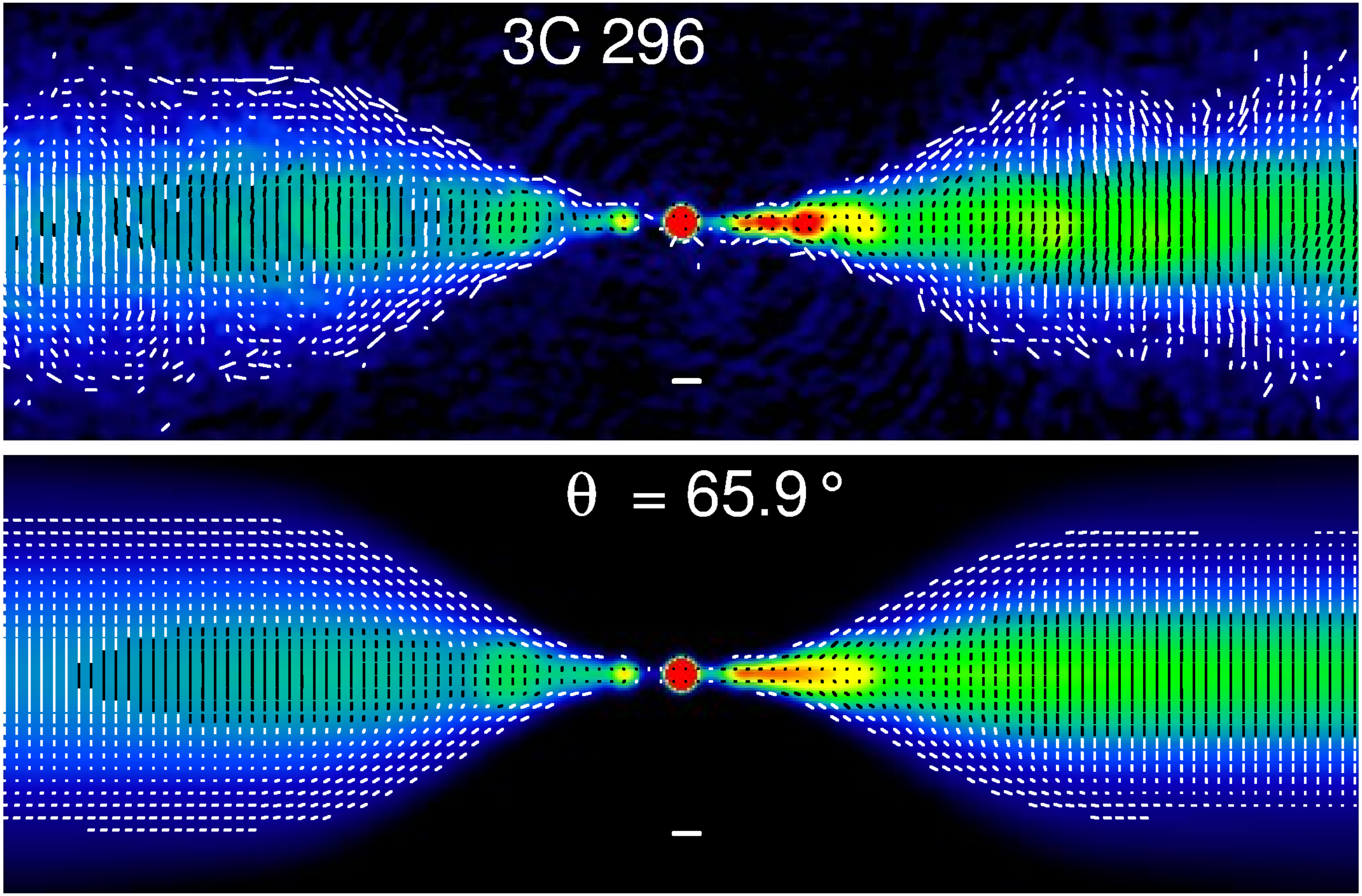
Polarization Observations with ALMA

Robert Laing (ESO)



Outline

- Science
  - Physical mechanisms
  - Some potential targets
- Instrumental
  - How do we measure and calibrate (linear) polarization
  - Cycle 2 details

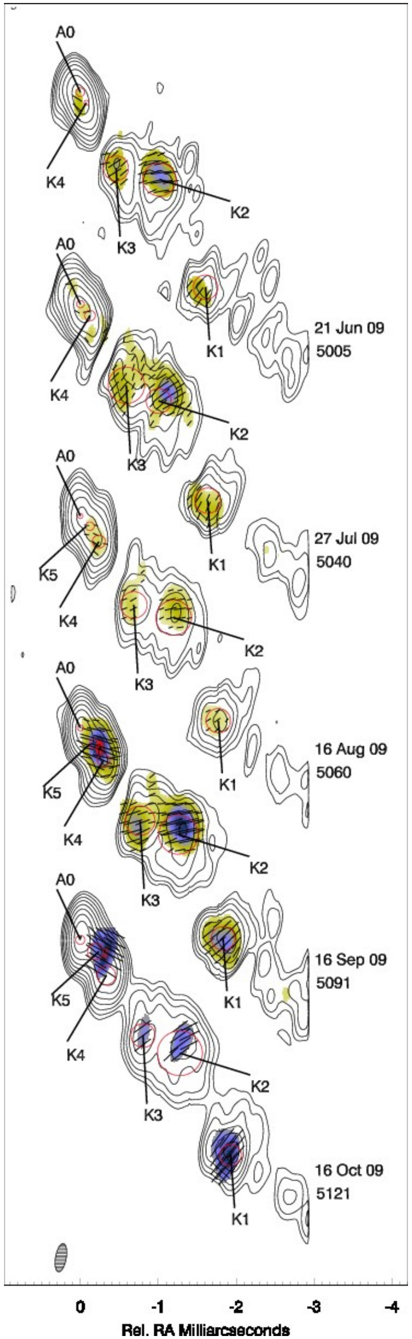
Physical Mechanisms

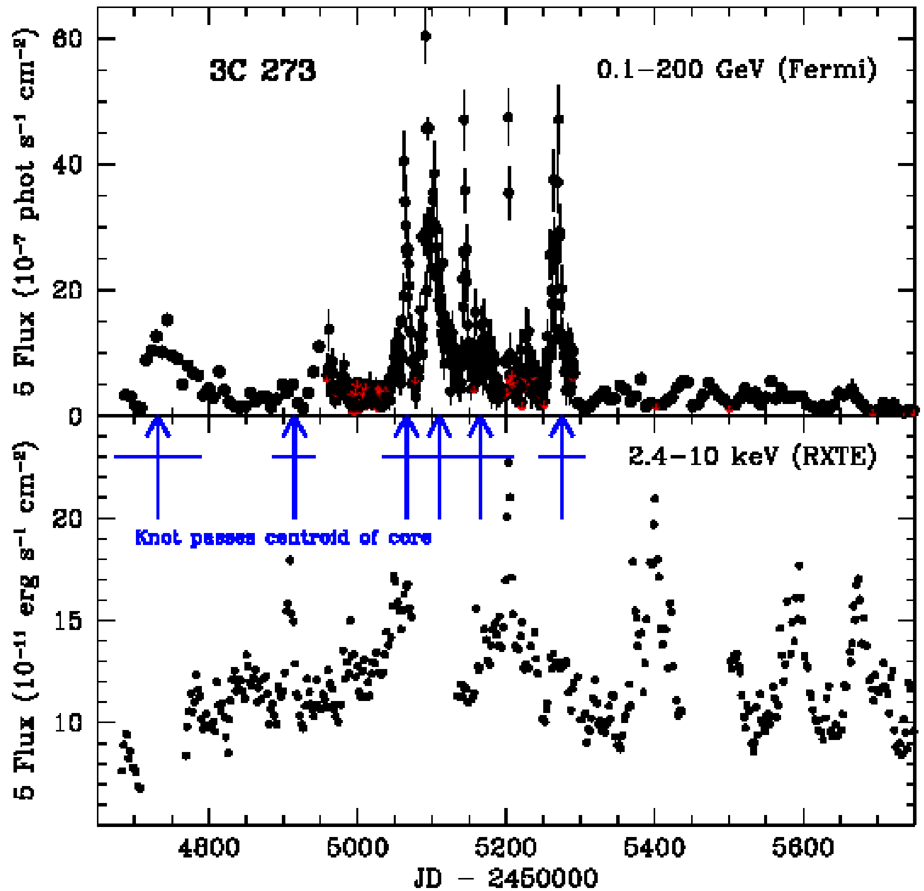
- Continuum
  - Synchrotron – ultrarelativistic electrons spiralling in B-field
  - Gyro-synchrotron (lower energies)
  - Aligned dust grains – minor axis of grain parallel to field
- Line (not Cycle 2)
  - Zeeman splitting
  - Goldreich-Kylafis
  - Masers

