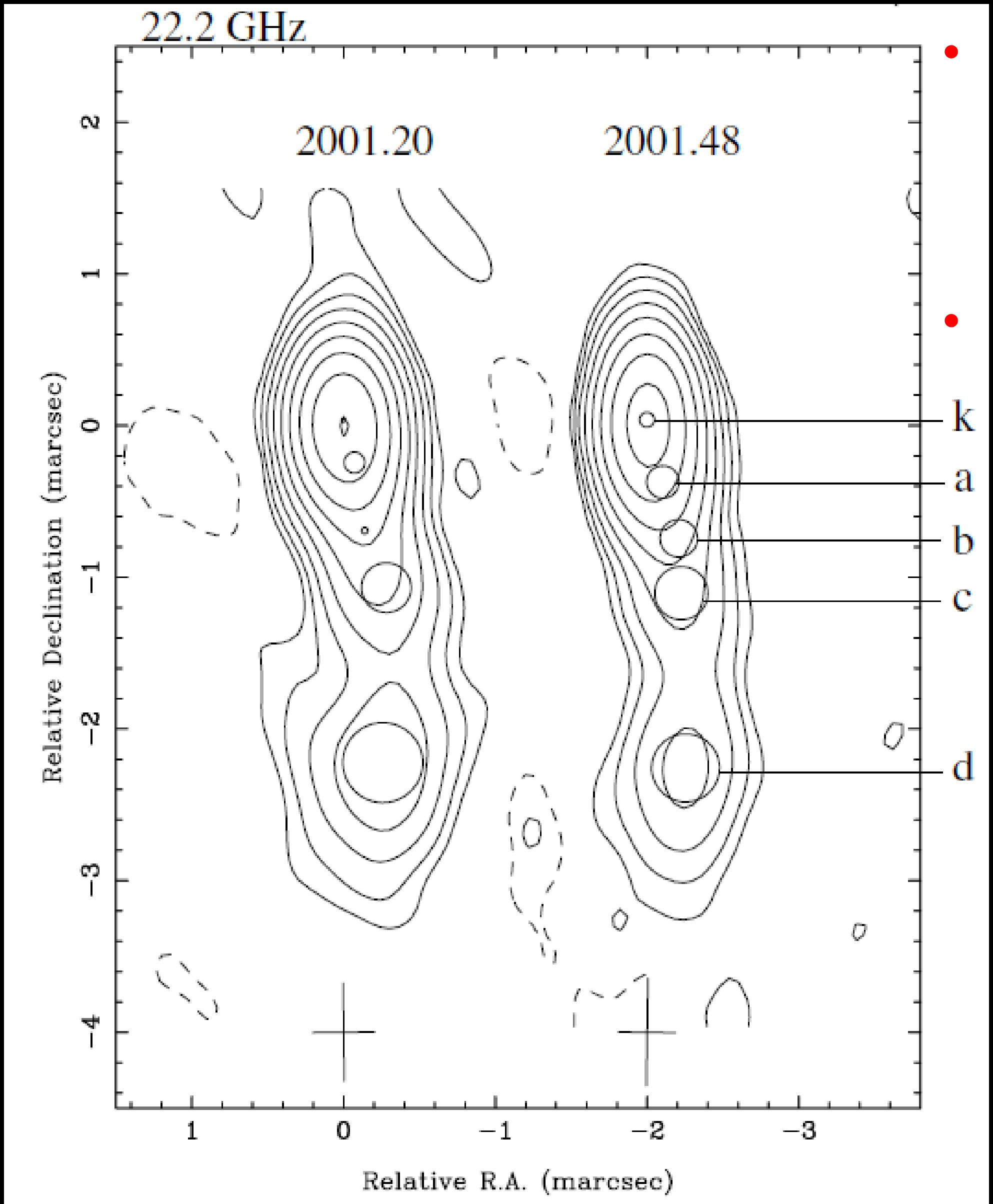
High precision position measurements of the cores in 3C66A and 3C66B

Zhiqiang Shen
Shanghai Astronomical Observatory

F. Gao (Shanghai Astro. Obs.), G.-Y. Zhao (Shanghai Astro. Obs.),
H. Sudou (Gifu Univ.) et al.

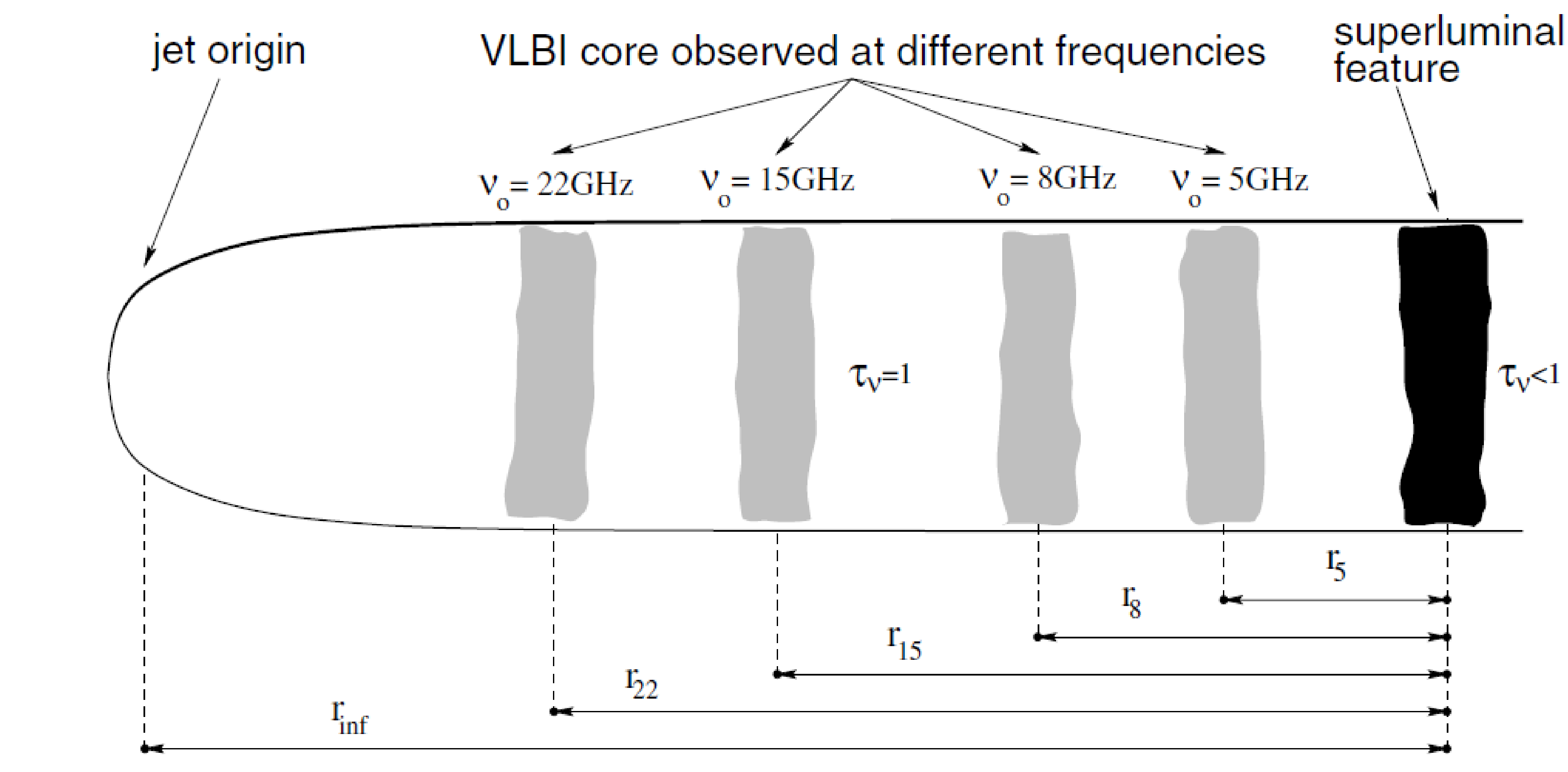
JD6 : The Connection between Radio Properties and High Energy Emission in AGN, 2012 August 23
XXVIII IAU GENERAL ASSEMBLY, BEIJING, China, 2012

VLBI core and jets



- Core: **base of the radio jets; flat spectrum; compact and bright; optically-thick; located in a region with an optical depth τ ≈ 1**
- Jets: **optically-thin components; steep spectra; superluminal motion**

Frequency-dependent core position



A scheme illustrating the frequency-dependent position shift of the VLBI core. Adopted from Lobanov (1996).

