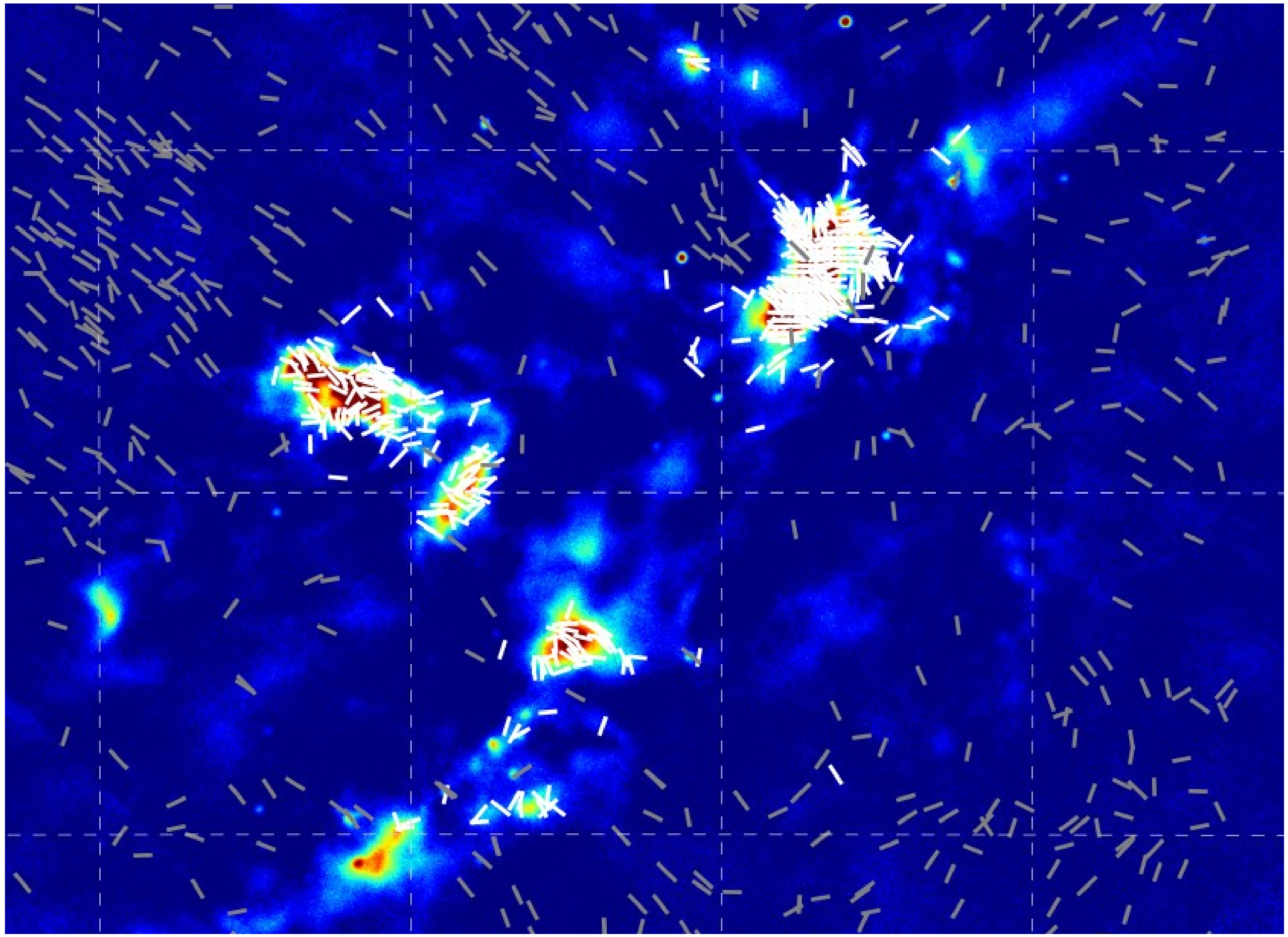
The JCMT BISTRO Survey: Grain alignment in the Ophiuchus Molecular Cloud



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Zooming in on Star Formation, Nafplio, 11th June 2019

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

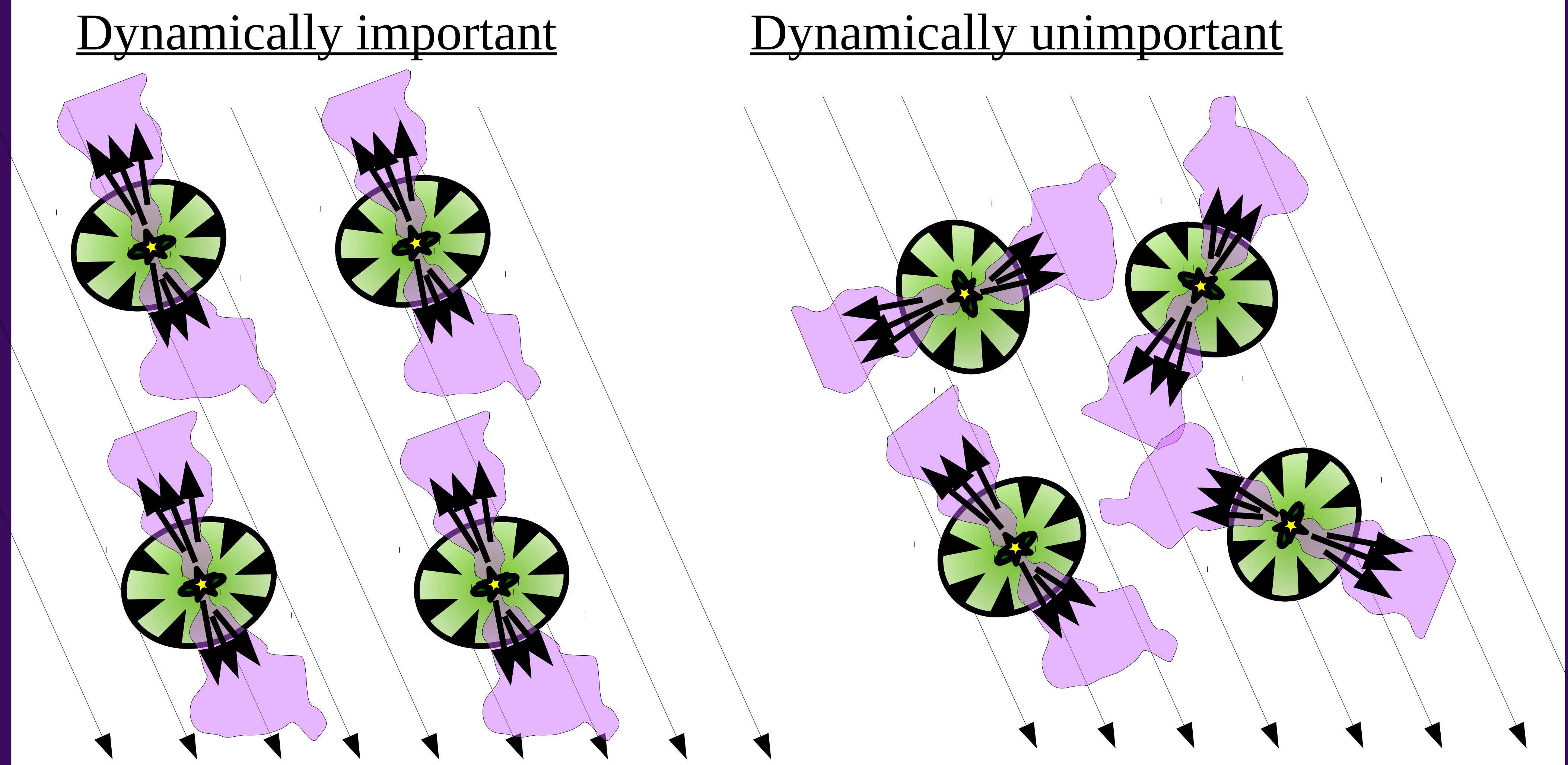
- P.I.s: Derek Ward-Thompson (UK), Pierre Bastien (Canada), Keping Qiu (China), Tetsuo Hasegawa (Japan), Woojin Kwon (Korea), Shih-Ping Lai (Taiwan)

- 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**

Are magnetic fields dynamically important in protostellar cores?

