Study for the physical properties of AGN jets by radio imaging analyses of jet structure from the Schwarzschild-radius to galactic scales

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Nakahara et al. (2020), AJ, 159, 14
Nakahara et al. (2019), ApJ, 878, 61
Nakahara et al. (2018), ApJ, 854, 148

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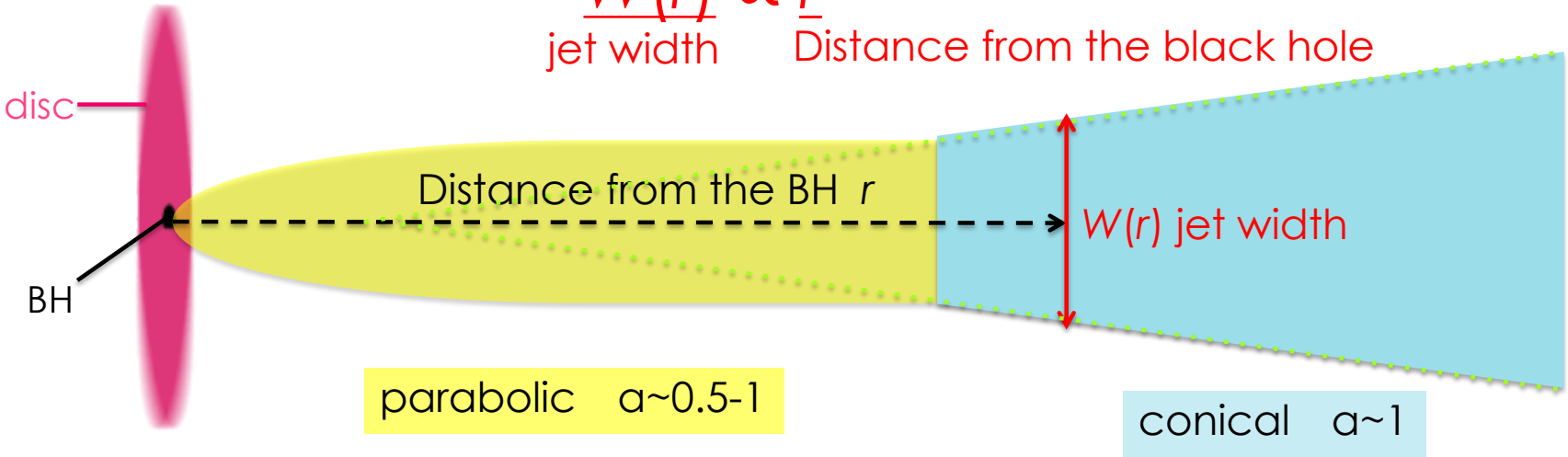
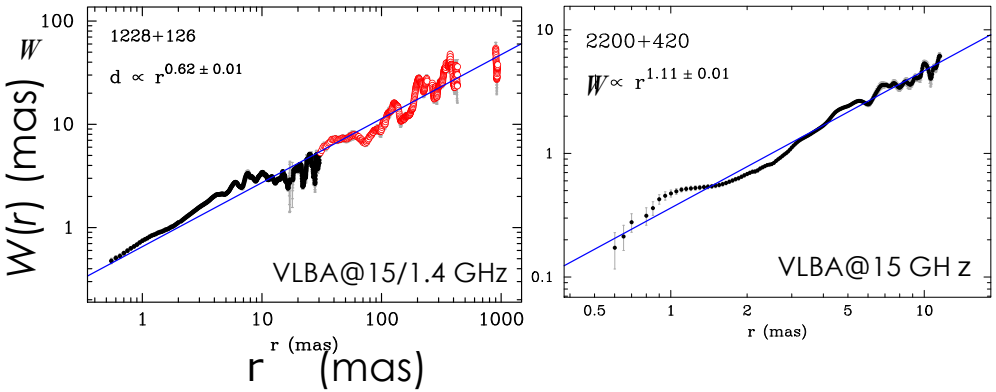
Introduction

The measurement of AGN jet structure profile

$$\underbrace{W(r)}_{\text{jet width}} \propto \underbrace{r}_{\text{Distance from the black hole}}{}^{a}$$



ref:pushkarev2017, Kovalev 2018



The jet structures were measured by radio observation in narrow range of ***r*** in most cases.

Theoretical model

The external pressure of the surrounding medium

$$P_{ext} \propto r^{-b}$$

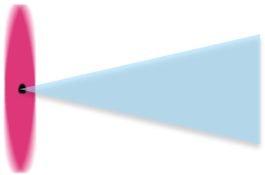
(r : Distance from the BH)

Jet width $W(r) \propto r^{\frac{b}{4}}$ $(a = \frac{b}{4})$

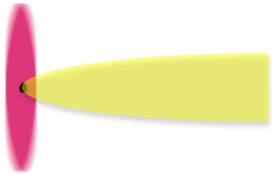
Komissarov+ 2009; Nakamura+ 2008 他

power-law index of the external pressure b	power-law index of the jet a	Structure
4	1	→ conical
2 ~ 4	0.5 ～ 1	→ parabolic
< 2	< 0.5	→ over-collimation

conical

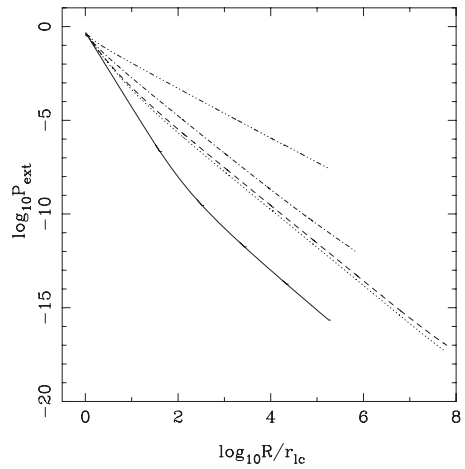


parabolic



cylindrical (over-collimation)

Example for the external pressure profile

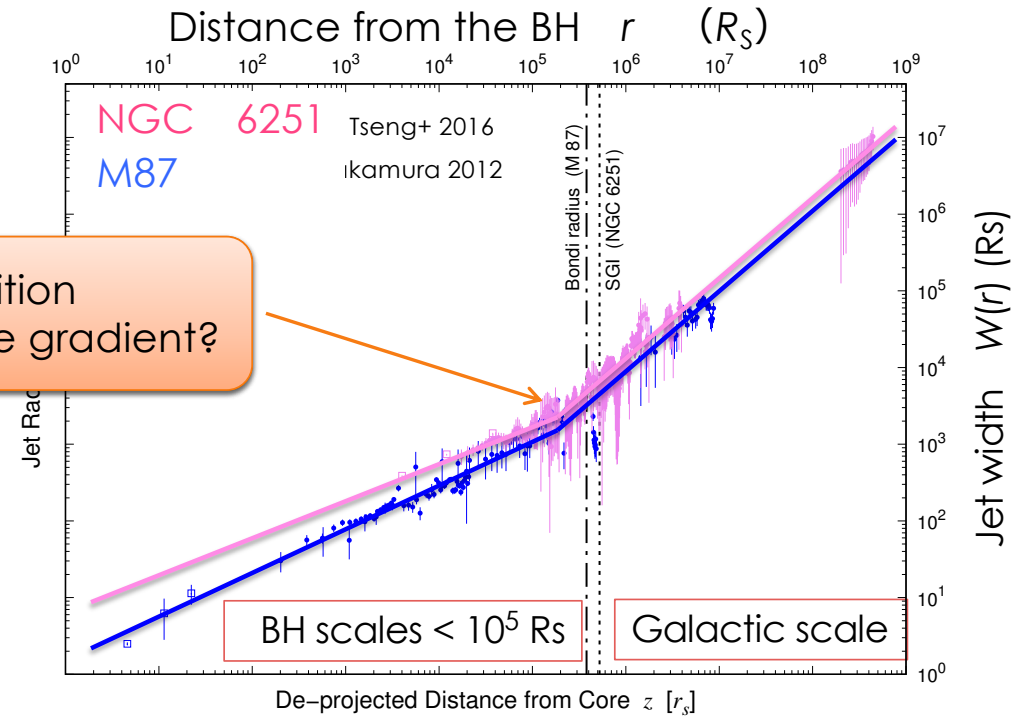


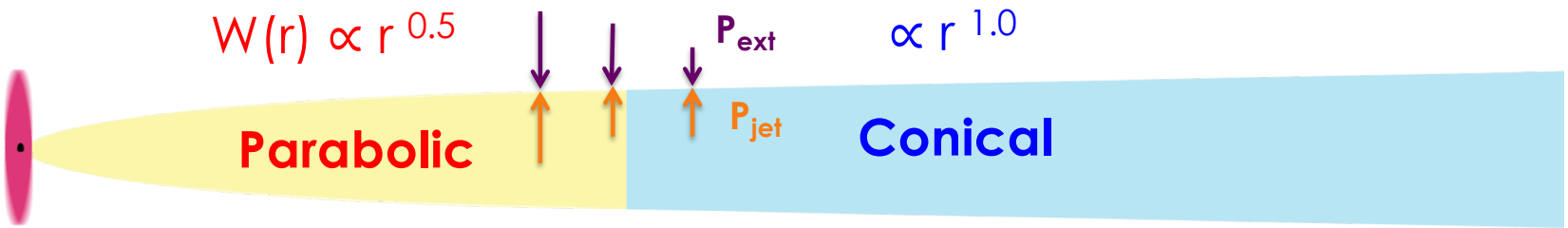
Komissarov et al. 2009

Introduction

The profile of jet width covering the range from the Schwarzschild radius scale to the galactic scale

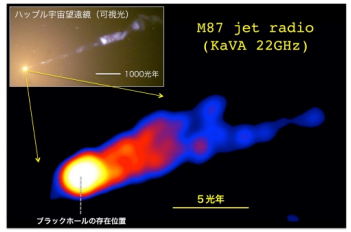
The structural transition
→ Transition of the pressure gradient?



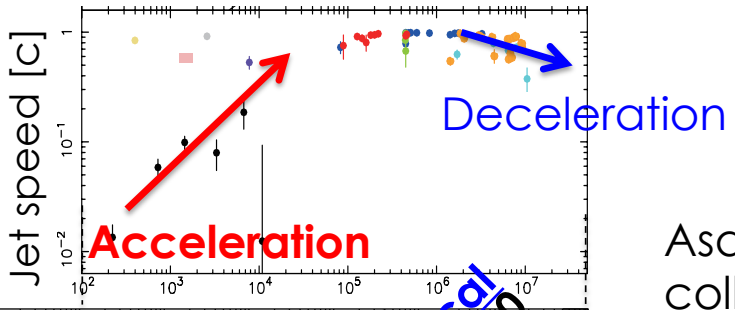


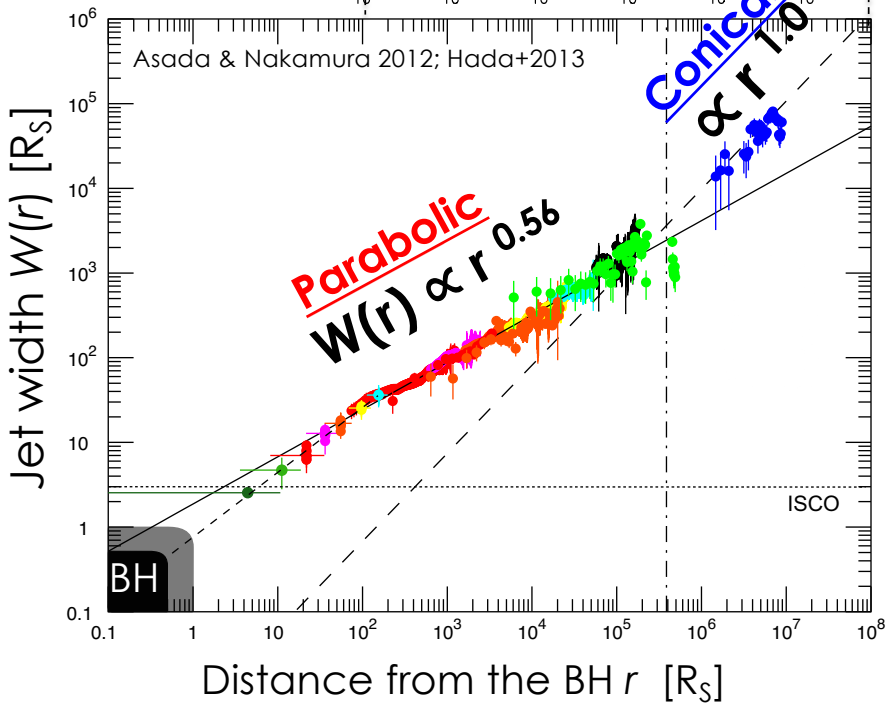
Introduction

Correspondence between the jet collimation and acceleration regions in M87

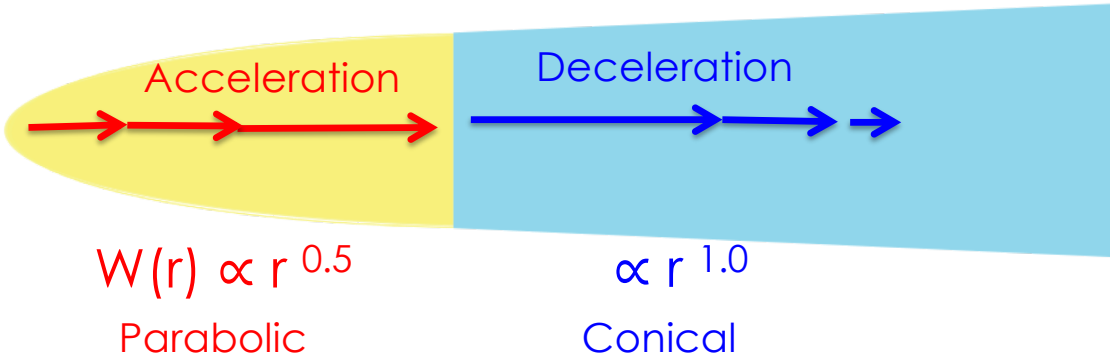


Asada & Nakamura 2014





Asada & Nakamura 2014 discovered that the jet collimation region is corresponding to the acceleration region in M87.



Aim of this work

We measured the jet width profiles covering the range from the blackhole gravitational sphere ($< 10^5 R_S$) to the galactic scale

- Previous 2 samples + this work 3 samples → total 5 samples

- Increase the number of samples
- Clarify the characteristics of jets (e.g. properties and differences)

APPROACH

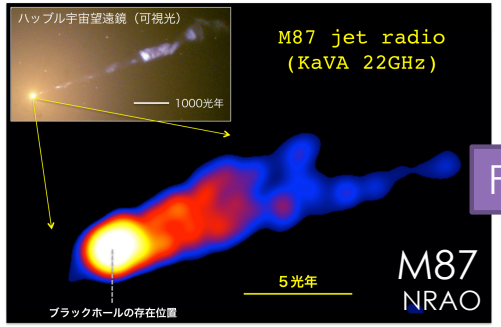
Targets

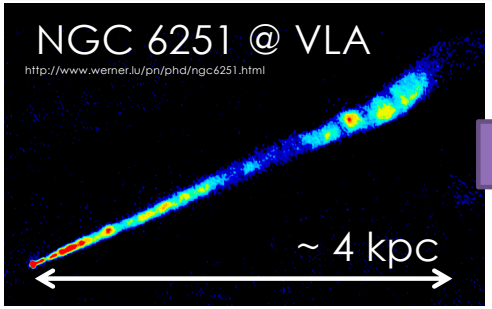
Does the structure change depending on the type of jet ?

