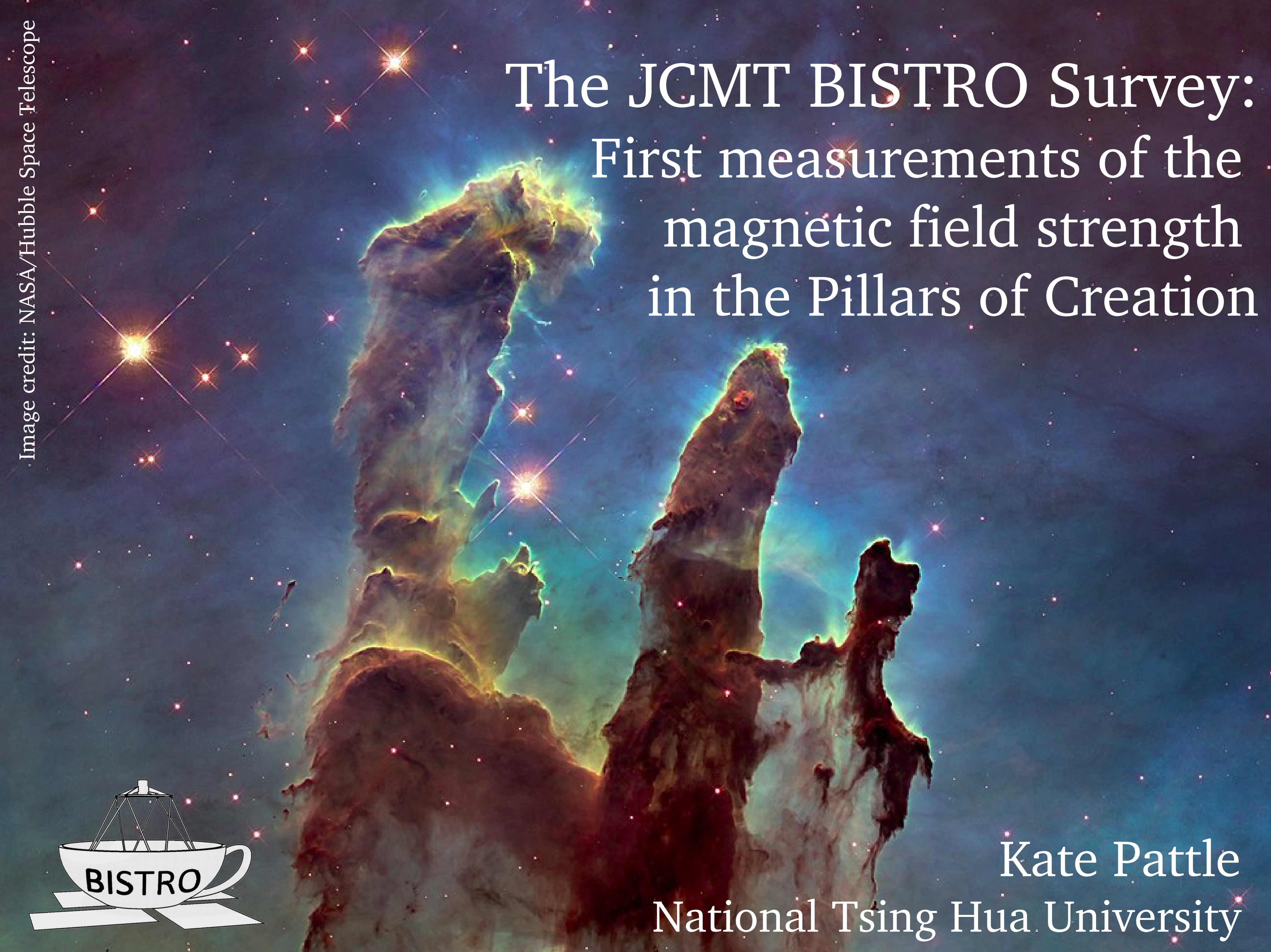

Image credit: NASA/Hubble Space Telescope

The JCMT BISTRO Survey: First measurements of the magnetic field strength in the Pillars of Creation

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BISTRO

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Miju Kang
Sung-ju Kang
Gwanjeong Kim
Jongsoo Kim
Kee-Tae Kim
Kyoung Hee Kim
Mi-Ryang Kim
Shinyoung Kim
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BISTRO: Overview

- A JCMT Large Program mapping nearby star-forming regions in polarized light
- >120 survey members across 6 partner regions and the East Asian Observatory
- P.I.s: Derek Ward-Thompson (UK), Keping Qiu (China), Tetsuo Hasegawa (Japan), Woojin Kwon (Korea), Shih-Ping Lai (Taiwan), Pierre Bastien (Canada)
- 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**
M16: **Pattle et al. 2018, ApJ 860 L6**
Ophiuchus B: **Soam et al. 2018, ApJ 861 65**

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

What is the role of magnetic fields in star formation?

"The argument in the past has frequently been a process of elimination: one observed certain phenomena, and one investigated what part of the phenomena could be explained; then the unexplained part was taken to show the effects of the magnetic field. It is clear in this case that, the larger one's ignorance, the stronger the magnetic field."

– Lodewijk Woltjer, 1966

Magnetically-dominated paradigm:

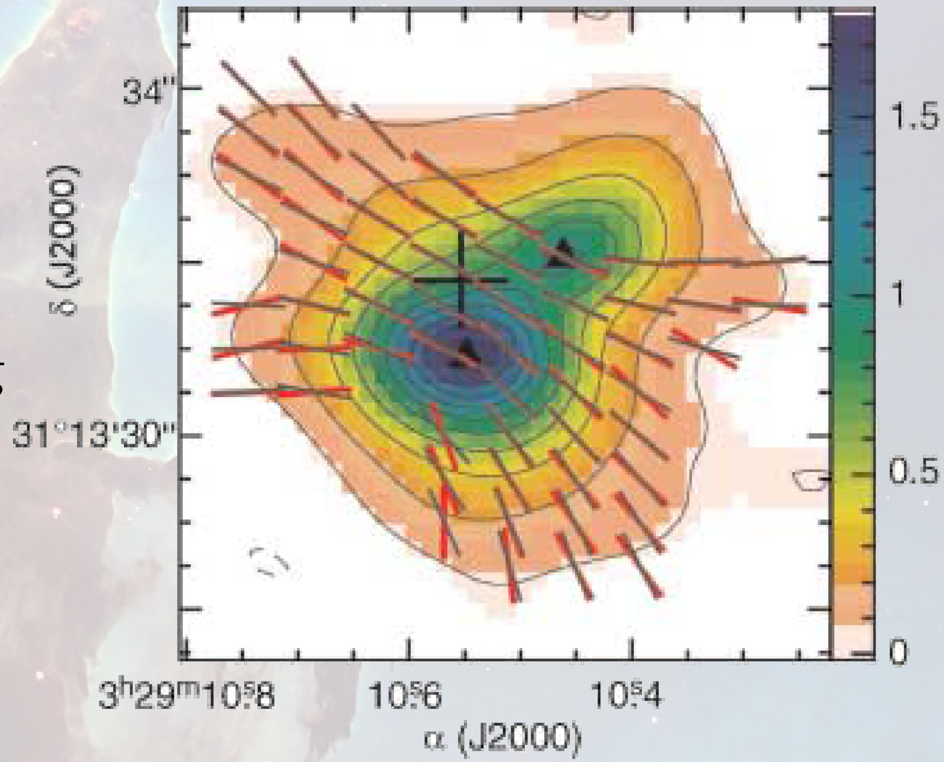
- Cores form in a magnetically subcritical environment (magnetic field strong enough to support against gravitational collapse) and evolve to gravitational instability slowly, through ambipolar diffusion

- Modelled extensively by Mouschovias and collaborators (Mouschovias 1991, Mouschovias & Ciolek 1999, etc.)

- Ambipolar diffusion-driven evolution should produce a characteristic 'hourglass' magnetic field morphology in star-forming cores

- This morphology has been observed in some cases: e.g. Girart et al. 2006

Girart et al. 2006, Science 313 812



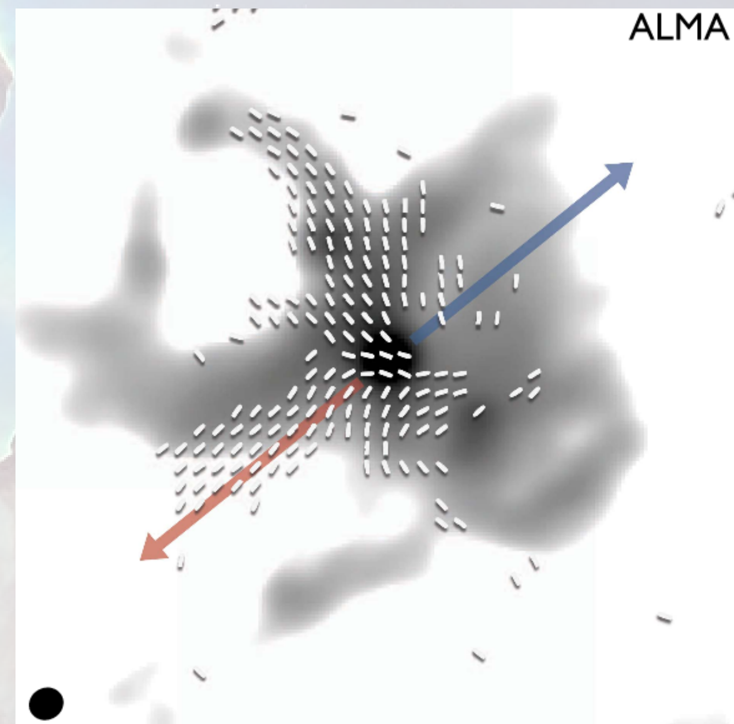
Turbulence-dominated paradigm:

- 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.