Synchrotron polarization with ALMA

- High fractional linear polarization
  - $(3\alpha+3)/(3\alpha+5) \approx 0.7$ for uniform field ($I \propto \nu^{-\alpha}$)
- Optically thin synchrotron emission has a $\nu^{-0.5}$ or steeper spectrum, and system temperatures/atmosphere are worse at high frequencies, so why observe with ALMA?
  - Resolution (e.g. mm VLBI)
  - Emission is optically thick, scattered or free-free absorbed at longer wavelengths
  - Highly variable polarized emission
  - Faraday rotation is too high at longer wavelengths (across beam or along line of sight)
  - There are real differences in structure between mm and cm (or m) wavelengths

mm-wave and γ-ray emission



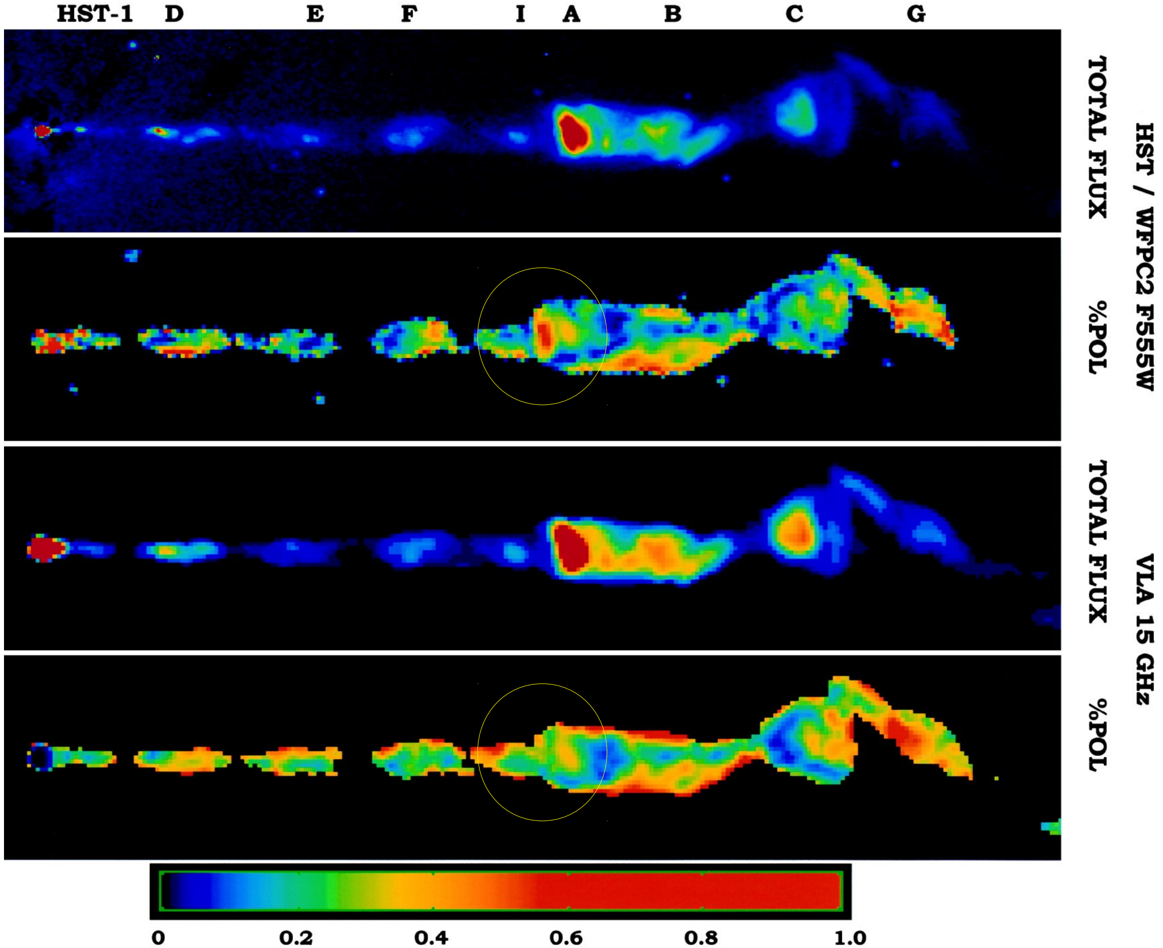


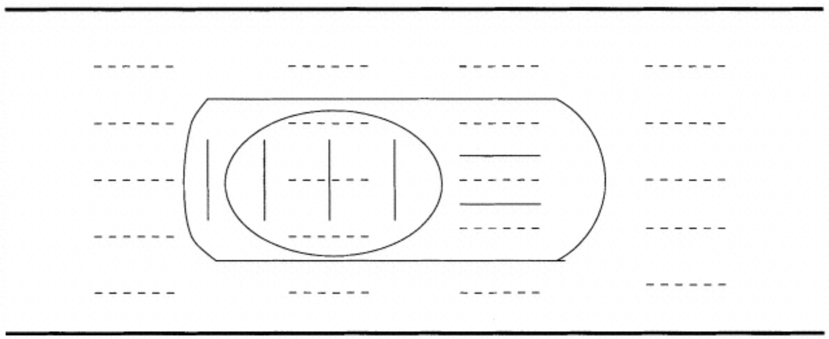
Marscher et al. (2012)

- AGN cores = optically thick jet bases; variable
- Polarization gives projected field in brightest components
- Combine with VLBI (new components, jet direction)

Structural differences?

- Differences in jet polarization are observed between (e.g.) radio and optical bands in M87 (Perlman et al. 1999)





Higher energy electrons trace different field structures?

Frequencies differ by a factor of 40 000

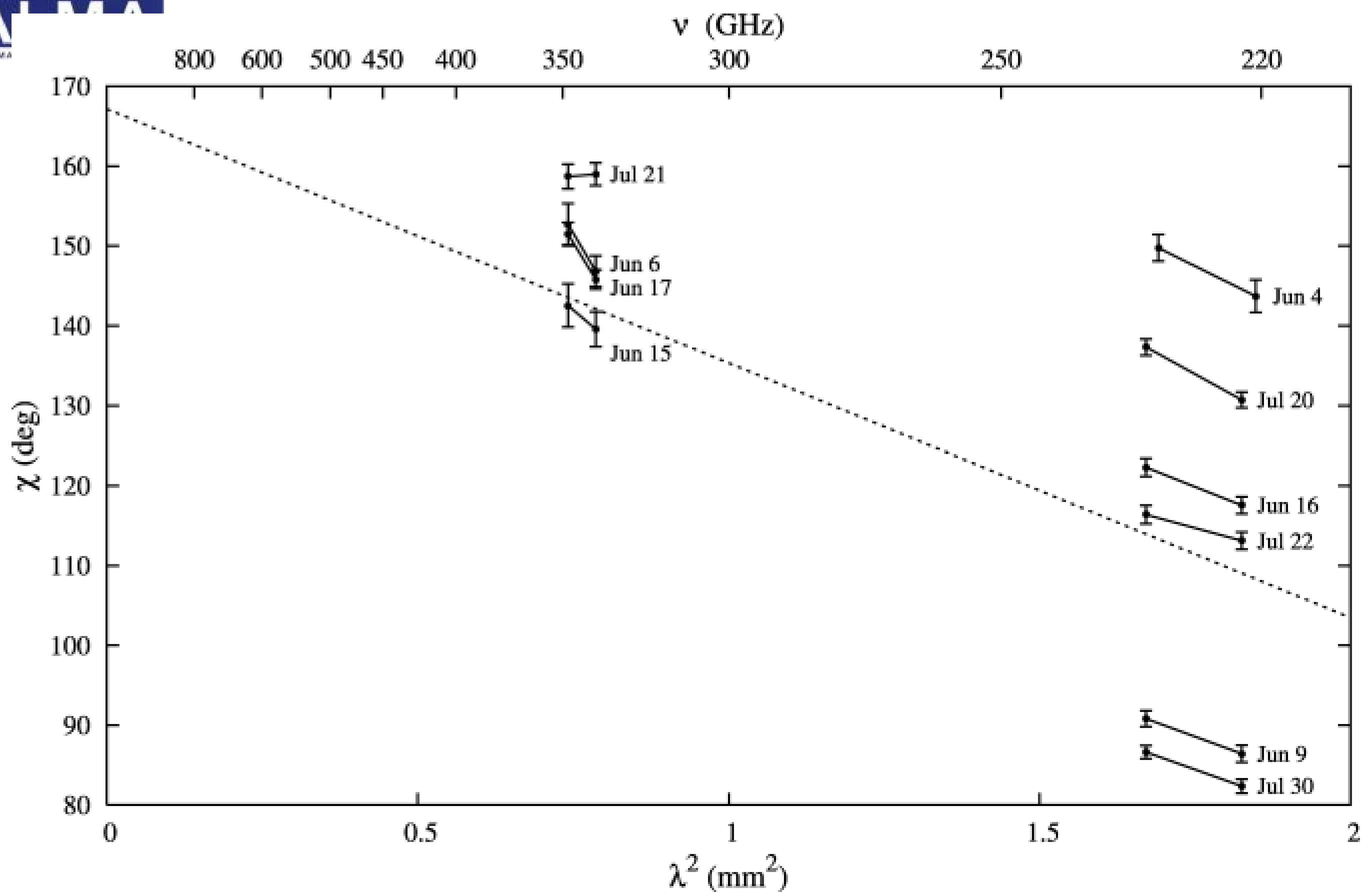
Faraday rotation

- Rotation of plane of linear polarization as radiation passes through a magnetized (thermal) plasma
- Normal modes are circularly polarized; propagation speeds are different

$$\Delta\Psi_{[\mathrm{rad}]} = \Psi(\lambda)_{[\mathrm{rad}]} - \Psi_{0\,[\mathrm{rad}]} = \lambda^2_{[\mathrm{m}^2]}\,\mathrm{RM}_{[\mathrm{rad\,m}^{-2}]},$$

$$\mathrm{RM}_{[\mathrm{rad\,m}^{-2}]} = 812\int_0^{L\,[\mathrm{kpc}]} n_{\mathrm{e}[\mathrm{cm}^{-3}]}\, B_{z[\mu\mathrm{G}]}\,\mathrm{d}z_{[\mathrm{kpc}]}\,,$$

