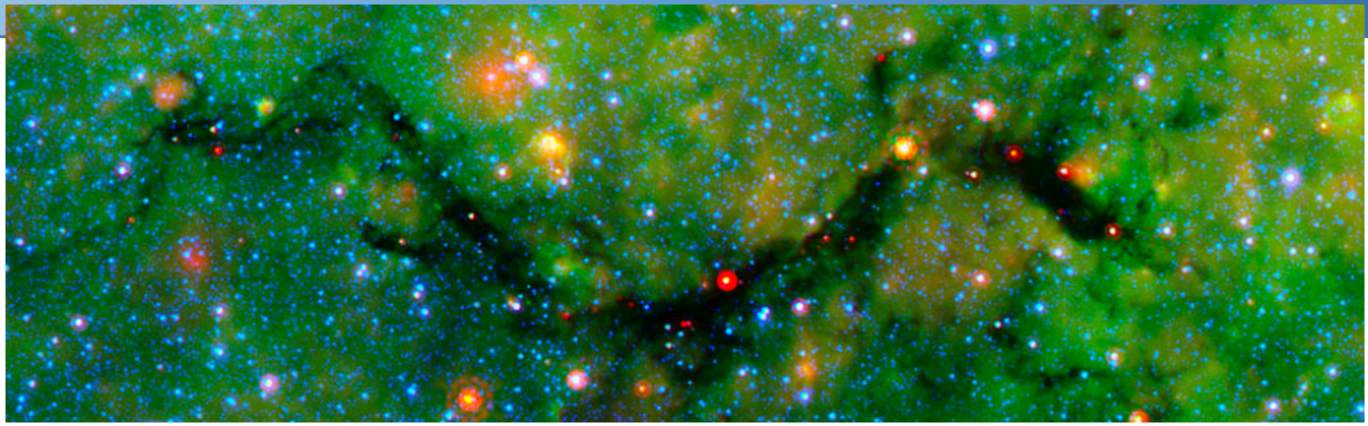

Image Credit: *Spitzer* GLIMPSE+MIPGSAL

FIELDMAPS

FIlaments Extremely Long and Dark: a Magnetic Polarization Survey: A SOFIA Legacy Program

Ian Stephens

Worcester State University

6/1/2022

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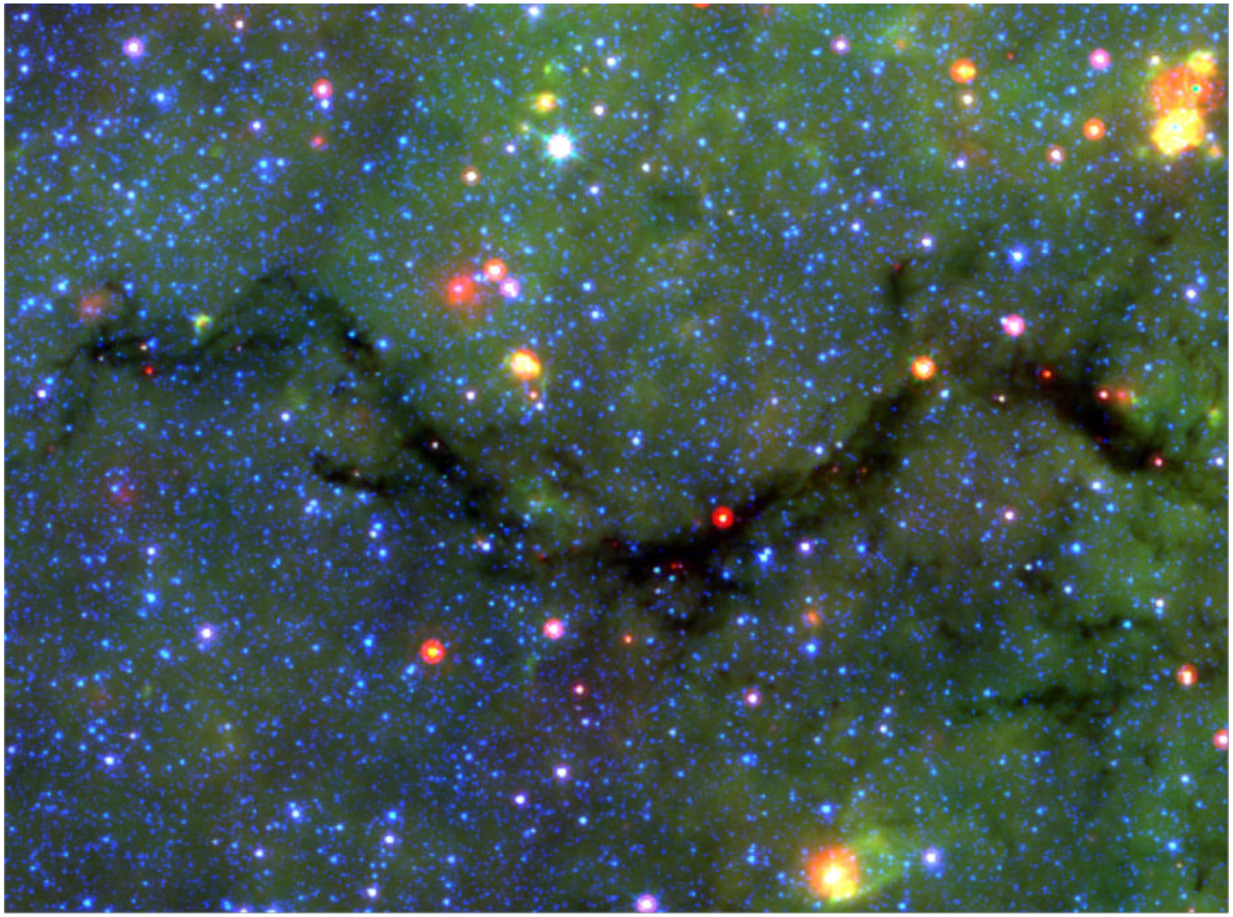
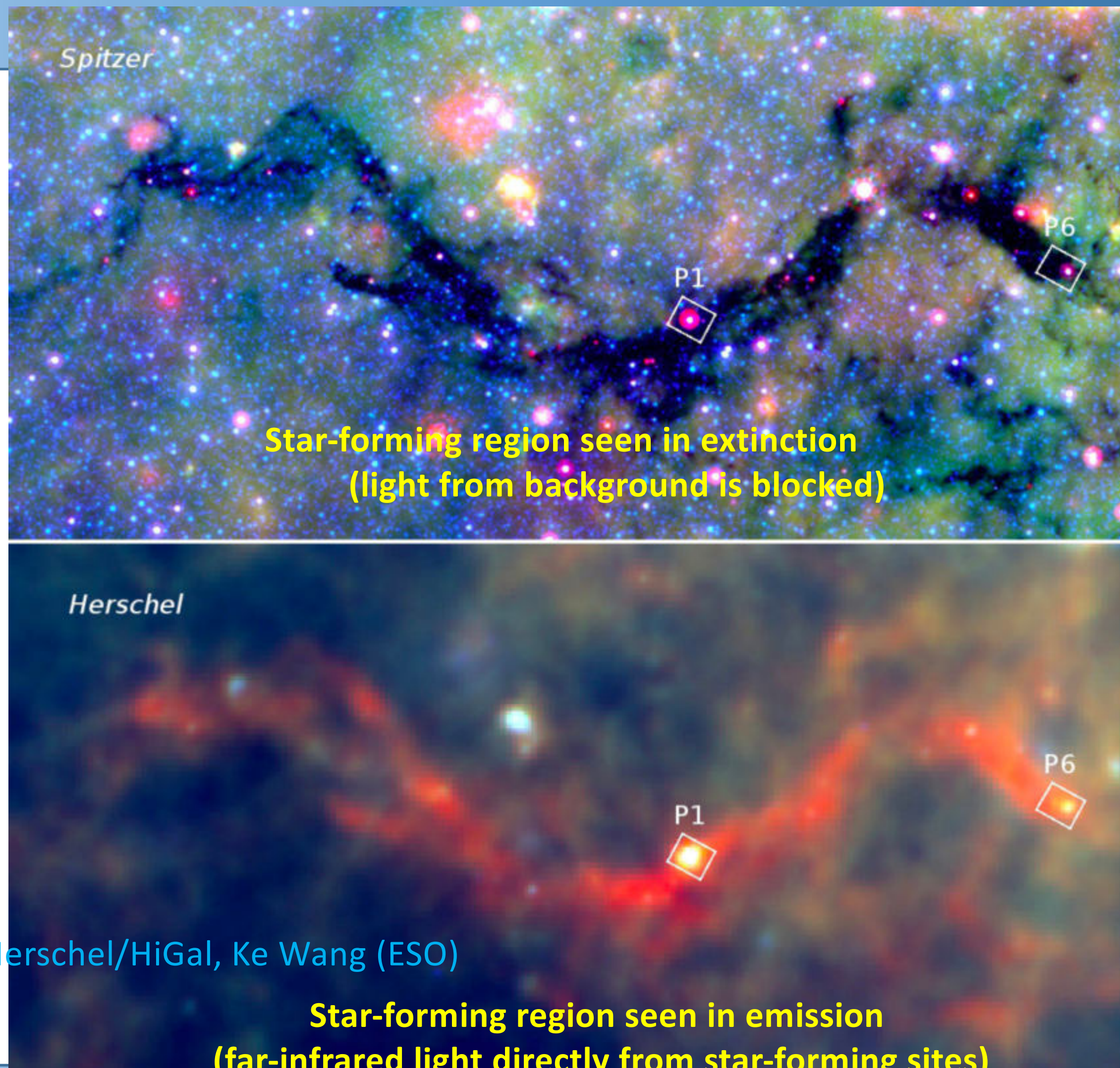


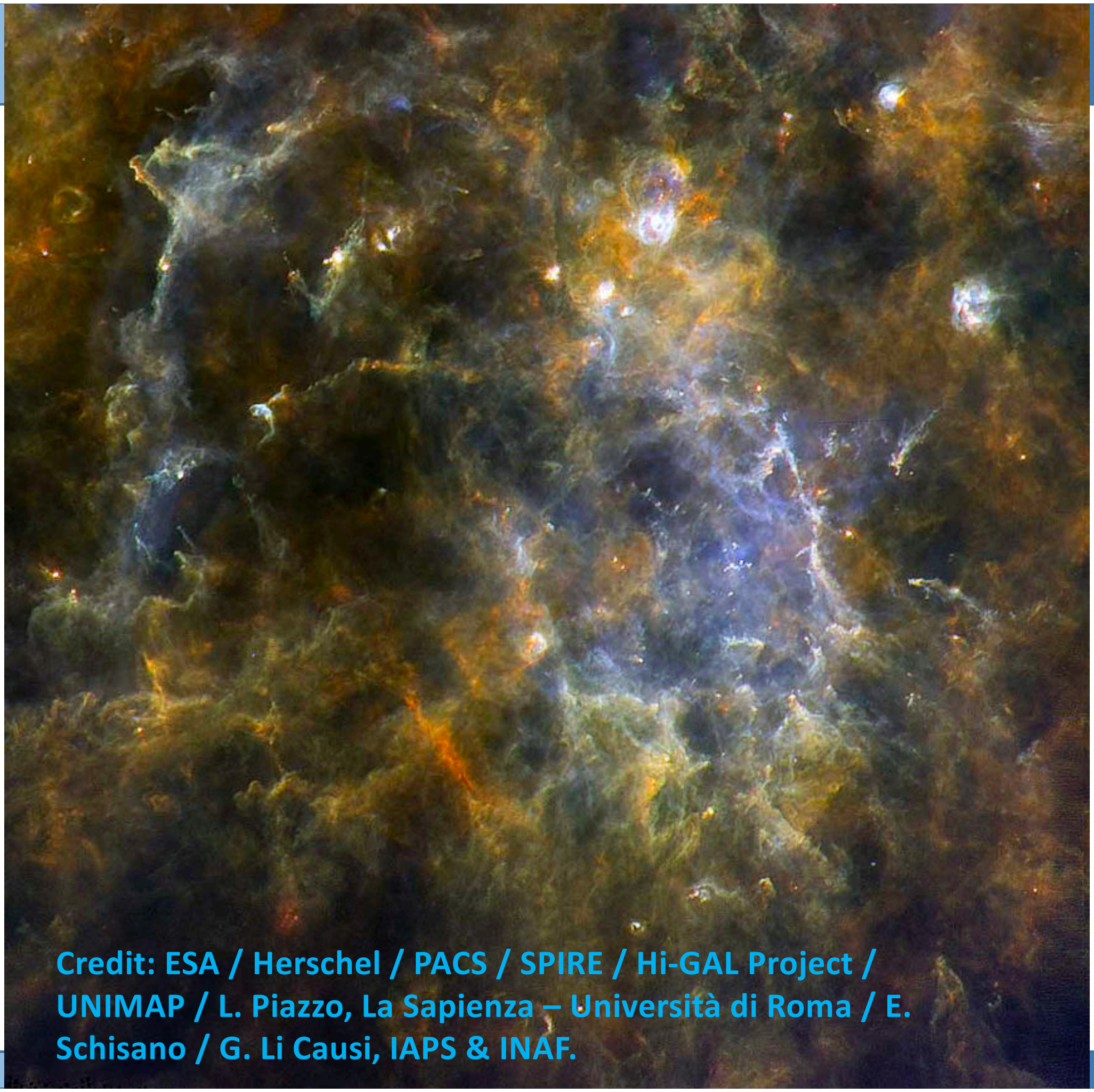
Spitzer Observations
(GLIMPSE+MIPSGAL)

Stars Form in Filaments

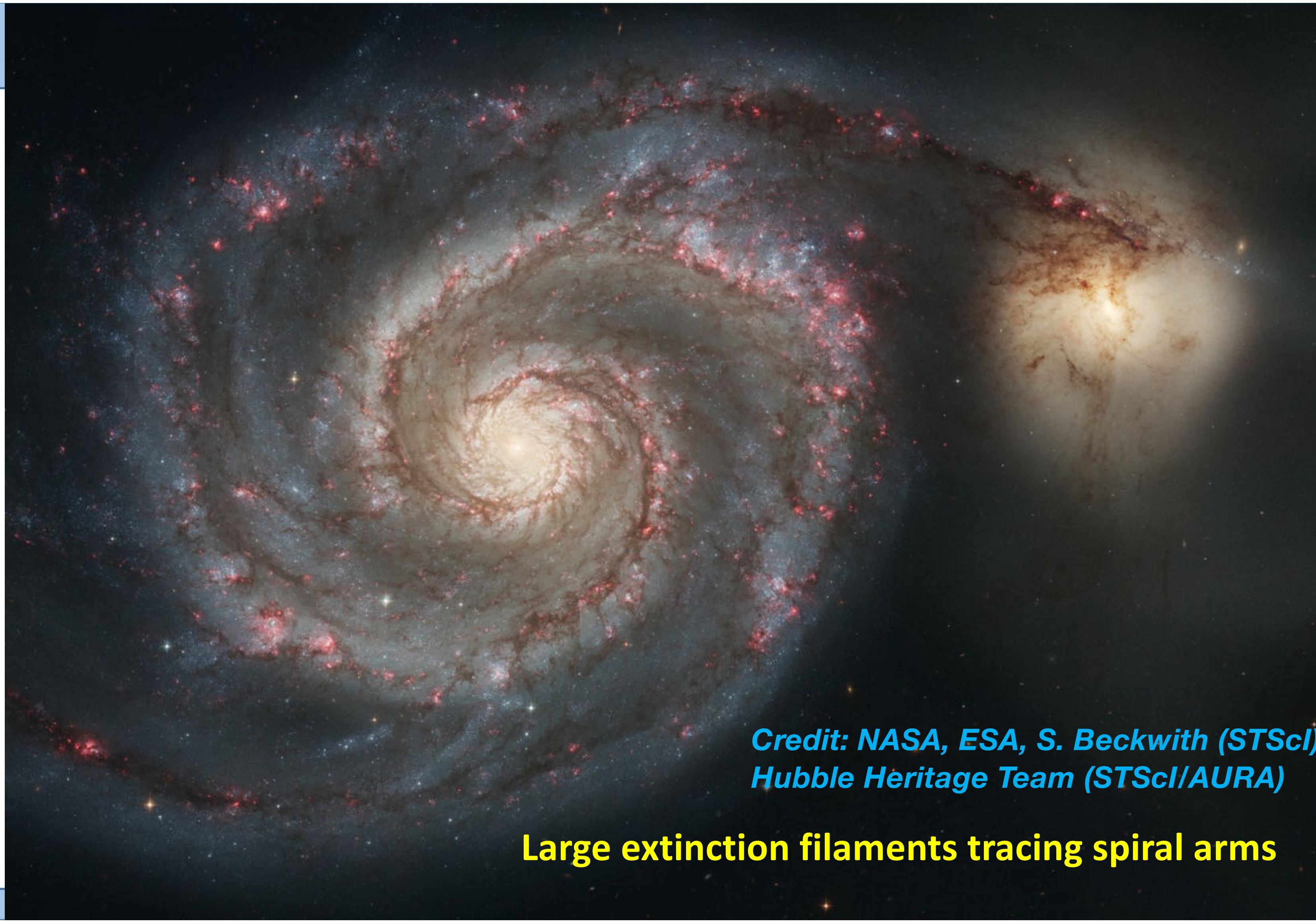


Spitzer/GLIMPSE/MIPSGAL, Herschel/HiGal, Ke Wang (ESO)

Herschel Observations of Orion


Credit: ESA / Herschel / PACS / SPIRE / Hi-GAL Project /
UNIMAP / L. Piazzo, La Sapienza – Università di Roma / E.
Schisano / G. Li Causi, IAPS & INAF.


Credit: ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized
Sky Survey 2. Acknowledgment: Davide De Martin.

