The core shift measurements for two-sided jets affected by Free-Free absorption using VLBA

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Collaborators

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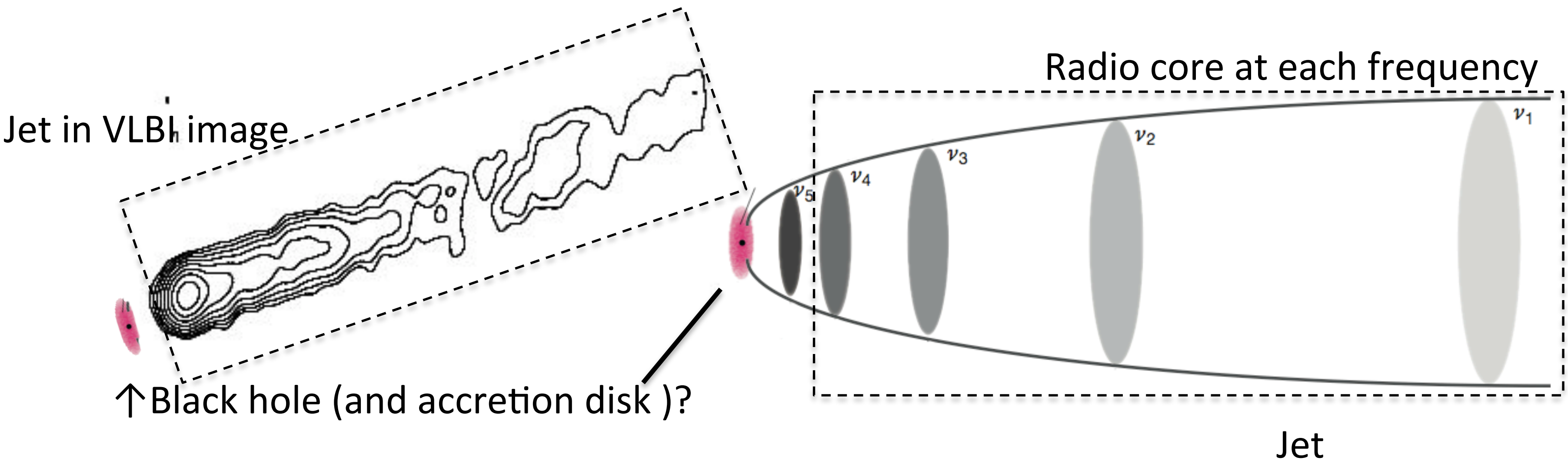
Outline

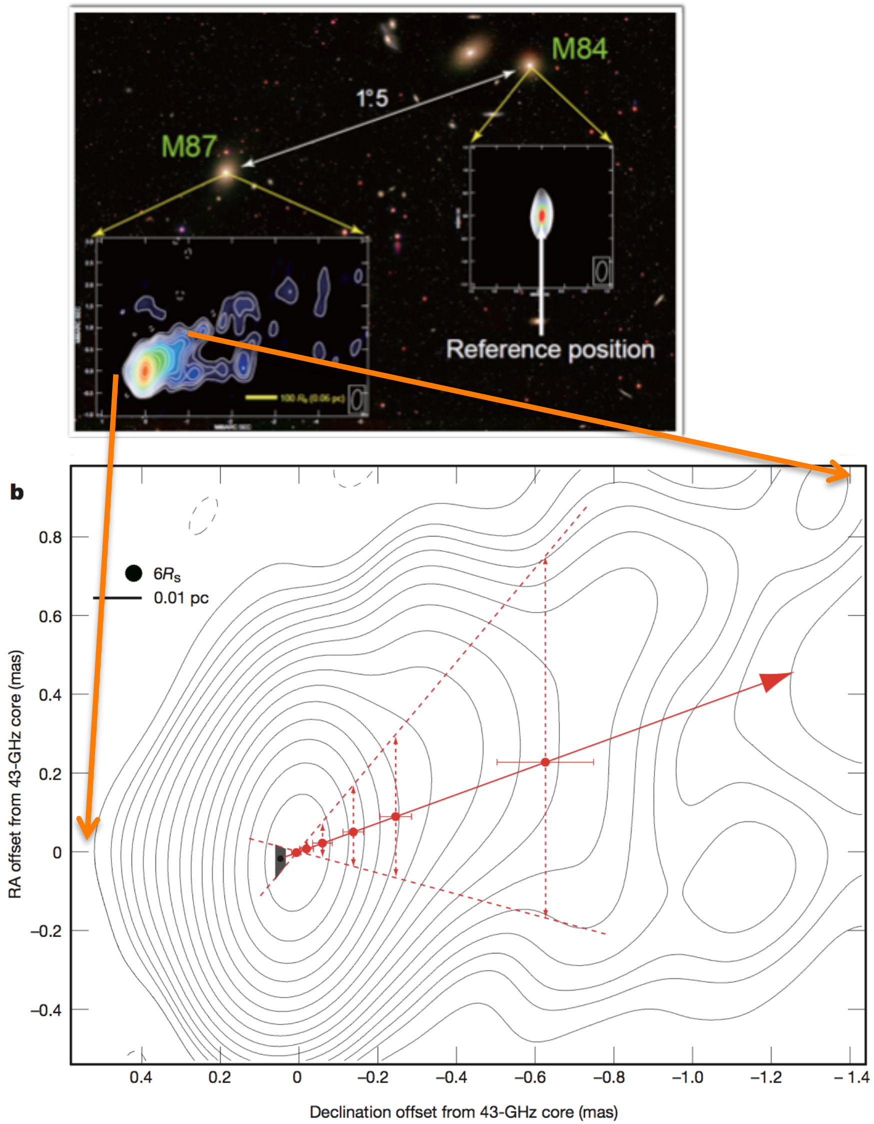
- Introduction of Our project
  - Core shift measurements for two-sided jet
    - Where is the position of the black hole?
  - Our Targets
    - NGC 4261, 3C 84, Cen A, Cyg A
- Results of NGC 4261
  - The black hole position
  - The interpretation of the counter jet core shift

Opacity effect

- Radio core ： Peak intensity at the upstream of a jet
- Core position
  - The base of jet is absorbed (It's stronger at lower frequency.)
  - Core positions seem to be different at each frequency (= core shift)
  - Core position ≠ position of the jet base



The case of M 87 (Hada+2011 *Nature*)



- ◆ Accurate determination of the position of the jet base in M 87
- (14–23) ± 4 Rs away from 43 GHz radio core.

- ■ The higher frequency is, the closer core is to the jet base

⇒ core (@ν→∞)→ jet base

Jet base = BH position ?