Galactic Centre



Marrone et al. (2007)
SMA

RM = -5.6 x 10^5 radm^{-2}

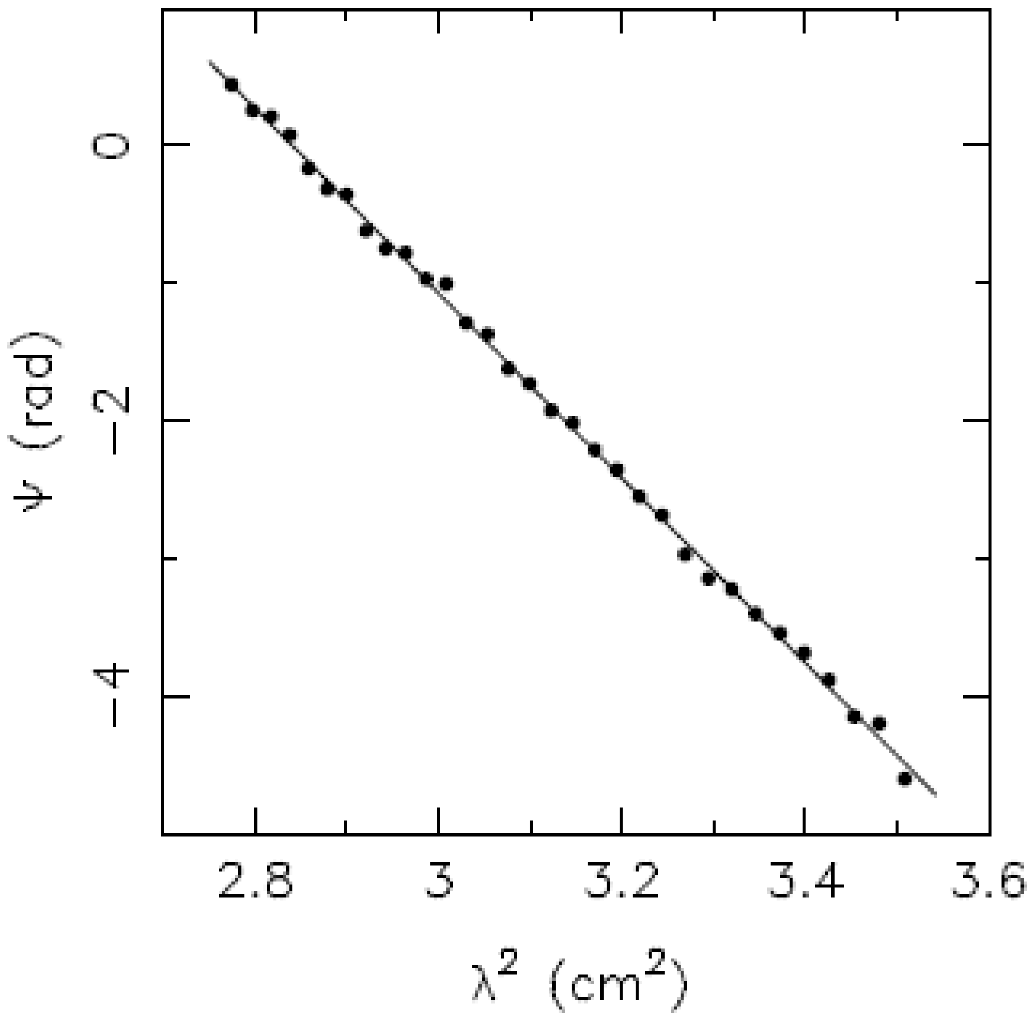
Translates to a limit on accretion rate if B is in equipartition

10^{-9} – 10^{-7} $M_\odot$/yr
(depends on geometry)

Poor λ^2 fits, complicated by variability

Can we do this for other accreting systems, using jets as background sources?

Galactic Centre Magnetar

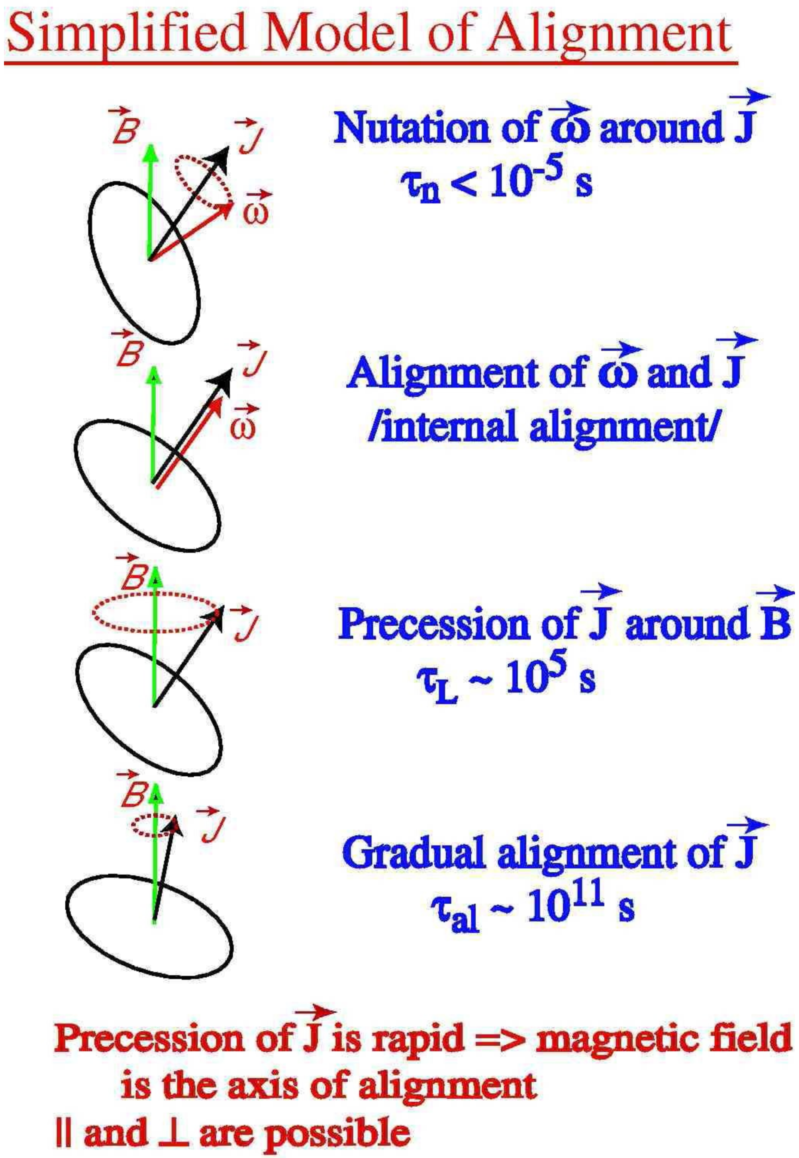


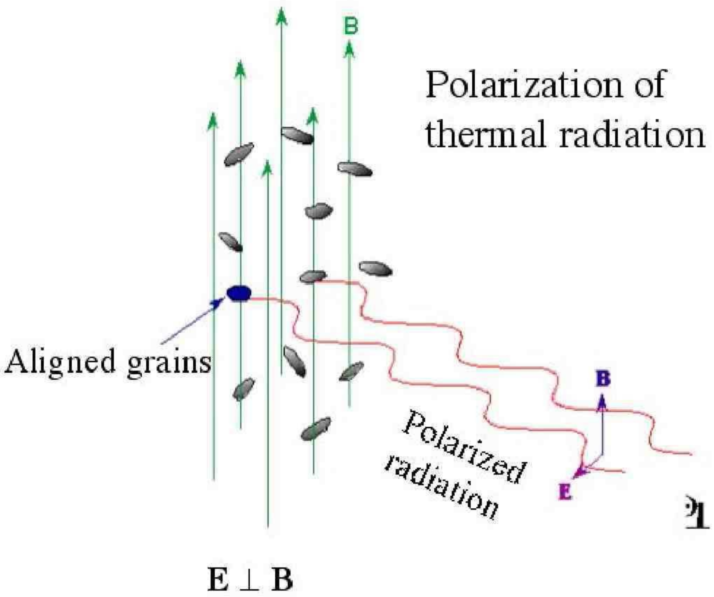
Magnetar near the Galactic Centre

Shannon & Johnston (2013)

