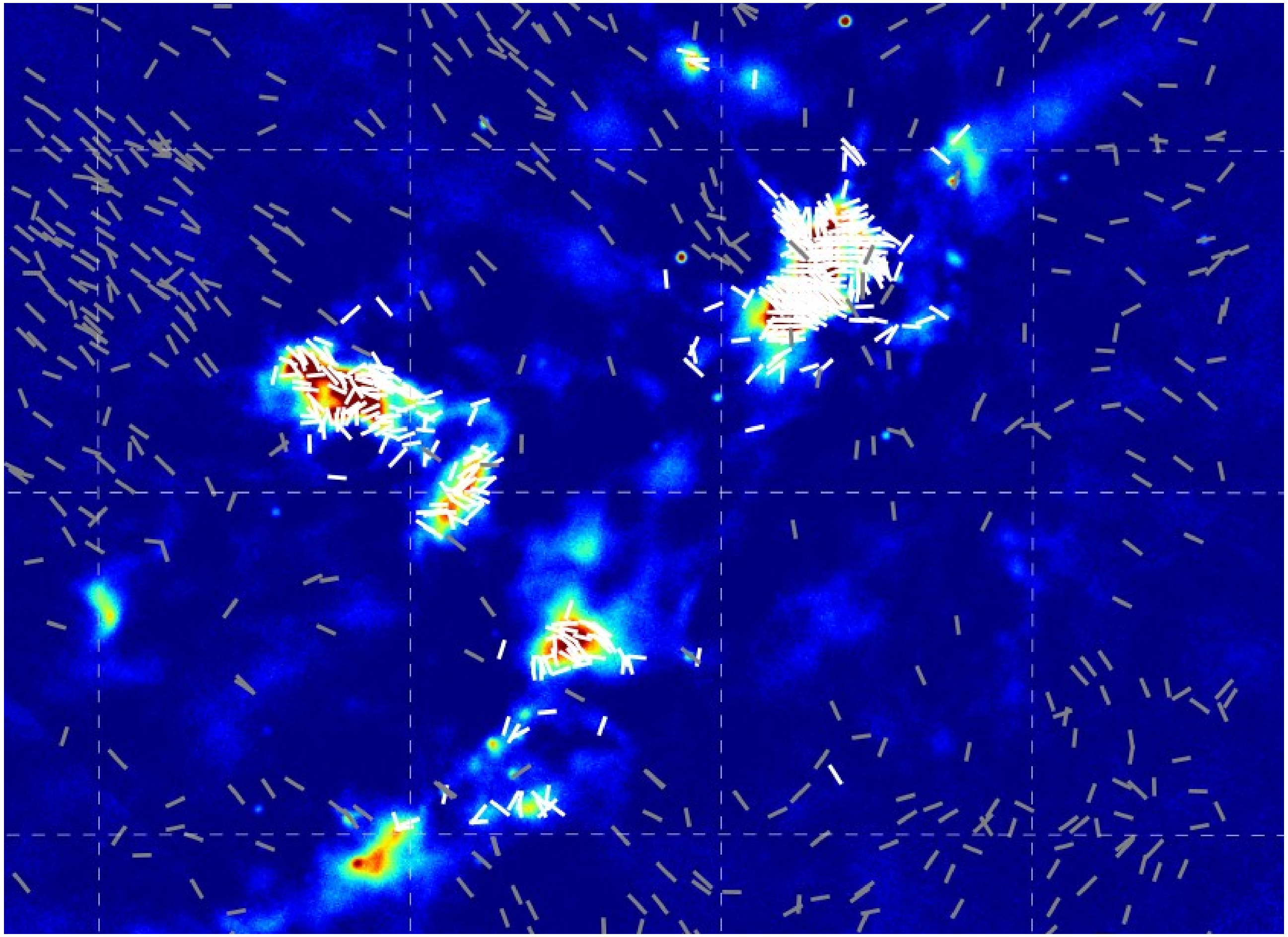
The JCMT BISTRO Survey:
Grain alignment in the Ophiuchus Molecular Cloud



