Galactic Eco-Systems, 28 Feb. - 04 March 2022, Lake Arrowhead, California

The Role of B-Fields in Star Formation

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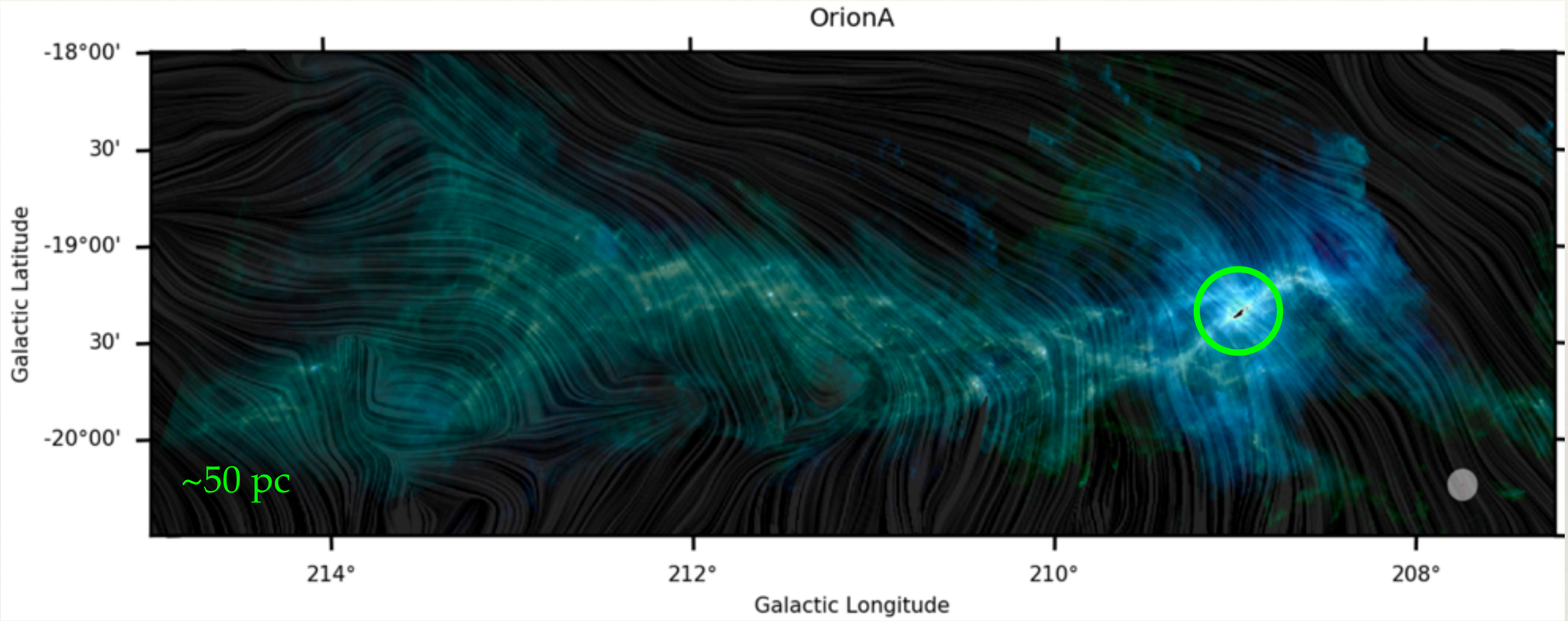
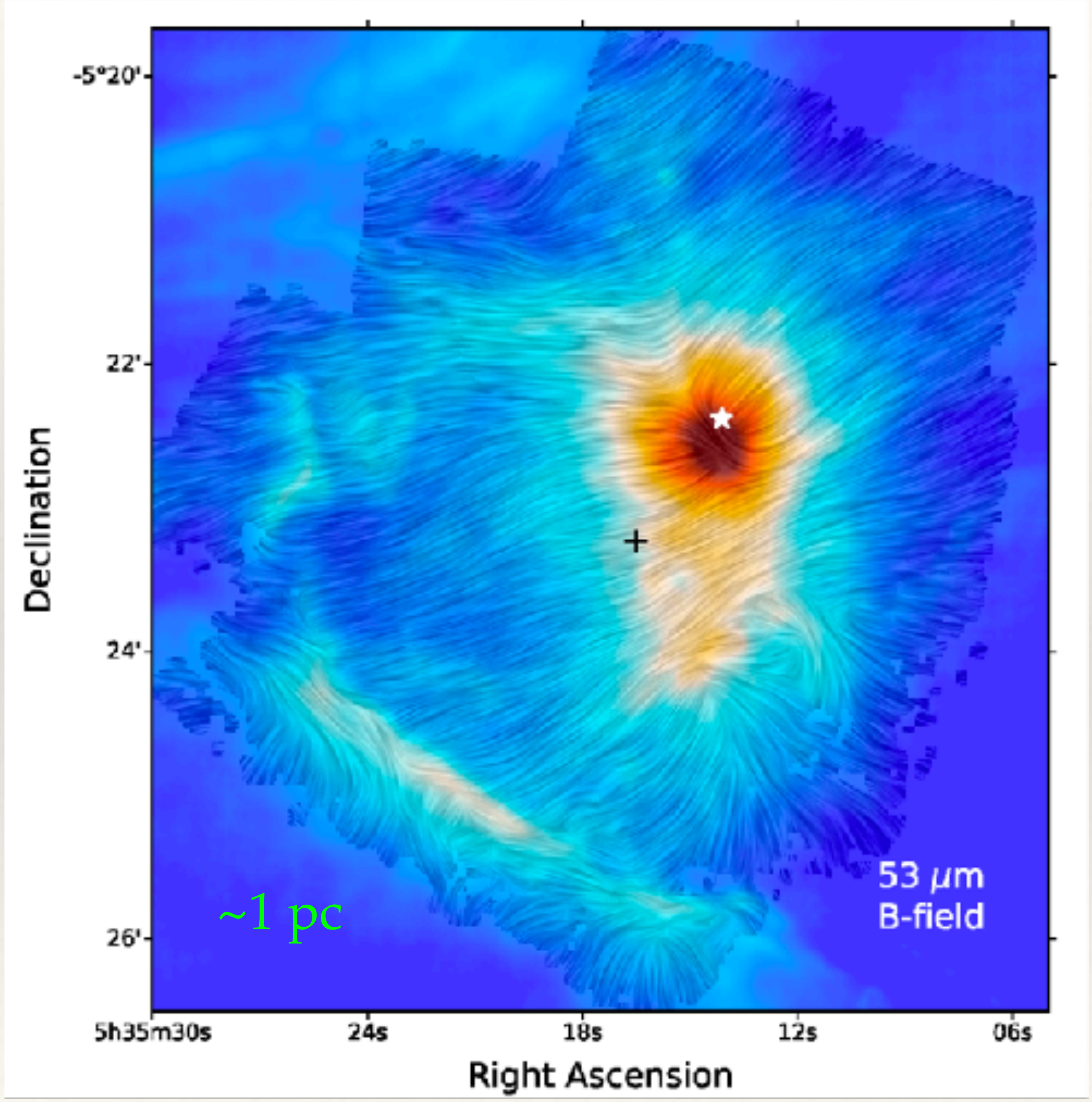
BOSTON UNIVERSITY

Dense ISM Magnetized on all scales



Planck 353 GHz, Soler et al. 2020

Dense ISM Magnetized on all scales



SOFIA HAWC+, Chuss et al. 2019

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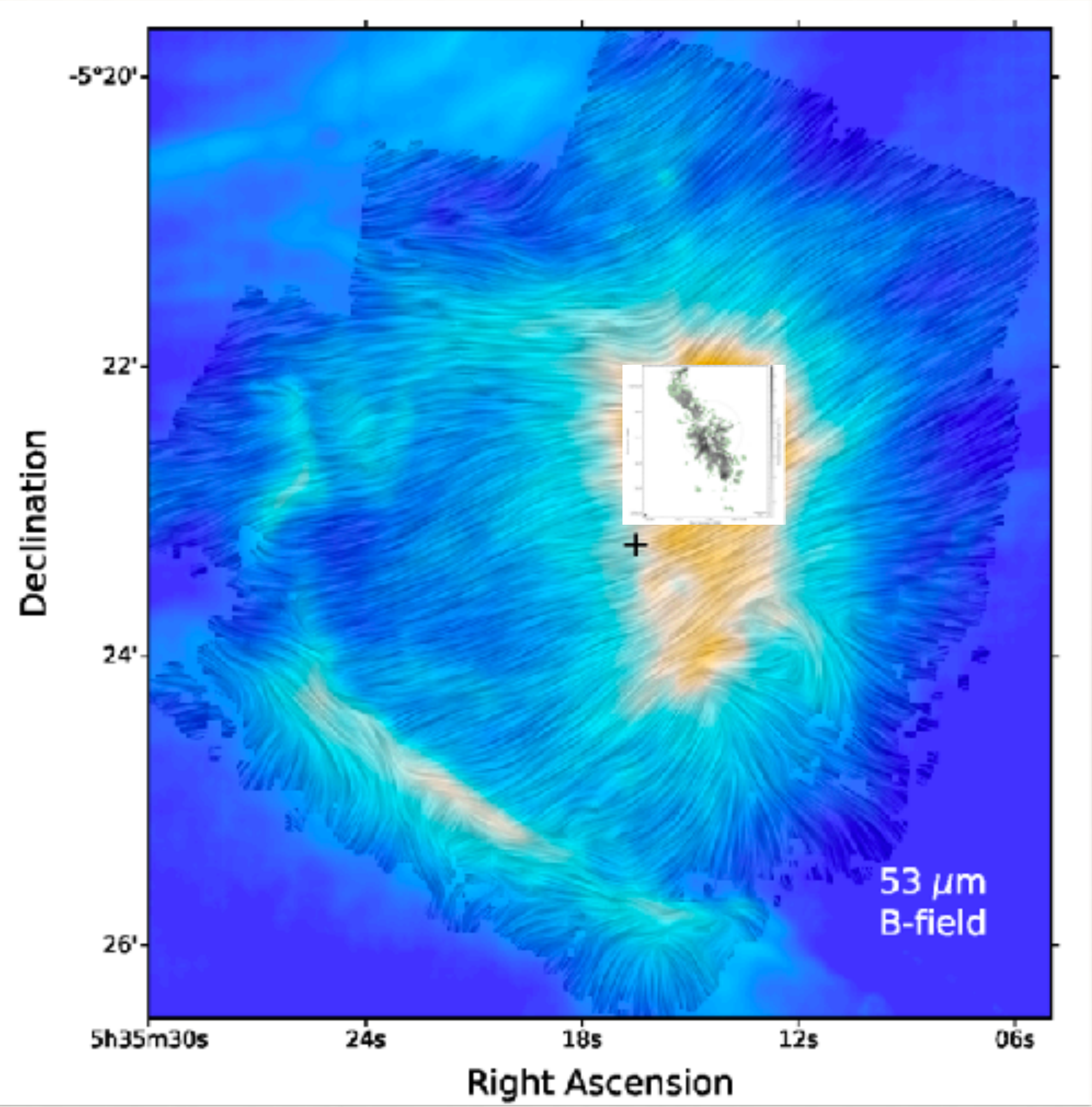

SOFIA HAWC+, Chuss et al. 2019

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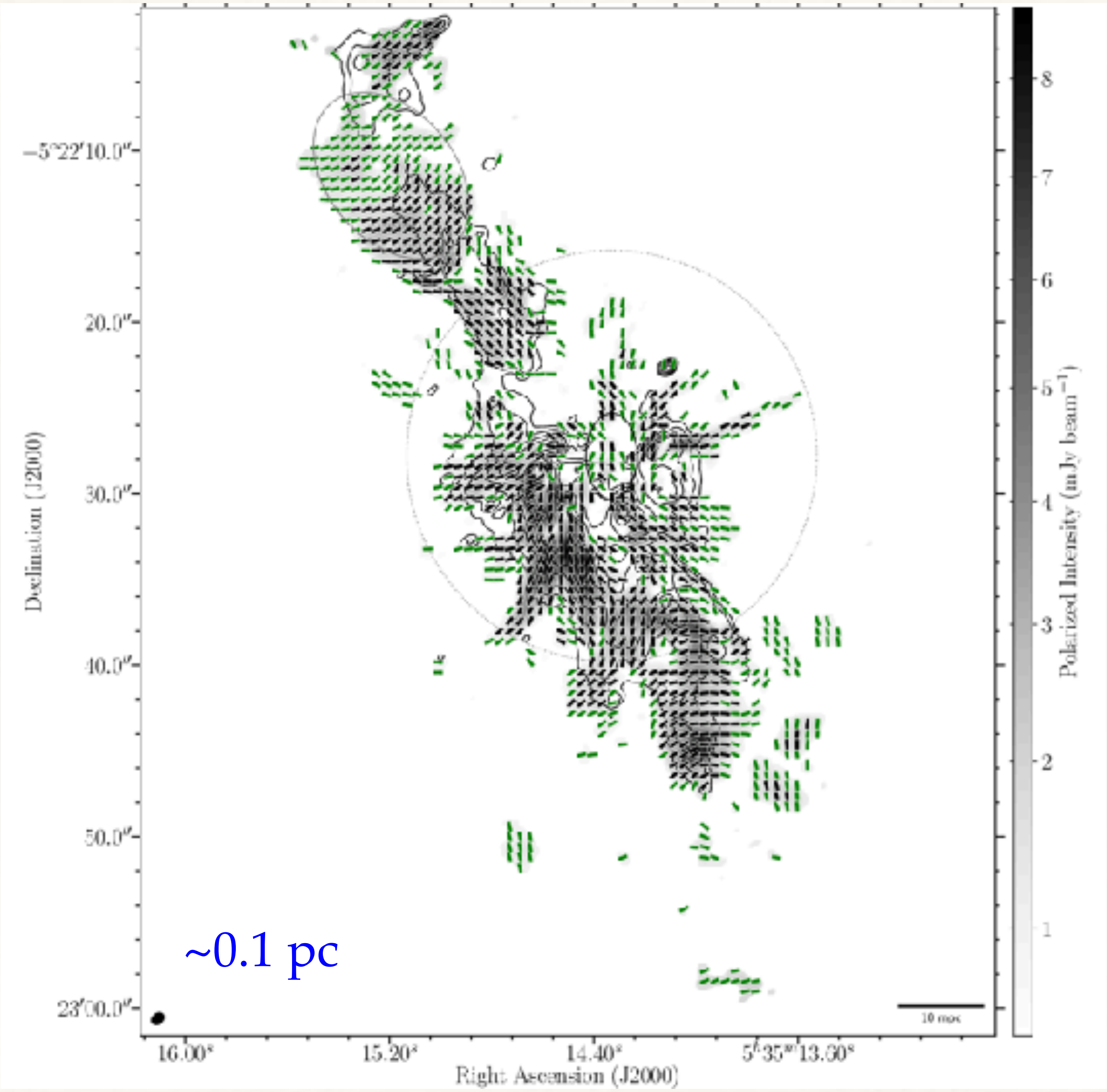


ALMA 1mm, Cortes et al. 2021

Tools & Techniques

near-IR extinction
(diffuse gas)

far-IR emission
(envelope and cores)

sub-mm emission
(dense gas)

λ →

Tools & Techniques

Dust grains in molecular clouds become aligned with their major axes preferentially oriented perpendicular to the magnetic field most likely through radiative torques (Lazarian 2007, Andersson, Lazarian, Vaillancourt ARAA 2015)

Wavelength	Method	Facility	Resolution
1-2 μm	extincted starlight	MIMIR/Perkins IAGPOL/PdD SIRPOL/IRSF	Pencil beam
217 μm	dust continuum	SOFIA/HAWC+	19”
870 μm	dust continuum	APEX, JCMT, CSO	10-18”
1mm/870 μm	dust continuum	SMA, ALMA	<2”

Pattle & Fissel 2019 for an observation overview

Recipe for Star Formation

Gravity vs. Magnetic Field:

$$\mu = \frac{(M/\phi_B)}{(M/\phi_B)_{cr}}$$

mass–to–flux ratio

$\mu > 1$ => gravity dominates

"Turbulence" vs. Magnetic Field:

$$M_A = 3^{1/2} \frac{\sigma_v}{\sigma_A} = (P_{gas}/P_B)^{1/2}$$

Alfven Mach number

$M_A > 1$ => turbulence dominates

Analysis of Polarized Dust Emission

Chandrasekhar-Fermi formula:

