Magnetic Fields in Blazar Jets: Constraints from Full Stokes Observations

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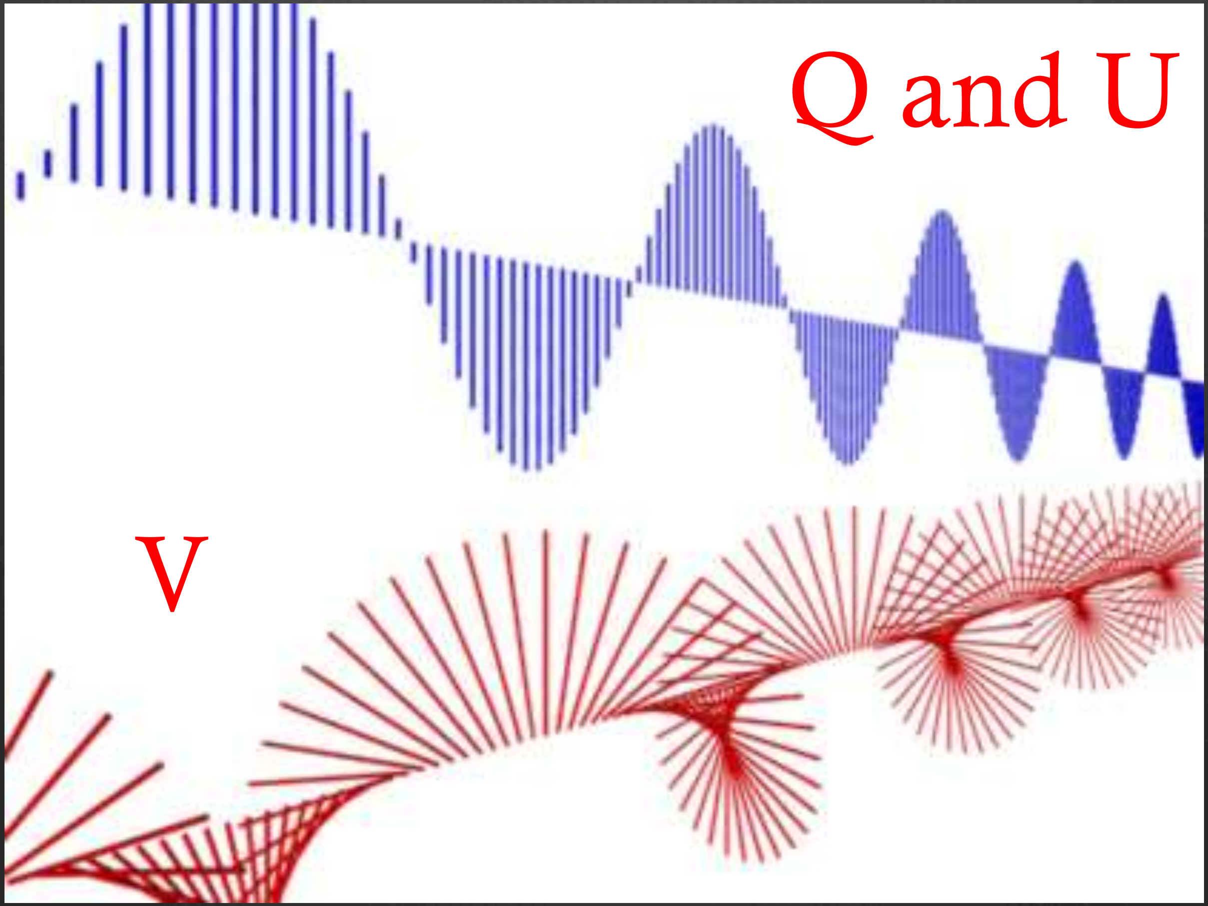
“Full Stokes” Polarization

- Stokes I + …



http://physics.nad.ru/Physics/English/ellf_tmp.htm

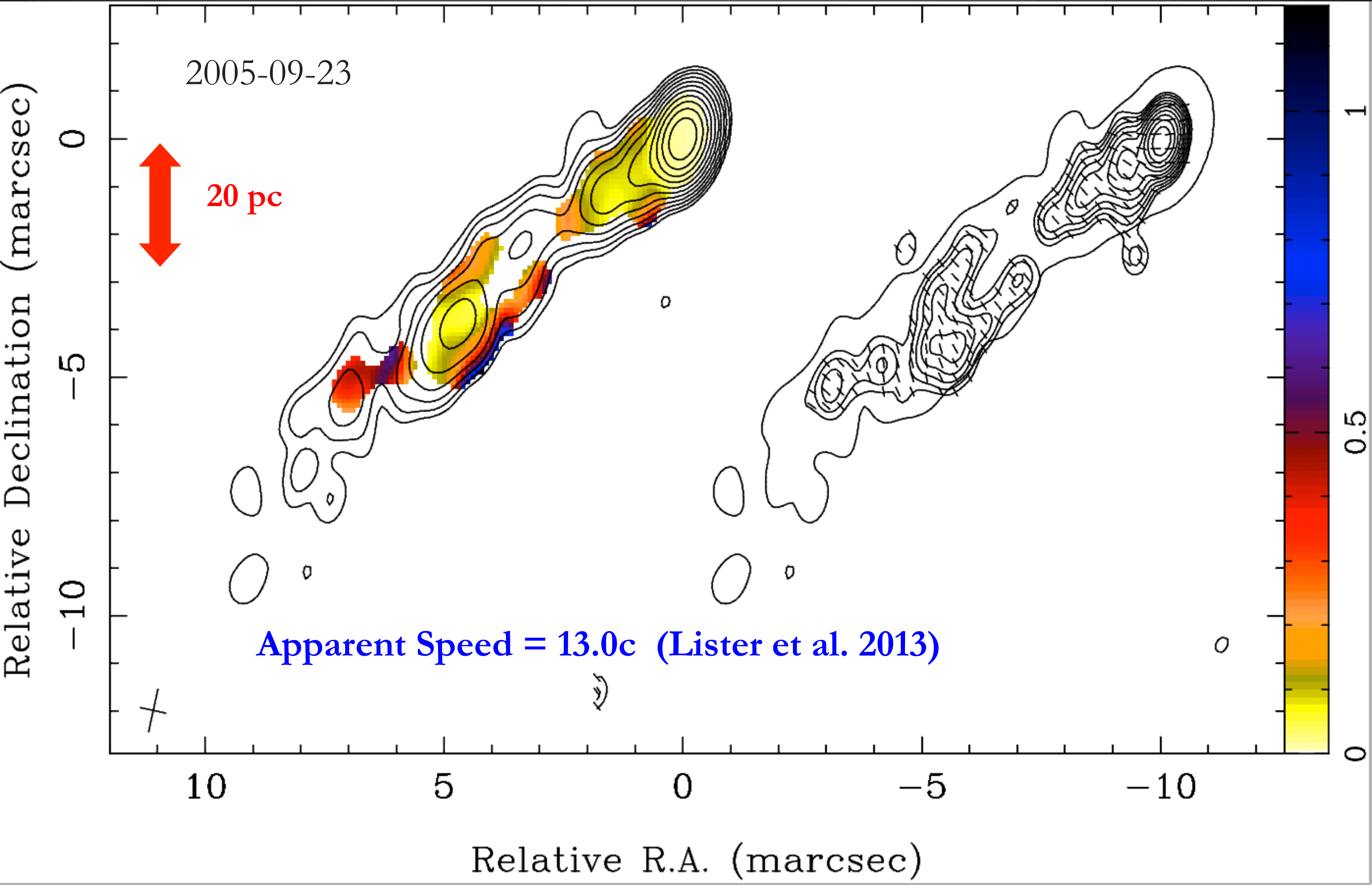
Studying Blazar Jets with Polarization

- 3-D magnetic field structure of jets
  - Role in collimation & acceleration of jets
  - Connection with SMBH/Accretion Disk?
- Low energy particle population
  - Particle acceleration mechanisms
  - Particle content & kinetic luminosity of jets
- Tracer of jet flow and hydrodynamics
  - Shock, shear, aberration, etc…
- Probe of material + fields external to jets
  - Sheath or boundary layers
  - Narrow line region

Linear Polarization as a Probe

- Emitted Polarization
  - ~ 70% for optically thin radiation, uniform B-field
  - Sensitive to net field order in plane of sky

MOJAVE: Quasar 0333+321 (NRAO 140) z = 1.26



Linear Polarization as a Probe

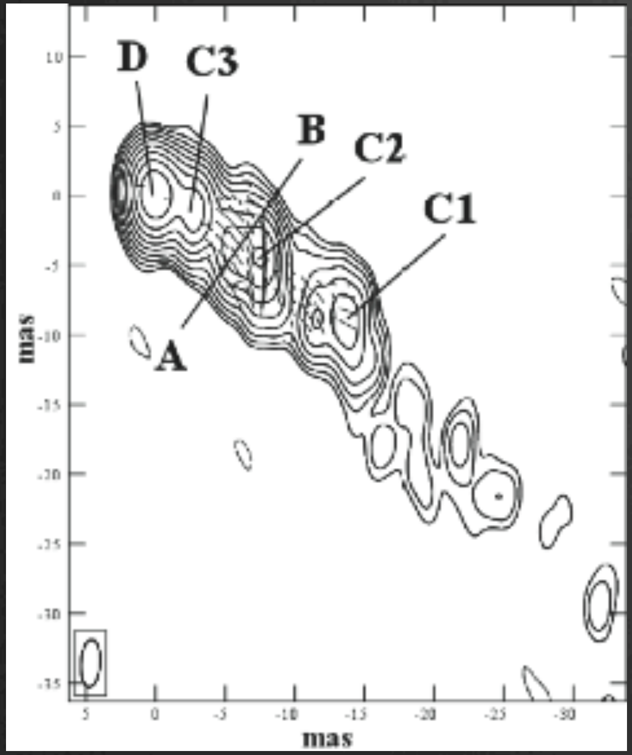
- Emitted Polarization
  - ~ 70% for optically thin radiation, uniform B-field
  - Sensitive to net field order in plane of sky
- Bi-refringence: *Faraday Rotation*

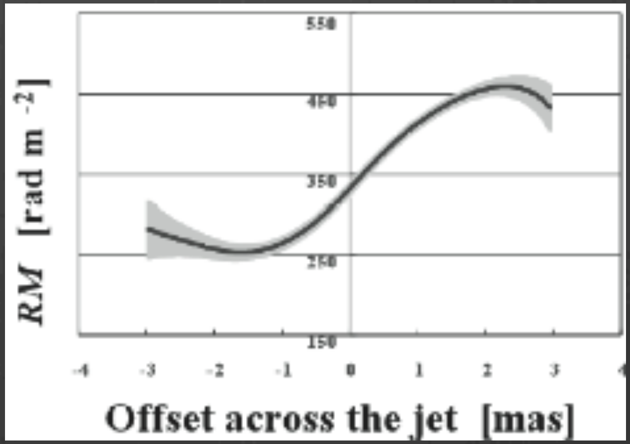
  → *rotates the plane of polarization*
  - Sensitive to field order along the line of sight
  - Sensitive to charge sign of "rotating" particles
  - Stronger for lower energy particles

    → Significant (Dominant ?) contribution by external thermal matter

Evidence for Large Scale Order

- Gradients in Faraday Rotation Across Jets…
  (e.g. Asada et al. 2002,2012; Gabuzda et al. 2004,2014; Hovatta et al. 2012)
  - Due to Toroidal field structures within jets and/or in a boundary layer surrounding them?



