The JCMT BISTRO Survey: Magnetic fields in high-mass star-forming regions

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On behalf of the BISTRO Survey Team

Image credit: NASA/Hubble Space Telescope

BISTRO: Overview

- A JCMT Large Program mapping nearby (<2kpc) star-forming regions in polarized light

- >120 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

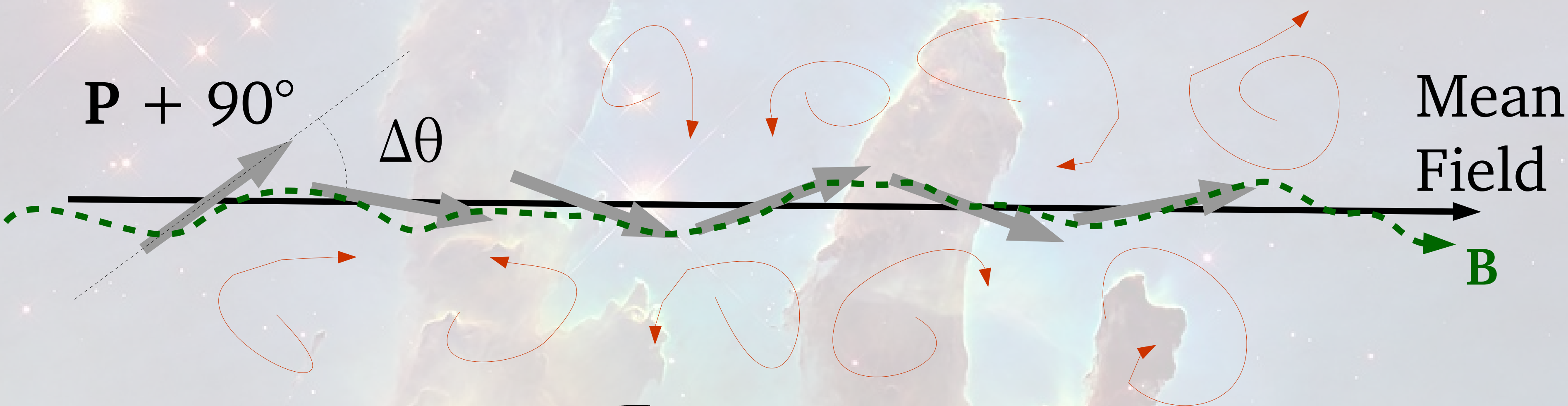
Survey paper: **Ward-Thompson et al. 2017, ApJ 842 66**
Orion A: **Pattle et al. 2017, ApJ 846 122**
Ophiuchus A: **Kwon et al. 2018, ApJ 859 4**
Ophiuchus B: **Soam et al. 2018, ApJ accepted, arXiv:1805.06131**
M16: **Pattle et al. 2018, ApJ 860 L6**

BISTRO: Scientific Goals

- To map the magnetic field within cores and filaments, on scales of ~1000-5000 AU
- To determine magnetic field strengths in nearby molecular clouds using the Chandrasekhar-Fermi method (through synthesis with Gould Belt Survey HARP data)
- To investigate the relative importance of magnetic fields and turbulence to star formation
- To test the model of magnetic funnelling of material onto filaments (André et al. 2013; Palmeirim et al. 2013)
- To investigate the role of magnetic fields in shaping protostellar evolution
- To investigate the effect of magnetic fields on bipolar outflows from young protostars

A brief aside on the 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).



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

(c.f. Crutcher et al. 2004)

$$\approx 9.3\sqrt{n(\mathrm{H_2})(\mathrm{cm^{-3}})}\,\frac{\Delta v(\mathrm{km\,s^{-1}})}{\sigma_\theta(^\circ)}\,\mu\mathrm{G}$$

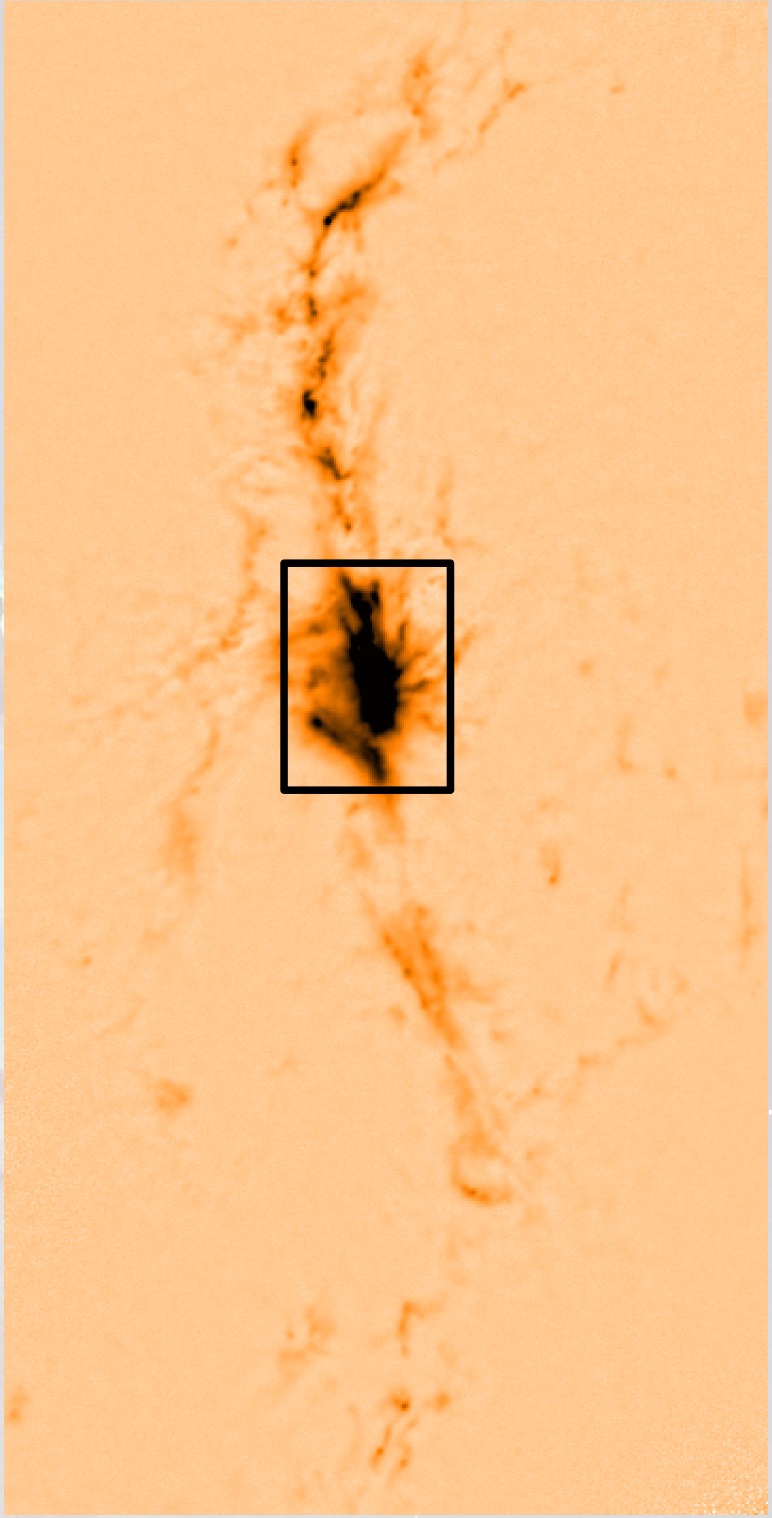
Orion A and OMC 1

The Orion Nebula is the nearest high-mass star-forming region, located at 388 pc (Kounkel et al. 2017).