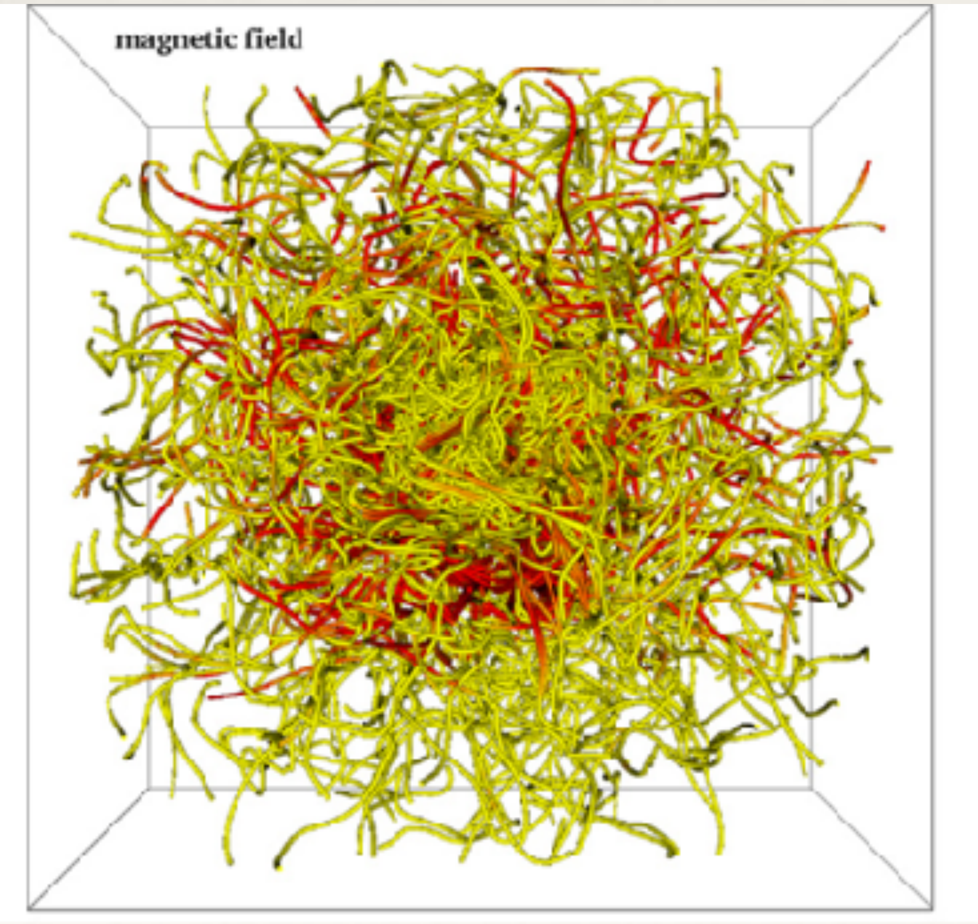
$$\sigma_\phi \propto \frac{\rho^{1/2}\sigma_v}{B_{pos}}$$

Kinetic Energy

Straightness of field lines

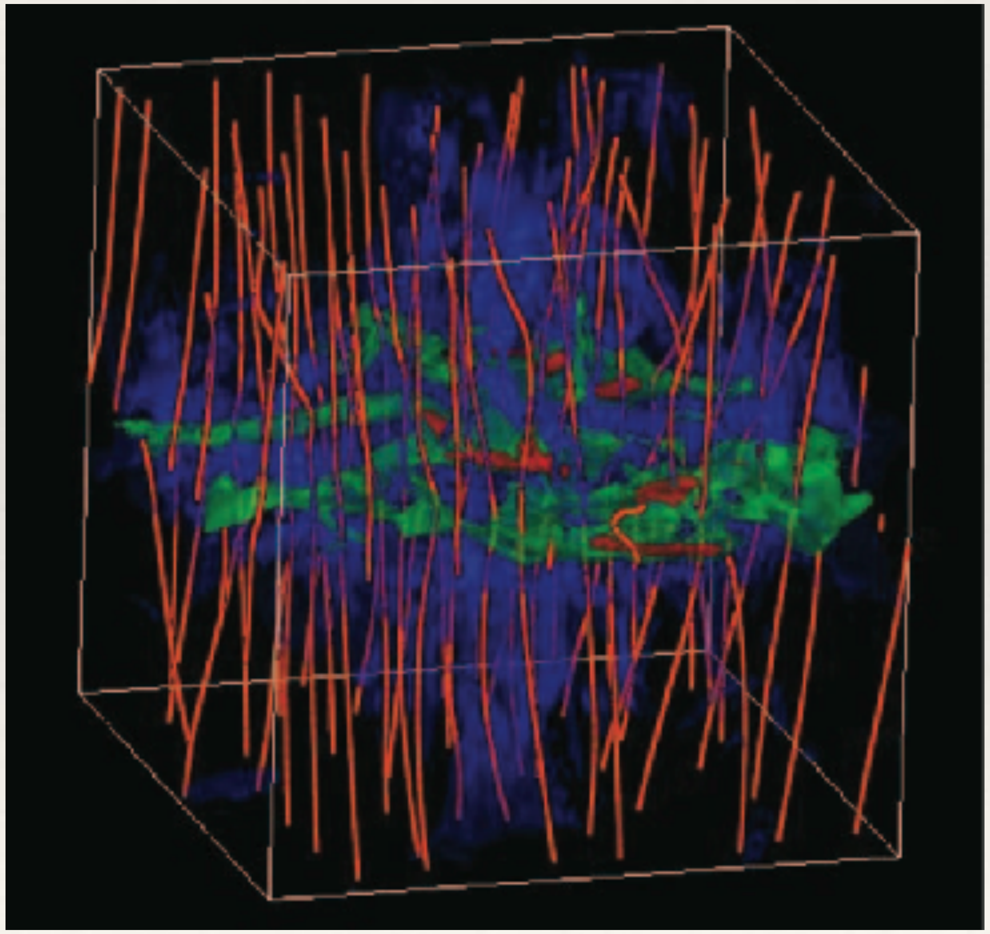
Magnetic Energy

Weak Field



Federrath. 2011

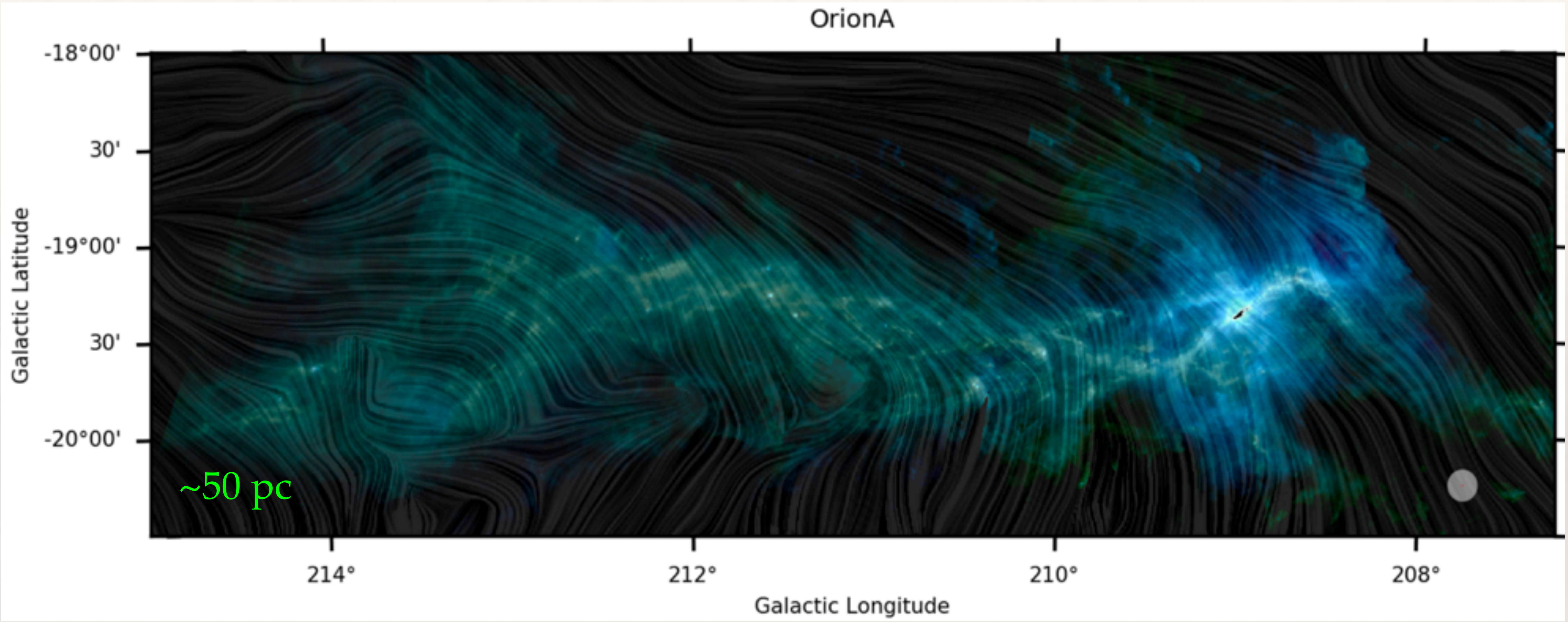
Strong Field



Nakamura & Li 2008

Giant Molecular Clouds

Cloud Structure and Magnetic Fields

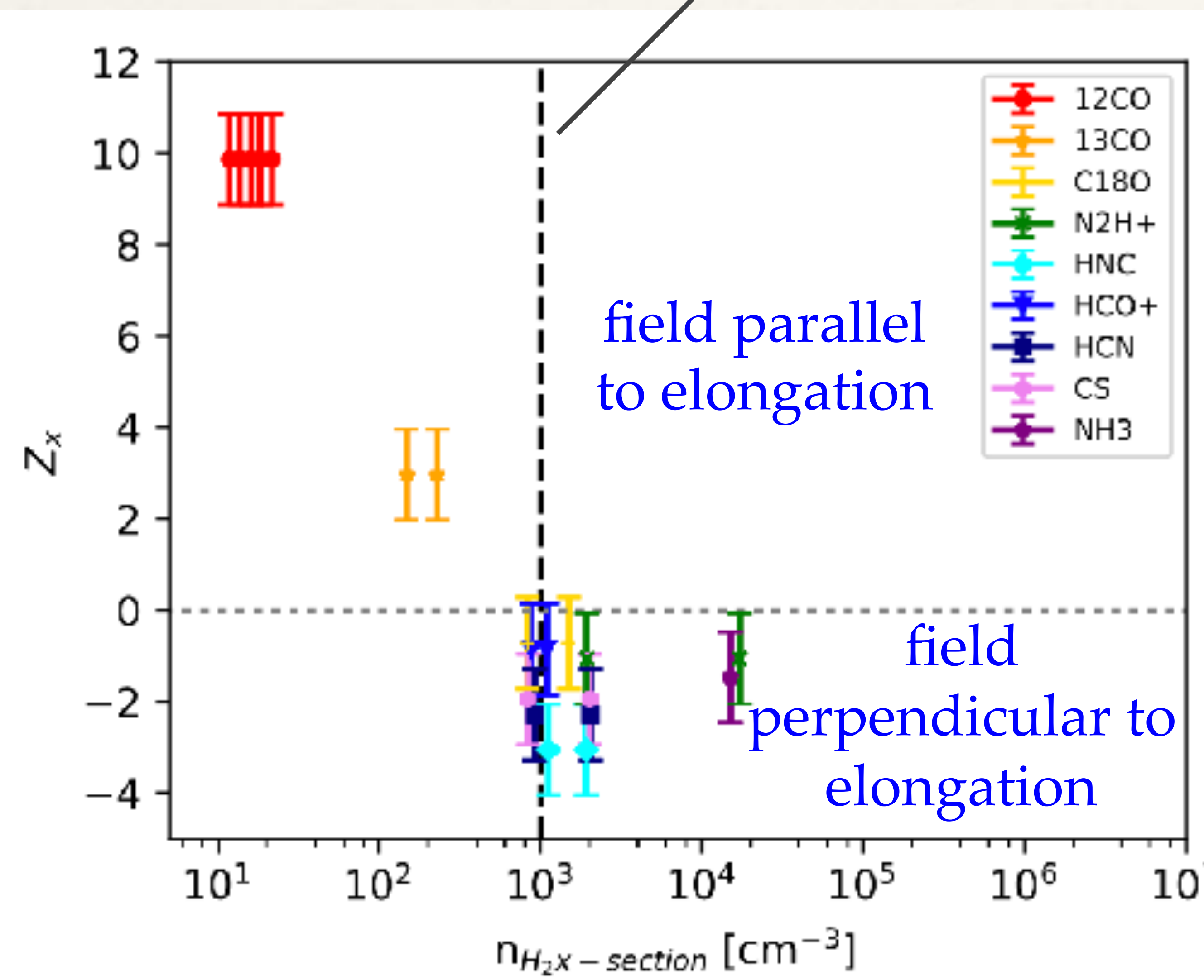


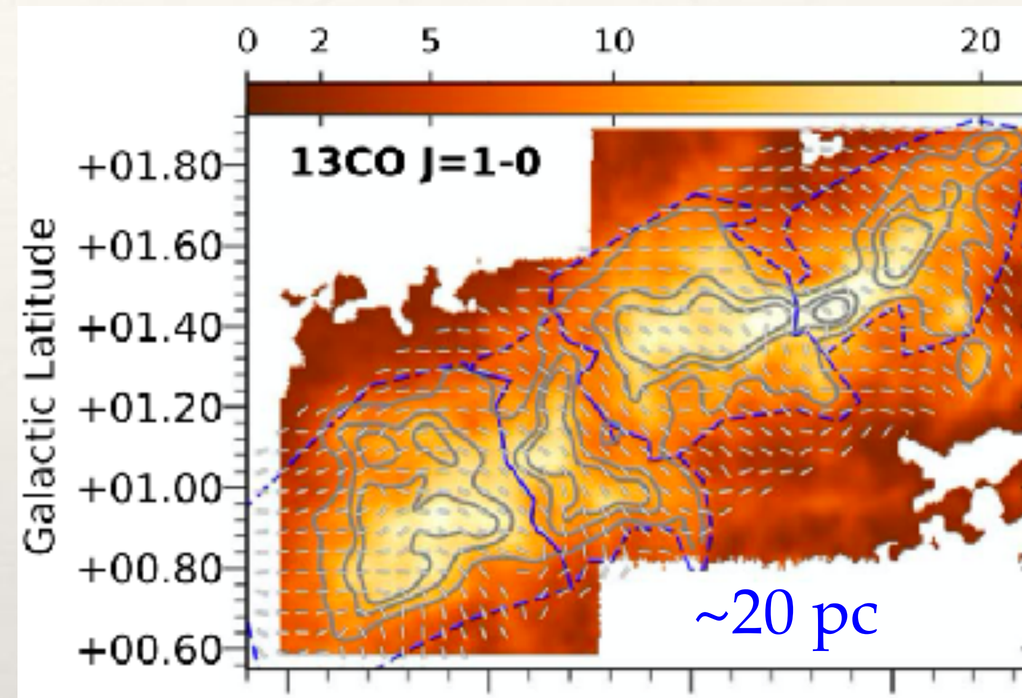
PlanckXXXV, Soler et al. 2020

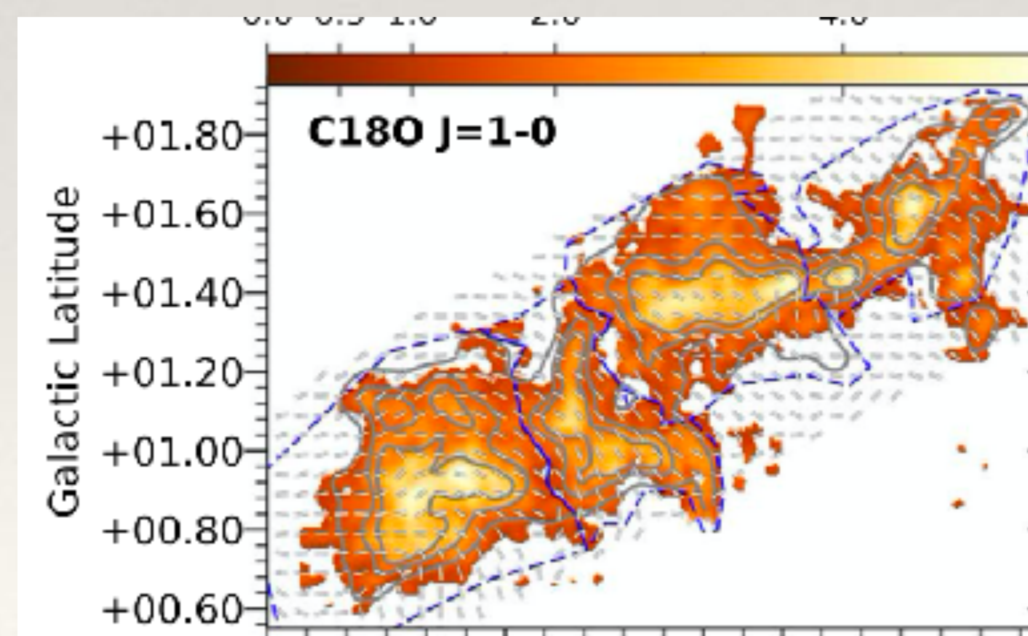
"mean relative orientation between N_H and $B_\perp$ toward these regions increases progressively from 0°, where the N_H structures lie mostly parallel to $B_\perp$, with increasing N_H, in many cases reaching 90°, where the N_H structures lie mostly perpendicular to $B_\perp$"

