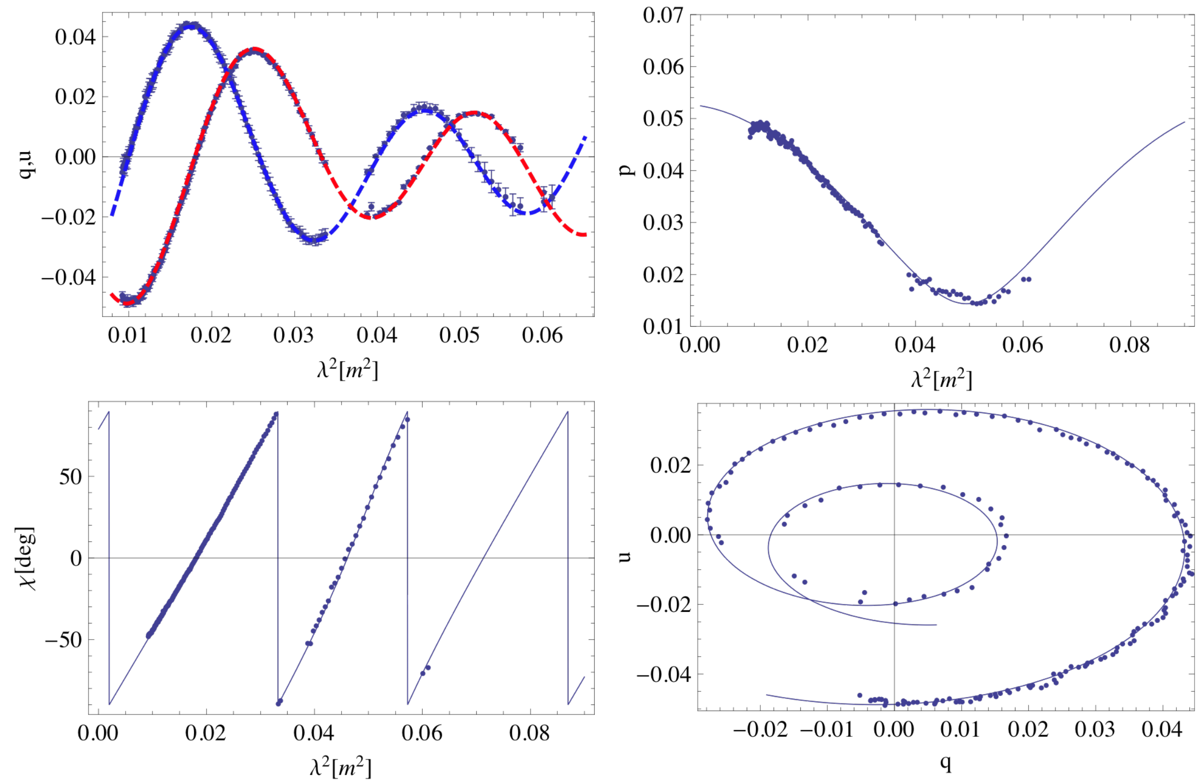


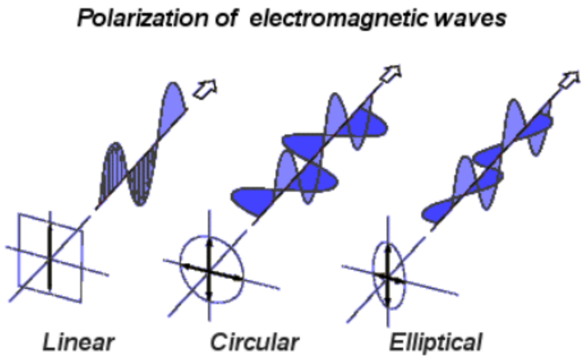
Polarization II

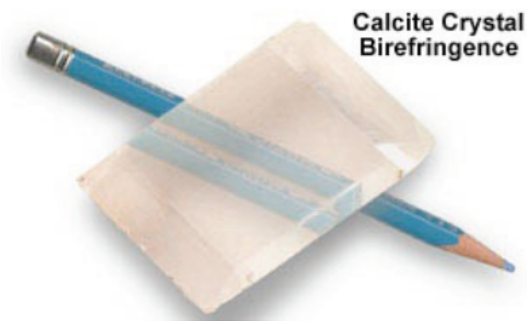
Shane O'Sullivan, OCE Postdoctoral Fellow, CASS

CASS Radio School, Parkes, Sept 2011

Polarization

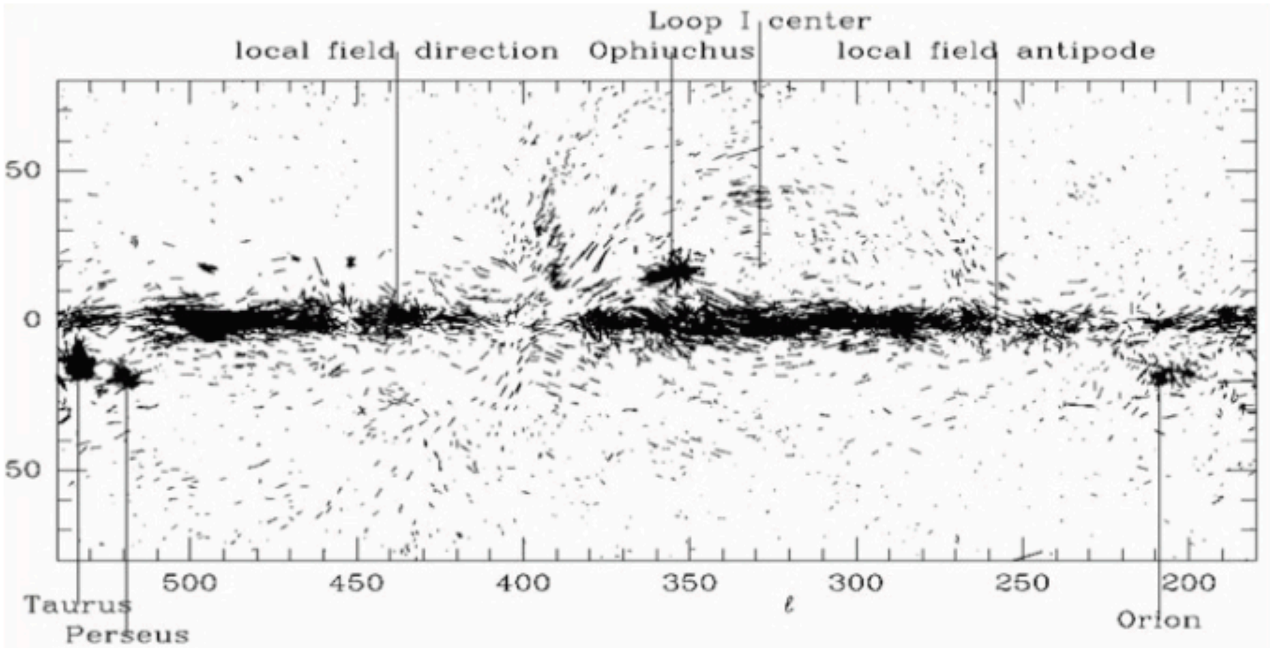
- Electromagnetic waves have direction, amplitude, frequency and polarization
- Measure power => time-average of E(t).E(t)*
- Integrated starlight => unpolarized
- Synchrotron radiation => linearly polarized
- Coherent radiation (masers) => can be highly polarized



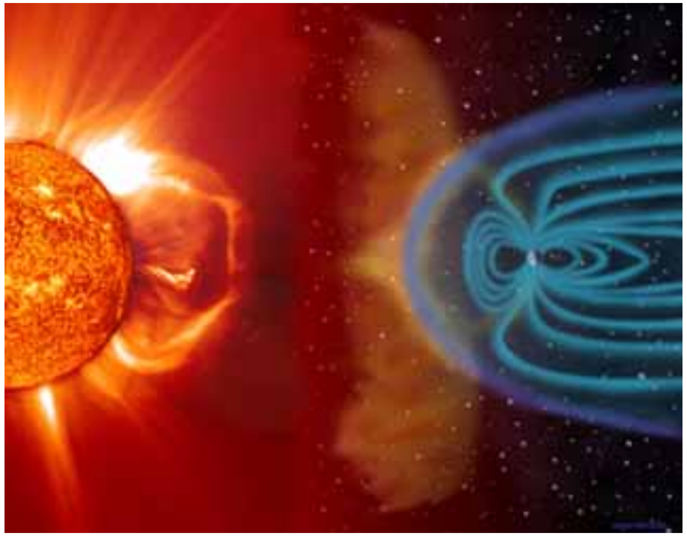


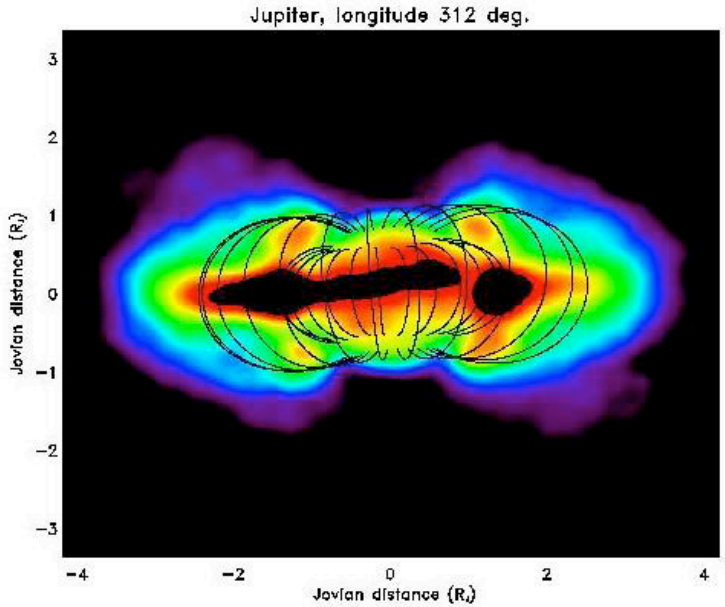
Polarization

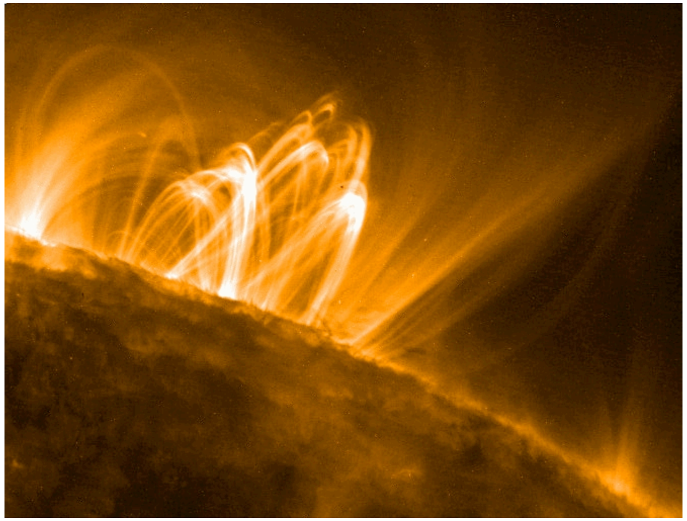
- Polarization => strength, orientation and degree of order of magnetic field in the emitted region
- Multi-frequency polarization => physics of emission region + investigation of material that can change the state of polarization along the line of sight

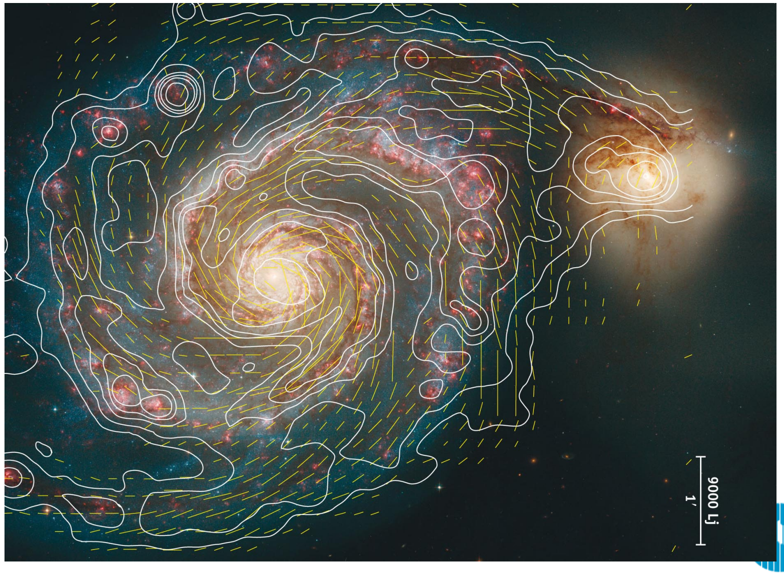


The Universe is magnetized









3. DYNAMICAL EFFECTS

Let me finally turn to the dynamical effects associated with the galactic magnetic field. If we believe that the field strength is of the order of 15×10^{-6} gauss, as seems to be implied by the synchrotron observations, we cannot expect strong dynamical effects of the magnetic field on the scale of the Galaxy as a whole. On the other hand, *in individual spiral arms* the magnetic field will be dynamically quite important, and it certainly should ultimately be taken into account also in the theories of spiral structure that have been *en vogue* during this conference. But the idea which was perhaps current in some quarters several years ago (cf. Woltjer 1962), that the magnetic fields might be of dominant dynamical importance, seems by now to be unlikely. The argument in the past has frequently been a process of elimination: one observed certain phenomena, and one investigated what part of the phenomena could be explained; then the unexplained part was taken to show the effects of the magnetic field. It is clear in this case that, the larger one's ignorance, the stronger the magnetic field.

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the larger one's ignorance, the stronger the magnetic field.

