Polarization Leakage and Calibration

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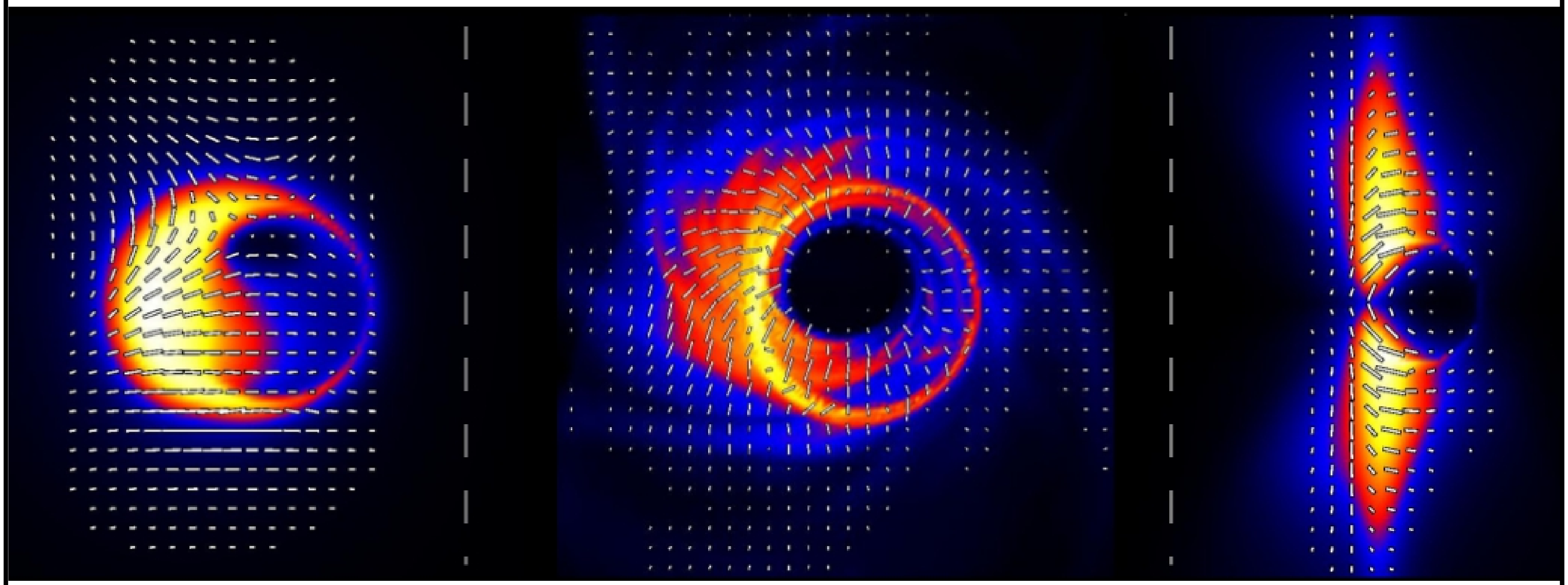
Polarimetry with VLBI

Goal: Study images of each of the Stokes parameters

$$I, \underbrace{Q, U}_{\text{Linear Polarization}}, V$$

Total Flux

Circular Polarization



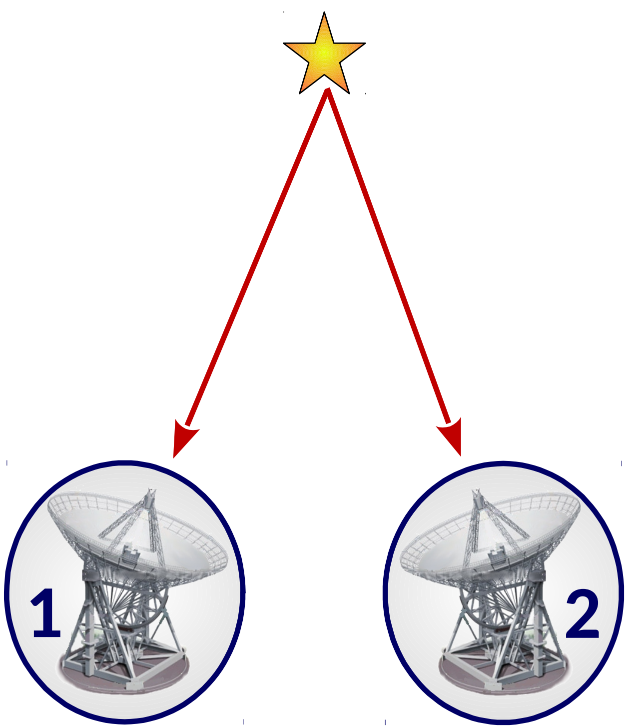
Simulated Images Courtesy of Avery Broderick and Jason Dexter

