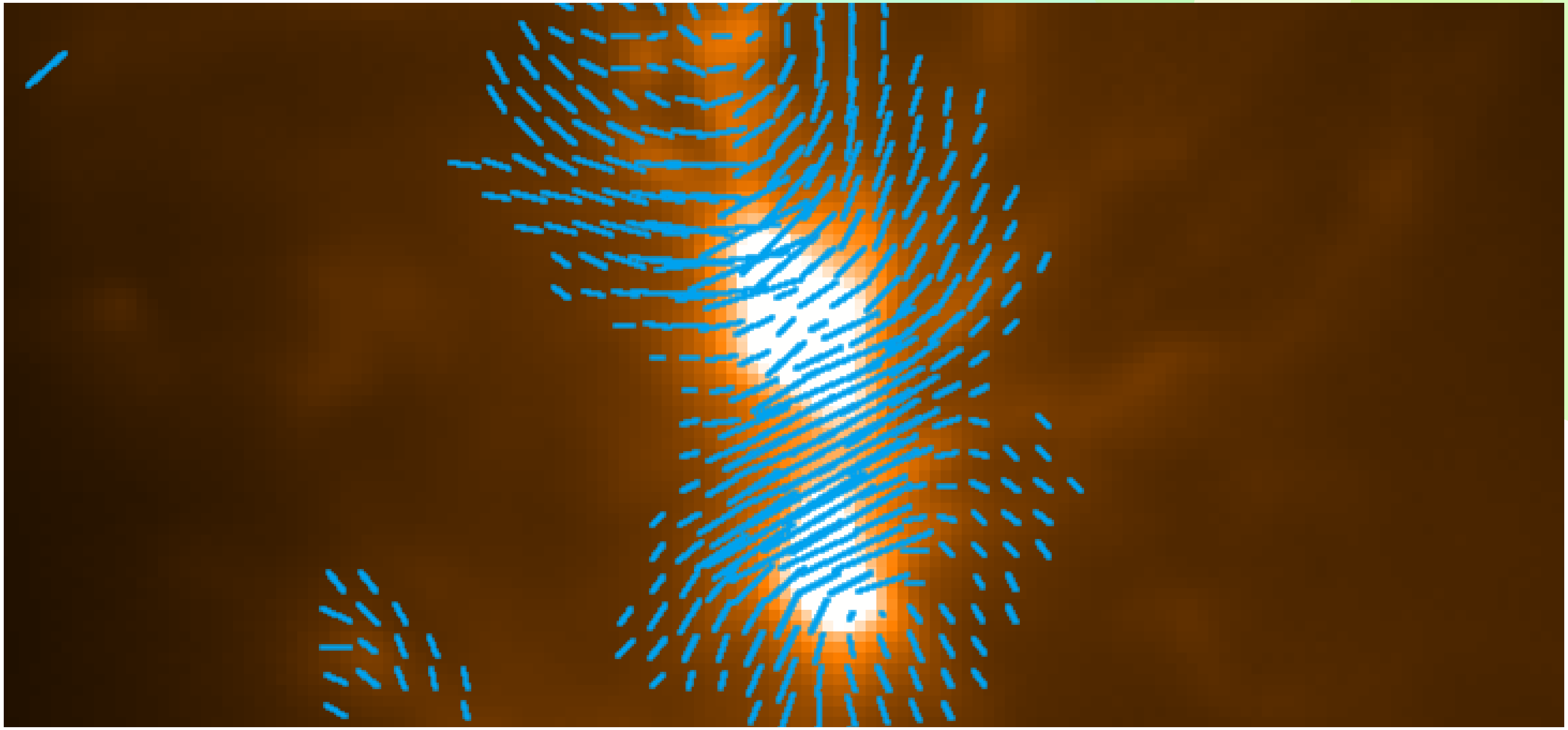
The Magnetic Field Strength and Energy Balance of OMC 1



Credit: POL-2 Commissioning Team

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JEREMIAH HORROCKS INSTITUTE

BISTRO

JCMT Gould Belt Legacy Survey

uclan University of Central Lancashire

Acknowledgements:

BISTRO: Derek Ward-Thompson, Woojin Kwon, Tetsuo Hasegawa, Shih-Ping Lai, Keping Qiu, Pierre Bastien, Ray Furuya, Simon Coudé, Jongsoo Kim, Chang Won Lee, Andy Pon, Sarah Sadavoy, among many others

East Asian Observatory: David Berry, Jess Dempsey, Per Friberg, Sarah Graves, Harriet Parsons

Gould Belt Survey: James Di Francesco, Jenny Hatchell, Helen Kirk, among many others

BISTRO: Overview

- We are a JCMT Large Program aimed at mapping the Gould Belt star-forming regions in polarised light

- >100 survey members across 6 partner regions and the East Asian Observatory

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

- BISTRO-1 awarded 224 hours of observing time to map:
  Ophiuchus, Orion A & B, Perseus, Serpens Main, Taurus L1495/B211, Auriga, IC5146

- BISTRO-2 (2017) awarded a further 224 hours to map:
  More of Orion, more of Perseus, Serpens Aquila, M16, DR15, DR21, NGC 2264, NGC 6334, Mon R2, Rosette

Survey paper: **Ward-Thompson et al. 2017, ApJ 842 66**

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

POL-2: The Instrument

- A single-beam imaging polarimeter mounted on the SCUBA-2 camera on the JCMT (15m)
- Measures linear polarisation (Stokes Q & U)
- Takes data at 850μm (353 GHz) and 450μm (667 GHz) simultaneously. 850μm commissioned; 450μm commissioning ongoing
- 14" resolution at 850μm, sensitive to spatial scales $\lesssim$5', mapping mode produces 12'-diameter maps with the option of mosaicing
- For details: Friberg et al. 2016, SPIE 9914 03

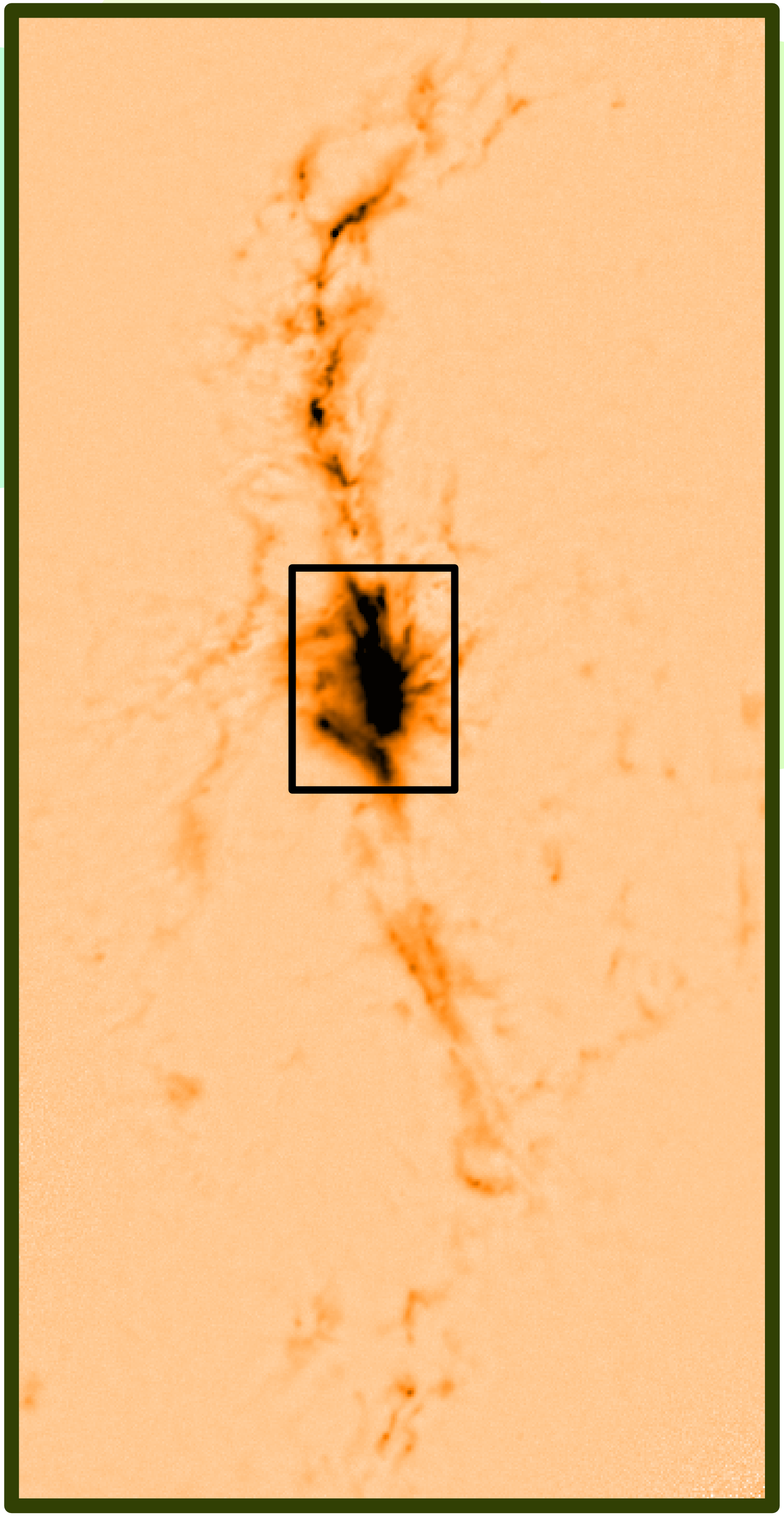
Orion A and OMC 1

The Orion Nebula is the nearest high-mass star-forming region.

