POLARIZATION IN FORMING STARS

PROBING SMALL SCALES WITH CARMA

Chat Hull

UC Berkeley

Radio Astronomy Laboratory

SOFIA Science Center Colloquium • Moffett Field, Calif. • 23 May 2012

Collaborators

CARMA 1mm dual-pol commissioning

- Dick Plambeck
- Greg Engargiola
- All the OVRO staff

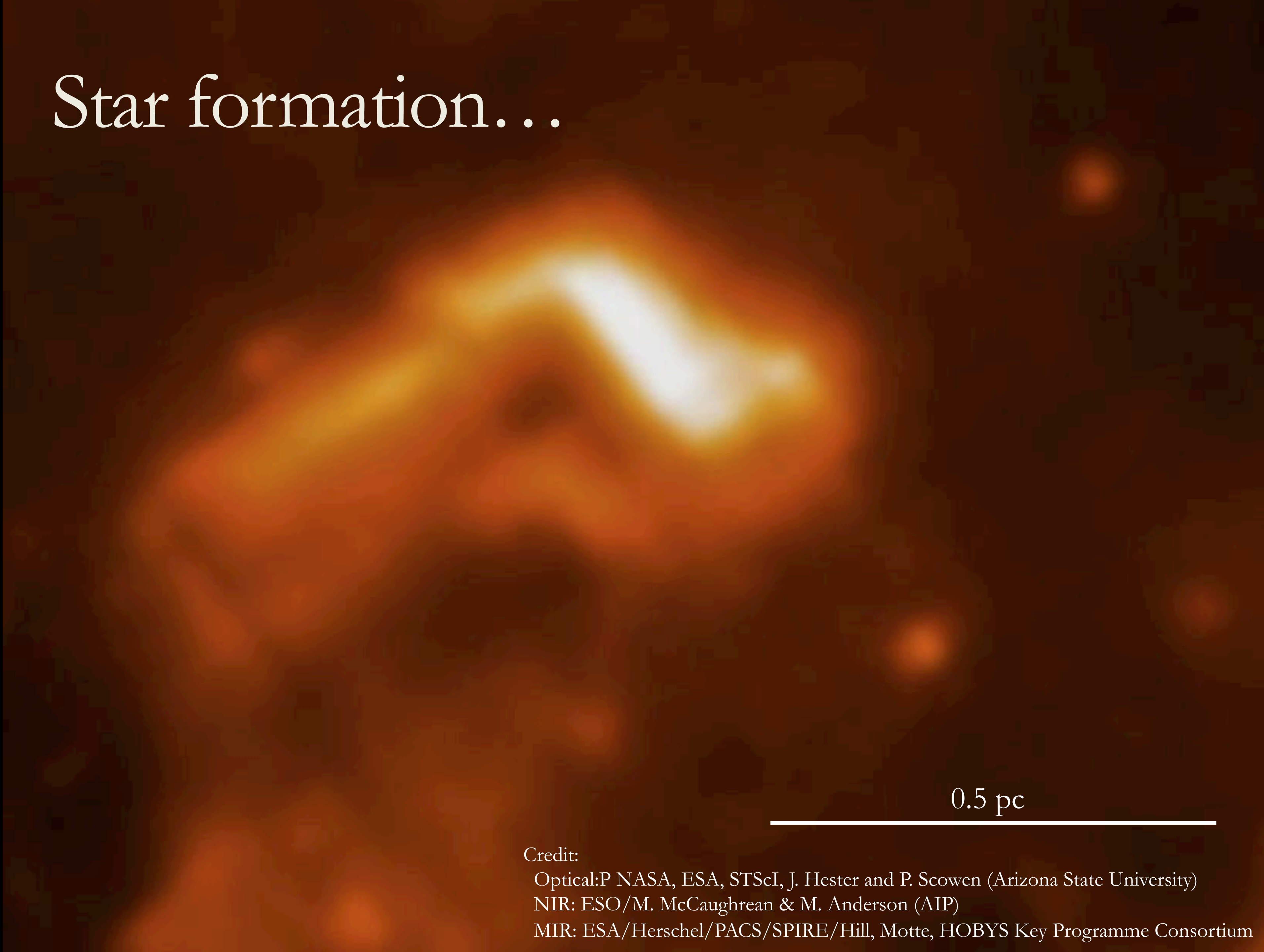
TADPOL project

- **UC Berkeley**
  Dick Plambeck, Meredith Hughes, Mel Wright, Carl Heiles, Geoff Bower
- **University of Maryland**
  Marc Pound, Alberto Bolatto, Katherine Jameson, Lee Mundy
- **Caltech**
  Thushara Pillai, John Carpenter, James Lamb, Nikolaus Volgenau
- **University of Illinois, Urbana-Champagne**
  Ian Stephens, Leslie Looney, Woojin Kwon, Dick Crutcher, Nick Hakobian
- **University of Chicago**
  Roger Hildebrand
- **Other**
  Jason Fiege (Manitoba), Erica Franzmann (Manitoba), Martin Houde (UWO, Caltech), Dan Marrone (Arizona), Brenda Matthews (HIA), John Vaillancourt (USRA-SOFIA)

Outline

- **B-fields in star formation**
  - Motivation & overview
- **B-fields from large to small scales**
  - B-field regulation of SF from large to small scales
  - Alignment of B-field in core, and outflow direction
- **The TADPOL survey**
  - Probing B-fields at dense-core scales
  - Polarization modeling
- **The CARMA dual-polarization system**
  - How we made it all work

Star formation…

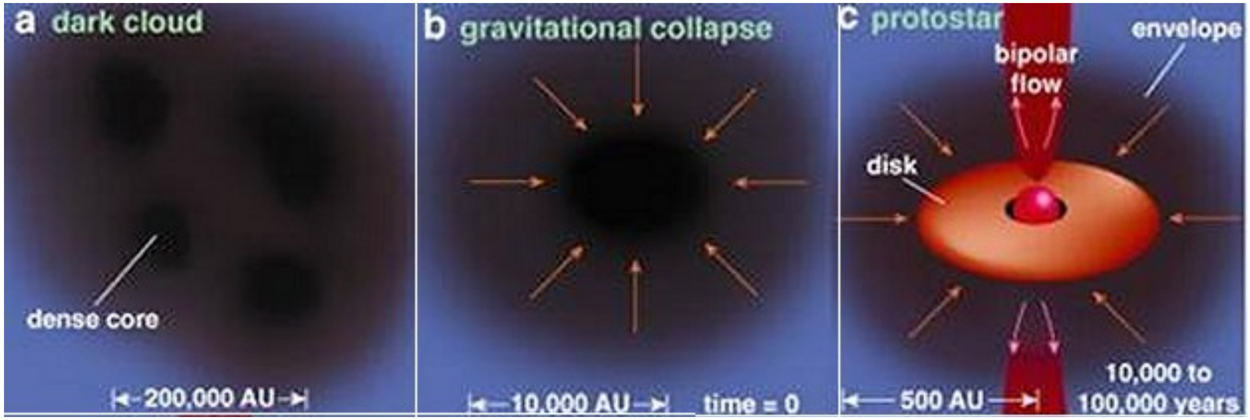


Credit:
Optical:P NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)
NIR: ESO/M. McCaughrean & M. Anderson (AIP)
MIR: ESA/Herschel/PACS/SPIRE/Hill, Motte, HOBYS Key Programme Consortium

Non-magnetized star formation

- **Pulling in:**
  - Gravity
- **Pushing out:**
  - Turbulent pressure
  - Thermal pressure
  - Rotational support

Dark cloud | **Dense core** | **Protostar**



10 pc | 1 pc | 0.1 pc

Credit: Spitzer Science Center

Magnetized star formation

- **Pulling in:**
  - Gravity
- **Pushing out:**
  - Turbulent pressure
  - Thermal pressure
  - Rotational support
  - $\boxed{\textbf{Magnetic pressure}}$

- **Will the cloud collapse?**

$$\frac{E_{\rm grav}}{E_{\rm mag}} < 1$$

"Subcritical"
(**WILL NOT** collapse)

$$\frac{E_{\rm grav}}{E_{\rm mag}} > 1$$

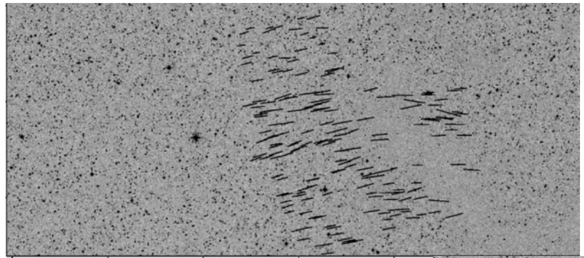
"Supercritical"
(**WILL** collapse)

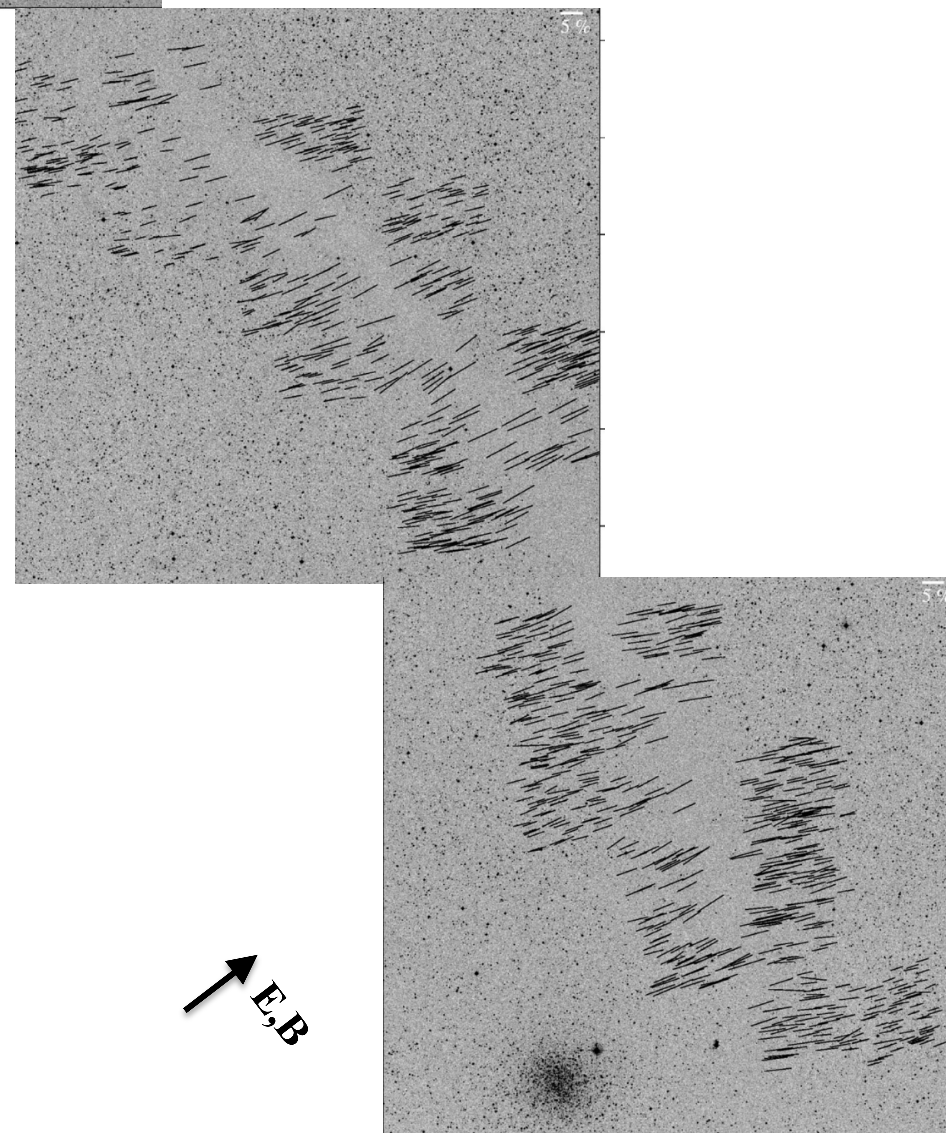
OUR QUESTIONS

How important are B-fields in star formation?

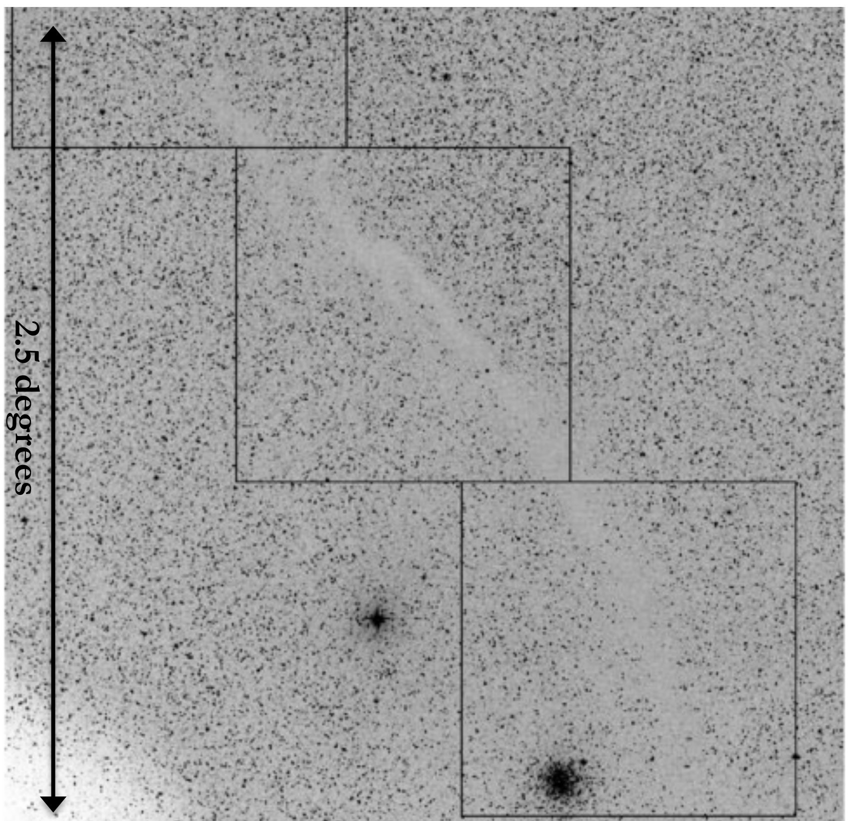
On what scales are B-fields important?

Large-scale: ordered fields



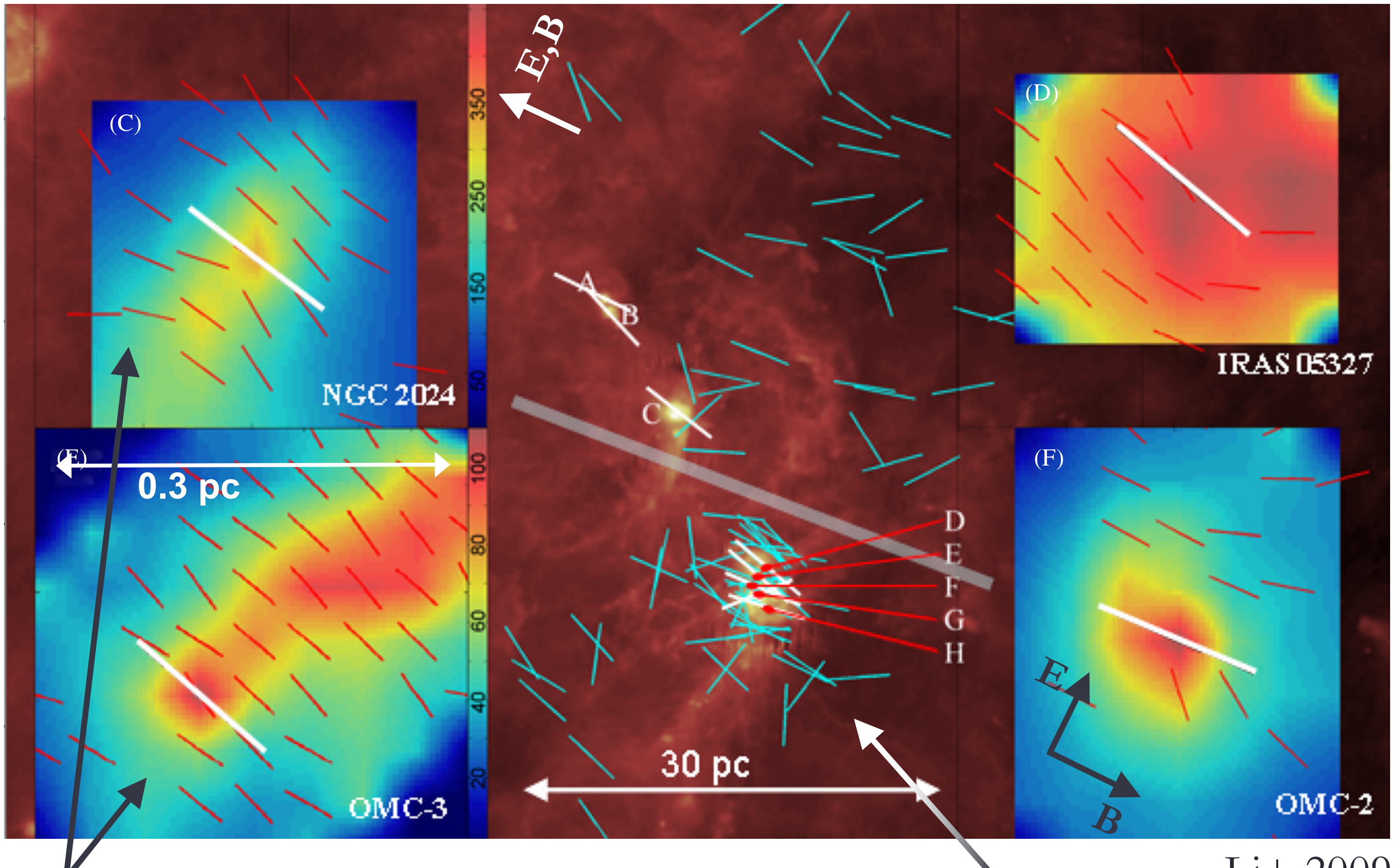


Musca dark cloud



Images: Pereyra & Magalhães 2004

Large-scale: consistent B-field in clouds & cores



Li+ 2009

Sub-mm CSO data
n ~ 10^5 cm^{-3}
L ~ 0.3 pc

IRAS data
n ~ 1 cm^{-3}
L ~ 100 pc

Smaller-scale: still important?

