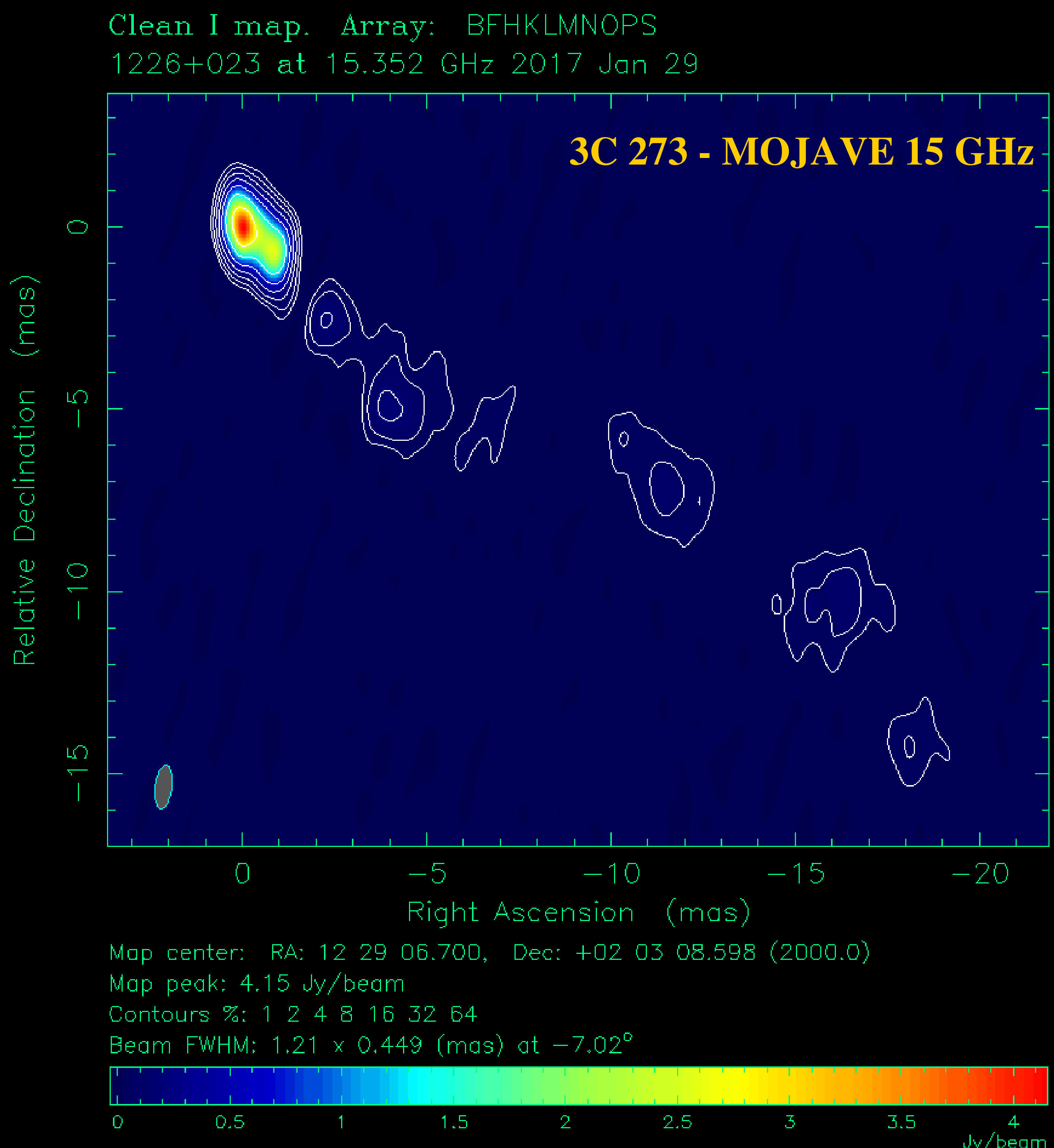
Revealing the nature of the core through multi-frequency polarization observations with the **KVN, SMA, and JCMT**

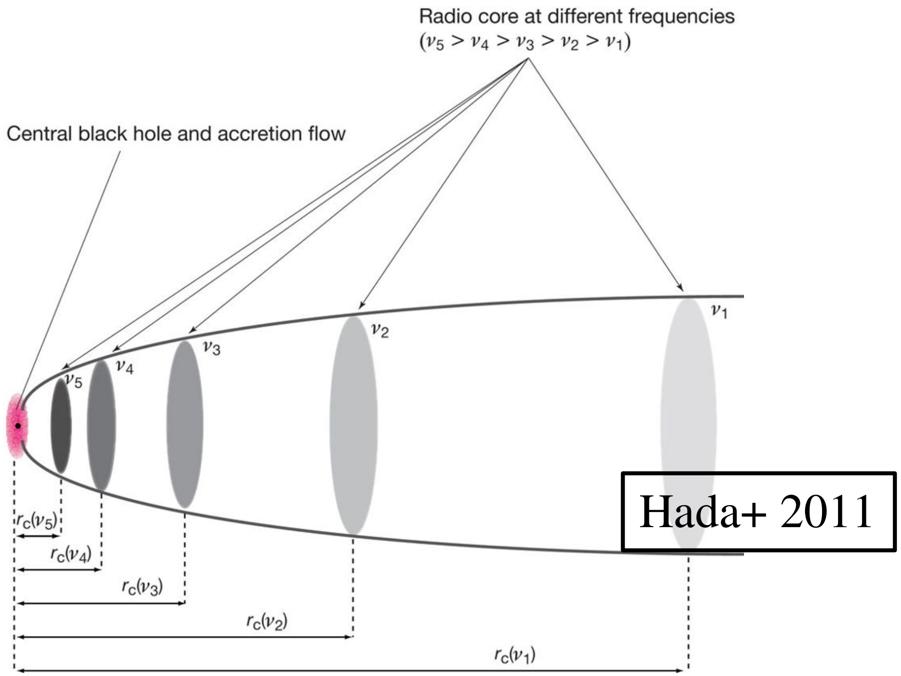
Jan. 2019 | Hilo

Minchul Kam & Naeun Shin


Clean I map. Array: BFHKLMNOPS
1226+023 at 15.352 GHz 2017 Jan 29
3C 273 - MOJAVE 15 GHz
Relative Declination (mas)
0
−5
−10
−15
0
−5
−10
−15
−20
Right Ascension (mas)
Map center: RA: 12 29 06.700, Dec: +02 03 08.598 (2000.0)
Map peak: 4.15 Jy/beam
Contours %: 1 2 4 8 16 32 64
Beam FWHM: 1.21 x 0.449 (mas) at −7.02°
0
0.5
1
1.5
2
2.5
3
3.5
4
Jy/beam

- What is the core?

1. τ=1 surface

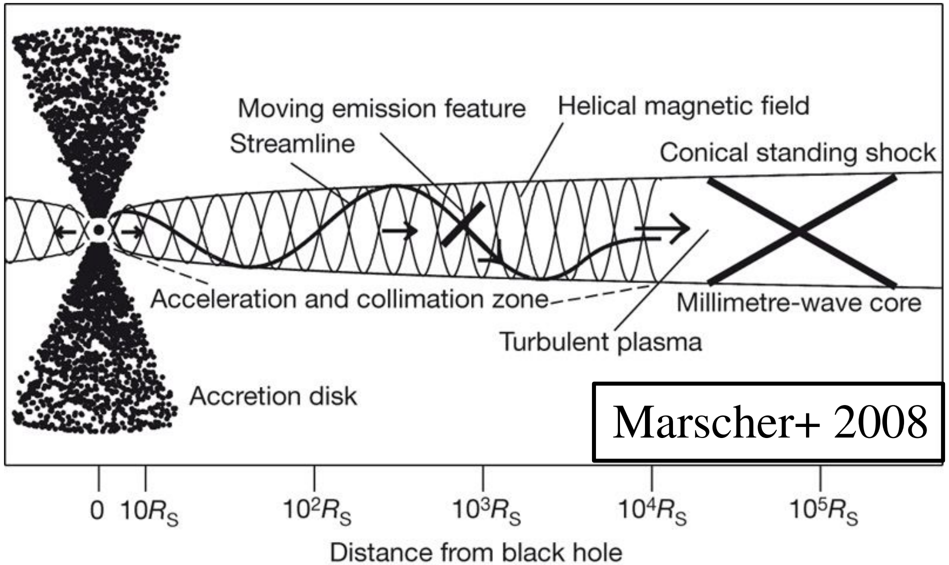


The core location is dependent of ν due to SSA

→ the core-shift effect is observed

(e.g., O'Sullivan & Gabuzda 2009).

2. Standing (recollimation) shock



The core location is independent of ν when ν is high enough

→ the core-shift effect is not expected

(e.g., Dodson+ 2017).

- What is the core?

1. τ=1 surface

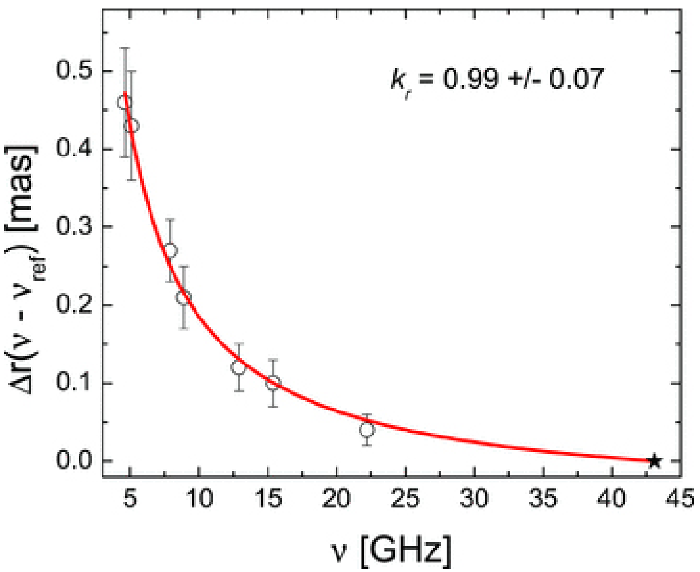
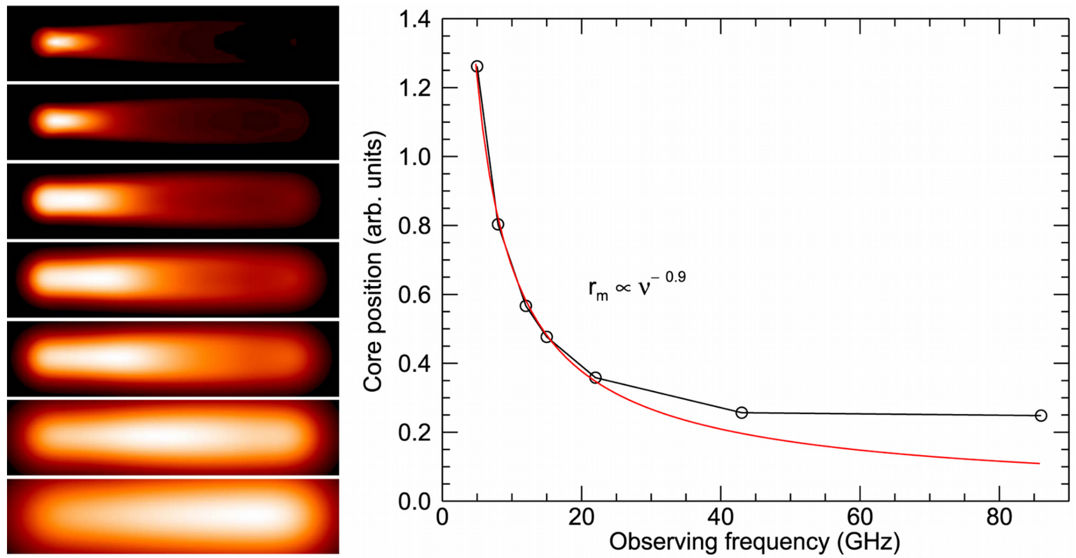


Table 3. Averaged core-shifts using 43 GHz as the reference frequency for 2200+420, plotted in Fig. 3.

ν (GHz)	Δr (mas)	$\Delta r_{\rm projected}$ (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

2. Standing (recollimation) shock



Dodson+ 2017

The core location is independent of ν when ν is high enough

→ the core-shift effect is not expected (e.g., Dodson+ 2017).

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

$N_e \propto d^{-a}$ — Power-law assumption α = 2 : Conical or Spherical Jets

$B_{\|} \propto d^{-1}$ — Dominated by BΦ

$B_z \propto d^{-2}$ $B_\phi \propto d^{-1}$ — Prediction of helical B -field geometry

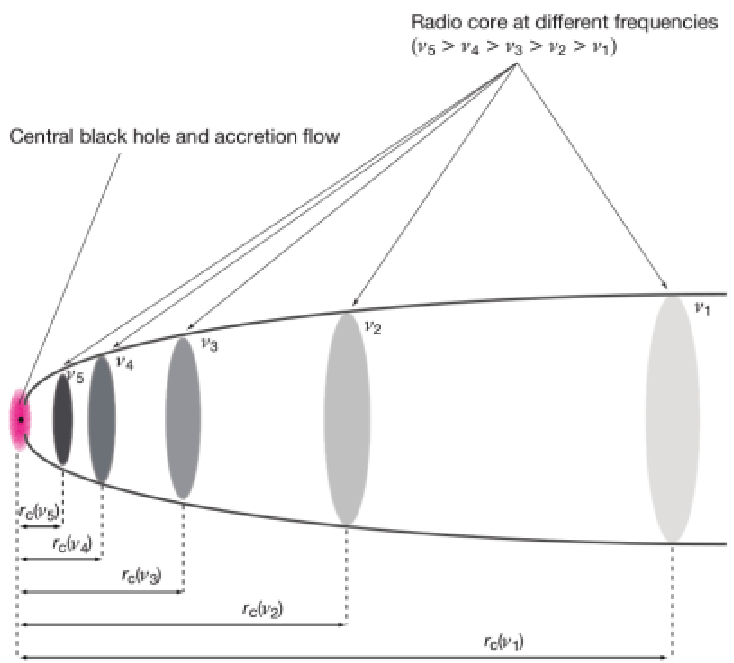
$$\rightarrow |\mathrm{RM}| \propto d^{-a} \quad (a=2)$$

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

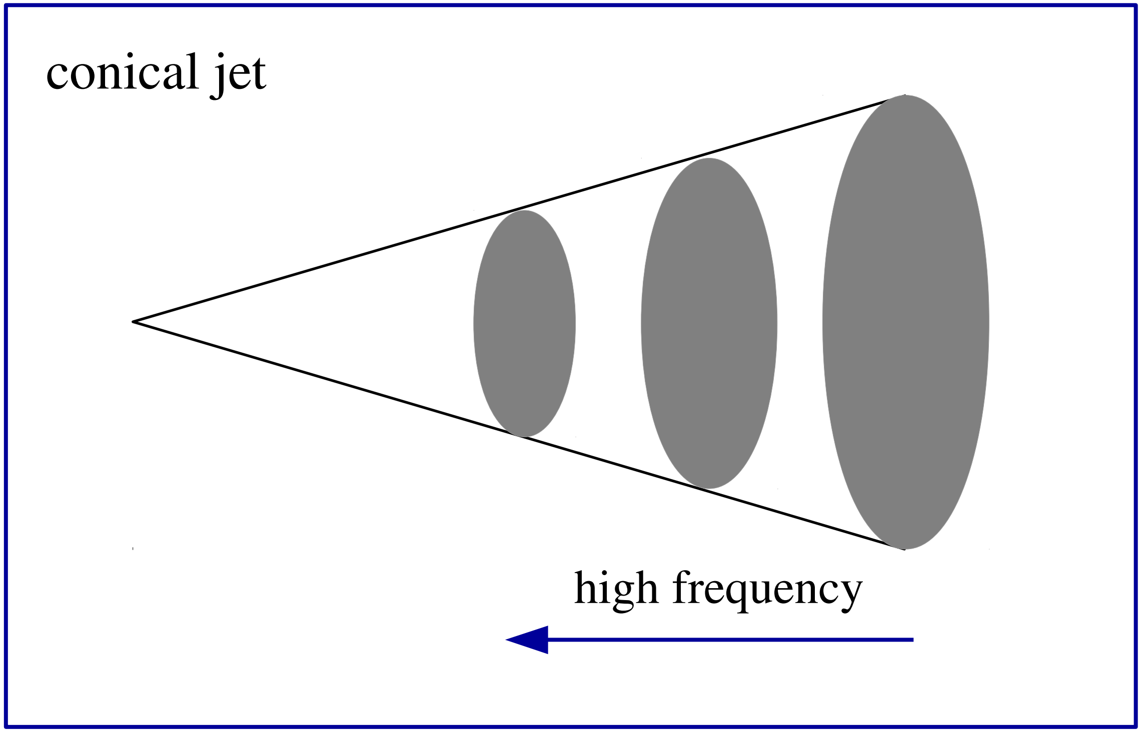
Jorstad+ 2007

$$d_{\mathrm{core},\nu} \propto \nu^{-1} \rightarrow |\mathrm{RM}_{\mathrm{core},\nu}| \propto \nu^{a} \quad (\alpha=2)$$