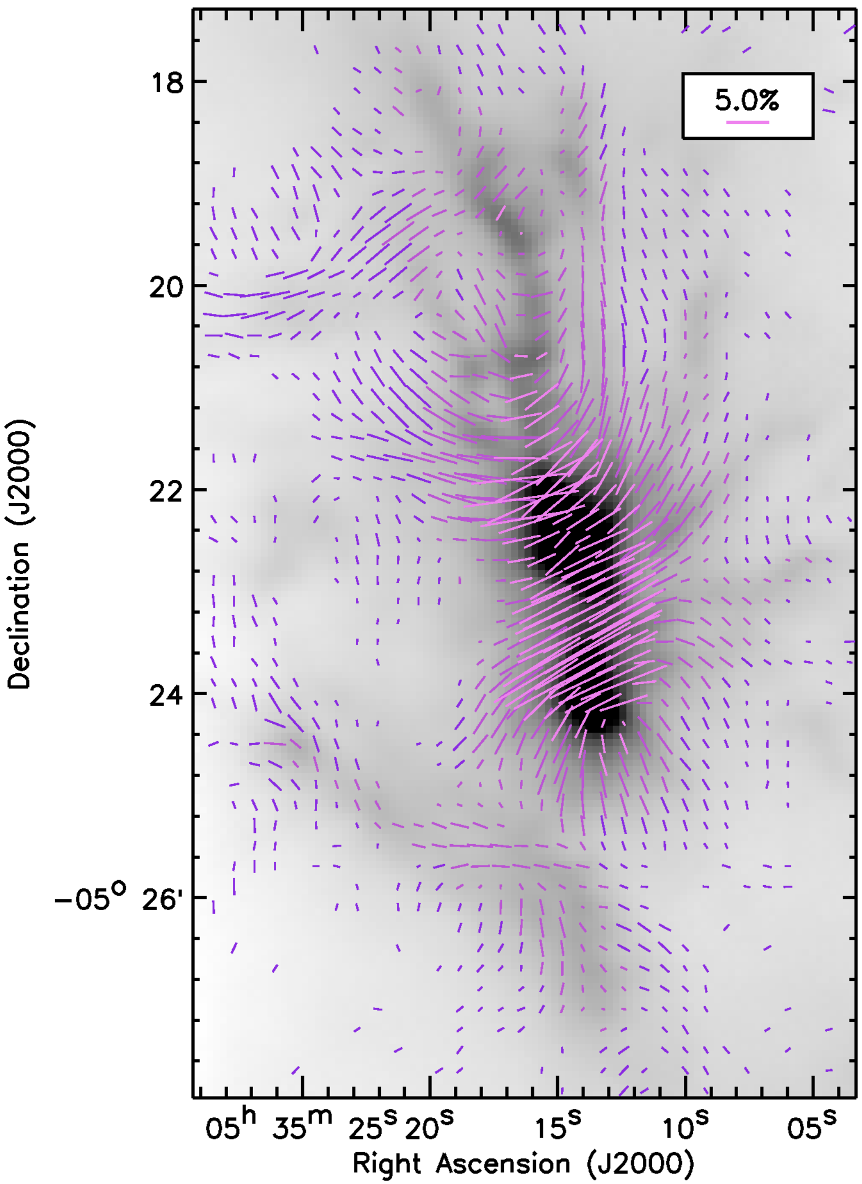
OMC 1 is a dense molecular cloud which is a site of ongoing high-mass star formation located in the centre of the Orion A “integral filament”, at a distance of 388 pc (Kounkel et al. 2017)

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



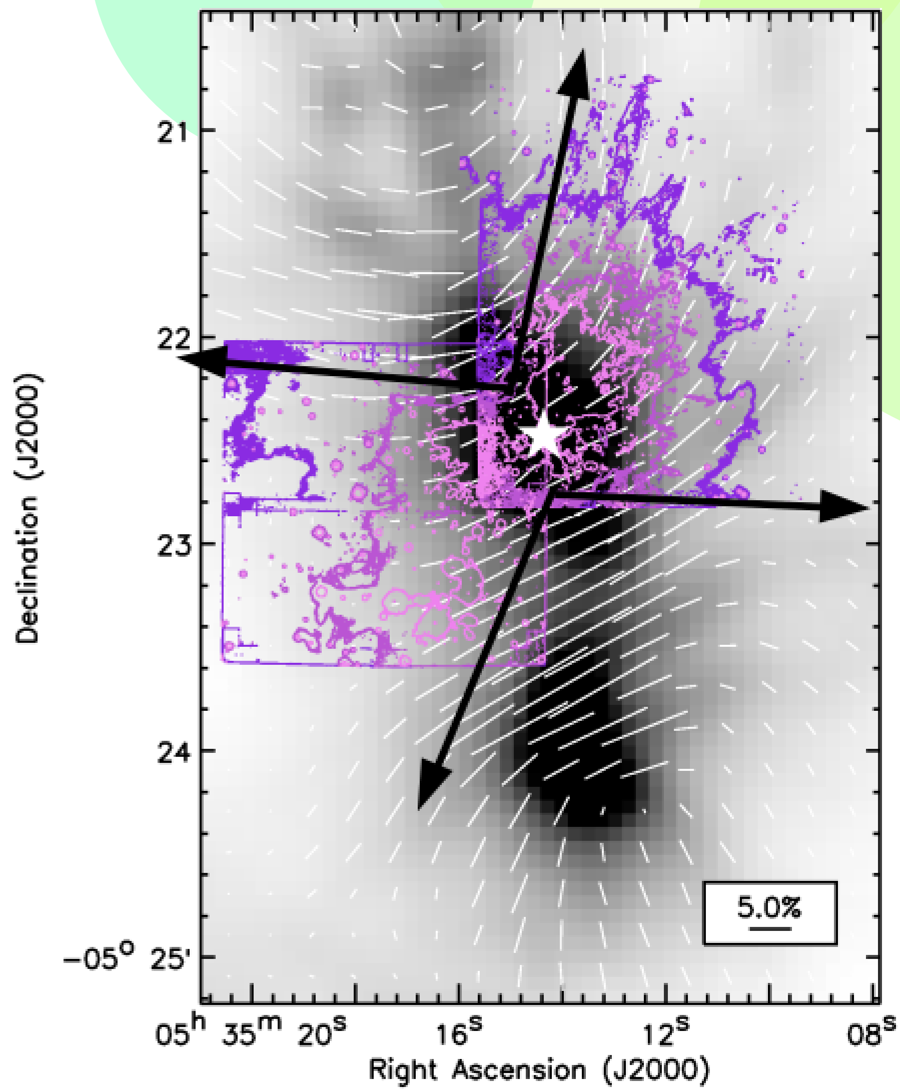
- Observed in January 2016 as part of POL-2 commissioning and BISTRO science programmes
- ~2mJy/beam RMS sensitivity on 12” pixels
- Vectors rotated to trace magnetic field
- Note ‘hourglass’ morphology (c.f. Schleuning 1998)

The BN/KL outflow

- a wide-angle explosive outflow with multiple ejecta (the "bullets of Orion"; Allen & Burton 1993)

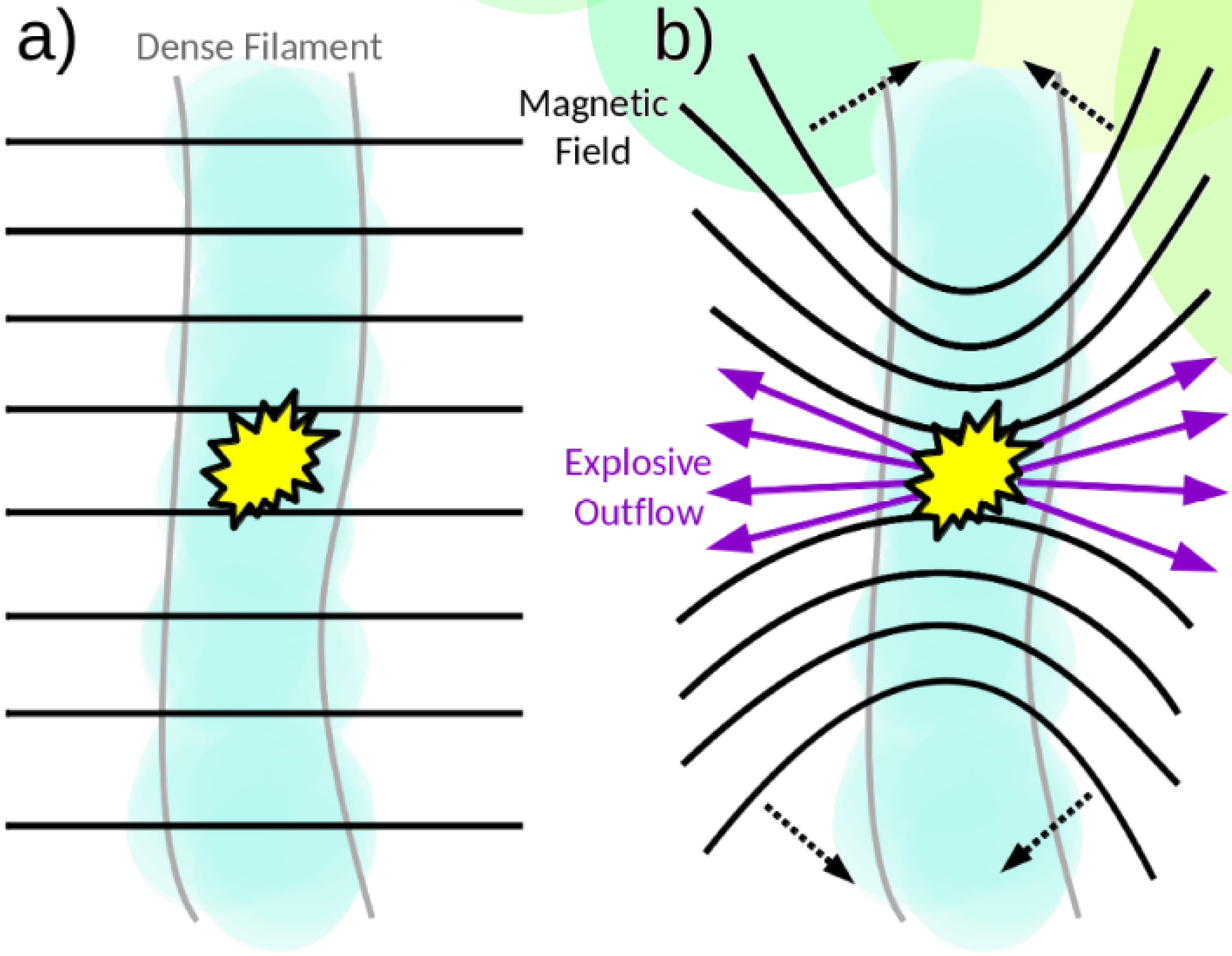
- one of the most energetic outflows observed in a star-forming region: contains ~4x10^{47} erg of energy (Kwan & Scoville 1976)