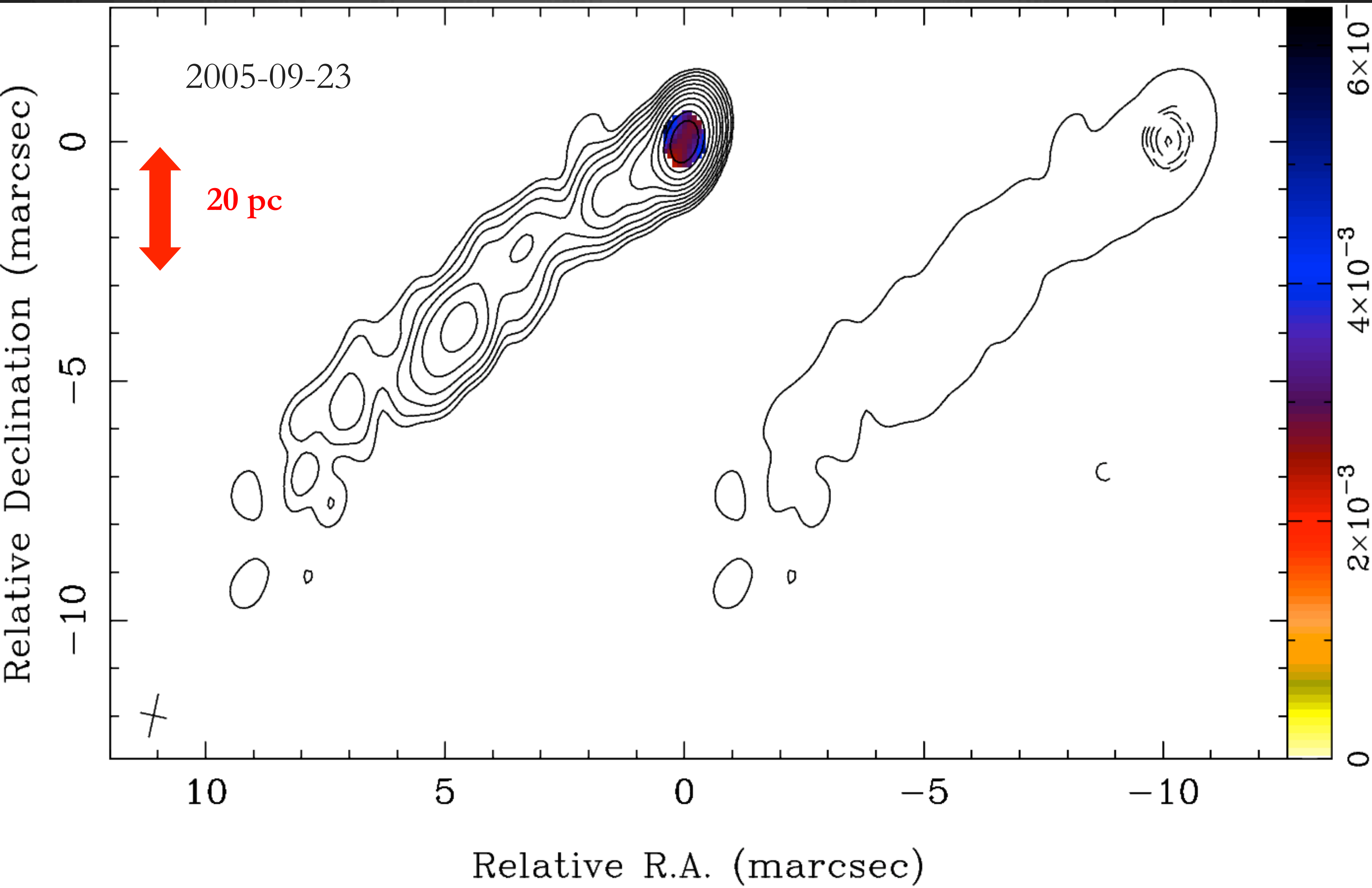


3C 273
Asada et al. 2002

Multiple Scales and Epochs:
Zavala & Taylor 2005;
Attridge et al. 2005;
Asada et al. 2008; Hovatta et al. 2012

Circular Polarization as a Probe

MOJAVE: Quasar 0333+321 (NRAO 140) z = 1.26

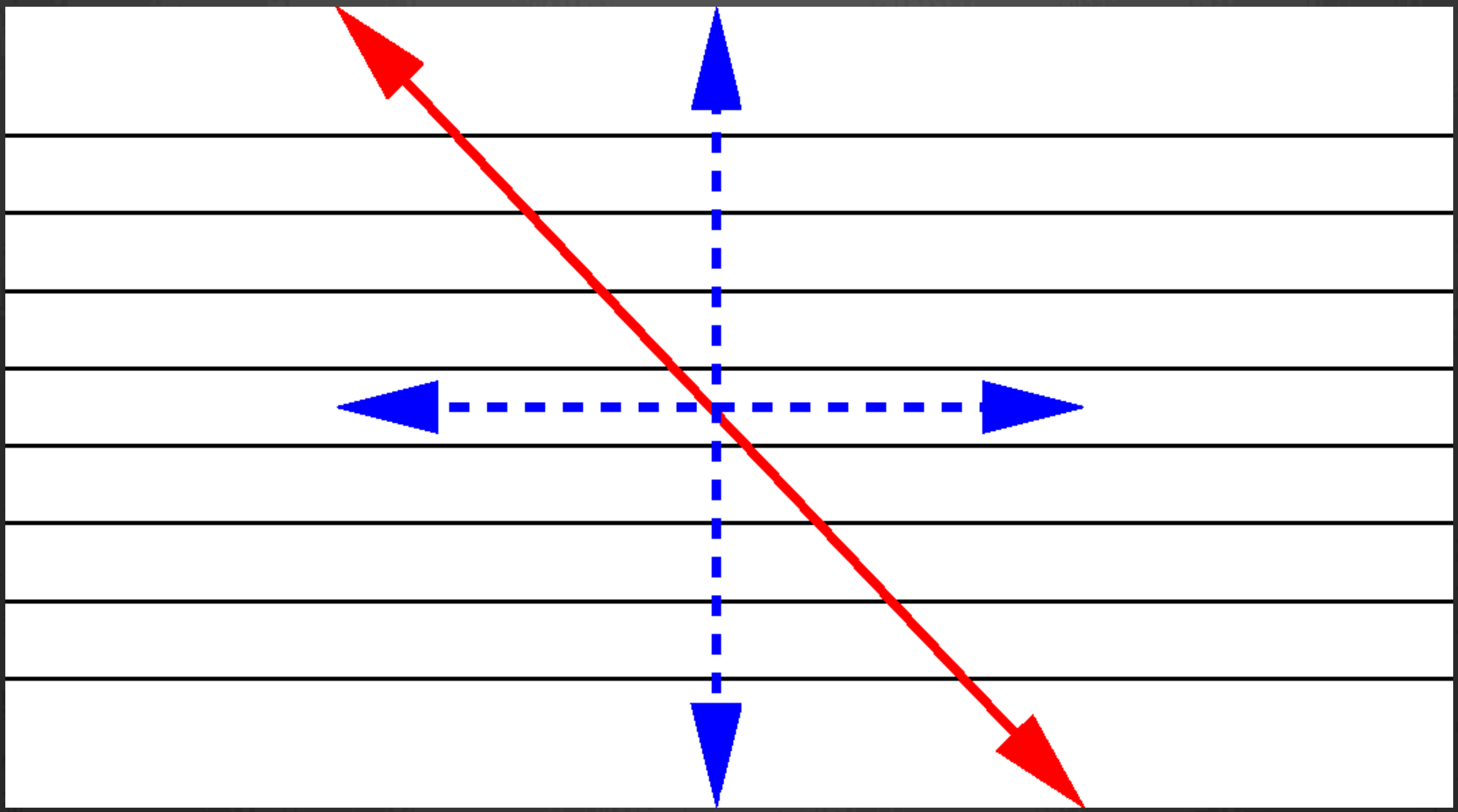


Circular Polarization as a Probe

- Emitted Polarization: *Intrinsic CP*
  - $m_c \sim 1/\gamma$ ~ 1% for low optical depth, uniform B-field
  - Sensitive to net field order along the line of sight
  - Sensitive to charge sign of radiating particles
- Bi-refringence: *Faraday Conversion*

  → *converts linear to circular polarization*
  - Requires field order in the plane of the sky
  - Charge sign of the "converting" particles unimportant
  - Stronger for lower energy *relativistic* particles
  - No significant contribution by external thermal matter

Faraday Conversion



Faraday Conversion

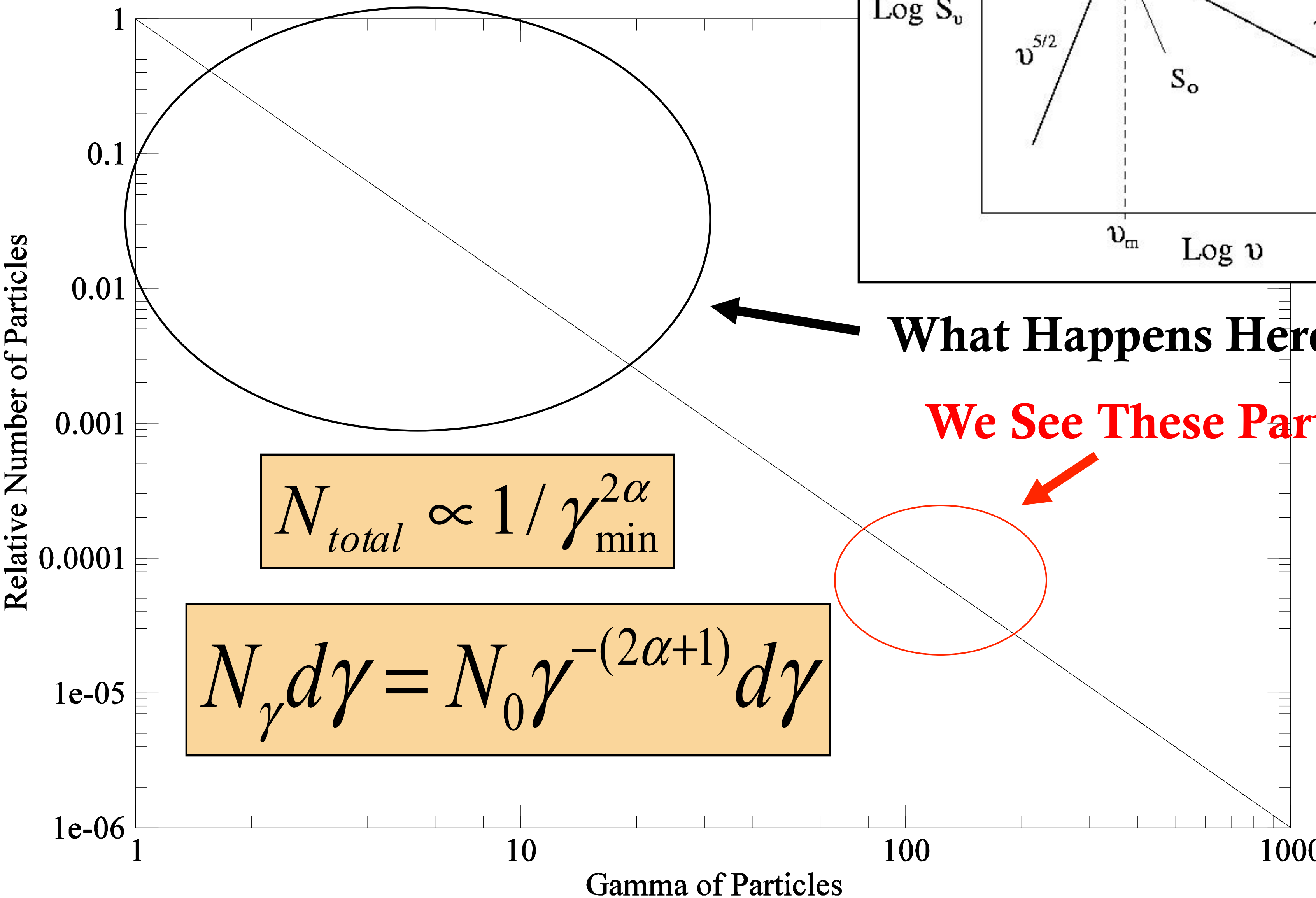
- Cannot Convert Polarization at 0 or 90 Degrees
- Conversion Due to Field Asymmetry…

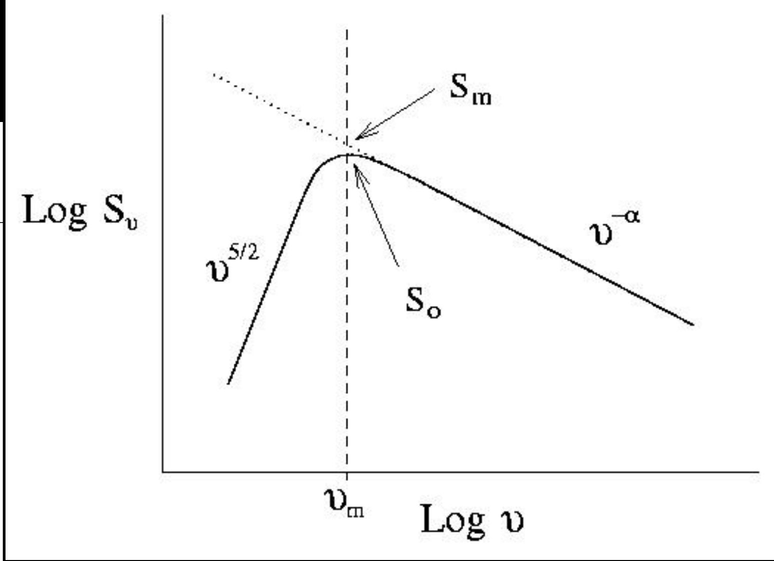
$$m_c \propto \ln\left(\frac{\gamma}{\gamma_{\min}}\right)$$

