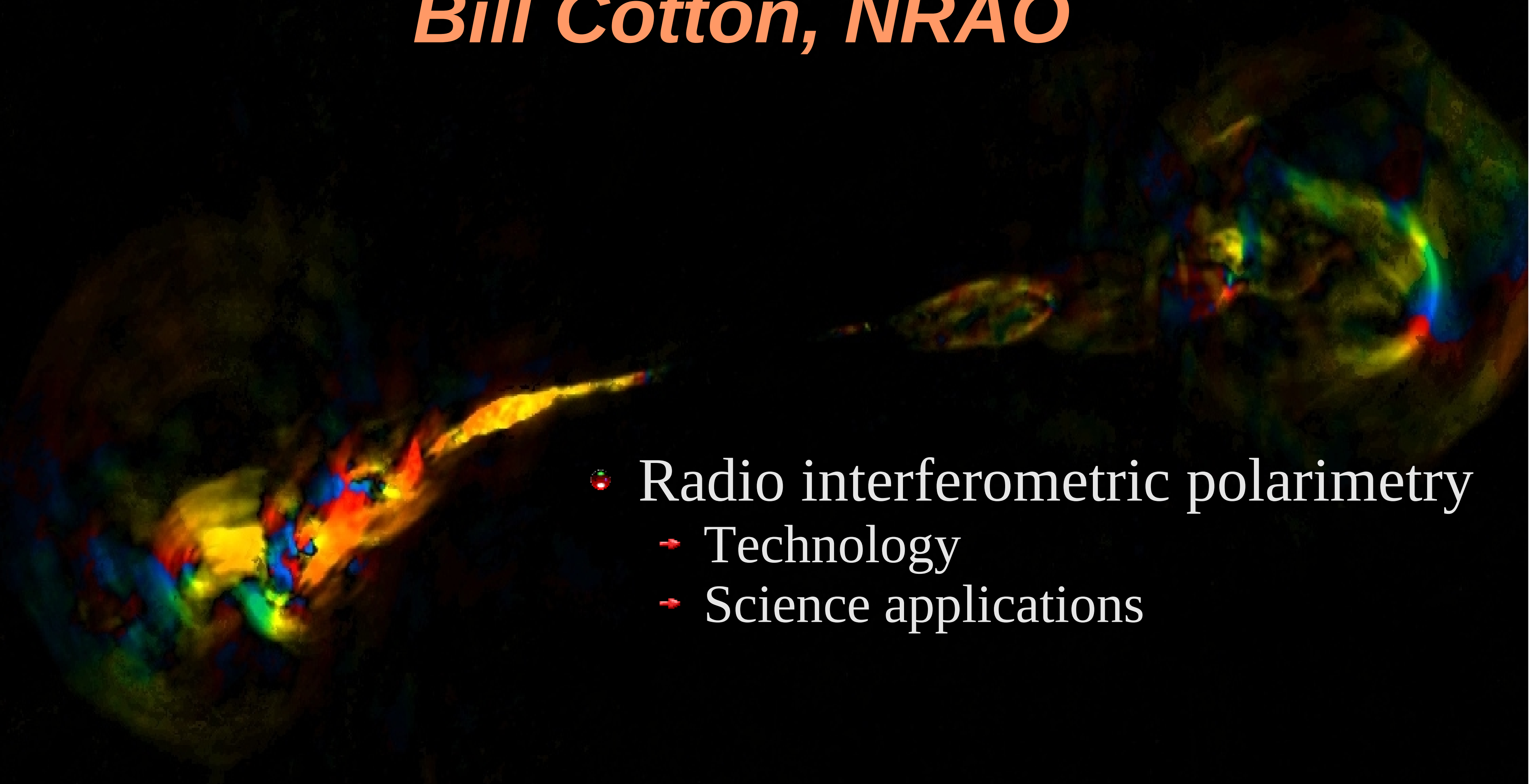
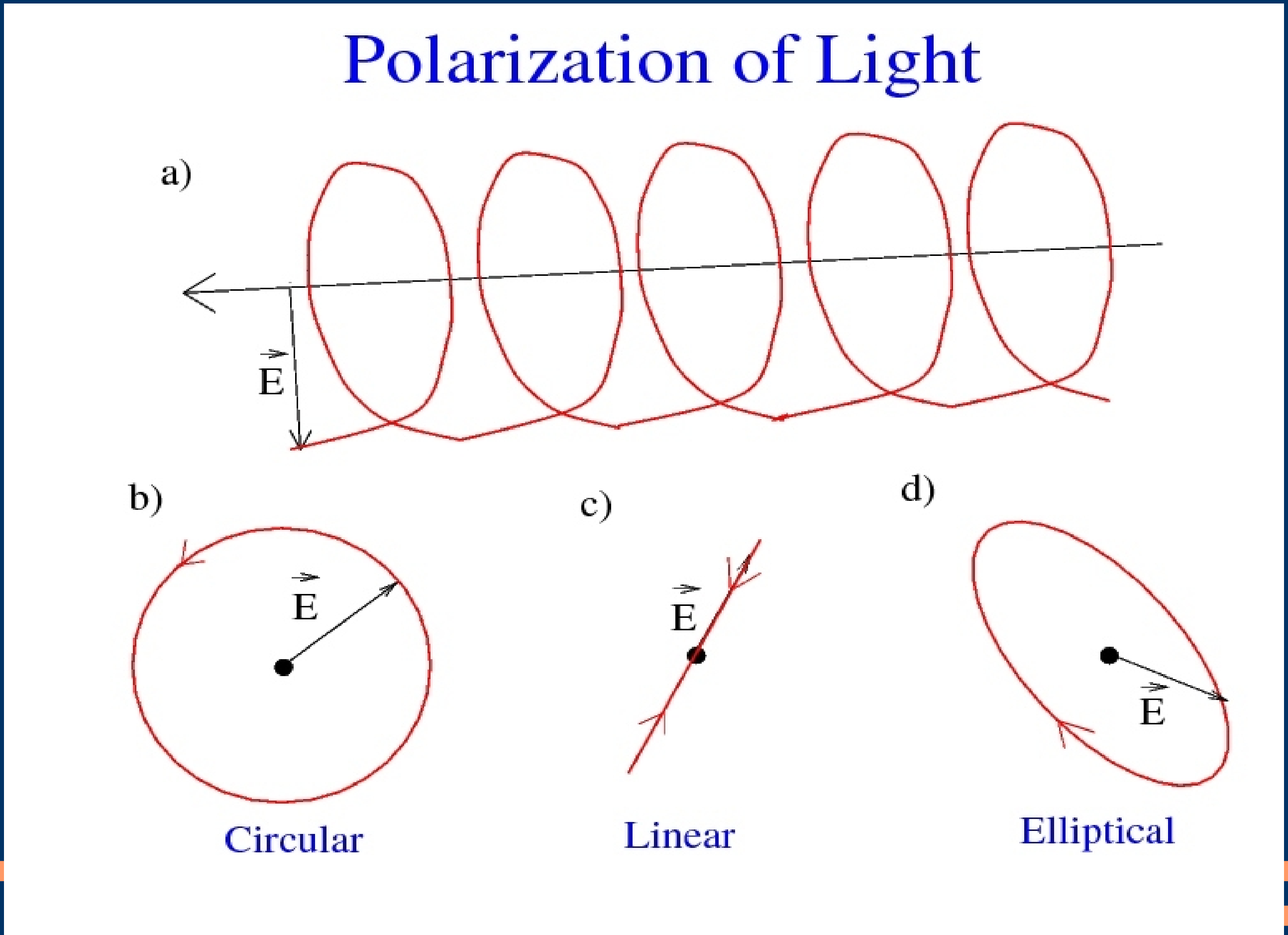
Radio Polarimetry
Bill Cotton, NRAO



- Radio interferometric polarimetry
  - Technology
  - Science applications

What is polarization?

- Light is oscillating E and B fields
- “Polarization is how the wave oscillates



Polarization State

- Light from incoherent source at most partially polarized.
- Multiple polarization states but some may dominate over others
- Describe partially polarized light by Stokes parameters:
  - I = Total intensity
  - Q + jU = Linear polarization
  - V = circular polarization

Interferometer Sensitivity

- Phase sensitive detectors measure a single polarization state.
- Orthogonal detectors needed to fully measure field
  - Right and left hand circular
  - Crossed linear
- All four correlation products needed from interferometer

Relations of Stokes Parameters to Correlations to 1st order

Circular feed correlations:

$$v_{rr} = \tfrac{1}{2} g_{ip} g^*_{kp} (I + V),$$
$$v_{rl} = \tfrac{1}{2} g_{ip} g^*_{kq} ((d_{ip} - d^*_{kq}) I + \ e^{-2j\chi} (Q + jU)),$$
$$v_{lr} = \tfrac{1}{2} g_{iq} g^*_{kp} ((d^*_{kp} - d_{iq}) I + \ e^{2j\chi} (Q - jU)),$$
$$v_{ll} = \tfrac{1}{2} g_{iq} g^*_{kq} (I - V).$$

χ is parallactic angle,
gs are instrumental complex gains,
ds are polarization "leakage" terms

Relations of Stokes Parameters to Correlations to 1st order

Linear feed correlations:

$$v_{pp} = \tfrac{1}{2} g_{ip} g^*_{kp} (I + Q\ \cos 2\chi + U\ \sin 2\chi),$$
$$v_{pq} = \tfrac{1}{2} g_{ip} g^*_{kq} ((d_{ip} - d^*_{kq}) I - Q\ \sin 2\chi + U\ \cos 2\chi + jV),$$
$$v_{qp} = \tfrac{1}{2} g_{iq} g^*_{kp} ((d^*_{kp} - d_{iq}) I - Q\ \sin 2\chi + U\ \cos 2\chi - jV),$$
$$v_{qq} = \tfrac{1}{2} g_{iq} g^*_{kq} (I - Q\ \cos 2\chi - U\ \sin 2\chi),$$

χ is parallactic angle,
gs are instrumental complex gains,
ds are polarization "leakage" terms

Interferometric response

- Response varies with parallactic angle
- V_{rr} and V_{ll} insensitive to linear polarization to first order.

