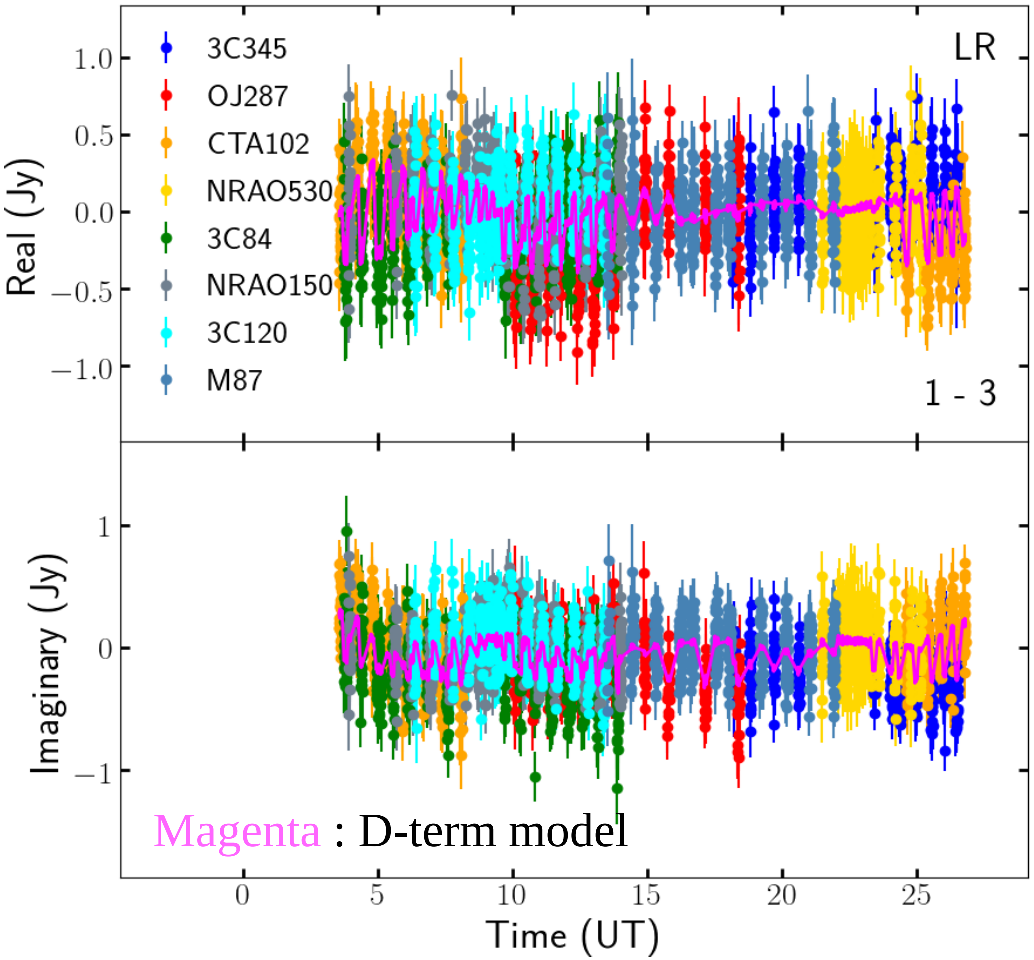
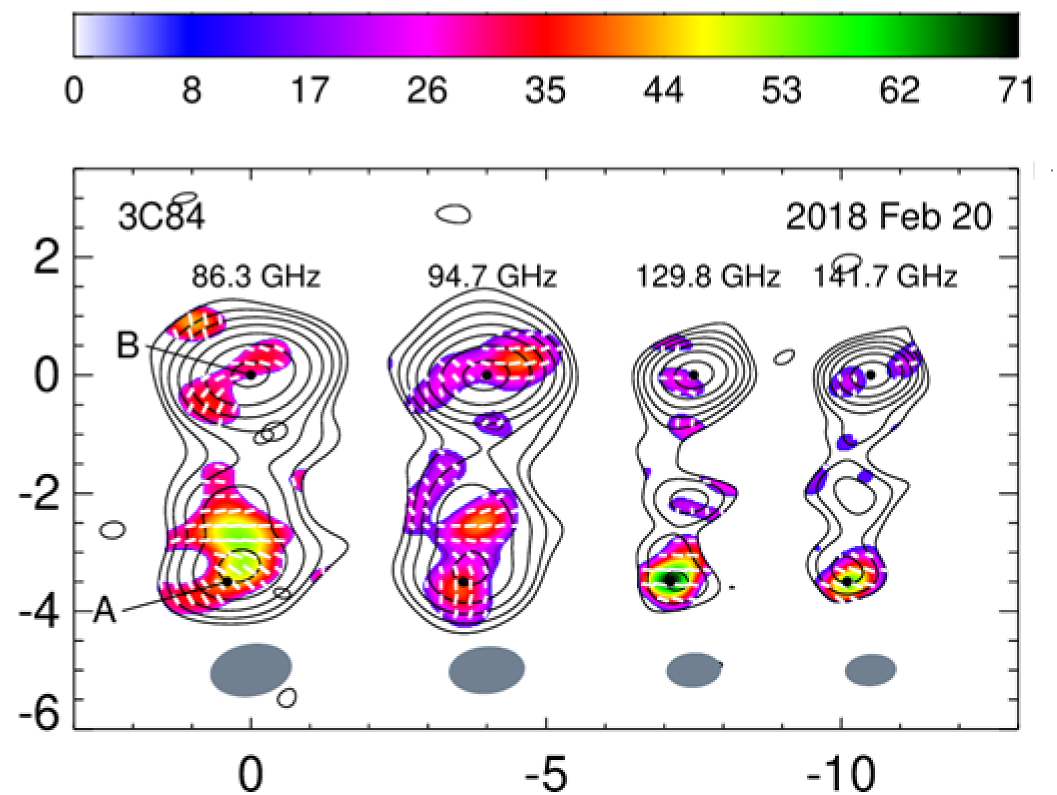
A new strategy for polarization calibration of VLBI data





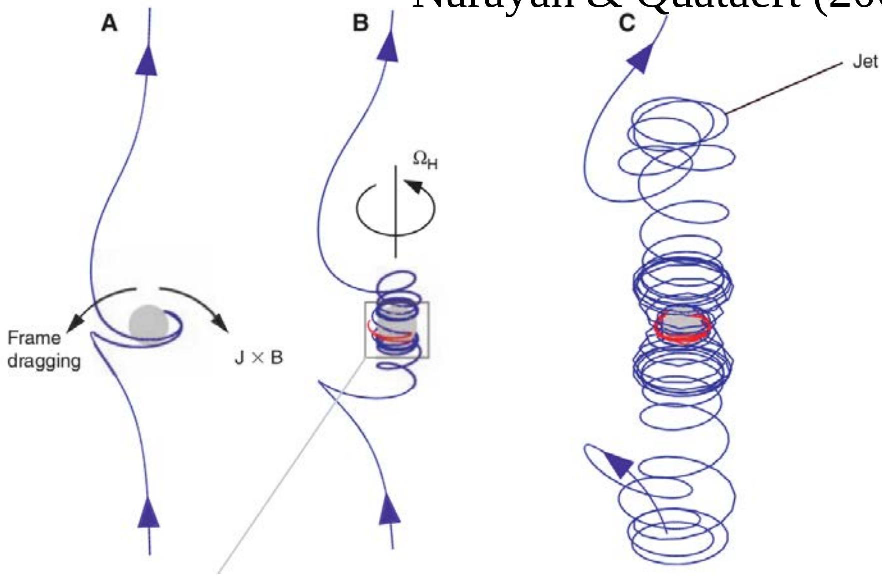
Jongho Park (ASIAA)

in collaboration with Do-Young Byun, Youngjoo Yun (KASI), Cheng-Yu Kuo (NSYSU), Ivan Marti-Vidal (Univ. Valencia)

Polarimetry with VLBI

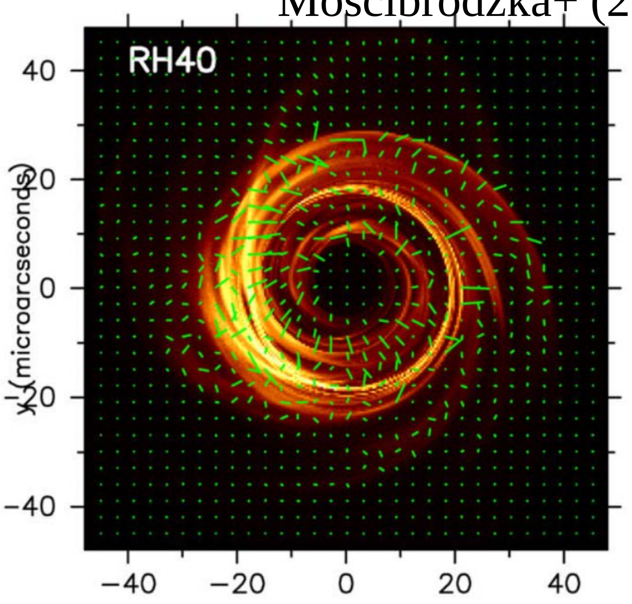
Theory & Simulation

Narayan & Quataert (2005)



Jet Launching Mechanism

Moscibrodzka+ (2017)



Black Hole Accretion

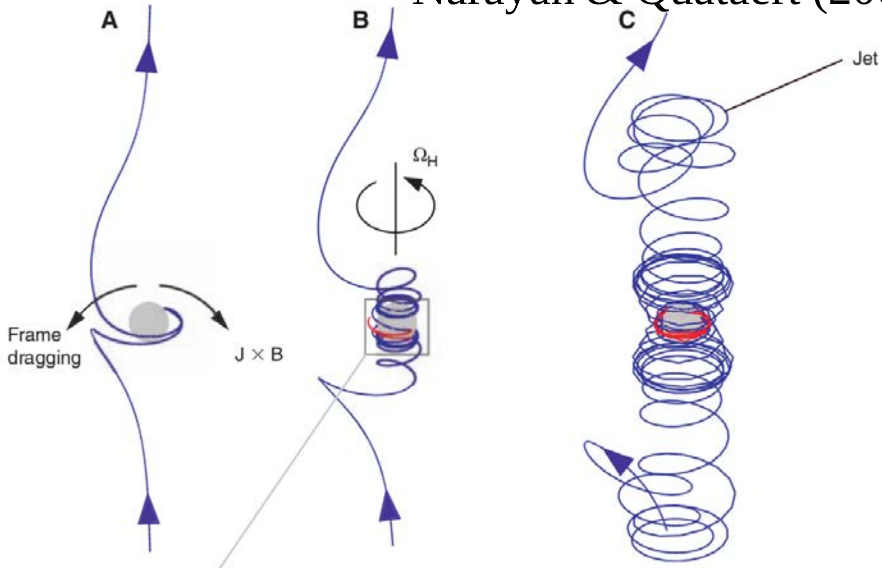
Magnetic Field + High Resolution

→ VLBI Polarimetry

Polarimetry with VLBI

Theory & Simulation

Narayan & Quataert (2005)



Jet Launching Mechanism

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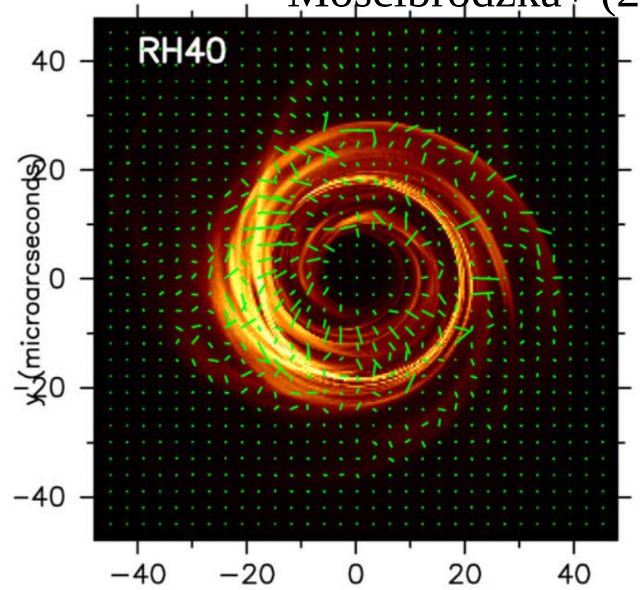
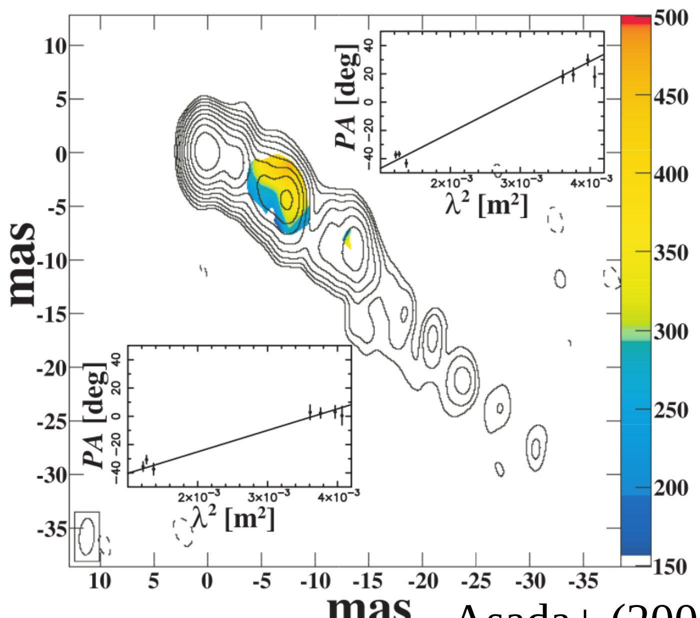


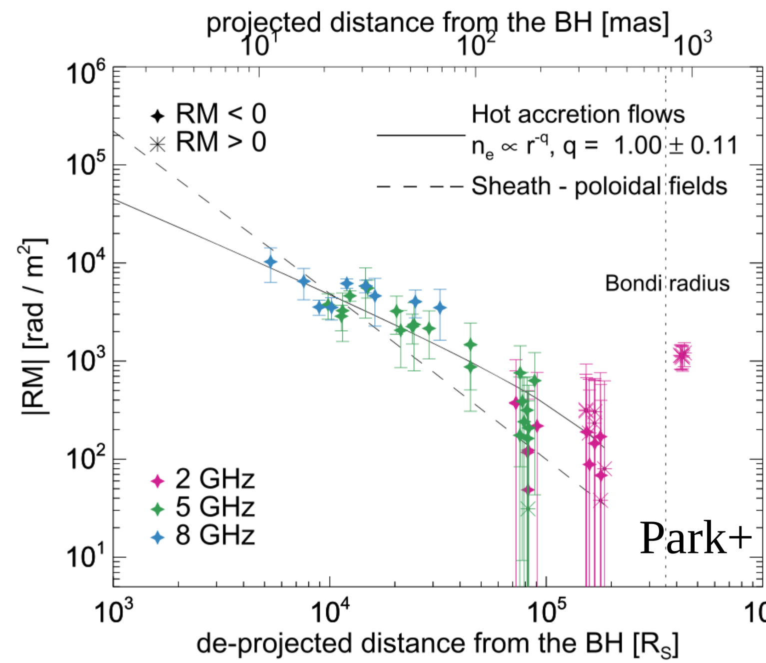
Black Hole Accretion

Observations



Asada+ (2002)

B field geometry



Park+ (2019)

Accretion Dynamics & rate

Observed Voltages

$$\boxed{\begin{aligned} V_L \\ V_R \end{aligned}} \begin{aligned} &= G_L(E_L + D_L E_R e^{-2i\phi}) \\ &= G_R(E_R + D_R E_L e^{2i\phi}) \end{aligned}$$

Polarimetry with VLBI : (known to be) not easy

Observed Voltages

$$V_L = G_L(\boxed{E_L} + D_L E_R e^{-2i\phi})$$
$$V_R = G_R(\boxed{E_R} + D_R E_L e^{2i\phi})$$

'Correct' source signal

Polarimetry with VLBI : (known to be) not easy

Observed Voltages

$$V_L = G_L(E_L + \boxed{D_L E_R e^{-2i\phi}})$$
$$V_R = G_R(E_R + \boxed{D_R E_L e^{2i\phi}})$$

'Correct' source signal

'Instrumental' polarization (often called "D-Terms")

: a fraction of the signal from the opposite polarization is 'leaked'
→ needs to be properly calibrated.

