Probing the innermost regions of AGN jets and their magnetic fields with RadioAstron at tens of μas resolution

J. L. Gómez (IAA), A. Lobanov (MPIfR),
G. Bruni (MPIfR), Y. Kovalev (ASC), A. Marscher (BU),
S. Jorstad (BU), et al.
on behalf of the RadioAstron polarization KSP team

Blazars through Sharp Multi-Wavelength Eyes — Málaga, May 30- June 3, 2016

A KSP for polarimetric Space-VLBI with RadioAstron

Goal

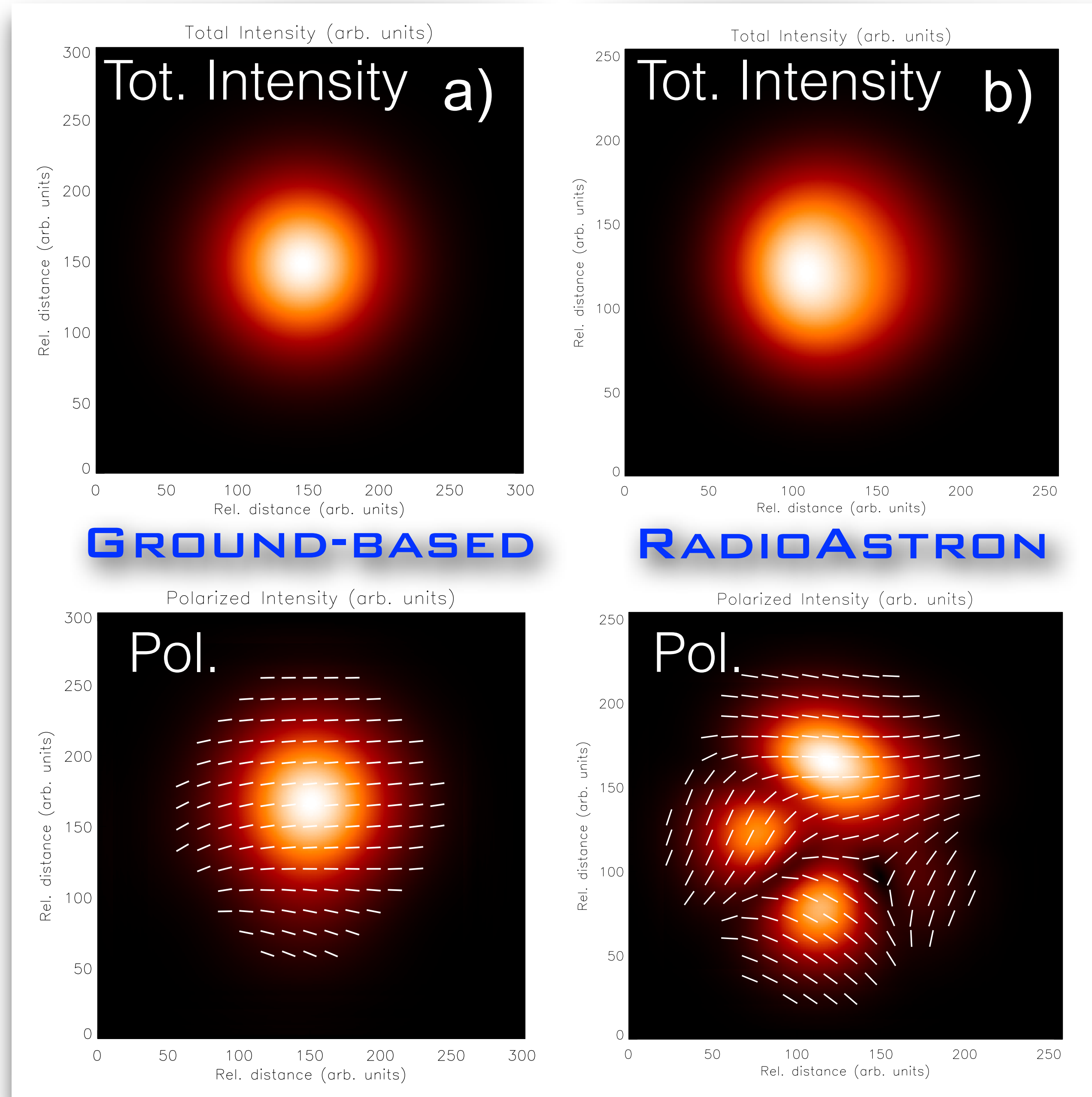
RadioAstron provides the first true full-polarization capabilities for Space-VLBI.

Our goal is to exploit the unprecedented high angular resolution polarization capabilities of RadioAstron to probe the innermost regions of AGN jets and their magnetic fields.

Faraday rotation analysis to determine the 3D structure of the magnetic field.

Comparison with 3D RMHD+emission simulations to study the jet formation and high-energy emission. Testing whether γ-ray flares are produced by the interaction of moving components and a recollimation shock at the core.

Marscher (2014)
TEMZ model numerical simulations



Recollimation shock model for the core (Marscher 2014).

Early Science			
Target	**Date**	**Band**	**Status**
0642+499	9 March 2013	L	Lobanov et al. (2015)

AO-1, AO-2, and AO-3 Observations				
Target	**Date**	**Band**	**Correlation**	**Status**
BL Lac	29 Sep. 2013	L	Yes	Imaging
BL Lac	11 Nov. 2013	K	Yes	Gómez et al. (2016)
3C273	18 Jan. 2014	K	Yes	Bruni et al. (in prep.)
3C273	13 June 2014	L	Yes	
3C279	10 March 2014	K	No	
OJ287	04 April 2014	K	Yes	Imaging
0716+714	3 January 2015	K	No	
3C345	30 March 2016	L	No	
OJ287	16 April 2016	L	No	
OJ287	25 April 2016	K	No	
3C345	4 May 2016	K	No	

Scheduled AO-4 Observations		
Target	**Date**	**Band**
3C454.3	8 October 2016	K
CTA102	17 October 2016	K
OJ287	7 March 2017	K

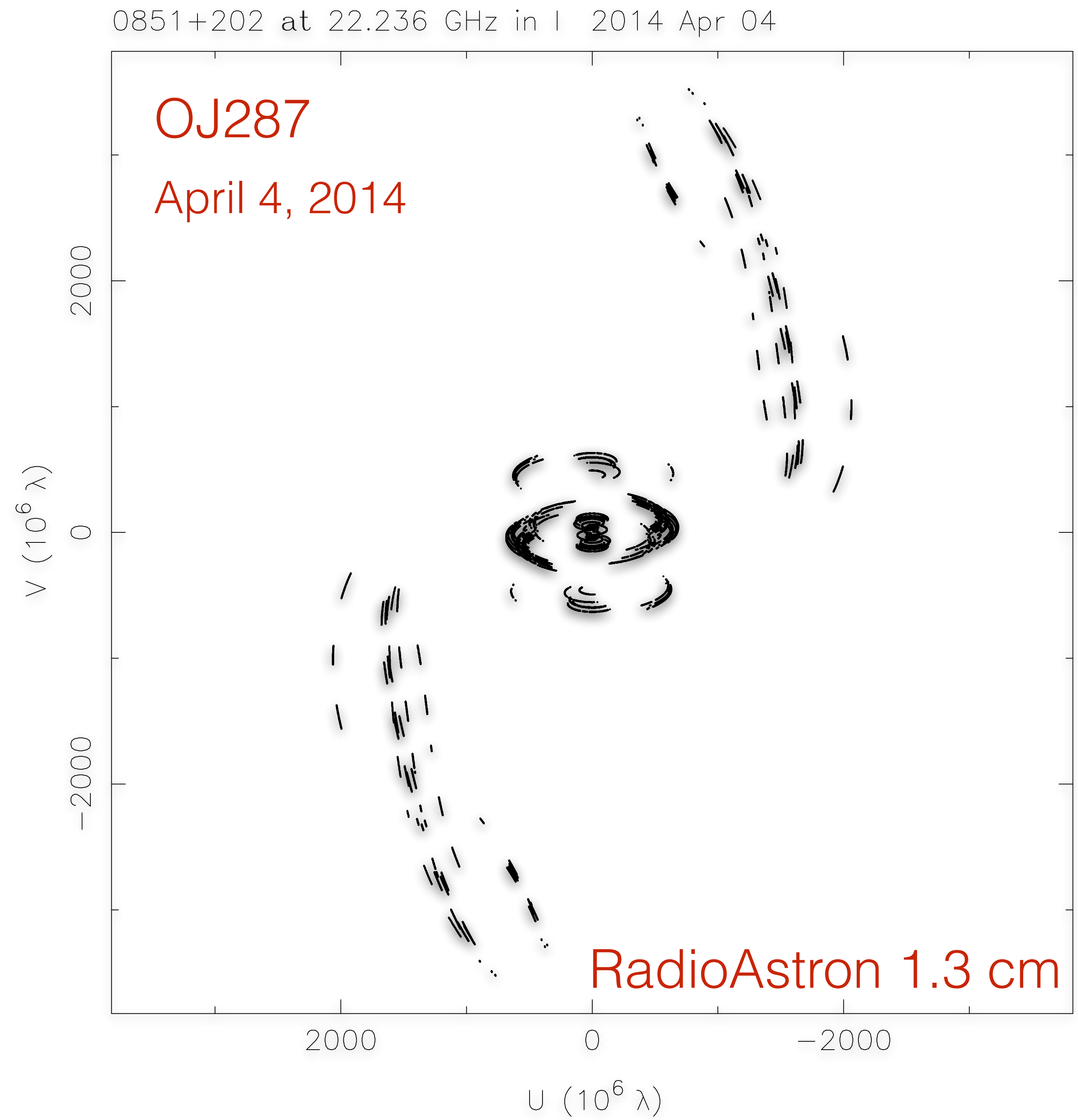
Observations of OJ287 at K-band

RadioAstron observations of **OJ287 at 1.3 cm** were performed in April 4, 2014.

OJ287 was observed together with 12 ground antennas including the EVN, KVN, and GBT.

Ground-space fringes (SNR~50) have been detected throughout the whole experiment, reaching **~4 Earth diameters** in projected length.

Ground-space fringes detected at a record spacing of 15.2 Earth diameters (April 18th, SNR~11.5) by the RadioAstron Survey (PI Kovalev). **Combination with our KSP observations allows imaging OJ287 at a potential angular resolution of ~10 µas**.



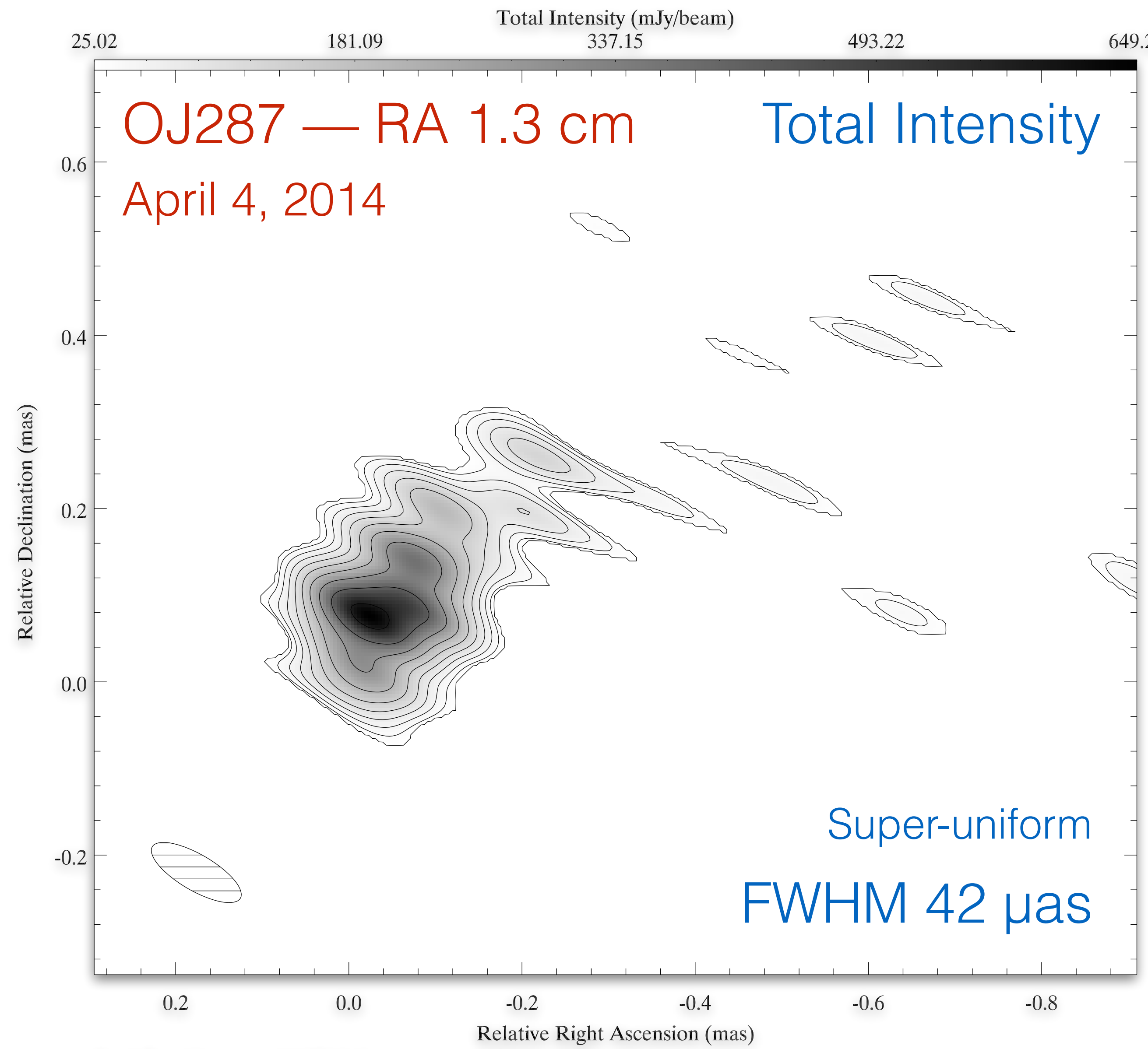
Observations of OJ287 at K-band PRELIMINARY ANALYSIS

RadioAstron observations of **OJ287 at 1.3 cm** were performed in April 4, 2014.

OJ287 was observed together with 12 ground antennas including the EVN, KVN, and GBT.

Ground-space fringes (SNR~50) have been detected throughout the whole experiment, reaching **~4 Earth diameters** in projected length.

Maximum angular resolution for super-uniform weighting of 42 μas. No polarization detected in preliminary analysis.



Peak Total Intensity 0.6493 Jy/beam (min. at 25.02 mJy/beam)
Total Intensity Contours 3.85,5.47,7.76,11.02,15.63,22.19,31.49,44.68,63.42,90% of peak
Beam FWHM 0.118x0.042 mas at 59.721 deg.

Observations of OJ287 at K-band

RadioAstron observations of **OJ287 at 1.3 cm** were performed in April 4, 2014.

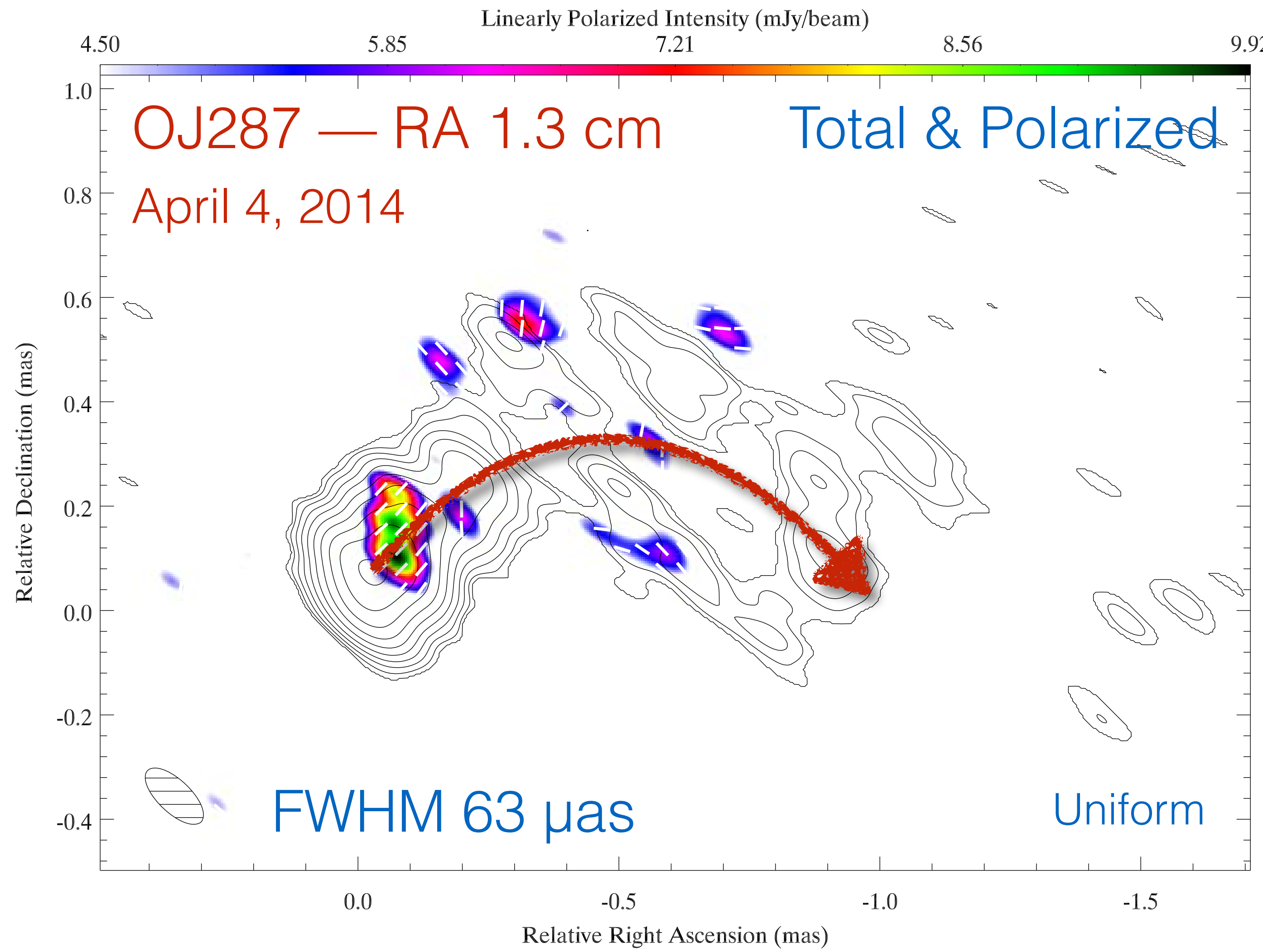
OJ287 was observed together with 12 ground antennas including the EVN, KVN, and GBT.

Ground-space fringes (SNR~50) have been detected throughout the whole experiment, reaching **~4 Earth diameters** in projected length.

Maximum angular resolution for super-uniform weighting of 42 µas. No polarization detected in preliminary analysis.

Uniform weighting provides an angular resolution of 63 µas. Polarization is detected near the core area.

The jet bends abruptly at ~0.5 mas from the core.



Peak Total Intensity 0.8408 Jy/beam (min. at 5.00 mJy/beam - Pol. 45.4% peak)
Total Intensity Contours 0.59,1.04,1.81,3.17,5.54,9.67,16.89,29.50,51.53,90% of peak
Beam FWHM 0.142x0.063 mas at 46.459 deg.