Relation to Gas Volume Density

transition density of 10^3 cm^{-3}

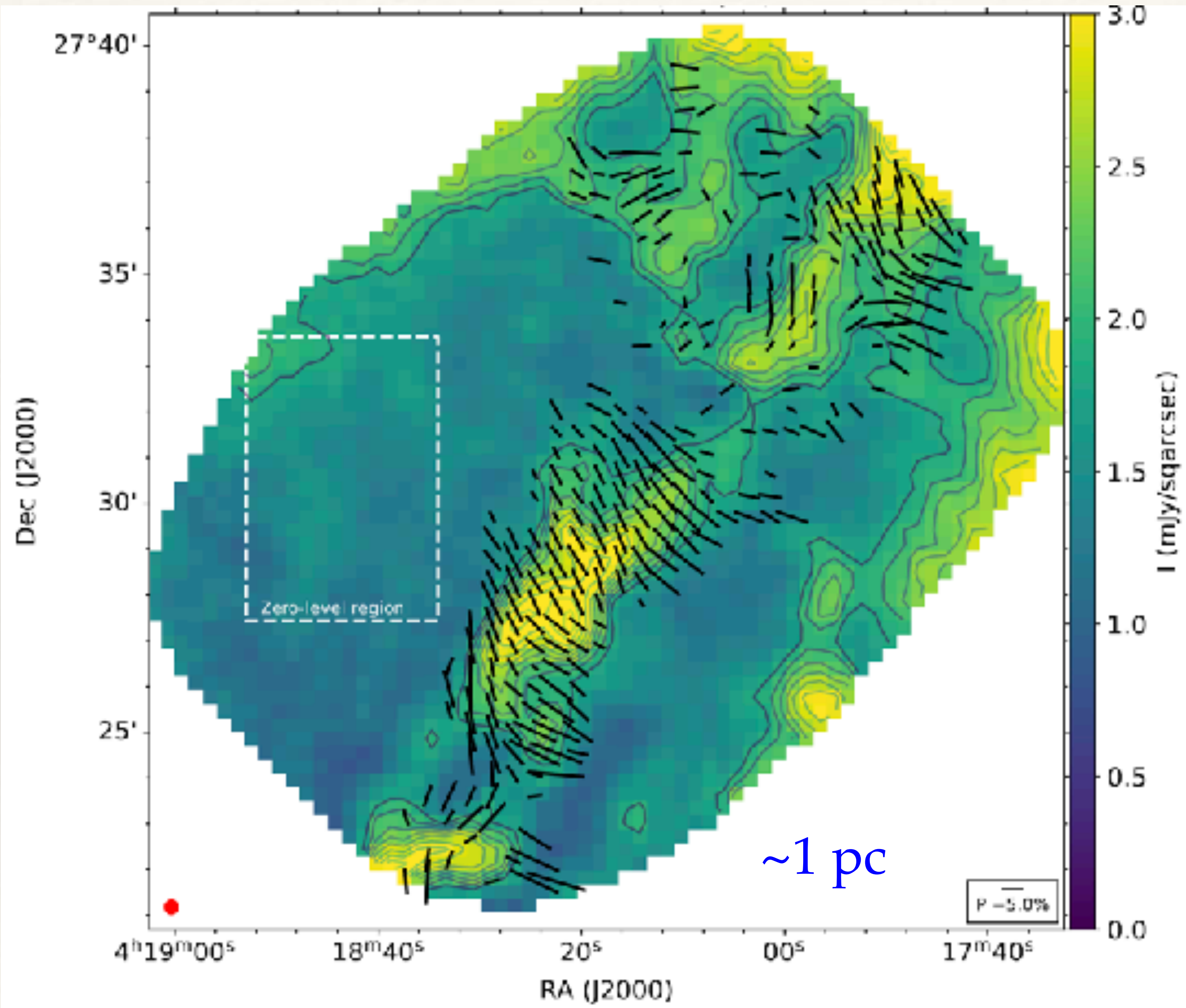


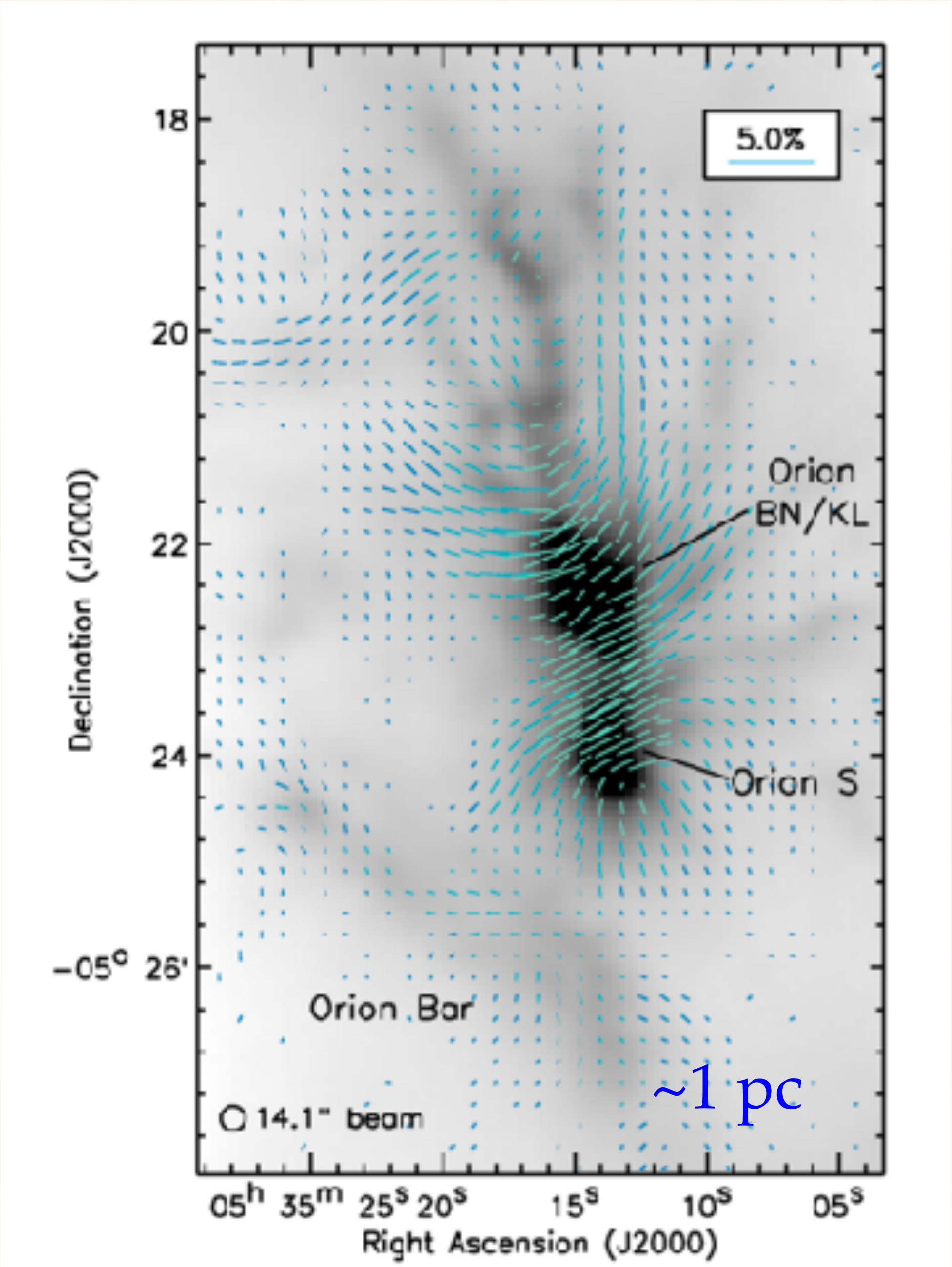




Fissel et al. 2019. See also Alina et al. 2019 for clump scale analysis

Zooming into Dense Filaments within GMCs

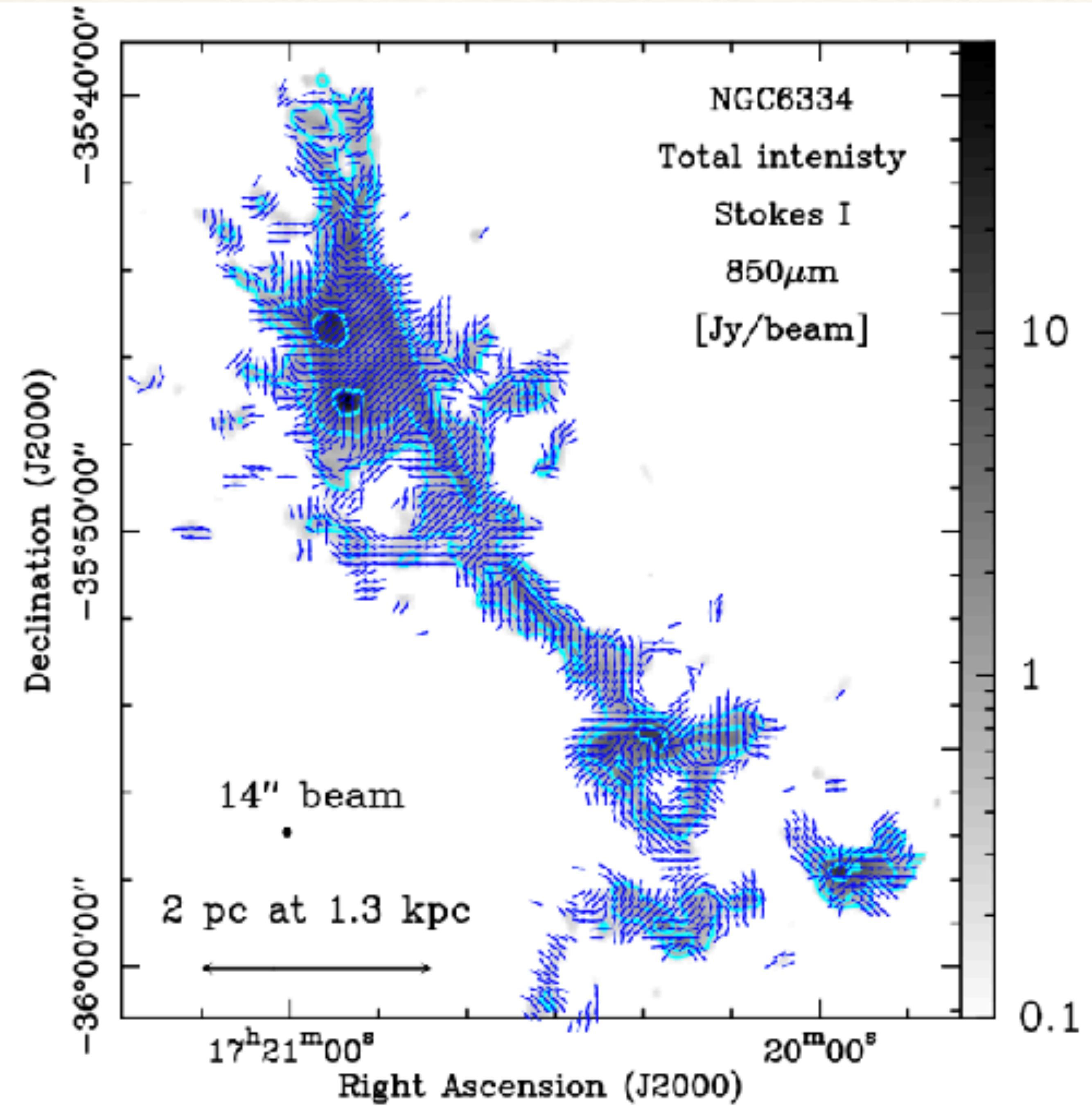




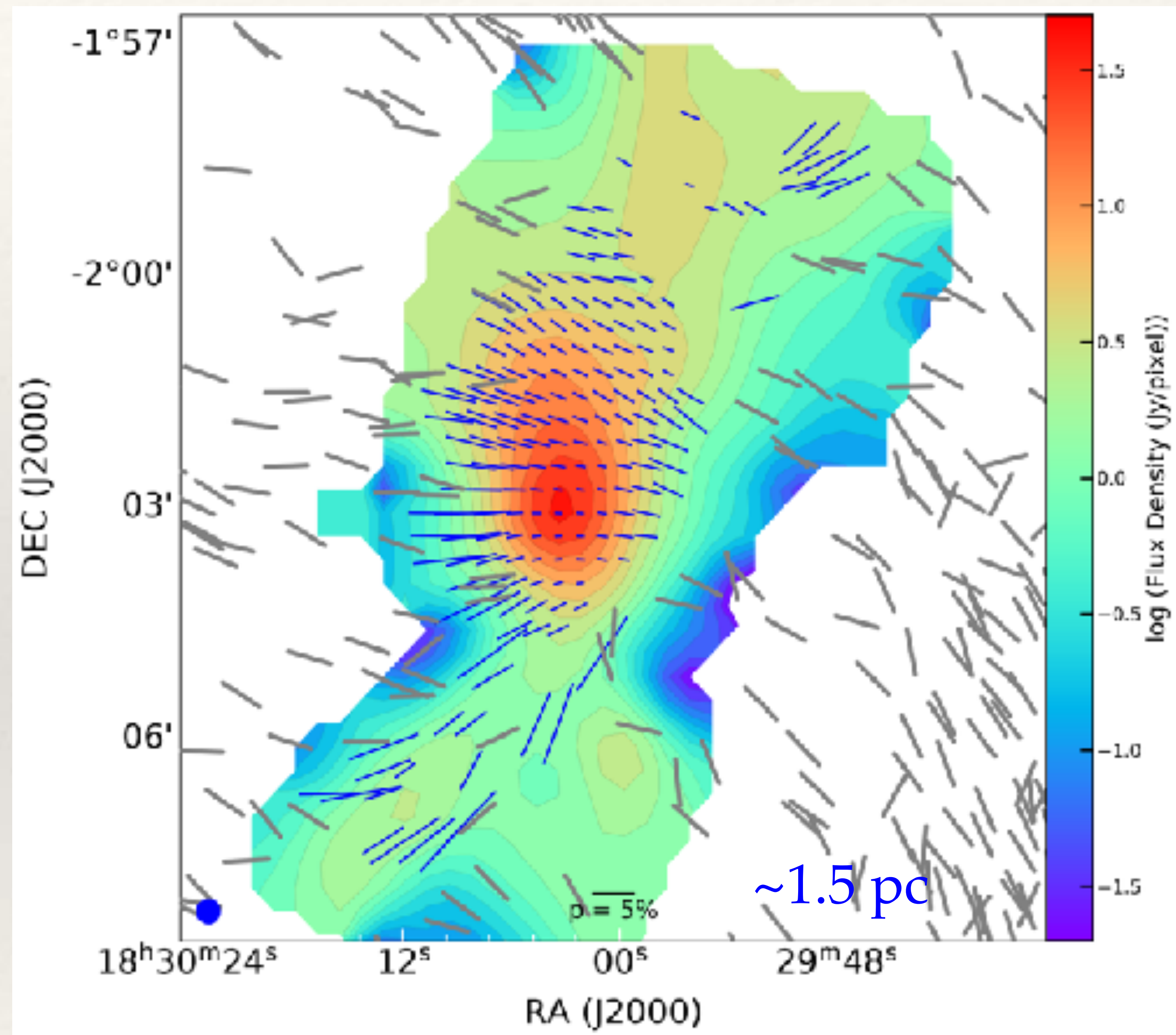
HAWC+ Band E, Li et al. 2021

POL2, Pattle et al. 2017

Zooming into Dense Filaments within GMCs

