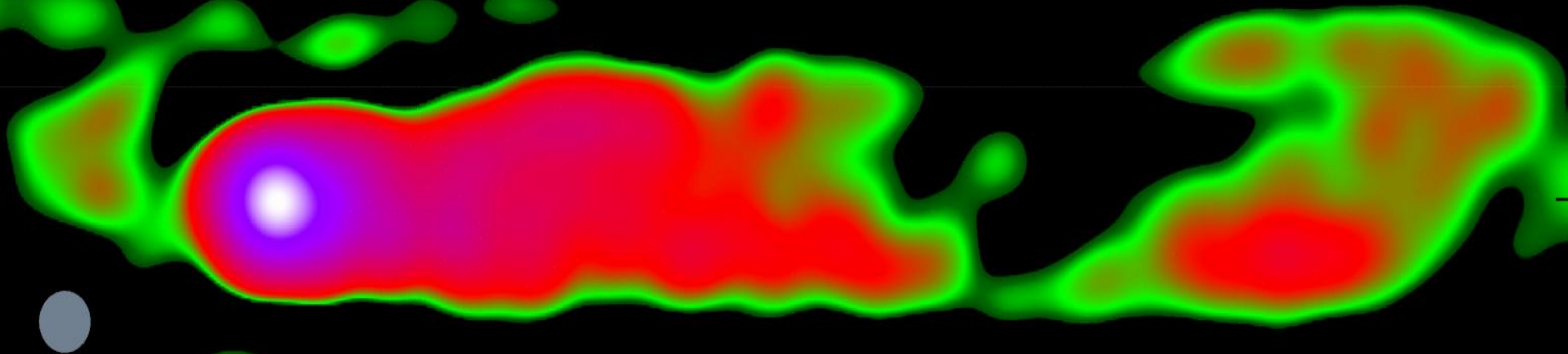
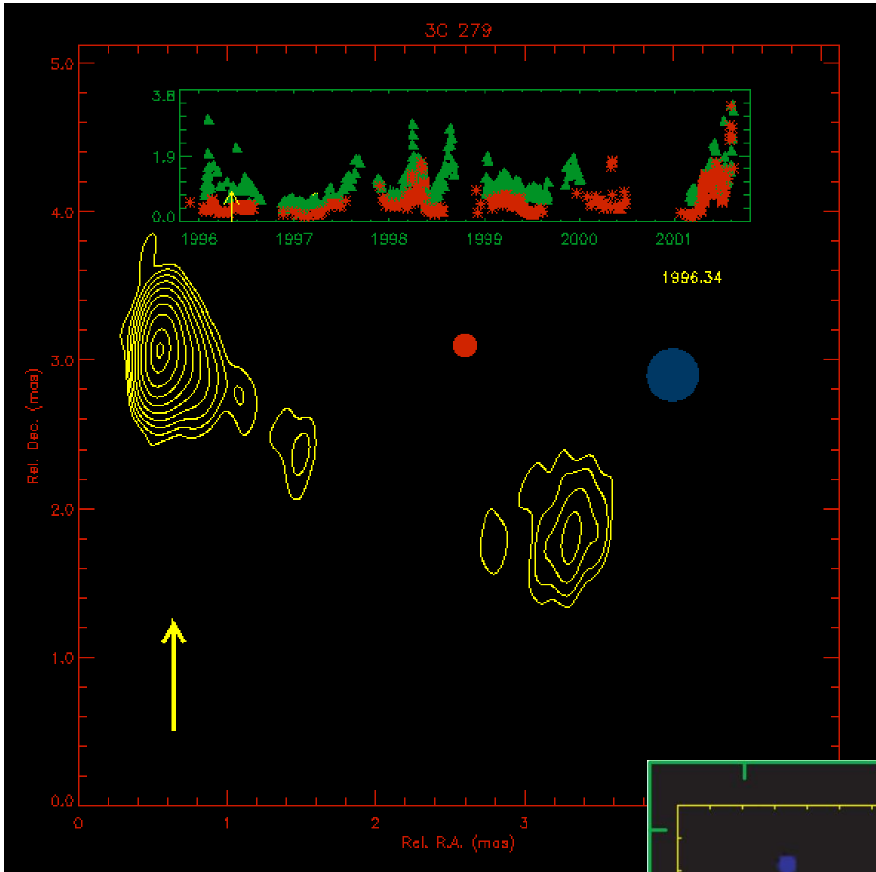
Probing the velocity field in the inner region of M87 jets with a KaVA large program: early science results



Jongho Park (SNU), Kazuhiro Hada (NAOJ), Motoki Kino (KASI), Hyunwook Ro (Yonsei Univ.), Sascha Trippe (SNU), on behalf of KaVA AGN SWG

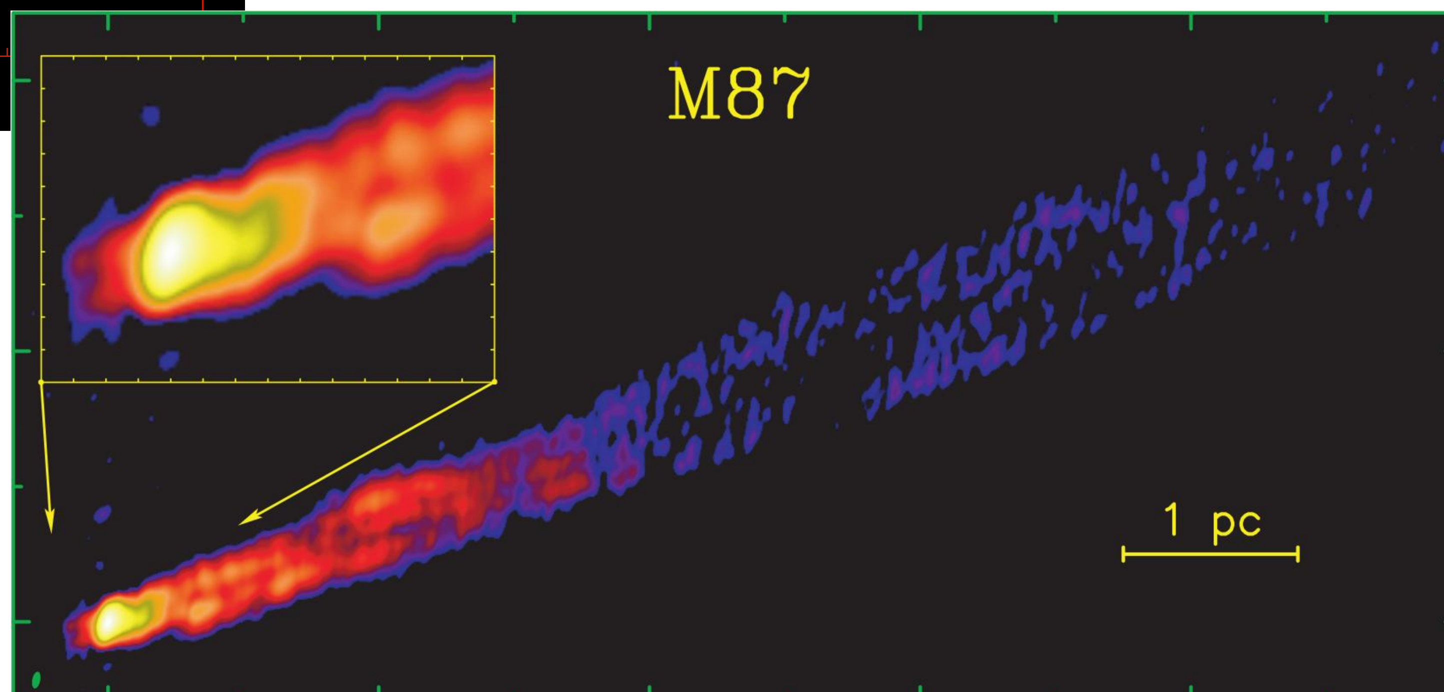
Where and How AGN jets are accelerated?



Boston Univ. blazar monitoring program

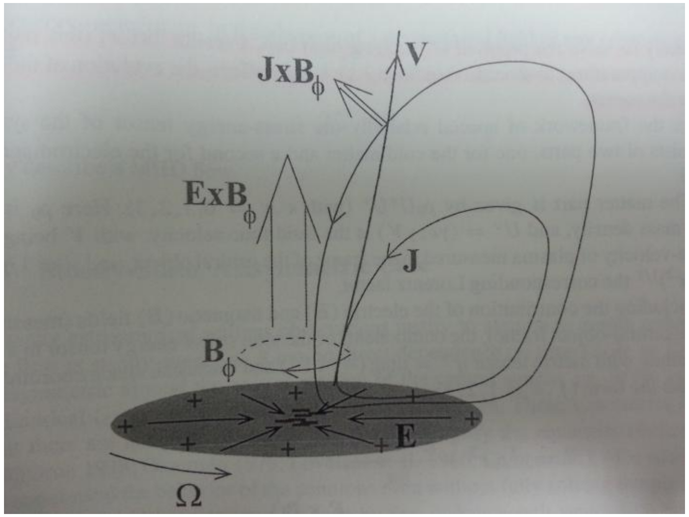
— Blazars usually show superluminal jets (a few ~ a few tens of the speed of light) on almost all spatial scales that can be probed with VLBI.
→ this indicates that we may not be able to study the mechanism of AGN jet acceleration with blazars.

— Nearby radio galaxies serve as an excellent laboratory for the astrophysics of jet acceleration.
→ M87 is a primary target thanks to its proximity (16.7 Mpc), large black hole mass (3~6 X 10^9 Msun), and brightness (~1 Jy at 22 GHz).