"Core-shift" effect in AGN Jets



Hada+2011



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Prediction of helical B -field geometry

→ $|RM| \propto d^{-a}$ (a=2)

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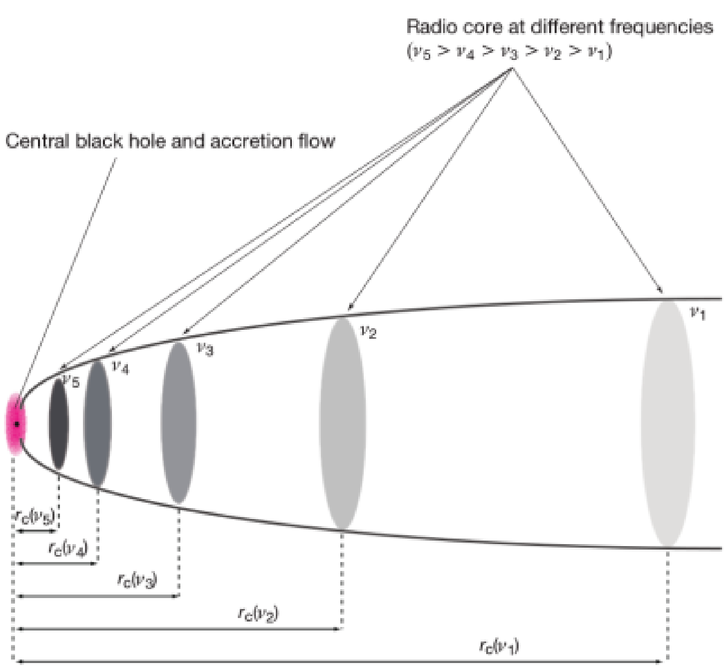

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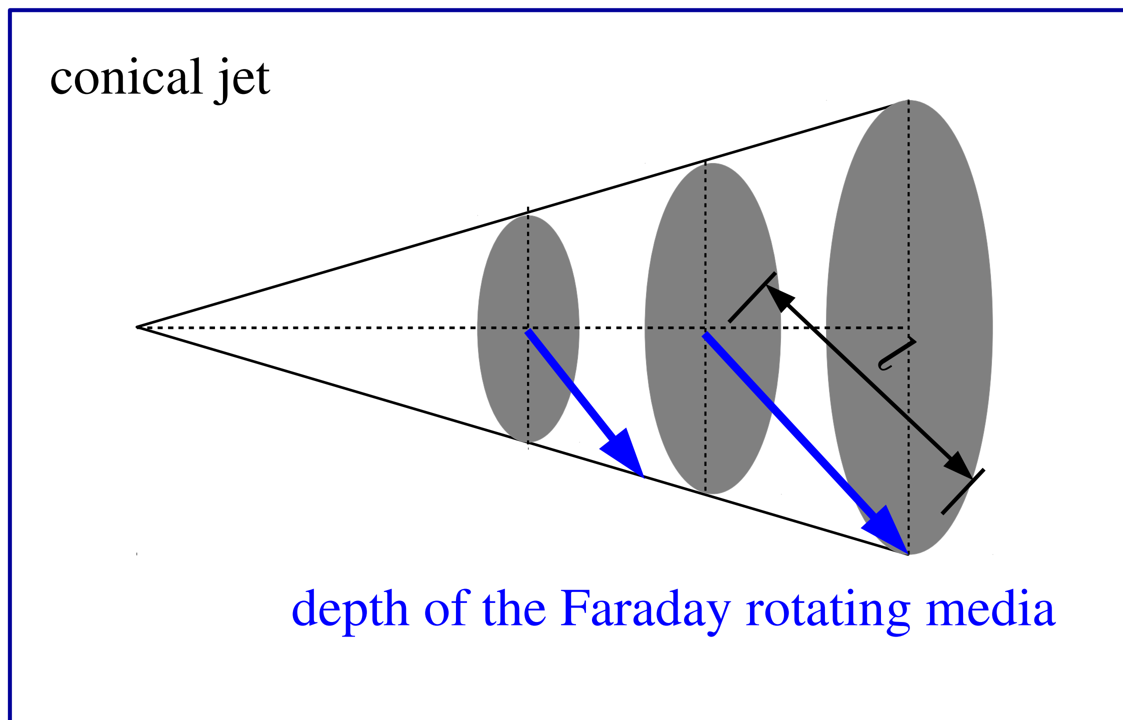

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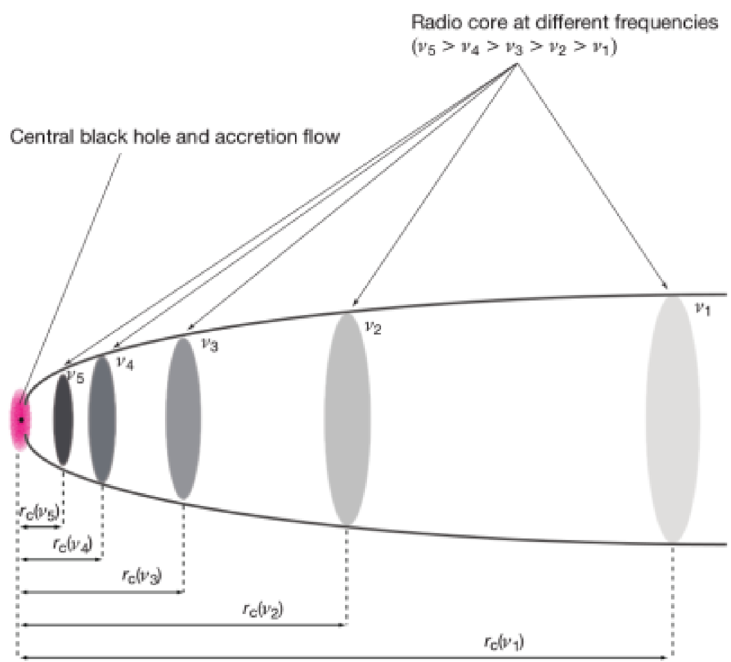
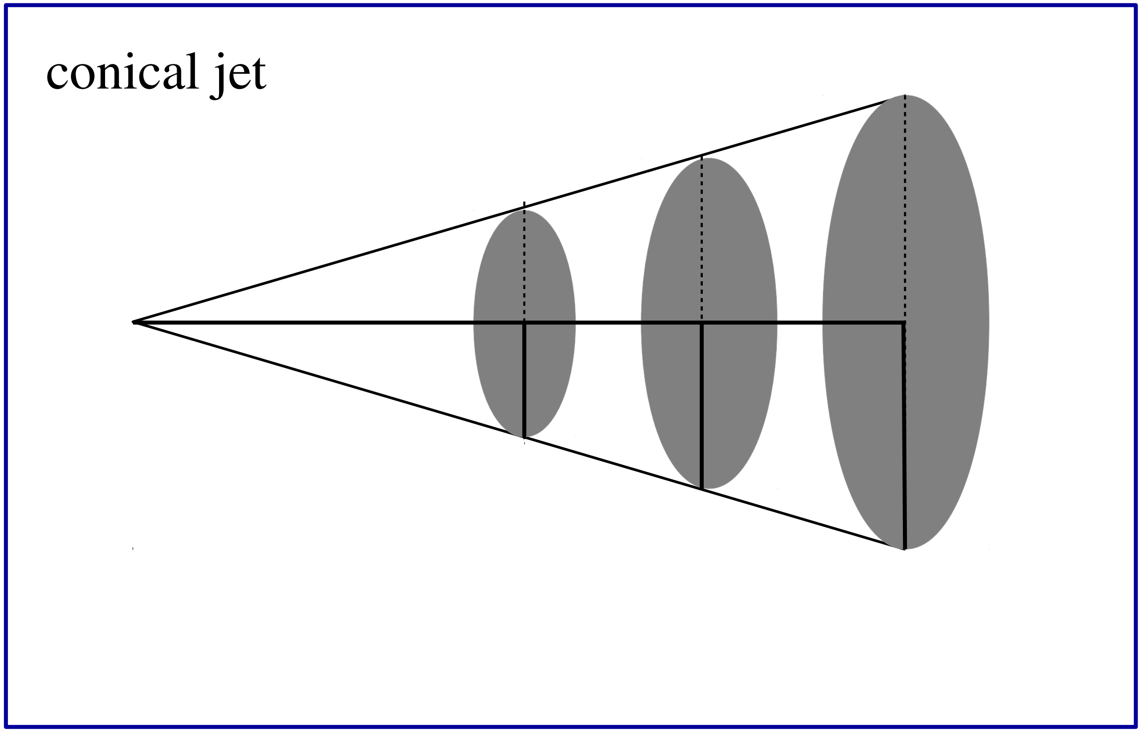


Hada+2011



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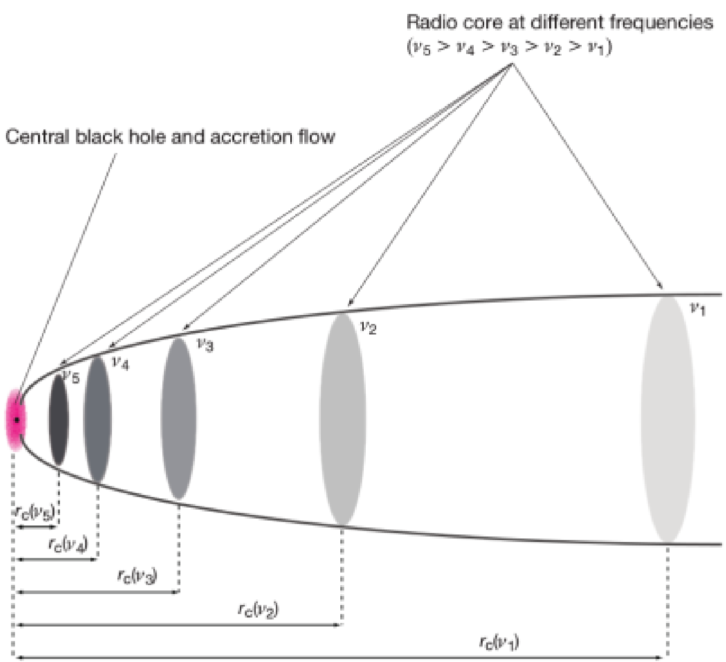

Hada+2011

helical B-field = radial + toroidal

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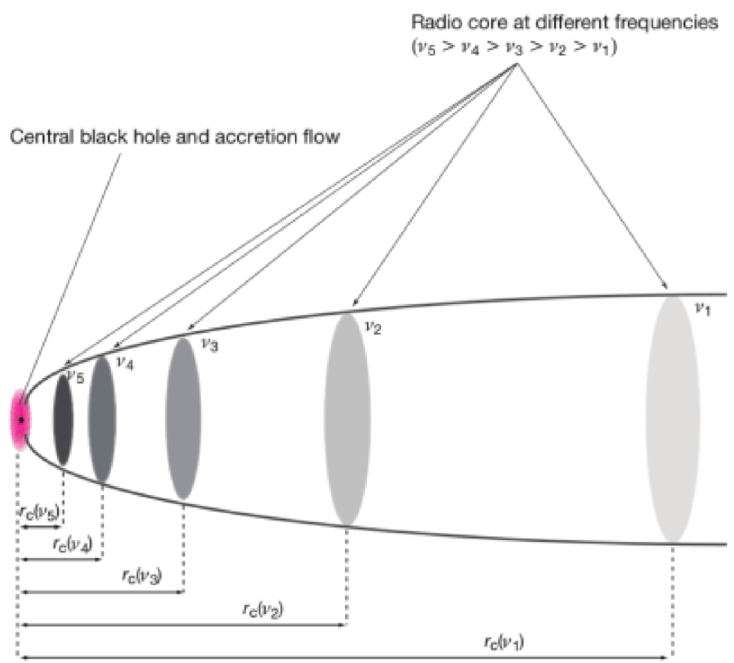

Hada+2011

$$RM \propto \int N_e B \, dl$$

$$l \propto d^{+1}$$

$$N_e \propto d^{-2}$$

$$B \propto d^{-1}$$

$$RM \propto d^{-2}$$

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→ $|\mathrm{RM}| \propto d^{-a}$ (a=2)

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$d_{\mathrm{core},\nu} \propto \nu^{-1}$ → $|\mathrm{RM}_{\mathrm{core},\nu}| \propto \nu^{a}$ (α=2)   Jorstad+ 2007

- 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)

limited frequency < 43 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.

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→ 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.

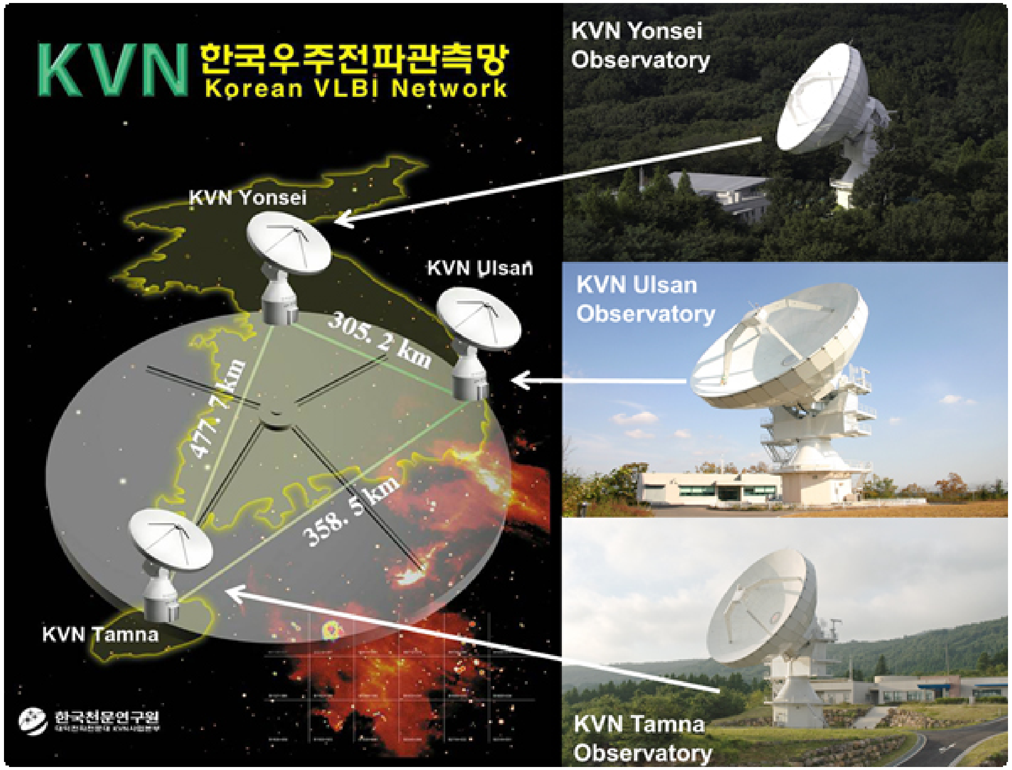
covers high frequencies
not simultaneous observation
small number of targets

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

→ We have launched a KVN large program.

- KVN monitoring program

1. Period : Dec. 2016 ~
2. Number of targets : 14 (the largest number!)
3. Frequency
   1) 22 / 43 / 86 / 129 GHz (~ May. 2018)
   2) 22 / 43 / 86 / 94 GHz (Jun. 2018 ~)



- simultaneous observation at 2 frequencies → **4 frequency within only 2 days!**

- The number of the **VLBI** available for **polarimetry at > 86 GHz** is very small.