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



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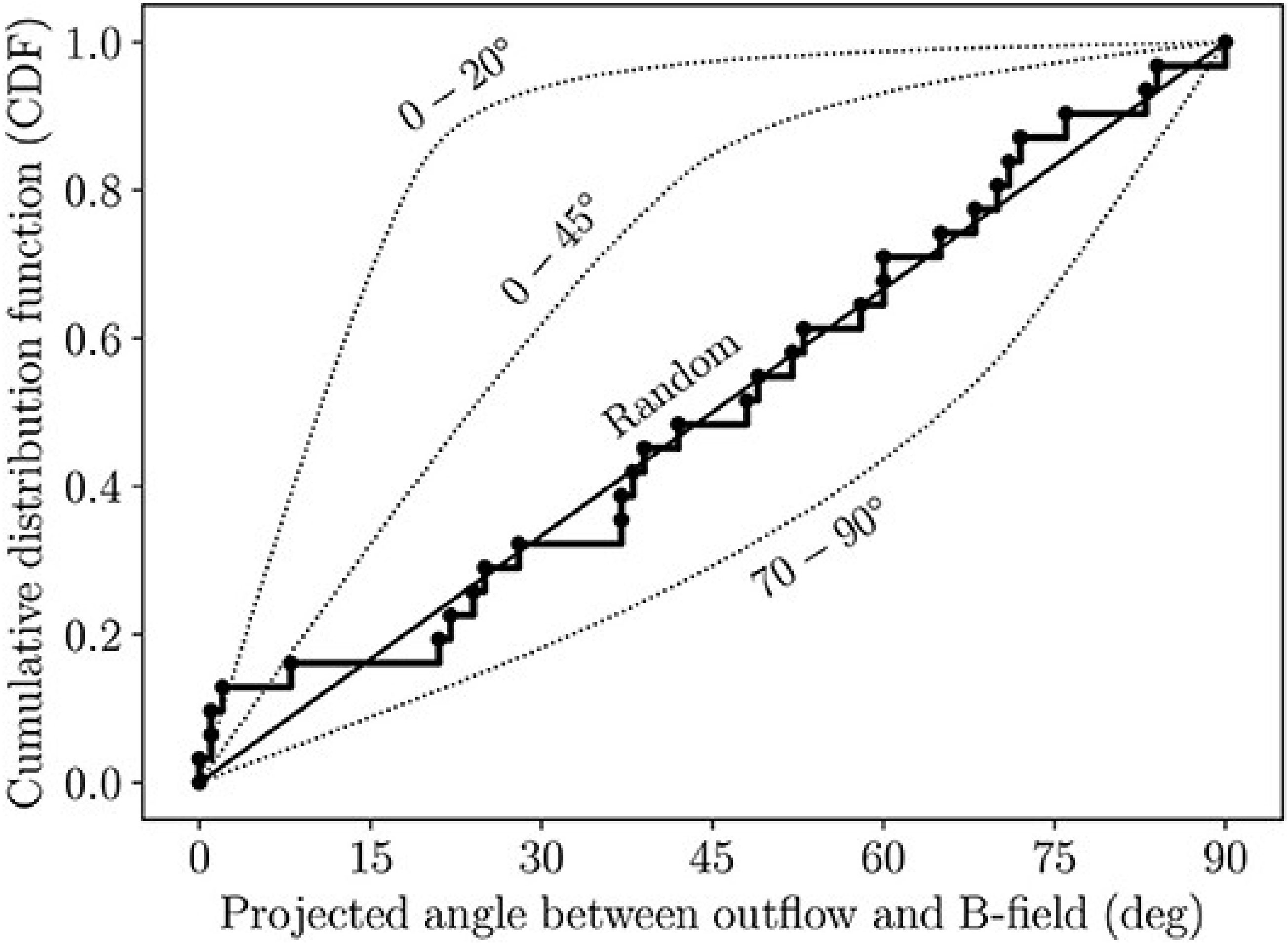

Hull & Zhang 2019, FrASS 6 3

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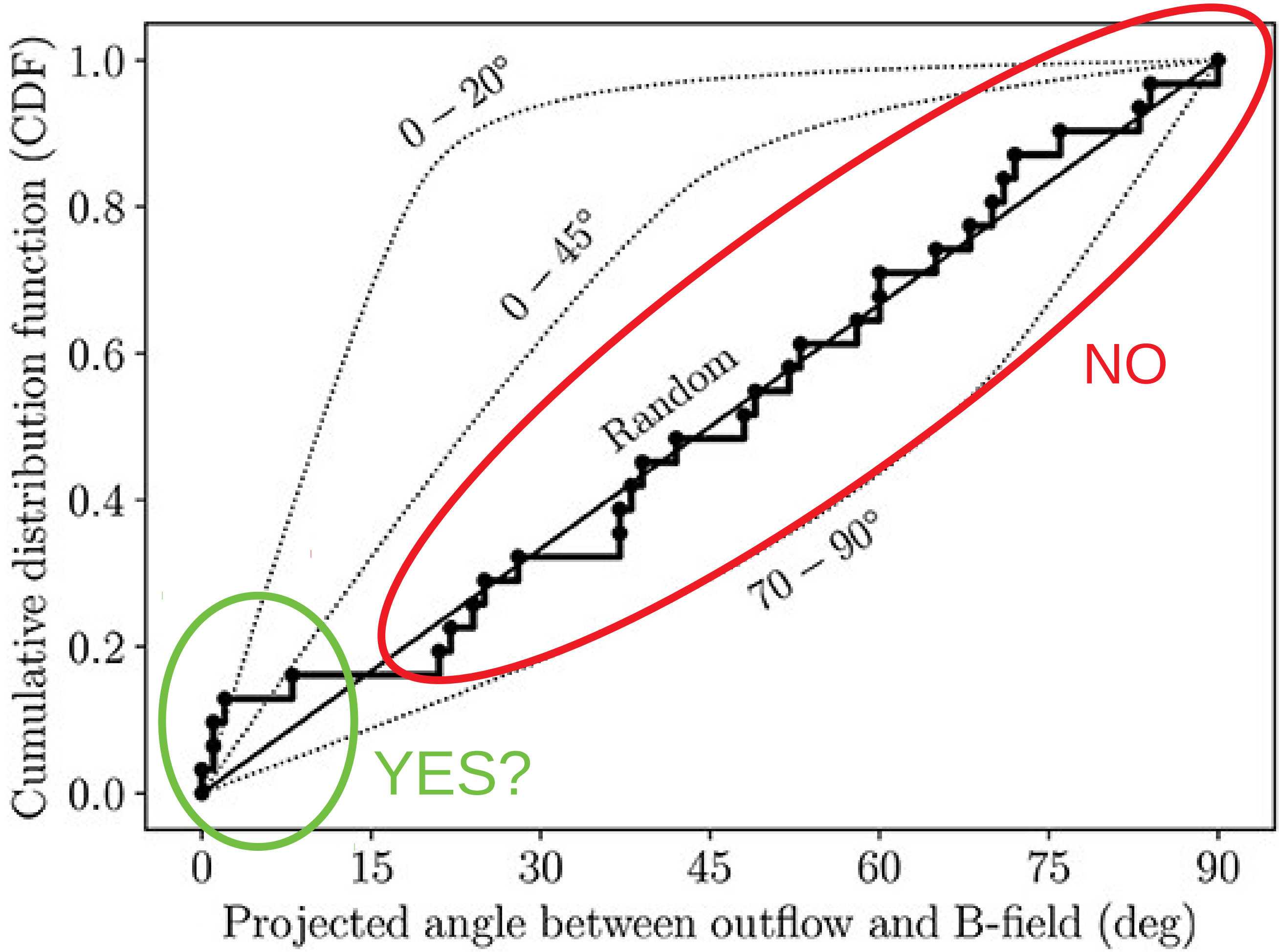
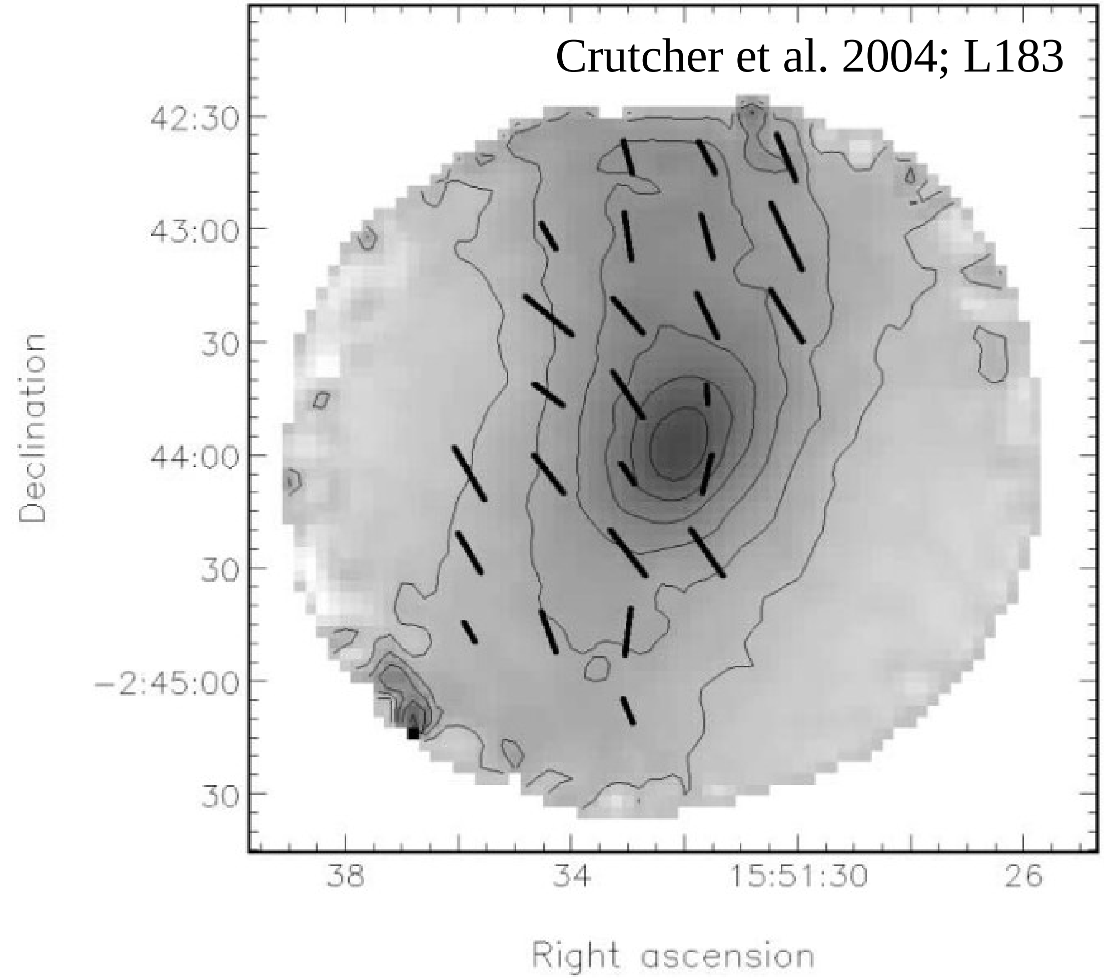


