Revealing the Nature of Blazar Radio Cores through Multi-Frequency Polarization Observations with KVN

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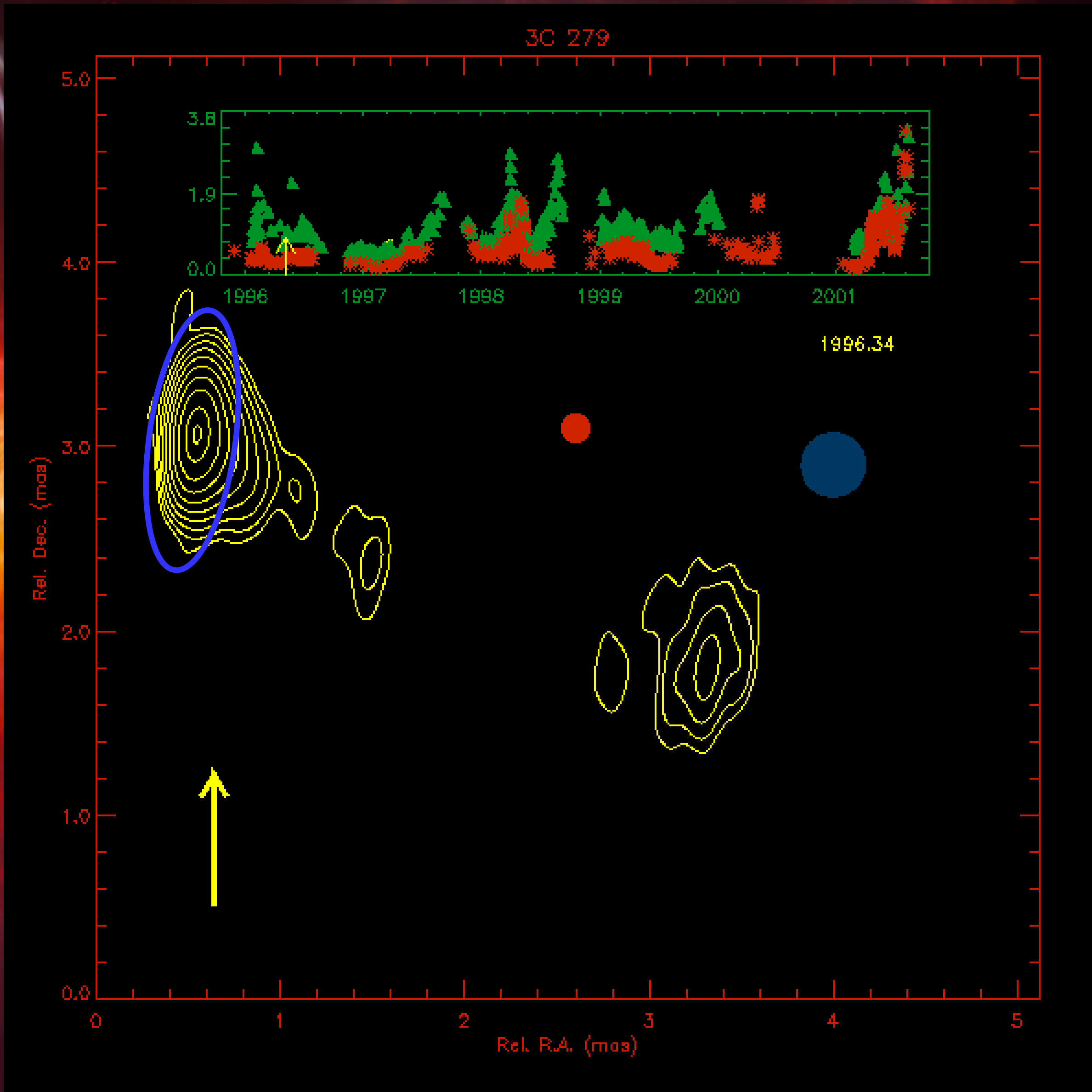
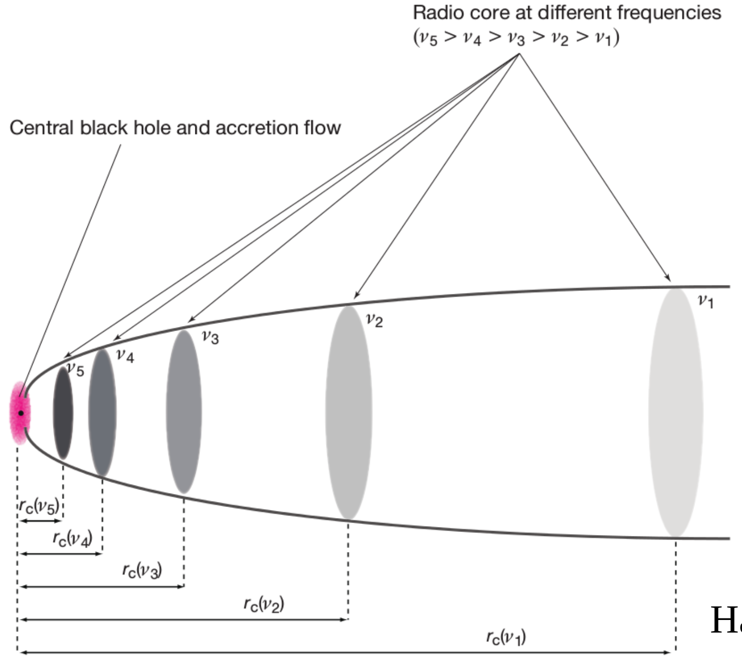
Co-I : Sascha Trippe,
Minchul Kam

Seoul National University



What is the core?

1. τ = 1 surface of the standard Blandford & Konigl (BK) conical jet model

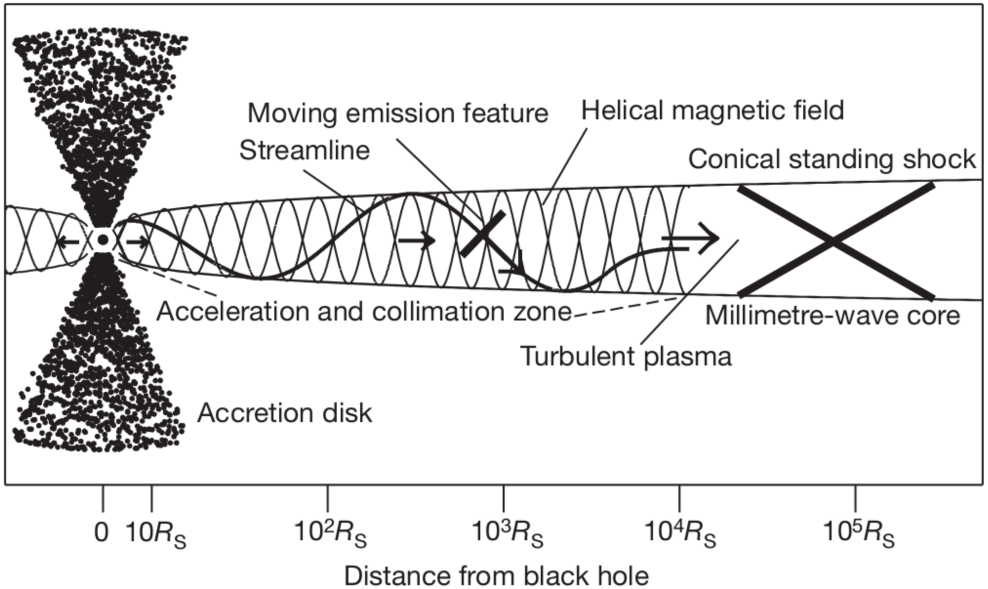


Hada+2011

"Core-shift" effect in AGN Jets

Core-shift effect in blazars has been confirmed by a number of observations at cm wavelengths (e.g., O'Sullivan & Gabuzda 2009).

2. a standing conical (recollimation) shock



Marscher+2008

No core-shift effect expected.
Supported by the coincidence of high-energy flares with the emergence of new jet components (e.g., Jorstad & Marscher 2016).

These apparently contradictory observations are reconciled if the radio core is a recollimation shock upstream of a BK jet that is optically thick at cm wavelengths.

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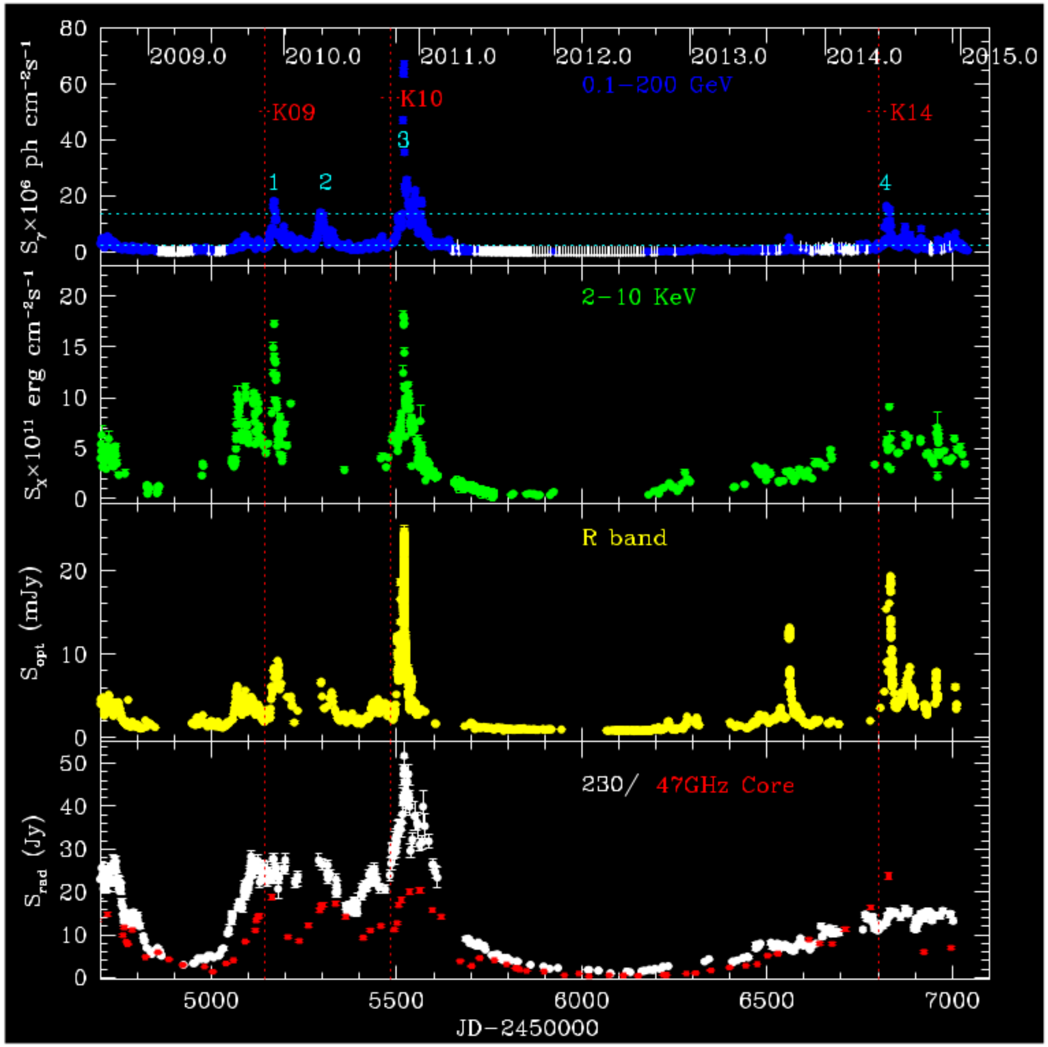

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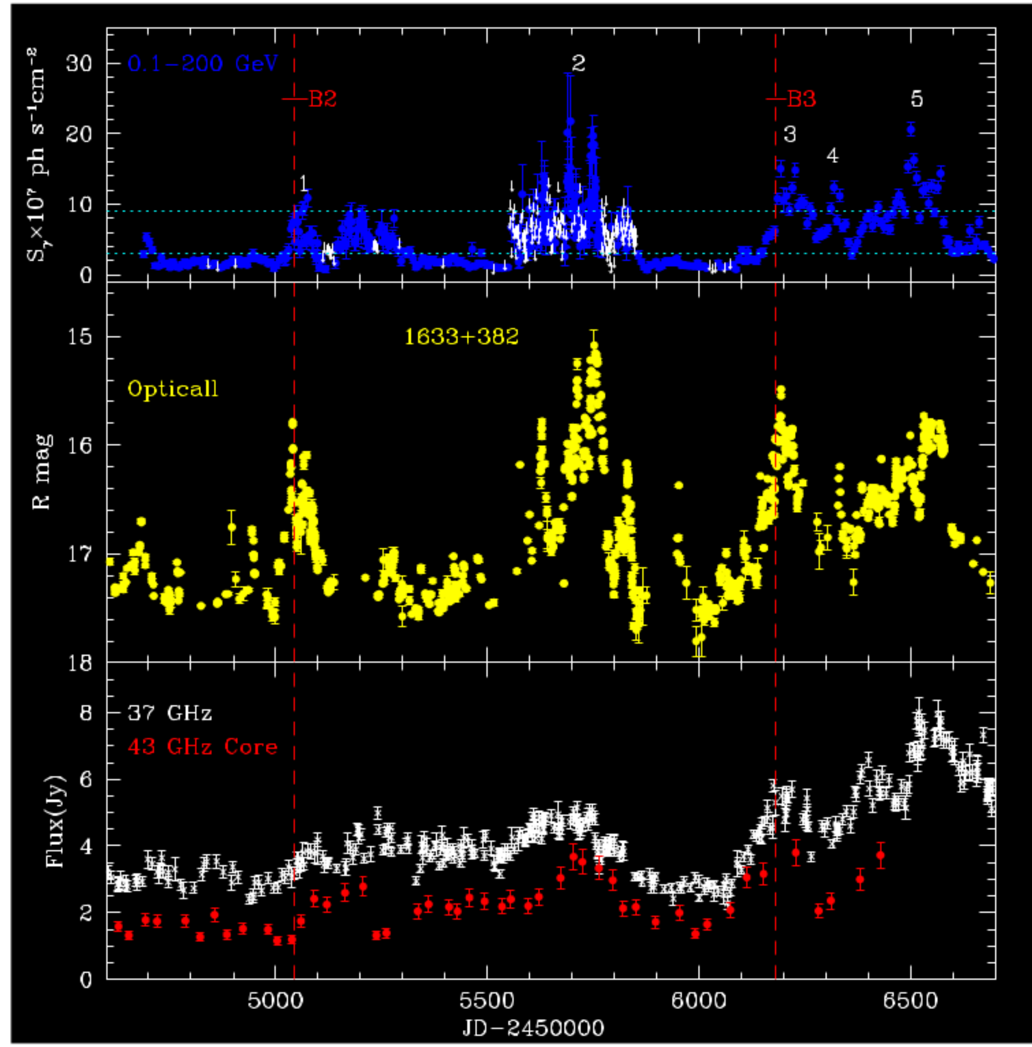

Jorstad & Marscher 2016

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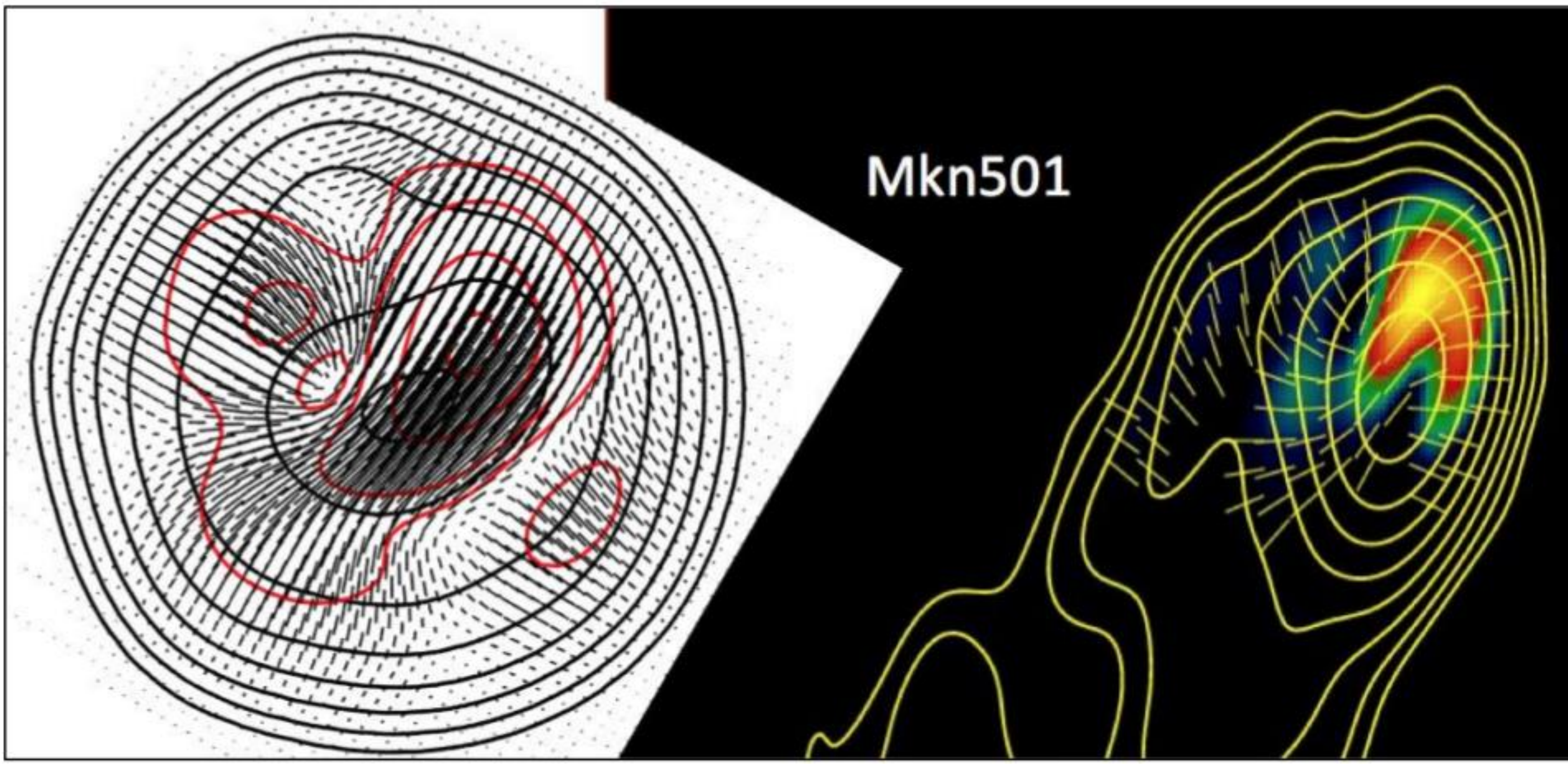
Radio core at different frequencies