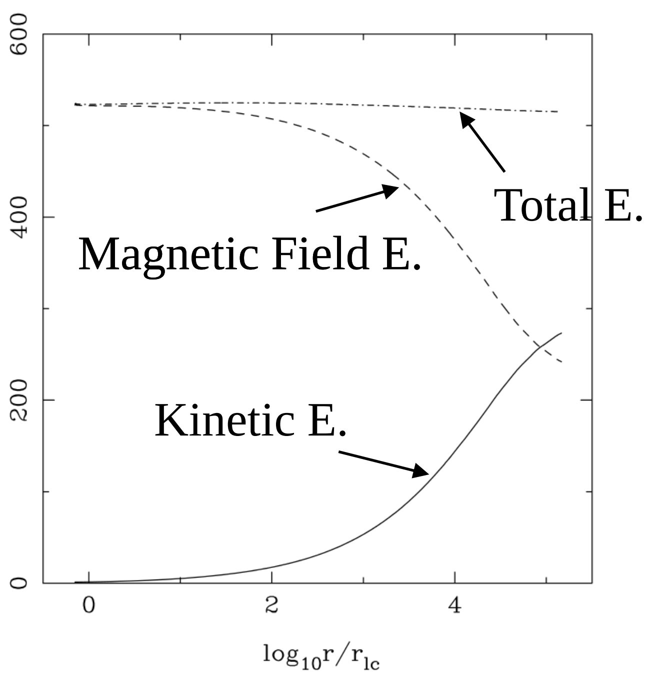


Kovalev+ 07

Jet collimation & acceleration are intimately related



"If the streamlines are more collimated than the current lines then the $J \times B_\phi / c$ force has a component along the bulk speed, accelerating the outflow, and a component normal to it, affecting its collimation." (Vlahakis 2015)



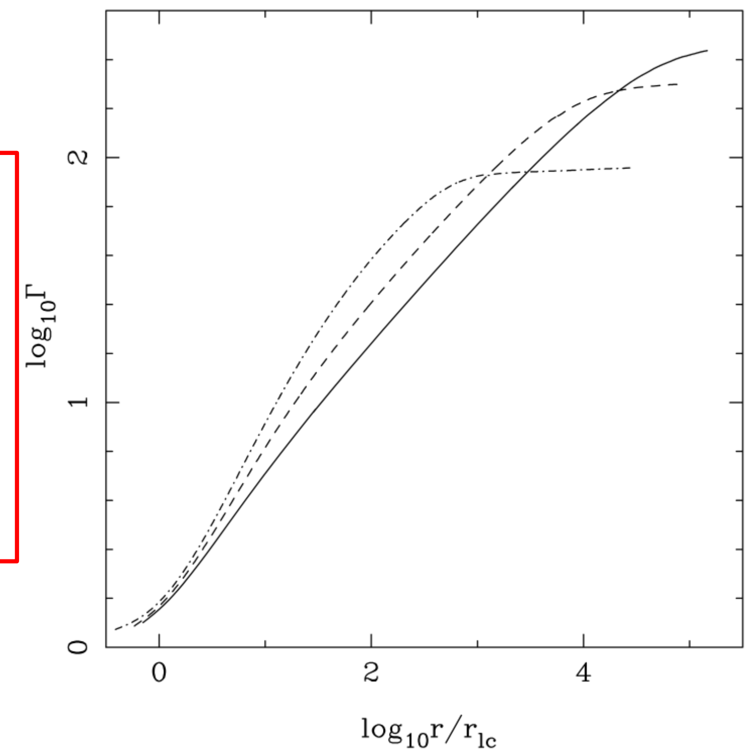
Poynting flux conversion into Kinetic energy

$$z \propto r^b$$

$$\Gamma \sim \frac{b}{\sqrt{b-1}} \frac{z}{r} \propto r^{b-1} \propto z^{(b-1)/b}$$

when $1 < b \leq 2$

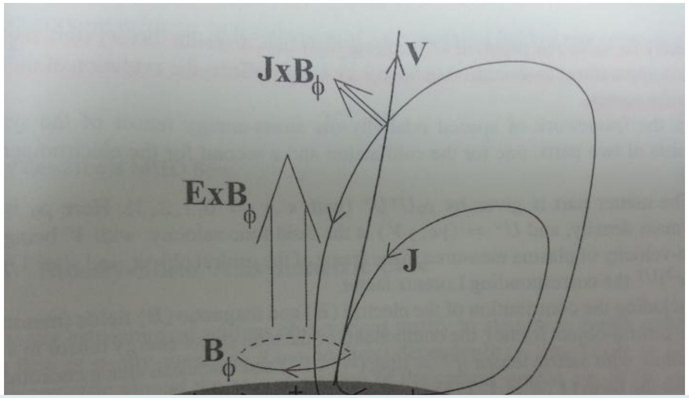
(paraboloidal)



Komissarov+ 09

Theoretical models for jet acceleration : magnetically driven acceleration

Jet collimation & acceleration are intimately related



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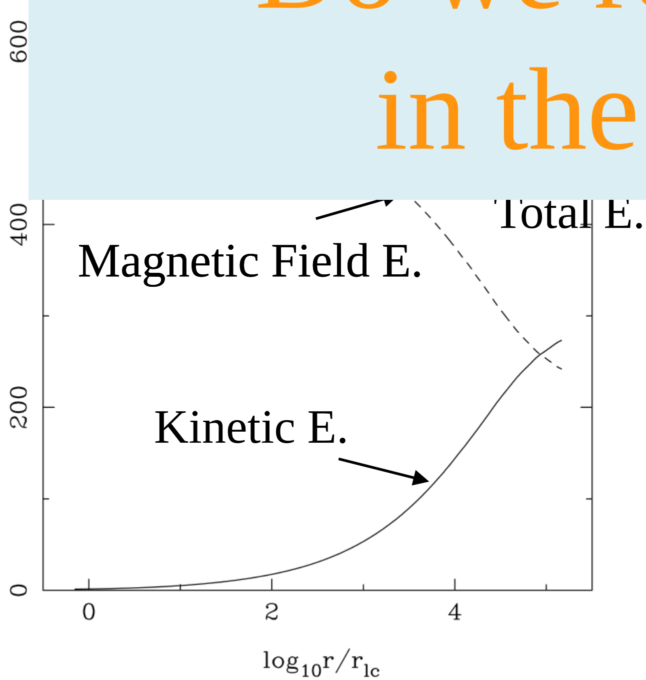
Do we really see jet acceleration in the M87 jet as expected?