Observations of OJ287 at K-band

RadioAstron observations of **OJ287 at 1.3 cm** were performed in April 4, 2014.

OJ287 was observed together with 12 ground antennas including the EVN, KVN, and GBT.

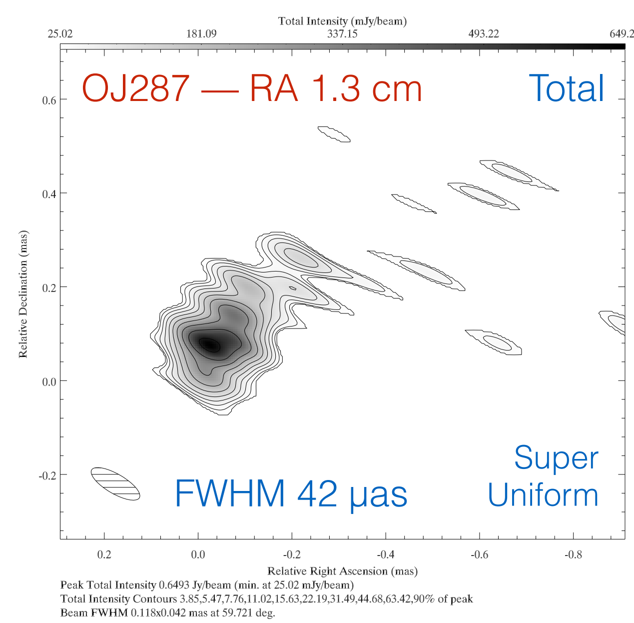
Ground-space fringes (SNR~50) have been detected throughout the whole experiment, reaching **~4 Earth diameters** in projected length.

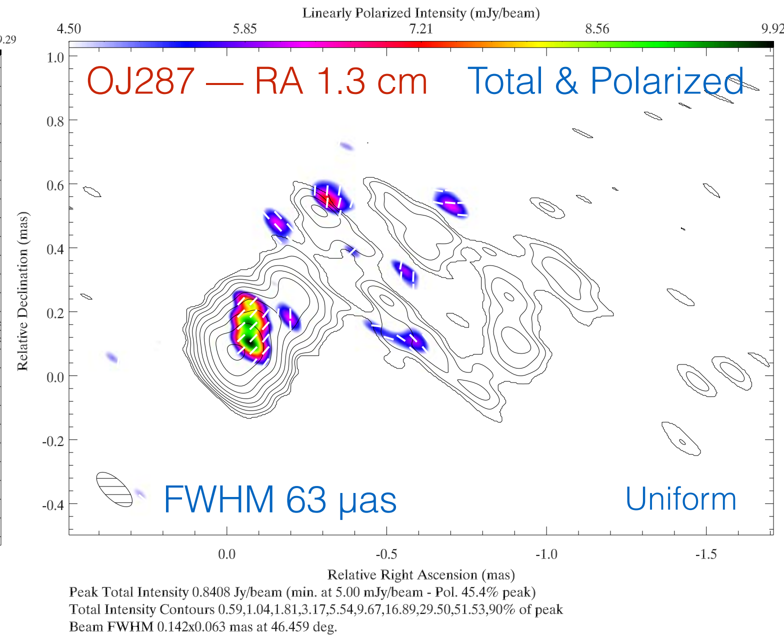
Maximum angular resolution for super-uniform weighting of 42 µas. No polarization detected in preliminary analysis.

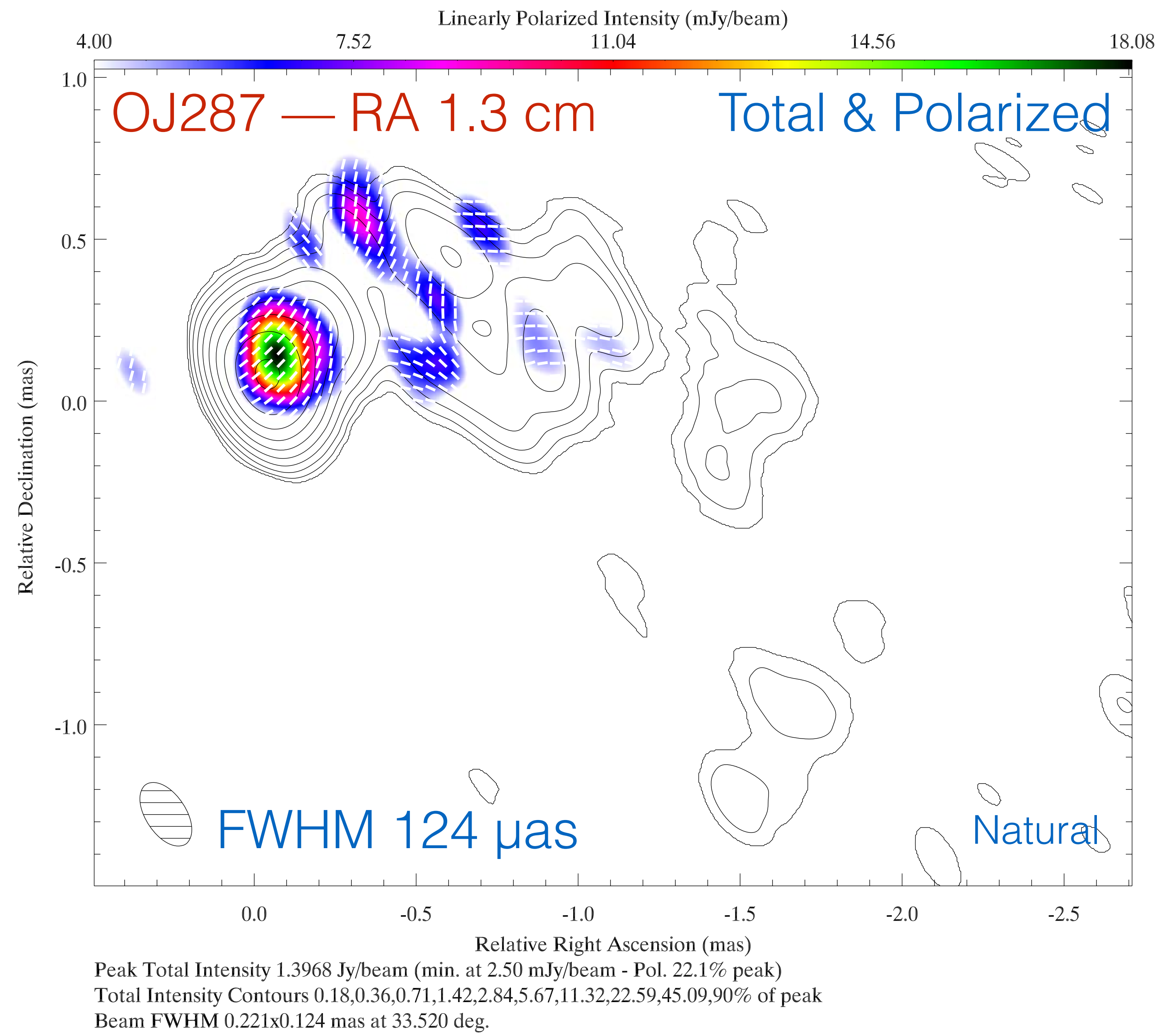
Uniform weighting provides an angular resolution of 63 µas. Polarization is detected near the core area.

The jet bends abruptly at ~0.5 mas from the core.

Natural weighting reveals that the bending continues to the south. EVPAs in the core aligned with the jet direction.







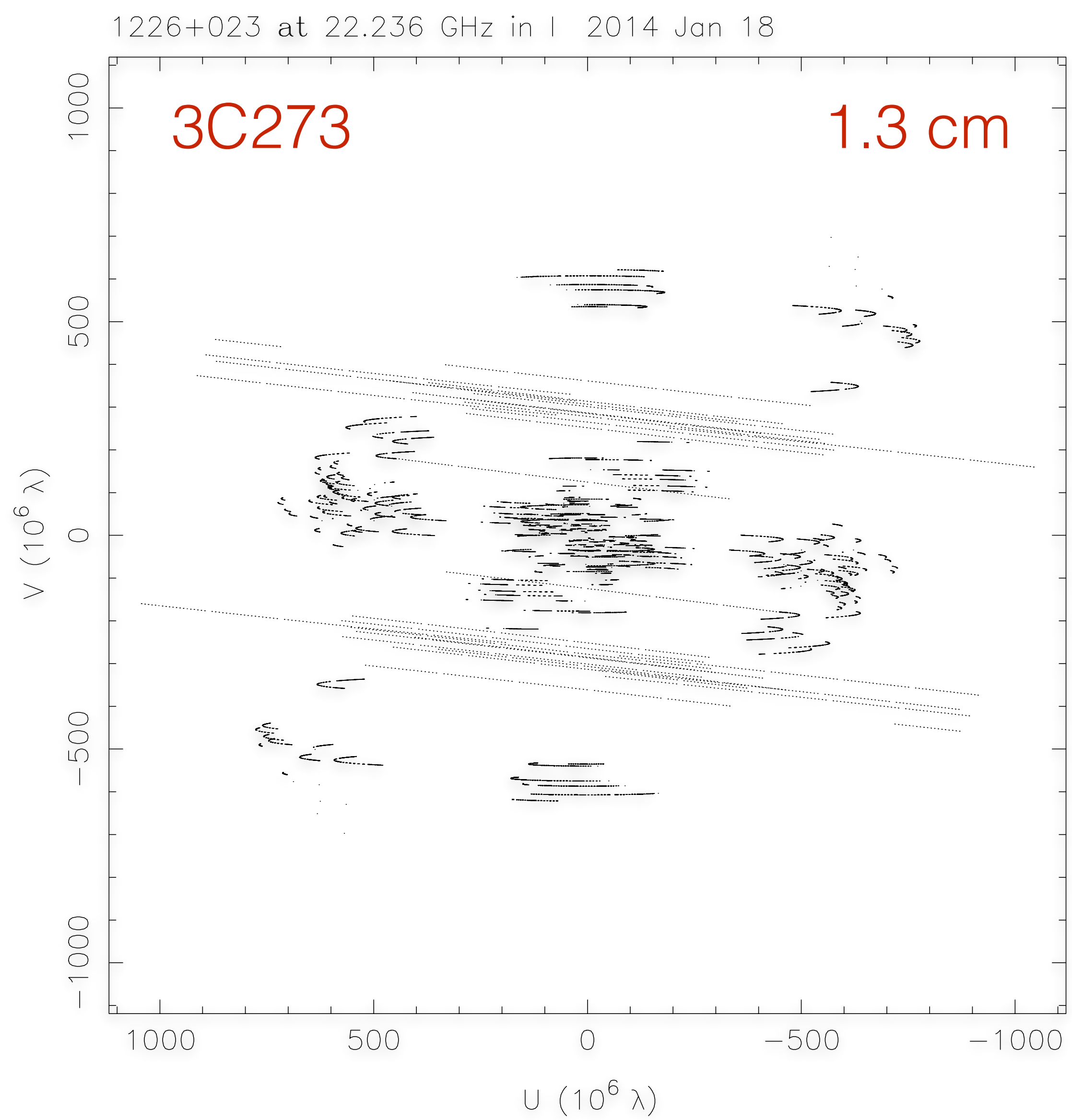
Observations of 3C273 at K-band

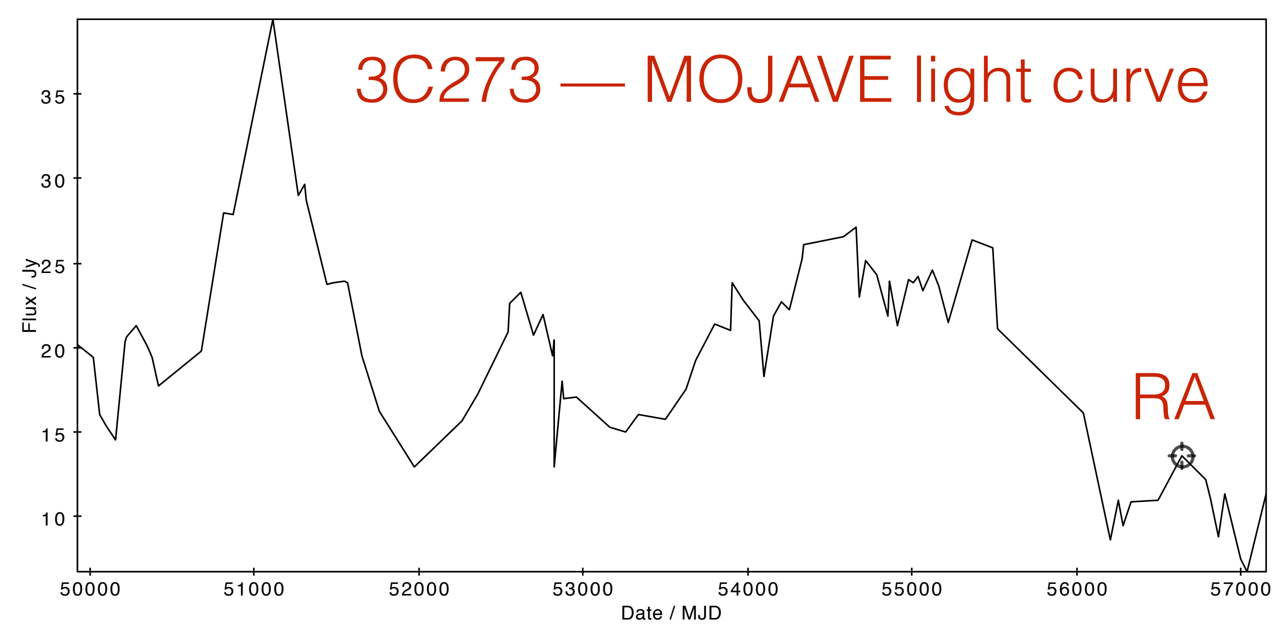
RadioAstron observations of **3C273 at 1.3 cm** were performed on January 18, 2014.

3C273 was observed together with 22 antennas on the ground array: AT, CD, HO, MP, KL, HH, EF, MC, TR, SV, ZC, GB, +VLBA.

Ground-space fringes have been found only for the last hour of the 16.8 hours experiment, yielding a maximum baseline length that barely exceeds one Earth's diameter.

RadioAstron observations performed during a quiescent state of the source.





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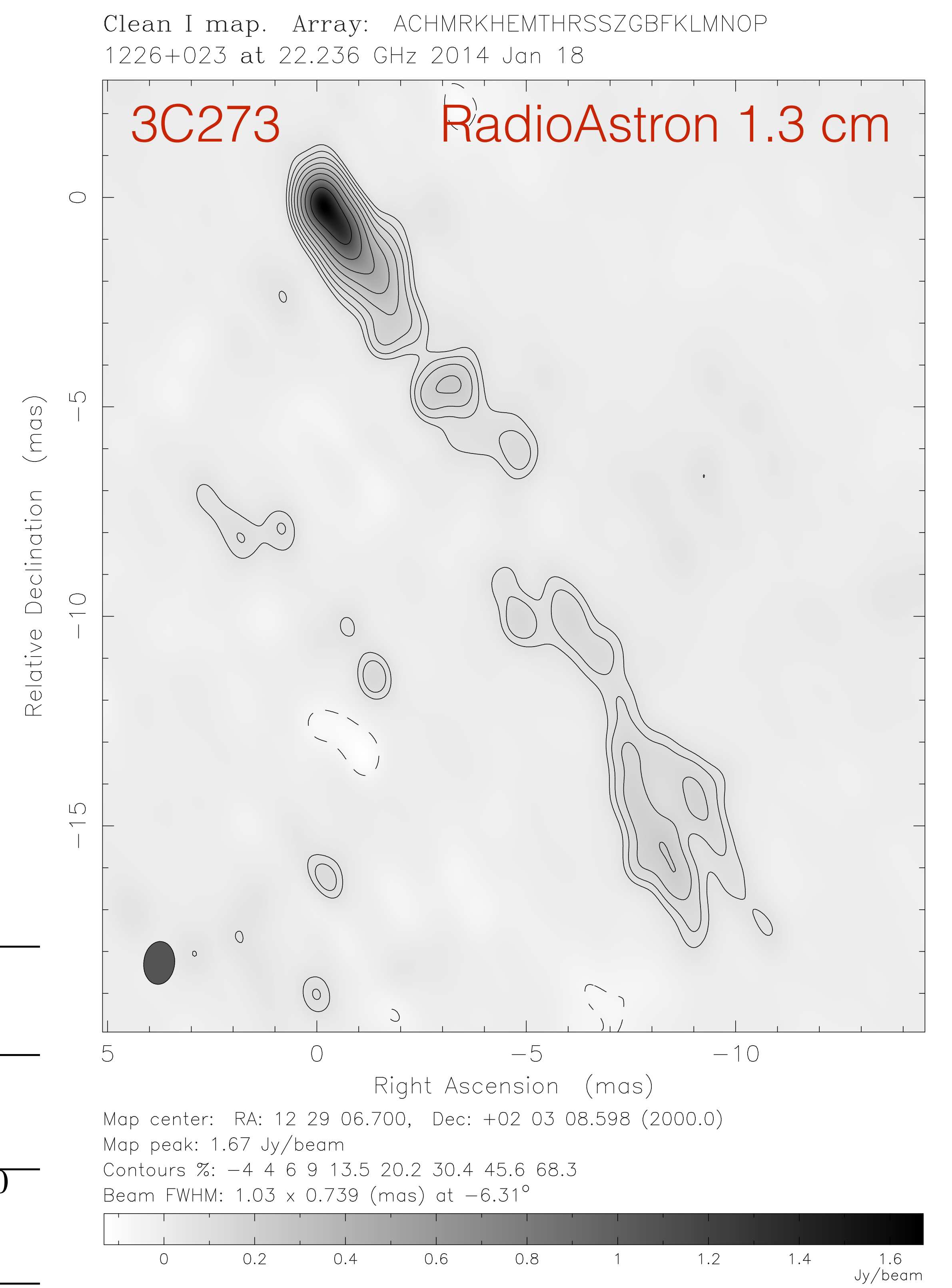
Ground-space fringes have been found only for the last hour of the 16.8 hours experiment, yielding a maximum baseline length that barely exceeds one Earth's diameter.

RadioAstron observations performed during a quiescent state of the source.

Maximum brightness temperatures do not exceed 2×10^{10} K!