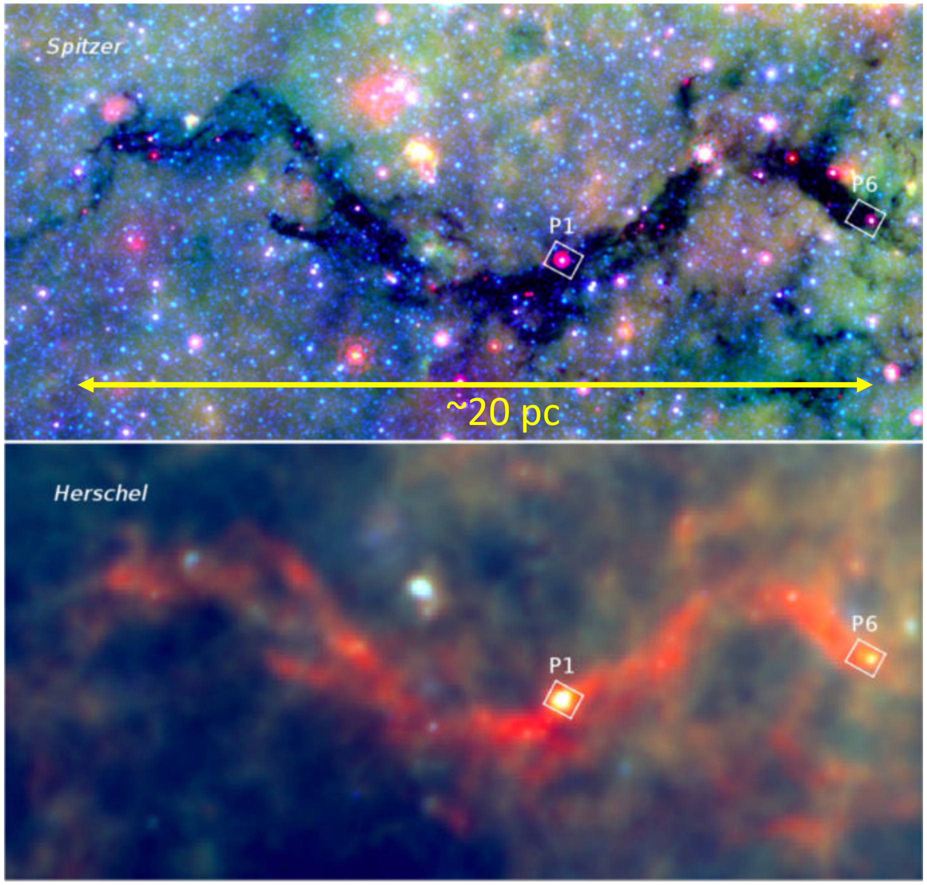

Credit: NASA, ESA, S. Beckwith (STScI) and the
Hubble Heritage Team (STScI/AURA)
Large extinction filaments tracing spiral arms

8

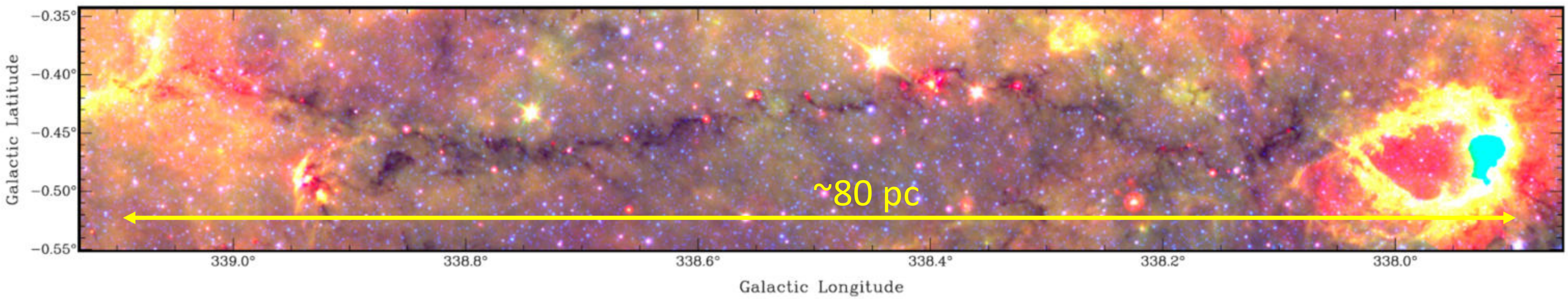
The Snake

Features also found in Milky Way

"The Snake"



Spitzer/GLIMPSE/MIPSGAL, Herschel/HiGal, Ke Wang (ESO)



"Nessie" Jackson et al. (2010)

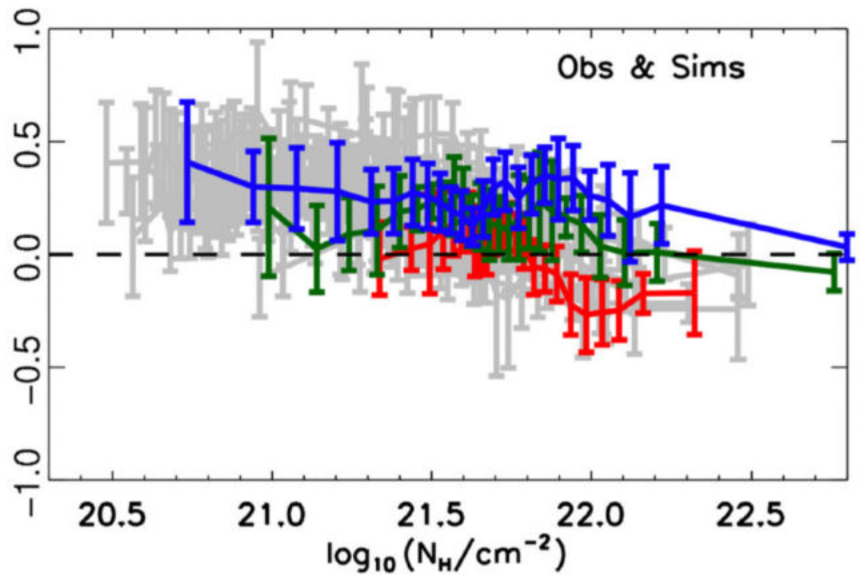

GLIMPSE+MIPSGAL
(e.g., Goodman et al. 2014; Zucker et al. 2015, 2018)

- “Bones of the Milky Way”
- Bones well observed
  - Dust continuum (Herschel, ground-based)
  - Molecular Lines
- Most parameters well constrained:
  - lengths, widths, aspect ratios, velocity information, masses, column densities, dust temperatures, Galactic altitudes, kinematic separation from arms in l − v space, and distances (e.g., Zucker et al. 2018)
  - notably not the magnetic field
    - star formation rate, flow direction, shape
    - collapse time-scale, fragmentation

- Original expectation: Fields will be perpendicular to the bones!
- Planck XXXV (didn't resolve filaments!)

Parallel with Filament

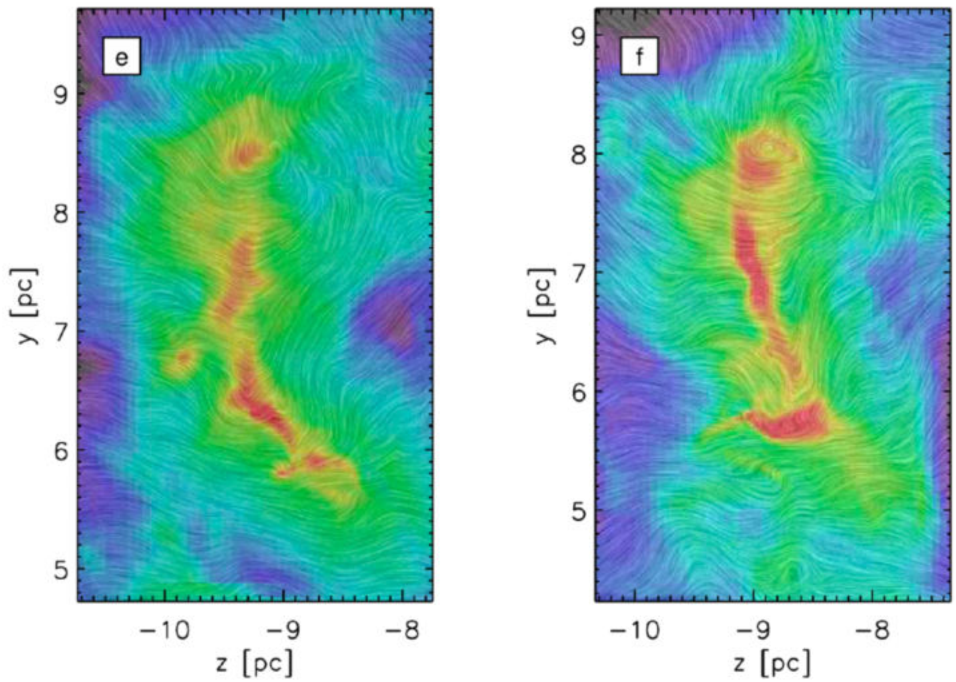
Perpendicular to Filament



Planck Collaboration XXXV (2016)

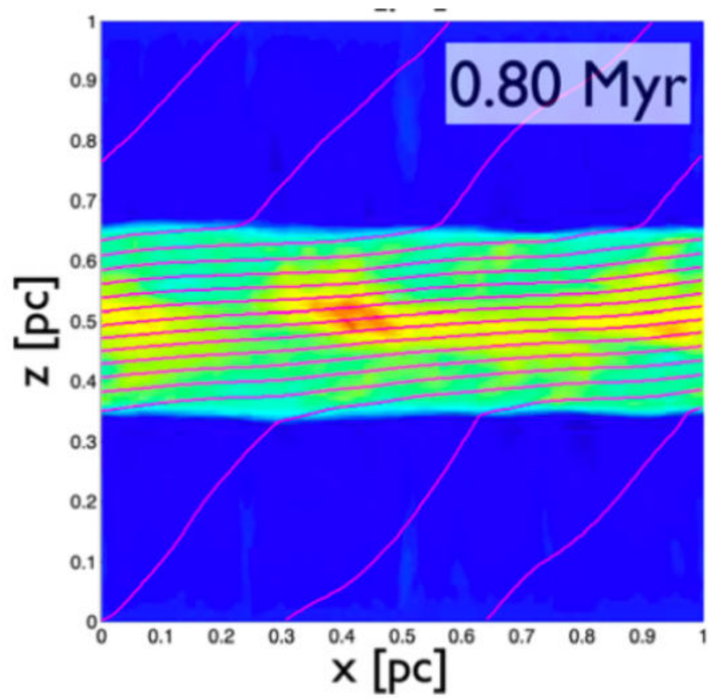
Gray: Observations
Colors: Simulations
Blue: Weak Fields
Green: Equipartion with Turbulence (Alfvenic)
Red: Strong Fields

- Original expectation: Fields will be perpendicular to the bones!
- Gravitational accretion flow of bones perpendicular to bones



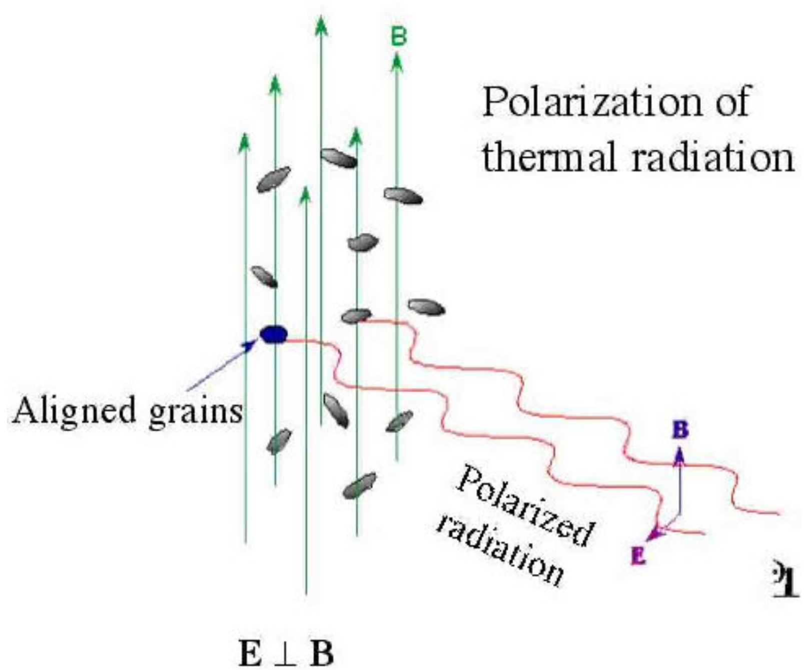
Gomez et al. (2018)

- Nevertheless, since we are resolving bones, we may see something else!
- Flows through the bones

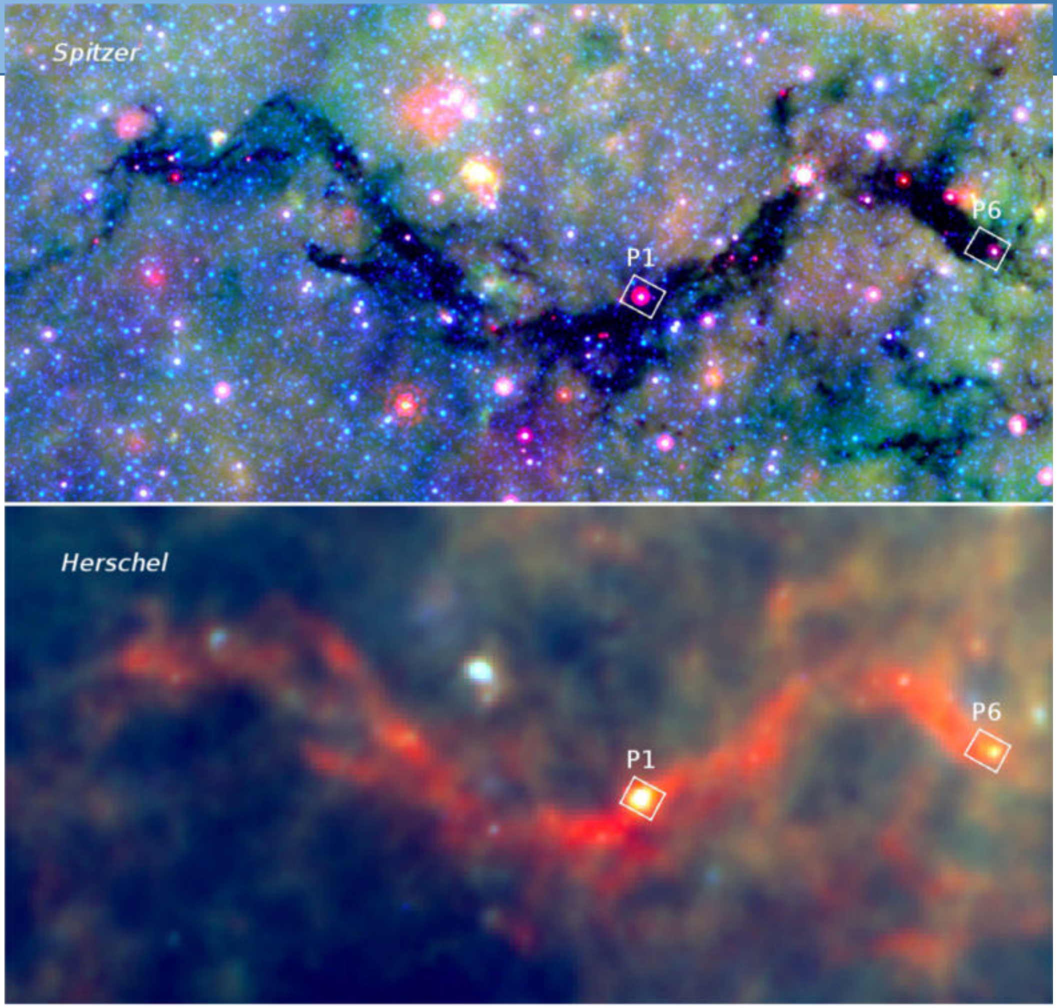


Chen & Ostriker et al. (2014)

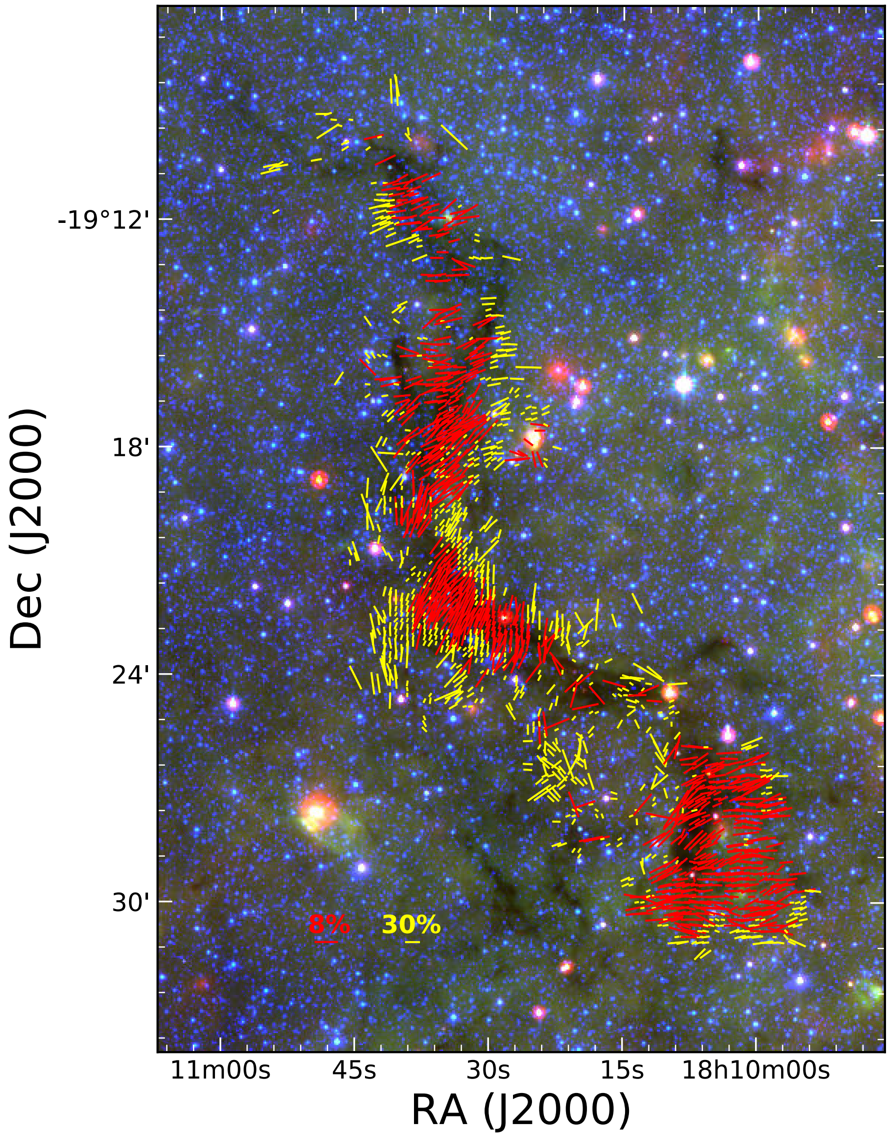
Spheroidal grains align with short axis perpendicular to B-field.



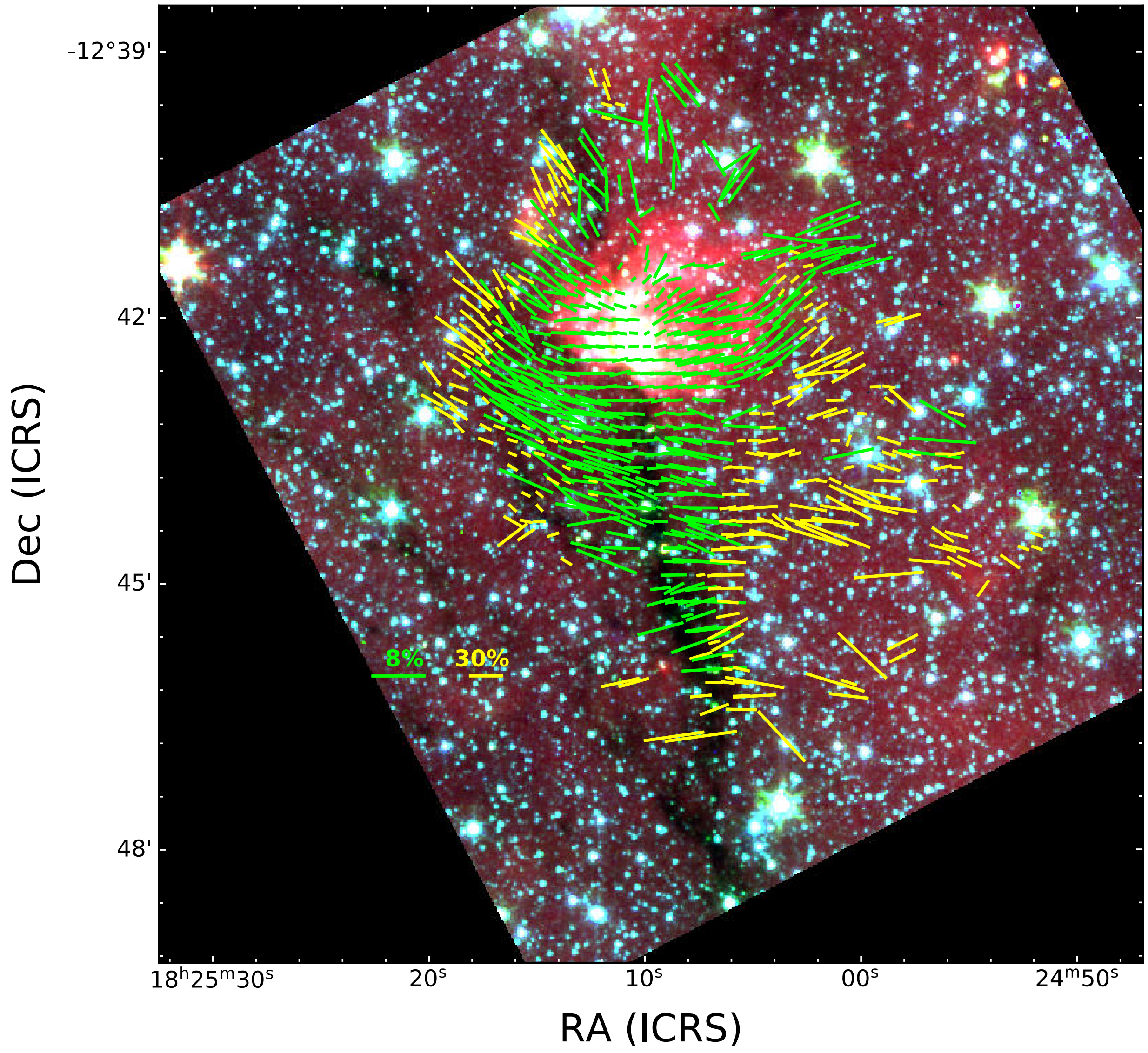
Lazarian (2007)



Spitzer/GLIMPSE/MIPSGAL, Herschel/HiGal, Ke Wang, European Southern Observatory


-19°12'
18'
24'
30'
Dec (J2000)
8%
30%
11m00s
45s
30s
15s
18h10m00s
RA (J2000)

First Try!



-12°39'
42'
45'
48'
Dec (ICRS)
8%
30%
18h25m30s
20s
10s
00s
24m50s
RA (ICRS)

First Try!

First Try

- Quite perpendicular
- Is this a ubiquitous feature?