Hull & Zhang 2019, FrASS 6 3

Are magnetic fields dynamically important in **prestellar** cores?

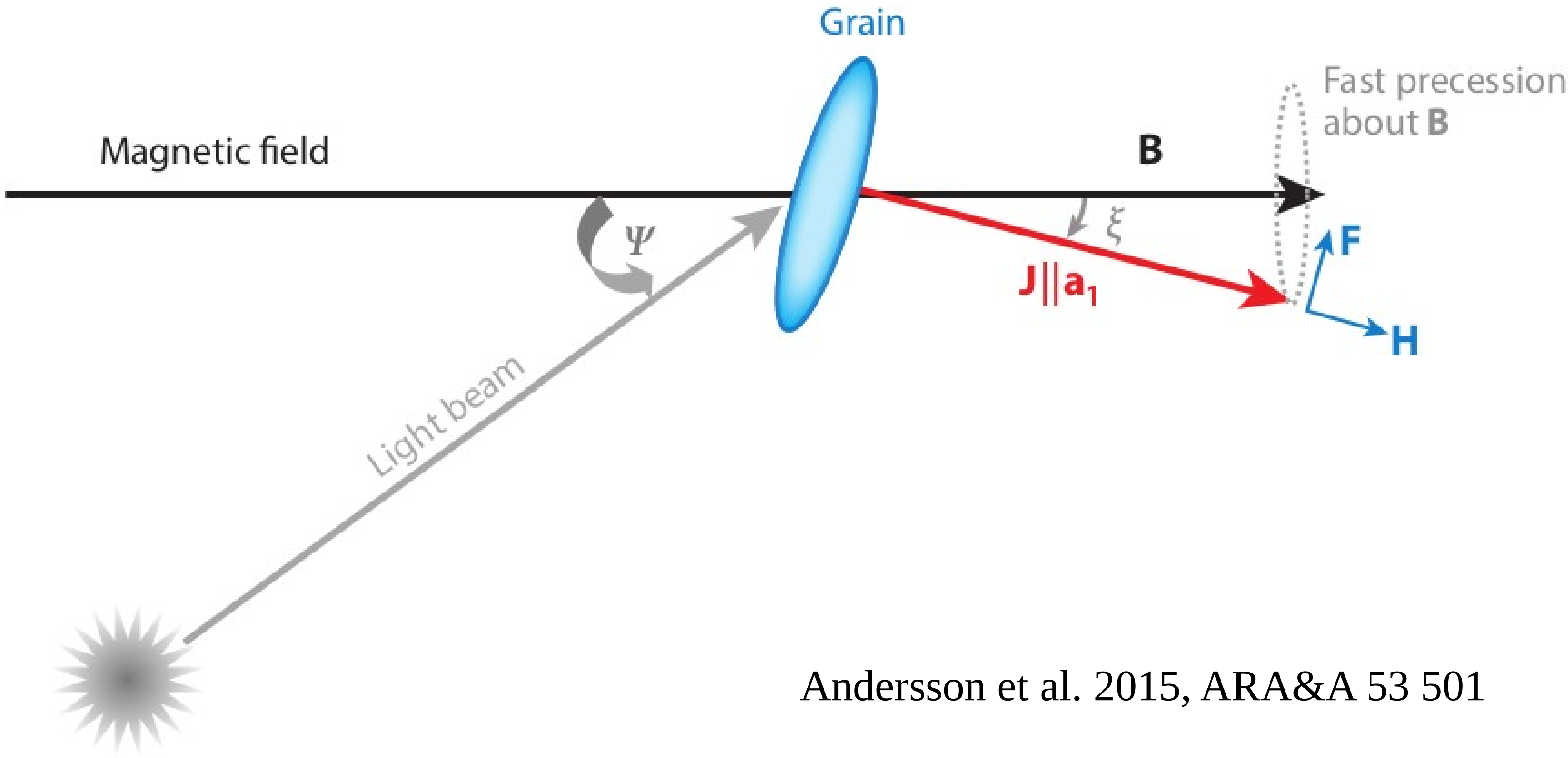
Prestellar core magnetic fields are:

- Approximately linear, often ~30º to the core's minor axis (a projection effect; Basu 2000)
- Generally without a clear hourglass morphology
- $\sim 10^1$-10^2 μG



