

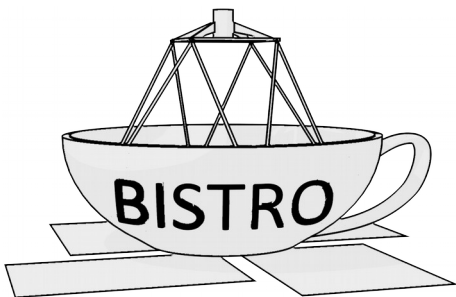
Magnetic fields and star formation in the Ophiuchus Molecular Cloud

Kate Pattle

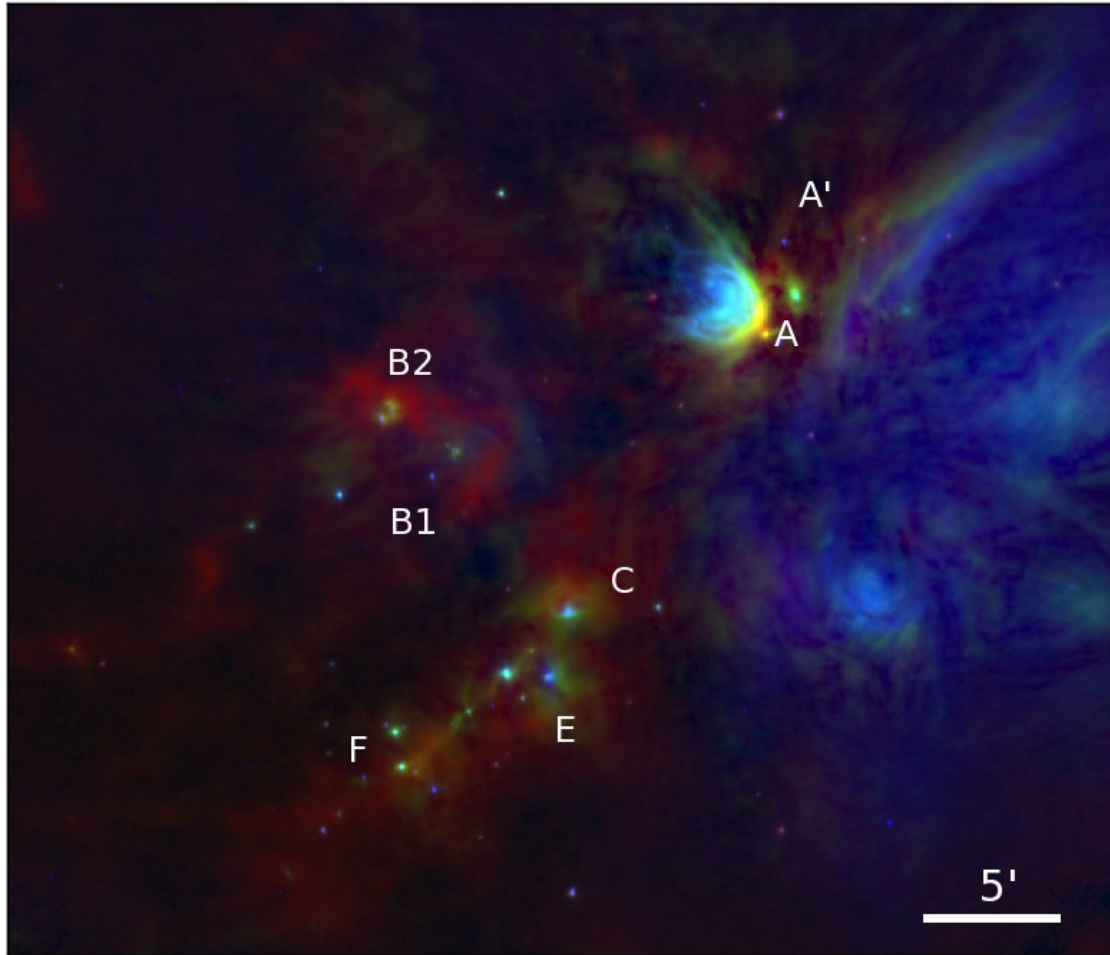
National University of Ireland Galway

18th February 2020

Magnetic Fields in the Universe 7



NUI Galway
OÉ Gaillimh



Key Collaborators:

Shih-Ping Lai (NTHU)

Sarah Sadavoy (Queens U.)

Jia-Wei Wang (ASIAA)

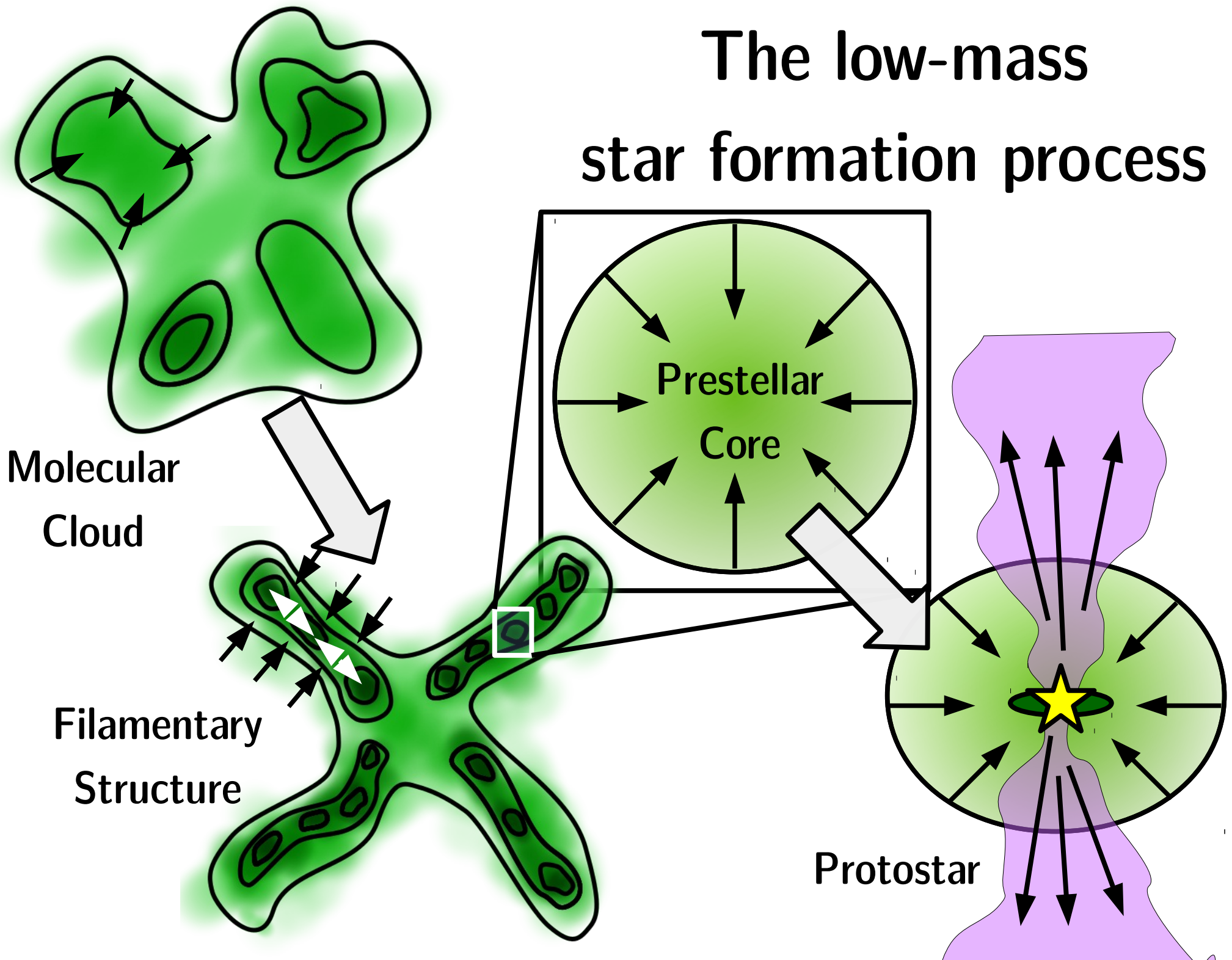
Tetsuo Hasegawa (NAOJ)

James Di Francesco (U. Victoria)

Derek Ward-Thompson (UCLan)

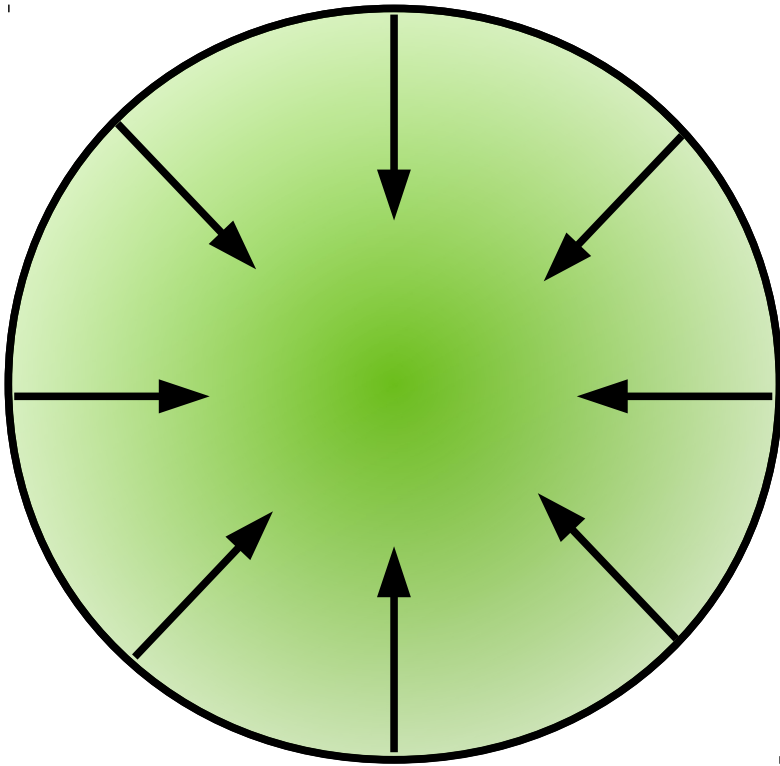
Ray Furuya (U. Tokushima)

