Magnetic Fields in Galactic Star Formation

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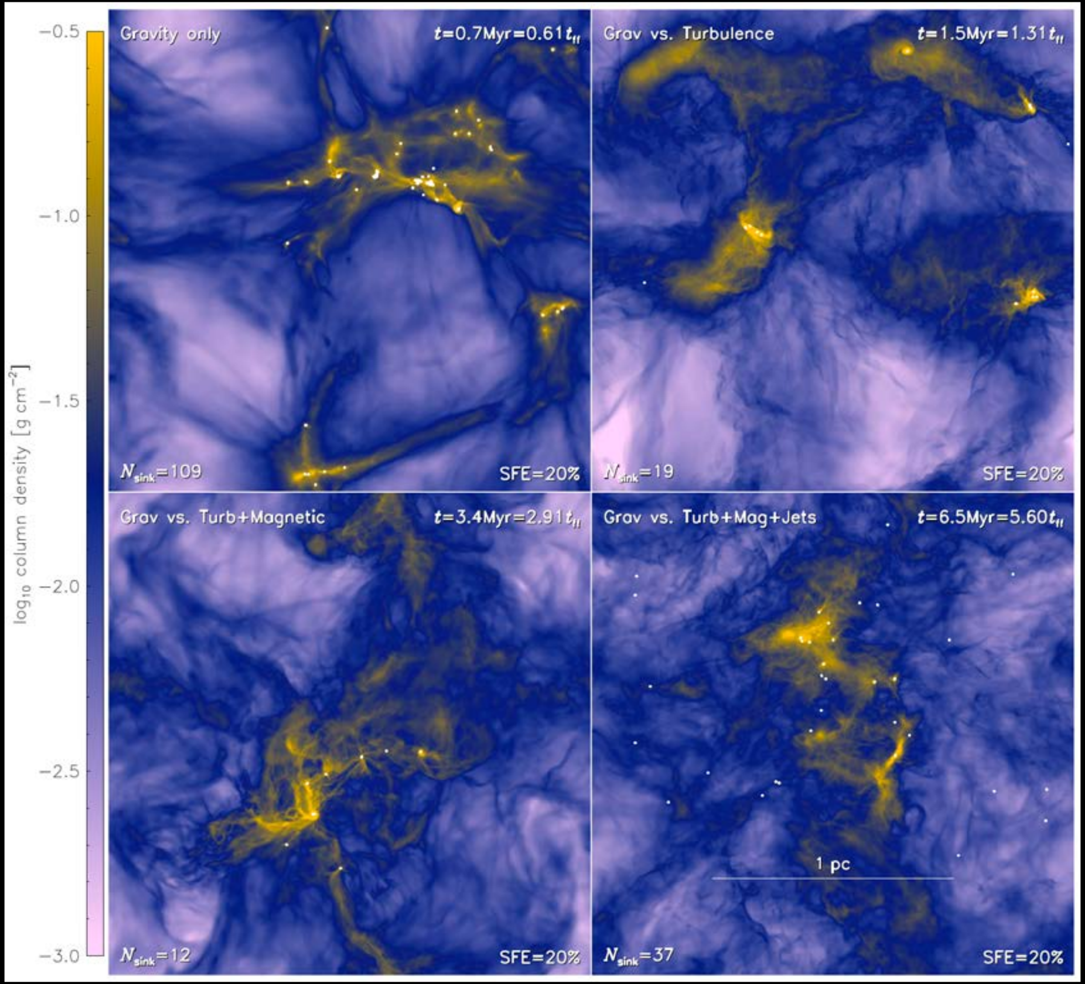
SOFIA Instrument Roadmap Workshop
Tuesday, June 23, 2020

Gravity

Gravity + Turbulence



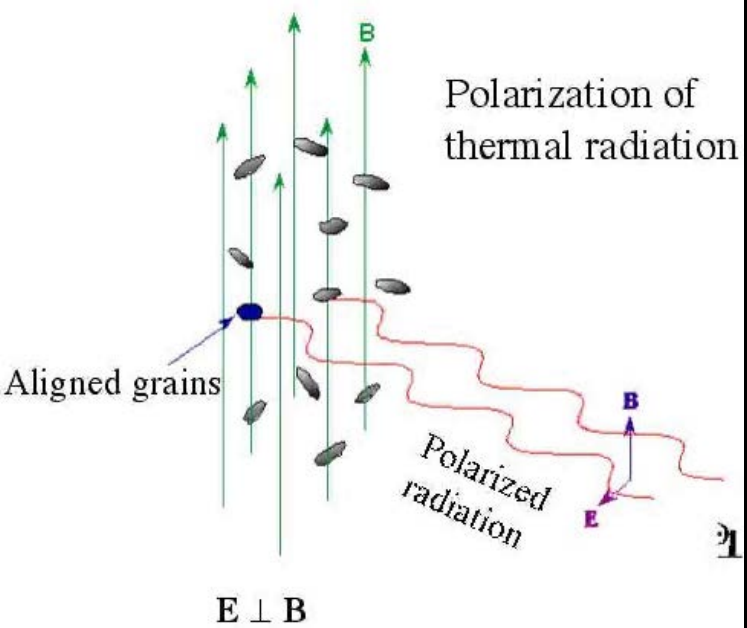
Gravity + Turbulence + Magnetic Fields

Gravity + Turbulence+ Magnetic Fields+ Jets

Column Density, Federrath (2015)

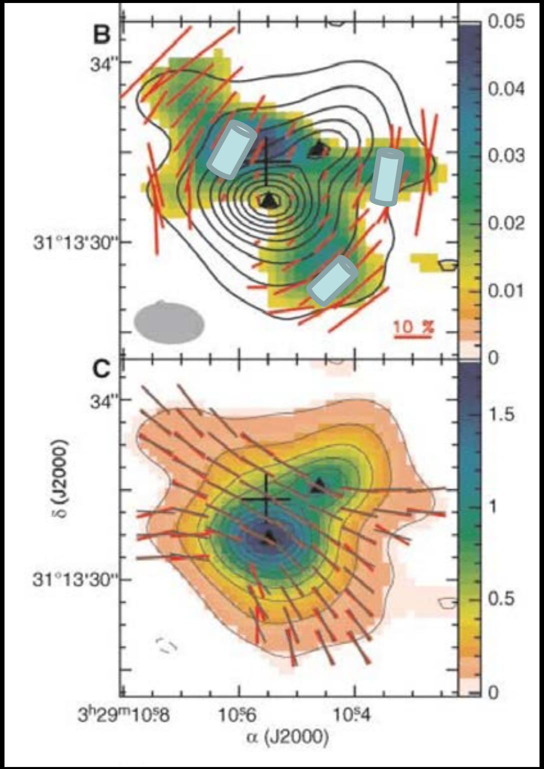
(Sub)millimeter Polarization

Spheroidal grains align with short axis perpendicular to B-field



Lazarian (2007)

(Sub)millimeter Polarization



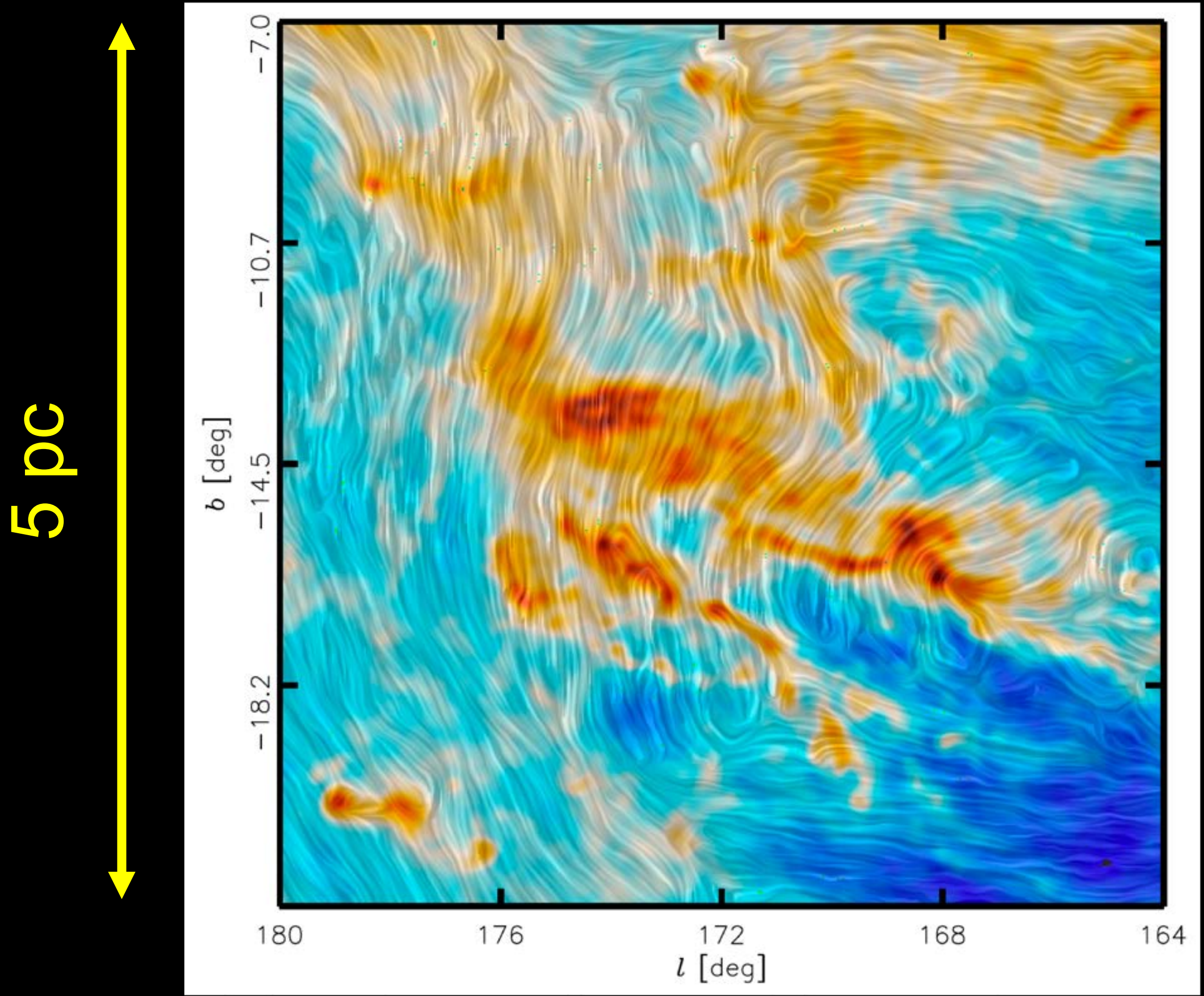
NGC1333 IRAS 4A
Girart et al. (2006)

Polarized Emission from Grains

Top Panel: Plotting Polarization "Vectors"

Bottom Panel: Rotate vectors by 90°, call it magnetic field direction

Works pretty darn well for things >100 AU.



Planck XXXV
Taurus

Planck XXXV

Did NOT resolve filaments
(10' resolution, ~0.4 pc resolution).

They did find:

1) Fields parallel to low density elongations
2) Fields perpendicular to high density elongations
3) To produce the above, simulations suggest magnetic field energy density must be as strong or stronger than turbulence

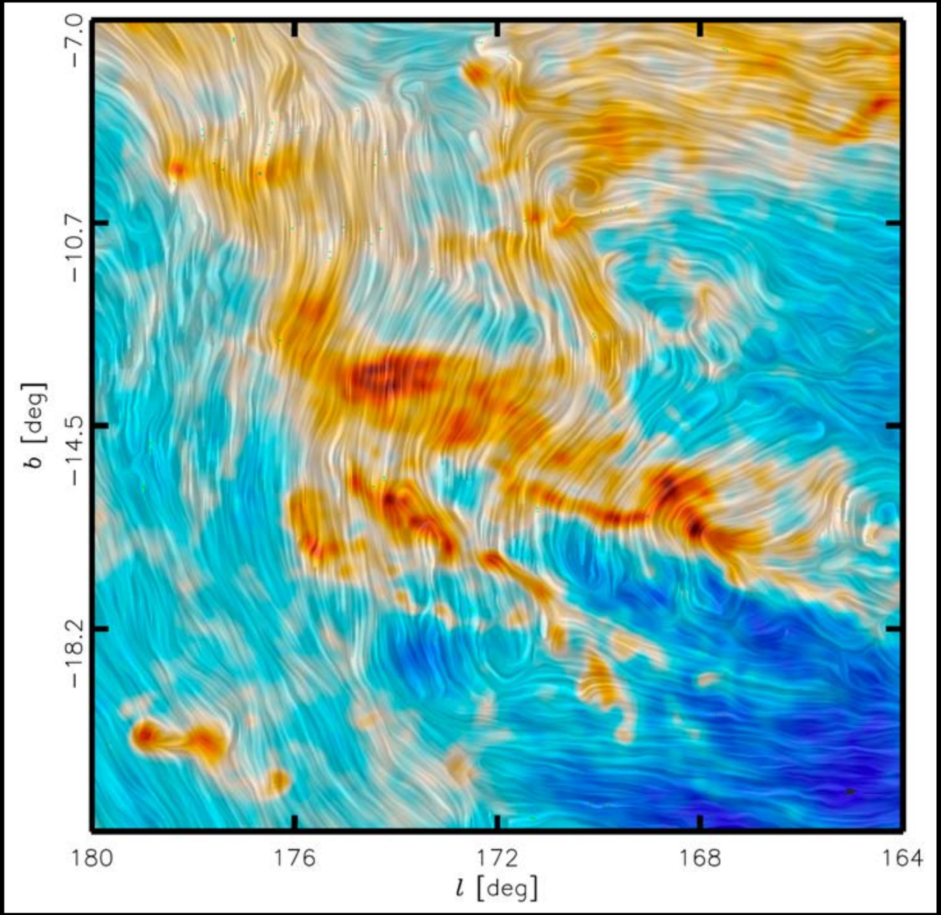


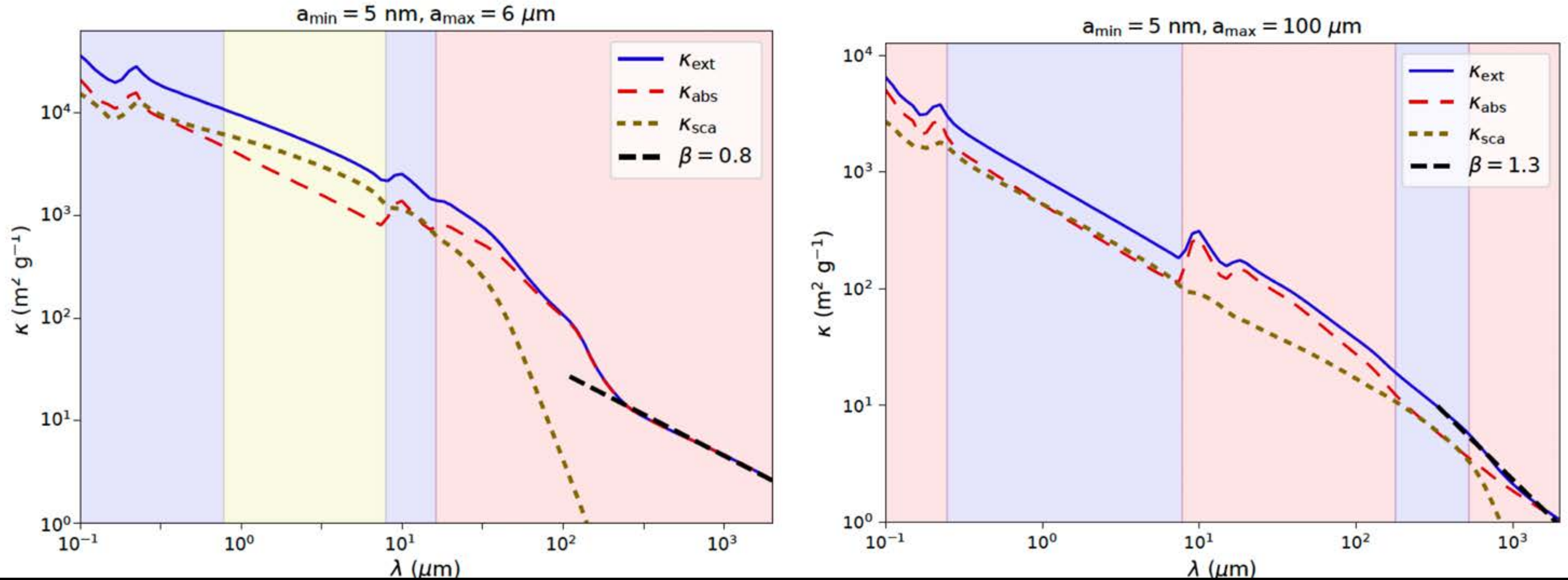
Table 1. HAWC+ basic optical specifications.

Band name	Band center (microns)	FWHM Bandwidth (microns)	Pixel size (arcsec)	Beam size (arcsec FWHM)	Polarimetry field of view[a] (arcmin)	Photometry field of view[a] (arcmin)	Instantaneous point-source sensitivity[b] (Jy $s^{0.5}$)
A	53	8.7	2.55	4.85	1.4×1.7	2.8×1.7	1.9
B	62	8.9	4.02	(footnote c)	2.1×2.7	4.2×2.7	(footnote c)
C	89	17	4.02	7.8	2.1×2.7	4.2×2.7	2.2
D	154	34	6.90	13.6	3.7×4.6	7.4×4.6	2.0
E	214	44	9.37	18.2	4.2×6.2	8.4×6.2	1.7

Harper et al. (2018)

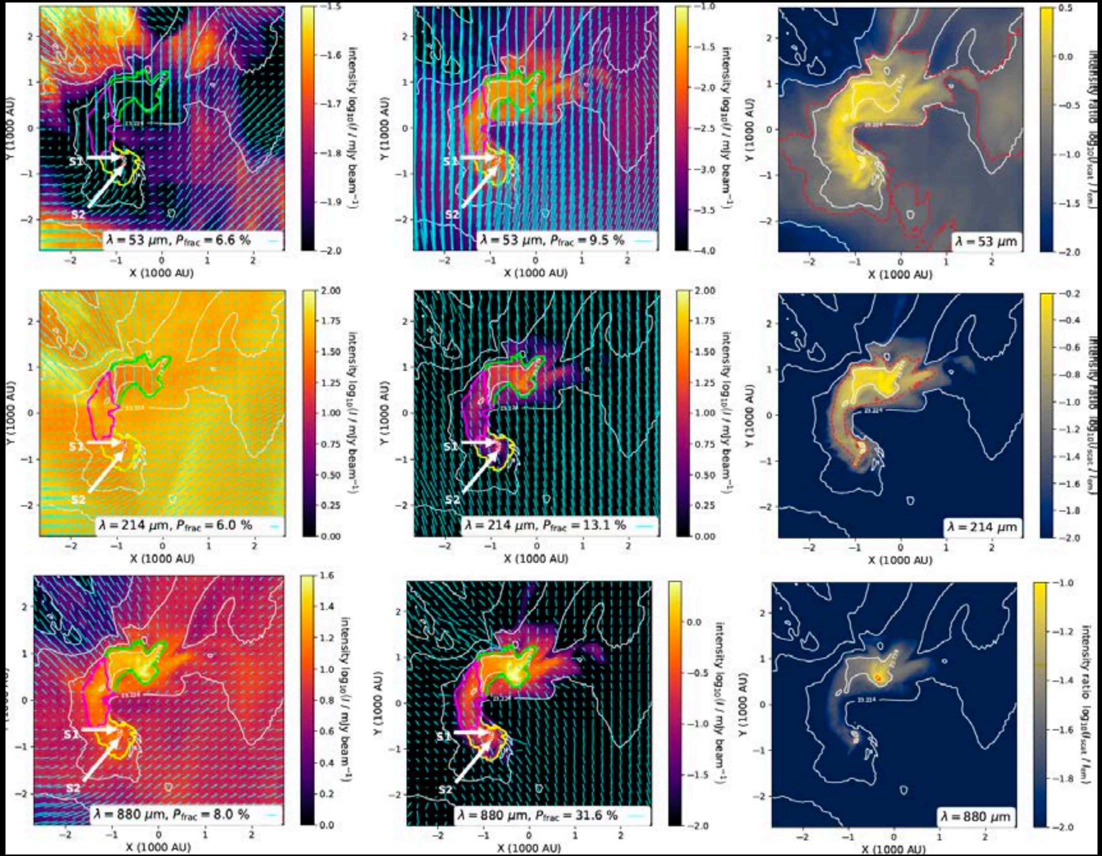
- Bridge Planck and ALMA
- Wavelength range peak for blackbodies of temperatures 13 – 55 K
  - Particularly important for polarization where signal only ~5% of total intensity
- More sensitive to warmer dust than (sub)millimeter polarimeters
  - More sensitive to diffuse emission