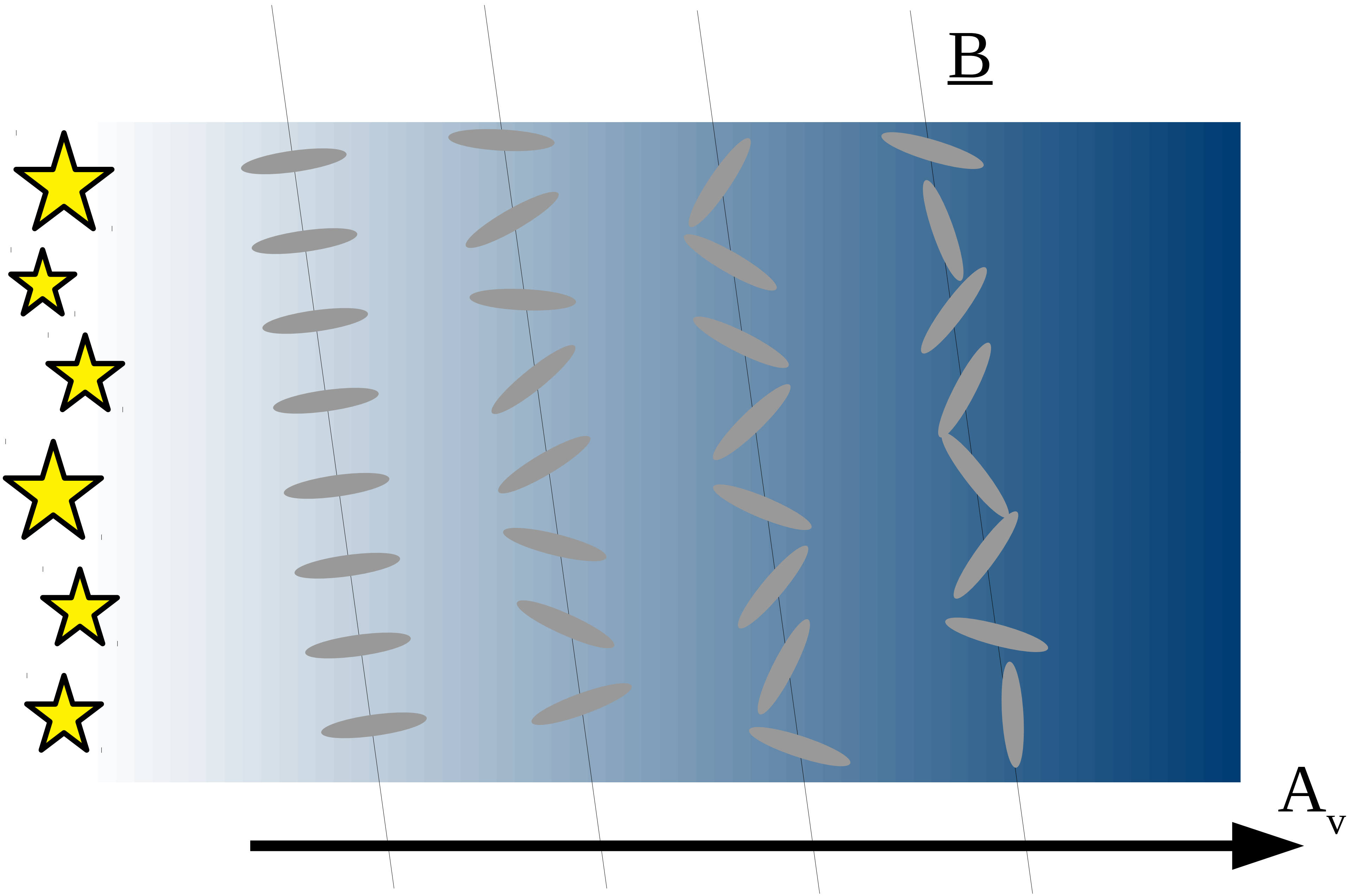
Question: How far into prestellar cores are our observations actually tracing?

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

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

We expect 0 < α < 1

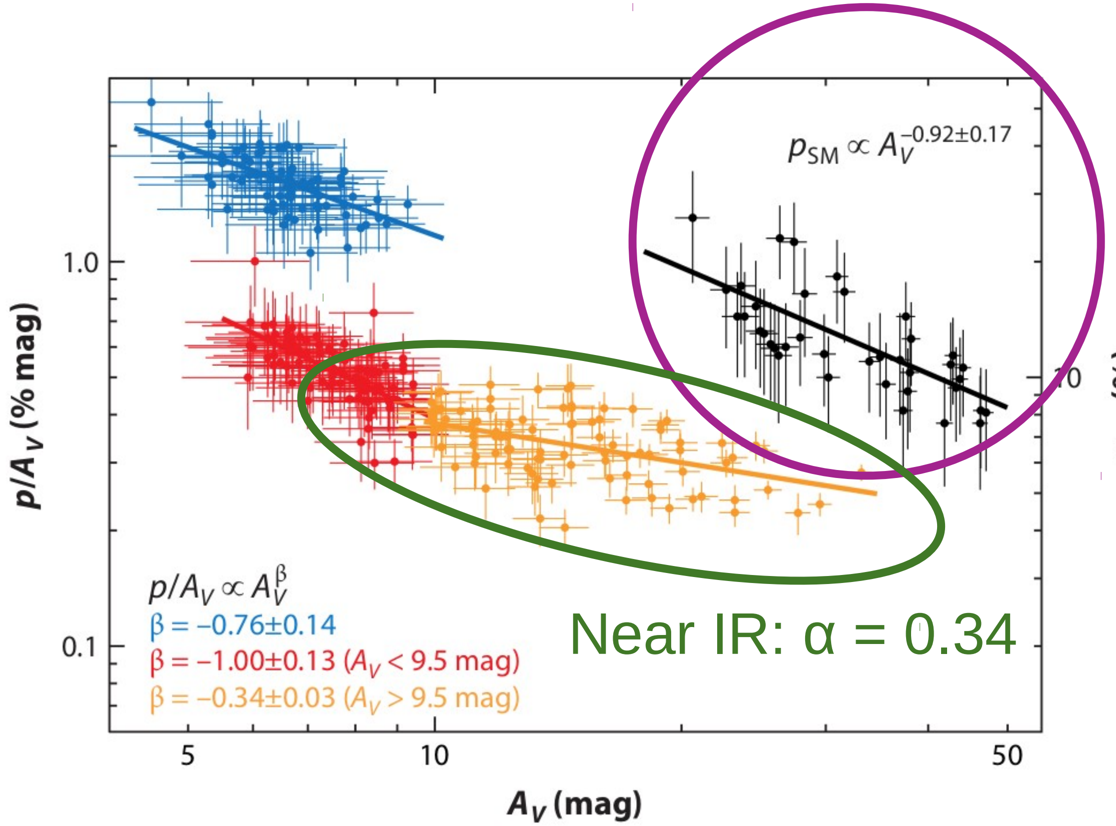
α = 0 indicates all grains are equally aligned – no depolarization

