HAWC+ Observations of the Magnetic Field in the Sickle: Explorations of Interface Instabilities

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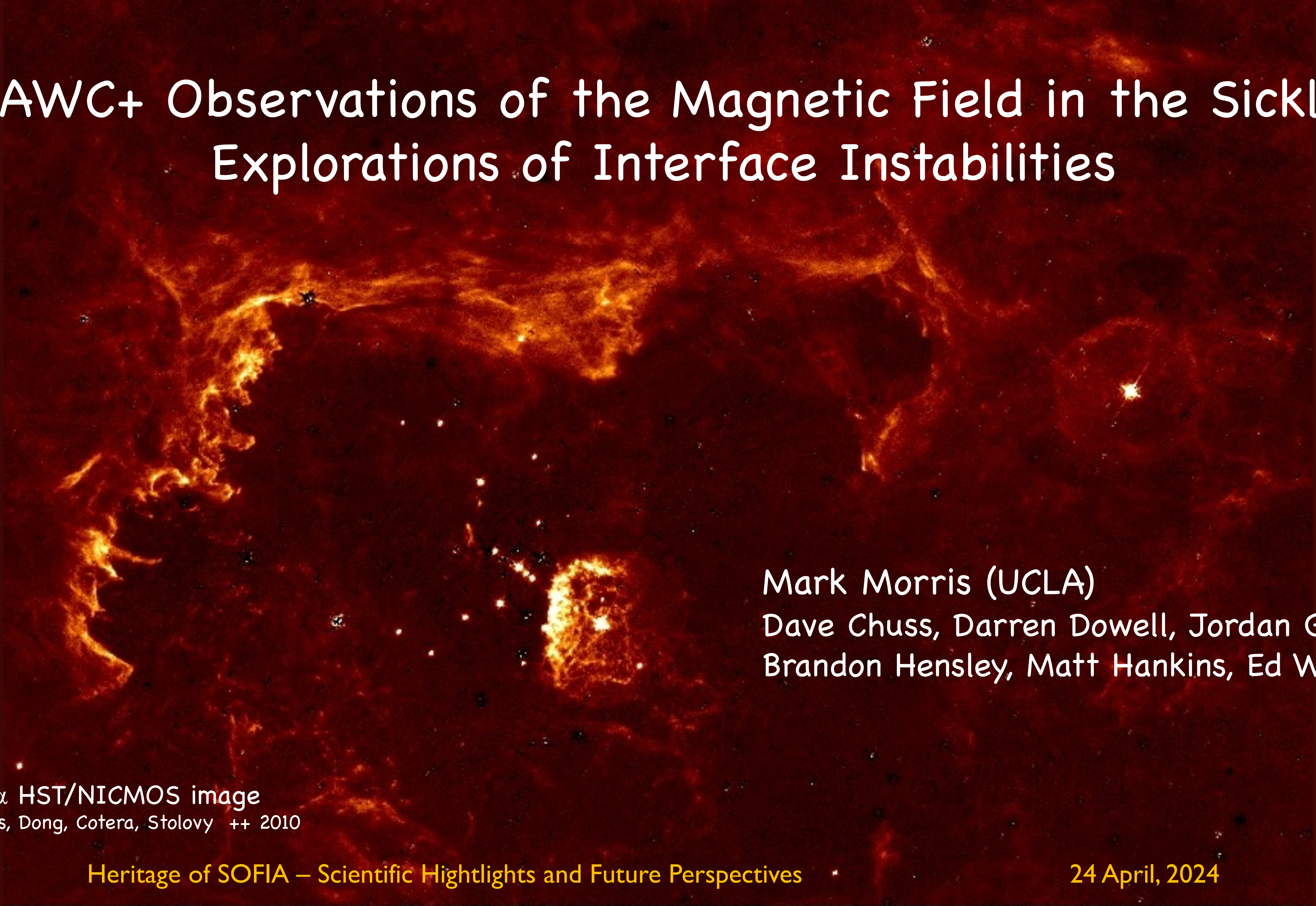
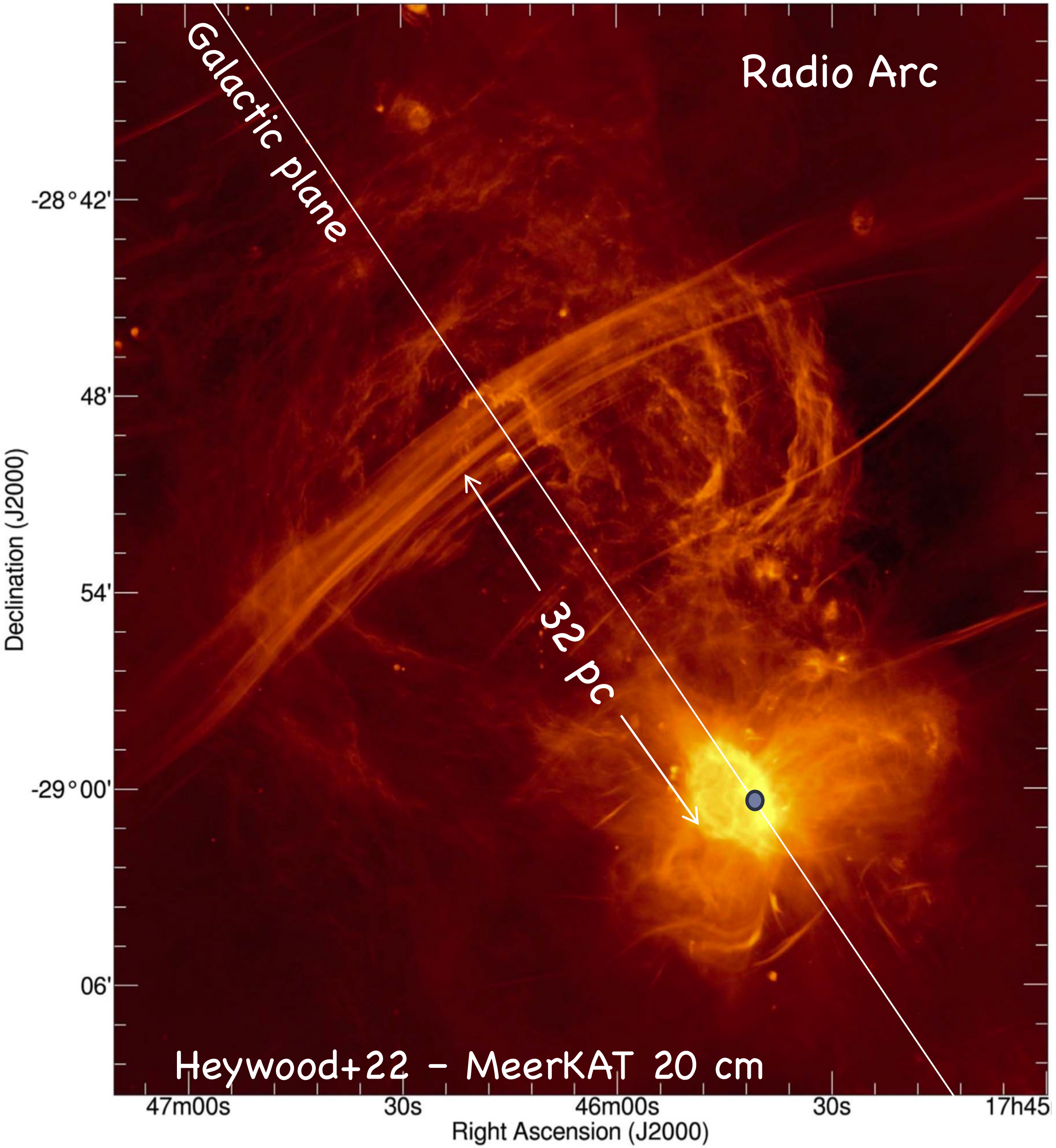
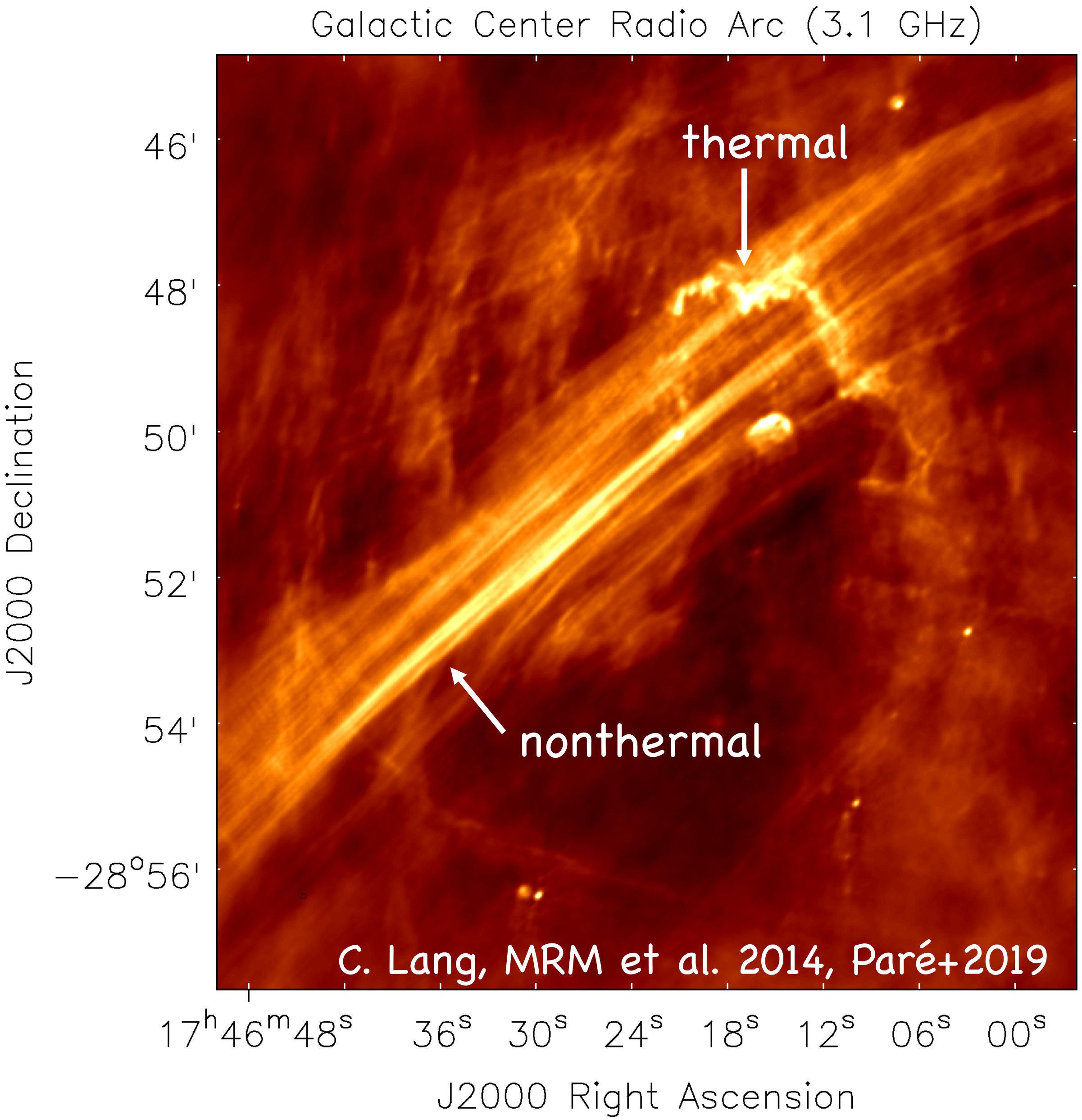