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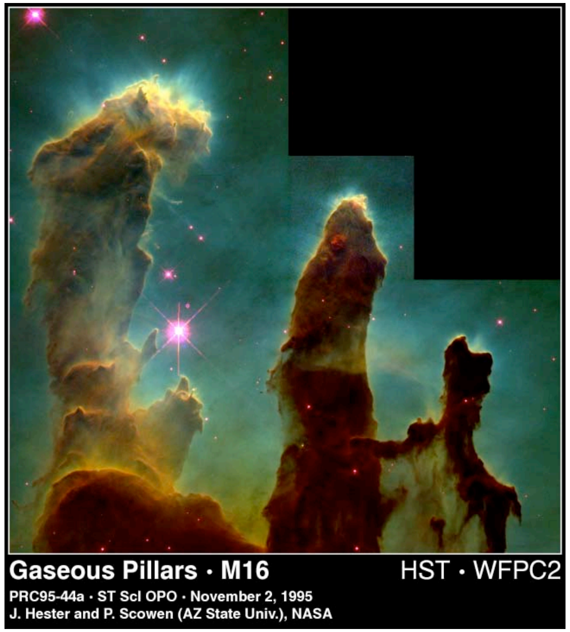
The Universe is magnetized

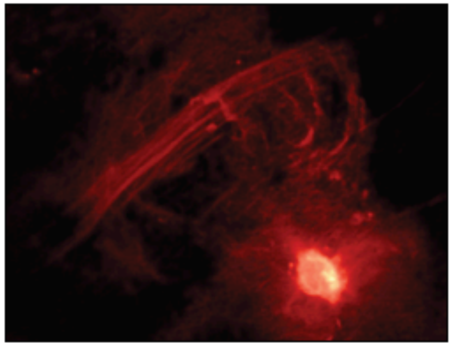
- Influence of magnetism
  - Star formation
  - Vertical structure of the Galaxy
  - Astronomical jets



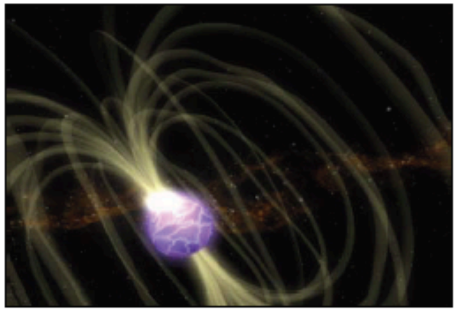
The Universe is magnetized

- High-z seed fields (Widrow 2002; Subramanian 2007) — $B \sim 10^{-30} - 10^{-20}$ G
- Intergalactic Medium — $B \sim$ 1-10 nG ?
- Intracluster Medium — $B \sim$ 0.1-1 μG
- Interstellar medium — $B \sim$ 1 μG – 10 mG
- Galactic Centre (Crocker et al. 2010; Ferrière 2010) — $B \sim$ 50 μG – 1 mG
- Main sequence star: HD 215441 (Babcock 1960) — $B_0 \approx$ 34 kG
- White dwarf: PG 1031+234 (Schmidt et al. 1986) — $B_0 \approx 10^9$ G
- Pulsar: PSR J1847-0130 (McLaughlin et al. 2003) — $B_0 \approx 9 \times 10^{13}$ G
- Magnetar: SGR 1806-20 (Kouveliotou et al. 1998, Israel et al. 2005) — $B_0 \approx 2 \times 10^{15}$ G, $B_i \approx 10^{16}$ G
- Cosmic strings (Ostriker et al. 1986) — $B \sim 10^{30}$ G
- Planck-mass monopoles (Duncan et al. 2000) — $B \sim 10^{55}$ G

Magnetic filaments in Perseus A (Fabian et al. 2008)

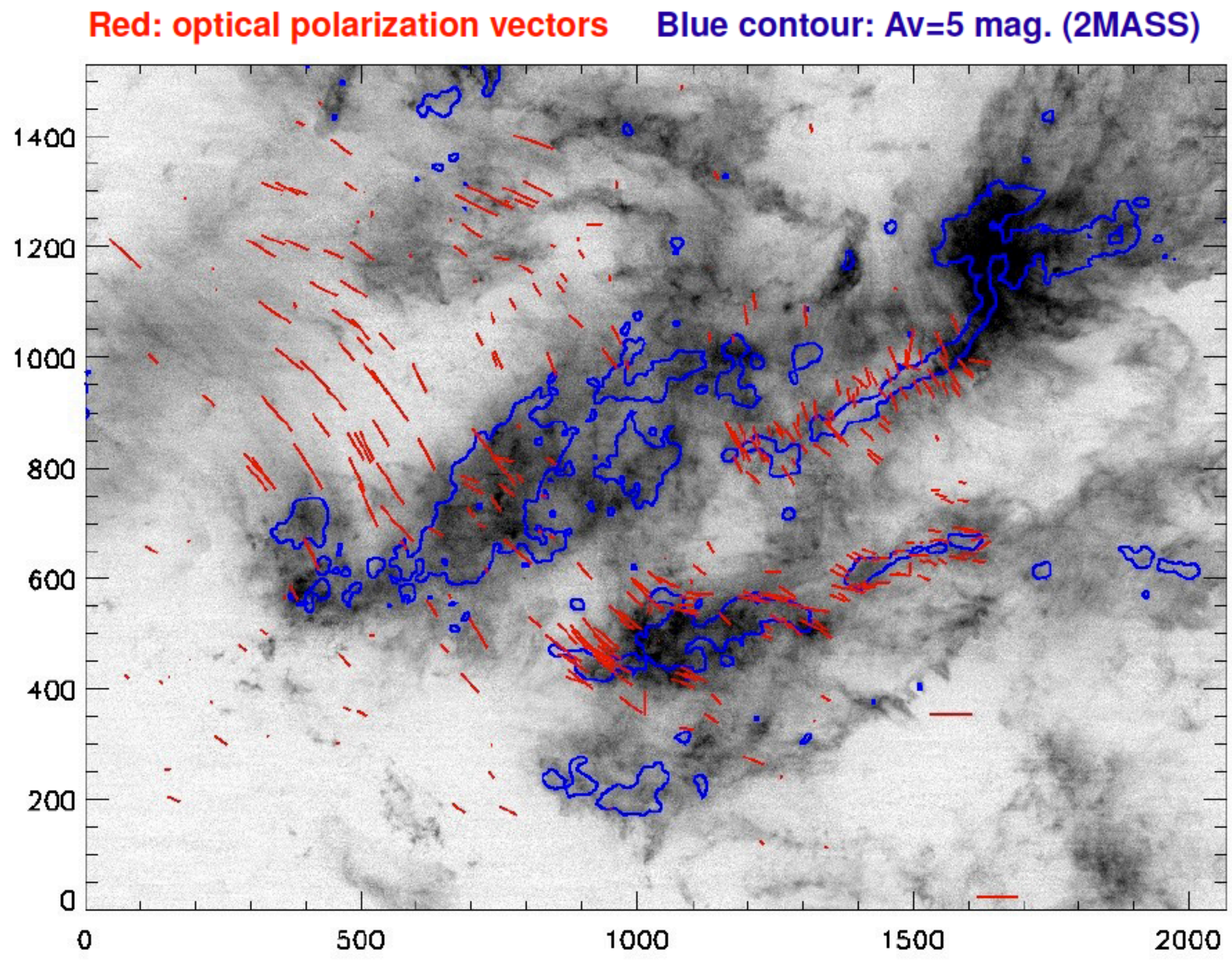


Galactic Centre (Yusef-Zadeh et al. 1984)



SGR 1806-20 giant flare (NASA)

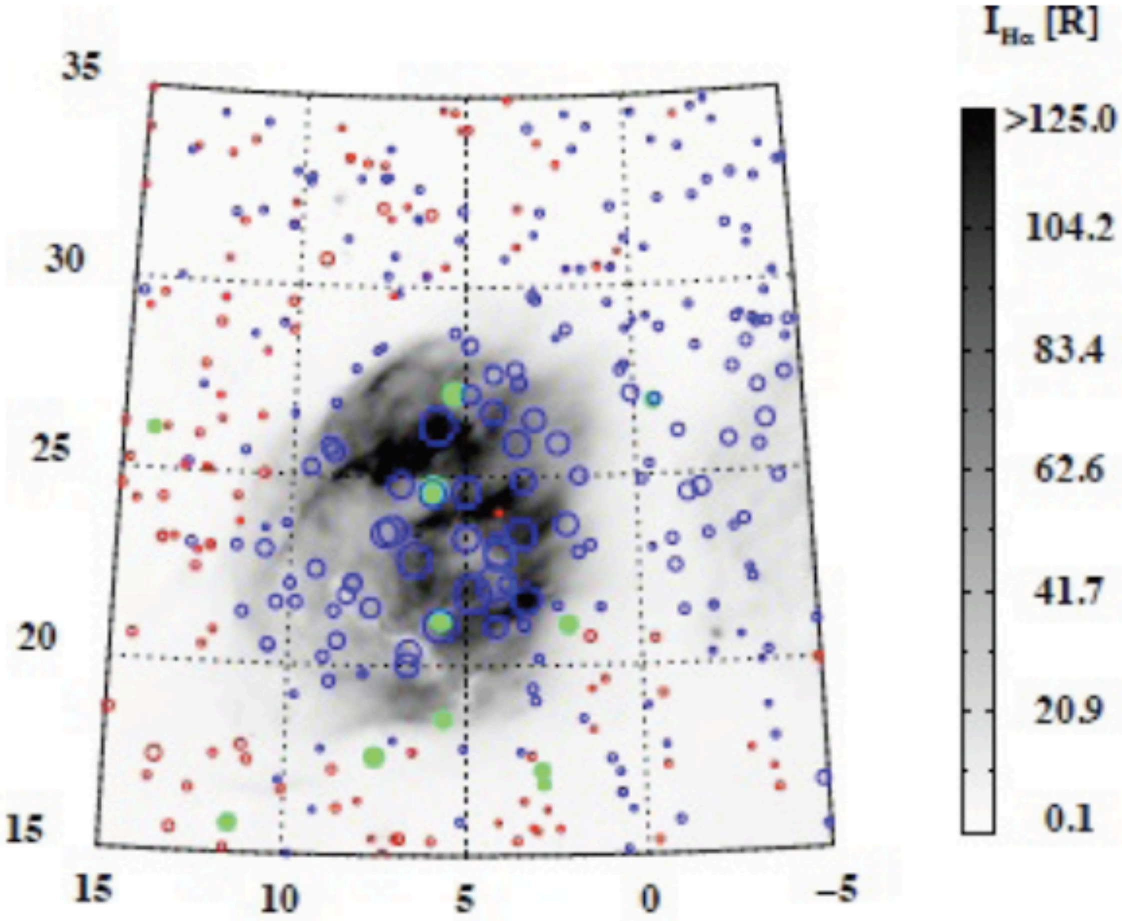
Background polarization as a magnetic field tracer



- Goldsmith et al. (2008)

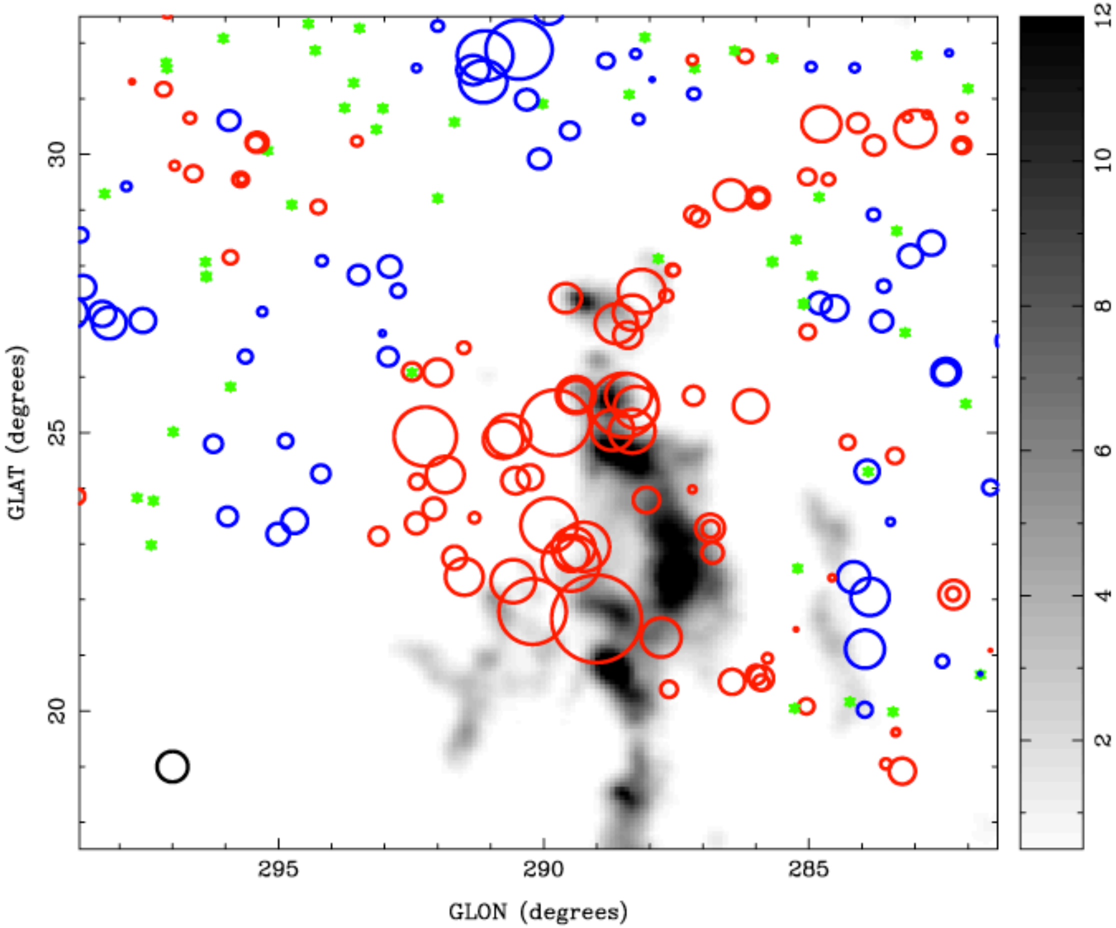
Background polarization as a magnetic field tracer

- Magnetic fields in HII regions (Harvey-Smith et al. 2011)



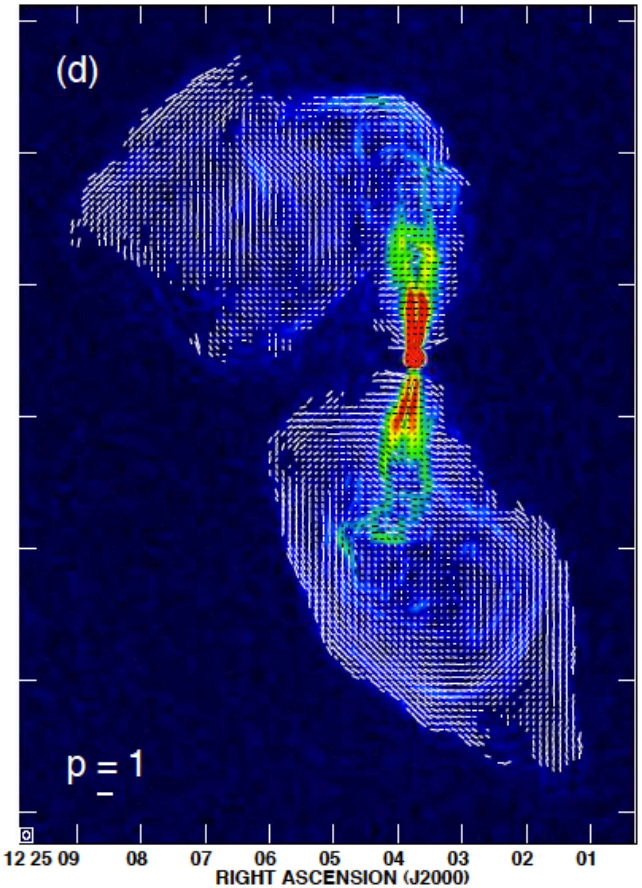
Background polarization as a magnetic field tracer