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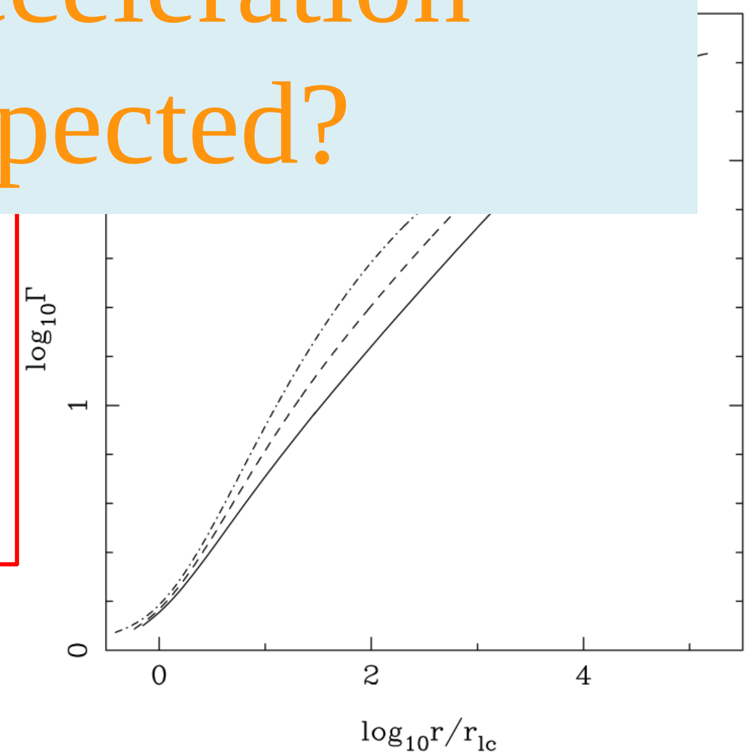
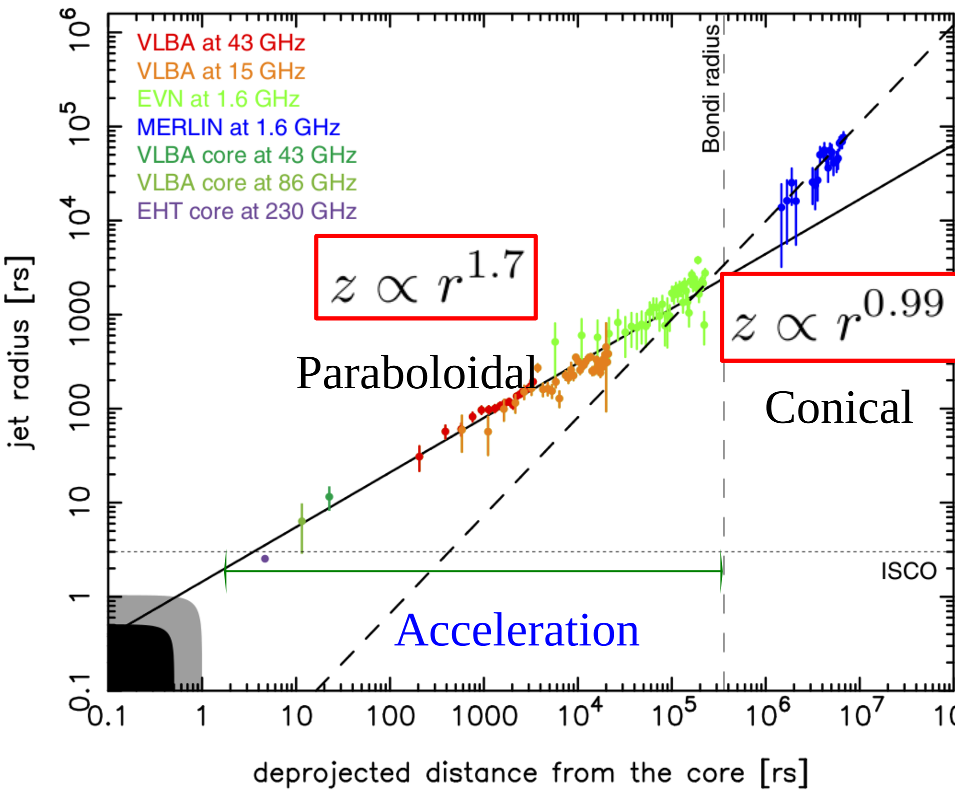
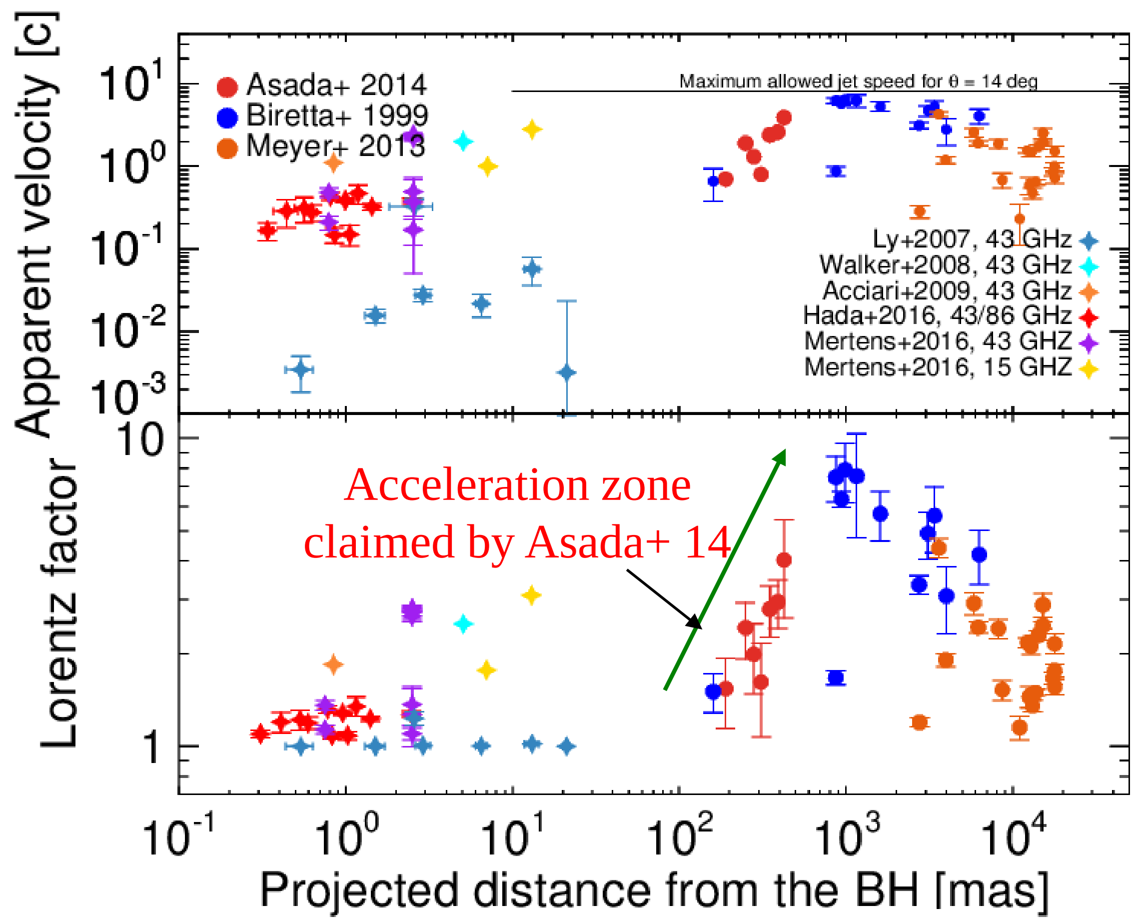


Komissarov+ 09

Previous observations of M87

Nakamura & Asada 2013





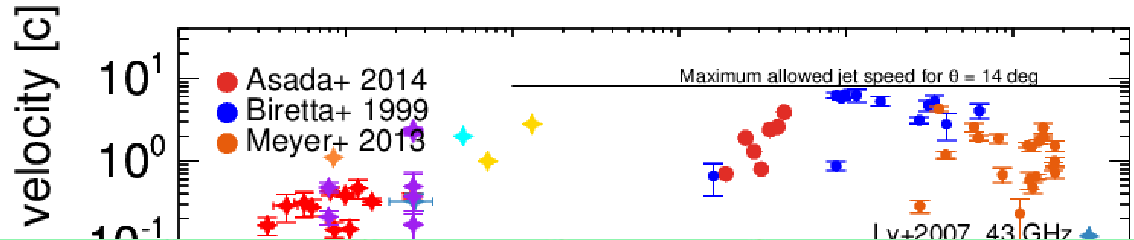
$$\Gamma \sim \frac{b}{\sqrt{b-1}}\frac{z}{r} \propto r^{b-1} \propto z^{(b-1)/b}$$

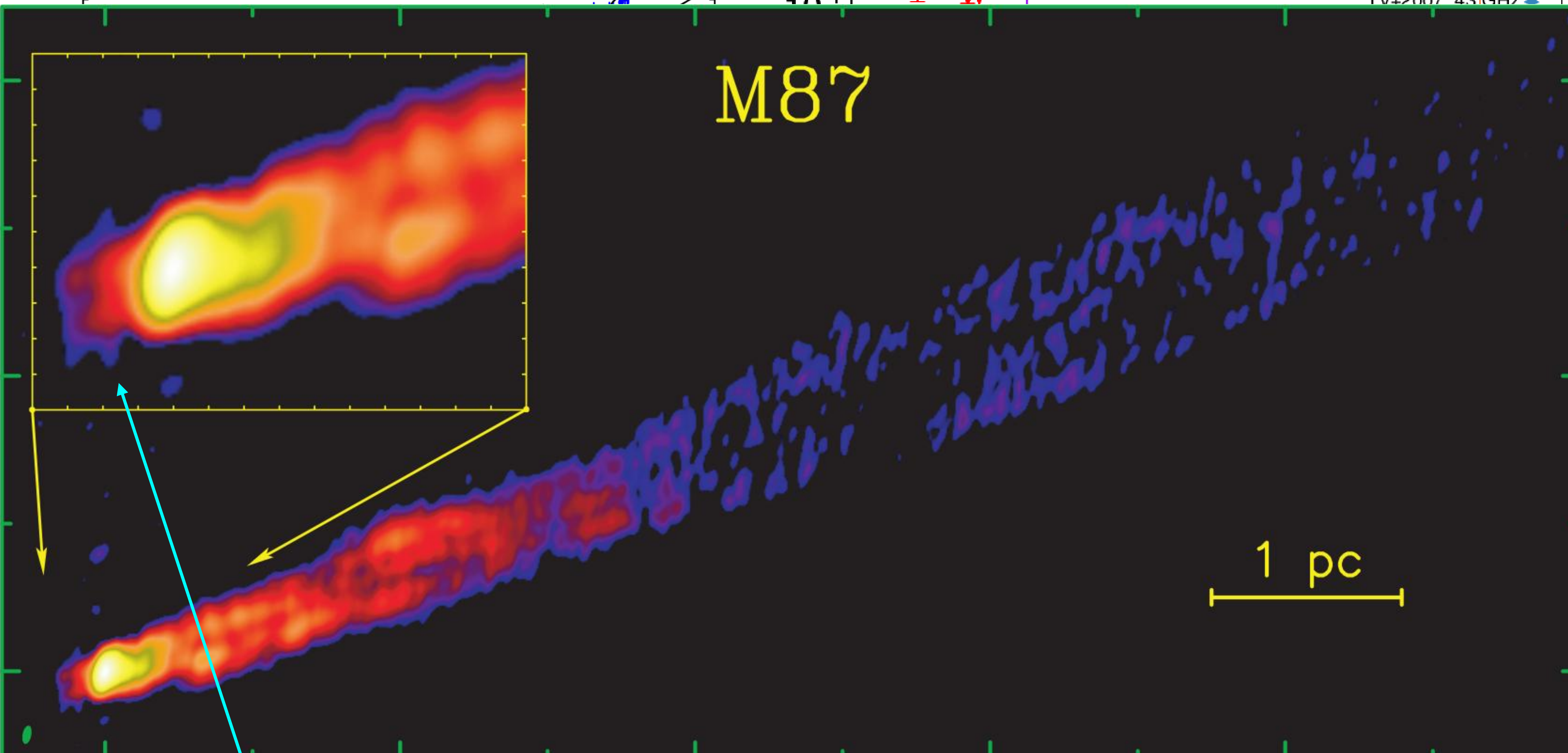
Question :

1. Why the acceleration zone is located at a few hundreds mas, while analytic & numerical studies expect gradual acceleration from the jet base?
2. If the jet shows a very slow motion in the inner region, why is the counter-jet observed only close to the jet base (<~ 3 mas)?

