Study of the TeV blazar Mrk 501 with mm-VLBI

Shoko Koyama

(Greenland Telescope group/ ASIAA)

Collaborators:

Motoki Kino, Marcello Giroletti, Keiichi Asada, Gabriele Giovannini, Monica Orienti, Akihiro Doi, Kotaro Niinuma, Guangyao Zhao, Rocco Lico, Masanori Nakamura, Kazuhiro Hada, Kazunori Akiyama, Hiroshi Nagai, Eduardo Ros, David Paneque, Tuomas Savolainen, Thomas Krichbaum, Minttu Uunila, Wen-Ping Lo

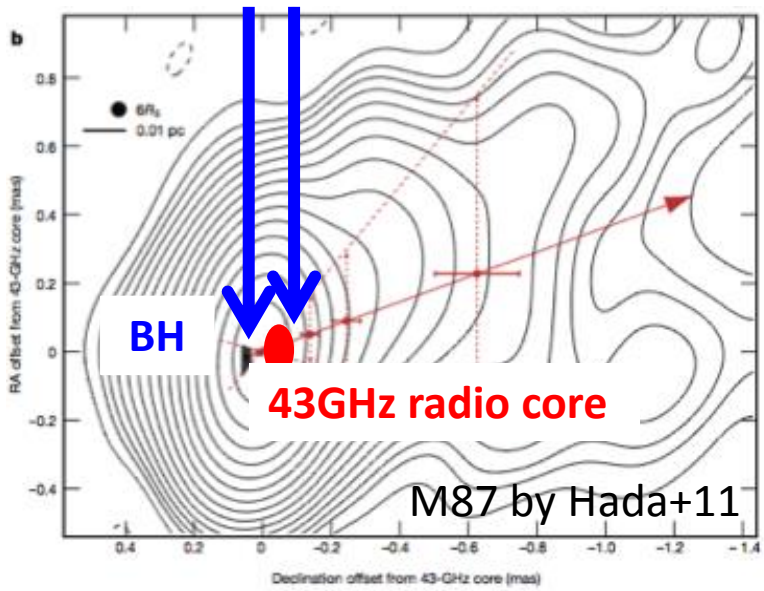
Contents

- Radio core astrometry of Mrk 501 with 43-GHz VLBI
- EHT+ALMA 2018 observations toward Mrk 501 at 230 GHz

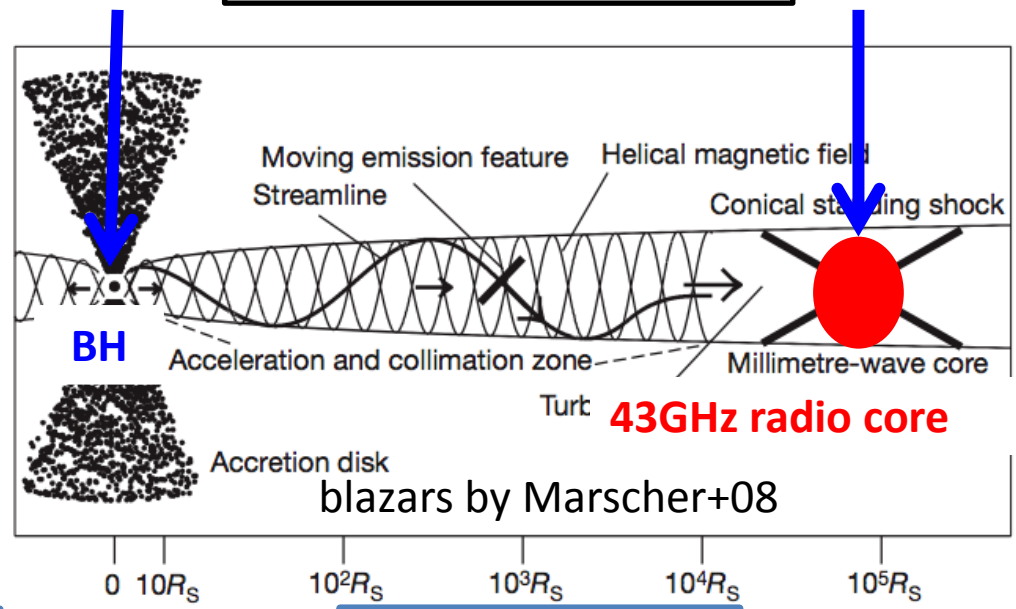
RADIO CORE ASTROMETRY

Locations between BH & radio core

$R_{bh\text{-}core}$~14-23R_s~0.01pc



$R_{bh\text{-}core}$~10^5R_s~ a few pc



multi-freq. core shift
+**VLBI phase referencing**
→**position accuracy ~beam/10**

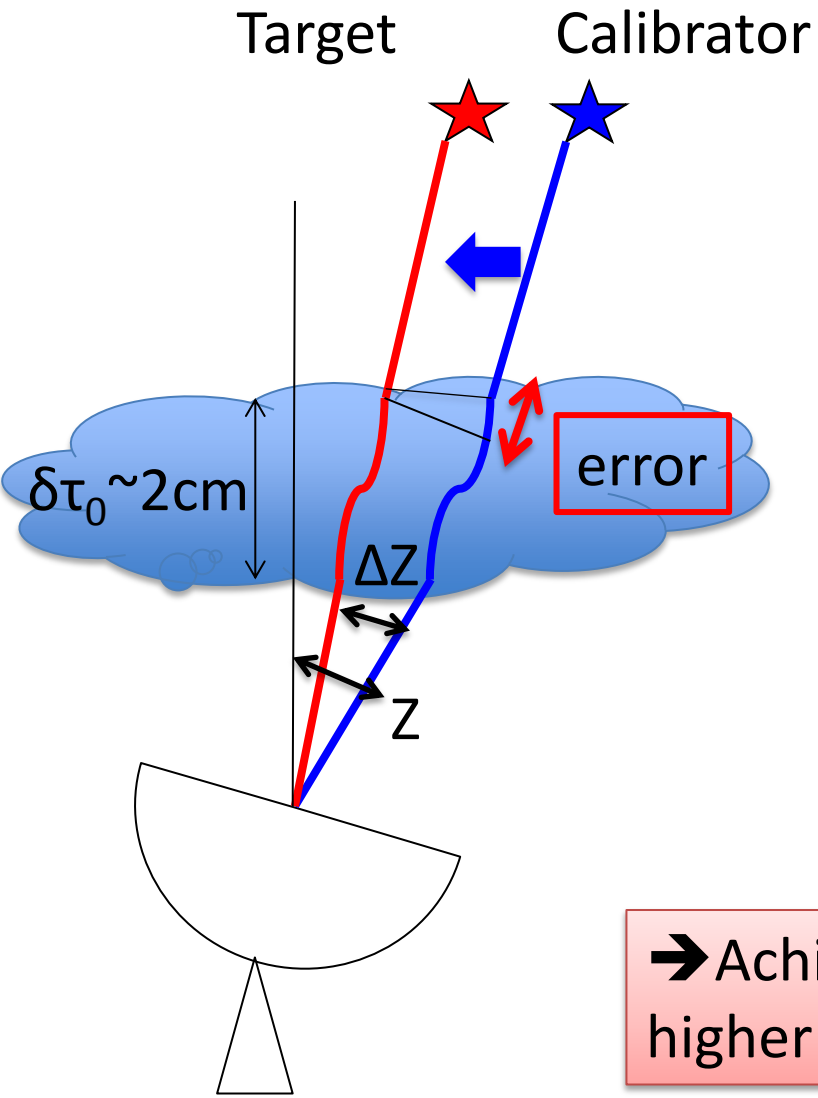
time lag method

- The locations of blazar radio cores at mm-wavelengths have not been studied with enough positional accuracy
- Blazar radio cores may wander if they are located far from the BH

Purpose

- Probe the precise location of radio cores in blazars
- Investigate the stability of it’s location

VLBI astrometry



Position accuracy of the target

$$dq \sim \frac{c\,dt_0}{D} \sec Z \tan Z \mathrm{D}Z$$

$\delta\tau_0$:atmospheric zenith delay, D:baseline, Z:zenith angle, ΔZ:separation

<u>e.g.: VERA</u>

D=2300 km, $\delta\tau_0$=2 cm, ΔZ=2° (Z=50°)

→δθ~0.12 mas (θ~0.6 mas @43 GHz)

<u>e.g.: VLBA</u>

D=8600 km, $\delta\tau_0$=2 cm, ΔZ=2° (Z=50°)

→δθ~0.04 mas (θ~0.2 mas @43 GHz)

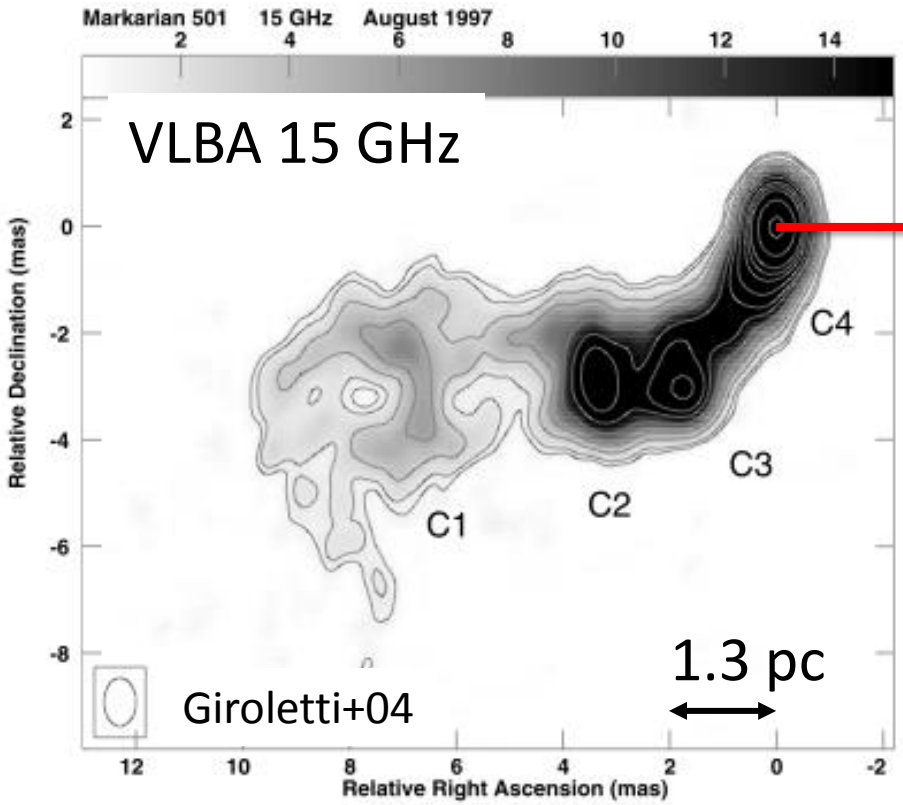
→Achieve a positional accuracy several times higher than the resolution

