Measuring polarization with radio interferometers

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National Radio Astronomy Observatory

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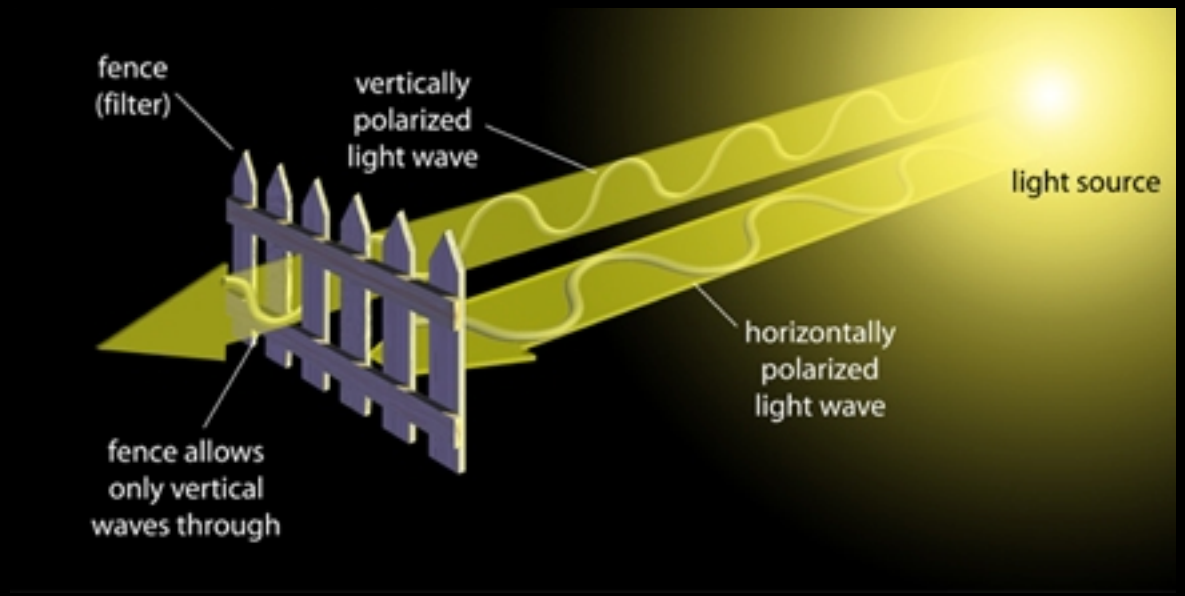
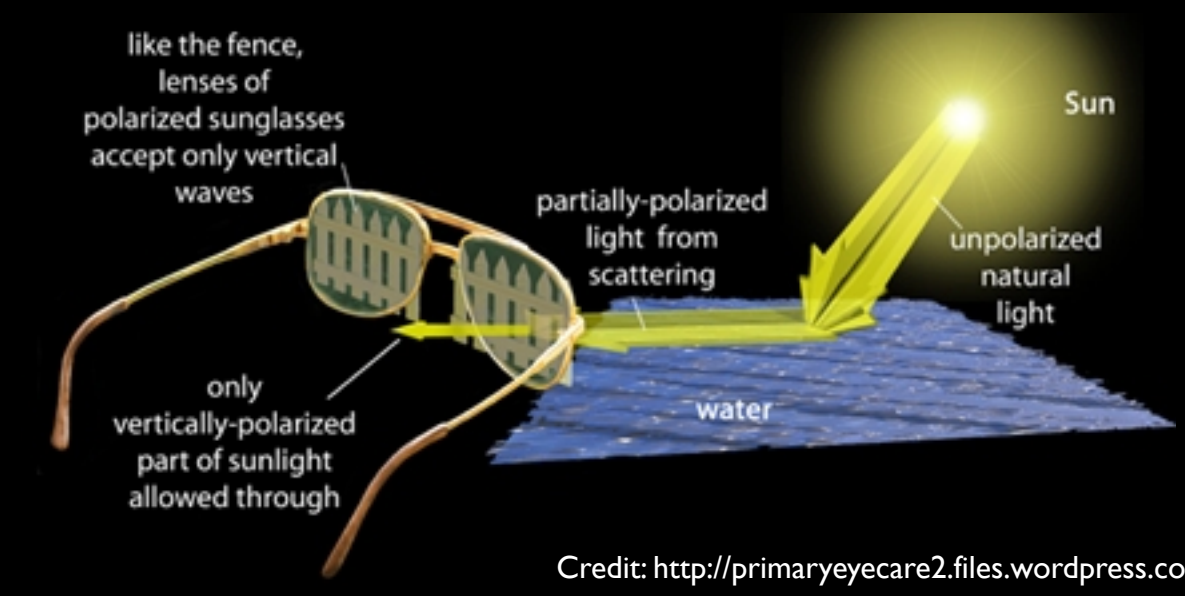
NRAO NAASC Interferometry Summer School
Green Bank, WV

What is polarization?

Polarization





Credit: http://primaryeyecare2.files.wordpress.com/2009/03/polarization.jpg

Why measure polarization?

Magnetic fields!

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.

LODEWIJK WOLTJER, 1966

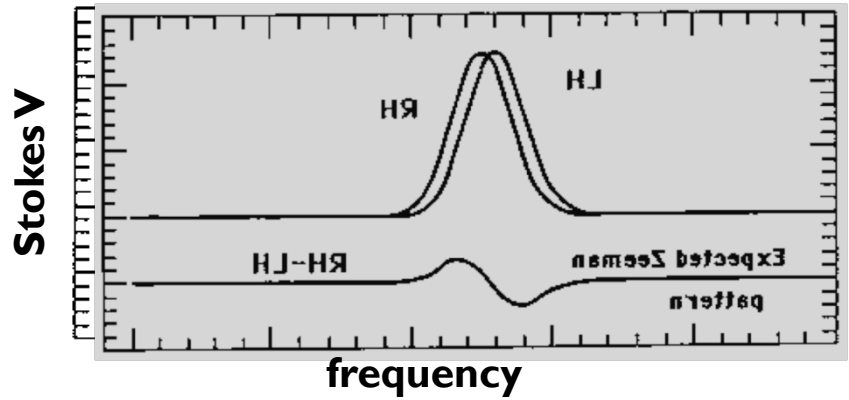
Credit: Tim Robishaw, Thesis, 2008

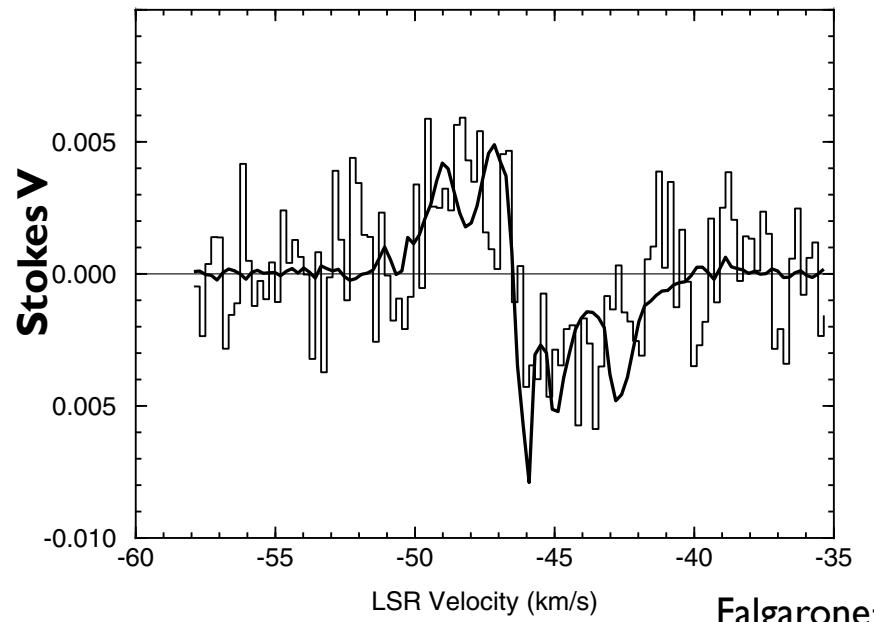
Effects caused by magnetic fields

- **Zeeman splitting**
- **Goldreich-Kylafis effect**
- **Synchrotron emission**
- **Faraday rotation**
- **Dust grain alignment**

Effects caused by magnetic fields

- **Zeeman splitting**
  - **Spectral line, measures $B_{||}$**
- Goldreich-Kylafis effect
- Synchrotron emission
- Faraday rotation
- Dust grain alignment

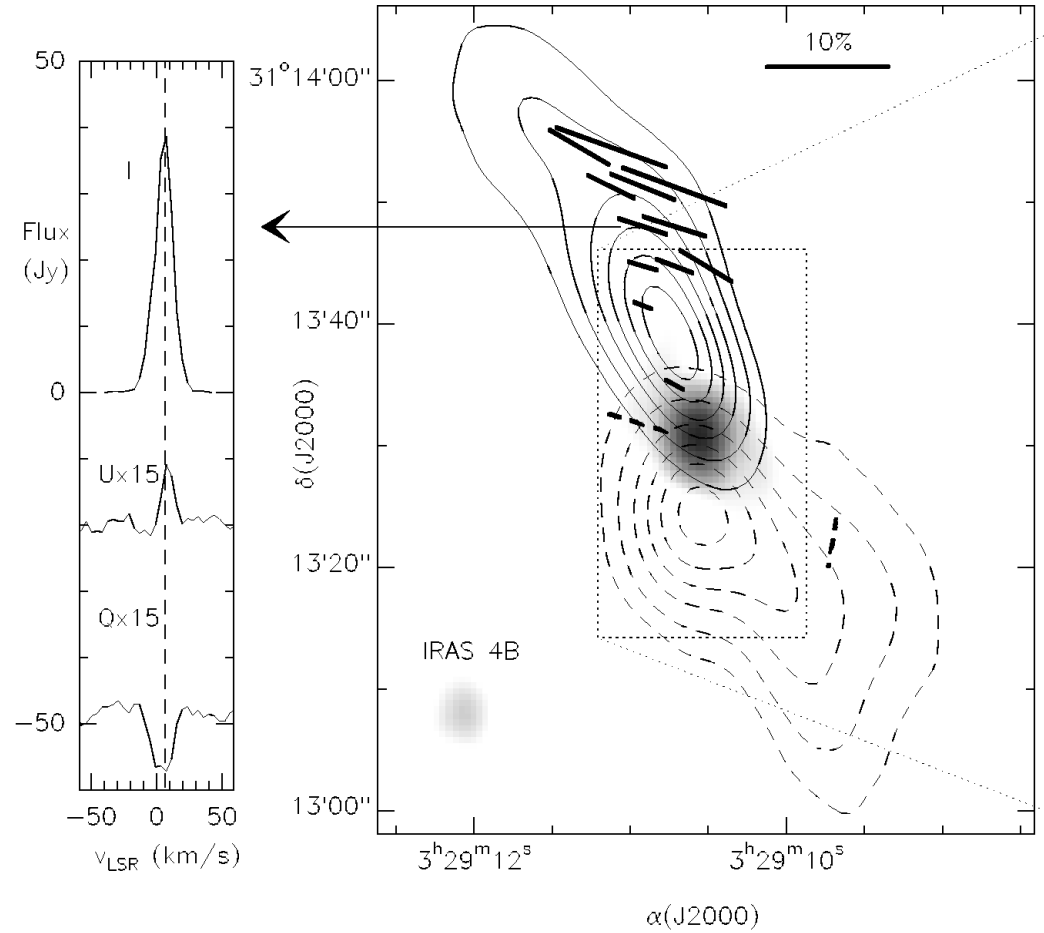




Falgarone+2008

Effects caused by magnetic fields

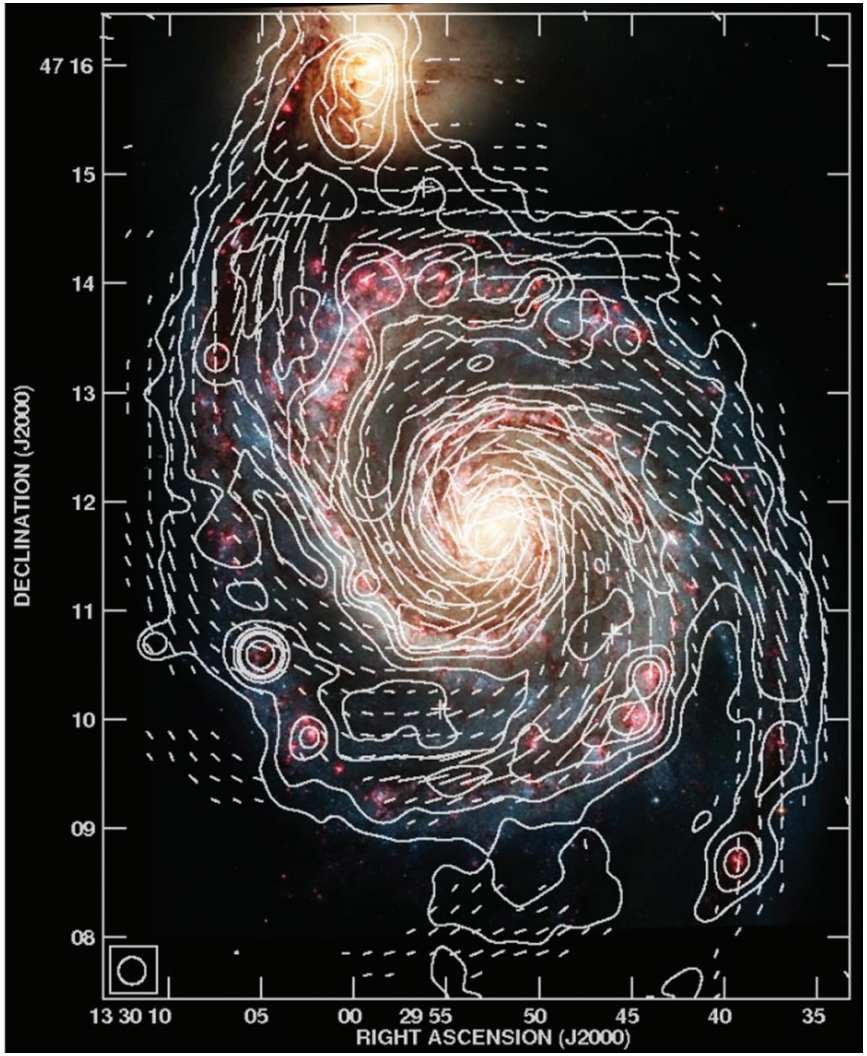
- Zeeman splitting
- **Goldreich-Kylafis effect**
  - **Spectral line, measures $B_\perp$ (90° ambig.)**
- Synchrotron emission
- Faraday rotation
- Dust grain alignment



Girart+1999

Effects caused by magnetic fields

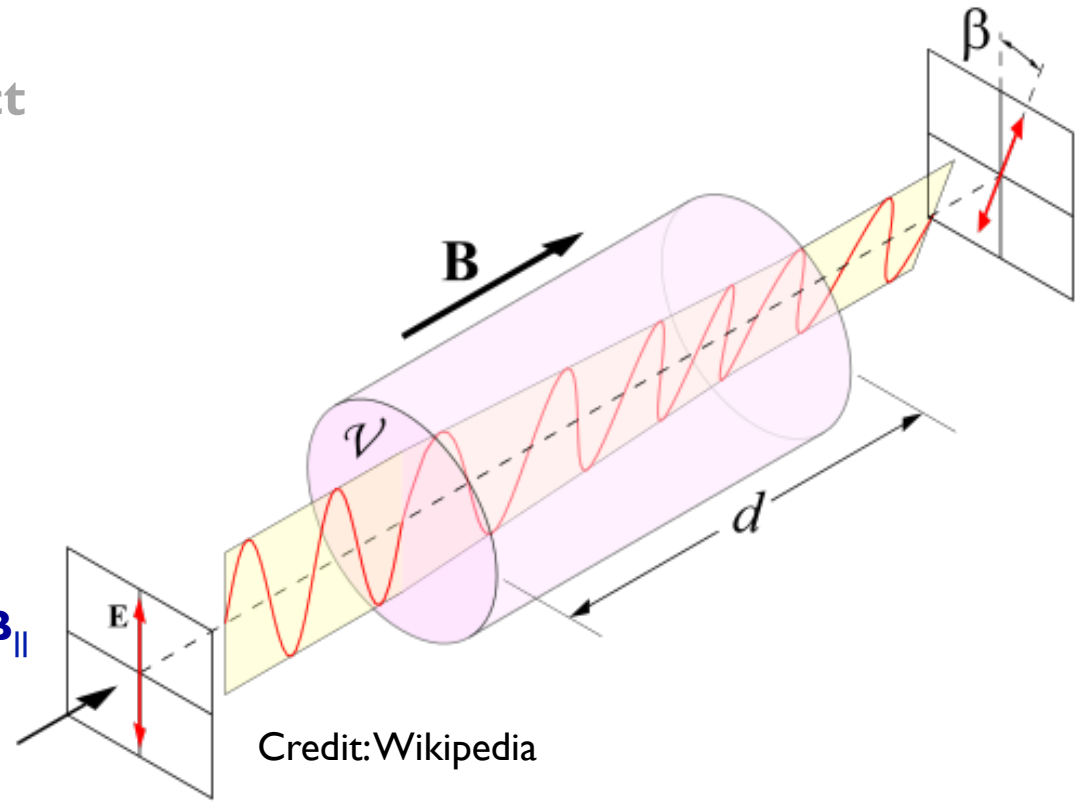
- Zeeman splitting
- Goldreich-Kylafis effect
- **Synchrotron emission**
  - **Continuum, measures $B_{\perp}$ or B_{tot}**
- Faraday rotation
- Dust grain alignment



Fletcher+2011

Effects caused by magnetic fields

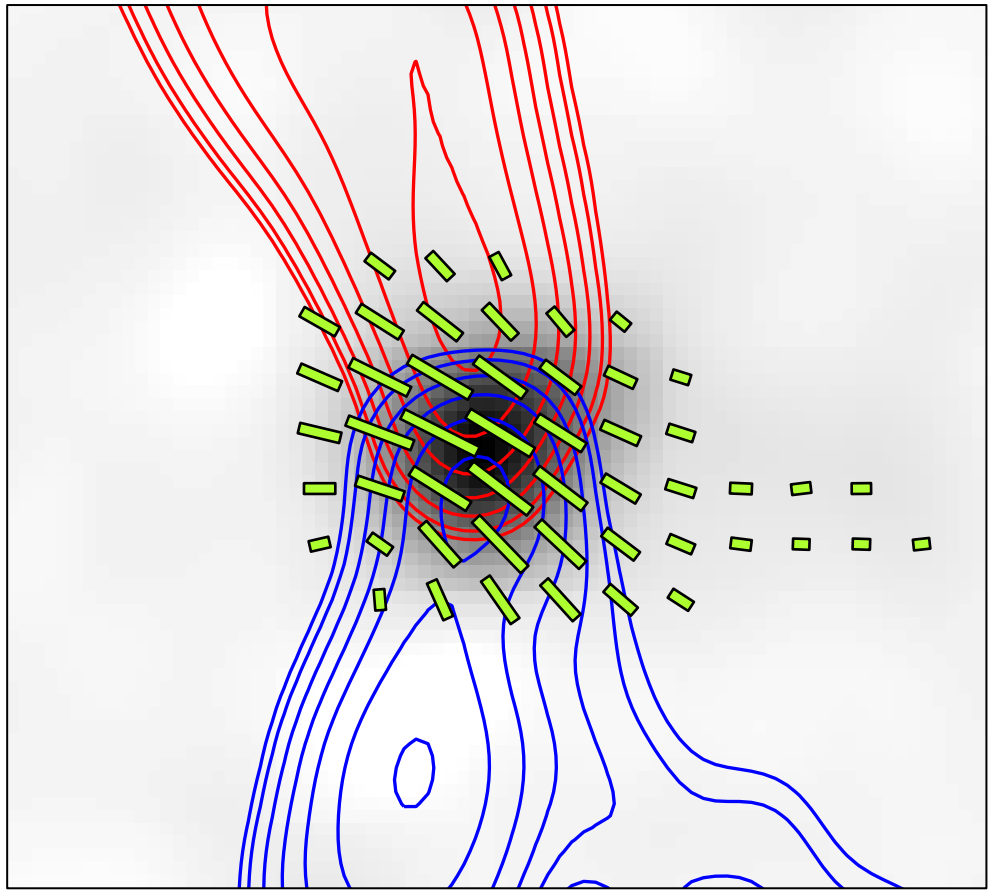
- Zeeman splitting
- Goldreich-Kylafis effect
- Synchrotron emission
- **Faraday rotation**
  - **Continuum, measures $B_{||}$**
- Dust grain alignment



