Probing the innermost regions of AGN jets and their magnetic fields

RadioAstron “Polarization KSP”

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on behalf of the polarization KSP team

Probing the innermost regions of AGN jets and their magnetic fields

RadioAstron “Polarization KSP”

Outline

- KSP scientific goals and status of AO-1 observations
- First polarization test at L-band
- Science observations of BL Lac at L-band
- Successful polarization 22 GHz observations of BL Lac
- Summary

A KSP for polarimetric Space-VLBI with RadioAstron

Goal

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

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

AO-2 Targets

- Observations proposed for 0716+714 (K-band), 1633+382 (K-band), and 3C345 (K and L-bands).
- Best uv-coverages for late 2014, early 2015.

AO-1 Observations

Target	Date	Band	Correlation
BL Lac	29 Sep. 2013	L	Prelim.
BL Lac	11 Nov. 2013	K	Yes
3C273	18 Jan. 2014	K	No
3C279	10 March 2014	K	No
OJ287	04 April 2014	K	No
3C273	13 June 2014	L	No

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First Polarimetric Test At L-band

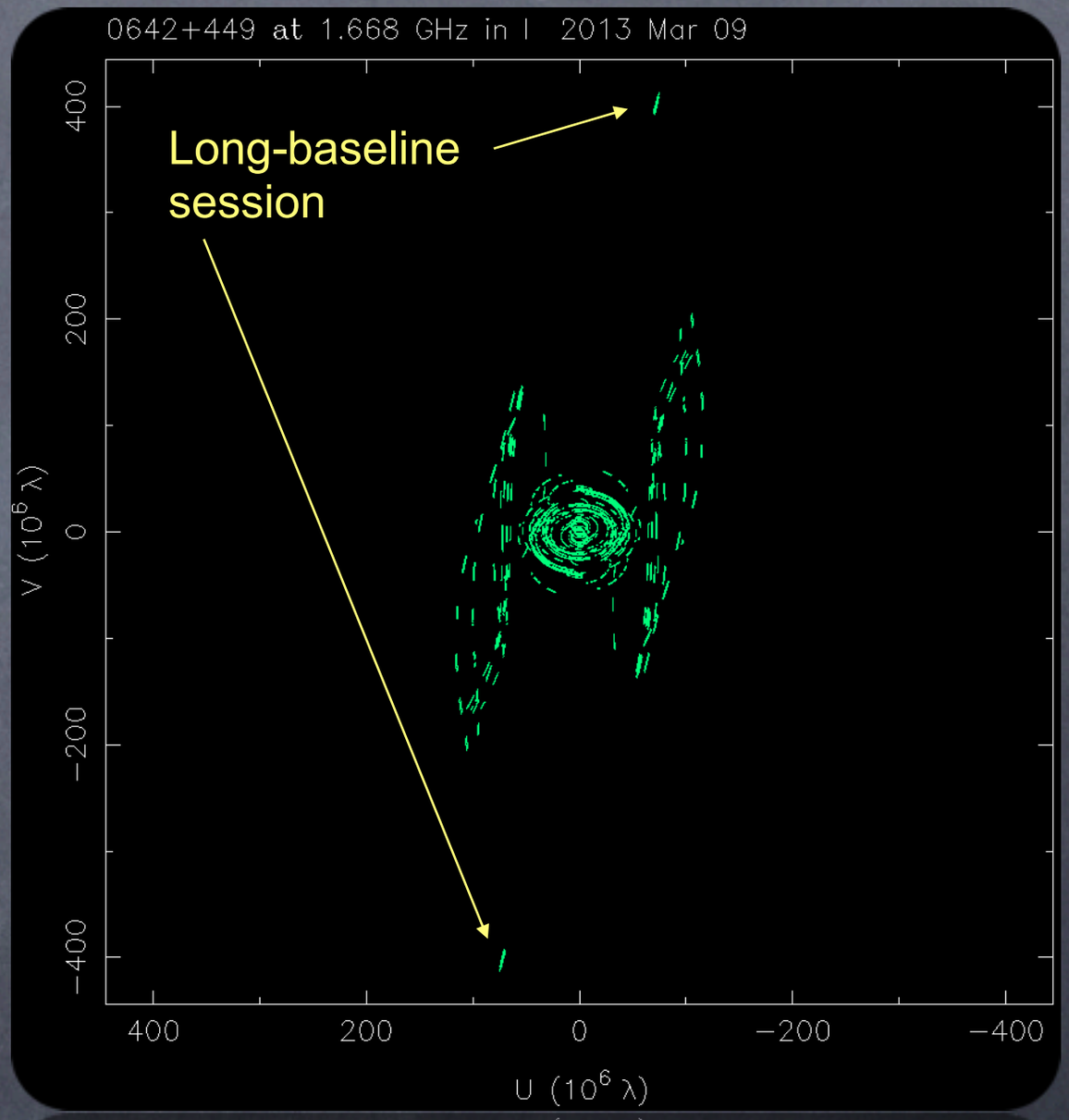
First polarimetric test observations were performed on March 9, 2013 at L-band on 0642+449 (GK047 proposal by Kovalev et al.)

This is a compact quasar at z=3.4 with a relatively flat spectrum and a total flux density of *S*=1.3 Jy at L-band, as measured from Effelsberg.

Low polarized source, with *m*=1.61±0.16%

A total of 12 antennas participated in the ground array: EF, JB, (ON), SH, TR, UR, NT, WB, HH, GB, and ZC.

Observations were carried out in two blocks one day apart. Long-baseline 1-hour session included EF, JB, WB and RA.



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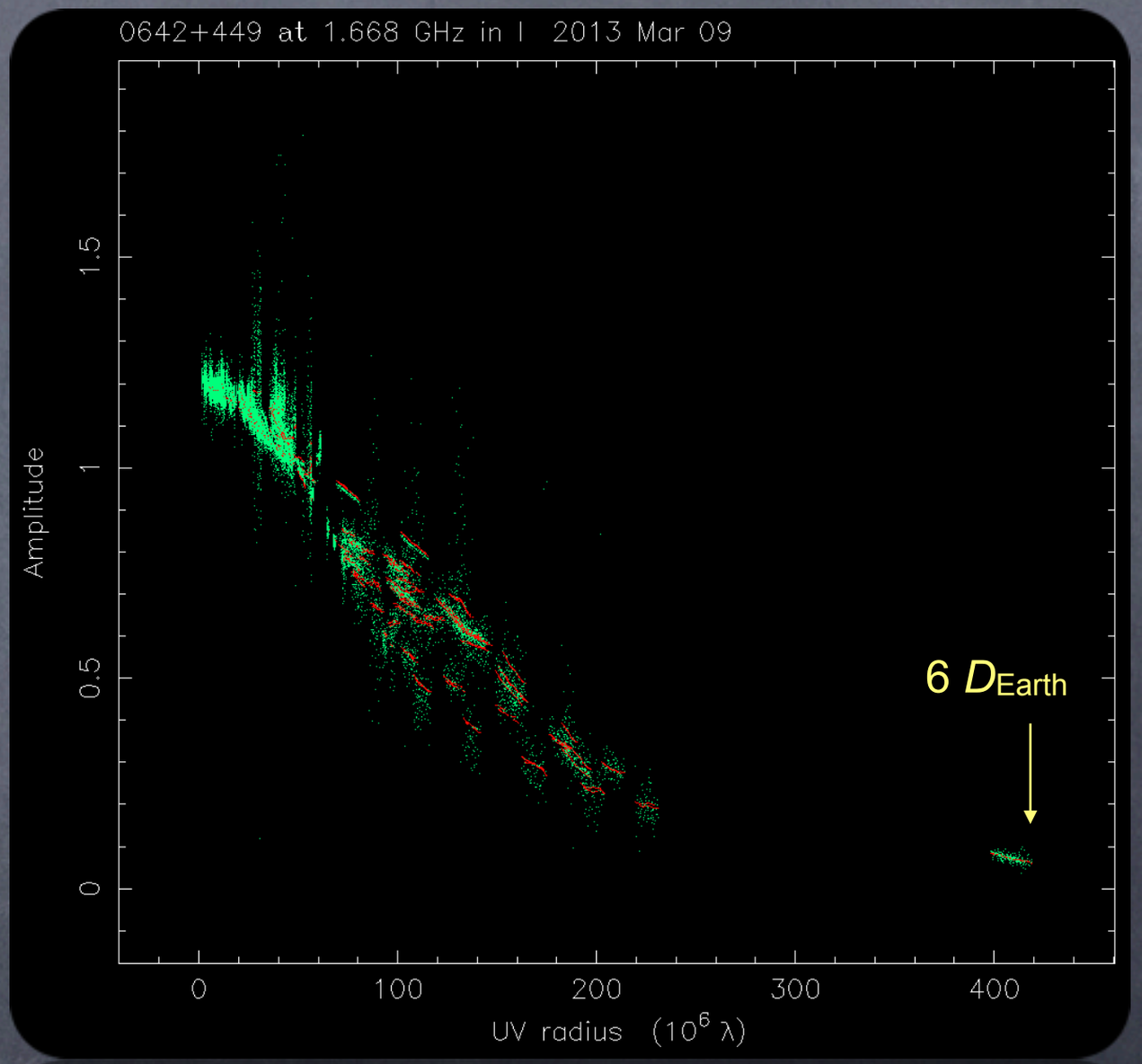
Ground-space baseline detections up to 6 D_{Earth}.



A KSP for polarimetric Space-VLBI with RadioAstron

First Polarimetric Test At L-band

Instrumental polarization (D-terms) are solved using AIPS's task LPCAL, yielding a significant reduction in the polarization rms.

D-terms are found to be very consistent across the two IFs. Values below 10%, except for UR and HH.

D-terms for RadioAstron are particularly consistent across IFs, and show an amplitude below 7% for RCP and below 8% for LCP.

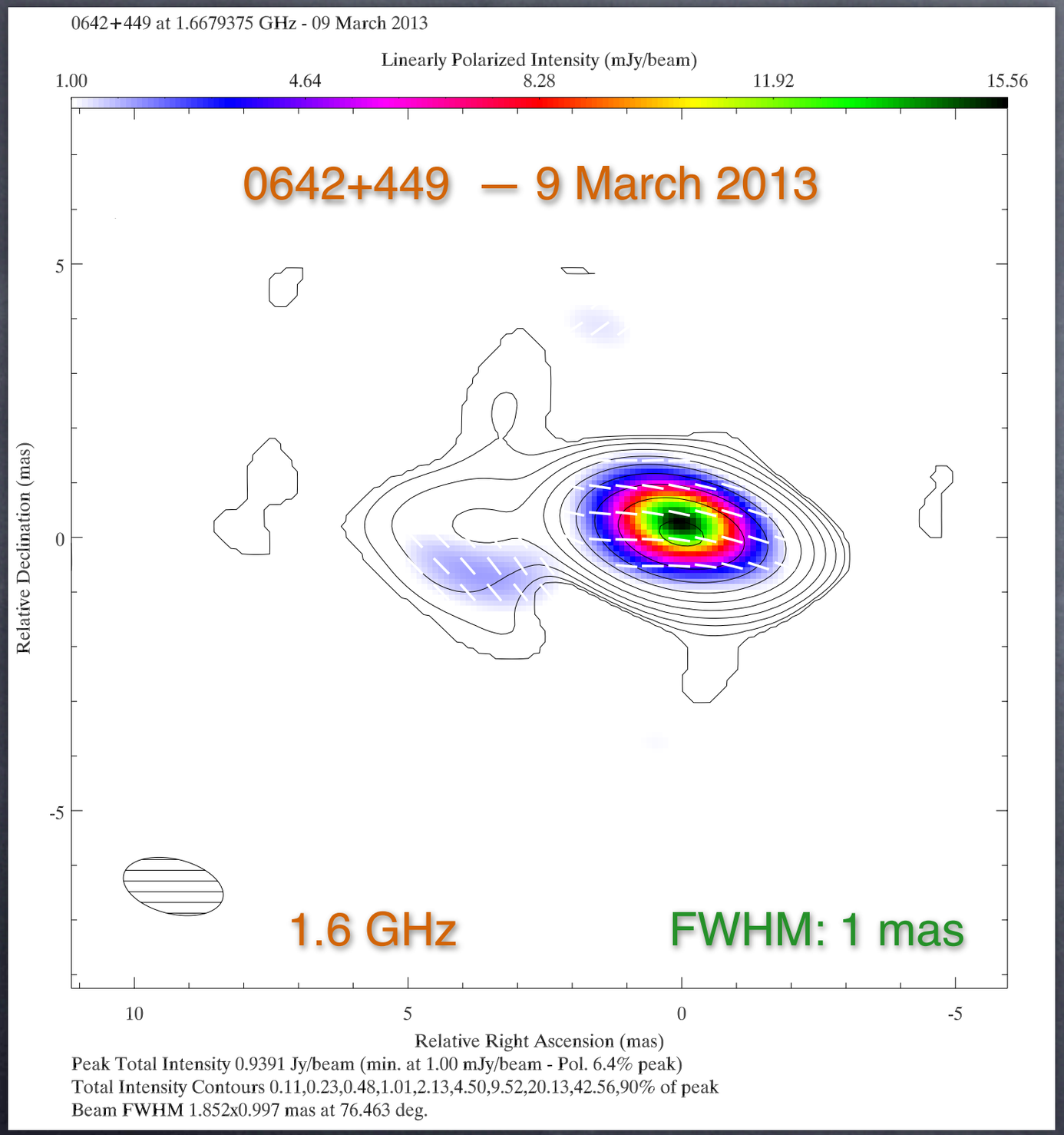
```
Ant   4 = RA       BX=  9999999.0000 BY=  9999999.0000 BZ=  9999999.0000
Mount=ORBI  Axis offset=  0.0000 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0685,  -64.5    0.0819, -116.1
Lin. approx. IF(  2) as amp, phase =  0.0701,  -64.6    0.0873, -116.2
```

Confirmation of RadioAstron polarization capabilities at L-band

```
Ant   1 = EF       BX=  4033947.2566 BY=   486990.7913 BZ=  4900430.9950
Mount=ALAZ  Axis offset=  0.0130 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0256, -136.5    0.0228,  -47.3
Lin. approx. IF(  2) as amp, phase =  0.0310, -138.4    0.0243,  -29.0

Ant   2 = JB       BX=  3822625.8509 BY=  -154105.3745 BZ=  5086486.1905
Mount=ALAZ  Axis offset=  0.0000 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0126,   -6.1    0.0353,  122.0
Lin. approx. IF(  2) as amp, phase =  0.0075,  159.5    0.0433,  115.9

Ant   3 = ON       BX=  3370965.9082 BY=   711466.2036 BZ=  5349664.2021
Mount=EQUA  Axis offset=  2.1500 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0000,    0.0    0.0000,    0.0
Lin. approx. IF(  2) as amp, phase =  0.0000,    0.0    0.0000,    0.0

Ant   4 = RA       BX=  9999999.0000 BY=  9999999.0000 BZ=  9999999.0000
Mount=ORBI  Axis offset=  0.0000 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0685,  -64.5    0.0819, -116.1
Lin. approx. IF(  2) as amp, phase =  0.0701,  -64.6    0.0873, -116.2

Ant   5 = SH       BX= -2831687.3922 BY=  4675733.4890 BZ=  3275327.5026
Mount=ALAZ  Axis offset= -0.0020 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0421,   27.1    0.0263,  159.3
Lin. approx. IF(  2) as amp, phase =  0.0362,   23.9    0.0283,  134.8

Ant   6 = TR       BX=  3638558.2512 BY=  1221969.9859 BZ=  5077036.8816
Mount=ALAZ  Axis offset=  0.0000 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0797,   13.6    0.0717,  160.2
Lin. approx. IF(  2) as amp, phase =  0.0871,   17.7    0.0760,  176.8

Ant   7 = UR       BX=   228310.2100 BY=  4631922.7617 BZ=  4367064.0710
Mount=ALAZ  Axis offset= -0.0040 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.1165,  124.7    0.0963, -157.6
Lin. approx. IF(  2) as amp, phase =  0.1332,  148.3    0.1168, -121.0

Ant   8 = NT       BX=  4934562.8353 BY=  1321201.5494 BZ=  3806484.7375
Mount=ALAZ  Axis offset=  1.8310 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0585,  101.3    0.0589,   25.3
Lin. approx. IF(  2) as amp, phase =  0.0531,   38.1    0.0536,  -35.5

Ant   9 = WB       BX=  3828445.4403 BY=   445223.8755 BZ=  5064921.7091
Mount=EQUA  Axis offset=  4.9500 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0259,   29.7    0.0089,  -47.6
Lin. approx. IF(  2) as amp, phase =  0.0196,   35.6    0.0070,  -14.8

Ant  10 = HH       BX=  5085442.7655 BY=  2668263.8046 BZ= -2768696.7456
Mount=EQUA  Axis offset=  6.6920 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.2170,    4.7    0.1988, -134.5
Lin. approx. IF(  2) as amp, phase =  0.1807,   51.5    0.0953,  -65.2

Ant  11 = GB       BX=   882589.4212 BY= -4924872.3610 BZ=  3943729.4258
Mount=ALAZ  Axis offset= -0.0880 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0535,  101.5    0.0512,   80.7
Lin. approx. IF(  2) as amp, phase =  0.0480,   90.3    0.0354,  100.6

Ant  12 = ZC       BX=  3451207.5372 BY=  3060375.4274 BZ=  4391915.0620
Mount=ALAZ  Axis offset= -0.0080 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0803,   13.6    0.0523,  -68.4
Lin. approx. IF(  2) as amp, phase =  0.0952,   -0.4    0.0721,  -73.4
```

A KSP for polarimetric Space-VLBI with RadioAstron

First Polarimetric Test At L-band



Contours show total intensity, color scale corresponds to polarized intensity and white bars indicate the EVPAs.