- Rotation Driven Conversion… ($\alpha = 0.5$)

$$m_c \propto \frac{\gamma^2 \ln\left(\gamma_{\min}\right)}{\gamma_{\min}^3} \ln\left(\frac{\gamma}{\gamma_{\min}}\right)$$

Power-Law Particle Distribution





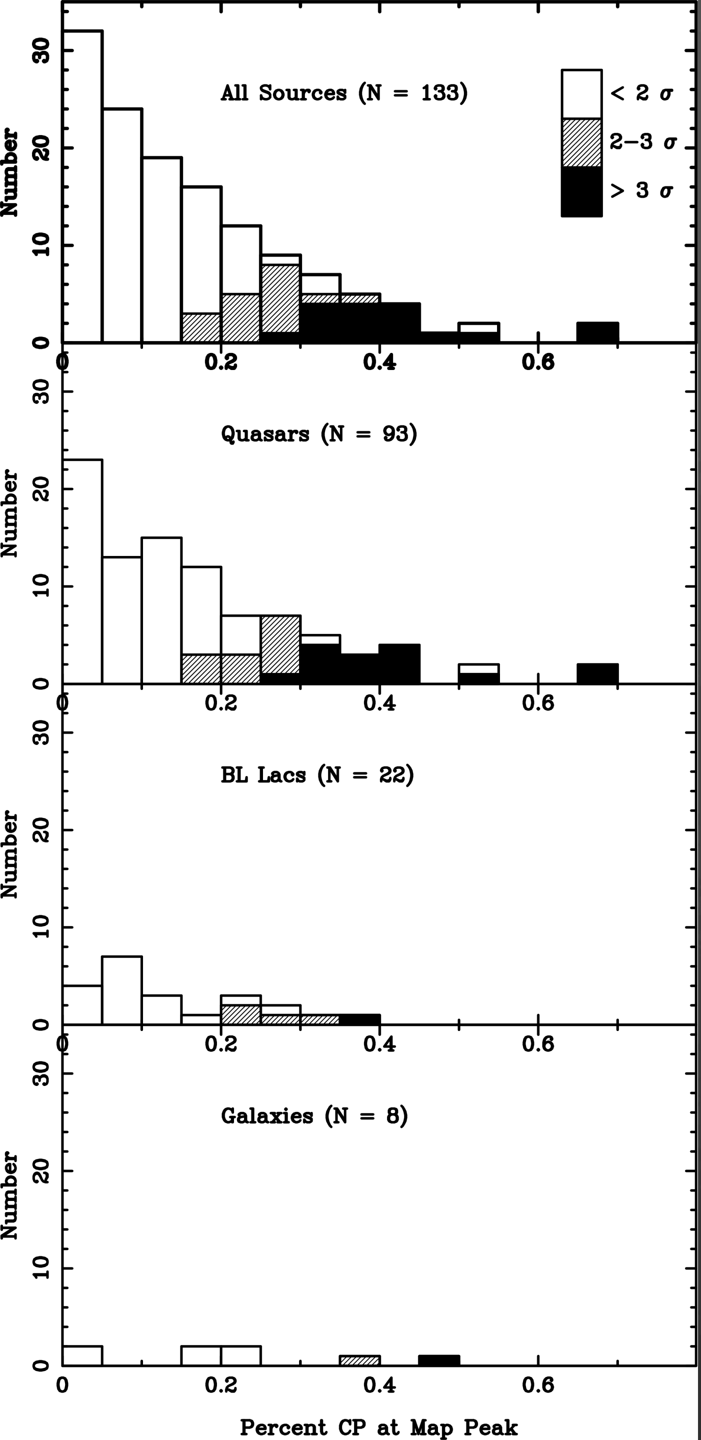
$$N_{total} \propto 1/\gamma_{\min}^{2\alpha}$$

$$N_\gamma d\gamma = N_0 \gamma^{-(2\alpha+1)} d\gamma$$

How Strong is CP?

- Typically < 0.1% in integrated measurements <= 5 GHz
  (e.g. Weiler & dePater 1983, Rayner et al. 2000)
  - 2-4% local CP inferred for IDV Source PKS 1519-273 (Marquart et al. 2000)
  - Exhibit variability (e.g. Komassaroff et al. 1984; Aller et al. 2003)

- Typically < 0.3% local CP in VLBA measurements <= 15 GHz
  (e.g. Homan, Attridge & Wardle 2001; Homan & Lister 2006; Vitrishchak et al 2008)
  - Most extreme: 3C 84 with 3% local CP (Homan & Wardle 2004)
  - First Epoch MOJAVE survey at 15 GHz, >= 0.3% detected in 16/115 sources (Homan & Lister 2006)

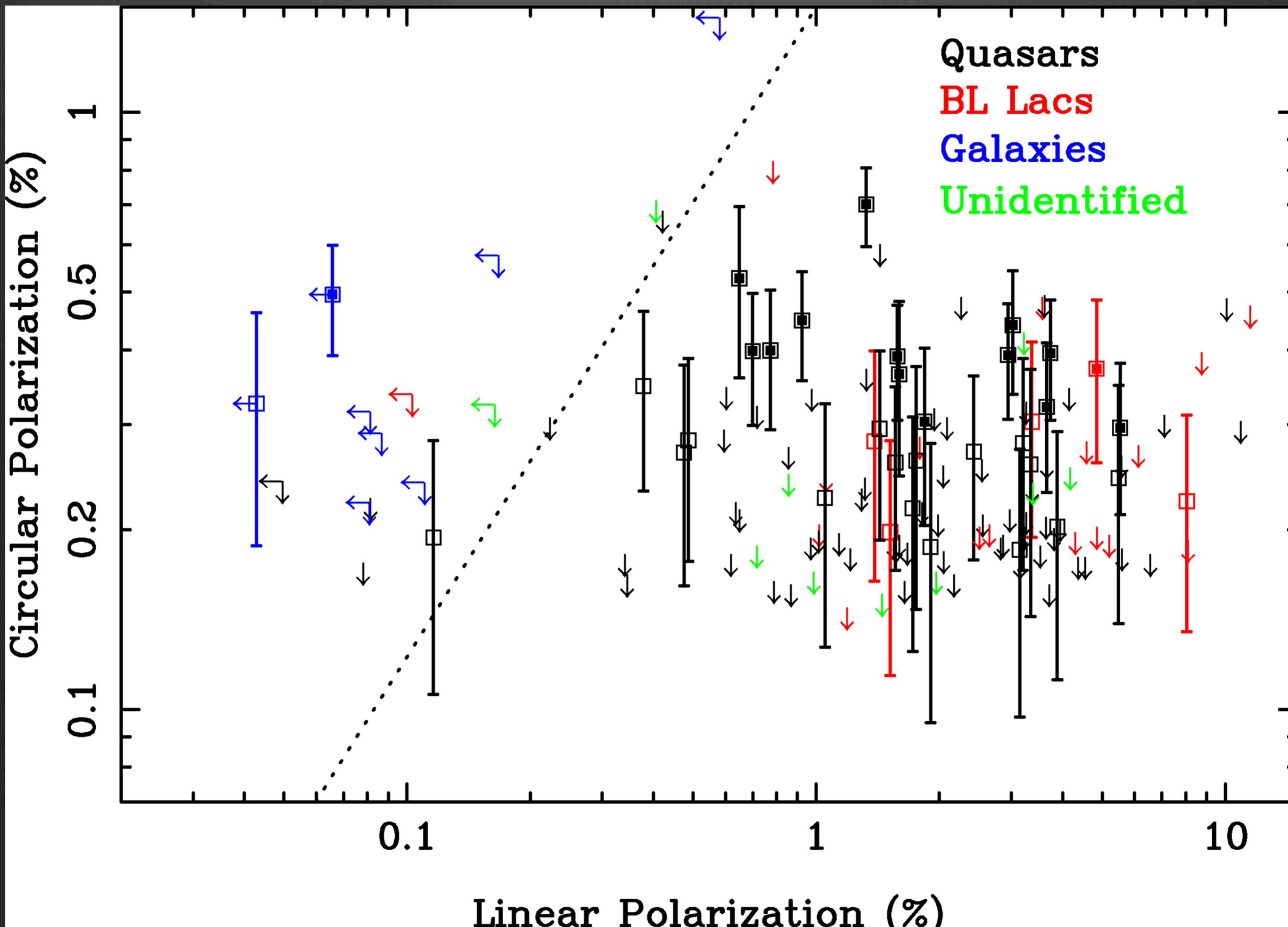


Distribution of Circular Polarization Measurements

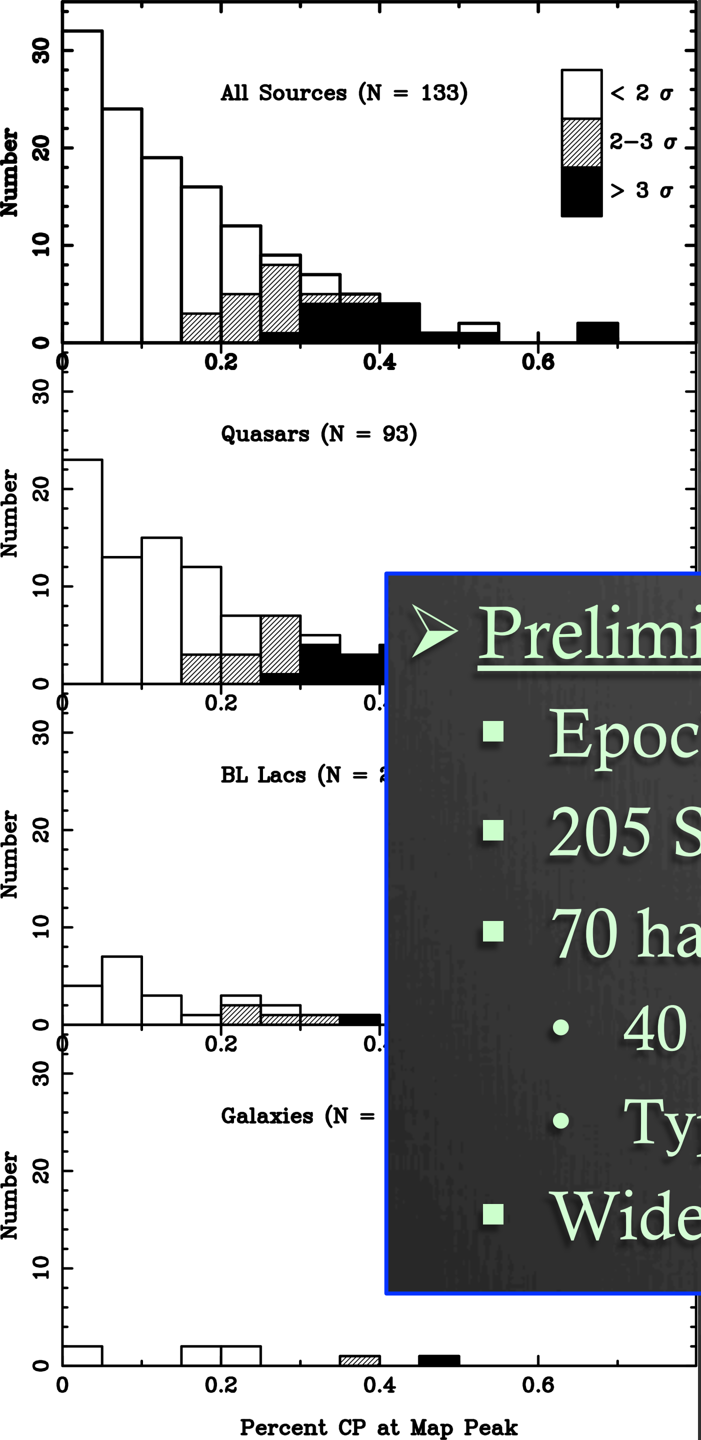
- First Epoch MOJAVE CP Results
- Strong CP (>= 0.3%) in 16 out of 115 sources

Homan & Lister (2006)

CP vs. LP at 15 GHz



Homan & Lister (2006)