Comp.	Flux [Jy]	Radius [mas]	Freq. [GHz]	T_b [K]
A	1.24590	0.287002	22	8.56×10^9
B	2.58145	1.18029	22	1.05×10^9
A	4.76423	0.364897	43	2.02×10^{10}
B	1.07640	0.479505	43	2.65×10^9

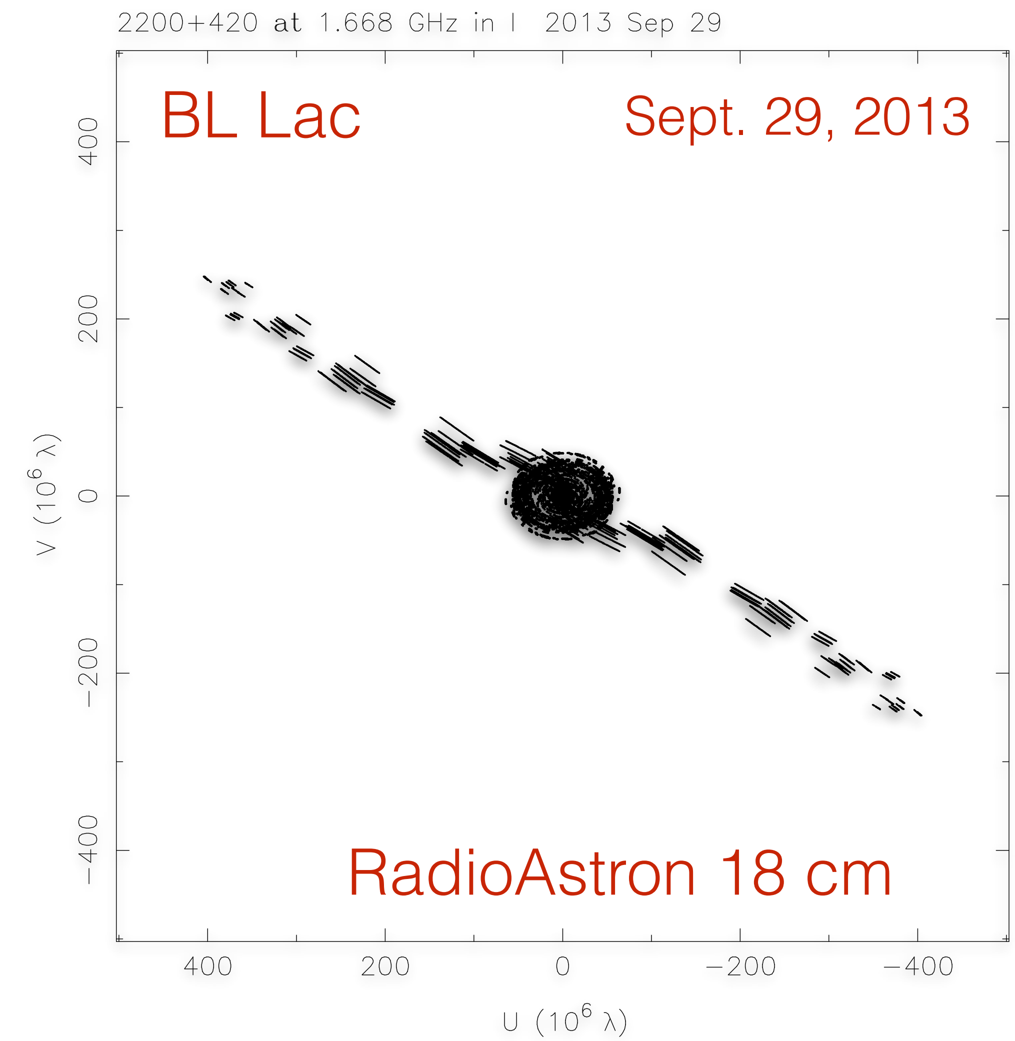


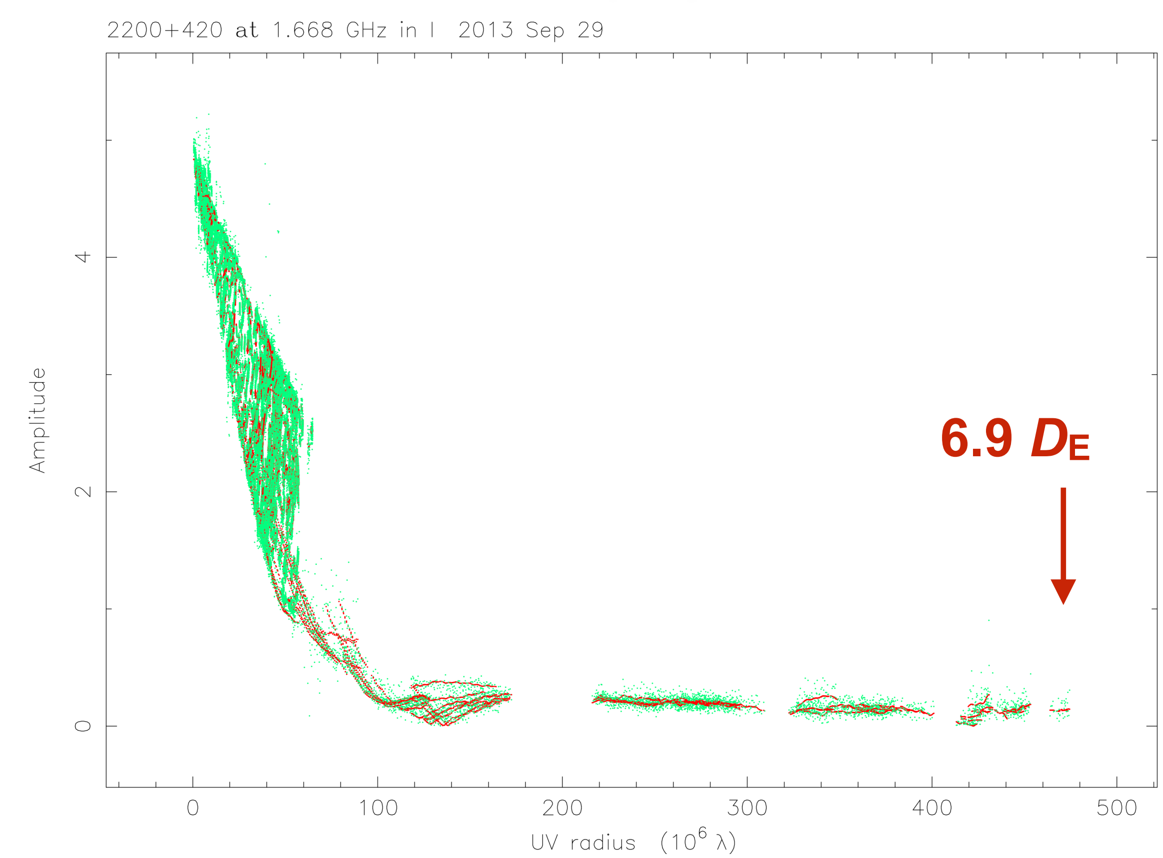
Observations of BLLac at L-band *PRELIMINARY ANALYSIS*

RadioAstron observations of **BL Lac at 18 cm** were performed in September 29, 2013.

BL Lac was observed together with 24 ground antennas: SV, ZC, BD, EF, GB, WT, NT, TR, JD, ON, UR, KL, SH, EV and the VLBA.

Ground-space fringes have been detected up to ~7 Earth's diameters in projected length.





Observations of BLLac at L-band

RadioAstron observations of **BL Lac at 18 cm** were performed in September 29, 2013.

BL Lac was observed together with 24 ground antennas: SV, ZC, BD, EF, GB, WT, NT, TR, JD, ON, UR, KL, SH, EV and the VLBA.

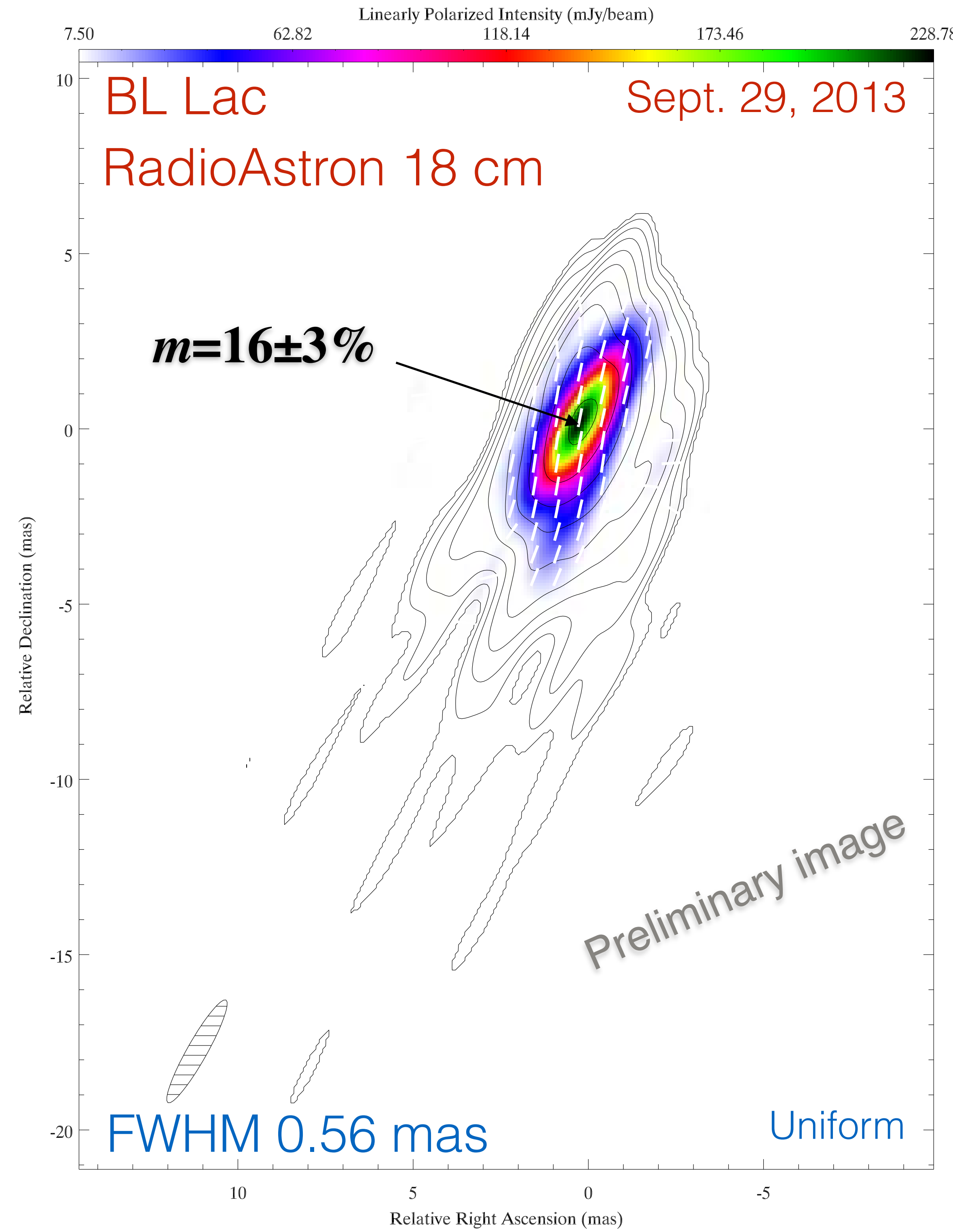
Ground-space fringes have been detected up to ~7 Earth's diameters in projected length.

Achieved angular resolution:
FWHM: 3.36x0.56 mas

5σ sensitivity:
4 mJy/beam in Total
7.5 mJy/beam in Polarization

Recovered 4.84 Jy of 5.2 Jy (Effelsberg)

Highly polarized component with *m*=16±3%, and EVPAs in the direction of the jet.



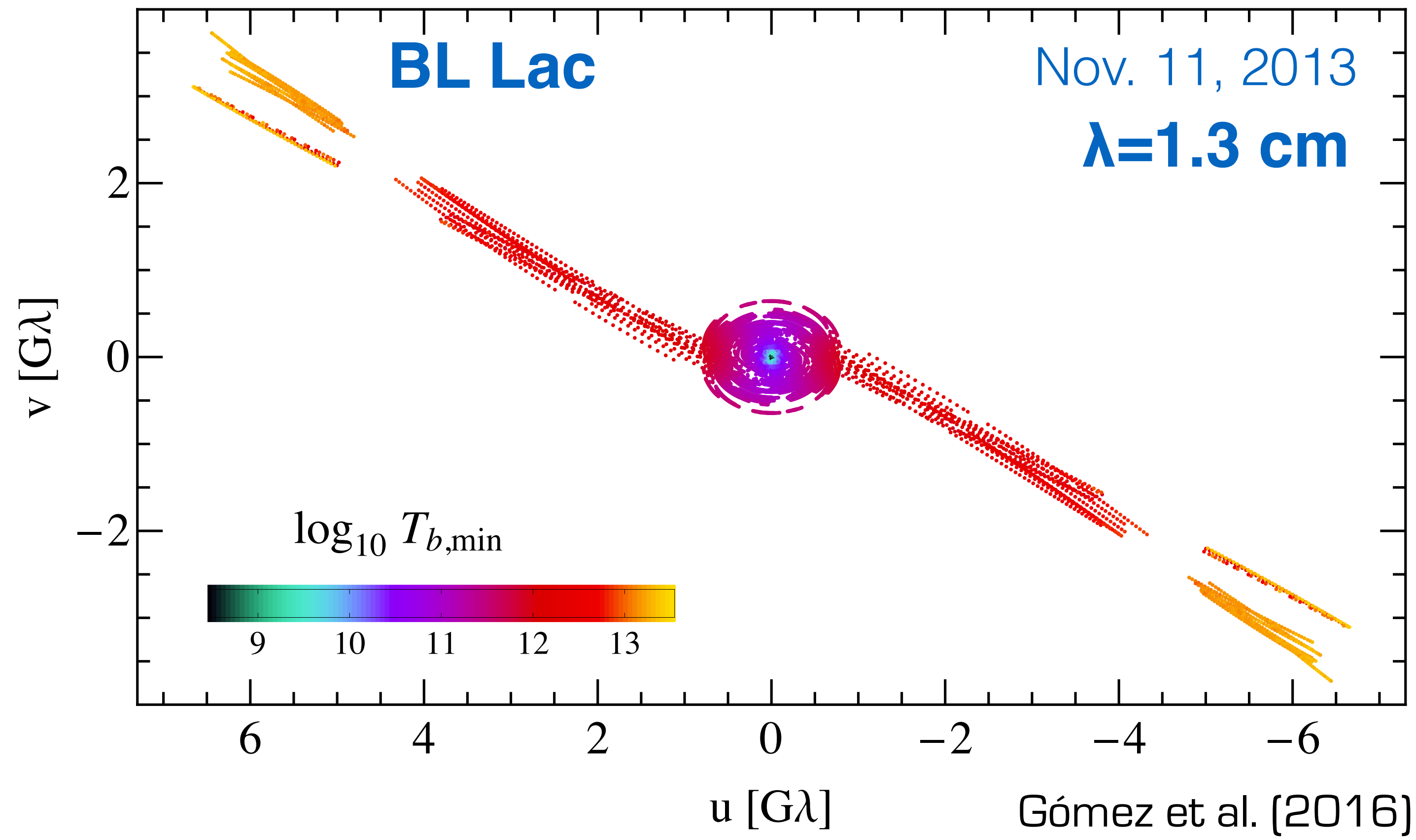
Peak Total Intensity 1.1098 Jy/beam (min. at 4.00 mJy/beam - Pol. 3.3% peak)
Total Intensity Contours 0.36,0.67,1.23,2.27,4.19,7.74,14.29,26.39,48.74,90% of peak
Beam FWHM 3.357x0.564 mas at -29.468 deg.

OBSERVATIONS OF BLLAC AT K-BAND

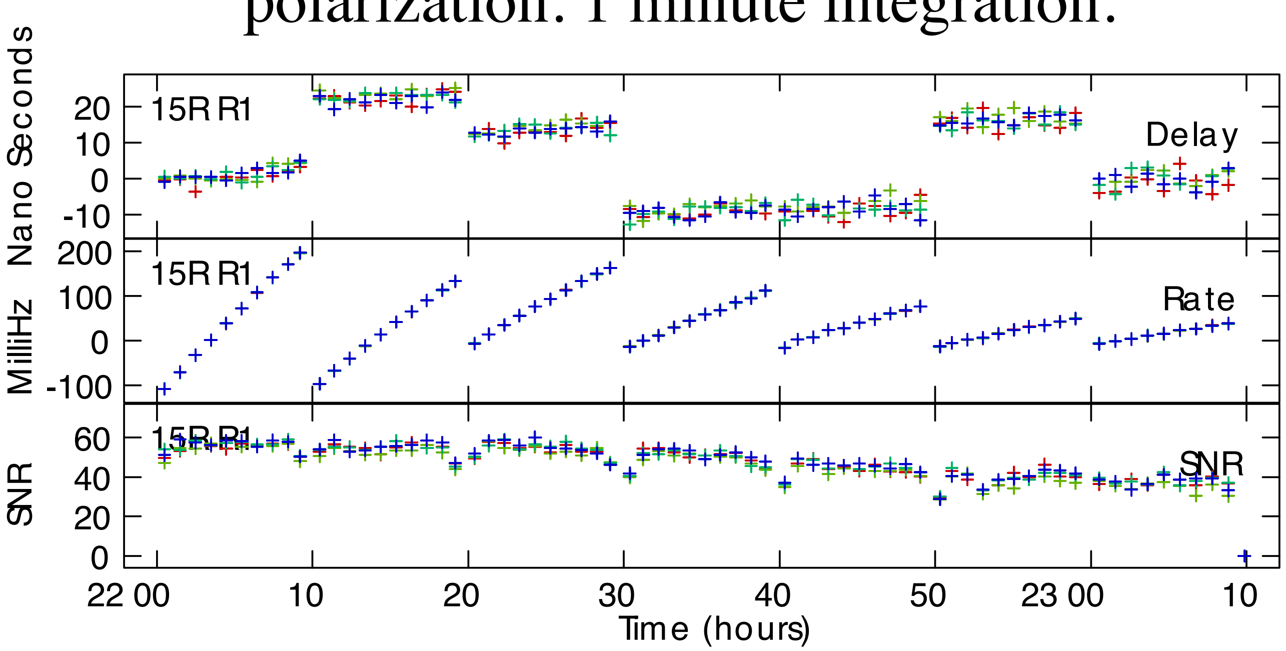
RadioAstron observations of **BL Lac at 1.3 cm** were performed in November 11, 2013.

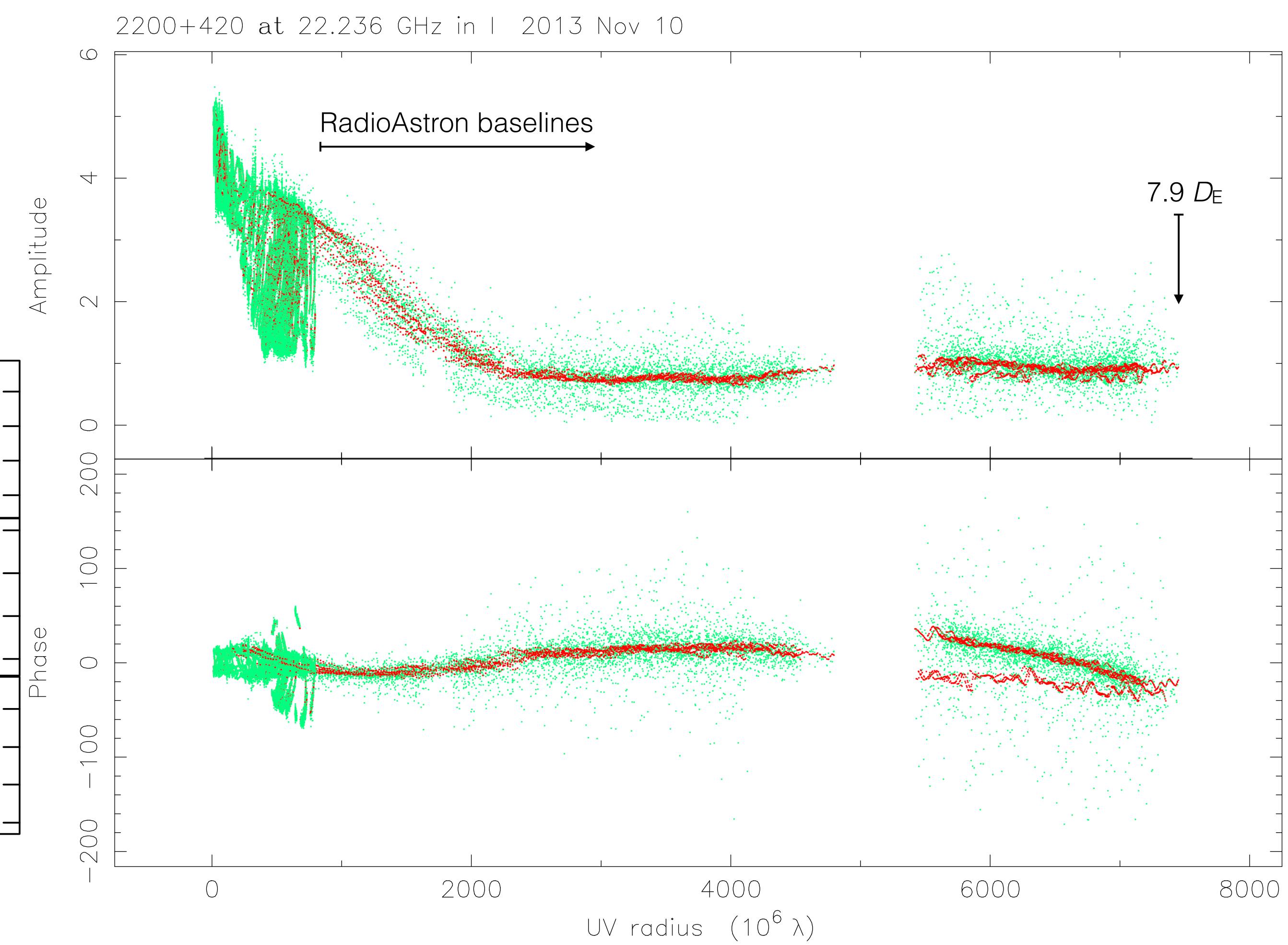
BL Lac was observed together with 15 ground antennas: EF, MH, ON, SV, ZC, MC, BD, BR, HN, KP, LA, NL, OV, PT, MK.