FR-I : edge-darkened・weak jet

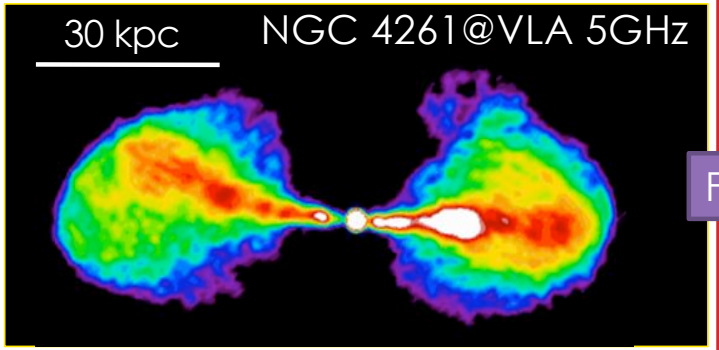
FR-II : edge-brightened・powerful jet

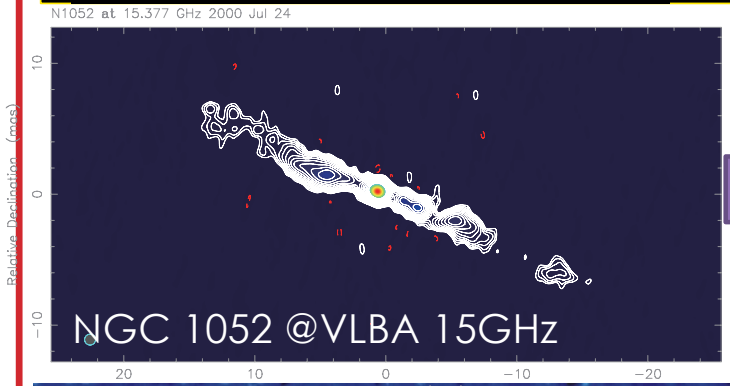
Previous works

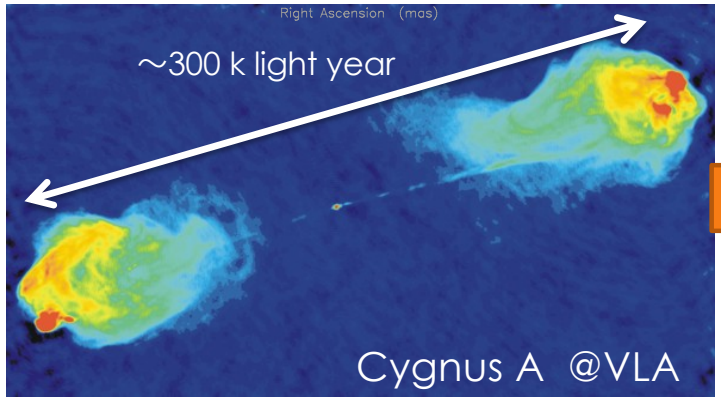




3 targets in this work

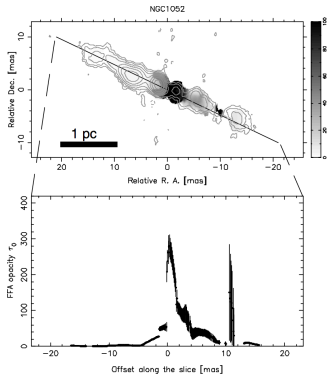






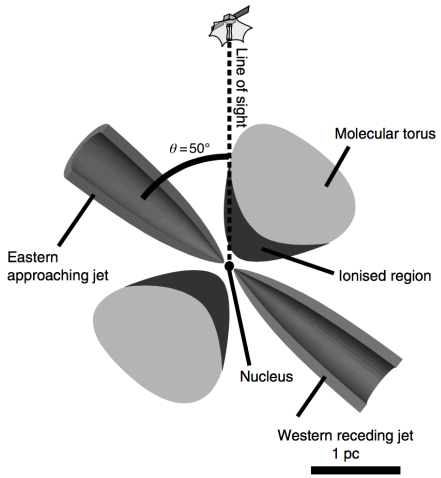
APPROACH

Targets



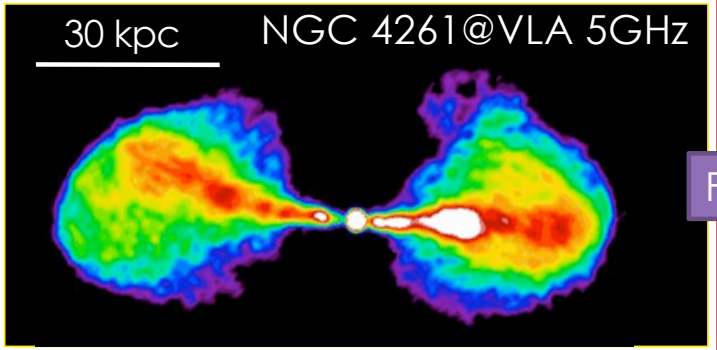
Plasma torus exists in NGC 1052

Kameno et al. 2001;
Kameno et al. 2003

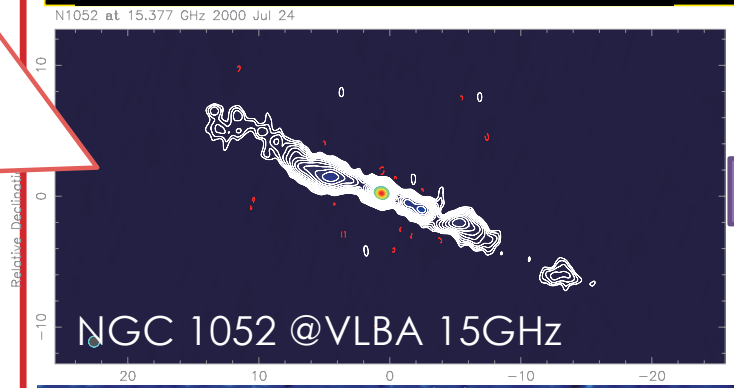


Other 2 samples appears to host thin disc

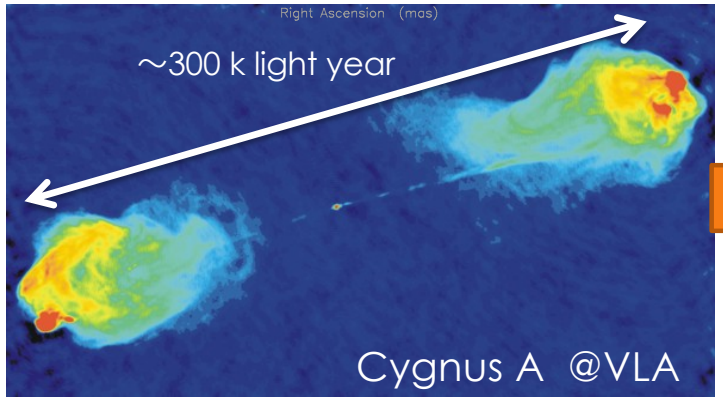
3 targets in this work



FR-I



FR-I



FR-II

APPROACH

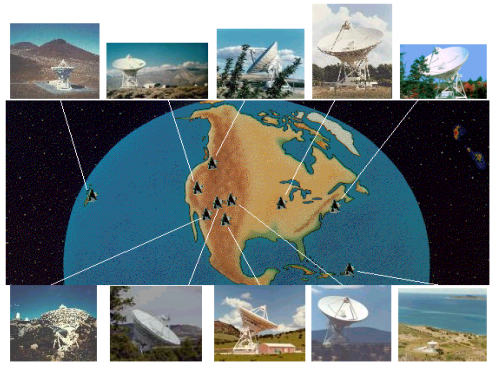
Targets

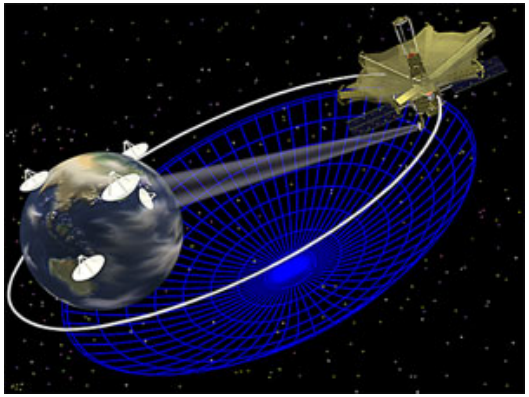
Selection points
- Massive black hole
- nearby galaxy
- The jet is covering the scale of structural transition (~10^5 R_S)
- Bi-polar jet can be seen continuously

Source	Distance (Mpc)	BH mass ($M_\odot$)	Analyzed region (R_S)	FR type	Bi-polar jet	Inclination (deg)
M 87 Asada+ 2012; Hada+ 2013	16.7	$(3\text{-}6)\times10^9$	10^0 -10^7 Structural transition@10^5	Type I	×	15°
NGC 4261	31.6	$4.9\pm1.0\times10^8$	**10^2 -10^9** **This work**	Type I	○	63°
Cygnus A Boccardi+ 2016; Bach 2005	249	7.5×10^9	**$10^{2.5}$ -10^9** **This work**	**Type II**	○	74.5°
NGC 1052	20	1.5×10^8	**10^2 -10^9** **This work**	Type I	○	57~86°
NGC 6251 Tseng+ 2016	103	$6\pm2\times10^8$	10^3 –10^9 Structural transition@10^5	Type I	×	19°

APPROACH

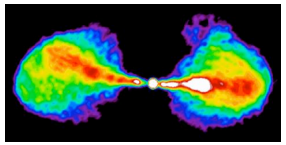
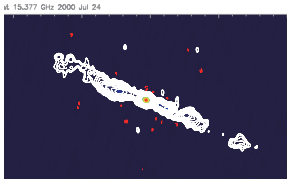
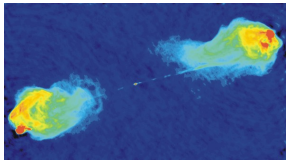
Telescopes and frequencies





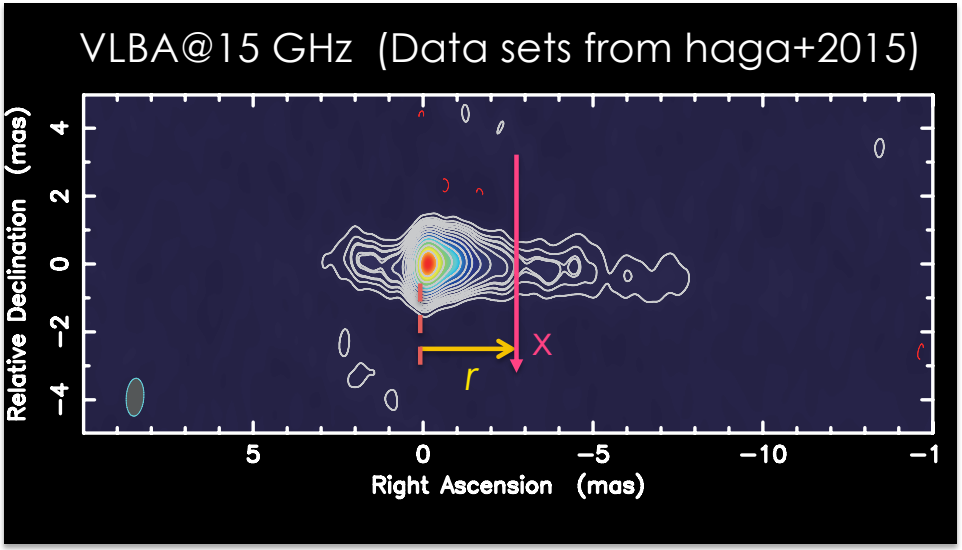
	Very Long Baseline Array (VLBA)	**VLBI Space Observatory Programme (VSOP)**	**Very Large Array (VLA)**
Base line length	8611km	30,000 km	36 km
Resolutions	0.17 mas~10mas	0.4~1.2 mas	0.1~8 arcsec
Frequencies	1.4/2.3/4.9/8.4/15/22/43 GHz	1.6/4.8 GHz	1.6/8.3/22 GHz

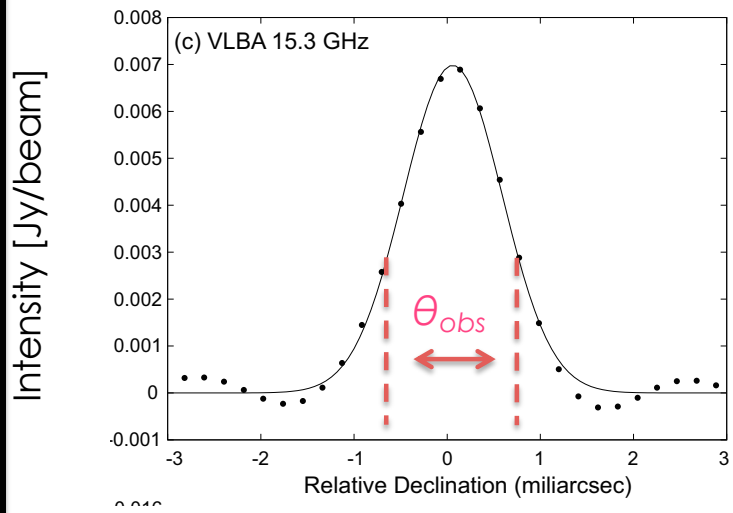
DATA

	Telescopes	Frequency ν [GHz]	date	Original data
NGC 4261 	VLBA	1.4/2.3/5.0/8.4	5/July/2003	Haga et al. 2015
		15/22/43	28/June/2003	
	VLA	1.4	Apr/1994	
		5.0	22/Apr/1984	Open data by C.C. Cheung
NGC 1052 	VSOP	1.6	7/Aug/2001	Kameno et al. 2003
		4.8	31/Jul/2001	
	VLBA	2.3/8.4/15.4	17/Aug/2001	
		15.4/22.1/43.2	24/Jul/2000	Sawada-satoh et al. 2009
	VLA	8.3	20/Jun/1998	NRAO Archive AR0396
Cygnus A 	VLBA	43	Oct/2007-2009	Boccardi et al. 2016
		4.9	Oct/2002-2003	Bach PhD. thesis
	VLA	22	4/Mar/1994	NRAO Archive GK0012
		4.9	1984	Perley et al. 1984 (NED)

METHOD

Measuring method of jet width





Definition of "de-convolved jet width" W_{jet}

$$\text{Fitted Gaussian} = a\exp\left(\frac{-(x-b)^2 4\ln 2}{\theta_{obs}^2}\right)$$

$$\theta_{obs}^2 = W_{\text{jet}}^2 + \theta_{beam}^2$$

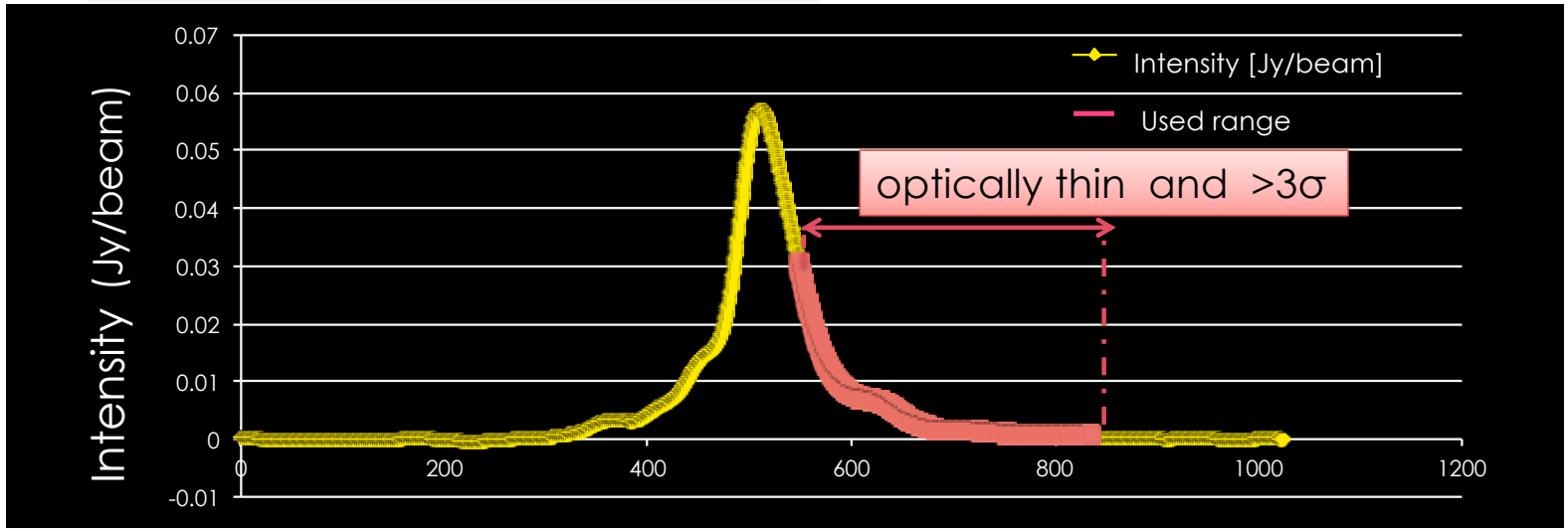
METHOD

Measuring method of "radiation" profile

only for NGC 4261

New approach for jet radial profile

sliced along the jet axis



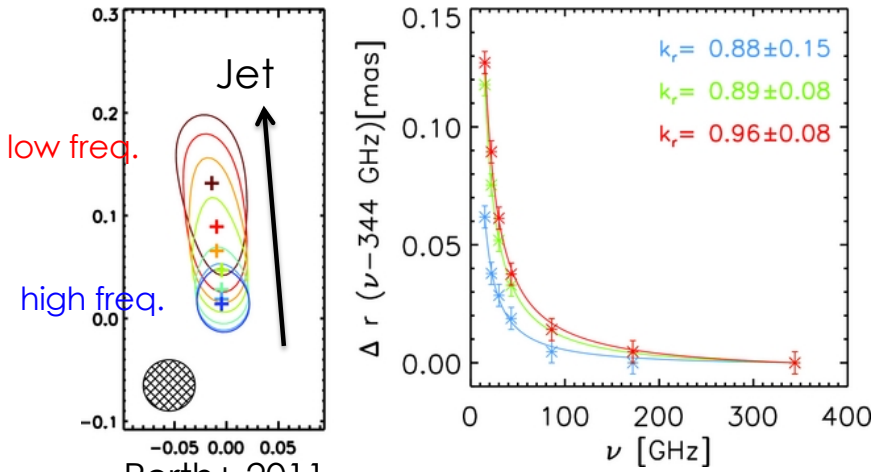
METHOD

Measuring method of the BH position

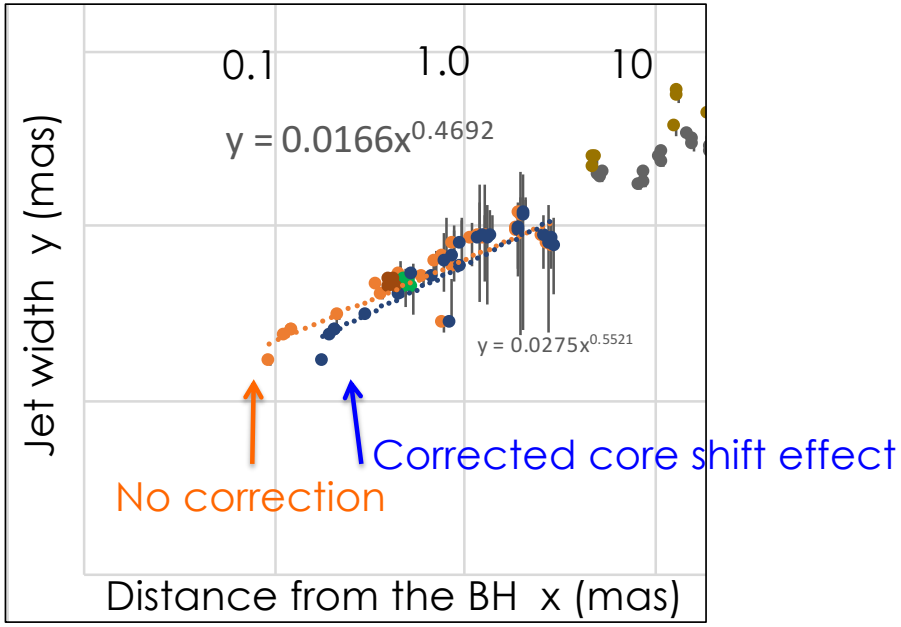
Correcting the core shift effect

- There is not always the black hole at the origin of the jet image
- Effect of optical thickness (frequency dependent)

It will change the results



Porth+ 2011



- NGC 4261: Already measured the BH position (Haga+2016)
- Cyg A: We decide the BH position by using the measured core position in Bach 2004
- NGC 1052: We decide the origin of jet by using the measured jet speed in Vermeulen+2003