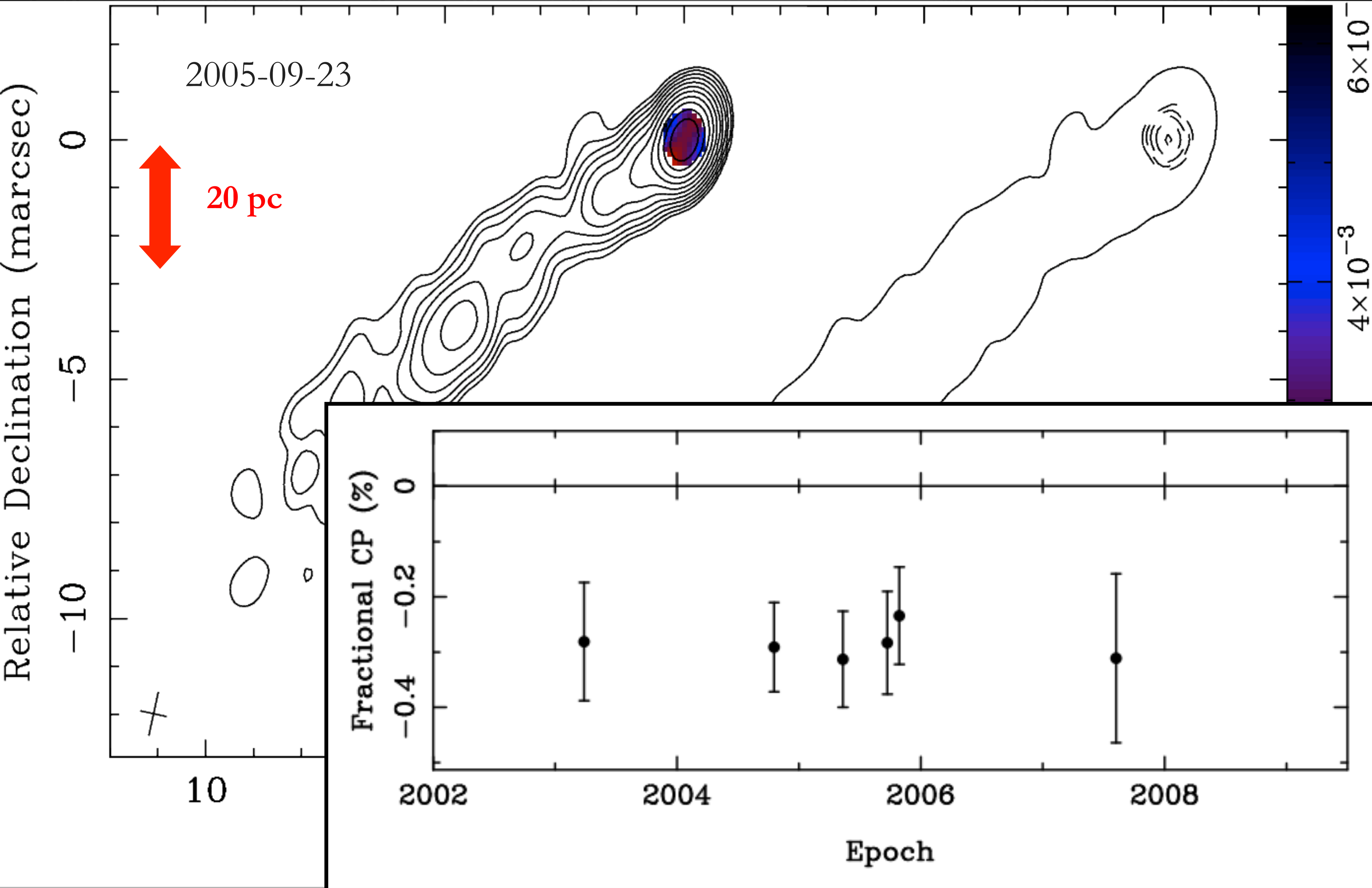


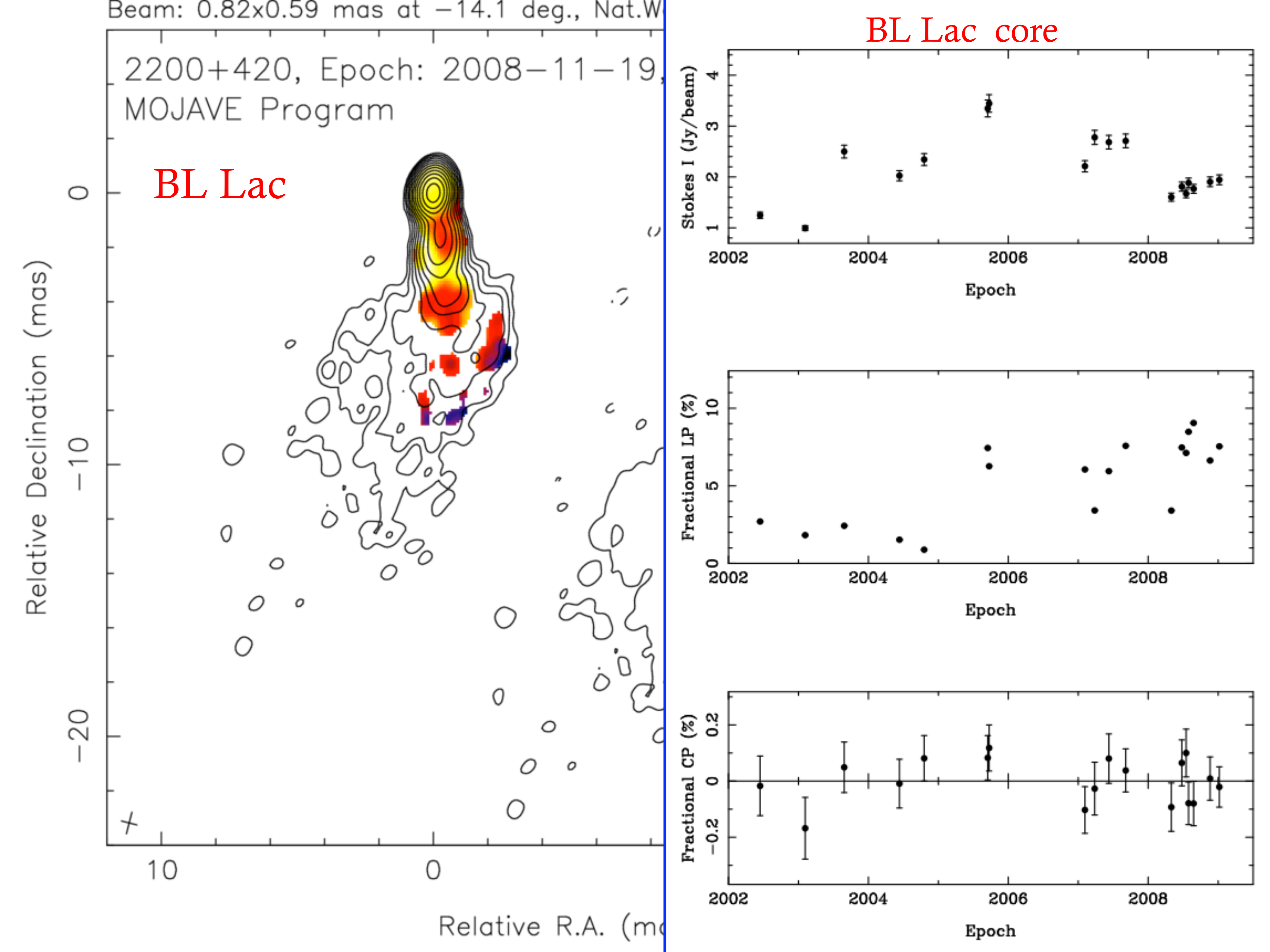
Distribution of Circular Polarization Measurements

- Preliminary Multi-Epoch Results:
  - Epochs 2002 to 2009
  - 205 Sources, average 6 epochs/source
  - 70 have at least one 3-sigma detection
    - 40 have multi-epoch 3-sigma detections
    - Typical level 0.3-0.7 %, a few up to 1%
  - Wide range of variability observed

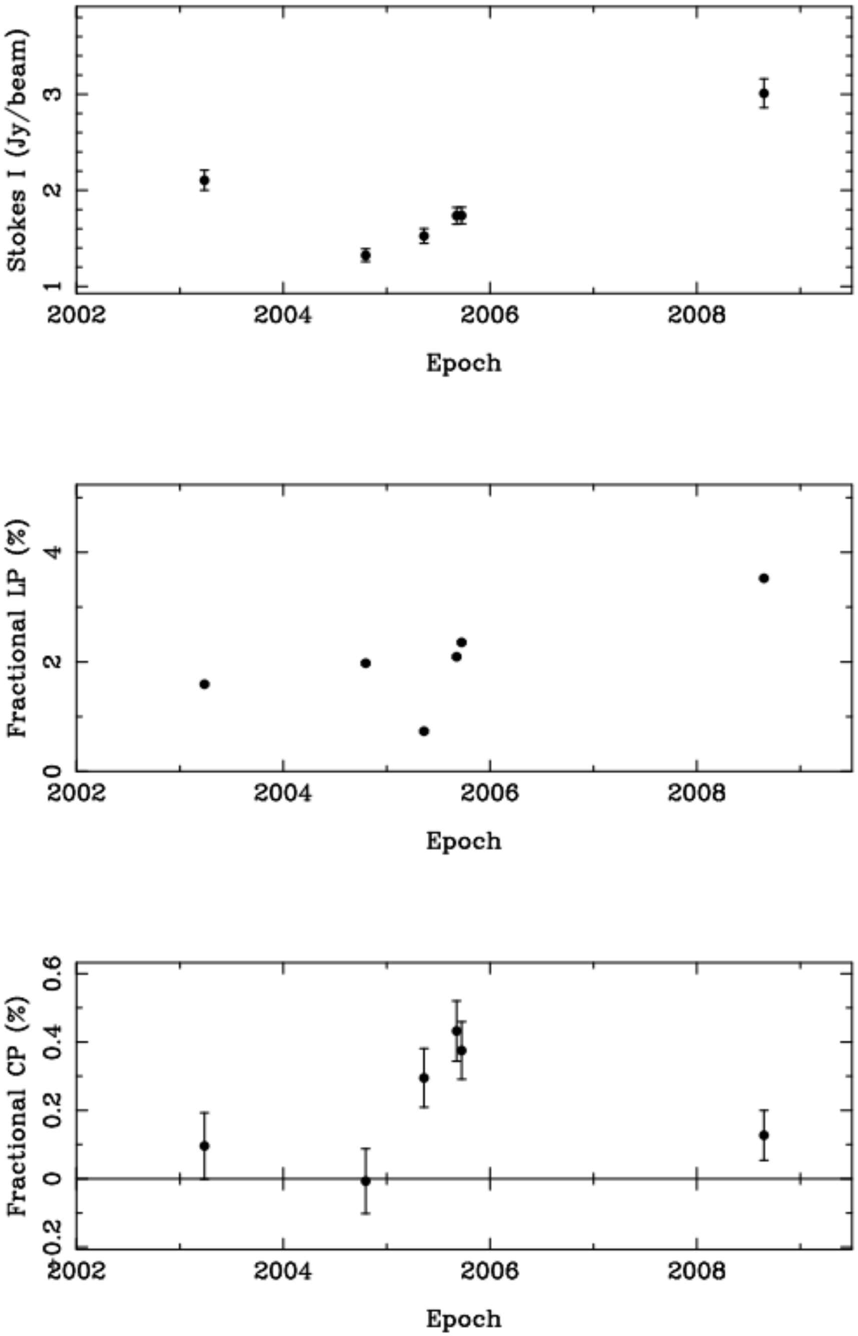
Homan & Lister (2006)