Paschen-α HST/NICMOS image
Wang, Morris, Dong, Cotera, Stolovy ++ 2010

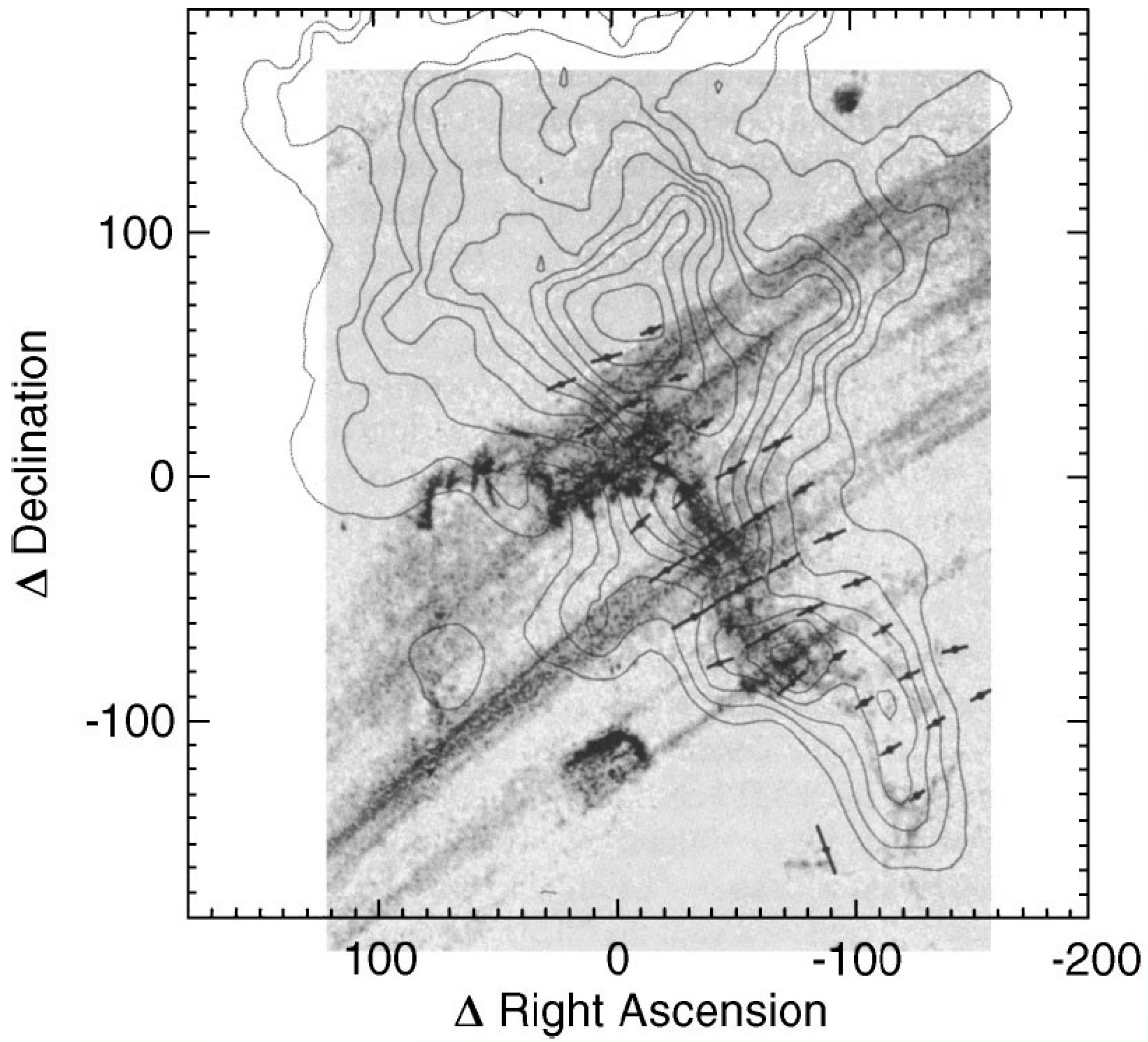


Radio Arc
Galactic plane
32 pc
Heywood+22 – MeerKAT 20 cm
-28°42'
48'
54'
-29°00'
06'
Declination (J2000)
47m00s
30s
46m00s
30s
17h45
Right Ascension (J2000)



Galactic Center Radio Arc (3.1 GHz)
thermal
nonthermal
C. Lang, MRM et al. 2014, Paré+2019
46'
48'
50'
52'
54'
−28°56'
J2000 Declination
17h46m48s
36s
30s
24s
18s
12s
06s
00s
J2000 Right Ascension

Nonthermal radio filaments show interactions with molecular clouds !



Contours:
CS 3-2 emission
(Serabyn & Güsten 1991)

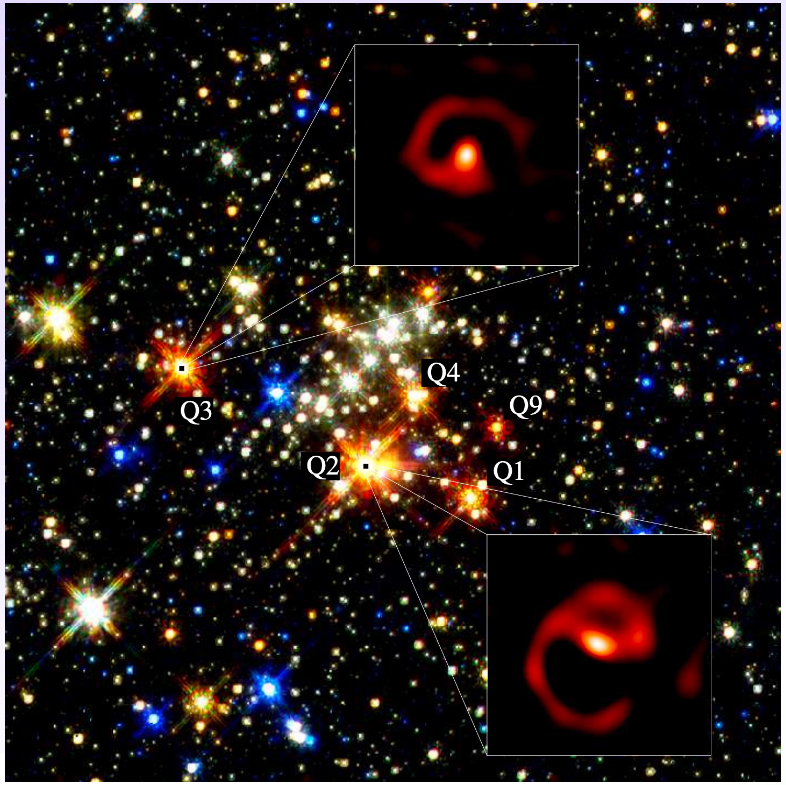
Grayscale:
6cm radio continuum

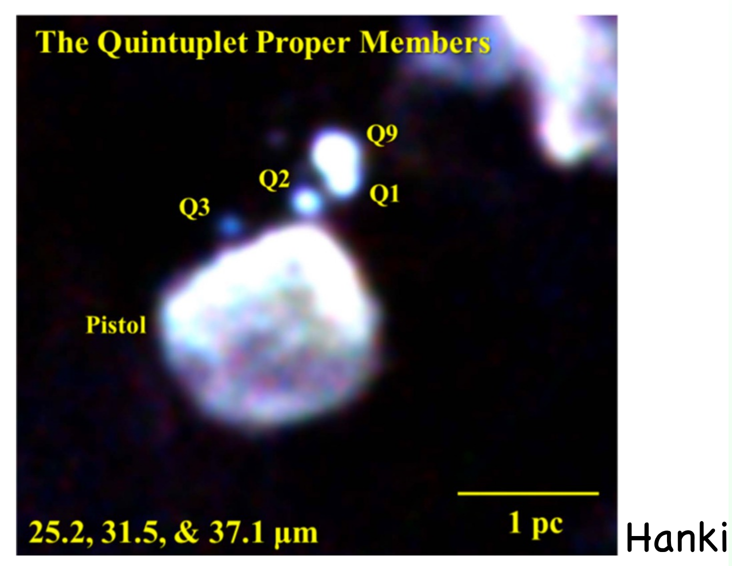
Vectors:
far-IR polarized E-vectors measured with the KAO
(Dotson et al. 2000, Chuss et al. 2003)

