Unveiling the role of the magnetic field at the smallest scales of star formation

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Overview

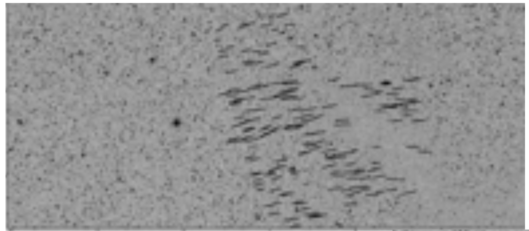
- **Introduction:** to magnetized star formation on large (~1 pc) & small (~1000 AU) scales
  - Default assumption: the "strong-field" case
- **Large-scale** observations suggest strong fields. **Small-scale** observations sometimes do…but not always
- ALMA results definitively show a weak-field case
- ALMA results also show a case where the magnetic fields are shaped by the bipolar outflow!

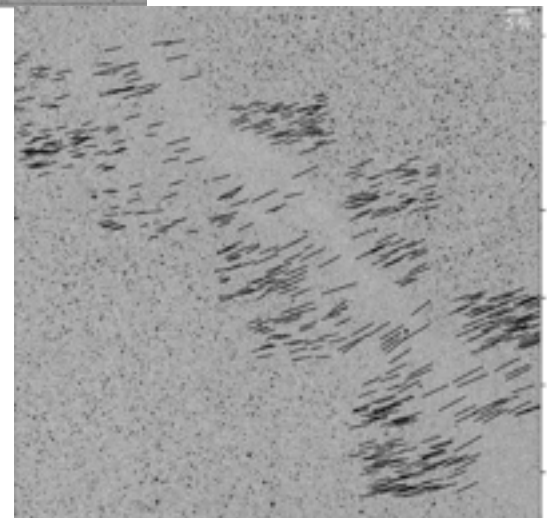
Scales of star formation

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

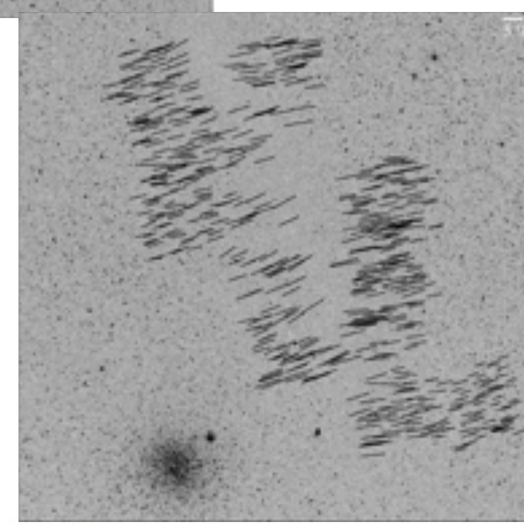
Intro:
Magnetized star formation on large (cloud, ~parsec) scales

Magnetic fields on cloud scales

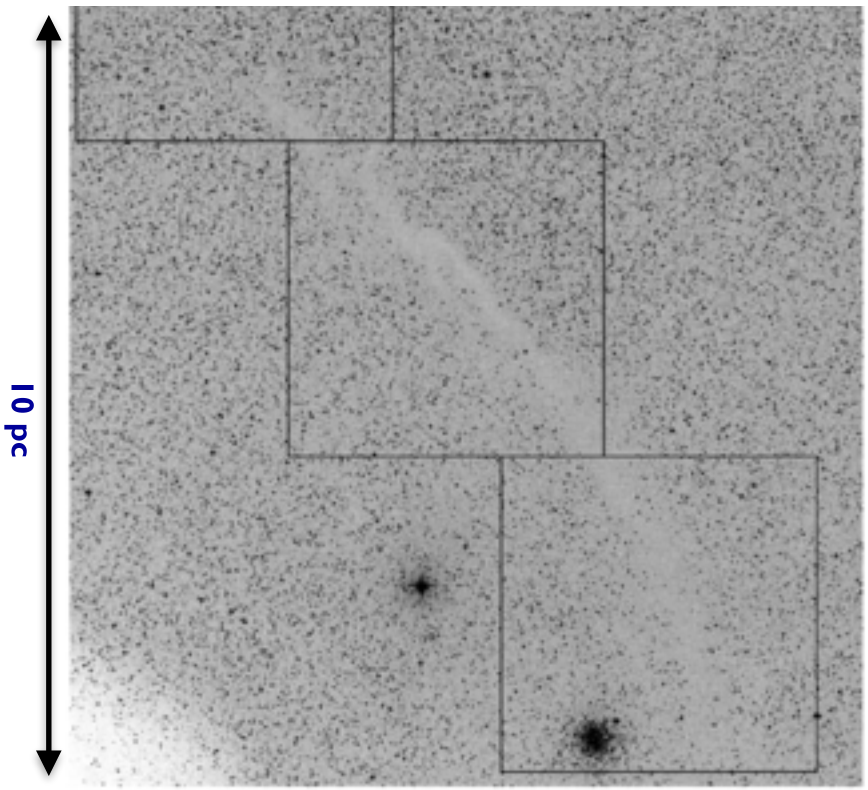




Fields perpendicular to cloud's long axis: fields may be dynamically important

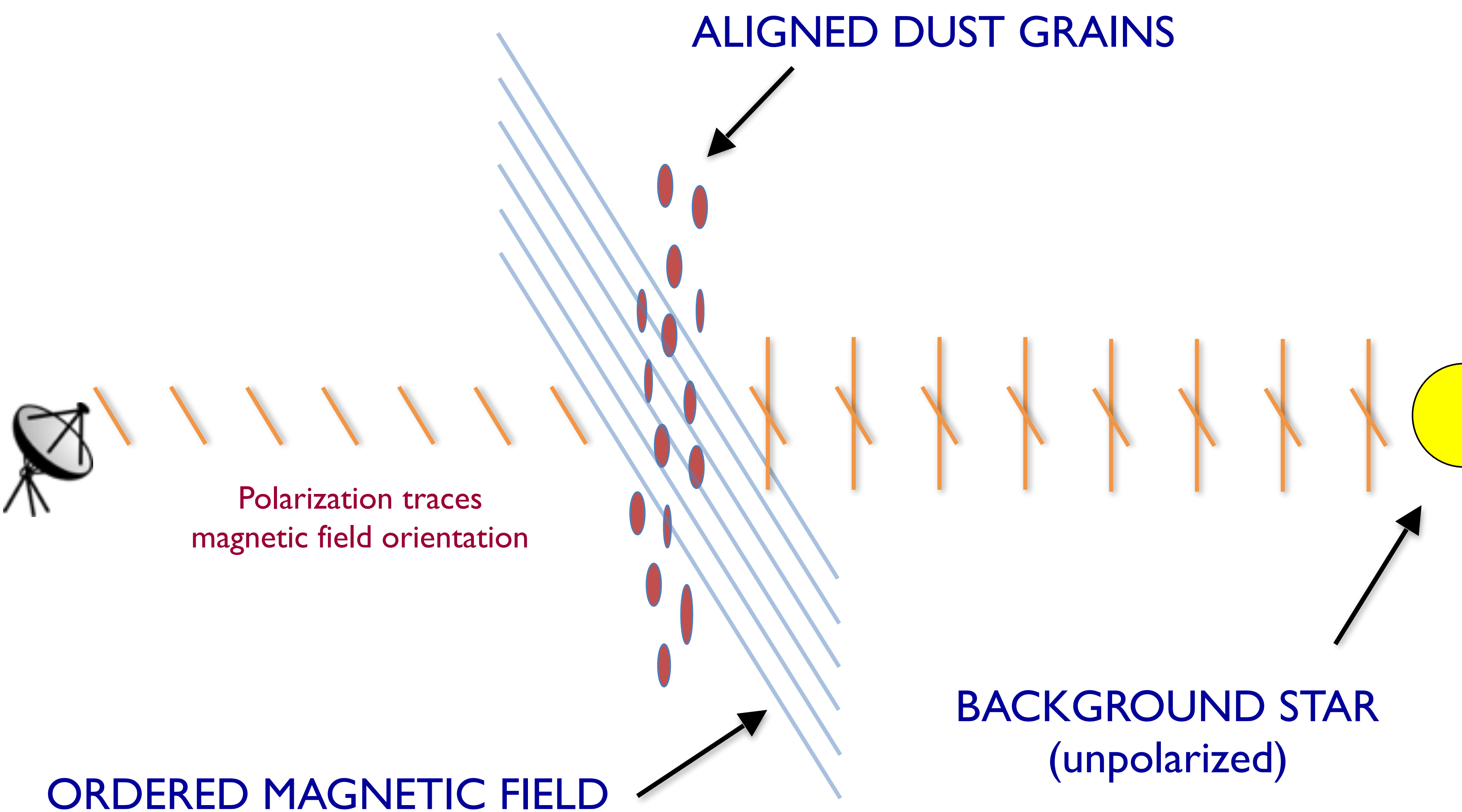


Musca dark cloud

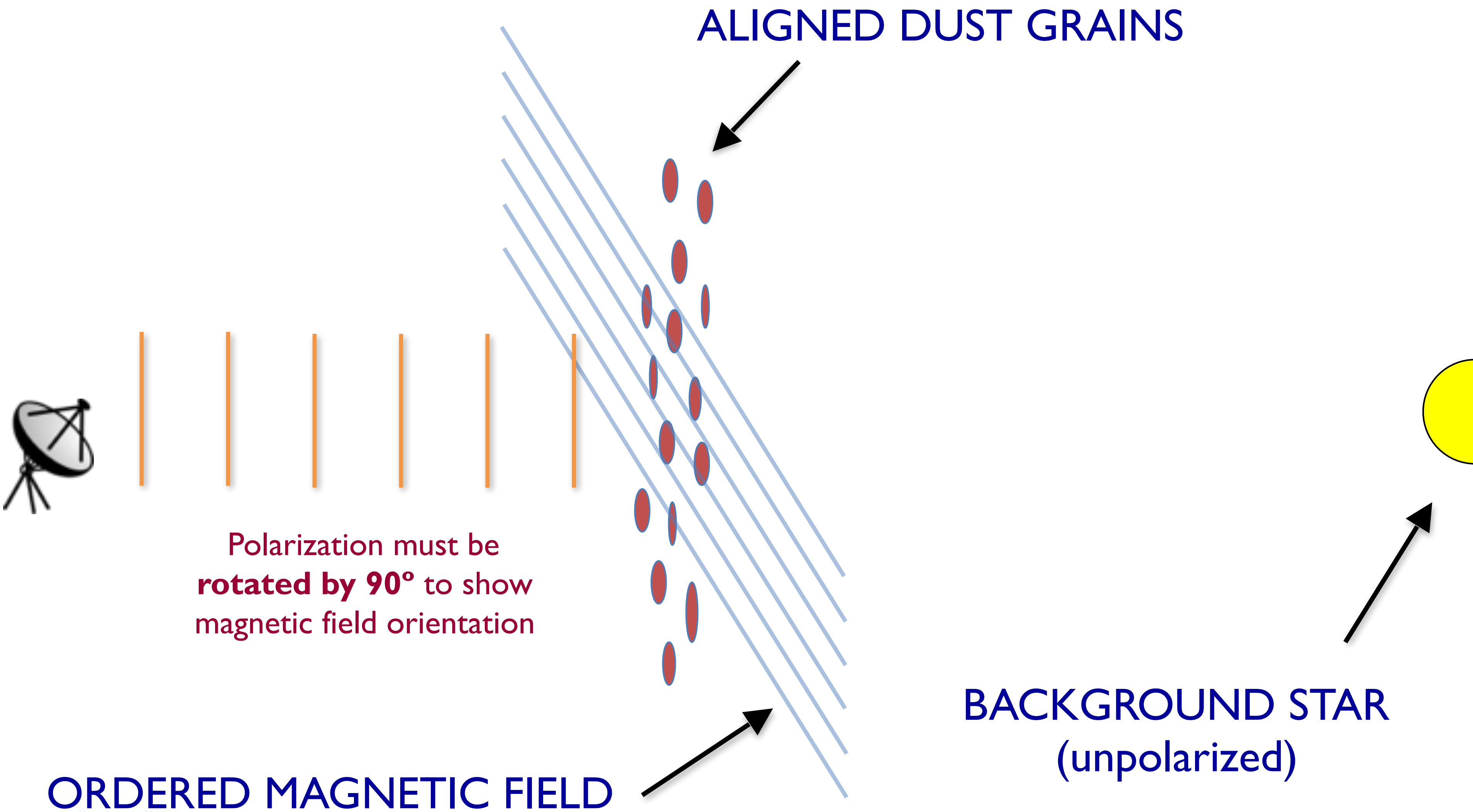


Pereyra & Magalhães 2004

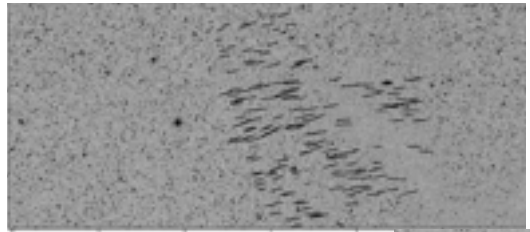
Polarization (dust absorption)

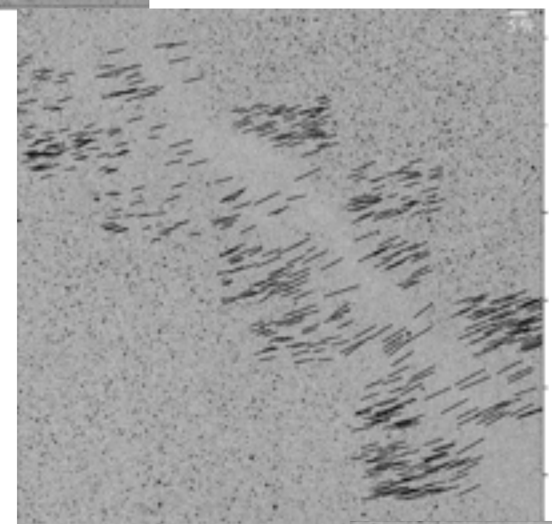


Polarization (dust emission)