MOJAVE: Quasar 0333+321 (NRAO 140) z = 1.26

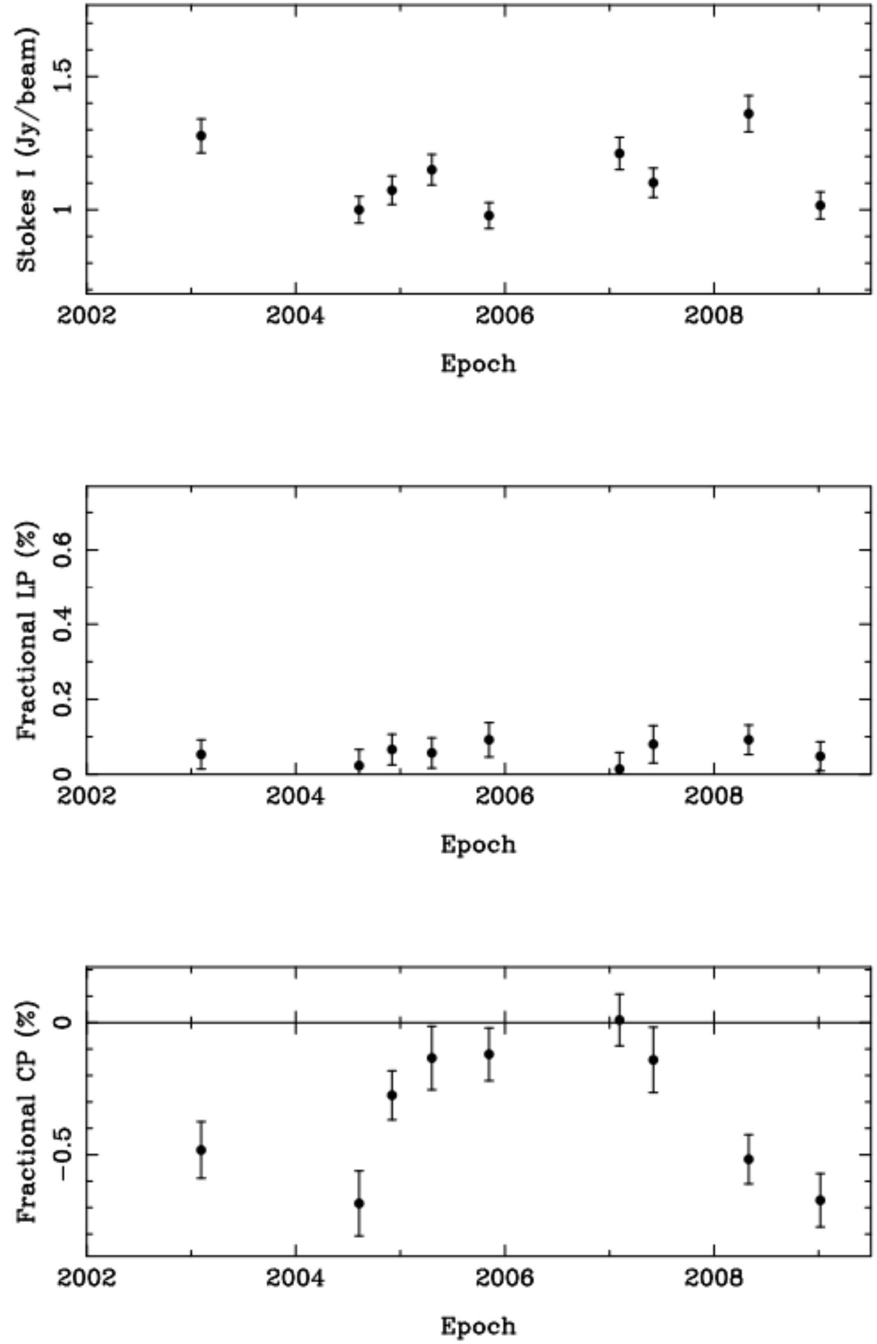



Beam: 0.82x0.59 mas at −14.1 deg., Nat.W
2200+420, Epoch: 2008−11−19,
MOJAVE Program
BL Lac
Relative Declination (mas)
0
−10
−20
10
0
Relative R.A. (m
BL Lac core
Stokes I (Jy/beam)
Fractional LP (%)
Fractional CP (%)
Epoch
2002
2004
2006
2008