Full Antenna Response

- Describe effects via 2 x 2 complex “Jones” matrices

$$\mathbf{E}' = \mathbf{J}\,\mathbf{E}$$

***E* is true electric field vector**
***E'* is measured field vector**
***J* is Jones matrix**

$$\mathbf{J_i} = \begin{pmatrix} \mathbf{A} & 0 \\ 0 & \mathbf{A}* \end{pmatrix} \begin{pmatrix} e^{-j\chi_i} & 0 \\ 0 & e^{j\chi_i} \end{pmatrix} \begin{pmatrix} \mathbf{g_{p,i}} & 0 \\ 0 & \mathbf{g_{q,i}} \end{pmatrix} \begin{pmatrix} 1 & \mathbf{d_{p,i}} \\ \mathbf{d_{q,i}} & 1 \end{pmatrix}$$

where A is complex atmospheric gain

Full Interferometer Response

- Interferometer ik response is outer product of antenna responses

$$\mathbf{V}_{\mathbf{ik}}^{\mathbf{obs}} = \mathbf{E}'_{\mathbf{i}} \otimes \mathbf{E}'^{*}_{\mathbf{k}} = (\mathbf{J}_{\mathbf{i}} \otimes \mathbf{J}^{*}_{\mathbf{k}})(\mathbf{E}_{\mathbf{i}} \otimes \mathbf{E}^{*}_{\mathbf{k}})$$

Calibration considerations

- Parallel hand calibration using circular feeds can ignore calibrator linear polarization
- Linear feed calibration cannot.
- Calibrators typically 1 – 10 % linear polarized

Polarization Calibration Considerations

- Instrumental and calibrator polarizations typically unknown *a priori*.
- Instrumental and source polarizations affected differently by parallactic angle
- Observations with a range of parallactic angle can separate.

Feed parameterization

- Feed response can be parameterized as:
  - Desired polarization plus “leakage”

$$\mathbf{J_i} = \begin{pmatrix} 1 & \mathbf{d_{p,i}} \\ \mathbf{d_{q,i}} & 1 \end{pmatrix}$$

  - Ellipticity and orientation of detected polarization

$$\mathbf{J_i} = \begin{vmatrix} cos(\frac{\pi}{4} + \theta_p)e^{-j(\phi_p)} & sin(\frac{\pi}{4} + \theta_p)e^{j(\phi_p)} \\ sin(\frac{\pi}{4} - \theta_q)e^{j(\phi_q)} & cos(\frac{\pi}{4} - \theta_q)e^{-j(\phi_q)} \end{vmatrix}$$

Where ϴ is ellipticity, φ is orientation.

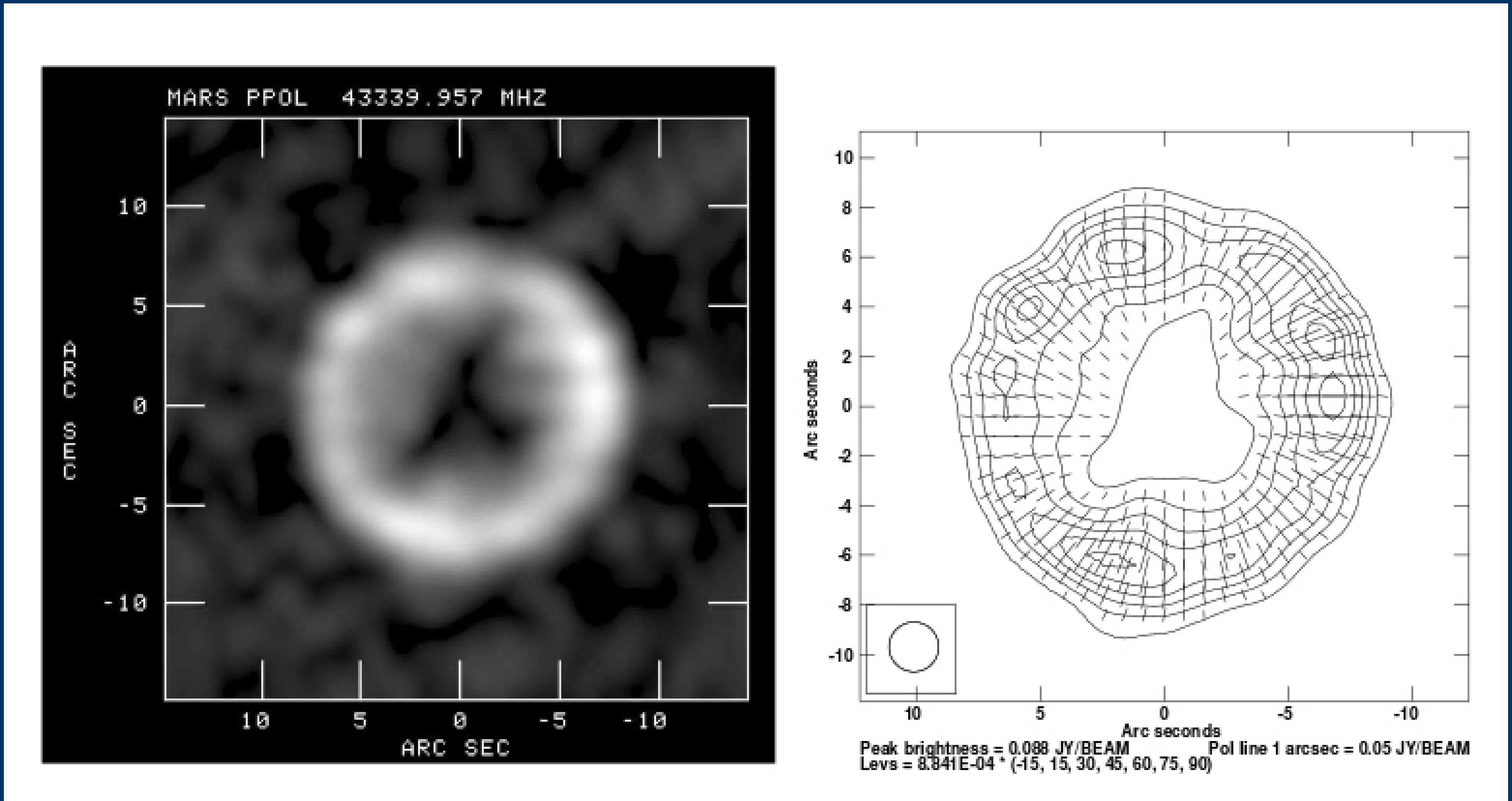
Feed parameterization, cont'd

- "Leakage" terms can use 1st order approximation
- Ellipticity/orientation must use nonlinear fit
- However, orientation can be (approximately) measured for linear feeds

EVPA calibration

- For circular feeds need source of known polarization
- For linear feeds can get approximate calibration from nominal feed orientation
- For VLBI always need external measurement of a calibrator
- $\lambda > 1$ cm use standard calibrators, 3C286, 3C48...
- $\Lambda <\sim 1$cm few good calibrators, can use radial pattern from planetary disks.