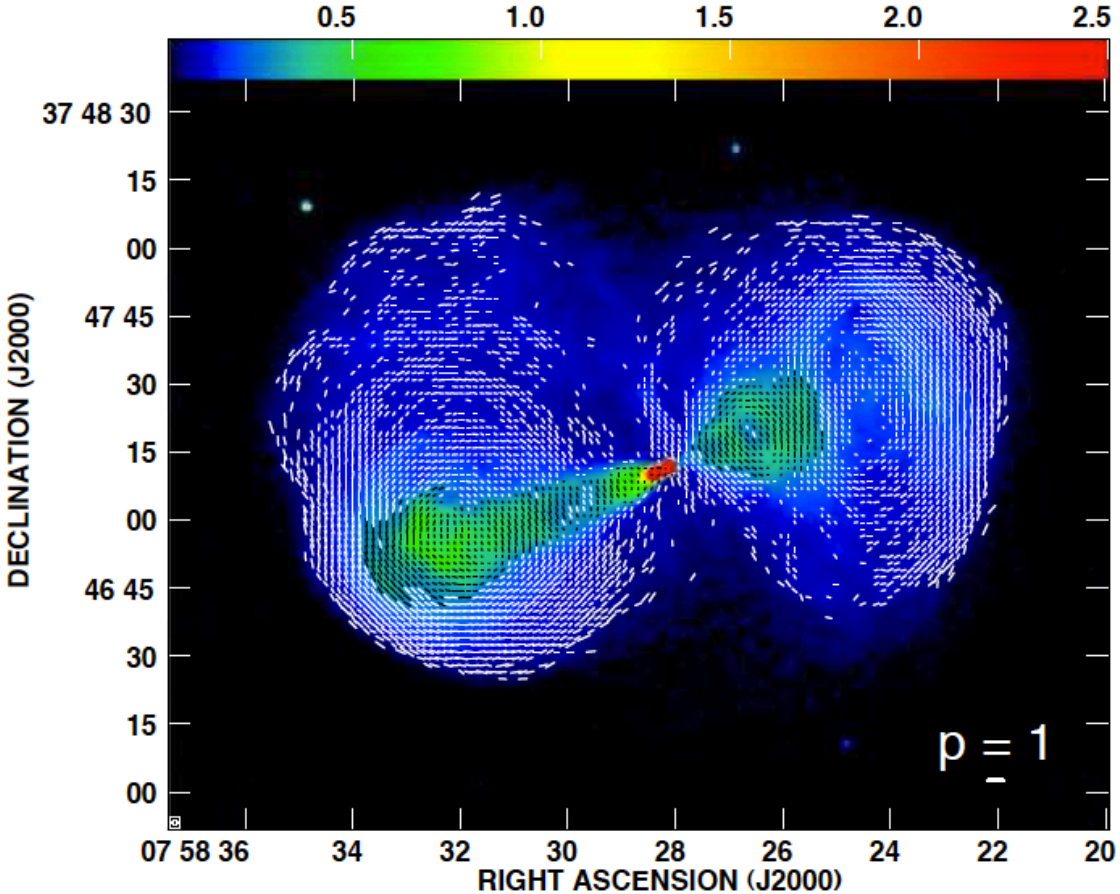
- B-fields in high velocity clouds (McClure-Griffiths et al. 2010)



Magnetic fields in radio galaxies

- Laing et al. (2011)

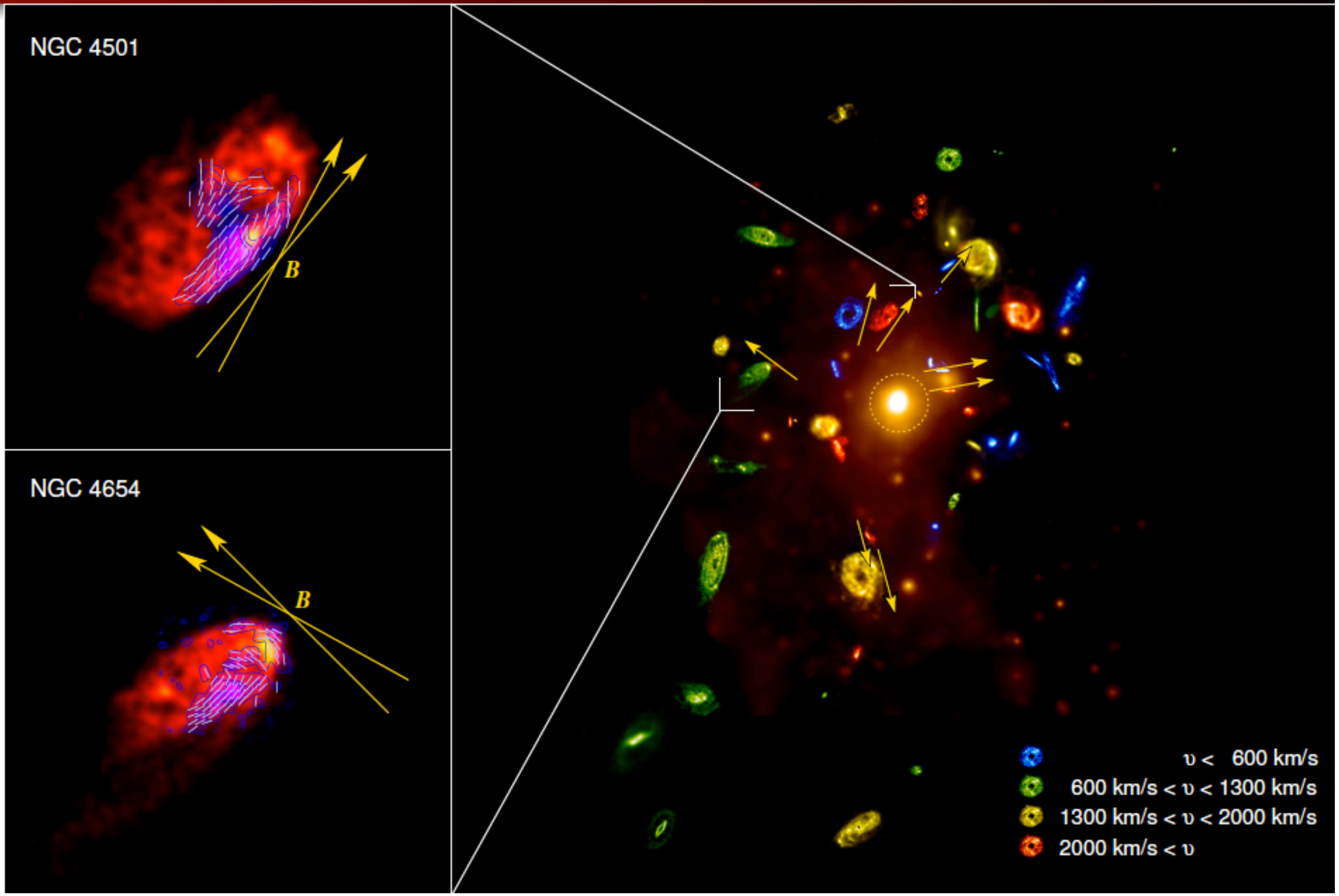




Magnetic fields in galaxy clusters

- Pfrommer et al.

Mapping out the magnetic field in Virgo



Stokes parameters

- Conway & Kronberg (1969)
- Circular feeds (eg. EVLA, eMERLIN)

$$I = v_{xx^*} + v_{yy^*}$$
$$Q = v_{xy^*} + v_{yx^*}$$
$$U = v_{xy^*} - v_{yx^*}$$
$$V = v_{xx^*} - v_{yy^*}$$

- Linear feeds (eg. ATCA, WSRT)

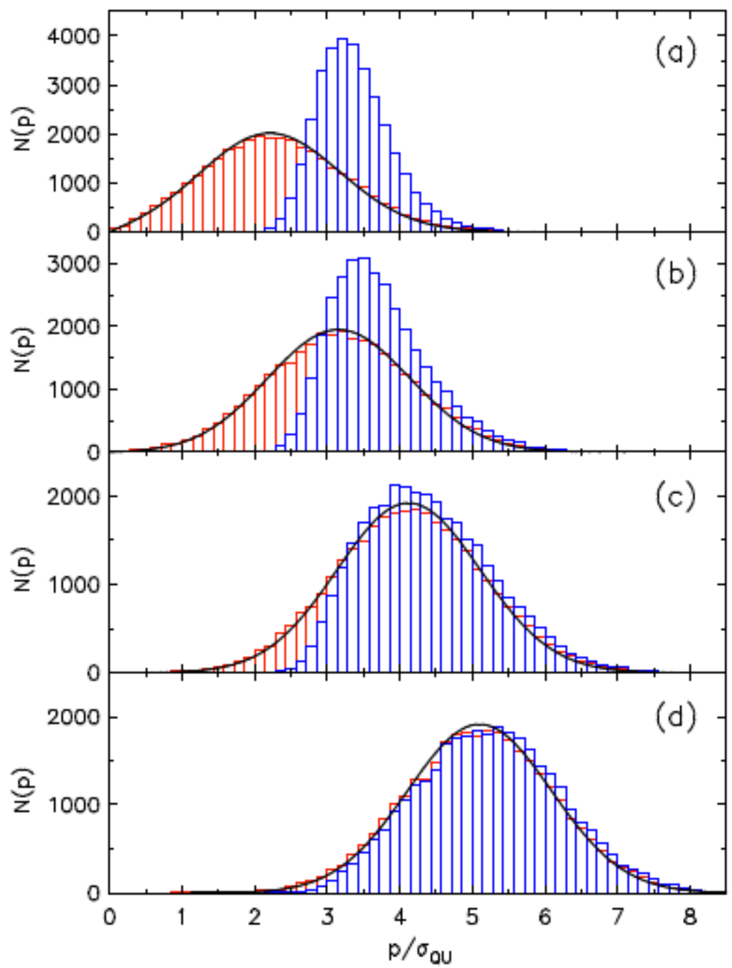
$$I = v_{xx^*} + v_{yy^*}$$
$$Q = v_{xx^*} - v_{yy^*}$$
$$U = v_{xy^*} + v_{yx^*}$$
$$V = v_{xy^*} - v_{yx^*}$$

$$LP = \sqrt{Q^2 + U^2}$$
$$\chi = \frac{1}{2} \tan^{-1}(U/Q)$$
$$CP = V$$

Polarization Bias

- Polarized intensity is a positive-definite quantity (ie. noise in Stokes Q and U results in a positive value for p even if no signal is present)
- Hence, polarization detection experiments must take this into account
- For SNR > 4, an effective estimator of the true polarized intensity is

$$p_0 = \sqrt{p^2 - 2.3\sigma_{QU}^2}$$

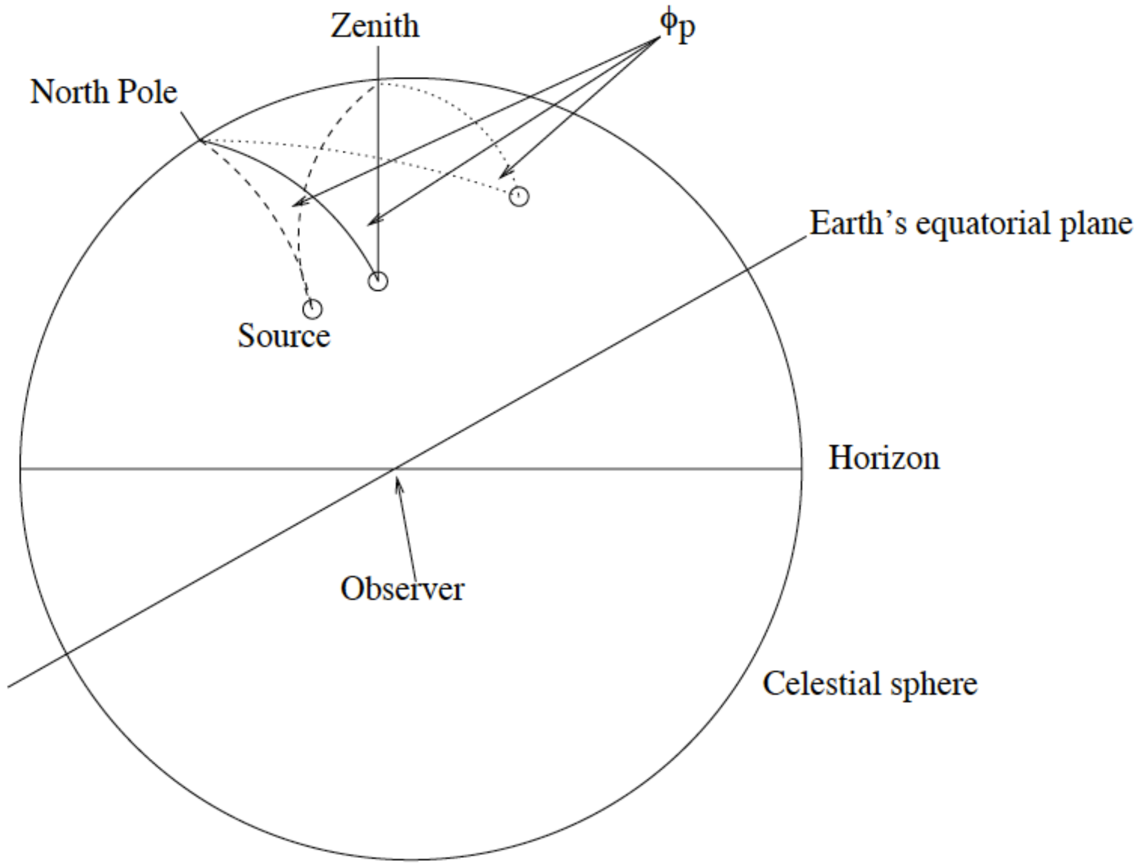


- George, Stil & Keller (2011)

Instrumental effects

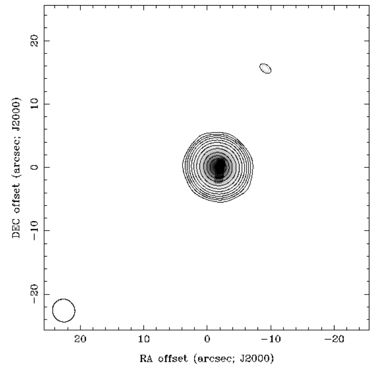
- If we had a perfectly engineered system we could just measure I, Q, U, V and be done
- Any real feed responds not only to it's intended linear/circular polarization but to the other one as well
- "Leakages" are generally small (1-10%) but in most cases the polarized signal of the target source has a similar (or smaller) level of polarization
- How do we disentangle the two effects?
- Source polarization remains the same while instrumental polarization changes as we track the source across the sky