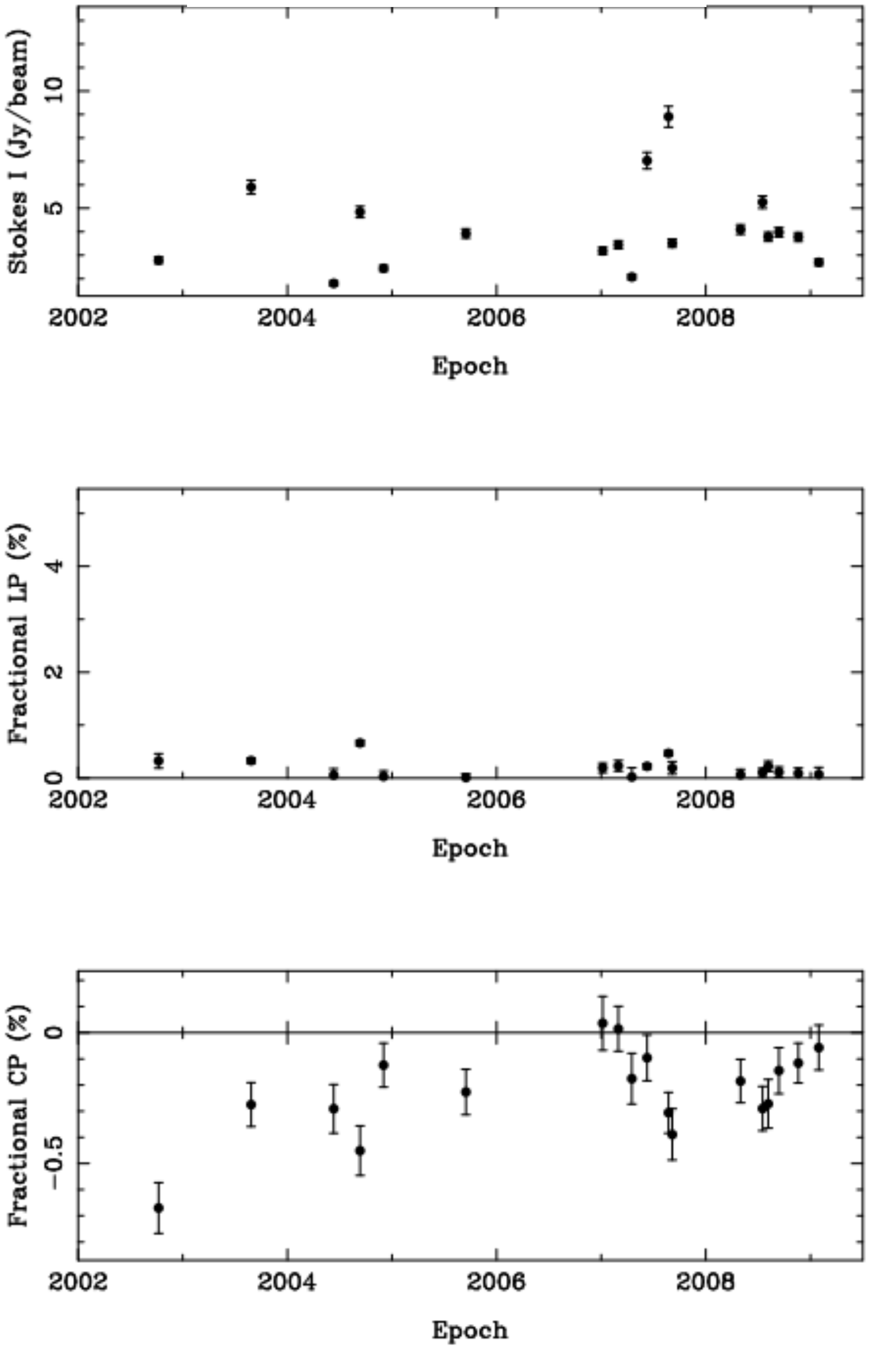
0202+319 Core



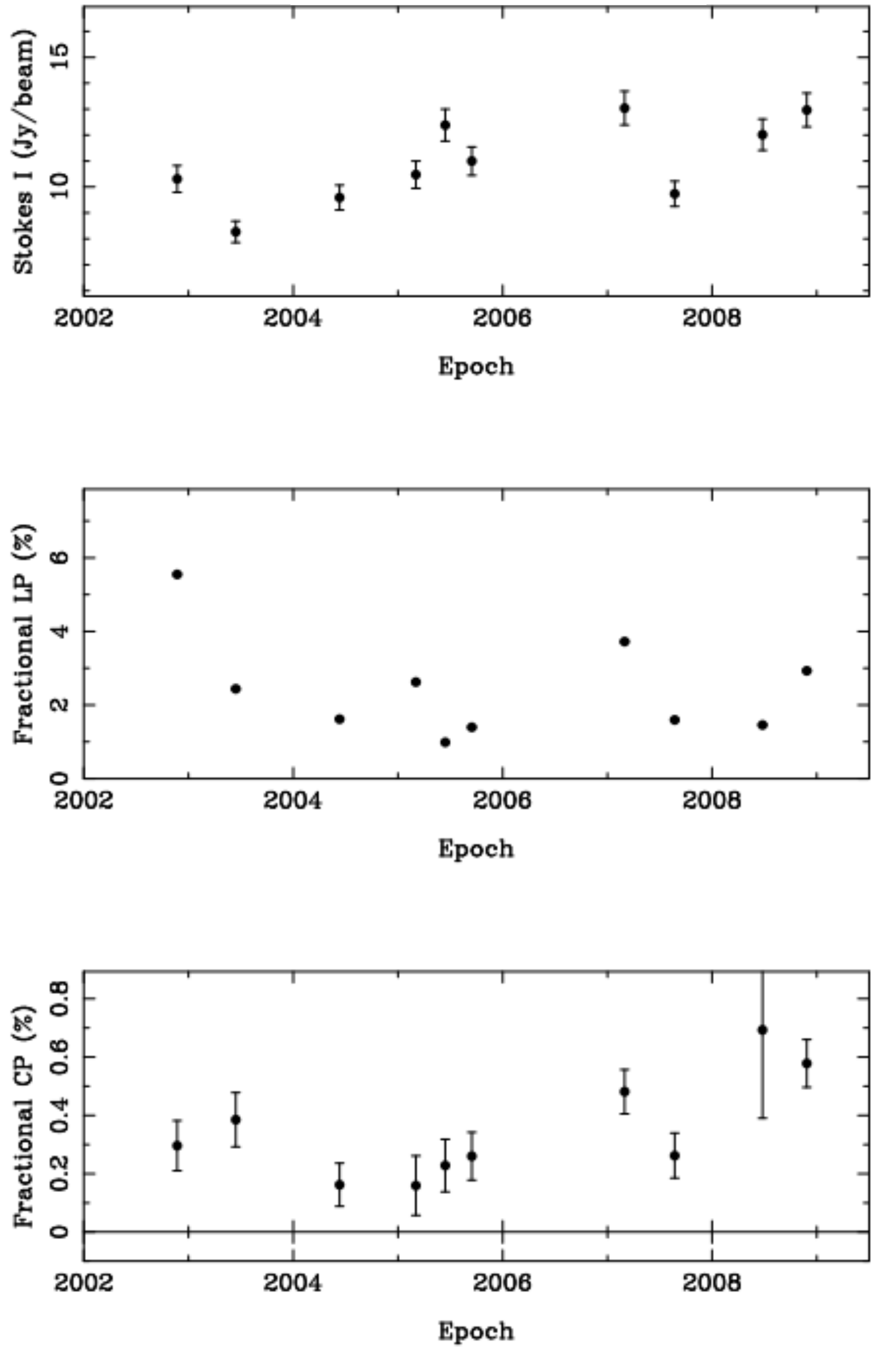
M87 Core



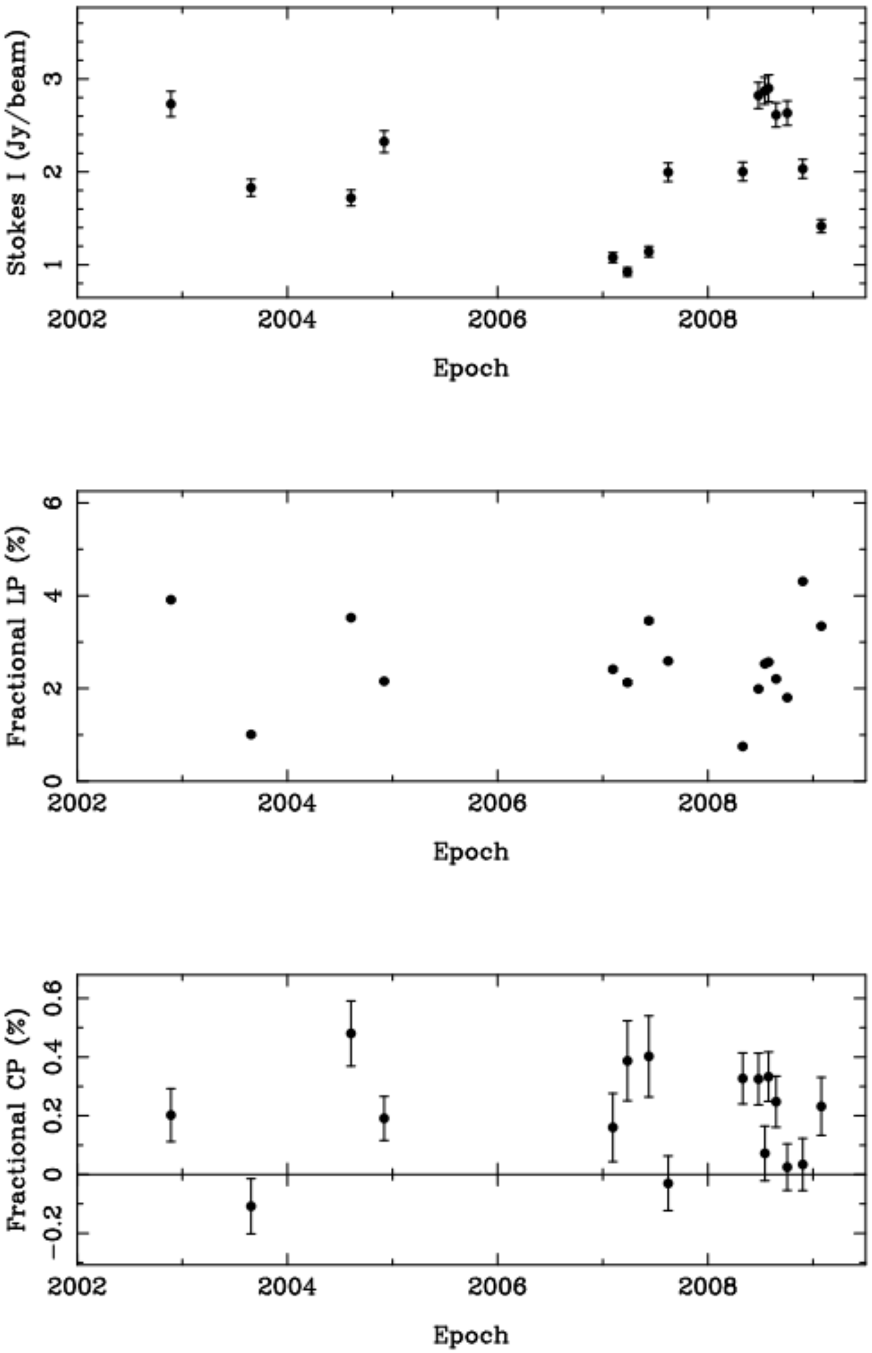
3C 273 Core



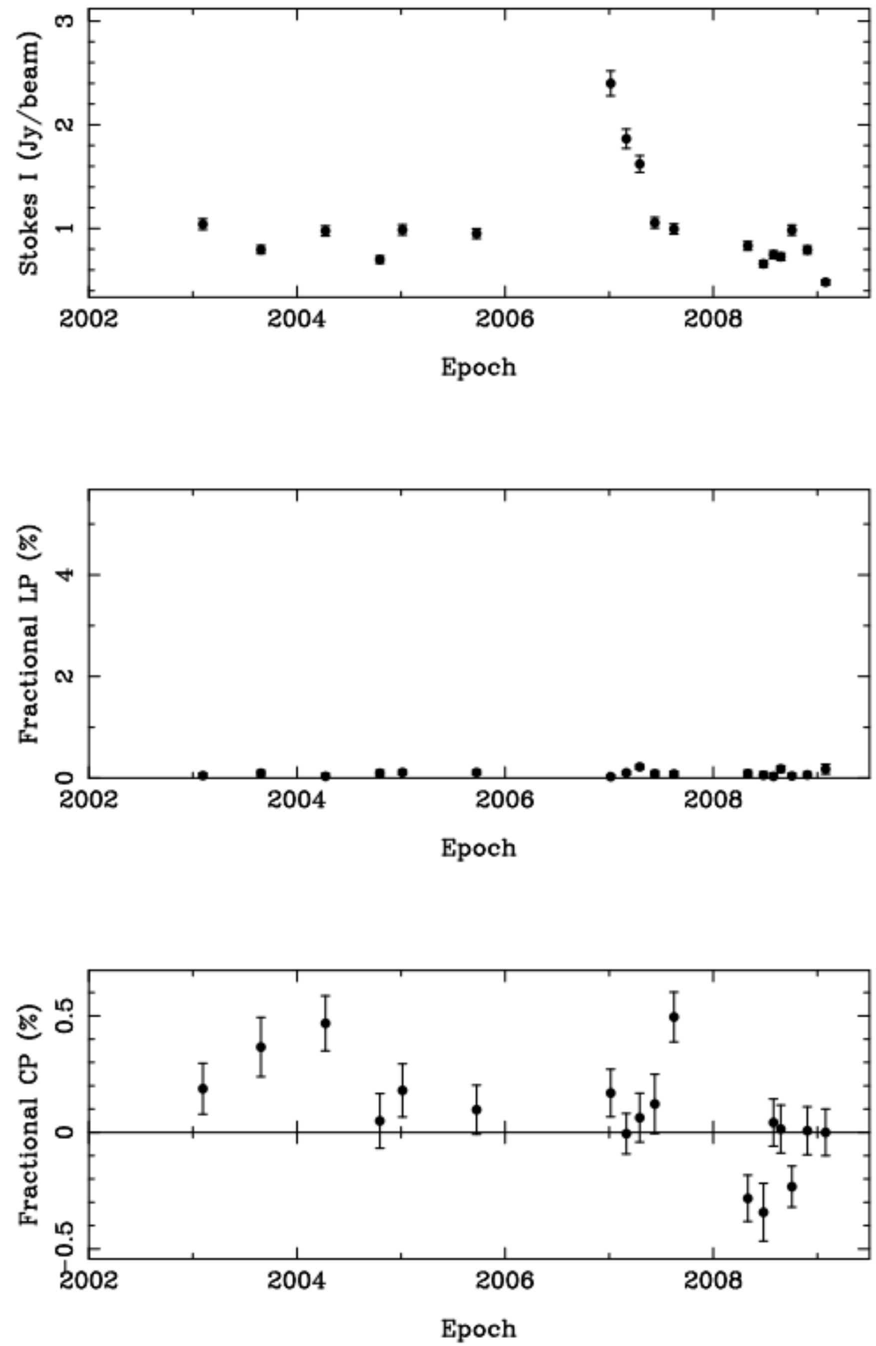
3C279 Core



PKS 1510-089 Core



3C120 Core



Sign Consistency of CP

- Evidence for sign consistency
  - ~ 3-5 years, but not perfect (Komessaroff et al. 1984)
  - ~ 1 year, during an outburst (Homan & Wardle 1999)
  - ~ 20 years for 5/6 sources (Homan, Attridge, & Wardle 2001)
  - ~ 20+ years demonstrated for Sgr A*

    (Bower et al. 2002, Munoz et al. 2012)

    → From a magnetically dominated region very near SMBH? (Johnson et al. 2015)
  - ~ From MOJAVE: 33 sources with multi-epoch 3-sigma CP detections spanning at least a year: 30/33 have a preferred sign

    → Median span for detections is 3.2 years

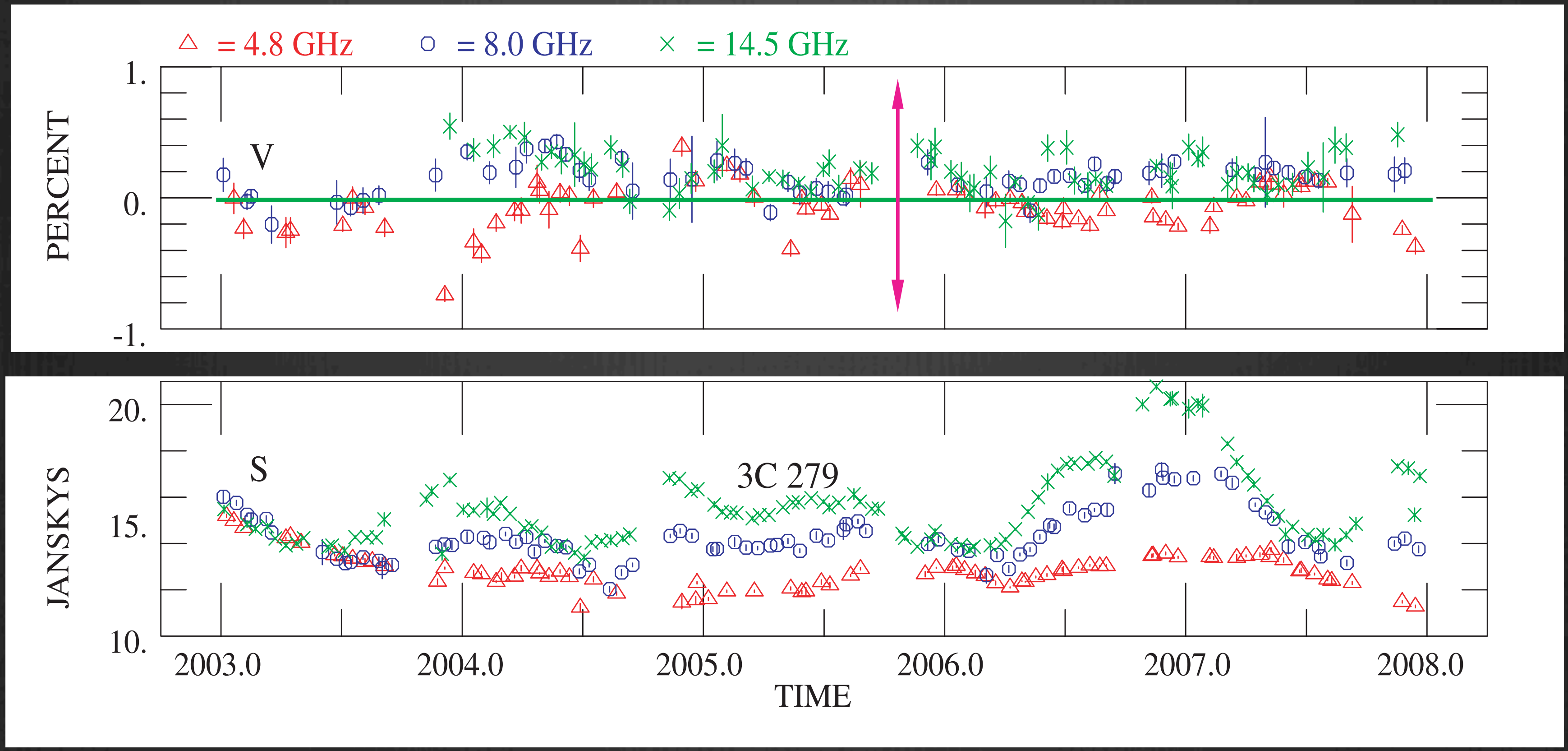
    ~13 years for 3C273 and 3C279 (1996-2009)

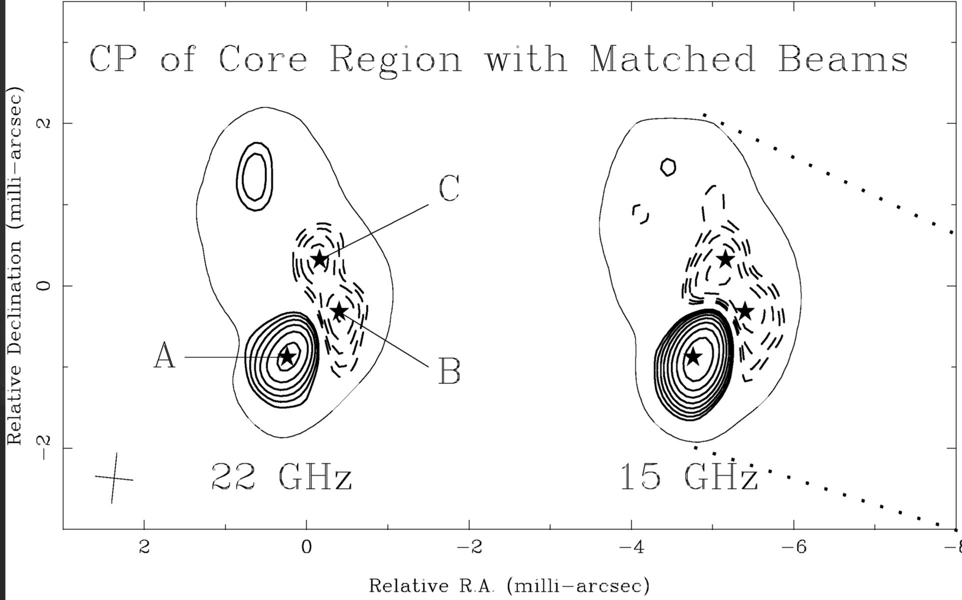
Implications of Sign Preference

- "Magnetic Memory" of the jet
  - If timescale <~ 1 outburst, could be due to just random field components remaining in beam
  - If timescale covers multiple outbursts, likely set by supermassive black-hole/accretion disk system….
    - Poloidal field component
    - Field Helicity (e.g. Hodge 1982, Enßlin 2003)

Frequency Dependence

- 3C 279 at UMRAO
  - Clear sign flips at 4.8 GHz
  - Due to opacity during outbursts? (Homan et al. 2009)