- Fields clearly are important between the ~100 pc and ~1 pc scales
- Are fields dynamically important once you get below the ~1 pc core scale?
- If so, B-fields should be:
  - **Well ordered**
  - **Aligned with outflows**, to allow for angular momentum transport (if past simulations are correct)

CARMA

Combine **A**rray for **R**esearch in **M**illimeter-wave **A**stronomy

Consortium: Berkeley, Caltech, Illinois, Maryland, Chicago

- 6 × 10-m, 9 × 6-m, 8 × 3.5-m telescopes
- Observations at 1 mm, 3 mm, and 1 cm
- Located in Cedar Flat, CA (near Bishop)

TADPOL survey

30 objects

Triples number of low-mass, forming stars observed to date

280 observing hours

CARMA C, D, & E arrays

1 – 4″ resolution

10× higher resolution than CSO & JCMT

Probes intermediate region between ~1 pc (single-dish) and ~100 AU (ALMA)

1 mm wavelength

Ideal for dust polarization, as well as CO(2-1)

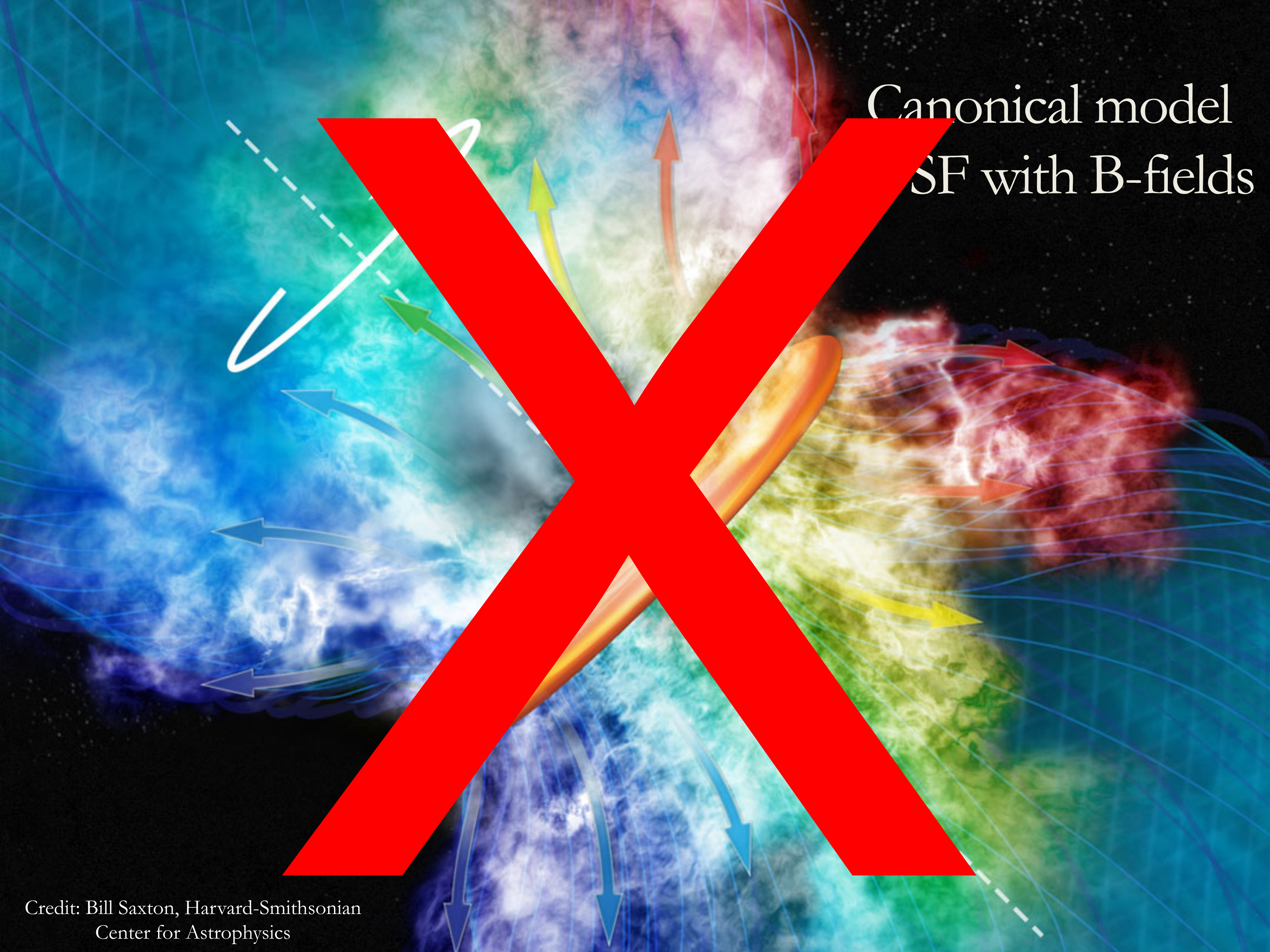
TADPOL survey goals

- **Isolated, star-forming cores**
  - Measure projected field vs. outflow directions
  - Model intrinsic field morphology

- **Extended regions**
  - Look for orderliness in B-fields on ~0.01 pc scales
  - Compare with larger-scale polarization in cloud envelopes
  - Also, turbulent power spectrum of B-field

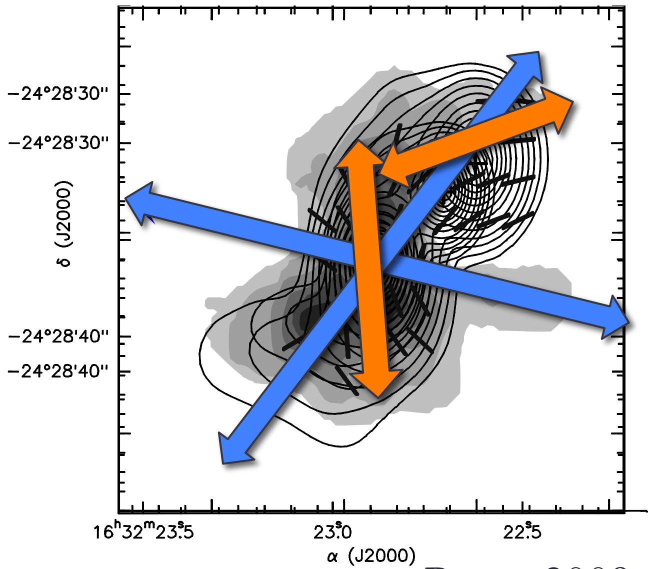
Smaller-scale: still important?

- Fields clearly are important between the ~100 pc and ~1 pc scales
- Are fields dynamically important once you get below the ~1 pc core scale?
- If so, B-fields should be:
  - **Well ordered**
  - **Aligned with outflows**, to allow for angular momentum transport (if past simulations are correct)


Canonical model
SF with B-fields
Credit: Bill Saxton, Harvard-Smithsonian
Center for Astrophysics