Polarimetry with VLBI

Coherency Matrix

$$\begin{pmatrix} \langle E_{1,\mathrm{R}}E^*_{2,\mathrm{R}}\rangle & \langle E_{1,\mathrm{R}}E^*_{2,\mathrm{L}}\rangle \\ \langle E_{1,\mathrm{L}}E^*_{2,\mathrm{R}}\rangle & \langle E_{1,\mathrm{L}}E^*_{2,\mathrm{L}}\rangle \end{pmatrix} \longleftrightarrow \underbrace{\tilde{I}}_{\text{Total Flux}},\ \underbrace{\tilde{Q},\ \tilde{U},}_{\text{Linear Polarization}}\ \underbrace{\tilde{V}}_{\text{Circular Polarization}}$$

Stokes Parameters



$$P = Q + iU$$

$$|Q|^2 + |U|^2 + |V|^2 \leq |I|^2$$

The phase of P (twice the **EVPA**) = polarization direction

Cross-hand fringes are usually much weaker!

Polarimetry with VLBI

Station actually measures:

$$\begin{pmatrix} E'_{\mathrm{R}} \\ E'_{\mathrm{L}} \end{pmatrix} = \underbrace{\begin{pmatrix} G_{\mathrm{R}} & 0 \\ 0 & G_{\mathrm{L}} \end{pmatrix}}_{\text{“Gain”}} \underbrace{\begin{pmatrix} 1 & D_{\mathrm{R}} \\ D_{\mathrm{L}} & 1 \end{pmatrix}}_{\text{“Leakage”}} \underbrace{\begin{pmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}}_{\text{Field Rotation}} \begin{pmatrix} E_{\mathrm{R}} \\ E_{\mathrm{L}} \end{pmatrix} \equiv \mathbf{J} \begin{pmatrix} E_{\mathrm{R}} e^{-i\phi} \\ E_{\mathrm{L}} e^{i\phi} \end{pmatrix}$$

Jones Matrix
(Lorentz Transformation)

Leakage introduces spurious linear polarization, often exceeding the signal

The field rotation is <u>critical</u> – the source and instrumental contributions respond differently!

Notice: This description is <u>arbitrary</u>. Specifying conventions is essential.

Fractional Polarization

Intrinsic fractional polarization

$$\frac{R_1 L_2^*}{R_1 R_2^*} \approx \left(\frac{G_{2,\mathrm{L}}}{G_{2,\mathrm{R}}}\right)^* \left[m e^{-2i\phi_2} + \underbrace{D_{1,\mathrm{R}} e^{2i\phi_{12}} + D_{2,\mathrm{L}}^*}_{\text{“Leakage”}}\right]$$

Field Rotation Angle

Unknown, but stable, phase

Gain amplitudes are easy with 3 sites:

$$\left|\frac{G_{1,\mathrm{R}}}{G_{1,\mathrm{L}}}\right| = \sqrt{\frac{\langle R_1 R_2^* \rangle}{\langle L_1 L_2^* \rangle} \times \frac{\langle R_3 R_1^* \rangle}{\langle L_3 L_1^* \rangle} \times \frac{\langle L_3 L_2^* \rangle}{\langle R_3 R_2^* \rangle}}.$$

Idea: Phase reference (weak) cross-hand visibilities to (strong) parallel-hand visibilities

<u>Immune to scatter broadening</u>

Fourier relationship no longer applies!