α = 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

Submillimetre: α = 0.92



Alves et al. 2014 A&A 569 L1

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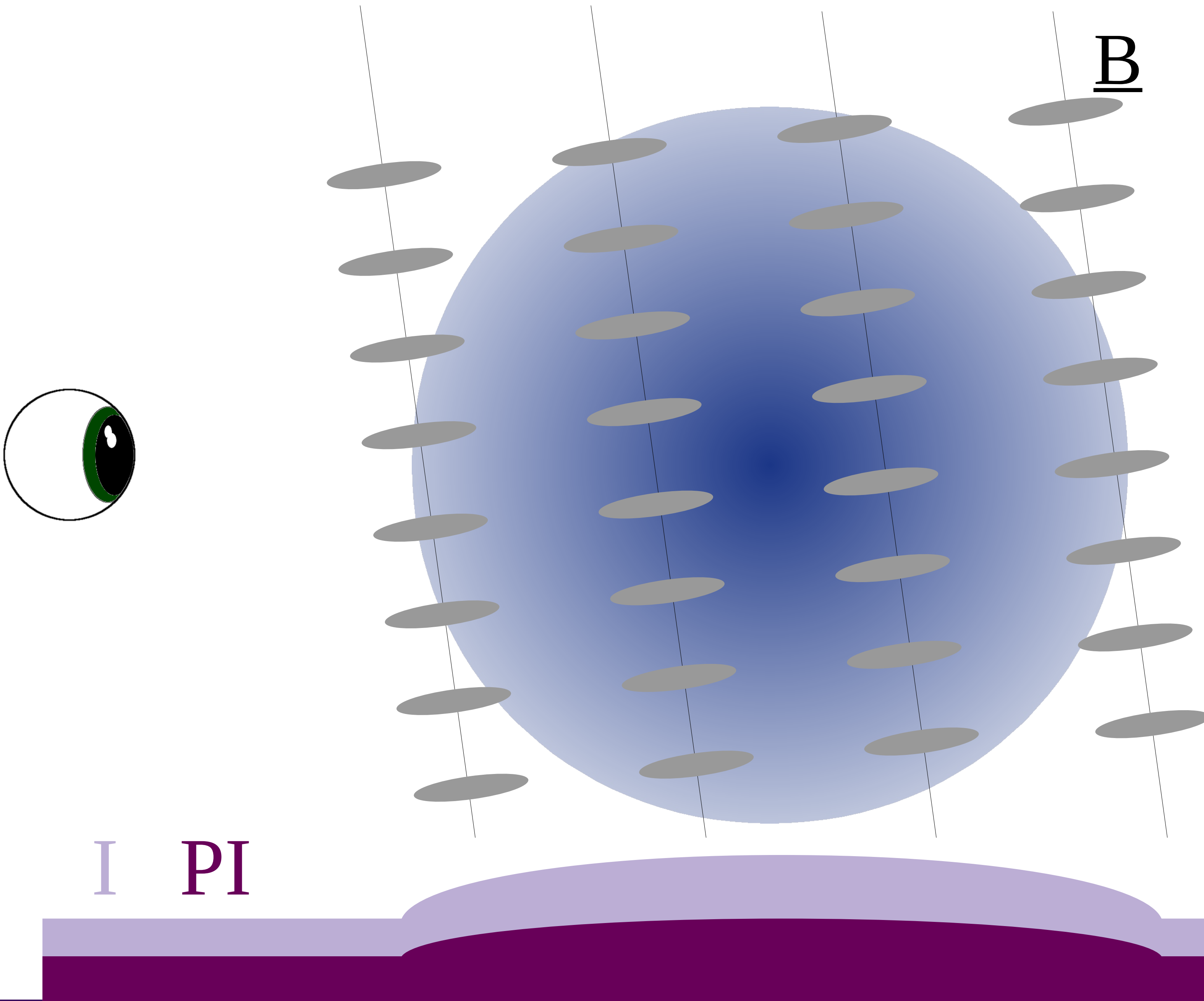

Perfect alignment:

PI ∝ I

p = constant

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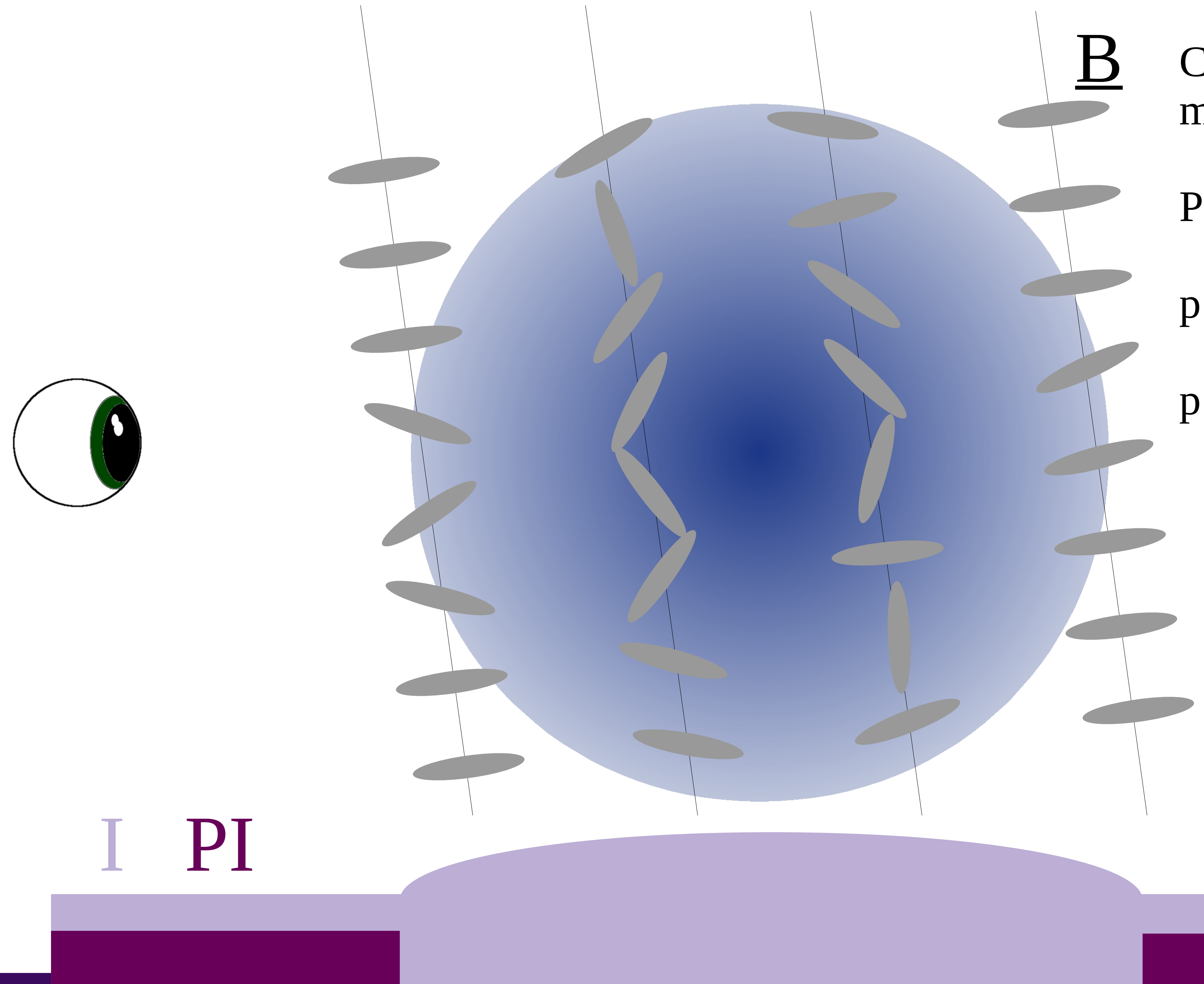


Complete misalignment:

PI (inside) = 0

p = PI(outside)/I

p ∝ 1/I

The effect of Ricean statistics on observed polarization fraction

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

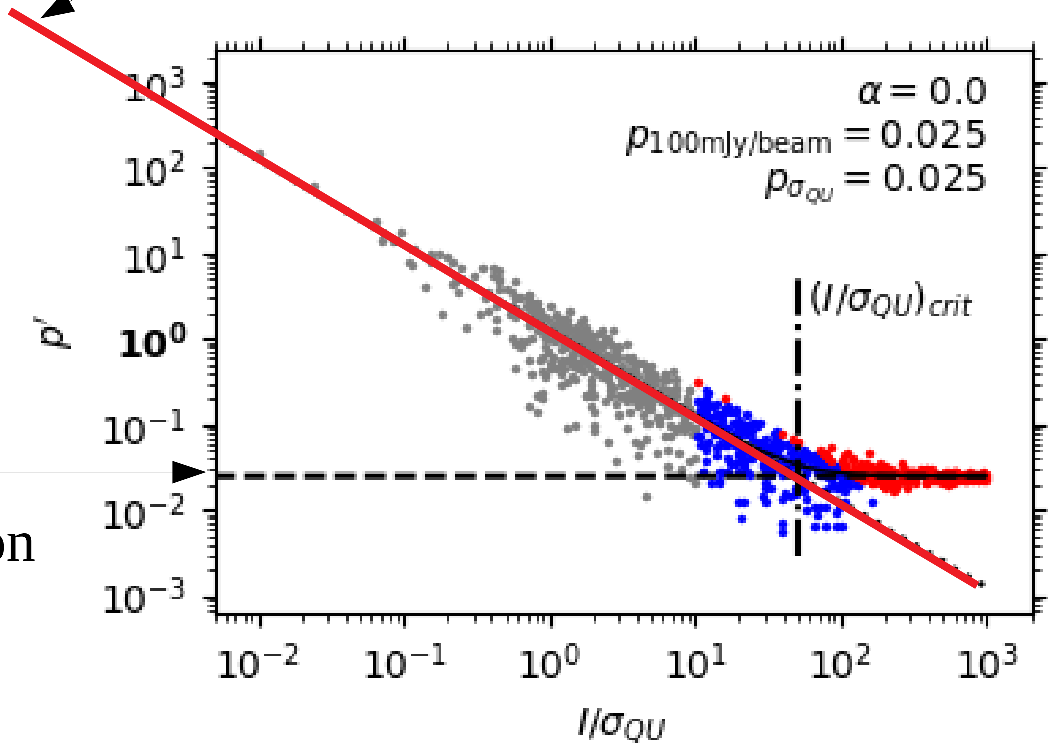
$$\mu_p = \sqrt{\frac{\pi}{2}} \sigma_p \mathcal{L}_{\frac{1}{2}} \left(-\frac{p^2}{2\sigma_p^2} \right)$$

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

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

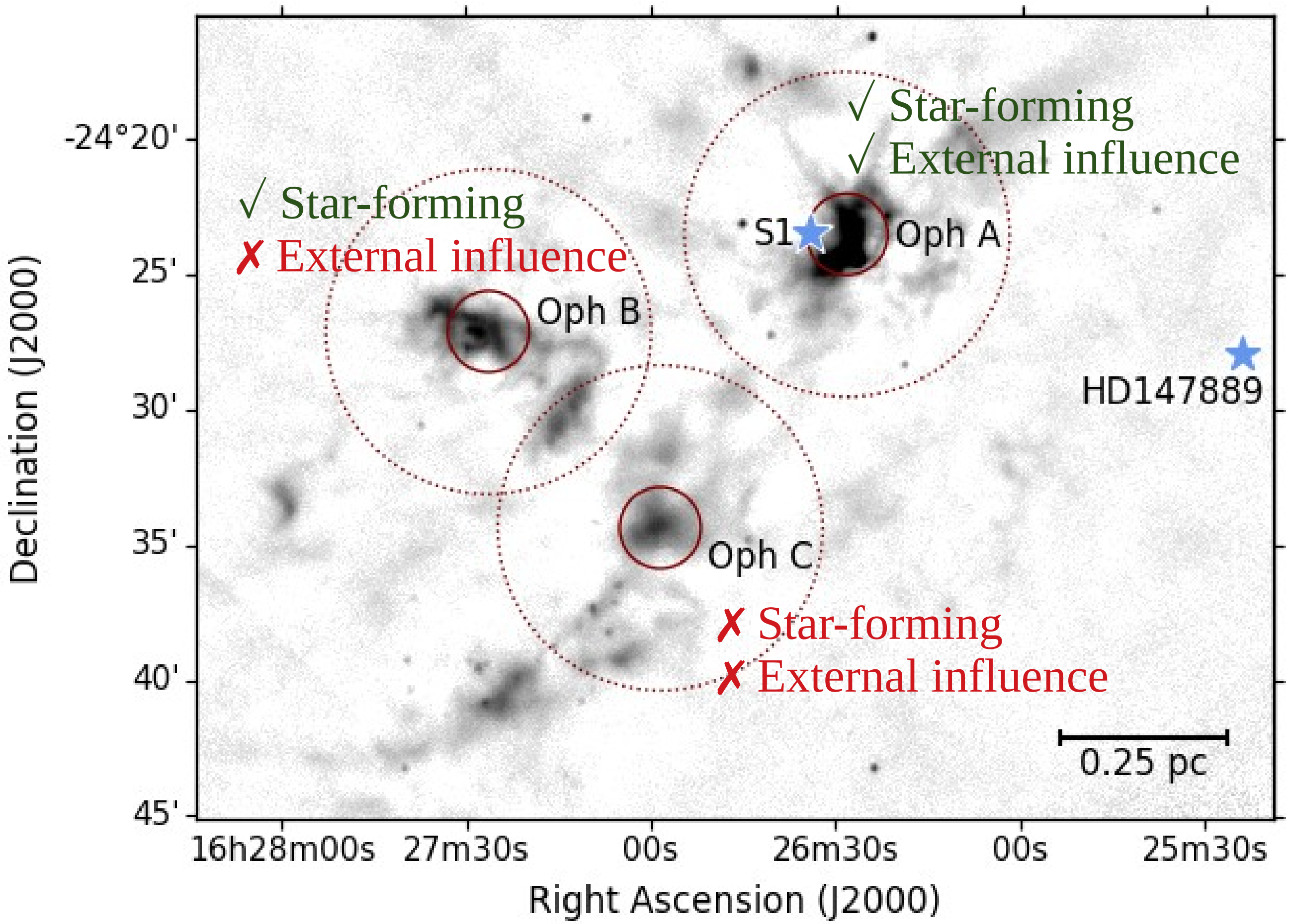
At low signal-to-noise,

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



Input model:
constant polarization fraction

The Ophiuchus Molecular Cloud



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

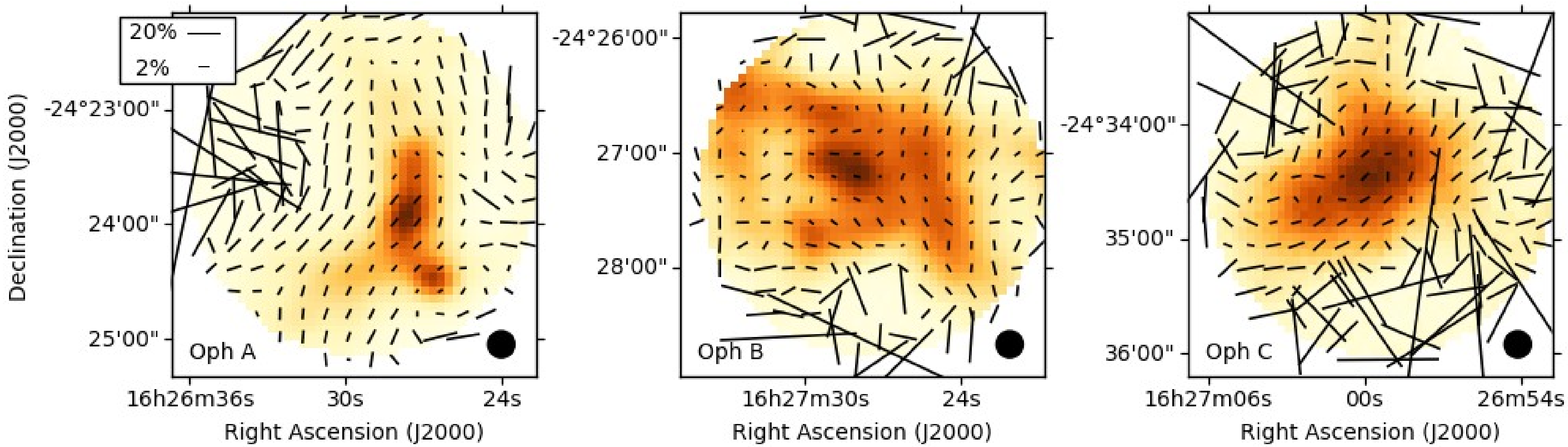
Contains a number of dense clumps with differing star formation histories in close proximity

