# FROM CLOUDS TO CORES TO ENVELOPES TO DISKS

## A MULTI-SCALE VIEW OF MAGNETIZED STAR FORMATION


**Chat Hull**

University of California, Berkeley

Radio Astronomy Laboratory


27 May 2014

ASTROPOL: Astronomical Polarimetry 2014

Session IV: ISM, Clouds, and Star Formation

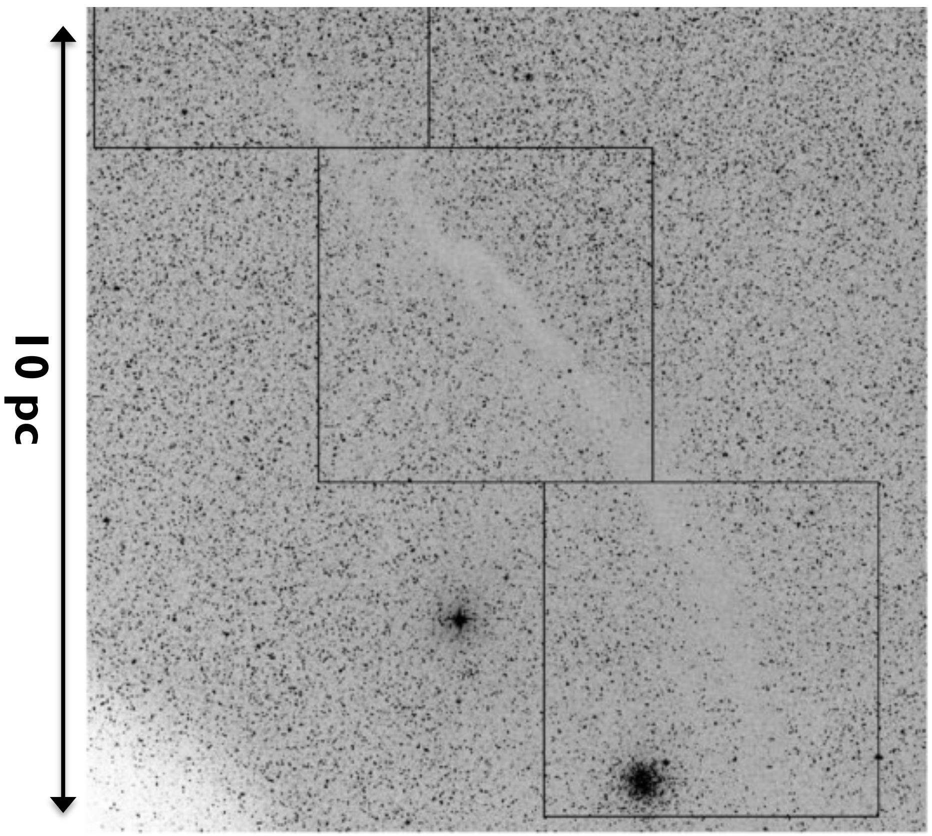
Grenoble, France

# Scales of star formation

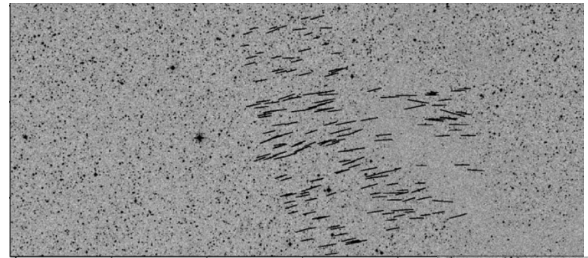
| | |
|---|---|
| > 1 pc | cloud |
| 0.1 pc | core |
| 1000 AU | envelope |
| < 100 AU | disk |

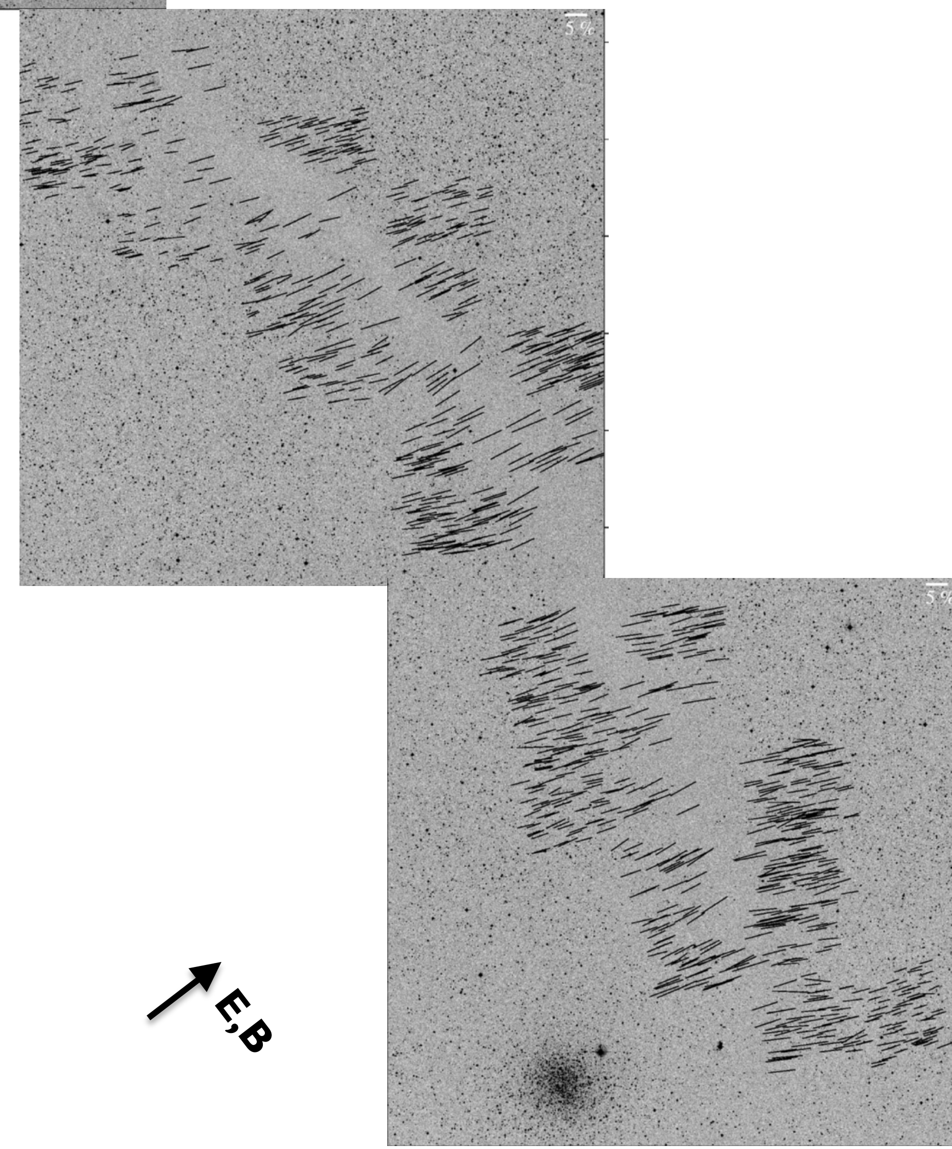
# Large-scale: ordered fields

Musca dark cloud

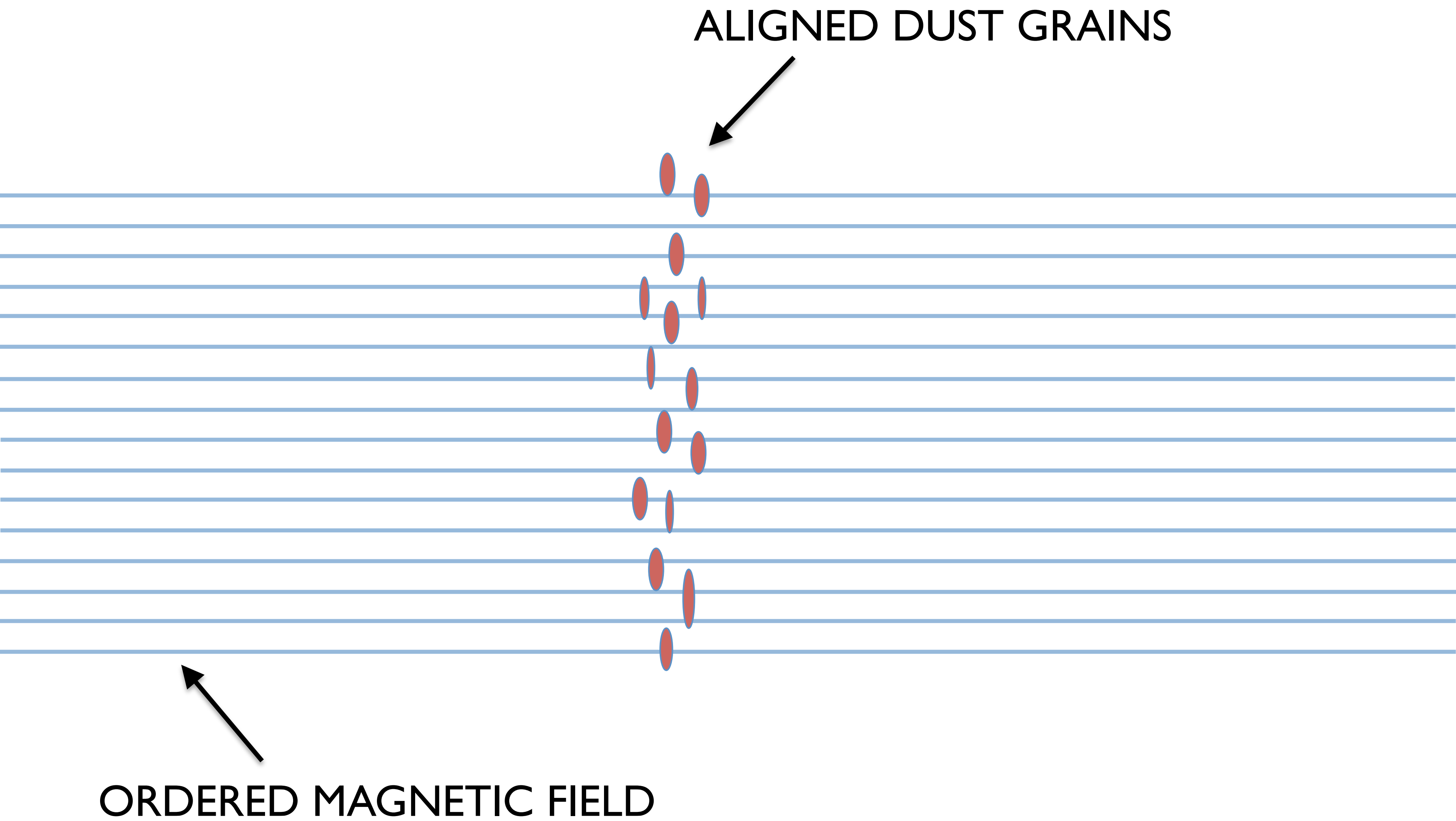



Pereyra & Magalhães 2004

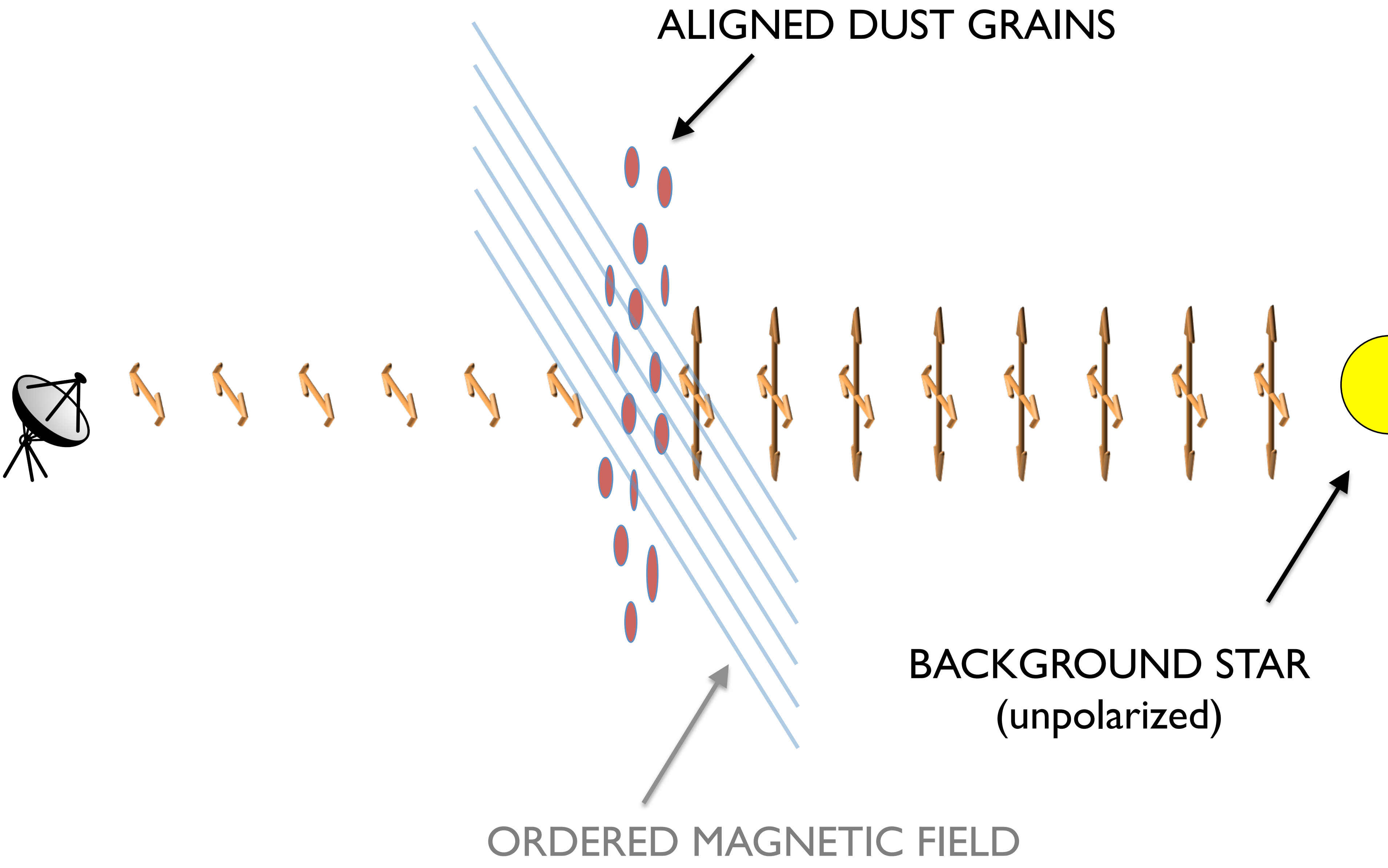


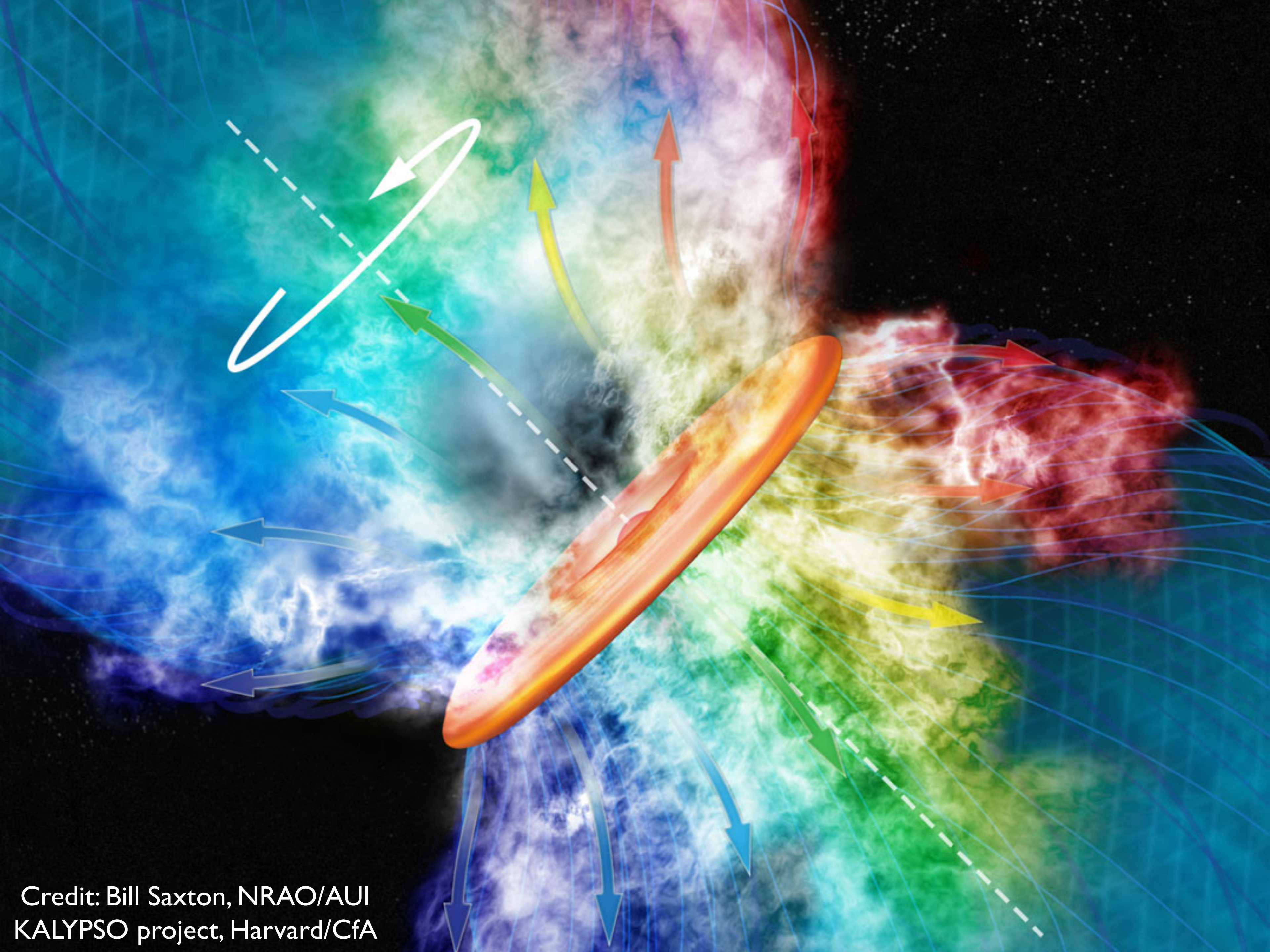


# Dust grain alignment



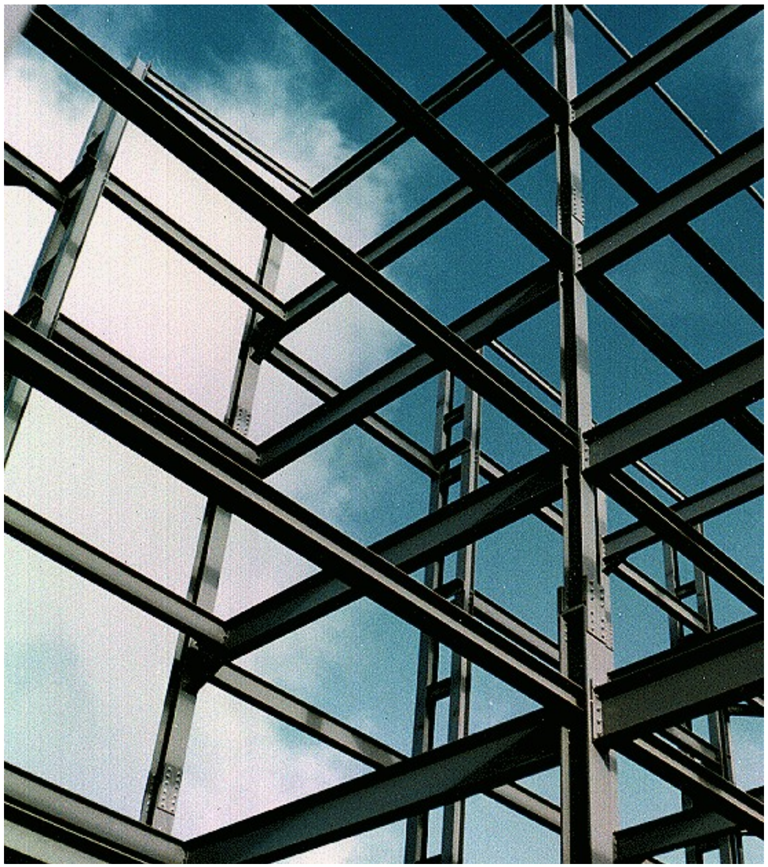
# Polarization (dust absorption)





Credit: Bill Saxton, NRAO/AUI
KALYPSO project, Harvard/CfA

# What is the role of magnetic fields in star formation?



Fundamental?

