TELETALK

Polarimetry of Star Forming Regions with HAWC+
SOFIA's Important Role

Judy Pipher

Outline

1. Why am *I* giving this talk?
2. Angular scales – how HAWC+ polarimetry fits in the post-Herschel/Planck Era, the JCMT/SMA and the ALMA eras
3. Two HAWC+ results on nearby star forming regions as examplars of what can be done, and what is needed
4. Turbulence and Magnetic Fields

Why am *I* giving this talk?

- As most of you will know, this is not my field
- But – I have been chair of the SOFIA Science Council (SSC) since the prior SOFIA NASA Project Scientist decided on a NASA only (not joint NASA-USRA) committee, and USRA realized it needed its own science council to report on science missions operations
  - **During the Senior Review discussions, as well as the replacement SOFIA Five Year Flagship Mission Review discussions, HAWC+ results were emphasized**
  - **I was asked to speak on HAWC+ at January 2018 AAS, SOFIA session**
- I am the Lead Editor for the AAS corridor Interstellar Matter and the Local Universe, so I am responsible for papers on these topics

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Magnetic Fields and Star Formation

- Andre (2017) reviews current understanding of star formation processes, emphasizing that narrow (~0.1 pc) dense filaments are the preferred location to form pre-stellar cores - NIR/MWIR polarimetry (extinction based) inadequate for dense regions
- Several classes of models of filament origin
  - Self-gravity (e.g. in high mass star forming regions as well as intermediate and low-mass)
  - Supersonic flows generate compressive planar MHD shock wave
  - Accretion to supercritical filaments: gravitational energy converted to turbulent energy
- 850 μm dust polarization observations galactic plane (Planck survey) reveal ordered B fields on >1-10 pc scales, including filaments (5′ – 10′ spatial resolution)

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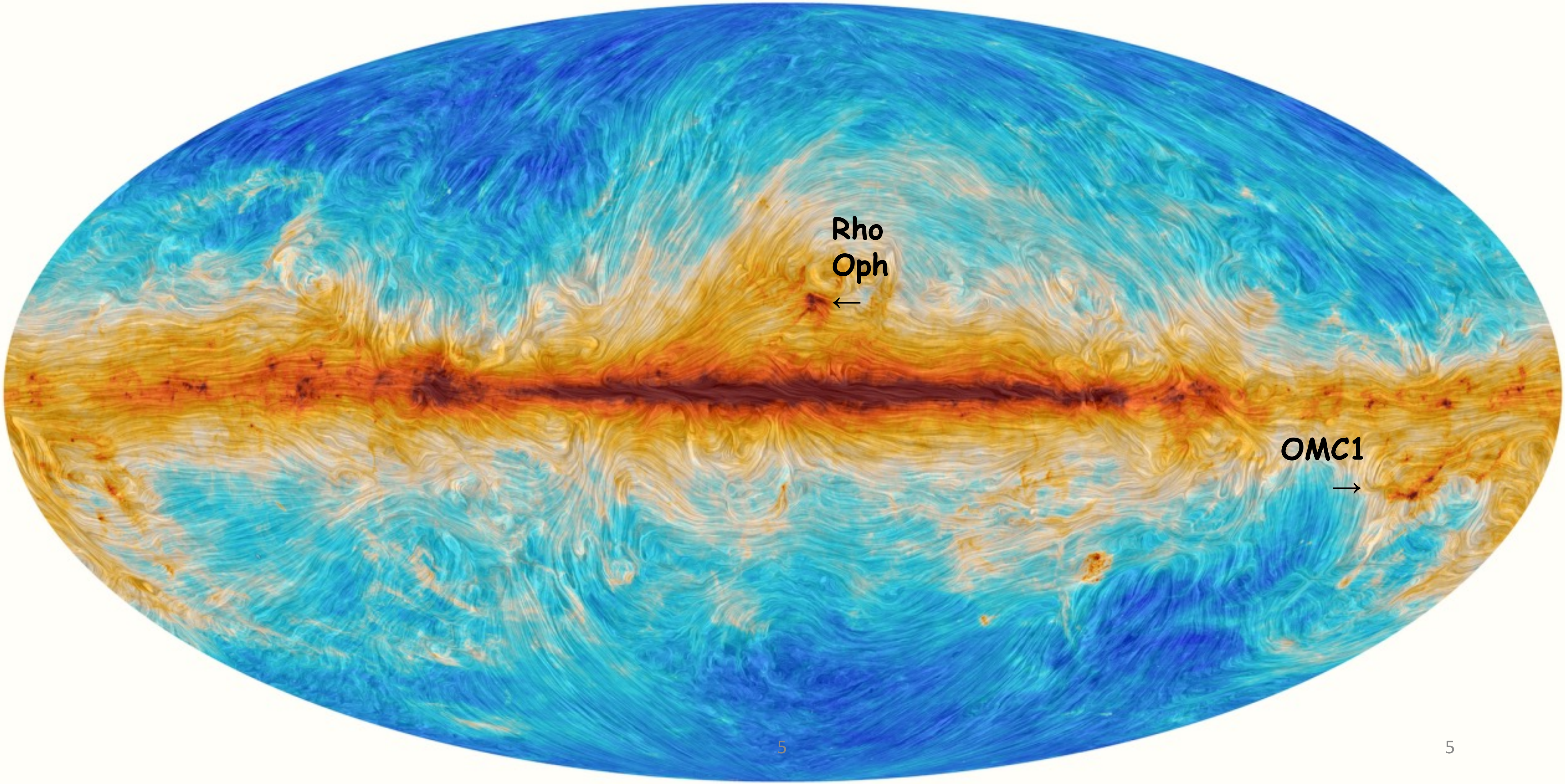
ESA/Planck polarization survey- magnetic field directions given by texture; 850 μm 10′ res.