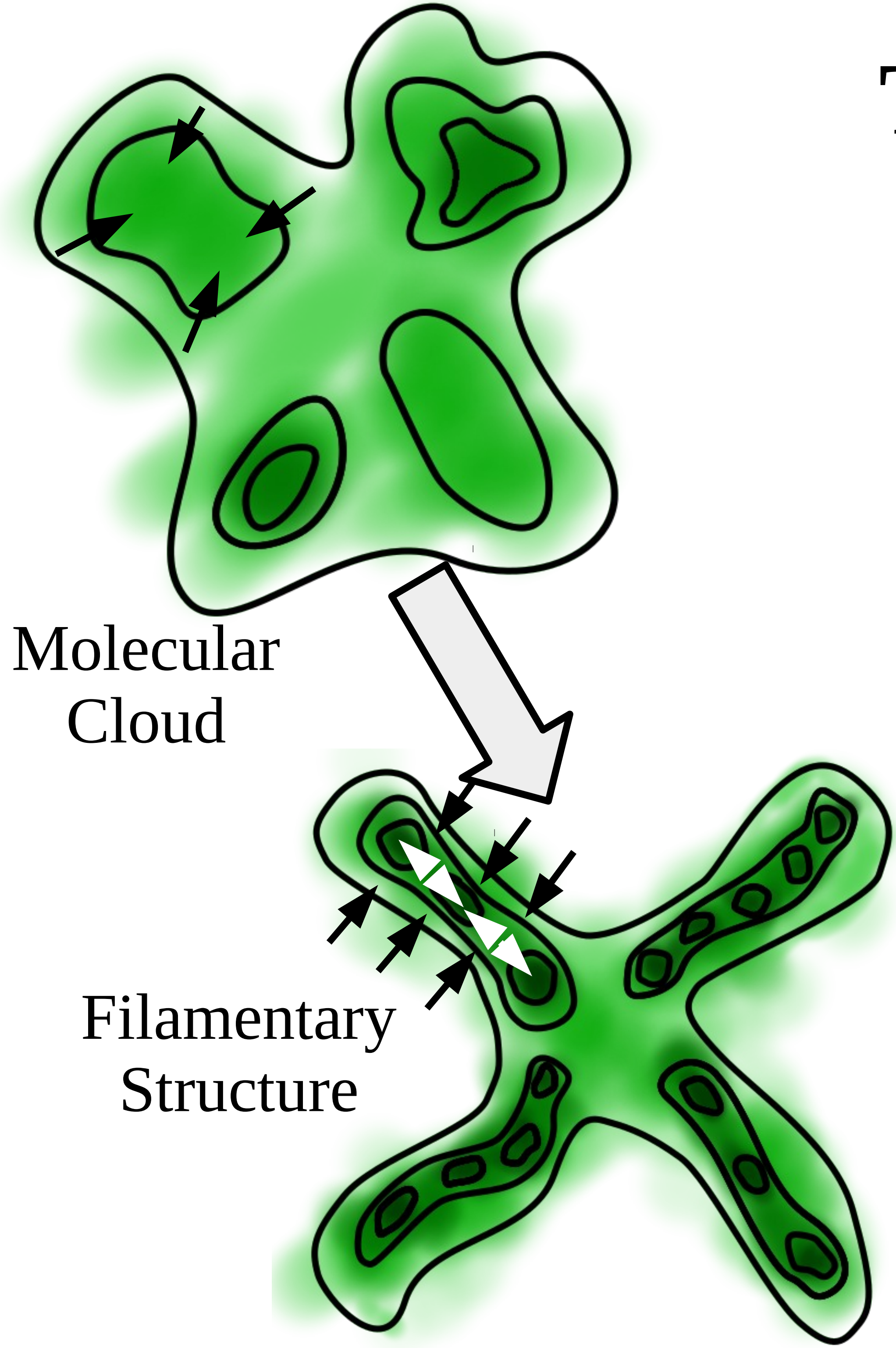
Kate Pattle

National Tsing Hua University

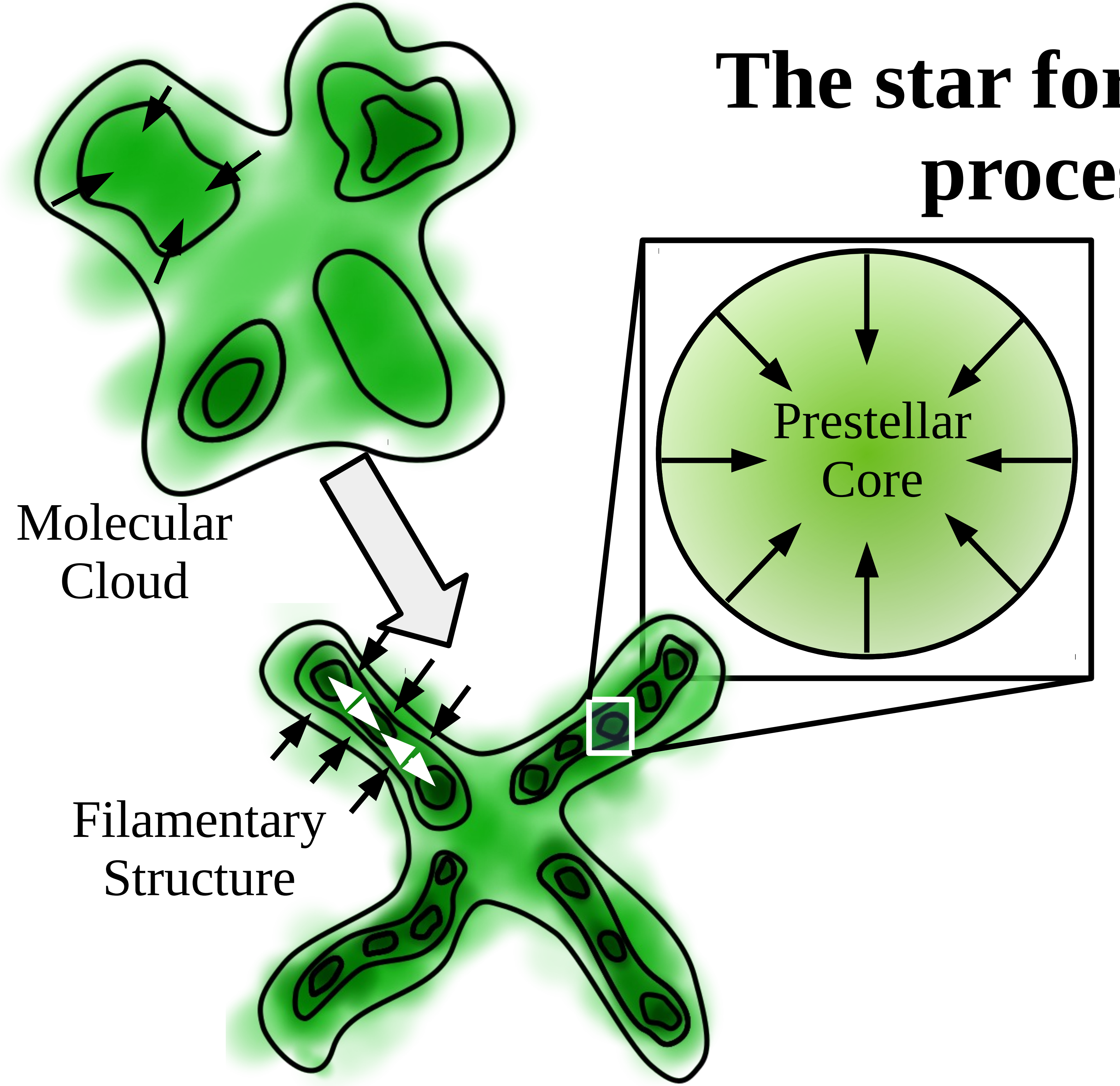
The star formation process

Molecular Cloud

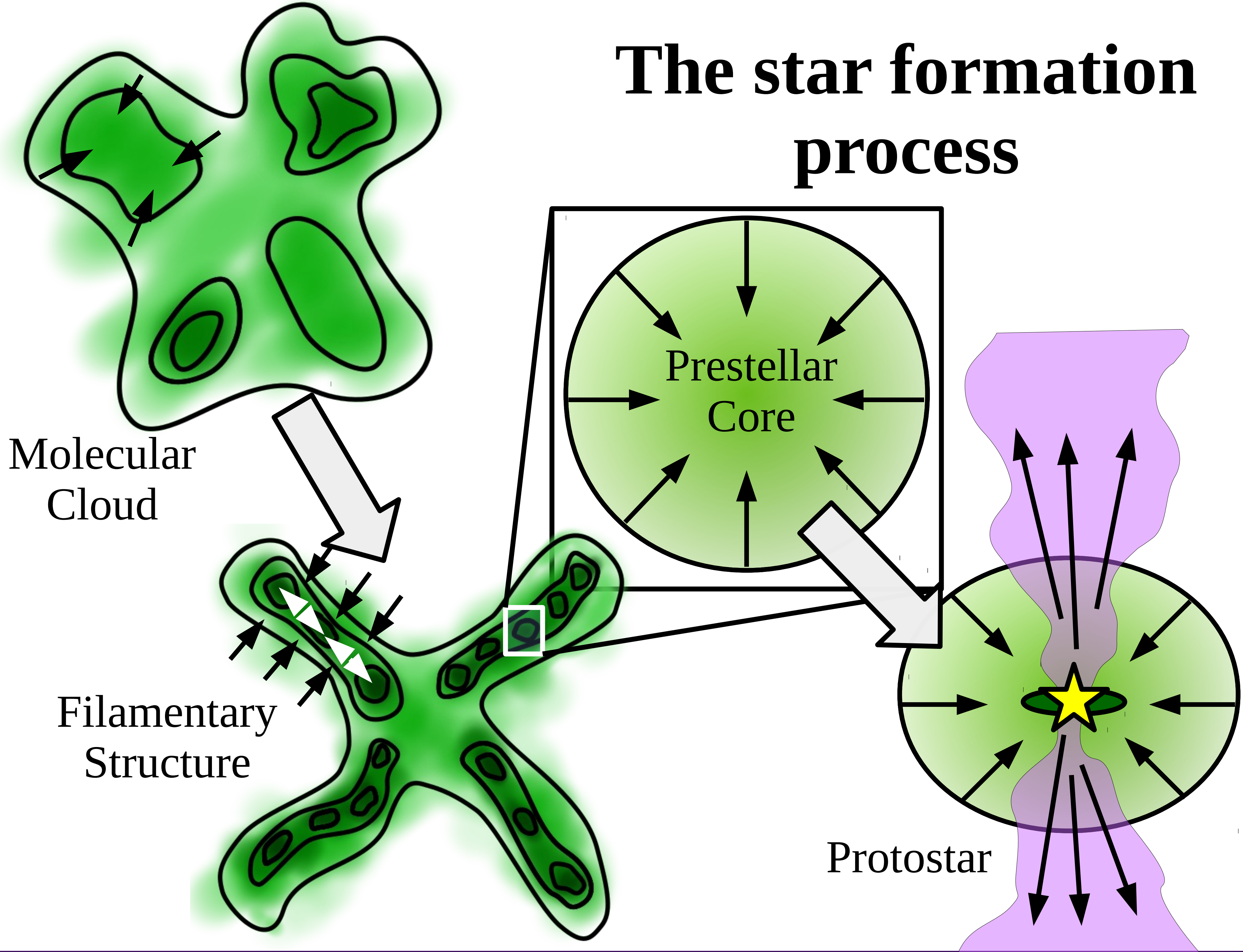
The star formation process



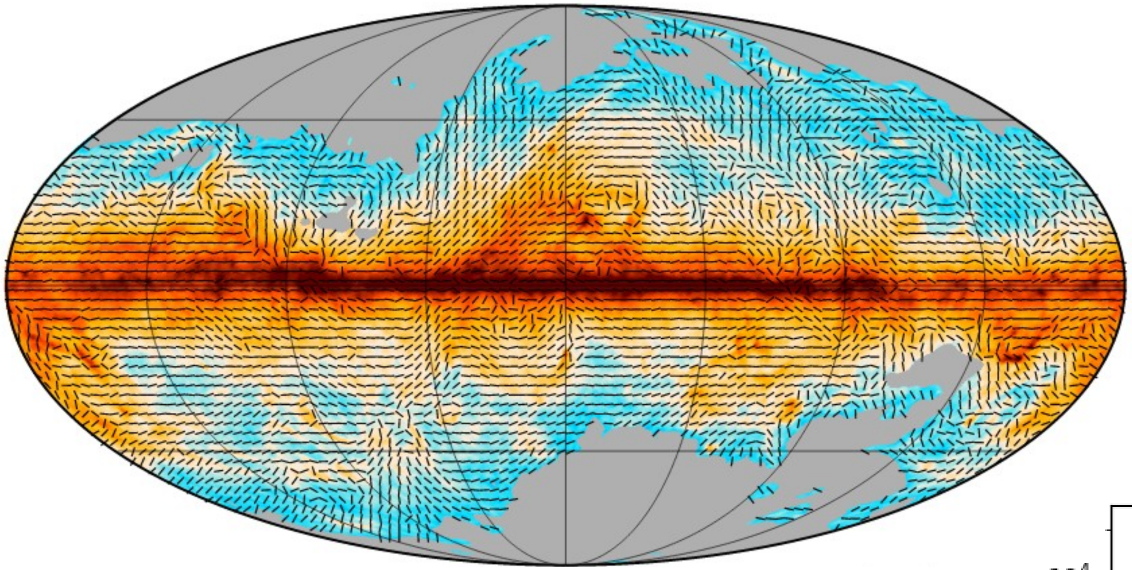
The star formation process



The star formation process



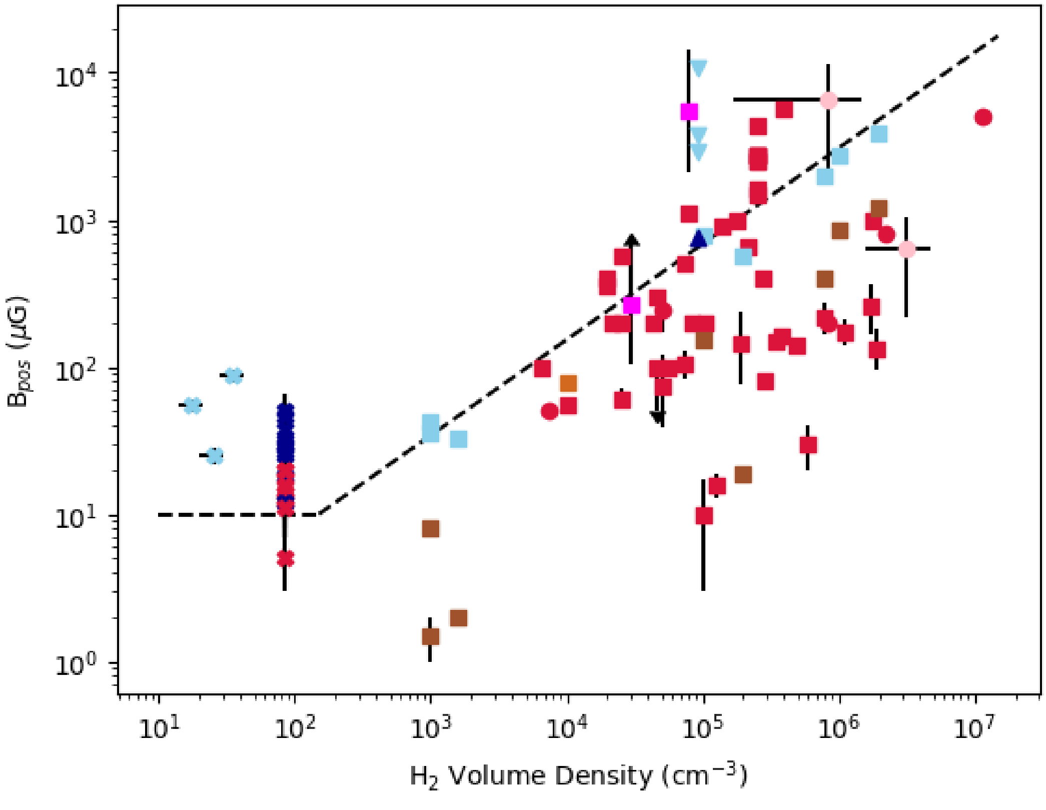
But what about the magnetic field?



Planck Int. XIX 2015, A&A 576 A104

The Milky Way's ISM is permeated by magnetic fields

Pattle & Fissel 2019, FrASS 6 15
(after Crutcher et al. 2010, ApJ 745 466)



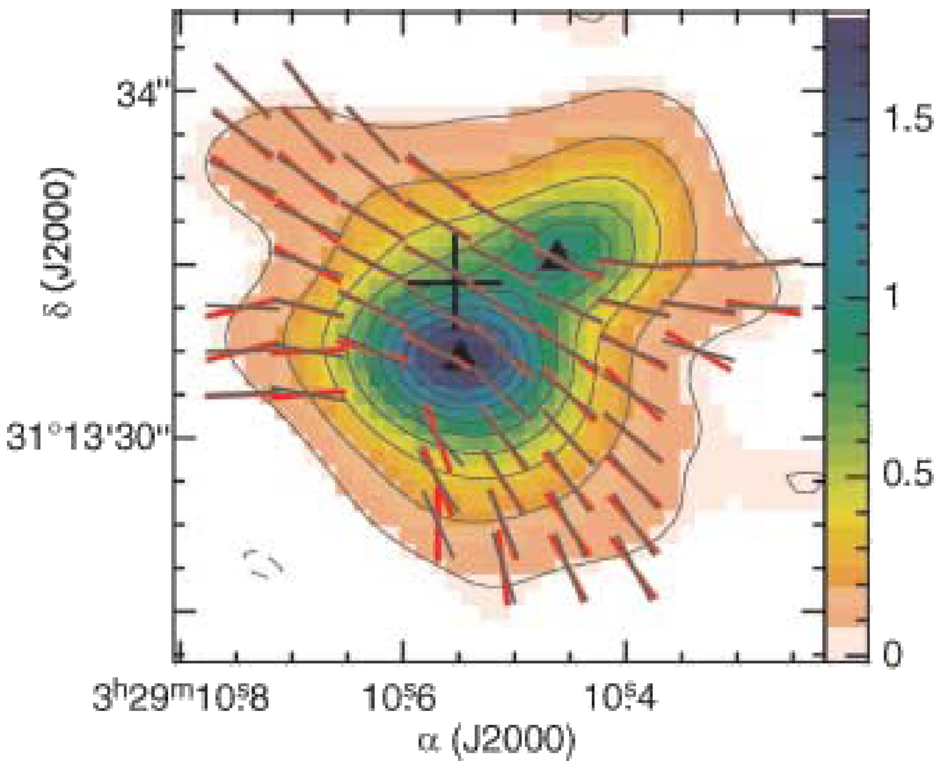
In molecular clouds the magnetic field strength can reach ~ 1 mG. But is it dynamically important?

Any complete theory of star formation needs to account for the role of magnetic fields.

What regulates star formation?

Magnetism OR Turbulence?

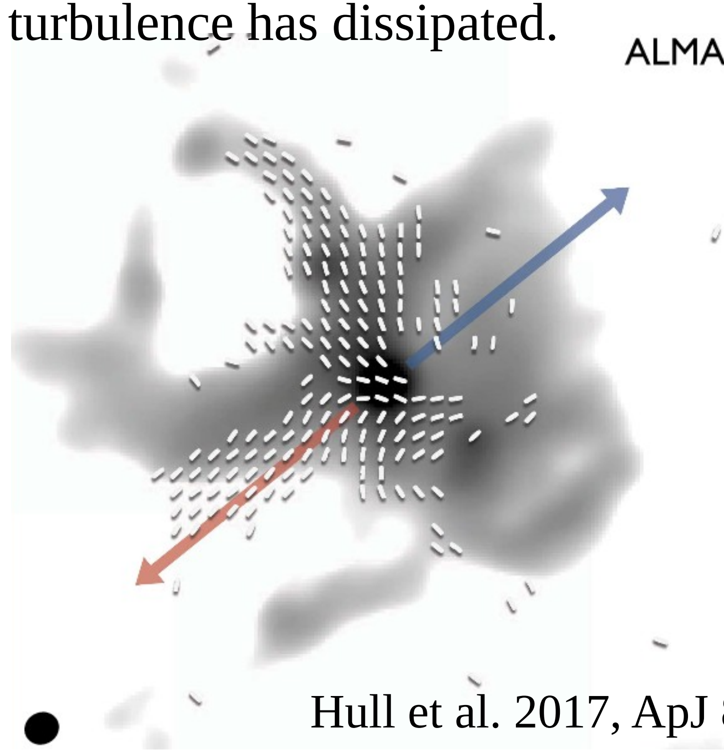
Cores form in a magnetically subcritical environment (magnetic field strong enough to support against gravitational collapse) and evolve to gravitational instability slowly, through ambipolar diffusion.



Girart et al. 2006, Science 313 812

Cores form in a magnetically supercritical environment (magnetic field **not** strong enough to support against gravitational collapse).

Molecular clouds form at stagnant points at the intersection of supersonic turbulent flows in the ISM. Stars form in regions in which turbulence has dissipated.



Hull et al. 2017, ApJ 842 L9

BISTRO: Overview

- A James Clerk Maxwell Telescope (JCMT) Large Program mapping nearby (<2kpc) star-forming regions in 850µm and 450µm polarized light with the POL-2 polarimeter

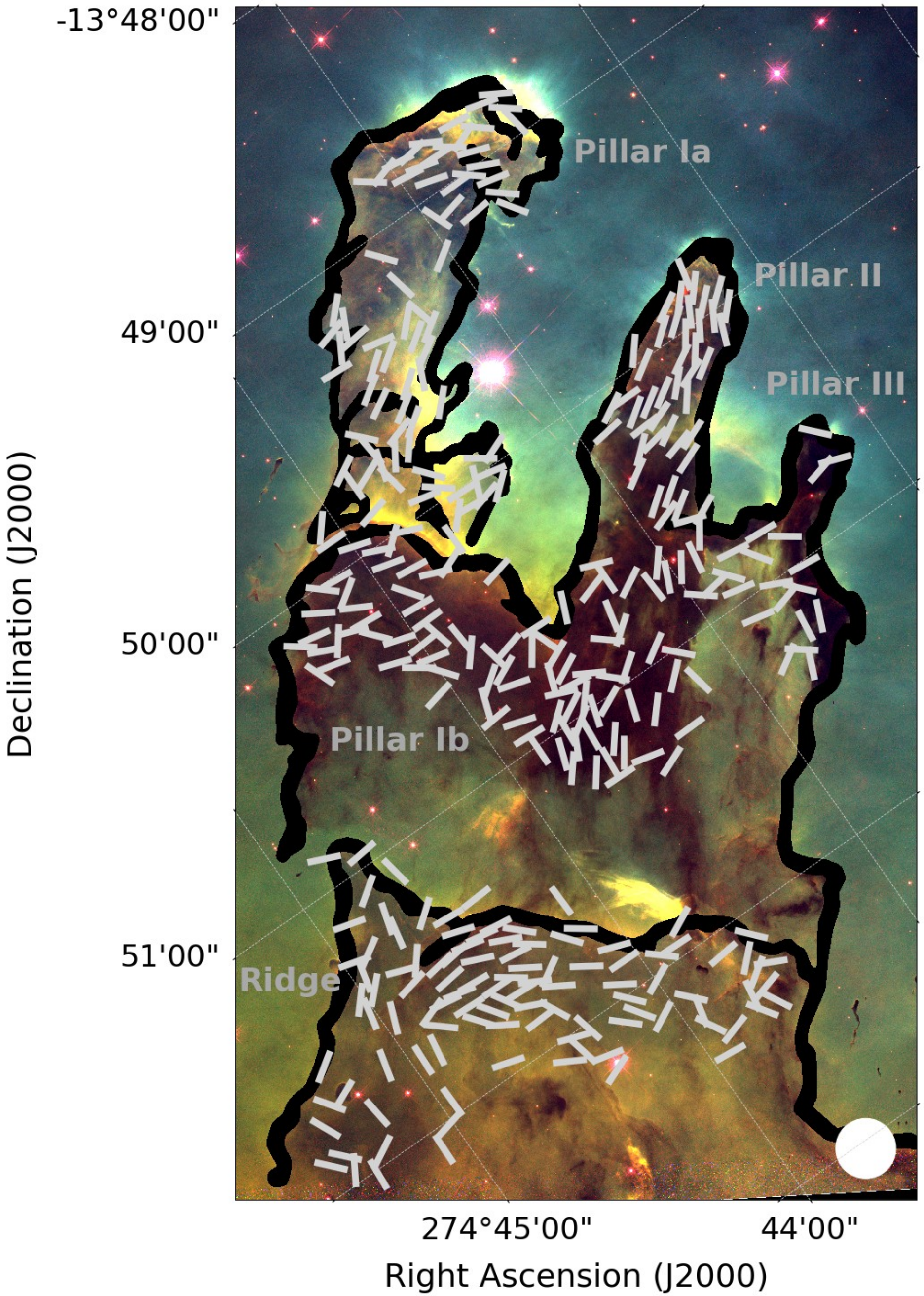
- ~140 survey members across 7 partner regions and the East Asian Observatory

- P.I.s: Derek Ward-Thompson (UK), Pierre Bastien (Canada), Keping Qiu (China), Tetsuo Hasegawa (Japan), Woojin Kwon (Korea), Shih-Ping Lai (Taiwan)

- BISTRO-1 and -2 awarded 448 hours of observing time to map:
  Ophiuchus, Orion A & B, Perseus, Serpens Main and Aquila, Taurus L1495/B211, Auriga, IC5146, M16, DR15, DR21, NGC 2264, NGC 6334, Mon R2, Rosette

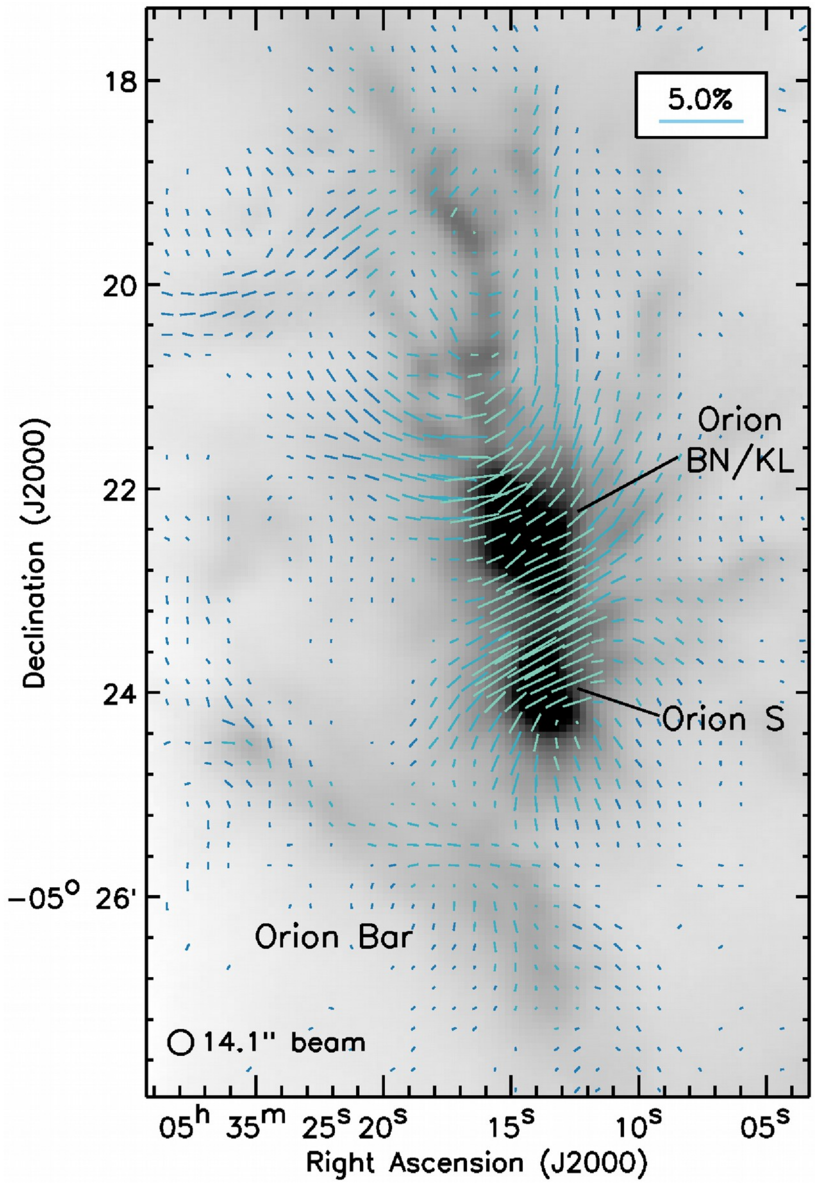
Survey paper: **Ward-Thompson et al. 2017, ApJ 842 66**
Orion A: **Pattle et al. 2017, ApJ 846 122**
M16: **Pattle et al. 2018, ApJ 860 L6**
Ophiuchus A: **Kwon et al. 2018, ApJ 859 4**
Ophiuchus B: **Soam et al. 2018, ApJ 861 65**
Ophiuchus C: **Liu et al. 2019, ApJ 877 43**
IC5146: **Wang et al. 2019, ApJ 876 42**
Perseus B1: **Coudé et al. 2019, ApJ 877 88**