Credit: Wikipedia

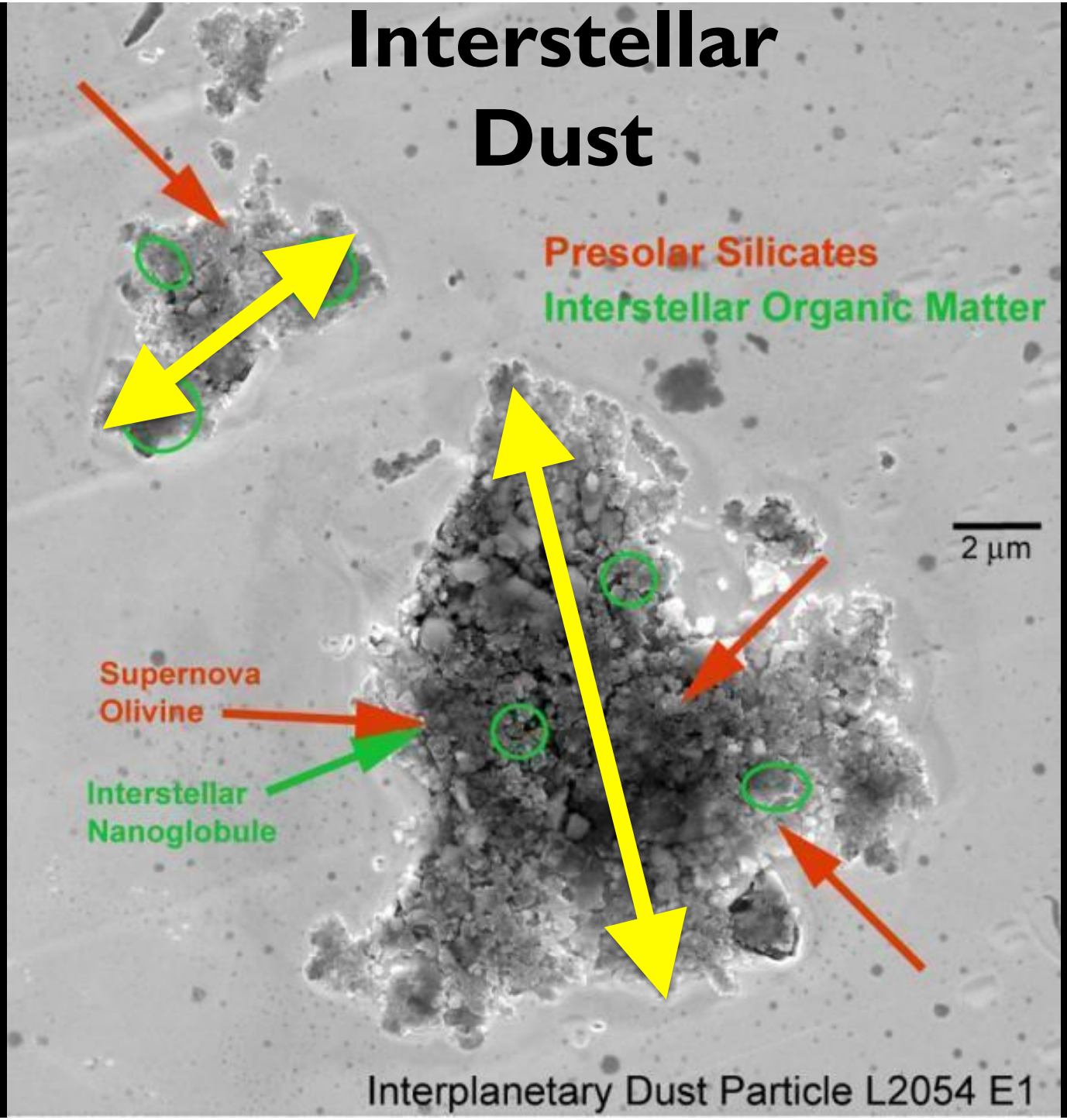
Effects caused by magnetic fields

- Zeeman splitting
- Goldreich-Kylafis effect
- Synchrotron emission
- Faraday rotation



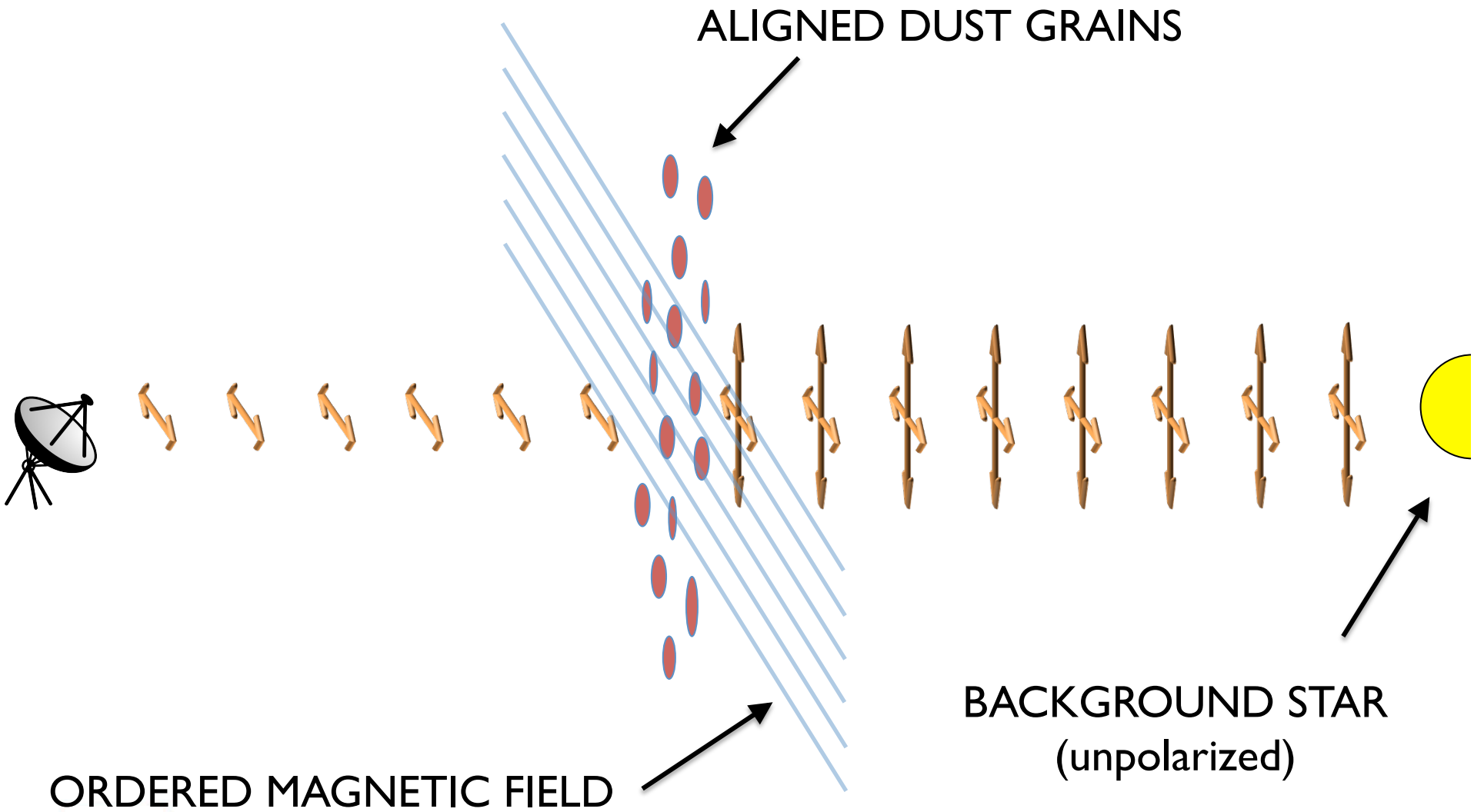
- **Dust grain alignment – continuum, measures $B_\perp$**

Interstellar Dust

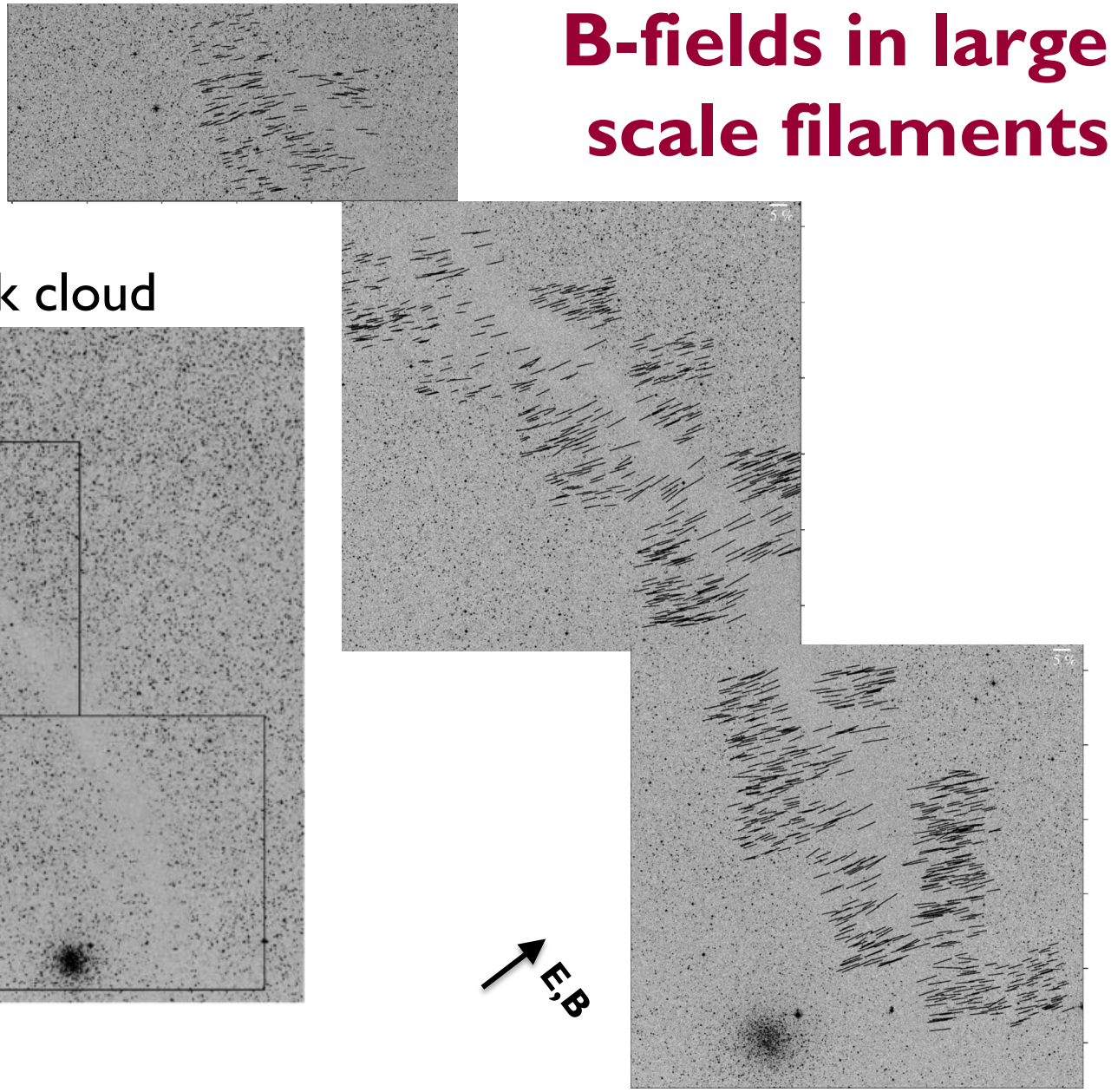


Credit: H. Busemann, U. of Manchester

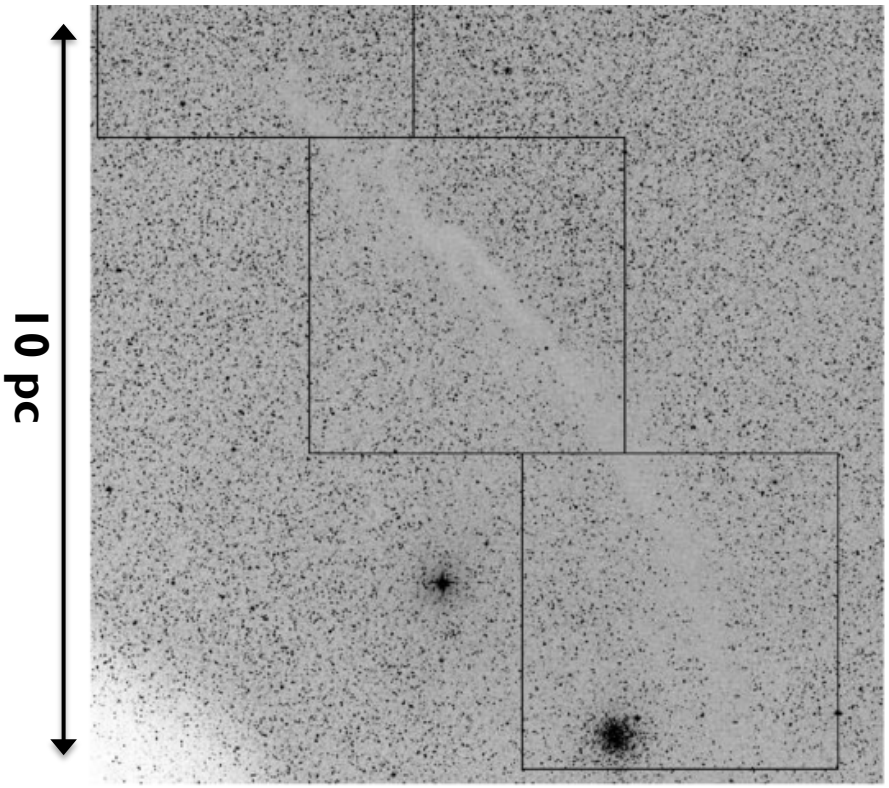
Polarization (via dust absorption)