Absolute orientation of the EVPAs obtained from comparison with Effelsberg.

Uniform weighting

FWHM: 1.85x1.00 mas

5σ sensitivity: 1.0 mJy/beam

A KSP for polarimetric Space-VLBI with RadioAstron

First Science Observations

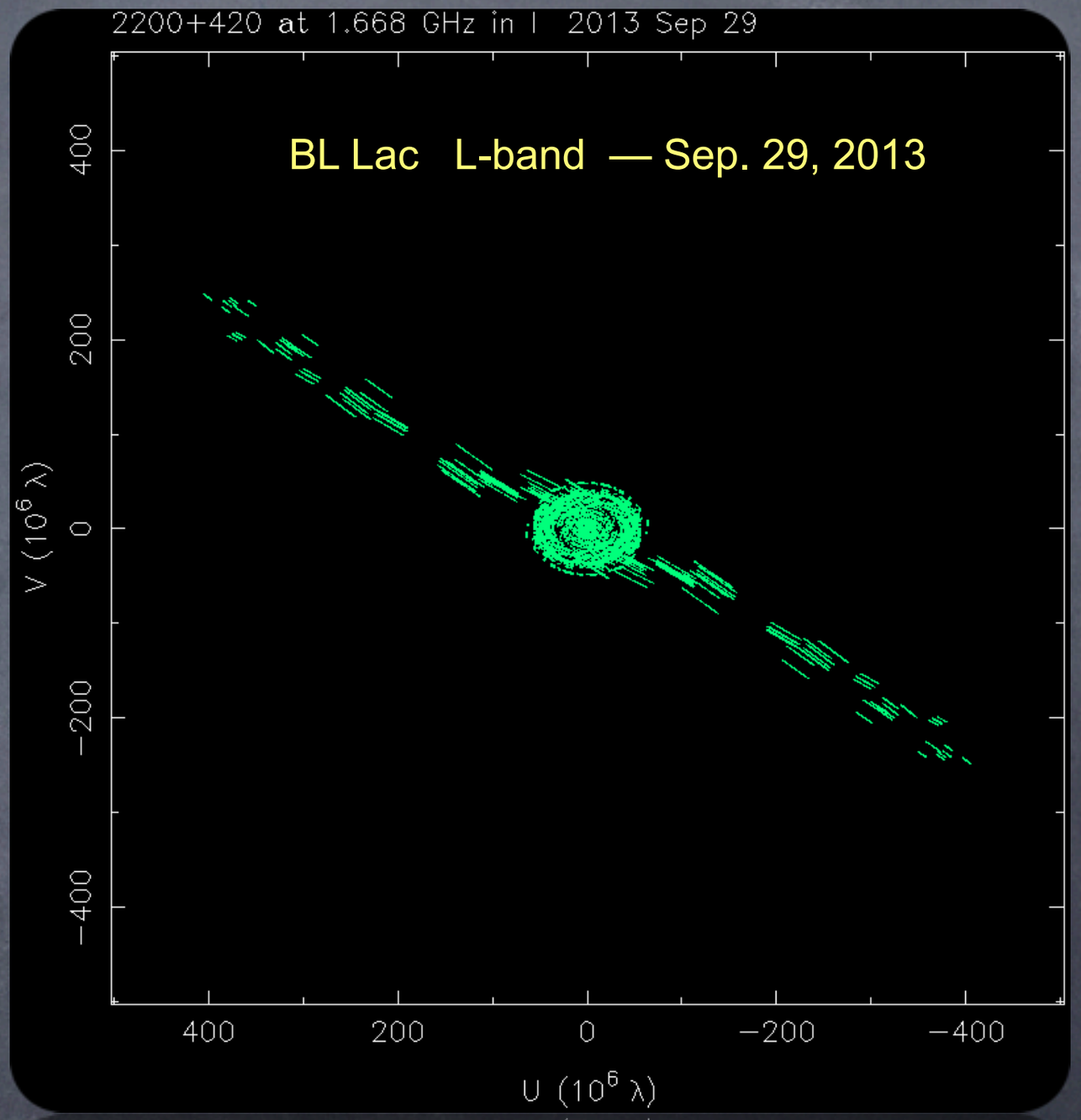
First science observations were performed on September 29, 2013.

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

Only a preliminary correlation has been obtained, with not fringes to some of the largest and most important antennas: GB, JB, EV, and KL.

Preliminary correlation includes 17 antennas: EF, BD, ON, SV, TR, UR, WB, ZC, SH, BR, FD, HN, NL, OV, PT, SC, and MK.

Simultaneous ground-only observations at C and X-bands.



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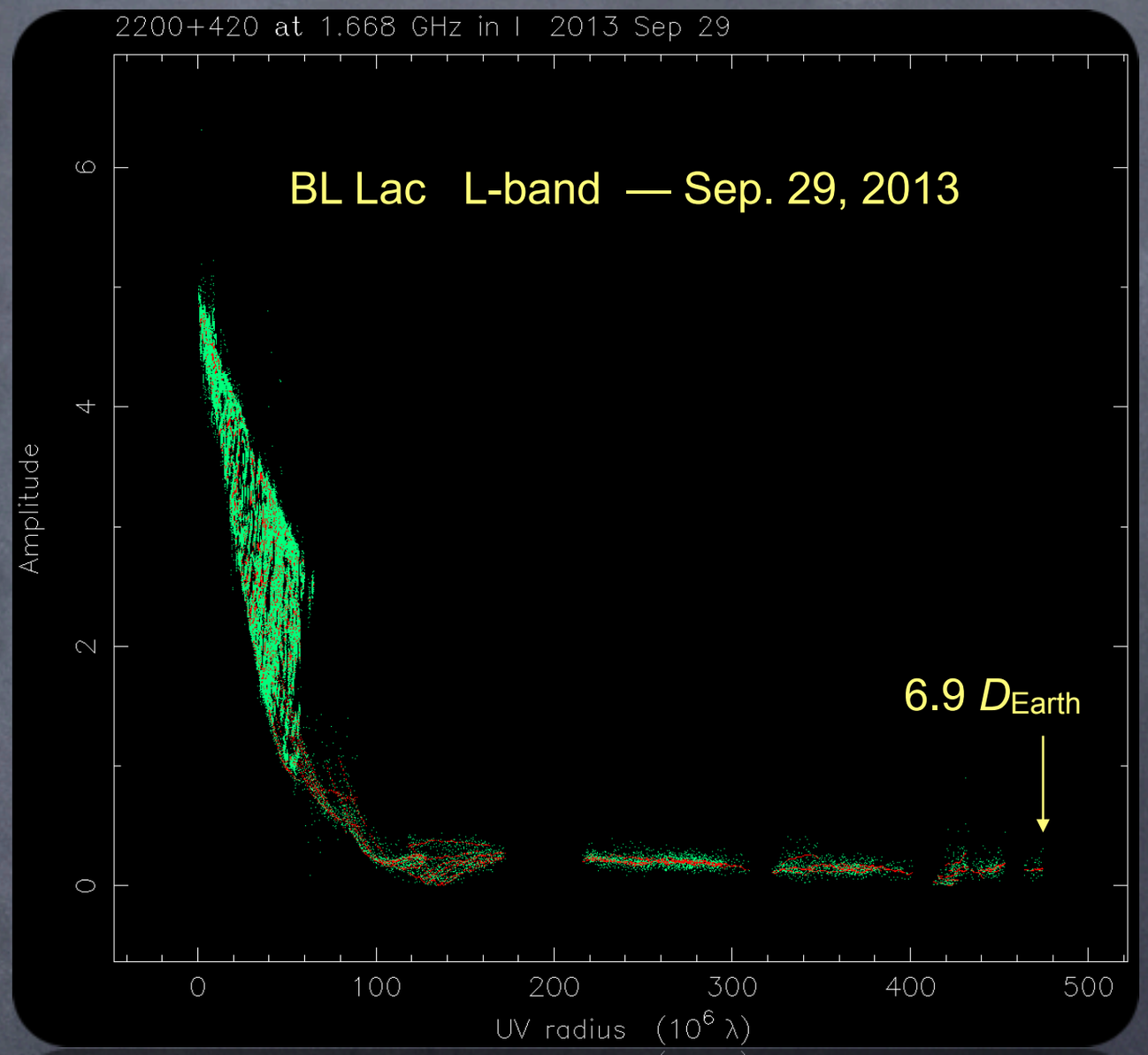
Preliminary correlation includes 17 antennas: EF, BD, ON, SV, TR, UR, WB, ZC, SH, BR, FD, HN, NL, OV, PT, SC, and MK.

Simultaneous ground-only observations at C and X-bands.

Ground-space baseline detections up to 6.9 D_{Earth}.



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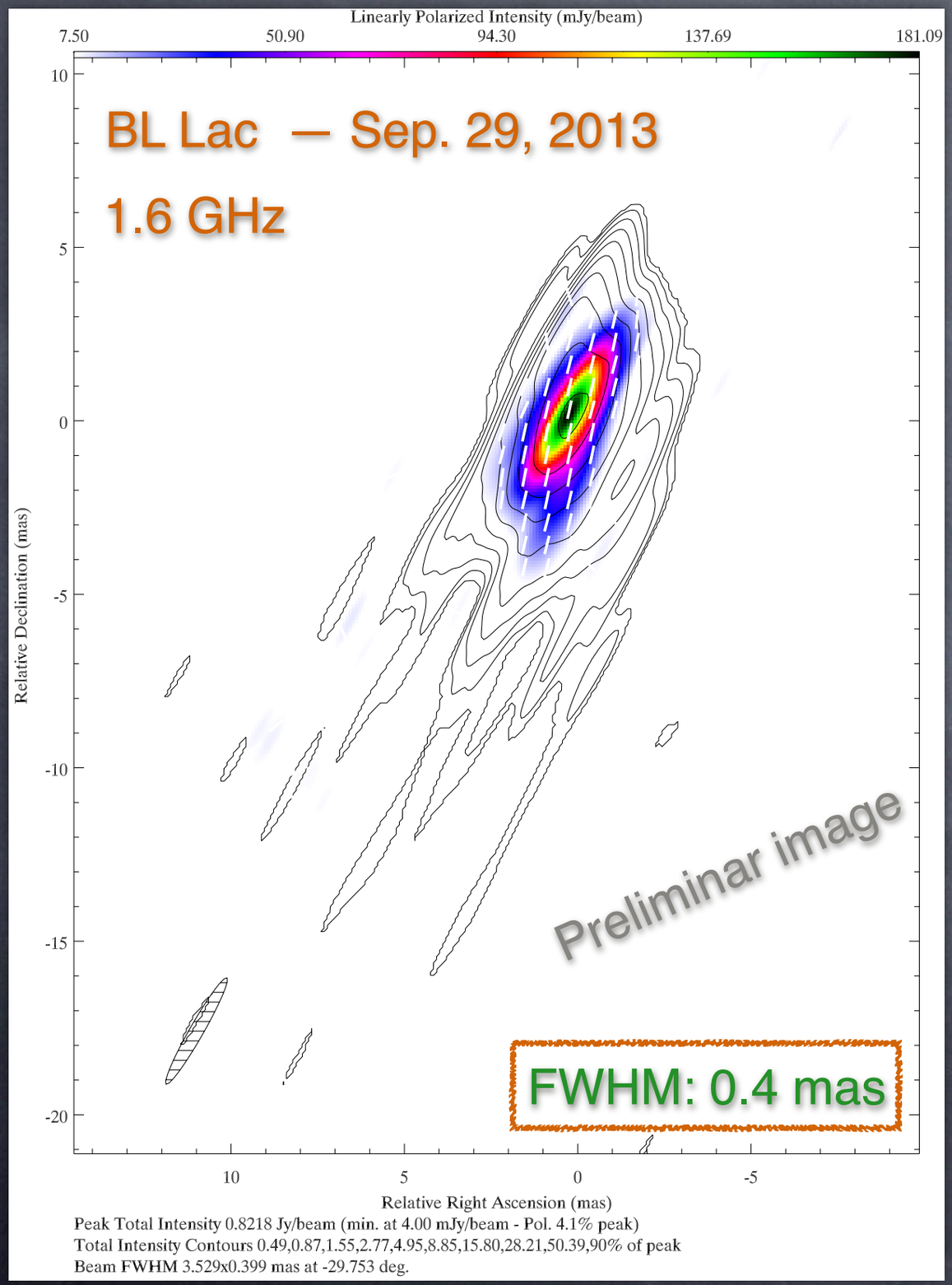
First Science Observations



Achieved angular resolution:
FWHM: 3.53x0.40 mas

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

Recovered 4.84 Jy of 5.2 Jy (Effelsberg)

Total intensity image shows three different components, while polarization shows a single component with EVPAs in the direction of the jet.

Calibration of the EVPAs through comparison with Effelsberg.

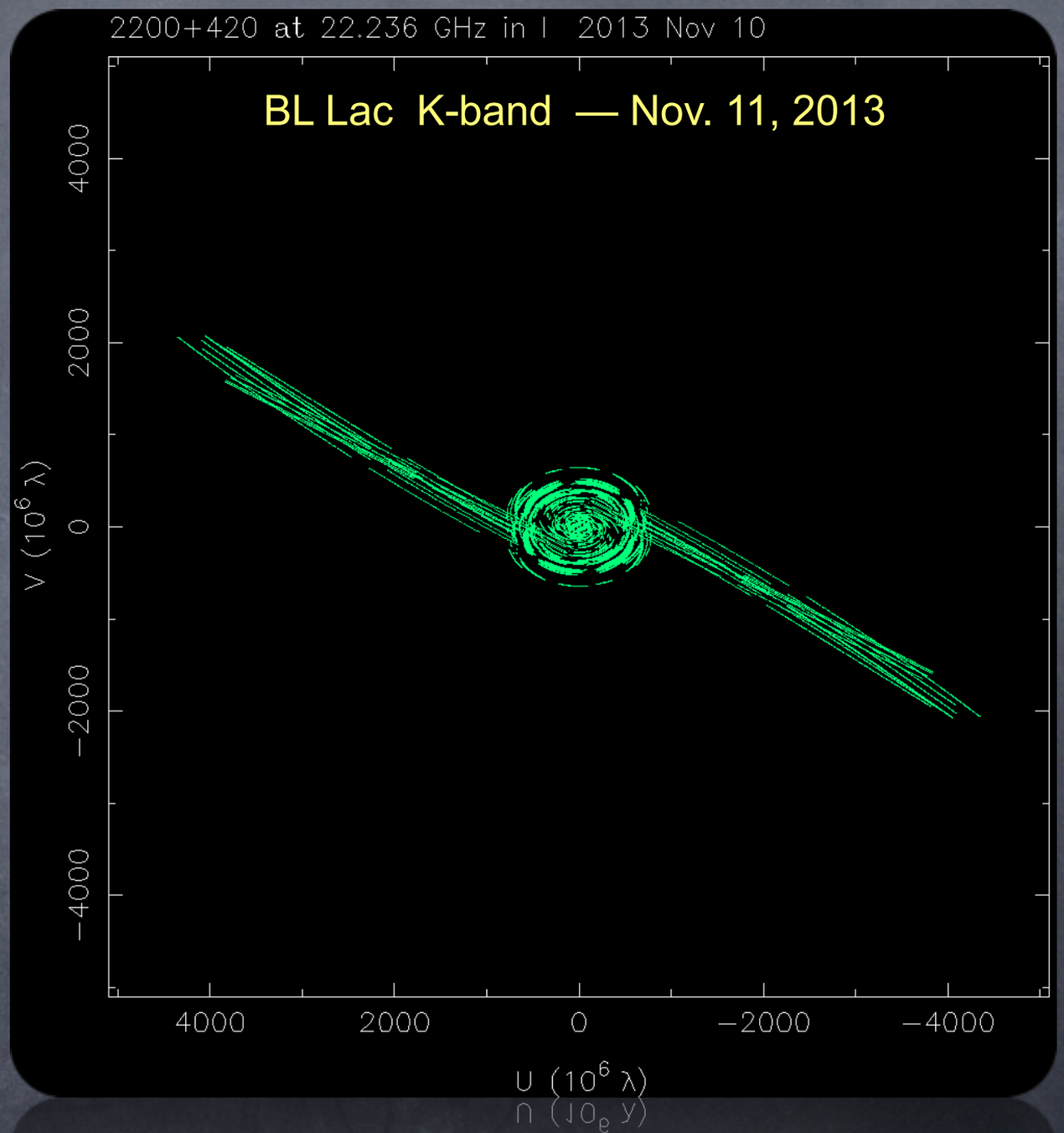
A KSP for polarimetric Space-VLBI with RadioAstron

First Science Observations at K-band

First science observations at 22 GHz were performed on November 11, 2013.

BL Lac was observed together with 26 antennas on the ground array: EF, YS, JD2, ON, NT, TR, MH, SV, ZC, MC, BD, KVN, SH, UR, and the VLBA.

Due to technical problems data was lost at FD, SC, YS, JB, TR, KVN (3), SH, and UR. A total of 16 antennas correlated, of which MC and BD contained bad data and were edited out.