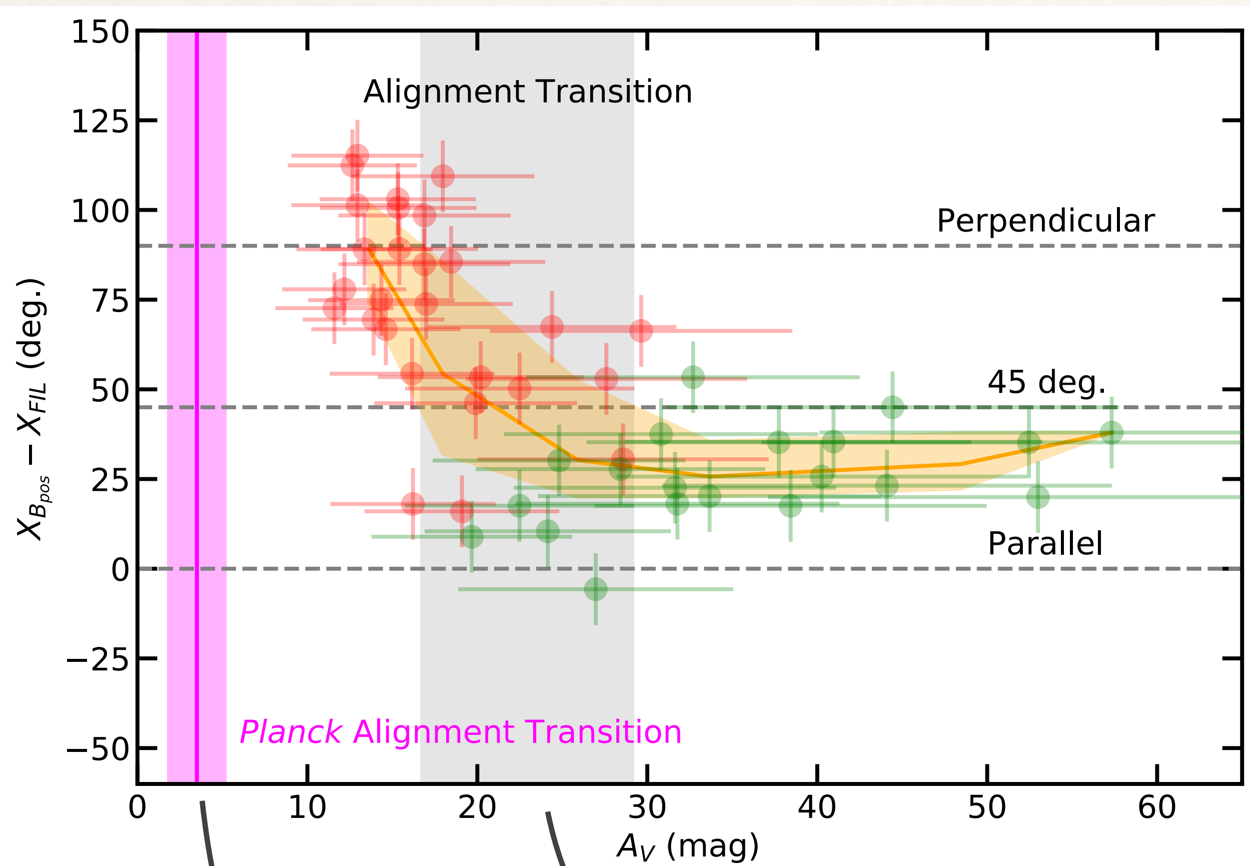


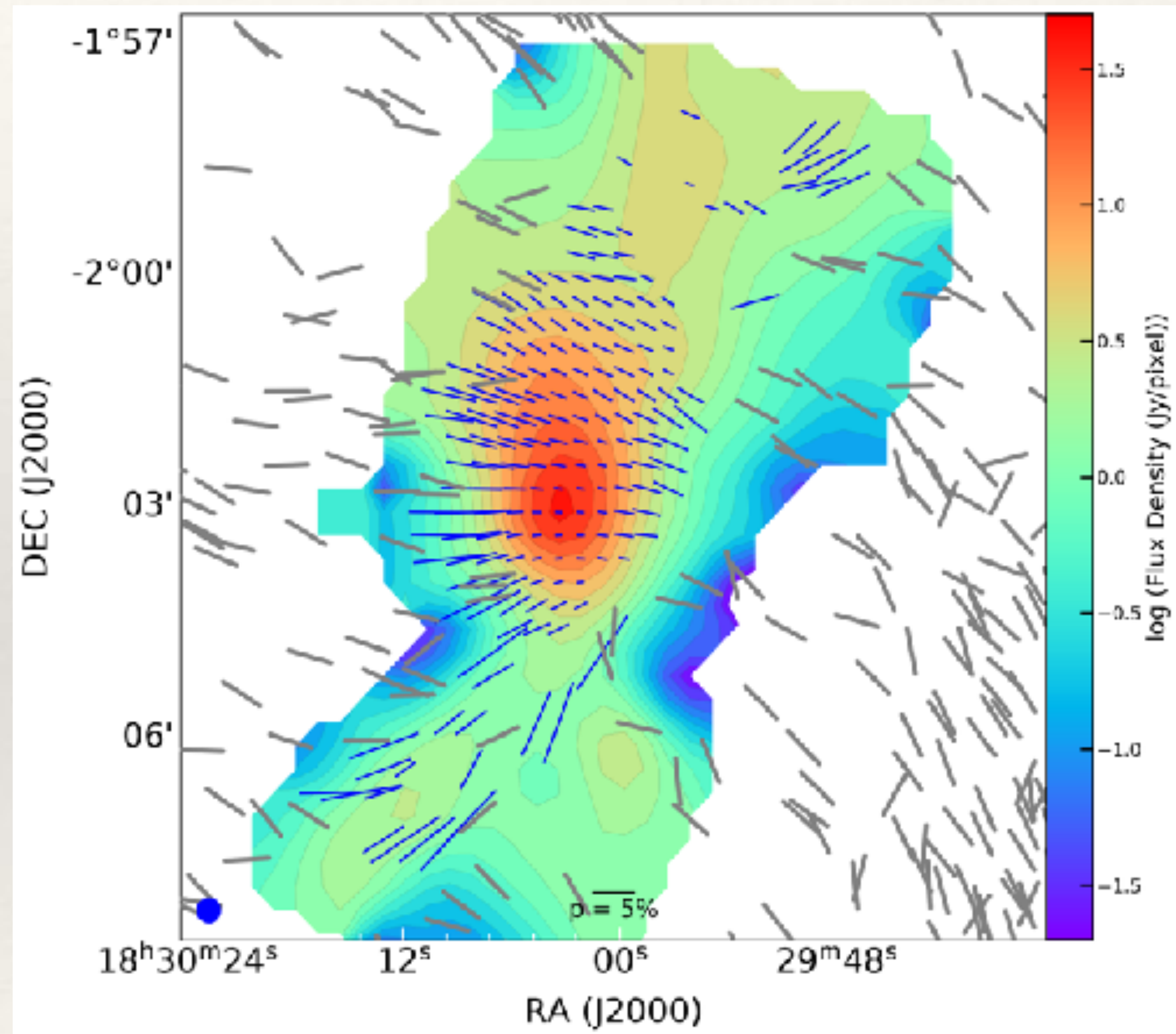
Arzoumanian et al. 2021



Pillai et al. 2020

Alignment Transition





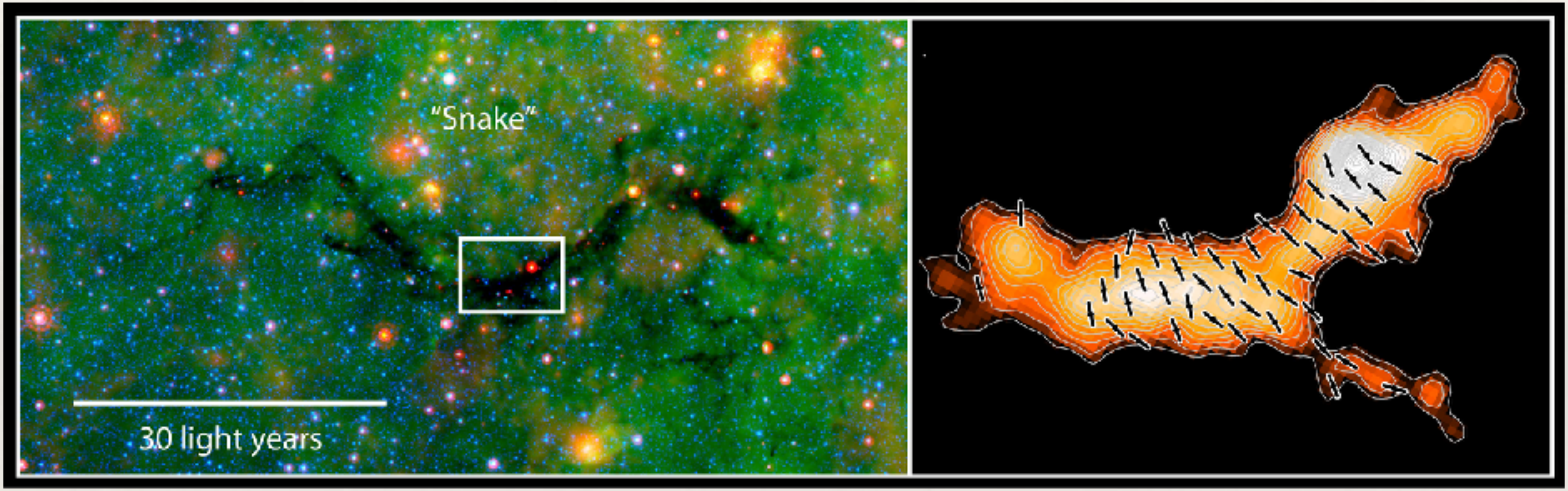
known transition
at low density

new transition
at high density

Pillai et al. 2020

Infrared Dark Clouds

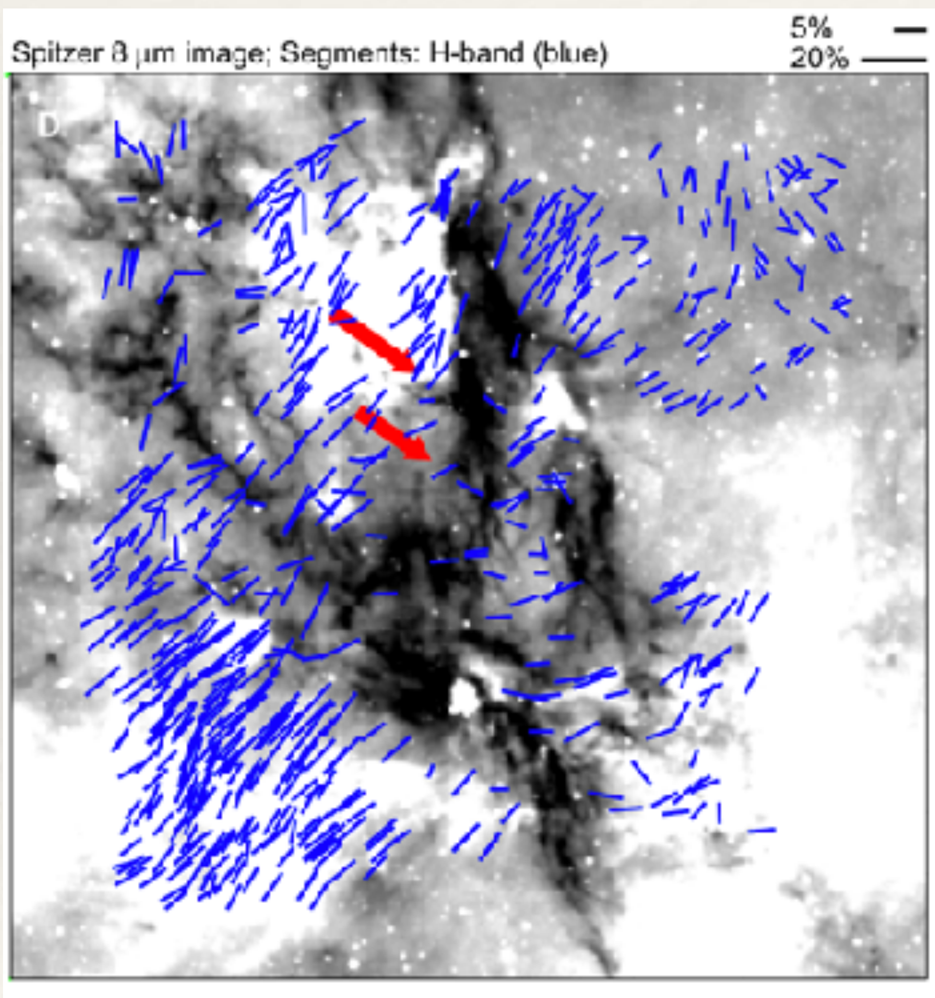
more massive molecular clouds, more representative of galactic SF