Previous observations of M87

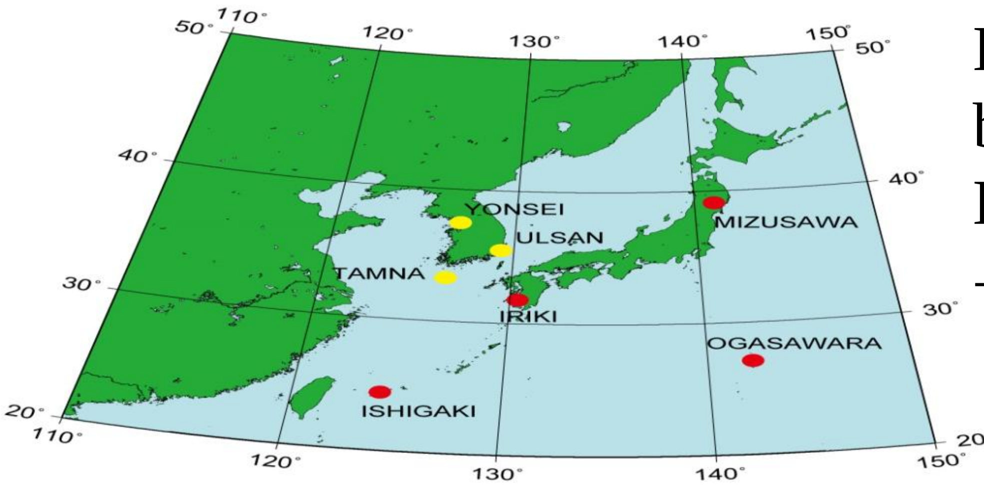
Nakamura & Asada 2013





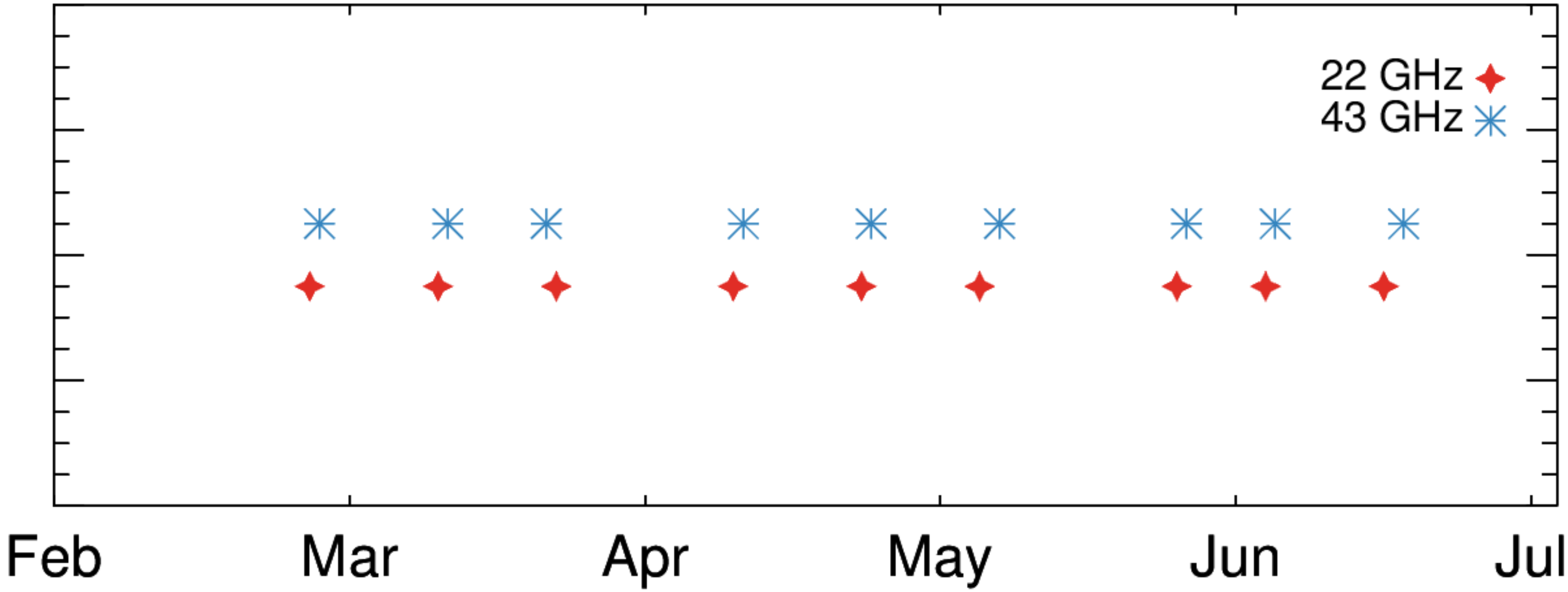
close to the jet base (3 mas).

A KaVA large program (LP) for studying the M87 jet kinematics



KaVA : 7 stations array with a maximum baseline length of ~2,000 km (3 from KVN, 4 from VERA)
→ angular resolution ~1 mas at 22 GHz

M87 is observed biweekly at 22 & 43GHz

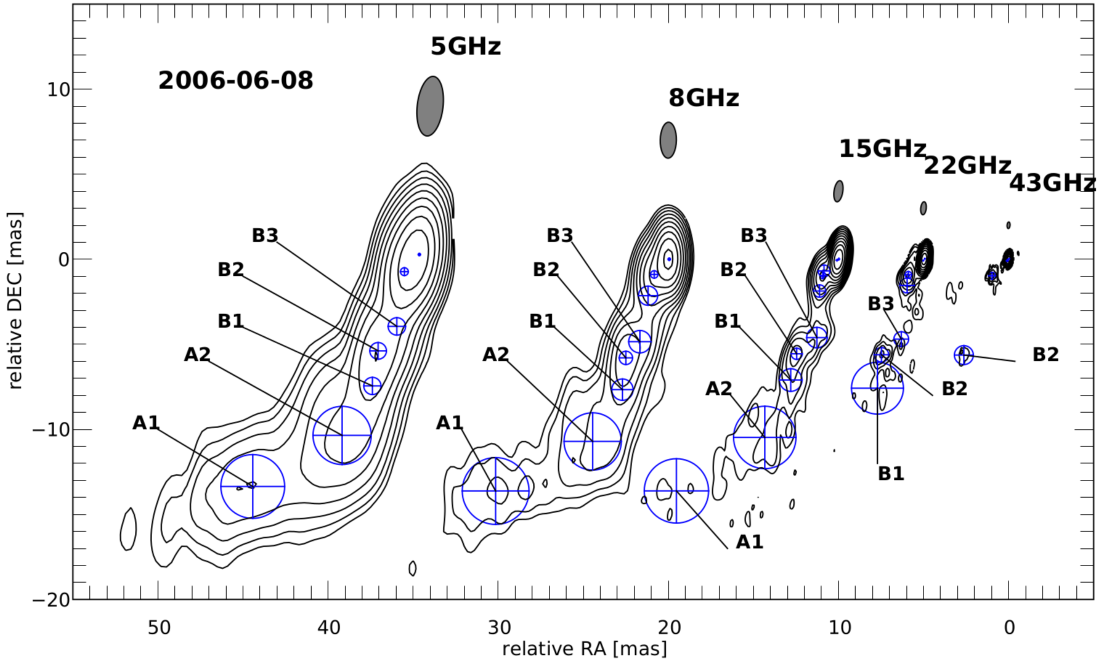


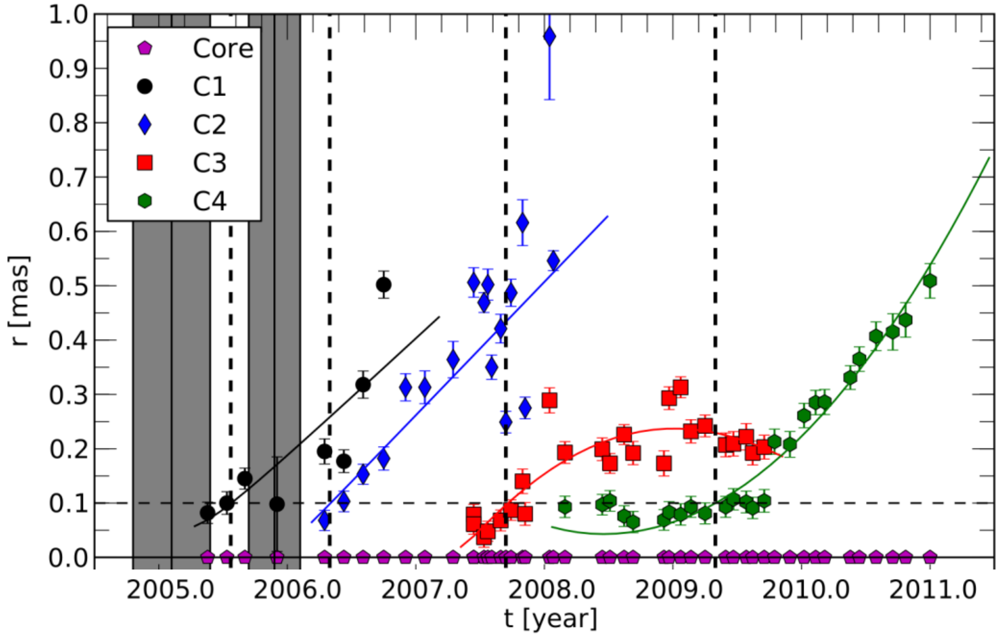
9 epochs, quasi-simultaneous at 22/43 GHz observations in 2016

How to measure the jet velocities?

Usually, for distant blazars...