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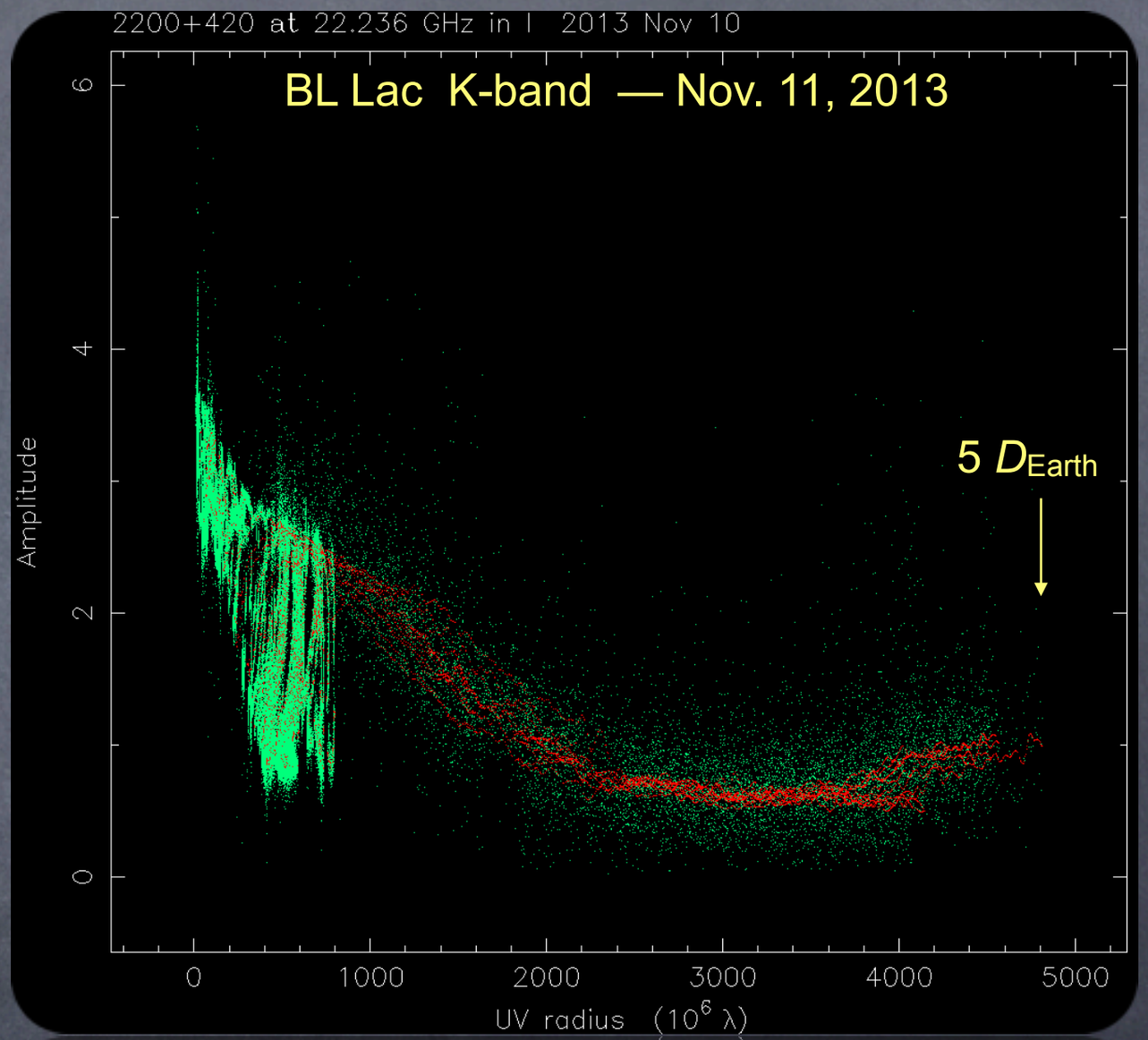
First science observations at 22 GHz were performed on November 11, 2013.

BL Lac was observed together with 26 antennas on the ground array: EF, YS, JD2, ON, NT, TR, MH, SV, ZC, MC, BD, KVN, SH, UR, and the VLBA.

Due to technical problems data was lost at FD, SC, YS, JB, TR, KVN (3), SH, and UR. A total of 16 antennas correlated, of which MC and BD contained bad data and were edited out.

Ground-space baseline detections up to 5 D_{Earth}.

Experiment scheduled to extent up to a maximum of 11.5 D_{Earth}, but no fringes have been obtained after EF stopped observing.



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First Science Observations at K-band

Instrumental polarization (D-terms) are solved using AIPS's task LPCAL on BL Lac, yielding very consistent results across the two IFs.

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

```
Ant  15 = RA       BX=  9999999.0000 BY=  9999999.0000 BZ=  9999999.0000
Mount=ORBI  Axis offset=  0.0000 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0951,  -63.6    0.0514,  147.1
Lin. approx. IF(  2) as amp, phase =  0.0967,  -58.7    0.0475,  142.8
```

Confirmation of RadioAstron polarization capabilities at 22 GHz

```
Ant   1 = BR       BX= -2112065.2172 BY= -3705356.5012 BZ=  4726813.6637
Mount=ALAZ  Axis offset=  2.1290 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0064,  -80.8    0.0124,   -8.1
Lin. approx. IF(  2) as amp, phase =  0.0070,  -74.6    0.0099,   12.2

Ant   2 = EF       BX=  4033947.2477 BY=   486990.8022 BZ=  4900431.0021
Mount=ALAZ  Axis offset=  0.0130 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.1075, -167.8    0.0816,  -58.6
Lin. approx. IF(  2) as amp, phase =  0.1018, -172.5    0.0773,  -67.9

Ant   3 = HN       BX=  1446374.8529 BY= -4447939.6746 BZ=  4322306.1822
Mount=ALAZ  Axis offset=  2.1300 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0251,   82.1    0.0123,  166.2
Lin. approx. IF(  2) as amp, phase =  0.0266,   62.9    0.0100,  145.6

Ant   4 = KP       BX= -1995678.8518 BY= -5037317.6923 BZ=  3357328.0133
Mount=ALAZ  Axis offset=  2.1310 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0147,  116.9    0.0071, -117.7
Lin. approx. IF(  2) as amp, phase =  0.0140,  108.3    0.0098, -159.9

Ant   5 = LA       BX= -1449752.5943 BY= -4975298.5702 BZ=  3709123.8339
Mount=ALAZ  Axis offset=  2.1310 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0179, -145.4    0.0062,  -25.2
Lin. approx. IF(  2) as amp, phase =  0.0180, -155.0    0.0022,  -32.7

Ant   6 = NL       BX=  -130872.5110 BY= -4762317.0886 BZ=  4226850.9930
Mount=ALAZ  Axis offset=  2.1300 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0240, -108.2    0.0363,  -25.8
Lin. approx. IF(  2) as amp, phase =  0.0201,  -94.3    0.0364,  -26.8

Ant   7 = OV       BX= -2409150.4168 BY= -4478573.1104 BZ=  3838617.3305
Mount=ALAZ  Axis offset=  2.1300 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0113,   39.8    0.0192,   79.6
Lin. approx. IF(  2) as amp, phase =  0.0117,   14.1    0.0221,   73.8

Ant   8 = PT       BX= -1640953.9498 BY= -5014816.0207 BZ=  3575411.7781
Mount=ALAZ  Axis offset=  2.1370 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0112,  170.8    0.0143,   10.7
Lin. approx. IF(  2) as amp, phase =  0.0103,  174.1    0.0111,   19.0

Ant   9 = MH       BX=  2892584.8330 BY=  1311715.6078 BZ=  5512640.1600
Mount=ALAZ  Axis offset= -0.0020 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0292,  160.6    0.0659,   31.6
Lin. approx. IF(  2) as amp, phase =  0.0398,  143.2    0.0438,   10.3

Ant  10 = ON       BX=  3370605.7892 BY=   711917.7337 BZ=  5349830.9127
Mount=ALAZ  Axis offset= -0.0080 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0329, -129.5    0.0482,  -28.2
Lin. approx. IF(  2) as amp, phase =  0.0316, -121.8    0.0464,  -28.0

Ant  11 = SV       BX=  2730173.6569 BY=  1562442.8028 BZ=  5529969.1538
Mount=ALAZ  Axis offset= -0.0070 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0446,  110.8    0.0363,   66.1
Lin. approx. IF(  2) as amp, phase =  0.0448,  114.0    0.0381,   66.4

Ant  12 = ZC       BX=  3451207.5231 BY=  3060375.4371 BZ=  4391915.0684
Mount=ALAZ  Axis offset= -0.0080 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0644,   91.2    0.0834, -109.7
Lin. approx. IF(  2) as amp, phase =  0.0820,   48.4    0.0677, -116.0

Ant  13 = MC       BX=  4461369.6800 BY=   919597.1425 BZ=  4449559.3934
Mount=ALAZ  Axis offset=  1.8270 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0000,    0.0    0.0000,    0.0
Lin. approx. IF(  2) as amp, phase =  0.0000,    0.0    0.0000,    0.0

Ant  14 = MK       BX= -5464075.1933 BY= -2495248.0494 BZ=  2148297.3837
Mount=ALAZ  Axis offset=  2.1340 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0192, -138.5    0.0314,  -58.8
Lin. approx. IF(  2) as amp, phase =  0.0158, -122.4    0.0347,  -58.5

Ant  15 = RA       BX=  9999999.0000 BY=  9999999.0000 BZ=  9999999.0000
Mount=ORBI  Axis offset=  0.0000 meters    IFA              IFB
Feed polarization type =                    R                L
Lin. approx. IF(  1) as amp, phase =  0.0951,  -63.6    0.0514,  147.1
Lin. approx. IF(  2) as amp, phase =  0.0967,  -58.7    0.0475,  142.8
```

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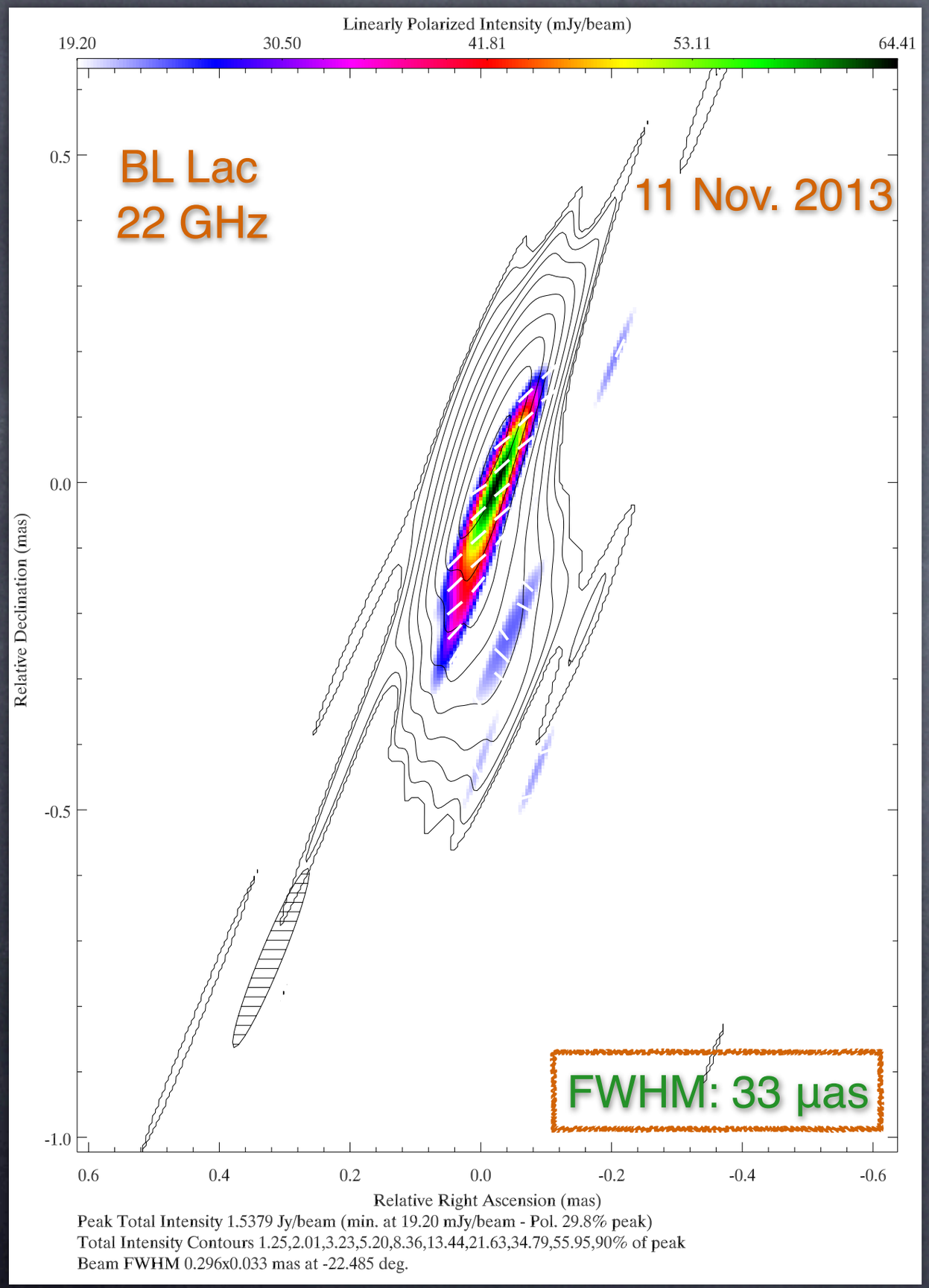


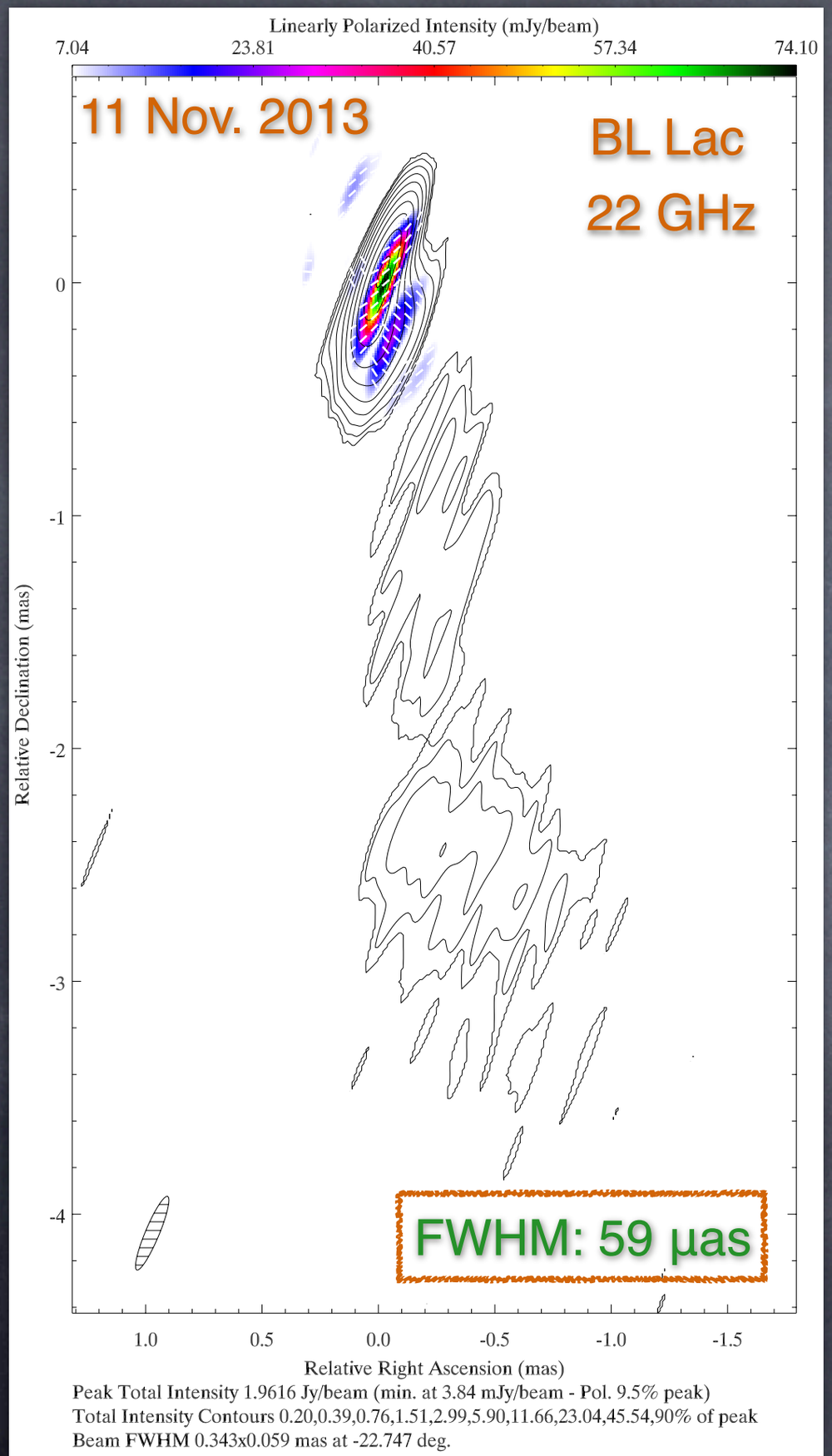
First polarization Space-VLBI image at 22 GHz

Achieved angular resolution:
FWHM: 0.296x0.033 mas

using uniform weighting with no amplitude error weighting. Achieved 5σ sensitivity of 20 mJy/beam.

Highest angular resolution polarization image obtained to date: 33 μas

A KSP for polarimetric Space-VLBI with RadioAstron



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using uniform weighting with no amplitude error weighting. Achieved 5σ sensitivity of 20 mJy/beam.