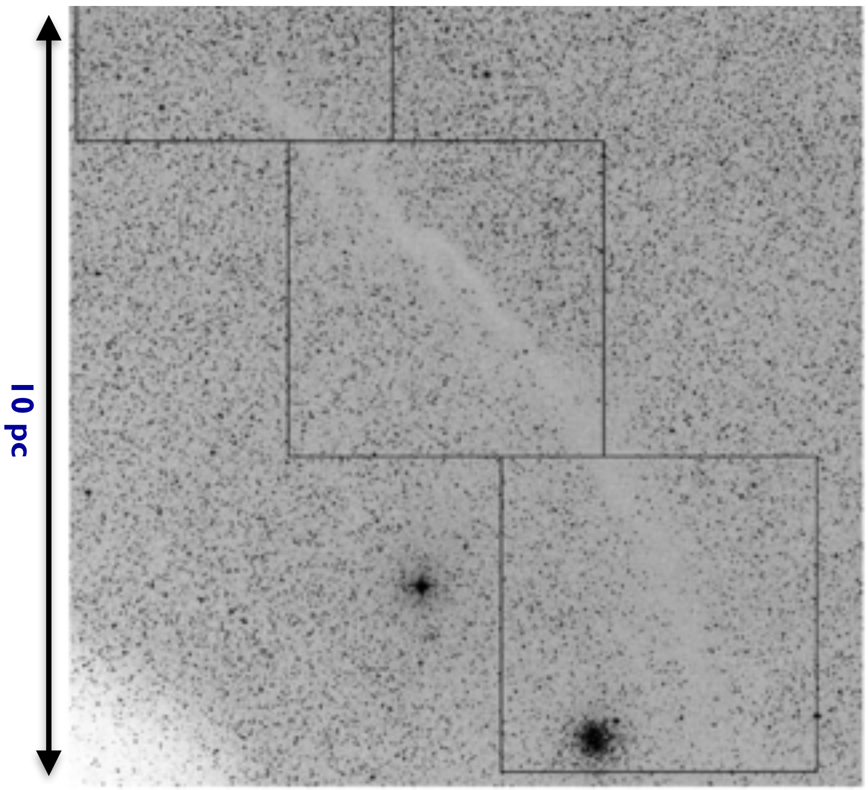


Magnetic fields on cloud scales

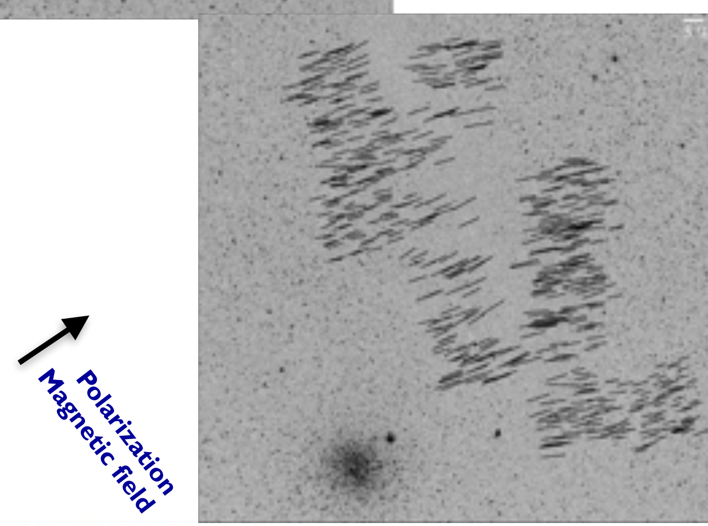




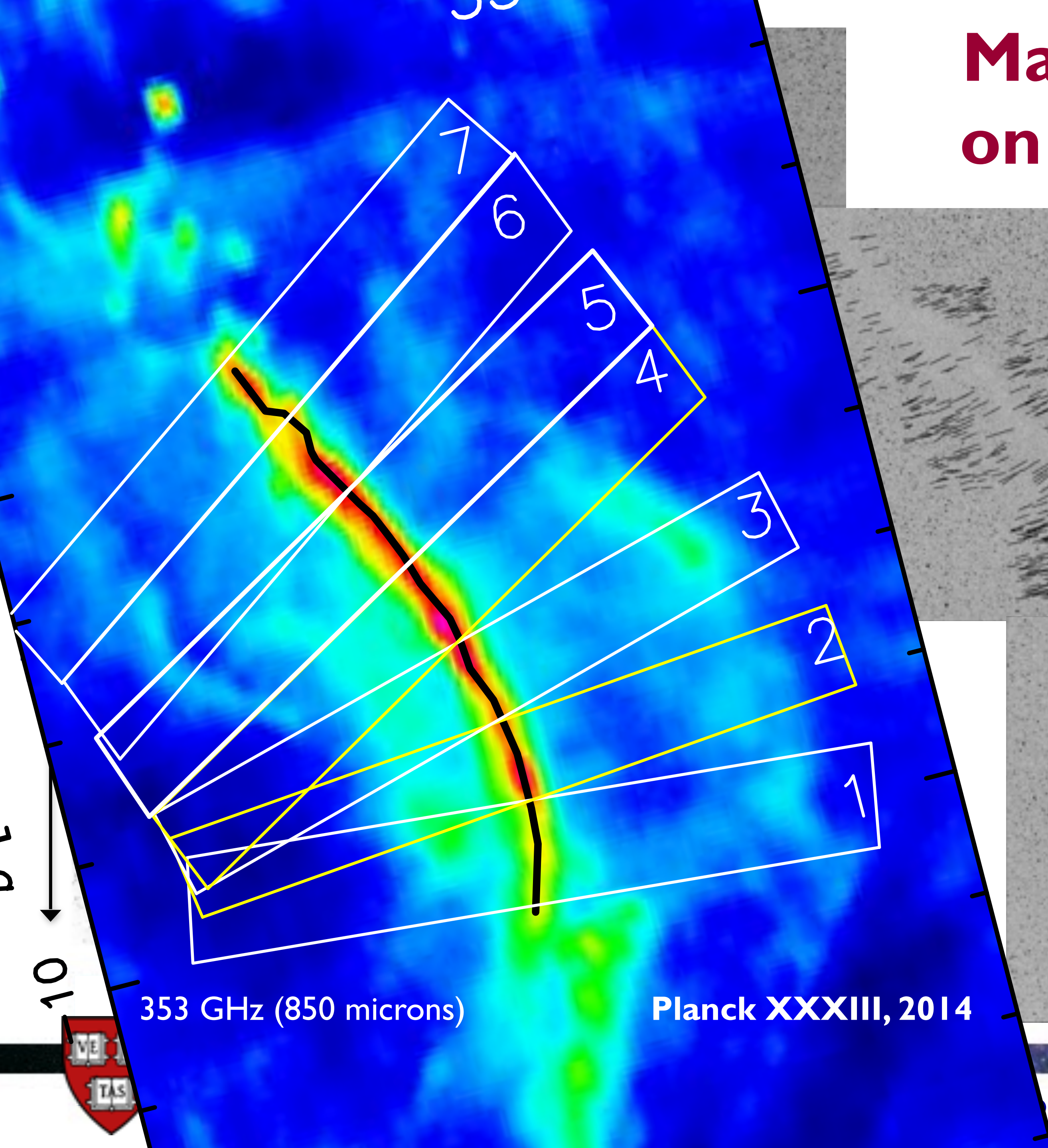
Musca dark cloud

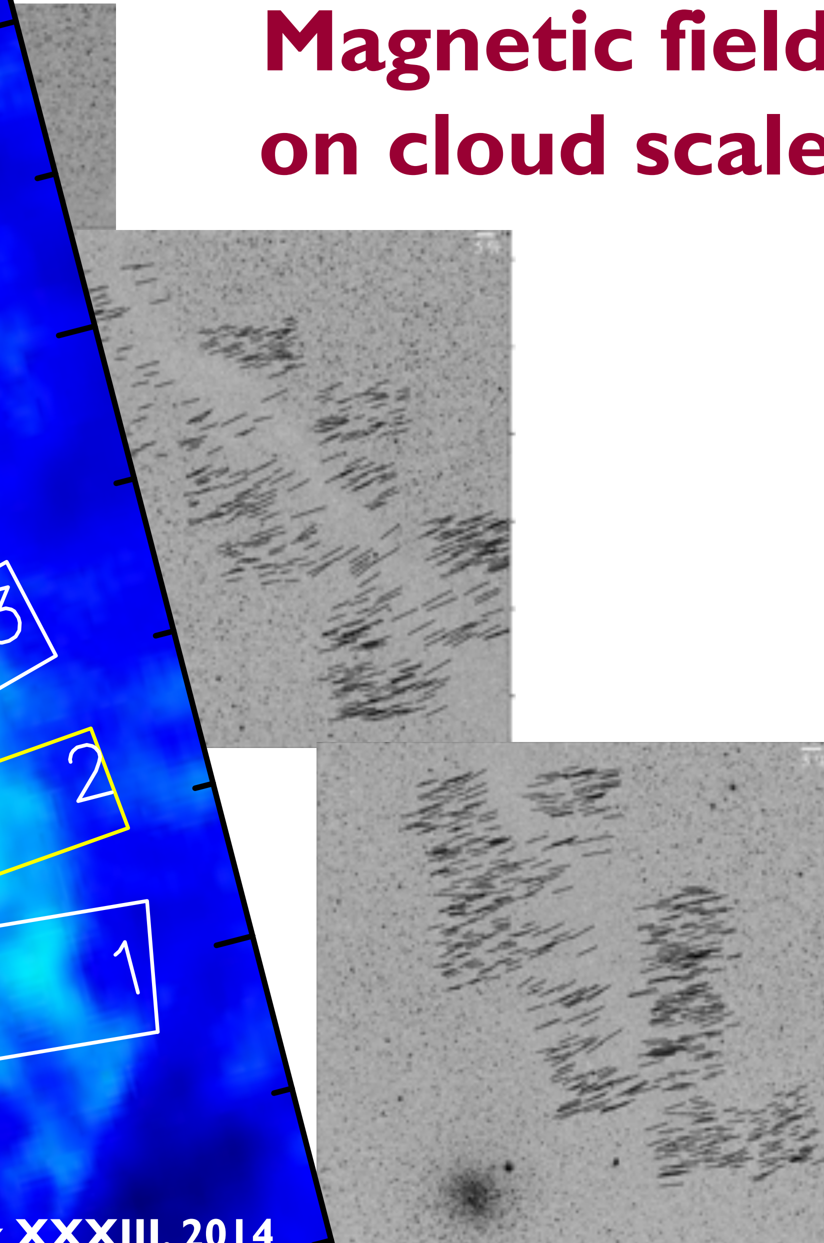


Pereyra & Magalhães 2004



Magnetic fields on cloud scales

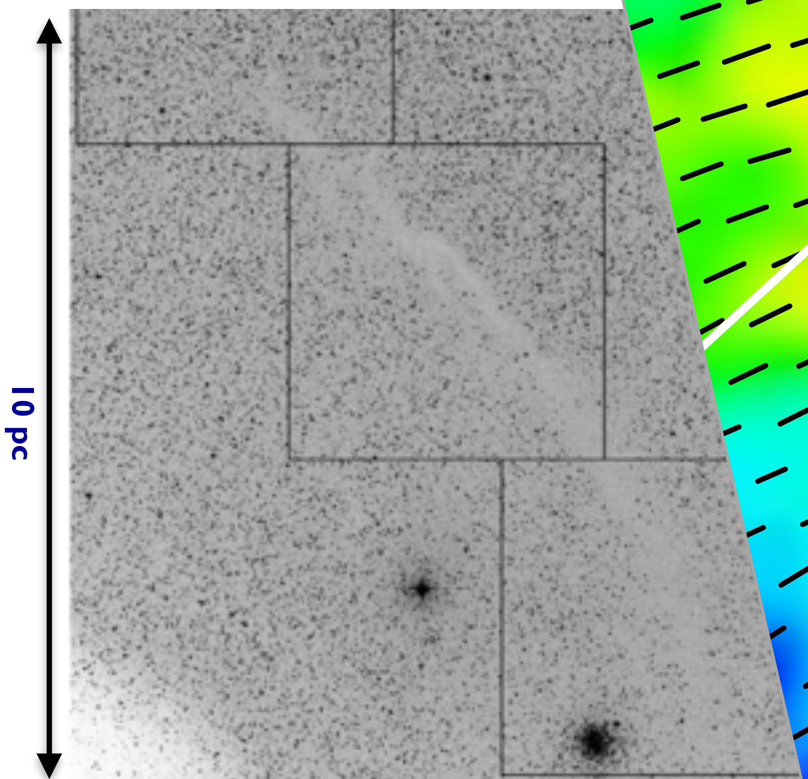




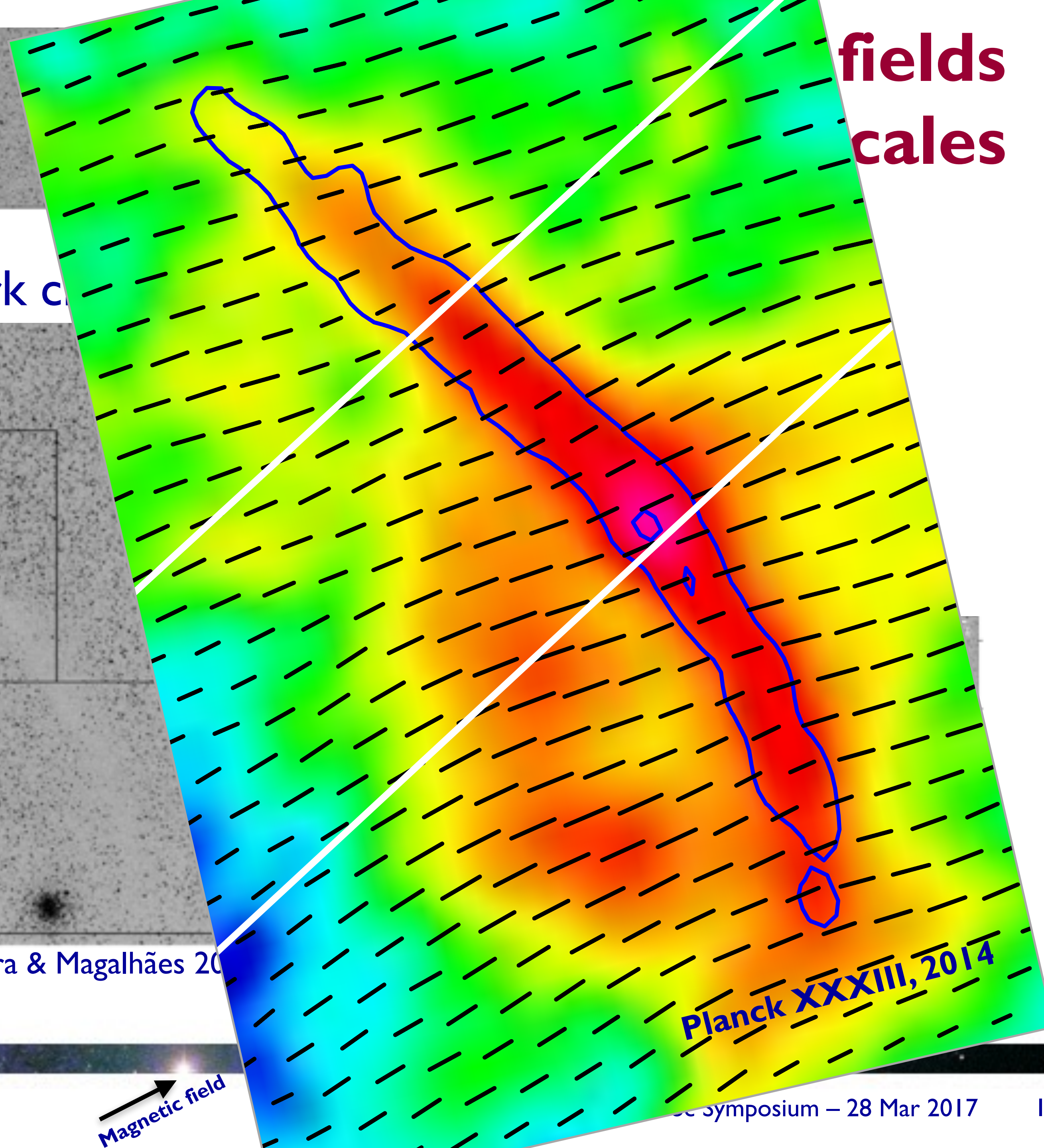
fields
cales

Magnetic field from dust emission (Planck) is consistent with dust absorption (optical)

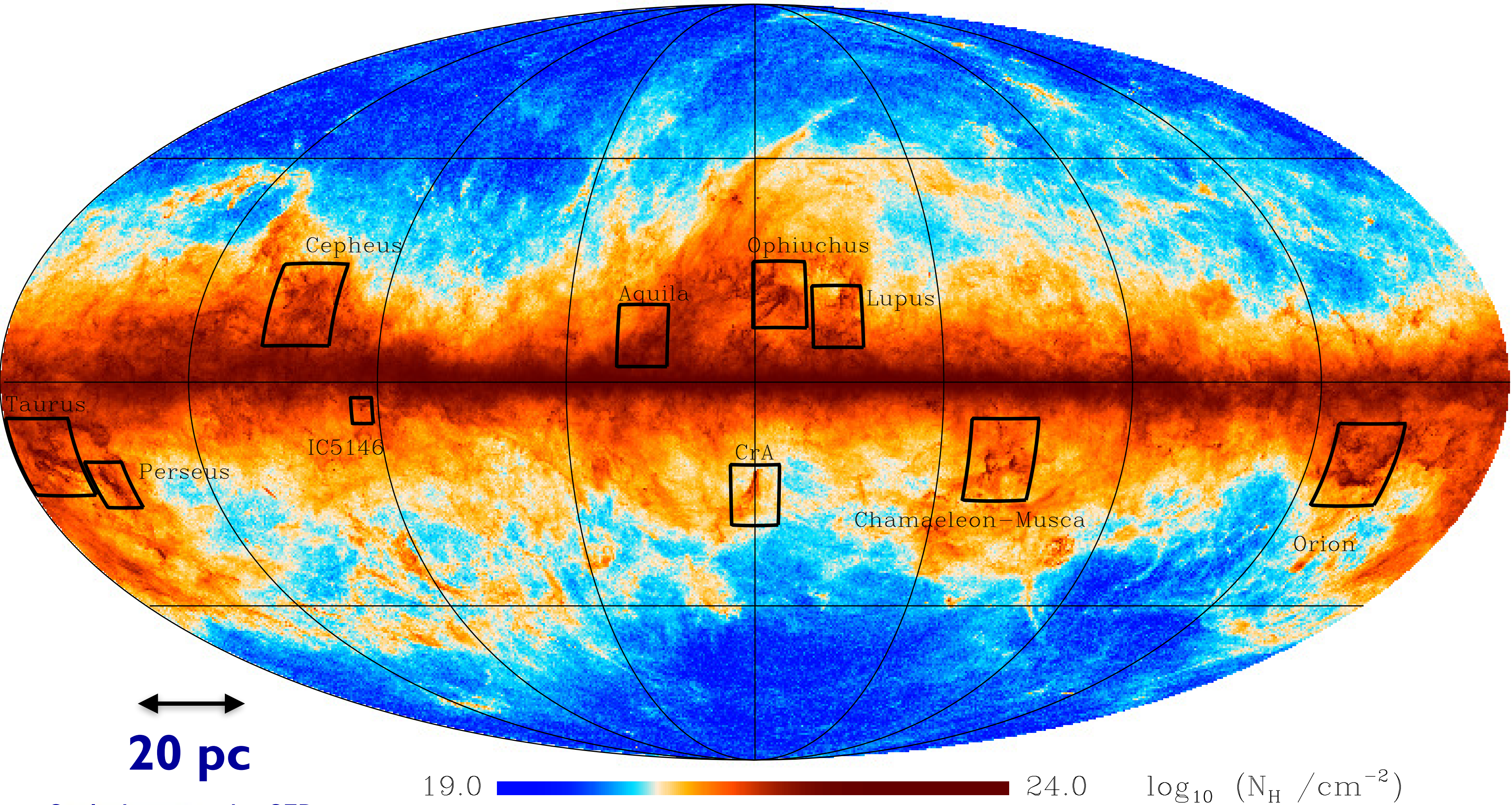
Musca dark c



Pereyra & Magalhães 20



Magnetic fields on large (Planck) scales

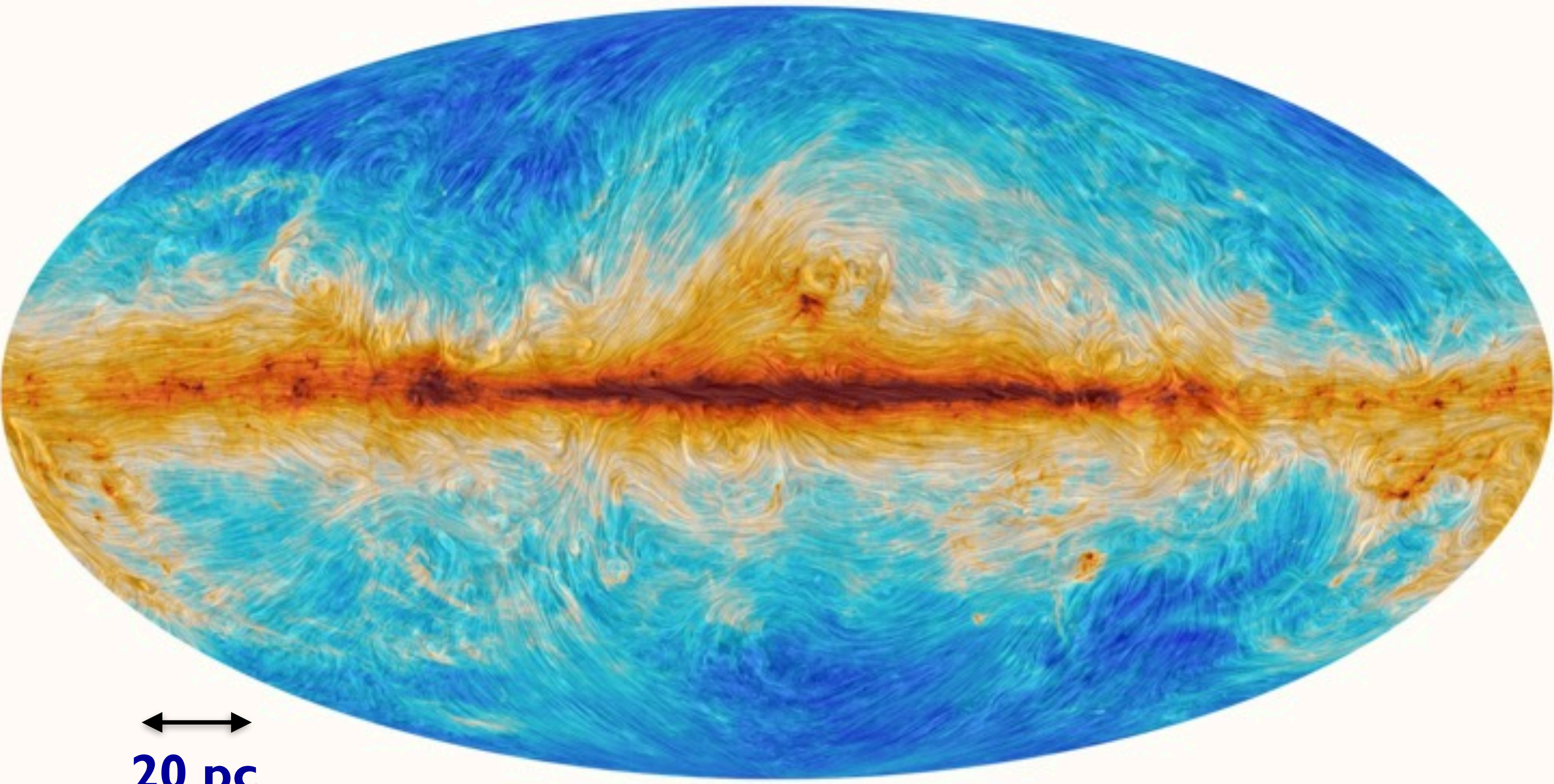


20 pc

Scaled to nearby SFRs

Planck Collaboration 2015, paper XXXV

Magnetic fields on large (Planck) scales



20 pc

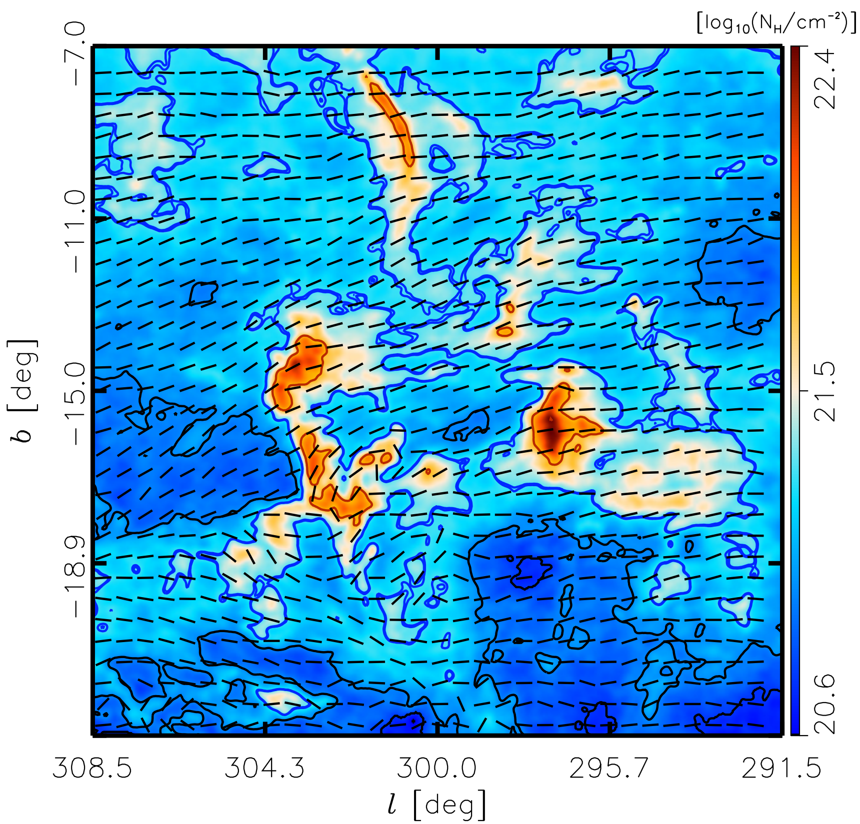
Scaled to nearby SFRs

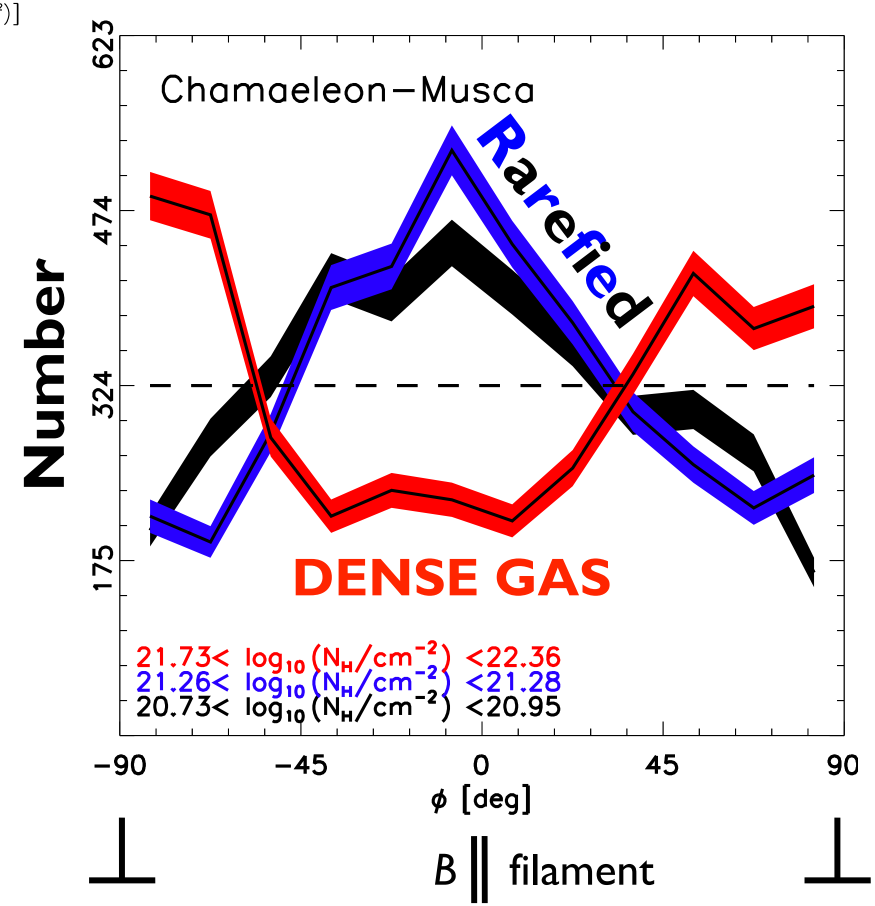
Planck Collaboration
planckandthemagneticfield.info