- likely to have been formed by an encounter between Orion sources BN, n and I around 500 years ago (Gomez et al 2005; Bally & Zinnecker 2005)

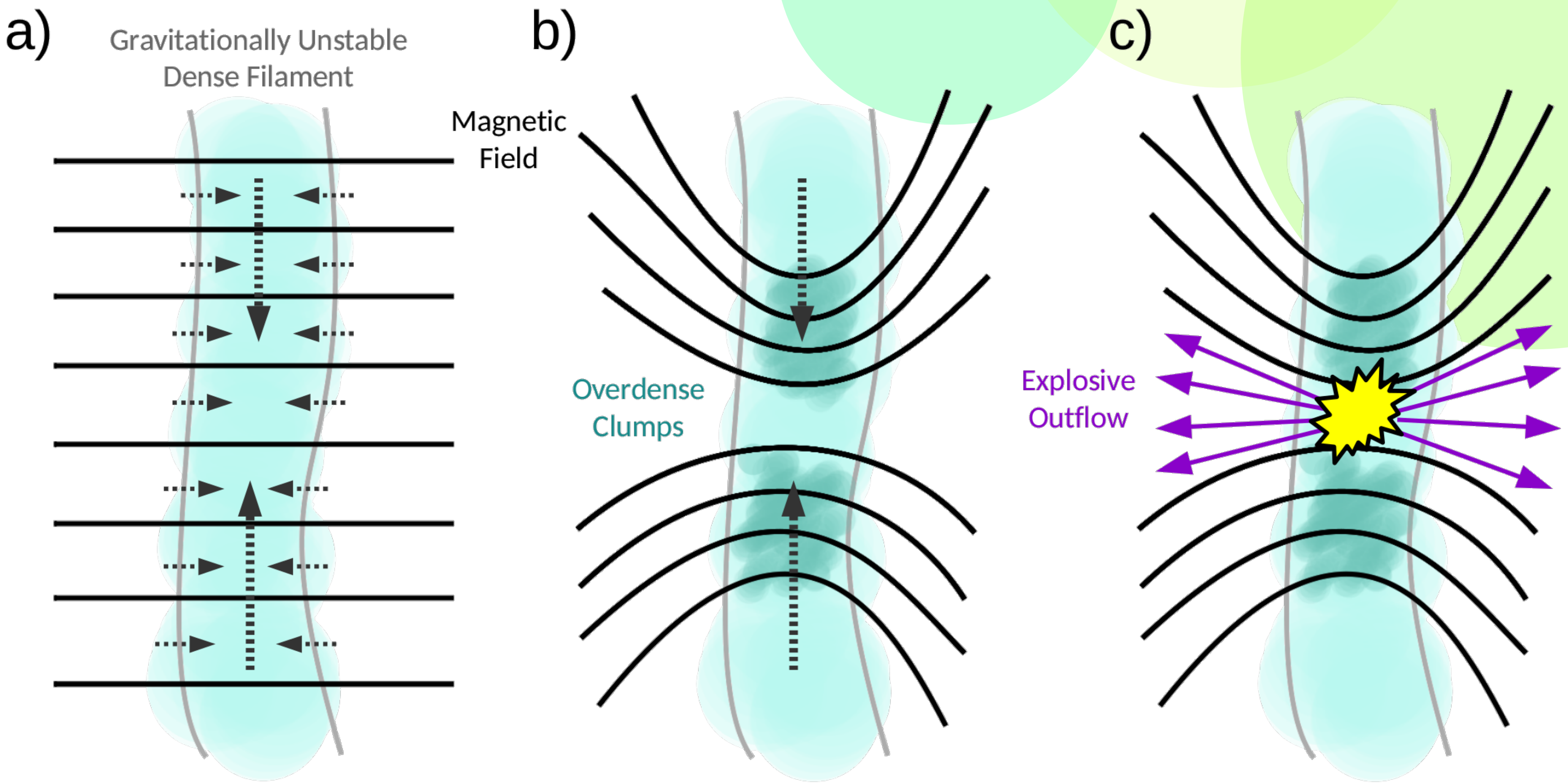


Contours: H_2 emission Bally et al. 2015

Hypothesis 1: Outflow shapes field

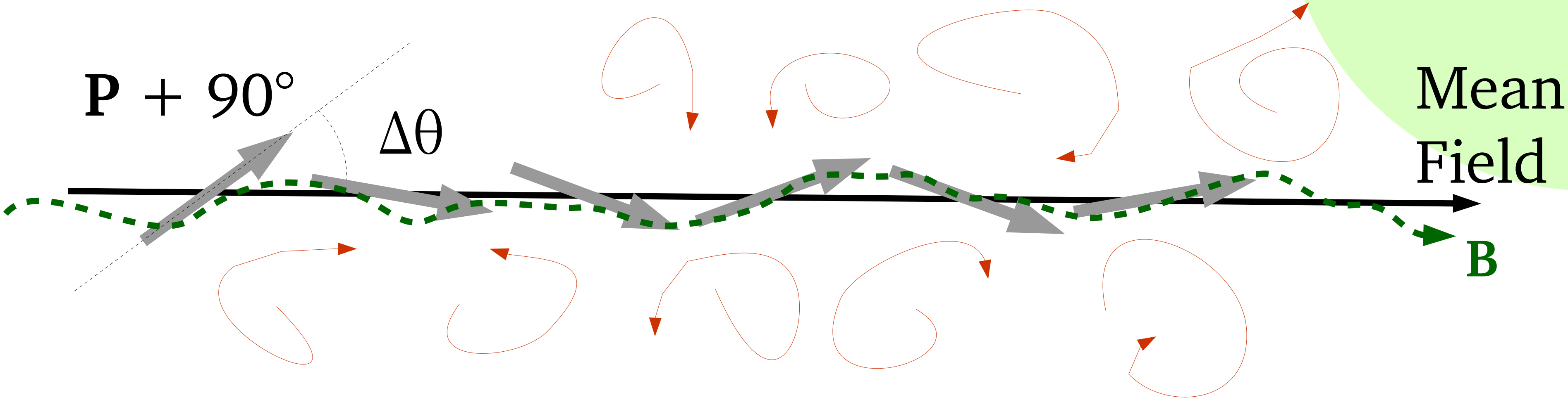


Hypothesis 2: Field shapes outflow



Chandrasekhar-Fermi Method

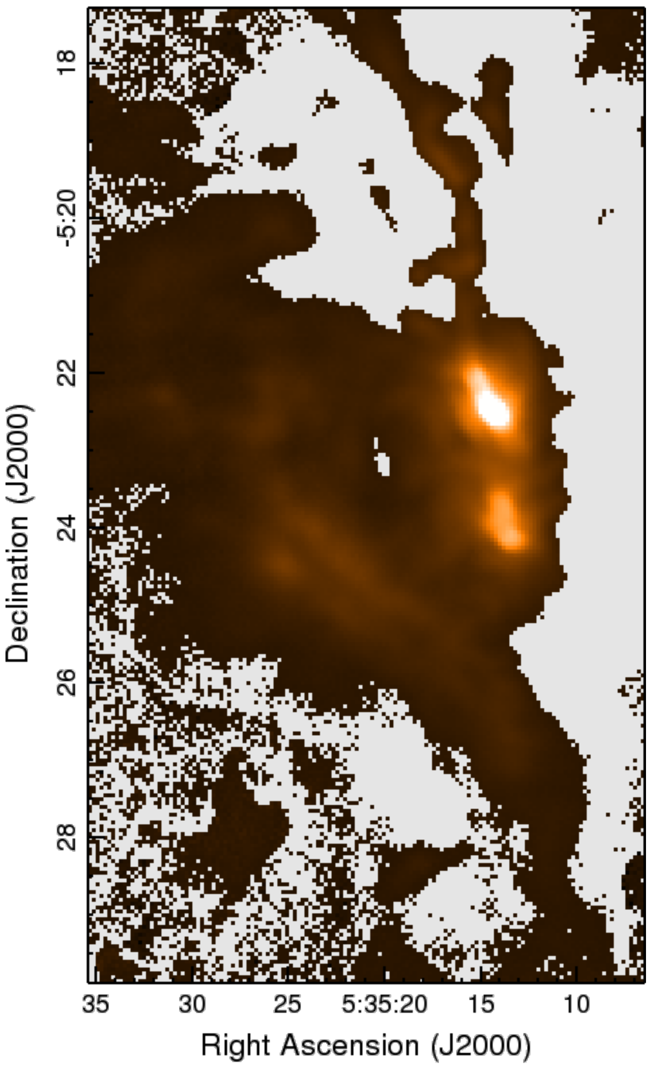
Assumes equipartition between non-thermal motions and the magnetic field: deviation in angle from the mean field direction is taken to be the result of distortion of the field by small-scale non-thermal motions (see Chandrasekhar & Fermi 1953).



