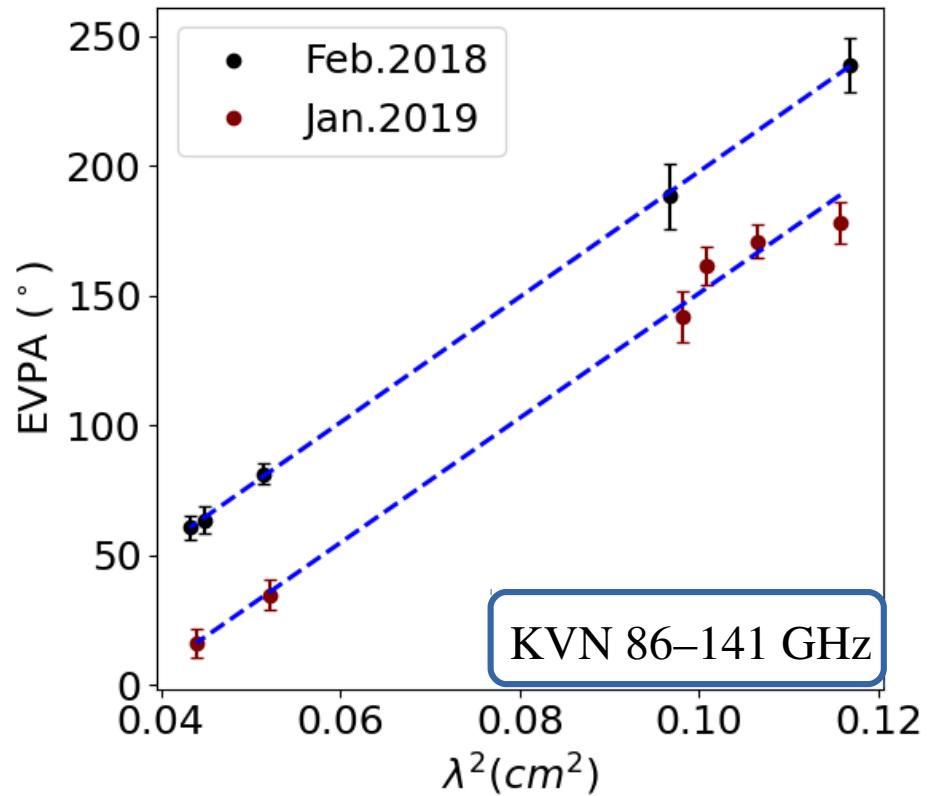
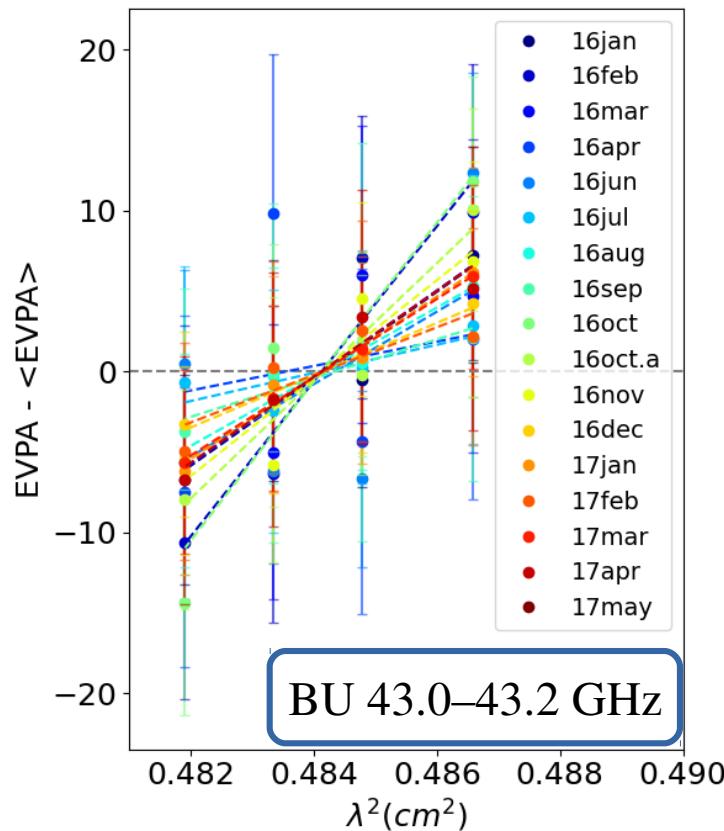


Probing the presence of the external medium at the jet head (C3) of 3C 84



Minchul Kam (Seoul National University)

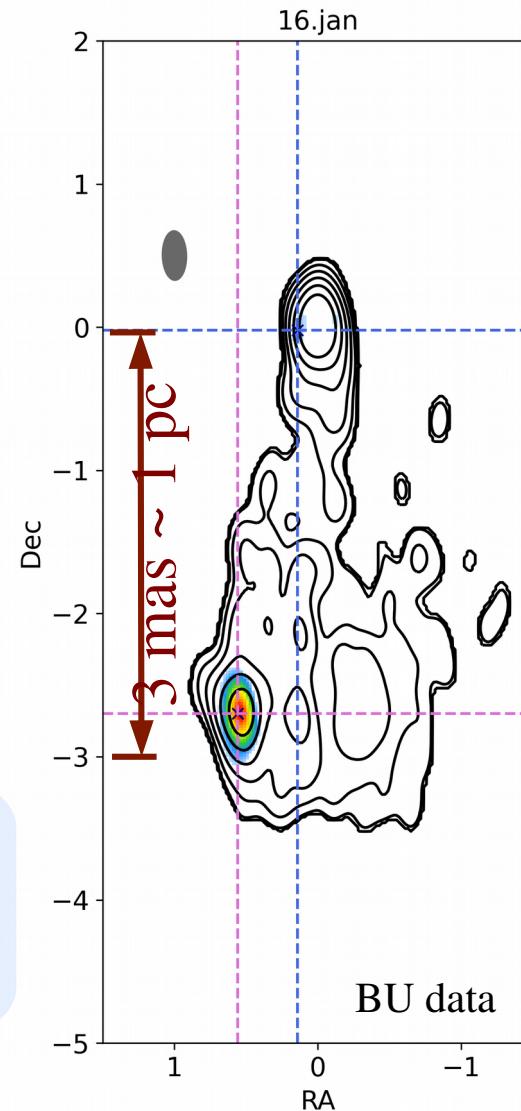
Collaborators: Sascha Trippe, Jongho Park, Jeffrey Hodgson

3C 84 at the center of NGC 1275

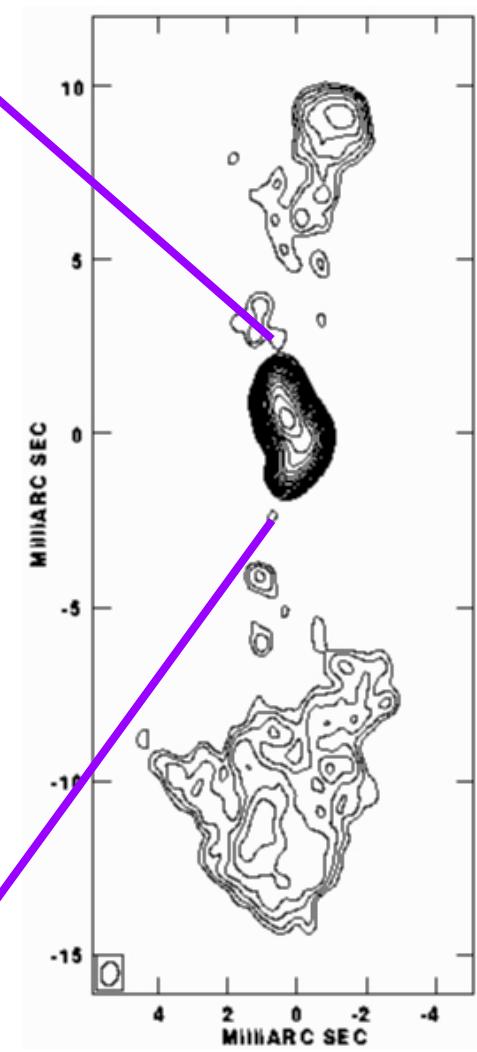
- (Sub-) Parsec-scale jet is resolved.
- The latest jet ejection was in 2003 (Suzuki+ 13)
→ very early stage of jet

optimal laboratory to investigate
the formation & evolution of jets!