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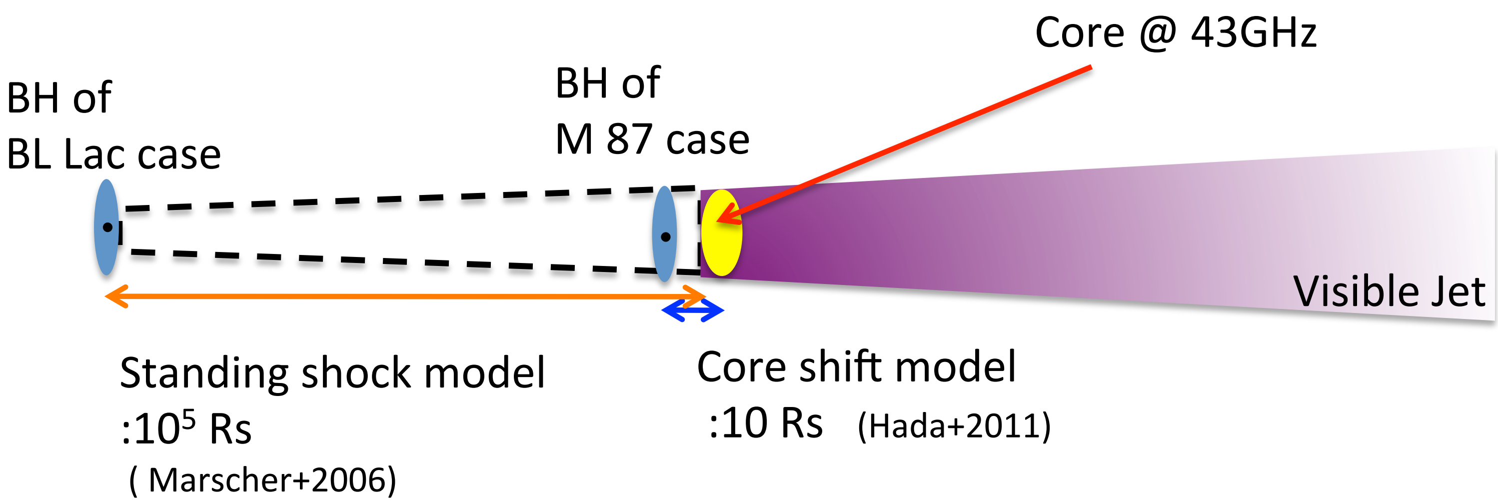
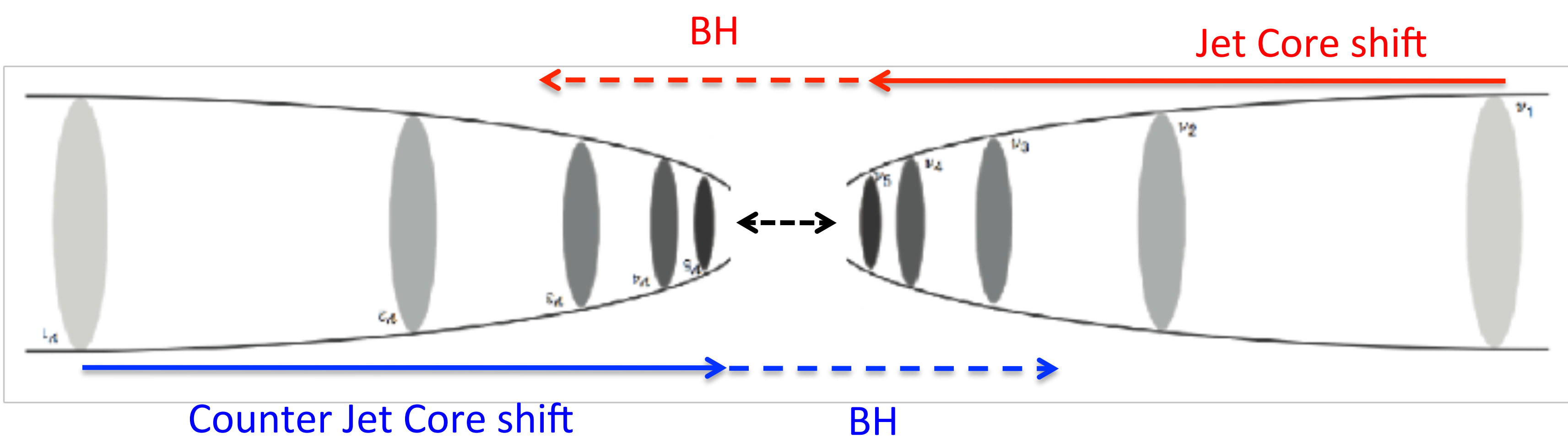
- One-sided jet cases
  core (@ ν → ∞): lower limit of distance to BH



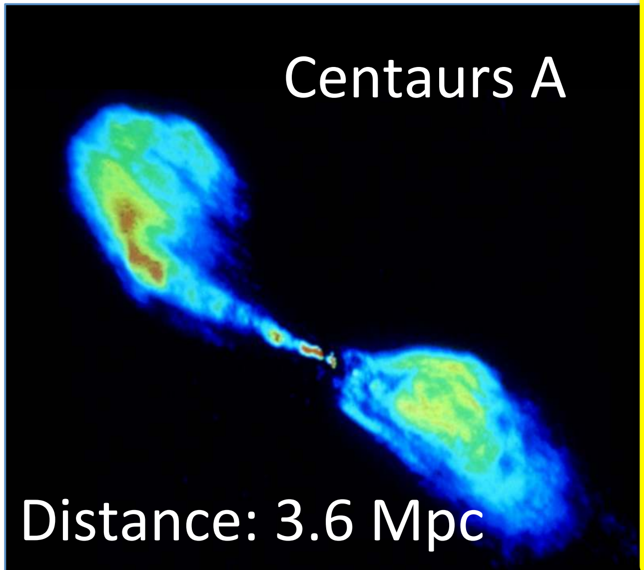
- Two-sided jet cases
  - can limit range of BH position unambiguously