Fromm+ 13





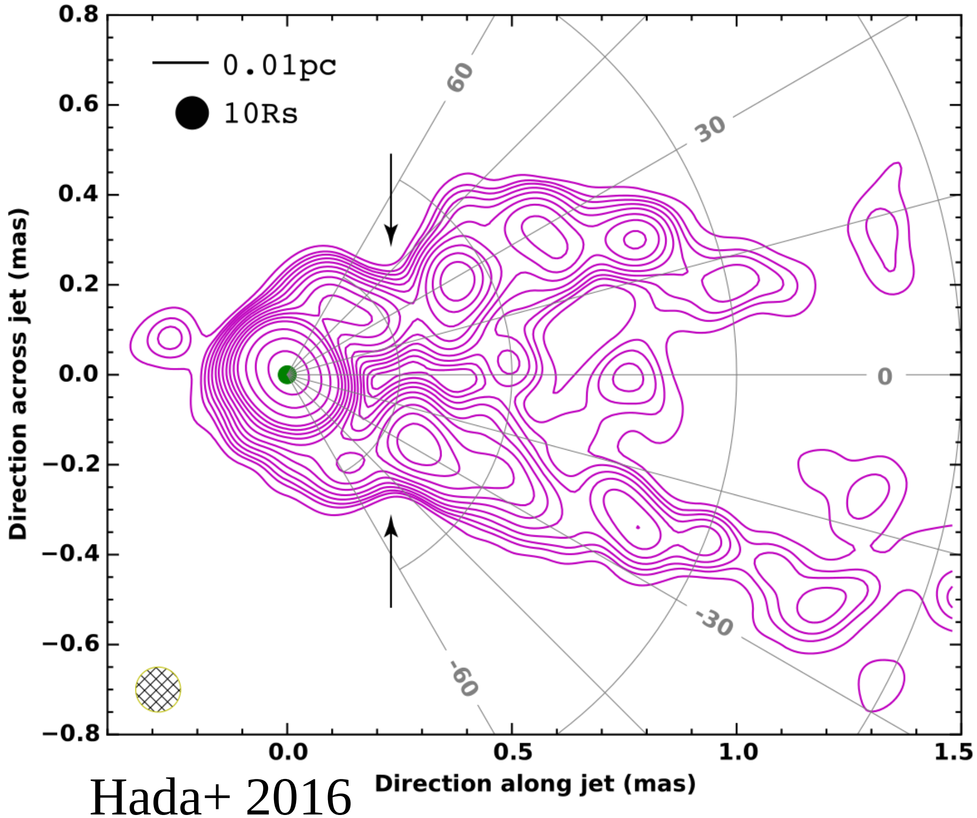
Modelfit : describe each localized jet brightness as a circular (elliptical) 2D Gaussian function.

→ works really well for almost all cases because...

(i) the jet emission is knotty. → described well by only several Gaussians

(ii) the jet angular velocity is not large (even for very fast super-luminal motions) because the source is distant. → component identification is straightforward.

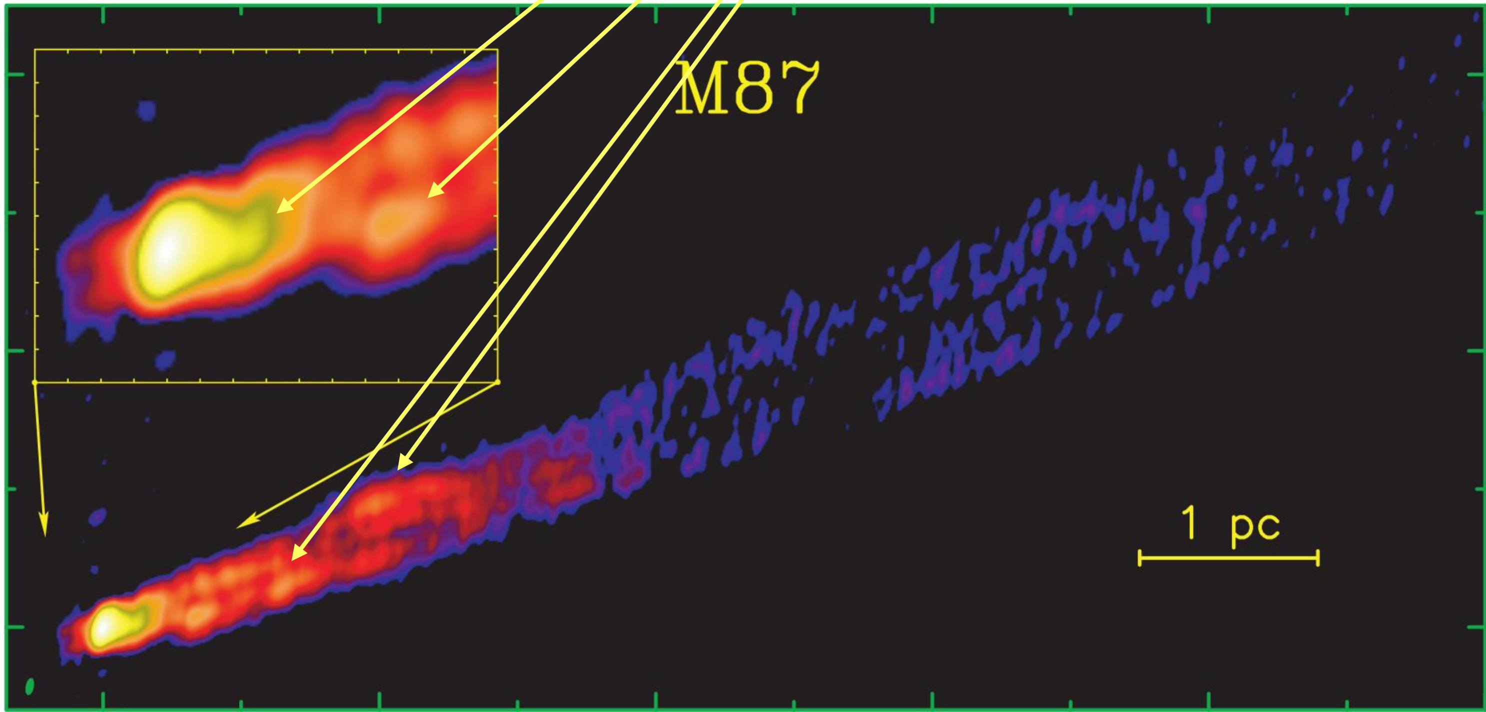
But, for M87...



Hada+ 2016

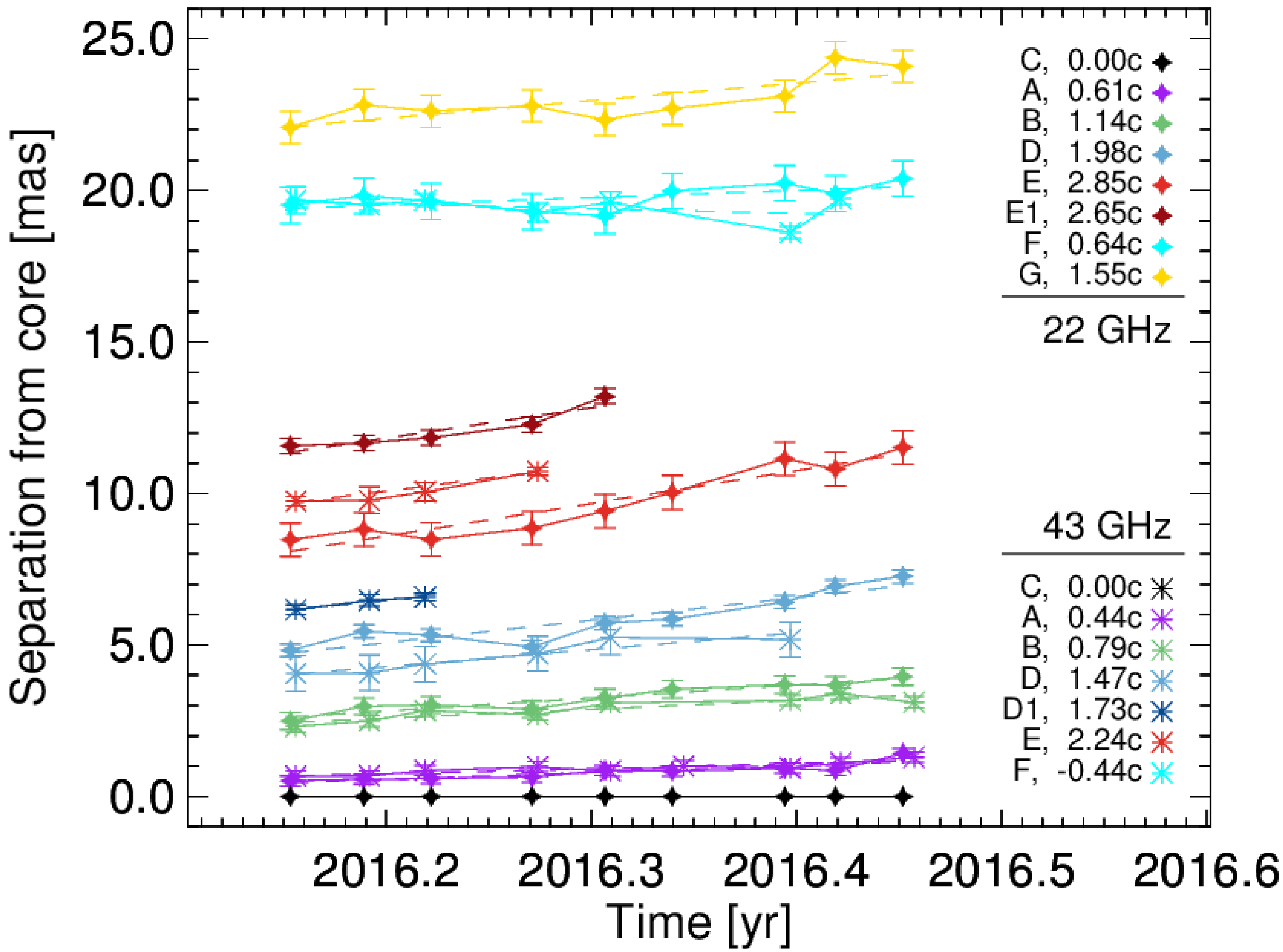
The jet is smooth and shows edge(limb)-brightened feature!
→ applying modelfit technique is not straightforward and it must be done really carefully.