VLBA 43 GHz

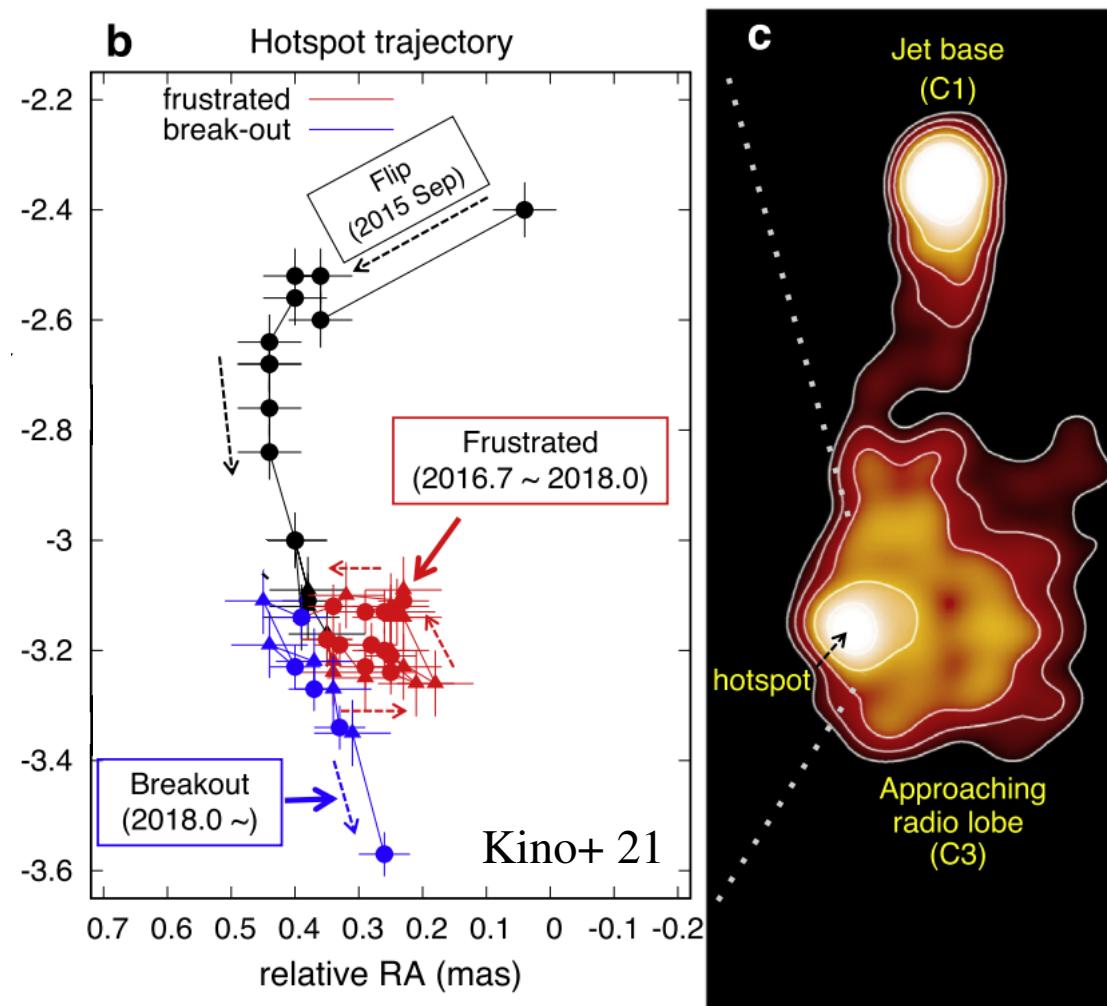


VLBA 15 GHz

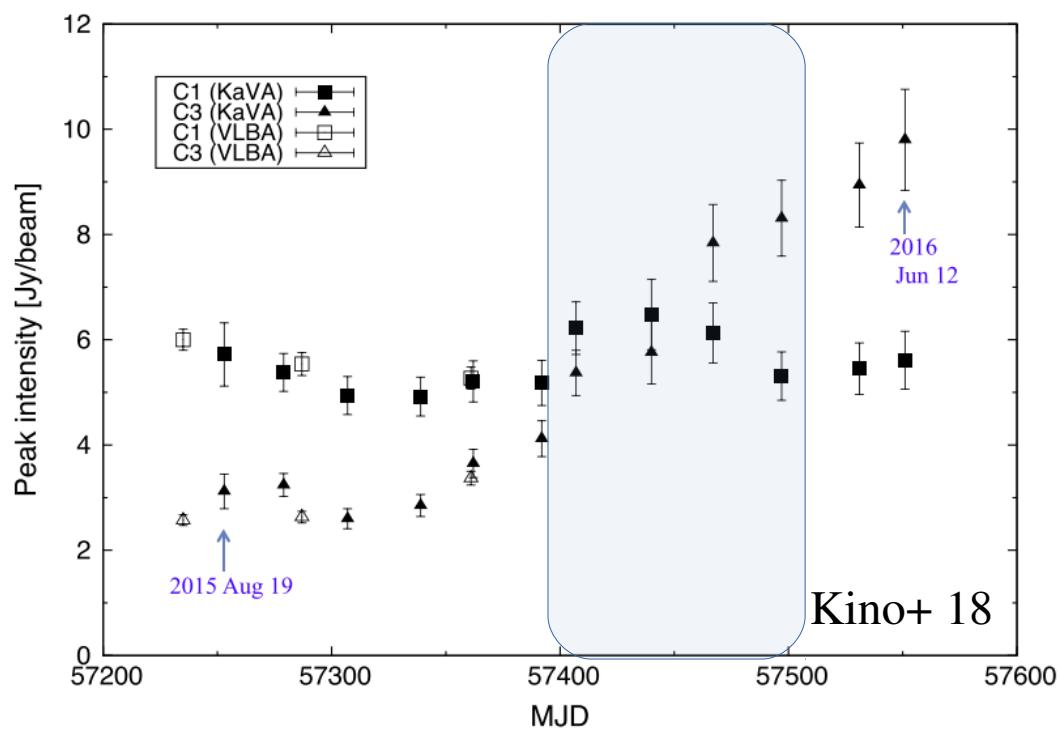


MOJAVE image

The jet (C3) was stagnant for ~1.5 year (2016-2017).

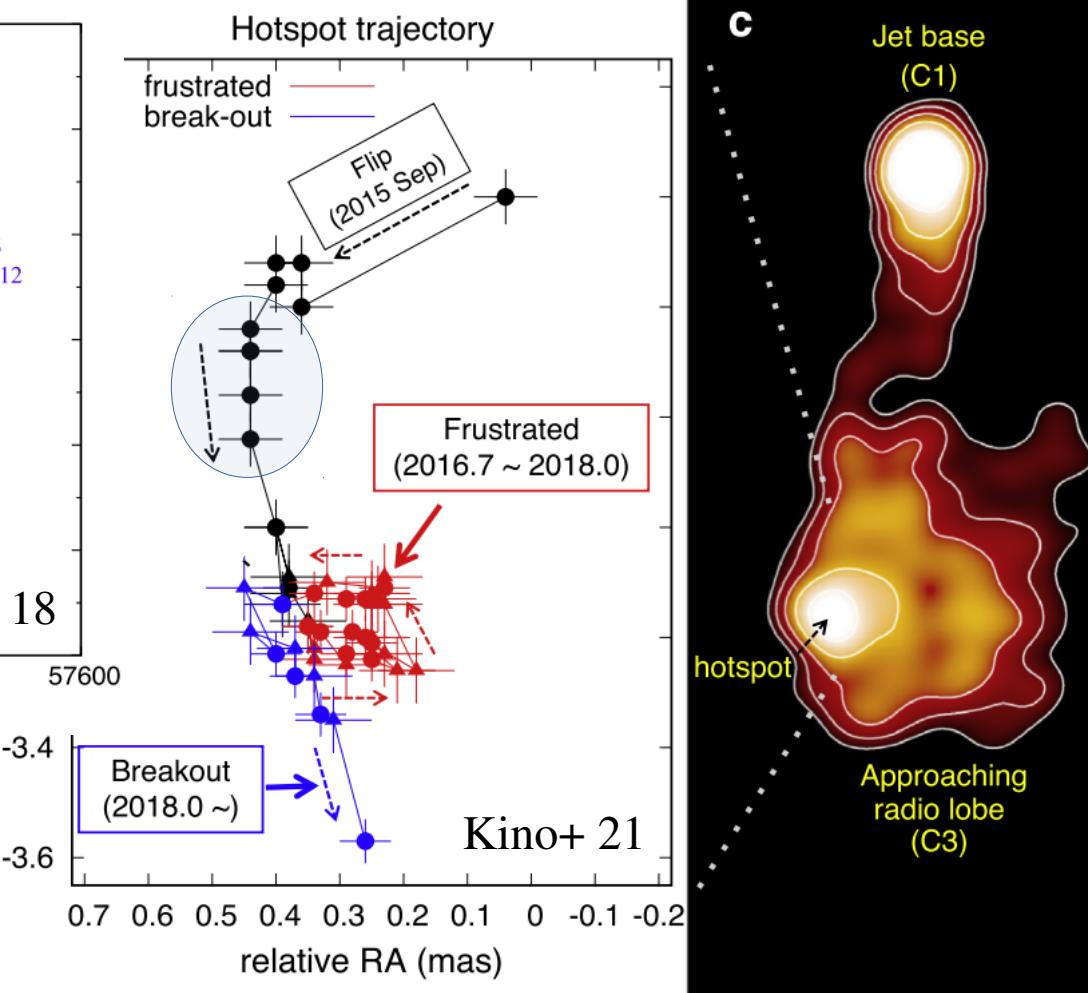


The collision between the jet and the ambient medium (2016-2017)?