Morris & Serabyn 1996

Quintuplet Cluster

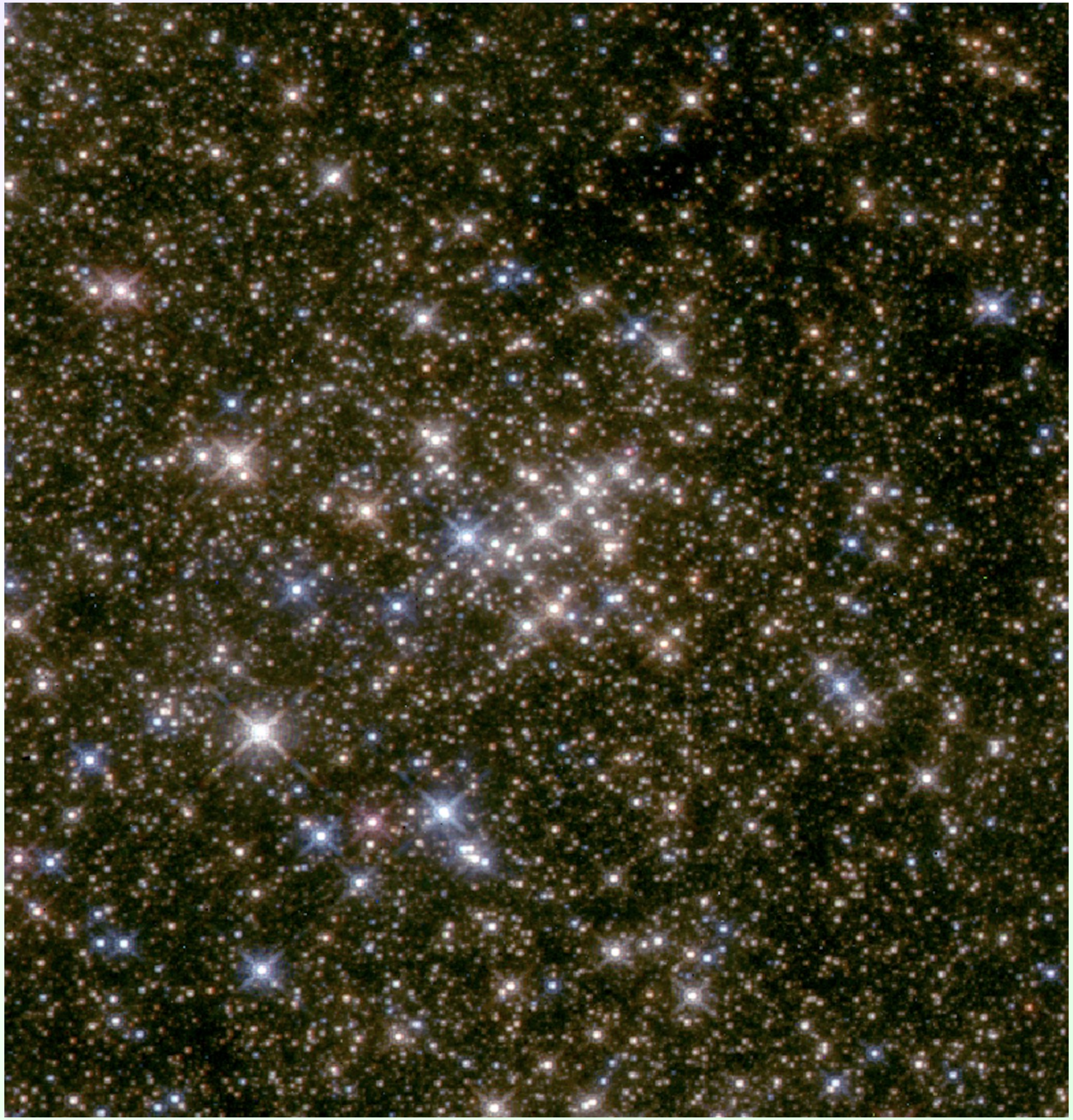
Tuthill+2006 HST NICMOS

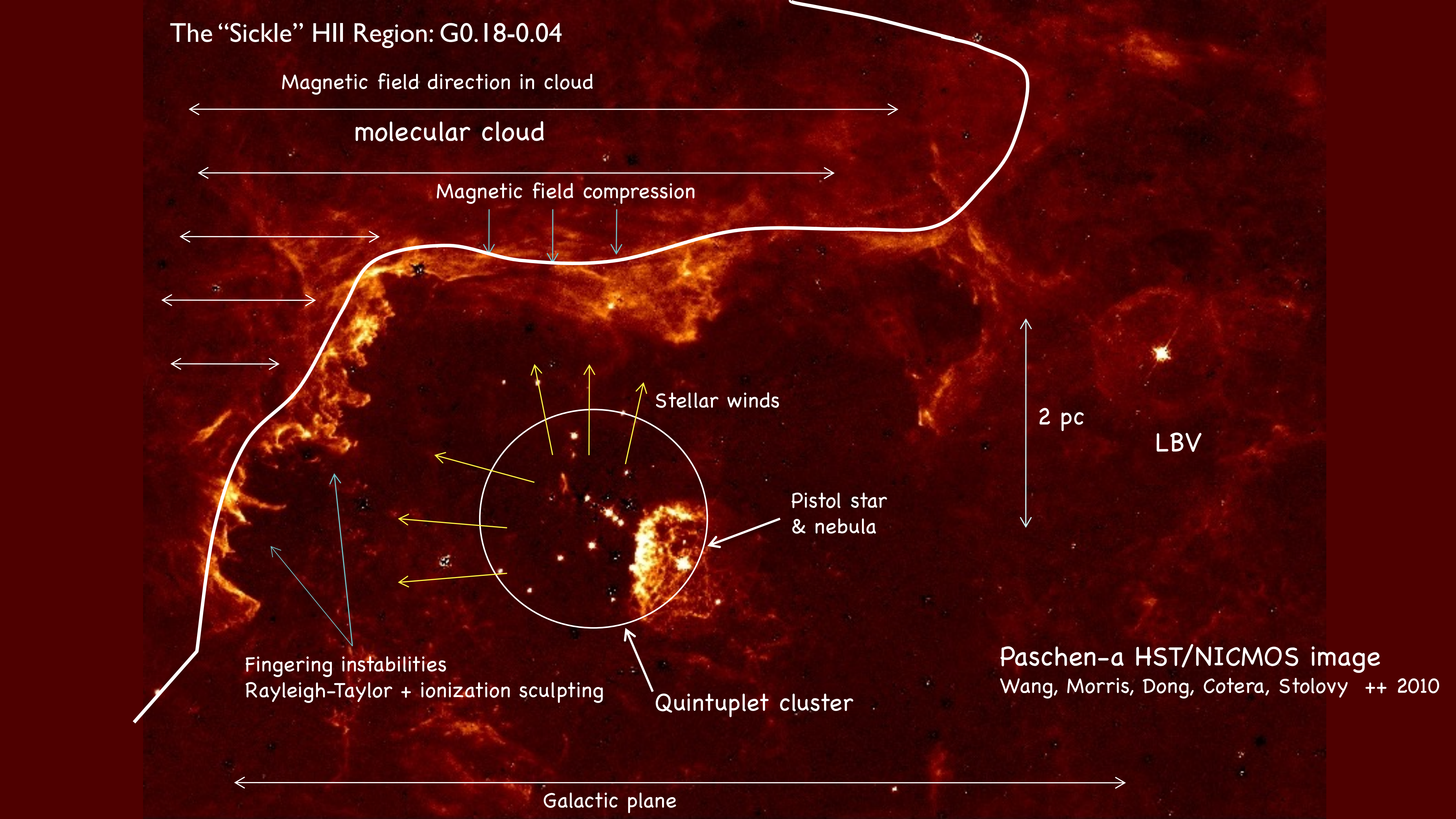




Hankins et al. 2016

HST - Hosek

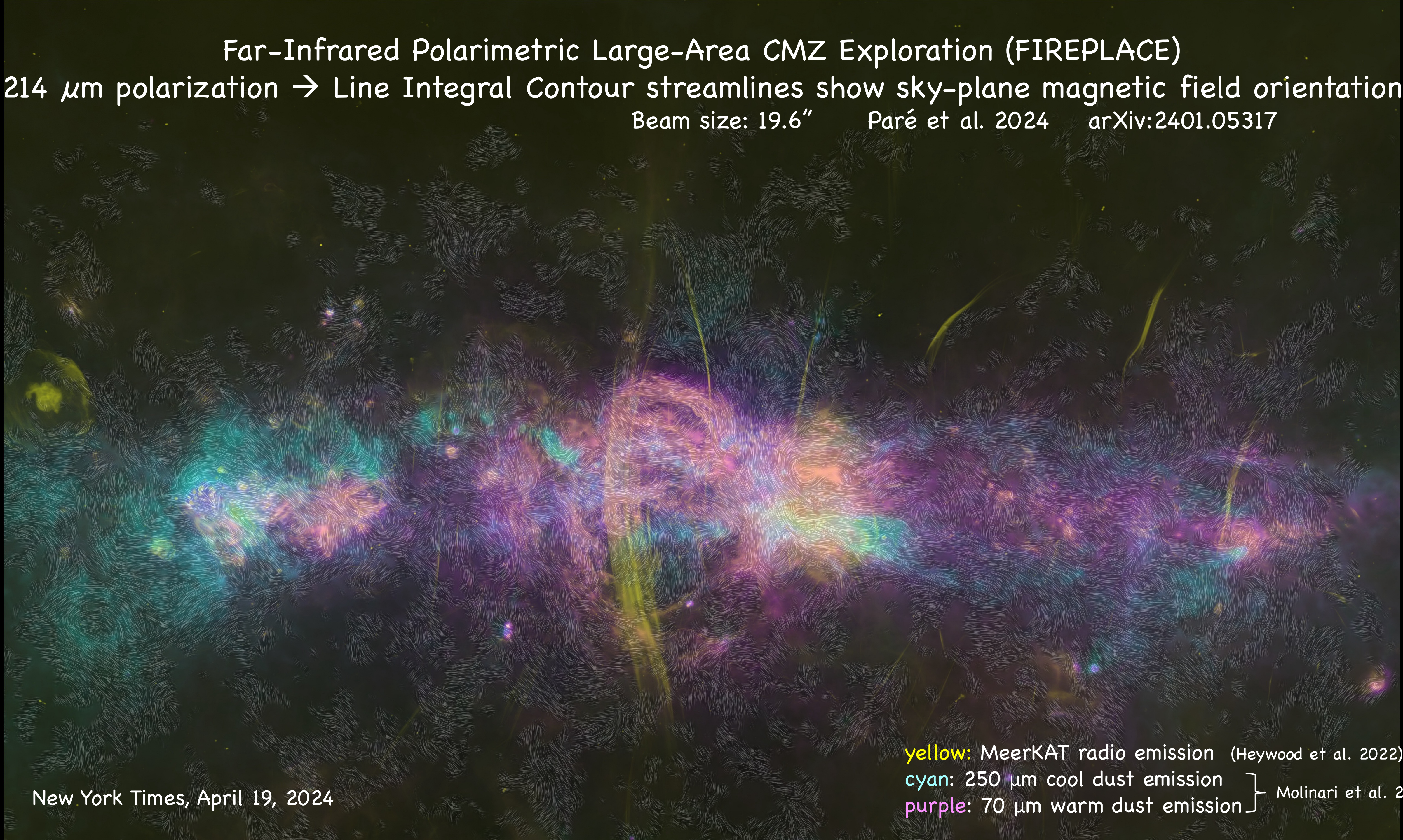


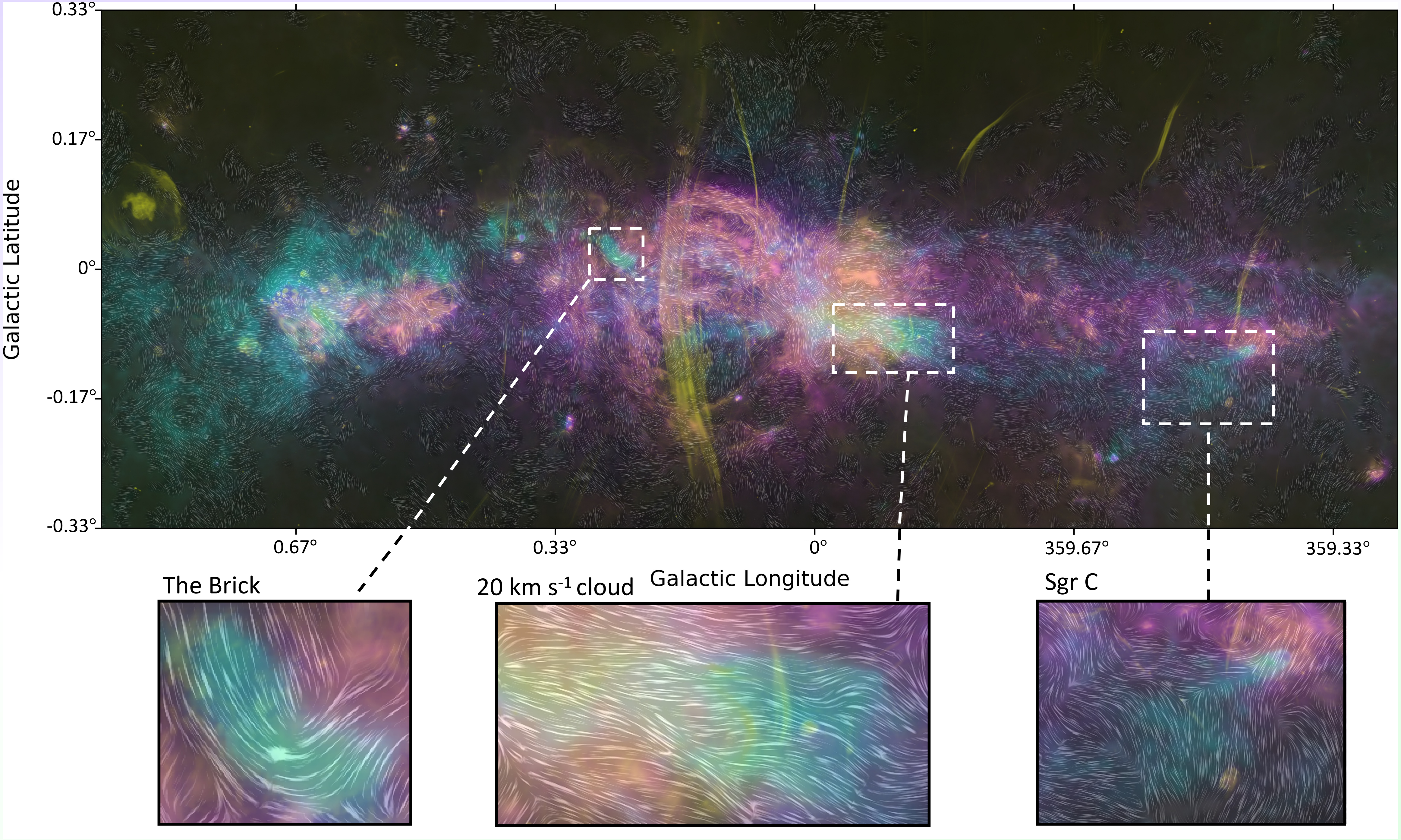

The "Sickle" HII Region: G0.18-0.04
Magnetic field direction in cloud
molecular cloud
Magnetic field compression
Stellar winds
2 pc
LBV
Pistol star & nebula
Fingering instabilities
Rayleigh-Taylor + ionization sculpting
Quintuplet cluster
Paschen-a HST/NICMOS image
Wang, Morris, Dong, Cotera, Stolovy ++ 2010
Galactic plane

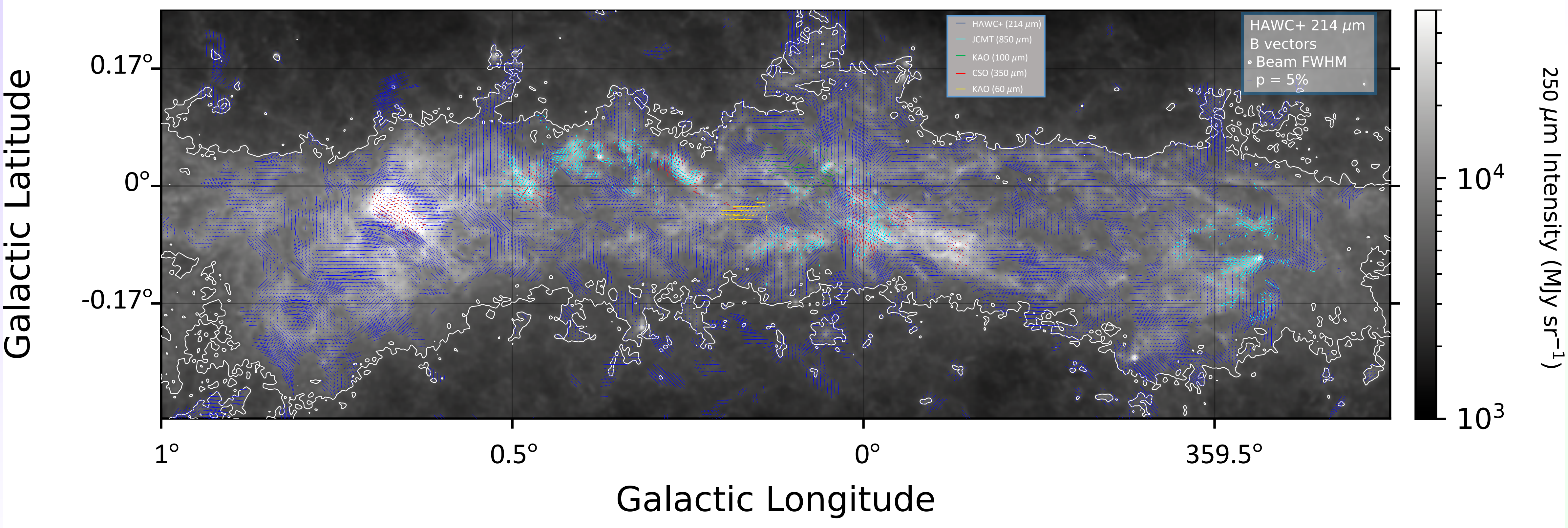
Observations with the SOFIA imaging polarimeter HAWC+

First, an aside:

polarimetric observations of the whole Central Molecular Zone at 214 μm


Far-Infrared Polarimetric Large-Area CMZ Exploration (FIREPLACE)
214 μm polarization → Line Integral Contour streamlines show sky-plane magnetic field orientation
Beam size: 19.6″
Paré et al. 2024
arXiv:2401.05317
yellow: MeerKAT radio emission
(Heywood et al. 2022)
cyan: 250 μm cool dust emission
purple: 70 μm warm dust emission
Molinari et al. 2011
New York Times, April 19, 2024


0.33°
0.17°
0°
-0.17°
-0.33°
Galactic Latitude
0.67°
0.33°
0°
359.67°
359.33°
Galactic Longitude
The Brick
20 km s-1 cloud
Sgr C



Three recent FIREPLACE papers:

SOFIA/HAWC+ Far-Infrared Polarimetric Large Area CMZ Exploration (FIREPLACE) Survey

I. General Results from the Pilot Program Natalie Butterfield et al. 2024, ApJ 963, id. 130

II: Detection of a Magnetized Dust Ring in the Galactic Center Natalie Butterfield et al. 2024 in press arXiv:2401.01983