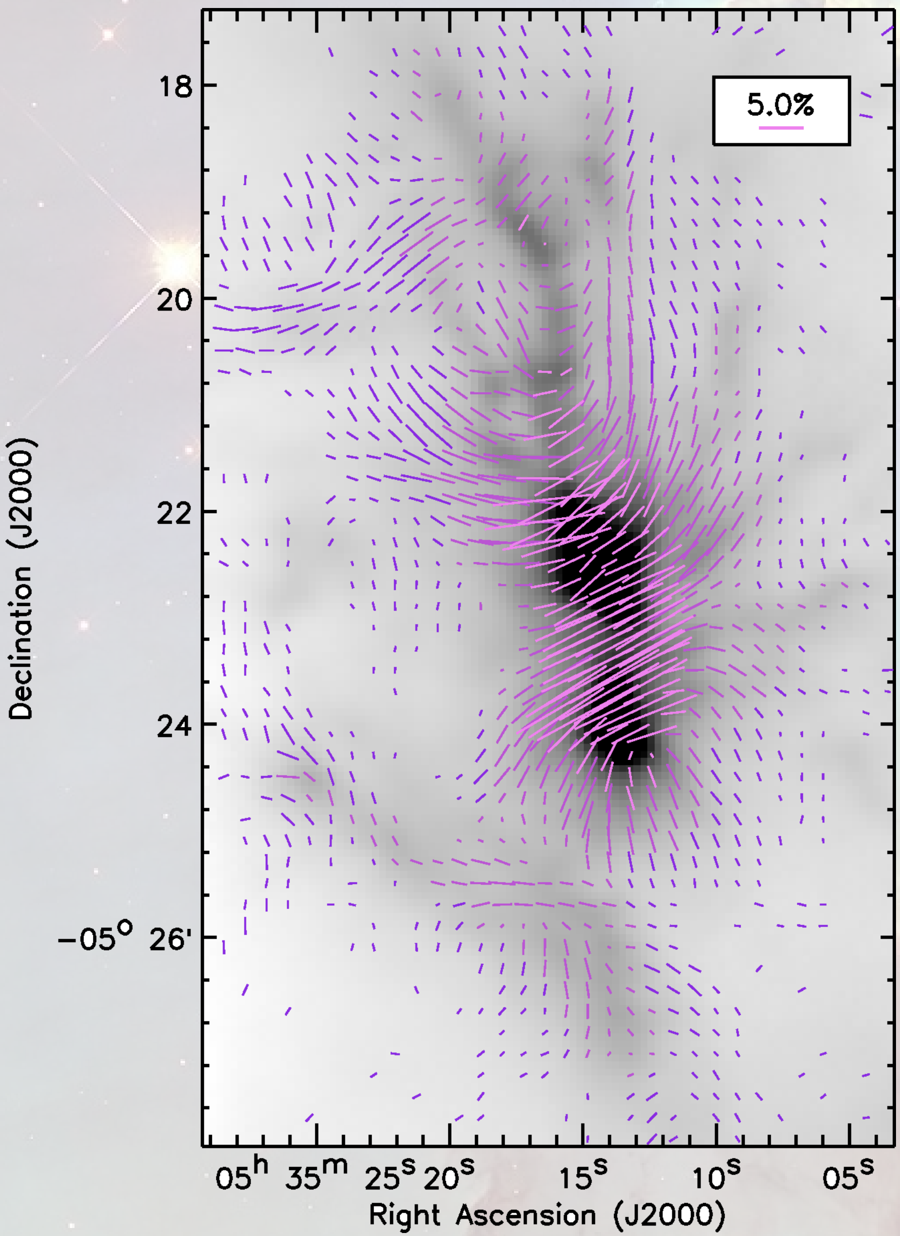
OMC 1 is a dense molecular cloud which is a site of ongoing high-mass star formation located in the centre of the Orion A “integral filament”.

OMC 1 is located behind the Trapezium cluster, and bounded on one side by the Orion Bar PDR.

