Max-Planck-Institut
für Radioastronomie

IMPRS astronomy & astrophysics Bonn and Cologne

Polarimetric millimeter VLBI observations of 3C 84

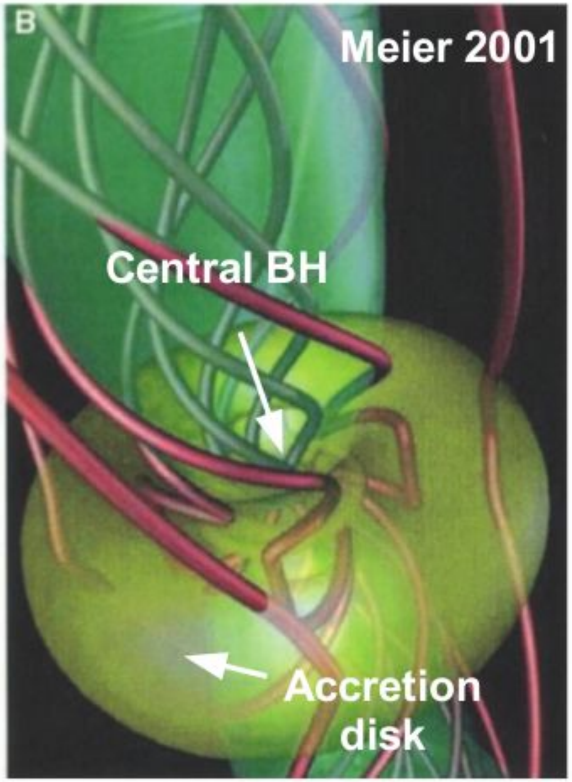
Jae-Young Kim
Max Planck Institute for Radio Astronomy

Collaborators : T. P. Krichbaum, A. P. Marscher, S. G. Jorstad, I. Agudo, C. Thum, J. A. Hodgson, N. R. MacDonald, E. Ros, R. -S. Lu, M. Bremer, P. de Vicente, M. Lindqvist, S. Trippe, and J. A. Zensus

Kim, J. -Y., Krichbaum, T. P., Marscher, A. P., et al. 2018, A&A, submitted

14th EVN Symposium 2018, Granada, Spain

Polarimetry of AGN jets

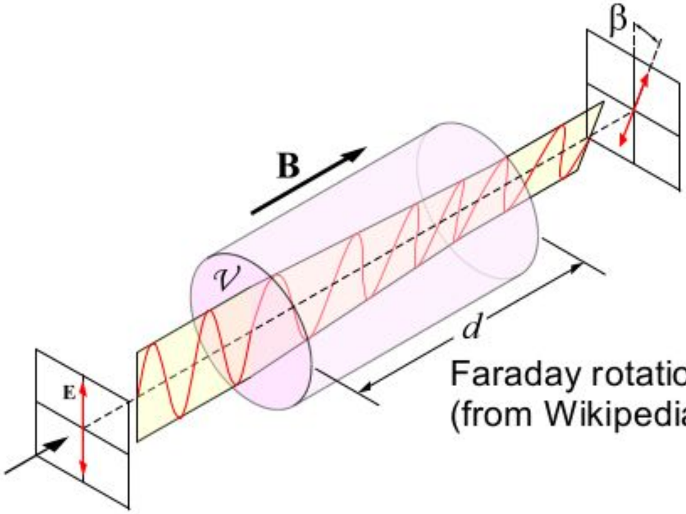


Theory

- Synchrotron radiation is **highly linearly polarized** (~70% fractional).
- Polarized radiation **modified** by the **magnetic field geometry** and **matter** distribution **in/around the jets**

Observation

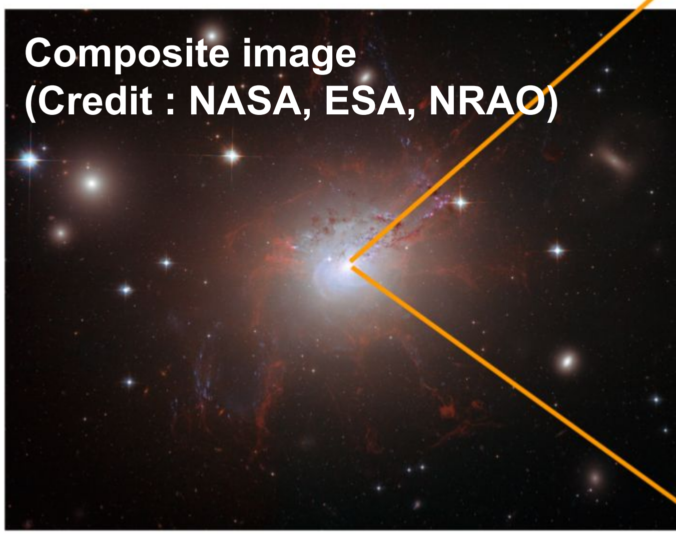
- **Strong polarization** → three-dimensional field topology, field strength etc.
- **Weak (or no) polarization** → depolarization mechanisms (e.g., Faraday rotation), order and disorder of the B-field geometry, ...



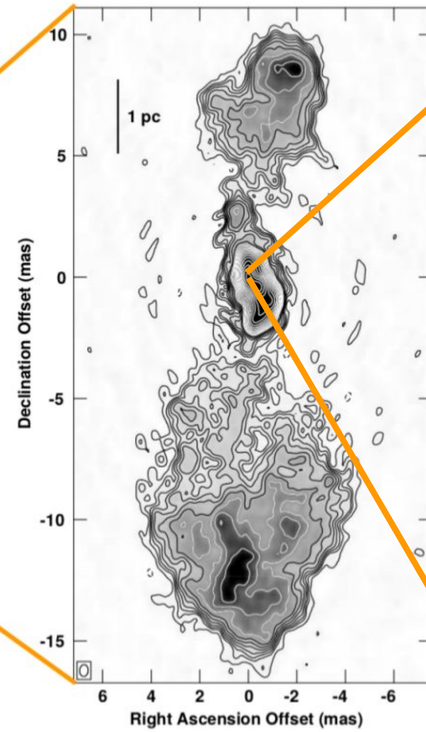
Faraday rotation (from Wikipedia)

Talks by Gomez, Kravchenko, J.H.Park, ... and posters by Traianou, Casadio, MacDonald, Fuentes, D.W. Kim, Knuettel, ...

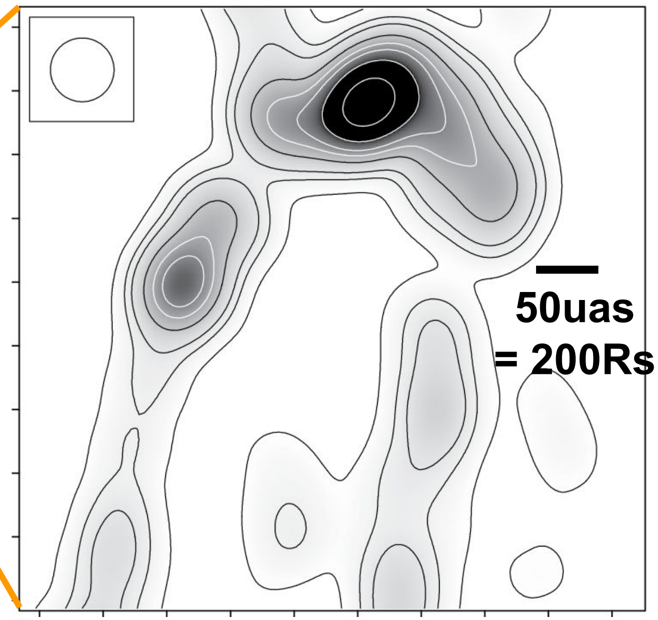
The Radio Galaxy 3C 84 (NGC 1275)



Walker+02 (VLBA+VLA 22GHz)



Giovannini+ 18 (RadioAstron 22GHz)