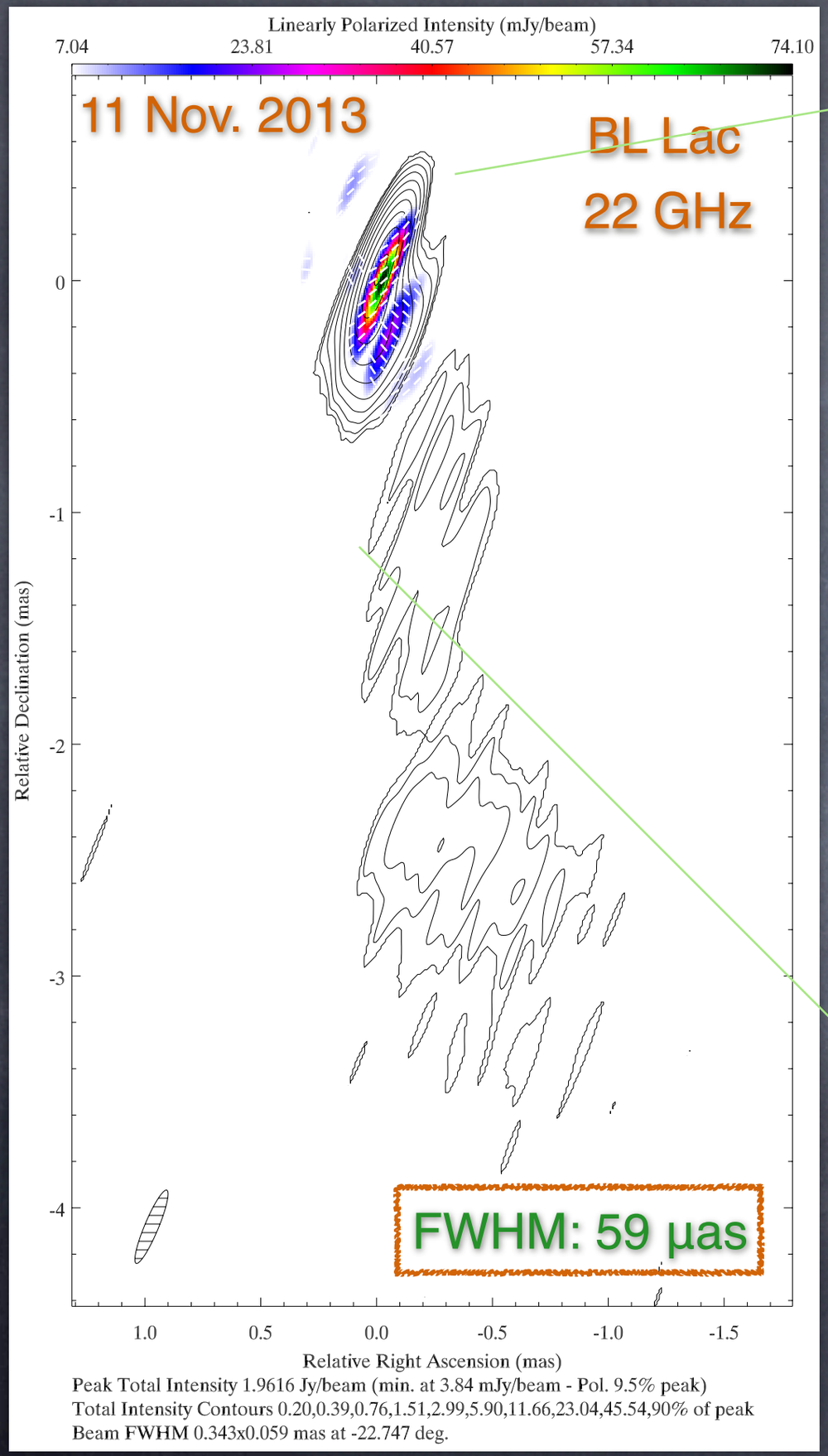
Highest angular resolution polarization image obtained to date: 33 μas

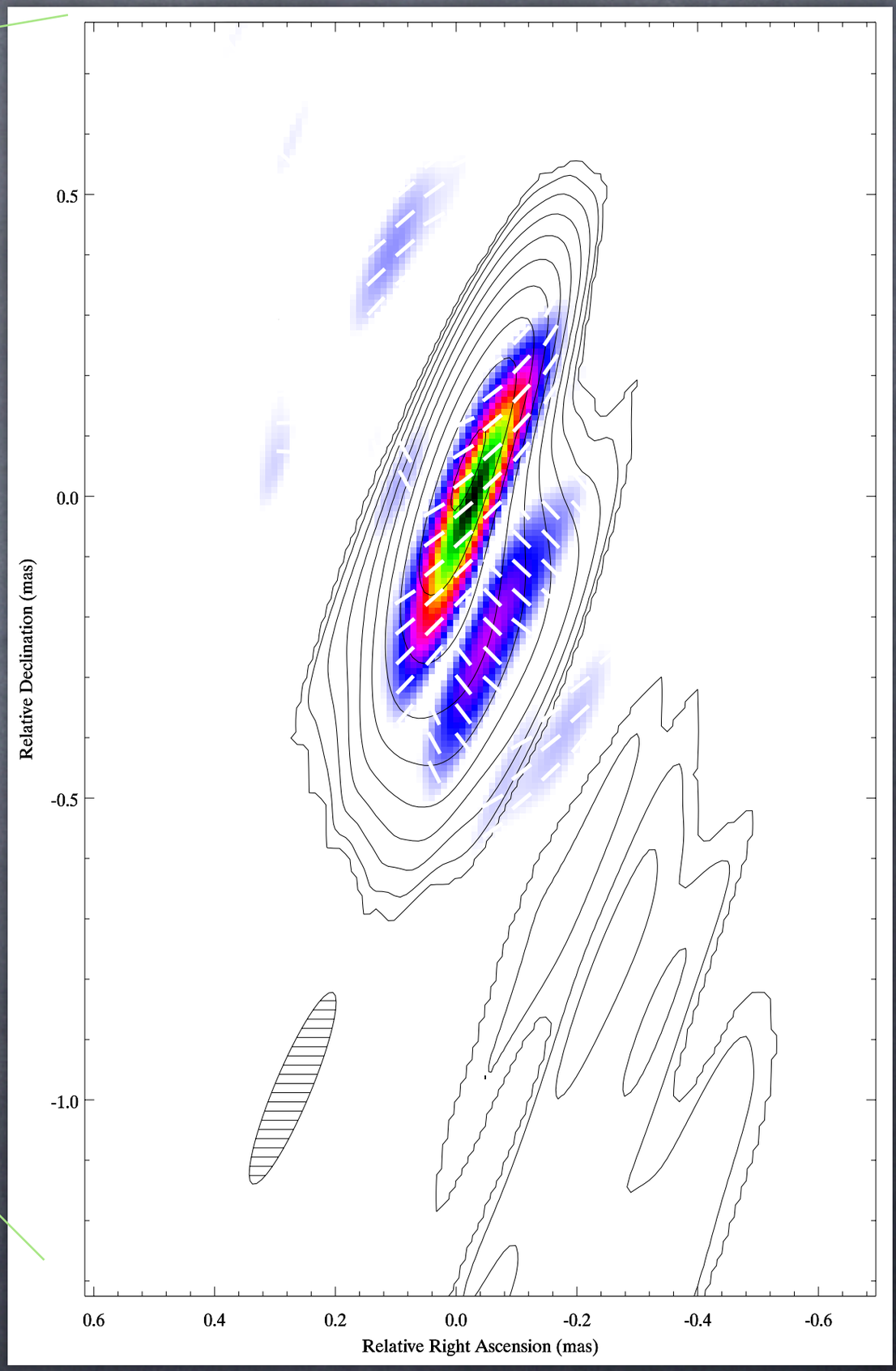
Image with uniform weighting provides an angular resolution of

FWHM: 0.343x0.059 mas

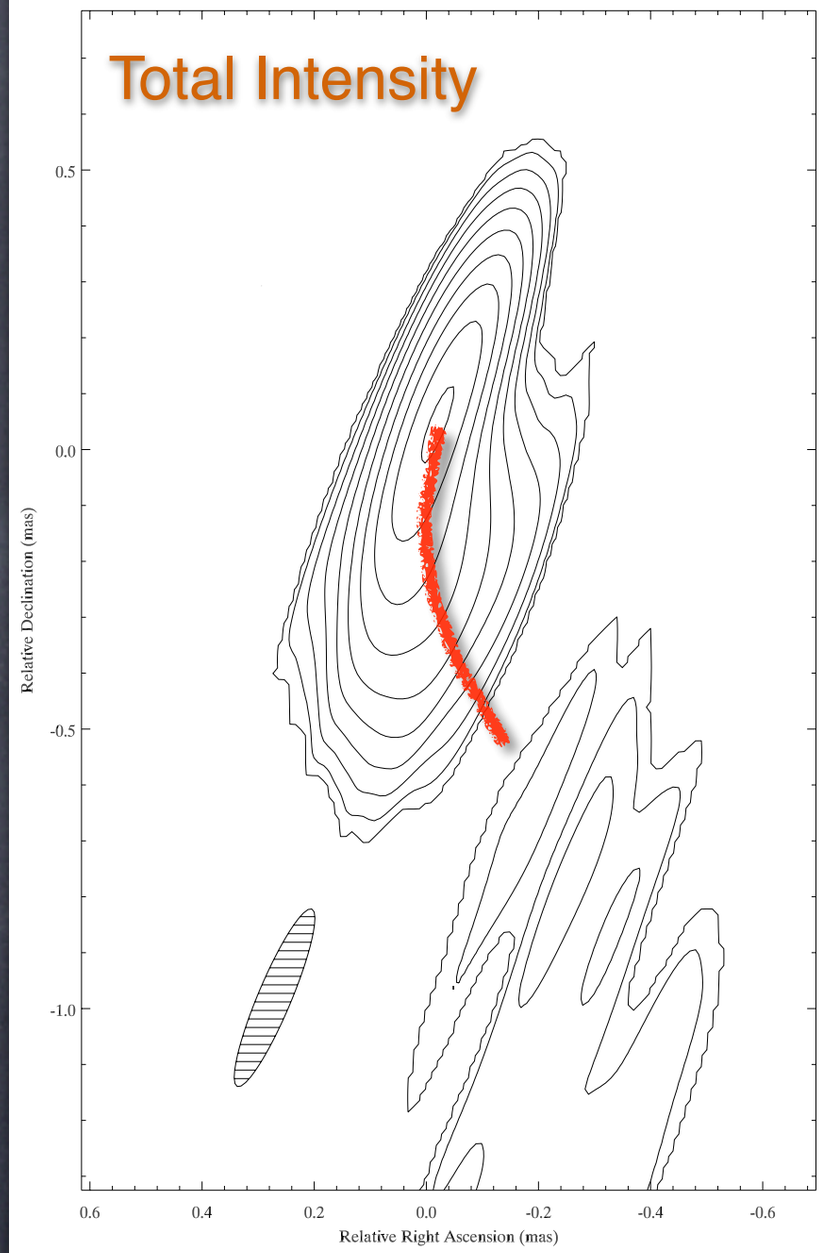
and a 5σ sensitivity of 4 mJy/beam in total intensity and 7 mJy/beam in polarization.

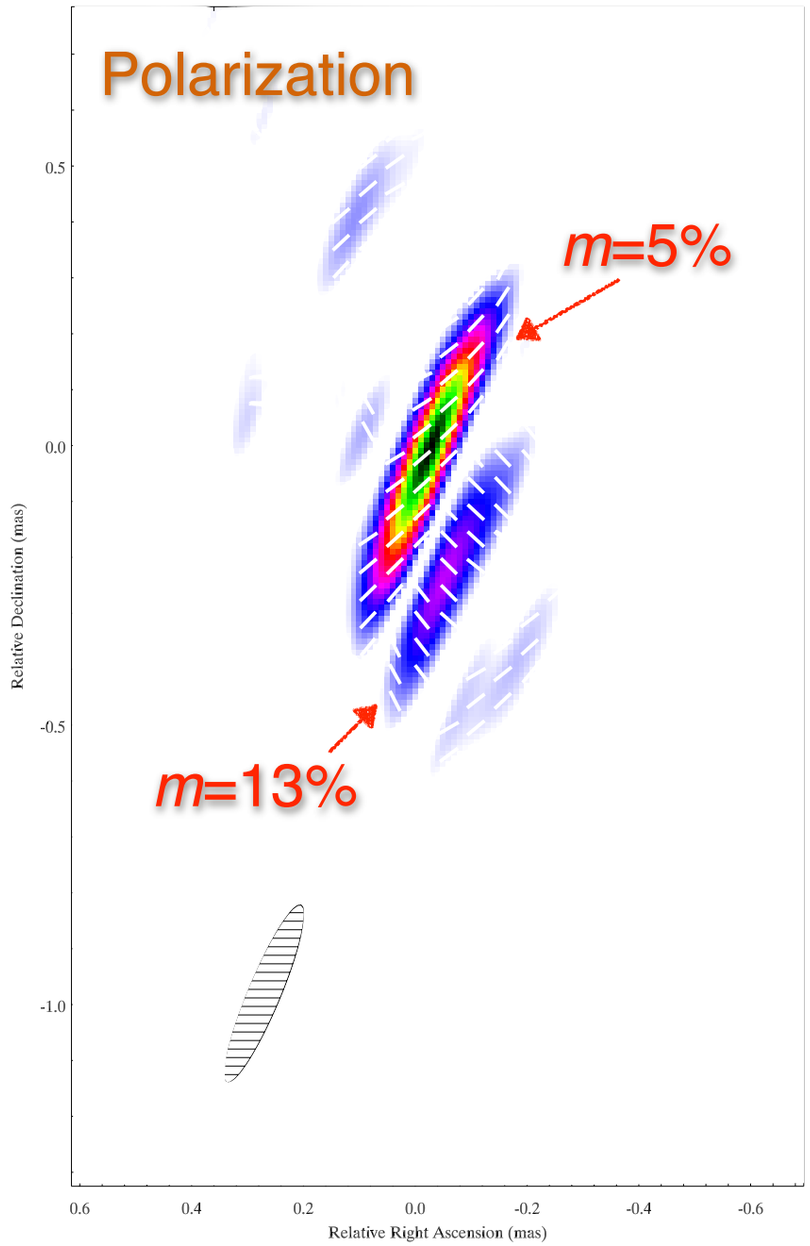
A KSP for polarimetric Space-VLBI with RadioAstron