Image: CO-subtracted 850μm SCUBA-2 data; JCMT GBS IR2 reduction



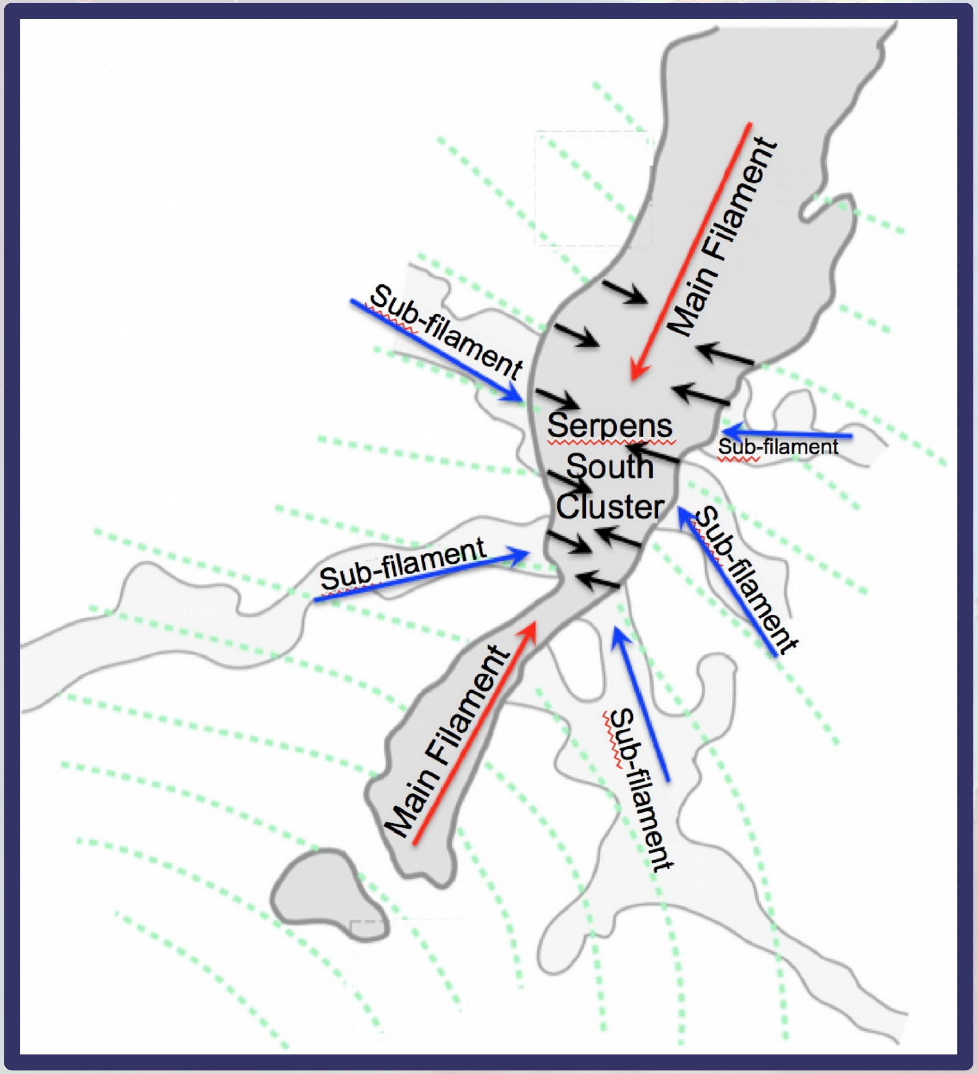
The magnetic field of OMC 1



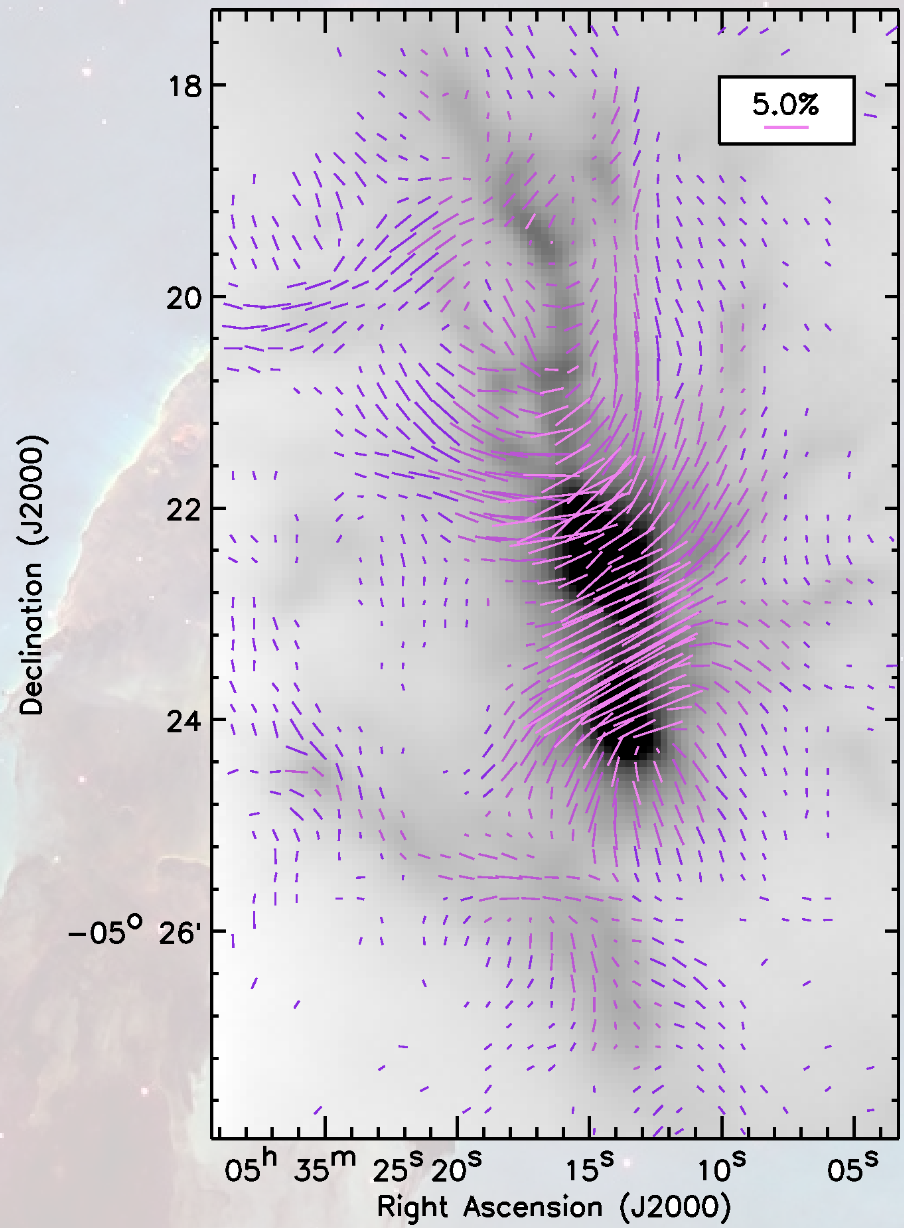
- Observed in January 2016 as part of POL-2 commissioning and BISTRO science programmes
- ~2mJy/beam RMS sensitivity on 12" pixels
- Vectors rotated to trace magnetic field
- Note 'hourglass' morphology (c.f. Schleuning 1998)

Ward-Thompson et al. 2017, ApJ 842 66;
Pattle et al. 2017, ApJ 846 122

Magnetic fields in self-gravitating filaments

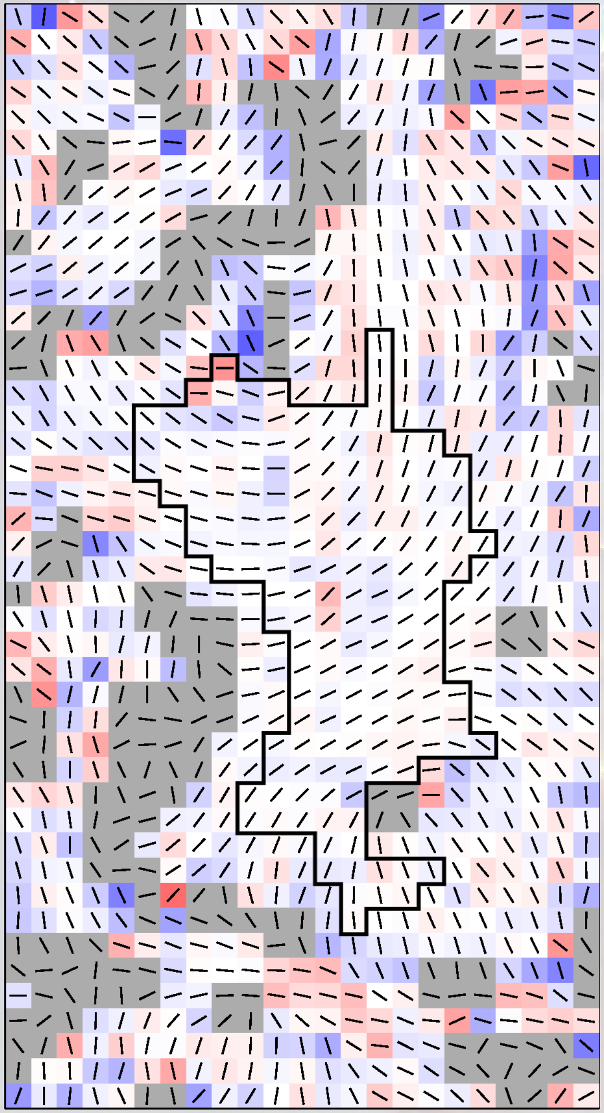


André et al. 2013



Ward-Thompson et al. 2017, ApJ 842 66
Pattle et al. 2017, ApJ 846 122

Energetics analysis of OMC 1



Chandrasekhar-Fermi analysis: **B = 6.6 ± 4.7 mG**

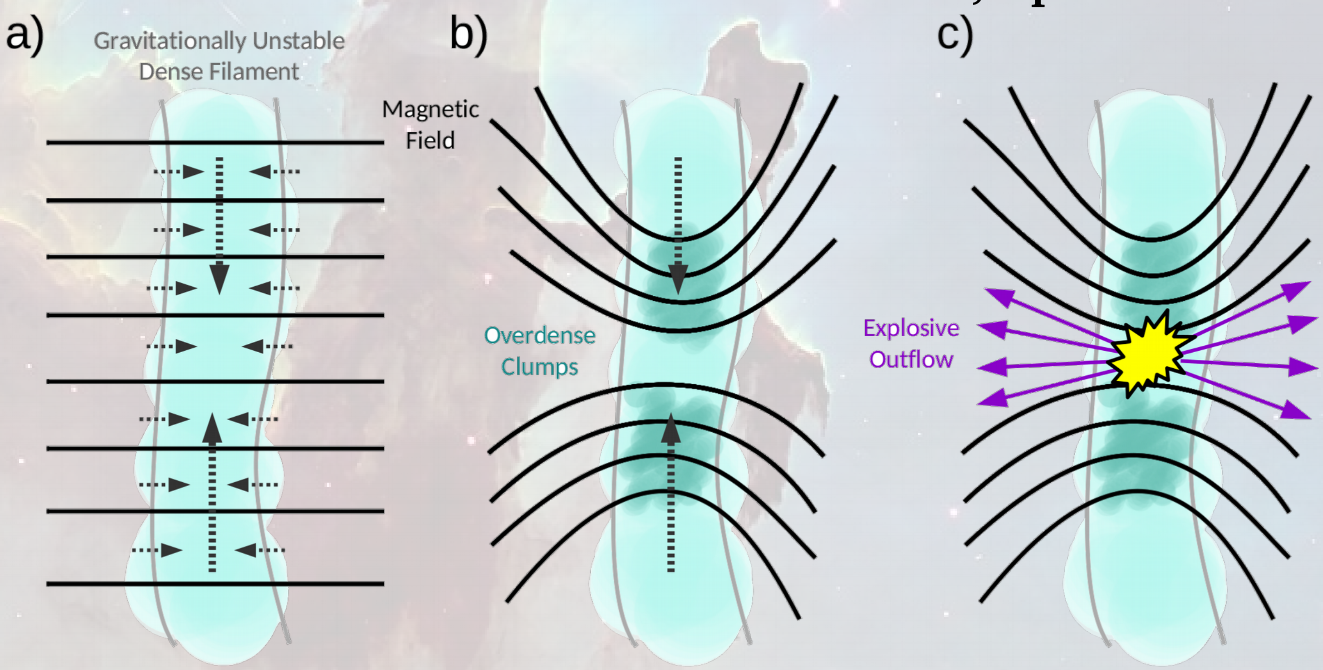
$U_B \sim 1.6 \times 10^{-7}$ J m^{-3}

$U_G \sim (0.5 – 8.8) \times 10^{-7}$ J m^{-3}

$U_{outflow} \sim 1.5 \times 10^{-7}$ J m^{-3} (not uniformly distributed)

