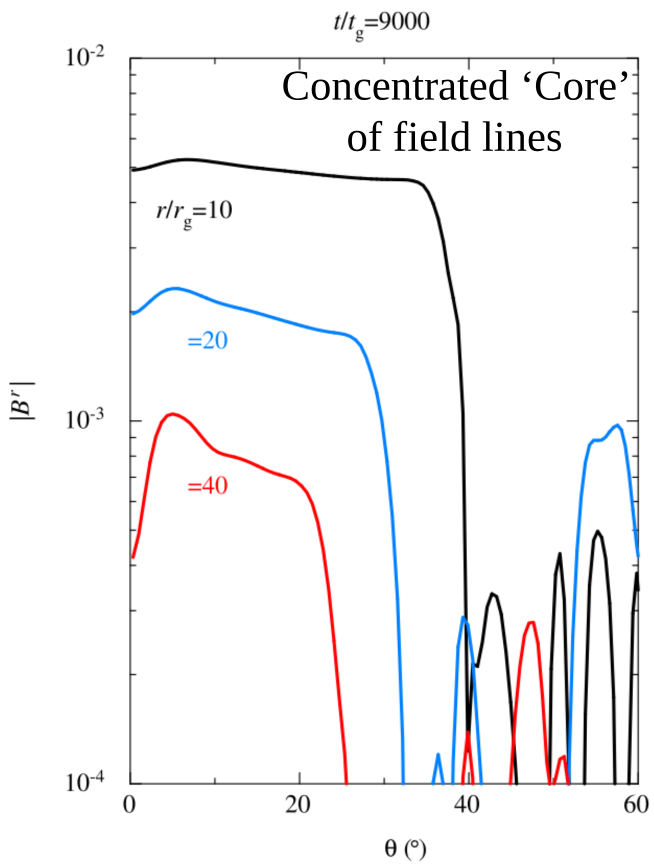
Discussion: Slow Jet Acceleration

Nakamura+ (2018)





