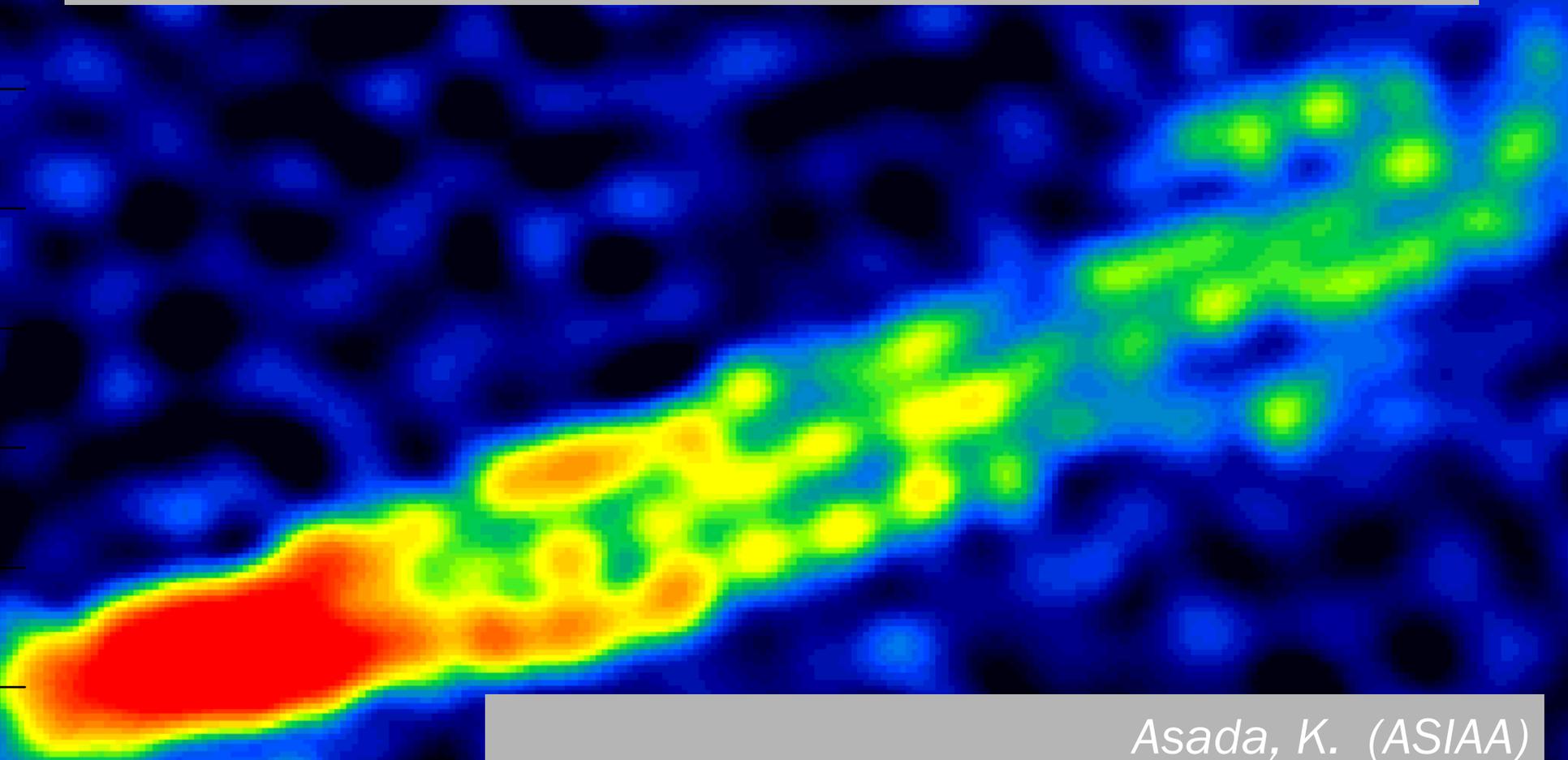


Spine/Sheath structure of M87 jet



*Asada, K. (ASIAA)
Nakamura, M., Pu, H. Y., and GLT team (ASIAA)*

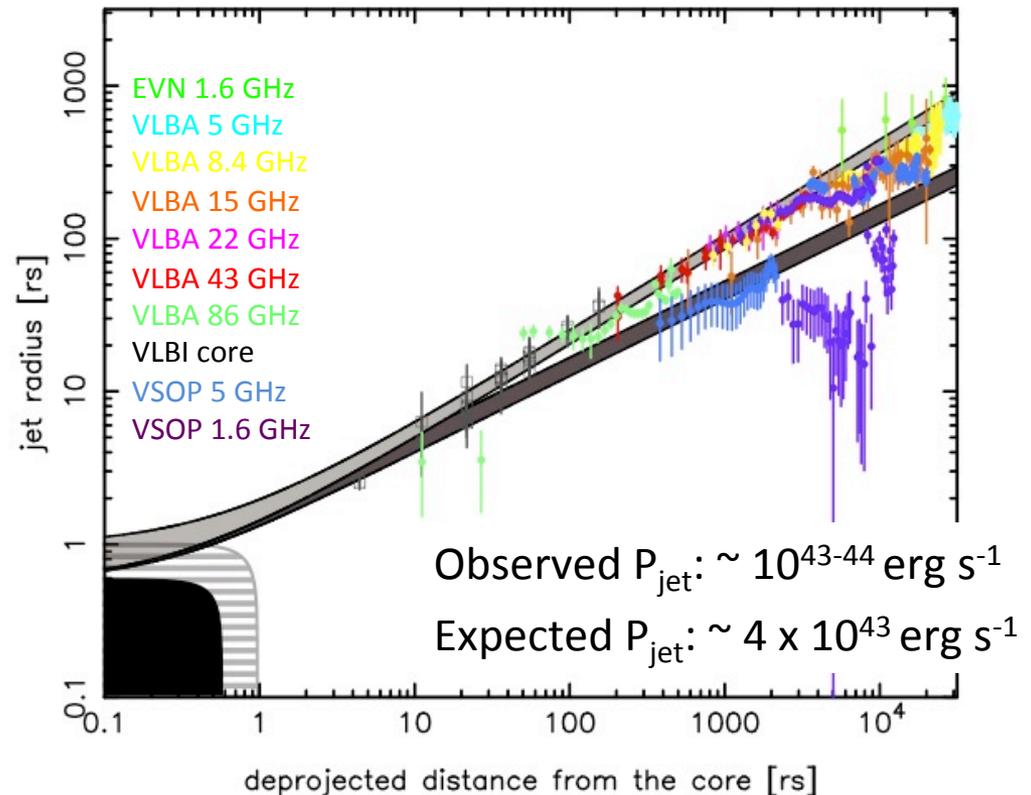
Summary and outline of this talk

Our Summary:

- We intensively investigate structure of M87 jet with VLBI.
- It can be explained with GRMHD BZ type jet with MAD in terms of its structure and power.

Outline:

- Introduction
- GMVA observation
- VSOP observation



GLT is on-going

Short summary of GLT status

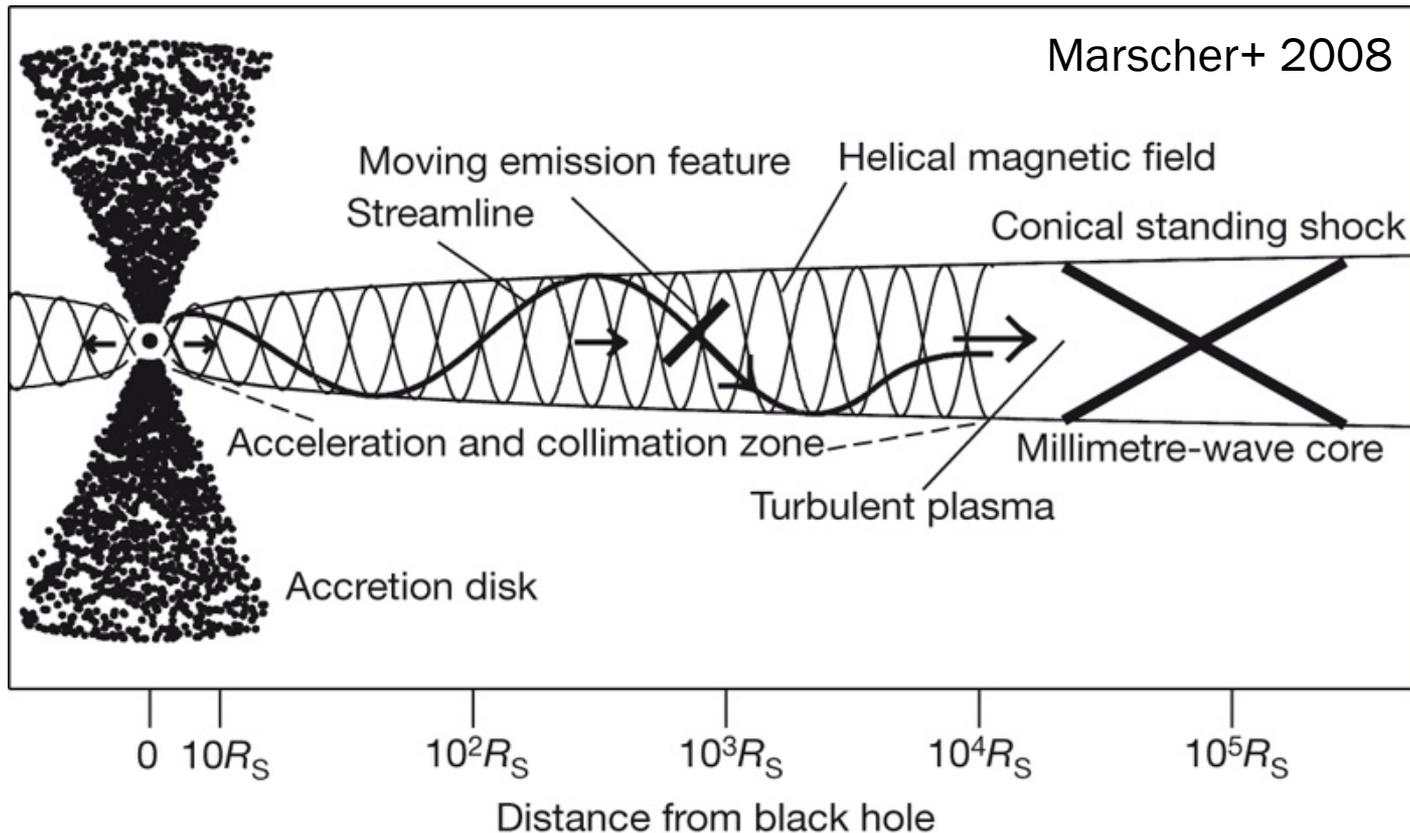
- Greenland Telescope (GLT) project has initiated in 2011 aware 12m ALMA prototype for VLBI.
- Goodness of the site for mm/submm VLBI has been confirmed
- Retrofit of the telescope has been nearly finished.
- GLT will be shipped by boat in June/July in this year
- We expect to have VLBI first lights in 2017/2018 from Thule, and join EHT/GMVA observations.



Introduction



Acceleration and Collimation Zone (ACZ)



How to probe jet collimation and acceleration:

- Collimation: Streamline
- Acceleration: Velocity Field
- Magnetic Field: Polarimetry and RM

(e.g., Talks by Johnson, Wardle, Gomez, Gabuzda, Laing, Homan, Hovatta)

Importance of M 87

□ M 87 (Virgo A*)

- 1st discovered relativistic jet

Curtis 1918, Publications of Lick
Observatory 13, 31

- Low-Luminosity AGN:

$$\sim 10^{42} \text{ erg s}^{-1} (\sim 10^{-6} L_{\text{edd}})$$

Typical AGN with radiatively inefficient
accretion flow (RIAF)

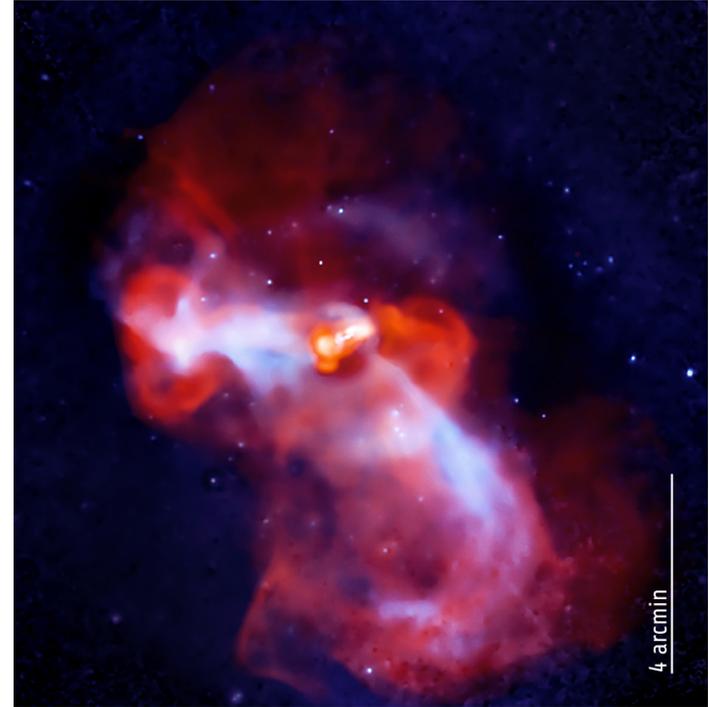
- High Energy activities

Up to TeV gamma-ray

Miss-aligned BL Lac?