Incidental?

# B-fields vs. outflows

# Multi-scale comparisons: B-fields vs. outflows

**1 pc**

**0.1 pc**

**1000 AU**

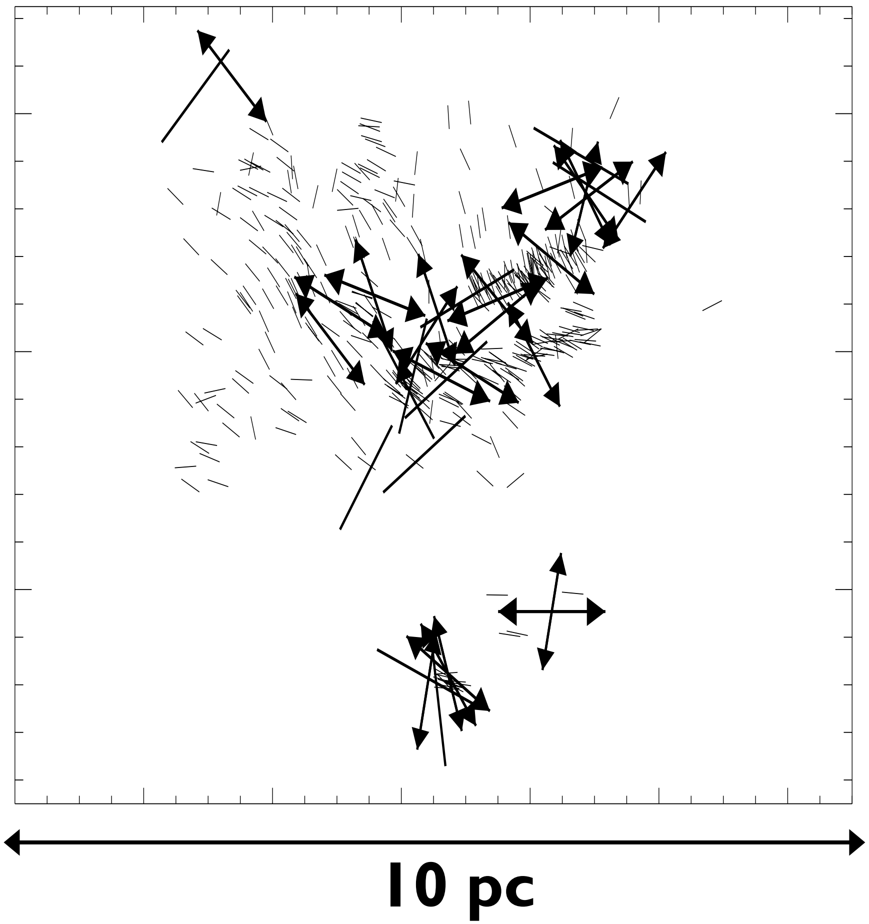
**100 AU**

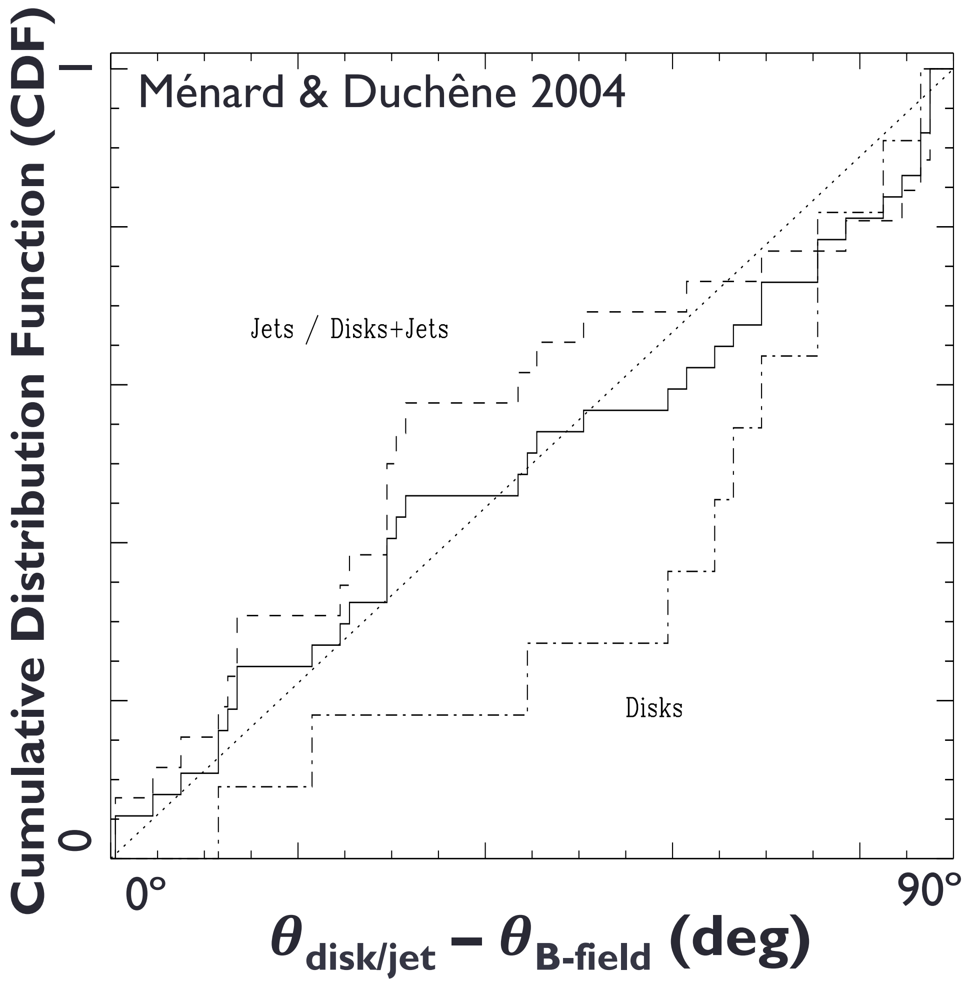
**RANDOM**

Ménard & Duchêne 2004
Targon+ 2011

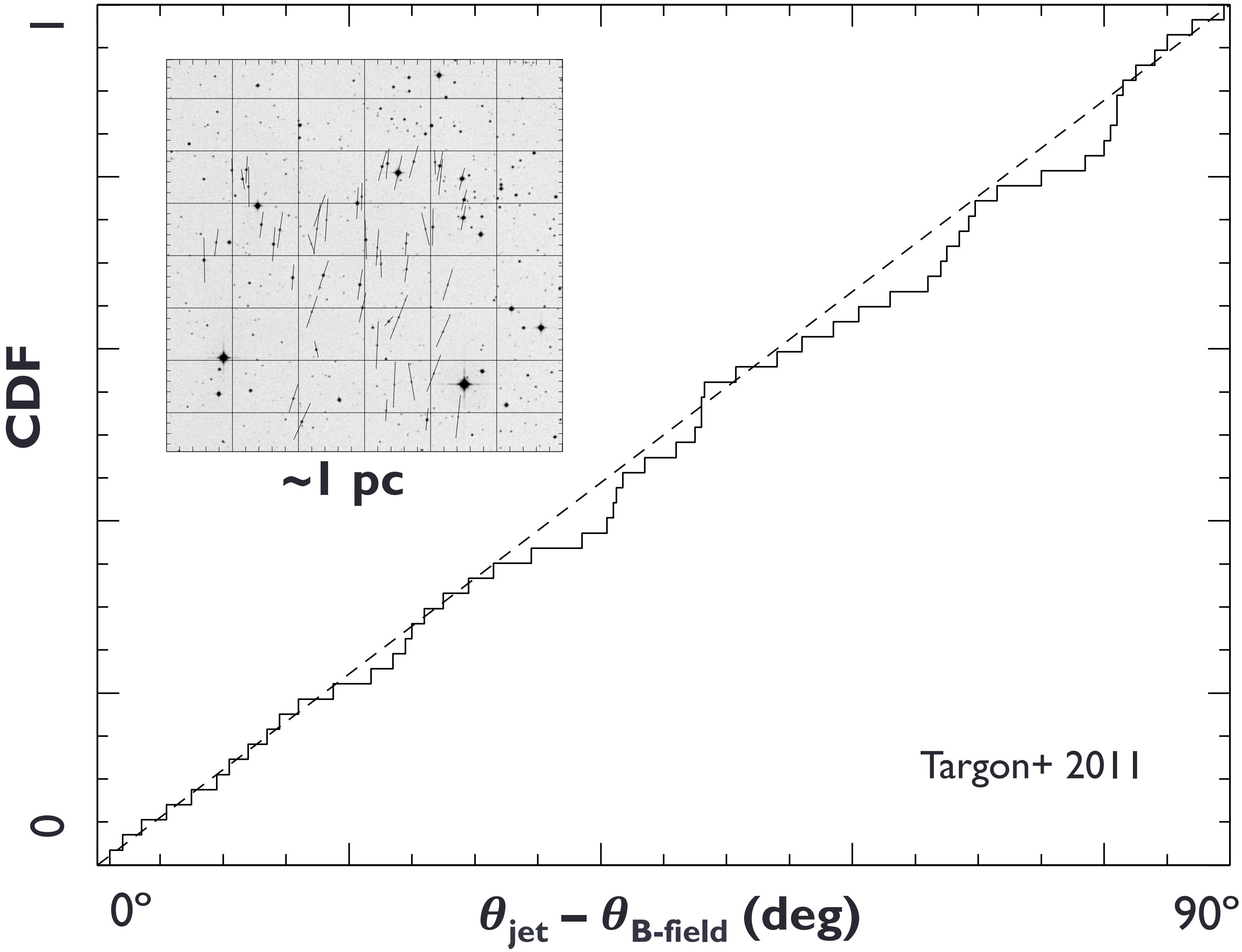
# Misalignment of B-fields and disks/jets