Polarimetry with VLBI : not easy

$$V_L = G_L(E_L + D_L E_R e^{-2i\phi})$$
$$V_R = G_R(E_R + D_R E_L e^{2i\phi})$$

$$\downarrow$$

$$R_i L_j = G_{iR} G^*_{jL} \left(P_{ij} + D_{iR} I e^{2i\phi_i} + D^*_{jL} I e^{2i\phi_j} + D_{iR} D^*_{jL} P^*_{ij} e^{2i(\phi_i + \phi_j)} \right)$$
$$L_i R_j = G_{iL} G^*_{jR} \left(P^*_{ij} + D_{iL} I e^{-2i\phi_i} + D^*_{jR} I e^{-2i\phi_j} + D_{iL} D^*_{jR} P_{ij} e^{-2i(\phi_i + \phi_j)} \right)$$

Polarimetry with VLBI : not easy

$$V_L = G_L(E_L + D_L E_R e^{-2i\phi})$$
$$V_R = G_R(E_R + D_R E_L e^{2i\phi})$$

Cross-hand visibilities

$$\boxed{R_i L_j} = G_{iR} G^*_{jL} \left(P_{ij} + D_{iR} I e^{2i\phi_i} + D^*_{jL} I e^{2i\phi_j} + D_{iR} D^*_{jL} P^*_{ij} e^{2i(\phi_i + \phi_j)} \right)$$
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Polarimetry with VLBI : not easy

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Source-intrinsic signal

Polarimetry with VLBI : not easy

$$V_L = G_L(E_L + D_L E_R e^{-2i\phi})$$
$$V_R = G_R(E_R + D_R E_L e^{2i\phi})$$

Cross-hand visibilities

$$R_i L_j = G_{iR} G^*_{jL} \left(P_{ij} + D_{iR} I e^{2i\phi_i} + D^*_{jL} I e^{2i\phi_j} + D_{iR} D^*_{jL} P^*_{ij} e^{2i(\phi_i+\phi_j)} \right)$$
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Source-intrinsic signal

D-Terms
(that we want to calibrate!)

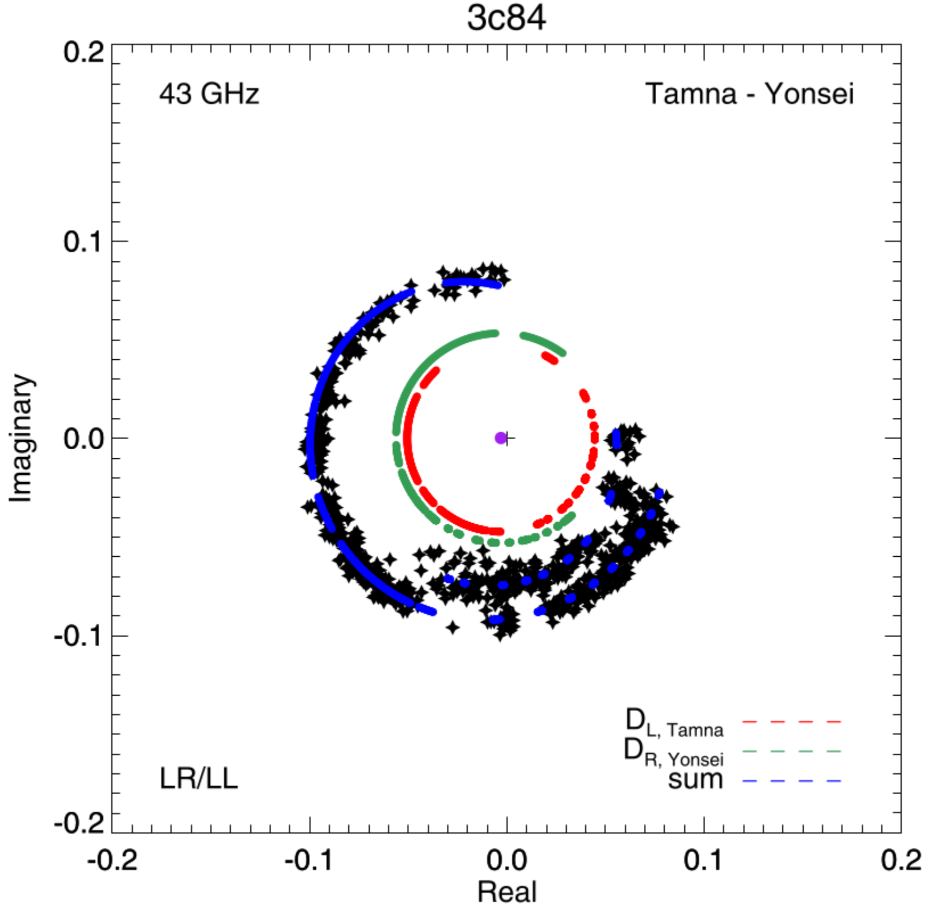
Polarimetry with VLBI : not easy

$$R_i L_j = G_{iR} G^*_{jL} \left(P_{ij} + D_{iR} I e^{2i\phi_i} + D^*_{jL} I e^{2i\phi_j} + D_{iR} D^*_{jL} P^*_{ij} e^{2i(\phi_i + \phi_j)} \right)$$

$$L_i R_j = G_{iL} G^*_{jR} \left(P^*_{ij} + D_{iL} I e^{-2i\phi_i} + D^*_{jR} I e^{-2i\phi_j} + D_{iL} D^*_{jR} P_{ij} e^{-2i(\phi_i + \phi_j)} \right)$$

φ : Parallactic angles

Sinusoidal variation over parallactic angles
(Or "circular rotation" on the complex plane)



AIPS task LPCAL : a conventional calibration tool

$$\tilde{r}_{ij}^{RL}(u,v) = P(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D^*_{jL} r_{ij}^{RR}(u,v) e^{2i\phi_j} + P^*(u,v) D_{iR} D^*_{jL} e^{2i(\phi_i+\phi_j)}$$

$$\tilde{r}_{ij}^{LR}(u,v) = P^*(u,v) + \underbrace{D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D^*_{jR} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + P(u,v) D_{iL} D^*_{jR} e^{-2i(\phi_i+\phi_j)}}_{\text{D-Terms}}$$

Source Polarization

2nd order terms

What AIPS LPCAL does is...

'Model' visibility
for total intensity

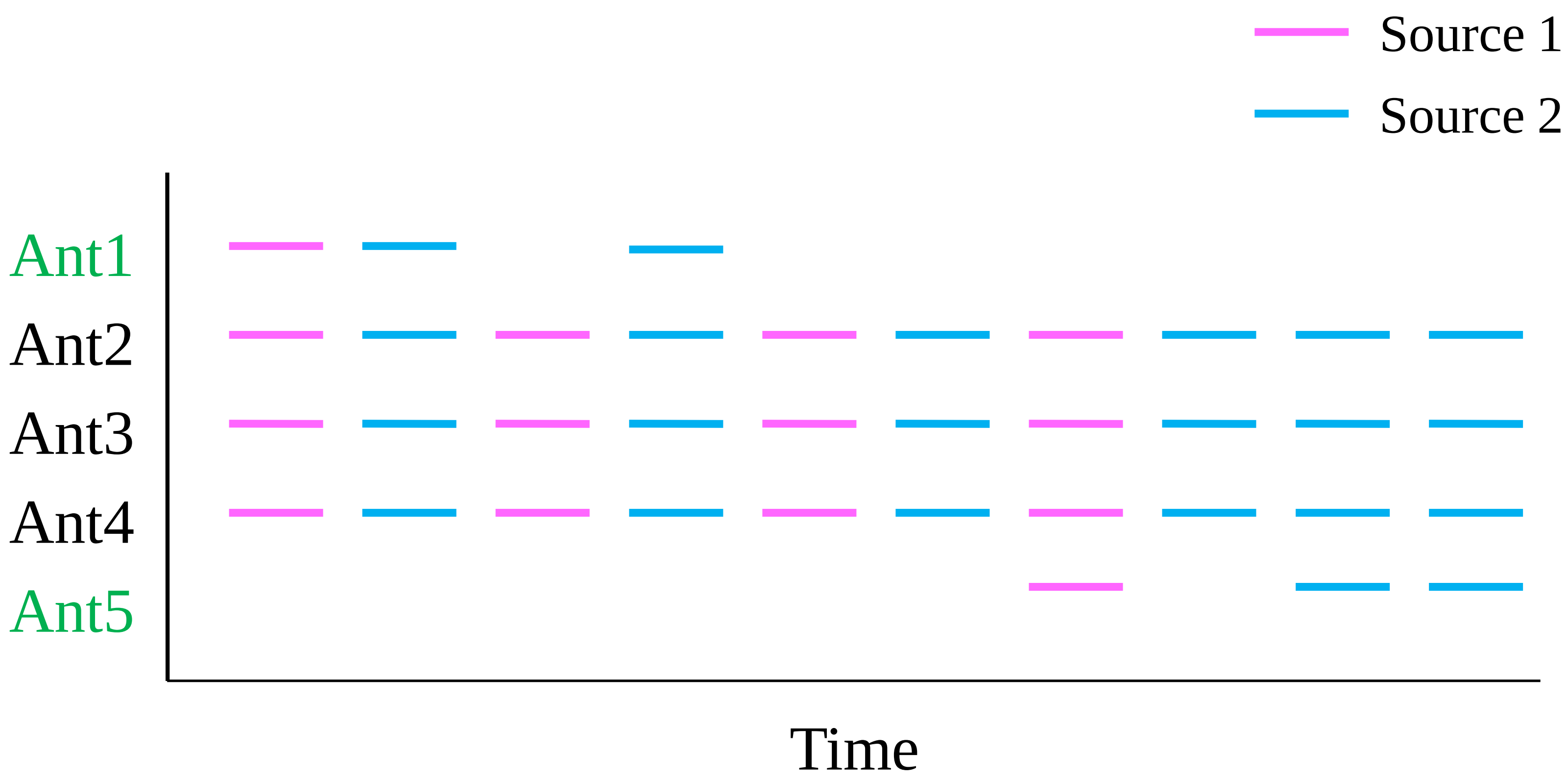
$$\tilde{r}_{ij}^{RL}(u,v) = pF(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D^*_{jL} r_{ij}^{RR}(u,v) e^{2i\phi_j} + \cancel{p^* F(u,v) D_{iR} D^*_{jL} e^{2i(\phi_i+\phi_j)}}$$

$$\tilde{r}_{ij}^{LR}(u,v) = p^* F(u,v) + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D^*_{jR} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + \cancel{pF(u,v) D_{iL} D^*_{jR} e^{-2i(\phi_i+\phi_j)}}$$

Assume a 'constant fractional polarization' for a source

Ignore

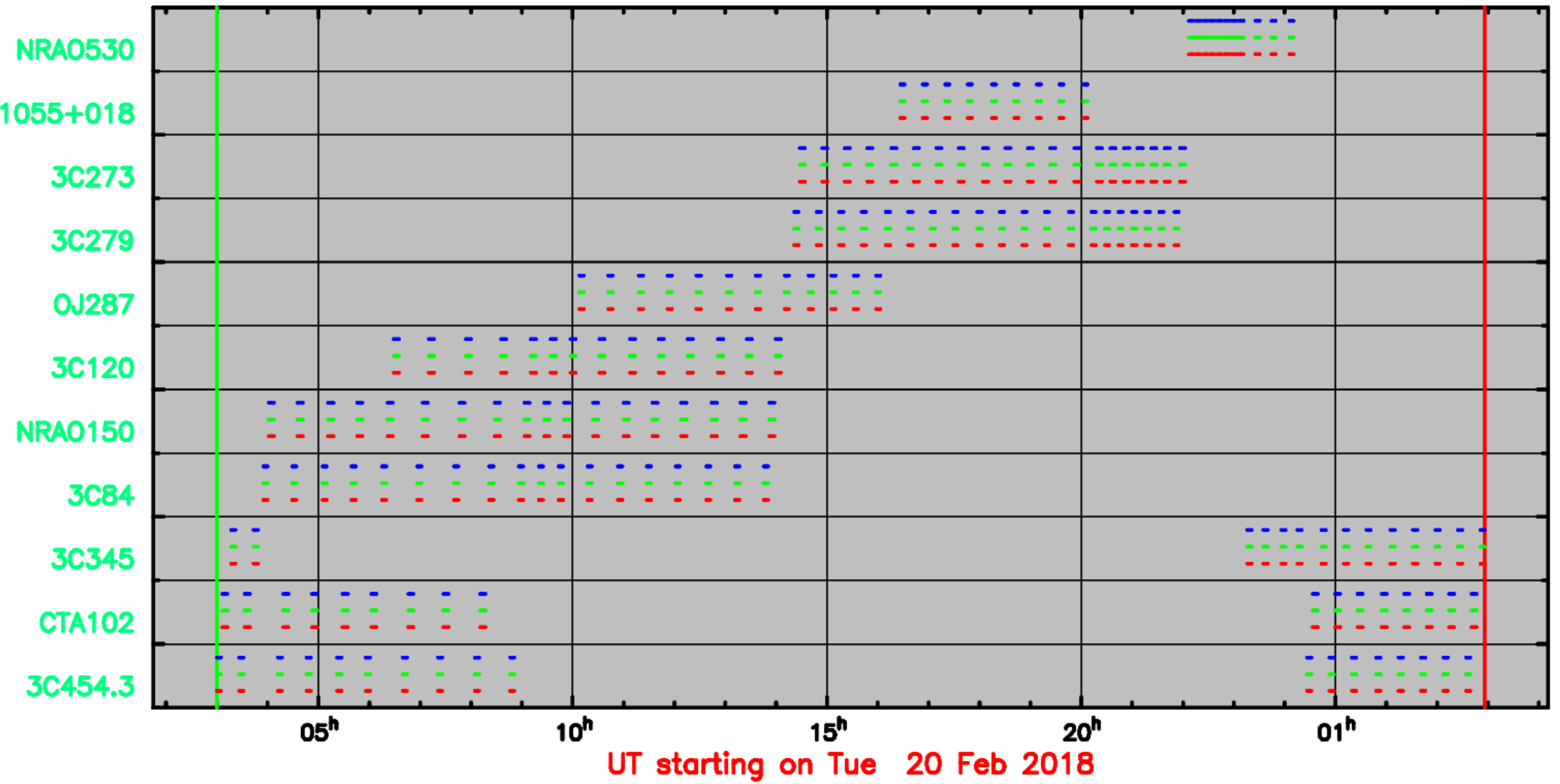
LPCAL can fit the model to ‘a single source’ visibility data



1. There are often not many scans for ‘long baseline antennas’.
→ D-term estimation accuracy is limited for those antennas.

Some situations where LPCAL does not show a good performance...

LPCAL can fit the model to ‘a single source’ visibility data



2. When we have a small number of antennas (such as the KVN).
→ difficult to determine which source is ‘the best calibrator’?

Some situations where LPCAL does not show a good performance...

LPCAL ignores the 2nd order terms.

$$\tilde{r}_{ij}^{RL}(u,v) = \sum_s p_s F_s(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D_{jL}^{*} r_{ij}^{RR}(u,v) e^{2i\phi_j} + \cancel{\sum_s p_s^{*} F_s(u,v) D_{iR} D_{jL}^{*} e^{2i(\phi_i+\phi_j)}}$$

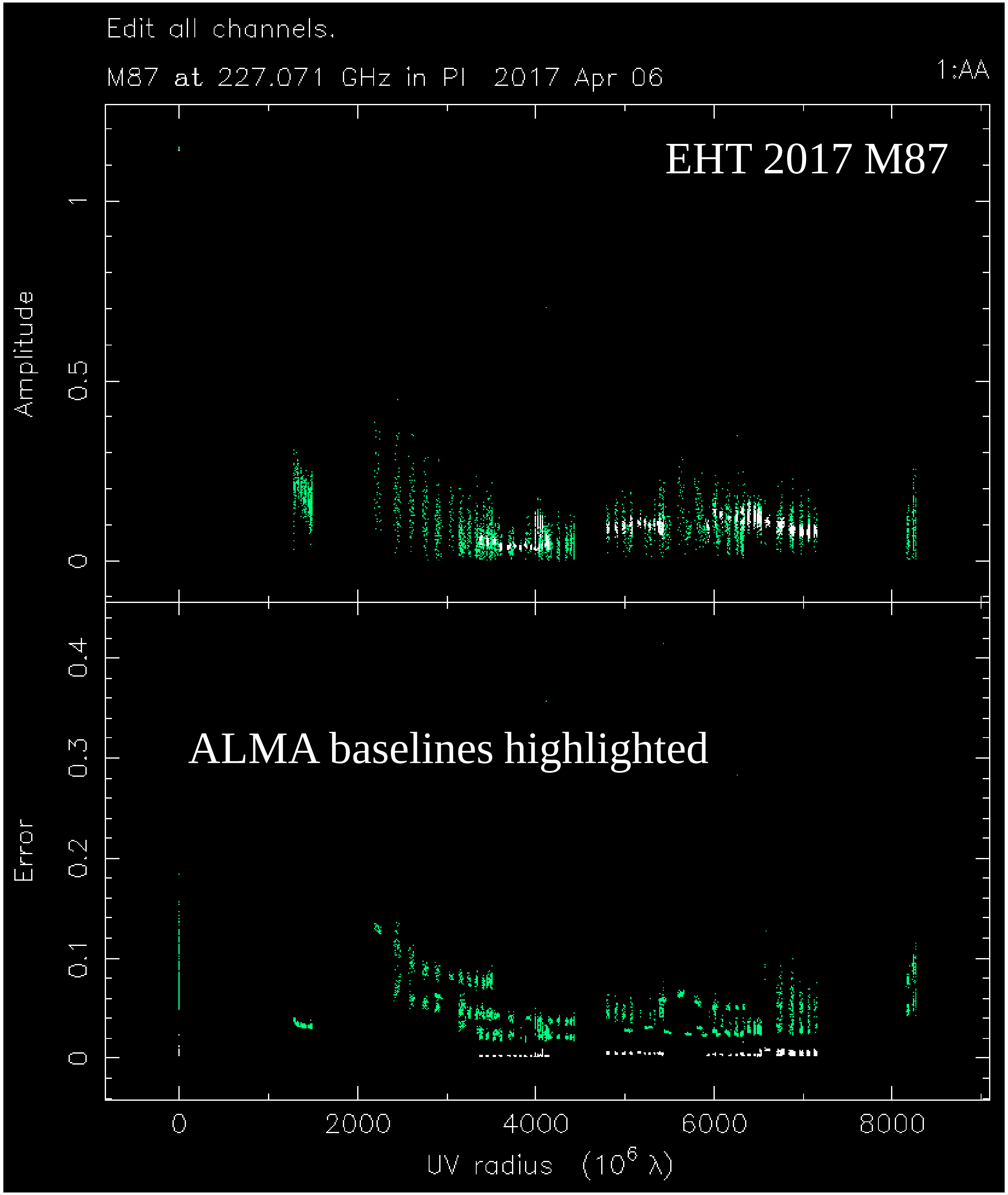
$$\tilde{r}_{ij}^{LR}(u,v) = \sum_s p_s^{*} F_s(u,v) + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D_{jR}^{*} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + \cancel{\sum_s p_s F_s(u,v) D_{iL} D_{jR}^{*} e^{-2i(\phi_i+\phi_j)}}$$

Ignore

3. When the D-terms are large and source polarization is large

→ cannot ignore the 2nd order terms.