M16: Pattle et al. 2018, ApJ 860 L6



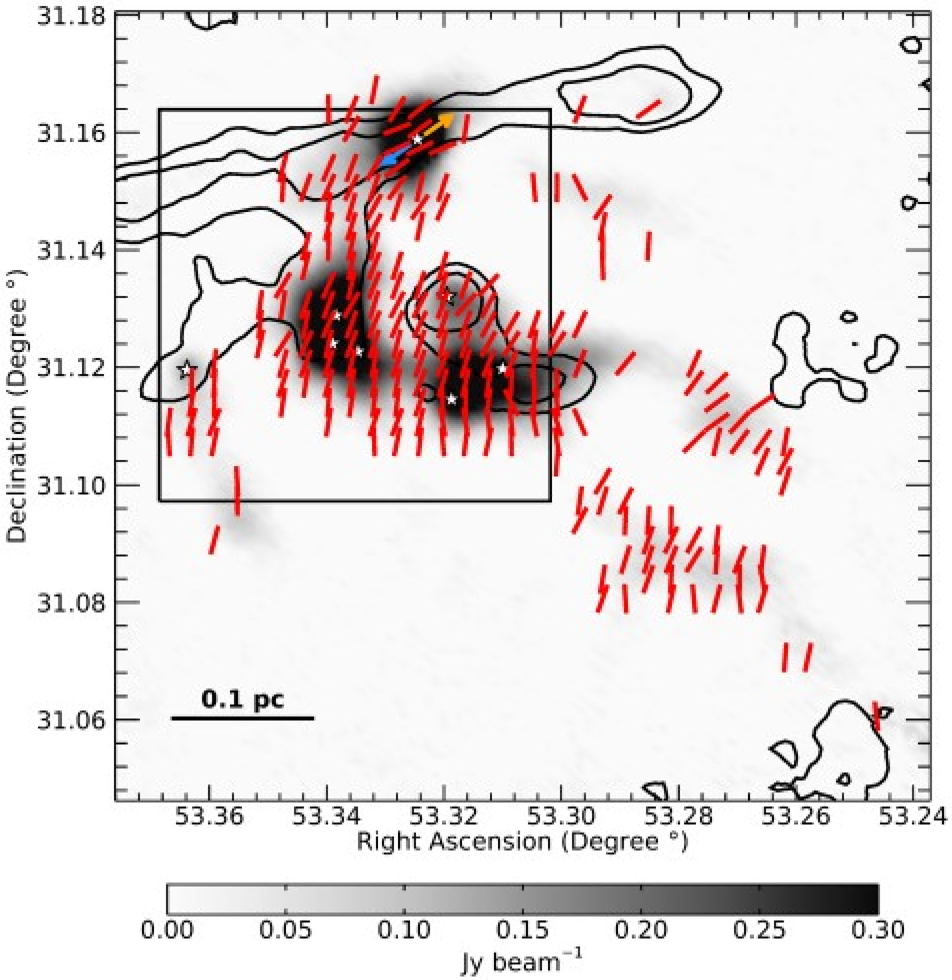
- Ordered magnetic field, running along length of pillars
- Field strength in Pillar II ~170-320μG
- Magnetic field strong enough to support the pillars against pressure-driven radial collapse
- Field cannot support the pillars against destruction by the shock front
- Initially dynamically negligible field compressed by shock front passage?
- Linear resolution ~ 0.12 pc

Orion A: Pattle et al. 2017, ApJ 846 122



- Highly ordered magnetic field morphology
- "Hourglass" magnetic field suggestive of global gravitational collapse along the Integral Filament – not ambipolar-diffusion-driven collapse
- Magnetic field strength 6±4 mG
- The magnetic field may have been compressed to become dynamically important?
- Linear resolution ~ 0.03 pc

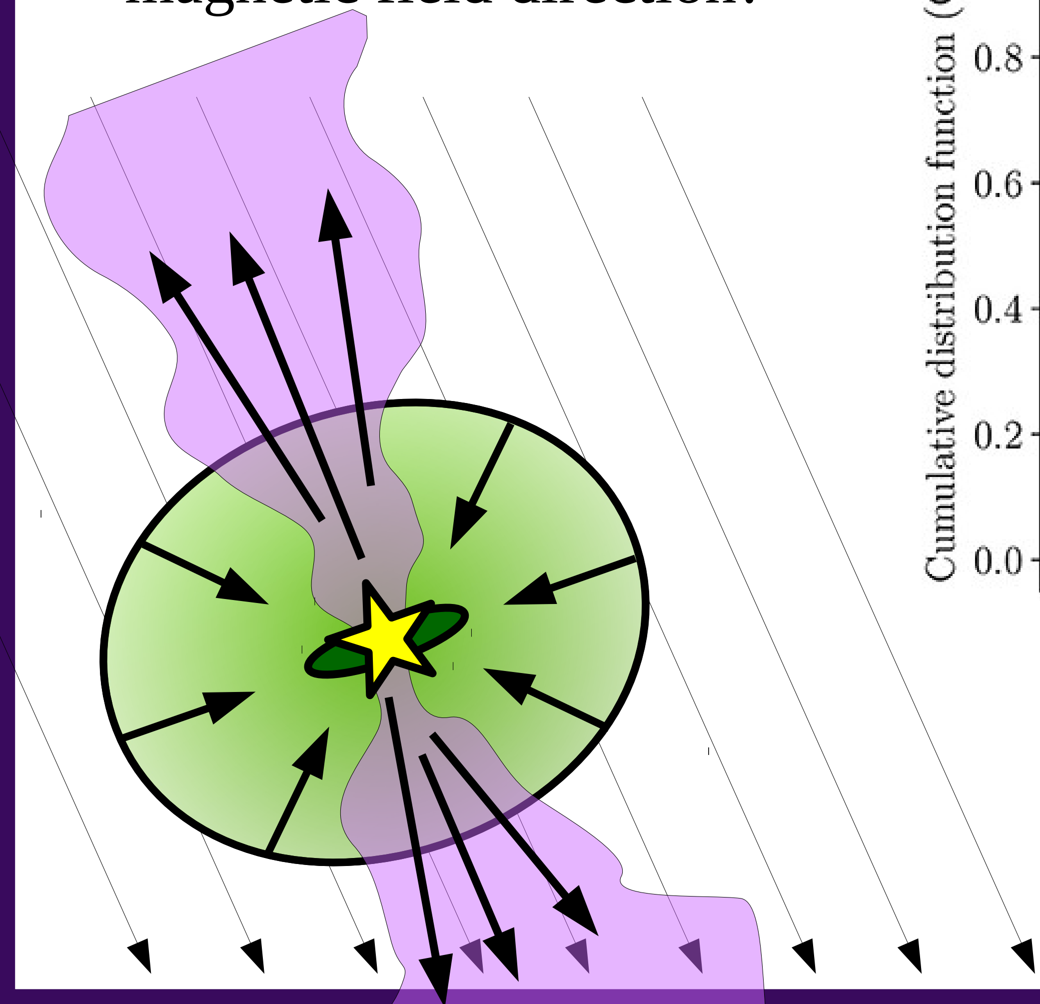
Perseus B1: Coudé et al. 2019, ApJ resubm.

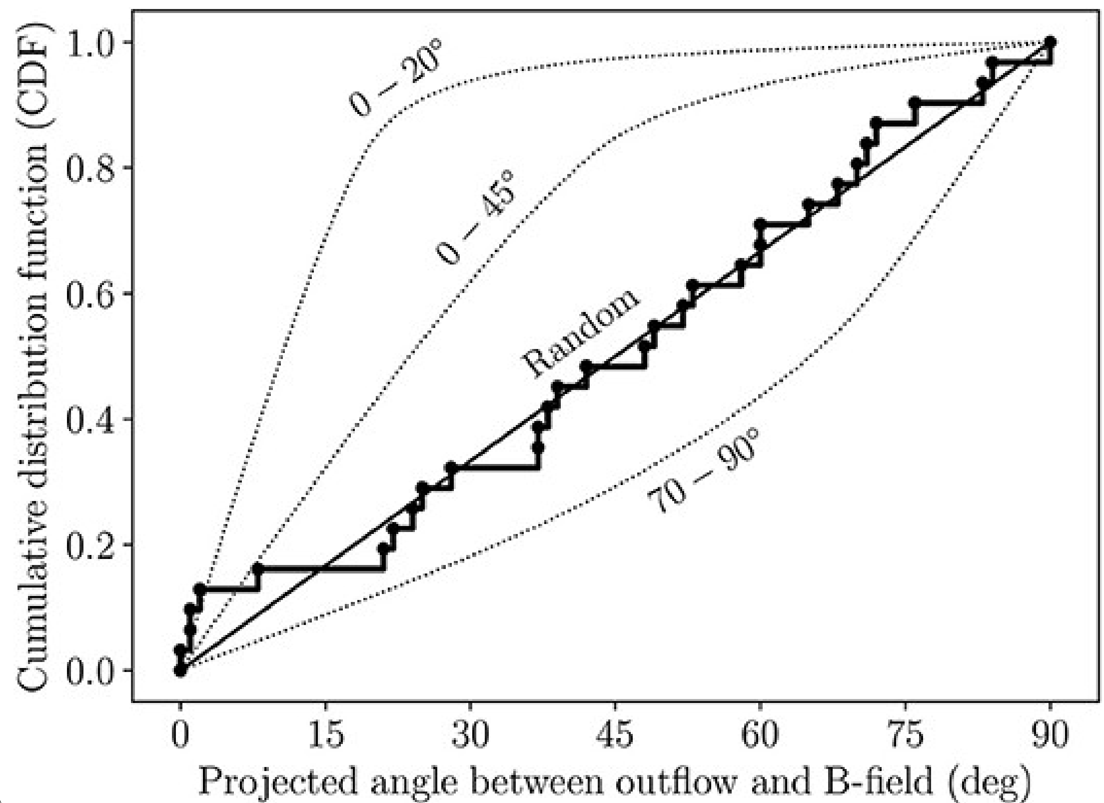


- Ordered magnetic field across the region
- Magnetic field strength 120±60 μG
- Magnetically supercritical: turbulence dominates over magnetic field
- Linear resolution ~0.02 pc

Are magnetic fields dynamically important in protostellar cores?

A test: are protostellar outflows aligned with the magnetic field direction?



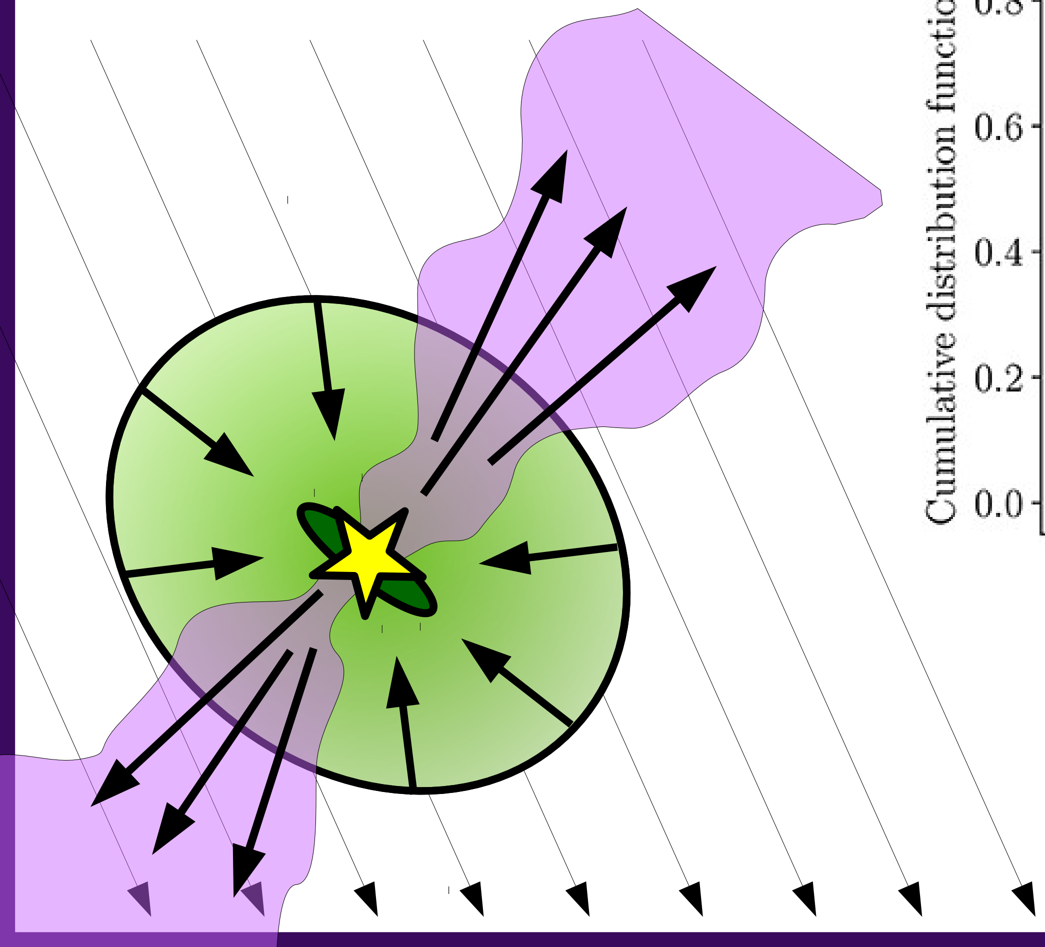


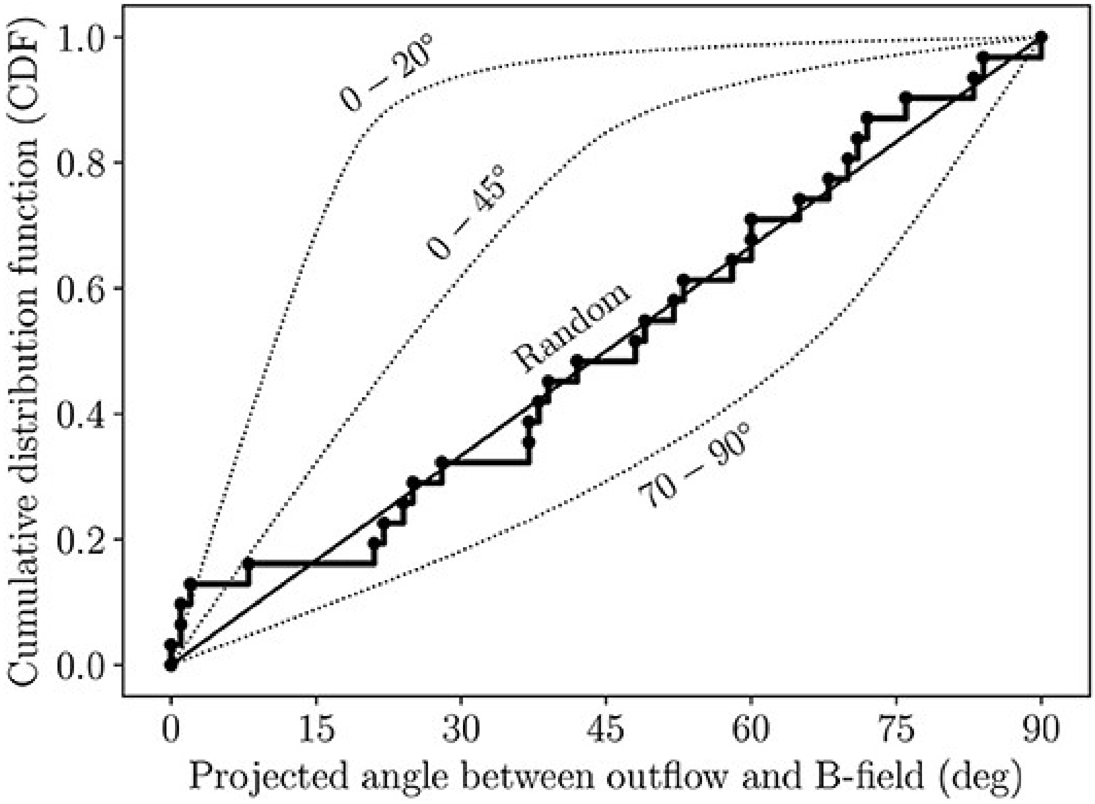
Hull & Zhang 2019, FrASS 6 3

B

Are magnetic fields dynamically important in protostellar cores?

A test: are protostellar outflows aligned with the magnetic field direction?