- Magnetic fields cannot stop collapse, but can contribute to the support of regions in the later stages of collapse.

- Modelled by, e.g. Padoan & Nordlund 1999, MacLow & Klessen 2004.

- Magnetic field should not show hourglass morphology (e.g. Hull et al. 2017)



Hull et al. 2017, ApJ 842 L9

The usual argument:
What drives the physics of star formation: magnetism, turbulence or gravity?

Today's question:
What happens if you take magnetised gas and give it a (somewhat orderered) shove?

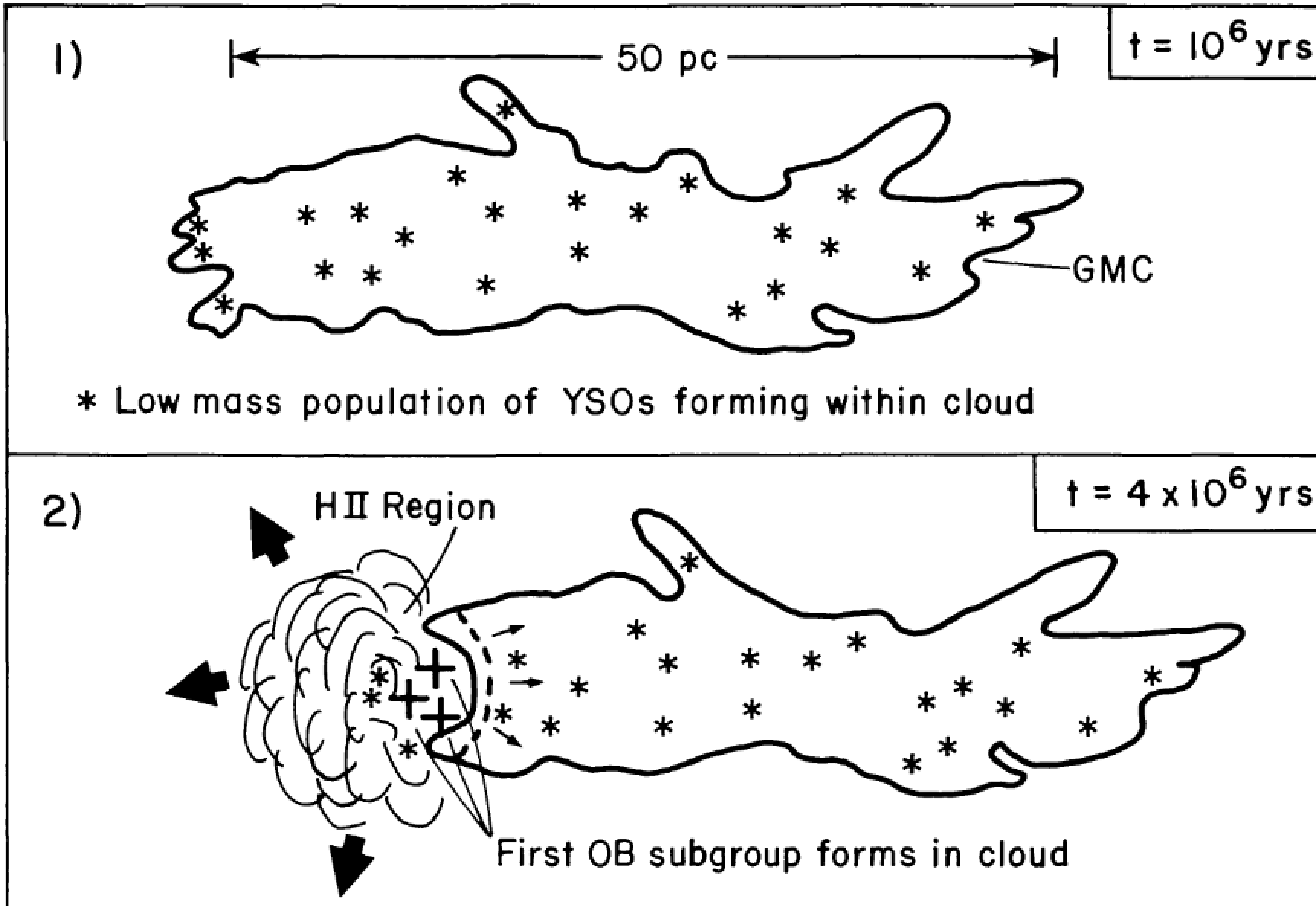
Classical HII Regions

"Their gas is ionized globally, often by several ionizing sources. It expands hydrodynamically as a whole and disrupts the parent molecular cloud, revealing both the embedded high-mass and lower mass stellar population for optical and near-IR observations"