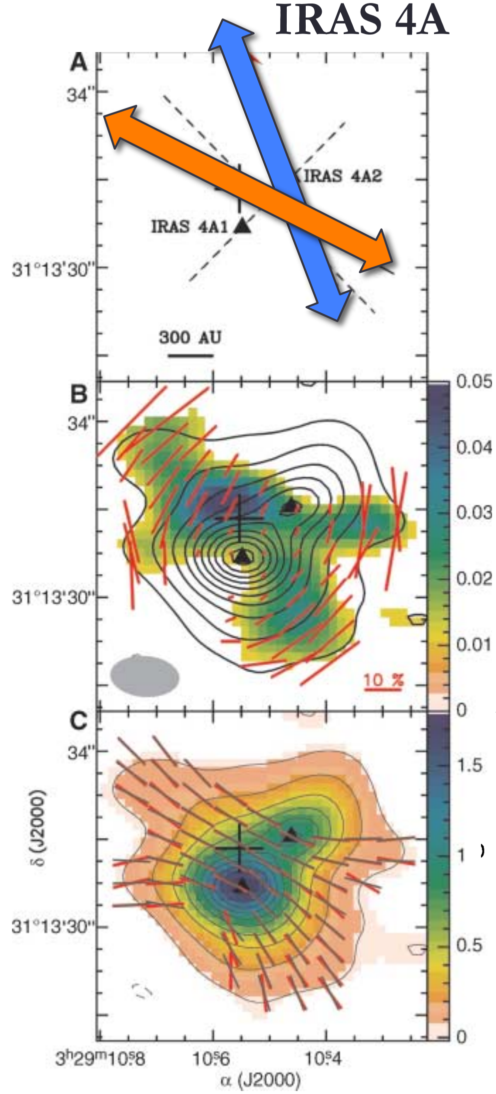
Misalignment of B-fields and outflows

IRAS 16293



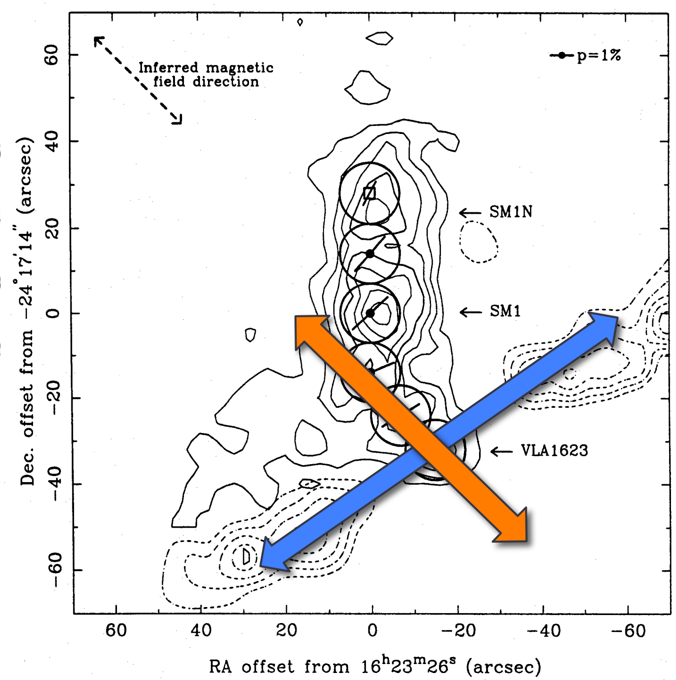
Rao+ 2009

IRAS 4A



Girart+ 2006

VLA 1623

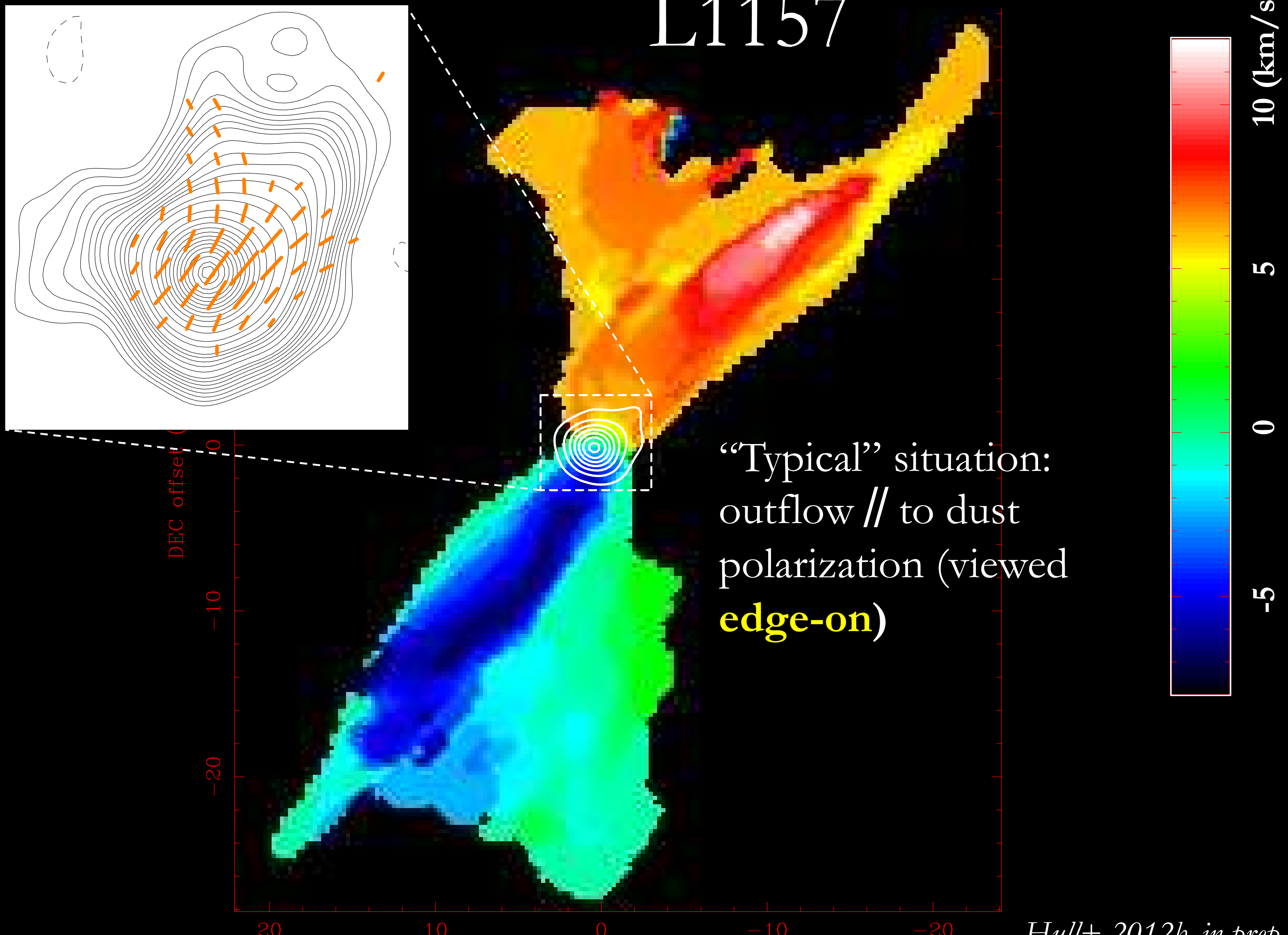


Holland+ 1996

Outflow

B-field

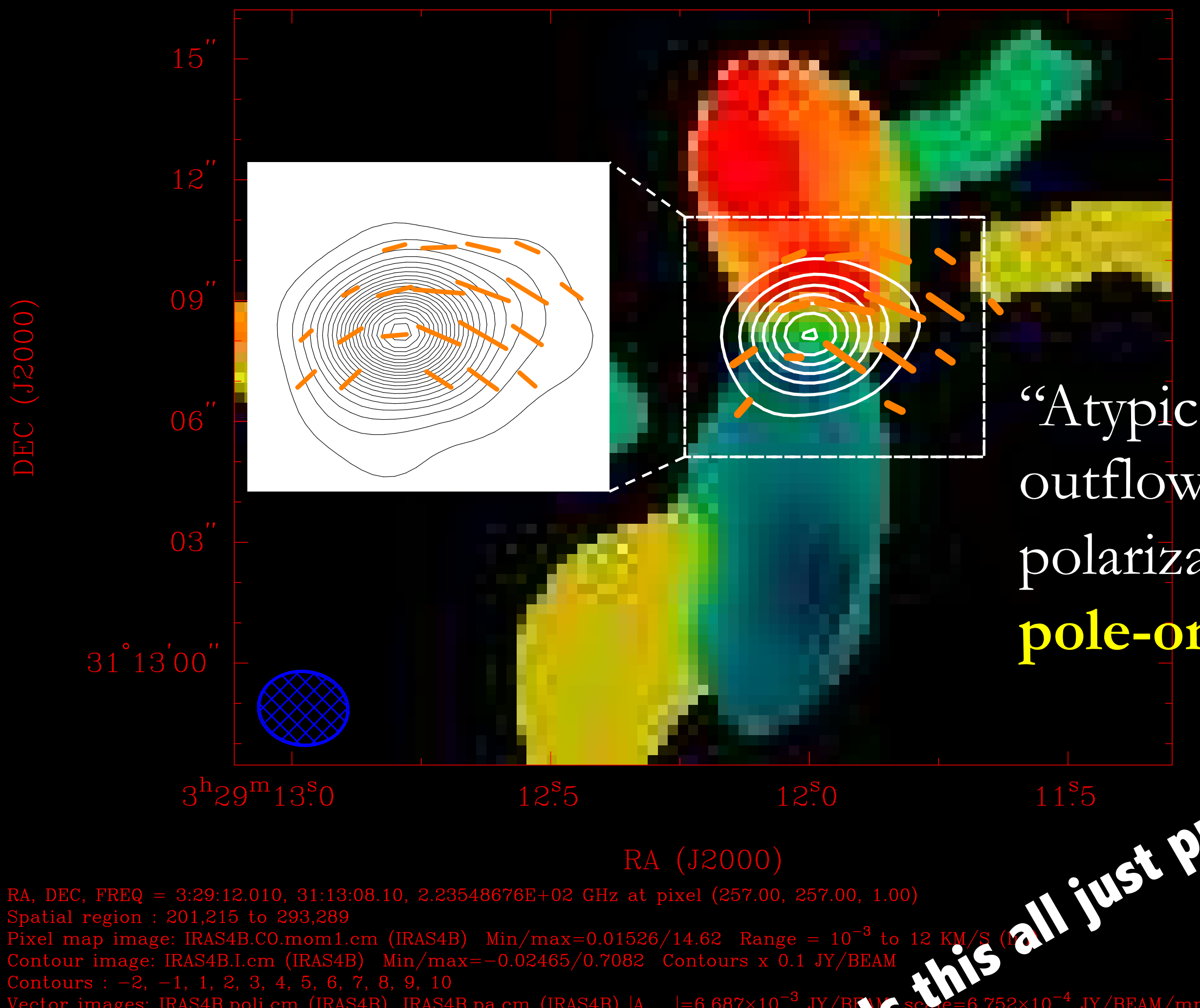
L1157



"Typical" situation: outflow // to dust polarization (viewed **edge-on**)

Hull+ 2012b, in prep.

NGC 1333-IRAS 4B



"Atypical" situation: outflow ⊥ to dust polarization (seen **pole-on**)

Is this all just projection effects?!

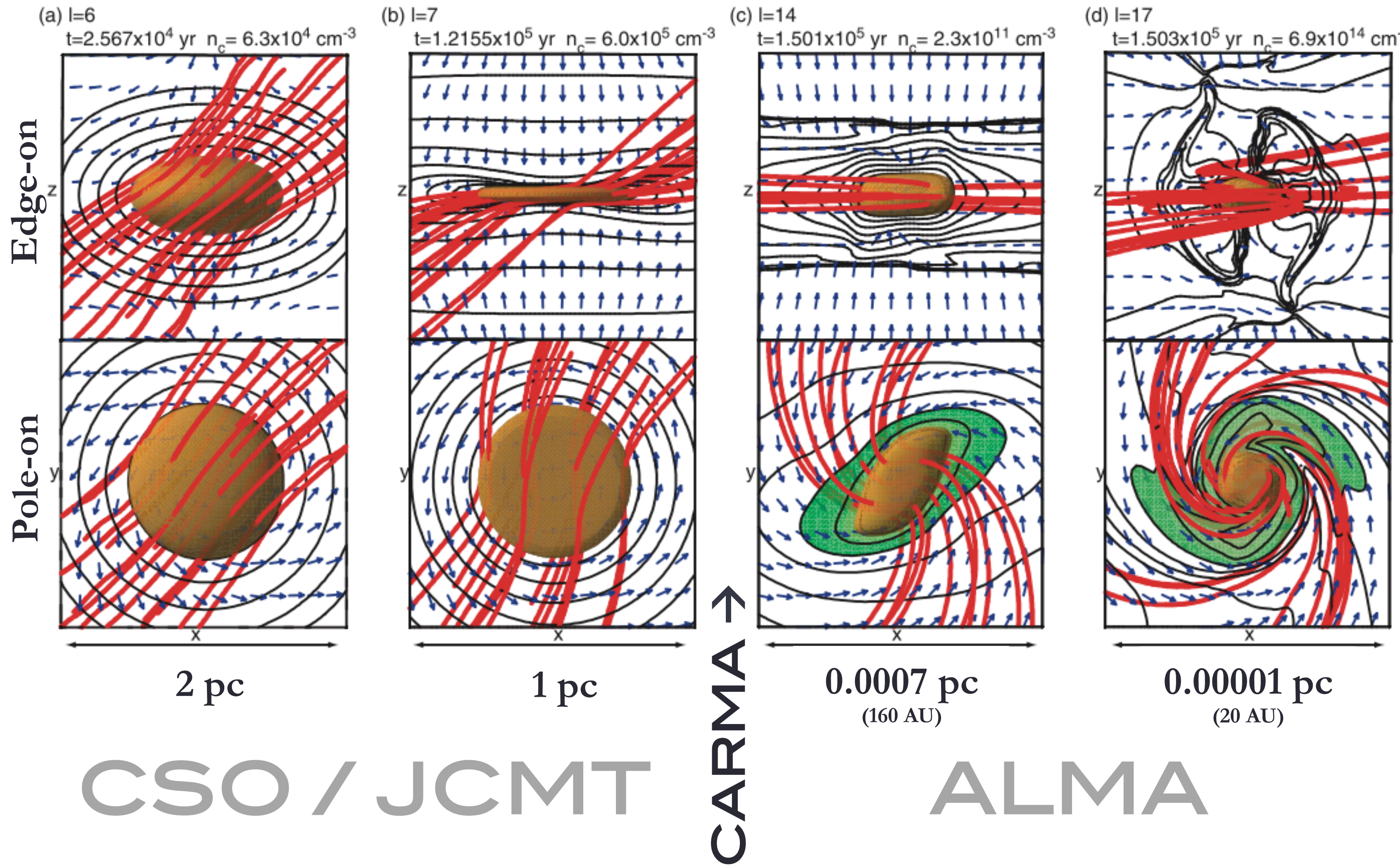
Hull+ 2012b, in prep.

Smaller-scale: still important?

- Fields clearly are important between the ~100 pc and ~1 pc scales
- Are fields dynamically important once you get below the ~1 pc core scale?
- If so, B-fields should be:
  - **Well ordered**
  - **Aligned with outflows**, to allow for angular momentum transport (if past simulations are correct)

It's all about **resolution** (and **sensitivity**…)

Machida+ 2006

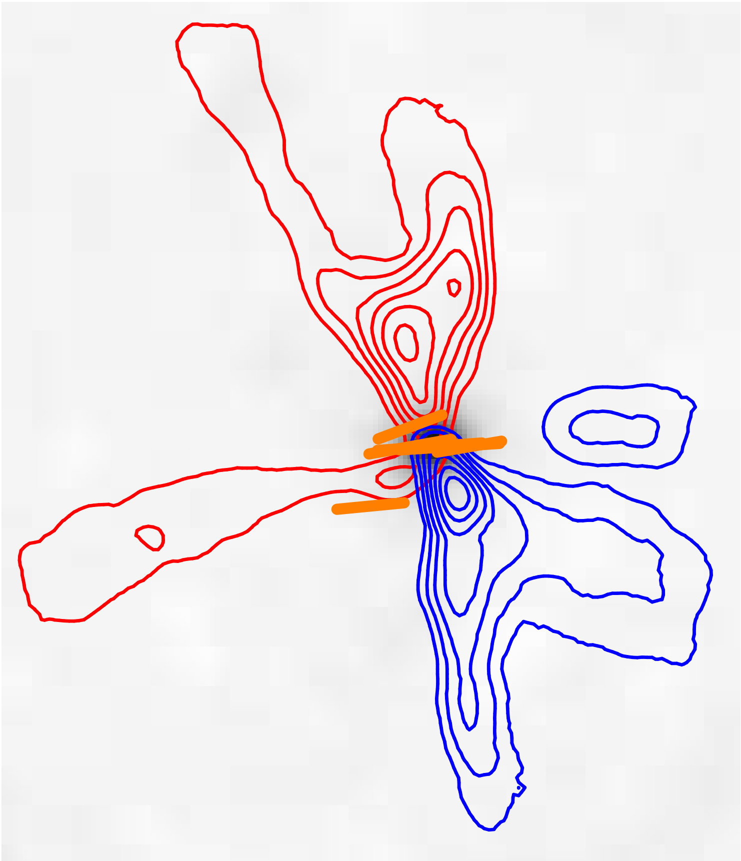


At **d = 500 pc,** the D-array synthesized beam (at 1 mm) spans 2″, or **0.005 pc** (1000 AU)