Recent GRMHD Simulations



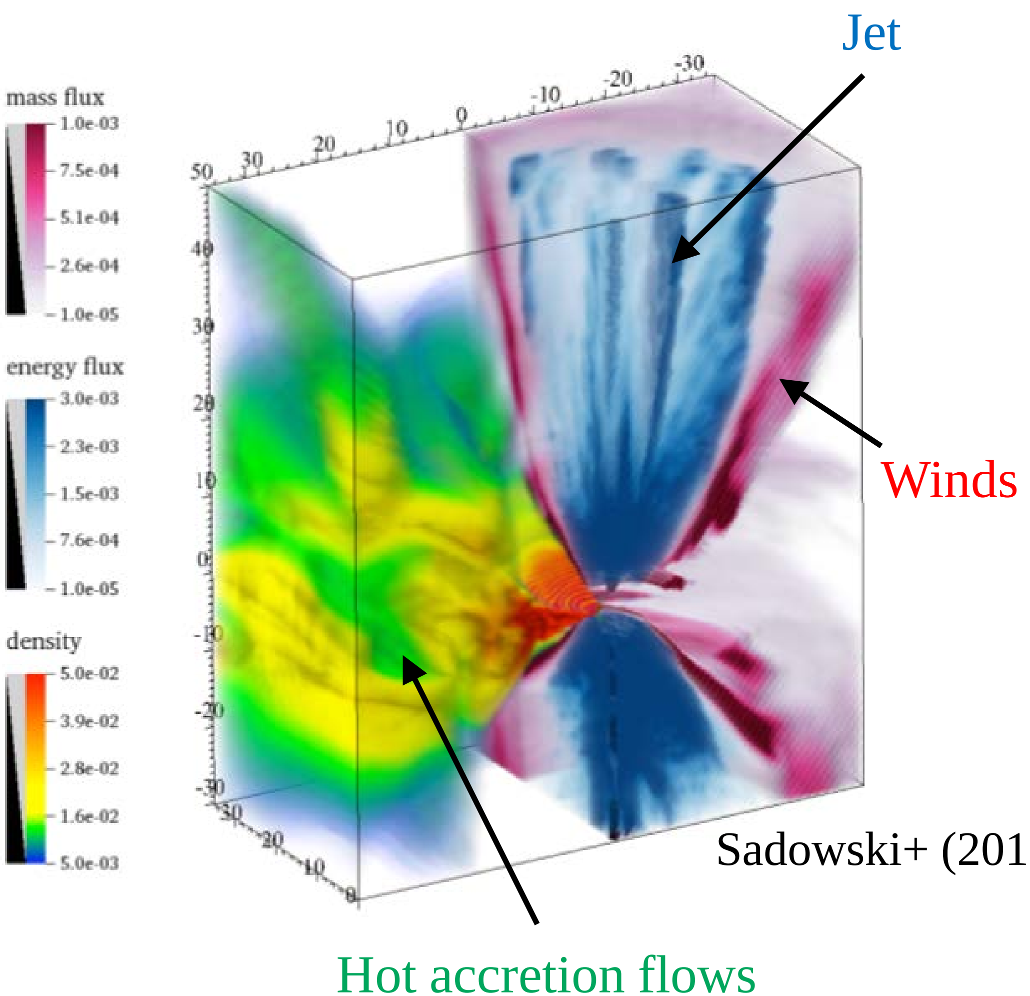
Tchekhovskoy+ (2009), FFE model

$$B_p(R) \propto R^{-\xi}$$

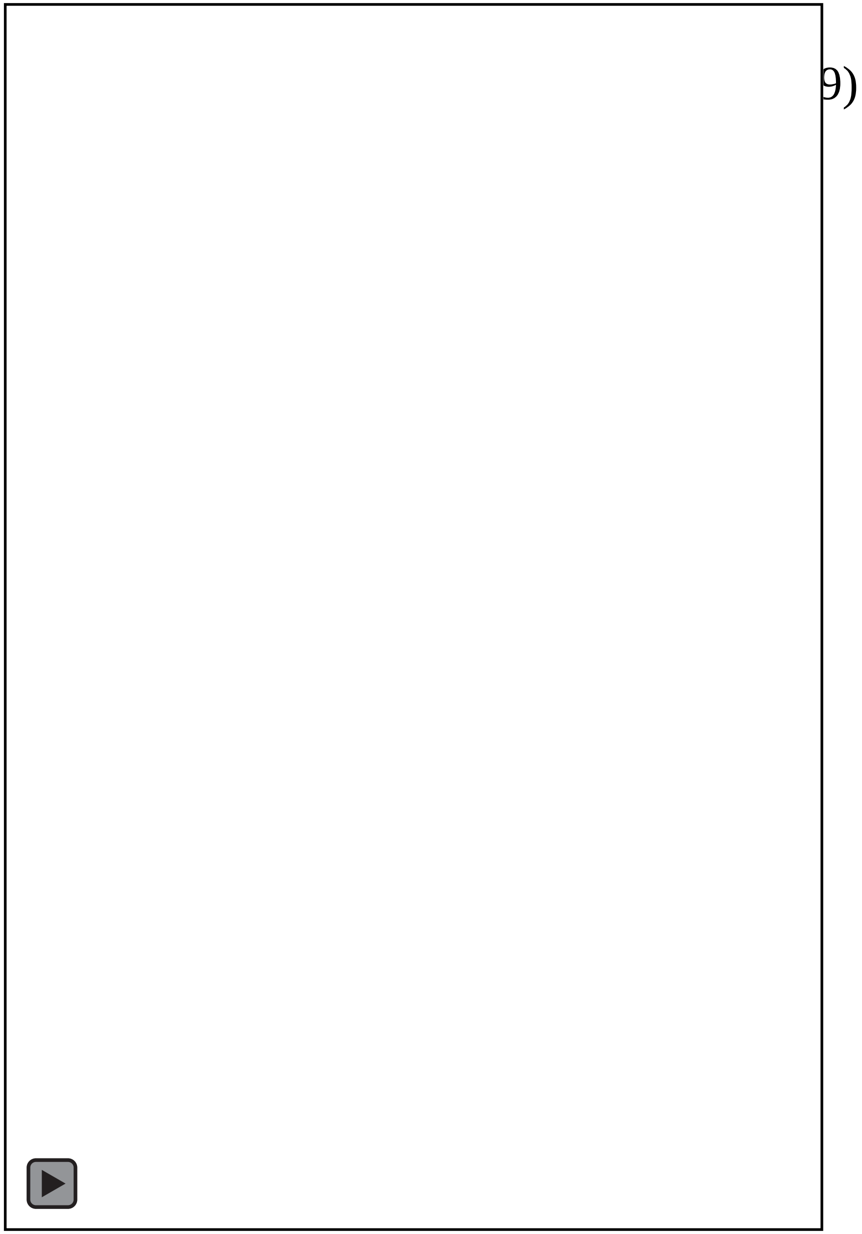
$$\frac{\gamma}{\mu} \approx \frac{\xi}{2}$$

The Poynting flux conversion may not be as efficient as in an ideal case.