The low-mass star formation process

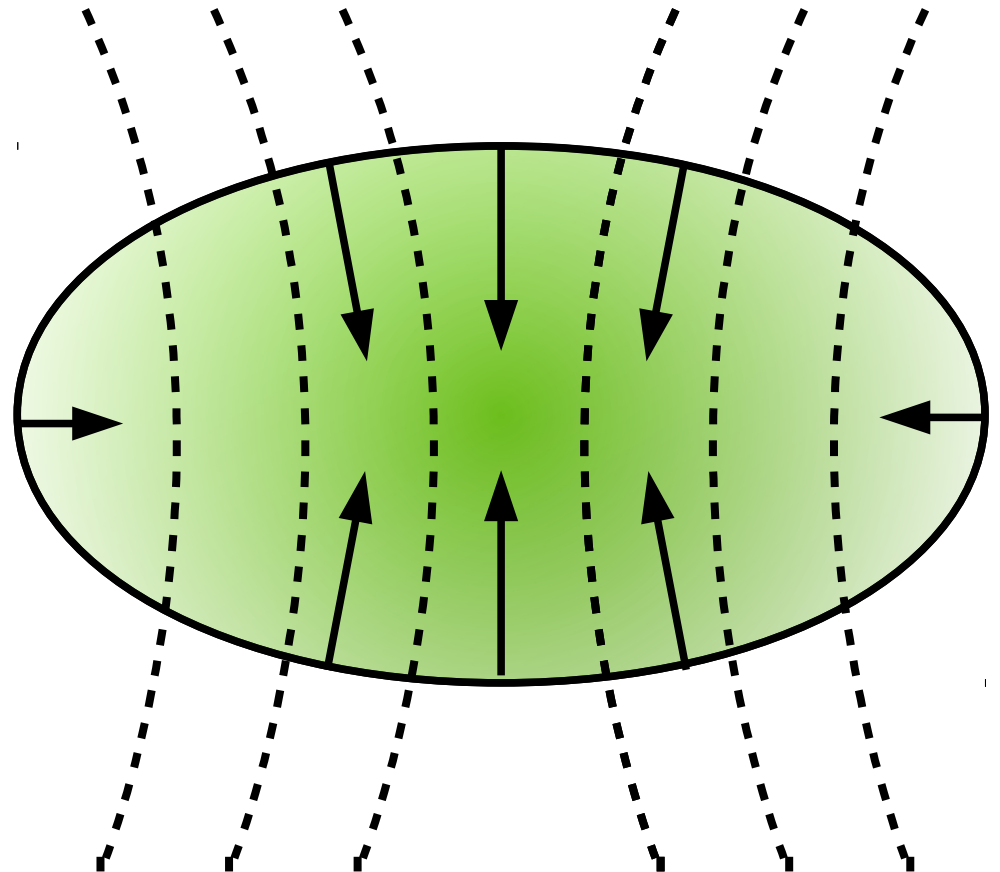


Gravitational collapse:

Without a magnetic field



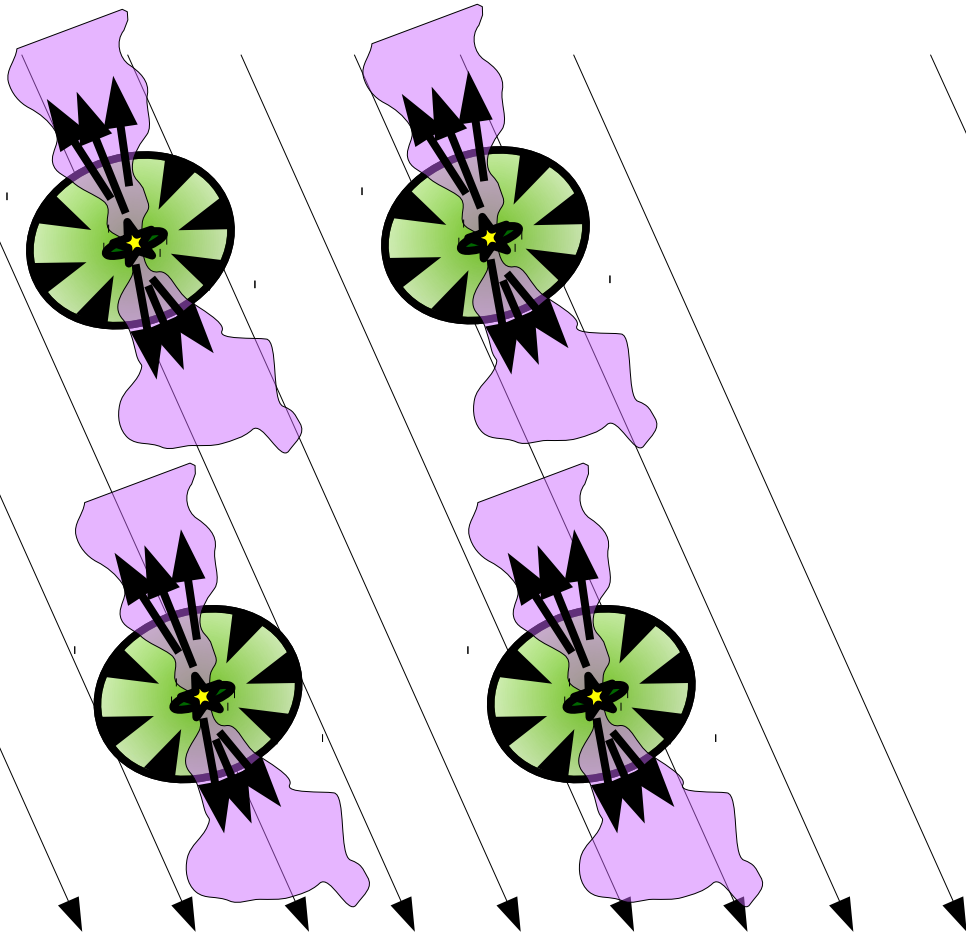
With a strong magnetic field



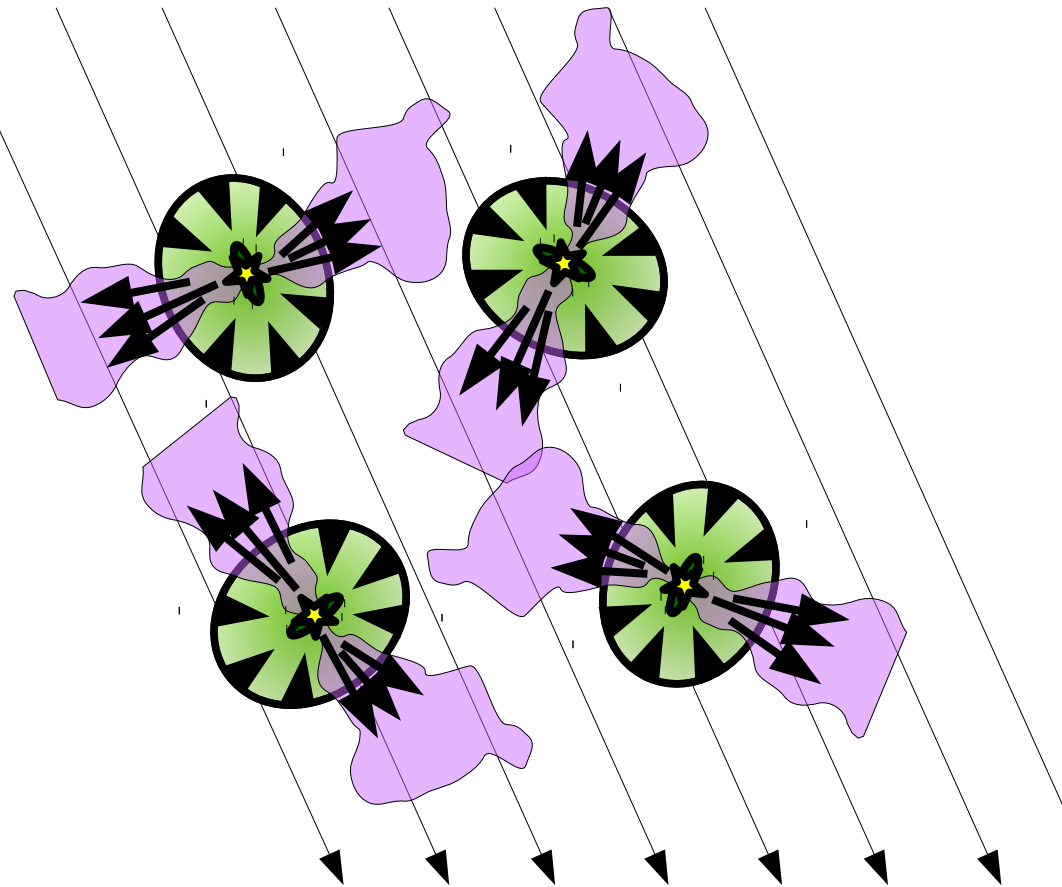
Are magnetic fields dynamically important in protostellar cores?