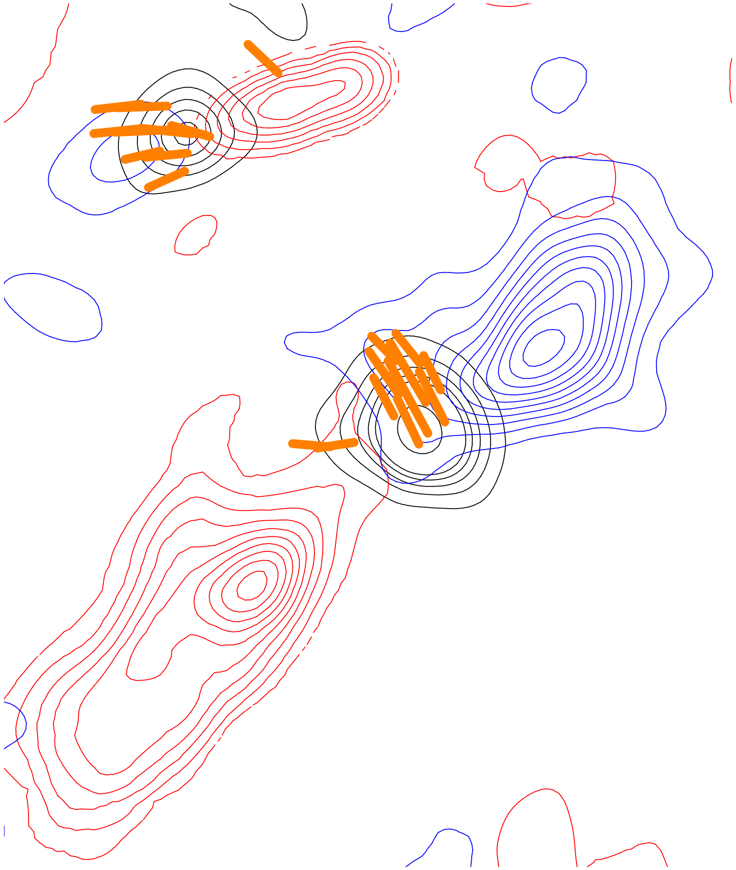
More TADPOL results

Isolated cores

IRAS 2A

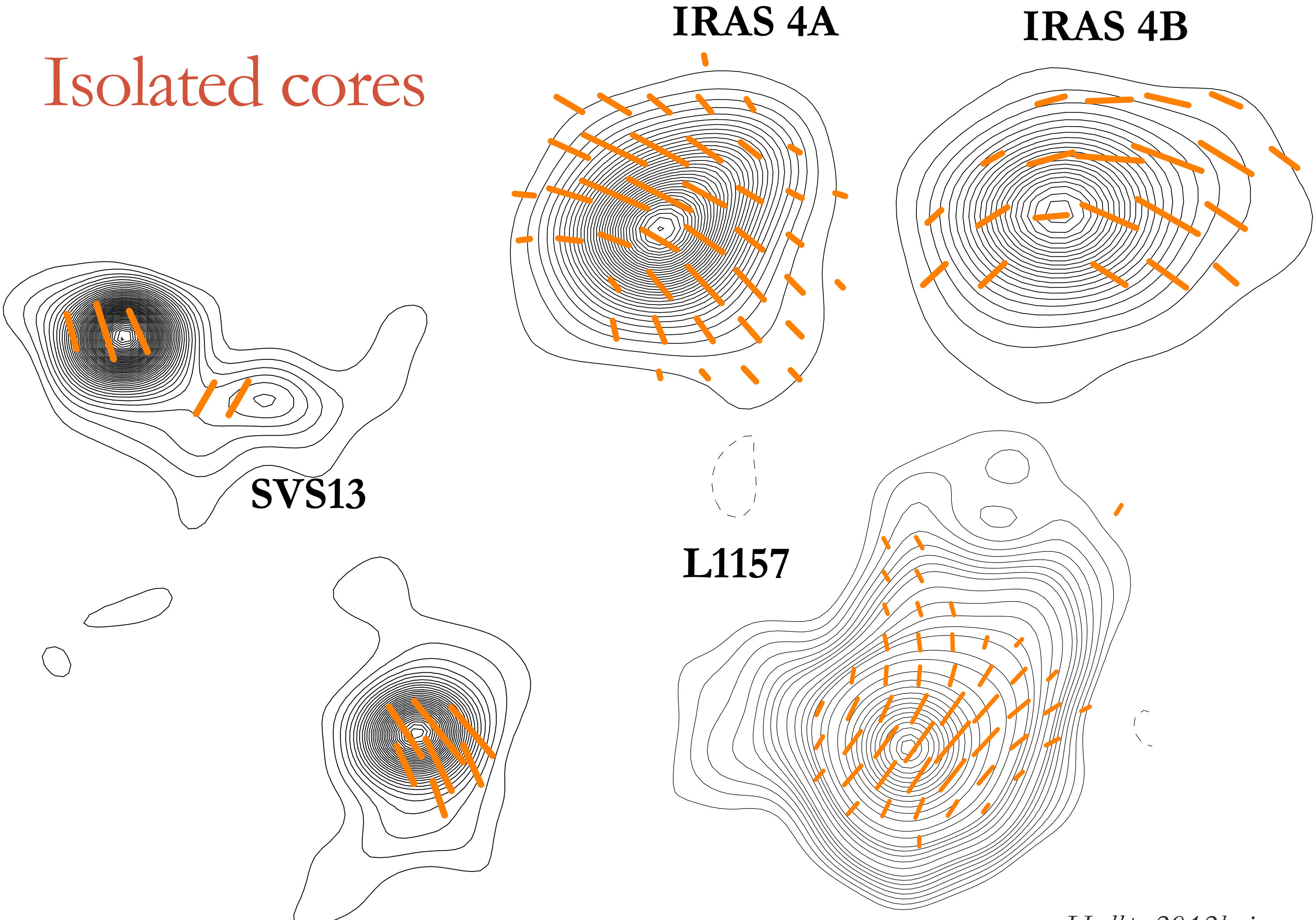


Ser-emb 8



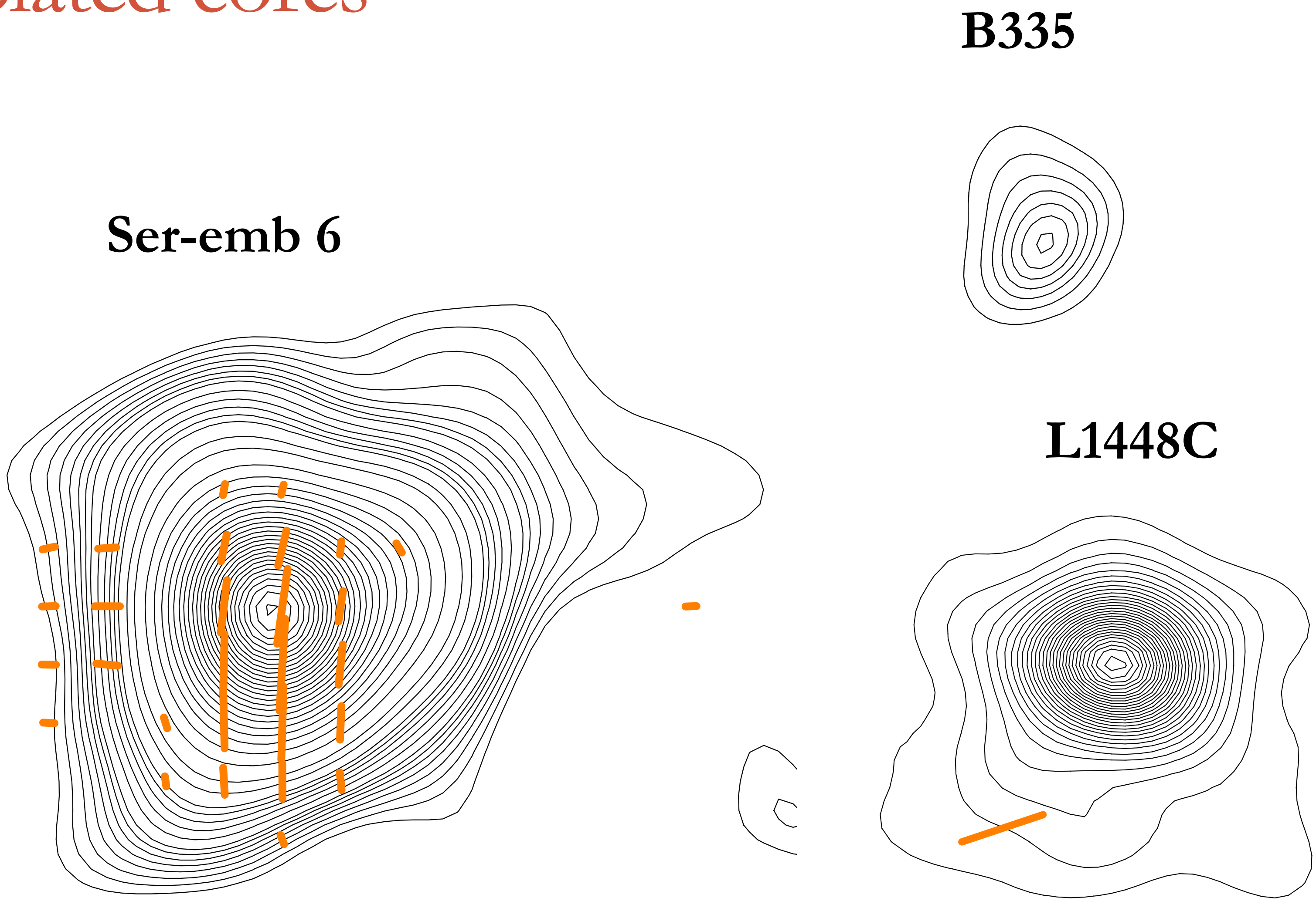
Hull+ 2012b, in prep.

Isolated cores



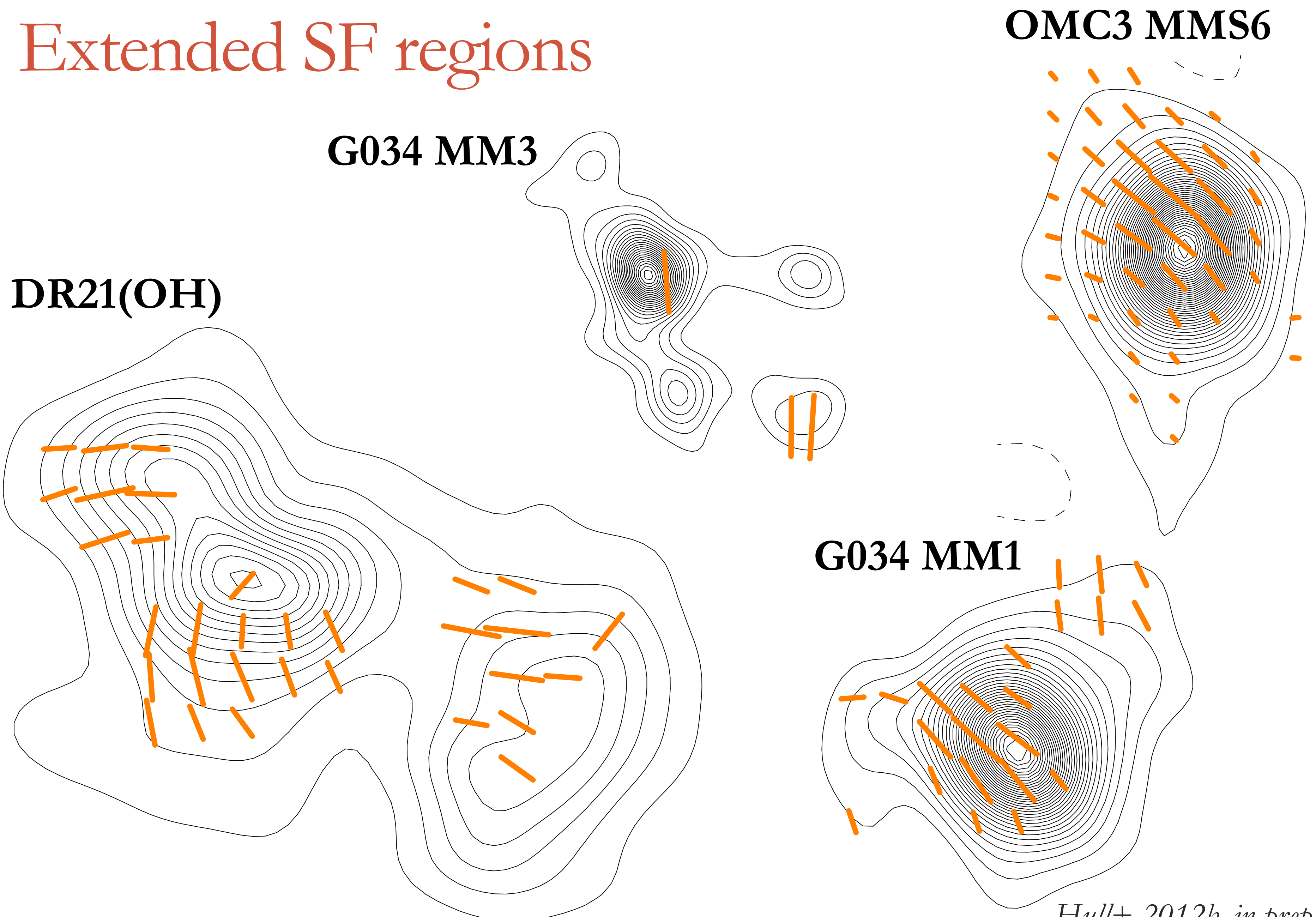
Hull+ 2012b, in prep.

Isolated cores



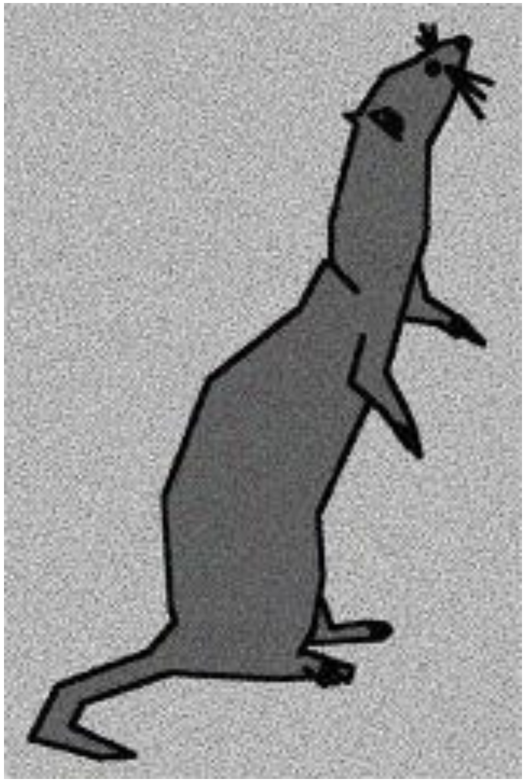
Hull+ 2012b, in prep.

Extended SF regions



Hull+ 2012b, in prep.

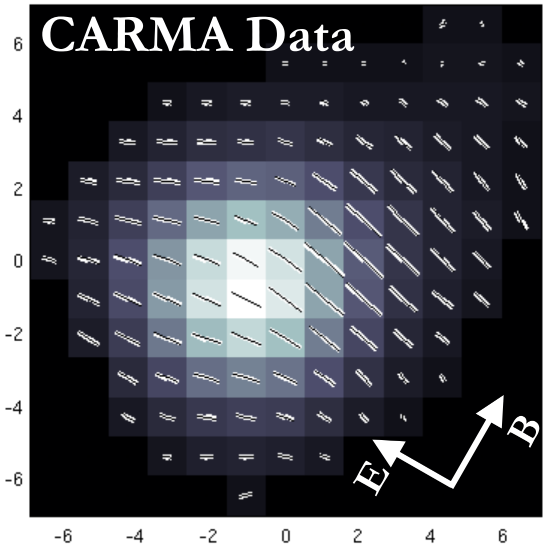
Polarization modeling

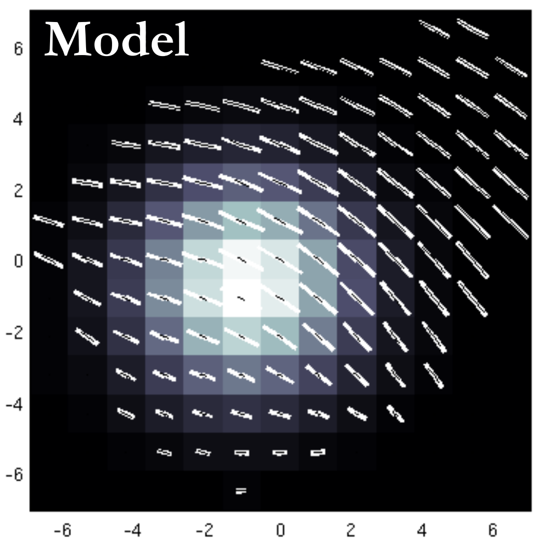


Ferret is a genetic-algorithm-based optimization code designed by Jason Fiege (Manitoba); *PolCat,* which produces the models, was largely developed by Erica Franzmann (Manitoba)

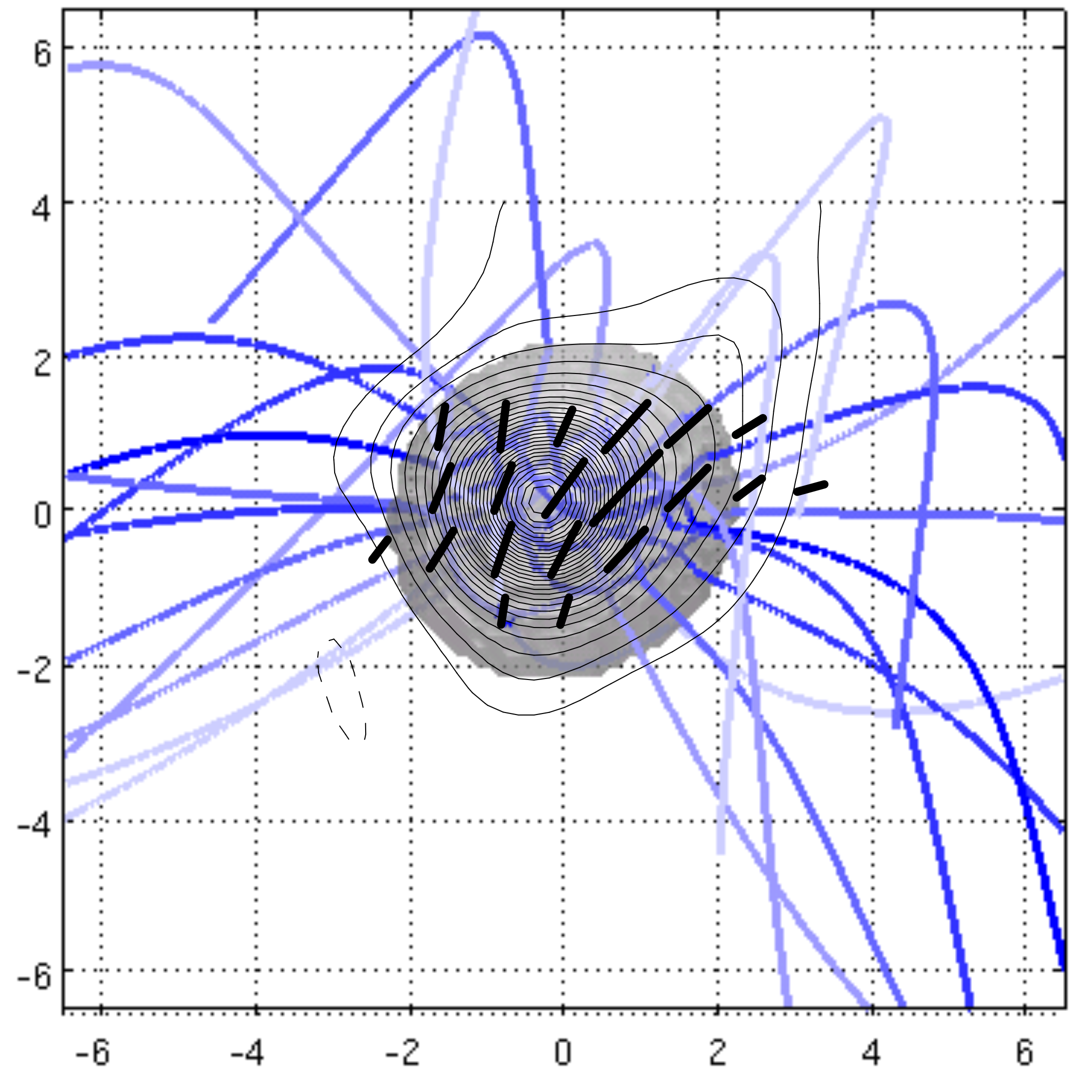
- *PolCat* produces cloud models, and *Ferret* takes those models, compares them with data, and finds the most likely combination of parameters:
  - Inclination angle
  - Toroidal/poloidal B-field components
  - Core ellipticity
  - Density contrast
  - Pressure contrast

L1157 model (preliminary)