Some situations where LPCAL does not show a good performance...



4. When antennas have quite different sensitivities (e.g., ALMA + EHT, GBT + VLBA)
→ We must properly take antenna weights into account (not possible for LPCAL).

How to improve?

$$\tilde{r}_{ij}^{RL}(u,v) = \sum_s p_s F_s(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D_{jL}^* r_{ij}^{RR}(u,v) e^{2i\phi_j} + \sum_s p_s^* F_s(u,v) D_{iR} D_{jL}^* e^{2i(\phi_i+\phi_j)}$$

$$\tilde{r}_{ij}^{LR}(u,v) = \sum_s p_s^* F_s(u,v) + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D_{jR}^* r_{ij}^{LL}(u,v) e^{-2i\phi_j} + \sum_s p_s F_s(u,v) D_{iL} D_{jR}^* e^{-2i(\phi_i+\phi_j)}$$

Let's develop a new algorithm which fits the model to 'multiple sources' visibilities simultaneously.

Possible advantages are

(i) increase in 'effective' signal-to-noise ratio (we have more data points).
(ii) improvement of the D-term accuracy thanks to the 2nd order terms included.
(iii) less efforts and time required (no need to figure out which calibrator is the best)
(iv) controlling weights for different antennas and sources are flexible (which might be important for the EHT).

How does it work?

Extract the visibilities and weights into ascii files — ParselTongue

↓

Obtain the best-fit D-Term model — Python code

↓

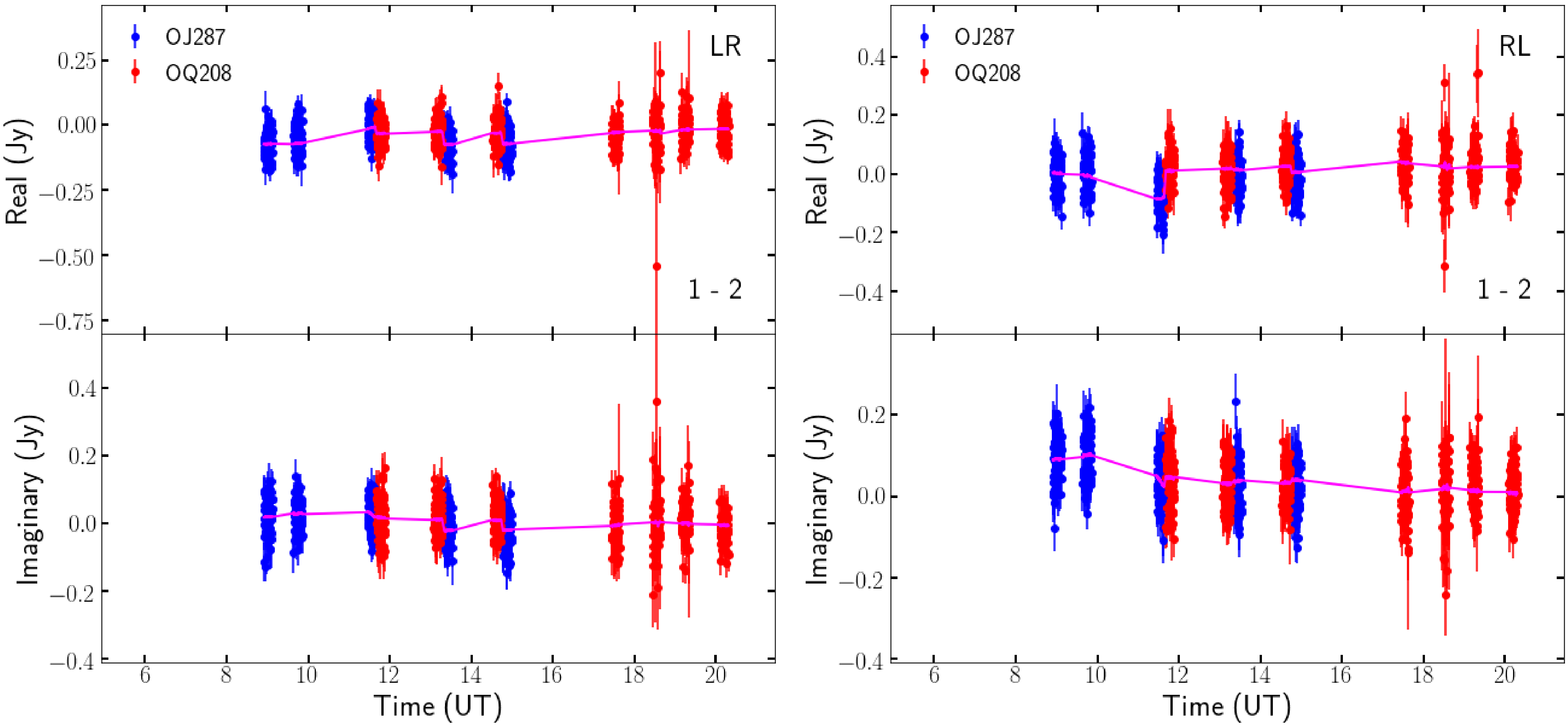
Obtain the D-Term calibrated UVfits file — ParselTongue

All these processes can be done by running a single script.
It takes a few minutes to less than 15 minutes depending on the data size

Does it work well?

VLBA

Brewster – Fort Davis



Circles : LHS (**data**)
Magenta : RHS (**model**)

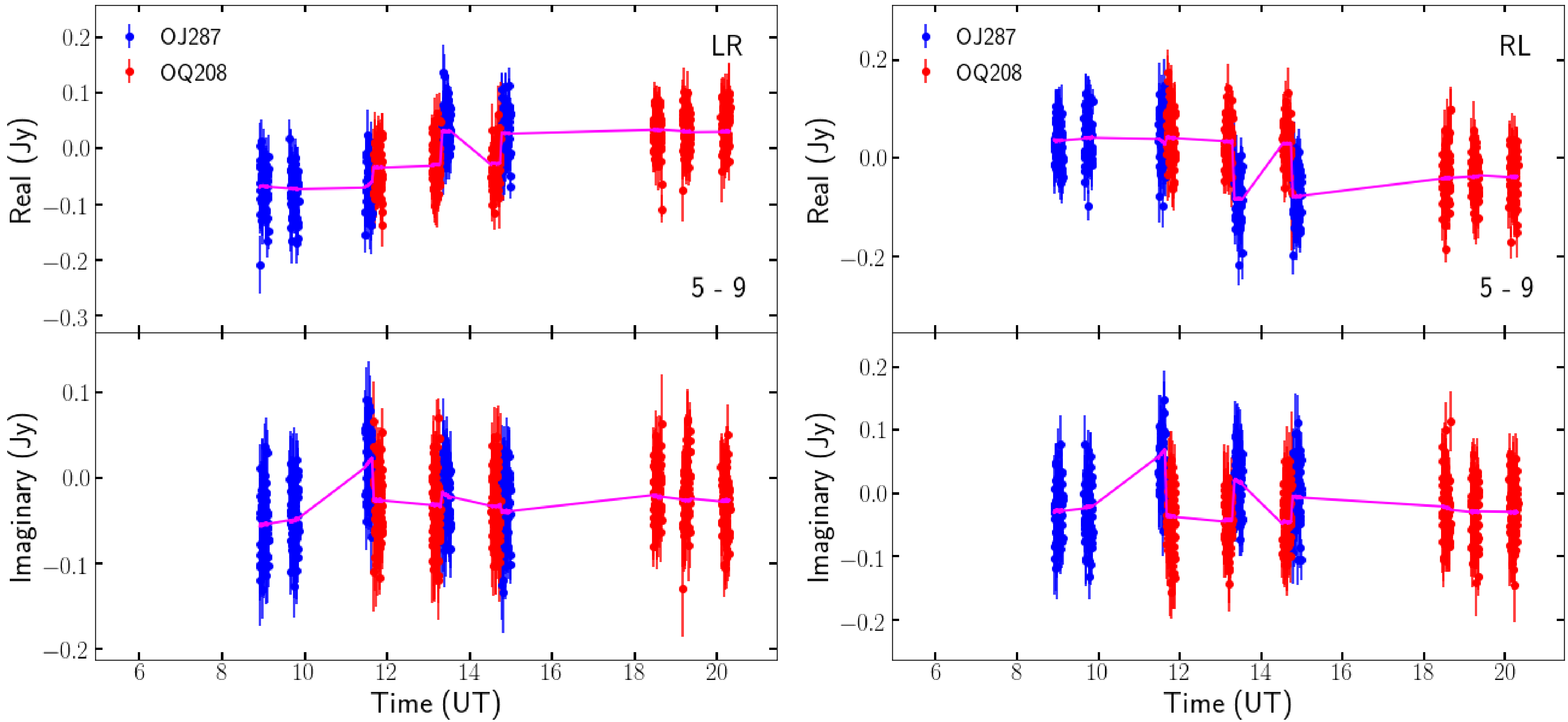
$$\tilde{r}_{ij}^{RL}(u,v) = pF(u,v) + D_{iR}r_{ij}^{LL}(u,v)e^{2i\phi_i} + D_{jL}^{*}r_{ij}^{RR}(u,v)e^{2i\phi_j} + p^{*}F(u,v)D_{iR}D_{jL}^{*}e^{2i(\phi_i+\phi_j)}$$

$$\tilde{r}_{ij}^{LR}(u,v) = p^{*}F(u,v) + D_{iL}r_{ij}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^{*}r_{ij}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^{*}e^{-2i(\phi_i+\phi_j)}$$

Does it work well?

VLBA

Los Alamos – Pie Town



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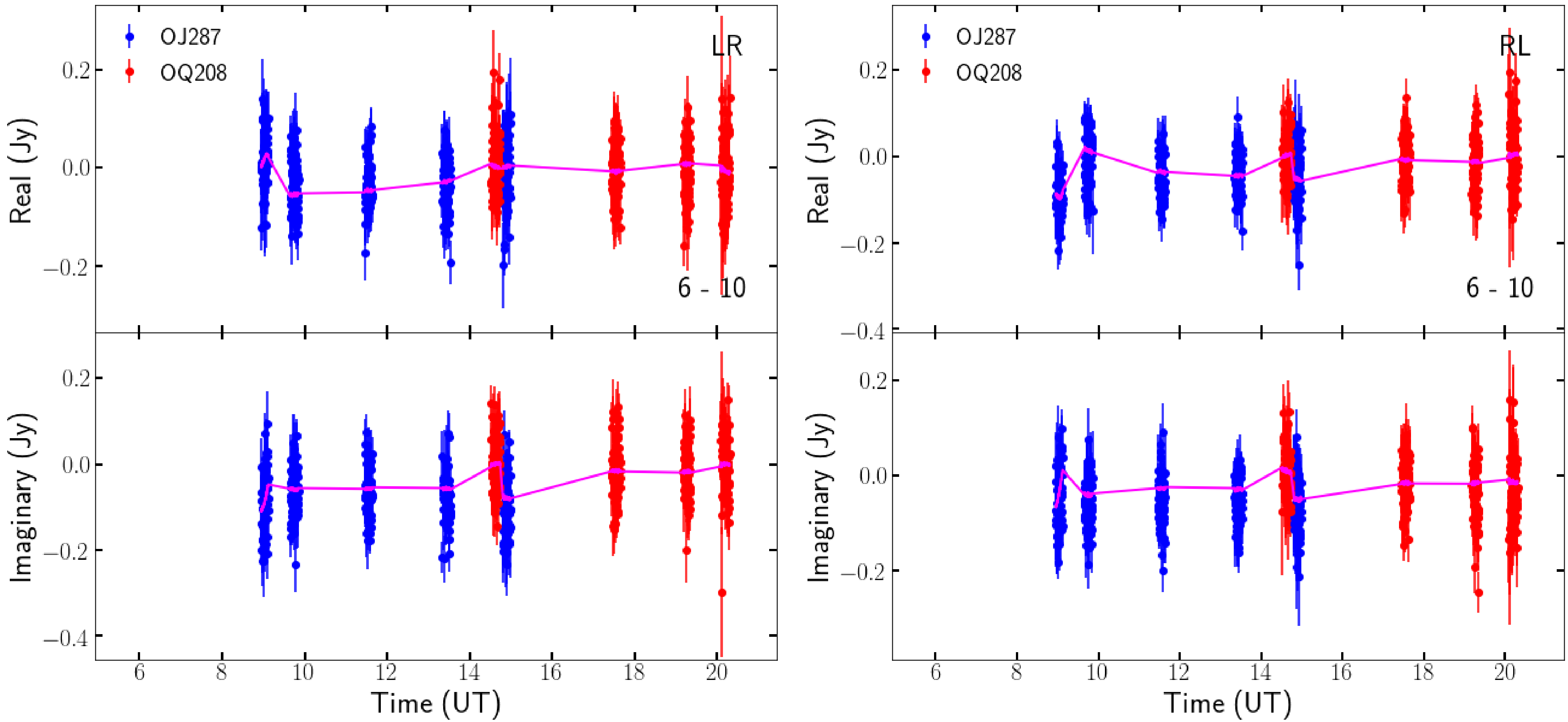
Does it work well?

VLBA

Mauna Kea – Saint Croix



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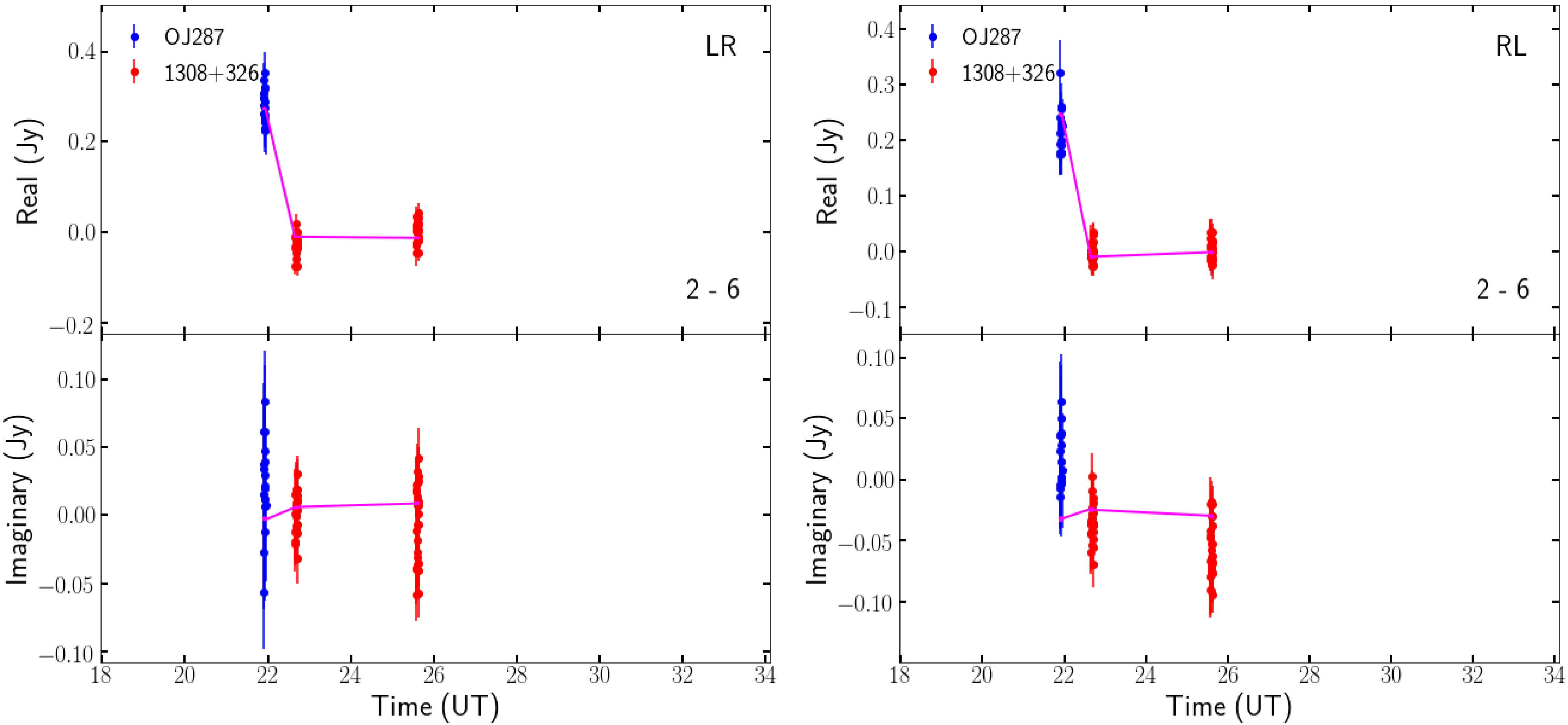
Does it work well?