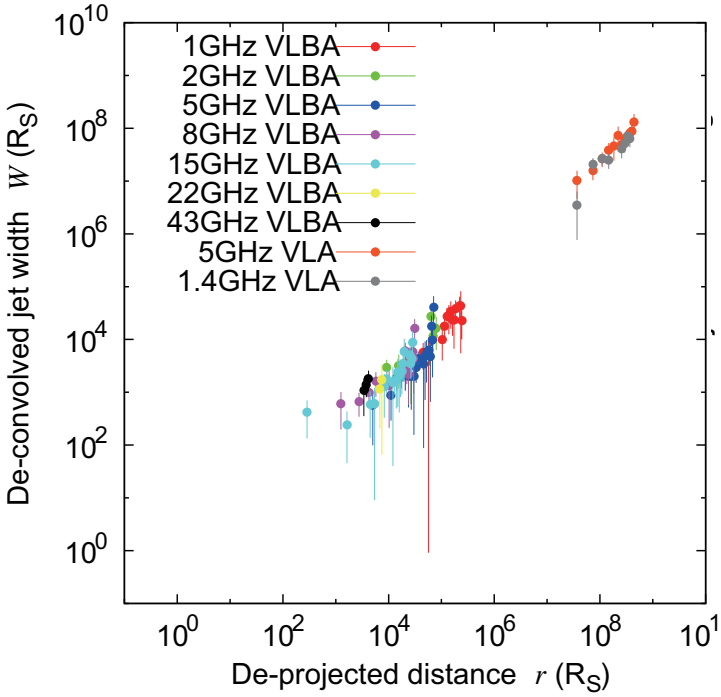
RESULTS

- Jet width profiles
  - NGC 4261
  - NGC 1052
  - Cygnus A
- Radiation profile
  - NGC 4261

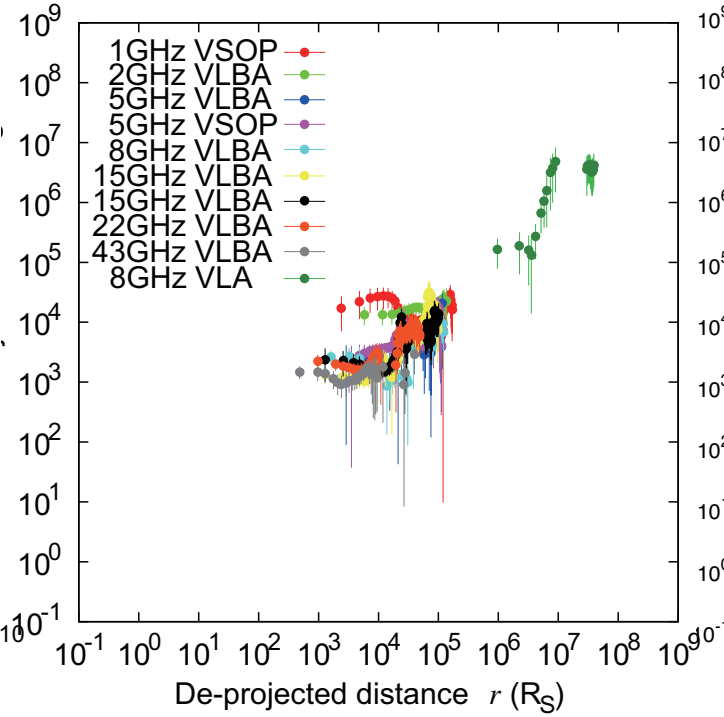
RESULTS

Approaching jet (AJ) width profiles

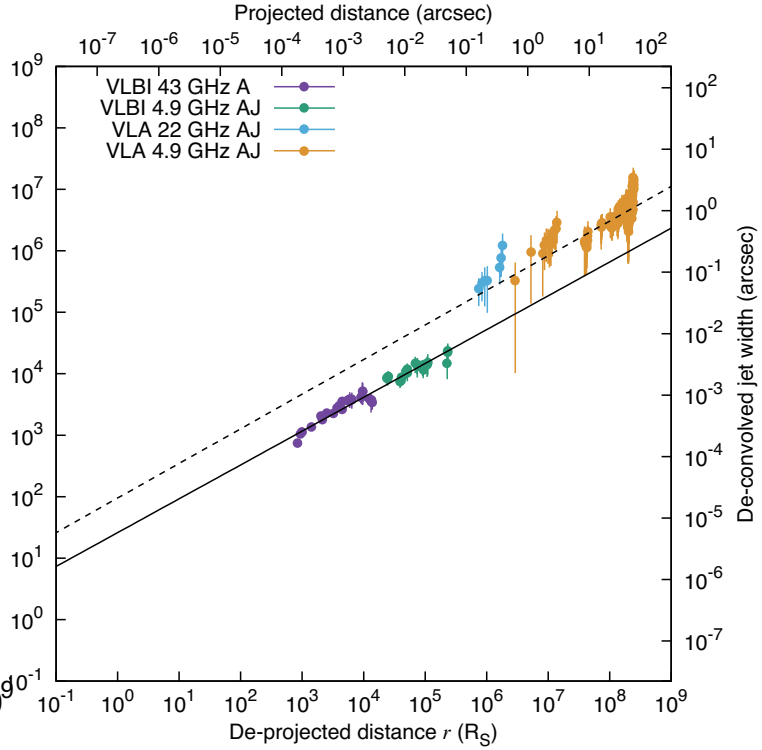
NGC 4261



NGC 1052



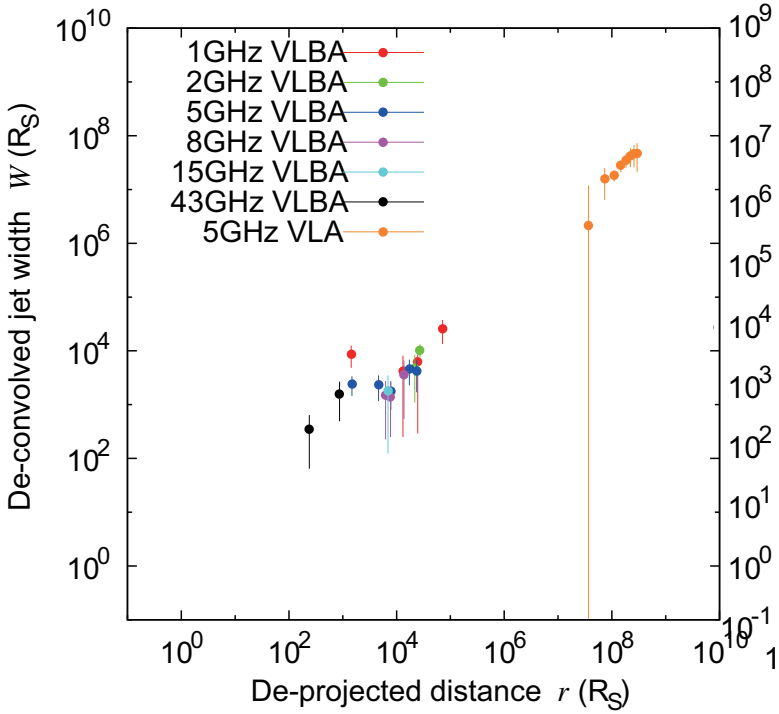
Cygnus A



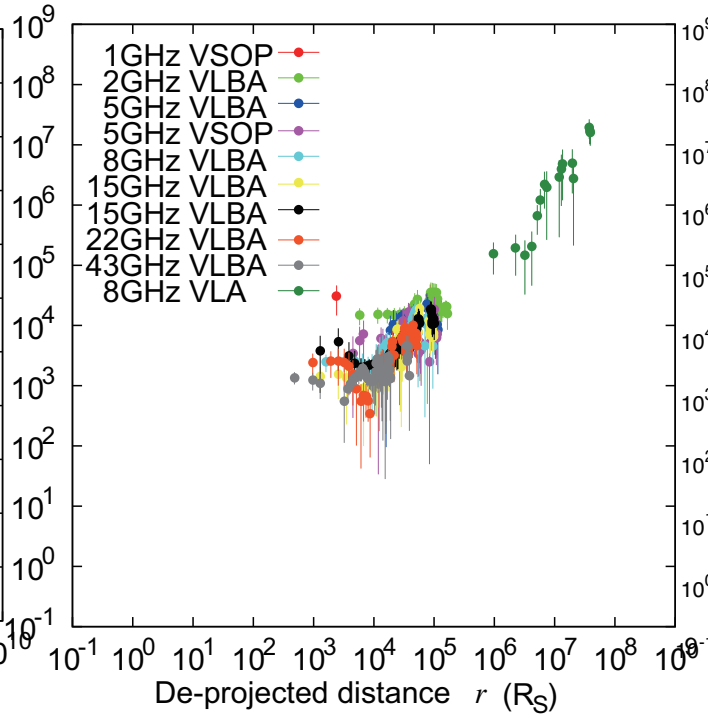
RESULTS

Counter jet (CJ) width profiles

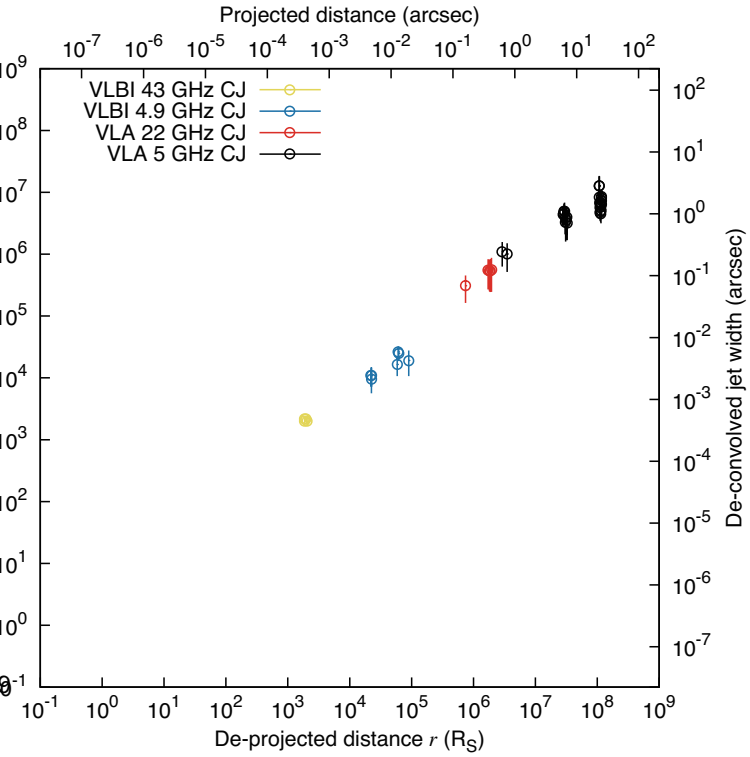
NGC 4261



NGC 1052

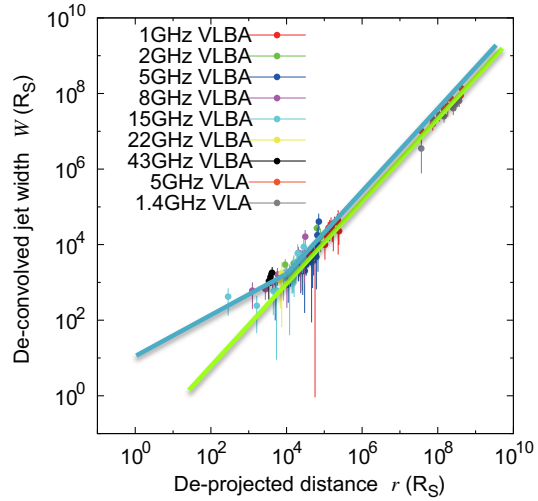


Cygnus A



RESULTS

Fitting function and results



- Power-law (PL) fit

$$W_{jet}(r) = W_0 r^a$$

- Broken power-law (BPL) fit

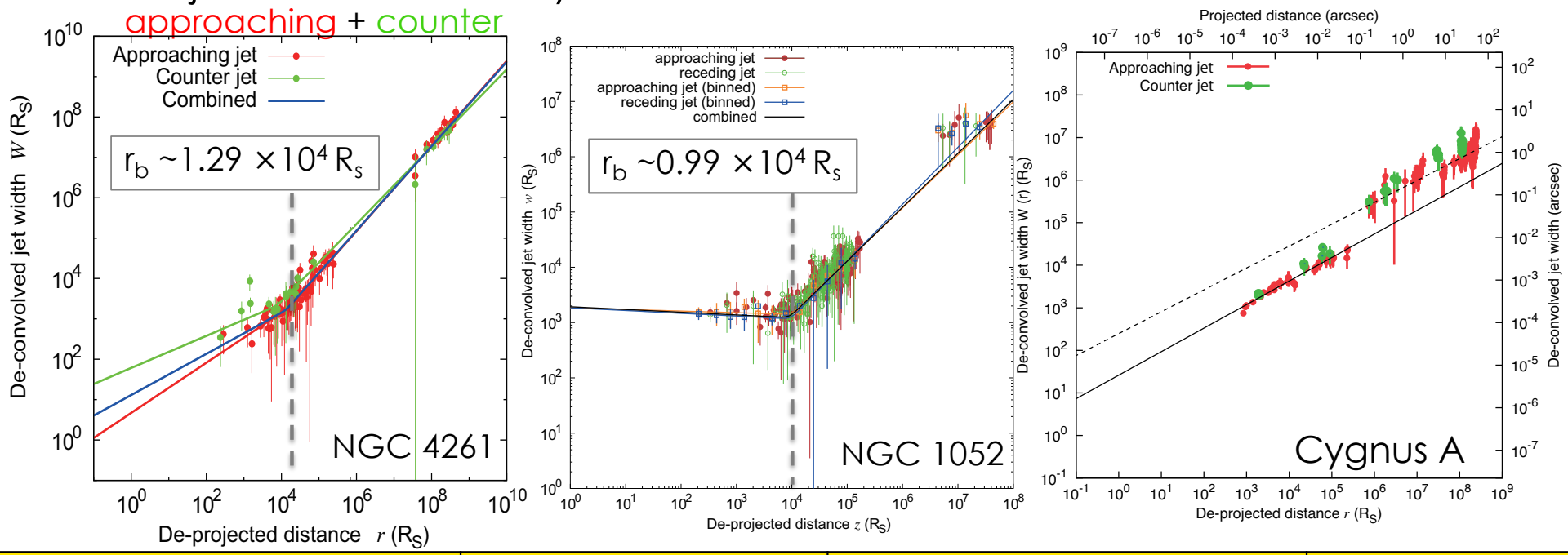
$$W_{\rm jet}(r) = W_0\ 2^{\frac{a_{\rm u}-a_{\rm d}}{s}} \left(\frac{r}{r_{\rm b}}\right)^{a_{\rm u}} \left(1+\left(\frac{r}{r_{\rm b}}\right)^{s}\right)^{\frac{a_{\rm d}-a_{\rm u}}{s}}$$

	NGC 4261			NGC 1052		Cygnus A	
	Width AJ	Width CJ	radiation AJ	Width AJ	width CJ	width AJ	width CJ
PL	△	△	×	×	×	2xPL ○	○
BPL	○	○	○	○	○	-	-

RESULTS

Fitting results ($r = 10^3 \sim 10^9\ R_S$)

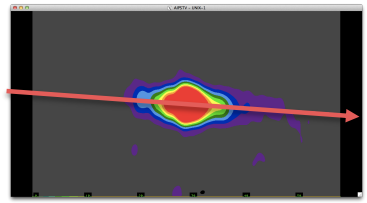
1. The approaching and counter jet structure is symmetric within the error
2. NGC 4261 and NGC 1052 have a structural transition
3. Cygnus A does not have a transition but have a big gap in one order
4. The jet width varies by source

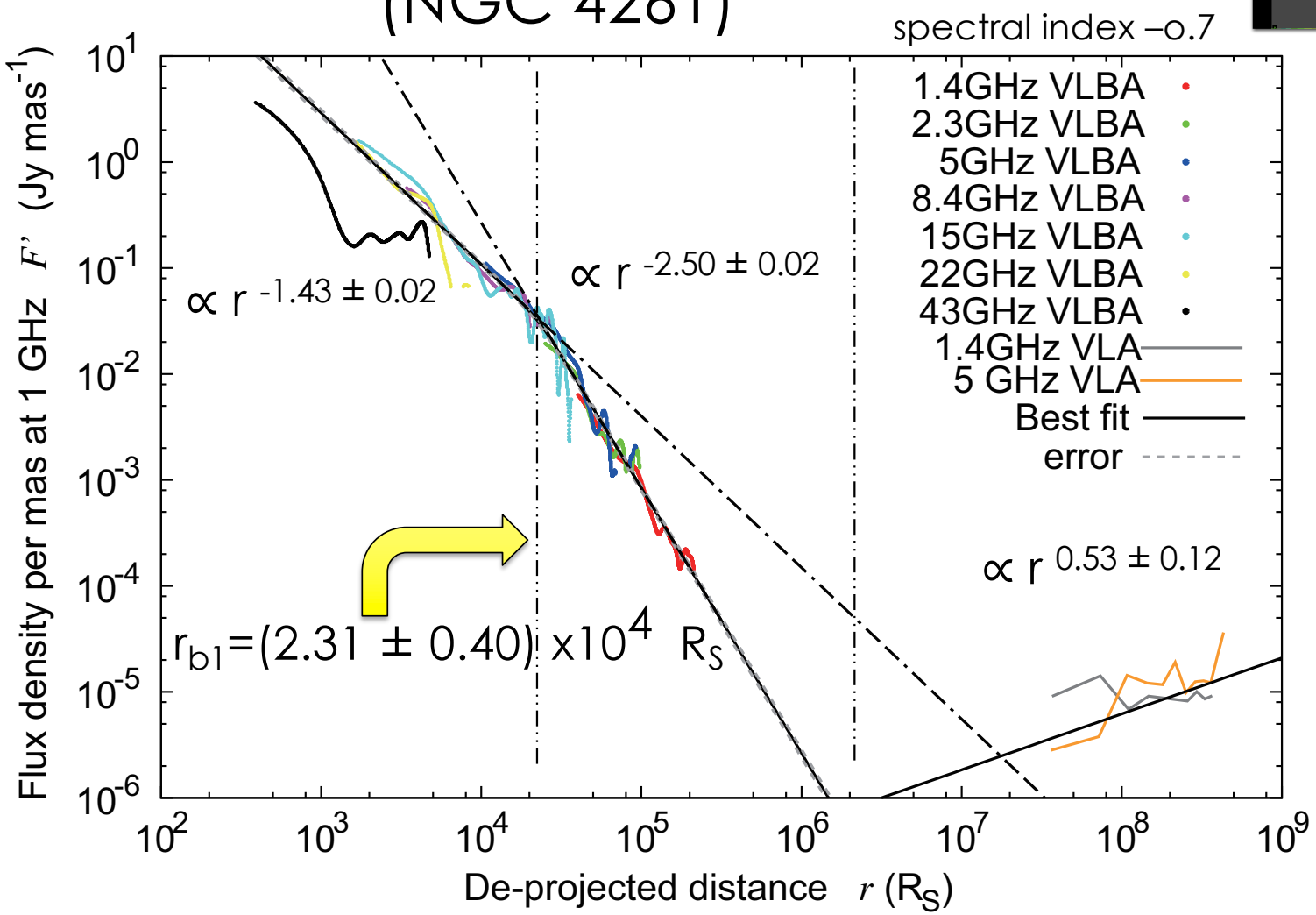


	NGC 4261	NGC 1052	Cygnus A
Power-law index in upstream	0.51±0.13 parabolic	0.03 ± 0.06 over-collimation	0.55 ± 0.02 parabolic
Power-law index in downstream	1.05±0.01 conical	0.92 ± 0.03 conical	0.51 ± 0.03 parabolic