RM = -6.7 x 10^4 rad m^{-2}

Polarized emission from dust grains



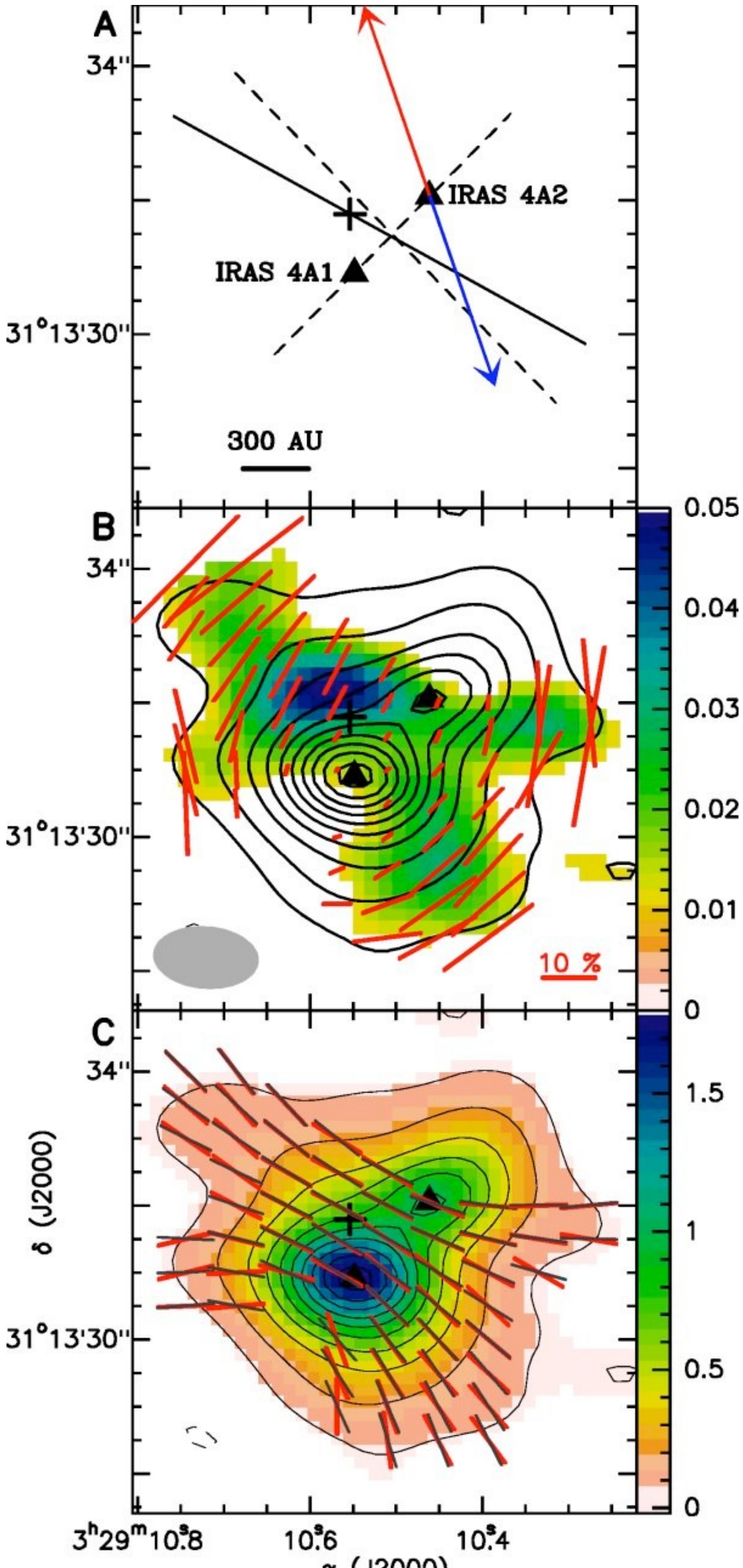


Dust grains tend to align minor axis with magnetic field

E-vectors perpendicular to projection of B

Lazarian (2007)

Star formation



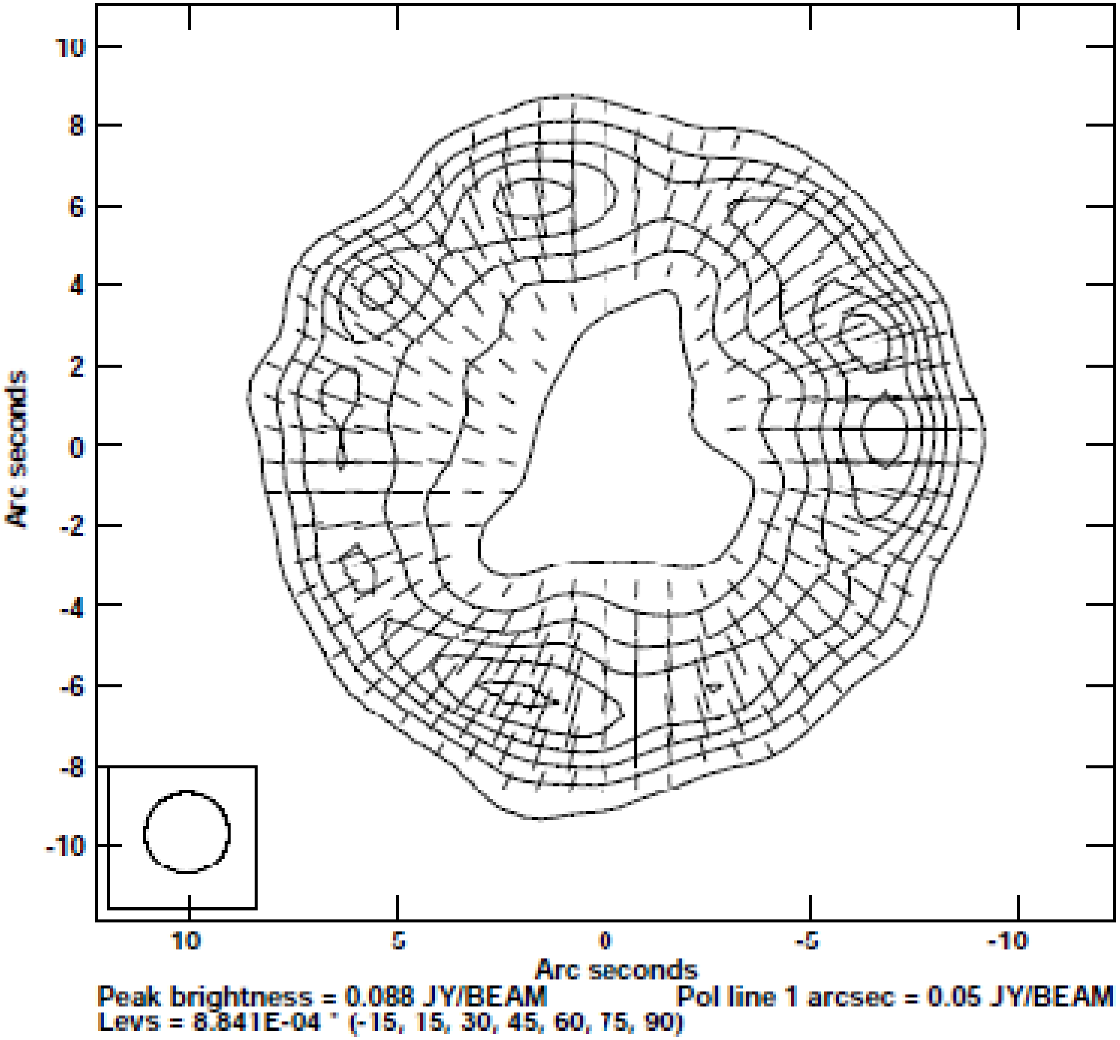
E vectors

B vectors

NGC1333 IRAS 4A
Girart et al. (2006)
SMA 345 GHz

Magnetic field in star formation ("hourglass" shape after collapse)

Mars, 43 GHz, VLA



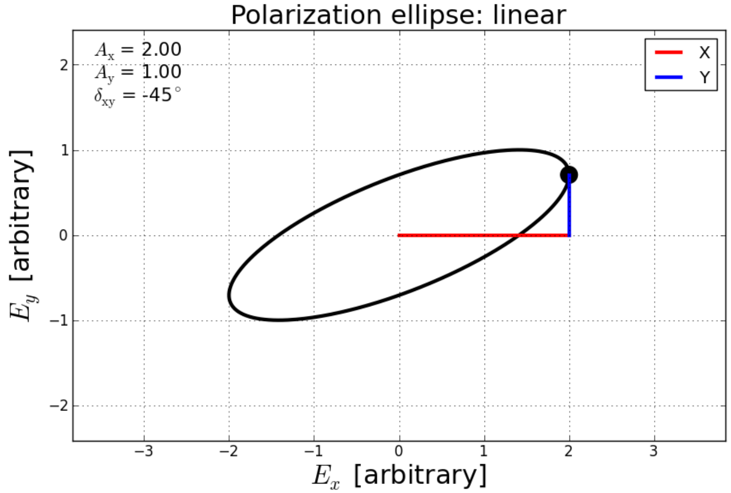
Thermal emission

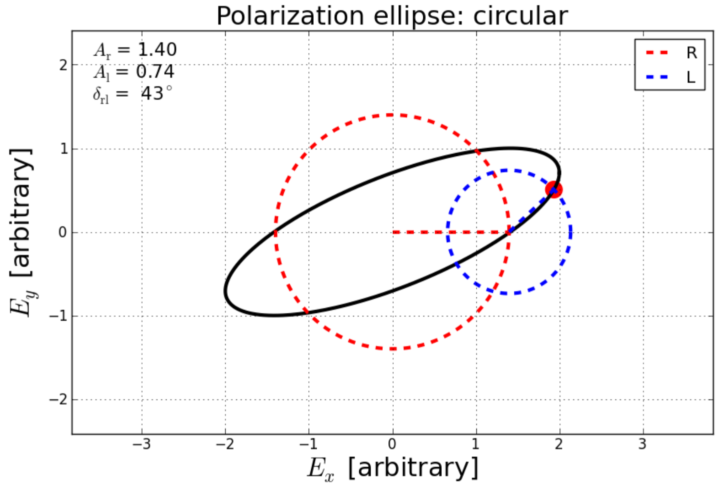
Radial **E**-vectors

Perley & Butler (2013)

Description of Polarization

- Monochromatic wave (or a single photon) **E**-vector is elliptically polarized





Head of E-vector traces an ellipse

Can express in orthogonal linear or right/left circular basis

3 parameters required:
 2 axes and orientation of ellipse
or 2 linear amplitudes and relative phase
or 2 circular amplitudes and relative phase (+ sense of rotation)