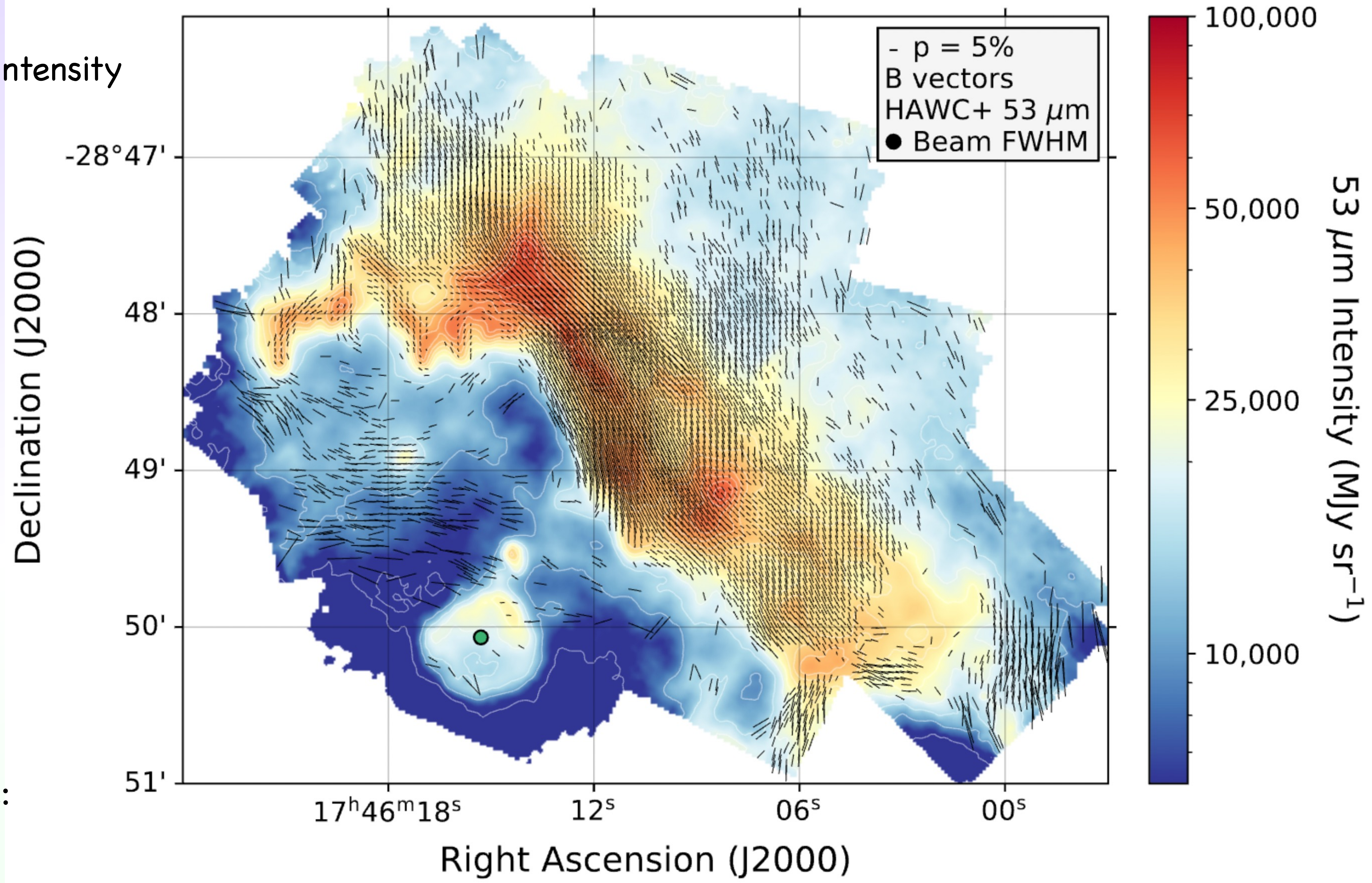
III: Full Survey Data Set (DR2) Dylan Paré et al. in press arXiv:2401.05317

… and more to come

HAWC+ observations of the Sickle

- 53 μm band
- beam diameter 4.85″
- standard chop-nod-dither mode with 4 half-wave plate positions at each dither position & 4 dither positions for each field
- **4,516** Nyquist-sampled polarization measurements that survive the data cuts

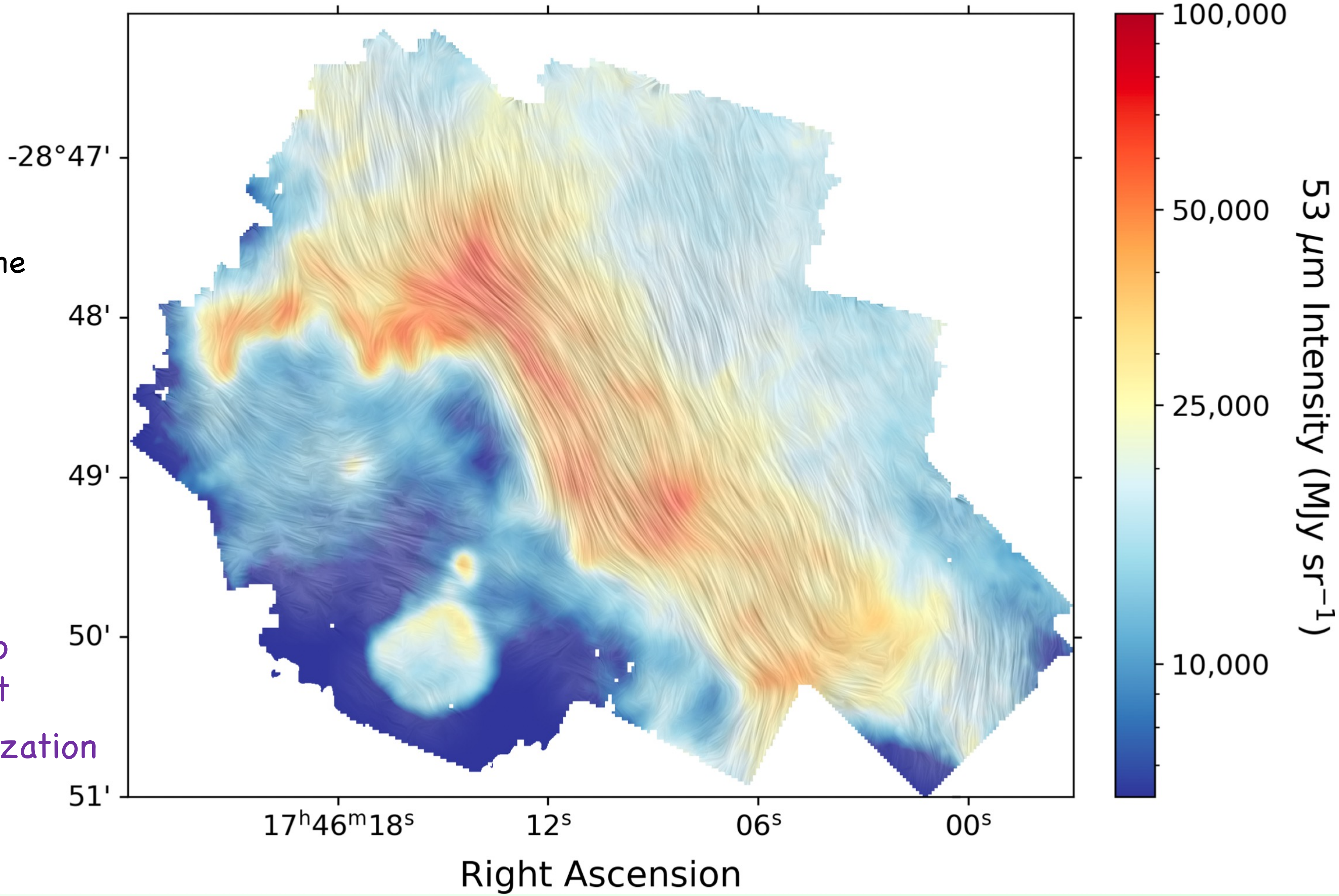
Color:
total 53 μm intensity



Green circle:
Pistol star

LIC Version

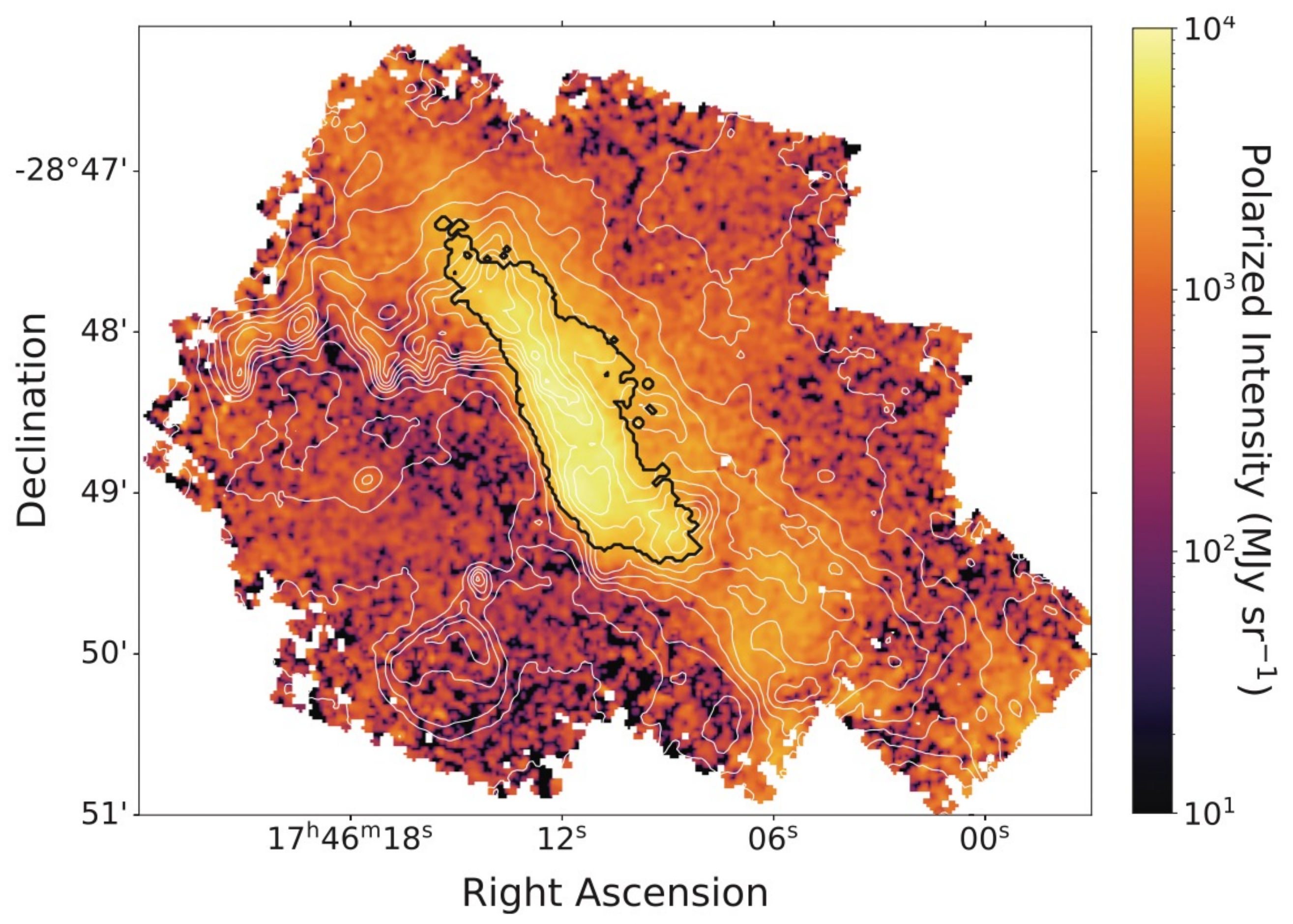
Note the overall uniformity of the magnetic field direction, parallel to the Galactic plane