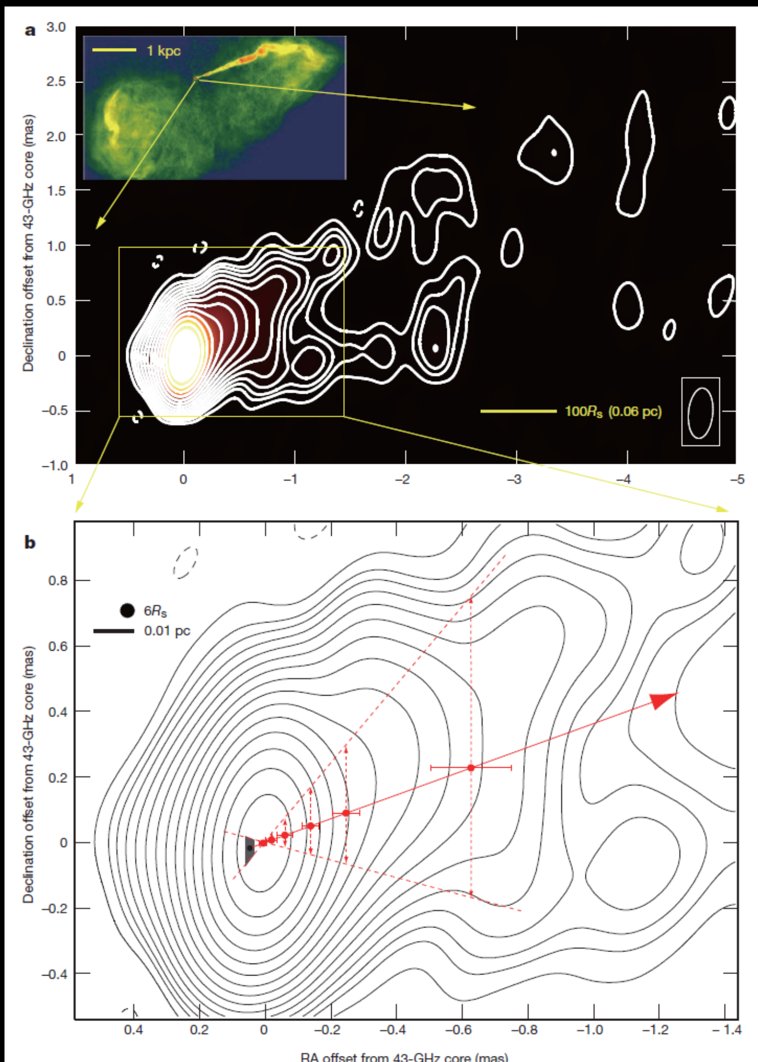
- **The core position along the jet is a function of the observing frequency $r_{\rm core} \propto \nu^{-1/k_r}$, because of the variation in the optical depth caused by SSA, FFA and pressure/density gradient in the jet.**
- **SSA and equipartition, kr=1; otherwise kr can be deviated from unity.**

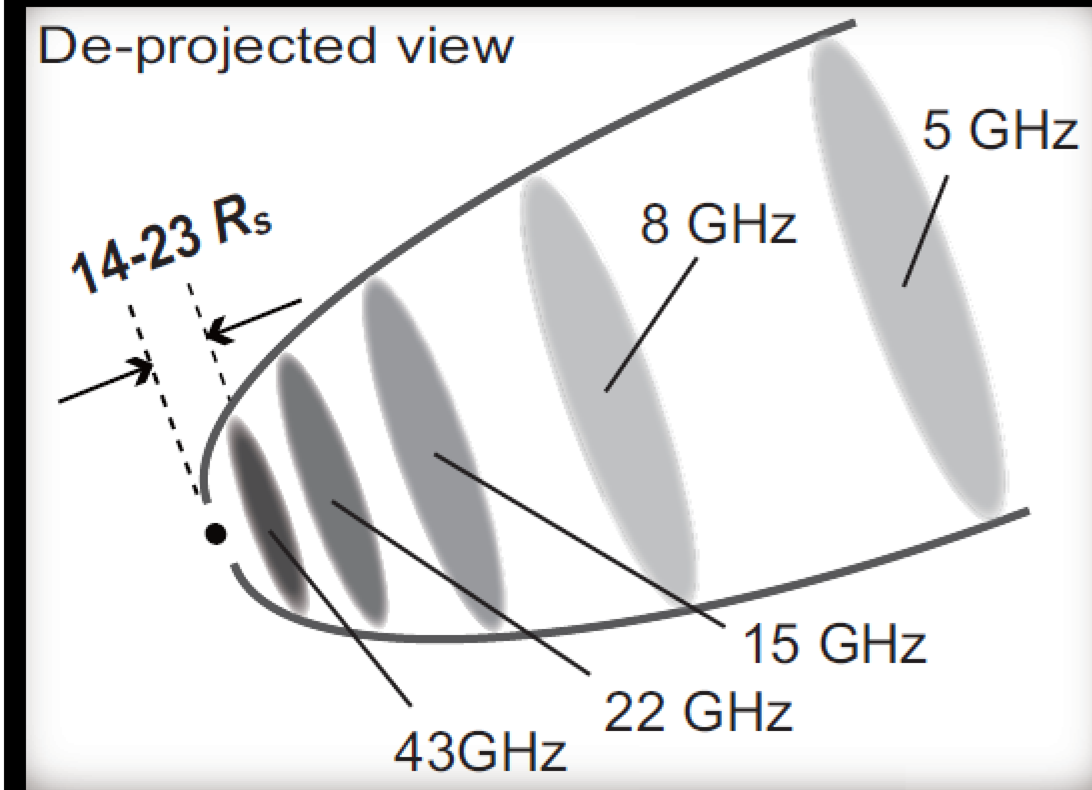
Core shift

- Optically-thin jet feature, whose position is not expected to change with frequency, is chosen as the reference to determine the optically-thick frequency-dependent core position.
- Core shift: frequency-dependent shift in the core position
- Various applications:
  - changes in the core position measured between 3+ frequencies can be used to determine physical and geometrical parameters of the relativistic jet origin (e.g. the black hole – jet connection in M87 (Hada et al. 2011))
  - alignment of radio and optical reference frame: Radio-optical reference frame connection: An average ~0.1 mas shift between the radio (4cm) and optical (6000 A) (Kovalev et al. 2008)

An origin of the radio jet in M87 at the location of the central black hole

(Hada et al. 2011, Nature, 477, 185)





to determine the upstream end of the jet. The data reveal that the central engine of M87 is located within 14–23 R_s of the radio core at 43 GHz. This implies that the site of material infall onto the black hole and the eventual origin of the jet reside in the bright compact region seen on the image at 43 GHz.

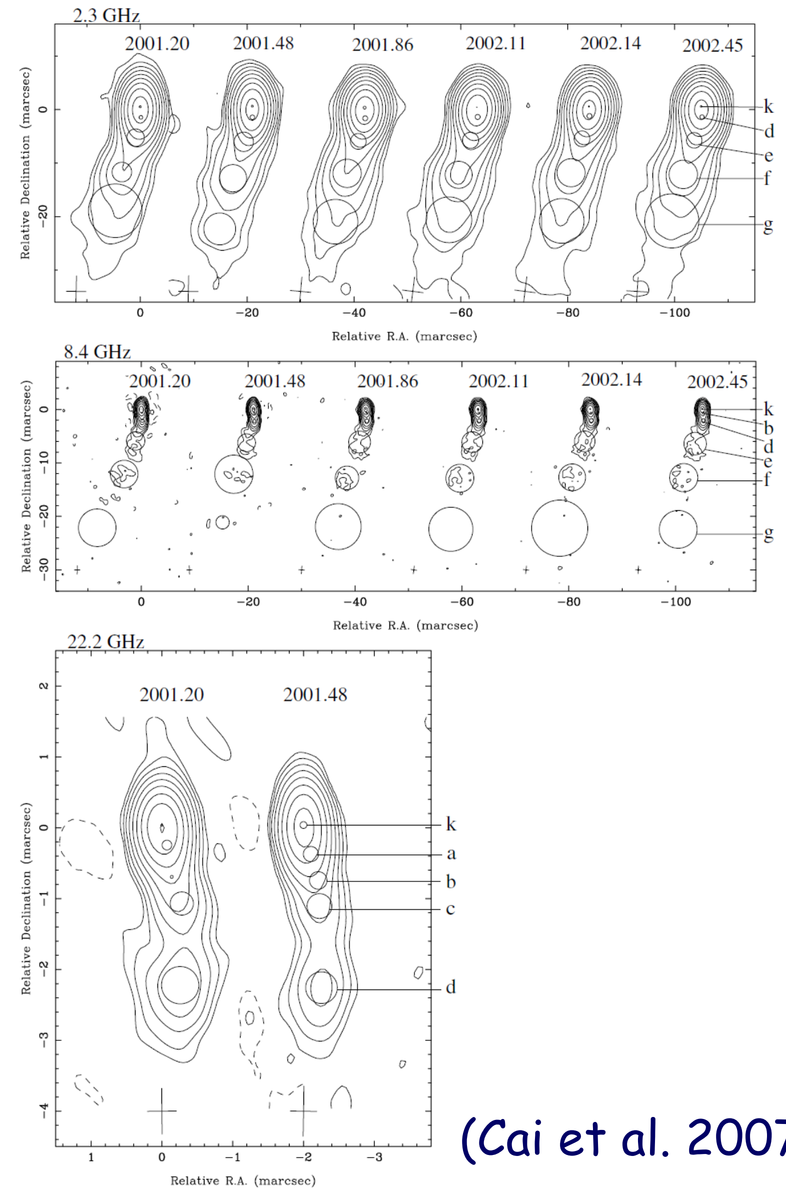
3C66A

- A low frequency peaked BL Lac object at z=0.444 (1mas ~ 5.69pc)
- Prominent variability at radio, IR and optical
- One-side core-jet structure with a PA~180°
- Detected superluminal motion

  (poster by Zhao et al.

