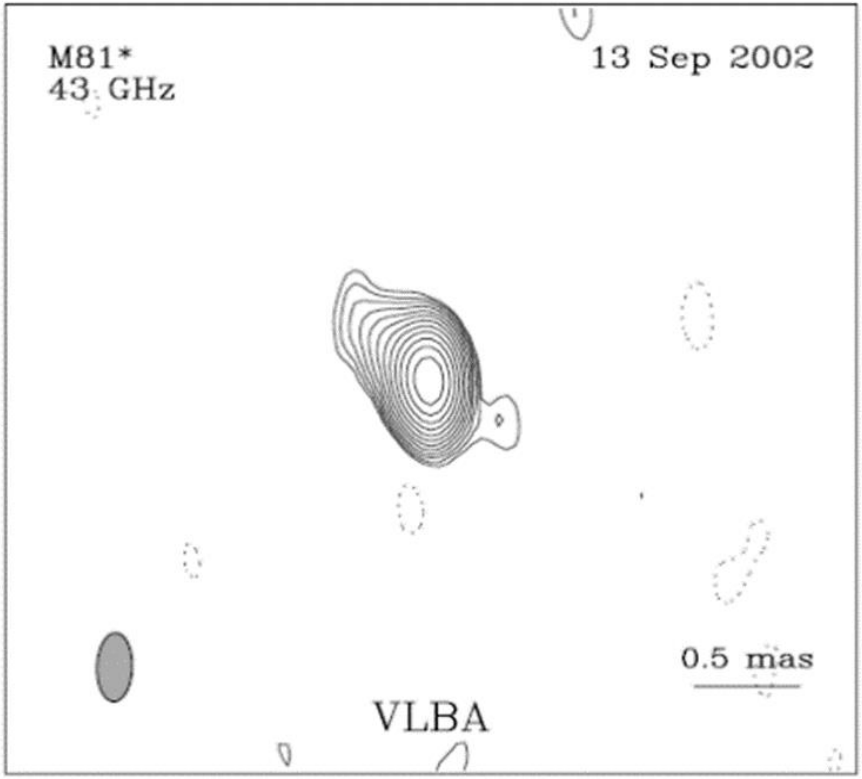
VLBI imaging of M81* at 3.4 mm

Wu Jiang[1], Zhiqiang Shen[1], Dongrong Jiang[1], Ivan Marti-Vidal[2], Noriyuki Kawaguchi[1]

1. Shanghai Astronomical Observatory, CAS
2. Chalmers University of Technology, Onsala Space Observatory, Sweden

2017/11/1

The LLAGN in M81



E. Ros,et al. A&A , 2012.

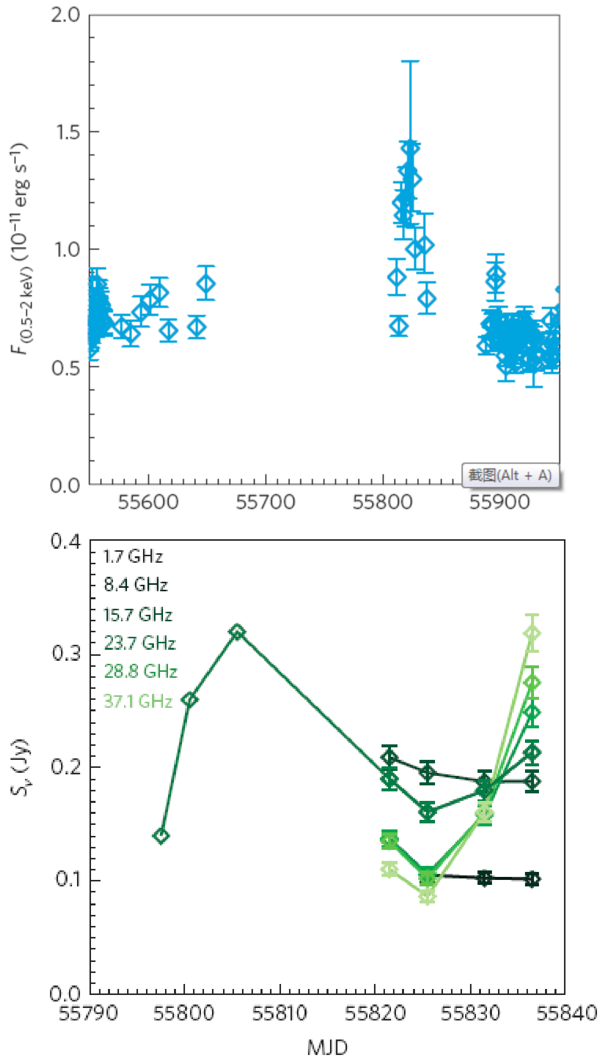
1 μas ~ 3 R_{sch}

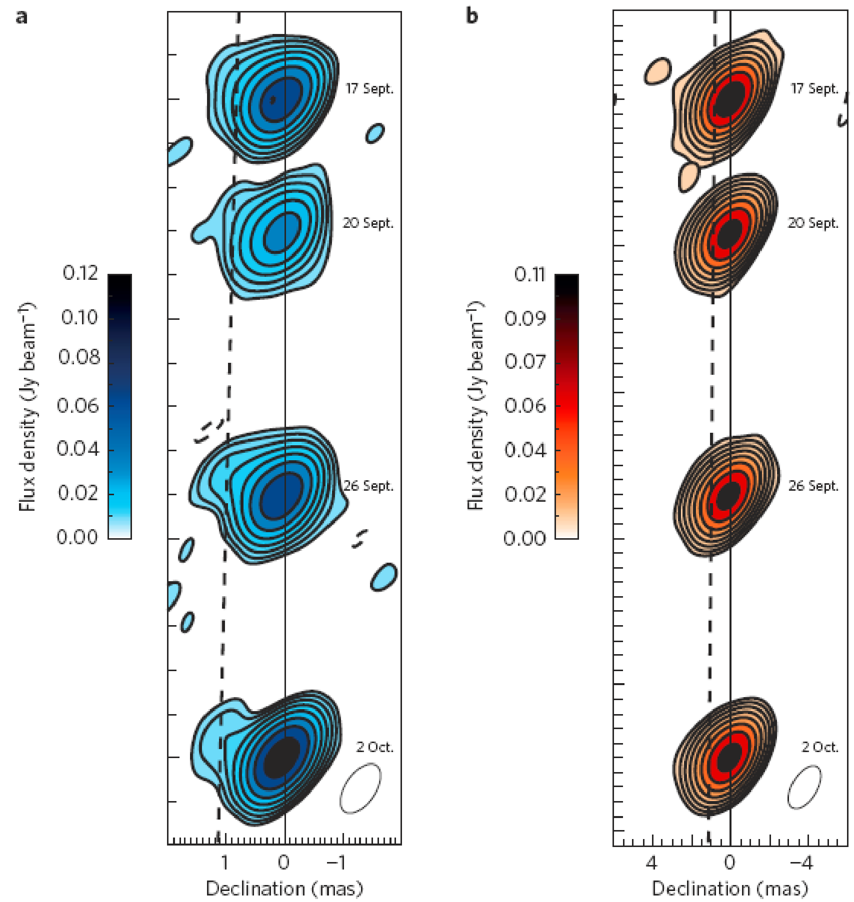
Low Luminosity AGN (**LLAGN**) in spiral galaxy M81

- Distance: **3.96 + 0.29 Mpc** (Bartel et al. 2007)
- Radio luminosity ~ **10^{37} ergs/s** (e.g., Ho et al. 1999). 0.13 Jy@Xband (NED)
- X-ray luminosity ~ **10^{40} ergs/s** (e.g., Reynolds et al. 2009).
- Spectral index **+0.3** up to ~200GHz (Reuter & Lesch 1996).
- Estimated mass of SMBH: **~7×10^{7}** $M_\odot$(e.g., Deveraux et al. 2003).
- **R_{sch} ~ 1×10^{-5} pc**

Discrete jet

Discrete knot ejection from the jet after low energy X-ray flare in 2011.