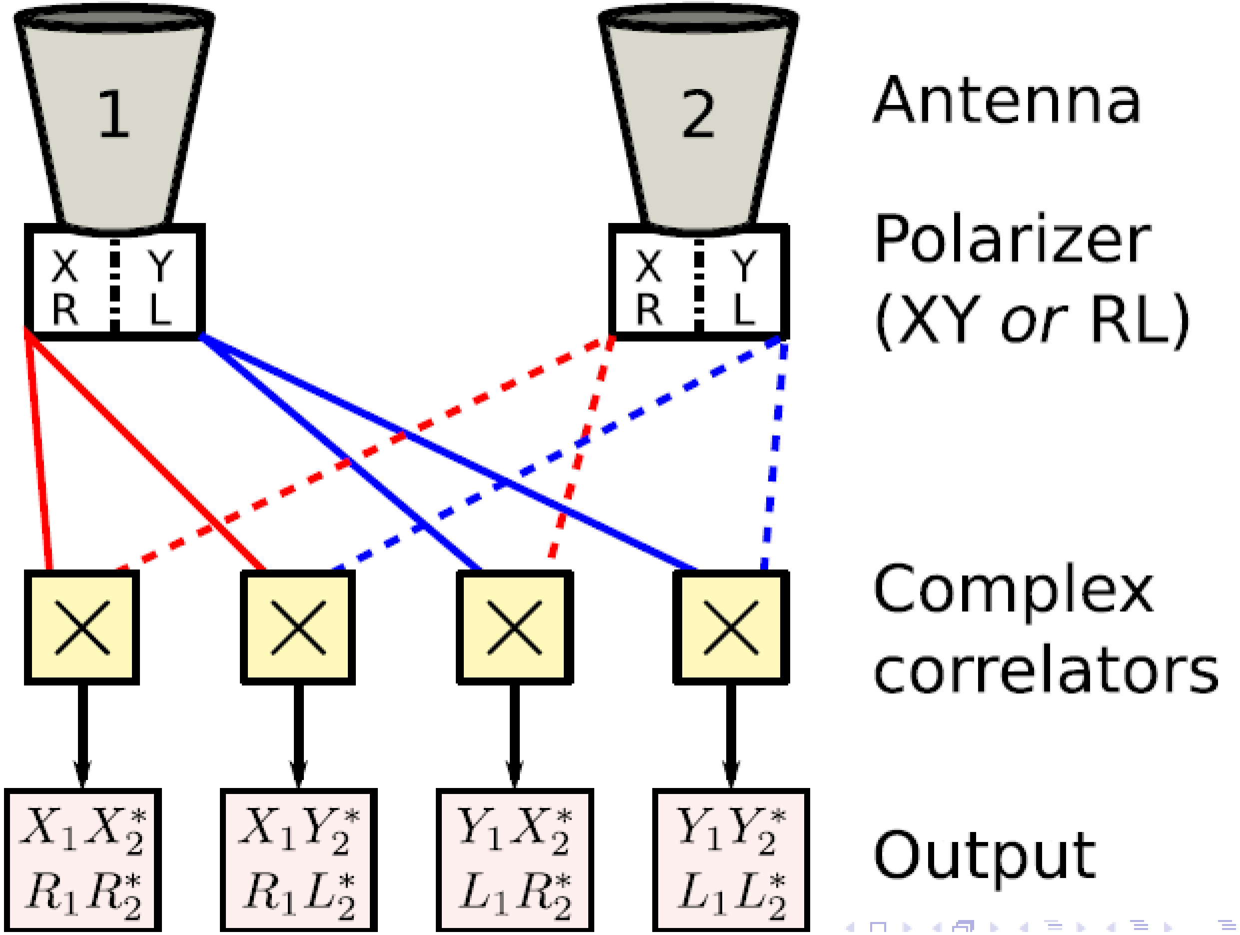
Stokes Parameters

- Stokes (1852)
- Monochromatic wave has $I^2 = Q^2 + U^2 + V^2$

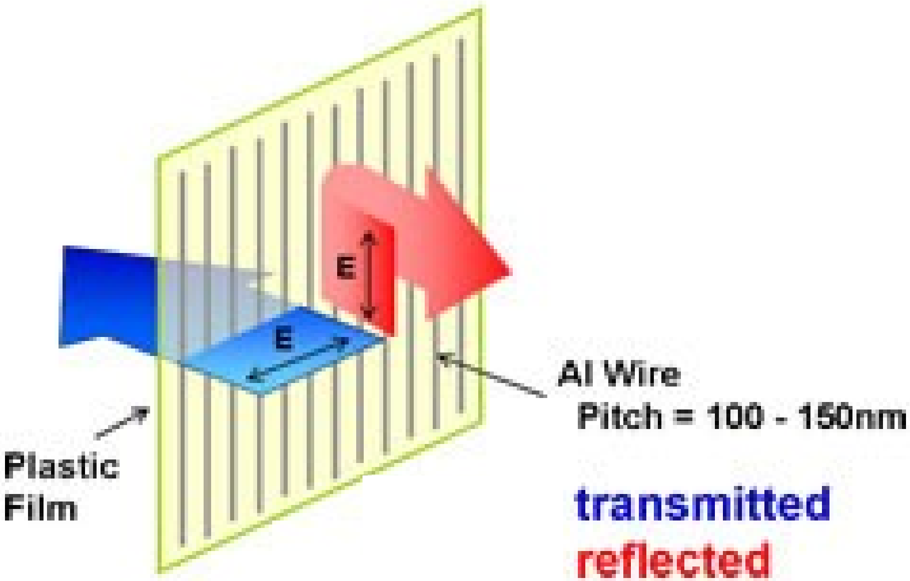
$$I = A_x^2 + A_y^2 \qquad I = A_r^2 + A_l^2$$
$$Q = A_x^2 - A_y^2 \qquad Q = 2A_rA_l \cos\delta_{rl}$$
$$U = 2A_xA_y \cos\delta_{xy} \qquad U = 2A_rA_l \sin\delta_{rl}$$
$$V = 2A_xA_y \sin\delta_{xy} \qquad V = A_r^2 - A_l^2$$

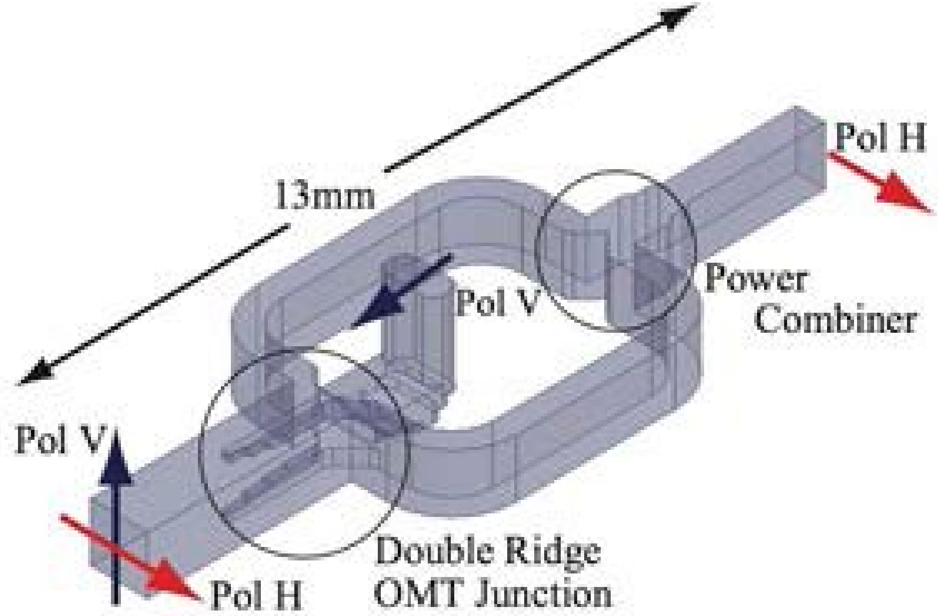
- In general have a finite bandwidth, random phases, so $I^2 > Q^2 + U^2 + V^2$
- Q and U describe linear polarization; V circular
- Fractional linear $(Q^2 + U^2)^{1/2}/I$; circular $|V|/I$
- Position angle of linear (1/2)arctan(U/Q)

Polarized cross-correlations



How does ALMA measure polarization?





Wire grid (Band 7, 9, 10)

Ortho-mode transducer (Bands 3, 4, 5, 6, 8)

Linearly polarized feeds

ALMA receivers all have linearly-polarized feeds (like WSRT, ATCA; unlike VLA). For an **ideal** system:

$$\mathbf{V}_{ij} = \begin{pmatrix} V_{XX} \\ V_{XY} \\ V_{YX} \\ V_{YY} \end{pmatrix} = \begin{pmatrix} \langle s_{X,i} s^*_{X,j} \rangle \\ \langle s_{X,i} s^*_{Y,j} \rangle \\ \langle s_{Y,i} s^*_{X,j} \rangle \\ \langle s_{Y,i} s^*_{Y,j} \rangle \end{pmatrix} = \begin{pmatrix} I + Q' \\ U' + iV \\ U' - iV \\ I - Q' \end{pmatrix}$$

$$\begin{aligned} Q' &= Q \cos 2\psi + U \sin 2\psi \\ U' &= -Q \sin 2\psi + U \cos 2\psi \end{aligned}$$

$\mathbf{V}_{ij}$ is the vector of visibilities for antennas i and j

V_{XX}, V_{YY} are the **parallel-hand** visibilities

V_{XY}, V_{YX} are the **crossed-hand** visibilities

$s_{X,i}$ is the X polarization signal from antenna i, etc.

Q', U' are defined with respect to the feed system

Q, U are true Stokes parameters defined on the sky

ψ is the **parallactic angle**

Messy reality – Jones matrices

In practice, separation between the two linear polarizations is not perfect, and some of polarization X leaks into Y and vice versa. We assume **linearity**.

Machinery for handing this is the measurement equation, which uses Jones matrices.

Here, $s_{X,i}$ is the true X polarization signal for antenna i,

$s_{X,i}^{OBS}$ is the corrupted signal

$\mathbf{J}_i$ is the Jones matrix

$$\mathbf{s}_i^{\mathrm{OBS}} = \begin{pmatrix} s_{X,i}^{\mathrm{OBS}} \\ s_{Y,i}^{\mathrm{OBS}} \end{pmatrix} = \begin{pmatrix} J_{XX,i} & J_{XY,i} \\ J_{YX,i} & J_{YY,i} \end{pmatrix} = \mathbf{J}_i \mathbf{s}_i$$

This is useful, because $\mathbf{J}_i$ can be written as a product of simpler matrices.