Multiwavelength also tells us grain properties



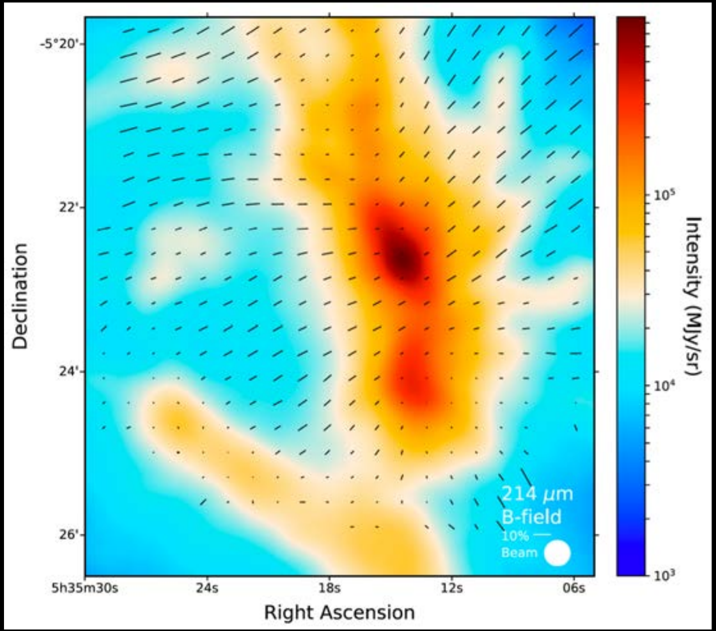
Kuffmeier et al. (2020)

MHD Simulations + POLARIS
Kuffmeier et al. (2020)

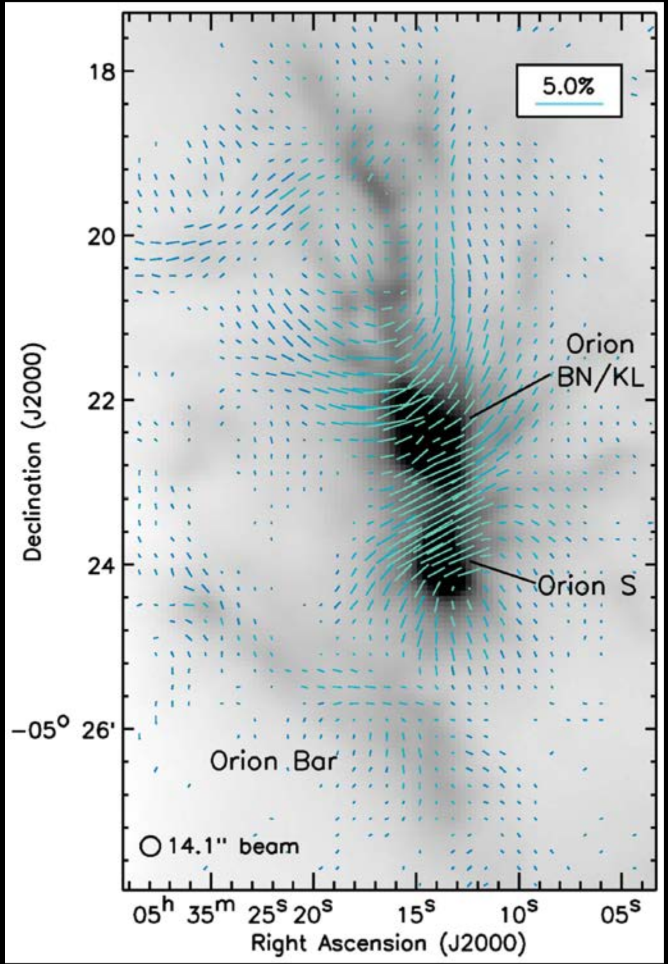


At wavelengths < 200 μm, significant self-scattering + dichroic extinction

OMC-1

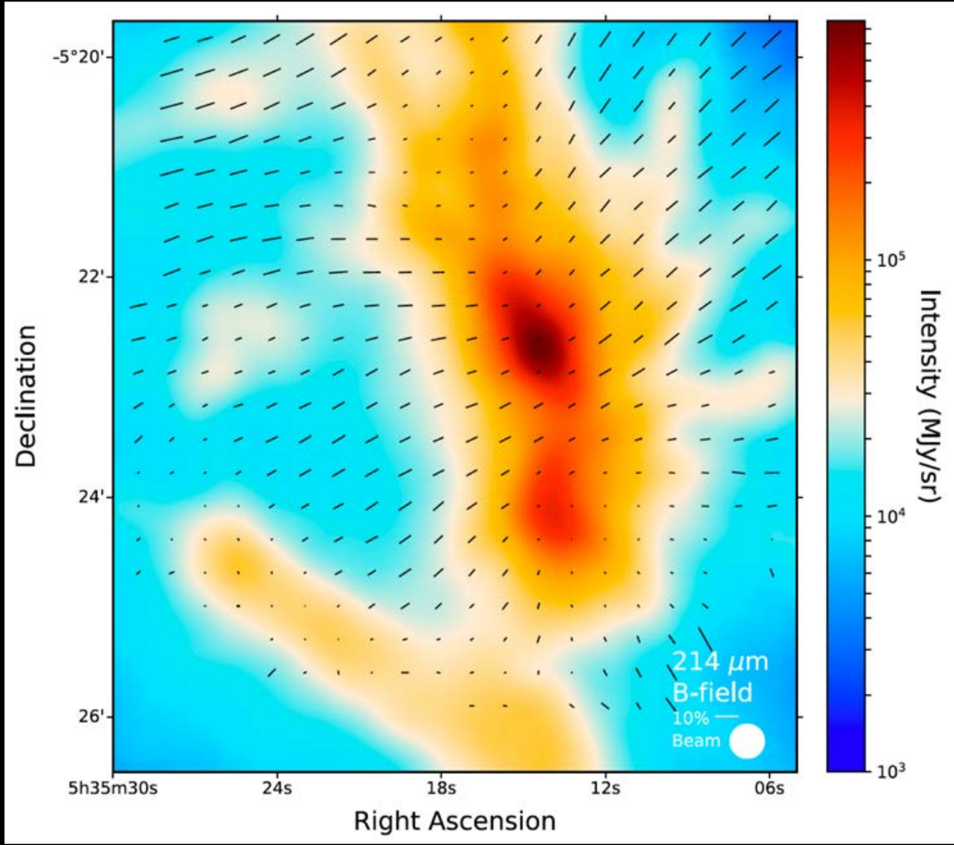


HAWC+, Band-E (214 μm, 18.2″), Chuss et al. (2019)
0.5 hrs total time (~15 min on source)



JCMT Pol-2, Pattle et al. (2017)
21 observations, 14 hours on source

OMC-1



HAWC+, Band-E (214 μm, 18.2″), Chuss et al. (2019)
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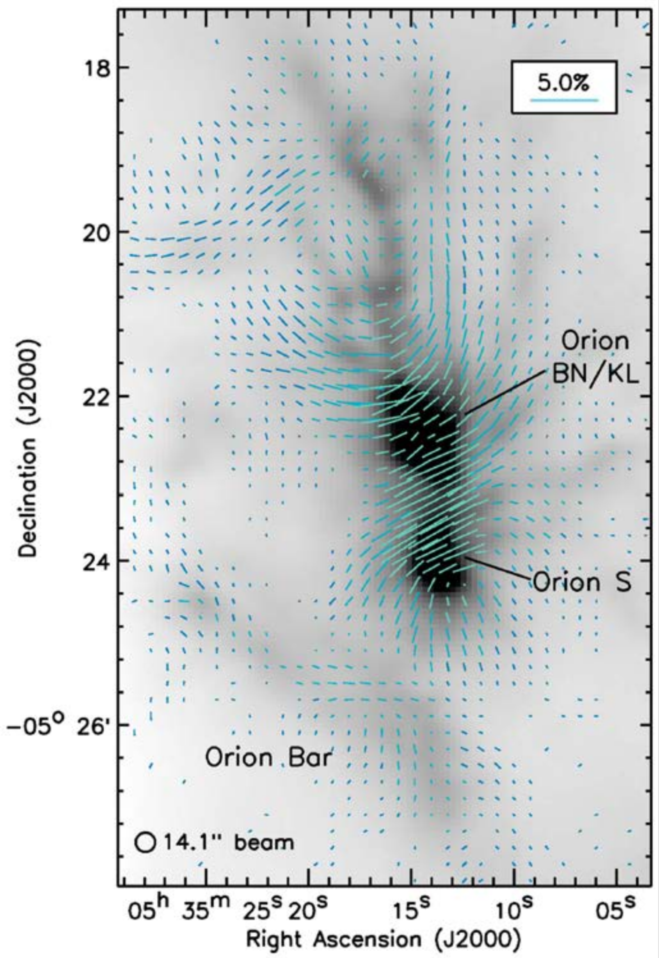
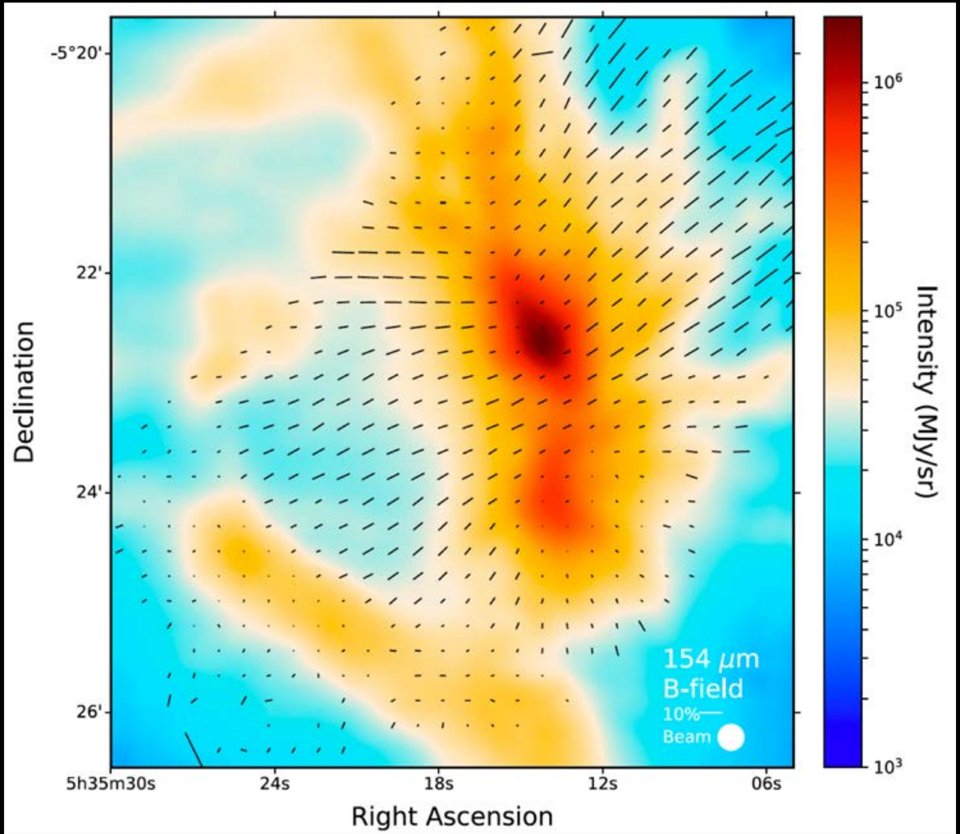


JCMT Pol-2, Pattle et al. (2017)
21 observations, 14 hours on source

OMC-1



HAWC+, Band-D (154 μm, 13.6″), Chuss et al. (2019)
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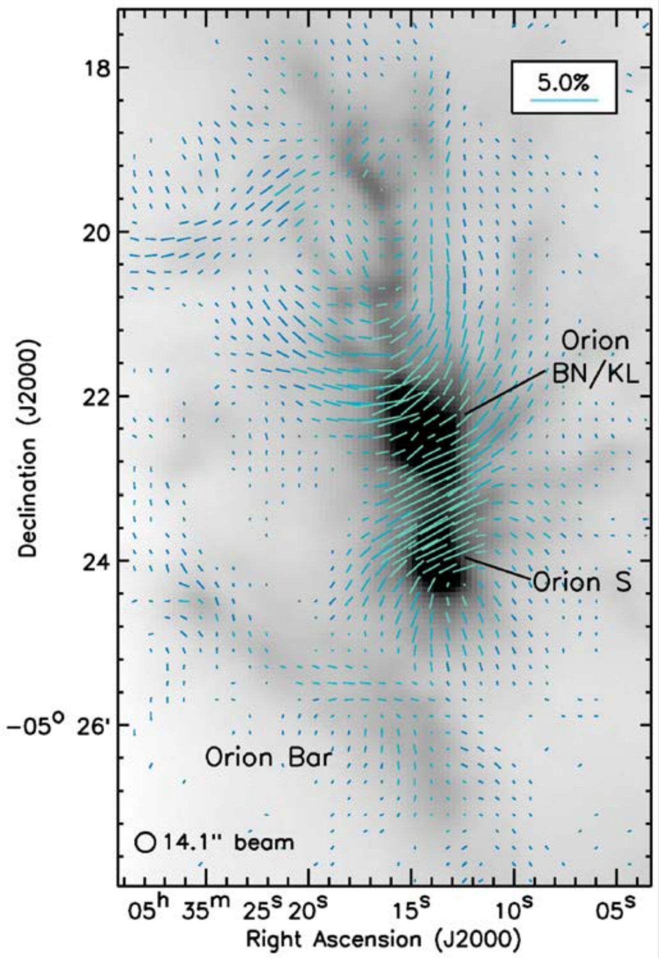
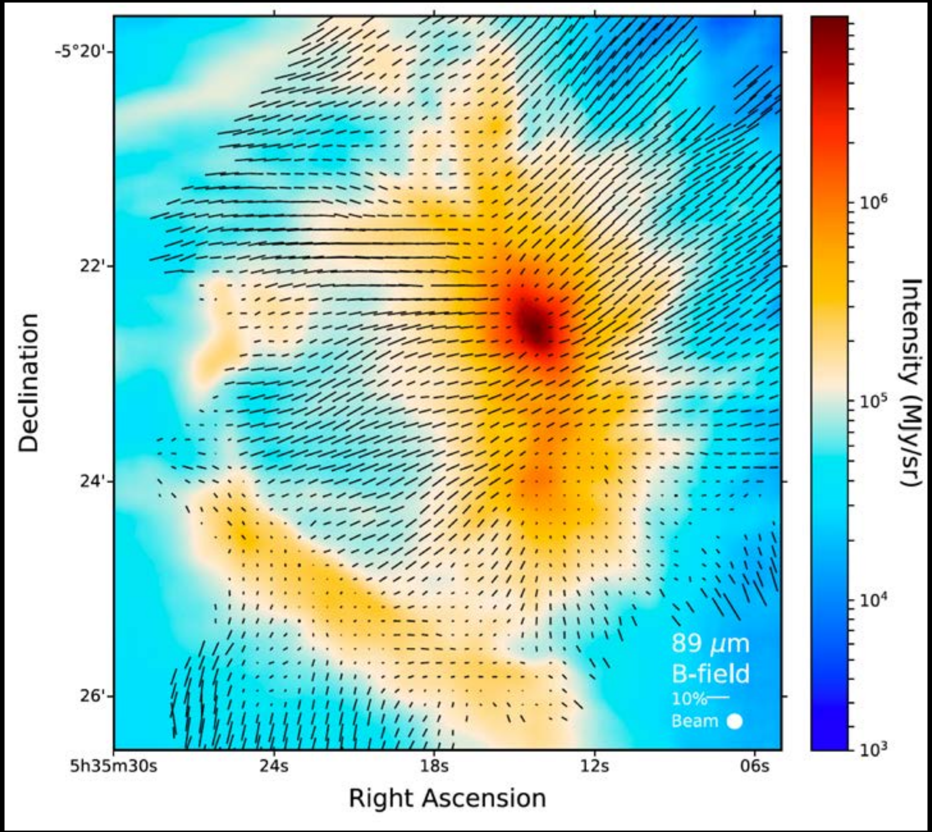
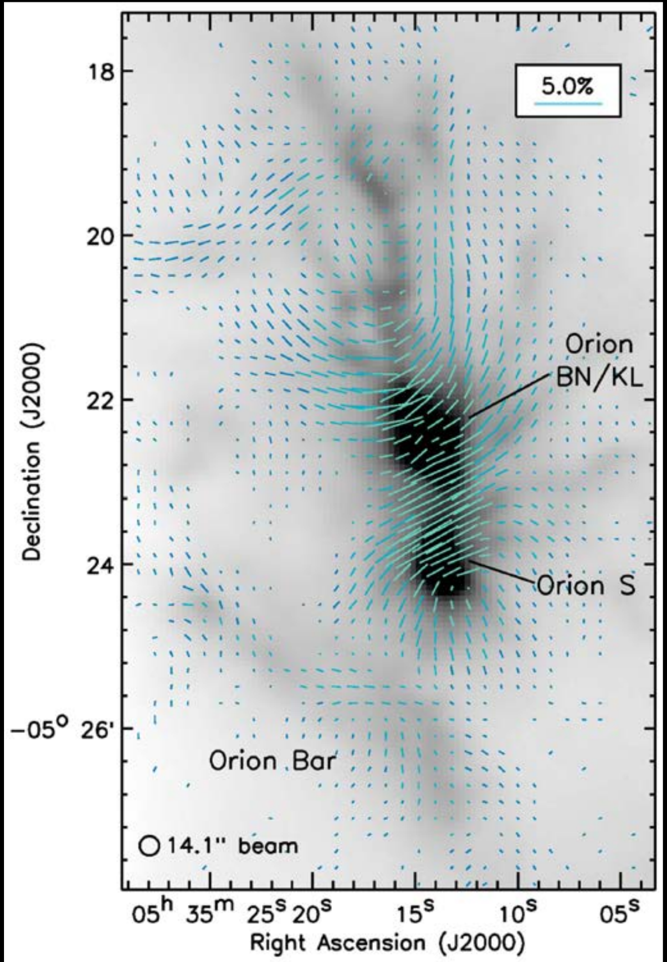