Radio knot motion, $v_{app}/c=0.51\pm0.17$

Magnetic field 1.9<B<9.2 G

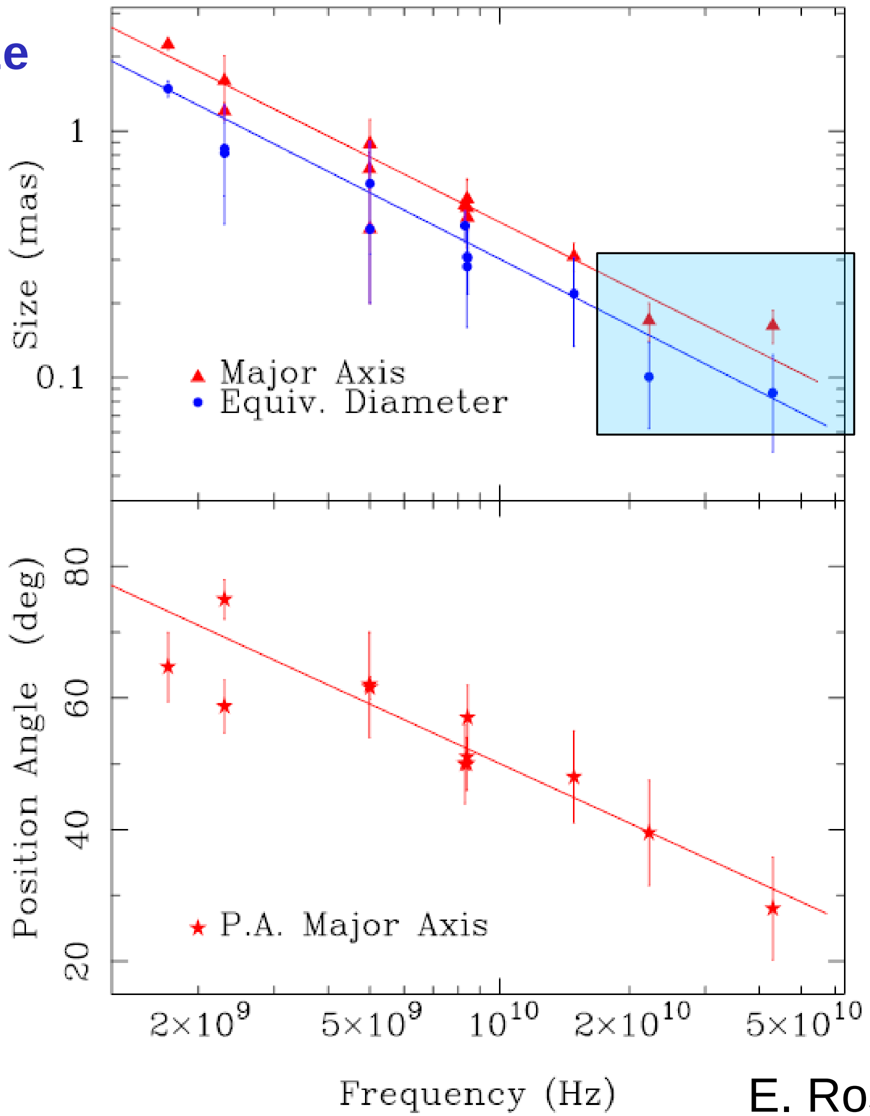
Ashley L. King, et al. Nature Physics, 2016.

Look into the M81 core and jet

Core size and P.A. of frequency(wavelength) dependence.

Core size

P.A.



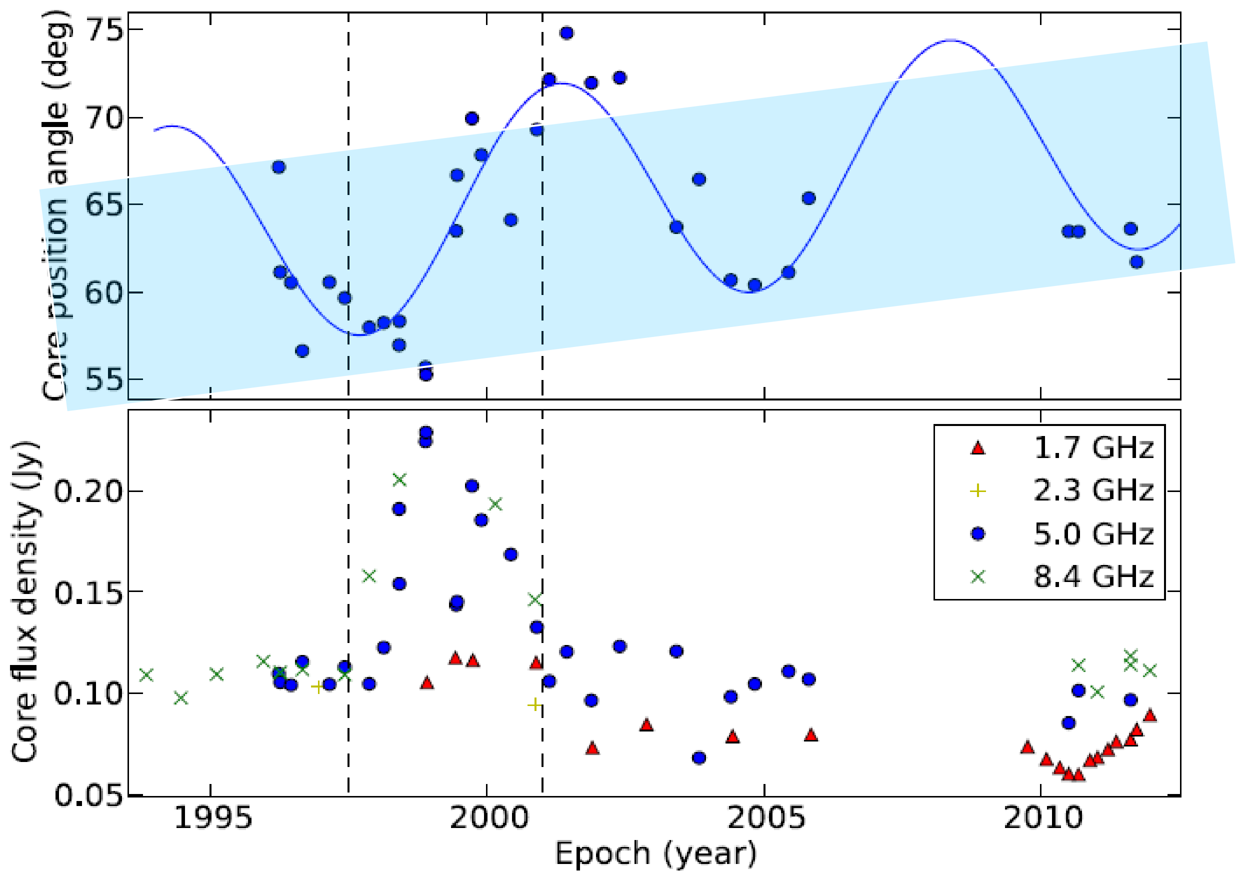
$\propto \nu^{0.88}$

A flat tendency?
Need to be checked at 3 mm.

E. Ros,et al. A&A , 2012.

Precession of jet

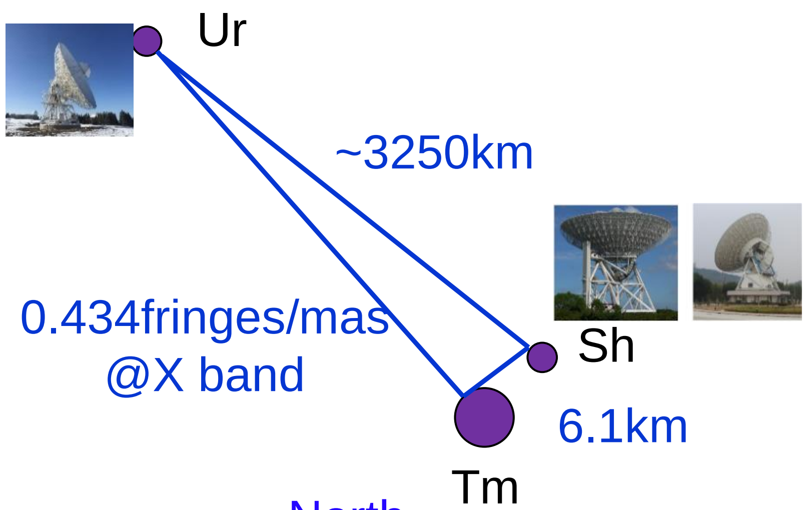
The P.A. observed at 5GHz showed a precession period of 7.27 yr and a speed of drifting 0.54 degree/yr.