HSA

Effelsberg – Los Alamos



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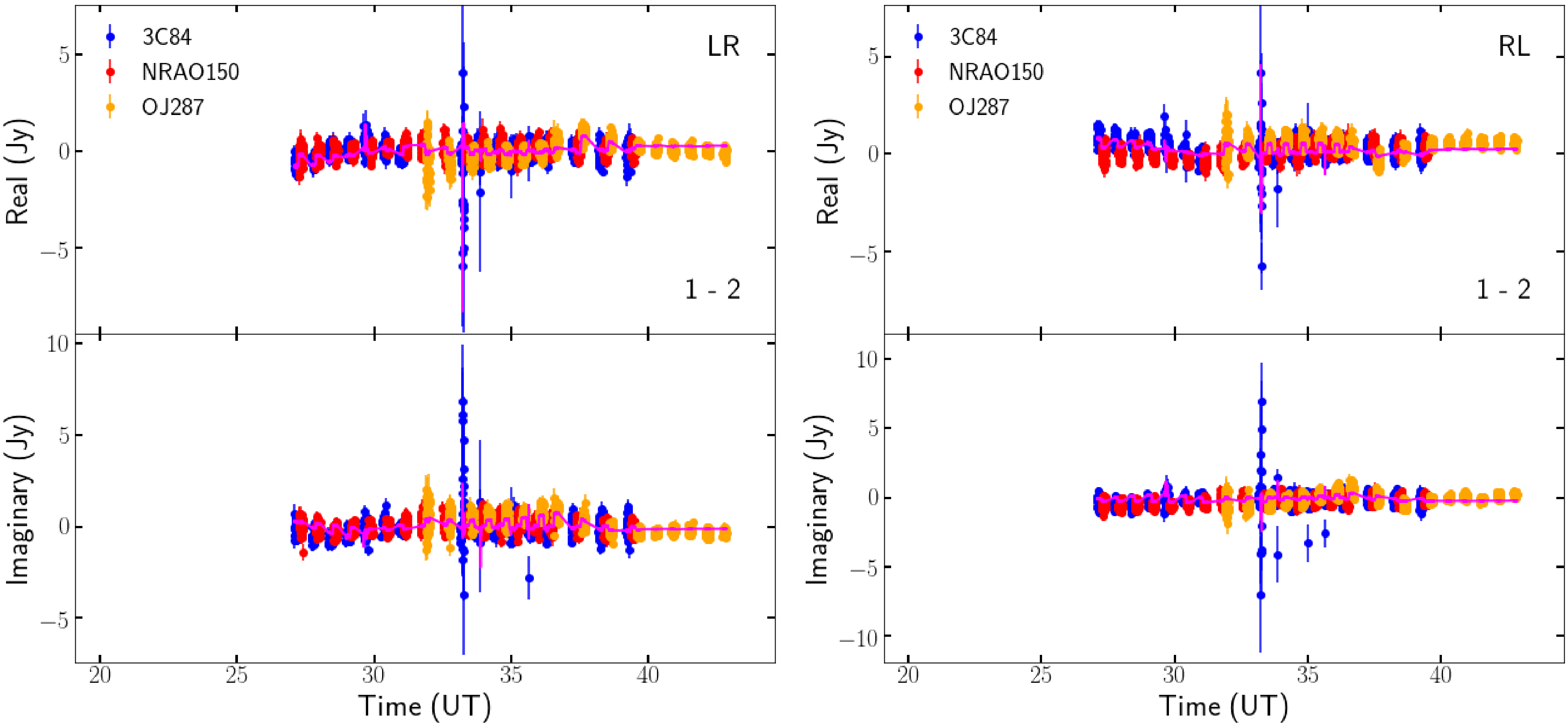
Does it work well?

KaVA (5 Stations)

Mizusawa - Iriki



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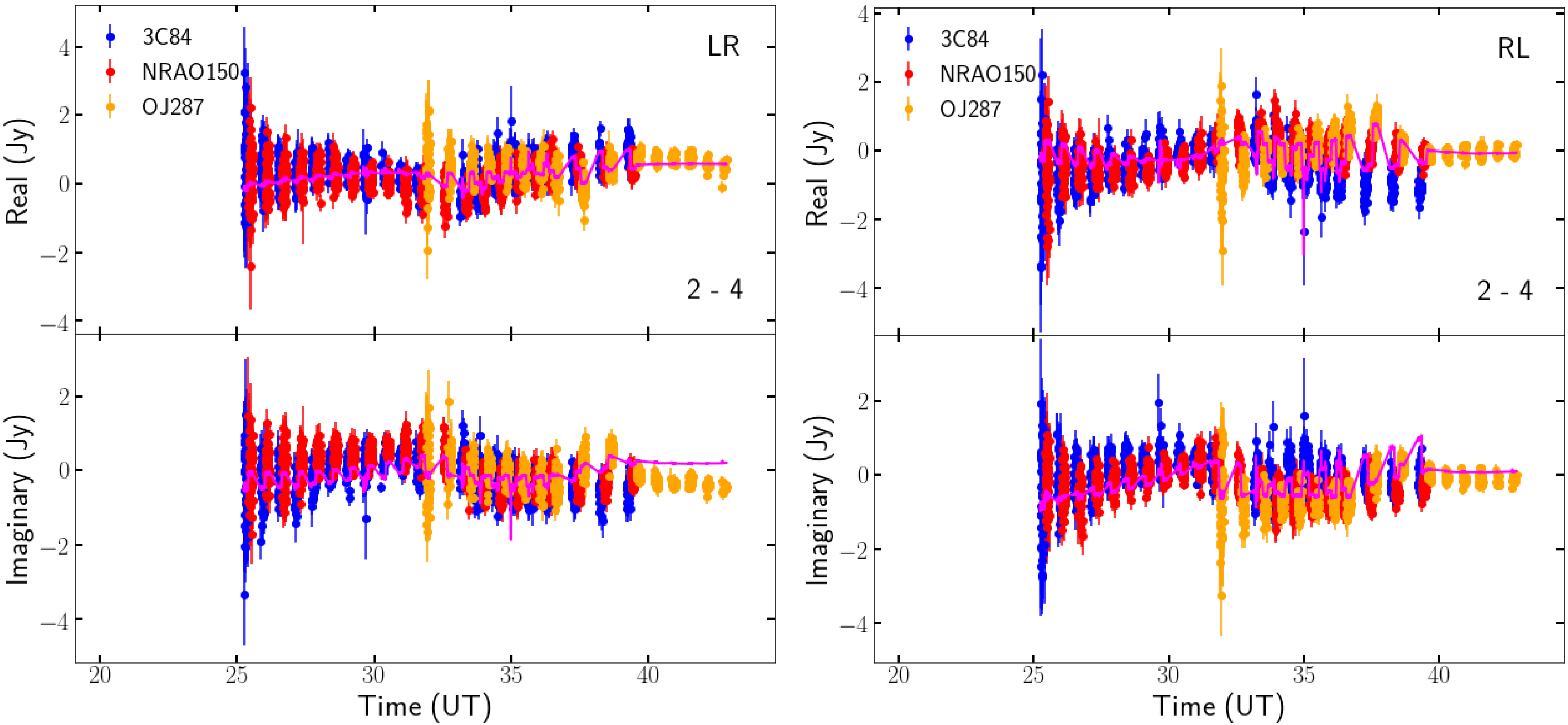
Does it work well?

KaVA (5 Stations)

Iriki - Ulsan



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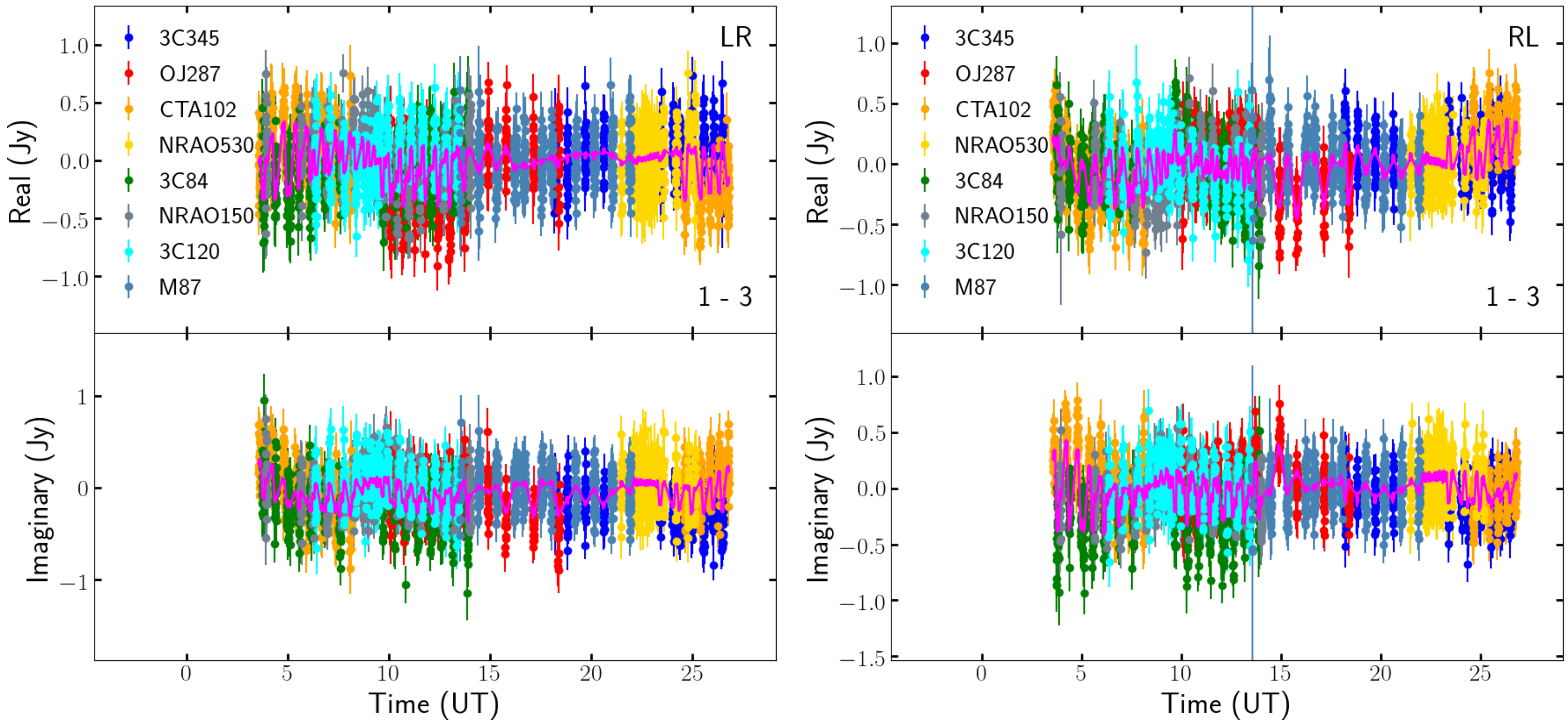
Does it work well?

KVN

Tamna – Yonsei



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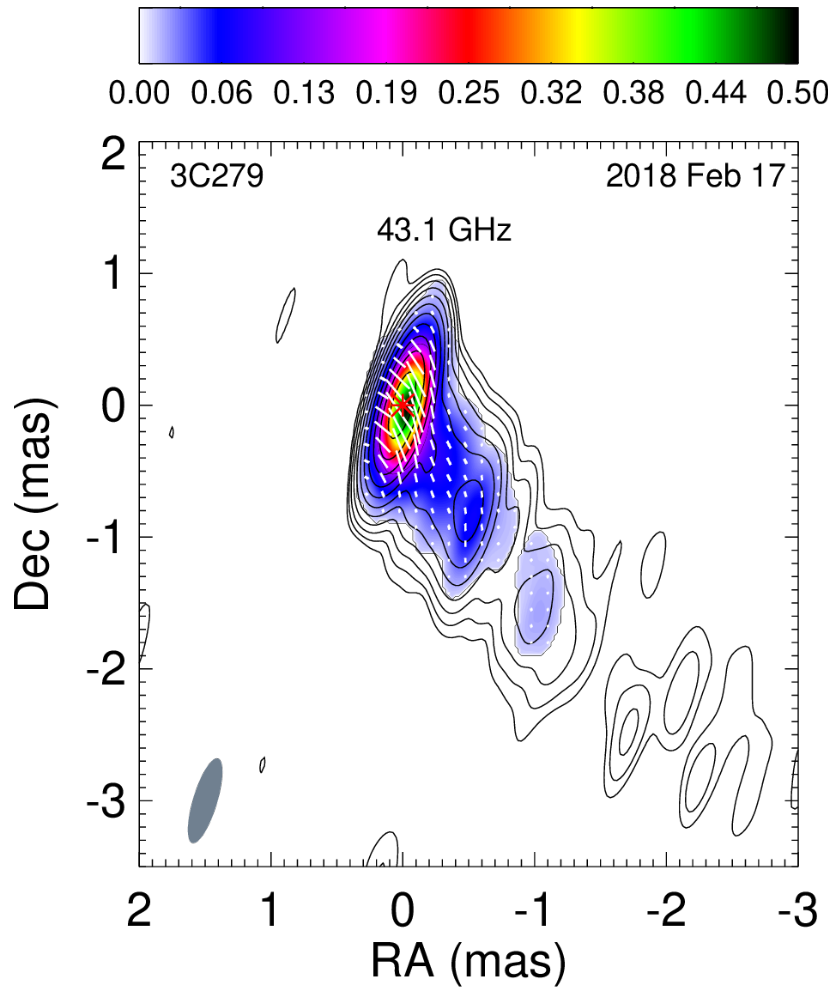
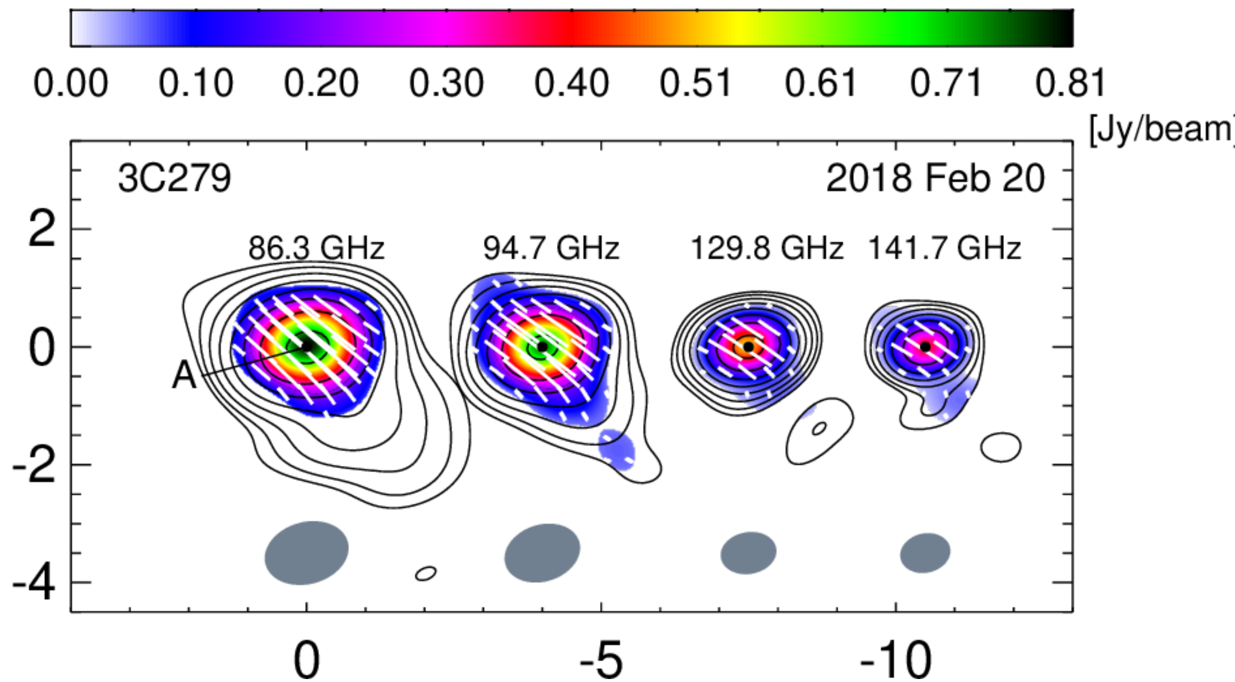
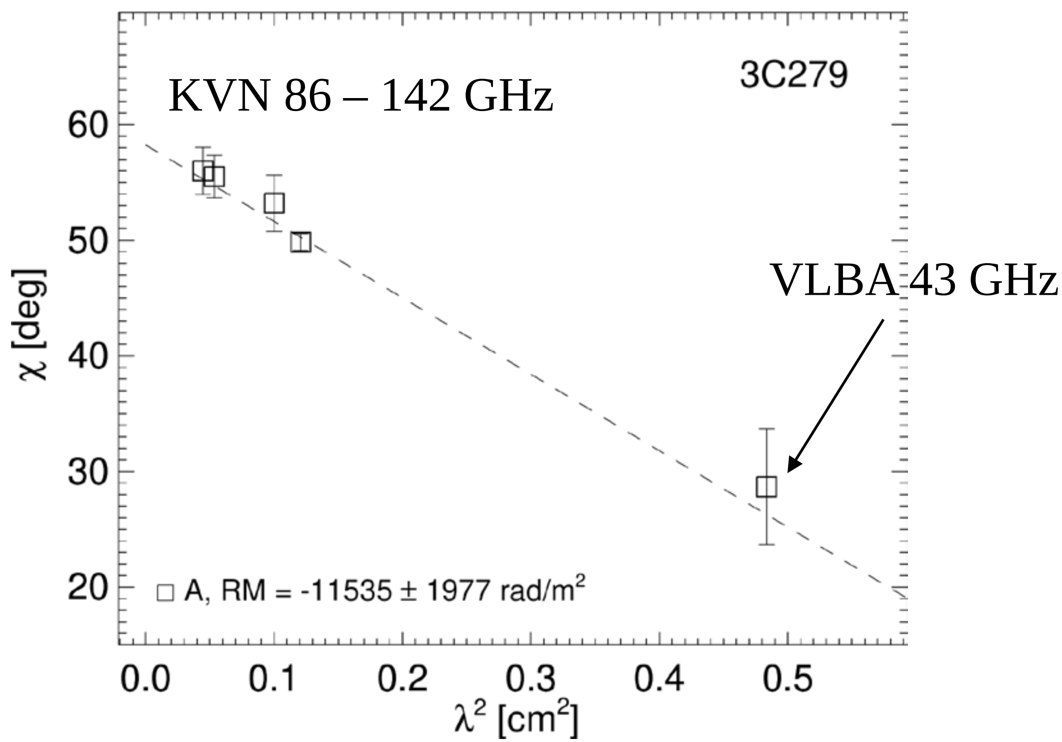
Probing the linear polarization of AGN jets at mm wavelengths with the KVN