Ground-space fringes up to projected baseline distance of 7.9 Earth's diameters in projection.



Perigee: Independent solutions for IF and polarization. 1 minute integration.





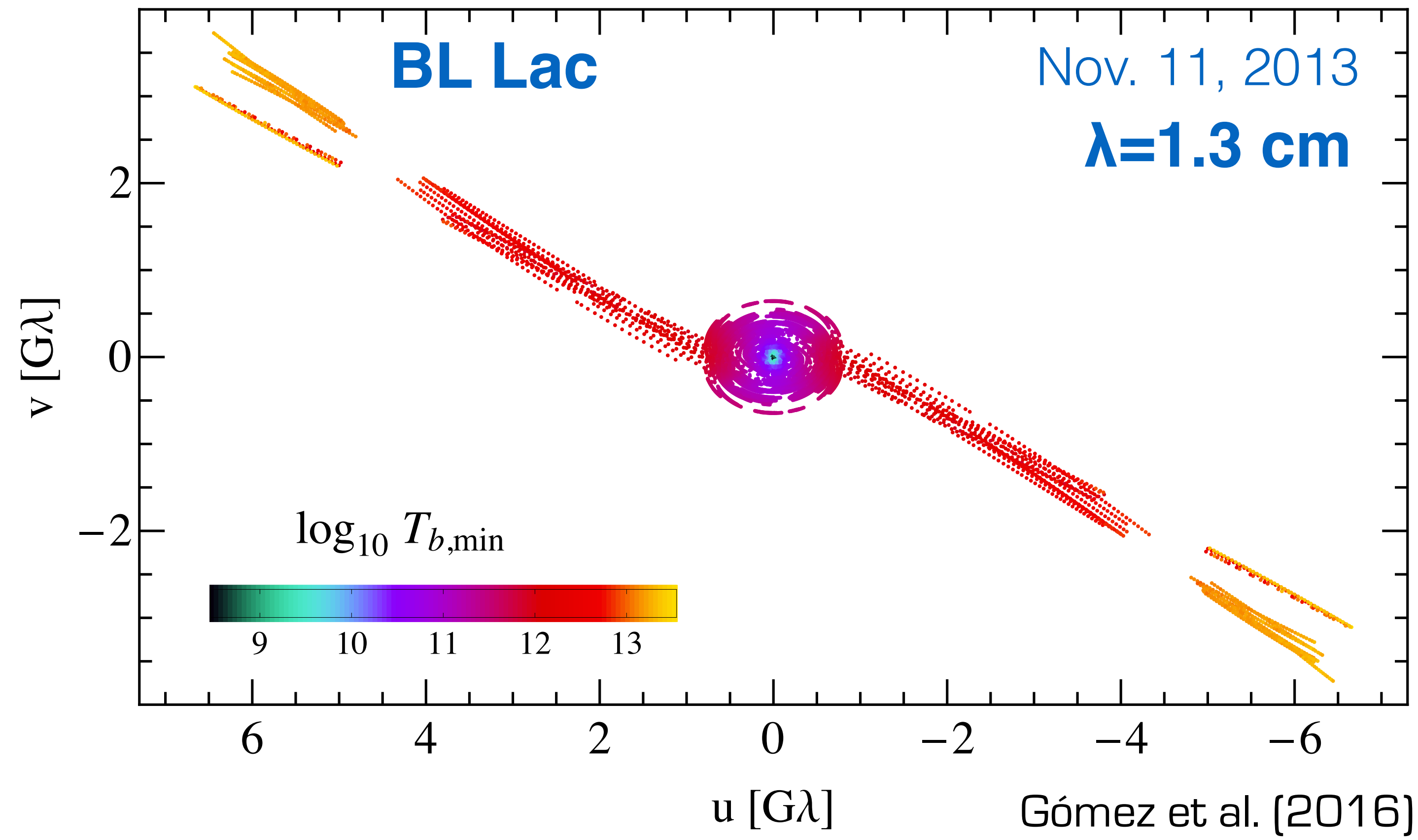
Observations of BLLac at K-band (Gómez et al. 2015, submitted)

RadioAstron observations of **BL Lac at 1.3 cm** were performed in November 11, 2013.

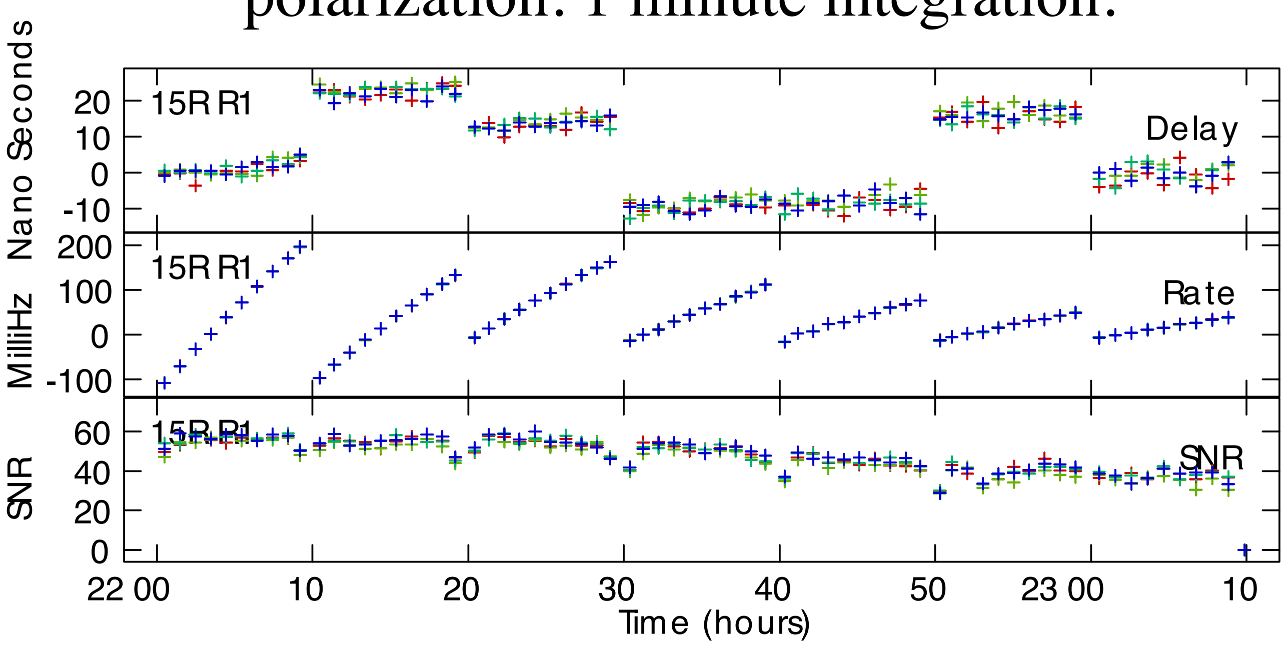
BL Lac was observed together with 15 ground antennas: EF, MH, ON, SV, ZC, MC, BD, BR, HN, KP, LA, NL, OV, PT, MK.

Ground-space fringes up to projected baseline distance of 7.9 Earth's diameters in projection.

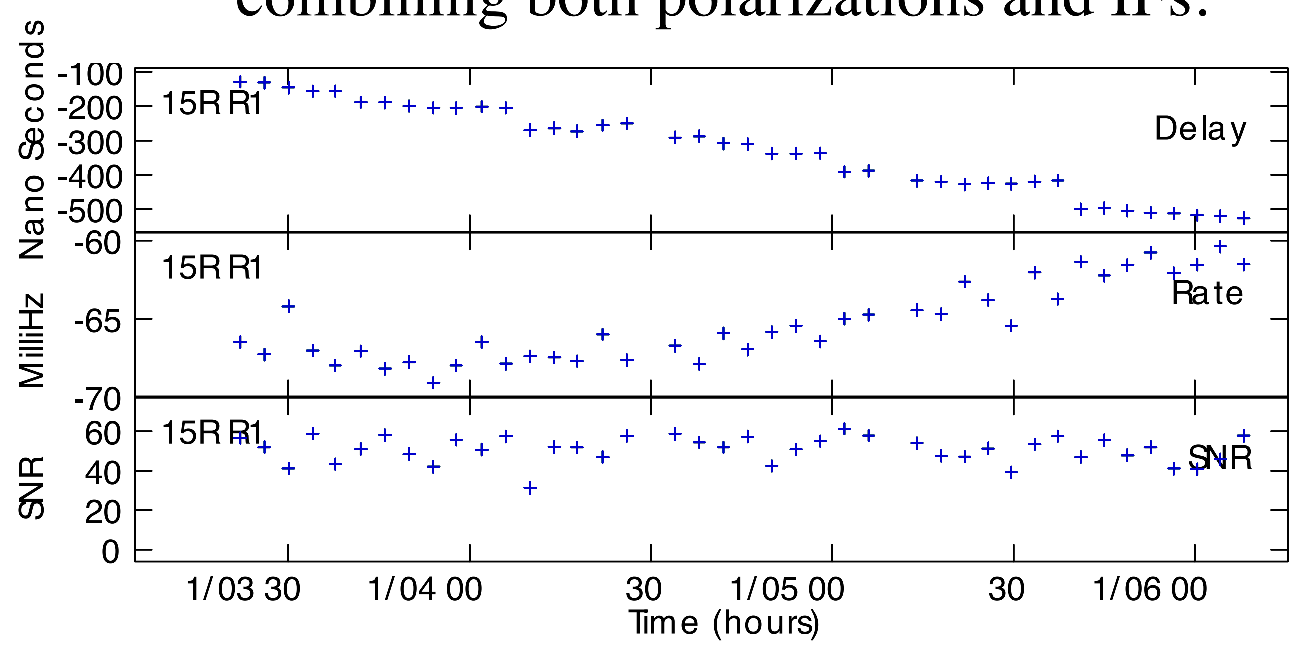
Reliable fringe detection (SNR~50) until the tracking station changed from Puschino to Green Bank.



Perigee: Independent solutions for IF and polarization. 1 minute integration.



Long baselines: 4 minutes integration combining both polarizations and IFs.



Observations of BLLac at K-band

RadioAstron observations of **BL Lac at 1.3 cm** were performed in November 11, 2013.

BL Lac was observed together with 15 ground antennas: EF, MH, ON, SV, ZC, MC, BD, BR, HN, KP, LA, NL, OV, PT, MK.

Ground-space fringes up to projected baseline distance of 7.9 Earth's diameters in projection.

Reliable fringe detection (SNR~50) until the tracking station changed from Puschino to Green Bank.

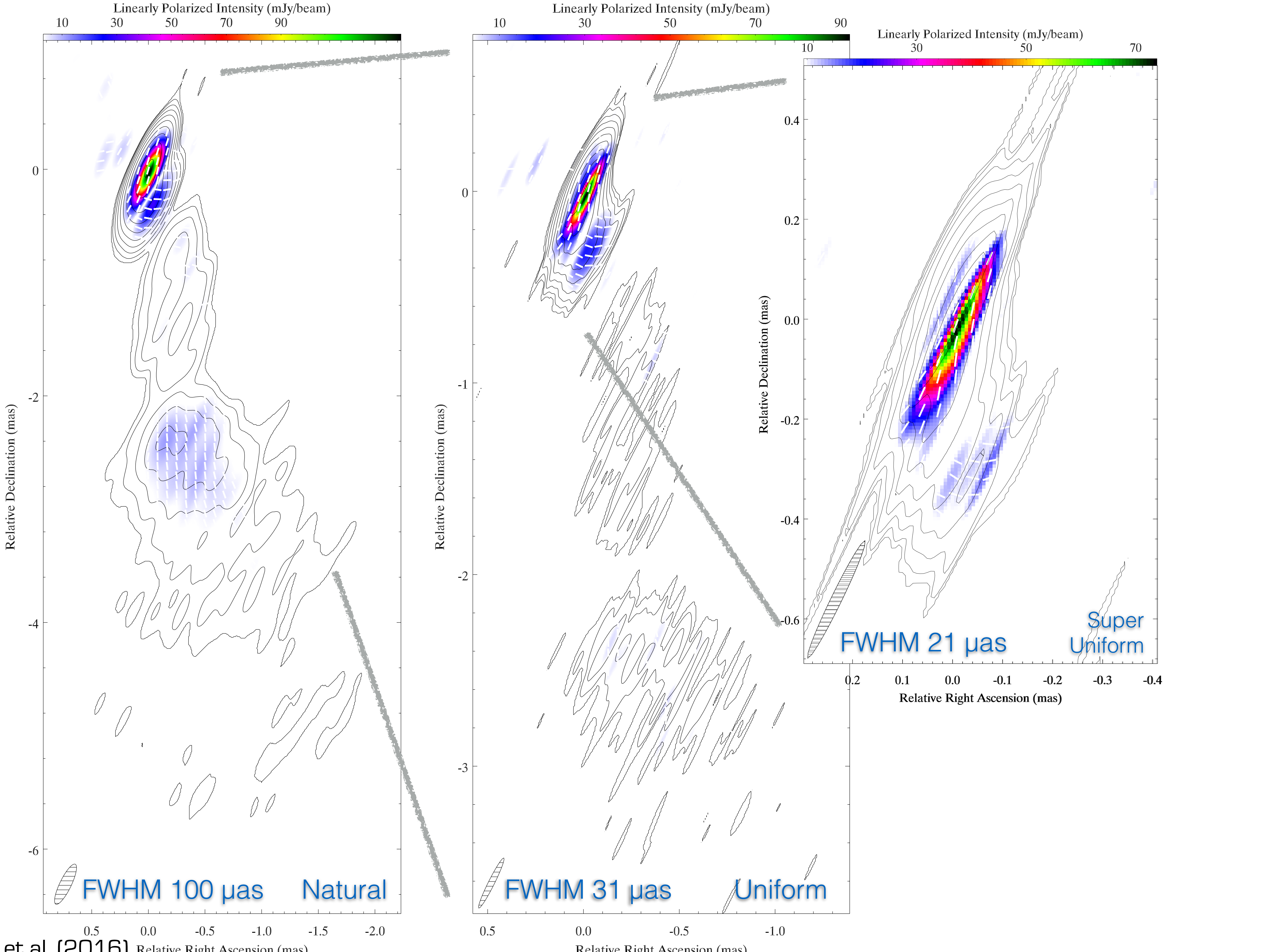
D-terms for RadioAstron are particularly consistent across IFs, and show an amplitude of ~9% for RCP and below 5% for LCP.

Confirmation of RadioAstron polarization capabilities at 22 GHz.

TABLE 1
Instrumental polarization (D-terms) at 22 GHz

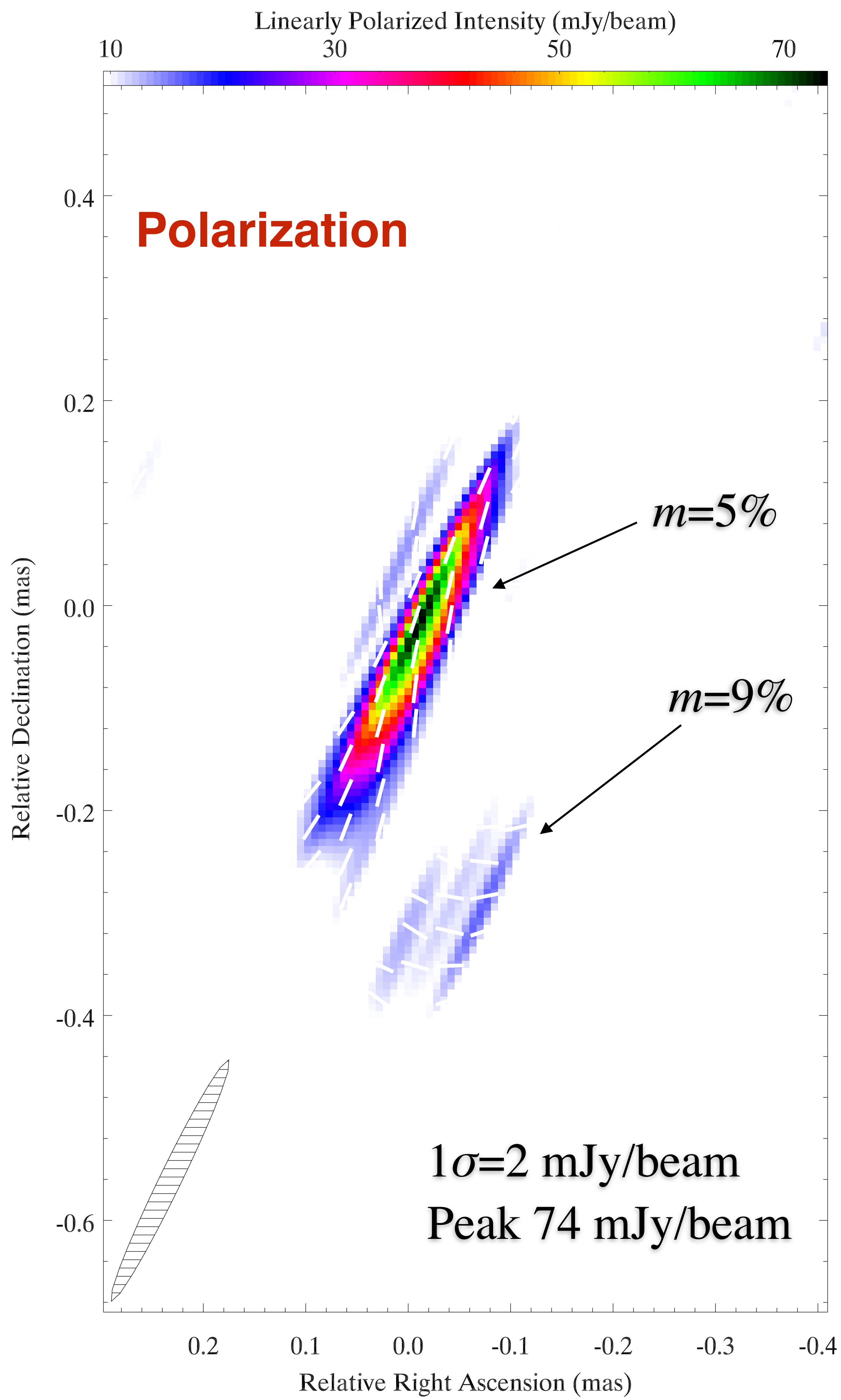
Antenna	RCP		LCP	
	m [%]	χ [°]	m [%]	χ [°]
SRT	9.3±0.5	21±5	4.5±0.3	72±5
	8.8±0.8	20±4	4.4±0.2	68±8
BR	1.4±0.7	−73±18	0.8±0.4	−165±22
	1.4±0.7	−86±23	0.7±0.3	−196±24
EF	9.9±0.7	−91±4	8.1±0.5	−126±7
	9.3±0.8	−98±3	7.5±0.3	−130±6
HN	2.3±0.2	174±16	2.2±0.6	90±6
	2.2±0.4	149±14	2.0±0.8	85±11
KP	1.1±0.3	−160±8	1.1±0.4	−167±12
	0.9±0.4	−182±5	1.0±0.3	−194±8
LA	2.4±0.6	−62±7	1.0±0.4	−124±8
	2.7±0.7	−75±6	0.8±0.6	−126±11
NL	3.6±0.5	−43±5	3.8±0.2	−106±9
	3.1±0.6	−43±7	4.0±0.4	−104±8
OV	2.0±0.8	118±8	2.3±0.4	18±7
	2.2±0.8	94±6	2.7±0.4	13±11
PT	1.4±0.3	−85±11	2.0±0.5	−74±9
	1.4±0.4	−77±12	2.0±0.6	−65±12
MH	1.9±0.9	−116±8	8.2±1.3	−41±9
	2.9±0.8	−152±6	5.5±0.9	−57±8
ON	4.1±0.8	−43±4	5.3±0.5	−87±7
	4.2±0.9	−38±8	5.2±0.6	−82±12
SV	4.8±0.3	179±7	4.1±0.5	−2±5
	4.7±0.2	178±10	4.0±0.3	0±4
ZC	6.1±0.7	162±13	8.3±0.8	168±9
	8.3±0.6	111±10	6.9±0.9	165±5
MC	0.9±0.7	109±10	6.1±0.6	41±8
	2.6±0.9	87±11	5.5±0.9	42±11
MK	3.3±0.4	−64±8	2.9±0.3	−135±5
	3.5±0.6	−67±12	2.9±0.5	−130±9
BD	7.7±0.8	−99±7	6.4±0.6	−179±6
	8.1±0.9	−103±8	6.7±0.8	−178±9