RESULTS

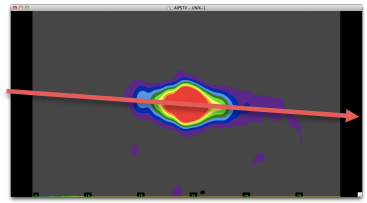
Radiation profile along the jet axis (NGC 4261)

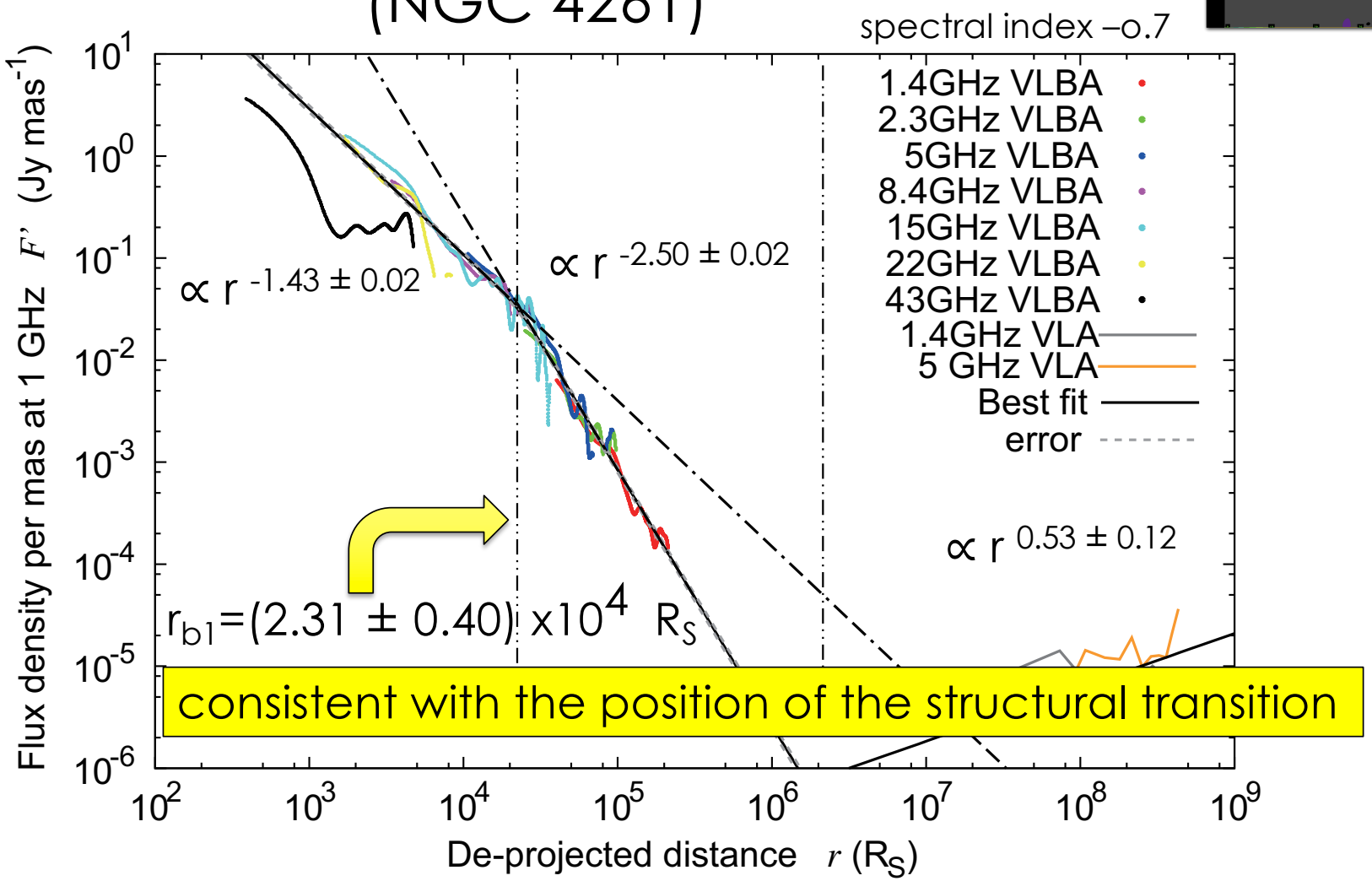




RESULTS

Radiation profile along the jet axis (NGC 4261)

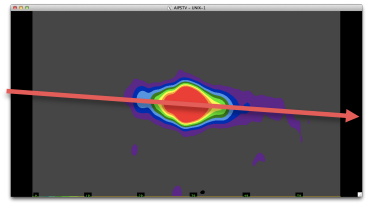


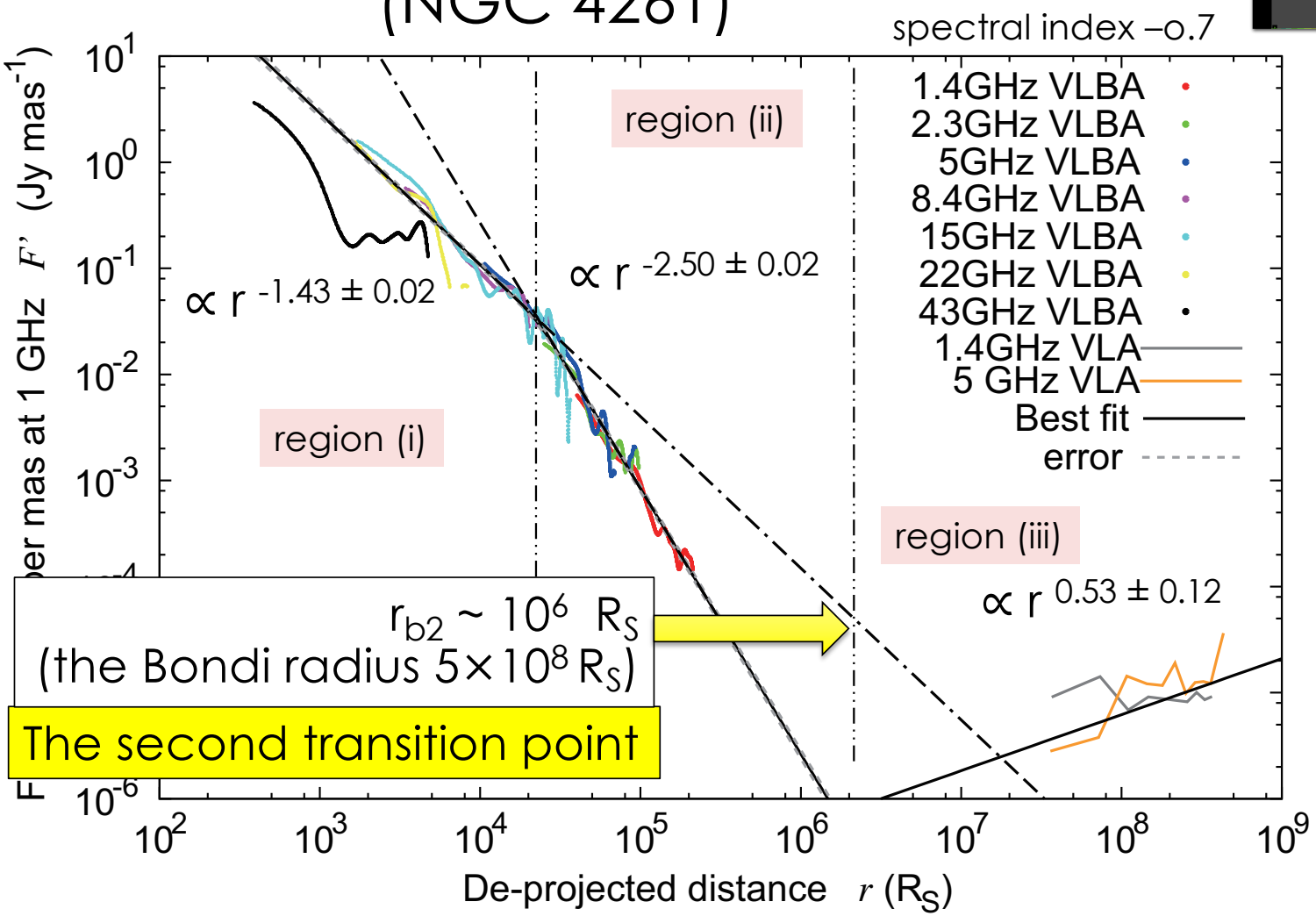


consistent with the position of the structural transition

RESULTS

Radiation profile along the jet axis (NGC 4261)





$r_{b2} \sim 10^6\ R_S$
(the Bondi radius $5\times10^8\ R_S$)

The second transition point

DISCUSSION

- **Physical properties**
  calculated by using the jet width profile
  and the radiation profile
  - NGC 4261

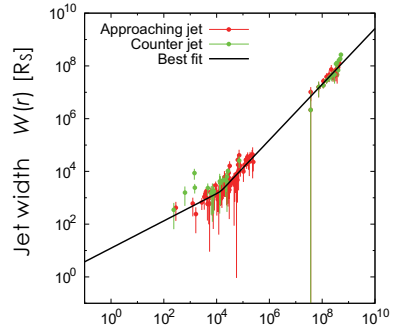
- **Discussion about characteristics of 5 samples**
  - Difference between FR-I and FR-II
  - Torus in NGC 1052
  - Jet width deference in 5 samples
  - A big gap in Cygnus A

DISCUSSION

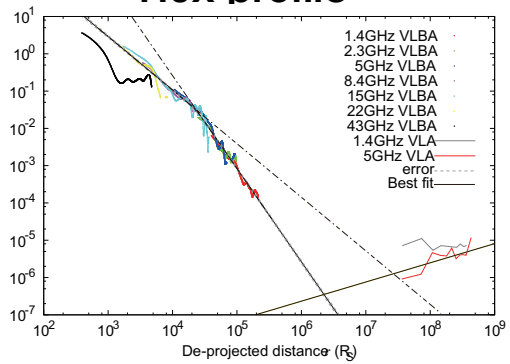
Calculation procedure of the physical properties using jet width and radiation profiles of NGC 4261

Measurements

Jet width profile



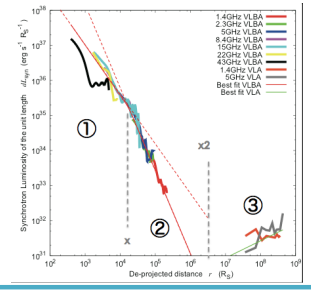
Flux profile



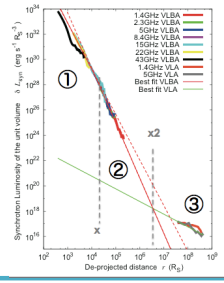
- Synchrotron Theory
- Equipartition Assumption

Calculation results

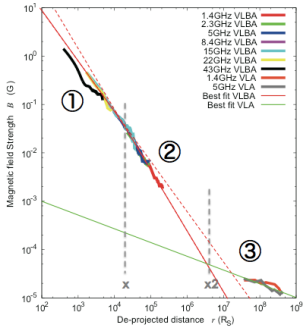
Synchrotron luminosity per jet length [erg/s/R_s]



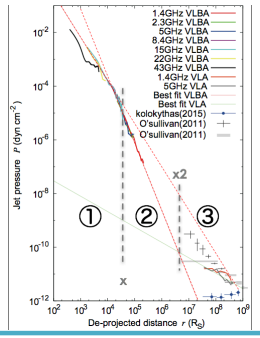
Synchrotron luminosity per unit volume [erg/s/R_s^3]



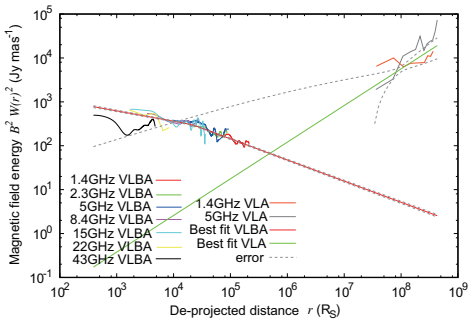
Magnetic field B(r) [G]



Jet pressure P(r) [dyn/cm^2]



Magnetic energy $B(r)^2W(r)^2$ [erg]



DISCUSSION

5 jet properties

A. Synchrotron luminosity per volume: L_{syn}/v [erg/s/R_s^3]

$L_{syn} = I(r) \times W(r) \times \theta_{beam}$

B. Synchrotron luminosity per unit jet length: L_{syn}/l [erg/s/R_s]

C. Jet pressure: P(r) [dyn cm^{-2}]

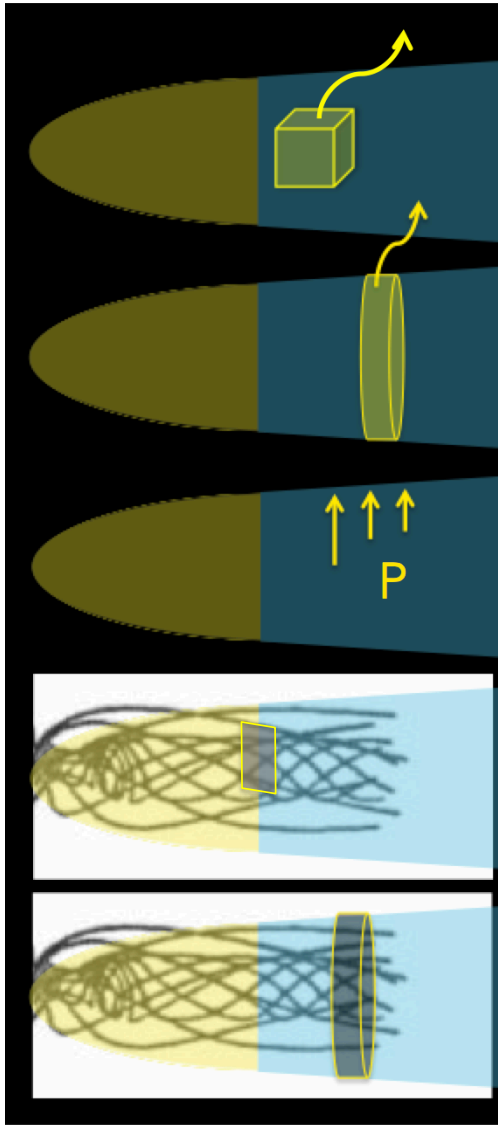
$$P_{\rm radio} = \frac{B_{\rm eq}^2}{2\mu_0\epsilon} + \frac{(1+k)E_{\rm e}}{3V\phi}$$

D. Magnetic field strength: B(r) [G]

$B_{eq} = (6\pi(1+k)\, c_{12}\, L_{syn}\, \Phi^{-1}\, V^{-1})^{2/7}$

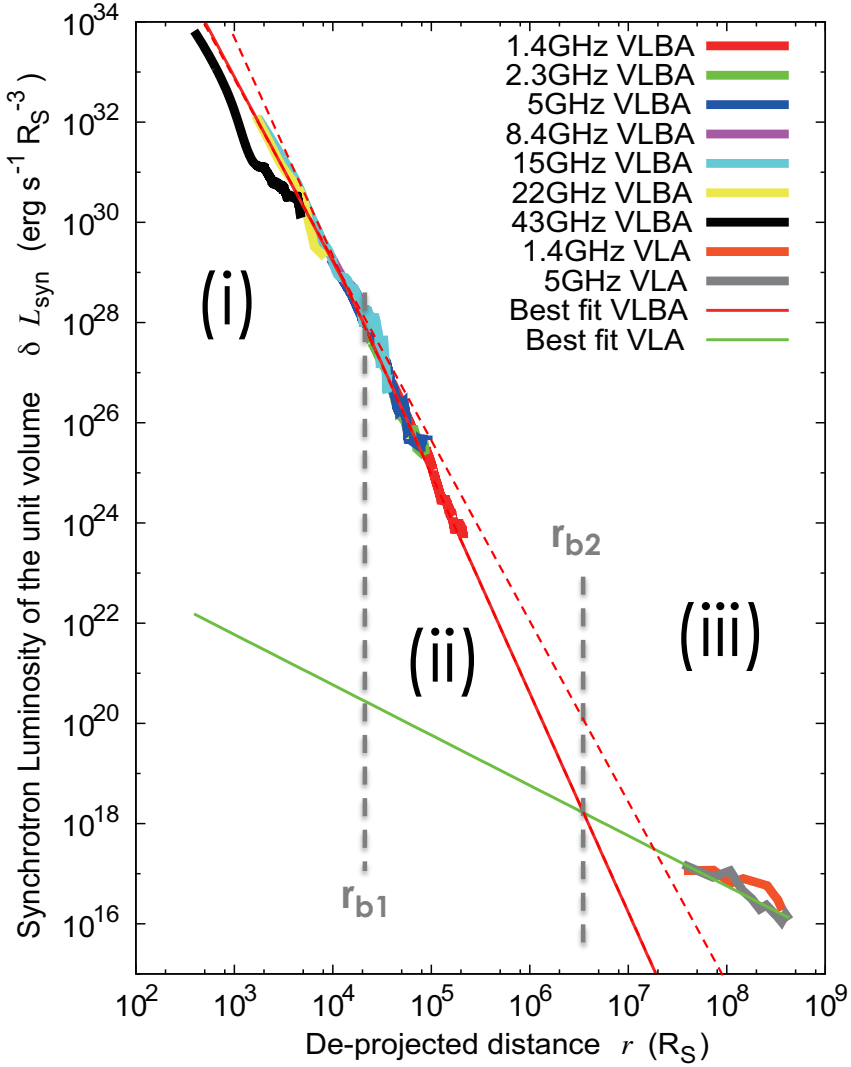
E . Magnetic energy: $B(r)^2 W(r)^2$ [erg]