HRO analysis

HRO = "Histogram of Relative Orientation" (see Soler+2013)

The HRO characterizes the relationship between **magnetic fields** and **filamentary structures** in the dust and gas

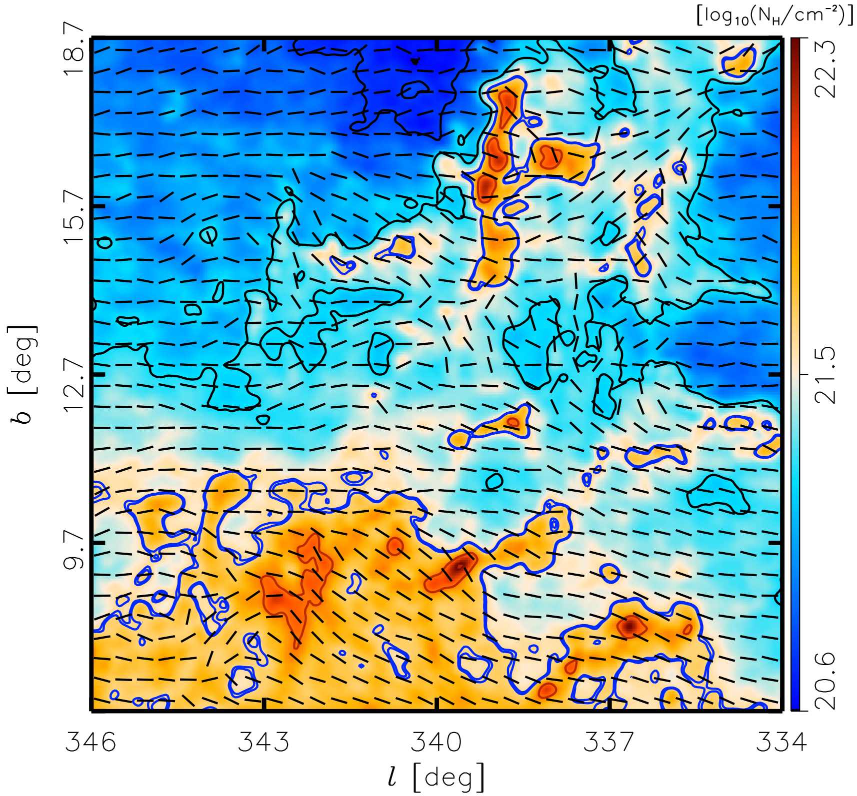




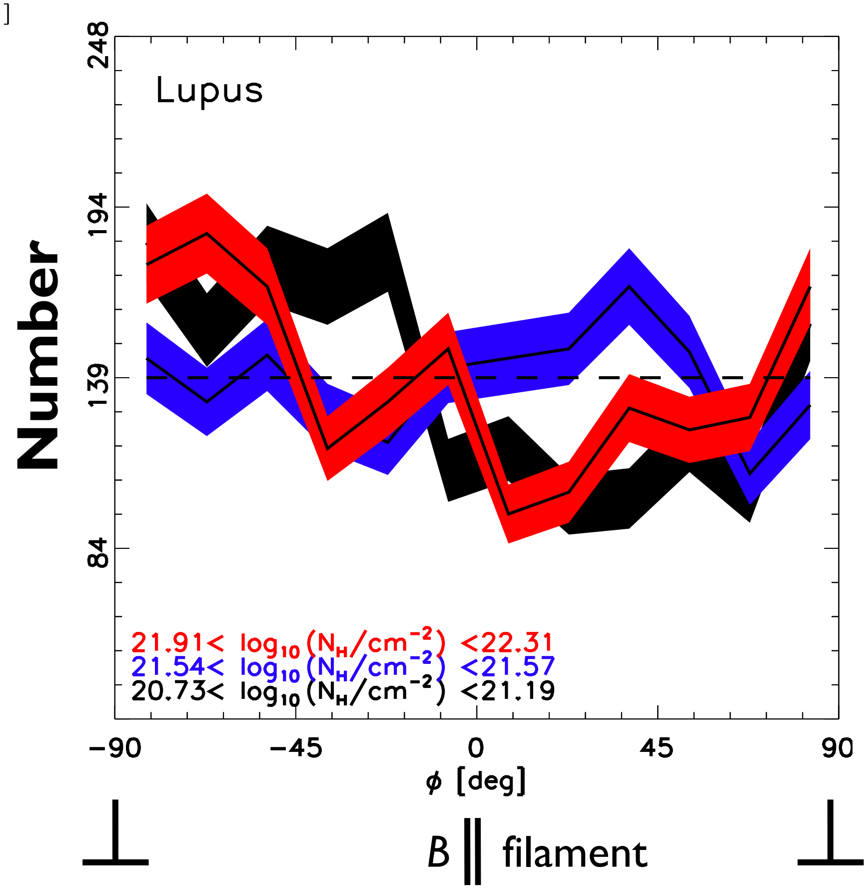
Planck XXXV (Soler+2015)

HRO analysis

A random HRO indicates that the magnetic field is not dictating the morphology of the star-forming material



Planck XXXV (Soler+2015)



Musings on large (Planck) scales

Planck conclusions:

- B-fields in **dense** gas tend to be ⊥ to filament axis
  – Formed by gravitational collapse along field lines?
- B-fields are important on large (~pc) scales
  – **But what about small (<1000 AU) scales?**

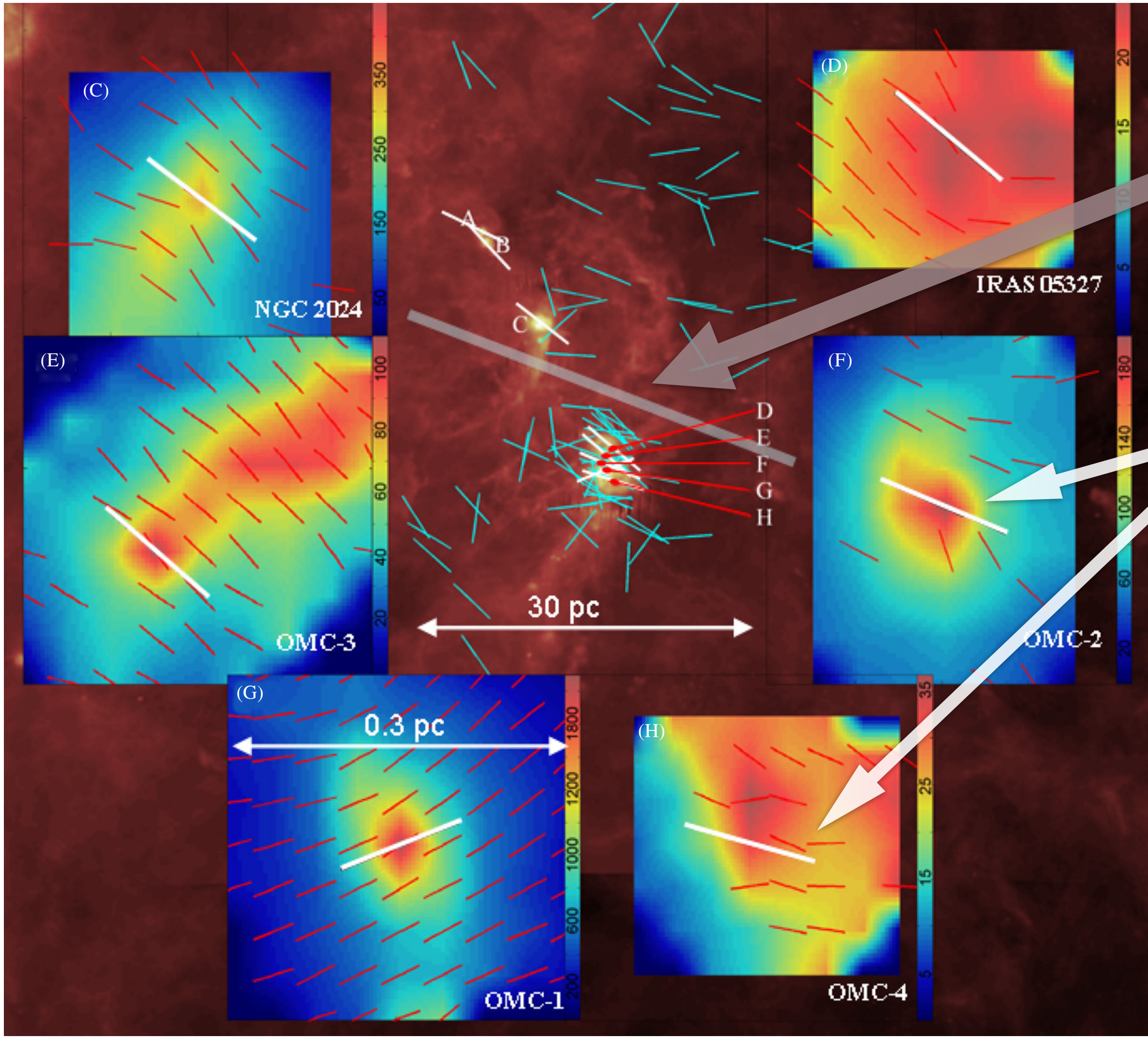
What is the role of the magnetic field in star formation?

Fundamental?

Incidental?

Intro:
Magnetized star formation on small (<1000 AU) scales

The "strong-field" scenario



The large-scale magnetic field in the ISM (~100 pc) seems to be preserved…

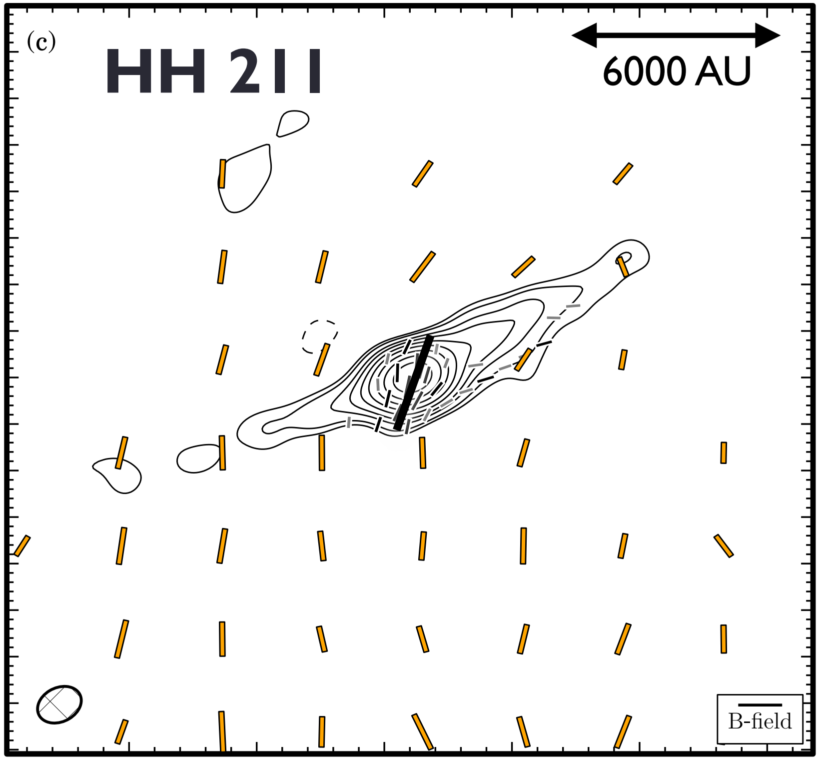
…in the small-scale cores (0.1 pc)

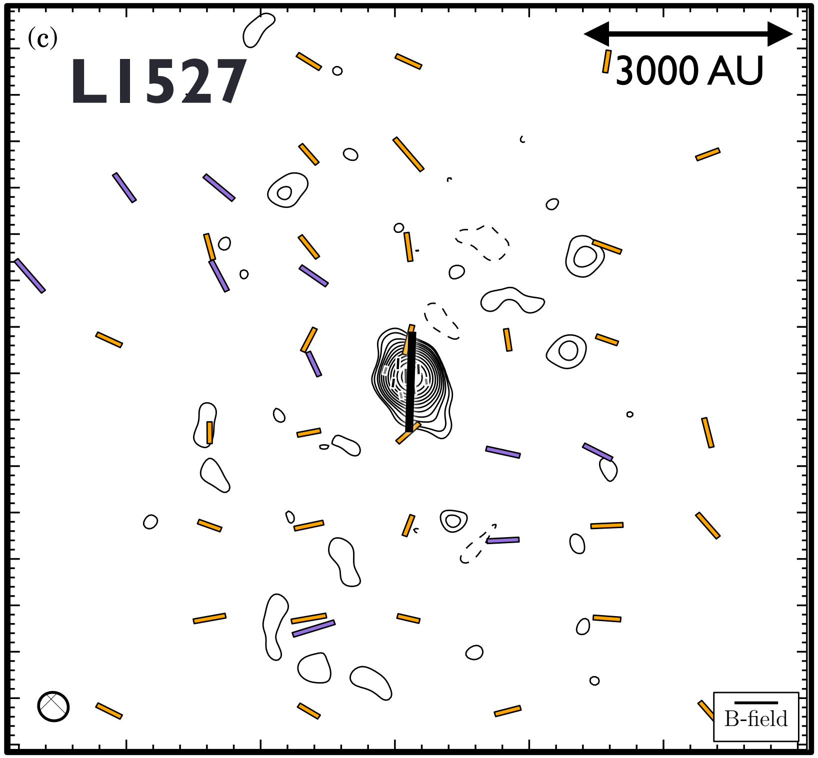
Hua-bai Li+2009

Consistent fields at even *smaller* scales …sometimes…

Magnetic field orientation is frequently consistent from 10,000 → 1000 AU scales…

…but sometimes it isn't

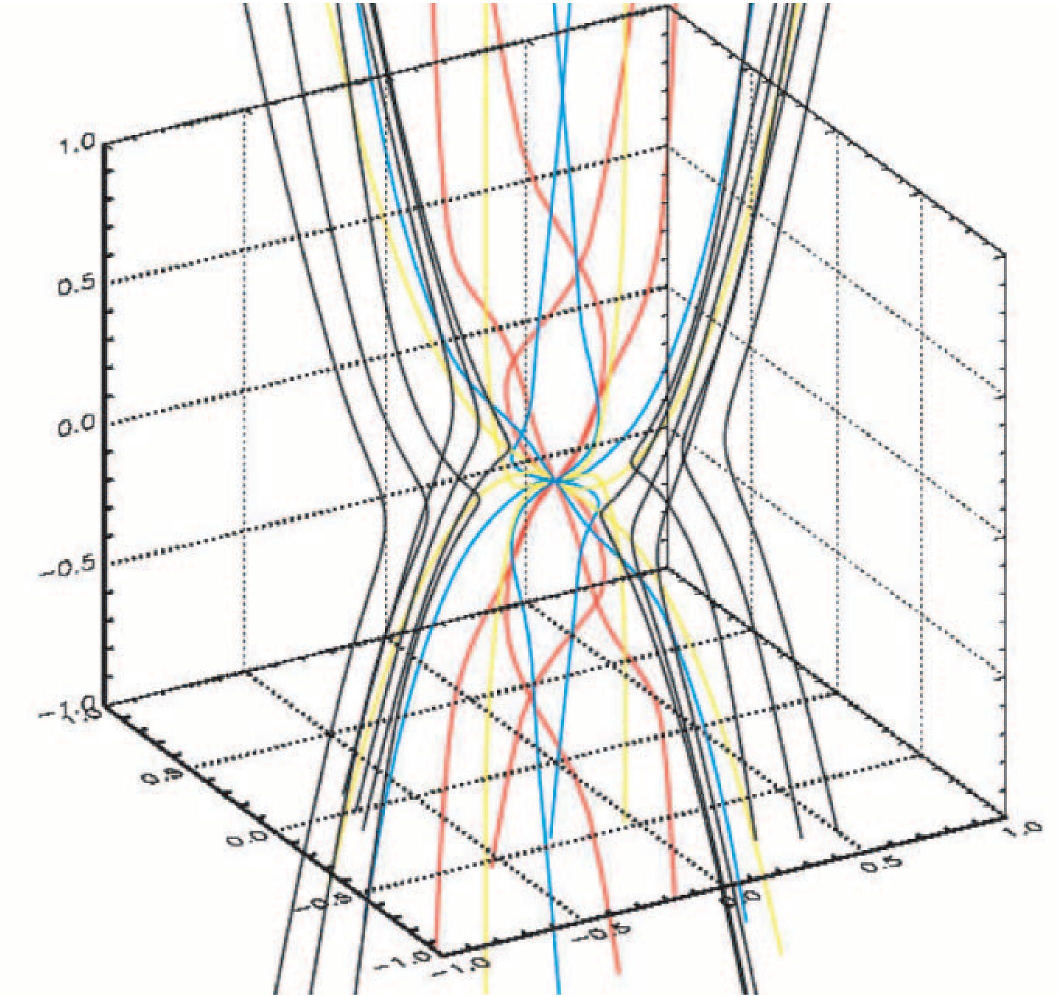




Hull+2014, TADPOL survey

See also Davidson+2014, incl. **C. Hull**

The canonical picture: hourglass fields

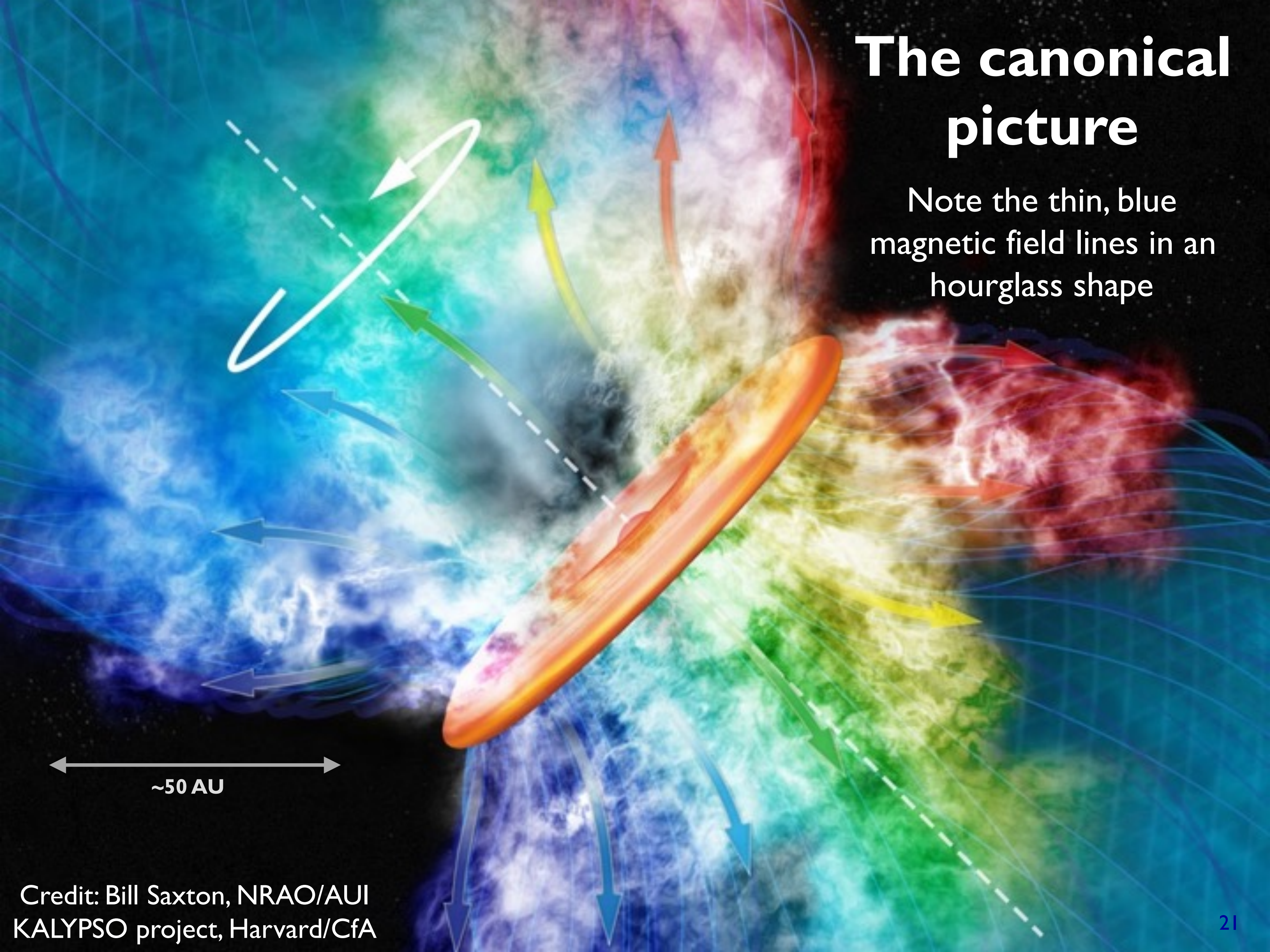


The typical initial condition for the magnetic field in models of star-forming cores is an **hourglass** with its symmetry axis aligned with the core's rotation axis (see also Fiedler & Mouschovias 1993)