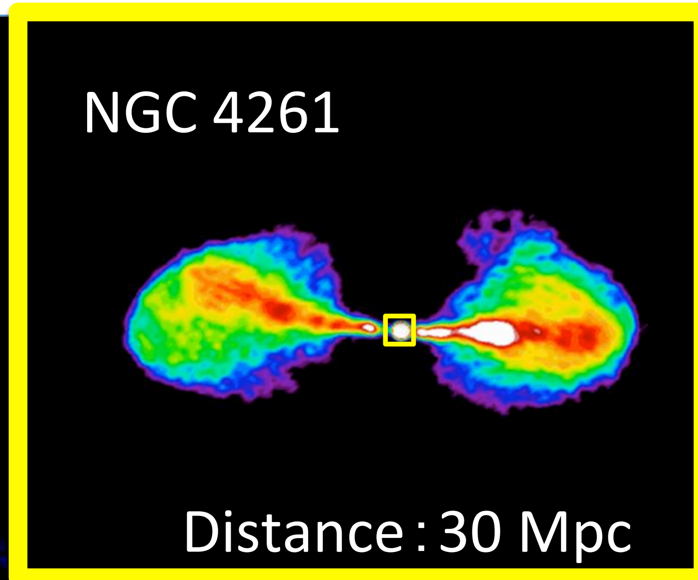
The goal of our research

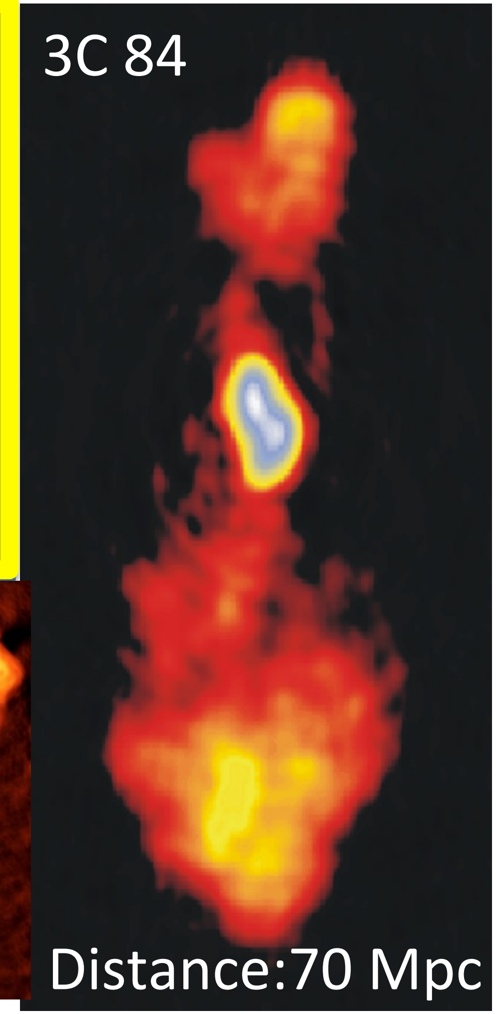
- Measurements of counter jet core shift
- determine true position of BH

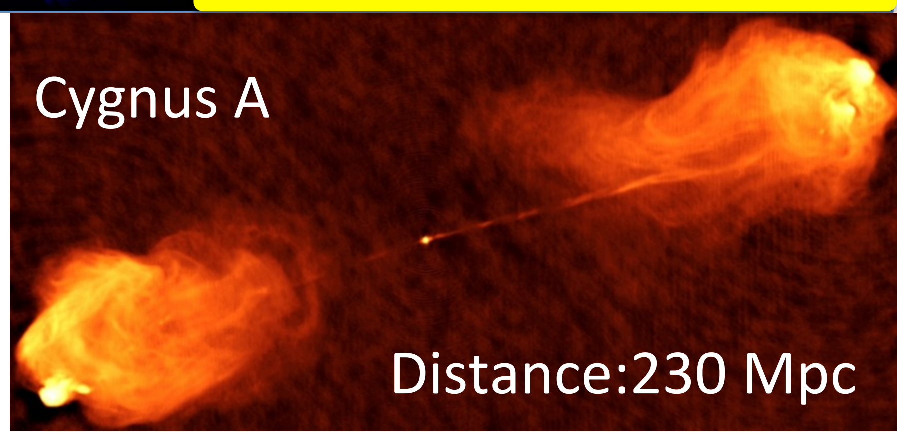


Our targets with two sided jet









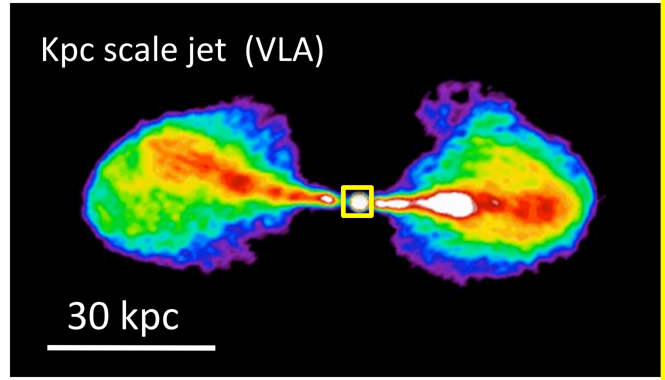
NGC 4261

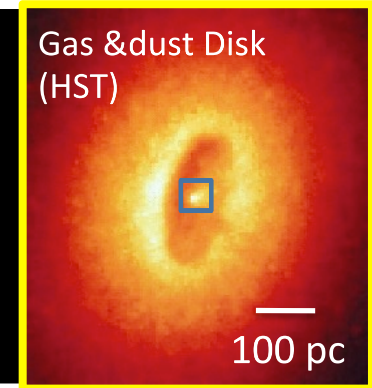
- FR-I radio galaxy
- 31.6 Mpc (z=0.0075)
  - 1 mas ~ 0.15 pc (Tonry +2001)
- BH : 4.9×10^{8} M_{sun}

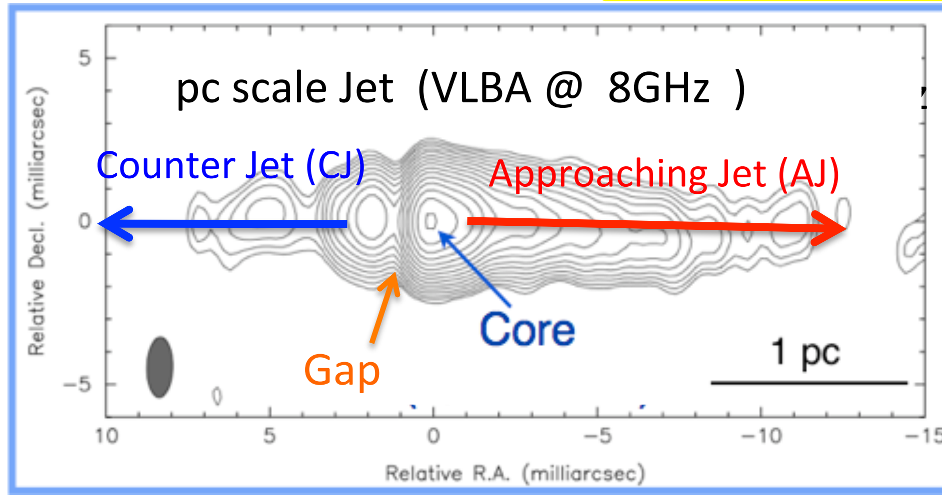
  (Ferrarese + 1996)
- Viewing angle :

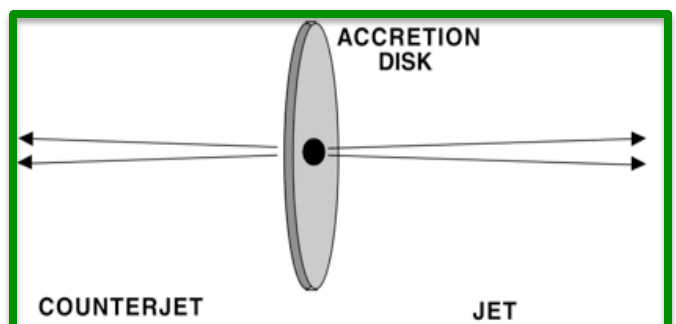
  θ = 63 ± 3°

  (Pinner +2001)
- Intensity gap
  - The obscuration by disk
    - Edge-on, geometrically-thin, cold disk (10^4 K)