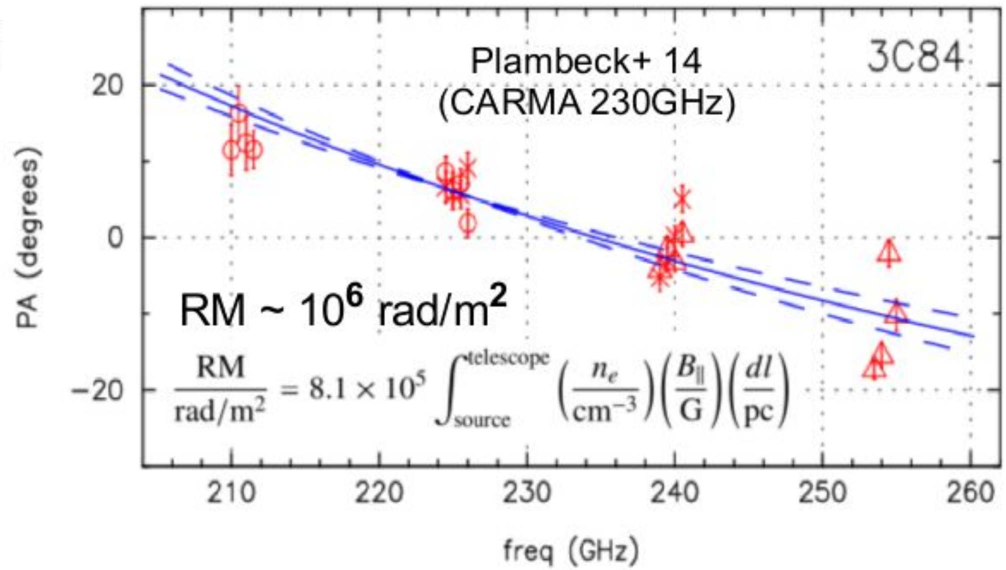


- BH mass **~8x10^8 Msun** (Scharwachter+2013), **distance ~75 Mpc**
  --> GMVA resolution **<u>50</u>uas ~ <u>0.017</u> pc ~ <u>200</u> Rs**

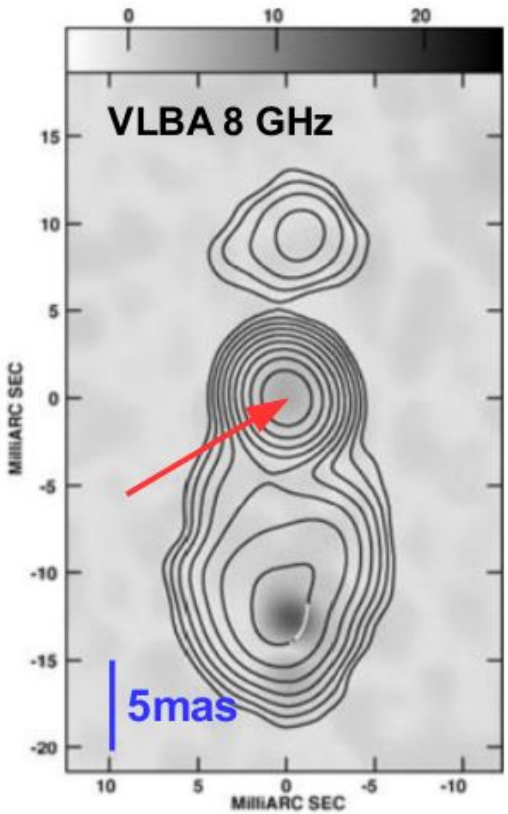
- **Highly edge-brightened jet** (similar to M87; Kim+2018b),
  one of best sources for the **jet formation and evolution** studies

Talks by Giovannini, Savolainen, J. Oh, ...; posters by Hodgson, M. Kam, ...

Polarization properties at cm- and mm-regime

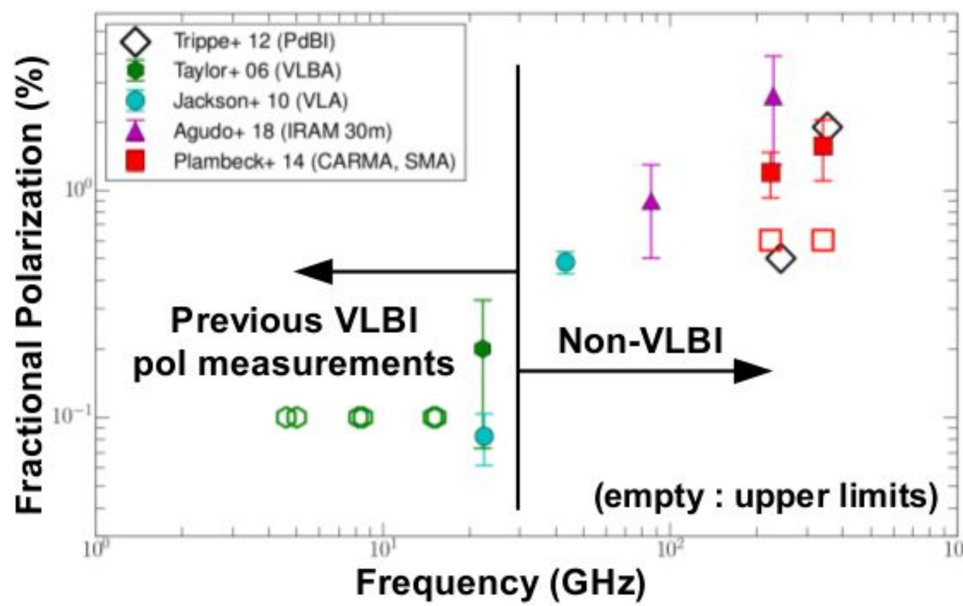


Taylor+06 (grey : linear pol)

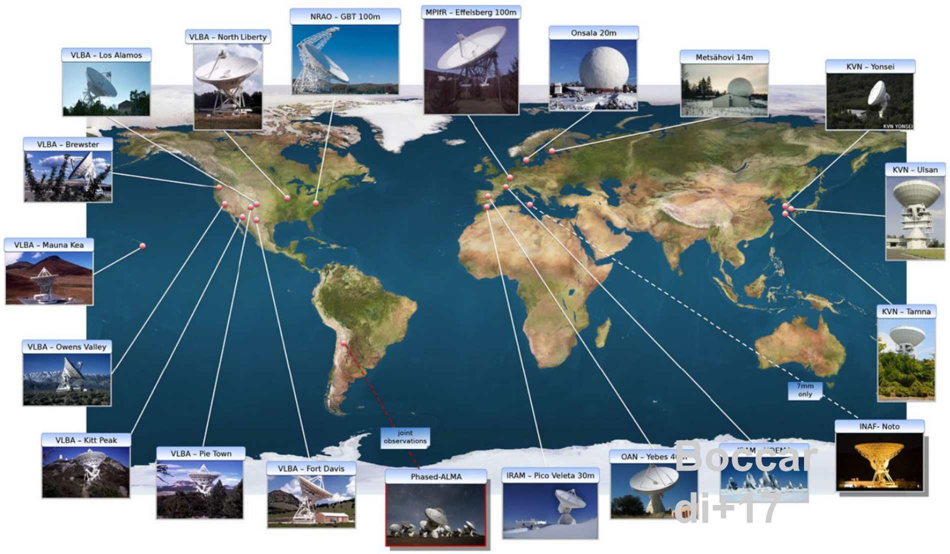


No core linear pol at 2-22GHz (**<0.1% fractional**)

At mm, strong linear pol (**~1-4%**) and extreme Faraday rotation (typical RM ~ **10^3 rad/m^2 in other AGNs**; Hovatta+12)



Near-in-time cm-/mm- VLBI and ALMA observations of 3C84



Global Millimeter VLBI Array (GMVA) at 86GHz

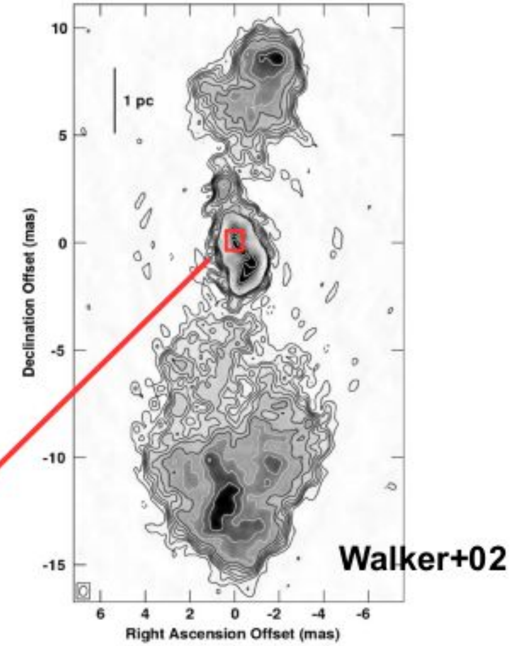
Atacama Large mm-/sub-mm Array (ALMA)