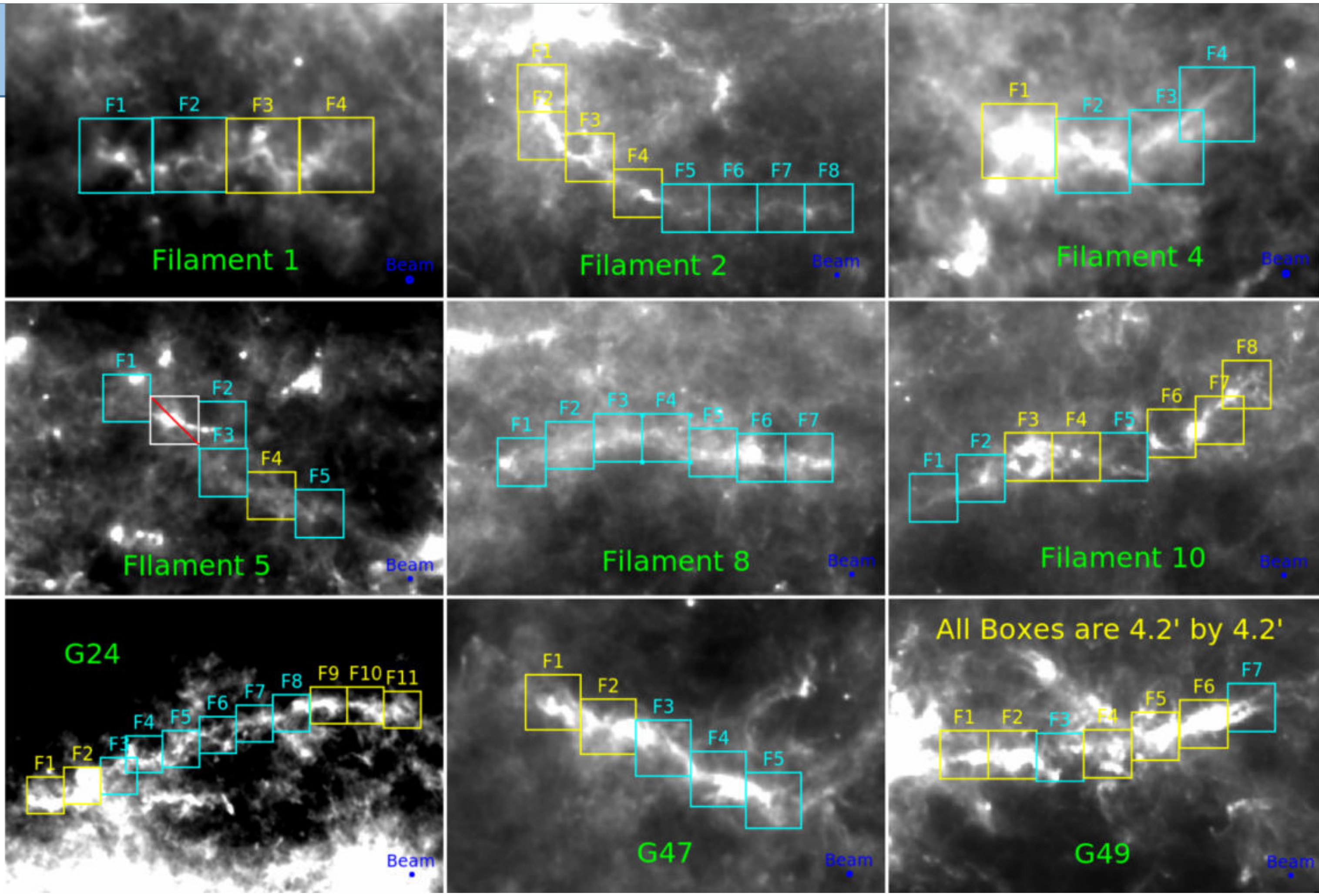
- We teach our Astronomy 101 students that most stars form due to the compression in the spiral potential. Fields likely play a role.

- It would be beneficial to survey the entirety of many bones

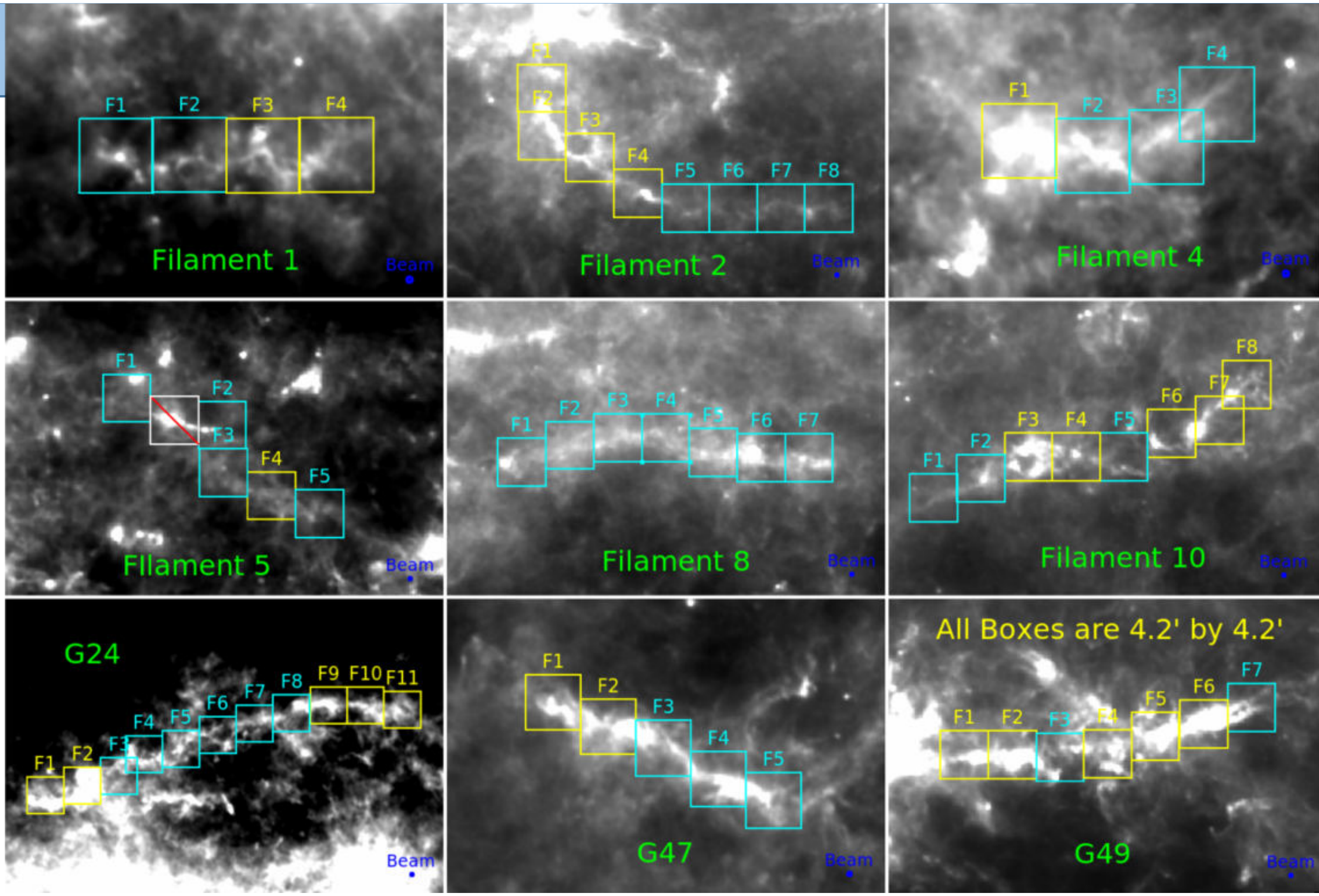
FIELDMAPS

Major Goals:

- **Role of magnetic fields in Bones**
  - ➢ Critical for collapse?
- **Whether magnetic fields vary for bones in the arm vs interarm regions**
  - ➢ Compression in spiral potential vs sheared and stretched
- **Overall morphology**
  - ➢ (e.g., perpendicular fields vs fields guiding flow through the bones)
- **Setup a Legacy data product** that can used for studying how star-forming gas collects in the magnetized spiral potential



Above shows NMC. OTF actual



FIELDMAPS: FIlaments Extremely Long and Dark: a MAgnetic Polarization Survey

FIELDMAPS

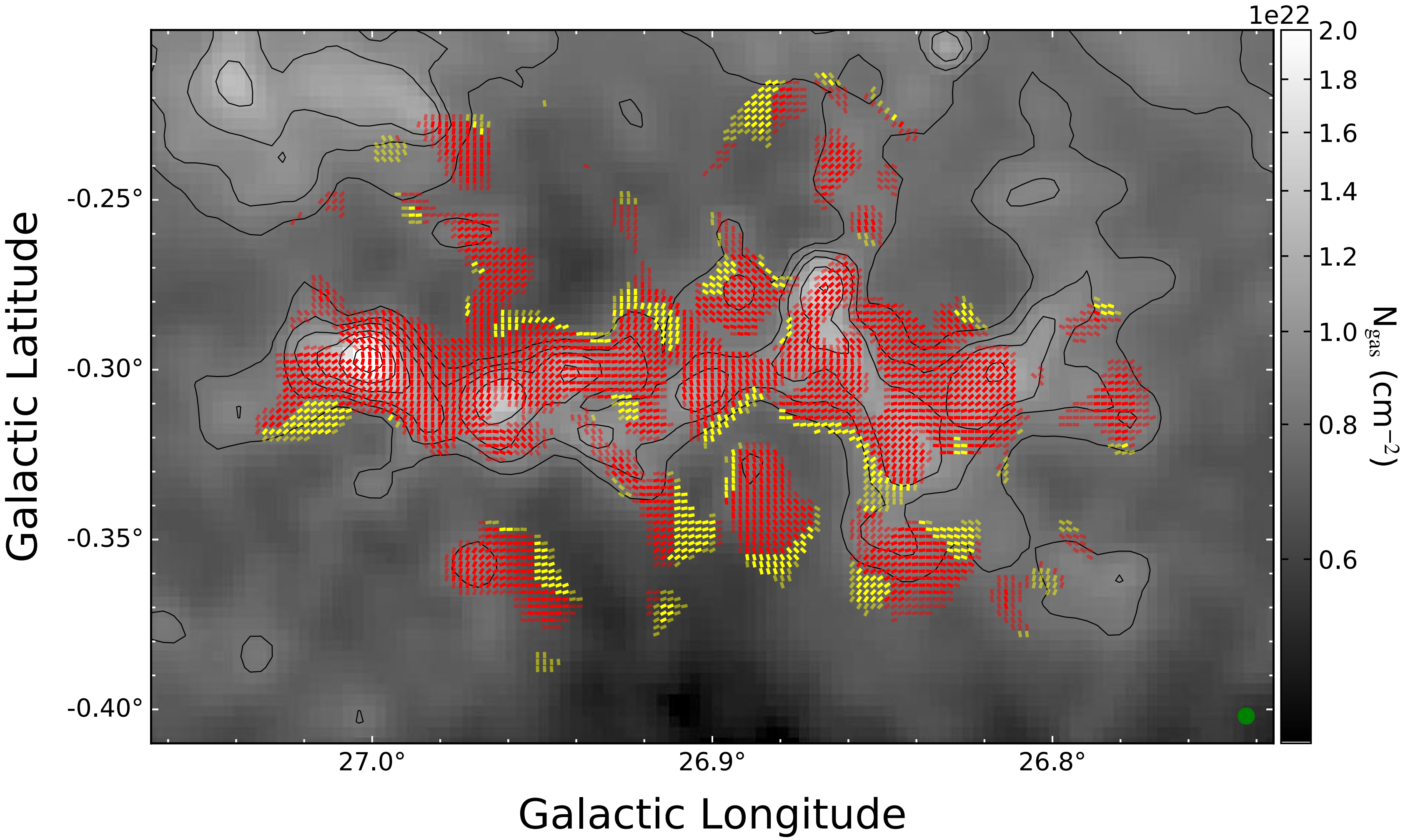
Novel:
Magnetic fields of bones have not been significantly studied, but are the largest, dense filamentary structures in the Galaxy.

The bones are potentially the best way to study how star-forming gas collapses in the magnetized Spiral potential for all galaxies. The key missing component of the bone analysis it the magnetic field.

This is a pioneering phase.

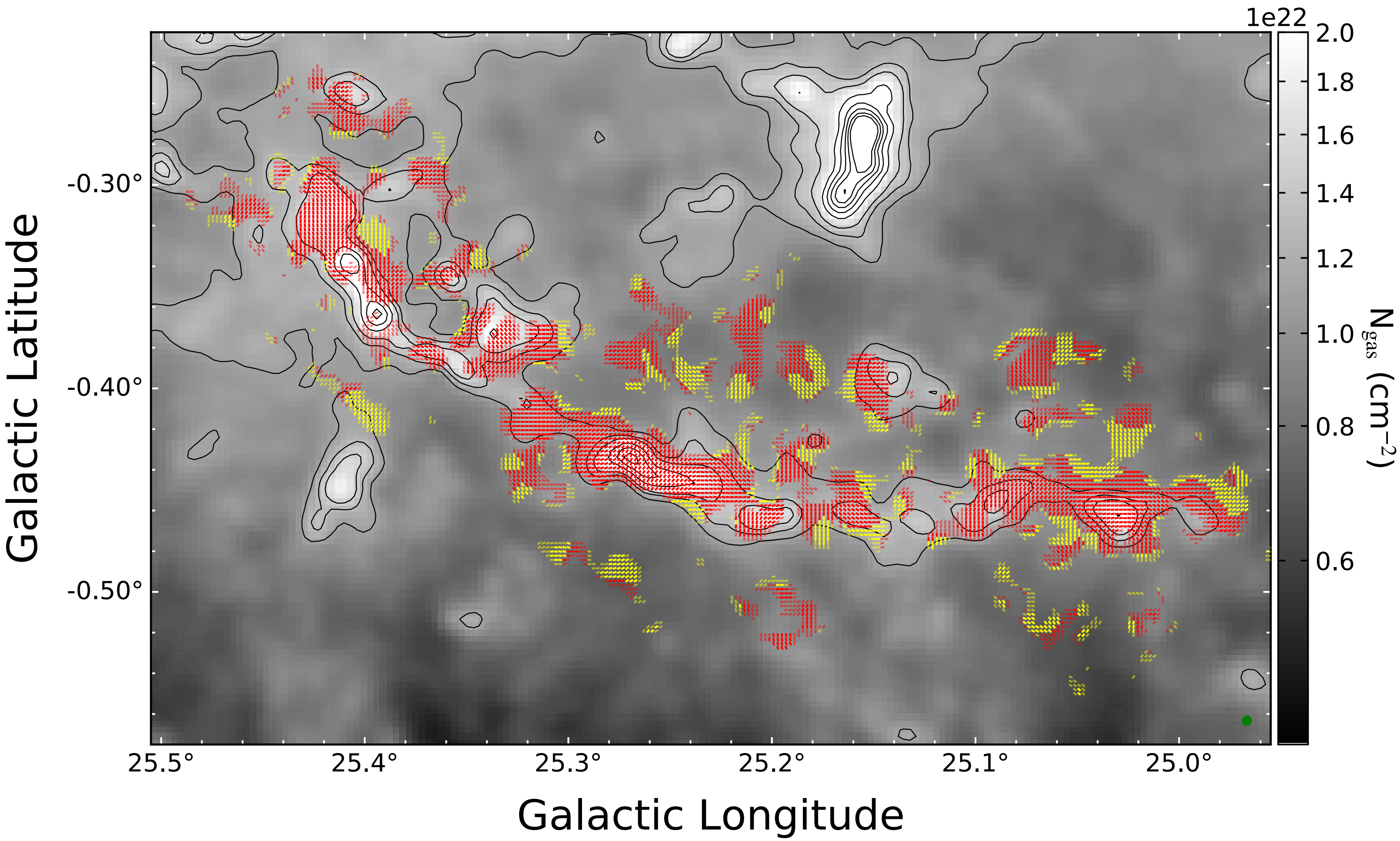
We expected all perpendicular

Filament 1



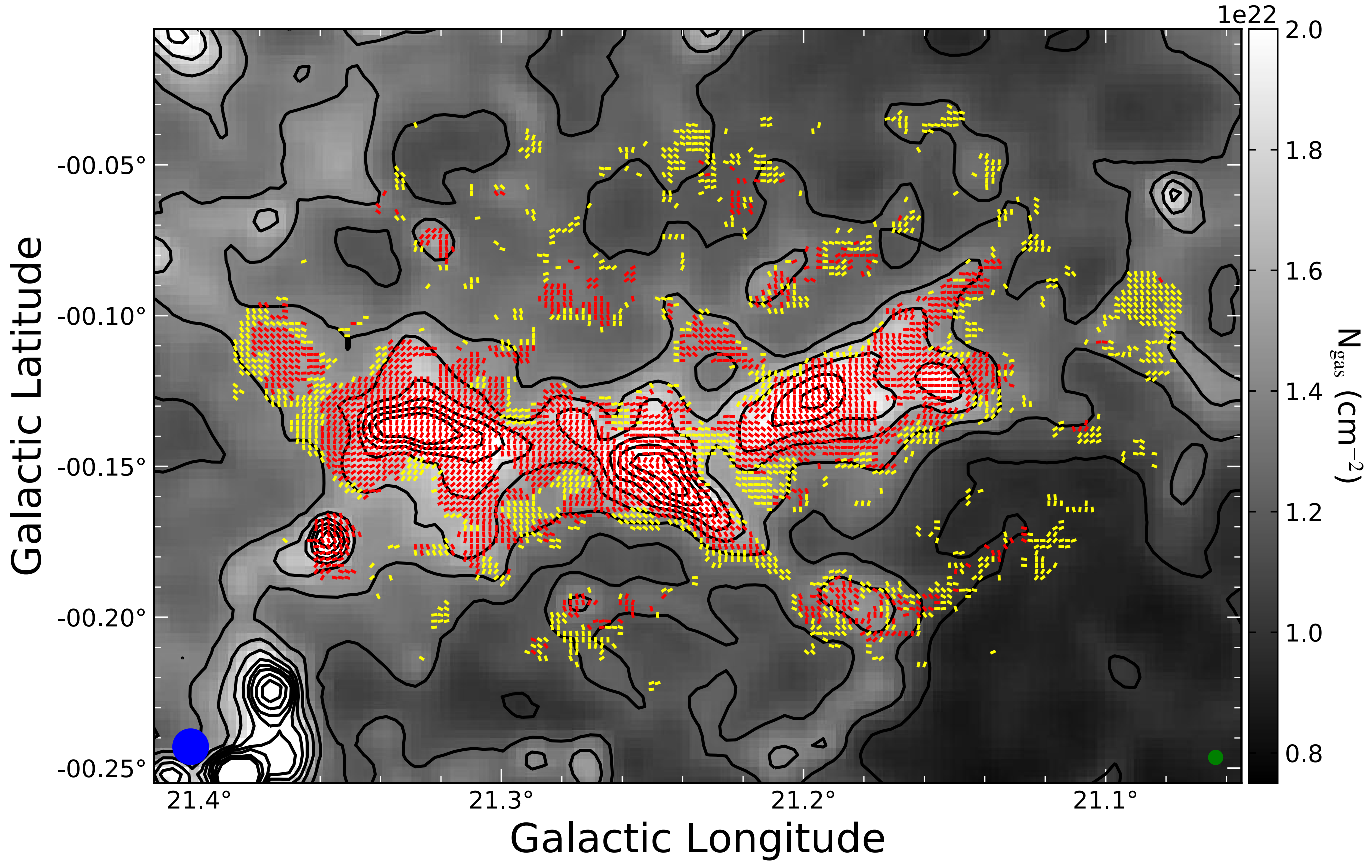
1e22
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
N_{gas} (cm^{-2})
-0.25°
-0.30°
-0.35°
-0.40°
Galactic Latitude
27.0°
26.9°
26.8°
Galactic Longitude