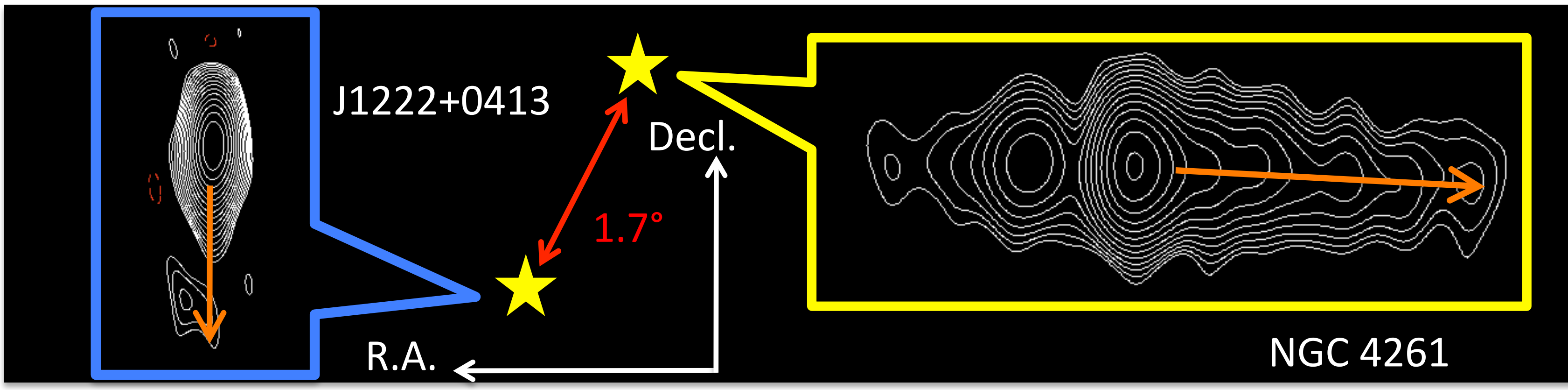


Jones +2000.2001

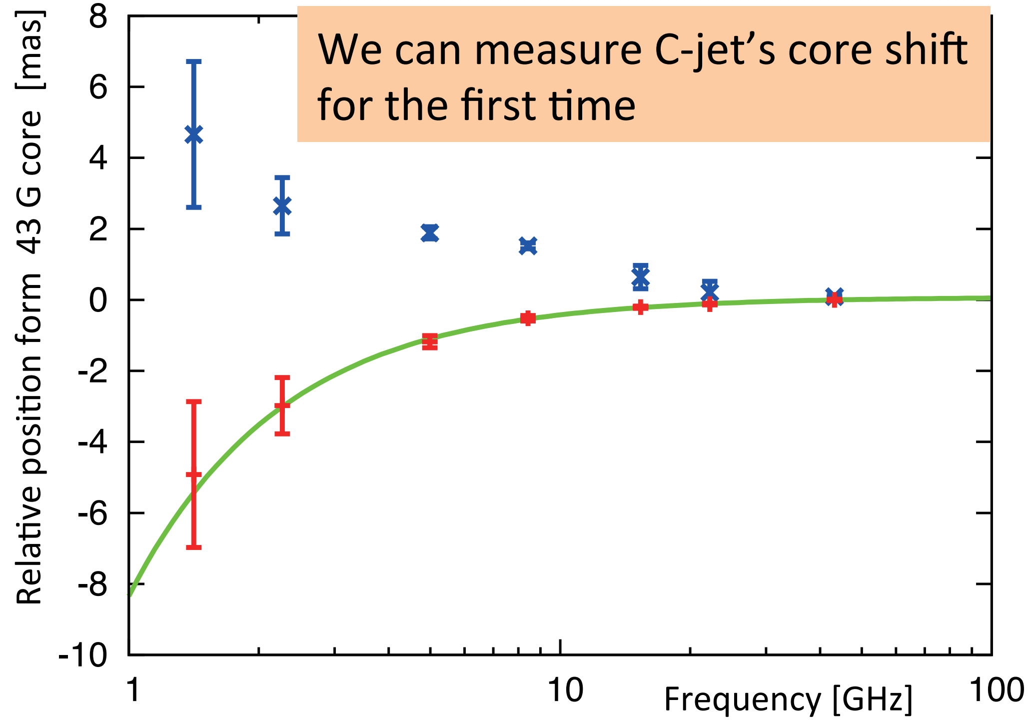
Observational summary

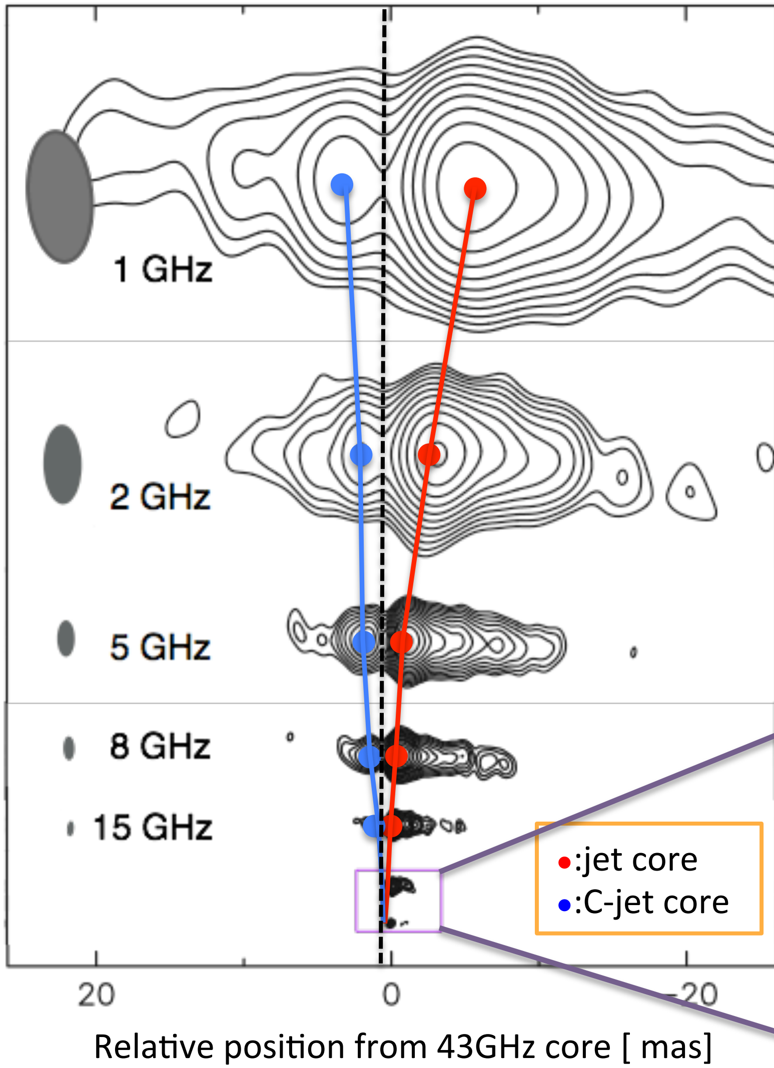
Telescope	VLBA (10 antennas)
Observation mode	Phase-referencing
Frequency [GHz]	1.4/2.3/5.0/8.4/15/22/43
Date	28th June, 2003 (15, 22, 43 GHz)
	5th July, 2003 (1, 2, 5, 8 GHz)
Calibrator	J1222+0413