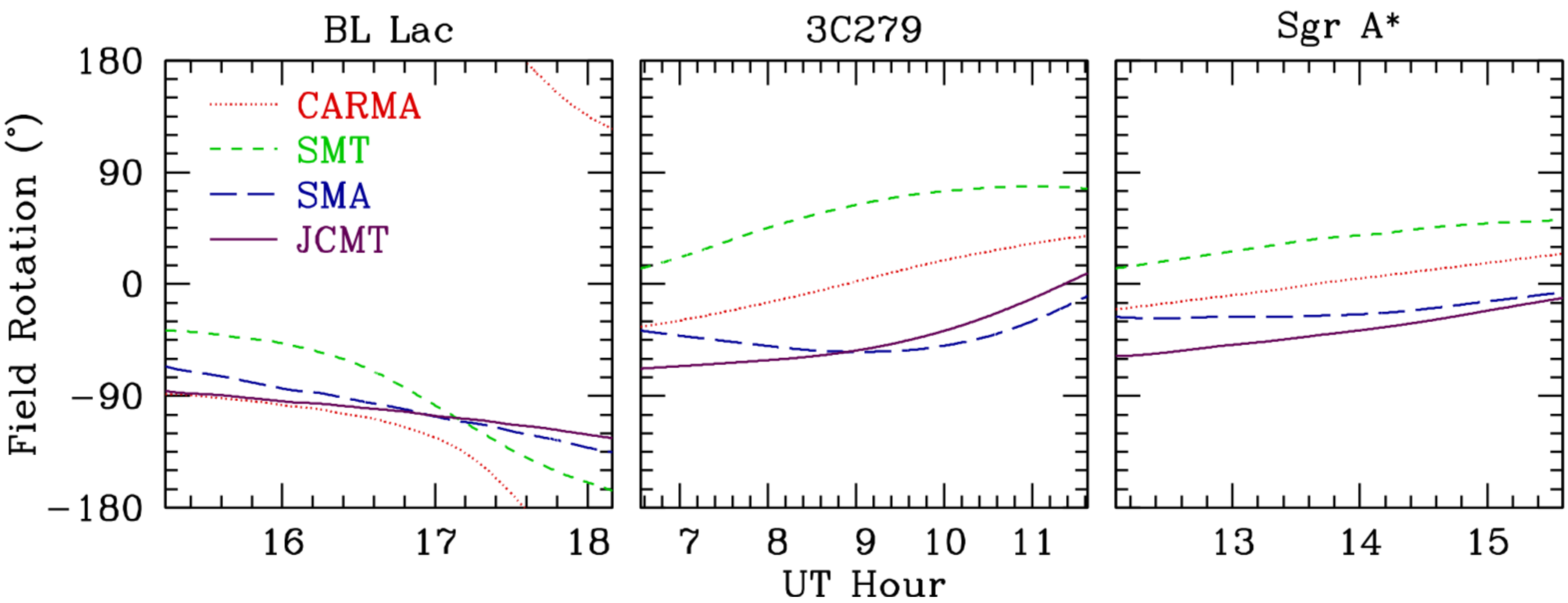
Calibration Degeneracies

$$\frac{R_1 L_2^*}{R_1 R_2^*} \approx \left(\frac{G_{2,\mathrm{L}}}{G_{2,\mathrm{R}}}\right)^* \left[m e^{-2i\phi_2} + \underbrace{D_{1,\mathrm{R}} e^{2i\phi_{12}} + D_{2,\mathrm{L}}^*}_{\text{“Leakage”}} \right]$$

Notice: For sites with identical field rotation angles ϕ_x, D_R and D_L don't decouple