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Polarized Dust Emission and Inferred Magnetic Fields

- Non-spherical grains spin due to radiative torques – RATs - from the anisotropic radiation field (Lazarian and Hoang 2017; Draine and Weingartner 1996; Lazarian 2007). Spinning grains preferentially align with short axes parallel to magnetic field lines.
- Polarized dust extinction from background starlight is parallel to the B field; polarized thermal emission is orthogonal to the B field.
- Alternative mechanisms include Rayleigh self scattering from grains in an anisotropic radiation field when grain size exceeds the λ (Kataoka et al. 2015, 2017), and grain alignment from RATs along the flux gradient of the radiation field.
- Chandesekhar-Fermi (CF) theory to translate polarization into Magnetic field intensities and directions

Assessing the role of magnetic fields from polarization data means comparing data with numerical simulations and/or relying on theoretical models!

SOFIA HAWC+ is uniquely positioned to play an important role

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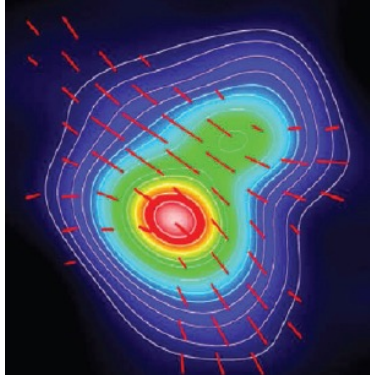
What do different protostellar core formation models say about B field geometry?



- Older models based on magnetic support of molecular clouds
  - Gas falls parallel to the field lines; B field lines frozen in the matter, mass dragged field lines form an ordered hourglass shape of region

- On small scales close to protostar, may see a variety ofpolarization mechanisms in play at different wavelengths (HL Tau)

- Turbulent models, where magnetic fields are weak and B field lines deformed by the turbulent environment (Ser-emb8)
  - Lead to wildly disordered B field lines (recent ALMA observations of this protostar fits turbulent model in part)

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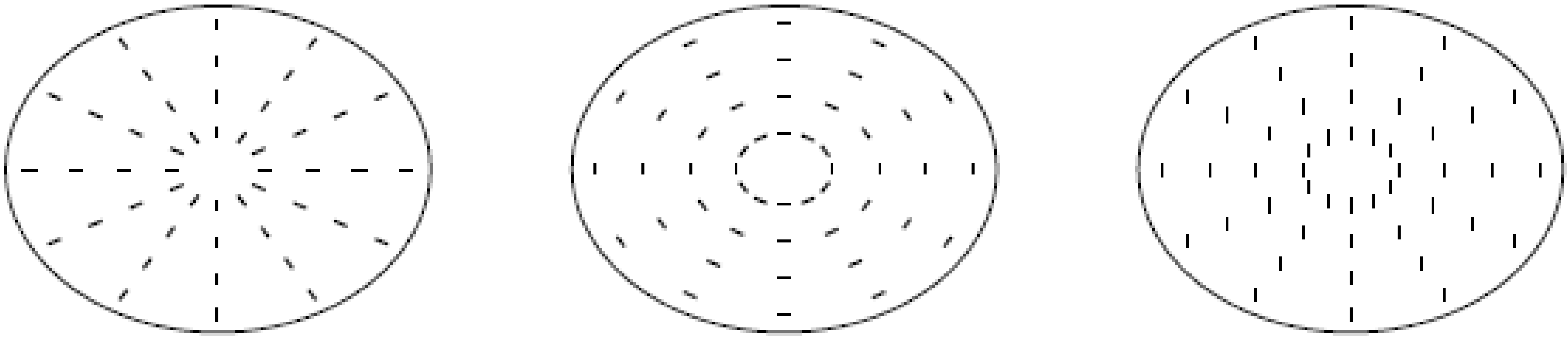


Figure 3. Schematic illustrations for the differences of polarization vectors of each mechanism of polarization of thermal dust emission. The major axis is in the horizontal direction. Note that each panel represents E-vectors. (a) Grain alignment with the toroidal magnetic fields. (b) Grain alignment with the radiation fields. (c) Self-scattering of the thermal dust emission

HL Tau at different wavelengths – polarization at 3.1 mm in ring due to grain alignment with radiation field. Polarization at 1.3 mm dues to scattering. Often get combinations of polarization mechanisms at small spatial scales.