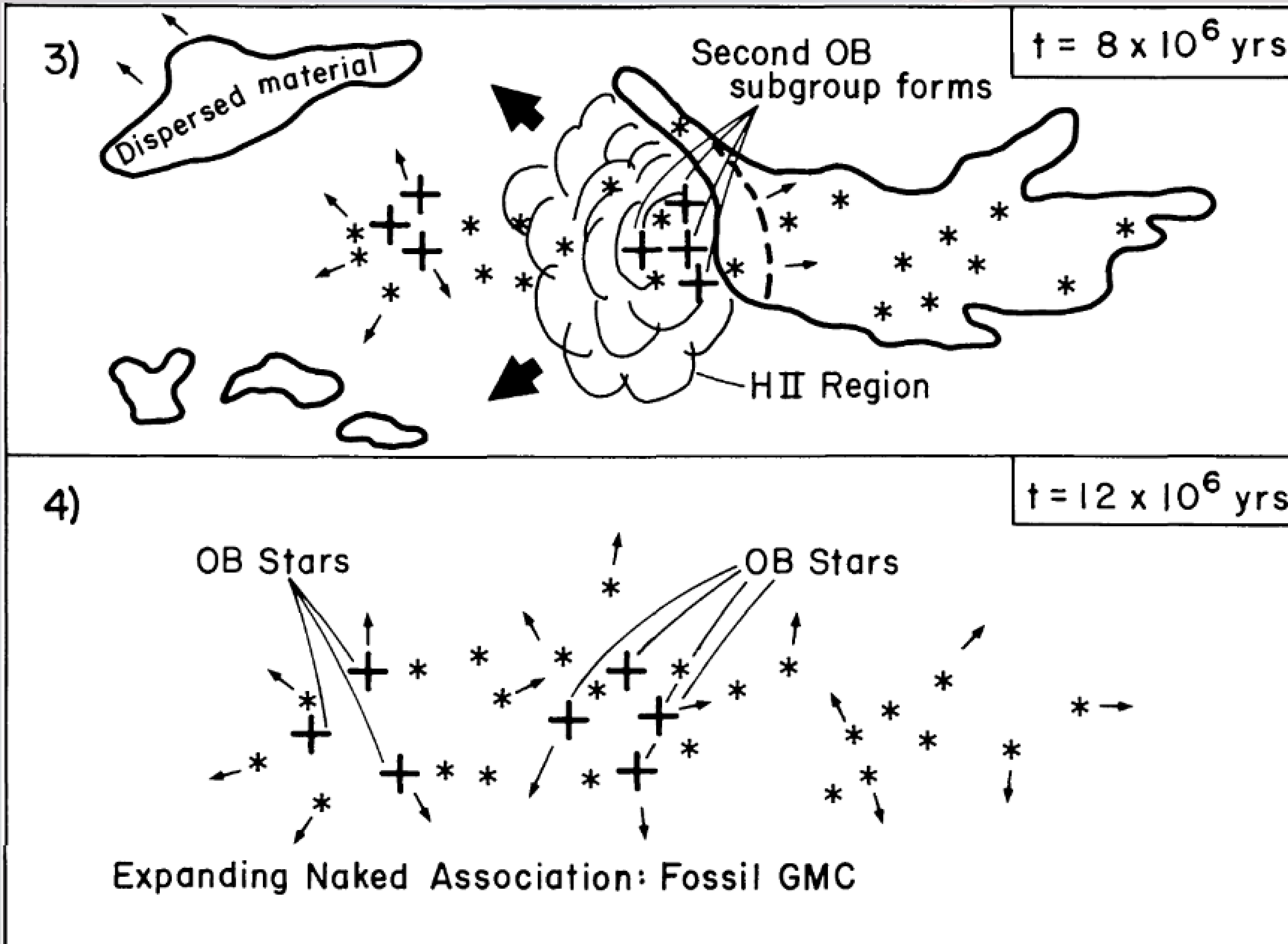
– Zinnecker & Yorke 2007, ARA&A 45 481

NGC 604; NASA/HST archive

Sequential/triggered star formation



Lada 1987 IAUS 115 1



Lada 1987 IAUS 115 1

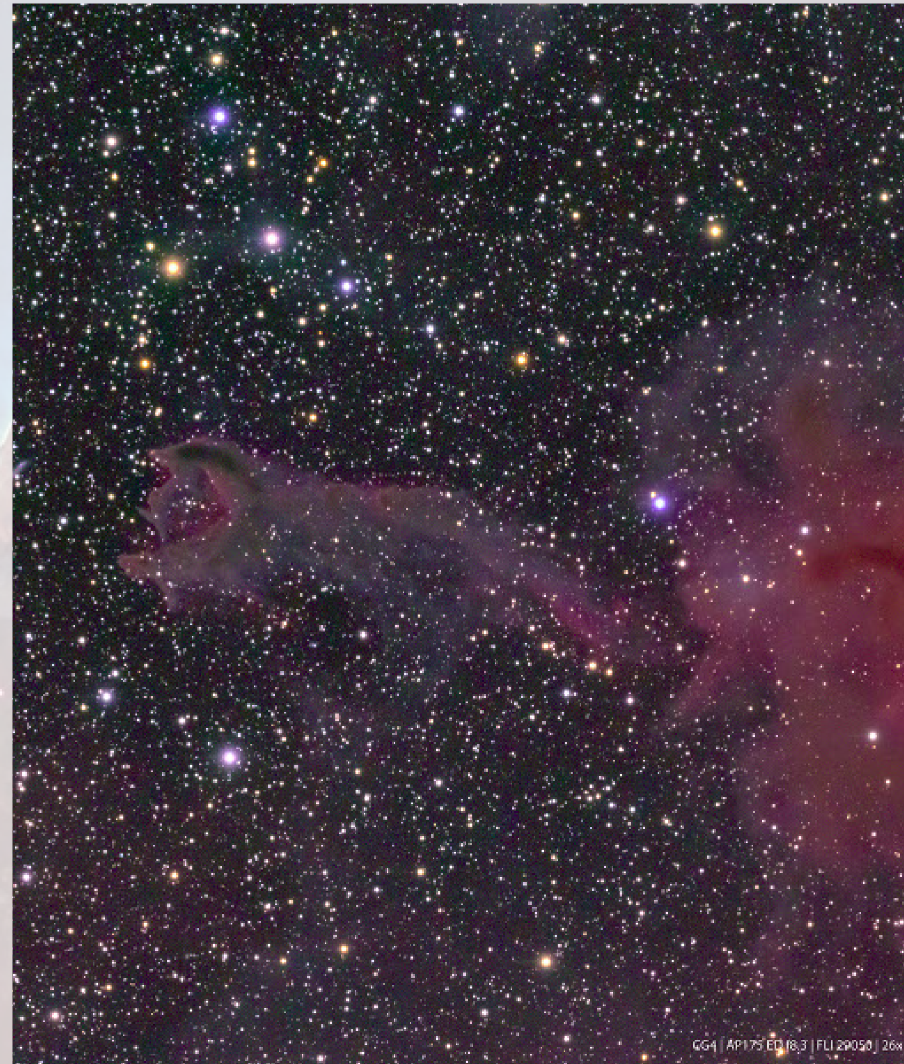
Photoionized columns

- Formed at the interface between an HII region and its parent molecular cloud
- Column of dense molecular gas protrudes into ionized region
- Formation mechanism disputed: do they form behind pre-existing overdensities or through instabilities in the shock front?
- Erosion by HII region: potential sites of triggered star formation?

Horsehead Nebula; NASA/HST archive

Cometary globules

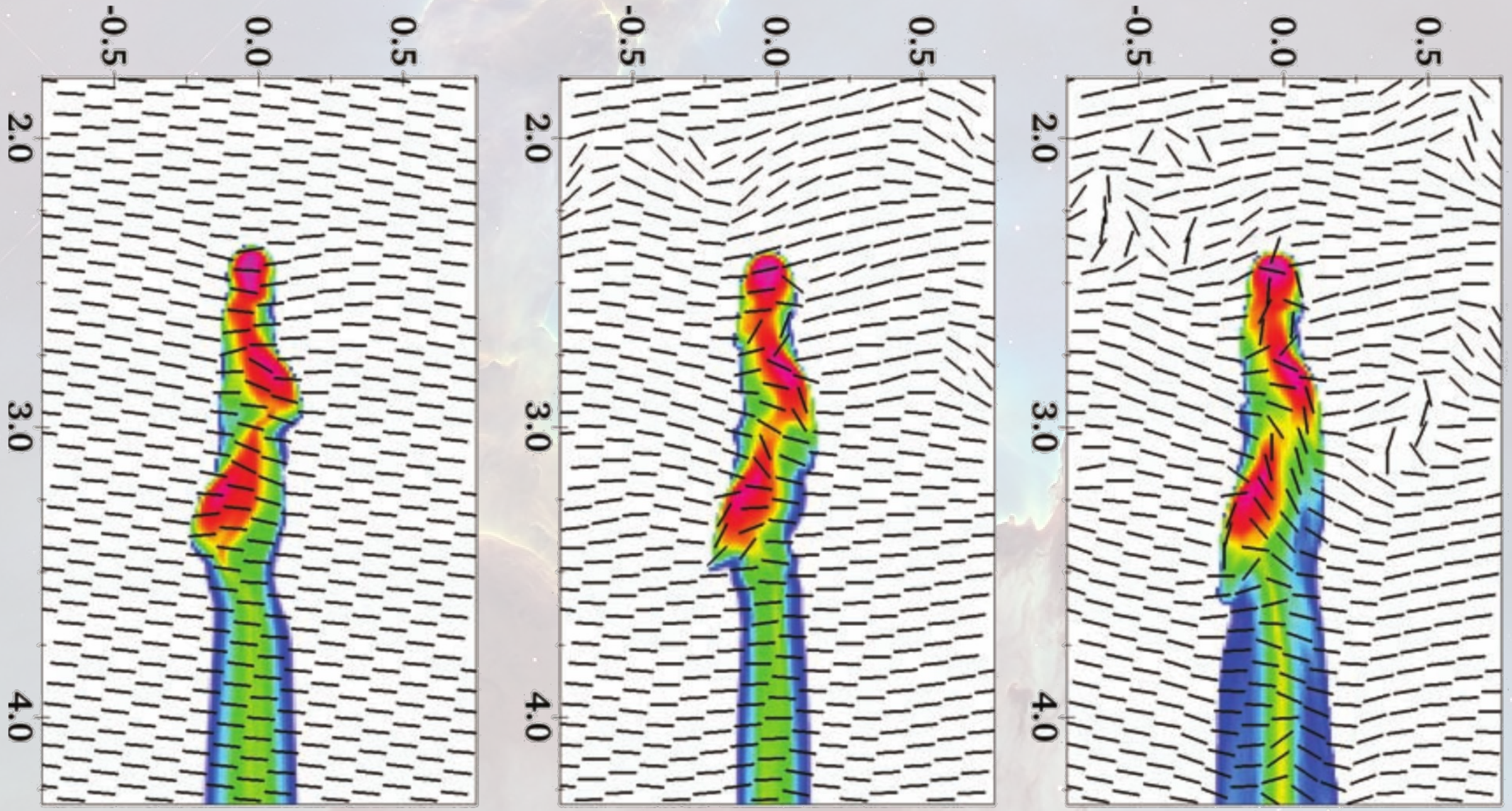
- Isolated clumps of molecular gas within HII regions
- Irradiated by the ionizing source, show a bright rim and a comet-like tail
- Often sites of active (low-mass) star formation
- The future of photoionized columns? (e.g. Bertoldi & McKee 1993)