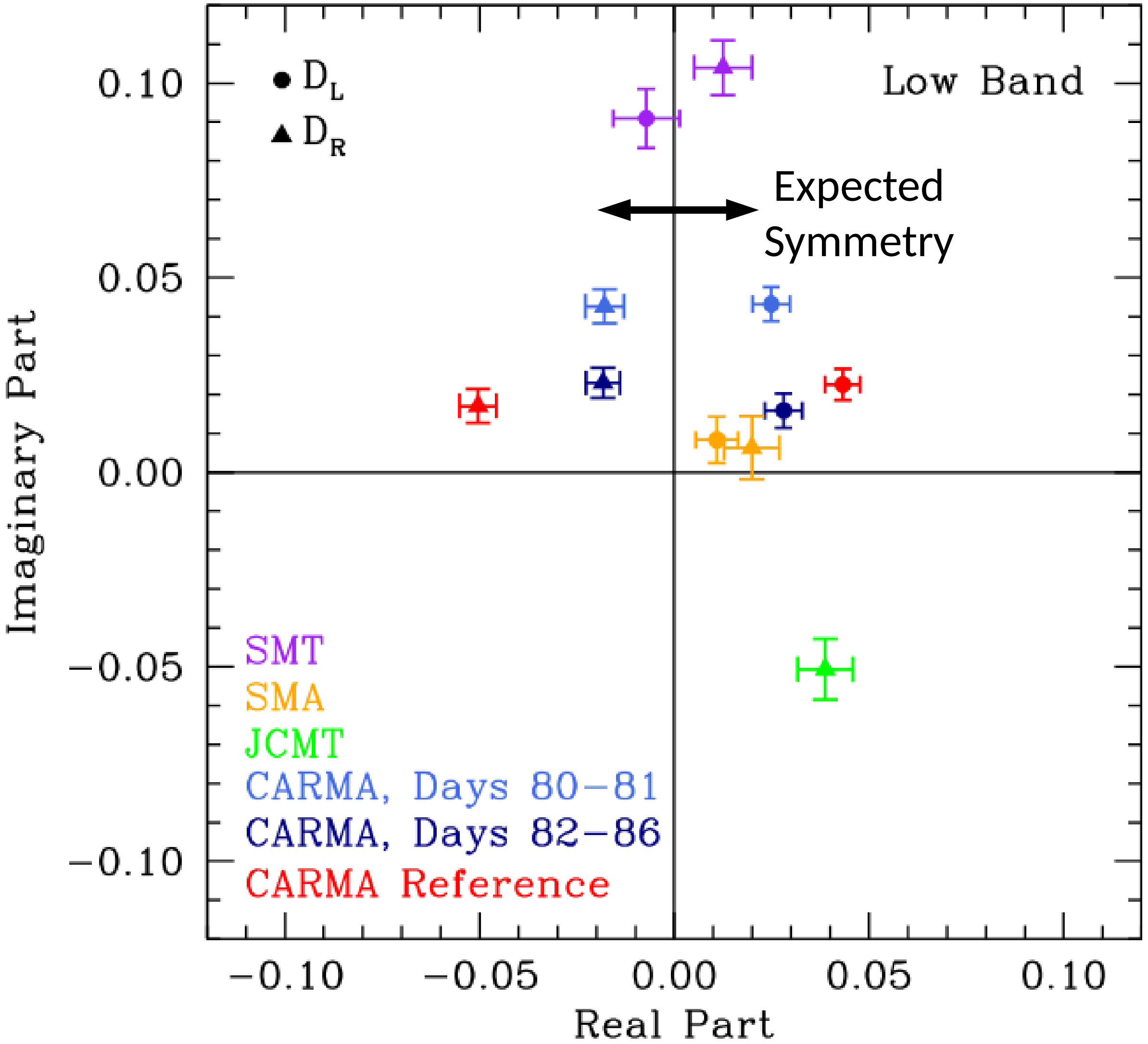
This is the case with most arrays (e.g., the SMA and CARMA)