JCMT Pol-2, Pattle et al. (2017)
21 observations, 14 hours on source

OMC-1

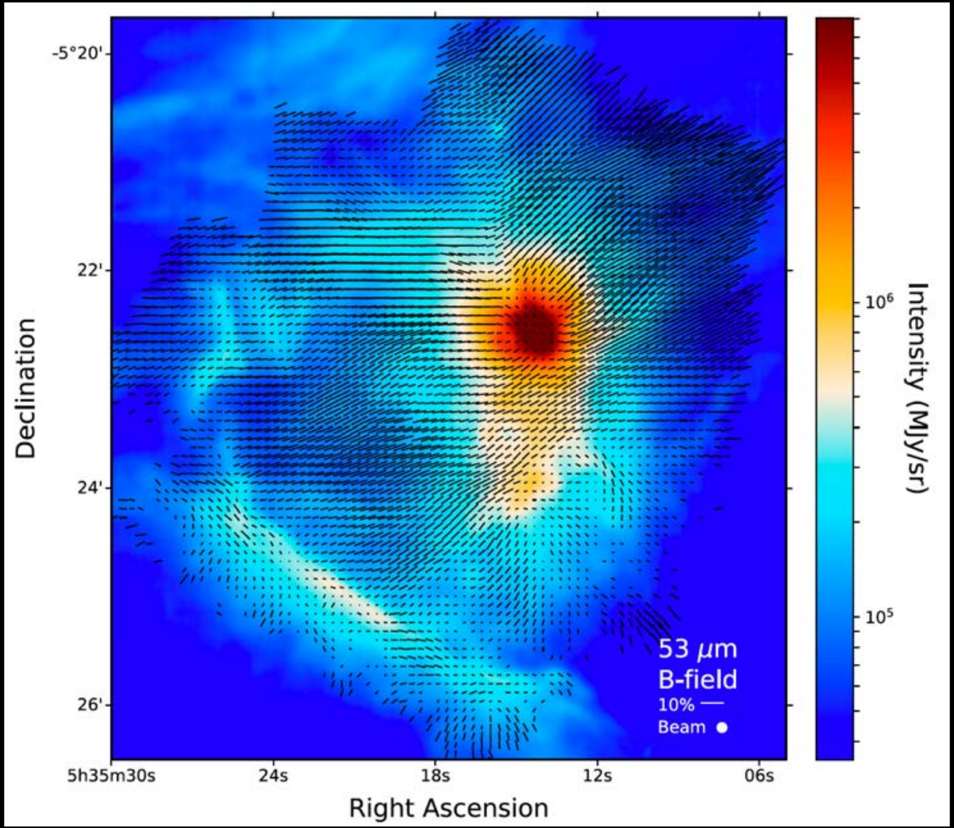


HAWC+, Band-C (89 μm, 7.8″), Chuss et al. (2019)
2.4 hrs total time (~0.8 hr on source)

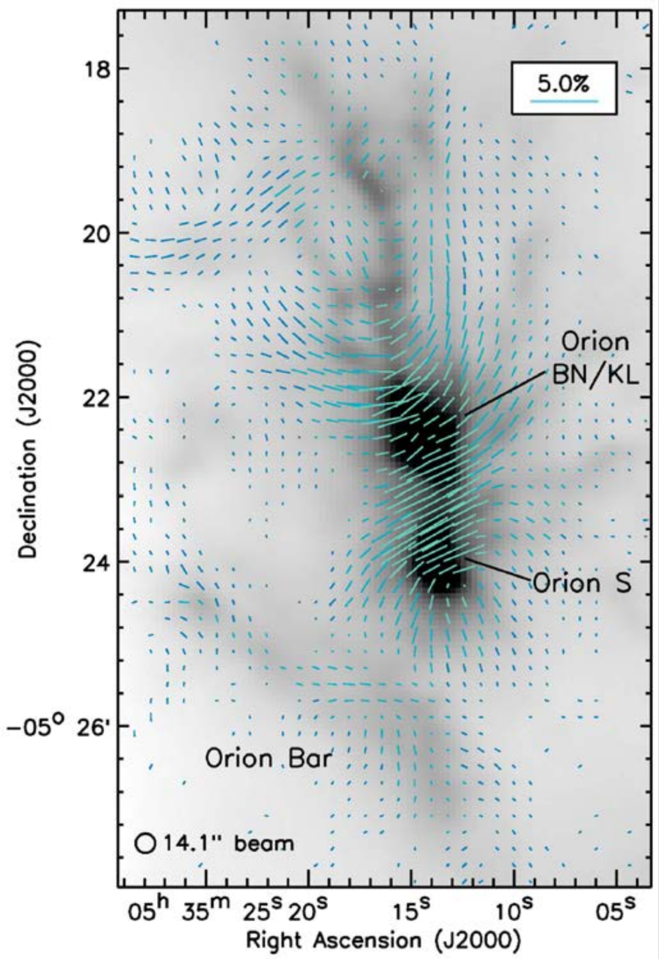


JCMT Pol-2, Pattle et al. (2017)
21 observations, 14 hours on source

OMC-1

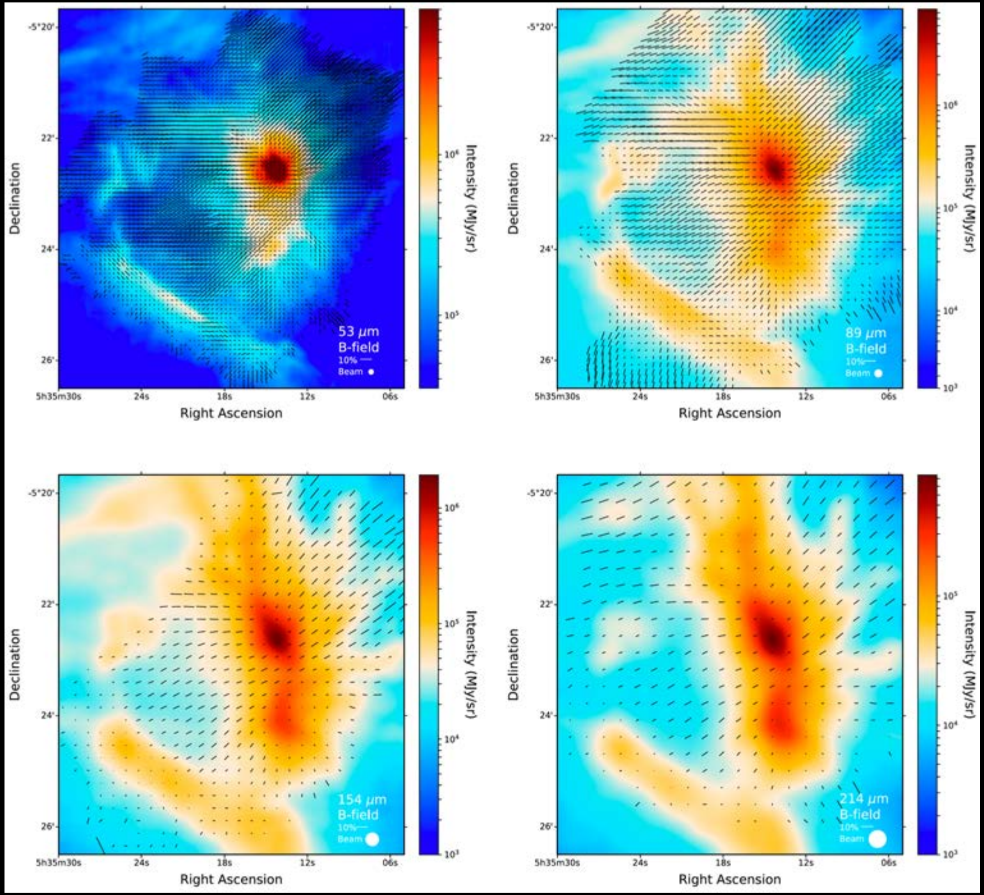


HAWC+, Band-A (54 μm, 4.85″), Chuss et al. (2019)
3.5 hrs total time (~1 hr on source)

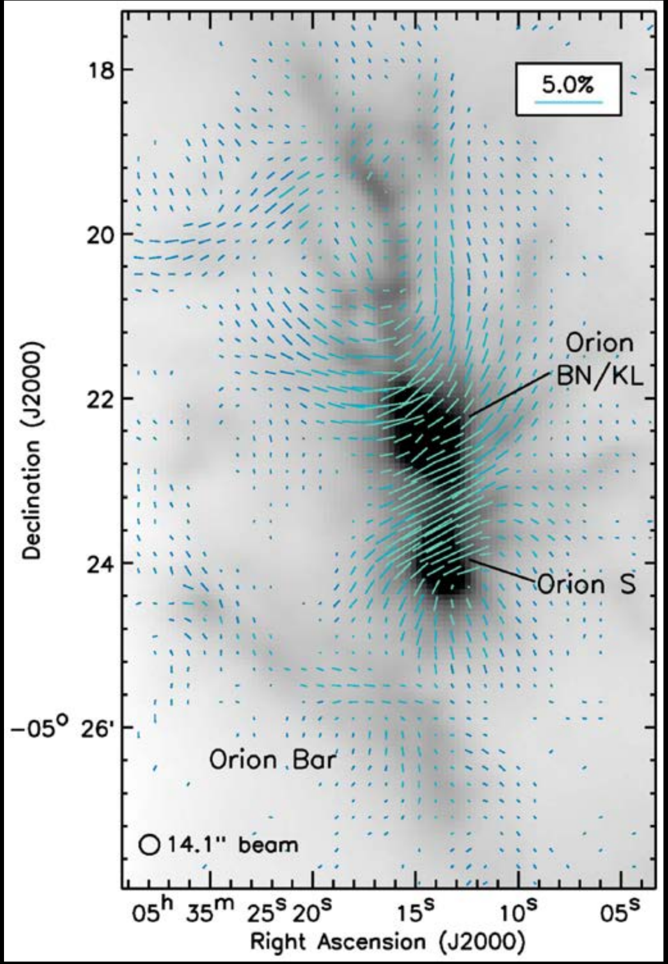


JCMT Pol-2, Pattle et al. (2017)
21 observations, 14 hours on source

OMC-1

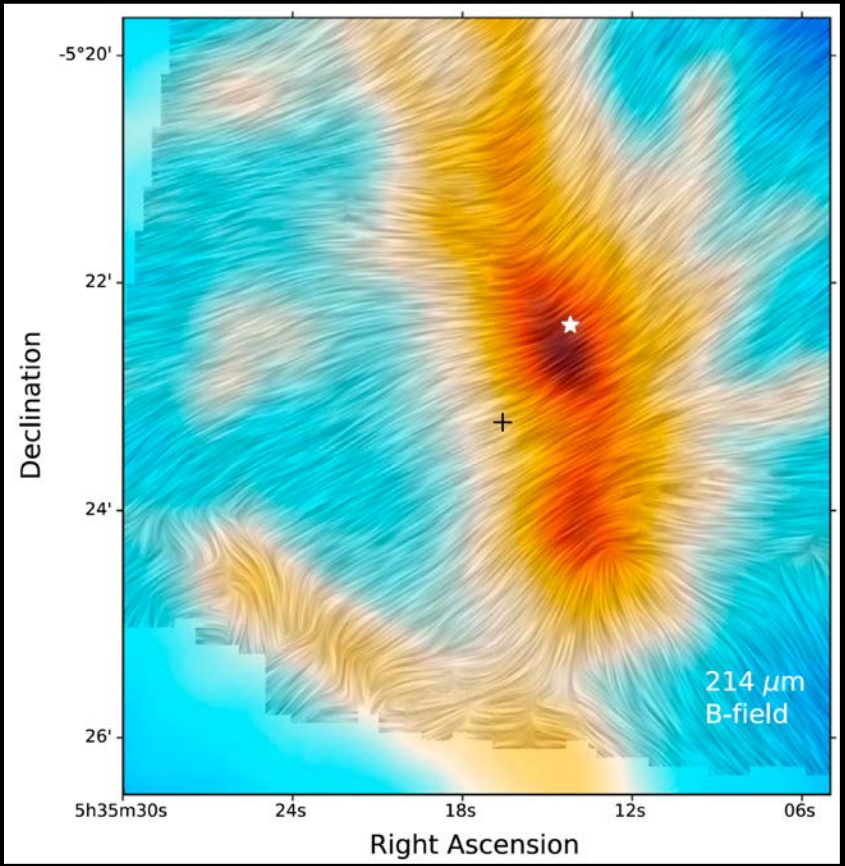


Chuss et al. (2019)

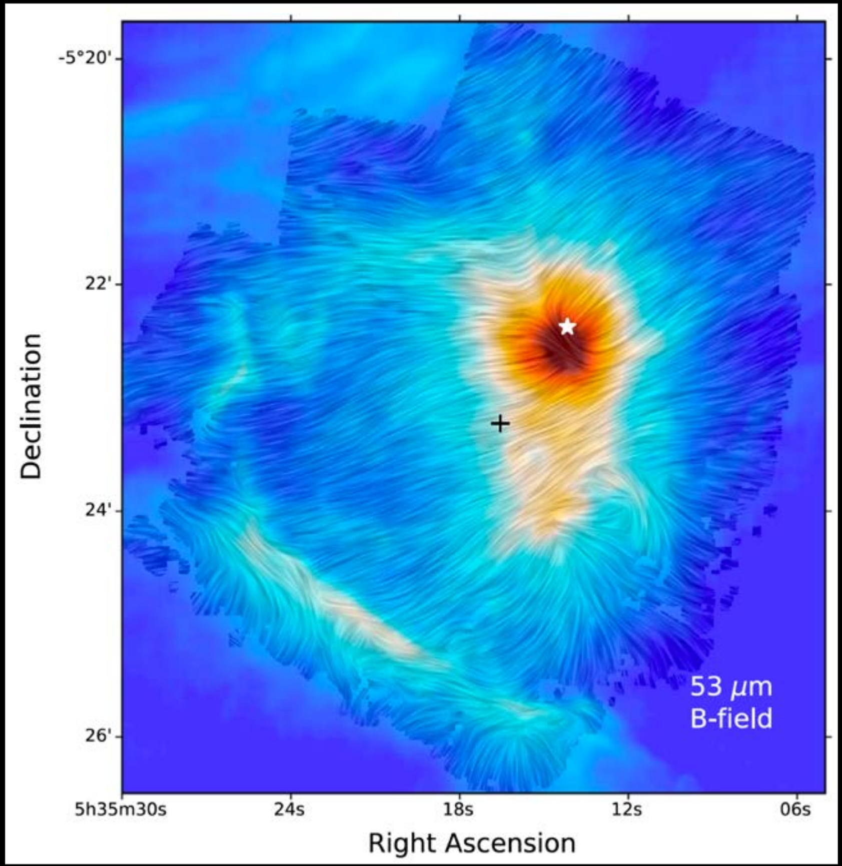


JCMT Pol-2, Pattle et al. (2017)

21 observations, 14 hours on source

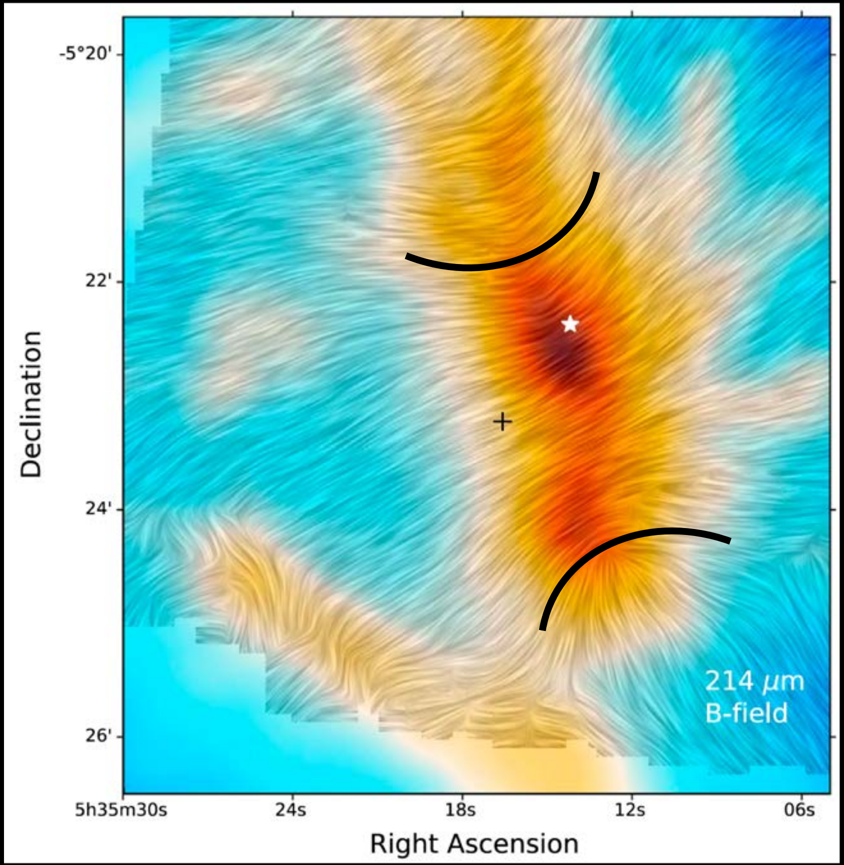


HAWC+, Band-E (214 μm, 18.2″)

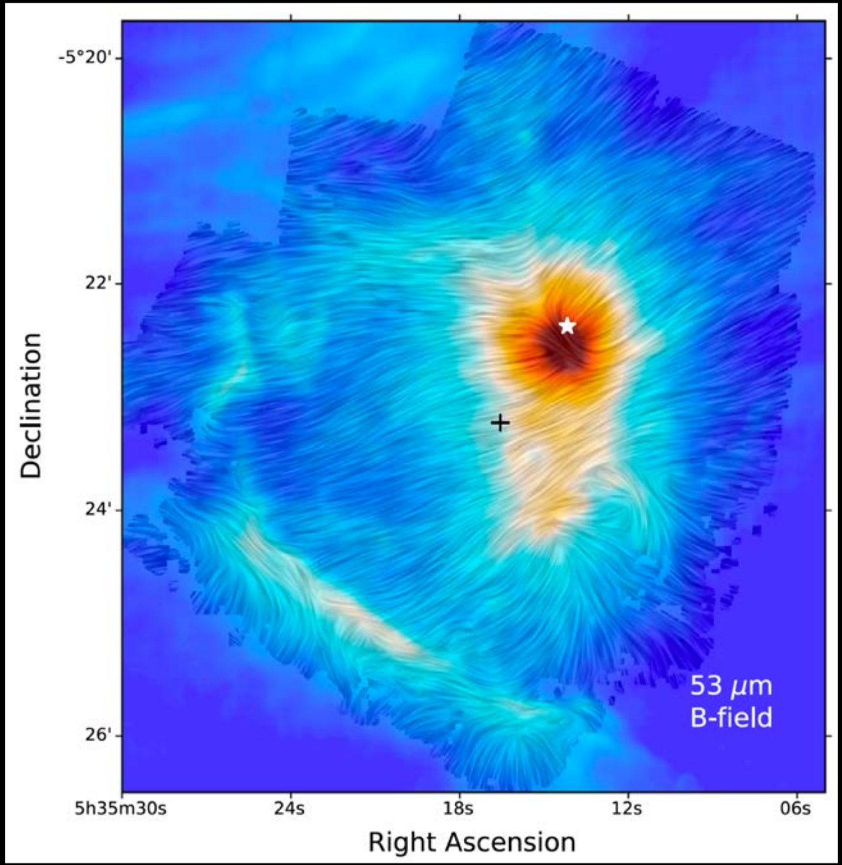


HAWC+, Band-A (54 μm, 4.85″)

Chuss et al. (2019)

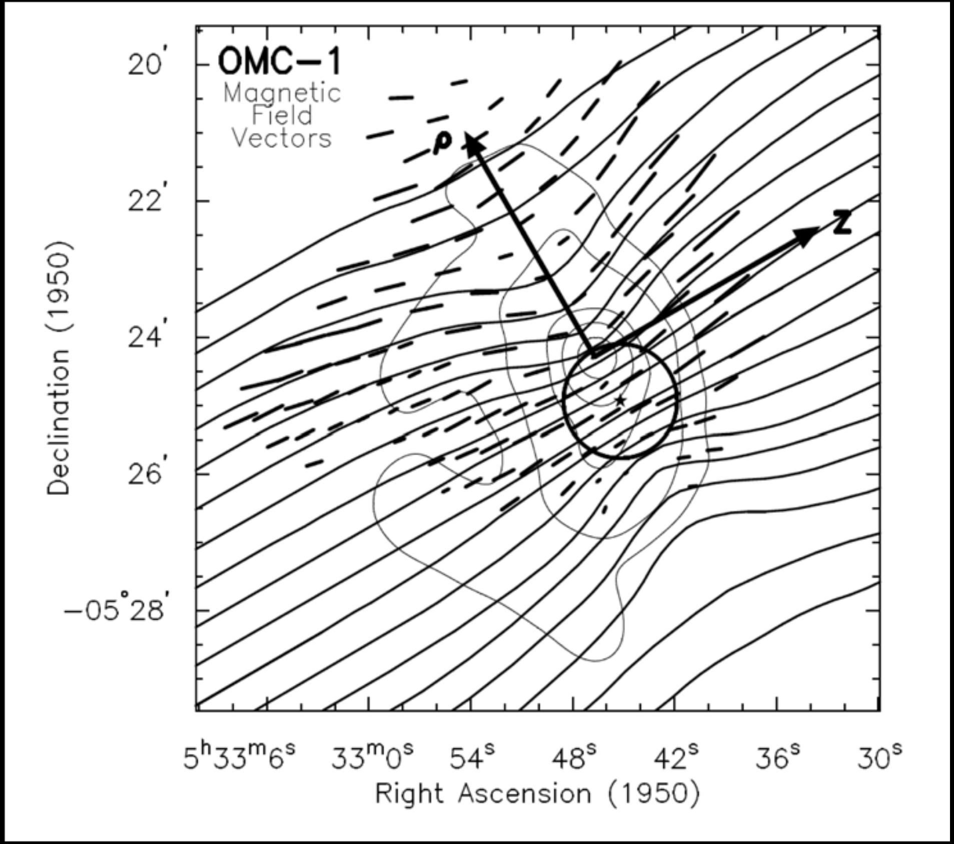


HAWC+, Band-E (214 μm, 18.2″)