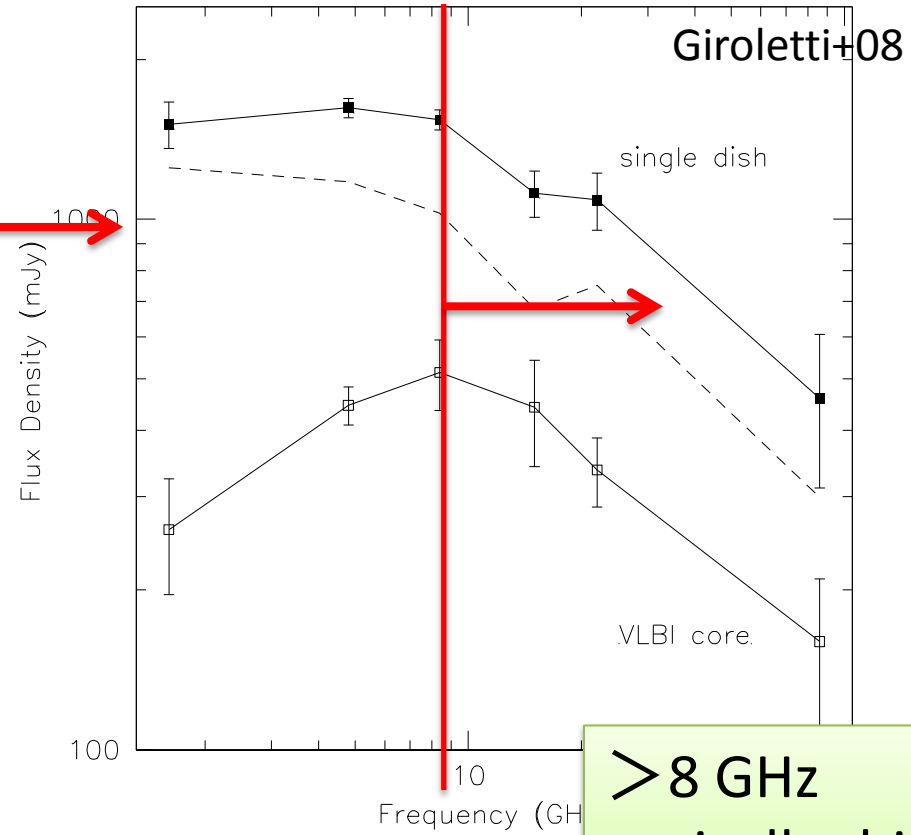
Target: TeV γ-ray blazar Mrk 501

①One of the closest blazars
z=0.034, 1 mas=0.66 pc

②Multiple close calibrators

③Radio core spectrum





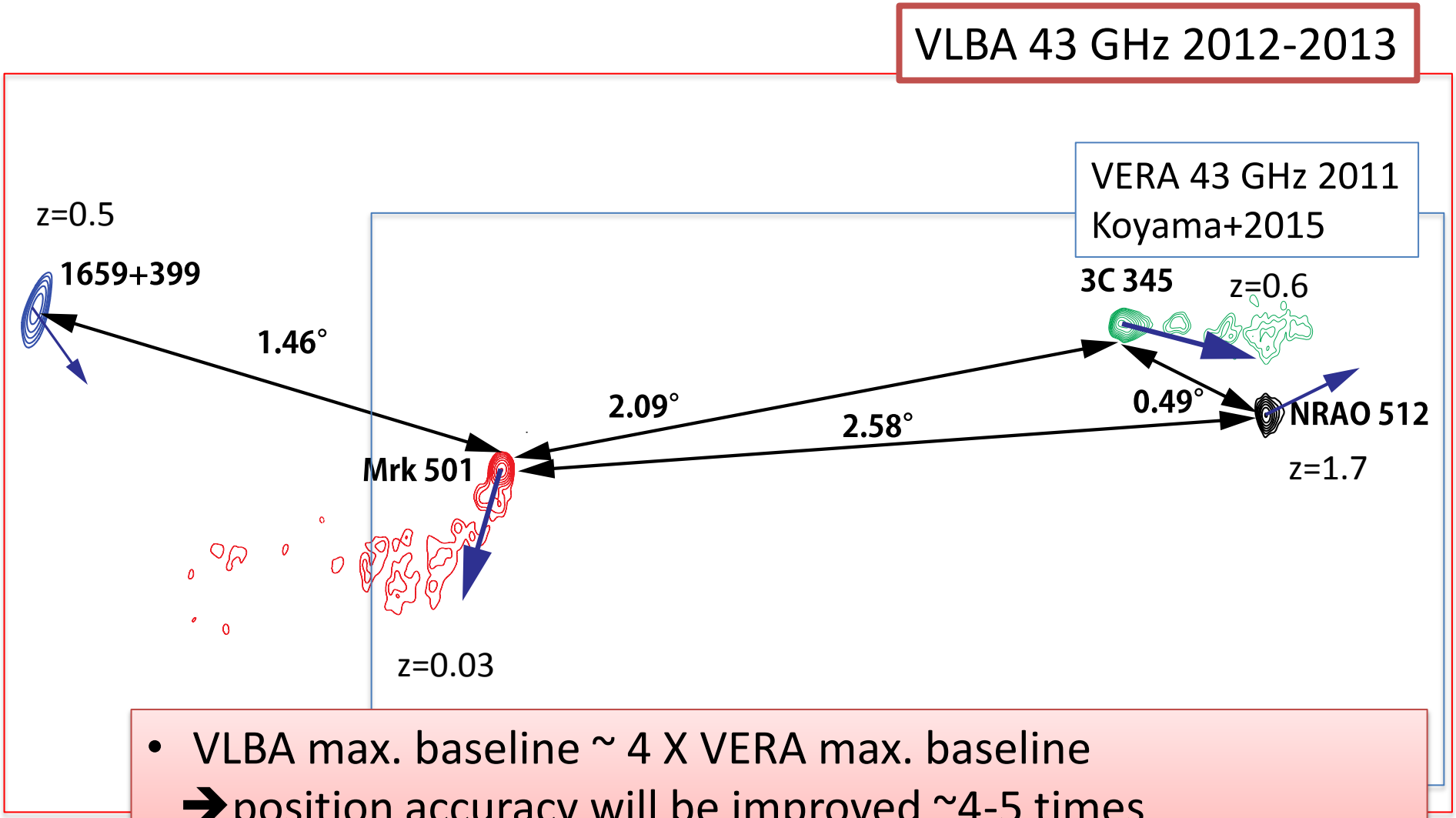
>8 GHz
optically thin

→The best source for radio core astrometry

Radio core astrometry with VLBI 43 GHz

- VERA : 4 stations
  - Obs. time : 8 hrs/1d
  - Obs. date
    - 2011.Feb.15,16,17,18
    - 2011.Oct.20,21,23,24
  - Obs. mode
    - 2beam mode (VERA 7)
      - Abeam(1IF=16Mhz):3C 345
      - Bbeam(15IF=240Mhz): NRAO 512 & Mrk 501
- VLBA : 10 stations
  - Obs. time : 4 hrs/1d
  - Obs. date
    - 2012. 2/12, 3/16, 5/6, 6/11, 2013. 1/18, 2/15
  - Obs. mode
    - Fast switching below 30sec
    - BW= 128MHz