$$B_{\rm pos} = Q\sqrt{4\pi\rho}\,\frac{\delta v}{\delta\theta} \approx 9.3\sqrt{n({\rm H_2})}\,\frac{\Delta v}{\langle\Delta\theta\rangle}$$

$$B_{\rm pos} = \frac{\pi}{4}|\mathbf{B}|$$ (c.f. Crutcher et al. 2004)

Volume Density:

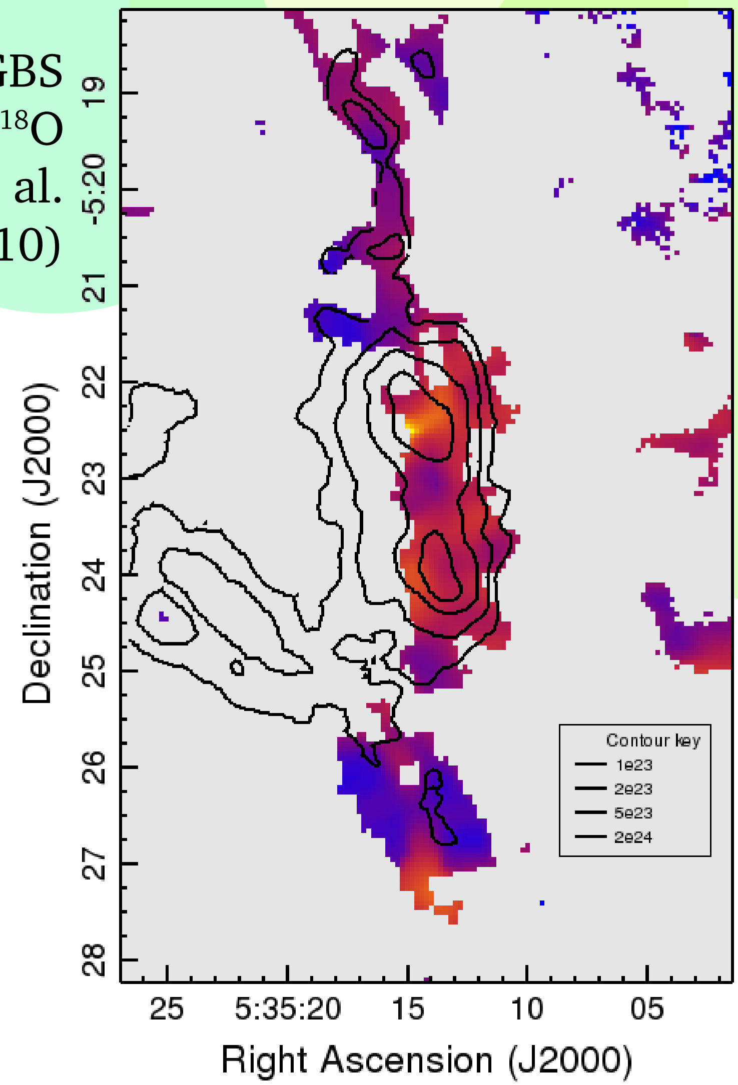


JCMT GBS
SCUBA-2
450μm/850μm
Salji et al.
(2015a,b)

$$n(\mathrm{H_2}) = \frac{2N(\mathrm{H_2})}{\pi r}$$
$$= (0.8 \pm 0.6) \times 10^{6}\ \mathrm{cm^{-3}}$$

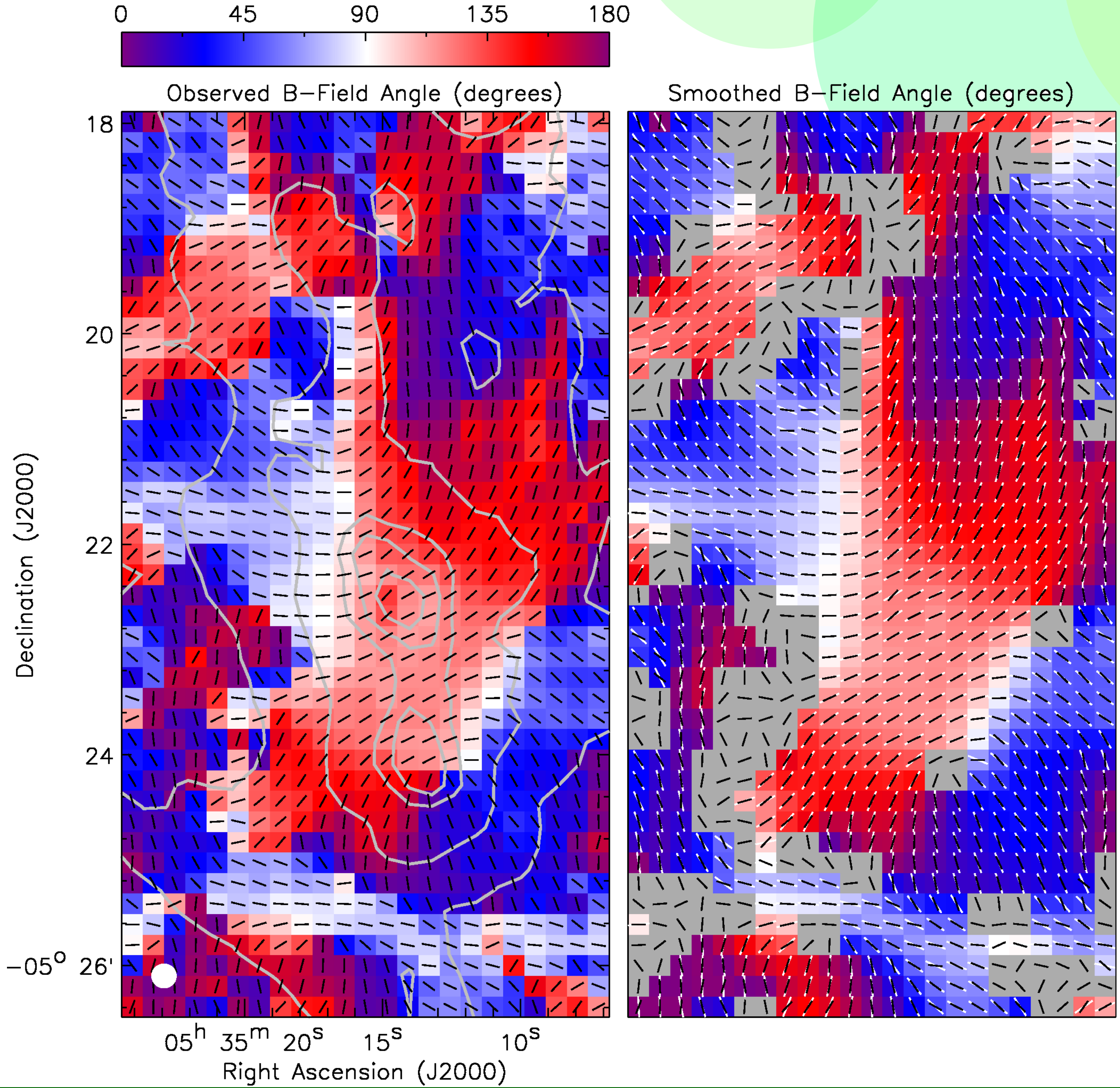
Velocity Dispersion:

JCMT GBS
HARP $C^{18}O$
Buckle et al.
(2010)



Median 1D FWHM velocity dispersion in well-fitted pixels with S/N > 5: 3.19 km s^{-1}