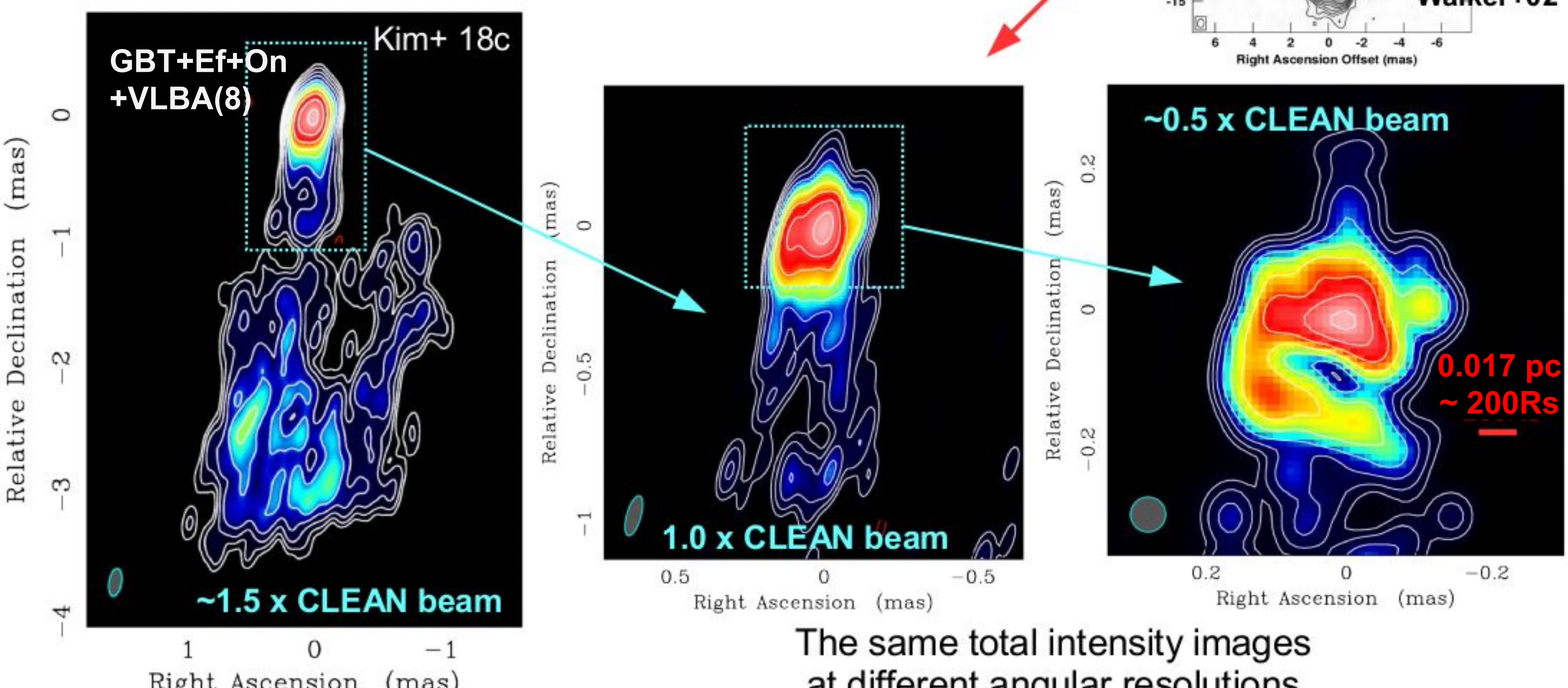
All quasi-simultaneously in May 2015 :

- GMVA 86GHz full-track (May 16th)
- VLBA 15GHz (MOJAVE; May 18th) and 43GHz (BU; May 11th)
- 7 more VLBA 43GHz data sets during 2015 (BU)
- ALMA 97.5, 233, and 343.5GHz observations (May 31th; archival)

GMVA observations of 3C84 at 86GHz

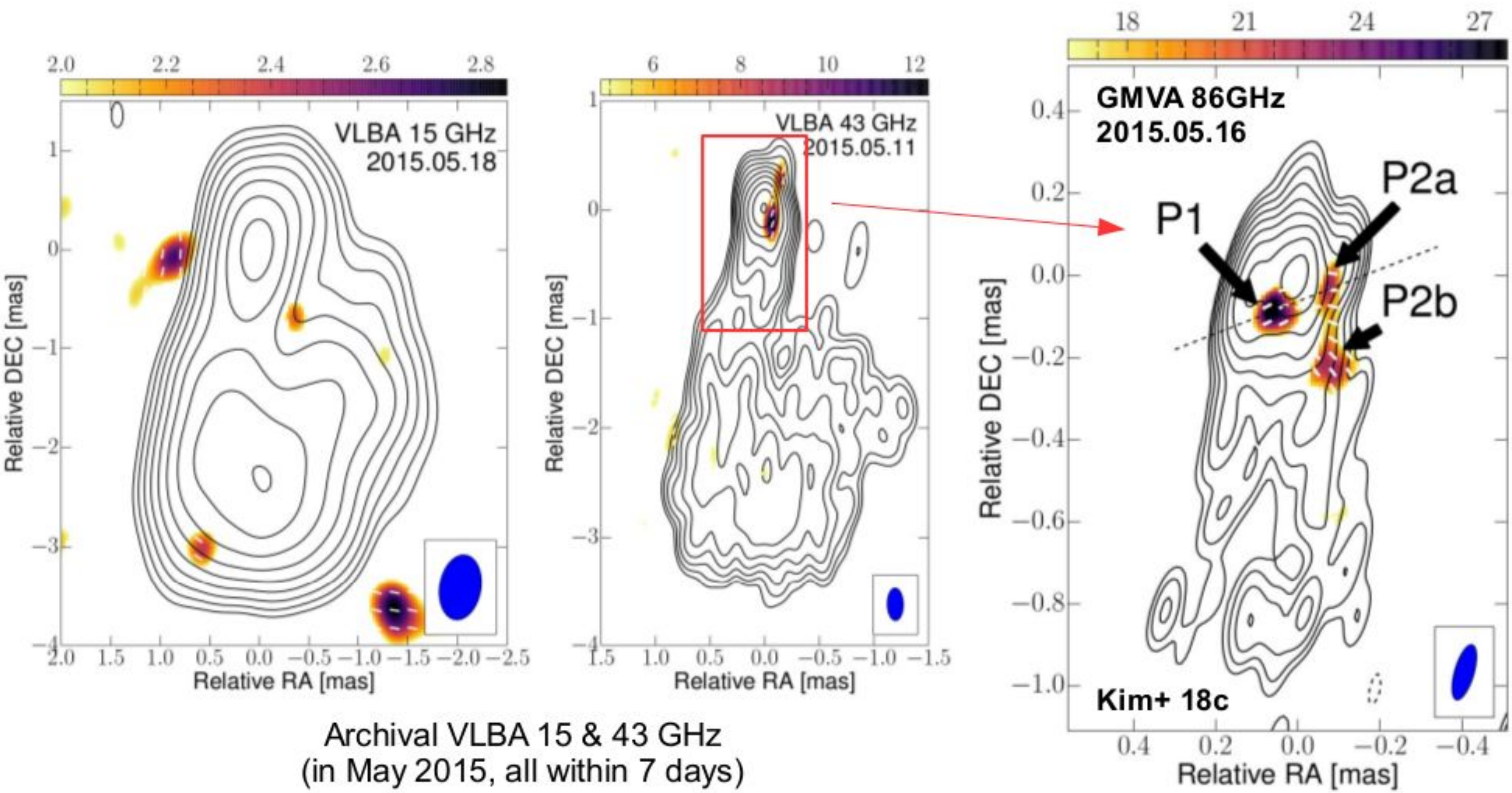
- Highest-sensitivity and resolution image of 3C84 to date (at this frequency).
- Wide limb-brightened jet seen.





The same total intensity images at different angular resolutions

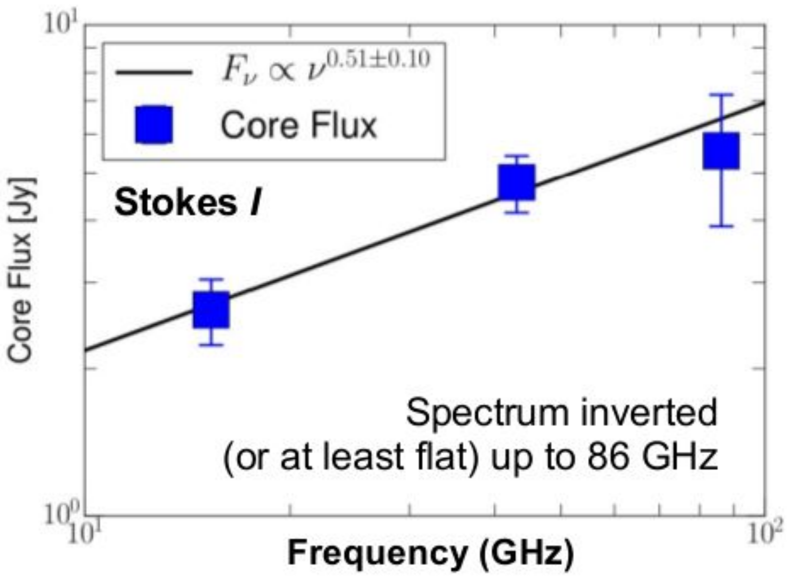
Polarization detection in the VLBI core region