Parallactic Angle



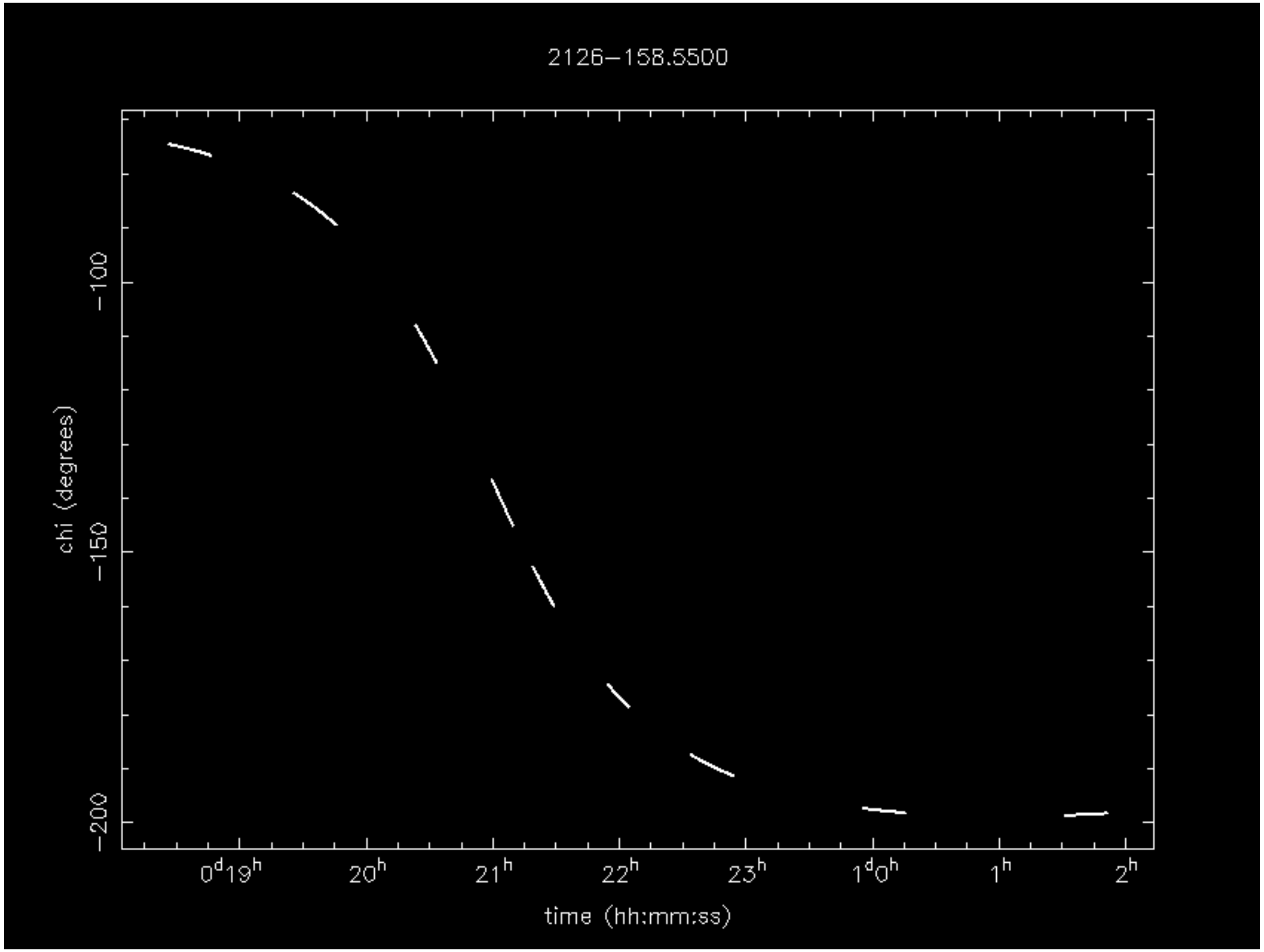
Polarization calibrator

- Your calibrator should be
  - Compact
  - Bright
  - Strongly polarized

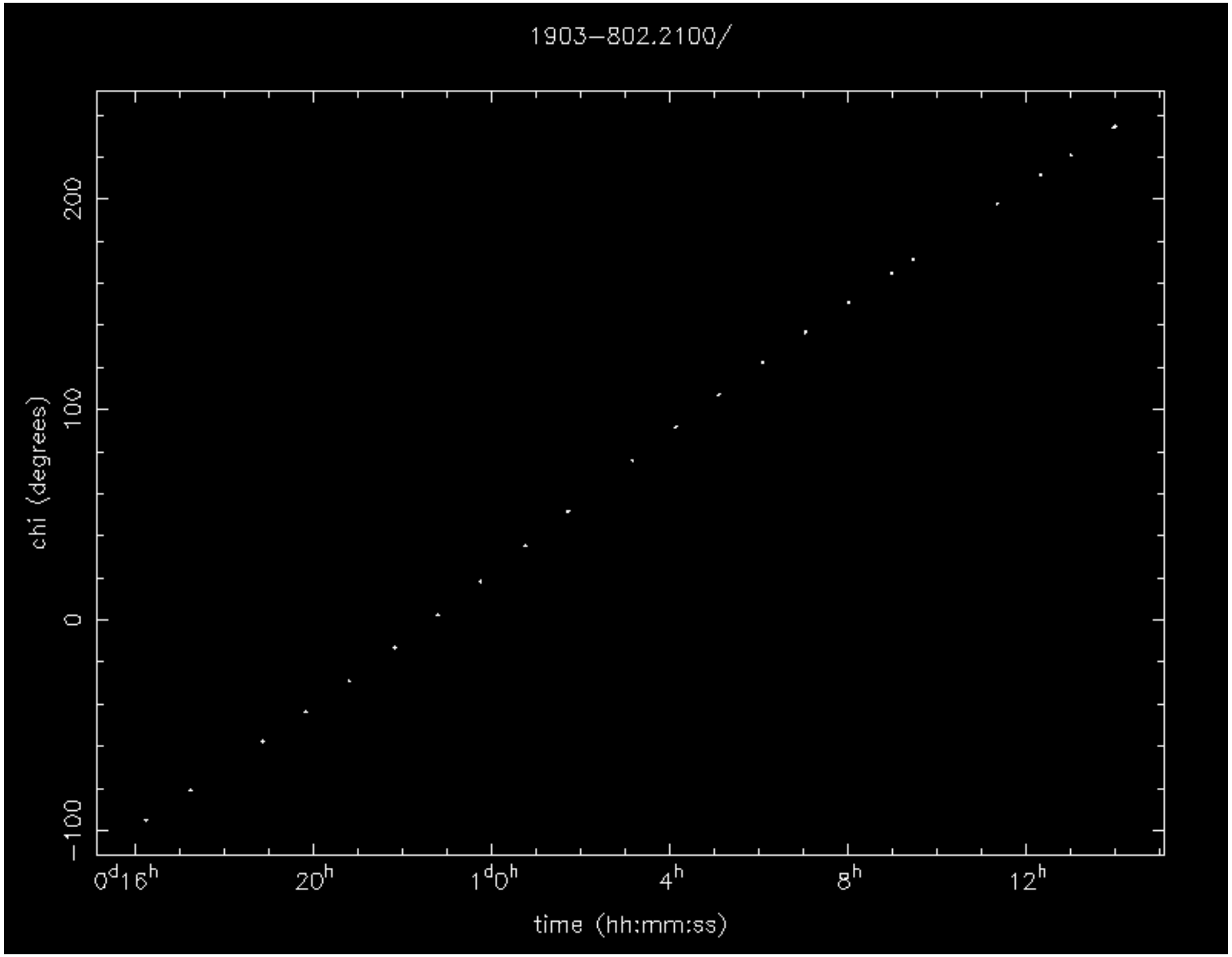


- Observe across a large range of parallactic angle (90 degrees or more)
- Parallactic angle variation depends on telescope latitude and source declination
  - At low Dec, para. angle range is small
  - At high Dec, para. angle range large but variation slow
  - Intermediate Dec good but beware of sources that pass close to the zenith since para. angle changes rapidly

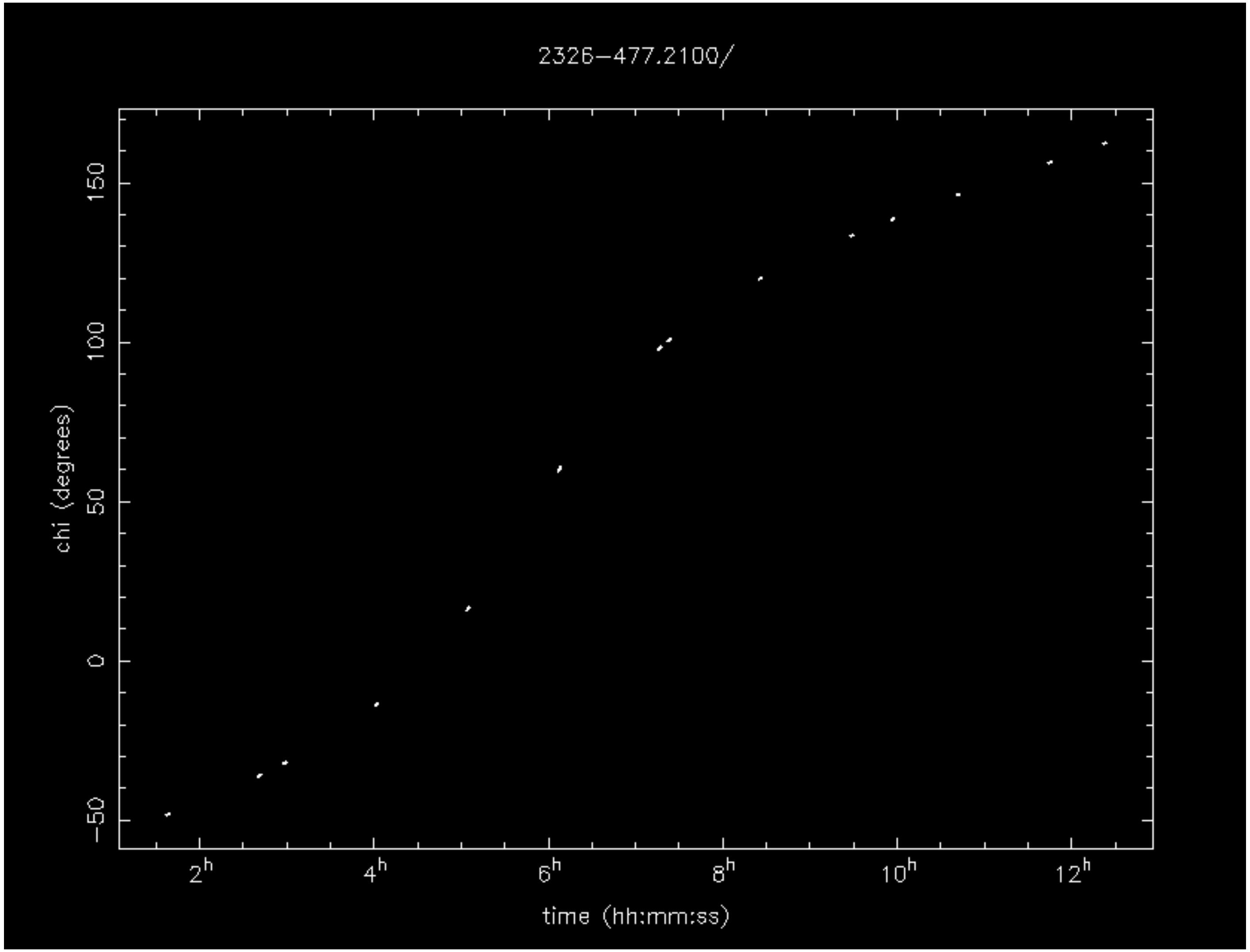
3 hrs => 100 degrees



7 hrs => 100 degrees

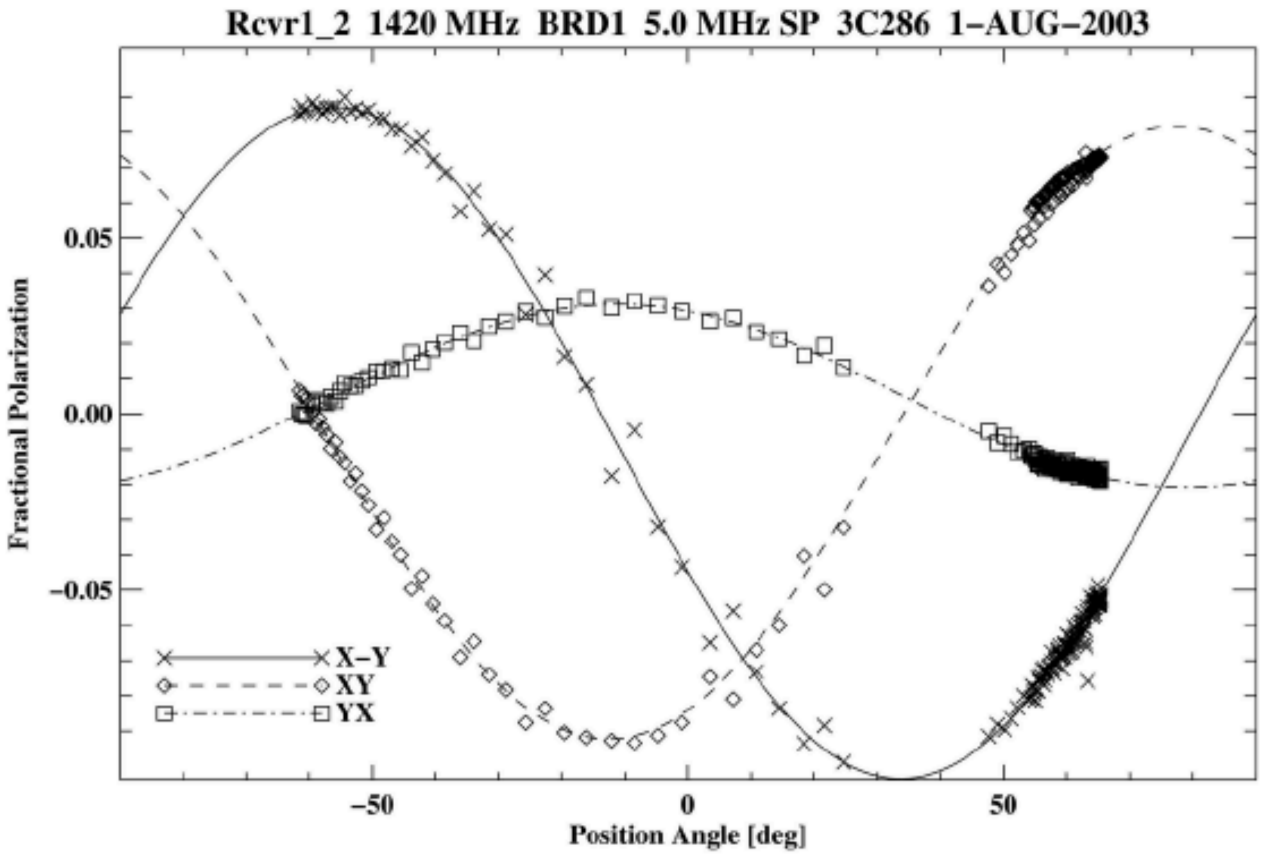


4 hrs => 100 degrees



Polarization calibration

- Observed Stokes parameters for 3C286
- Stokes V should be zero



Polarization calibration

- Instrumental effects => Mueller matrix, 16 elements but only 7 independent parameters
- Multiply the observed Stokes vectors by the inverse of the system Mueller matrix (Heiles 2002)

$$\begin{pmatrix} V_{xx} + V_{yy} \\ V_{xx} - V_{yy} \\ V_{xy^*} + V_{yx^*} \\ V_{xy^*} - V_{yx^*} \end{pmatrix} = \begin{pmatrix} m_{II} & m_{IQ} & m_{IU} & m_{IV} \\ m_{QI} & m_{QQ} & m_{QU} & m_{QV} \\ m_{UI} & m_{UQ} & m_{UU} & m_{UV} \\ m_{VI} & m_{VQ} & m_{VU} & m_{VV} \end{pmatrix} \cdot \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