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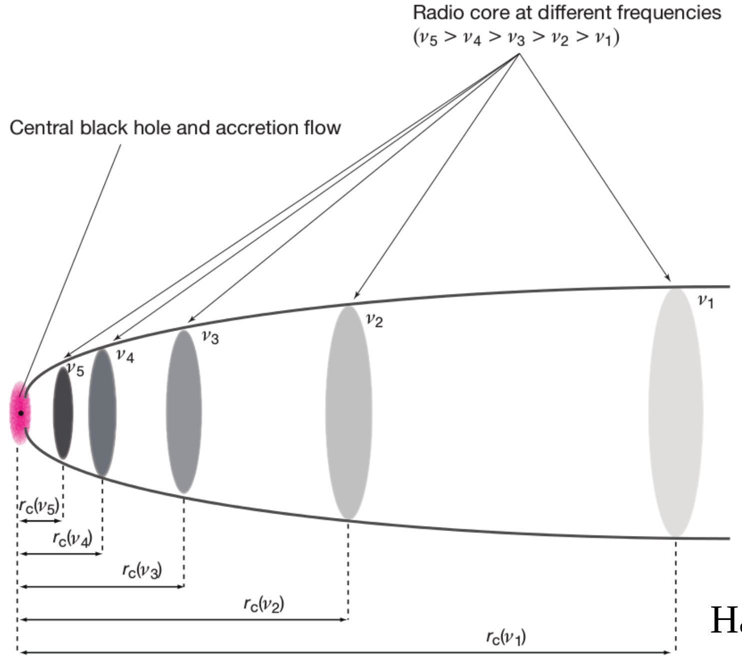

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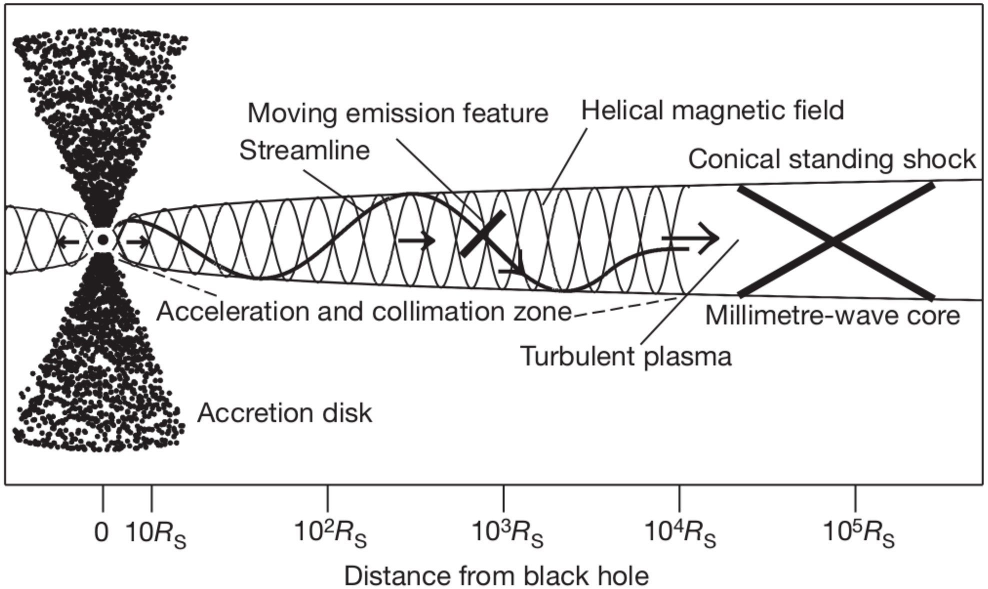

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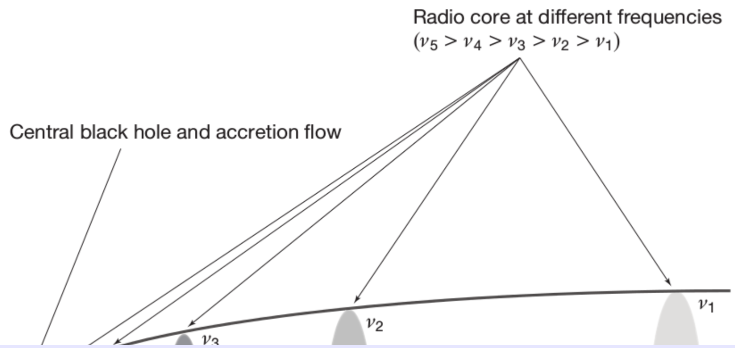

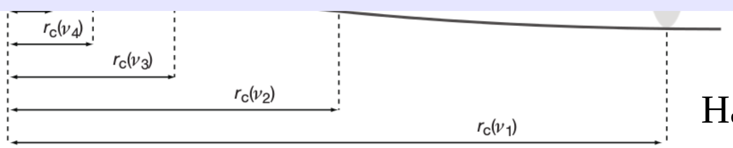

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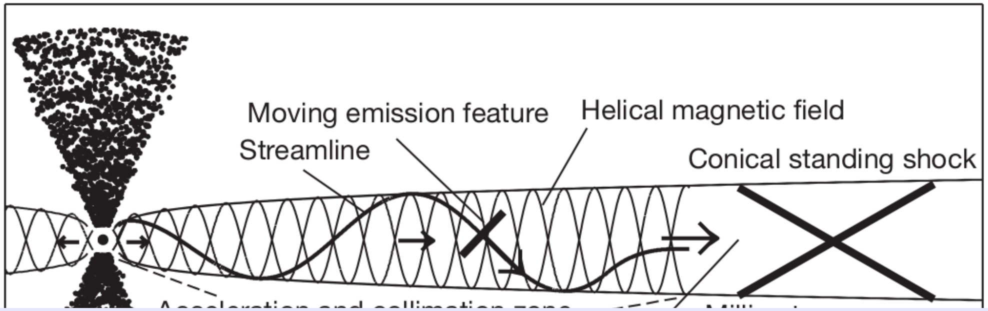

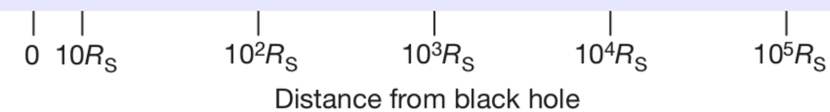

Marscher+2008

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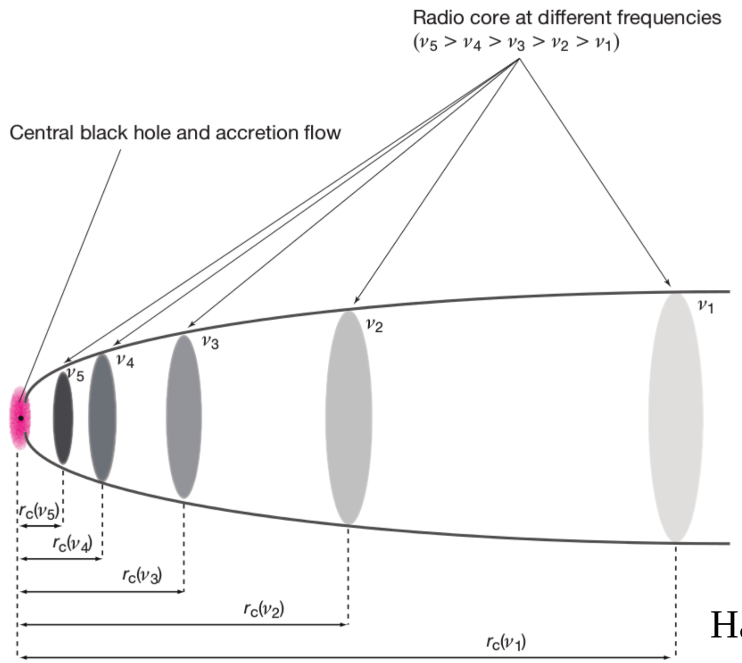
Supported by the coincidence of high-energy flares with the emergence of new jet components (e.g., Jorstad & Marscher 2016).

At which frequency the VLBI cores of blazars are free from opacity effects and can be identified with a standing recollimation shock?

These apparently contradictory observations are reconciled if the radio core is a recollimation shock upstream of a BK jet that is optically thick at cm wavelengths.

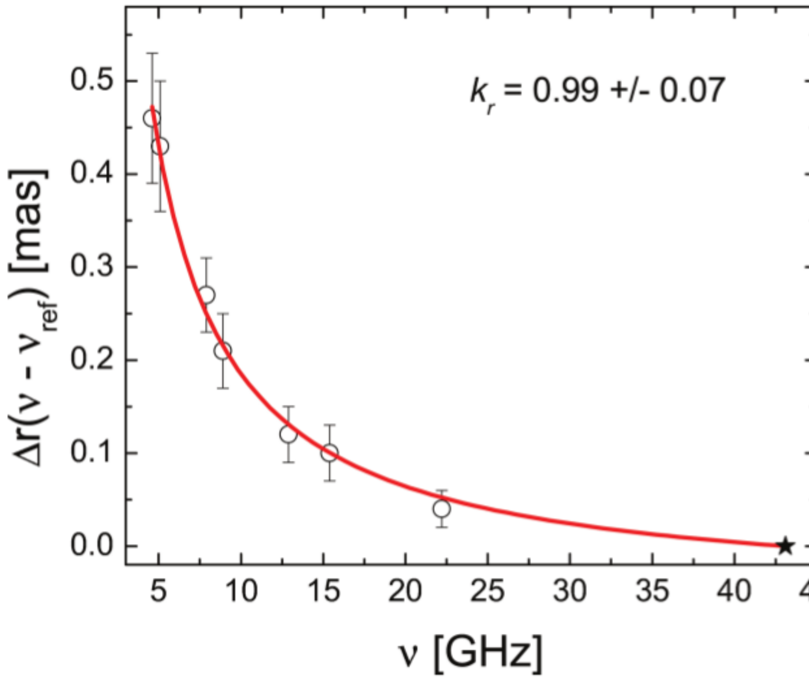
Astrometry : challenging



Hada+2011

$$d_{\mathrm{core},\nu} \propto \nu^{-1}$$

Expected amount of core shift
is already comparable to
astrometric uncertainty at 22 GHz.



ν (GHz)	Δr (mas)	$\Delta r_{\mathrm{projected}}$ (pc)	Fraction of beam (per cent)
4.6	0.46 ± 0.07	0.60 ± 0.09	17
5.1	0.43 ± 0.07	0.56 ± 0.09	17
7.9	0.27 ± 0.04	0.35 ± 0.05	16
8.9	0.21 ± 0.04	0.27 ± 0.05	14
12.9	0.12 ± 0.03	0.16 ± 0.04	11
15.4	0.10 ± 0.03	0.13 ± 0.04	10
22.2	0.04 ± 0.02	0.05 ± 0.03	5

O'Sullivan & Gabuzda 2009

Rotation Measure (RM) of the cores

— Rotation measure in the cores is expected to increase as function of observing frequencies according to :

$$\mathrm{RM} \propto \int N_e B_{\|} dl$$

$$l \propto d$$

↑ Conical geometry

$$N_e \propto d^{-a}$$

$$B_{\|} \propto d^{-1}$$

↑ Dominated by BΦ

Power-law assumption
α = 2 : Conical or Spherical Jets

$$B_z \propto d^{-2} \quad B_\phi \propto d^{-1}$$

Prediction of helical B -field geometry

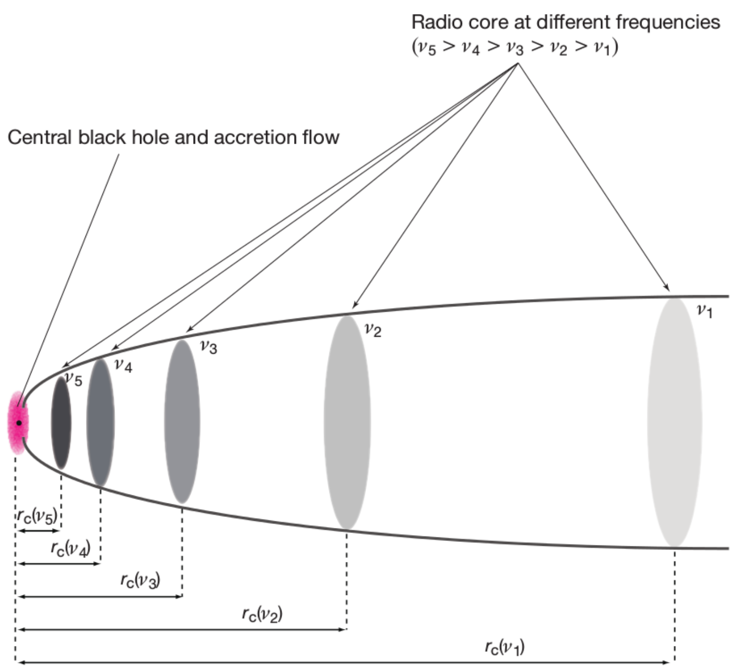
$$\longrightarrow \boxed{|\mathrm{RM}| \propto d^{-a}}$$

If there is no core shift, no frequency dependence of RM is expected!

Jorstad+ 2007

$$d_{\mathrm{core},\nu} \propto \nu^{-1} \longrightarrow \boxed{|\mathrm{RM}_{\mathrm{core},\nu}| \propto \nu^{a}}$$

"Core-shift" effect in AGN Jets



Hada+2011

α = 0.9 ~ 3.8 : Osullivan & Gabuzda 2009 (5-43 GHz)
α ~ 1.8 : Jorstad+ 2007 (8-350 GHz)
α ~ 1.9 : Trippe+ 2012 (86-230 GHz)
α ~ 3.6 : Algaba+ 2013 (12-43 GHz)
α ~ 2.5 : Kravchenko+ 17 (1-15 GHz)
→ all indicates that B-field and particle density becomes higher as one goes into "deep" in the jets at least at ≤ 230 GHz but the number of sources is quite limited.

The frequency dependence of RM continues to mm wavelengths or not?

→ We have launched a KVN large program.