- 2nd largest apparent size of r_s (= 8 uas)

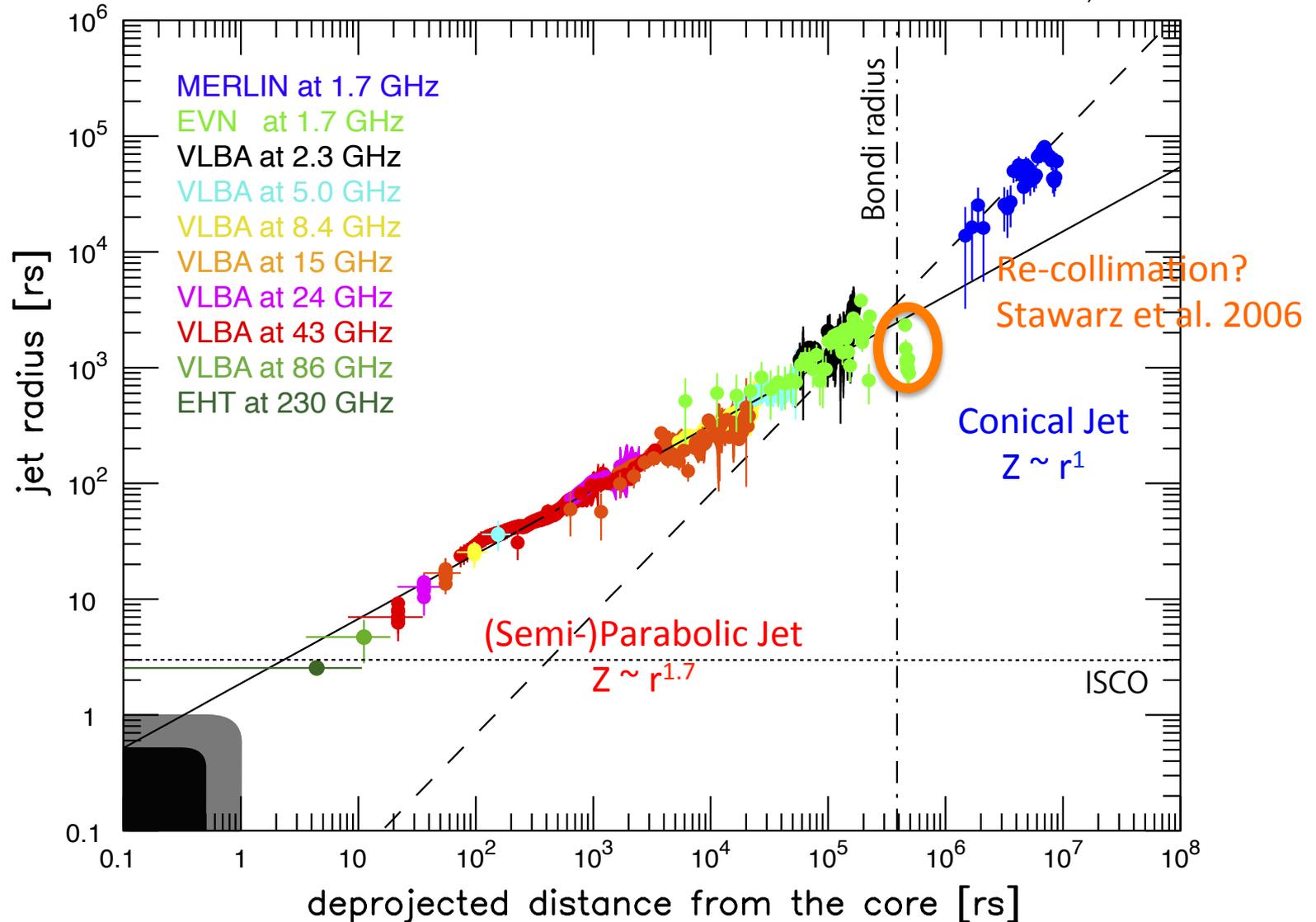
$$M_{\text{BH}} = 6.6 (3.5) \times 10^9 M_{\text{sun}}; D = 16.7 \text{ Mpc}$$



Best Source to understand AGN jet !!

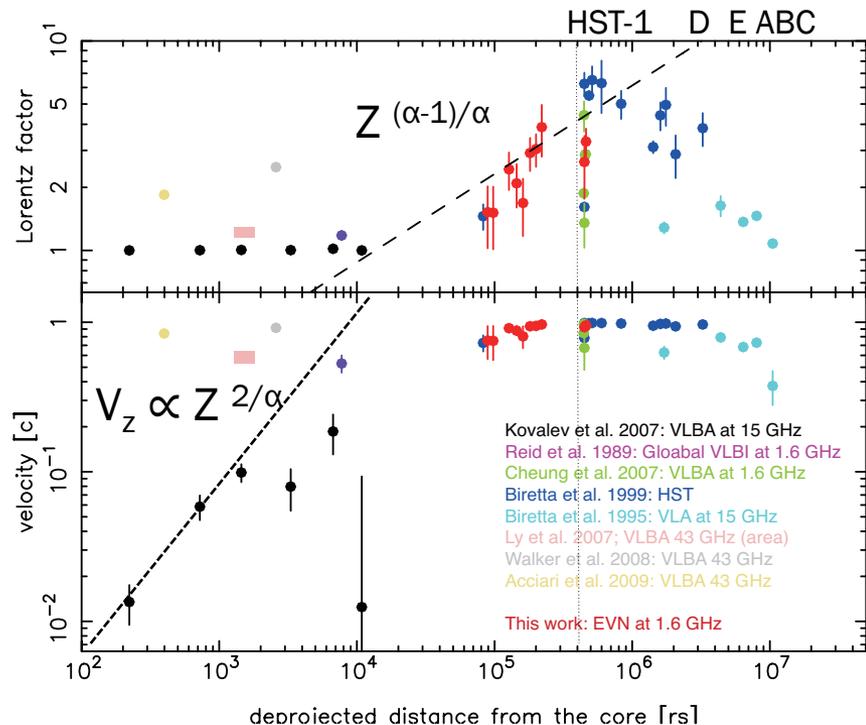
Streamline of M 87

Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013

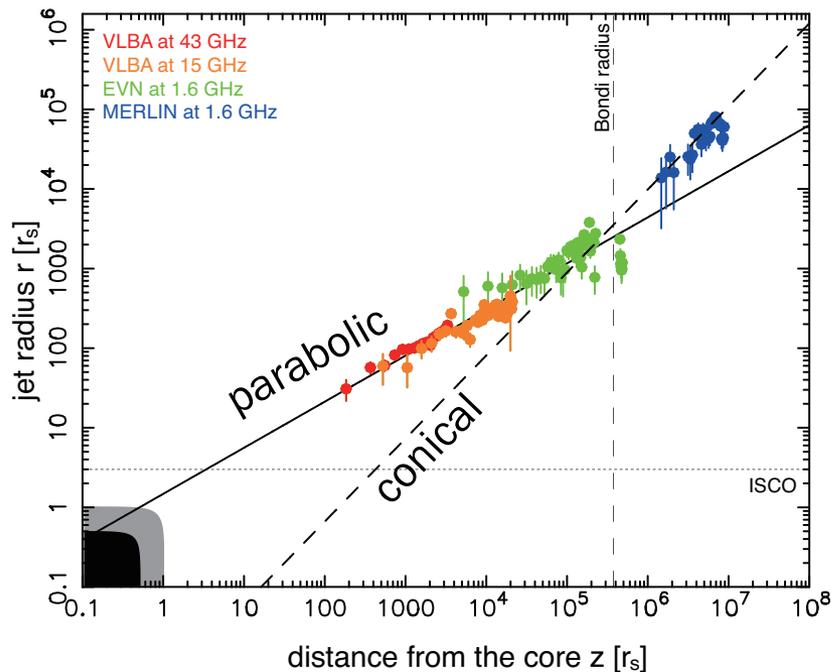


Acceleration and Collimation of the M 87 jet

Asada, K. et al. 2014, ApJL, 781, 2



Asada & Nakamura 2012, ApJ, 745, 28



In relativistic regime,

$$\Gamma \propto Z^{(\alpha-1)/\alpha}$$

Komissarov et al. 2009 MNRAS, 394, 1182

In non-relativistic regime,

$$V_z \propto Z^{2/\alpha}$$

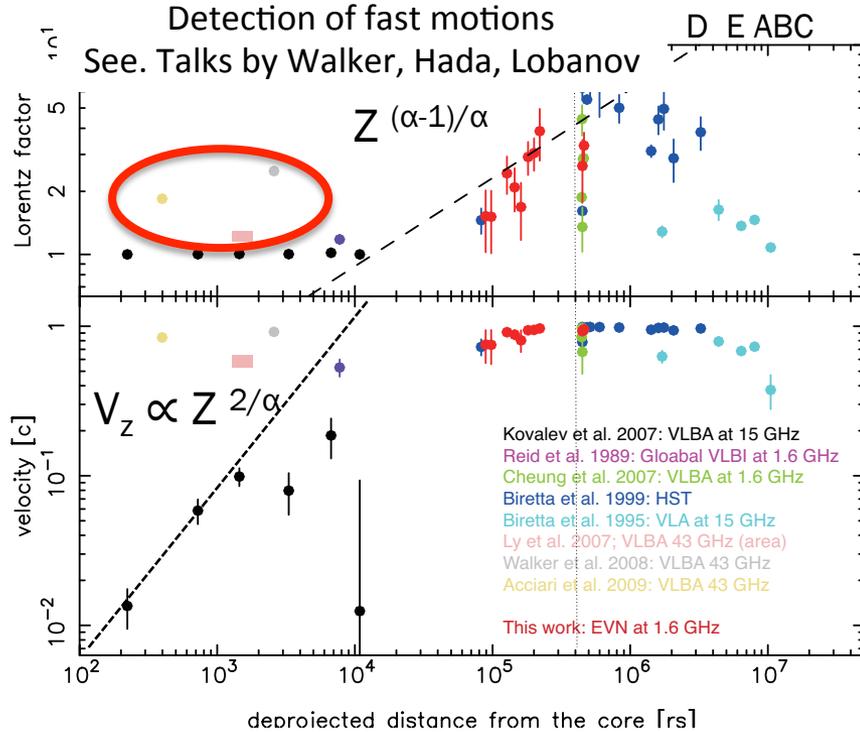
Nakamura & Asada 2013, ApJ,

α : power-law index of streamline (= 1.7)

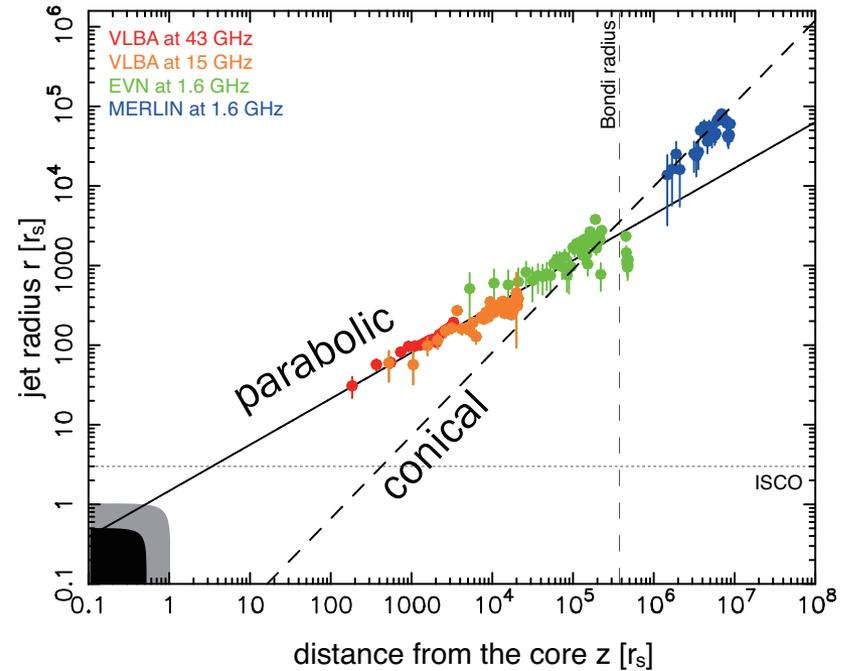
Simultaneous acceleration and collimation
of jet within re-collimation shock region.