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

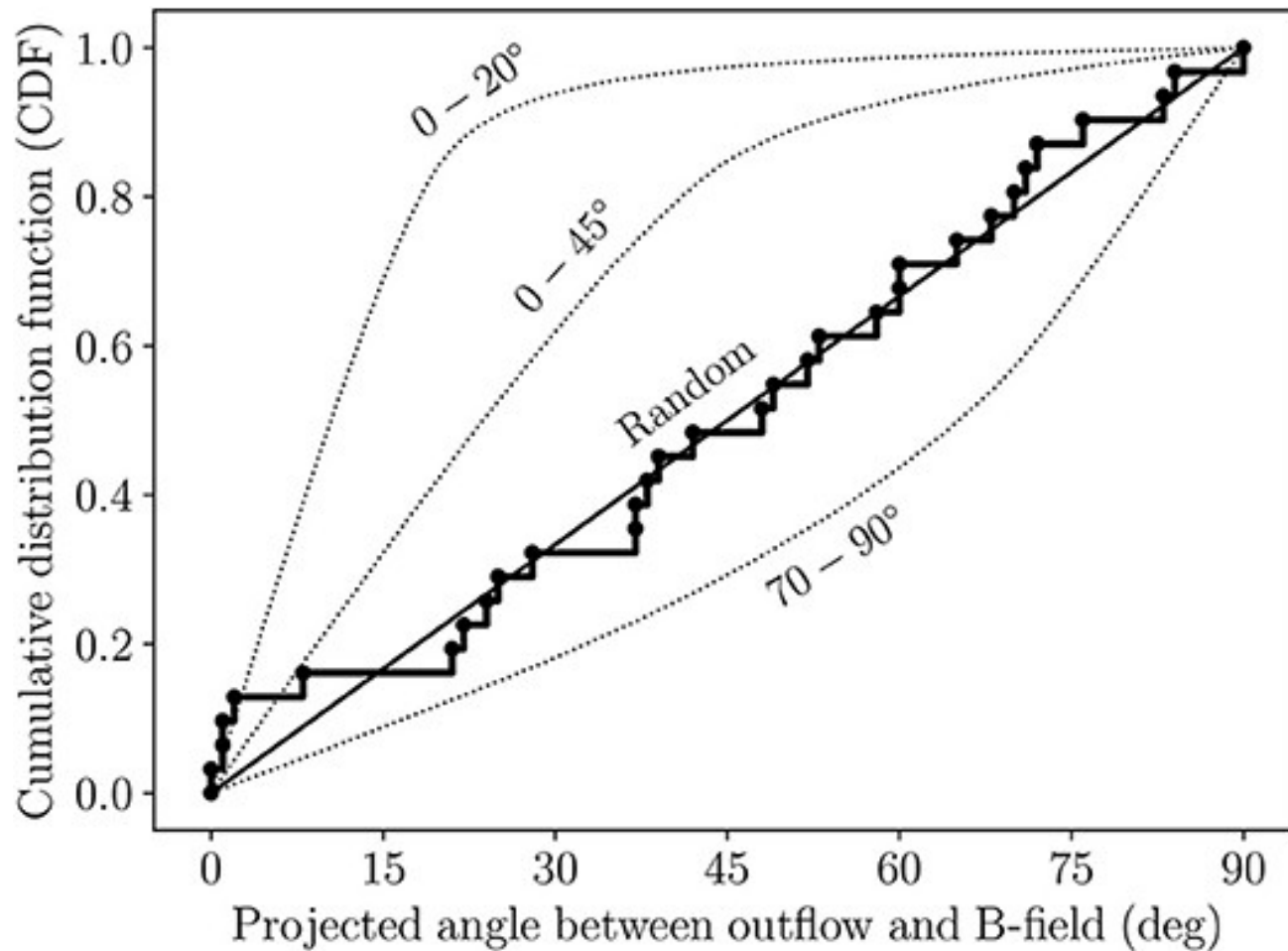
Dynamically important



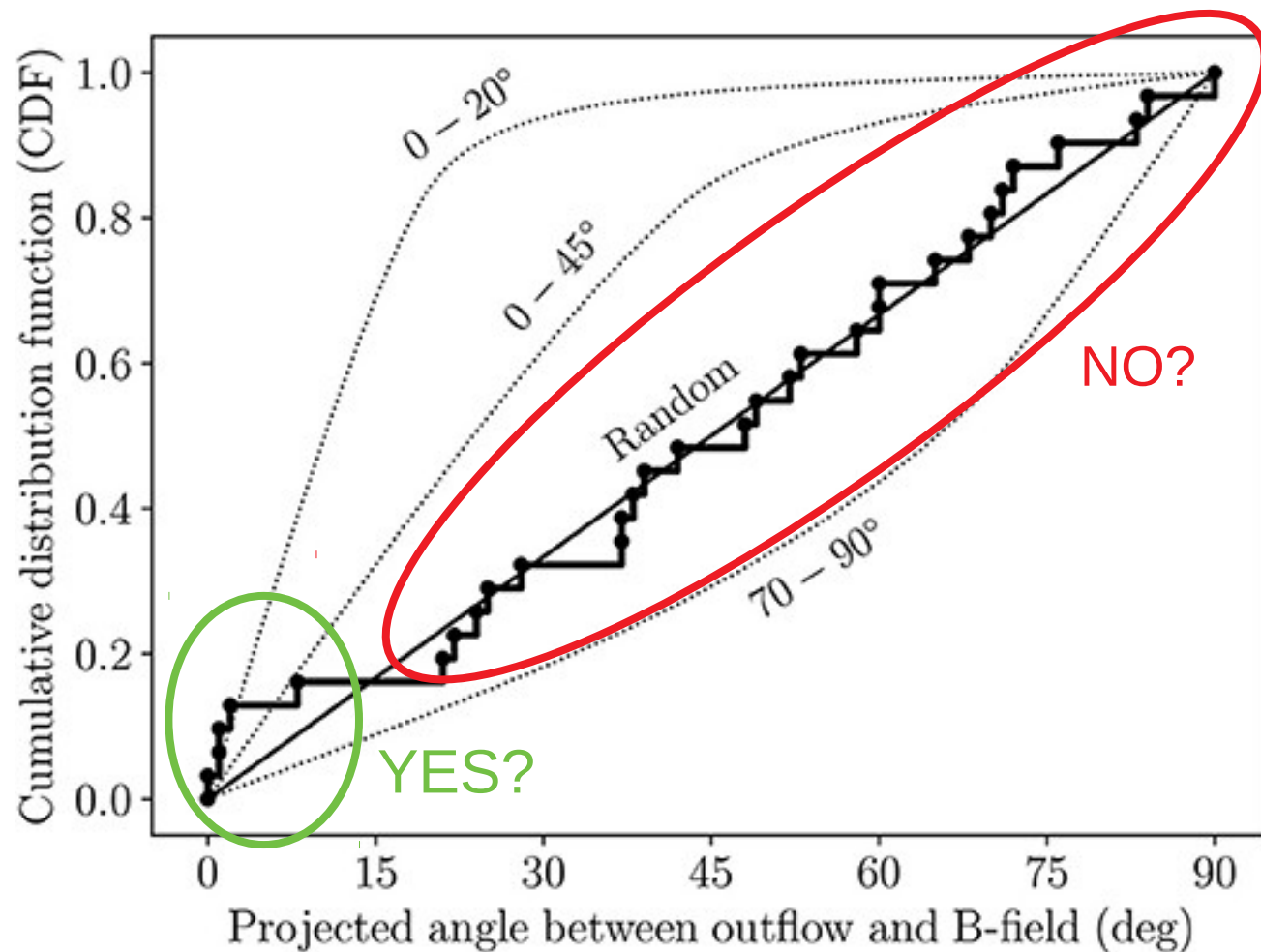
Dynamically unimportant



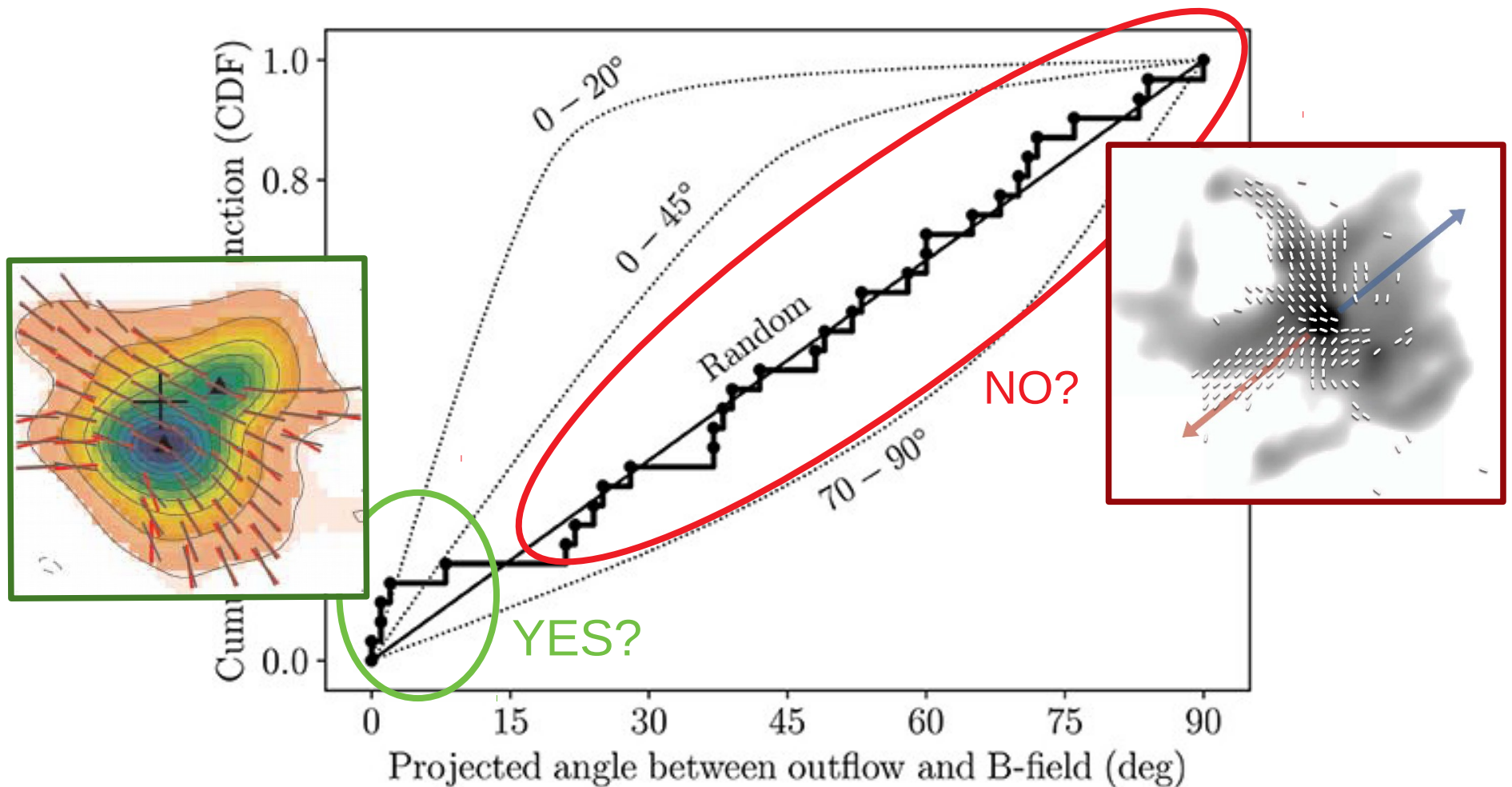
Are magnetic fields dynamically important in protostellar cores?



Are magnetic fields dynamically important in protostellar cores?