- Obtaining the observation time for monthly monitoring is very difficult.

- **The only VLBI polarimetric monitoring program at multi-frequencies including > 86 GHz.**

- monitoring for > 3 years → **time evolution analysis** is possible !

Period : 2016 DEC ~

p16st01i (22 & 86GHz), p16st01j (43 & 86GHz) / Dec 9, 10

p17st01a (22 & 86GHz), p17st01b (43 & 129GHz) / Jan 16, 17

p17st01c (22 & 86GHz), p17st01d (43 & 129GHz) / Feb 26, 27

p17st01e (22 & 86GHz), p17st01f (43 & 129GHz) / Mar 22, 23

p17st01g (22 & 86GHz), p17st01h (43 & 129GHz) / Apr 21, 22

p17st01i (22 & 86GHz), p17st01j (43 & 129GHz) / Jun 1, 2

p17st02a (22 & 86GHz), p17st02c (43 & 129GHz) / Sep. 24, 25

p17st02d (22 & 86GHz), p17st02e (43 & 129GHz) / Oct. 25, 26

p17st02f (22 & 86GHz) , p17st02g (43 & 129GHz) / Nov. 17, 18

p17st02h (22 & 86GHz) , p17st02i (43 & 129GHz) / Dec. 15, 16

p18st01a (22 & 86GHz) , p18st01b (43 & 139GHz) / Feb. 12, 13

p18st01e1 (22 & 86GHz) , p18st01f1 (43 & 129GHz) / May. 1, 2

p18st01g (22 & 86GHz) , p18st01h (43 & 94GHz) / Jun. 8, 9

p18st01i (22 & 86 GHz), p18st01j (43 & 94 GHz) / Oct. 2, 3

p18st01k (22 & 86 GHz), p18st01l (43 & 94 GHz) / Oct.31 & Nov.1

p18st01m (22 & 86 GHz), p18st01n (43 & 94 GHz) / Nov.30 & Dec.1

test – various targets

fixed 14 targets

We had 800 hr observation for the last 2 years.

	DEC 2016	JAN 2017	FEB	MAR	APR	JUN
3C84	O	O	O	O	O	O
3C273	O	O	O	O	O	O
3C279	O	O	O	O	O	O
OJ287	O	O	O	O	O	O
3C454.3	O	O	O	O	O	O
CTA102	O	O	O		O	O
3C345	O	O	O		O	
1510-089	O	O	O	O	O	O
1749+096			O	O		O
BLLAC			O	O	O	
1055+018			O	O	O	
1611+343					O	
1633+382				O		
0235+164				O	O	O
NRAO 530					O	
0716+714					O	O
3C120					O	
0336-019					O	

Targets of the KVN monitoring program (Sep. 2017 ~)

[Quasars – 8]

3C 273 (z~0.158)

3C 279 (z~0.538)

3C 345 (z~0.595)

3C 454.3 (z~0.859)

NRAO530 (z~0.902)

CTA102 (z~1.037)

NRAO150 (z~1.51)

1633+38 (z~1.814)

[BL Lac – 5]

BL Lac (z~0.069)

0716+714 (z~0.3)

OJ287 (z~0.306)

1749+096 (z~0.322)

0235+164 (z~0.94)

[Radio galaxy – 1]

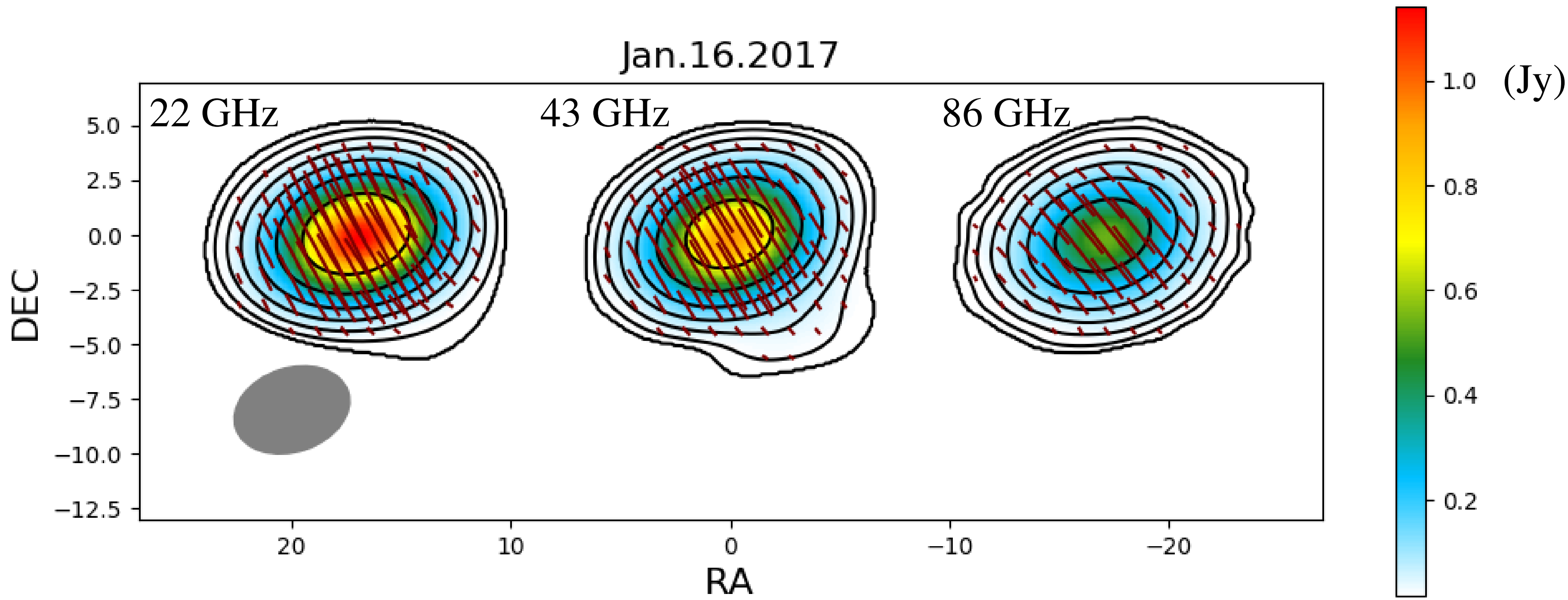
3C 84 (z~0.018)

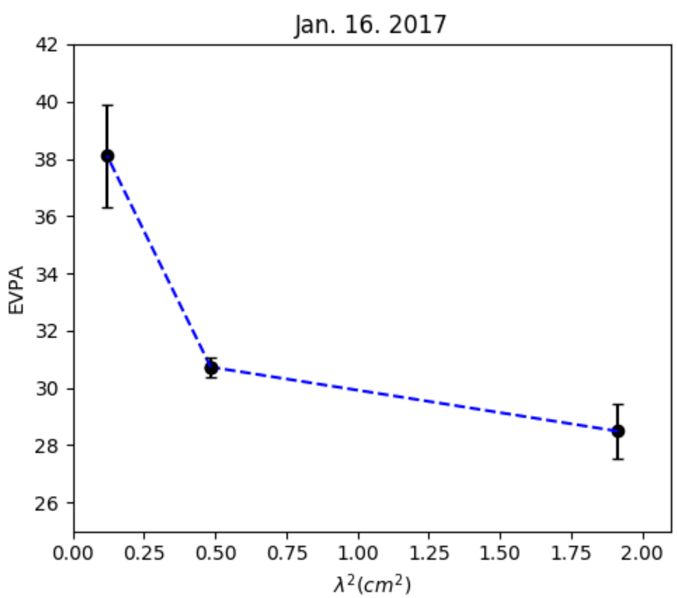
Total : 14 sources

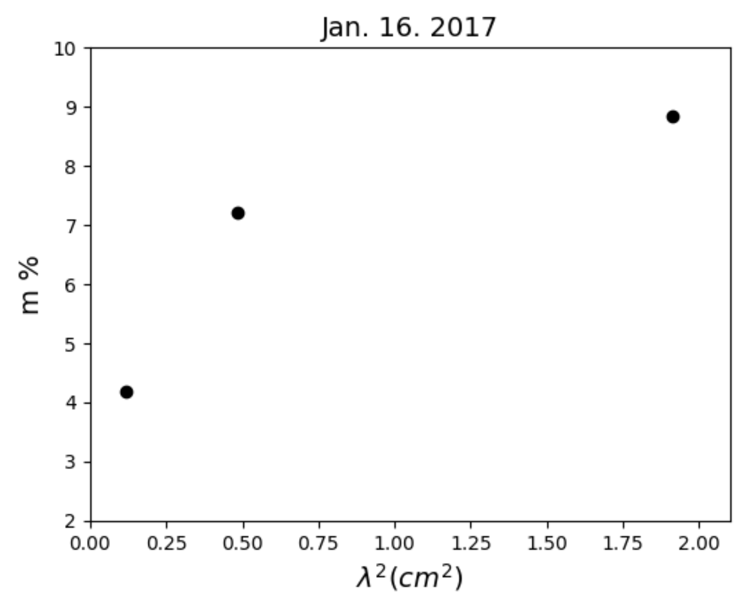
	DEC 2016	JAN 2017	FEB	MAR	APR	JUN
3C84	O	O	O	O	O	O
3C273	O	O	O	O	O	O
3C279	O	O	O	O	O	O
OJ287	O	O	O	O	O	O
3C454.3	O	O	O	O	O	O
CTA102	O	O	O		O	O
3C345	O	O	O		O	
1510-089	O	O	O	O	O	O
1749+096			O	O		O
BLLAC			O	O	O	
1055+018			O	O	O	
1611+343					O	
1633+382				O		
0235+164				O	O	O
NRAO 530					O	
0716+714					O	O
3C120					O	
0336-019					O	

Polarization maps at 22 / 43 / 86 GHz

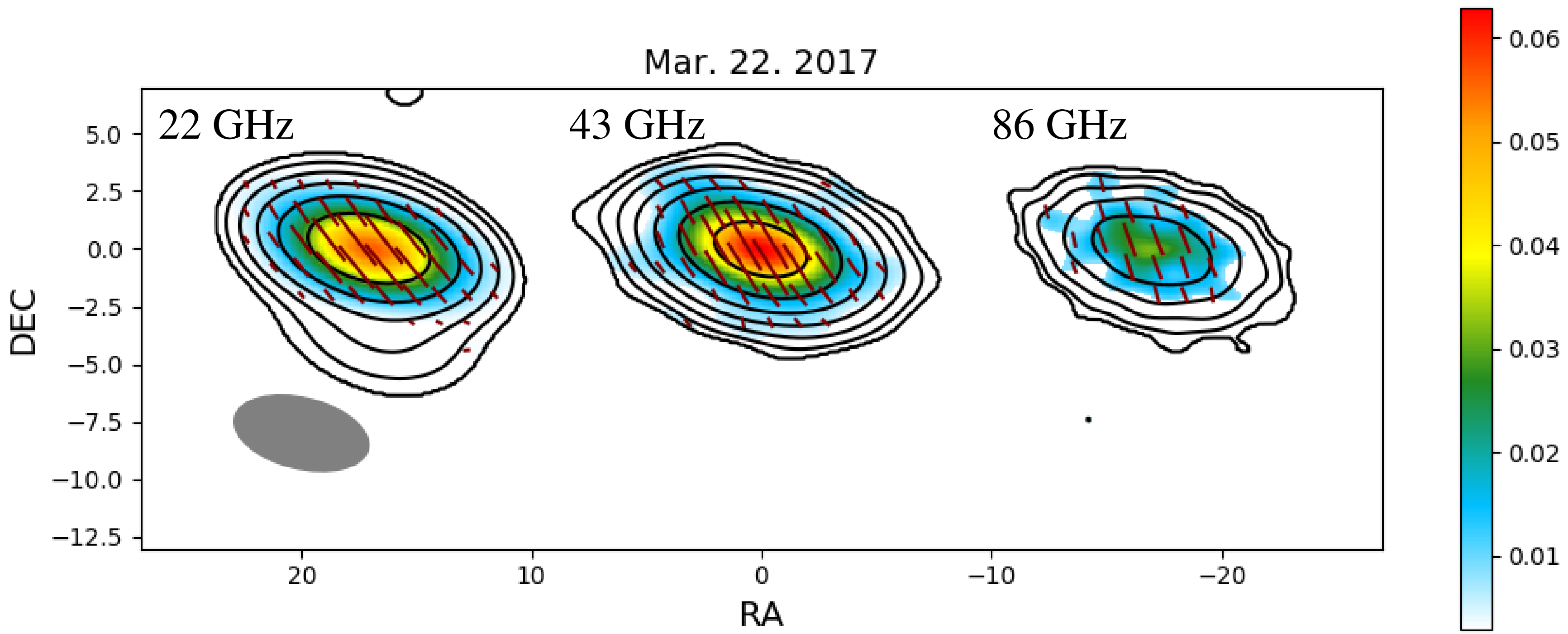
- 3C 279 (Jan. 2017)