Acceleration and Collimation of the M 87 jet

Asada. K. et al. 2014. ApJL. 781. 2



Asada & Nakamura 2012, ApJ, 745, 28



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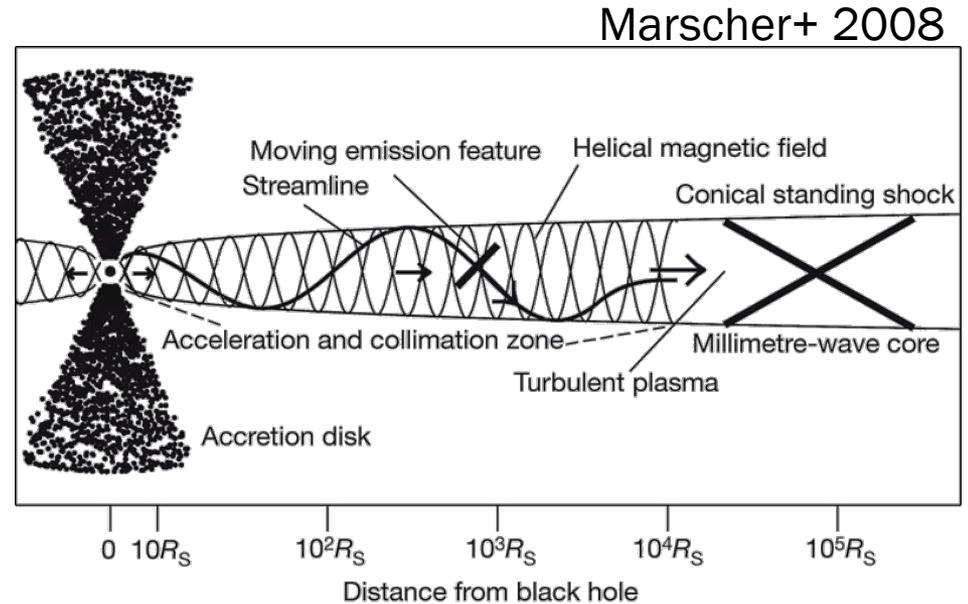
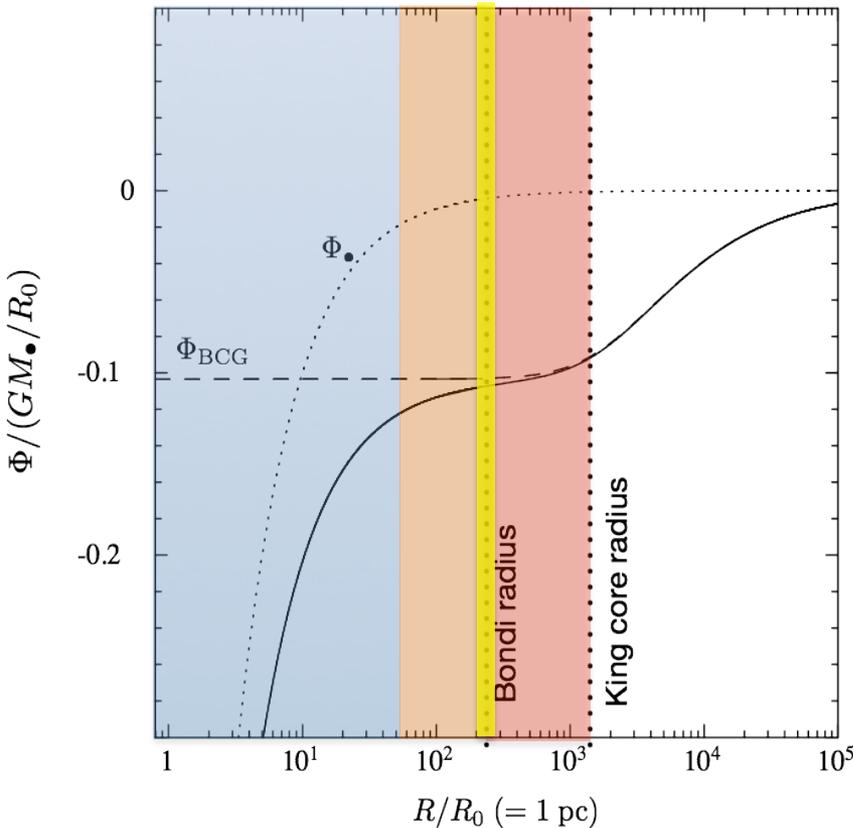
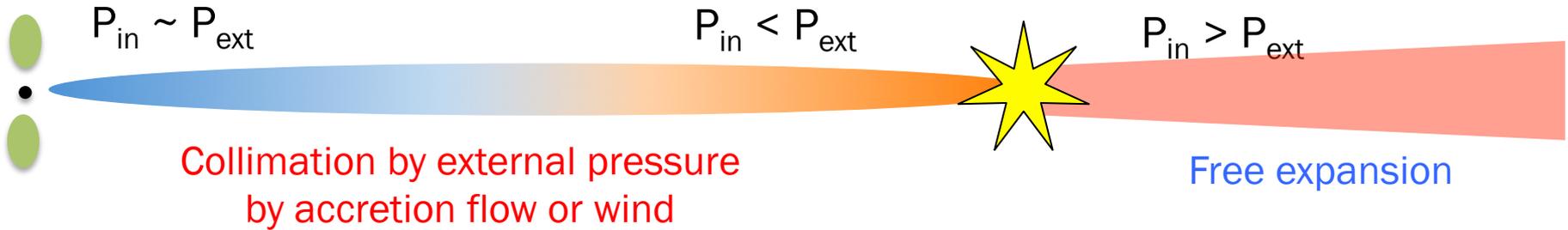
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Nakamura & Asada 2013, ApJ,

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Simultaneous acceleration and collimation
of jet within re-collimation shock region.

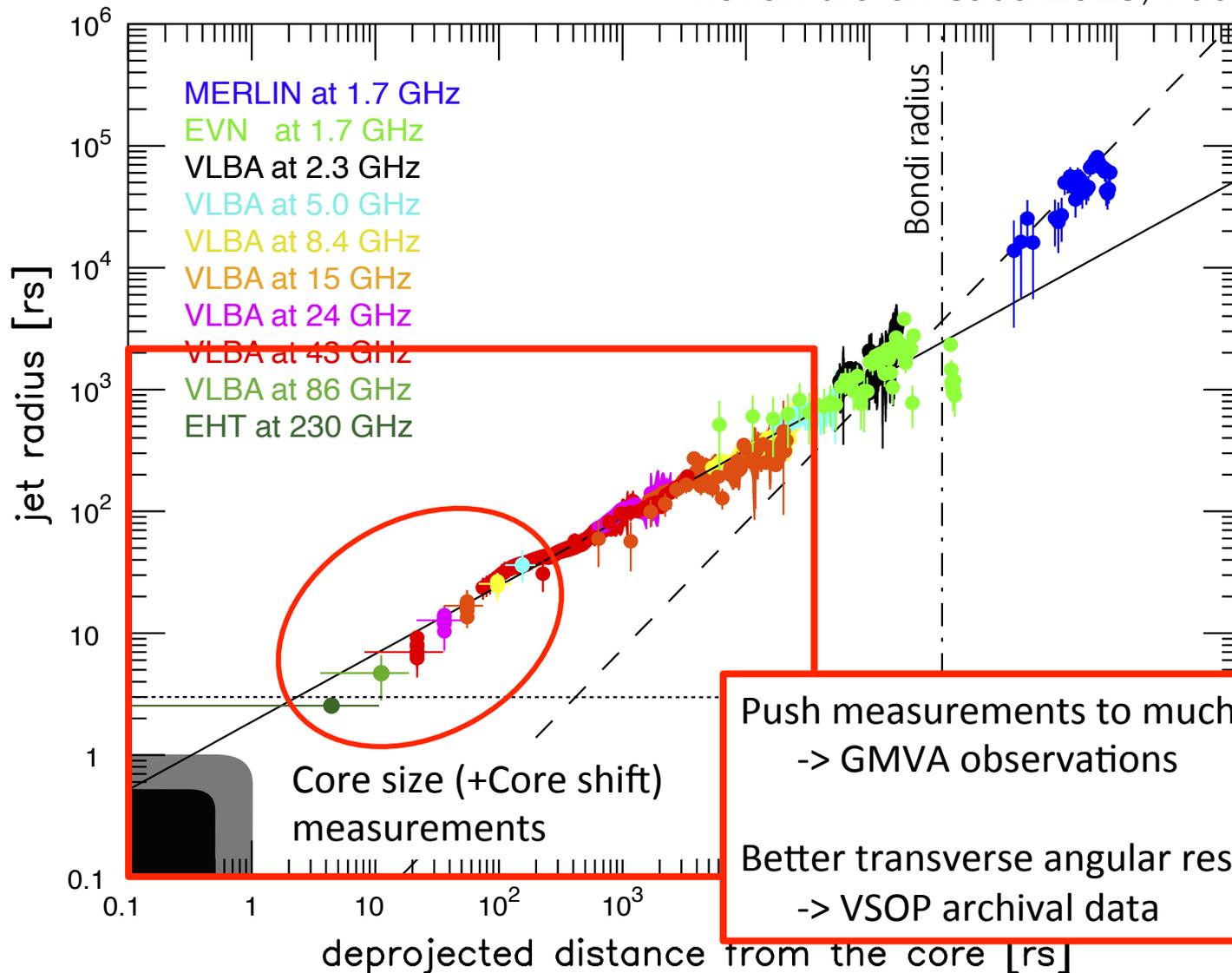
Acceleration and Collimation of the M 87 jet



Simultaneous acceleration and collimation of jet within re-collimation shock region.

Objectives

Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013



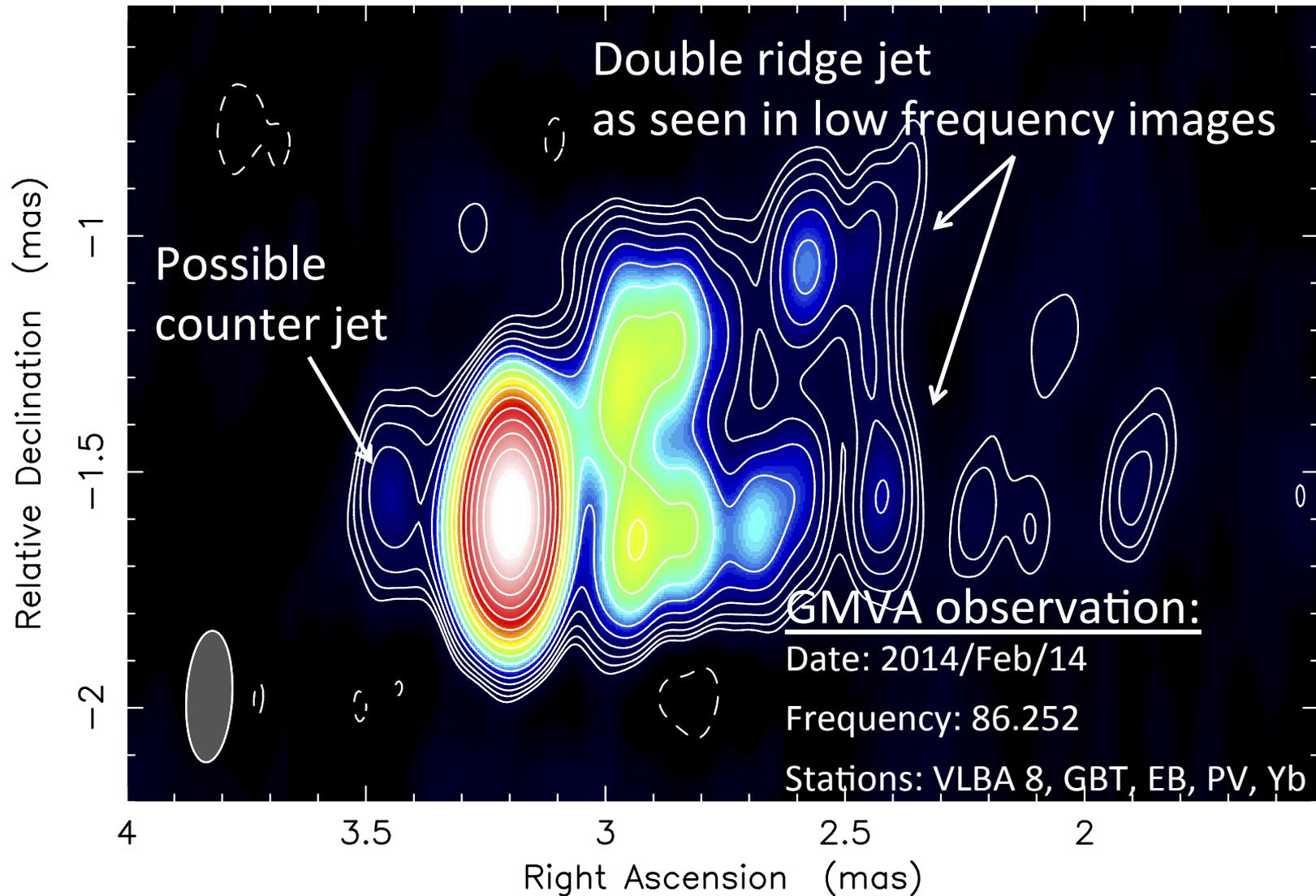
Push measurements to much inner region
-> GMVA observations

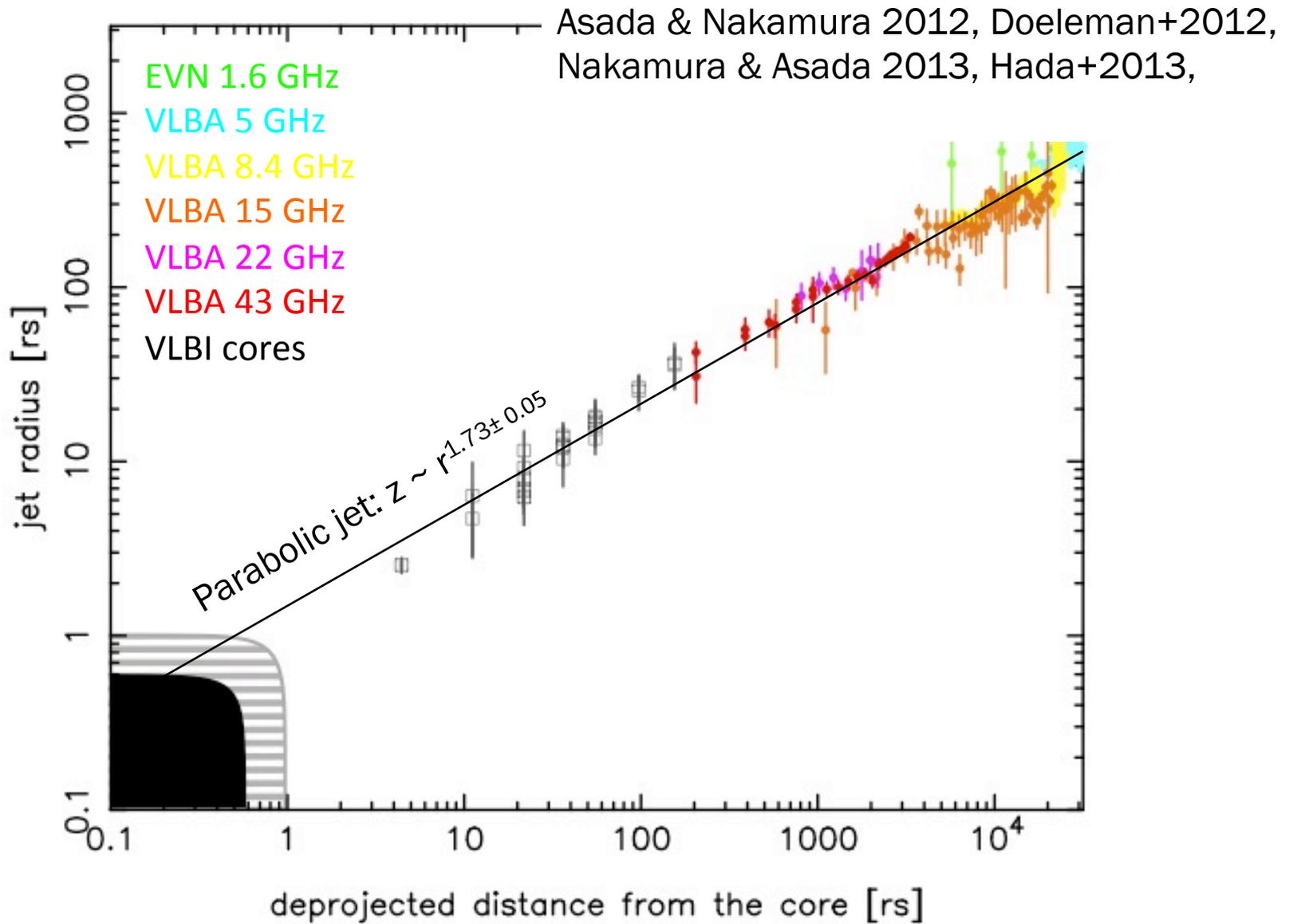
Better transverse angular resolution
-> VSOP archival data