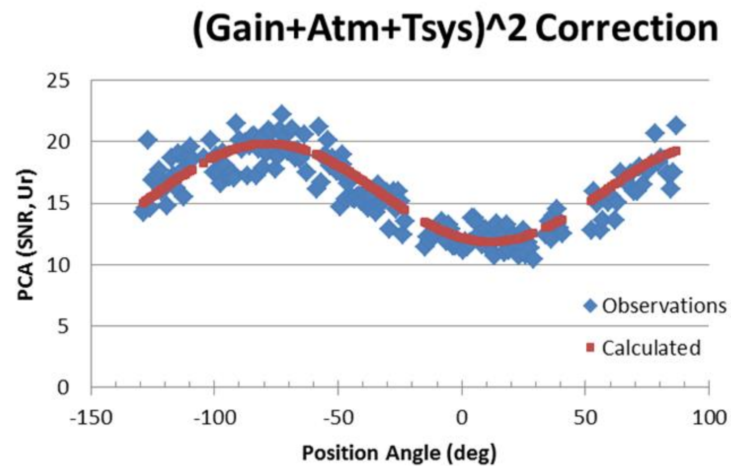


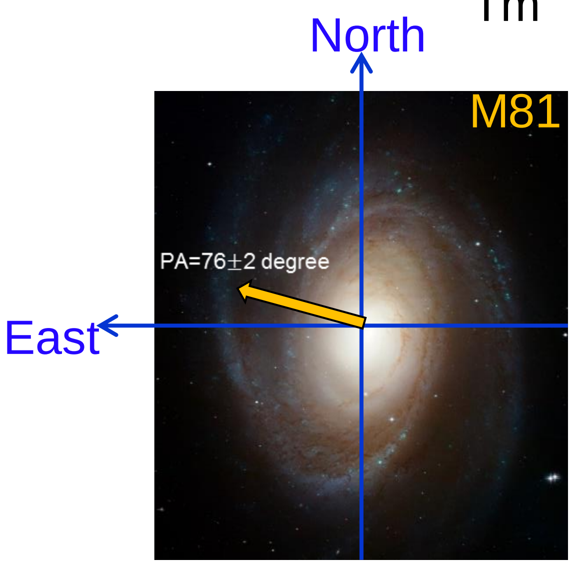
I. Martí-Vidal, et al. A&A, 2011.

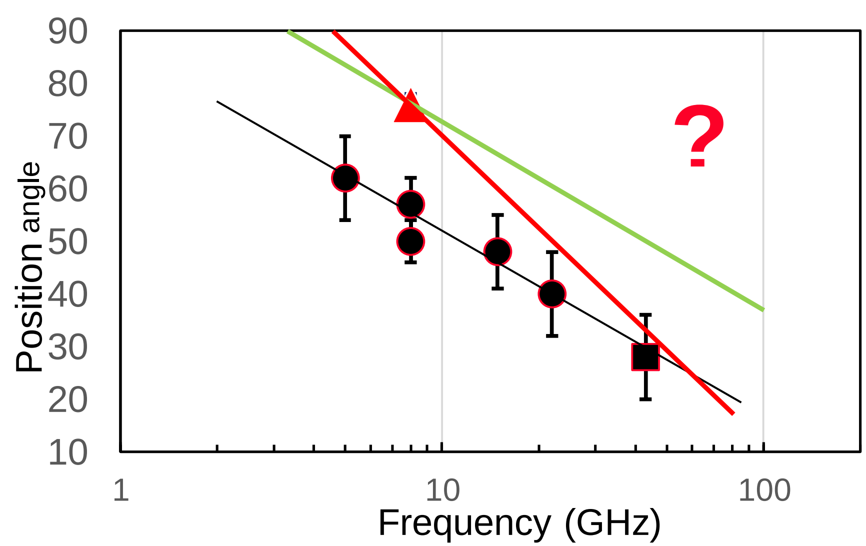
P.A. change of jet ?

Pseudo Closure Amplitude(PCA) measurement









Kawaguchi N., et al. PASJ, 2015

Motivations

Sensitivity of VLBI array

$$SEFD = \frac{8kT_{sys}}{\eta\pi D^2\sqrt{2BT}}$$

Thanks to the development of modern technology:

- ✓ More/Big antenna dish — *D*
- ✓ Wide band receiver
- ✓ High frequency sampling
- ✓ High speed recording
  - } *B*
- ✓ Fast frequency-switching / simultaneous multi-frequency receiving system — *T*

Motivations

With improvement factor 1-2 (D), 10 (B), >10 (T), current VLBI sensitivity > sqrt(100) even at 3mm.

100mJy level targets ≠ faint sources

Higher sensitivity (sub-mJy@mm) makes weaker sources approachable:

- ✓ Nearby low luminosity sources, such as M81*
- ✓ High redshift sources

VLBA observation on M81 at Q/W band

Observation summary

Date *Feb. 2016, clean weather.*

Dur *8 h.*

Sta. *8 VLBA station with 86G capability.*

Freq ***Q/W band, 43860/87720 MHz***

fast freq. switching + PR (SFPR)

Rec. *256MHz BW, full pol, 2 Gbps*

Corr. *@scorro*

Object	RA	DEC	Flux@86G	Separation Angle	**Type**
M81*	09:55:33.1730	+69:03:55.061	71 mJy	0	AGN, Target
0954+658	09:58:47.2451	+65:33:54.818	1.16 Jy	3.5 deg	QSO, Phase and amplitude calibrator
1044+719	10:48:27.6199	+71:43:35.938	0.87 Jy	5.2 deg	QSO, Polarization calibrator
OJ287	08:54:48.8749	+20:06:30.641	2.7 Jy		Calibrator, D term calibrator

VLBA observation on M81 at Q/W band

Basic idea of fast frequency-switching phase-referencing (FFPR)

$$\phi_t^{obs} - \gamma\tilde{\phi}_r^{int} = \underbrace{\phi_t^{tru}}_{\text{True vis.}} + \underbrace{\left(\phi_t^{pos} - \gamma\tilde{\phi}_r^{pos}\right)}_{\text{Core shift}} + \left(\phi_t^{ant} - \gamma\tilde{\phi}_r^{ant}\right) + \left(\phi_t^{tro} - \gamma\tilde{\phi}_r^{tro}\right) + \left(\phi_t^{ins} - \gamma\tilde{\phi}_r^{ins}\right) + \left(\phi_t^{ion} - \gamma\tilde{\phi}_r^{ion}\right)$$