However, the jet still shows local brightness-enhancement regions, which indicates that we are able to use *modelfit* for the kinematics study.



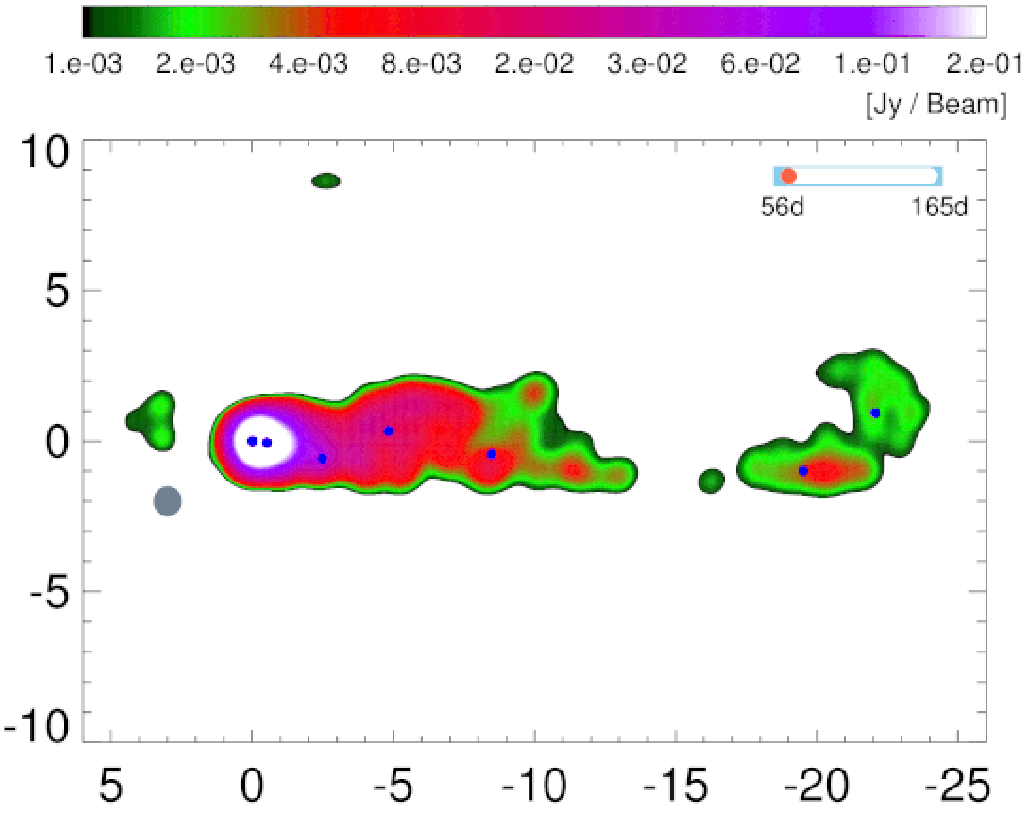
Kovalev+ 07

— Another independent check is to compare the results at 22/43 GHz. If different components trace different jet regions indeed, then they should be consistent with each other.

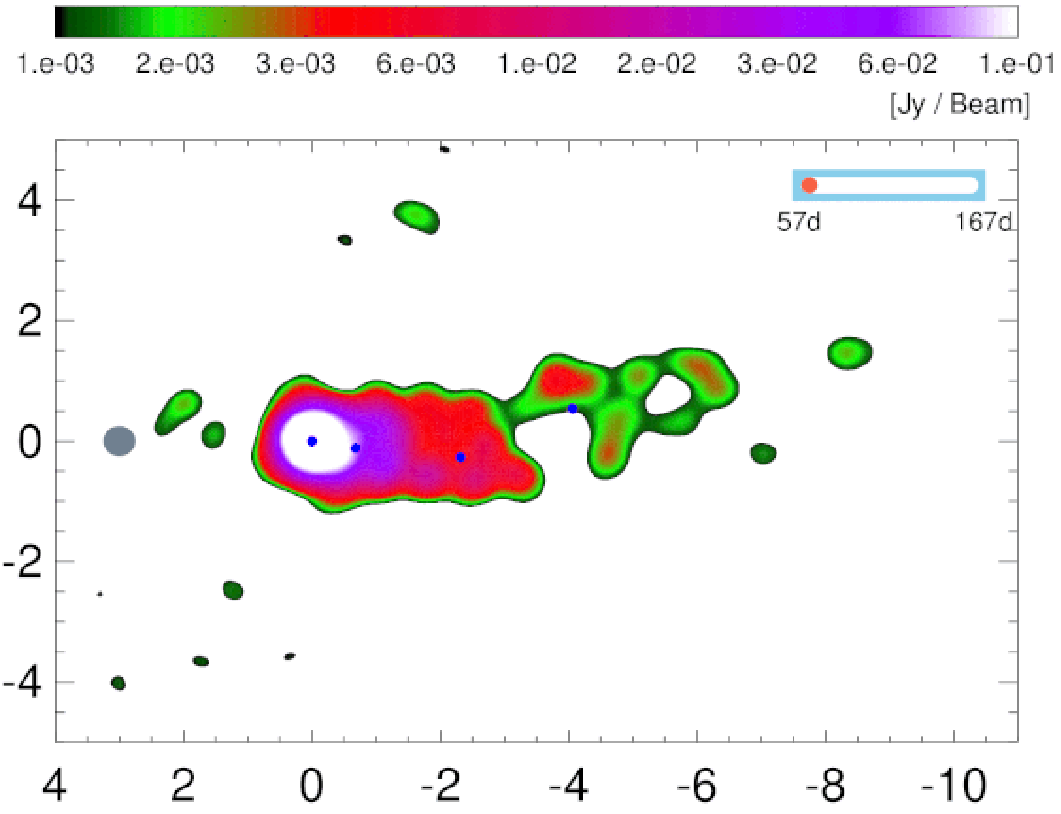


— The results are consistent with each other within errors.