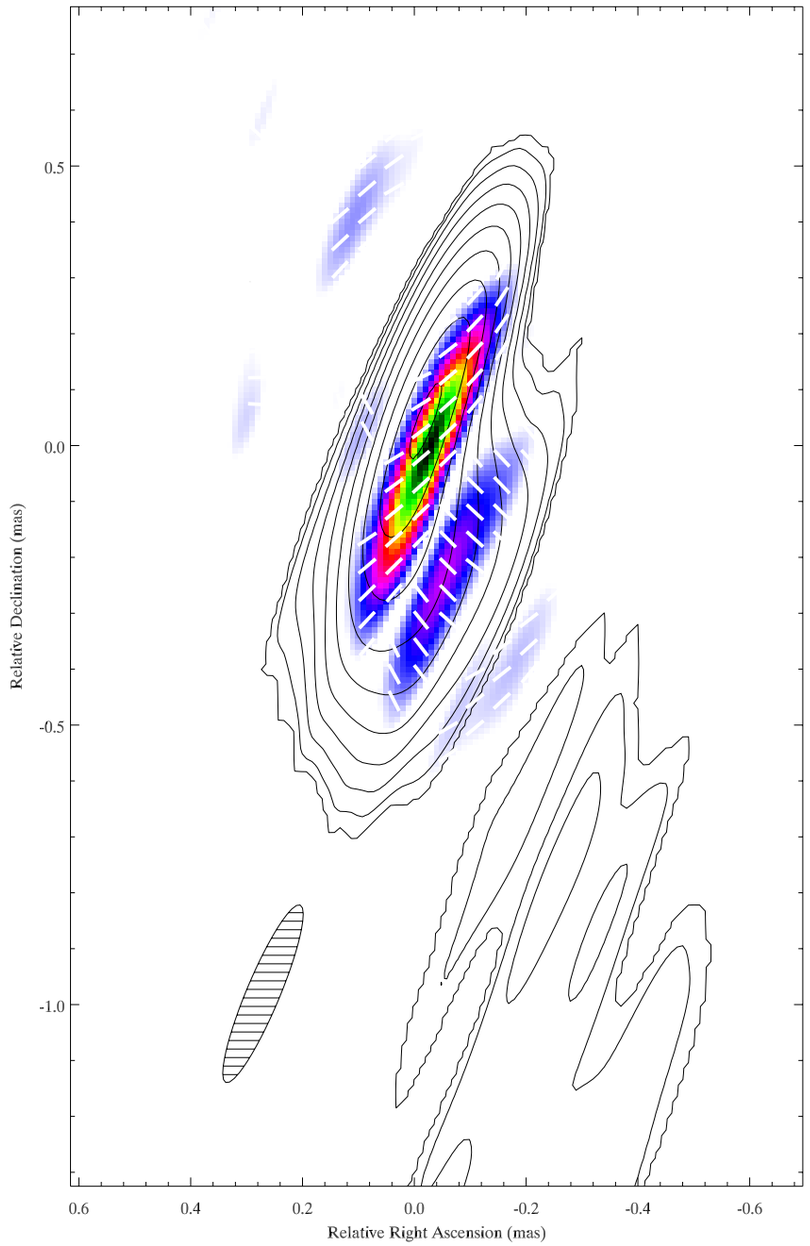




A KSP for polarimetric Space-VLBI with RadioAstron





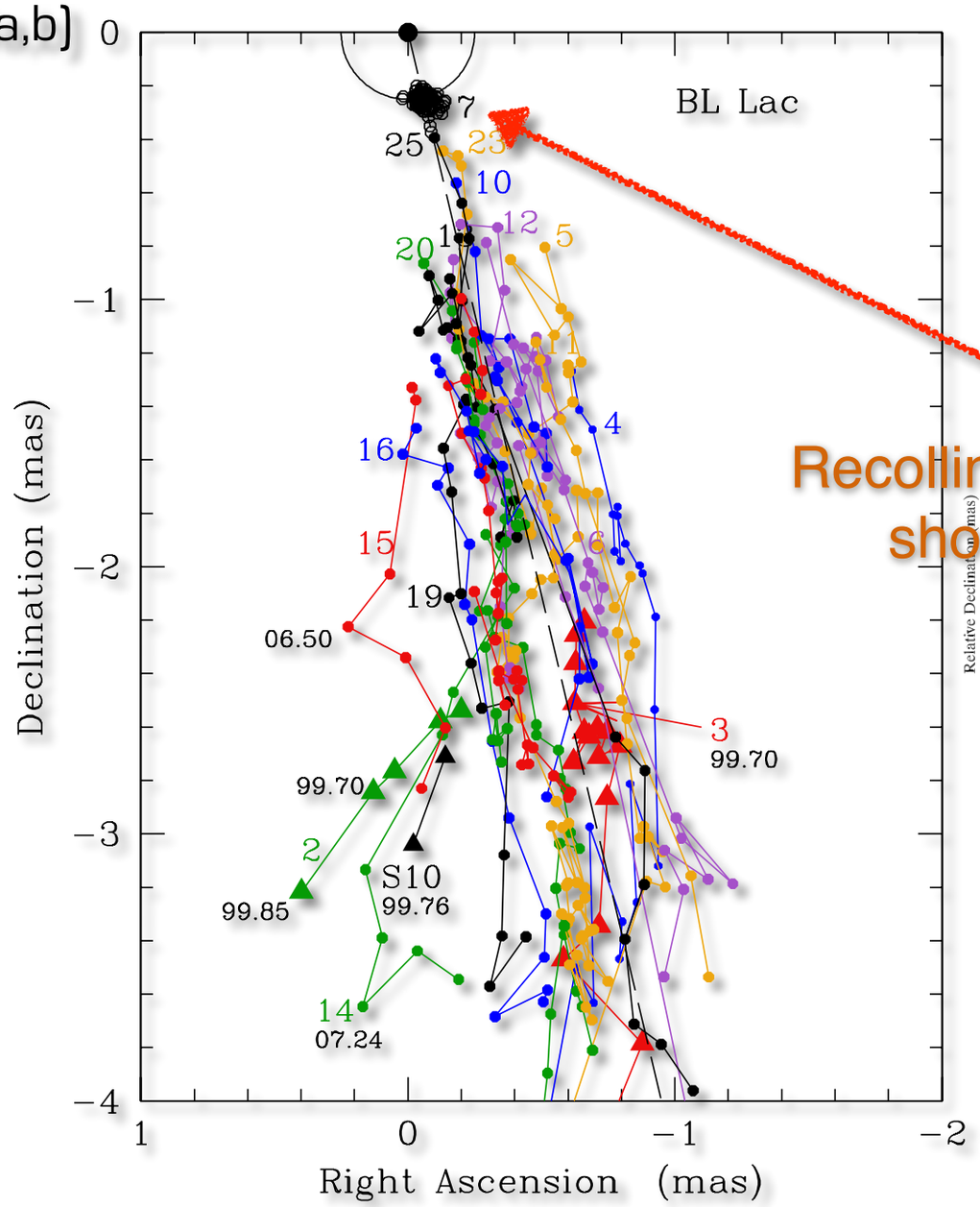


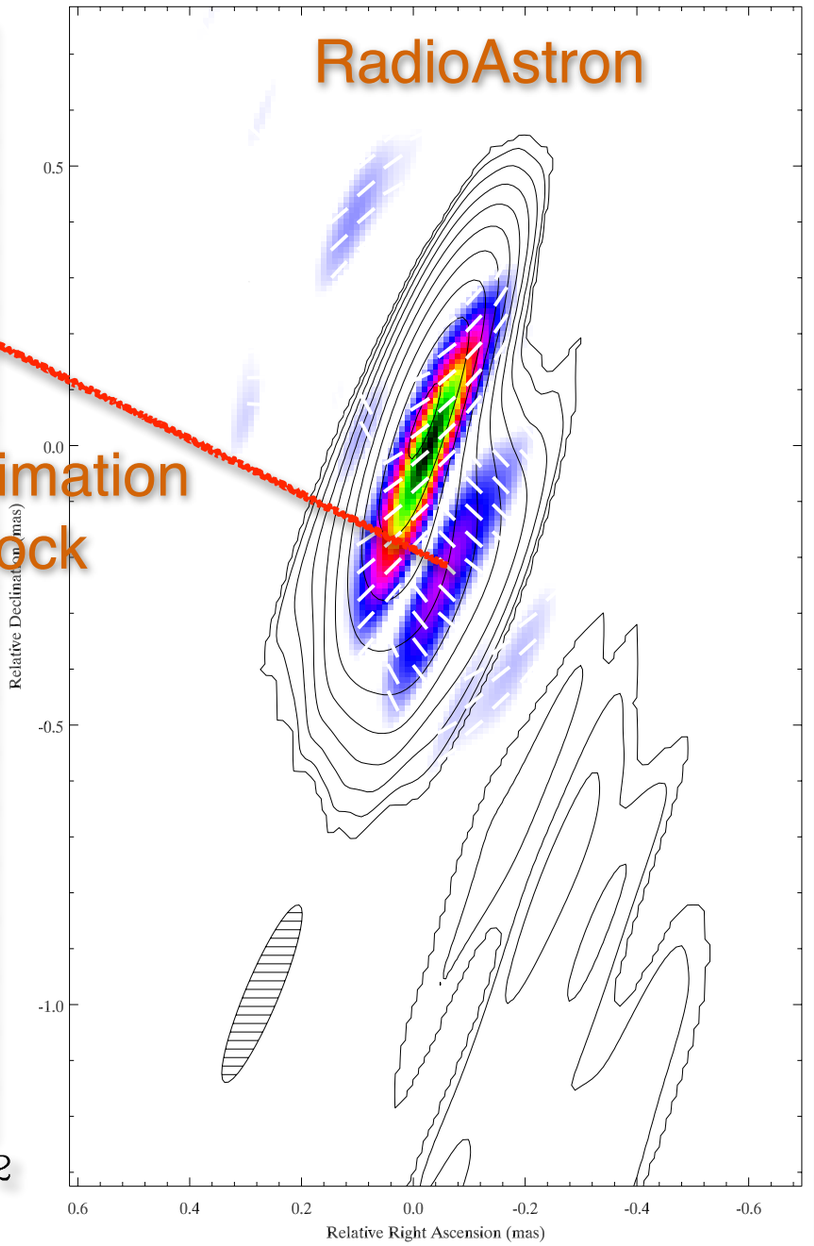
- Total intensity shows a highly bent structure in the innermost 0.5 mas.
- Highest resolution in the direction of the jet.

- Two components.
- Core EVPAs perpendicular to the jet direction.
- Component with aligned EVPAs

A KSP for polarimetric Space-VLBI with RadioAstron

Cohen et al. (2014a,b)



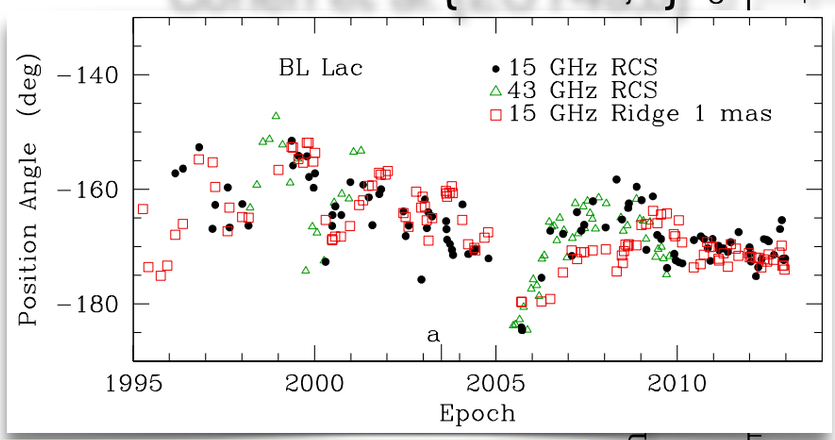


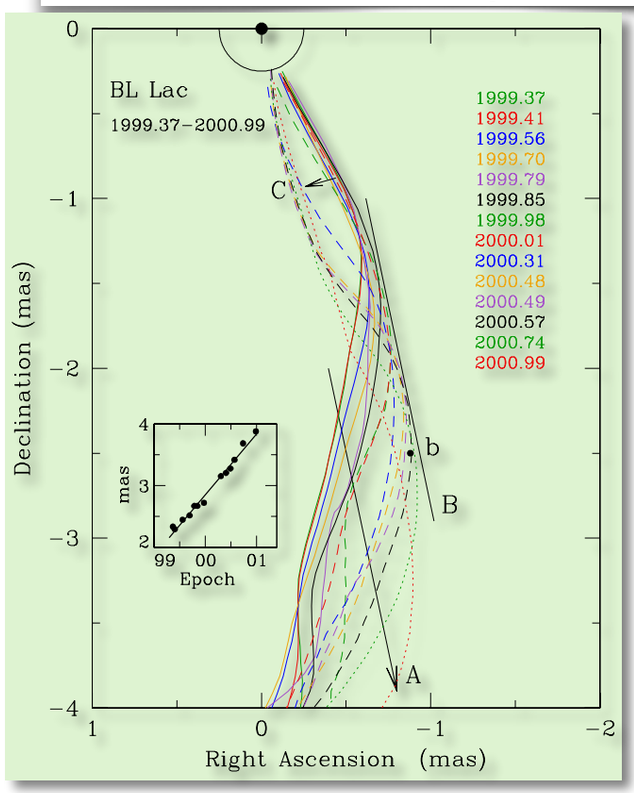
- Comparison with Cohen et al. (2014a,b) observations reveals that our component at 0.3 mas corresponds to their C7.
- C7 is identify by Cohen et al. (2014a,b) as a recollimation shock.

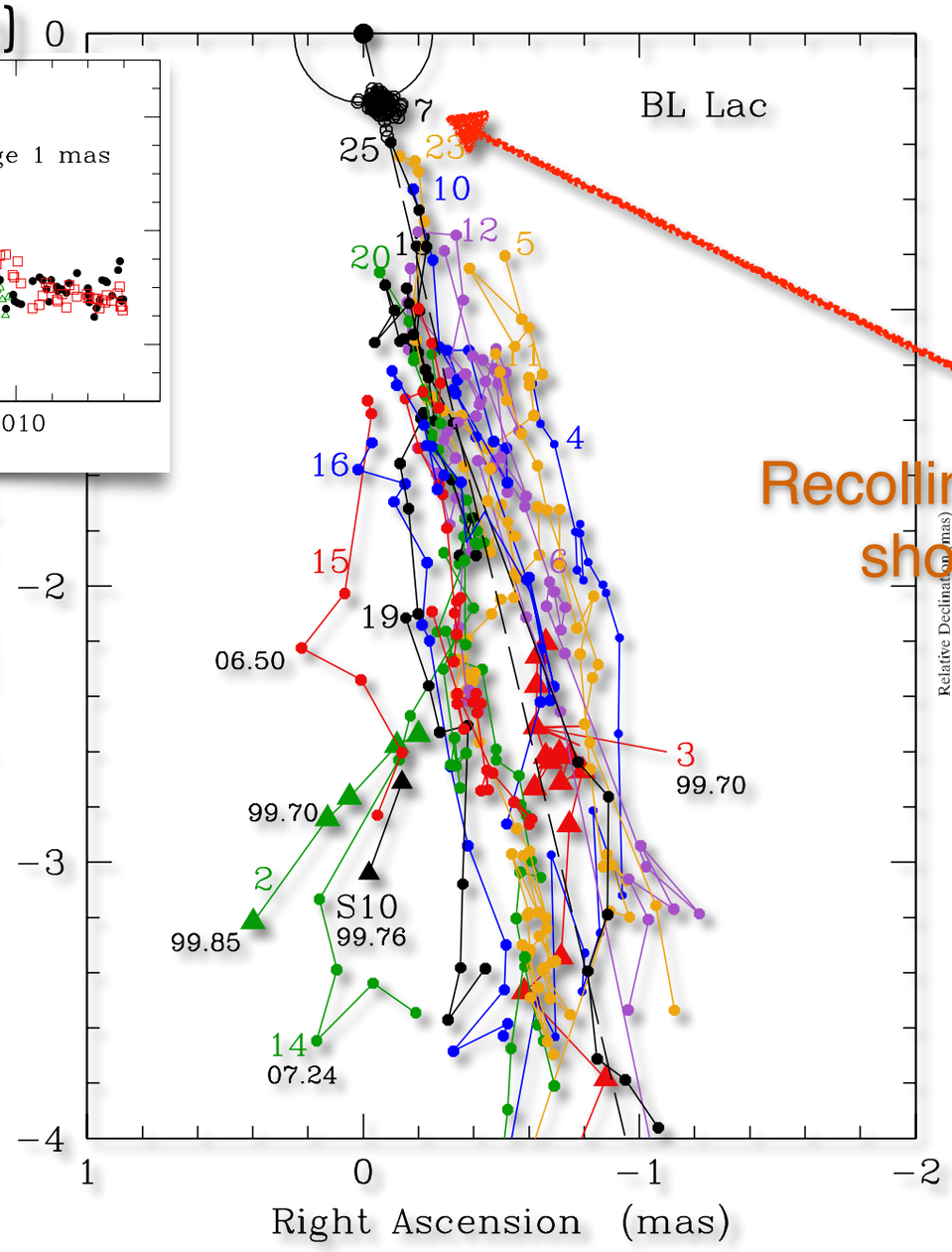
- Our RadioAstron observations reveal that C7 has a polarization orthogonal to the core, and aligned with the jet direction.

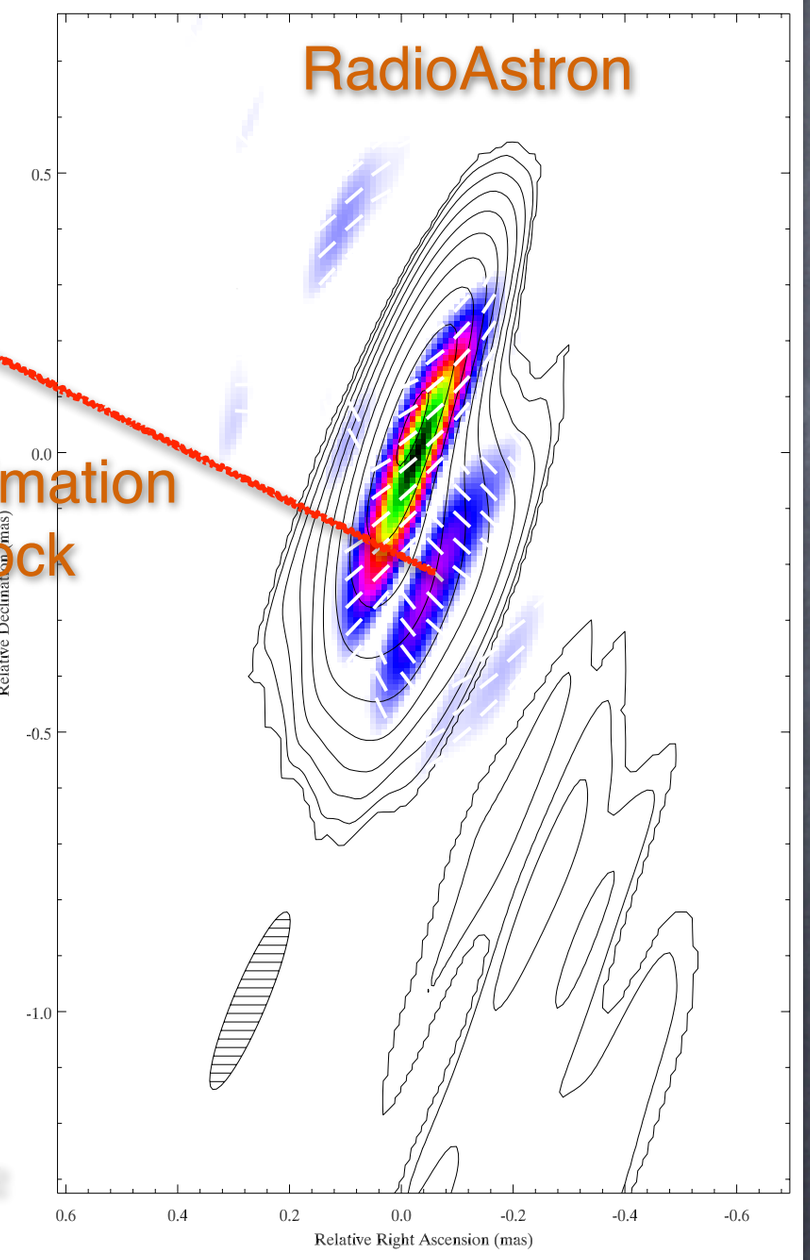
A KSP for polarimetric Space-VLBI with RadioAstron

Cohen et al. (2014a,b)