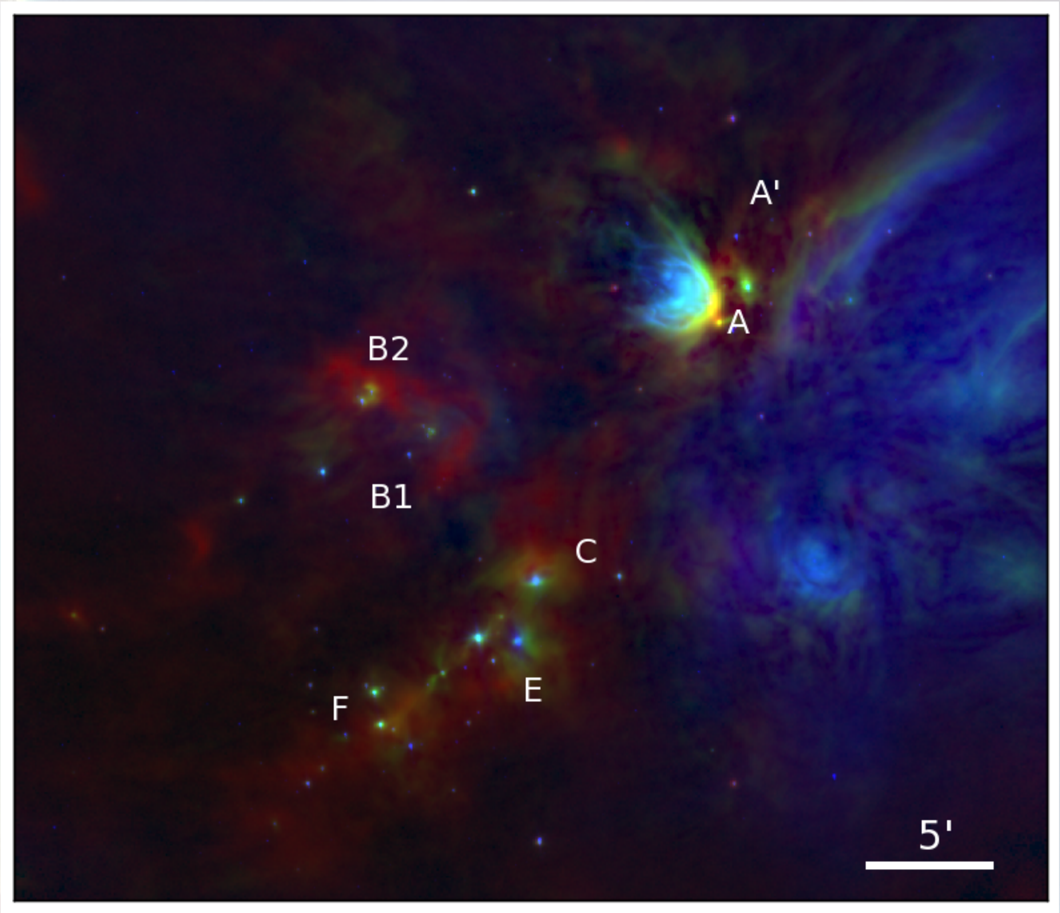
Hourglass magnetic field morphology created by gravitational collapse of filament; "Bullets of Orion" explosive outflow morphology constrained by magnetic field geometry?

Pattle et al. 2017, ApJ 846 122



The Ophiuchus Molecular Cloud

- A nearby (~140pc) site of low-to-intermediate-mass star formation
- Strong westerly influence from the Sco OB2 association
- Significant variation in properties, behaviour and star formation history within the region

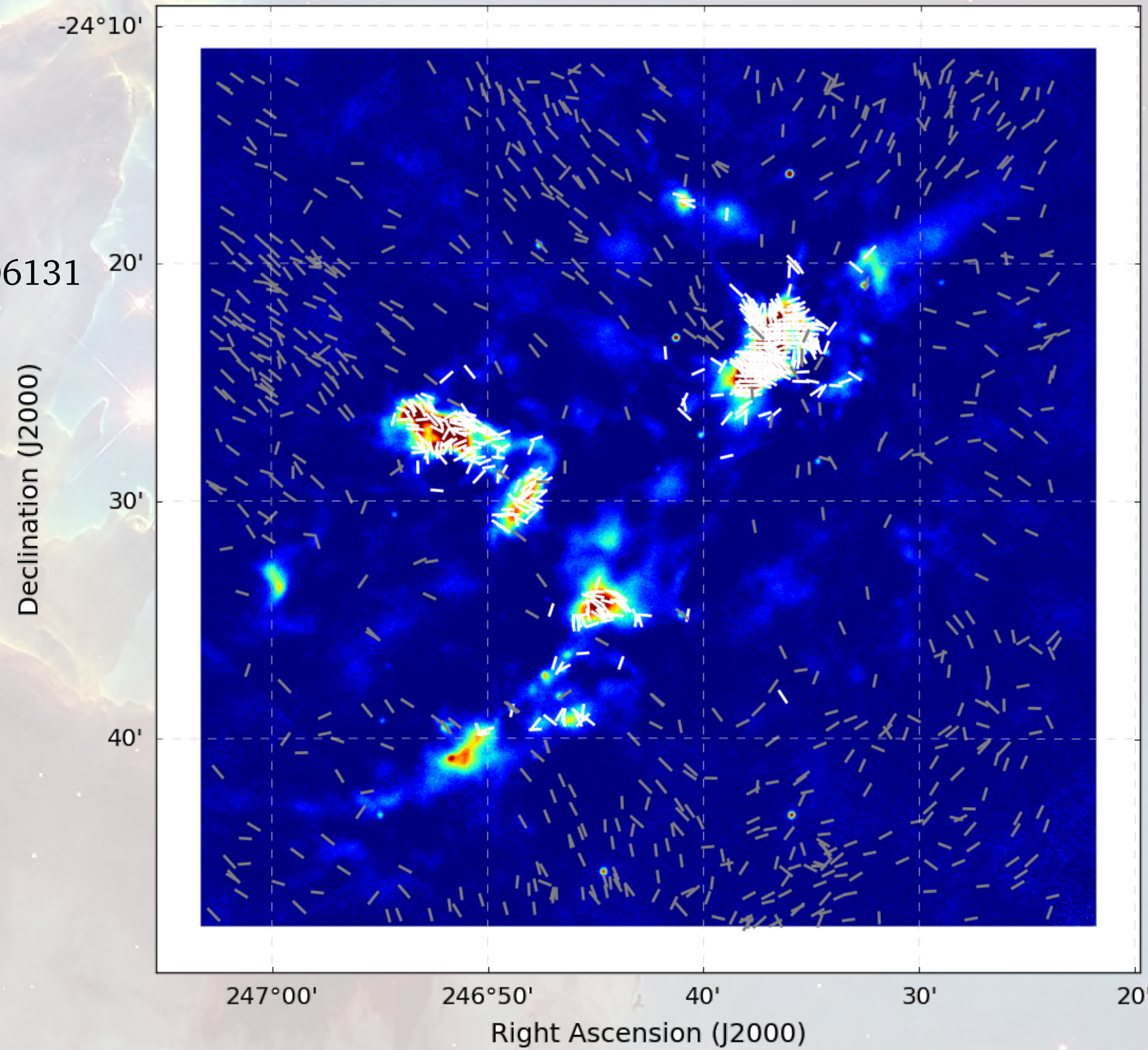


R: SCUBA-2 850μm, G: Herschel 100μm, B: Spitzer 8μm
Pattle et al. (2015) MNRAS 450 1094