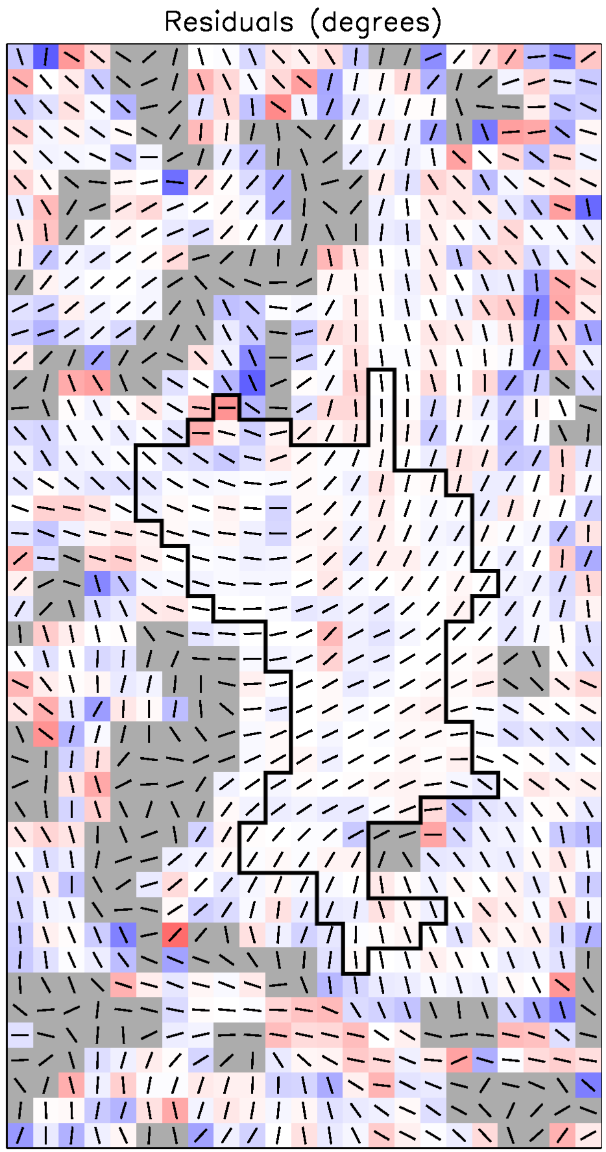
Deviation in angle: Unsharp masking approach



Mean field direction determined by smoothing with a 3x3 pixel box.

Pixels with >90° changes in angle inside the smoothing box excluded.

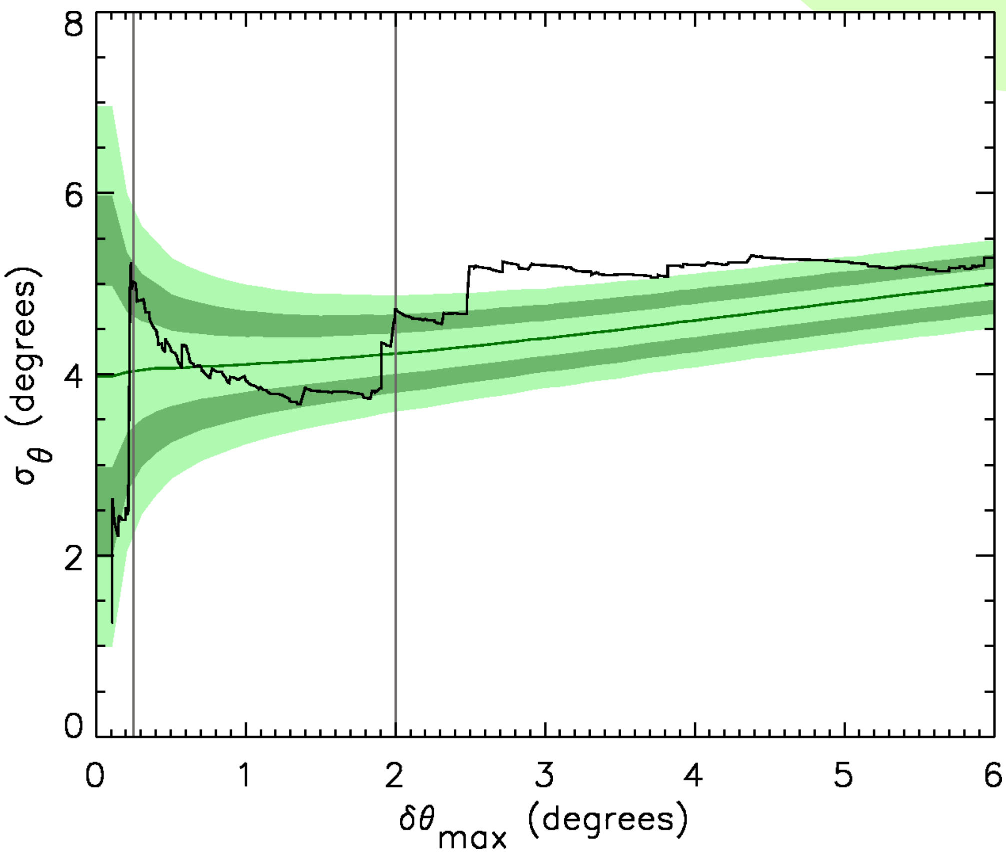
Deviation in angle: Unsharp masking approach



$$\Delta\theta = \theta_{obs} - \langle\theta\rangle$$

In pixels where P/DP > 5 and $\delta\theta_{max}$ < 2.0°:

$\langle\sigma(\Delta\theta)\rangle$: 4.0° ± 0.3°



Magnetic field strength estimates

$$B_{\text{pos}} = Q\sqrt{4\pi\rho}\,\frac{\delta v}{\delta\theta} \approx 9.3\sqrt{n(\text{H}_2)}\,\frac{\Delta v}{\langle\Delta\theta\rangle}$$

$\Delta v = 3.12 \pm 0.73$ km s^{-1}

$\langle\sigma(\Delta\theta)\rangle = 4.0^\circ \pm 0.3^\circ$

$n(\text{H}_2) \approx (0.8 \pm 0.6) \times 10^6$ cm^{-3}

Best estimate:
$B_{pos} = 6.6 \pm 4.7$ mG

This value is consistent with previous estimates for OMC 1 (Hildebrand et al. 2009), and with values measured in other star-forming regions (Curran & Chrysostomou 2007)

Magnetic energy density

Using our measured magnetic field strength, we can estimate magnetic energy density in OMC 1:

$$U_B = \frac{|\mathbf{B}|^2}{2\mu_0}$$

If $B = 6.6$ mG, then $U_B = 1.7\times10^{-7}$ J m^{-3}

How does this compare to the other sources of energy in OMC 1?

Gravitational potential energy density of the BN/KL – S system

From our column density map:

Mass of BN/KL: 1000 $M_\odot$

Mass of S: 285 $M_\odot$

Treating the system as a uniform cylinder:

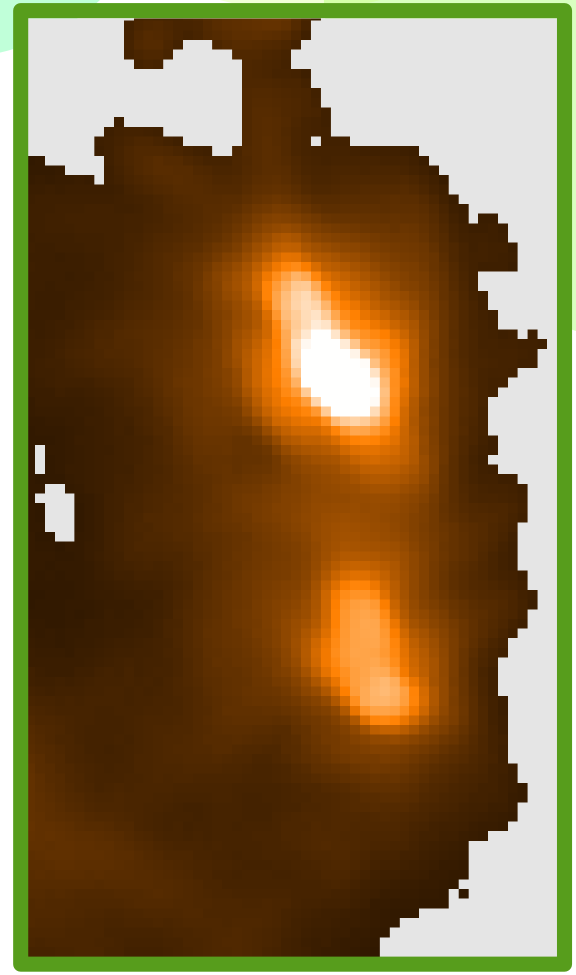
$$U_G = 1.9 \times 10^{-7}\ \mathrm{J\ m^{-3}}$$

Treating the system as a pair of point sources:

$$U_G = 0.5 \times 10^{-7}\ \mathrm{J\ m^{-3}}$$

Treating the system as a prolate spheroid:

$$U_G = 8.8 \times 10^{-7}\ \mathrm{J\ m^{-3}}$$



Outflow energy density

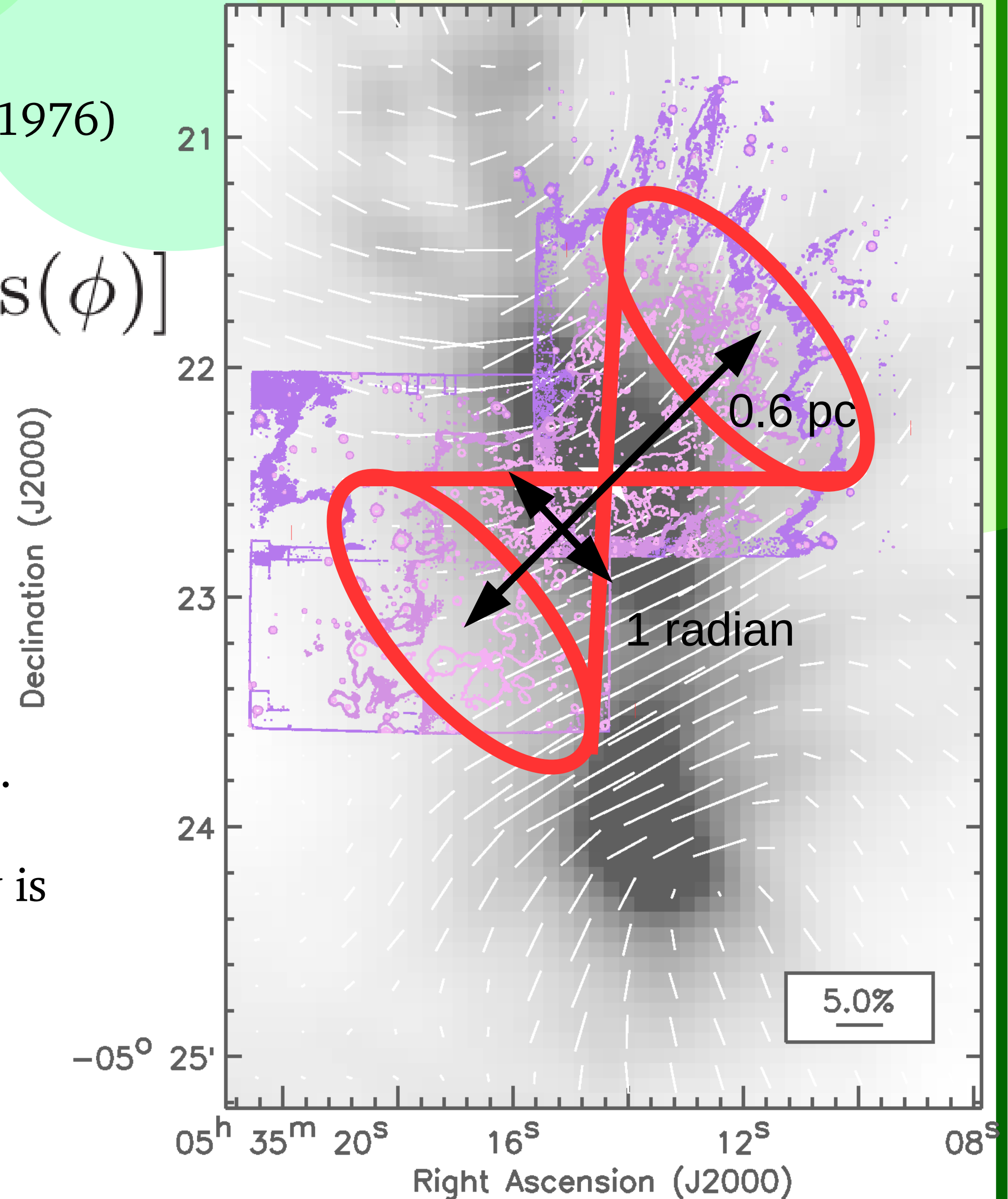
$$\sim 4\times 10^{40}\ \mathrm{J}$$ (Kwan & Scoville 1976)

$$V_{\mathrm{outflow}} = 2 \times \frac{2\pi r^3}{3}\left[1 - \cos(\phi)\right]$$

$$V_{\mathrm{outflow}} = 2.7 \times 10^{47} \mathrm{m}^3$$

$$U_{\mathrm{outflow}} \sim 1.5 \times 10^{-7}\,\mathrm{J\,m}^{-3}$$

However, knots are ballistic Herbig-Haro objects. Total energy in knots $\sim 10^{37}$ J (Allen & Burton 1993). The large majority of the outflow energy is in the highly-collimated central outflow.



It seems that in OMC 1, if it doesn't have $\sim 10^{40}$ J of energy and an energy density of $\sim 10^{-7}$ Jm^{-3}, it's not worth talking about:

$U_B \sim 1.6 \times 10^{-7}$ 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)

So how can we tell which forces determine the magnetic field morphology?

Alfvén and ballistic velocities

$$c_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

B = 6.4 ± 2.1 mG,
c_A = 9.1± 3.0 km s^{-1}

Max. Alfvénic field deviation in 500 yr: (4.6 ± 1.5) × 10^{-3} pc

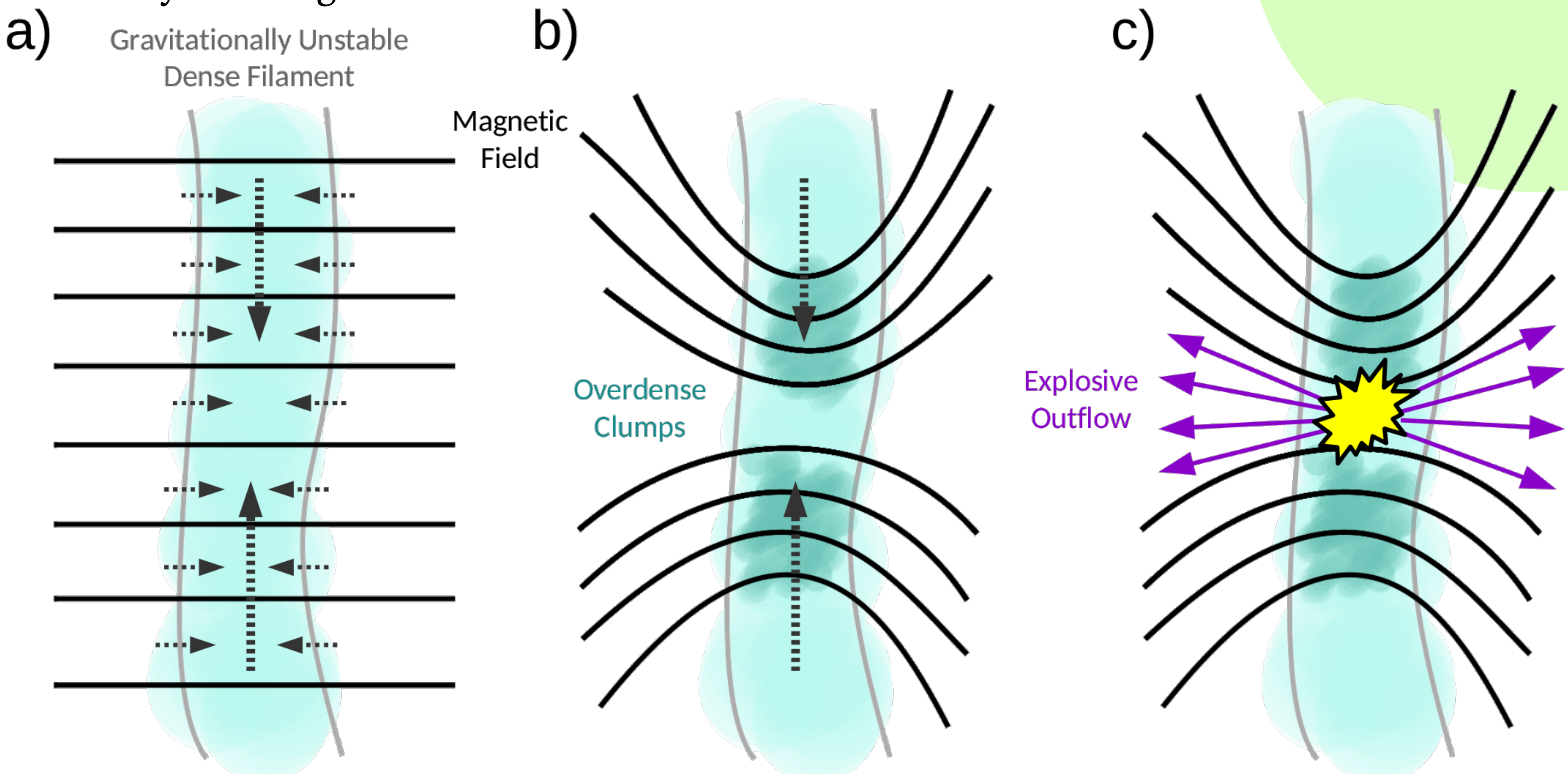
However, ejecta velocities are supersonic and super-Alfvénic: Typical LOS ejecta velocity is ~150 km/s (Bally et al. 2017).

Max. distance travelled in 500 yr: ~10^2 pc

Hence, the outflow **cannot** have caused the observed deviation in magnetic field lines in OMC 1 in the time since its formation.

Our results suggest that:

- The magnetic field strength and the gravitational force between BN/KL and S are in approximate balance
- The ‘hourglass’ magnetic field shape may have been produced by the gravitational interaction. The magnetic field may have been compressed until equilibrium was reached
- The orientation of the BN/KL outflow has, on large scales, been determined by the magnetic field