B-fields in large-scale filaments

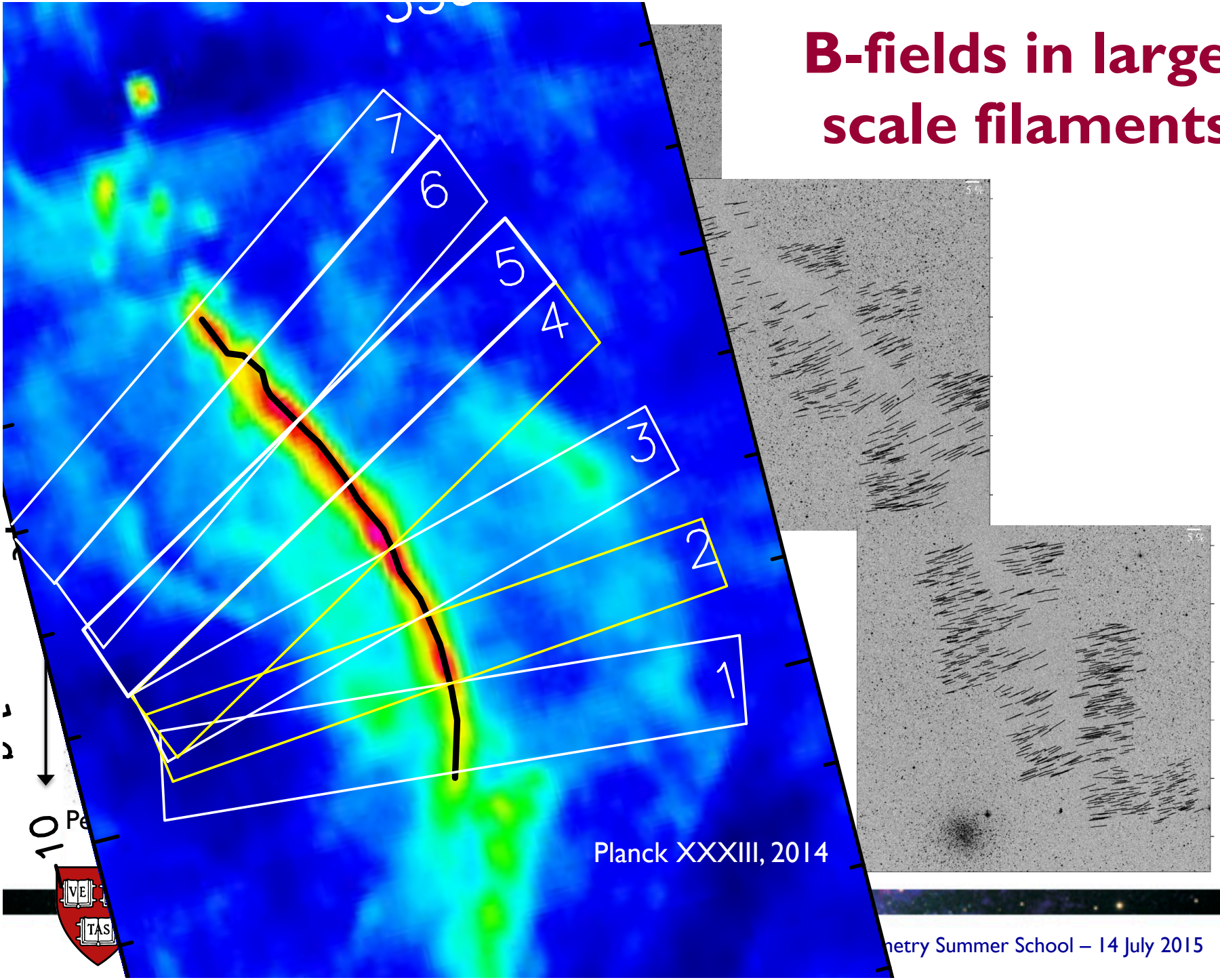


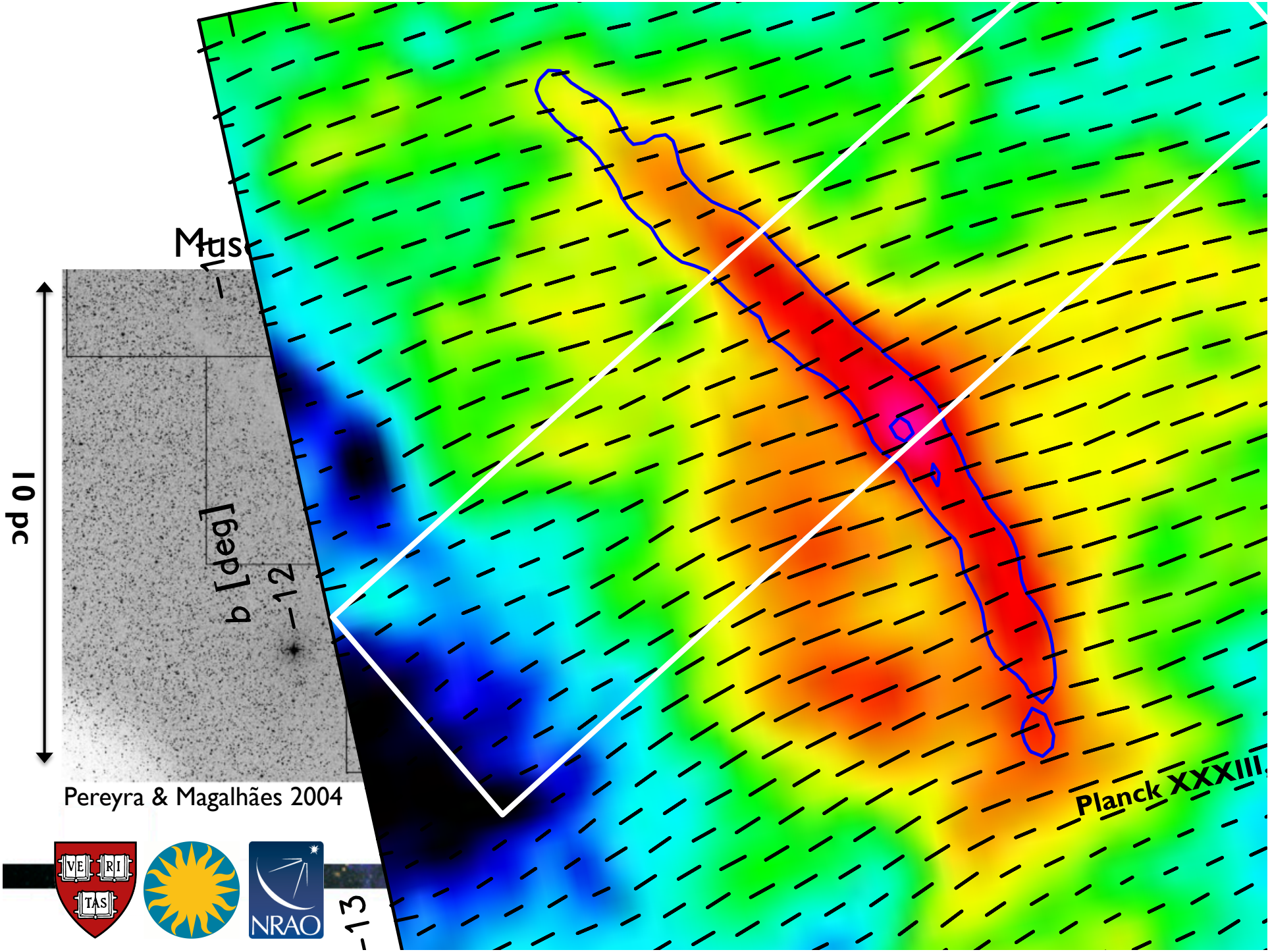
Musca dark cloud



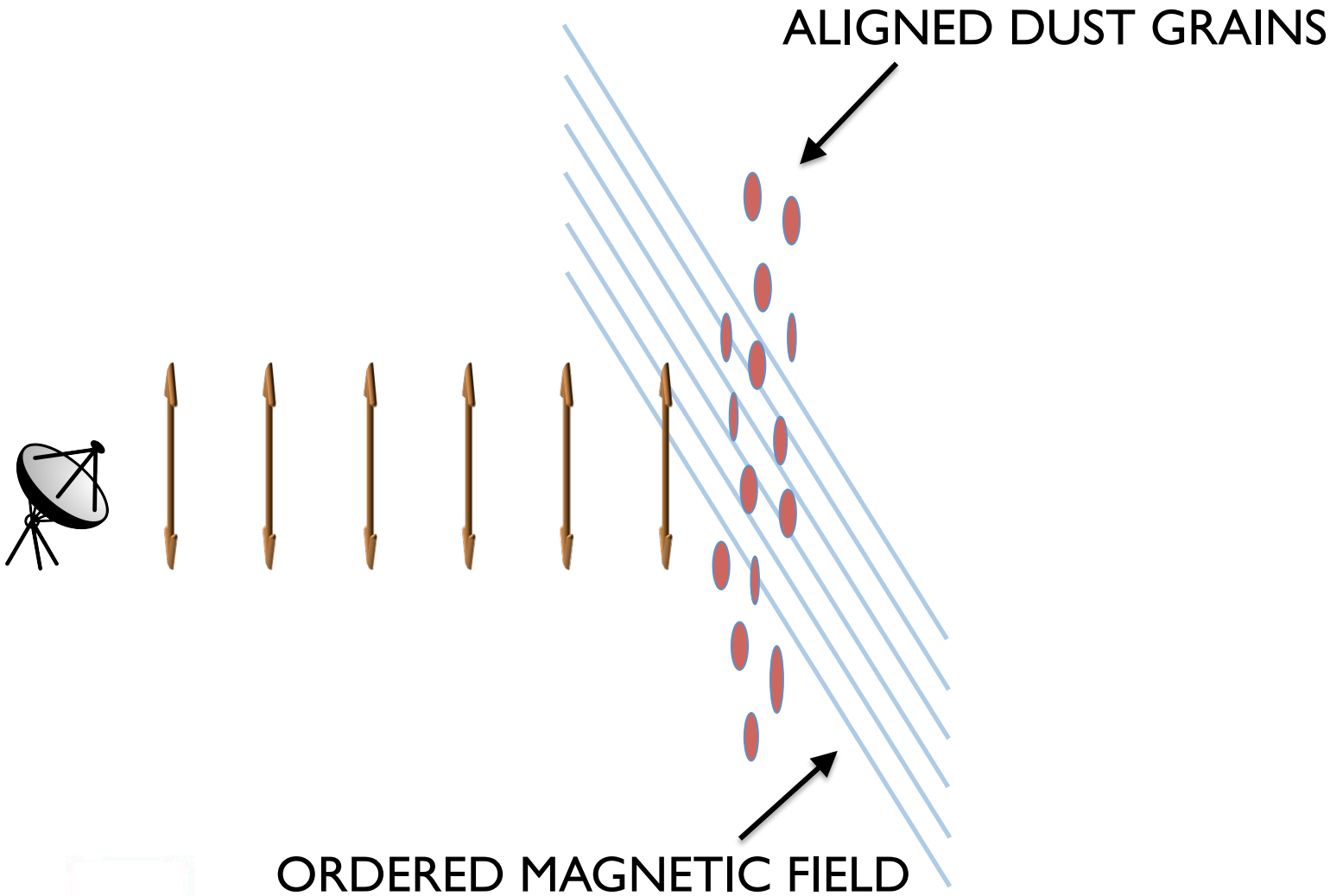
Pereyra & Magalhães 2004

B-fields in large-scale filaments



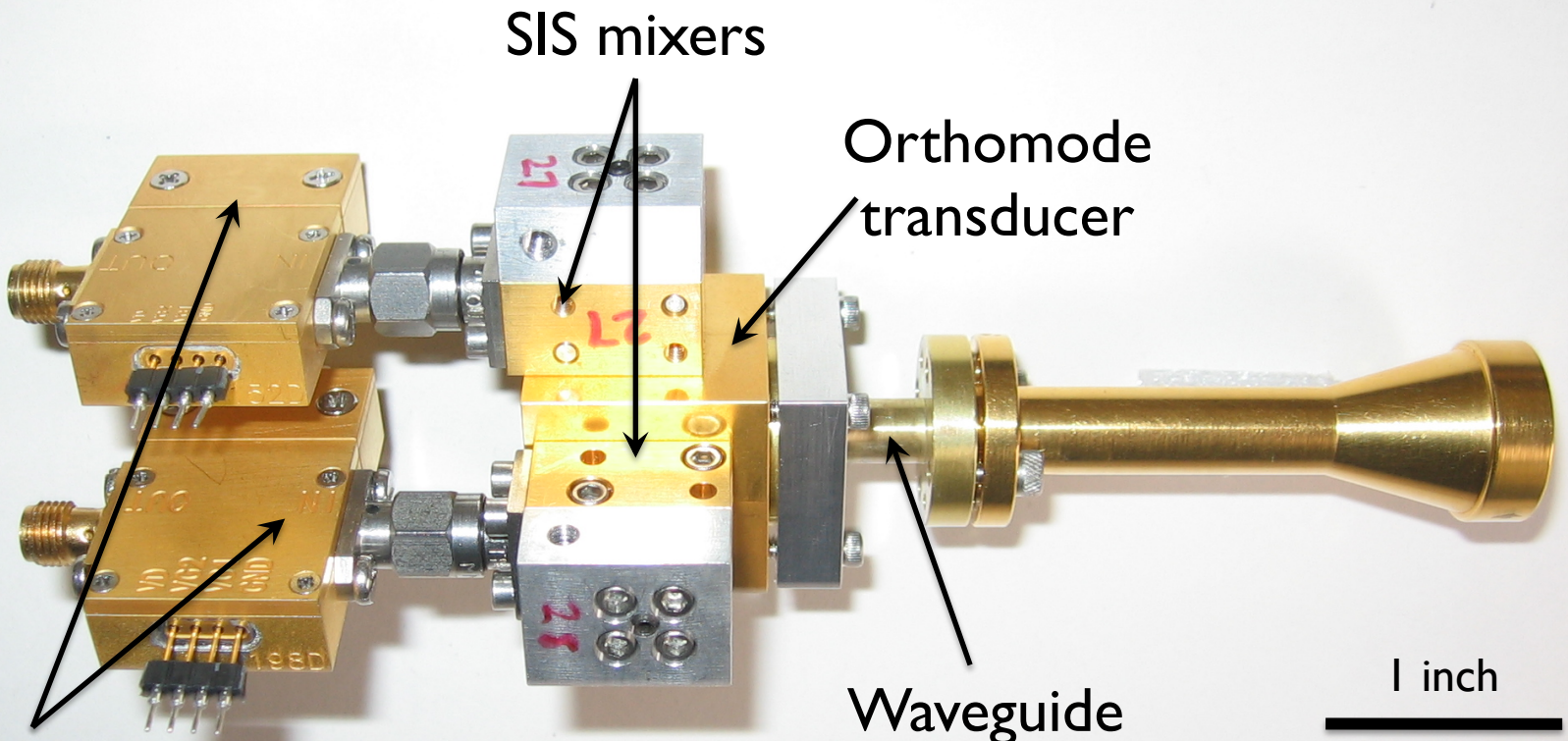

Mus
−11
b [deg]
−12
−13
10 pc
Pereyra & Magalhães 2004
Planck XXXIII
VE RI TAS
NRAO

Polarization (dust emission)



How to measure polarization

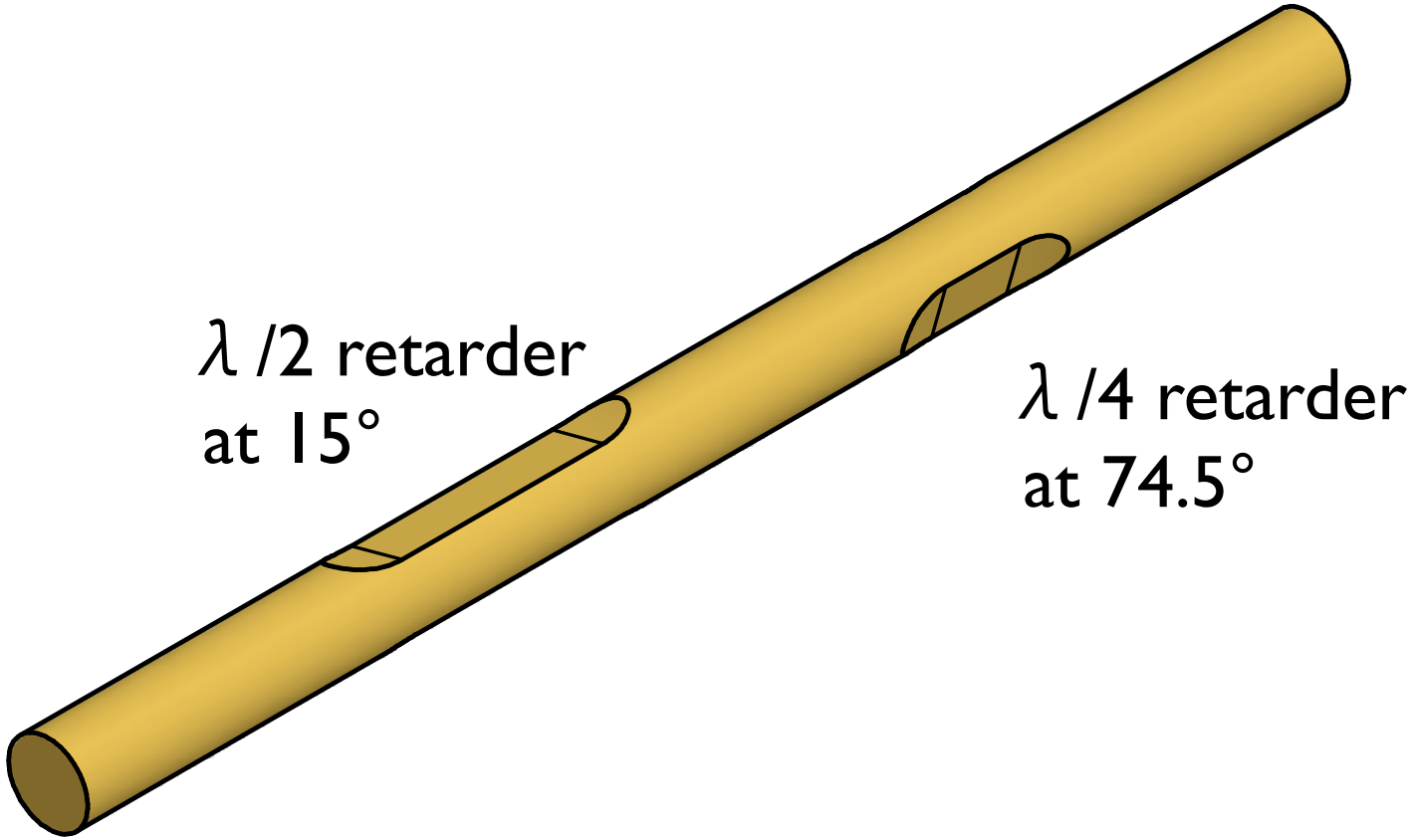
CARMA 1.3 mm dual-polarization receivers



Hull & Plambeck 2015, CARMA Memo #64
Hull & Plambeck 2015

Photo credit: Dick Plambeck

2-section polarizer



Plambeck & Engargiola, CARMA Memo #54

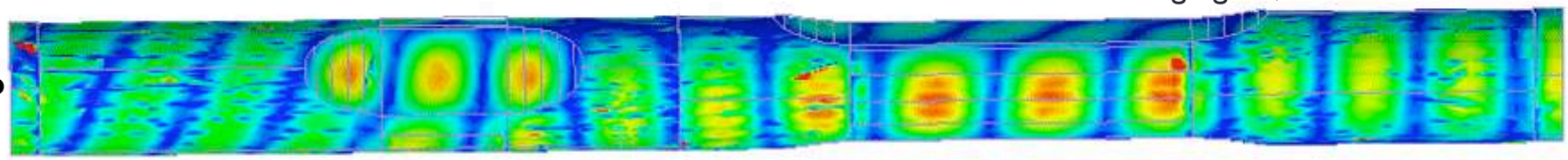
Polarizer simulation

← Feed horn (sky)

OMT →

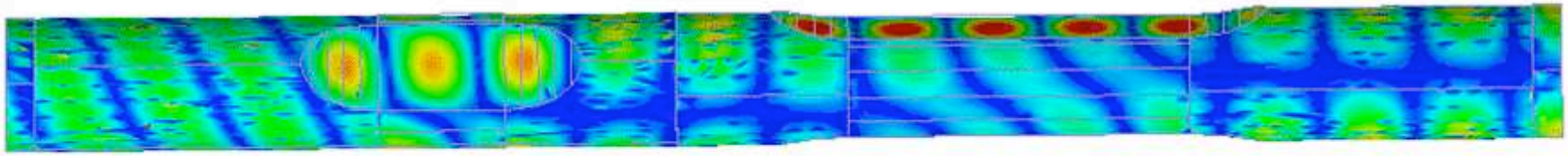
Plambeck & Engargiola, CARMA Memo #54

RCP

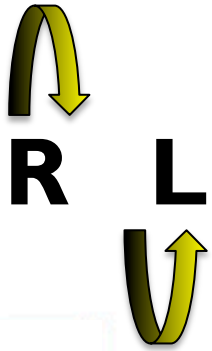


X

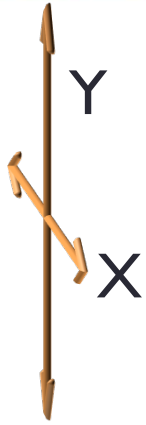
LCP



Y

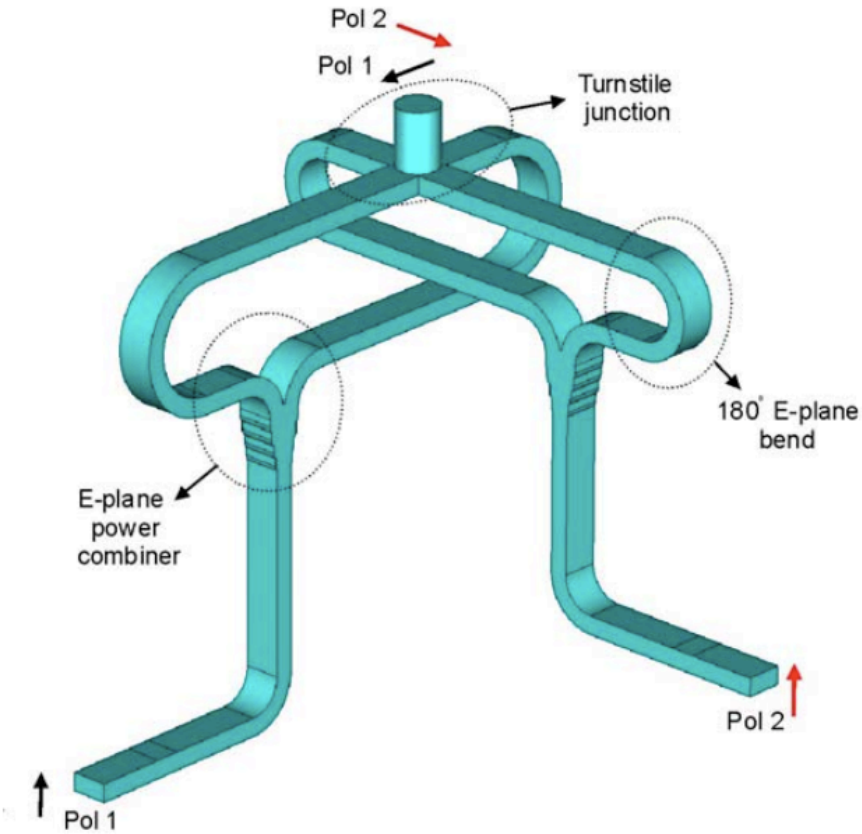


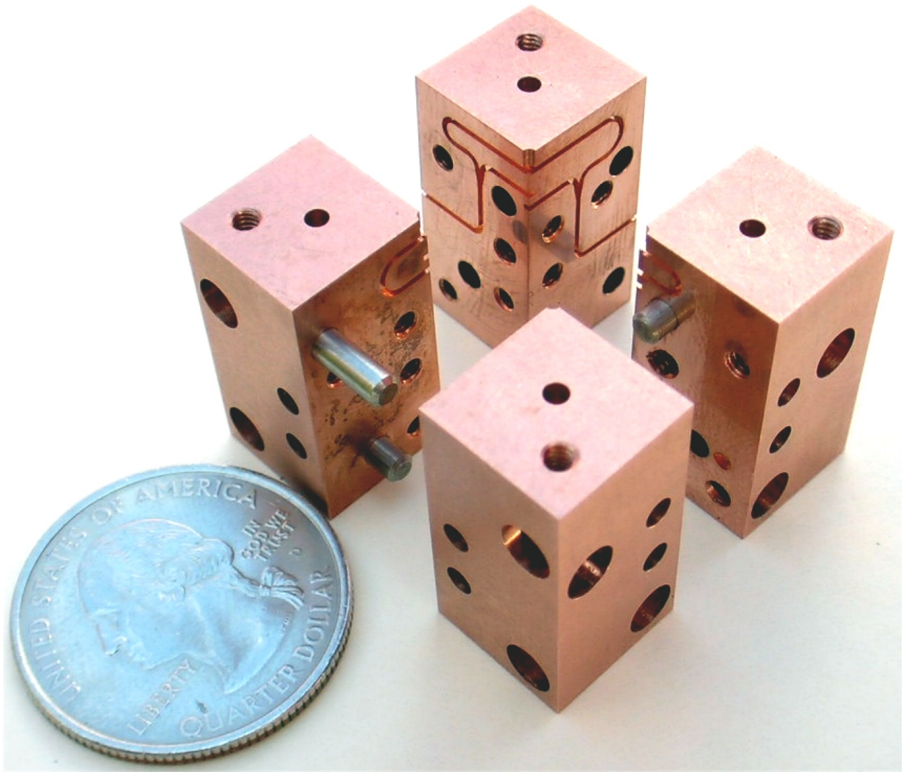
→ → →



Orthomode transducer

Separates orthogonal *linear* polarizations



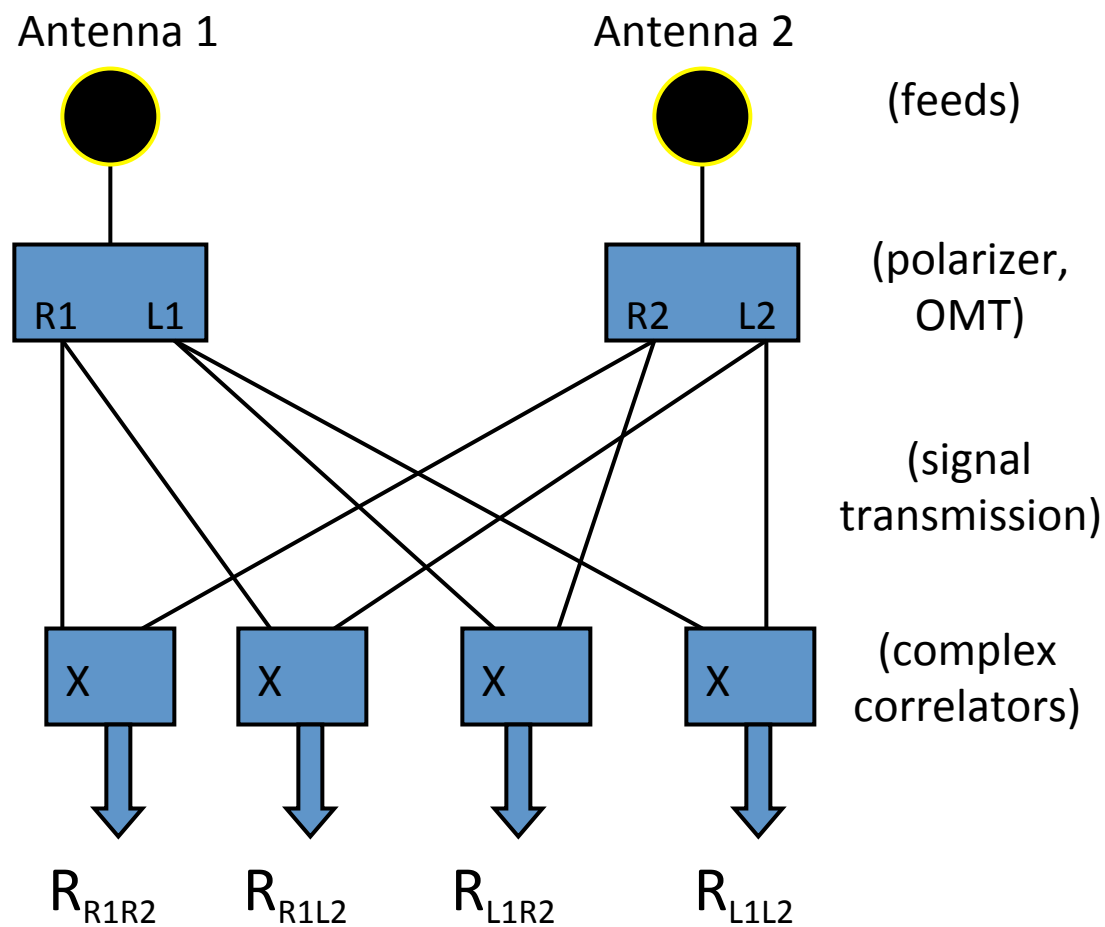


Navarrini & Plambeck 2006, IEEE-MTT, 54, 272-277

Four Complex Correlations per Pair of Antennas

- **Two** antennas with **two** orthogonal polarizations produce **four** complex correlations.