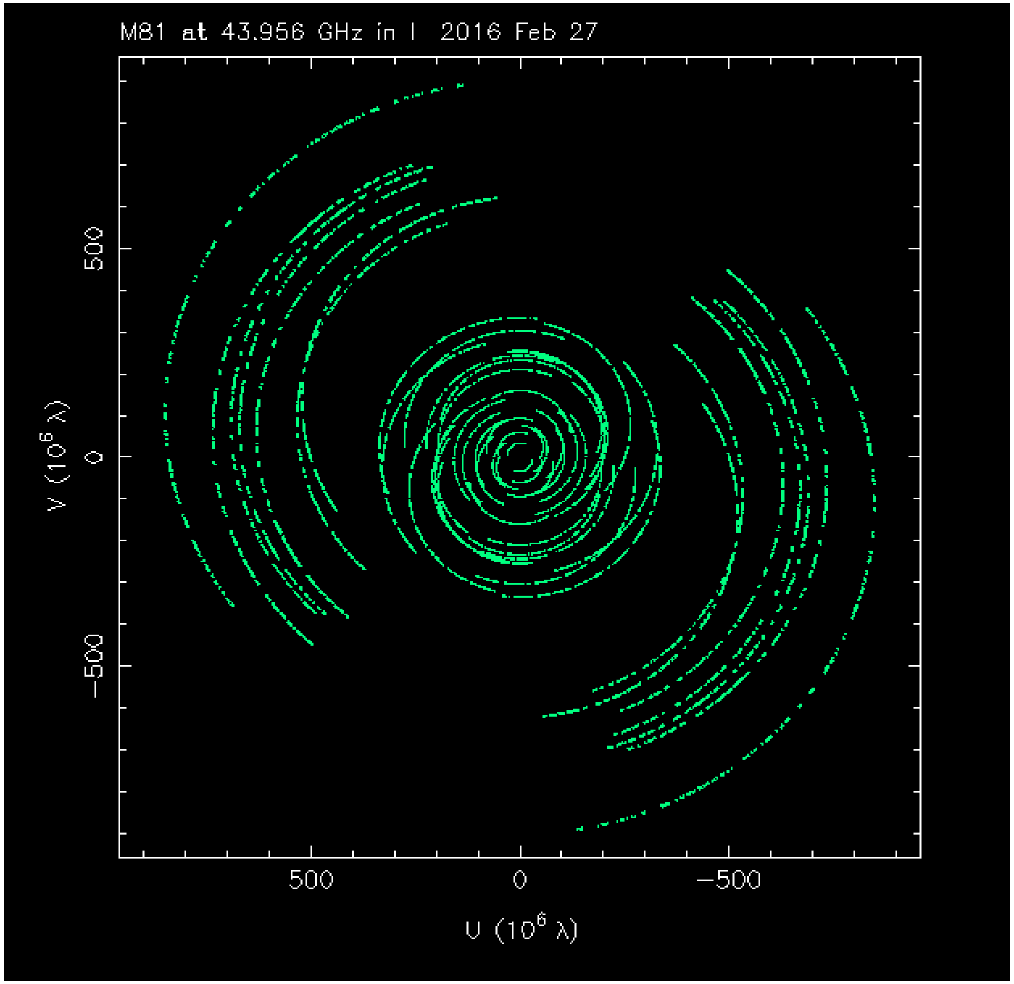
=0, removable

to be removed

After source frequency phase referencing (SFPR), we have,

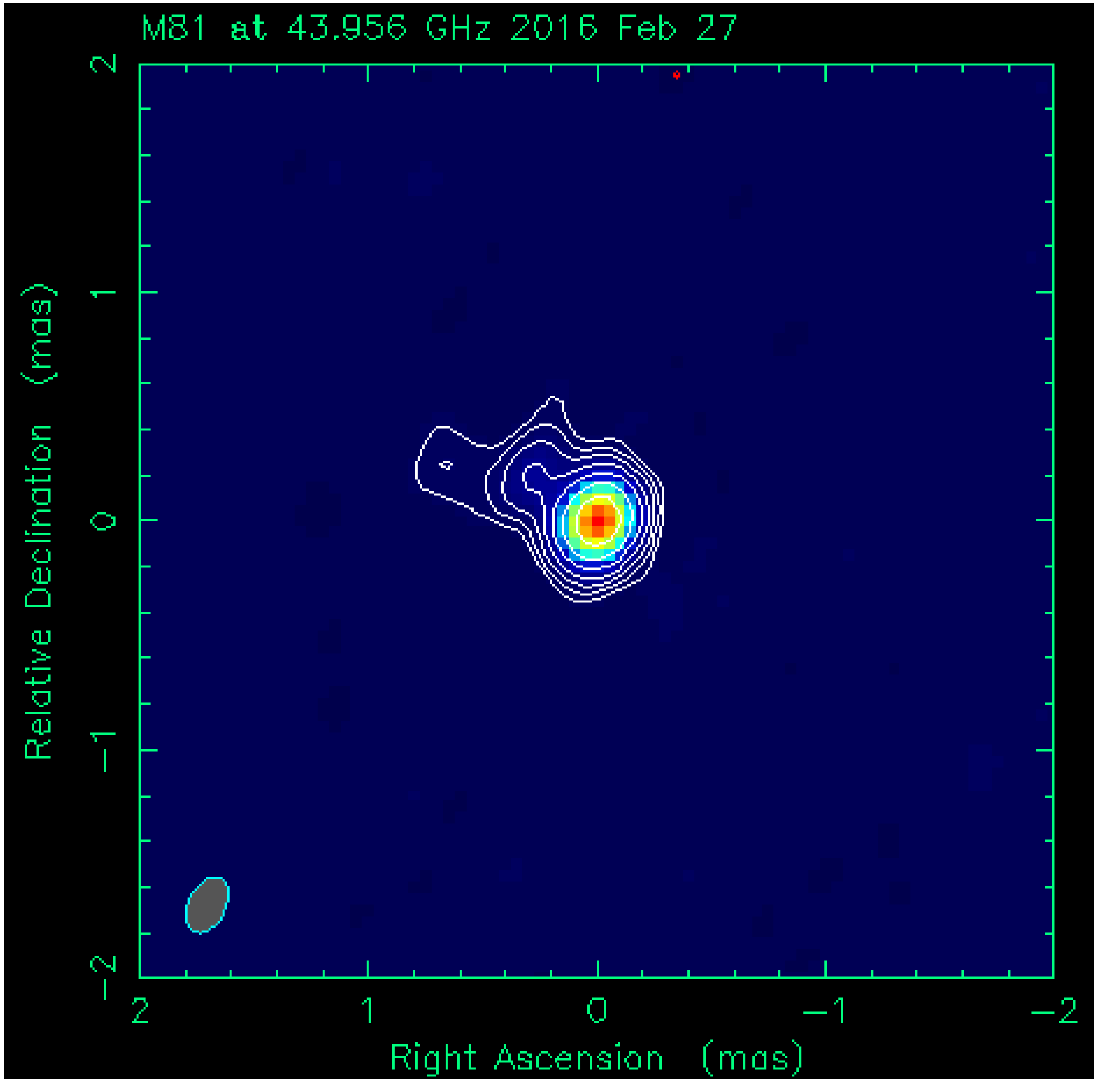
$$\underbrace{\phi_{tar,\nu_t}^{obs} - \gamma\hat{\phi}_{tar,\nu_r}^{int}}_{\text{FFPR of target}} - \underbrace{\left(\phi_{cal,\nu_t}^{obs} - \gamma\hat{\phi}_{cal,\nu_r}^{int}\right)}_{\text{FFPR of calibrator}} = \underbrace{\phi_{tar,\nu_t}^{tru}}_{\text{True vis. of target}} + \underbrace{2\pi D_{\nu_t}(\theta_{tar} - \theta_{cal})}_{\text{Relative core shift}} + \Delta\phi_n$$

VLBA observation on M81 at Q/W band



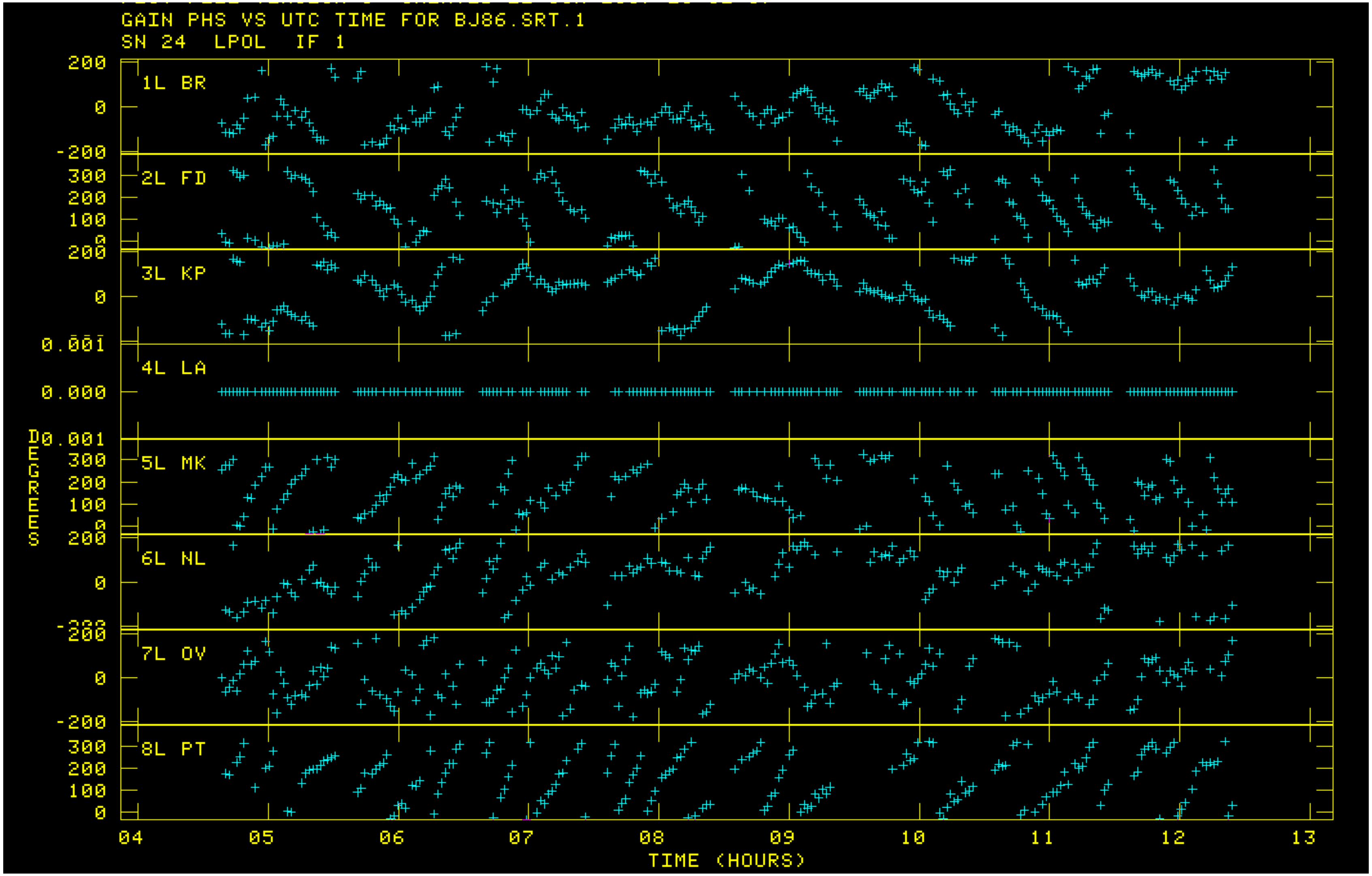
UV tracks of M81* (Q).