- Comparing orientations of large-scale B-field with disks/jets in T Tauri stars



# Misalignment of B-fields and disks/jets



# Multi-scale comparisons: B-fields vs. outflows

**1 pc**

**0.1 pc**

**1000 AU**

**100 AU**

**RANDOM**

Ménard & Duchêne 2004
Targon+ 2011

# Multi-scale comparisons: B-fields vs. outflows

**1 pc**

**0.1 pc**

**1000 AU**

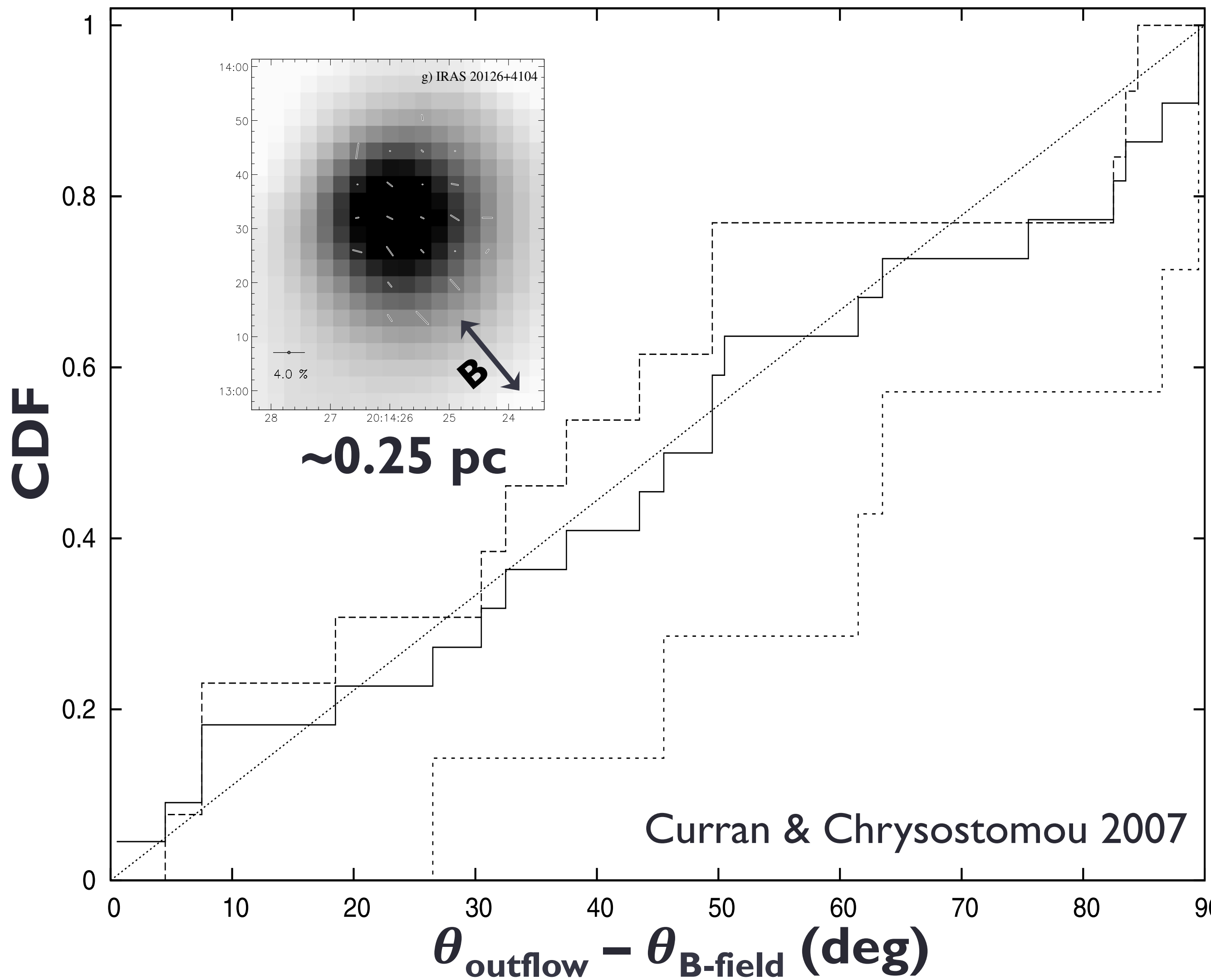
**100 AU**

**RANDOM (high mass)**
Curran & Chrysostomou 2007

**ALIGNED (low mass)**
Chapman+ 2013

# Misalignment of B-fields and outflows

- Comparing B-fields with outflows on the core (~0.1 pc) scale



# Multi-scale comparisons: B-fields vs. outflows

**1 pc**

**0.1 pc**

**1000 AU**

**100 AU**

**RANDOM (high mass)**
Curran & Chrysostomou 2007

**ALIGNED (low mass)**
Chapman+ 2013

# Multi-scale comparisons: B-fields vs. outflows

1 pc

0.1 pc

**1000 AU**

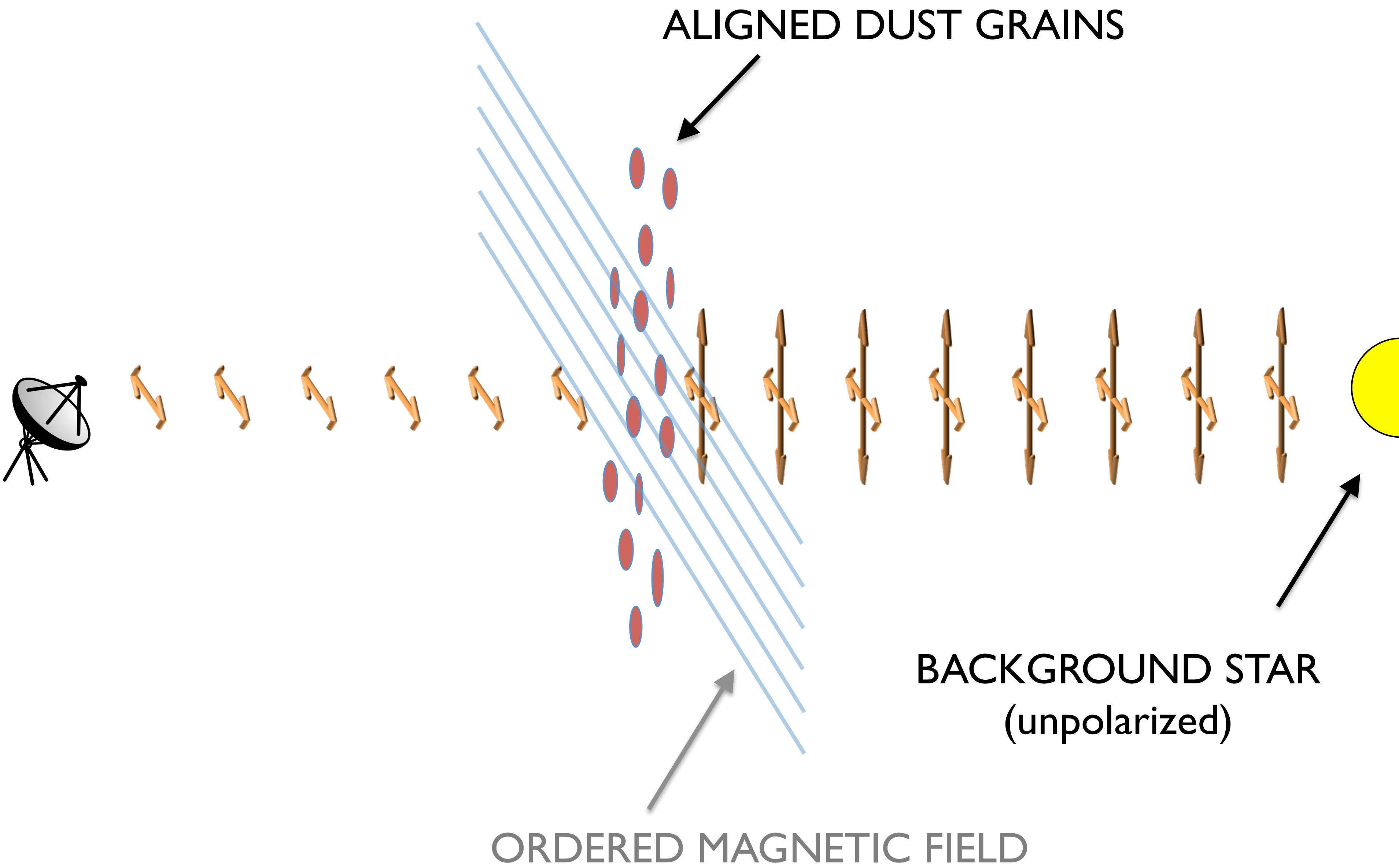
**100 AU**

**RANDOM**

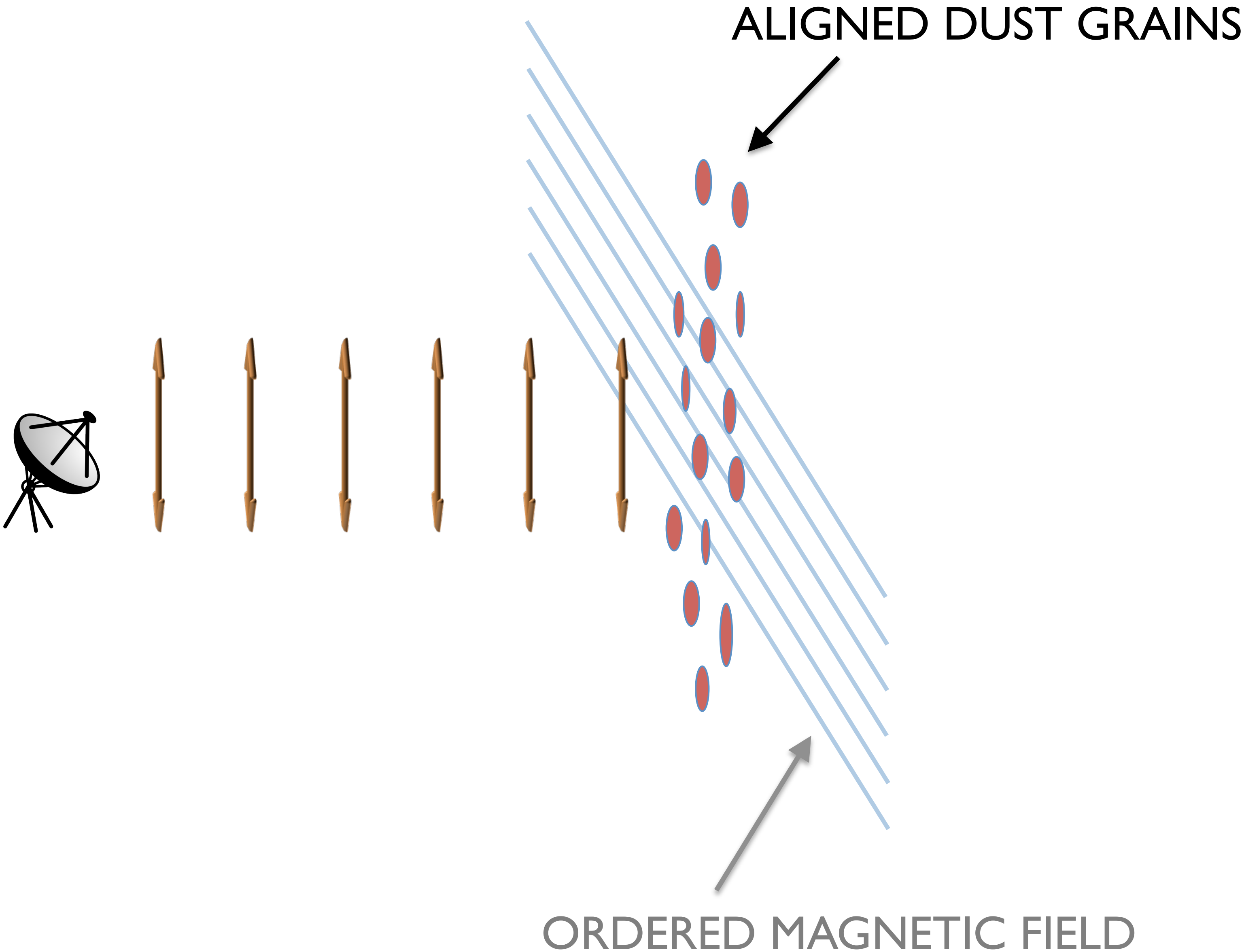
**Or preferentially ⊥ ?**

Hull+ 2013a

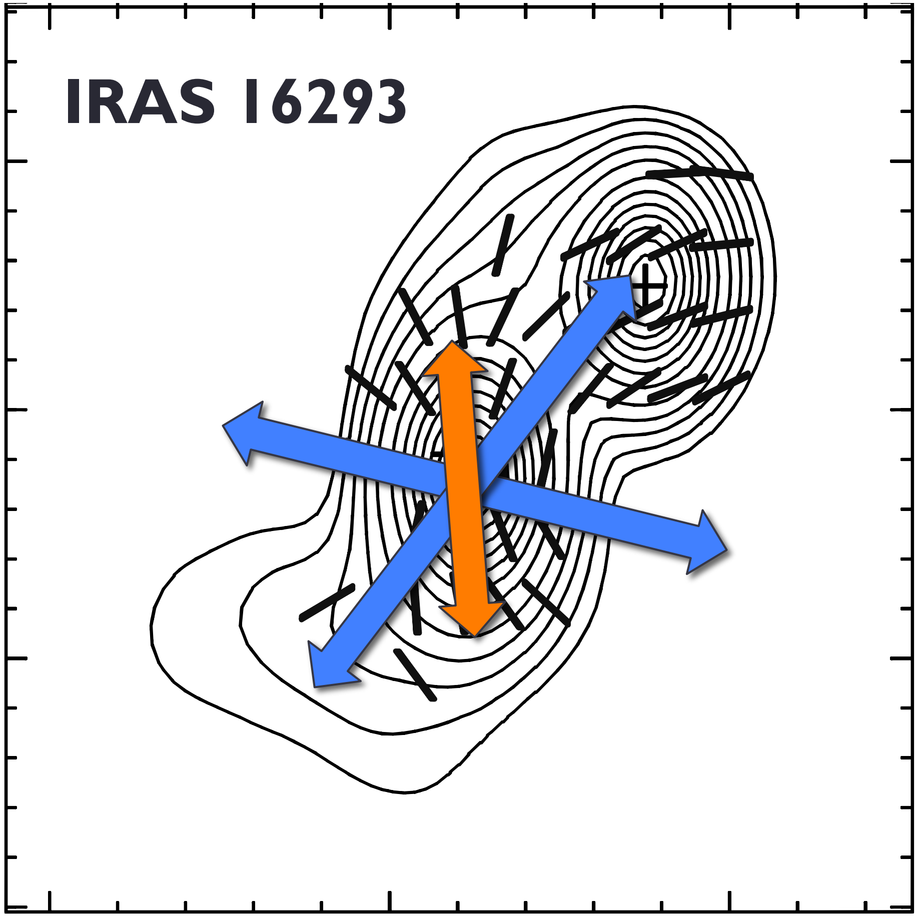
# Polarization (dust absorption)



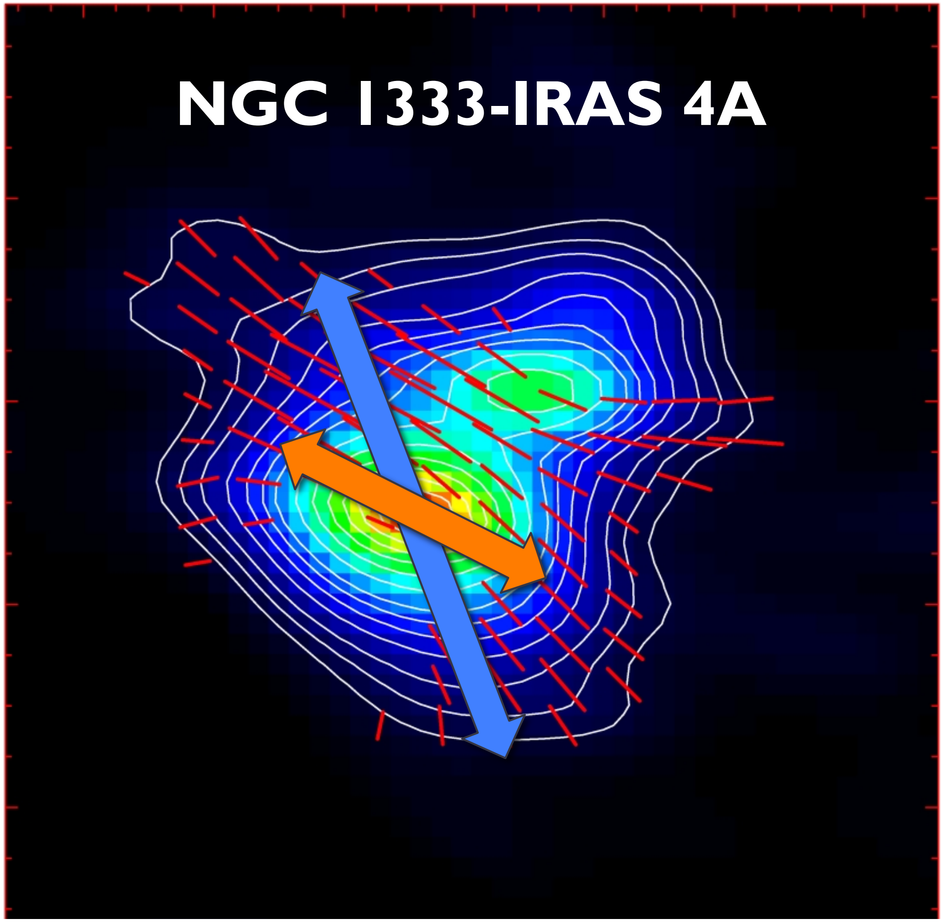
# Polarization (dust emission)



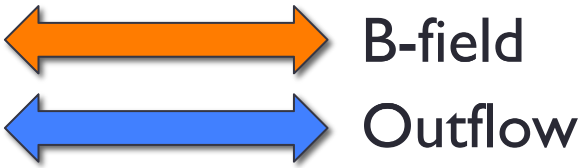
# Misalignment of B-fields and outflows




Rao+ 2009




Girart+ 2006



# CARMA

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

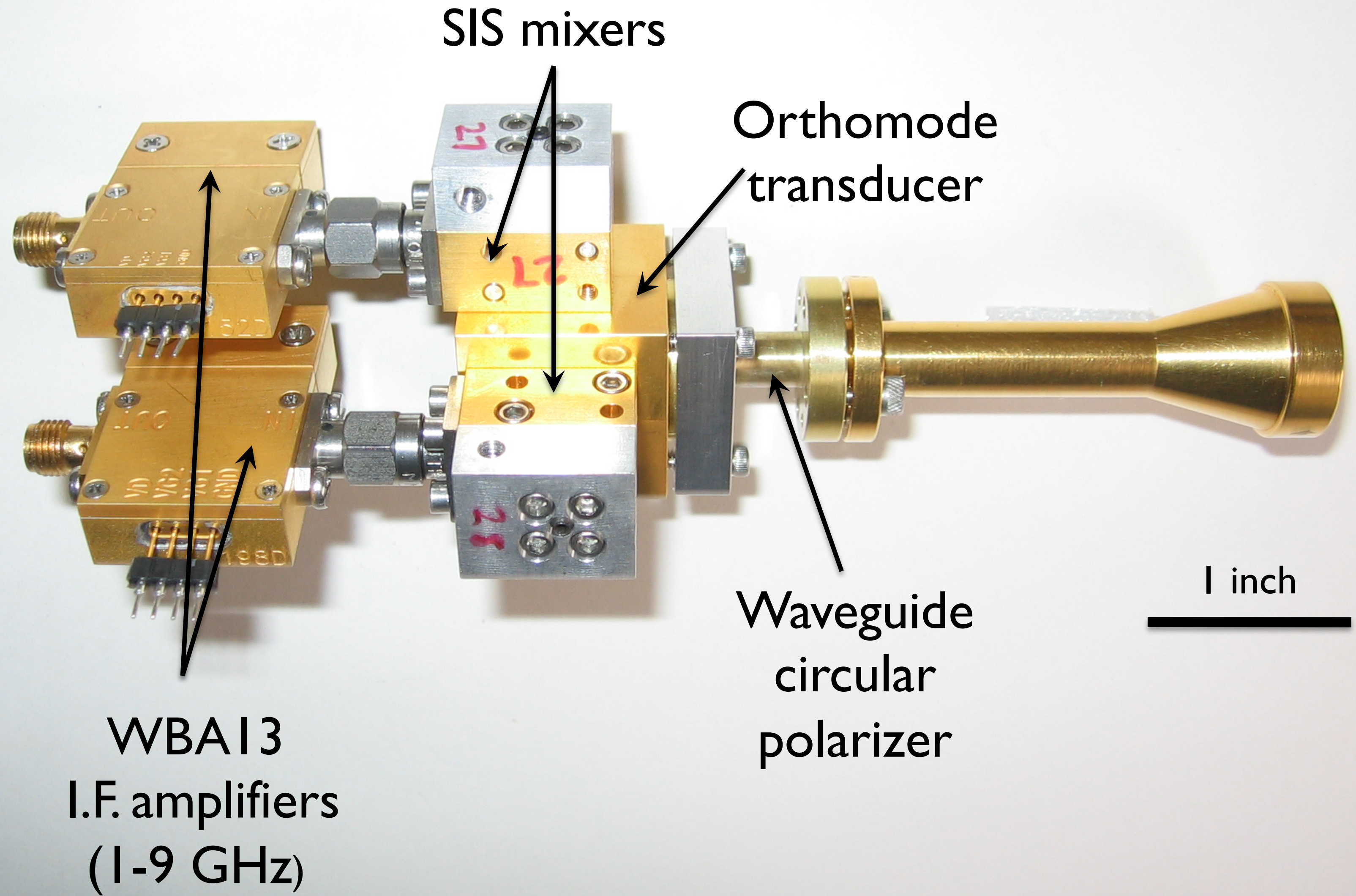
Consortium: Berkeley, Caltech, Illinois, Maryland, Chicago

– 6 × 10-m, 9 × 6-m, and 8 × 3.5-m telescopes

– Observations at 1 cm, 3 mm, and **1 mm (polarization!)**

– Located in Cedar Flat, CA (near Bishop)

# 1 mm dual-polarization receivers




Credit: Dick Plambeck

# TADPOL survey

# TADPOL collaboration

- **UC Berkeley**
  Chat Hull (PI), Dick Plambeck, 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**
  Leslie Looney, Dick Crutcher, Nick Hakobian
- **Other**
  Dan Marrone (Arizona), Meredith Hughes (Wesleyan), John Vaillancourt & Göran Sandell (USRA-SOFIA), John Tobin (NRAO), Ian Stephens (BU), Jason Fiege & Erica Franzmann (Manitoba), Martin Houde (UWO, Caltech), Brenda Matthews (NRC-CNRC), Woojin Kwon (SRON)

# TADPOL survey

**37 sources**

Largest survey of star-forming cores to date

**>500 observing hours**

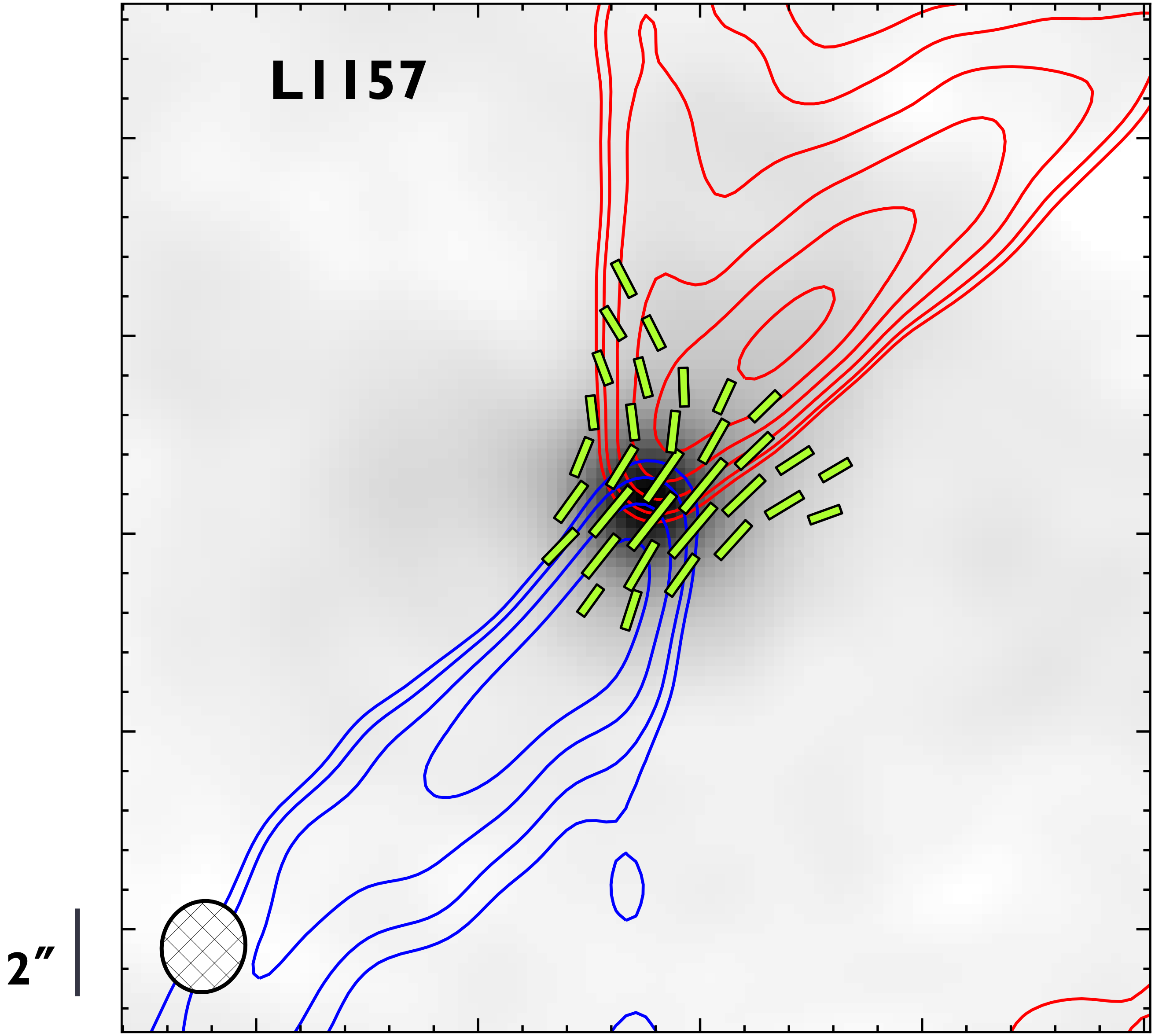
CARMA C, D, & E arrays

**1 – 4" resolution**

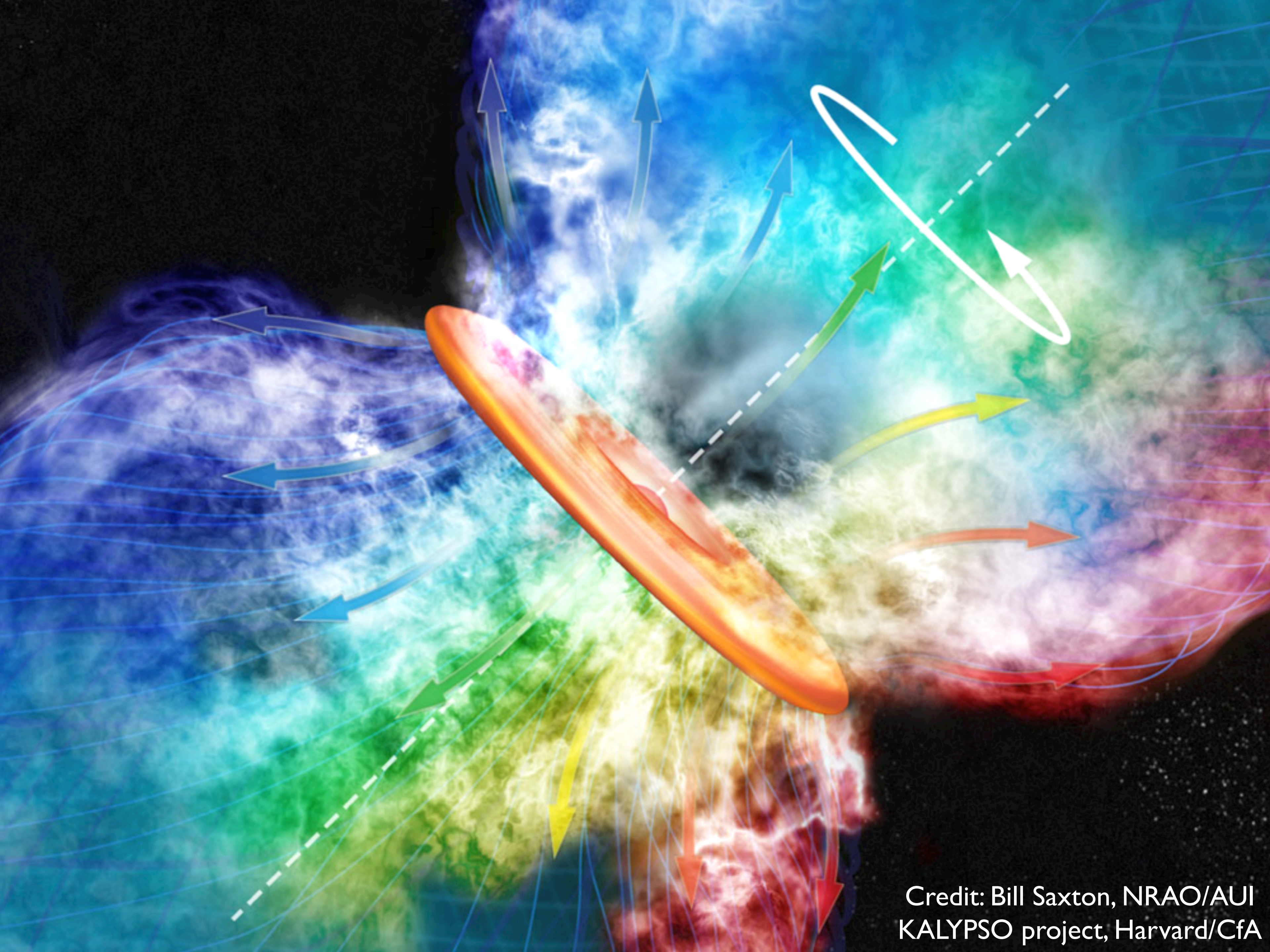
10× higher resolution than CSO & JCMT

Probes intermediate region between ~0.1 pc (single-dish) and ~100 AU (ALMA)