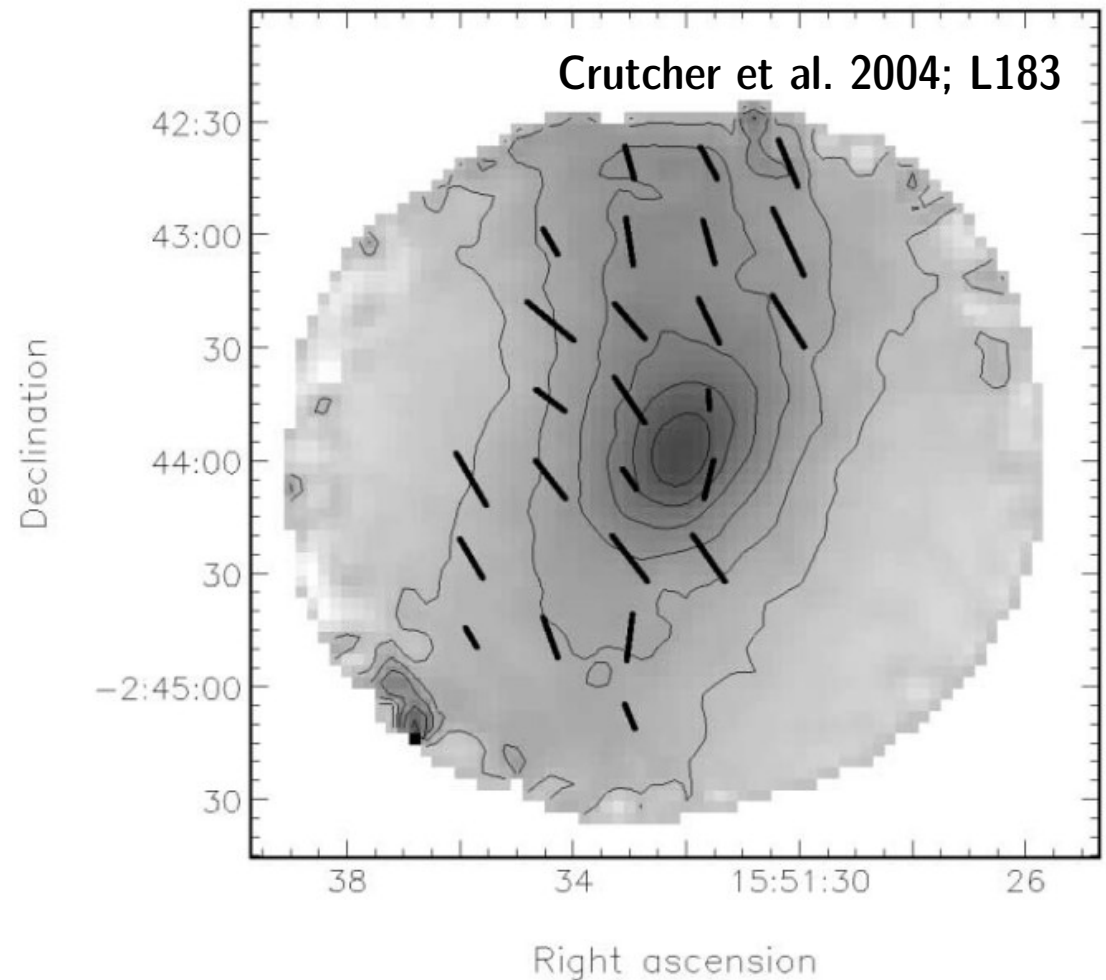
Are magnetic fields dynamically important in protostellar cores?



Are magnetic fields dynamically important in prestellar cores?

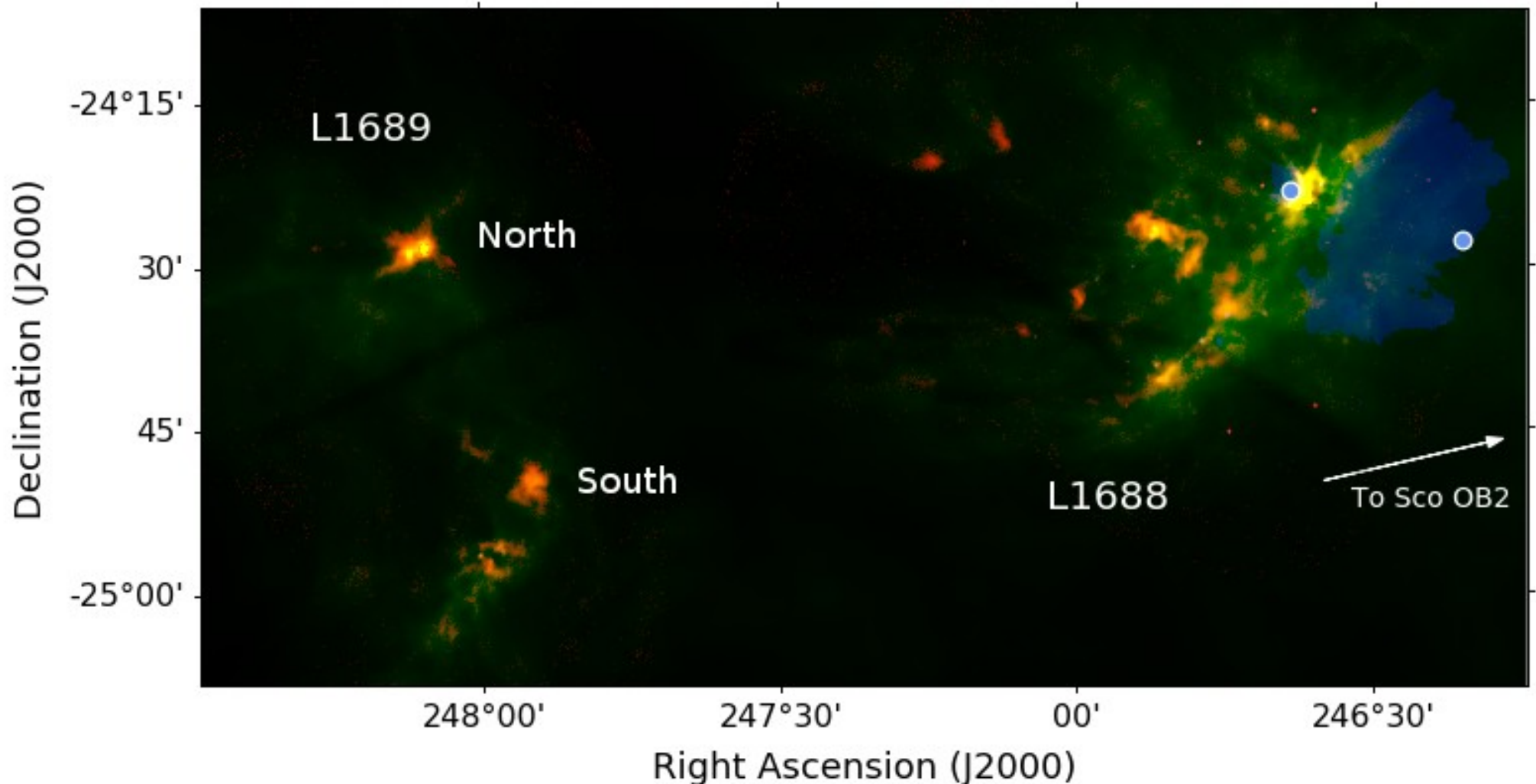
Prestellar core magnetic fields are:

- Approximately linear, often $\sim 30^\circ$ to the core's minor axis (a projection effect; Basu 2000)
- Generally without a clear hourglass morphology
- $\sim 10^1\text{--}10^2 \mu\text{G}$



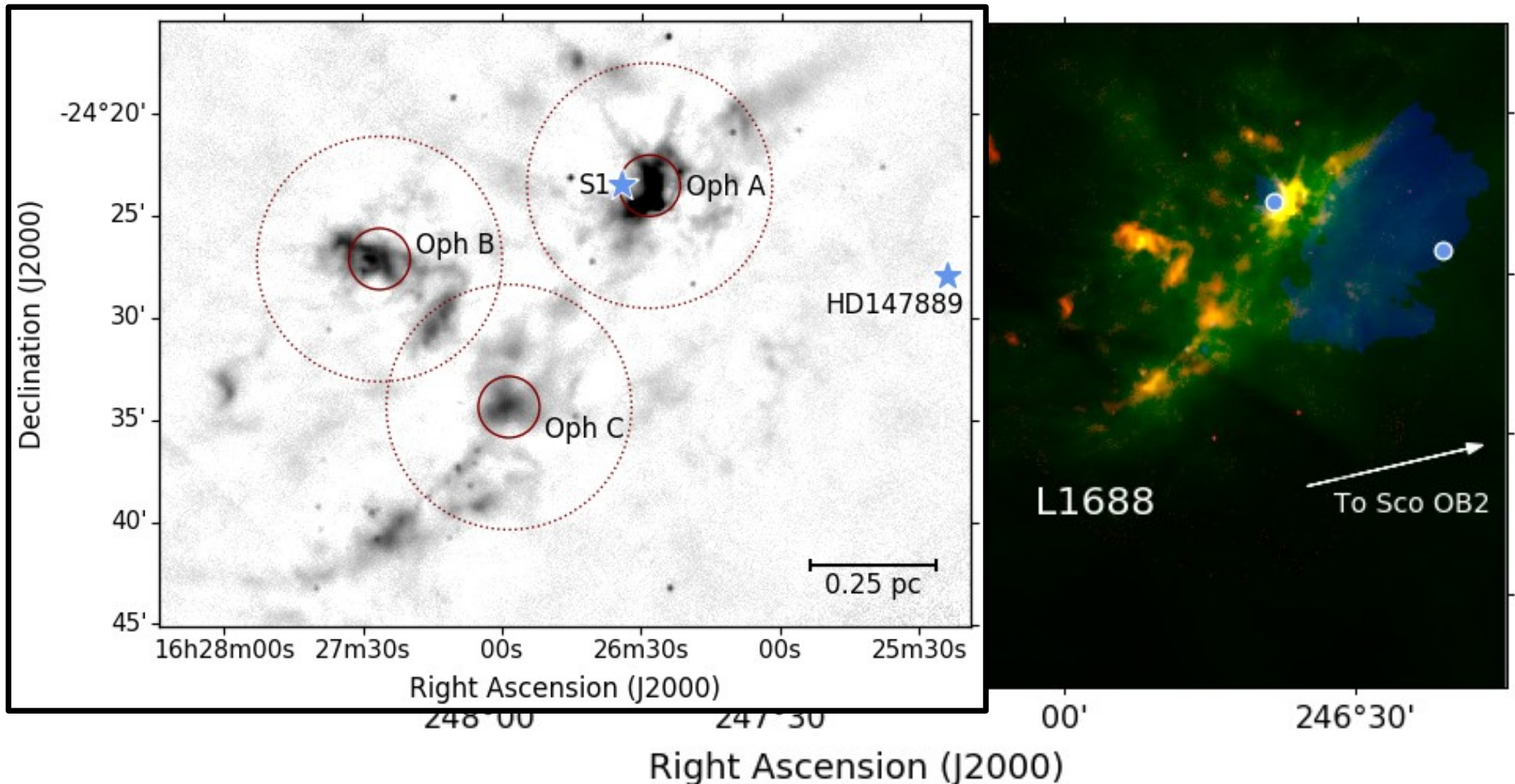
The Ophiuchus Molecular Cloud

Clustered low-to-intermediate-mass star formation, located at ~ 140 pc (Ortiz-Léon et al. 2017).