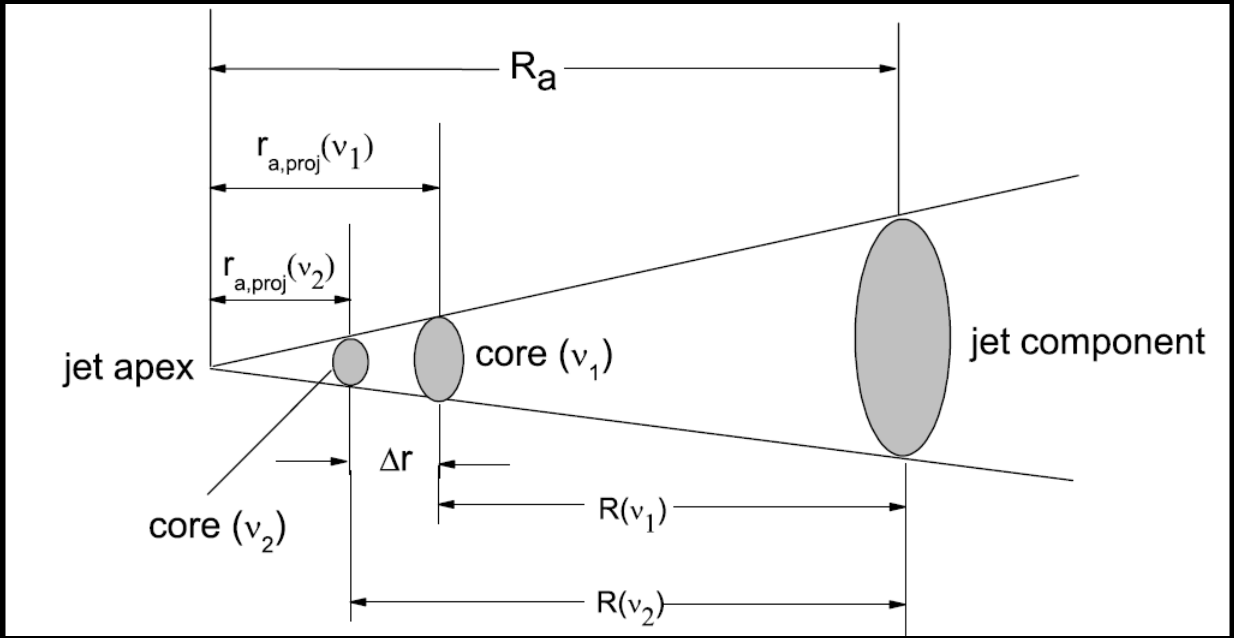
  IAUS290-1-0111)

- 2001-2002, multi-epoch VLBA imaging at three bands (2.3, 8.4 and 22 GHz) (Cai et al. 2007)
- Core: SSA spectrum with peak frequency of 6.52 GHz



(Cai et al. 2007)

Core shift in 3C66A (Cai et al. 2007)



$$r_{a,\mathrm{proj}}\ (\mathrm{mas}) = \Delta r_{\mathrm{mas}}(\nu_1, \nu_2) \frac{\nu_1^{1/k_r} \nu_2^{1/k_r}}{\nu_2^{1/k_r} - \nu_1^{1/k_r}} \cdot \nu^{-1/k_r}, \quad (1)$$

$$R_a(\mathrm{mas}) = R + r_{a,\mathrm{proj}}, \quad (2)$$

	2001.20	2001.48	2001.86	2002.11	2002.14	2002.45	Average
Δr_{mas}	0.23 ± 0.032	0.21 ± 0.036	0.21 ± 0.028	0.36 ± 0.028	0.37 ± 0.032	0.24 ± 0.036	0.27 ± 0.032
$r^{2.3}_{a,\mathrm{proj}}$	0.32 ± 0.044	0.29 ± 0.050	0.29 ± 0.038	0.50 ± 0.038	0.51 ± 0.044	0.33 ± 0.050	0.37 ± 0.044
$r^{8.4}_{a,\mathrm{proj}}$	0.087 ± 0.012	0.079 ± 0.014	0.079 ± 0.010	0.14 ± 0.010	0.14 ± 0.012	0.090 ± 0.014	0.10 ± 0.012
R_a	2.31 ± 0.016	2.36 ± 0.024	2.29 ± 0.022	2.30 ± 0.022	2.30 ± 0.016	2.31 ± 0.024	2.31 ± 0.021

Notes: Δr_{mas} is defined to be the positional offset of the core relative to the jet apex, and is equivalent to the observed positional difference of component d at 2.3 and 8.4 GHz, $r^{2.3}_{a,\mathrm{proj}}$ and $r^{8.4}_{a,\mathrm{proj}}$ are the estimated separation (from Eq. (1)) of the core from the jet apex at 2.3 GHz and 8.4 GHz, respectively, and R_a (from Eq. (2)) is the estimated separation of component d from the jet apex, which is independent of frequency.

3C66A (new data in 2006)

- MOJAVE data; core flux increased around 2006 Nov 10
- Search for VLBA dataset
  - 8.4 & 22.2 GHz data observed on 2006 Dec 3 & 10 : from VLBA archive data (BB228)
  - 15.4 GHz data: from MOJAVE archive

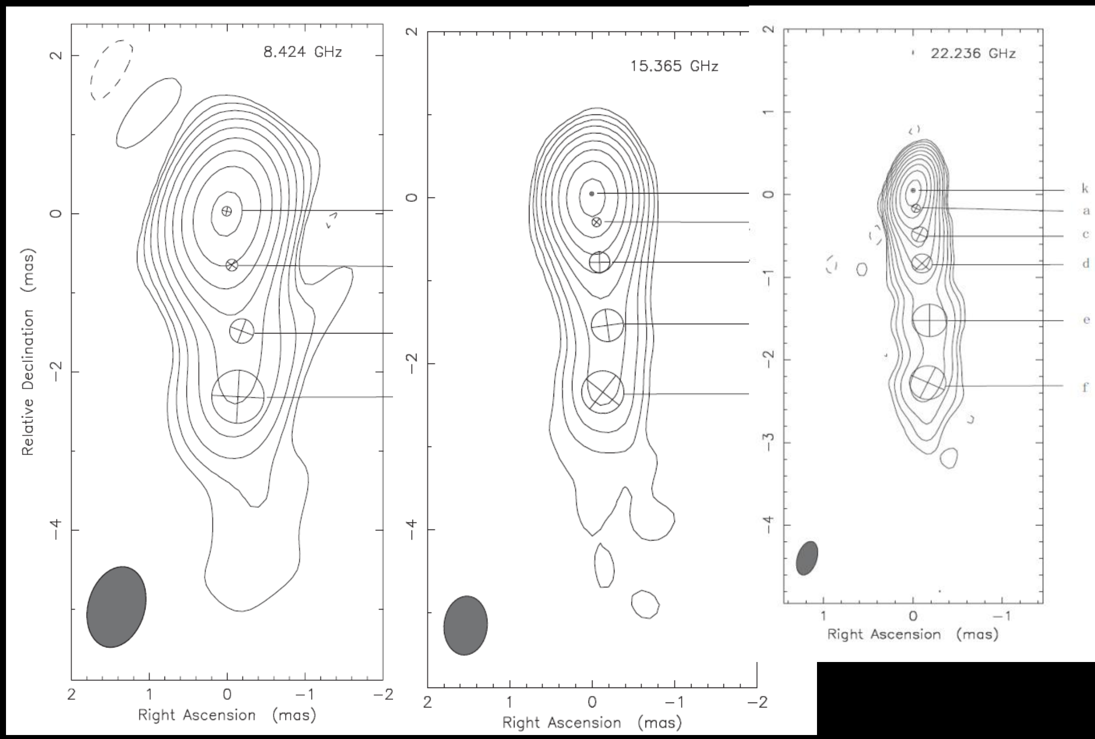
ν (GHz)	8.4	15.4	22.2
r (mas)	0.681	0.829	0.883
Major beam size (mas)	1.0	0.7	0.4

- We obtained:

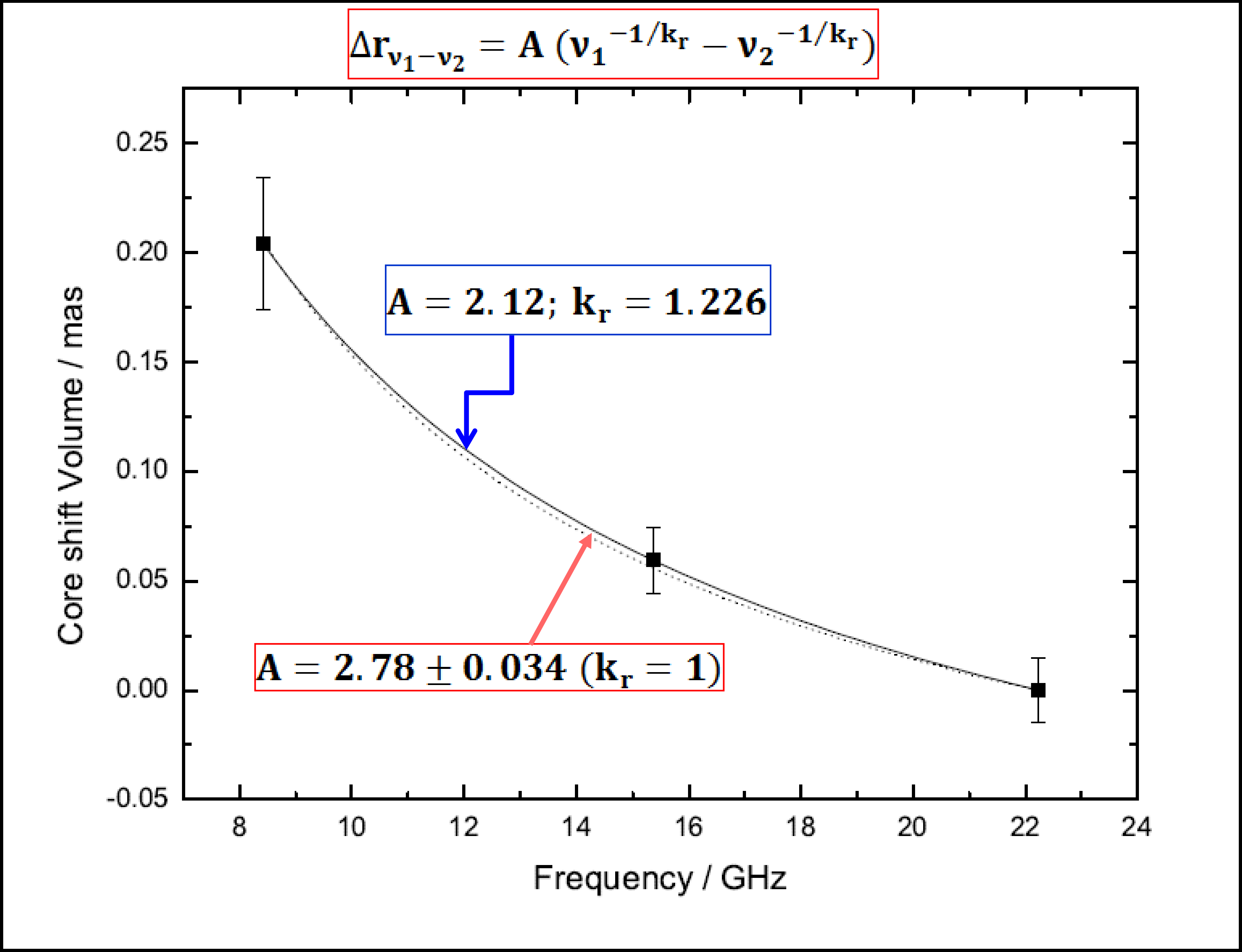
Δ r(8.4-15.4) = 0.148 mas

Δ r(8.4-22.2) = 0.202 mas

Δ r(15.4-22.2) = 0.054 mas



Core Shift Fitting



comparison

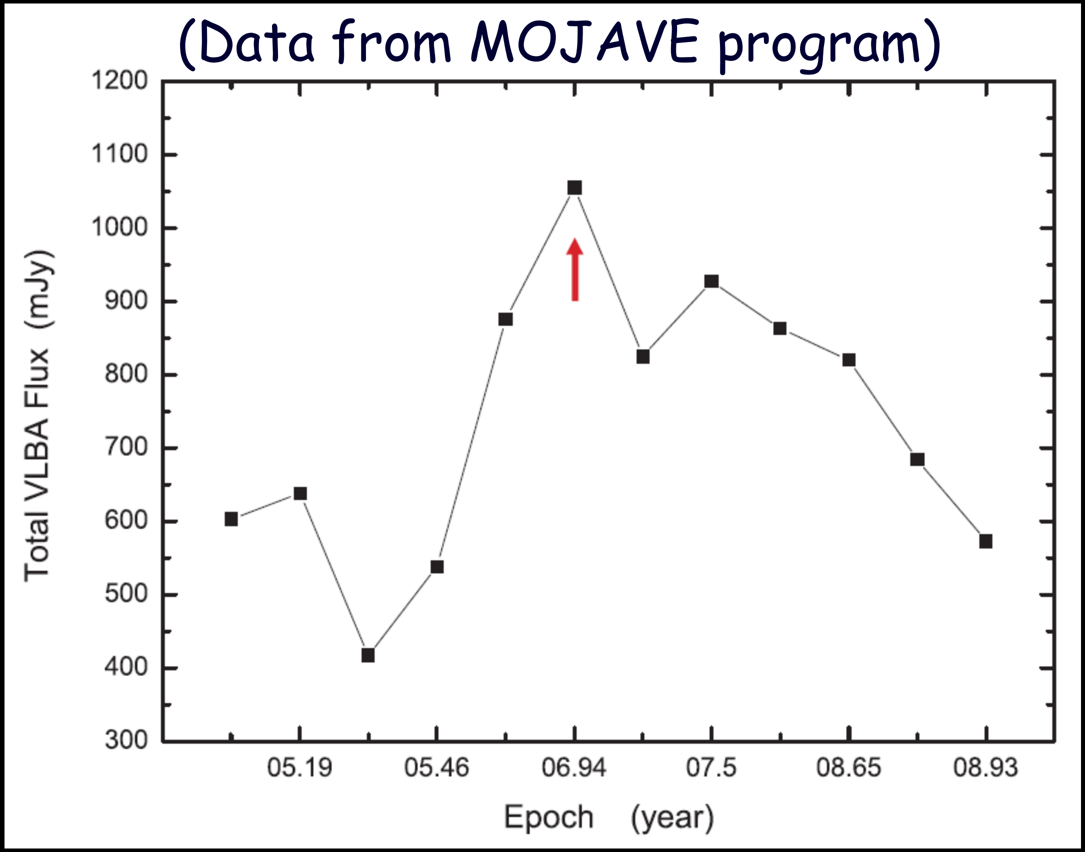
- With the fitting results $\Delta r_{\nu_1-\nu_2} = 2.78\,(\nu_1^{-1} - \nu_2^{-1})$, one can estimate the core shift values between 2.3GHz and 8.4 & 22.2 GHz to compare with the previous results in 2001 (Cai et al. 2007).

Epoch	2001.20	2001.48	**2006.94**
Core flux at 8.4GHz (Jy)	0.564 ± 0.06	0.637 ± 0.06	**0.755 ± 0.07**
Δr (2.3-8.4) (mas)	0.23 ± 0.03	0.21 ± 0.03	**0.88 ± 0.06**
Δr (2.3-22.2) (mas)	0.28 ± 0.03	0.24 ± 0.03	**1.08 ± 0.06**

- It shows that the core shift in 2006 is about 4 times that in 2001.

A flare

- 3C 66A showed a significant increase in the 15GHz core flux density at the end of 2006



- Temporal core flare/outburst may cause the change in the core shift (Kovalev et al. 2008)

core flare vs. jet flare

core flare !

- Two types of radio flares (Zhou et al. 2000)
  - ■ The jet flare

    — no significant time lag between different frequencies

    X — change in the orientation of the jet

    (no such change seen from 15 GHz images from 2006.86 to 2008.88)
  - ■ The core flare

    — significant time lag

    ✓ — core flux density increased

    ✓ — new component emerged from the central core region

	2001.20	**2006.94**
	0.29 ± 0.01	0.217 ± 0.015
	——	0.532 ± 0.015
Reference jet component	0.74 ± 0.02	0.883 ± 0.015

Changes due to flare?

Following Lobanov (1998), we have

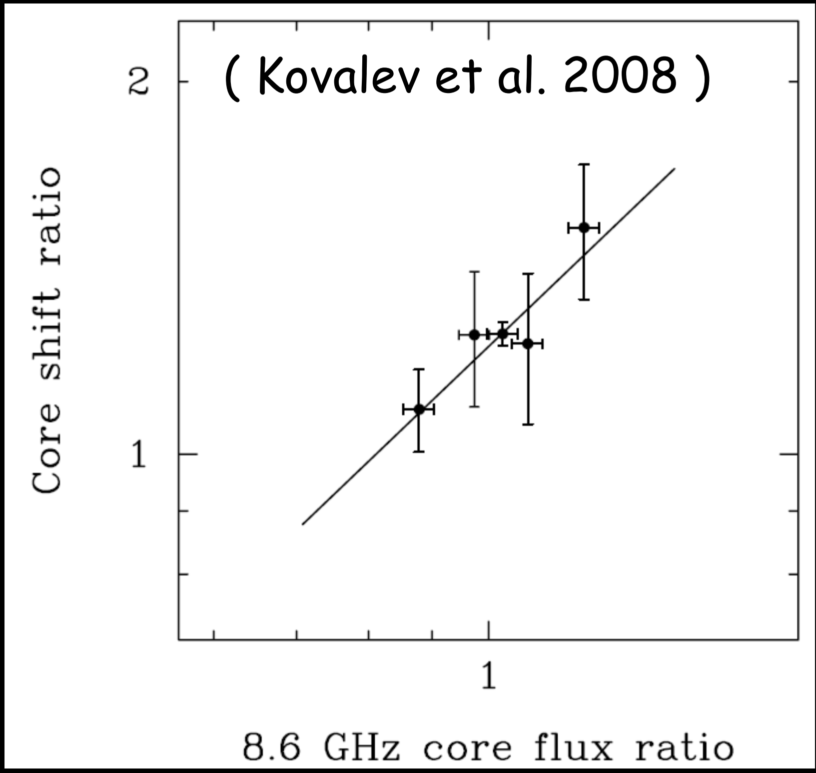
$$\Delta r \propto S_{\rm core}^{2/3}\delta_{\rm j}^{2/3}\beta_{\rm j}^{-2/3}\Gamma_{\rm j}^{-4/3}$$

With $S_{\rm core} \propto \delta_{\rm j}^{2-\alpha} N_0 B_{\rm core}^{1-\alpha}$, we can derive

$$\Delta r \propto \left(\delta_{\rm j}^{3-\alpha} N_0 B_{\rm core}^{1-\alpha} \beta_{\rm j}^{-1} \Gamma_{\rm j}^{-2}\right)^{2/3}$$