Signal corruption in outline

$$\mathbf{s}_i^{\mathrm{OBS}} = \mathbf{B}_i \; \mathbf{G}_i \; \mathbf{D}_i \; \mathbf{X}_i \; \mathbf{P}_i \; \mathbf{s}_i^{\mathrm{TRUE}}$$

$$\mathbf{B}_i = \begin{pmatrix} b_X(\nu) & 0 \\ 0 & b_Y(\nu) \end{pmatrix}$$

Bandpass

$$\mathbf{G}_i = \begin{pmatrix} g_X & 0 \\ 0 & g_Y \end{pmatrix}$$

Complex gain

$$\mathbf{D}_i = \begin{pmatrix} 1 & d_X(\nu) \\ d_Y(\nu) & 1 \end{pmatrix}$$

Leakage

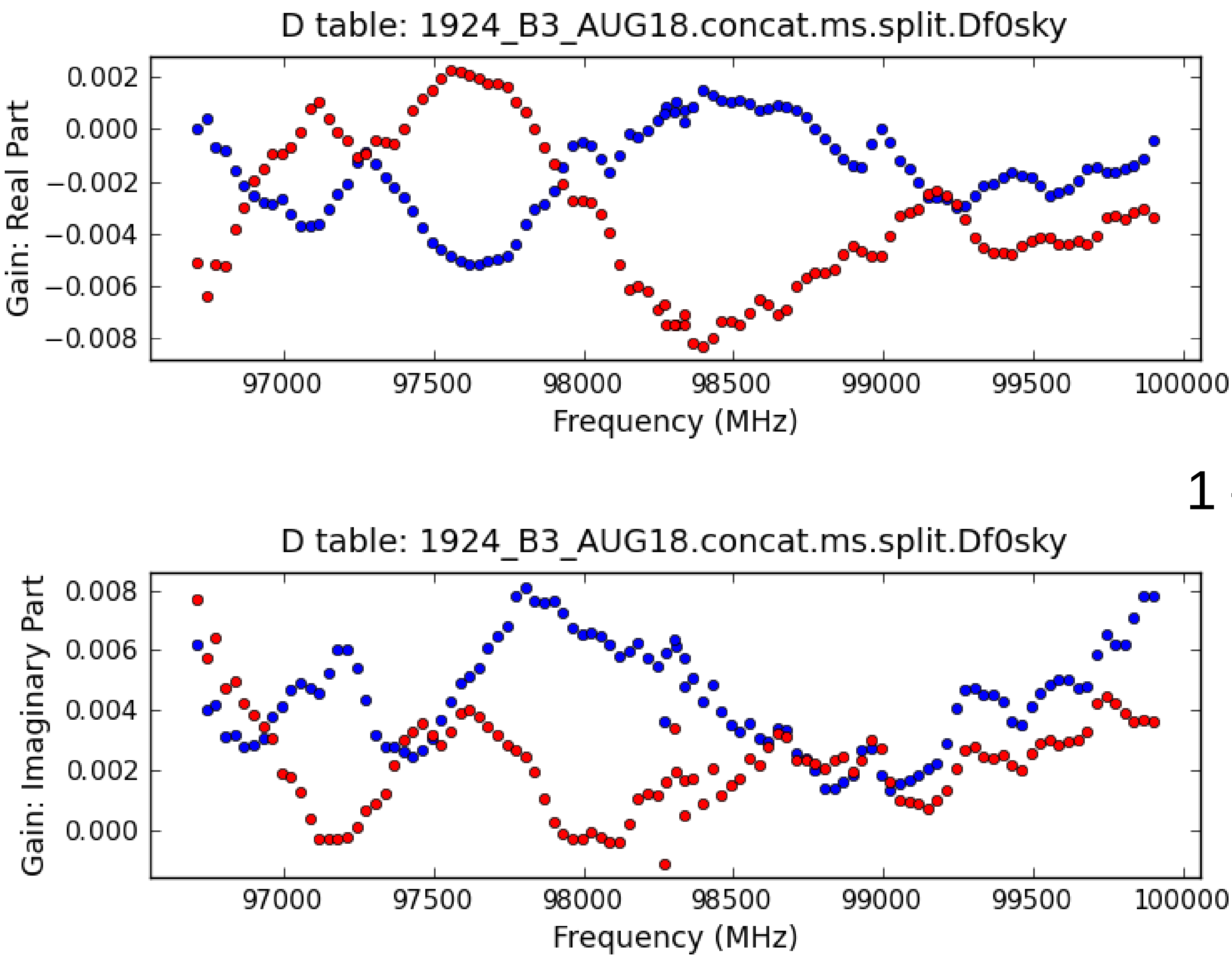
$$\mathbf{X}_i = \begin{pmatrix} \exp[i\rho(\nu)] & 0 \\ 0 & 1 \end{pmatrix}$$