GMVA observation on M 87

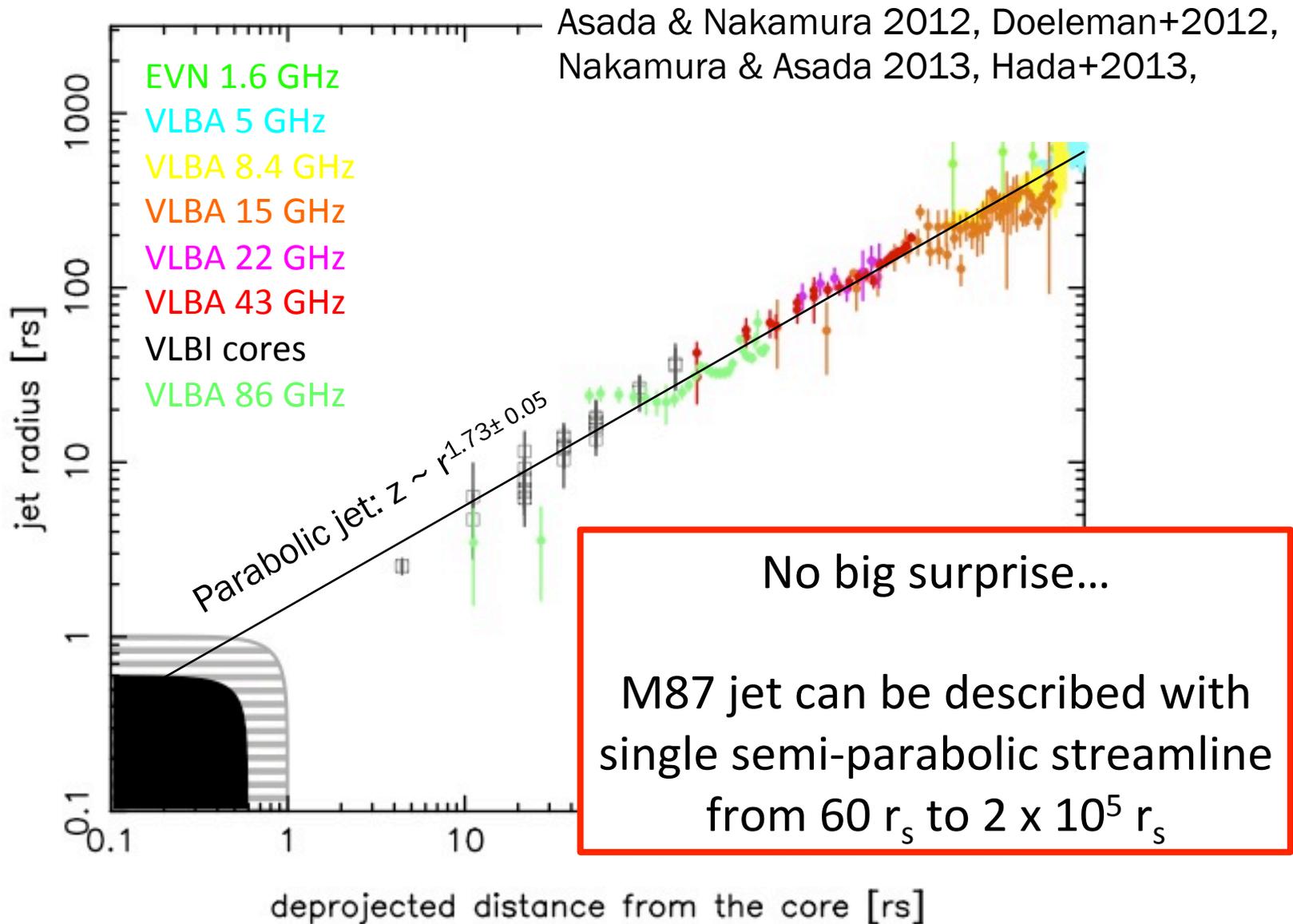


GMVA image in 2014 Feb.

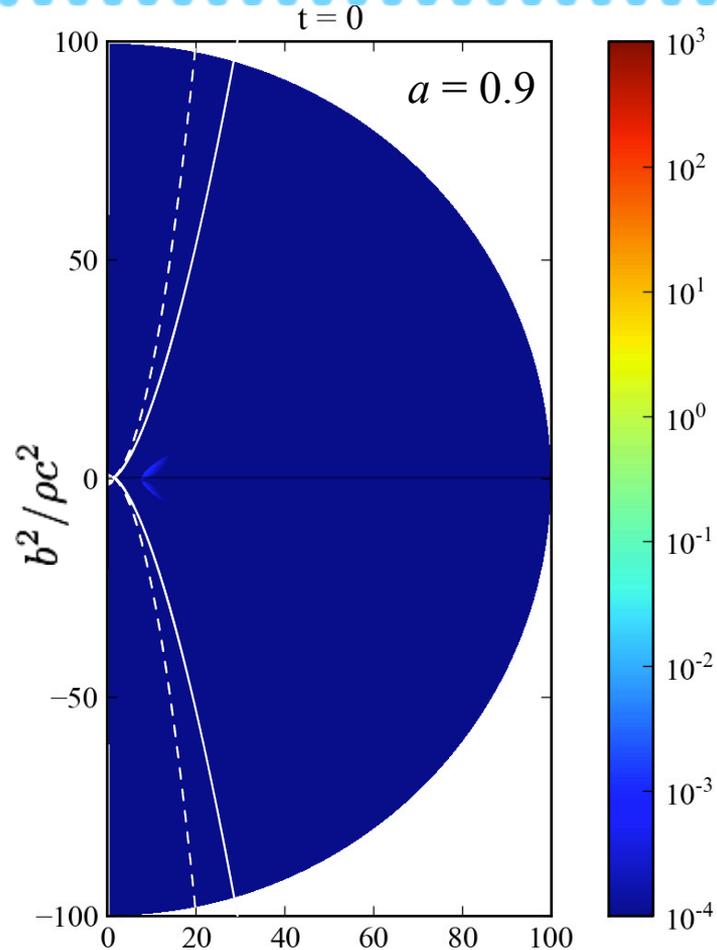
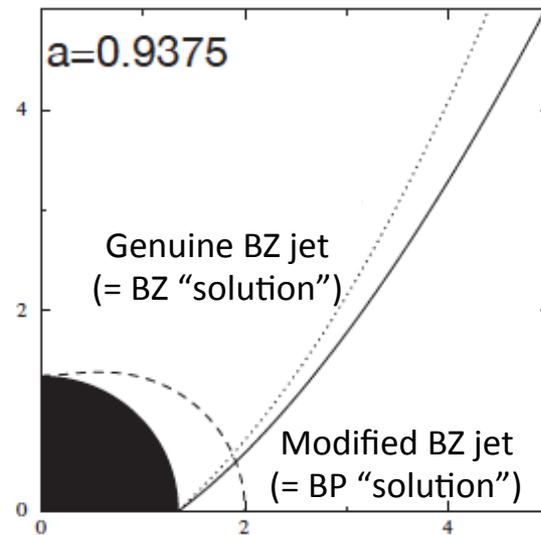
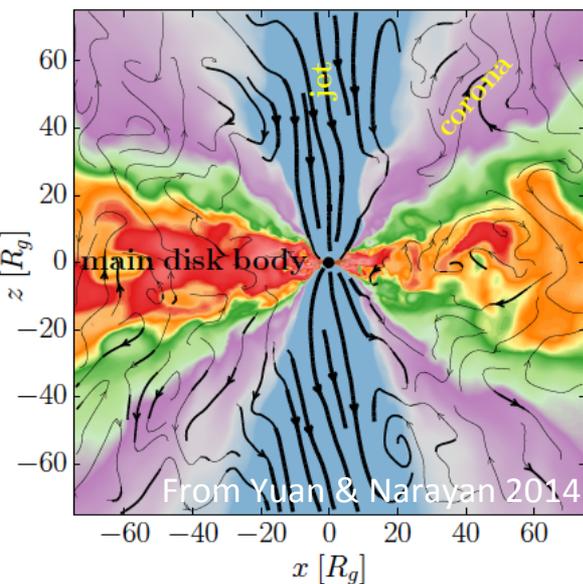




Updated Streamline with GMVA image



What is the observed jet width?



- If MAD is in action, RIAF would be much suppressed in the vertical direction, and BP type field structure is expected for BZ jet

Tchekhovskoy 2015

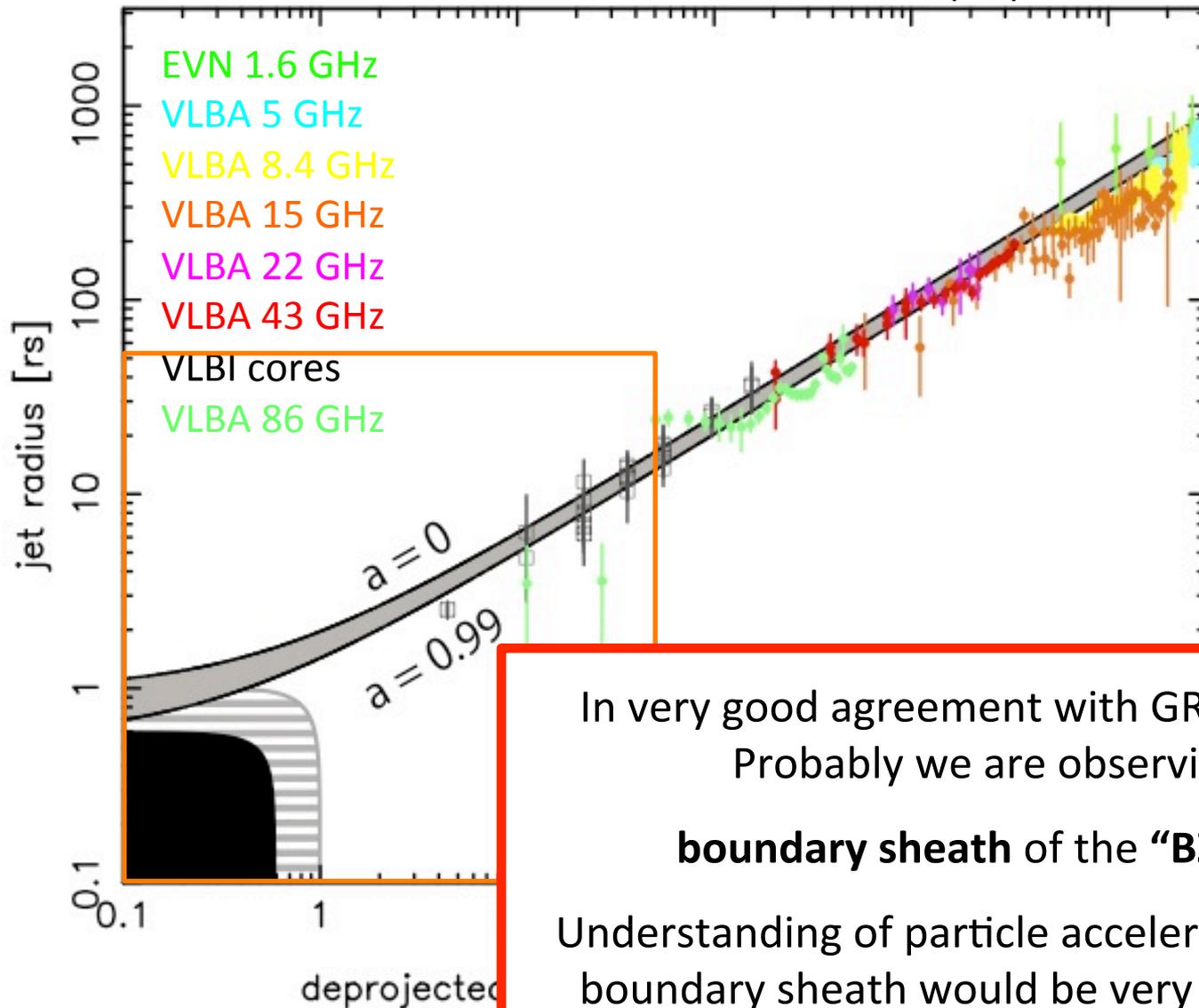
Nakamura+ in prep.