An Extreme Case

3C84 (z = 0.017)

	m_c (15 GHz)	m_c (22 GHz)	spectrum
A	+3.2 ± 0.1 %	+2.3 ± 0.2 %	$\nu^{-0.9 \pm 0.3}$
B	–0.7 ± 0.1 %	–1.3 ± 0.2 %	$\nu^{+1.7 \pm 0.6}$
C	–0.6 ± 0.1 %	–1.0 ± 0.2 %	$\nu^{+1.4 \pm 0.7}$

Homan & Wardle 2004

Expected Spectrum For Optically Thin Emission

- Intrinsic

$$m_c \propto \upsilon^{-0.5}$$

- Conversion

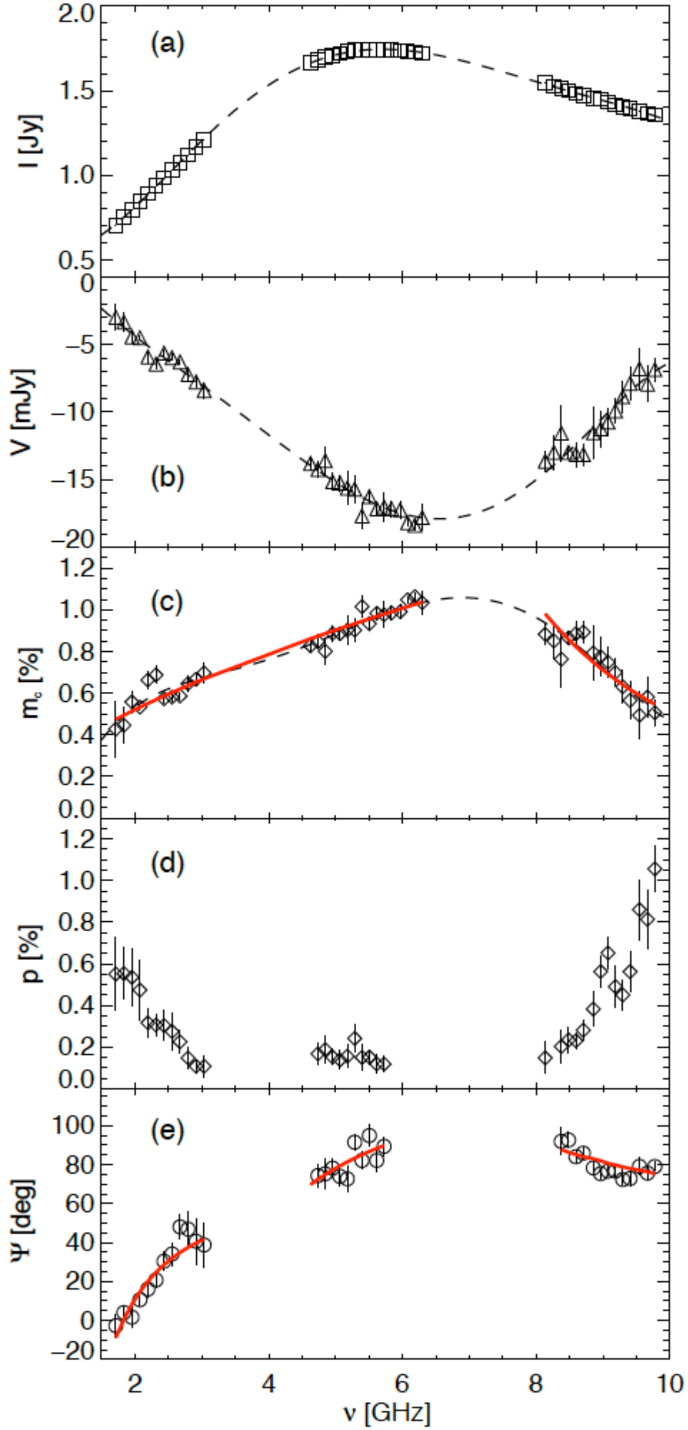
$$m_c \propto \upsilon^{-3}$$

Or Steeper…

Spectrum of CP

- Optical Depth
  - Optical Depth can modify spectrum and/or flip sign
  - Inhomogeneous jet structure may further complicate spectrum (e.g. Wardle & Homan 2003)
  - CP appears strongest near $\tau \sim 1$, <u>but</u> that may be a selection effect

- Stronger at higher frequencies?
  - Vitrishchak et al. (2008) found multiple examples of strong CP (0.5-1.5%) at 43 GHz
  - Agudo et al. (2010, 2014), IRAM observations at 86 GHz had a smaller detection rate than MOJAVE but similar strong/stronger cases when detected: ~ 0.5% up to 2.0%



PKS 2126-158

(O'Sullivan et al. 2013)

- Extremely Detailed Spectra
  - ATCA broad band + crossed linear feeds
  - Optically Thick Emission:

$$m_c \propto \upsilon^{+0.60\pm0.03}$$

  - Optically Thin Emission:

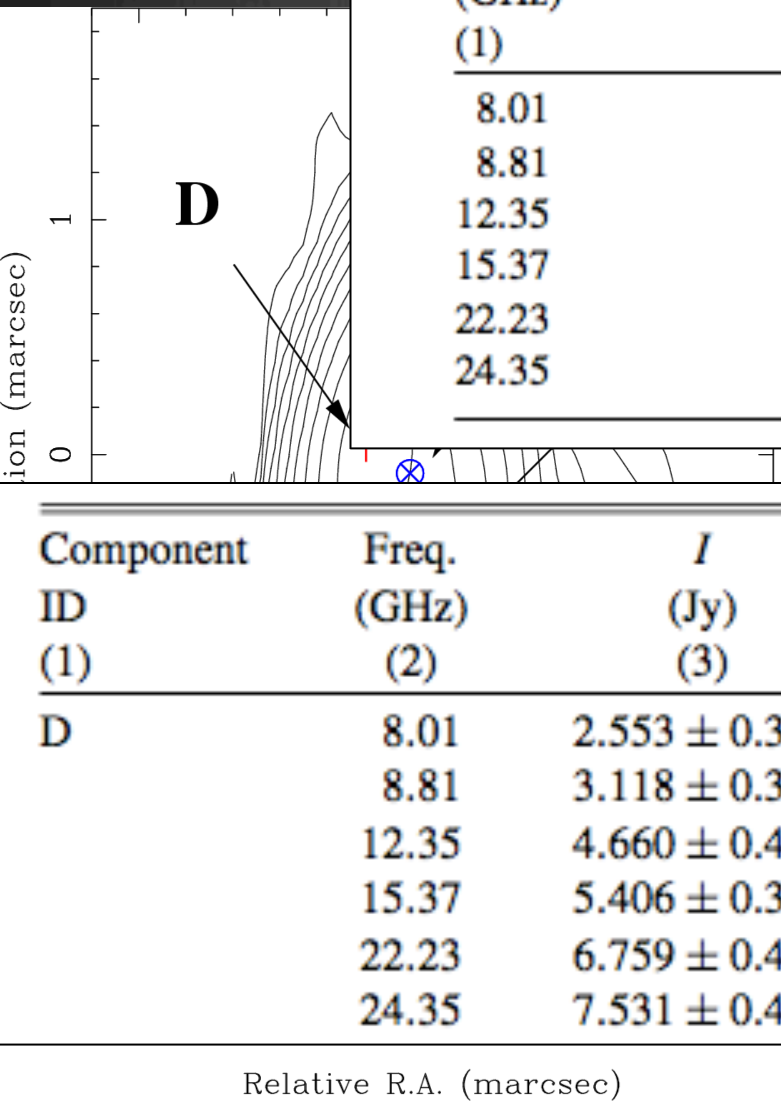
$$m_c \propto \upsilon^{-3.0\pm0.4}$$

→ Consistent w/ Faraday Conversion

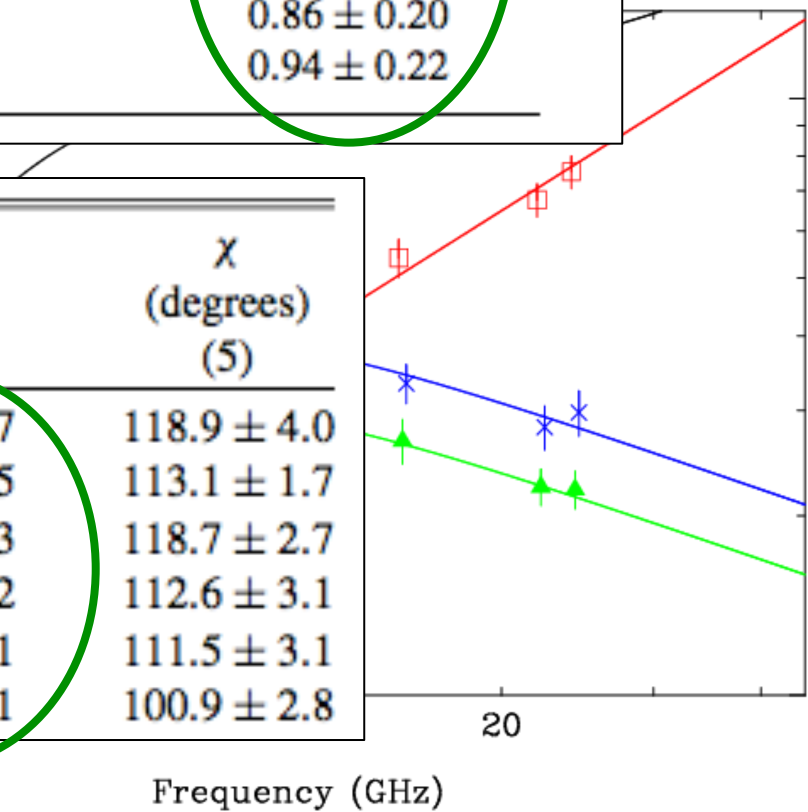
l. 2009

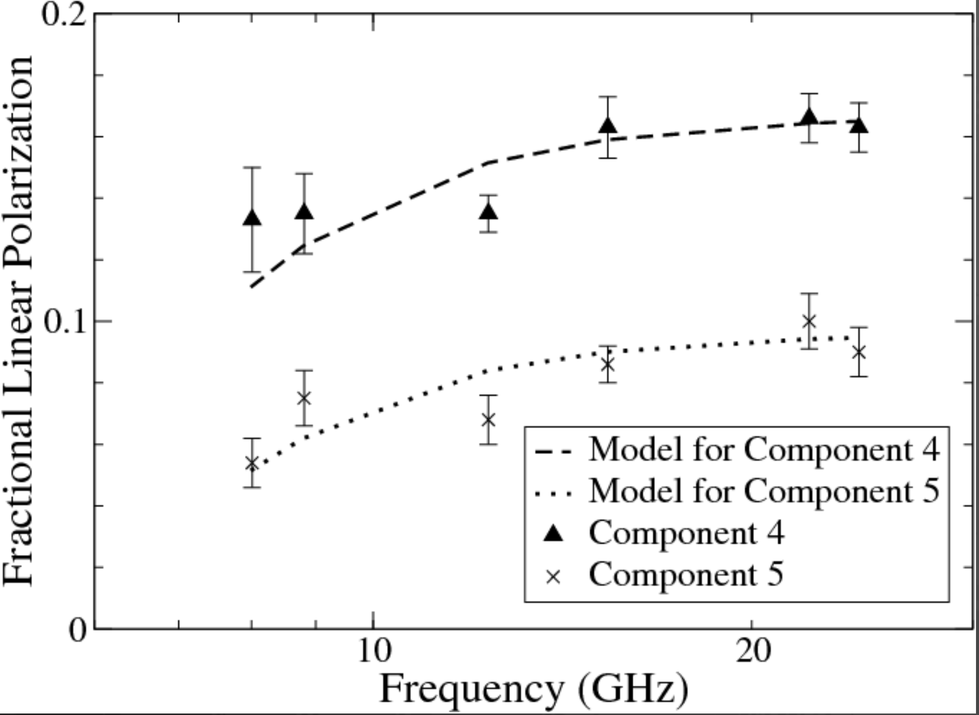
Table 1
Circular Polarization of Core Region

Measured Values		If All Stokes V on "D"
Freq. (GHz) (1)	V (mJy) (2)	m_c (%) (3)
8.01	50.8 ± 9.6	1.99 ± 0.38
8.81	48.2 ± 8.0	1.55 ± 0.26
12.35	...	...
15.37	47.6 ± 7.9	0.88 ± 0.15
22.23	58.2 ± 13.4	0.86 ± 0.20
24.35	71.0 ± 16.5	0.94 ± 0.22