Assuming that B_{core} and δ_j change weakly (Lobanov & Zensus 1999), we have

$$\Delta r \propto N_0^{2/3} \propto S_{\rm core}^{2/3}$$



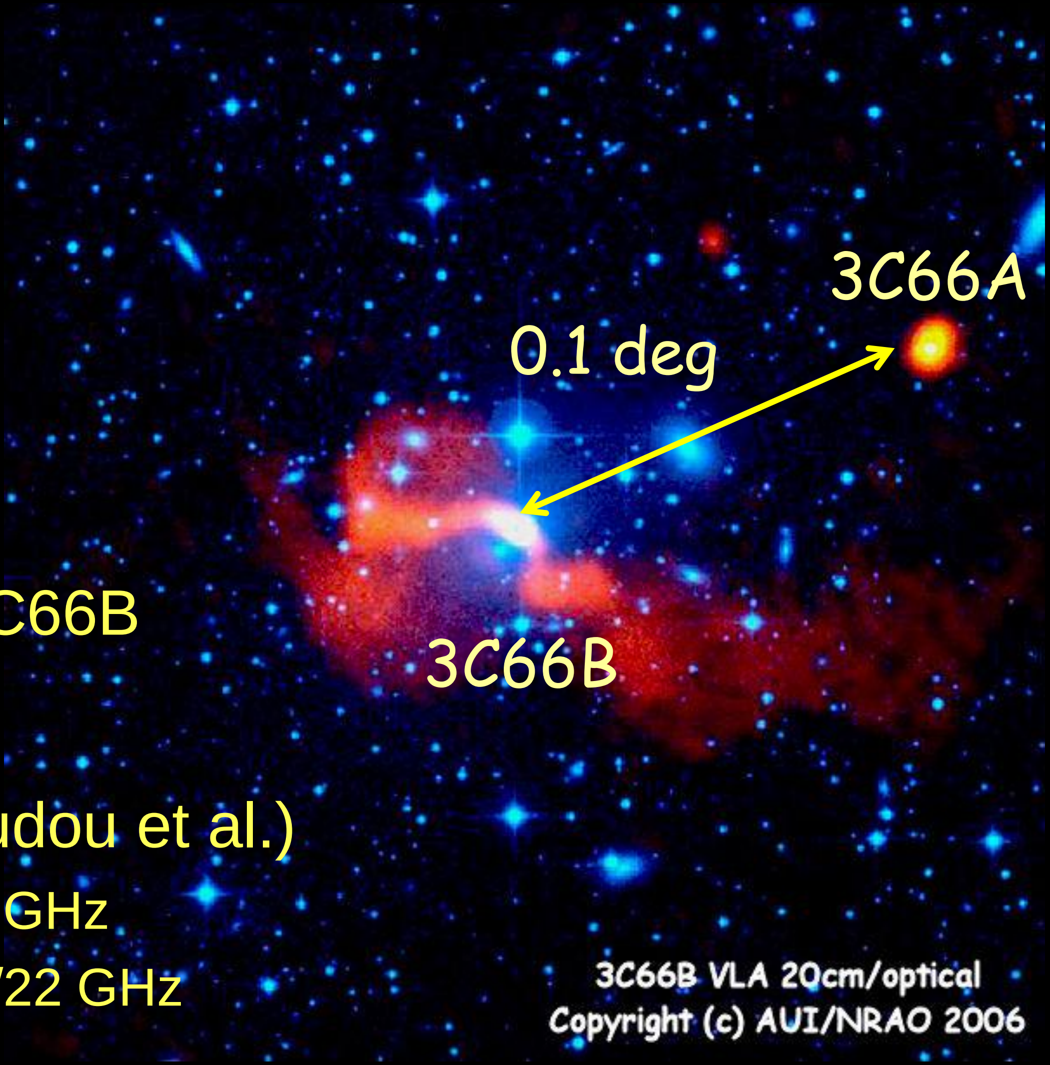
So we can test the relation between core flux density and core shift.

Our data indicate a core shift ratio of 4.0 (0.88/0.22) , this would require a core flux density increase by a factor of 8 (inconsistent with 1.3 from the data at 8.4 GHz).

Therefore, some other parameters (such as B_{core}) also change during the flare.

3C66A & 3C66B : an ideal pair

- 3C66B
  - z~0.02, radio galaxy
  - Merged E galaxy ?
- 3C66A
  - z~0.444, BL Lac object
  - One side core-jet
  - Fermi detected
  - Position reference of 3C66B
- Θs = 0.1 degree
- VLBA observations (Sudou et al.)
  - 2001-2002, 6 epochs at 2/8 GHz
  - 2004-2005, 4 epochs at 2/8/22 GHz



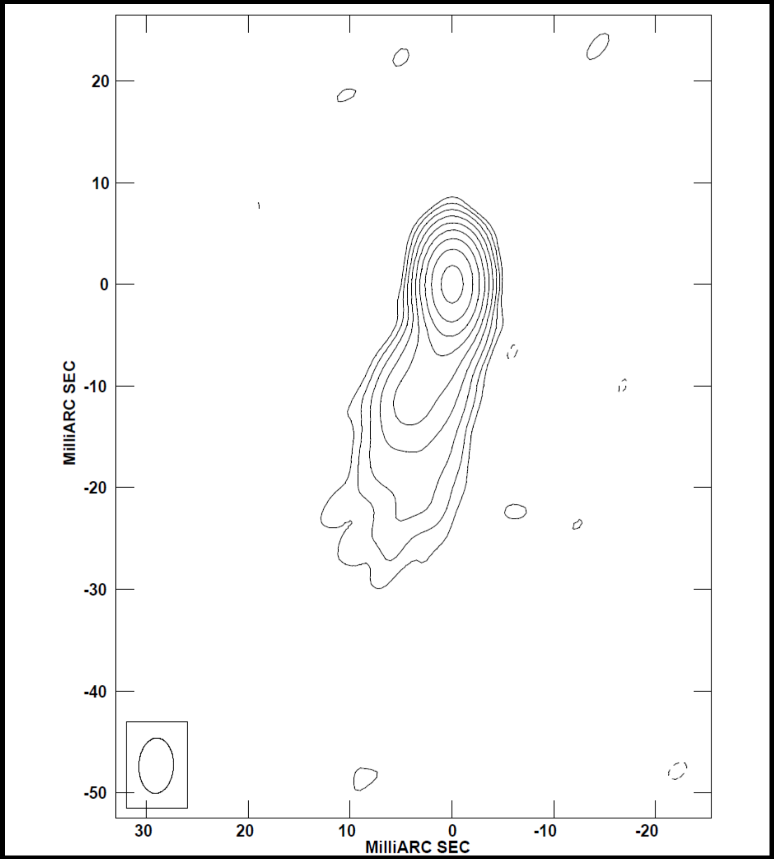
2004-5 VLBA Observations

- VLBA project BS144
  - 4 epochs: 2004.80, 2005.05, 2005.35, 2005.54

  - 3 frequencies:
    - 2.3 & 8.4 GHz;
      - In-beam mode; ~70 min
      - Fast-switching mode; ~30 min
    - 22 GHz; fast-switching mode; ~40 min

  - 4 IFs, 8MHz each;

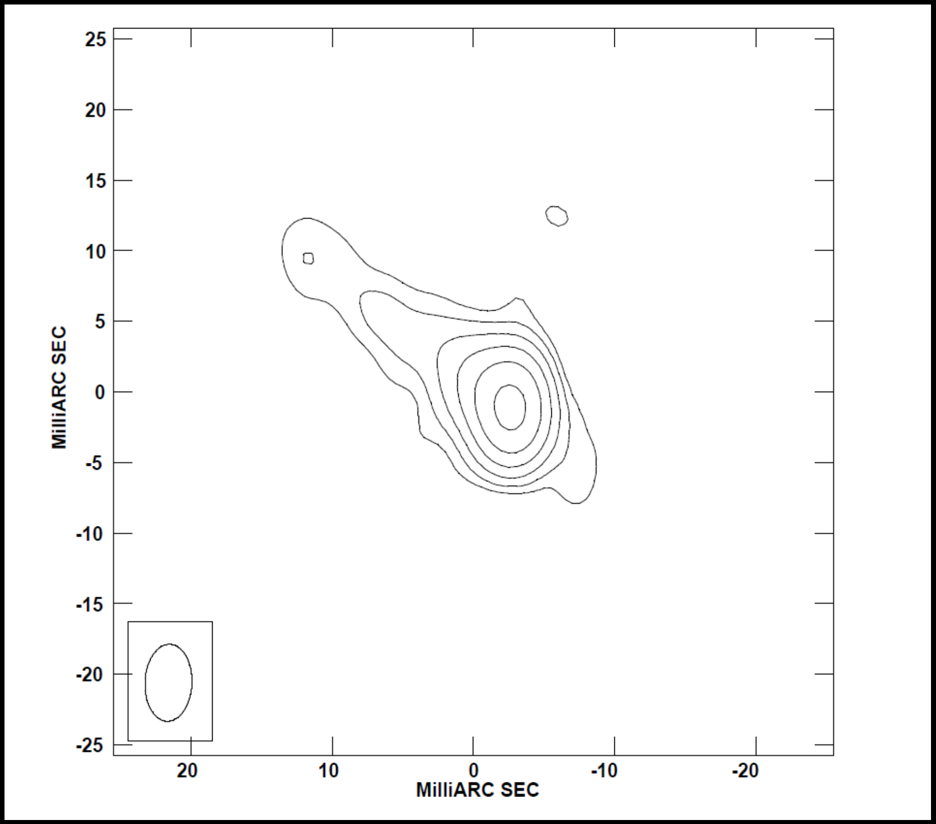
Results: Maps



3C 66A at 2.3 GHz at 2005.05

Beam: 5.43*3.41 mas at P.A. 2.26°

Contour: 1.5mJy/beam* (-1, 1, 2, 4, …, 256)

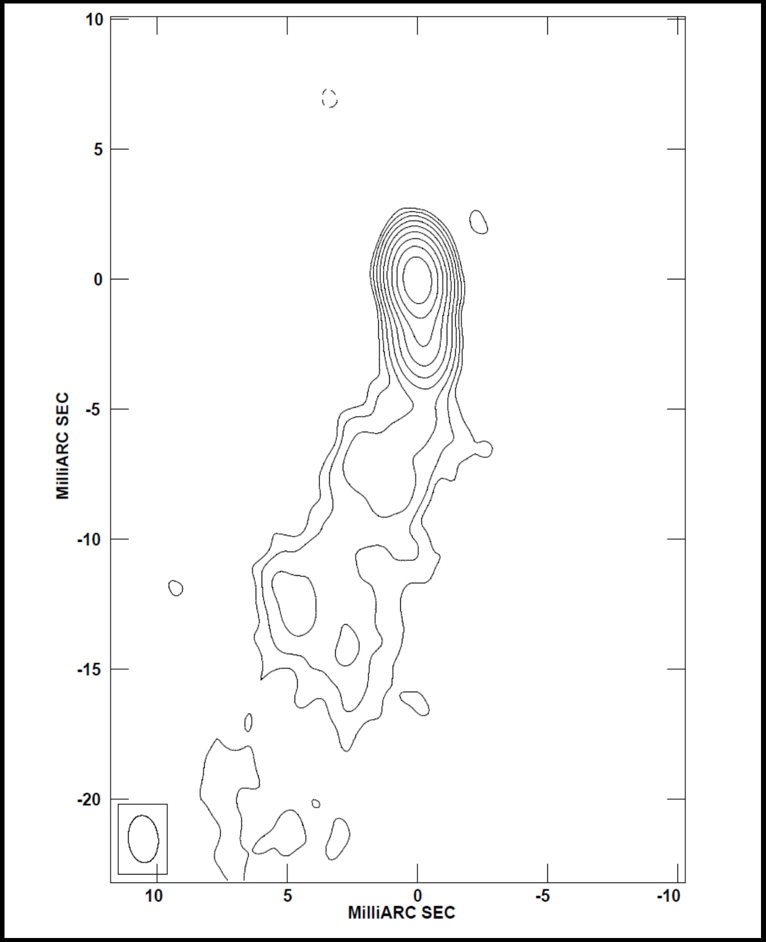


3C 66B at 2.3 GHz at 2005.05

Beam: 5.46*3.33 mas at P.A. -2.34°

Contour: 2.5mJy/beam* (-1, 1, 2, 4, …, 32)