- Genuine BZ jet: $\sim r^{-2}$
- Modified BZ jet: $\sim r^{<-2}$

GRMHD jet seems to trace the BP solution !!

Updated Streamline with GMVA image

Asada+ in prep., Nakamura+ in prep.



In very good agreement with GRMHD jet!!
Probably we are observing

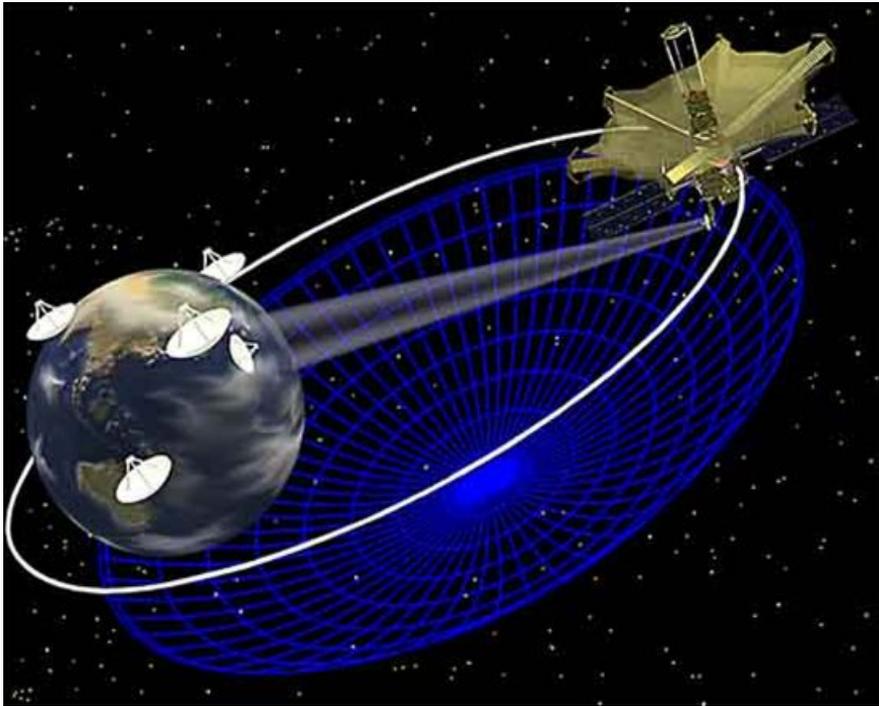
boundary sheath of the “BZ” jet

Understanding of particle acceleration at the
boundary sheath would be very important

VSOP images of M 87



VSOP images



Not radioastron, “classic” VSOP

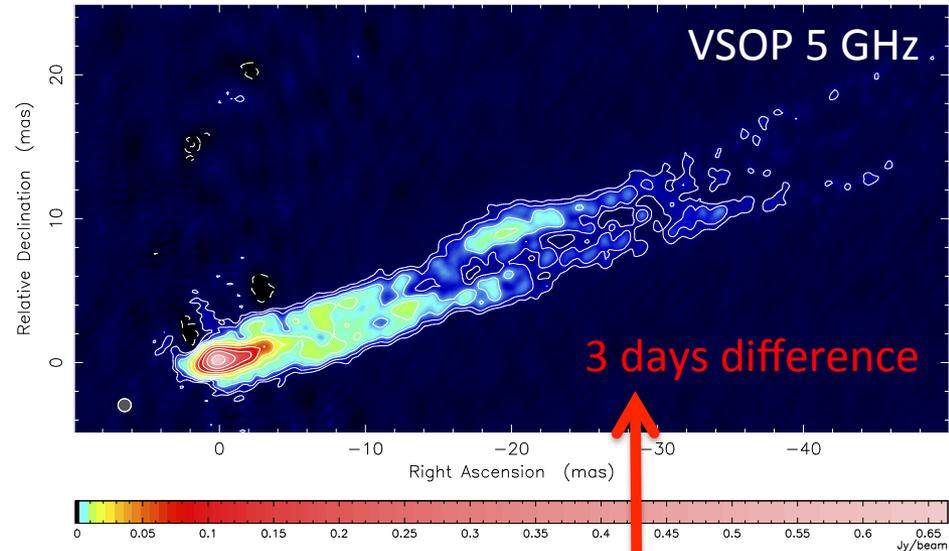
Freq. 1.6 and 5 GHz

G stations: VLBA10 ++

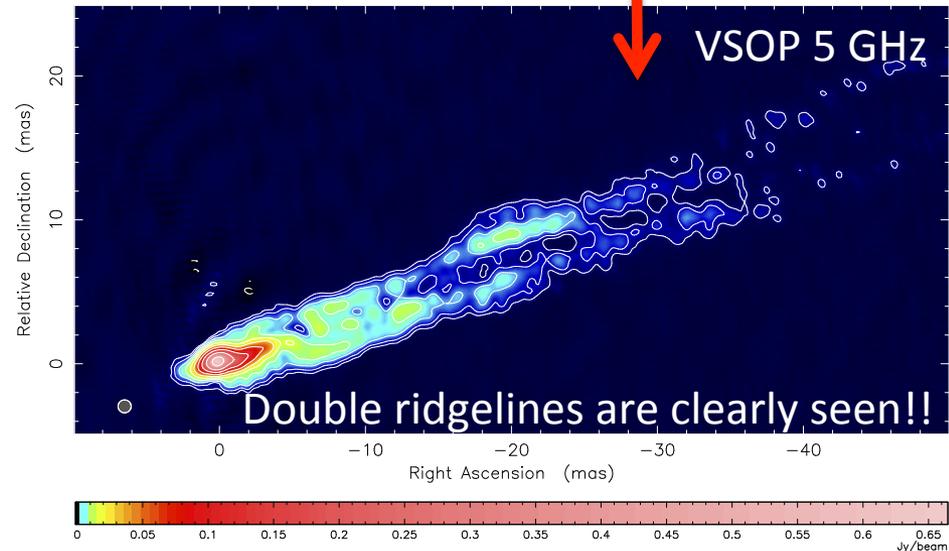
Epoch: 2000 March

Some of the images are re-production of Dodson+2006

J1230+12 at 4.816 GHz 2000 Mar 20



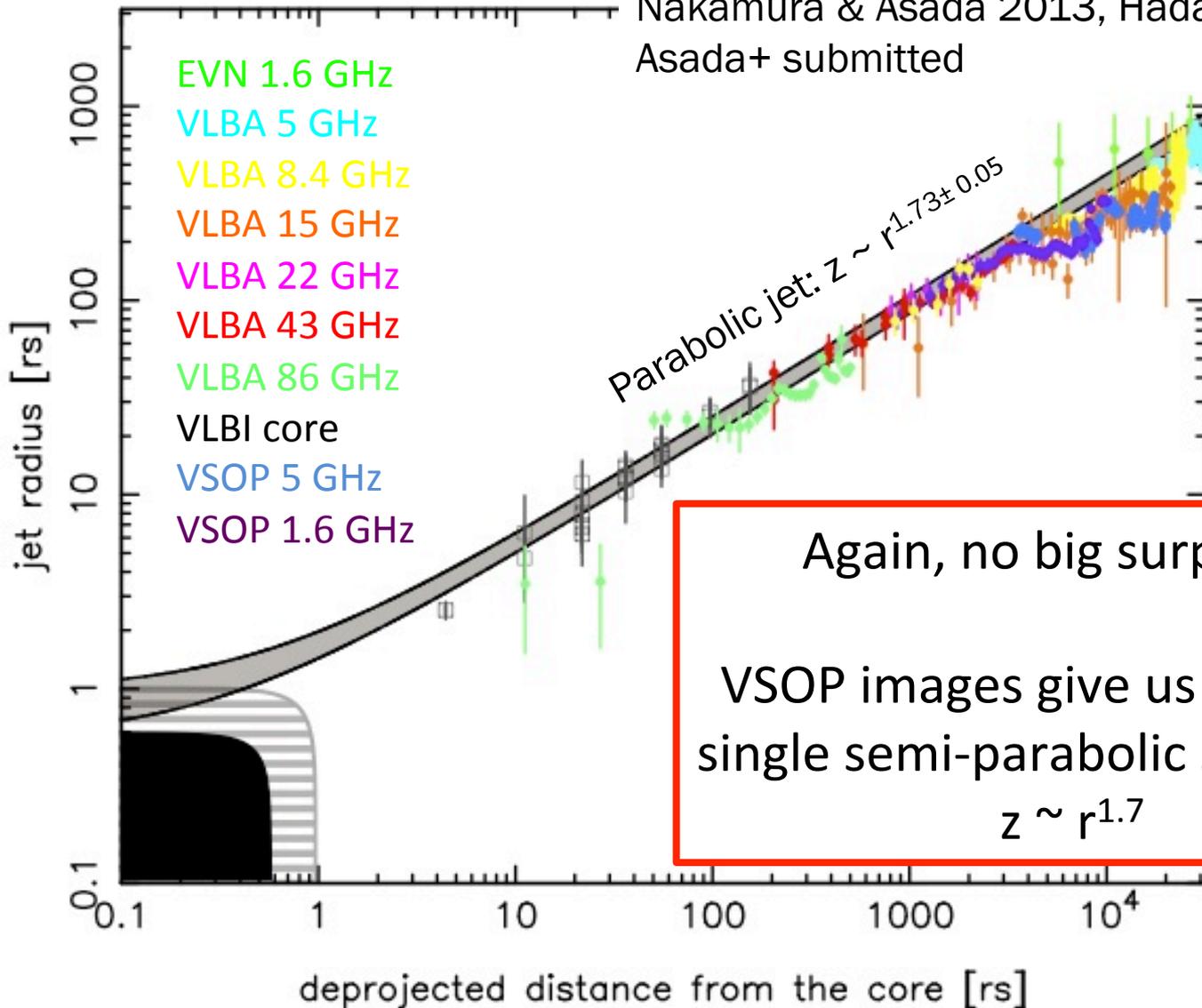
J1230+12 at 4.866 GHz 2000 Mar 23



Updated Streamline with VSOP images



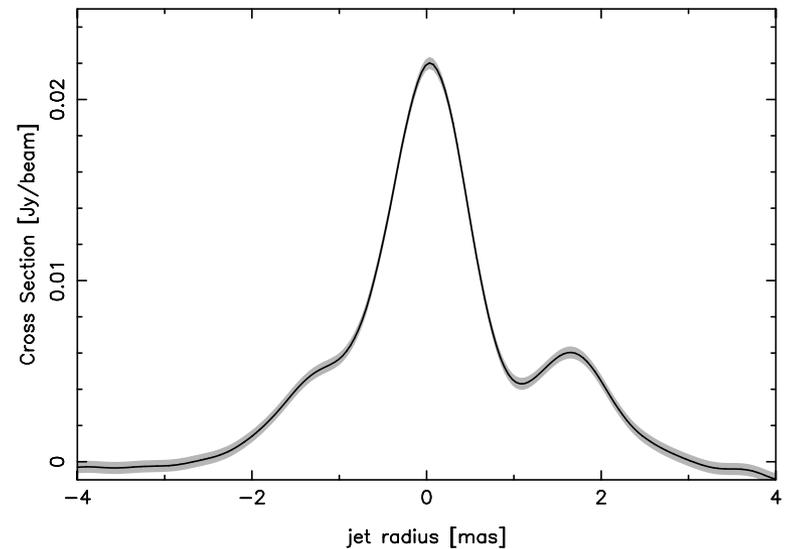
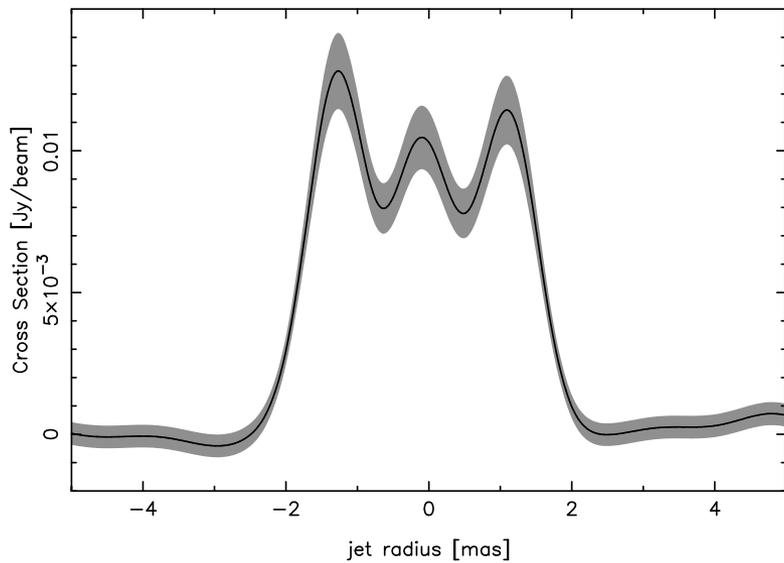
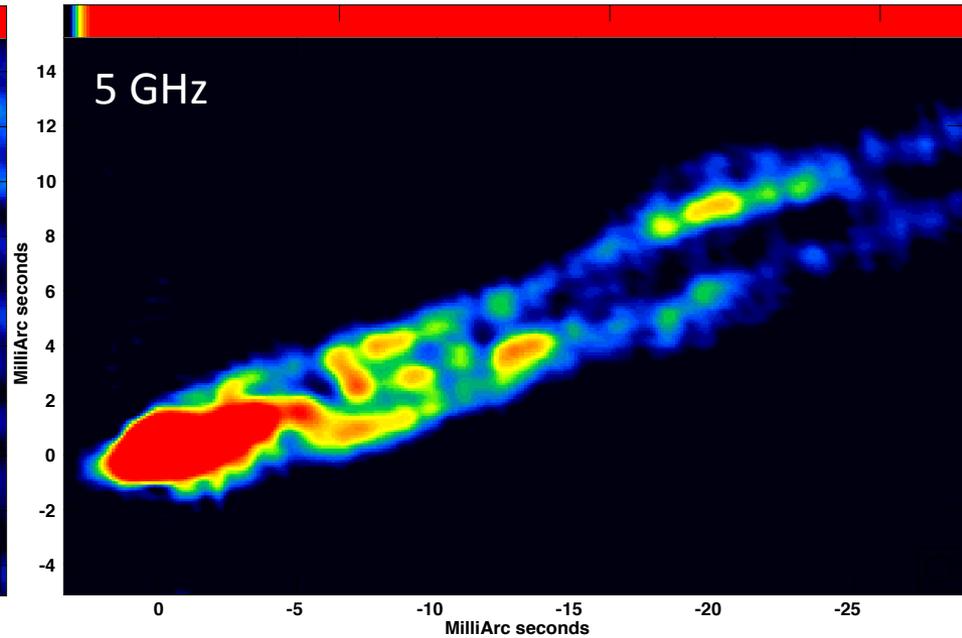
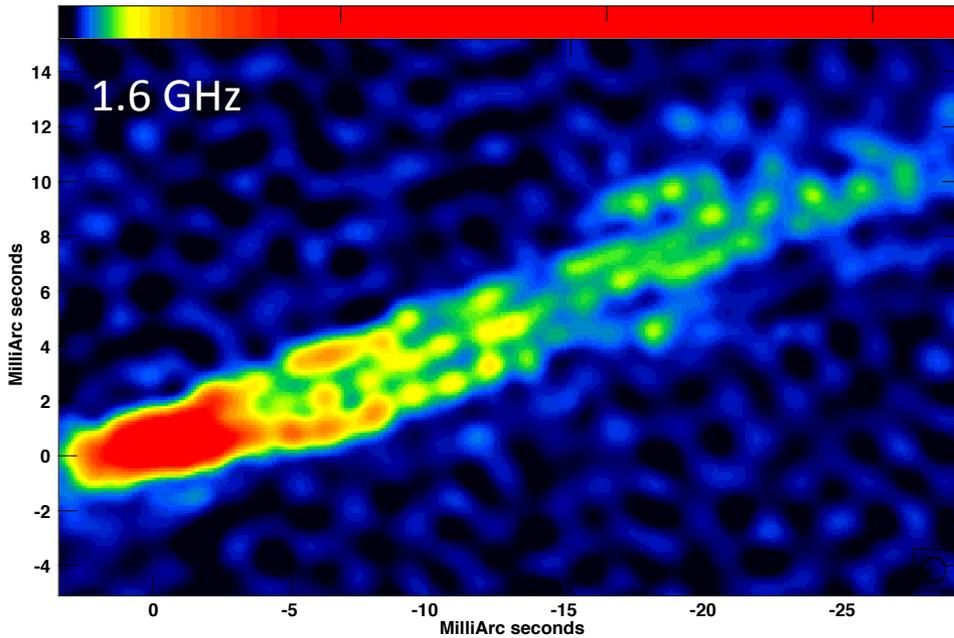
Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013
Asada+ submitted