The KVN Large Program

— Cadence : every 1~2 months, depending on KVN's situation

— Observation time : two 24 hour sessions; one for 22/86 GHz, the other for 43/129 GHz

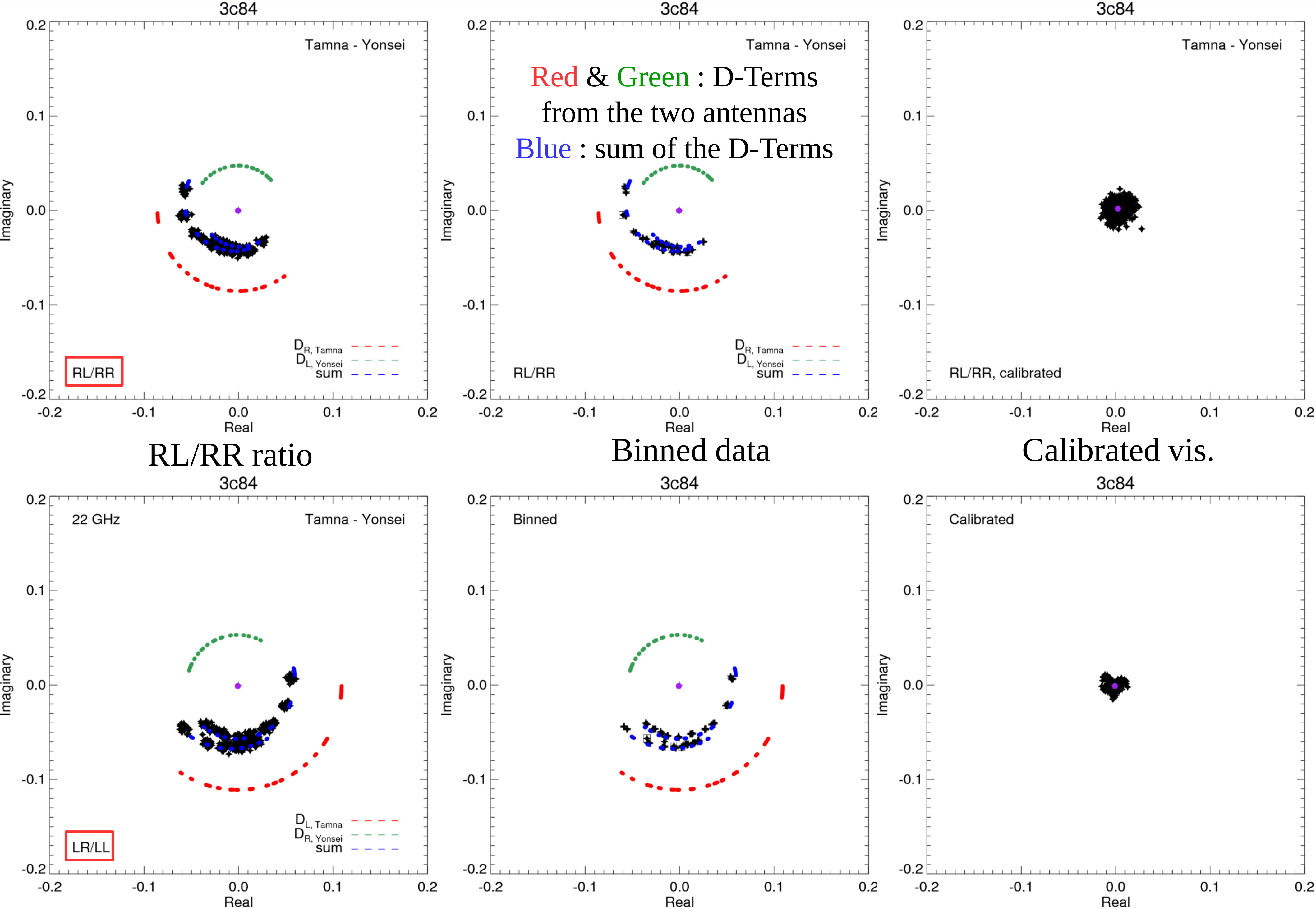
— Source : roughly 10~15 sources.

— Calibration :
D-Term – 3C 84 (very low linear pol.), compact polarized sources such as OJ 287, CTA 102
EVPA correction – using nearby KVN single dish observations of bright, polarized sources.

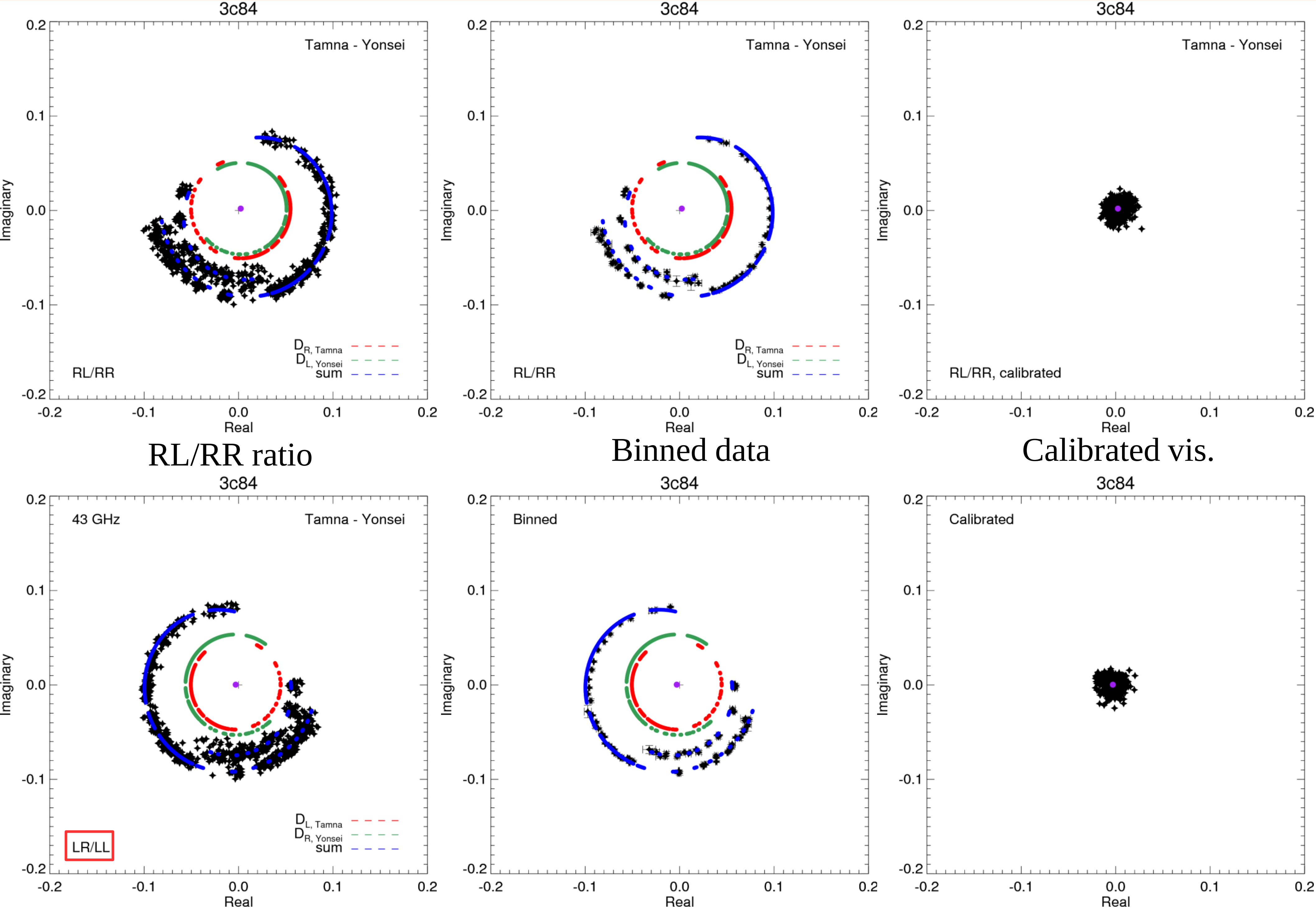
— Early science results : based on the first 3 epochs of the program.

Date	Source	Freq.	D-Term	EVPA
2016 Dec 09-10	3C 273, 3C 279, 3C 454.3, 3C 84, 3C 345, CTA 102, OJ 287, 1510-089, 1749+096	22/86, 43/86 (No 129)	3C 84, OJ 287	3C 279, OJ 287 ($\Delta\chi \approx 2$ deg)
2017 Jan 16-17	3C 273, 3C 279, 3C 454.3, 3C 84, 3C 345, CTA 102, OJ 287	22/86, 43/129	3C 84, OJ 287 CTA 102	3C 279, OJ 287 ($\Delta\chi \approx 2$ deg)
2017 Mar 22-24	3C 273, 3C 279, 3C 454.3, 3C 84, BL Lac, OJ 287, 0235+164, 1055+018	22/86, 43/129	3C 84, OJ 287, 3C 454.3	3C 279, 3C 273, OJ 287, 3C 454.3 ($\Delta\chi \approx 3$ deg)

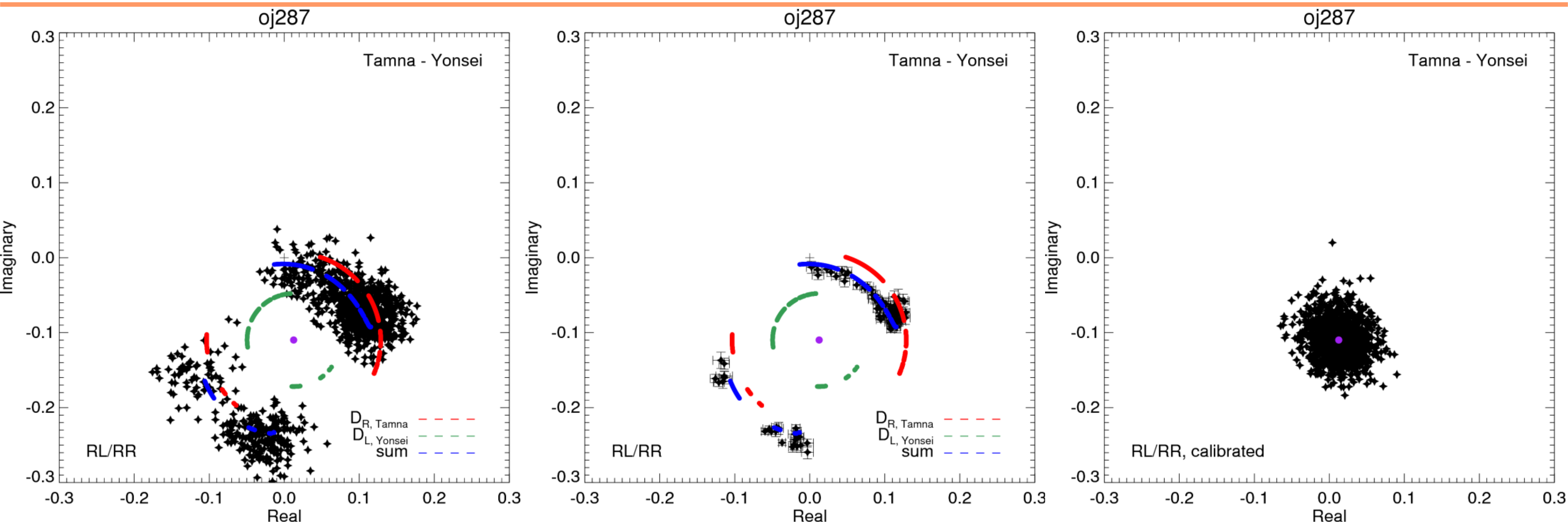
D-Term correction results : 22 GHz, 3C 84



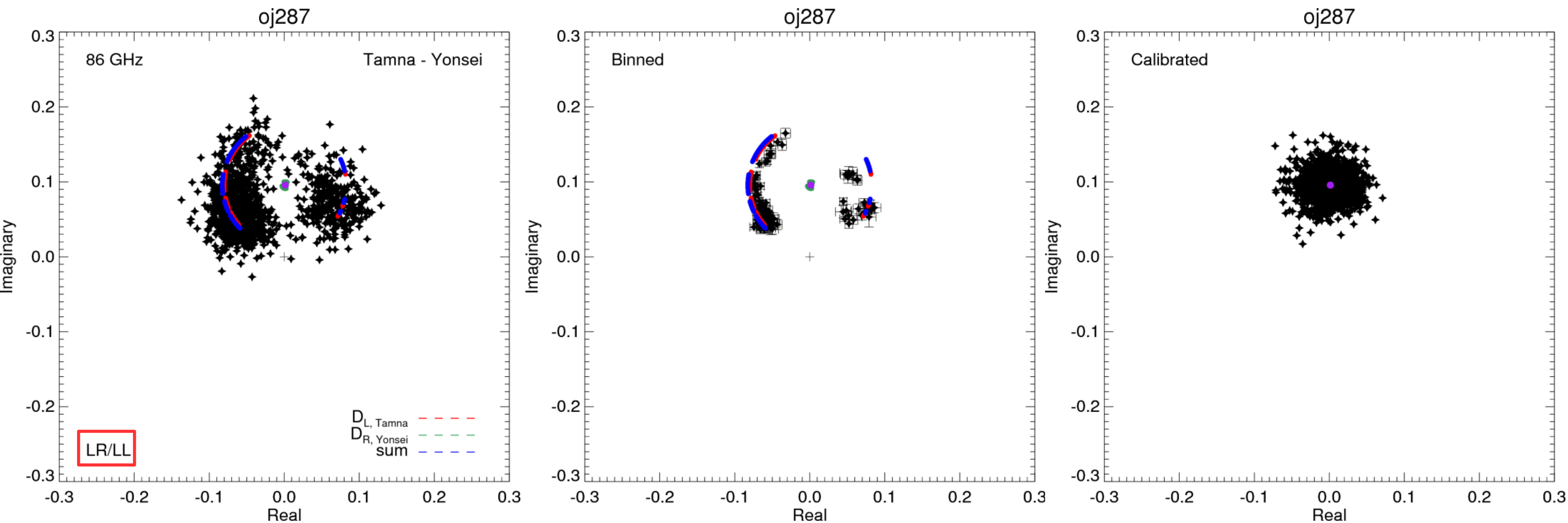
D-Term correction results : 43 GHz, 3C 84



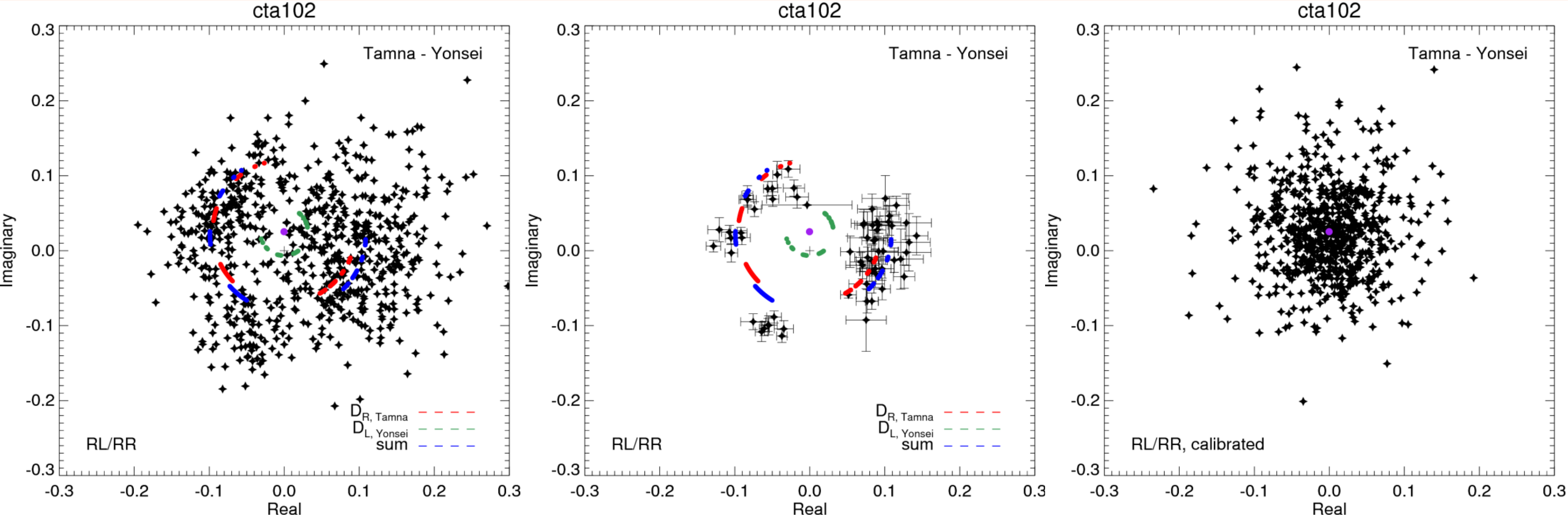
D-Term correction results : 86 GHz, OJ 287



RL/RR ratio | Binned data | Calibrated vis.