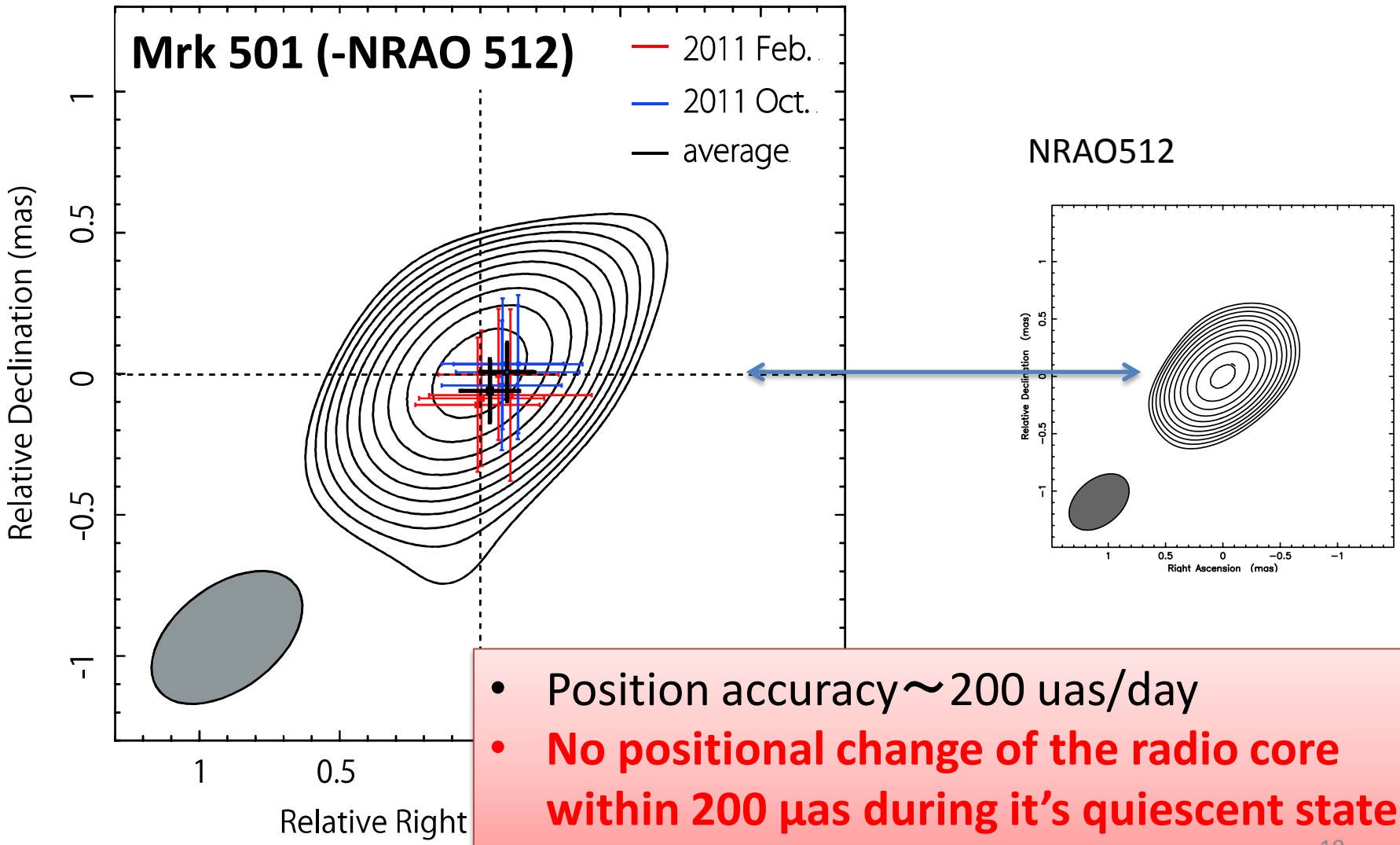
Configuration of sources around Mrk 501



- VLBA max. baseline ~ 4 X VERA max. baseline
  ➔position accuracy will be improved ~4-5 times
- Closer calibrator 1659+399 is also available for check source

Results of VERA 43GHz astrometry

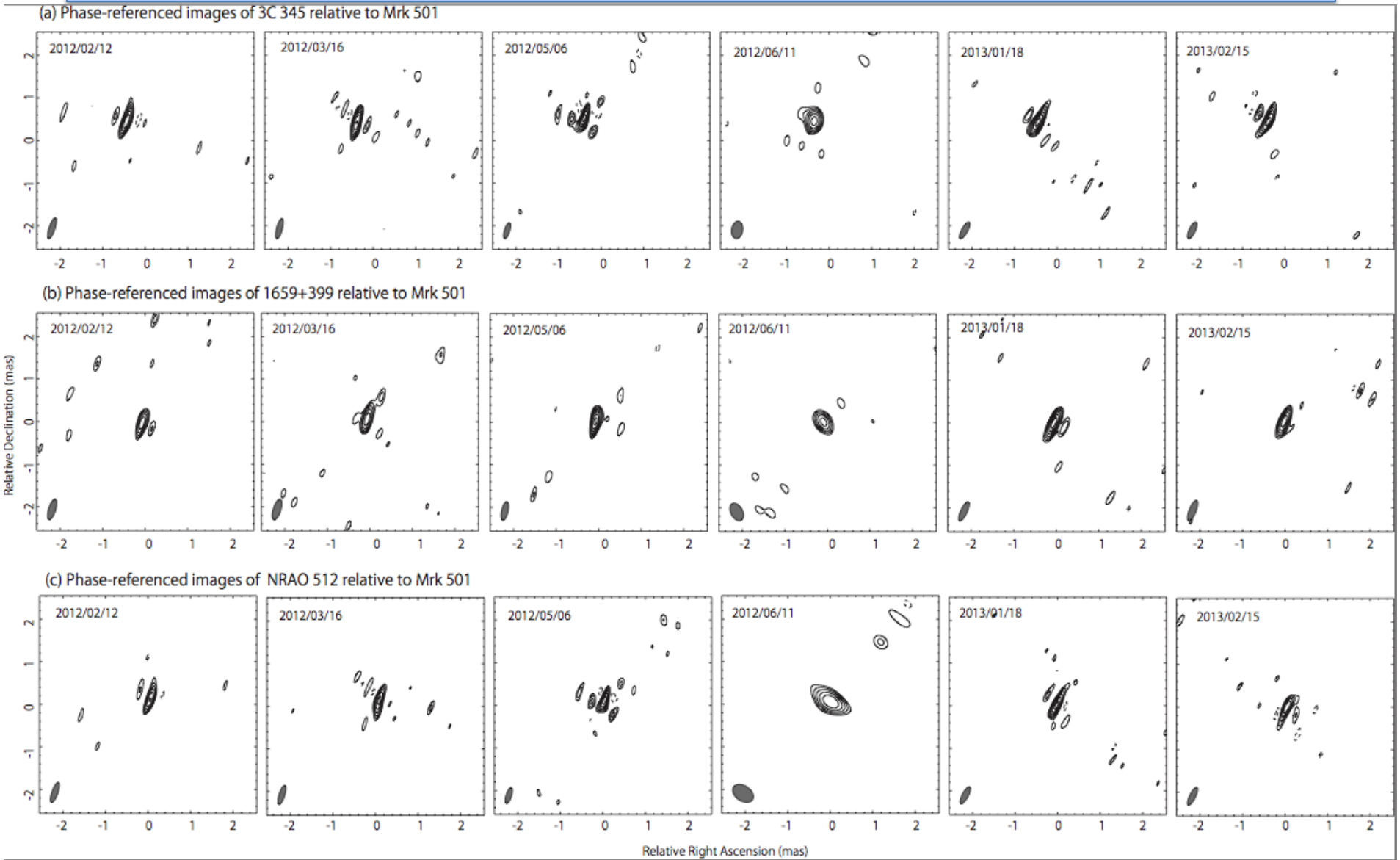
Koyama+2015



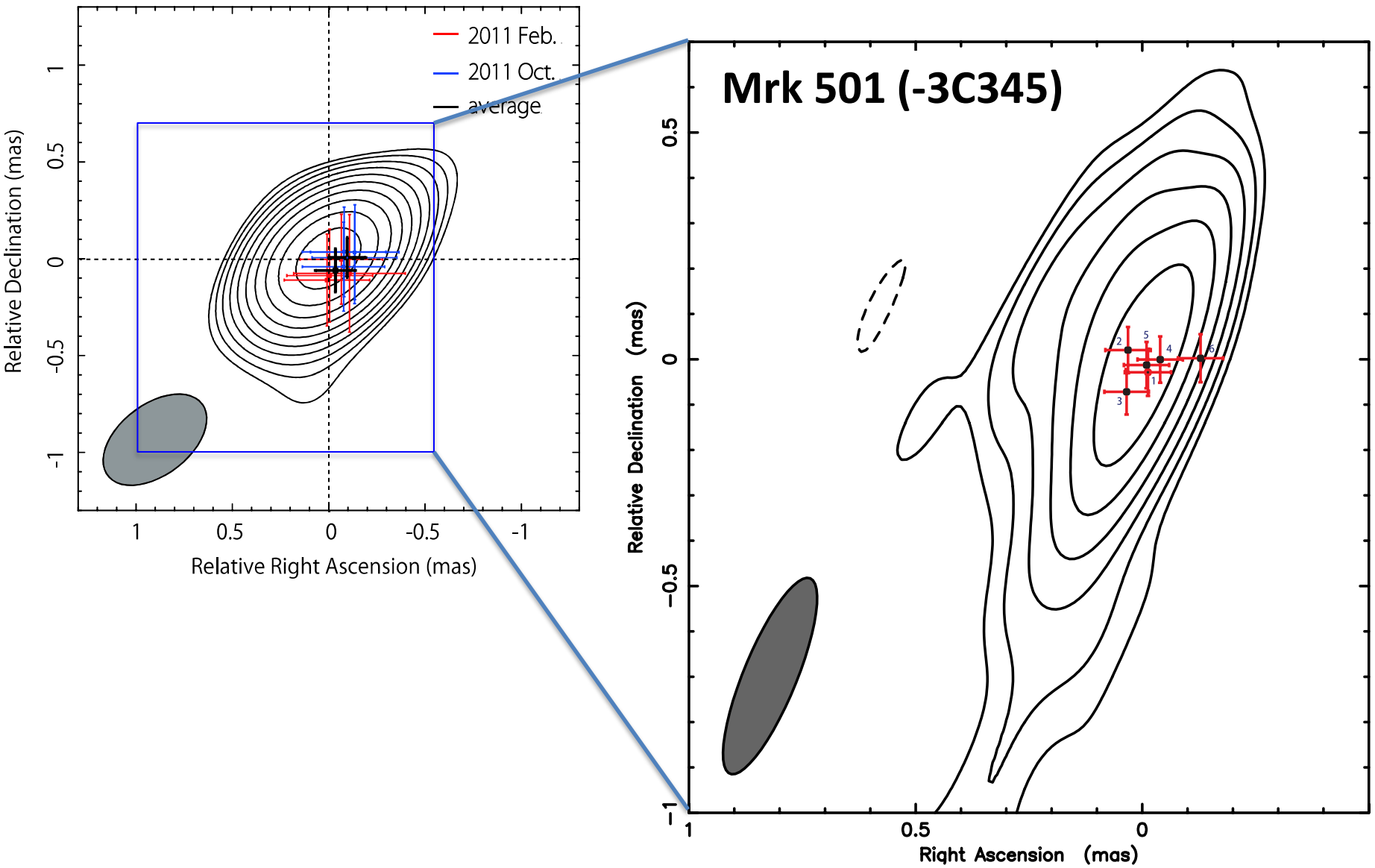
- Position accuracy～200 uas/day
- **No positional change of the radio core within 200 μas during it's quiescent state**