# TADPOL results

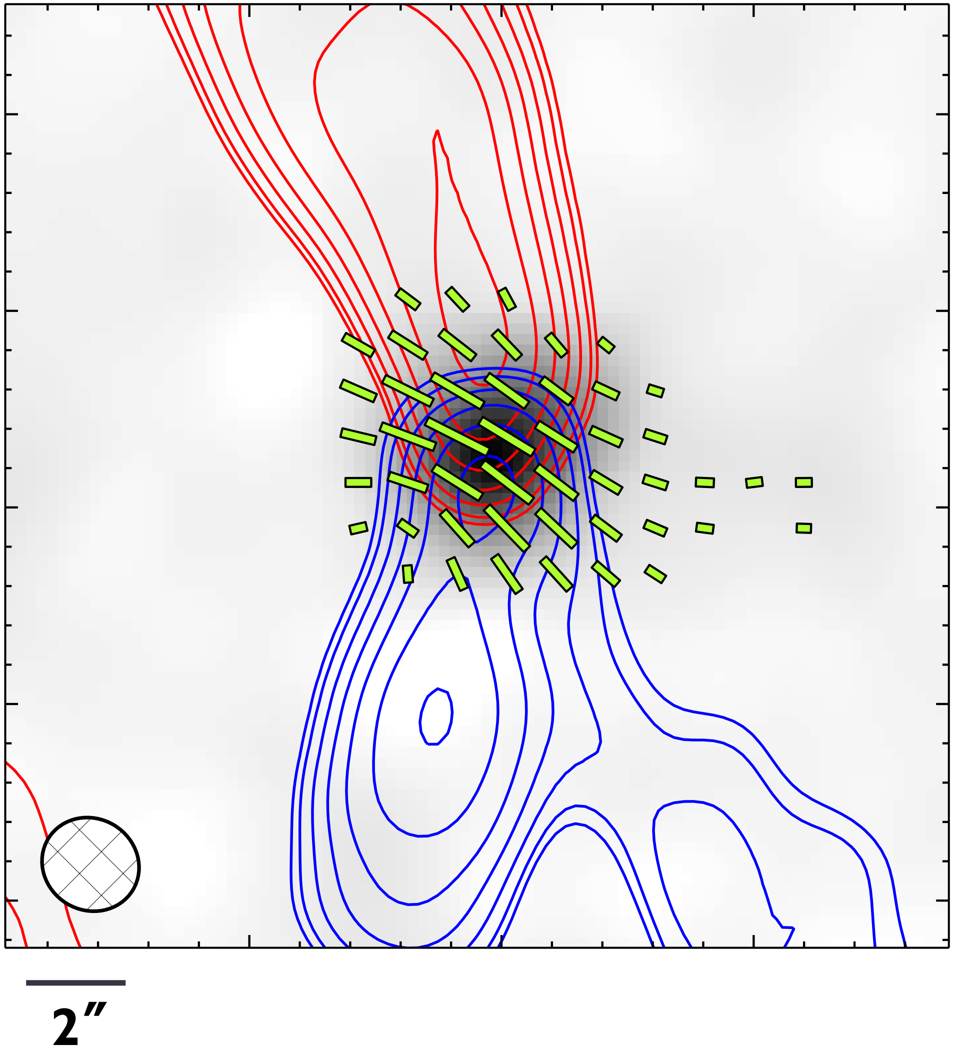



See also: Stephens+ (incl. C.H.) 2013, ApJL, 769, L15

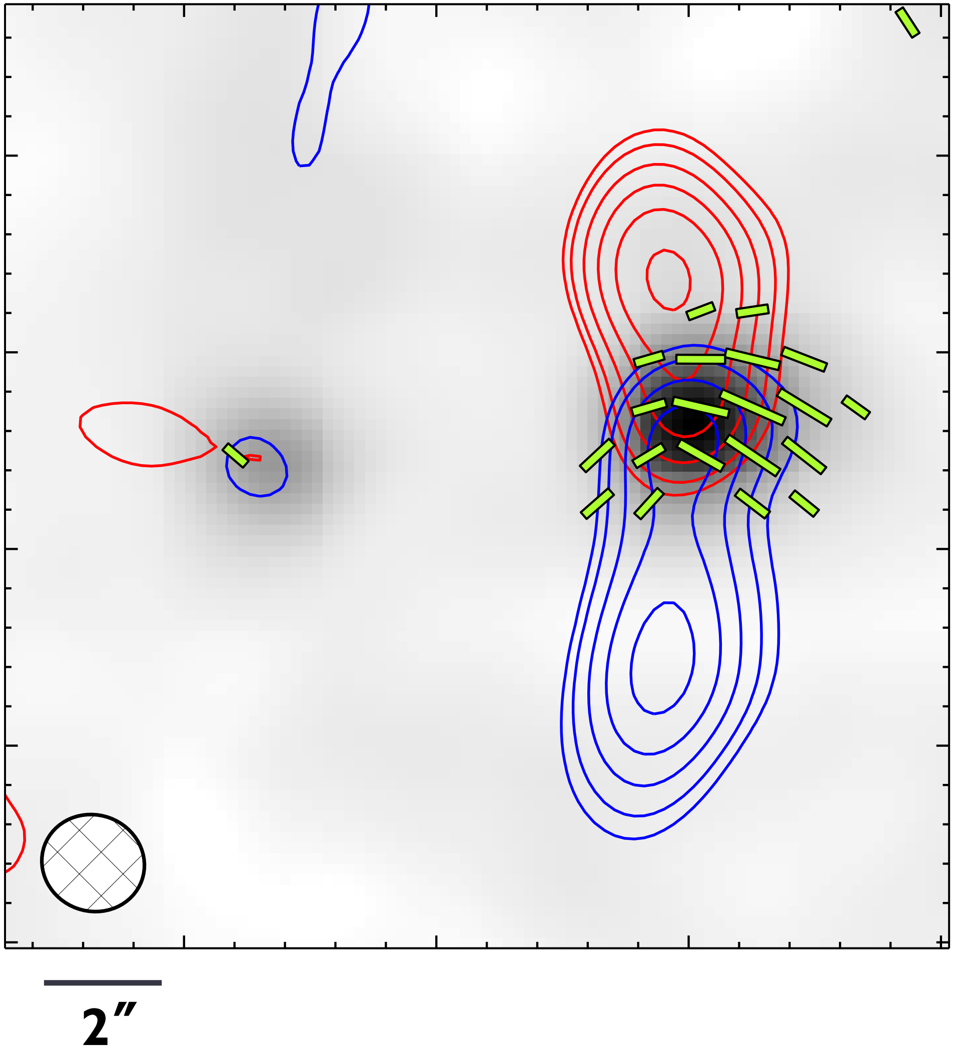

Credit: Bill Saxton, NRAO/AUI
KALYPSO project, Harvard/CfA

# TADPOL results

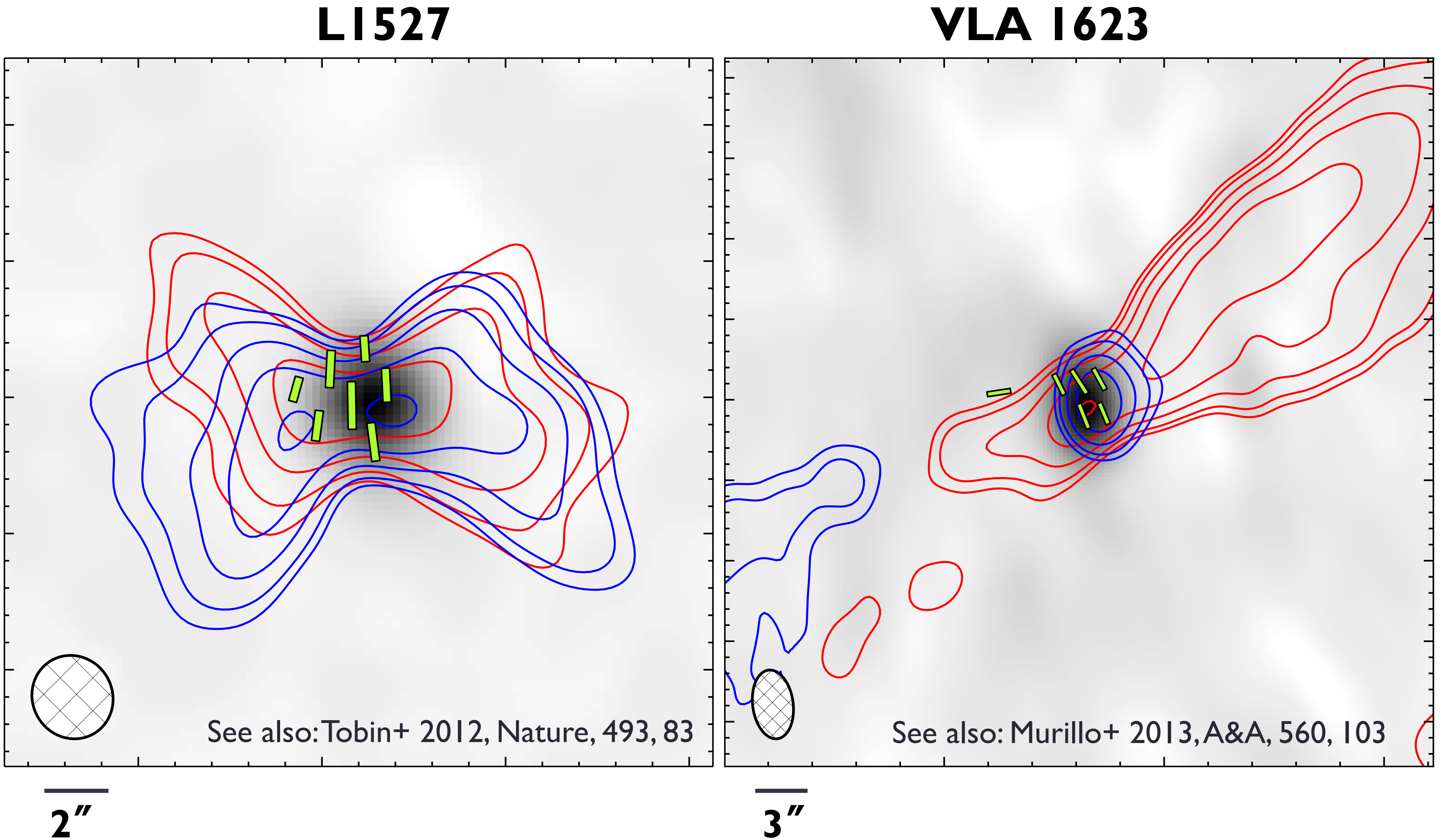
## NGC 1333-IRAS 4A



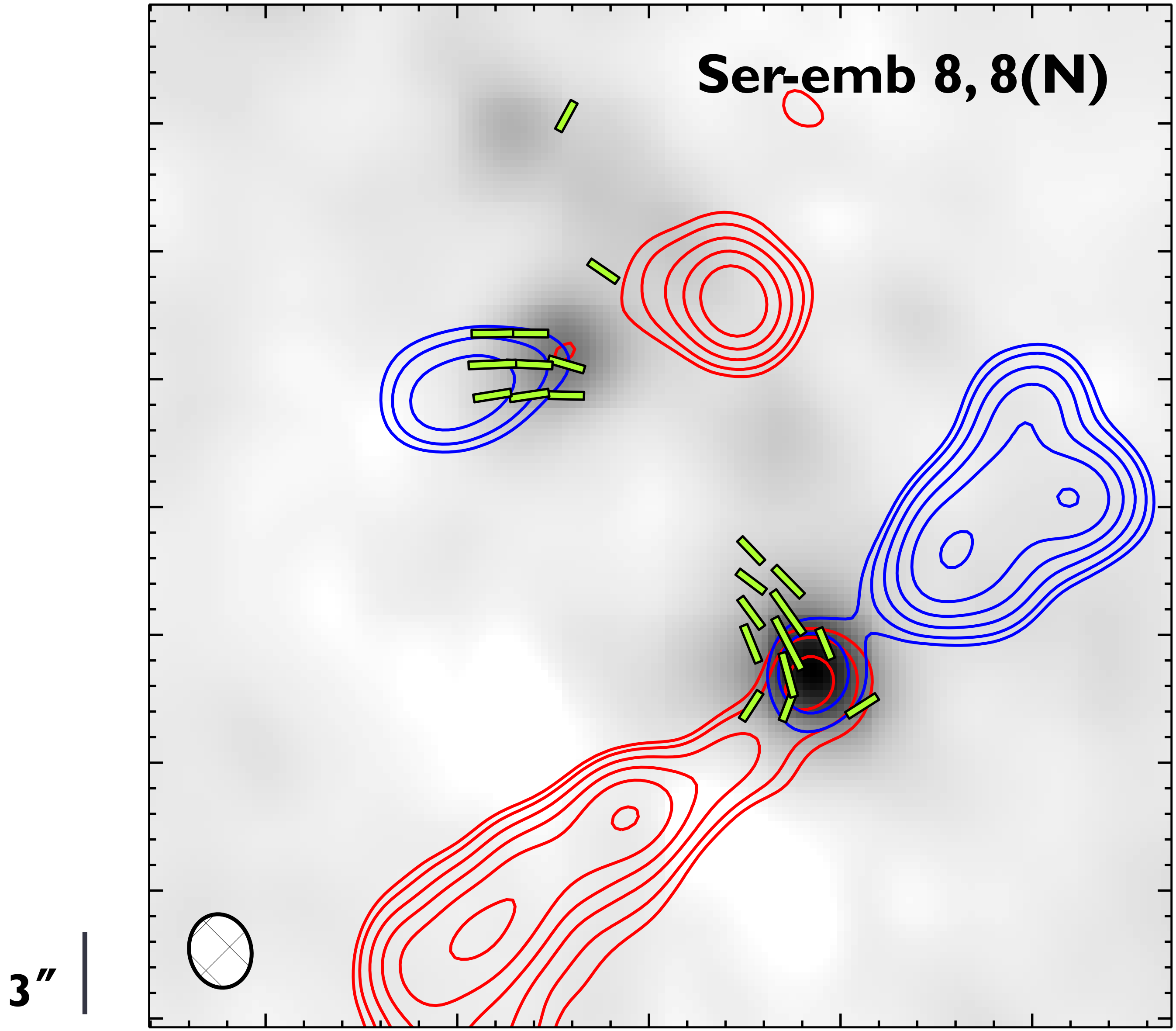

## NGC 1333-IRAS 4B, 4B2



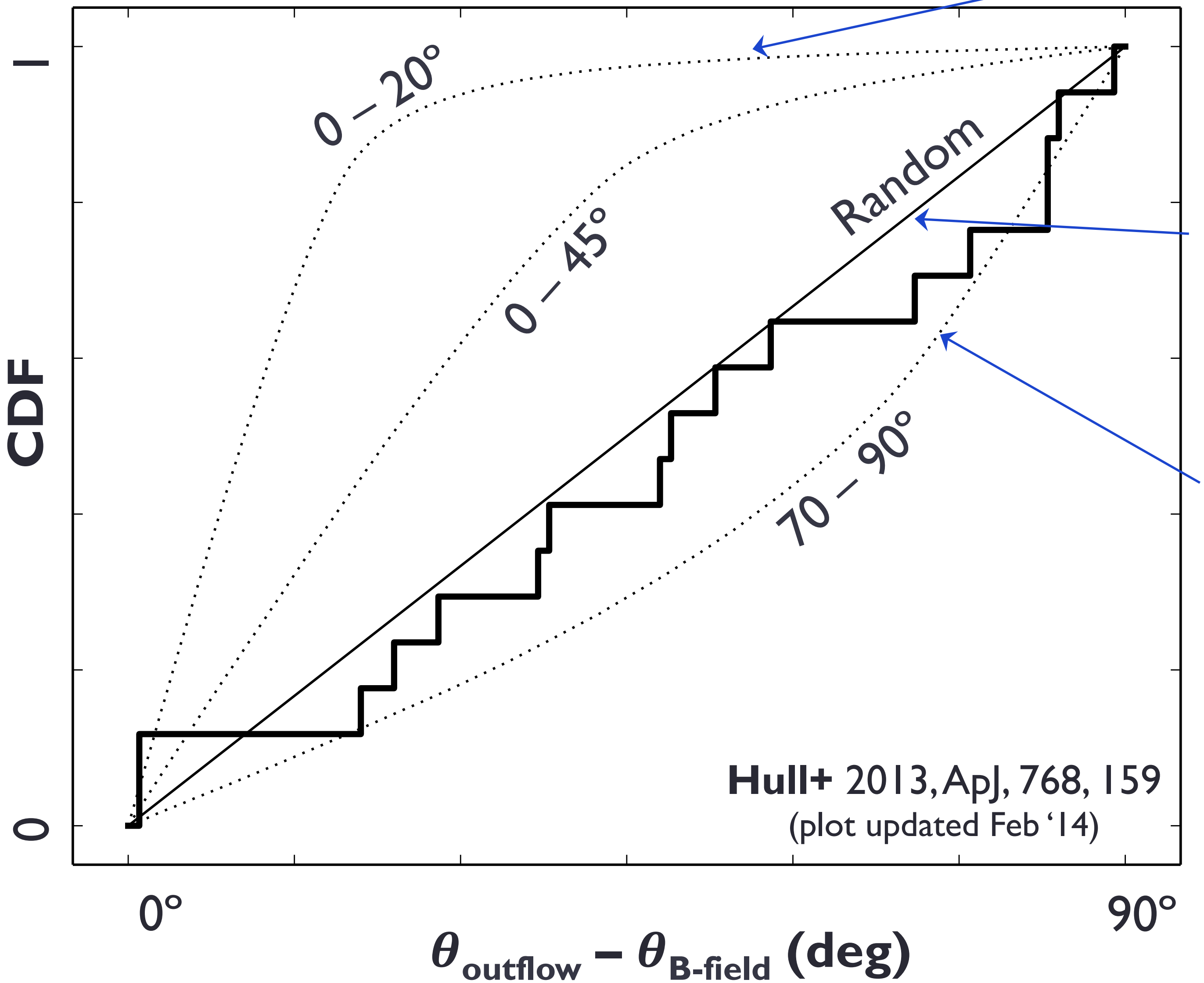
# TADPOL results



# TADPOL results



# Outflow vs. B-field: distribution




**Simulation:** outflows & B-fields aligned within a 20° cone (tightly aligned)

**Simulation:** outflows & B-fields are randomly oriented

**Simulation:** outflows & B-fields aligned between 70–90° (preferentially