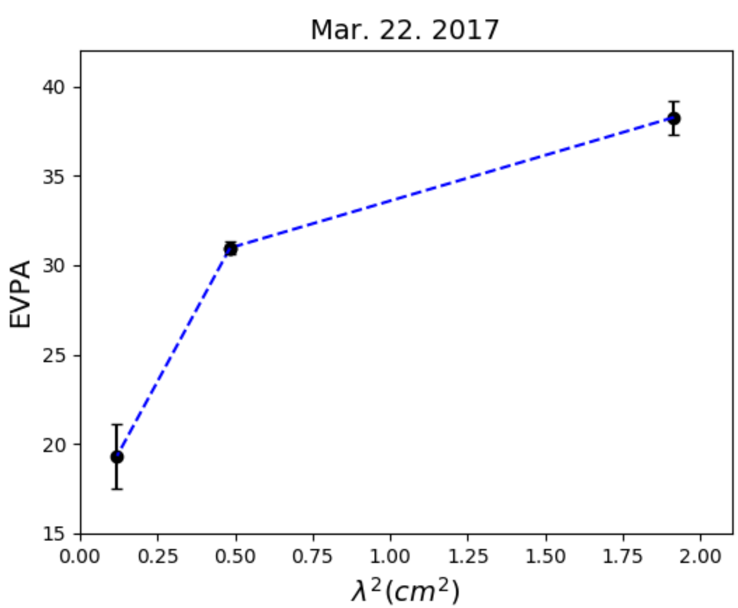


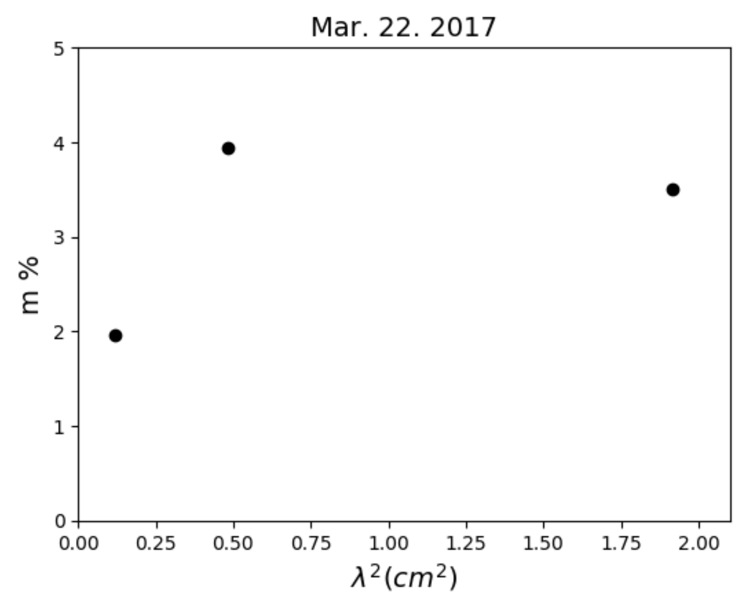




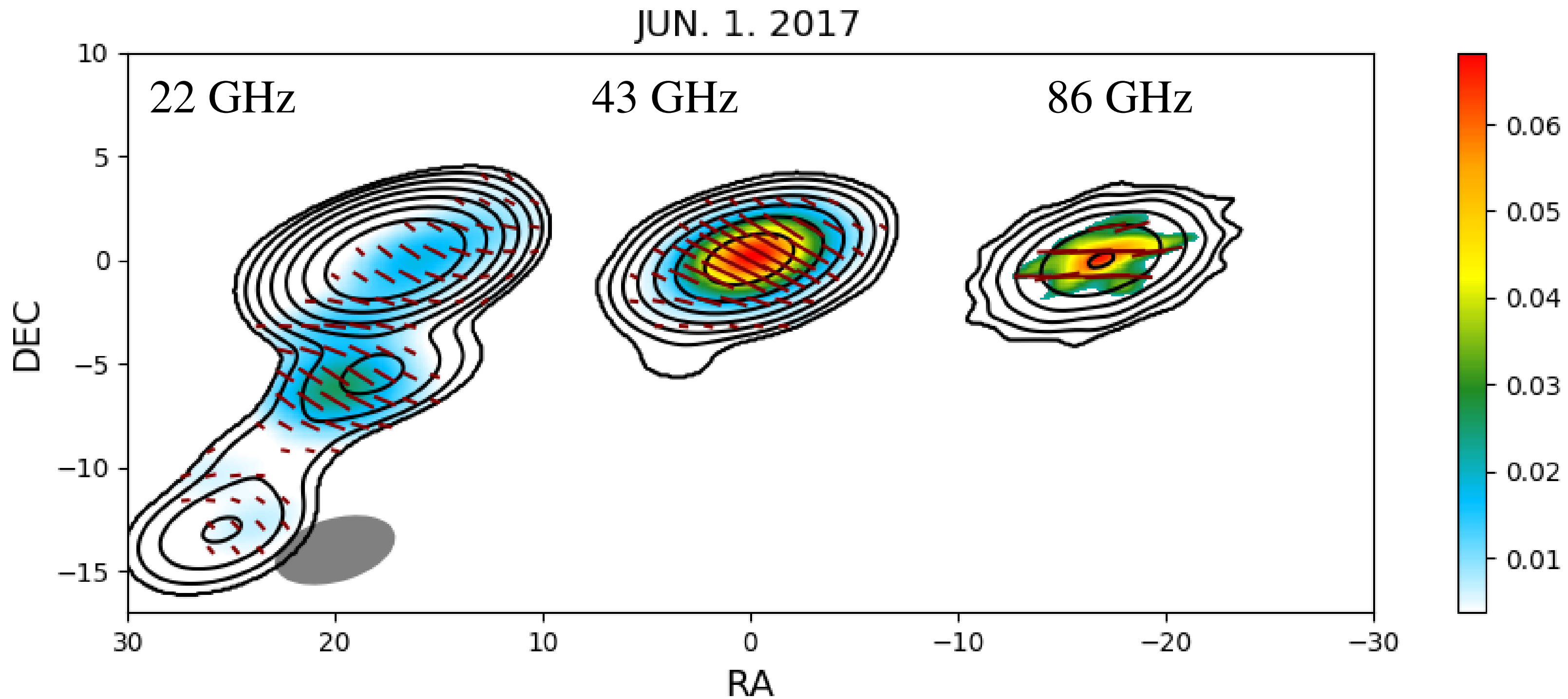
- BL Lac (Mar. 2017)

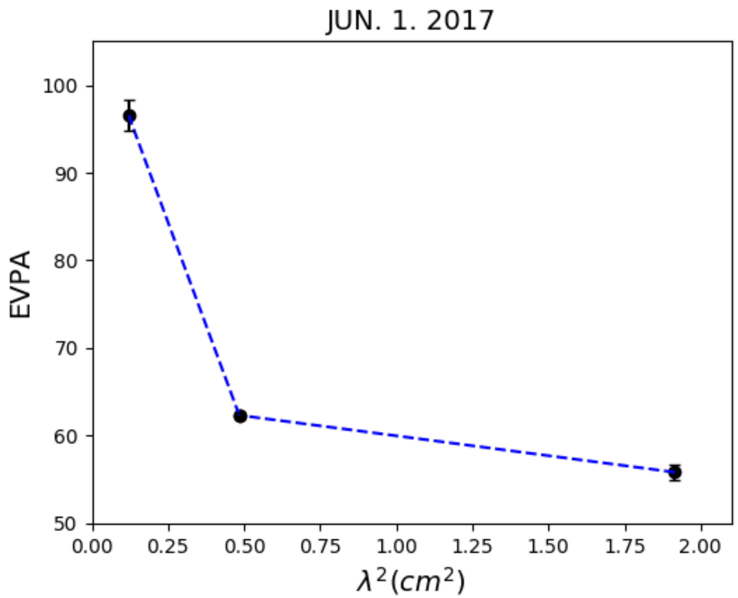


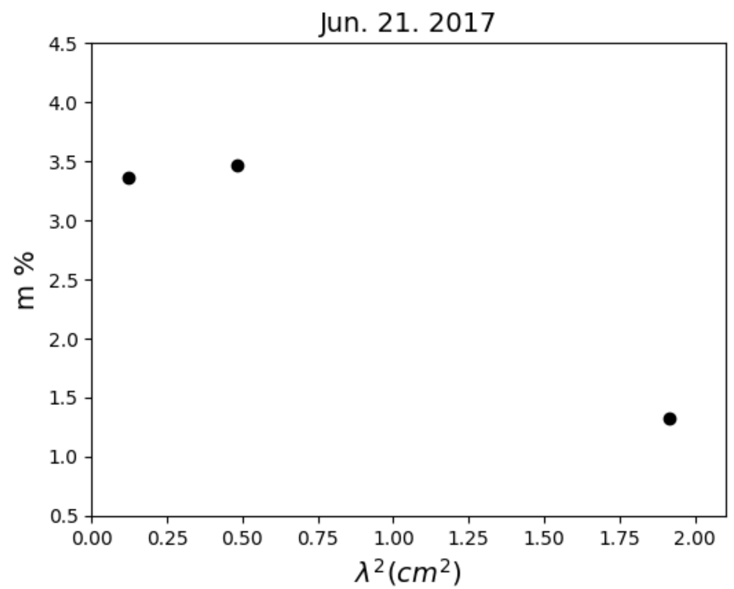




- CTA 102 (Jun. 2017)





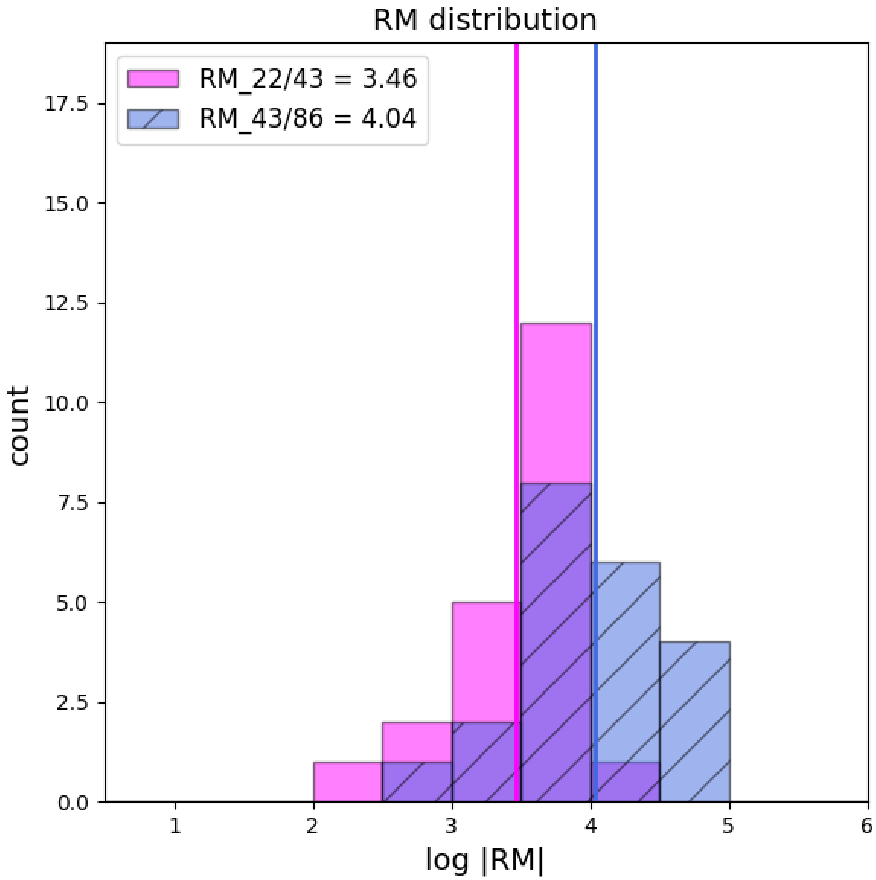


Result I : RM distribution

Result II : RM $\leftrightarrow$ frequency

Result III : Transition frequency

- Result I : RM distribution



RM (22 ↔ 43 GHz) ~ $2900\, rad/m^2$

RM (43 ↔ 86 GHz) ~ $11000\, rad/m^2$

RM increases at higher frequency!

~~3C 273~~, 3C 279, 3C 345, ~~3C 454.3~~, ~~OJ287~~, BLLAC, CTA102, 0235+164, 0336-019, 0716+714, 1055+018, ~~1510-089~~, 1611+343, 1633+38, 1749+096, ~~NRAO530~~

→ excluded the sources with complex polarization structures near the core

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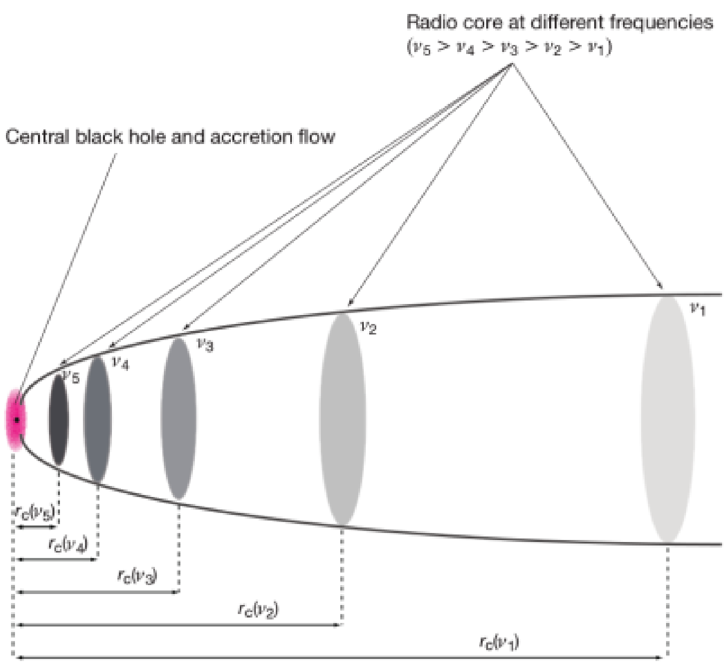

Hada+2011

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Jorstad+ 2007

$$d_{\mathrm{core},\nu} \propto \nu^{-1} \longrightarrow \boxed{|\mathrm{RM}_{\mathrm{core},\nu}| \propto \nu^{a}} \ (\alpha=2)$$

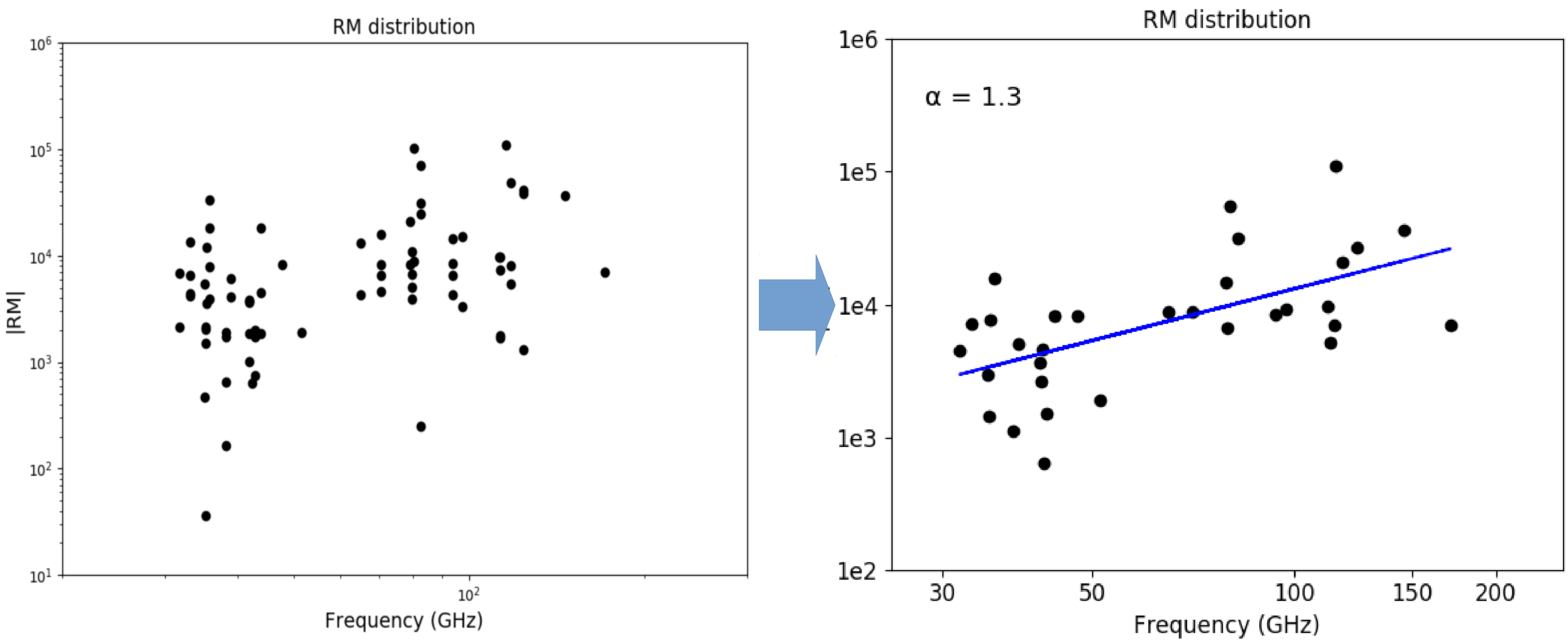
If there is core-shift effect, α~2

If there is no core-shift, α < 2

low freq (cm) → α ~ 2

high freq (mm/sub-mm) → α < 2

- Result II : α distribution



α~1.3 : smaller than 2 → deviate from the conical jet assumption !

→ smaller α at higher frequency?

→ Will the RM be saturated at higher frequency?