Results of VLBA 43GHz astrometry

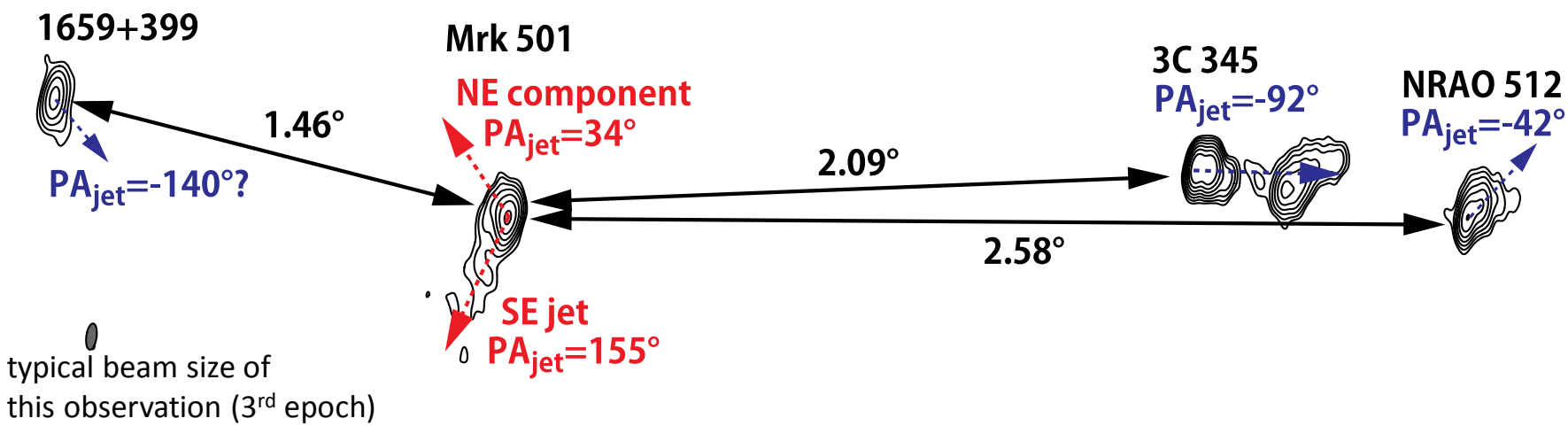
Koyama+in prep.



Results of VLBA 43GHz astrometry



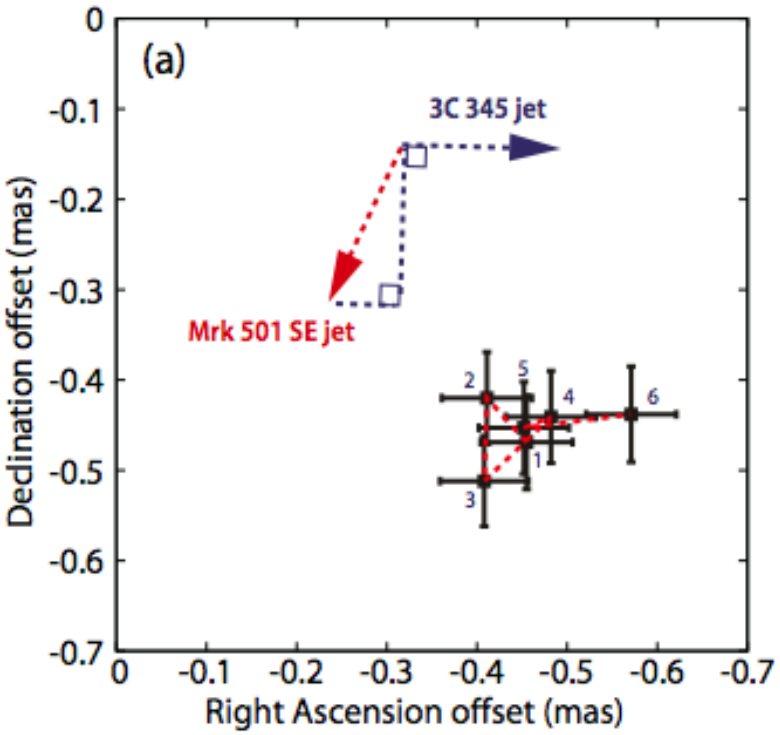
Jet position angles with VLBA 43 GHz

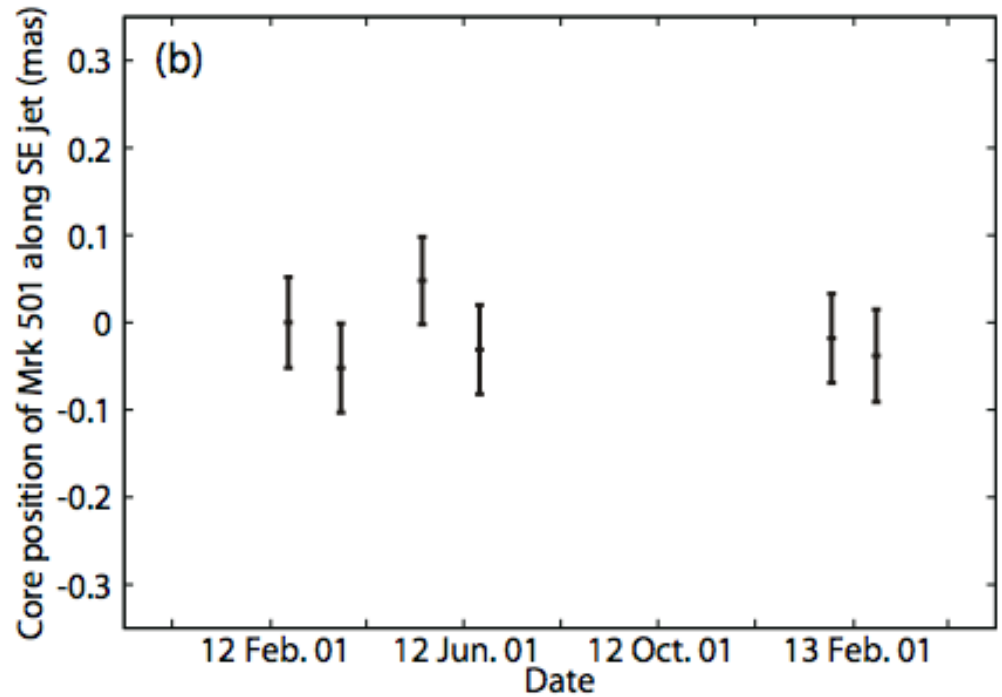


Extract the radio core positions orthogonal to the jet direction of calibrators, then project it to the jet directions of Mrk 501

Results of VLBA 43GHz astrometry

Mrk 501 (-3C345)

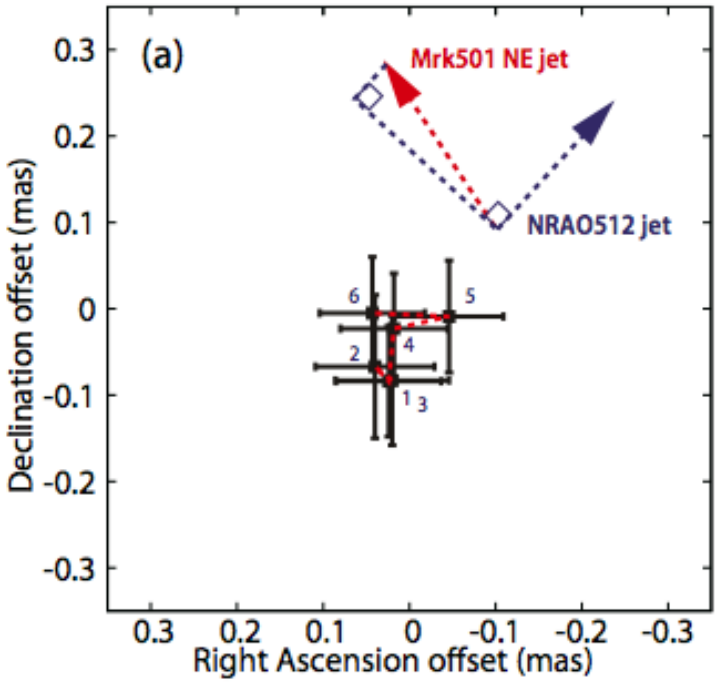


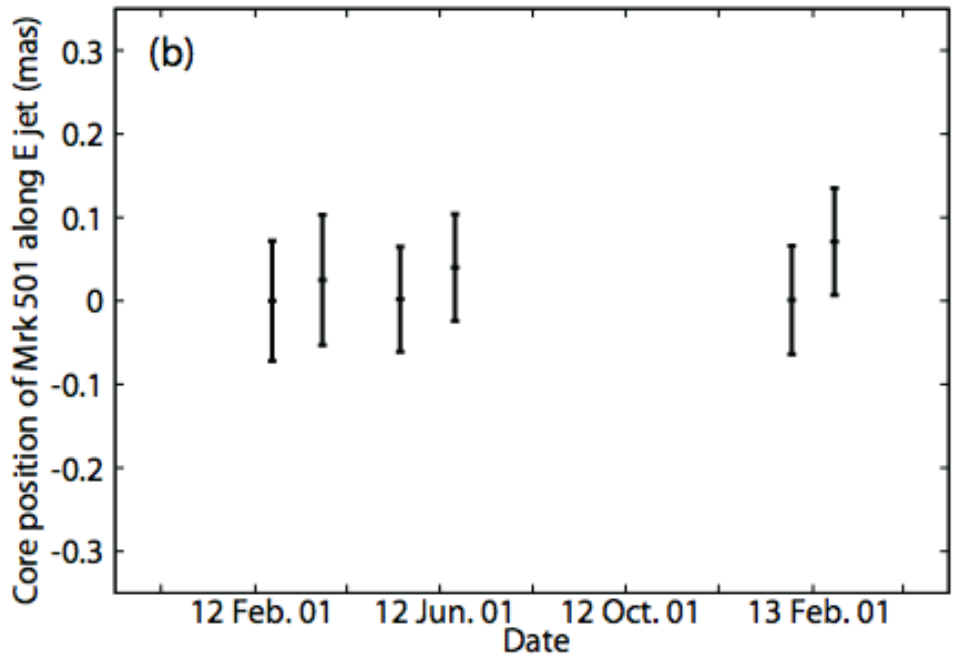


- Position accuracy～50 μas/day
- **No positional change of the radio core within 42 μas (1σ) along it's SE jet (78%)**