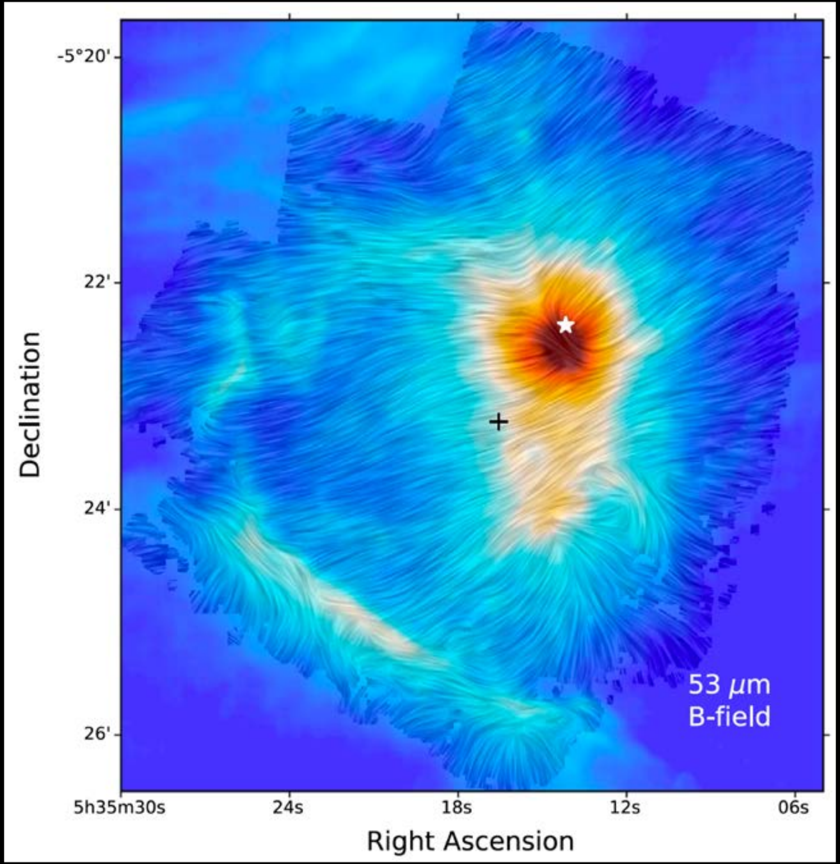


HAWC+, Band-A (54 μm, 4.85″)

Chuss et al. (2019)

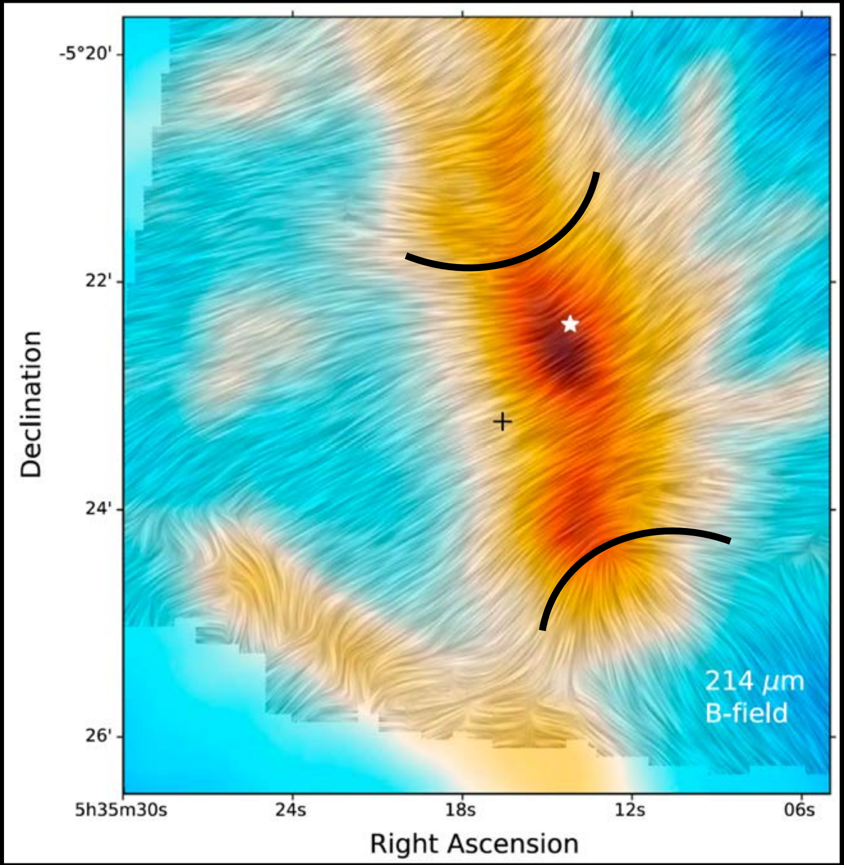


KAO 100 μm, Schleuning (1998)



HAWC+, Band-A (54 μm, 4.85″)

Chuss et al. (2019)



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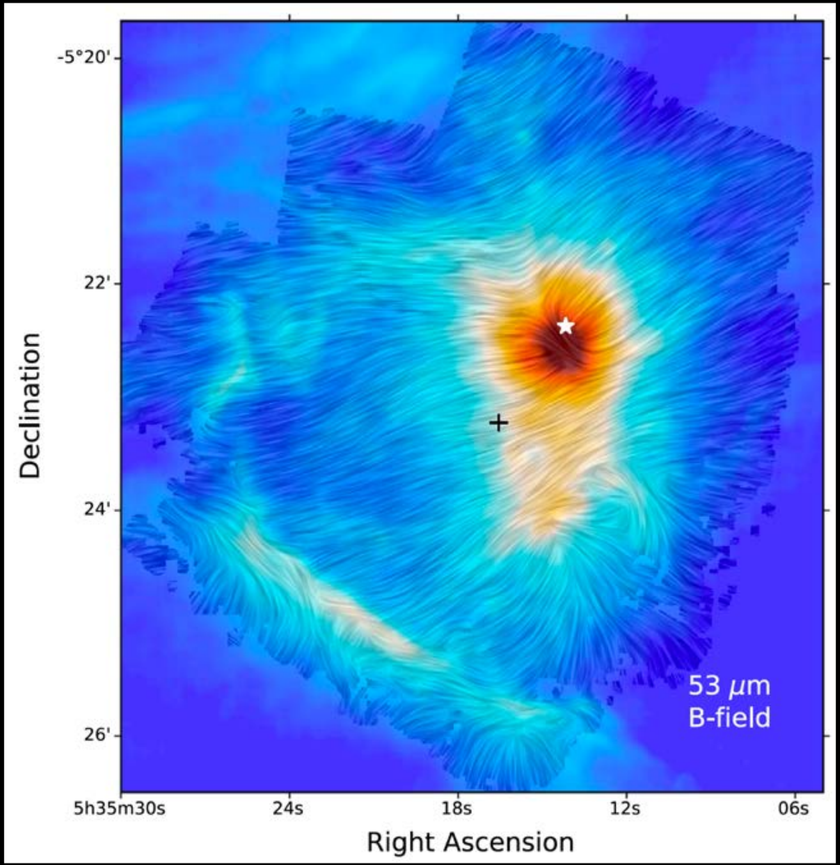

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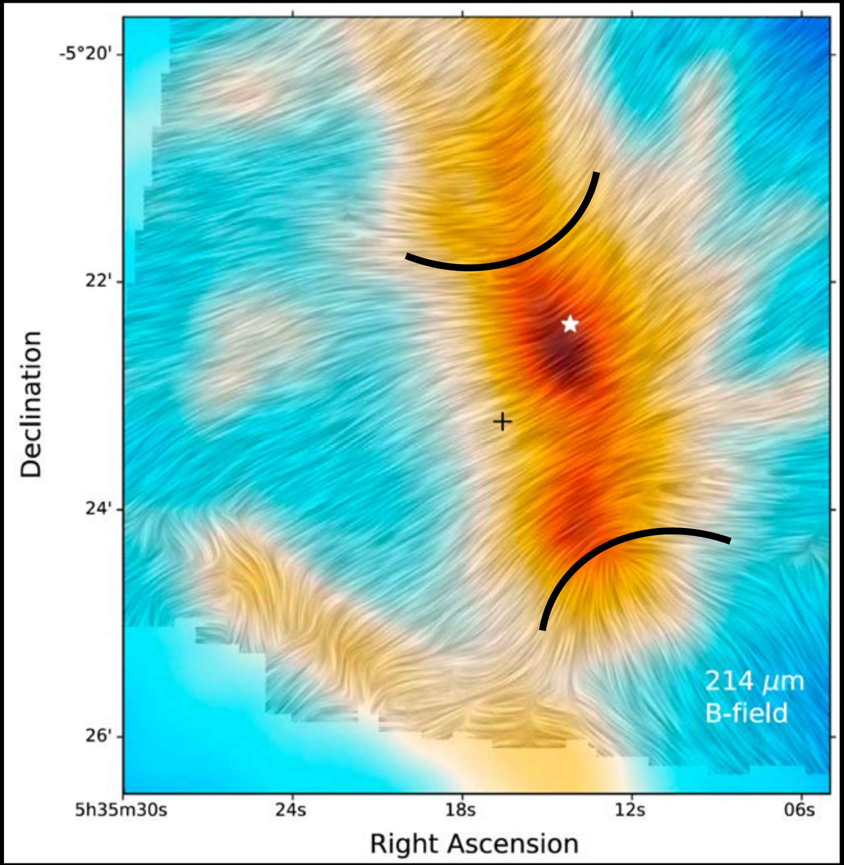
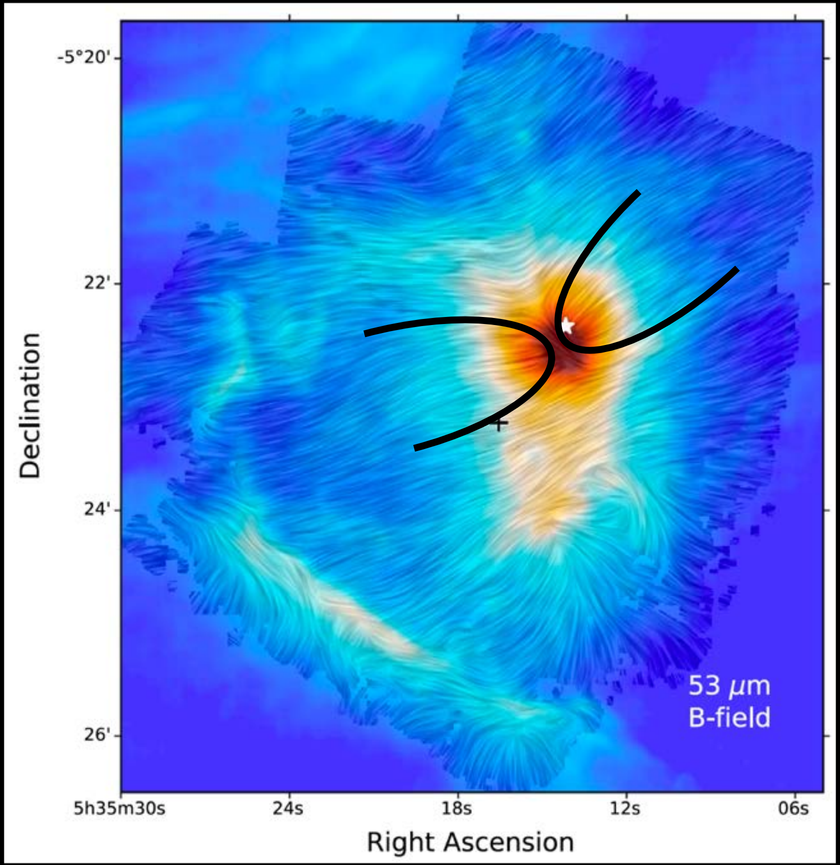
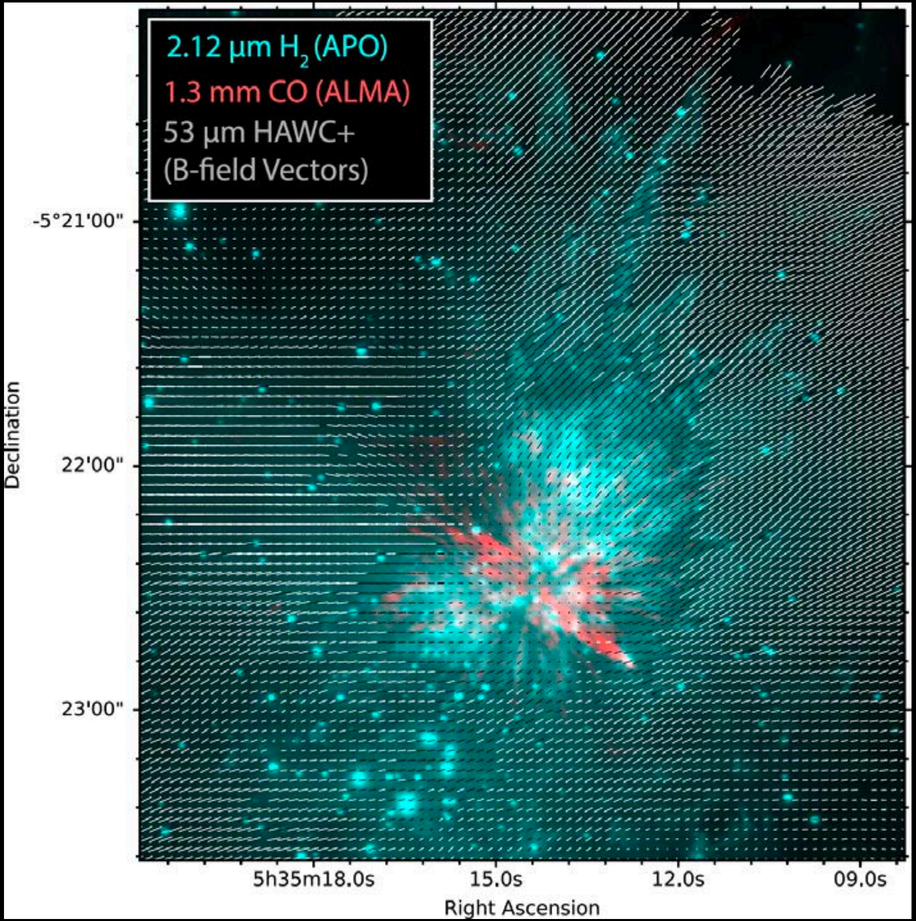


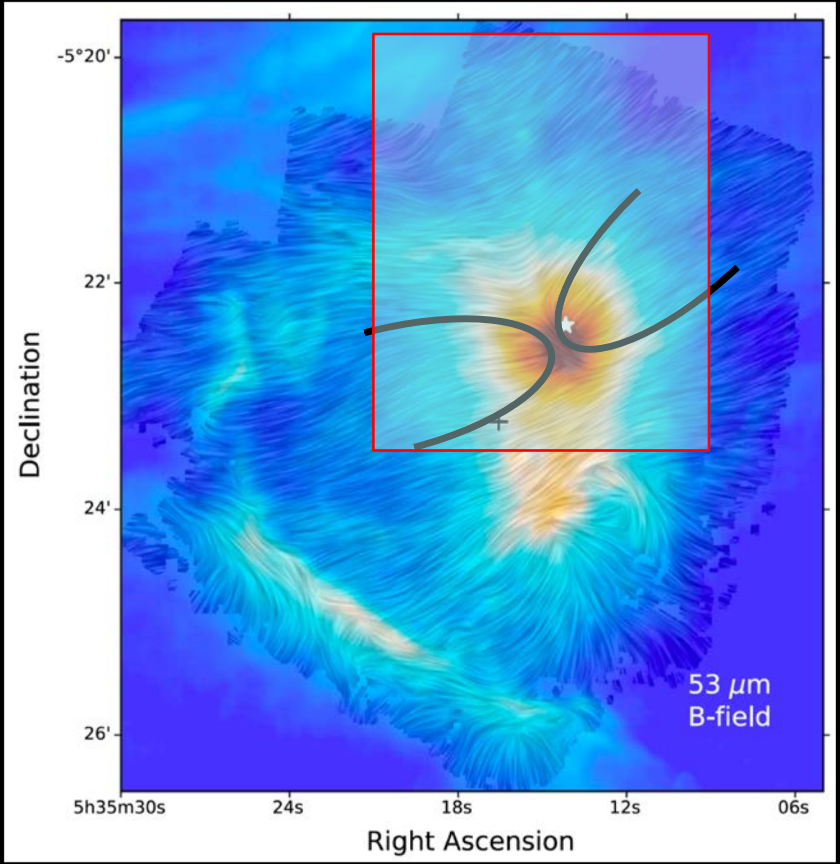
HAWC+, Band-E (214 μm, 18.2″)



HAWC+, Band-A (54 μm, 4.85″)

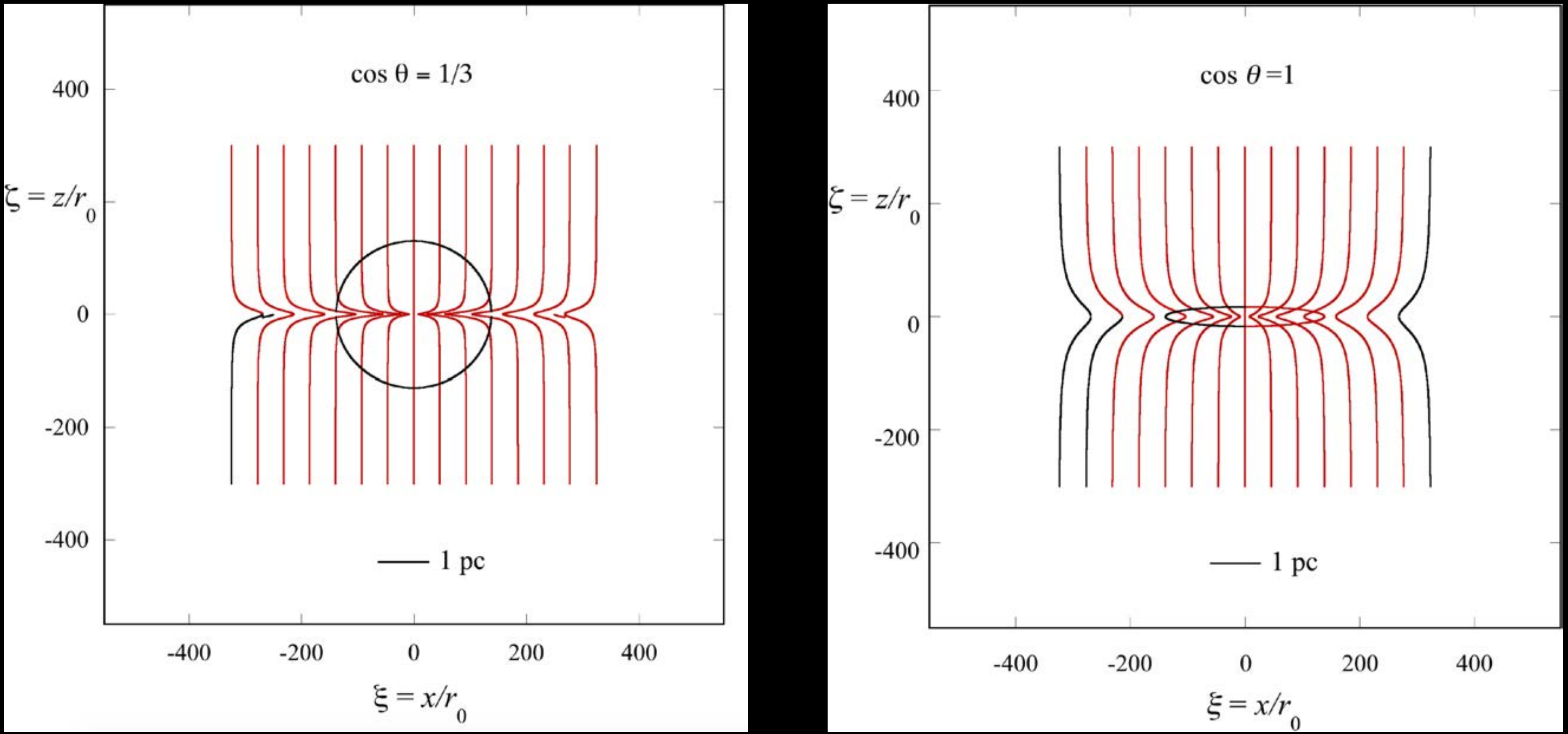
Chuss et al. (2019)