CG 4; CEDIC Team

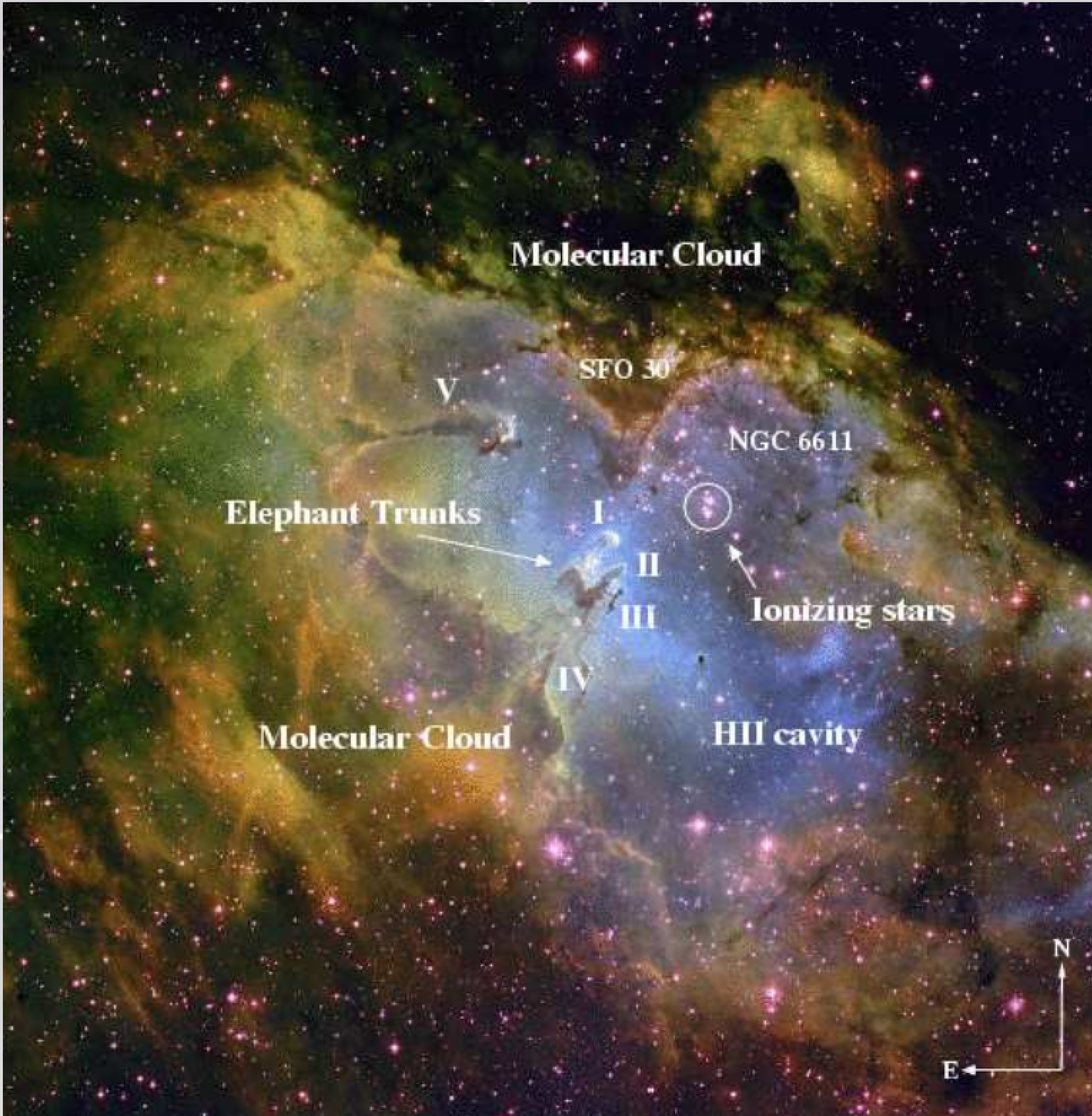
Mackey & Lim (2011):

Strong field → Intermediate → Weak field



M16: The Eagle Nebula

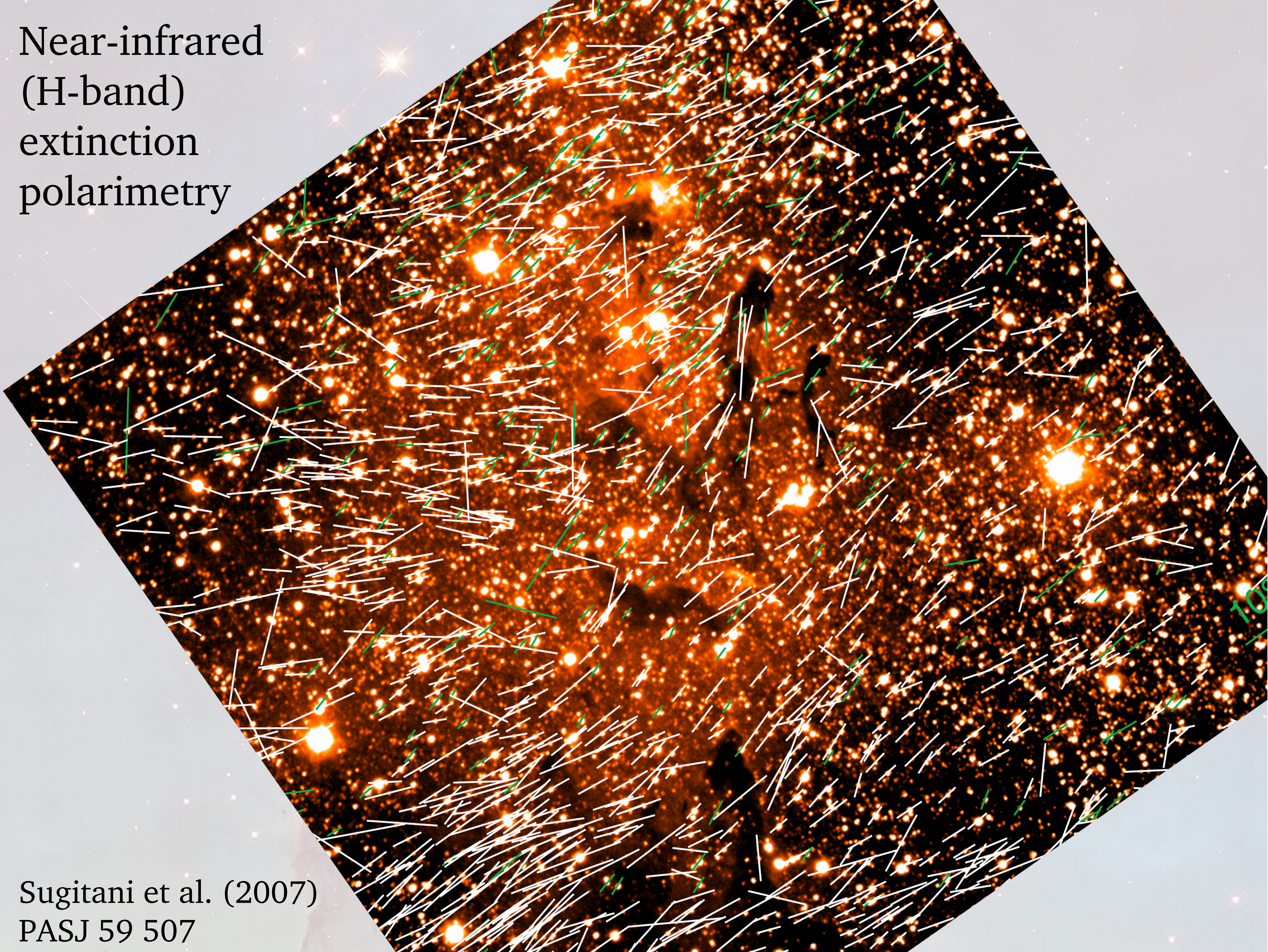
- High-mass star-forming region
- HII region driven by NGC 6634 cluster
- Distance: 1.8±0.2 kpc (Dufton et al. 2006)
- The “Pillars of Creation”: photoionized columns famously imaged by the Hubble Space Telescope (Hester et al. 1996)



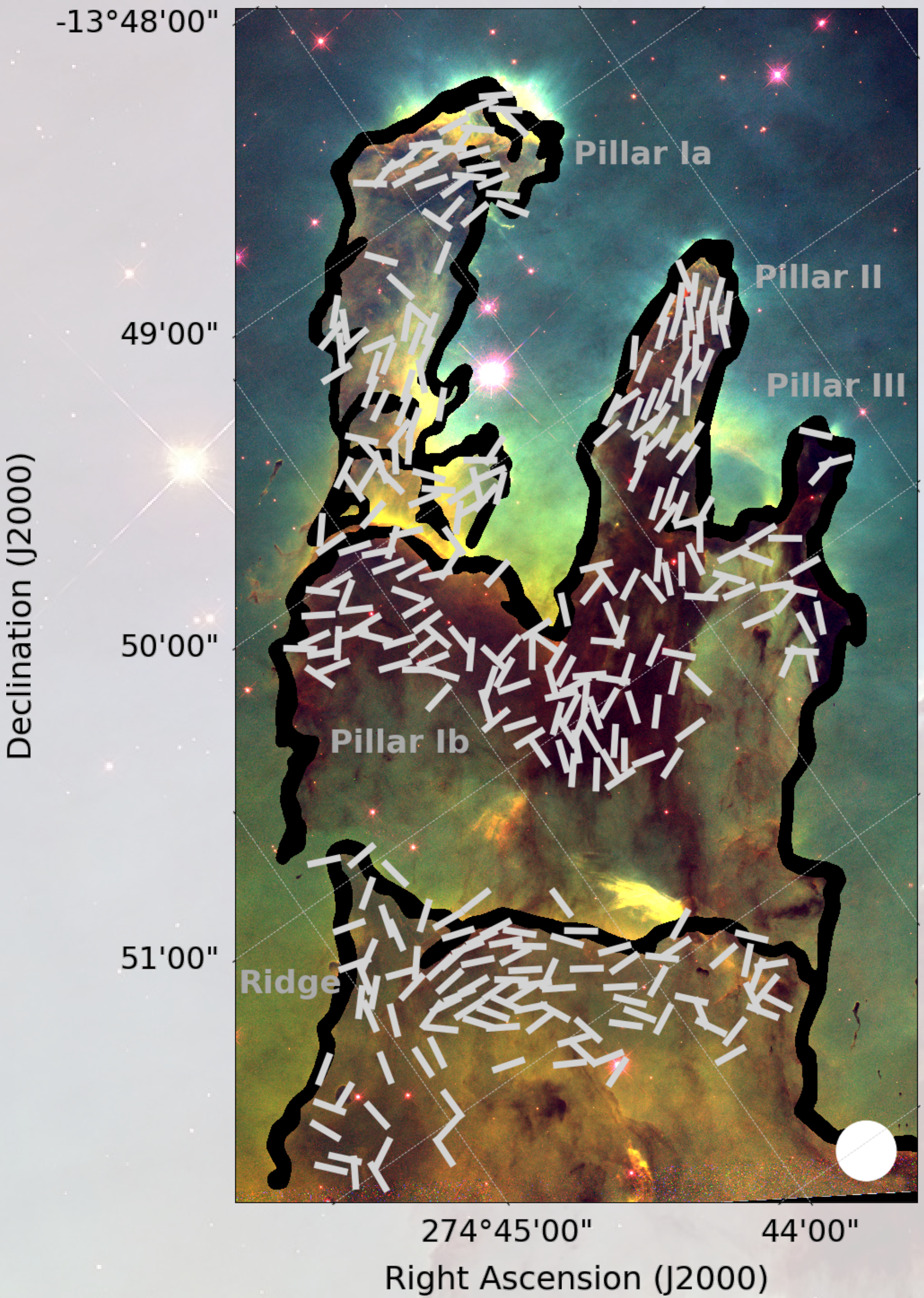
Oliveira (2008)
Handbook of Star-Forming Regions Vol. II