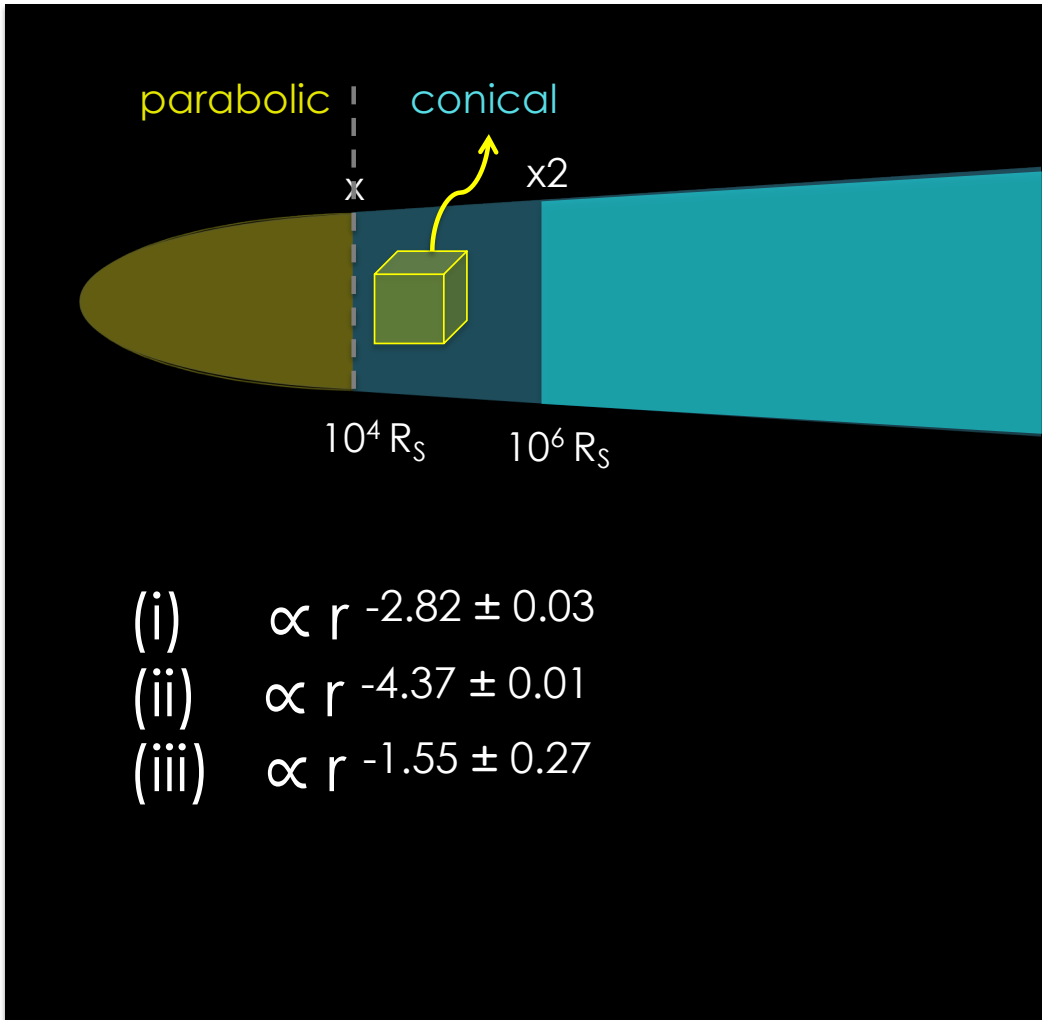
$U_B = \frac{1}{2}\, \mu_0^{-1}\, B_{eq}^2\, \pi W(r)^2$



DISCUSSION

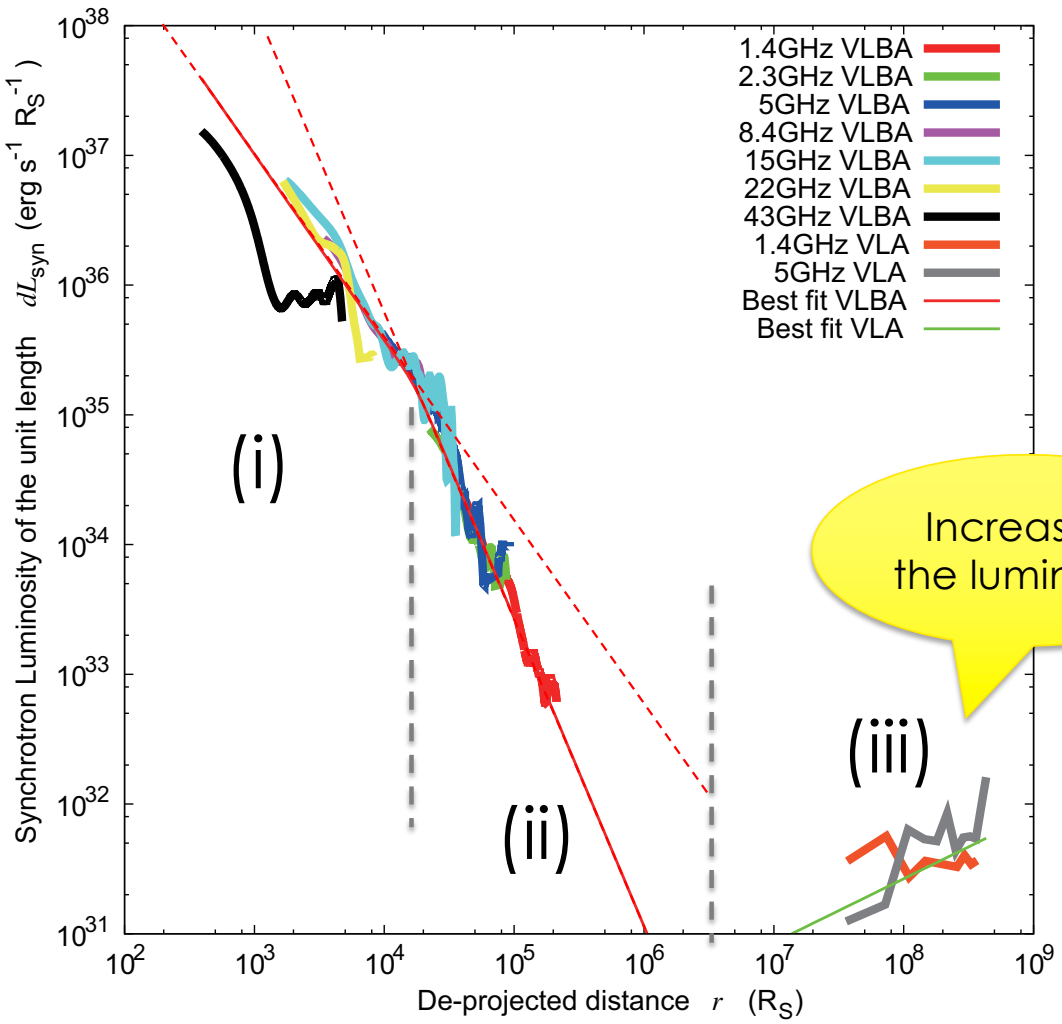
A. Synchrotron luminosity per unit volume L_{syn}/v [erg/s/R_s^3]



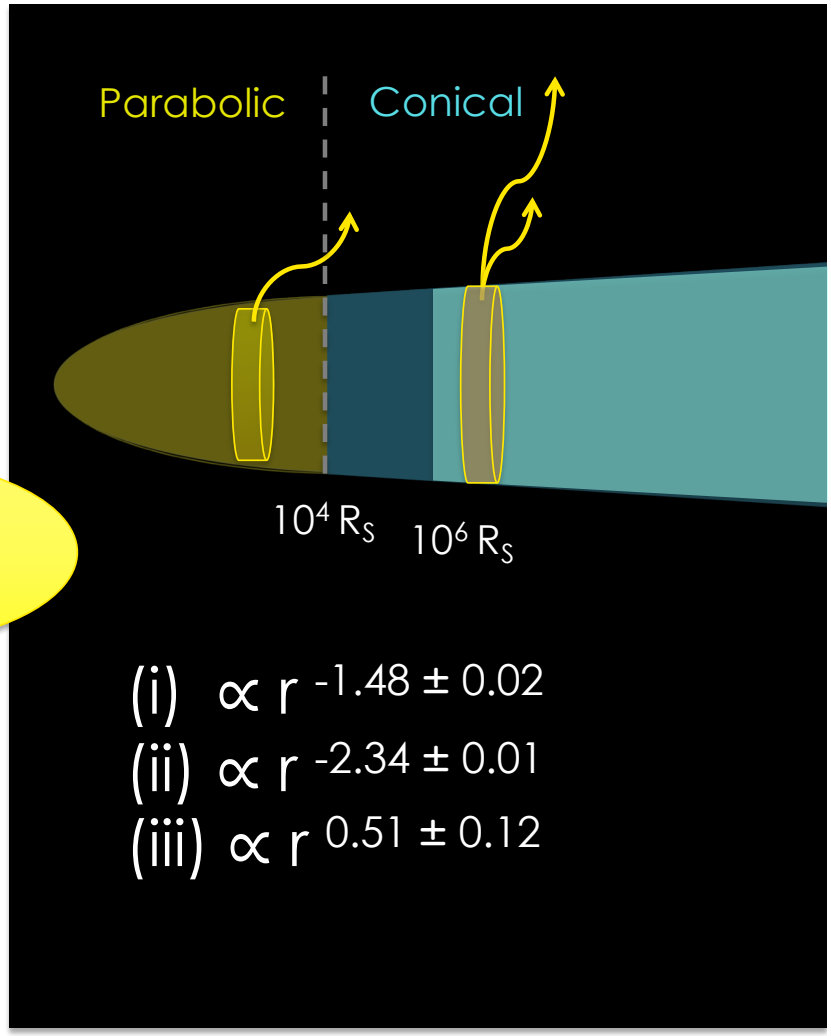


DISCUSSION

B. Synchrotron luminosity per unit jet length L_{syn}/l [erg/s/R_s]

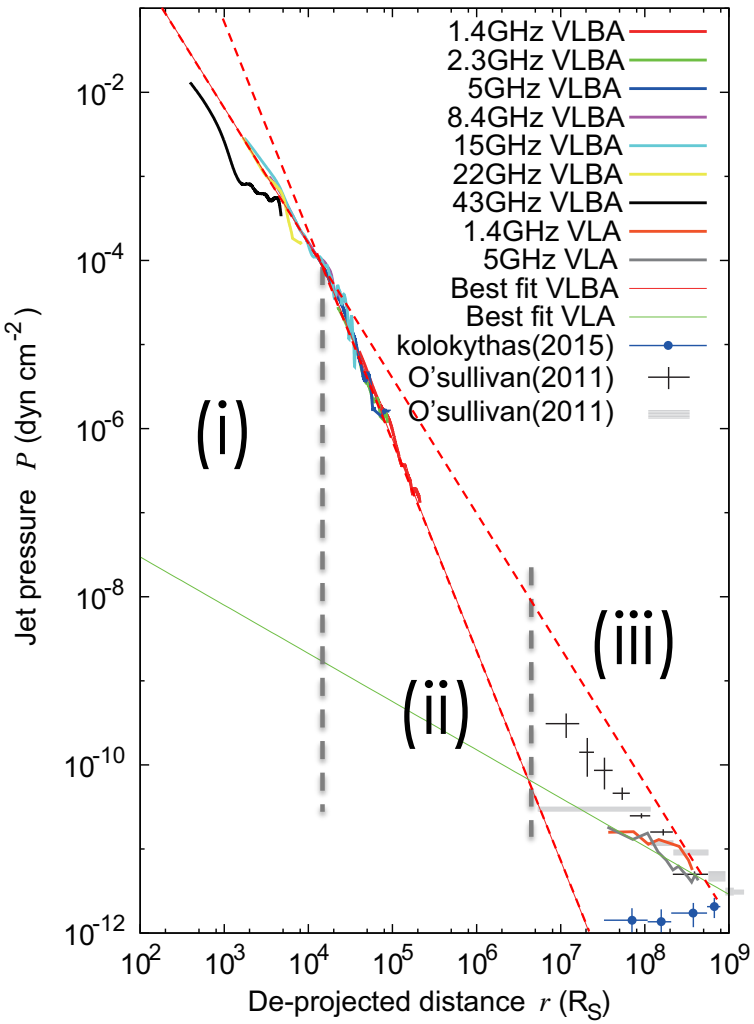


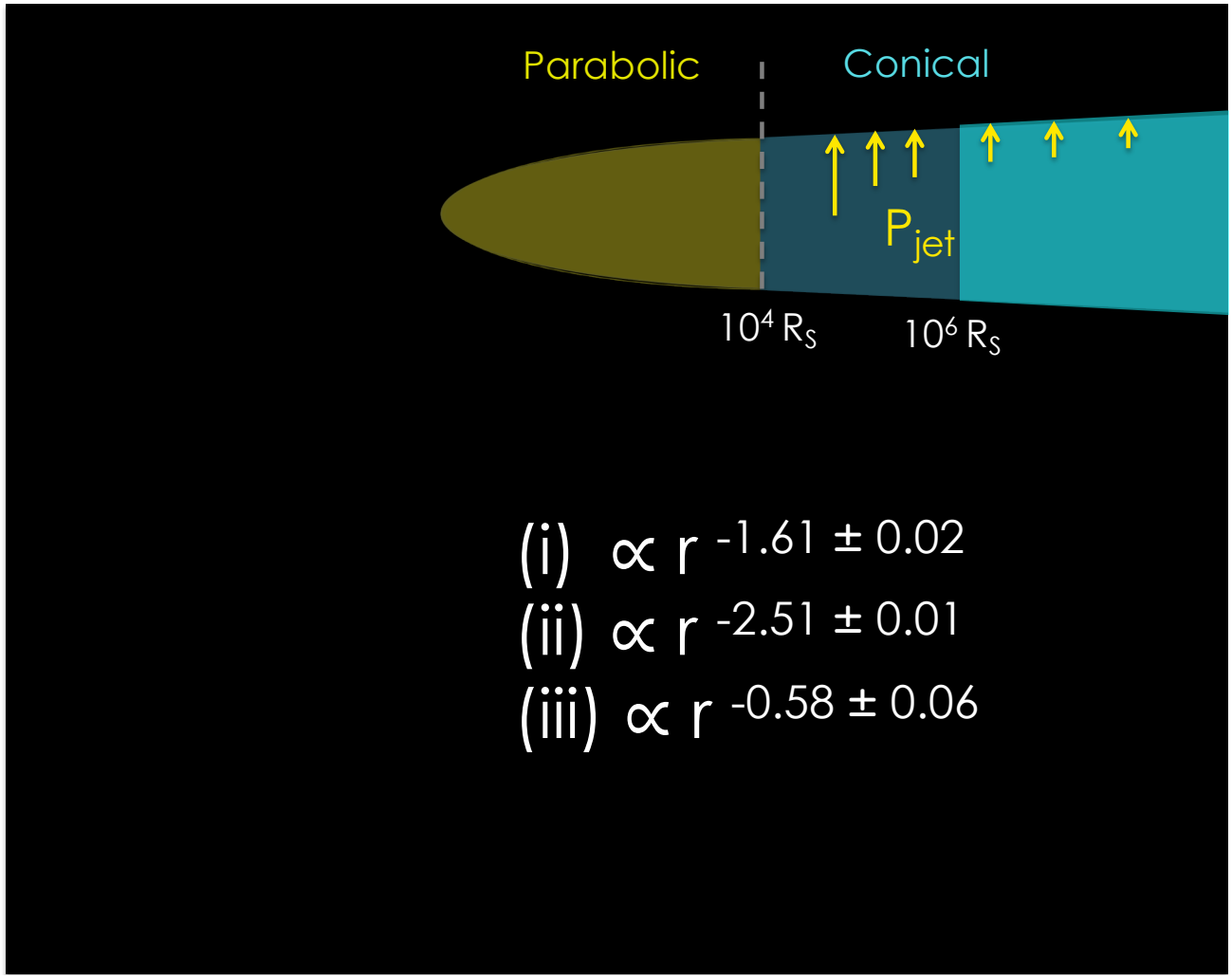
Increasing the luminosity



DISCUSSION

C. Jet pressure P(r) [dyn cm^{-2}]





(i) $\propto r^{-1.61 \pm 0.02}$

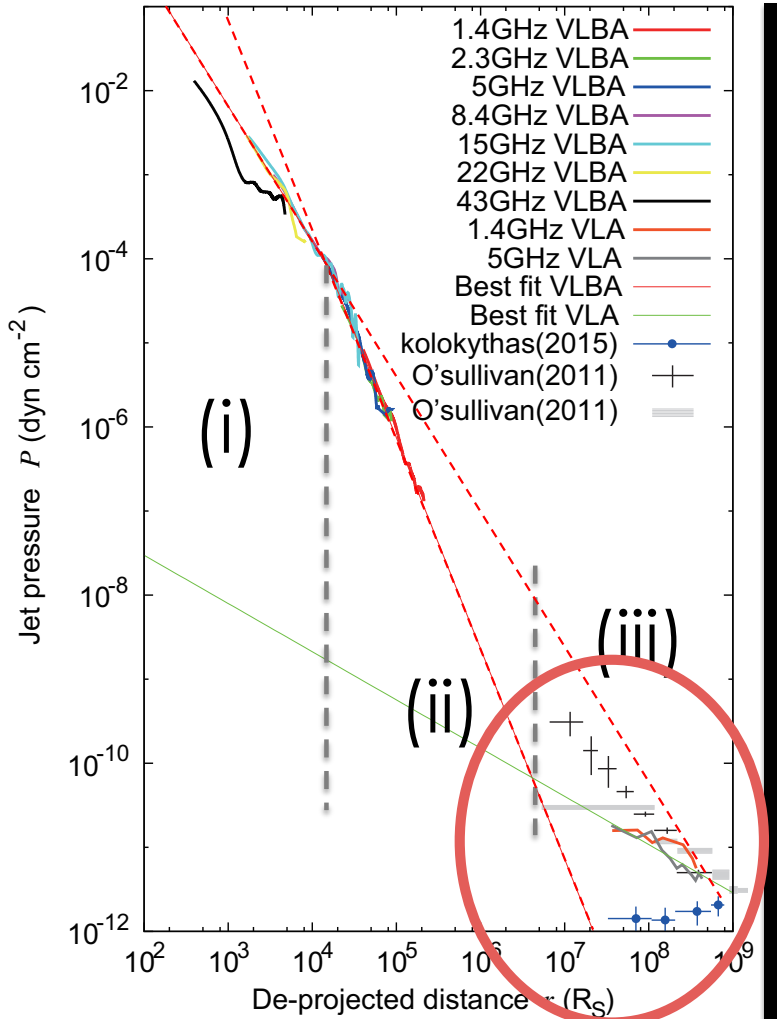
(ii) $\propto r^{-2.51 \pm 0.01}$

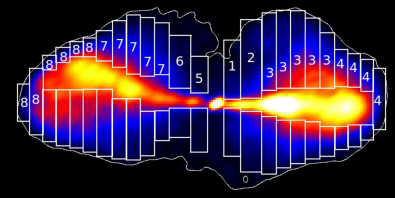
(iii) $\propto r^{-0.58 \pm 0.06}$

DISCUSSION

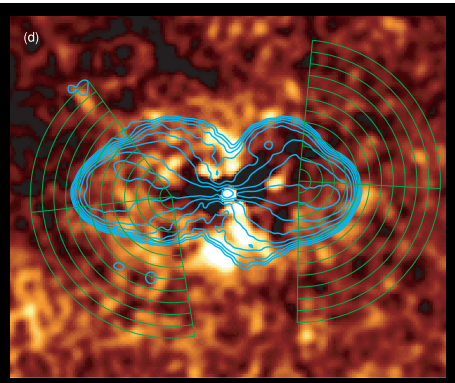
C. Jet pressure P(r) [dyn cm^{-2}]