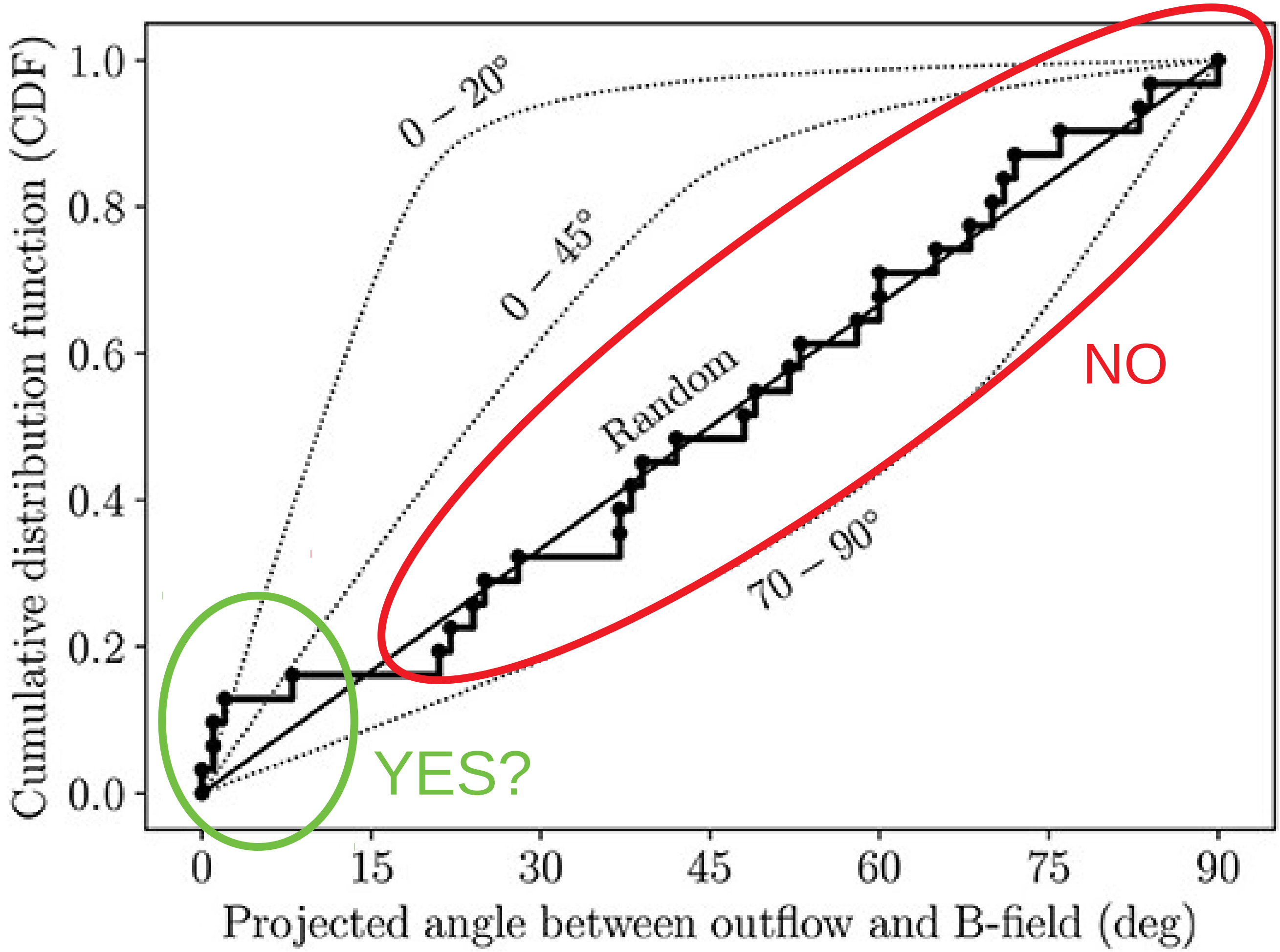




Hull & Zhang 2019, FrASS 6 3

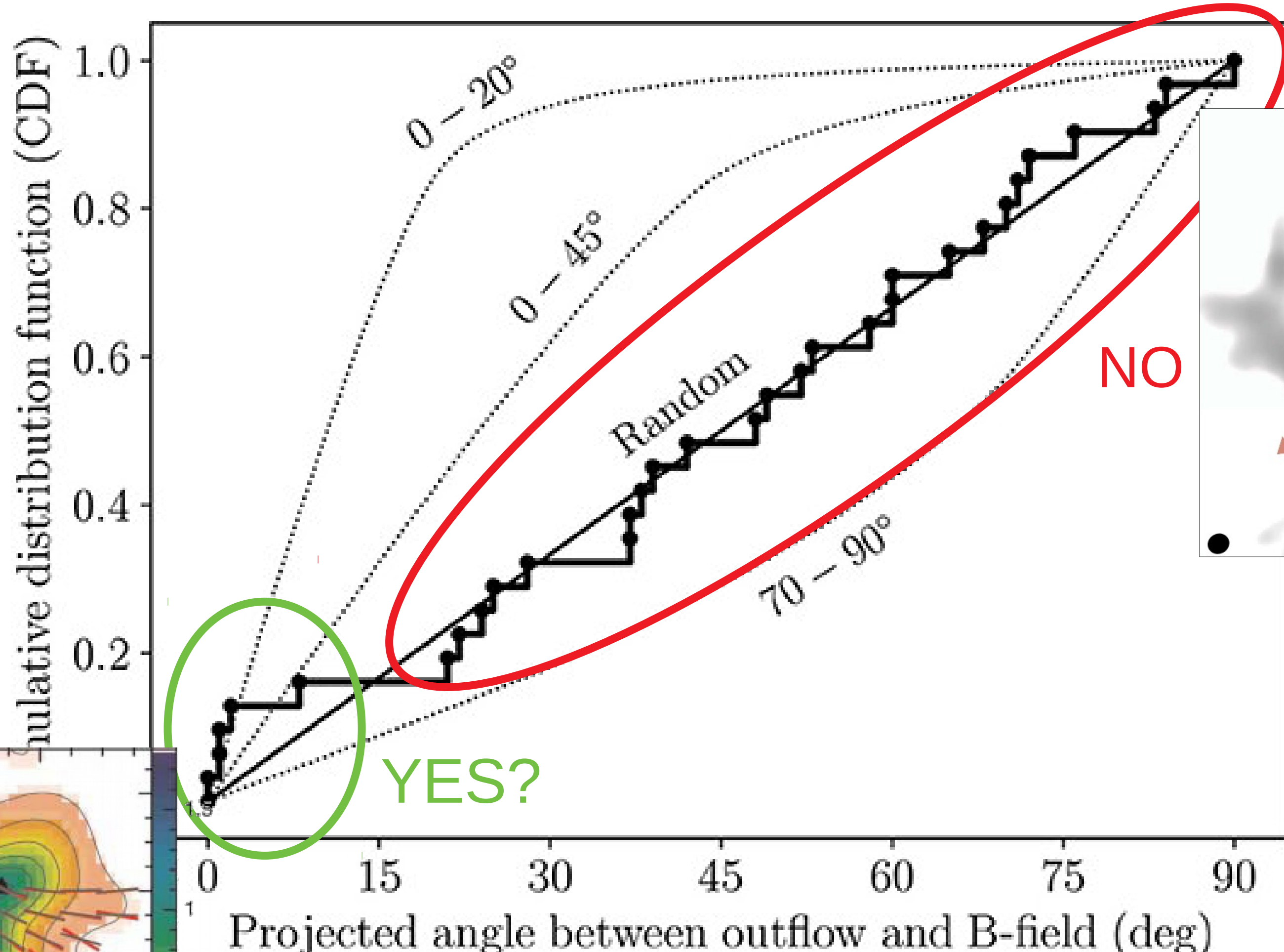
B

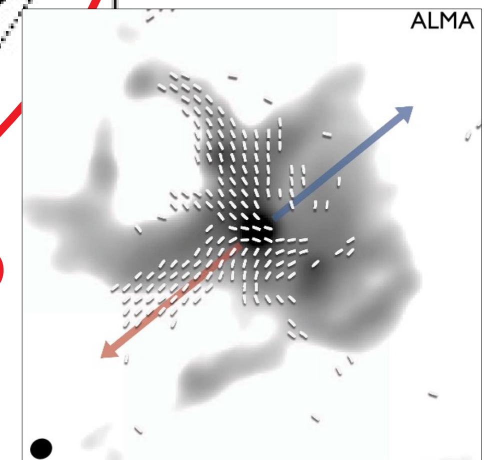
Are magnetic fields dynamically important in protostellar cores?

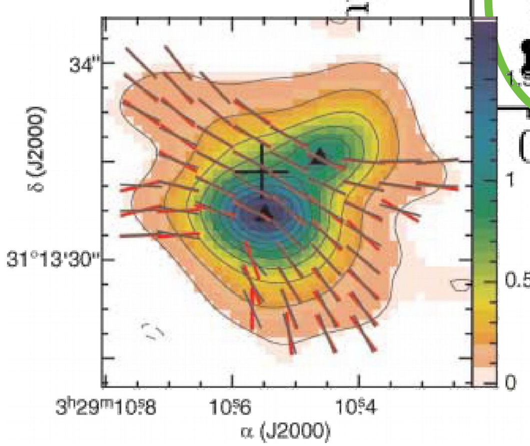


Hull & Zhang 2019, FrASS 6 3

Are magnetic fields dynamically important in protostellar cores?

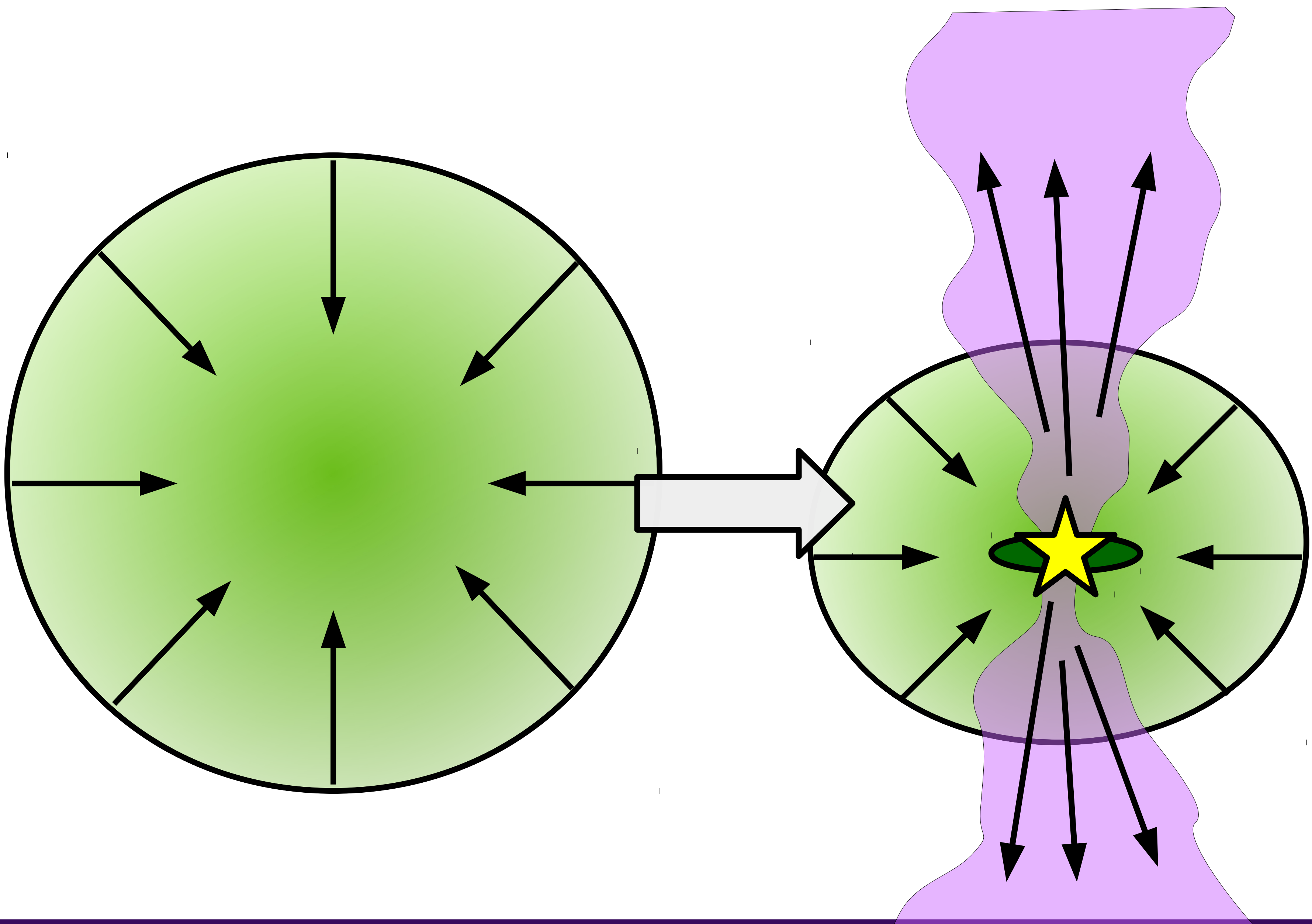






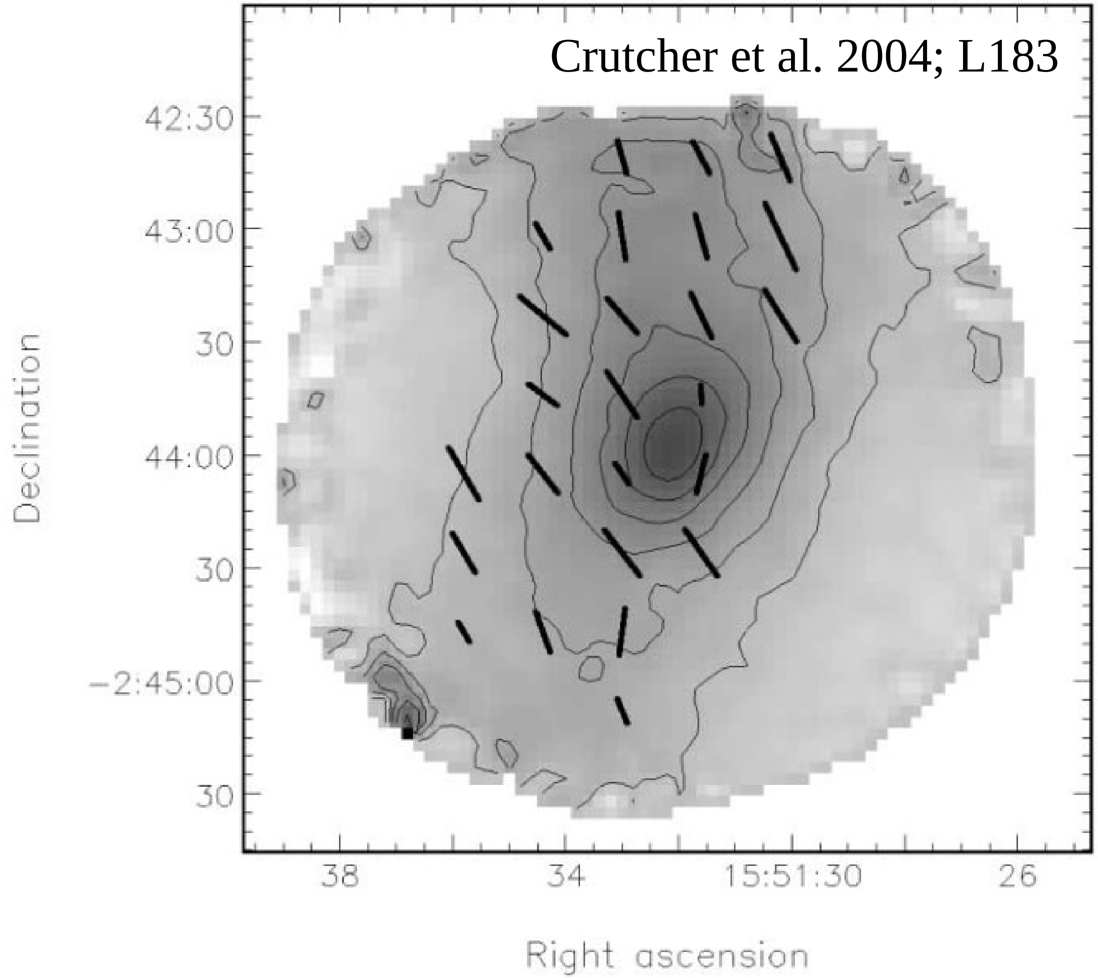
Hull & Zhang 2019, FrASS 6 3

So are magnetic fields dynamically important in **prestellar** cores?



What do magnetic fields in prestellar cores look like?

- Approximately linear, often ~30º to the core's minor axis (a projection effect; Basu 2000)
- Generally no clear hourglass morphology
- Magnetic field strengths ~10^1-10^2 μG



Question: How far into star-forming clumps are our observations actually tracing?