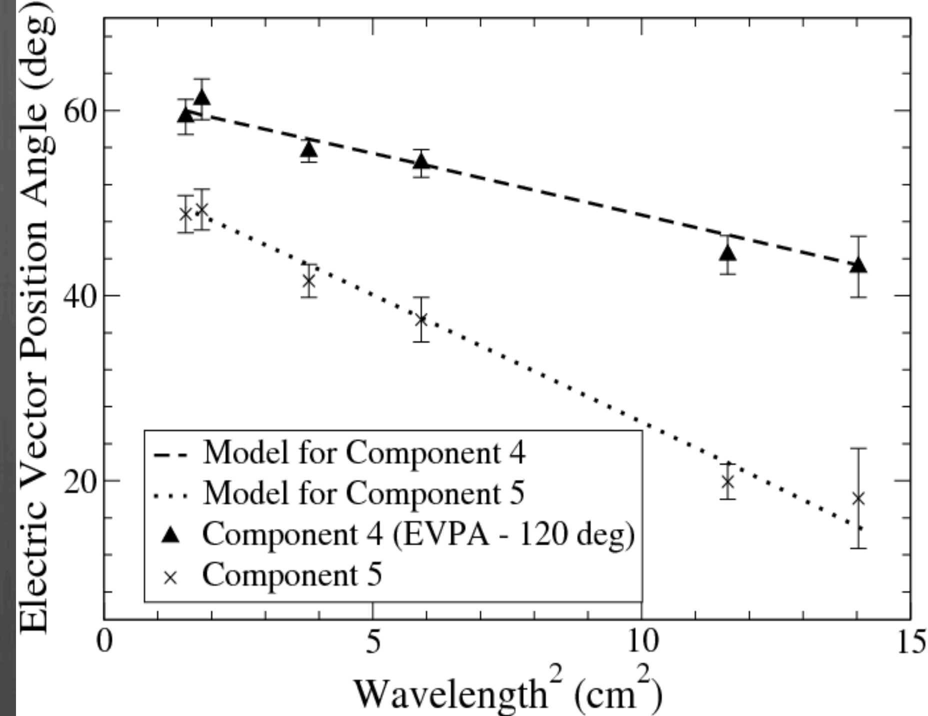


Component ID (1)	Freq. (GHz) (2)	I (Jy) (3)	m_l (%) (4)	χ (degrees) (5)
D	8.01	2.553 ± 0.301	3.3 ± 0.7	118.9 ± 4.0
	8.81	3.118 ± 0.304	3.9 ± 0.5	113.1 ± 1.7
	12.35	4.660 ± 0.441	3.0 ± 0.3	118.7 ± 2.7
	15.37	5.406 ± 0.393	2.5 ± 0.2	112.6 ± 3.1
	22.23	6.759 ± 0.431	2.4 ± 0.1	111.5 ± 3.1
	24.35	7.531 ± 0.476	2.2 ± 0.1	100.9 ± 2.8

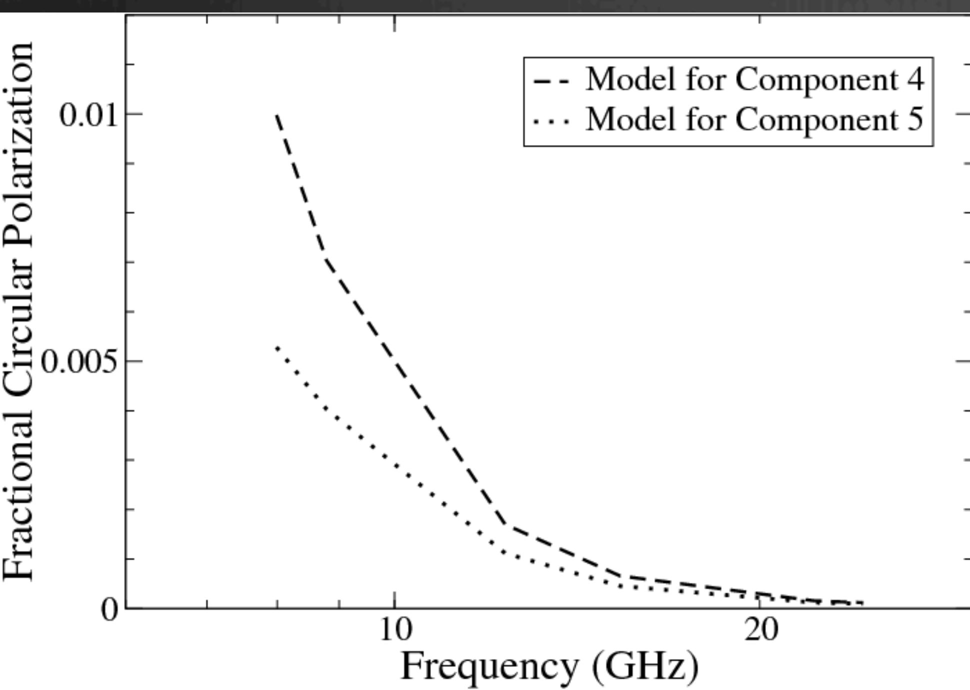




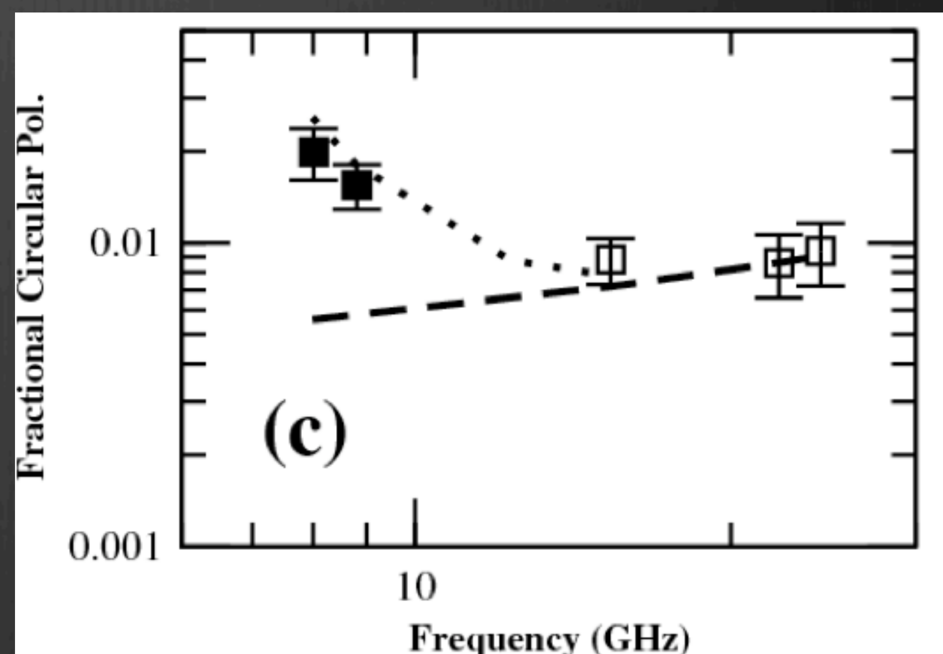
Fractional Linear Polarization
Frequency (GHz)
0
0.1
0.2
10
20
Model for Component 4
Model for Component 5
Component 4
Component 5



Electric Vector Position Angle (deg)
Wavelength^2 (cm^2)
20
40
60
0
5
10
15
Model for Component 4
Model for Component 5
Component 4 (EVPA - 120 deg)
Component 5



Fractional Circular Polarization
Frequency (GHz)
0
0.005
0.01
10
20
Model for Component 4
Model for Component 5



Fractional Circular Pol.
Frequency (GHz)
0.001
0.01
10
(c)

Multi-band Radiative Transfer

- For Jet Core Region in 3C279
  (Homan et al. 2009)
  - Model: Inhomogeneous Core ("D")
    + Two homogeneous components ("4" and "5")
  - Intrinsic CP important at high frequency
  - Faraday Conversion dominates at lower frequency

- Estimated Physical Parameters
  - Relativistic low energy cutoff: $5 \leq$ [illegible]$_1 \leq 35$
  - Strong poloidal magnetic field in core of jet:
    → Estimated flux: 2×10^{34} - 1×10^{35} G cm^2
  - Jet is dynamically dominated by protons.

Particle Content

- First parsec-scale CP observations of 3C279
  (Wardle et al. 1998)
  - *Faraday Conversion*
  - Low cutoff in relativistic particle spectrum ([illegible]$_1 \leq 20$)
    - → large number of particles in jet
    - → electron-positron jet on K.E. grounds
      (e.g. Celotti & Fabian 1993)
  - Could there be thermal matter in the jet instead?
    (Beckert & Falcke 2002; Ruskowski & Begelman 2002)

- Six-Frequency Observations: *Intrinsic + Faraday Conversion*
  (Homan et al. 2009)
  - *Intrinsic* → Likely not pair dominated
  - *Conversion* → Low energy particle cutoff: $5 \leq$ [illegible]$_1 \leq 35$

Summary

- Circular polarization is typically a small fraction < 0.3% of Stokes-I emission on VLBI scales in cm-wavelengths
  - ~ 20% of sources show repeated detections ≥ 0.3%, and tend to be variable but with a preferred sign for that jet

    → A persistent component of ordered field…. set by the SMBH/ Accretion disk system?
  - Faraday Conversion is the likely mechanism at cm-wavelength

    → Can constrain low energy relativistic particle spectrum
  - Intrinsic CP may play a important role at shorter wavelengths

    → May be possible to constrain net magnetic flux in jet

    → Linear polarization results at 229 GHz by Agudo et al. (2014) indicate a more highly ordered field, and higher sensitivity CP studies would be valuable.

- Little correlation is seen with other source properties and most sources are not detected.
  - What can we learn from the non-detections?

MOJAVE Team

http://www.physics.purdue.edu/astro/MOJAVE/

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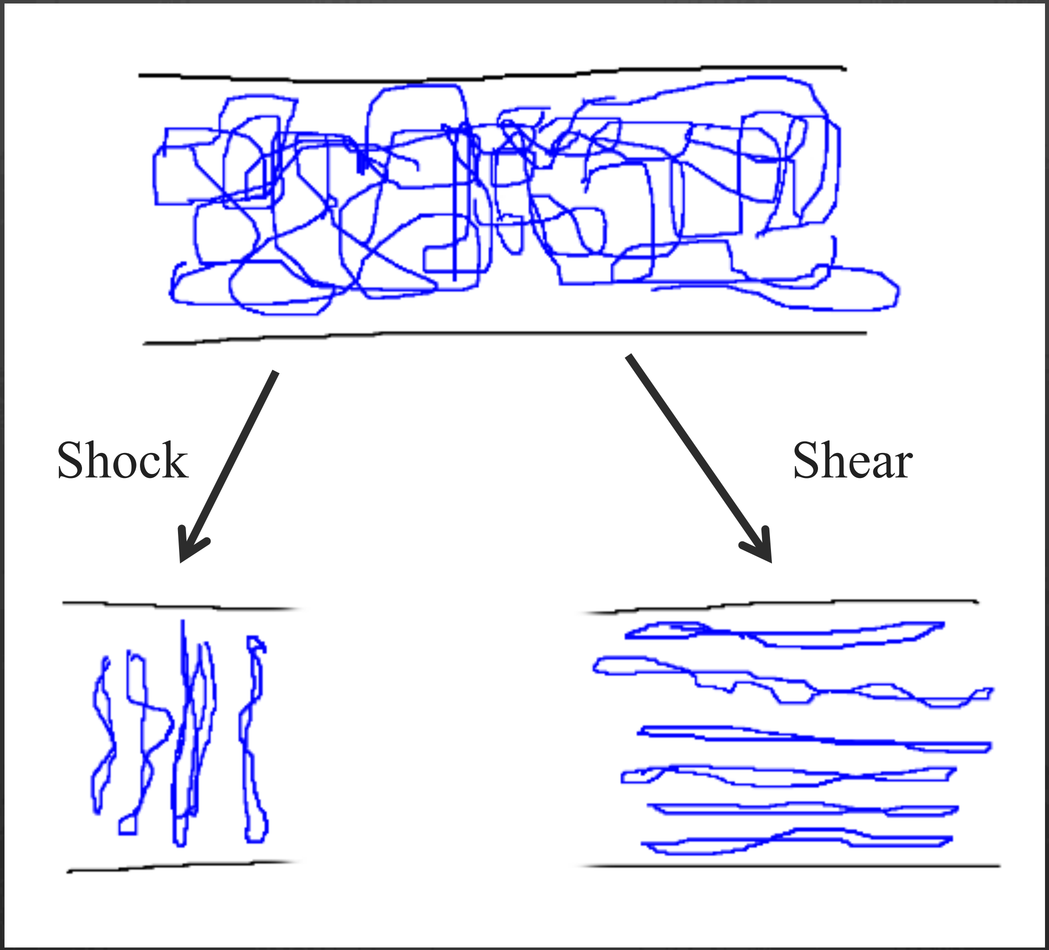
Possible Field Order in Jets



Possible Field Order in Jets