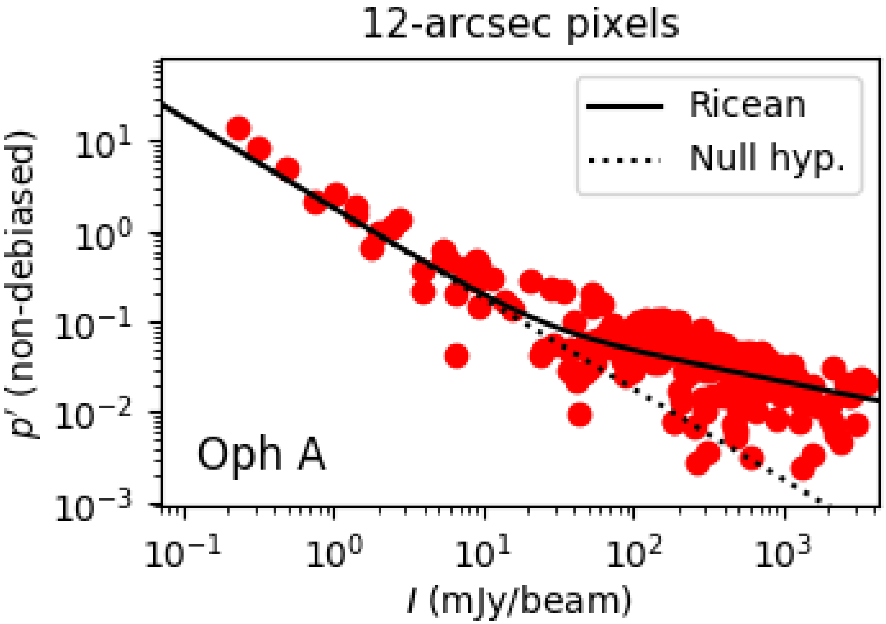
Global influence from Sco OB2 association, ~11pc to the west

Two embedded B stars

An excellent laboratory for testing star formation theories

Measuring α in Ophiuchus L1688





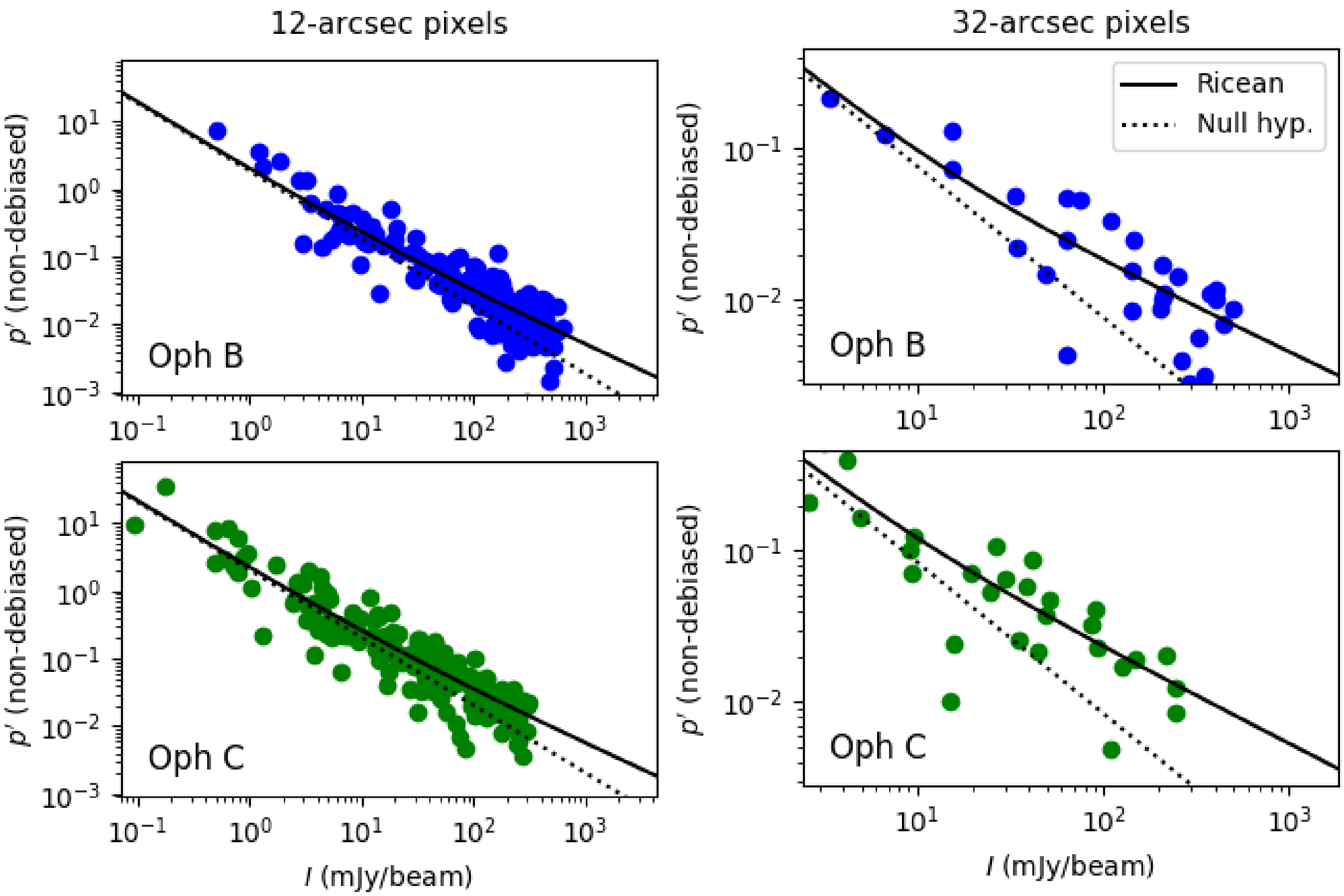
Oph A: $\alpha = 0.34$, $p_{100mJy/beam} = 4.7\%$