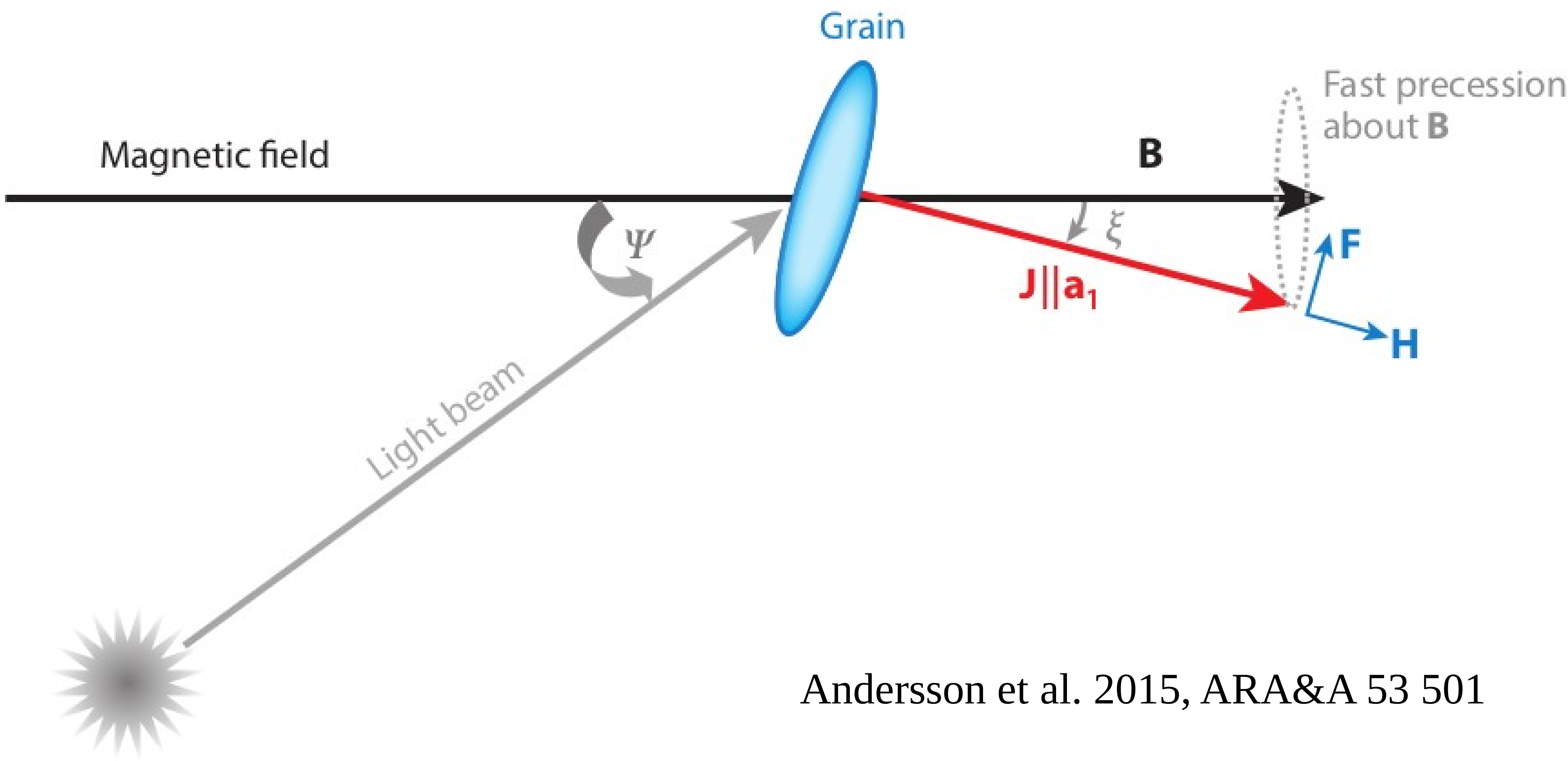
Proposed grain alignment mechanisms:

- **Davis-Greenstein:** grains are spun up by collisions with gas. Paramagnetic dissipation of energy leaves the grains aligned with the magnetic field

- **Mechanical alignment:** gas flows along the magnetic field direction; grains align with their angular moment perpendicular to the differential gas-dust flow

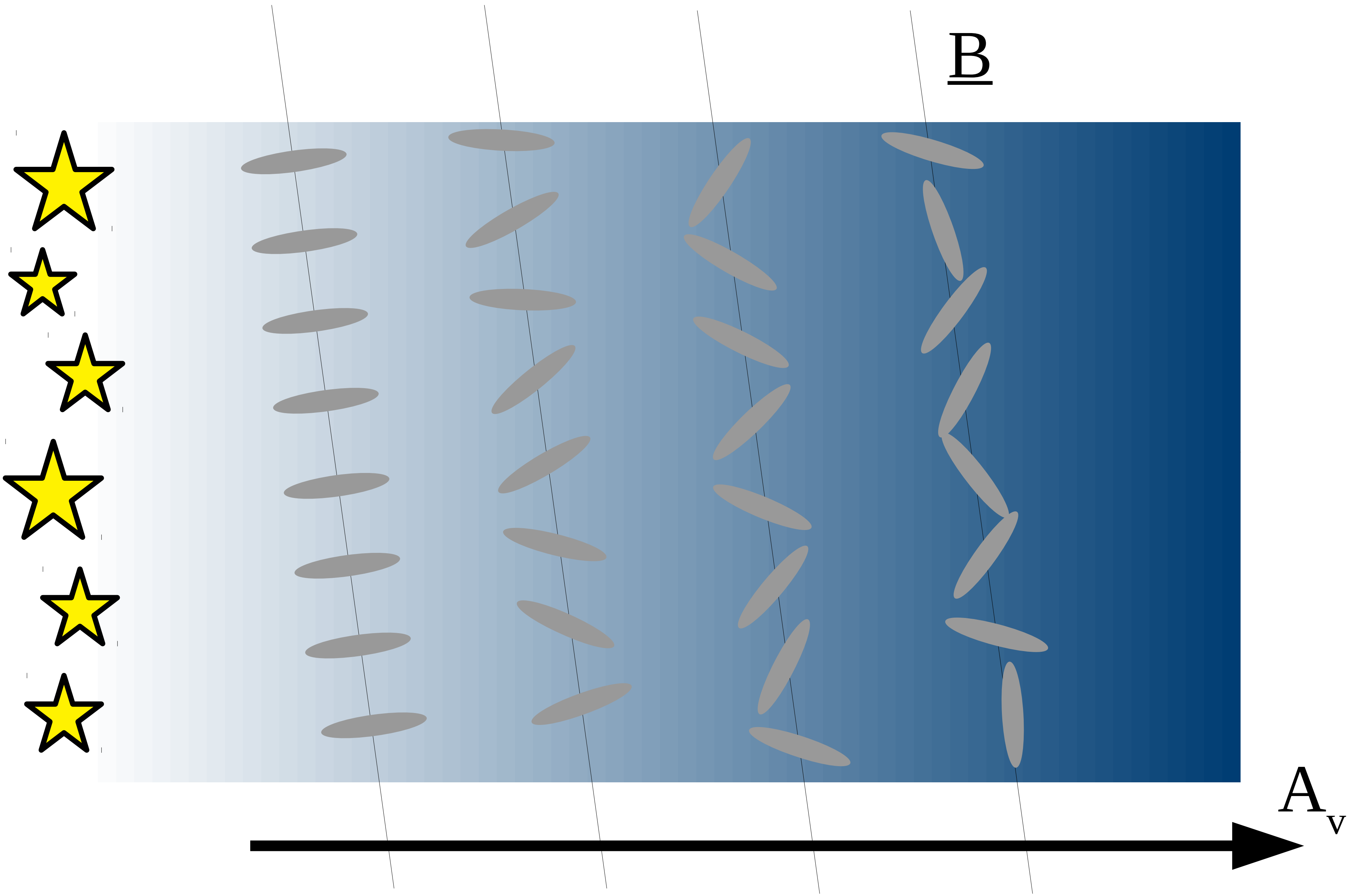
- **Radiative torque alignment:** differential extinction cross sections for left-and right-circularly polarized light induce torques on (hence spins up) irregular grains. Paramagnetic grains become magnetised, and precess around the magnetic field direction

Radiative torque alignment: differential extinction cross sections for left-and right-circularly polarized light induce torques on (hence spins up) irregular grains. Paramagnetic grains become magnetised, and precess around the magnetic field direction



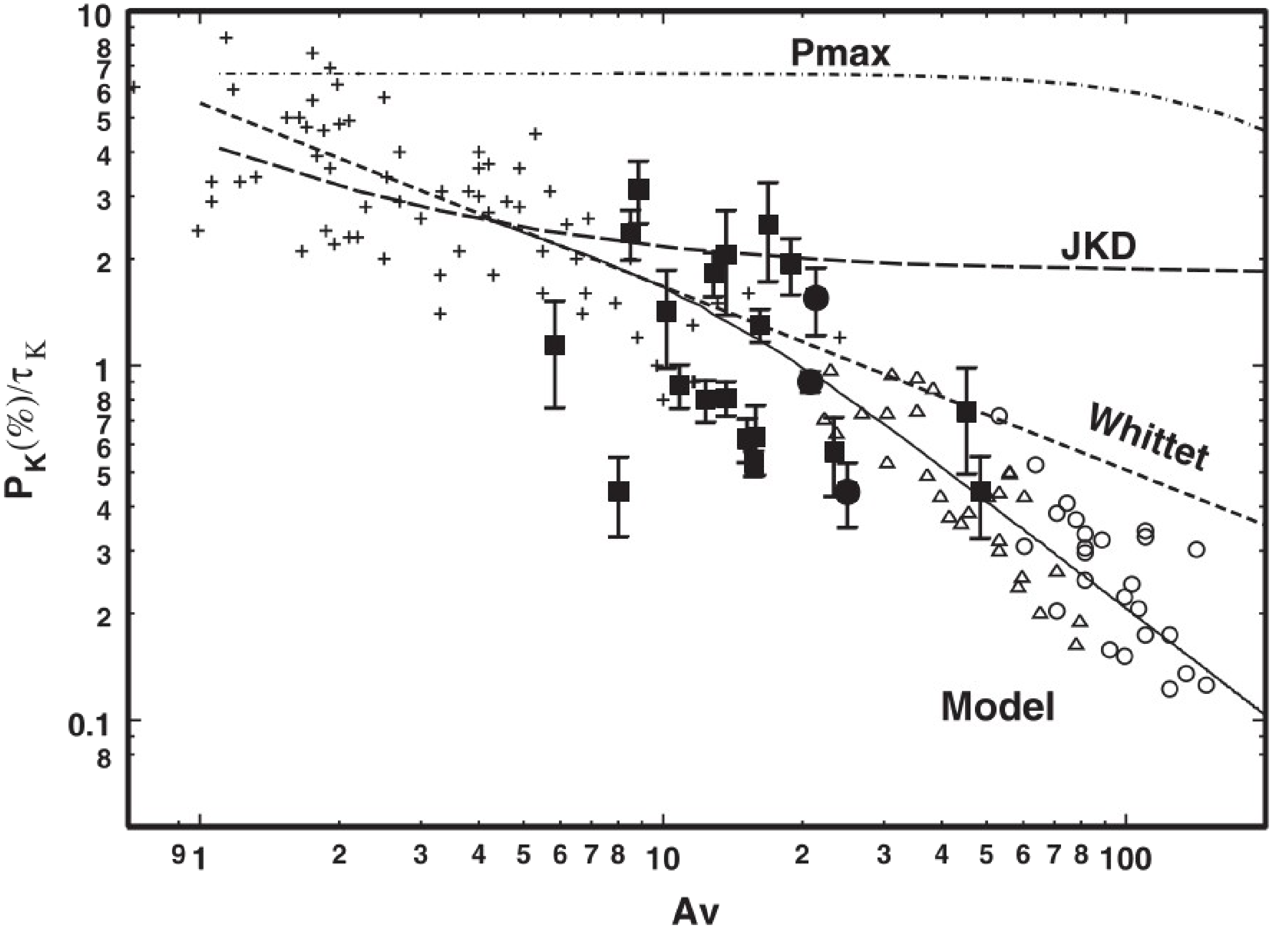
Andersson et al. 2015, ARA&A 53 501

What material is actually traced by polarization observations?



Polarization efficiency as a measure of grain alignment

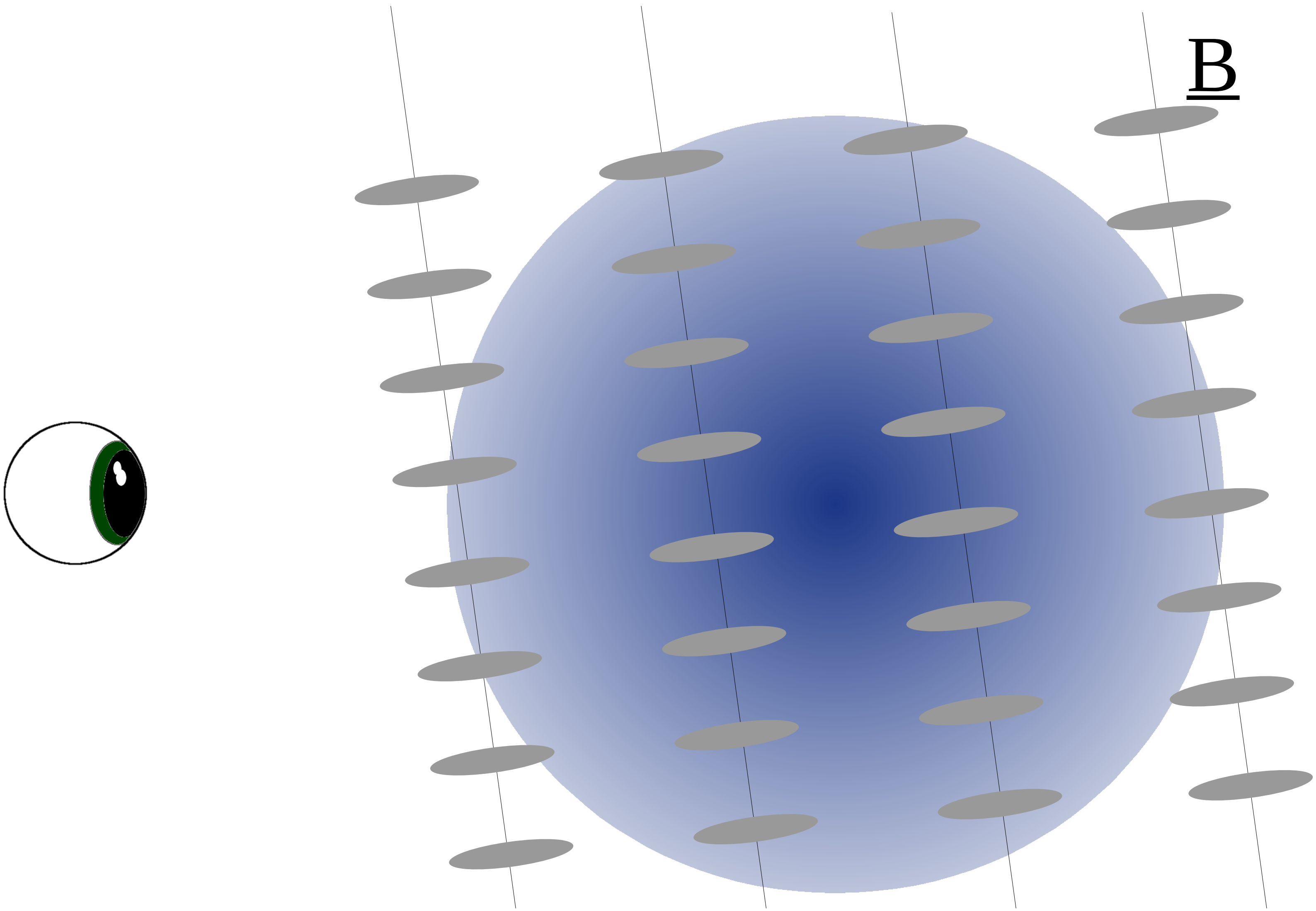
- Jones et al. (2015) propose that grains are entirely misaligned at $A_V > 20$
- If there is linearly decreasing grain alignment with optical depth: $\log(P/\tau) \sim -0.5\log(A_V)$
- If all polarized emission comes from a thin skin: $\log(P/\tau) \sim -1.0\log(A_V)$



Jones et al. (2015), AJ 149 31

<u>In the submillimetre:</u>
polarization efficiency = polarization fraction
I proportional to A_V (for isothermal, optically thin emission...)

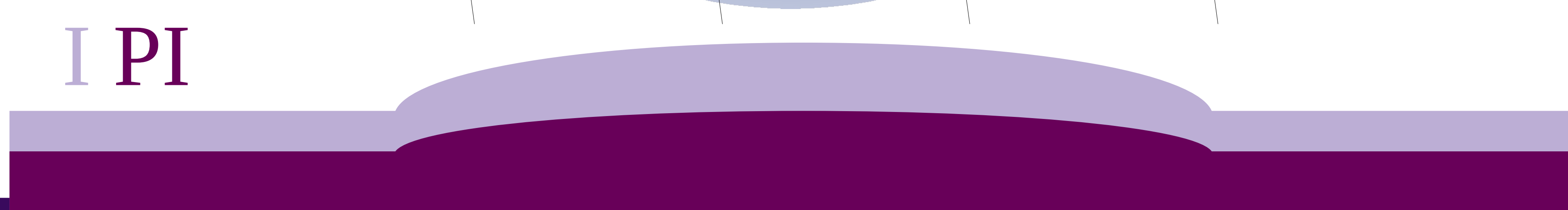
What material is actually traced by polarization observations?