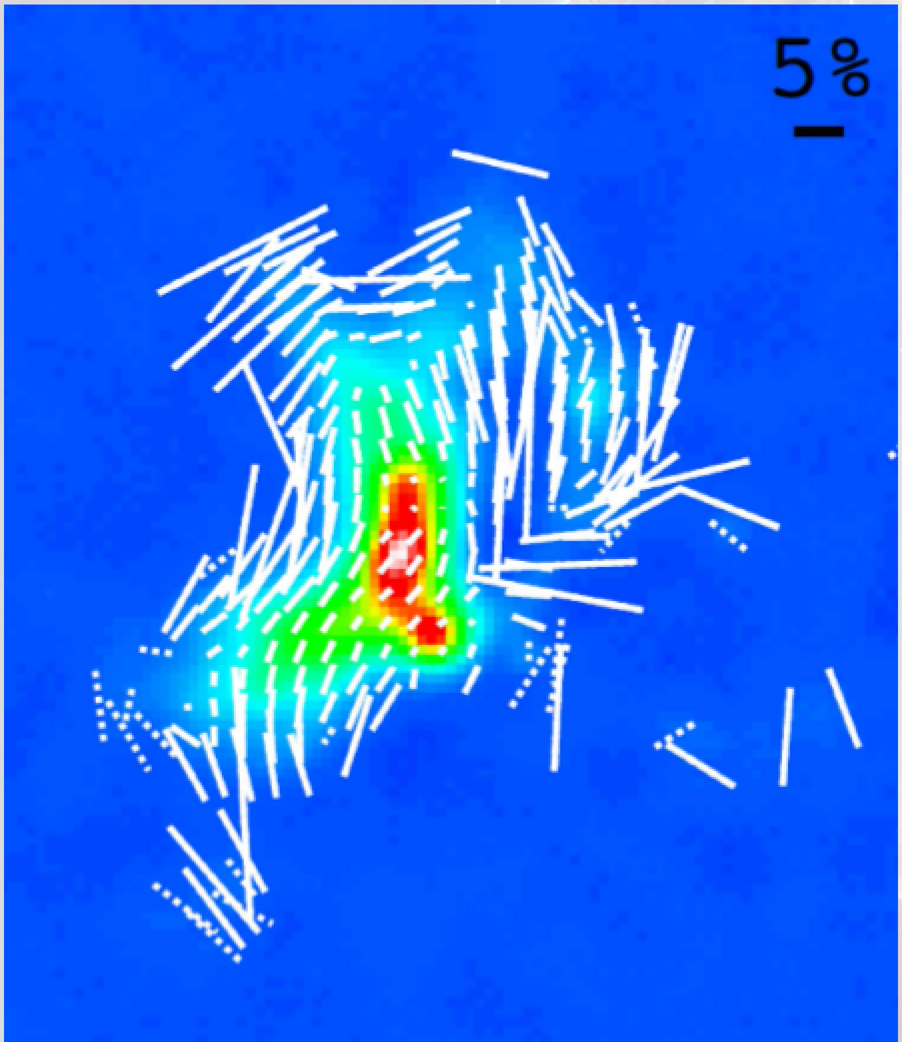
The Ophiuchus Molecular Cloud: magnetic field morphology

<u>White vectors:</u>
BISTRO POL-2 850μm
Oph A: Kwon et al., ApJ 859 4
Oph B: Soam et al., arXiv:1805.06131
Oph C: Qiu et al., in prep.

<u>Grey vectors:</u>
H-band extinction polarization
Kwon et al. (2015), ApJS 220 17

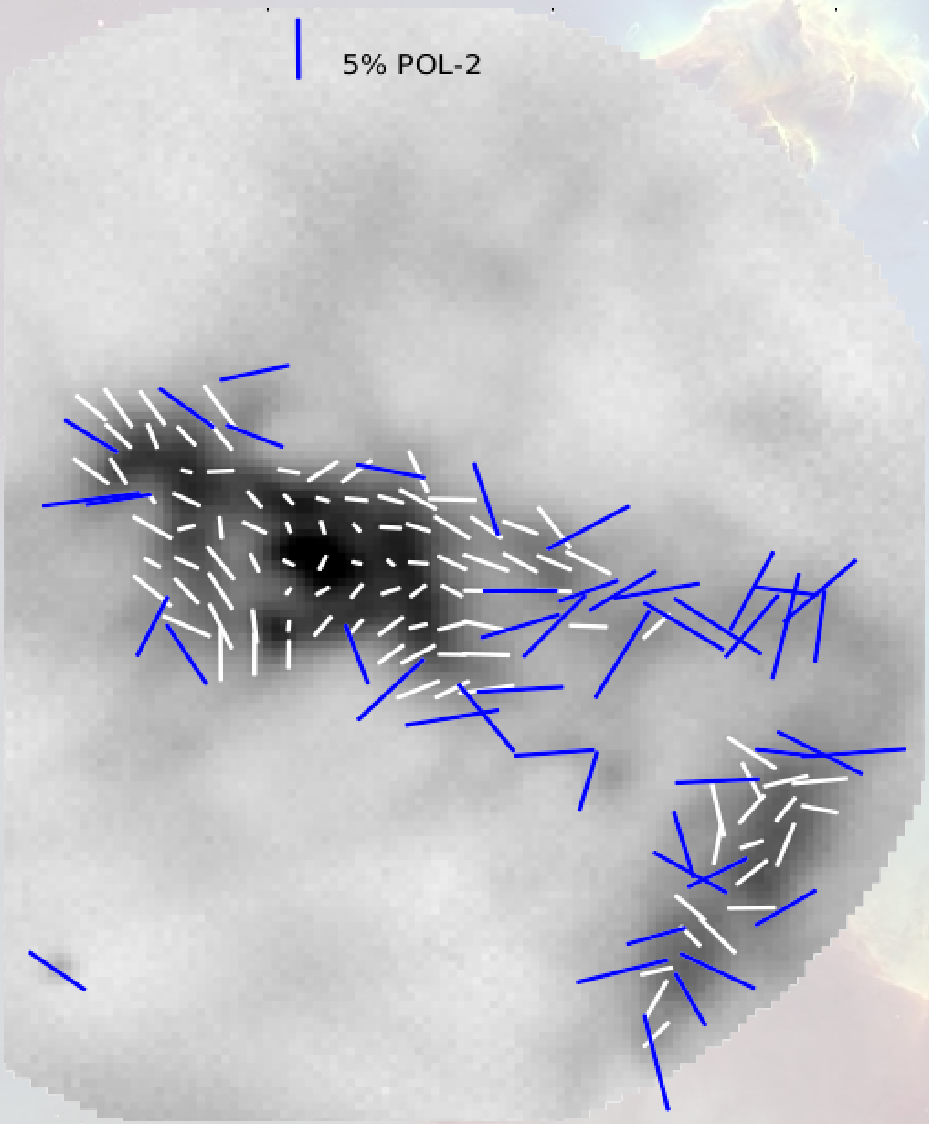


Oph A: Kwon et al. 2018, ApJ 659 4



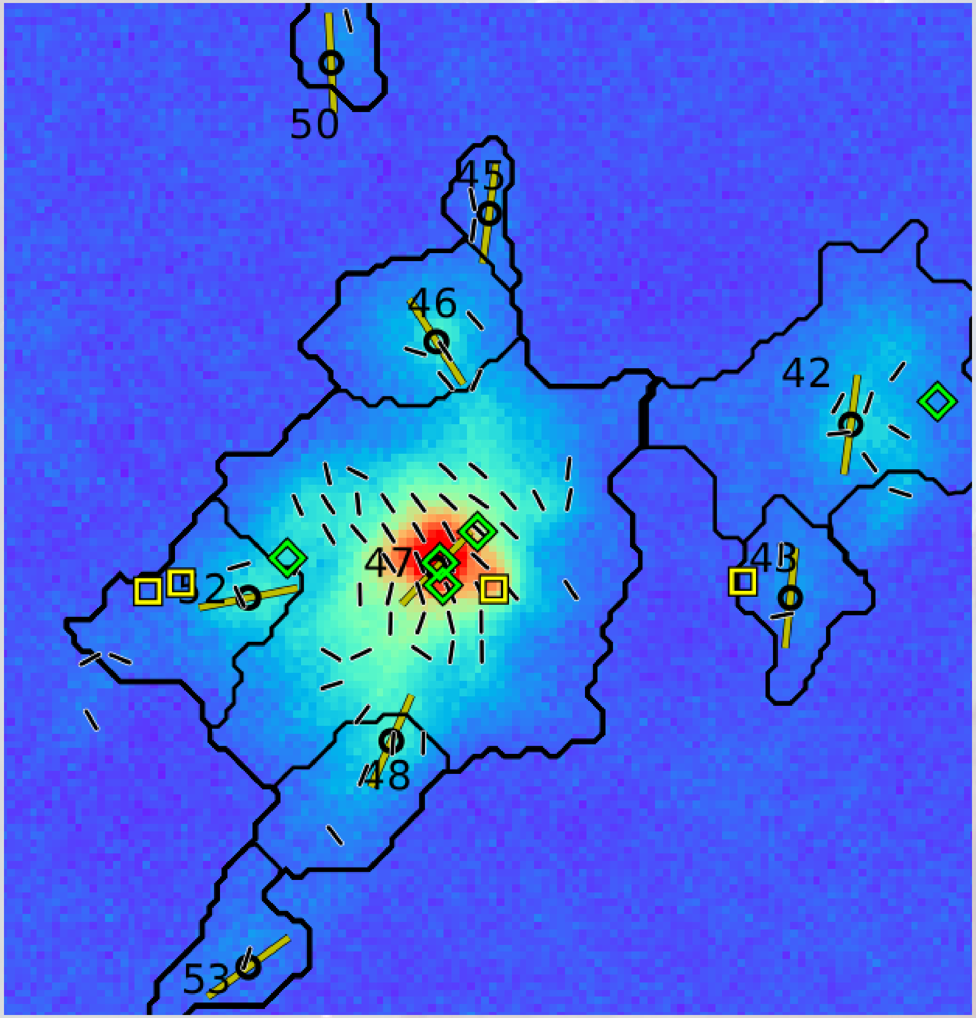
- Actively forming stars (contains outflow-driving sources)
- Sandwiched between two B stars
- Well-ordered magnetic field with significant variation across the region
- Magnetic field strength ranges from 200μG to 5mG