VLBA image of M81 at Q band



Clean map of M81 at 43GHz.
Uniform weighting
RMS=0.23 mJy/beam
Dynamic range ~320

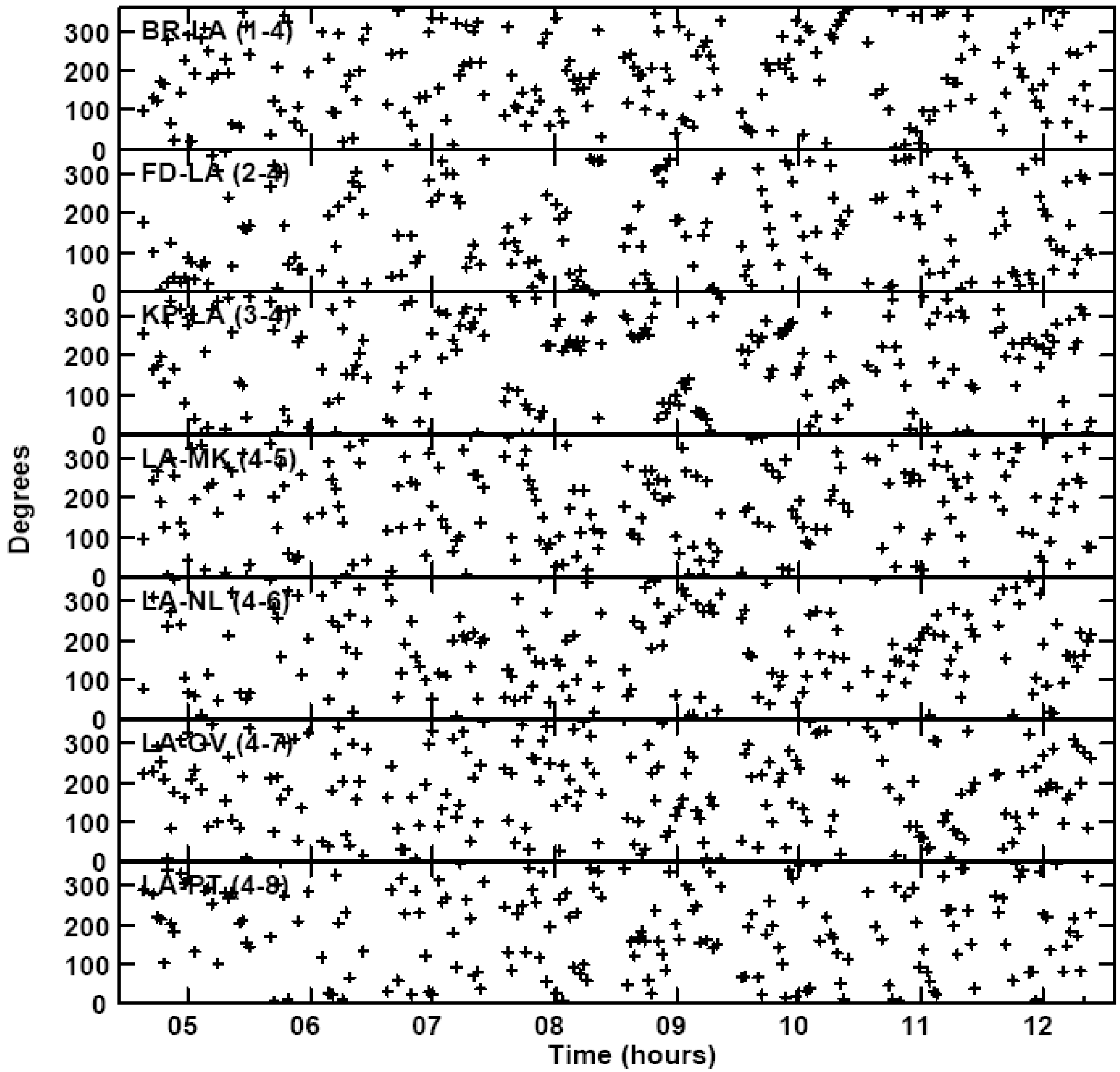
VLBA image of M81 at W band



7 mm phases of M81* for SFPR at 3.4 mm, ref: LA.

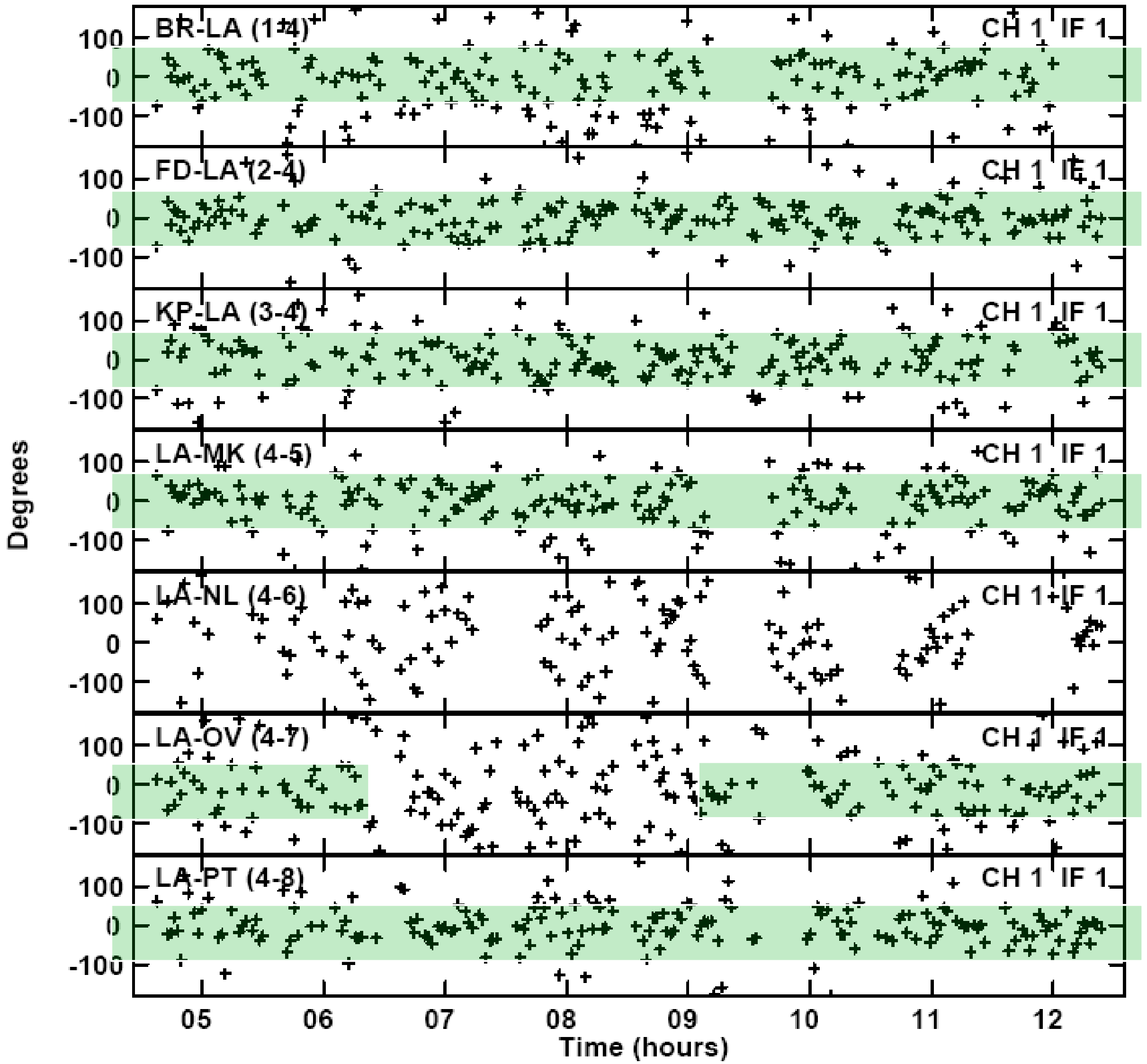
VLBA image of M81 at W band

Phases at 3.4mm before SFPR.