Planetary polarization pattern



Mars with VLA, Perley & Butler, 2013

Relative v. Absolute calibration (work in progress)

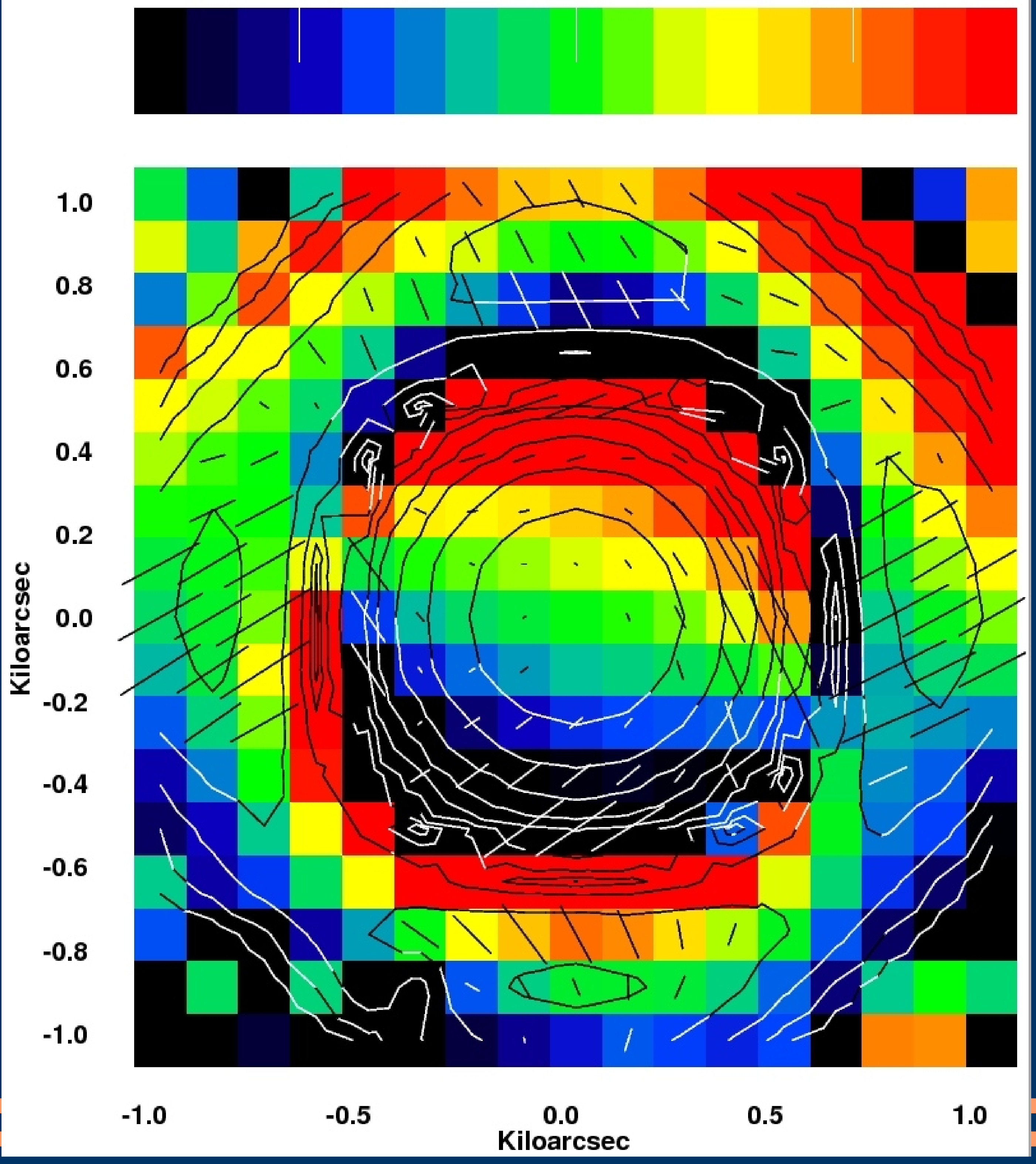
- For short baselines poln. eqn. are degenerate to first order.
- For first order solutions must fix values for one feed.
- Approximate (relative) calibration may limit dynamic range
- Not degenerate for VLBI, parallactic angles are different.
- Full nonlinear fit can break degeneracy using higher order terms

Beam Polarization

- Instrumental polarization varies across antenna pattern.

EVLA Beam

Contours = Stokes I
Vectors = Lin. Poln.
Color = circular poln



Science Applications: Emission Processes

- Thermal emission generally unpolarized
- Nonthermal emission usually polarized.
- Synchtotron:
  - Highly relativistic electrons in magnetic field
  - up to 60-70% linear
  - <<1% circular
  - Very common in AGN, SNR
  - Polarization aligned with magnetic field
  - Optically thin, E vector ⊥ to B field
  - Optically thick, E vector ‖ to B field

Emission processes, cont'd

- Cyclotron
  - Mildly relativistic charged particles in magnetic field
  - Frequently strong circular polarization
  - Sometimes seen in solar and stellar flares
- Masers
  - Frequently strongly polarized but poorly understood.

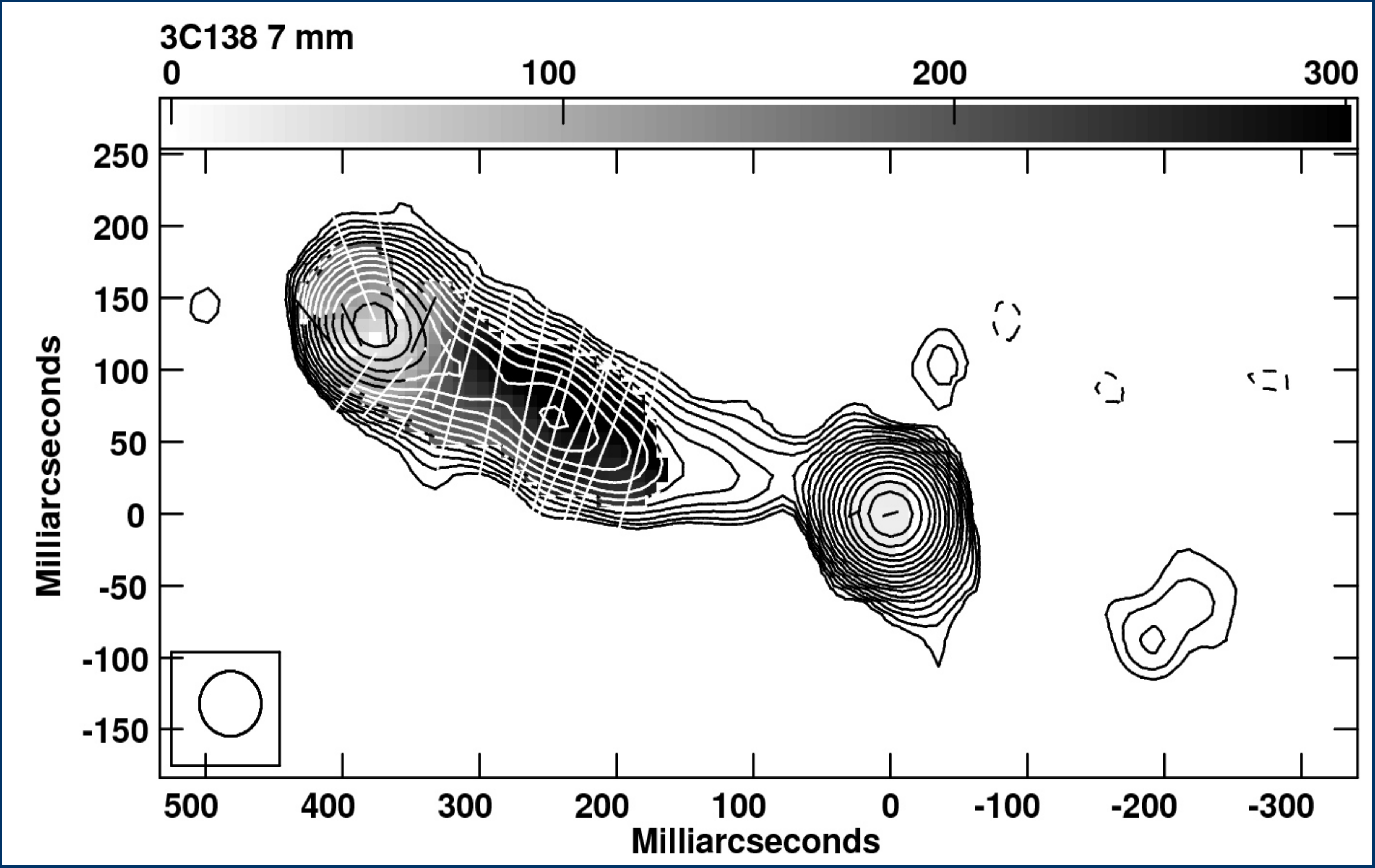
Emission processes, cont'd

- Zeeman splitting
  - Molecular energy states may be split by magnetic field
  - Right and left circular polarization emitted at different frequencies
  - Circular polarization with symmetric "S" profile
  - Important for measuring magnetic fields

Magnetic field orientation

- Polarization in an optically thin synchrotron source gives the magnetic field orientation.