Result I : RM distribution

Result II : RM $\leftrightarrow$ frequency

Result III : Transition frequency

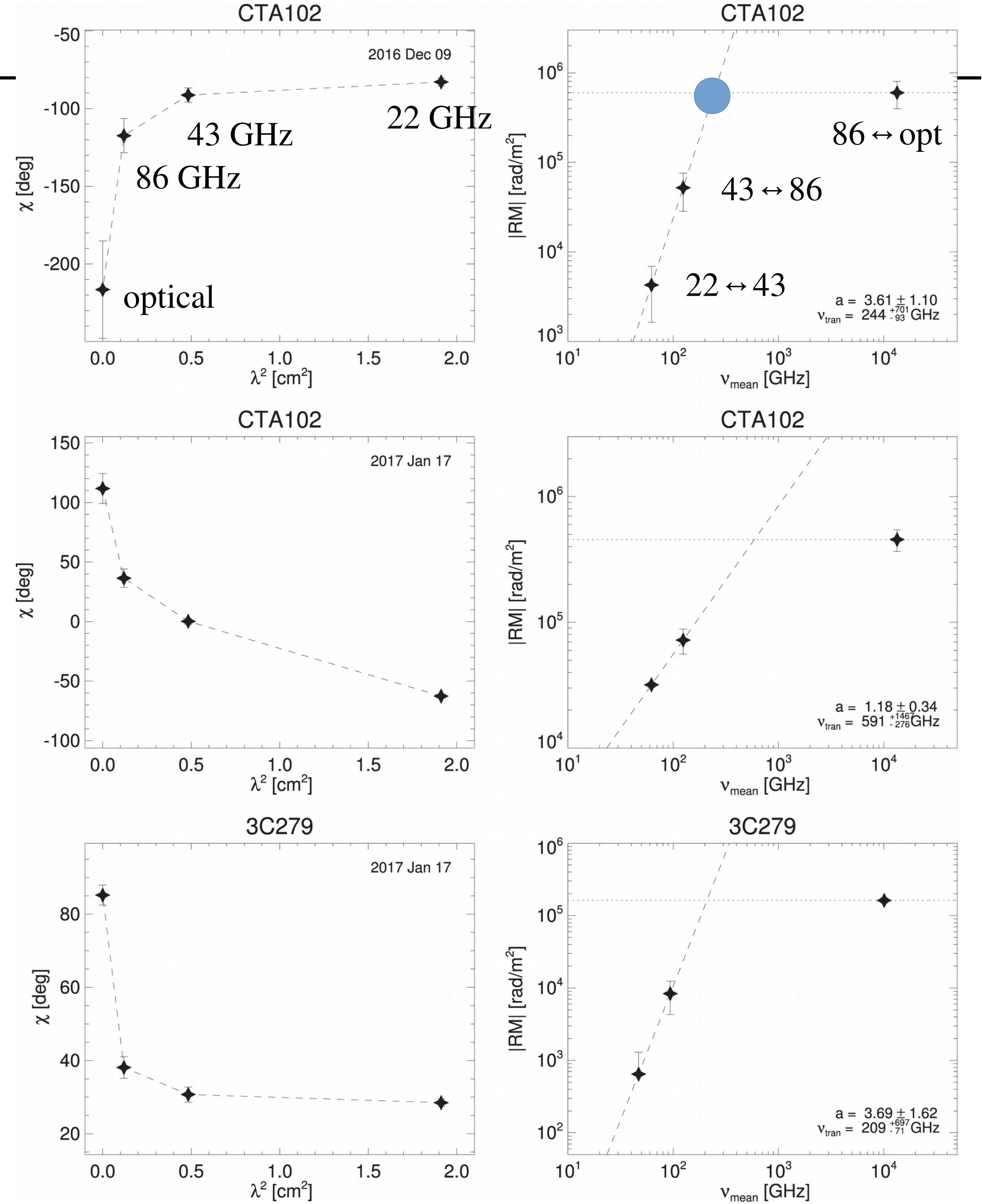
- Result III : Transition frequency

assumption :

1. RM will be saturated at high freq.
2. the saturated RM = RM (86 ↔ opt)

The transition frequencies span

138 GHz ~ 591 GHz (rest frame)



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Revealing the Nature of Blazar Radio Cores through Multifrequency Polarization Observations with the Korean VLBI Network

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Abstract

We study the linear polarization of the radio cores of eight blazars simultaneously at 22, 43, and 86 GHz with observations obtained by the Korean VLBI Network (KVN) in three epochs between late 2016 and early 2017 in the frame of the Plasma-physics of Active Galactic Nuclei project. We investigate the Faraday rotation measure (RM) of the cores; the RM is expected to increase with observing frequency if core positions depend on frequency owing to synchrotron self-absorption. We find a systematic increase of RMs at higher observing frequencies in our targets. The RM–ν relations follow power laws with indices distributed around 2, indicating conically expanding outflows serving as Faraday rotating media. Comparing our KVN data with contemporaneous optical polarization data from the Steward Observatory for a few sources, we find indications that the increase of RM with frequency saturates at frequencies of a few hundred gigahertz. This suggests that blazar cores are physical structures rather than simple $\tau = 1$ surfaces. A single region, e.g., a recollimation shock, might dominate the jet emission downstream of the jet-launching region. We detect a sign change in the observed RMs of CTA 102 on a timescale of ≈1 month, which might be related to new superluminal components emerging from its core undergoing acceleration/deceleration and/or bending. We see indications for quasars having higher core RMs than BL Lac objects, which could be due to denser inflows/outflows in quasars.

But we have two difficulties.

1. Frequency gap between 86 GHz $\leftrightarrow$ opt is too far.

2. How do we know that the core flux is larger than the flux coming from the region beyond the core?

- Result III : Transition frequency

assumption :

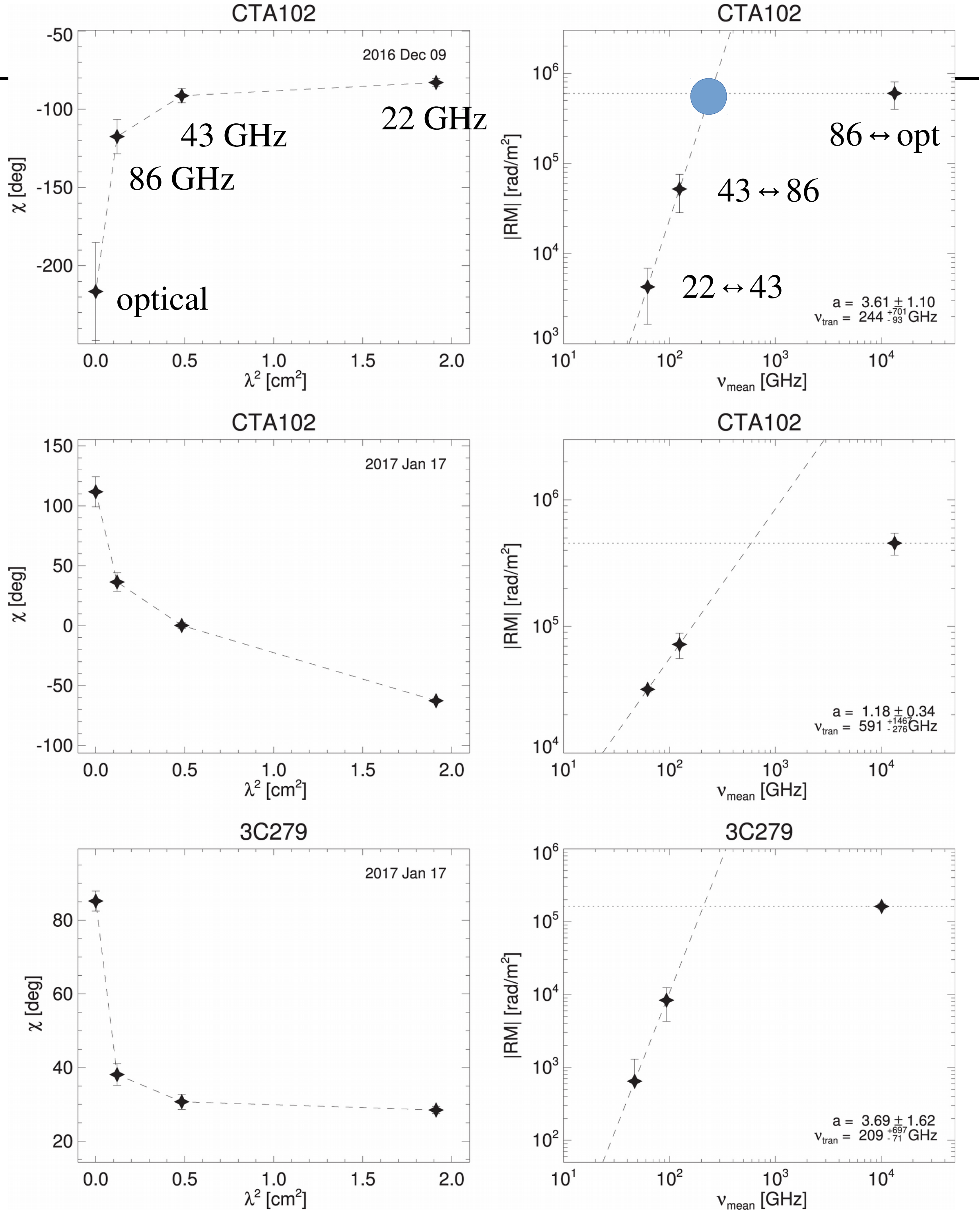
1. RM will be saturated at high freq.

2. the saturated RM = RM (86 ↔ opt)

The transition frequencies span

138 GHz ~ 591 GHz (rest frame)

Frequency gap between 86 GHz ↔ opt is too far → need to fill the gap!



The SMA & JCMT (230~350 GHz) cover the frequency gap!

[Quasars – 8]

3C 273 (z~0.158)

3C 279 (z~0.538)

3C 345 (z~0.595)

3C 454.3 (z~0.859)

NRAO530 (z~0.902)

CTA102 (z~1.037)

NRAO150 (z~1.51)

1633+38 (z~1.814)

[BL Lac – 5]

BL Lac (z~0.069)

0716+714 (z~0.3)

OJ287 (z~0.306)

1749+096 (z~0.322)

0235+164 (z~0.94)

[Radio galaxy – 1]

3C 84 (z~0.018)

KVN : 22 ~ 94 GHz → 23.5 ~ **265** GHz

KVN + SMA / JCMT : 22 ~ 350 GHz → 23.5 ~ **1000** GHz !!

- The SMA / JCMT data connect the KVN ↔ optical !

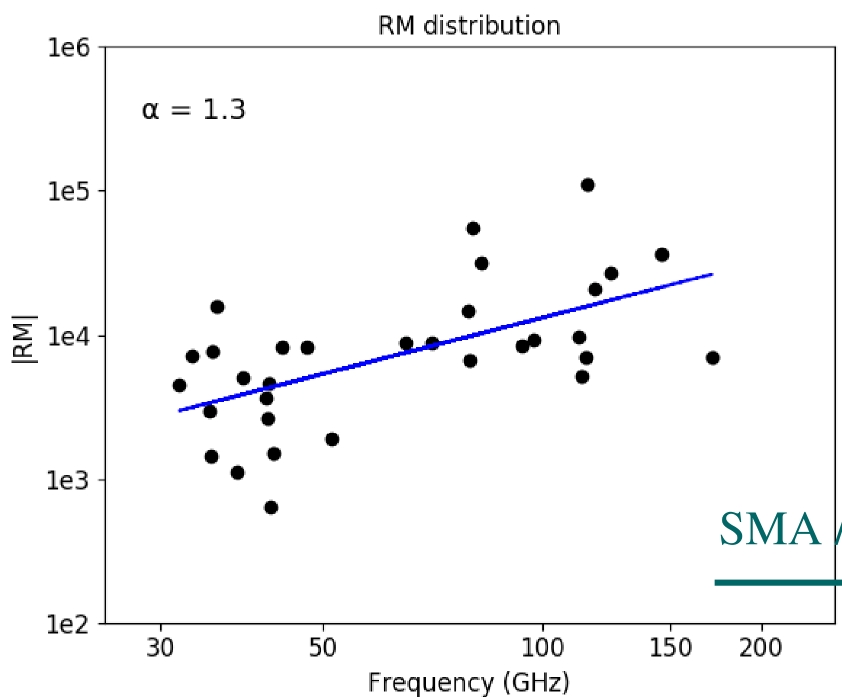
KVN + SMA / JCMT observation :

→ 22 / 43 / 86 / 94 / 129 / 141 / 230 / 340 GHz

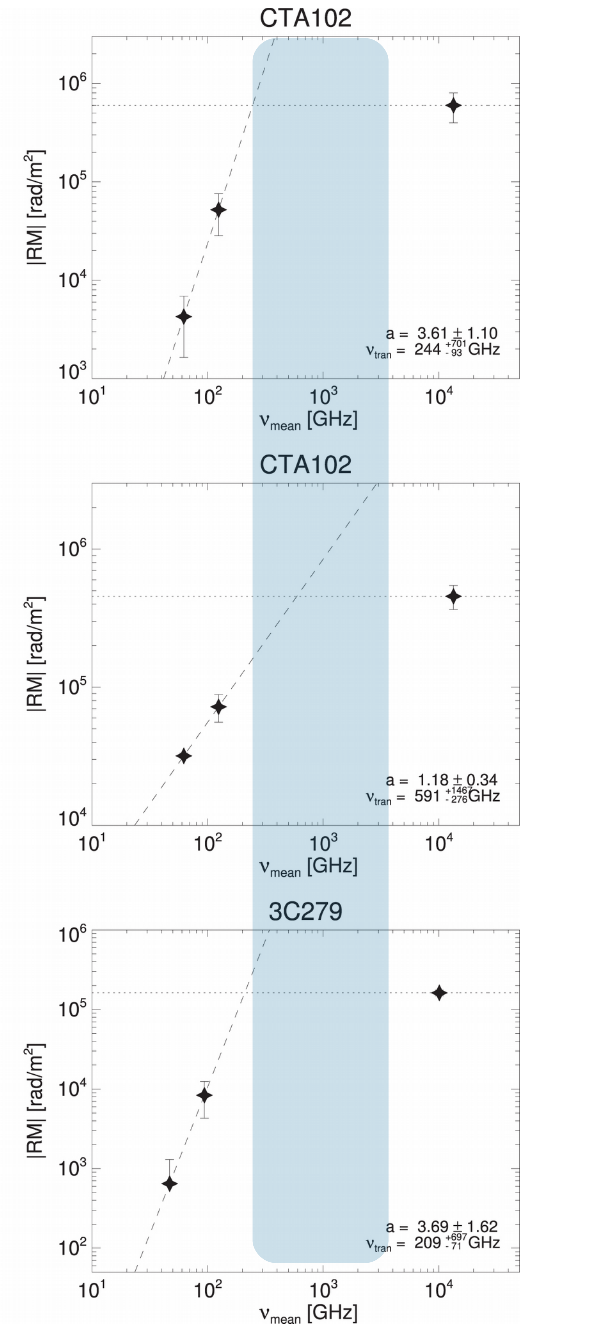
KVN (VLBI) (S/D) SMA & JCMT

→ fill the frequency gap between the KVN ↔ optical

→ more realistic saturated RM & transition frequency



SMA / JCMT

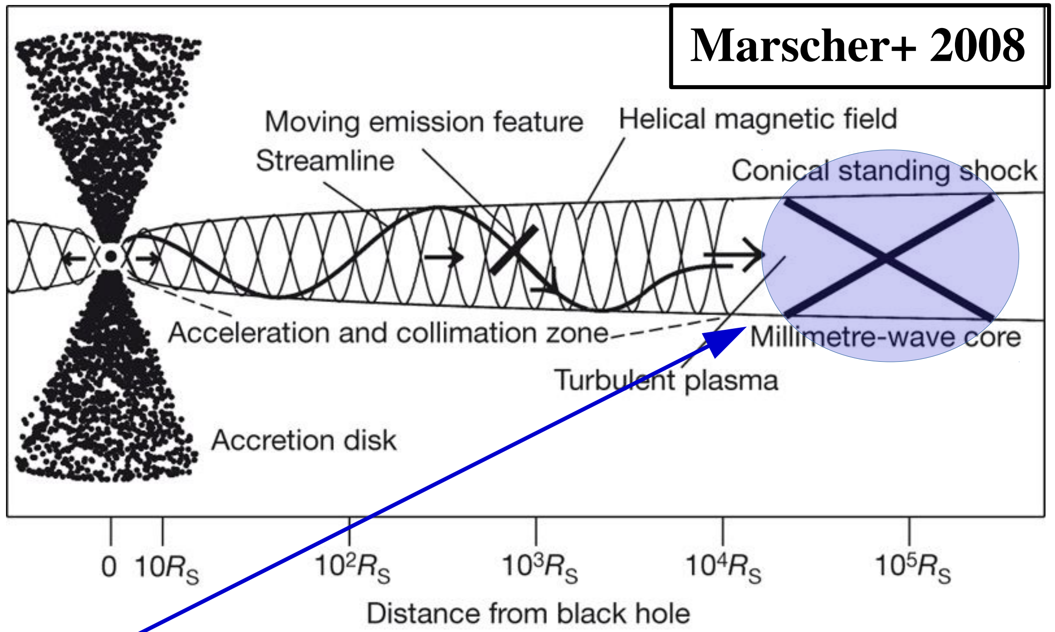


But we have two difficulties.