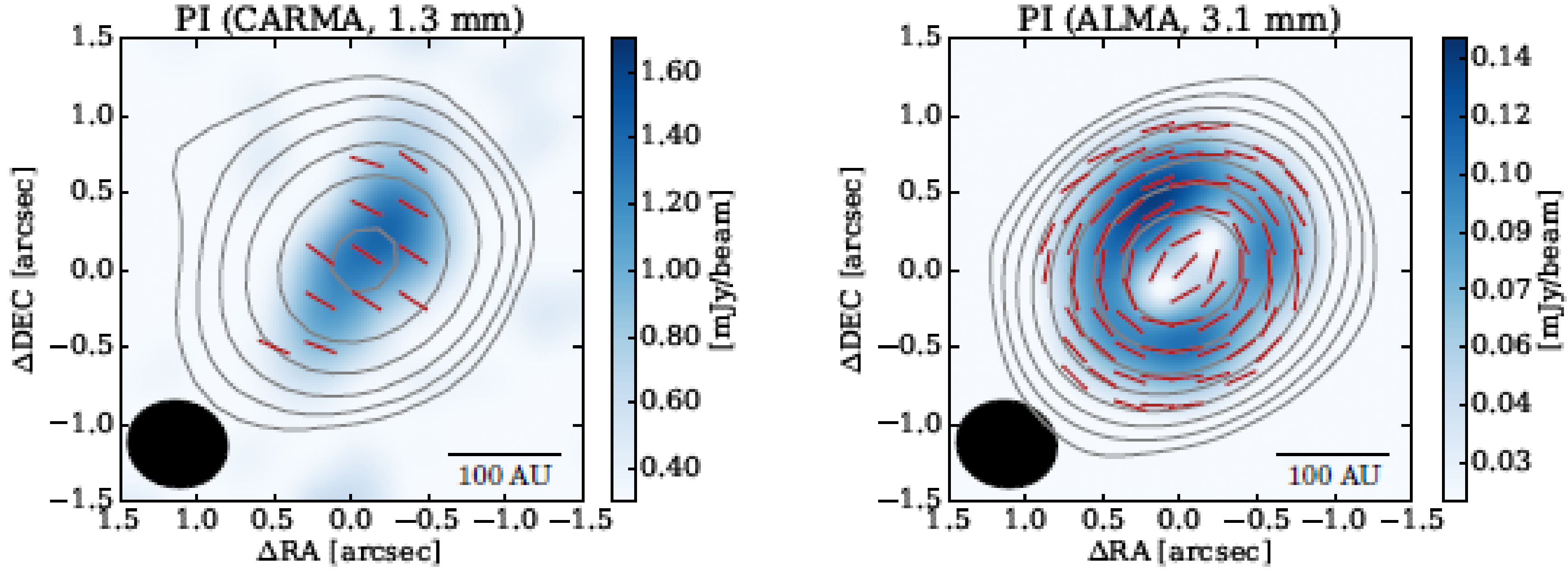
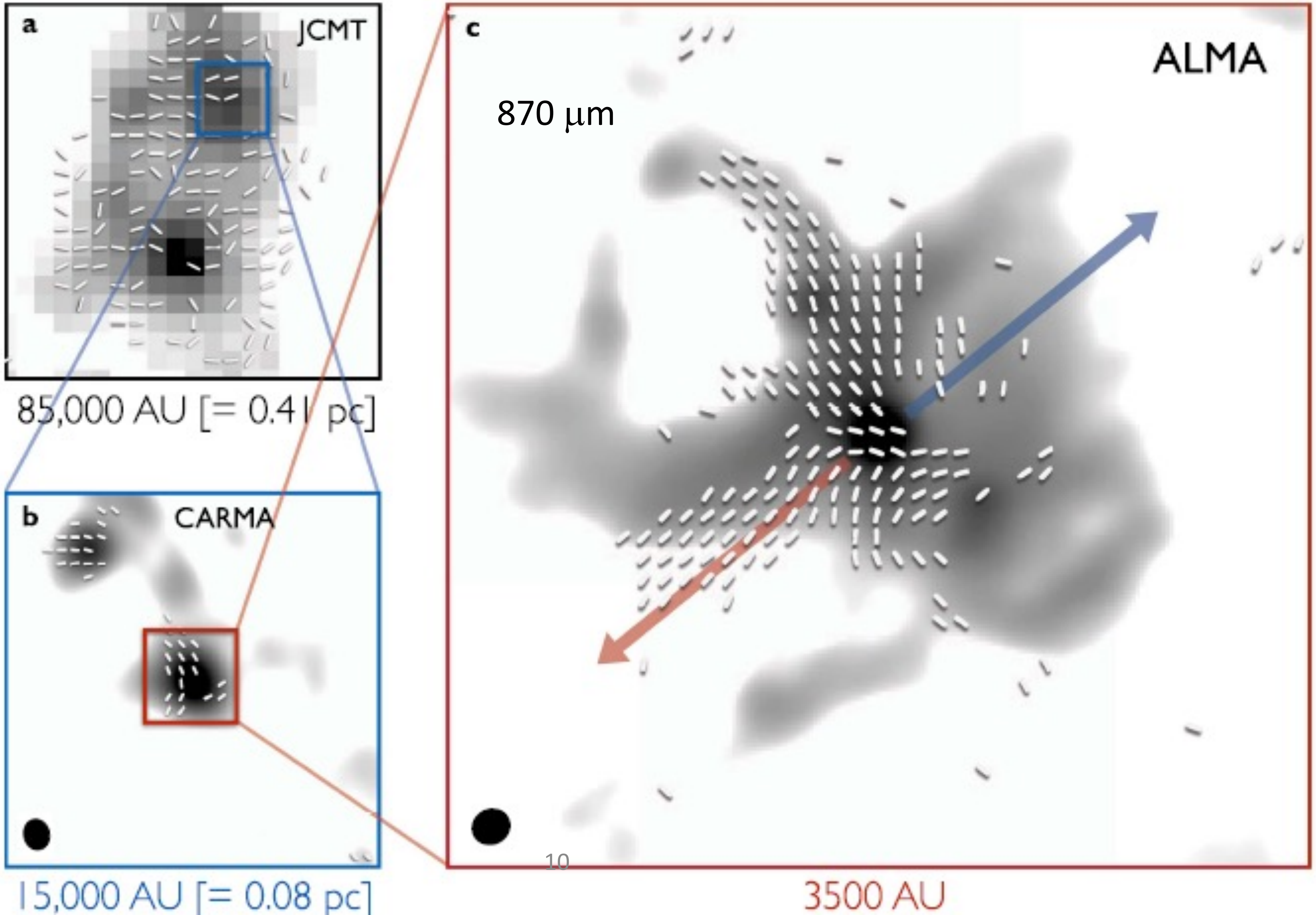