Field Rotation Angles

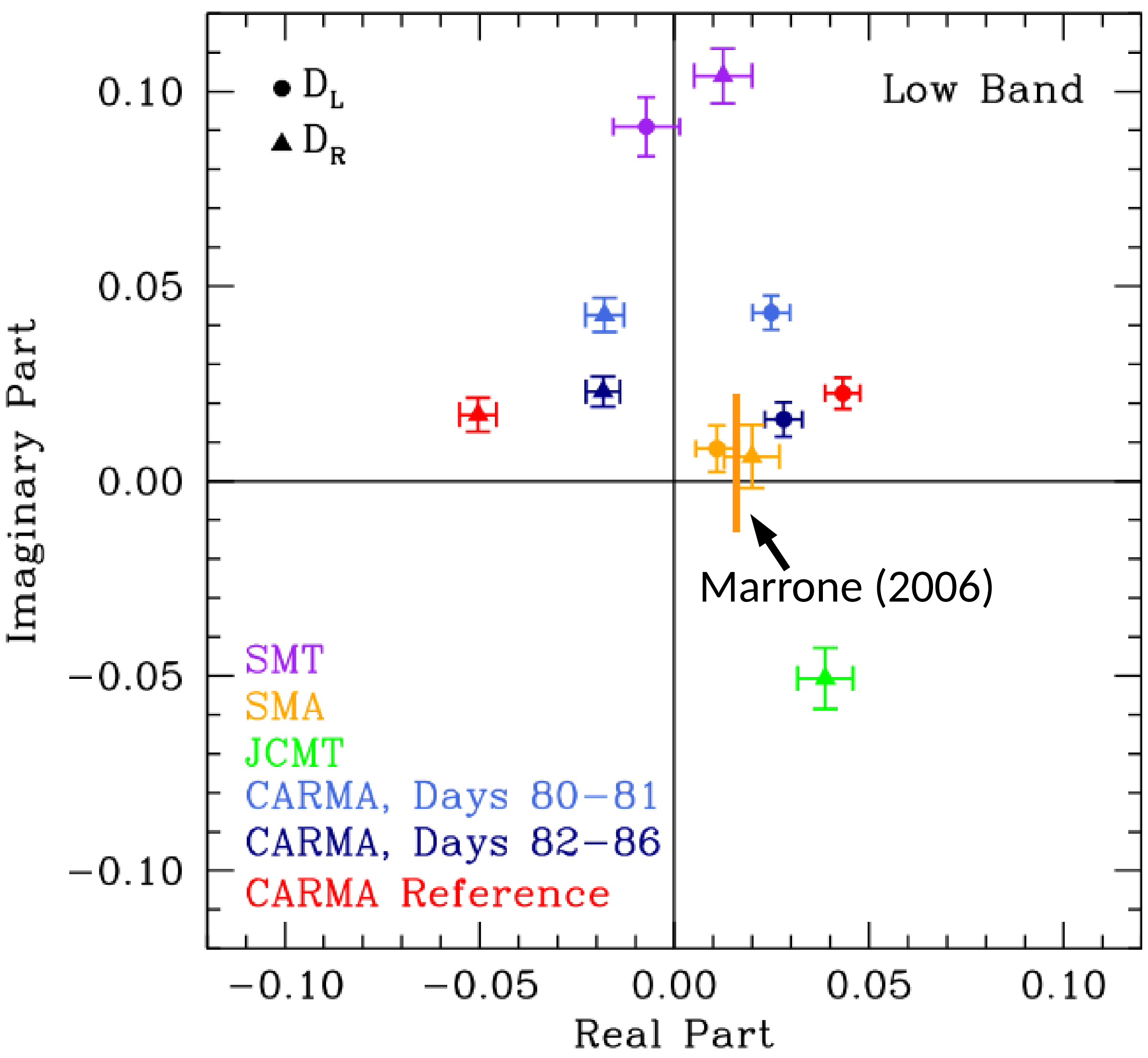


Remember, leakage terms rotate by twice the field-rotation angle

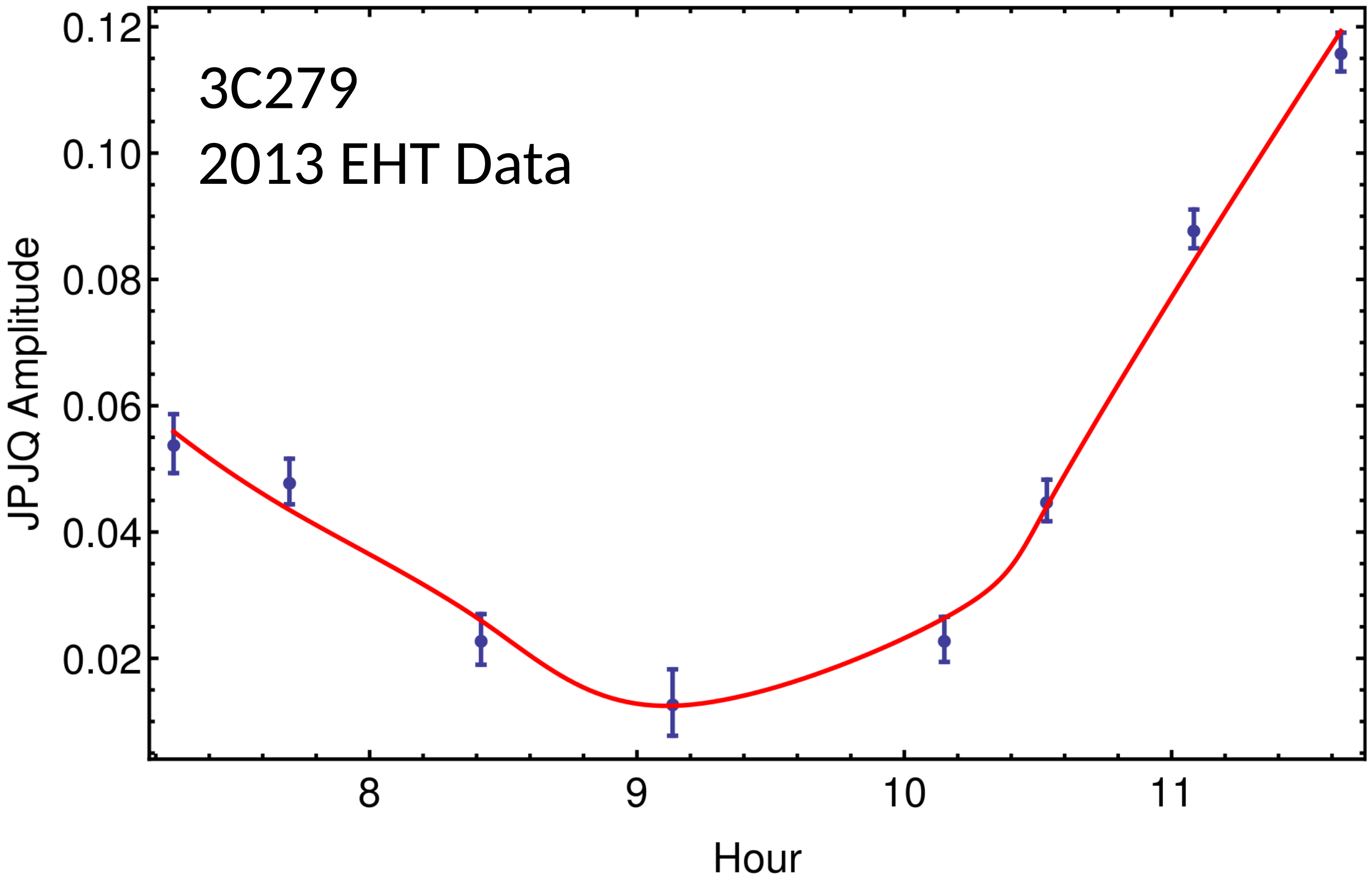
Derived Leakage Terms



Leakage Terms vs. Array Measurements



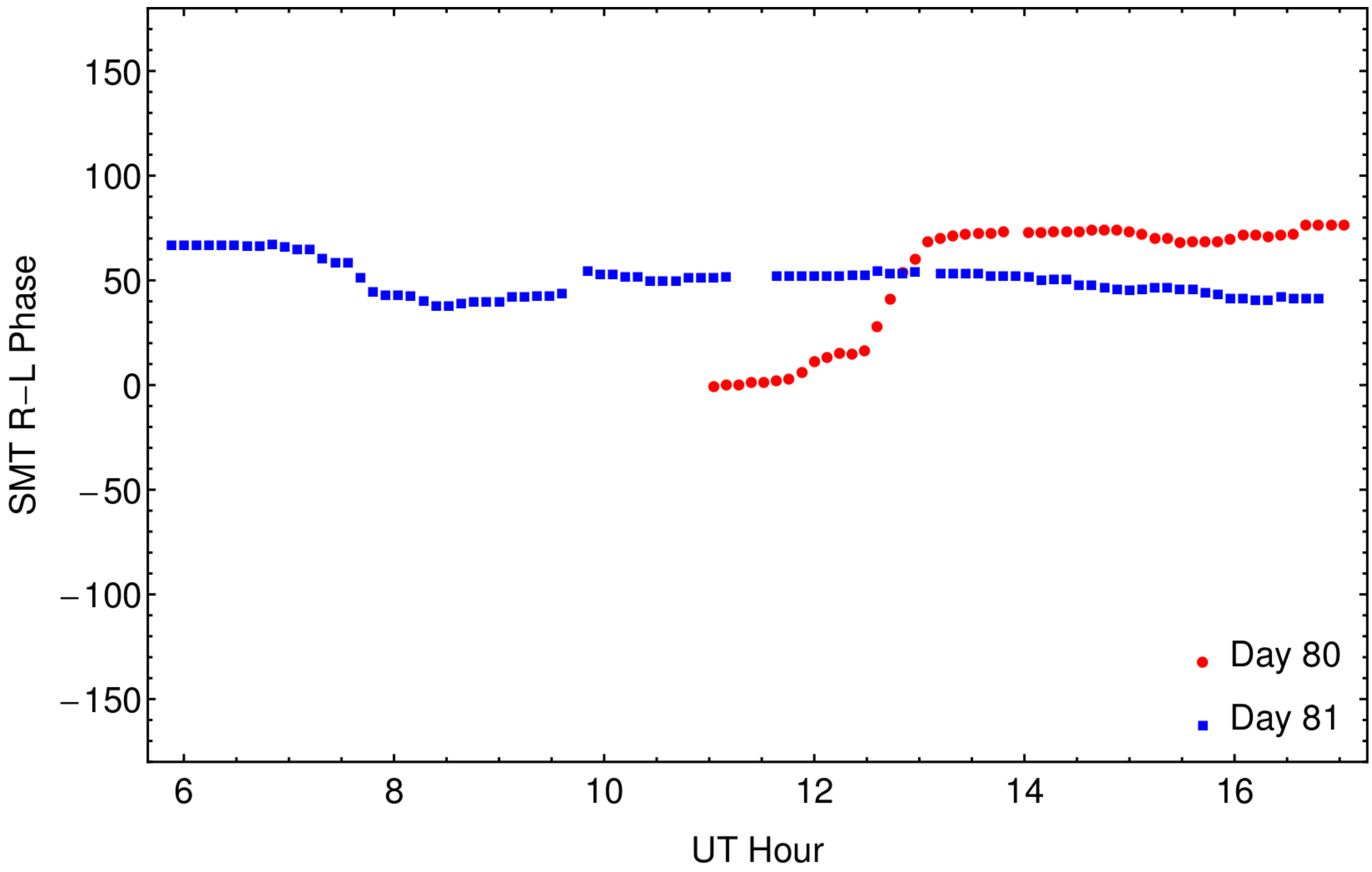
JCMT-SMA



Note: The SMA and the JCMT have different field rotation angles

Leakage effects show up in fractional polarization amplitudes for non-simultaneous scans!

SMT R/L Phase Drift



Unexpected! We need to be careful about building a framework upon false assumptions.

Leakage can Affect Visibility Amplitudes!

$$\langle R_1 R_2^* \rangle \approx \tilde{I}(\mathbf{u}_{12}) G_{1,\mathrm{R}} G_{2,\mathrm{R}}^* e^{-i(\phi_1-\phi_2)} \left[1 + \breve{m}^* \left(-\mathbf{u}_{12}\right) D_{1,\mathrm{R}} e^{2i\phi_1} + \breve{m} \left(+\mathbf{u}_{12}\right) D_{2,\mathrm{R}}^* e^{-2i\phi_2} + \breve{v} \left(\mathbf{u}_{12}\right)\right]$$
$$\langle L_1 L_2^* \rangle \approx \tilde{I}(\mathbf{u}_{12}) G_{1,\mathrm{L}} G_{2,\mathrm{L}}^* e^{+i(\phi_1-\phi_2)} \left[1 + \breve{m} \left(+\mathbf{u}_{12}\right) D_{1,\mathrm{L}} e^{-2i\phi_1} + \breve{m}^* \left(-\mathbf{u}_{12}\right) D_{2,\mathrm{L}}^* e^{2i\phi_2} - \breve{v} \left(\mathbf{u}_{12}\right)\right]$$

Up to ~10% effect on amplitudes
Introduces non-closing phase errors!

Summary

Polarization is a rich source of information for VLBI but precise calibration is essential.

Polarization leakage affects many things

- Spurious linear polarization
- Biased visibility amplitudes
- Biased closure phases

Calibration for past EHT data appears to be secure

- Leakage terms are $\lesssim$10%
- No evidence yet for strong elevation-dependent effects
- The role of circular polarization isn't yet clear

The most difficult problems to calibrate are those we don't expect

- SMT R-L phase drift

Summary

But… we're learning that the EHT can be very well calibrated

Differences from other arrays:

1. Co-located sites with different field rotation angles (SMT and JCMT)
2. Strong polarization on long baselines
3. Heterogeneous array
4. Long observing tracks

Calibration corrections are large but accurate