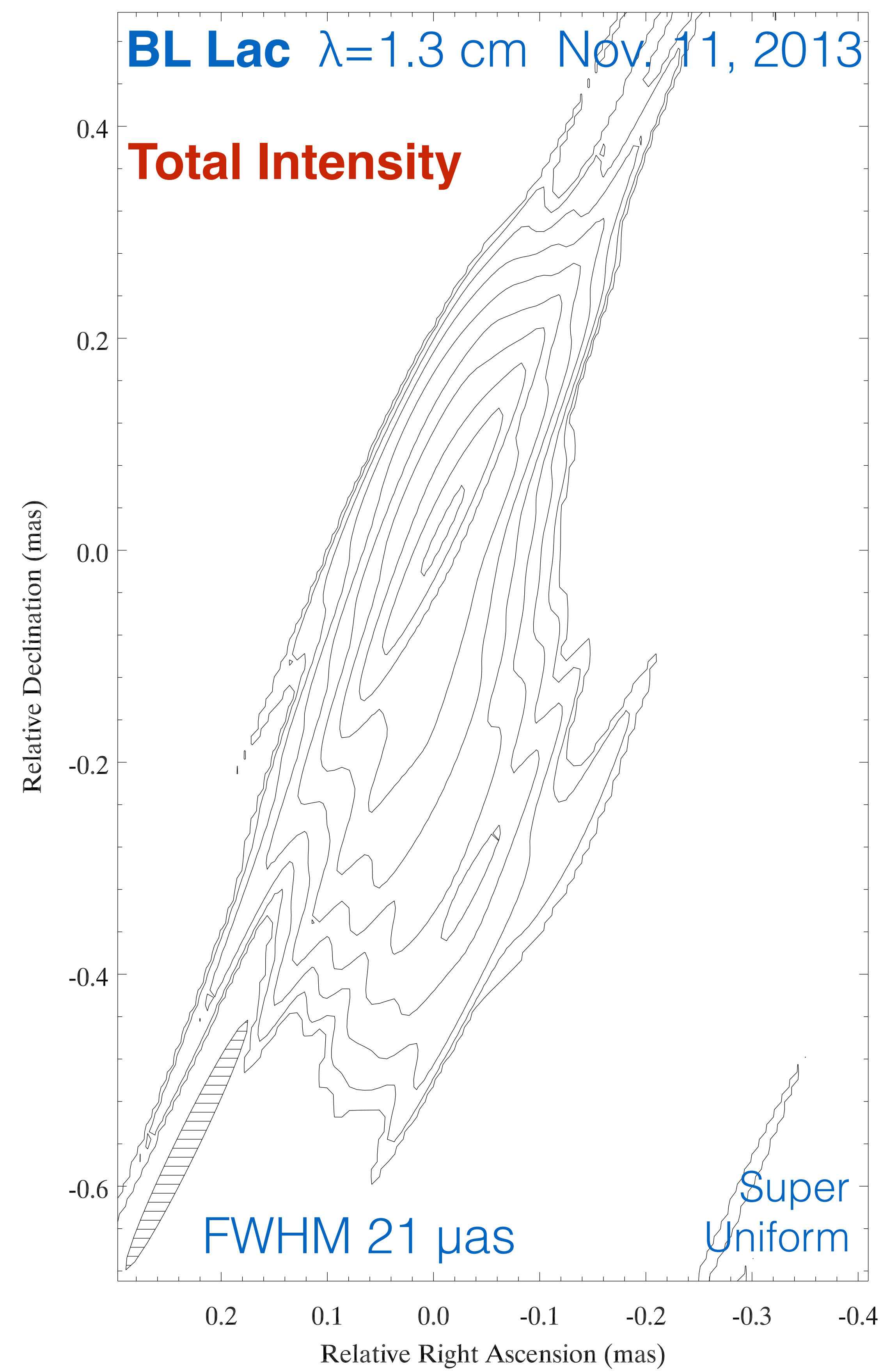
Observations of BLLac at K-band



Gómez et al. (2016)

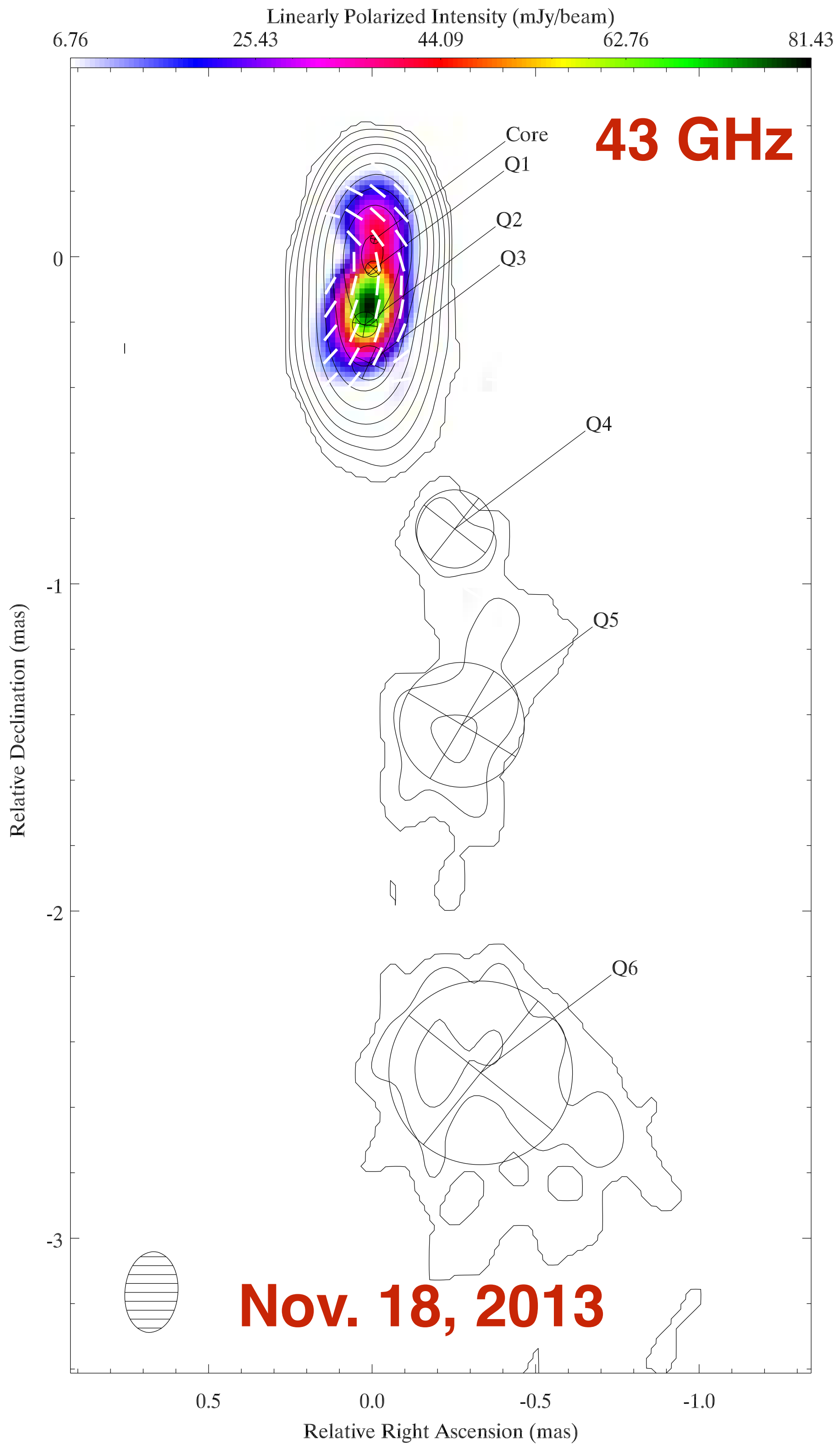
Observations of BLLac at K-band



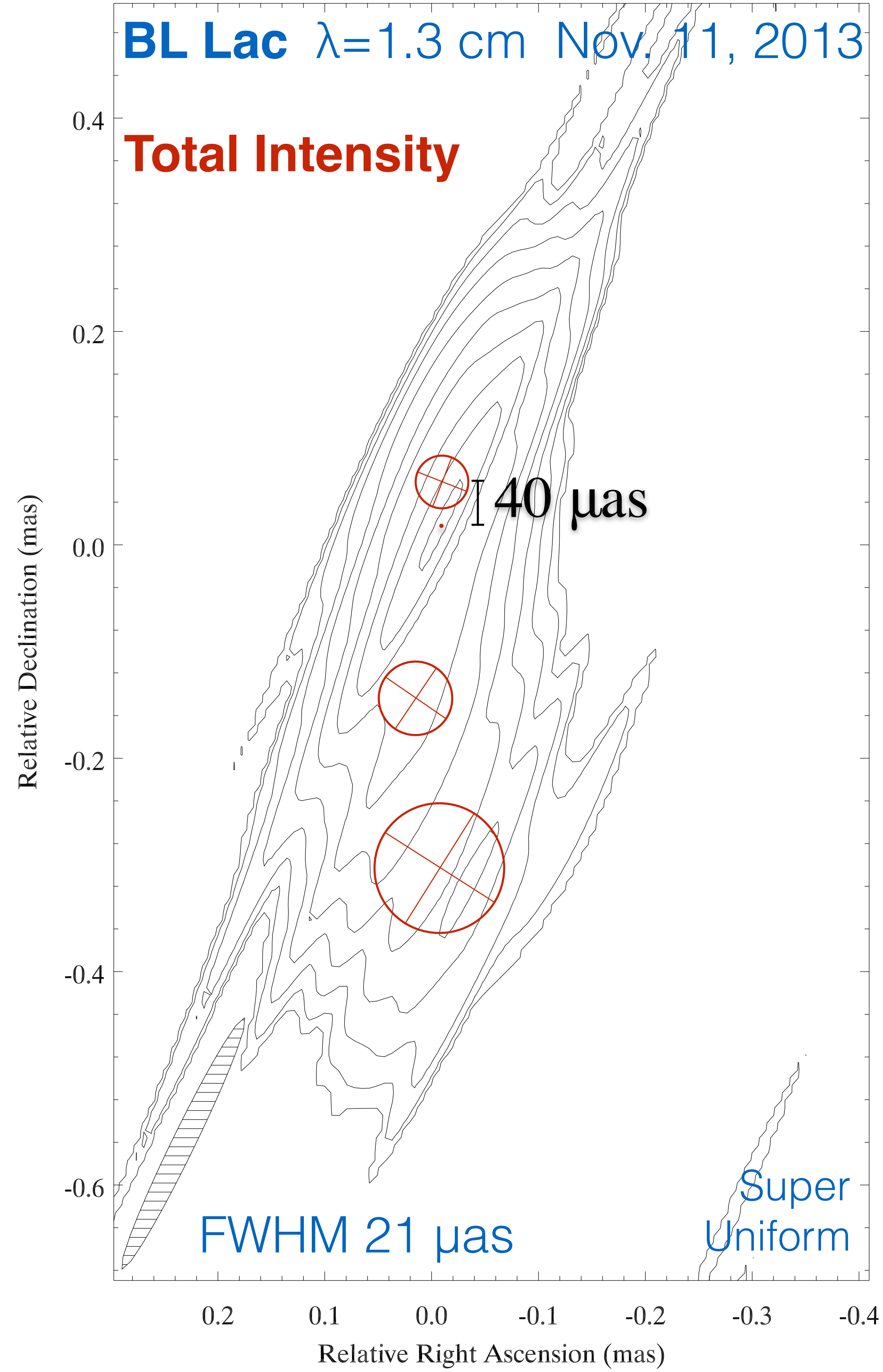


Observations of BLLac at K-band

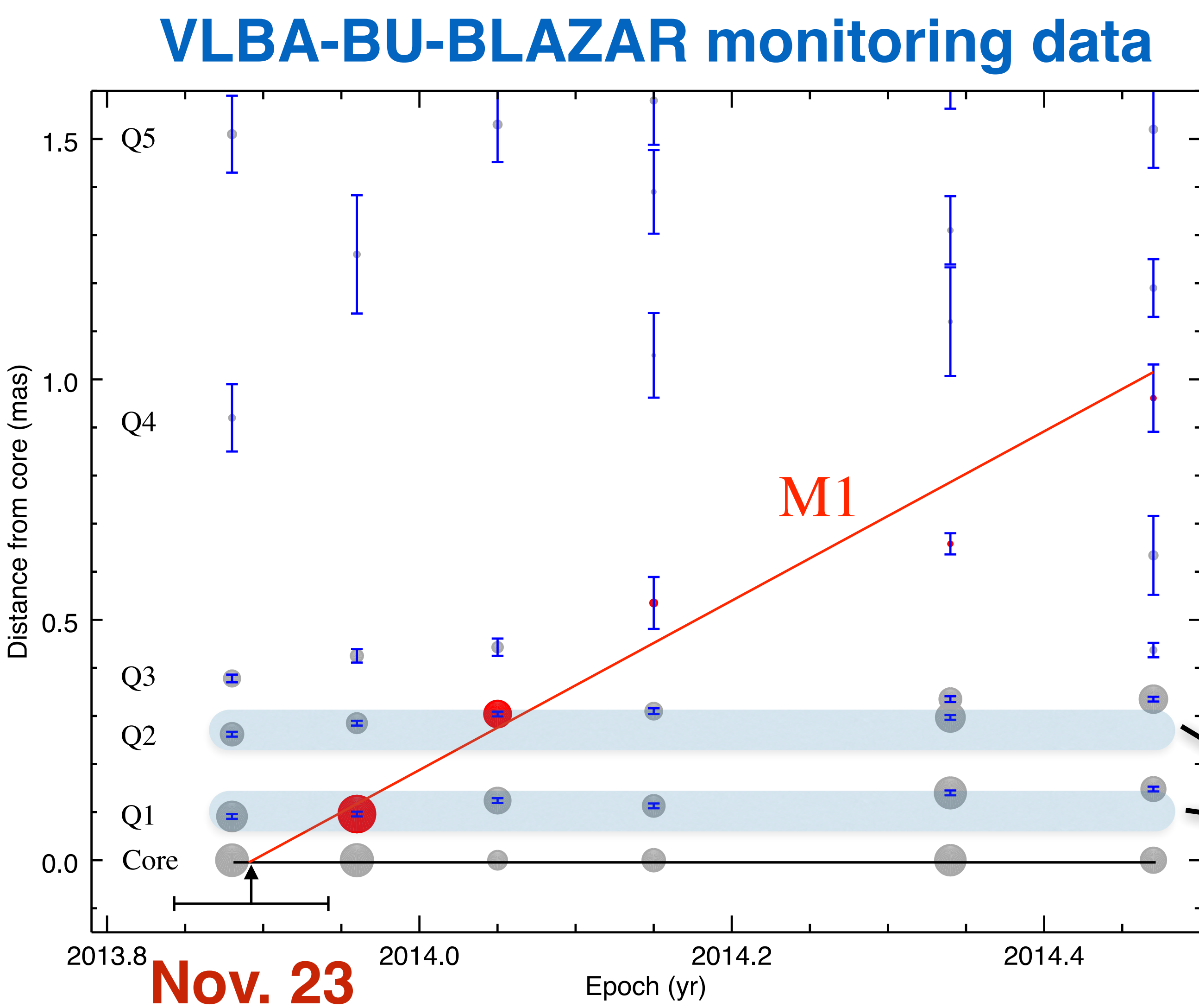
VLBA-BU-BLAZAR monitoring data



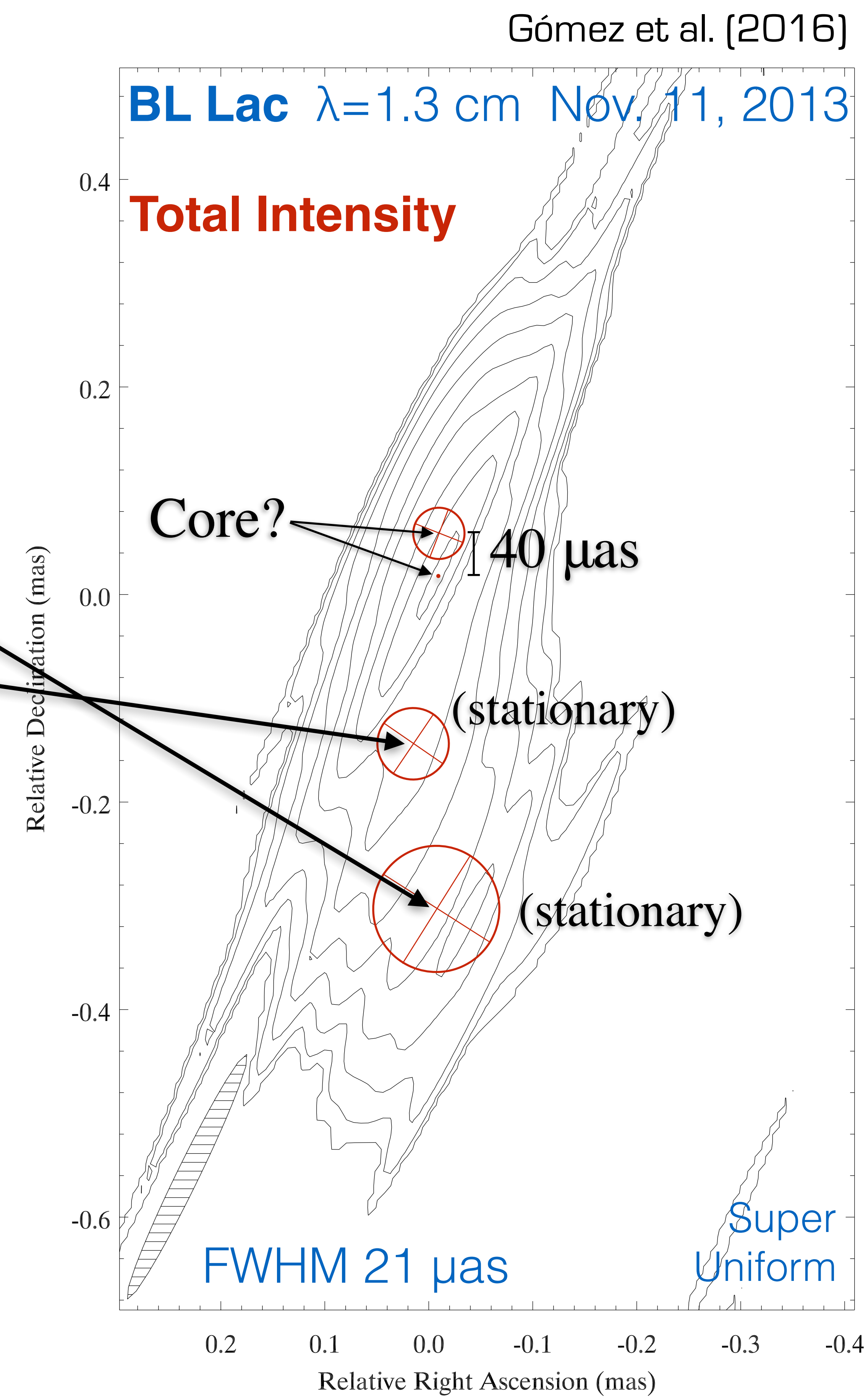
Gómez et al. (2016)