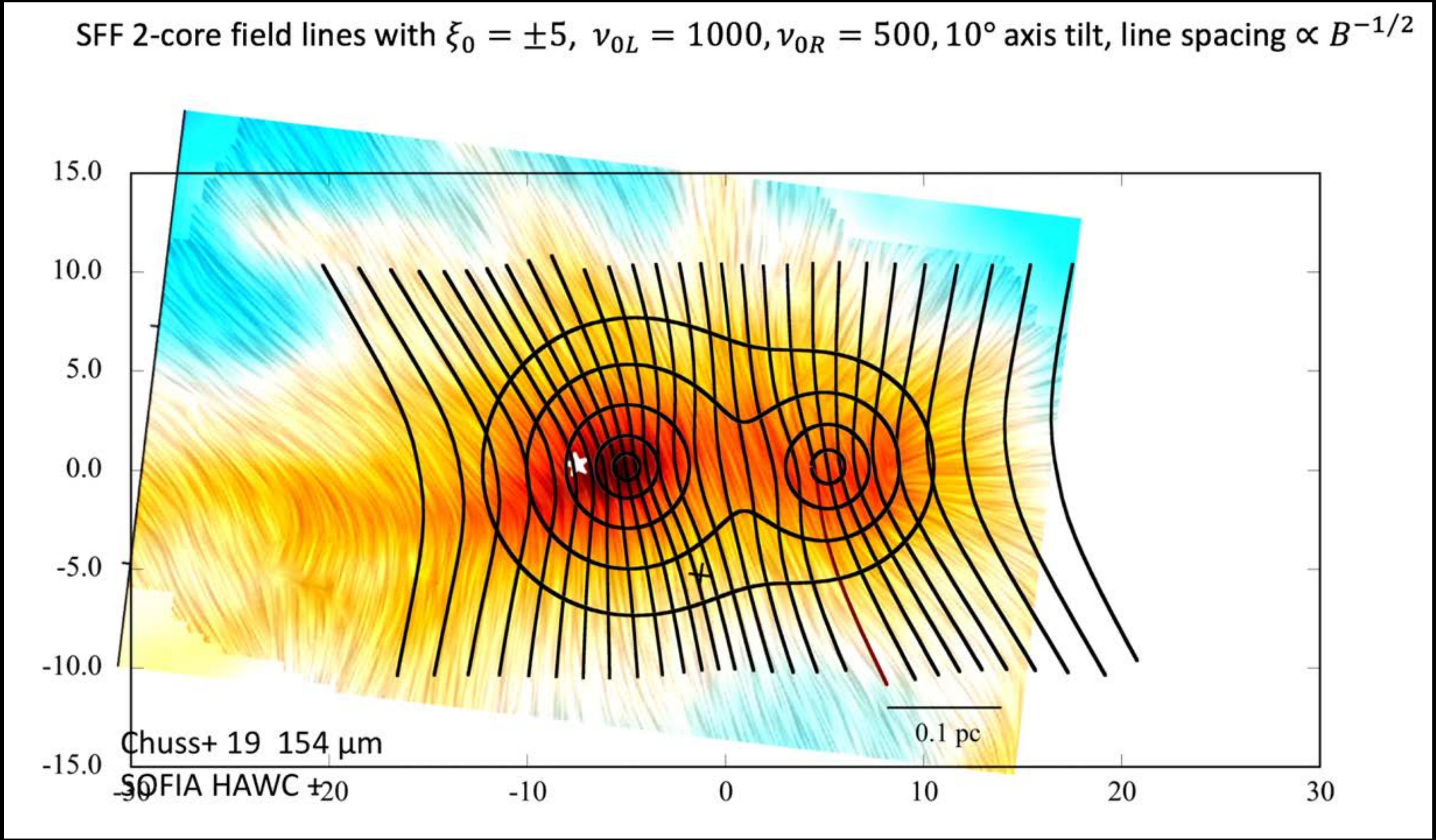
Estimates different energy densities

BN/KL shapes field at small scales
Helps confine it far out.



Spherical Flux Freezing Model; Myers et al. (2018, 2020)

Provides estimate for field strength everywhere



Consistent with flux-freezing. Made possible from large maps
(Spherical Flux Freezing Model; Myers et al. (in prep, 2018, 2020)

SOFIA and Filaments

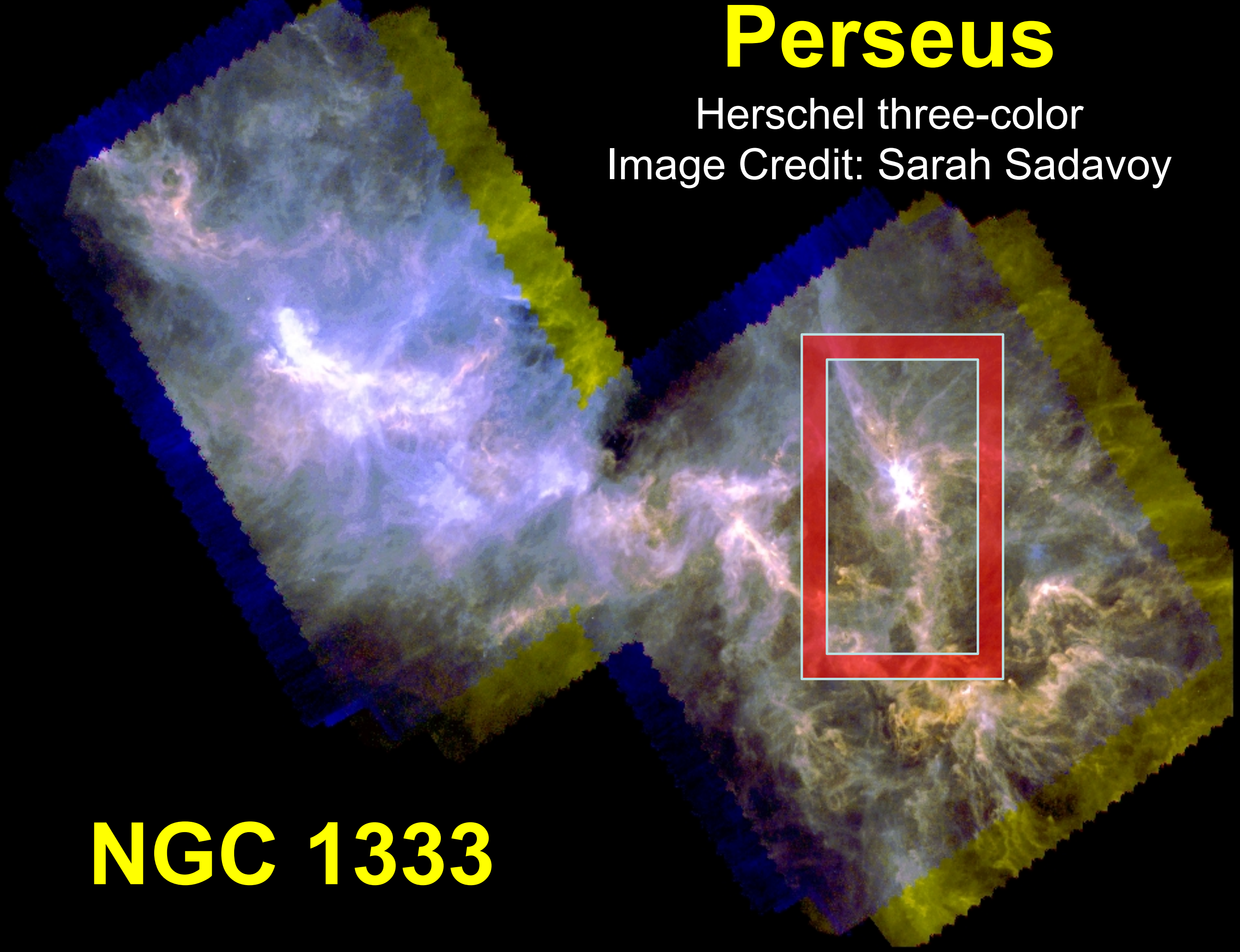
Herschel, Orion

Star Formation is Typically Within Filaments

Magnetic Fields?

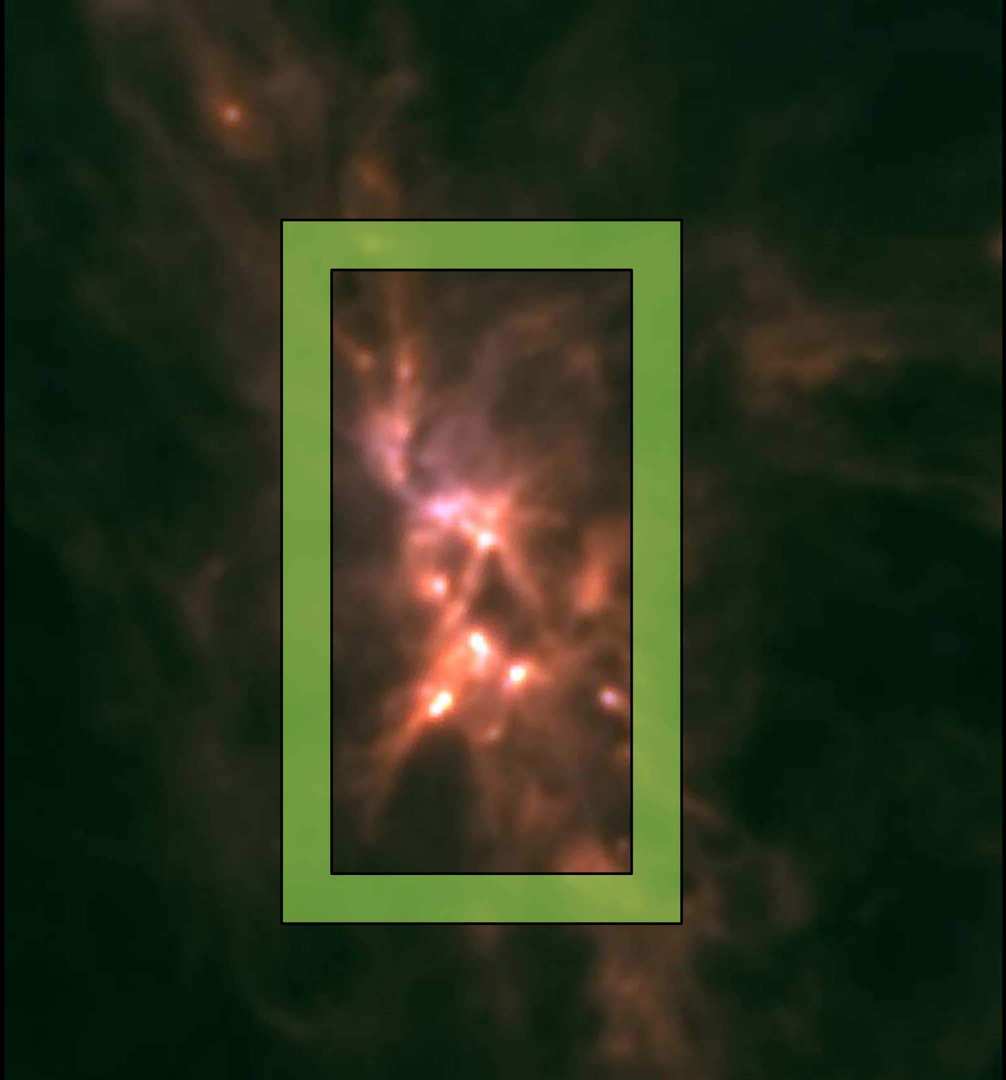
Perseus

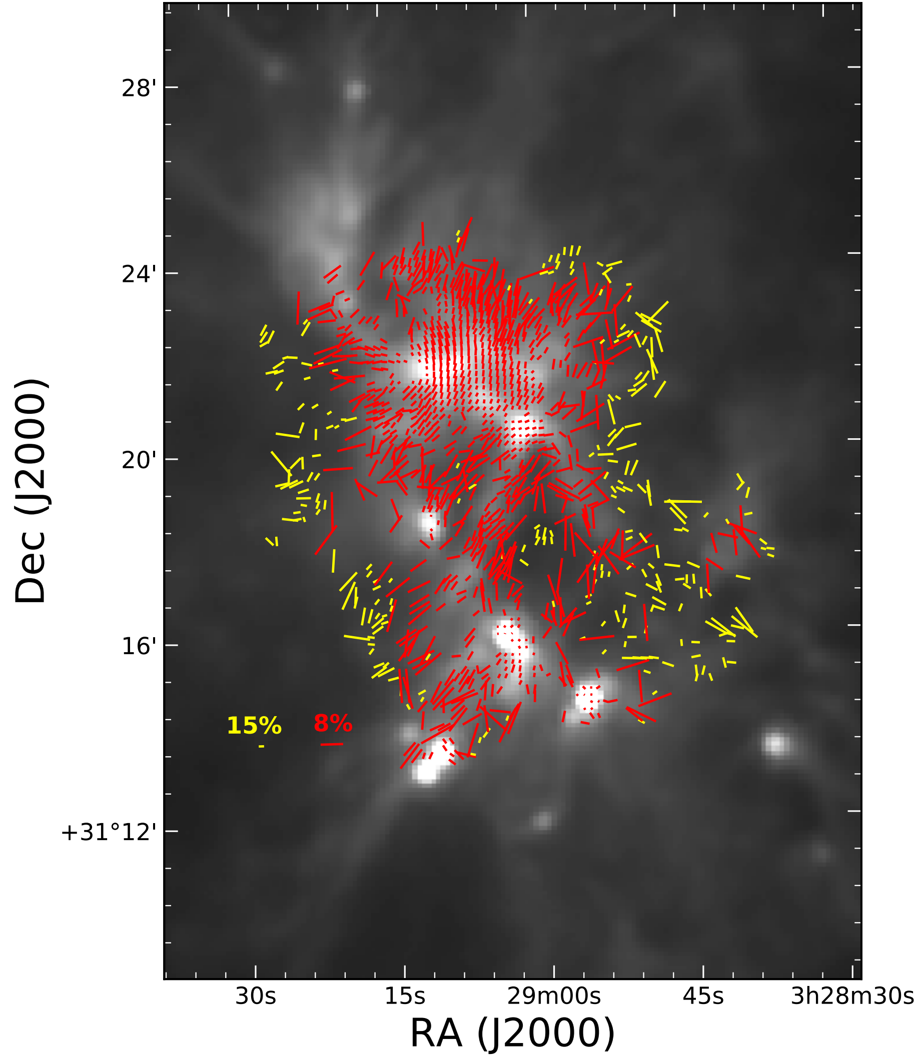
Herschel three-color
Image Credit: Sarah Sadavoy



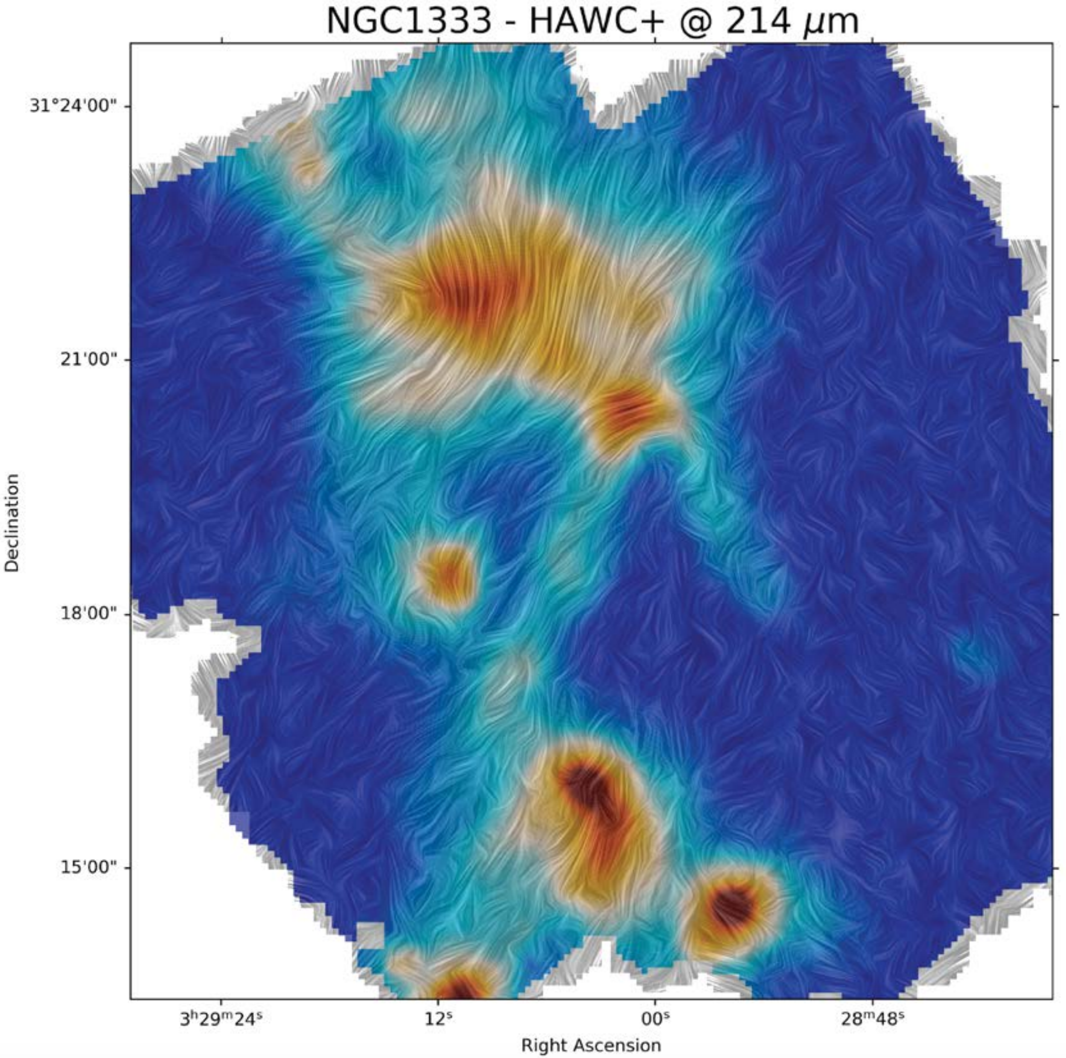
NGC 1333

Herschel three-color



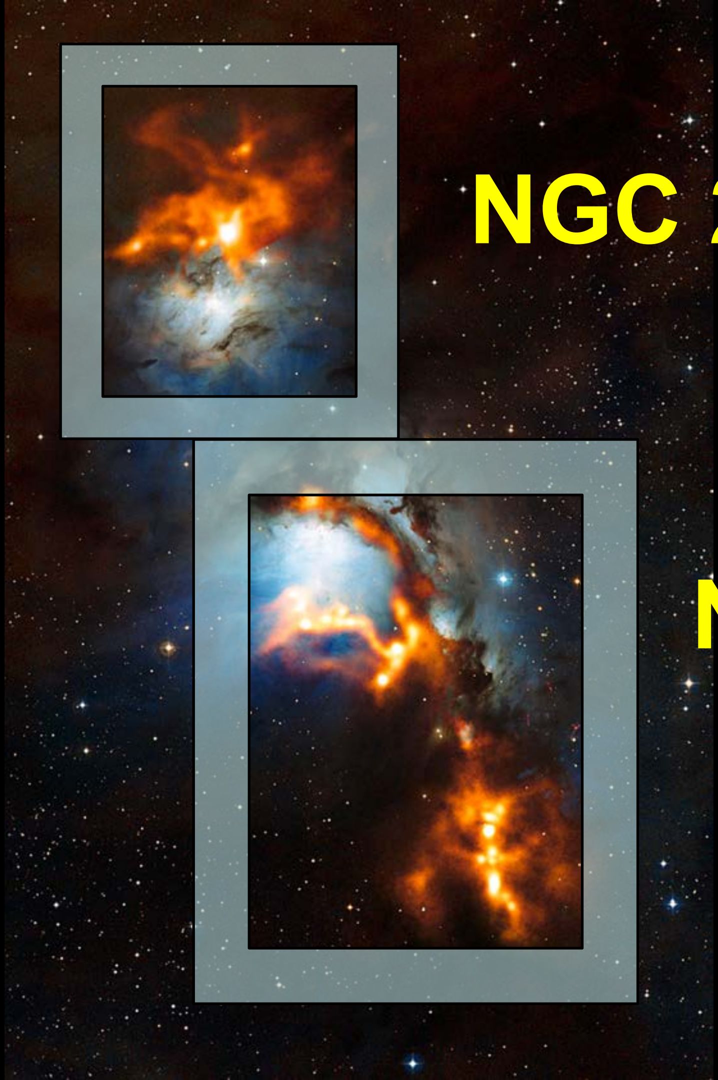


HAWC+ 214 μm
Stephens et al.