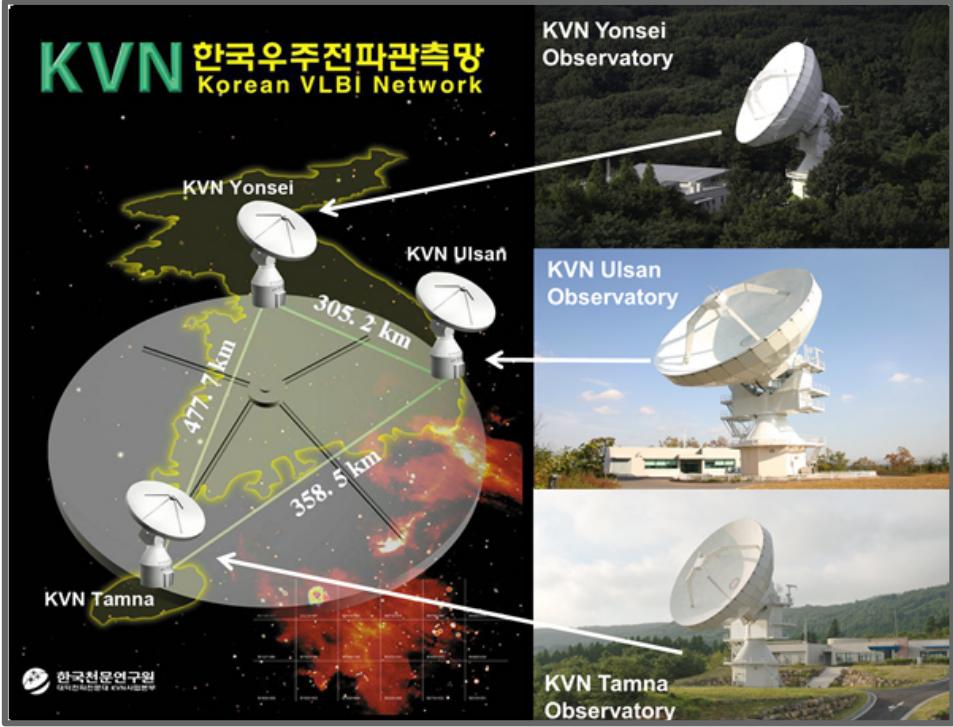
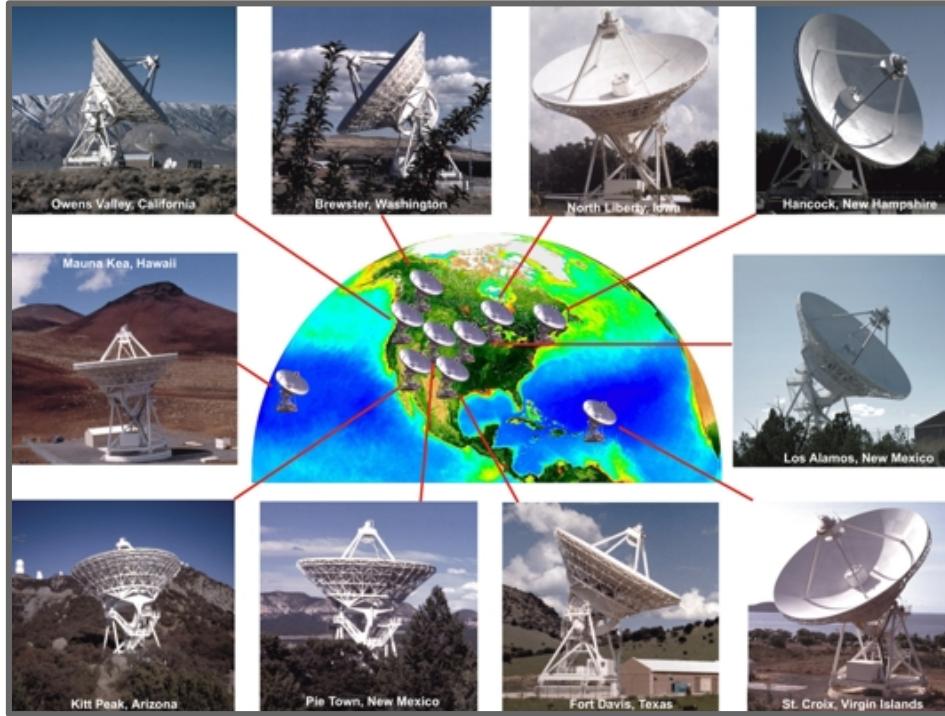
stagnation + flare

→ collision with the ambient medium?



The ambient medium is **too dim** to be directly observed.