Results of VLBA 43GHz astrometry

Mrk 501 (-NRAO512)

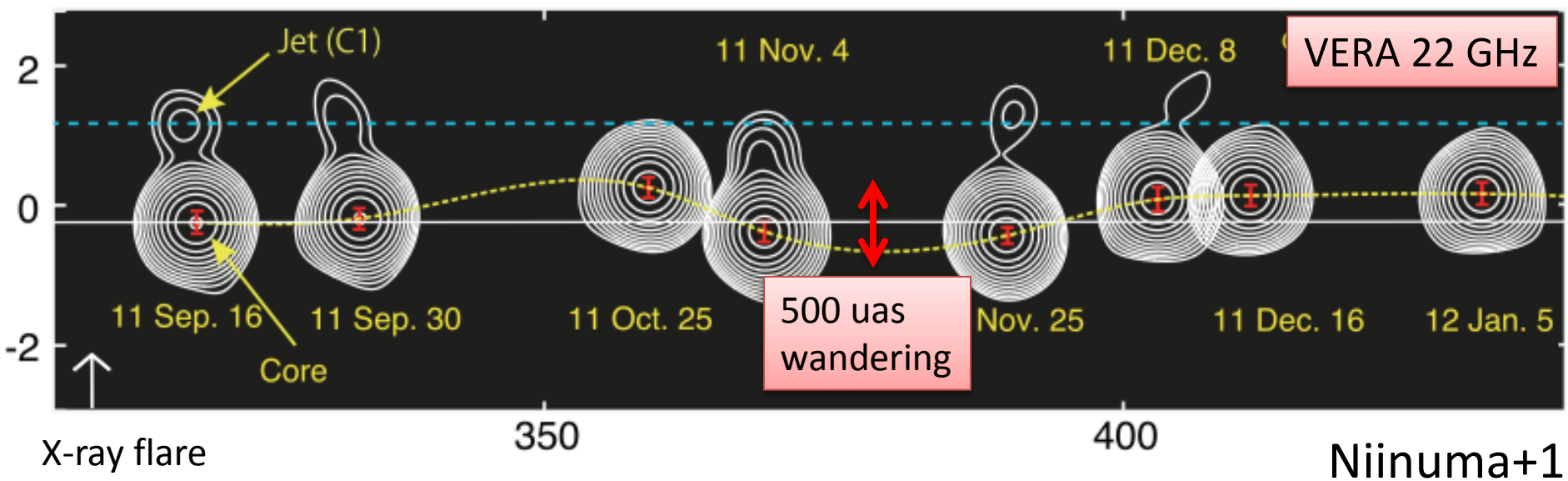




- Position accuracy～70 μas/day
- **No positional change of the radio core within 56 μas (1σ) along it's SE jet (97%)**

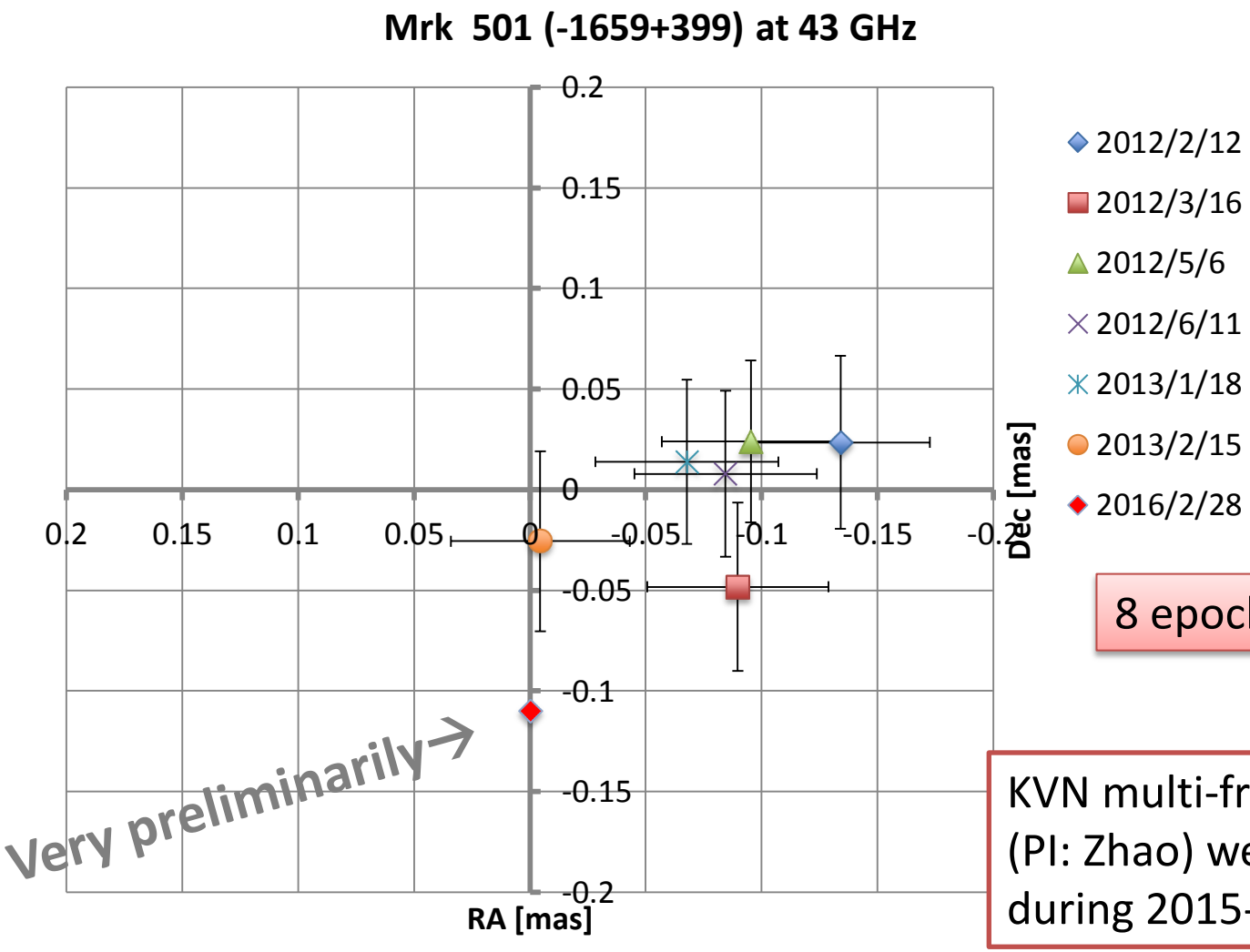
Summary and discussions

- The radio core of Mrk 501 doesn't wander significantly even with VLBA, begin stable enough along its NE and SE jets during it's quiescent state. This suggests that the radio core could be located close to the BH
- On the other hand, we found a significantly wandering radio core in Mrk 421 soon after it's historical X-ray flare. It could be related to the source activity.



Niinuma+15

VLBA multi-frequency astrometry of Mrk 501 in 2016 PI: M. Giroletti (Fermi-GI project)