M87 jet movies at 22/43 GHz

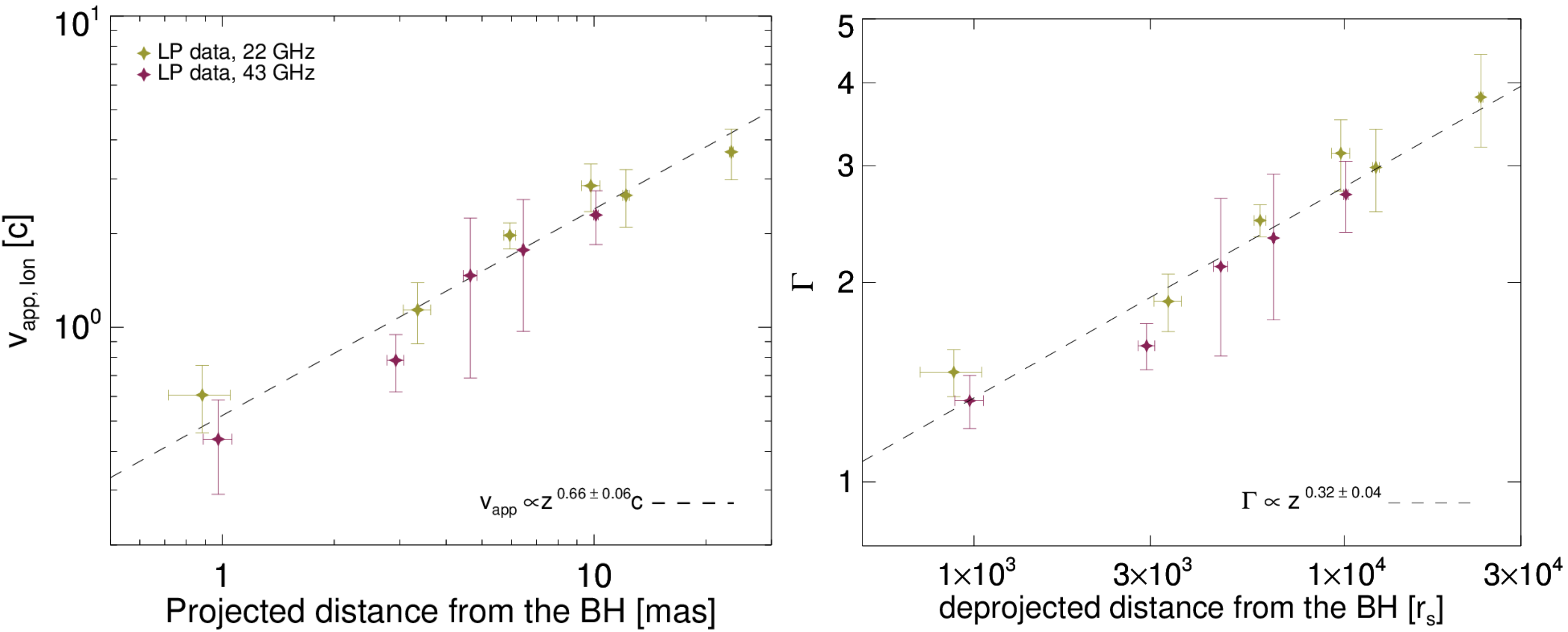


22 GHz



43 GHz

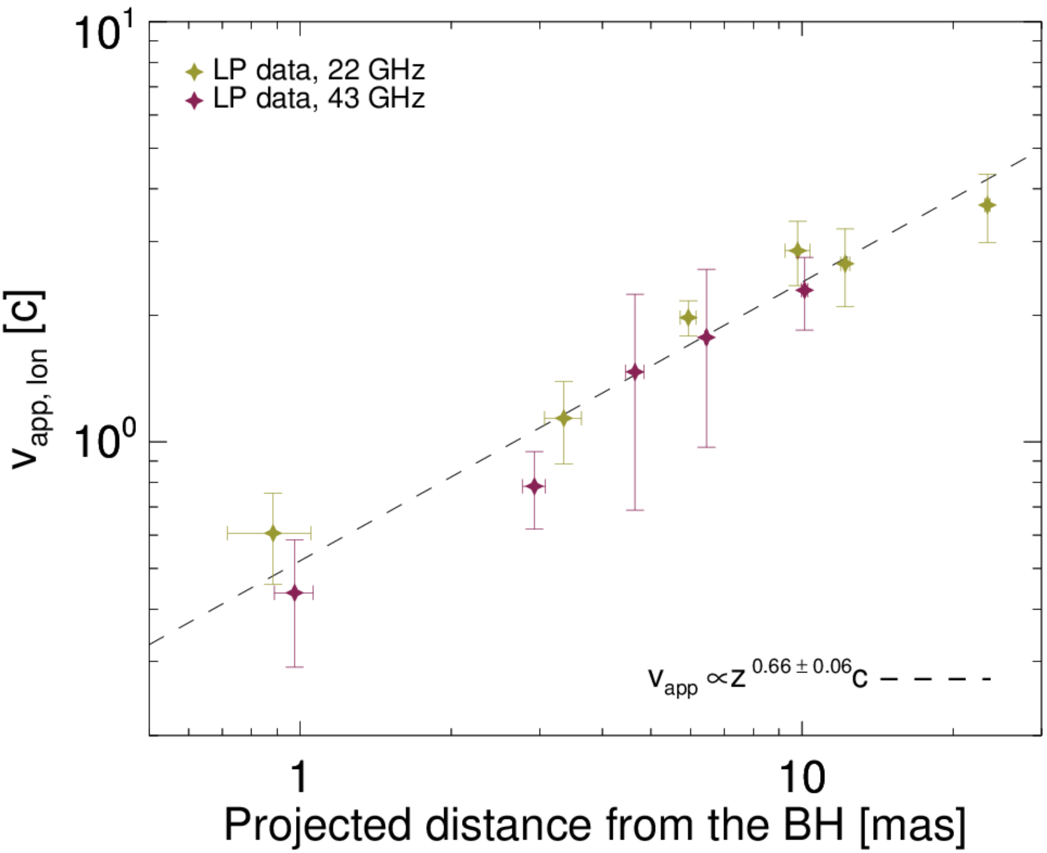
Discovery of a new jet acceleration profile in the M87 jet

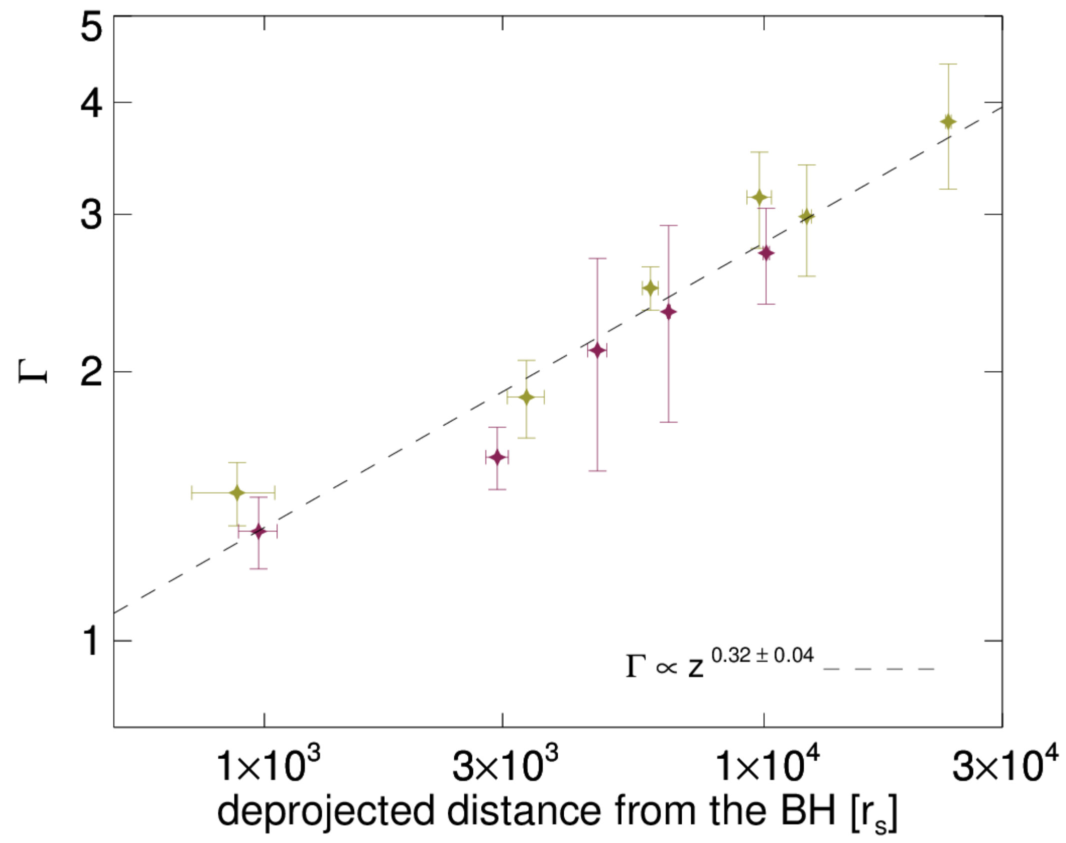


— Both the apparent velocity and the Lorentz factor increase as function of distance from the black hole following power-laws.

→ discovery of jet acceleration in the inner jet region! (at least at <~ 30 mas)

Discovery of a new jet acceleration profile in the M87 jet



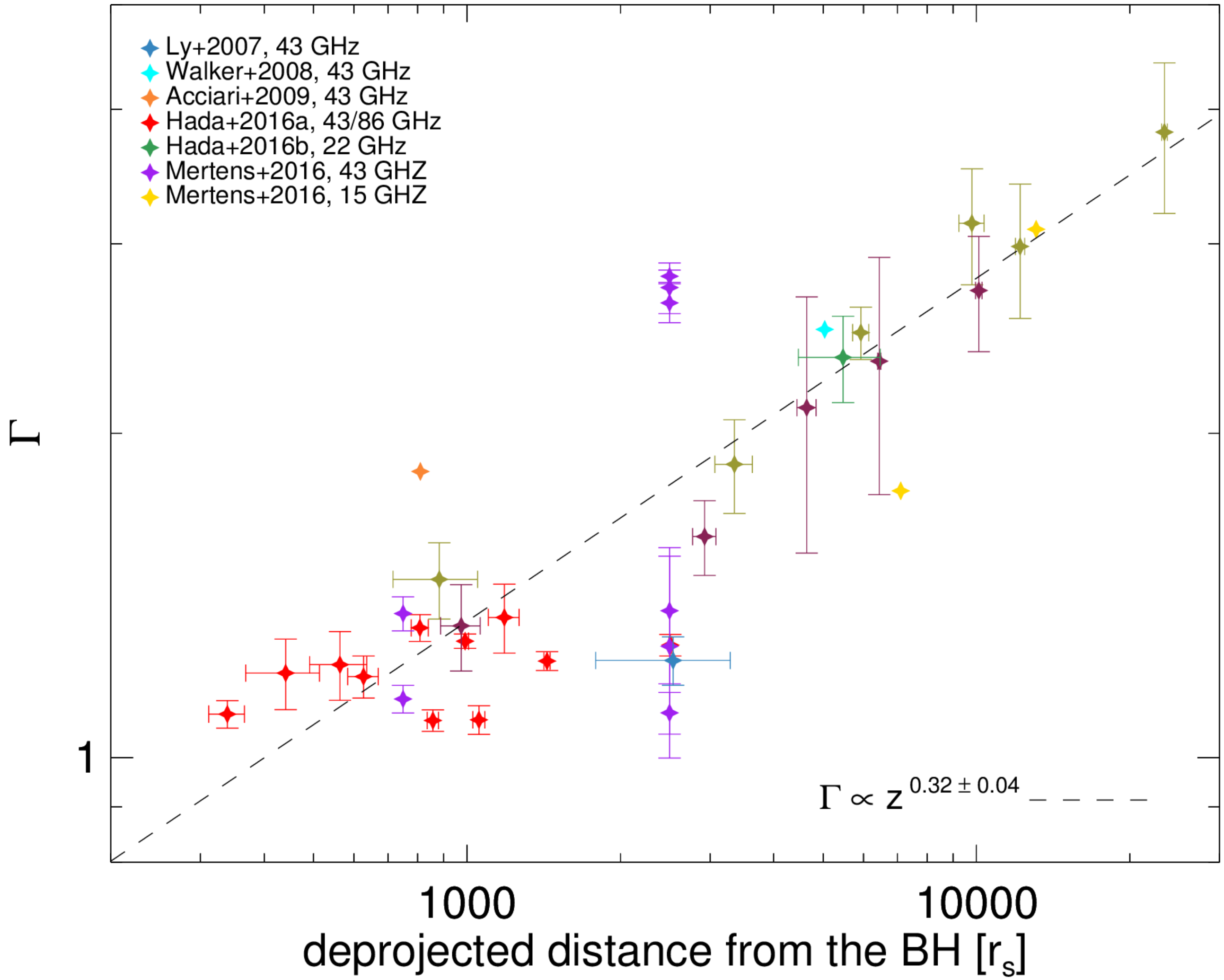


$$\Gamma \propto z^{0.32\pm0.04}$$

$$\Gamma \sim \frac{b}{\sqrt{b-1}}\frac{z}{r} \propto r^{b-1} \propto z^{(b-1)/b} = z^{0.41}, \text{ where b} = 1.7$$