misaligned)

# Multi-scale B-fields

# Multi-scale comparisons: B-fields

**> 1 pc**

**0.1 pc**

**1000 AU**

**100 AU**

**CONSISTENT**

Hua-bai Li+ 2009

# Multi-scale comparisons: B-fields

1 pc

0.1 pc

1000 AU

100 AU

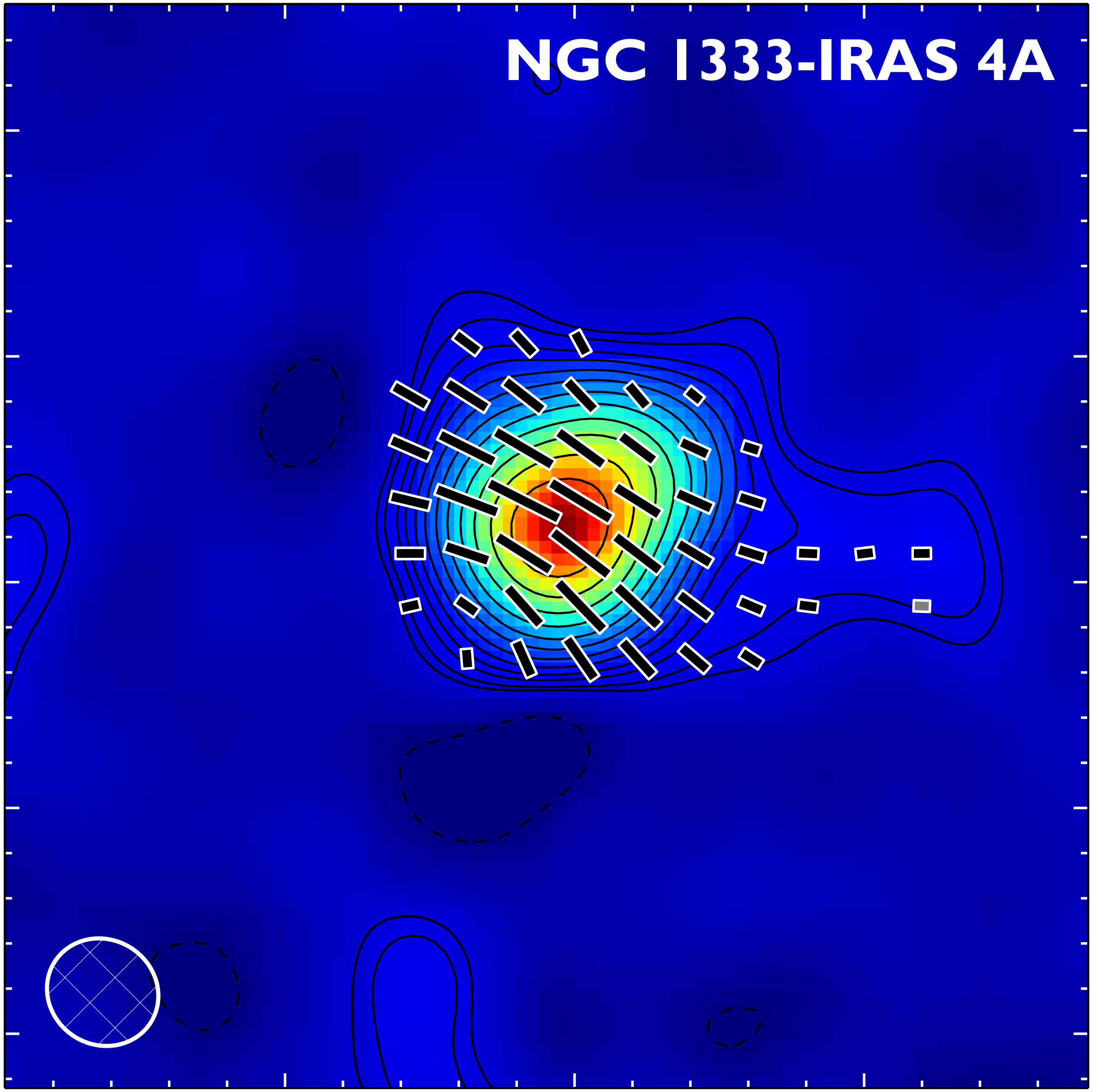
**(Not always) consistent**

Hull+ 2014

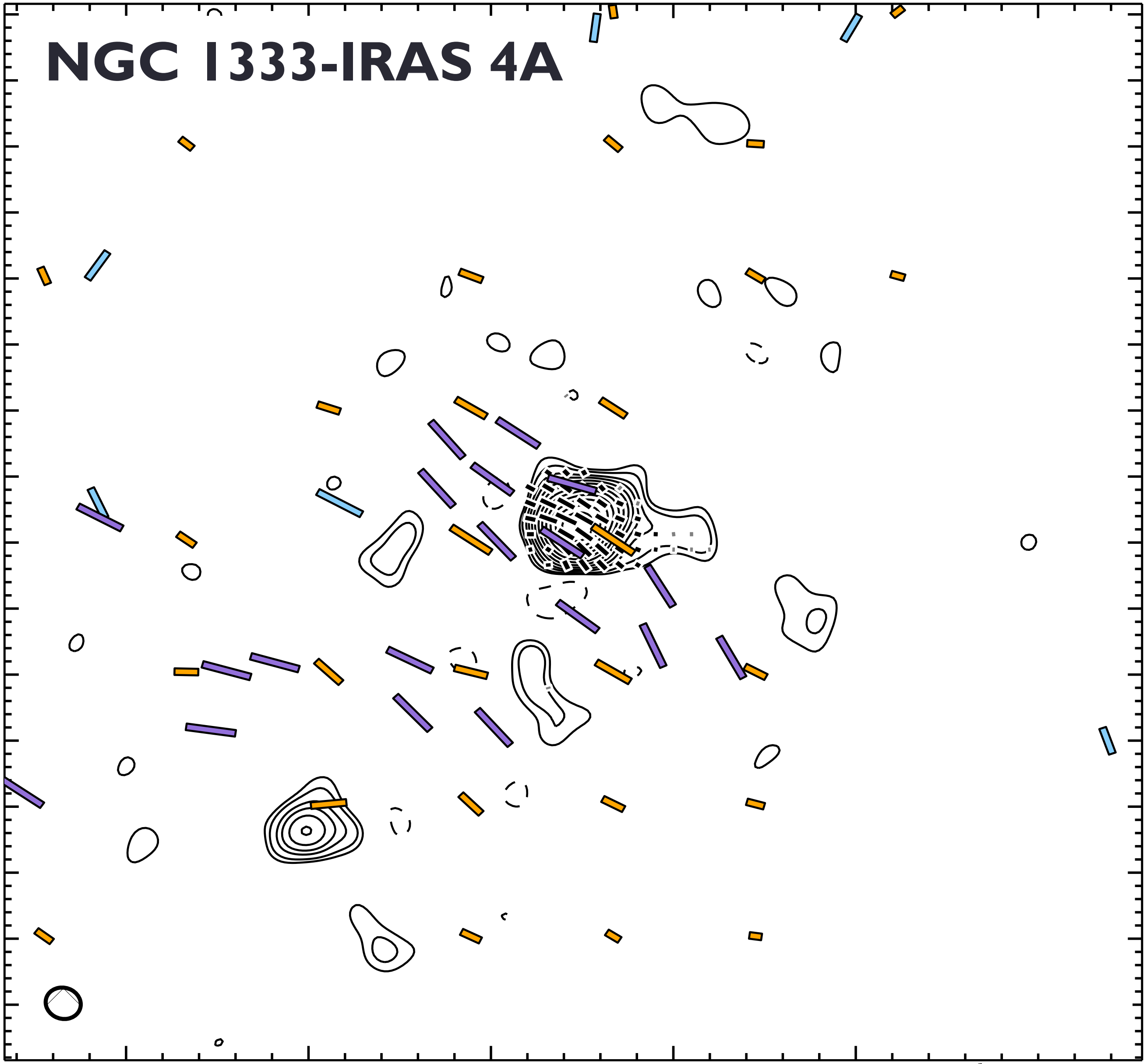
Chapman+ 2013

Davidson+ (incl. C.H.) (in prep)

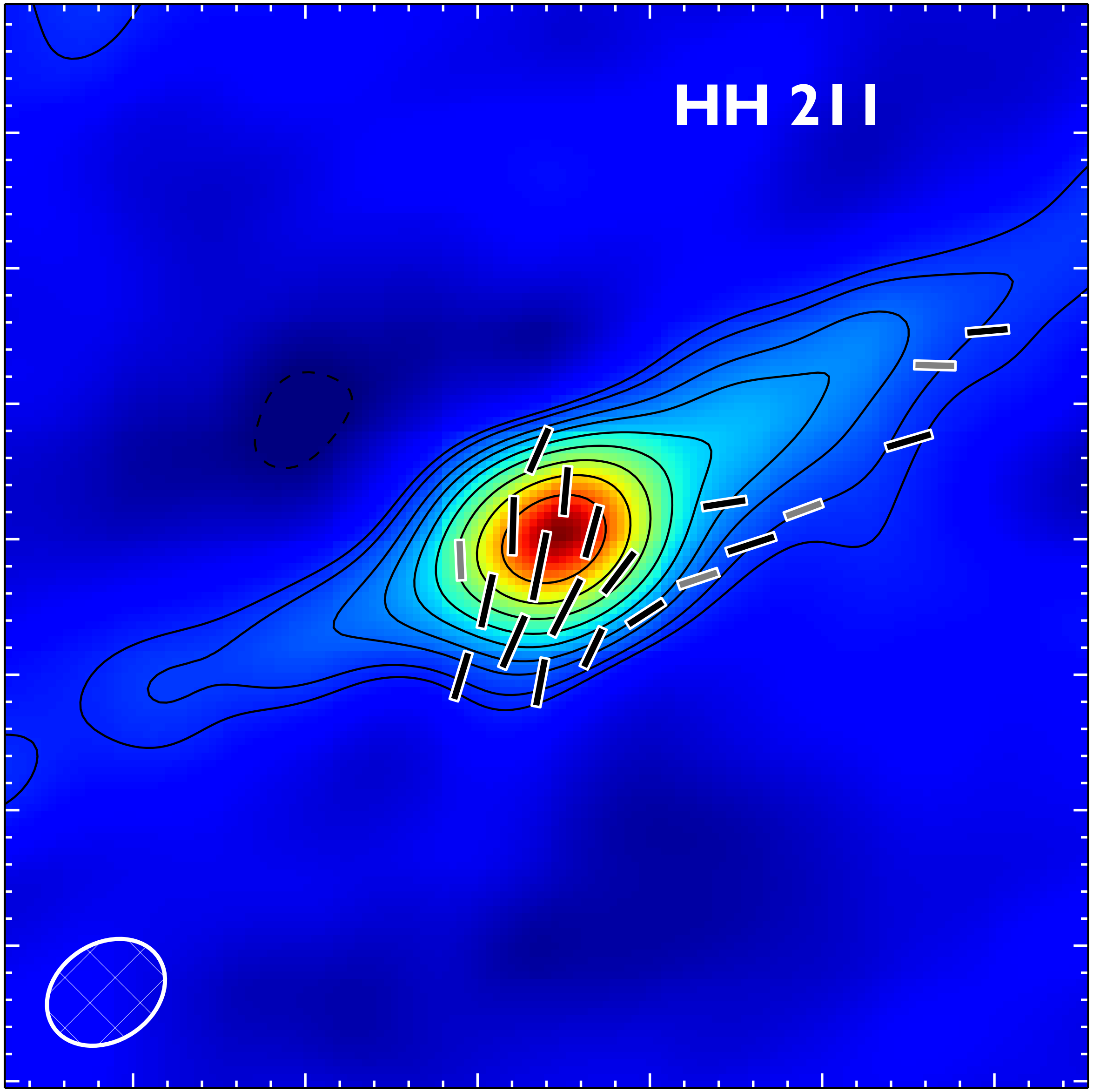
# Cores with **consistent** large-to-small B-fields



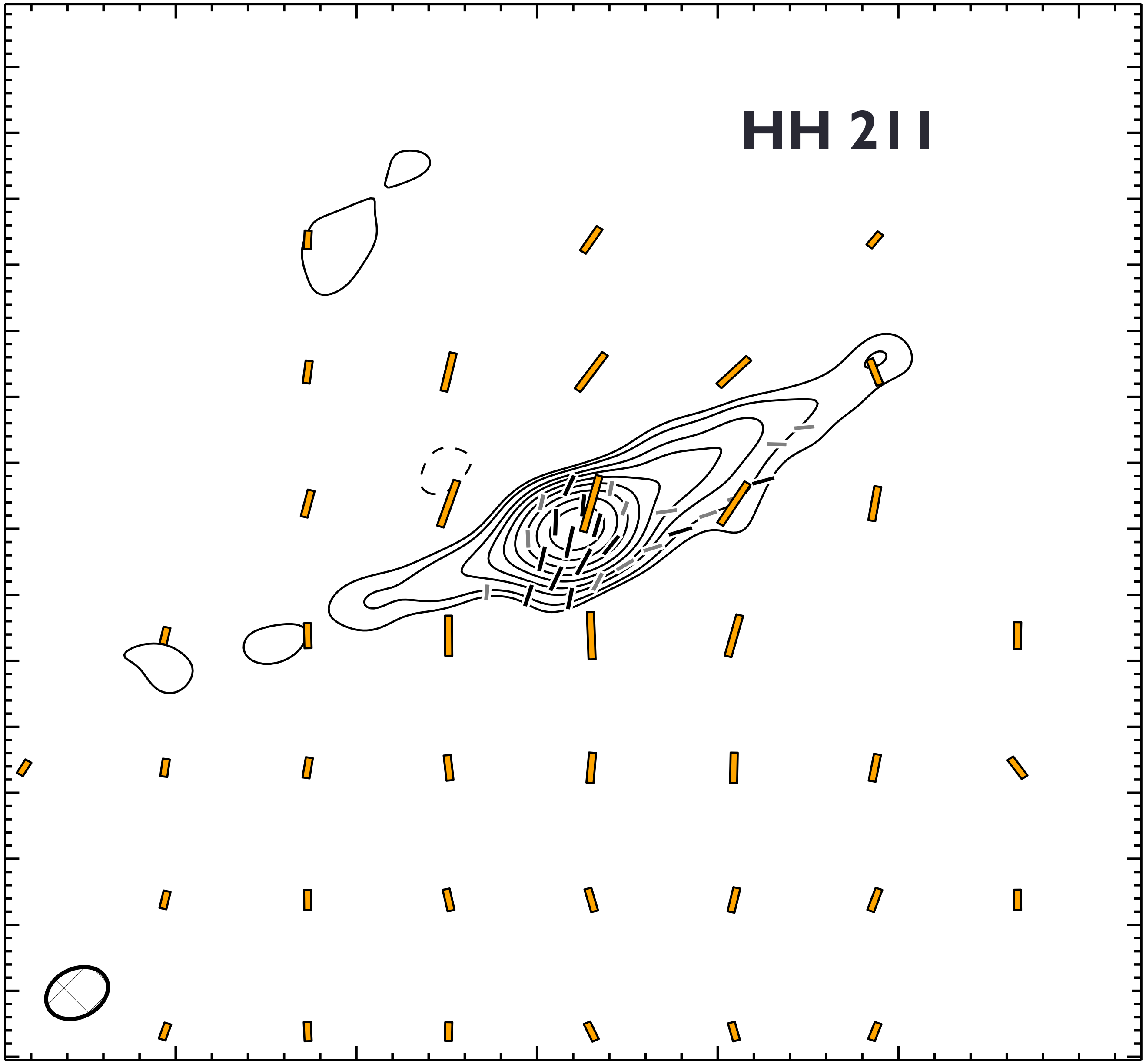
# Cores with **consistent** large-to-small B-fields



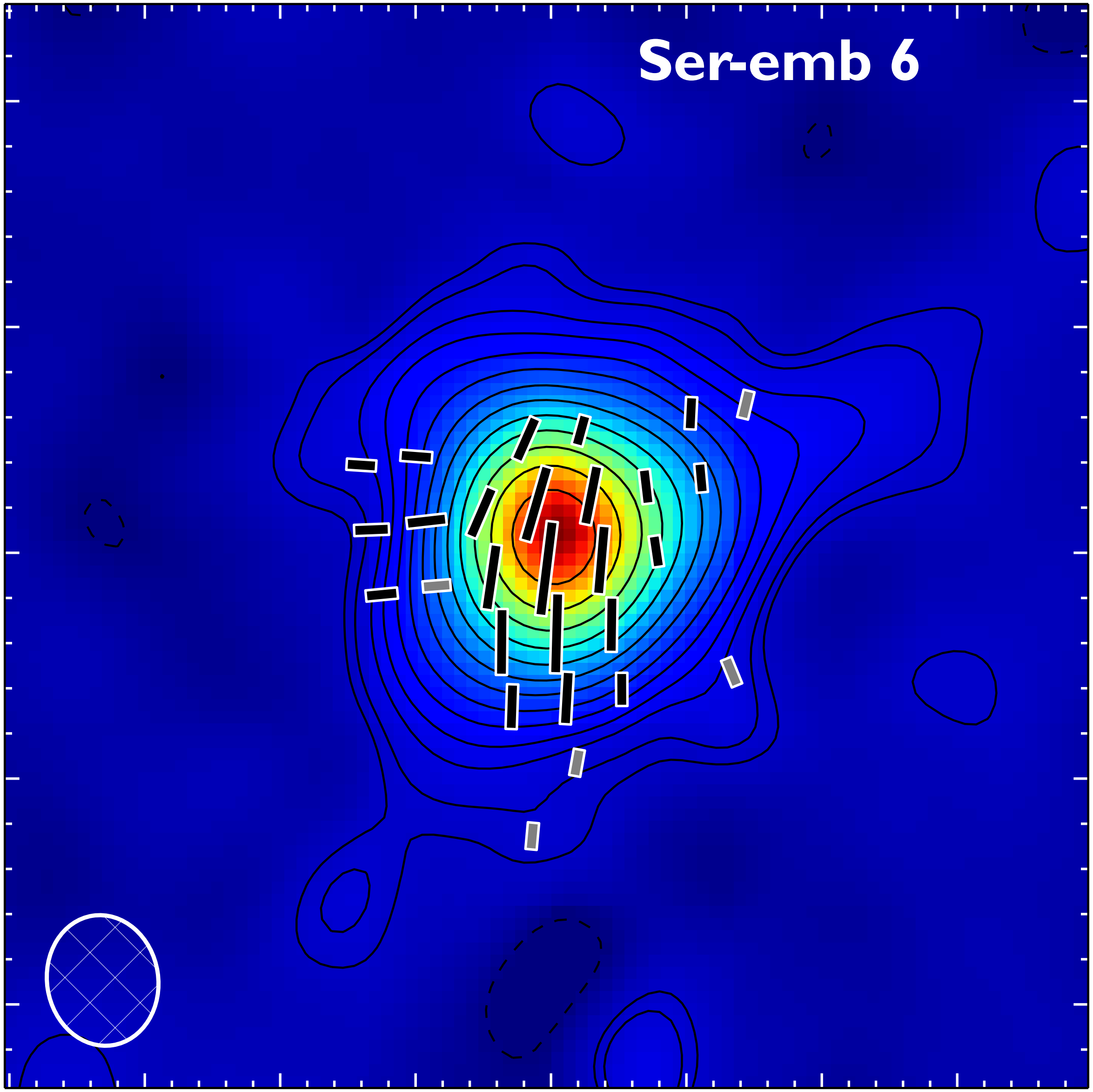
# Cores with **consistent** large-to-small B-fields