→ An alternative way : **Faraday rotation!** $RM \propto \int_{LoS} n_e B dl$



VLBA (BU) 43 GHz

- Jan.2016 - May.2017

→ IF 1 : 43.0075 GHz

IF 2 : 43.0875 GHz

IF 3 : 43.1515 GHz

IF 4 : 43.2155 GHz

KVN 86-141 GHz

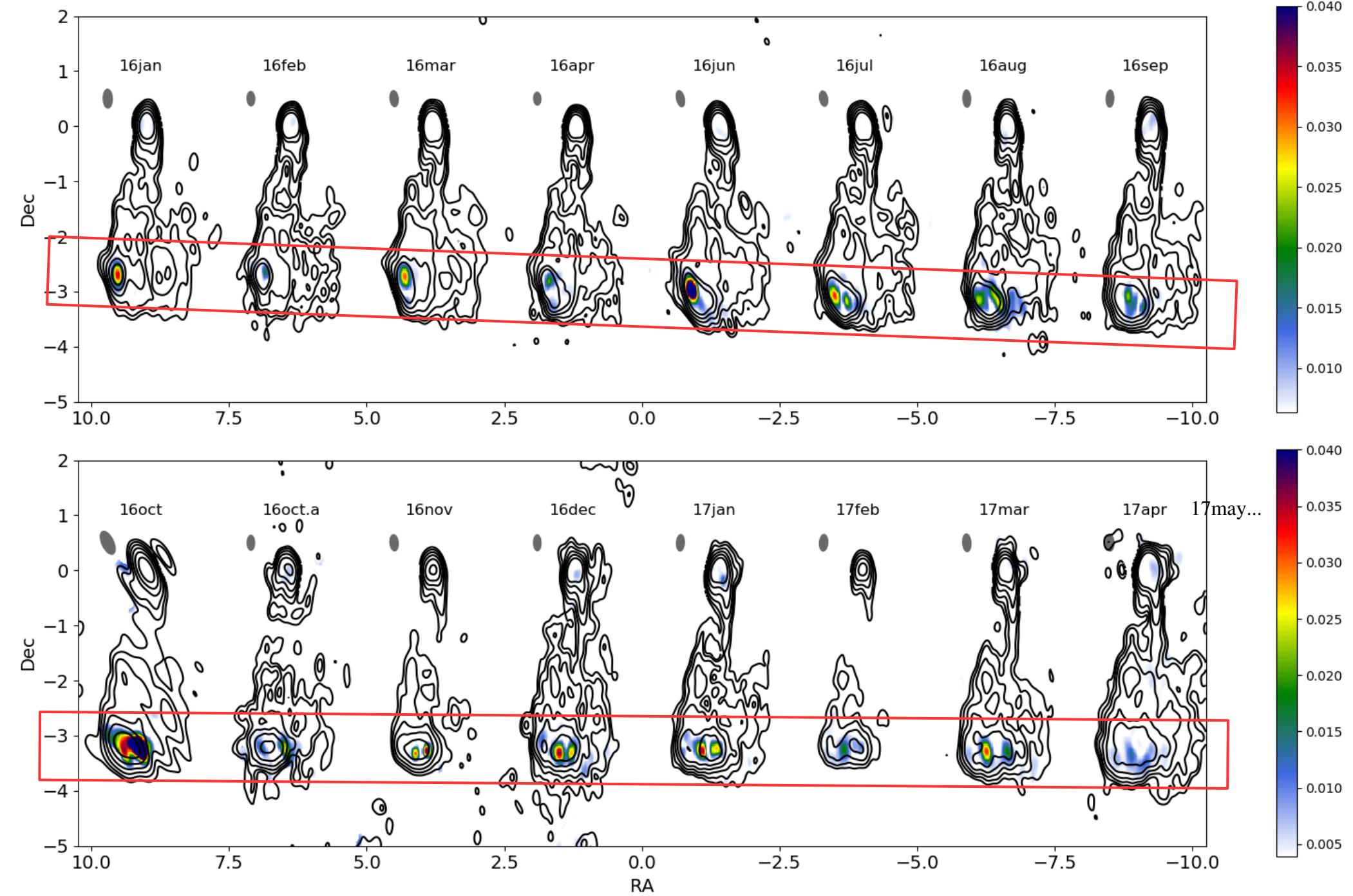
- Feb. 13-21. 2018

→ 86/ 95/ 129/ 139/ 141 GHz

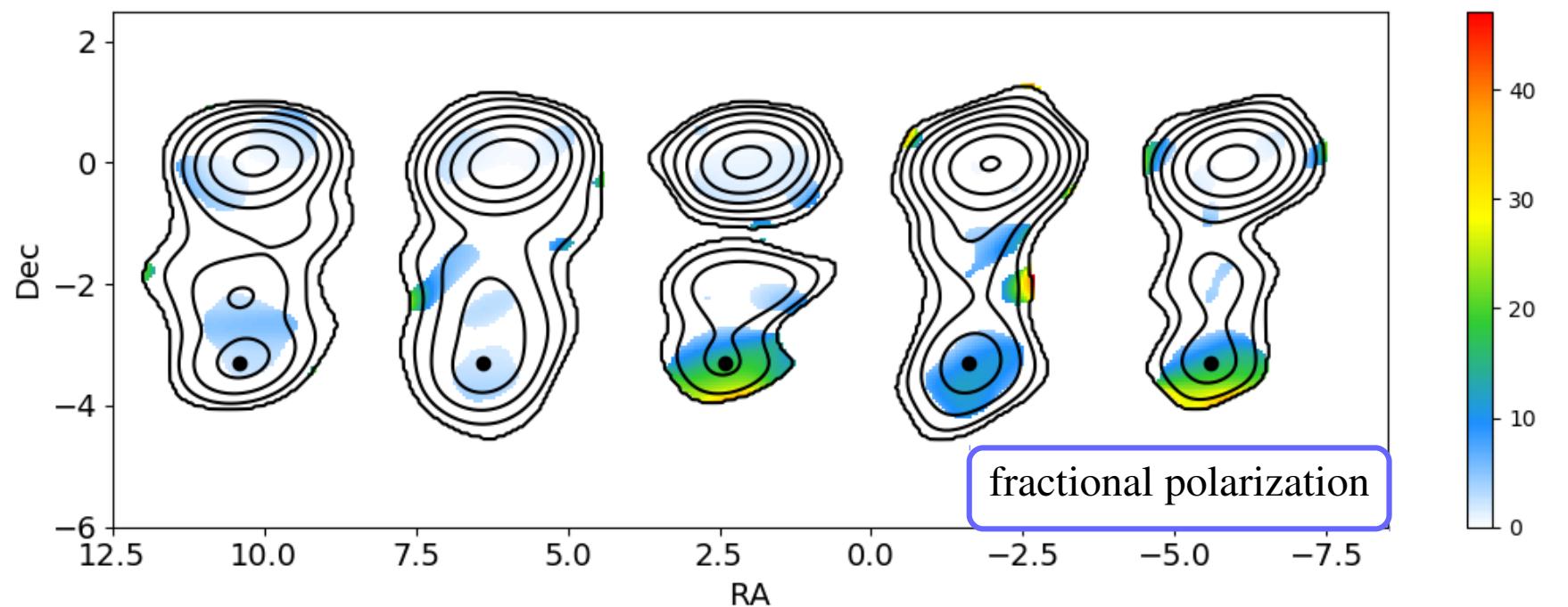
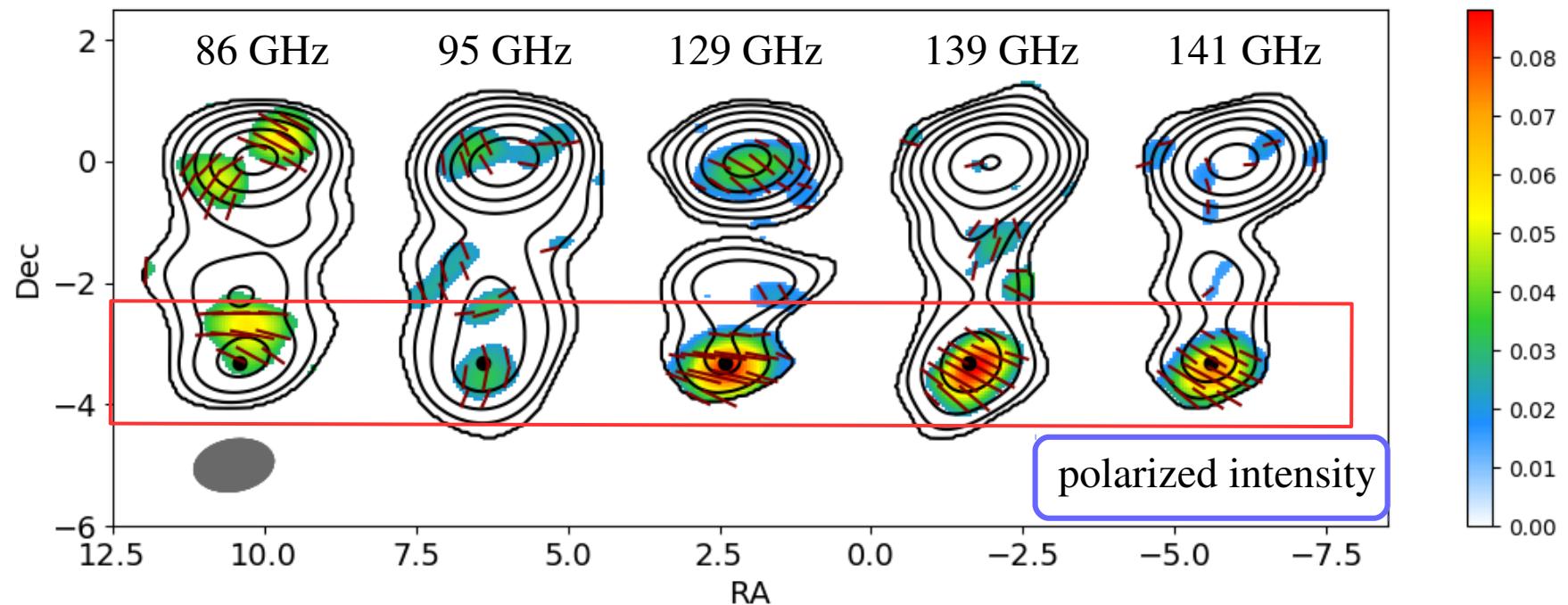
- Jan. 2-8. 2019

→ 86/ 90/ 92.5/ 94/ 129/ 141 GHz

BU images (Jan. 2016 ~ May. 2017)

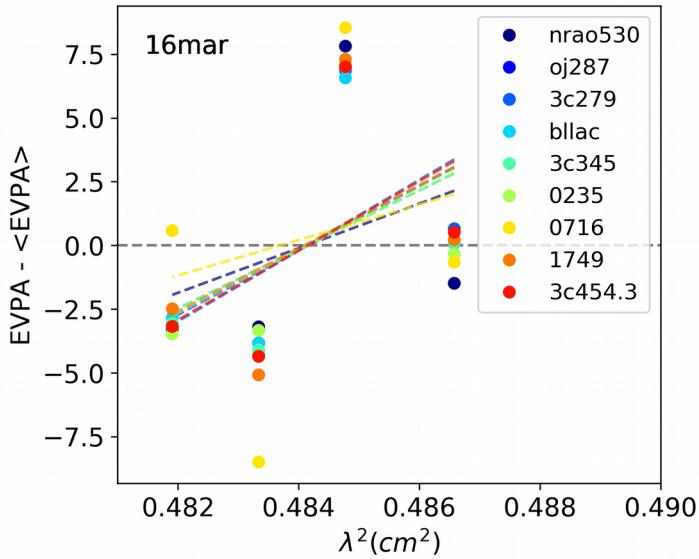


KVN images (Feb. 2018)



Removing the artificial RM (EVPA scatter) from the BU data

calibrators only

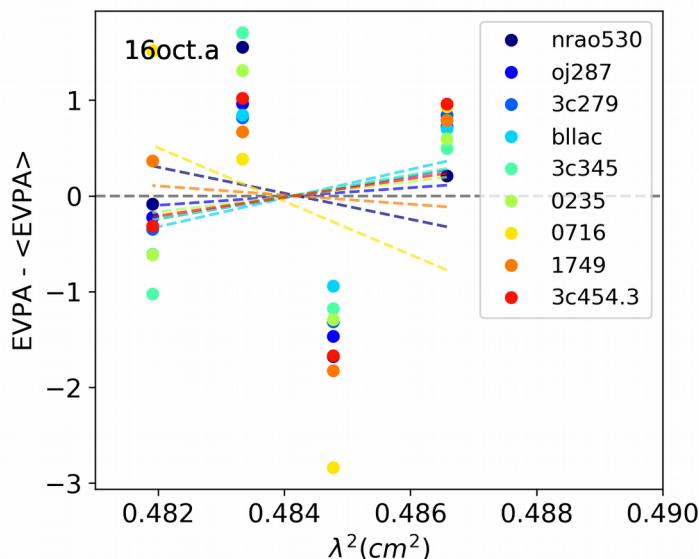


A small scatter of EVPA gives a large (artificial) RM

$$\Delta\theta = 5^\circ - 6^\circ \rightarrow RM = 2 \times 10^5 rad m^{-2}$$

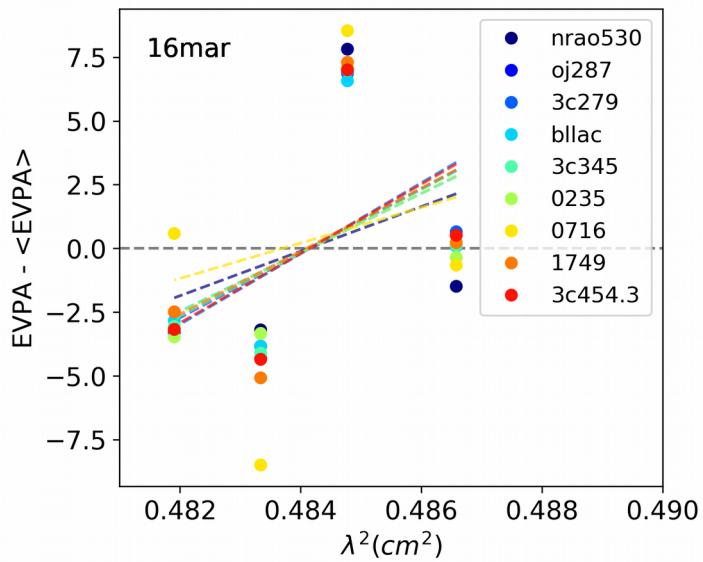
We selected 6~9 comparison sources:

- known to have much smaller RM at 43 GHz
- identical calibration (priv. comm. with BU group)
- polarization detected at all four IFs