Allen, Li, & Shu 2003

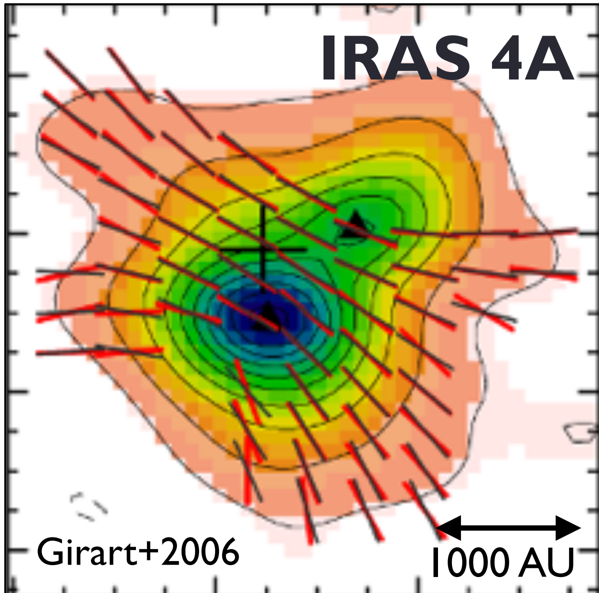
The canonical picture

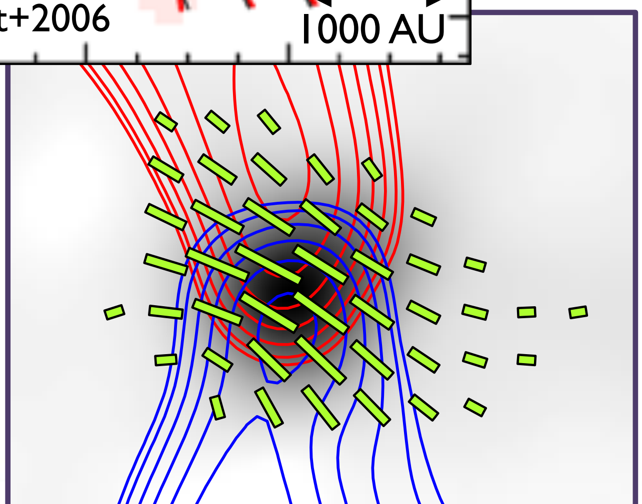
Note the thin, blue magnetic field lines in an hourglass shape

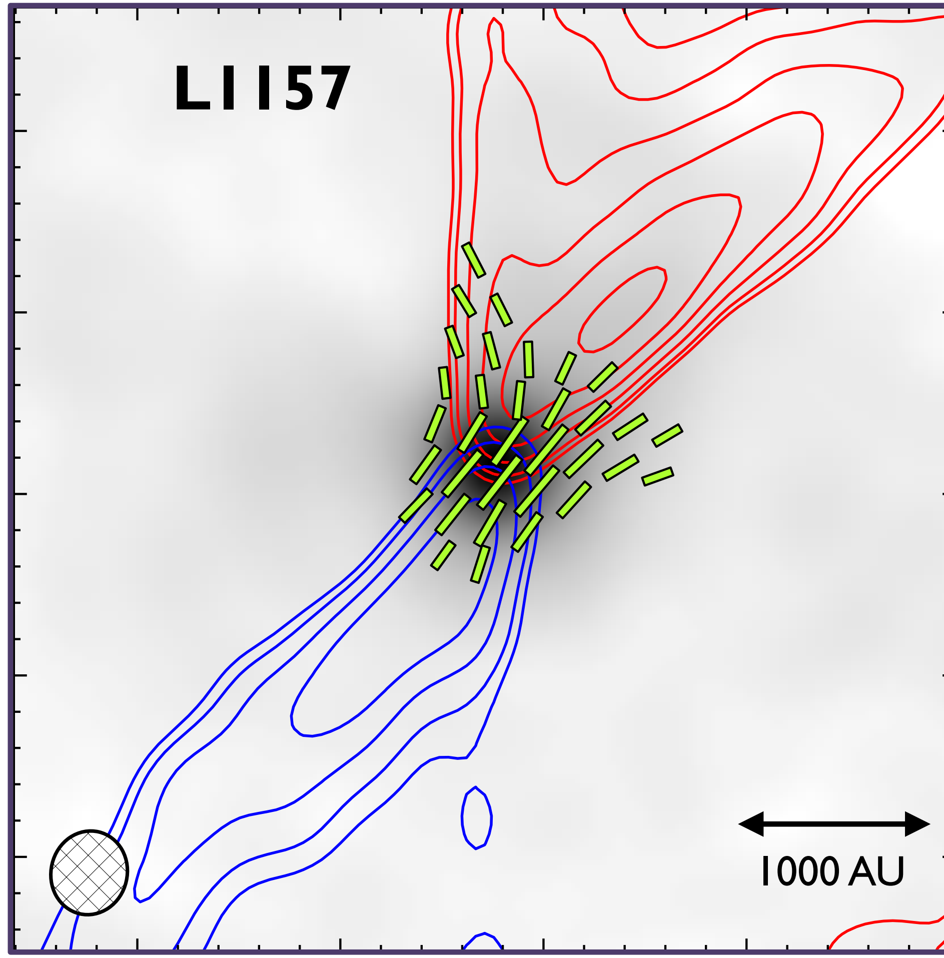


Credit: Bill Saxton, NRAO/AUI
KALYPSO project, Harvard/CfA

Sightings of the fabled hourglass B-field







Hull+2014, TADPOL survey

See also Stephens+2013, incl. **C. Hull**

CARMA

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

Consortium: Berkeley, Caltech, Illinois, Maryland, Chicago

Photo credit: C. Hull

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

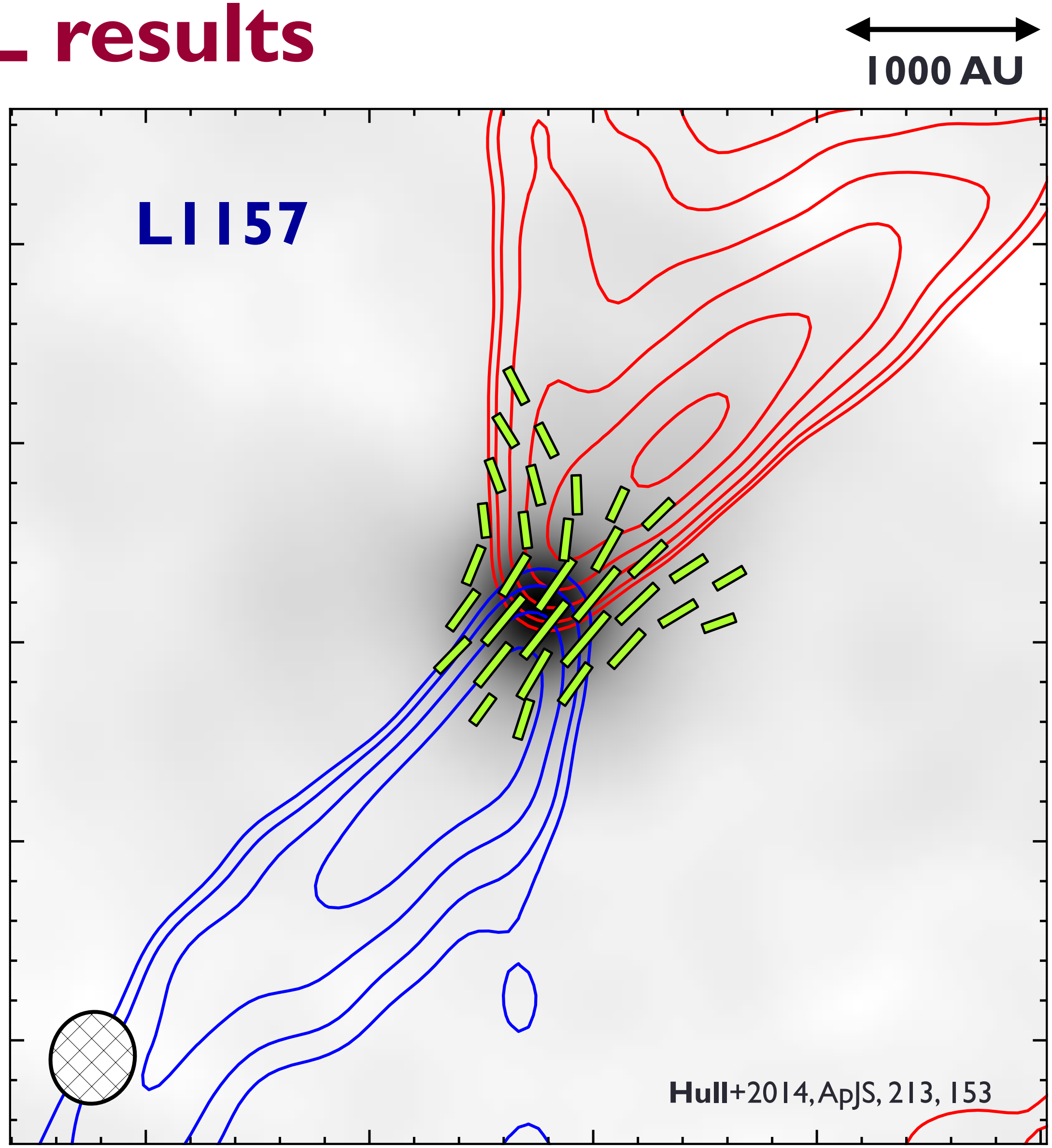
– Observations at 1 cm, 3 mm, and **1 mm (polarization!)**

– Was located in Cedar Flat, CA (near Bishop)

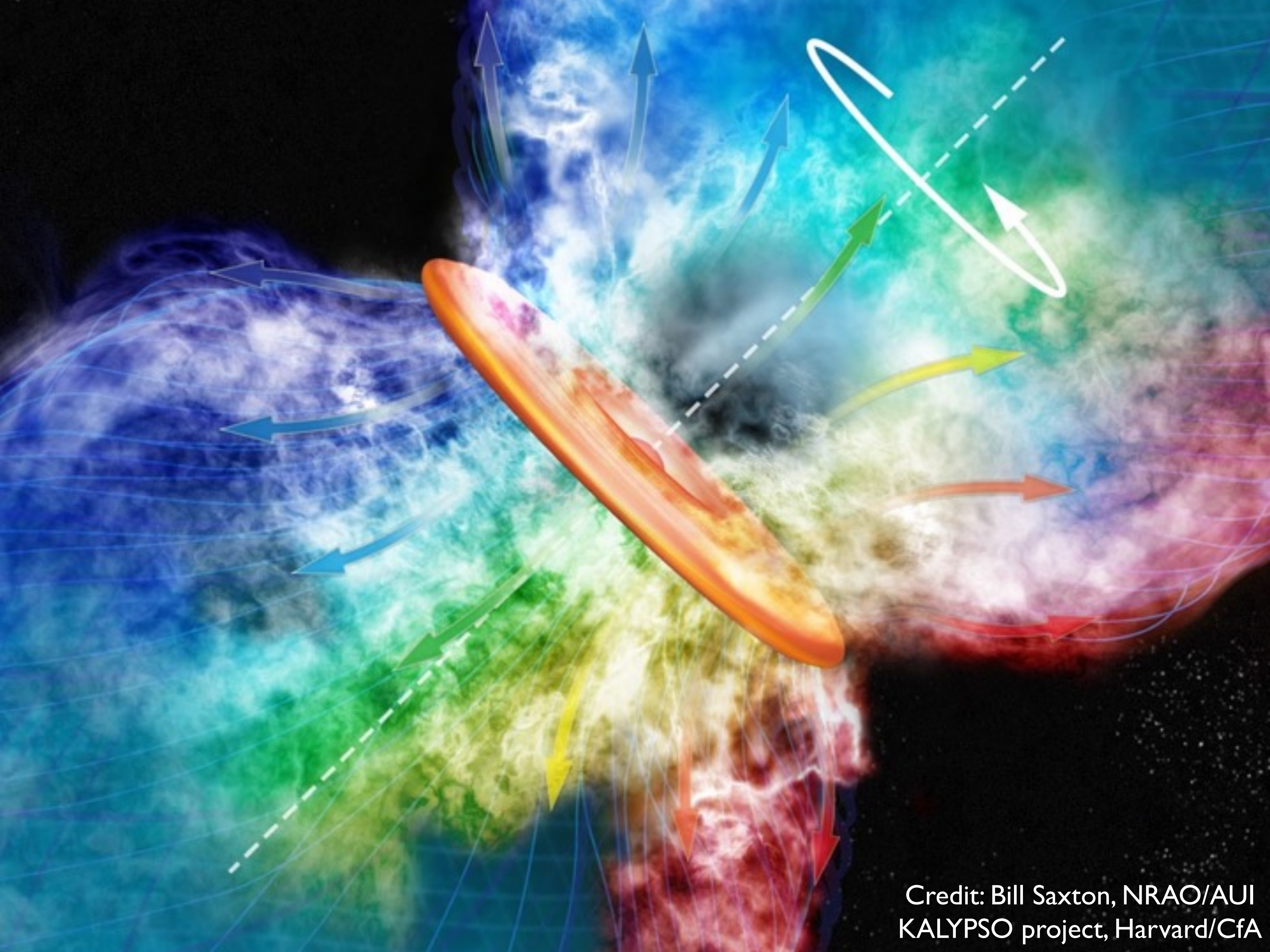
← This is me installing a 1 mm polarization receiver between 2010 and 2012

TADPOL survey

TADPOL results



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


Credit: Bill Saxton, NRAO/AUI
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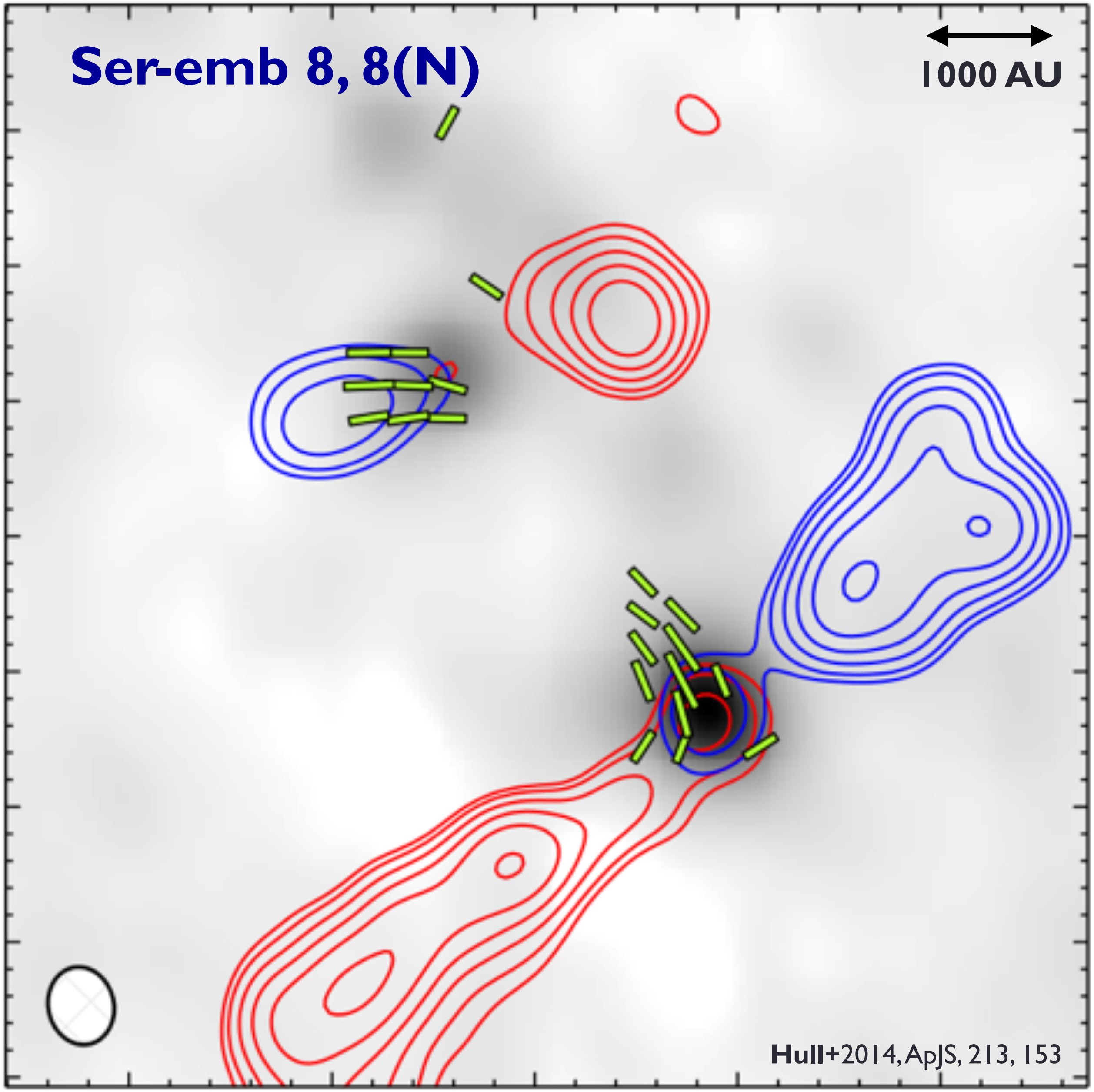
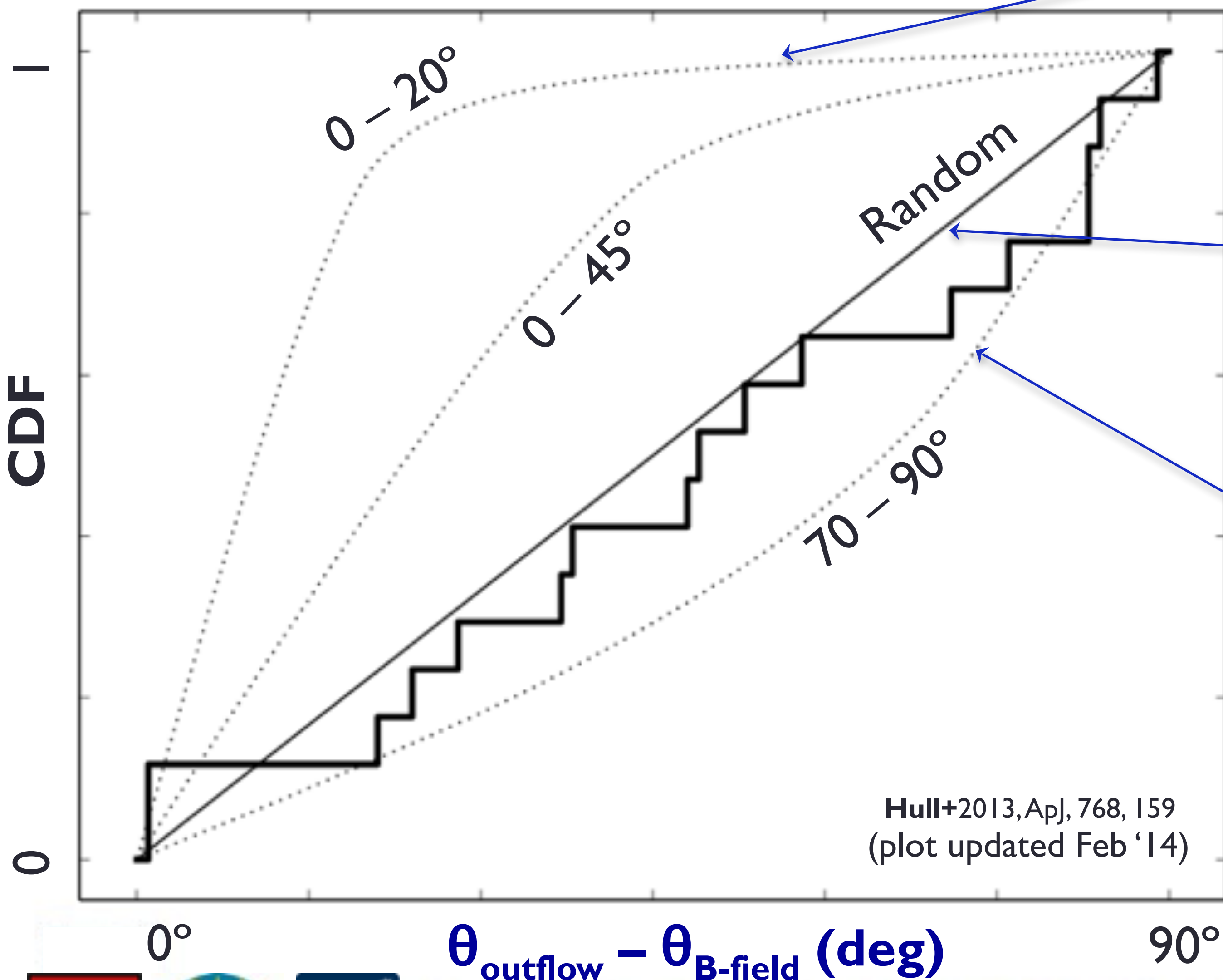
TADPOL results



Outflow vs. B-field: distribution



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

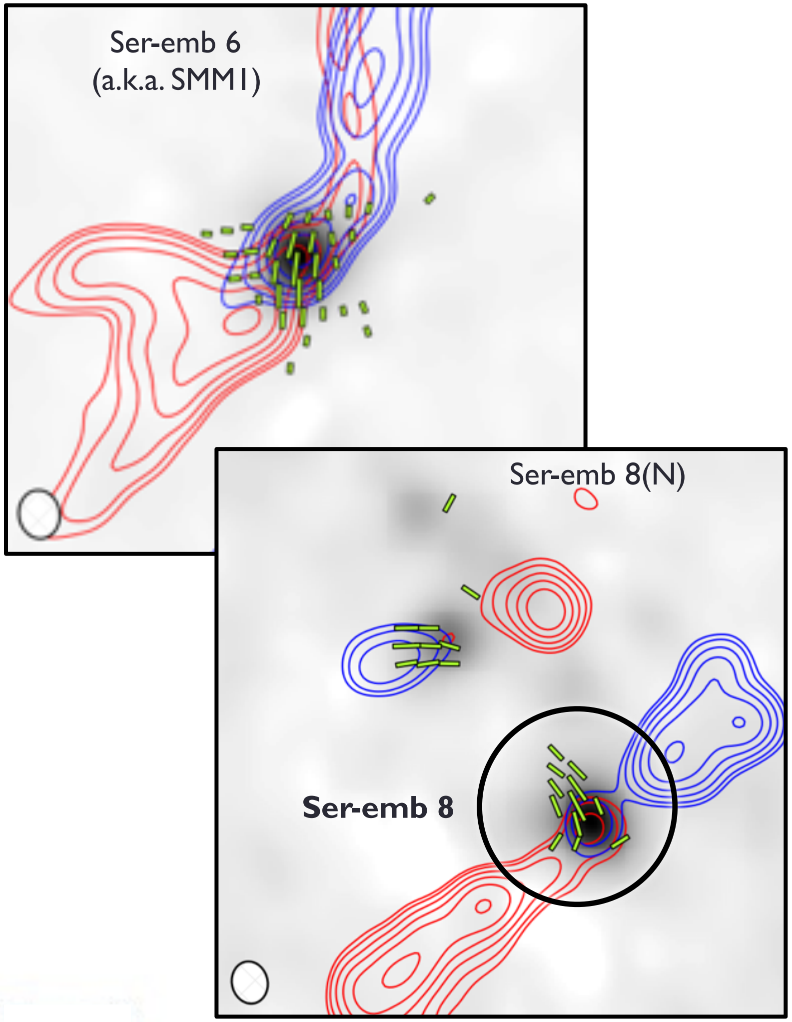
Simulation: outflows & B-fields are randomly oriented

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

ALMA observations


ALMA
Photo credit: C. Hull

Cycle 2, 3, & 4 ALMA obs.