Discussion: Slow Jet Acceleration

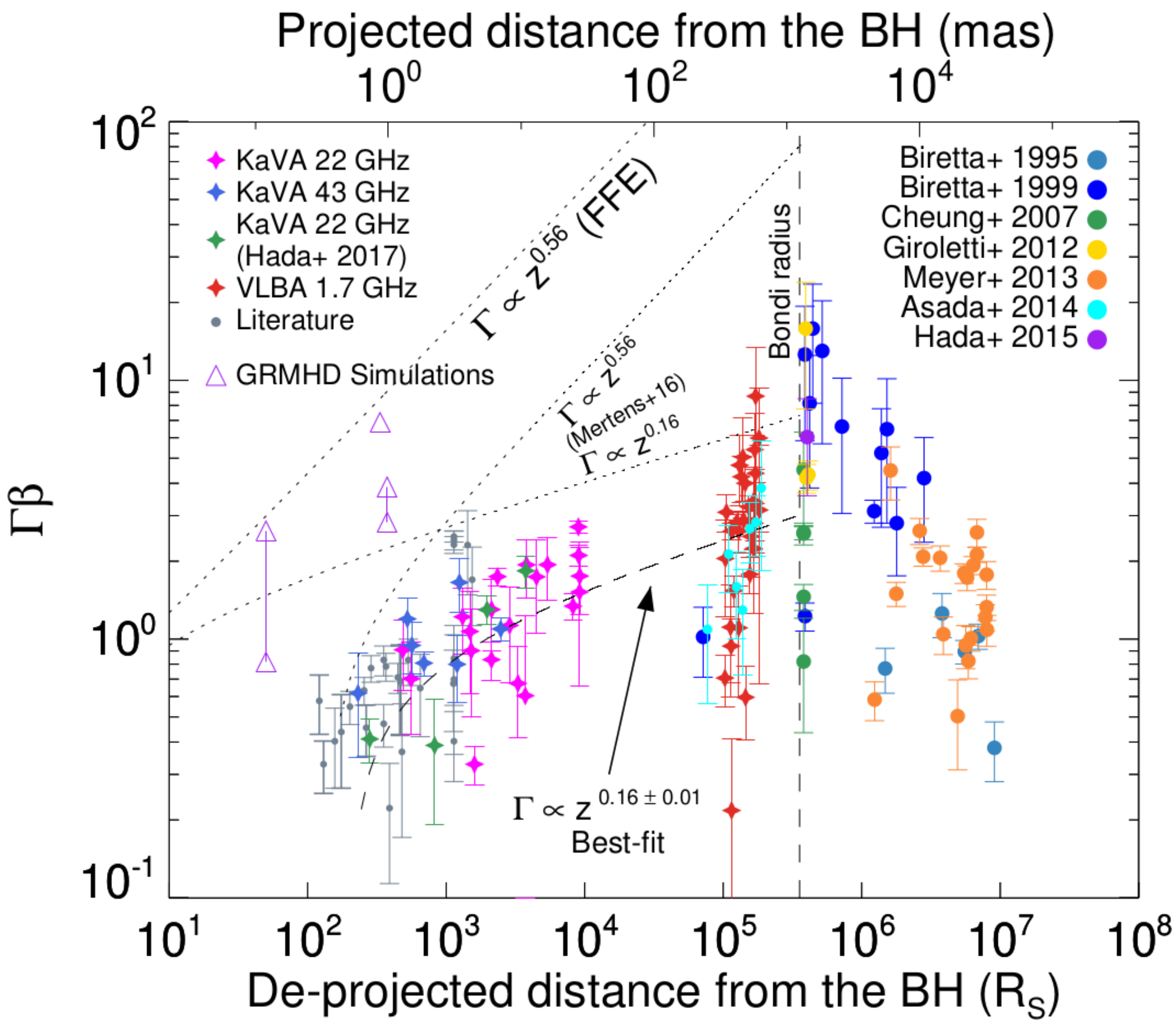


Sadowski+ (2013)



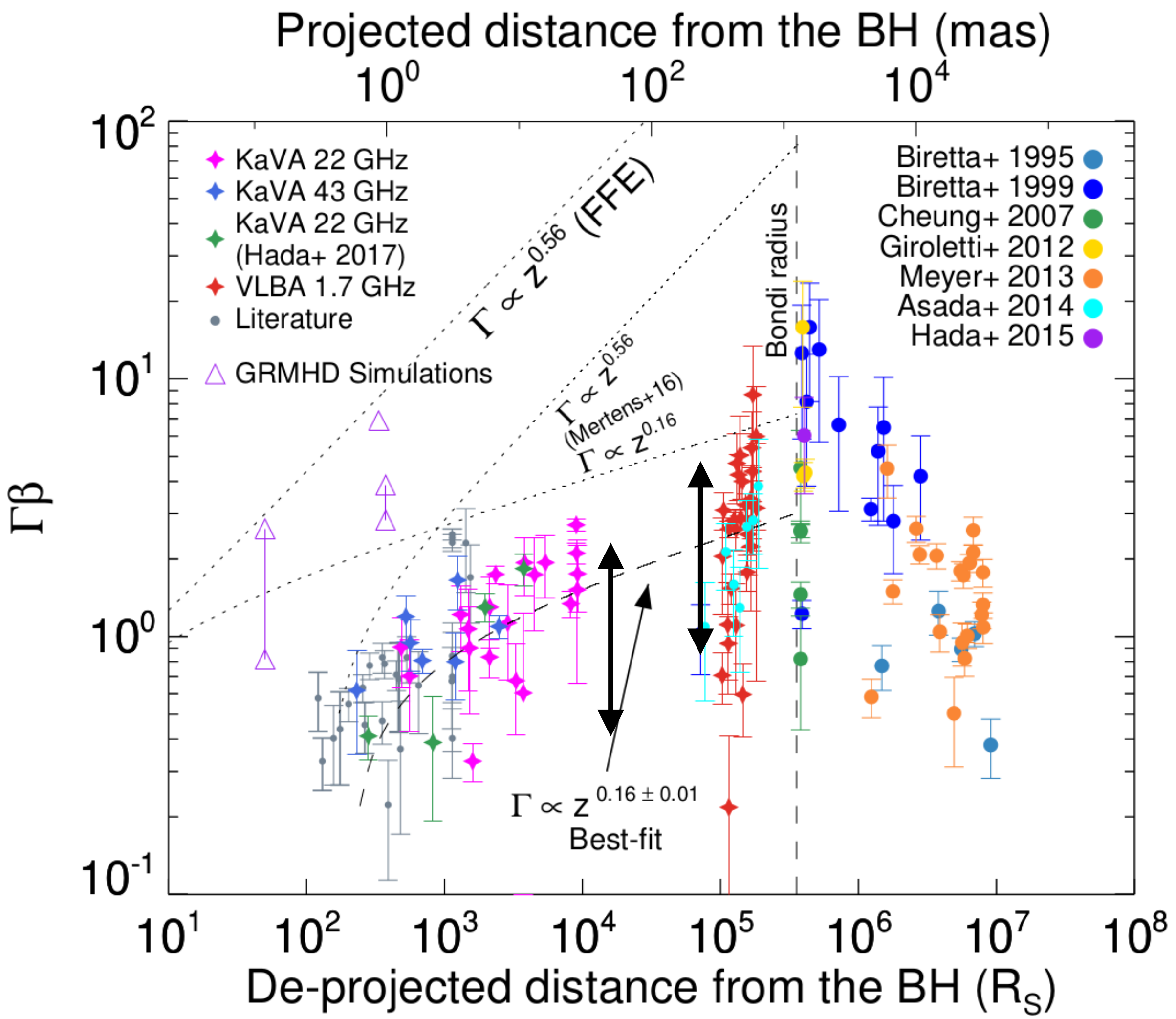
Additional mass entrainment from the outer slower winds?

Discussion: Velocity Stratification



— At a given distance bin, a wide range of speed is observed at all distances we probed.