compared to external pressure in kpc scale

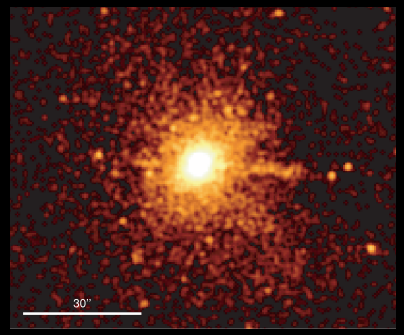




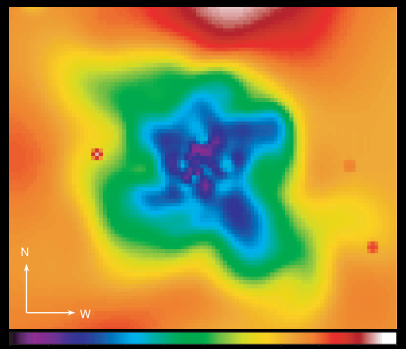
←VLA image
The lobe pressure measured by Kolokythas+ 2015



↑ XMM-Newton image



←Chandra image
O'sullivan+2011



gas temperature kev

Measured
the temperature of hot gas gathered by the lobe
and the electron density

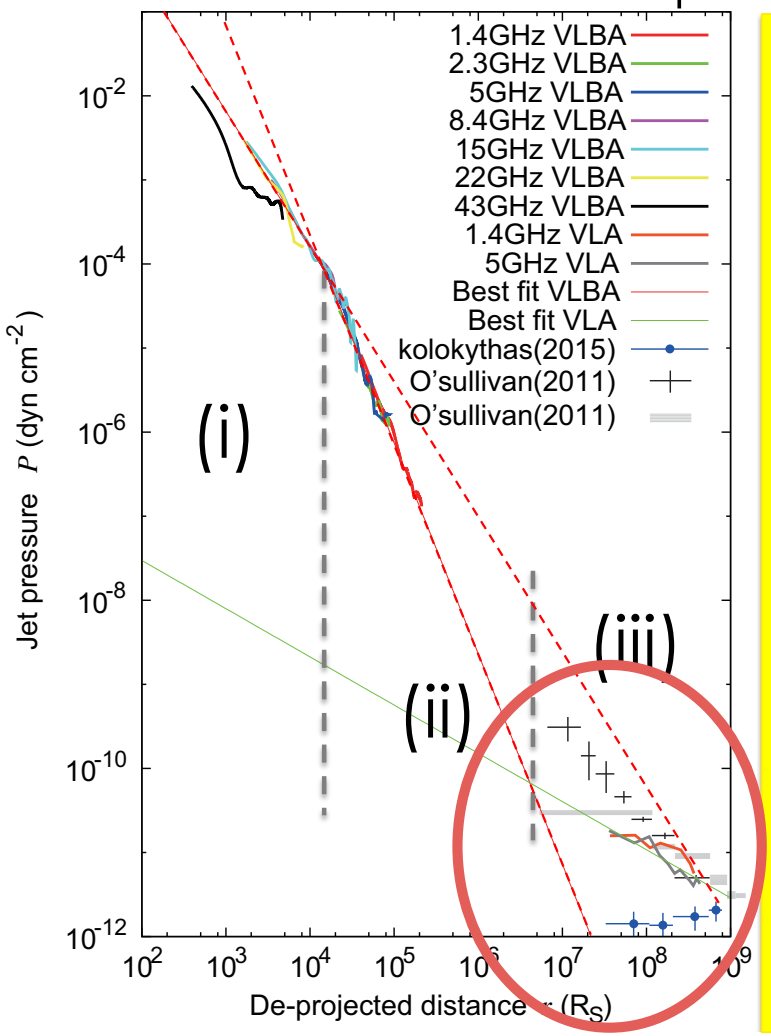
$P_{ext}=nkT$; $n=n_e$

P_{ext} : External pressure of the lobe

DISCUSSION

C. Jet pressure P(r) [dyn cm^{-2}]

compared to external pressure in kpc scale



The jet pressure
≒ The hot gas pressure in X-ray @ >10^7 R_S

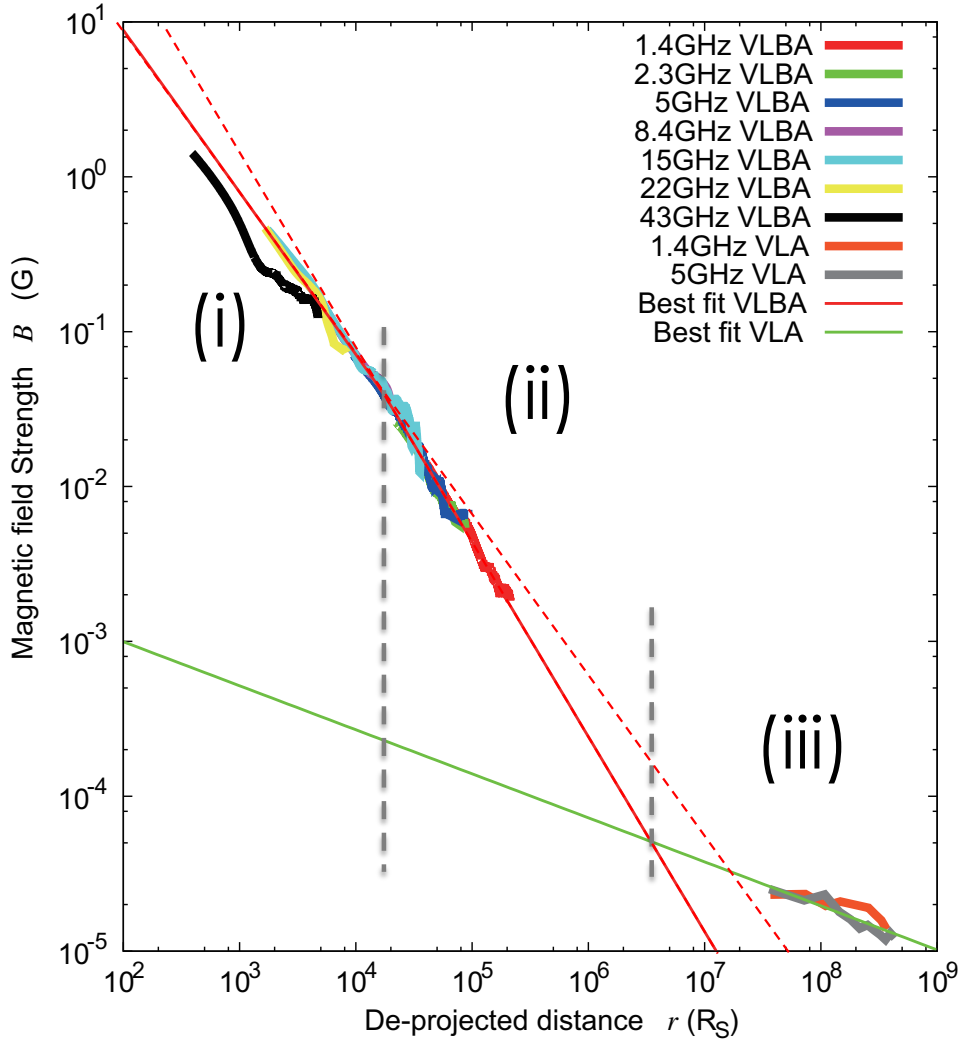
<u>The jet pressure measurement of this study is consistent with the X-ray result at kpc scales</u>

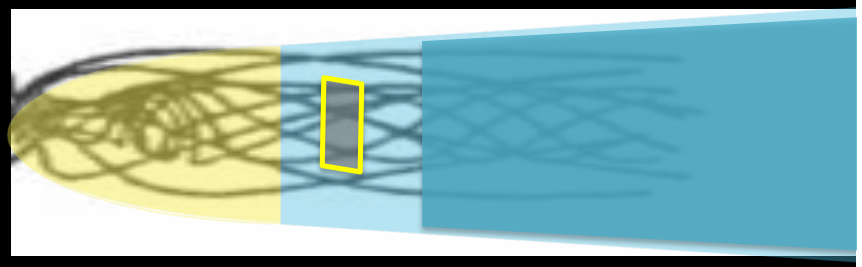
The first measurement of the pressure distribution in <10^7 R_S by using VLBI/radio interferometry.

(In the case of the jet pressure is controlled by the external pressure)

DISCUSSION

D. Magnetic field strength B(r) [G]





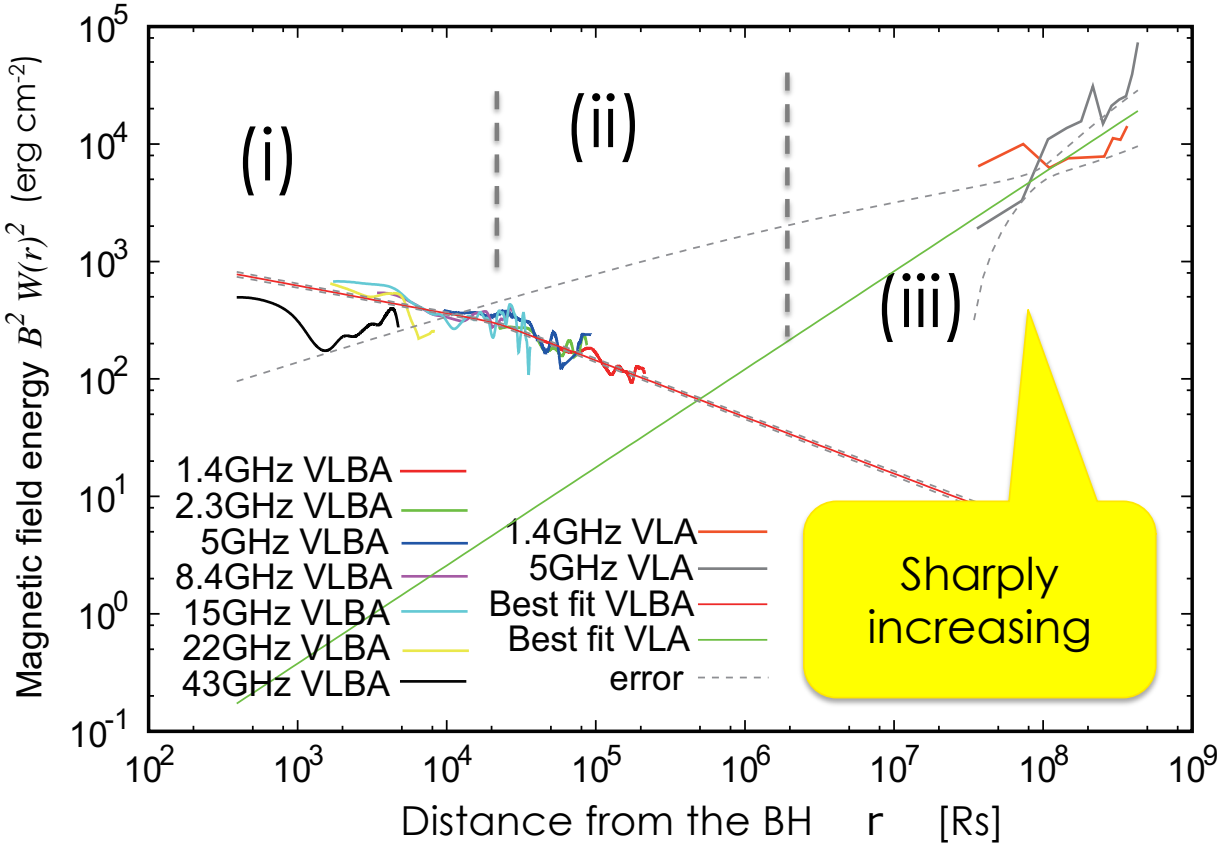
(i) $\propto r^{-0.81 \pm 0.01}$

(ii) $\propto r^{-1.25 \pm 0.01}$

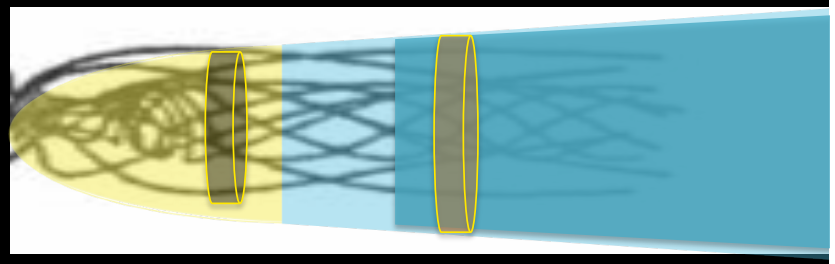
(iii) $\propto r^{-0.29 \pm 0.03}$

DISCUSSION

E. Magnetic energy $\propto B^2W(r)^2$ [erg/R_S]



Decrease the energy in (i) and (ii)
Energy is injected into the magnetic field in (iii)



The total energy per unit jet length

(i) $\propto r^{-0.24 \pm 0.01}$
(ii) $\propto r^{-0.48 \pm 0.01}$
(iii) $\propto r^{-0.83 \pm 0.15}$

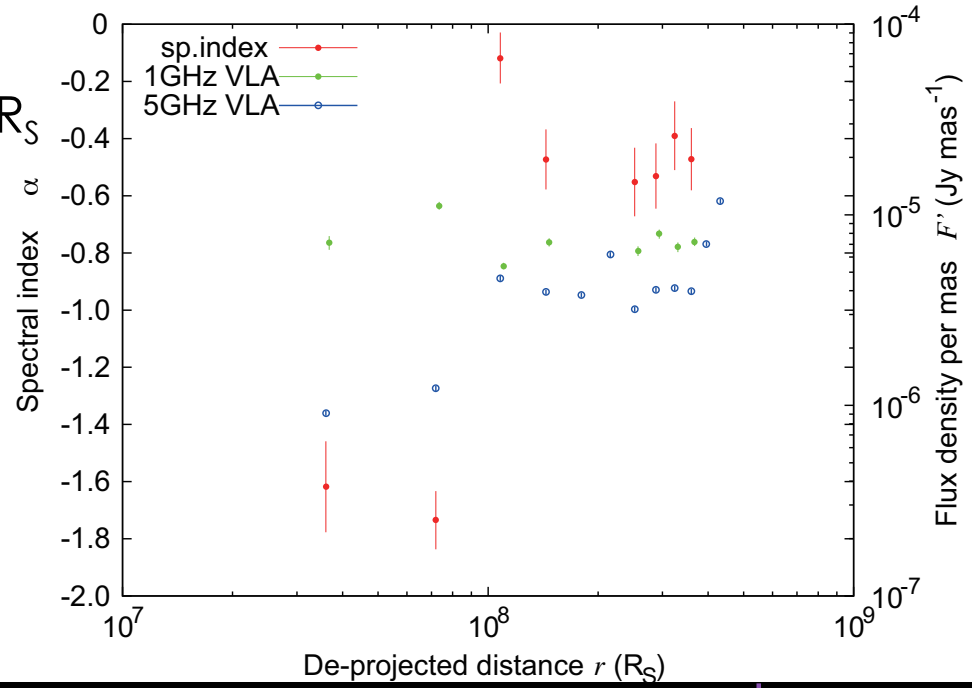
DISCUSSION

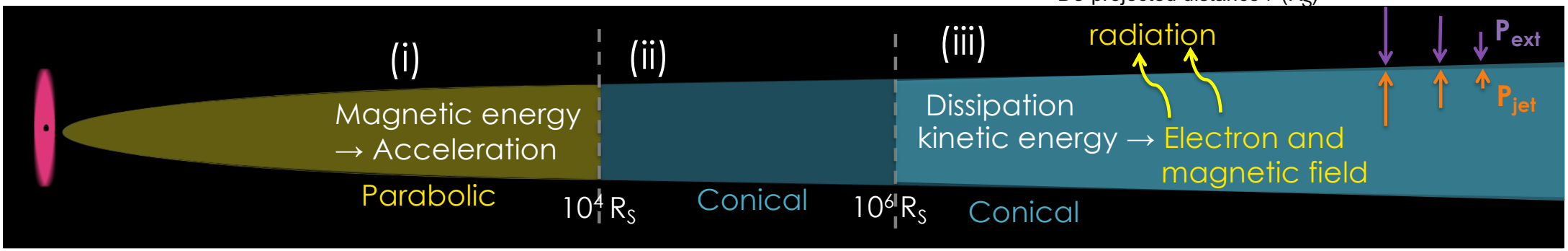
The transition of spectral index in region (iii)