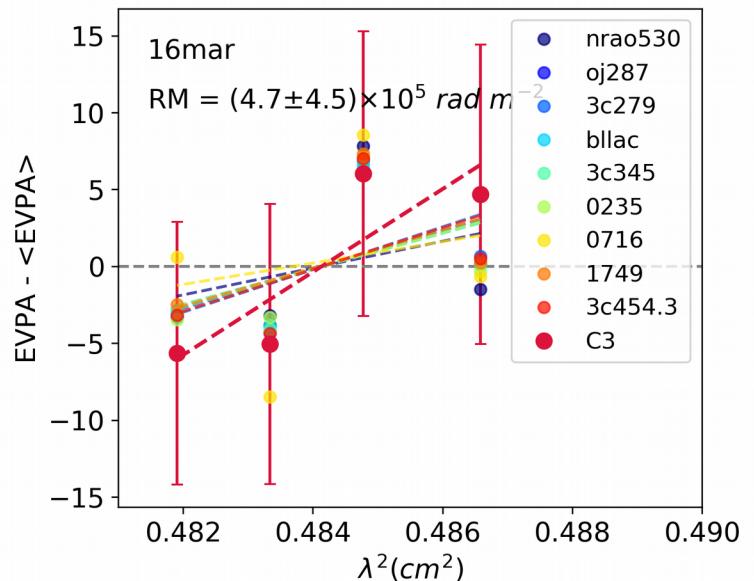


Removing the artificial RM (EVPA scatter) from the BU data

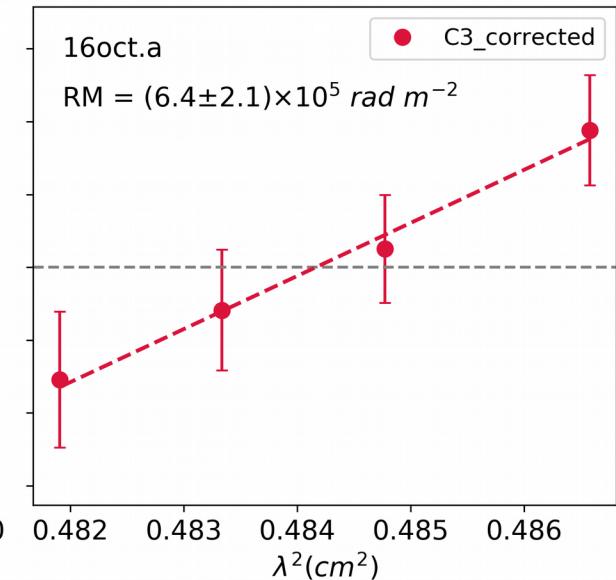
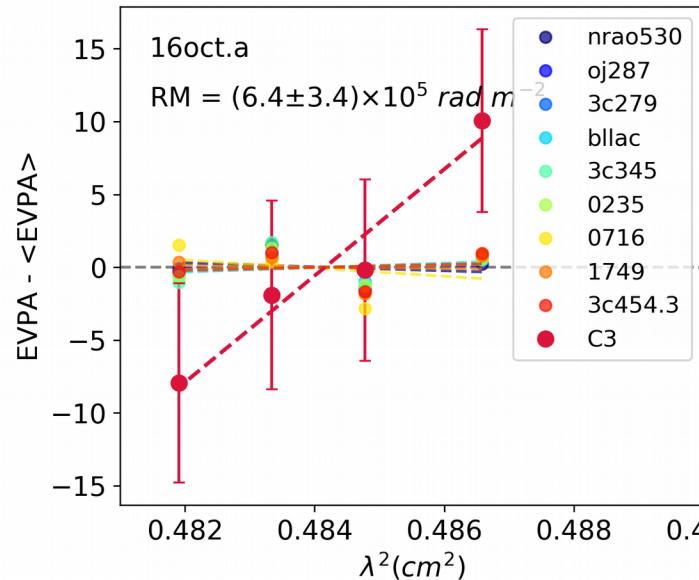
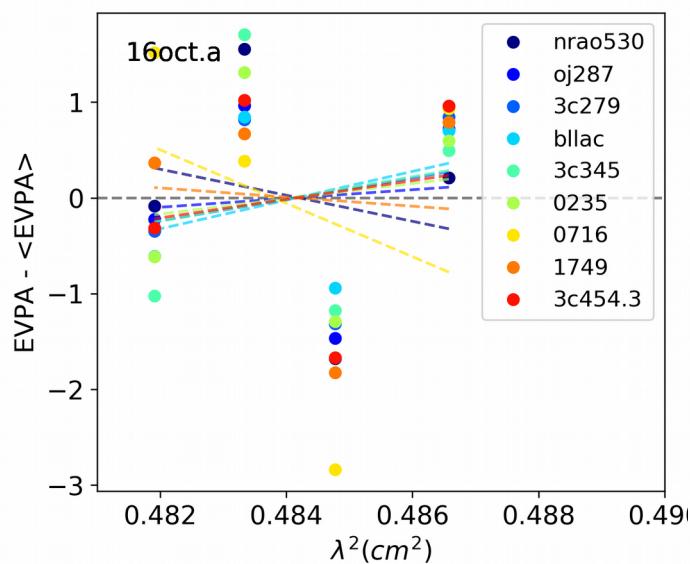
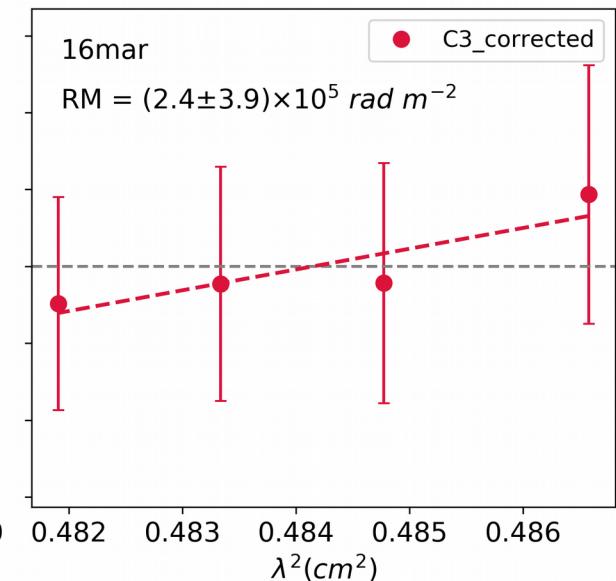
calibrators only



calibrators & C3

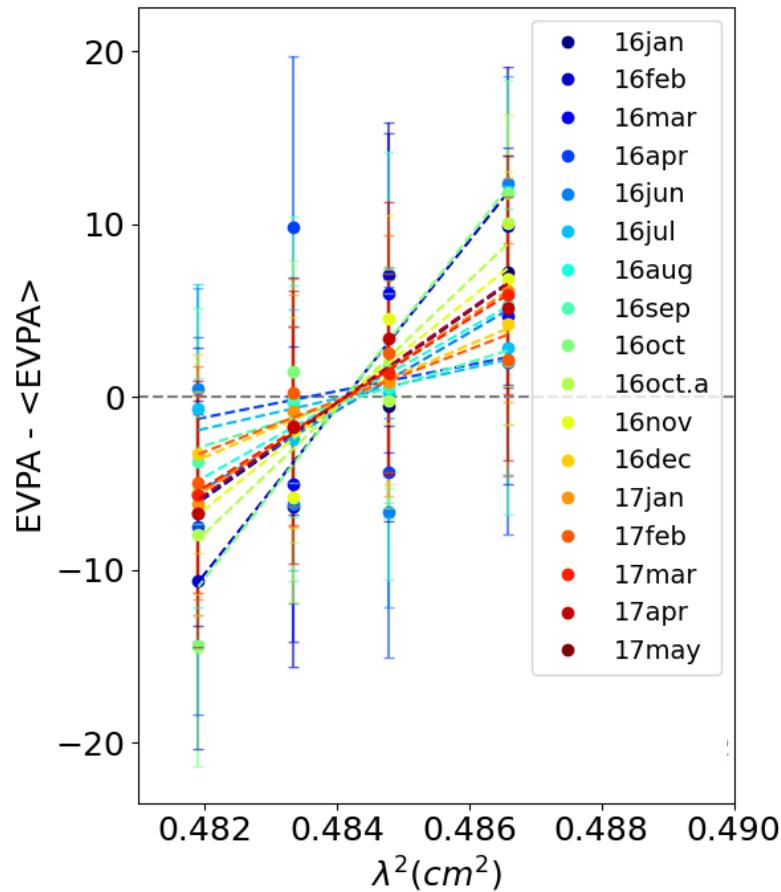


C3 after correction

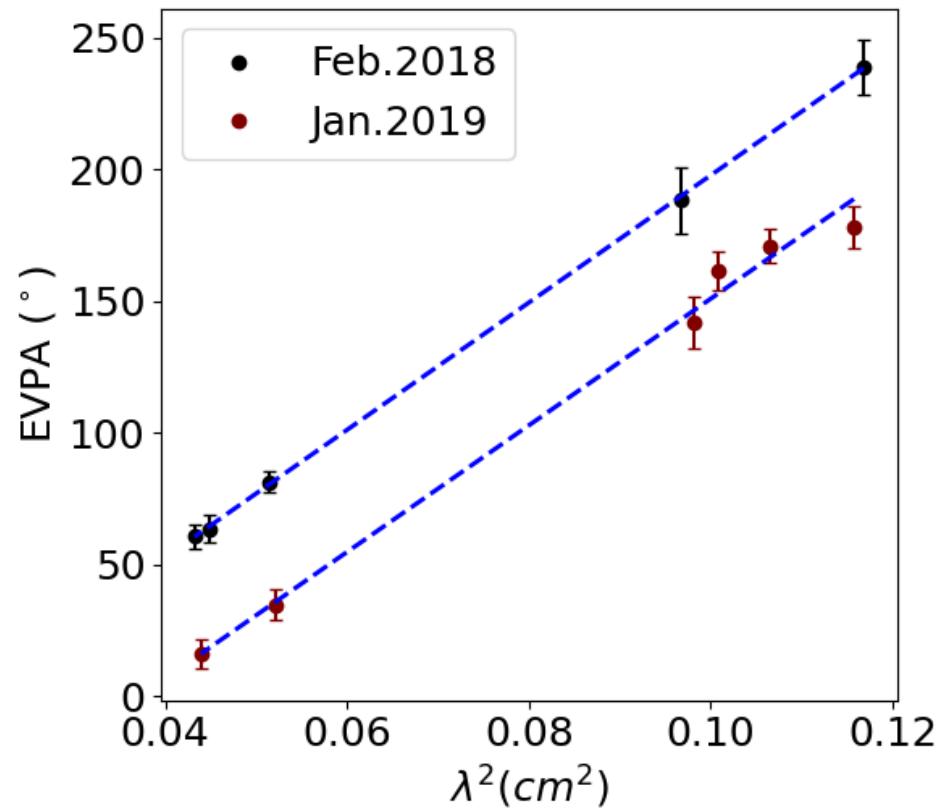


RM at C3 is almost constant from 43 to 141 GHz!

BU 43 GHz



KVN 86-141 GHz



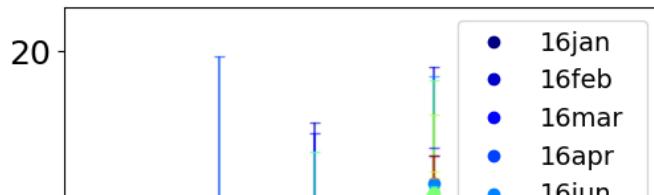
$$\langle RM \rangle = (3.3 \pm 0.4) \times 10^5 \text{ rad m}^{-2}$$

$$RM = (4.2 \pm 0.2) \times 10^5 \text{ rad m}^{-2}$$

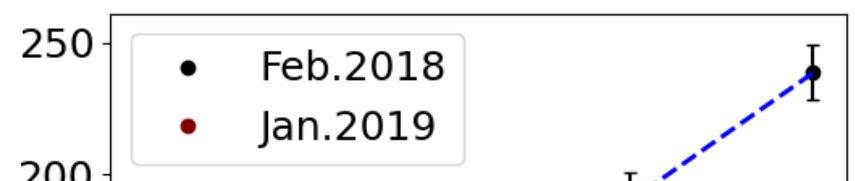
$\langle RM \rangle = (8.7 \pm 2.3) \times 10^5 \text{ rad m}^{-2}$ at SMA 230 GHz (Plambeck+ 14)

RM at C3 is almost constant from 43 to 141 GHz!