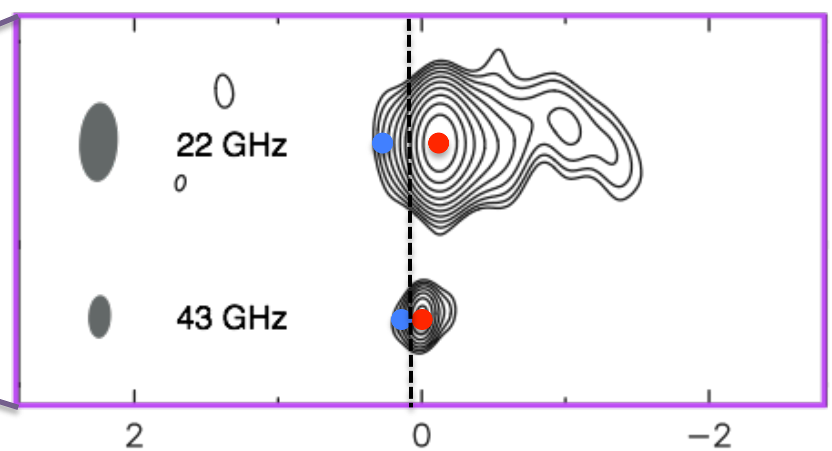
- 43 GHz resolution beam size
  ～ 0.15 [mas] ～ 0.04 pc ～ 1000 Rs



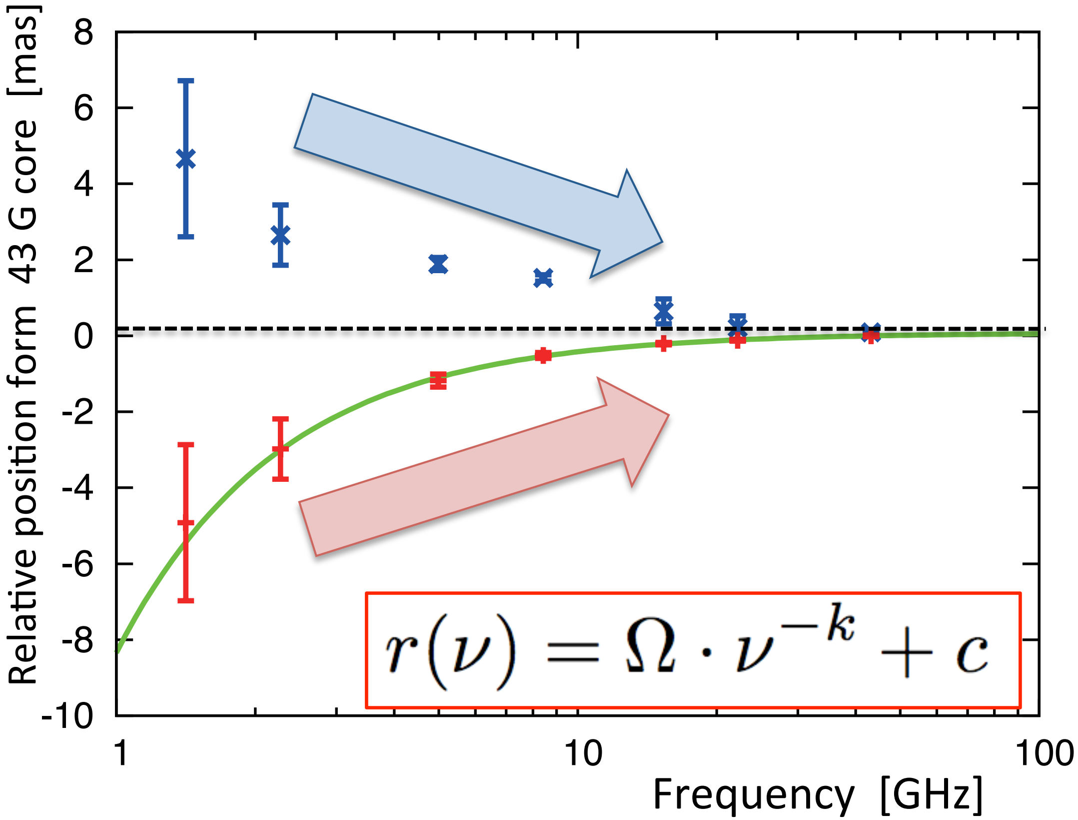
Continuum maps and core shift measurements