1. Frequency gap between 86 GHz $\leftrightarrow$ opt is too far.

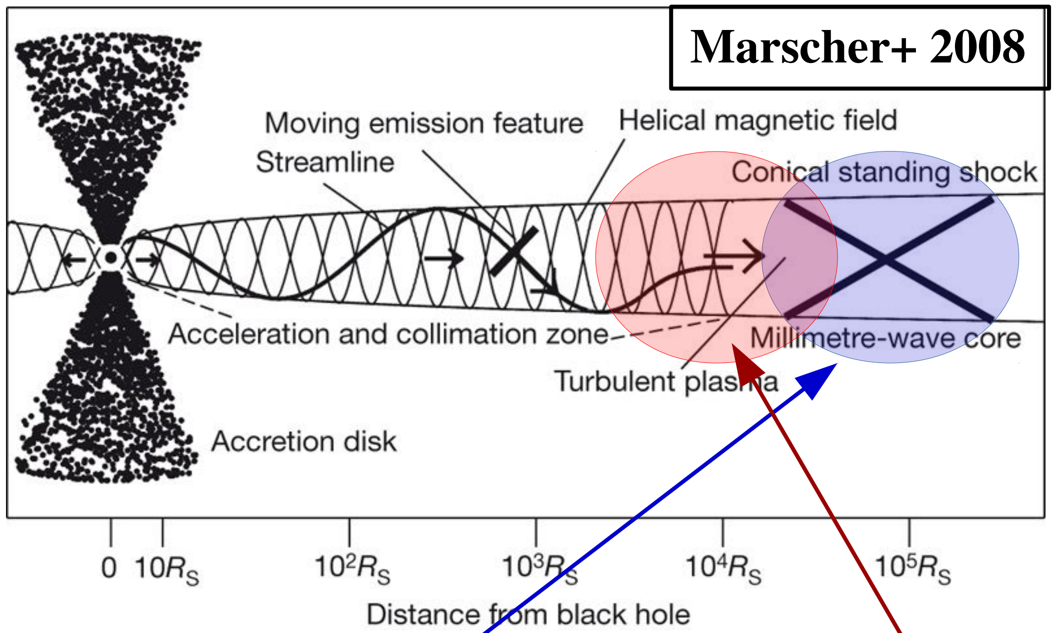
2. How do we know that the core flux is larger than the flux coming from the region beyond the core?

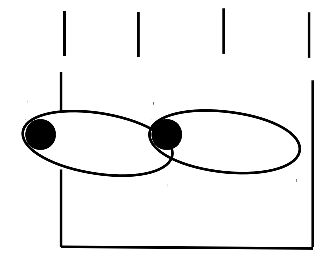
- The recollimation shock is the brightest region?



If the recollimation shock exists, the core RM will be saturated.

- The recollimation shock is the brightest region?



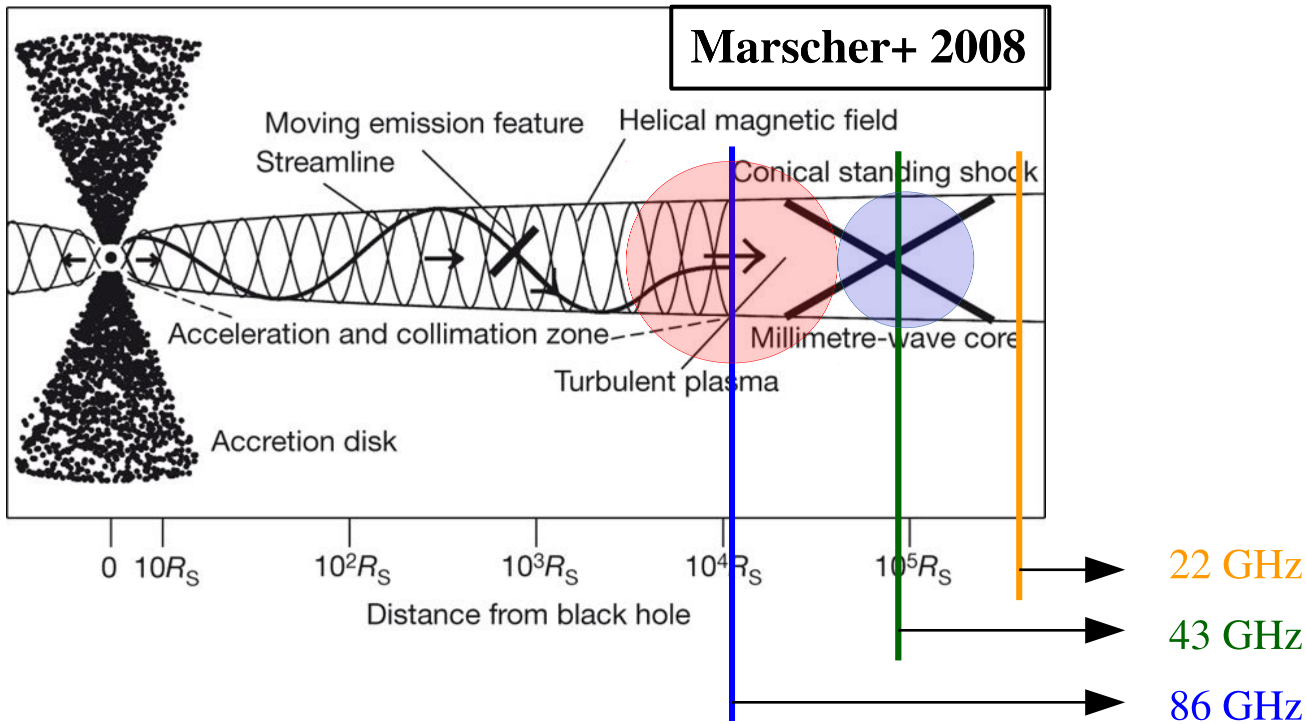


If the recollimation shock exists, the core RM will be saturated.

→ assumption : the recollimation shock > the emission from deeper region beyond the core

→ If not, RM would keep increasing at higher frequency even though the recollimation shock exists (deeper region → larger RM).

- Time evolution study is necessary!



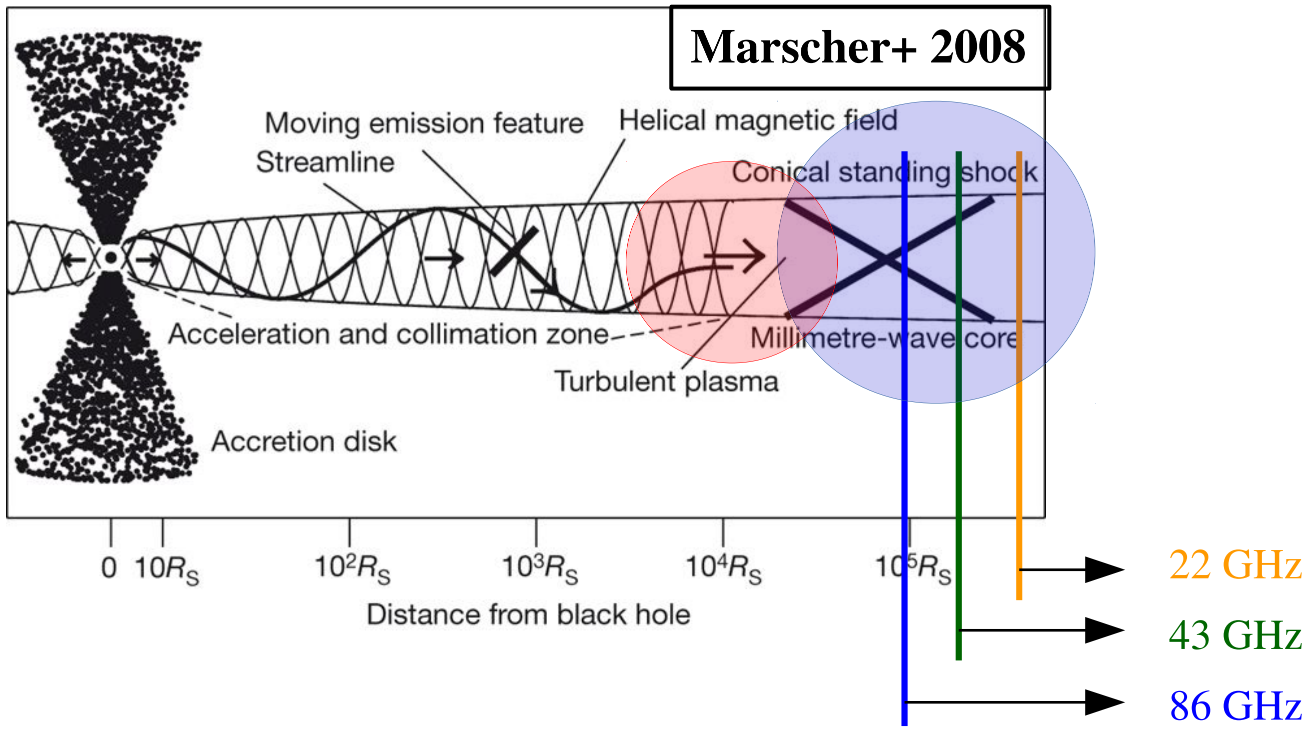
i) If recollimation shock is less bright :

→ deeper region / larger RM

ii) If recollimation shock is brighter :

→ the core / smaller RM

- Time evolution study is necessary!



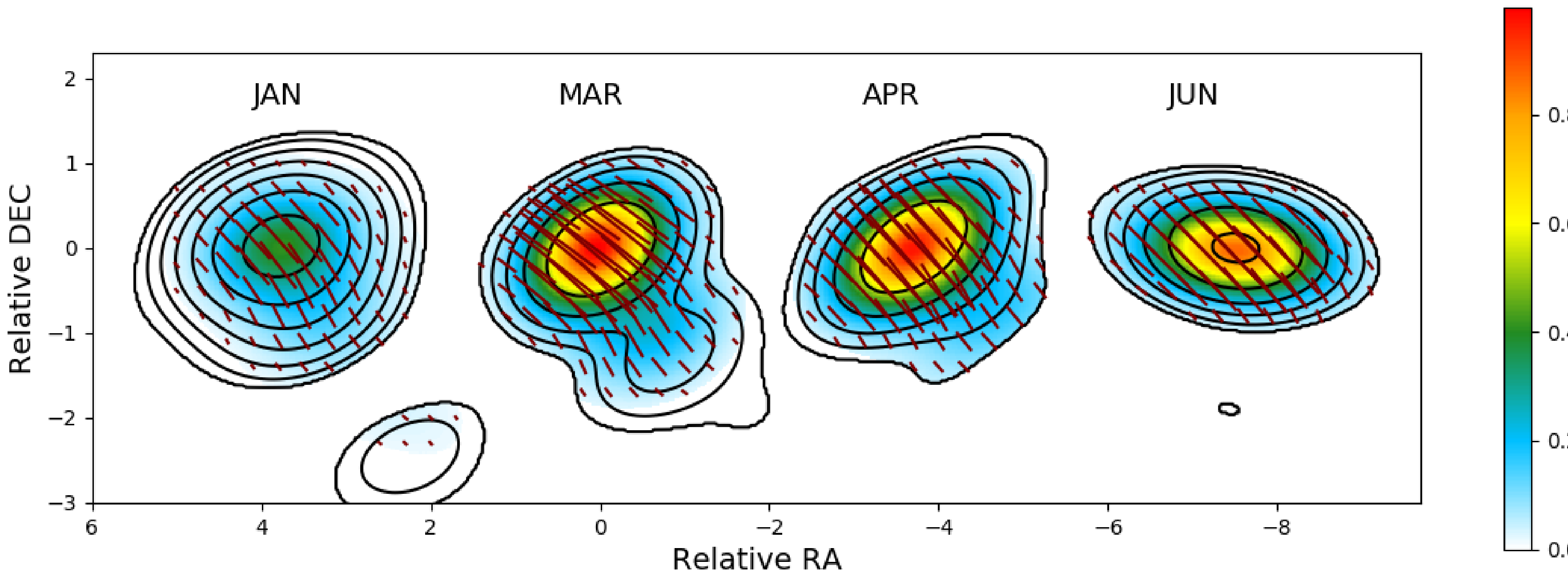
i) If recollimation shock is less bright :

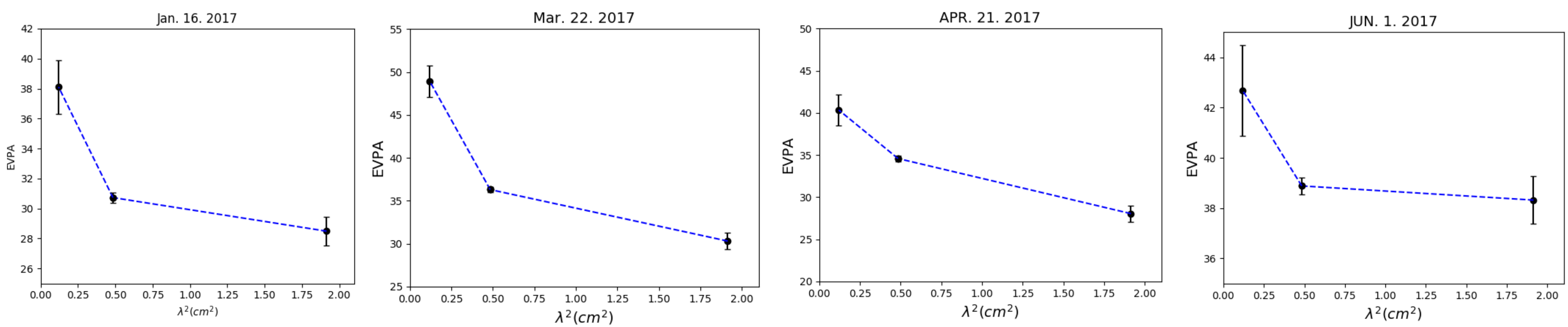
→ deeper region / larger RM

ii) If recollimation shock is brighter :