BU 43 GHz



KVN 86-141 GHz



Evidence of the ambient medium between the jet \leftrightarrow observer!

$$RM = 4 \times 10^5 \text{ rad m}^{-2}, n_e \sim 10^4 \text{ cm}^{-3}, d \sim 0.1 \text{ pc} \longrightarrow \vec{B} \sim 0.5 \text{ mG}$$

$$RM = 4 \times 10^5 \text{ rad m}^{-2}, n_e \sim 10^4 \text{ cm}^{-3}, d \sim 1 \text{ pc} \longrightarrow \vec{B} \sim 0.05 \text{ mG}$$

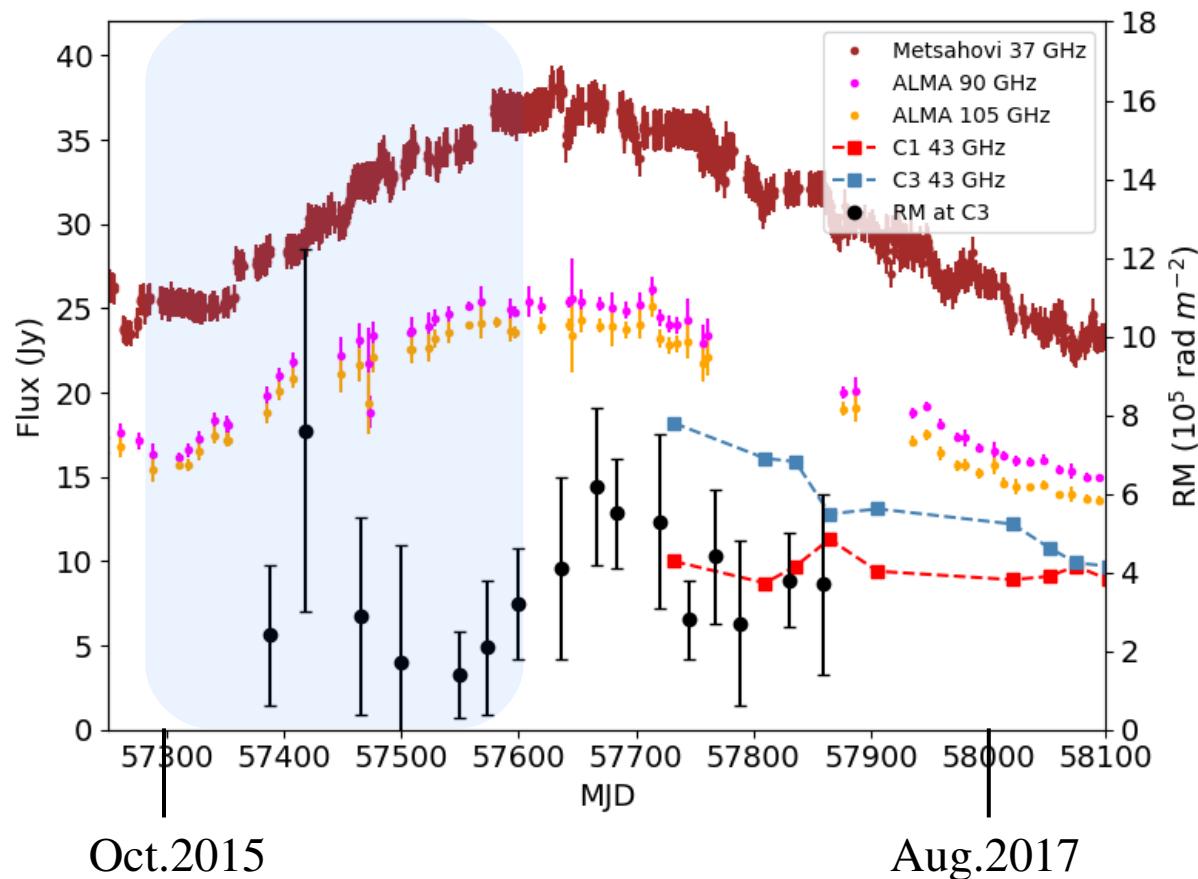
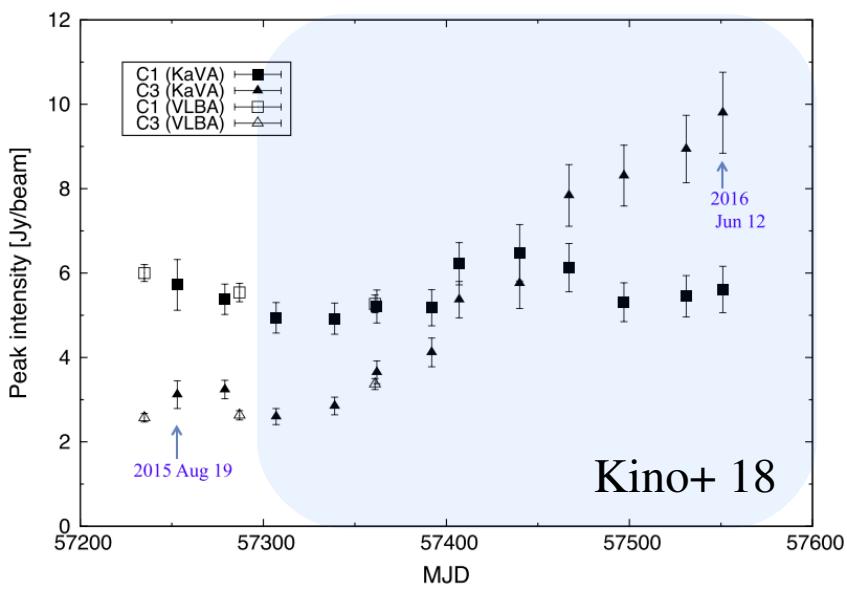


$\langle RM \rangle = (3.3 \pm 0.4) \times 10^5 \text{ rad m}^{-2}$

$RM = (4.2 \pm 0.2) \times 10^5 \text{ rad m}^{-2}$

$\langle RM \rangle = (8.7 \pm 2.3) \times 10^5 \text{ rad m}^{-2}$ at SMA 230 GHz (Plambeck+ 14)

No strong correlation between the light curves and RM at C3

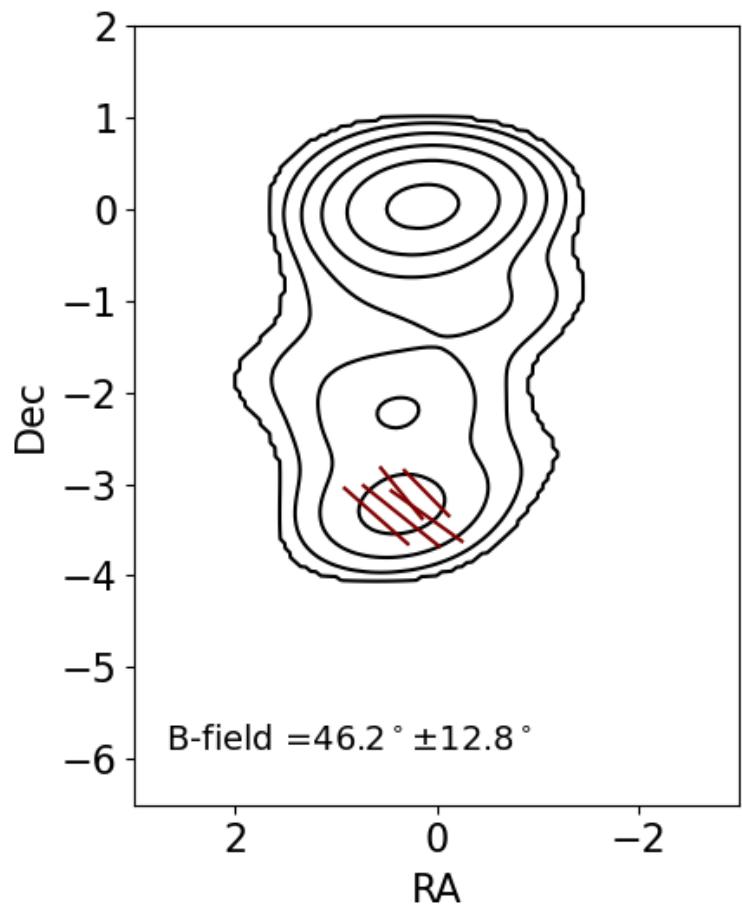
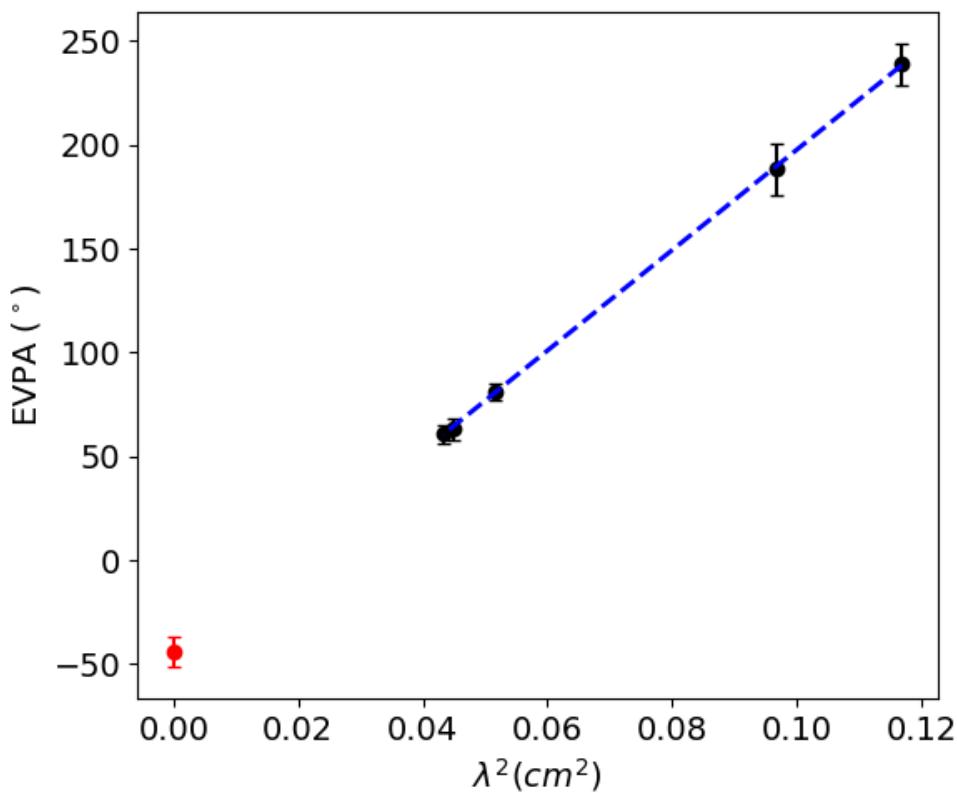


C3 shows flare between Oct.2015 and Aug.2017, whereas RM doesn't

→ another evidence that the origins of the flux and RM are different.