Oph B: Soam et al. 2018, ApJ in press, arXiv:1805.06131



- 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

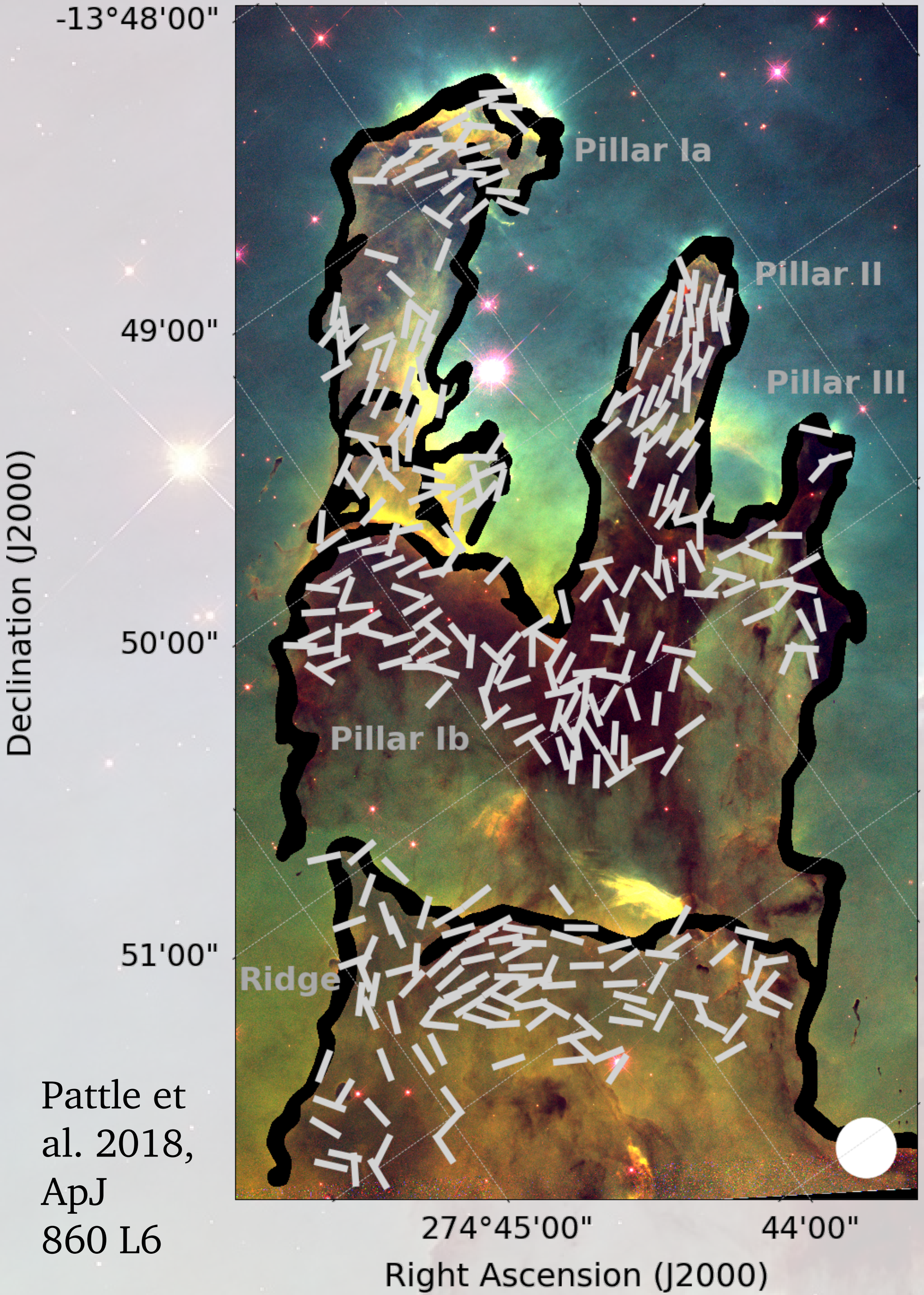
IC5146: Wang et al, in prep.



- A hub-filament system, perhaps high-mass (distance uncertain; either 460pc or 950pc)
- Magnetic fields approximately perpendicular to major axis of hub
- Magnetic field strength $\sim 300\mu G$

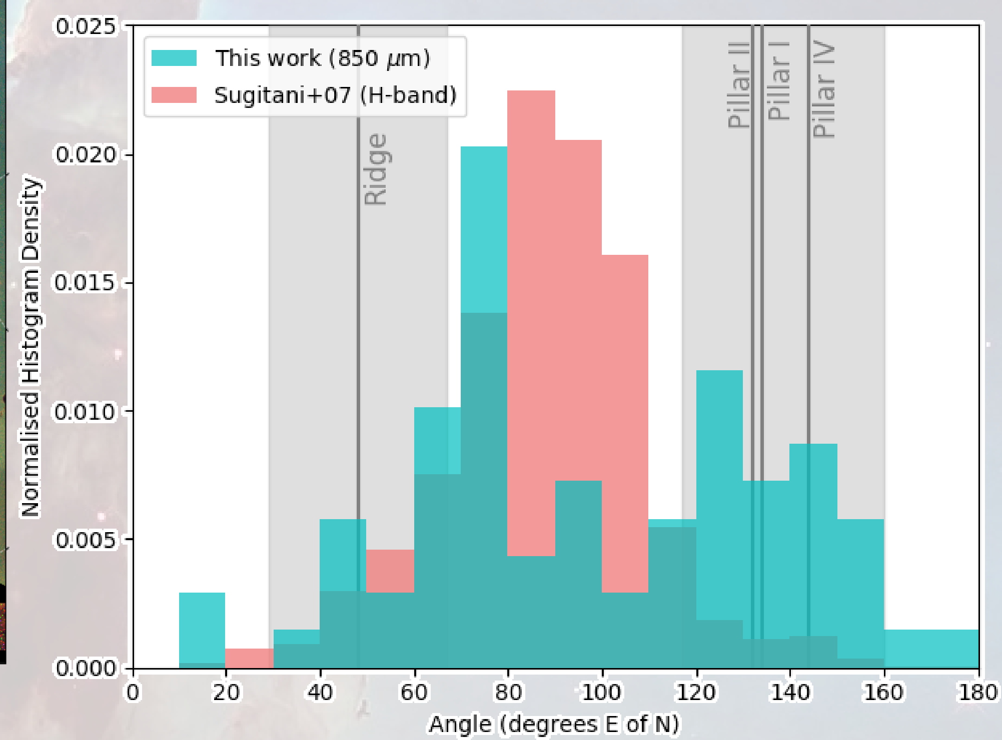
M16: The Eagle Nebula

- High-mass star-forming region
- H_{II} region driven by NGC 6634 cluster
- Distance: 1.8 ± 0.2 kpc (Dufton et al. 2006)
- The "Pillars of Creation": photoionized columns famously imaged by the Hubble Space Telescope (Hester et al. 1996)