- Standard calibration software packages will do this for you (eg. Miriad, AIPS)

Polarization calibration

1. Flux scale
2. I ⇔ Q leakage
3. I ⇔ U leakage
4. I ⇔ V leakage
5. Alignment => PA calibration
6. Ellipticity, Q ⇔ V
7. XY phase, U ⇔ V

- If you don't know the Stokes parameters of your calibrator then you need parallactic angle coverage

Polarization calibration

1. Flux scale
2. I ⇔ Q leakage
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7. XY phase, U ⇔ V

•Constrained using calibrator with known Stokes parameters

- If you don't know the Stokes parameters of your calibrator then you need parallactic angle coverage

Polarization calibration

1. Flux scale
2. I ⇔ Q leakage
3. I ⇔ U leakage
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•Need calibrator with known polarization angle

- If you don't know the Stokes parameters of your calibrator then you need parallactic angle coverage

Polarization calibration

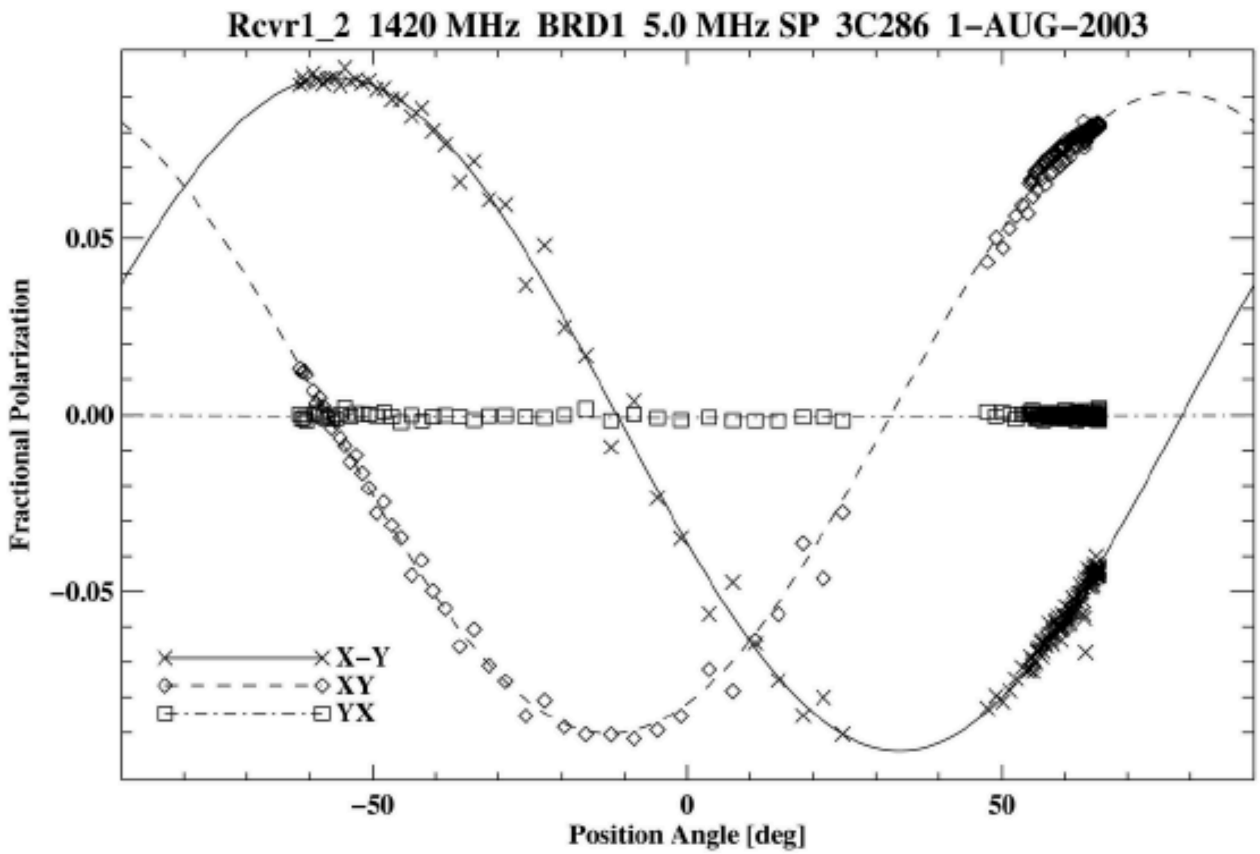
1. Flux scale
2. I ⇔ Q leakage
3. I ⇔ U leakage
4. I ⇔ V leakage
5. Alignment => PA calibration
6. Ellipticity, Q ⇔ V
7. XY phase, U ⇔ V

- Stokes V ~ 0 for most calibrators so no need to worry too much unless you require very high precision

- If you don't know the Stokes parameters of your calibrator then you need parallactic angle coverage

Polarization calibration

- After calibration
- Stokes V = 0, Stokes Q,U symmetric about zero



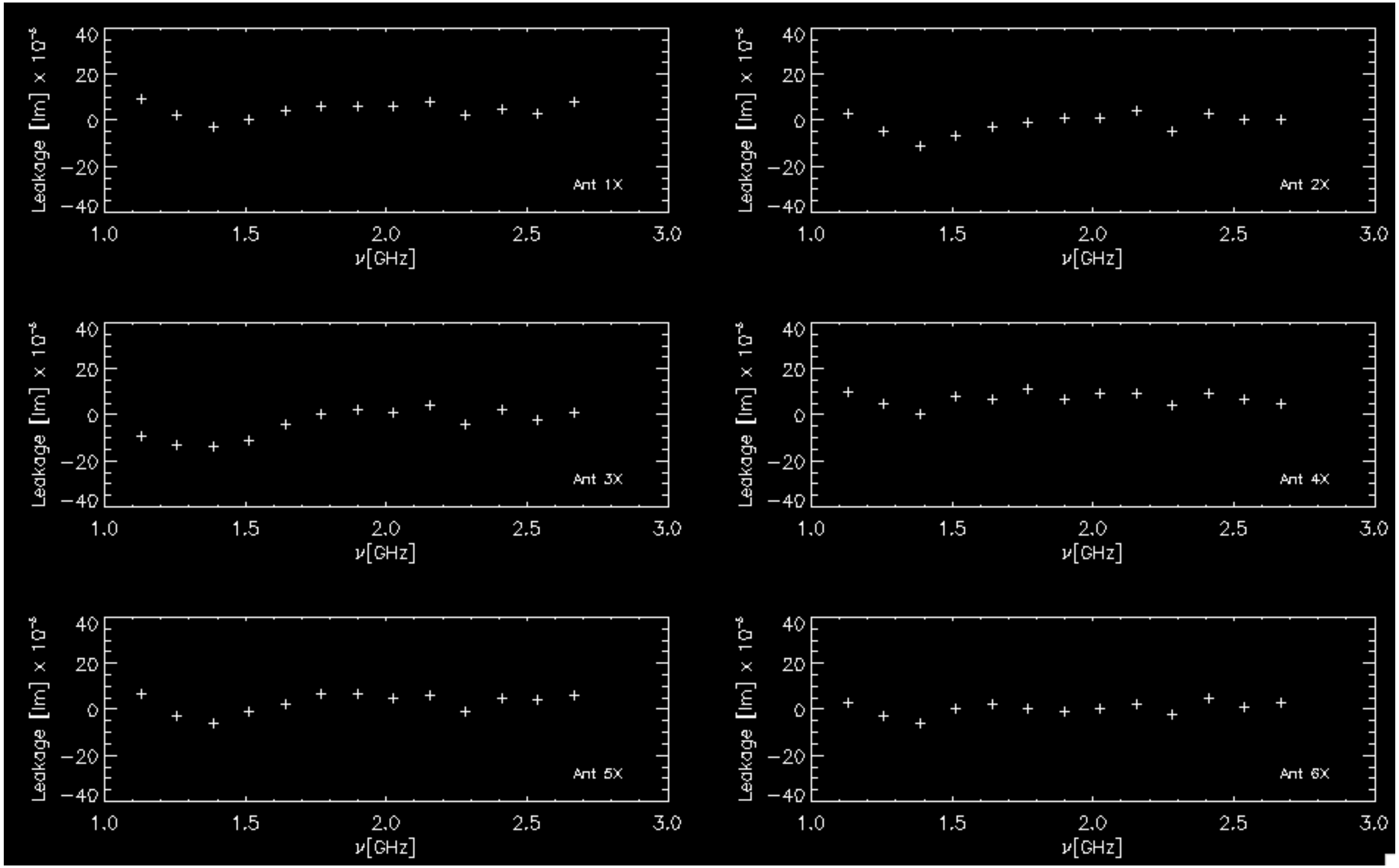
Polarization calibration

- Polarization angle correction
  - After solving for the leakages we are left with a phase offset between the two feeds on the reference antenna which means the polarization angle needs to be corrected
  - The ATCA uses an online measurement (injection of a calibration signal) to calibrate the polarization angle however other telescope (eg. EVLA) require observations of a source with known polarization angle
- Of course if you have a source whose polarization properties are known to a better accuracy than you wish to achieve on your target source then you don't need parallactic angle coverage
- Particular calibration strategy depends on the telescope you are using and the accuracy you wish to achieve

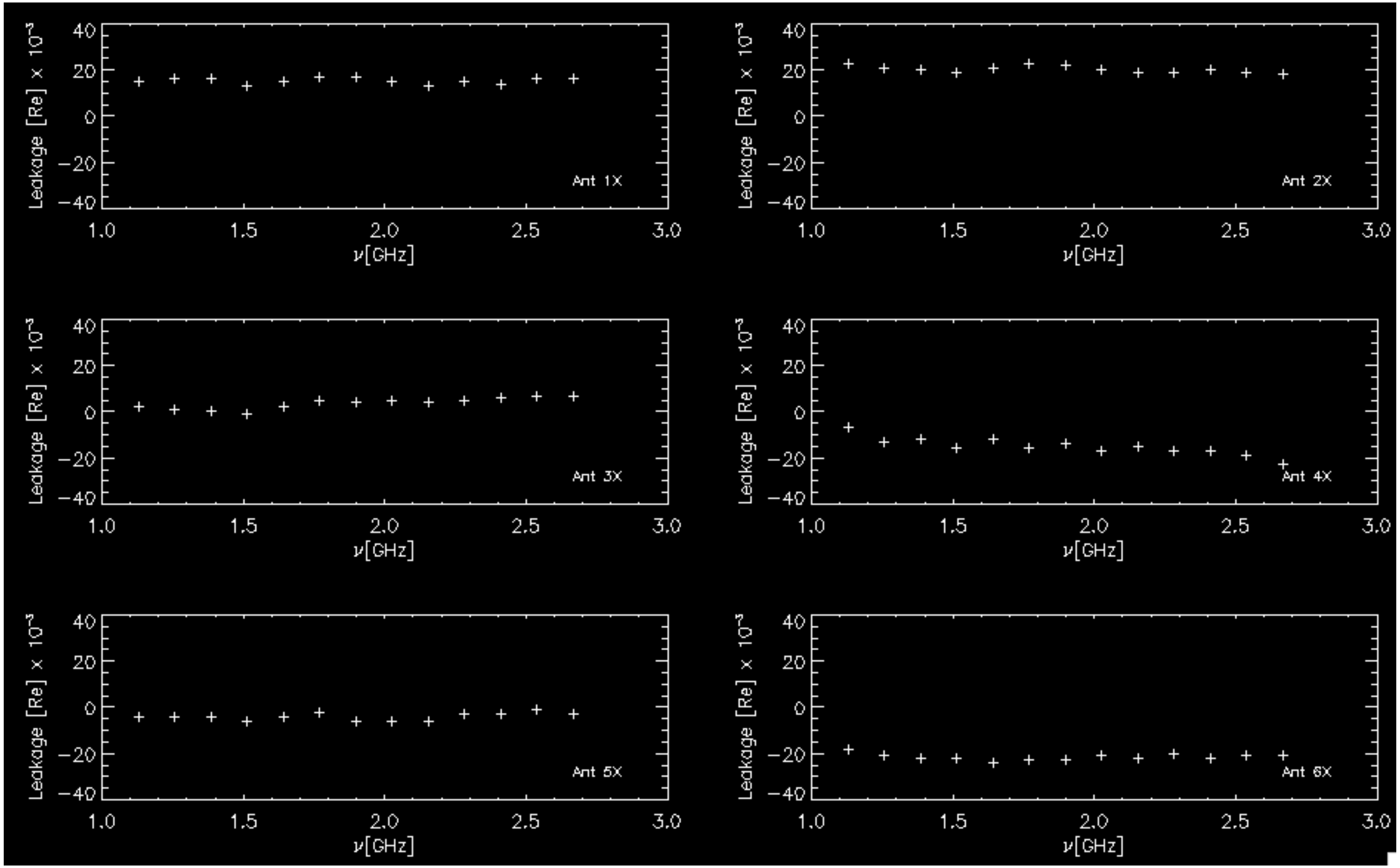
Wide bandwidth polarization calibration

- New wide bandwidth systems on EVLA and ATCA
- New challenges for polarization calibration
- Time-dependent frequency-dependent bandpass solutions and time-dependent frequency-independent gain solutions previously found using standard software packages
- Single leakage solution sufficient for narrow bandwidths
- Software needed to be modified to calculate frequency-dependent leakages
(ie. calculate solutions in frequency sub-bands)