Figure 2. Comparison of the polarization images between $\lambda = 1.3$ mm (CARMA Stephens et al. 2014) and $\lambda = 3.1$ mm (ALMA, this observation). The ALMA image is smoothed to have the same beam size of CARMA, where the beam size is $0.65'' \times 0.56''$ with the PA of 79.5 degrees. The color scale represents the polarized intensity while the grey contours represent the continuum emission. The levels of the grey contours are $(10, 20, 40, 80, 160, 320, 640, 1280) \times \sigma_I$ where $\sigma_I = 2.1$ mJy/beam for the CARMA data and $\sigma_I = 0.017$ mJy/beam ALMA data. 9

Hull et al. 2017 Multiscale view of B field around Ser-emb8: disordered weak B fields

870μm

1.3 mm



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- HAWC+ provides polarimetry in the far IR from 53-216 μm in 4-5 channels at angular resolutions of 5.4" to 18" – currently the ***only*** facility to offer polarimetry in this wavelength range

- Near and mid-IR imaging polarimeters (scattering, extinction regimes) provide information on more diffuse clouds, or foregrounds of denser clouds – all dust along LOS

- Sub-mm polarimeters: Ground-based facilities such as JCMT SCUBA 2 POL-2 at 14" resolution; SMA at 1", and ALMA at scales ≥10 mas and all at longer wavelengths (emission regime, probe cooler dust; scattering for larger dust grains)

HAWC+ bridges the *wavelength* gaps – probes warm and cooler dust – primarily polarization due to emission from aligned grains

HAWC+ bridges the *angular scale* gap between Planck and ALMA, as does SCUBA

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Planck statistical finding: Low density filaments *aligned* with B field lines; dense star forming filaments are *perpendicular* to B field lines

(Caveat: Planck required careful background subtraction for each Stokes parameter to ascertain B field directions in filaments)

  - Clear that better spatial resolution required to reveal **internal** filamentary polarizations – e.g. HAWC+. Need to understand densities, temperatures and dynamics of these regions as well (upGREAT, FIFI-LS). Turbulence driven velocity gradients may provide a distinct connection between turbulence and magnetic fields – so far theoretical investigations only

- Understanding the fragmentation properties of dense cores leading to a few high mass stars vs. a cluster of low and intermediate mass stars may depend on the mass to magnetic flux ratio.

- HAWC+ can isolate Molecular Cloud cores' magnetic fields for comparison with large scale B field structure from Planck – subtle differences with submm/mm polarimeters

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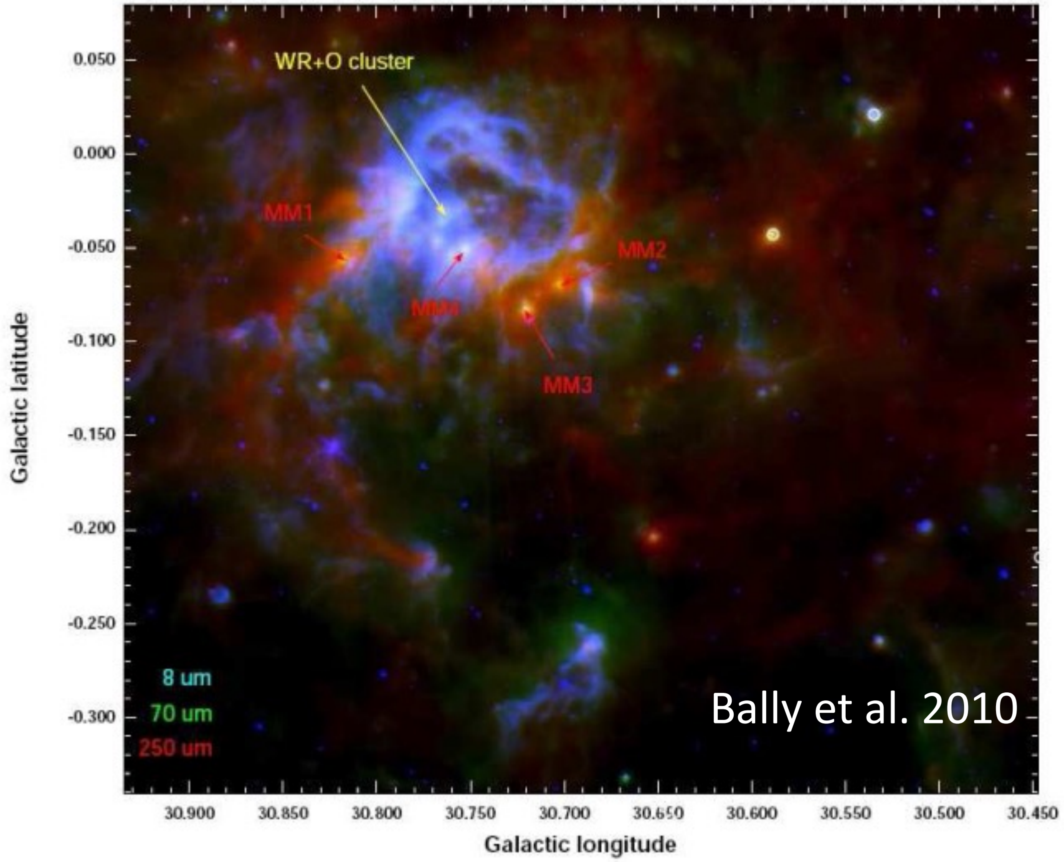