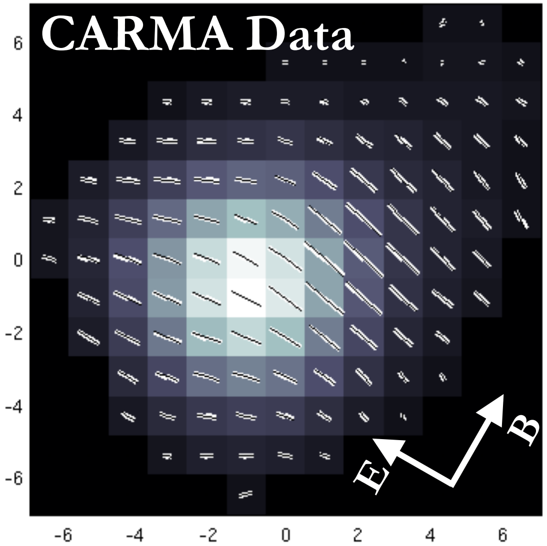


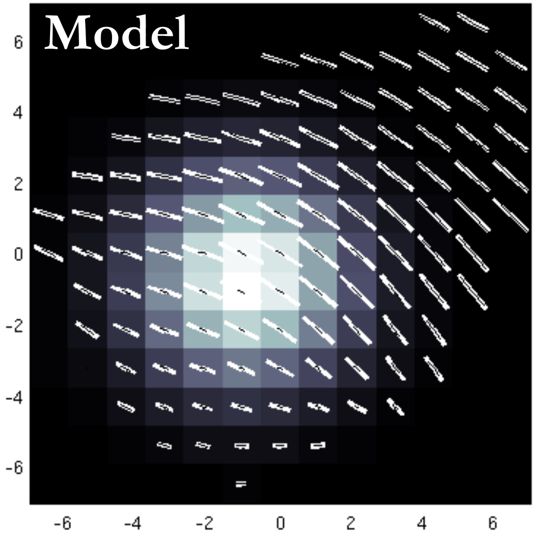
Plane-of-sky view

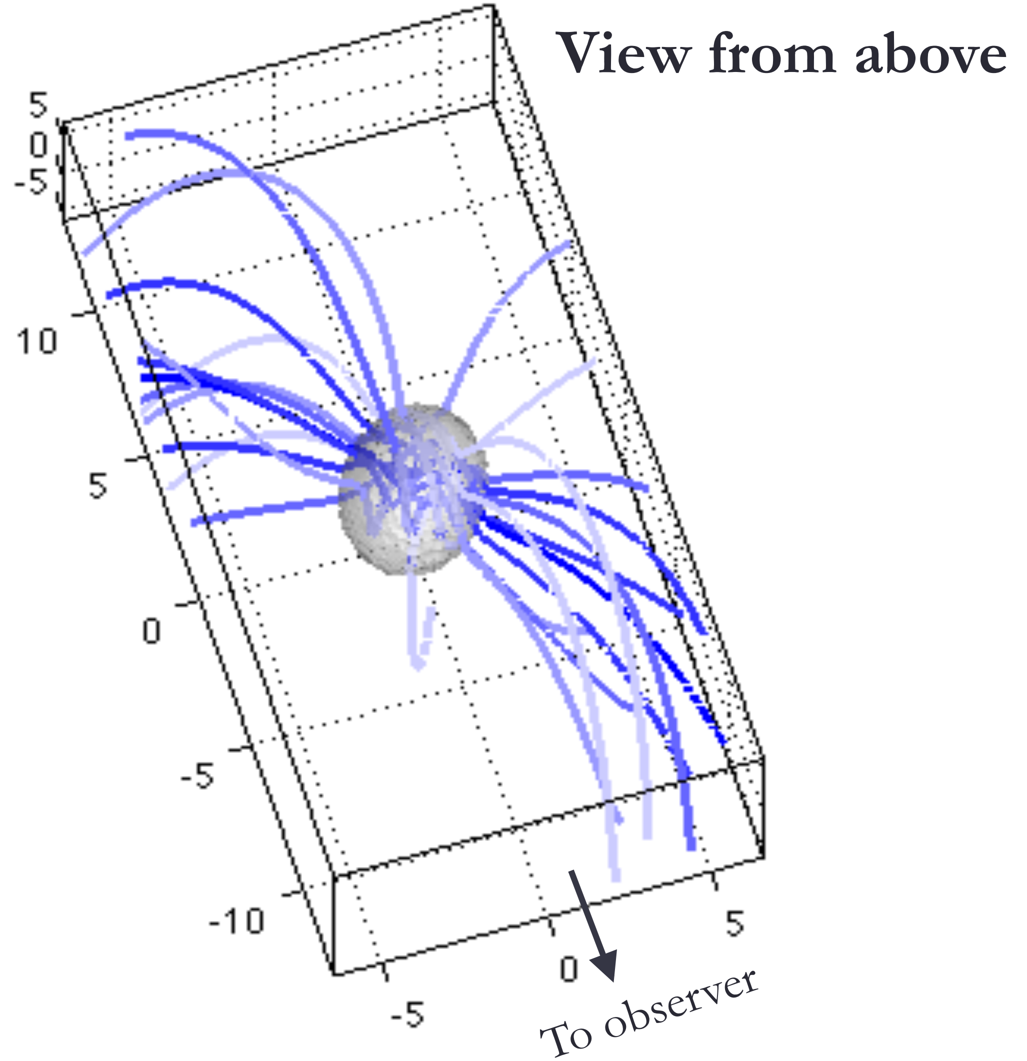


Models courtesy of E. Franzmann (Manitoba)

L1157 model **(preliminary)**

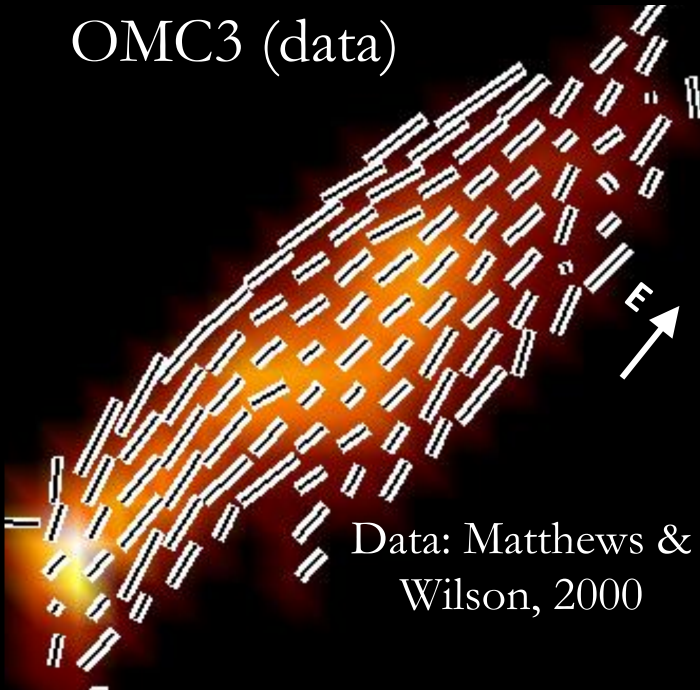




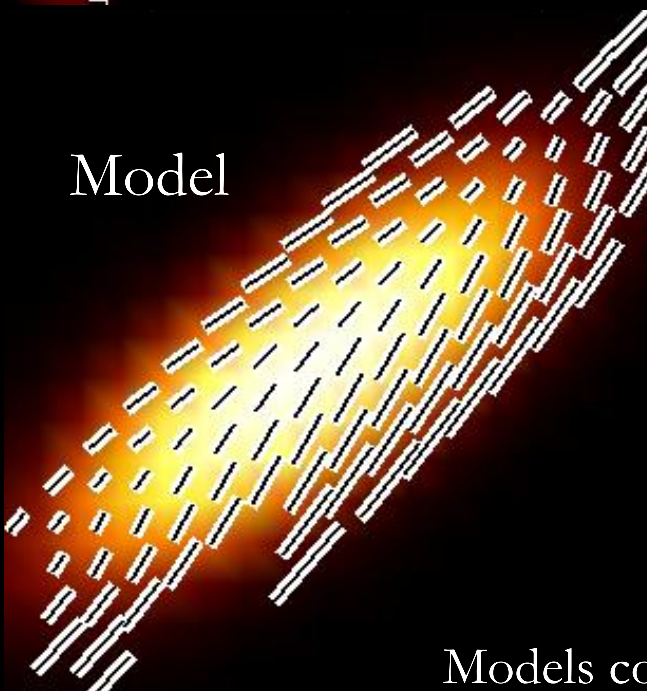


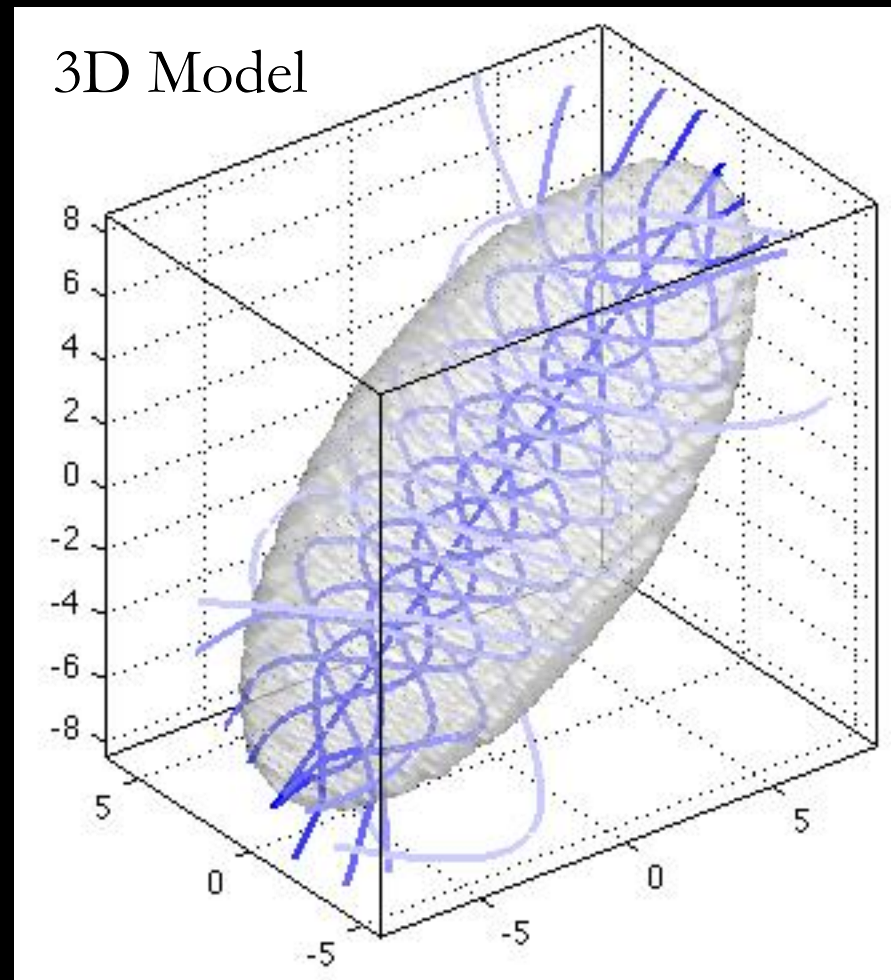
Models courtesy of E. Franzmann (Manitoba)

Observations & Simulations



Data: Matthews & Wilson, 2000





Models courtesy of E. Franzmann (Manitoba)

Other science made possible by CARMA polarization

- **SgrA* RM** with simultaneous CARMA/SMA observations *[Marrone, Hull, Plambeck Bower+]*
- **SgrA* polarization variability** during 1 mm VLBI *[Hull, Plambeck, Bower+]*
- **M82** dust polarization *[Bolatto, Hull, Plambeck+]*
- **Turbulent power spectrum** in extended cores using B-field dispersion *[Houde, Hildebrand, Vaillancourt, Hull, Plambeck+]*
- **Eagle Nebula** dust polarization *[Pound, Mackey, Hull, Plambeck+]*
- RM synthesis toward **low-luminosity AGN** *[Bower, Hull, Plambeck+]*
- **Quasar RM** at 1 & 3 mm *[Hull, Plambeck, Wright, Heiles+]*
- **T Tauri star** disk polarization *[Hughes, Hull, Plambeck+]*

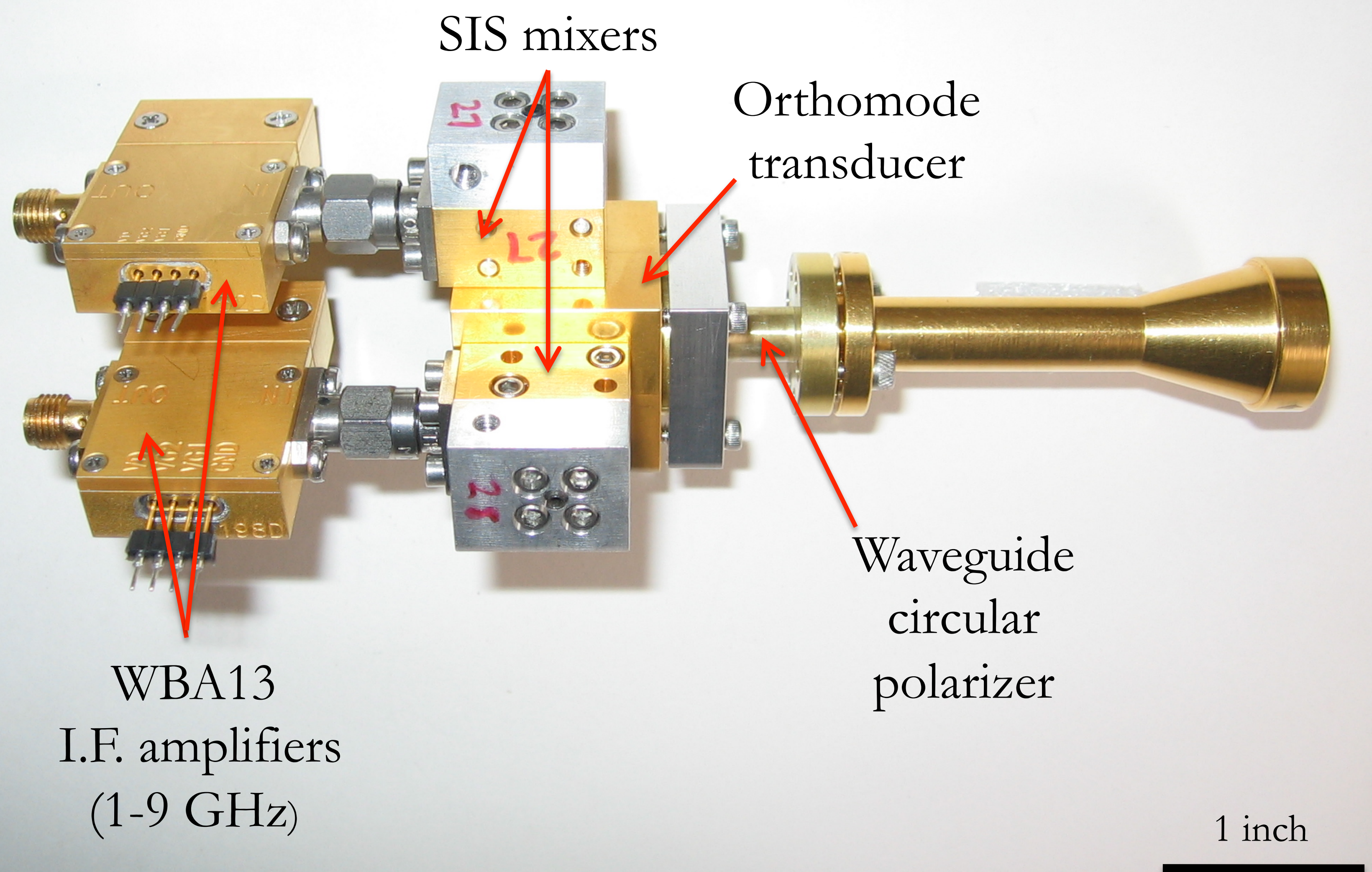
Roadmap to functionality

- **Hardware testing**
  - Mixers
  - Orthomode transducers
  - Polarizers
- **Hardware installation**
- **Calibration**
  - XY phase
  - Leakages