- From these four outputs, we want to generate the four complex **Stokes parameters**: I, Q, U, and V



Slide credit: Rick Perley

Stokes parameters

Linear feeds

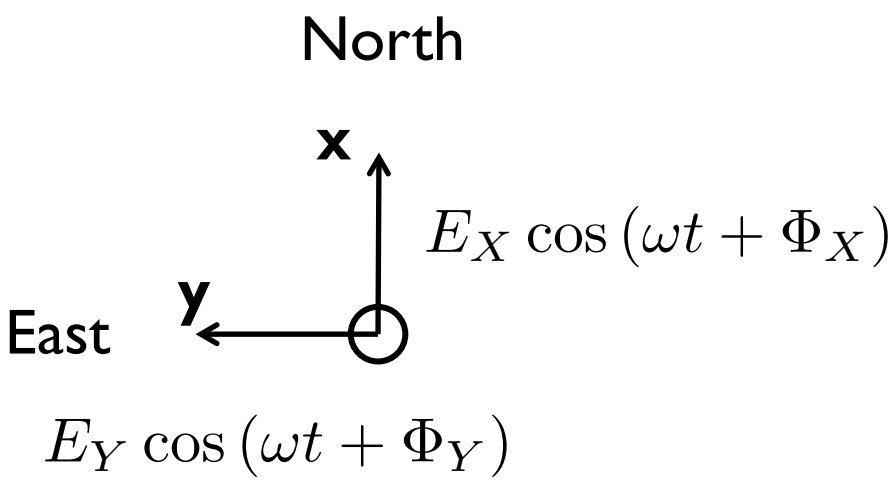
$$
\begin{aligned}
I &= \langle E_X E_X^* \rangle + \langle E_Y E_Y^* \rangle \\
Q &= \langle E_X E_X^* \rangle - \langle E_Y E_Y^* \rangle \\
U &= \langle E_X E_Y^* \rangle + \langle E_X^* E_Y \rangle \\
V &= -i \left(\langle E_X E_Y^* \rangle - \langle E_X^* E_Y \rangle \right)
\end{aligned}
$$

Circular feeds

$$
\begin{aligned}
I &= \langle E_R E_R^* \rangle + \langle E_L E_L^* \rangle \\
Q &= \langle E_R E_L^* \rangle + \langle E_R^* E_L \rangle \\
U &= -i \left(\langle E_R E_L^* \rangle - \langle E_R^* E_L \rangle \right) \\
V &= \langle E_R E_R^* \rangle - \langle E_L E_L^* \rangle \ .
\end{aligned}
$$

Hull & Plambeck 2015

Stokes parameters



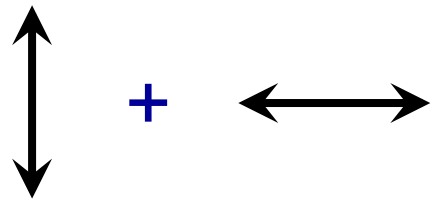
$$\delta_{XY} = \Phi_X - \Phi_Y$$

	Linear	**Circular**
I	$= A_X^2 + A_Y^2$	$= A_R^2 + A_L^2$
Q	$= A_X^2 - A_Y^2$	$= 2A_R A_L \cos\delta_{RL}$
U	$= 2A_X A_Y \cos\delta_{XY}$	$= -2A_R A_L \sin\delta_{RL}$
V	$= -2A_X A_Y \sin\delta_{XY}$	$= A_R^2 - A_L^2$

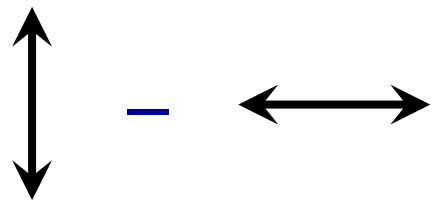
Slide credit: Dick Plambeck, Rick Perley

Stokes parameters

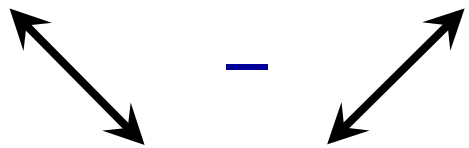
I



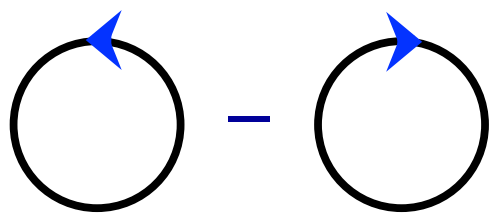
Q



U



V



RCP = CCW as viewed by the receiver

Stokes parameters – derived quantities

Polarization position angle (PA)

$$\chi = \frac{1}{2} \arctan \frac{U}{Q} \ , \quad 0 < \chi < \pi.$$

Polarization fraction

$$\Pi_{\rm tot} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$

$$\Pi_{\rm lin} = \frac{\sqrt{Q^2 + U^2}}{I}$$

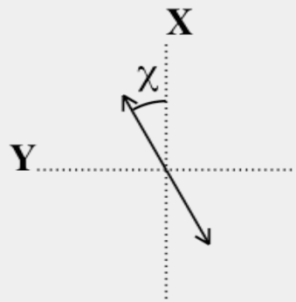
$$\Pi_{\rm circ} = \frac{V}{I}$$

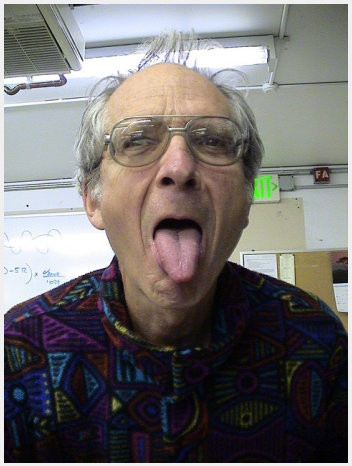
- Units: Jy/beam
- **Q**, **U**, and **V** can be plotted just as **I** can
- **I** is always positive; **Q**, **U**, **V** can be positive or negative
- If **Q**, **U**, **V** = 0, the source is unpolarized

Regarding polarization position angle…

HEY!!! LINEAR POLARIZATION "DIRECTION" ??

Look at the figure again:





THERE'S NO ARROWHEAD ON THAT "VECTOR"!! That's because it's the angle 2χ, not χ, that's important.

Carl likes "segtor" (!)

The correct word may be "polar" (?)

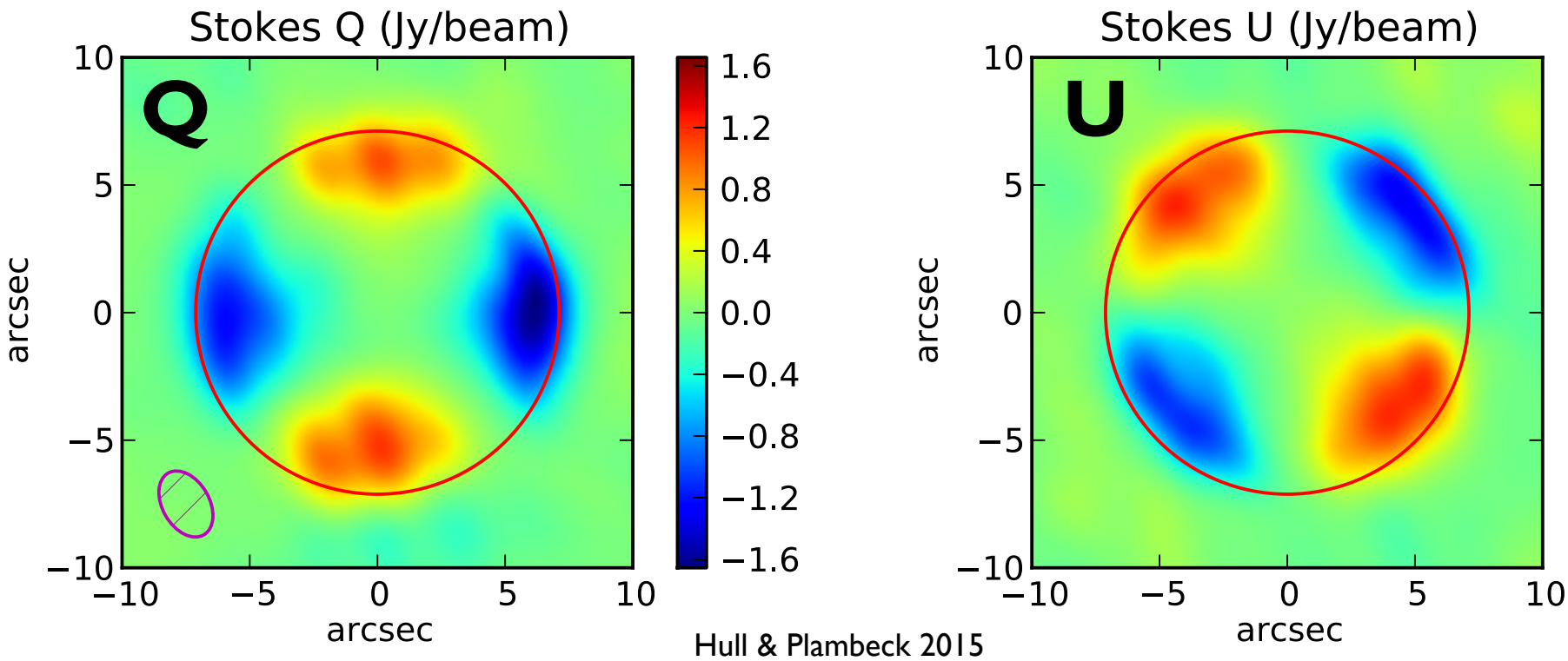
I usually use "line segment"

Moral of this story:

- **NEVER** say "linear polarization **DIRECTION**".
- **INSTEAD**, always say "linear polarization **ORIENTATION**".

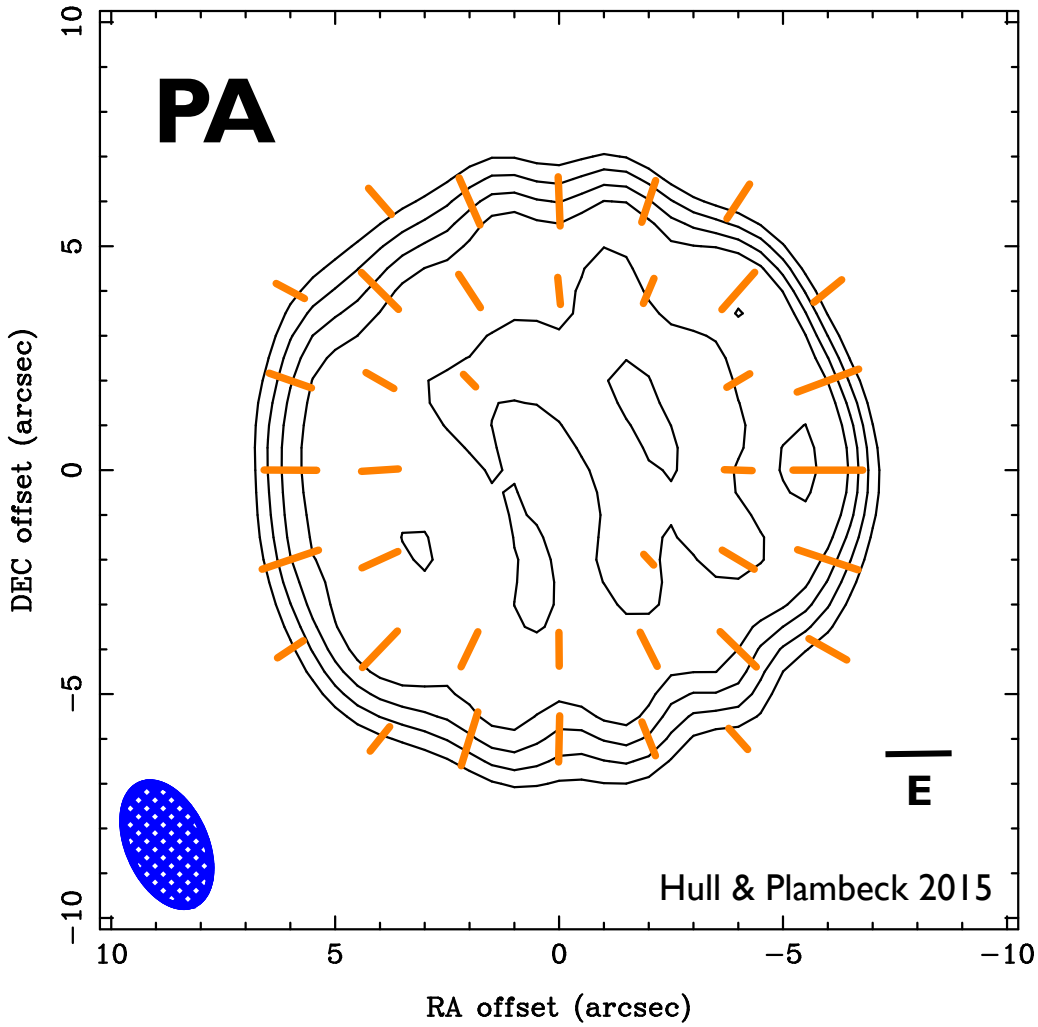
Slide credit: Carl Heiles

Example: Mars – CARMA data

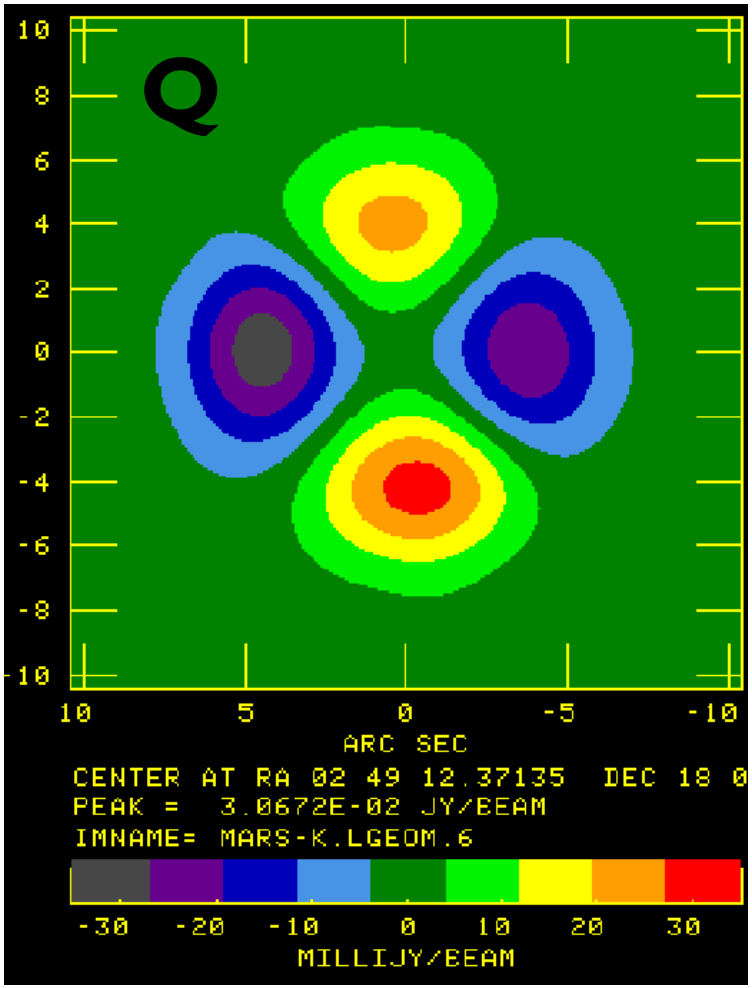


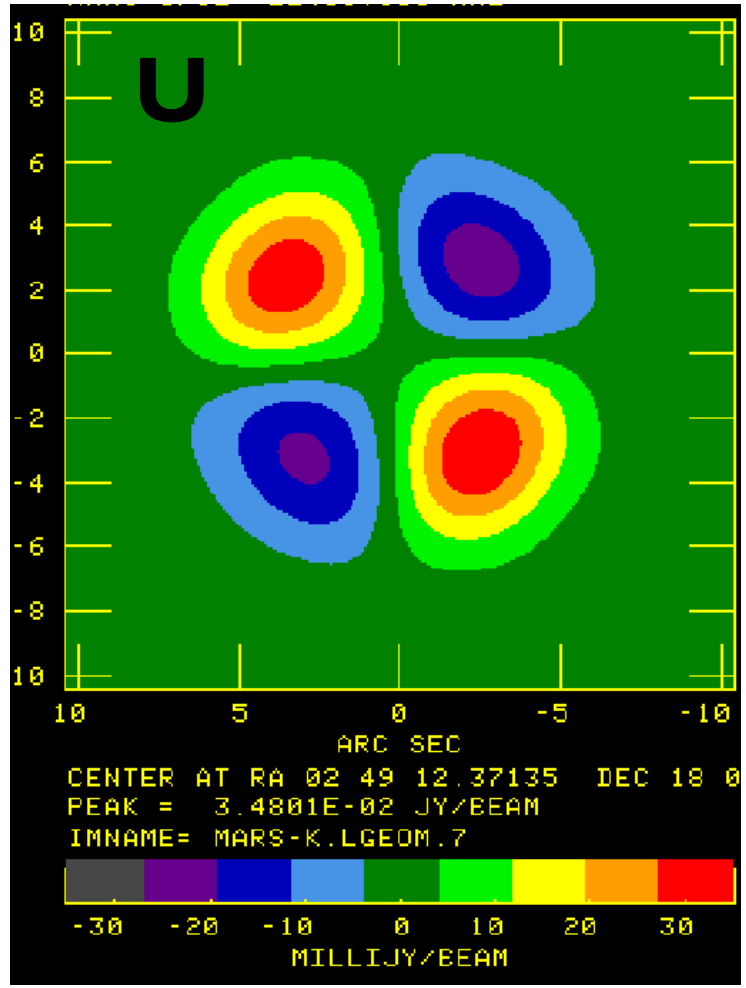
Hull & Plambeck 2015

Example: Mars – CARMA data



Example: Mars – VLA data





Slide credit: Rick Perley

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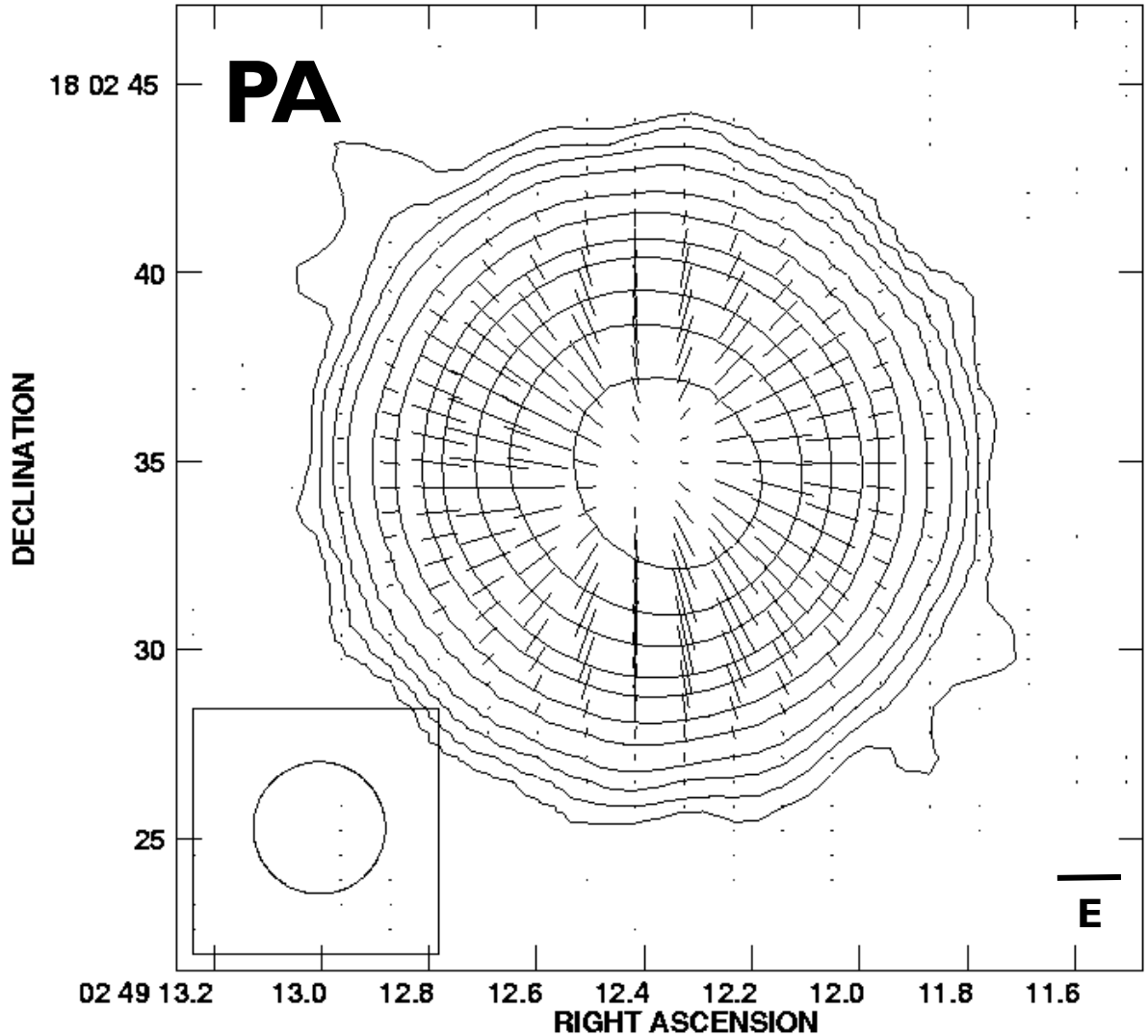