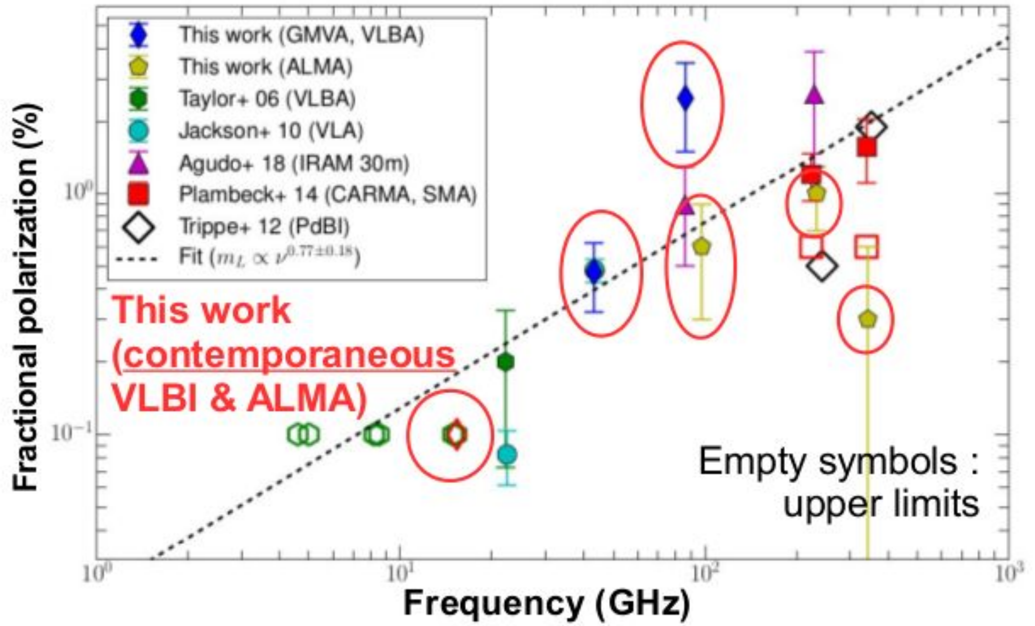


Archival VLBA 15 & 43 GHz
(in May 2015, all within 7 days)

Polarization features in the core region detected at high significance (~7σ and ~6σ at 43 and 86GHz). At 15GHz, upper limit ~ 0.1%

Spectra of the total flux and fractional linear polarization

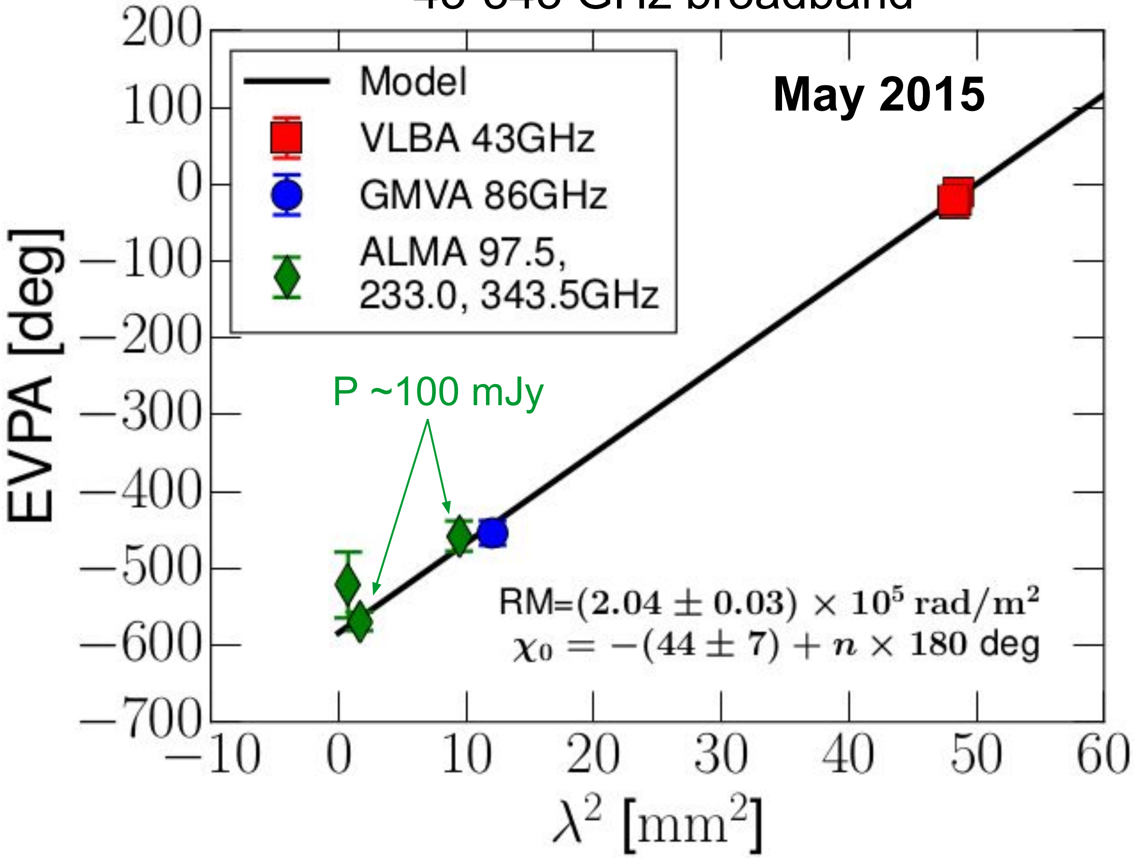




- Significantly inverted total intensity spectrum
  → **turn-over frequency > 86GHz** (cf. Hodgson+17).
- **Significant increase** of linear polarization at **higher frequencies** both on single-dish and VLBI scales (the latter in VLBI core).