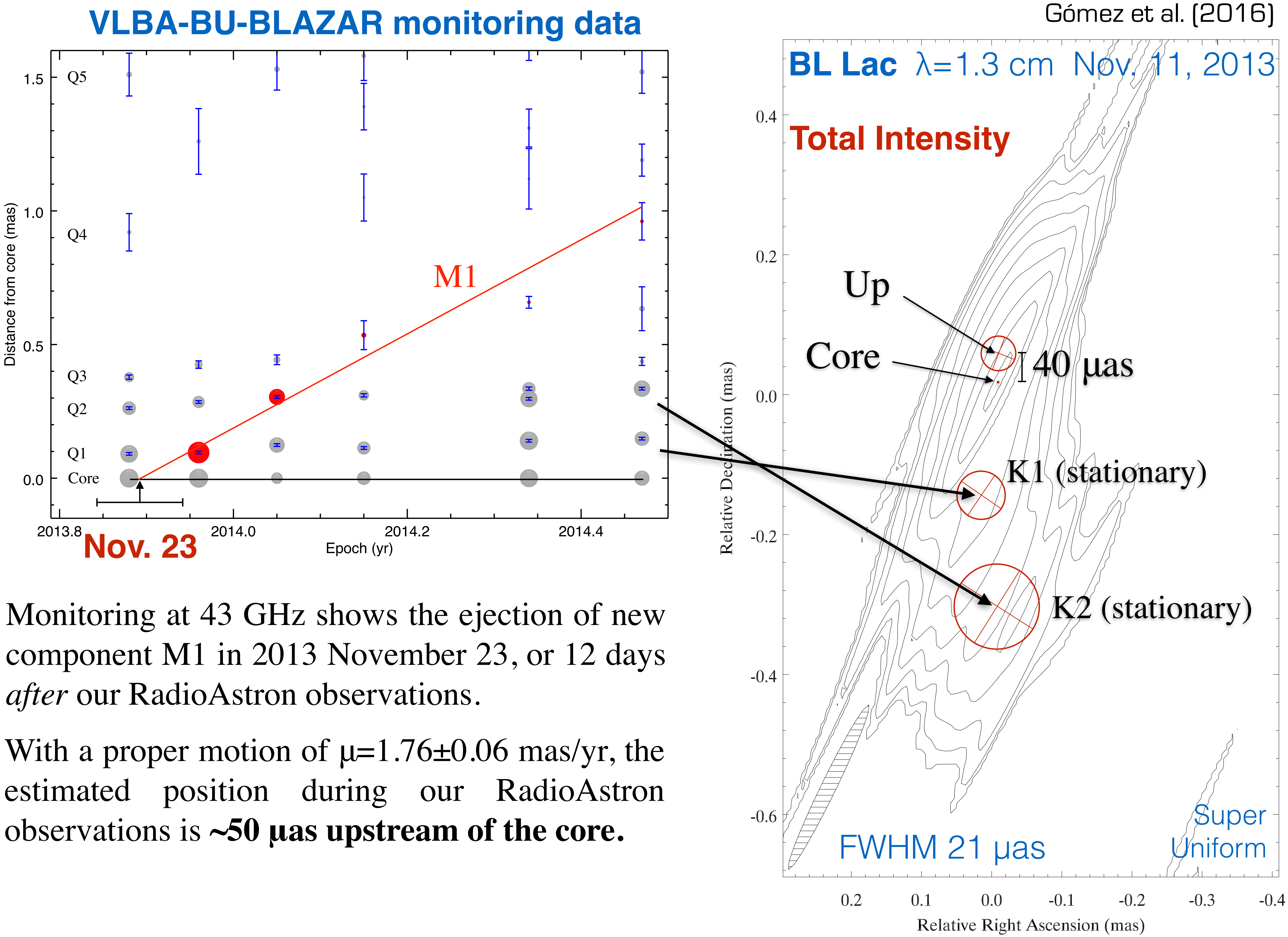
Observations of BLLac at K-band



Monitoring at 43 GHz shows the ejection of new component M1 in 2013 November 23, or 12 days *after* our RadioAstron observations.



Observations of BLLac at K-band

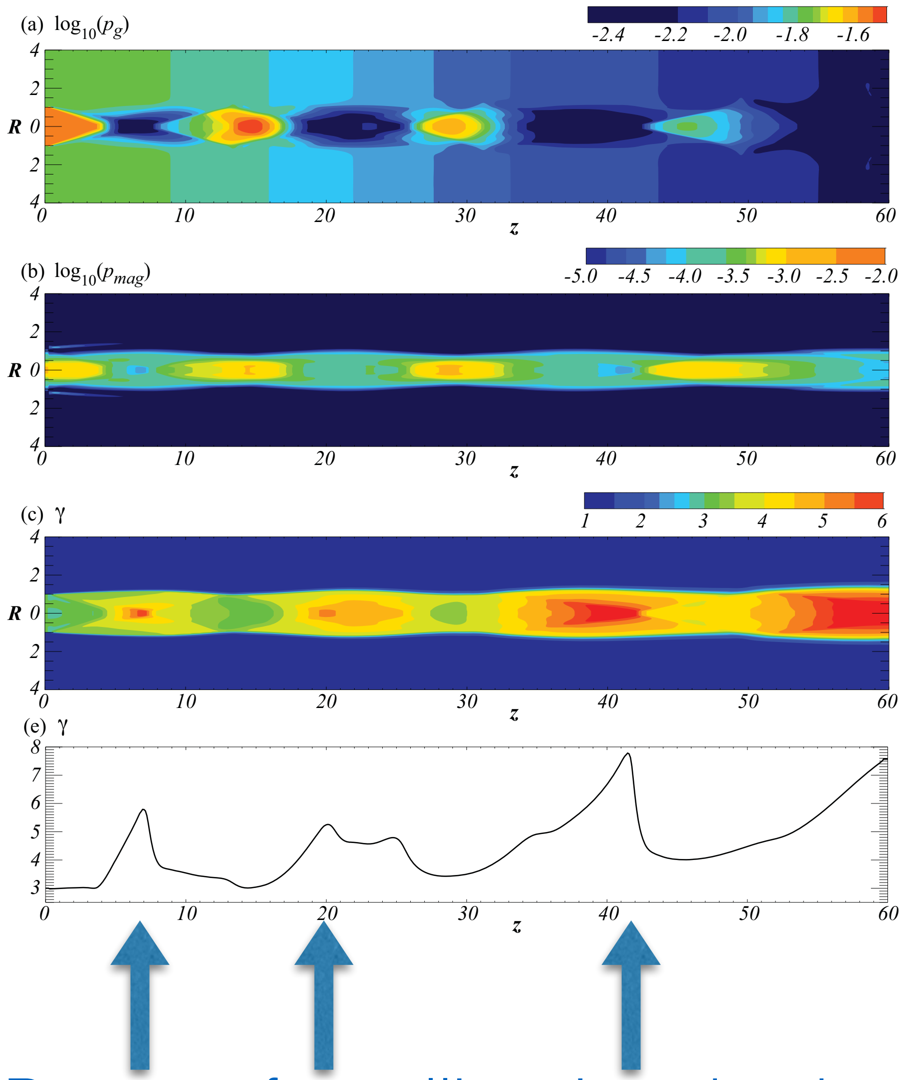


Monitoring at 43 GHz shows the ejection of new component M1 in 2013 November 23, or 12 days *after* our RadioAstron observations.

With a proper motion of μ=1.76±0.06 mas/yr, the estimated position during our RadioAstron observations is **~50 μas upstream of the core.**

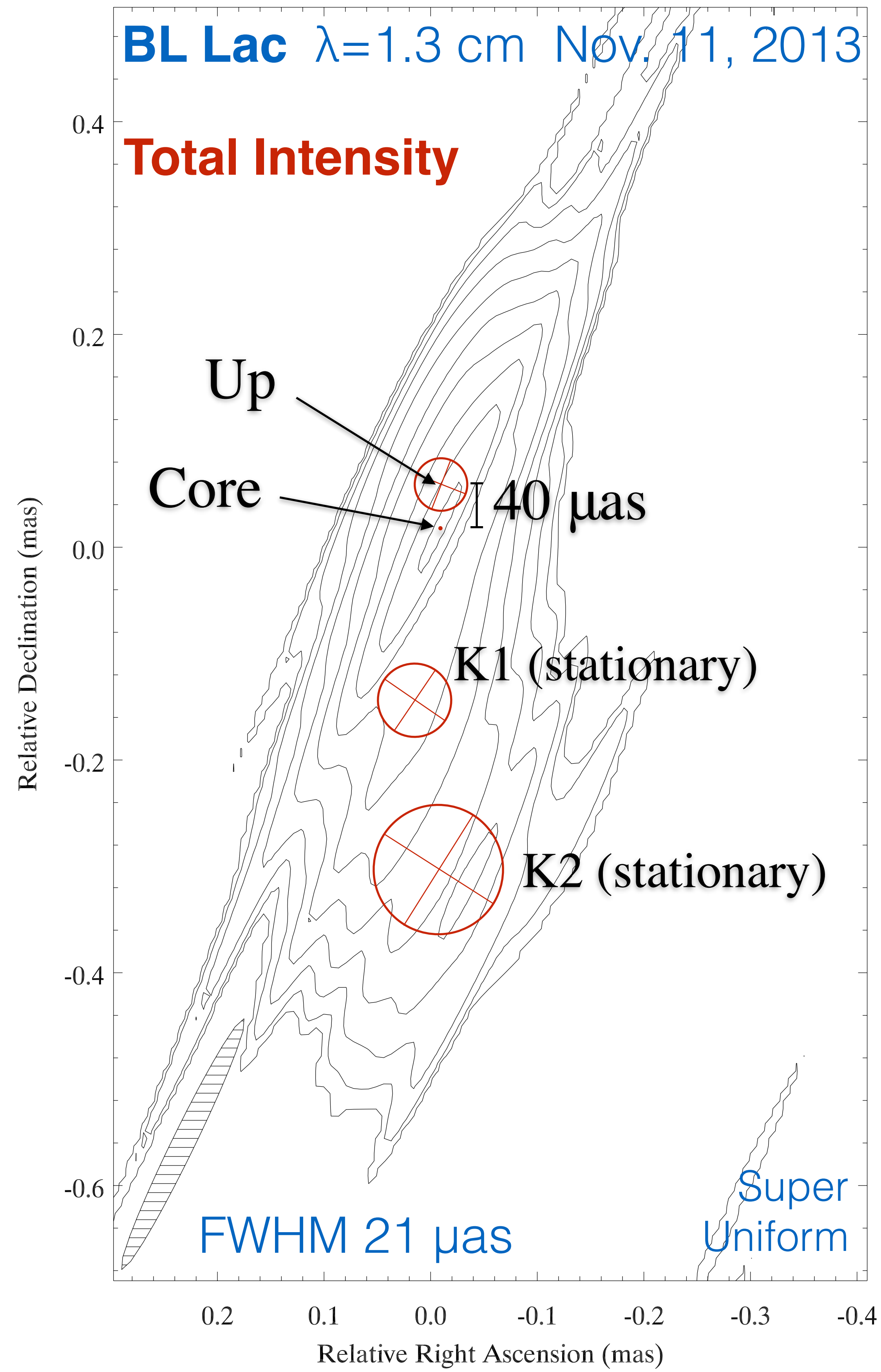
Observations of BLLac at K-band

This opens the possibility that **the core is a recollimation shock at ~40 μas for the jet apex**, in a pattern that includes also components K1 and K2 at ~100 μas and ~250 μas, respectively.



Pattern of recollimation shocks

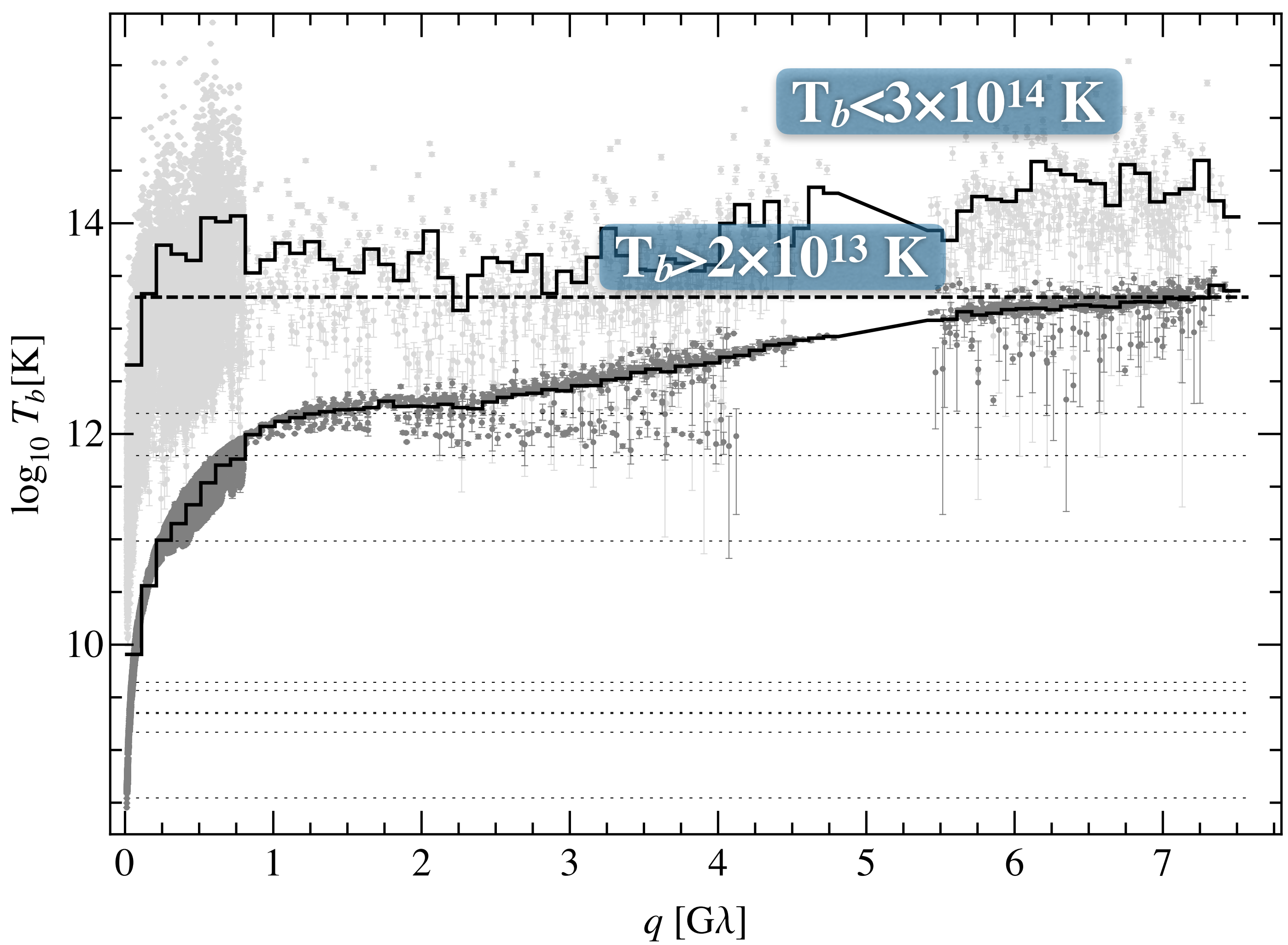
Gómez et al. (2016)



RMHD simulations reproduce the relative distance between components Core, K1, and K2 as recollimation shocks.