Core shift fitting on approaching jet

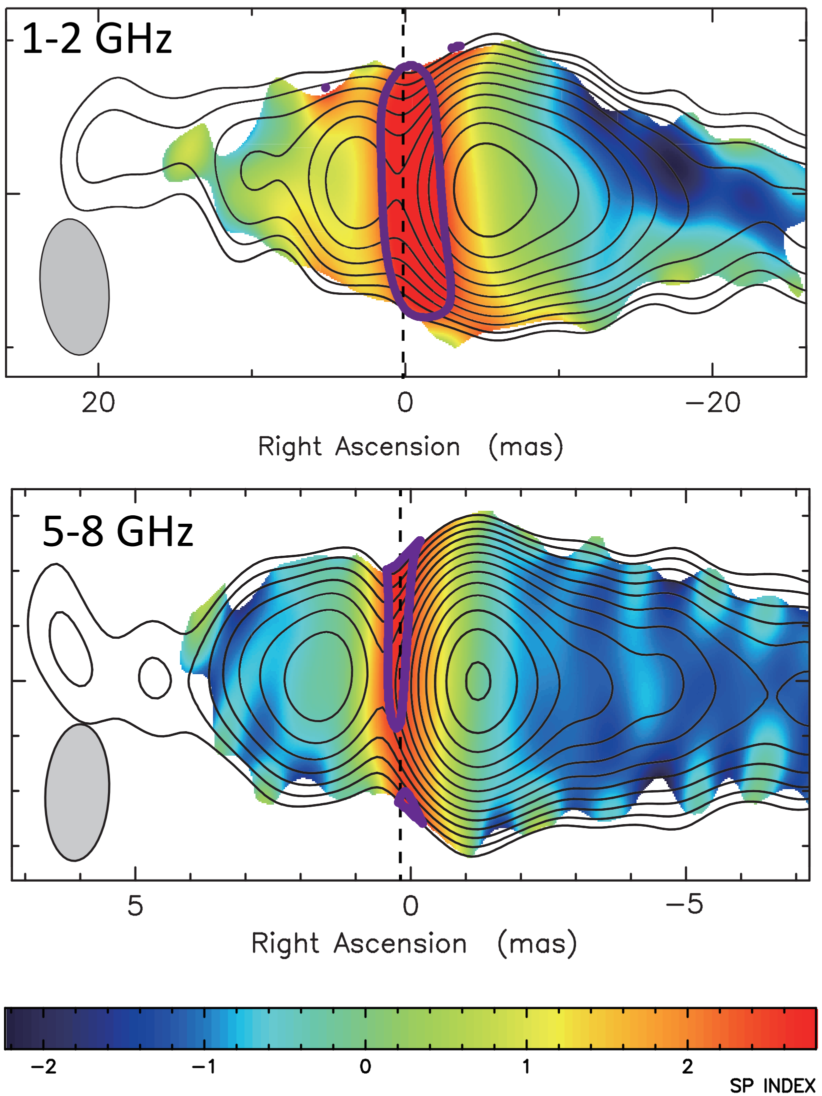


	Value	error
Ω	-8.42	± 0.86
k	1.22	± 0.06
c	0.082	± 0.016

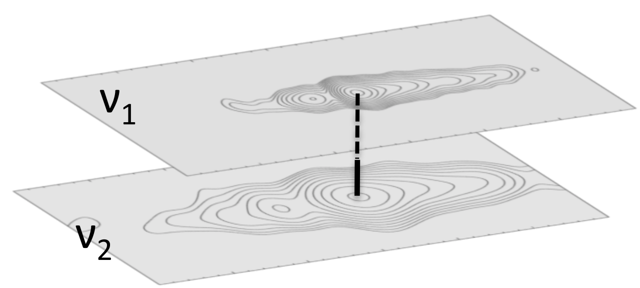
Parameter c was determined to be 82 ± 16 µas (~310 ± 60 Rs) from 43 GHz core

- Core_AJet@43GHz < c < Core_CJet@43GHz
- c (core @ ν→∞) = BH position

Spectral index map ($S_\nu \propto \nu^\alpha$)



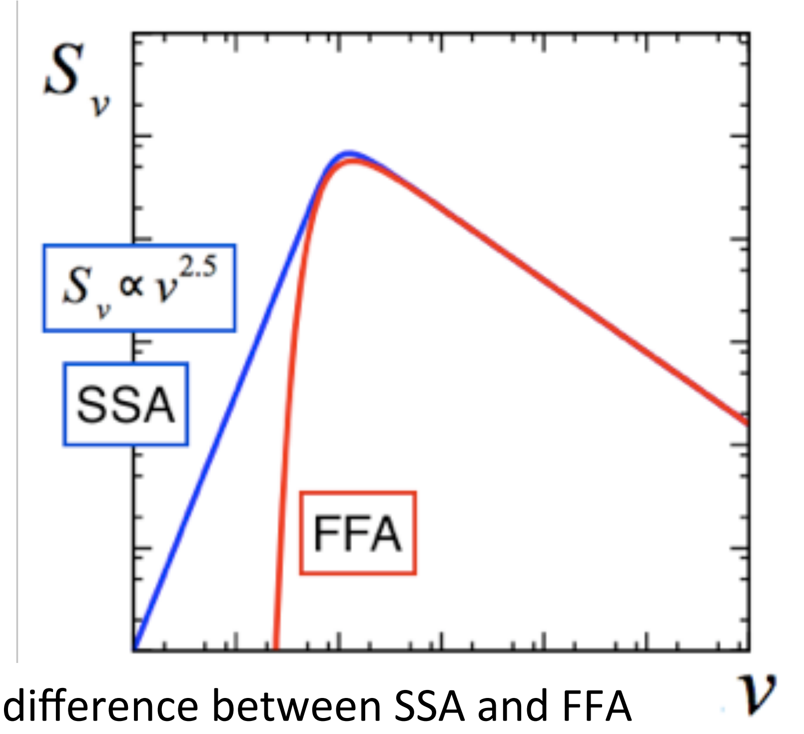
- Overlay maps at adjacent frequency
  - Considered core shift
  - Using same beam
- $\alpha > 2.5$ (inside heavy line)
  - 1-2, 5-8, 8-15 GHz



core shift is caused by SSA or/and FFA

- Absorption at low frequency
  - Jet itself： synchrotron self-absorption (SSA)
  - Obscuration of accretion matter :free-free absorption (FFA)

- $\alpha_{SSA} \leqq 2.5$



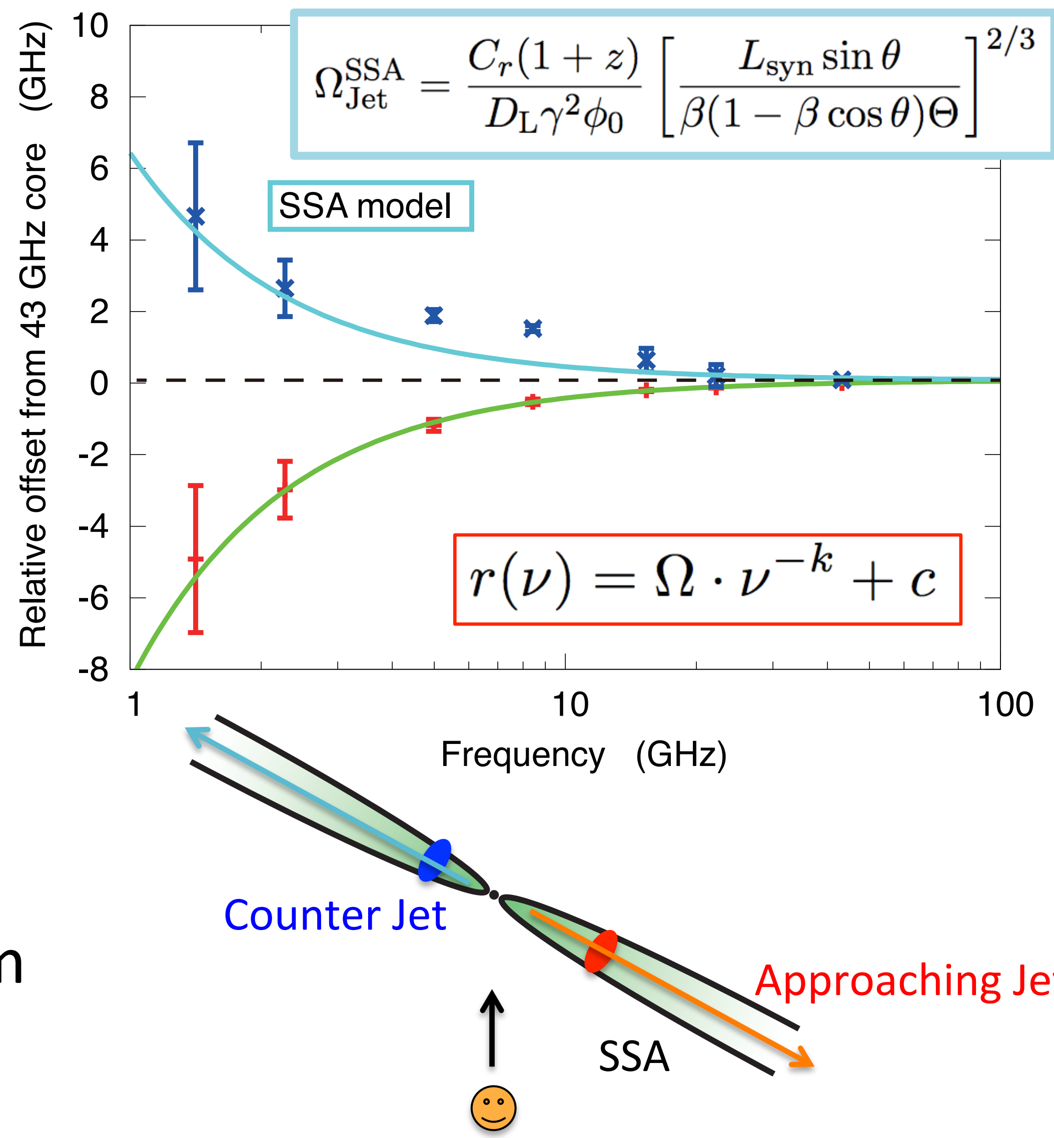
The spectral difference between SSA and FFA