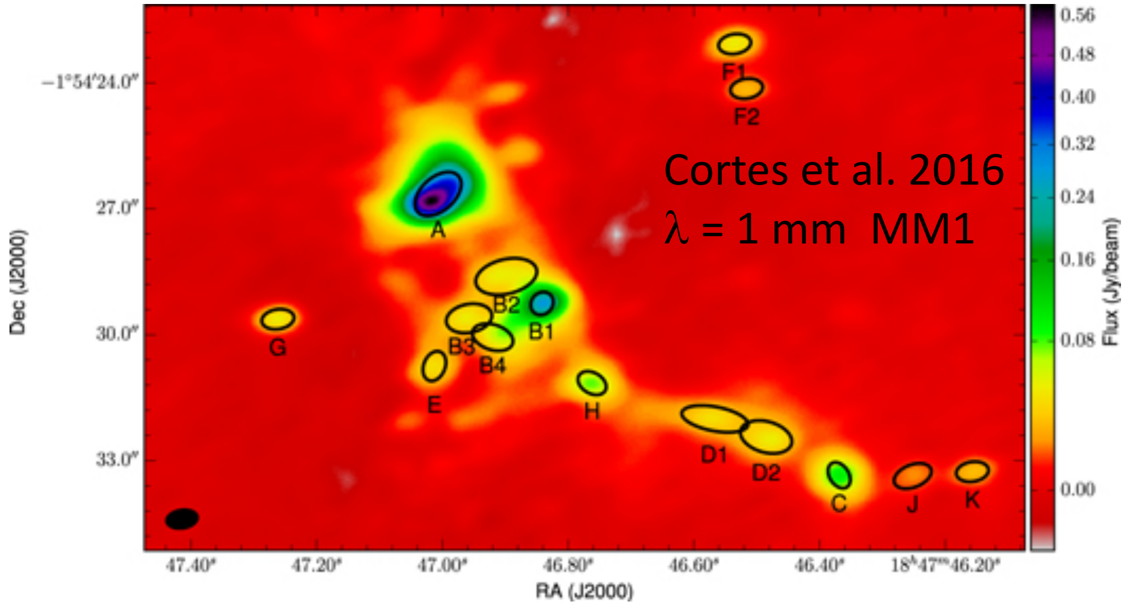

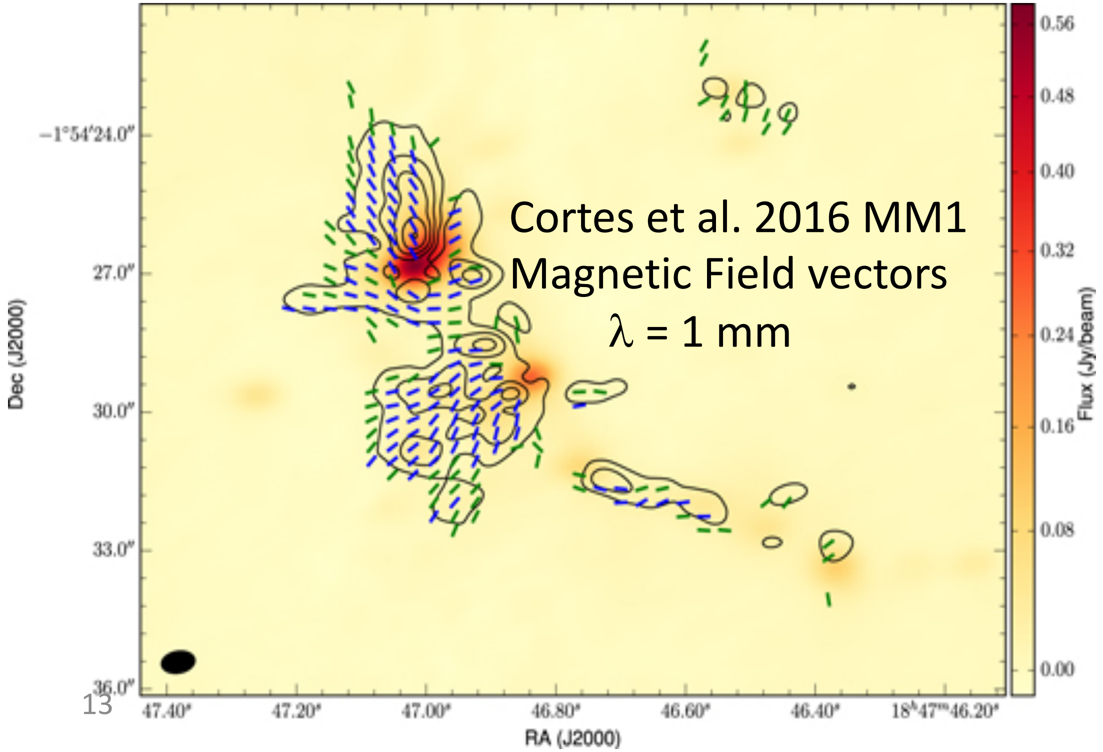

W43 Filamentary structure in the IRDCs such as