Simple case



Magnetic field runs along jet, wraps around lobe

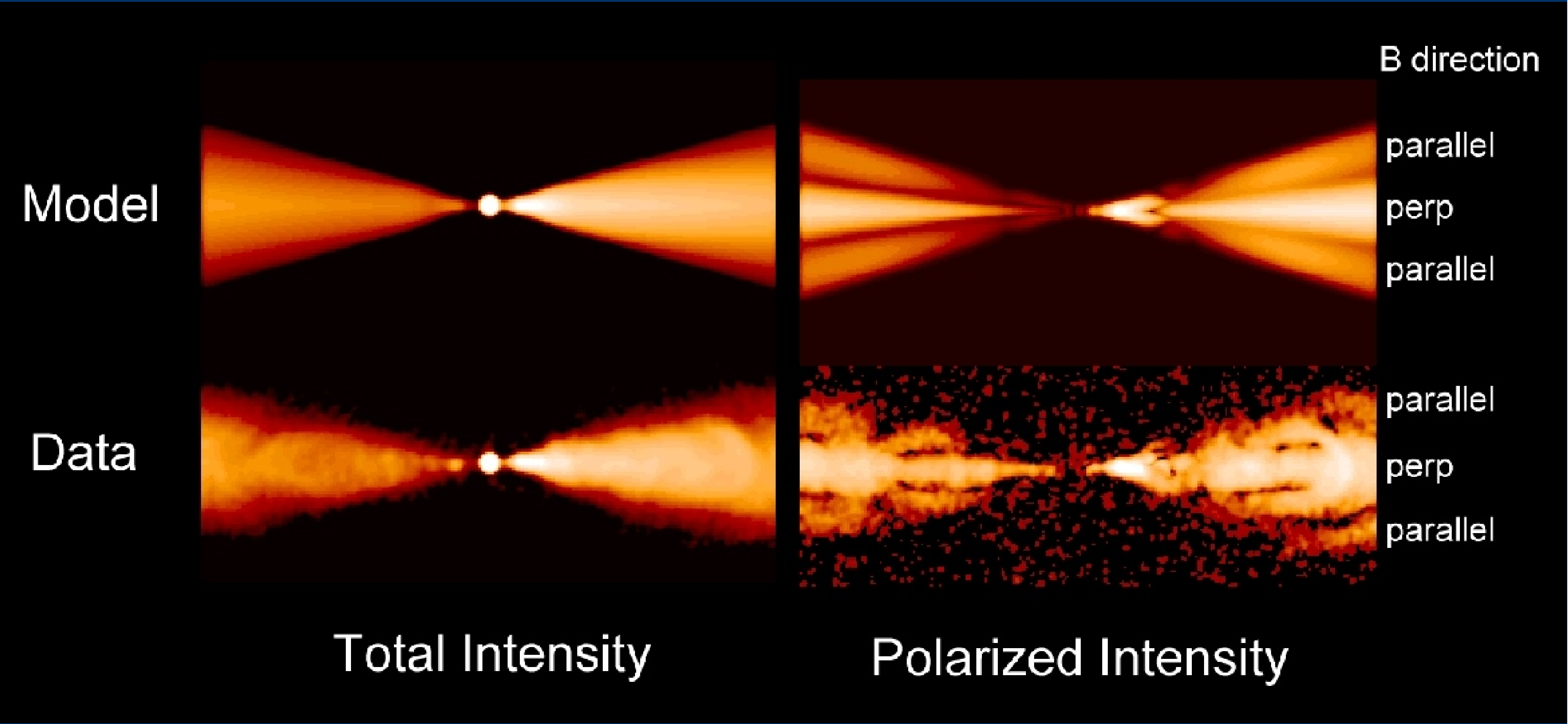
Complex case

Color gives E vector orientation

Source kinematics

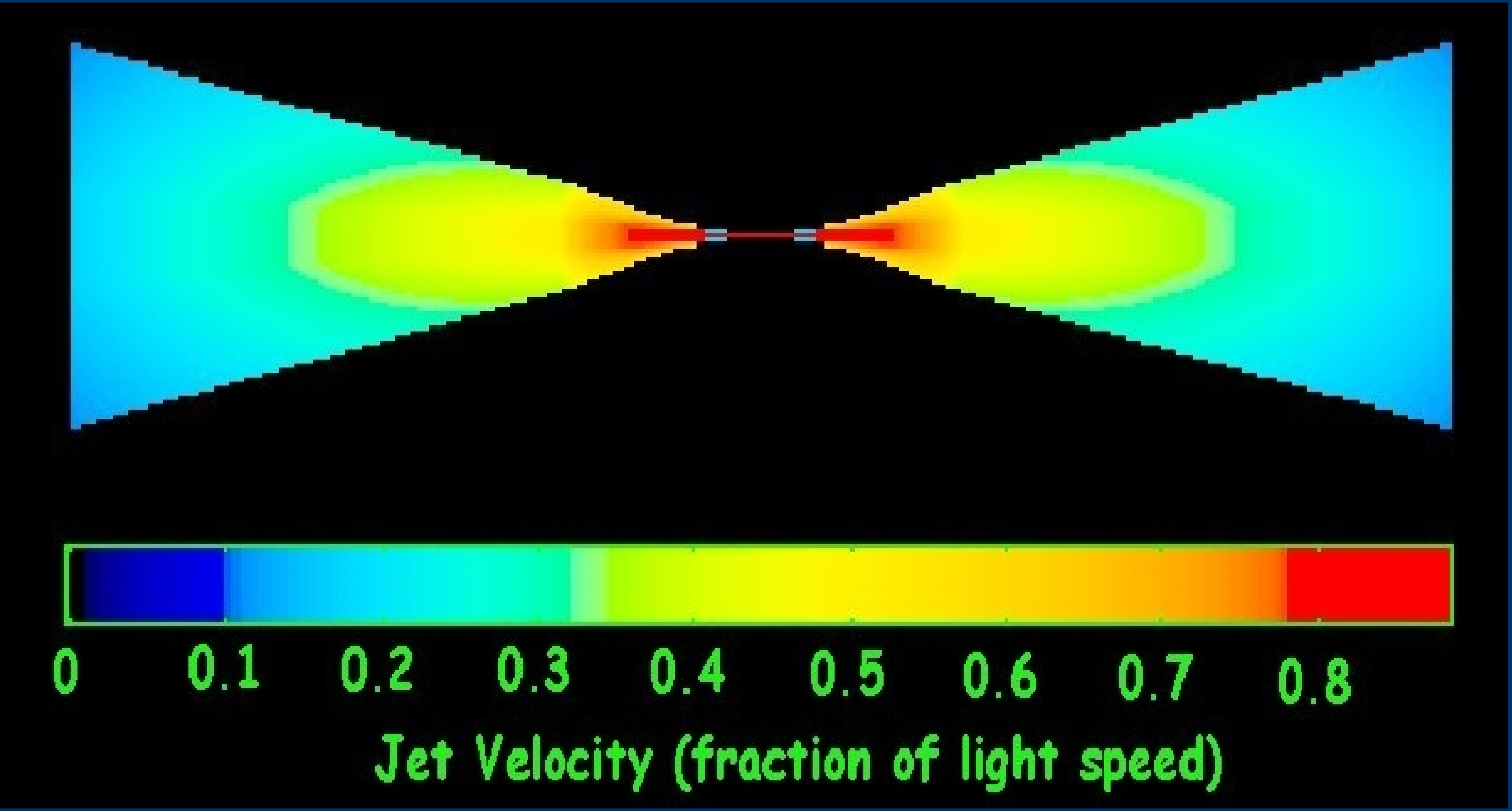
- Bridle/Laing modeling
- Relativistic aberration modifies polarization angle
- Can be used in modeling relativistic jets (Laing + Bridle)
- Model well behaved (i.e. straight) inner FR I jets

3C31 kinematic modeling



Highly relativistic spine, slower sheath,

3C31 kinematic model



Transmission effects:
Faraday rotation

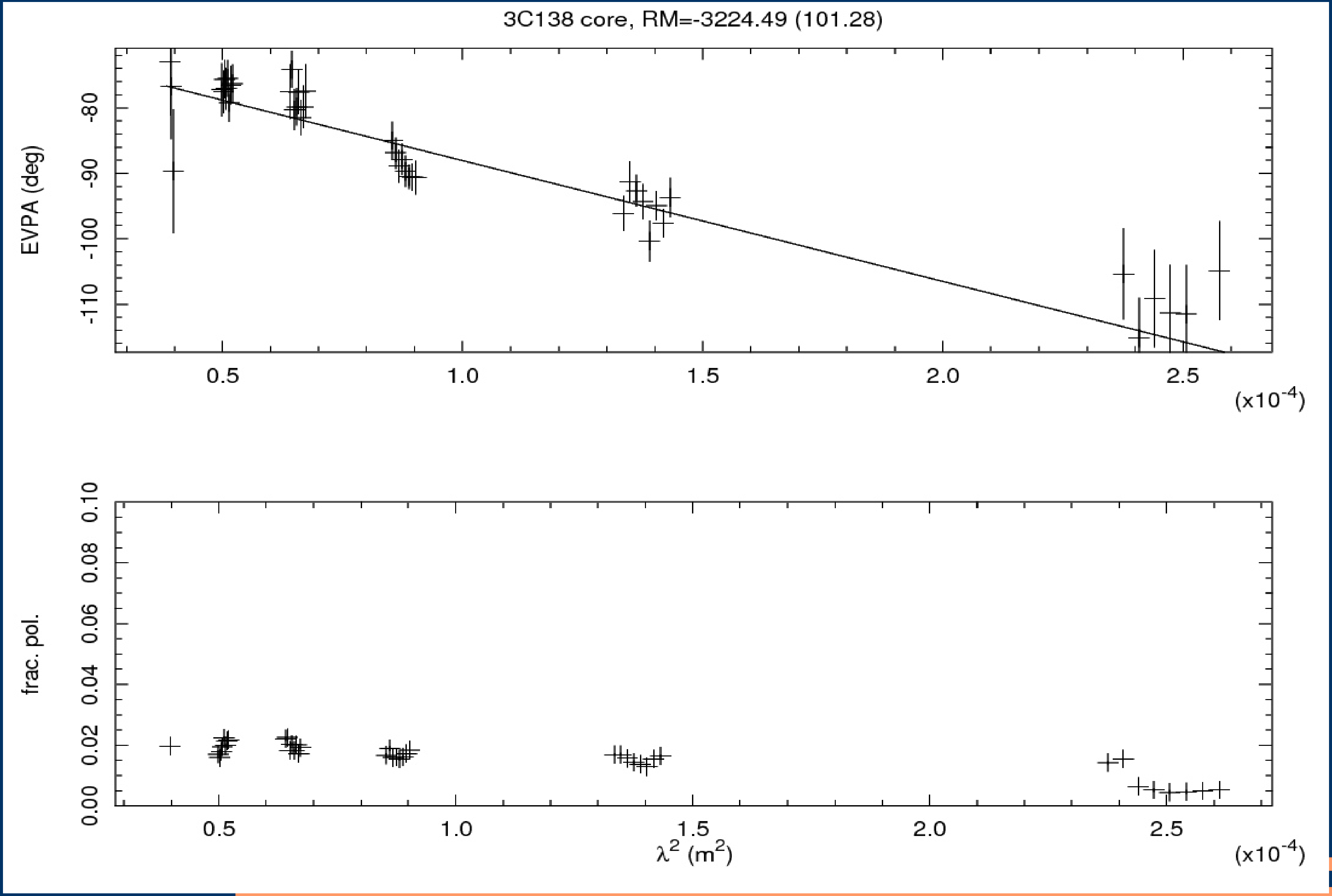
- Magnetized plasma is birefringent and will rotate plane of linear polarization: Faraday rotation.