Slide credit: Rick Perley

Polarization calibration

Extra calibration steps

XY (or RL) phase

Leakage

(Wide-field calibration)

XY phase calibration

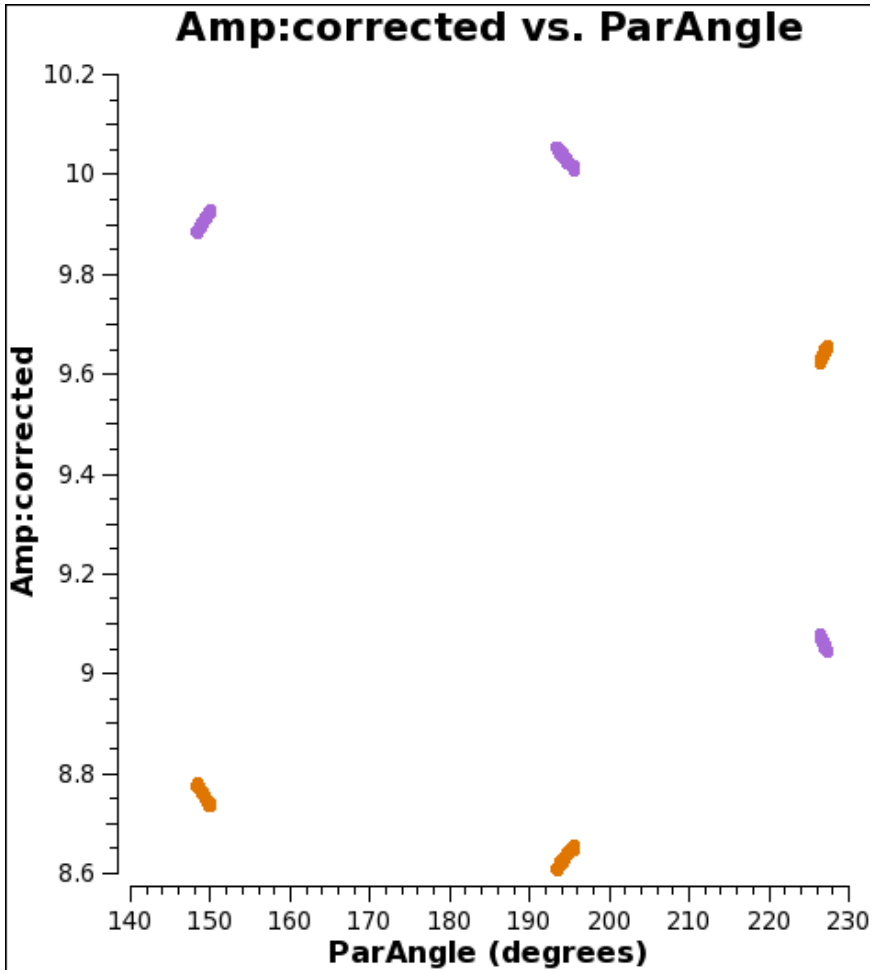
There is a **phase difference** between X & Y (or R & L) on each telescope

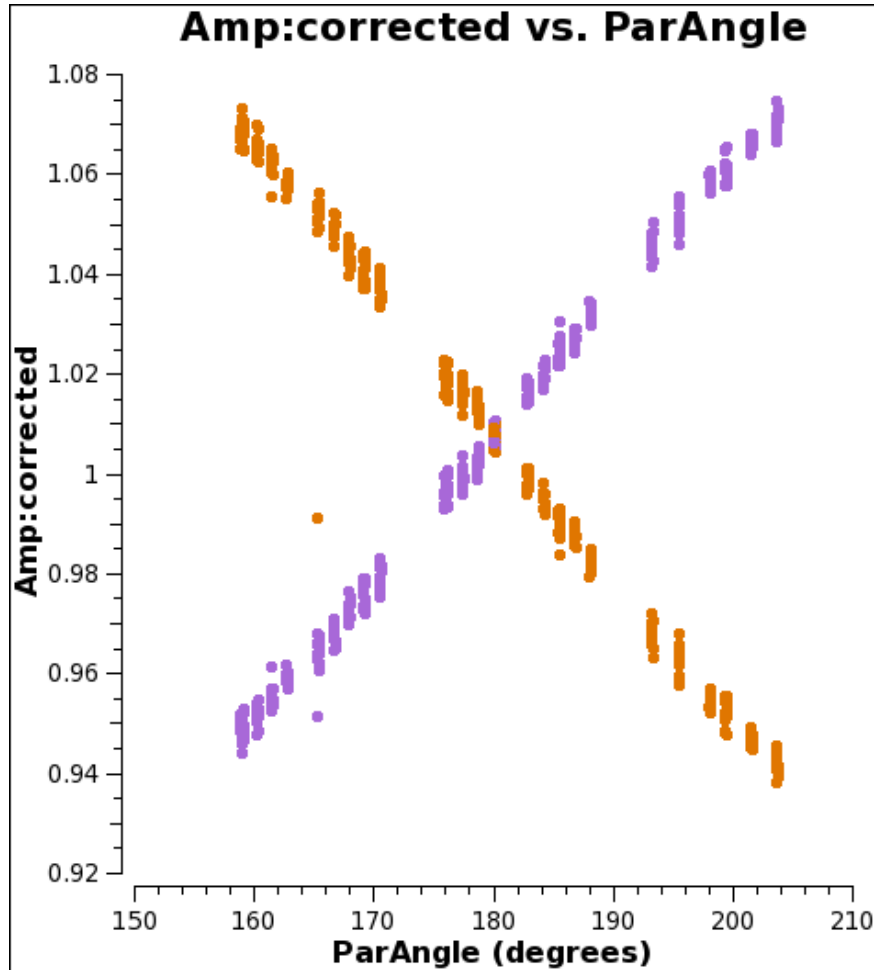
Need to measure it to get the proper polarization position angle (PA) of the radiation!

Measurement methods

- Wire grids, beacon, rocky planet/moon, (satellite?!)
- Known source (3C286)
- Monitoring of gains over time (dual-linear only) ←

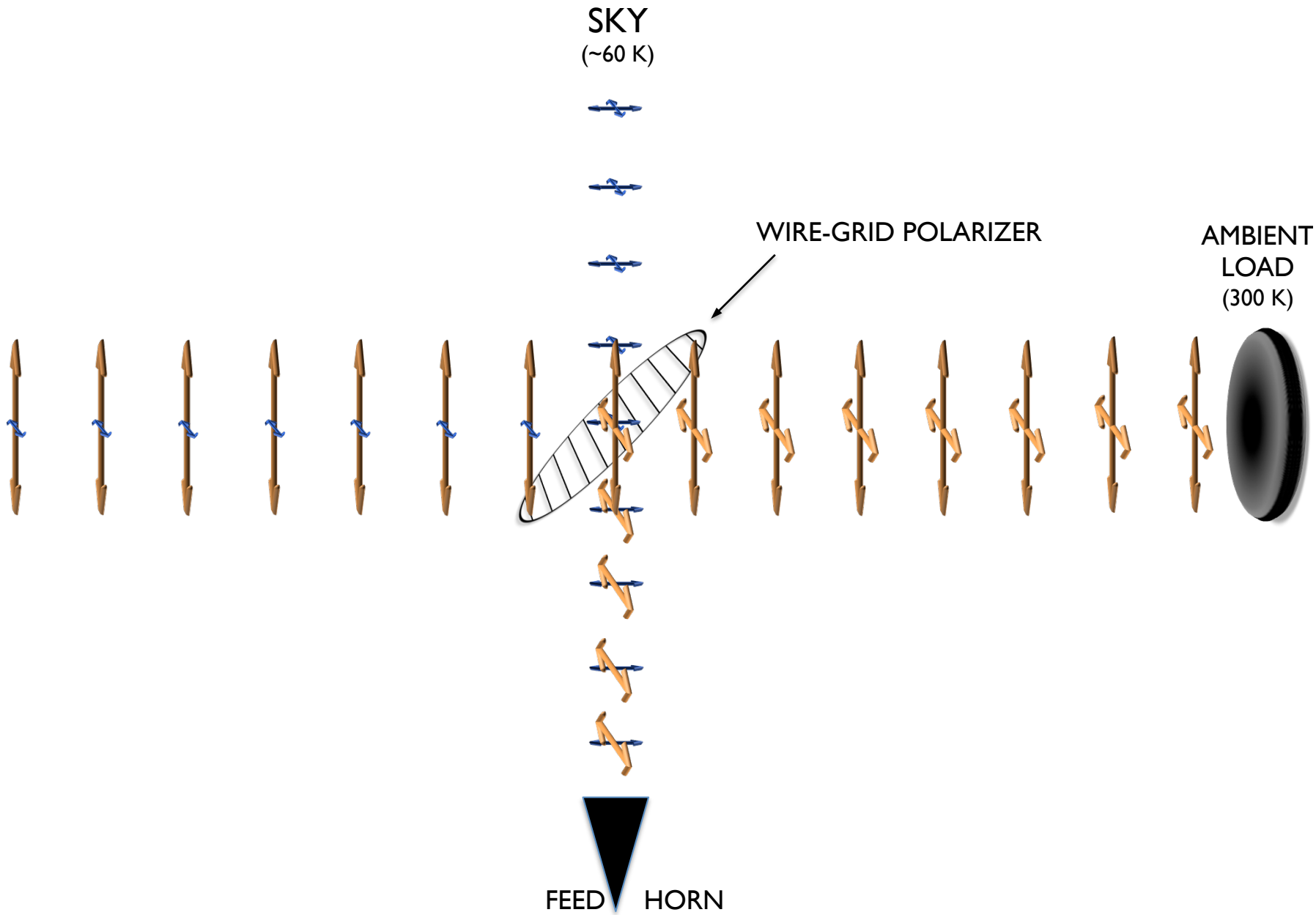
XX vs. YY amplitude vs. time (ALMA)





3C286 CASA Guide

XY phase calibration – wire grids



Leakage calibration

Receivers are **imperfect:** there is cross-coupling between X & Y (or R & L) receivers on each telescope

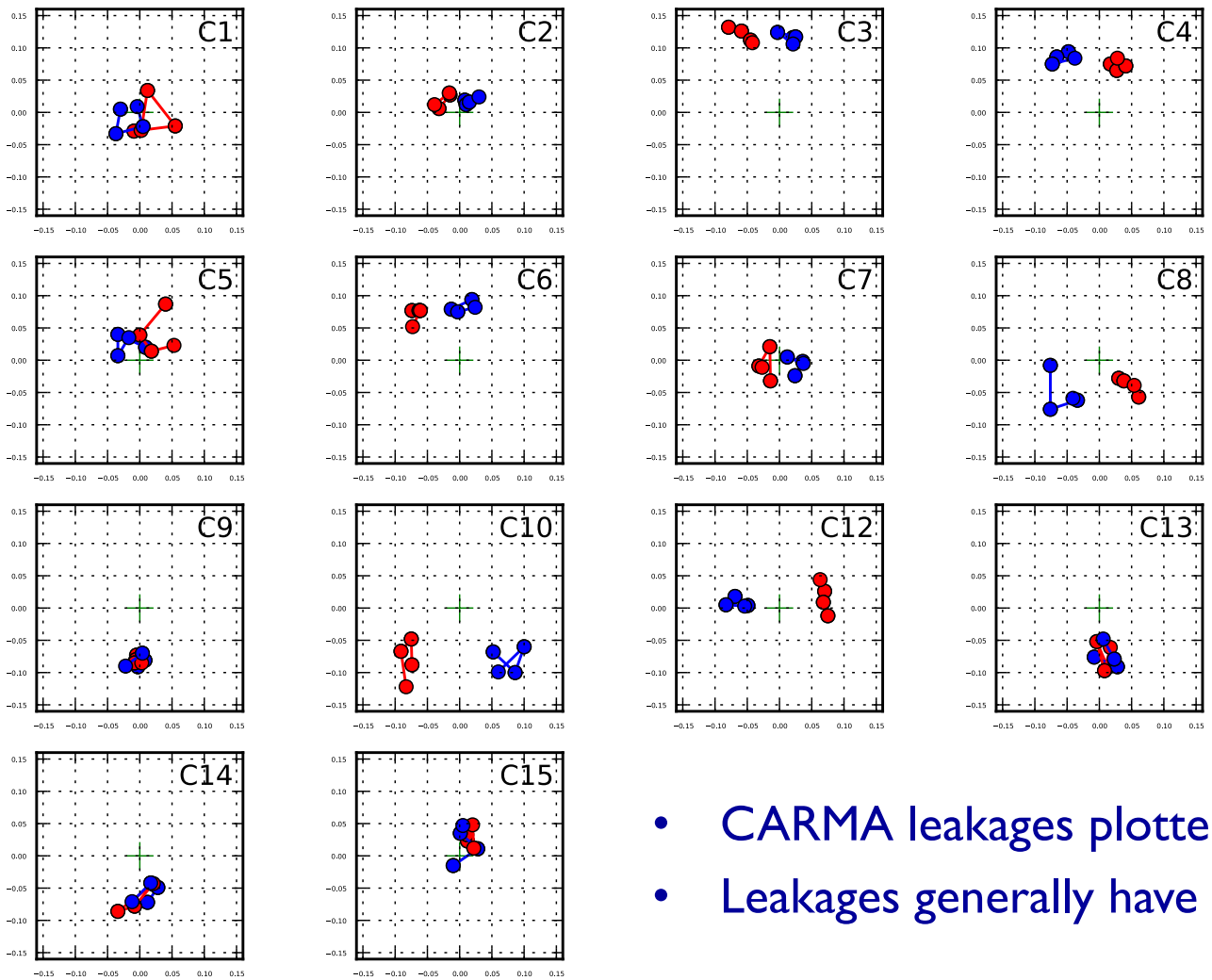
Due to imperfections in the hardware, crosstalk in the correlator, reflections in the receiver, etc.

$$V_{X,\mathrm{obs}} = V_{X,\mathrm{true}} + D_X V_{Y,\mathrm{true}}$$
$$V_{Y,\mathrm{obs}} = V_{Y,\mathrm{true}} + D_Y V_{X,\mathrm{true}}$$

Measurement methods

- Observe bright source over wide range of parallactic angle
- Observe bright source of known polarization (difficult at mm)

Leakage terms



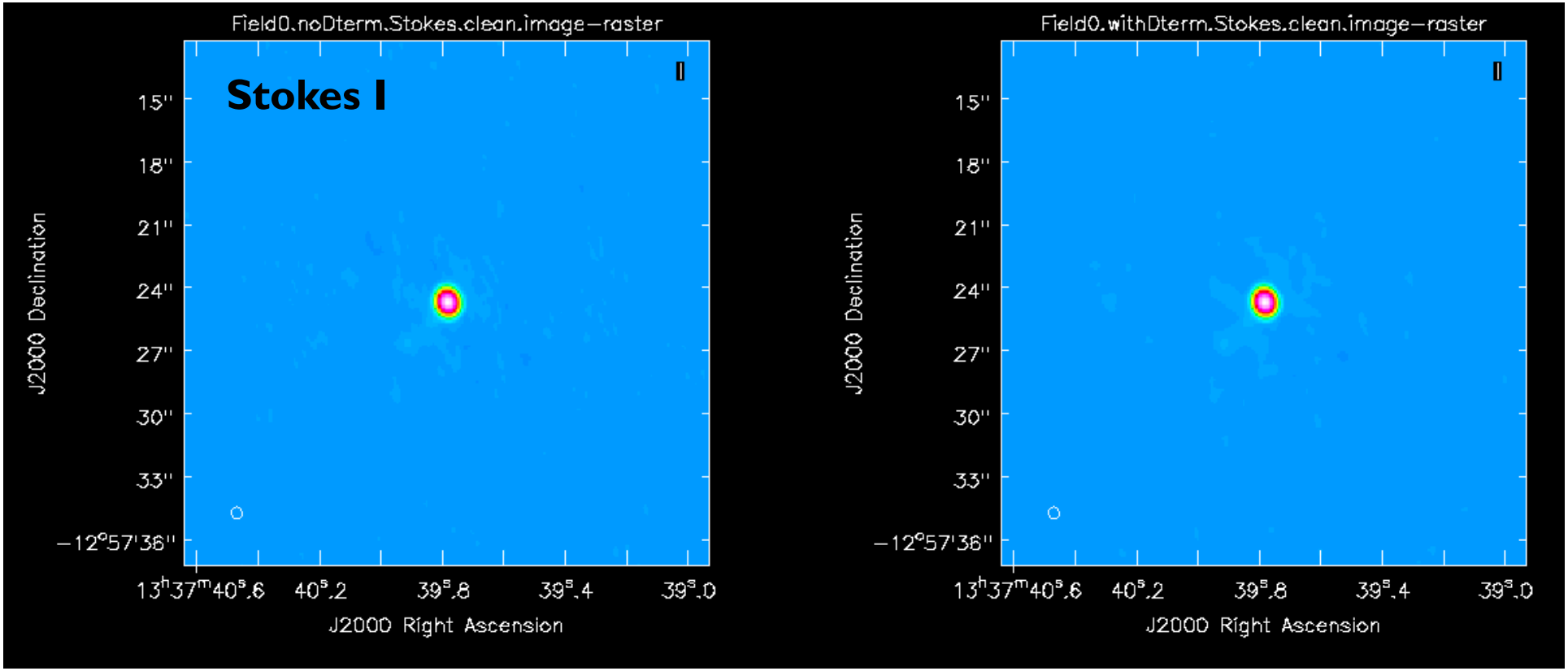
10% leakage amp

- CARMA leakages plotted in the complex plane
- Leakages generally have amplitudes < 10%