luminous MM1. The MM objects surround the large WR and O star cluster. **B fields not strong enough to prevent further collapse**

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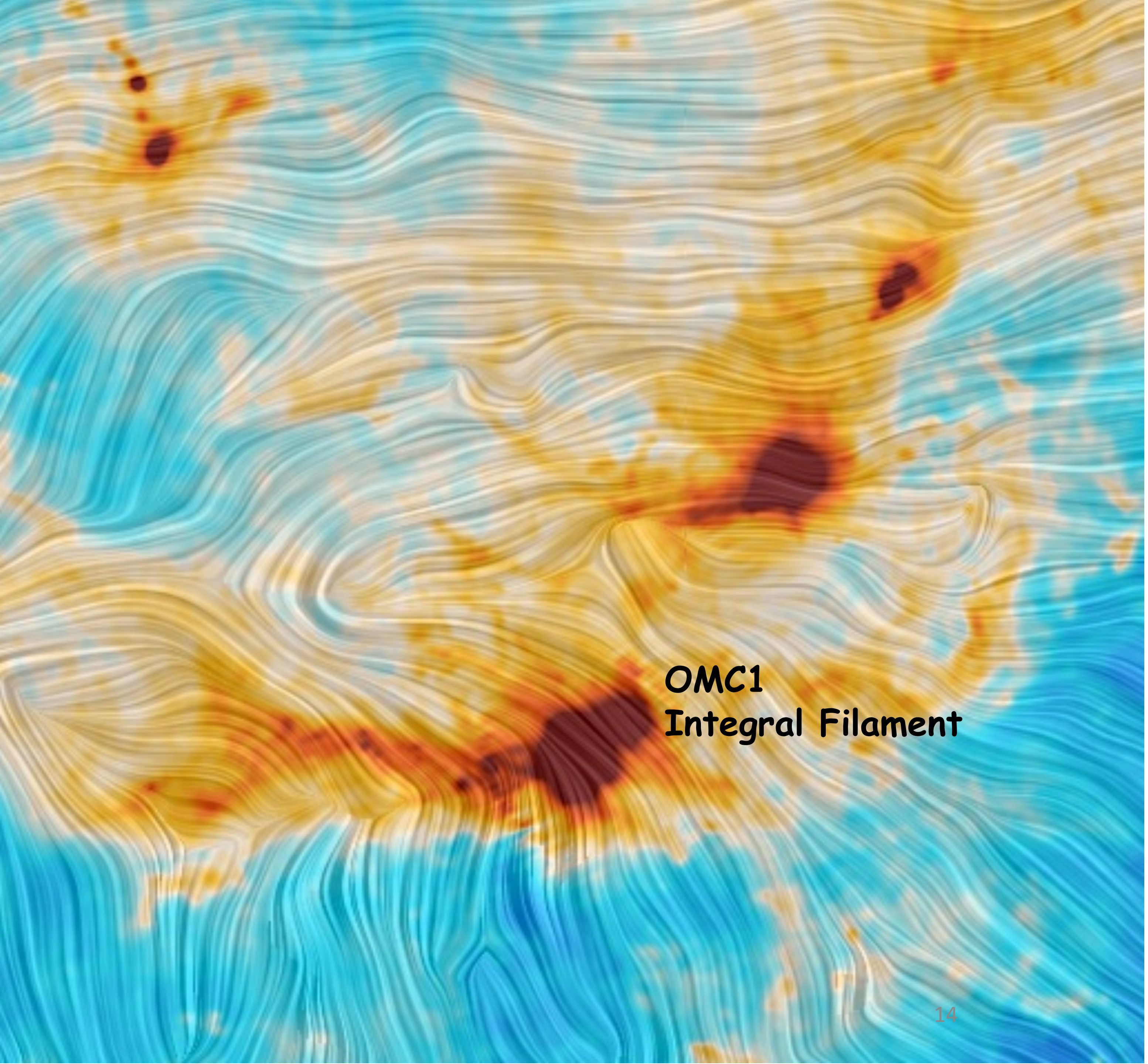
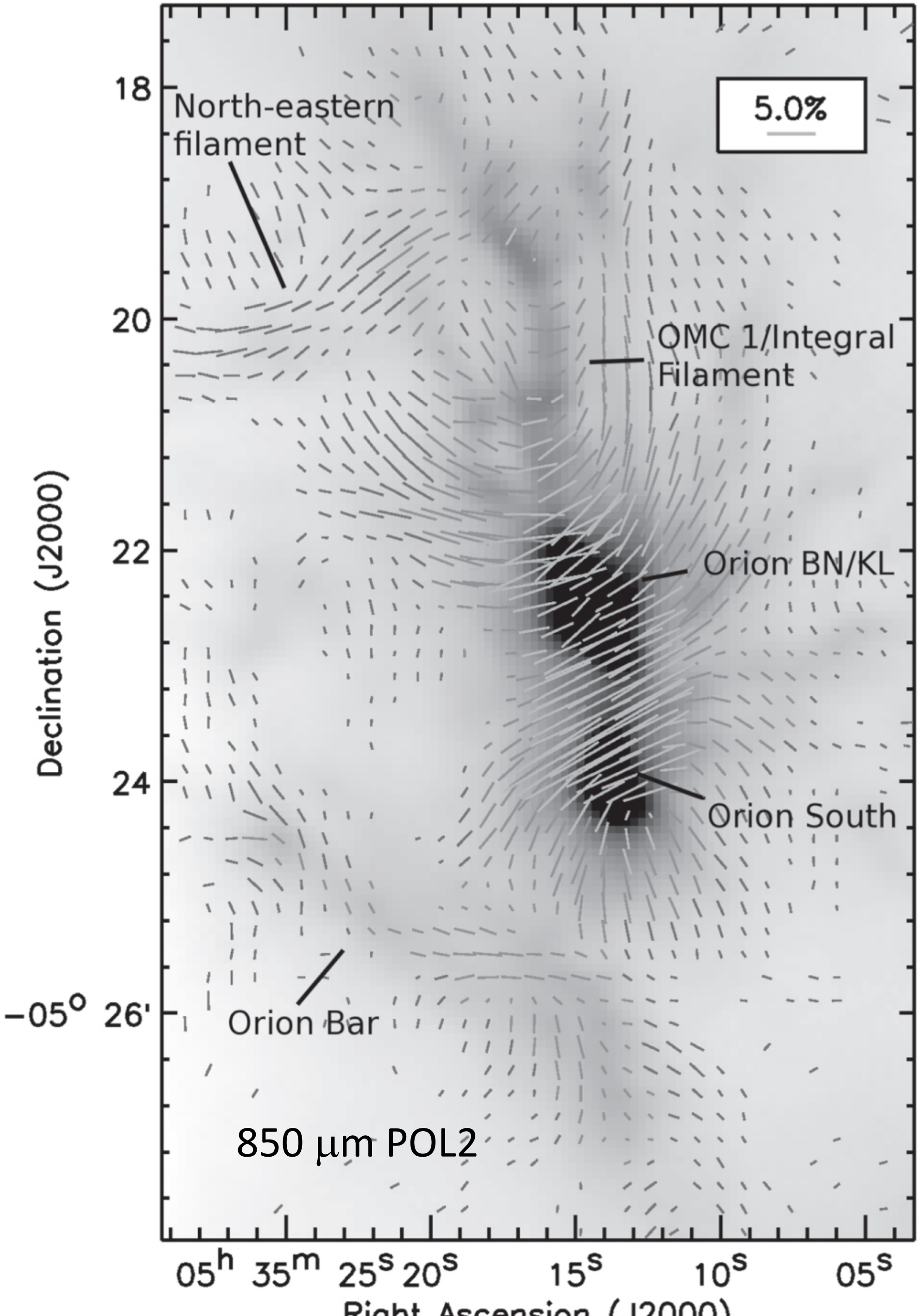