Filament 2



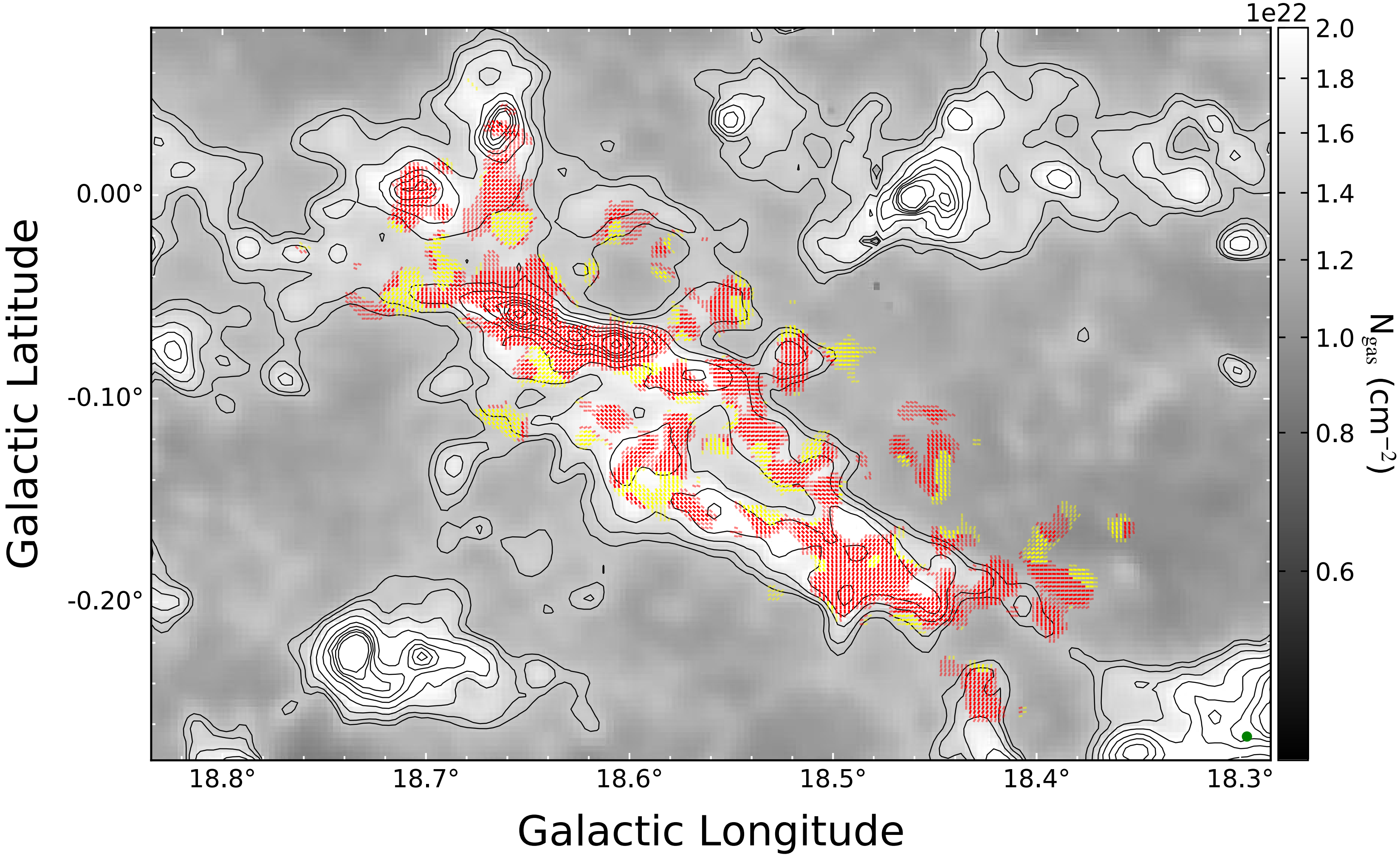
1e22
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
N_{gas} (cm^{-2})
-0.30°
-0.40°
-0.50°
Galactic Latitude
25.5°
25.4°
25.3°
25.2°
25.1°
25.0°
Galactic Longitude

Filament 4



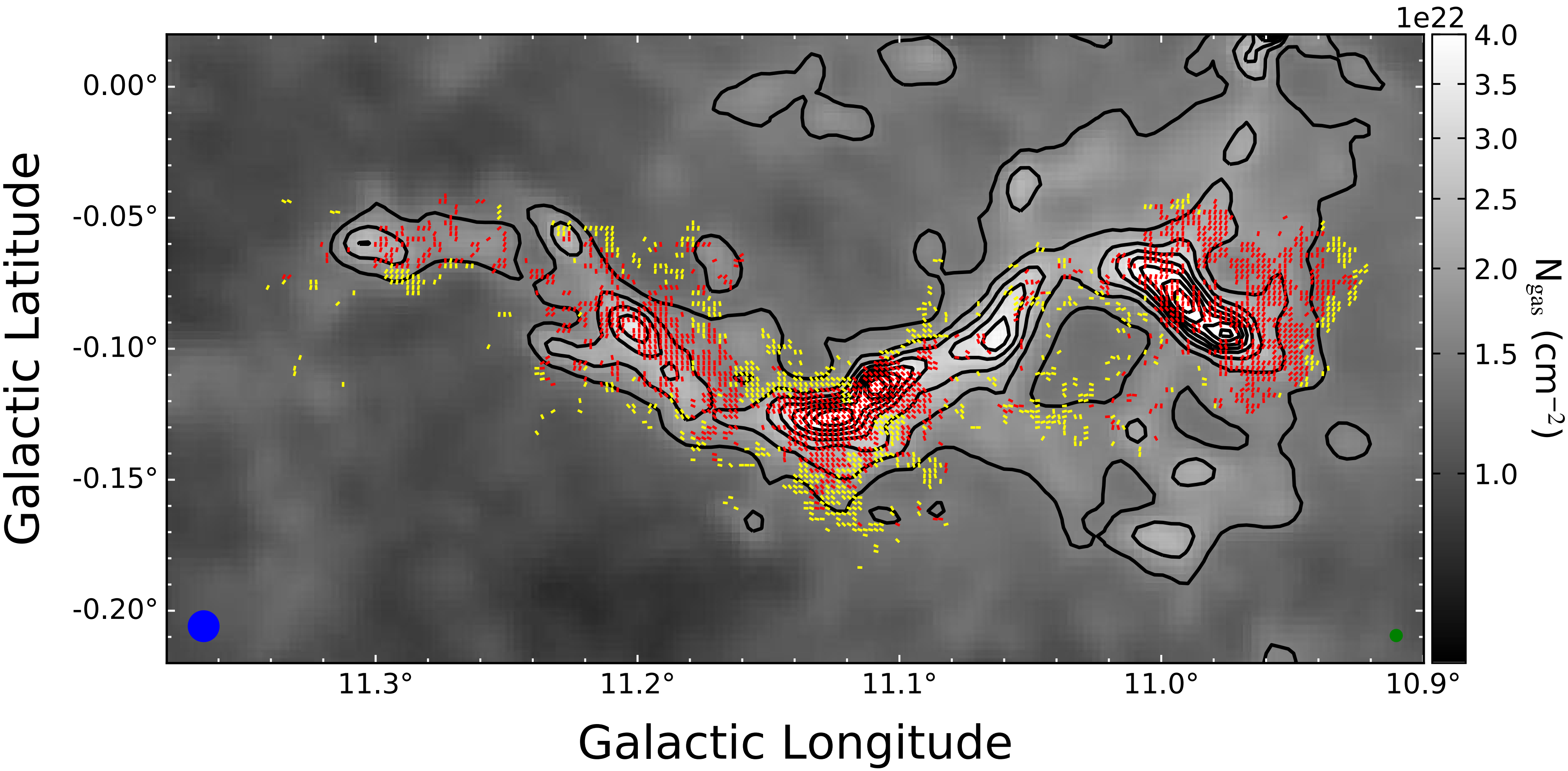
1e22
2.0
1.8
1.6
1.4
1.2
1.0
0.8
N_{gas} (cm^{-2})
Galactic Latitude
-00.05°
-00.10°
-00.15°
-00.20°
-00.25°
21.4°
21.3°
21.2°
21.1°
Galactic Longitude

Filament 5

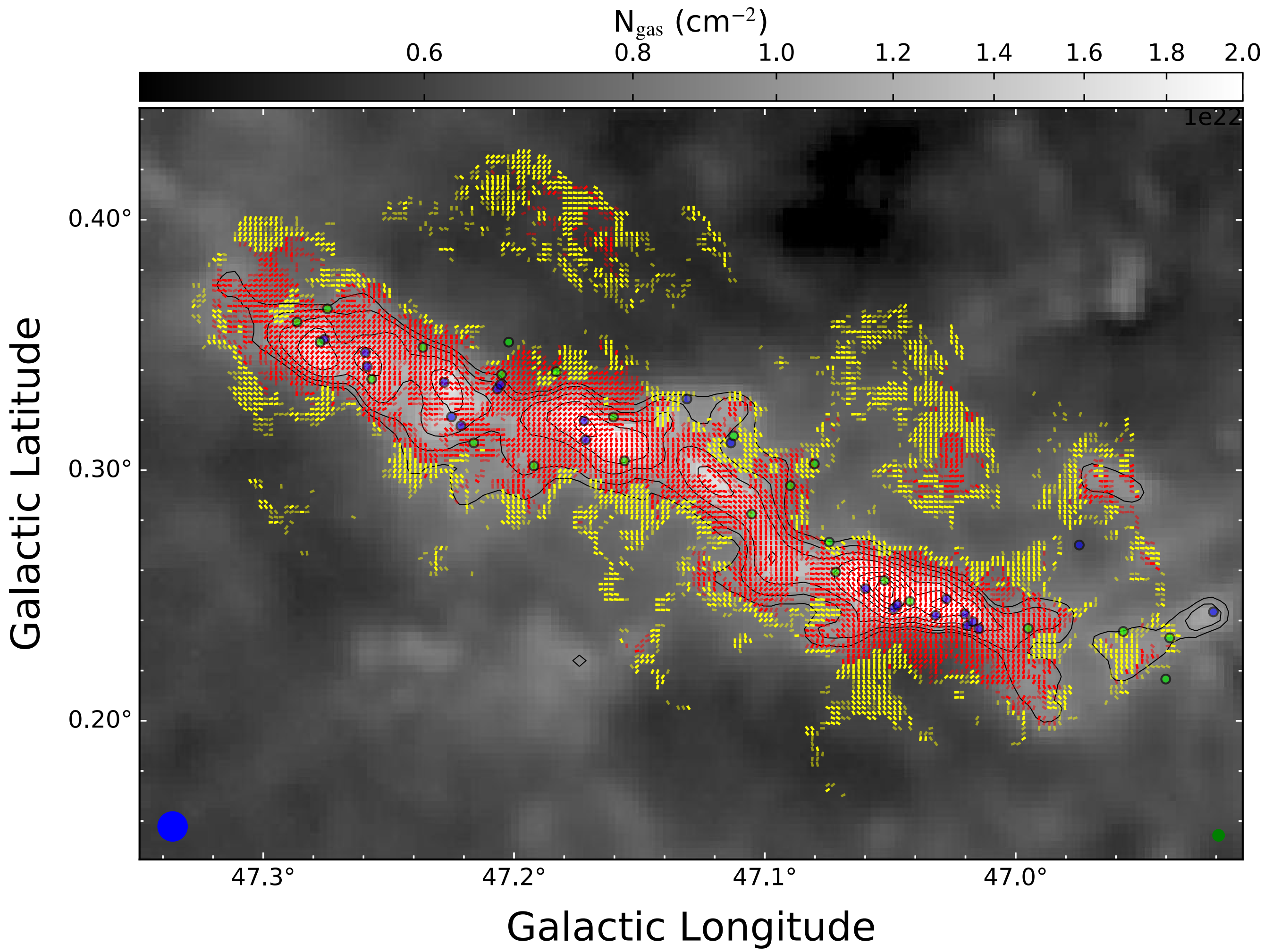


1e22
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
N_{gas} (cm^{-2})
0.00°
-0.10°
-0.20°
Galactic Latitude
18.8°
18.7°
18.6°
18.5°
18.4°
18.3°
Galactic Longitude

Snake (Filament 6)

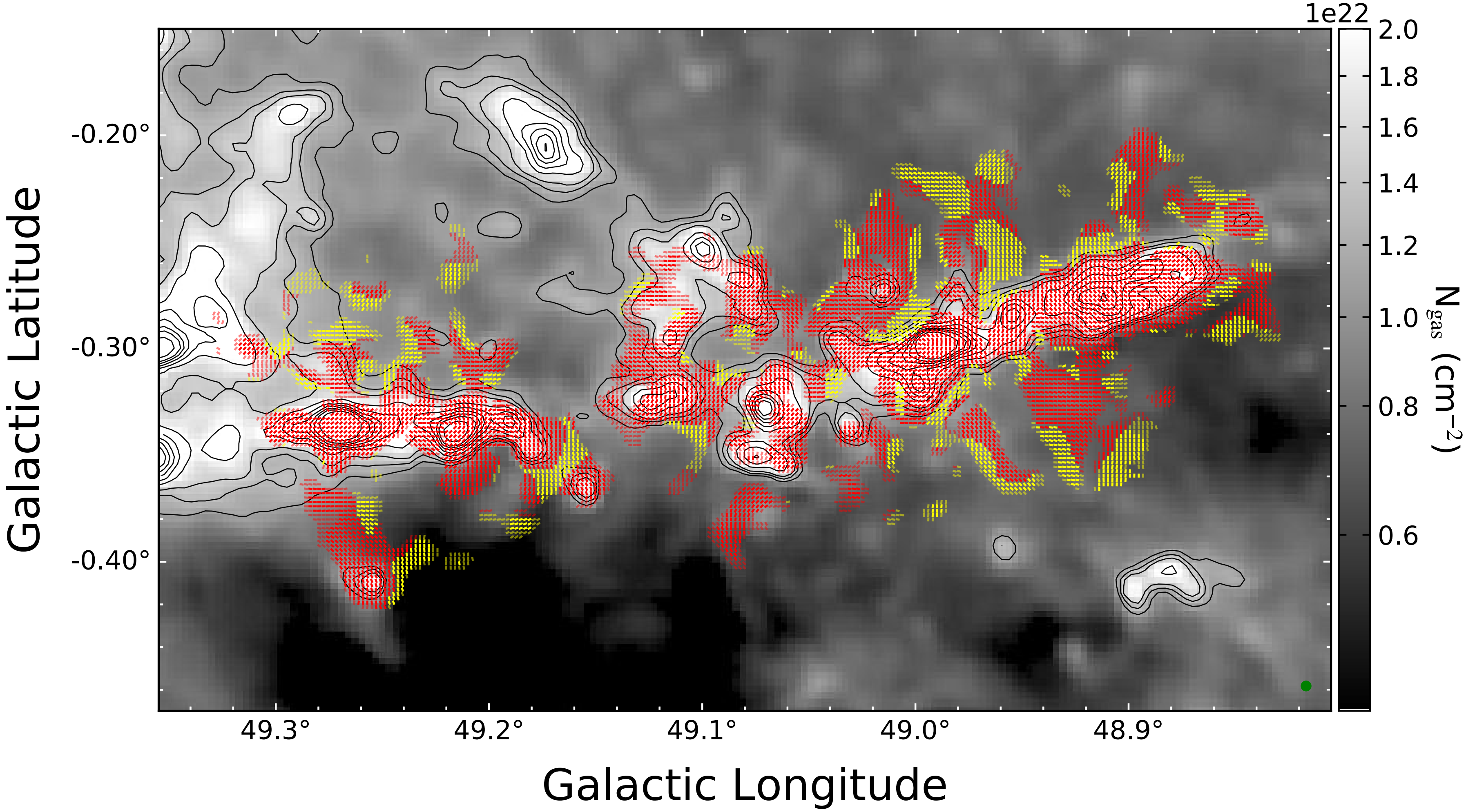


G47



Stephens et al. (2022)

G49

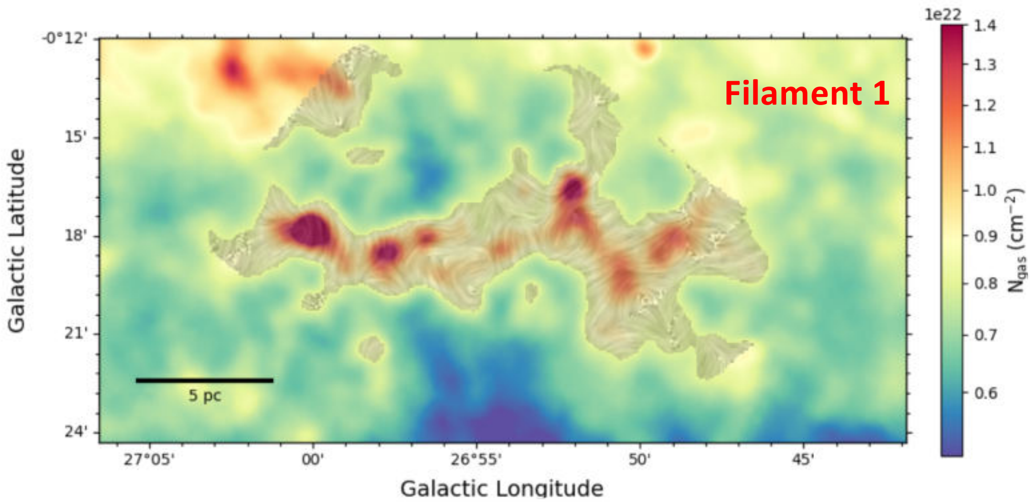

1e22
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
N_{gas} (cm^{-2})
-0.20°
-0.30°
-0.40°
Galactic Latitude
49.3°
49.2°
49.1°
49.0°
48.9°
Galactic Longitude

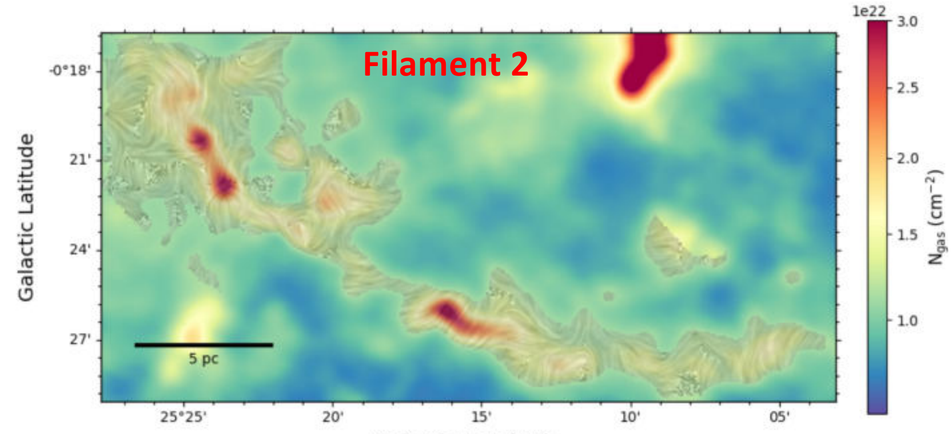
First Try

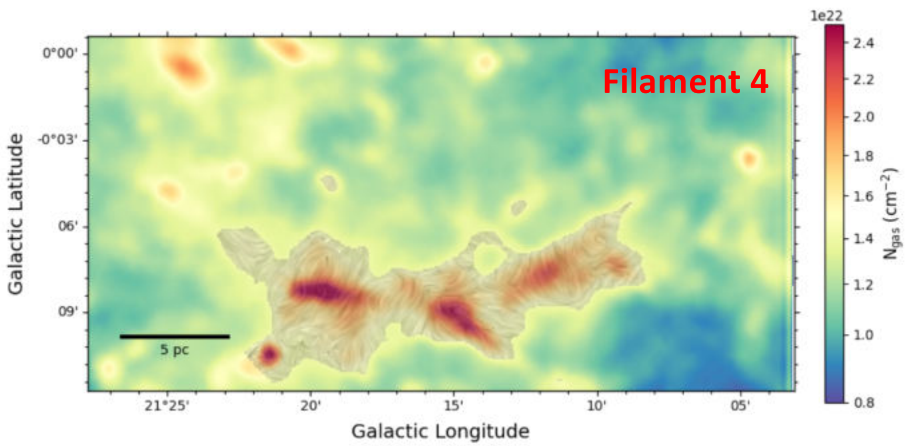
- Quite perpendicular
- Is this a ubiquitous feature?
  - **Additional tries say “Nope!”**
    - **But maybe at the highest densities**

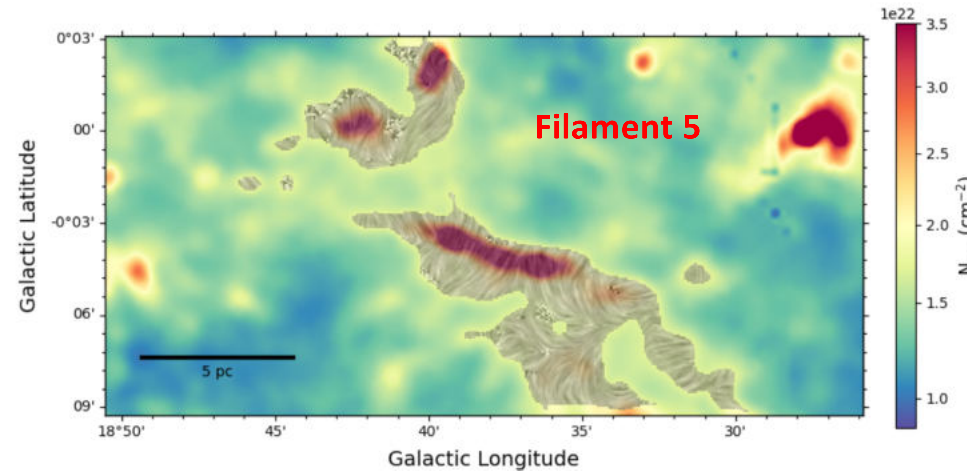
Line Interval Convolutions (LICs)