Discussion: Velocity Stratification



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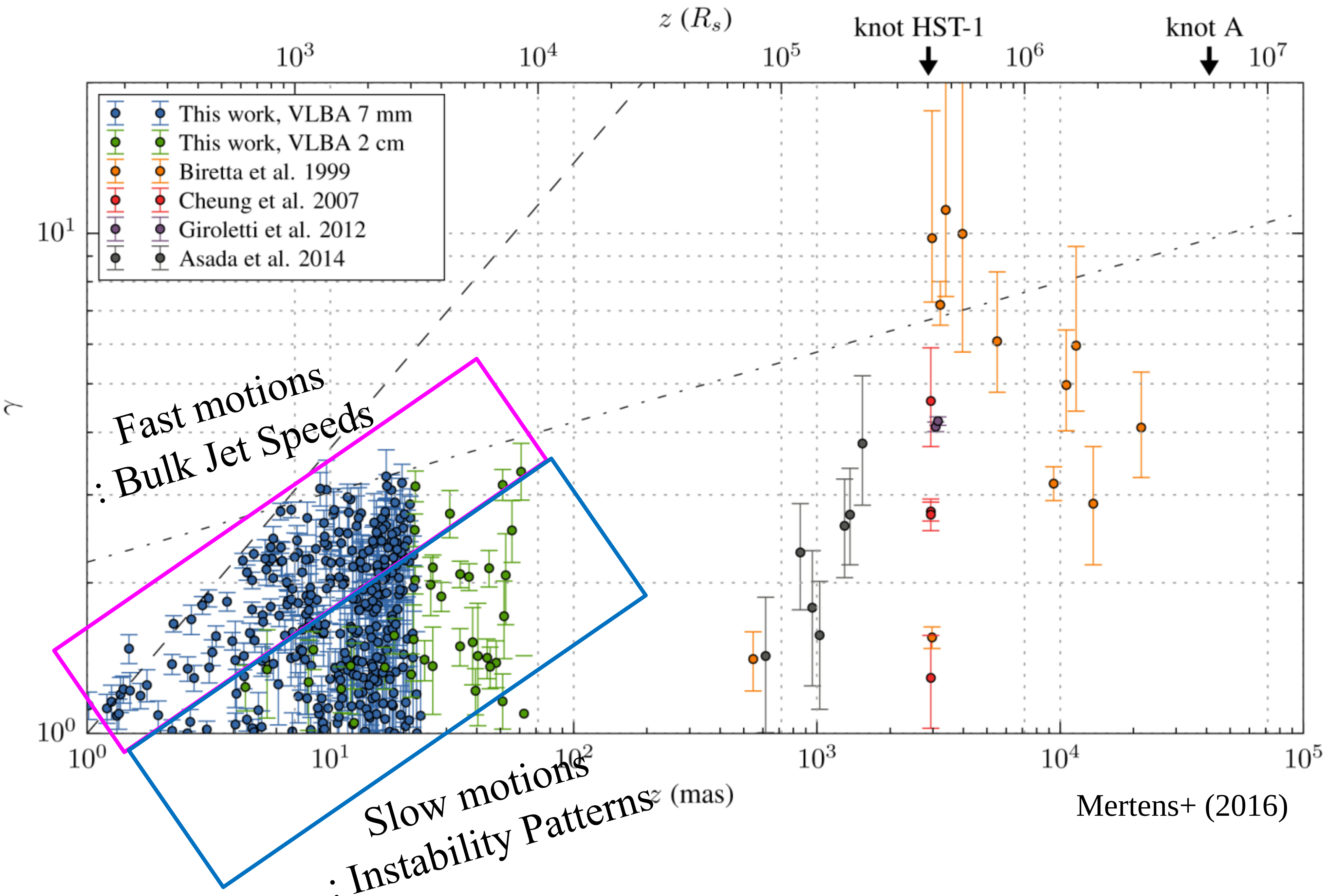
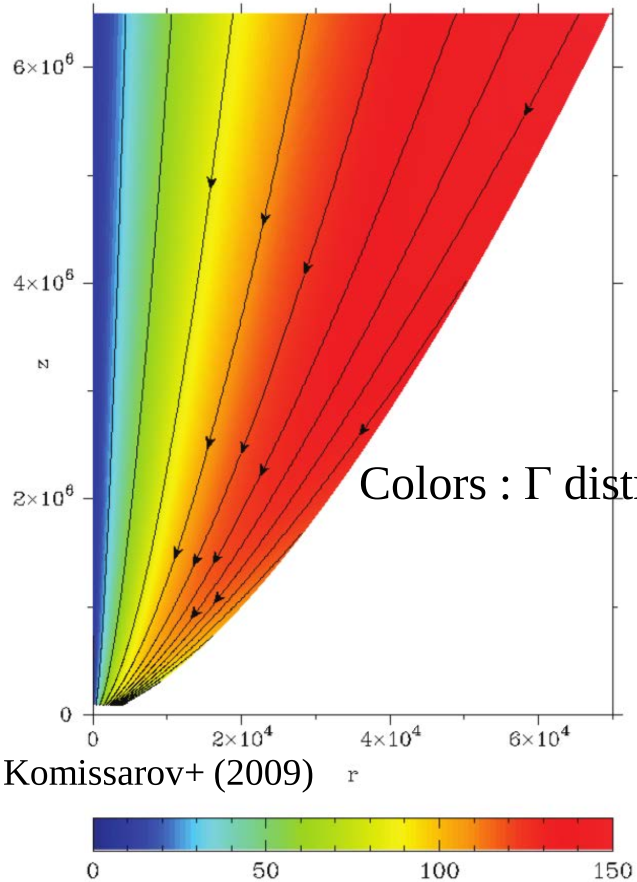
Discussion: Velocity Stratification