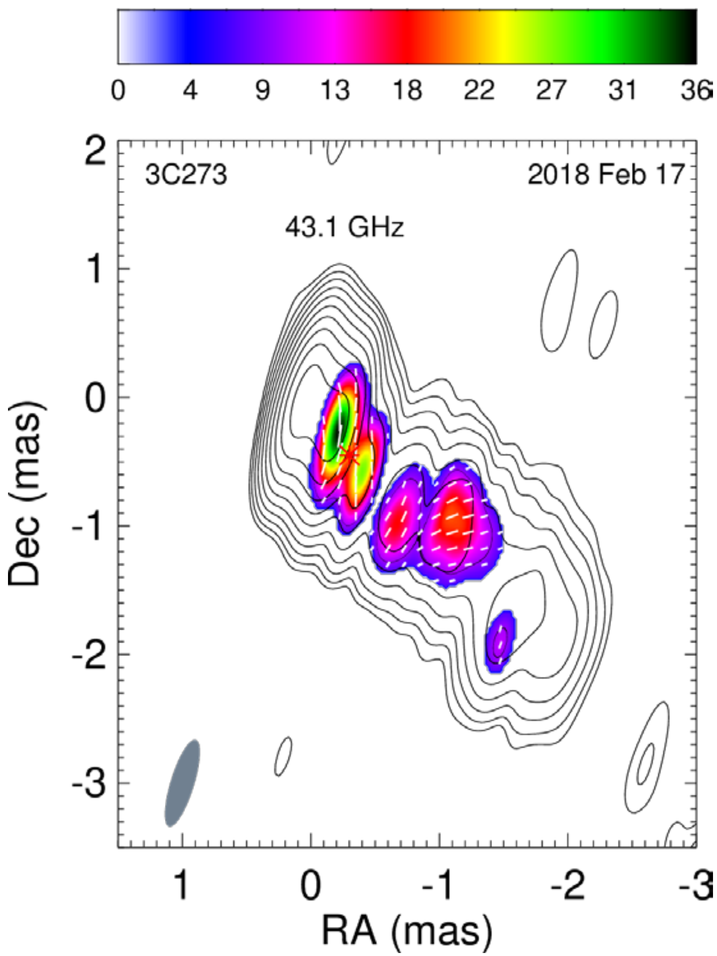


VLBA (BU) 43 GHz





Probing the linear polarization of AGN jets at mm wavelengths with the KVN



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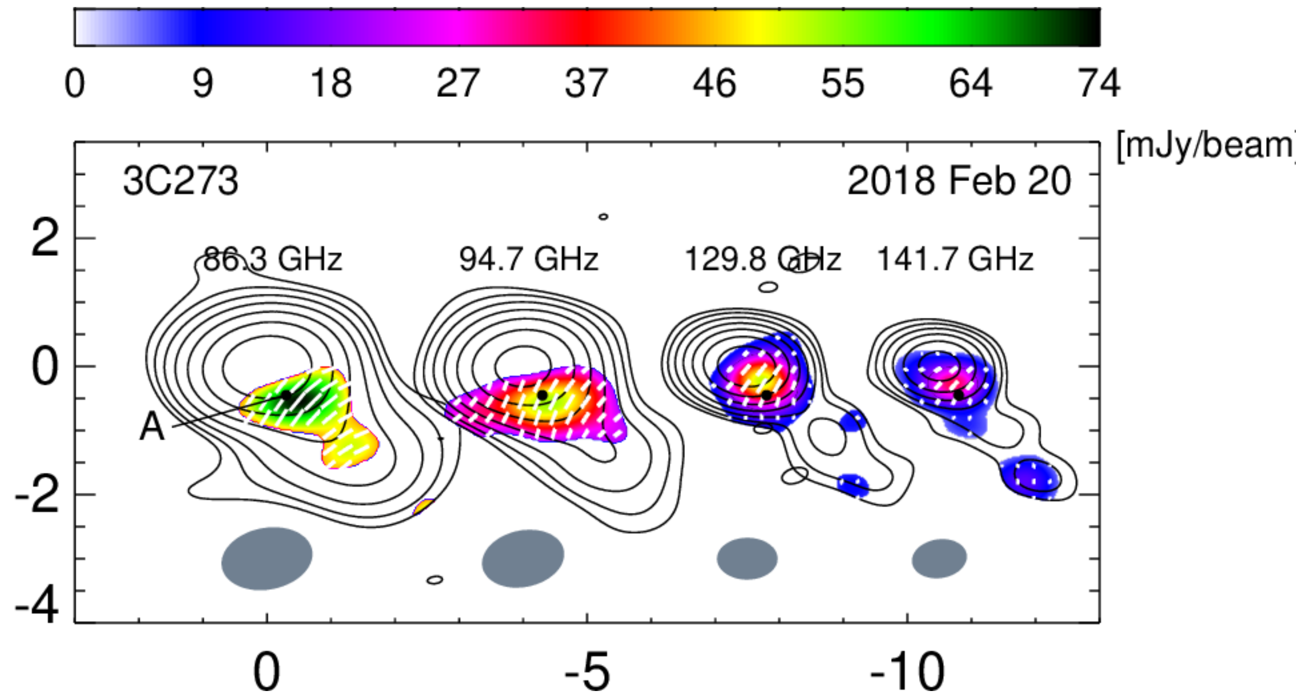
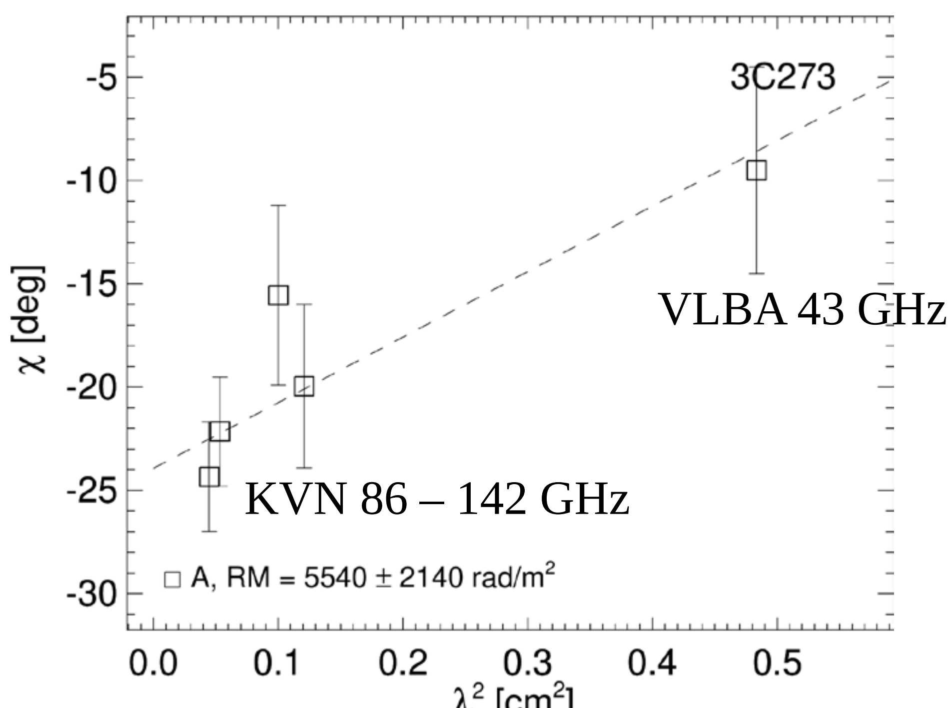
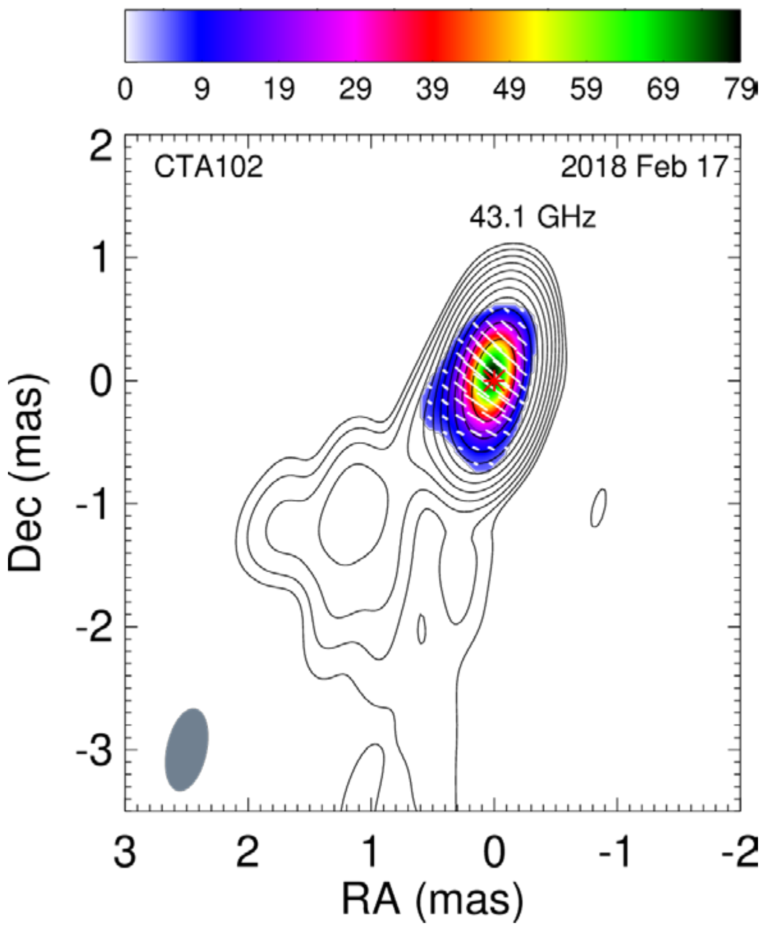