Credit: Leah Zuckerman



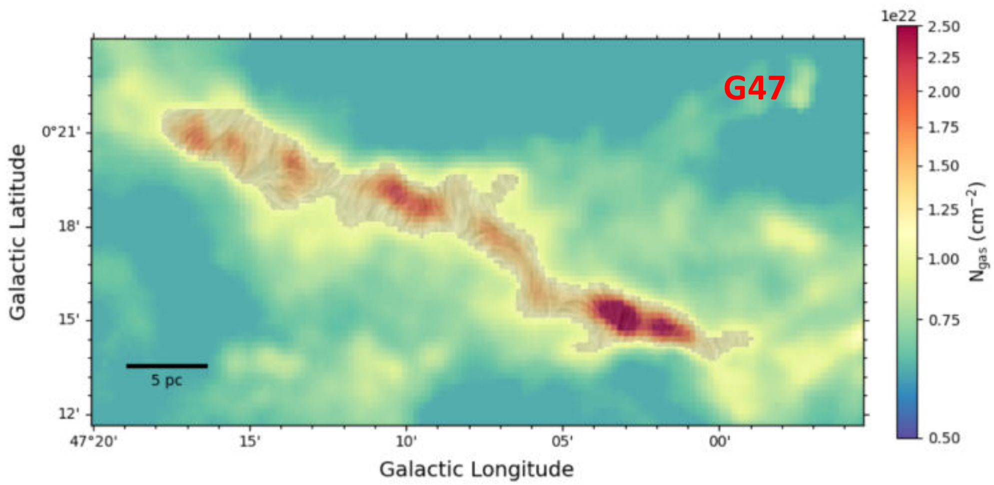


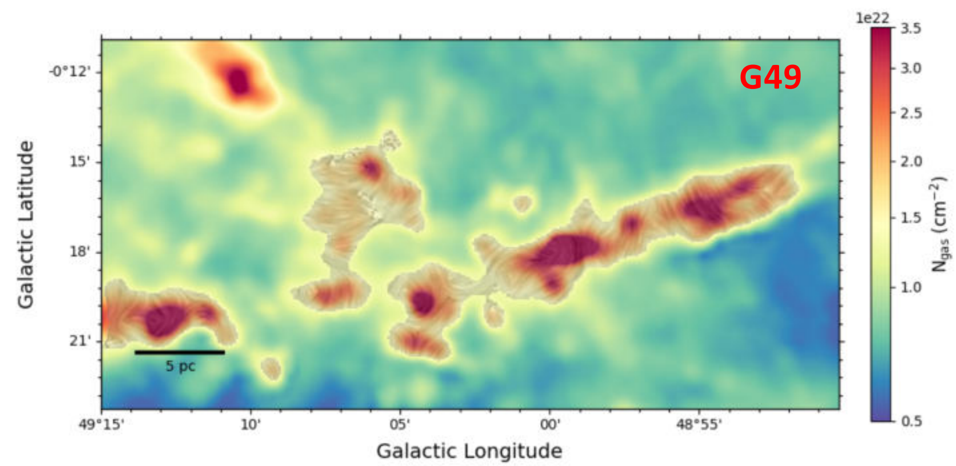




Line Interval Convolutions (LICs)

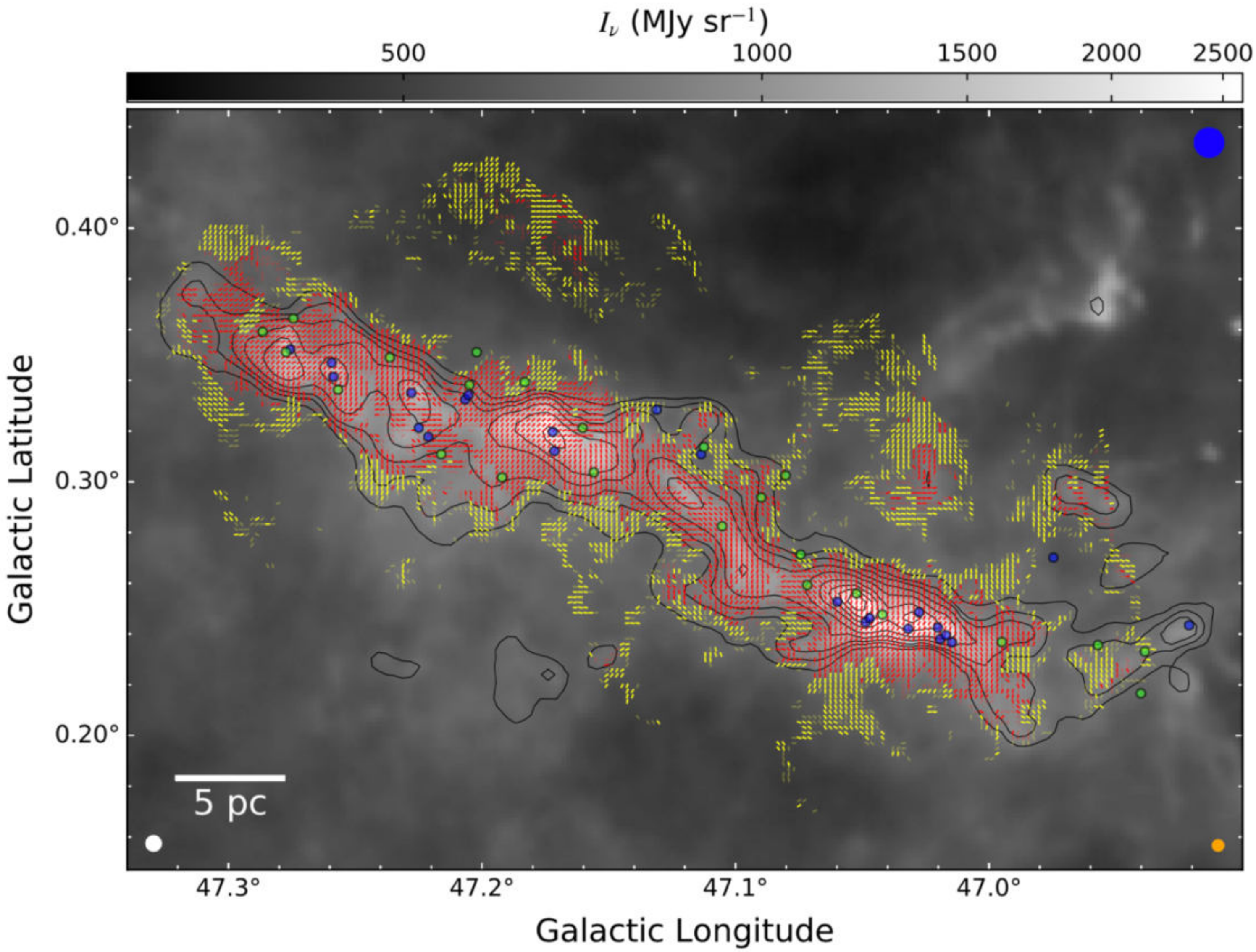
Credit: Leah Zuckerman

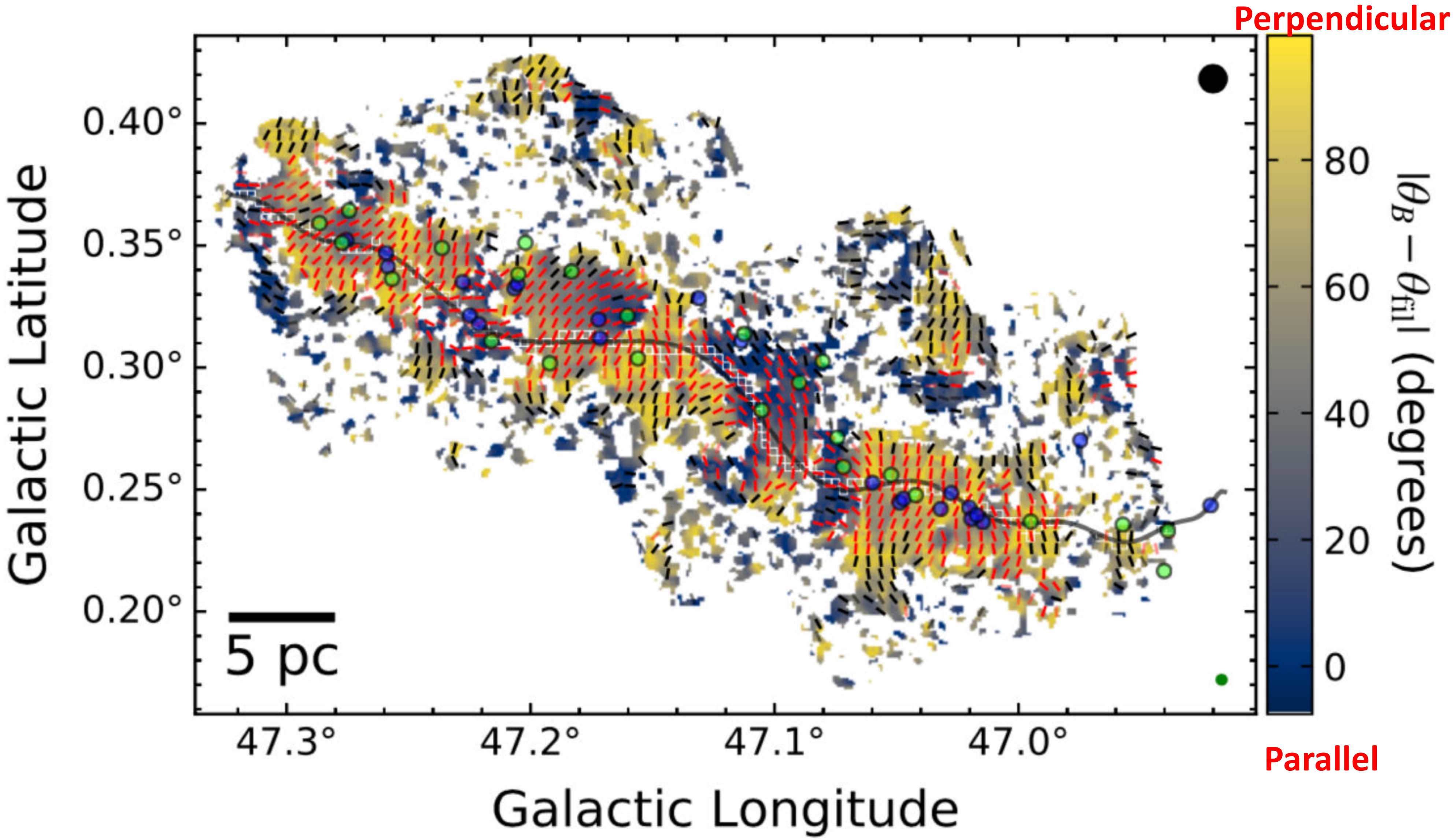




- G47 in ApJL
- Stephens et al. (2022)

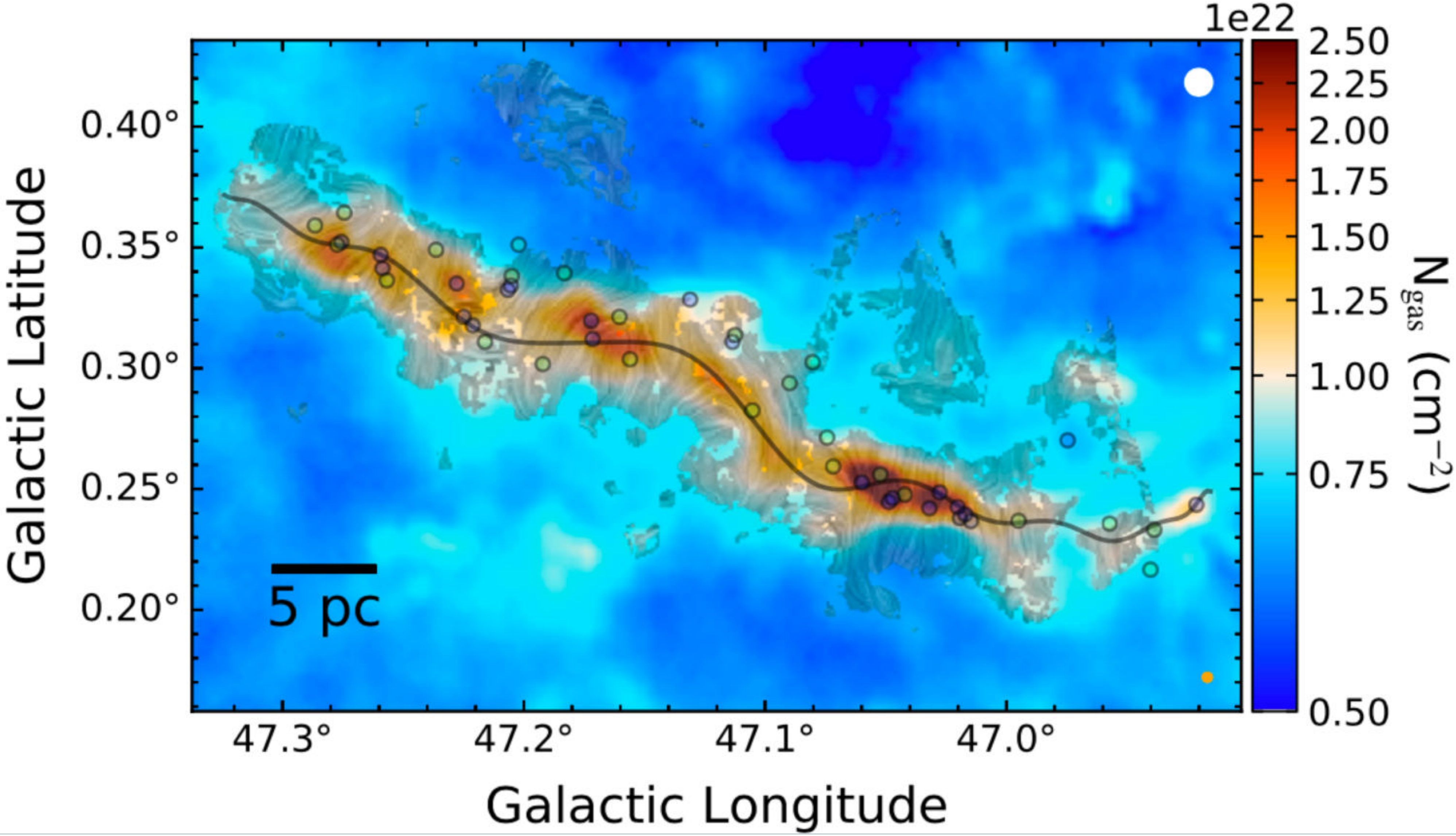
- **Green** and **Blue** circles: Locations of Young Stellar Objects (Zhang et al. 2019)





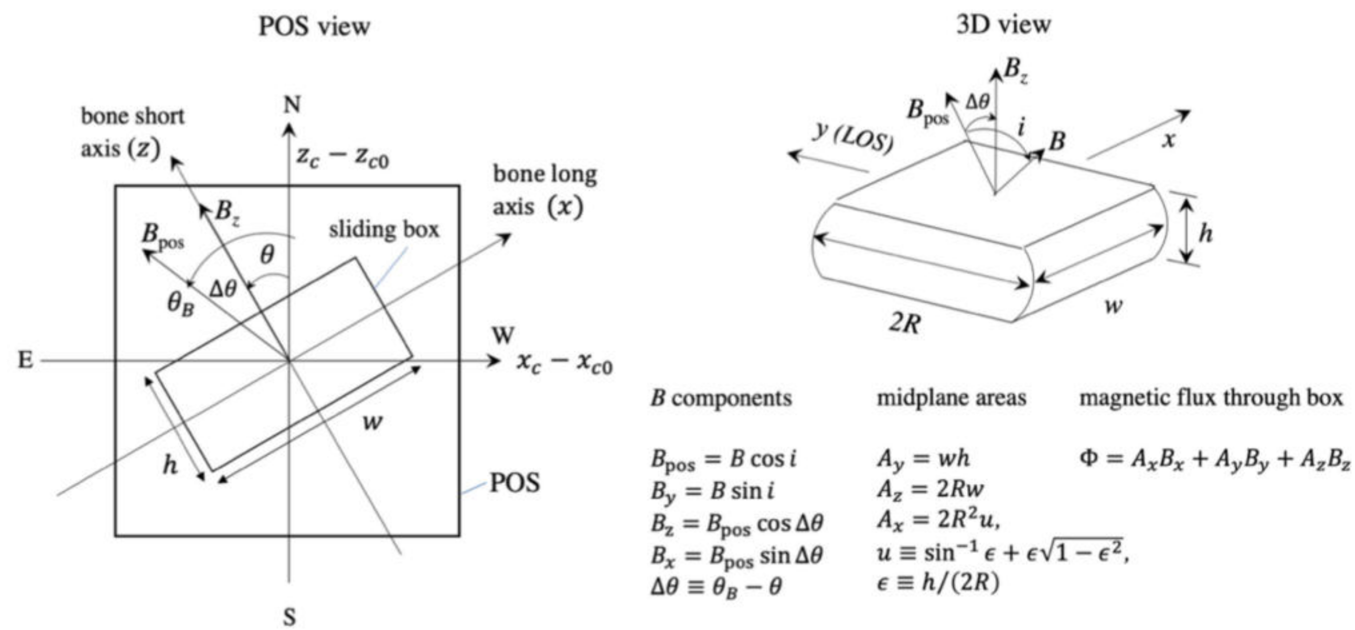
Perpendicular
Parallel
Galactic Latitude
Galactic Longitude
0.40°
0.35°
0.30°
0.25°
0.20°
47.3°
47.2°
47.1°
47.0°
5 pc
80
60
40
20
0
$|\theta_B - \theta_{\rm fil}|$ (degrees)

Credit: G47: ESA/Herschel/PACS/SPIRE/Ke Wang et al. 2015; Polarization map: Stephens et al., 2022


1e22
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
N_{gas} (cm^{-2})
0.40°
0.35°
0.30°
0.25°
0.20°
Galactic Latitude
5 pc
47.3°
47.2°
47.1°
47.0°
Galactic Longitude

Moving Box Analysis

- Slide a moving box down the spine of G47 (can change angle)
- Use the DCF technique to estimate B-field and mass-to-magnetic flux ratio in each box



Stephens et al. (2022)

Moving Box Analysis

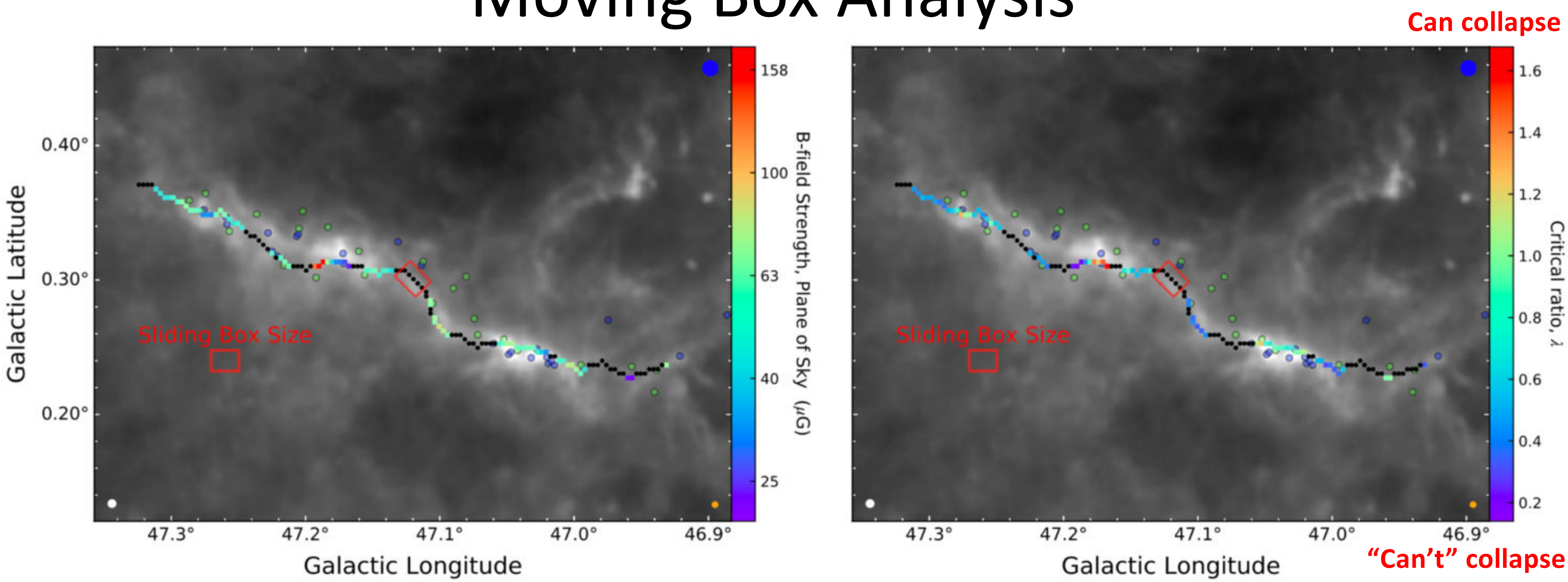
- Critical Ratio

$$\lambda = \frac{(M/\Phi)_{\text{observed}}}{(M/\Phi)_{\text{crit}}}$$

(Crutcher et al. 2004)