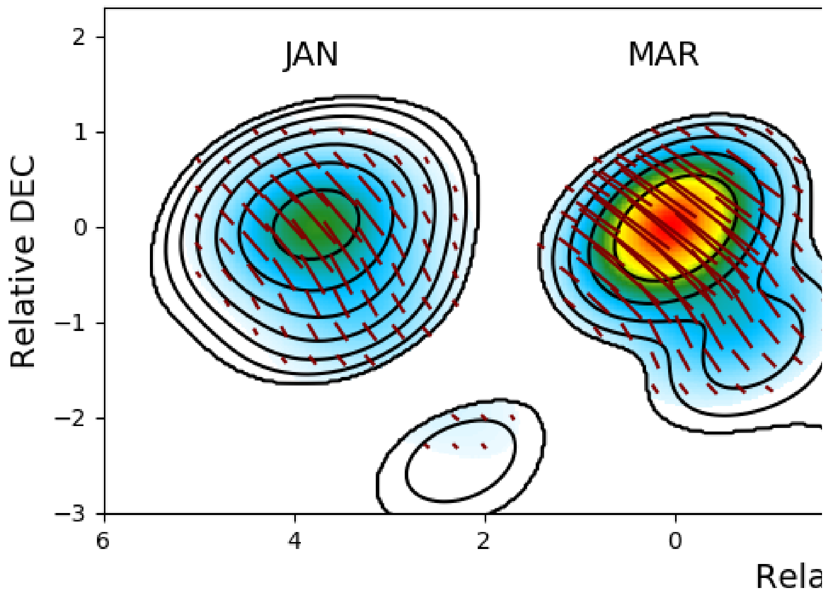
→ the core / smaller RM

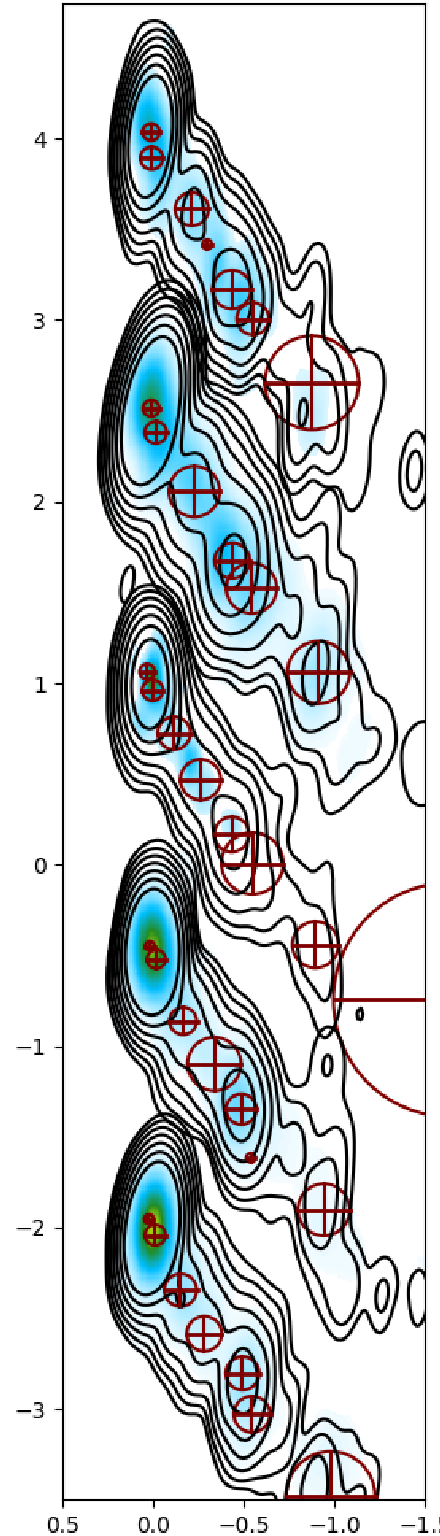
- RM : 3C 279 at 86 GHz

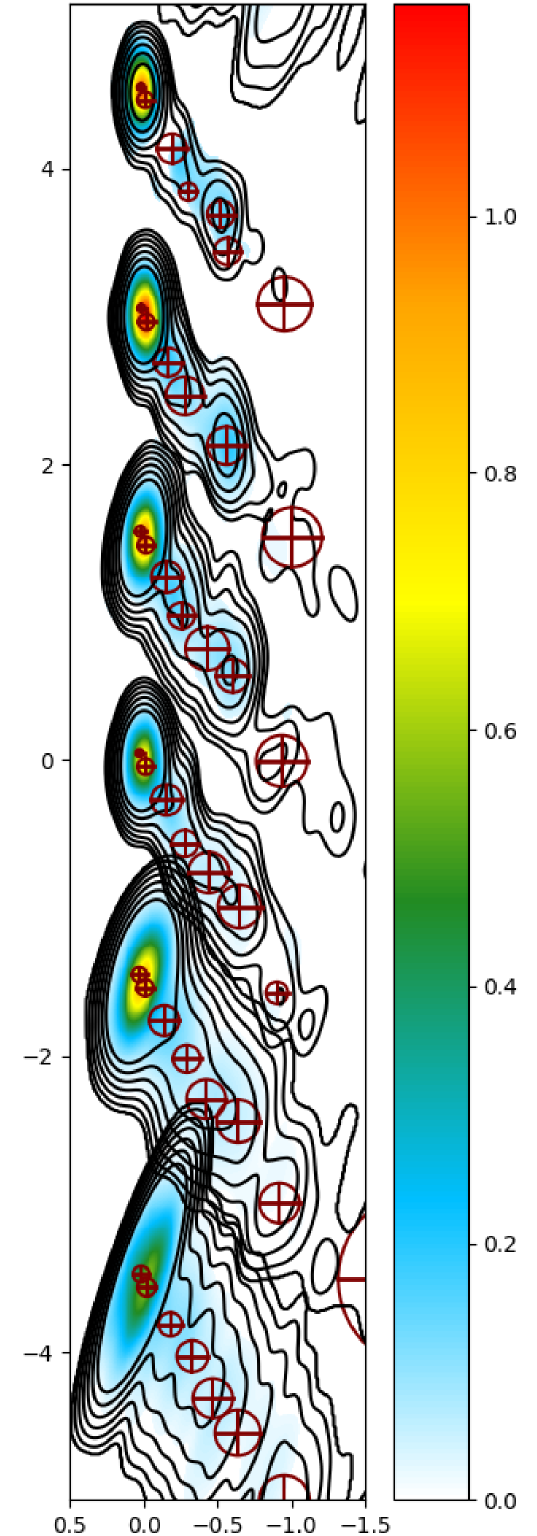




- RM : 3C 279





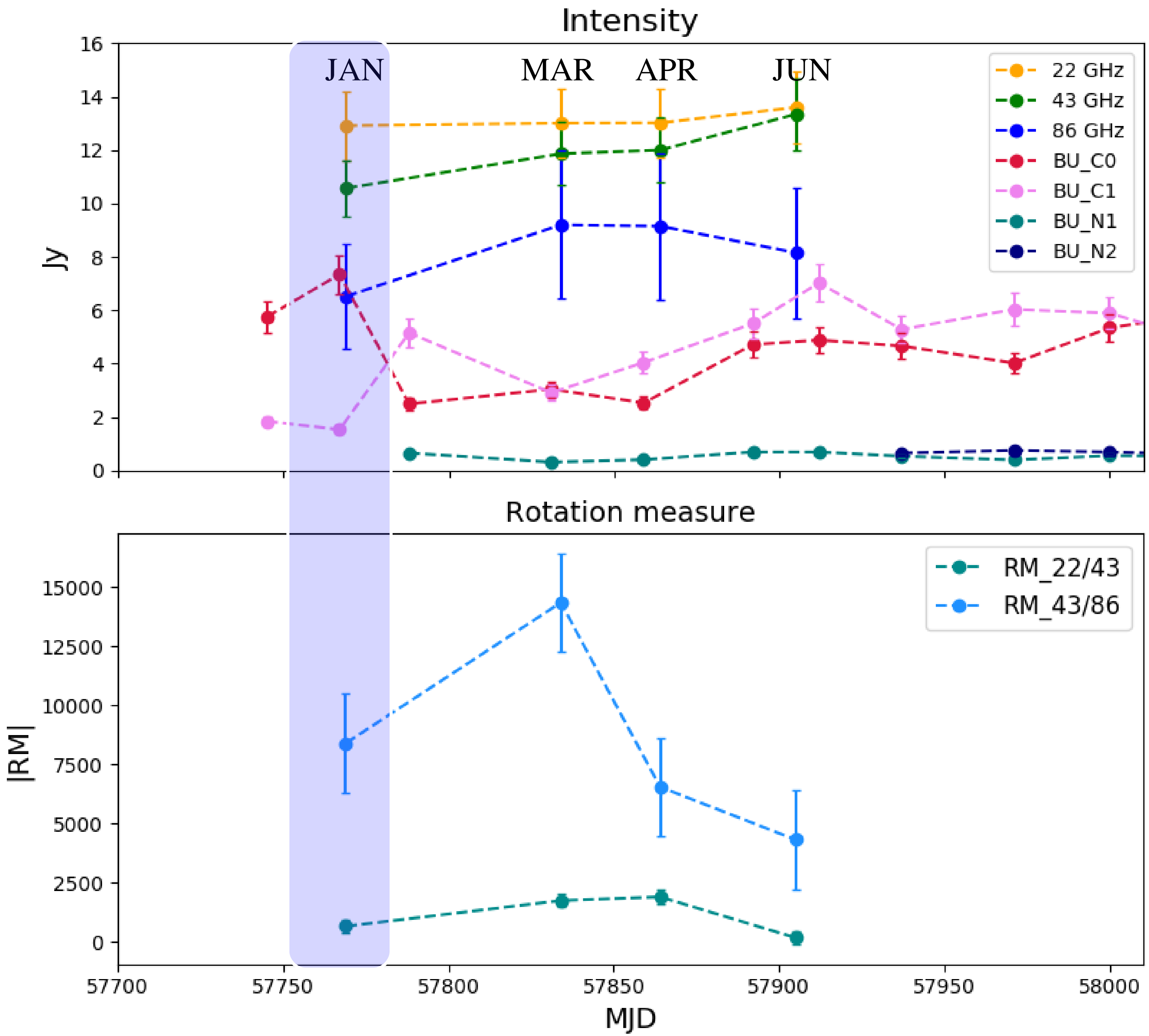


When the core flux is brigher,

do we see the smaller RM?

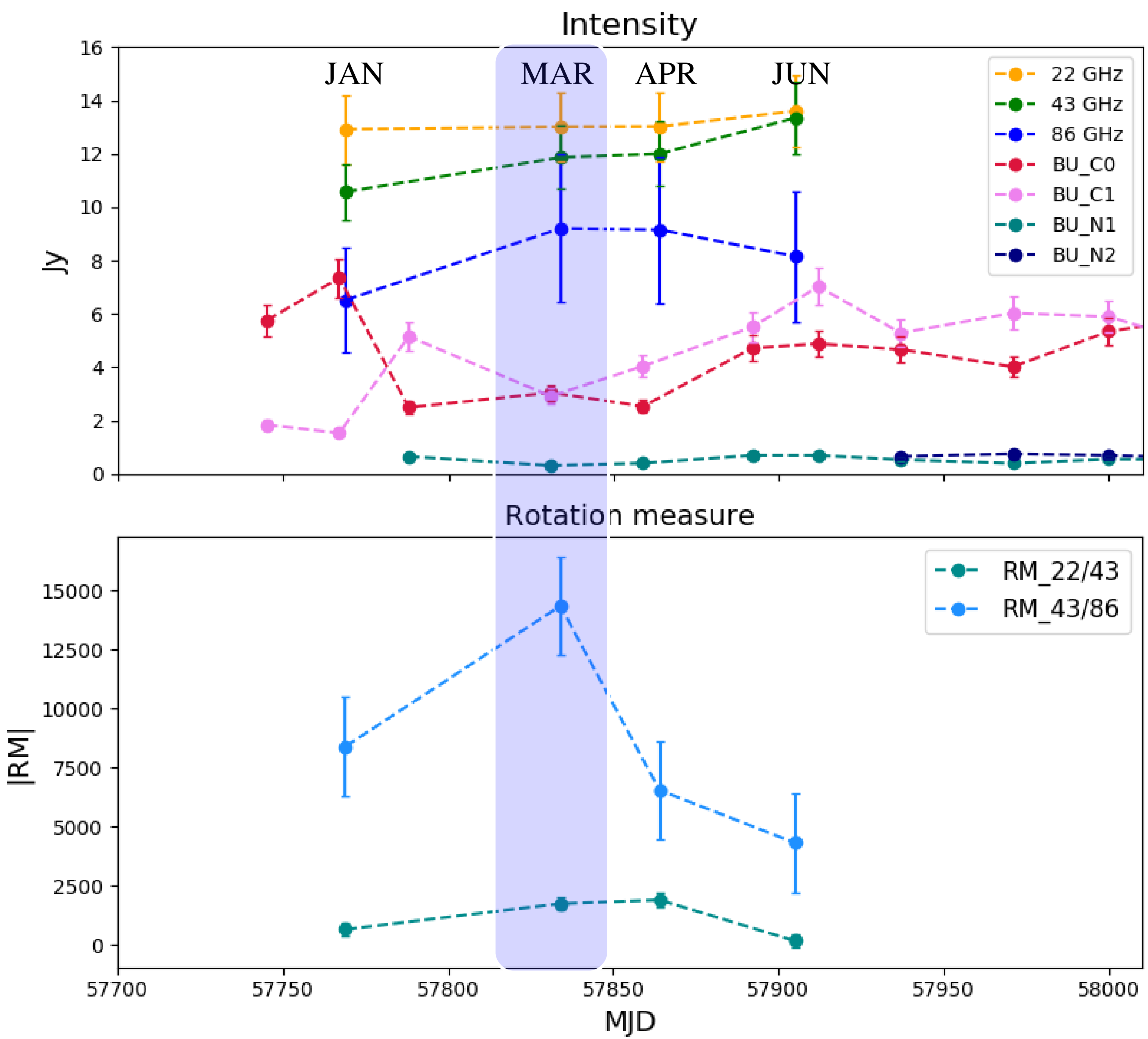
→ If so, we will be able to obtain saturated RM & transition frequency when the core is bright.

- RM : 3C 279



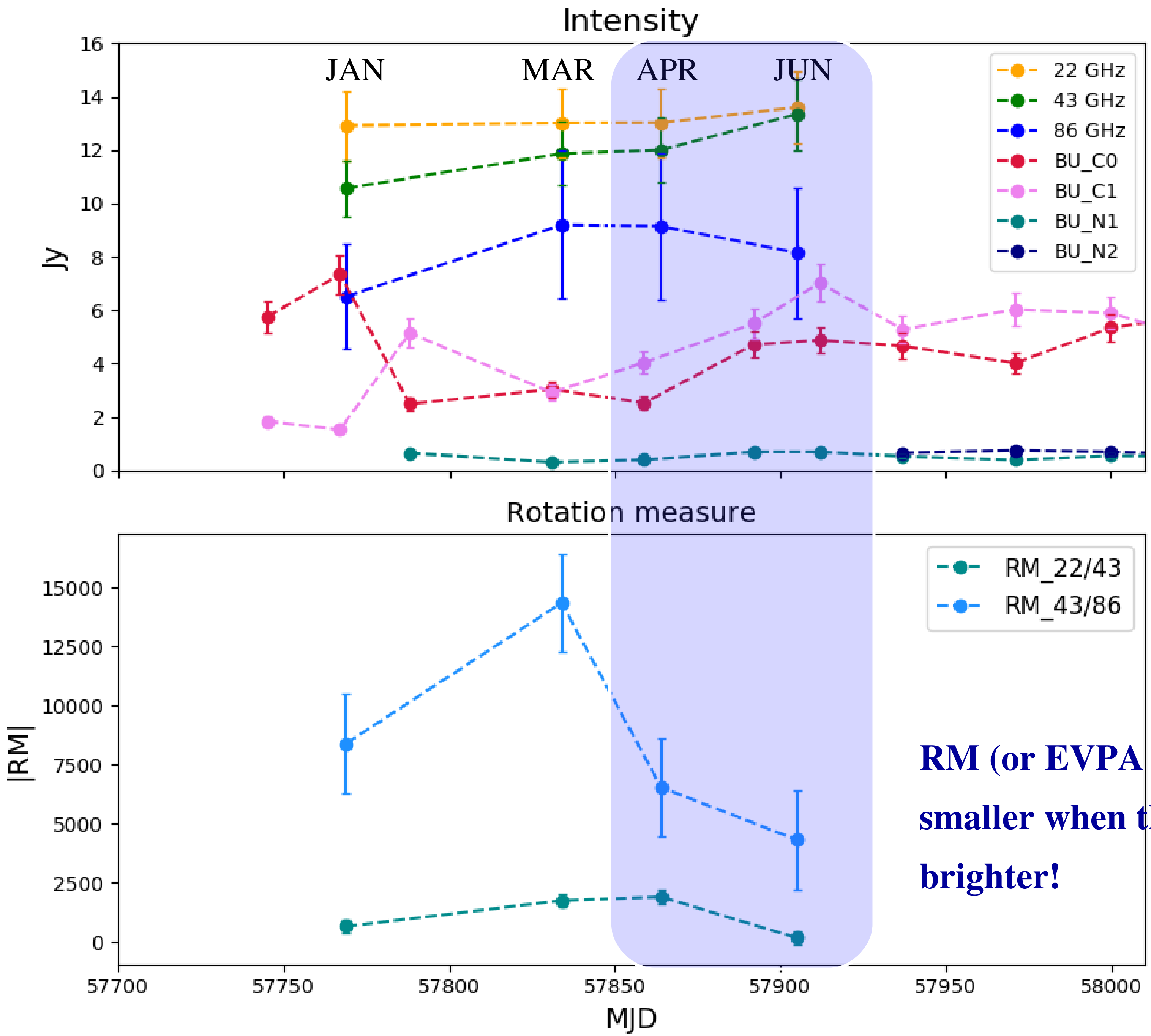
Intensity
JAN
MAR
APR
JUN
22 GHz
43 GHz
86 GHz
BU_C0
BU_C1
BU_N1
BU_N2
Jy
16
14
12
10
8
6
4
2
0
Rotation measure
RM_22/43
RM_43/86
|RM|
15000
12500
10000
7500
5000
2500
0
57700
57750
57800
57850
57900
57950
58000
MJD