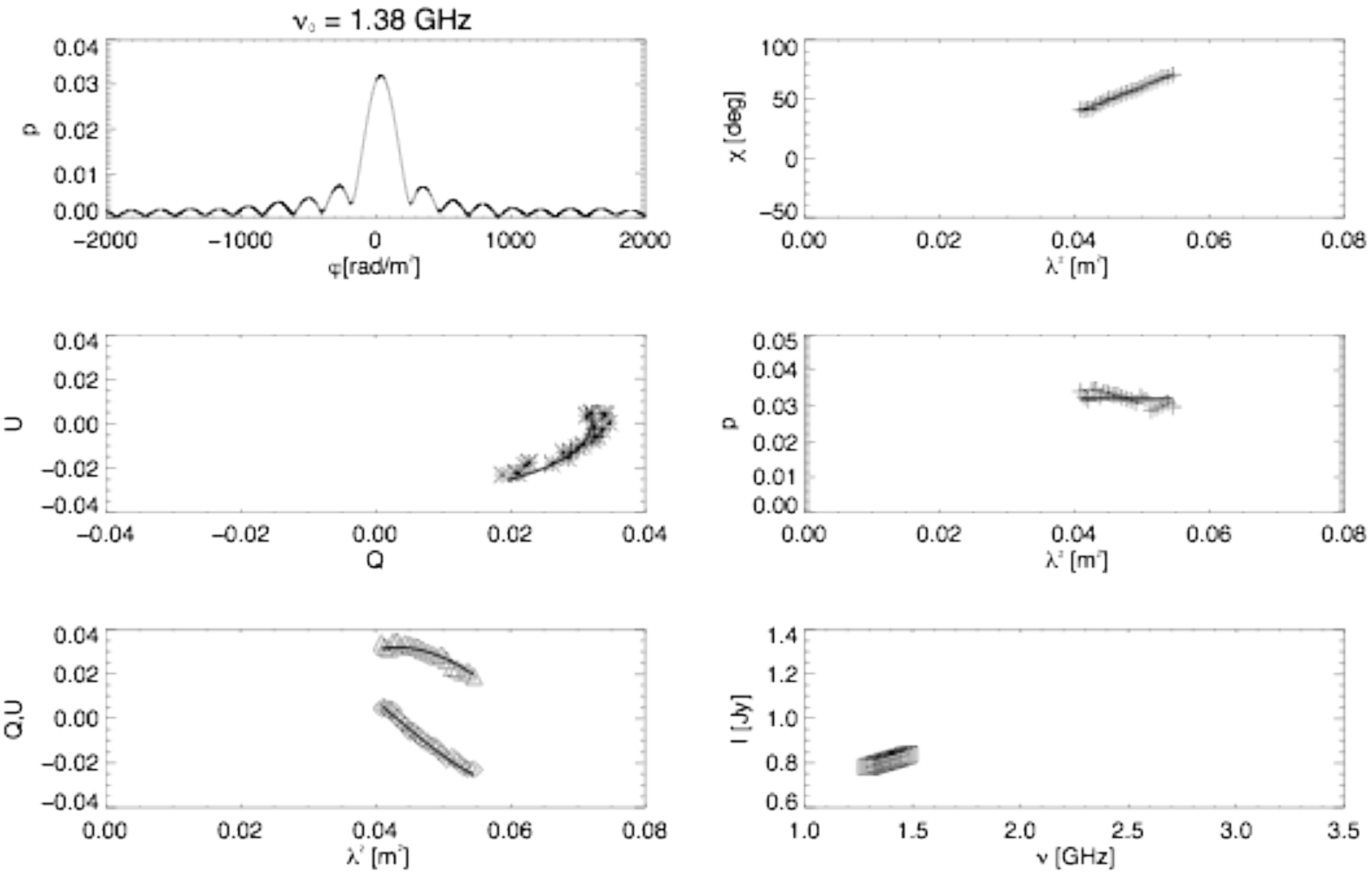
Feed ellipticity



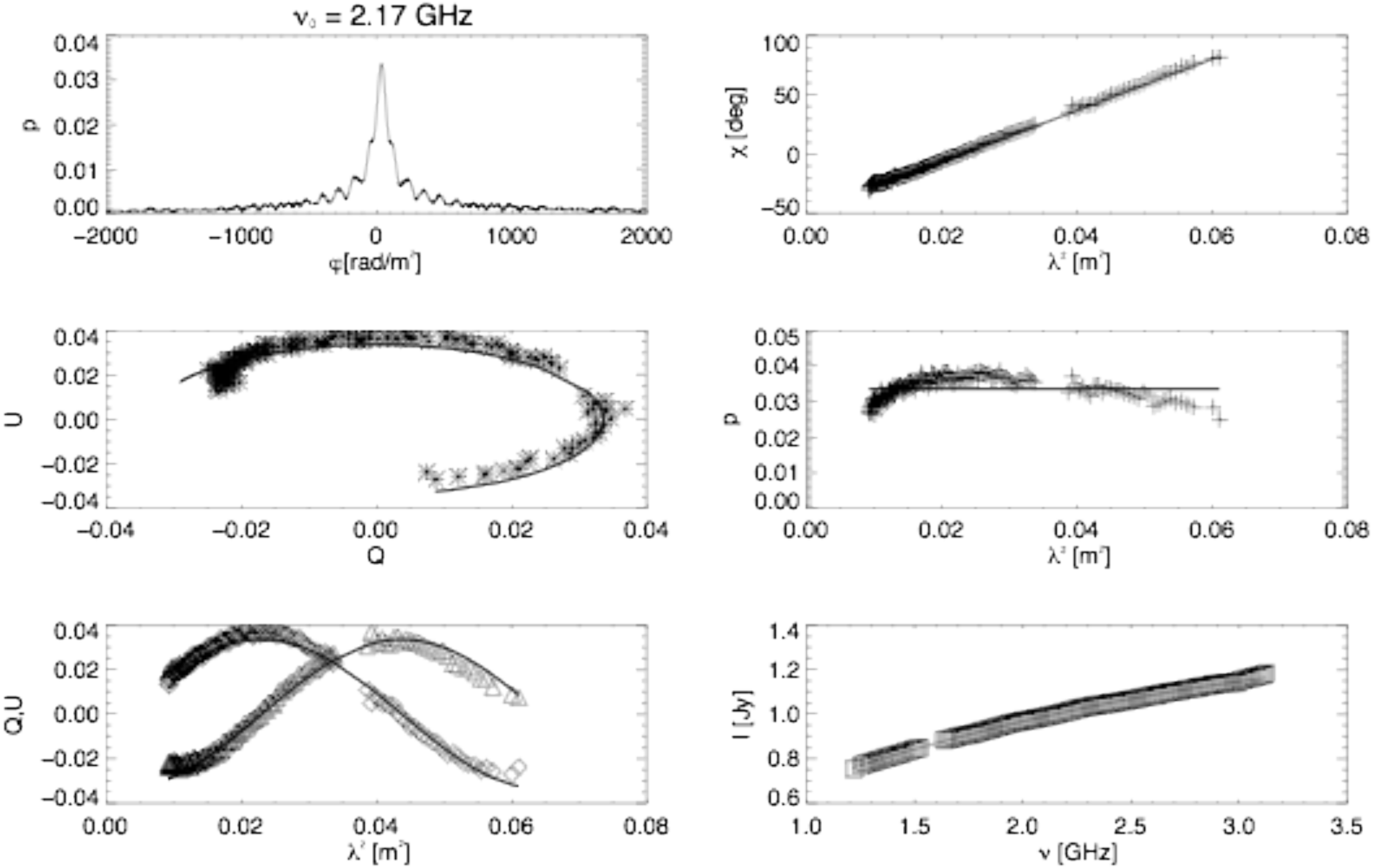
Feed misalignment



ATCA Example (200 MHz b/w)



ATCA Example (2 GHz b/w)



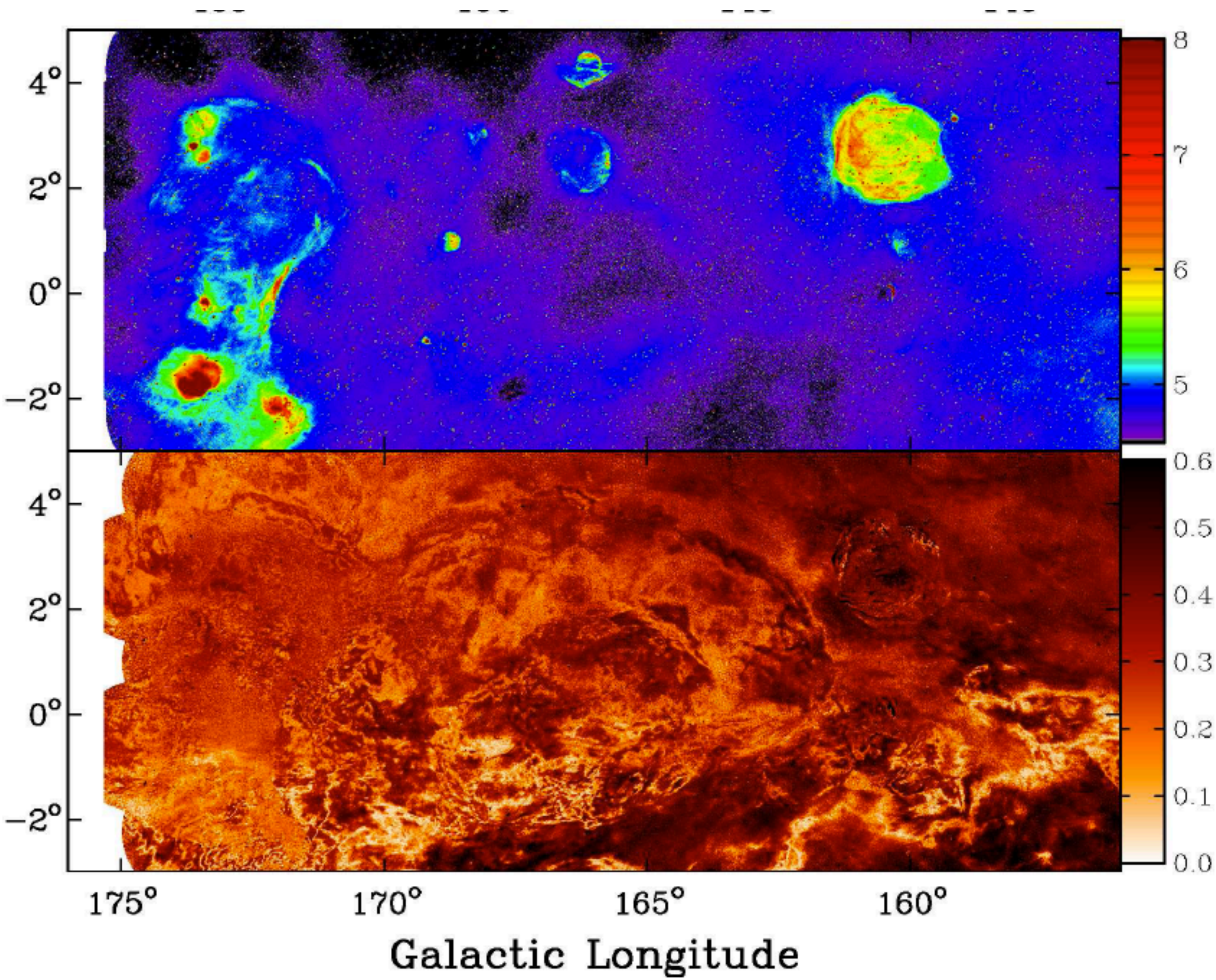
How to measure magnetic fields?

- Zeeman splitting: the splitting of a spectral line into several components in the presence of a magnetic field => compare with lab measurements to find magnetic field strength
- Circular polarization from synchrotron radiation

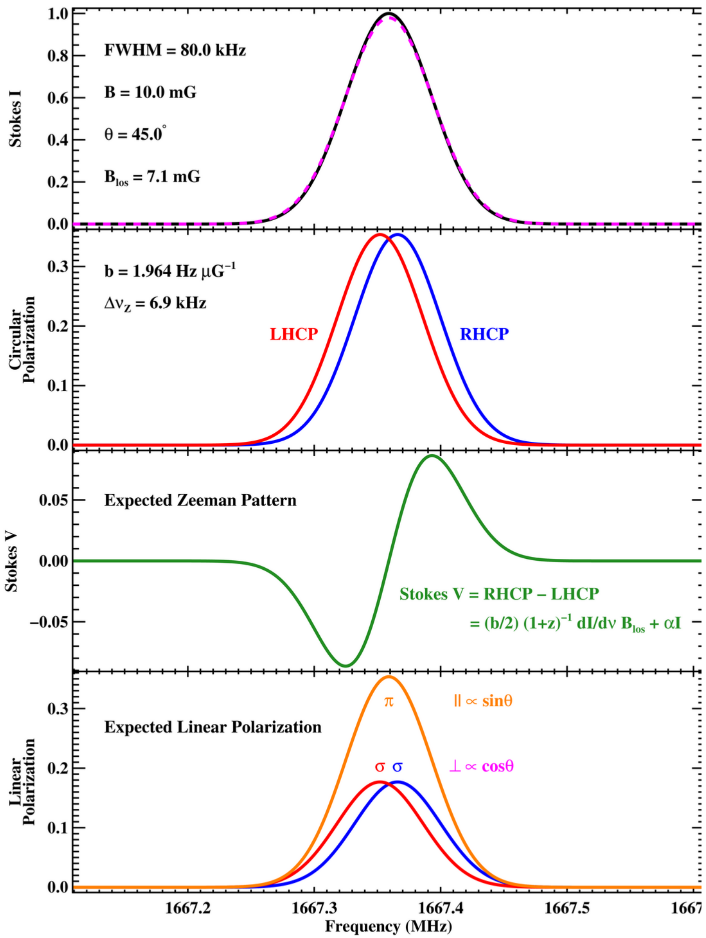
$$m_{\mathrm{c}} = \epsilon_{\alpha}^{\nu} \left(\frac{\nu_{B\perp}}{\nu} \right)^{0.5} \frac{B_{\mathrm{u,los}}}{B_{\perp}^{\mathrm{rms}}}$$