- $\lambda < 1$: Magnetic fields can support against gravitational collapse
- $\lambda > 1$: Magnetic fields cannot support against collapse

Moving Box Analysis

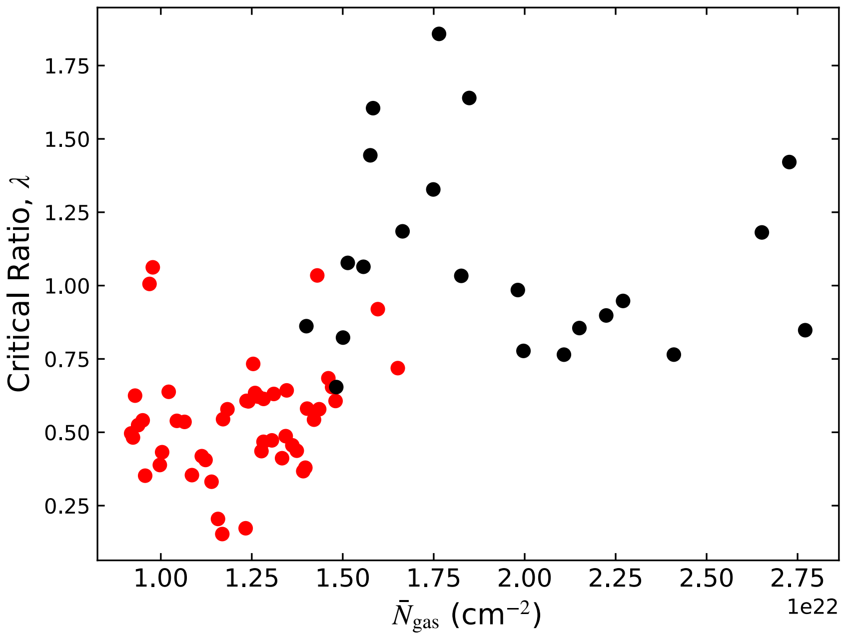


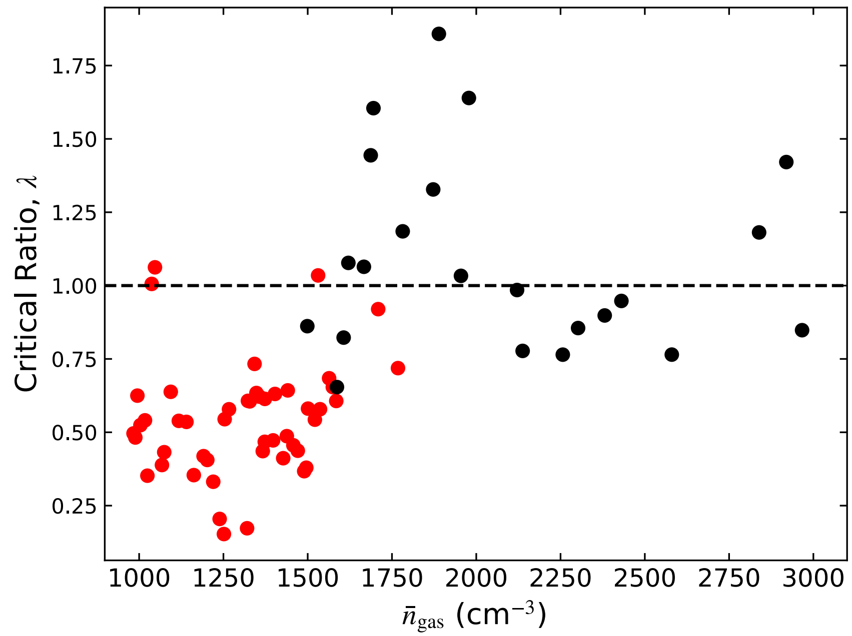
Fields strong enough to support against collapse along a lot of the bone. However, not necessarily toward areas with recent star formation

- **Higher densities are more likely to collapse**
- **Correlated with locations of known YSOs**

Can collapse

"Can't" collapse





Spherical Flux Freezing (SFF) model

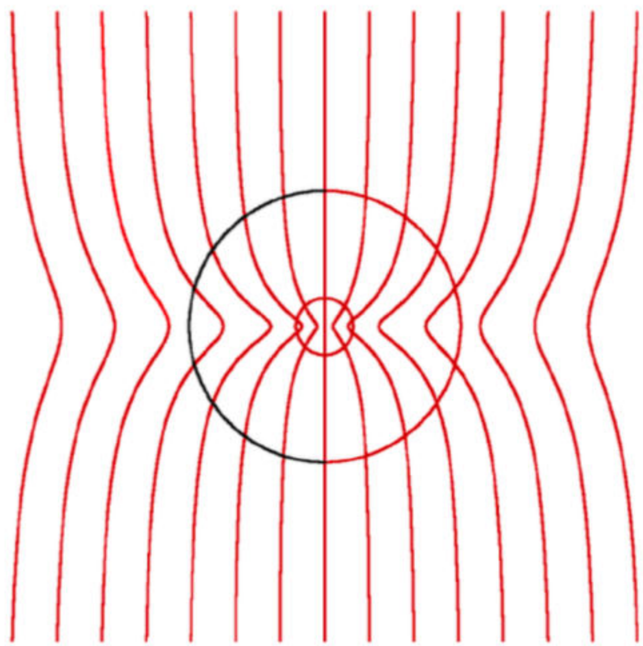
Four reasonable assumptions:

- Background density
- Background B-field
- Collapse to a Plummer spheroid
- Flux-freezing

Straightforward to calculate the magnetic field throughout entire spheroid

Myers et al. (2018, 2020)

Also can do forward-modeling

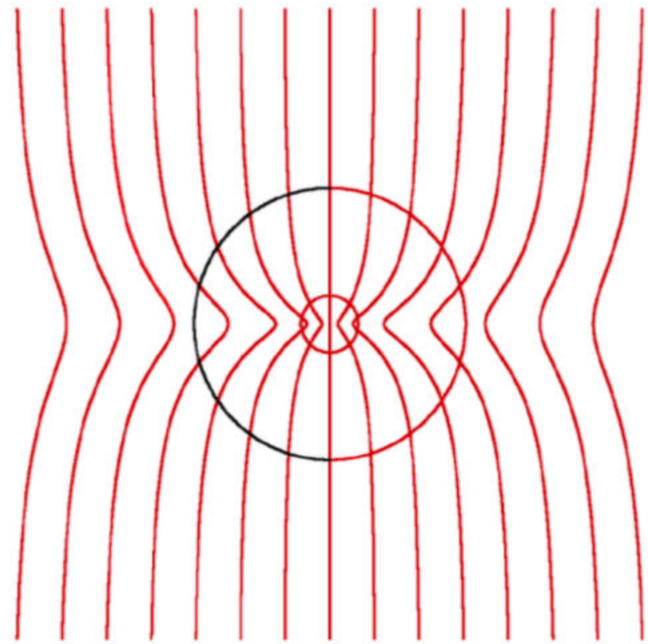


Example of sphere above. Can be applied to any spheroid (including inclined) as well as multiple combined

Spherical Flux Freezing (SFF) model

Also can do forward-modeling

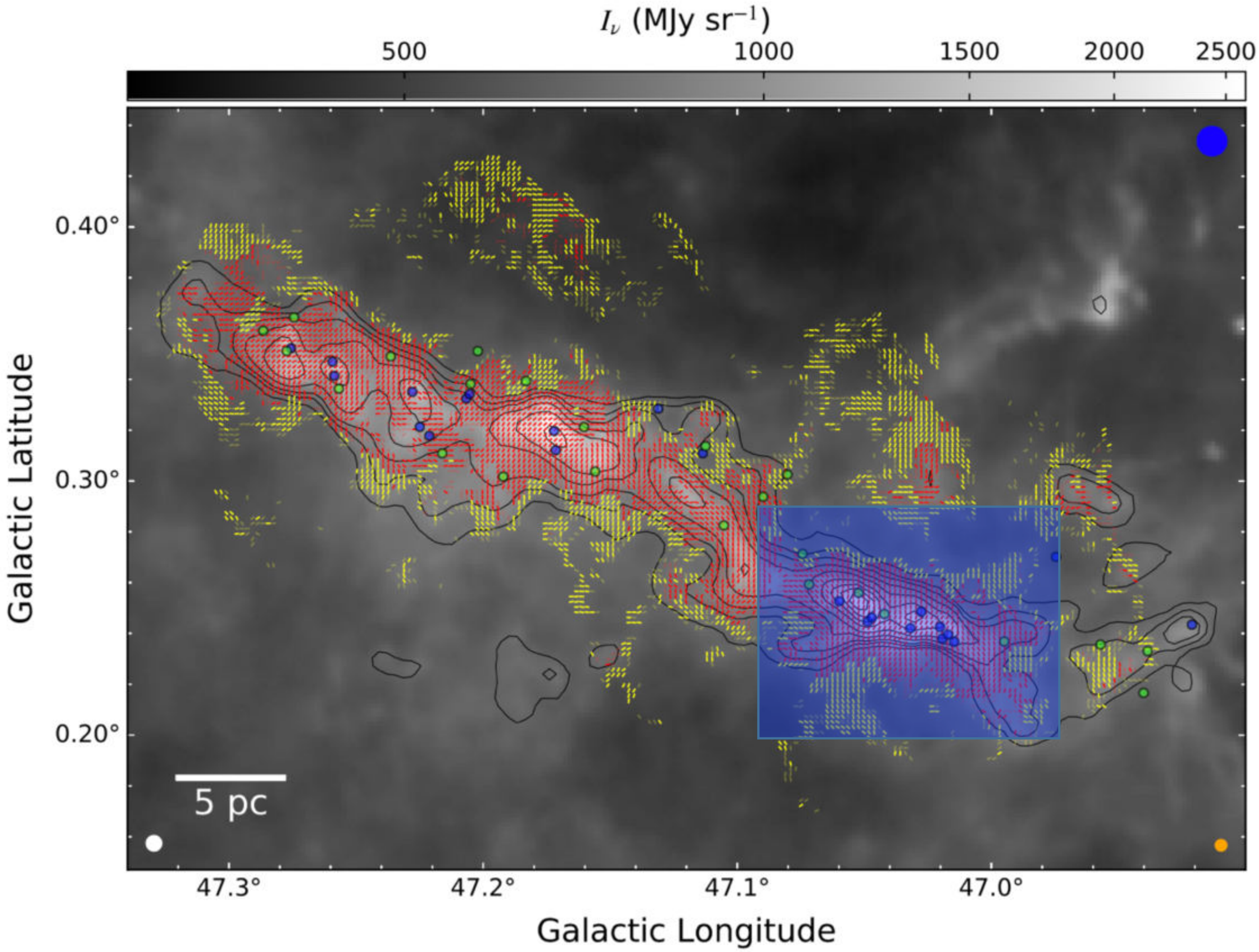
- Fit the spheroids column density maps with Plummer spheroids to determine field morphology
- Use DCF technique to calculate the field strength in area
- This gives you the magnetic field strength everywhere



Example of sphere above. Can be applied to any spheroid (including inclined) as well as multiple combined

Myers et al. (2020)

- G47 in ApJL
- Stephens et al. (2022)

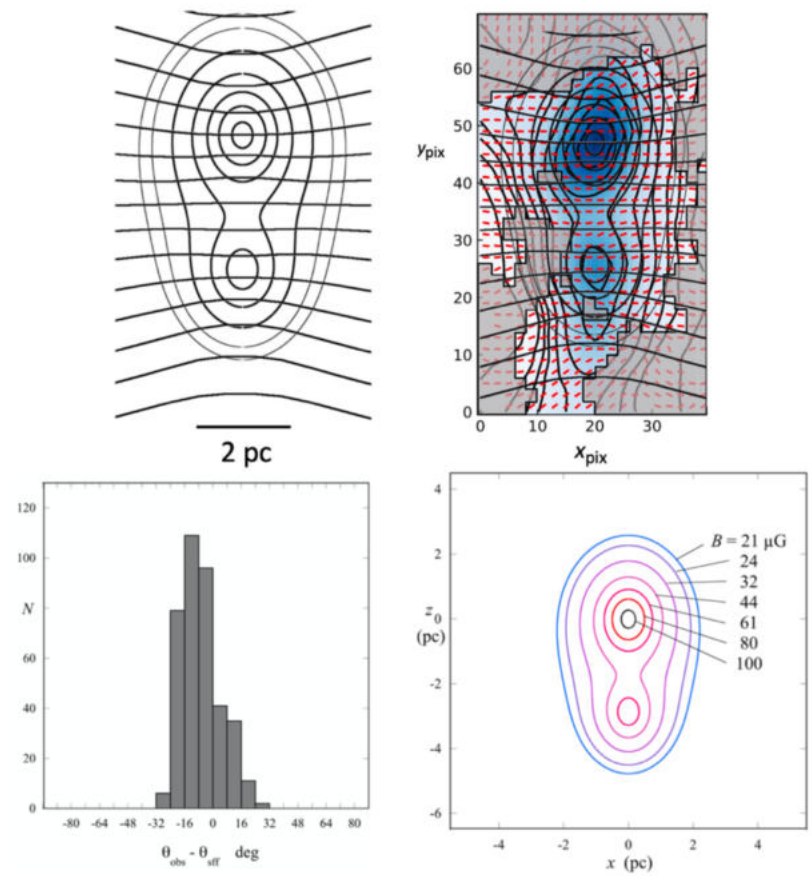


Spherical Flux Freezing (SFF) model

Applied to G47 using two spheroids

Peak field strength: 108 μG
Average field strength: 56 μG

Mass-to-magnetic flux parameter: 1.7
(critical for collapse)



Stephens et al. (2022)

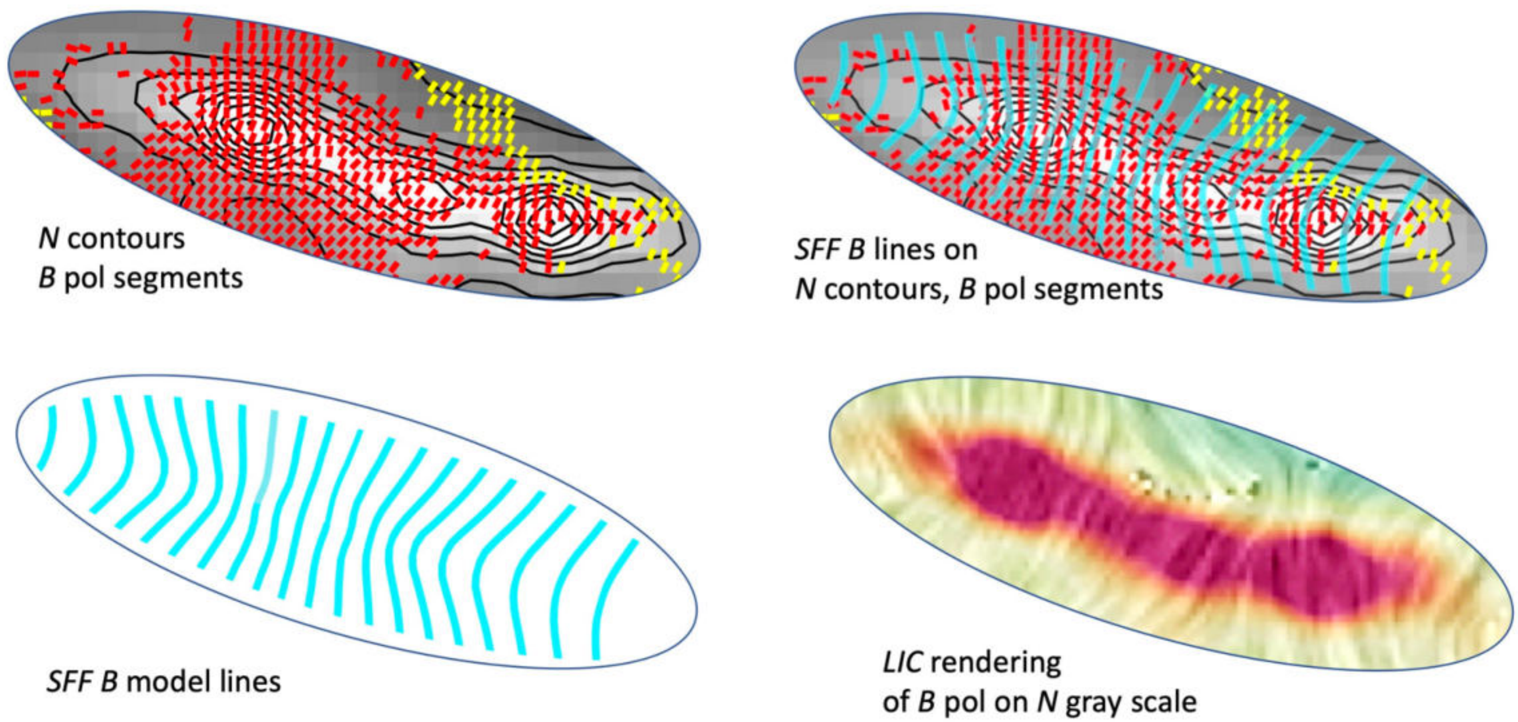
Quick summary of G47 Results

- Magnetic fields are structured but not ubiquitously perpendicular
- Field strengths of ~20 μG to 100 μG
- Fields are strong enough to support bone, except in locations of active star formation (highest column densities)
  - Potentially unstable to gravitational collapse at smaller scales

Spherical Flux Freezing (SFF) model

Proof of Concept: Filament 5

FIELDMAPS project: Filament 5 *SOFIA* polarization, *N* column density, *B* field lines

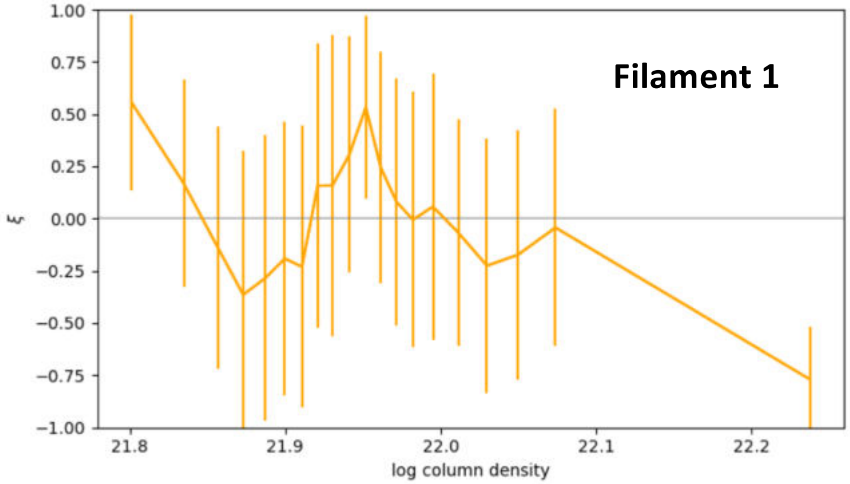


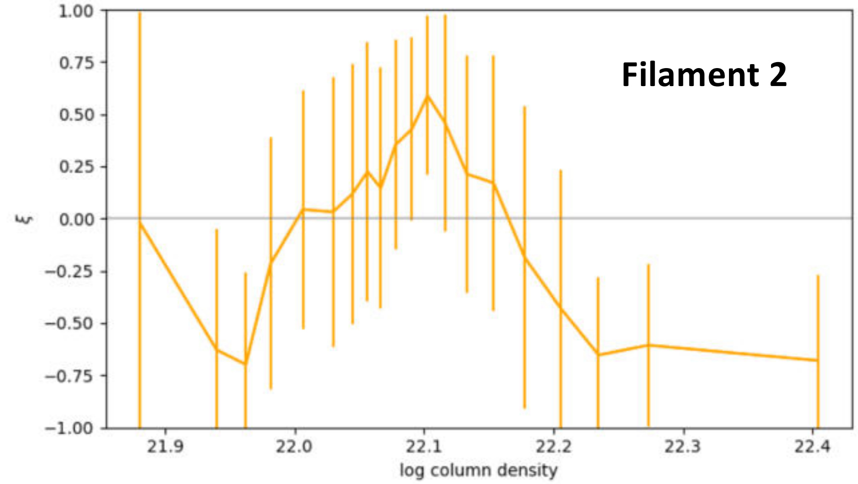
PCM 19Oct21

Histograms of Relative Orientations (HROs)