- RM : 3C 279

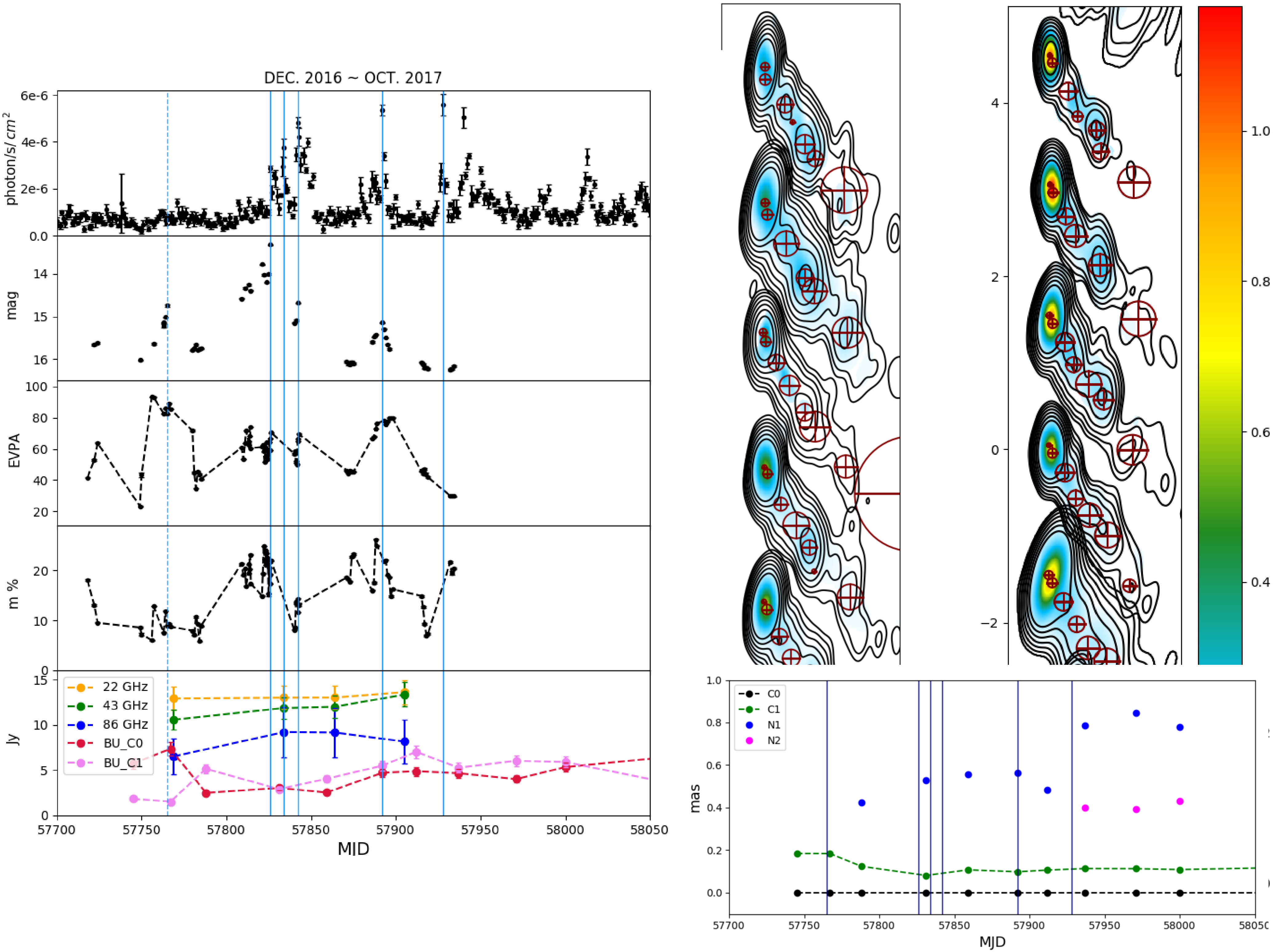


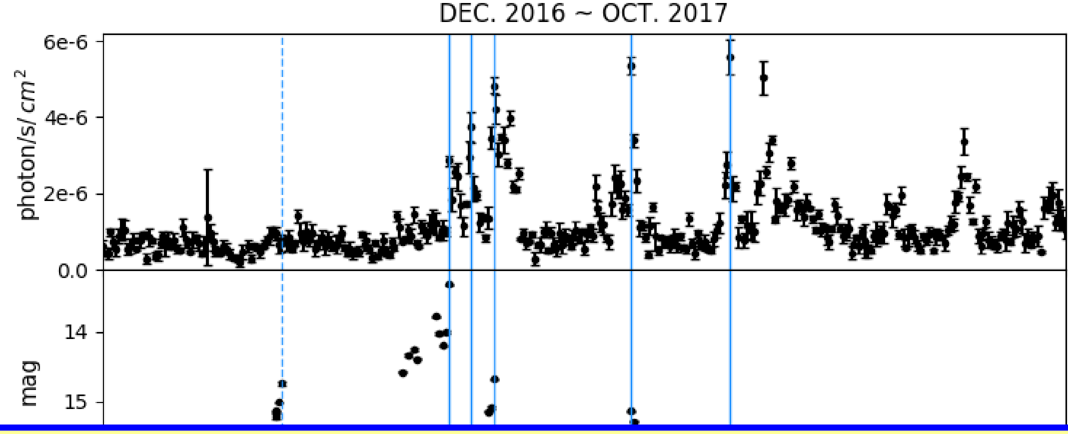
Intensity
JAN
MAR
APR
JUN
22 GHz
43 GHz
86 GHz
BU_C0
BU_C1
BU_N1
BU_N2
Jy
16
14
12
10
8
6
4
2
0
Rotation measure
RM_22/43
RM_43/86
|RM|
15000
12500
10000
7500
5000
2500
0
57700
57750
57800
57850
57900
57950
58000
MJD

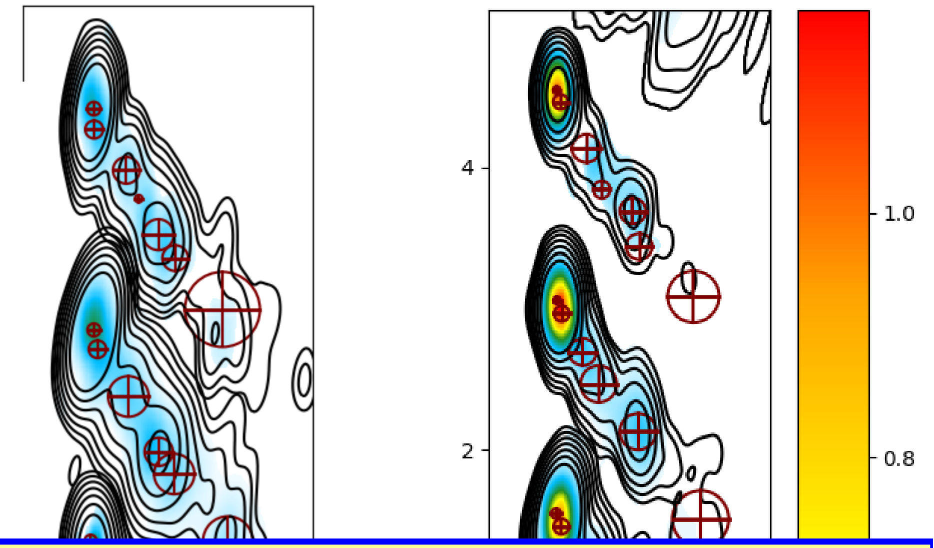
- RM : 3C 279



RM (or EVPA difference) is smaller when the core is brighter!

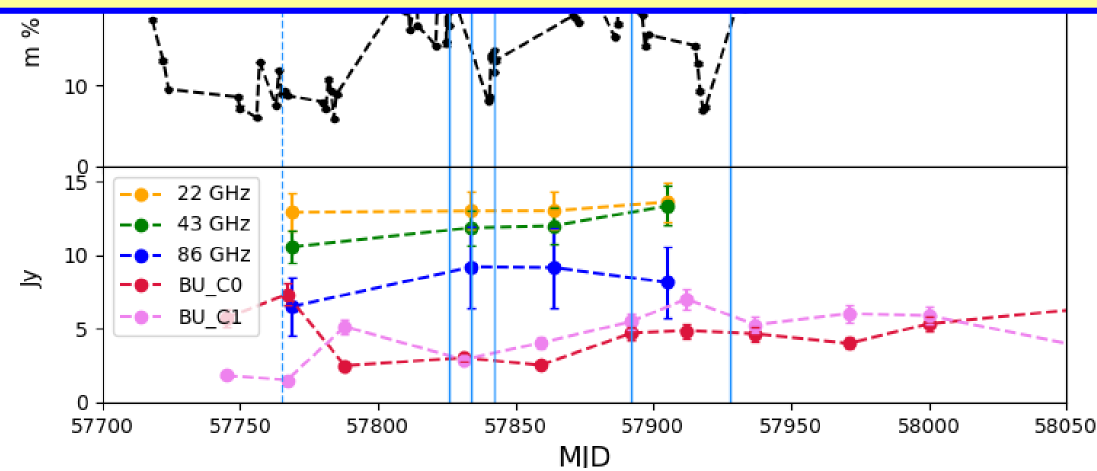

DEC. 2016 ~ OCT. 2017
photon/s/cm^2
6e-6
4e-6
2e-6
0.0
mag
14
15
16
EVPA
100
80
60
40
20
m %
20
10
0
Jy
15
10
5
0
22 GHz
43 GHz
86 GHz
BU_C0
BU_C1
57700
57750
57800
57850
57900
57950
58000
58050
MJD
4
2
0
−2
1.0
0.8
0.6
0.4
mas
1.0
0.8
0.6
0.4
0.2
0.0
C0
C1
N1
N2
57700
57750
57800
57850
57900
57950
58000
58050
MJD

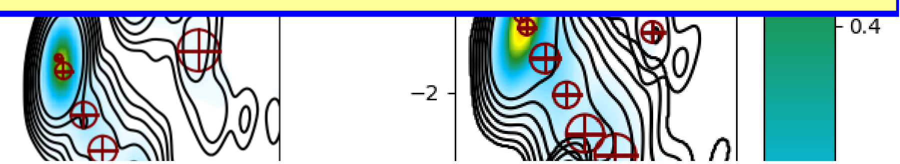


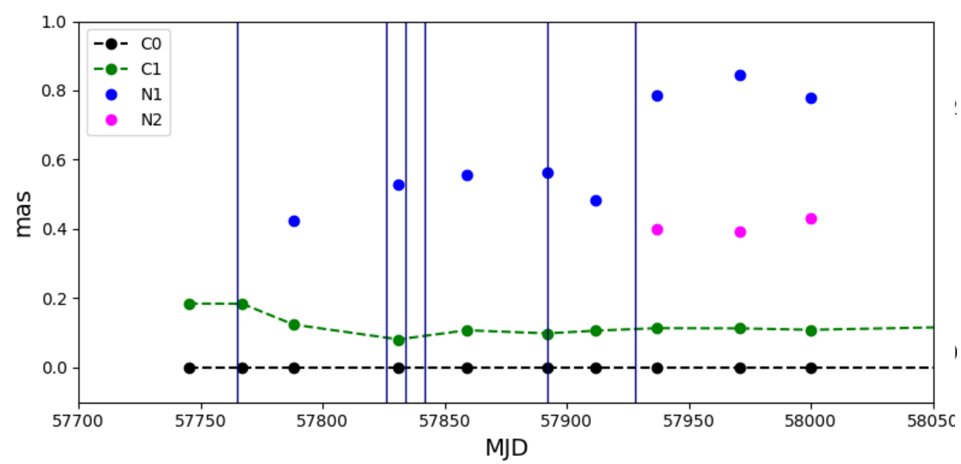


It becomes possible to explore the evolution of the jet

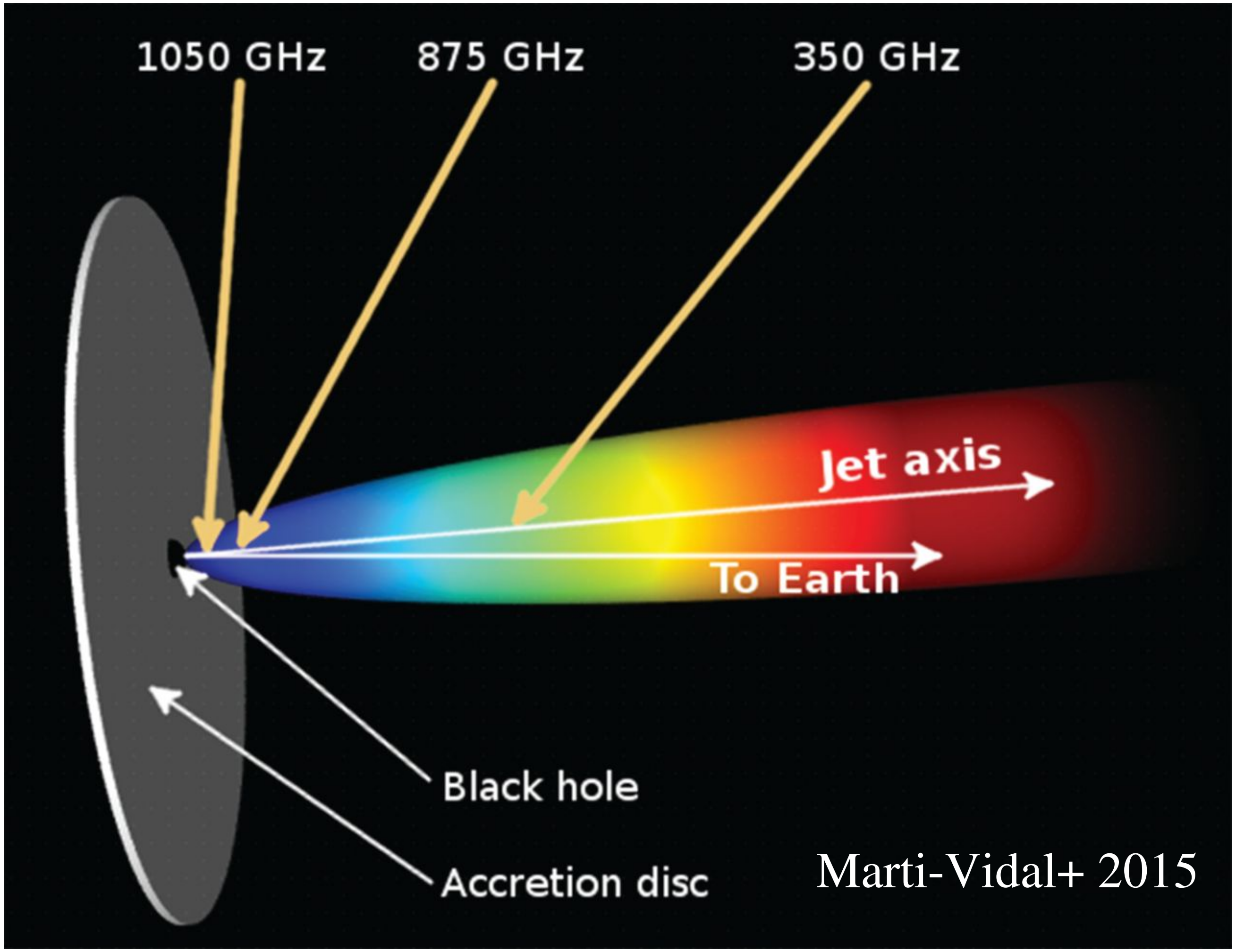
from the upstream of the core!







- Large RM around the jet base was detected!



Marti-Vidal+ 2015

→ PKS 1830-211 (z~2.5)

→ ALMA 100~300 GHz

→ $RM \sim 10^{8}\, rad/m^{2}$

Hovatta+ 2018

→ 3C 273 (z~0.158)

→ ALMA 223~243 GHz

→ $RM \sim 3\times10^{5}\, rad/m^{2}$

KVN / SMA / JCMT cover **23~1000 GHz** in the rest frame!

- KVN / SMA / JCMT (+ optical) collaboration can unveil the nature of the core !

1. Is the core RM saturated at sub-mm?

   → probe the core is the recollimation shock.

2. How large is the saturated RM / transition frequency?

   → the nature of the core

3. Modeling the fractional polarization

   → the origin of the Faraday rotation

4. Time evolution analysis (+ BU 43 GHz, gamma-ray, optical)

   → observe not only downstream but also upstream of the core!

The KVN / SMA / JCMT collaboration can explore the nature of the core !

- What's next?

1. The SMA / JCMT observation for various targets is necessary

   → bridge the frequency gap between the KVN 22/43/86 GHz ↔ optical

   → covers much wider frequency range in the rest frame

2. Multi-epoch observation is necessary

   → when the core is brighter : the recollimation shock (saturated RM, transition freq)

   → when the core is less bright : the region beyond the core

   → evolution of the core region