Probing the linear polarization of AGN jets at mm wavelengths with the KVN



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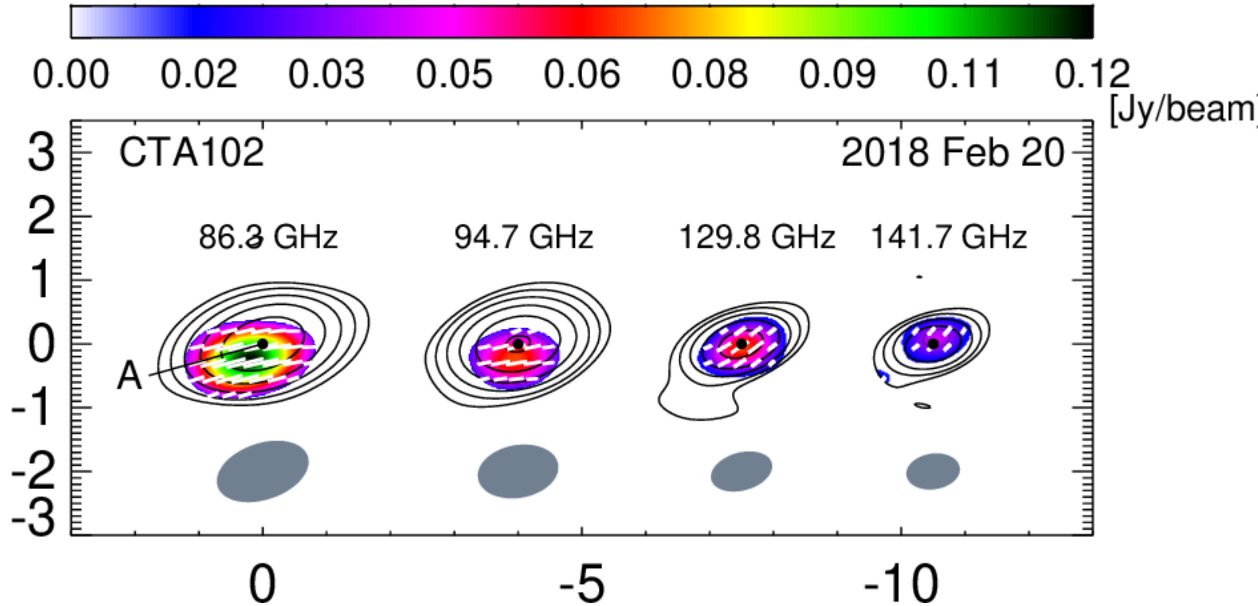
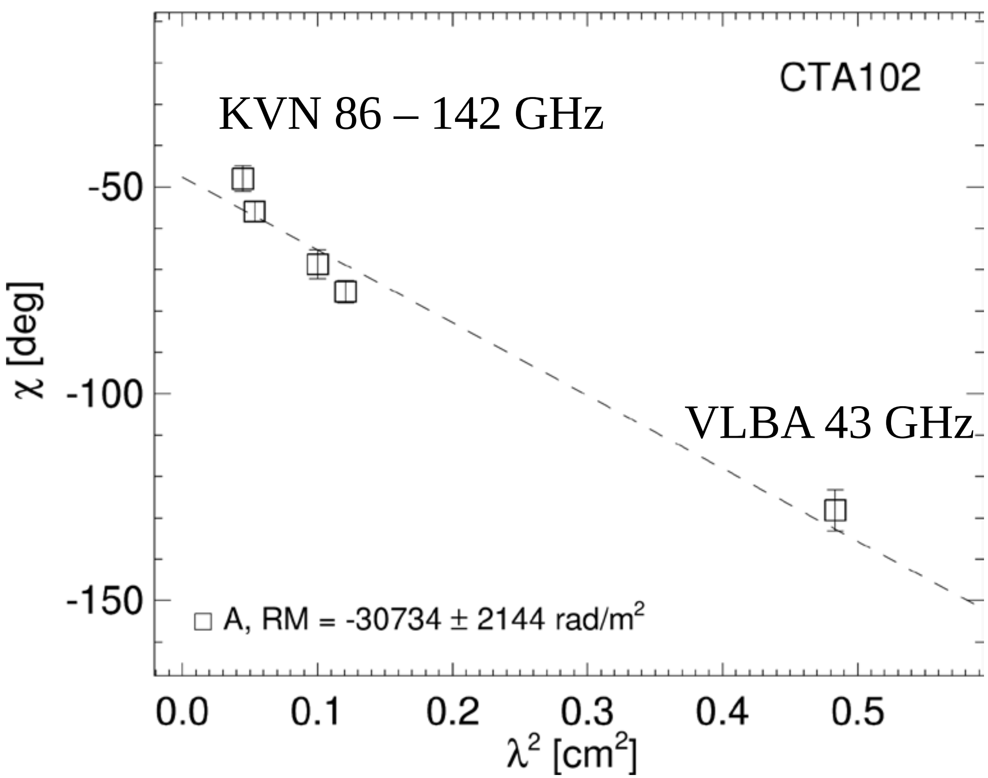
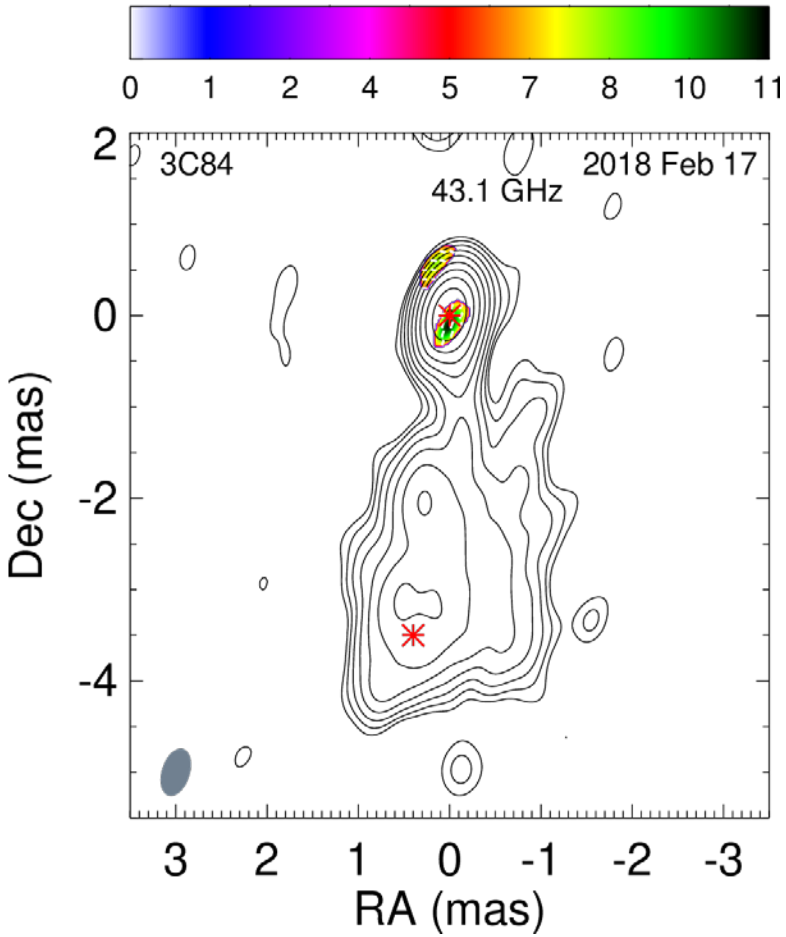
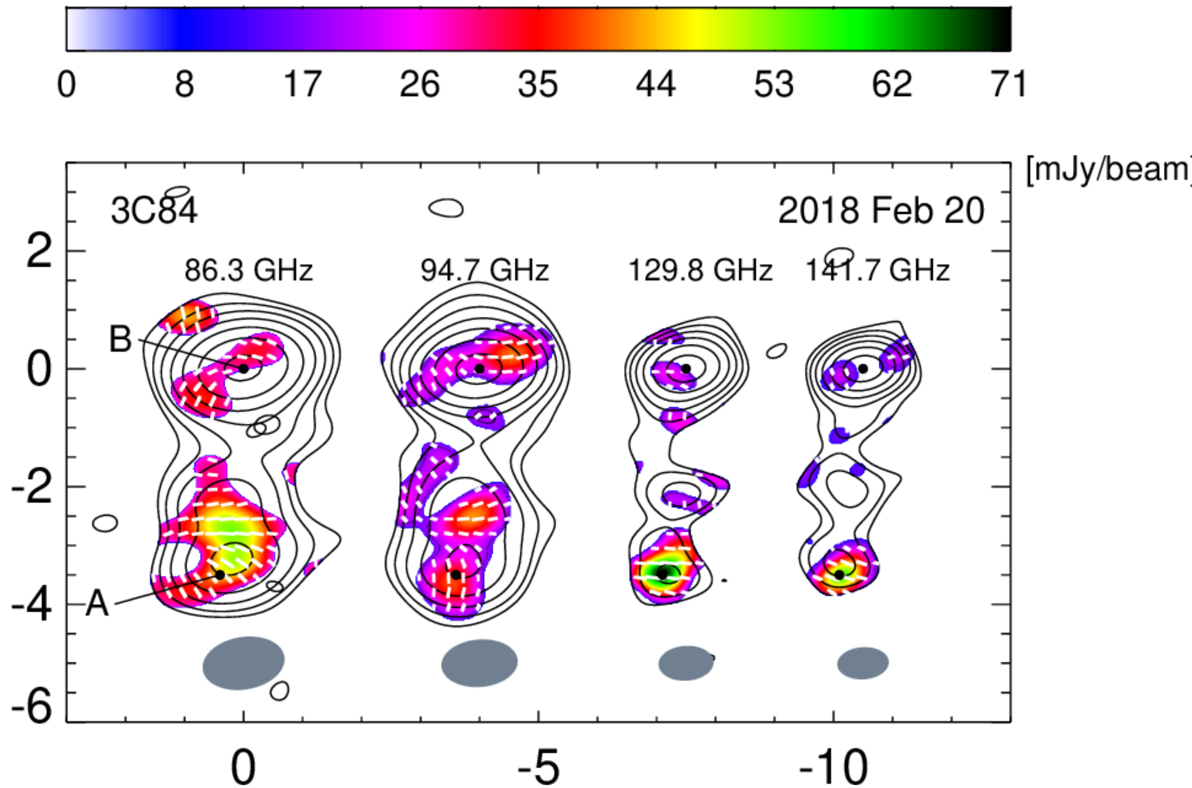


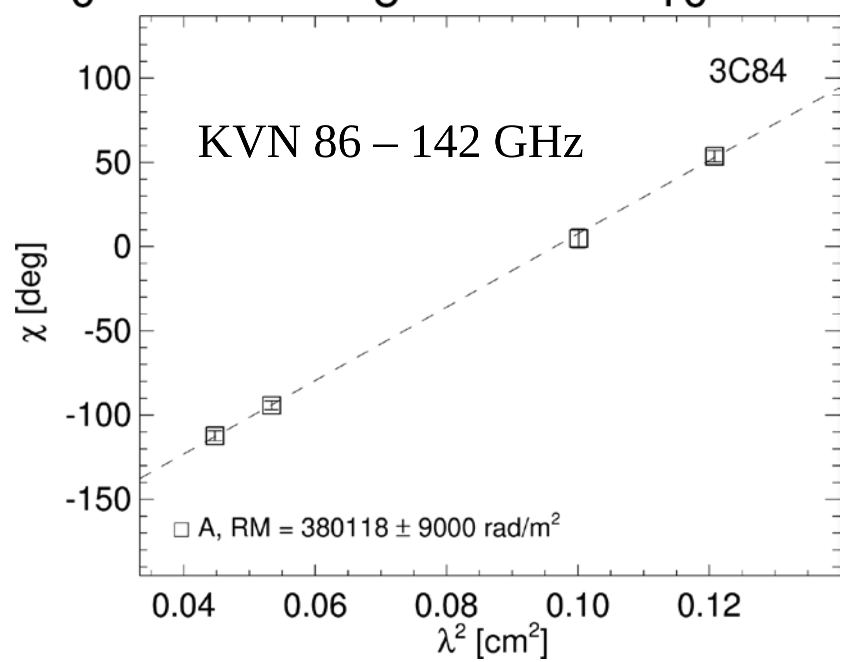


Probing the linear polarization of AGN jets at mm wavelengths with the KVN



VLBA (BU) 43 GHz





Summary

— A new algorithm for polarization calibration of VLBI data has been developed. Which advantages does it have?

(i) It increases effective signal to noise ratio and improves the calibration accuracy.
→ powerful for studying low-polarization sources (such as M87!).

(ii) It will solve the problem of global VLBI arrays that there is not much common sky for a single source.
→ will be important for on-going and future global VLBI studies by using GMVA + ALMA, EHT + ALMA, and satellite missions.

(iii) It is easy to use (you can just run a single script).
→ Don’t spend much time to figure out which calibrator is the best. You can use all!

(iv) It will be very effective for future KVN polarization observations where we have a small number of baselines but usually have many different sources observed.
→ You can do a unique science with the KVN (linear polarization and Rotation Measure analysis at 2 ~ 3 mm).

Please use my code for your studies!

AIPS task LPCAL : a conventional calibration tool

$$\tilde{r}_{ij}^{RL}(u,v) = P(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D_{jL}^{*} r_{ij}^{RR}(u,v) e^{2i\phi_j} + P^{*}(u,v) D_{iR} D_{jL}^{*} e^{2i(\phi_i+\phi_j)}$$
$$\tilde{r}_{ij}^{LR}(u,v) = P^{*}(u,v) + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D_{jR}^{*} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + P(u,v) D_{iL} D_{jR}^{*} e^{-2i(\phi_i+\phi_j)}$$

Source Polarization

D-Terms

2nd order terms

‘Model’ visibility
for total intensity

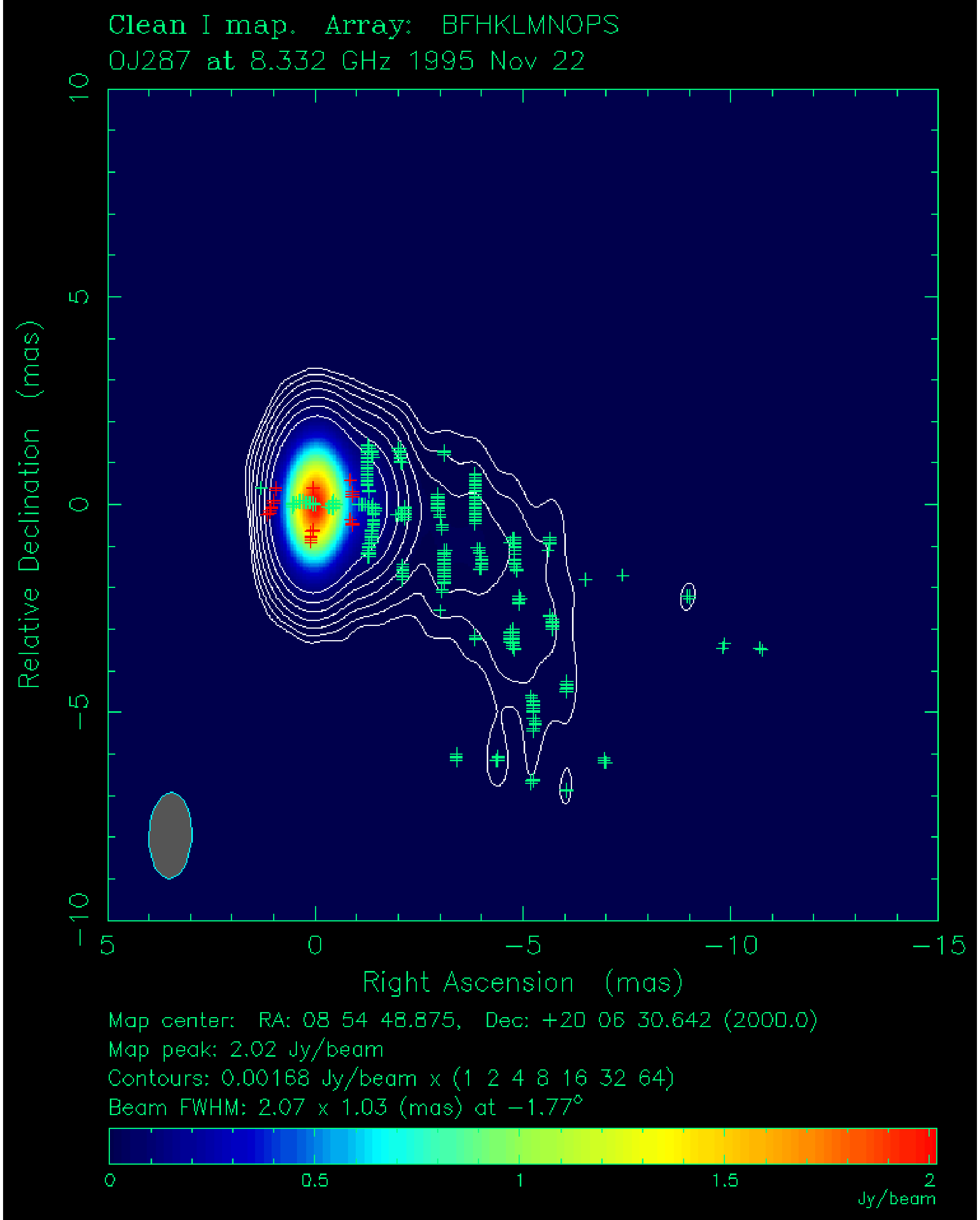
What AIPS LPCAL does is...

$$\tilde{r}_{ij}^{RL}(u,v) = \boxed{pF(u,v)} + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D_{jL}^{*} r_{ij}^{RR}(u,v) e^{2i\phi_j} + \cancel{p^{*}F(u,v) D_{iR} D_{jL}^{*} e^{2i(\phi_i+\phi_j)}}$$
$$\tilde{r}_{ij}^{LR}(u,v) = \boxed{p^{*}F(u,v)} + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D_{jR}^{*} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + \cancel{pF(u,v) D_{iL} D_{jR}^{*} e^{-2i(\phi_i+\phi_j)}}$$

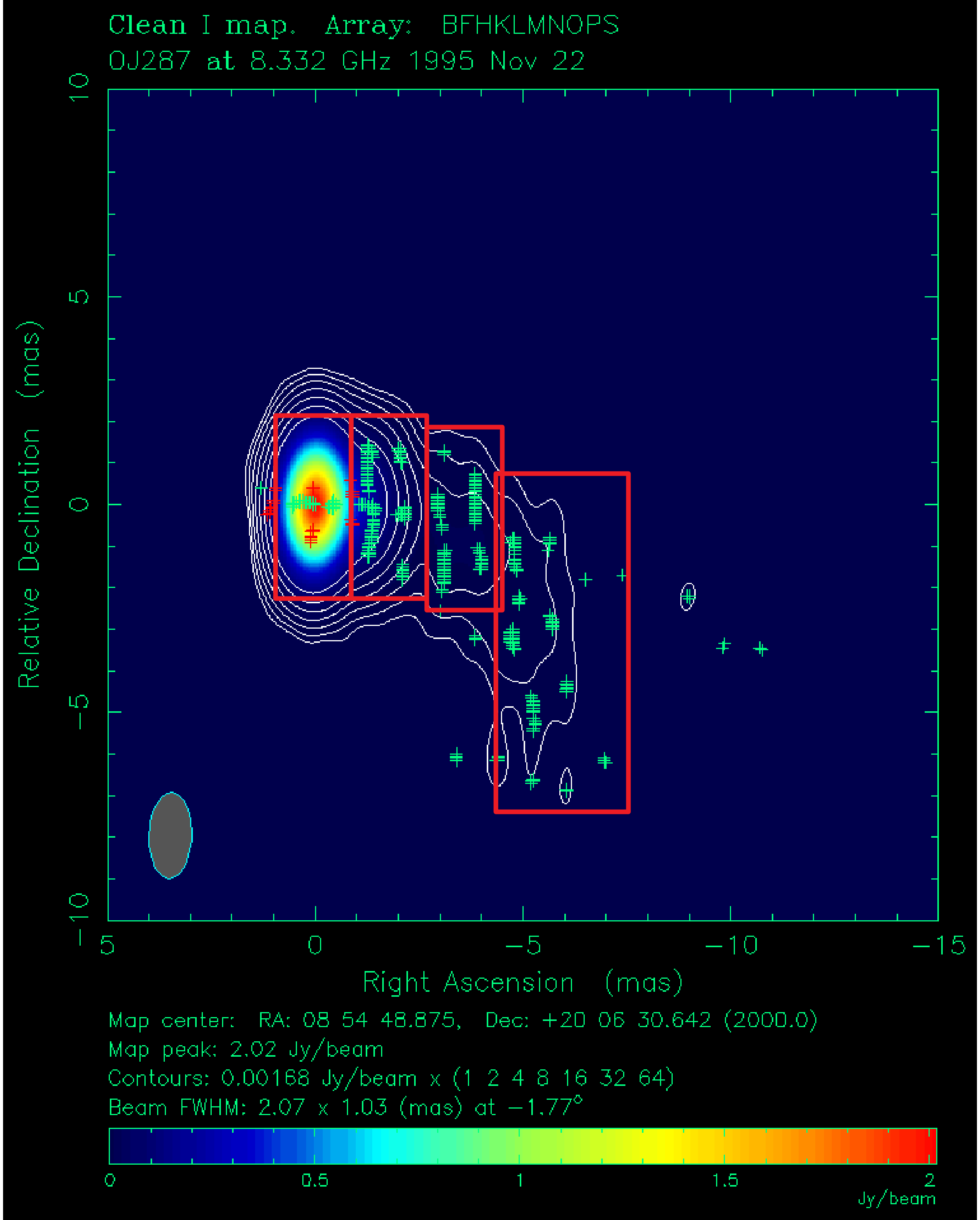
Ignore

Assume a ‘constant fractional polarization’ for a source

There is almost no astronomical object having a constant polarization across its structure.