Hull+2014, TADPOL survey

Class 0

CORE POLARIZATION

(PI: Hull)

0.36″ dust pol @ 850 um

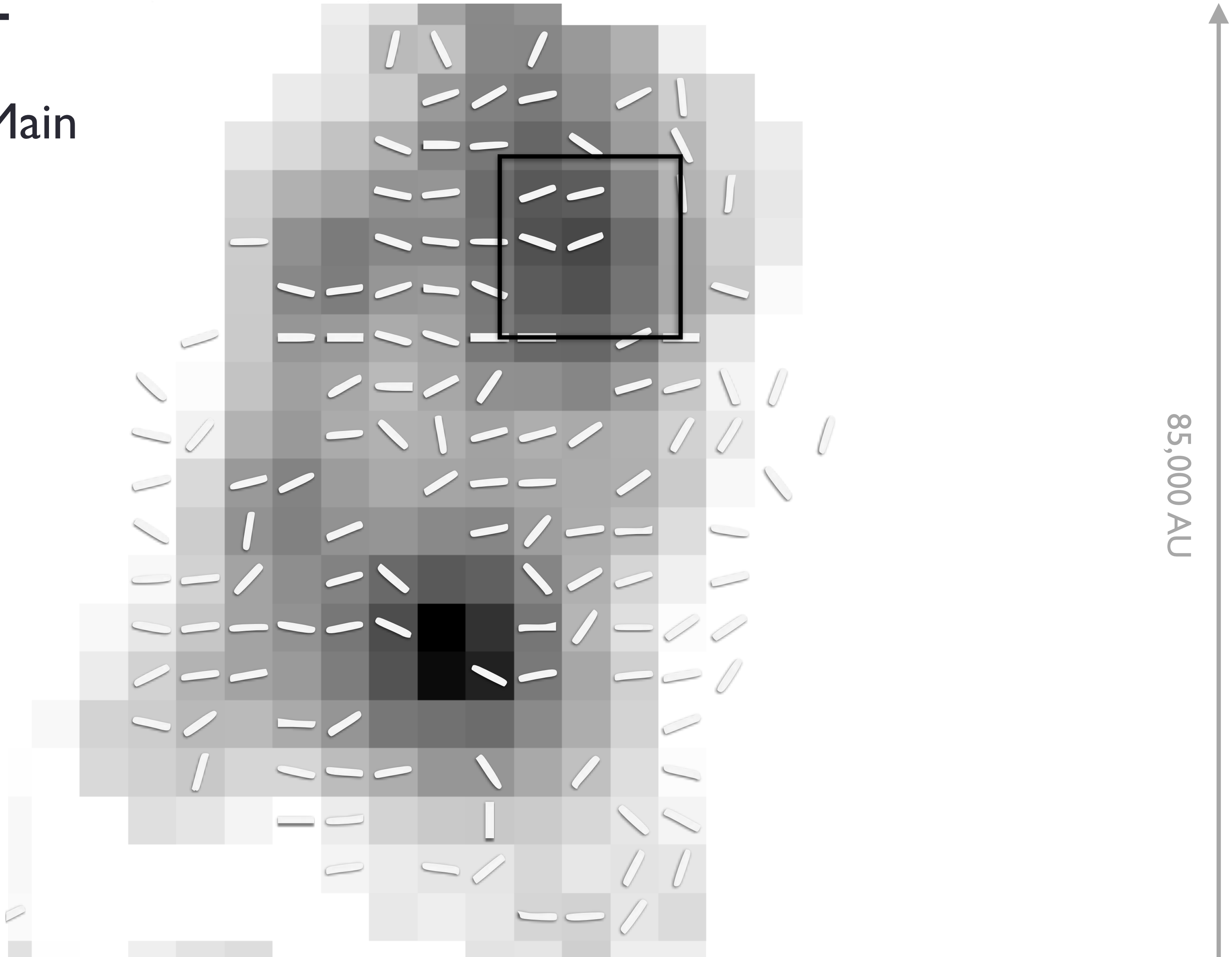
0.36″ and 1″ lines & continuum @ 1 mm

Cycles 3 & 4: 0.06″ dust pol @ 850 um

Probing **~1000 →25 AU** disk scales

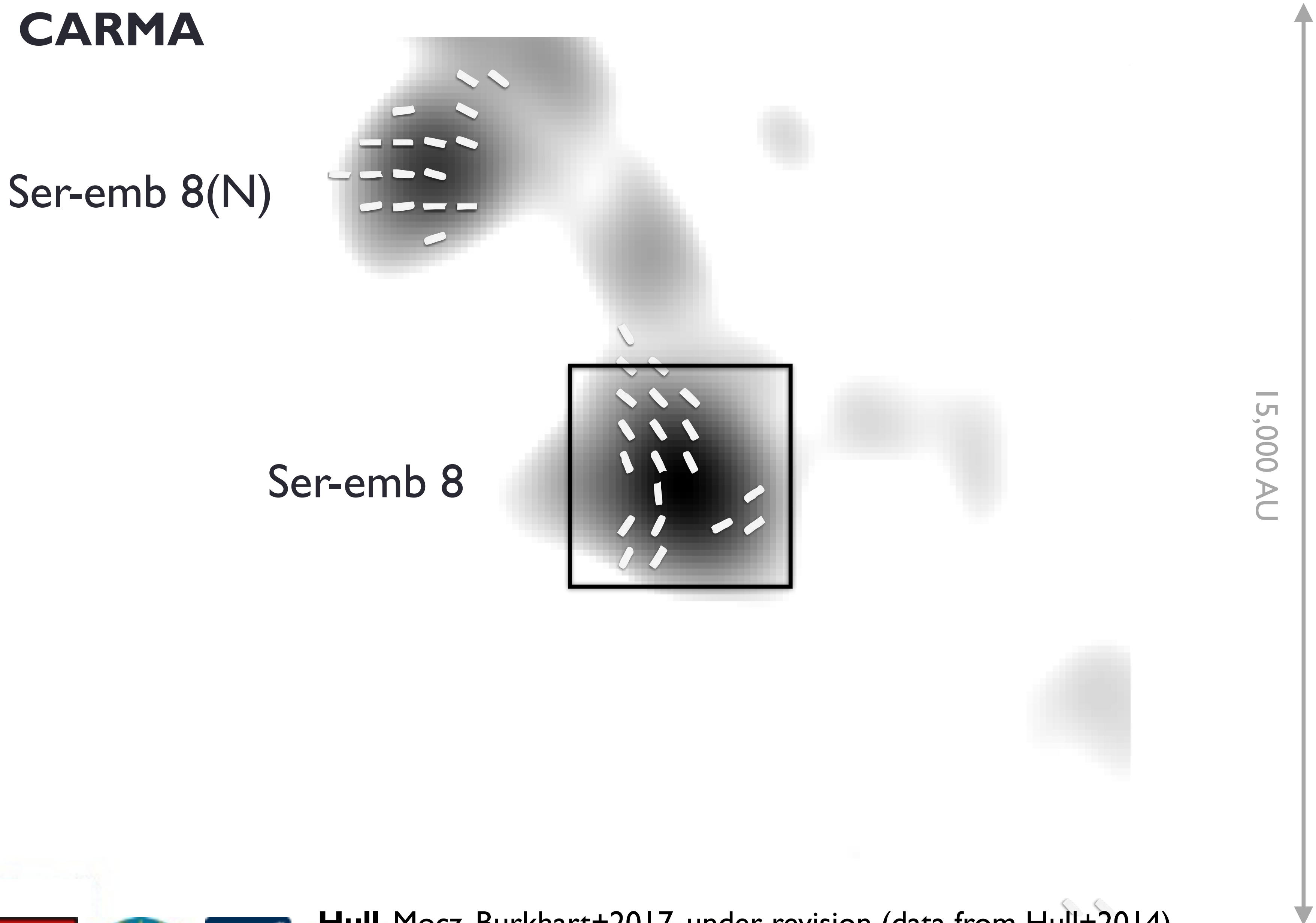
JCMT

Serpens Main



Hull, Mocz, Burkhart+2017, under revision (data from Matthews+2009)

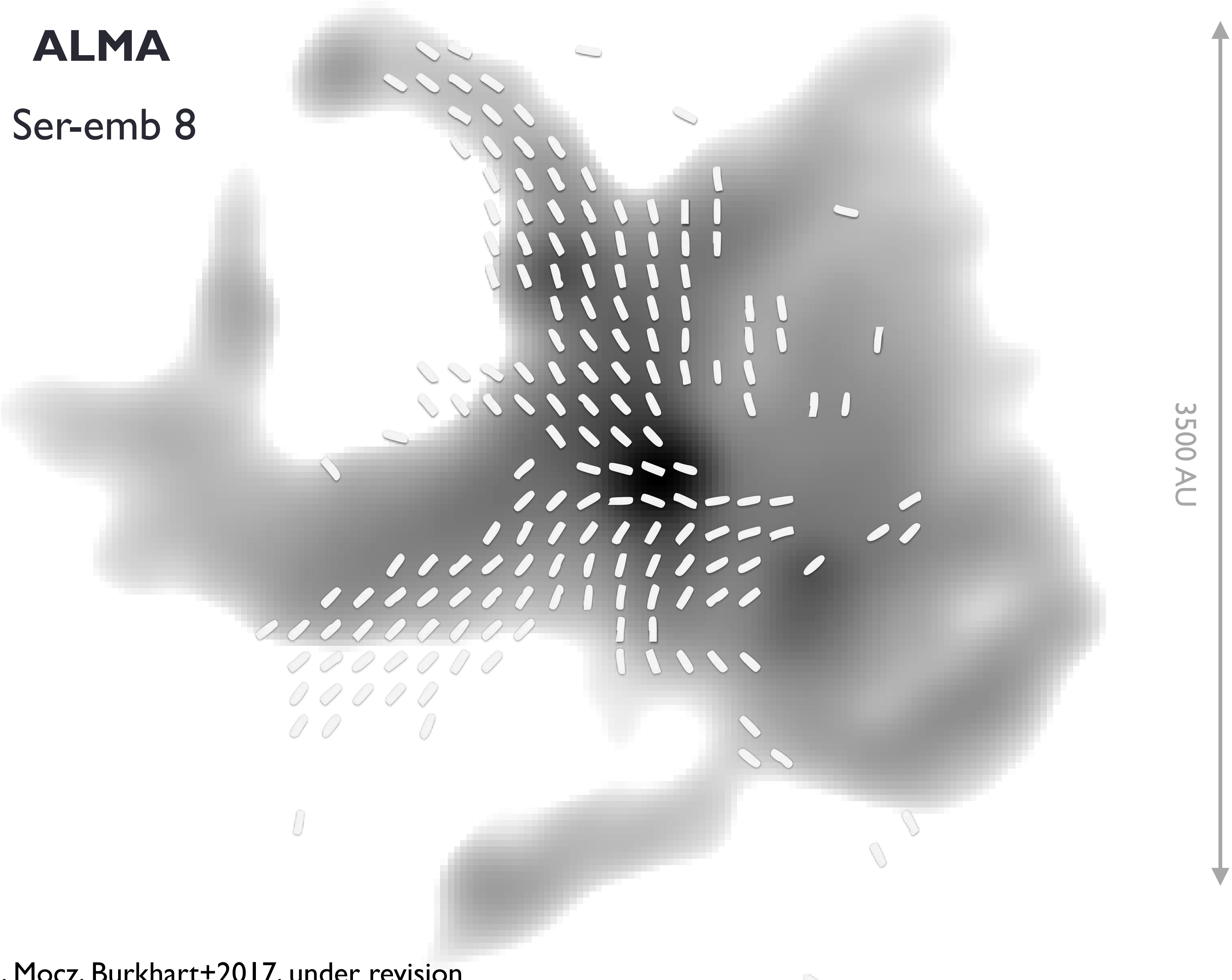
CARMA



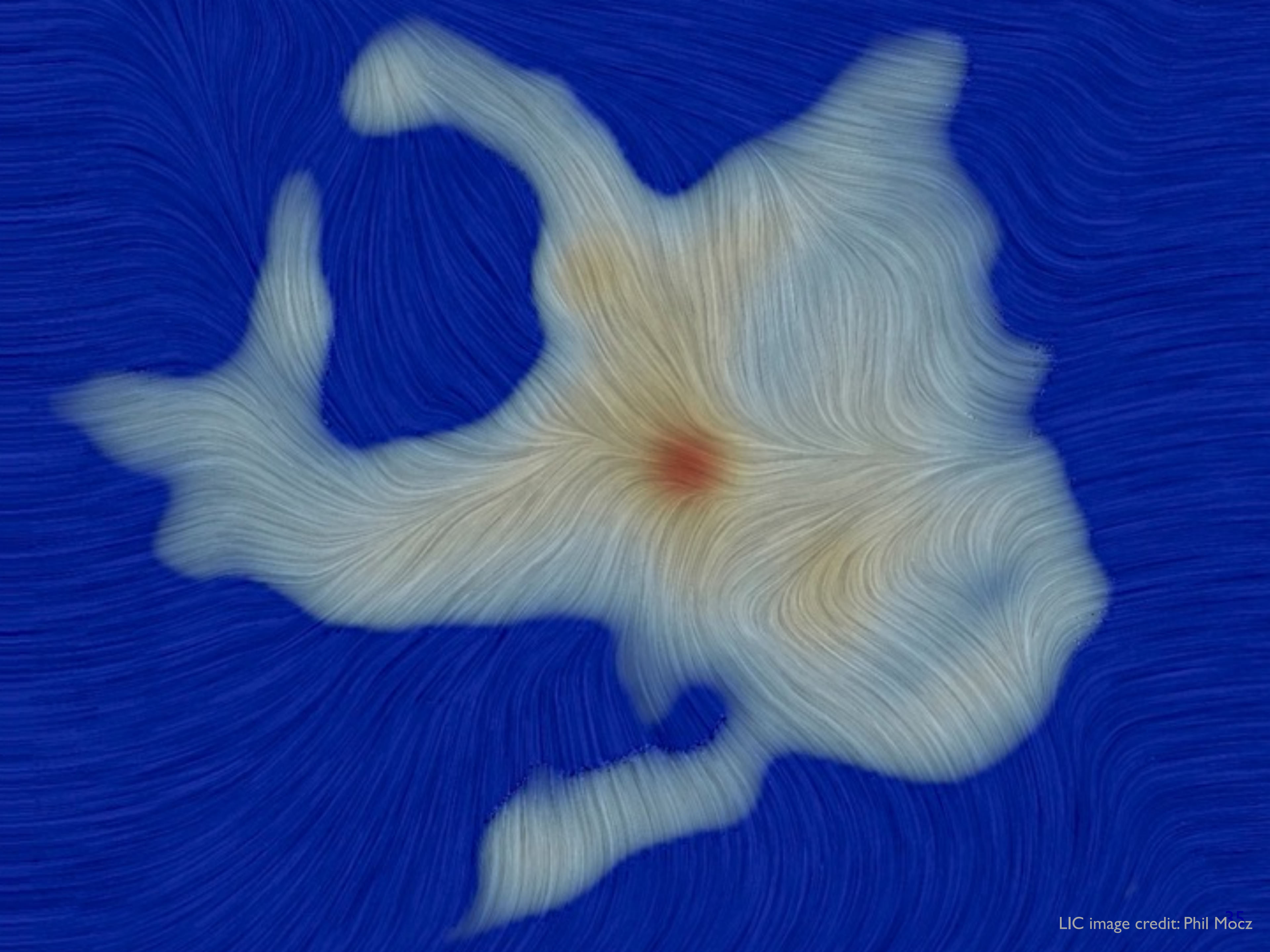
Hull, Mocz, Burkhart+2017, under revision (data from Hull+2014)