Reference antenna phase difference

$$\mathbf{P}_i = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix}$$

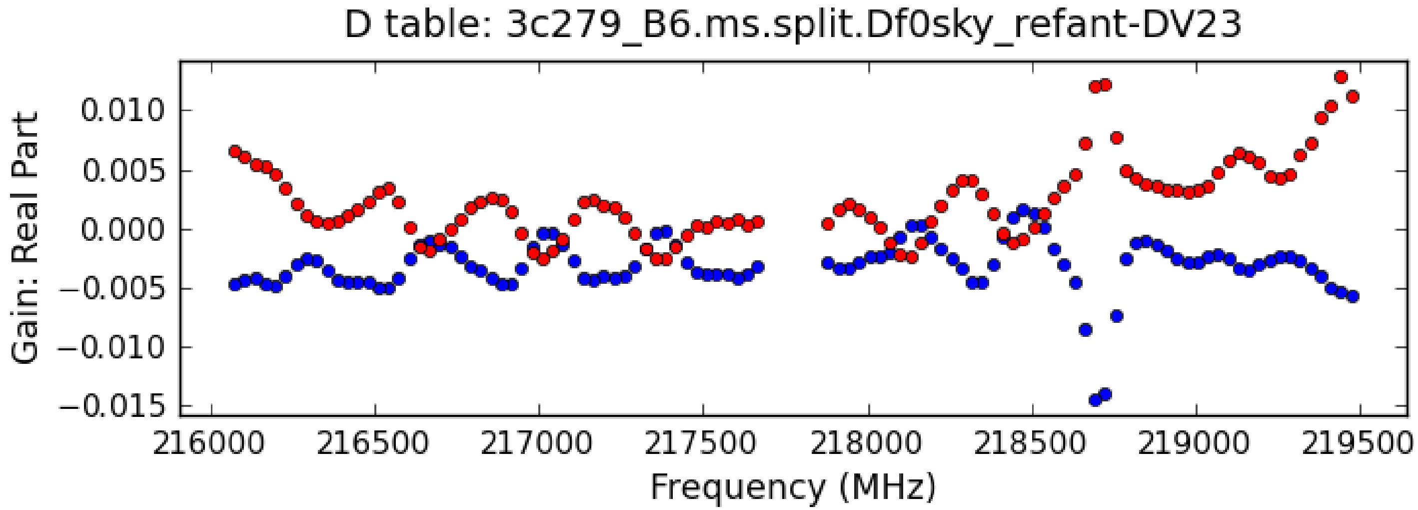
Parallactic angle

Band 3 D-terms

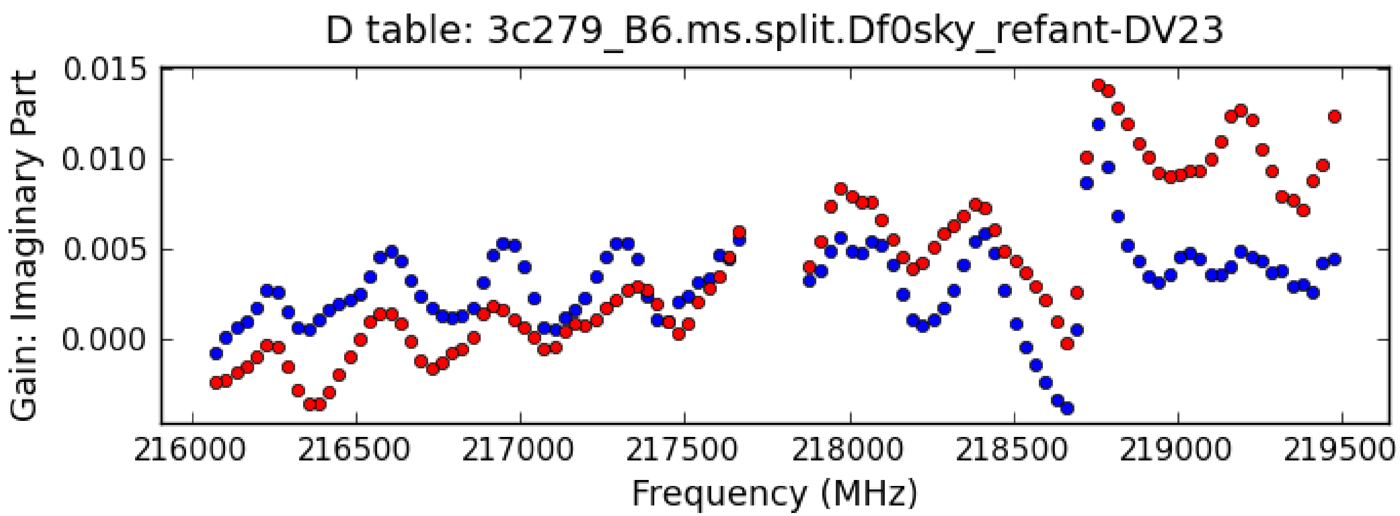


1 – 3%

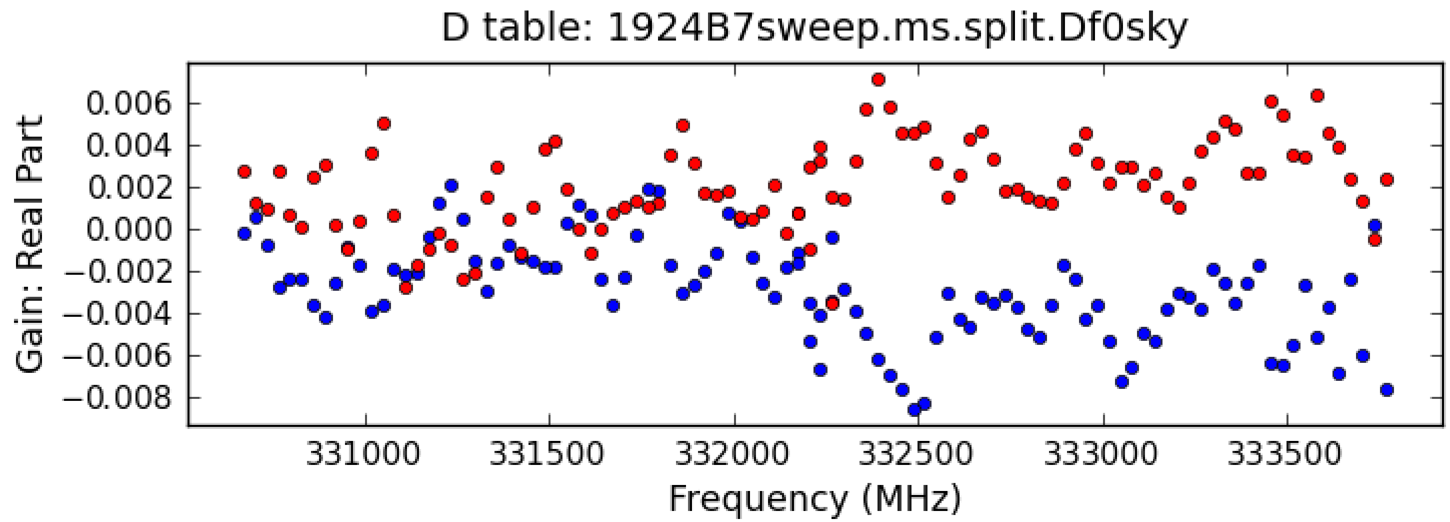
Band 6 D-terms

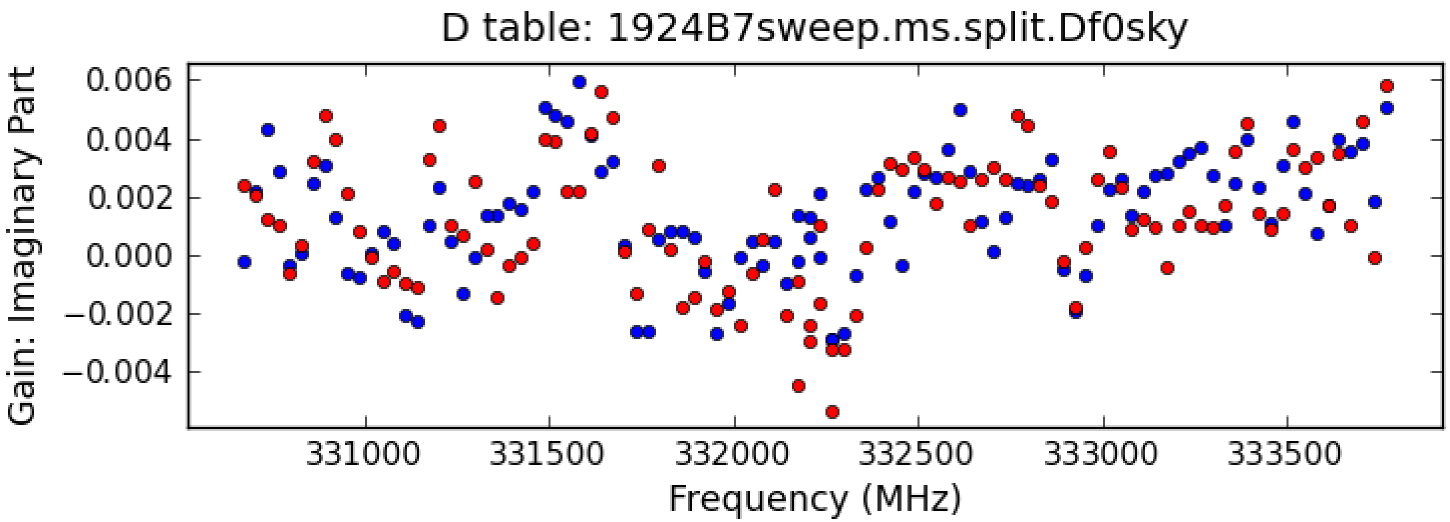


2 – 5%



Band 7 D-terms





<2%

The ghastly details

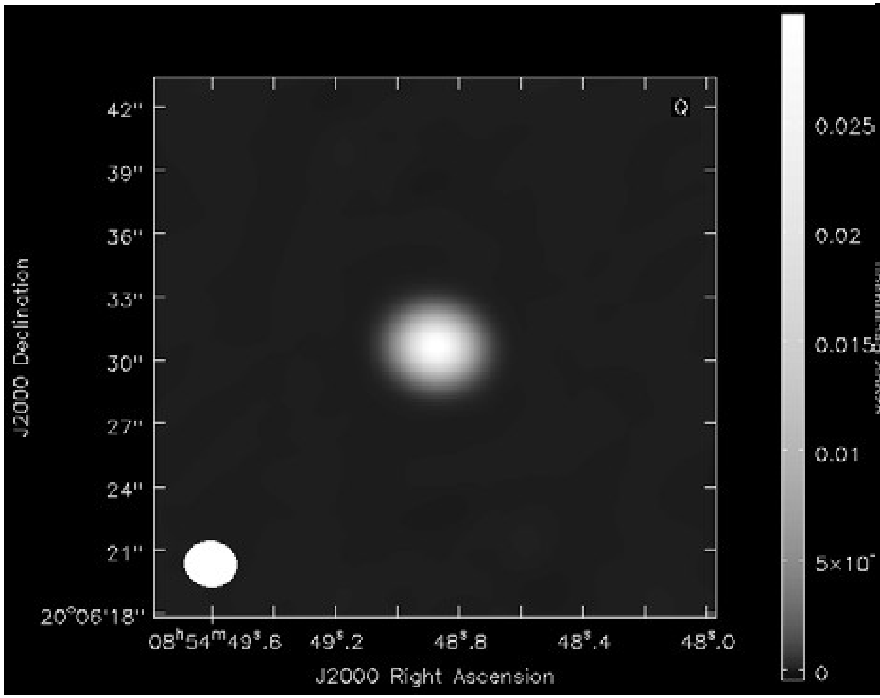
$$
\begin{aligned}
V_{XX} &= \exp(2i\rho)[I + Q' + U'(d^*_{Xj} + d_{Xi})] \\
V_{XY} &= \exp(i\rho)[U' + iV + I(d^*_{Yj} + d_{Xi}) + Q'(d^*_{Yj} - d_{Xi})] \\
V_{YX} &= \exp(i\rho)[U' - iV + I(d_{Yj} + d^*_{Xi}) + Q'(d_{Yi} - d^*_{Xi})] \\
V_{YY} &= I - Q' + U'(d^*_{Yj} + d_{Yi})] \\
Q' &= Q\cos 2\psi + U \sin 2\psi \\
U' &= -Q \sin 2\psi + U \cos 2\psi
\end{aligned}
$$

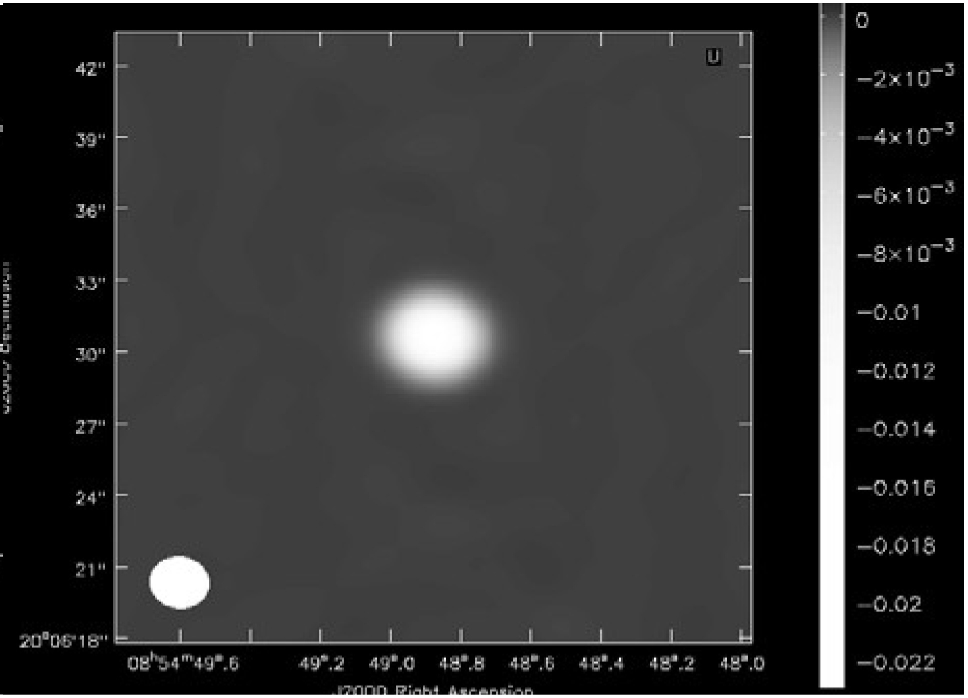
Linearised equations (neglect terms in d^2 and dV)
N antennas and N(N-1)/2 baselines
2N complex d terms per antenna, ρ, Q, U and V to be determined
ψ known a priori

Make ≥3 measurements of polarized calibrator at different parallactic angles assuming that everything is stable.