Pure SSA model

- The difference of A-Jet / C-Jet
  - beaming factor
    - δ (β, θ)

      β : 0.46, θ: 63°
  - $\Omega_{CJ} < \Omega_{AJ}$
- Model
  - 5–8 GHz
    : lager than pure SSA expectation
  - Others

    : as expectation from pure SSA core shift



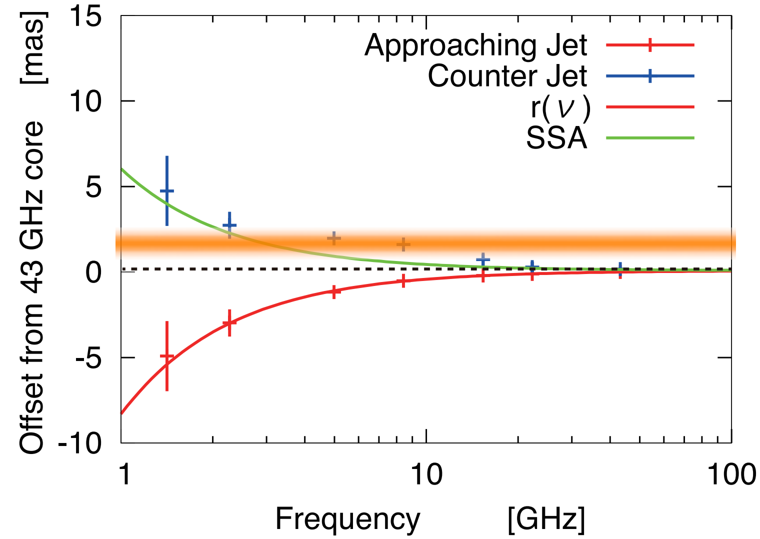
SSA + FFA model

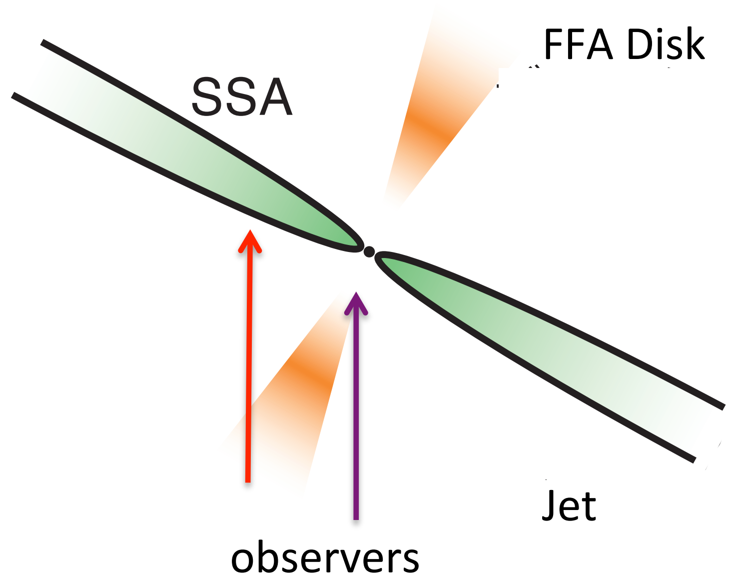
- SSA jet + FFA disk
  - 5, 8 GHz: affected by FFA disk
  - Other : consistent with pure SSA
- Limited regions within 0.4 pc

$$\tau_{\mathrm{FFA}} \propto n_{\mathrm{e}}^{2} T^{-1.5} L \nu^{-2.1}$$

τ_{FFA} : FFA opacity, n_e: electron density, T : temperature
L : path length in absorbers

- ν ≦ 2 GHz
  : outside disk (low density)
- ν ≧ 15 GHz
  : too high temperature
  : frequency dependence