ALMA

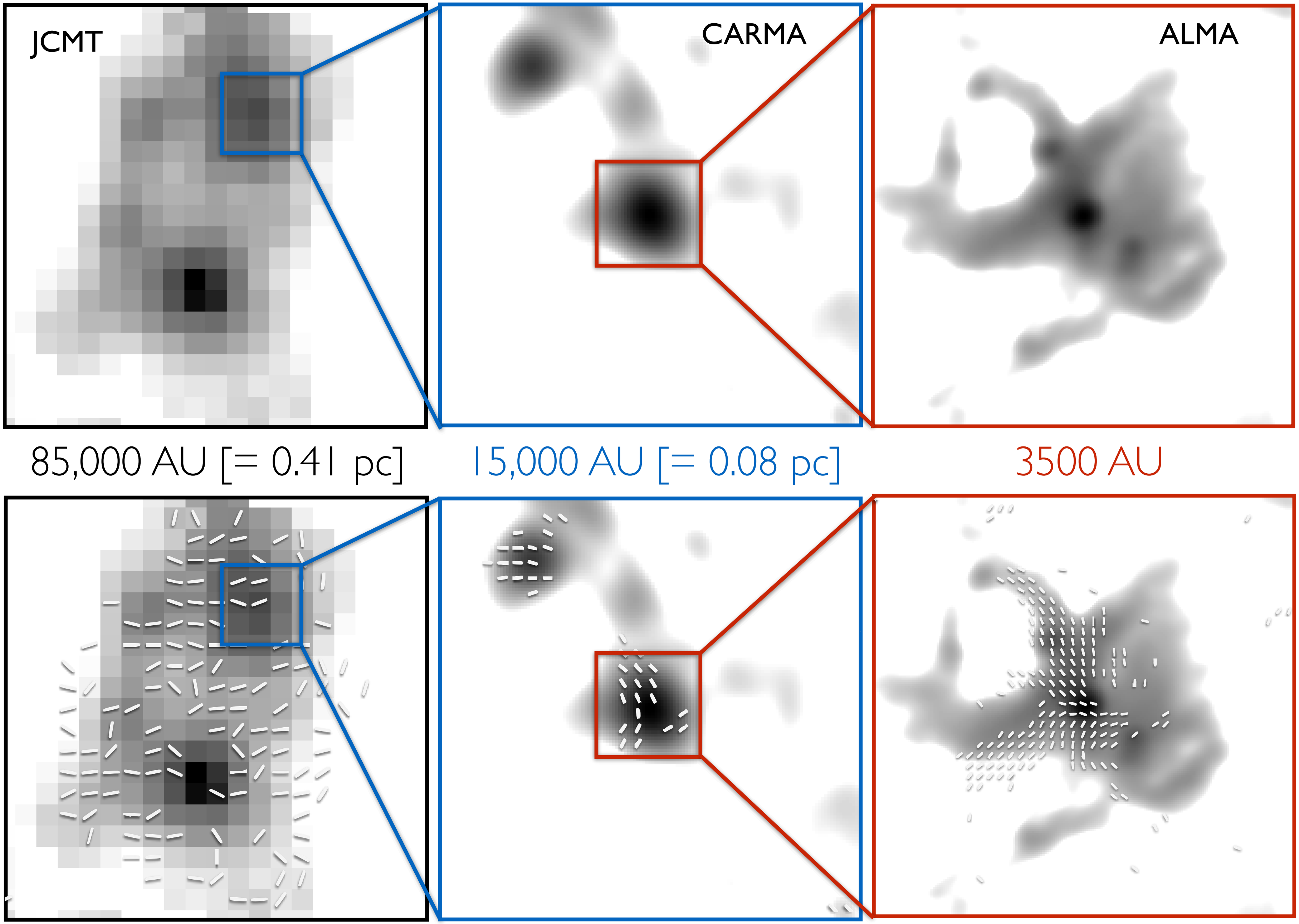
Ser-emb 8



Hull, Mocz, Burkhart+2017, under revision



LIC image credit: Phil Mocz



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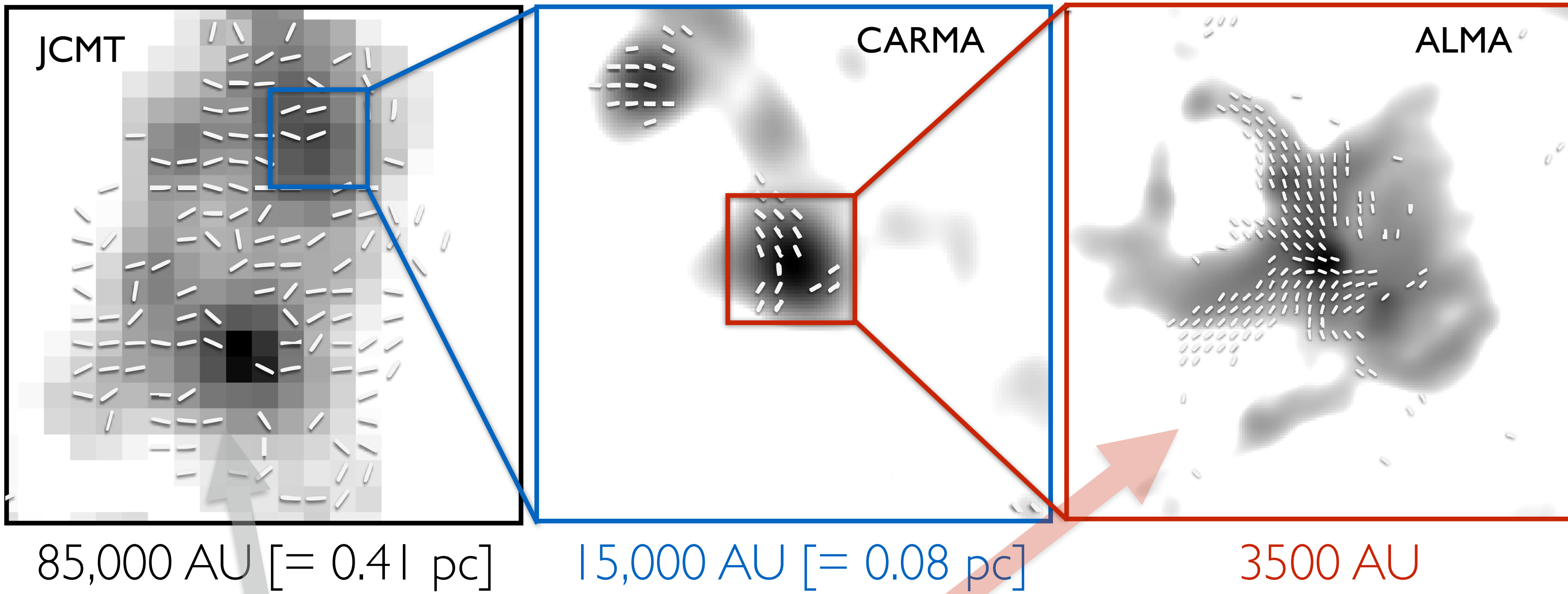


The ALMA-scale magnetic field, which is "attached" to the forming stellar system, is *not* reminiscent of the large-scale field.

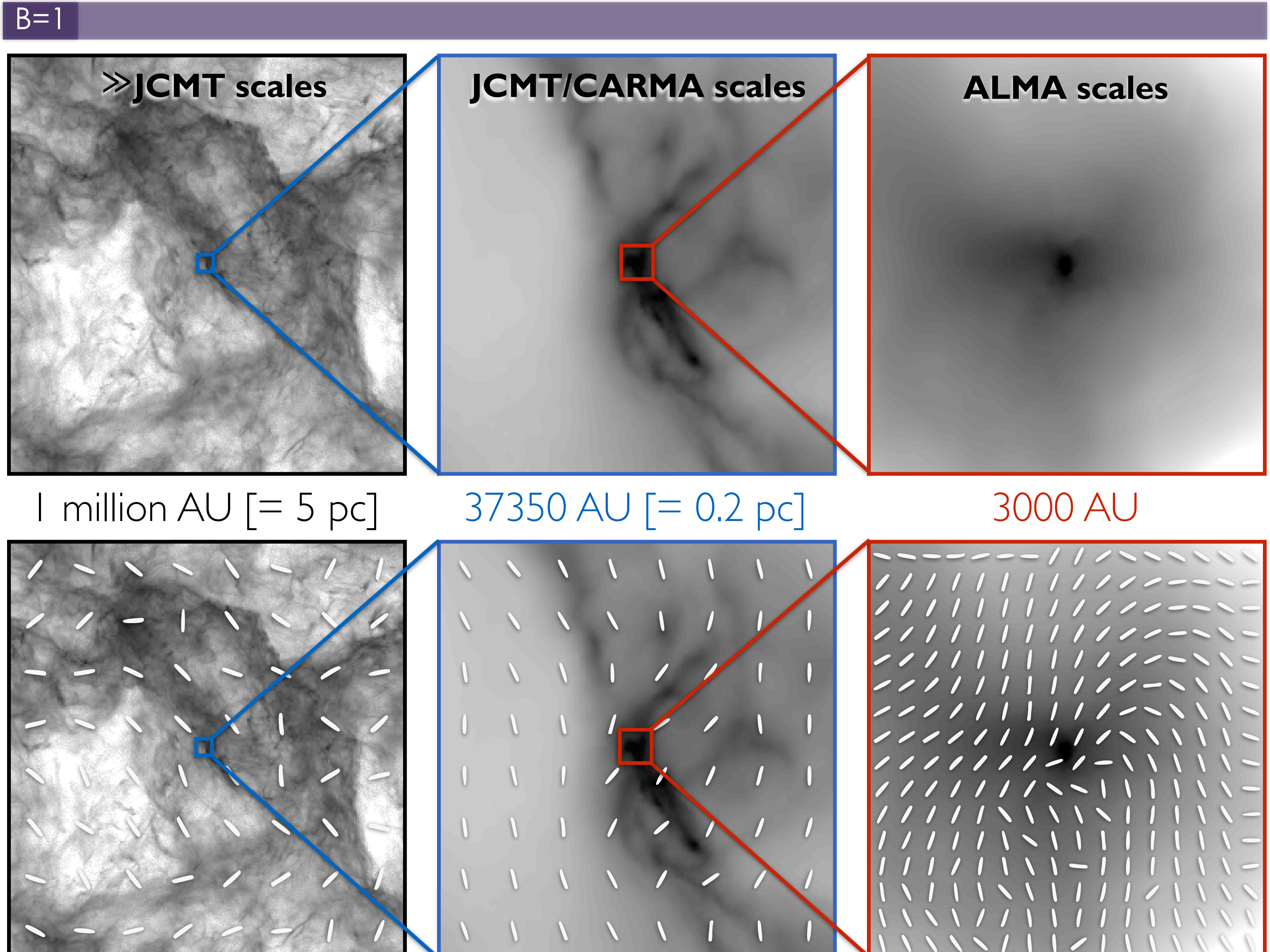
No hourglass!

This is in contrast to 50 years of theory, and to recent papers such as Li+2009, who suggested that the large-scale mean field direction could be preserved all the way down to the scale of forming stars.

Hull, Mocz, Burkhart+2017, under revision

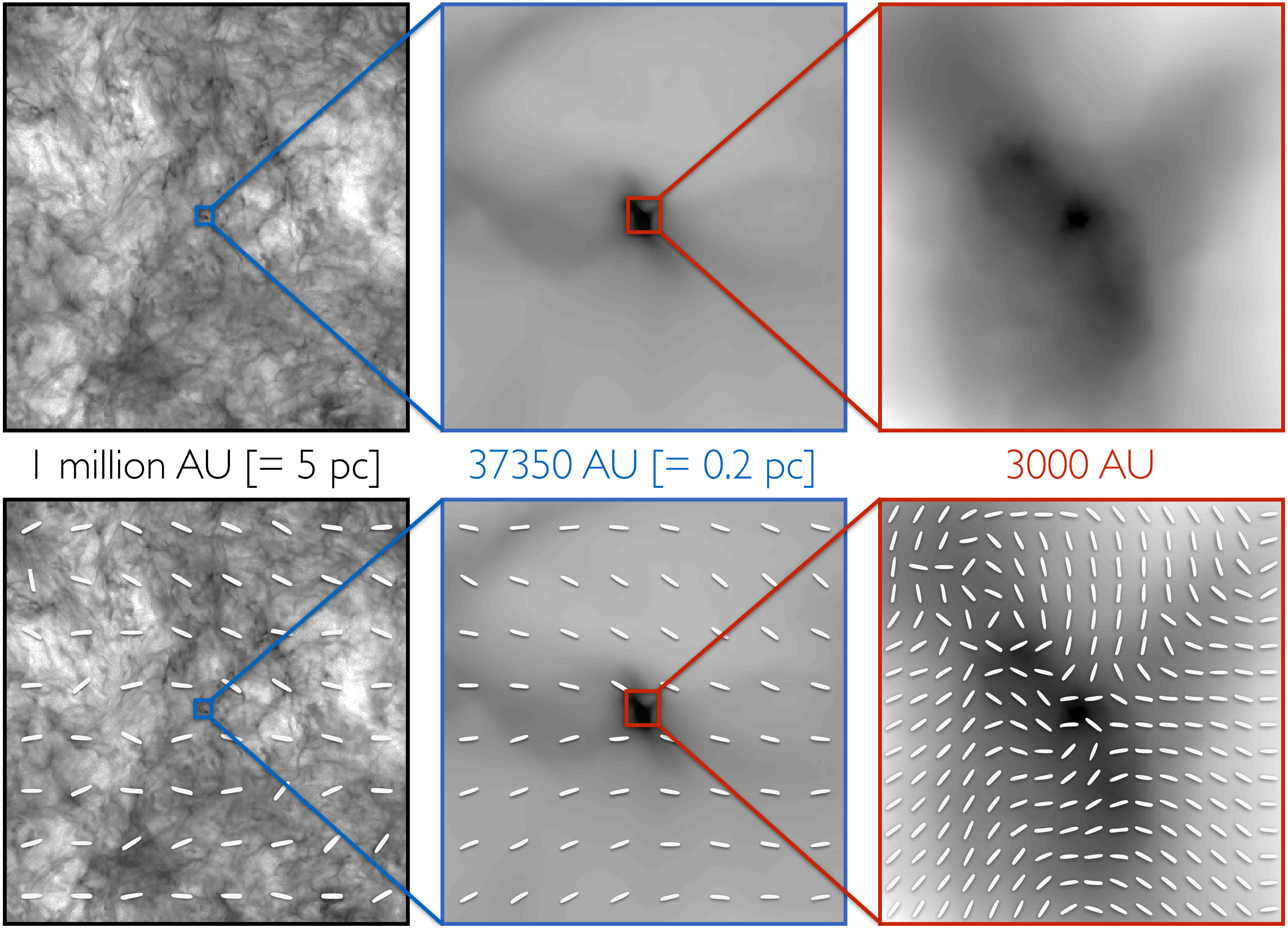
Keep an eye on the magnetic field strength here (in microgauss)

AREPO simulations

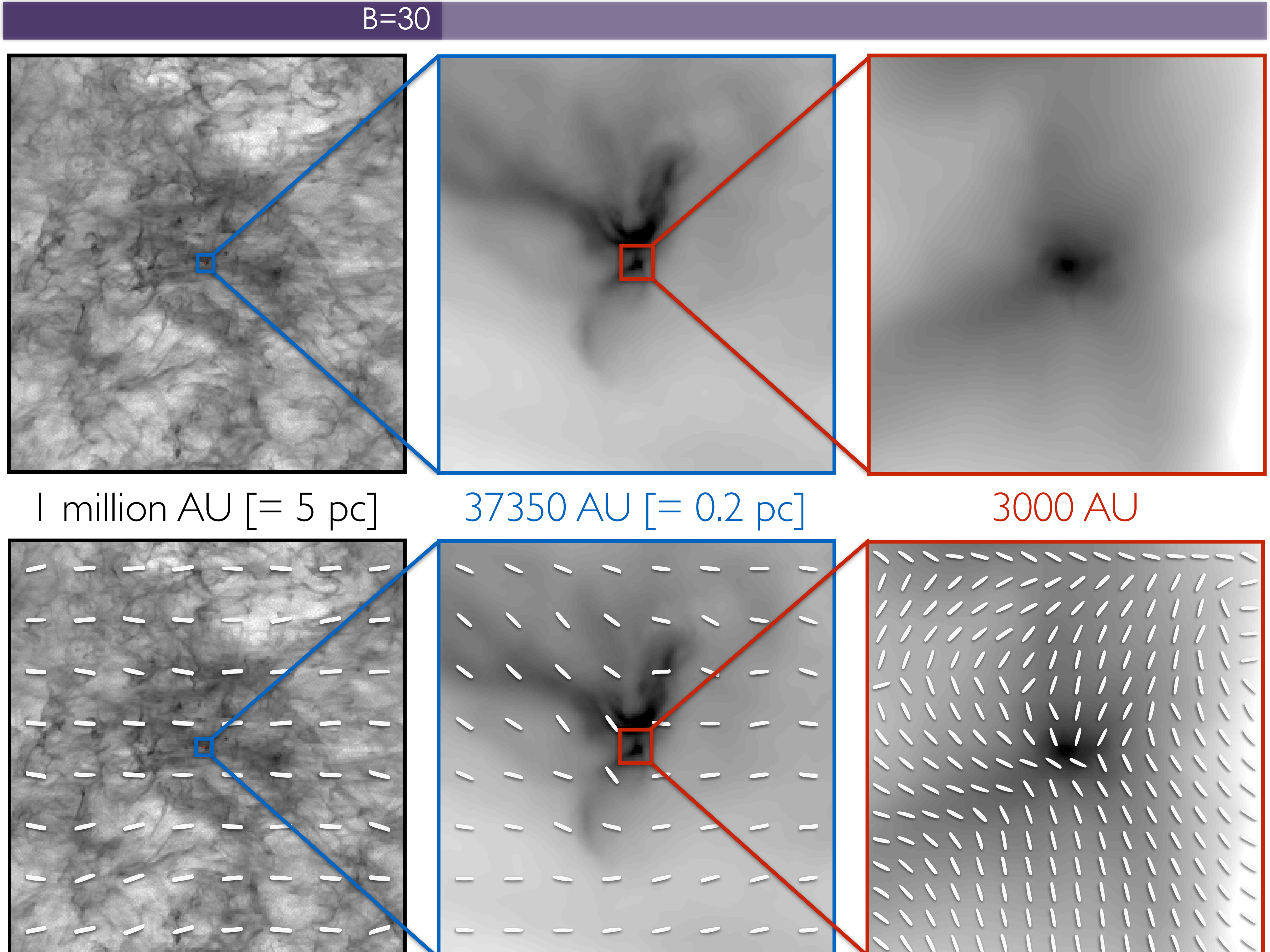


Hull, Mocz, Burkhart+2017, under revision

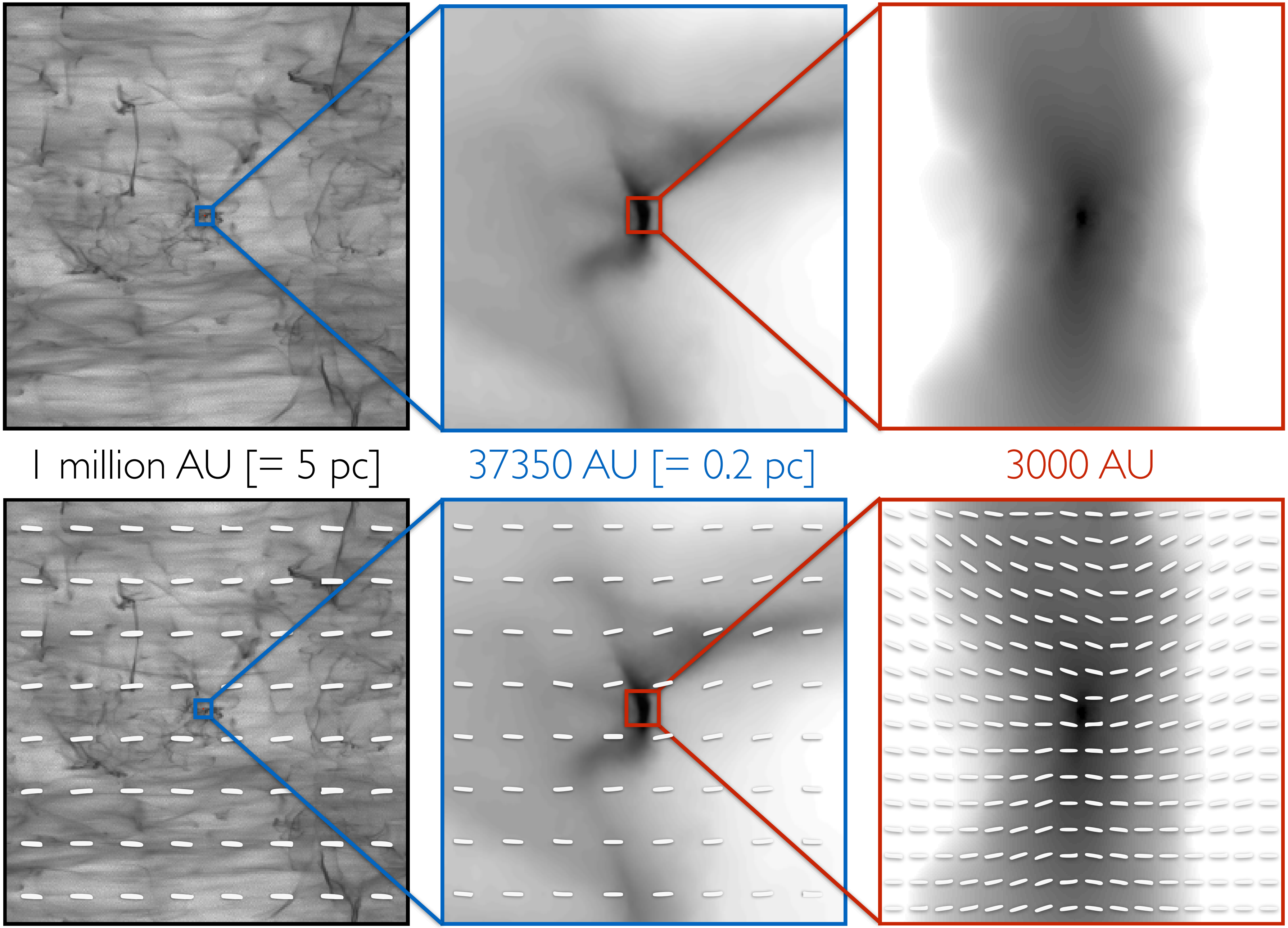
B=10



Hull, Mocz, Burkhart+2017, under revision



Hull, Mocz, Burkhart+2017, under revision



Hull, Mocz, Burkhart+2017, under revision

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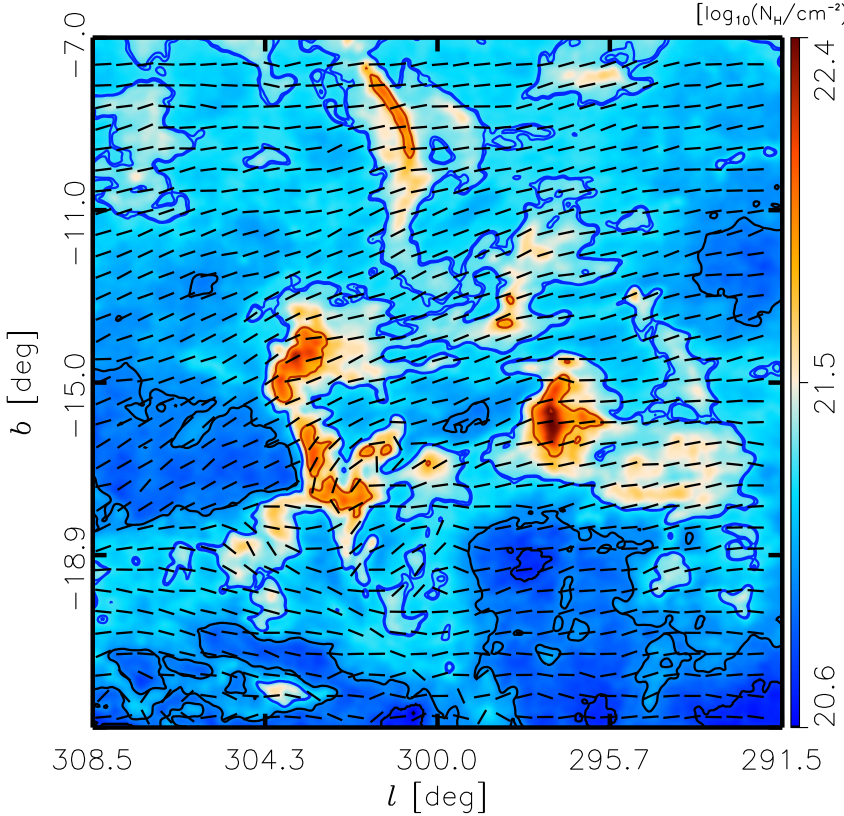
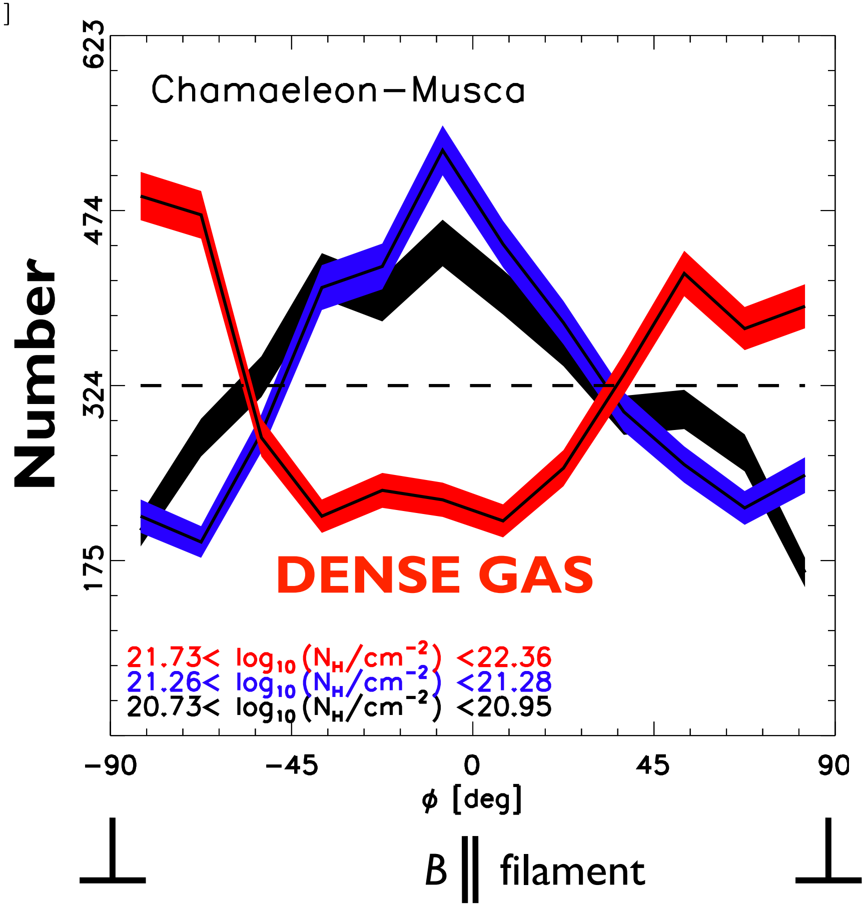
The HRO characterizes the relationship between **magnetic fields** and **filamentary structures** in the dust and gas