The VLBI core Faraday rotation measure at mm-wavelengths

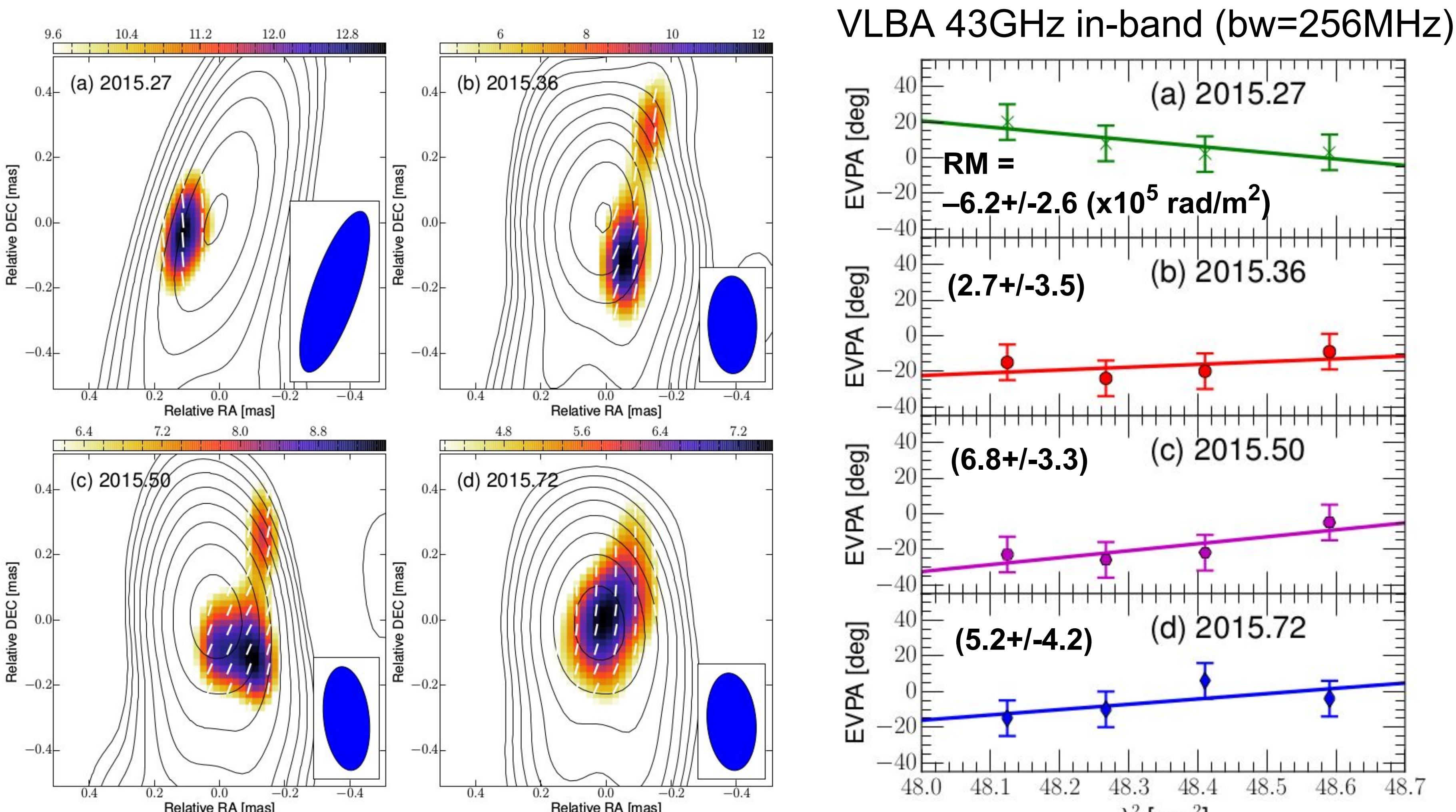
43-343 GHz broadband



Direct detection of the large RM in the VLBI core region for the first time

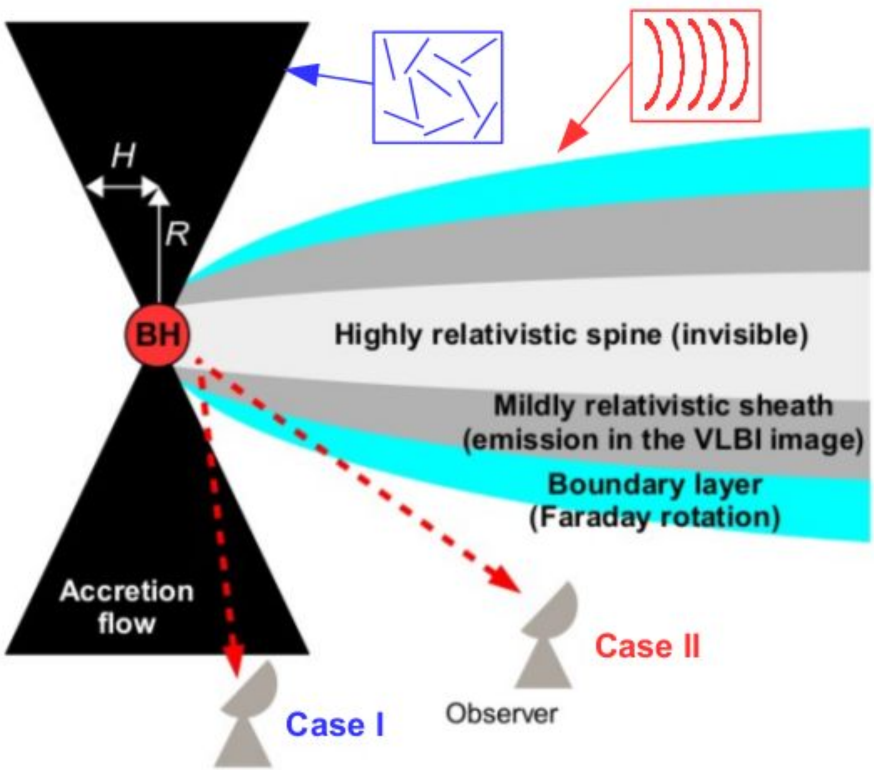
- Flat spectral index of the polarized flux density by ALMA
- Suggest a high-opacity origin (likely the core)
- Good λ^2 fit with all measurements.

Time-variability in the polarization morphology & RM



Conservative EVPA errors < 5deg
(from calibrators)

Geometry of two different depolarization scenarios

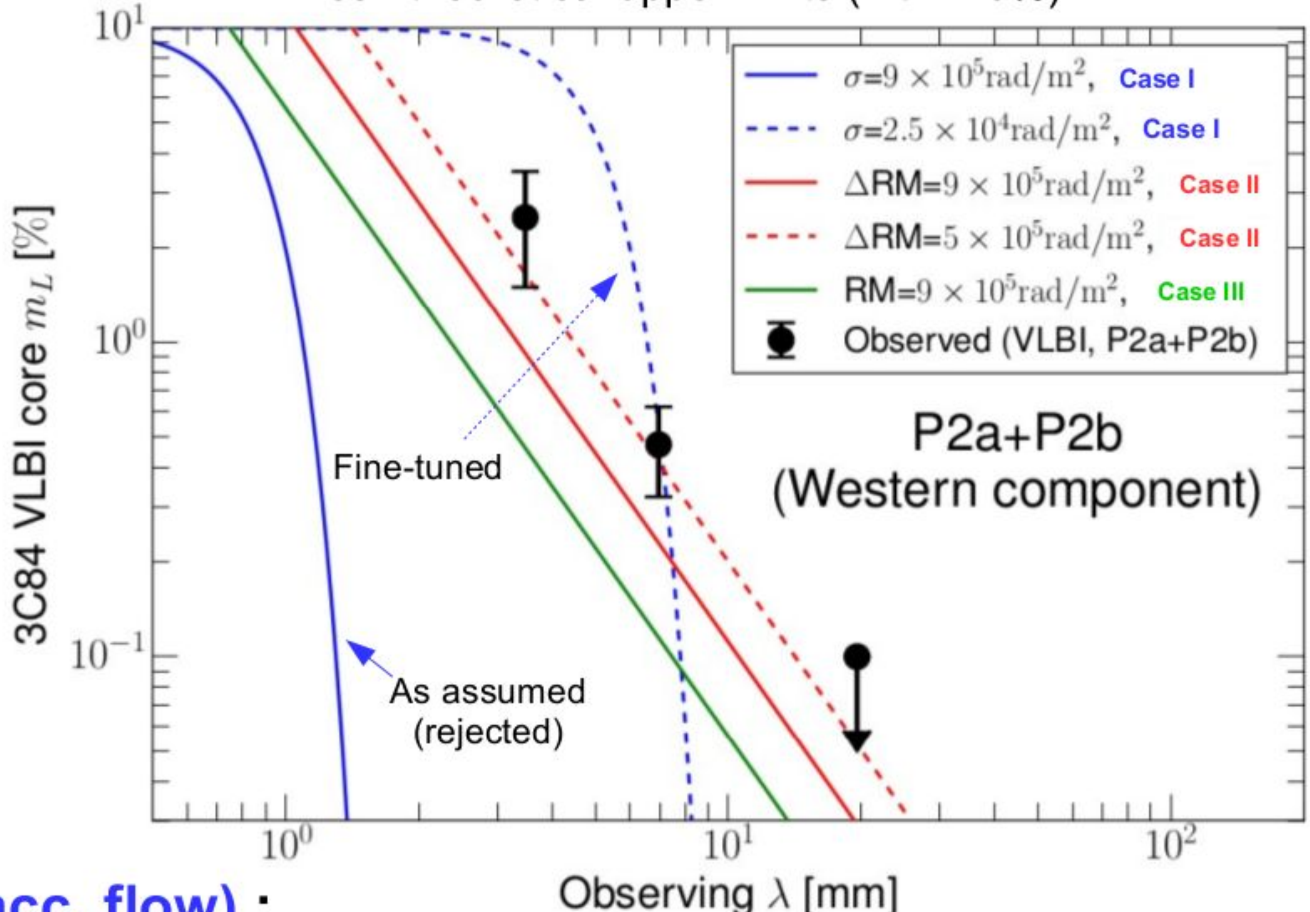


External Faraday depolarization:

- **Case I** : turbulent accretion flow (**random, turbulent magnetic fields;** e.g., Balbus & Hawley 91,98)
- **Case II** : jet boundary layer (**ordered magnetic fields but with smooth RM gradient;** e.g., Zavala+05, Hovatta+12, Gabuzda+17)

<u>Case I (accretion flow) depolarizes much more at longer wavelength</u>
→ can distinguish between them over wide range of frequencies

Lines : theoretical upper limits (m_0 = 10%)



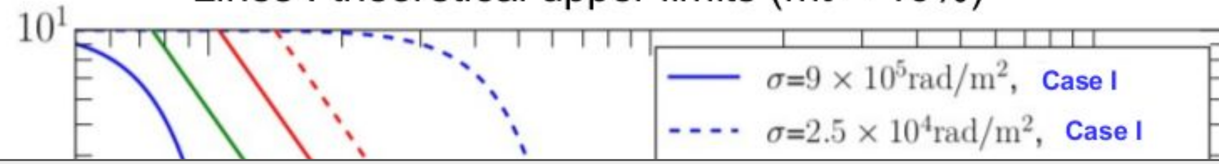
Case I (acc. flow) :