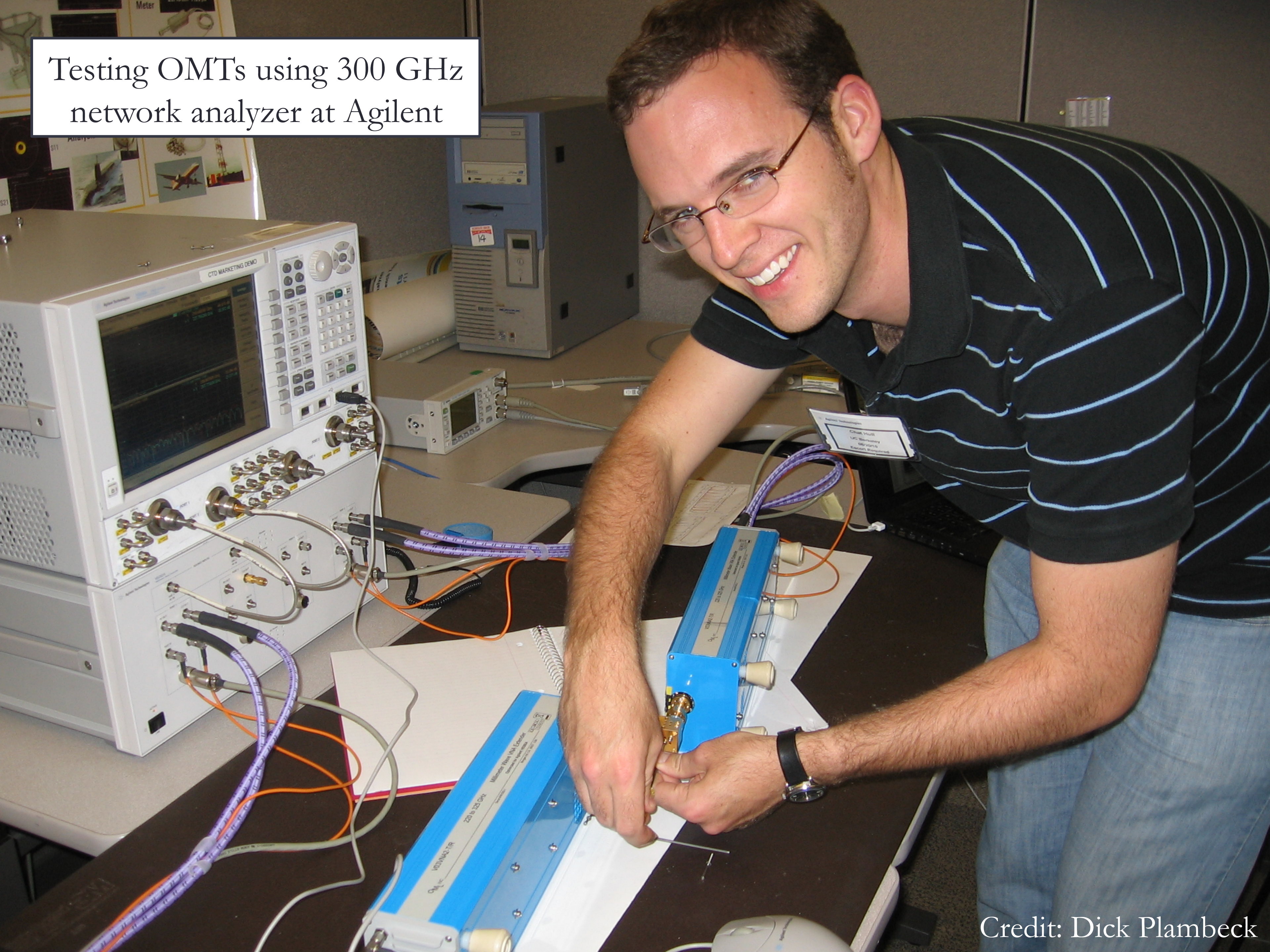
CARMA

Combine **A**rray for **R**esearch in **M**illimeter-wave **A**stronomy

1 mm dual-polarization receivers

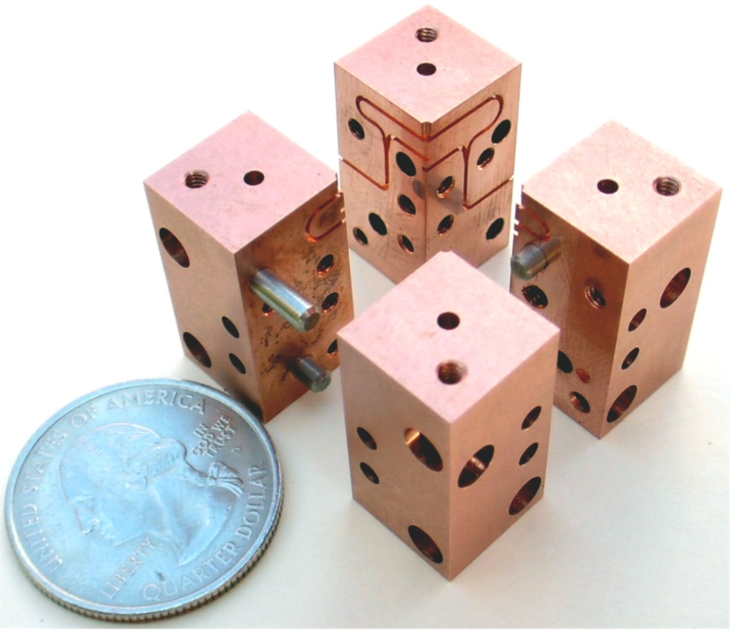


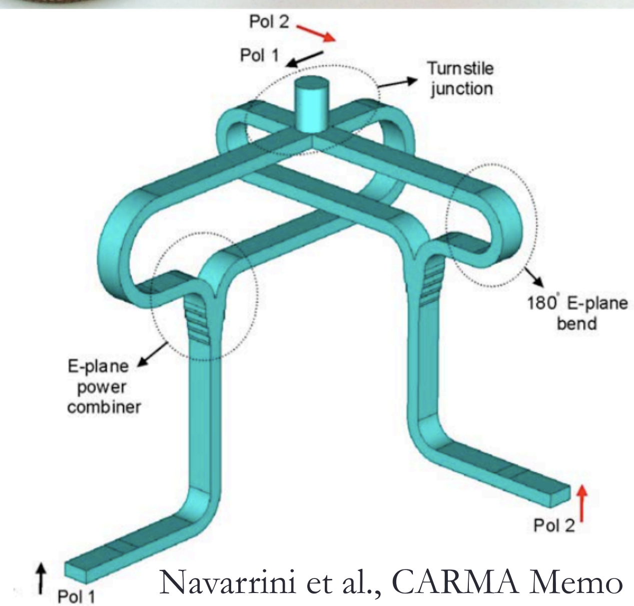
Testing OMTs using 300 GHz network analyzer at Agilent



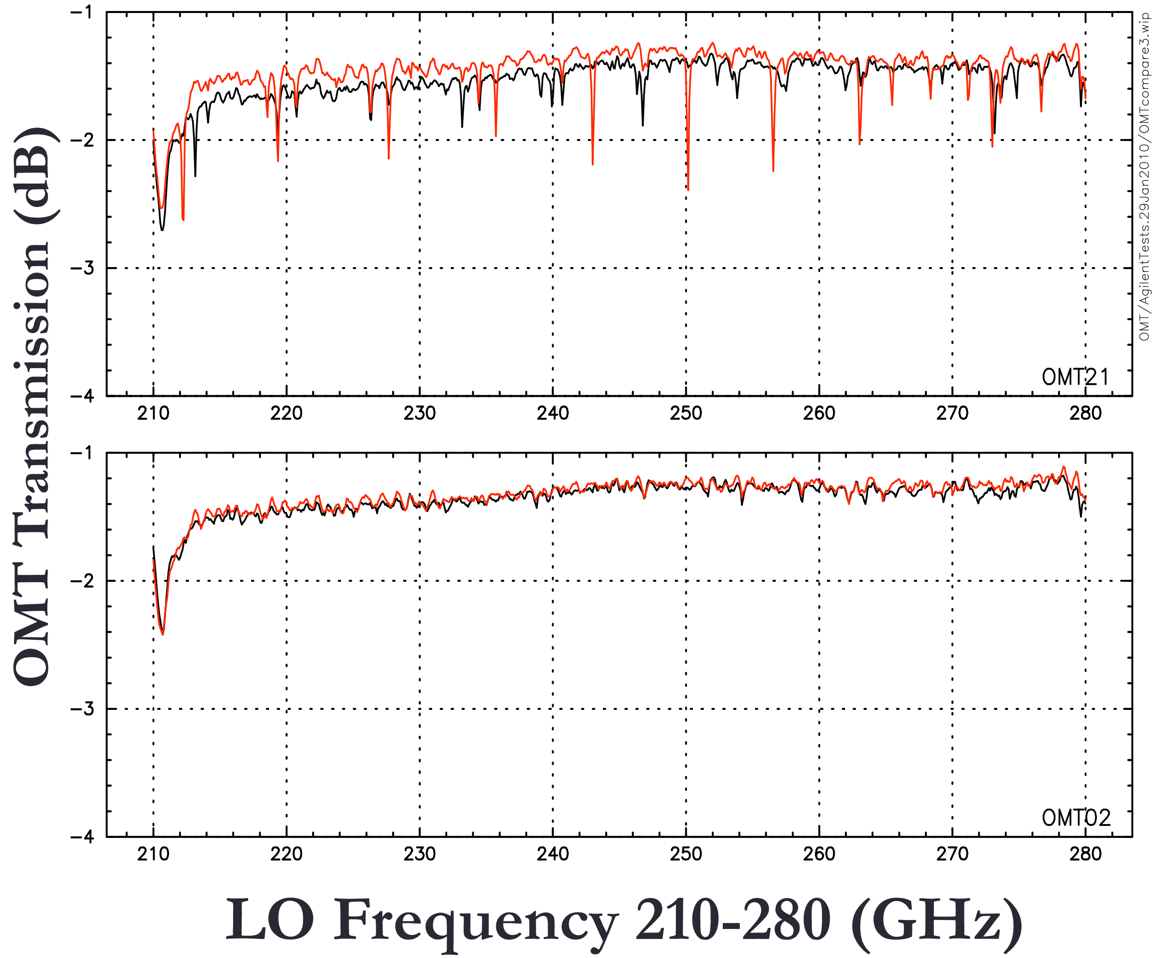
Credit: Dick Plambeck

Hardware testing: orthomode transducers

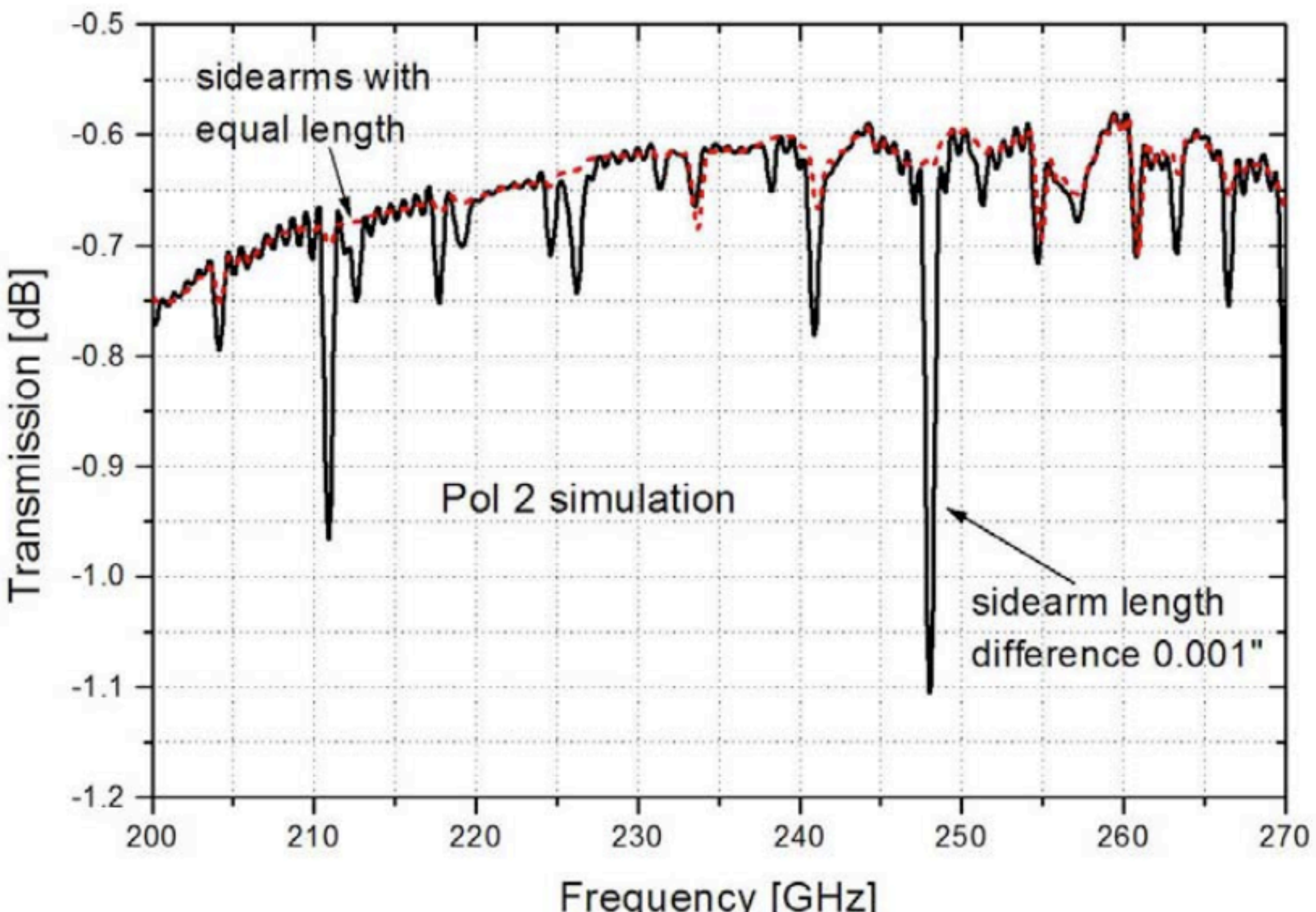




Navarrini et al., CARMA Memo #32

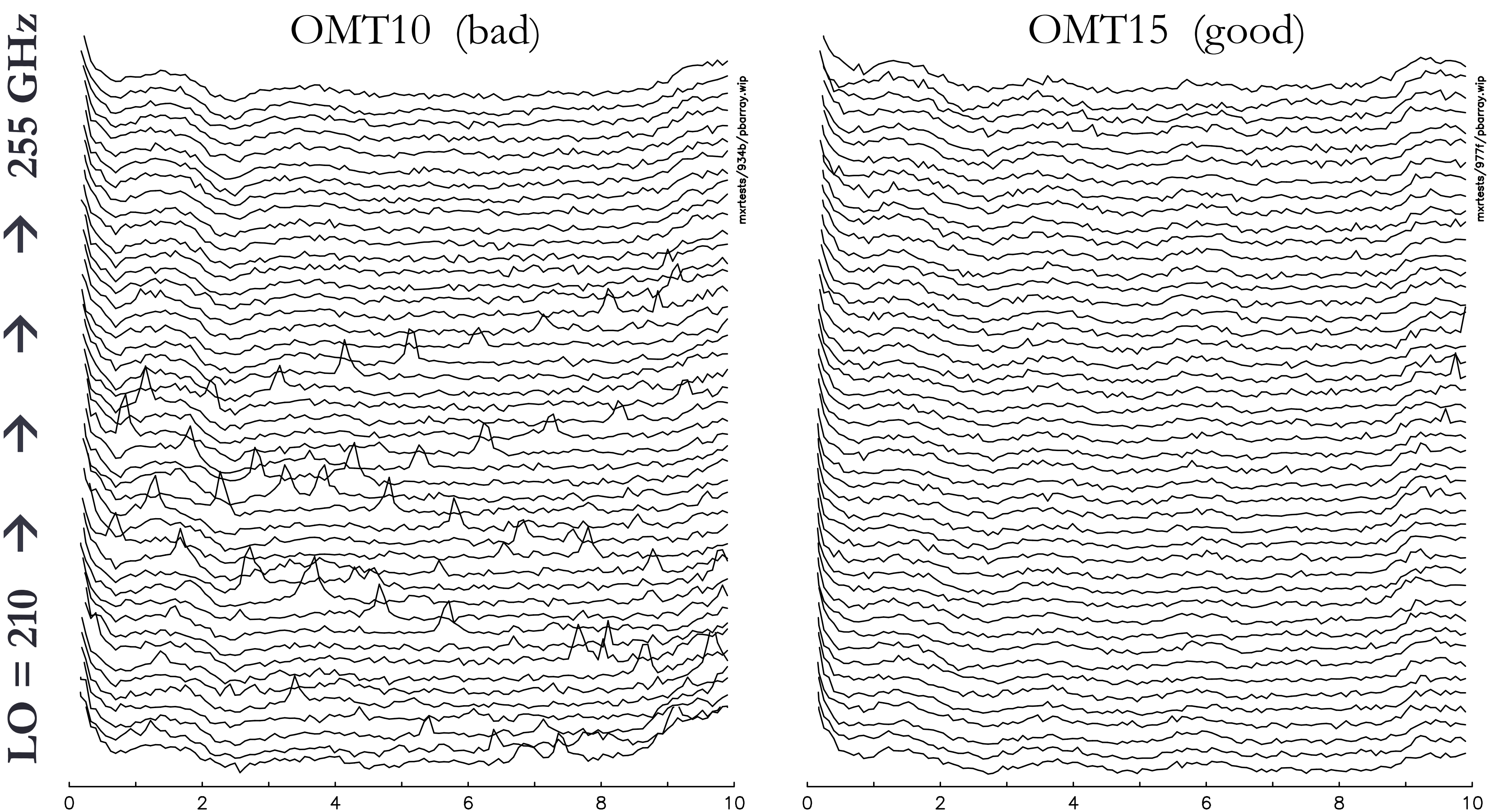


Unequal sidearm lengths in OMT can cause resonances (simulation)