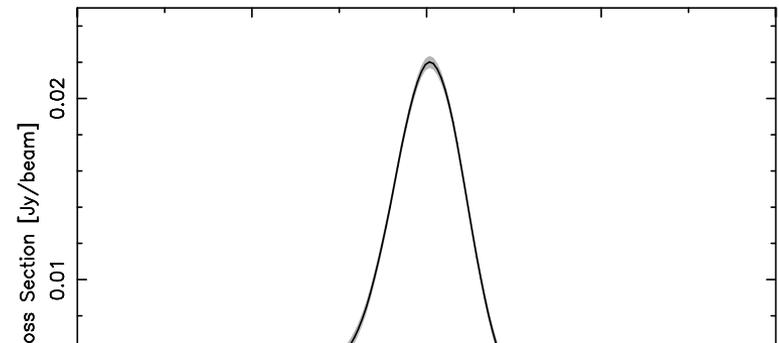
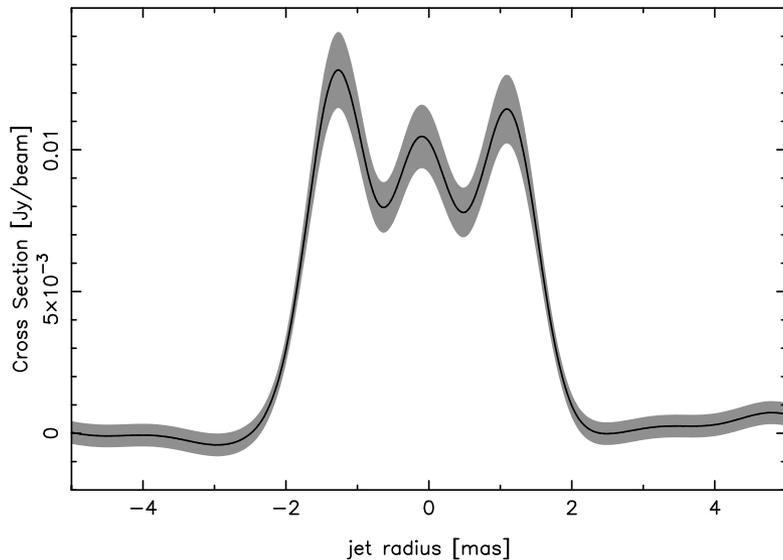
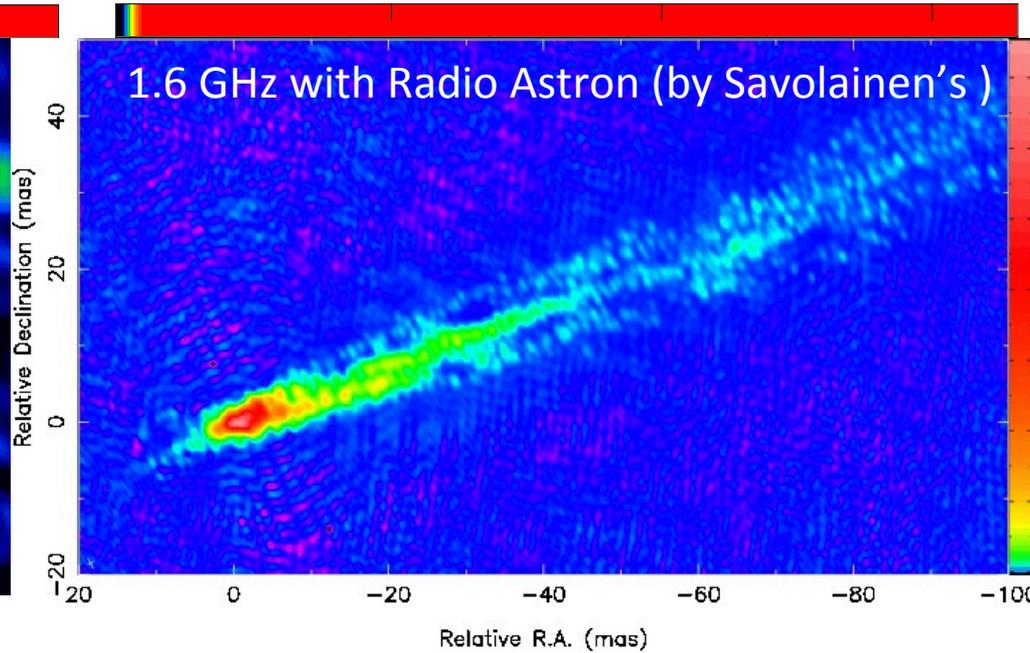
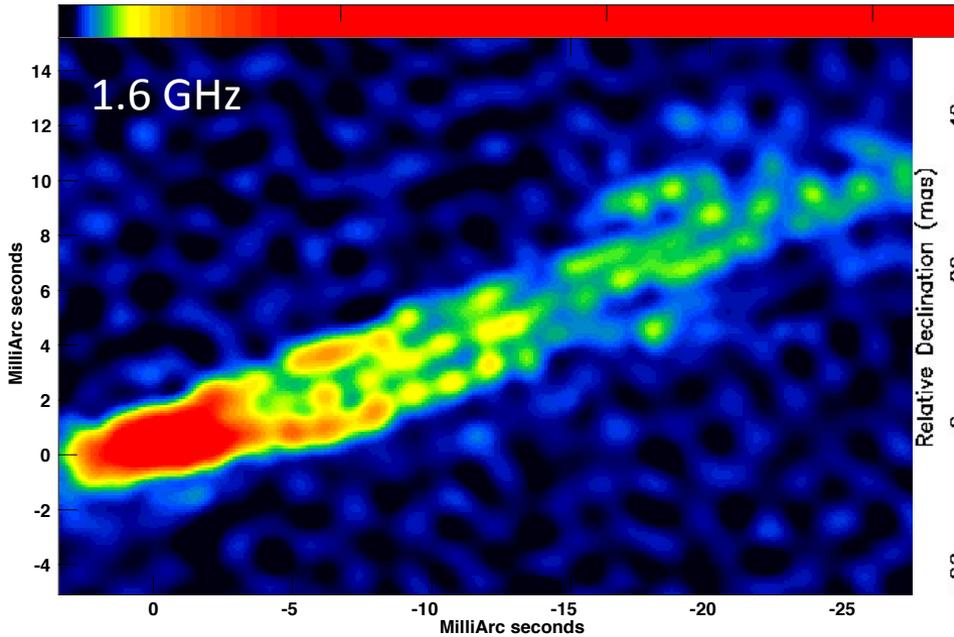
Again, no big surprise...

VSOP images give us the same
single semi-parabolic streamline
 $z \sim r^{1.7}$

Three ridges with VSOP images



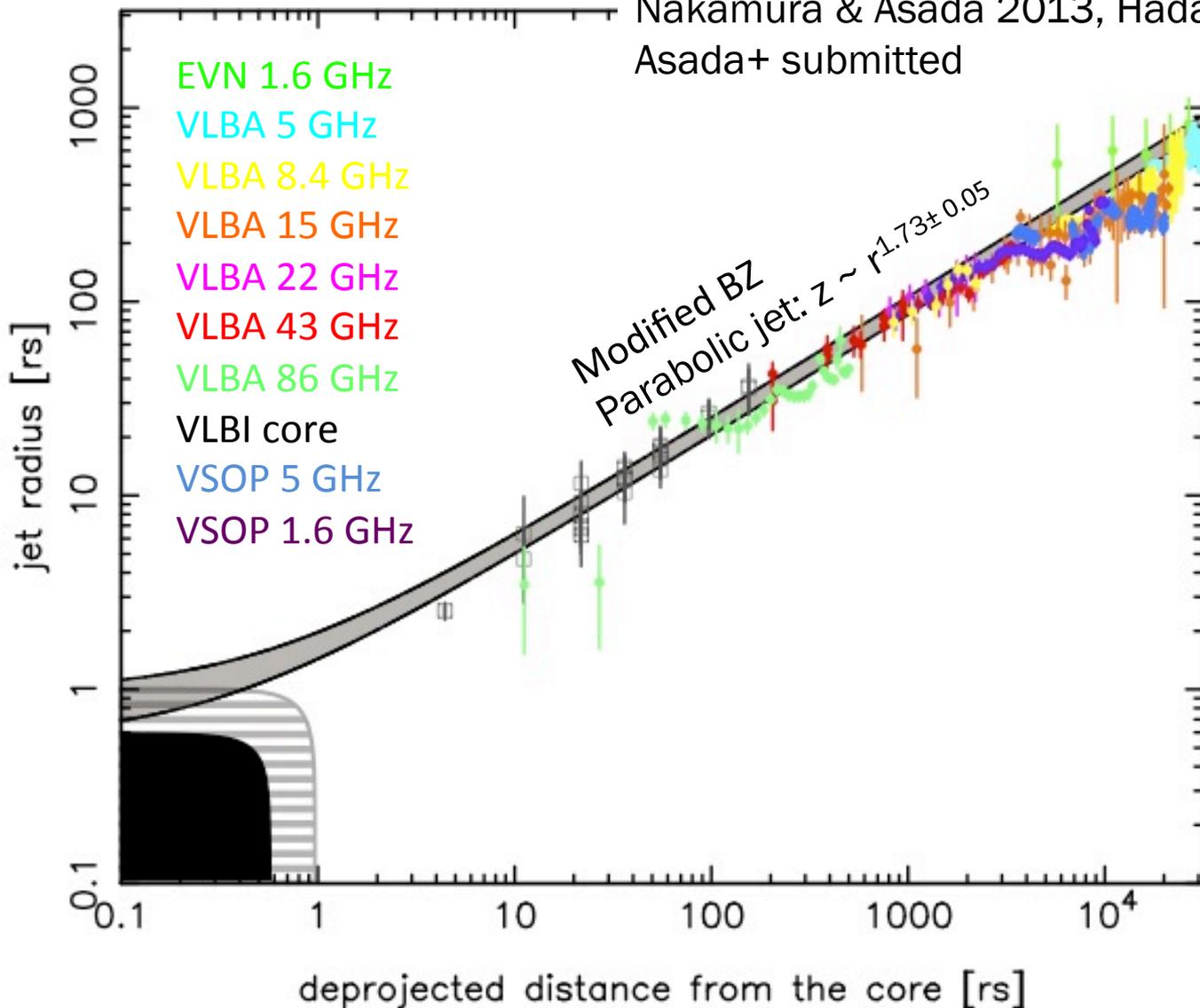
Three ridges with VSOP images



Similar structures are seen in Radioastron (Savolainen's talk) and VLBA (following talk by Hada) images as well.