D-Term correction results : 129 GHz, CTA 102



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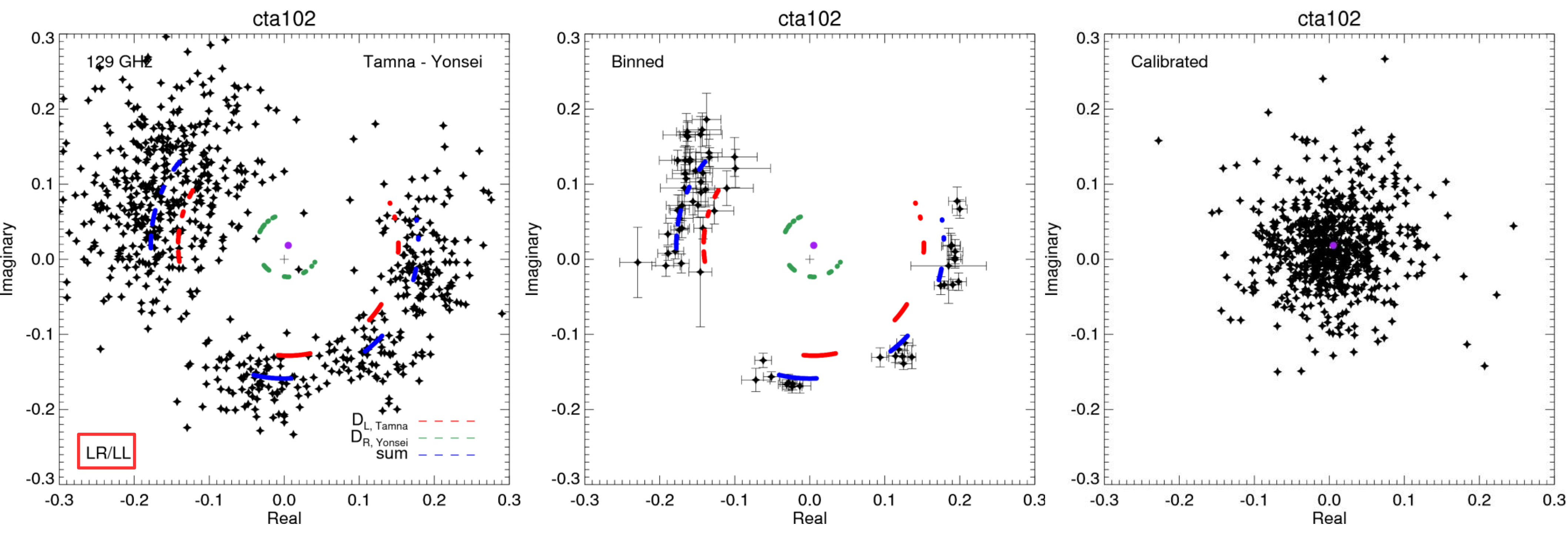
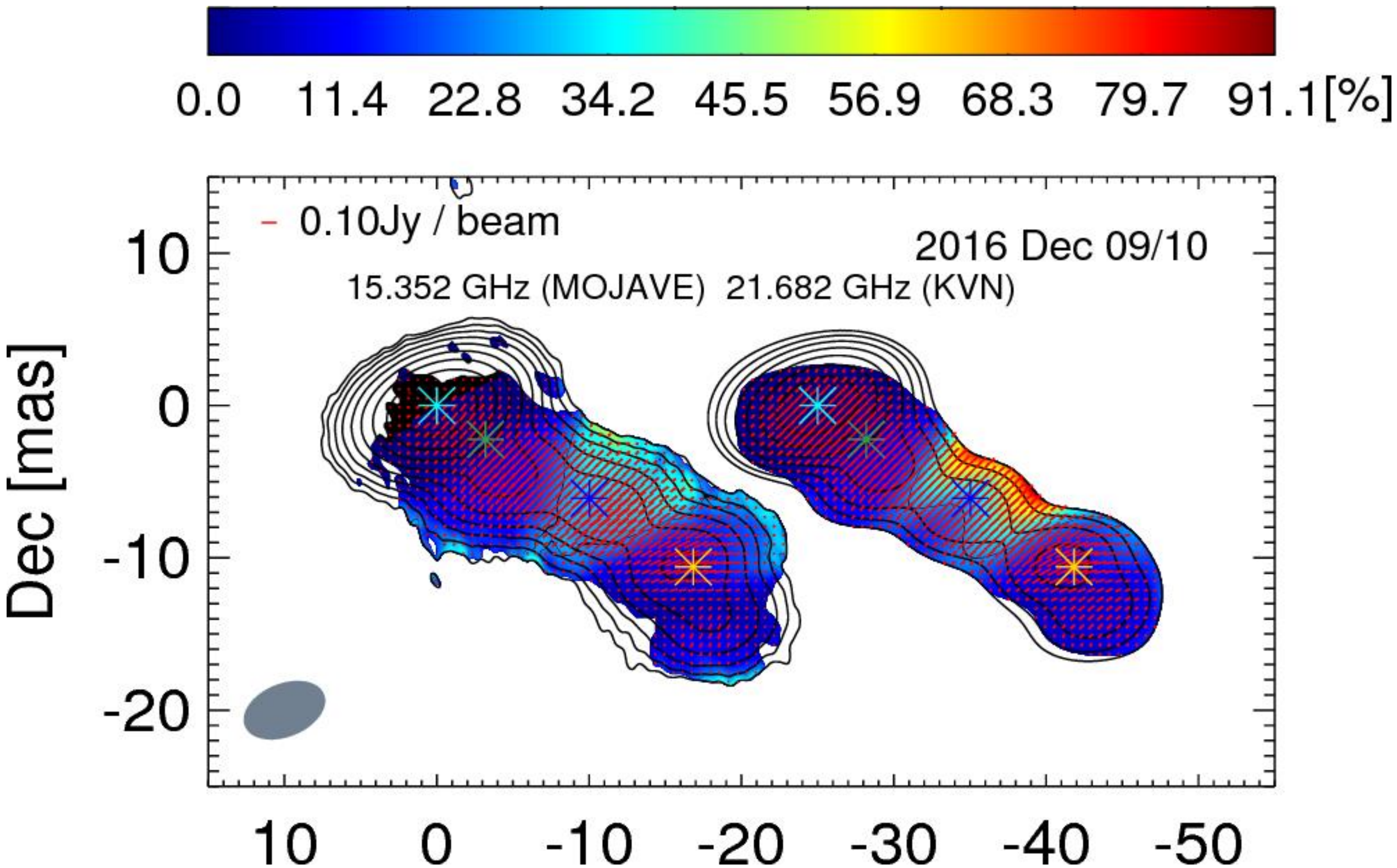


Reliability check – comparison with contemporaneous MOJAVE / BU data



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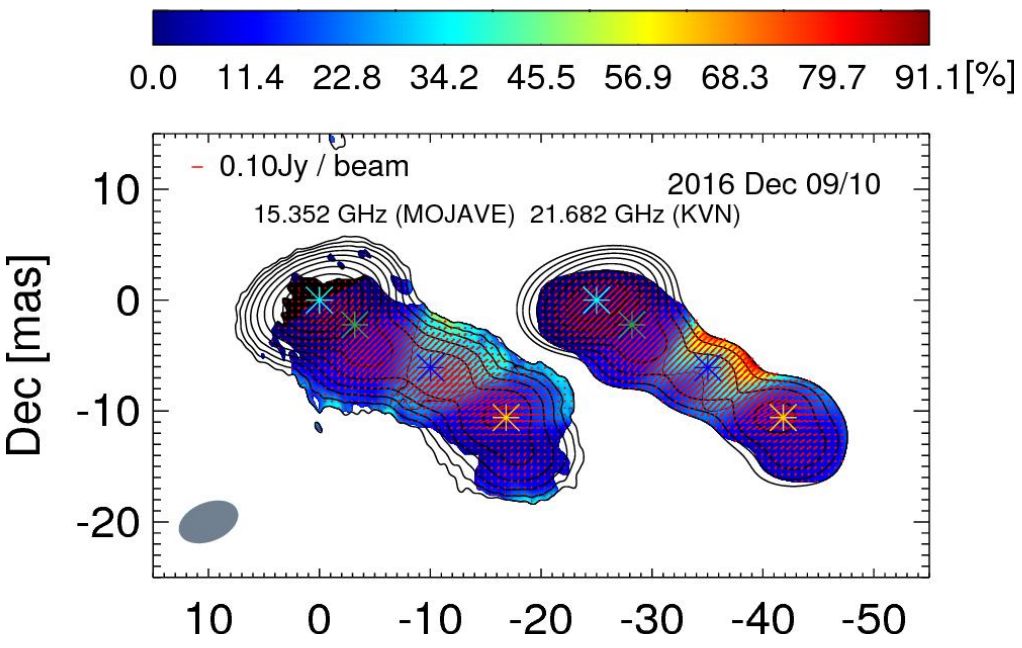

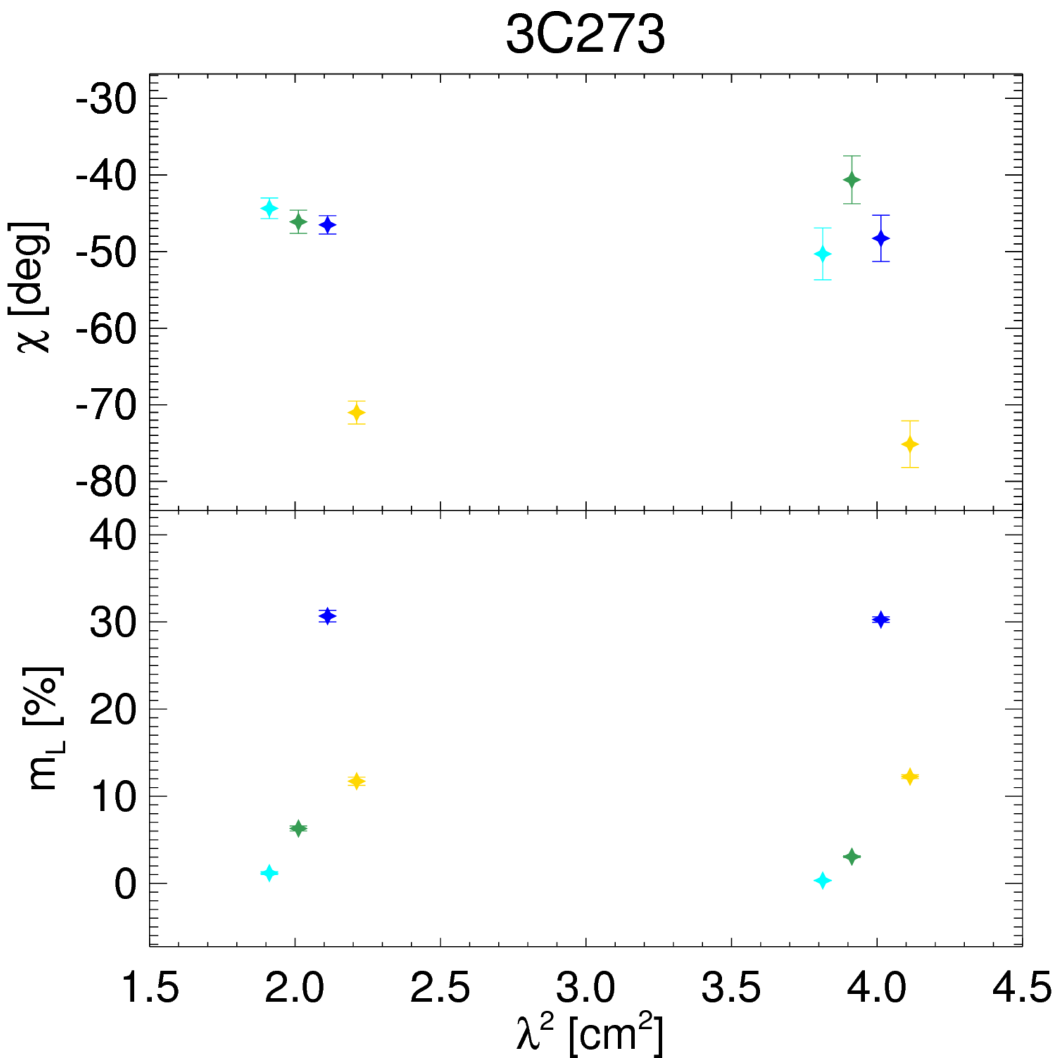

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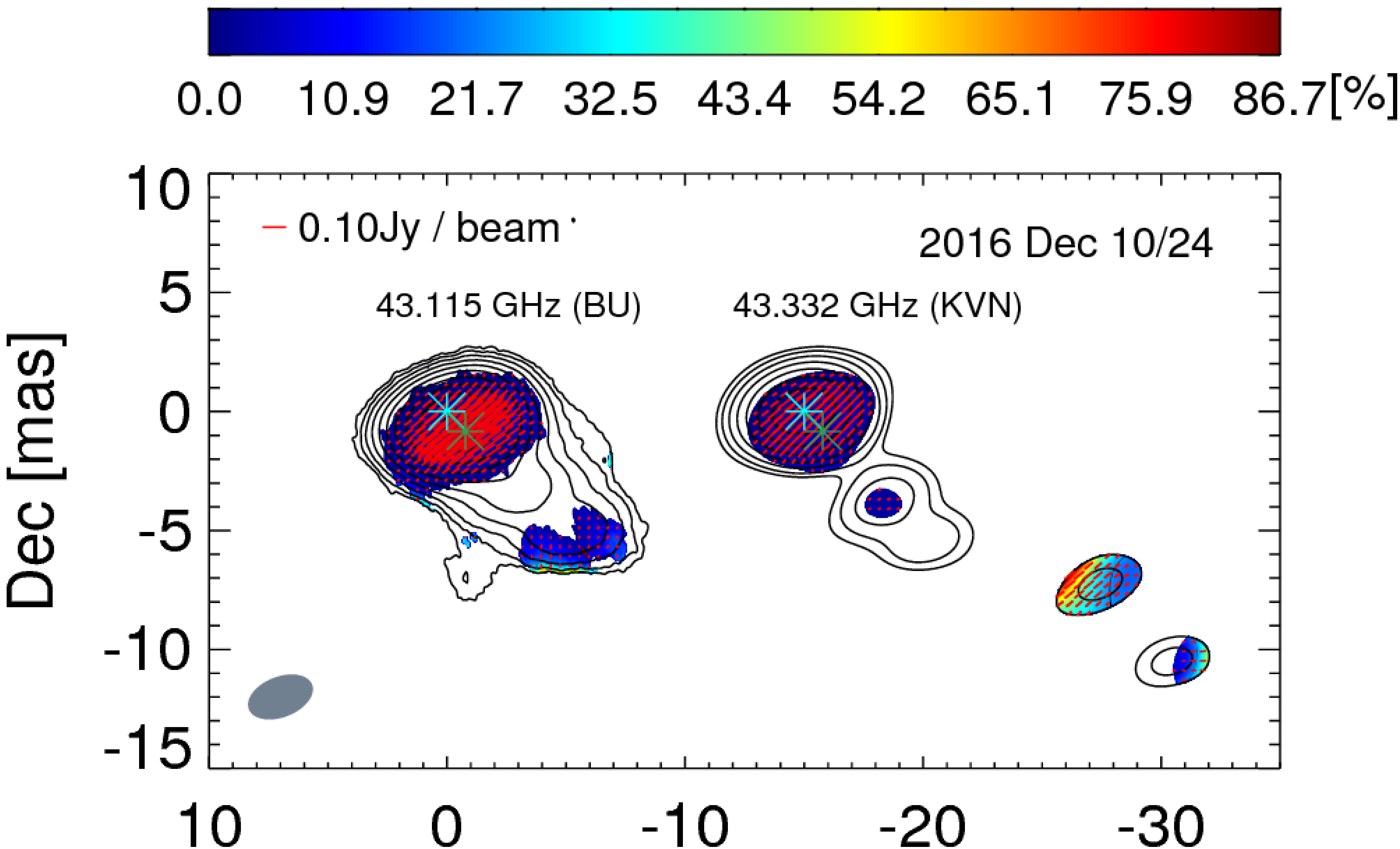