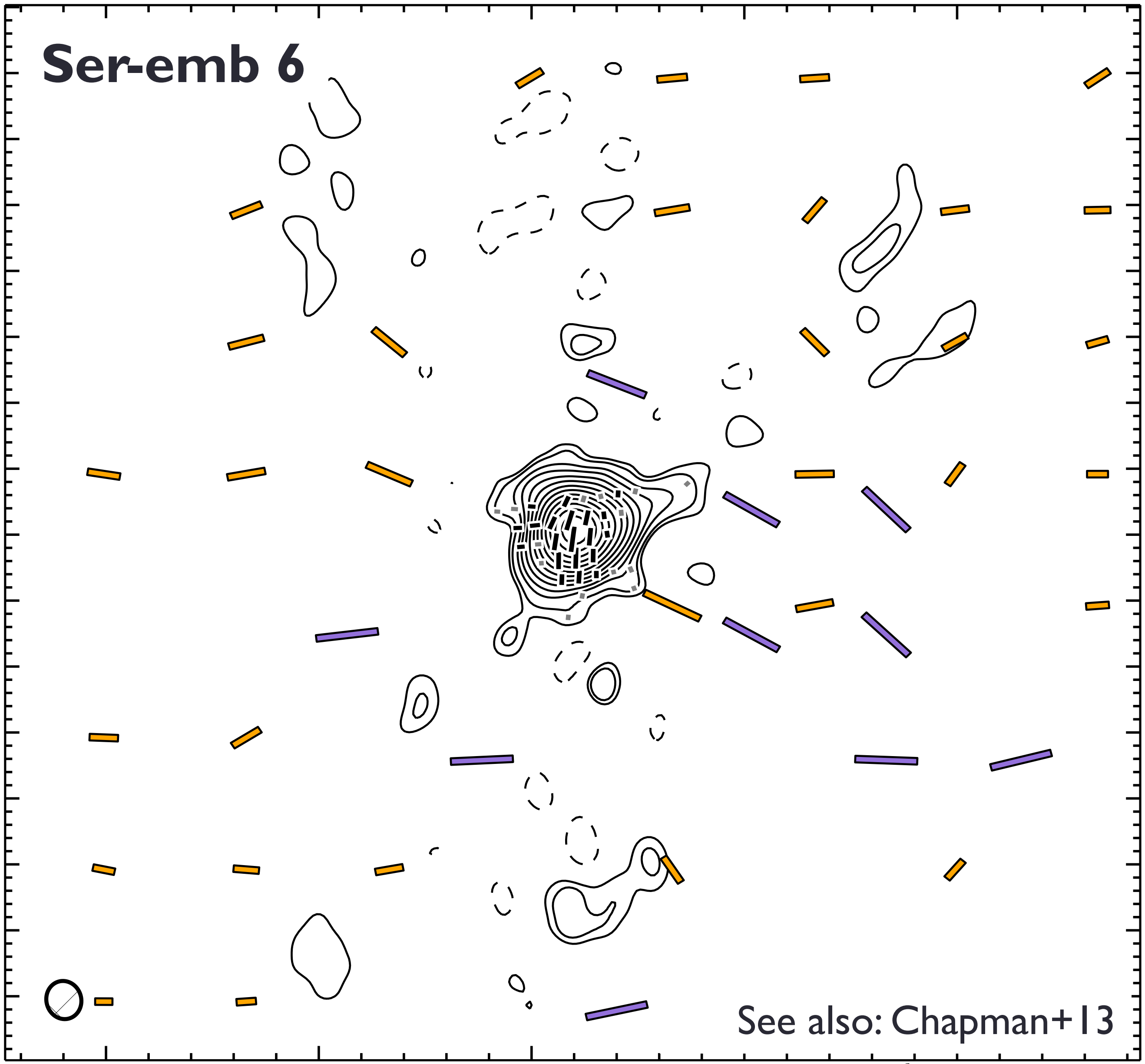
# Cores with **consistent** large-to-small B-fields



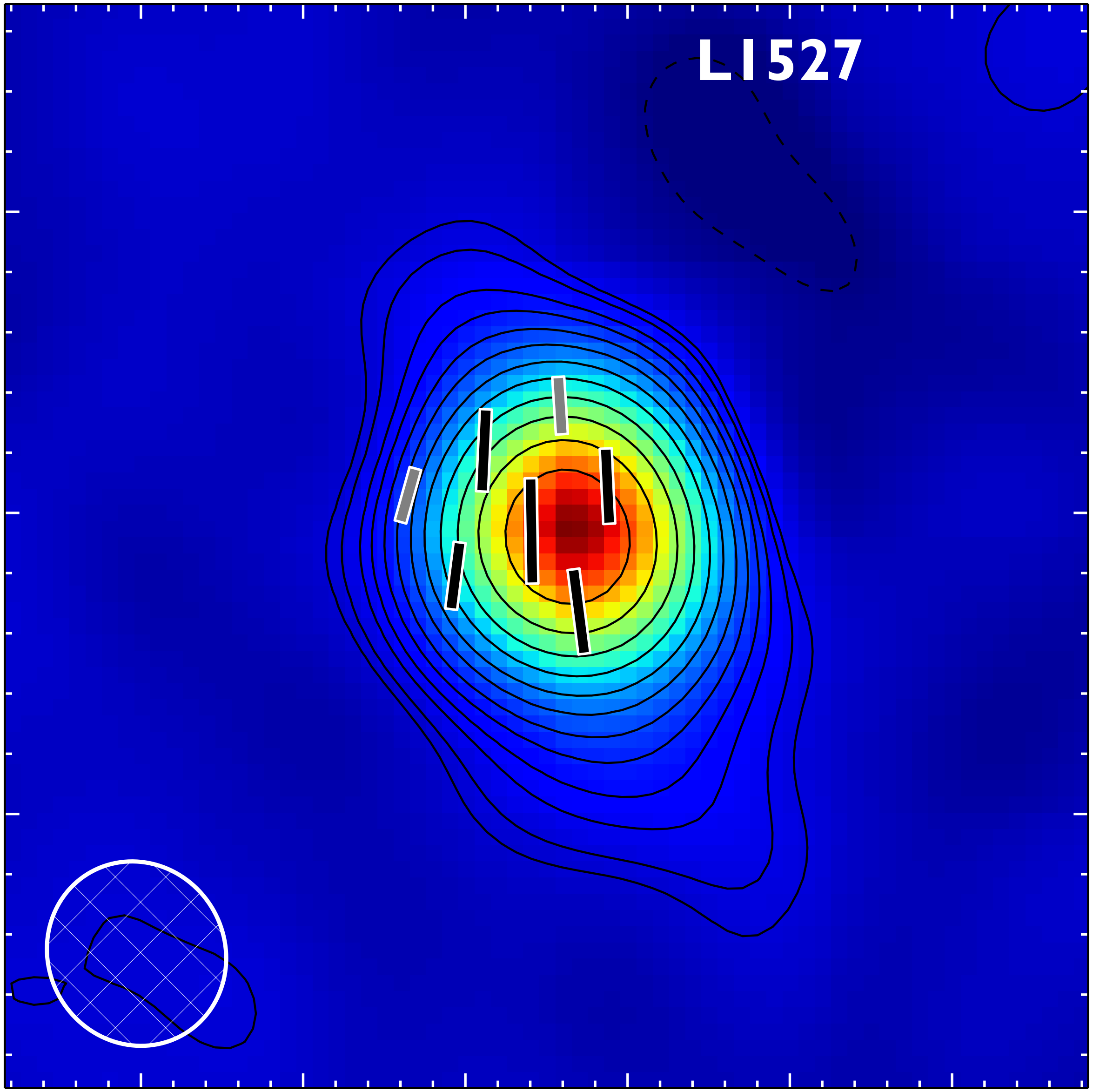
# Cores with **INconsistent** large-to-small B-fields



# Cores with **INconsistent** large-to-small B-fields

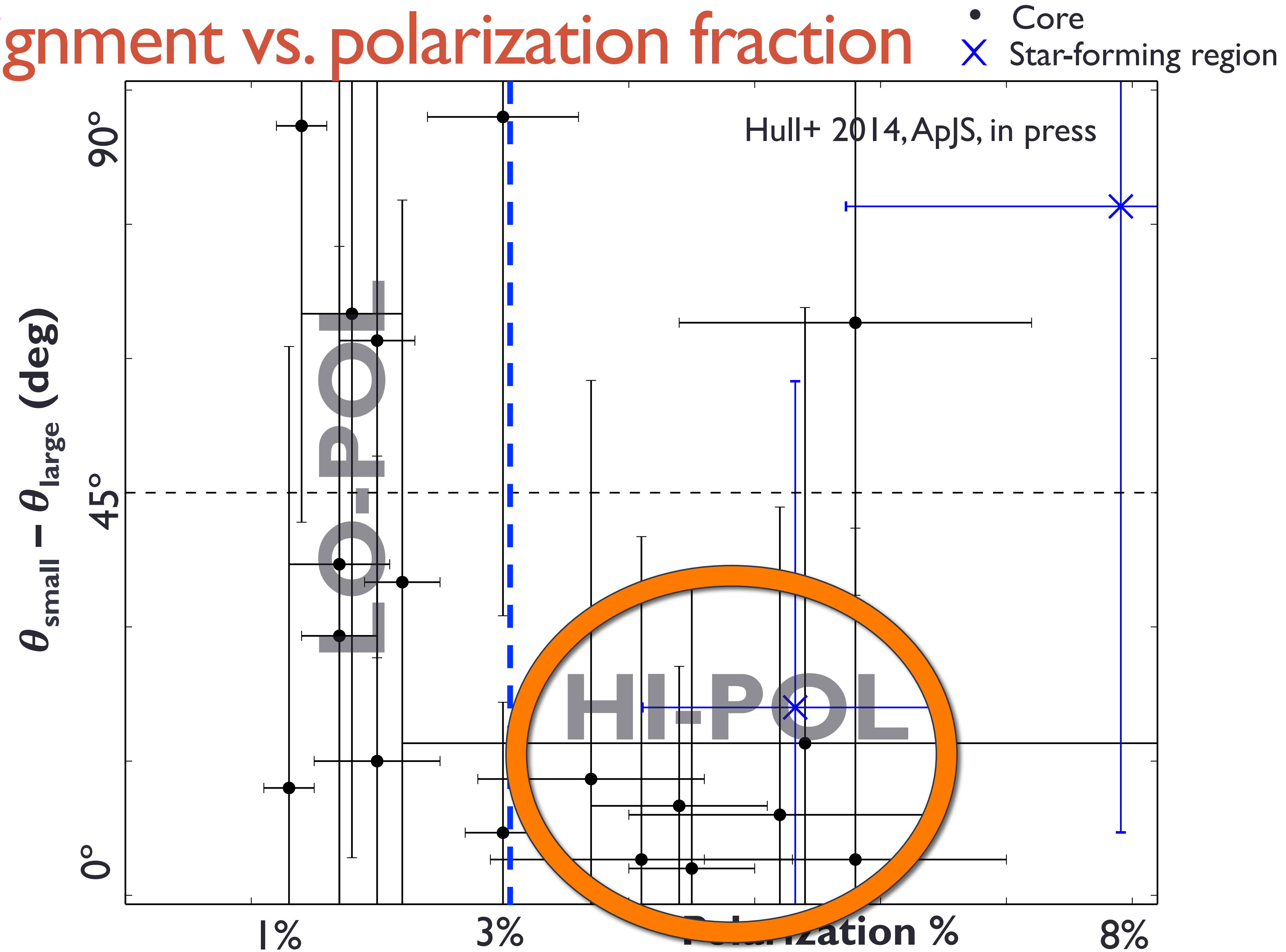


# Cores with **INconsistent** large-to-small B-fields



# Cores with **IN**consistent large-to-small B-fields

# Alignment vs. polarization fraction



# Cores: two populations

## HI-POL

(P > 3%)

$B_{sm} \parallel B_{lg}$

Outflows <u>random</u> w.r.t. $B_{sm}$

## LO-POL

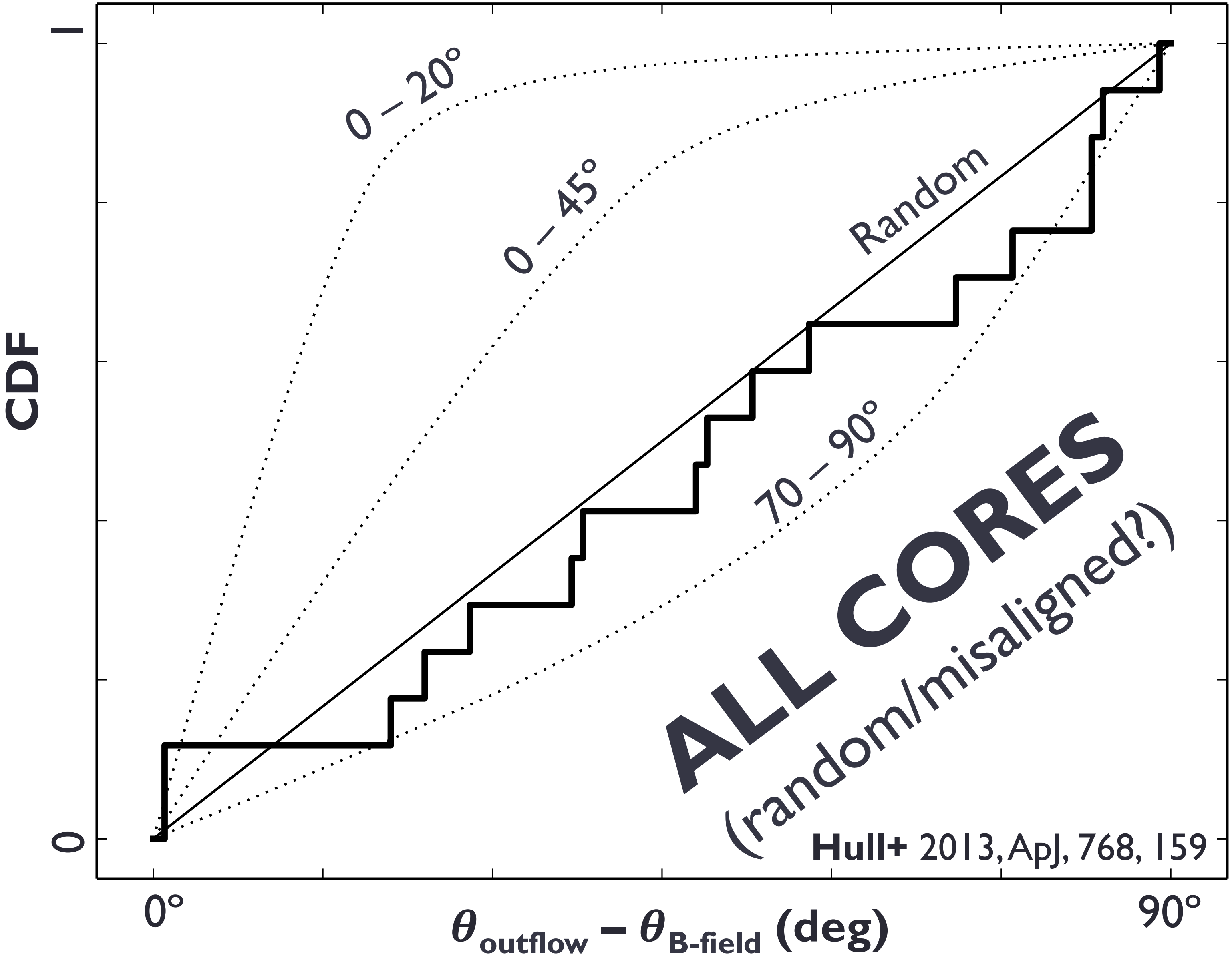
(P < 3%)

$B_{sm} \nparallel B_{lg}$

Outflows $\perp B_{sm}$

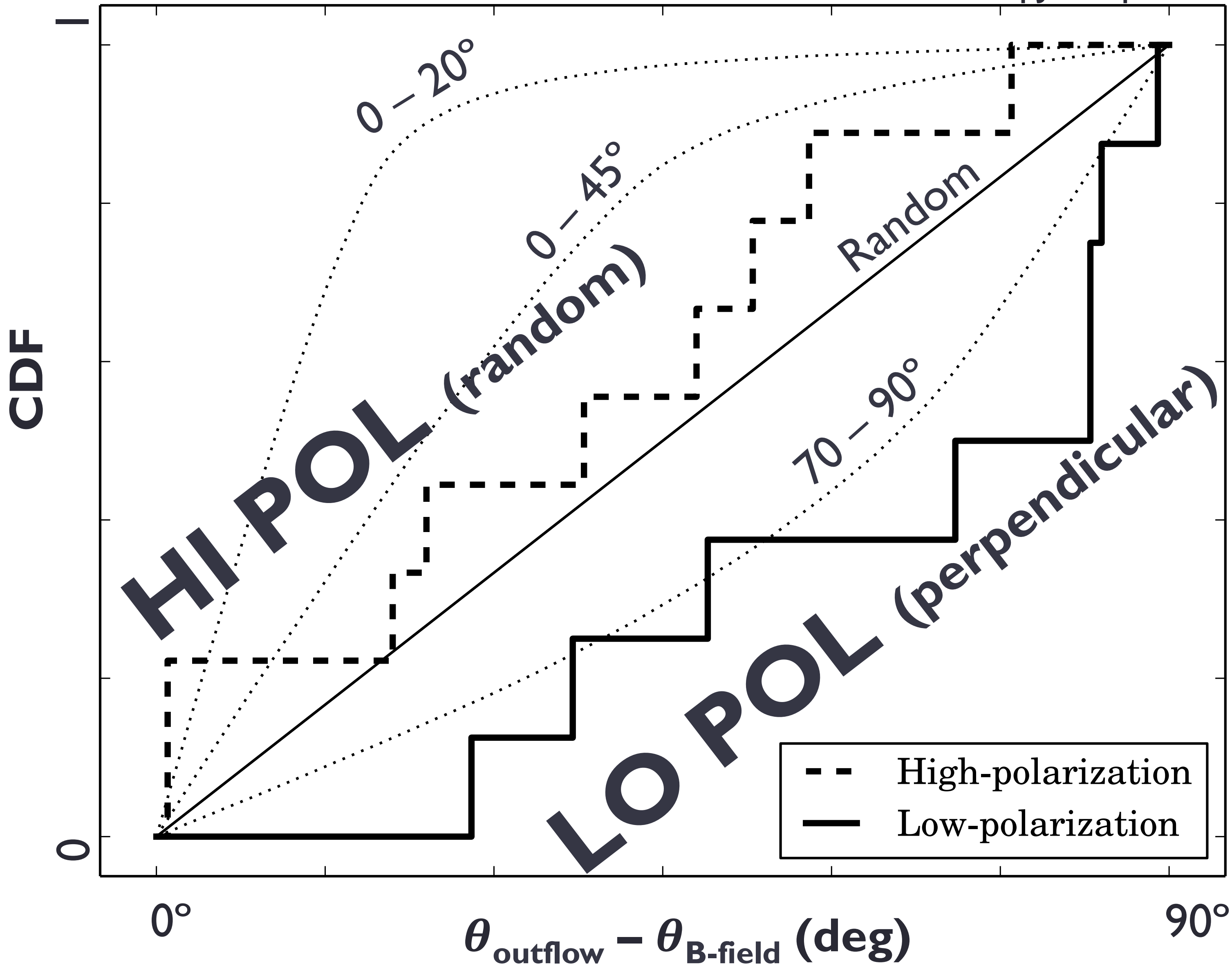
Back to outflows!