$$\chi = \chi_0 + \mathrm{RM} \cdot \lambda^2$$

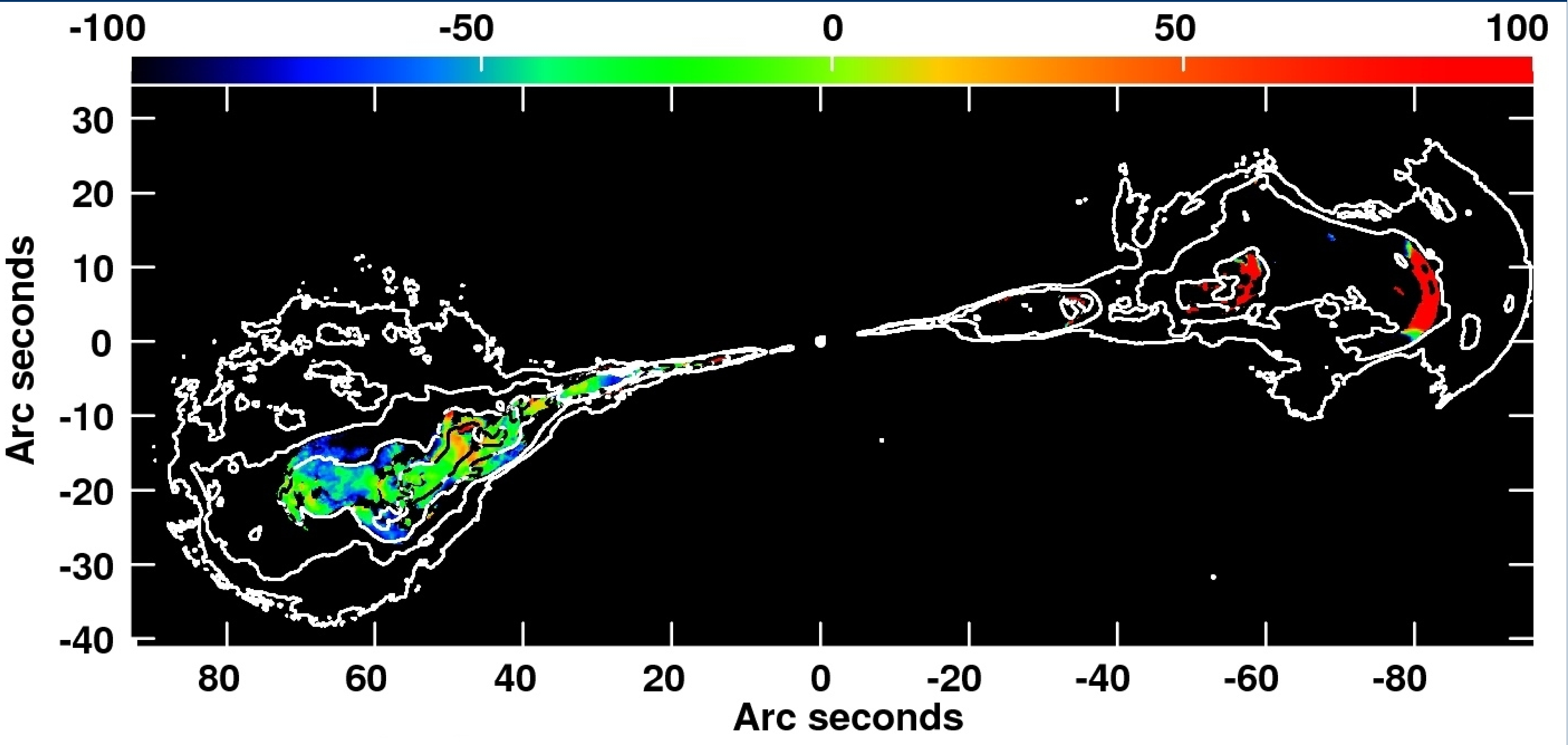
where

$$\mathrm{RM} = \frac{e^3}{8\pi^2 \epsilon_0 m^2 c^3} \int n_e \boldsymbol{B}_{||} d\boldsymbol{l}$$

Quasar Faraday Rotation



Faraday Rotation example



Dense screen in West (depolarized), variable in East

Rotation Measure Synthesis

- If Faraday screen varies across source or is intermingled simple Faraday rotation insufficient
- Fourier transform of polarization in λ^2 space reveals, multiple or complex structure.
- Faraday Dispersion Function ($F(\phi)$):

$$F'(\phi) = F(\phi) \star R(\phi) = K \int P(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

***where** P is Q + j U,*

ϕ = Faraday depth

$R(\phi)$ = transfer function

$\star$ denotes convolution

Rotation Measure Synthesis, cont'd

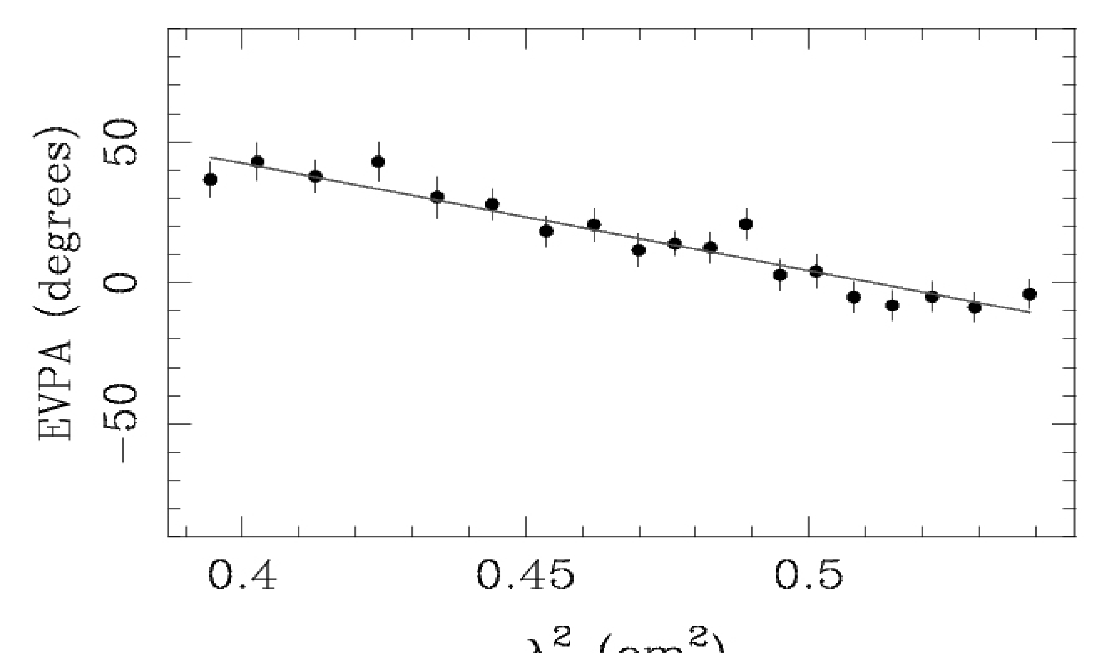
- Derived Faraday dispersion Function convolved with transfer function
- Need to deconvolve, e.g. CLEAN

Example

- EVLA 7 mm observation of magnetar near Galactic center (E. Kravchenko)
- Large Rotation measure but simple structure.