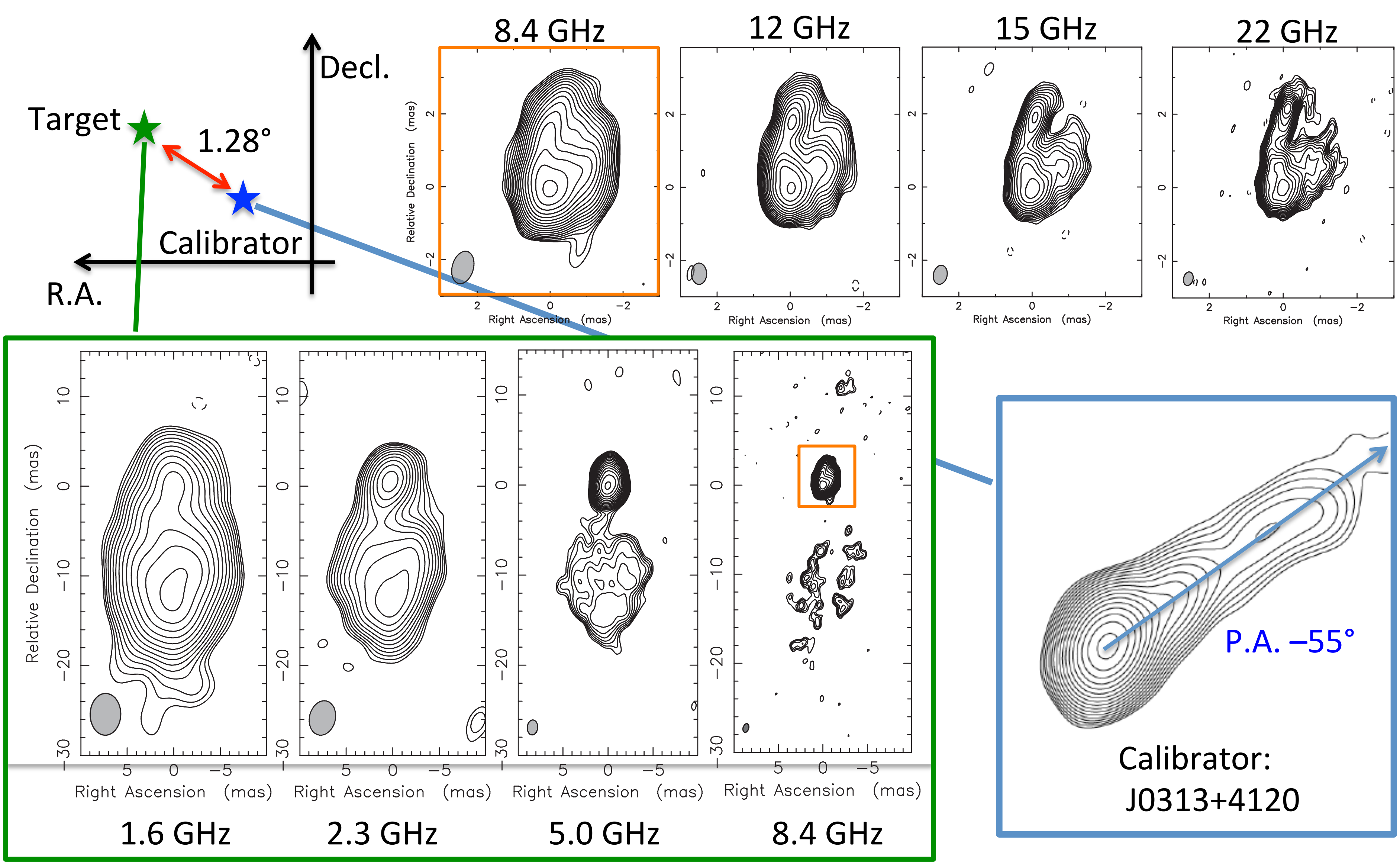


Summary

- We measured core shift of NGC 4261 not only on main jet side but also counter jet.
  - The jet base practically represent the BH position.
  - The BH position of NGC 4261 is determined unambiguously.
    - It is located within 82 ± 16 μas (310± 60 Rs) from 43 GHz core
- C-Jet core shift can't be interpreted as pure SSA core shift.
  - Contribution of FFA disk

Going on analysis

3C 84 phase referencing observation



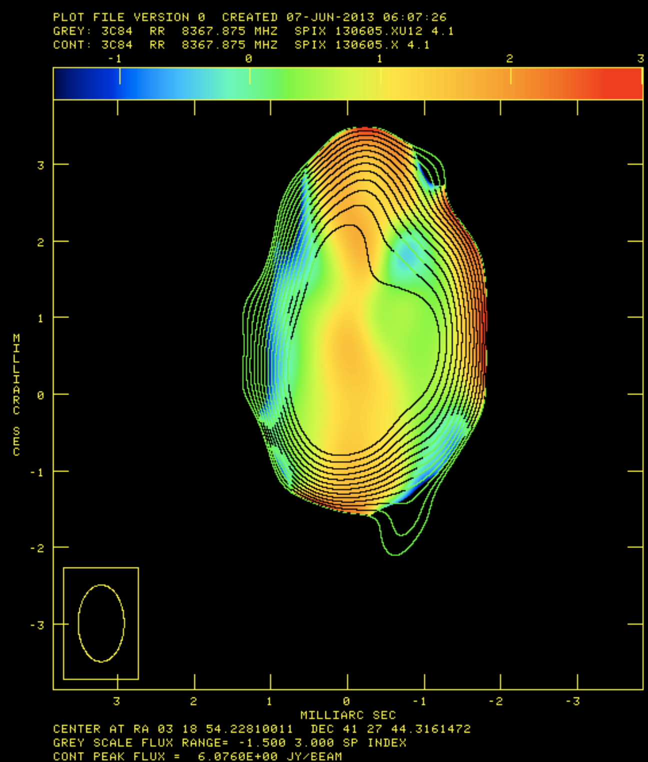
Thank you for your attention!

Observational summary

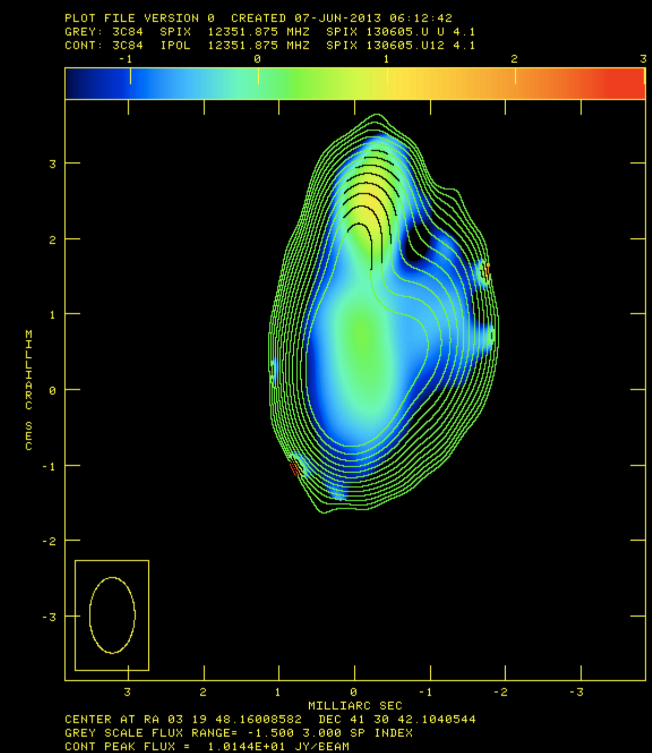
Telescope		VLBA (10 antennas)	
Observation mode		Phase-referencing	
Date		24th January, 2013	
Freq. [GHz]	OST [min]	Pol.	BW [MHz]
1.6	15	LL/RR	256
2.3	15	RR*	256
5.0	30	LL/RR	256
8.4	15	RR*	256
12	40	LL/RR	256
15	40	LL/RR	256
22	70	LL/RR	256
43	120	LL/RR	256

- 3C 84 (NGC 1275)
  - Distance: 70 Mpc
    - 1mas～ 0.35 pc
- New Mark 5C system
  - Data rate : 2Gbps

Spectral index maps



8-12 GHz



12-15 GHz

Error budget (μas)

Frequency [GHz]	**1.4**	**2.3**	**5.0**	**8.4**	**15.4**	**22.2**	**43.2**
Beam size/ SNR	52	24	10	6	4	3	2
Ionosphere	2006	779	161	57	17	8	2
Troposphere	13	13	13	13	13	13	13
Core identification	349	60	17	40	0.2	5	3
Earth orientation	5	5	5	5	5	5	5
Antenna position	2	2	2	2	2	2	2
Apriori Source coordinates	1	1	1	1	1	1	1
Total error (RSS)	**2055**	**792**	**170**	**77**	**30**	**23**	**19**