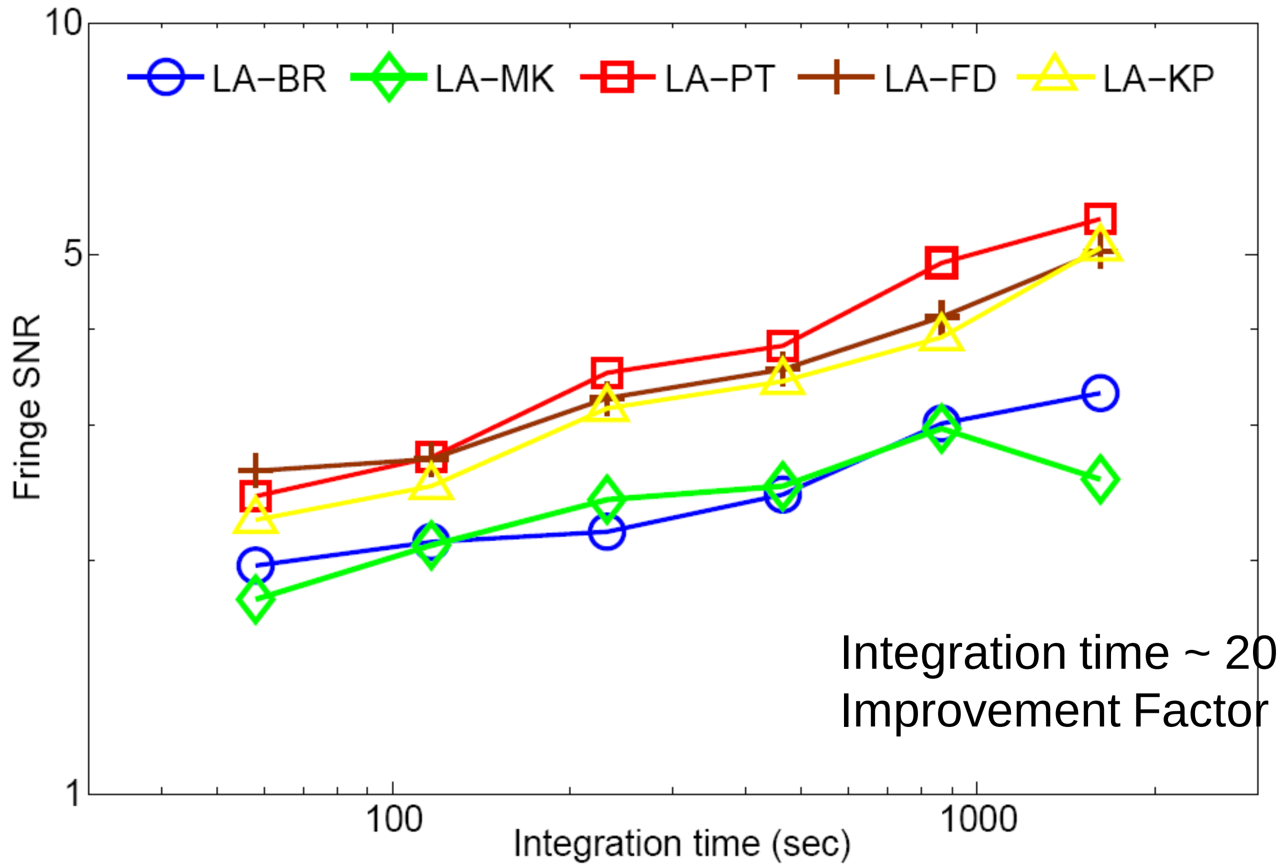


VLBA image of M81 at W band

Phases of M81* at 3.4mm with SFPR.



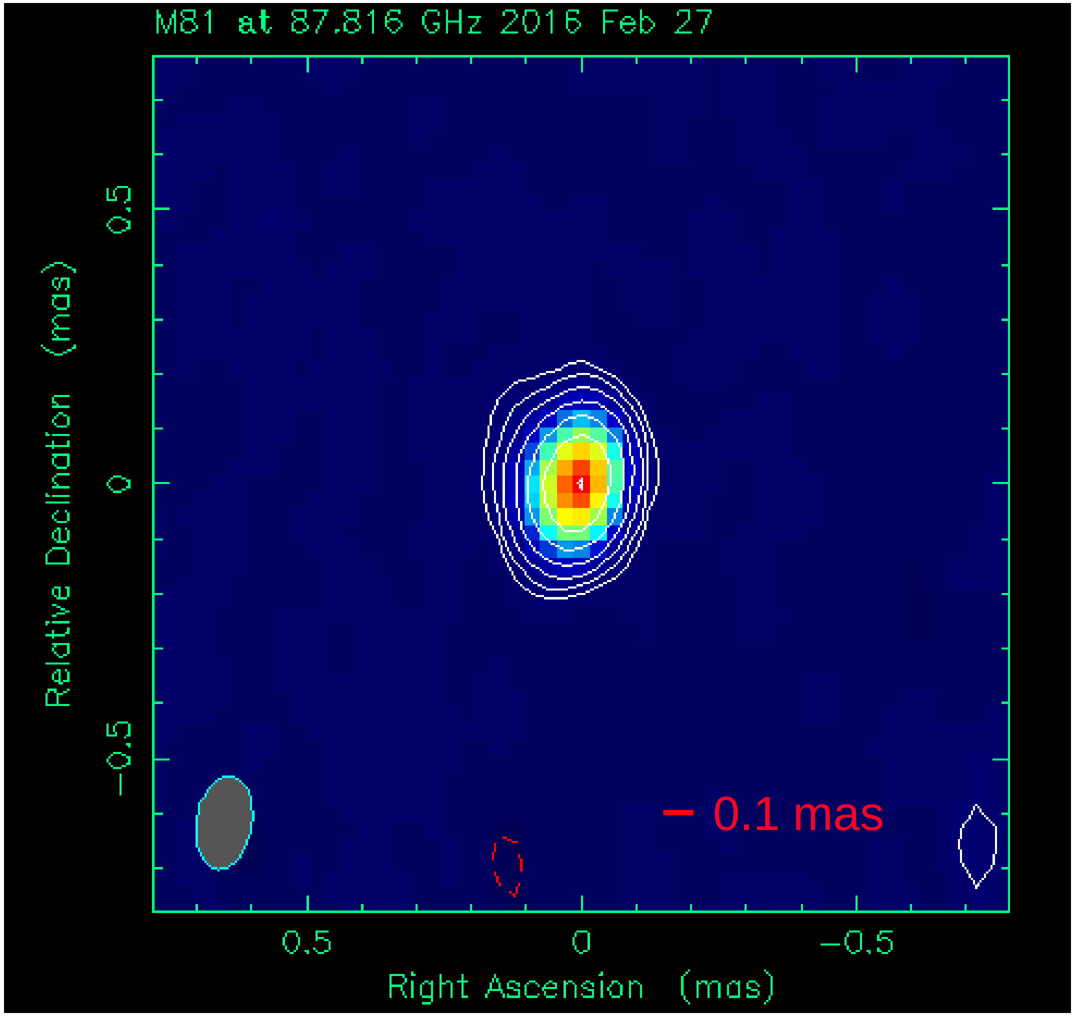
VLBA image of M81 at W band



Integration time ~ 20 min
Improvement Factor ~60 (T)