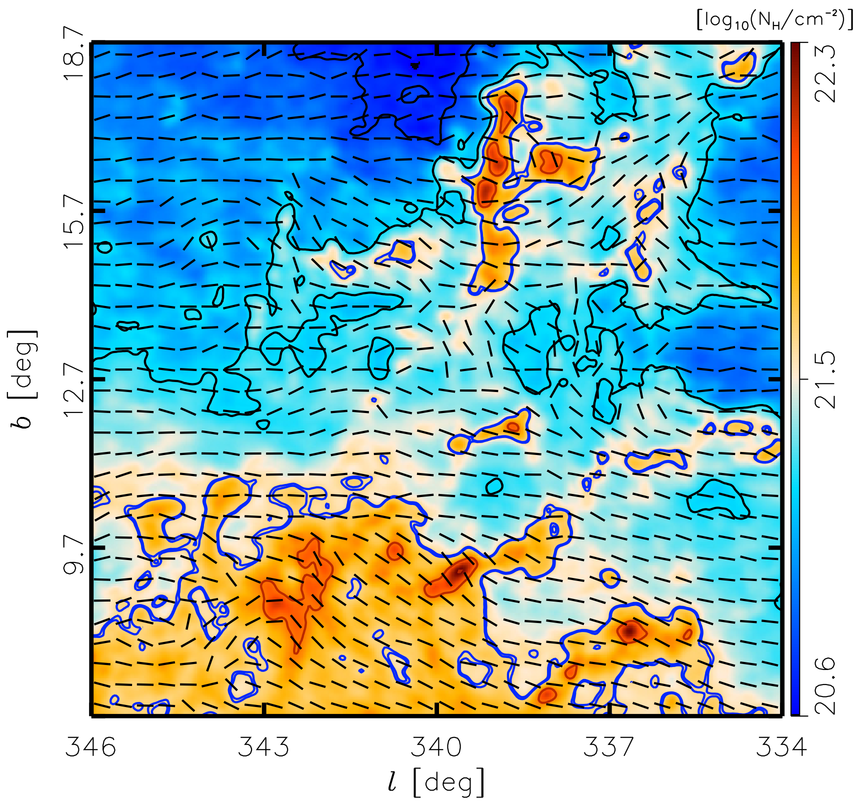


Planck XXXV (Soler+2015)

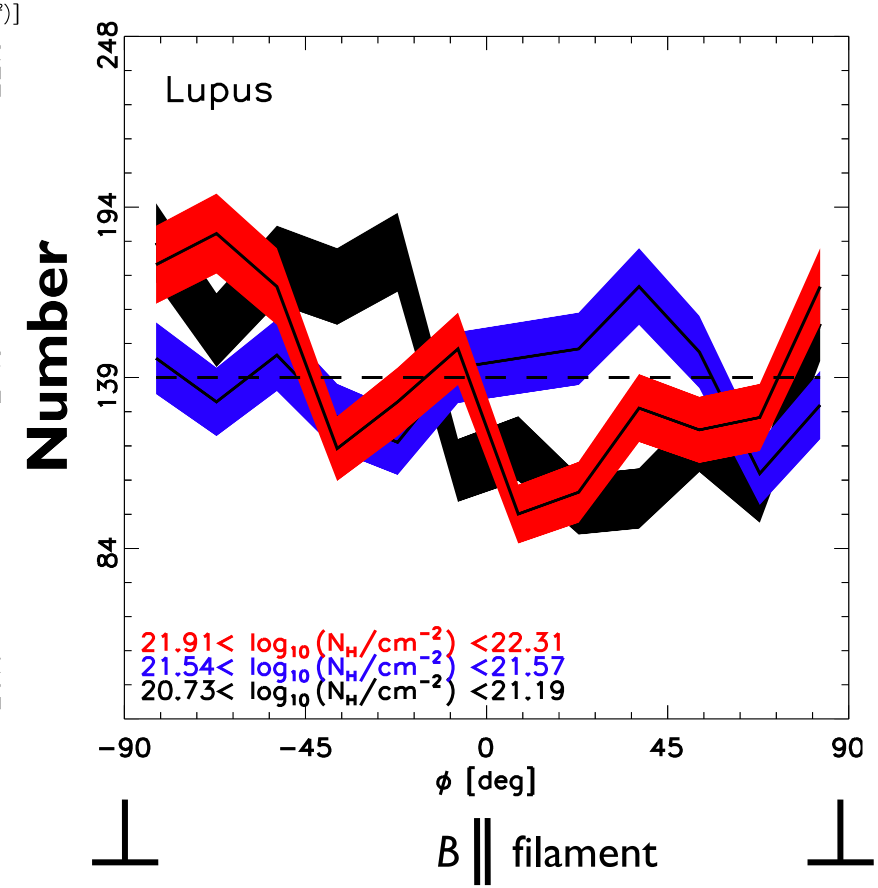


HRO analysis

A random HRO indicates that the magnetic field is not dictating the morphology of the star-forming material

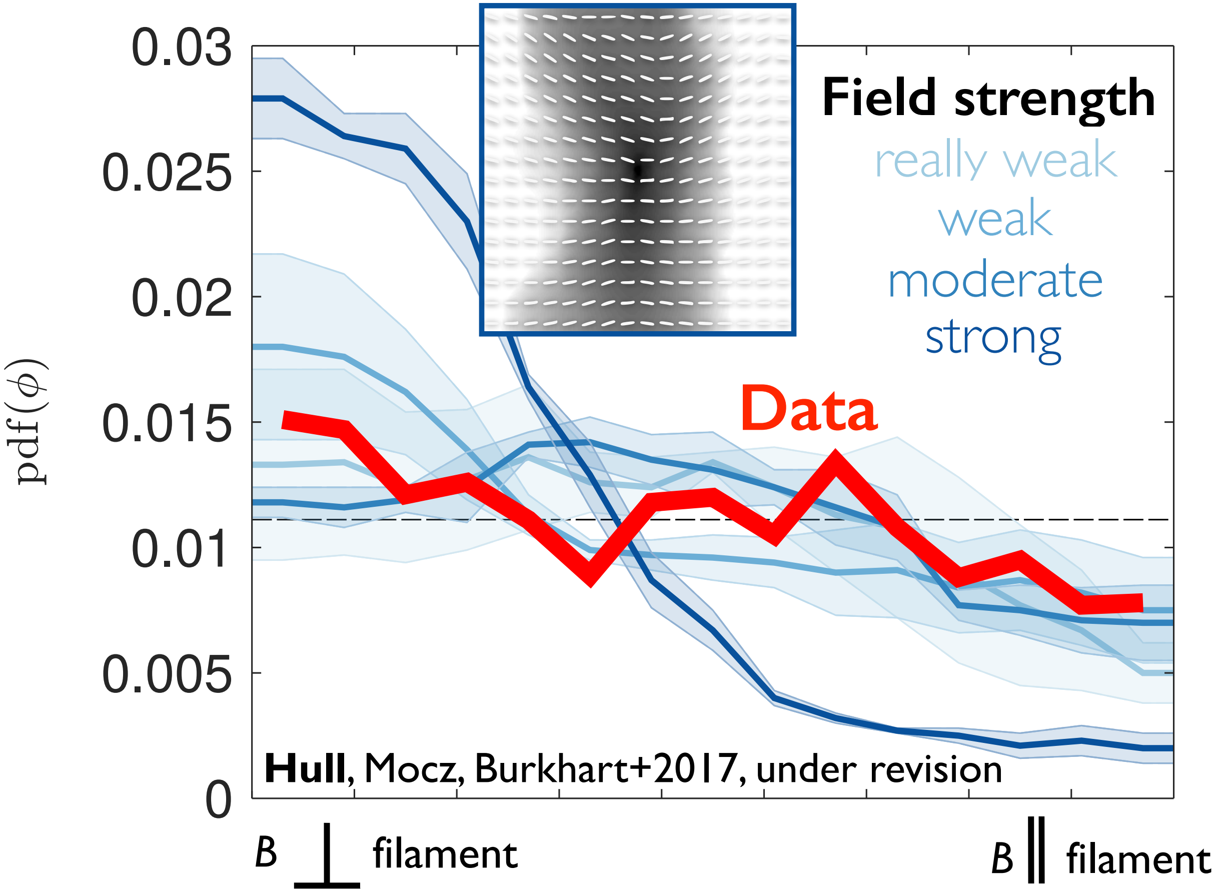


Planck XXXV (Soler+2015)

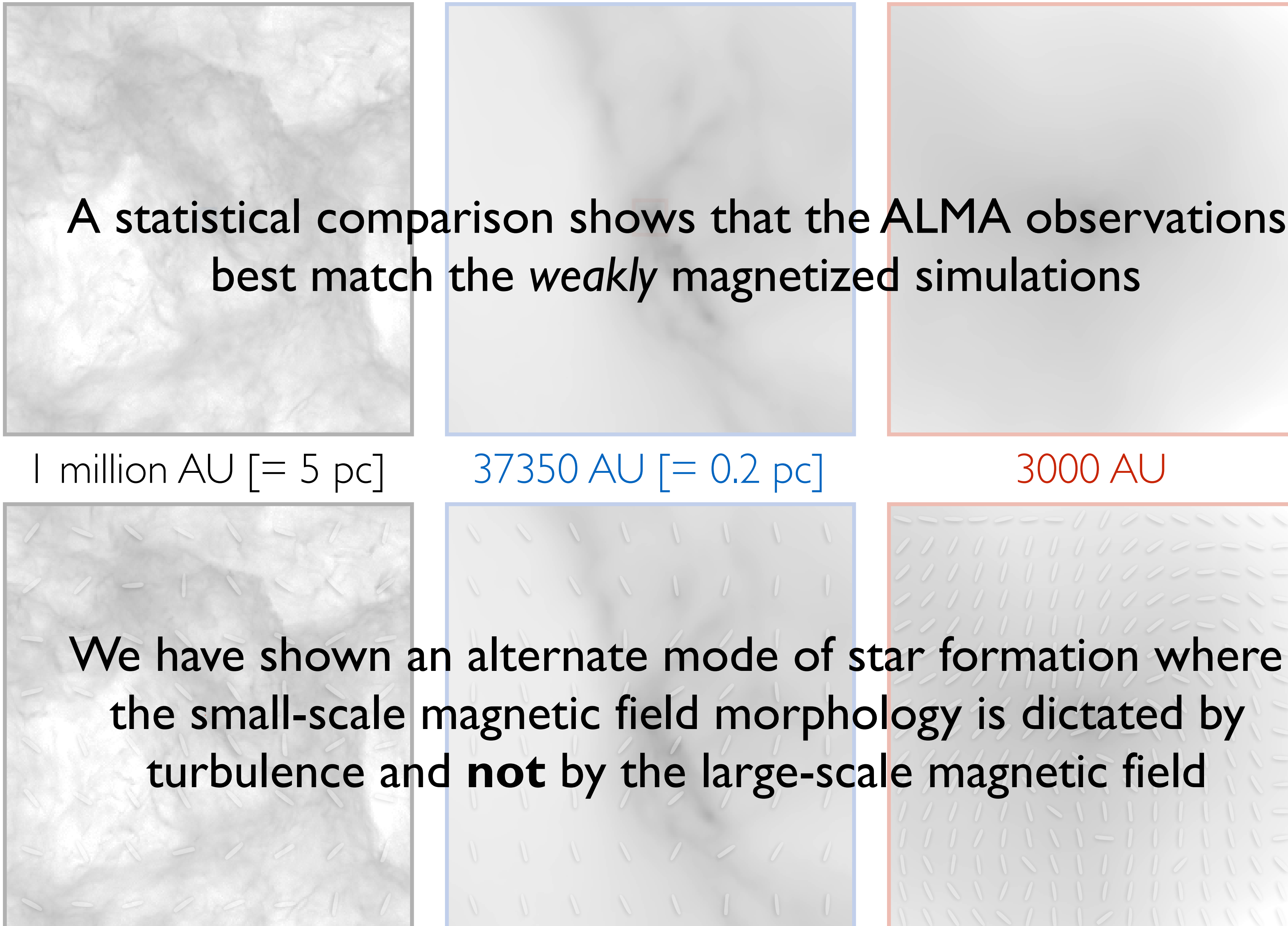


HRO analysis: ALMA & AREPO

The **ALMA data** exhibit a random HRO.
The **strongly magnetized simulation**, has a dynamically important magnetic field, but is *inconsistent* with our ALMA data

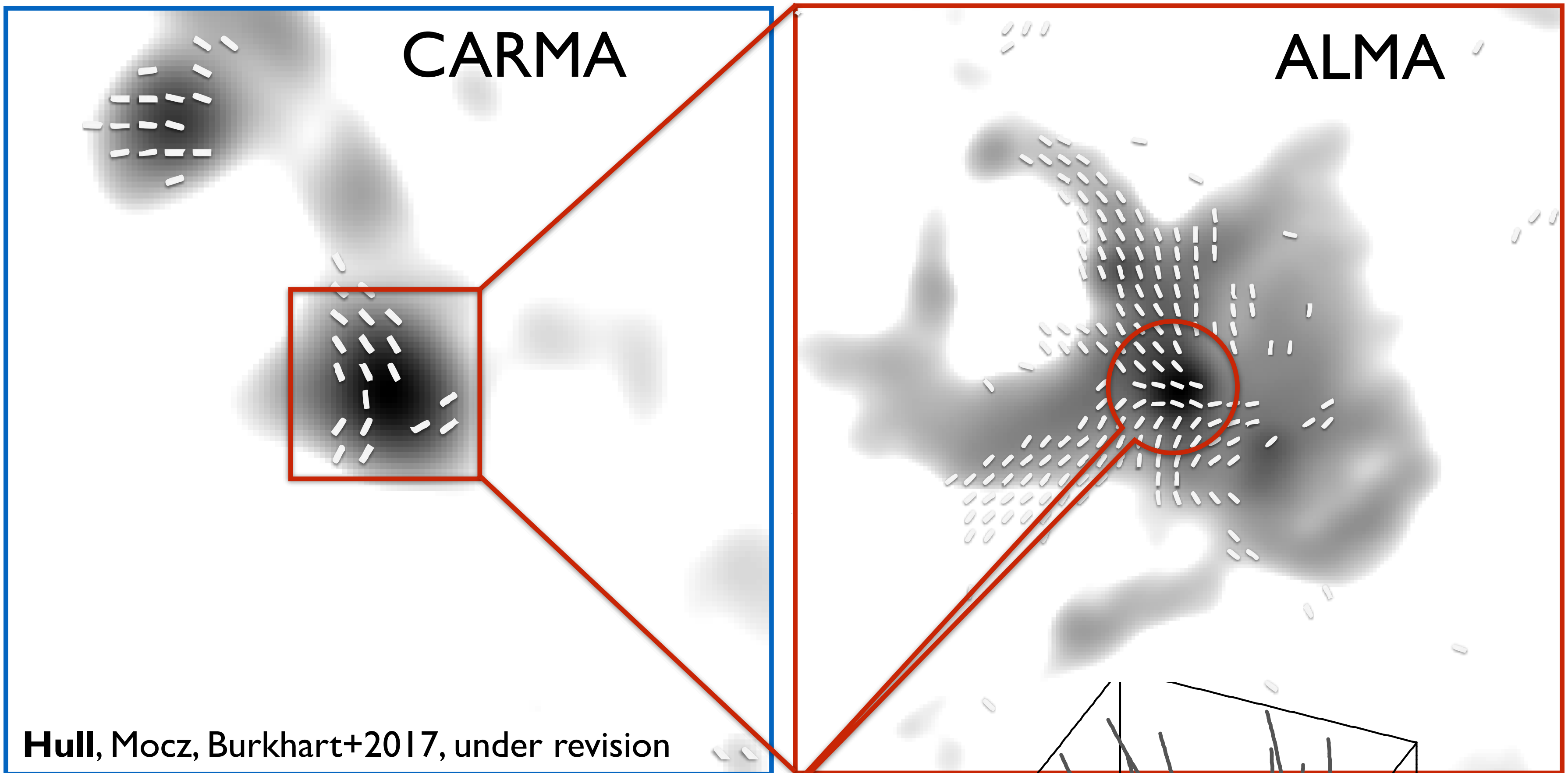


A statistical comparison shows that the ALMA observations best match the *weakly* magnetized simulations

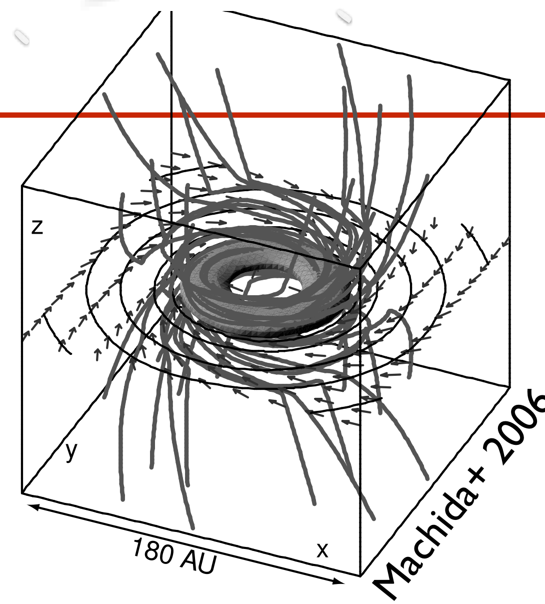


We have shown an alternate mode of star formation where the small-scale magnetic field morphology is dictated by turbulence and **not** by the large-scale magnetic field

Hull, Mocz, Burkhart+2017, under revision



FUTURE WORK: are the deviations at small scales due to toroidal wrapping of fields by disk rotation?