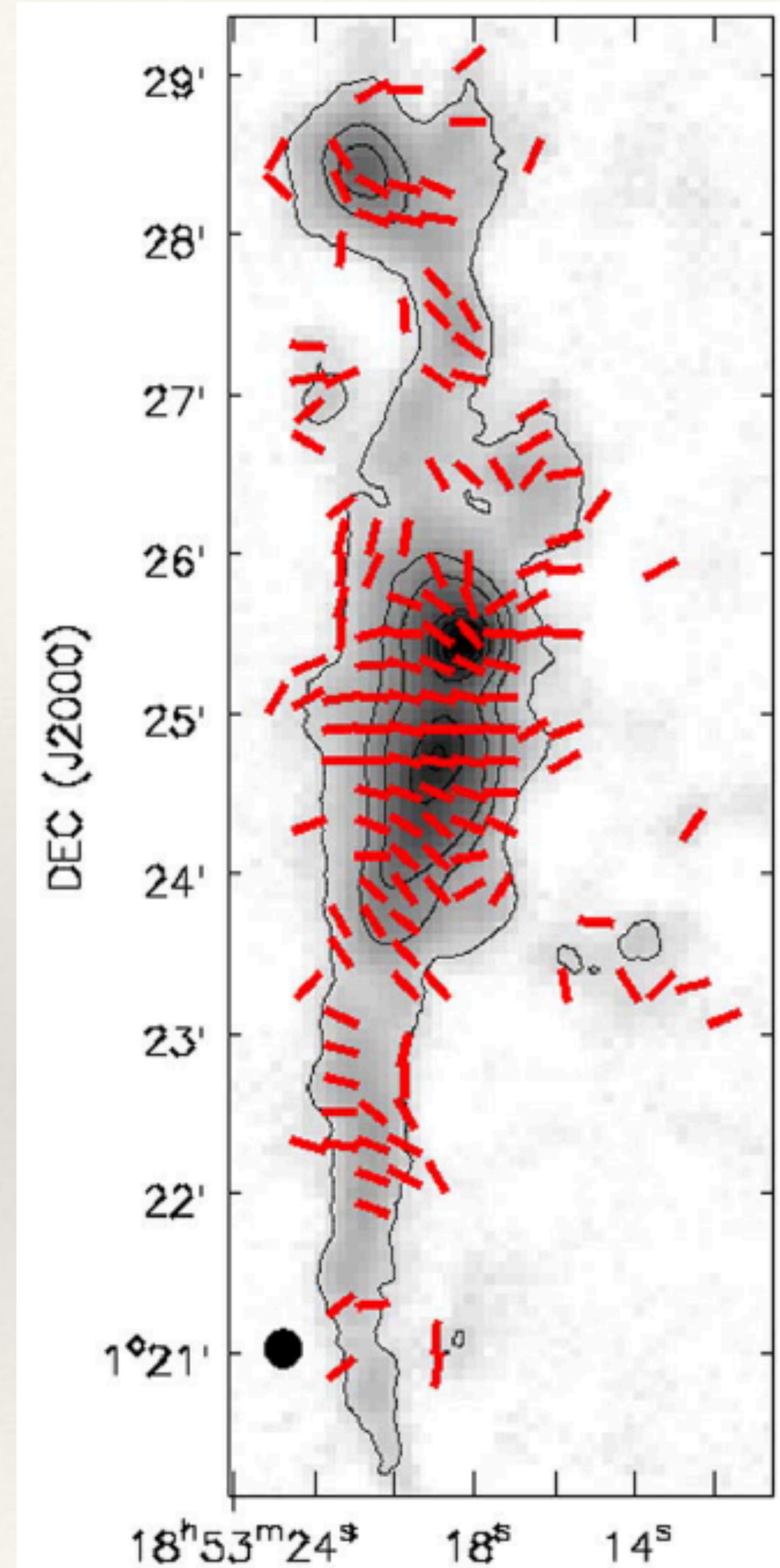
Pillai et al. 2015

small angular extent => cannot use Planck

general observation:
magnetic field oriented perpendicular to filaments

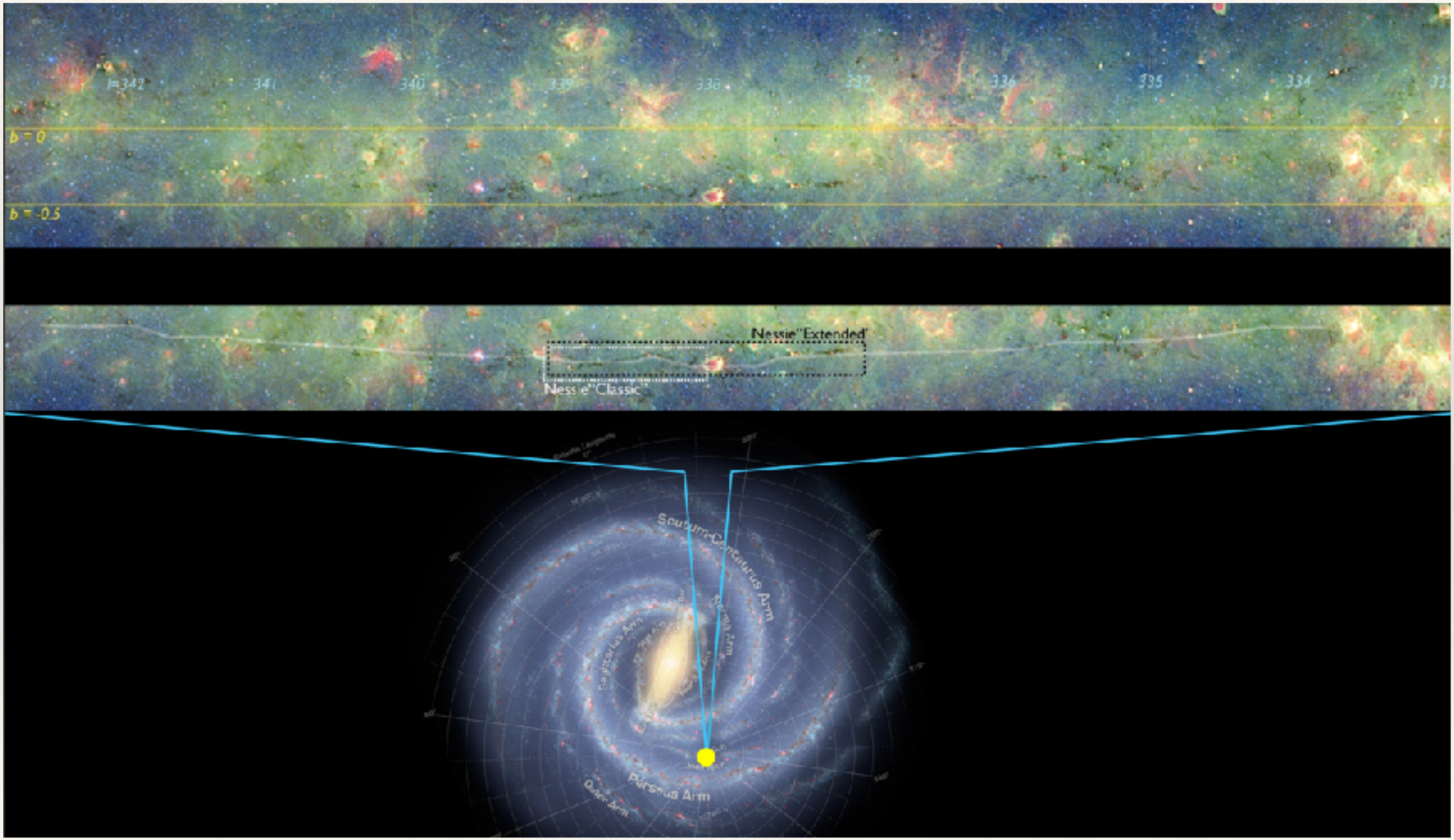


Santos et al. 2016



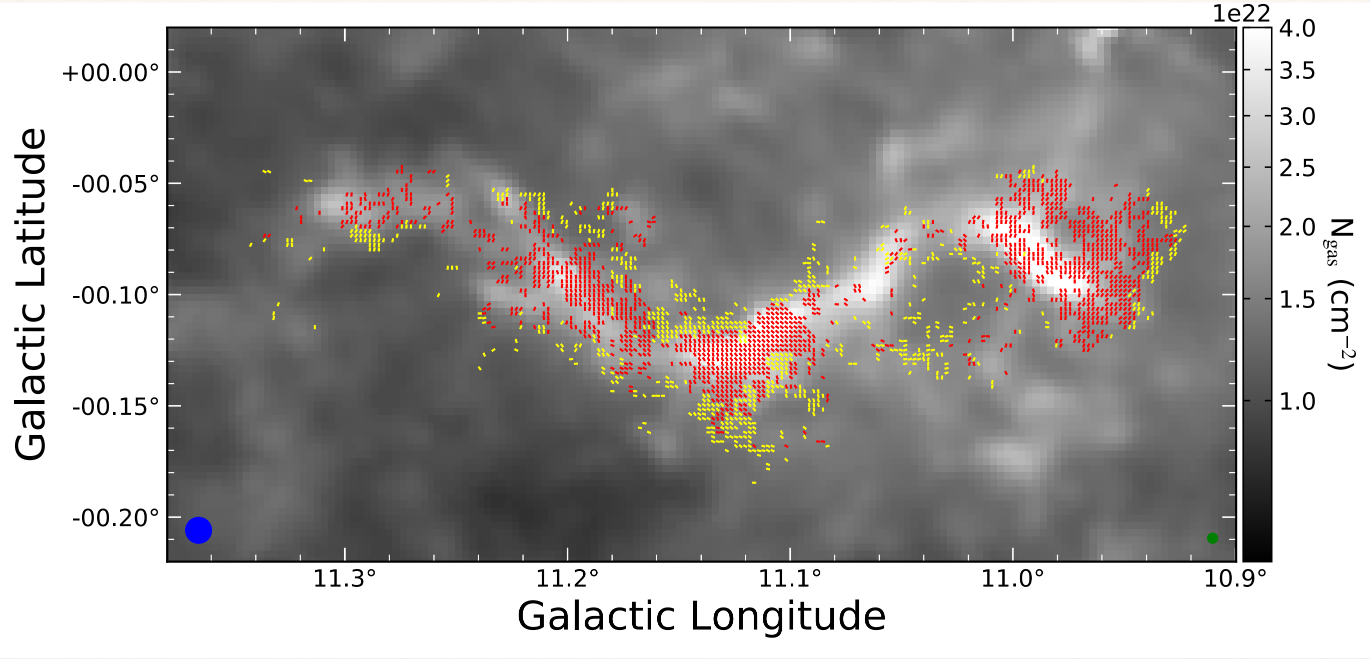
Soam et al. 2019

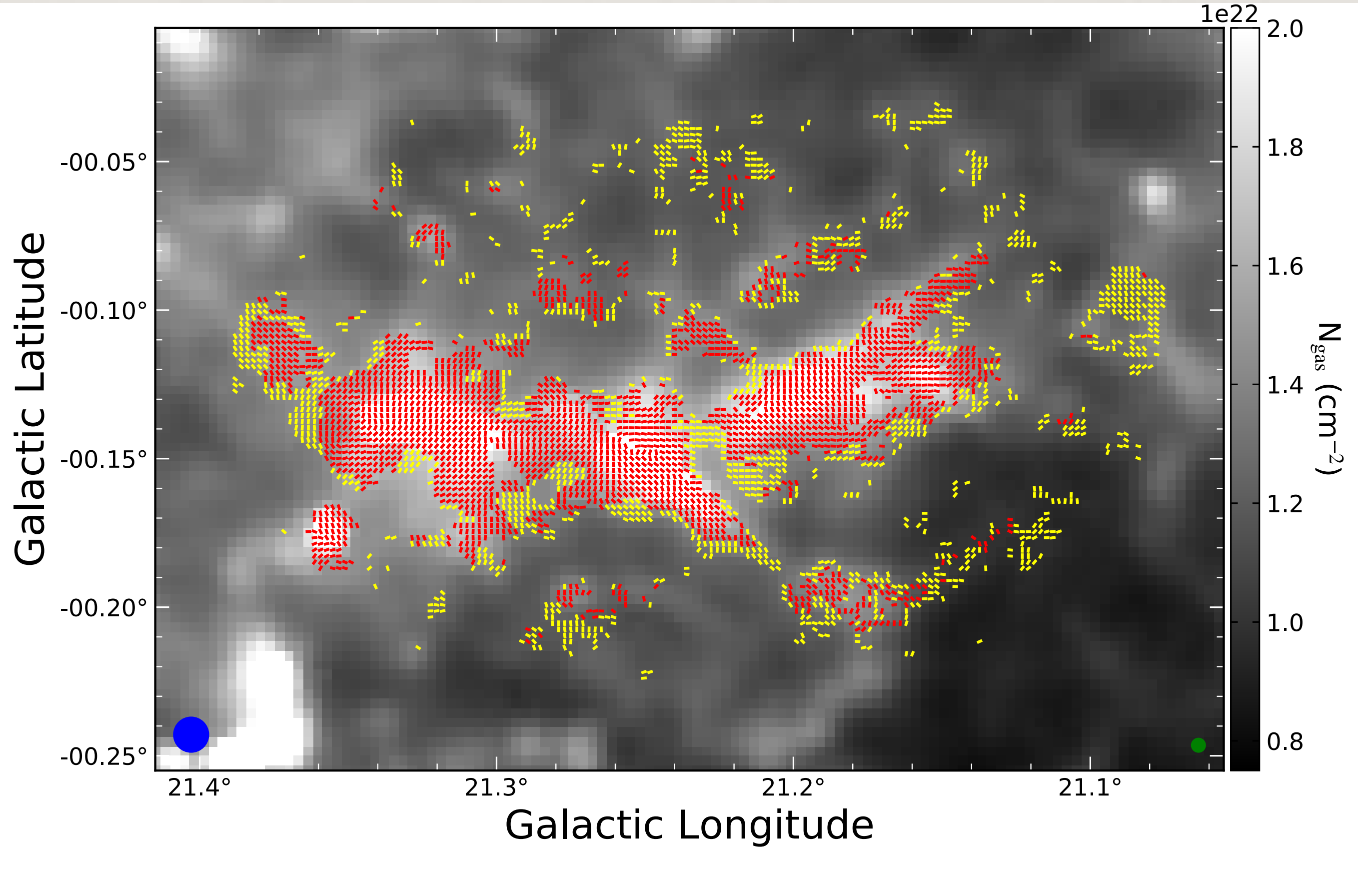
Even more Extreme IRDCs: Galactic Bones



Jackson et al. 2010, Goodman et al. 2014

SOFIA HAWC+: FIELDMAP Survey



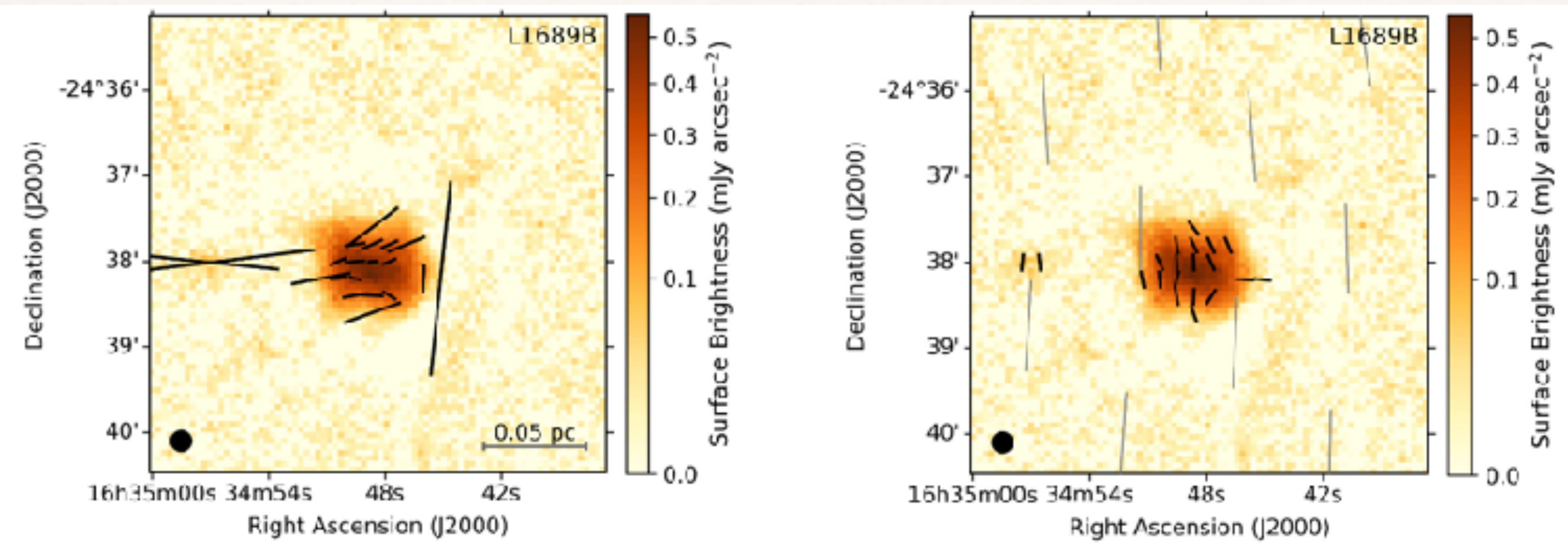


about a dozen Galactic Bones

Stephens et al. 2022

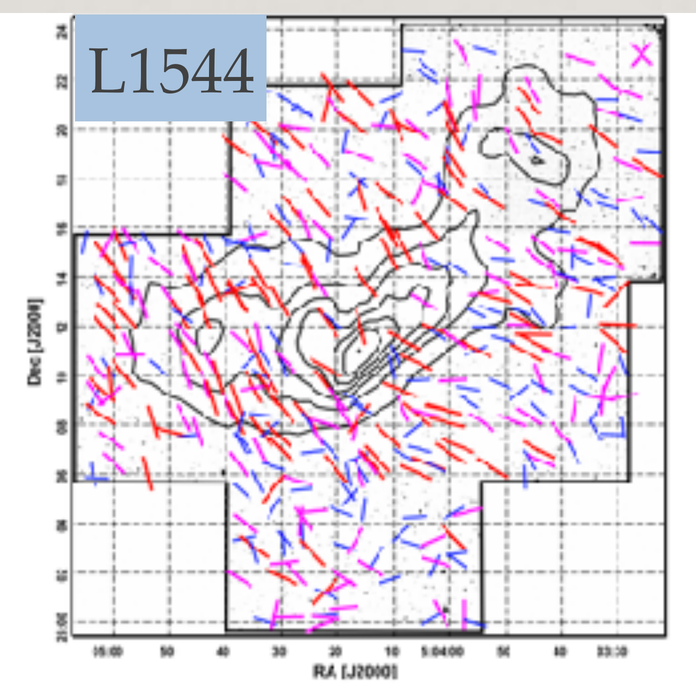
Dense Cores

Low-Mass Prestellar Cores