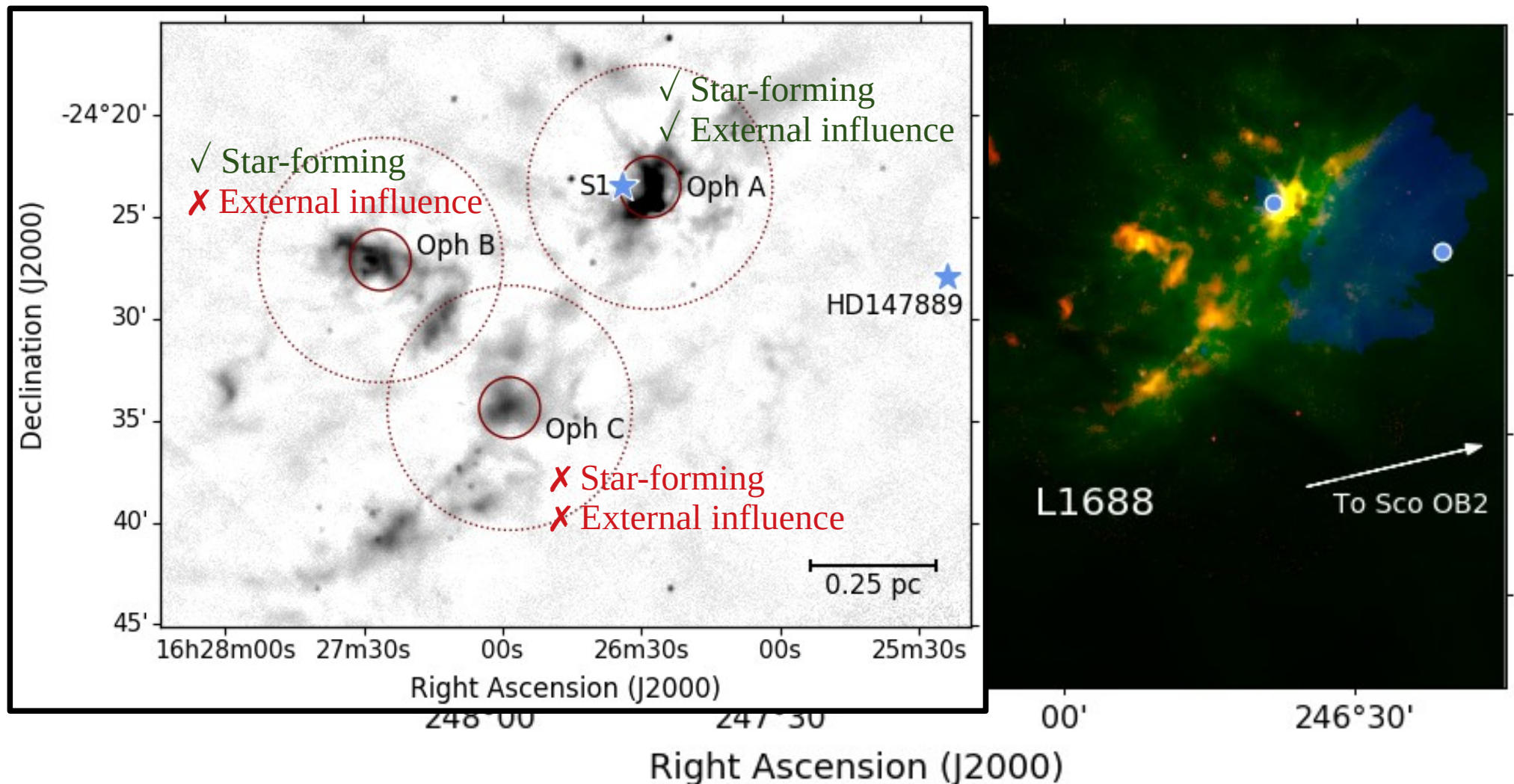
The Ophiuchus Molecular Cloud

Clustered low-to-intermediate-mass star formation, located at ~ 140 pc (Ortiz-Léon et al. 2017).

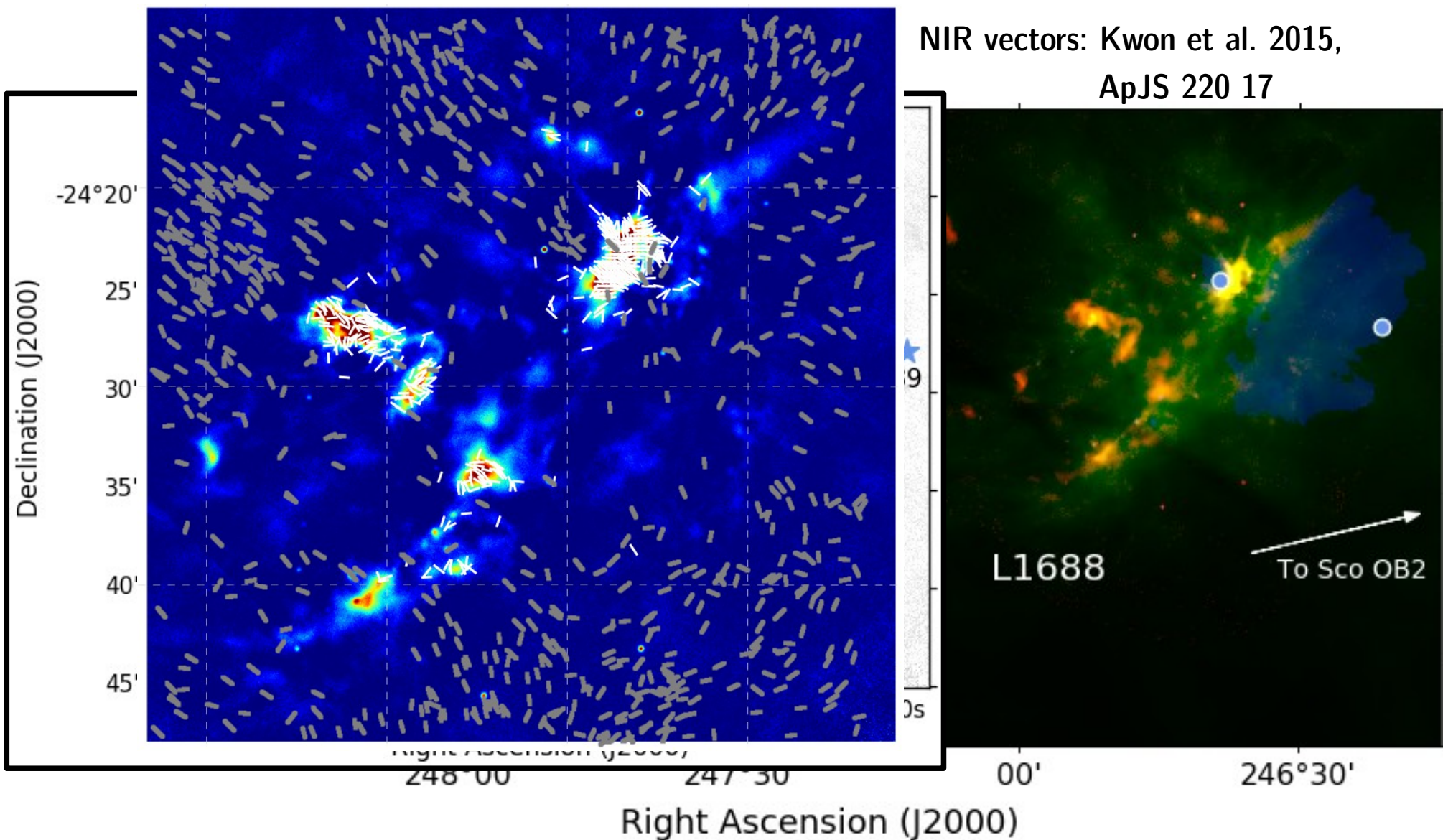


The Ophiuchus Molecular Cloud

Clustered low-to-intermediate-mass star formation, located at ~ 140 pc (Ortiz-Léon et al. 2017).