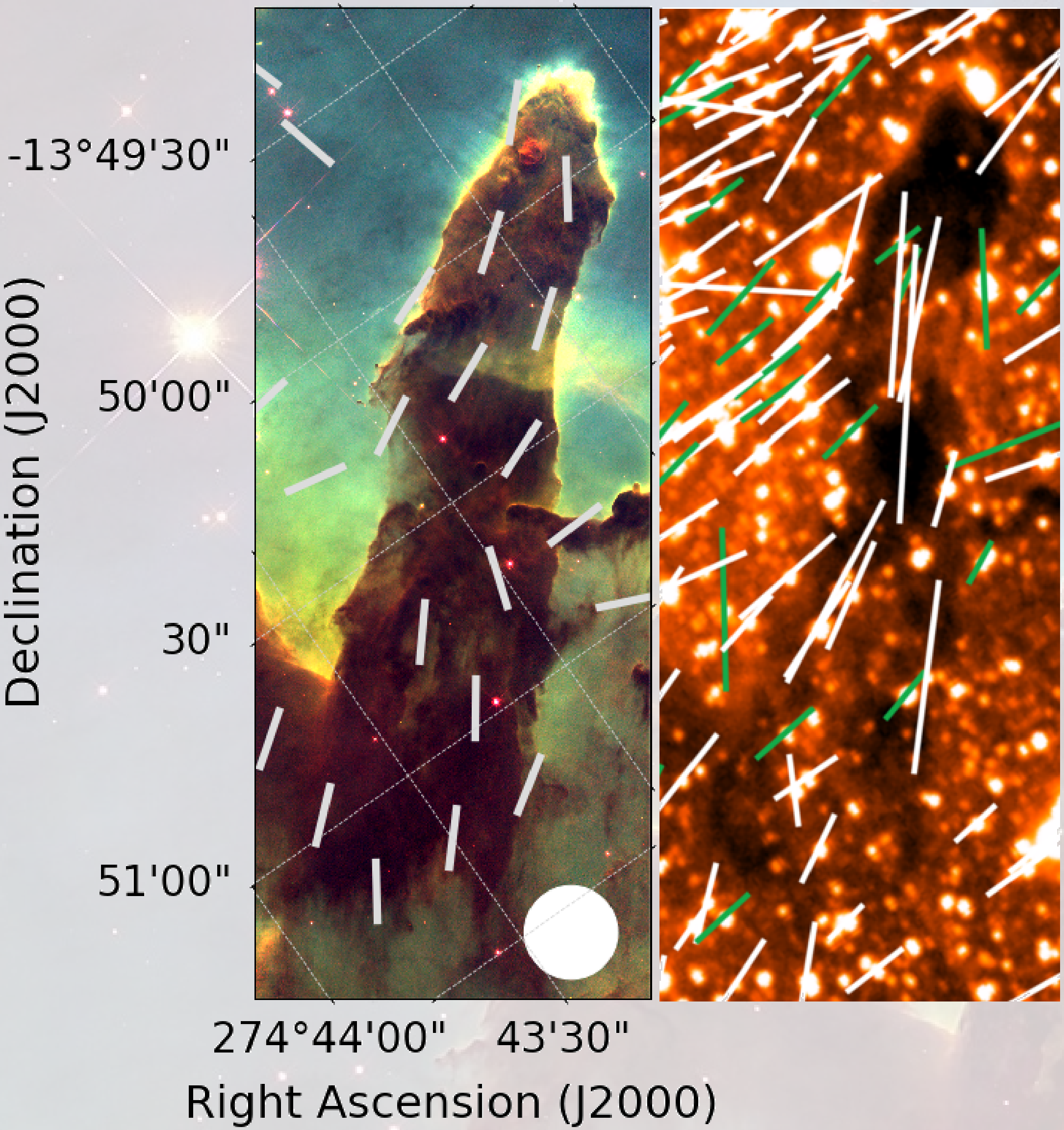


The magnetic field within the pillars:

- is parallel to the axis of the pillars
- is ~ perpendicular to the magnetic field in the HII region
- is ordered
- Shows hints of depolarization at the pillar tips (reversal of direction?)



Pattle et al. 2018, ApJ 860 L6



Magnetic field strength in Pillar II:

- $\sigma_\theta = 14.4^o$
- $n(H_2) \sim 5 \times 10^4\ cm^{-3}$

  (Ryutov et al. 2005)
- $\Delta v \sim 1.1 - 2.1$ km/s

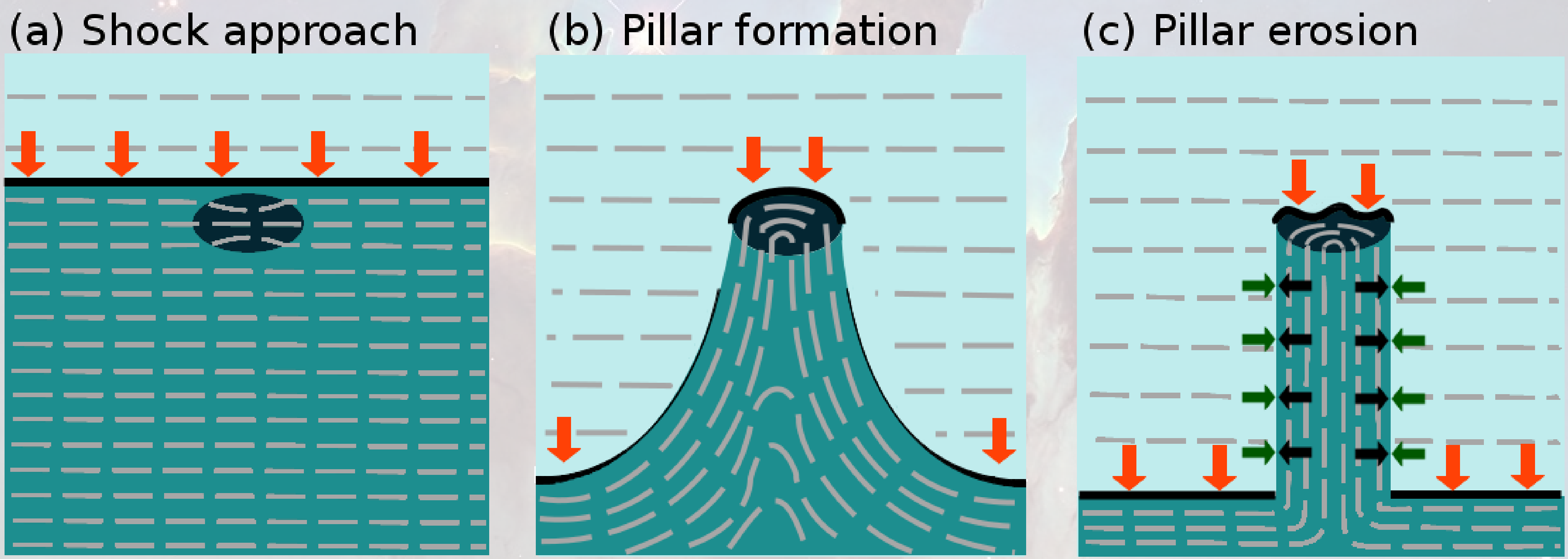
  (White et al. 1999)

$\Rightarrow$ **$B_{pos} \approx 170 - 320\ \mu G$**

Pattle et al. 2018, ApJ 860 L6

Simple energetics analysis suggests:

- The pillar head is being ablated by the interaction with the HII region
- The pillar walls are in approximate pressure equilibrium, with magnetic pressure and non-thermal internal gas pressure being balanced by non-thermal external gas pressure and non-negligible self-gravity
- Thermal internal and external gas pressures are significantly smaller than other terms