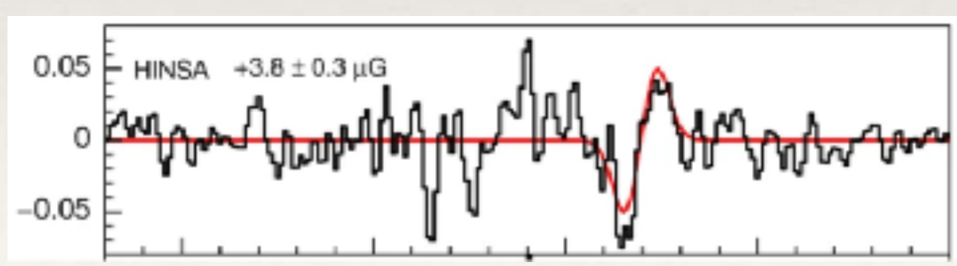
Pattle et al. 2021

μ~1



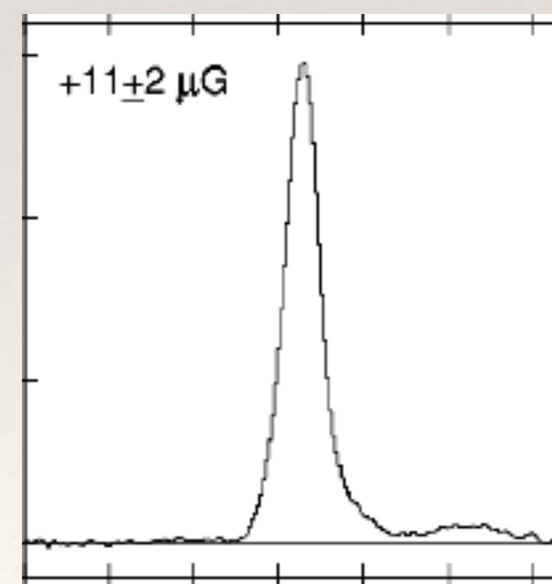
Clemens et al. 2016

L1544 Envelope, HI, μ ~ 3.5



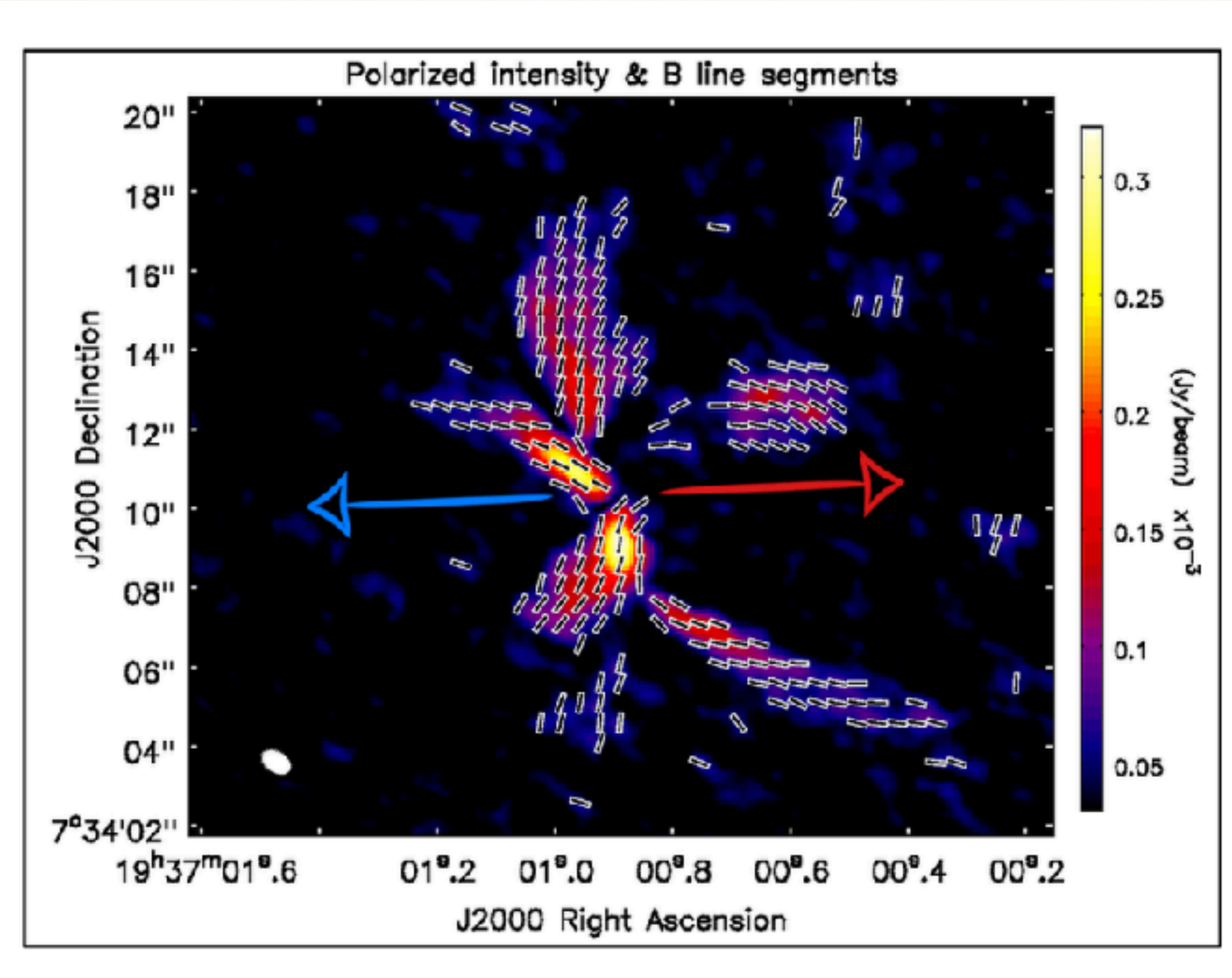
Ching et al. 2022

L1544 Core, OH



Crutcher et al. 2009

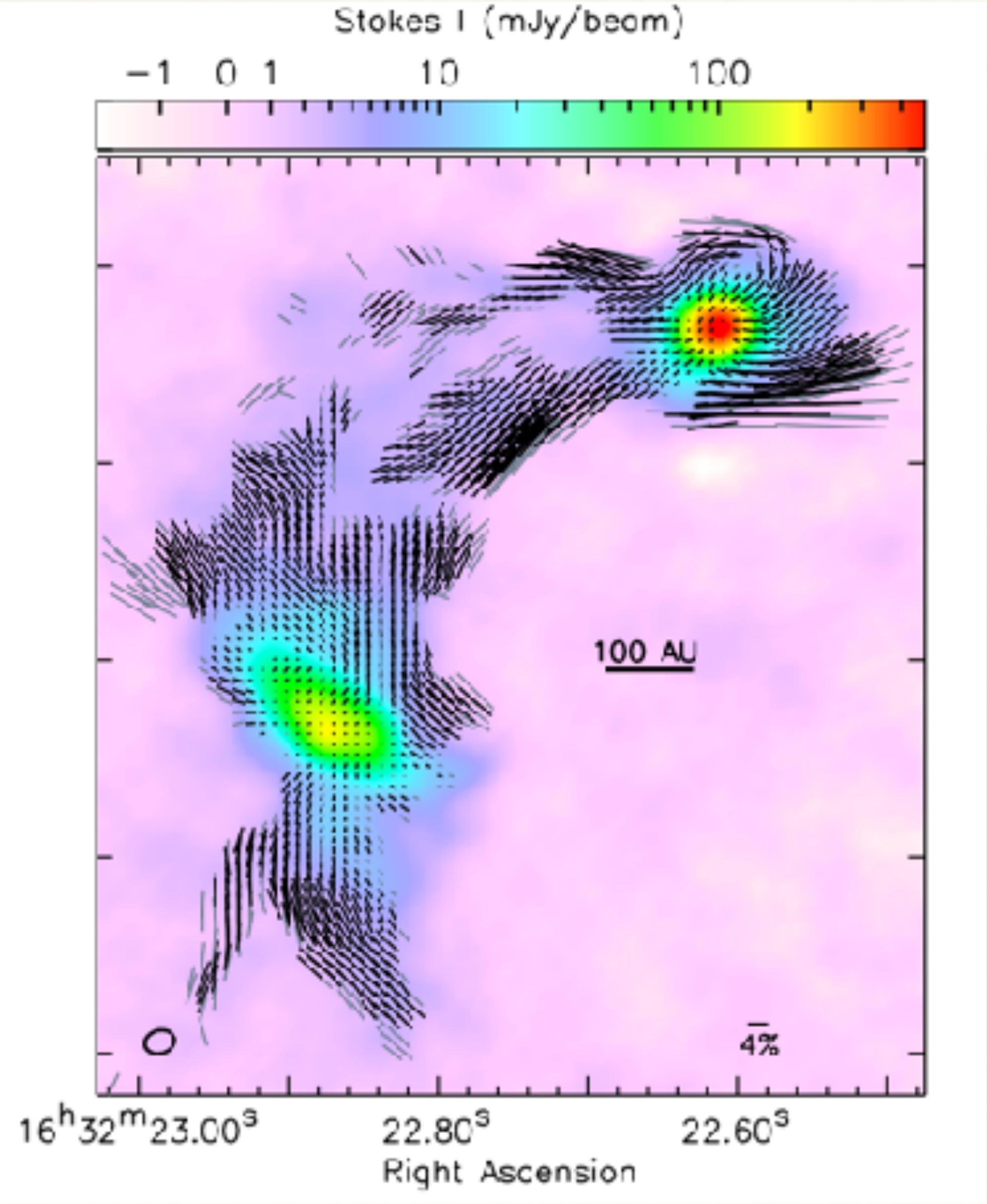
Protostellar Cores

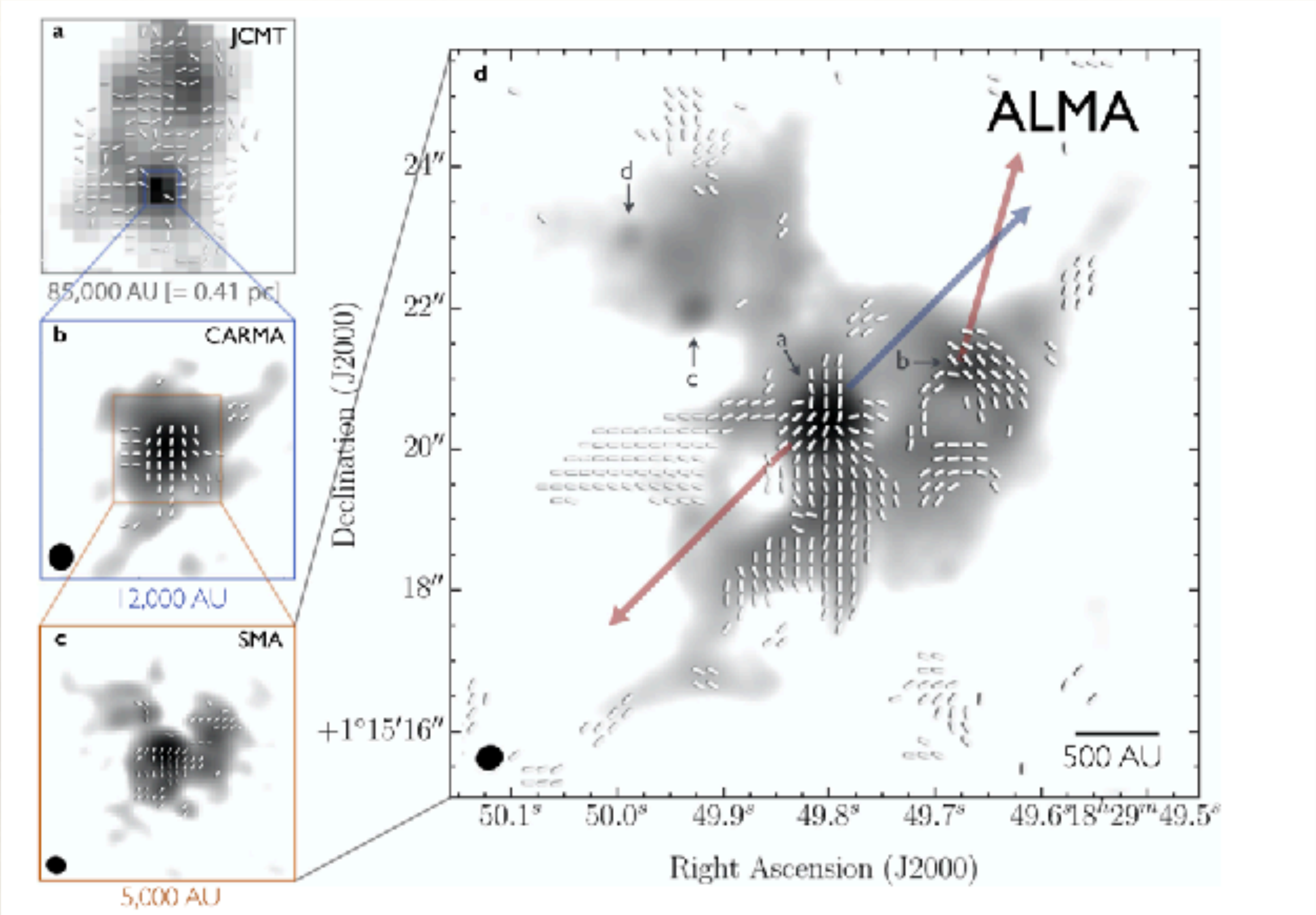


structure resembles pinched magnetic field

Maury et al. 2018. See also Girart et al. 2006

More complex systems as well

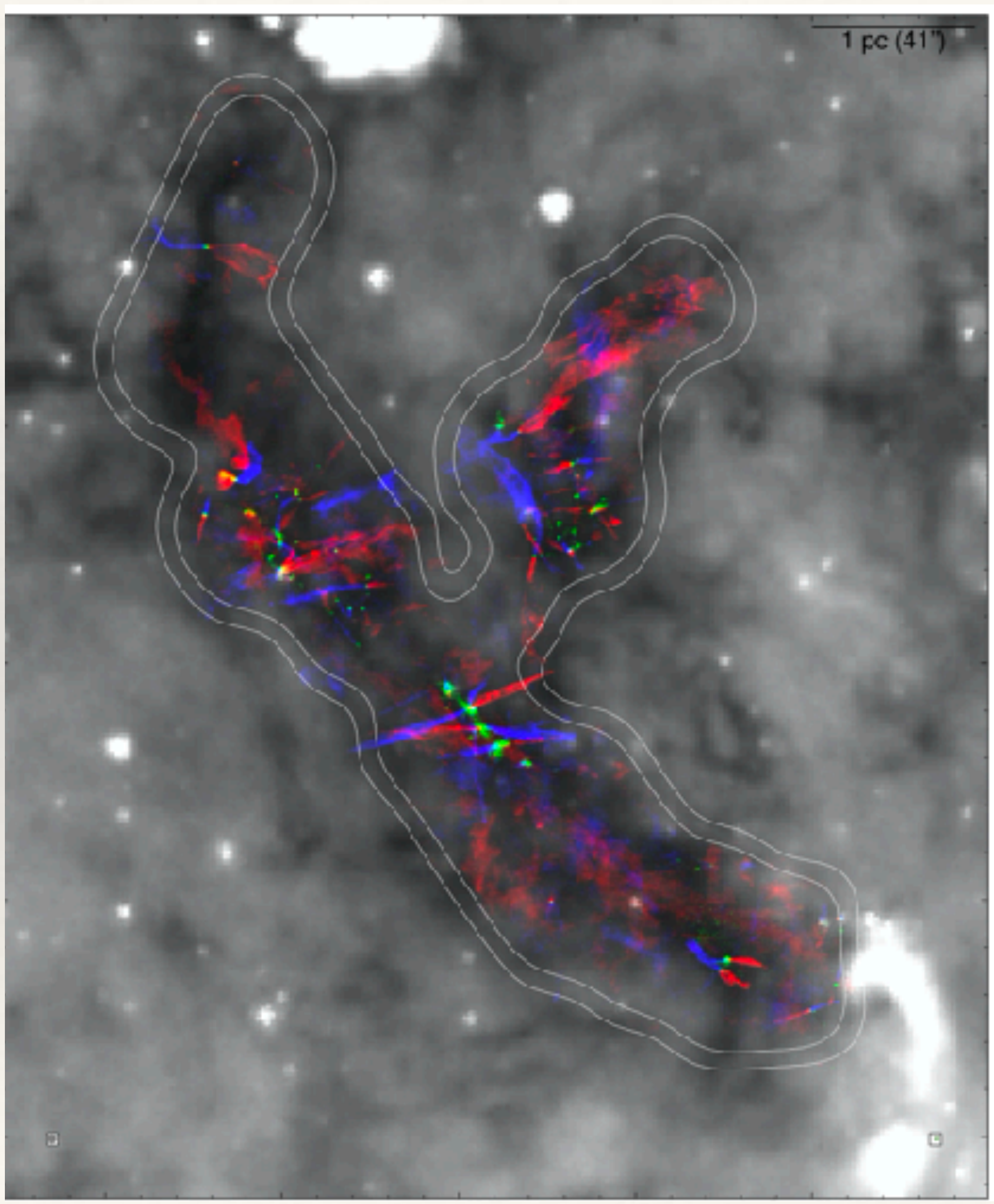


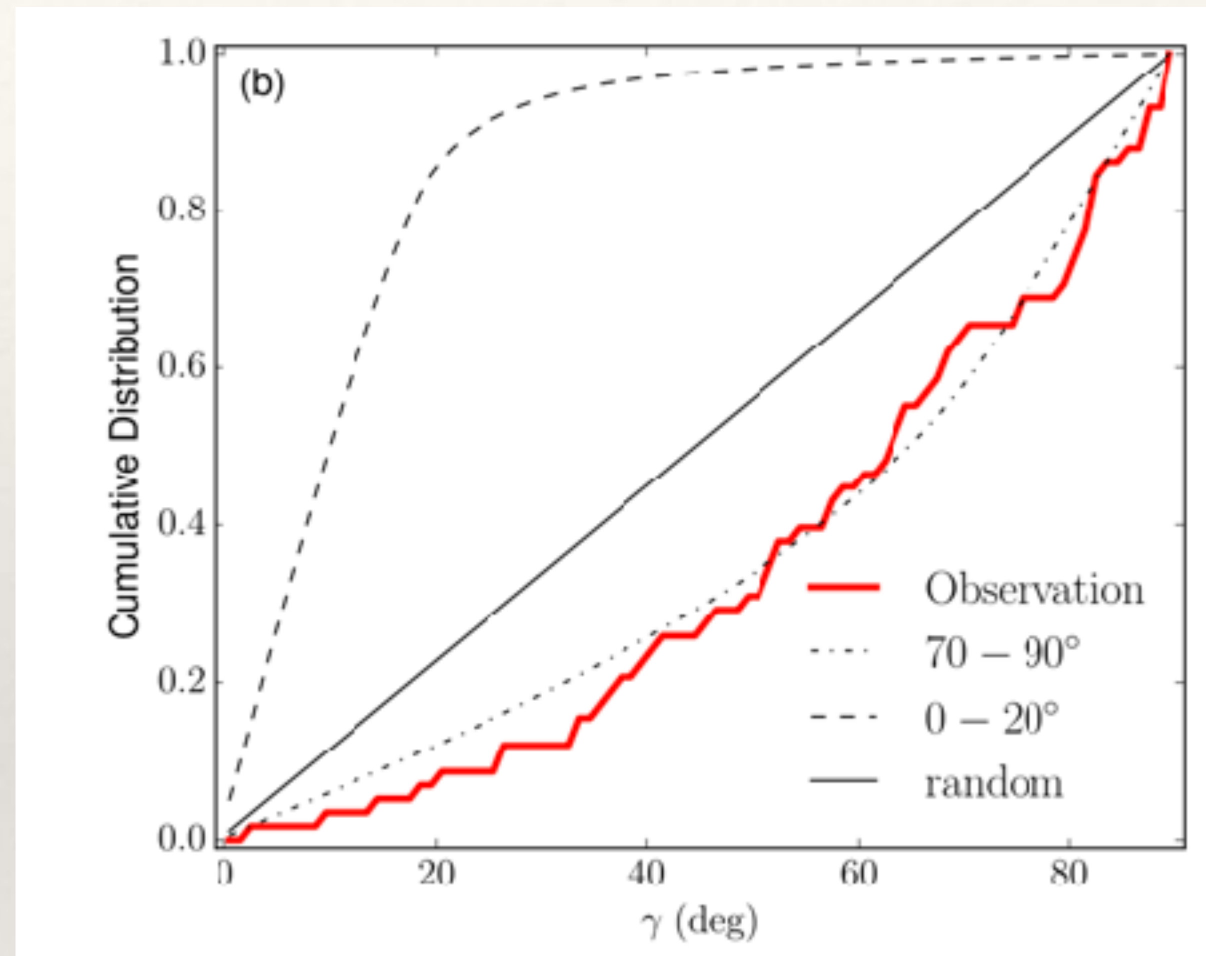


Sadavoy et al. 2019

Hull et al. 2017

High-Mass Cores