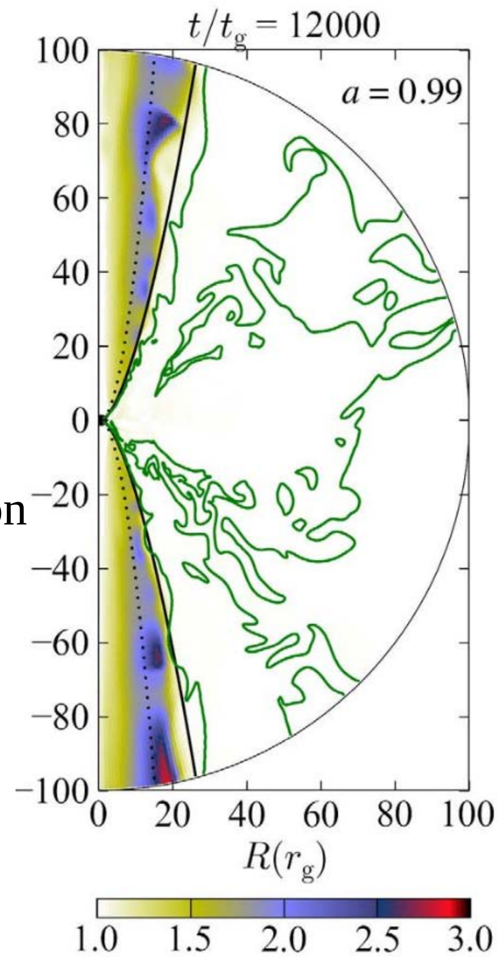


Discussion: Velocity Stratification

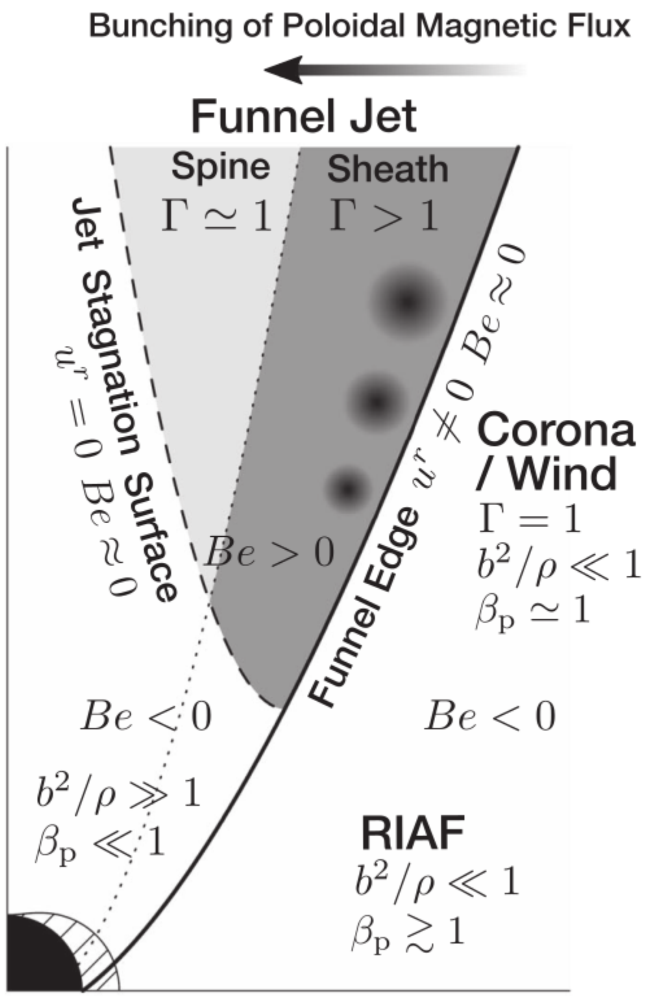


Colors : Γ distribution

SRMHD Simulations



GRMHD Simulations



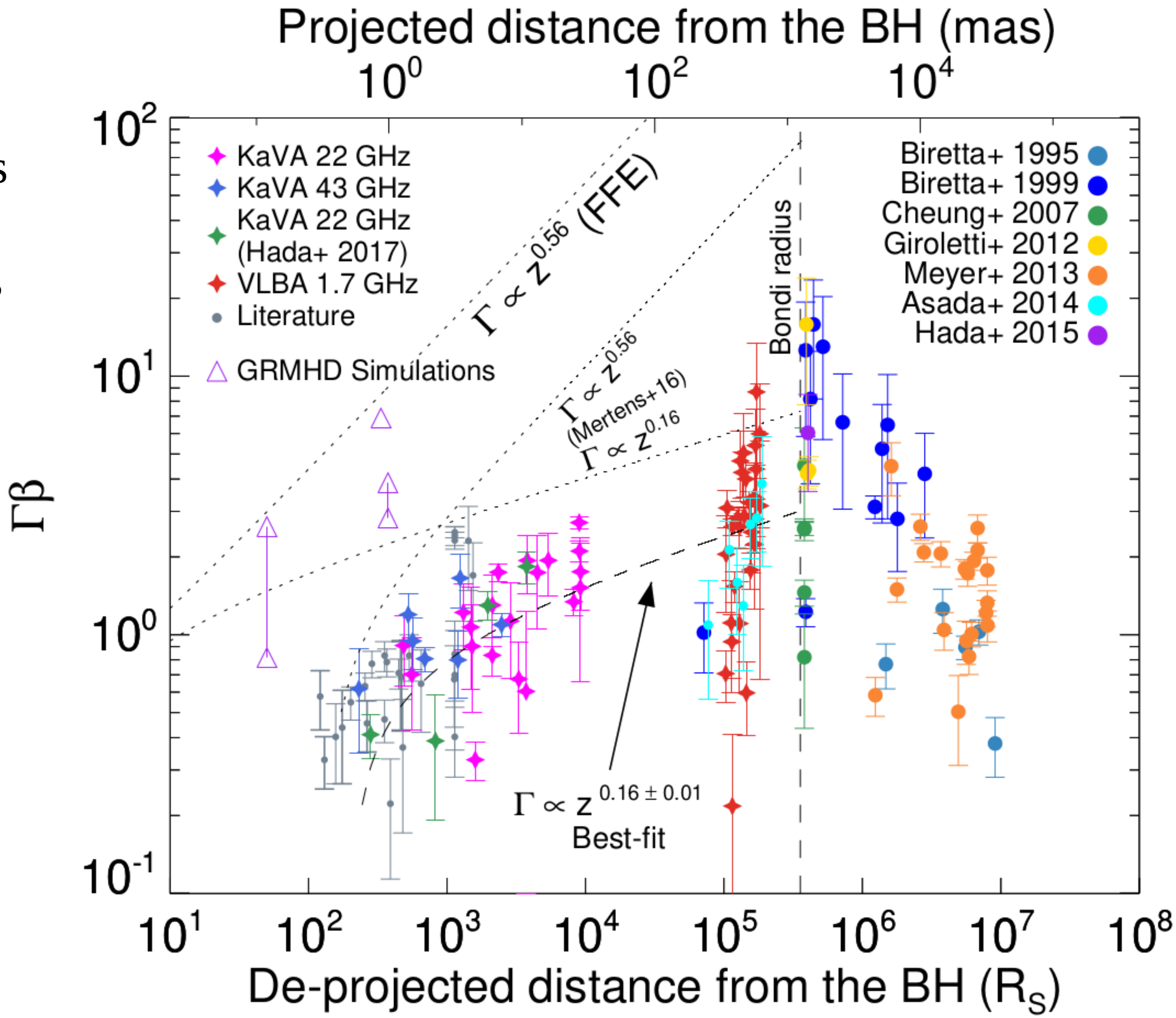
Nakamura+ (2018)

— At a given distance bin, a wide range of speed is observed at all distances we probed.