Clean I map. Array: BFHKLMNOPS
OJ287 at 8.332 GHz 1995 Nov 22
Relative Declination (mas)
Right Ascension (mas)
10
5
0
−5
−10
5
0
−5
−10
−15
Map center: RA: 08 54 48.875, Dec: +20 06 30.642 (2000.0)
Map peak: 2.02 Jy/beam
Contours: 0.00168 Jy/beam x (1 2 4 8 16 32 64)
Beam FWHM: 2.07 x 1.03 (mas) at −1.77°
0
0.5
1
1.5
2
Jy/beam



Assume a constant fractional polarization for the CLEAN components in each 'box'

AIPS task LPCAL : a conventional calibration tool

$$\tilde{r}_{ij}^{RL}(u,v) = P(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D_{jL}^{*} r_{ij}^{RR}(u,v) e^{2i\phi_j} + P^{*}(u,v) D_{iR} D_{jL}^{*} e^{2i(\phi_i+\phi_j)}$$
$$\tilde{r}_{ij}^{LR}(u,v) = P^{*}(u,v) + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D_{jR}^{*} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + P(u,v) D_{iL} D_{jR}^{*} e^{-2i(\phi_i+\phi_j)}$$

Source Polarization

D-Terms

2nd order terms

‘Model’ visibility for each source sub-components

What AIPS LPCAL does is...

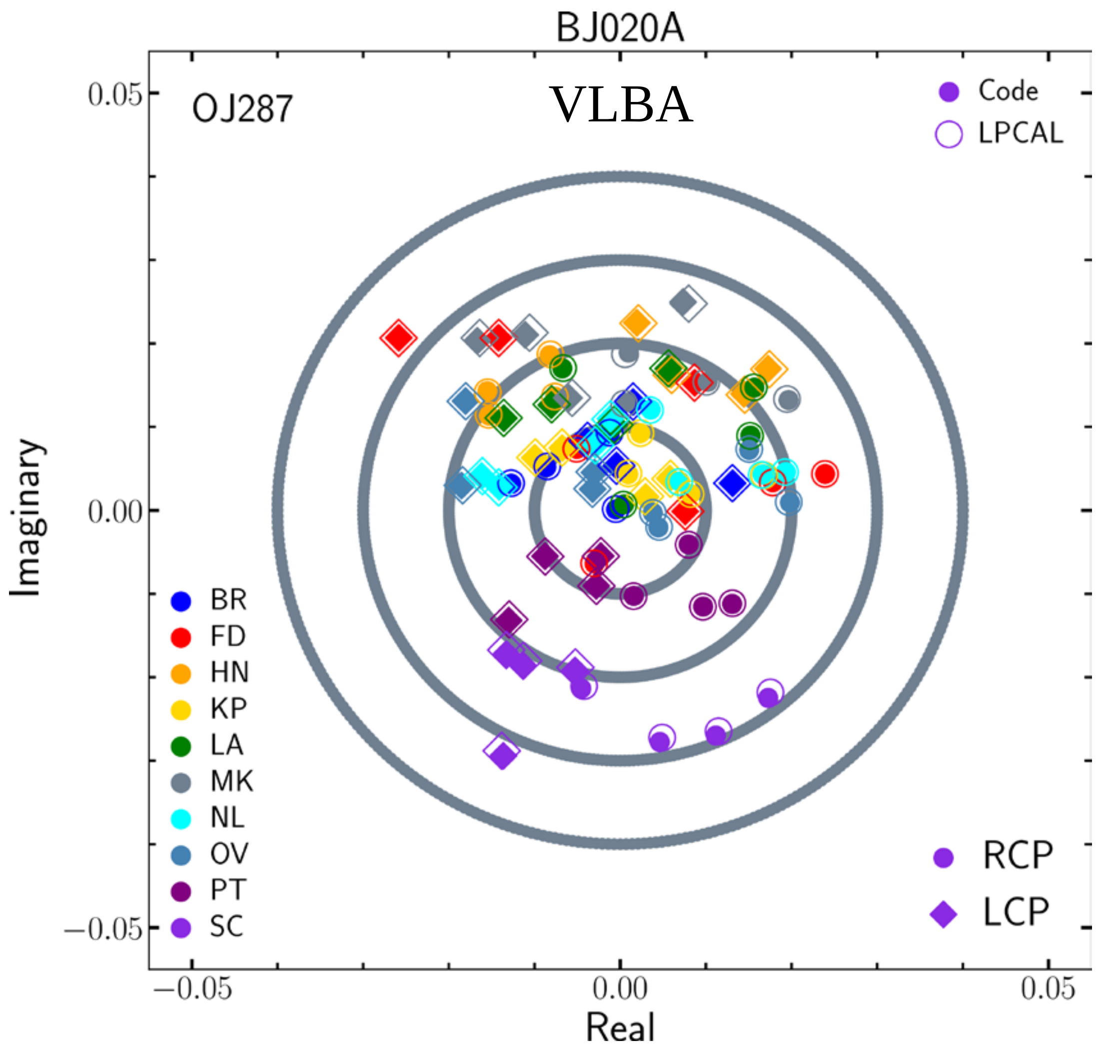
$$\tilde{r}_{ij}^{RL}(u,v) = \sum_s p_s F_s(u,v) + D_{iR} r_{ij}^{LL}(u,v) e^{2i\phi_i} + D_{jL}^{*} r_{ij}^{RR}(u,v) e^{2i\phi_j} + \cancel{\sum_s p_s^{*} F_s(u,v) D_{iR} D_{jL}^{*} e^{2i(\phi_i+\phi_j)}}$$
$$\tilde{r}_{ij}^{LR}(u,v) = \sum_s p_s^{*} F_s(u,v) + D_{iL} r_{ij}^{RR}(u,v) e^{-2i\phi_i} + D_{jR}^{*} r_{ij}^{LL}(u,v) e^{-2i\phi_j} + \cancel{\sum_s p_s F_s(u,v) D_{iL} D_{jR}^{*} e^{-2i(\phi_i+\phi_j)}}$$

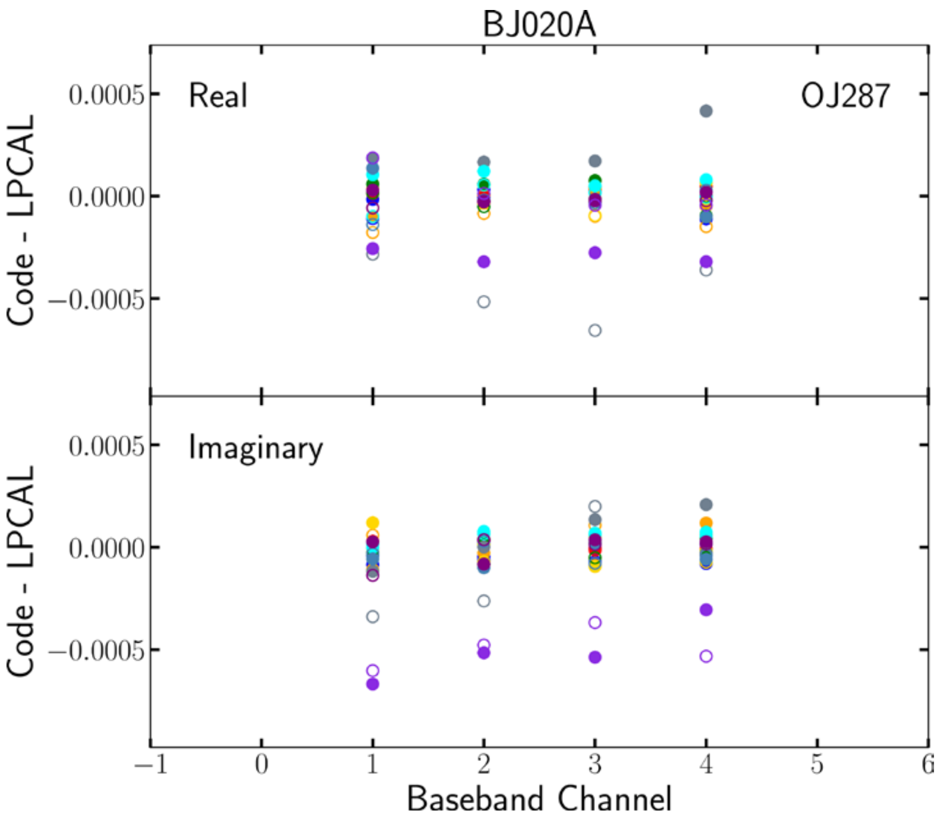
Ignore

Assume a ‘constant fractional polarization’ for each source sub-components

Does it work well?

Filled : Code, Open : LPCAL

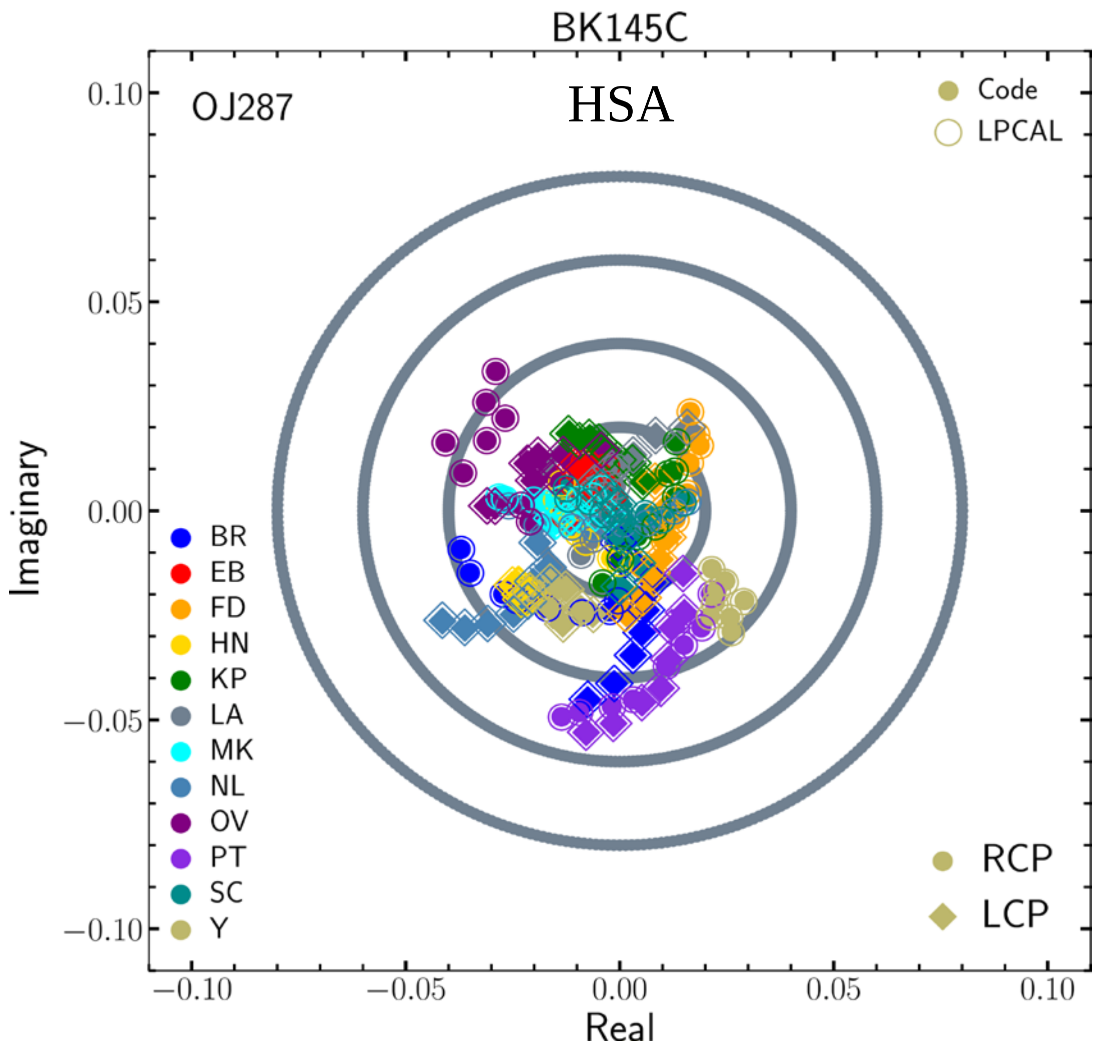


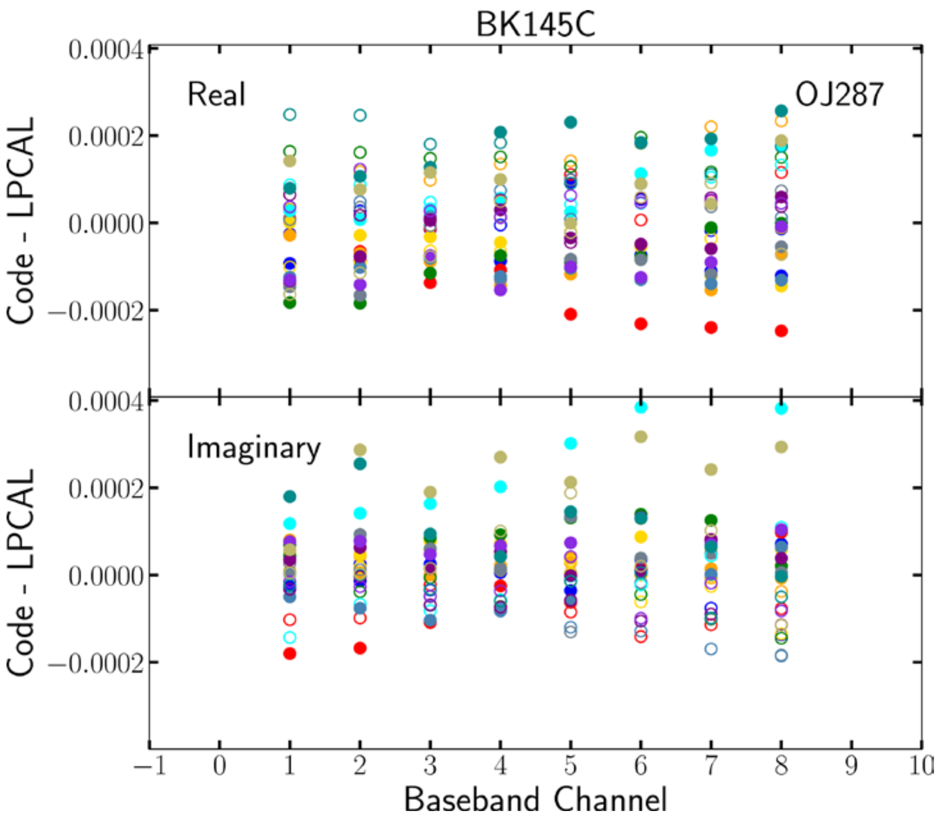


When ignoring the 2nd order terms and comparing with the LPCAL result, they are consistent within ~10^{-4} levels.

Does it work well?

Filled : Code, Open : LPCAL





When ignoring the 2nd order terms and comparing with the LPCAL result, they are consistent within ~10^{-4} levels.