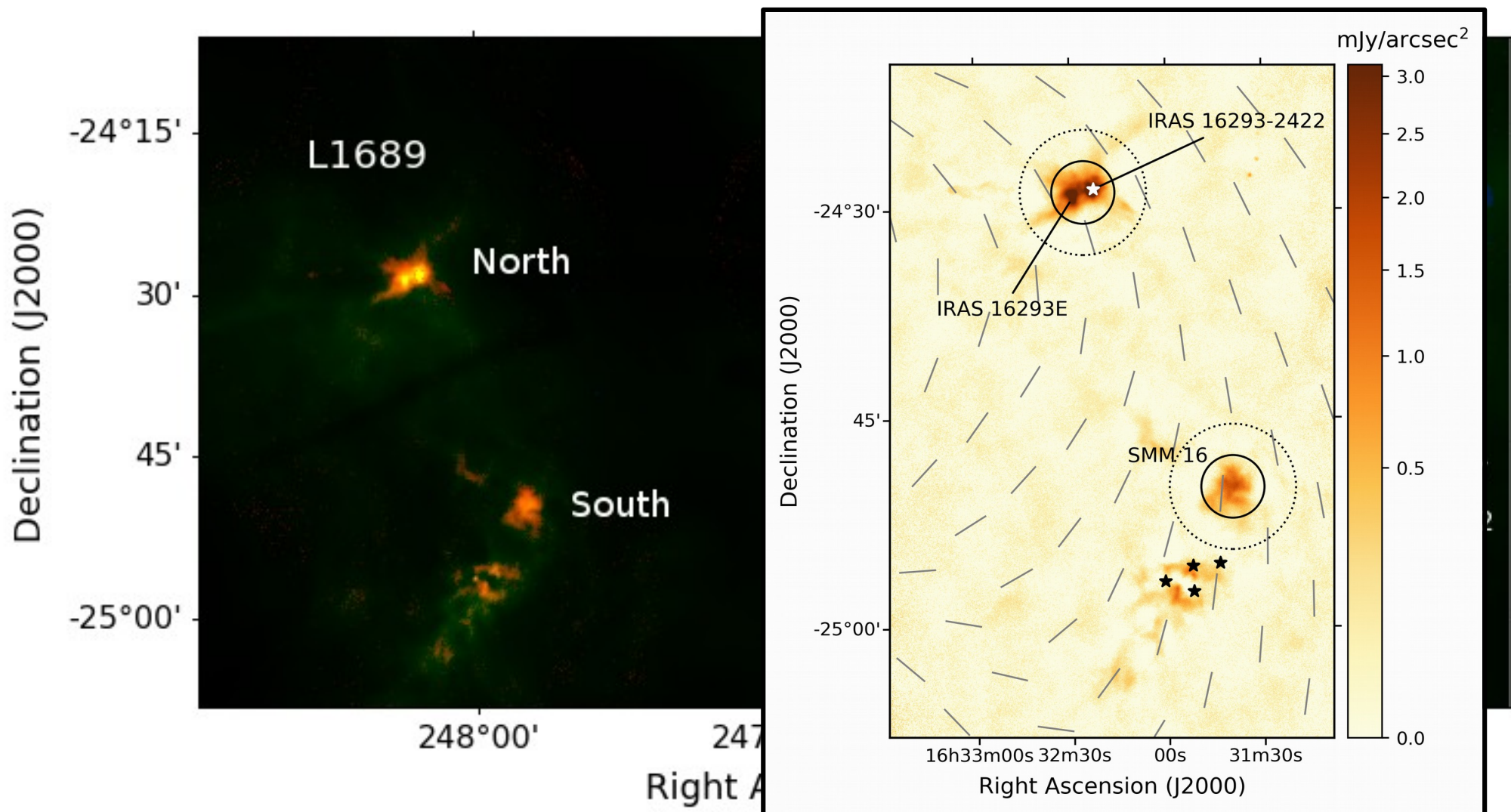


The Ophiuchus Molecular Cloud

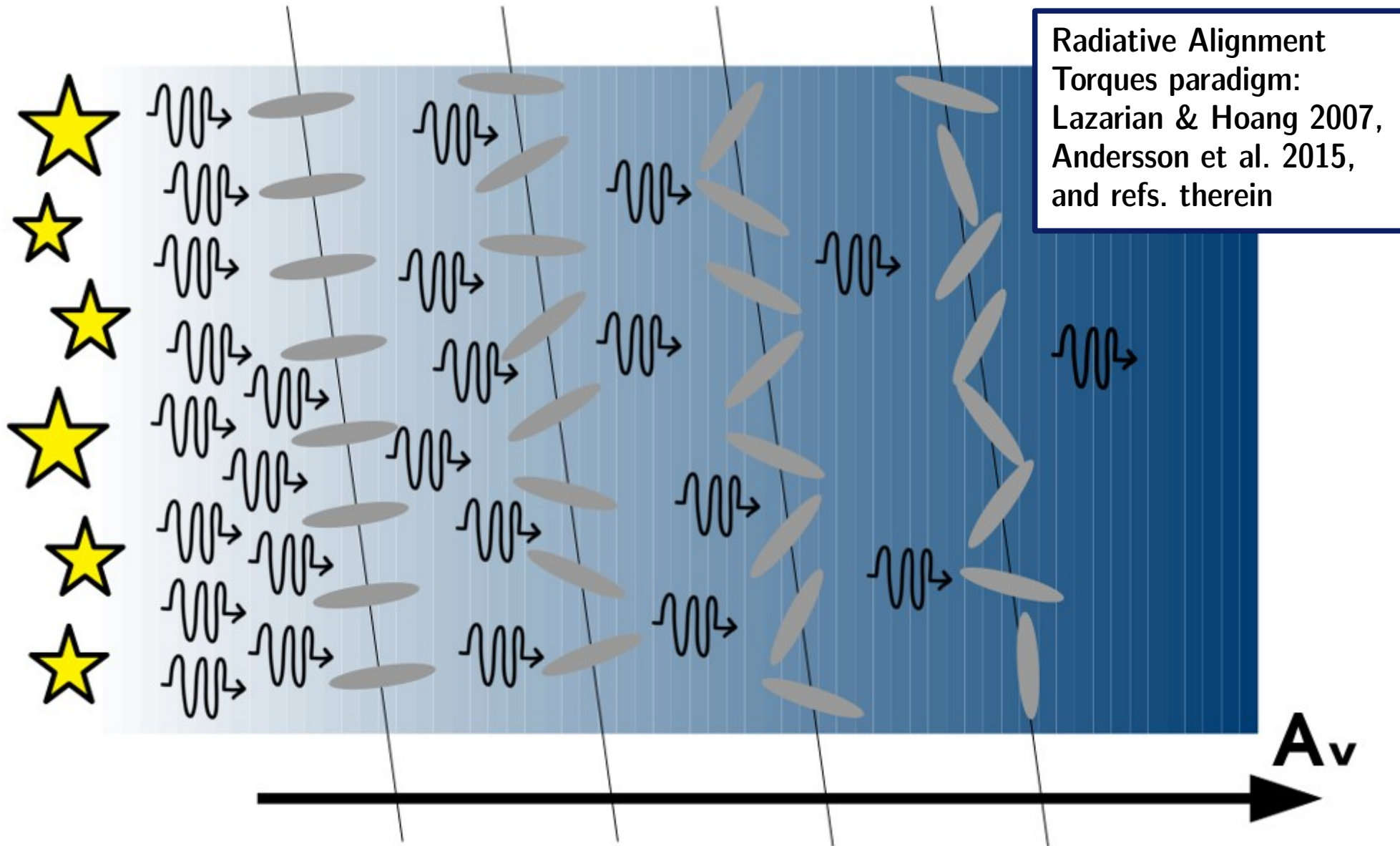


The Ophiuchus Molecular Cloud

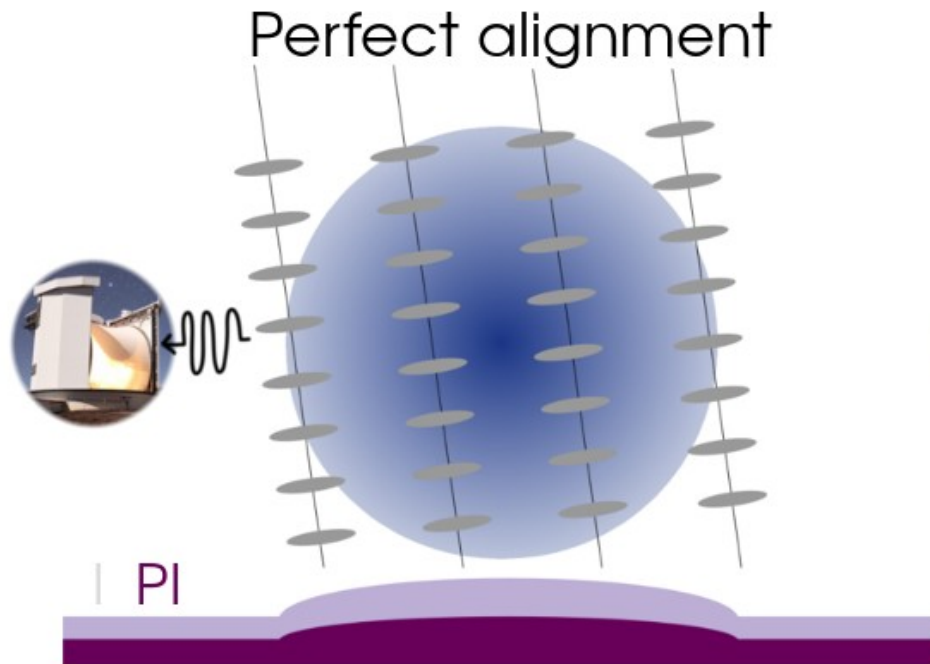
Clustered low-to-intermediate-mass star formation, located at ~ 140 pc (Ortiz-Léon et al. 2017).



A sanity check: Are grains actually aligned with the magnetic field?



Polarization efficiency as a measure of grain alignment



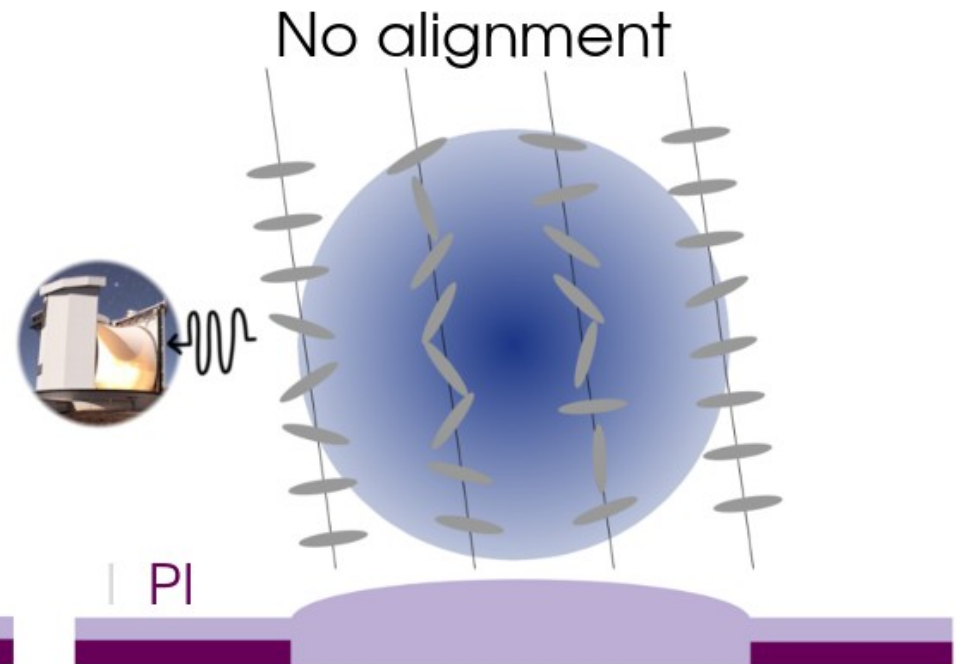
Polarized intensity (PI) $\propto I$
 $\Rightarrow p = PI/I = \text{constant}$