8 epochs in 2016

KVN multi-frequency observations (PI: Zhao) were also performed during 2015-2016

EHT+ALMA 230 GHZ OBSERVATIONS TOWARD MRK501 IN 2018

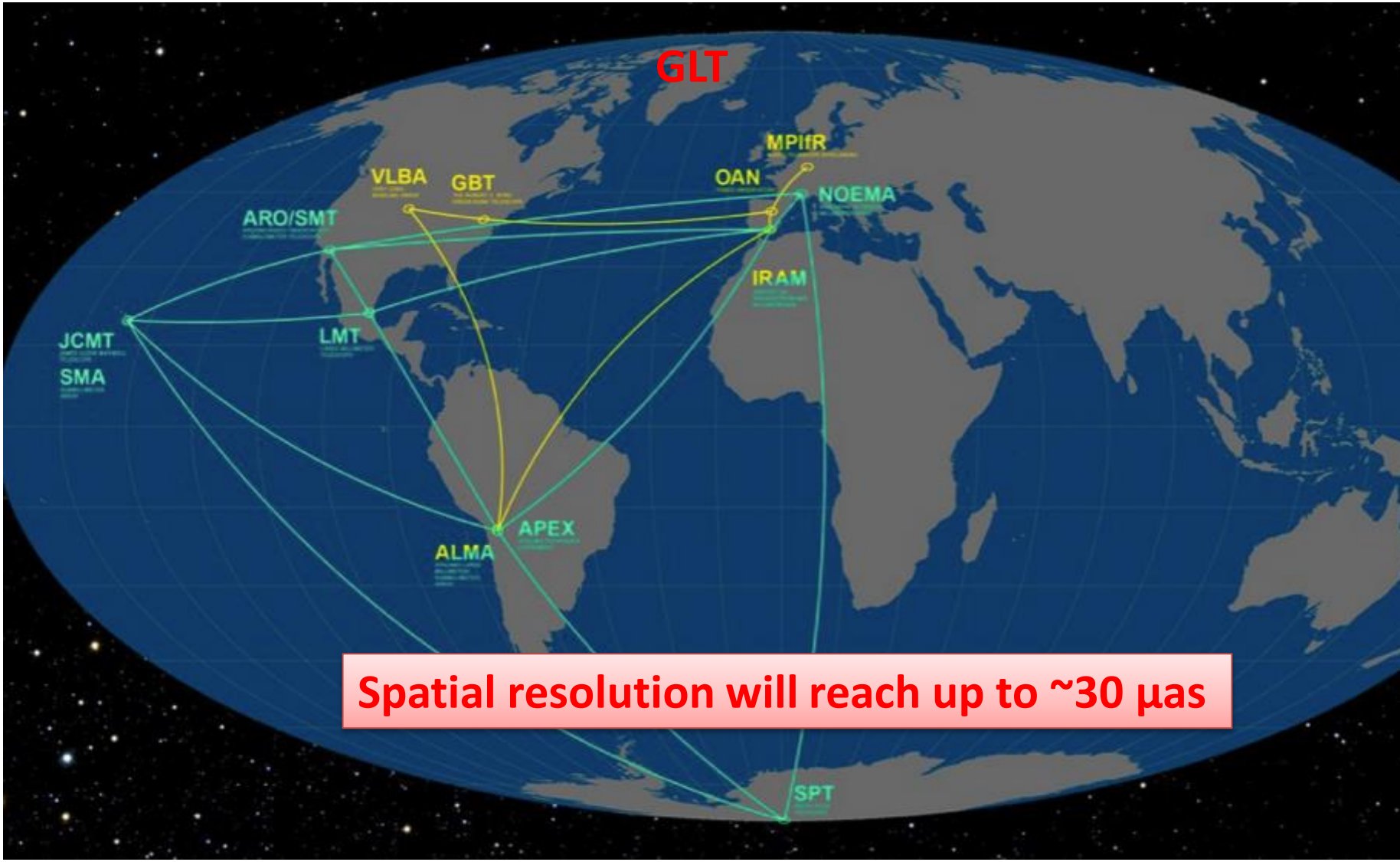
Our EHT proposal toward Mrk 501

1. Probing the size comparable to γ-ray emitting region
2. Discrimination of the jet foot point of a blazar

Approved by EHT and ALMA for 2018 April observations!!

(flux>0.5 Jy at 230 GHz with ACA is required)

EHT+ALMA 230 GHz in 2018



Spatial resolution will reach up to ~30 μas

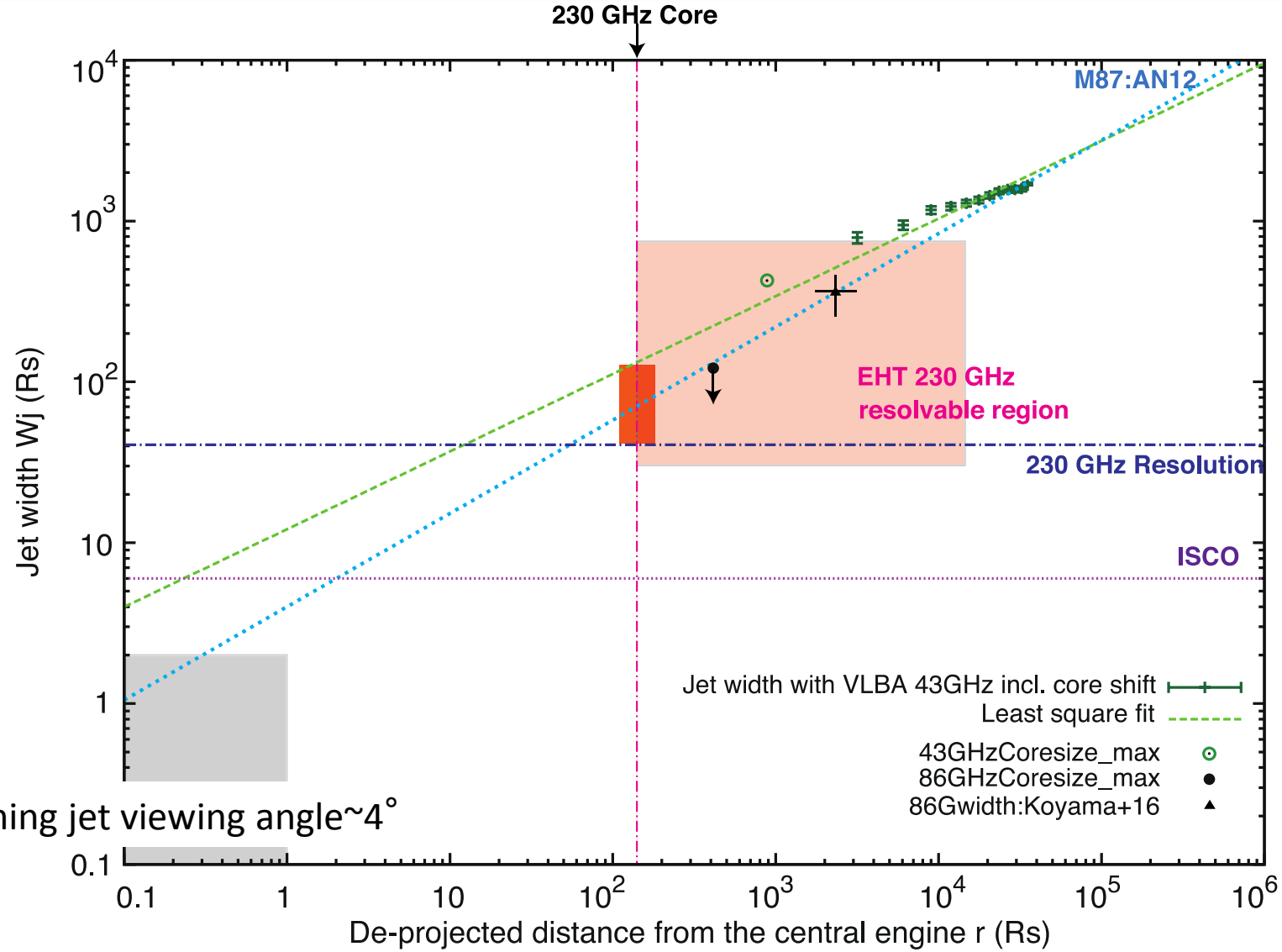
1. Probing the size comparable to γ-ray emitting region in Mrk 501

- One of the closest blazars
  - 1 mas = 0.66 pc
  - 30 μas = 2-3 × 10^{16}cm

    = 60 Rs (M_{BH}=3.4 × 10^9 M_{sun}, Barth+02)

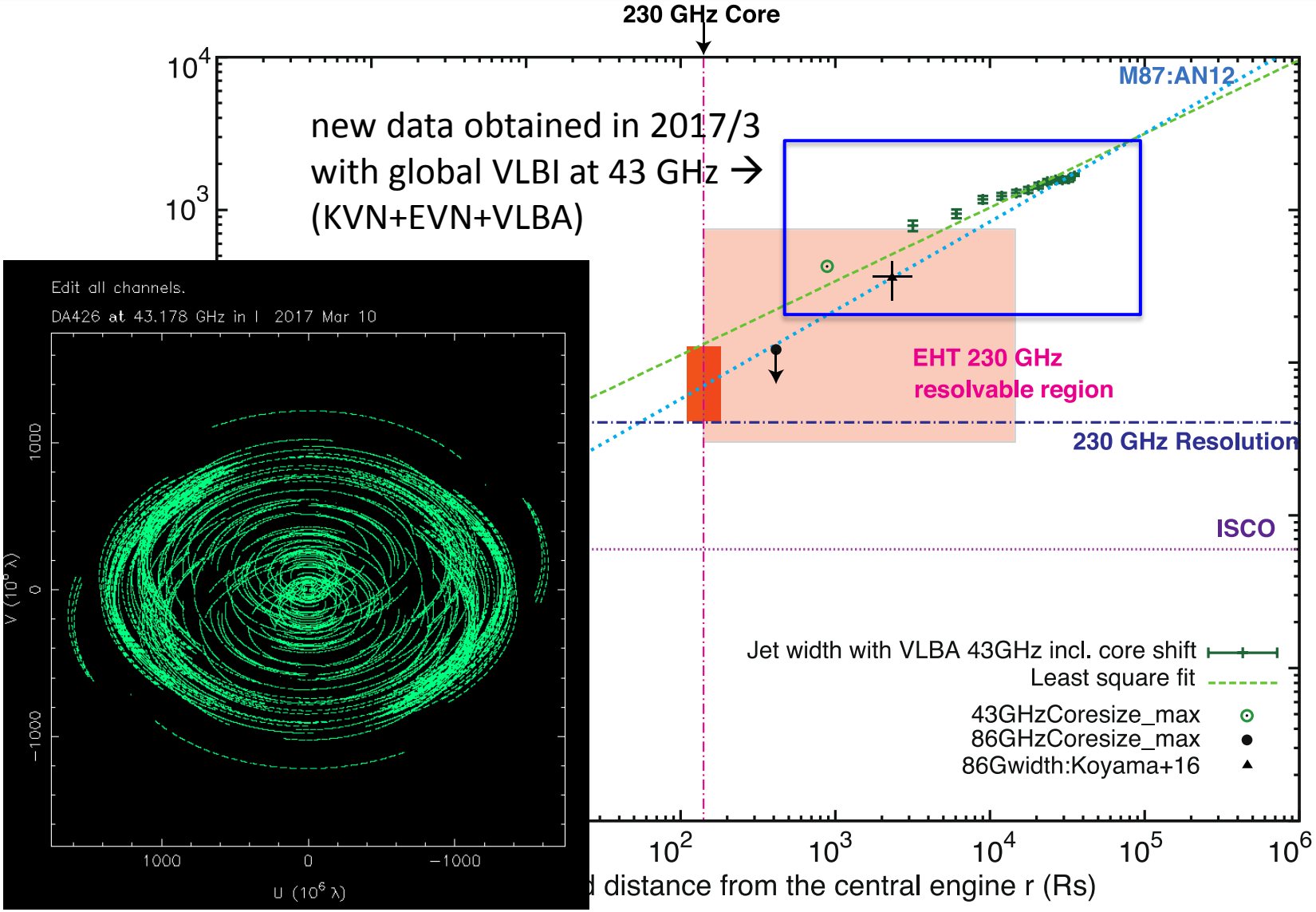
    →comparable to the size of γ-ray emission region with its prediction (variability, SED modeling)
  - First direct information to compare the possible observed size of γ-ray emission region in a blazar

2. Discrimination of jet foot point in a blazar: accretion disk or black hole?



Assuming jet viewing angle~4°

2. Discrimination of jet foot point in a blazar: accretion disk or black hole?




THANK YOU FOR LISTINING.