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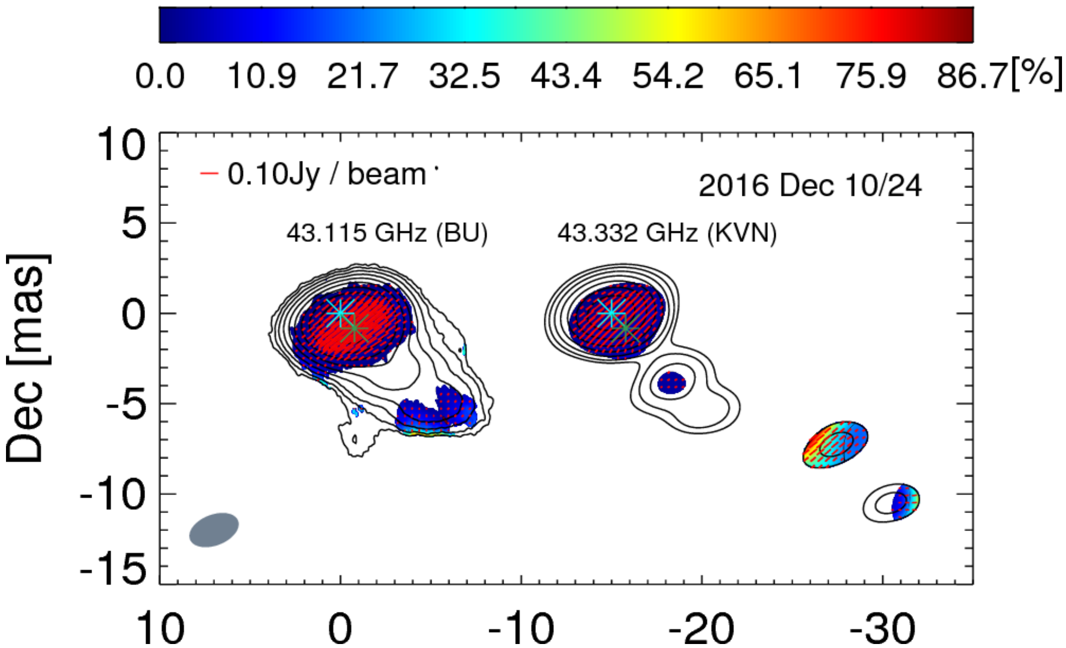
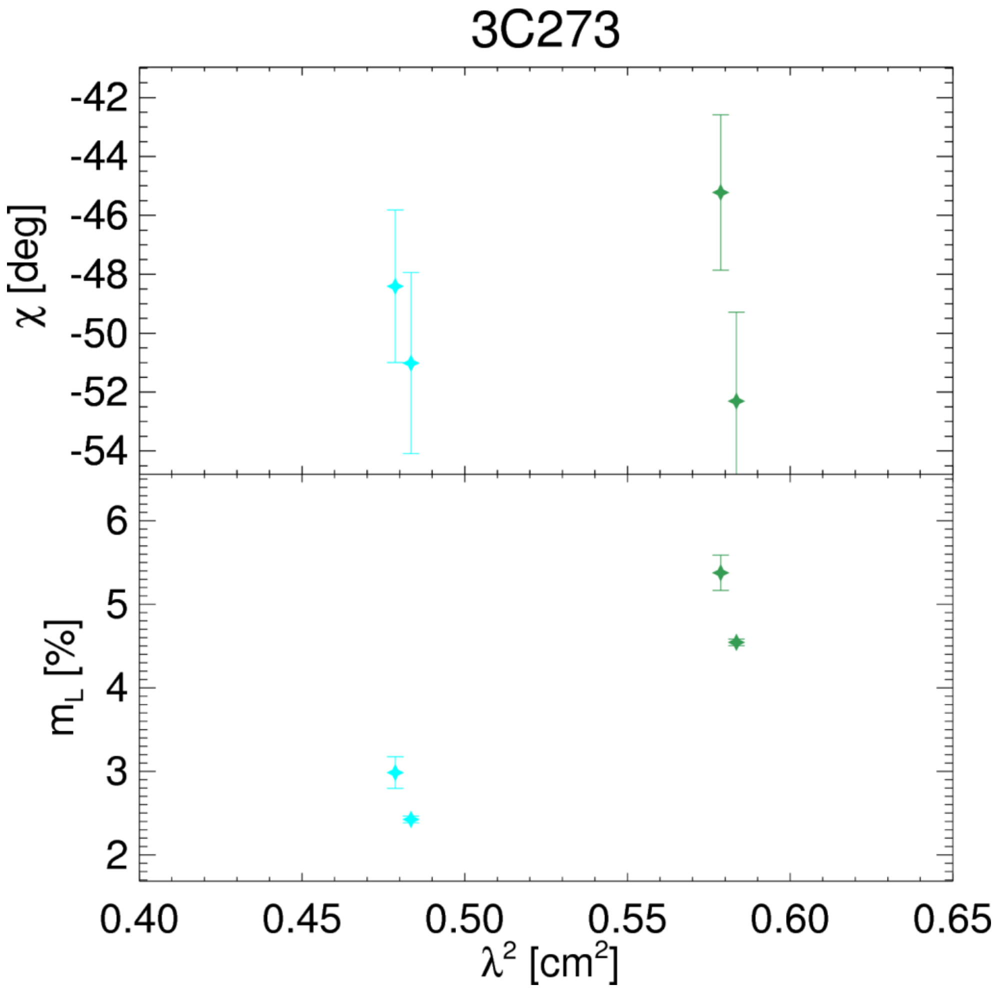
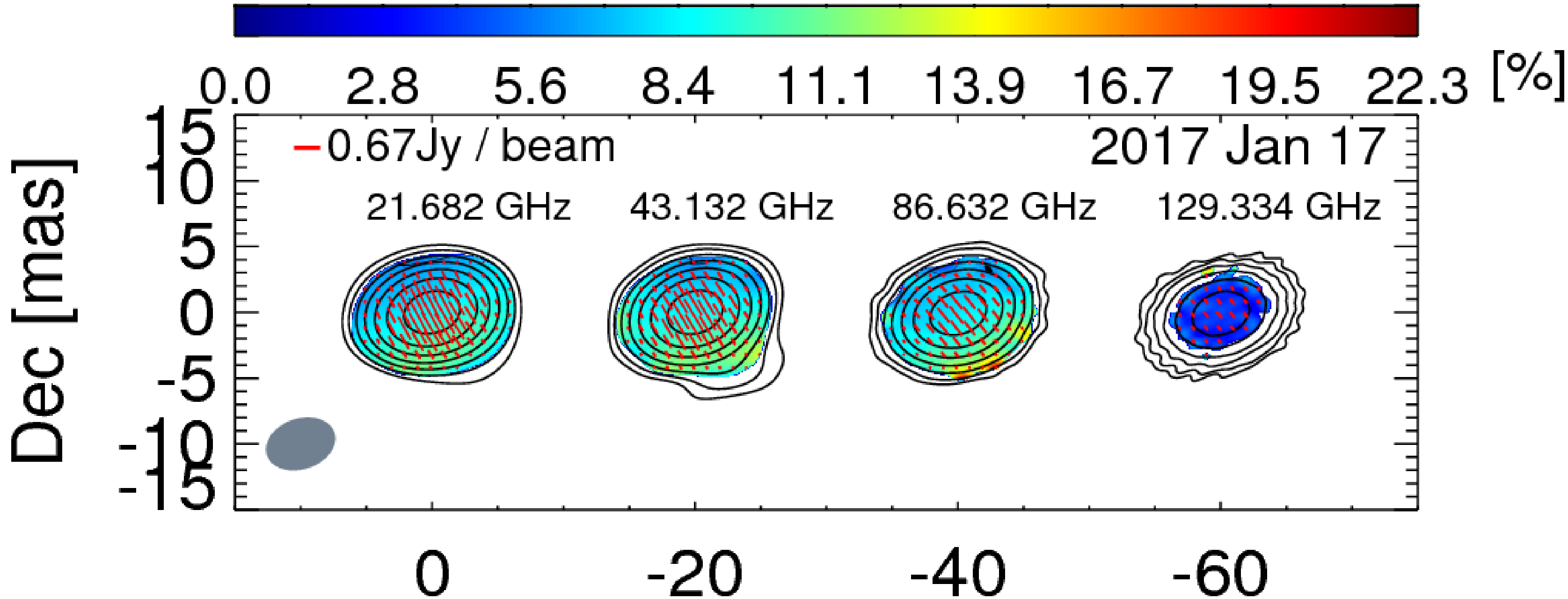
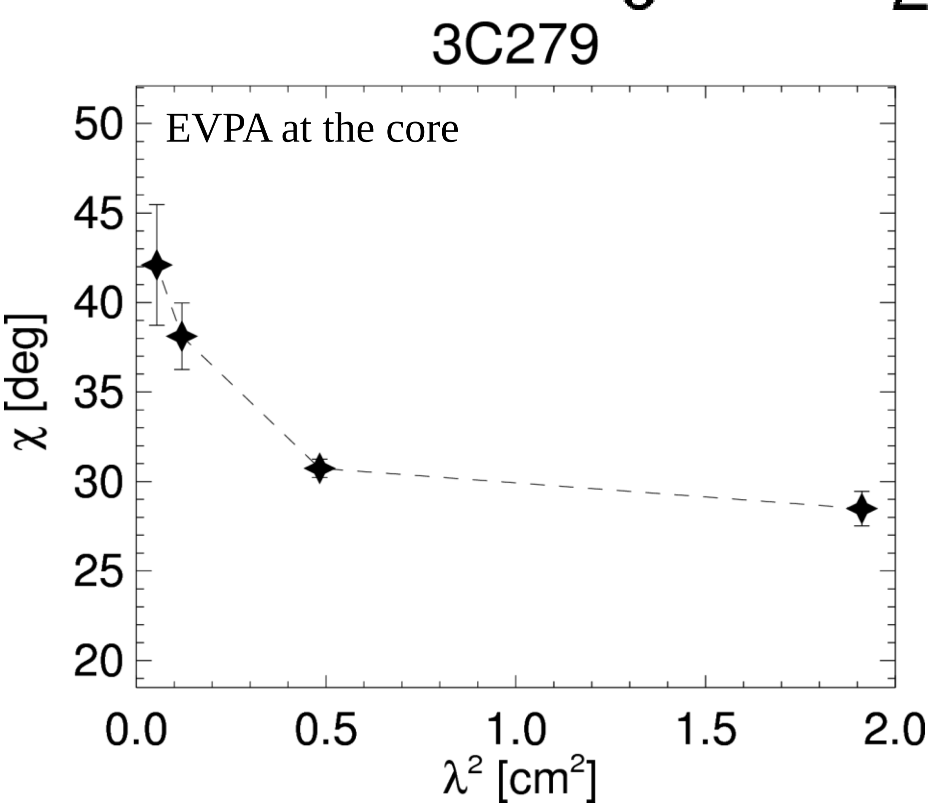
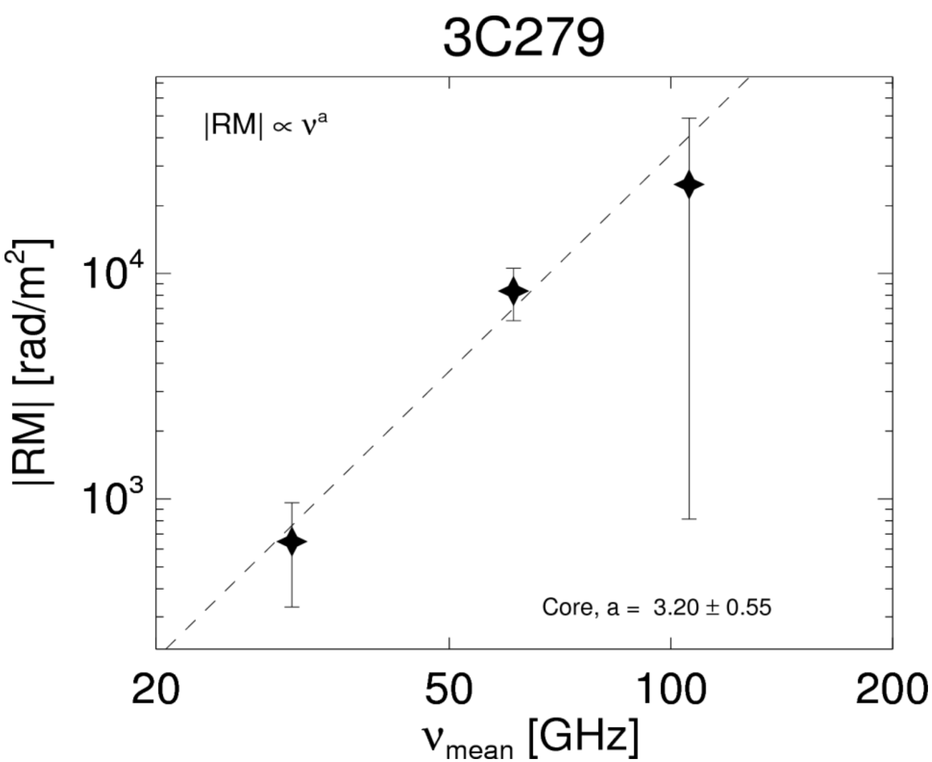




Polarization maps of representative sources







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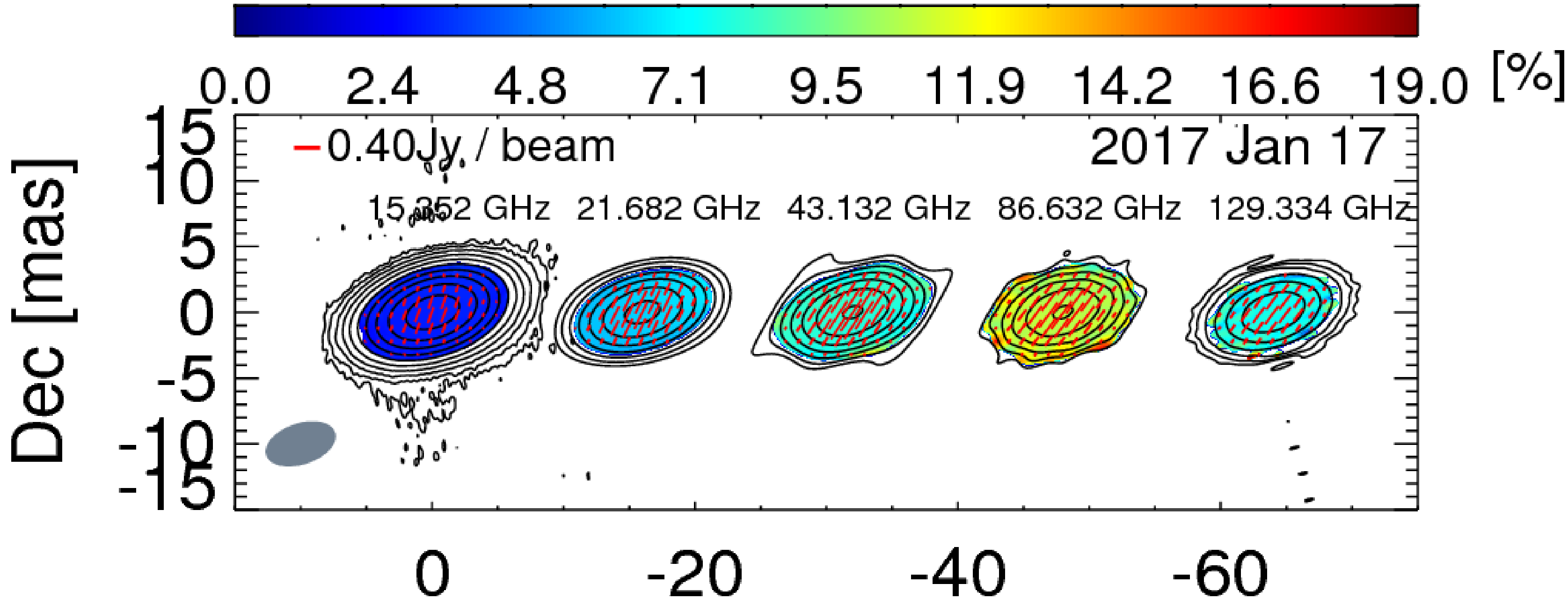