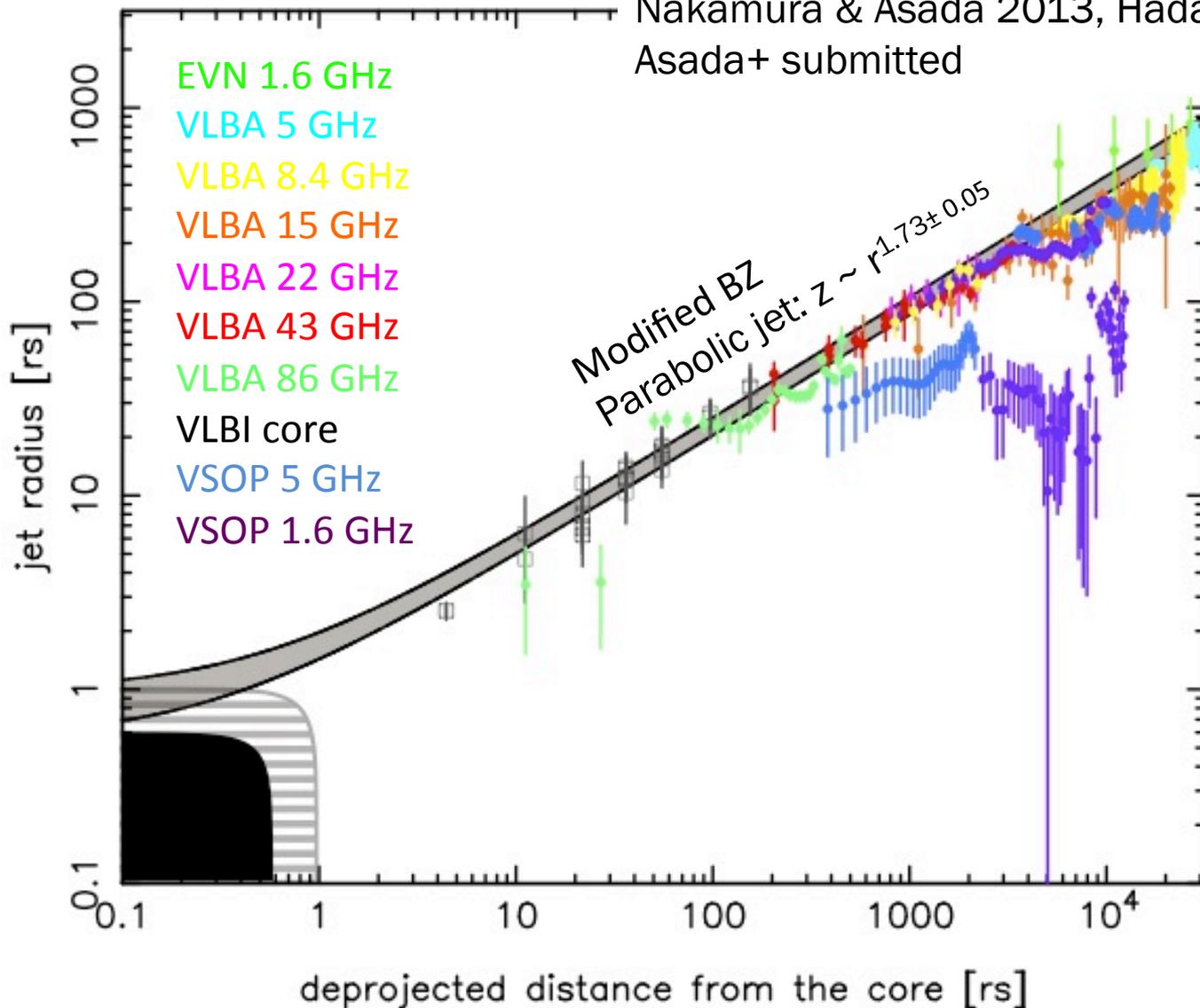
Updated Streamline with VSOP images

Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013
Asada+ submitted



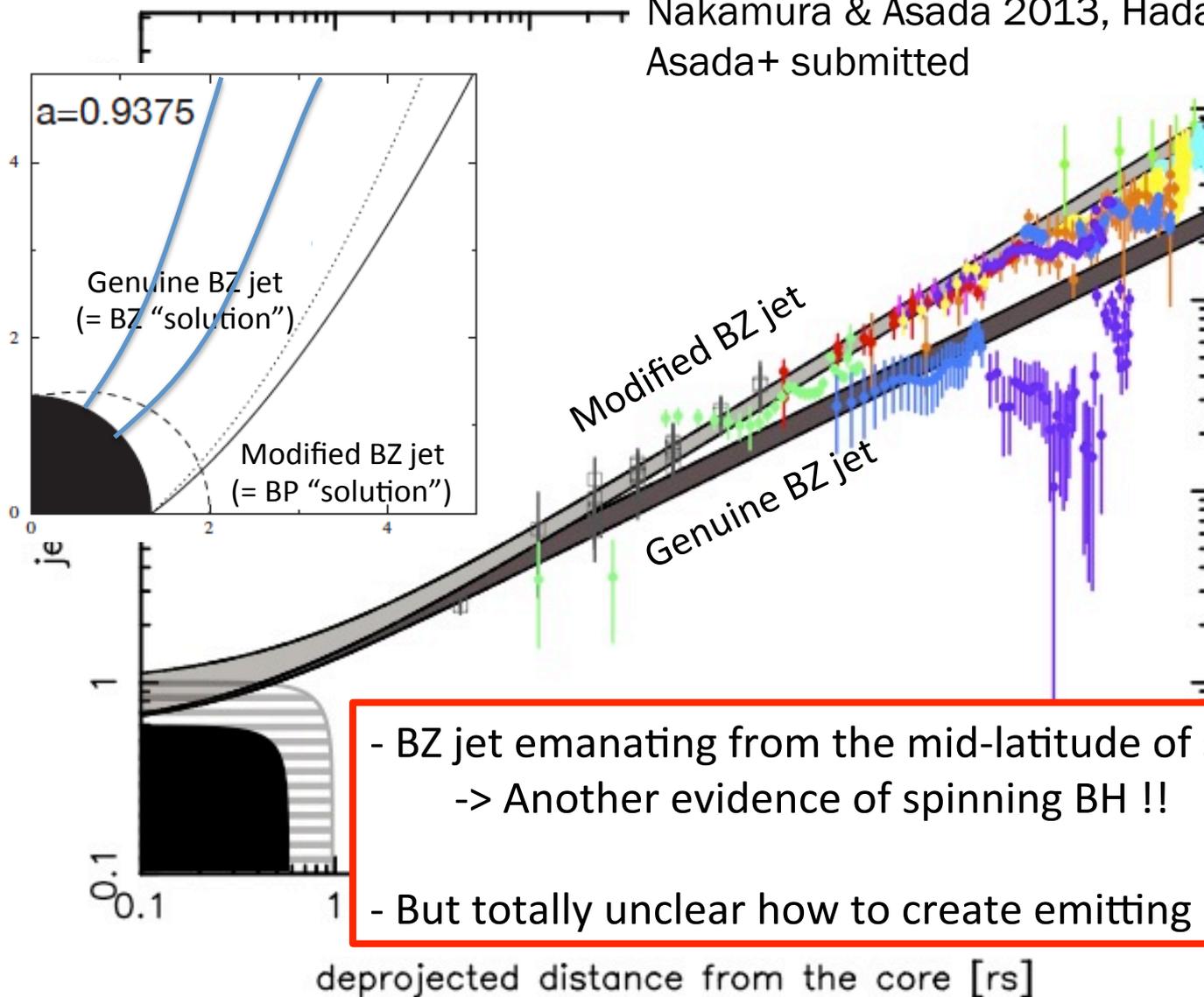
Updated Streamline with VSOP images

Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013
Asada+ submitted



Updated Streamline with VSOP images

Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013
Asada+ submitted



- BZ jet emanating from the mid-latitude of spinning BH?
-> Another evidence of spinning BH !!

- But totally unclear how to create emitting electrons.

Can BZ jet explain P_{jet} ?

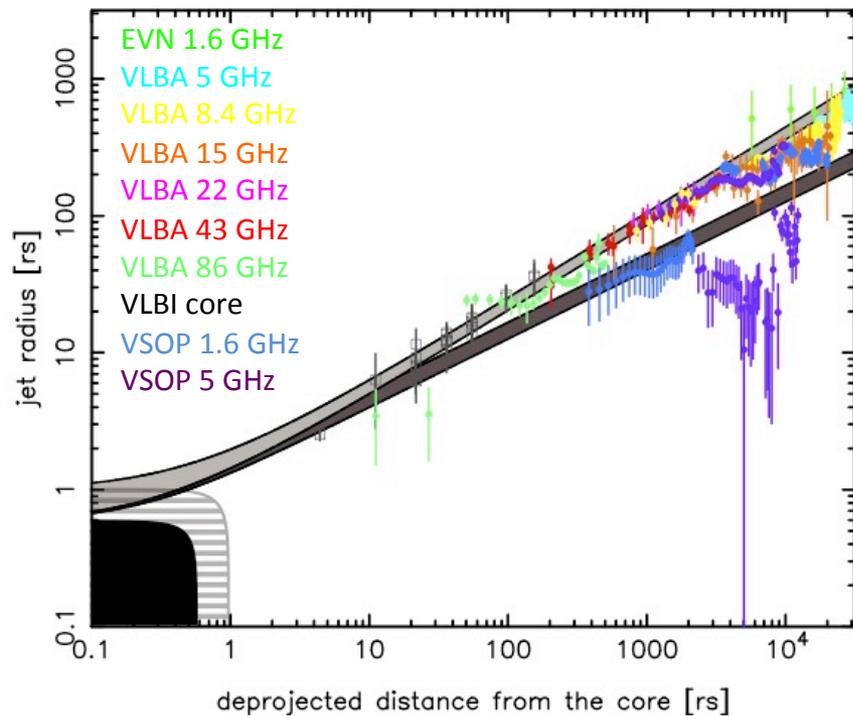
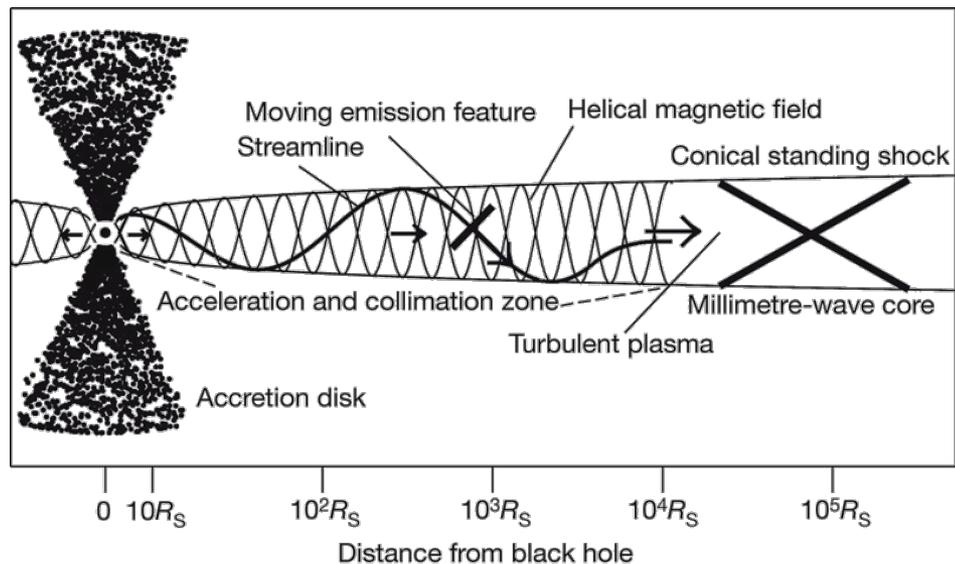


Table 3

Jet Power from the Published Literature

$L_j / \text{erg s}^{-1}$	Ref.
$\sim 10^{44}$	Bicknell & Begelman (1996)
2×10^{43}	Reynolds et al. (1996)
$\sim 10^{44}$	Owen et al. (2000)
3×10^{42}	Young et al. (2002)
$\sim 10^{44}$	Stawarz et al. (2006)
5×10^{43}	Bromberg & Levinson (2008)



$$P_{\text{jet}} \approx 2.5 \left(\frac{a_*}{1 + \sqrt{1 - a_*^2}} \right)^2 \left(\frac{\Phi}{\Phi_{\text{MAD}}} \right)^2 \dot{M}_{\text{BH}} c^2,$$