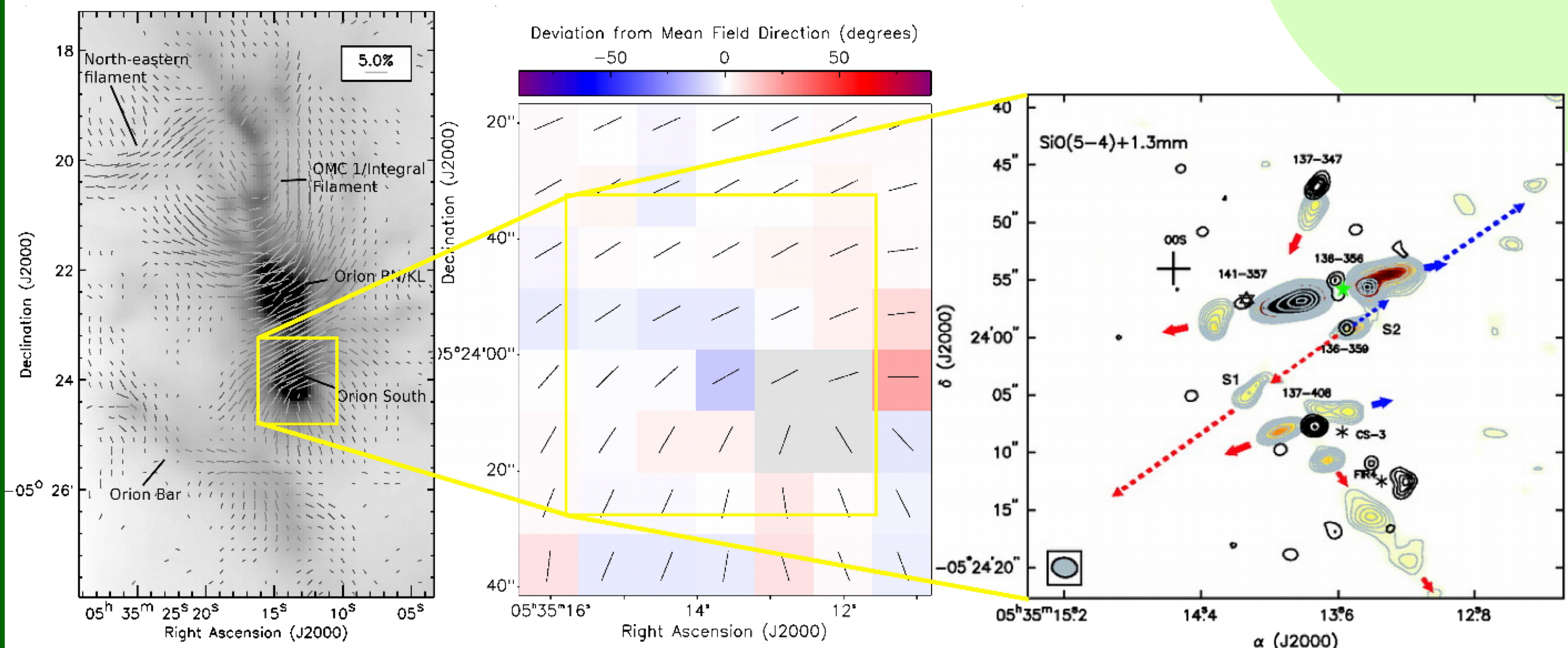


Finally: something about ALMA!

“Does magnetic field of the natal clump gas regulate outflows in a forming star cluster?”

PI: Ray Furuya, Co-Is: Pattle, Hasegawa et al.

- Band 7, 0.4-arcsec resolution dust continuum polarimetric imaging
- 4 outflow-driving sources in OMC1 South
- Grade B-ranked in Cycle 5



Conclusions:

- We measure a magnetic field strength of 6.6 ± 4.7 mG in the OMC 1 region of Orion A, comparable to more distant high-mass star-forming regions
- We find that the magnetic, gravitational and outflow energy densities in OMC 1 are all $\sim 10^{-7}$ J m^{-3}
- The Alfvén velocity in OMC 1 is sufficiently small that the deviations in the magnetic field of OMC 1 could not have been created in the lifetime of the BN/KL outflow
- We suggest that the 'hourglass' morphology of the magnetic field in OMC 1 is caused by distortion of an initially-uniform magnetic field by the gravitational interaction of Orion BN/KL and AS
- We further suggest that the orientation of the large-scale BN/KL outflow is constrained by the orientation of the magnetic field.
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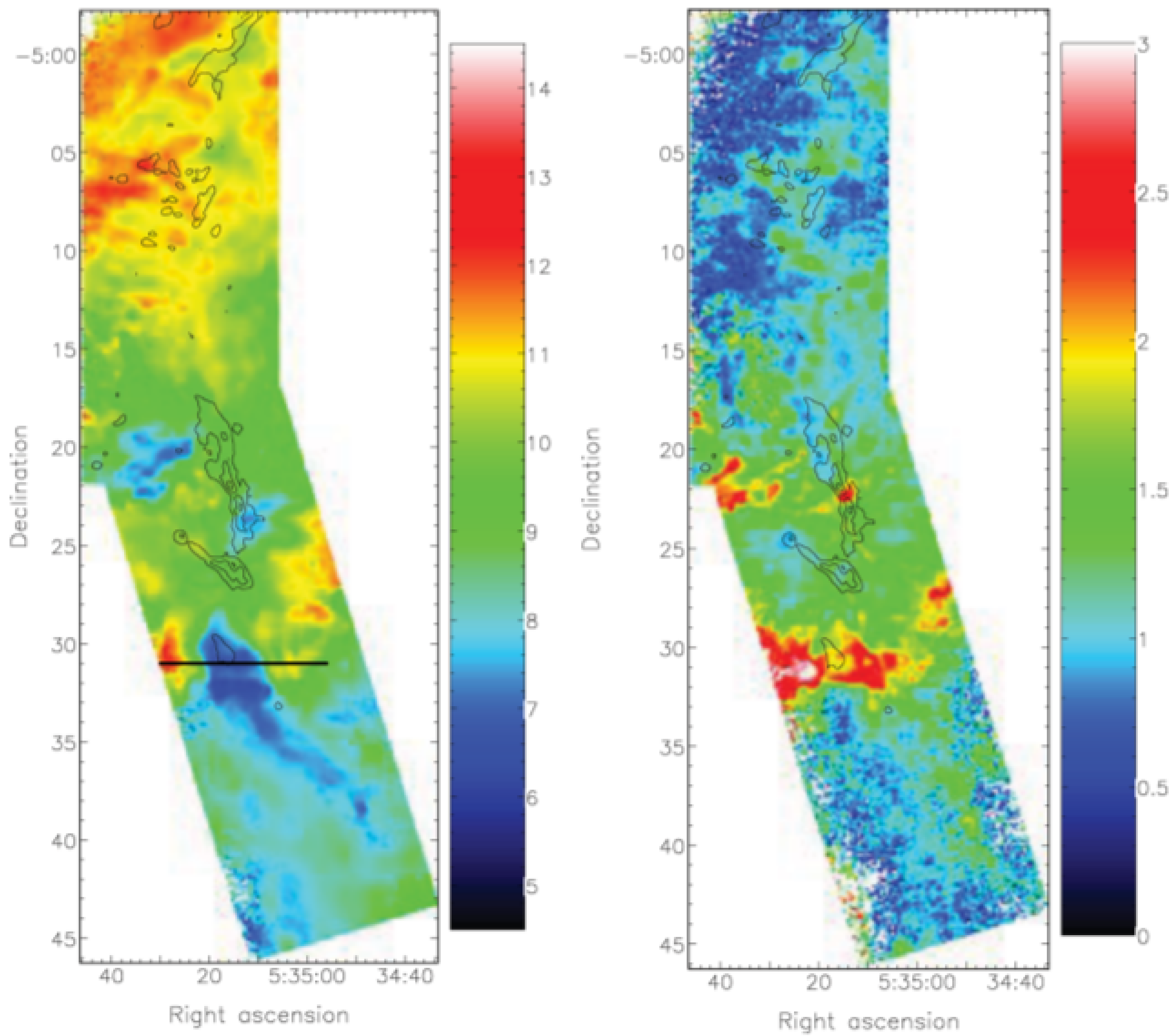
For more detail: **Pattle et al. 2017, ApJ 846 122**

Thank you!