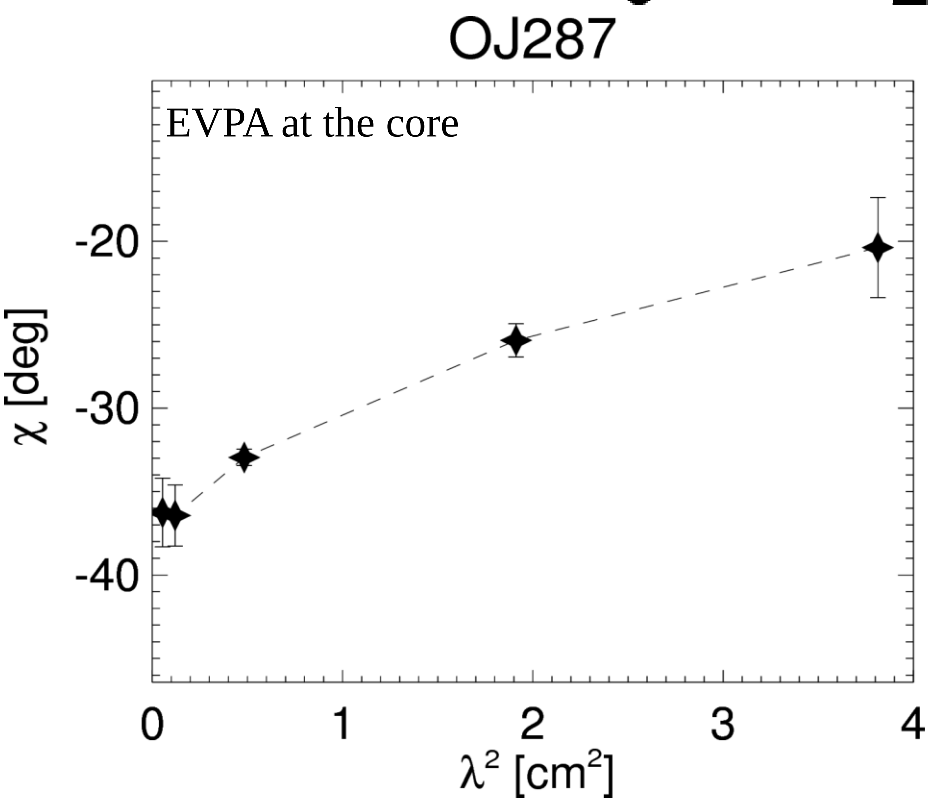

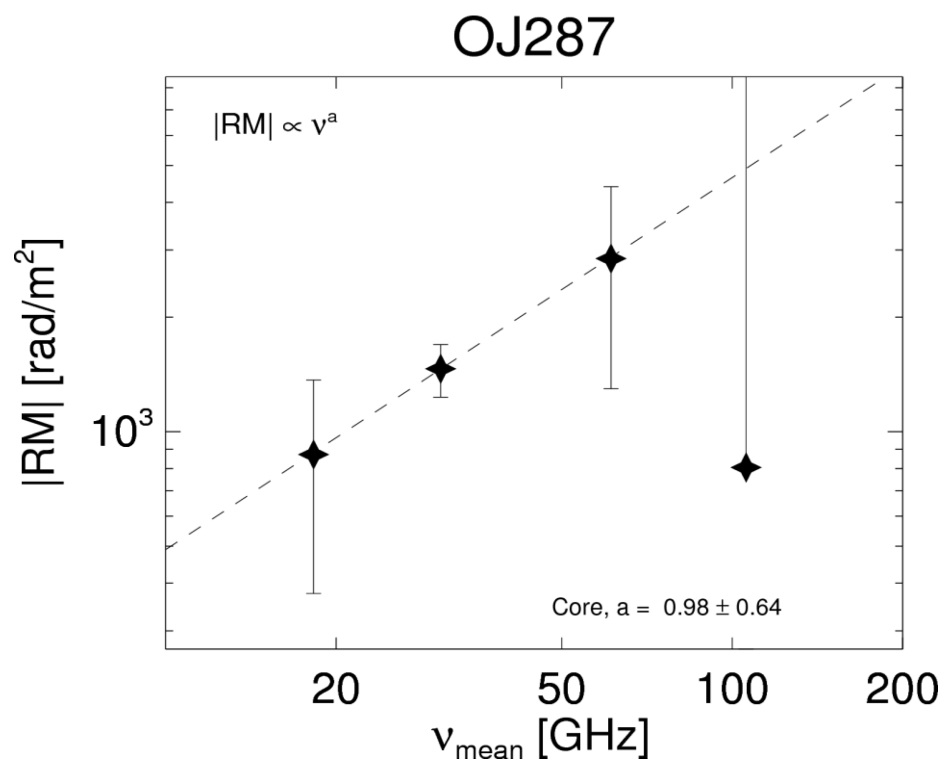

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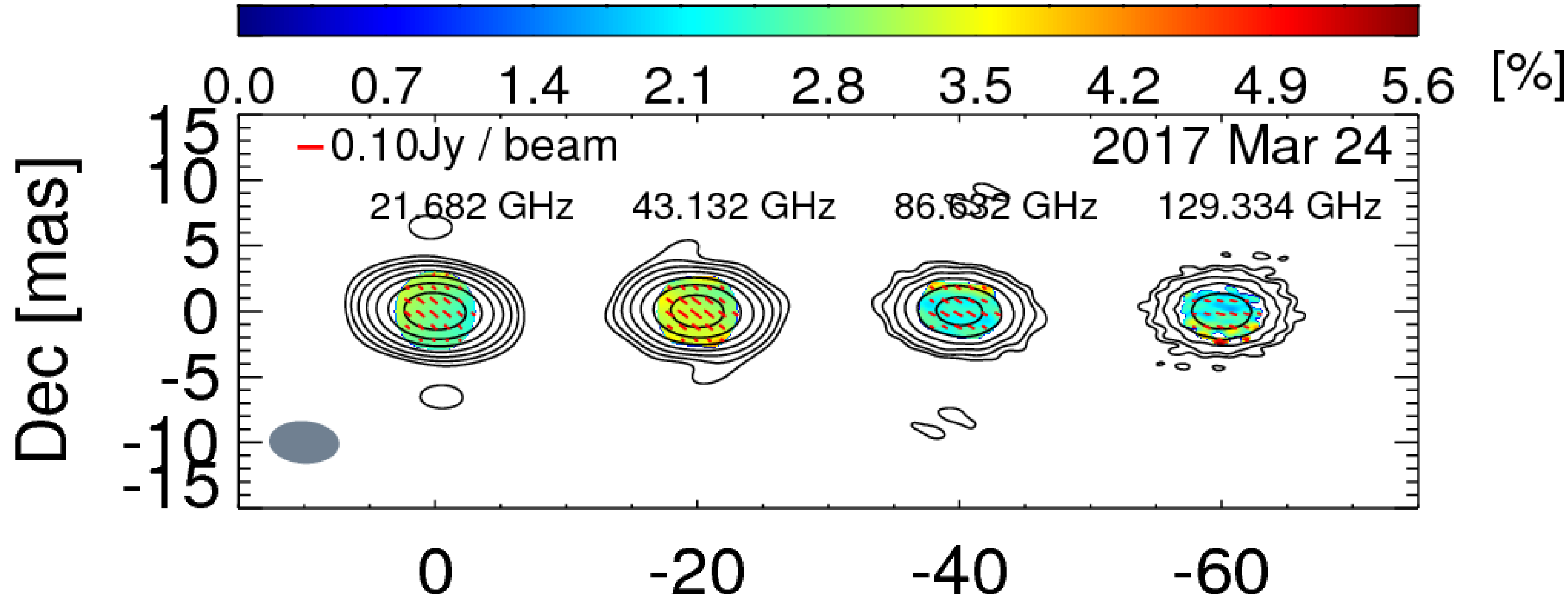
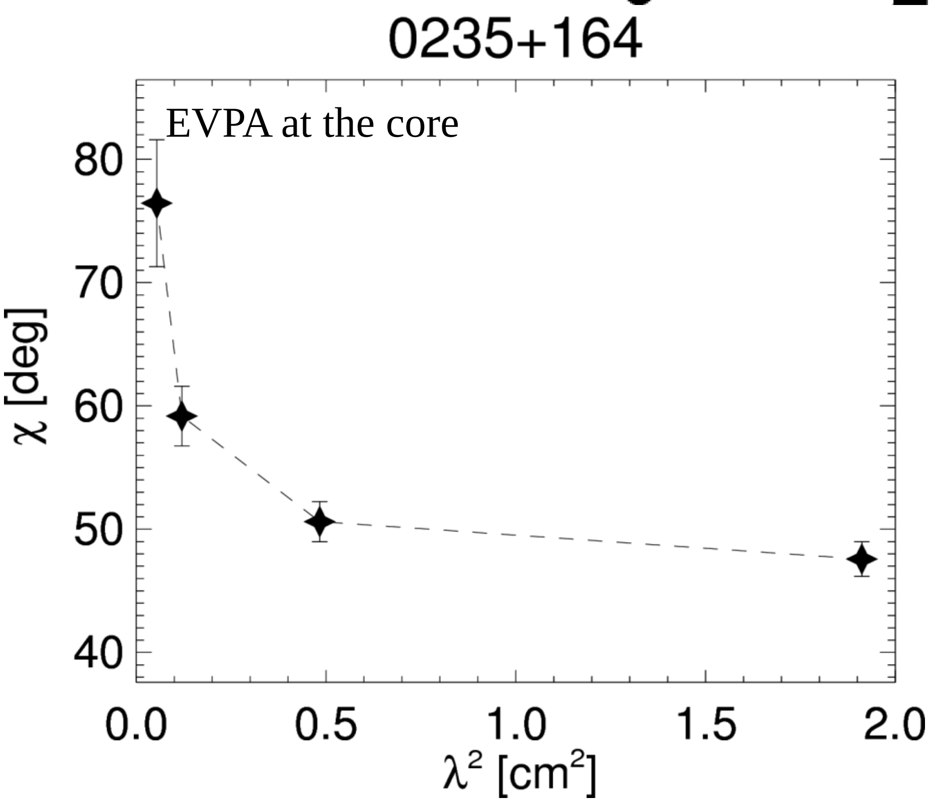
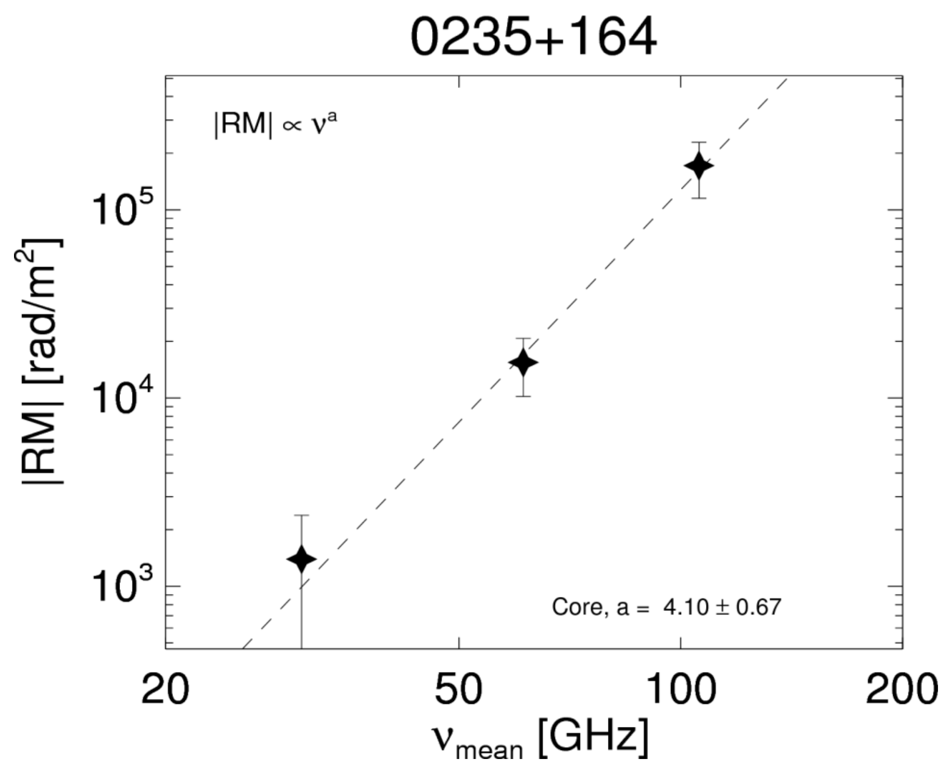
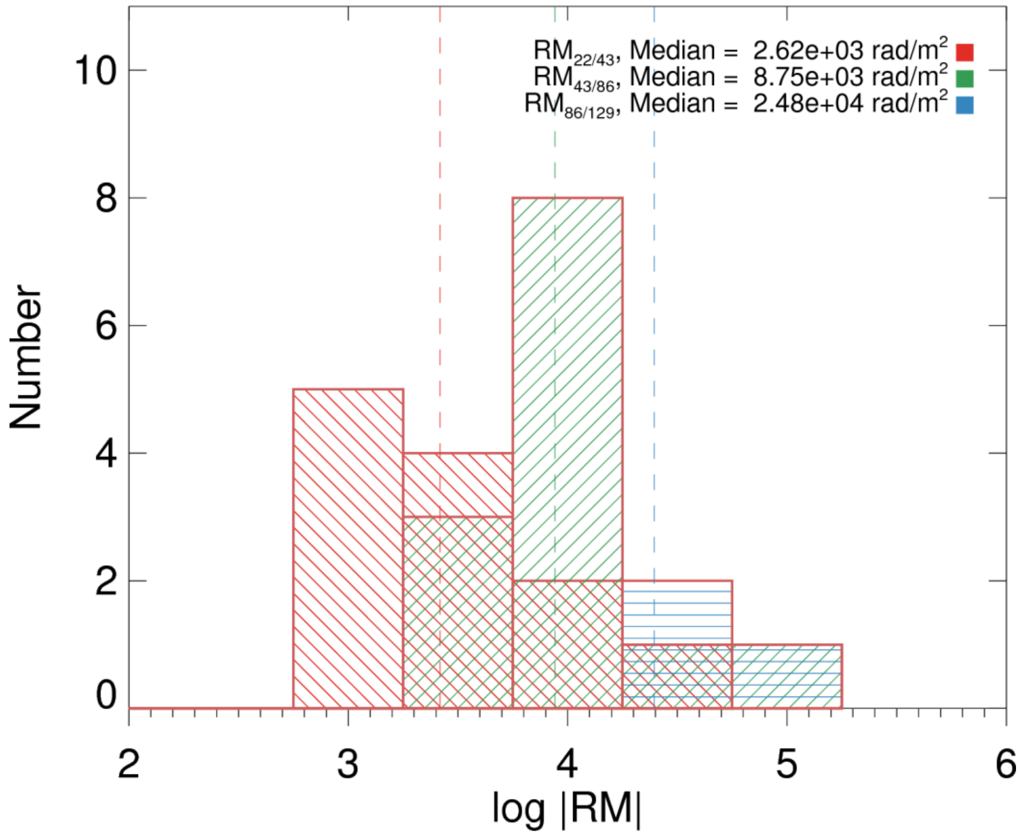
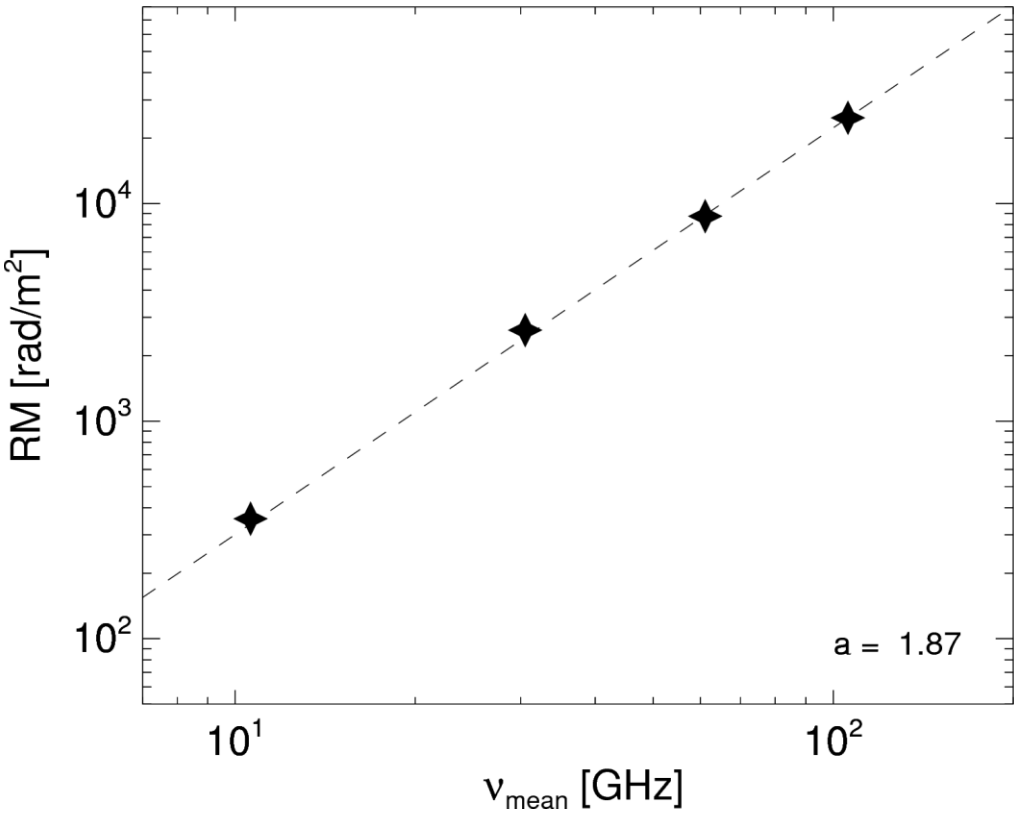






Discussion – 1. RM distributions with different frequency pairs

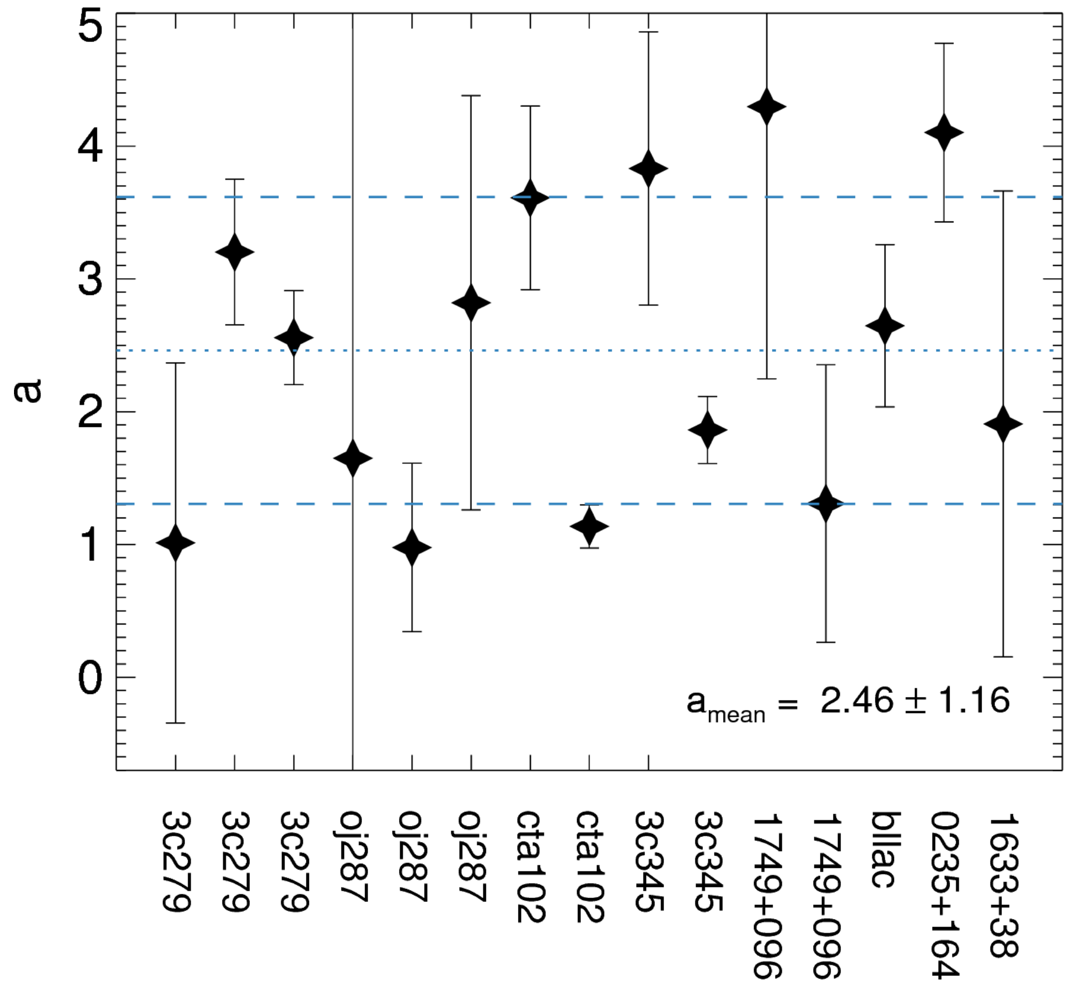




– We excluded the sources which might be contaminated by the polarized emission from inner jets based on recent BU maps.

– Though it is low number statistics, RMs increase with higher frequency pairs statistically with the power-law index of ~2.