Pattle et al. 2018, ApJ 860 L6

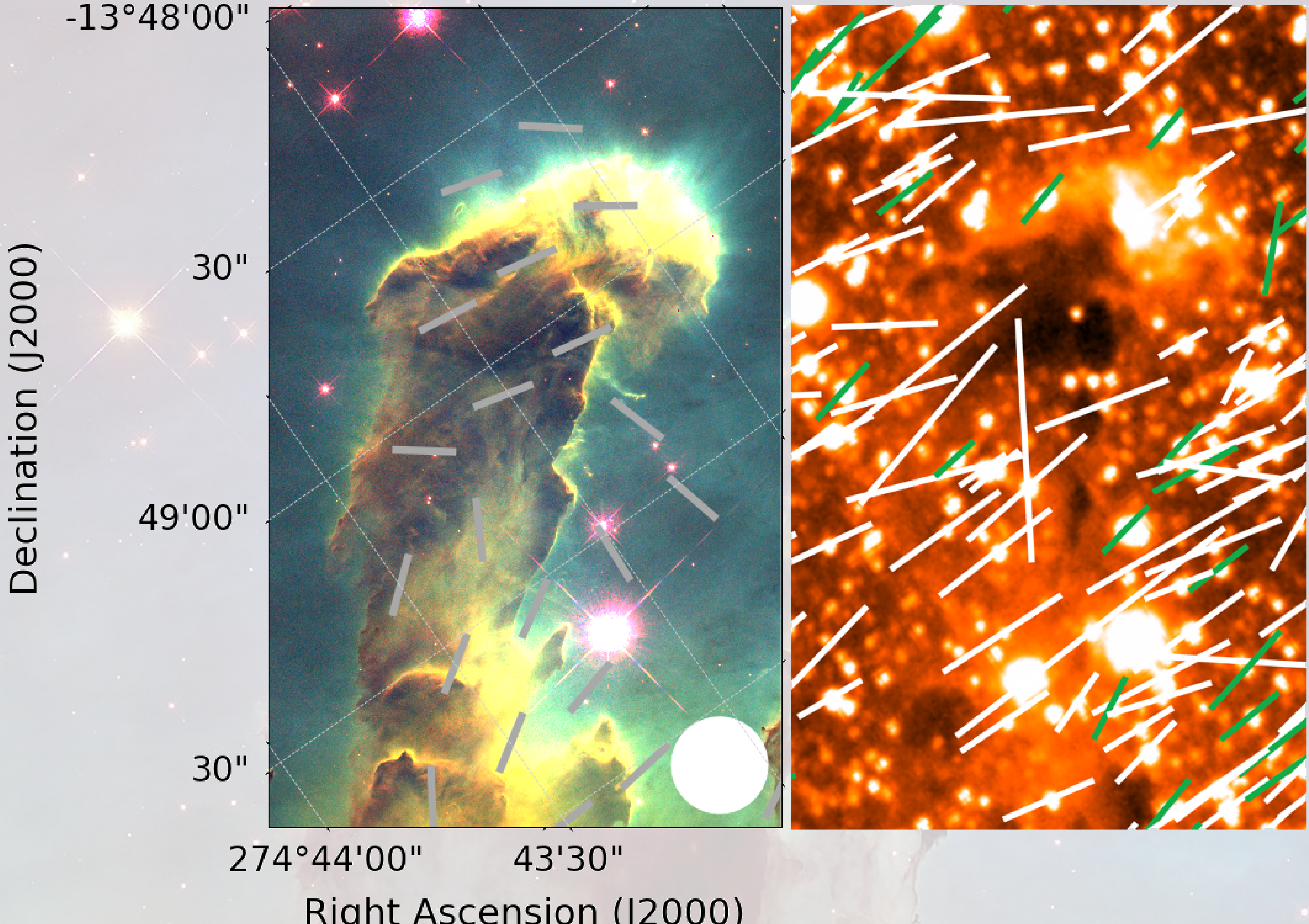
Summary

The BISTRO survey is providing wide-field, high-resolution single-dish polarimetric imaging of the high-density regions of sites of star formation to a distance of 2kpc.

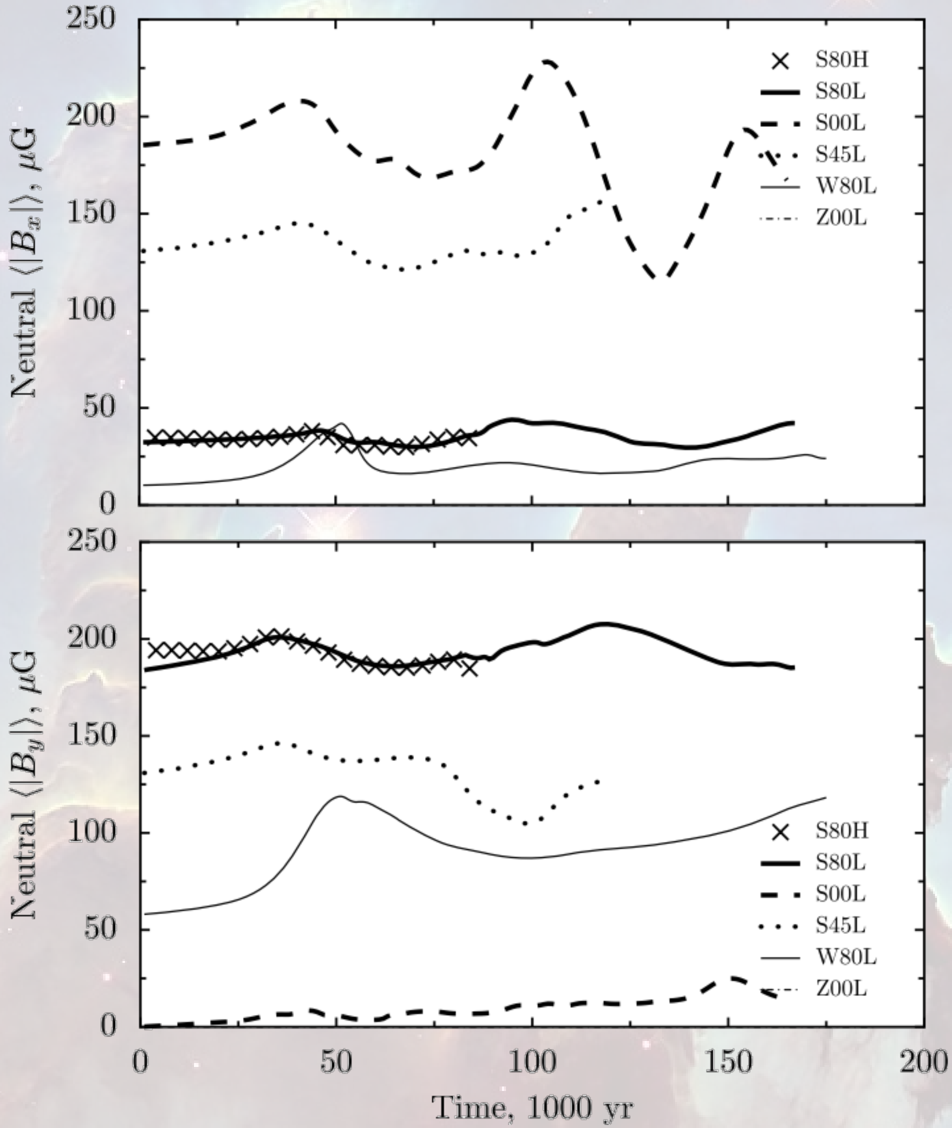
Our preliminary results include:

- Observations of an hourglass magnetic field in OMC 1, possibly channelling the large-scale BN/KL outflow (Pattle et al. 2017)
- Highly variable magnetic field strength and morphology in Ophiuchus (Kwon et al. 2018; Soam et al. 2018).
- Potential accretion along field lines in a hub-filament system in IC5146 (Wang et al, in prep.)
- The first measurements of the magnetic field in the dense gas of the Pillars of Creation, with a field strength suggesting the Pillars may be magnetically supported

Thank you, and watch this space!



-13°48'00"
30"
49'00"
30"
Declination (J2000)
274°44'00"
43'30"
Right Ascension (J2000)



Neutral $\langle|B_x|\rangle$, μG
S80H
S80L
S00L
S45L
W80L
Z00L
Neutral $\langle|B_y|\rangle$, μG
Time, 1000 yr

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Rachel Friesen
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