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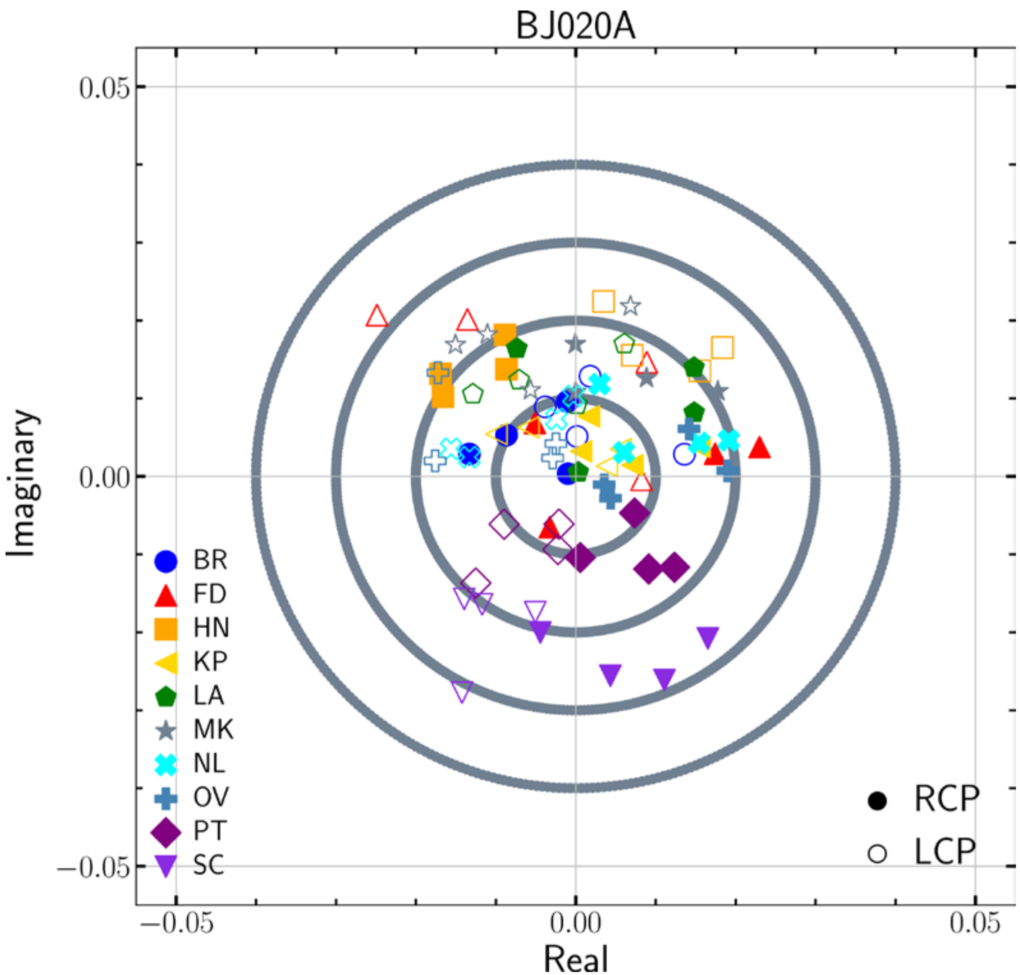
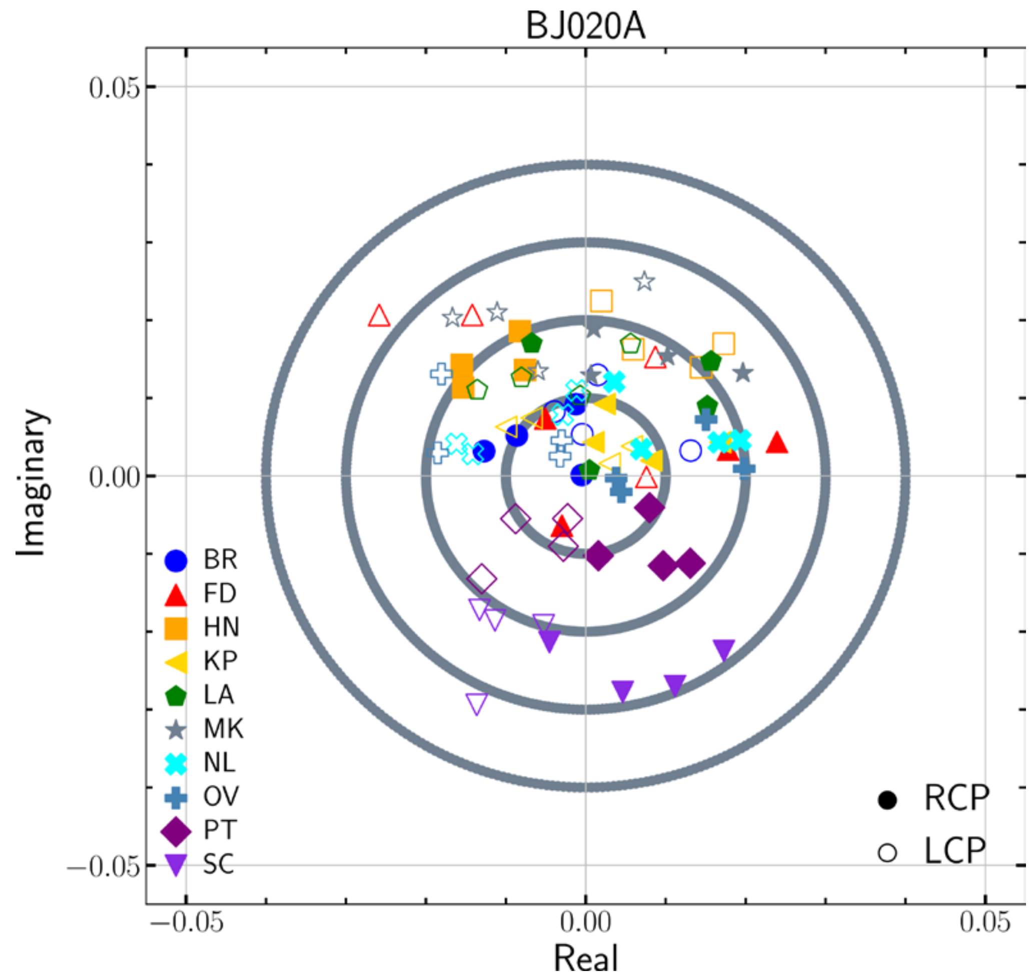
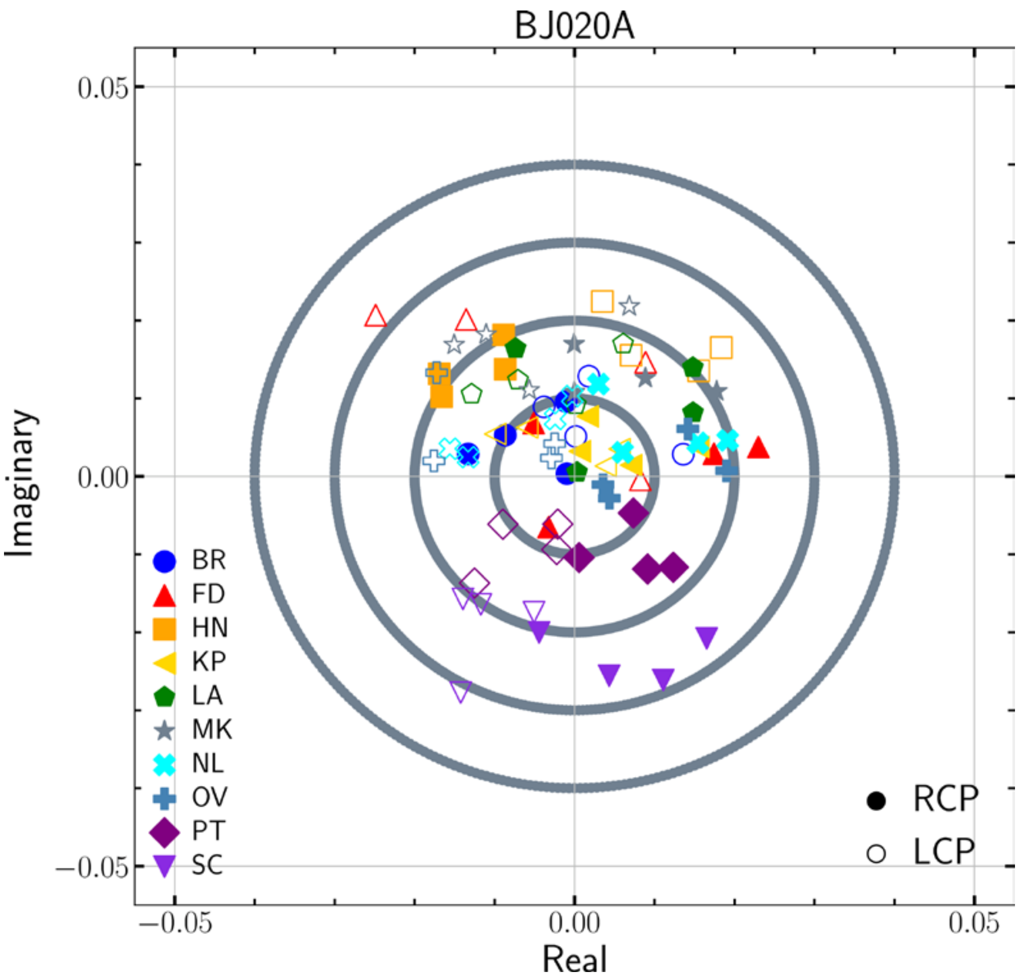


OJ 287 + OQ 208

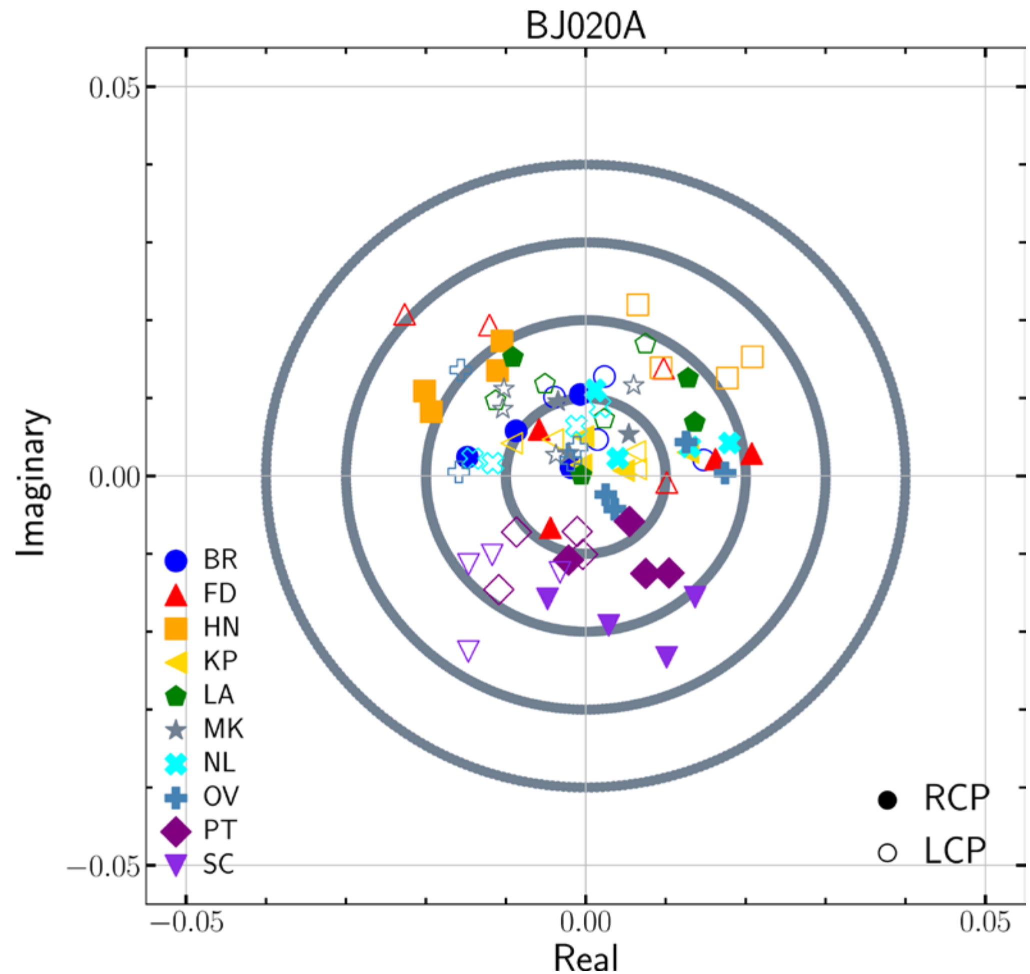


OJ 287

Does it work well?

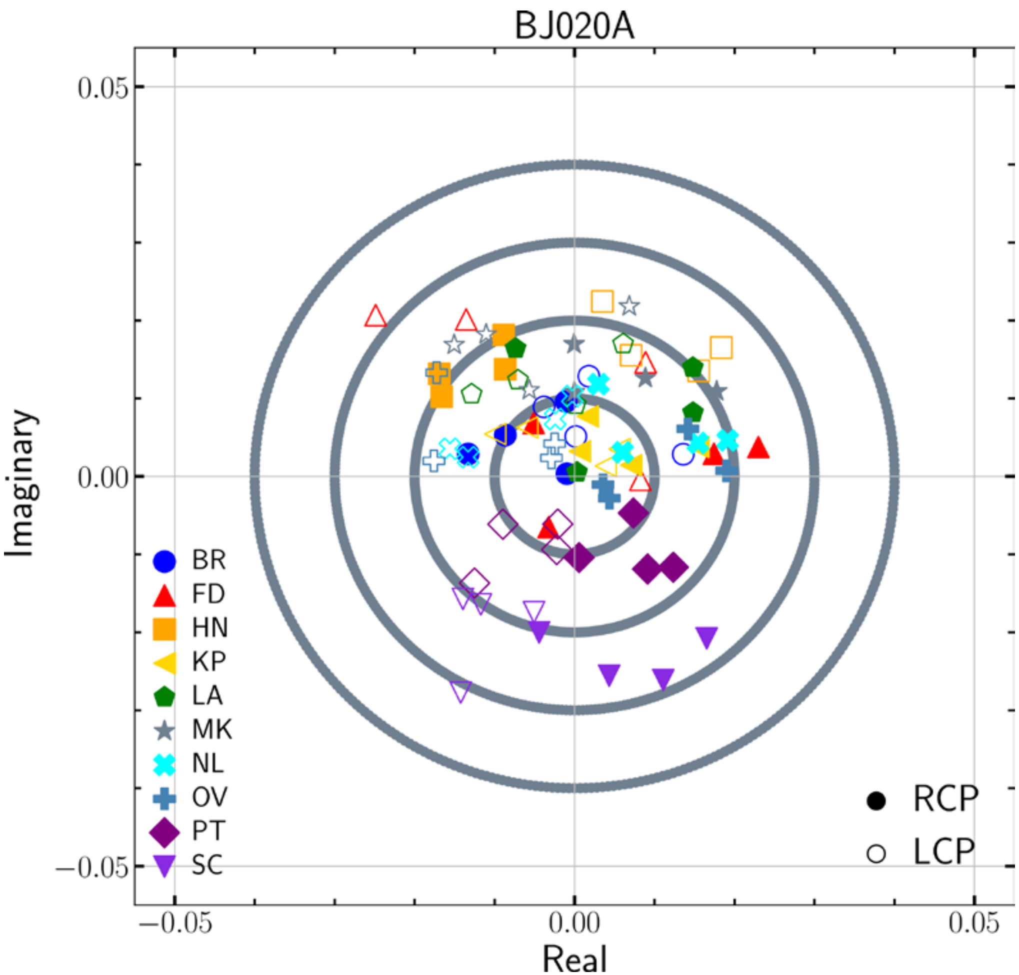


OJ 287 + OQ 208

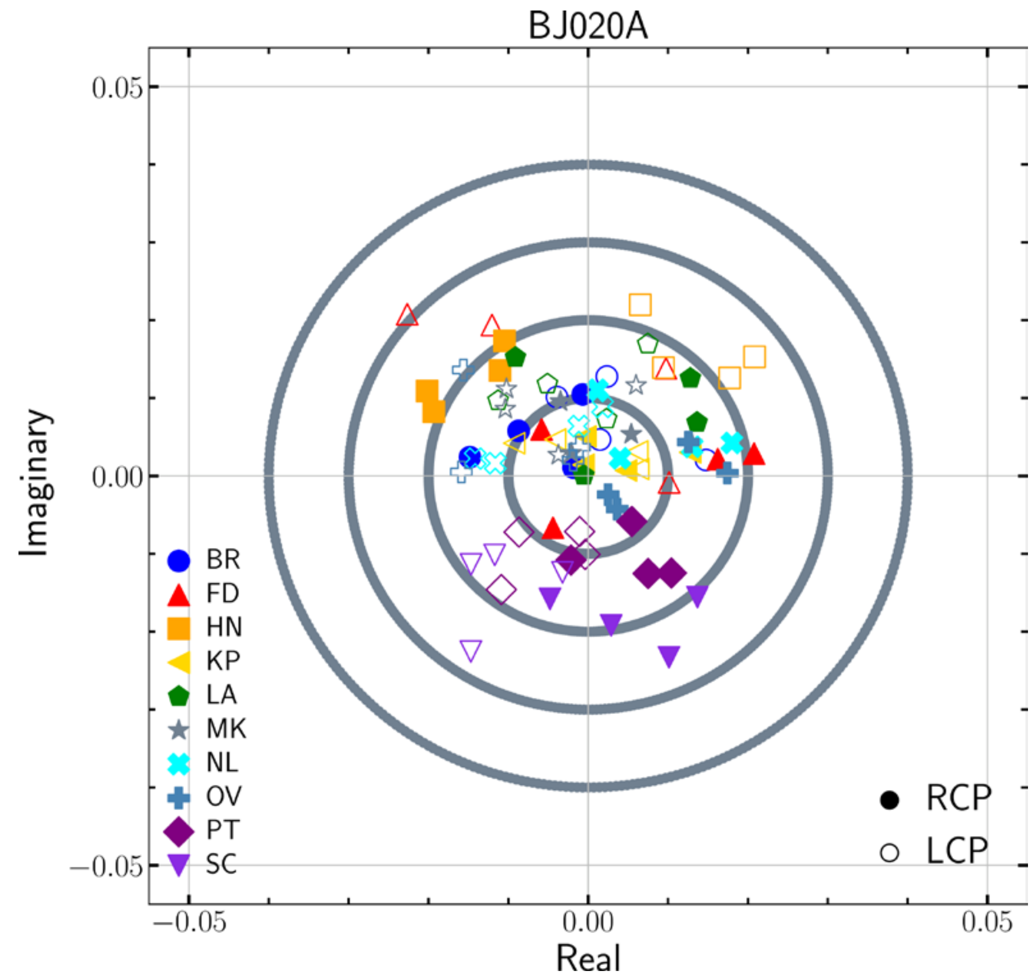


OQ 208

Does it work well?



OJ 287 + OQ 208



OQ 208

If the multi-source fitting code works well, then the results must be consistent with the single-source fitting results (because OJ 287 and OQ 208 are good calibrators).
→ This is the case!