Fringe SNR (86GHz) via Integration time

VLBA image of M81 at W band

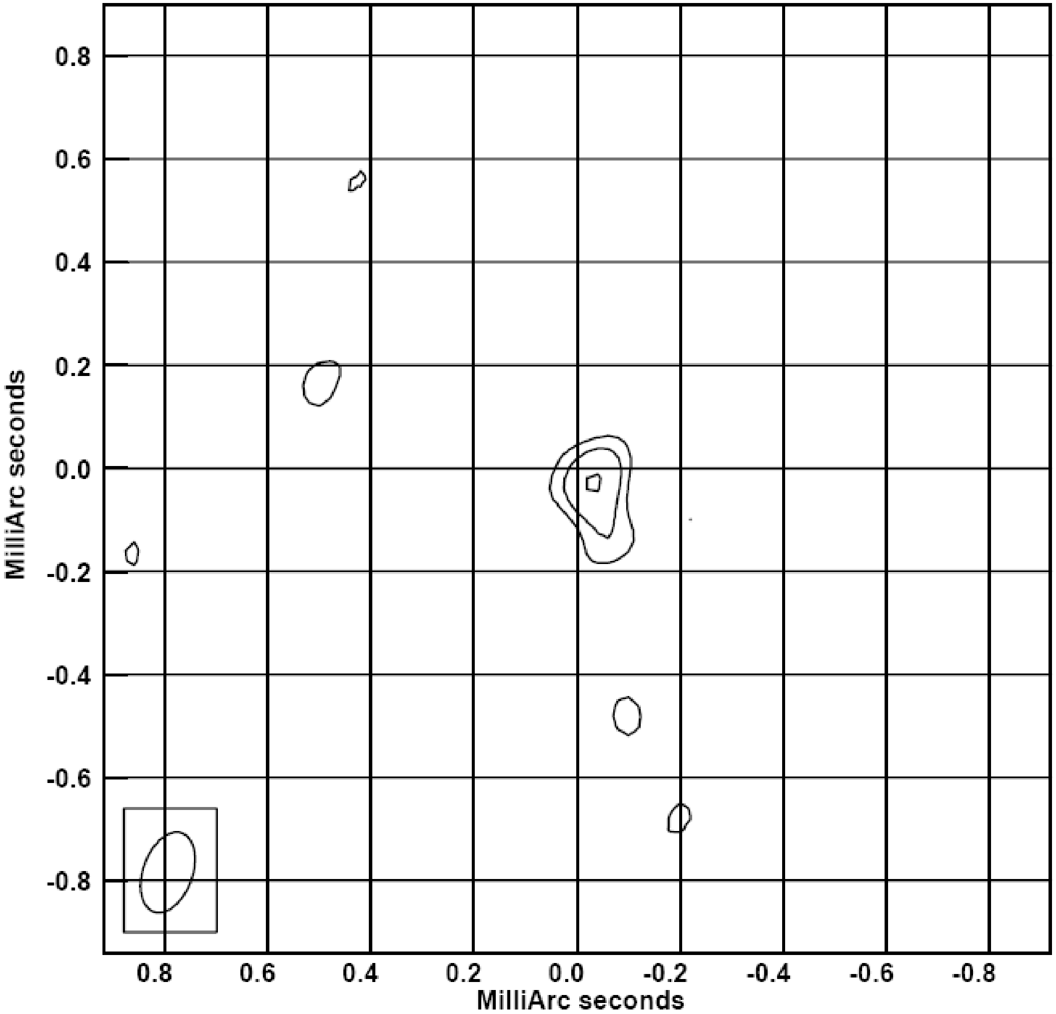


First image of M81* at 3.4 mm!

Clean map of 86G imaging
Natural weighting
Peak=45.3 mJy/beam
RMS=0.34 mJy/beam
Dynamic range ~ 130

0.1 mas ~ 0.0016 pc ~ 300 Rsch

VLBA image of M81 at W band



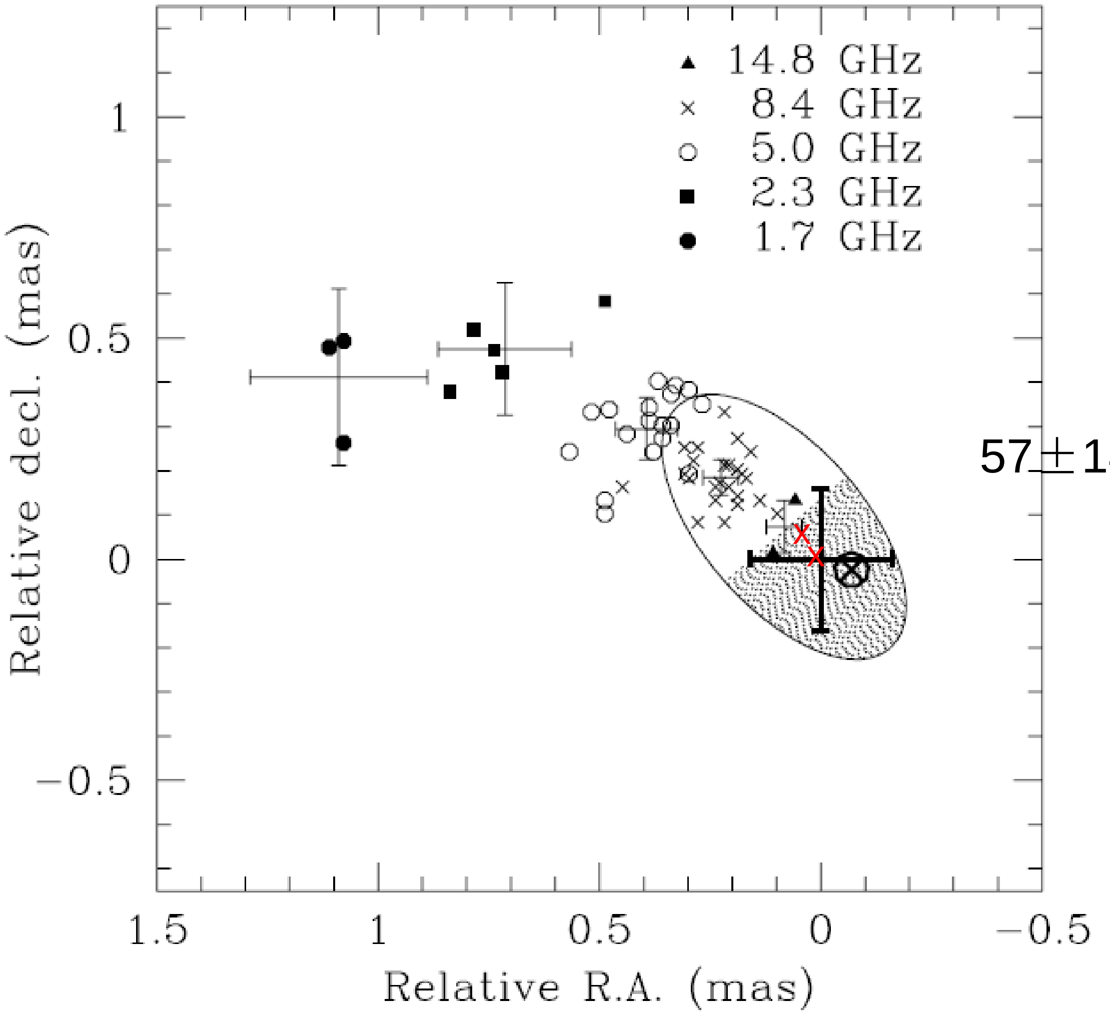
SFPR-ed map of M81*.