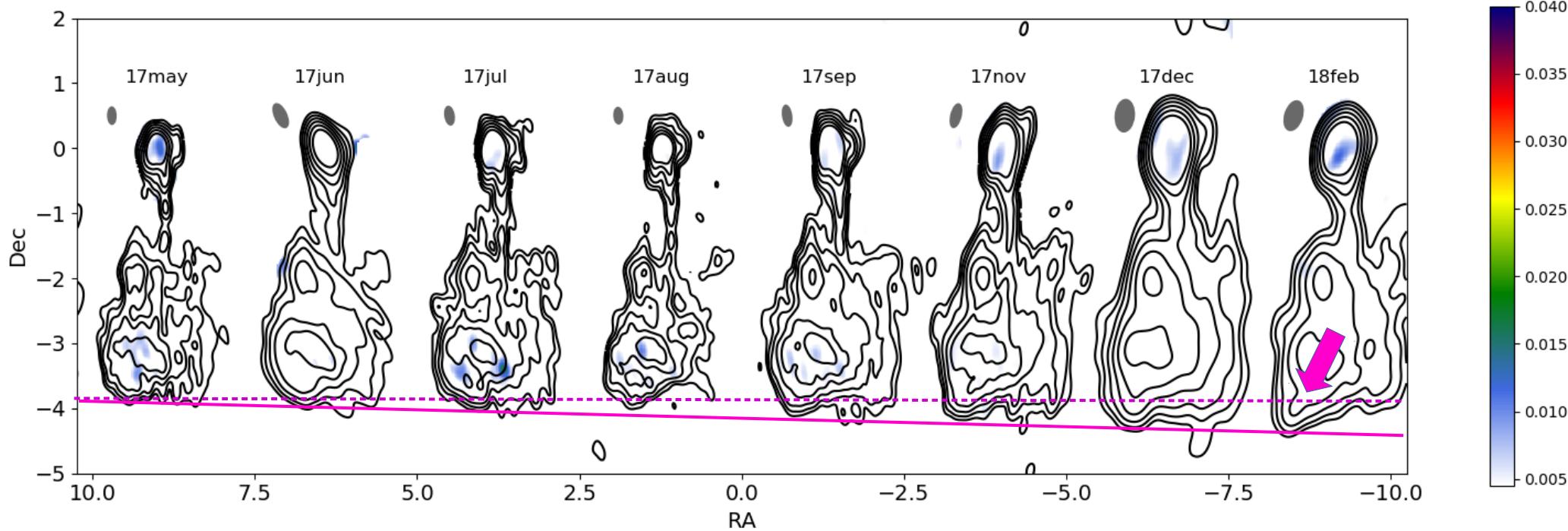
Changes in RM probably indicates non-uniformity of the ambient medium.

RM-corrected EVPA



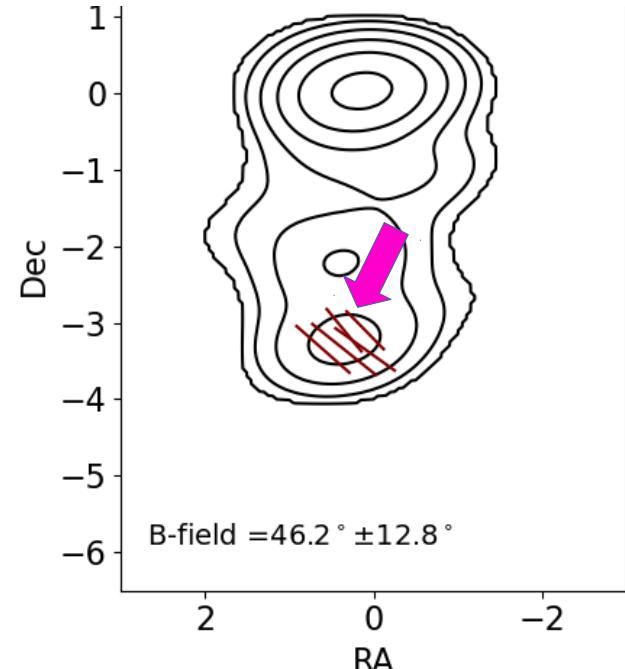
- We can estimate the intrinsic EVPA at C3 by correcting RM.
 - intrinsic EVPA : $-43.8^\circ \pm 12.8^\circ$
 - B-field orientation : 46.2°

Direction of the jet is perpendicular to the B-field.

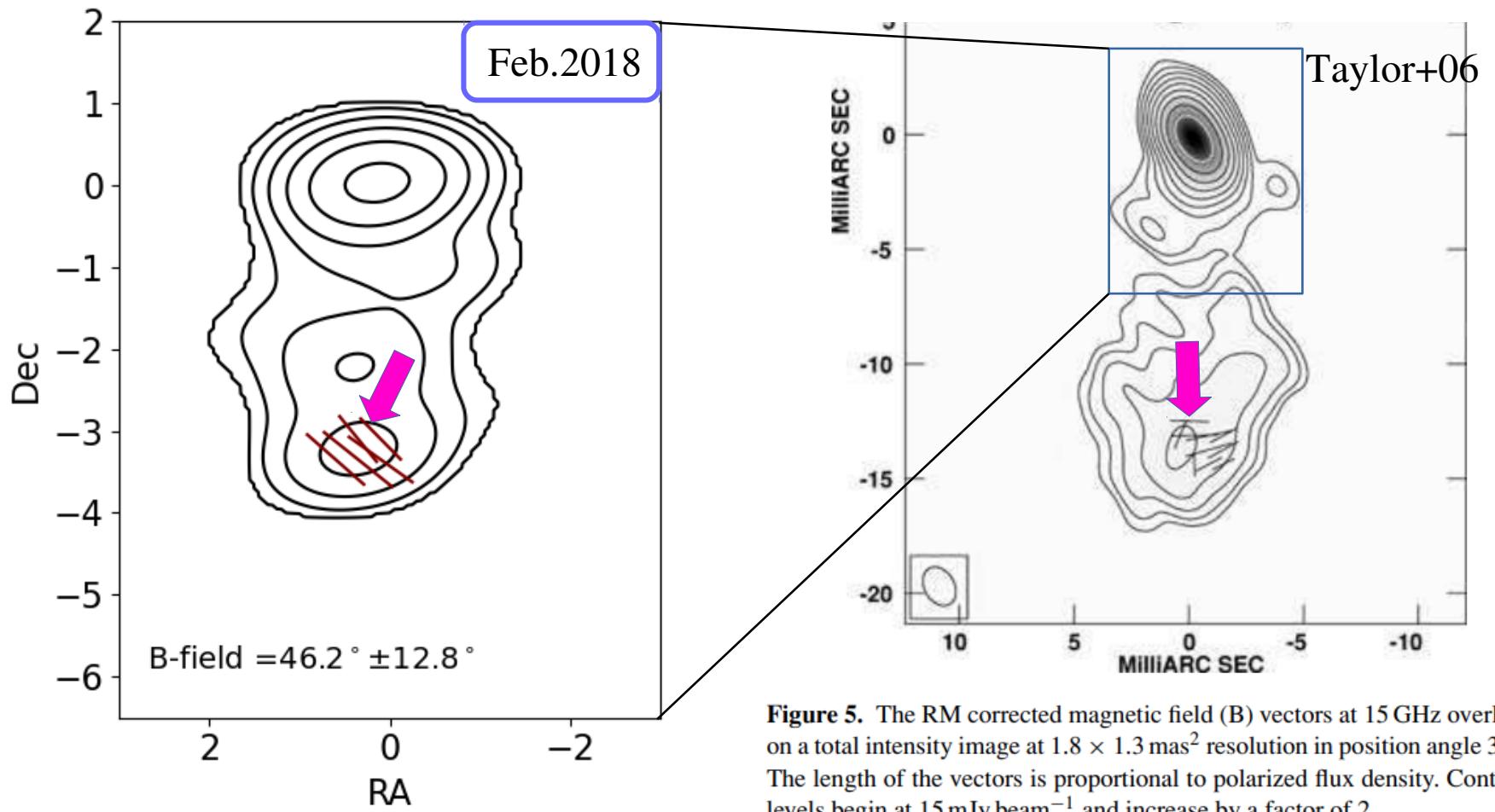


Why is polarization enhanced only at C3?

- shock between the jet (C3) \leftrightarrow ambient medium
- electrons & B-fields are compressed on the shock plane.
- B-fields become perpendicular to the jet direction?



Direction of the jet is perpendicular to the B-field.



- B-fields perpendicular to the jet direction suggests that it is compressed onto the shock plane between the jet and ambient medium.