Observations of BLLac at K-band

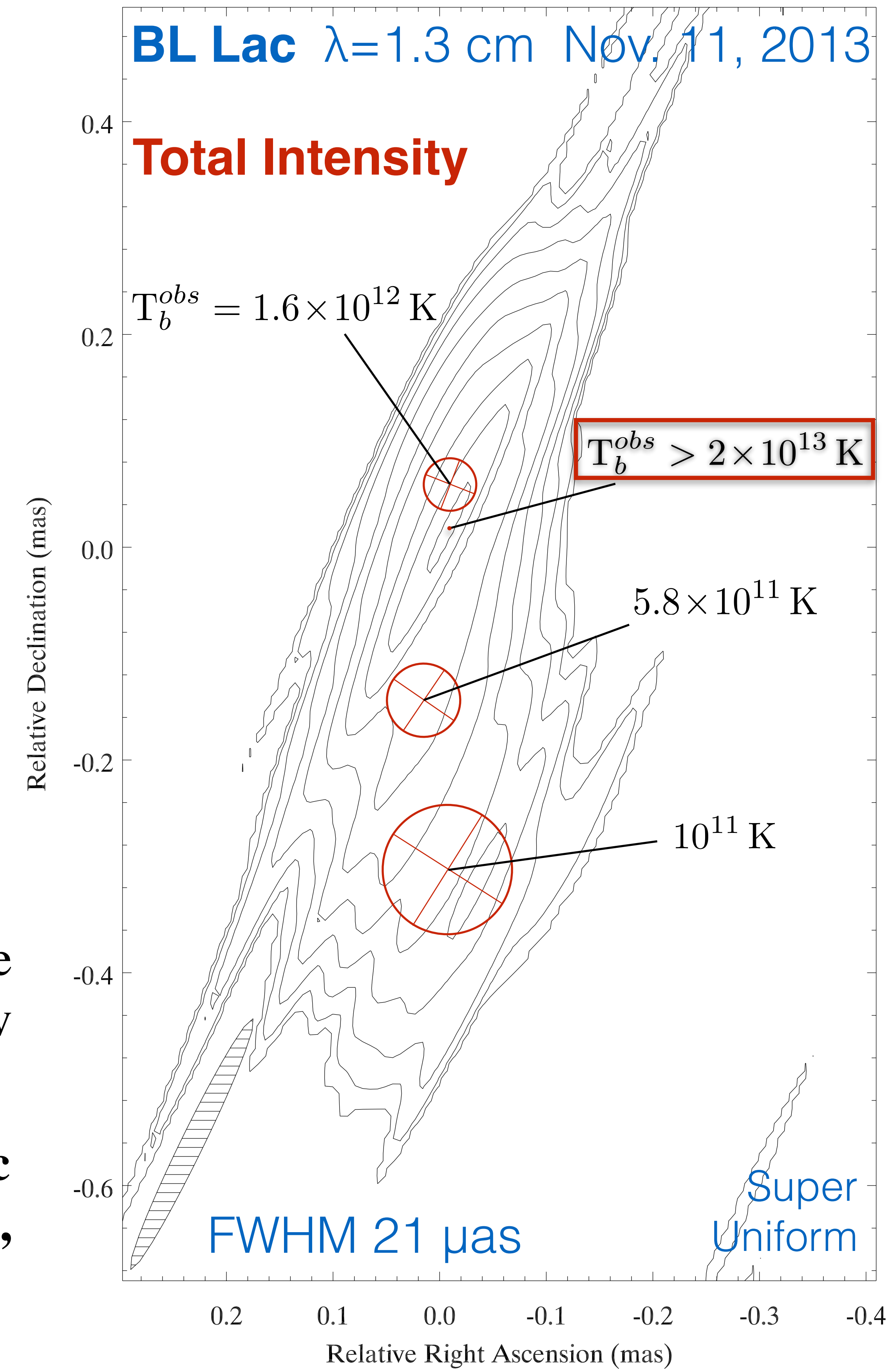
Unresolved core component has an *observed* brightness temperature of $T_b > 2\times10^{13}$ K.



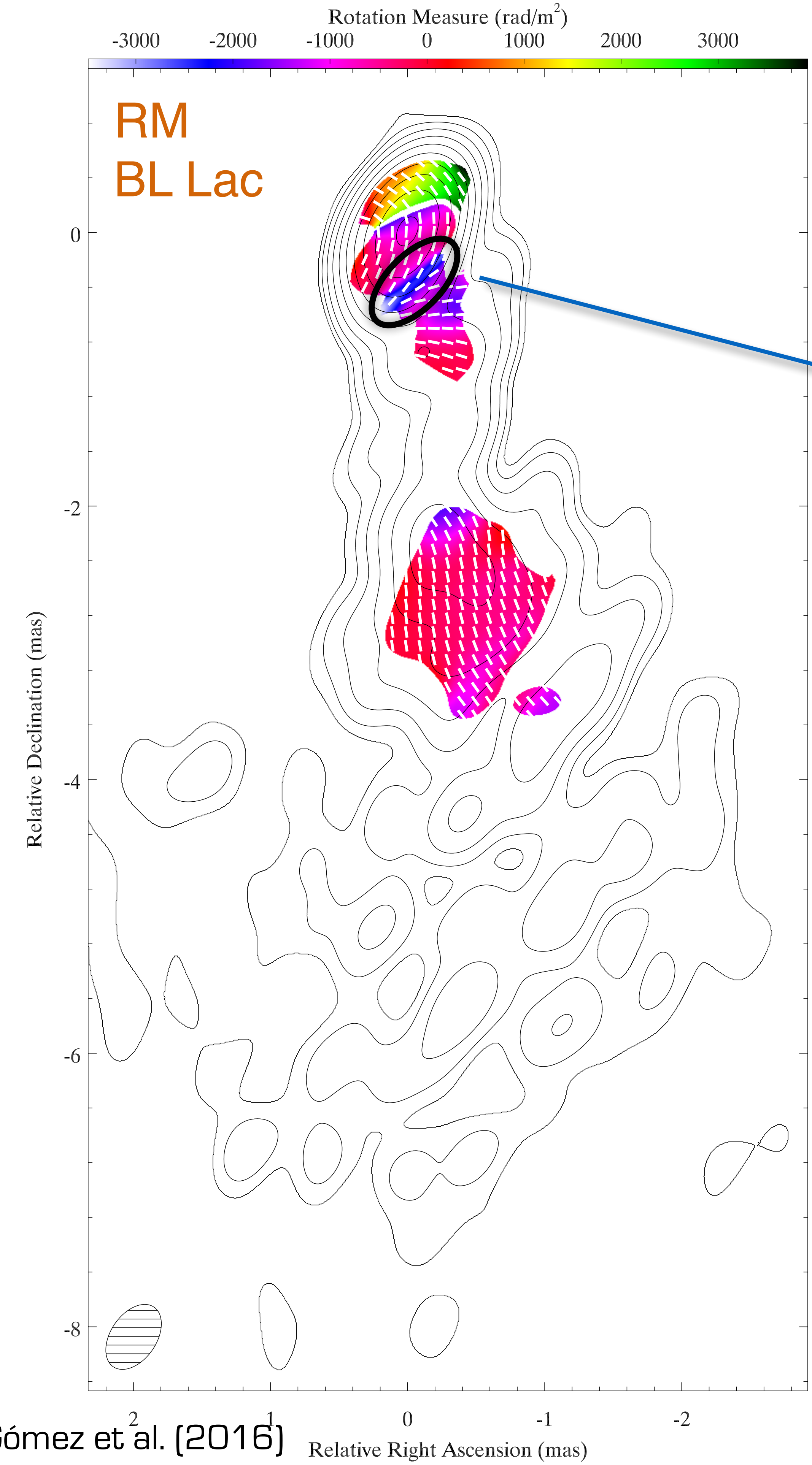
This is further supported by estimations from the visibilities amplitudes and their errors (Lobanov 2015).

From estimated δ=7.2 we obtain an **intrinsic brightness temperature $T_{b,int} > 3\times10^{12}$ K, suggesting departure from equipartition.**

Gómez et al. (2016)



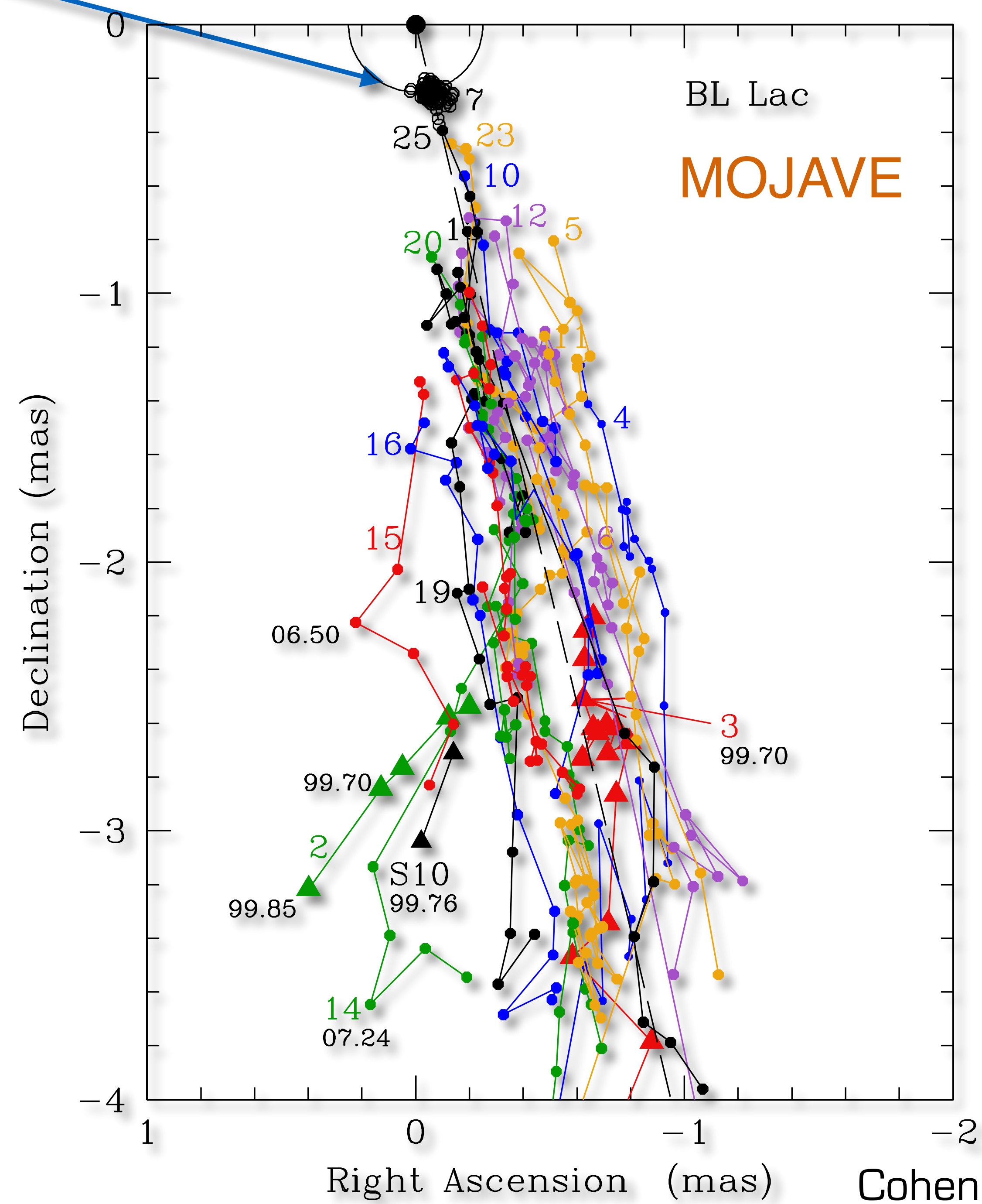
Observations of BLLac at K-band



Gómez et al. (2016)

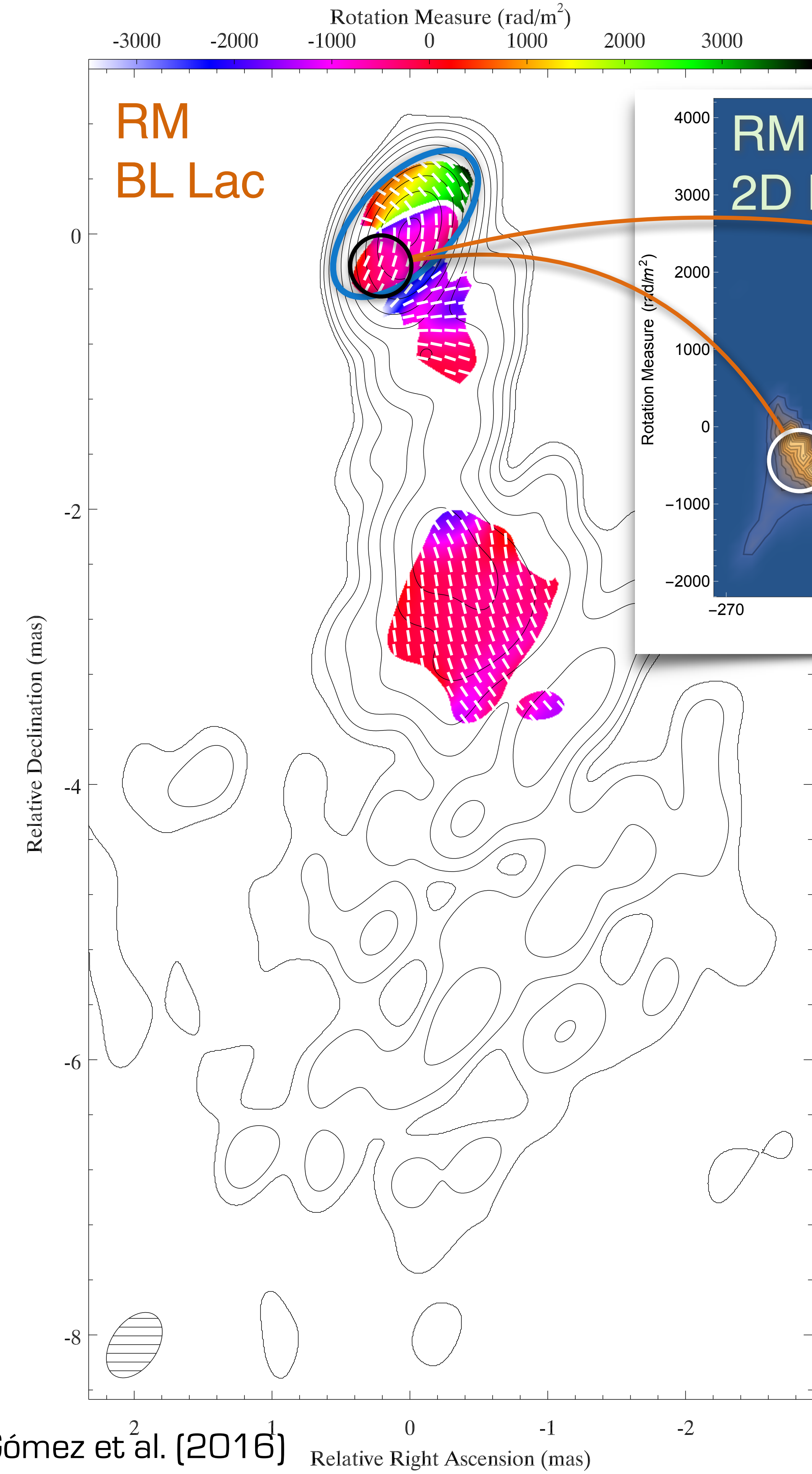
Region of enhanced RM and EVPA transition associated with recollimation shock K2.

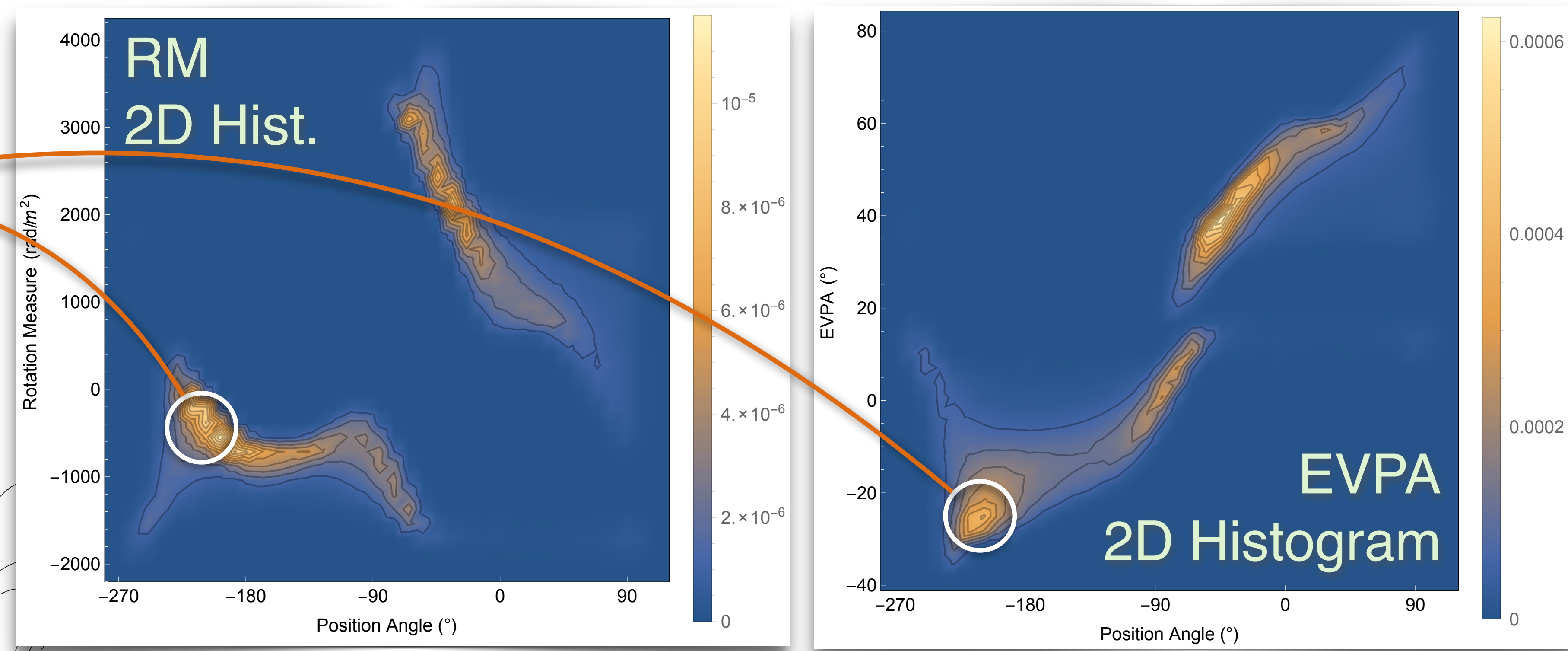
Component swings in position angle, triggering Alfvén waves in the jet ridge line, like waves on a whip (Cohen et al. 2014), interpreted also as a recollimation shock.