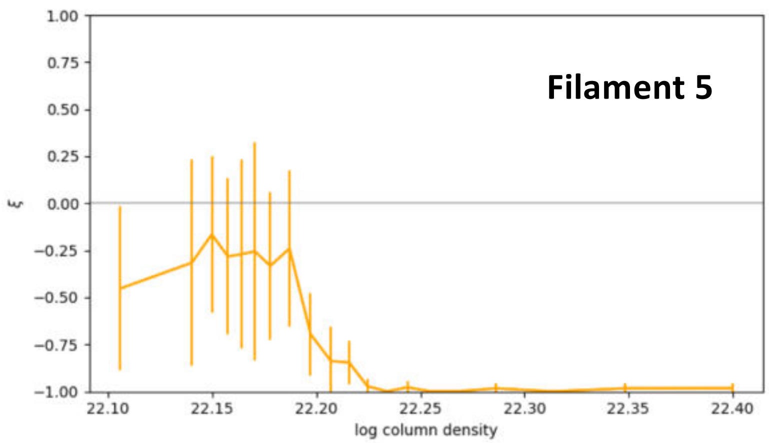
Fields Parallel w/ Bone

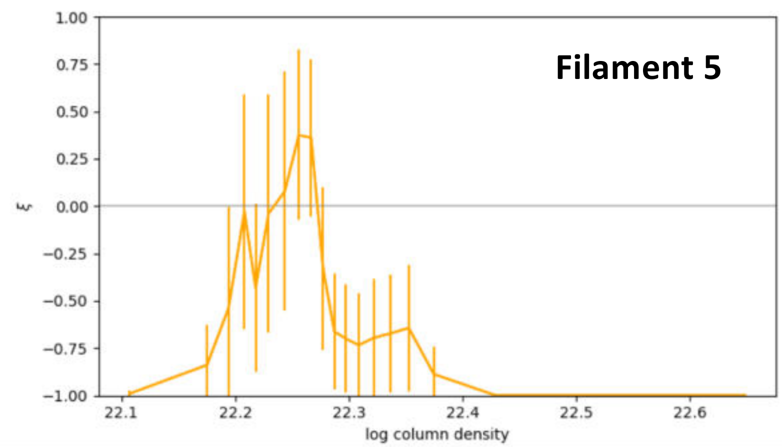
Fields Perpendicular w/ Bone





Credit:
Leah Zuckerman

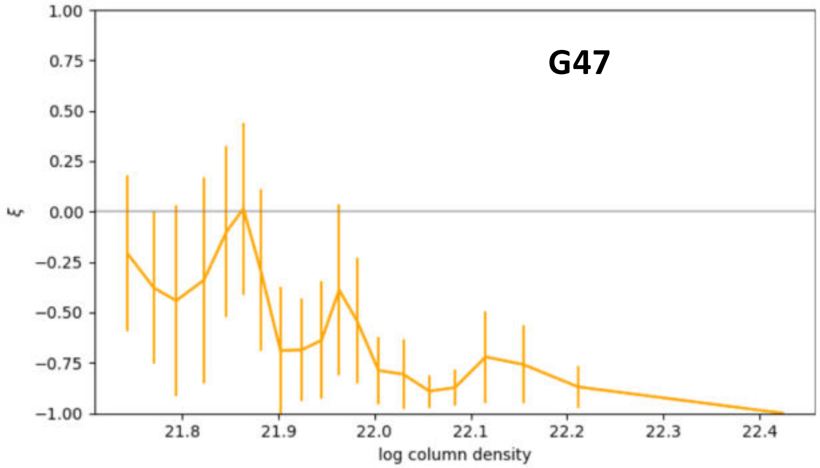


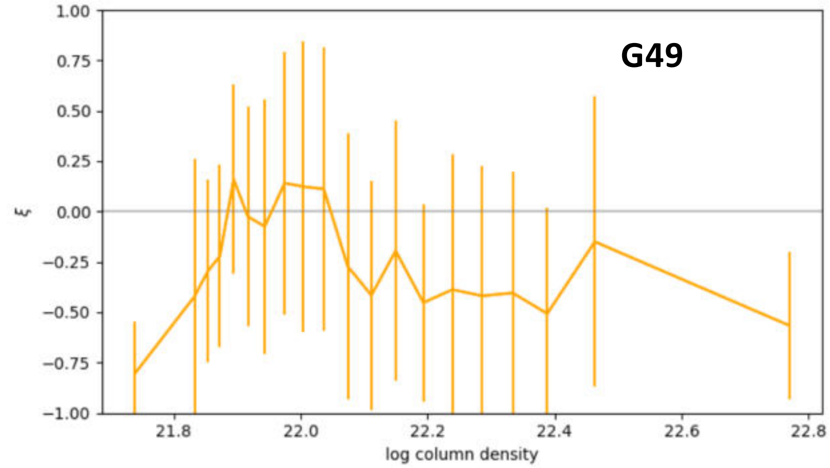


Histograms of Relative Orientations (HROs)

Fields Parallel w/ Bone

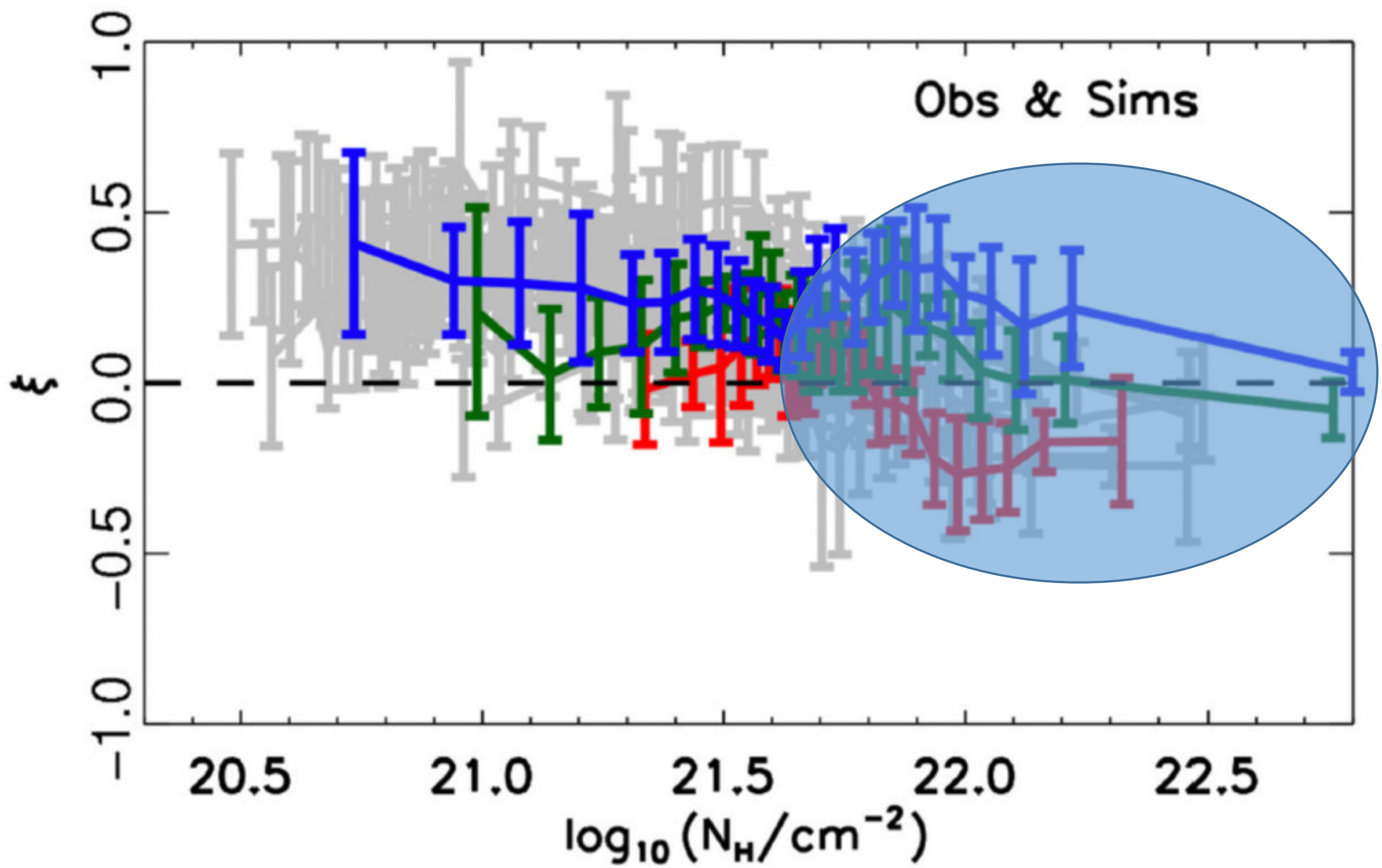
Fields Perpendicular w/ Bone





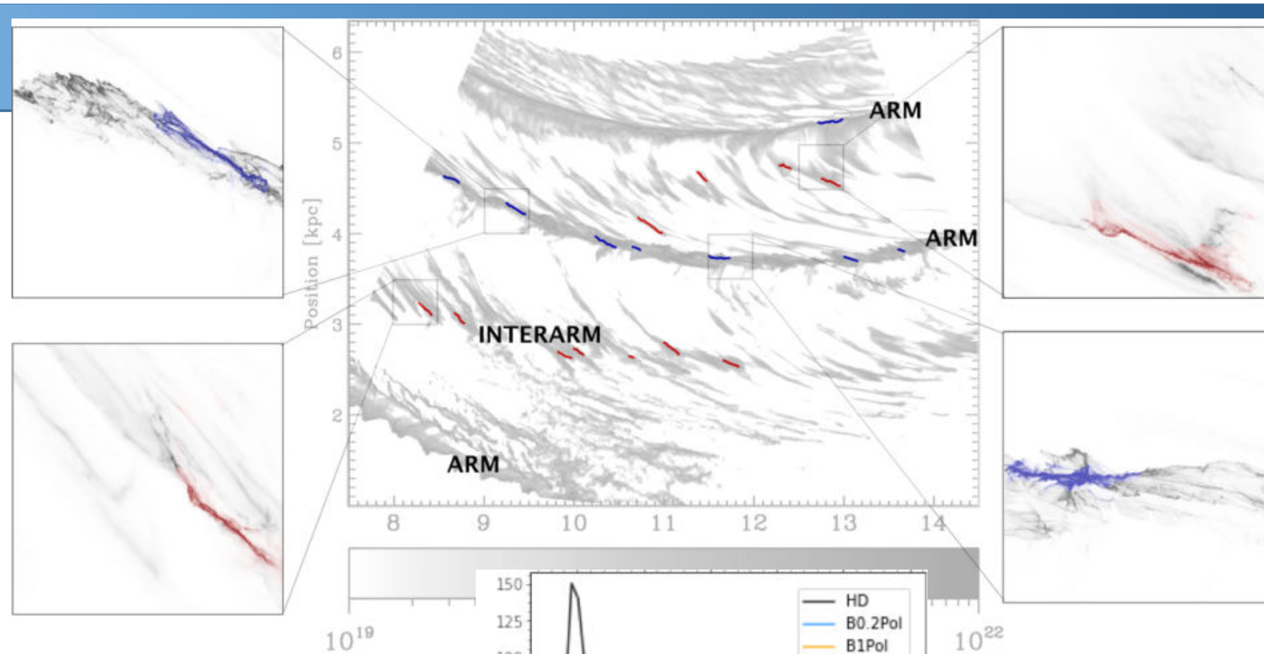
Credit:
Leah Zuckerman

High columns: Perpendicular with Bones. Otherwise, more random

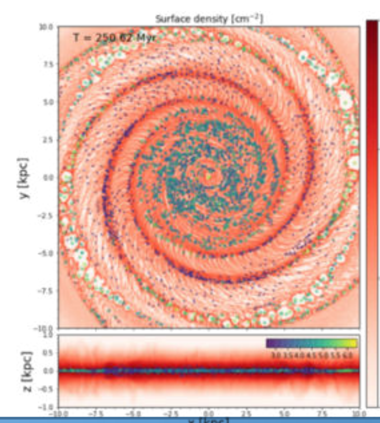

Obs & Sims
1.0
0.5
0.0
−0.5
−1.0
ξ
20.5
21.0
21.5
22.0
22.5
log10(NH/cm−2)

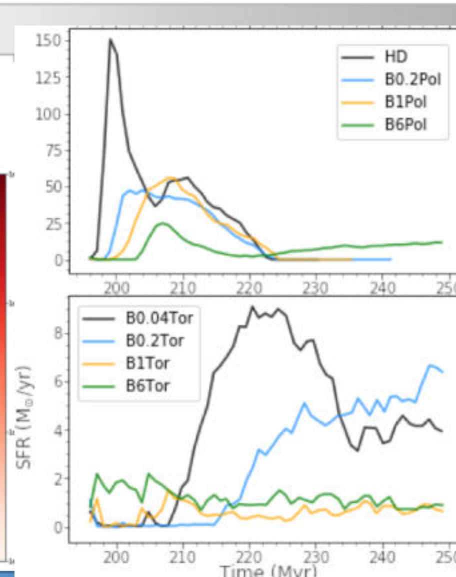
Simulations by team members
Rowan Smith et al. (2014, 2020)

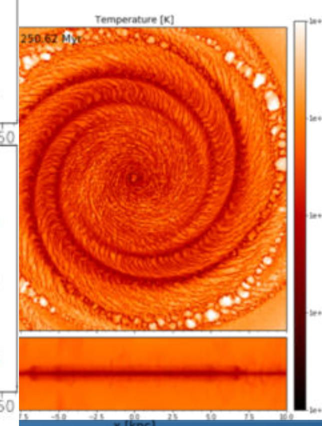
Observational comparisons
Zucker et al. (2019)

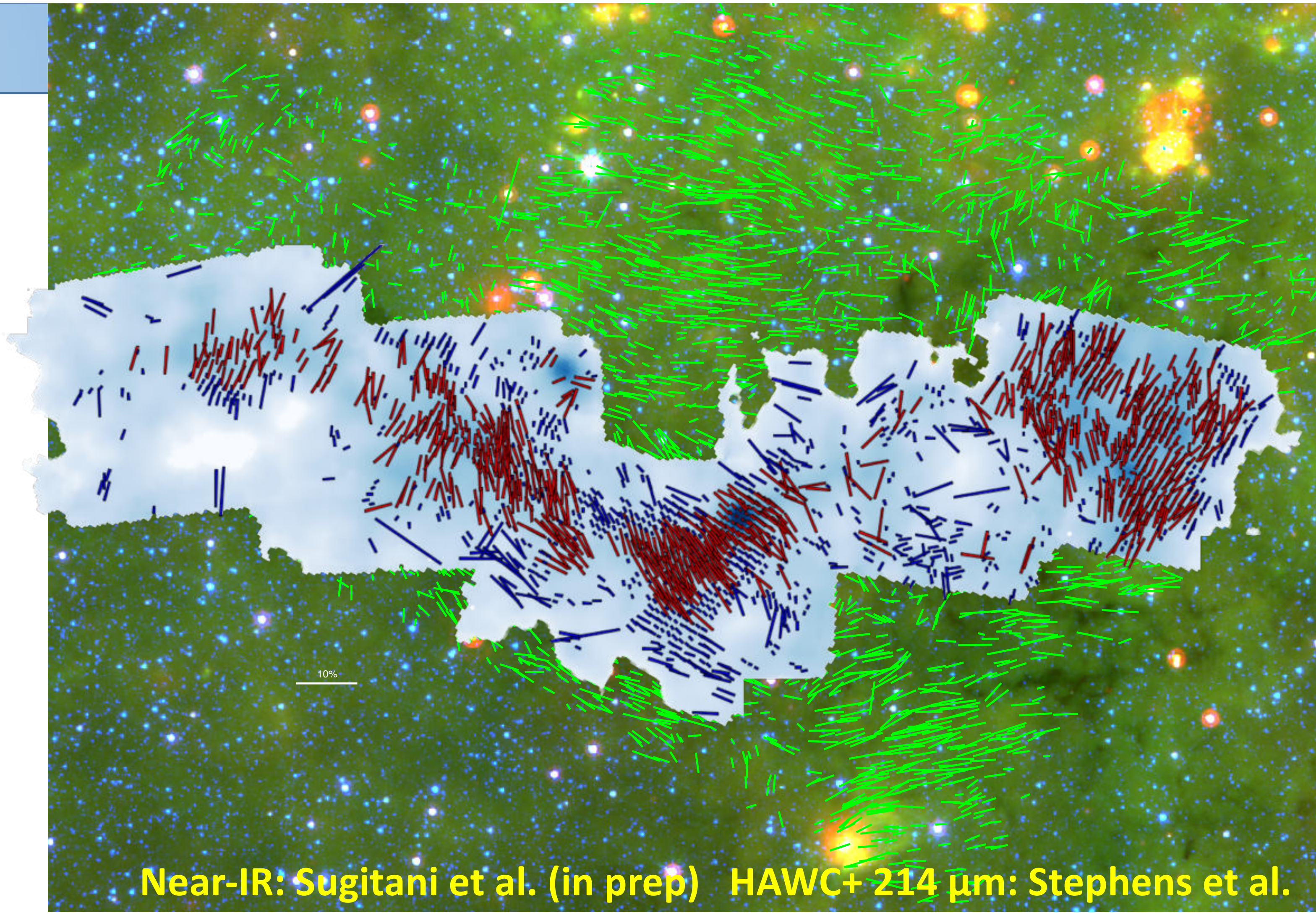


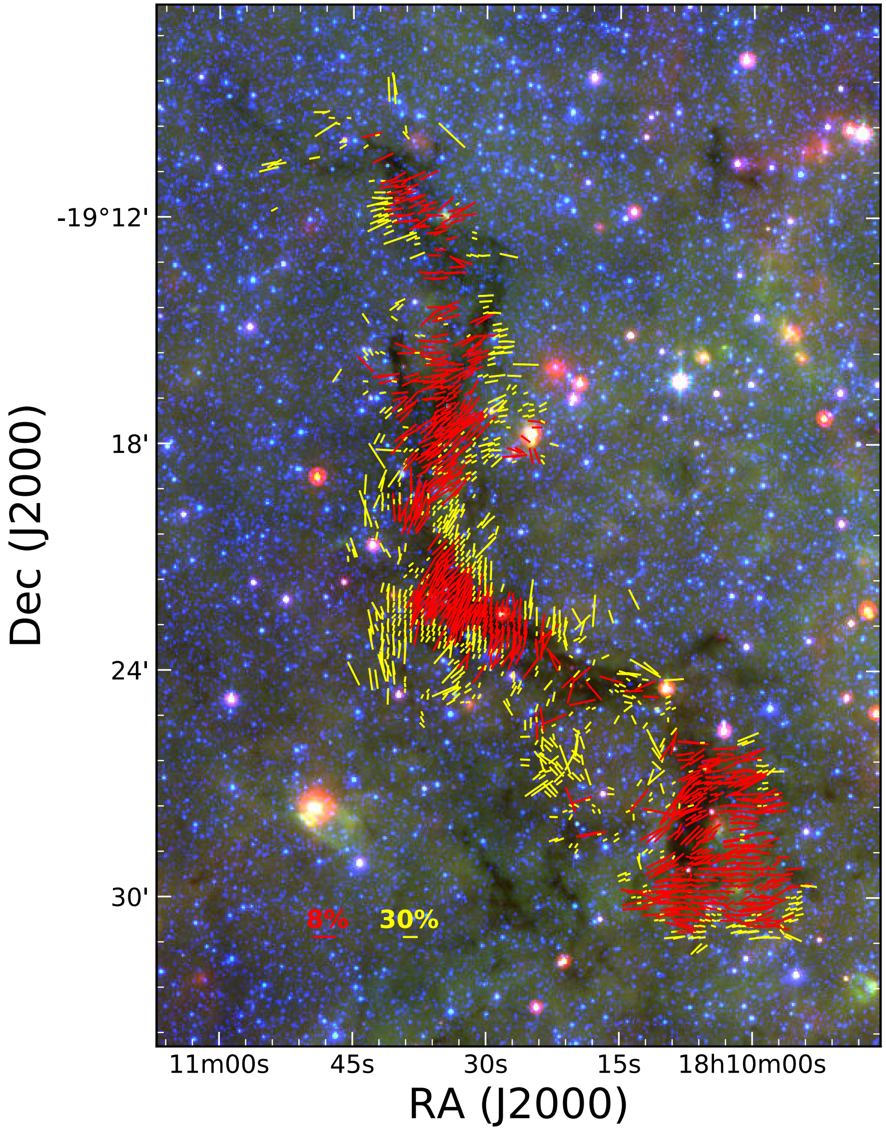
Initial simulations adding magnetic fields
Will compare using POLARIS code