— The observed jet may consist of ‘multiple streamlines’ following different acceleration profiles, naturally resulting in the lateral velocity stratification.

Discussion 3. Velocity Stratification

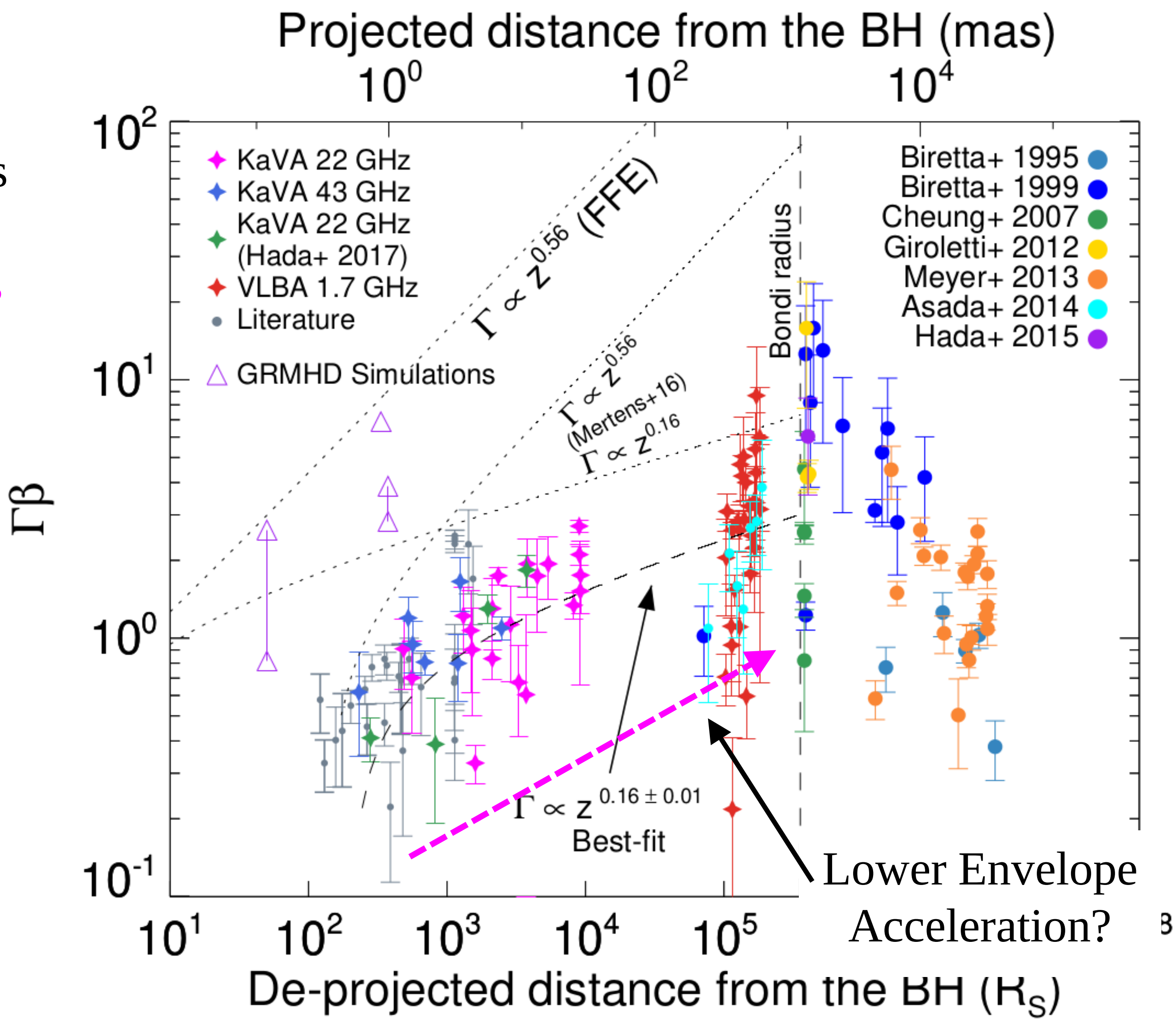
1. Instabilities
2. Multiple streamlines



— Whether the 'lower envelope' shows an acceleration feature or not would be important to test these scenarios.

Discussion 3. Velocity Stratification

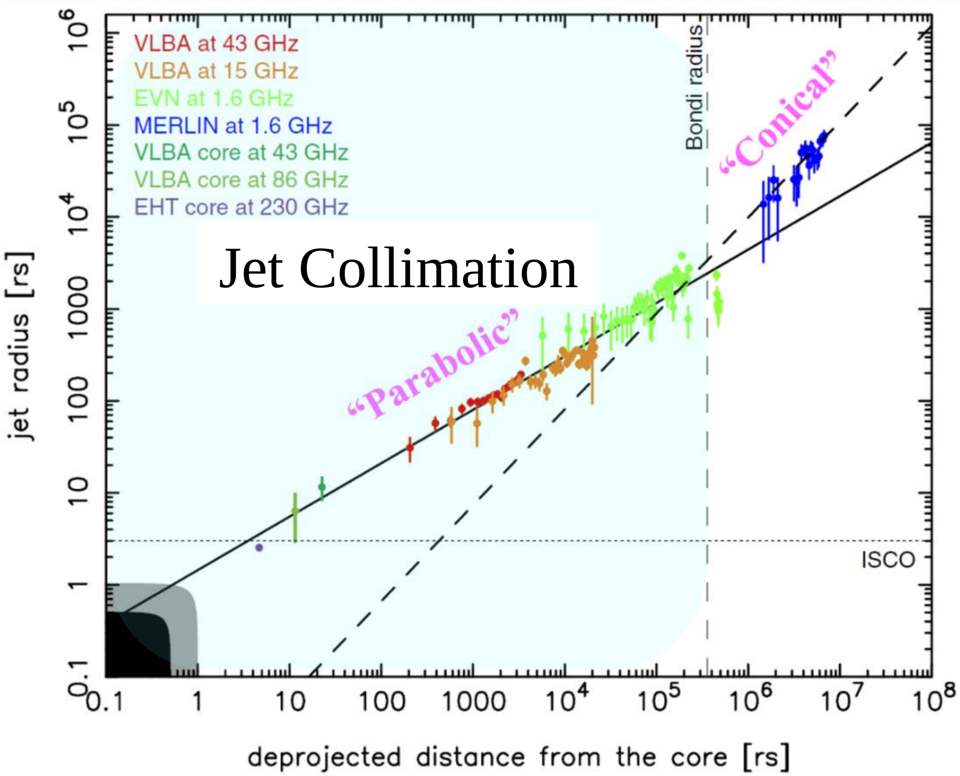
1. Instabilities
2. Multiple streamlines