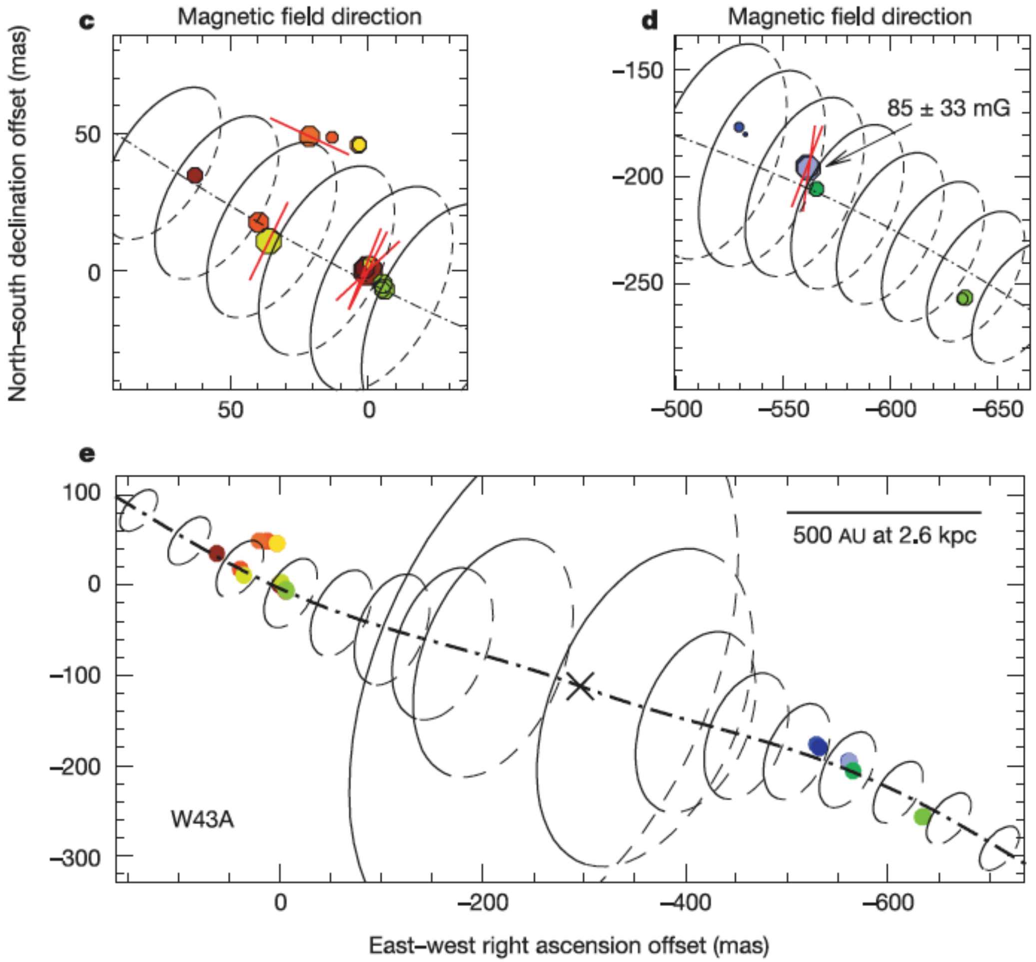
- Faraday rotation: integral along the line of sight of the electron density and line-of-sight magnetic field
- Gradient of Q and U (Gaensler et al. 2011, Nature)
  - Direct imaging of interstellar turbulence

ISM polarization structure



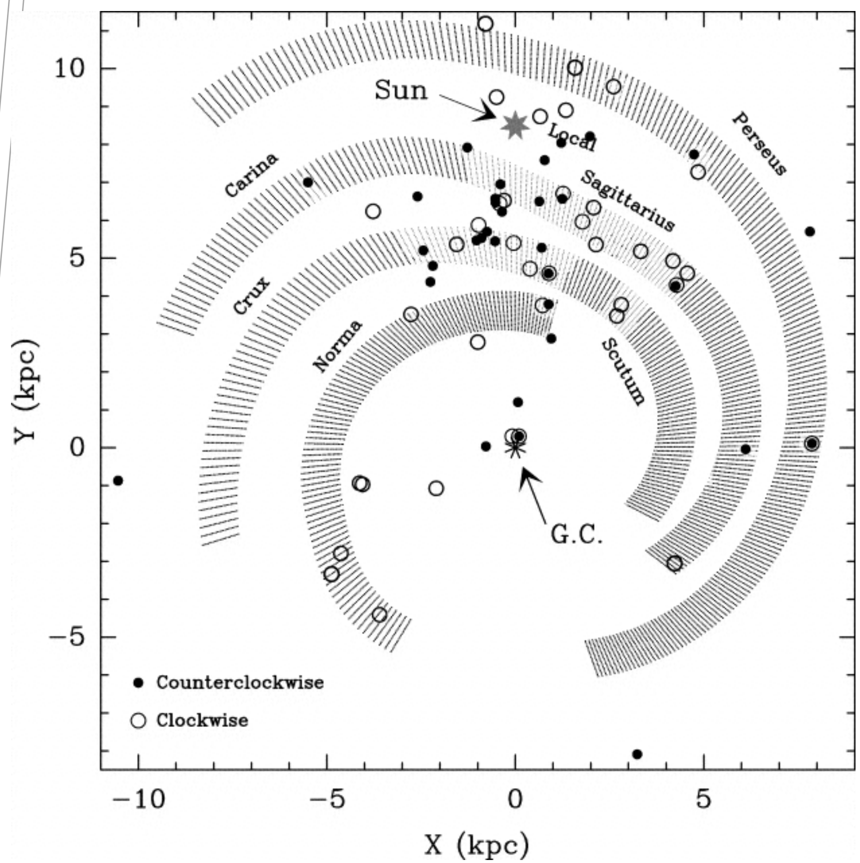
Zeeman splitting





- Vlemmings et al. (2006)

Zeeman splitting in masers

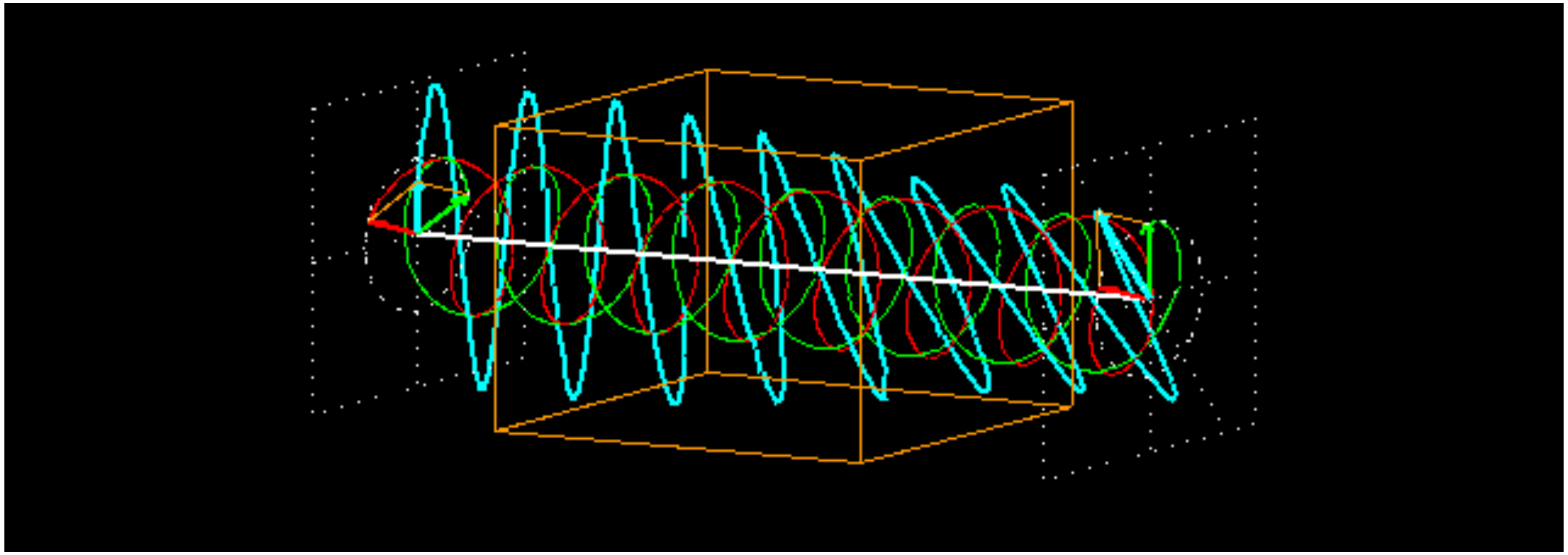


•Fish et al 2003

- Line-of-sight magnetic field directions deduced from OH maser Zeeman splitting.
- 74 star-forming regions:
  - 41 with an overall magnetic field oriented in a clockwise sense.
  - 33 with field oriented counterclockwise as viewed from above the Galactic center.
- Field consistency within 2-kpc of Sun.

Faraday rotation

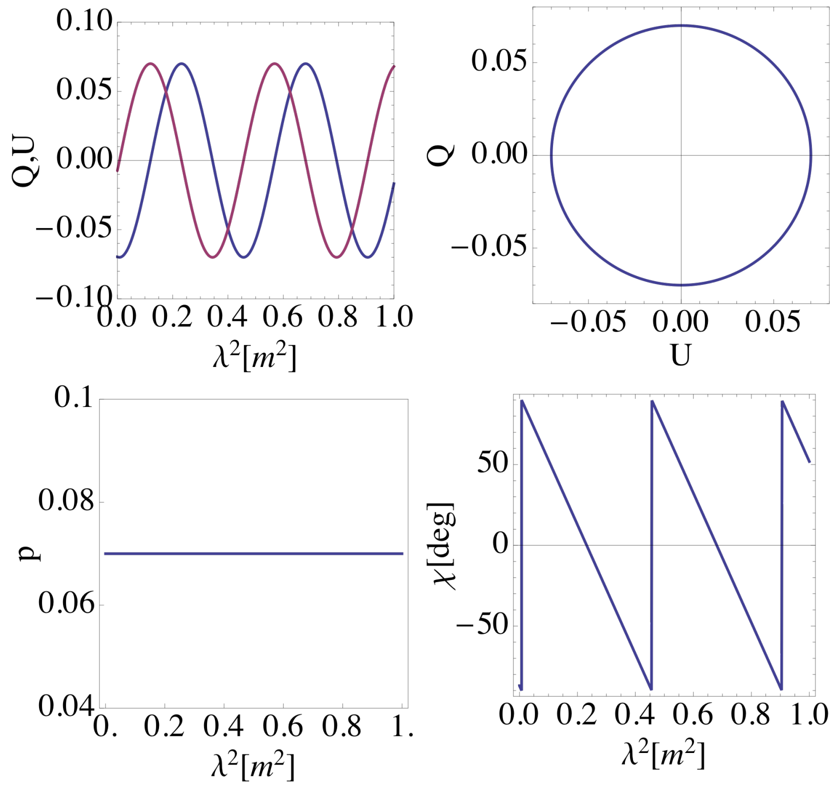
- Rotation of the plane of polarization as it propagates through a region with free electrons and a magnetic field

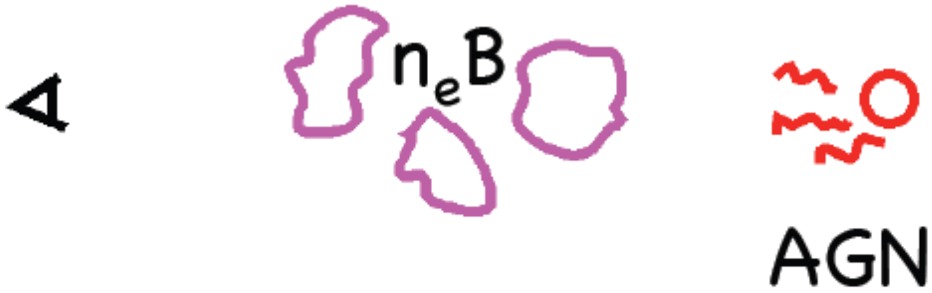


$$\chi_{\rm obs} = \chi_0 + \frac{e^3\lambda^2}{8\pi^2\varepsilon_0 m^2 c^3}\int n\boldsymbol{B}\cdot\mathbf{d}\boldsymbol{l} \equiv \chi_0 + \mathrm{RM}\lambda^2$$