Hull & Plambeck 2015

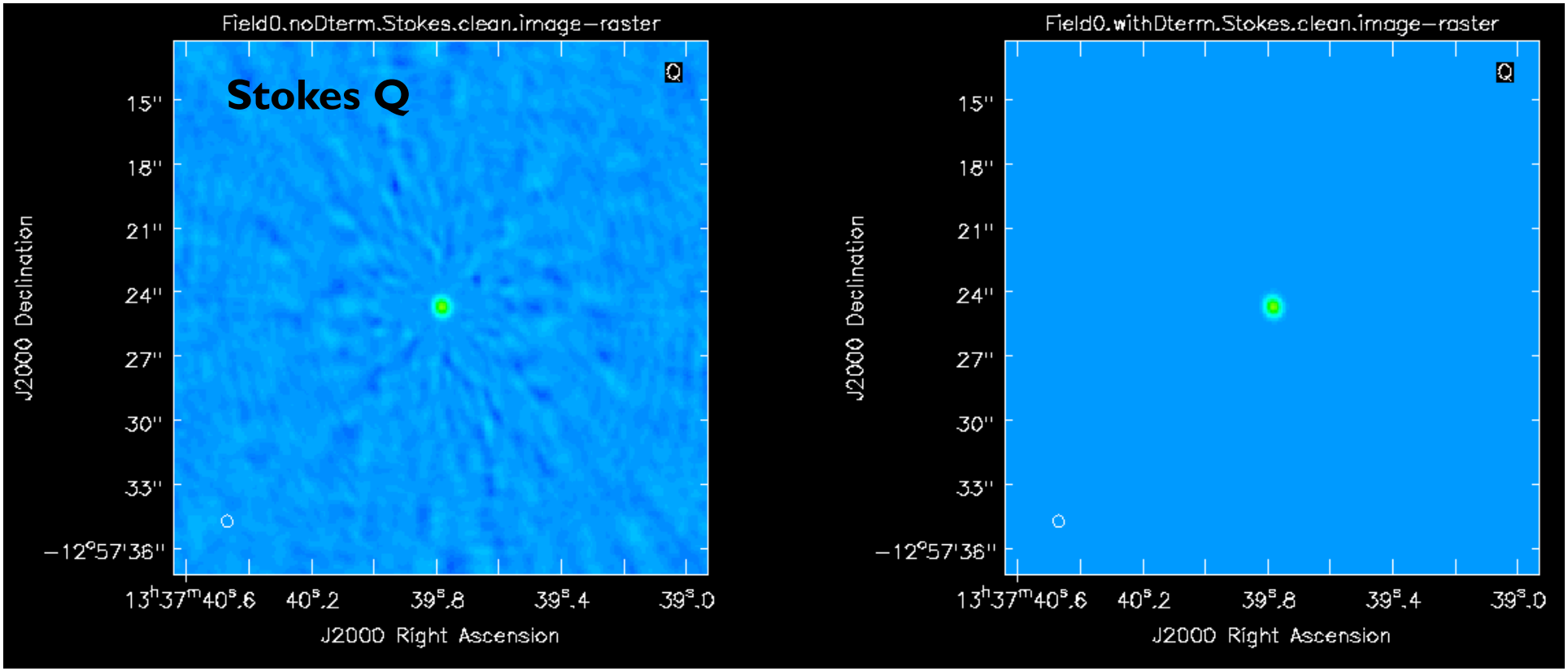
Leakage calibration

After leakage correction



Leakage calibration

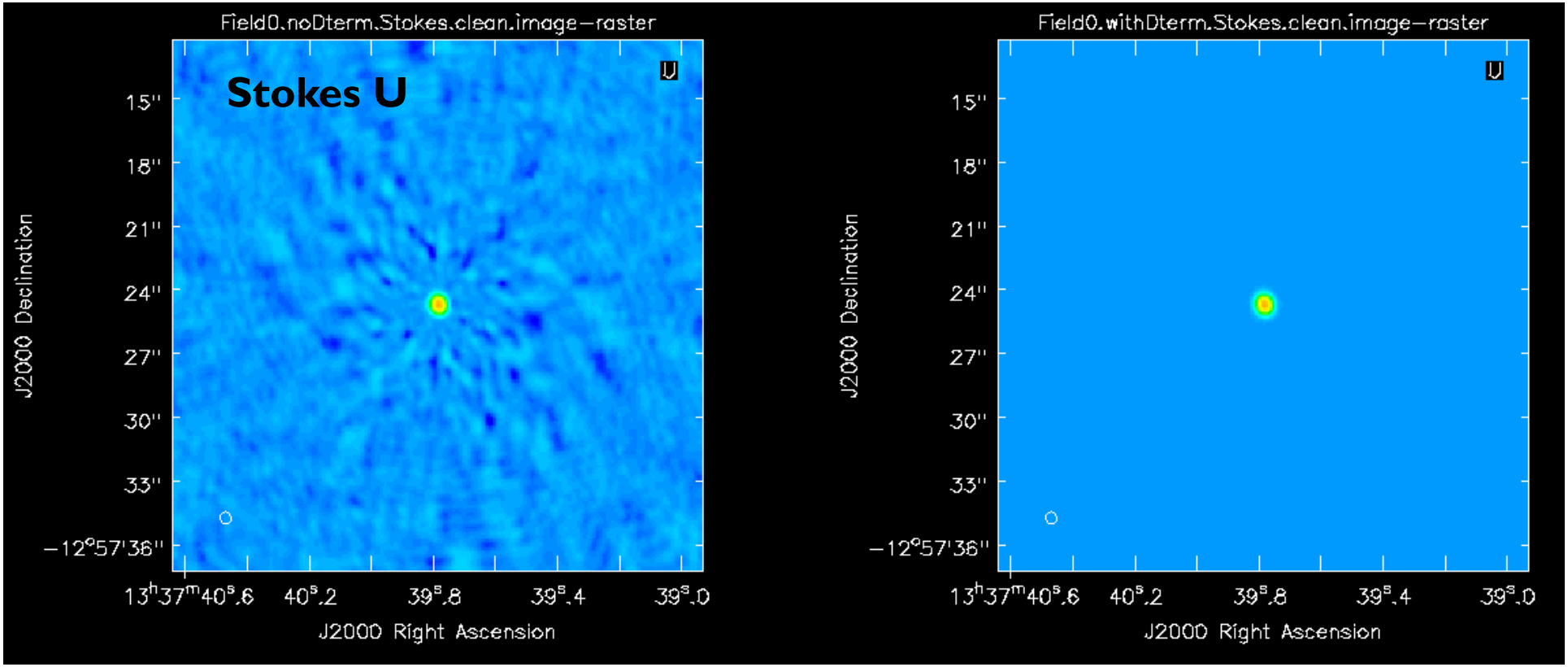
After leakage correction



3C286 CASA Guide

Leakage calibration

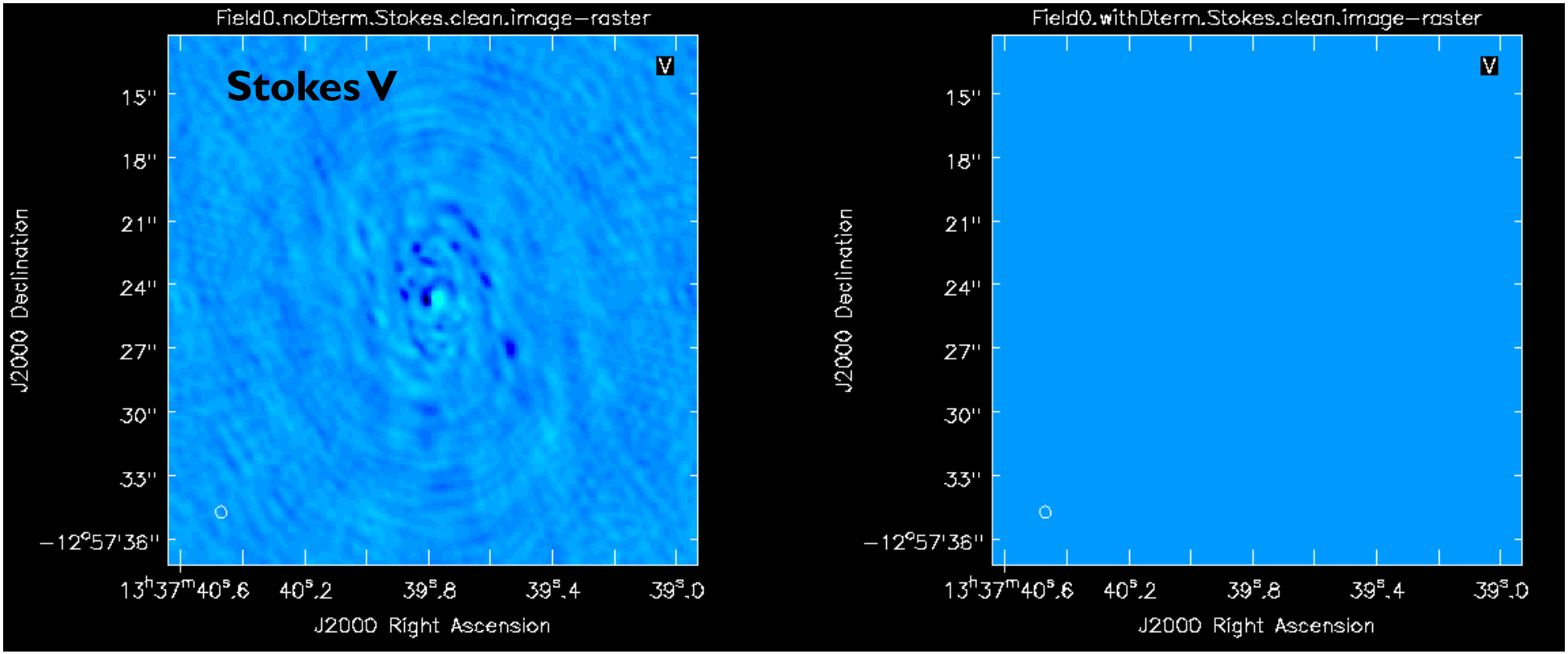
After leakage correction



3C286 CASA Guide

Leakage calibration

After leakage correction



Widefield polarization calibration

Polarization properties change across the primary beam!

- Due to antenna geometry

Measurement methods

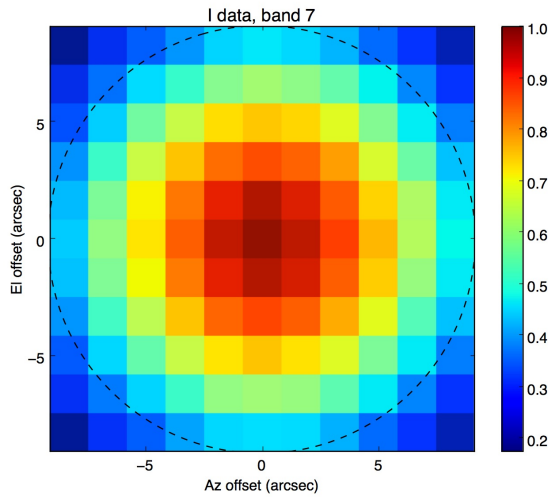
- Beam holography
- Observe a bright source in many offset positions in the beam

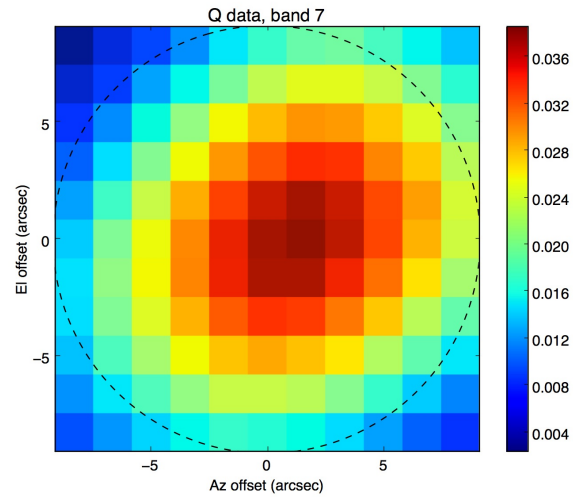
In practice, this is difficult to correct…but possible!