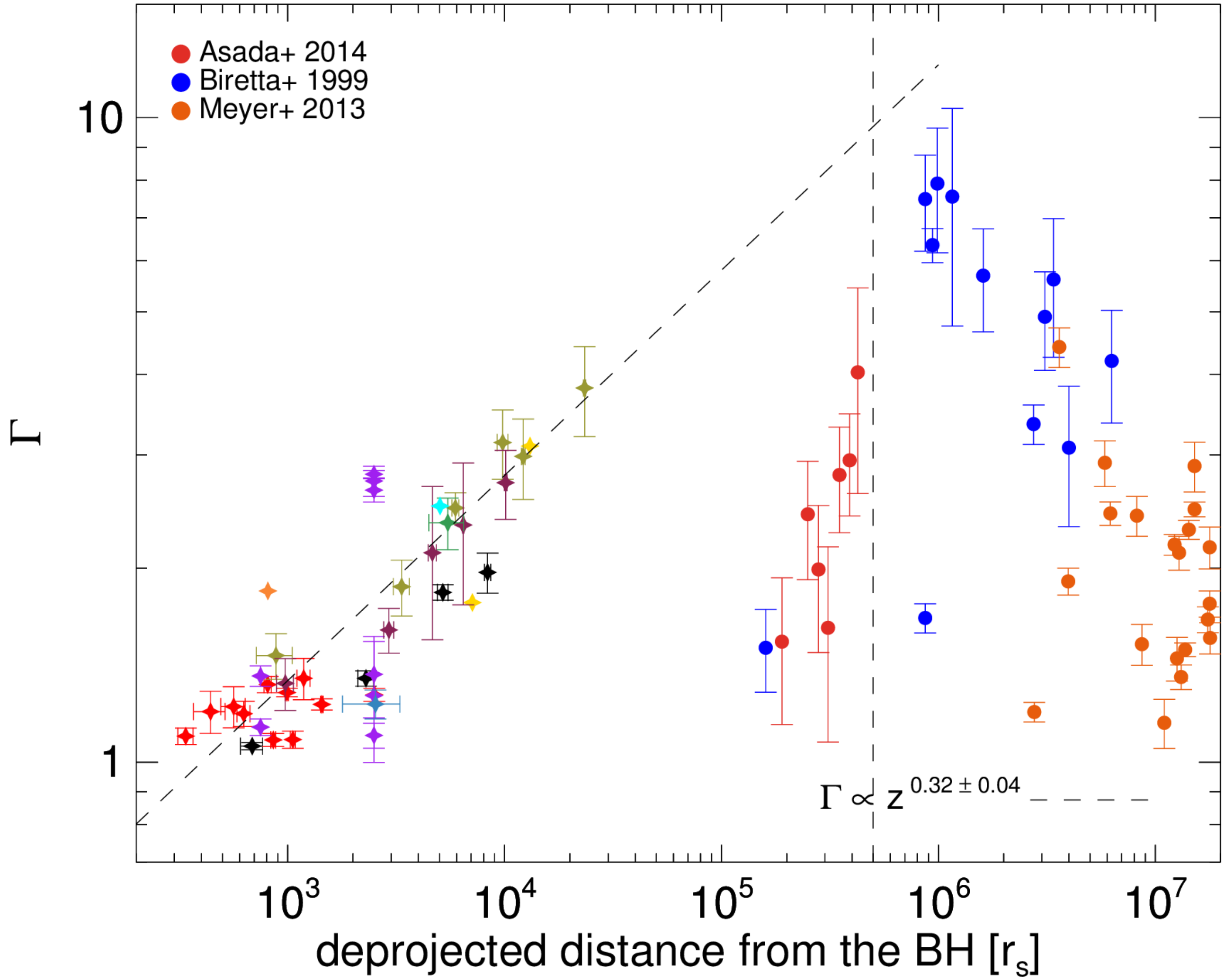
— The acceleration profile (power-law index) is different from the value expected from numerical simulations (Komissarov+ 09) by ~2 sigma.

Comparison with other studies



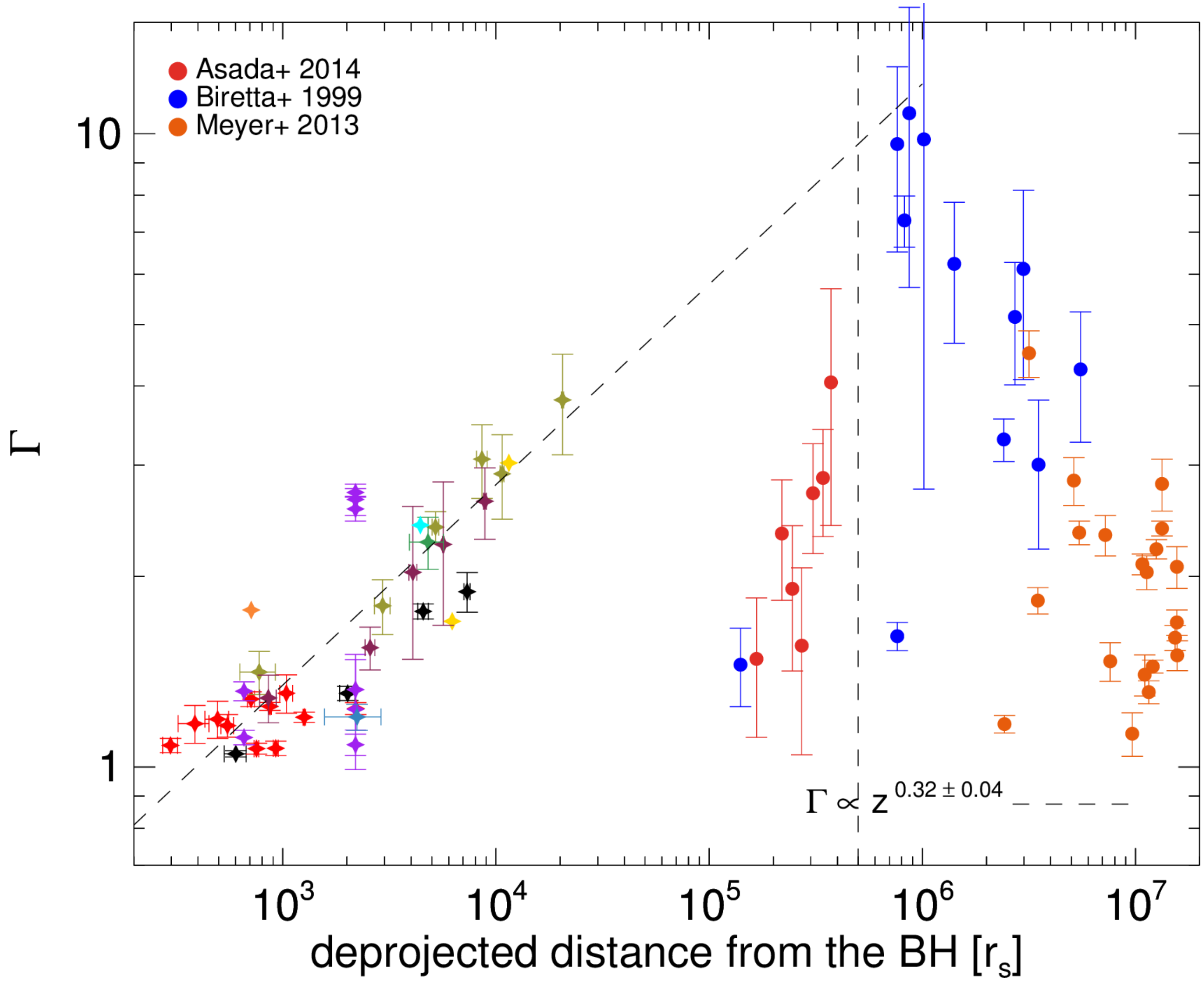
— In general, our results are in agreement with other studies.

Comparison with other studies



— If the acceleration continues to ~10^6 Rs, then the expected Lorentz factor at ~10^6 Rs is higher than the values of Biretta+ 1999. *But,*

Comparison with other studies



― But, when changing the jet viewing angle by 2 deg (14 deg → 16 deg), then the power-law is extended to ~10^6 Rs. Therefore, there is still a possibility that a single power-law acceleration holds over 3 orders of magnitude in distance (cf, the jet viewing angle : 14 ~ 20 deg).

Summary

- We discovered a new acceleration relation for the M87 jet with $\Gamma \propto z^{0.32\pm0.04}$ that might connect the sub-luminal motion in the inner jet (<~ 1 mas) to the super-fast motion ($\beta_{app} \approx 6c$) at z $\approx 10^6 R_s$.

- We found an indication of substantial transverse motion, which can be described as a helical jet model. An origin of the (quasi-)stationary emission at ~20 mas would be explained with this scenario.

- The KaVA large program continues for the next couple of years and will contribute to shed light on the long standing question of AGN jet acceleration & collimation mechanism.