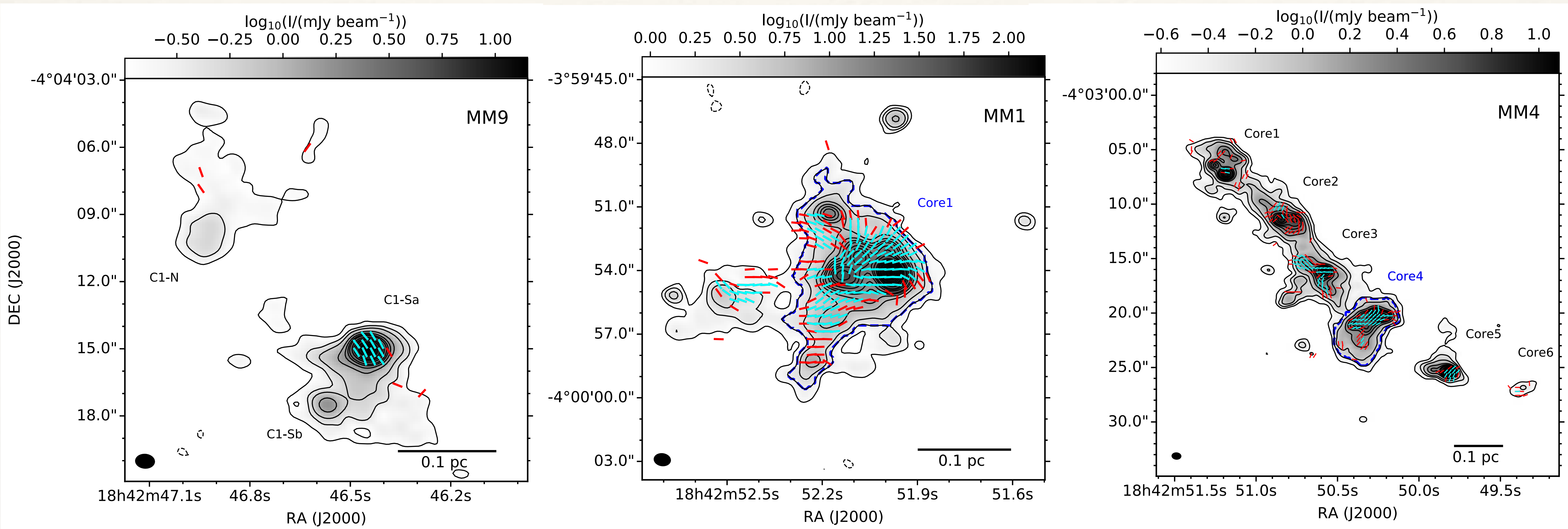


Shuo Kong et al. 2019

results:

- most outflows orthogonal to the parent filament
- Consequence of filament fragmentation?

High-Mass Cores



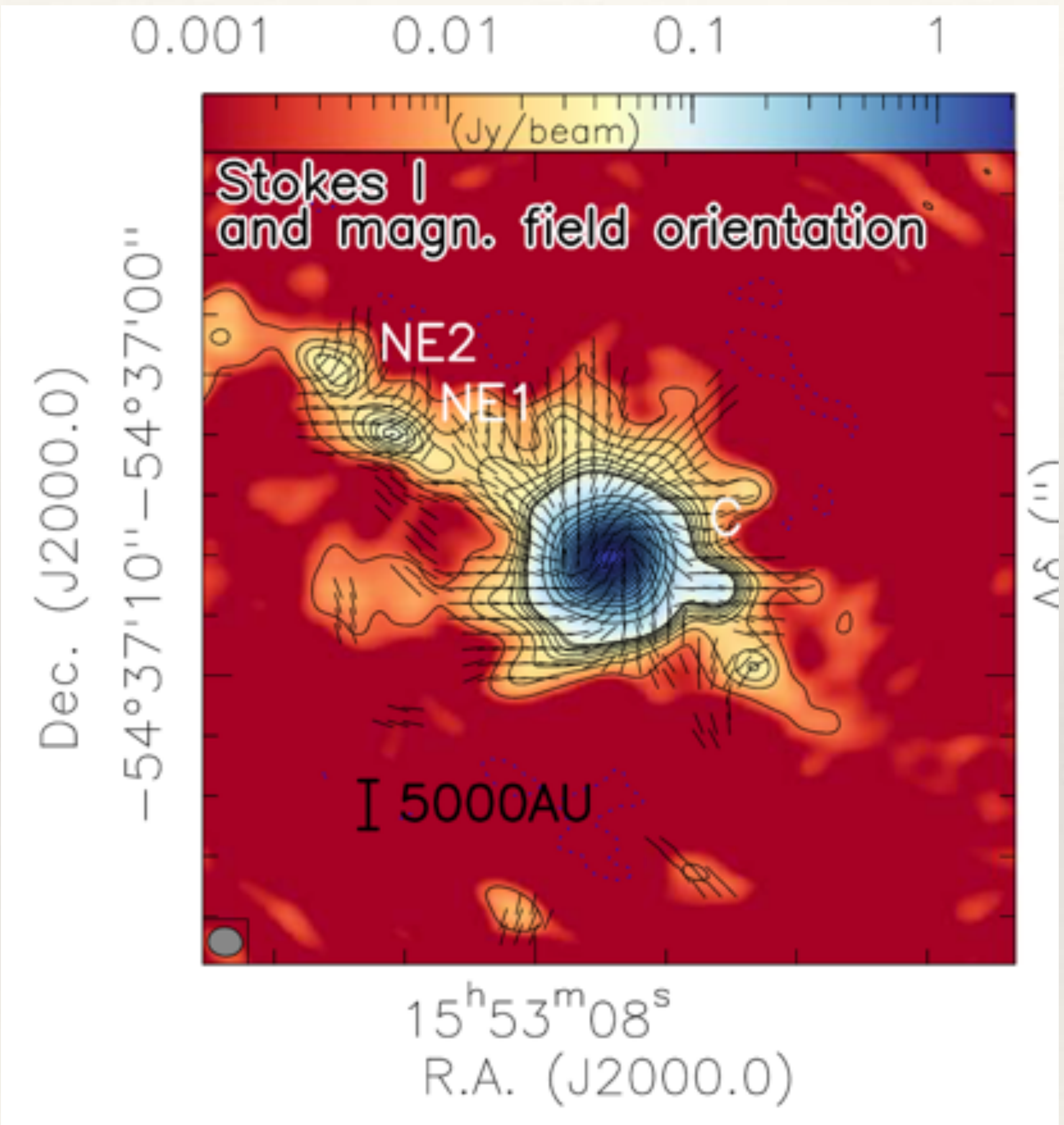
J. Liu et al. (2020)

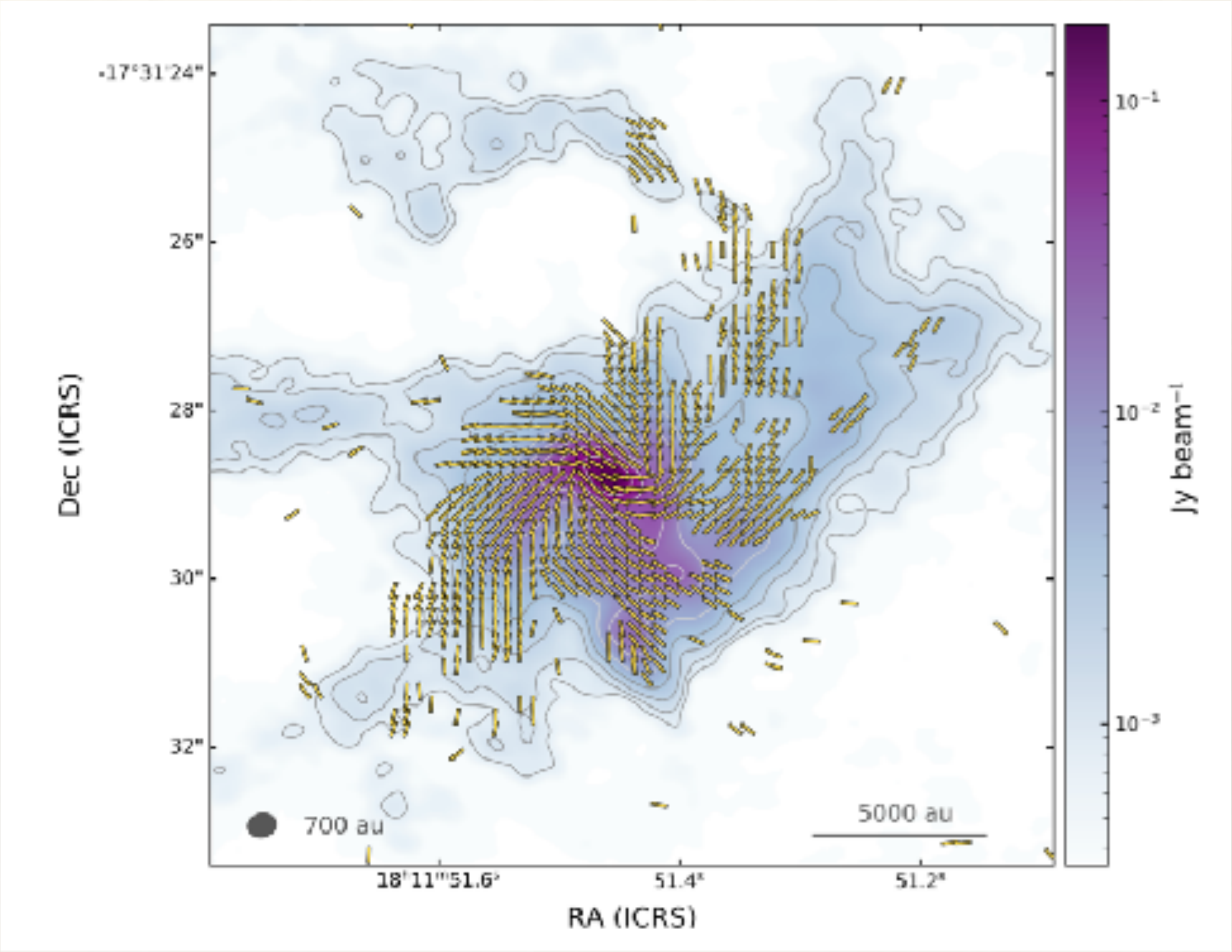
results:

complex magnetic orientation in a gravity–dominated regime

half of the outflows in the youngest cores aligned with core–scale *B*–field

High-Mass Protostars



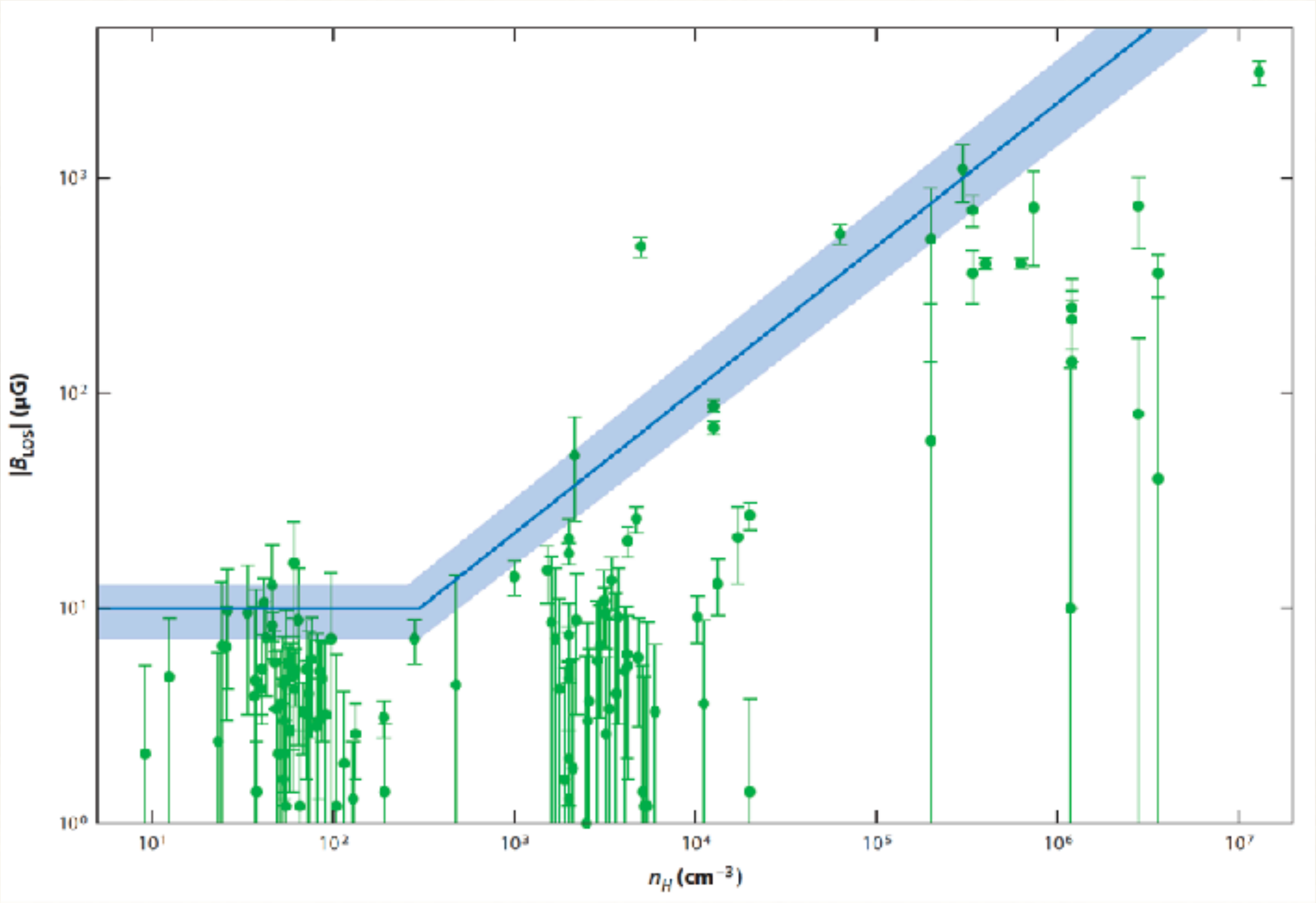


Sanhueza et al. 2021

Beuther et al. 2020

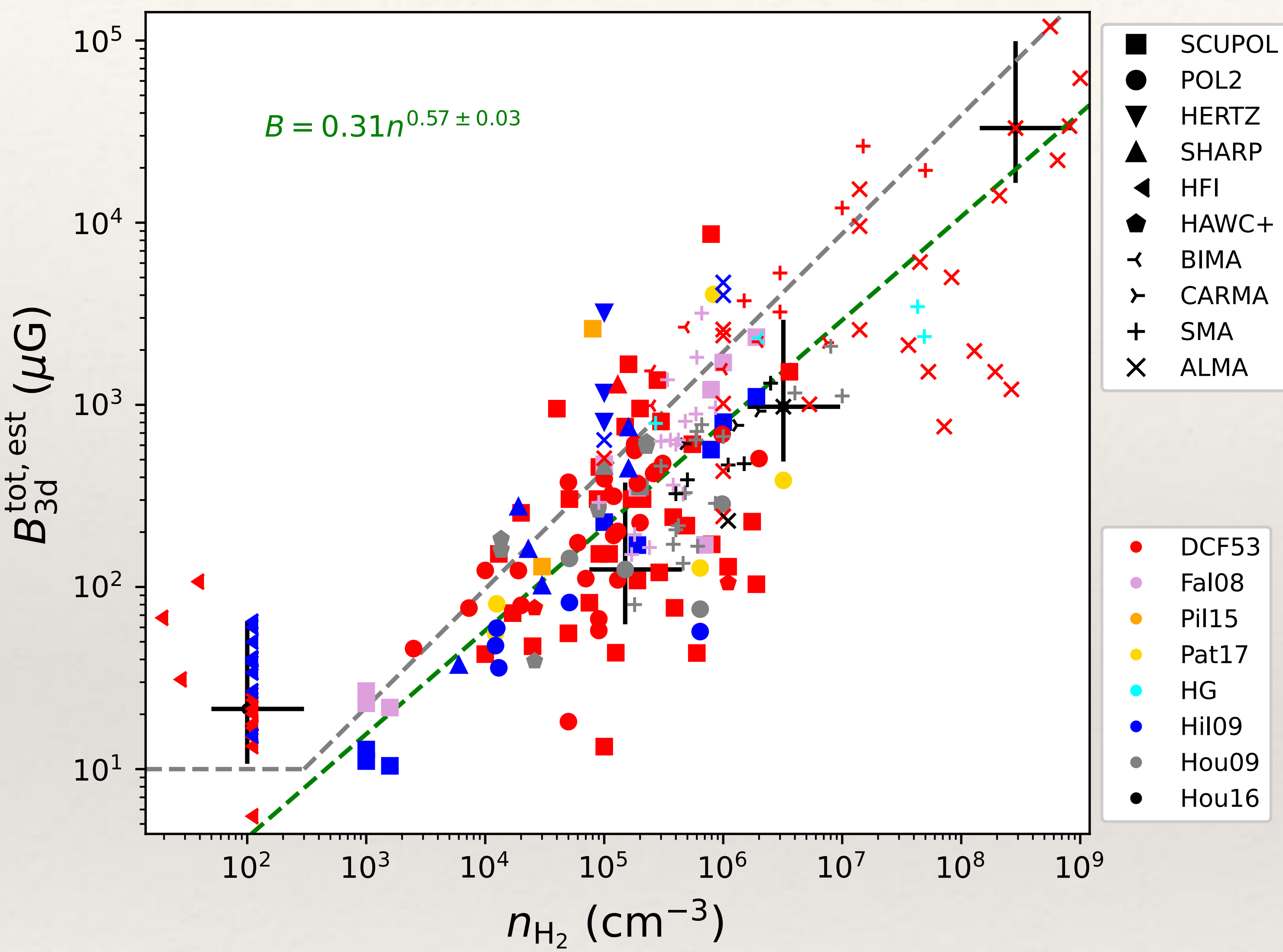
very complex field geometry on small spatial scales