The spectral index change -1.6 → - 0.6 in >10^8 R_S

→ Evidence of the particle acceleration

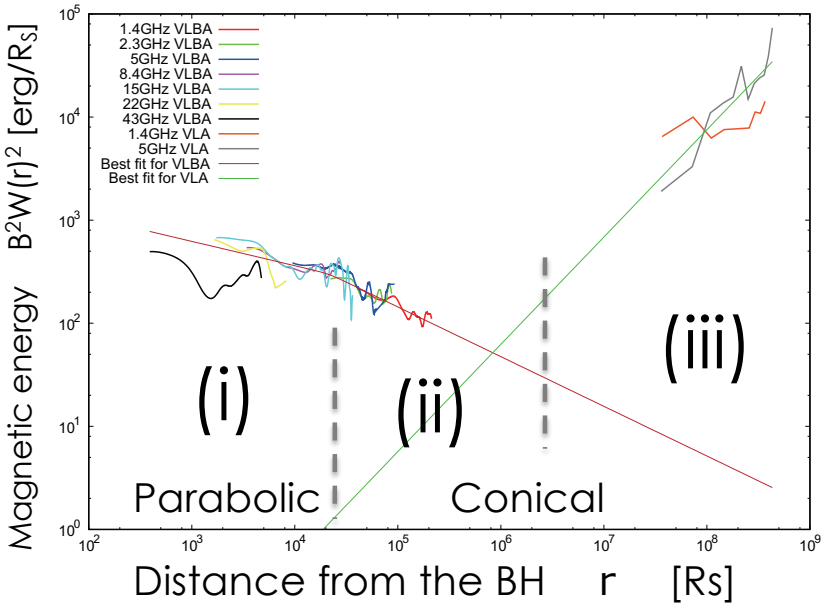
→ The kinetic energy is dissipated into the particle energy (and also magnetic energy)





DISCUSSION

Energetics of the jet from forming to dissipation

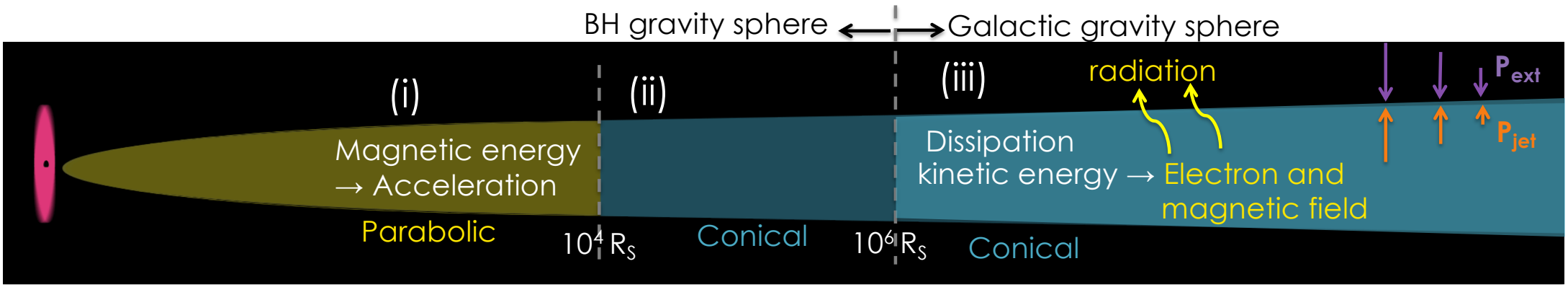


Decrease the energy in (i) and (ii)
Energy is injected into the magnetic field in (iii)

(i) (ii) Magnetic energy → Kinetic energy
(+ radiation energy?)
→ **bulk Acceleration**

(iii) Kinetic energy → Magnetic energy
→ **bulk Deceleration**

The first suggestion of the jet energetics by using observational results



DISCUSSION

Comparison of 5 samples
Jet structure and transition

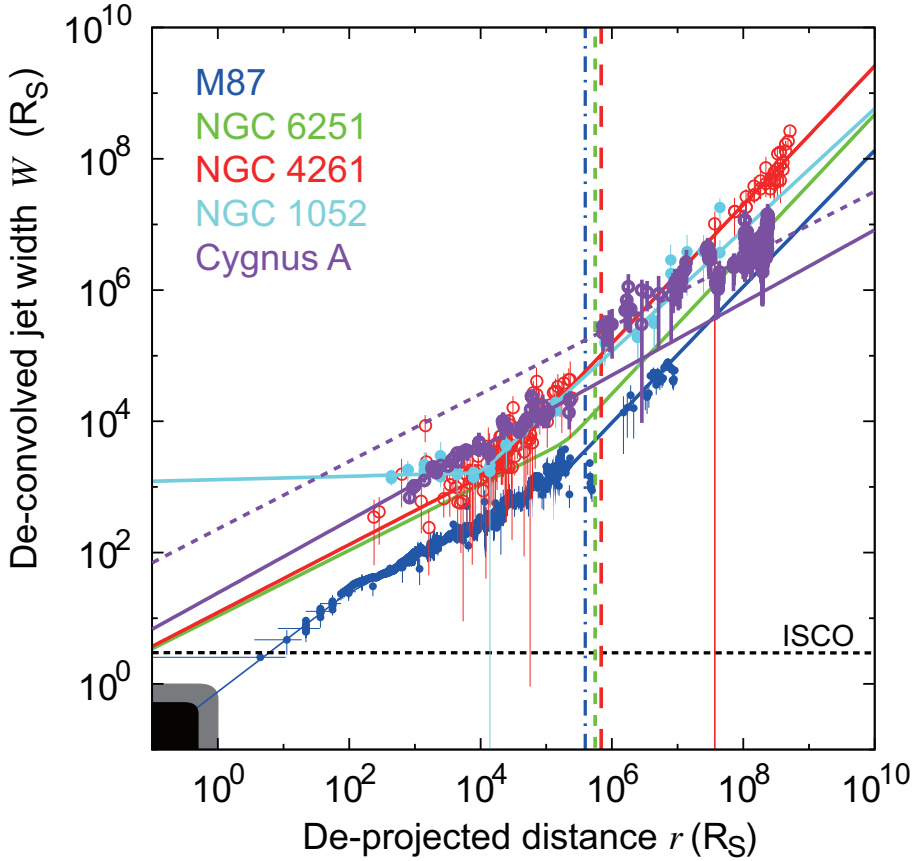
- Parabolic → Conical
  - M87 a~0.5→1
  - NGC 6251 a~0.5→1
  - NGC 4261 a~0.5→1
- Over-collimation → Conical
  - NGC 1052 a~0.03→1
  - (3C 84 a~0.25→?)

Nagai et al. 2014

FR I

- Parabolic → Parabolic
  - Cygnus A a~0.5→0.5

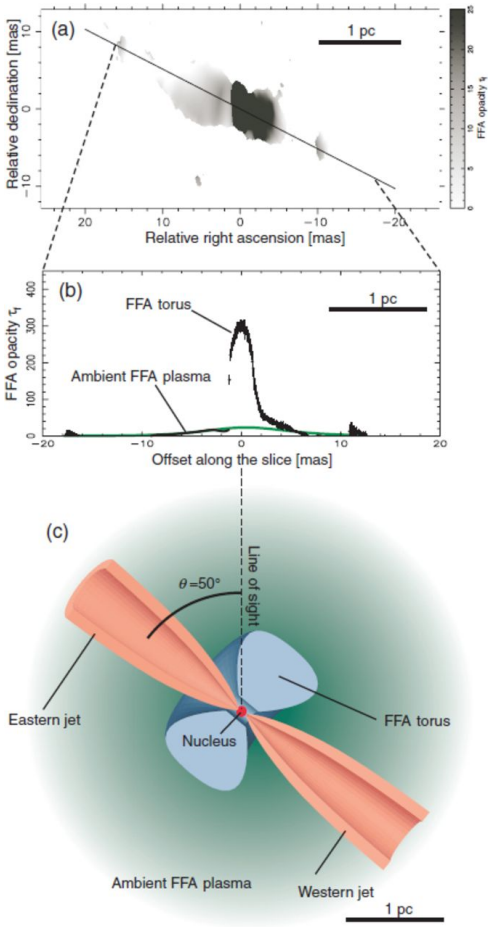
FR II



DISCUSSION

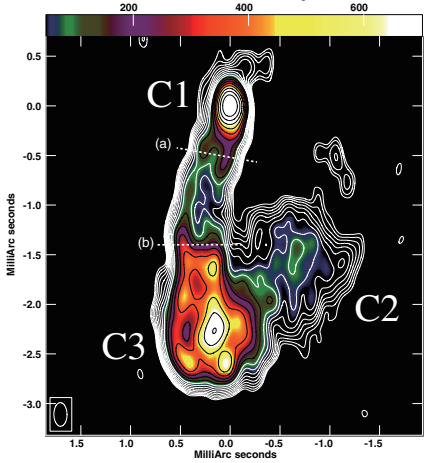
Over-collimation and plasma torus

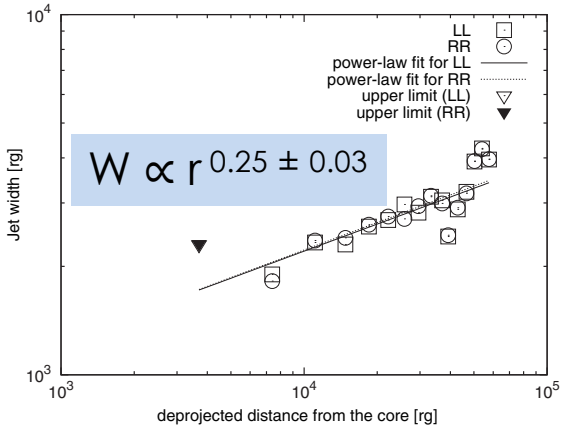
NGC 1052 hosts plasma torus

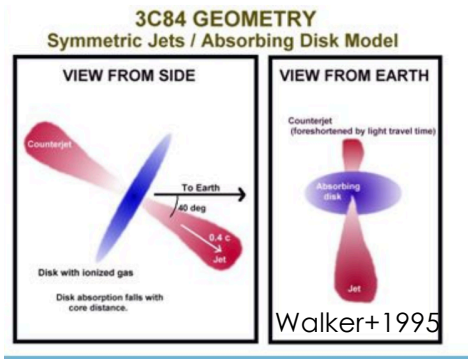


Kameno+2001

3C 84 also host plasma torus and over-collimation structure





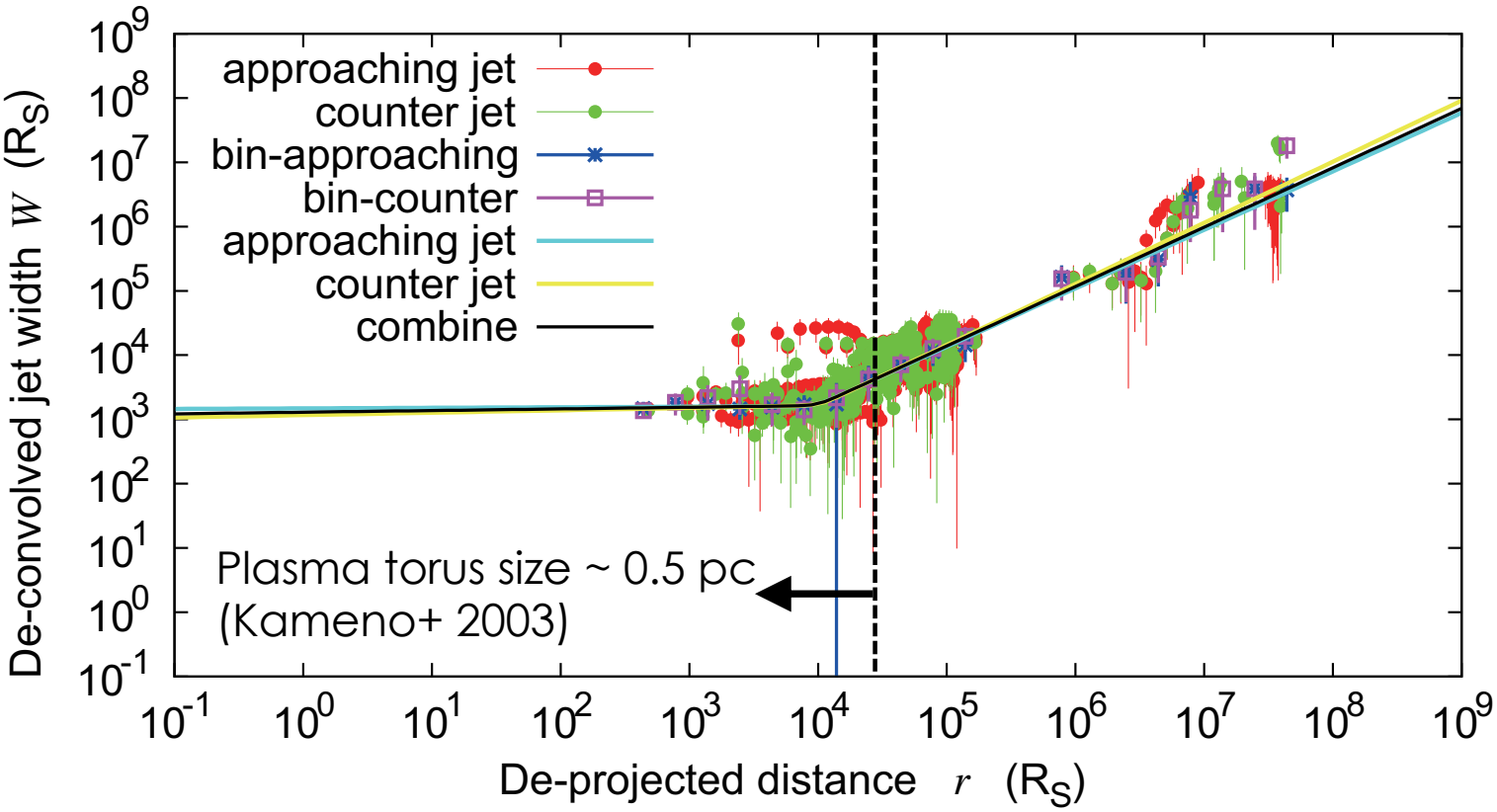


3C 84 jet suggests
$P_{ext} \propto r^{-1}$ (Nagai+14)

The external pressure by plasma torus makes $P \propto r^0$ (cylindrical) ? → Over collimation

DISCUSSION

The transition point is nearby the plasma torus size



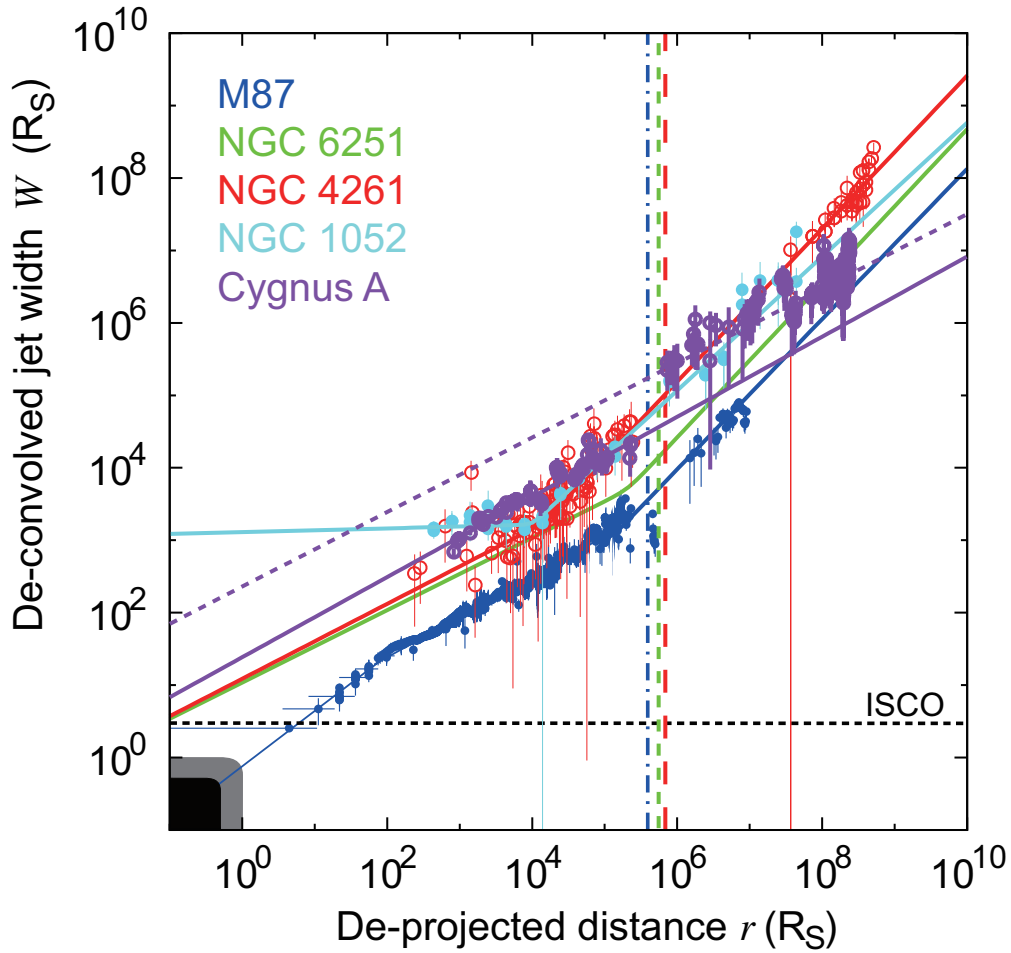
The torus (over-)collimates the jet in NGC 1052 (and 3C 84) ?