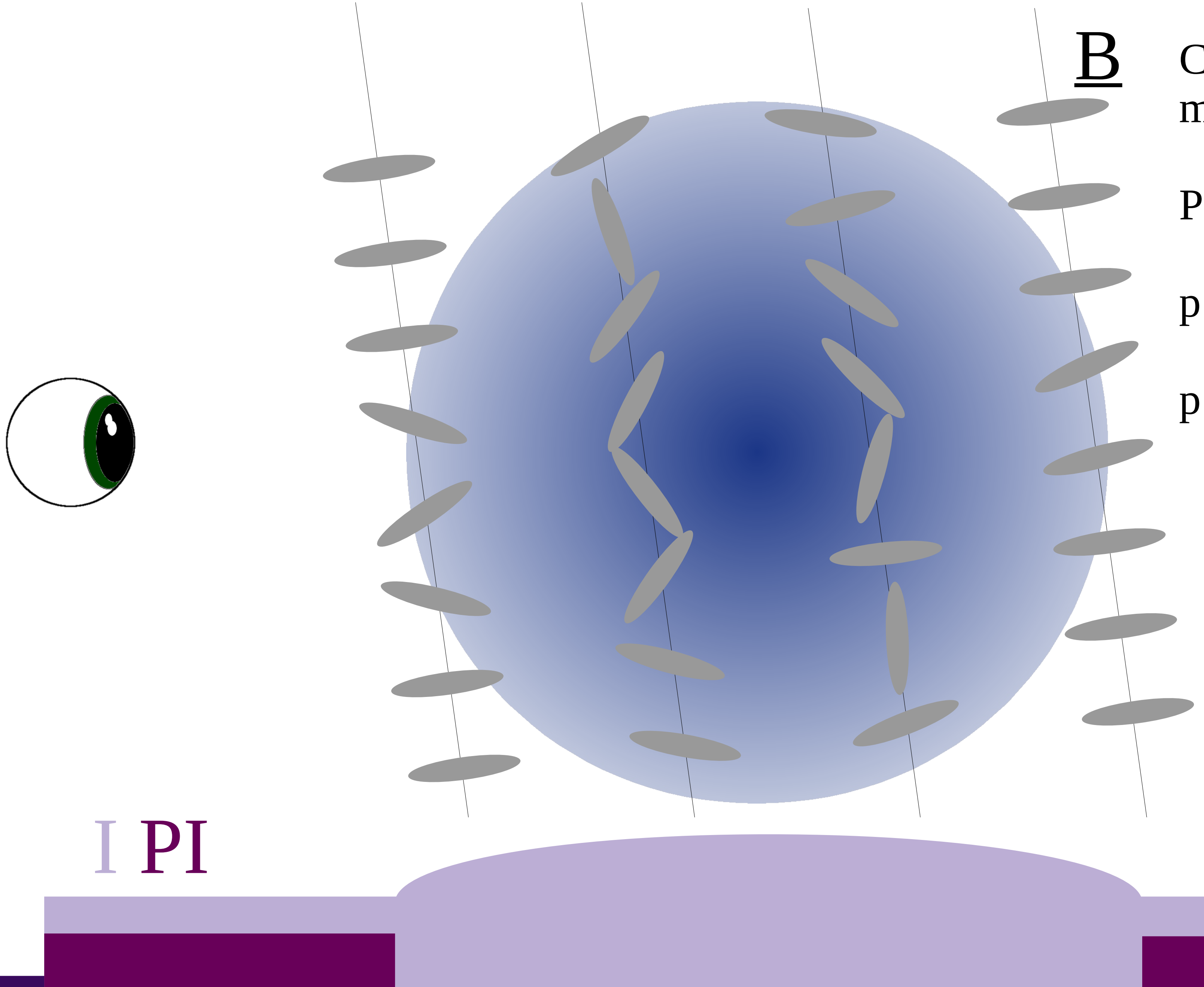
Perfect alignment:

PI ∝ I

p = constant



What material is actually traced by polarization observations?



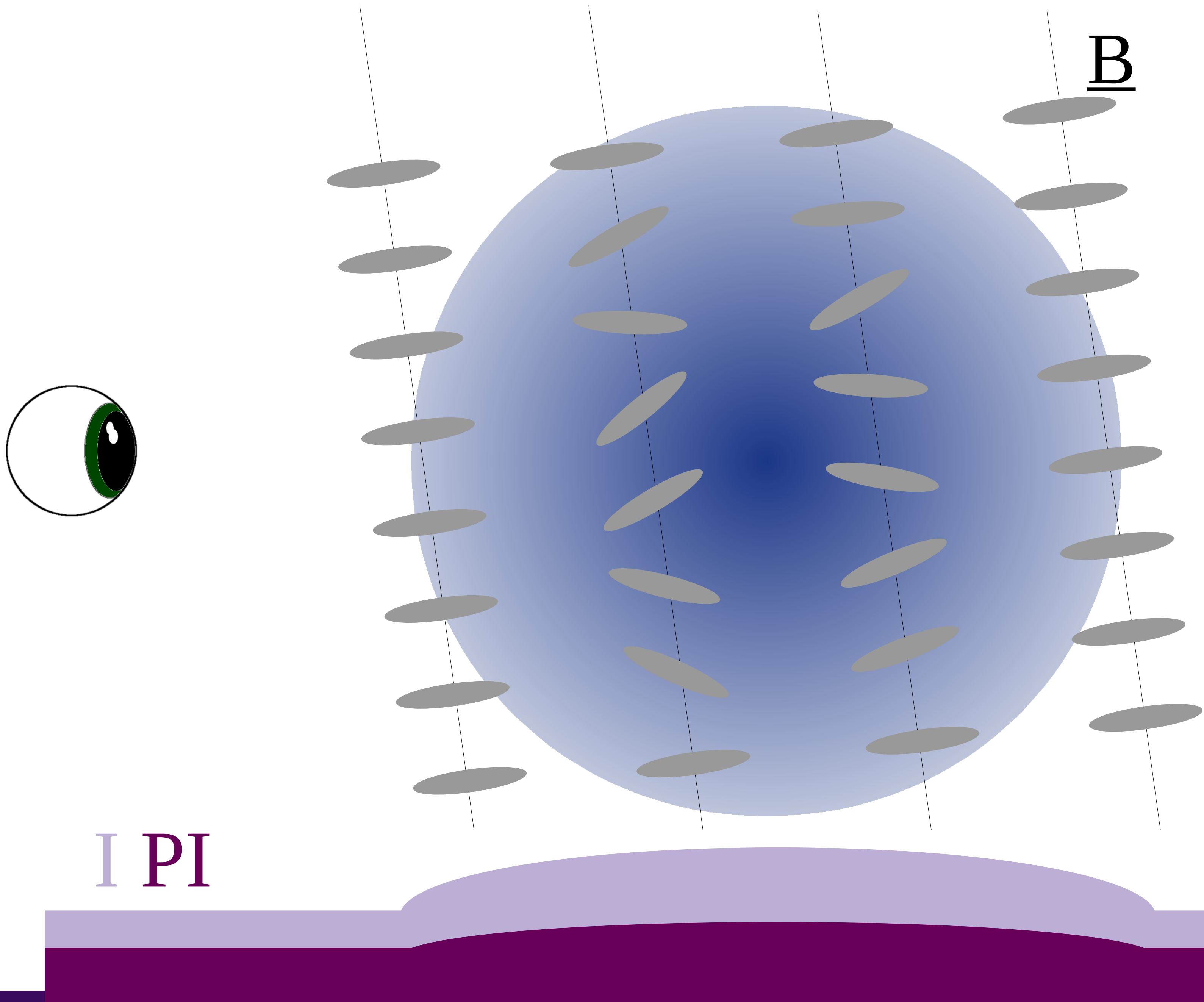
Complete misalignment:

PI (inside) = 0

p = PI(outside)/I

$p \propto 1/I$

What material is actually traced by polarization observations?



Some alignment:

PI increases with, but slower than, I

Polarization fraction $\propto I^{-\alpha}$

Polarization efficiency as a measure of grain alignment

$$p(I) = p_0 \left(\frac{I}{I_0} \right)^{-\alpha}$$

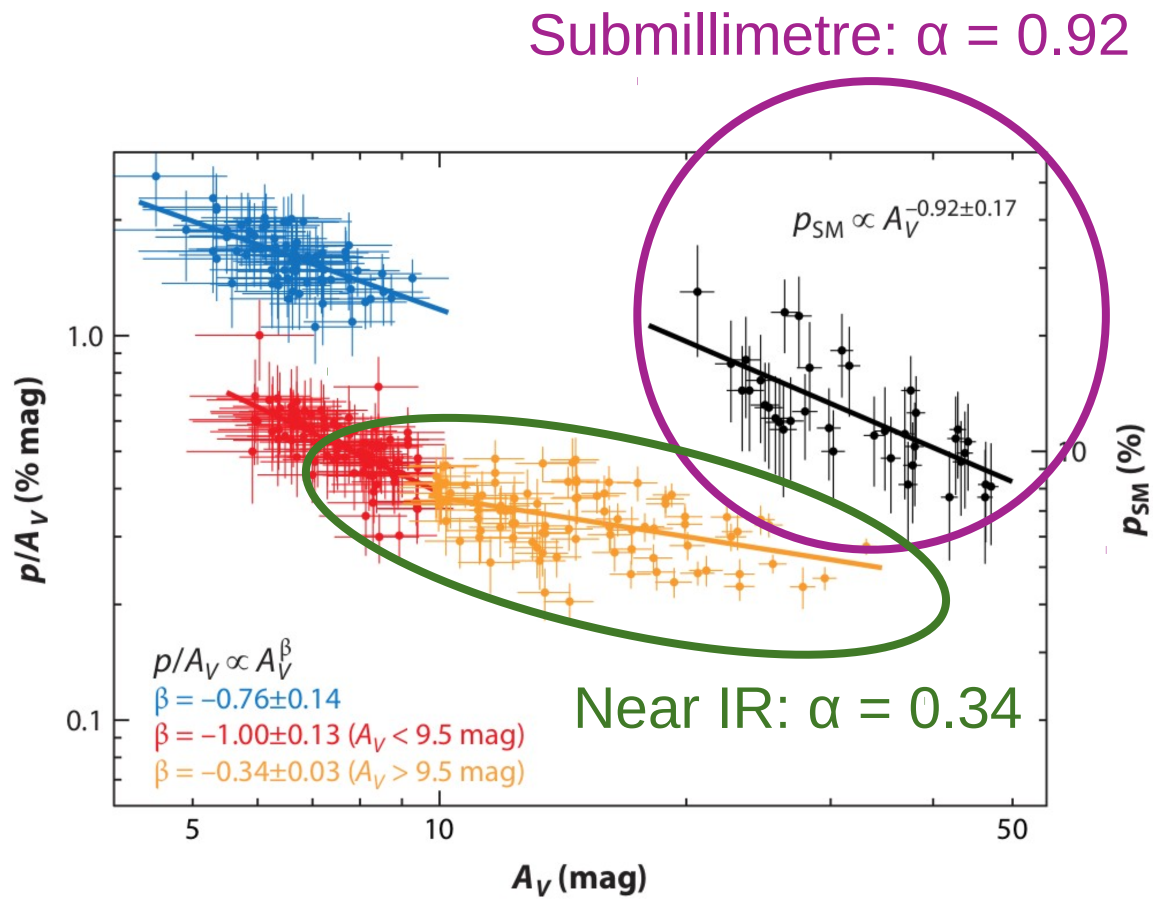
We expect $0 < \alpha < 1$

$\alpha = 0$ indicates all grains are equally aligned – no depolarization

$\alpha = 1$ indicates statistical noise in Stokes Q and U

Two possibilities:

- A genuine lack of signal in Q and U: complete depolarization
- Insufficient signal-to-noise to detect Q and U emission

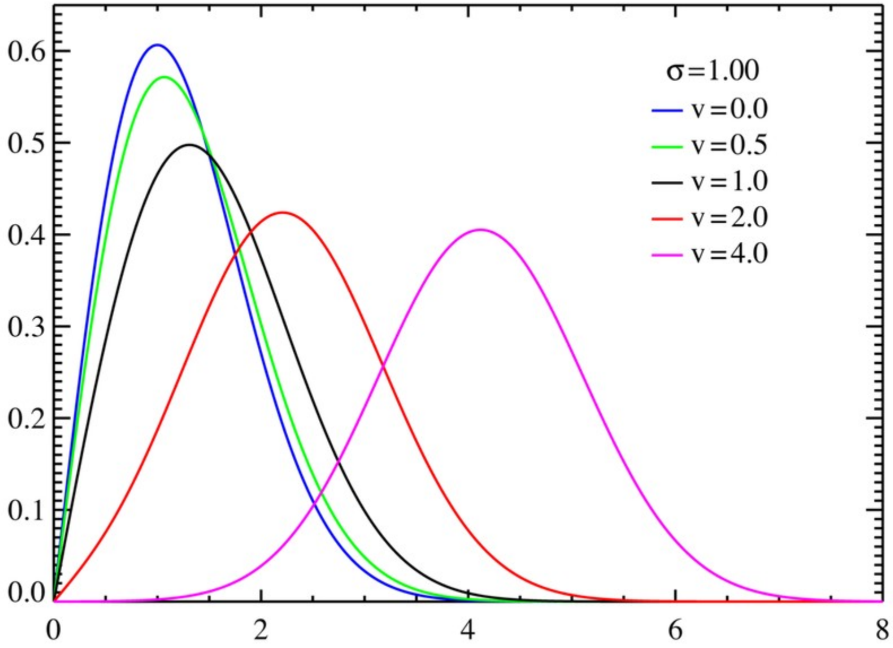


Alves et al. 2014 A&A 569 L1

The effect of Ricean statistics on observed polarization fraction

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

$$PDF_{Rice}(p'|p) = \frac{p'}{\sigma_p^2} \exp\left(-\frac{p'^2 + p^2}{2\sigma_p^2}\right) \mathcal{I}_0\left(\frac{p'p}{\sigma_p^2}\right)$$



At high S/N, the Ricean distribution tends to Gaussian behaviour.

At low S/N, the Ricean distribution creates a strong positive bias in observed data.

The effect of Ricean statistics on observed polarization fraction

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

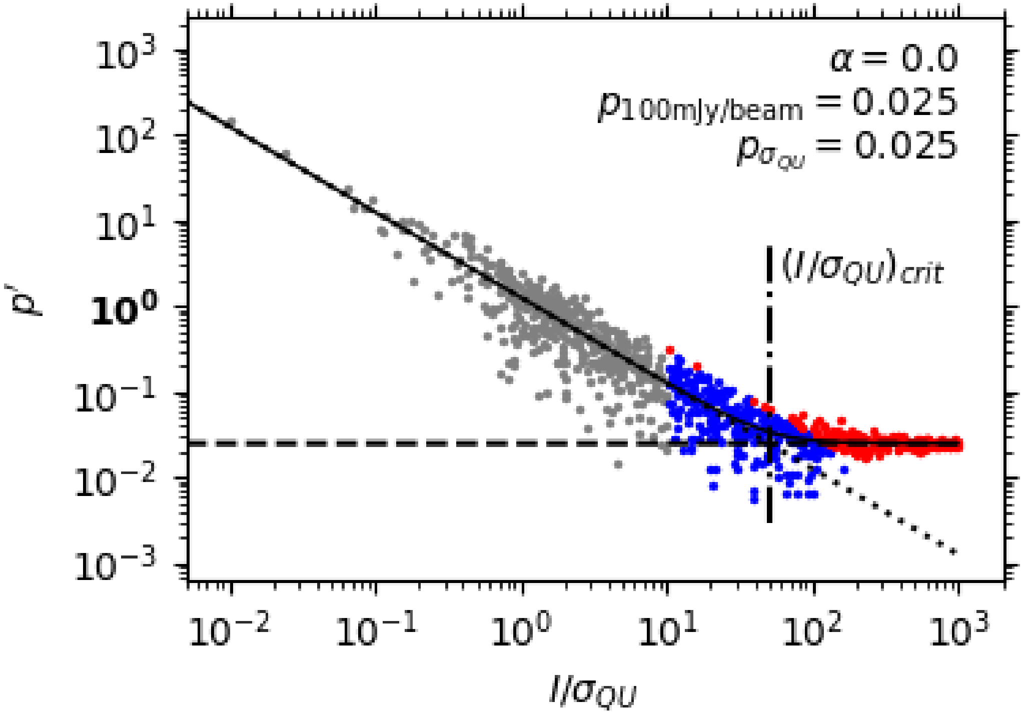
$$\mu_p = \sqrt{\frac{\pi}{2}}\sigma_p \mathcal{L}_{\frac{1}{2}}\left(-\frac{p^2}{2\sigma_p^2}\right)$$