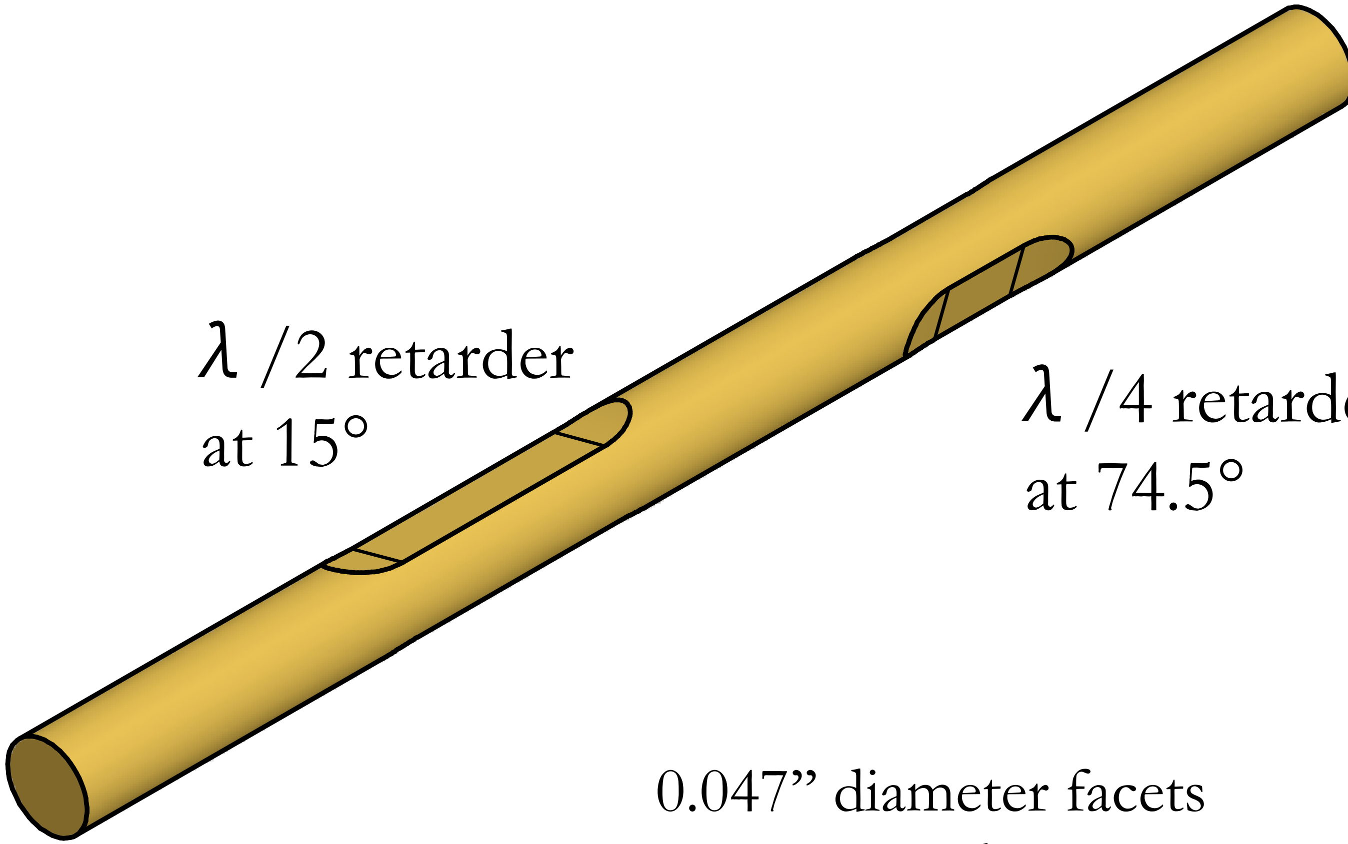
Navarrini et al., CARMA Memo #32

OMT passband tests at 4 K



IF Frequency: 1 – 10 GHz

2-section polarizer

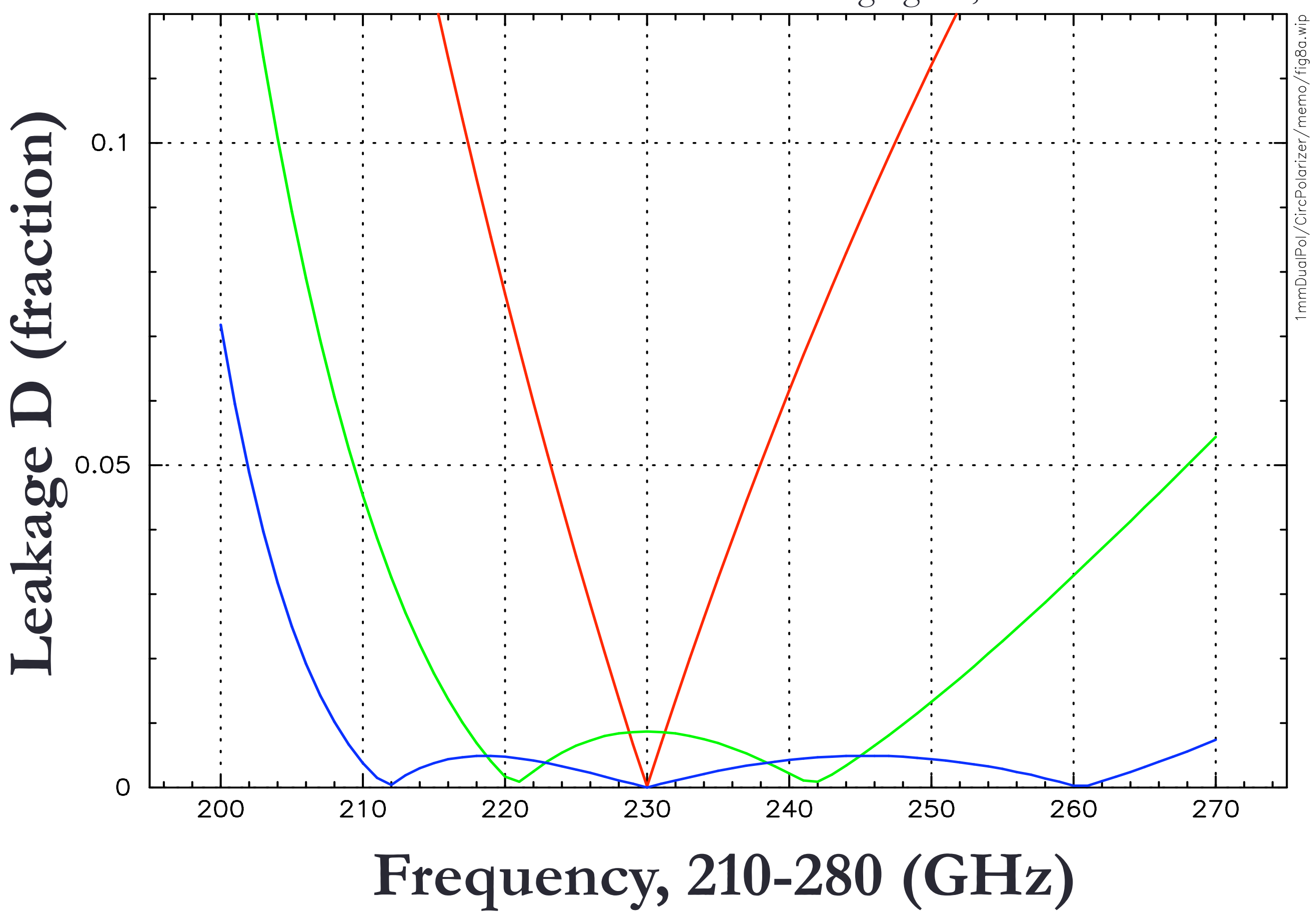


Plambeck & Engargiola, CARMA Memo #54

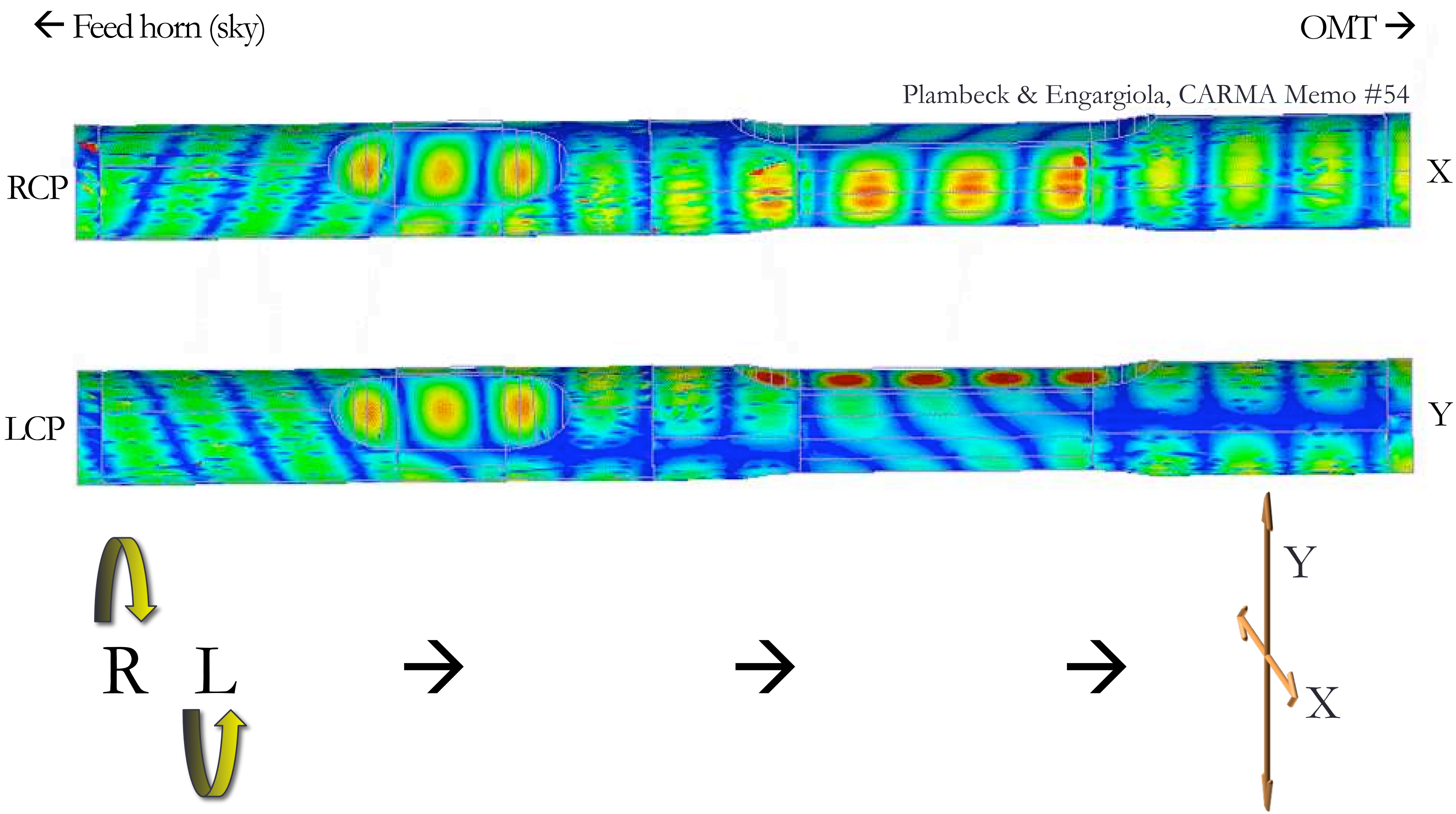
Leakages for 1-, 2-, & 3-section polarizers

$$\text{Leakage D:} \quad v'_r = v_r + D_r\, v_l$$

Plambeck & Engargiola, CARMA Memo #54



Polarizer simulation



Polarizer construction

Credit: Daning Chow

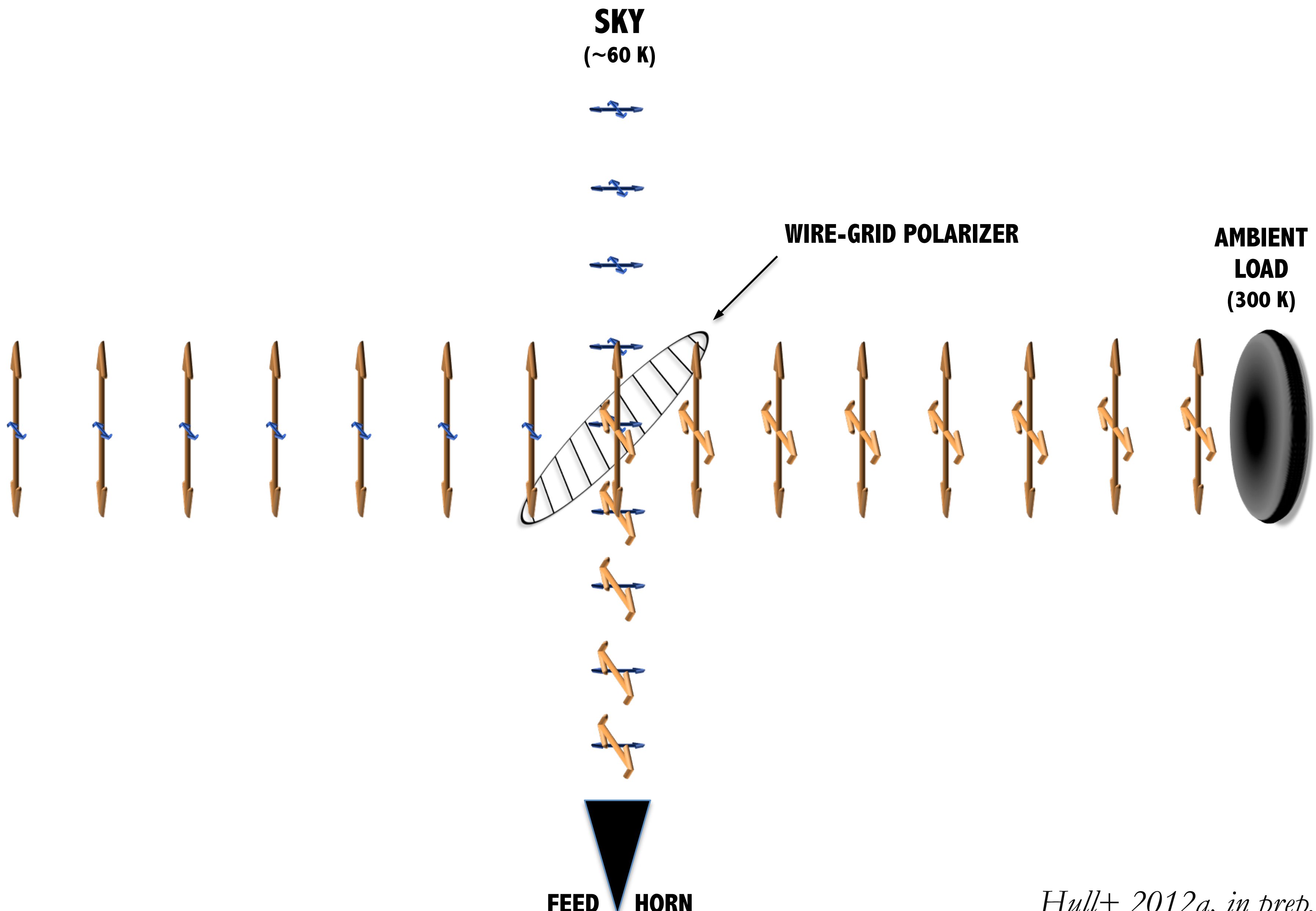
Polarization calibration

- Two main steps to calibrate a polarimeter:
  - XY phase
    - The absolute phase offset between the RCP and LCP receivers of an antenna
  - Leakage terms
    - The fraction of LCP radiation detected in the RCP receiver, and vice versa