SSA: $B \sim 100 \text{ G}$ ↑
Kino+ 2014, 15

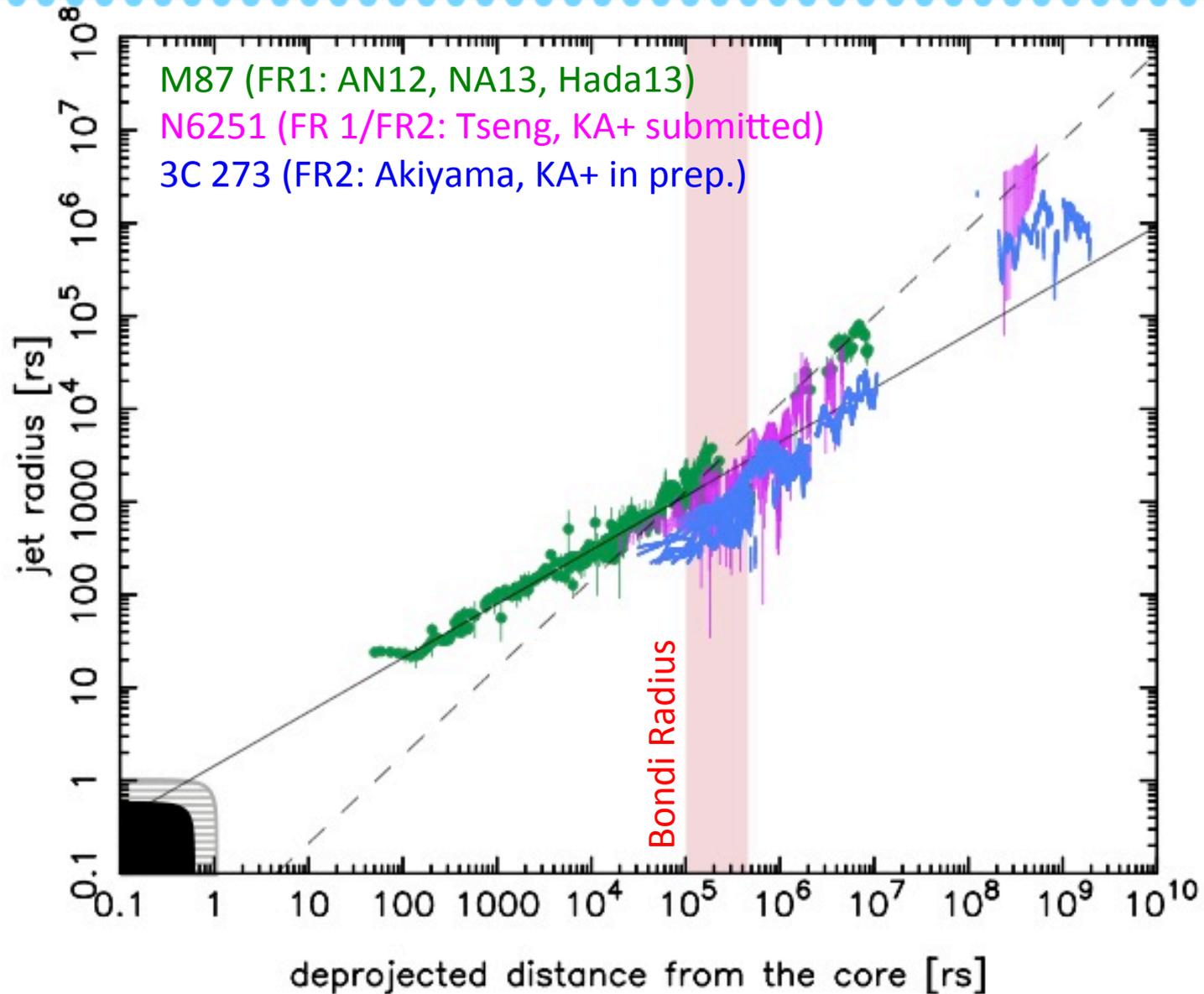
RM: $\dot{M}_{\text{BH}} \sim 4 \times 10^{-4} M_{\text{sun}} \text{ yr}^{-1}$ ↑
Kuo, Asada+2014, Asada in prep.

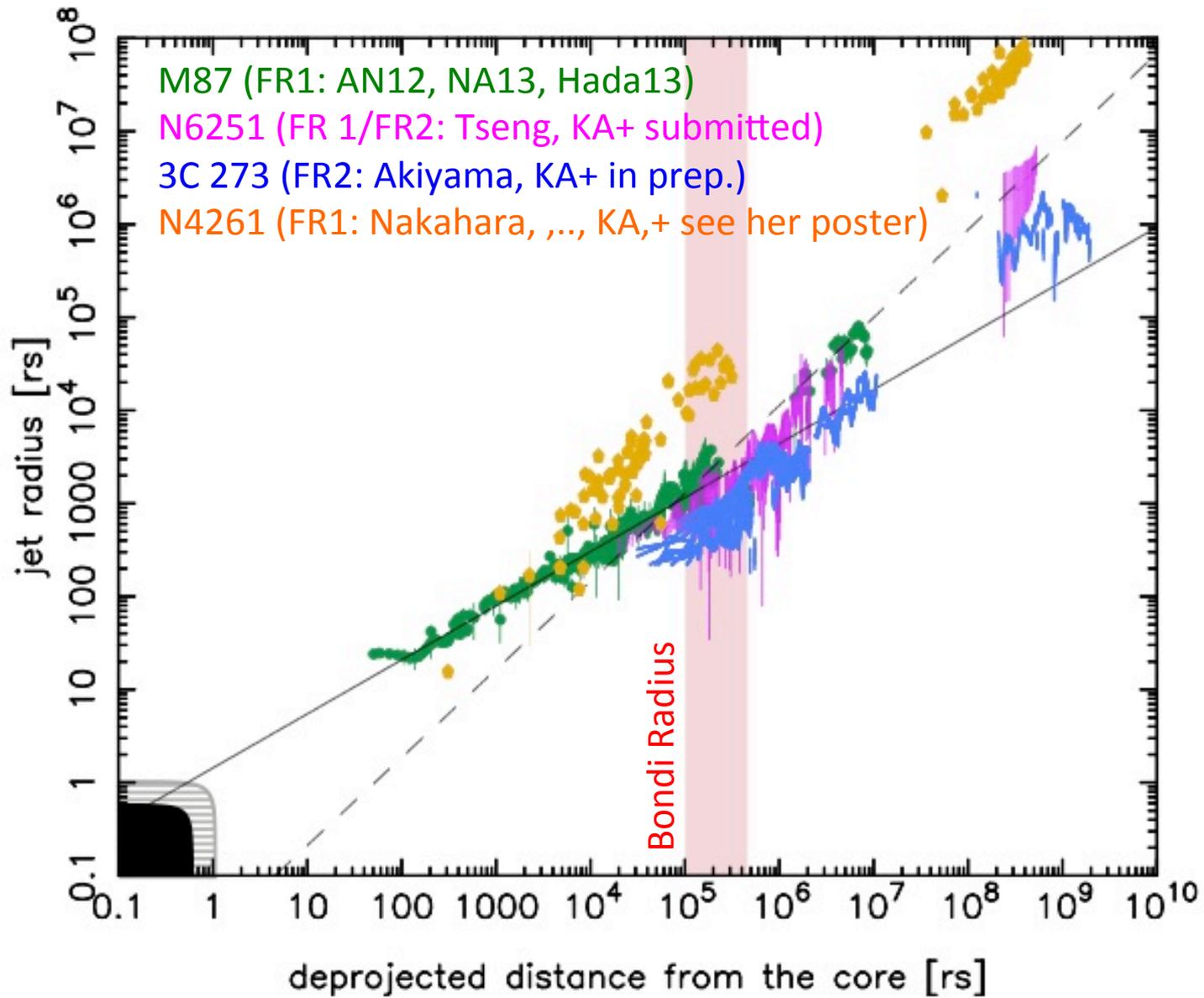
▶ $P_{\text{jet}} \sim 4 \times 10^{43} \text{ erg s}^{-1}$

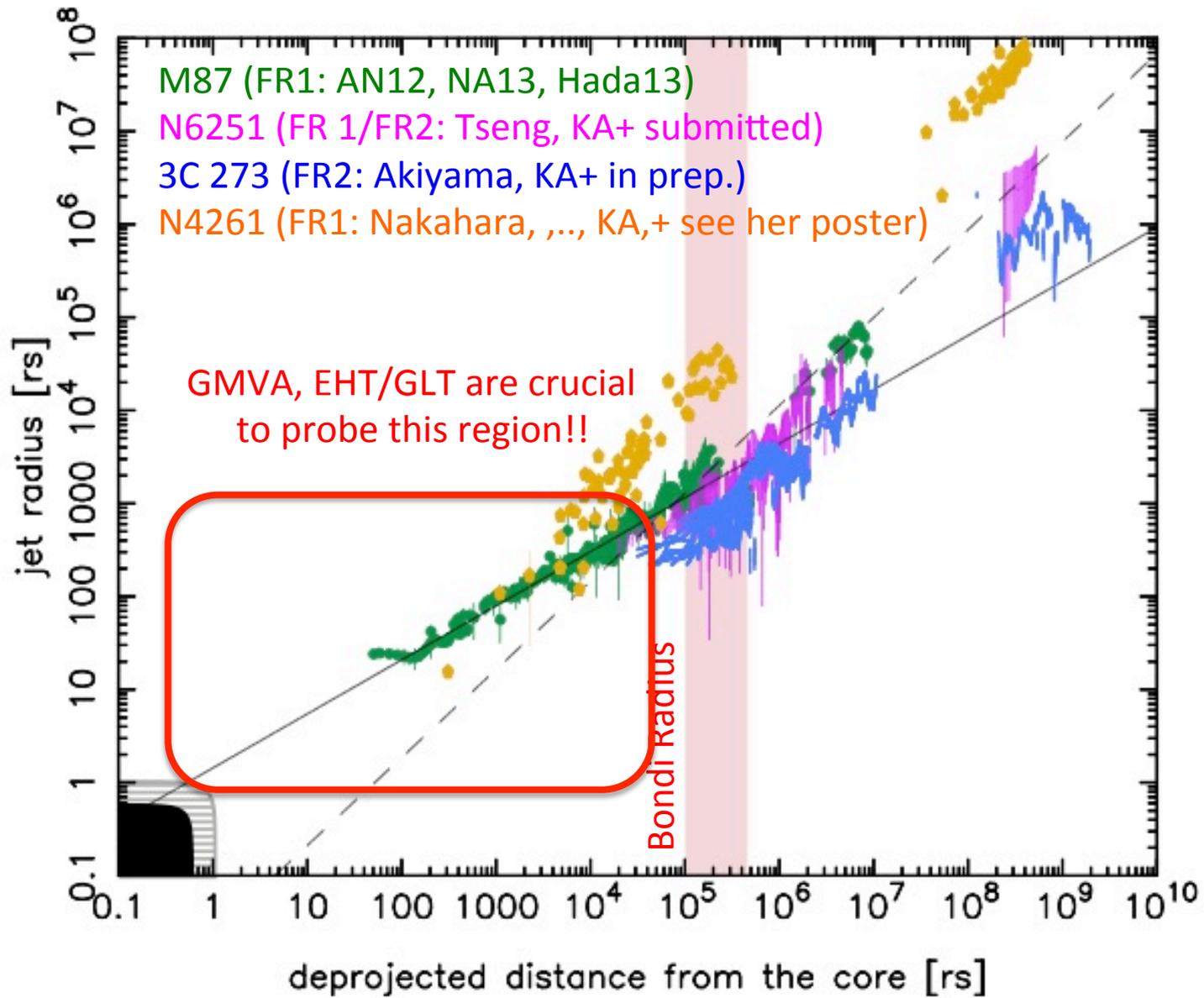
Transition from parabolic to conical?

A horizontal line of small, light blue dots spans the width of the slide, positioned below the text.

Comparison with the other sources







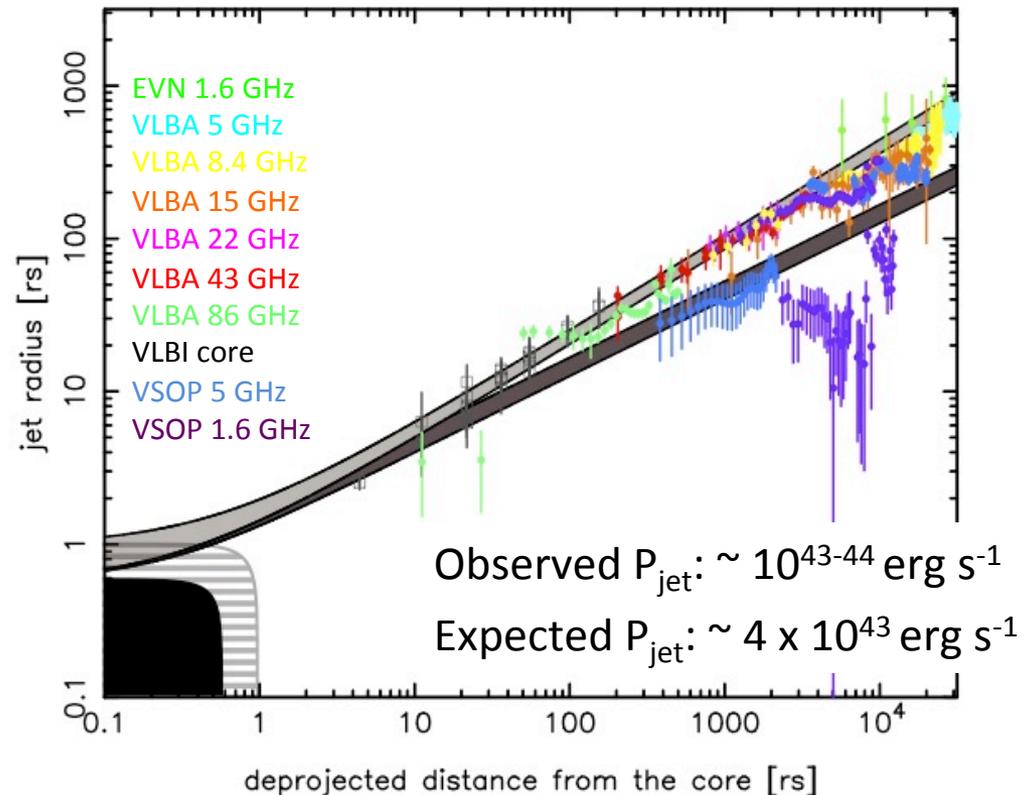
Summary



Conclusion

Our conclusion:

- We intensively investigate structure of M87 jet using VLBI.
- It can be explained with GRMHD jet with MAD in terms of structure and power.



Streamline of M 87 jet

Asada & Nakamura 2012, Doeleman+2012,
Nakamura & Asada 2013, Hada+2013