Cohen et al. (2014)

Observations of BLLac at K-band

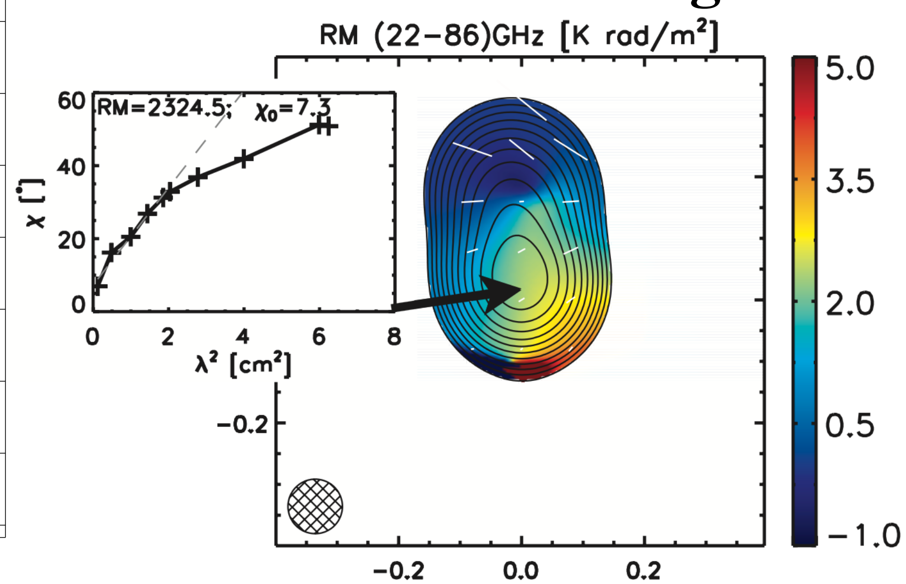




Gómez et al. (2016)

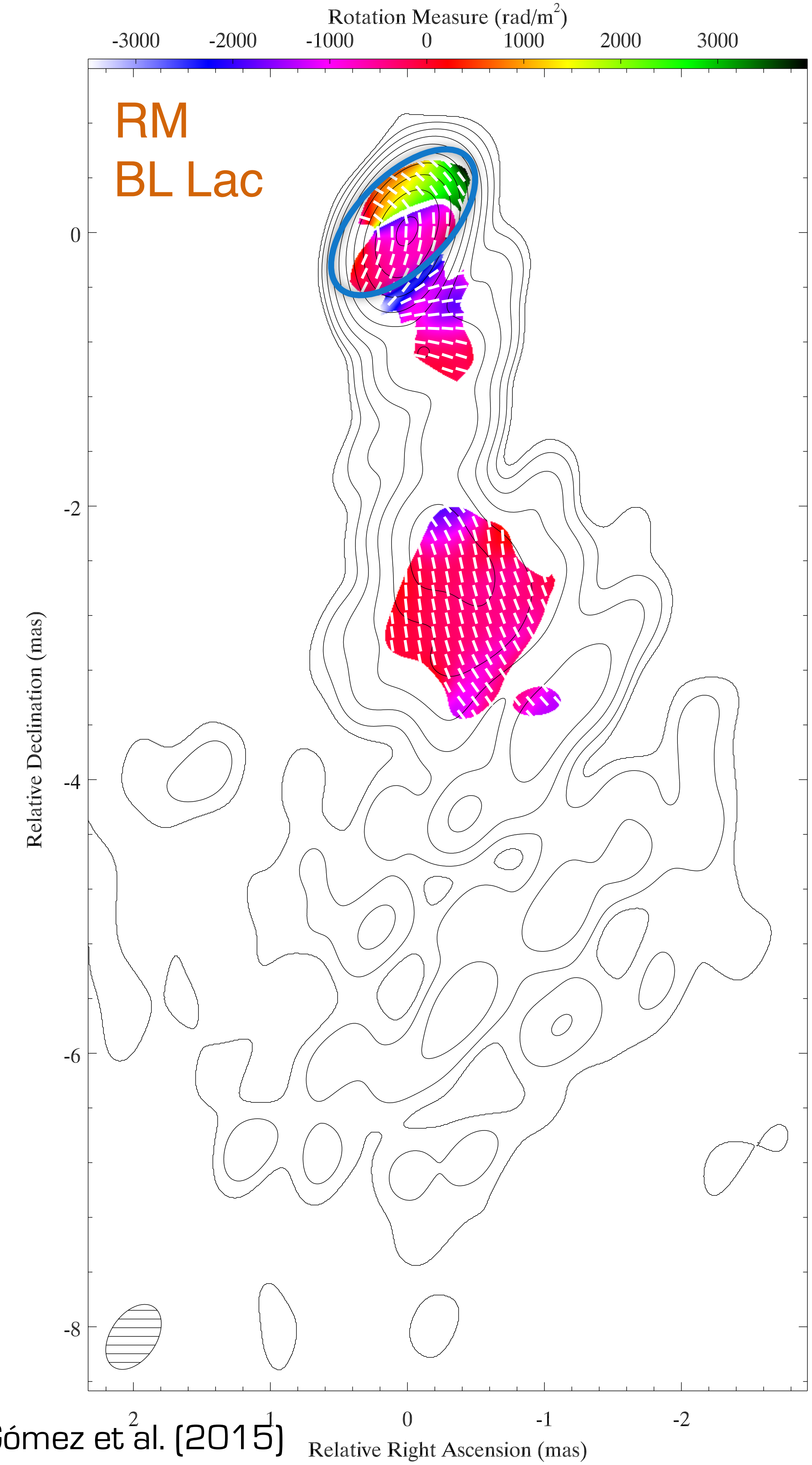
The core area shows a point symmetric structure in RM and EVPA, as shown in the 2D histograms as a function of position angle wrt the core in the selected area.

The polarization structure is consistent with the existence of a helical magnetic field threading the jet.

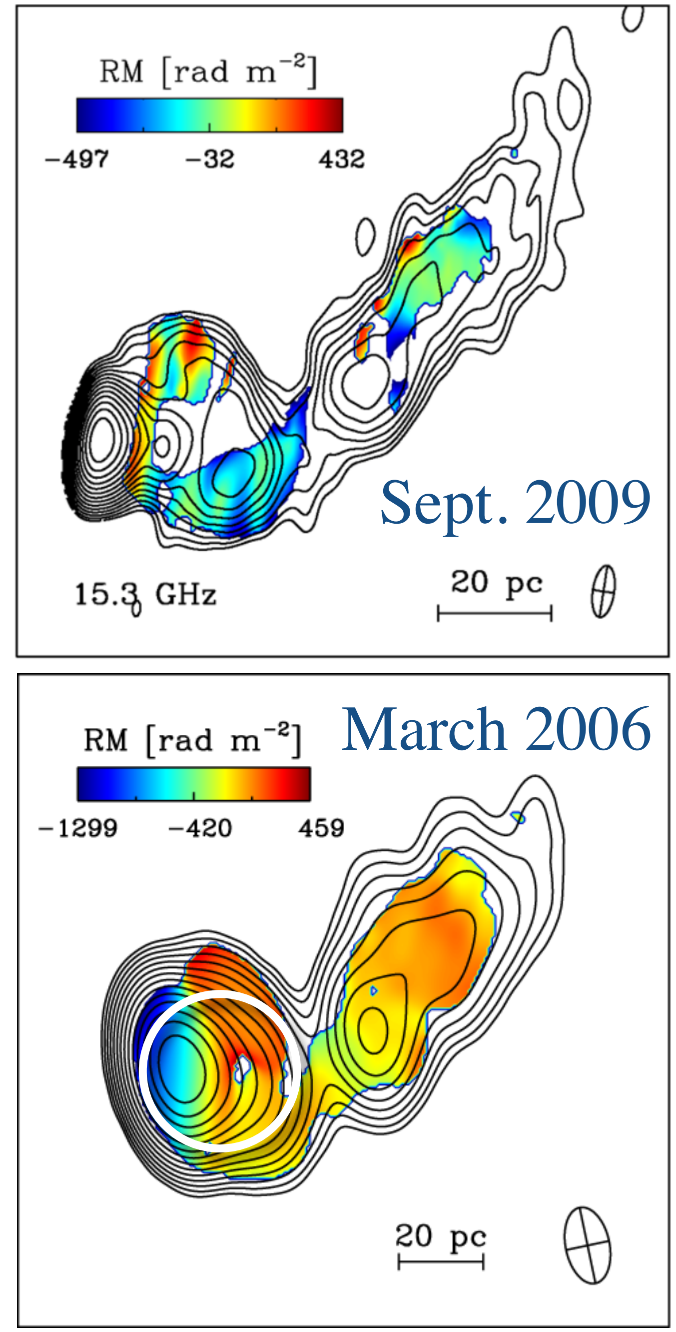


In agreement with RMHD simulations of jets with a helical magnetic field by Porth et al. (2011).

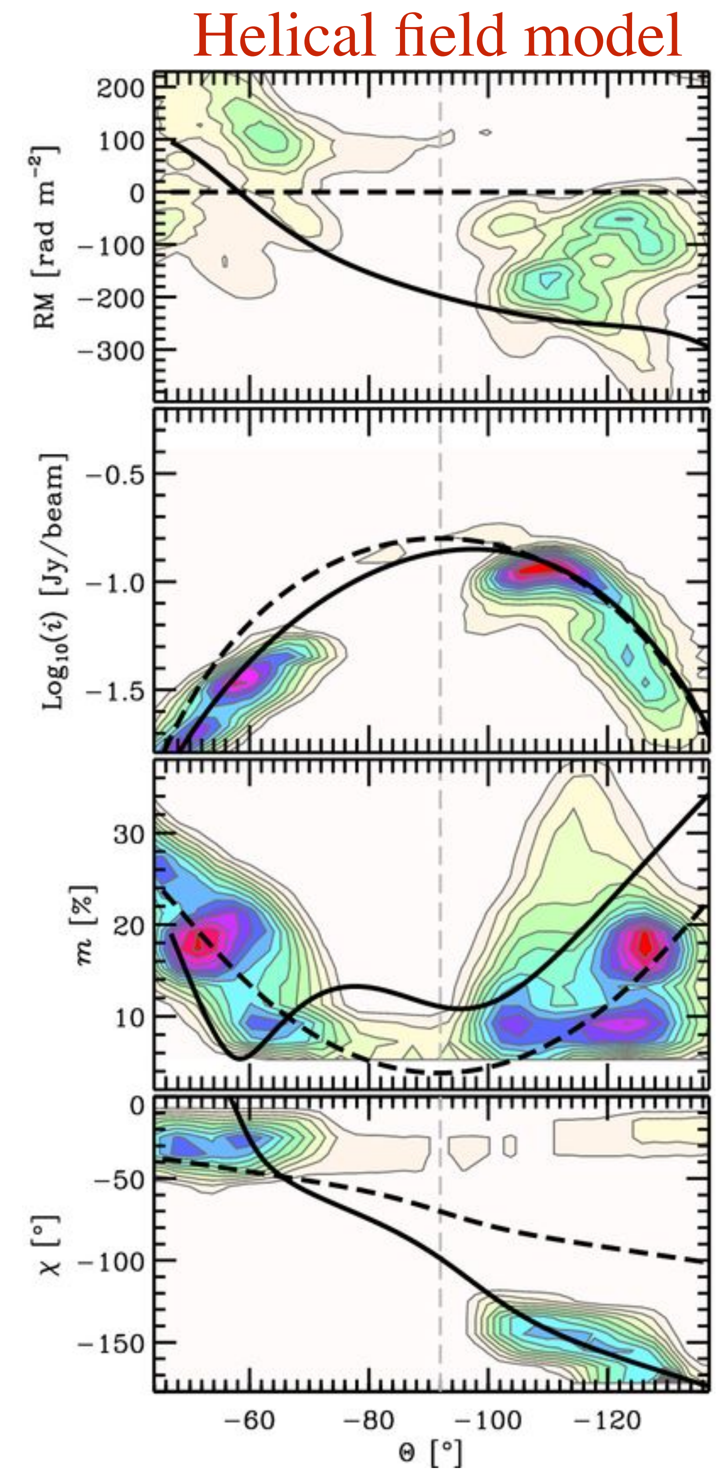
Observations of BLLac at K-band



Gómez et al. (2015)



Zamaninasab et al. (2013)



Similar point symmetric structure in RM and EVPA around the core found in 3C454.3, interpreted as produced by a helical magnetic field (Zamaninasab et al. 2013).

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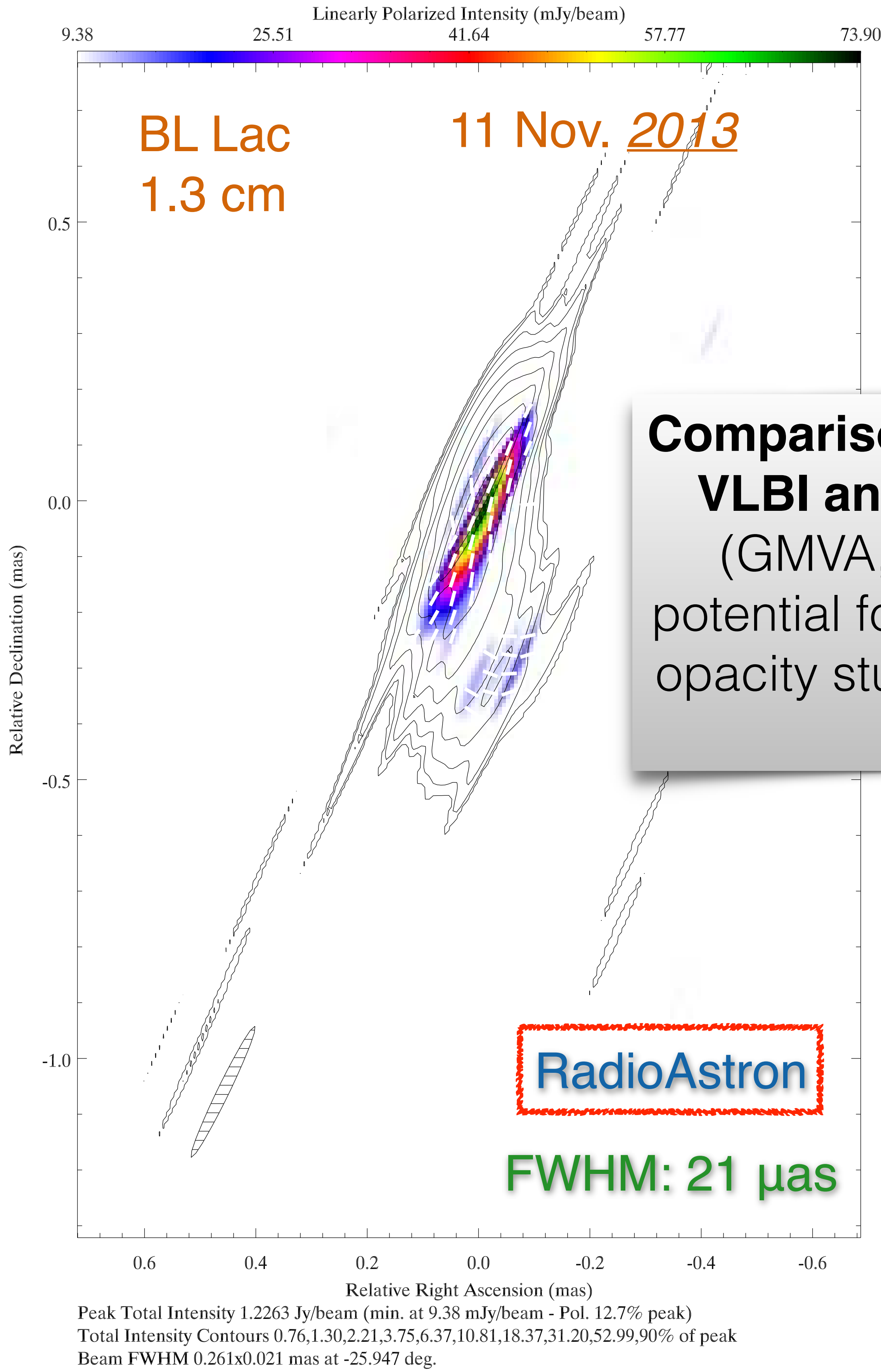
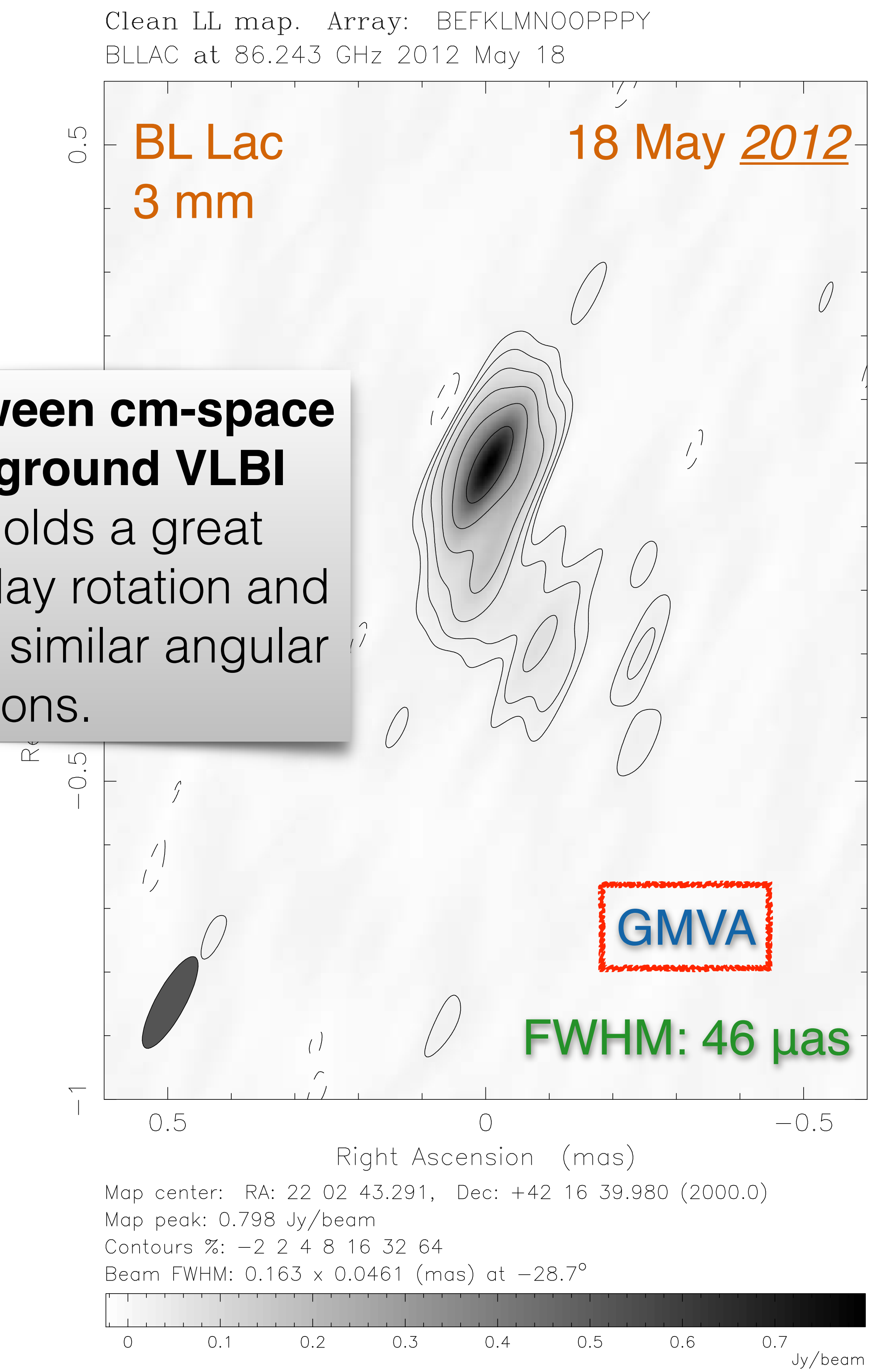


Comparison between cm-space VLBI and mm-ground VLBI (GMVA, EHT) holds a great potential for Faraday rotation and opacity studies at similar angular resolutions.



Summary

- Eleven RadioAstron observations carried out within our polarization KSP during AO-1, AO-2, and AO-3. Continued observations throughout AO-4.
- Confirmed polarization capabilities of RadioAstron for observations at 18 cm (Lobanov et al. 2015) and 1.3 cm (Gómez et al. 2016).

RadioAstron allows polarization imaging with angular resolutions of ~20 μas

- OJ287 imaged with an angular resolution of ~40 μas (4 D_E). Fringes detected up to 15.2 D_E, with a potential angular resolutions of ~10 μas.
- BL Lac imaged at L and K-bands. Ground-space fringes detected up to 8 D_E (7 D_E at L-band), achieving a maximum angular resolution of ~20 μas.
    - Evidence for emission upstream the core, and a pattern of three recollimation shocks (40, 100, 250 μas) that includes the core.
    - The *intrinsic de-boosted* brightness temperature of the core exceeds 3×10^{12} K, suggesting at the very least departure from equipartition.
    - The core area shows a point symmetric structure in RM and EVPAs, suggesting it is threaded by a helical magnetic field.