Far-infrared: ESA/Herschel/PACS/SPIRE/Hill, Motte, HOBYS Key Programme Consortium;
X-ray: ESA/XMM-Newton/EPIC/XMM-Newton-SOC/Boulanger

Near-infrared (H-band) extinction polarimetry

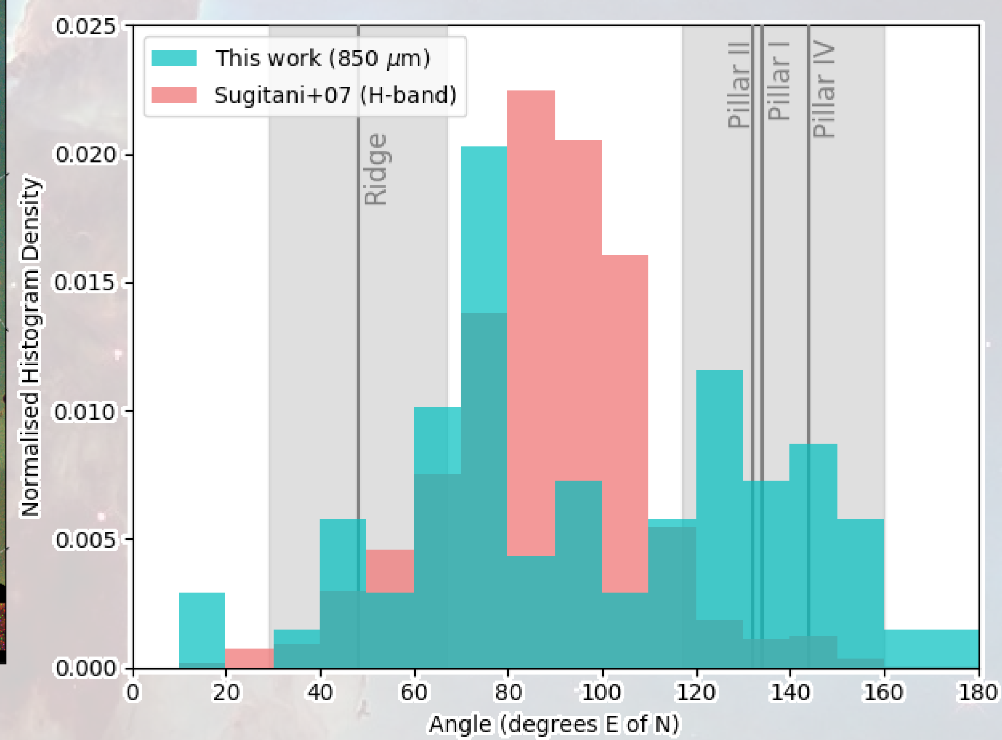


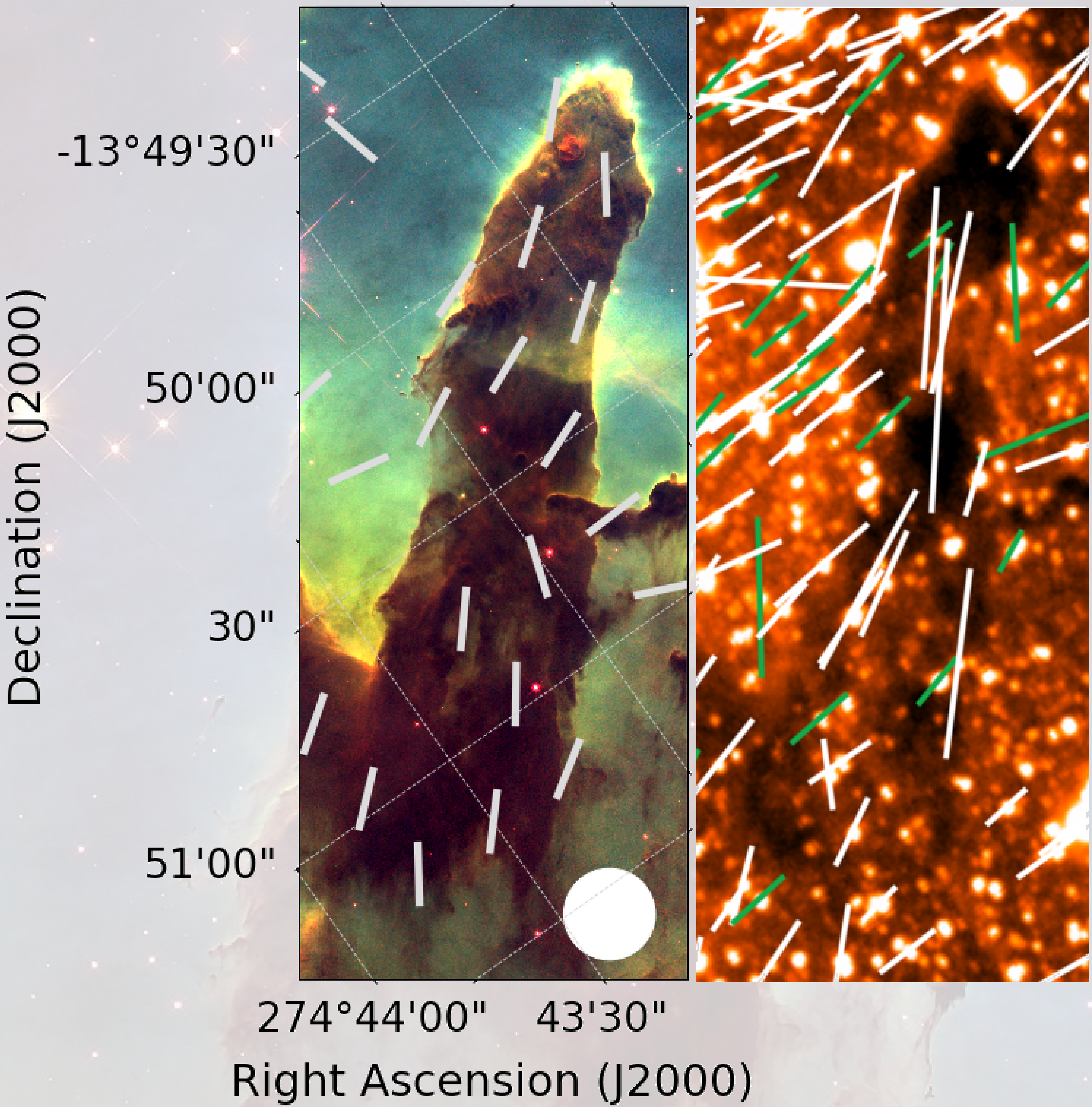
Sugitani et al. (2007) PASJ 59 507



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?)