Widefield polarization calibration – ALMA

Amplitudes

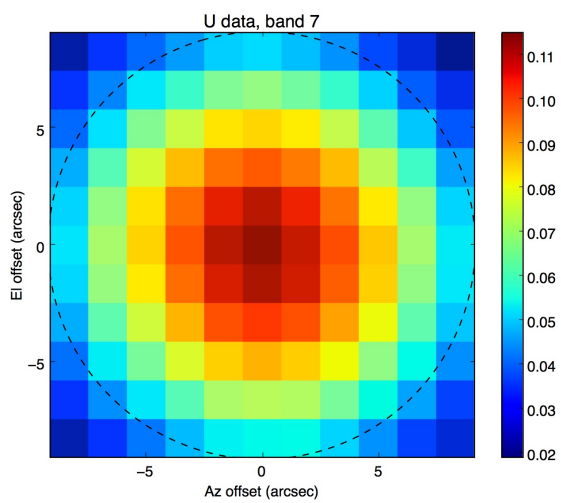
I

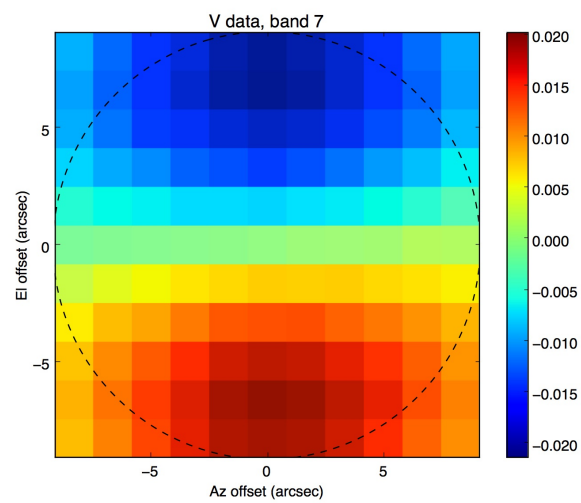




Q

U





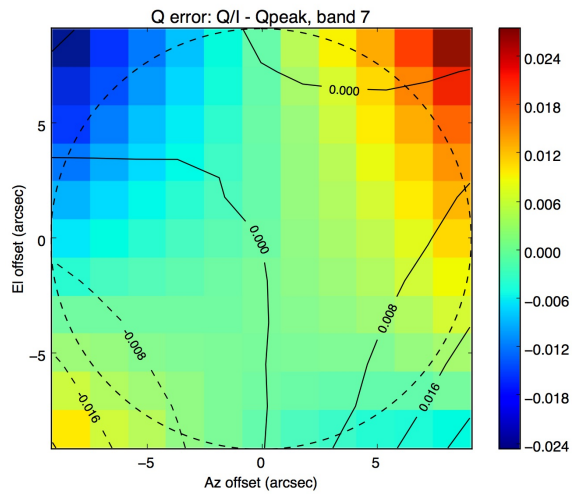
Squint

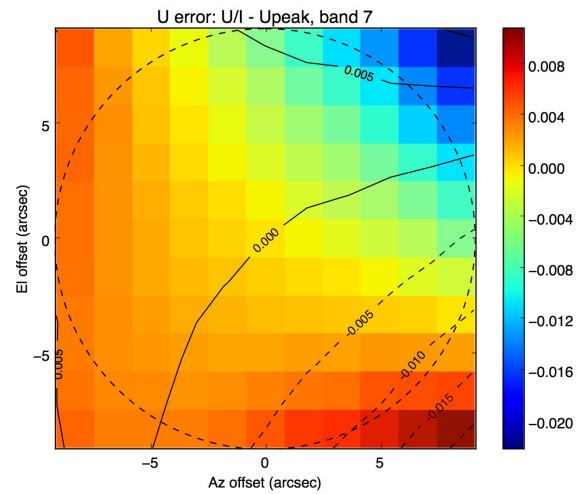
V

Widefield polarization calibration – ALMA

Errors

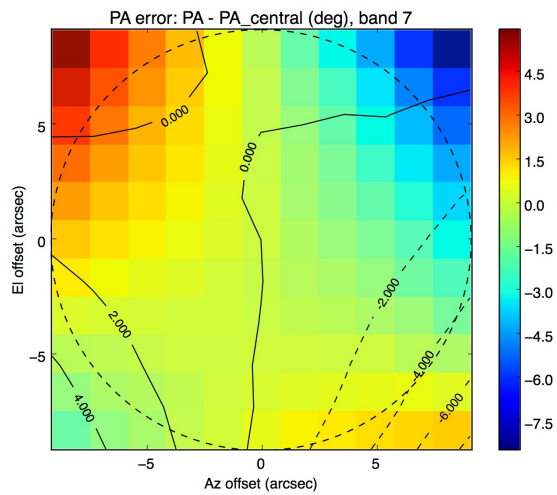
Q

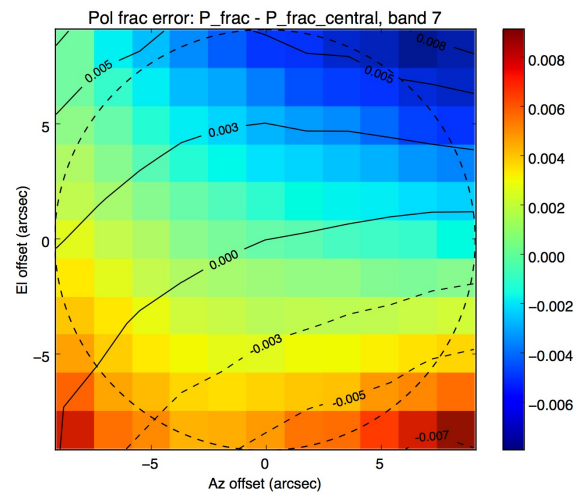




U

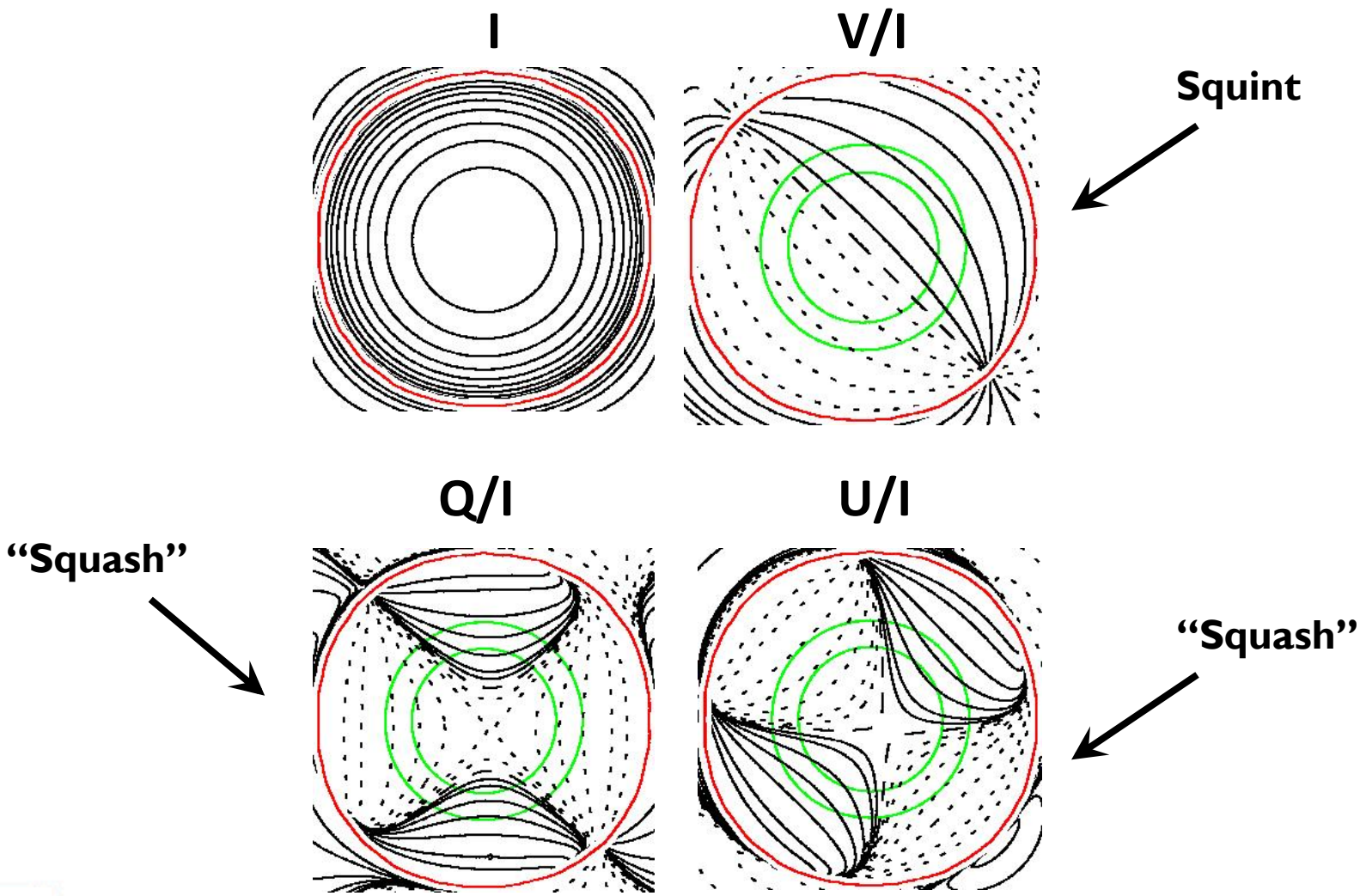
PA





%

Widefield polarization calibration – VLA



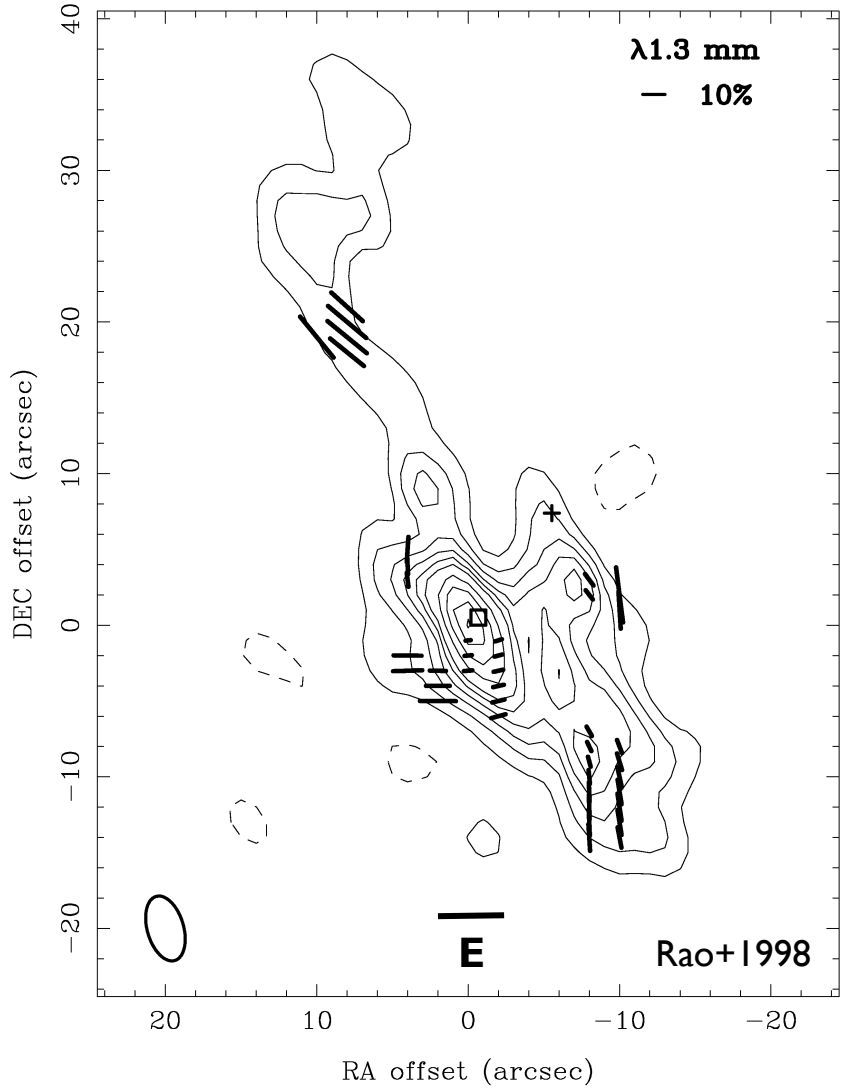
EVLA Memo #58; slide credit: Rick Perley

Real polarization data

BIMA

Image credit: NASA

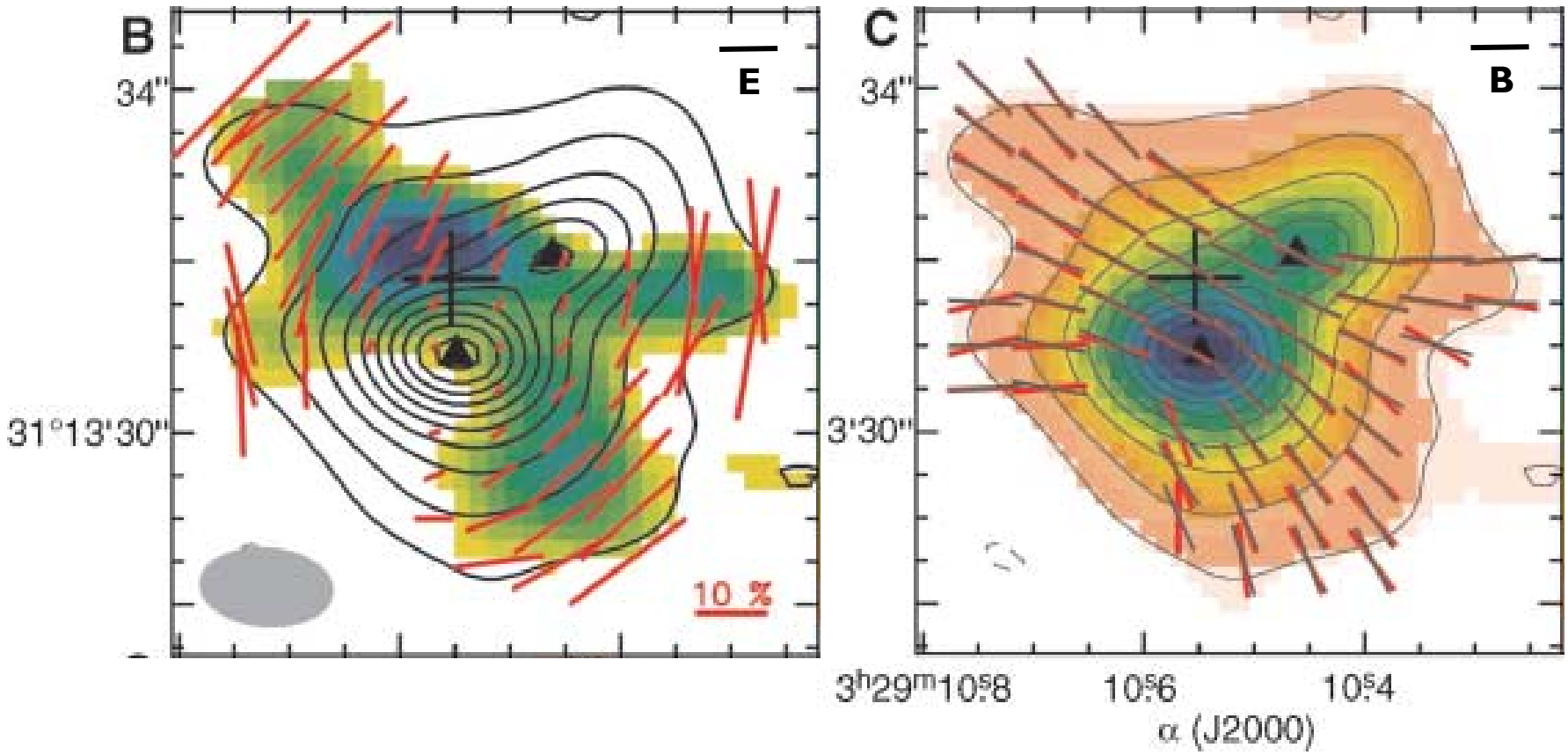
BIMA: Orion


λ1.3 mm
10%
E
Rao+1998
DEC offset (arcsec)
RA offset (arcsec)
40
30
20
10
0
−10
−20
20
10
0
−10
−20