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

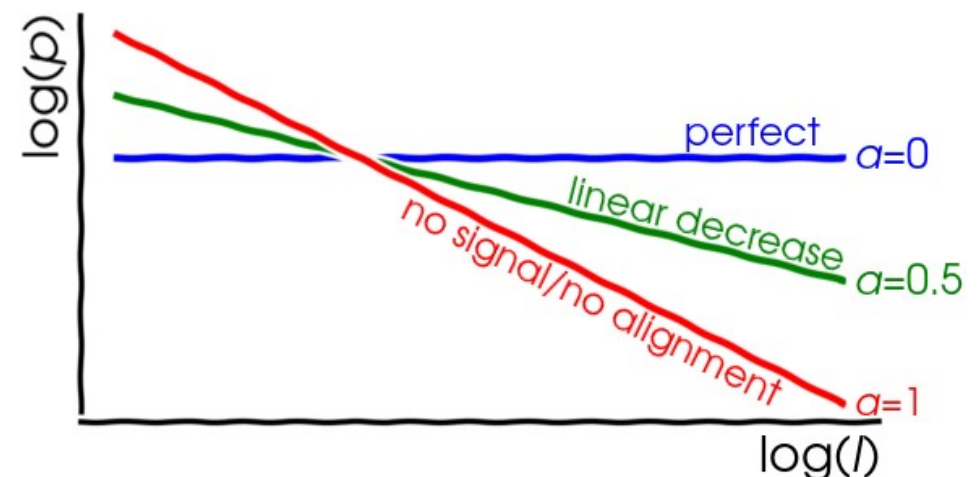
We expect $0 < \alpha < 1$

$\alpha = 0$ indicates all grains are equally aligned

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

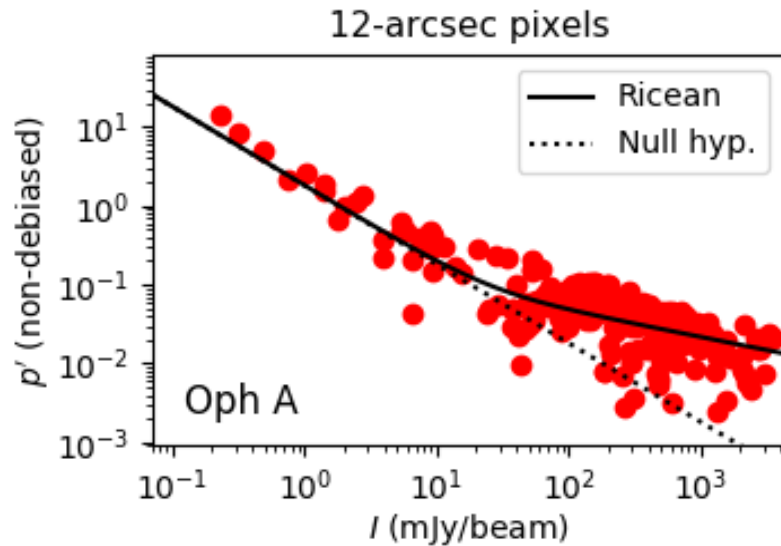


$PI(\text{inside}) = 0$
 $\Rightarrow p = PI(\text{outside})/I \propto 1/I$



Polarization fraction is Ricean-distributed: you will always measure $\alpha = 1$ at low S/N

Grain alignment in L1688



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

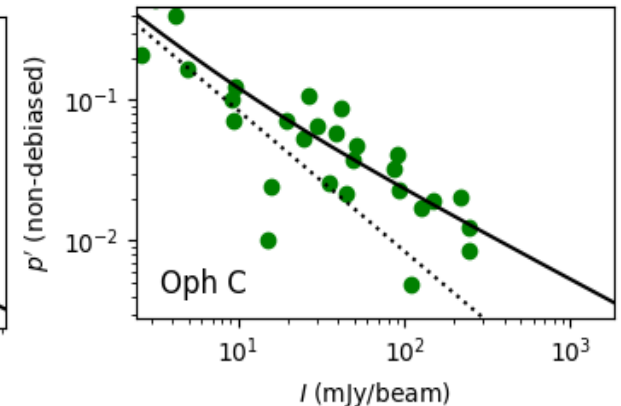
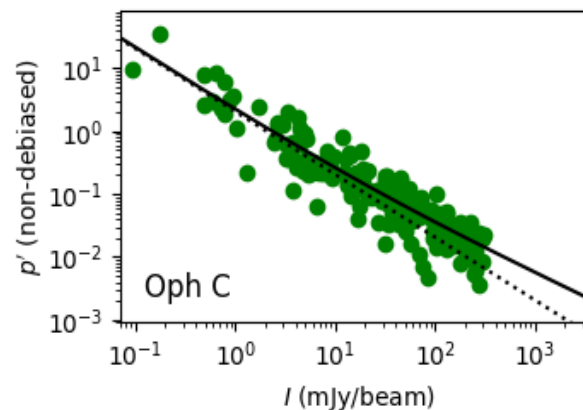
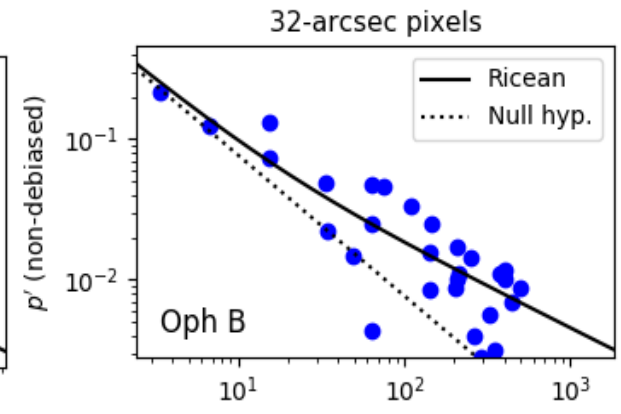
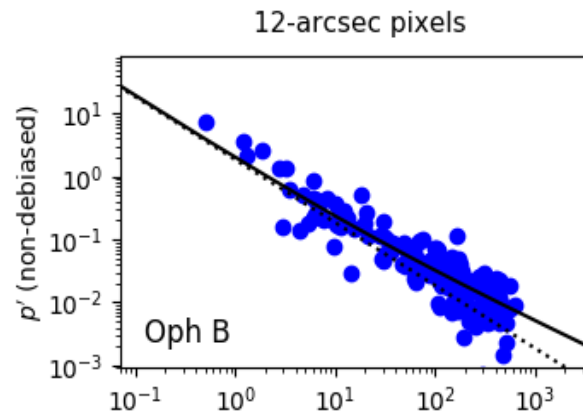
Grains appear to remain aligned at high densities in Oph A

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

Oph B & C:

$\alpha \sim 0.6 - 0.7$, $p_{100\text{mJy/beam}} \sim 2\%$

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



The radiation field of L1688

Region	Plane-of-sky distance (pc)		Upper-limit ionizing photon flux ($\text{s}^{-1}\text{m}^{-2}$)		
	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}

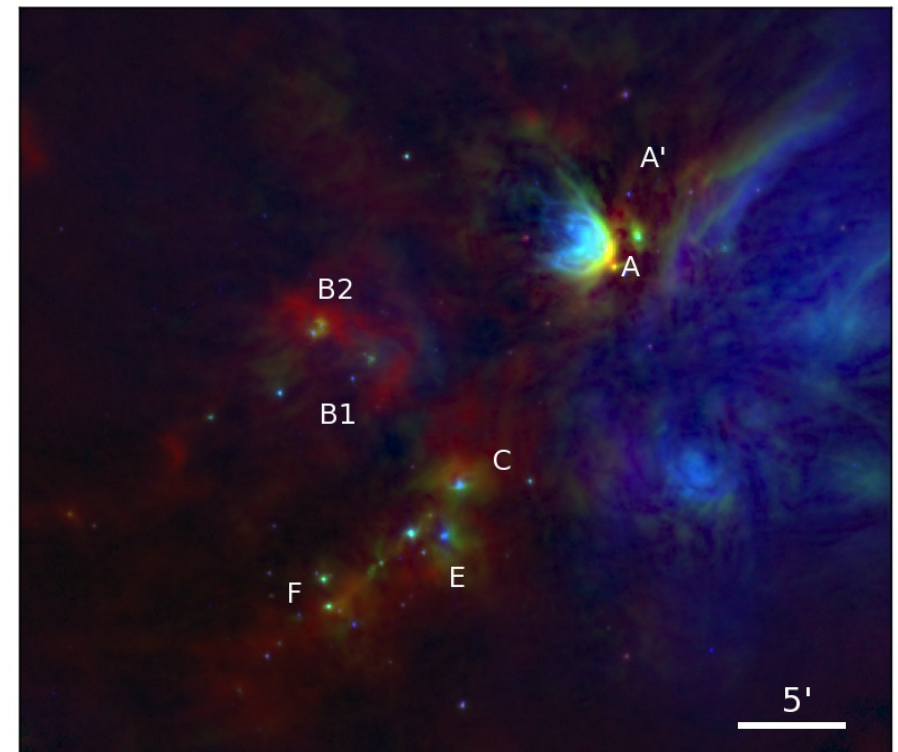
Ionizing photon flux on Oph A is an order of magnitude higher than on Oph B and C

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?

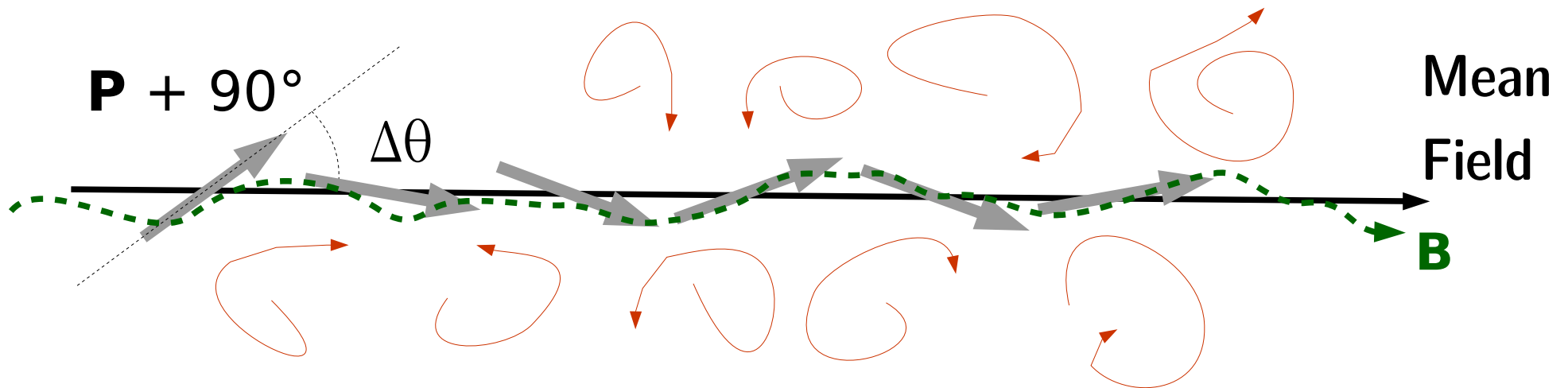
Much more detail can be found in:
Pattle et al. 2019, ApJ 880 27