Discussion – 2. α distribution

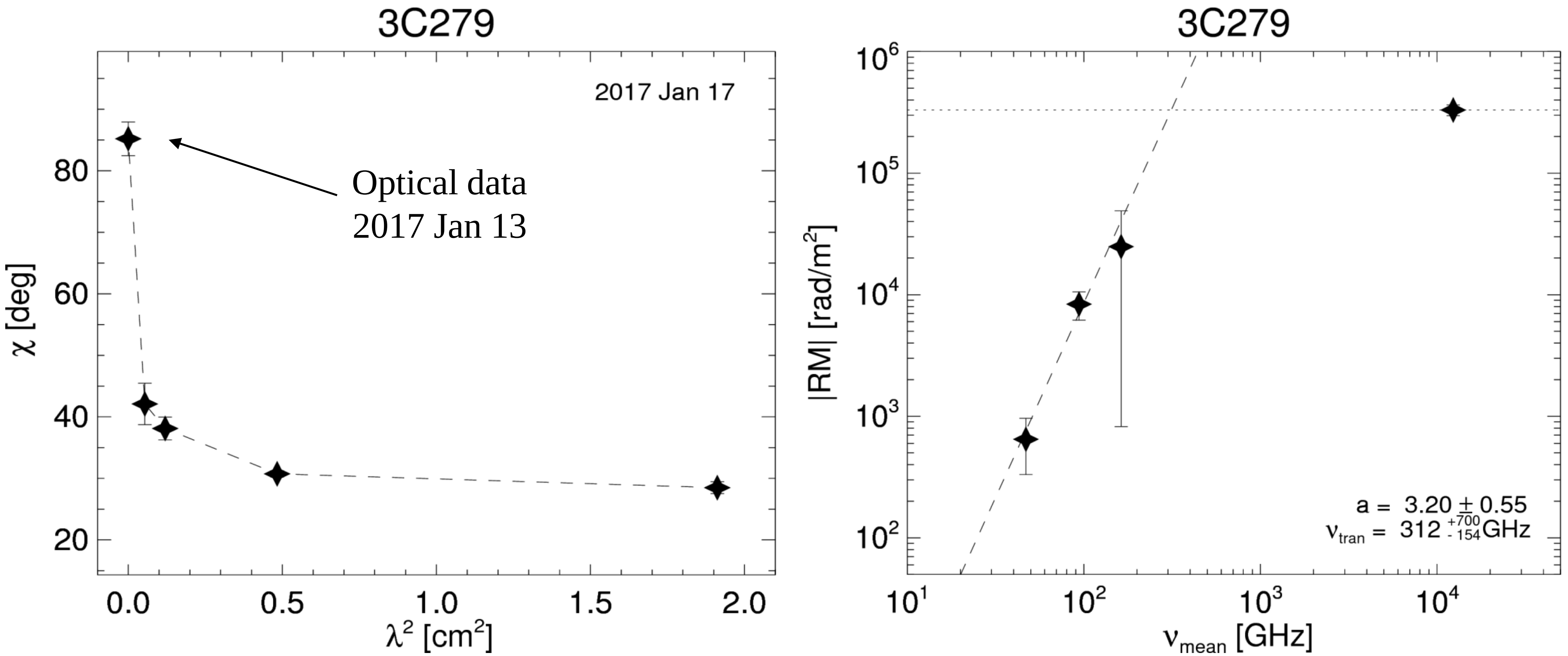


– The power-law indices of individual sources are distributed around 2 with the mean and standard deviation 2.46 ± 1.16.

→ in good agreement with conically expanding jet sheath being a source of the observed Faraday rotation.

– Different a values of different sources might be related to different jet geometry, different magnetic field configuration, etc.

Discussion — 3. transition frequency of RM dependence on ν



— We employed the public optical polarization data provided by the Steward observatory.

— We assumed that the direction of EVPA rotation at optical wavelength is the same as at radio frequencies.

— We also assumed that there is no EVPA rotation larger than pi between optical and radio.

— We obtained the frequency at which the power-law increase of RMs at mm wavelengths is expected to be saturated. We call it ν_{trans} (transition to completely optically thin).

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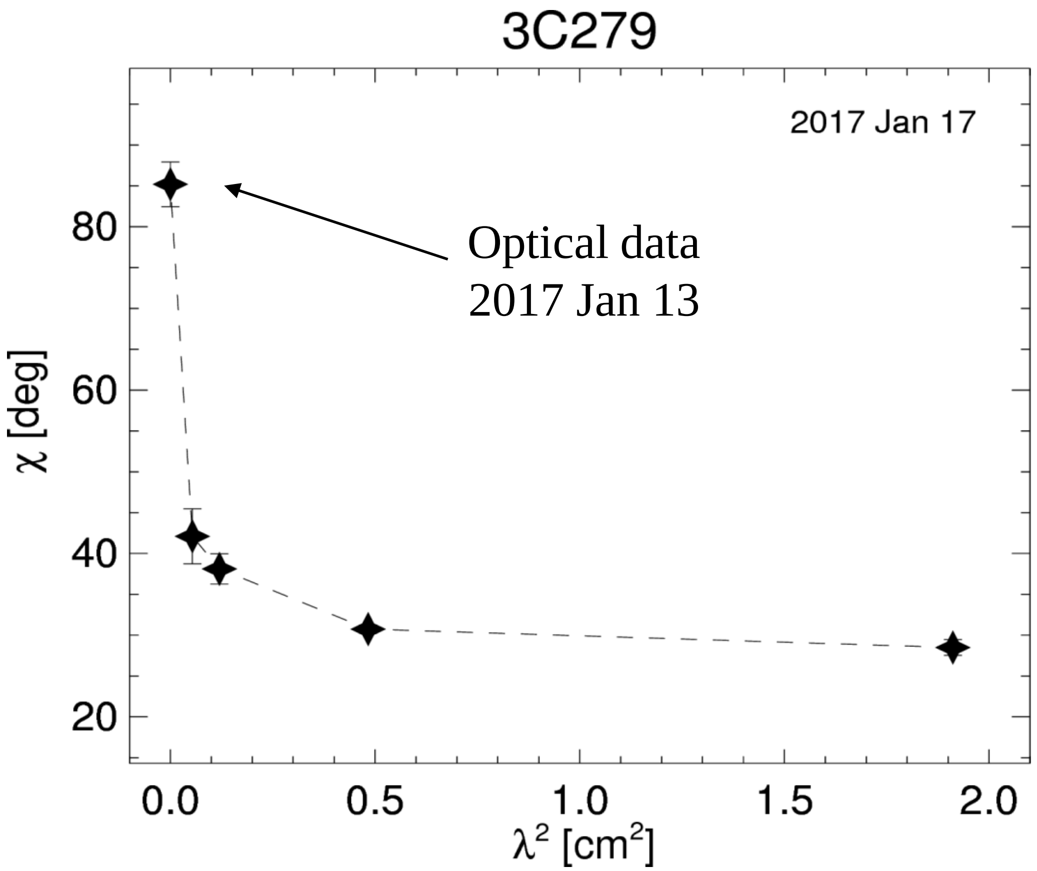

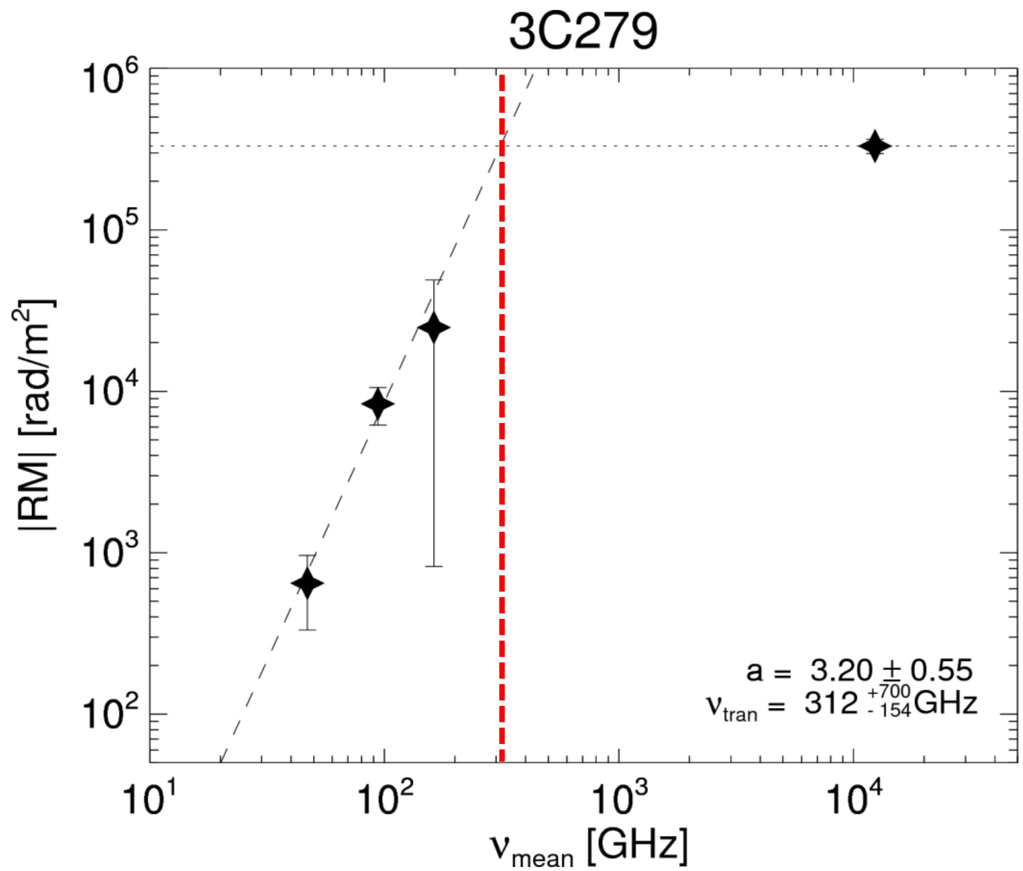

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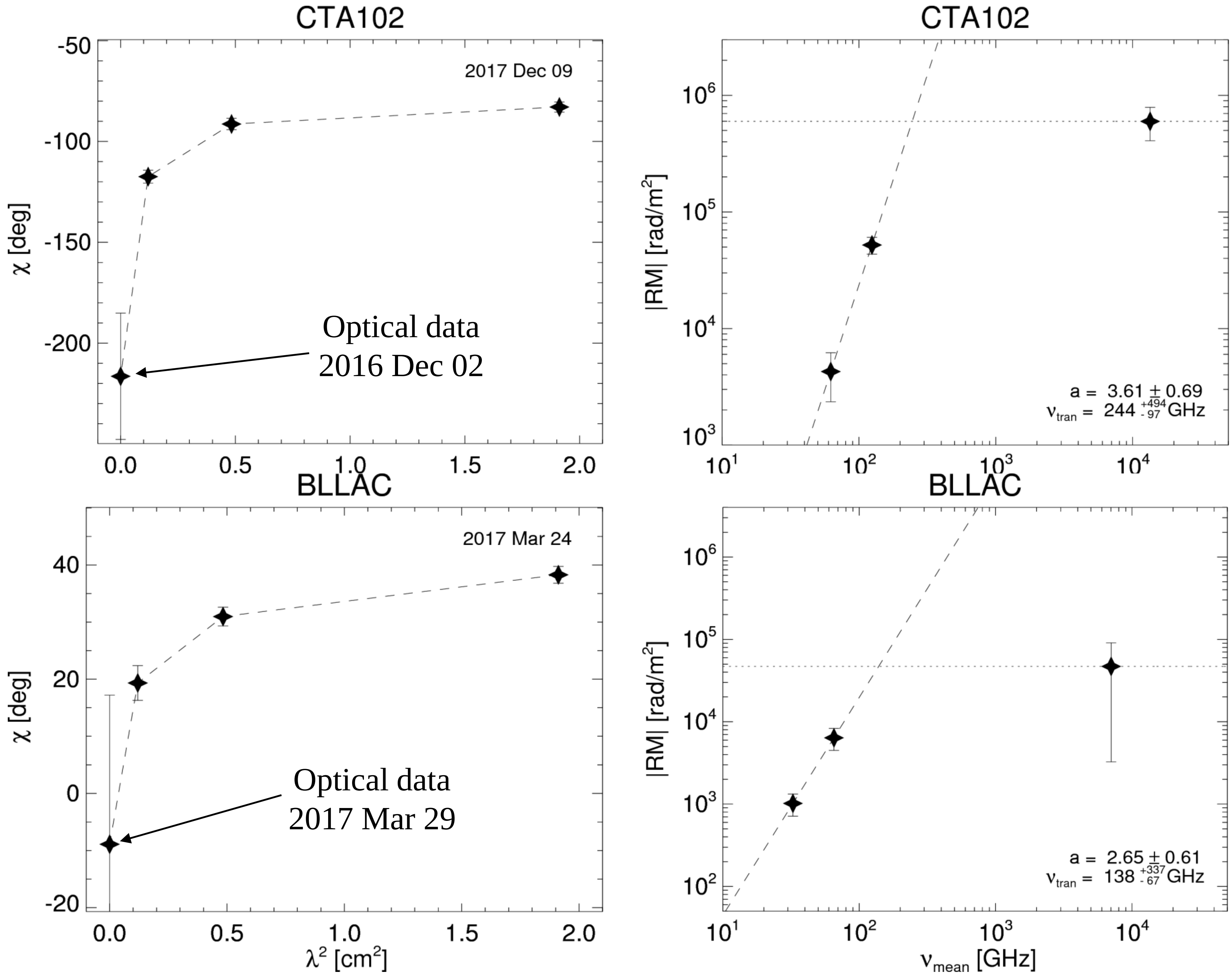

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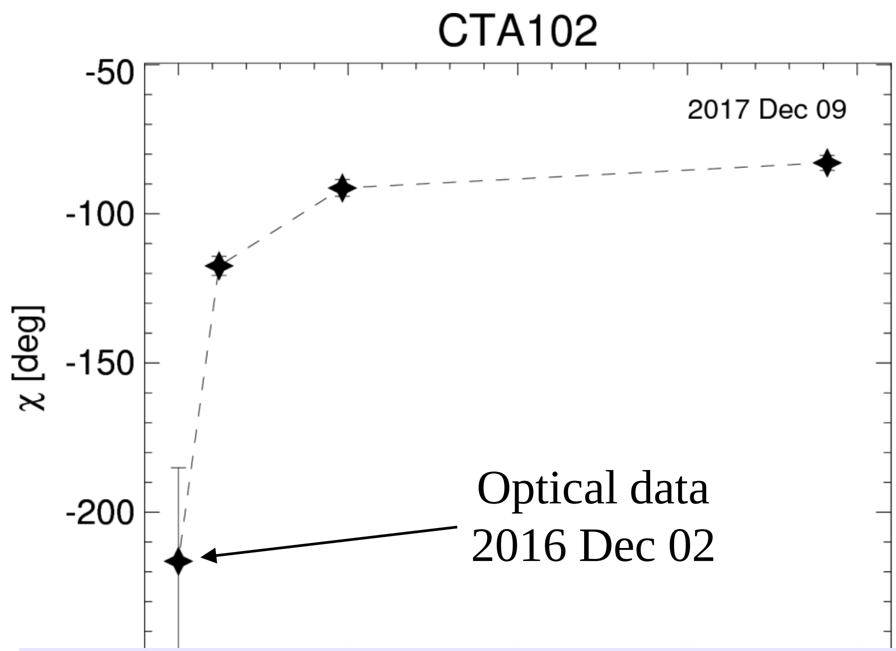
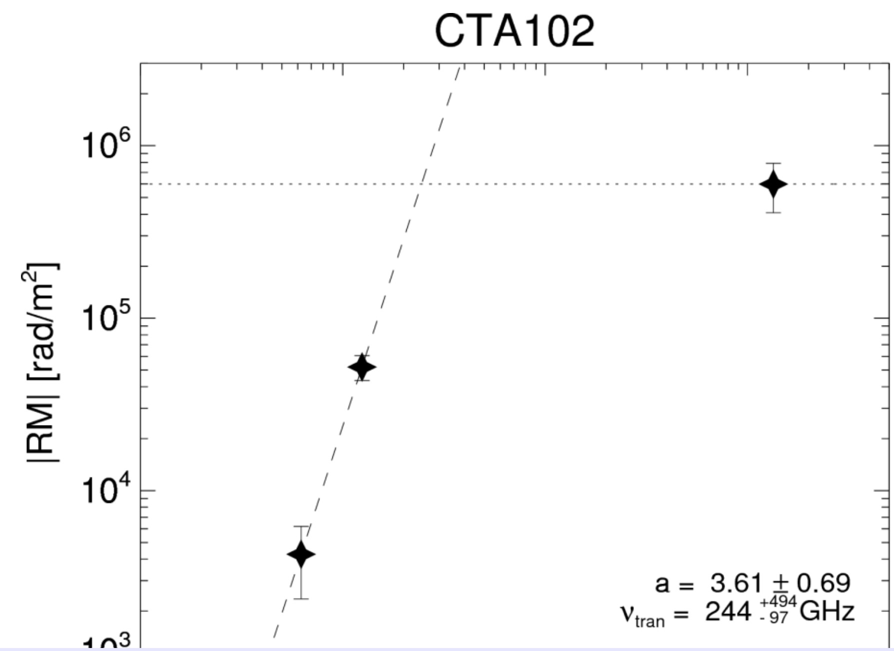
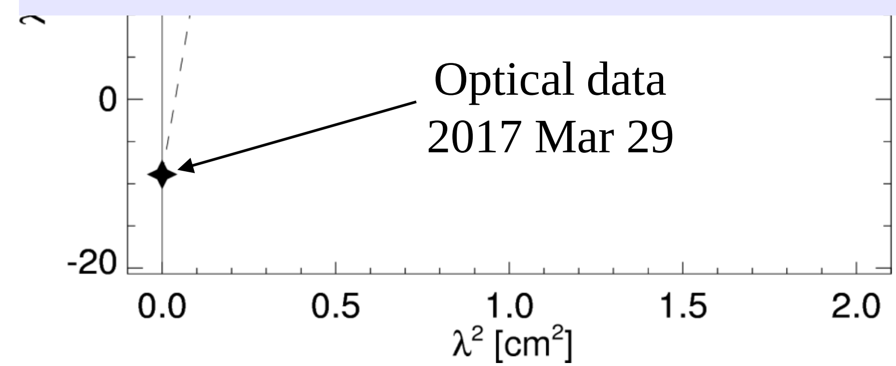
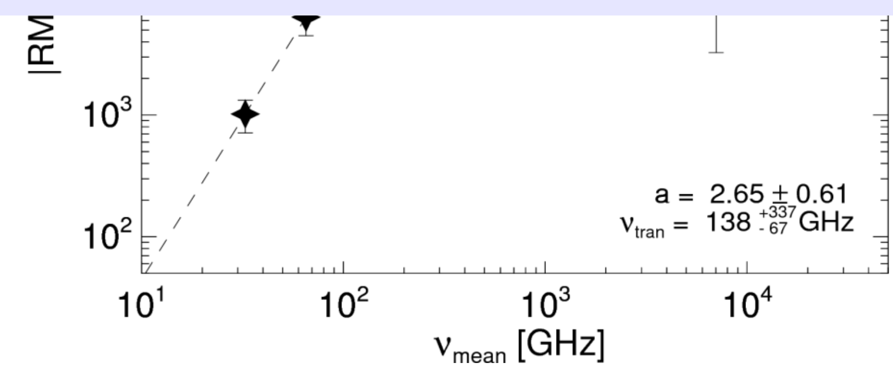