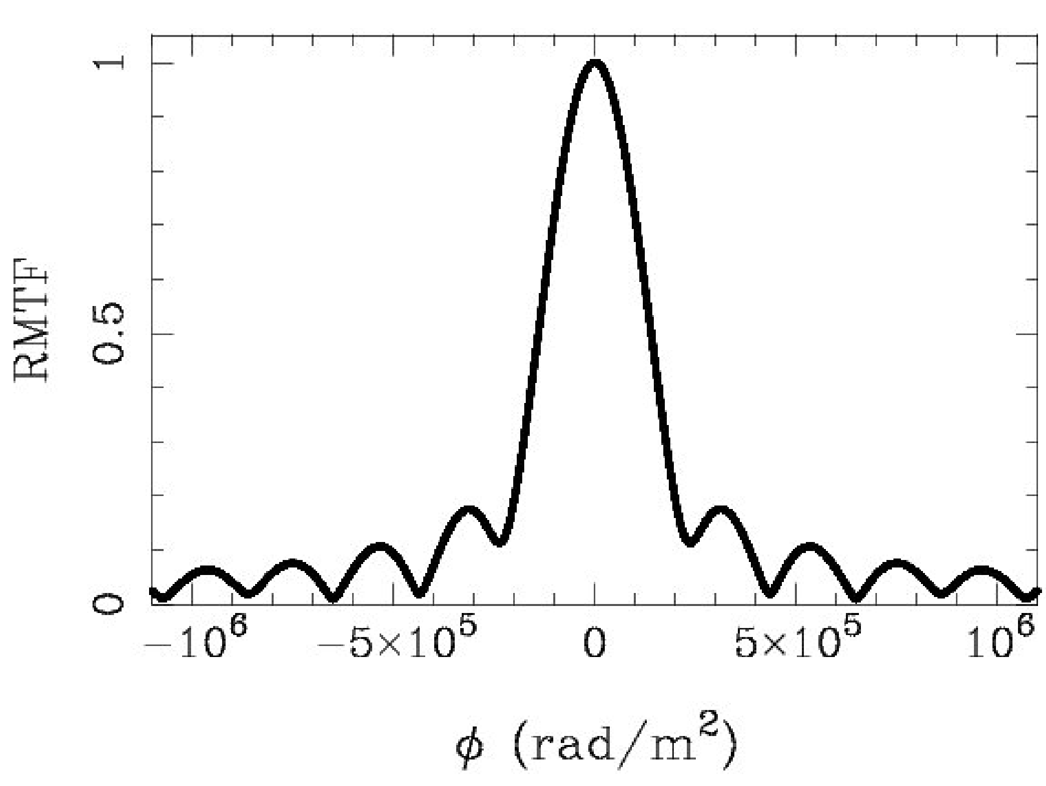
Pulsar

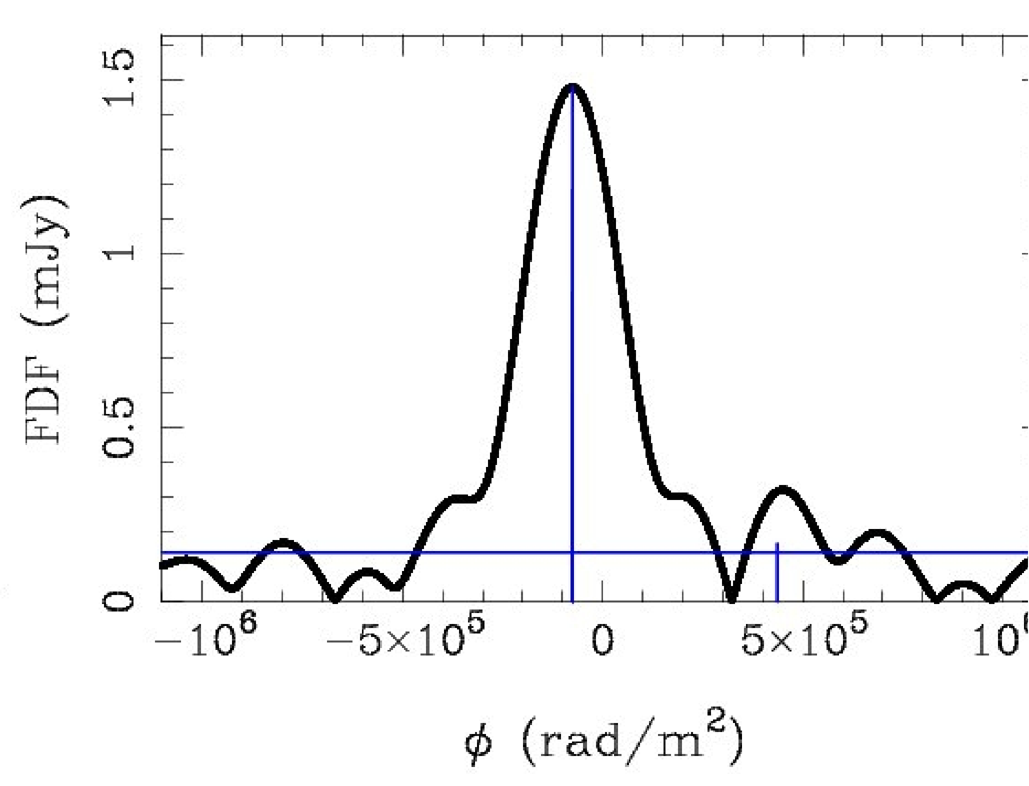
E. Kravchenko



Transfer fn

Dispersion fn

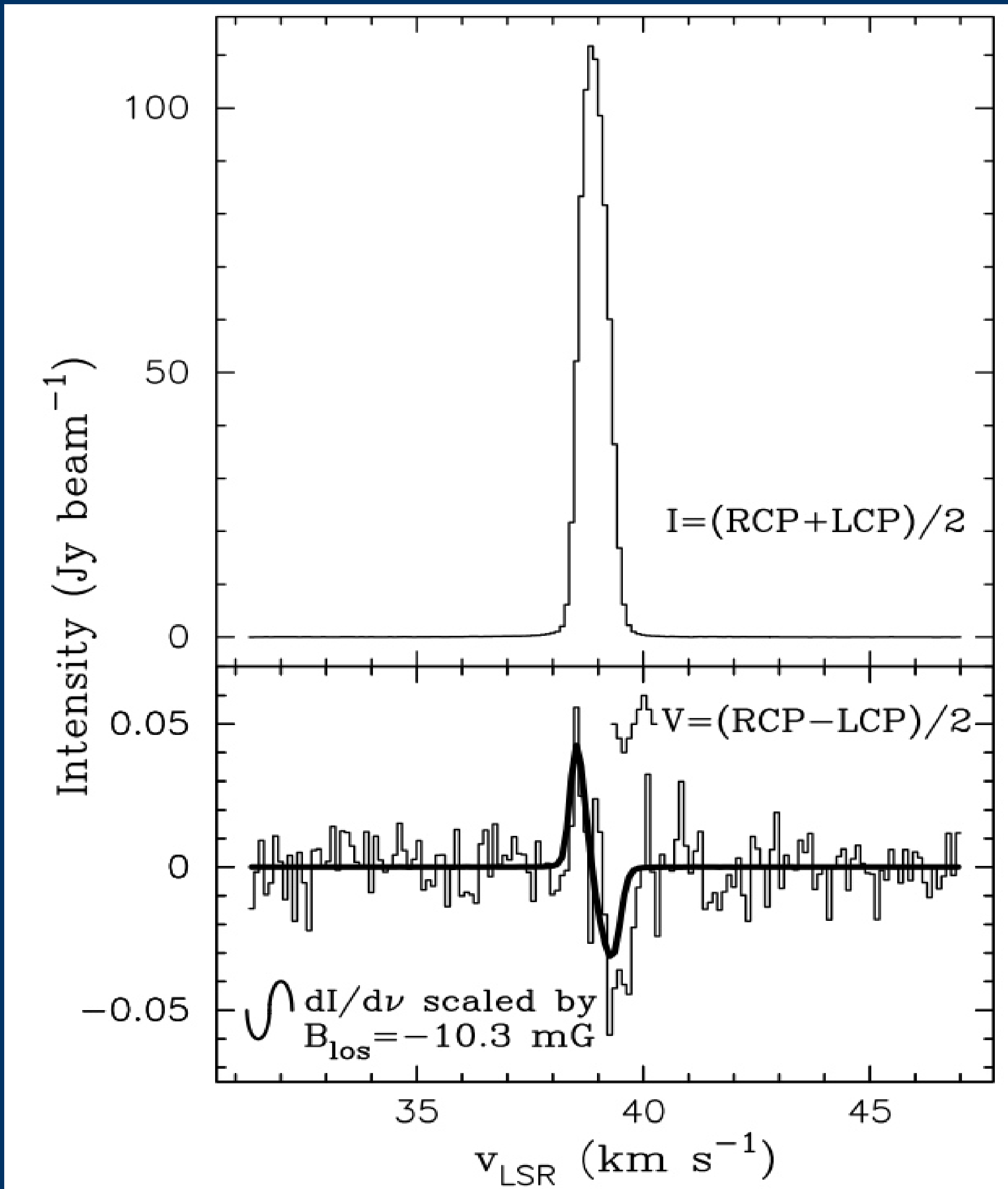




Circular polarization: Zeeman splitting

- Some molecular transitions sensitive to magnetic field.
  - B field removes degeneracy
  - Ordinary/extraordinary modes have different frequencies
  - Produces "S" shaped asymmetric circularly polarized lines
  - Amplitude proportional to strength of magnetic field along line of sight
- Direct measurement of magnetic field strength
- Need narrow lines ⇨ cold thermal gas or masers