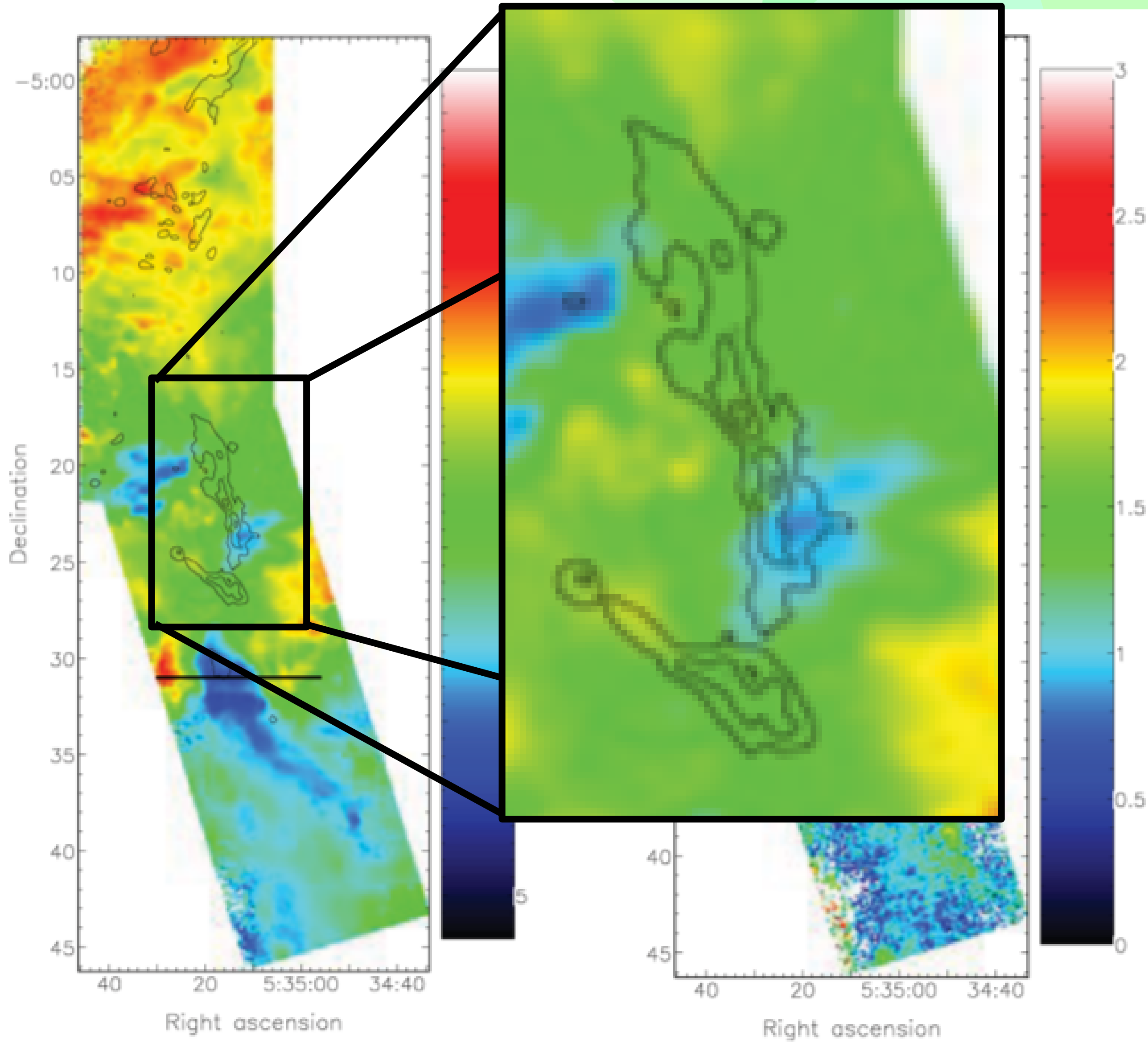
Velocity field in the OMC 1 region



HARP ^{13}CO measurements; Buckle et al. 2010

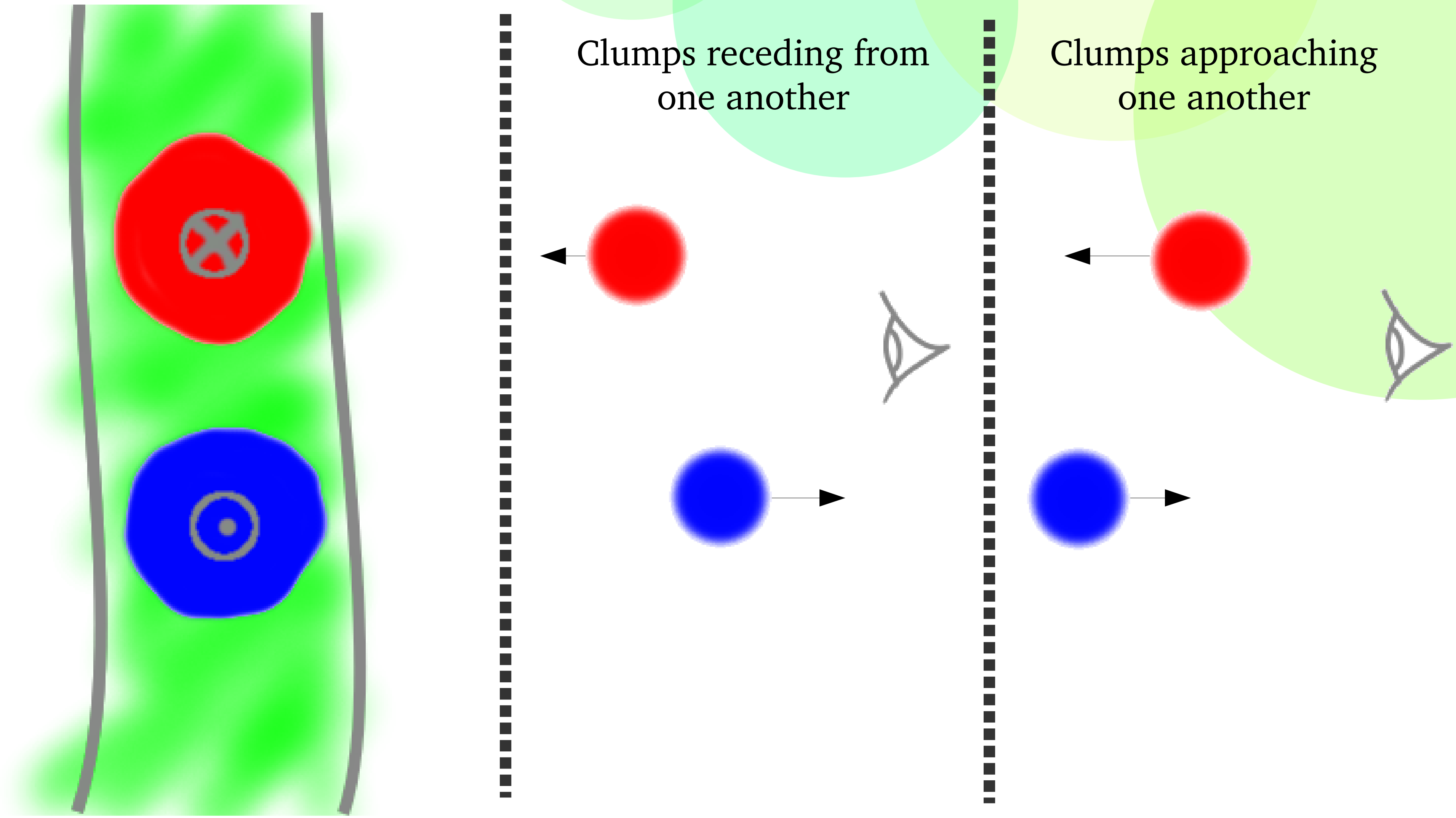
Figure 13. (a) ^{13}CO intensity weighted velocity map of Orion A, giving the velocity field in km s^{-1}. The black line marks the region between

Velocity field in the OMC 1 region



HARP ^{13}CO measurements; Buckle et al. 2010

There is more than one interpretation of this line-of-sight velocity…



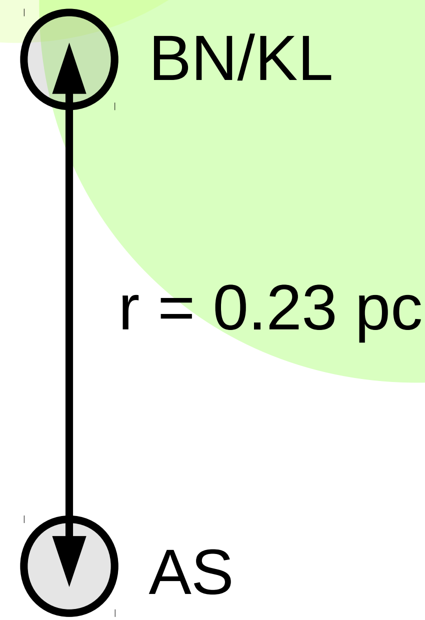
Hence, we cannot exclude either hypothesis using velocity data alone.

GPE density: point-source model

From our column density map:

Mass of BN/KL: 1000 $M_\odot$

Mass of AS: 285 $M_\odot$



GPE of two point sources: $E_G = -\frac{G M_1 M_2}{r}$

Plane-of-sky separation = 0.166 pc; for a conservative estimate of filament orientation, r = $0.166 \times (2)^{0.5} \sim 0.23$ pc:

$$E_G = -1.0 \times 10^{40} \text{ J}$$

Assuming OMC 1 is a cylinder with height $0.321 \times (2)^{0.5}$ pc and diameter 0.141 pc:

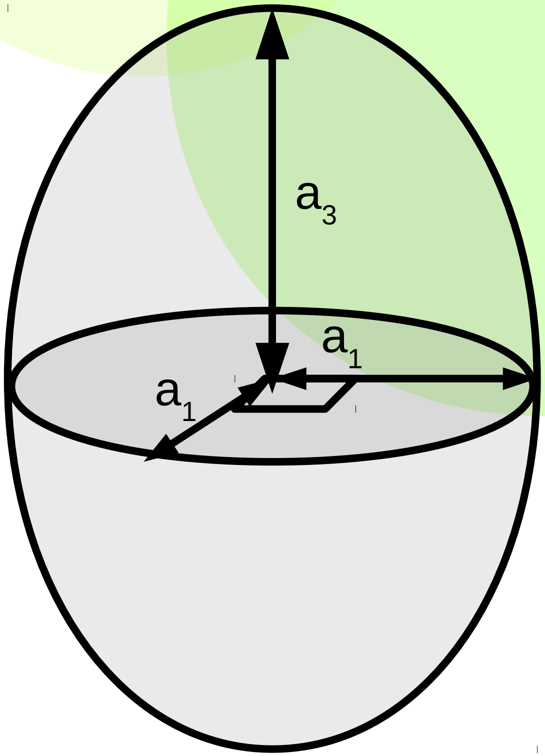
$$U_G = -0.5 \times 10^{-7} \text{ J m}^{-3}$$

GPE density: prolate spheroid model

Prolate-spheroid model:

$$E_G = -\frac{8}{15}\pi^2 G\rho^2 a_1^4 a_3 \times \frac{1}{e}\ln\left(\frac{1+e}{1-e}\right)$$

(e.g. Binney & Tremaine 2008)



Assuming the BN/KL-AS system is a prolate spheroid with mass 1465 $M_{\odot}$, semi-major axis a_3 = 0.16 pc and semi-minor axes a_1 = 0.071 pc:

$$E_G = -8.6 \times 10^{40}\ \mathrm{J}$$

$$U_G = -8.8 \times 10^{-7}\ \mathrm{J\ m^{-3}}$$