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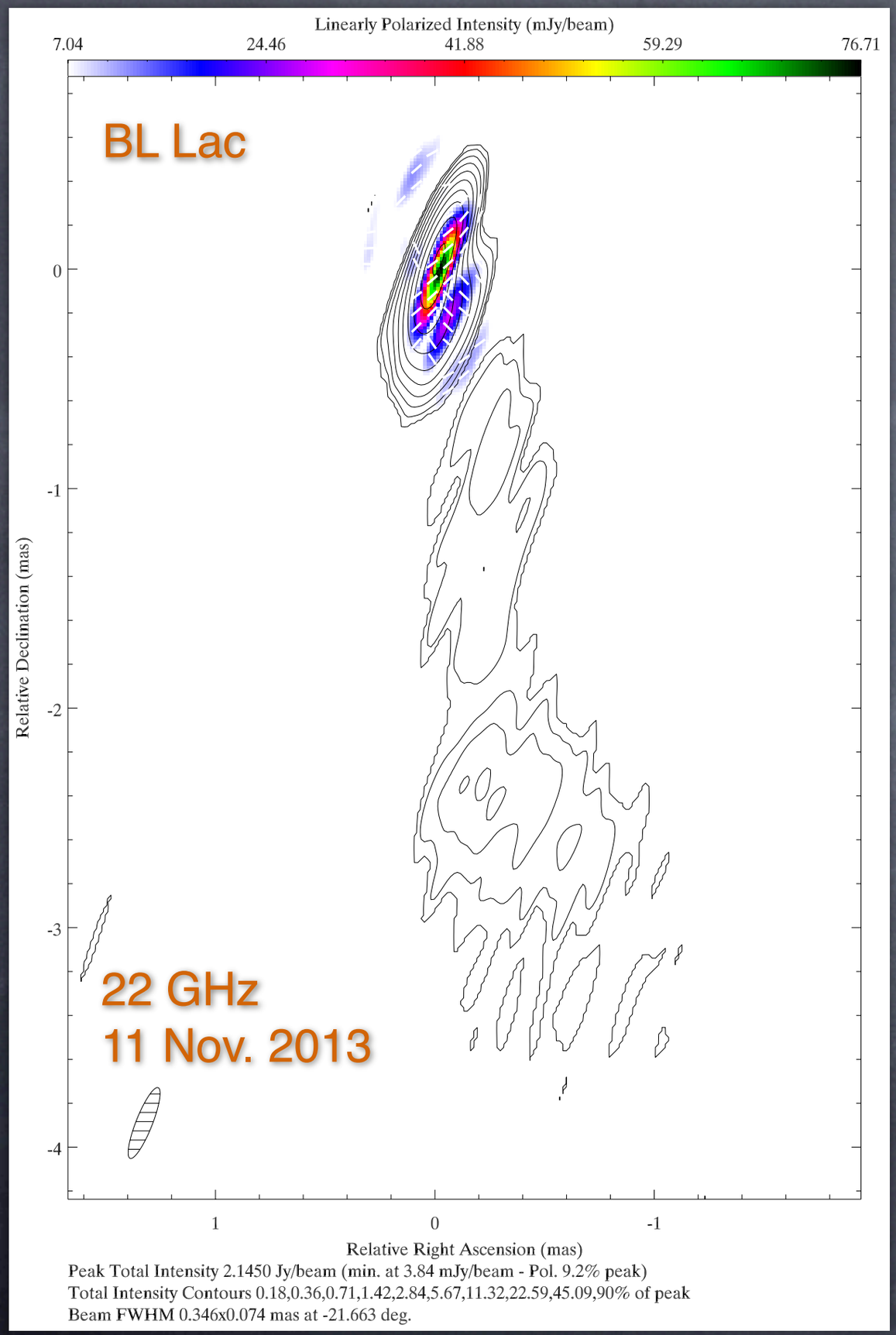
- C7 is identify by Cohen et al. (2014a,b) as a recollimation shock.

- Our RadioAstron observations reveal that C7 has a polarization orthogonal to the core, and aligned with the jet direction.
- C7 swings in position angle, triggering Alfvén waves in the jet ridge line, like waves on a whip.

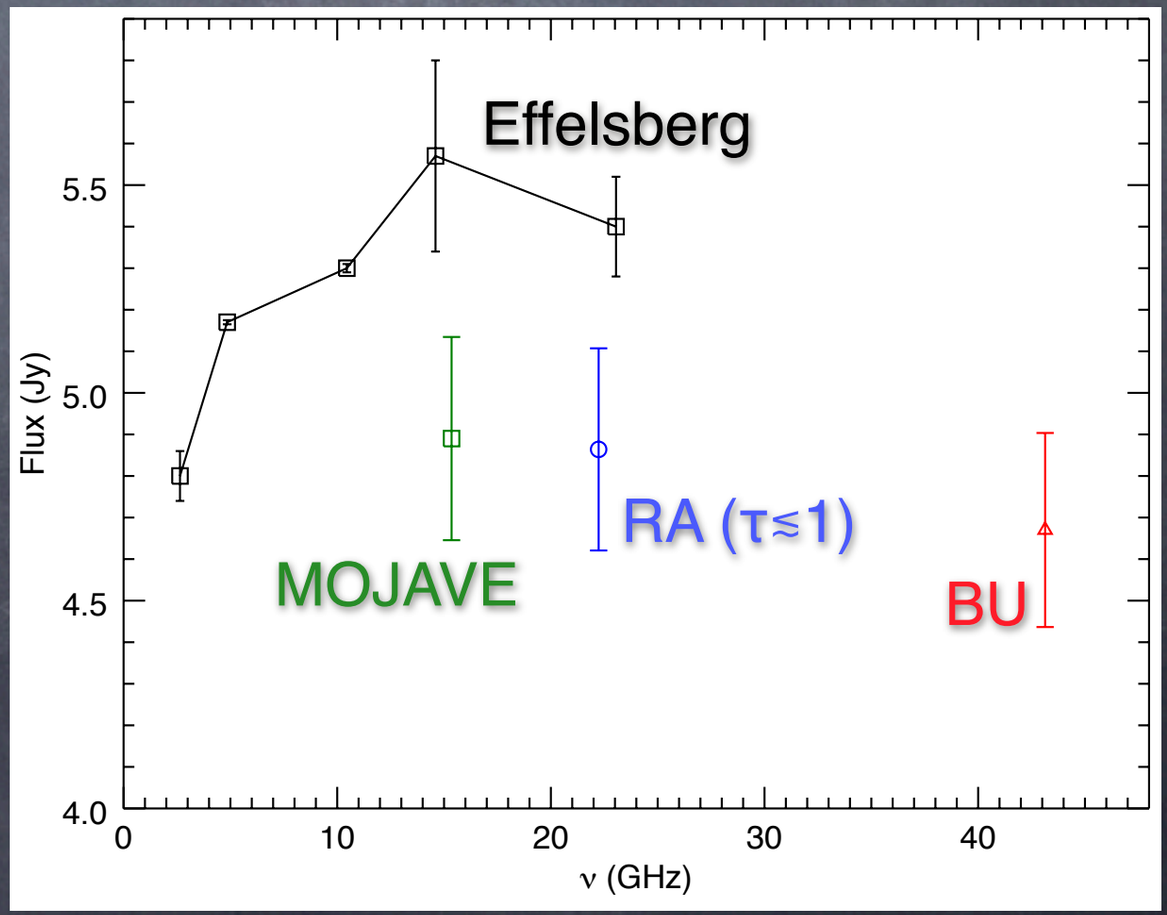
A KSP for polarimetric Space-VLBI with RadioAstron



Comparison with other wavebands:

- Q-band: Due to technical reasons polarization data only available for 6 VLBA antennas: BR, HN, KP, LA, NL, PT.
- U-band: Similar situation, with only 7 VLBA antennas: BR, HN, KP, LA, NL, OV, PT.

Opacity and Faraday rotation analysis performed through comparison with BU and MOJAVE data.



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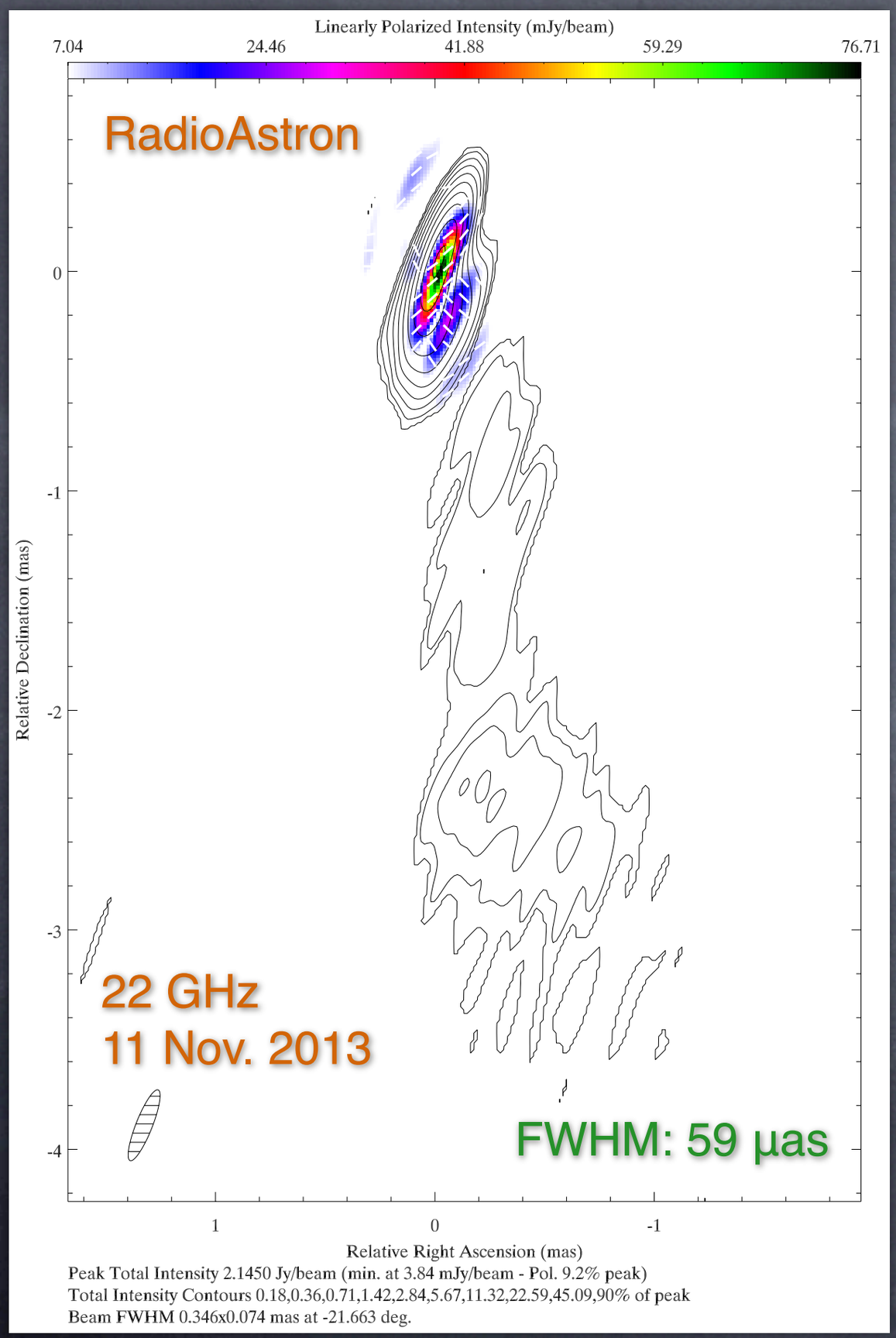