$$p << \sigma_p,\ \mu_p \rightarrow \sigma_p\sqrt{\pi/2}$$

$$\sigma_p \approx \sigma_{QU}/I$$

And so, at low signal-to-noise,

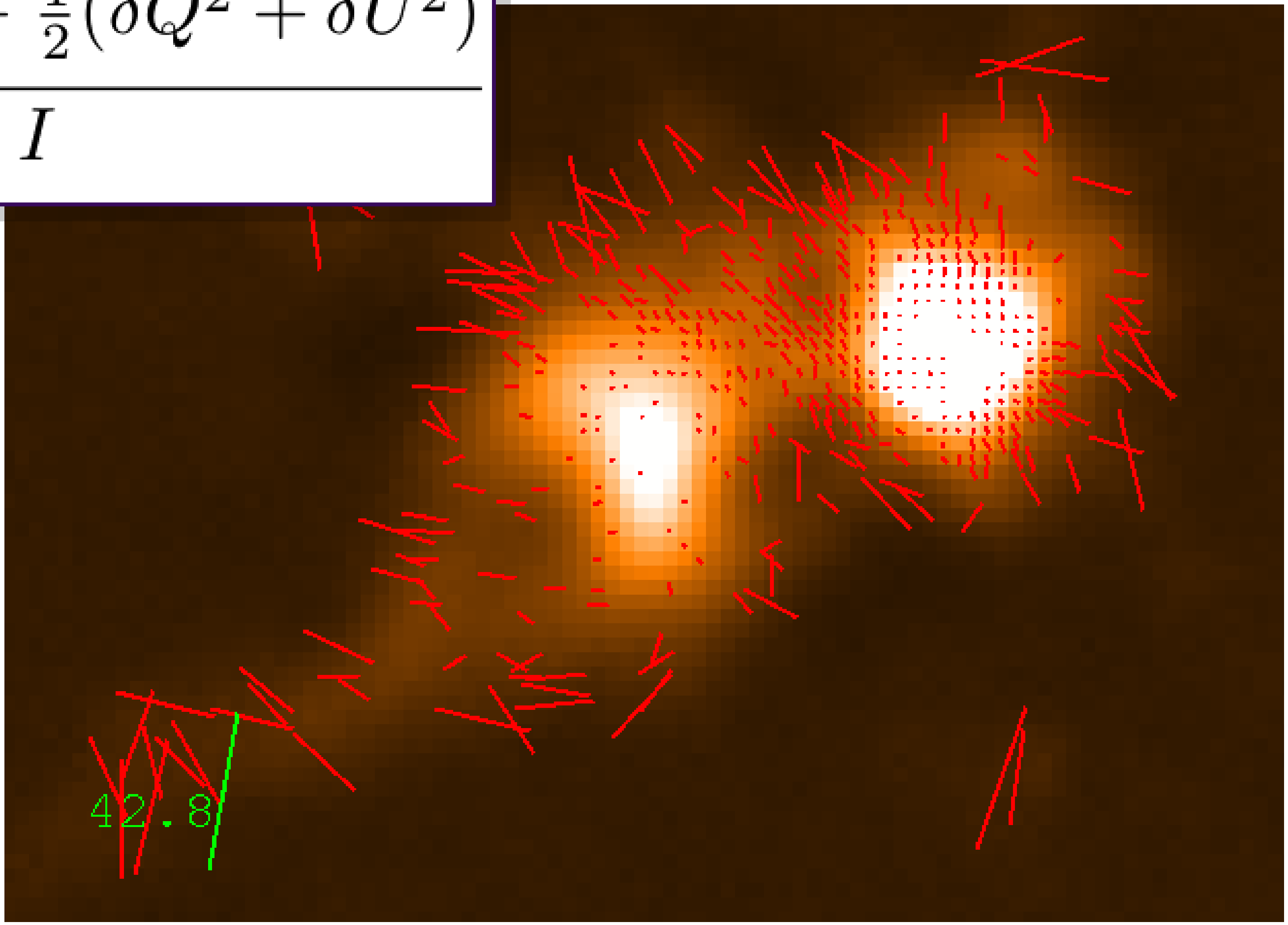
$$p' = \sqrt{\frac{\pi}{2}}\left(\frac{I}{\sigma_{QU}}\right)^{-1}$$



Statistical debiasing?

$$p'_{db} = \frac{\sqrt{Q^2 + U^2 - \frac{1}{2}(\delta Q^2 + \delta U^2)}}{I}$$

pol2map default method
(Wardle & Kronberg 1974)

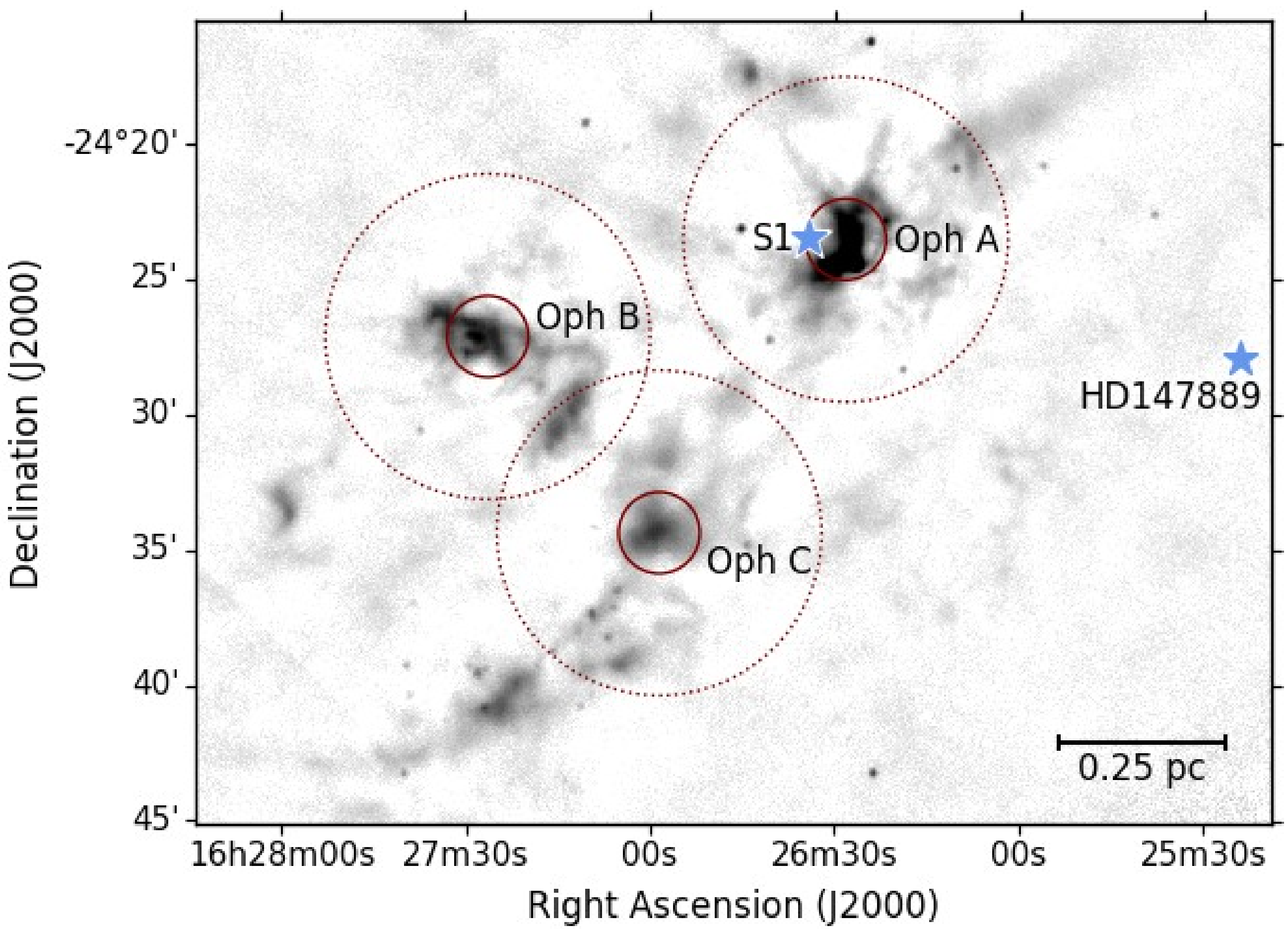


<u>Other methods:</u>
Simmons & Stewart 1985
Vaillancourt 2006
Quinn 2012
Montier et al. 2015a,b
Vidal et al. 2016
Müller et al. 2017

…and others I've missed?

p/dp > 3, I/dI > 10, **debiased**

The Ophiuchus Molecular Cloud



A nearby region of low-to-intermediate-mass star formation (138pc; Ortiz-Leon et al. 2018)

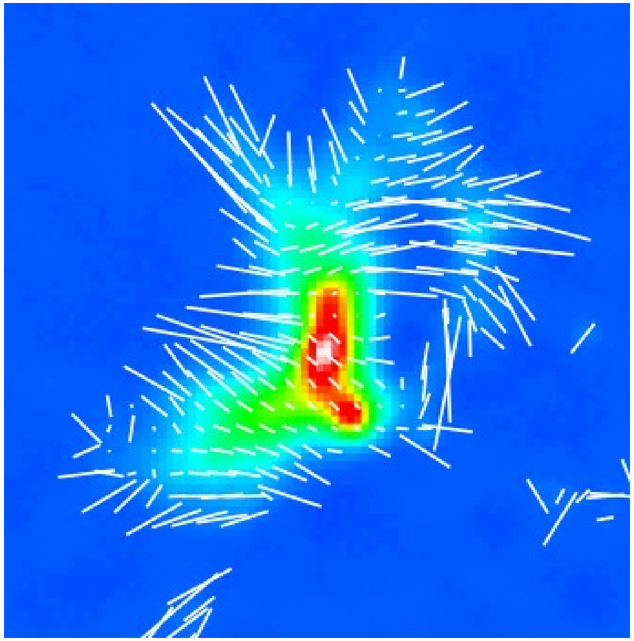
Contains a number of dense clumps with differing star formation histories in close proximity

Global influence from Sco OB2 association, ~11pc to the west

Two embedded B stars

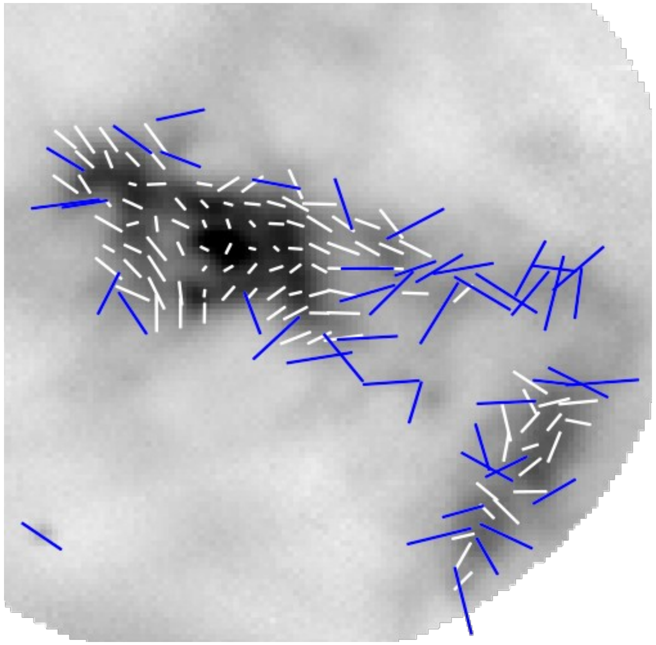
An excellent laboratory for testing star formation theories

Oph A
Kwon et al. 2018, ApJ 659 4



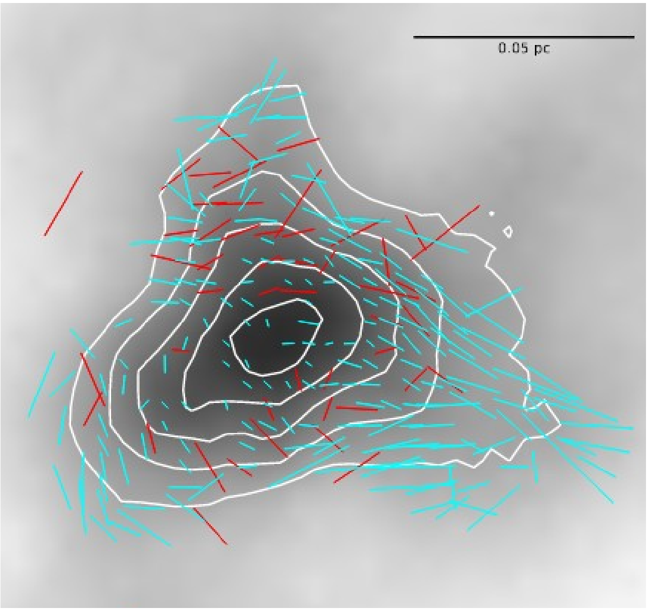
- Actively forming stars (contains outflow-driving sources)
- Sandwiched between two B stars
- Well-ordered magnetic field with significant variation across the region
- Magnetic field strength ranges from 200μG to 5mG

Oph B
Soam et al. 2018, ApJ 861 64



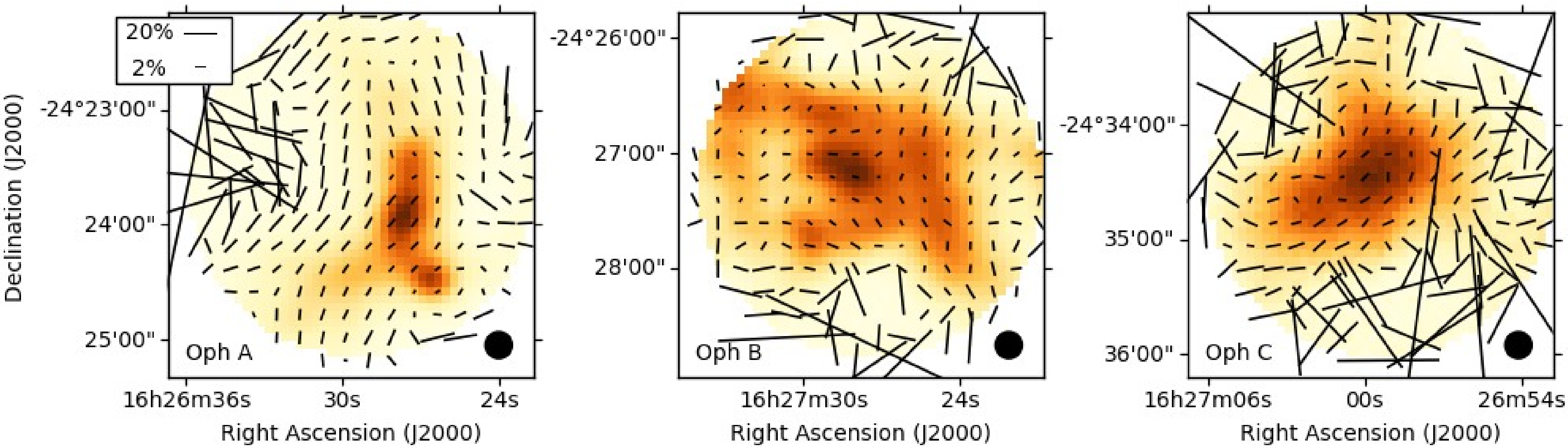
- Actively forming stars (contains outflow-driving sources)
- No sign of significant external influence
- Oph B1 (right): highly disordered field
- Oph B2 (left): somewhat ordered magnetic field with some similarity to large-scale 50° field
- Oph B2: Magnetic field strength 630±410 μG

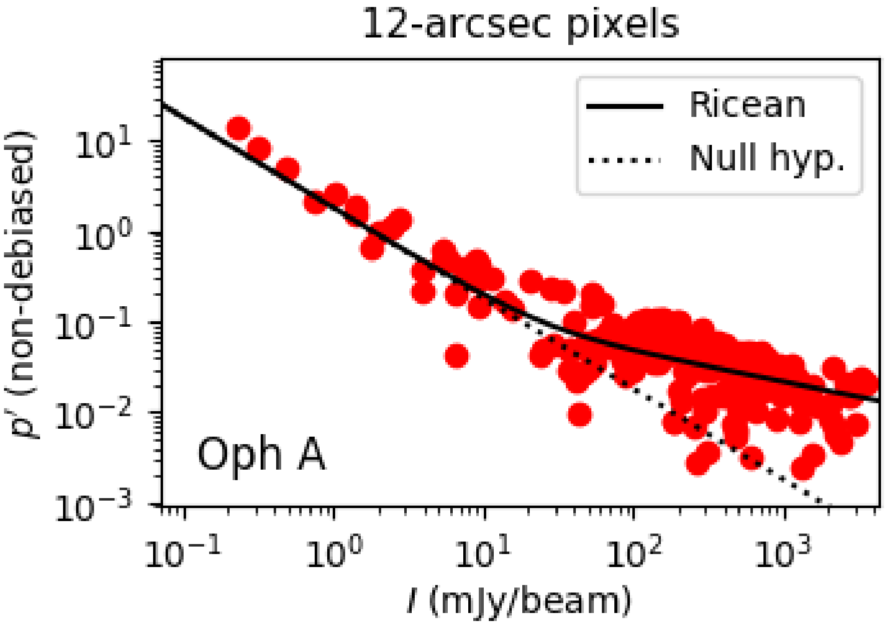
Oph C
Liu et al. 2018, ApJ in press
arXiv:1902.07734