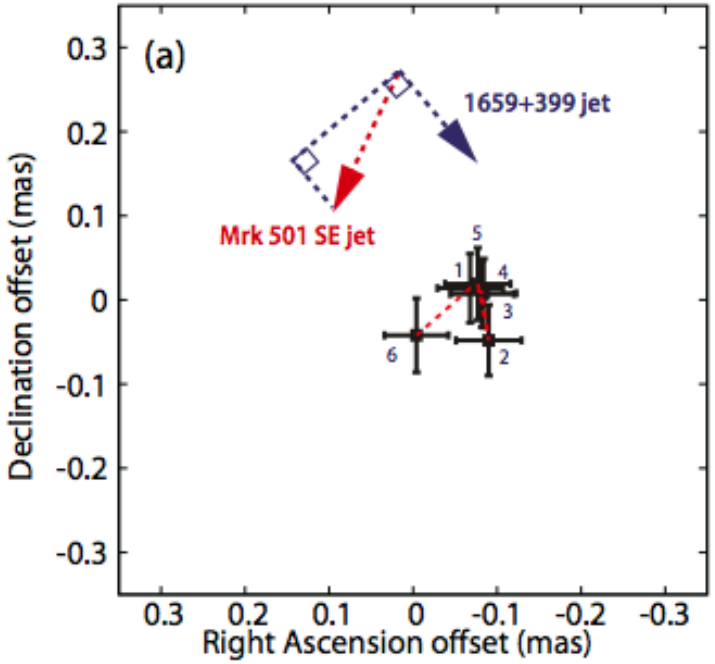
APPENDIX

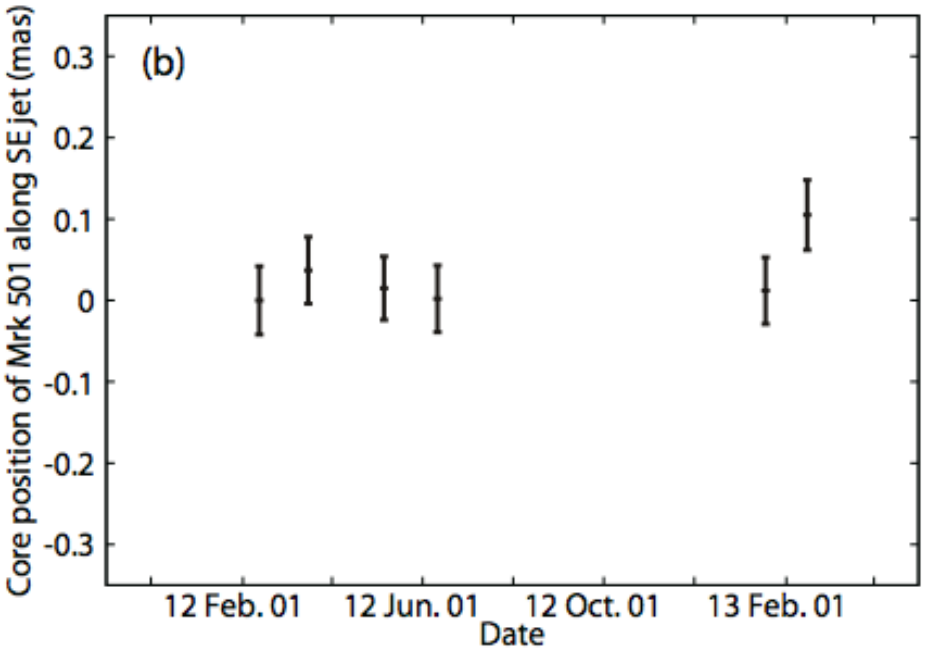
Global VLBI observations at 43 GHz

- Date: 2017 March 10
- 17 stations: KVN-Yonsei, KVN-Ulsan, KVN-Tamna, VLBA10 (BR, FD, HN, KP, LA, MK, NL, OV, PT, SC), Metsaehovi, Effelsberg, Onsala60m, Yebes
- Note: Noto Q-band receiver was failed, Effelsberg LCP was failed
- Mode: Dual-polarization, 16 MHz x 8 IFs = 128 MHz

Results of VLBA 43GHz astrometry

Mrk 501 (-1659+399)





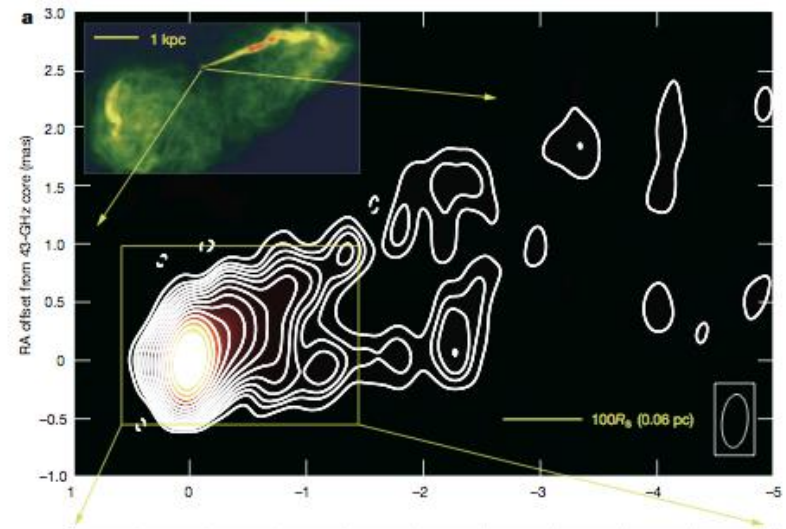
- Position accuracy～40 μas/day
- **No positional change of the radio core within 33 μas (1σ) along it's SE jet (50%)**

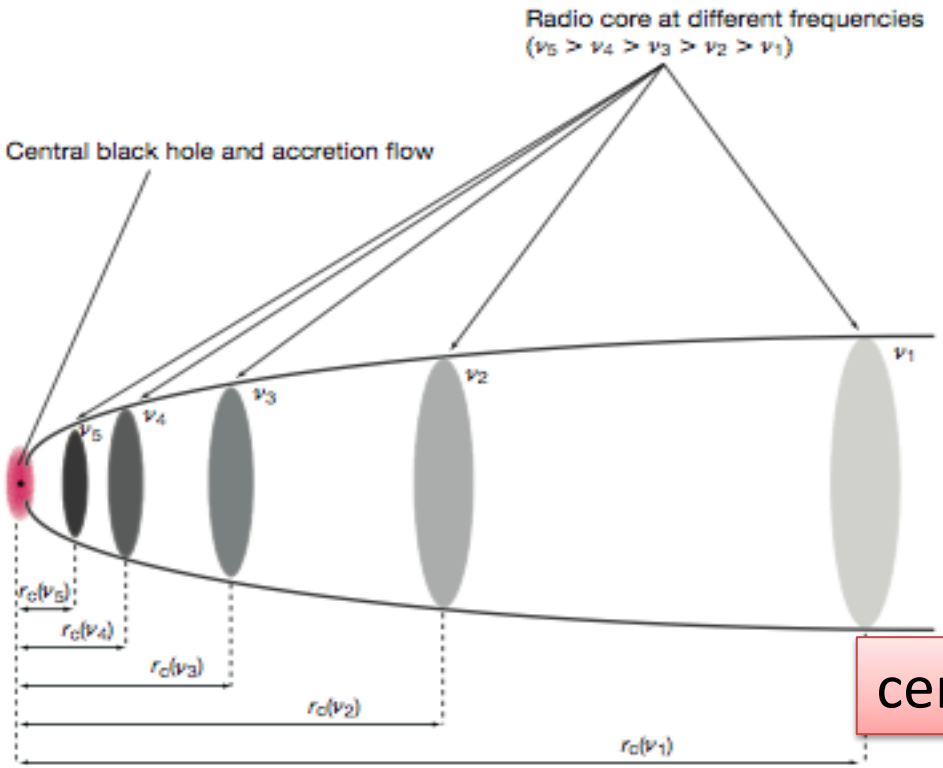
Location of radio core from central engine

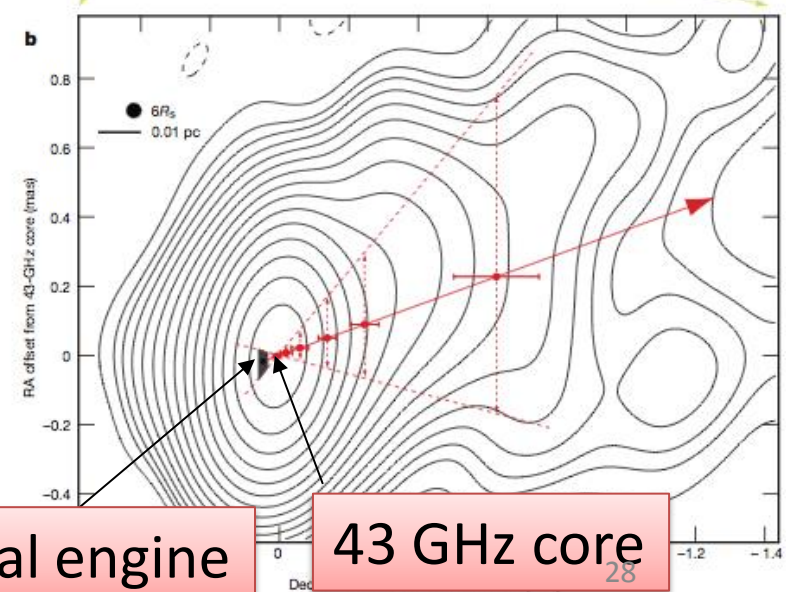
① Close case

- R_{core}~0.01 pc
- Radio galaxy:M87, NGC4261 (e.g.,Hada+2011, Haga+2015)
- Multi-freq. core shift + astrometry