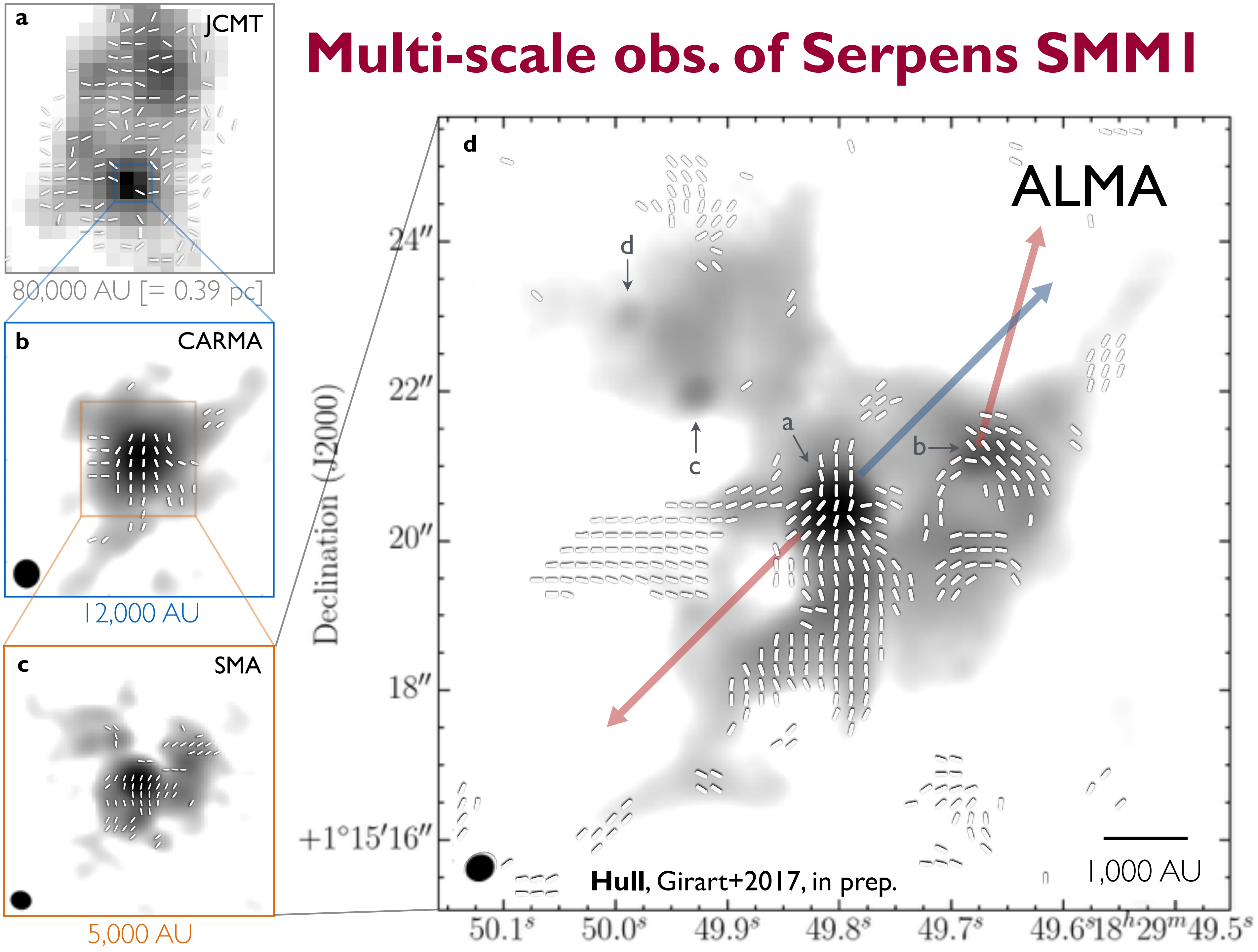


This will be answered by my Cycle 3 ~30 AU polarization observations, which were recently taken!

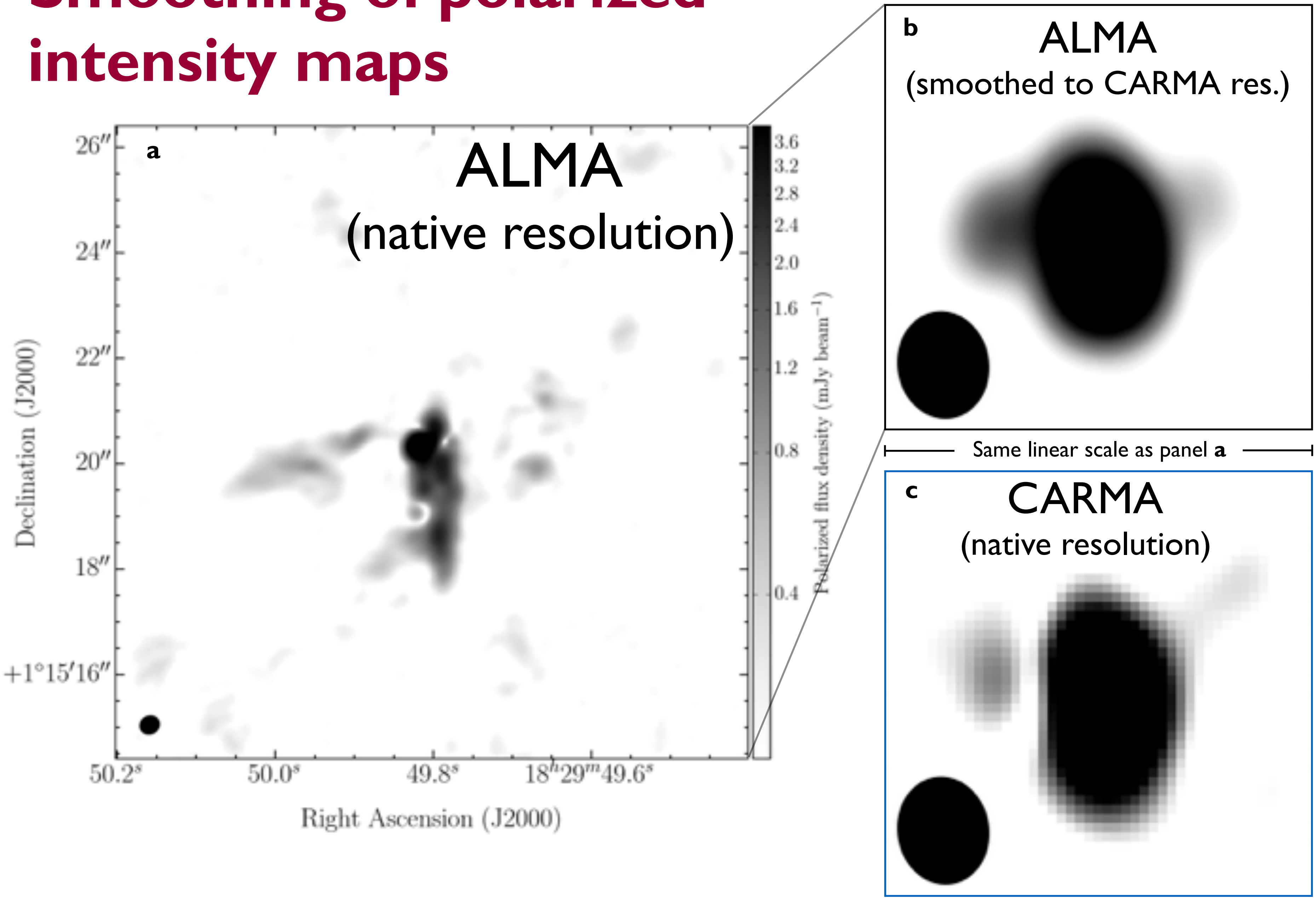
The plot thickens…

Serpens SMM1, the nearby neighbor of Ser-emb 8, has an outflow that is shaping the magnetic field!

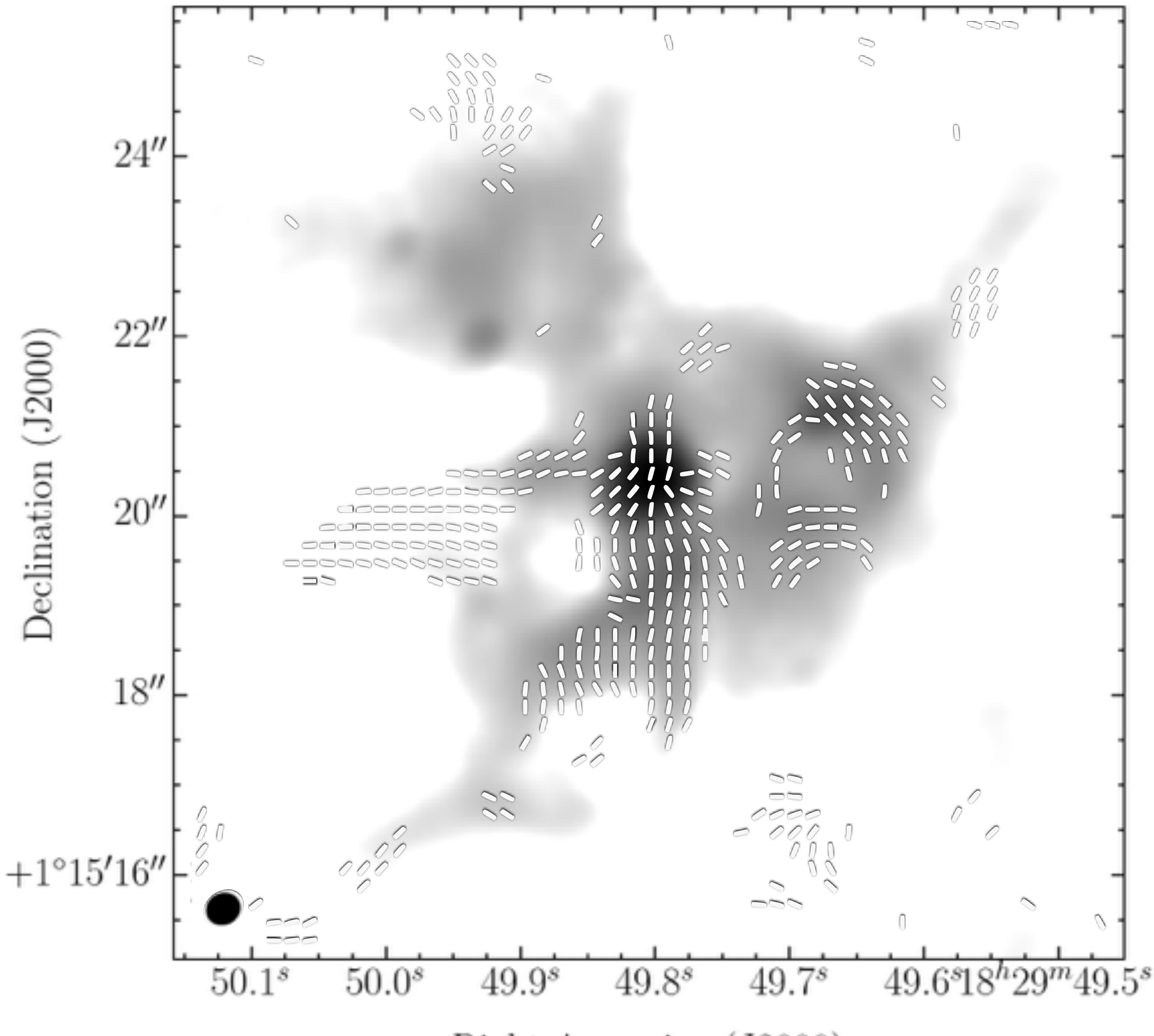
Multi-scale obs. of Serpens SMM1



Smoothing of polarized intensity maps



Hull, Girart+2017, in prep.



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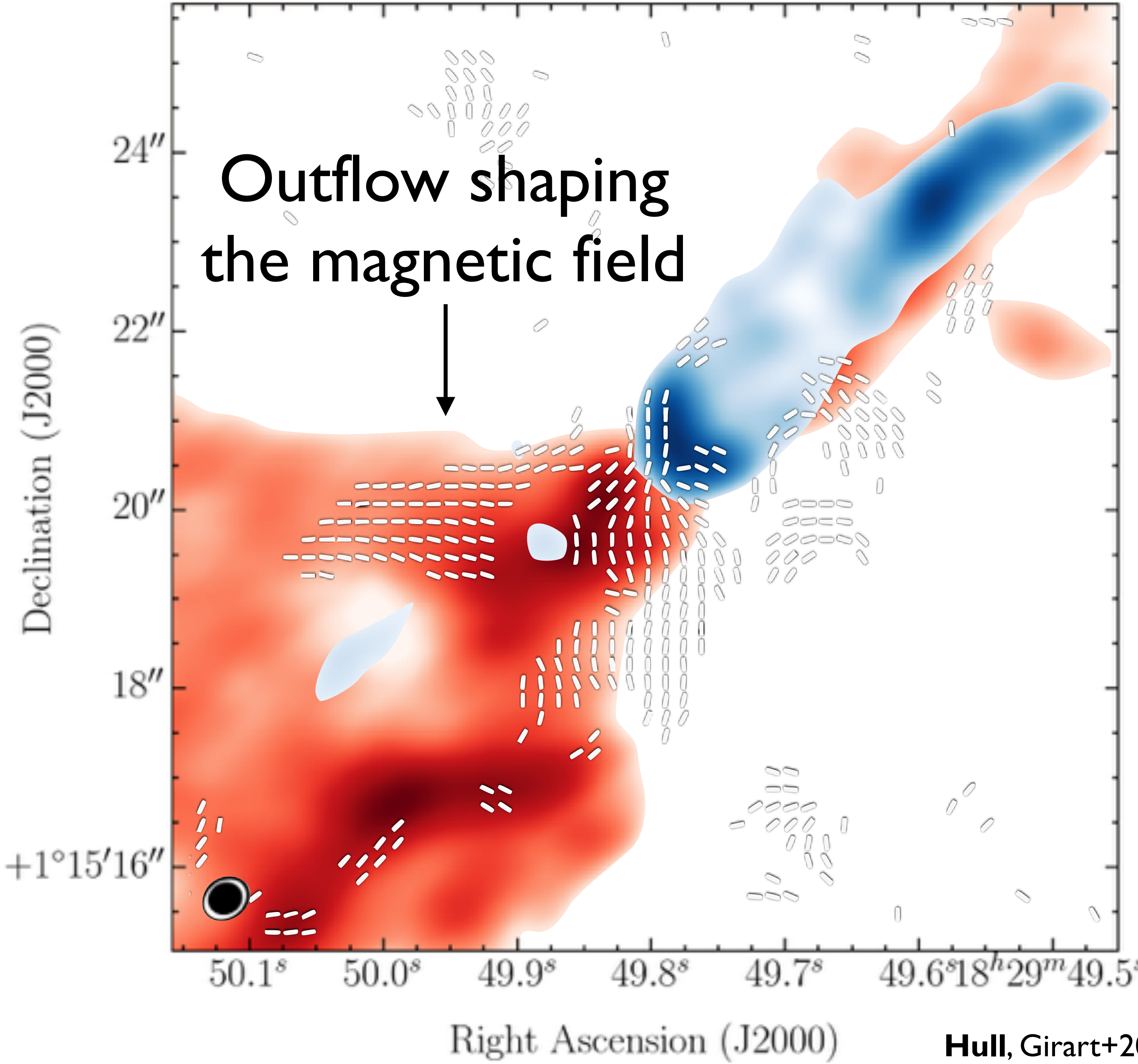
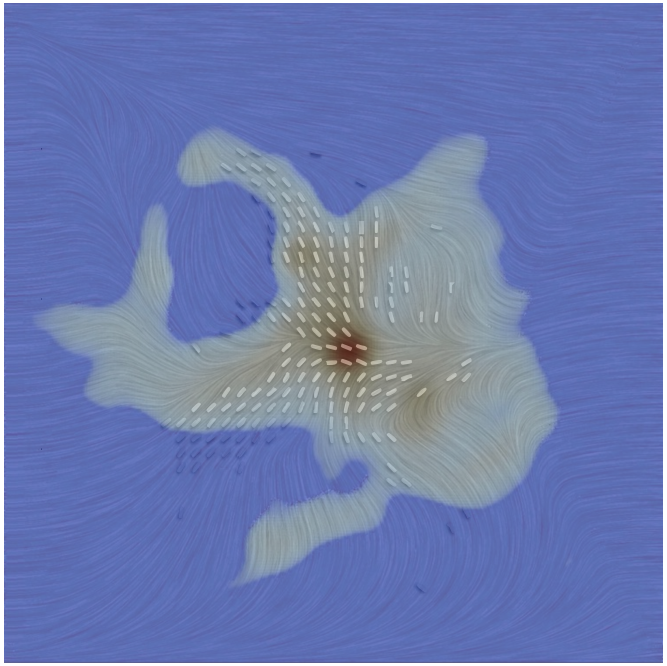
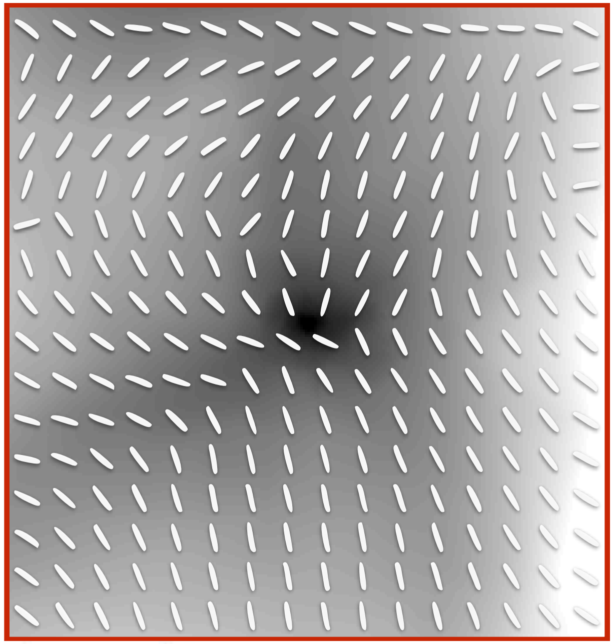


Hull, Girart+2017, in prep.

Summary (Ser-emb 8)

- ~100 AU resolution ALMA observations of magnetic fields in Ser-emb 8
- Field orientation **not** preserved from large scales
- No hourglass!

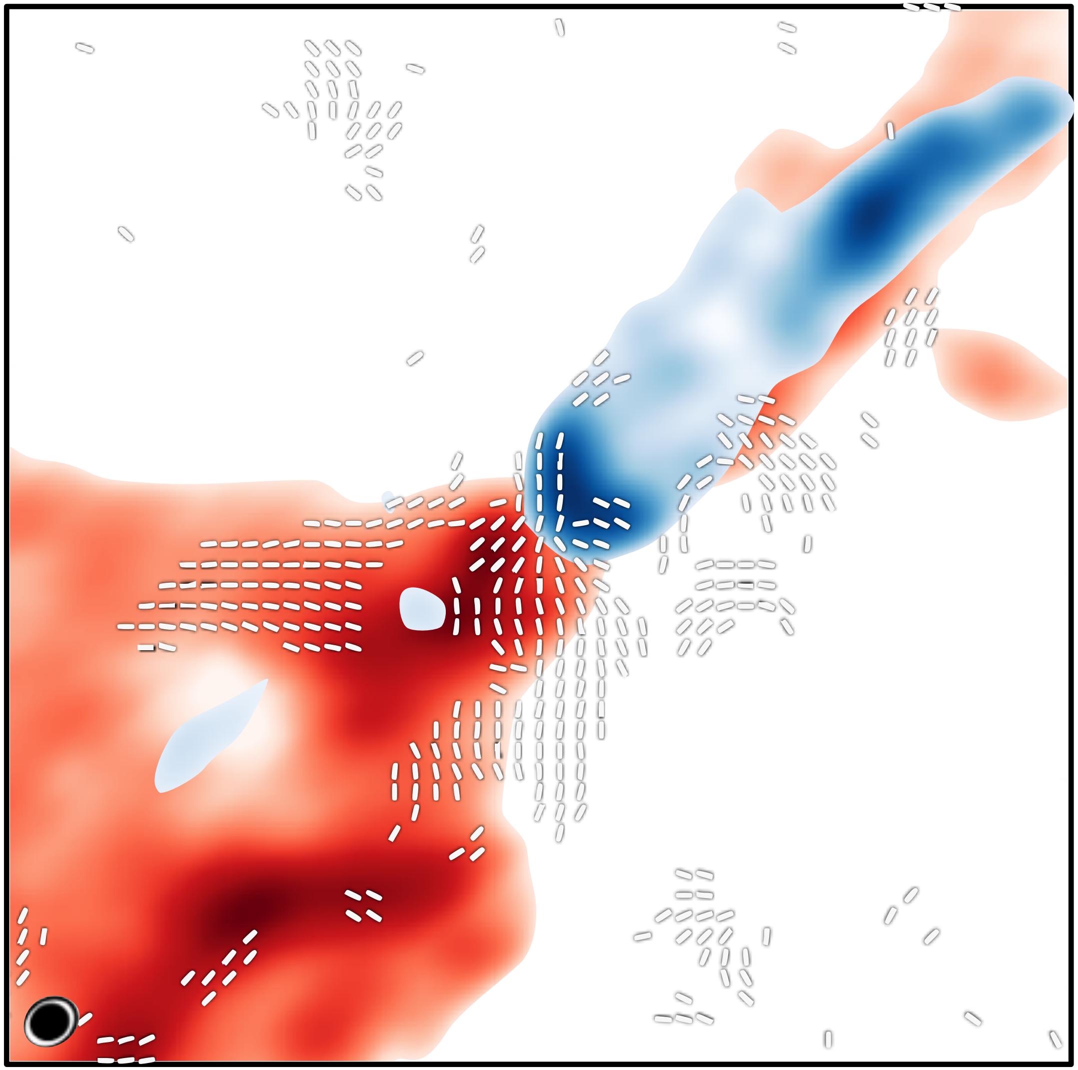




- High-DR, ALMA-resolution AREPO simulations
- Initial conditions of the cloud dictate what we see at small scales
- We see an alternate mode of star formation where the field morphology is dictated by turbulence and **not** by a strong B-field

Summary (Ser SMM1)

- The outflow from Serpens SMM1 appears to be shaping the magnetic field
- Why is this? More evolved?
- Hints of an hourglass… but one created by the outflow?



Fin