# Cores: **B-field vs. outflow alignment**

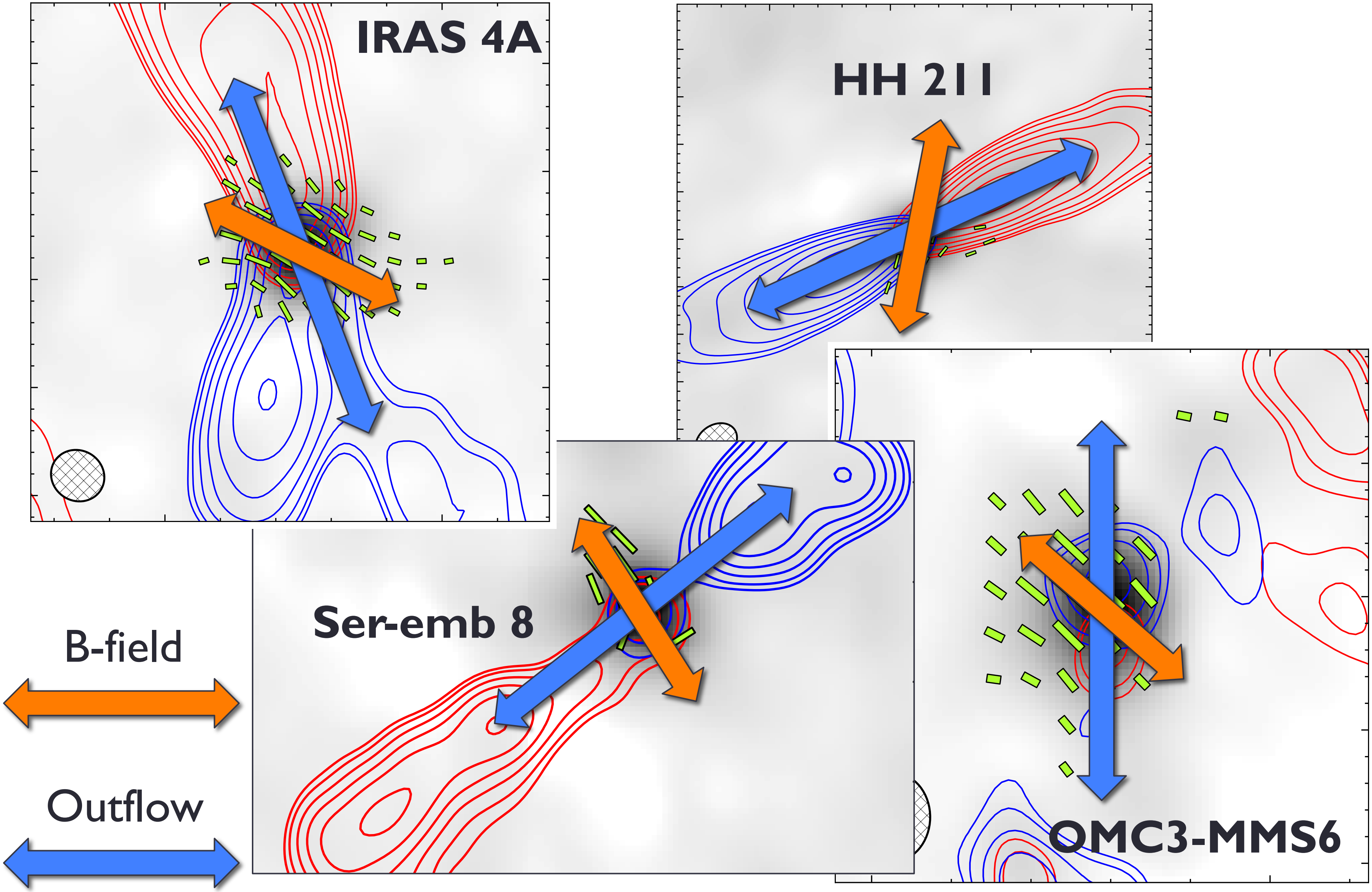


# Cores: **B-field vs. outflow alignment**

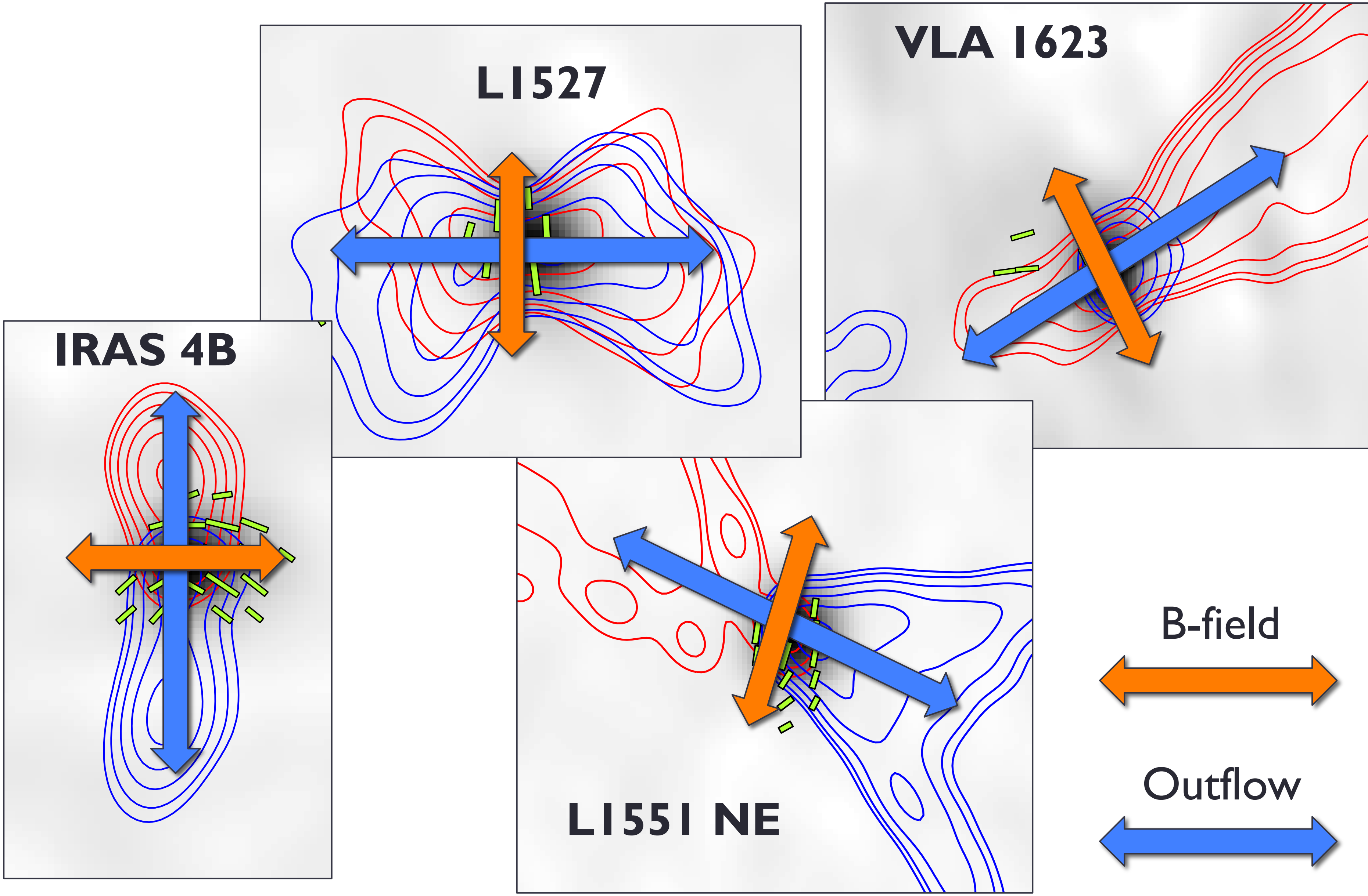
**Hull+** 2014, ApJS, in press



# HI-POL: B-fields random w.r.t. outflows



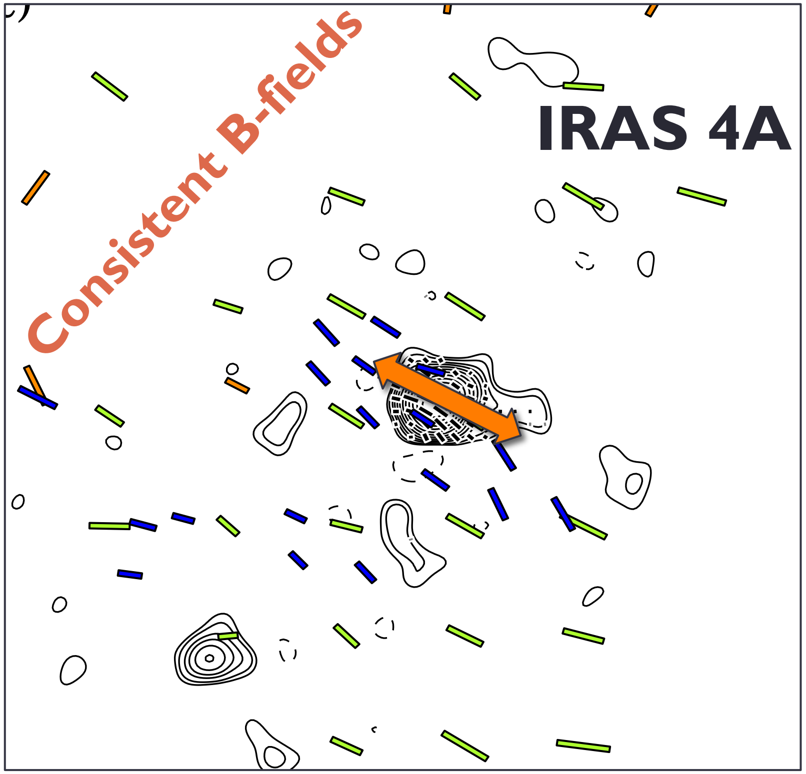
# LO-POL: B-fields ⊥ outflows



# HI-POL vs. LO-POL

- **HI-POL**

  - $U_B > U_{dyn}$
    - B-fields can resist twisting from dynamic effects

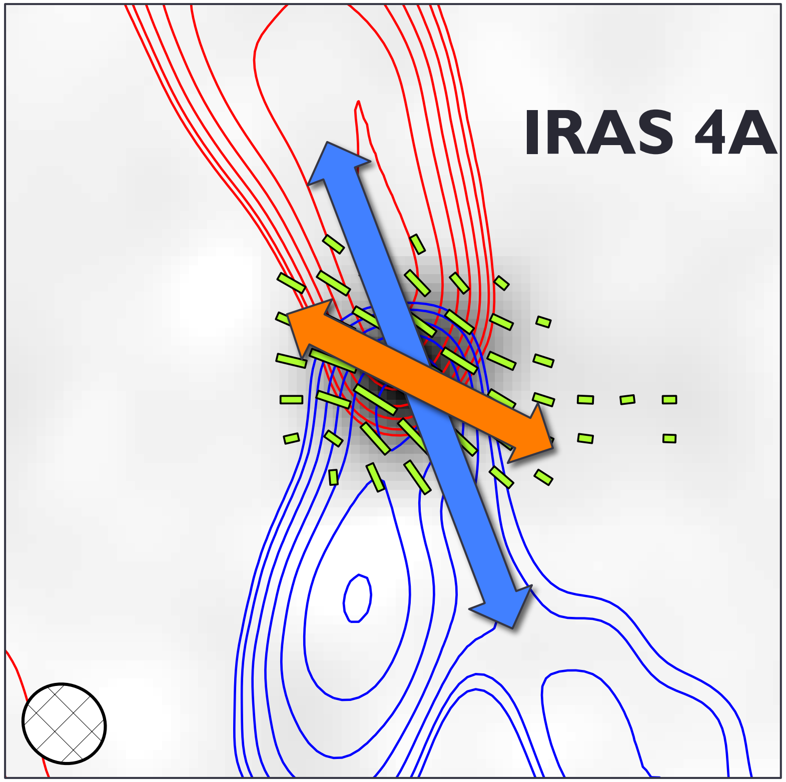



- Less line-of-sight twisting = higher polarization fraction
- Consistent large-to-small-scale B-fields

# HI-POL vs. LO-POL

- **HI-POL**

  - $U_B > U_{dyn}$
    - B-fields can resist twisting from dynamic effects




- Less line-of-sight twisting = higher polarization fraction
- Consistent large-to-small-scale B-fields
- **B-fields still are not correlated with outflows**
  - Angular momentum direction unaffected by "global field"

# HI-POL vs. LO-POL

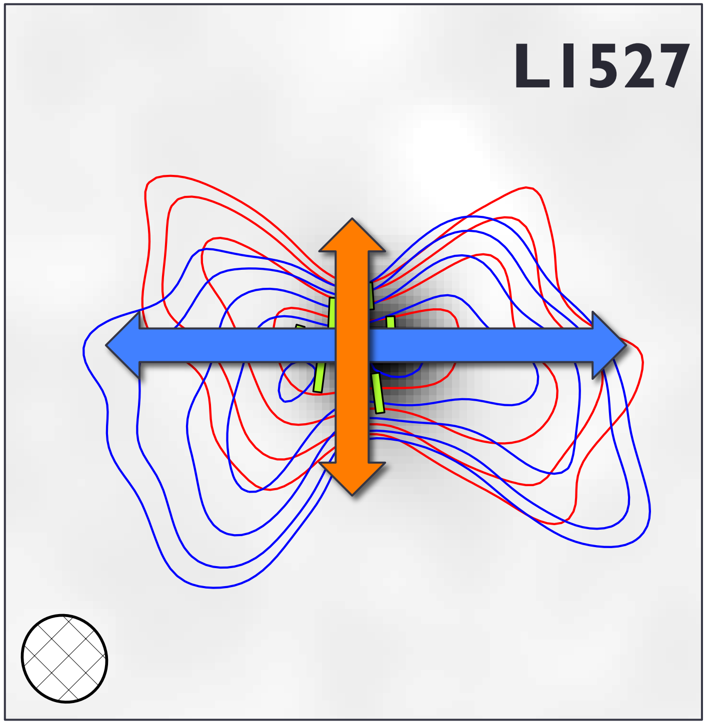
- **LO-POL**
  - $U_B < U_{dyn}$


- More line-of-sight twisting = **lower** polarization fraction
- **Inconsistent** large-to-small-scale B-fields

# HI-POL vs. LO-POL

- **LO-POL**

  - $U_B < U_{dyn}$
    - B-fields are **twisted by rotation**

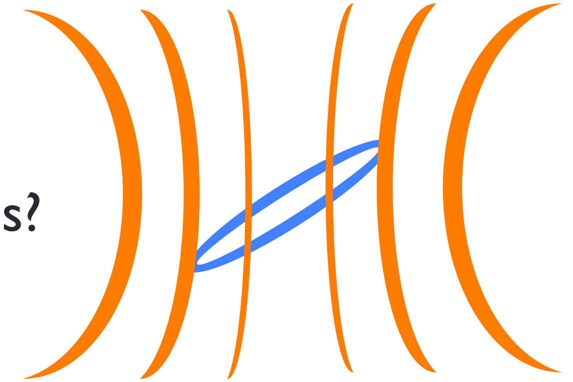



- More line-of-sight twisting = **lower** polarization fraction
- **Inconsistent** large-to-small-scale B-fields
- **B-fields are ⊥ to outflows**
  - No longer looking at global field

# HI-POL vs. LO-POL: open questions

## HI-POL

- Is our view just dominated by the global field?
- If so, are the fields actually twisted at smaller scales?



## LO-POL

- Are the twisted B-fields we see at 1000 AU
  consistent with B-fields at disk scales?

# FUTURE multi-scale comparison: B-fields

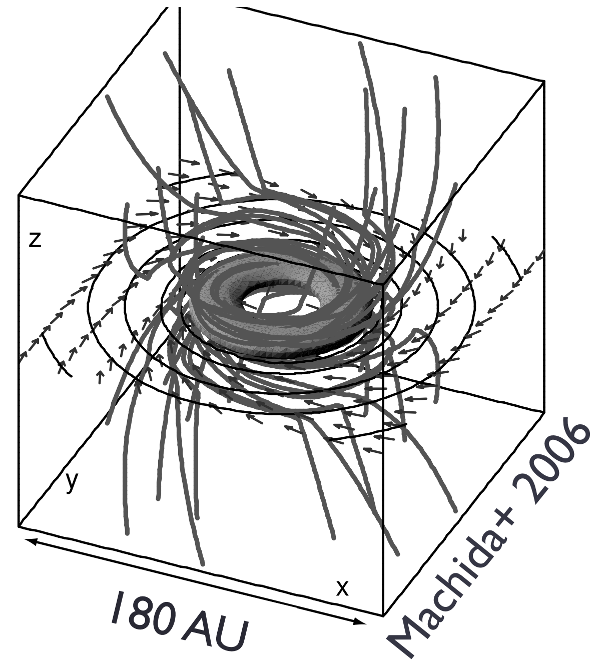
1 pc

0.1 pc

1000 AU

100 AU

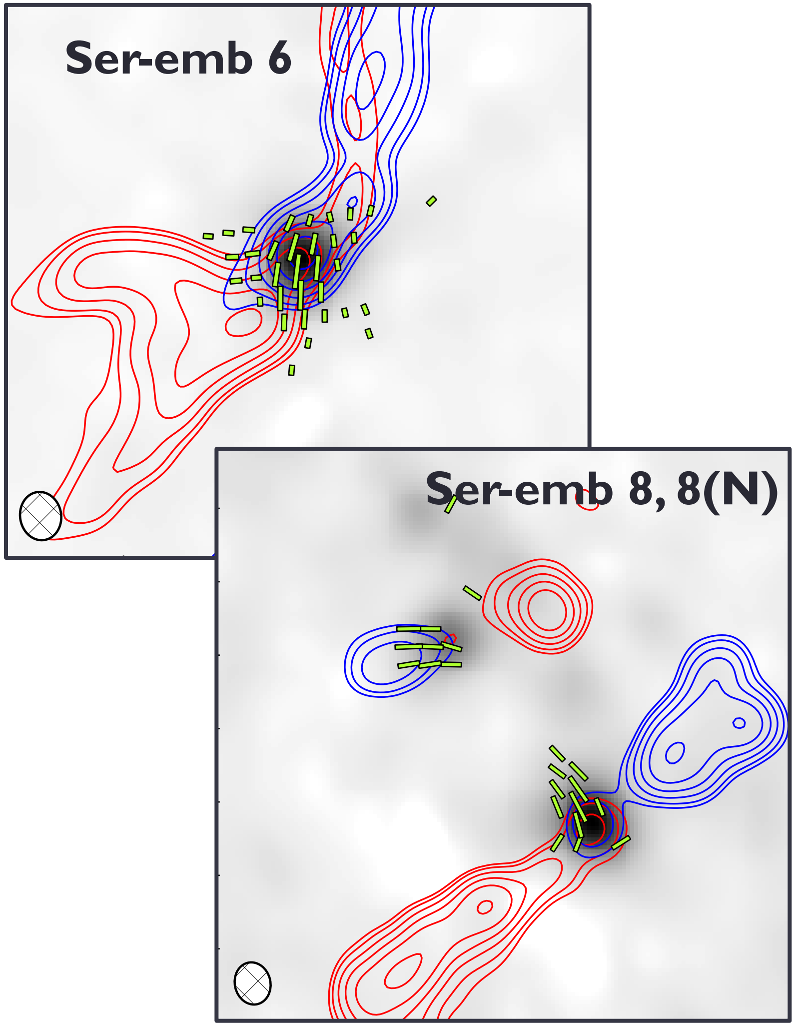
?




CARMA/SMA +
ALMA

# Future work with ALMA

# FUTURE: Cycle 2 ALMA observations




CARMA data: Hull+ 2014, ApJS, in press

### Class 0
## CORE POLARIZATION
(PI: Hull, high priority)

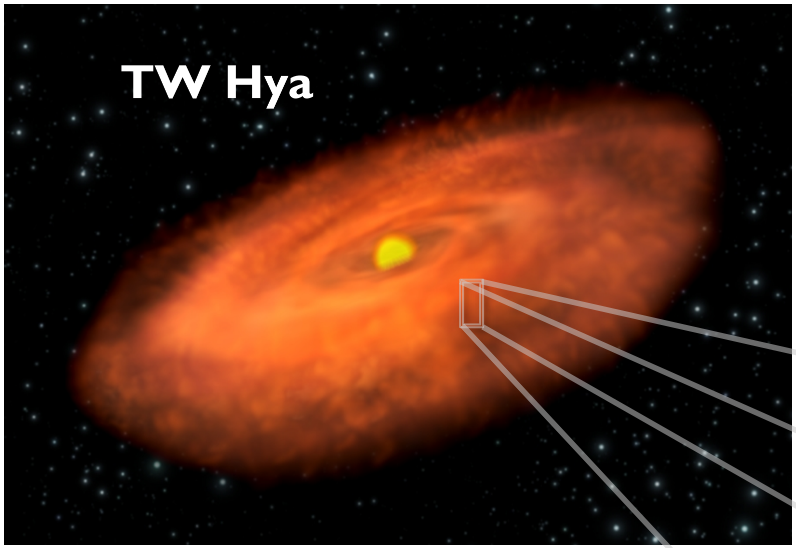
- 0.36” resolution @ Band 7 (dust pol)
  - Also outflow maps (@ Band 6)
- Probing **~150 AU** disk scales
- Are B-fields always toroidal?