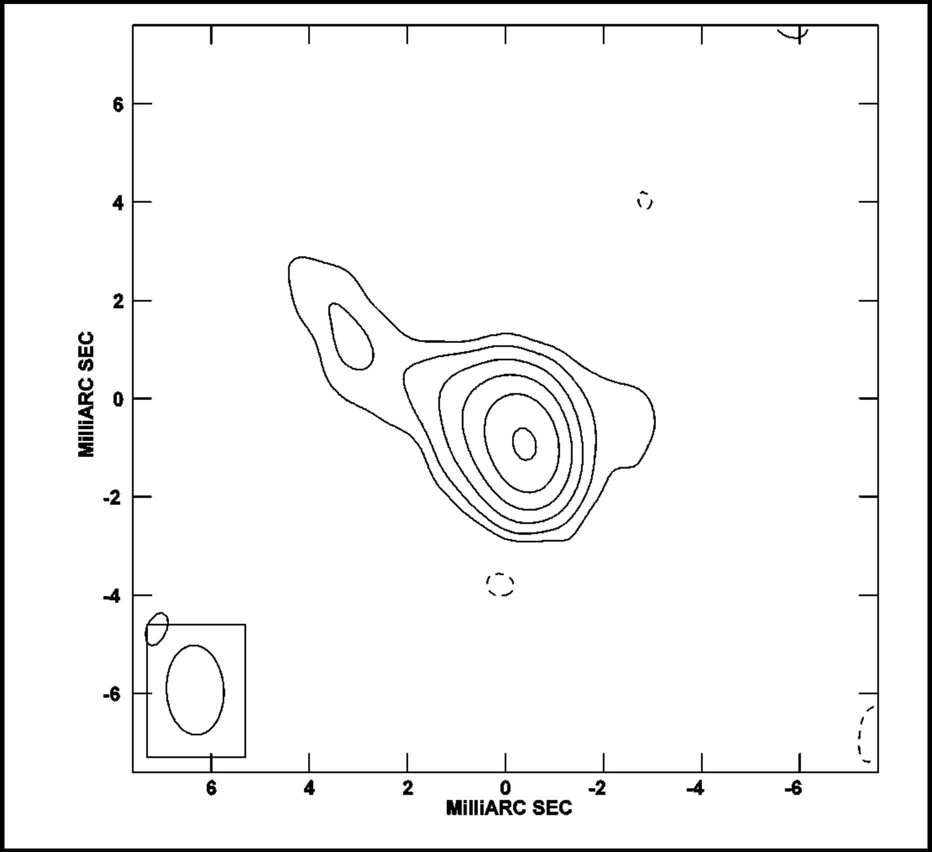
Results: Maps



3C 66A at 8.4 GHz at 2005.05

Beam: 1.82*1.15 mas at P.A. 5.14°

Contour: 1.0mJy/beam* (-1, 1, 2, 4, …, 256)

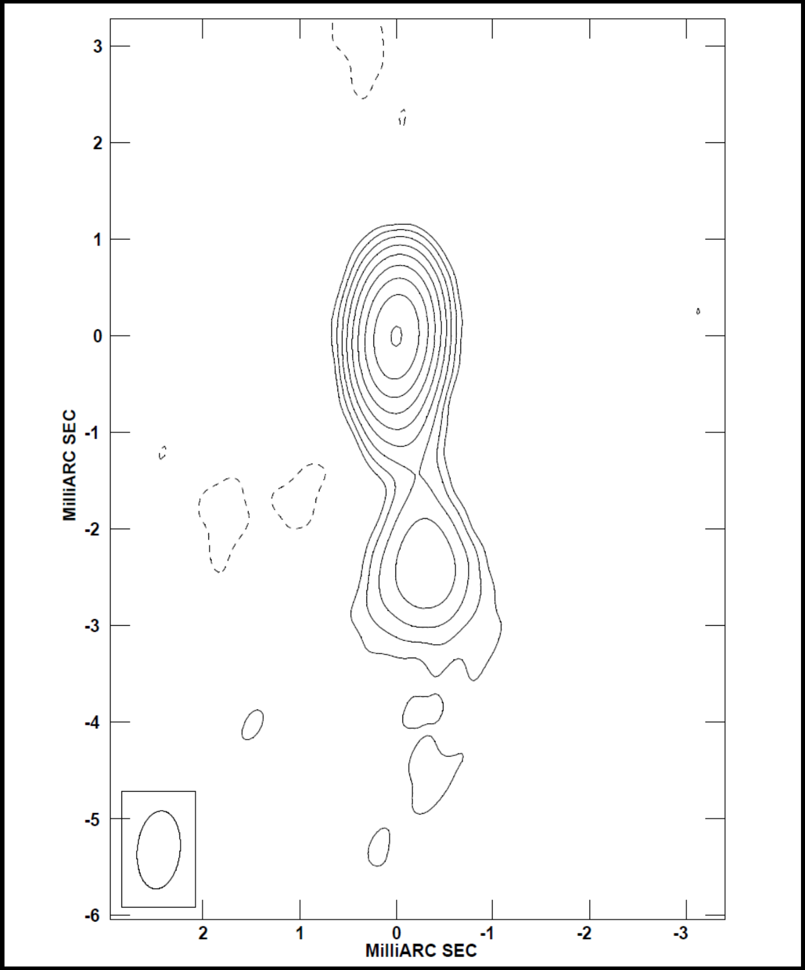


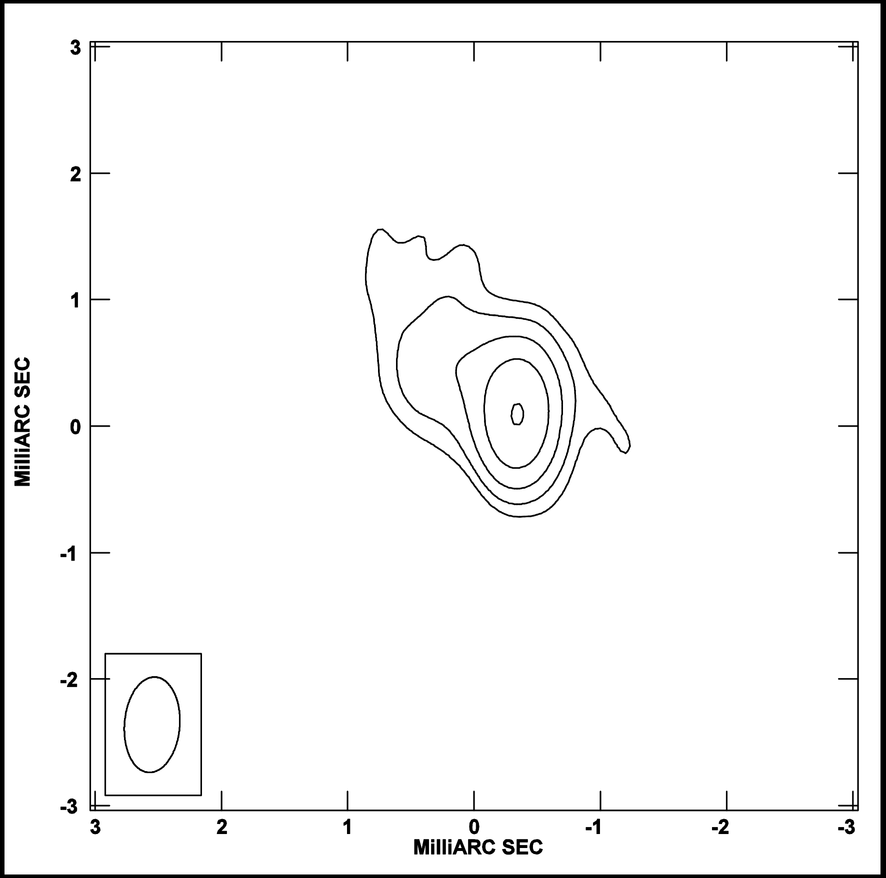
3C 66B at 8.4 GHz at 2005.05

Beam: 1.82*1.17 mas at P.A. 2.98°

Contour: 2.5mJy/beam* (-1, 1, 2, 4, …, 32)