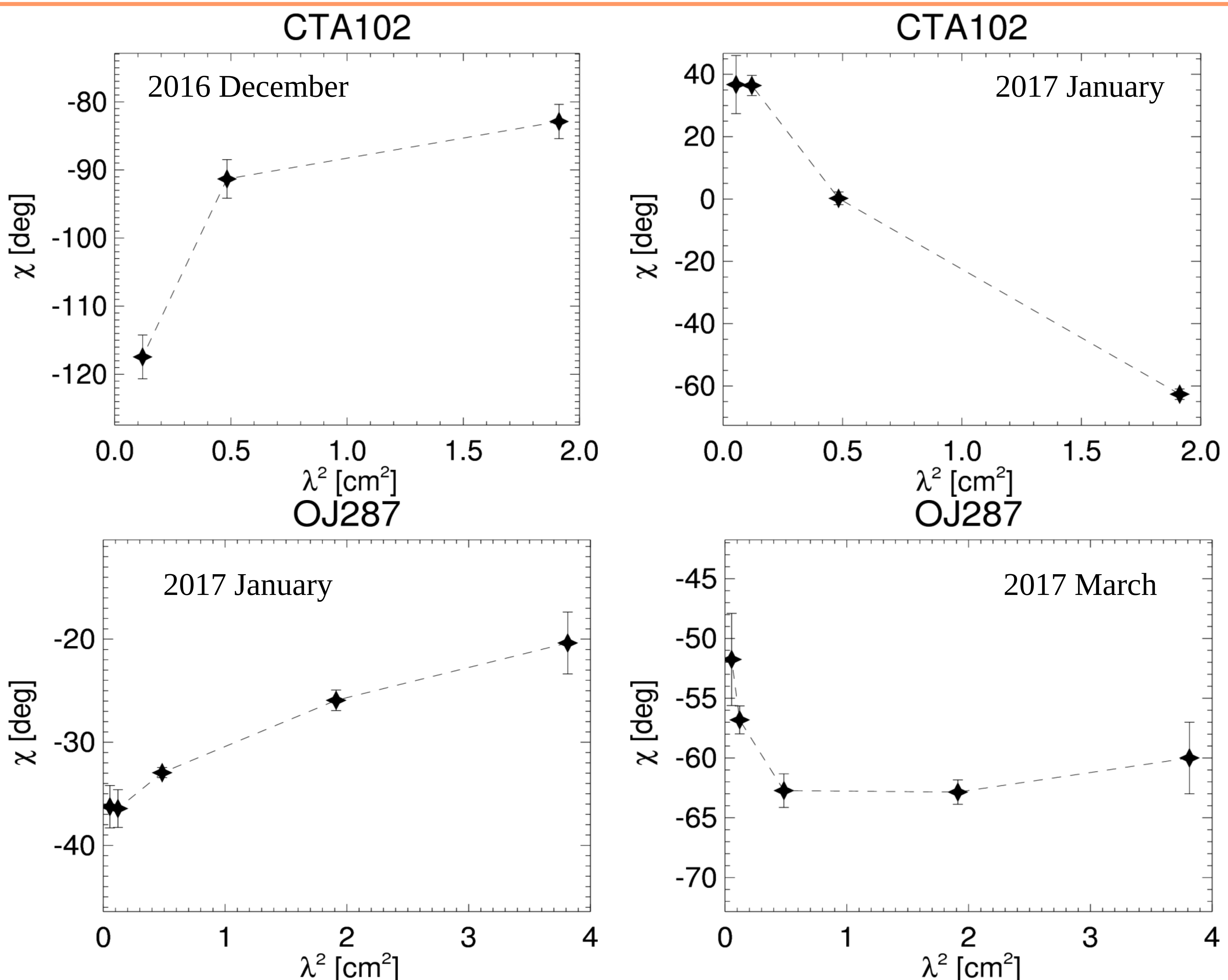
— Although the number of detection is too small, our data suggest that the blazar cores become fully transparent at ≈250 GHz in the source's rest frame and one may expect no core-shift or RM dependence on observing frequency above that frequency.

However, this is true only when the assumption of n pi ambiguity is valid. We will investigate this with sub-mm observations and IR polarimetry in future.





Discussion — 4. RM sign change in a few months



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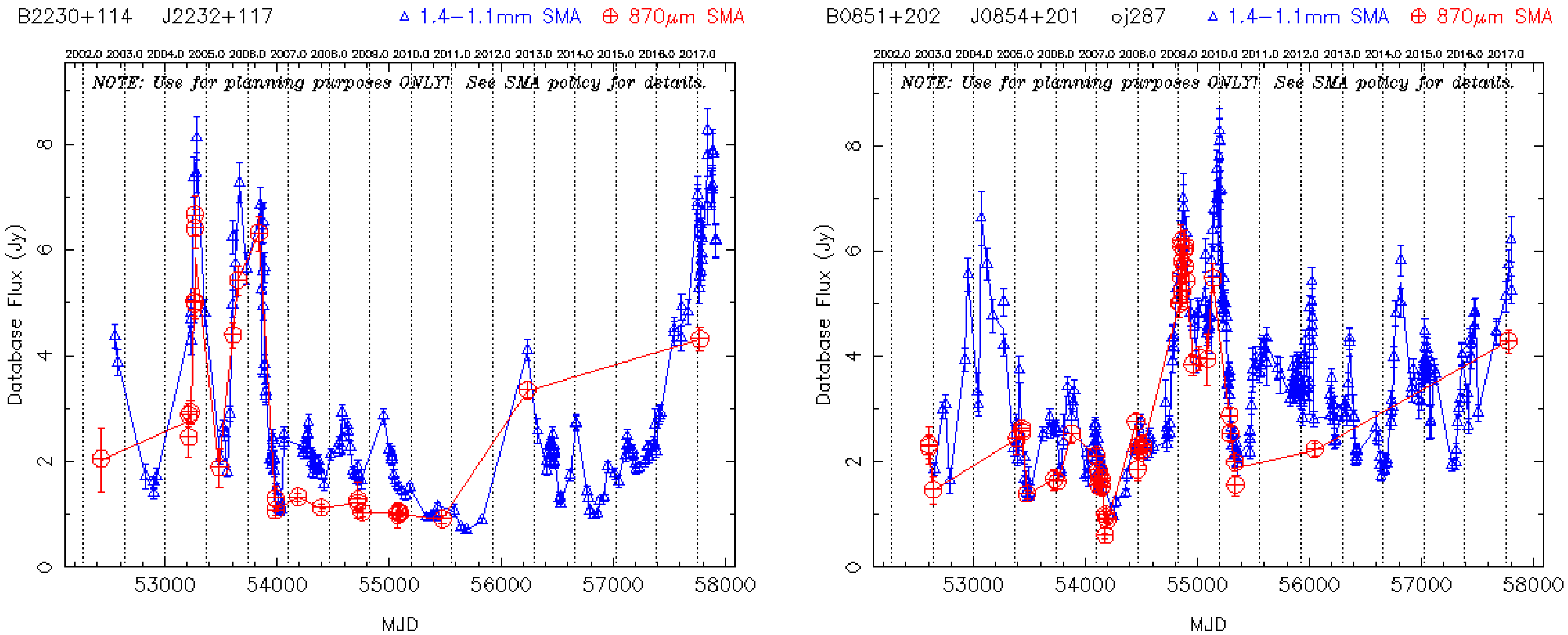
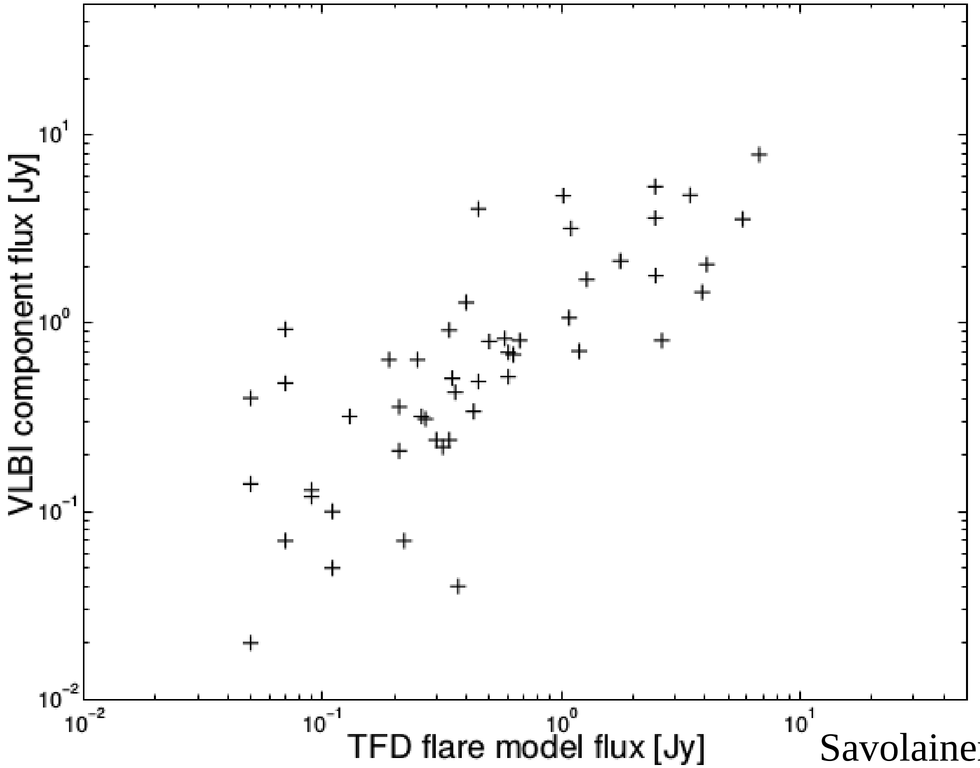


– Both sources are in strong flaring stages during our KVN observation period.

Discussion — 4. RM sign change in a few months

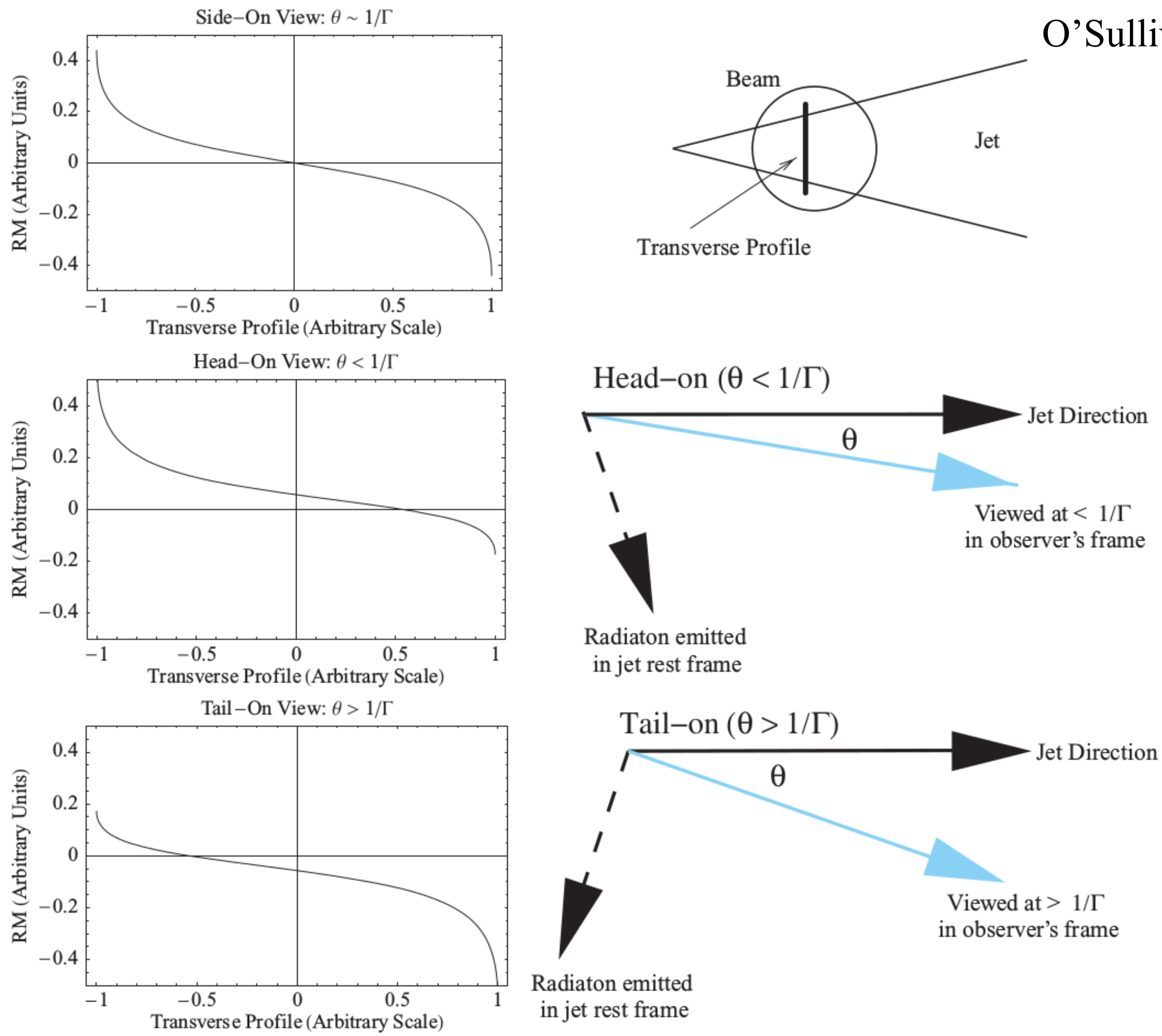


Savolainen+ 2002

- Both sources are in strong flaring stages during our KVN observation period.
- Most of the radio flares is associated with a new jet component emerging from the core.

Discussion — 4. RM sign change in a few months

O'Sullivan & Gabuzda (2009)



— It is very common that blazar jets are accelerated / decelerated and bent.

— $\theta\Gamma = 0.92$ (OJ 287) and 0.78 (CTA 102) from Jorstad+05.

→ it is easy for these sources to cross $\theta\Gamma = 1$ and the sign of observed RM changes when the flares are related with new jet components and they underwent acceleration/deceleration and /or jet bending.

Summary

— We found that Faraday rotation measure of the blazars VLBI core progressively increase at higher observing frequencies, which is well described by $RM \propto \nu^{a}$ with αmean = 2.46 ± 1.16.

— Comparing the dependence of RM on ν with contemporaneous optical polarization data with an assumption of no n pi ambiguity, we obtained the frequency at which the RM increase is saturated at a certain frequency and the core becomes fully transparent above the frequency, which is approximately 250 GHz in the source's rest frame.
→ there is an indication that the cores of blazars are a standing recollimation shock which becomes transparent at mm/sub-mm wavelengths.

— We found sign changes in the observed RMs of two sources in a few months. Since they are under strong flares at the time of our observation, we relate the sign change with the new jet components emerging from the core undergo acceleration/deceleration and/or jet bending, which leads to a change in the direction of our line of sight by relativistic abberation effect.

— Our large program is going to continue in the next years, which would allow us to perform more statistically rigorous study in future.