# FUTURE: Cycle 2 ALMA observations

### Class II

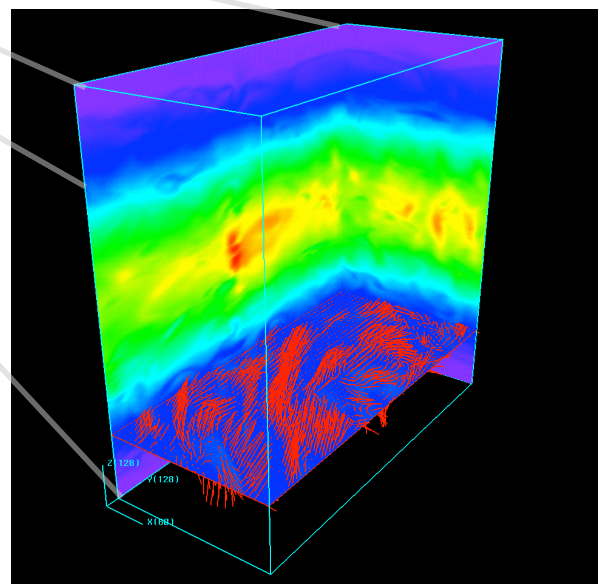
## DISK POLARIZATION

(PI: Hull, filler)




Credit: ESA/C. Carreau

- 0.1" resolution @ Band 7 (dust pol)
- Probing **~7 AU** elements within disk



Credit: Jim Stone (astro.princeton.edu/~jstone/images/3d-disk.gif)

# FUTURE: Cycle 2 ALMA observations

**Star-forming regions**

W43 (PI: Cortés, Co-I: Hull)

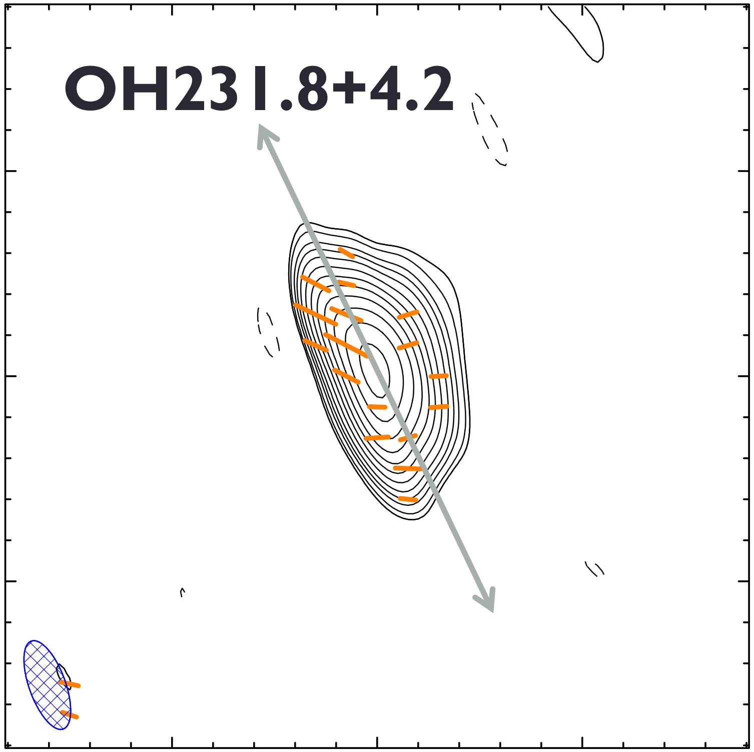
**Cores with disks**

VLA 1623, L1527 (PI: Looney)

**Class I/II disk**

HL Tau (PI: Stephens)

# FUTURE: Cycle 2 ALMA observations



CARMA data: Sabin & Hull (in prep)

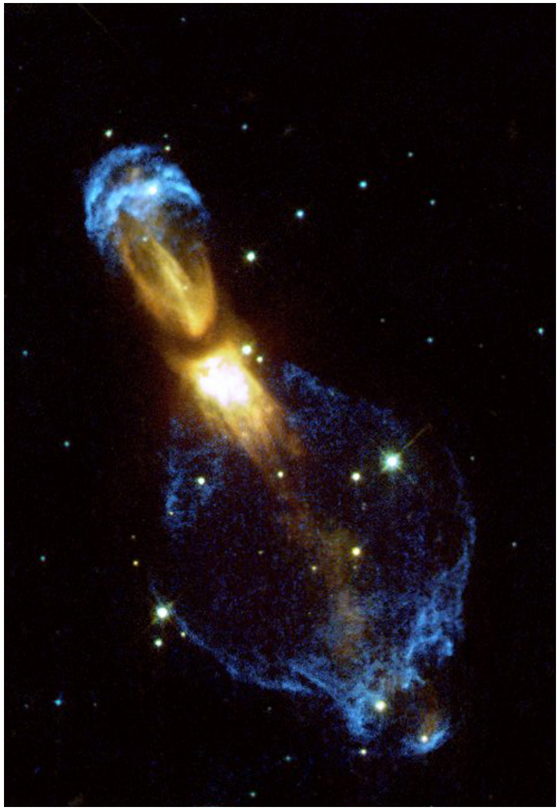
## PROTOPLANETARY NEBULAE!

(ALMA Co-I: Sabin)

←

OH231.8+4.2

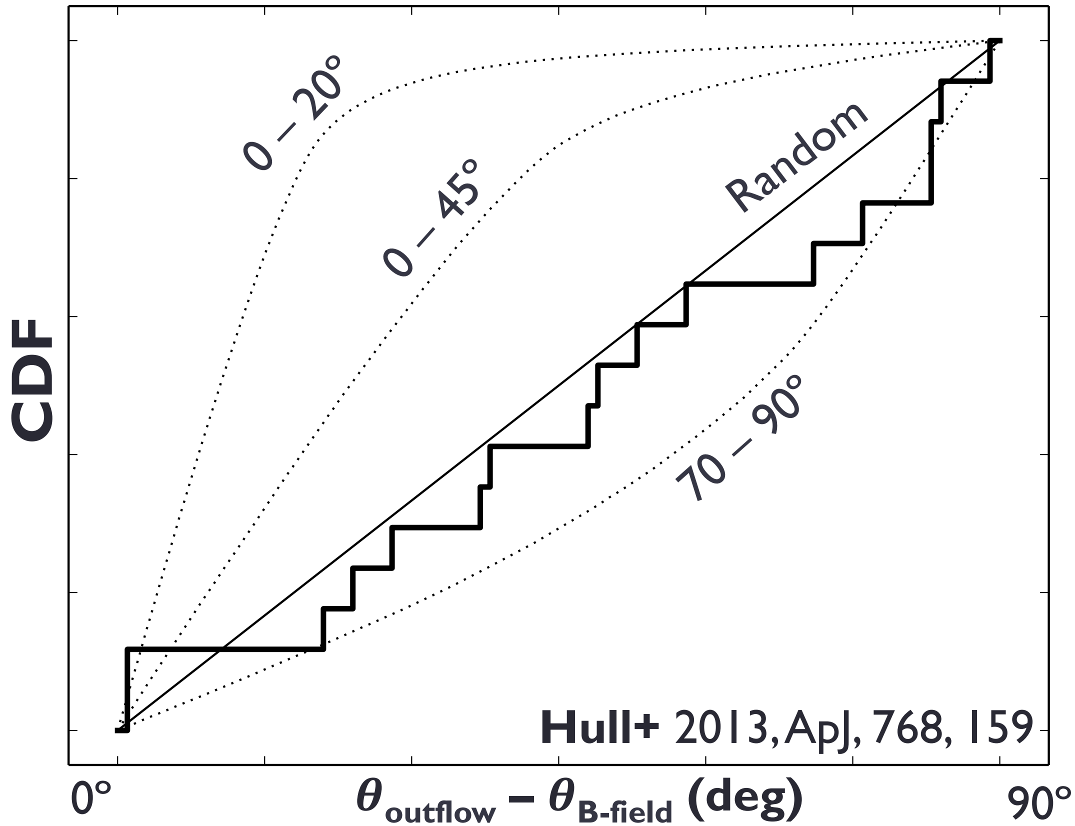
→



Credit: PNIC catalogue
astro.washington.edu/users/balick/PNIC

# Summary (1/4)

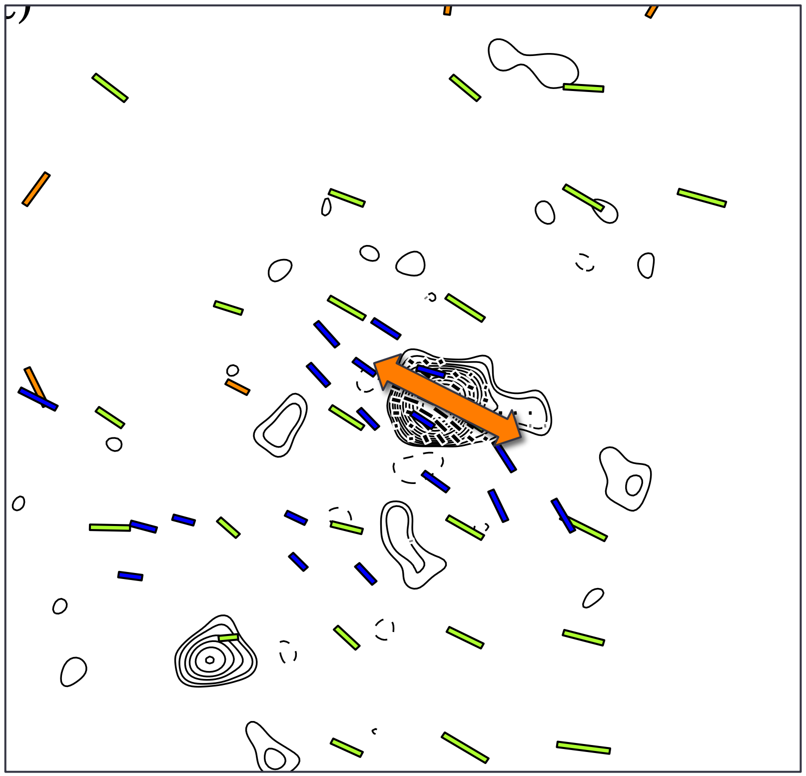
- B-fields are **randomly aligned** with respect to outflows at the ~1000 AU scale

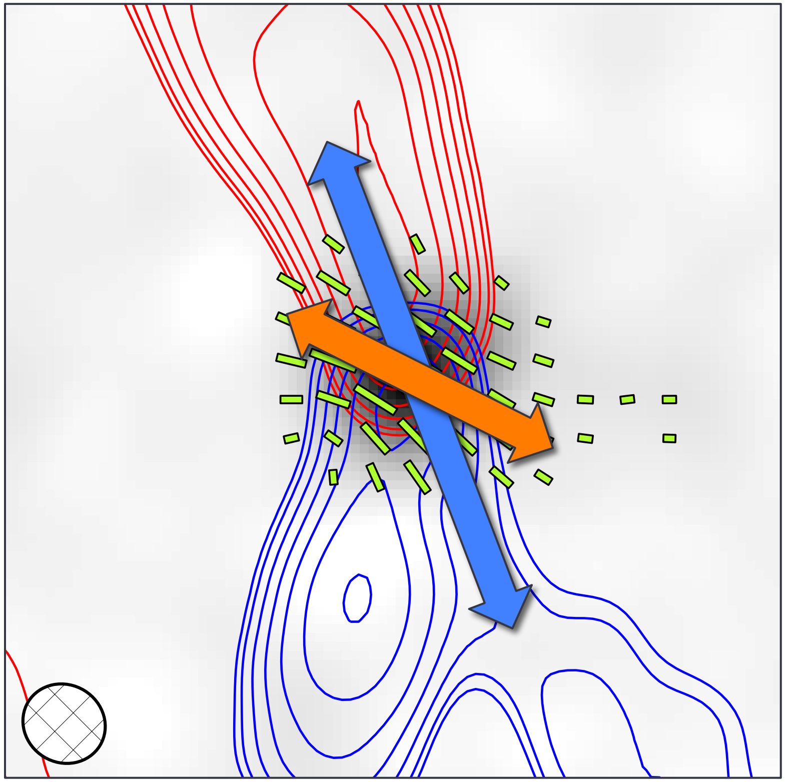



- Thus, circumstellar disks are misaligned with fields in the cores from which they formed

# Summary (2/4)

## HI-POL sources

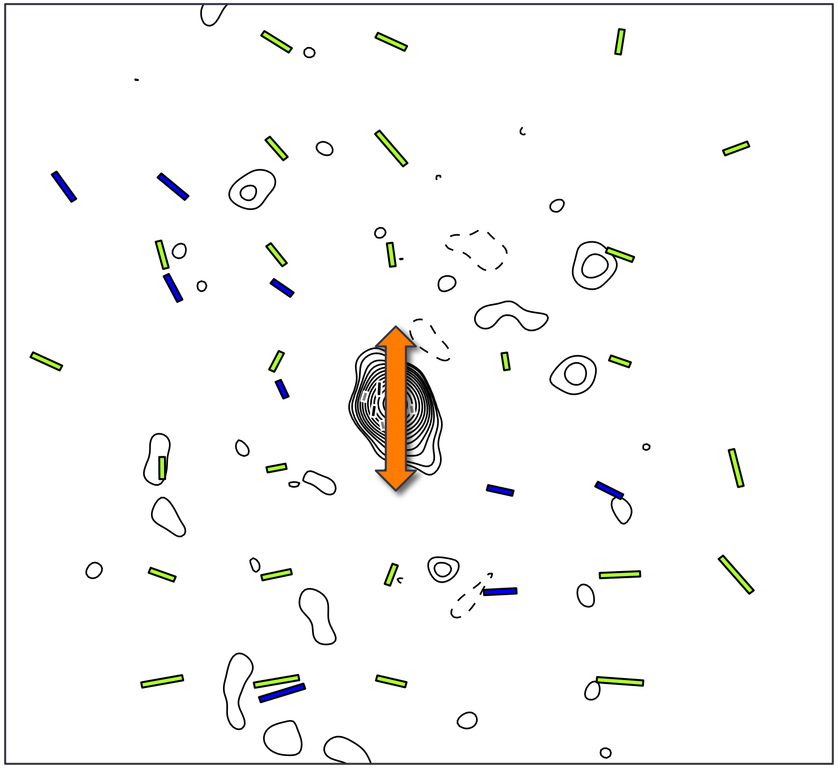


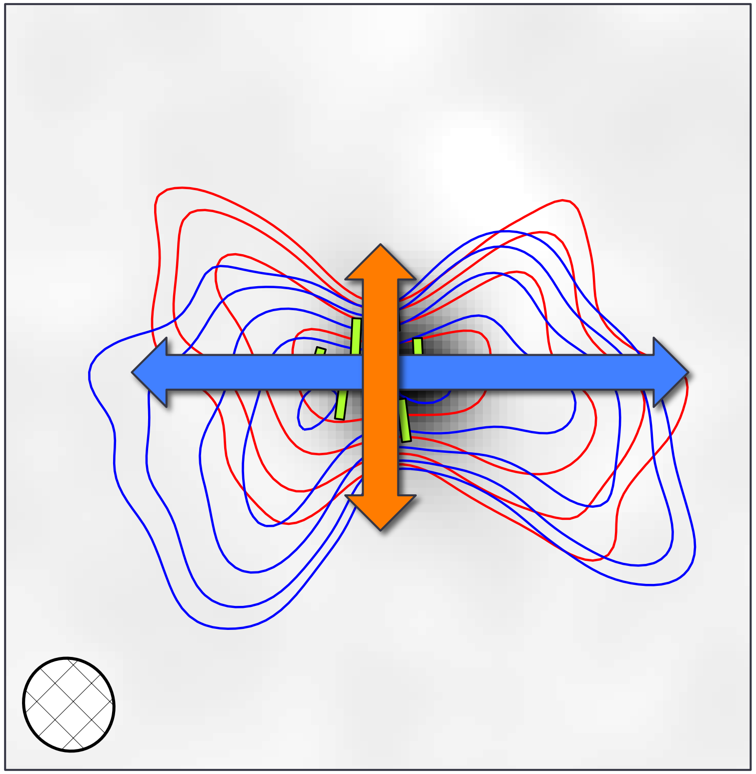


- Consistent large- to small-scale B-fields
- Outflows and B-fields are **randomly aligned**
- Global field doesn't affect final angular momentum

# Summary (3/4)

## LO-POL sources





- **IN**consistent large- to small-scale B-fields
- Outflows and B-fields are **perpendicular**
- Fields may be wrapped up by envelope rotation

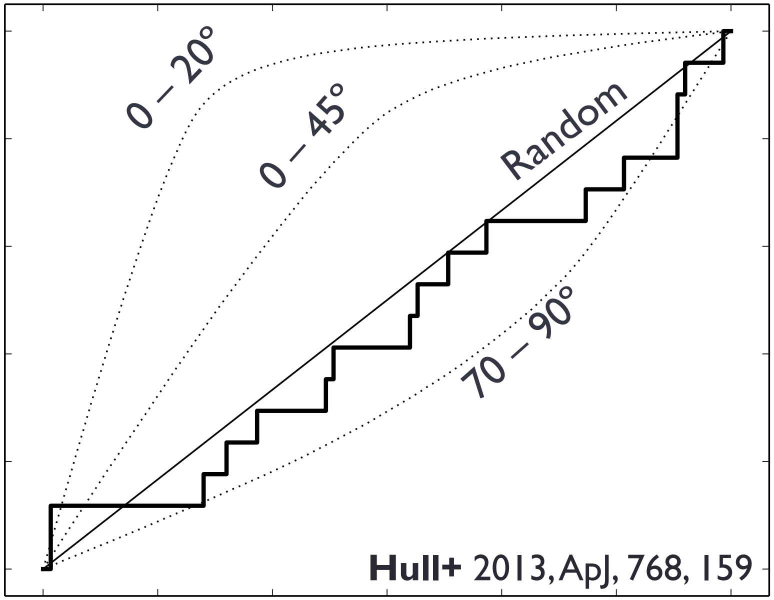
# Summary (4/4)

- Questions:
  - Why are B-fields and outflows randomly aligned?
  - What will disk-scale B-field measurements show?

- **TADPOL data release (ApJS, in press):** arXiv:1310.6653
- **TADPOL outflows vs. B-fields:** ApJ, 768, 159
- **TADPOL survey**: tadpol.astro.illinois.edu

# Summary

## (1) Random outflows vs. B-fields

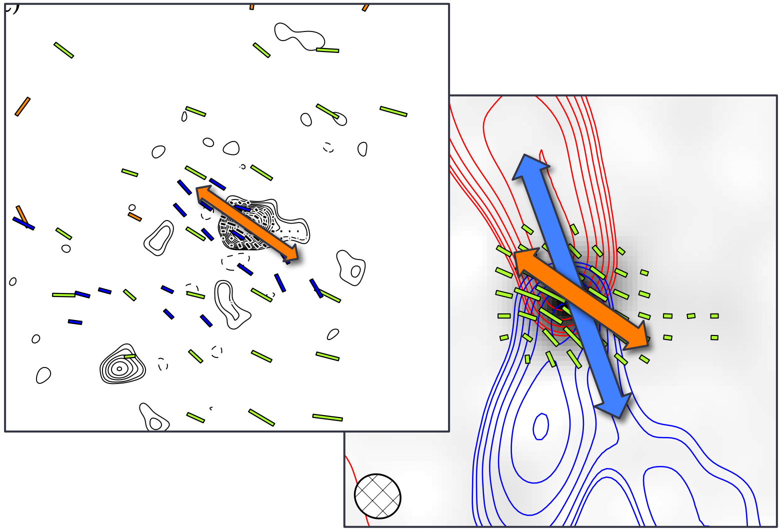



**TADPOL data release (ApJS, in press)**
arXiv:1310.6653

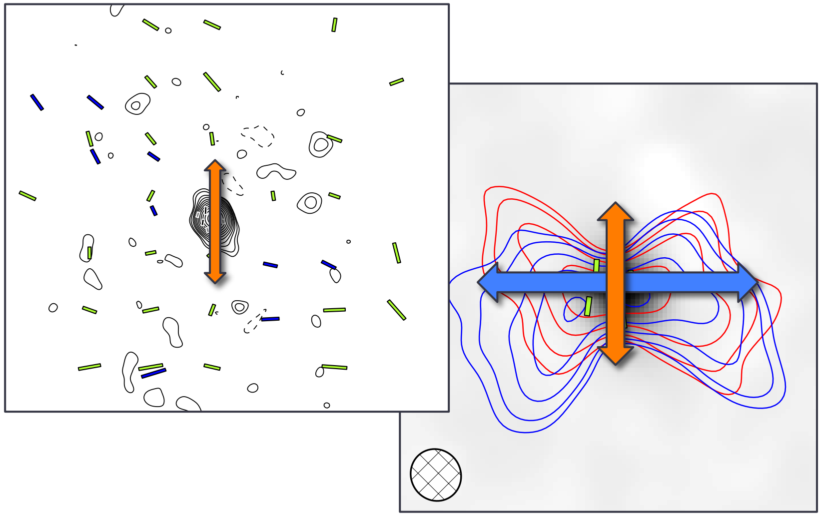
**TADPOL outflows vs. B-fields**
ApJ, 768, 159

**TADPOL survey**
tadpol.astro.illinois.edu

## (2) HI-POL: consistent B-fields, random outflows



## (3) LO-POL: B-fields wrapped by rotation



**Fin**