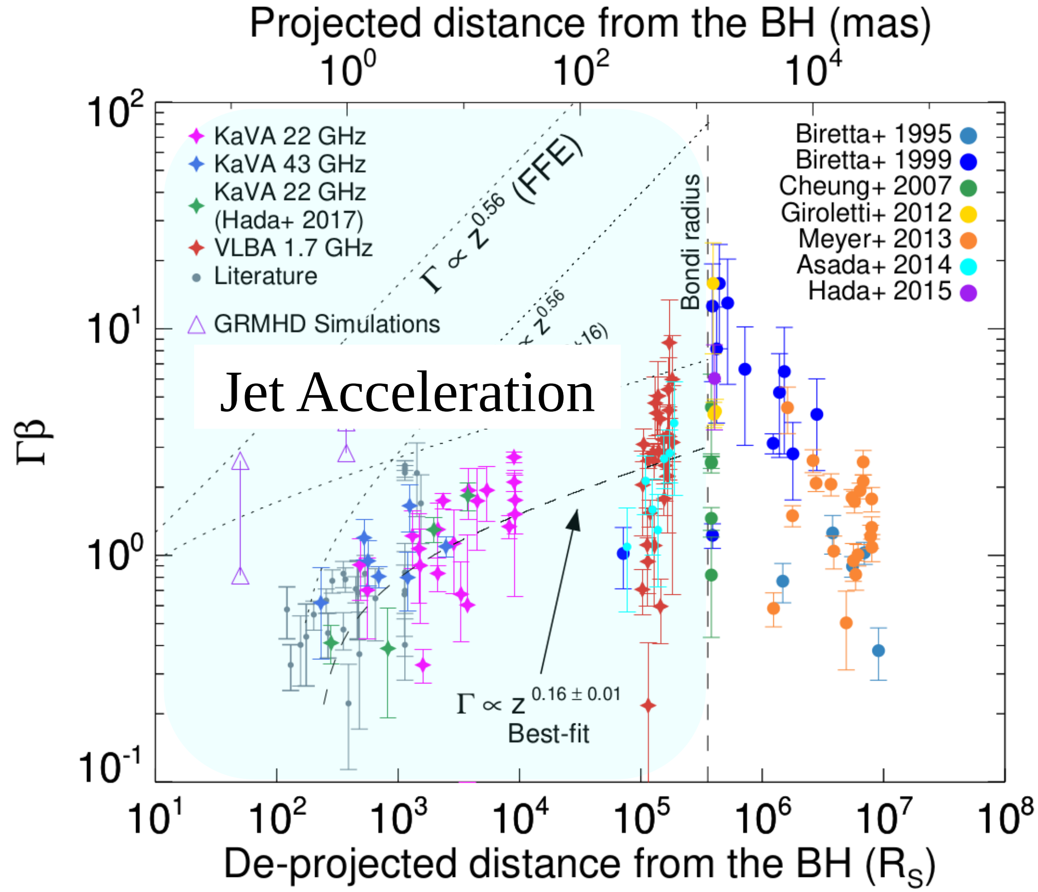
— Whether the 'lower envelope' shows an acceleration feature or not would be important to test these scenarios.

Conclusions (Park et al. 2019b, ApJ, 887, 147)

— We studied the jet kinematics by using the densely monitored data observed with KaVA at 22 and 43 GHz and using archival VLBA data at 1.7 GHz.
— We found that the M87 jet is gradually accelerated to relativistic speeds in the same region as the jet collimation zone, as predicted by MHD models.