Faraday rotation

- Background polarized AGN





$$P = Q + iU$$

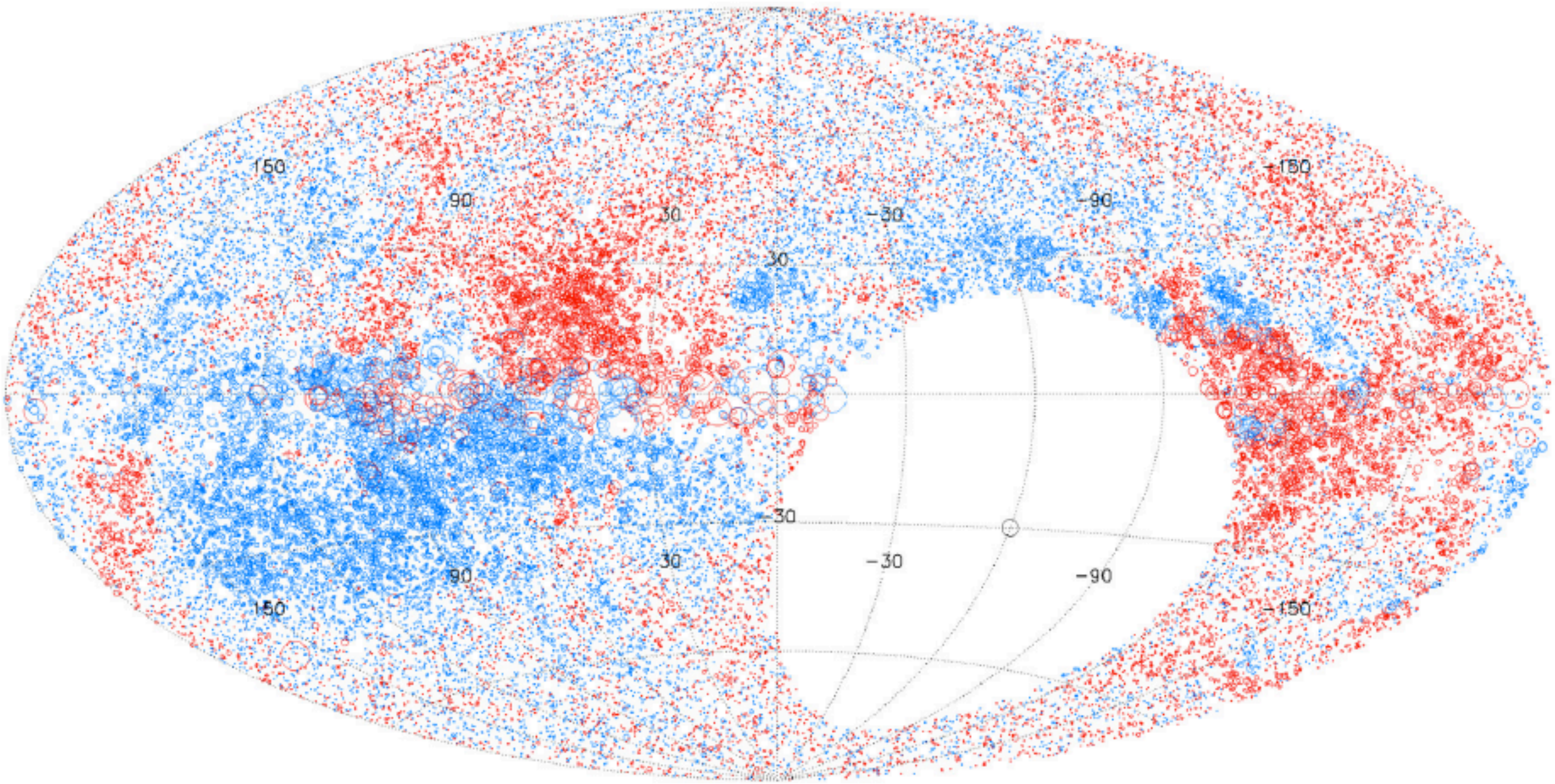
$$P = pe^{2i\chi}$$

$$P = p_0 e^{2i(\chi_0 + \mathrm{RM}\lambda^2)}$$

$$\mathrm{RM} = -7 \text{ rad m}^{-2}$$
$$p_0 = 7\ \%$$
$$\chi_0 = 93^\circ$$

Science Drivers

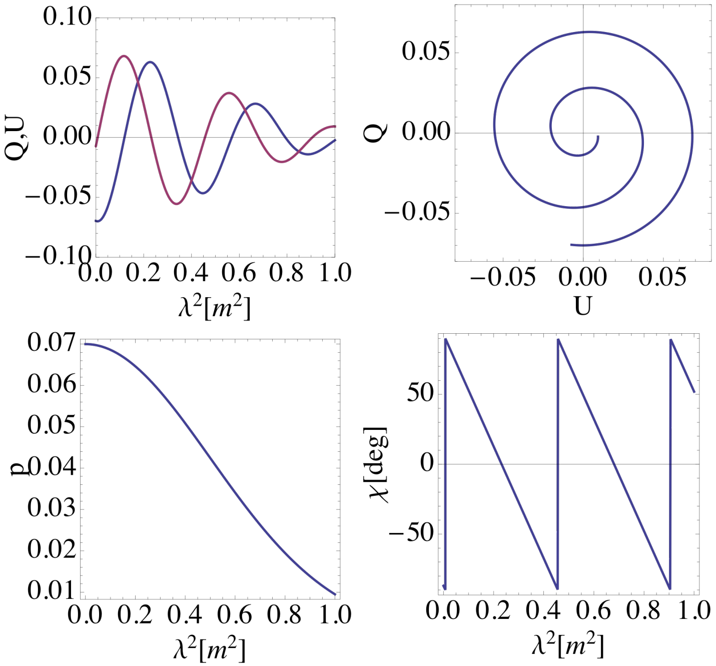
- Taylor et al. (2009): 37,543 RMs (1.365 & 1.435 GHz)

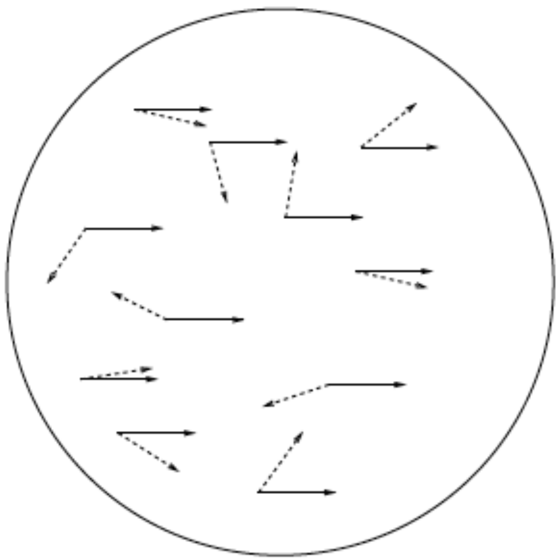


Depolarization mechanisms

- External Faraday Dispersion

$$P = p_0 e^{-2\sigma_{\mathrm{RM}}^2 \lambda^4} e^{2i(\Psi_0 + \mathrm{RM}\lambda^2)}$$



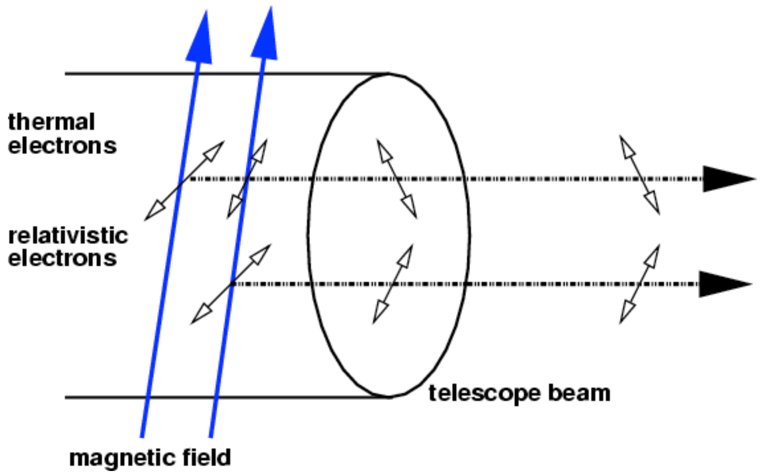


Original polarization vectors

Polarization vectors after Faraday rotation due to passage through an inhomogeneous region of magnetized plasma

Since each polarization vector is rotated by a different amount, the integrated total polarization observed in the region within the circle decreases –– this is called depolarization.

Depolarization mechanisms



- Differential Faraday Rotation

$$P = p_0 \frac{\sin R\lambda^2}{R\lambda^2} e^{2i(\chi_0 + \frac{1}{2} R\lambda^2)}$$

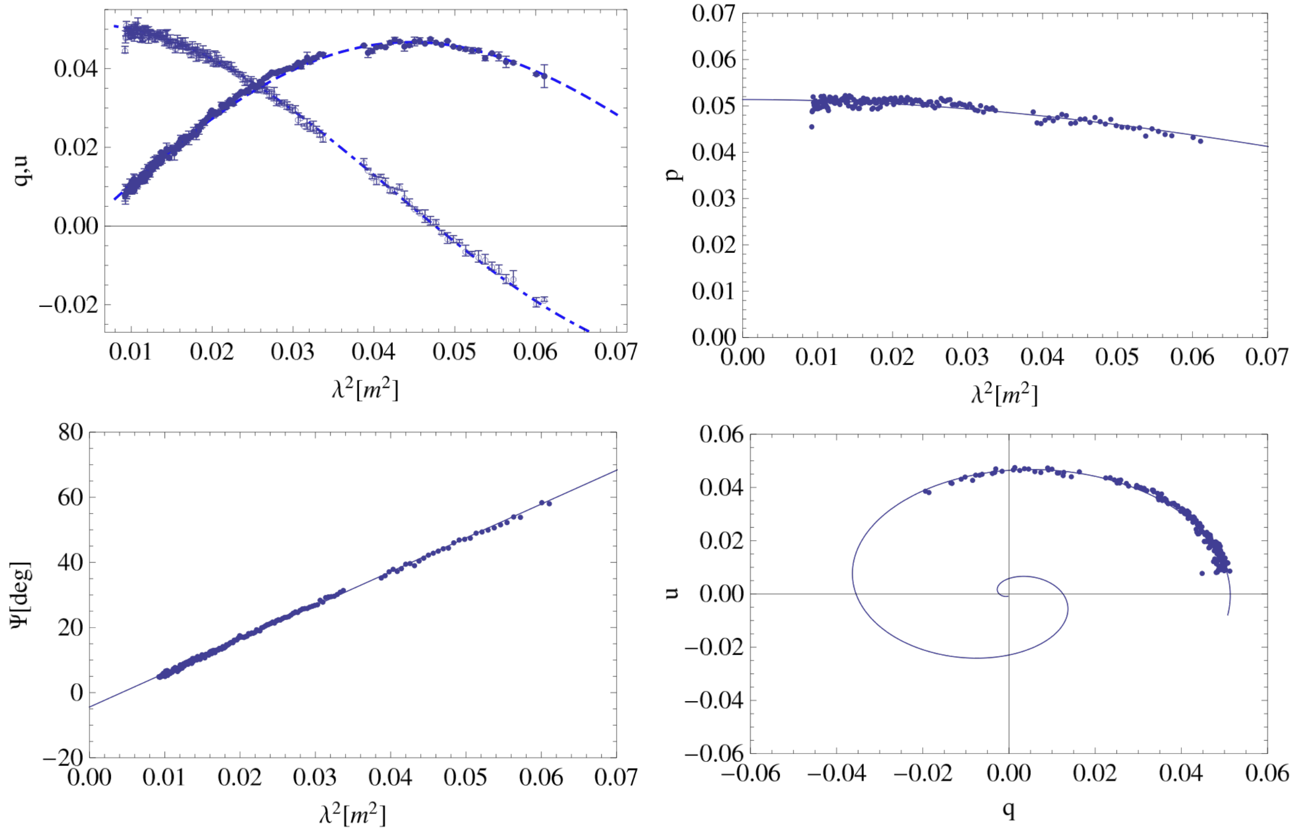
- Depolarization from interfering components

$$P = p_1 e^{2i(\chi_{01} + RM1\lambda^2)} + p_2 e^{2i(\chi_{02} + RM2\lambda^2)}$$

ATCA results

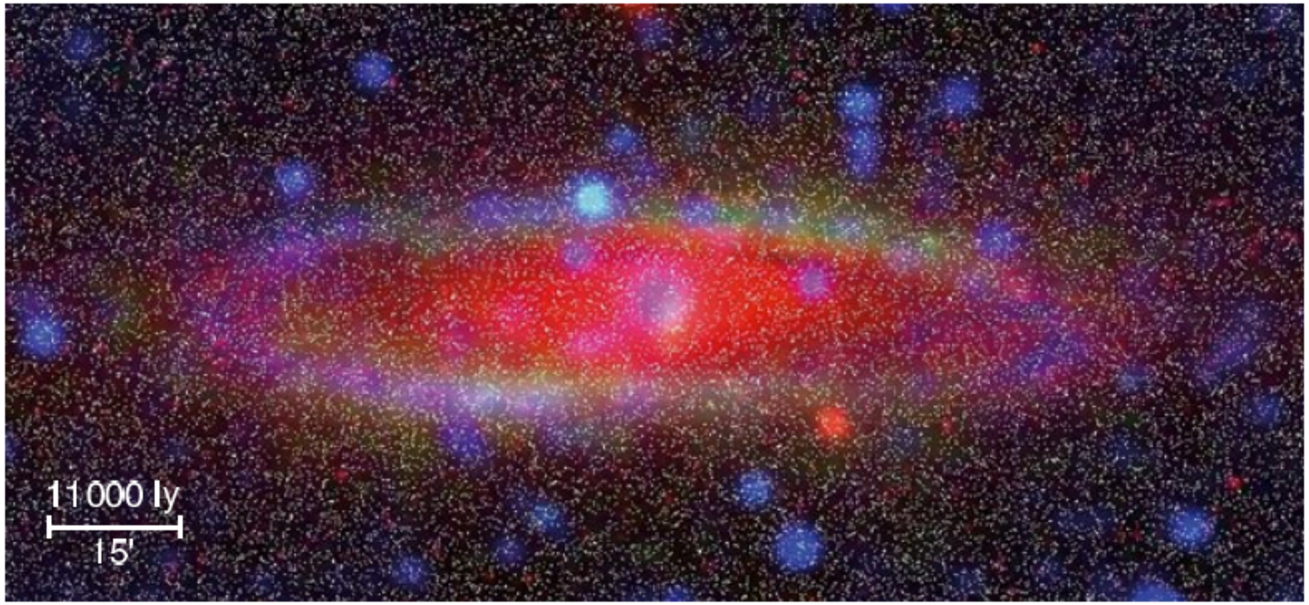
$$P = p_0 e^{2i(\chi_0 + RM\lambda^2)} e^{-2\sigma_{\mathrm{RM}}\lambda^4}$$

$$\mathrm{RM} = 18.4 \pm 0.2 \text{ rad m}^{-2}$$
$$p_0 = 5.1 \pm 0.1\%$$
$$\chi_0 = -4.6 \pm 0.4^\circ$$
$$\sigma_{\mathrm{RM}} = 4.7 \pm 0.3 \text{ rad m}^{-2}$$



Cosmic Magnetism

- Origin & Evolution: key science driver for SKA
- Using background sources as probes of the interstellar and intergalactic magneto-ionic medium
- “RM grid”: workhorse of ASKAP/SKA science

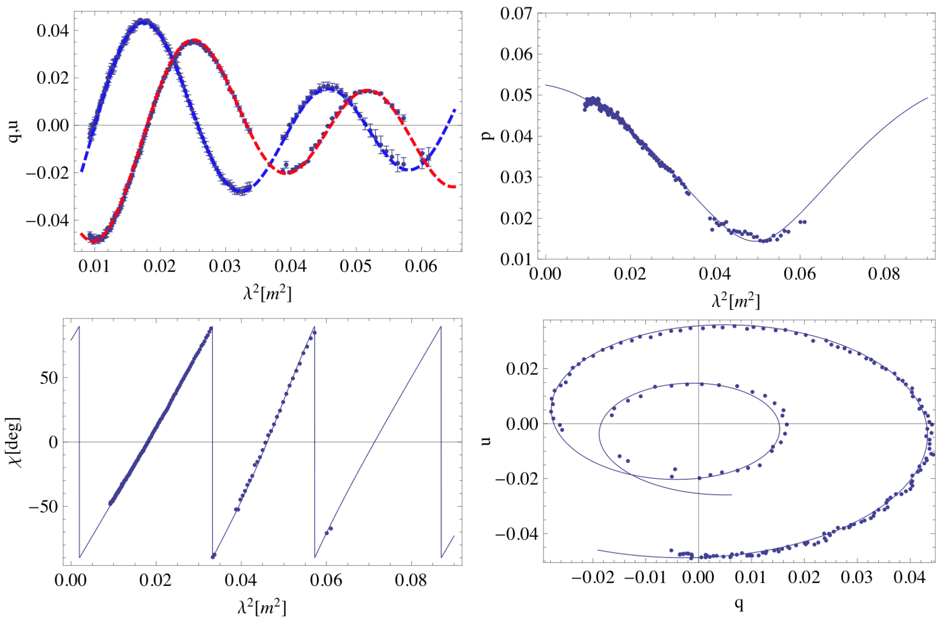


- Gaensler (2009)

Results: PKS B1610-771

- Steepening of dependence of polarization angle with wavelength squared as well as "re-polarization" at longer wavelengths => 2 RM components

$$P = p_{01} e^{2i(\chi_{01} + \mathrm{RM1}\lambda^2)} + p_{02} e^{2i(\chi_{02} + \mathrm{RM2}\lambda^2)}$$



$$\mathrm{RM1} = 108.2 \pm 0.3 \text{ rad m}^{-2}$$
$$\mathrm{RM2} = 78.8 \pm 0.5 \text{ rad m}^{-2}$$
$$p_{01} = 3.4 \pm 0.1\%$$
$$p_{02} = 1.8 \pm 0.1\%$$
$$\chi_{01} = 81.8 \pm 1.1^\circ$$
$$\chi_{02} = 73.6 \pm 0.6^\circ$$


Thank You
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