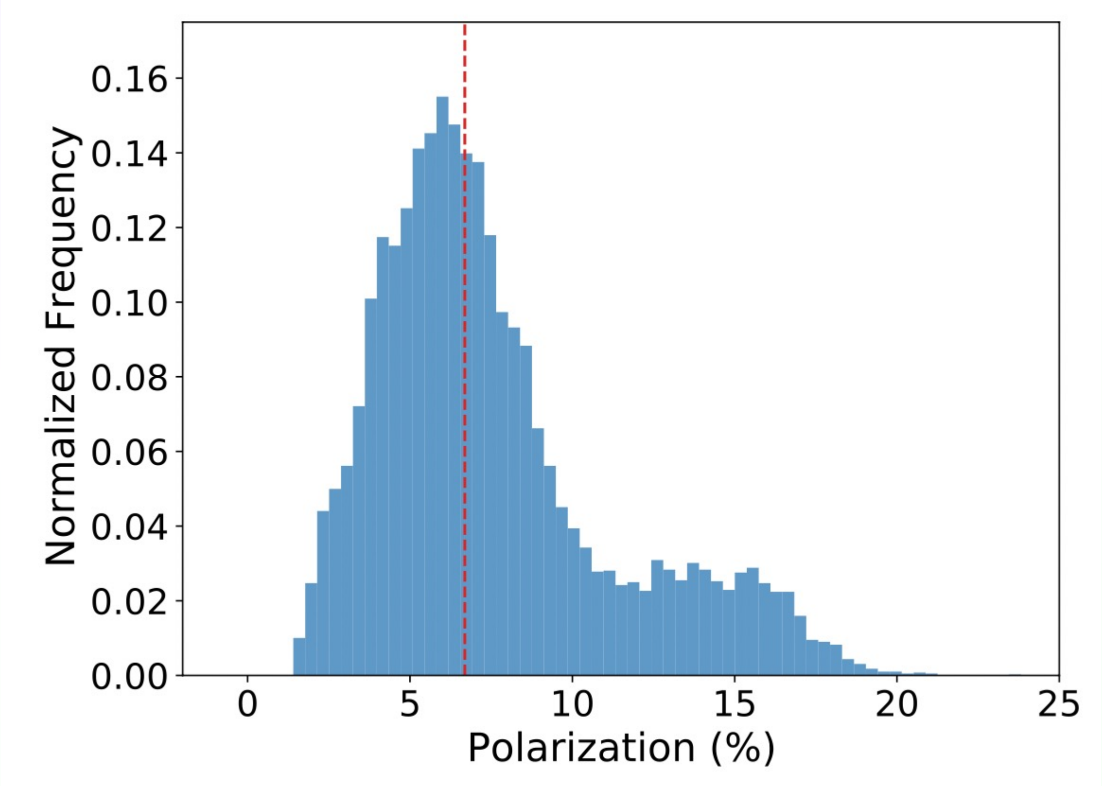


Note that there are two fronts:

1) field parallel to ionization front

2) Field ⊥ to ionization front





polarized intensity

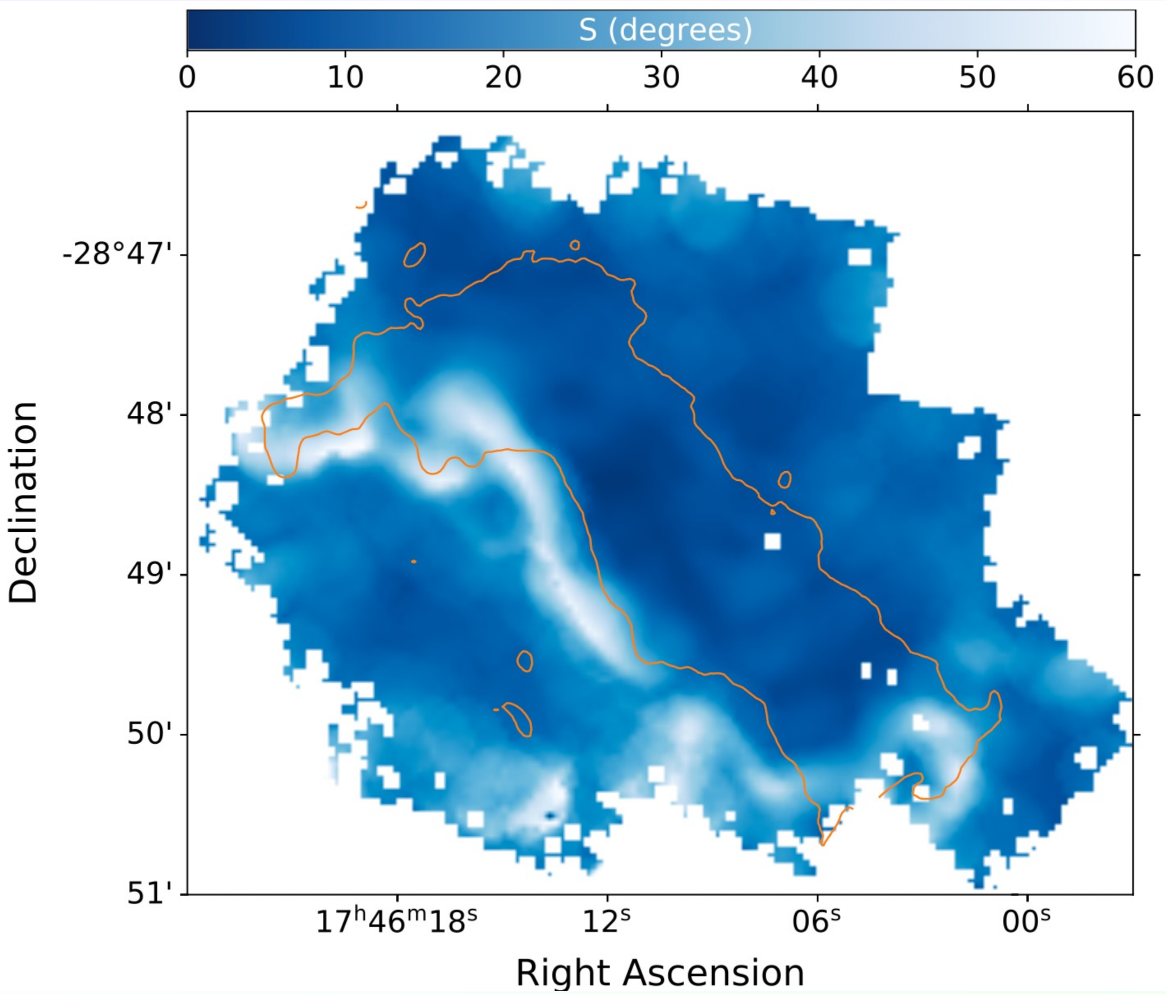
contours: total intensity

Distribution of percent polarization values

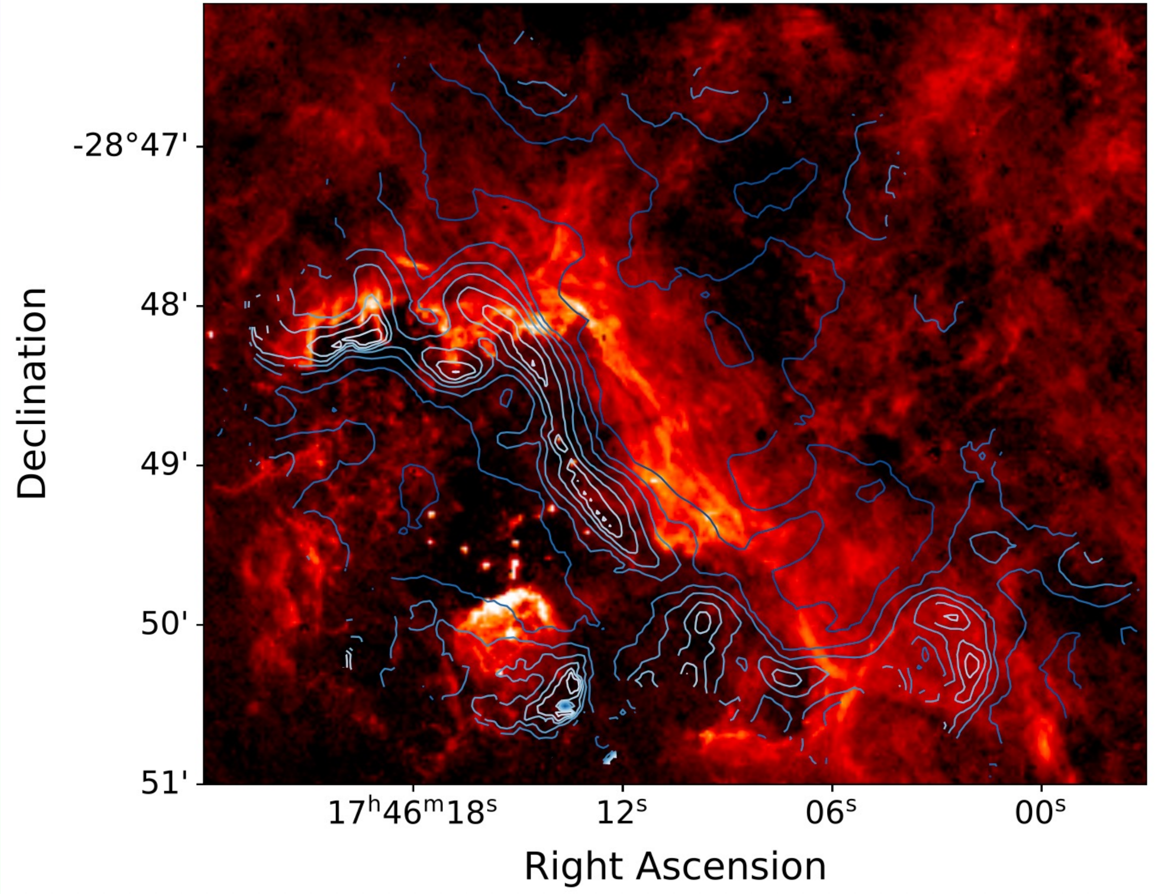
- polarization values are remarkably high, and extend to a maximum of **20%**
- consistent with Planck: $p_{\max} = 22^{+3.5}_{-1.4}\%$ at 850 μm