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

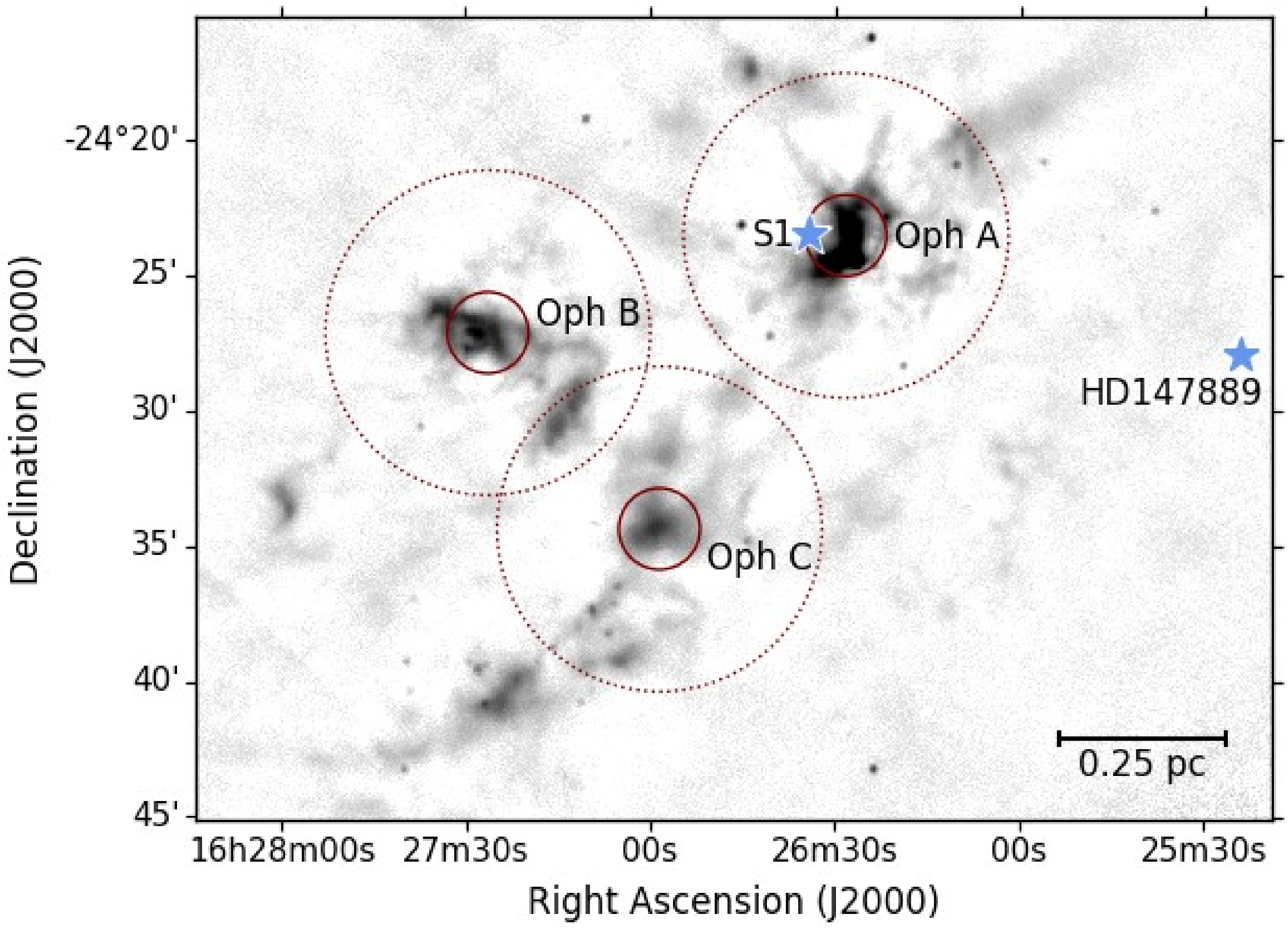


Oph B & C:

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



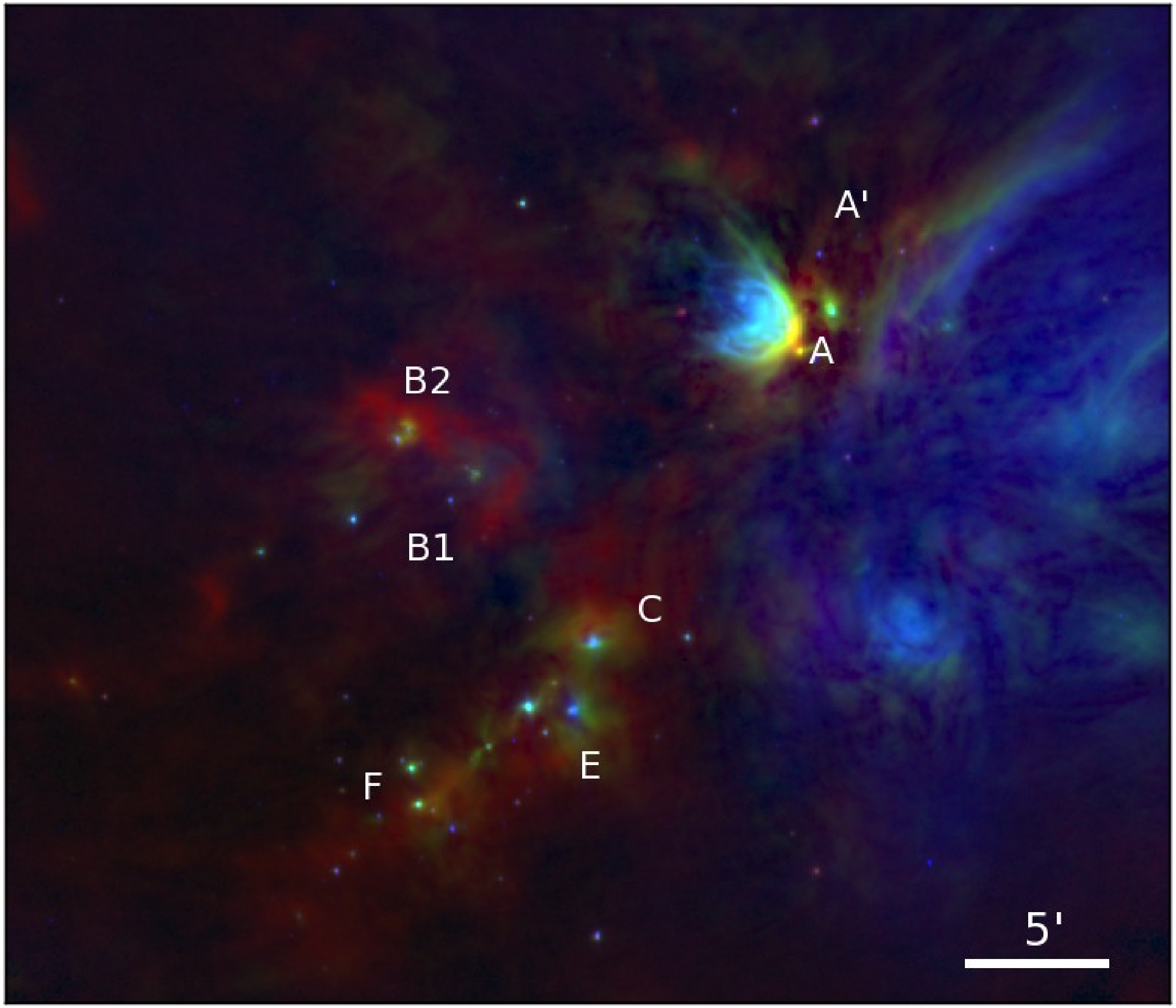
Global influence from Sco OB2 (West to East across cloud)

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

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The radiation field of Ophiuchus

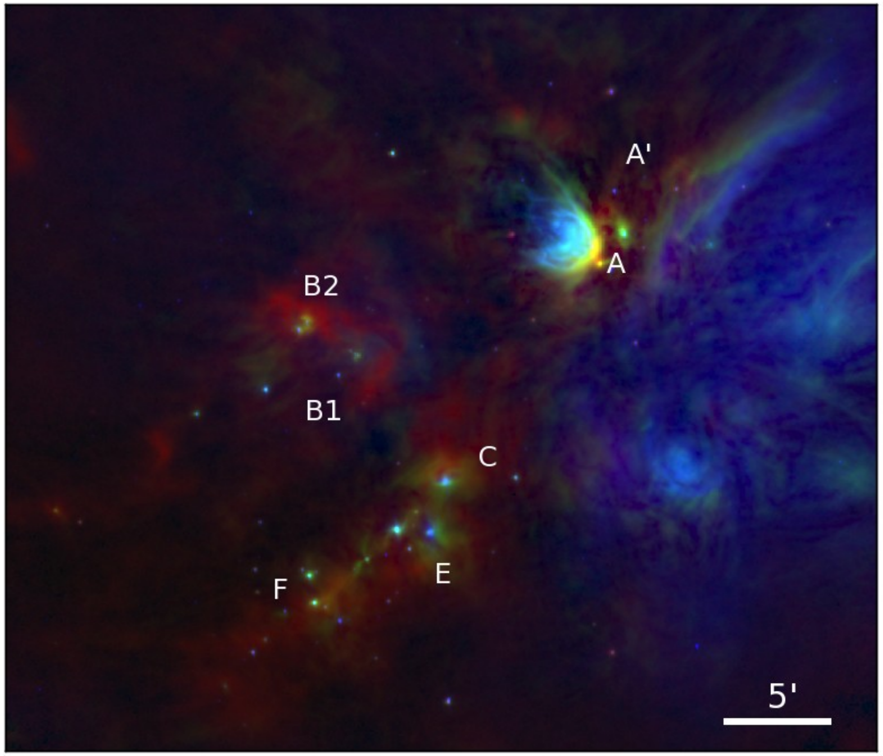
	Plane-of-sky distance (pc)		Upper-limit ionizing photon flux ($s^{-1}m^{-2}$)		
Region	HD147889	S1	HD147889	S1	Total
Oph A	0.62	0.05	7.0×10^{10}	1.5×10^{11}	2.2×10^{11}
Oph B	1.13	0.51	2.1×10^{10}	1.2×10^{9}	2.2×10^{10}
Oph C	0.91	0.50	3.2×10^{10}	1.2×10^{9}	3.4×10^{10}

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!