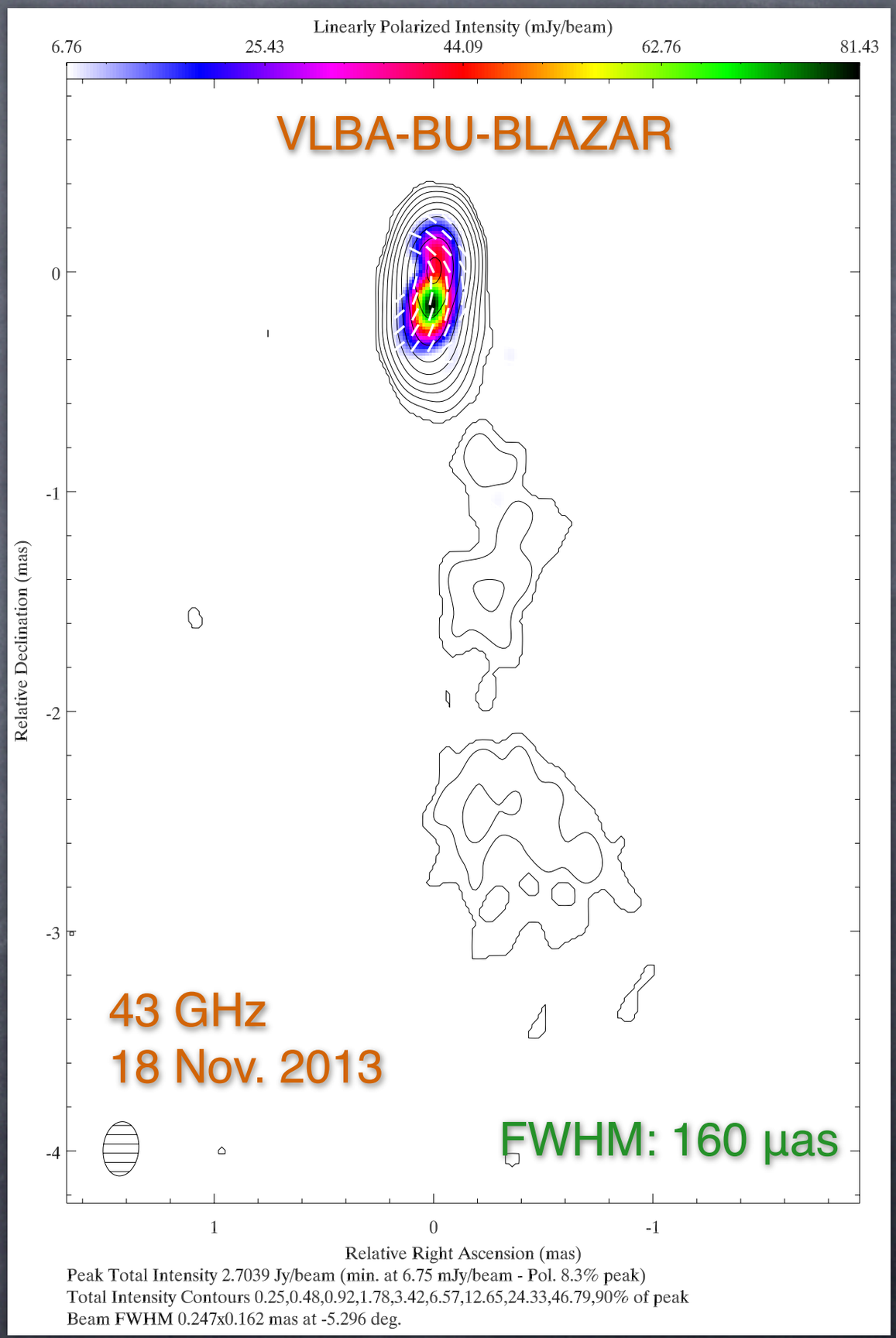

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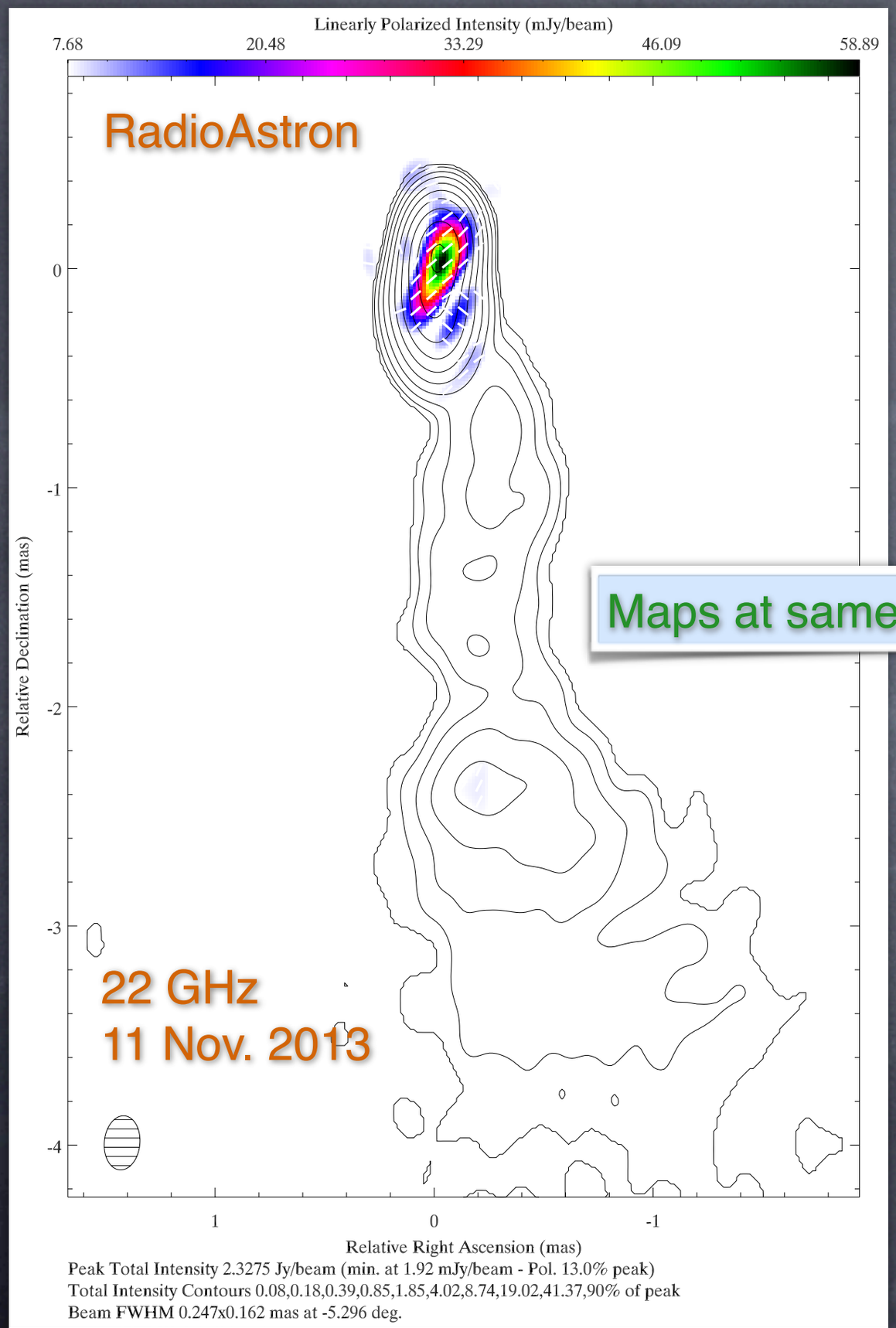
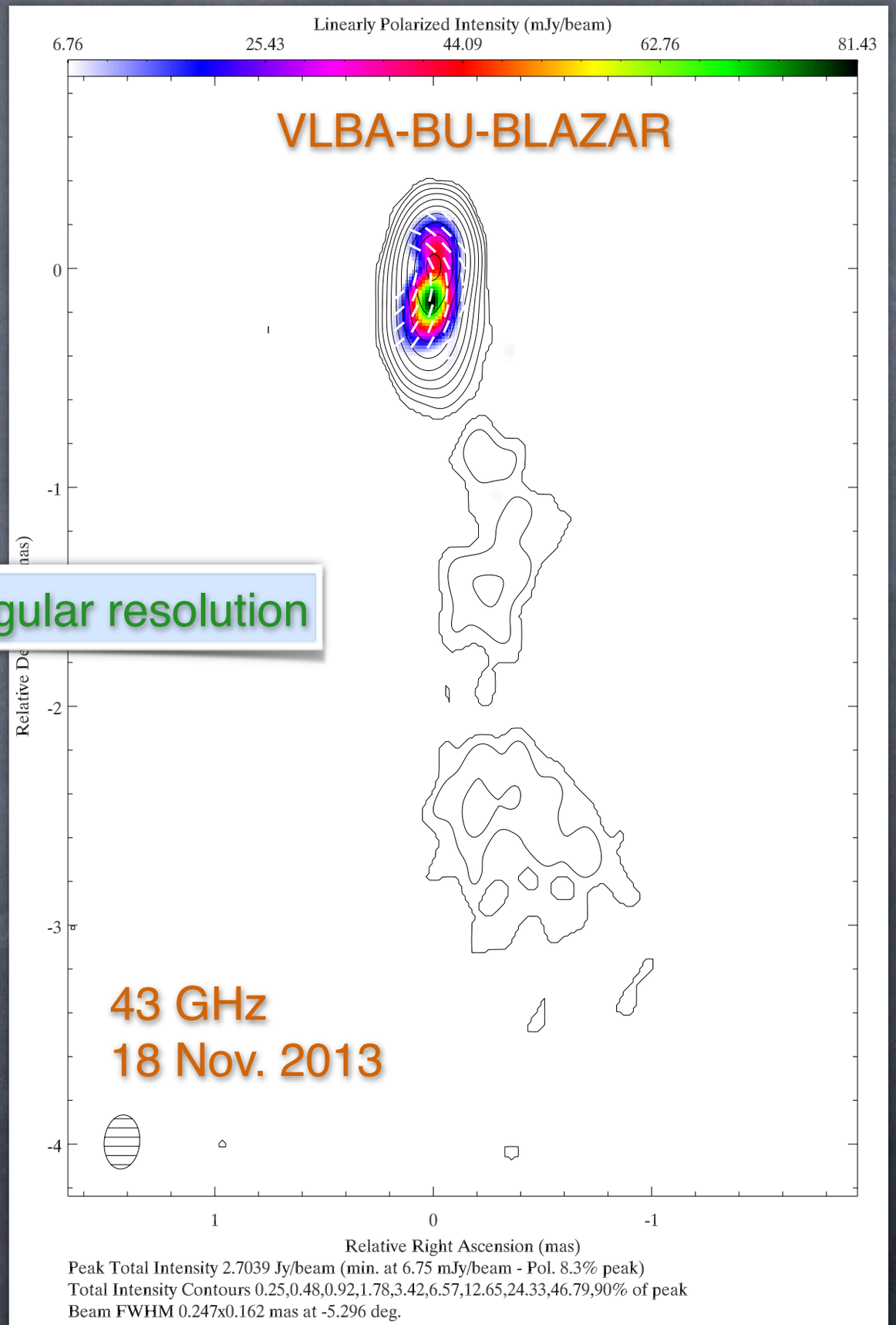


Maps at same angular resolution



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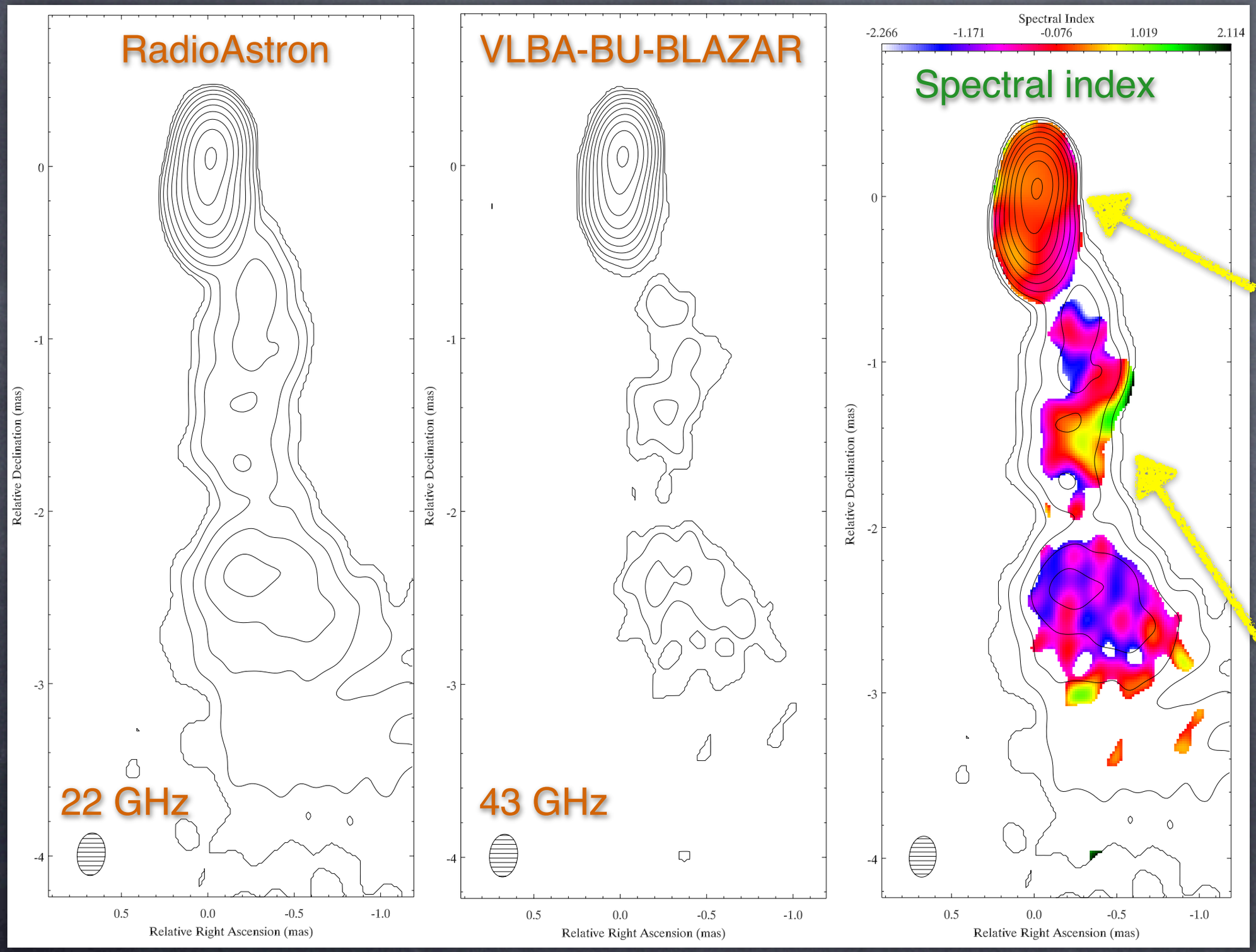
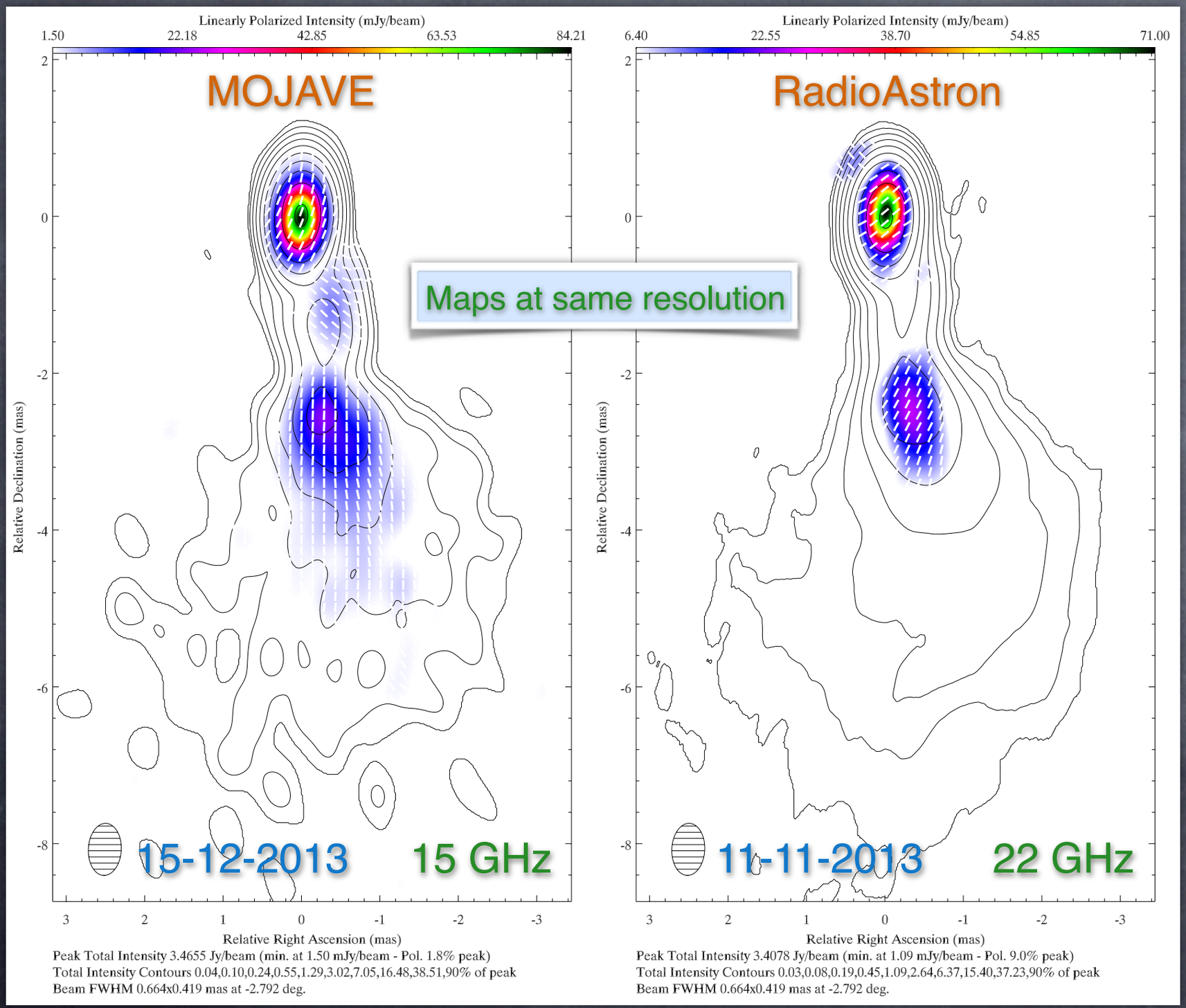


Core moderately thick with α≃0.12

Jet optically thin

A KSP for polarimetric Space-VLBI with RadioAstron

Map comparison across 15, 22, and 43 GHz for RM analysis



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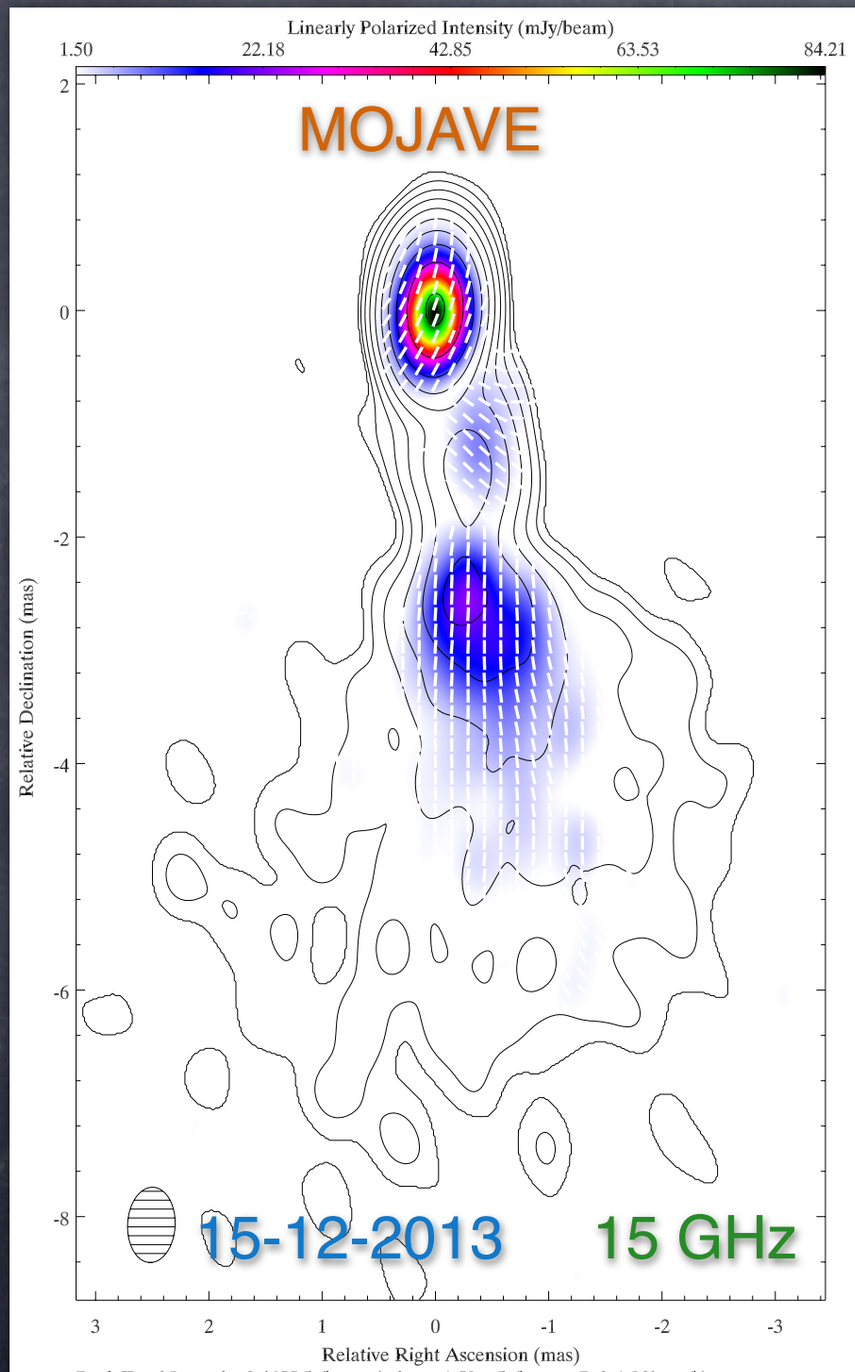
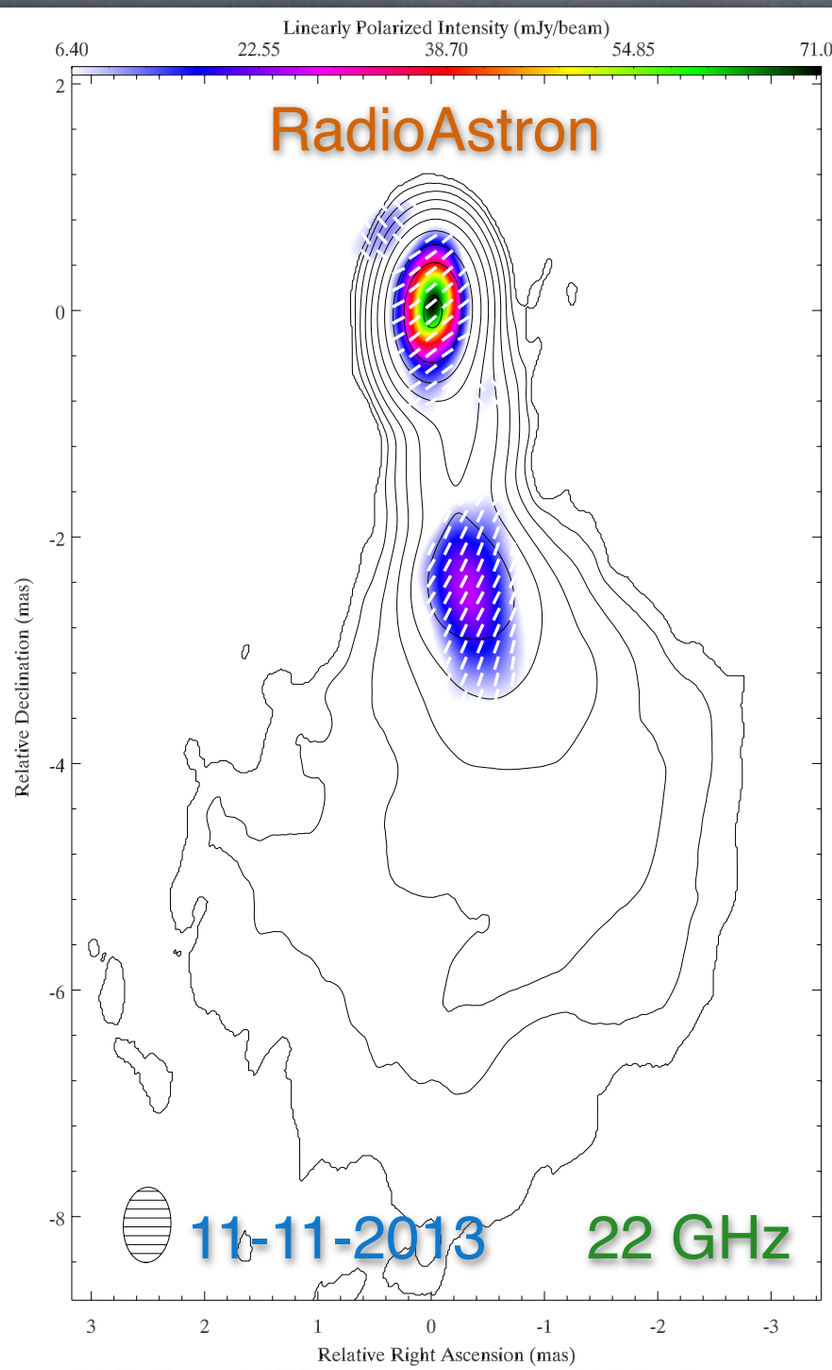
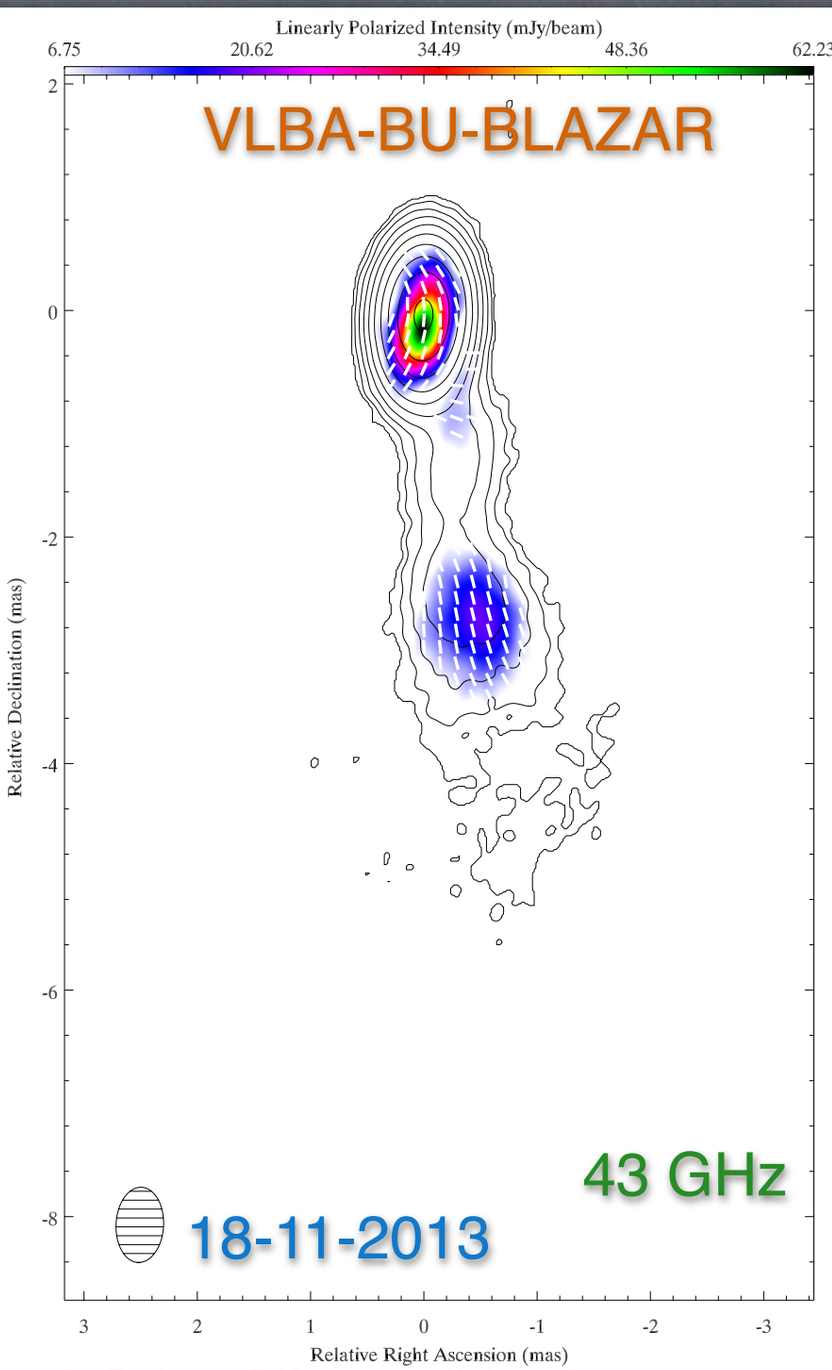
Map comparison across 15, 22, and 43 GHz for RM analysis