HAWC+ 214 μm
Soam et al.
Stephens et al.

M78
Orion B
Apex on Visible Light

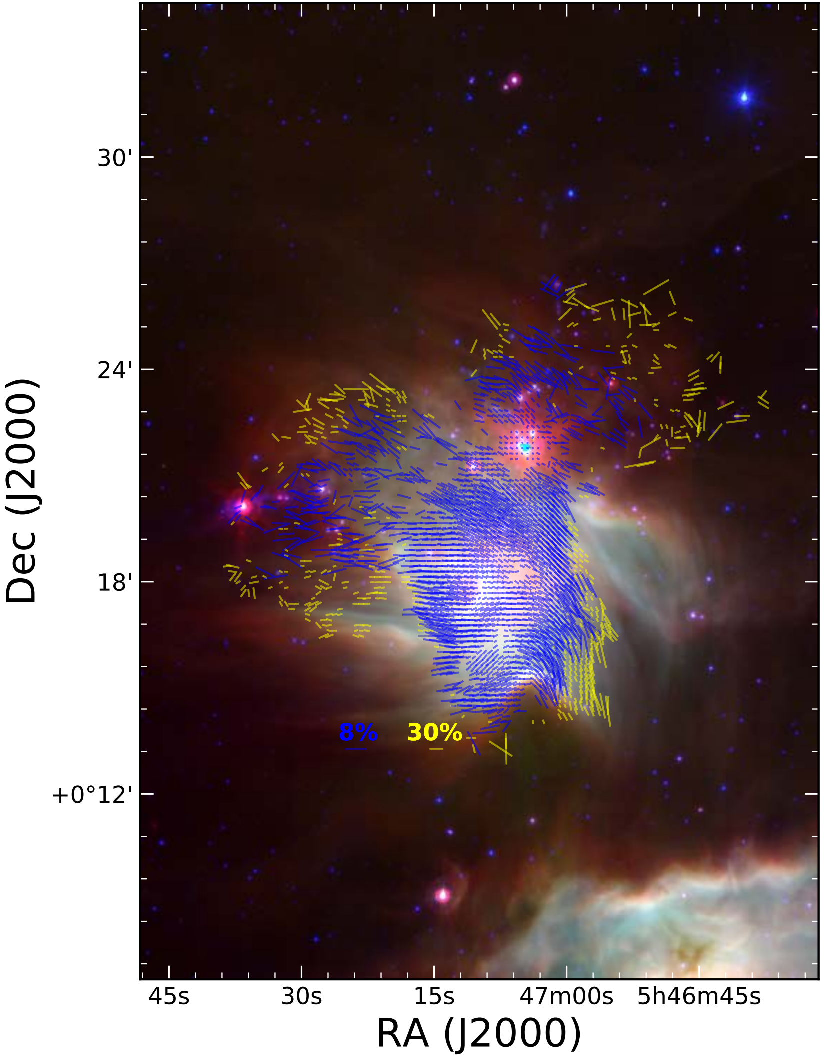


NGC 2071

NGC 2068

Image: ESO/APEX (MPIfR/ESO/OSO)/T. Stanke et al./Igor Chekalin/Digitized Sky Survey 2

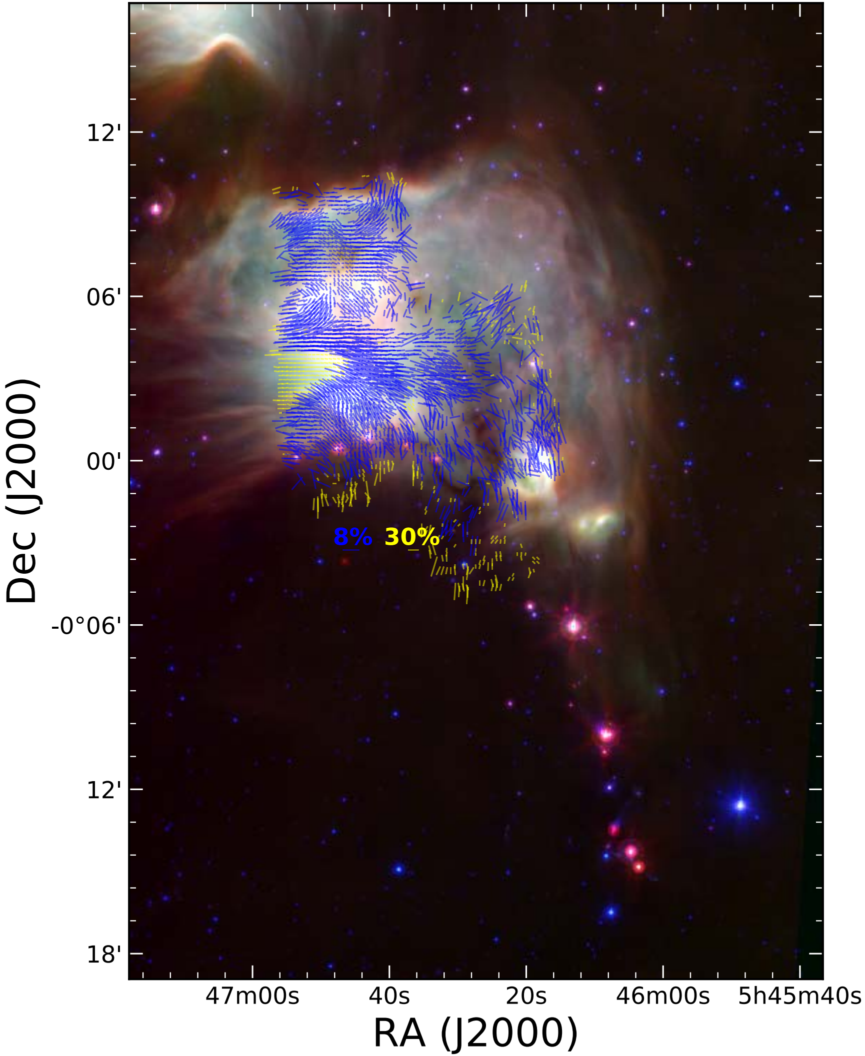
NGC 2071



HAWC+ 214 μm
Stephens et al.

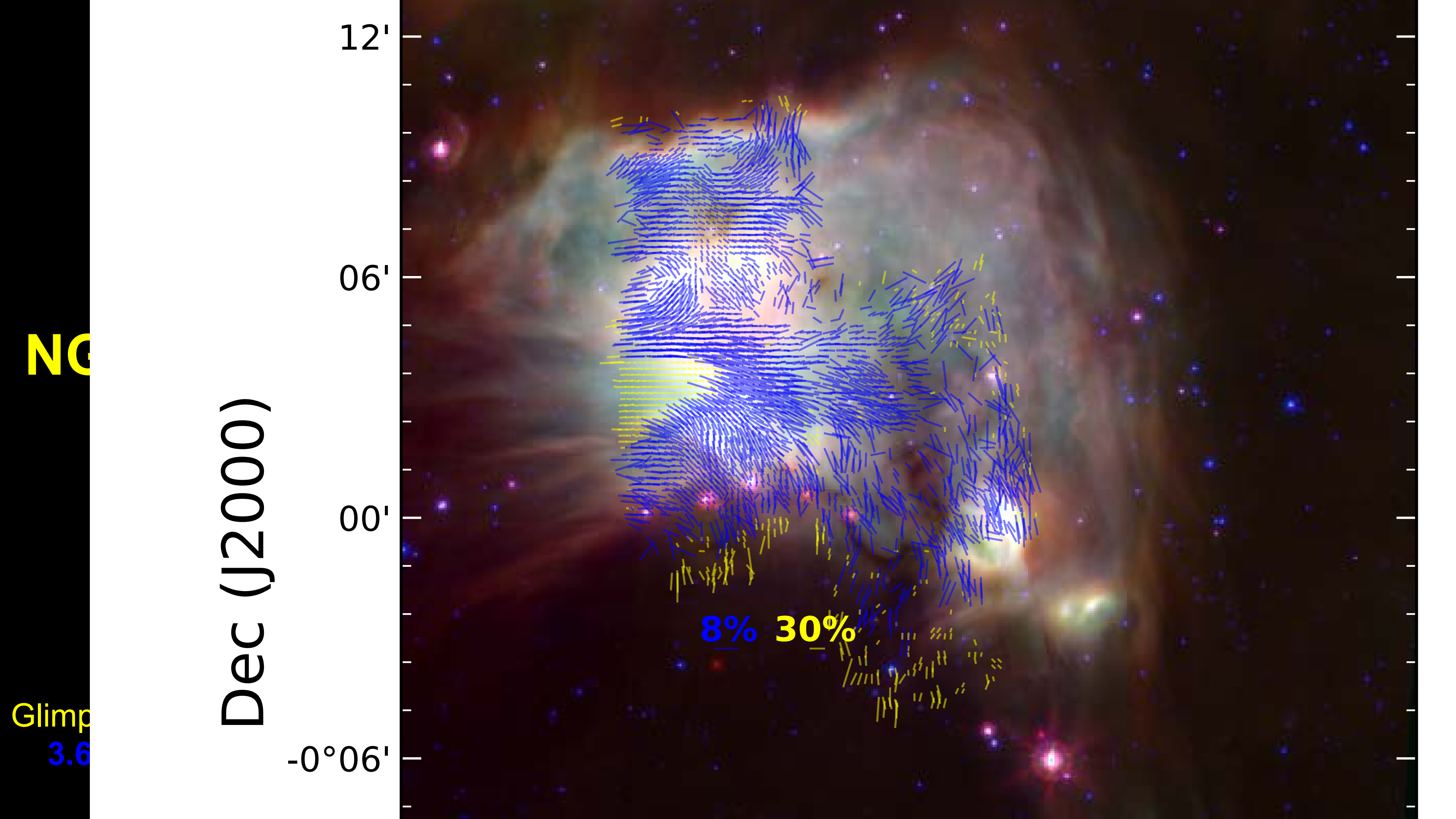
Glimpse+MIPSGAL,
3.6, 8.0, 24 μm

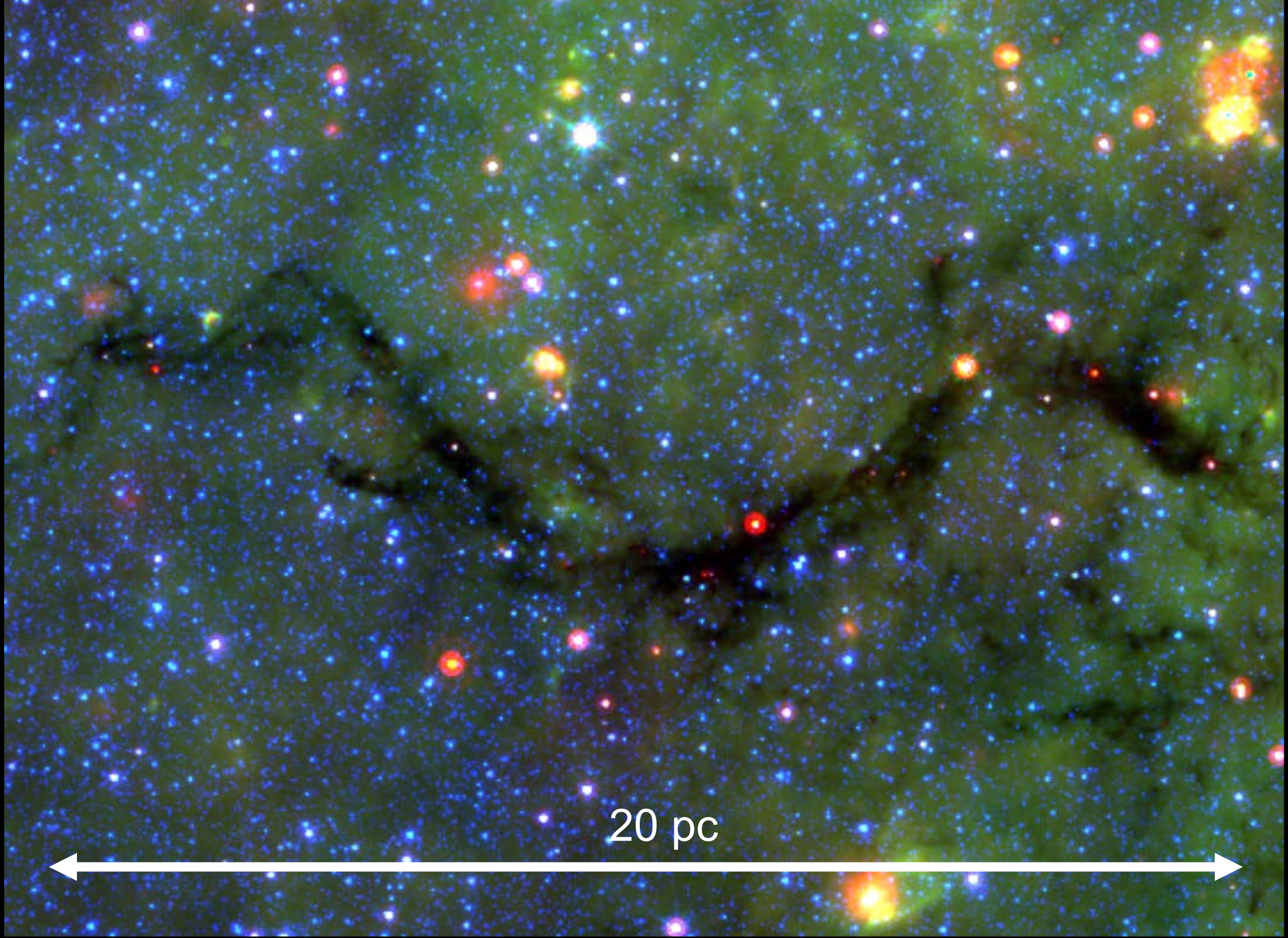
NGC 2068



HAWC+ 214 μm
Stephens et al.