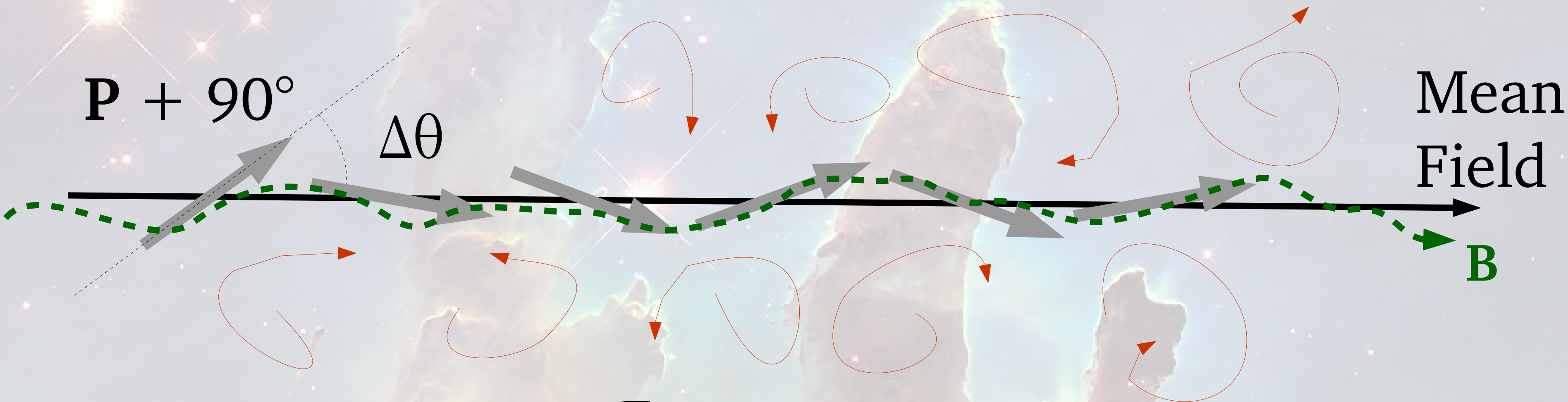




-13°49'30"
50'00"
30"
51'00"
Declination (J2000)
274°44'00"
43'30"
Right Ascension (J2000)

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 Davis 1951; Chandrasekhar & Fermi 1953).



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

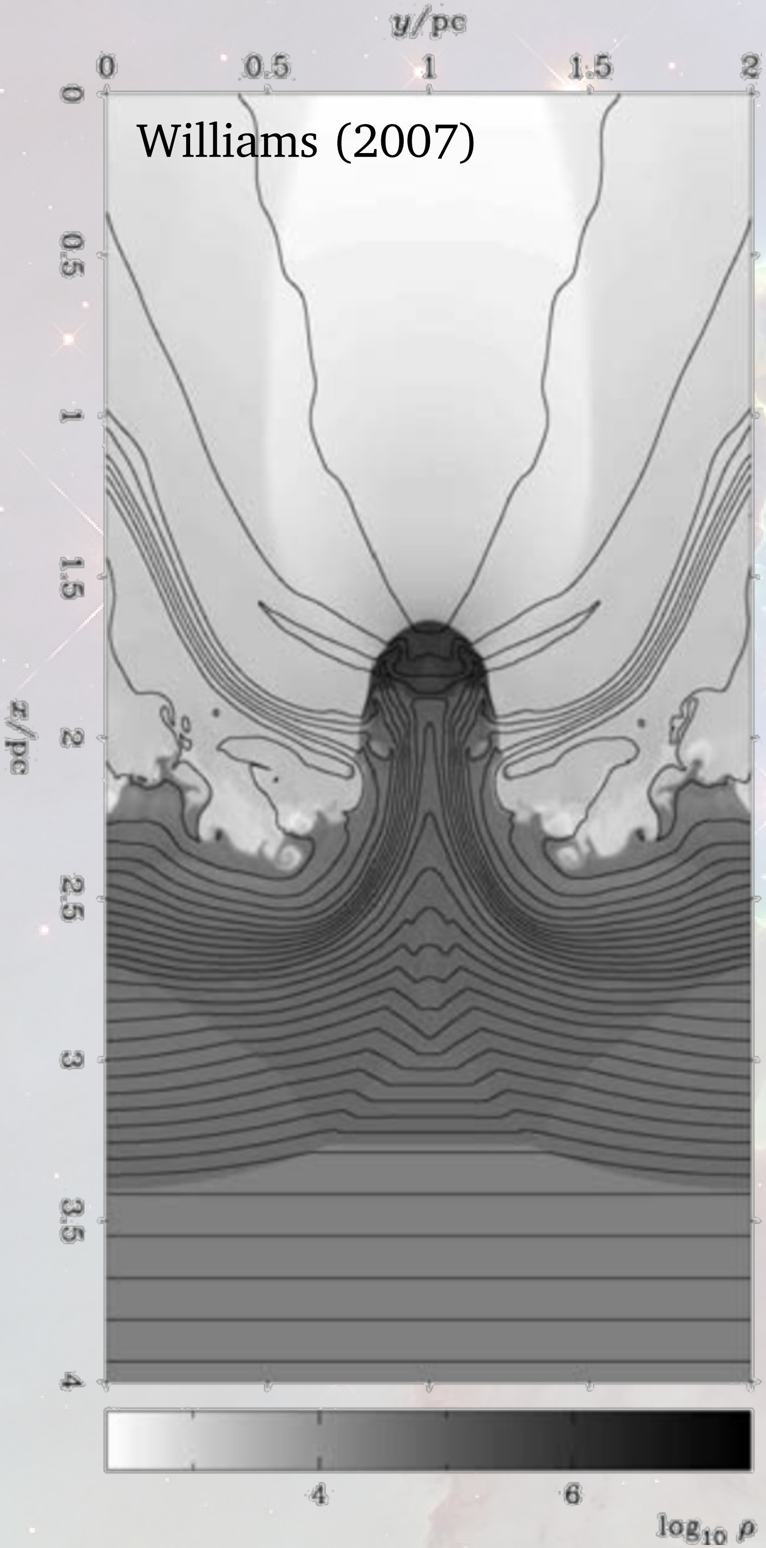
(c.f. Crutcher et al. 2004)

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

Magnetic field strength in Pillar II:

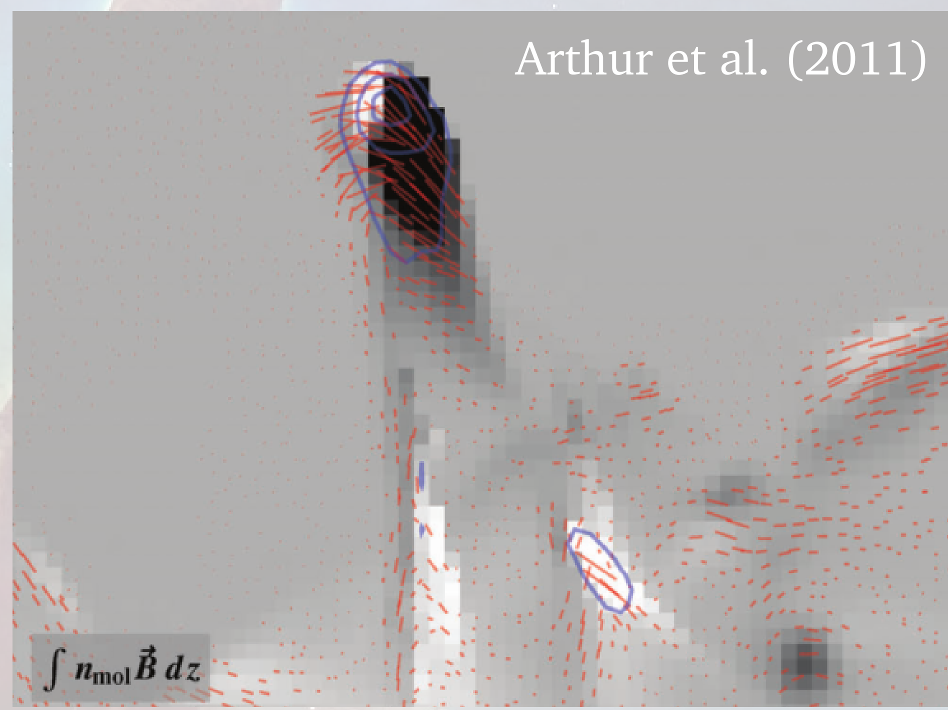
- $\sigma_\theta = 14.4^o$
- $n(H_2) \sim 5 \times 10^4\ cm^{-3}$ (Ryutov et al. 2005)
- $\Delta v \sim 1.1 – 2.1$ km/s (White et al. 1999)