Zeeman splitting

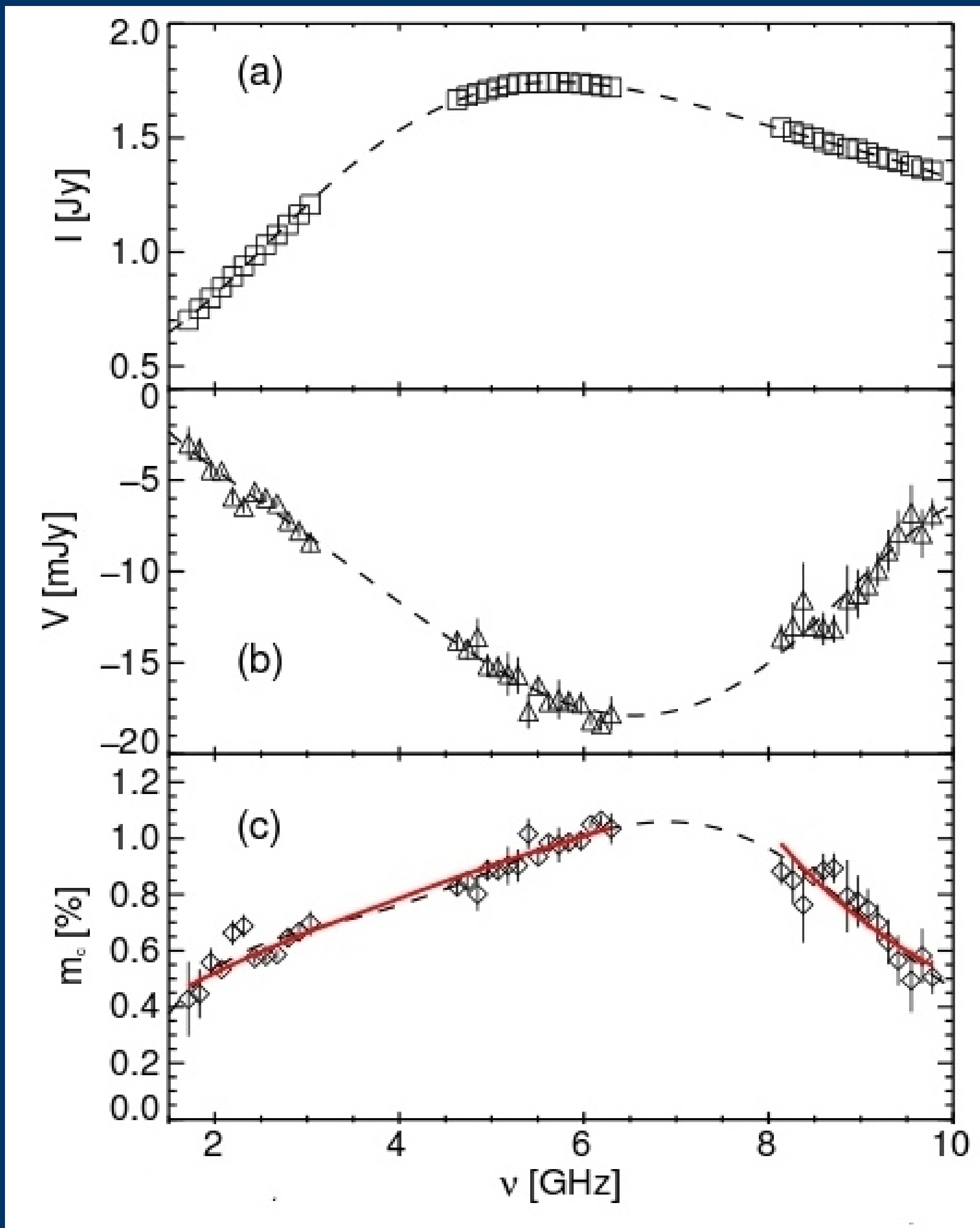


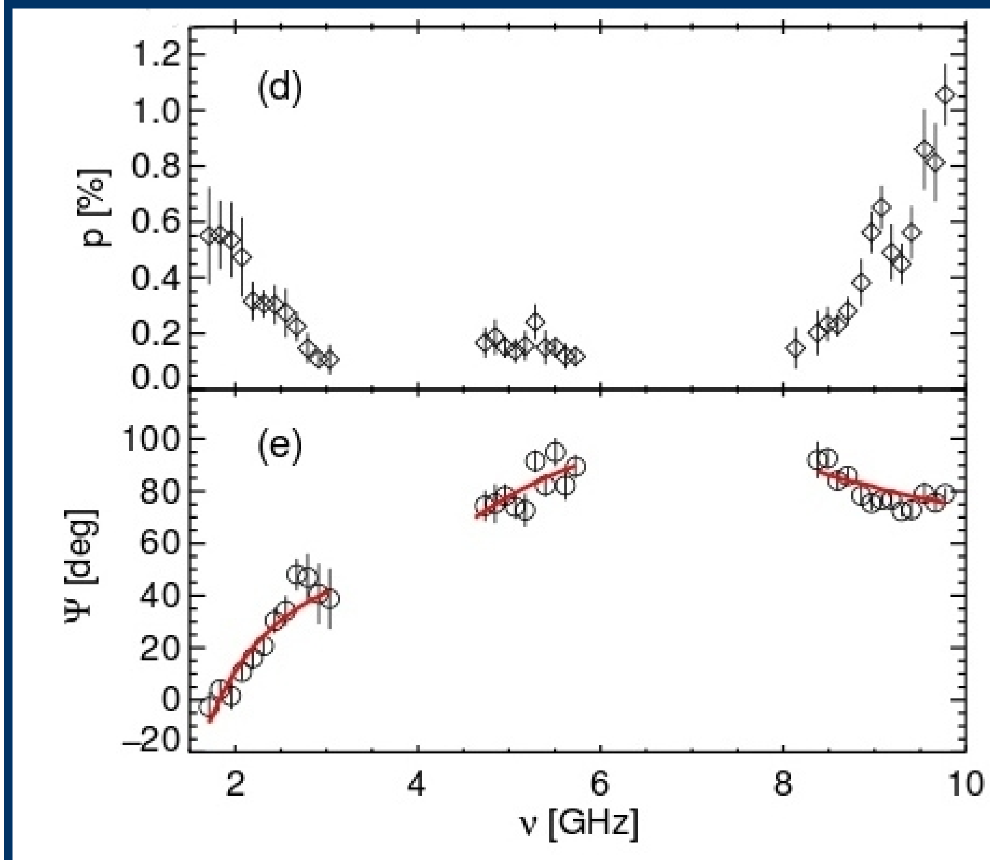
Water maser in star forming region.
Saram+ 2008, ApJ 674, 295

Circular polarization: Faraday conversion

- Synchtotron or maser emission linearly polarized
- Faraday effects in emitting regions can convert linear to circular
- Postulated for masers (Wiebe & Watson, 1998, ApJL, 503, L71).
- Seen in AGN (O’Sullivan+ 2013, MNRAS, 435,311)