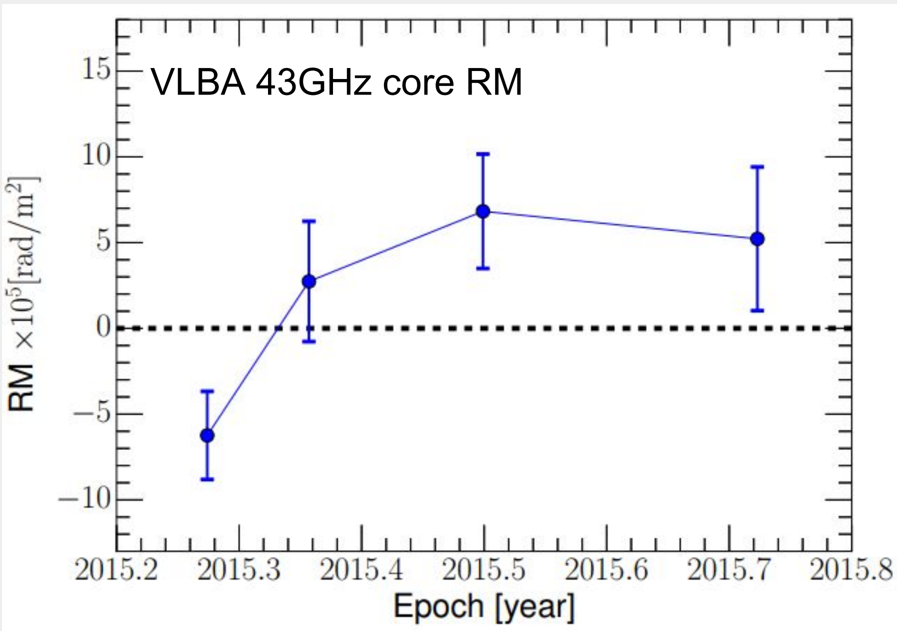
- Require very small RM dispersion **(~<1% of RM)**
- Require **highly ordered** B-field; **but less likely** (e.g., Plambeck+14, Johnson+16, Moscibrodzka+17)
- The accretion flow likely "thin"; H/R < 1.7 (0.7) for viewing angle 30 (60) deg

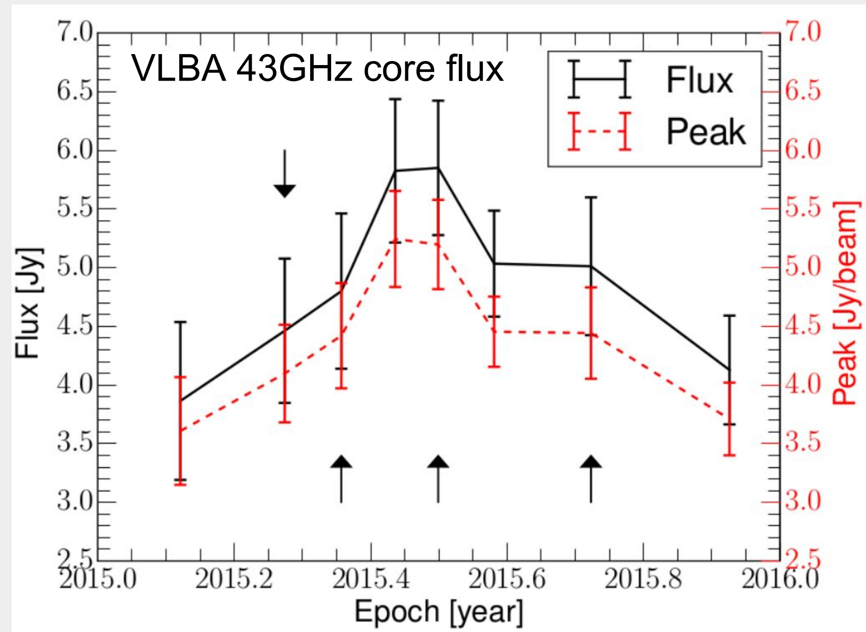
Case II (jet boundary) :

- **Better agreement** (weaker depol.)
- Also, may better explain the RM and pol. morphology time-variations
- Can we decompose B & n_e ?

Lines : theoretical upper limits (m_0 = 10%)







Also significant time-variability in both polarization (m_L, RM) and the VLBI core total flux density; **Indications for the jet-origin?**

and pol. morphology time-variations

- The accretion flow likely "thin"; H/R < 1.7 (0.7) for viewing angle 30 (60) deg

- Can we decompose B & n_e ?

If jet internal ...

$$B_{SSA} = 10^{-5} b(\alpha) \frac{\theta_m^4 \nu_m^5 \delta}{S_m^2 (1+z)} \quad \text{Gauss}$$

(Marscher 1983)

Assume synchrotron turn-over at 86GHz in the VLBI core →

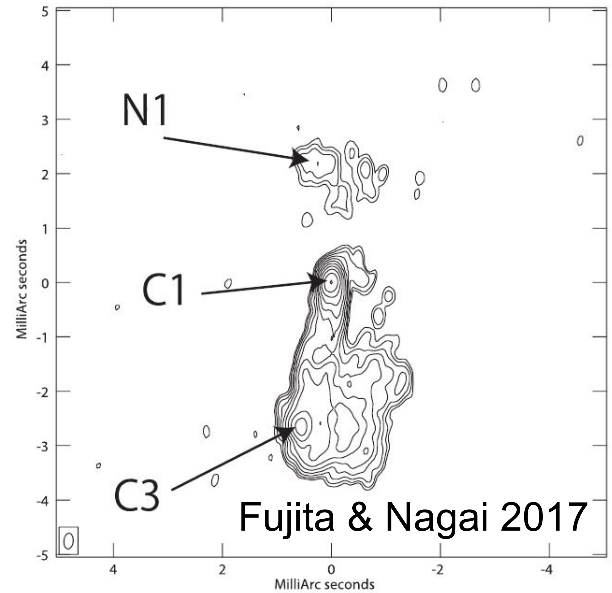
~(23+/-15)G

(cf. equipartition B ~ 1G)

↓

$$\frac{n_e}{\mathrm{cm}^{-3}} \sim 1.2 \times 10^{-6} \left(\frac{\mathrm{RM}}{\mathrm{rad/m^2}}\right) \left(\frac{B_{SSA}}{\mathrm{G}}\right)^{-1} \left(\frac{\theta_m}{\mathrm{pc}}\right)^{-1}$$

Average (thermal) ne→ **~(0.5+/-0.3) cm^{-3}** on in the sheath/boundary layer of the jet



- Recent detection of inner CJ (N1) and free-free absorption → ~8 cm^{-3} in the ambient medium (Fujita & Nagai 2017).
- Electron number density ratio between the jet and ambient medium → ~10

Highly magnetized and low density →
consistent with magnetic jet launching and collimation by dense ISM