→ Implies very efficient grain alignment and favorable geometry

Polarization angle dispersion – *greatest inside the ionization front, reflecting turbulence in the HII region*



Orange contour: 25,000 MJy sr^{-1} total intensity



Contours: polarization angle dispersion

Magnetic Field Strength along the main ridge of the Sickle:

→ apply the Davis-Chandrasekhar- Fermi (DCF Davis 1951; Chandrasekhar & Fermi 1953) technique

→ Modern methodology, in which both the large-scale ordered and the small-scale turbulent fields are taken into account (Hildebrand et al. (2009); Houde et al. (2009, 2011, 2016))

$$B_{\rm POS} = 2.5 \left(\frac{n(H_2)}{10^4\ {\rm cm}^{-3}}\right)^{1/2} \left(\frac{\sigma_v}{5.1\times10^5\ {\rm cm\,s^{-1}}}\right) \left(\frac{\Delta'}{0.79'}\right)^{-1/2}\ {\rm mG.}$$

Δ' is the cloud's effective depth, estimated using the autocorrelation of the polarized intensity (Houde et al. 2009)

σ_v is the velocity dispersion, derived from CS measurements (Serabyn & Güsten 1991)

$n(H_2)$ is the density of the cloud

The Pillars:

Magnetic Rayleigh-Taylor instabilities at the ionization front

Complex:

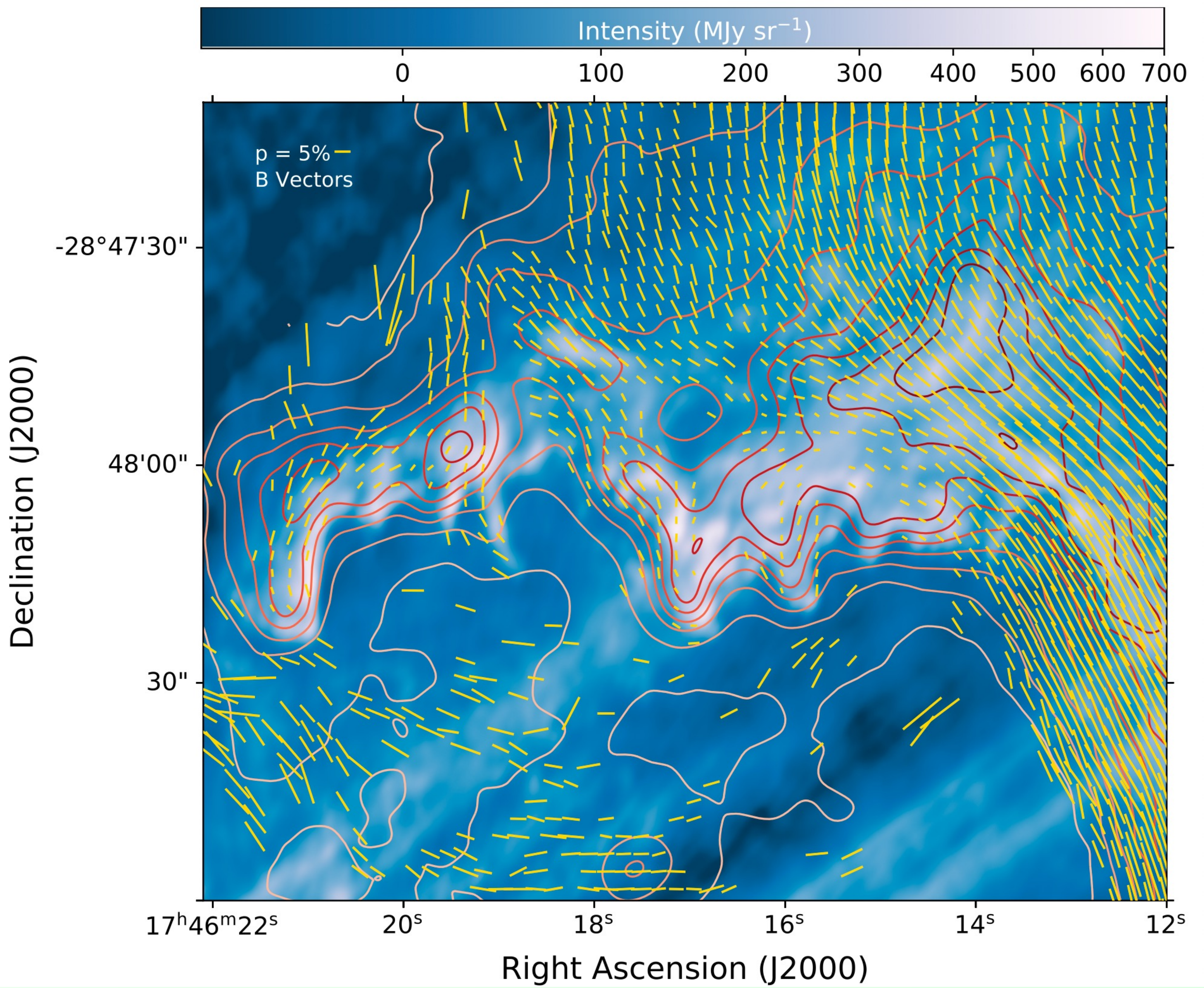
- ionizing radiation field
- collective stellar winds
- strong magnetic field

But the magnetic field orientation is a critical determinant →

B parallel to front → stability

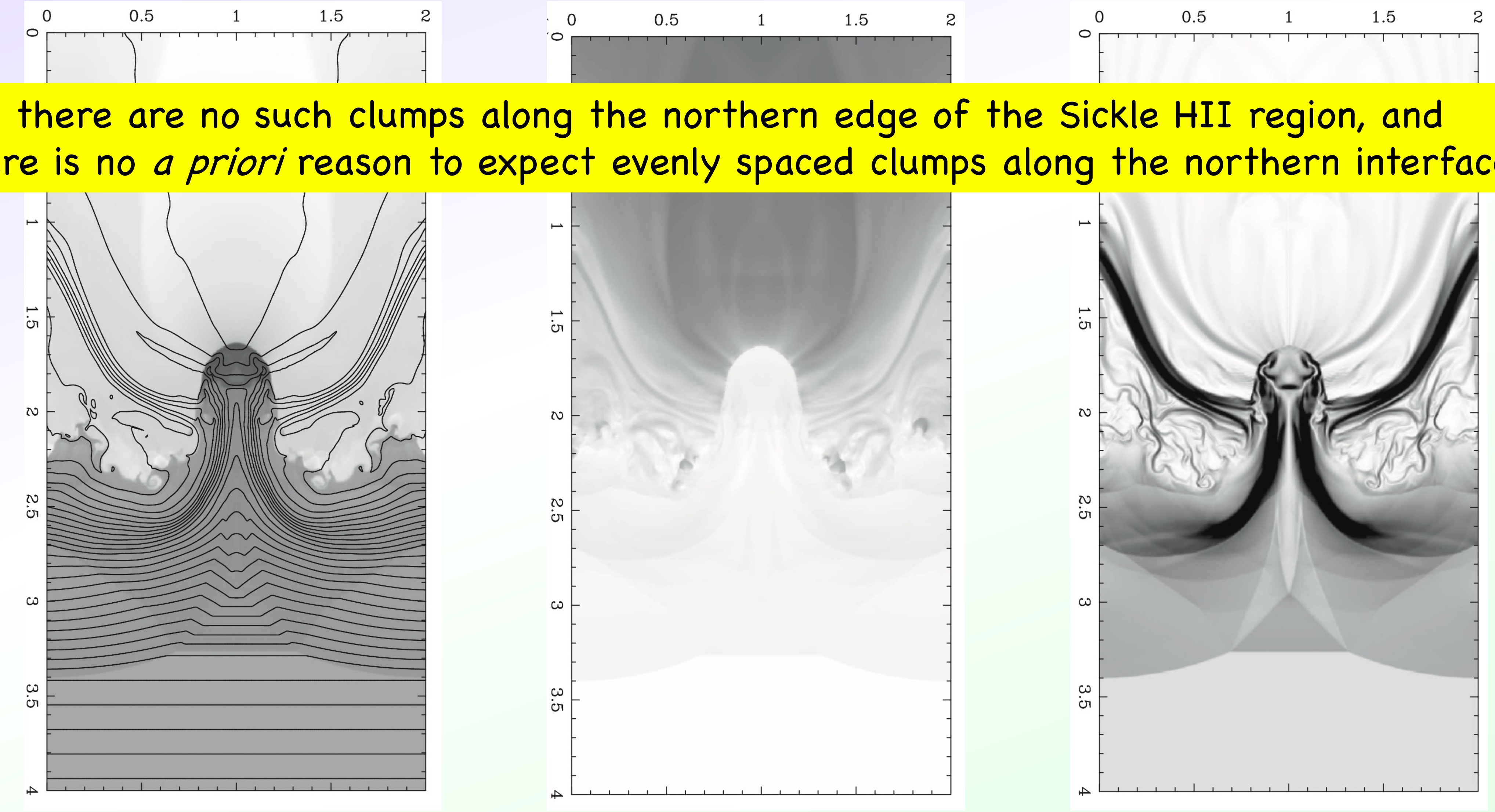
B perpendicular to front → pillar-forming instability