Faraday conversion – AGN ATCA

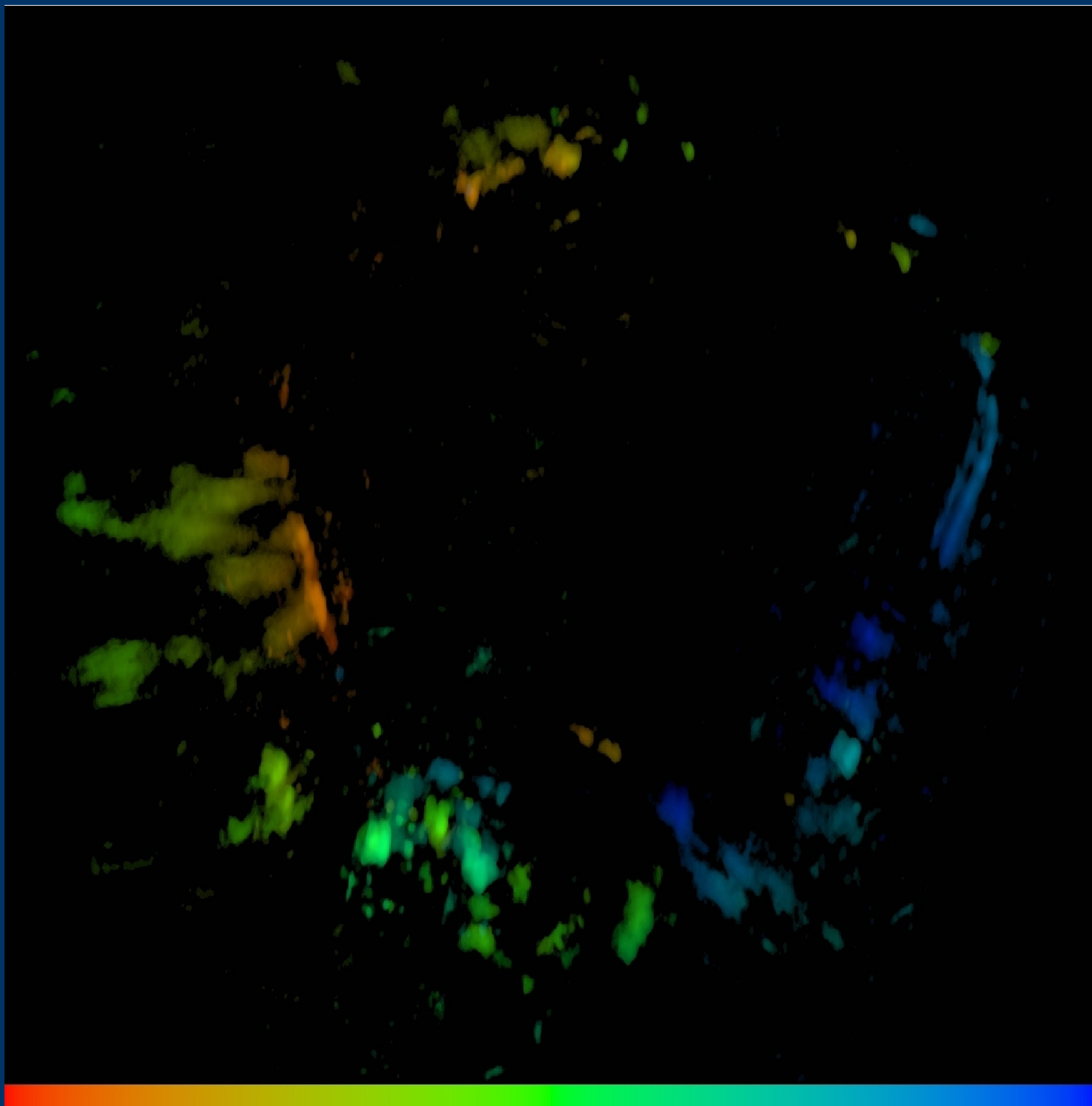




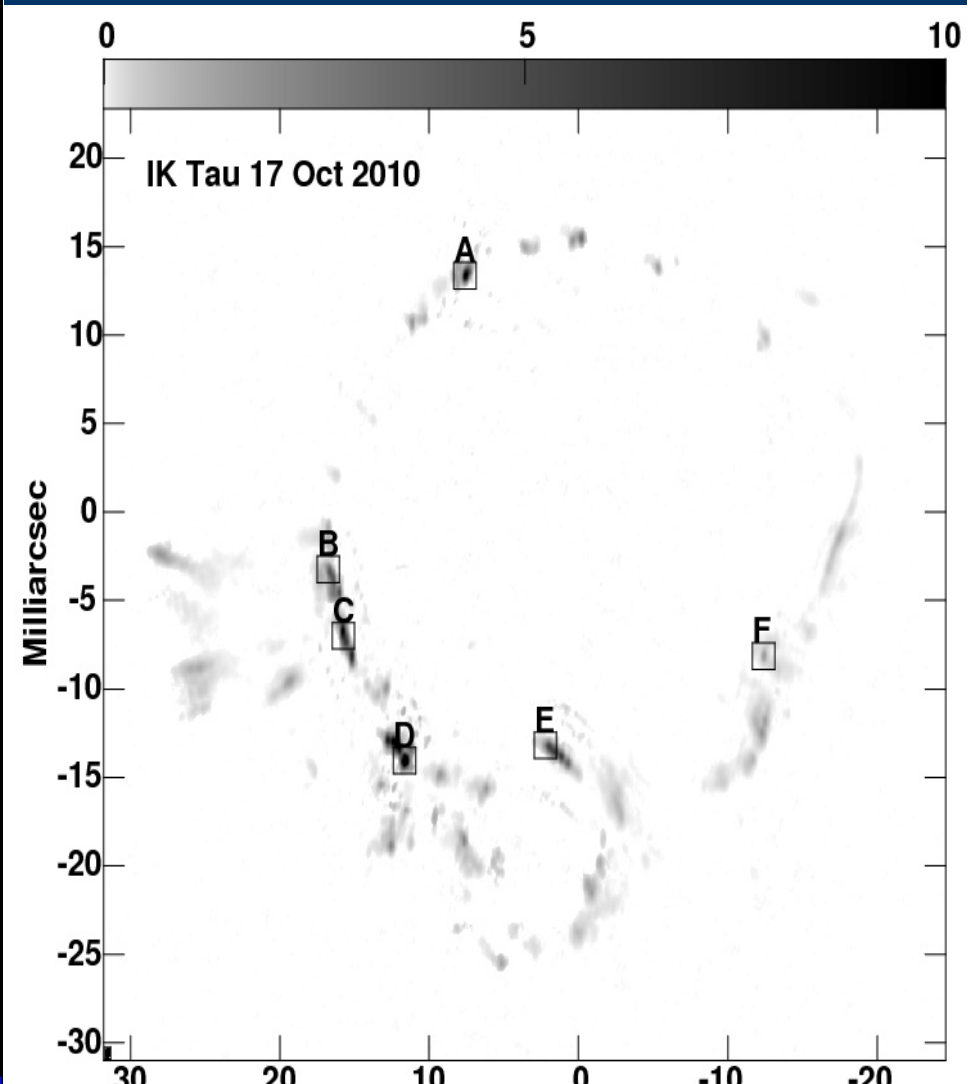
Non Zeeman circular polarization in Masers

- Masers can have strong circular polarization, may not be either Zeeman or Faraday conversion
  - (Cotton+ 2011, ApJ, 736, 96)

Non Zeeman circular polarization in masers

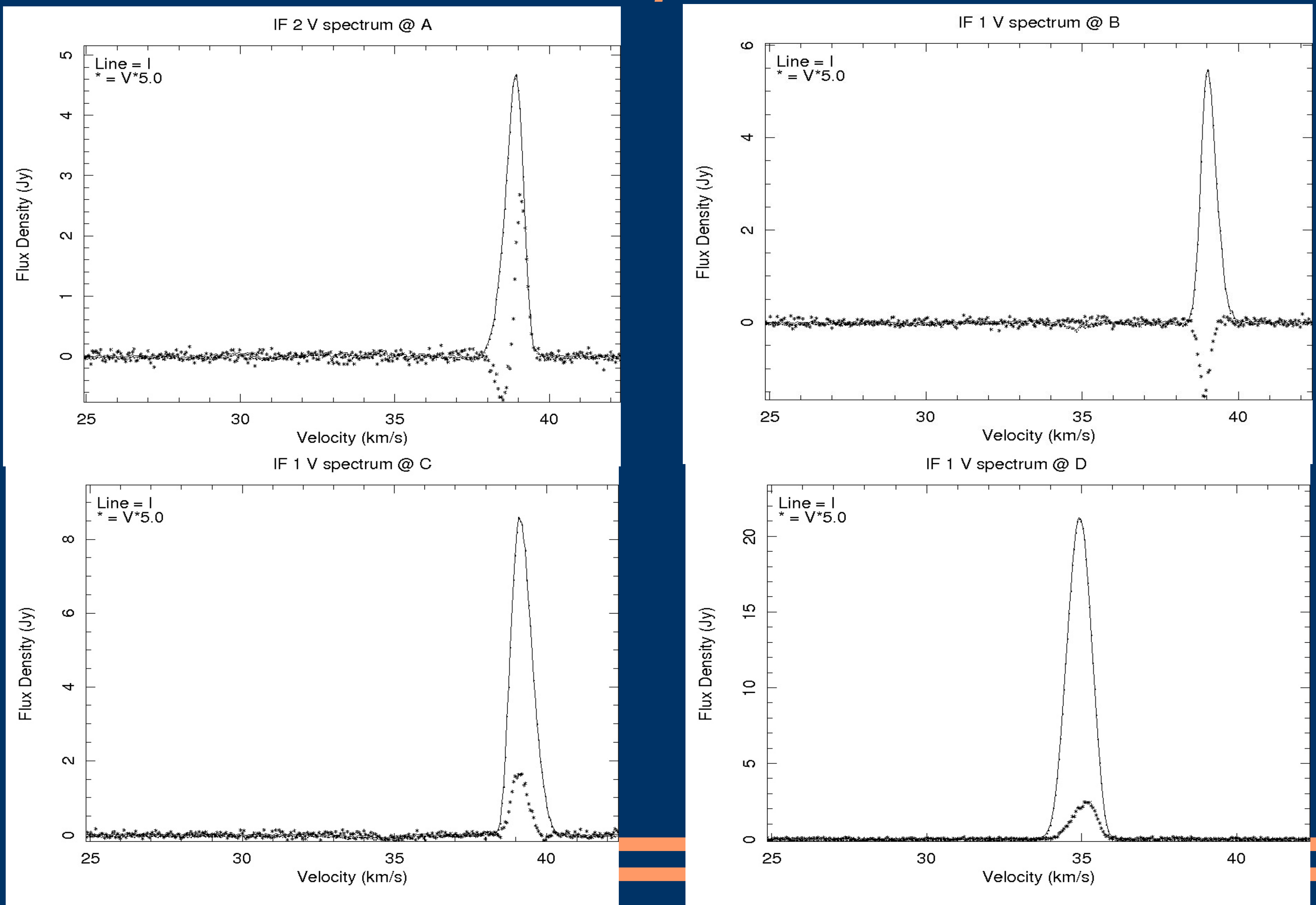


SiO masers in AGB star
with color coded velocities



Maser spot labels

Non Zeeman circular polarization in masers



Thank You