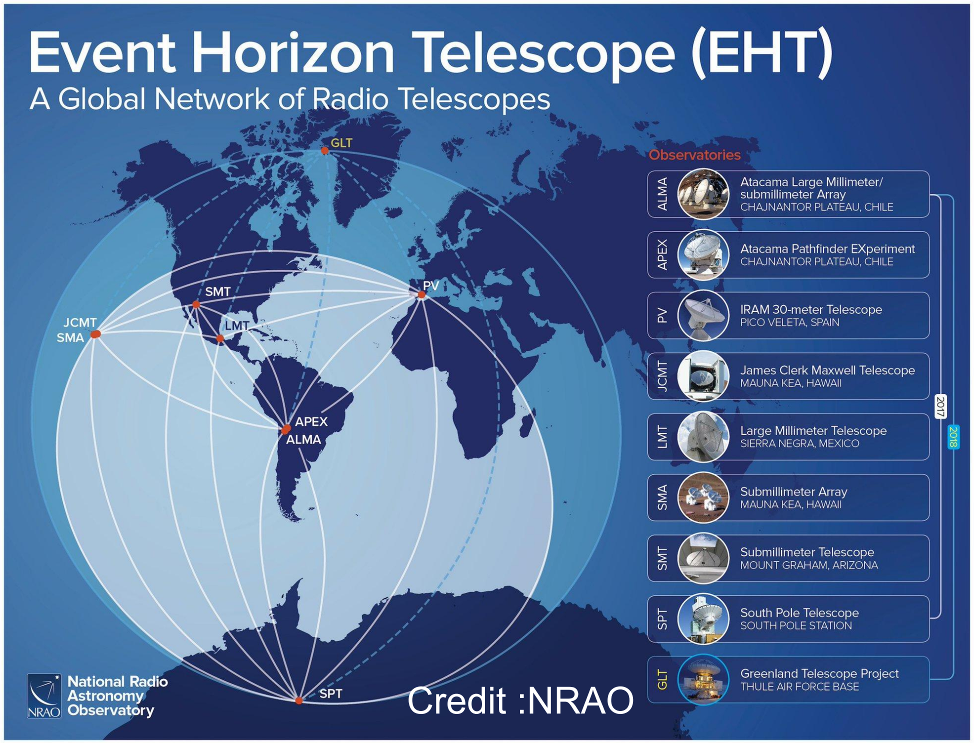
Main conclusions

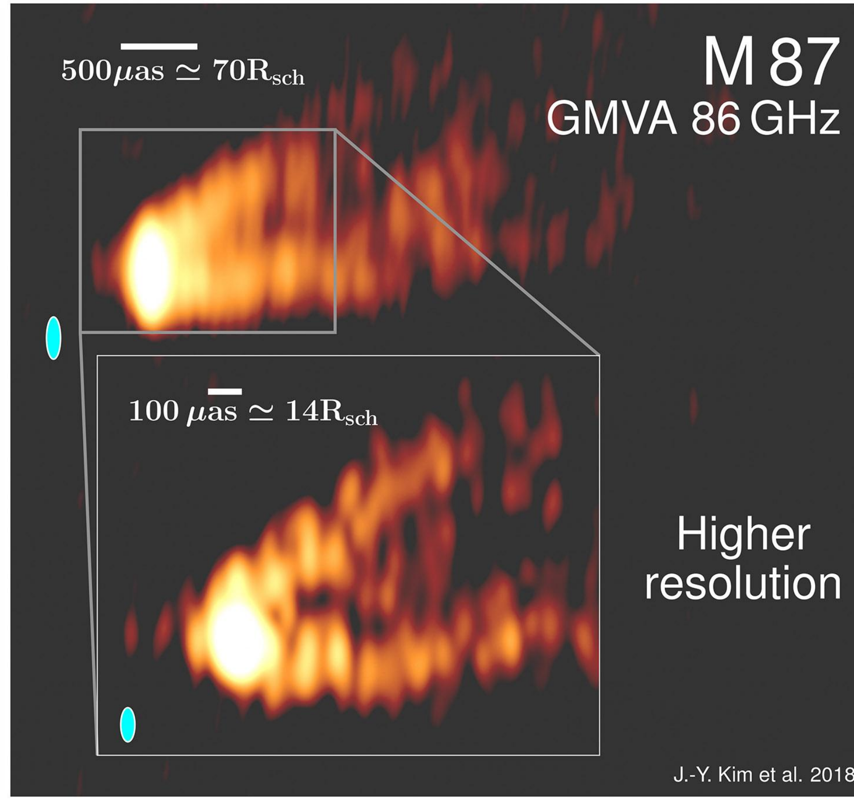
- **Confirm the very wide base of the jet in 3C84 found in the RadioAstron 22GHz observations**
  --> exotic jet collimation or launching of the sheath of the jet from the accretion disk

- **The VLBI core; inverted total spectrum up to 86GHz and stronger linear polarization at mm-wavelengths**
  --> Large opacity due to large magnetic field strength,less Faraday depolarization effect at shorter wavelengths

- **Very large RM in the VLBI core (~10^(5-6) rad/m^2) and polarization variability (including RM sign reversal)**
  --> Possibly jet-driven Faraday rotation in the sheath/shear layer; *B*~20G and *ne* ~ 0.5 cm^-3 (good for jet collimation?)

Outlook : observational aspect





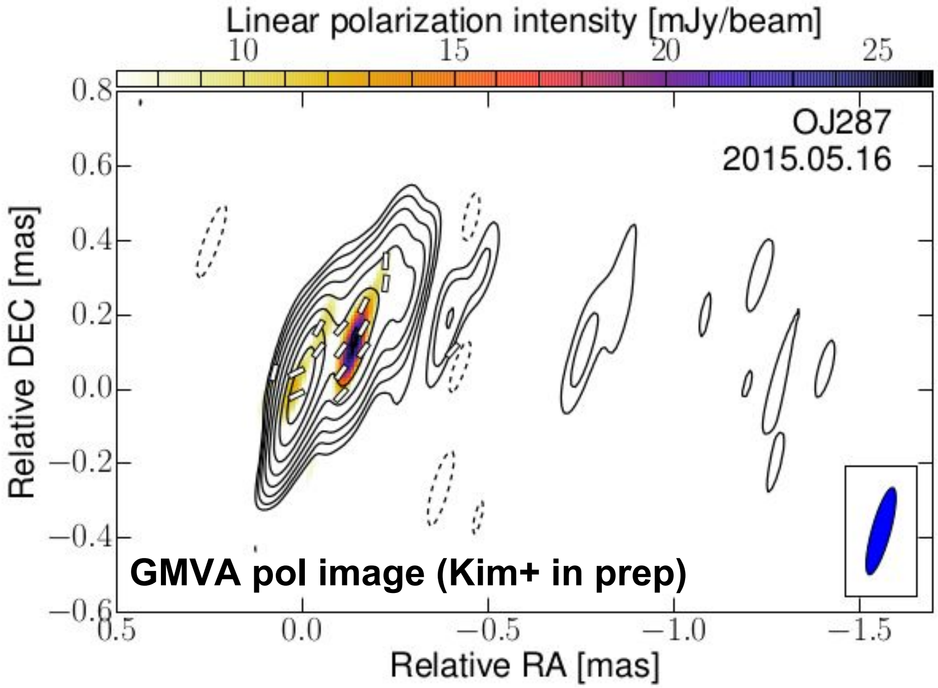
The innermost jet of the nearby giant galaxy M87
(Kim, J.-Y., et al., 2018, A&A, 616, A188)

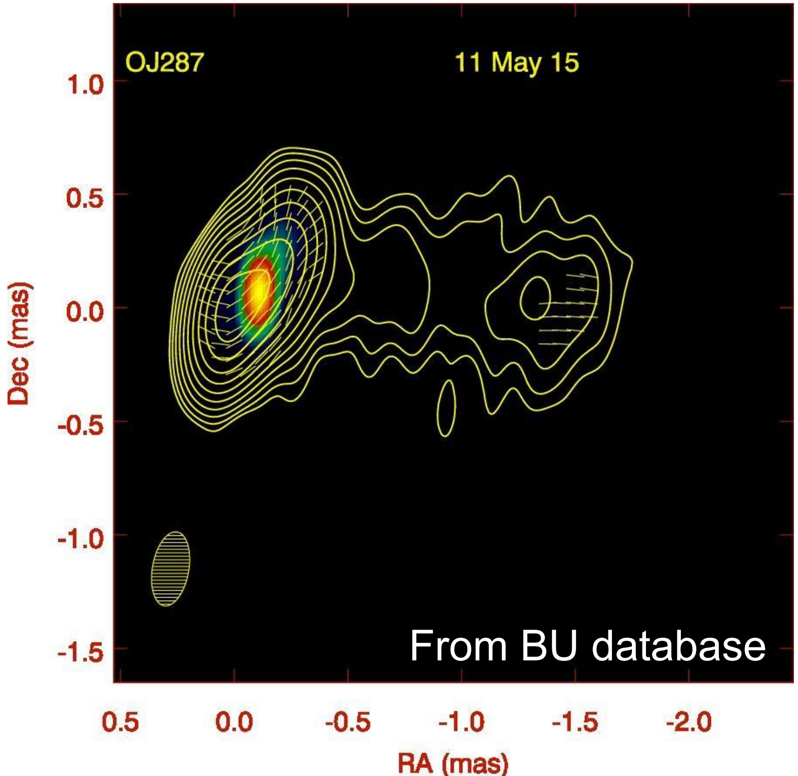
Higher-freq. VLBI observations of 3C84 (e.g.,with the EHT) and deeper into more nearby targets (e.g., M87)!