Results: Maps





3C 66A at 22 GHz at 2005.05

Beam: 0.8*0.44 mas at P.A. -5.75°

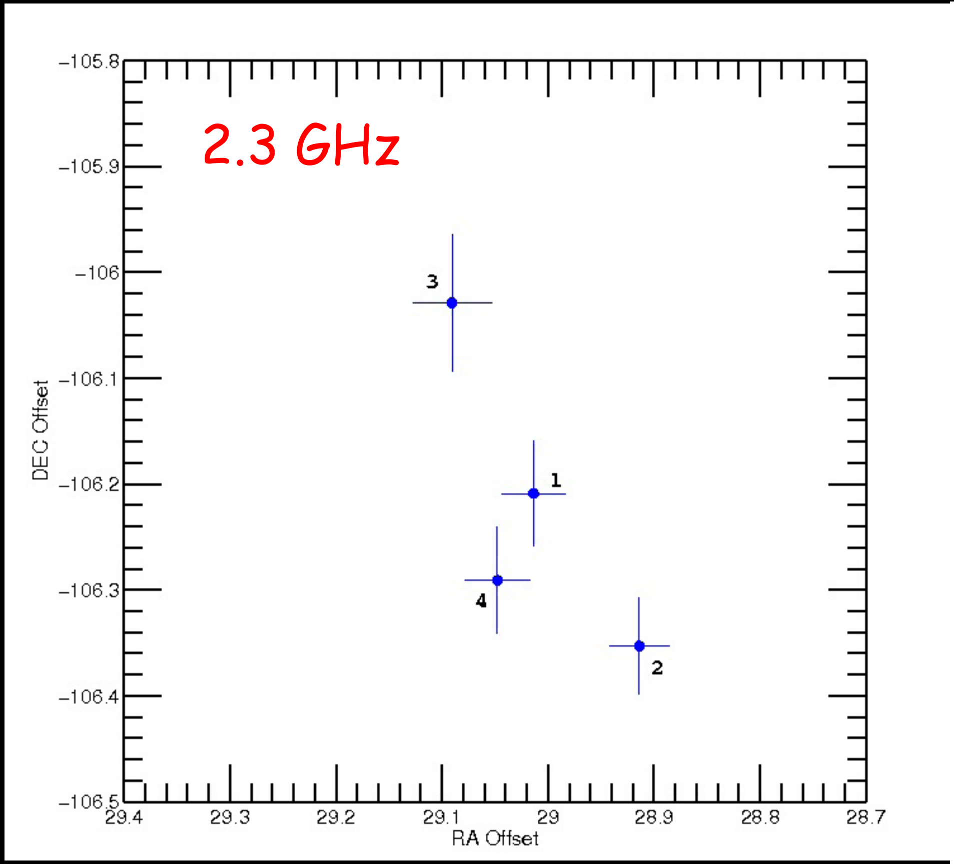
Contour: 1.5mJy/beam* (-1, 1, 2, 4, …, 256)

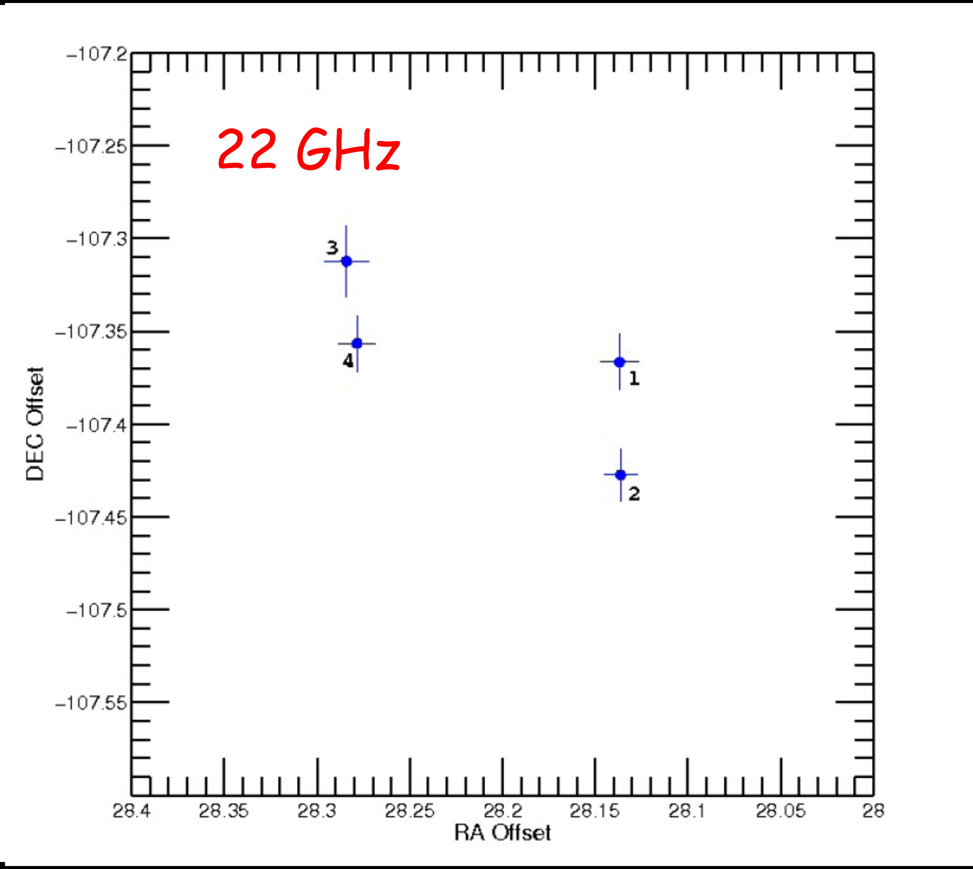
3C 66B at 22 GHz at 2005.05

Beam: 0.76*044 mas at P.A. -4.39°

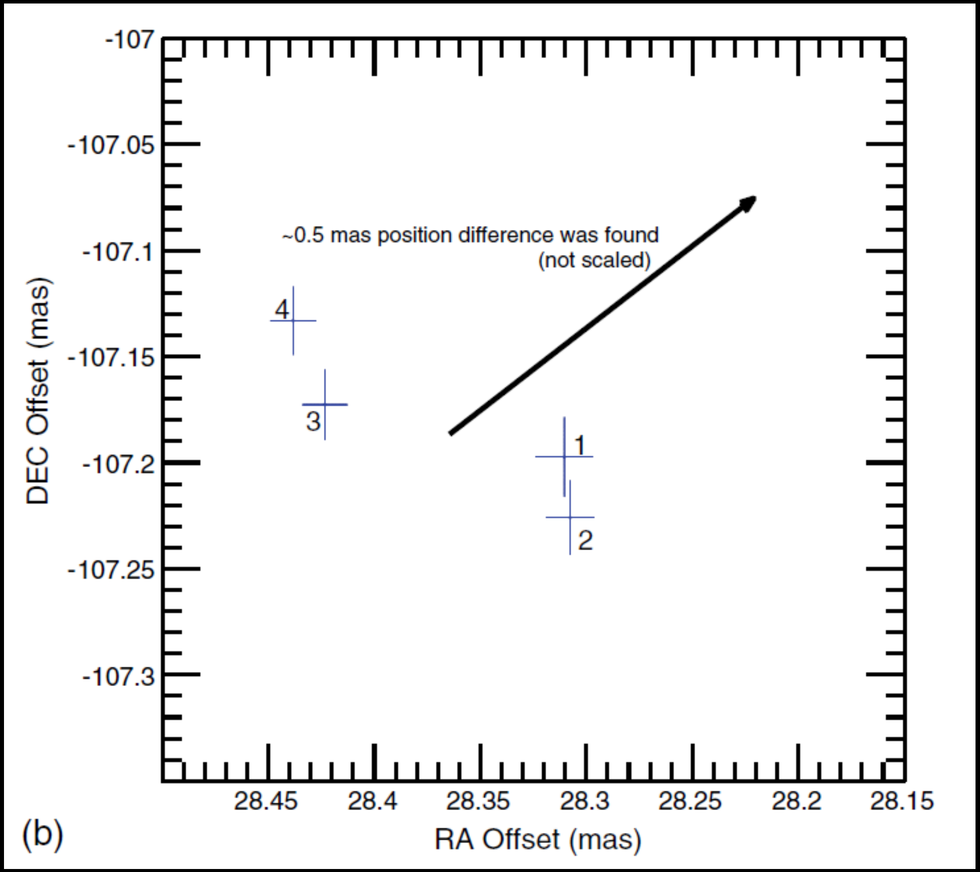
Contour: 2.5mJy/beam* (-1, 1, 2, 4, 8, 16)