Hada+11







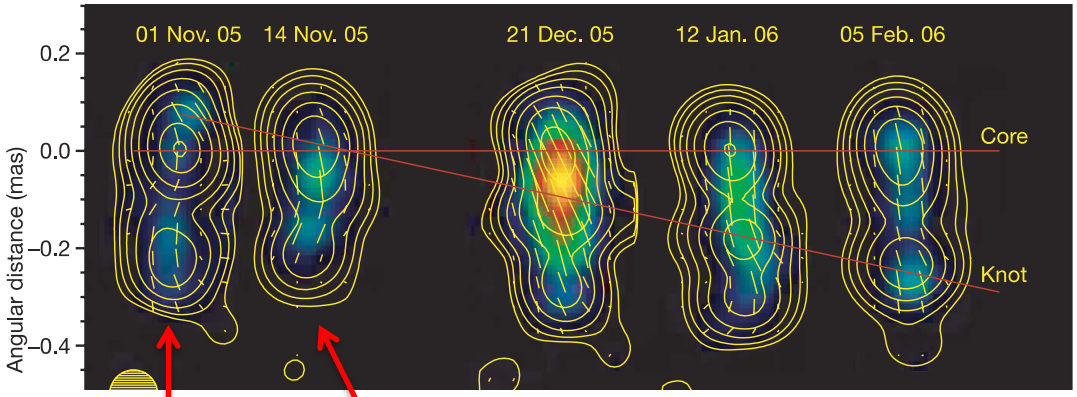
central engine

43 GHz core

Location of radio core from central engine

②Distant case

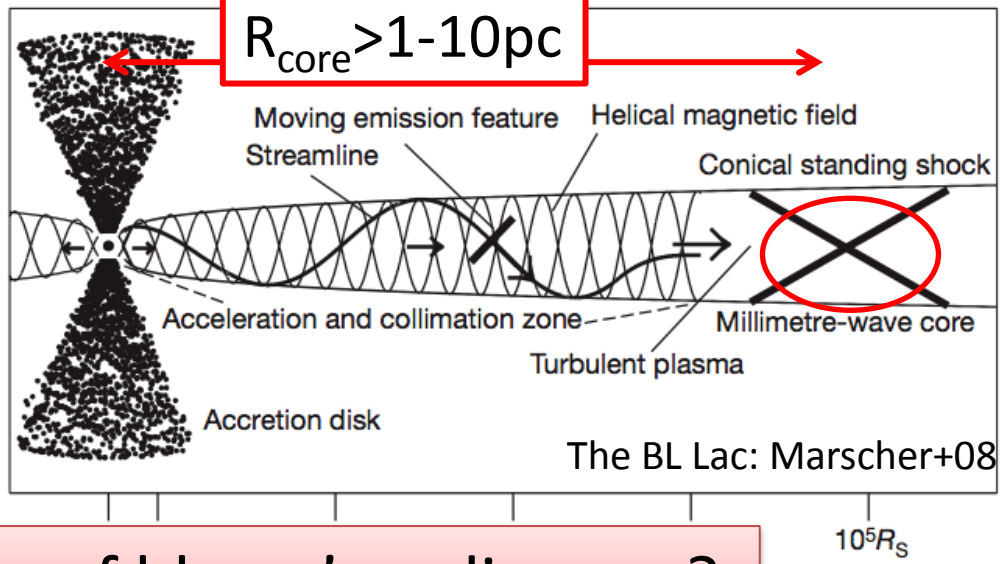
- R_{core}> 1-10 pc
- Several blazars
  - the BL Lac, OJ 287, 3C 454.3, PKS 1510-089, etc. (eg.Marscher+08, Agudo+12)
- Using time difference of light-curve between radio and γ-rays
- <u>Assuming radio core is stationary</u>



γ-ray flare

ejection of radio knot from core

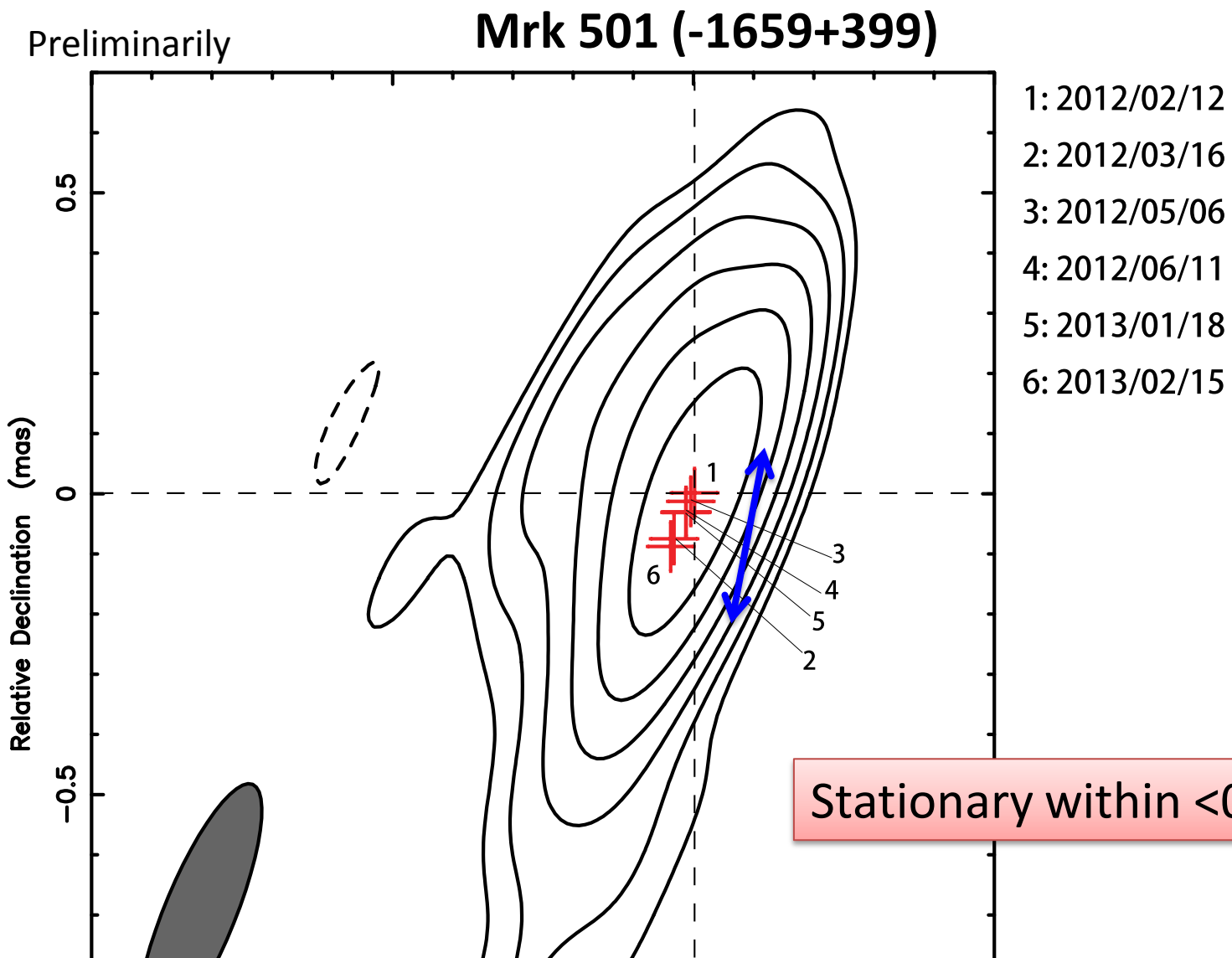
R_{core}>1-10pc



The BL Lac: Marscher+08

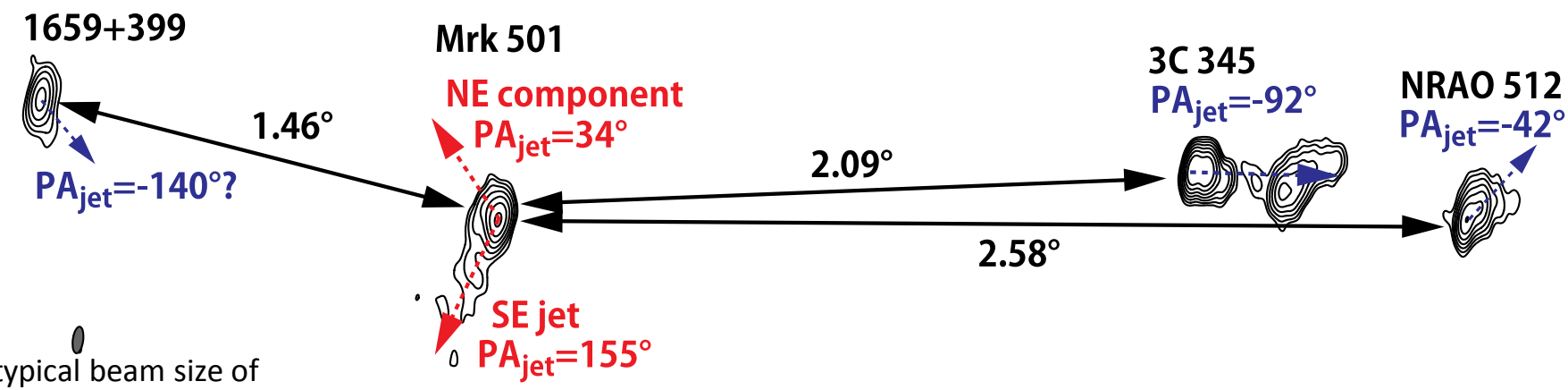
Where is the location of blazar's radio core?

Results of VLBA 43 GHz astrometry



Stationary within <0.2 mas

Jet position angles with VLBA 43 GHz



typical beam size of
this observation (3rd epoch)

- Jet position angles were averaged over 6 epochs.
  - 1659+399, NRAO 512, 3C345, NE : average of the PA of the innermost jet component
    - 1659+399, NRAO512 : only one jet component
    - 3C 345, NE : non-ballistic (straight) jet
  - SE jet: average of the PA of a few components in south-east direction because of its straightness