Relative core-shift
ΔRA = -35 μas
ΔDEC = -32 μas

B0954+658
180 $\pm$ 20 μas 4.6-8.9 GHz
direction 157^o (p.a. 23^o) at 43 G

Then, M81* 43-87 GHz
57 $\pm$ 14 μas @ -151^o

Core shift

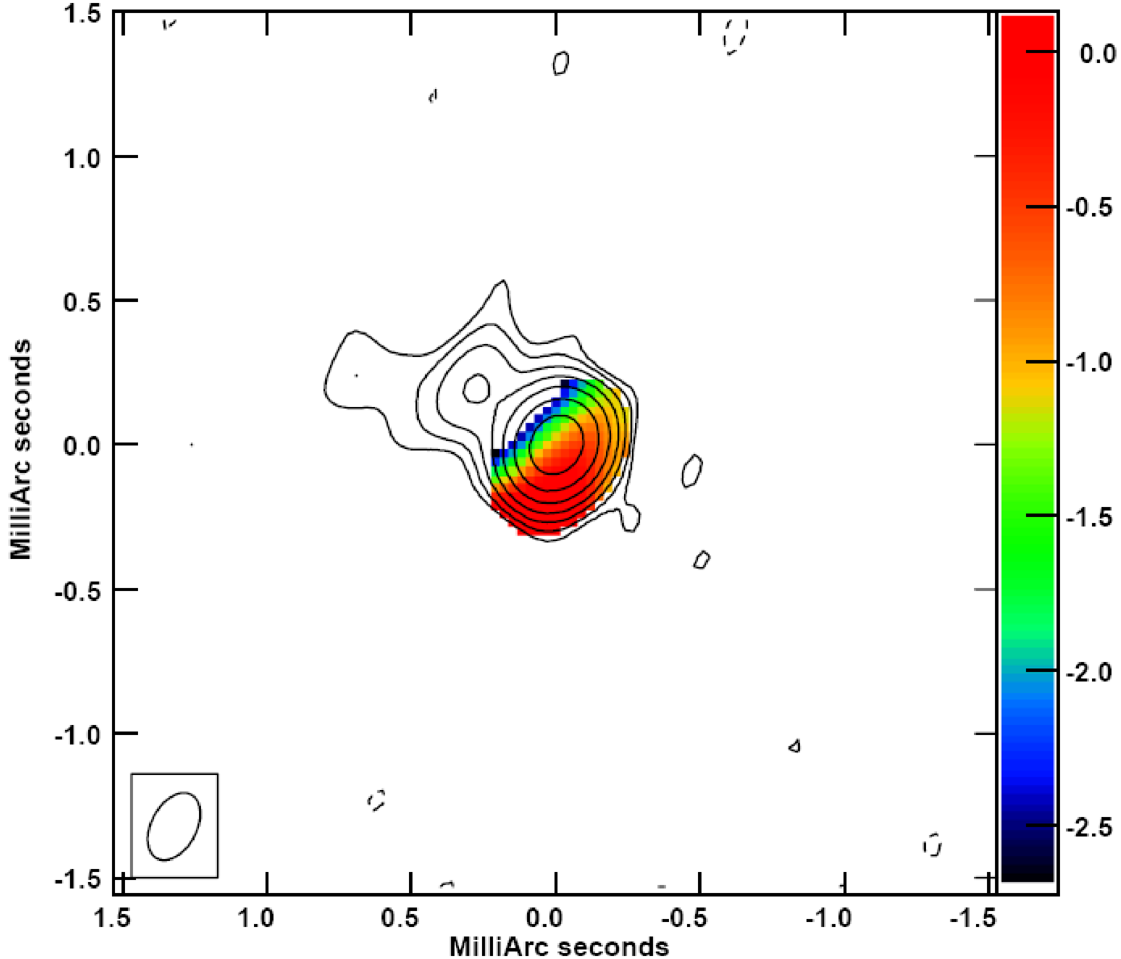


43 – 87 GHz

57±14 μas @ -151 deg

Bietenholz M. F., et al. APJ 2004.

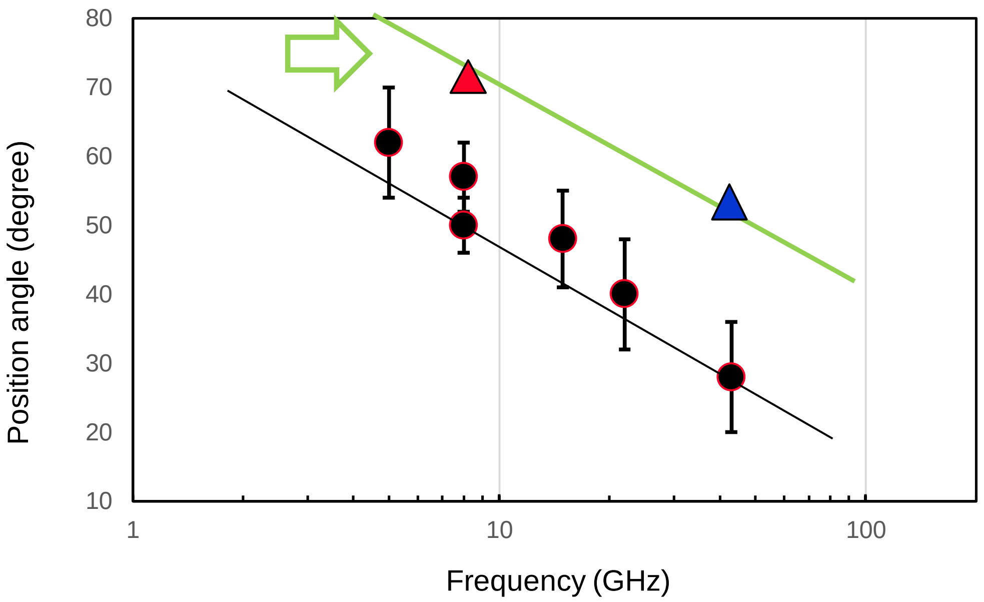
VLBA image of M81 at W band



Spectral index map of M81* (43-87 GHz)

Position angle changes

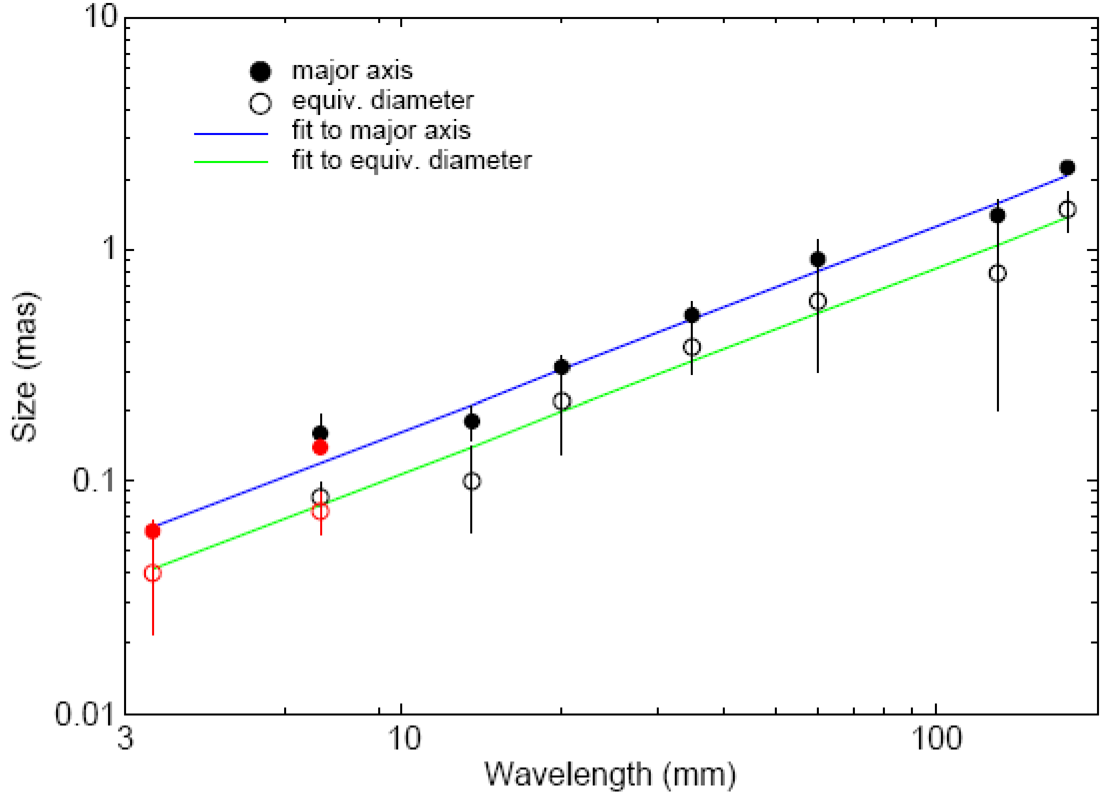
●Bietenholz M F et al. 1993.
■Ros E, et al. 2002.
▲CVN 2014   VLBA 2016 ▲



Position angle with respect to frequency.

- The PA-Frequency relation was shifted in parallel.
- Drifting speed is ~0.5 degree/year.

Core size



$\propto \lambda^{0.88}$

Core size in a power-law relationship to wavelength is valid at 3.4 mm.

Summary

1. The first image of M81* at 3.4 mm was successfully obtained with SFPR. DR ~ 130:1
2. Integration time at 3.4 mm increased from tens of second to tens of minutes with SFPR.
3. Core size in a power-law relationship with wavelength, $\propto \lambda^{0.88}$ is valid to 3.4 mm.
4. The minimum core size is constraint to ~80 R_{sch}.
5. Core shift of M81* from 43-87GHz is 57±14 μas, -151^{o}, preliminary spectral index map is also obtained.

Future plan

1. Multi-epoch multi-frequency observations on M81* for better understanding the core and jet.
2. Polarimetry study of M81* in mm-VLBI.

Thank you!