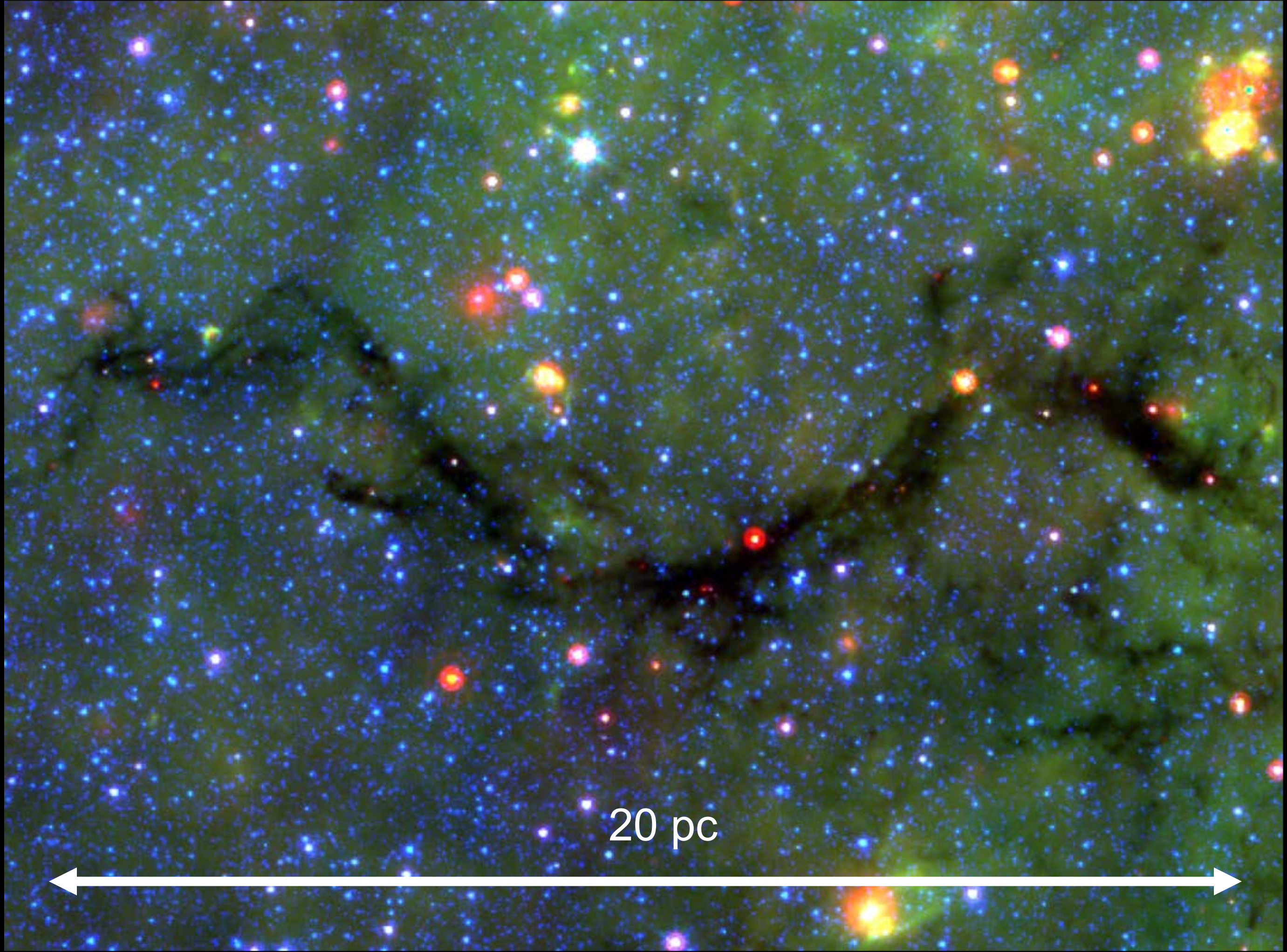
Glimpse+MIPSGAL,
3.6, 8.0, 24 μm


12'
06'
00'
-0°06'
Dec (J2000)
8%
30%

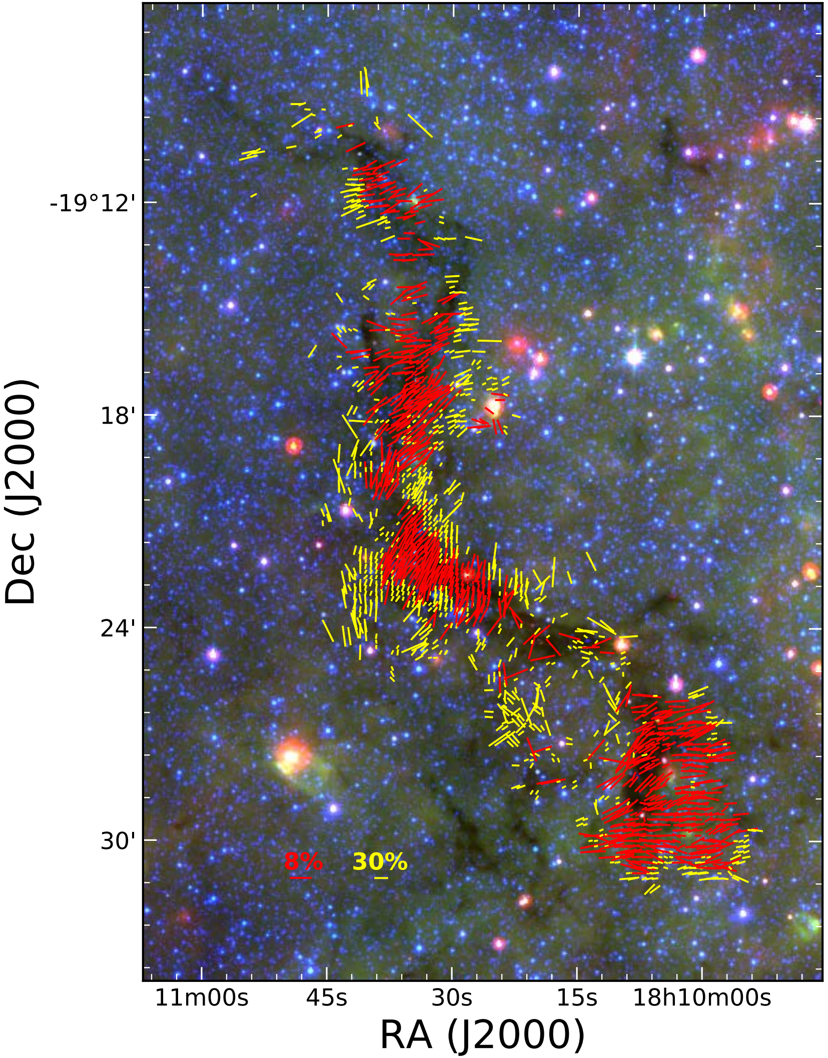


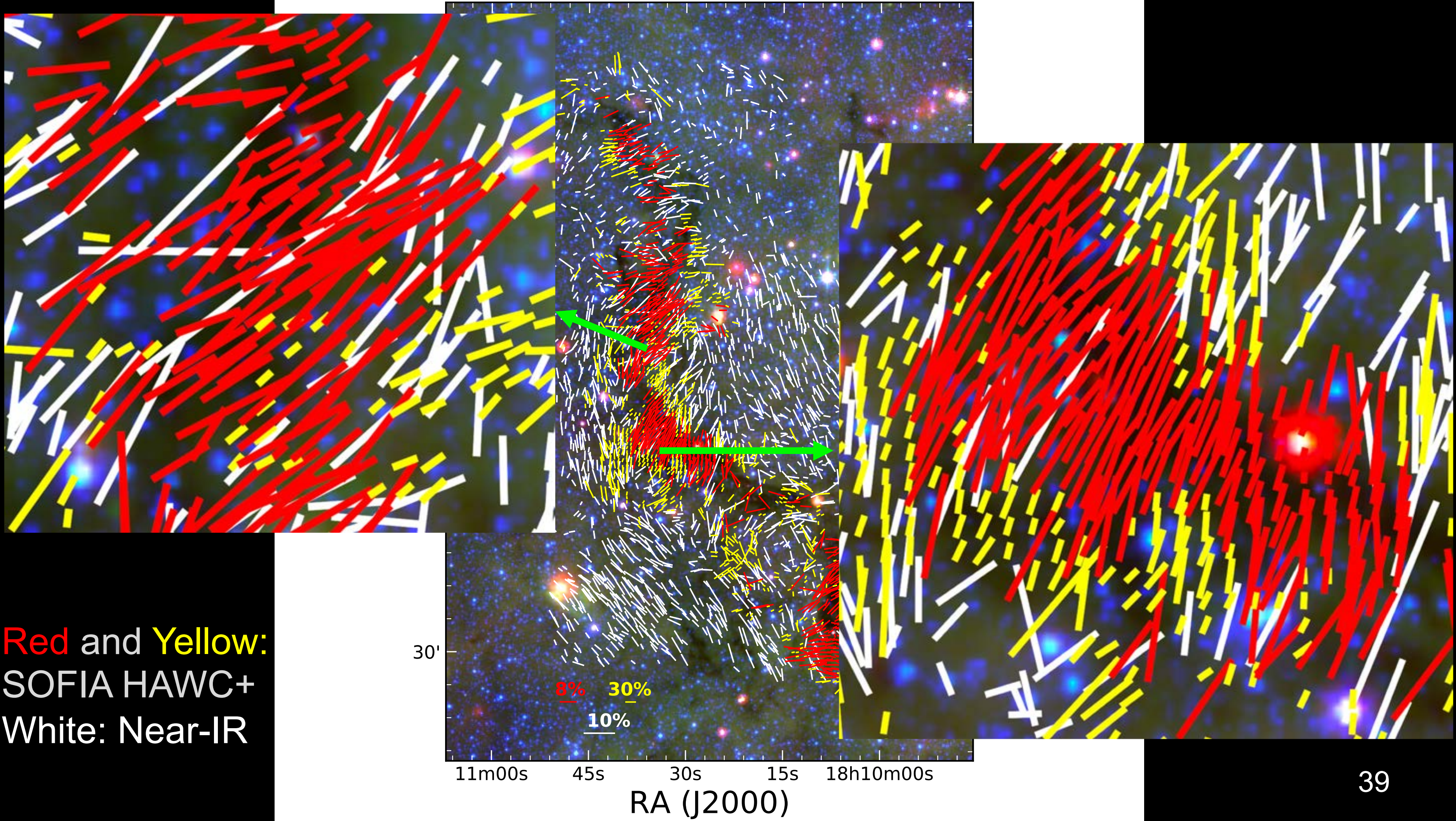
Spitzer IRAC+MIPS, **Snake**: High-mass Star-Forming Filament

M51, Credit: S. Beckwith (STScI) Hubble Heritage Team, (STScI/AURA), ESA, NASA

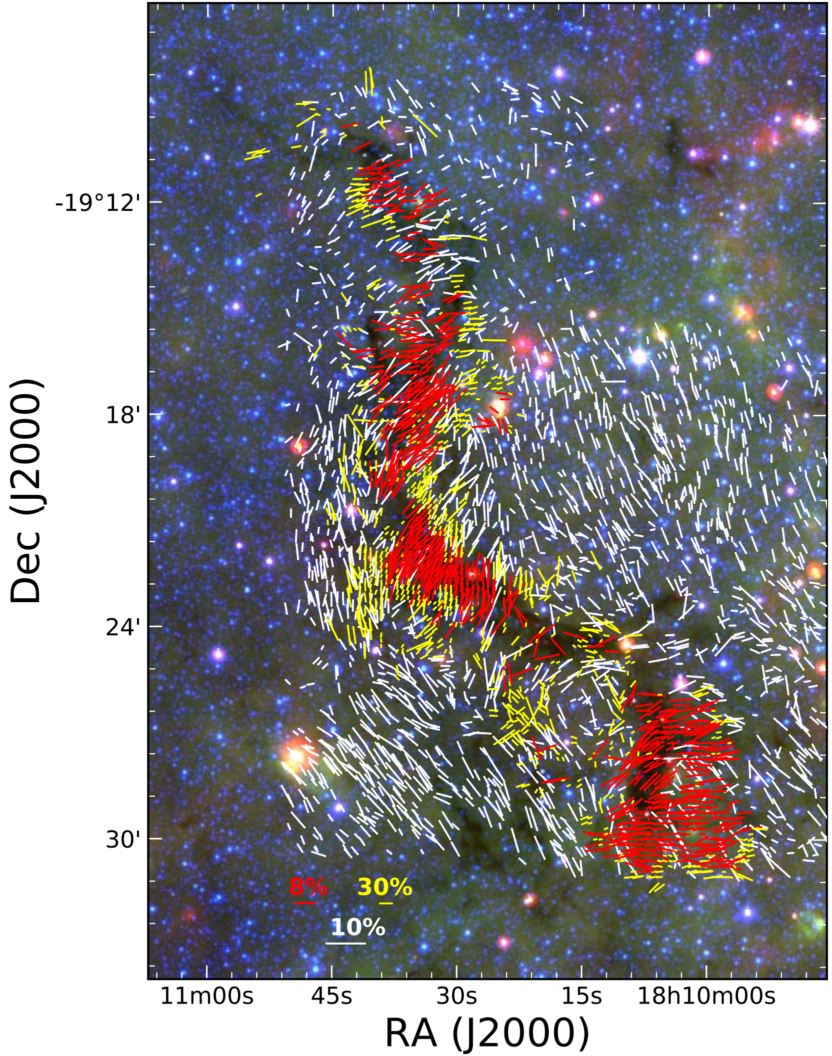


Spitzer IRAC+MIPS, Snake: High-mass Star-Forming Filament


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

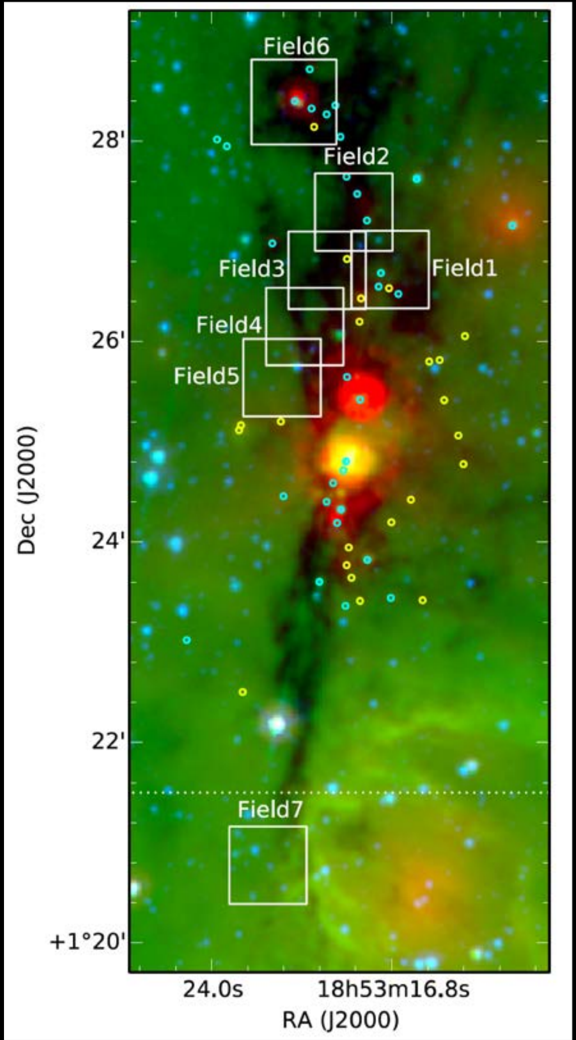


Red and Yellow: SOFIA HAWC+
White: Near-IR



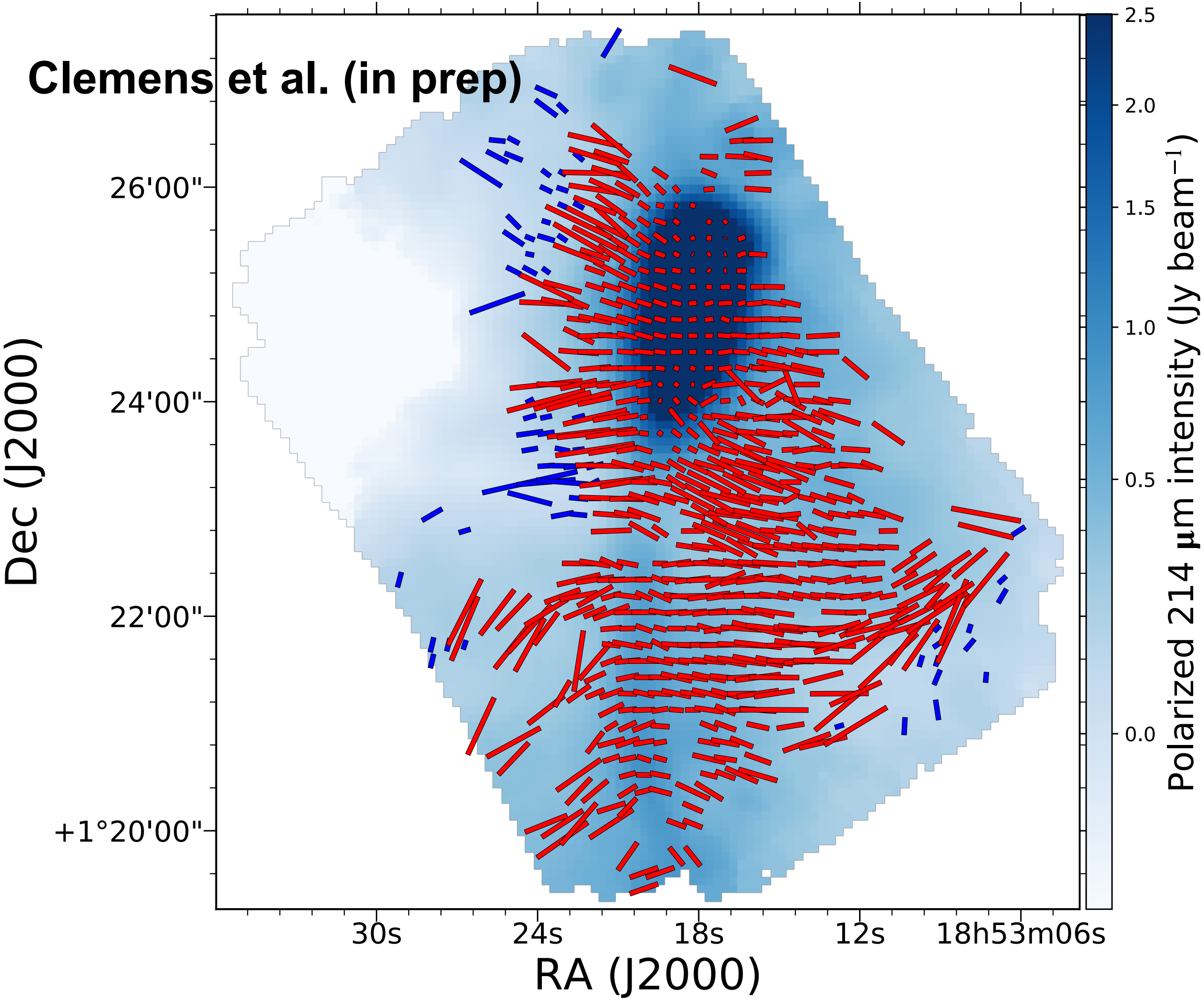
Near-IR: low densities
SOFIA: high densities

Significant Overlap



G34.43+00.24

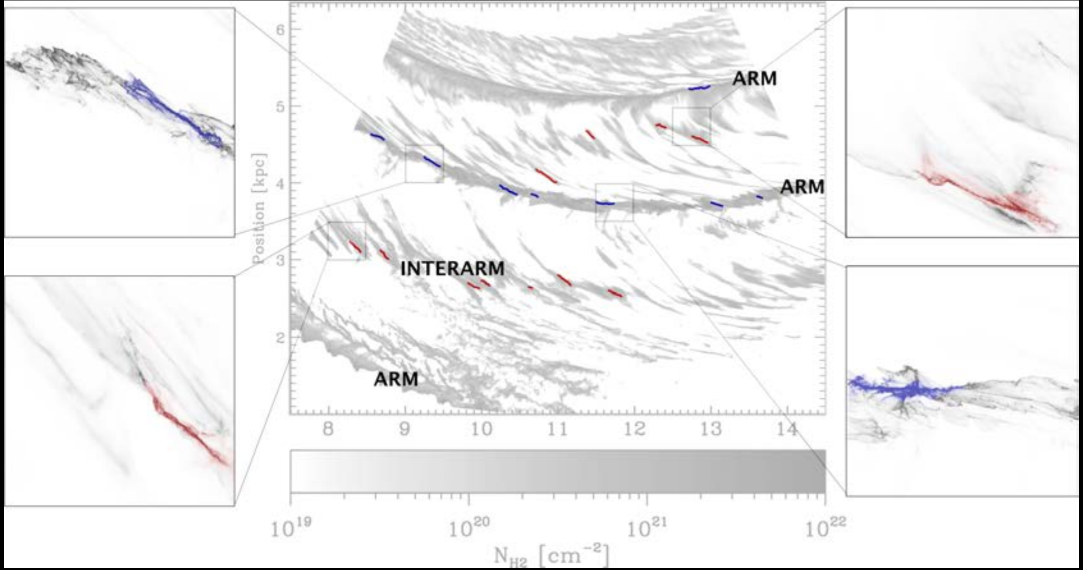
Foster et al. (2014)



Clemens et al. (in prep)
26'00"
24'00"
22'00"
+1°20'00"
Dec (J2000)
30s
24s
18s
12s
18h53m06s
RA (J2000)
2.5
2.0
1.5
1.0
0.5
0.0
Polarized 214 μm intensity (Jy beam^{-1})

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

PI: Ian Stephens

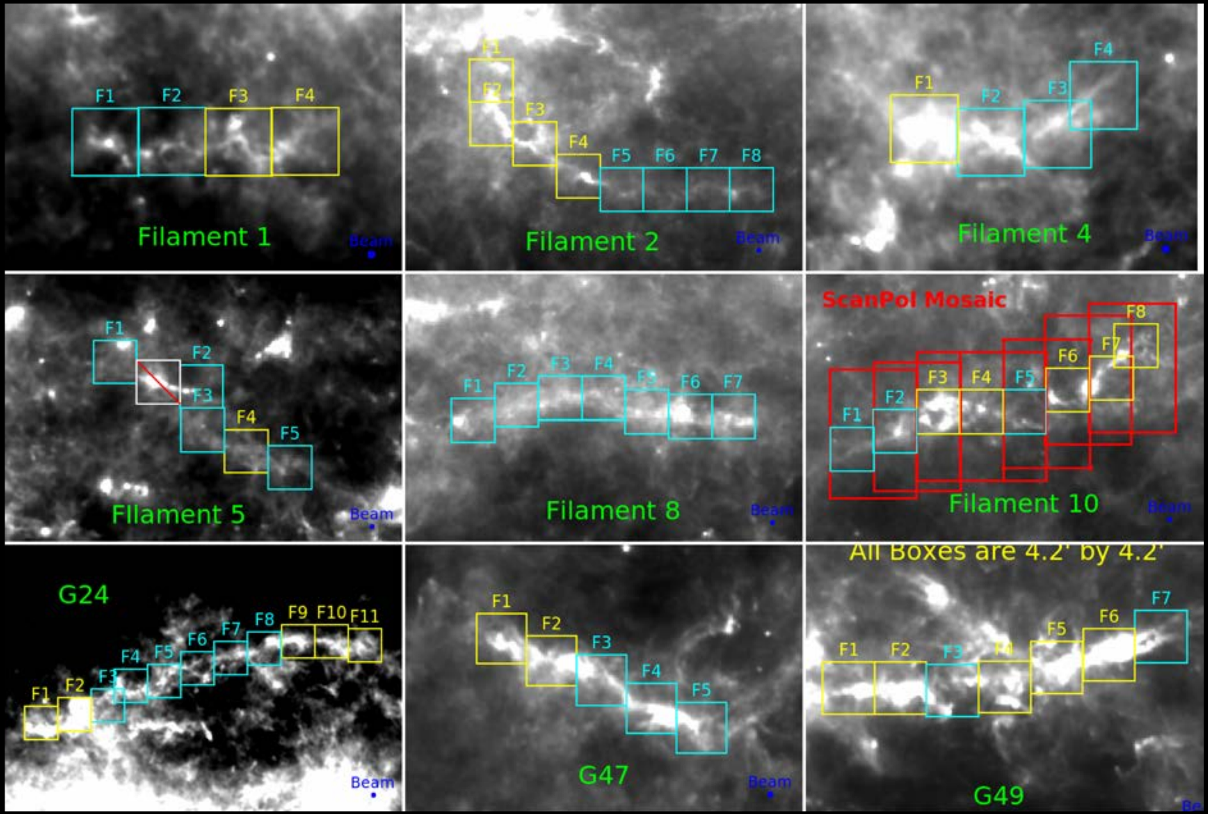


Zucker et al. (2019)

- The Bones of the Milky Way (Zucker et al 2015; 2018)
- Compare to simulations (Smith et al. 2014, 2019)
- 3D Field Morphology
- Giant filaments sheared versus compressed
- Can we see fields bend into filaments?