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

A recap of the Davis-Chandrasekhar-Fermi Method

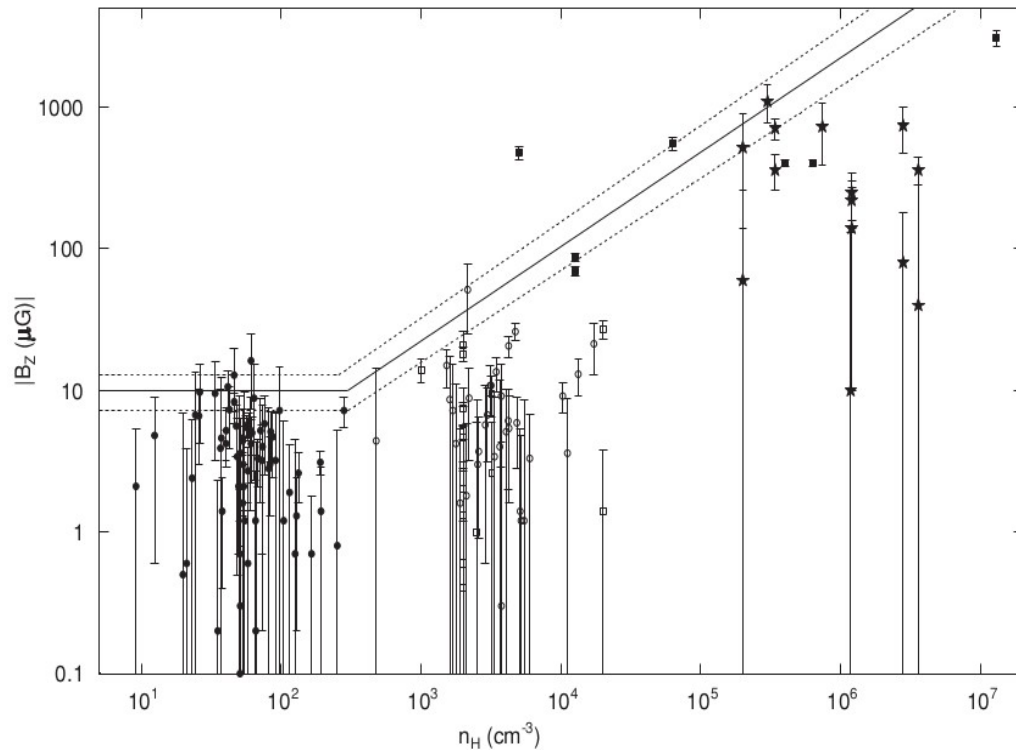
Assumes equipartition between non-thermal motions and the magnetic field: deviation in angle from the mean field direction is taken to be the result of distortion of the field by small-scale non-thermal motions (see Chandrasekhar & Fermi 1953, Davis 1951).



$$B_{\text{pos}} = Q \sqrt{4\pi\rho} \frac{\sigma_v}{\sigma_\theta}$$

(c.f. Crutcher et al. 2004)

Zeeman Effect (B_{los})

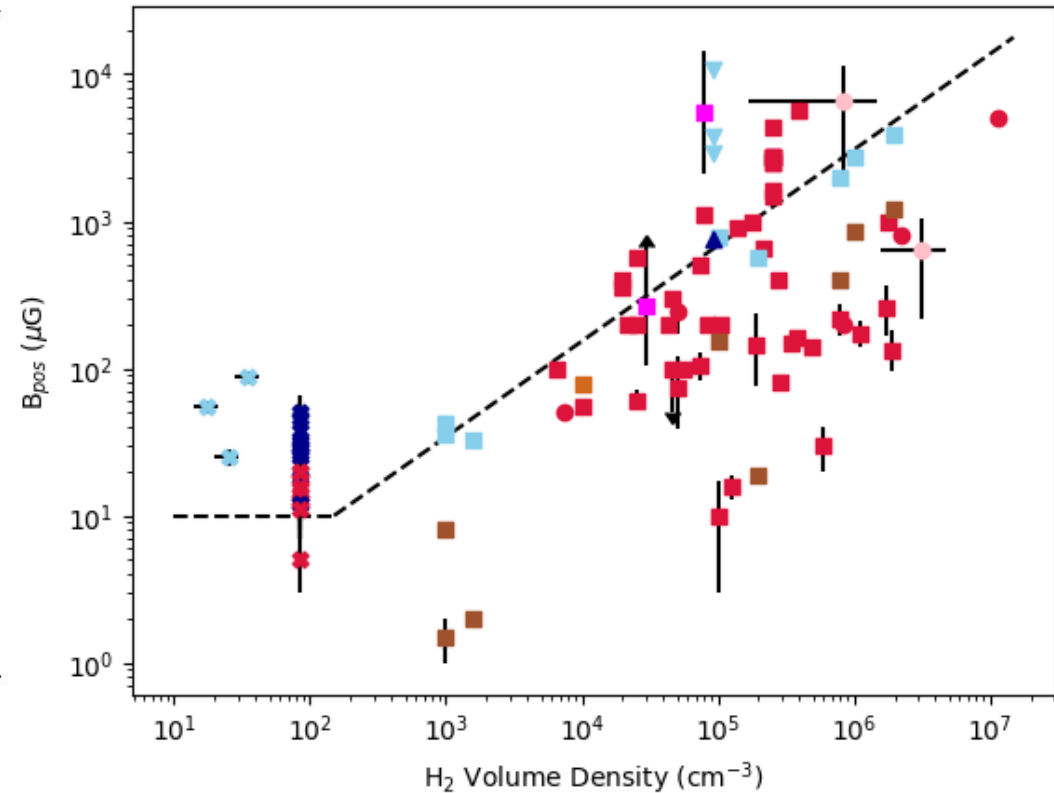


Crutcher et al. 2010, ApJ 745 466

DCF Method (B_{pos})

Reds: Classical DCF + variants

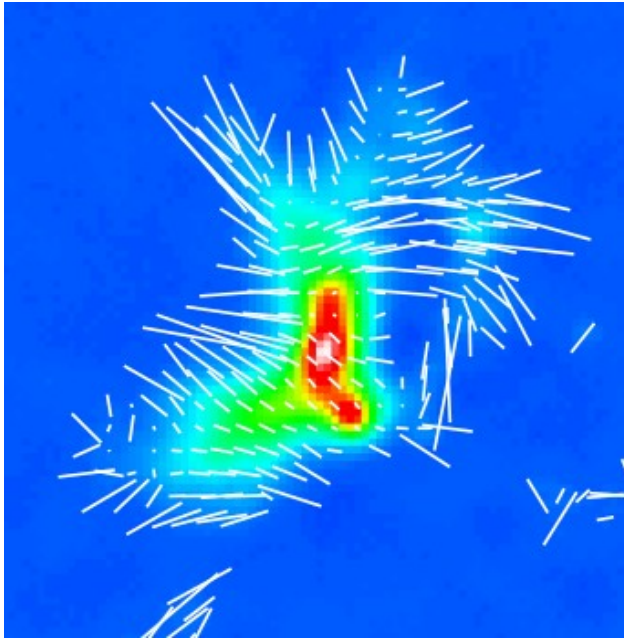
Blues: Structure-Function DCF variants



Pattle & Fissel 2019, FrASS 6 15

Oph A

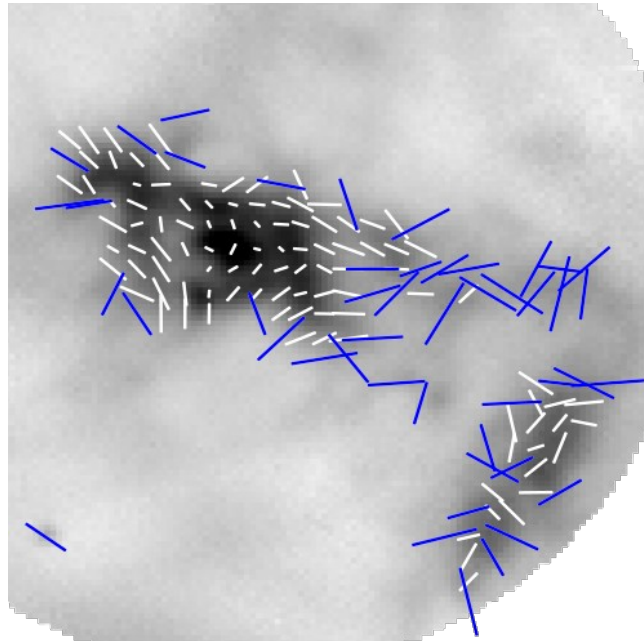
Kwon et al. 2018, ApJ 659 4



- 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 $200\mu\text{G}$ to 5mG

Oph B

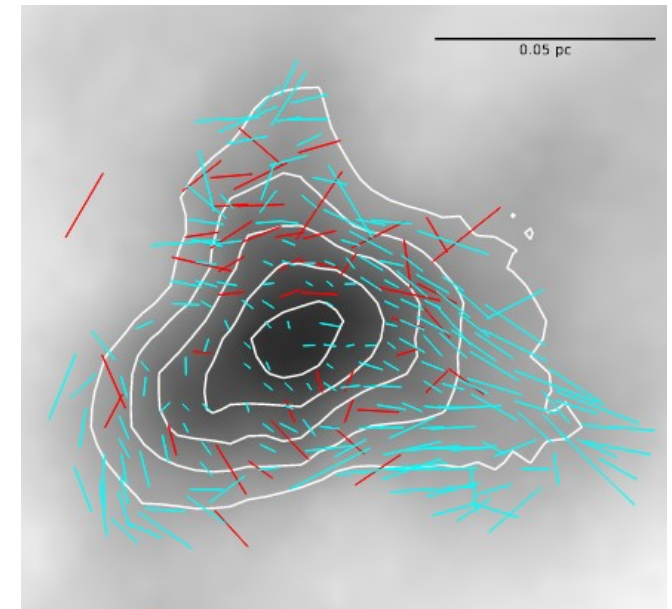
Soam et al. 2018, ApJ 861 64



- 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 $630 \pm 410 \mu\text{G}$

Oph C

Liu et al. 2019, ApJ 877 43



- 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 $\sim 100\text{--}200 \mu\text{G}$

**Slides with unpublished data
removed**

Summary

- Magnetic fields in the dense clumps of Ophiuchus are ordered, with strengths typically $\sim 10^2 \mu\text{G}$
- 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 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 and in L1689 retain some alignment with the magnetic field at high extinctions despite having a much weaker external radiation field than Oph A

Thank you!

(for more details on grain alignment, see Pattle et al. 2019, ApJ 880 27)