Peak Total Intensity 3.4655 Jy/beam (min. at 1.50 mJy/beam - Pol. 1.8% peak)
Total Intensity Contours 0.04,0.10,0.24,0.55,1.29,3.02,7.05,16.48,38.51,90% of peak
Beam FWHM 0.664x0.419 mas at -2.792 deg.

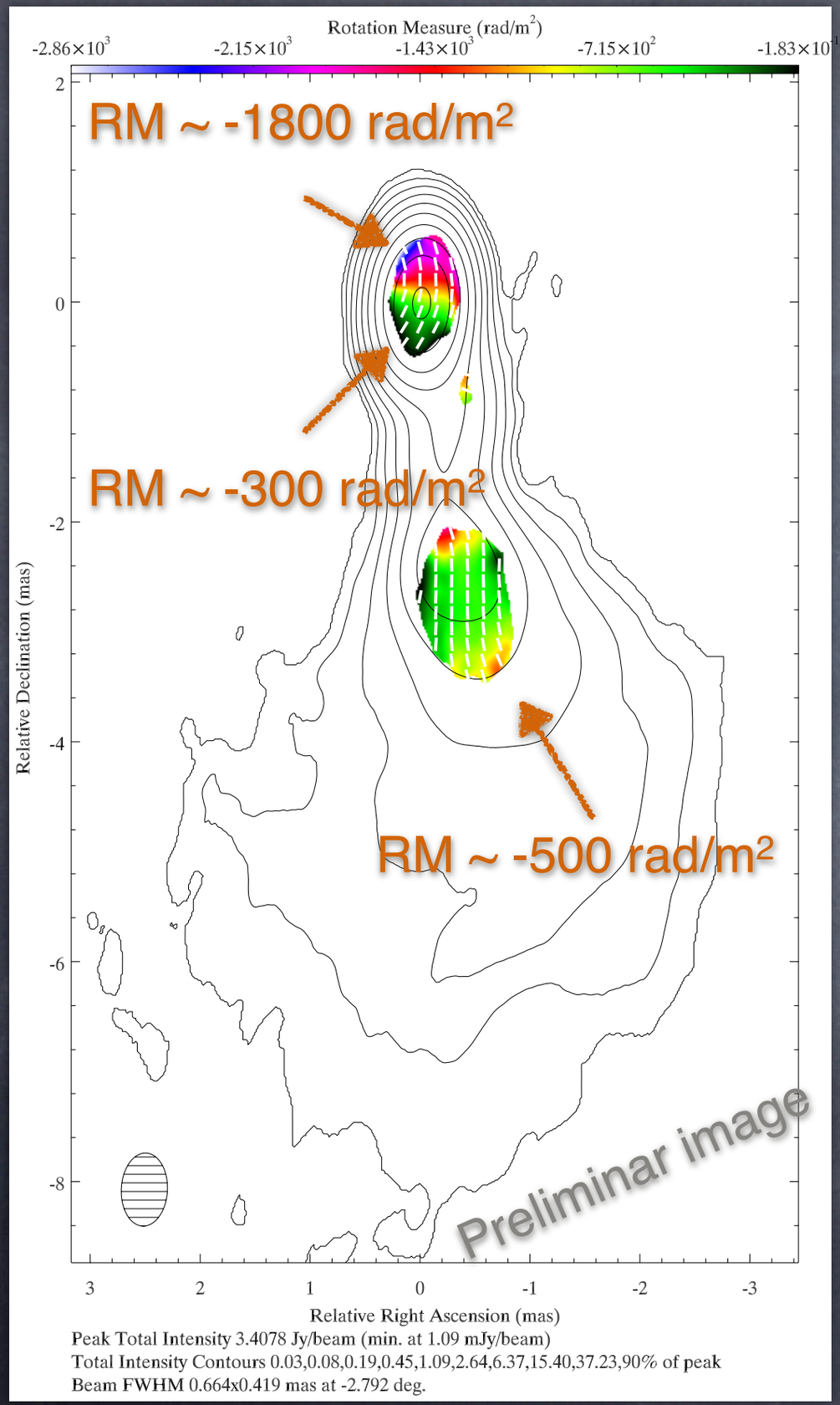


Peak Total Intensity 3.4078 Jy/beam (min. at 1.09 mJy/beam - Pol. 9.0% peak)
Total Intensity Contours 0.03,0.08,0.19,0.45,1.09,2.64,6.37,15.40,37.23,90% of peak
Beam FWHM 0.664x0.419 mas at -2.792 deg.



Peak Total Intensity 3.7395 Jy/beam (min. at 6.75 mJy/beam - Pol. 10.8% peak)
Total Intensity Contours 0.18,0.36,0.72,1.43,2.85,5.69,11.35,22.63,45.13,90% of peak
Beam FWHM 0.664x0.419 mas at -2.792 deg.

A KSP for polarimetric Space-VLBI with RadioAstron



Preliminar Faraday rotation analysis

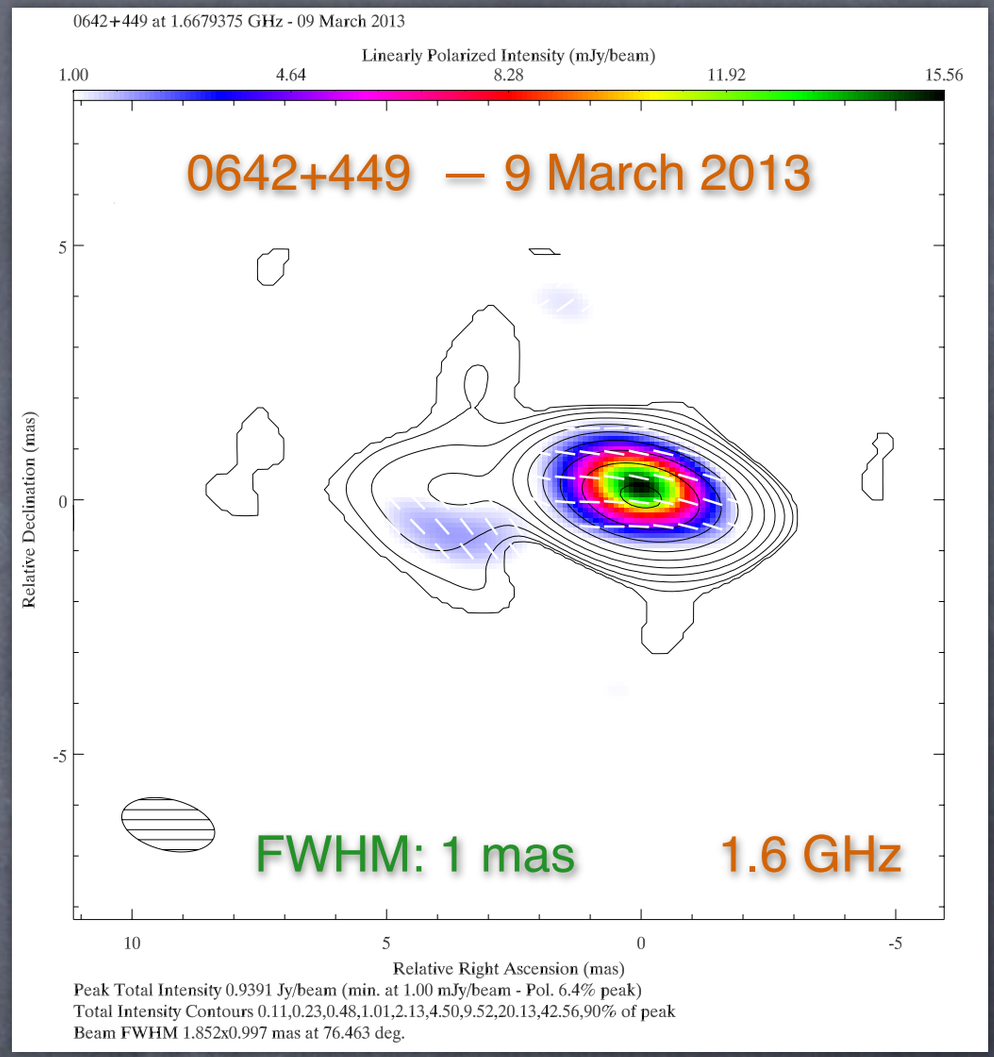
- Core region shows a gradient in RM, decreasing in the jet direction. Values change from ~ - 1800 rad/m² to -300 rad/m²
- Jet shows RM ~ - 500 rad/m²

Comparison with dedicated 3mm GMVA observations (PI Marscher) is underway.

A KSP for polarimetric Space-VLBI with RadioAstron

Summary

- Six RadioAstron observations carried out within our polarization KSP during AO-1. Continued observations throughout AO-2.
- First successful test polarization observations at L-band, showing small instrumental polarization, confirming RA polarization imaging capabilities.



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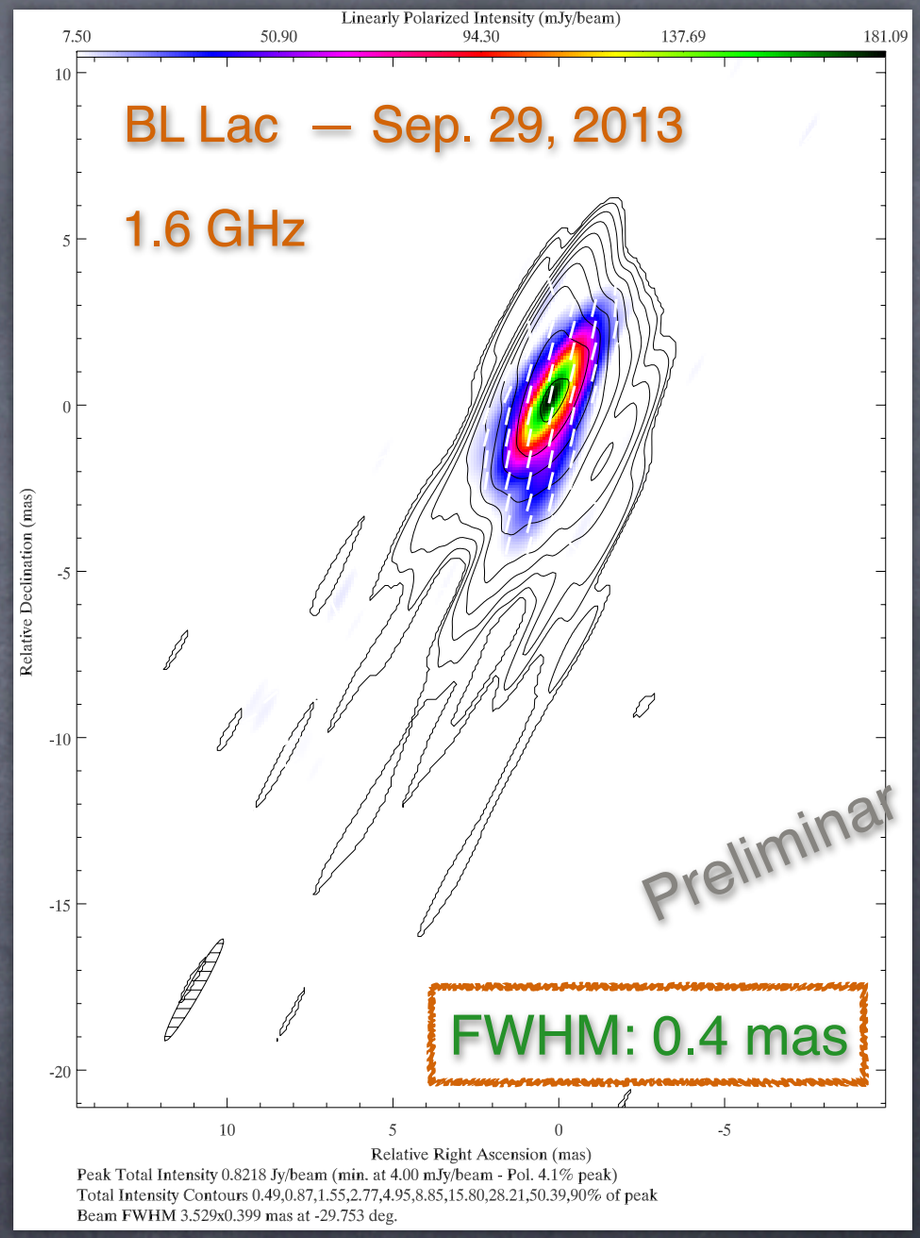

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- Observations of BL Lac at L-band with detections up to 6 D_{Earth}, providing first polarization 1.6 GHz space-VLBI image with 0.4 mas resolution.
- First successful space-VLBI polarimetric observations at 22 GHz, revealing the innermost magnetic field structure in BL Lac with an angular resolution of 33 μas, best to date.

RadioAstron allows polarization imaging with angular resolutions of ≲30 μas

- Preliminary science analysis through comparison with ground observations (BU, MOJAVE). Further comparison with dedicated GMVA observations.