Canonical Knowledge about Magnetic Fields



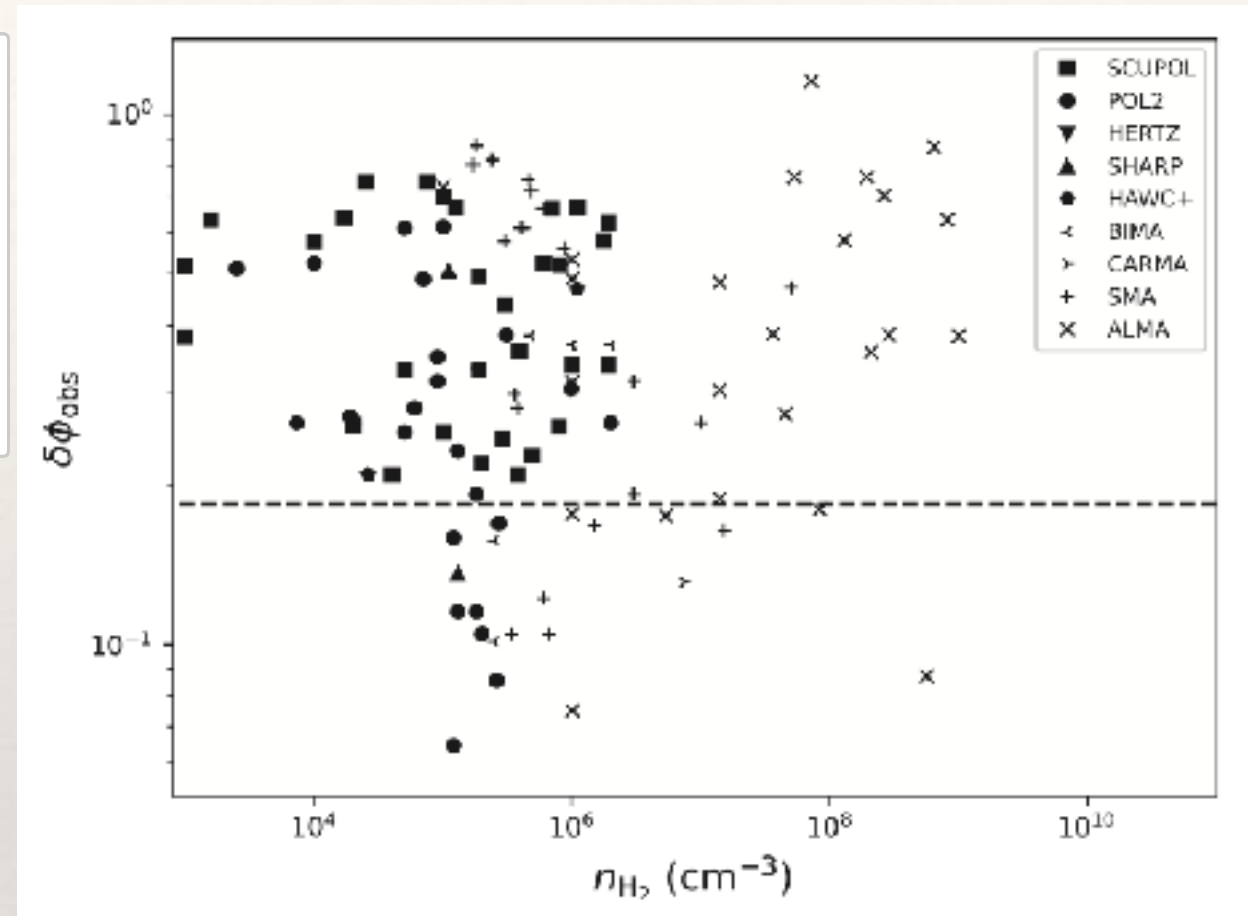
Crutcher (2010, 2012)

Compendium of Dust-Based Measurements



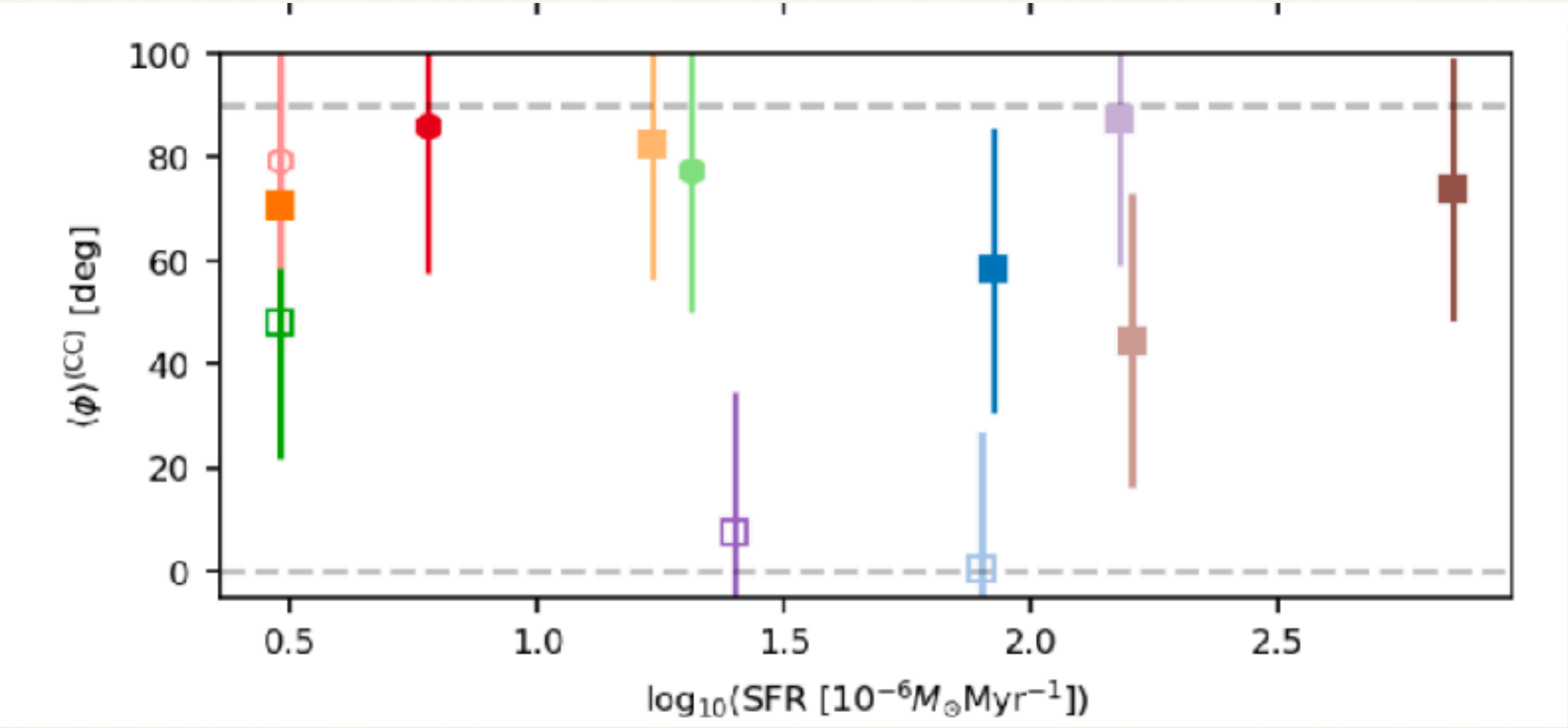
slope of 0.57
=> between prediction for strong and weak field

Liu et al. 2022



Data consistent with neither highly sub-Alfvenic nor super-Alfvenic turbulence

Magnetic Field vs. SF Rate



Soler 2019

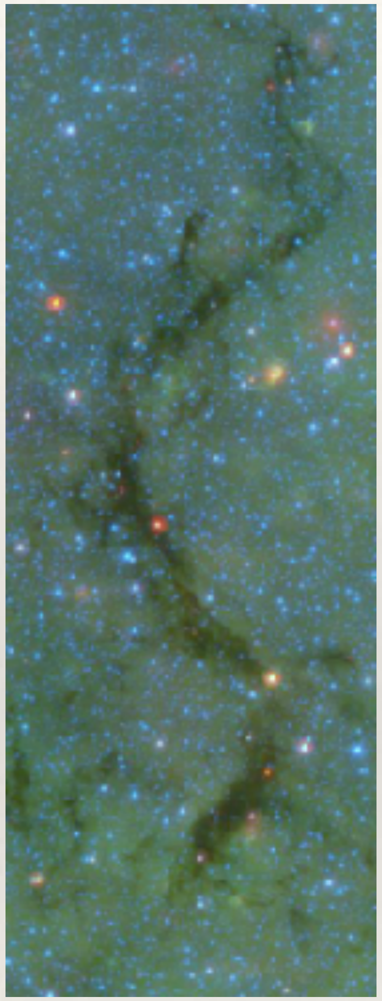
No obvious trend…

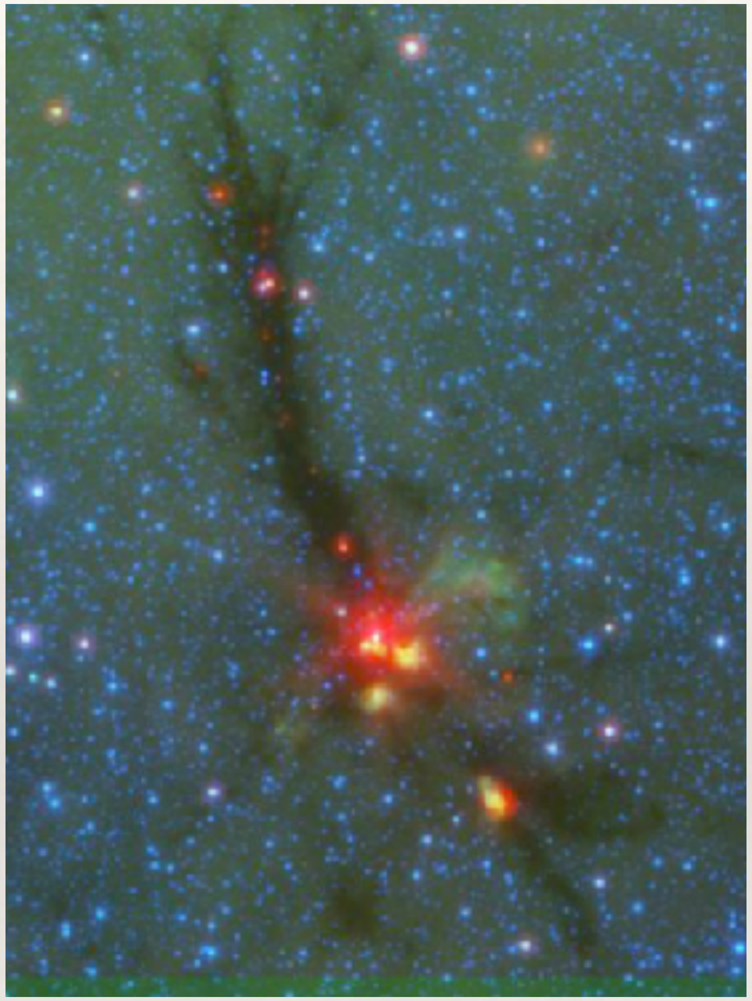
…but SFR per unit mass also hard to measure

Connection to Larger scale ISM

Borlaff et al. 2021, HAWC+

SIMPLIFI





Strategy: Pick filaments at different evolution. But different initial conditions

How does the Initial Sub-Alfvenic Field Evolve as Cloud Evolves?

SIMPLIFI Fact Sheet

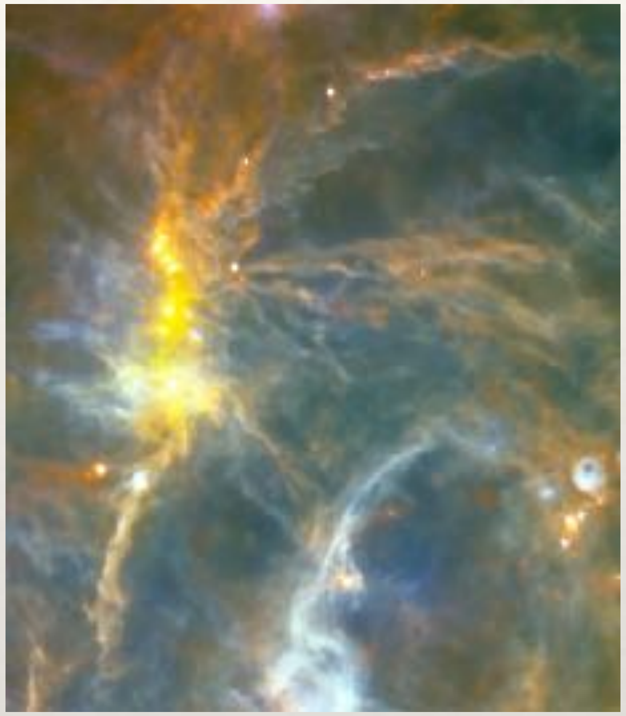
Status: Pilot Phase Fall 2021.

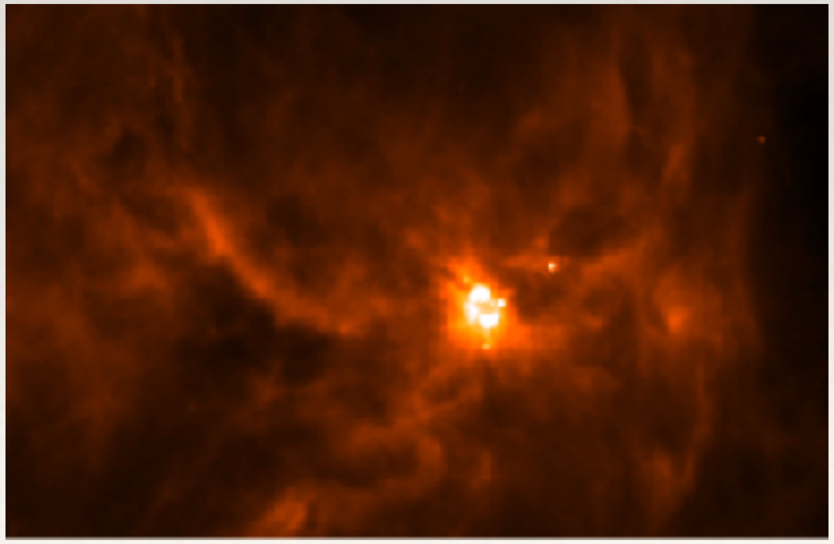
Main driver: SOFIA HAWC+ 217 micron dust continuum polarimetry at ~18” resolution

Complementary Polarization data: NIR polarization (H & K band with the MIMIR and Pico Dos Dias Instrument), ALMA dust continuum polarimetry for a subset

Spectral Lines: low J transitions of CO, ^{13}CO, $C^{18}O$, $N2H^{+}$, HCO+ etc.

Targets (full survey): Representative Gould Belt regions and Distant high-mass filaments





PI: T. Pillai
L. Fissel, D. Clemens, P. Myers, M. Heyer, P. Goldsmith, J. Kauffmann, D. Dowell, G. Franco, P. Hennebelle, K.M.Menten, F. Wyrowski, H. Wiesemeyer, J. Soler, K. Sugitani, Youngmin Seo, D. Seifried, S. Reissl, R. Banerjee

Summary

Summary

- MHD turbulence pervades large scale molecular cloud structure
- Magnetic field maps start to pinpoint gravity dominated regimes on cloud scales
- Limited data to establish any influence of magnetization on outflows or SFR
- Prestellar cores are magnetically critical to super-critical
- Hourglass field morphology observed towards some protostars
- Picture still unclear for high-mass stars inc. initial conditions
- A golden era for magnetic field studies in dense ISM with new instruments. Multi-wavelength and multi-scale polarimetry enabled by HAWC+/ALMA will play a major role in the near future.