SMA

Image credit: Jonathan Weintroub

SMA: NGC 1333-IRAS4A

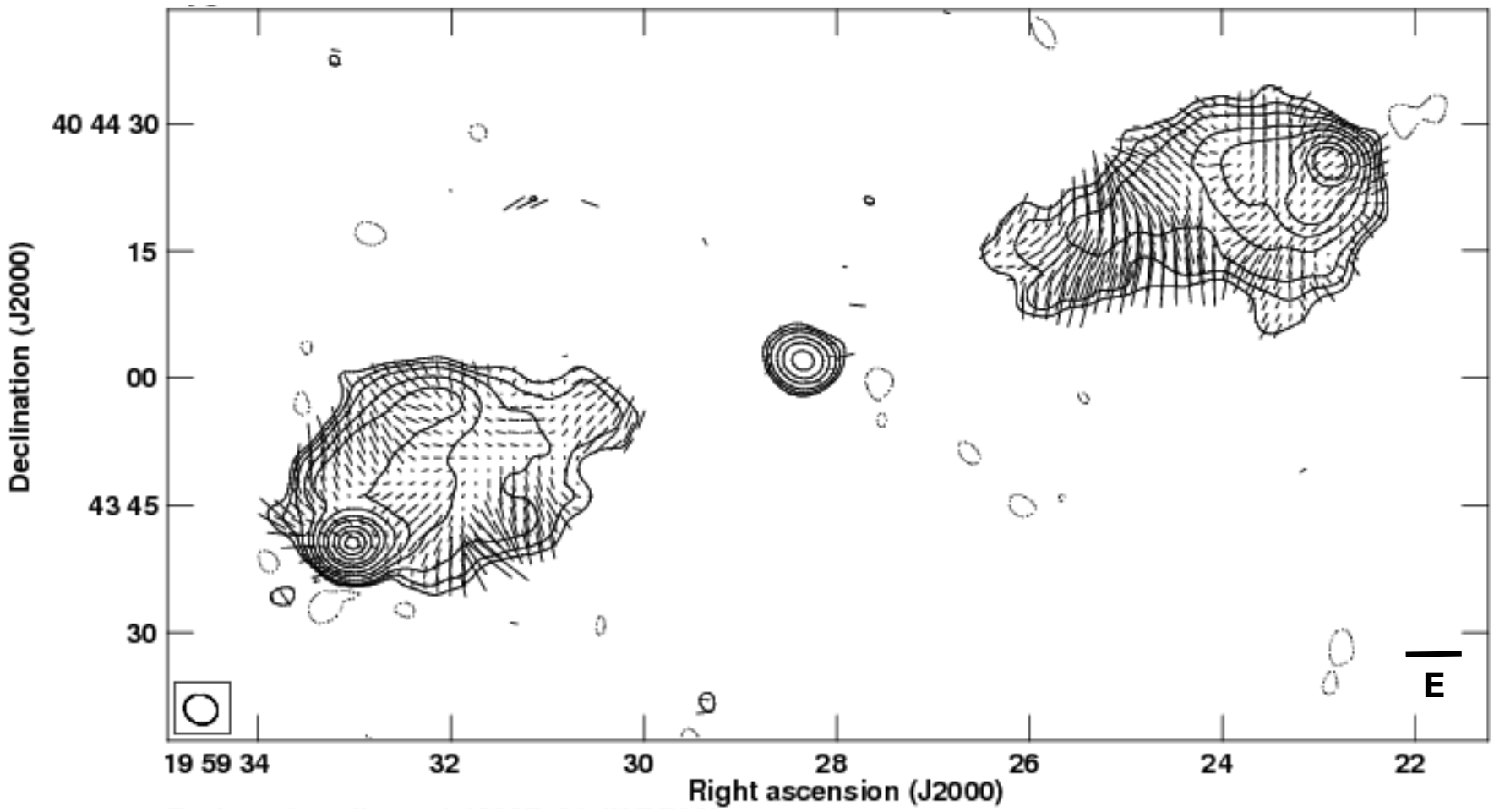


Girart+2006

VLA

Image credit: Jonathan Weintroub

VLA: Cygnus A

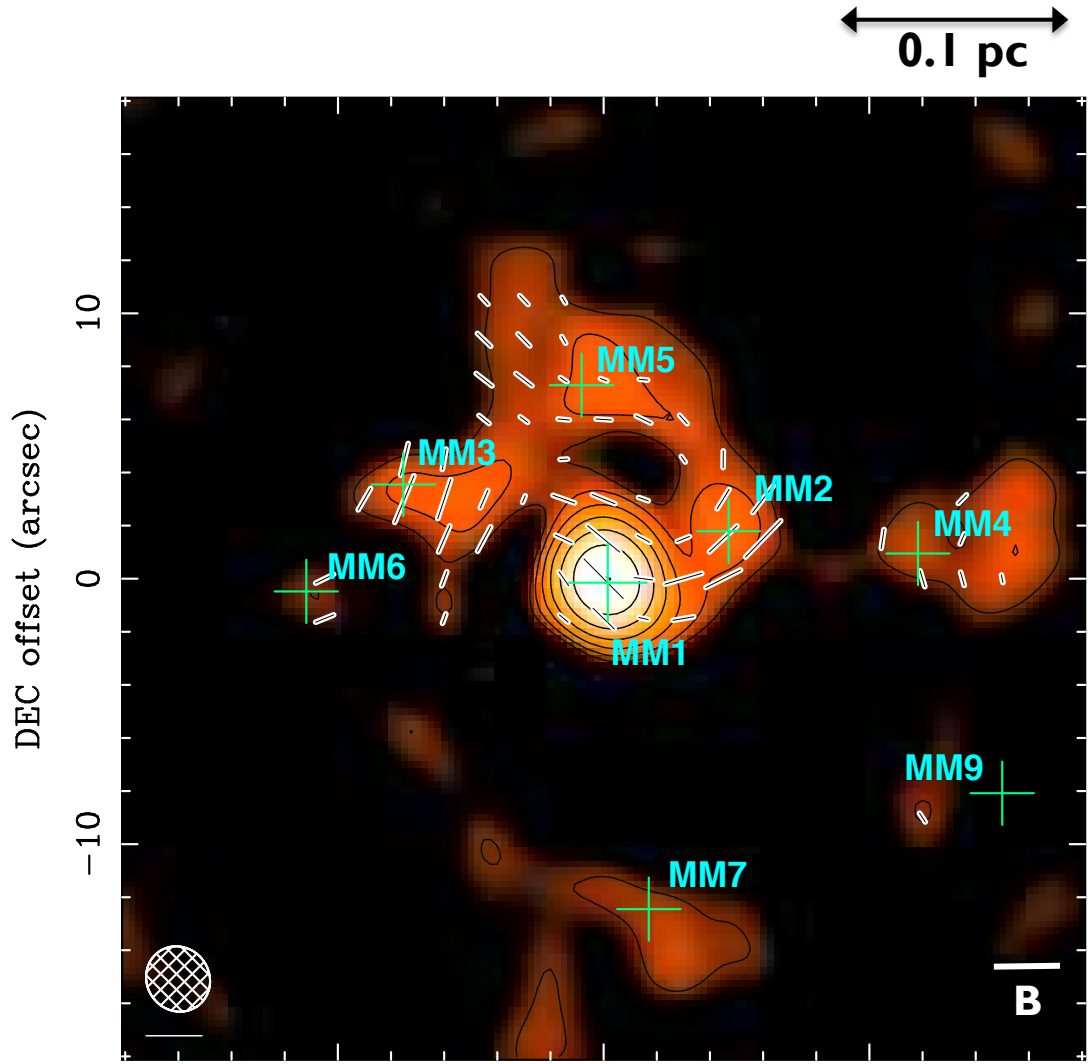


Slide credit: Rick Perley

CARMA

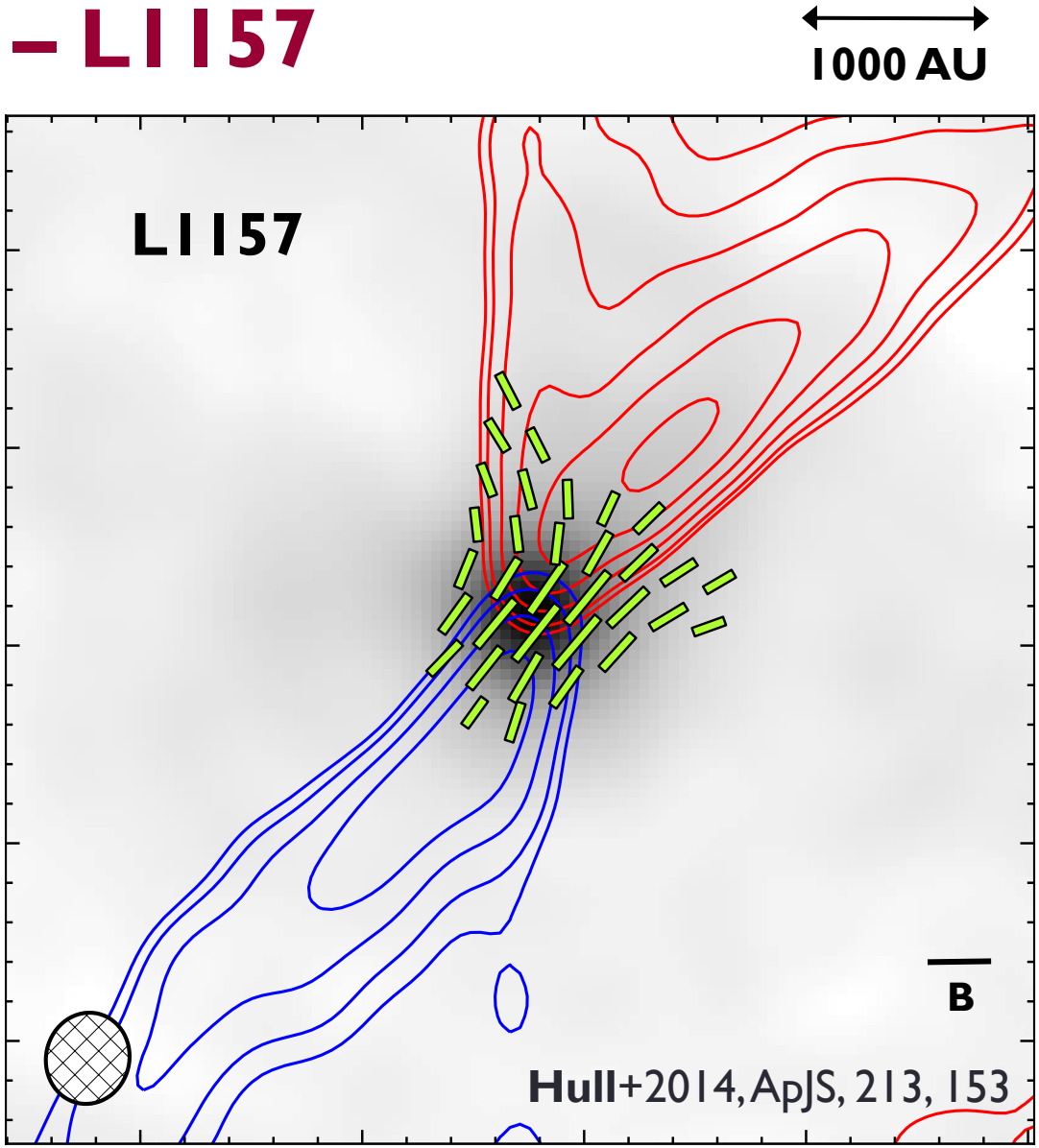
Image credit: Chat Hull

CARMA – NGC 7538



Wright, **Hull**+2014, ApJ, 796, 112

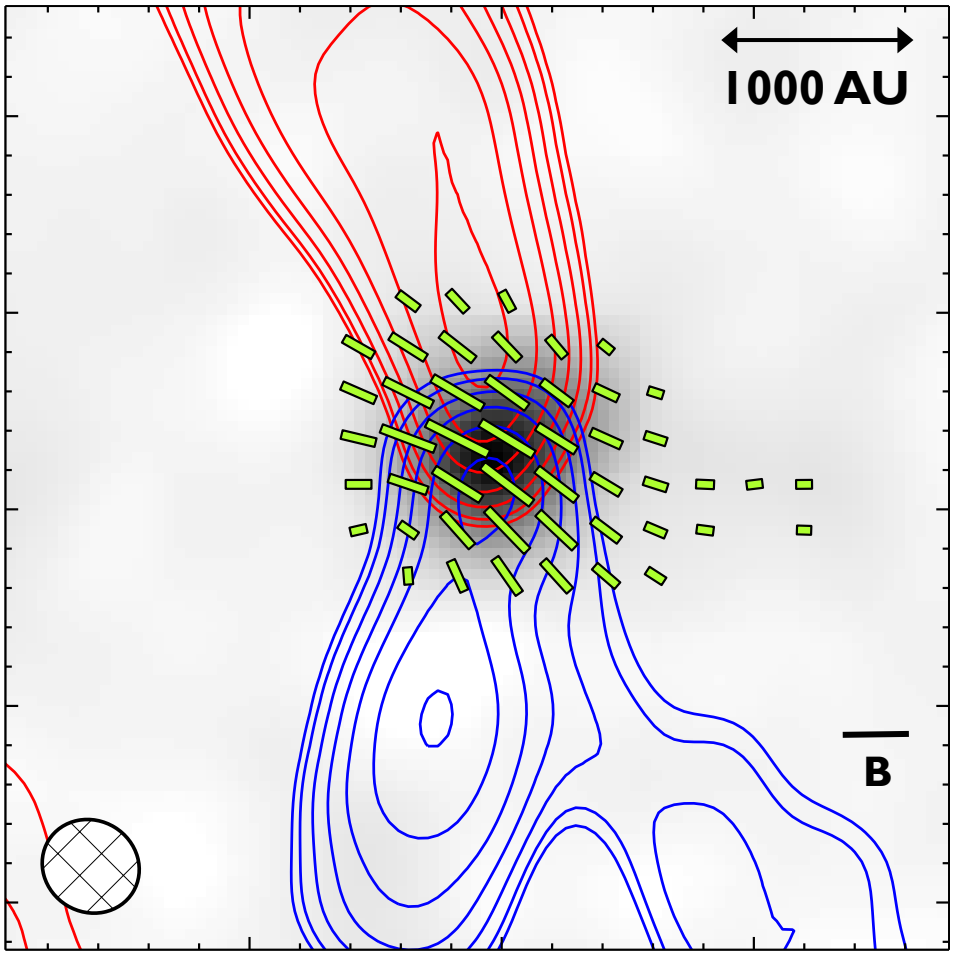
CARMA – L1157



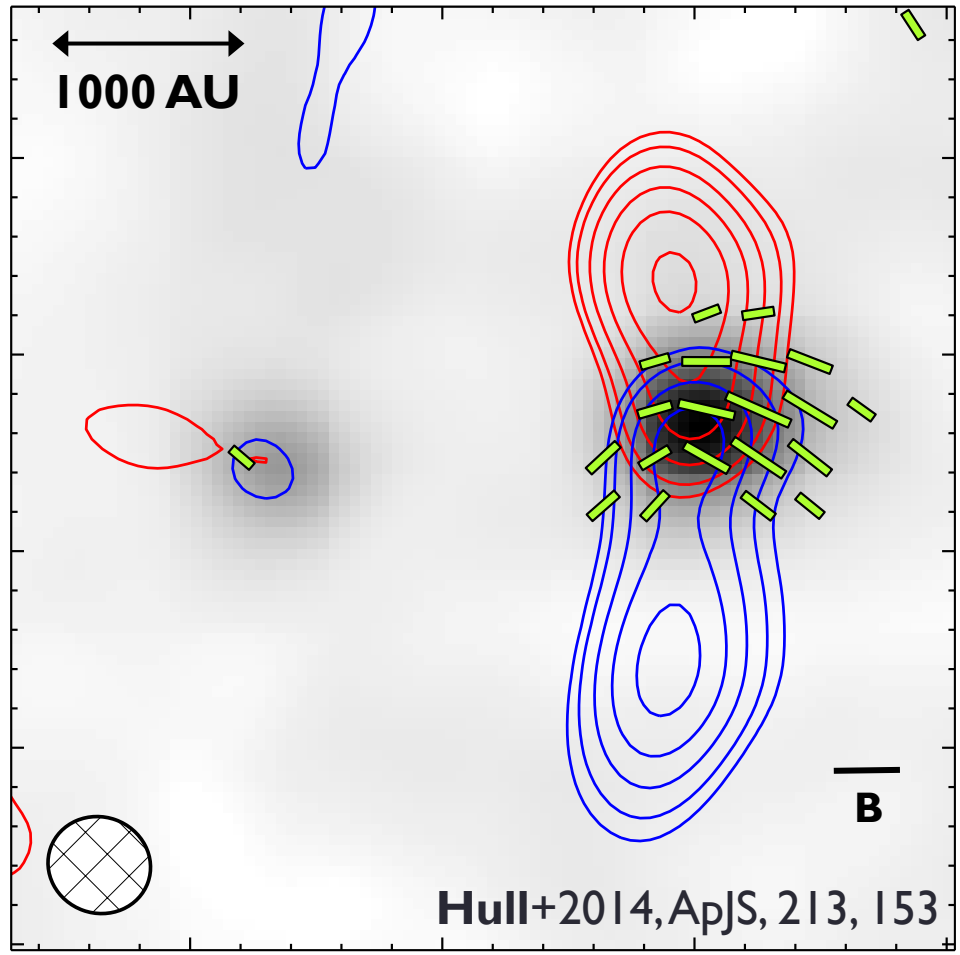
See also: Stephens+ (incl. C.H.) 2013, ApJL, 769, L15

CARMA

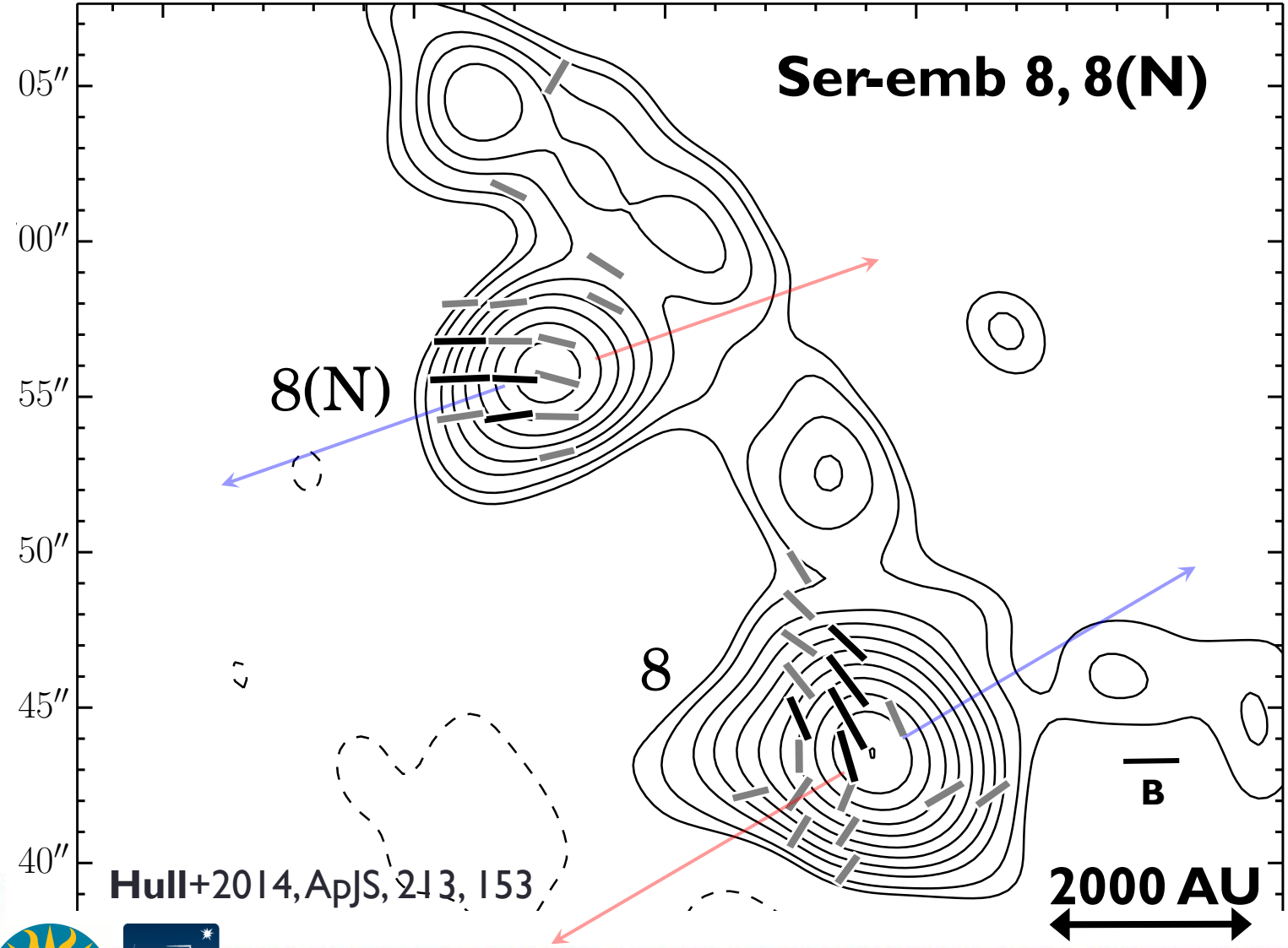
NGC 1333-IRAS 4A



NGC 1333-IRAS 4B, 4B2

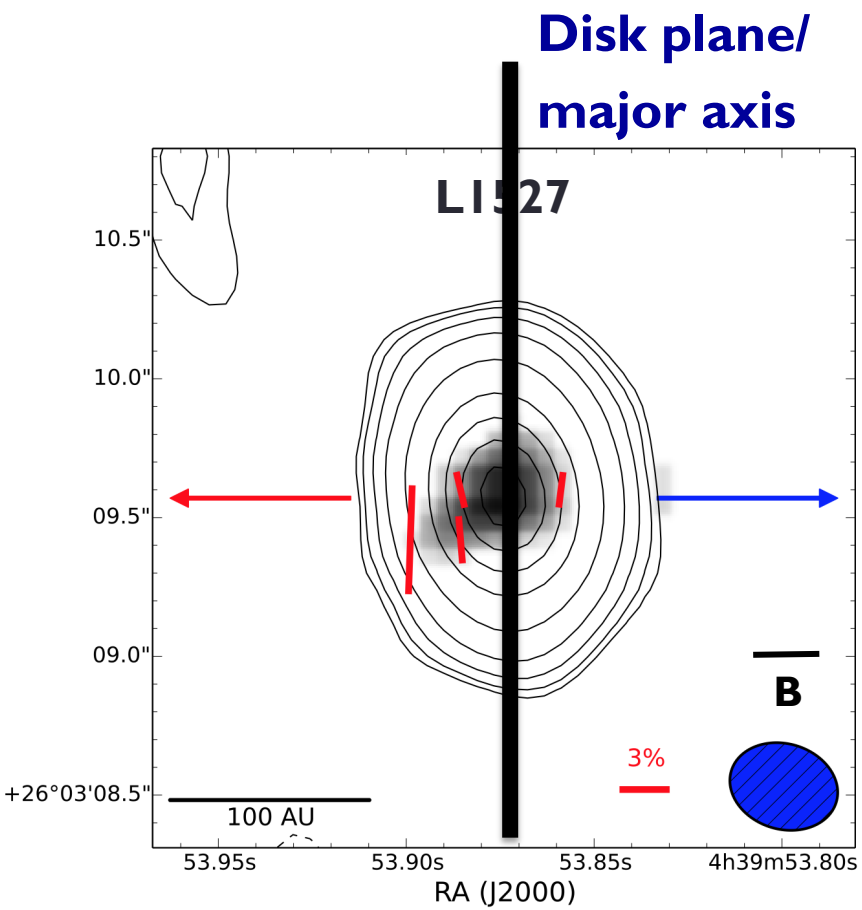


CARMA

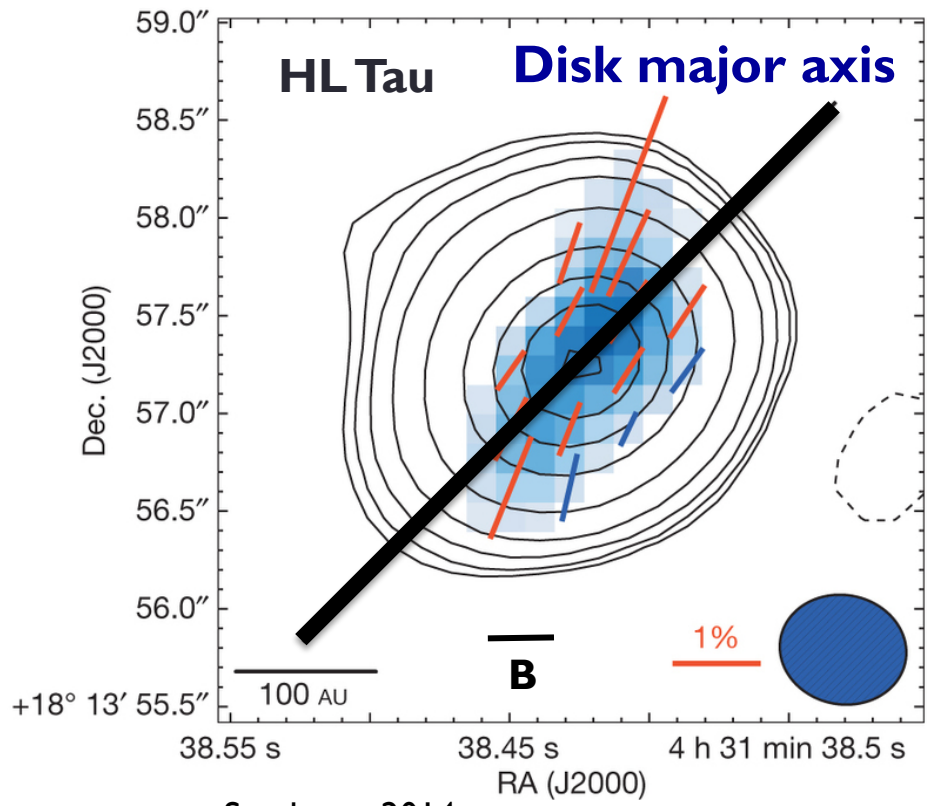


Hull+2014, ApJS, 213, 153

CARMA – Class 0 disk polarization



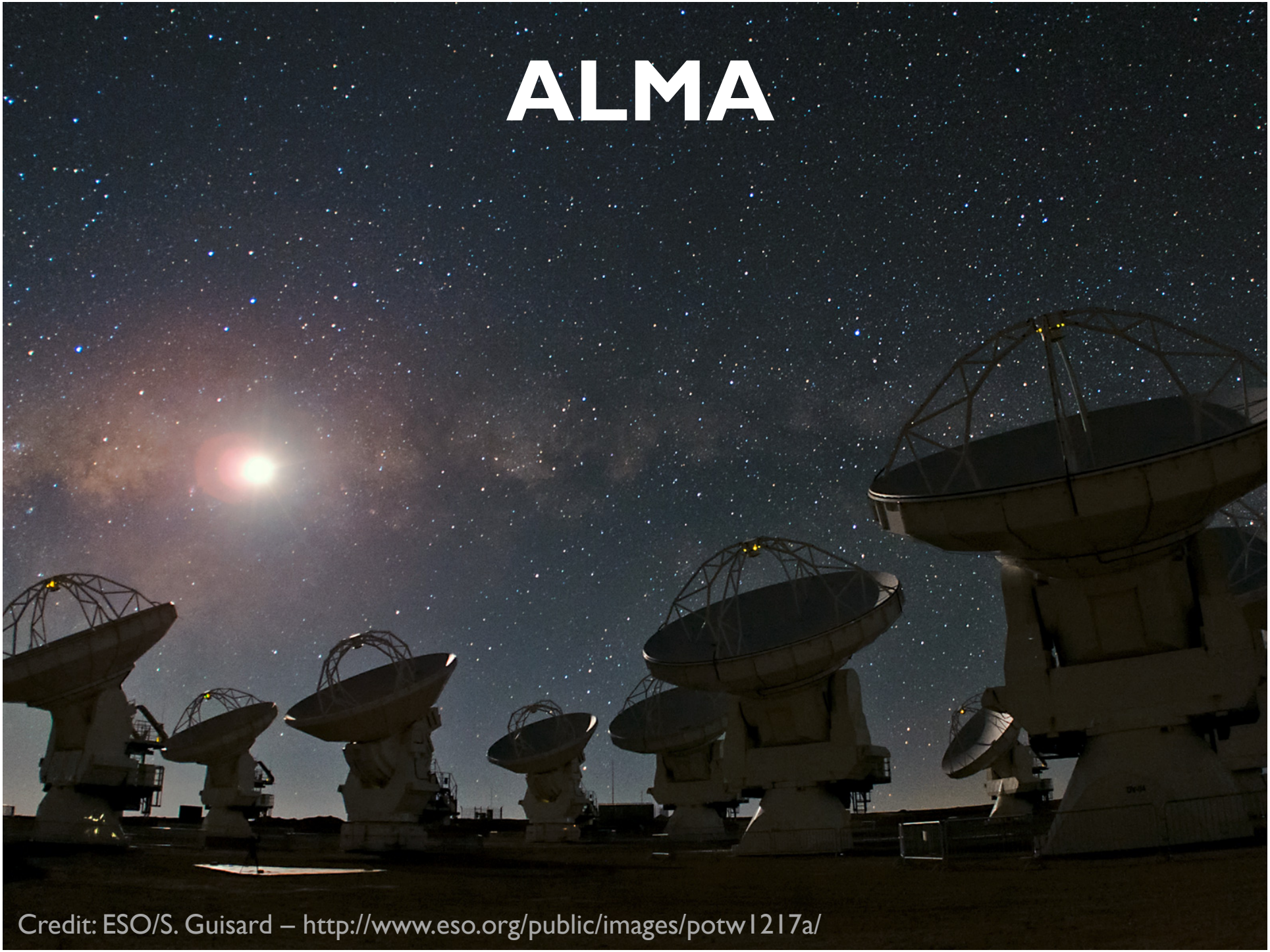
Segura-Cox+2015



Stephens+2014

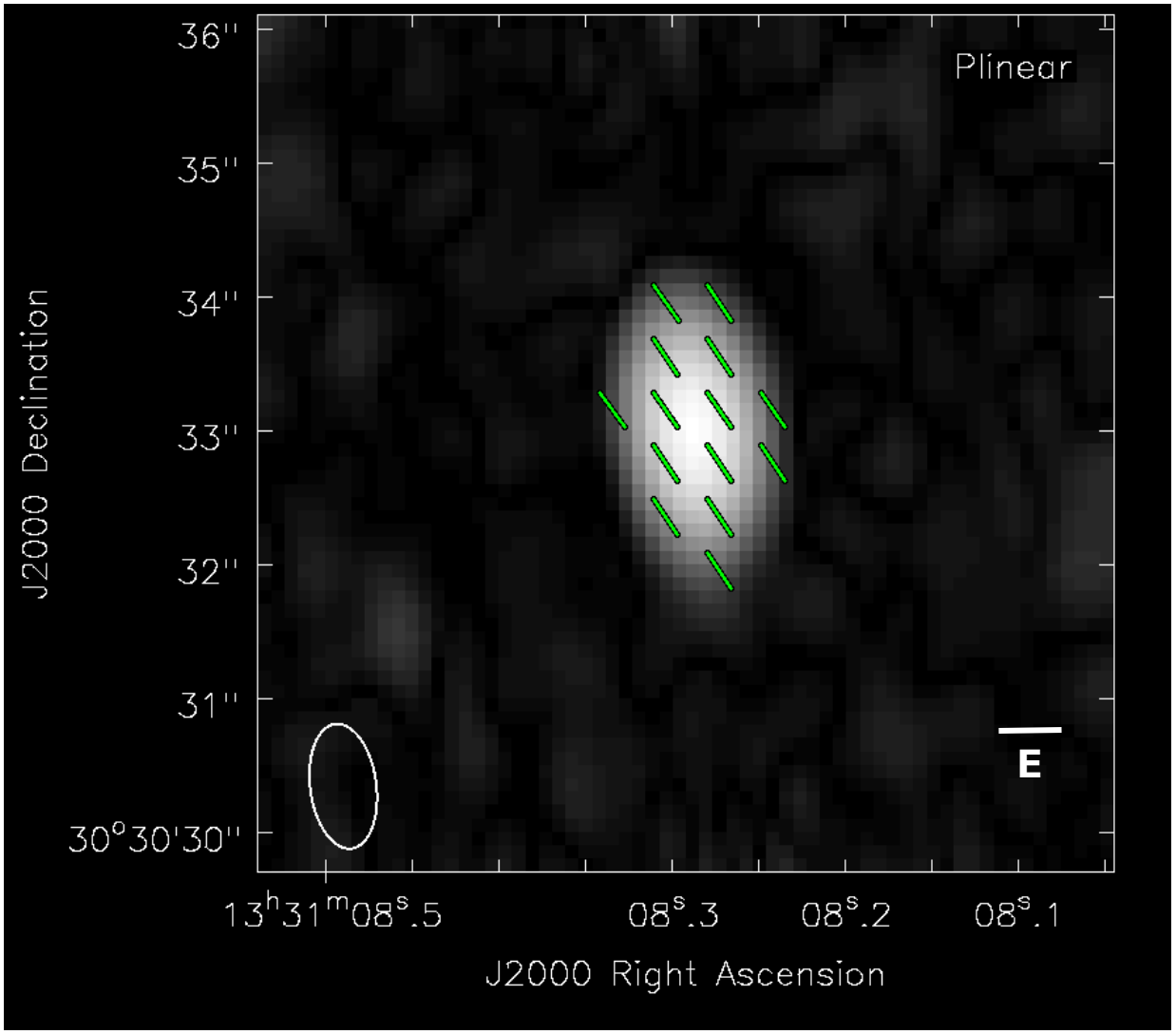
B-fields appear to be predominantly **toroidal**

ALMA



Credit: ESO/S. Guisard – http://www.eso.org/public/images/potw1217a/

ALMA – 3C286



ALMA Science Verification data

Summary

- Polarization is cool!
- Calibration is tricky…
- This was a qualitative taste of the subject
  - For beautiful math, see Rick Perley's VLA summer school talk
- Feel free to contact me with questions!

chathull.com

Fin