Faraday rotation (43 - 141 GHz)

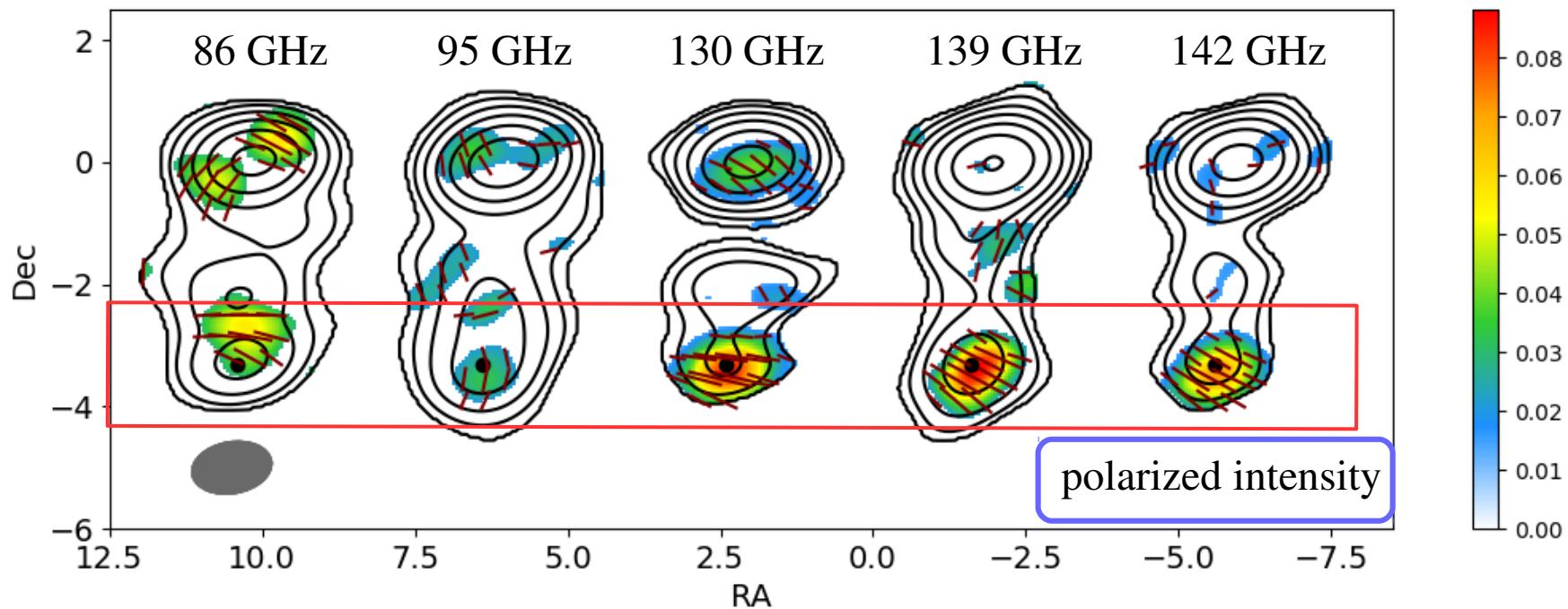
**The presence of the ambient medium
at the jet termination region (C3)**

No strong correlation
between the flux and RM

B-fields perpendicular
to the jet direction.

Additional implications of KVN results

Polarization at C3 tends to increase as a function of frequency.



Polarized flux at C3 : 40/ 44/ 110/ 150/ 126 mJy at 86/95/130/139/142 GHz

Polarized flux with SMA : 126 mJy at 230 GHz (Plambeck+ 14)

→ We cannot rule out the possibility that the polarized flux at 230 GHz would be dominated by C3.

All the RM values at 230 GHz are positive.

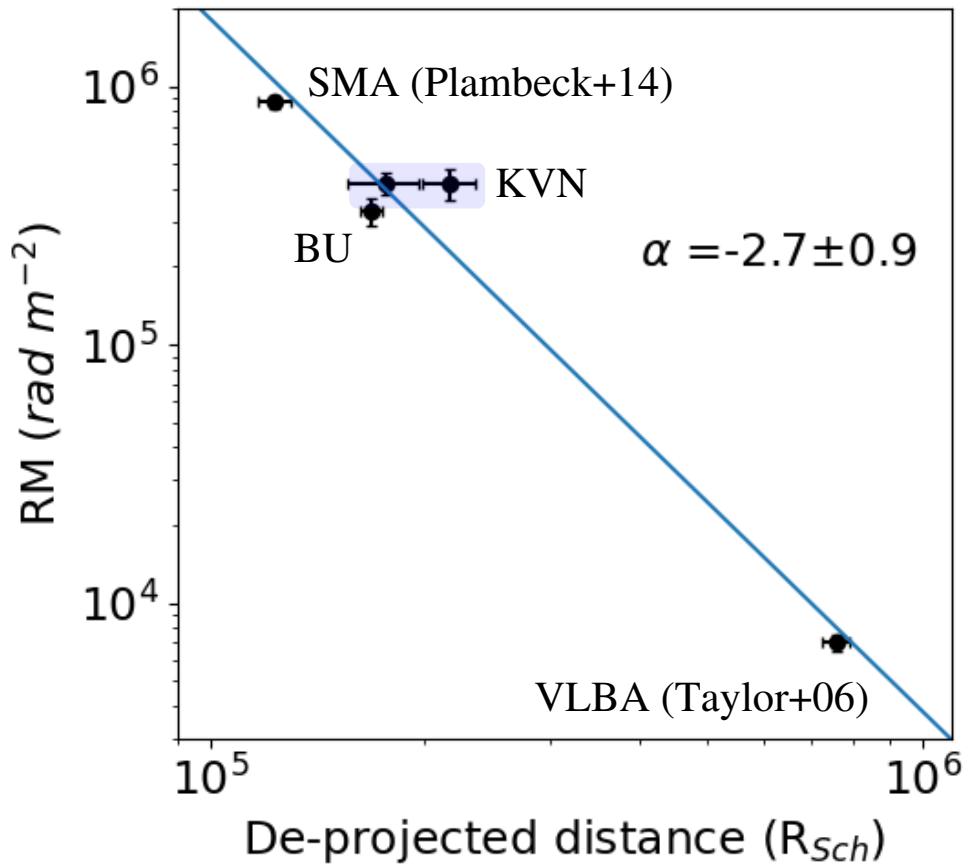
Epoch	ν_{LO} (GHz)	p^{a} (%)	χ^{b} (deg)	RM (10^5 rad m^{-2})
CARMA 1.3 mm				
2011 May 3	223.8	0.6	-63 ± 8	-14.0 ± 19.0
2011 Oct 27	223.8	1.2	-56 ± 2	9.8 ± 3.0
2011 Nov 9	223.8	1.3	-59 ± 2	7.9 ± 2.9
2012 Apr 7	223.8	1.2	-76 ± 3	9.1 ± 3.7
2012 Jun 24	223.8	1.5	40 ± 1	11.0 ± 2.1
2012 Jul 30	223.8	1.0	13 ± 2	14.1 ± 2.4
2012 Sep 2	223.8	1.5	-13 ± 1	10.6 ± 1.2
2012 Oct 18	223.8	1.0	-41 ± 2	8.5 ± 3.0
2012 Oct 30	223.8	0.8	-49 ± 4	8.9 ± 4.7
2012 Nov 24	223.8	1.2	-86 ± 2	7.0 ± 3.1
2013 Mar 22	226.3	1.4	43 ± 1	10.6 ± 2.3
2013 Mar 23	226.3	1.4	29 ± 2	8.1 ± 4.3
2013 Aug 4	232.5	1.5	5 ± 1	7.0 ± 0.9
SMA 1.3 mm				
2012 Jun 24	224.9	2.5	34 ± 1	7.2 ± 1.7
2012 Jul 20	226.9	1.4	12 ± 1	7.6 ± 2.7
2012 Sep 7	224.9	1.8	-14 ± 1	5.9 ± 2.1
2013 Jan 23	225.3	1.5	73 ± 1	3.7 ± 2.6
2013 Jul 5	226.9	3.2	61 ± 1	10.5 ± 1.2
2013 Aug 15	226.9	1.4	12 ± 1	8.4 ± 3.0
SMA 0.9 mm				
2011 Aug 20	341.7	2.2	85 ± 3	6.4 ± 20.6
2012 Jun 15	343.0	2.0	4 ± 2	16.3 ± 13.8
2012 Jul 3	340.1	1.5	-9 ± 1	0.0 ± 8.9
2012 Aug 8	340.1	1.4	-38 ± 2	9.4 ± 15.7
2012 Sep 2	340.8	2.0	-46 ± 3	3.2 ± 17.9
2012 Oct 14	341.4	1.5	-67 ± 1	9.6 ± 9.1
2013 Feb 1	341.6	0.6	32 ± 4	-22.5 ± 22.8
2013 Aug 25	341.6	1.4	-20 ± 2	-9.7 ± 11.6

All the RM values at C3 at 43 GHz are positive.

All the RM values at 230 GHz are positive.

→ Again, we cannot rule out the possibility that polarized flux and RM at 230 GHz are dominated by C3

RM as a function of distance?



$$|RM| \propto d^{-2.7}$$

$$RM \propto \int_{LoS} n_e B dl$$

If the RM measured with the SMA 230 GHz is dominated by C3...

- RM values seem to be expressed as a function of distance.

SMA : May 2011 – Aug. 2013

$$M_{BH} = 5 \times 10^7 M_{Sun}$$

BU : Jan. 2016 – May 2017

$$\theta_{jet} = 45^\circ$$

KVN : Feb. 2018, Jan. 2019

VLBA : Oct.-Nov. 2014

Summary

- **Evidence of the ambient medium**
 - i) Faraday rotation is constant from 43 to 141 GHz
BU 43.0-43.2 GHz : $\langle RM \rangle = (3.3 \pm 0.4) \times 10^5 \text{ rad m}^{-2}$
KVN 86-141 GHz : $RM = (4.2 \pm 0.2) \times 10^5 \text{ rad m}^{-2}$
 - ii) No strong correlation between the flux and RM at C3.
 - iii) B-field orientation at C3 is perpendicular to the jet direction.
- **Polarized flux at C3 increases at higher frequencies.**
 - We cannot rule out the possibility that the RM measured with the SMA 230 GHz is dominated by C3.