Pilot Legacy Survey Awarded: 15 of 42 hours
Full Legacy: 10 Filamentary “Bones”

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



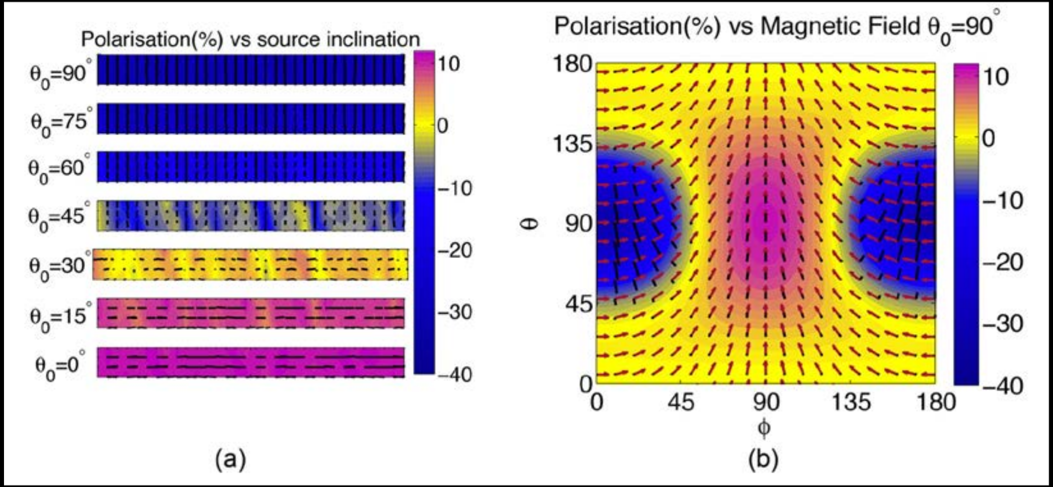
Pilot Survey Awarded: 15 of 42 hours
Full Legacy: 10 Filamentary "Bones"

Galactic SF, Magnetic Fields and SOFIA

- Bridge size-scale between Planck and ALMA
  - Connects dense ISM with Near-IR observations of diffuse ISM
- Great for large maps
  - Quicker than JCMT and can map diffuse areas
  - Southern sources
  - Scan-pol (on-the-fly mapping) makes imaging even faster
  - **Greatly would benefit from larger field of view (footprint) and less dead pixels**
  - Band B (62 μm) for multiwavelength studies
- Infrared guide camera

Ground State Alignment

- Ground State Alignment
  - Polarization of atoms/ions
  - Anisotropic radiation pumps and aligns atoms/ions in media
  - Magnetic field induces precession and realigns atoms/ions
- Potentially tells us the 3D field morphology



Zhang & Yen (2018)

Ground State Alignment

Submillimeter Lines

Species	Transition	Wavelength	max(P)
[C I]	$3P_1 \rightarrow 3P_0$	610 μm	21 per cent[a]
[C I]	$3P_2 \rightarrow 3P_1$	370 μm	18 per cent[b]
[C II]	$2P^\circ_{3/2} \rightarrow 2P^\circ_{1/2}$	157.7 μm	28.5 per cent[a]
[O I]	$3P_1 \rightarrow 3P_2$	63.2 μm	4.2 per cent[a]
[Si I]	$3P_1 \rightarrow 3P_0$	129.7 μm	20 per cent[a]
[Si I]	$3P_2 \rightarrow 3P_1$	68.5 μm	18 per cent[b]
[Si II]	$2P^\circ_{3/2} \rightarrow 2P^\circ_{1/2}$	34.8 μm	12.6 per cent[b]
[S I]	$3P_1 \rightarrow 3P_2$	25.2 μm	3.2 per cent[a]
[Fe II]	$a6D_{7/2} \rightarrow a6D_{9/2}$	26.0 μm	4.9 per cent[a]

Emission

Species	Transition	Wavelength	$\max(P/\tau)$
[C I]	$3P_1 \rightarrow 3P_2$	370 μm	2 per cent[a]
[O I]	$3P_2 \rightarrow 3P_1$	63.2 μm	30.8 per cent[b]
[O I]	$3P_1 \rightarrow 3P_0$	145.5 μm	49.1 per cent[c]
[S I]	$3P_2 \rightarrow 3P_1$	25.2 μm	30.1 per cent[d]
[S I]	$3P_1 \rightarrow 3P_0$	56.3 μm	45.2 per cent[e]
[Si I]	$3P_1 \rightarrow 3P_2$	370 μm	2 per cent[a]
[Fe II]	$a6D_{9/2} \rightarrow a6D_{7/2}$	26.0 μm	9.9 per cent[f]

Absorption

Zhang & Yen (2018)

[C II] Probably best candidate
(bright and high polarization)

Ground State Alignment

- Attempted with GREAT by rotating array about axis; analogous to rotating a half wave-plate
  - Miranda Caputo, B-G Andersson, et al.

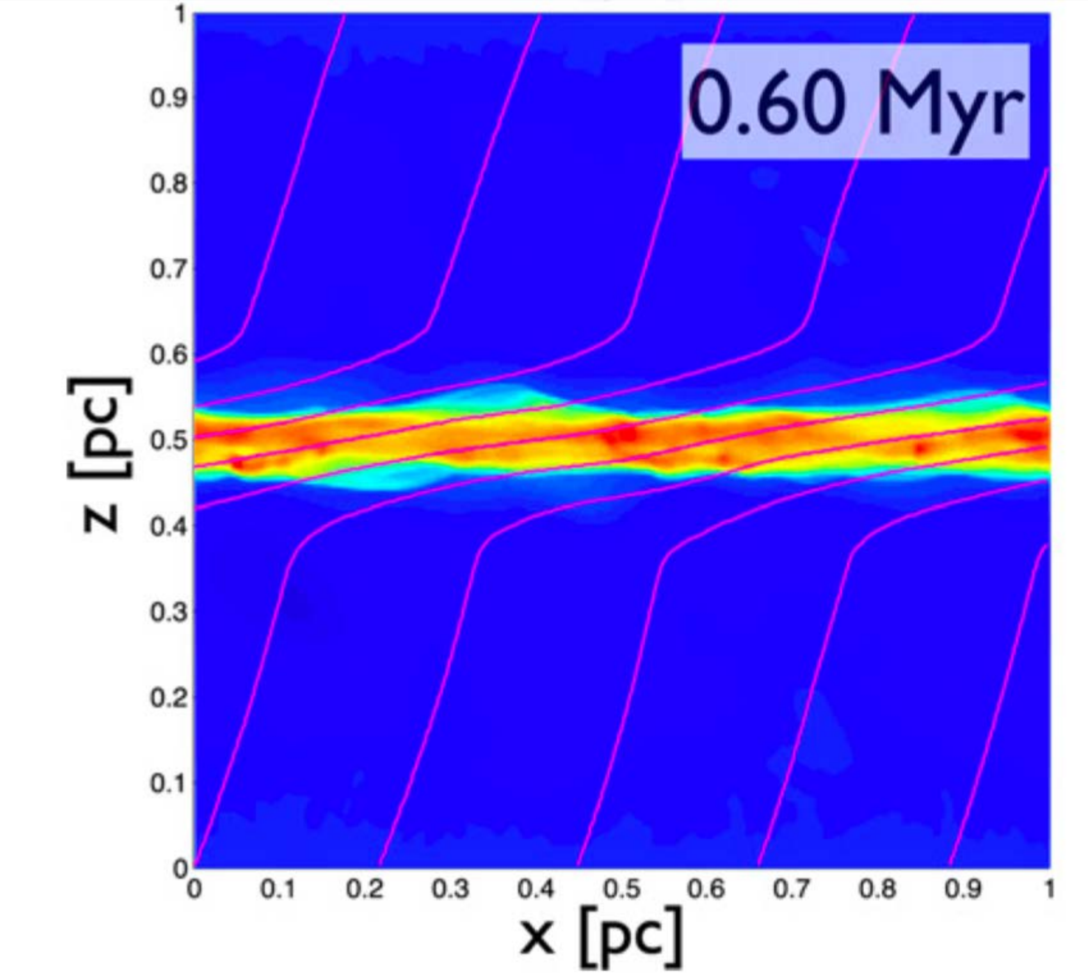
- Signal detected toward two sources, but seems consistent with instrumental polarization.

- Could possibly be done more efficiently with a very narrow filter with HAWC+

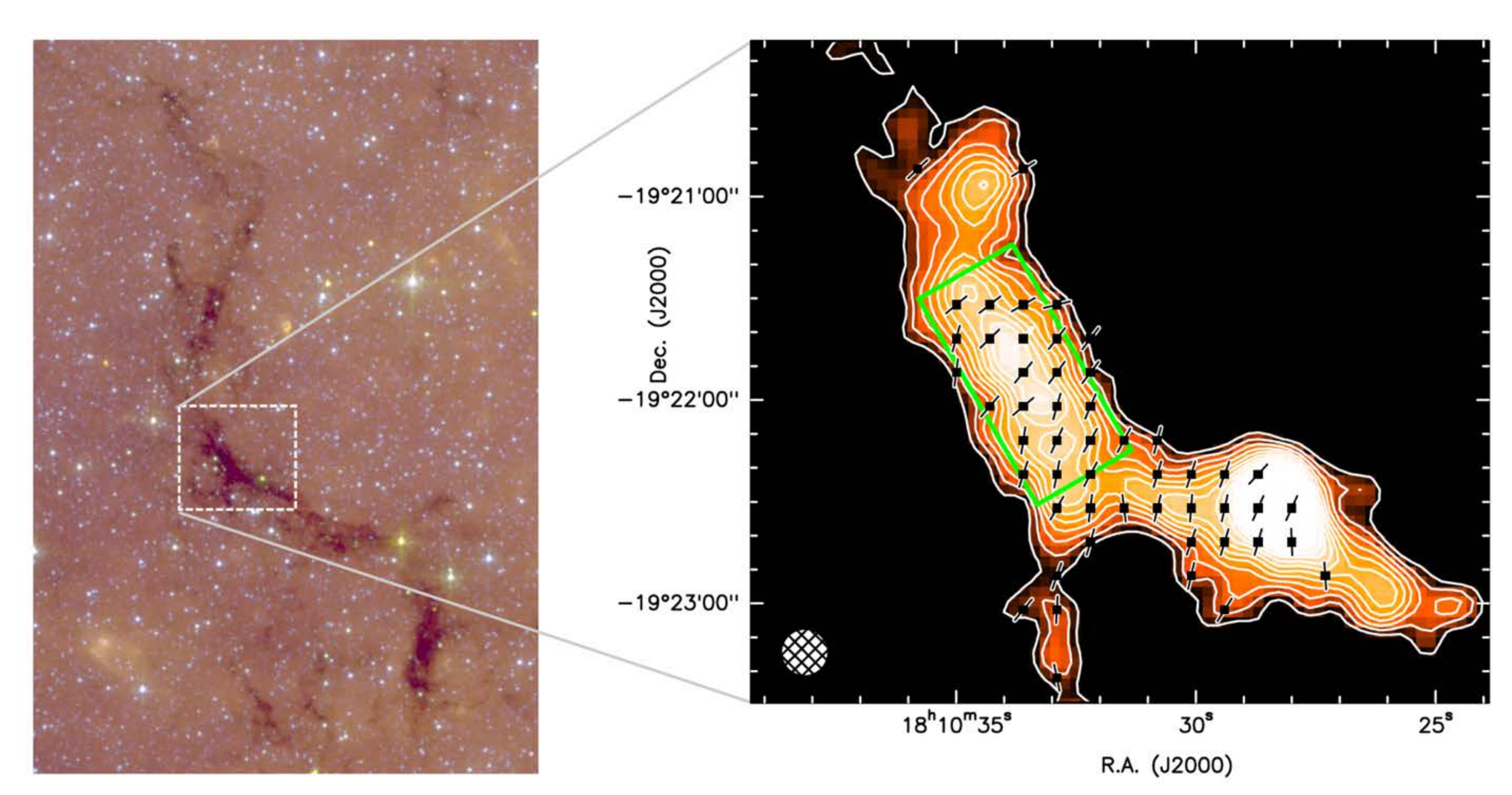
Galactic SF, Magnetic Fields and SOFIA

- Bridge size-scale between Planck and ALMA
  - Connects dense ISM with Near-IR observations of diffuse ISM
- Great for large maps
  - Quicker than JCMT and can map diffuse areas
  - Southern sources
  - Scan-pol (on-the-fly mapping) makes imaging even faster
  - **Greatly would benefit from larger field of view (footprint) and less dead pixels**
  - Band B (62 μm) for multiwavelength studies
- Infrared guide camera
- Perhaps best telescope to probe Ground State Alignment
  - Potentially provides 3D field morphology
  - Narrow-band filter for HAWC+

Backup Slides

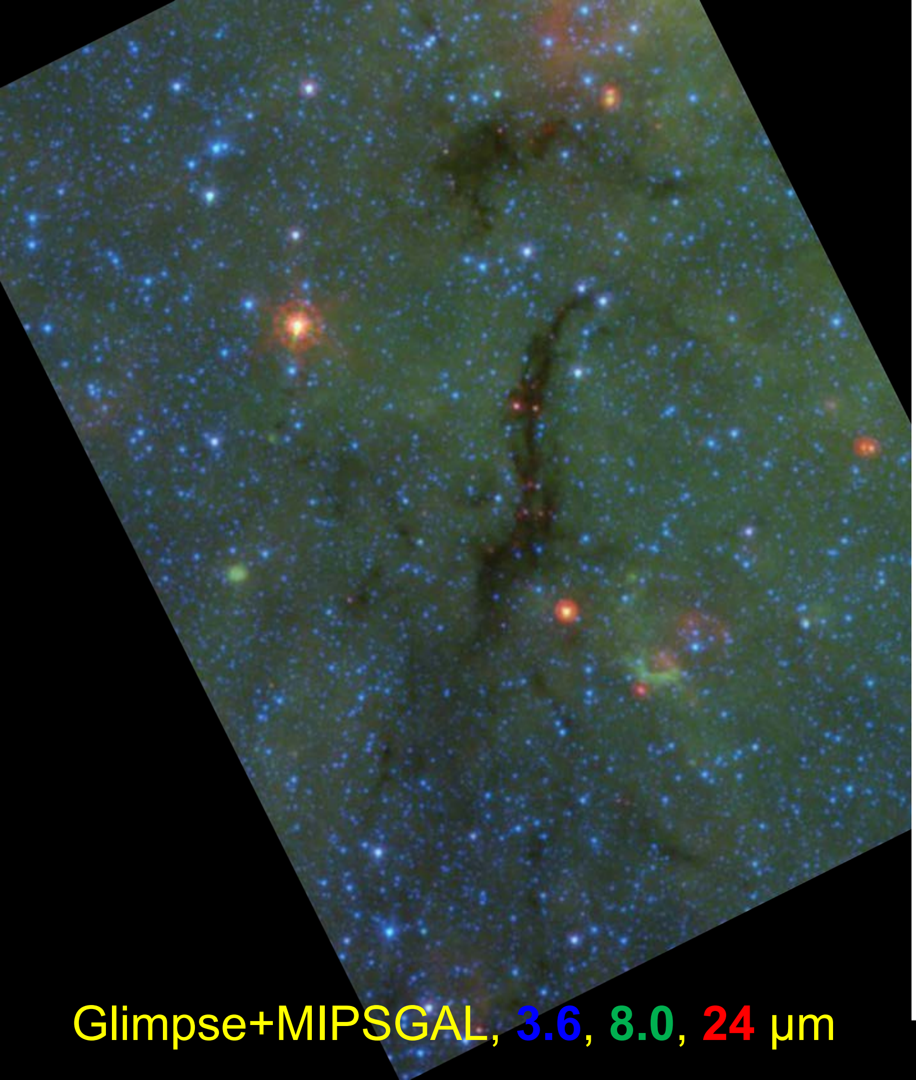


Chen & Ostriker (2014)

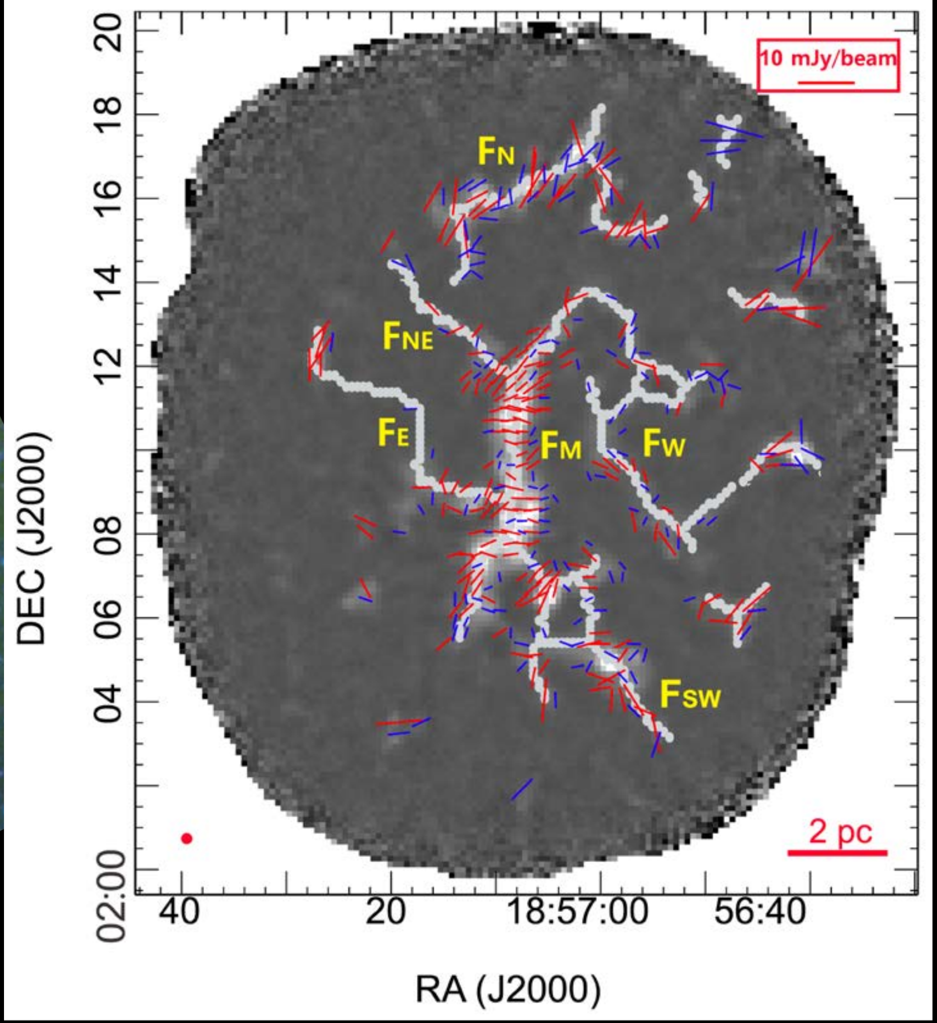


Pillai et al. (2015)

Over Filaments ~1 pc in size. What about larger structures?



Glimpse+MIPSGAL, 3.6, 8.0, 24 μm



JCMT, Liu et al. (2018)