⇒ unique determination

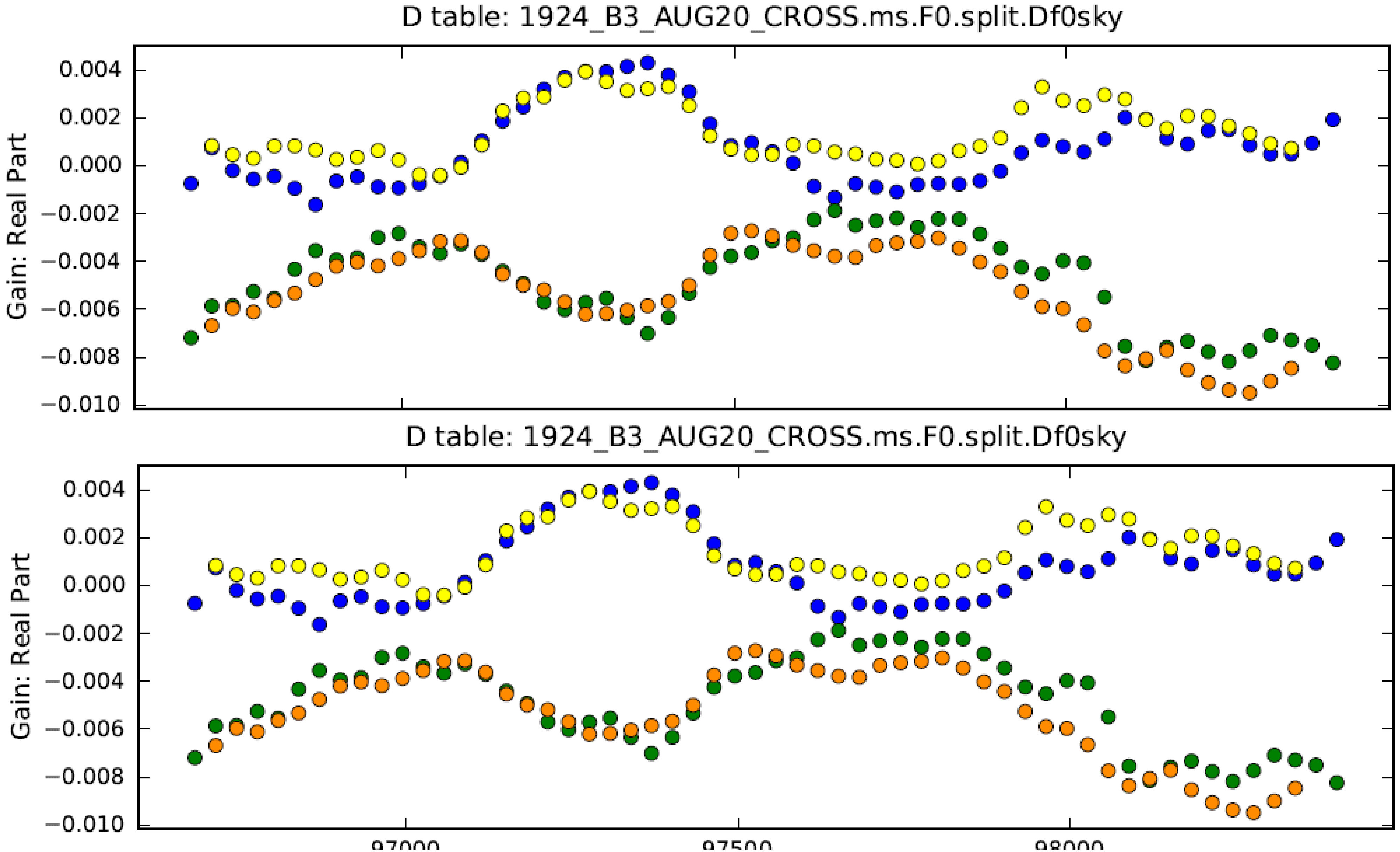
The end result





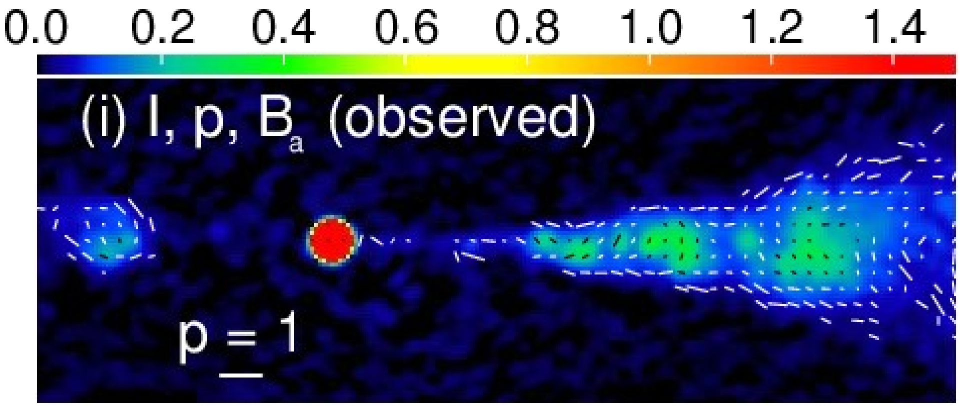
Q U
(after calibration)
rms a few x 0.01% of Stokes I

Stability over 2 days



Practicalities

- Typical fractional linear polarization 1 – 10% from synchrotron and thermal emssion
  - Calculate expected polarized flux density
  - Assume calibrate leakage terms to ~0.1%. Calculate spurious polarization from bright sources in the field.
  - Check S/N in Q and U (same calculation as for I in sensitivity calculator)



Cycle 2 Limitations (1)

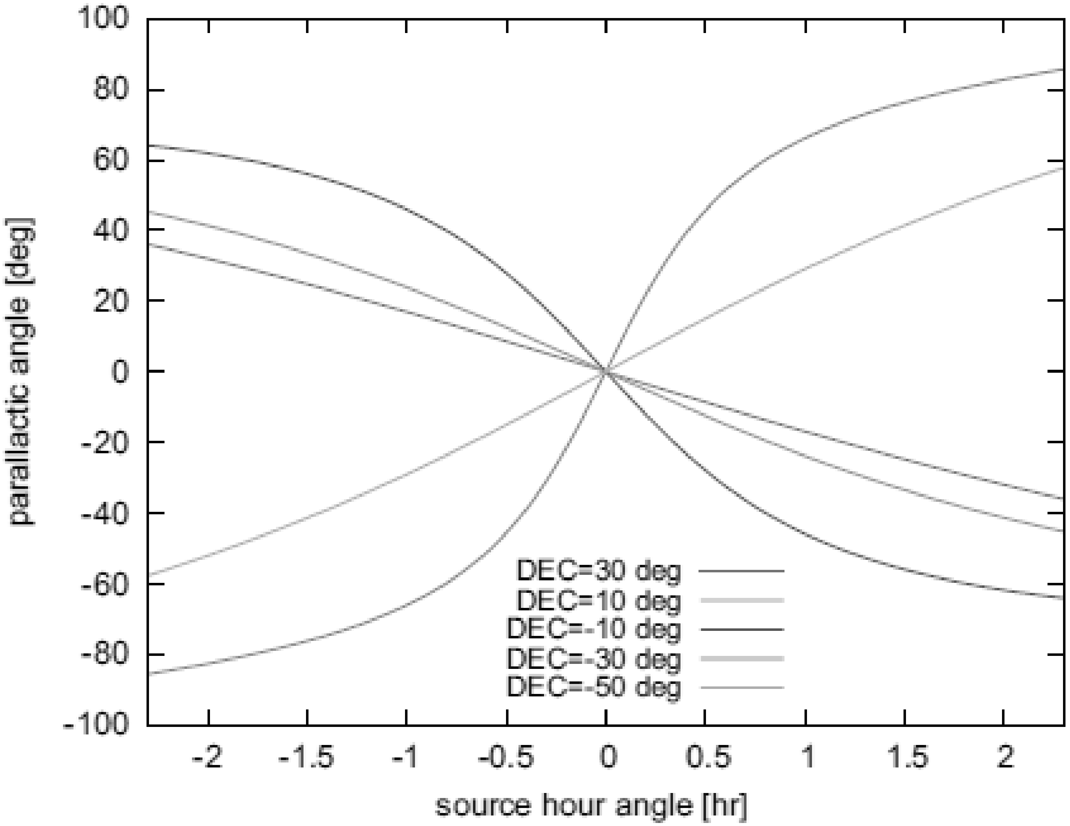
- Direction-dependent effects have been neglected
  - Have assumed that leakage terms do not vary across the field
  - Response is actually direction-dependent (e.g. deviations from axisymmetry in the receiver optics)
  - In practice, restrict observations to inner FWHM/3 of the antenna beam, where variations are small (accuracy better than 1% in linear polarization anticipated)
  - Therefore also no mosaic
  - In the future, these effects will be calibrated and corrected
- Stokes V calibration not commissioned
  - Use at your own risk

Cycle 2 Limitations (2)

- “Continuum” observations only (TDM). Selected “good” frequencies. 8 GHz bandwidth.
- Band 3, 6, 7
- No ACA, total power
- Observations long enough that leakage terms can be calibrated
  - Nominally 4 observations of calibrator (minimum 3 – as above)
  - $\approx 45^{o}$ parallactic angle coverage
  - $\lesssim 40^{o}$ from target
  - Observatory will find calibrator, but need to consider parallactic angle range in advance.
  - Once stability is verified, it should be possible to drop (some of) these requirements

Parallactic angle

$$\psi = \frac{\cos\phi \sin h}{\sin\phi \sin\delta - \cos\phi \sin\delta \cos h}$$



Fast variation for declination ≈ latitude; hour angle ≈ 0
(transit close to zenith)