$$\Rightarrow \mathbf{B_{pos} \approx 170 – 320\ \mu G}$$

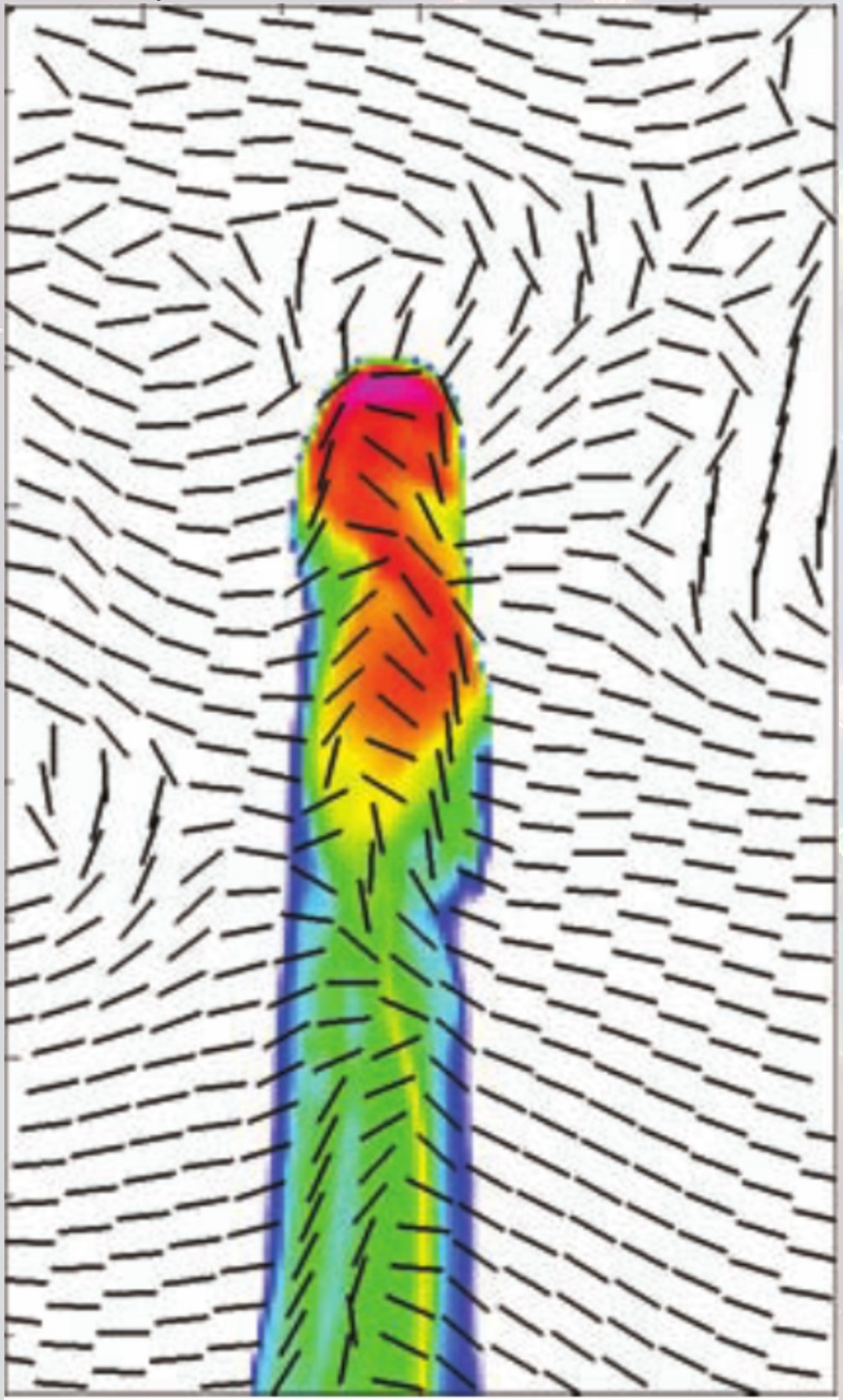


These results are qualitatively consistent with simulations of the compression of weakly magnetized dense gas to form pillars.

However, these simulations have to date been either low-resolution or two-dimensional.

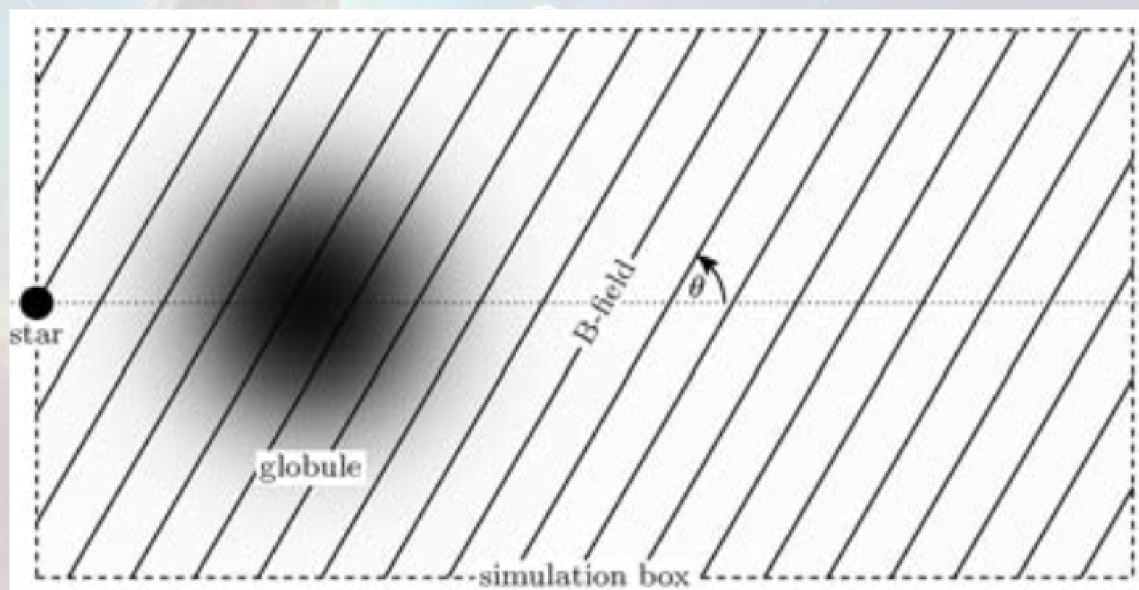


Mackey & Lim (2011)



Models in which pillars form behind isolated dense globules through radiation driven implosion/the rocket effect also show fields running along pillars (although with some disorder).

However, this requires a weak field (<50 μG) which has no means of being enhanced, and so is less consistent with our observations.



Henney et al. (2009)

Energetics:

Magnetic pressure: $P_B = B^2/8\pi$

$P_B/k = (0.9 - 3.0)\times10^7$ K cm^{-3}

HII region ablation pressure: $\sim1.6\times10^8$ K cm^{-3} (Ryutov 2005)

- The pillar head is being ablated by the interaction with the HII region

Thermal internal pressure: $P_{int} = nkT \sim 1\times10^6$ K cm^{-3} (T = 20 K)

Non-thermal internal pressure: $P_{nt,int} = nkT_{eff} \sim (0.4 - 1.5)\times10^7$ K cm^{-3}

(Taking White et al. 1999 velocity dispersions and μ=2.8)

- Non-thermal internal pressure dominates

Non-thermal external pressure: $P_{nt,ext} = nkT_{eff} \sim (0.4 - 1.5)\times10^7$ K cm^{-3}

(n=2n(H)=400 cm^{-3}, e.g. Williams 2007; T=8000 K, Hester et al. 1996; velocity dispersion 11.5 km s^{-1}, Higgs et al. 1979)

- Thermal external pressure considerably lower

Energetics:

Ostriker (1964) filament stability: $(M/L)_{crit} = 2c_s^{\,2}/G$

For $c_{s,eff} = 0.5 - 0.9$ km s^{-1} (White et al. 1999),

$(M/L)_{crit} = 120 - 400\ M_{\odot}pc^{-1}$

Estimated line mass of Pillar II:

If Pillar II has radius ~ 0.15 pc and n ~ 5×10^4 cm^{-3},

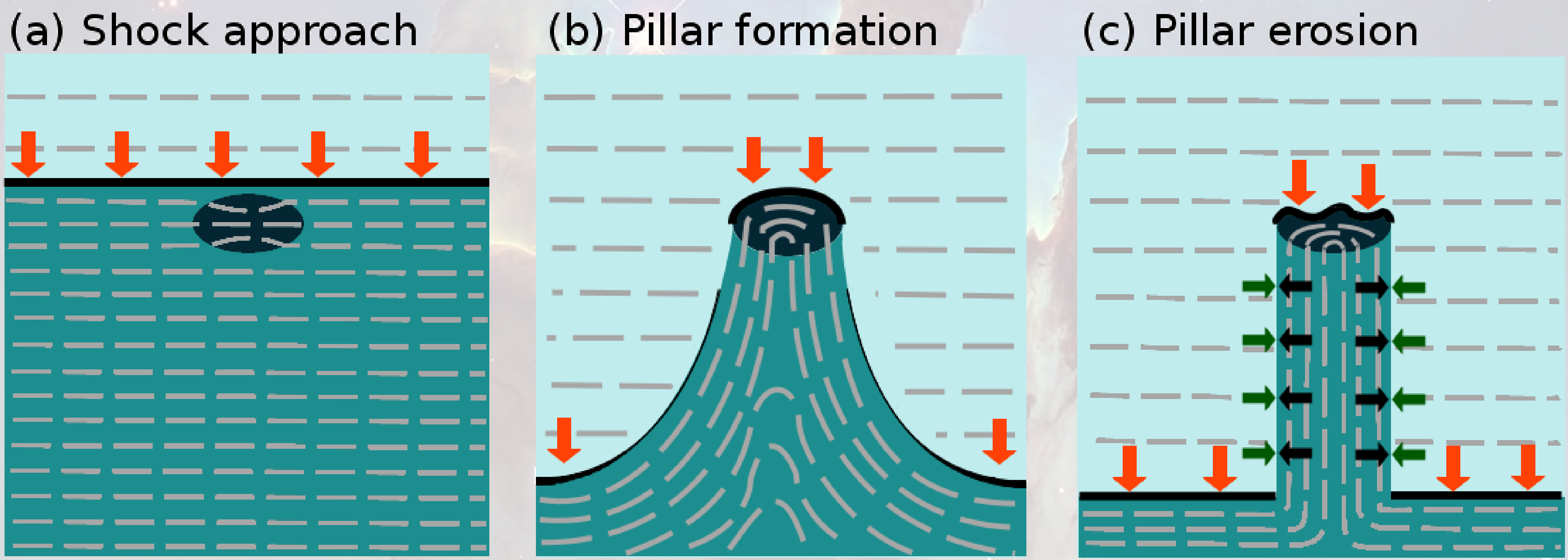
$(M/L) = \mu m_H n \pi r^2 \sim 250\ M_{\odot}pc^{-1}$, assuming cylindrical symmetry

Could Pillar II be marginally gravitationally unstable?