position measurements of 3C66B





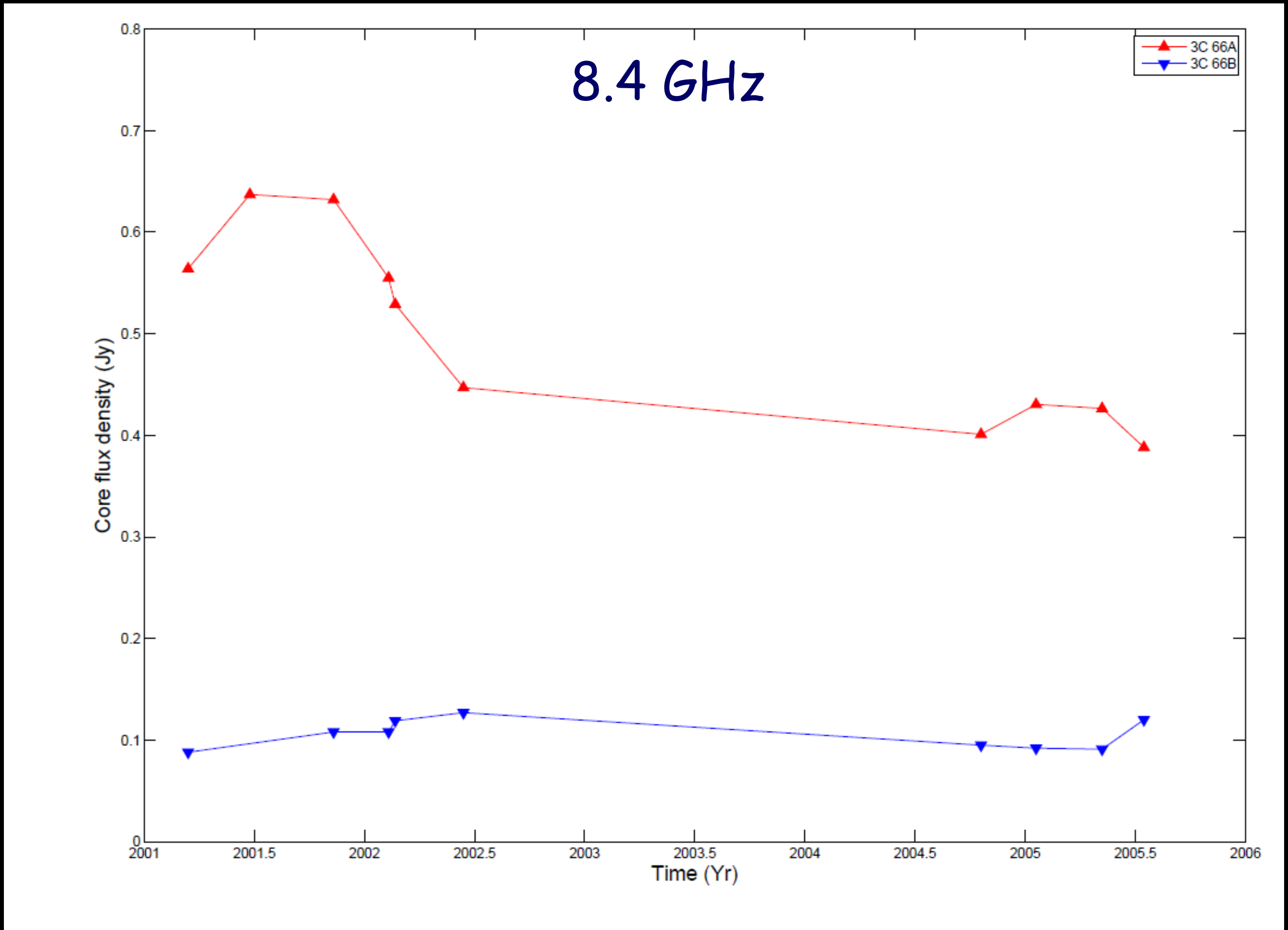
Results: position measurements



3C 66B positions at 8.4 GHz
(Zhao et al. 2011)

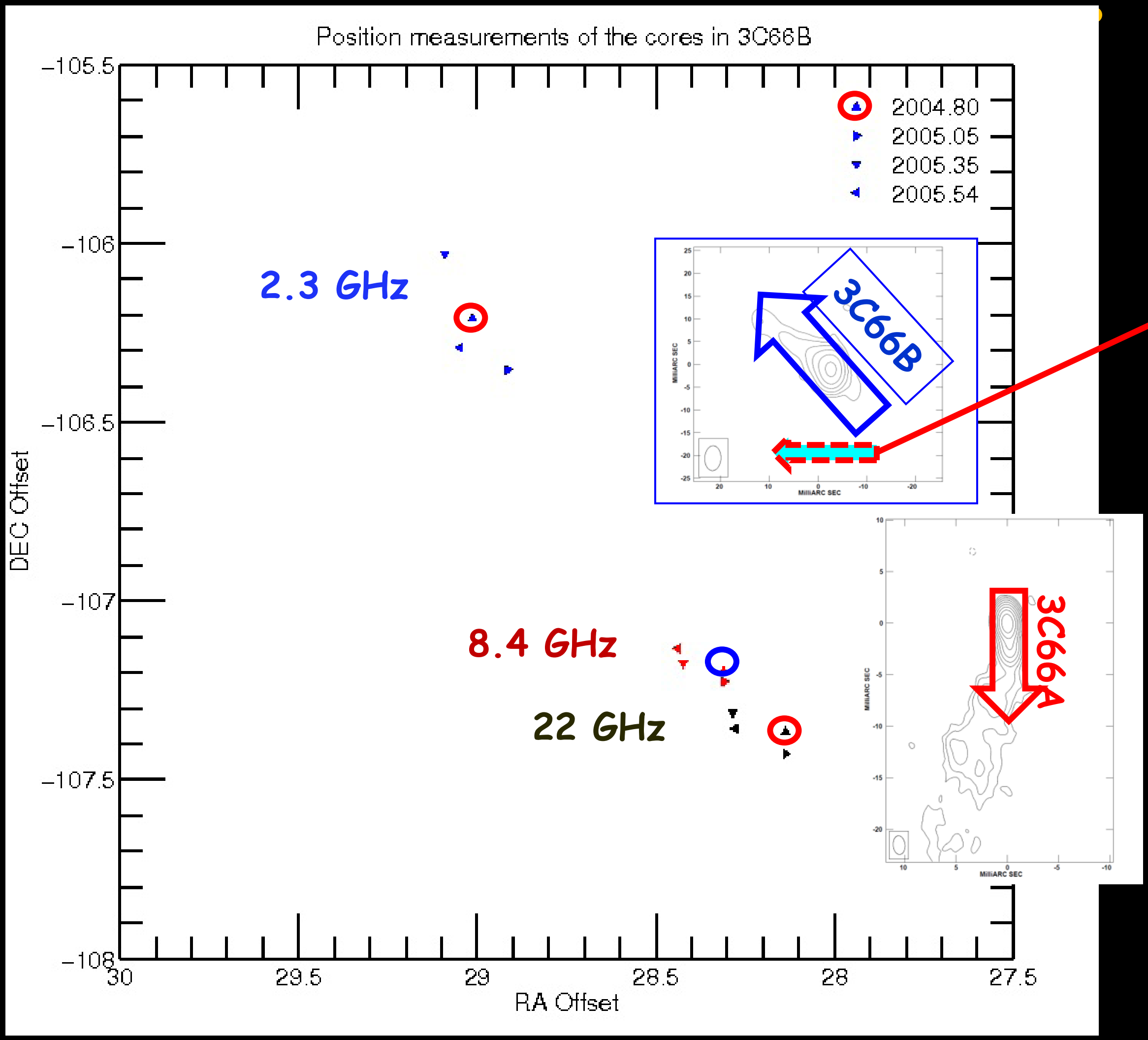
- A large difference was found compared to previous results
  - ~0.5 mas at 8.4 GHz
  - ~0.7 mas at 2.3 GHz

Light curves of the core in 3C66A & 3C 66B



3C 66B data from Sudou & Iguchi (2010);
3C 66A data from Cai et al. (2007) & Zhao et al. (in prep.)

Combined core-shift of two sources



- e.g. at epoch 2004.80

  measured core-shift between 2.3 & 8.4 GHz on 3C66B:

  R.A. : = 0.703 mas

  DEC: = 0.988 mas

For 3C 66B, P.A.≈55°

$r_{2.3\text{-}8.4}$=0.858 mas

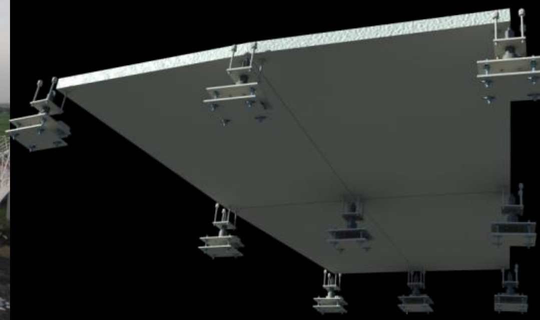
For 3C 66A, P.A. ≈180°

$r_{2.3\text{-}8.4}$=0.496 mas

(cf. 0.22 mas in 2001)

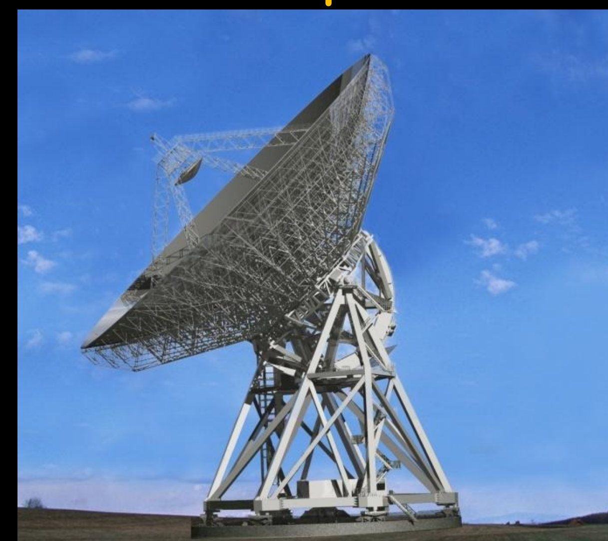
Puzzle (core flux vs. core shift)

- Compared with the results in 2001, the measured core shift is larger in 2006 when the core flux density is higher.
- But, in 2005, we got a larger core shift with a lower core flux density.
- **The difference in core shift result cannot be simply explained by the core flare activity; other parameters apart from core flux or mechanisms may have influence on the core shift**. *More data required!*
- Such kind of core shift effect has an impact on the high precision astrophysical and astrometric studies.



Shanghai 65m Radio Telescope

- 65-m in diameter fully steerable radio telescope
- Active surface system installed
- Covering 1.4 – 46 GHz with 8 bands
  - L(1.6GHz), S/X(2.3/8.4GHz)
    C(5GHz), Ku(15GHz), K(22GHz)
    Ka(30GHz), Q(43GHz)
- General-purpose (radio astronomy, geodynamics, single-dish, VLBI)



Funding Agencies:

- Chinese Academy of Sciences (CAS)
- Shanghai Municipality
- Chinese Lunar Exploration Project

Project Timeline

- **2008: funded; contract to CETC54 for the antenna construction**
- **2009: complete design (international review panel); start manufacturing; foundation laying ceremony**
- **2010-11: foundation completed; antenna construction (wheel-on-track, BUS, alidade, panels, …); active surface system (contract, design, fabrication, installation of actuators)**
- **2012: antenna completed; L/S/C/X band receivers in place; start commissioning observations; ready for participation in the Chinese Lunar Mission at S/X;**
- **2013-14: science observations at L/S/C/X bands; active surface tested, Ku/K/Ka/Q band commissioning;**
- **2015: project accomplished**

Shanghai 65m Radio Telescope

(as of August 16, 2012)