5 GHz radio map from Paré et al. 2019
Red contours: 53 μm total intensity



It is possible to produce a pillar using a strong density inhomogeneity →

Fate of a density clump at an ionization front interface   Williams 2007

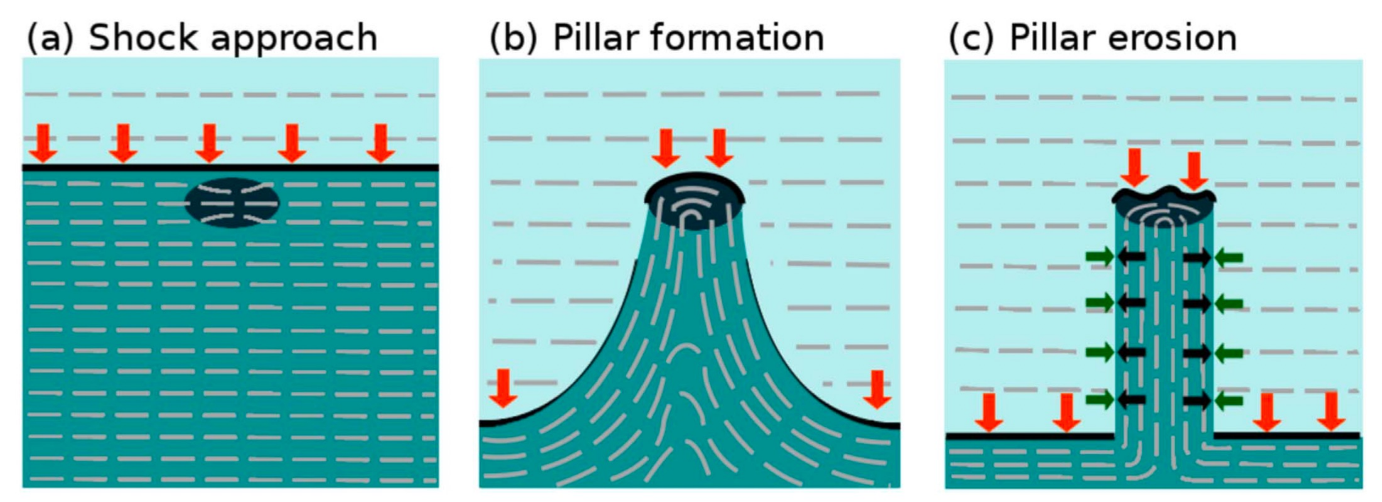


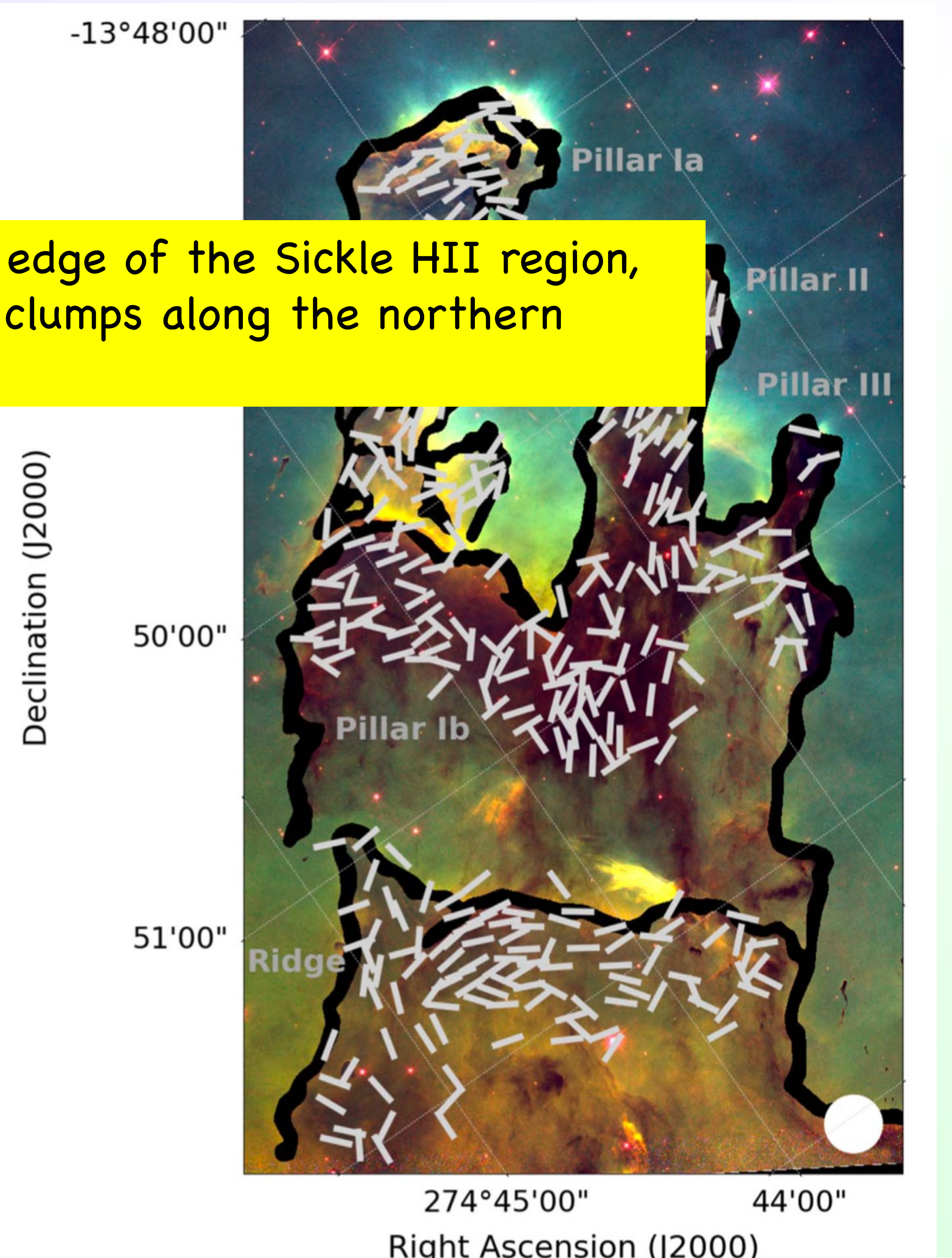
But there are no such clumps along the northern edge of the Sickle HII region, and there is no *a priori* reason to expect evenly spaced clumps along the northern interface

Field lines   velocity   field strength

This approach was also taken by Mackey & Lim 2011 and Prattle et al. (2018):

But again, there are no such clumps along the northern edge of the Sickle HII region, and there is no *a priori* reason to expect evenly spaced clumps along the northern interface

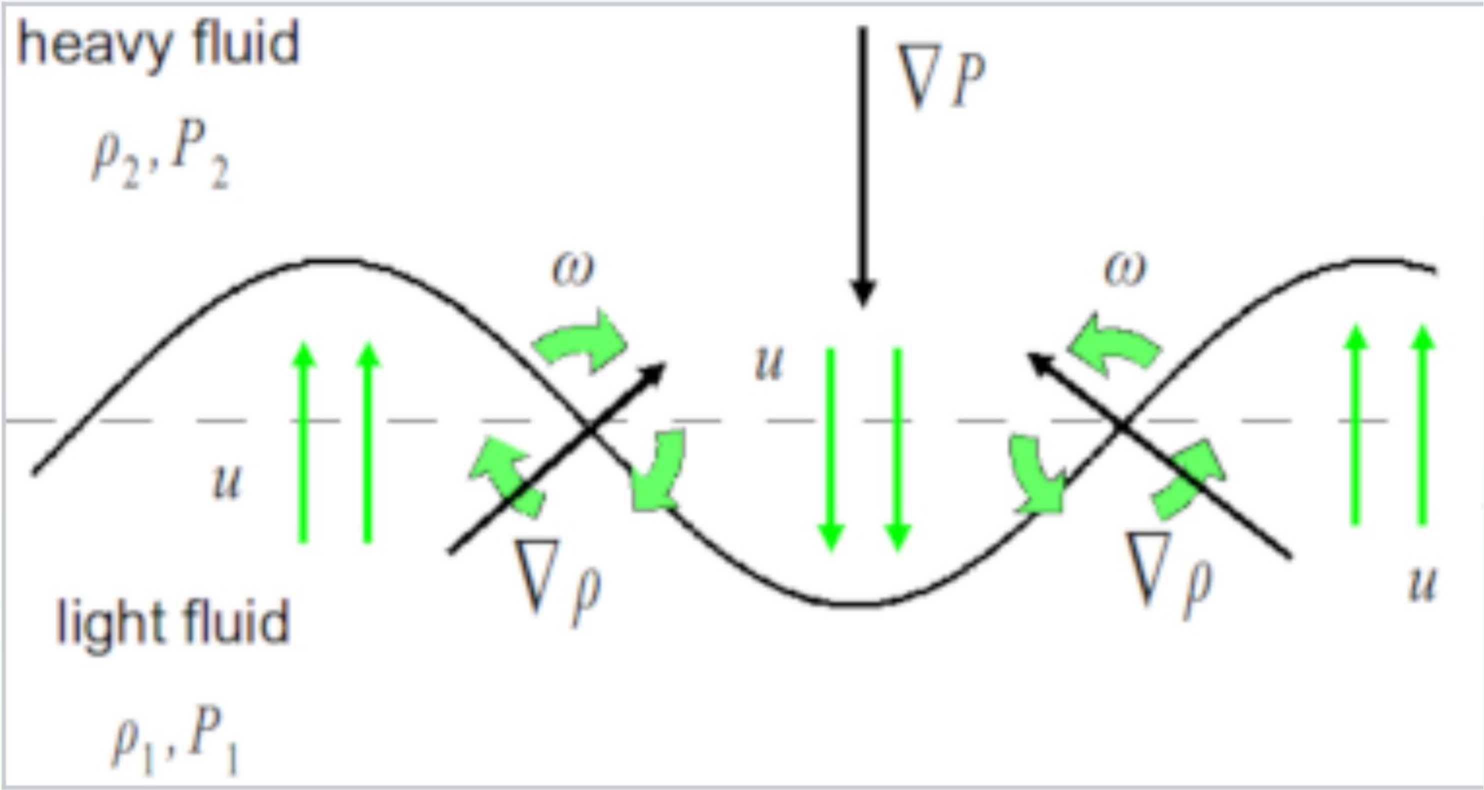




A classical Rayleigh-Taylor instability must be operating here:

→ modified by the orientation (and strength) of the magnetic field AND

→ the added complexity that the interaction front is an ionization front, where the "jet effect" adds to the local forces as it exerts a force on the cloud that is normal to the interface.



Summary

- The grains within the cloud at the interface with the Sickle HII region are exceptionally well aligned with the magnetic field within the cloud, and the geometry is probably very favorable, both for RAT alignment and for the field orientation, so polarization fractions are large, up to 20%

- The well-populated Quintuplet cluster of massive stars exerts a powerful influence on the neighboring cloud with its strong collective wind and high luminosity

- The dispersion in polarization angles reveals a chaotic zone just inside the ionization front where gas boiling off the ionization front encounters the strong collective winds from the cluster

- The ionization front along the Sickle HII region offers an ideal laboratory for exploring magnetic R-T instabilities that lead to pillar formation in the presence of a strong magnetic field