- Quiescent (few or no embedded protostars
- No sign of significant external influence
- Fairly well-ordered magnetic field, similar to large-scale 50° field
- Magnetic field strength ~100-200 μG

Measuring α in Ophiuchus L1688





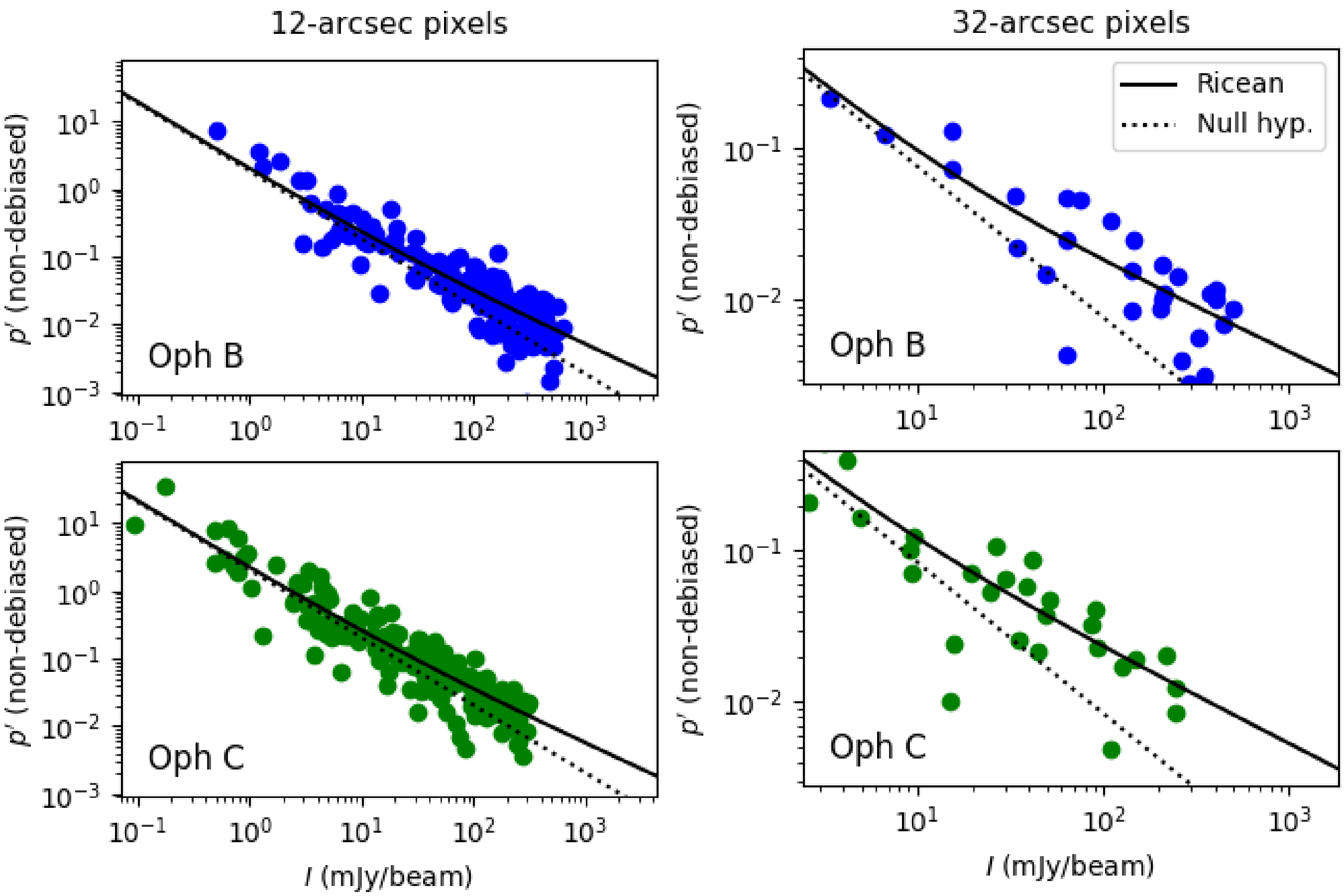
Oph A: α = 0.34, $p_{100mJy/beam}$ = 4.7%

Grains appear to remain aligned at high densities in Oph A.

Fitted function:

$$\mu_p = \sqrt{\frac{\pi}{2}}\sigma_p \mathcal{L}_{\frac{1}{2}}\left(-\frac{p^2}{2\sigma_p^2}\right)$$

Measuring α in Ophiuchus L1688

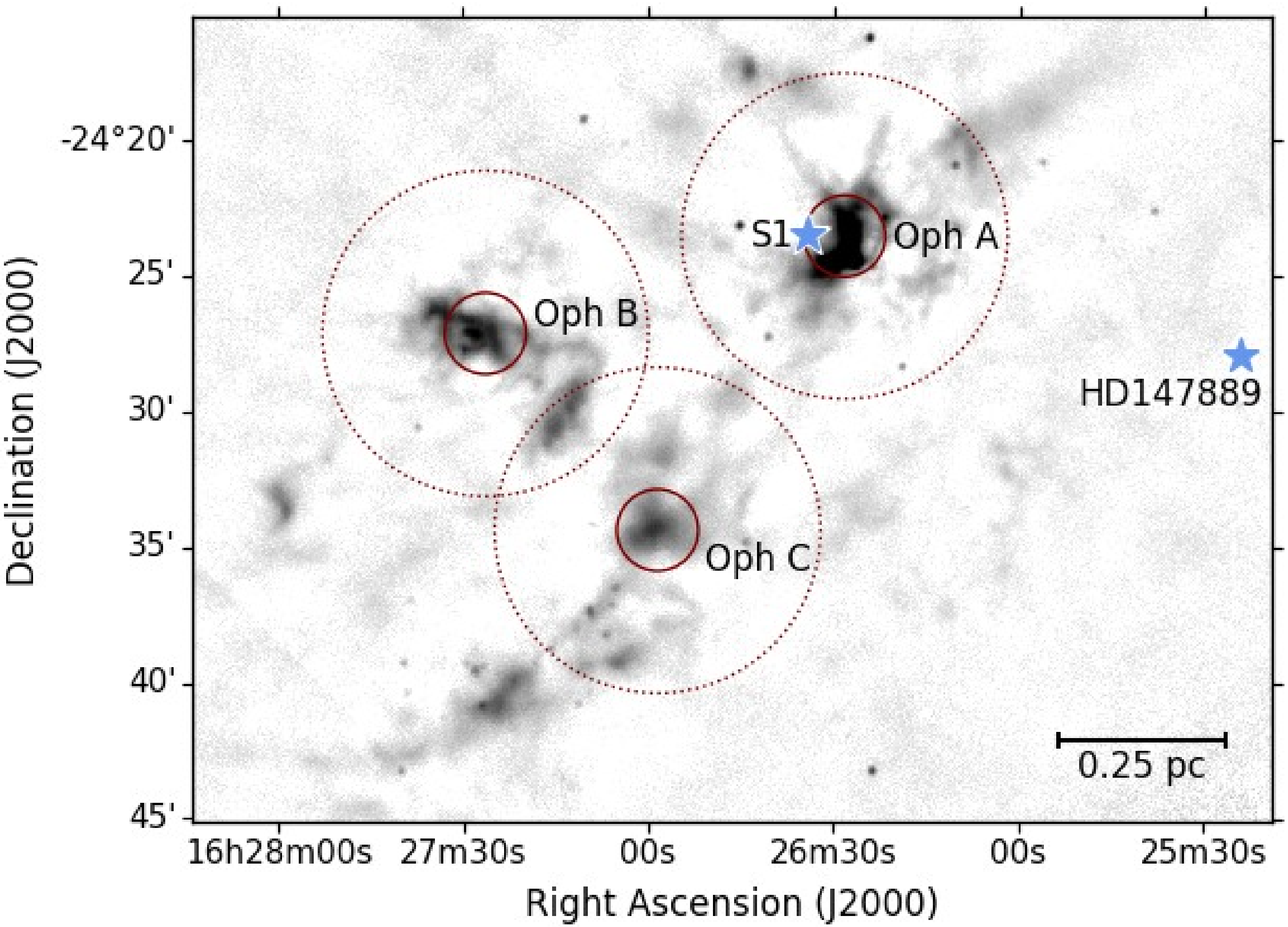


Oph B & C:

α ~ 0.6 - 0.7,
$p_{100mJy/beam}$ ~ 2%

Grains are not as well-aligned in Oph B & C as in Oph A, but some alignment persists

The radiation field of Ophiuchus



Pattle et al., in prep.

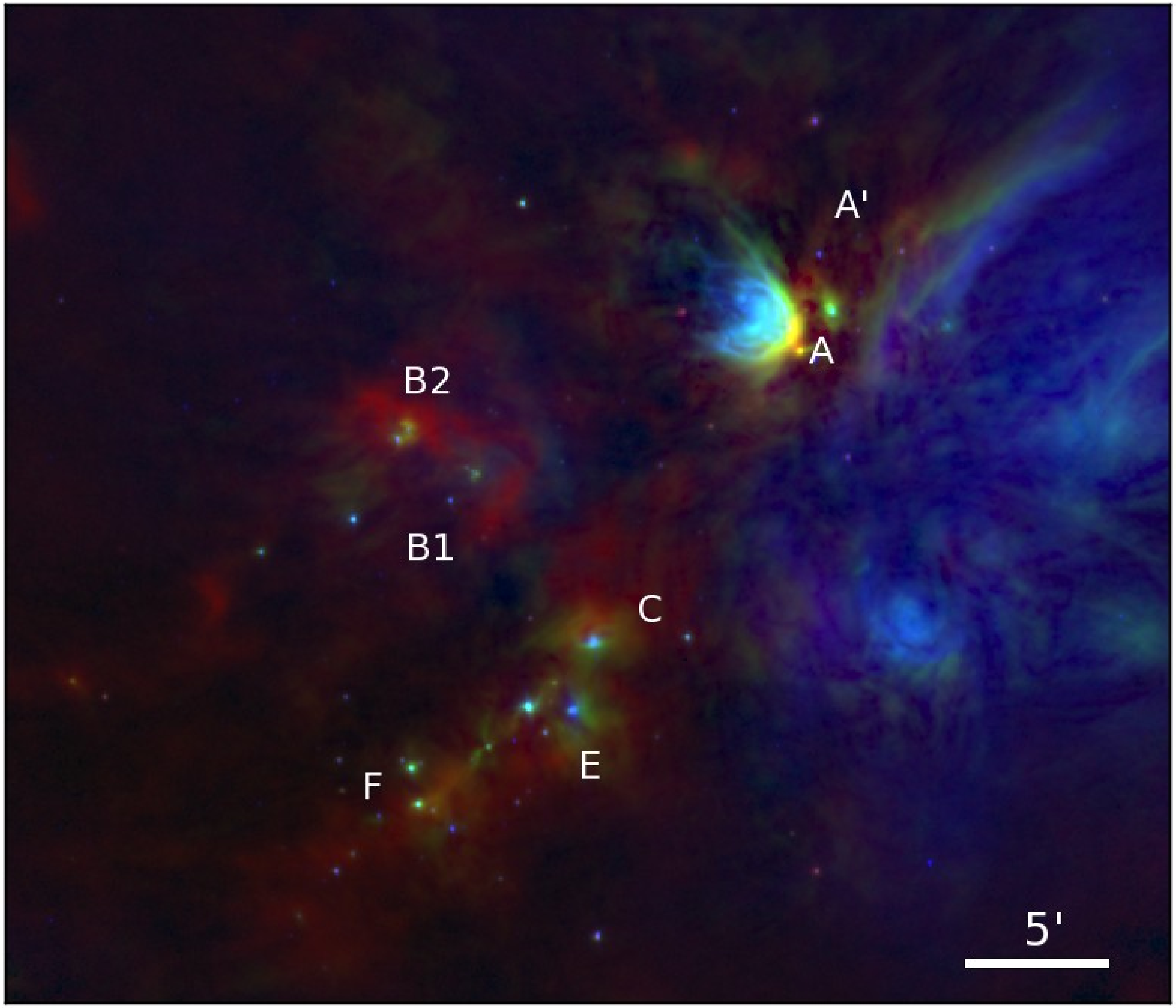
Global influence from Sco OB2 (West to East across cloud)

Two B stars, embedded in cloud, but not in clumps:

HD147889: B2V

S1: ~B4V

The radiation field of Ophiuchus



R: SCUBA-2 850μm, G: Herschel 100μm, B: Spitzer 8μm
Pattle et al. (2015) MNRAS 450 1094

Global influence from Sco OB2 (West to East across cloud)

Two B stars, embedded in cloud, but not in clumps:

HD147889: B2V

S1: ~B4V

The radiation field of Ophiuchus

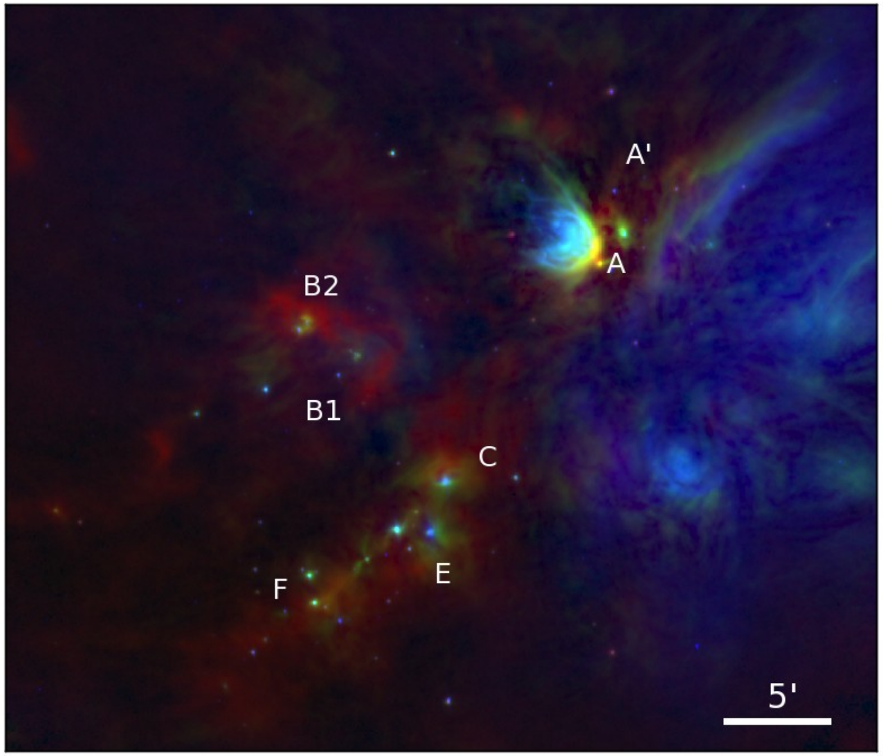
	Plane-of-sky distance (pc)		Upper-limit ionizing photon flux ($s^{-1}m^{-2}$)		
Region	HD147889	S1	HD147889	S1	Total
Oph A	0.62	0.05	7.0×10^{10}	1.5×10^{11}	2.2×10^{11}
Oph B	1.13	0.51	2.1×10^{10}	1.2×10^{9}	2.2×10^{10}
Oph C	0.91	0.50	3.2×10^{10}	1.2×10^{9}	3.4×10^{10}

Ionizing photon flux on Oph A is an order of magnitude higher than on Oph B and C

Oph A and B behave differently despite both actively forming stars

Oph B and C behave the same despite differing star formation histories

Are differences in grain alignment properties due to the higher (and bluer) radiation field on Oph A?



R: SCUBA-2 850µm, G: Herschel 100µm, B: Spitzer 8µm
Pattle et al. (2015) MNRAS 450 1094

Summary

- We generally see ordered, non-hourglass magnetic fields in dense clumps and cores
- Fitting a single power-law model is likely to result in overestimation of the extent to which grain alignment has been lost
- An accurate power-law index can in many cases be recovered by fitting the mean of the Ricean distribution
- Grains in the Oph A region are well-aligned with the magnetic field at high visual extinction, probably due to its strong external radiation field
- Grains in Oph B and C retain some alignment with the magnetic field at high extinctions despite having a much weaker external radiation field than Oph A
- The clumps' star formation history does not appear to affect the grain alignment
- Grain alignment in Ophiuchus appears to be driven by incident radiation field
- **Grains may remain aligned at much higher extinctions than has previously been believed to be the case**

Thank you!