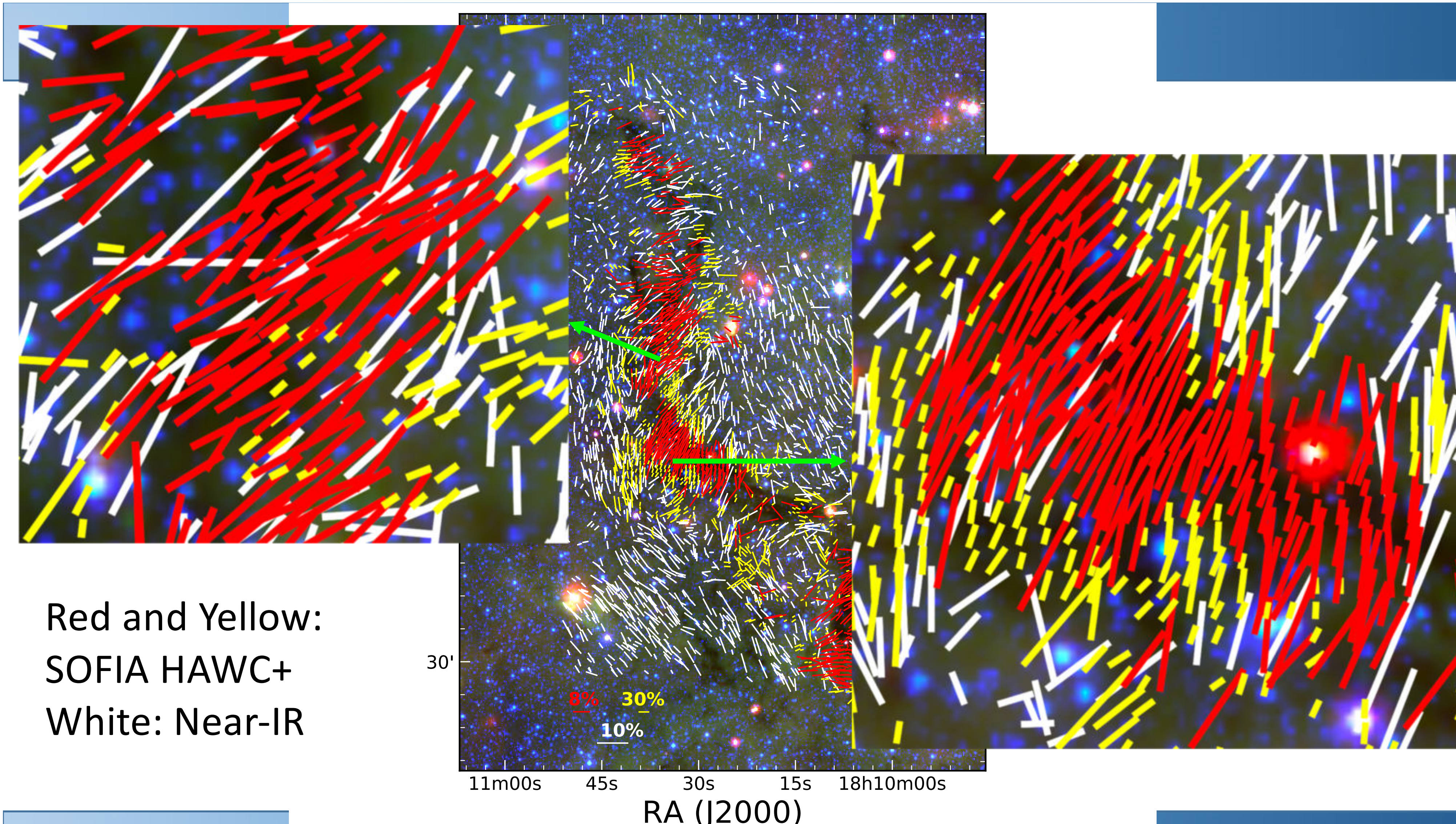




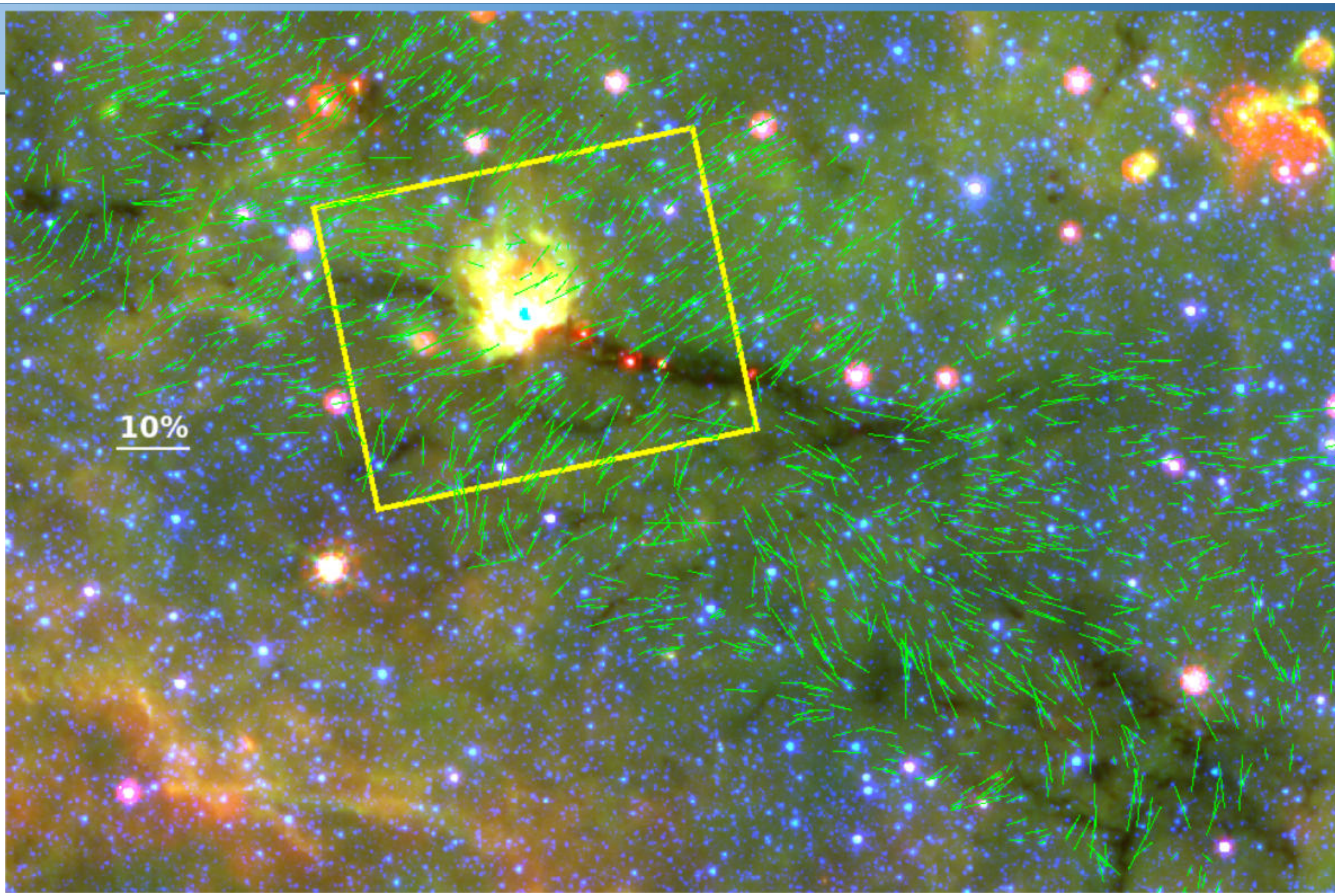



10%
Near-IR: Sugitani et al. (in prep)   HAWC+ 214 μm: Stephens et al.

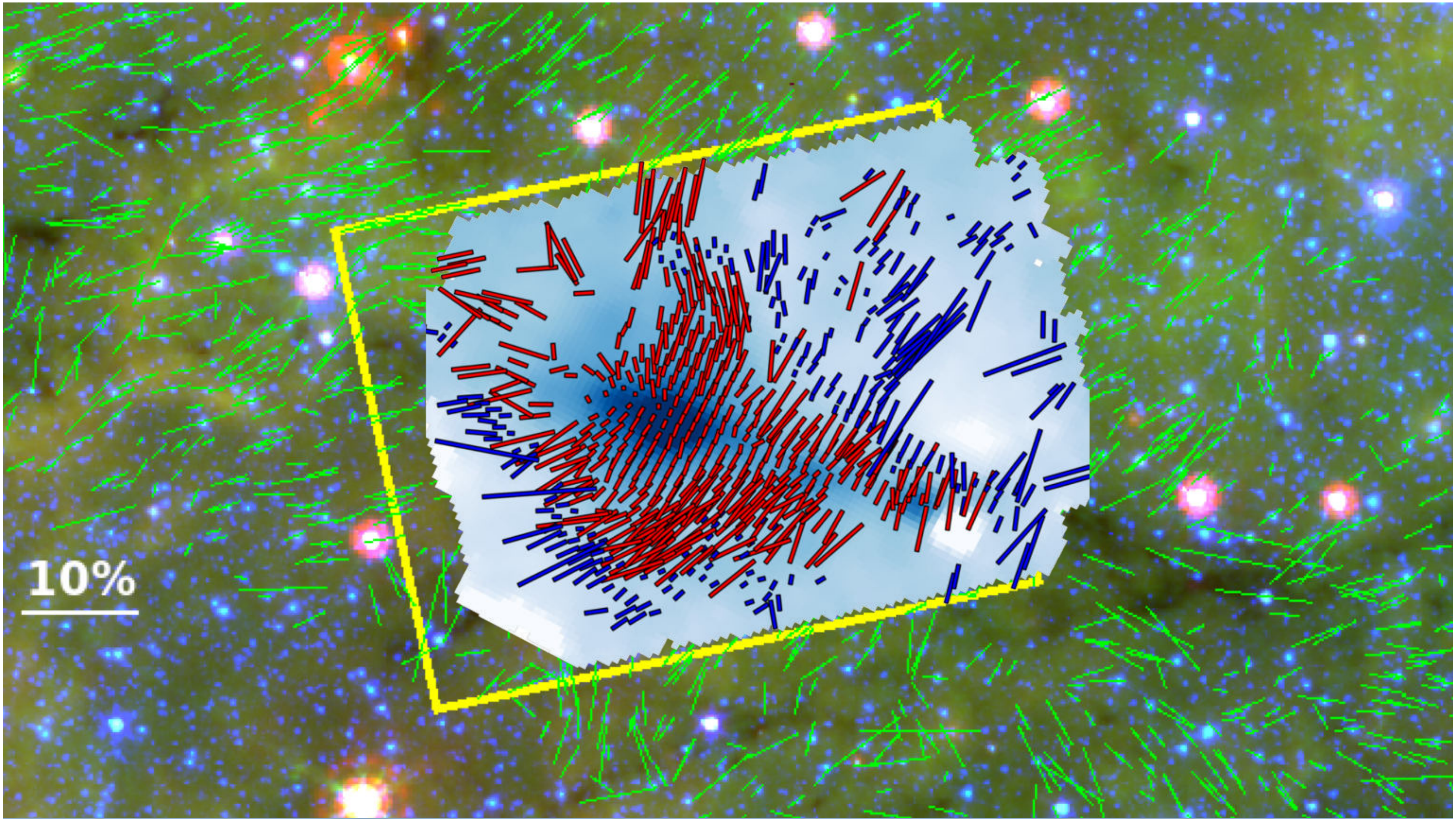

-19°12'
18'
24'
30'
Dec (J2000)
8%
30%
11m00s
45s
30s
15s
18h10m00s
RA (J2000)



Red and Yellow:
SOFIA HAWC+
White: Near-IR



Sugitani et al. (in prep)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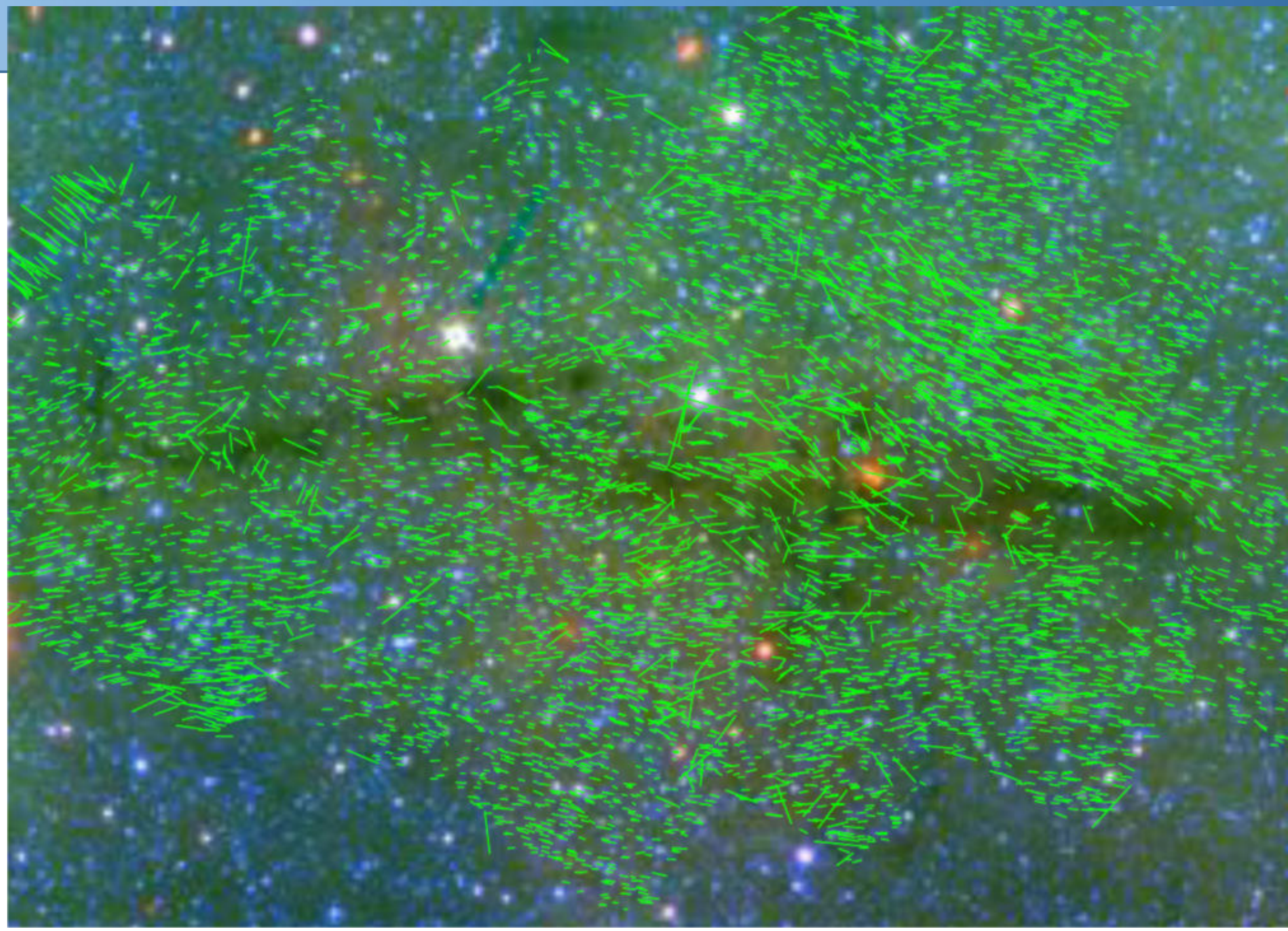
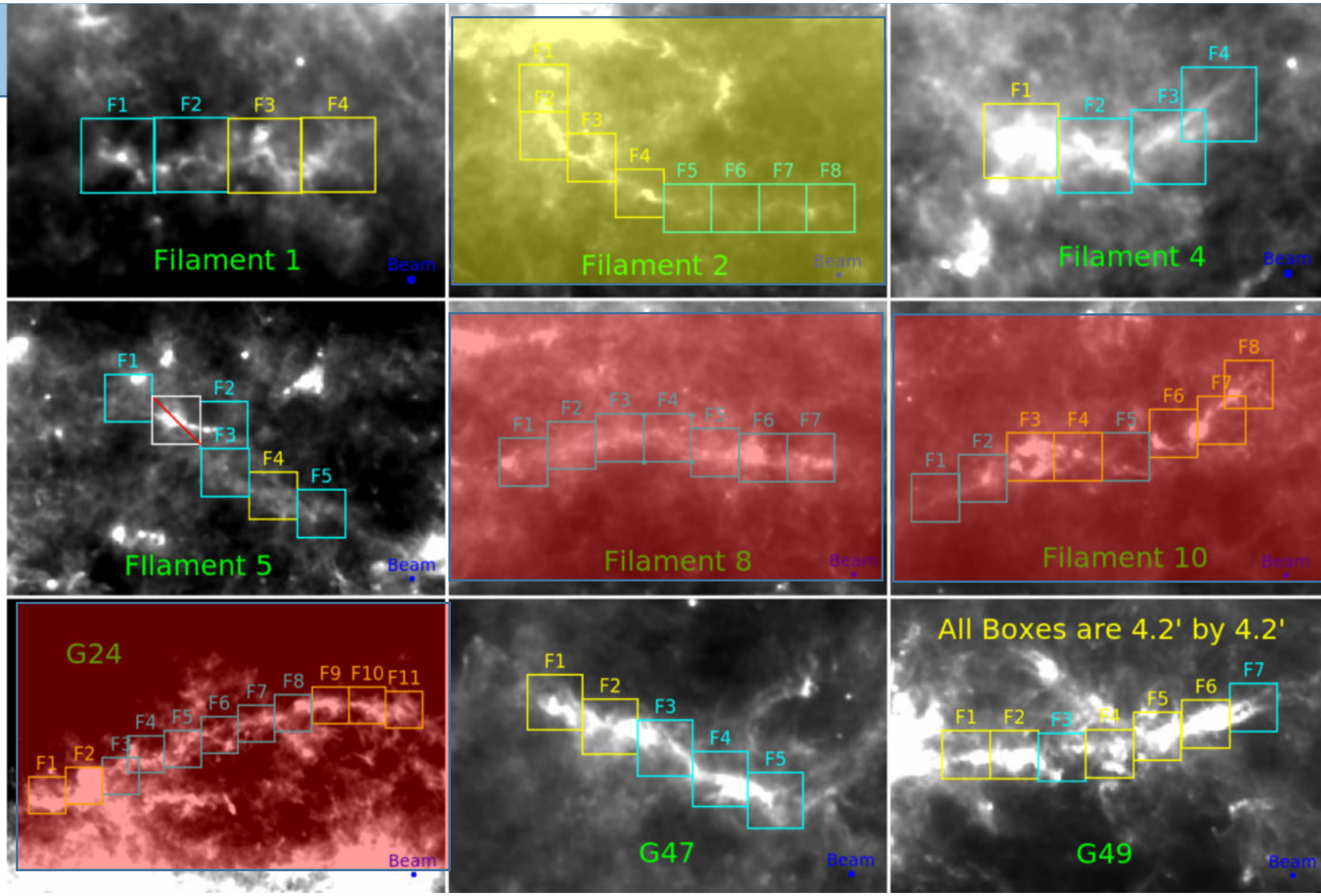


Sugitani et al. (in prep)

Perhaps the best map: Filament 8. Not yet observed



FIELDMAPS: FIlaments Extremely Long and Dark: a MAgnetic Polarization Survey

FIELDMAPS' Legacy

- Galaxy MHD Simulations have just reached the point where they achieve resolutions of SOFIA (e.g., Dobbs et al. 2016)
- Will be the best high-resolution data for understanding the role of magnetic fields in collecting star-forming gas in the spiral potential
- Ancillary data to be published with program:
  - Bone parameters from Zucker et al. (2015, 2018)
  - Near-IR polarization observations of all bones lead by Koji Sugitani
  - Molecular line data, e.g., NH_3 from the RAMPS survey (Hogge et al. 2018; in prep)
  - *Spitzer* and *Herschel* data (including column density and temperature maps)
  - YSO locations

Summary

- FIELDMAPS is probing how star-forming gas collapses into the magnetized spiral potential via observing the bones. We are look at the largest known filaments in the Galaxy. The key missing component is the B-field.
- Contrary to expectations, fields are not always perpendicular
- Fields appear to be significantly strong enough to provide support against collapse
- We have shown capability of measuring magnetic field strengths across the Bones and whether they are unstable to collapse
- We have upcoming simulations to compare with