XY phase calibration

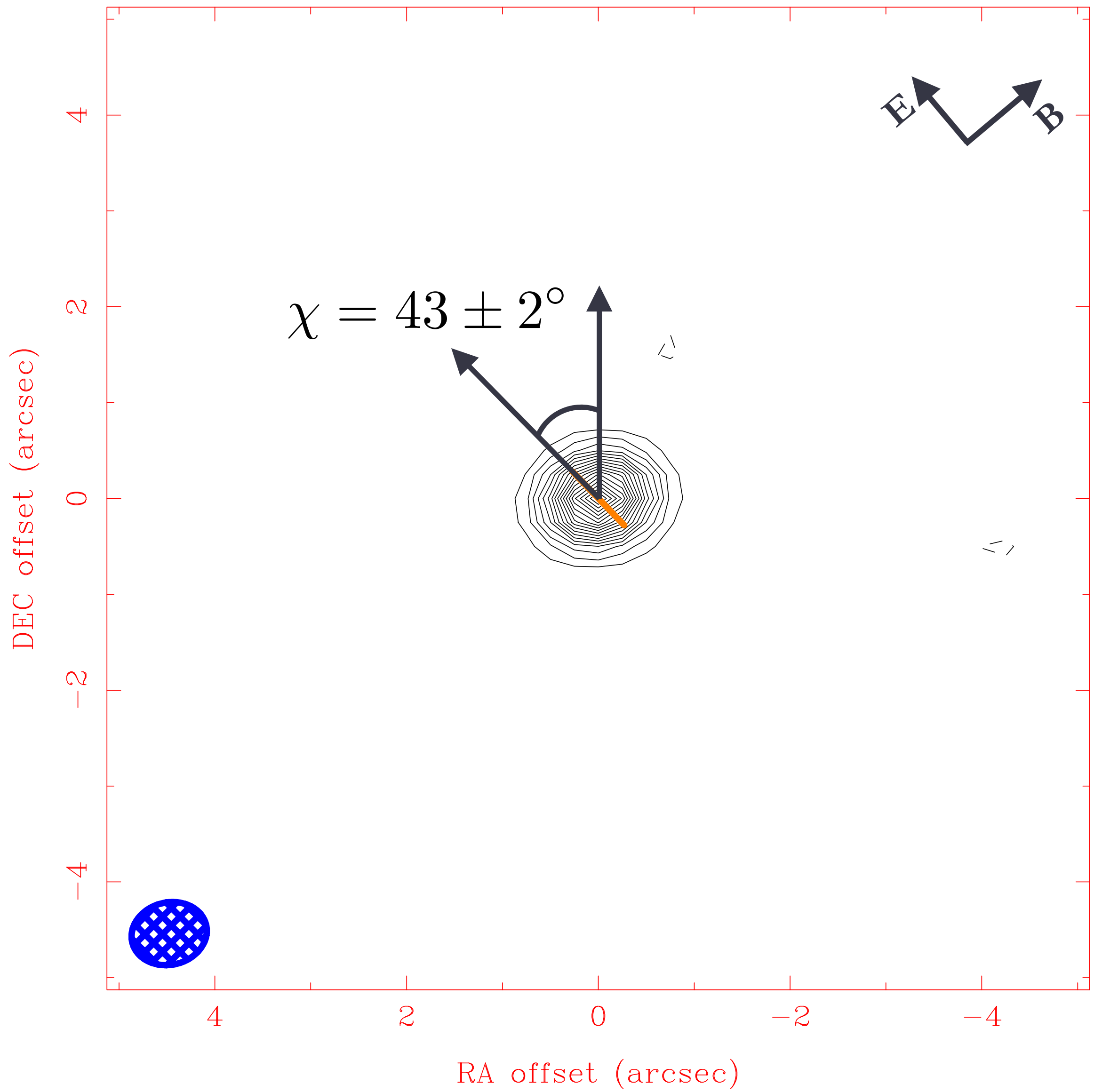
- How do we find an antenna's XY phase?
  - Observe a strongly polarized source with known position angle
    - These don't exist at mm wavelengths…

XY phase calibration

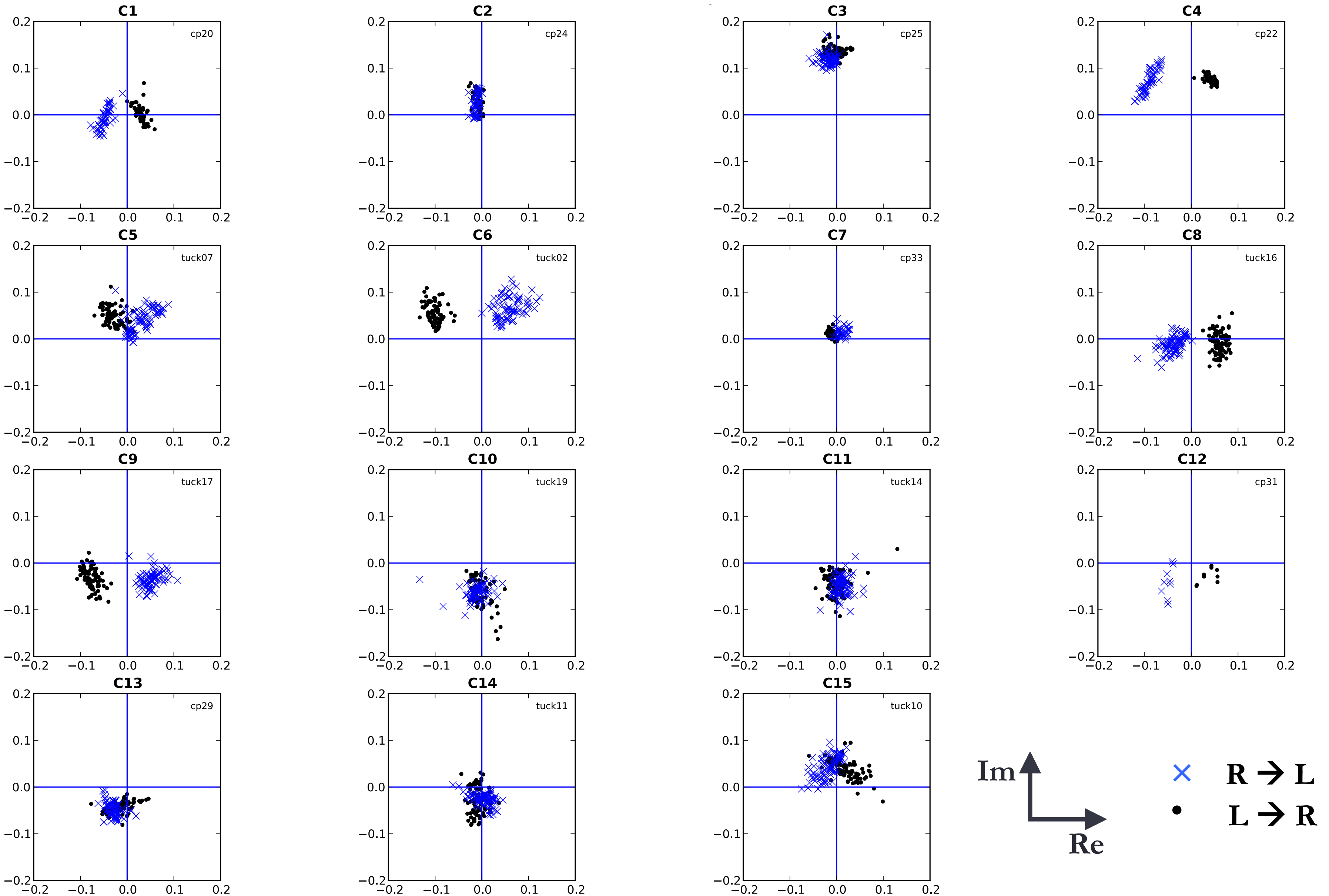


Hull+ 2012a, in prep.

3c286 polarization looks good



Leakages


C1
cp20
C2
cp24
C3
cp25
C4
cp22
C5
tuck07
C6
tuck02
C7
cp33
C8
tuck16
C9
tuck17
C10
tuck19
C11
tuck14
C12
cp31
C13
cp29
C14
tuck11
C15
tuck10
Im
Re
R → L
L → R

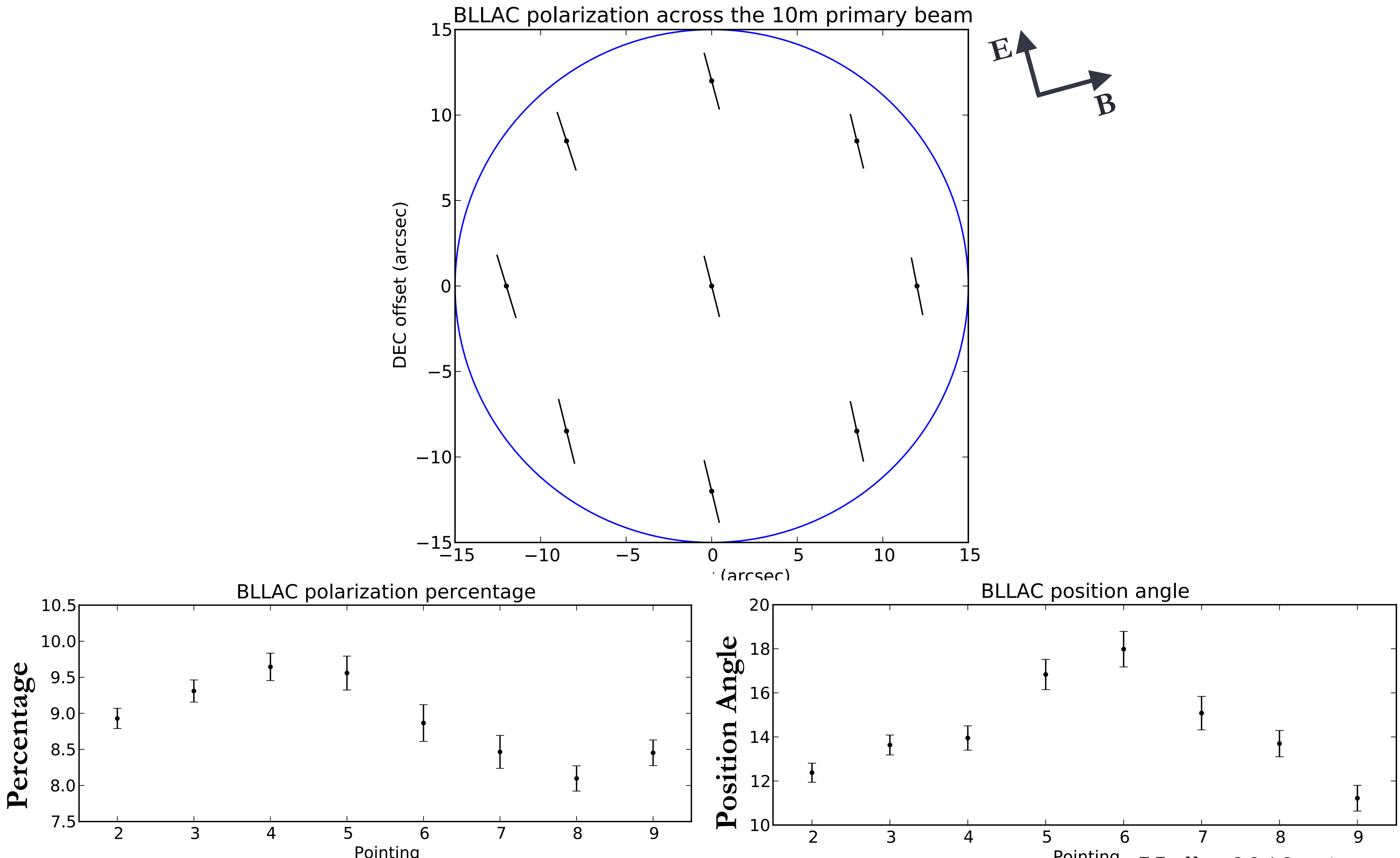
Conclusions

- **Hardware status**
  - CARMA polarization system is fully functional and (nearly) fully calibrated
- **TADPOL survey status**
  - ~50% complete; more to come in Fall 2012
- **Polarization science status**
  - Data reduction method/pipeline is almost complete
  - Many datasets are in hand
  - Analysis is gearing up, both protostellar and otherwise… stay tuned!

Fin

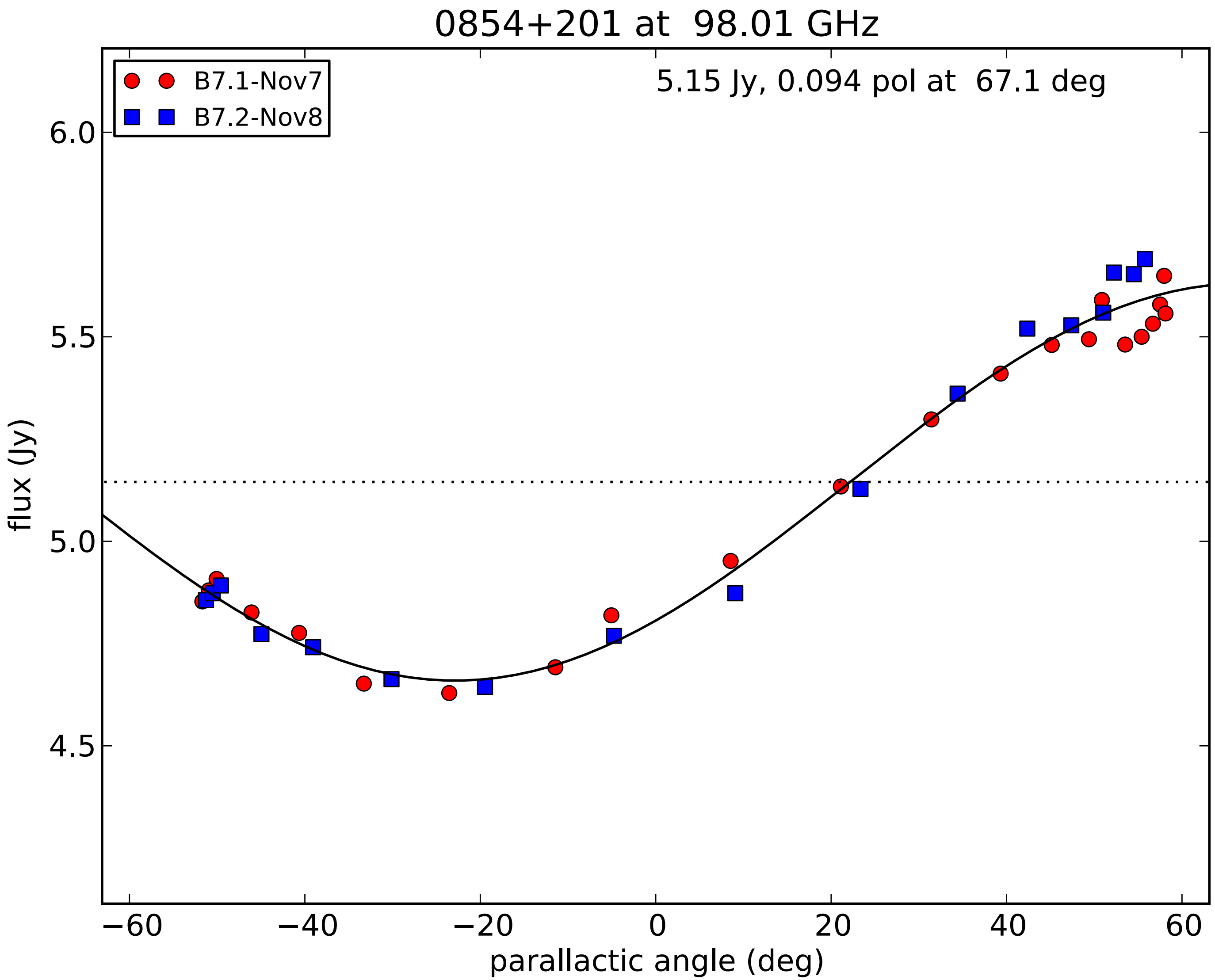
Extra slides

Calibration: Primary-beam polarization



Hull+ 2012a, in prep.

(Unintentional) 3 mm polarization with CARMA



Stokes parameters, for circular polarization

$$RR = I + V \qquad I = RR + LL$$

$$LL = I - V \qquad Q = RL + LR$$

$$RL = Q + iU \qquad iU = RL - LR$$

$$LR = Q - iU \qquad V = RR - LL$$

Polarization % and position angle uncertainties

NOTE:

- The position angle is measured counterclockwise from North
- A 3-sigma Q,U detection gives you an uncertainty of ~10°
- p_{db} is the debiased polarization (see Vaillancourt 2006)

$$p = \sqrt{Q^2 + U^2}$$

$$\delta p = p^{-1}\sqrt{Q^2\,\delta U^2 + U^2\,\delta Q^2}$$

$$p_{\mathrm{db}} = \sqrt{p^2 - \delta p^2}$$

$$\% = \frac{p_{\mathrm{db}} \pm \delta p}{I} \times 100\%$$

$$\chi = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

$$\delta\chi = \frac{1}{2}\frac{\delta p}{p_{\mathrm{db}}}$$