DISCUSSION

Comparison of 5 samples about Jet width

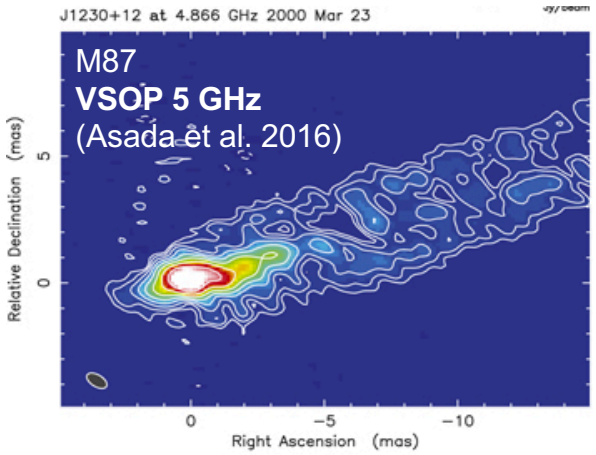
- Narrow jet : 2 sources
  - M87 (i~11 deg)
  - NGC 6251 (i~19deg)
- Broad jet : 3 sources
  - NGC 4261 (i~63 deg)
  - NGC 1052 (i~86 deg)
  - Cygnus A (i~75 deg)

	inclination
Narrow jet	small
Broad jet	large

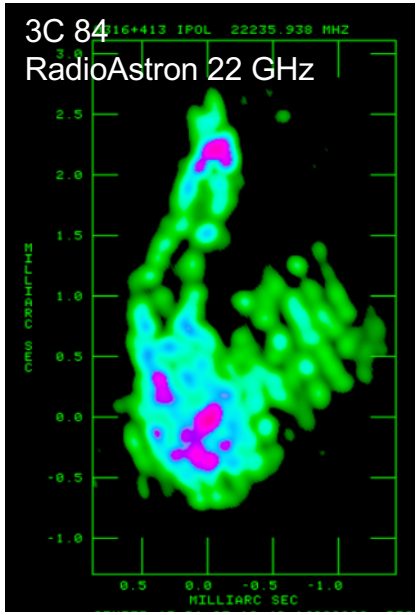


DISCUSSION

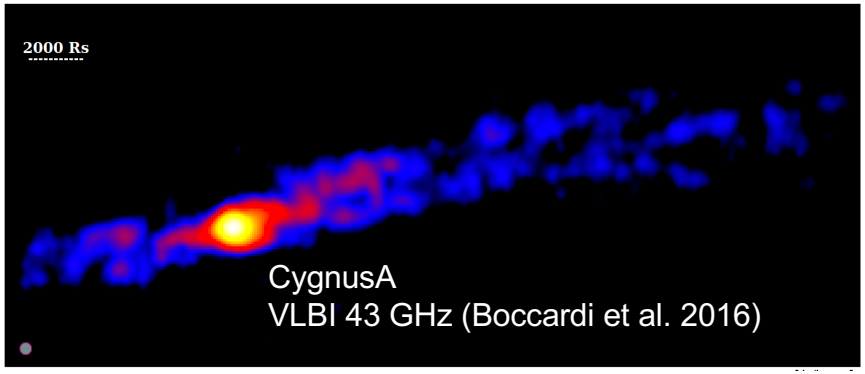
Layer of the jet

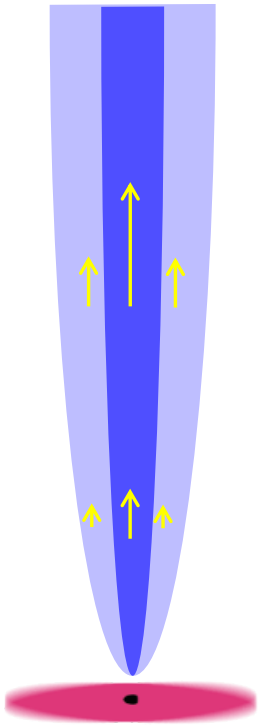


Crediti: RadioAstron / G.Giovannini(UniBo/INAF), M.Orienti (INAF)



- ☐ Limb-brightening (Observation)
- ☐ Spine--sheath (Theoretical model)



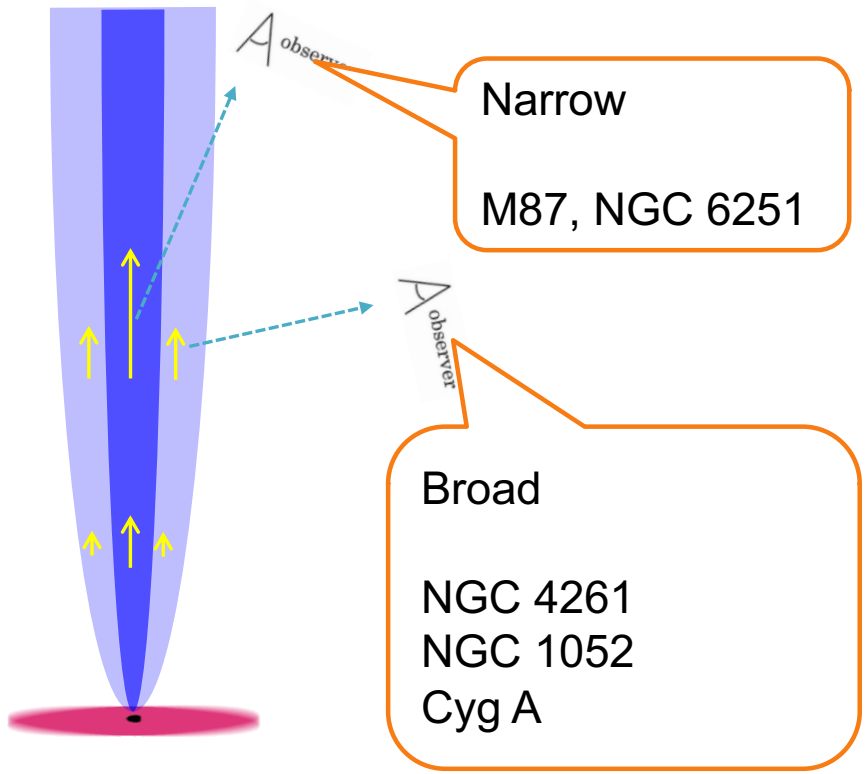


Inner and outer layer have different speed

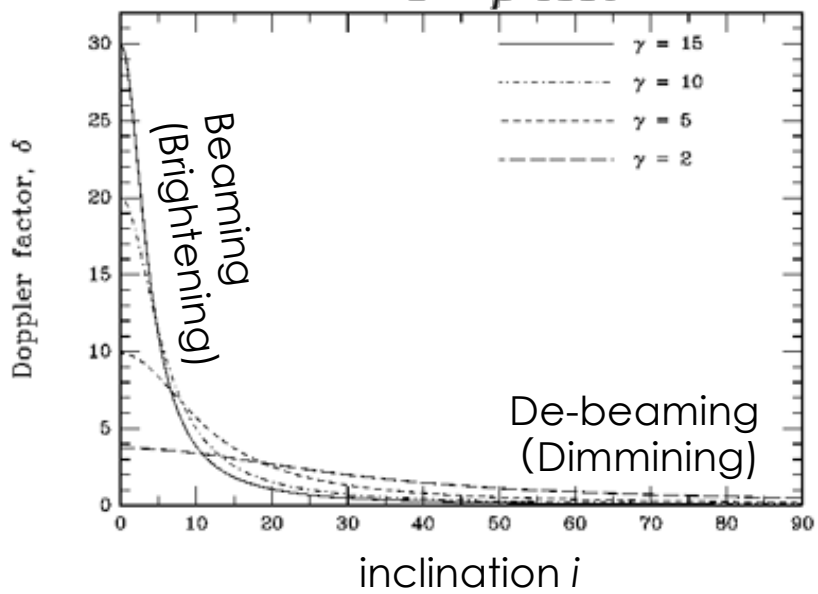
DISCUSSION

Beaming/de-beaming effect due to jet speed and inclination

Inclination small: faster layers get large Doppler factor (Brightening)
Inclination large: Slow layers are relatively brighter than fast layer although both layer get dark

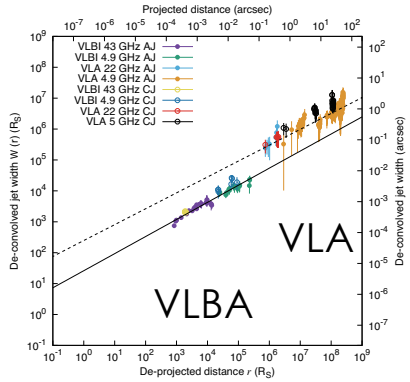


$$\mathfrak{D} = \frac{\sqrt{1-\beta^2}}{1-\beta\cos i}.$$



DISCUSSION

Big jump in Jet-width profile (Cygnus A)



Assumptions in each layer (1) different brightness temperature
(2) different jet speed

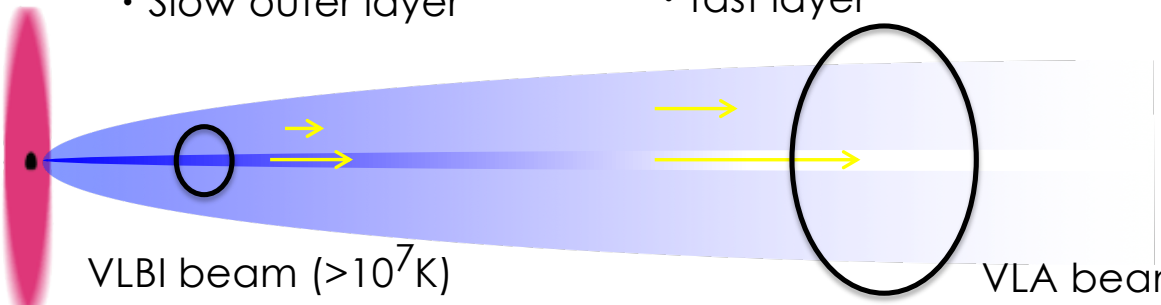
→ Think the beaming effect viewing from inclination ~75 deg

Co-moving flame
(No beaming effect)

- Low brightness($<10^6$K)
- Slow outer layer

- High brightness ($>10^8$K)
- fast layer

Observer flame
(Beaming effect)



VLBI beam ($>10^7$K)
cannot detect outer layer
because of detection limit

VLA beam ($>10^2$K)
cannot detect inner fast layer
because of de-beaming effect

DISCUSSION

Big jump in Jet-width profile (Cygnus A)

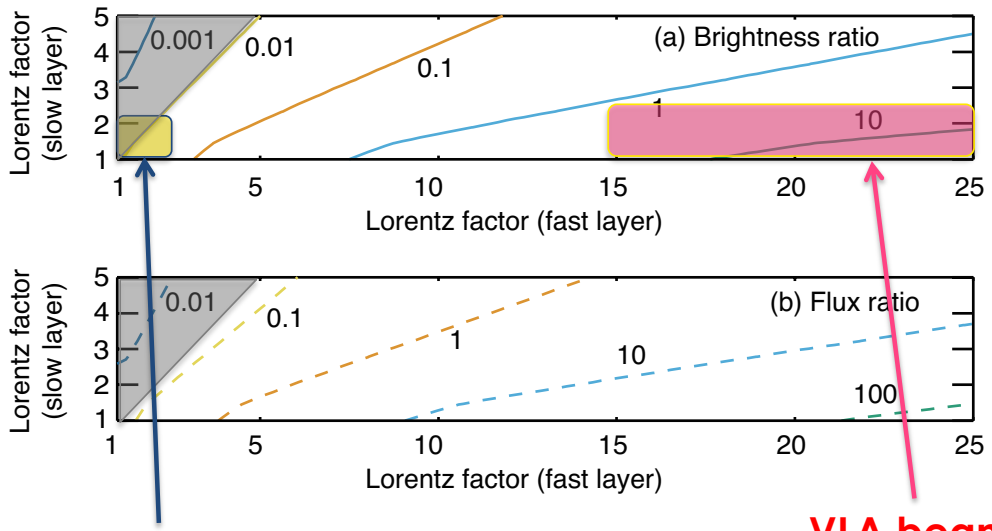
We considered quantitatively

- Brightness ratio

$$\frac{T^{\rm slow}_{\rm Bobs}}{T^{\rm fast}_{\rm Bobs}} = \frac{T^{\rm slow}_{\rm Bint}}{T^{\rm fast}_{\rm Bint}}\frac{\delta^p_{\rm slow}}{\delta^p_{\rm fast}} = \frac{T^{\rm slow}_{\rm Bint}}{T^{\rm fast}_{\rm Bint}}\left(\frac{\Gamma_{\rm slow}-\sqrt{\Gamma^2_{\rm slow}-1}\cos i}{\Gamma_{\rm fast}-\sqrt{\Gamma^2_{\rm fast}-1}\cos i}\right)^{-p}$$

- Flux ratio

$$\frac{S^{\rm slow}_{\rm obs}}{S^{\rm fast}_{\rm obs}} = \frac{T^{\rm slow}_{\rm Bint}}{T^{\rm fast}_{\rm Bint}}\frac{W_{\rm slow}}{W_{\rm fast}}\frac{\theta}{\theta}\frac{\delta^p_{\rm slow}}{\delta^p_{\rm fast}} = \frac{W_{\rm slow}}{W_{\rm fast}}\frac{T^{\rm slow}_{\rm Bobs}}{T^{\rm fast}_{\rm Bobs}}.$$



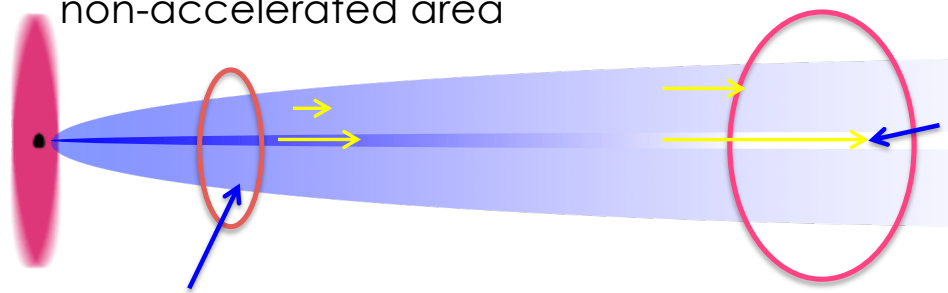
Intrinsic brightness ratio between inner and outer layer

$T^{\rm slow}_{\rm Bint}/T^{\rm fast}_{\rm Bint} = 0.01$

p=2-a; a~0.7(spectral index)
Γ: jet speed
δ: Doppler factor
W: Jet width
i: inclination angle
θ: Resolution of telescope

VLBI beam
non-accelerated area

VLA beam
Accelerated area

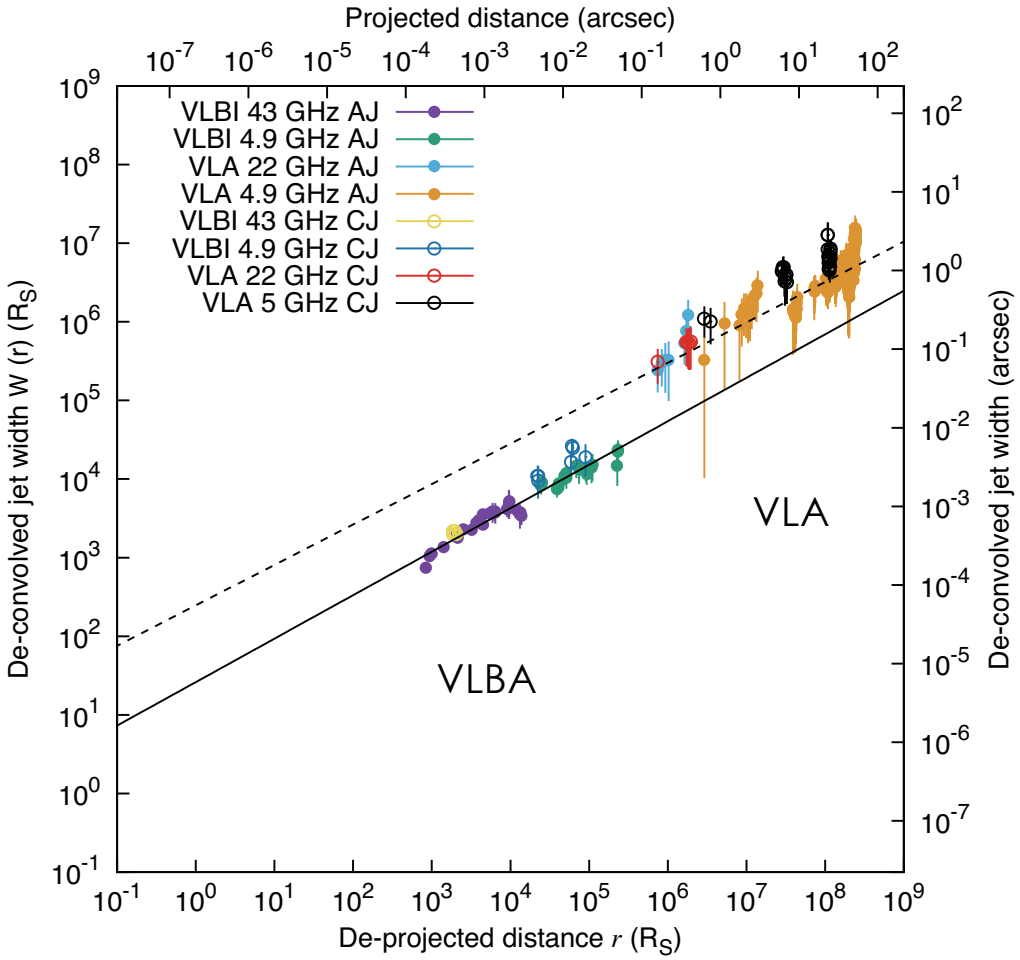


inner : cannot detect because of the de-beaming effect

outer : cannot detect because of detection limit of telescope

DISCUSSION

Big jump in Jet-width profile (Cygnus A)



Recent theoretical models suggest that outer layer is faster than the inner one,

e.g. Nakamura+ 2018

It is also possible that the big jump in Cygnus A jet is really expanding …
We have to more study for this mystery

Summary

We found common / different properties of AGN jet width profiles and approached its forming mechanism

1. Structure development (distance dependence)
   - The structural transition point depends on the object
   - Bipolar jets are quantitatively symmetric
   - Jet locally over-collimated by plasma torus
   - The structural transition differs between FR-I and FR-II type

2. Multi-layered structure?
   - 5 samples of jet width suggests multi-layer structure,
   - which causes differences in apparent jet width depending on the Inclination angle (beaming effect).

Summary

We suggest the energetics of NGC 4261 jet by observational measurements (jet-width & radiation profiles) at first.