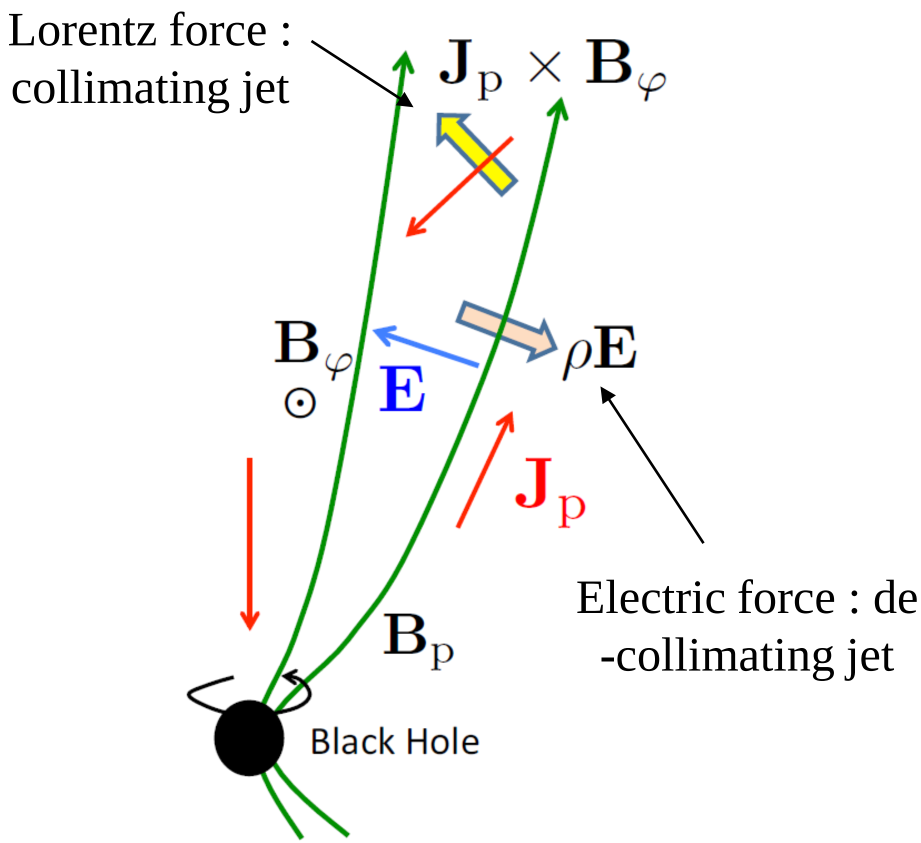


Nakamura & Asada (2013)



Backup Slides

Jet collimation by an external confining medium



$$\mathbf{E} + \frac{1}{c}\mathbf{V} \times \mathbf{B} = 0$$: ideal MHD approximation

$$\mathbf{E} \approx \mathbf{B}$$ When relativistic

→ electric force and Lorentz force become comparable

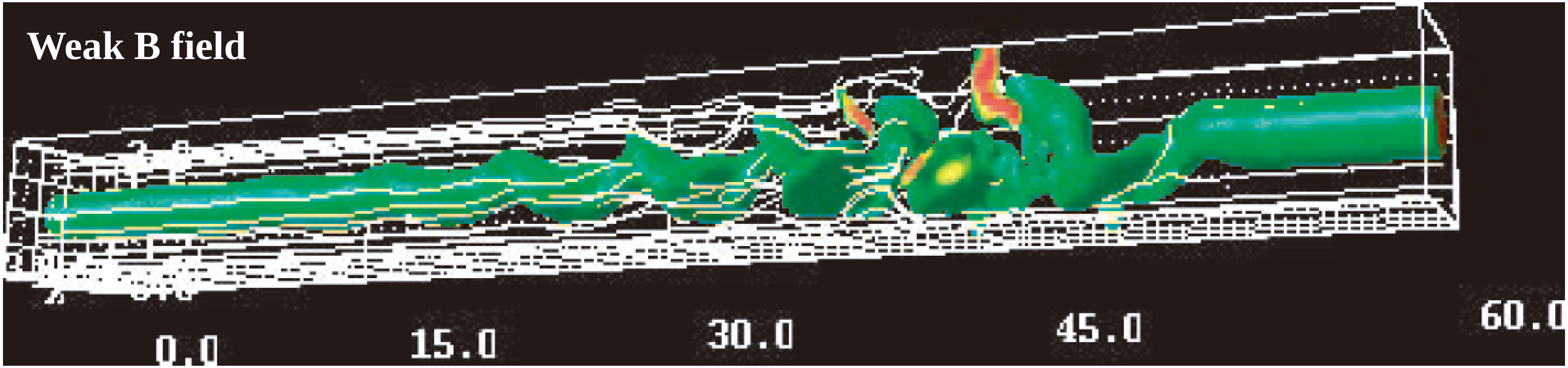
Or, jet inertia is too high to bend its direction in the comoving frame.

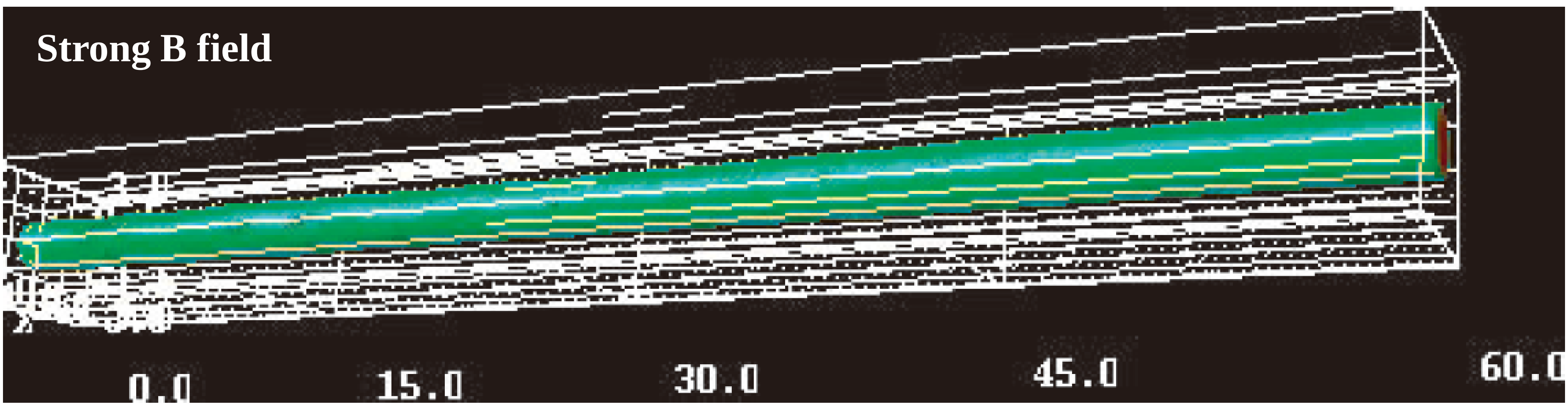
$$\mathbf{E}_{\mathrm{co}} \propto \mathbf{E} + \frac{\mathbf{V}}{c} \times \mathbf{B} = 0$$

Jets must be confined (or collimated) by an external medium!

AN EXTERNAL MEDIUM → JET COLLIMATION ↕ JET ACCELERATION

Mizuno+ (2007)


Weak B field
0.0
15.0
30.0
45.0
60.0


Strong B field
0.0
15.0
30.0
45.0
60.0