Appendix

OJ287 : one of GMVA pol calibrators

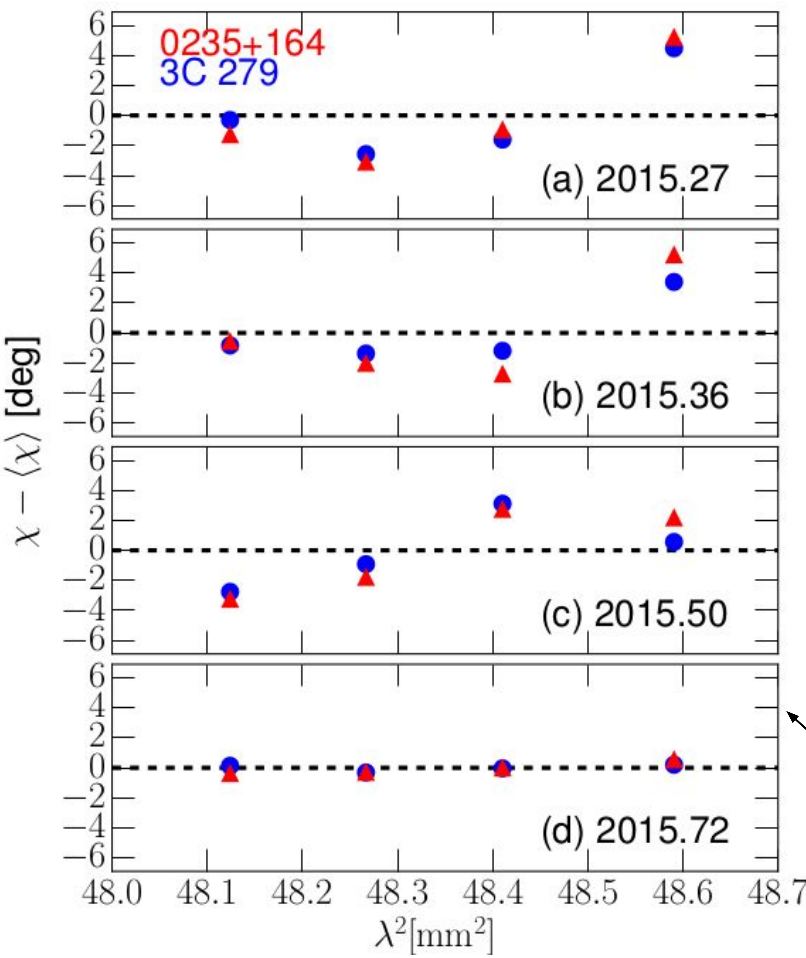
Station	RCP		LCP	
	m [%]	χ [deg]	m [%]	χ [deg]
(1)	(2)	(3)	(4)	(5)
BR	5.8 ± 2.7	$-(106 \pm 16)$	7.2 ± 2.7	$-(48 \pm 20)$
EB	4.5 ± 2.1	56 ± 24	2.3 ± 2.5^a	98 ± 40^a
FD	7.9 ± 2.9	23 ± 13	7.0 ± 3.6	$-(141 \pm 25)$
GB	1.7 ± 2.4^a	$-(162 \pm 46)^a$	2.6 ± 1.3	$-(66 \pm 44)^a$
KP	3.1 ± 2.8	178 ± 30	3.8 ± 1.7	88 ± 14
LA	10.7 ± 1.6	139 ± 9	10.1 ± 2.1	32 ± 13
MK	3.9 ± 3.1	11 ± 25	4.3 ± 1.9	$-(90 \pm 23)$
NL	4.8 ± 1.6	$-(167 \pm 21)$	3.7 ± 1.3	70 ± 13
ON	5.9 ± 1.9	$-(178 \pm 27)$	4.8 ± 2.4	$-(4 \pm 36)$
OV	3.6 ± 2.4	$-(48 \pm 38)$	5.4 ± 1.7	$-(127 \pm 21)$
PT	8.2 ± 5.6	7 ± 8	9.6 ± 3.4	$-(134 \pm 21)$

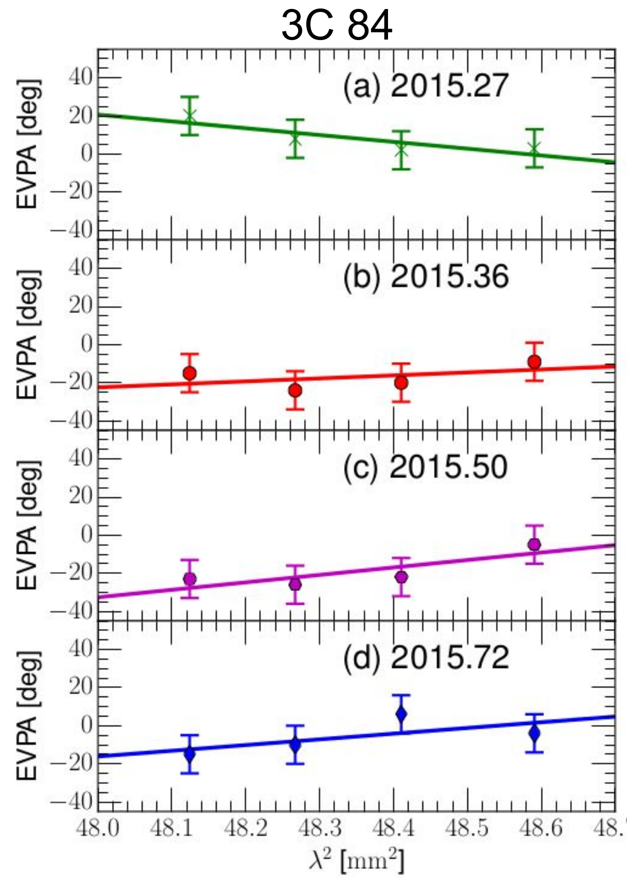




EVPA rotation within the 43GHz band

VLBI core EVPAs of calibrators with completely identical sub-band polcal & EVPA correction



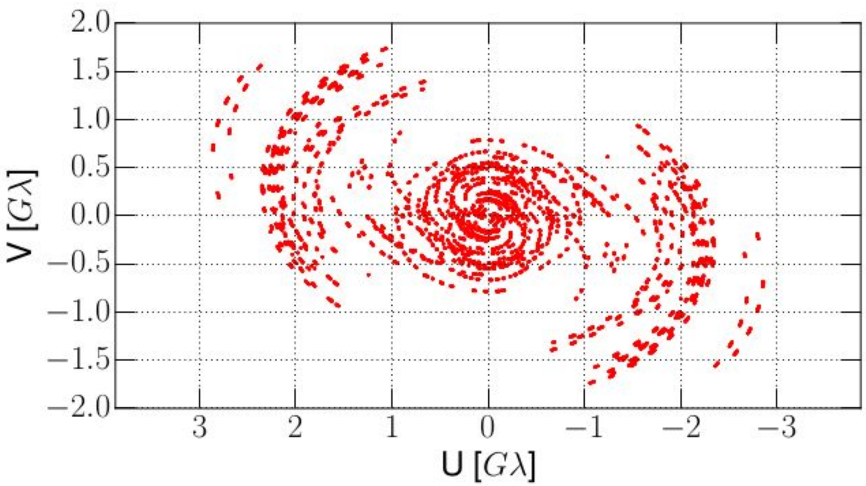


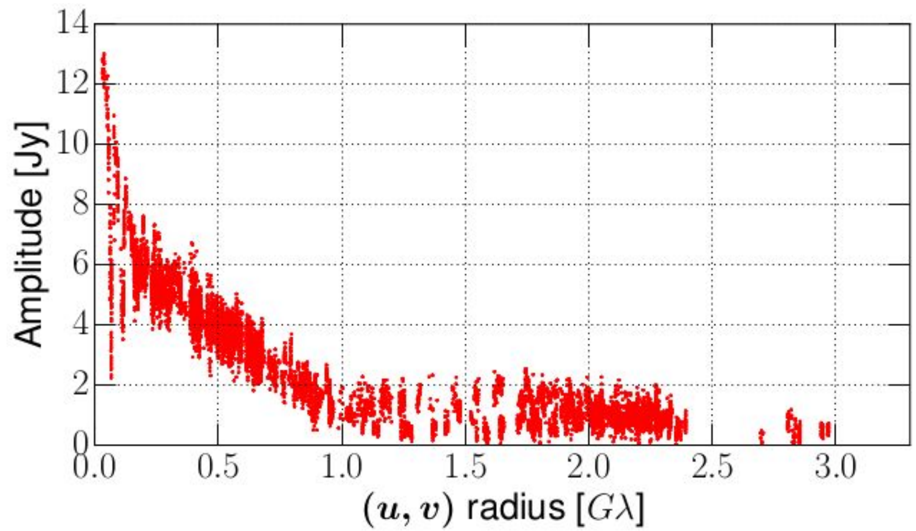
Small but strongly correlated changes.
Most likely systematic, “residual” calibration errors.

Residual EVPA calibration errors : ~< 5 deg

RM > (1-2)x10^5 rad/m^2 can be source-intrinsic and significant.

3C84 GMVA uv-coverage and radial visibility amplitude distribution





Depolarization models

1. A foreground screen with *disordered* magnetic field geometry and *random* RM fluctuations.

2. A foreground screen with *ordered* magnetic field geometry and a *smooth* RM gradient across the observing beam.

$$\text{Case I}: \quad m_{obs} = m_0 \exp(-2\sigma^2\lambda^4) \tag{4.9}$$

$$\text{Case II}: \quad m_{obs} = m_0 \left| \frac{\sin(\Delta\mathrm{RM}\lambda^2)}{\Delta\mathrm{RM}\lambda^2} \right| \tag{4.10}$$