Energetics analysis suggests:

- The magnetic field cannot prevent the pillar heads being ablated by the HII region unless it is significantly compressed on small scales

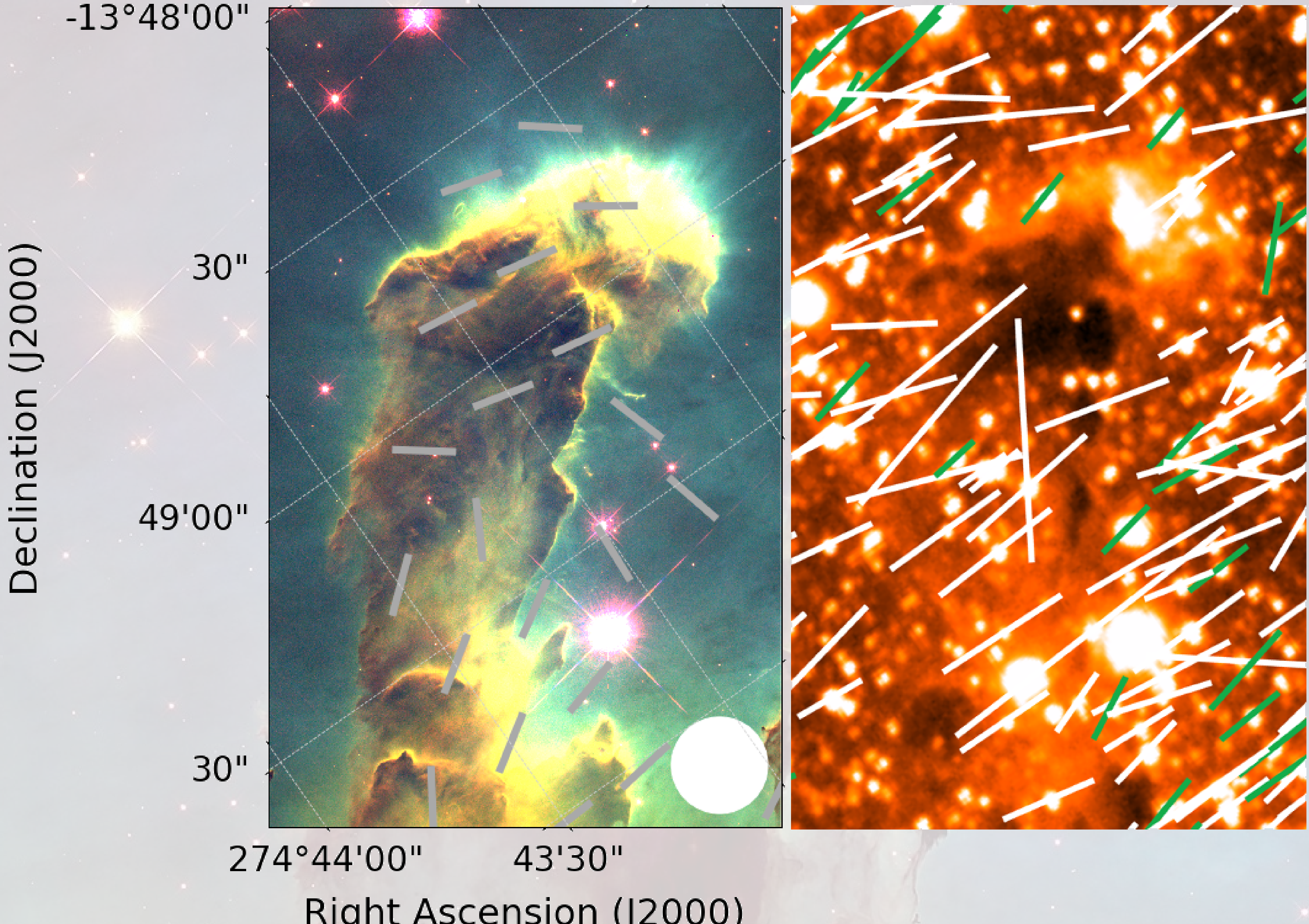
- The pillar walls are in approximate pressure equilibrium, with magnetic pressure and non-thermal internal gas pressure being balanced by non-thermal external gas pressure and non-negligible self-gravity



Summary

- We have performed the first observations of the magnetic field in the dense gas of the Pillars of Creation
- The magnetic field runs parallel to the Pillars’ lengths, and approximately perpendicular to the field in the surrounding photoionized region
- We find a magnetic field strength $B_{pos} \approx 170 – 320\ \mu$G in Pillar II
- This value is larger than that permitted by models where fields are aligned by RDI effects, but could have been created by compression of an initially dynamically negligible field in pillar formation
- Our results suggest that the pillar walls are in magnetically-supported equilibrium with their surroundings, while the pillar heads are being eroded by the shock interaction
- For more details see **Pattle et al. 2018 ApJ 860 L6**

Thank you!



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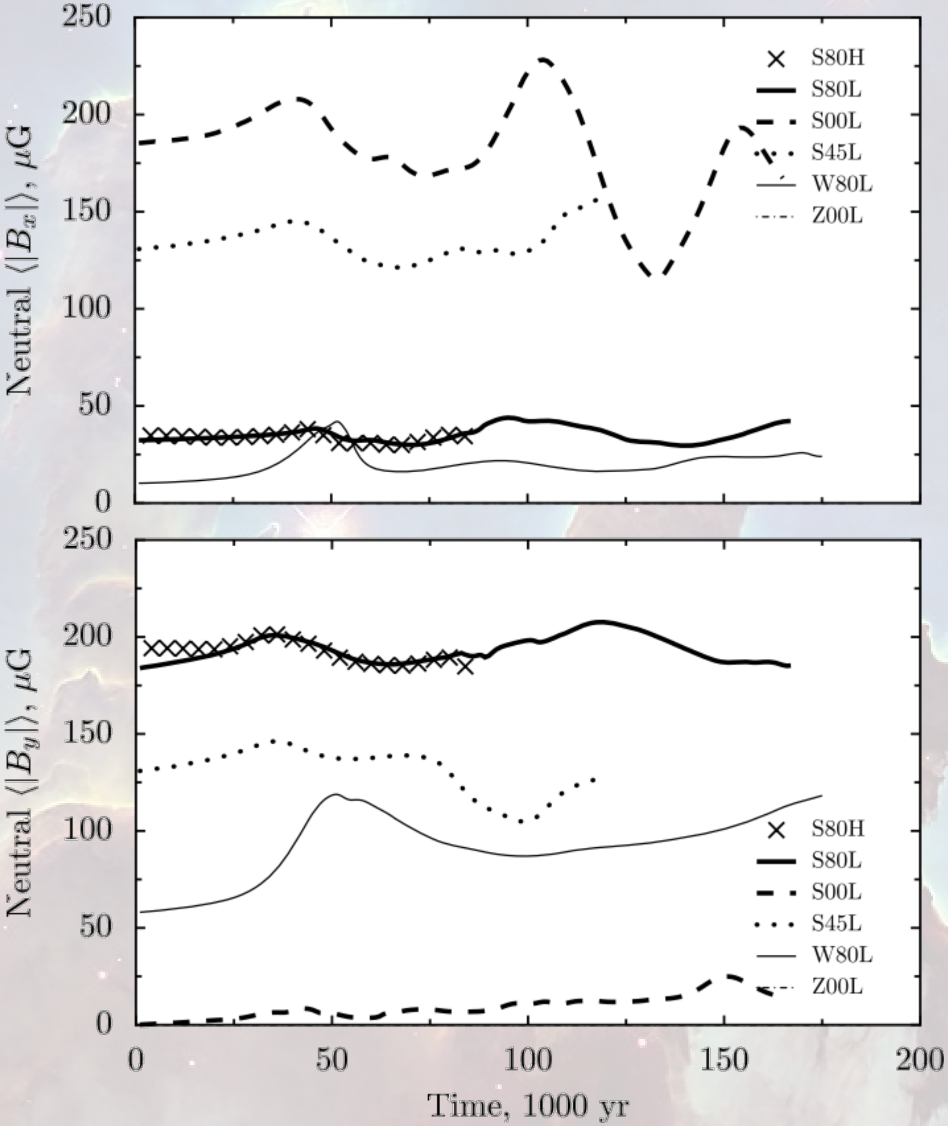

Neutral ⟨|B_x|⟩, μG
Neutral ⟨|B_y|⟩, μG
Time, 1000 yr
0
50
100
150
200
250
S80H
S80L
S00L
S45L
W80L
Z00L