Zoom in on Planck OMC1 - 850 μm

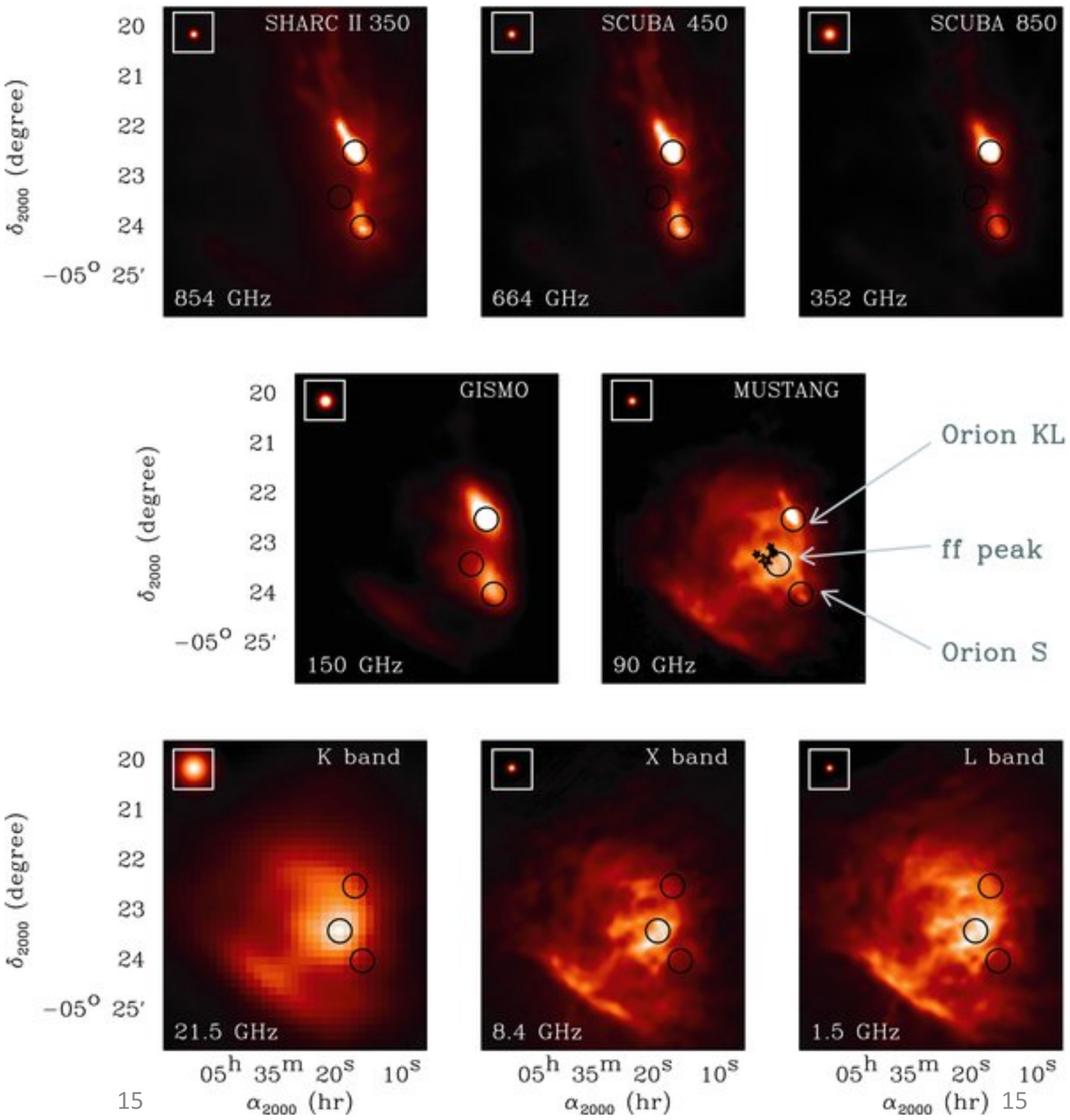
Direction of magnetic field vectors shown – vary from perpendicular to the OMC1 Integral Filament (which contain the star formation regions M42, BN/KL, Orion S), to || to the galactic plane.

Polarization directions can be affected by density, bulk gas motions, turbulence etc.

Spatial scale 5′



North-eastern filament
OMC 1/Integral Filament
Orion BN/KL
Orion South
Orion Bar
5.0%
850 μm POL2
Declination (J2000)
Right Ascension (J2000)



SHARC II 350
854 GHz
SCUBA 450
664 GHz
SCUBA 850
352 GHz
GISMO
150 GHz
MUSTANG
90 GHz
Orion KL
ff peak
Orion S
K band
21.5 GHz
X band
8.4 GHz
L band
1.5 GHz

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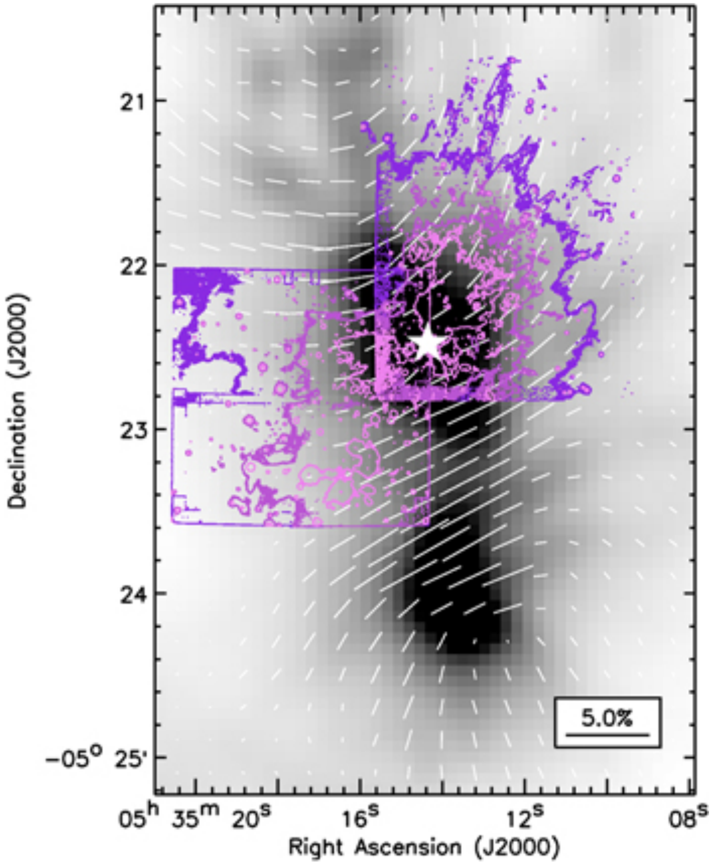
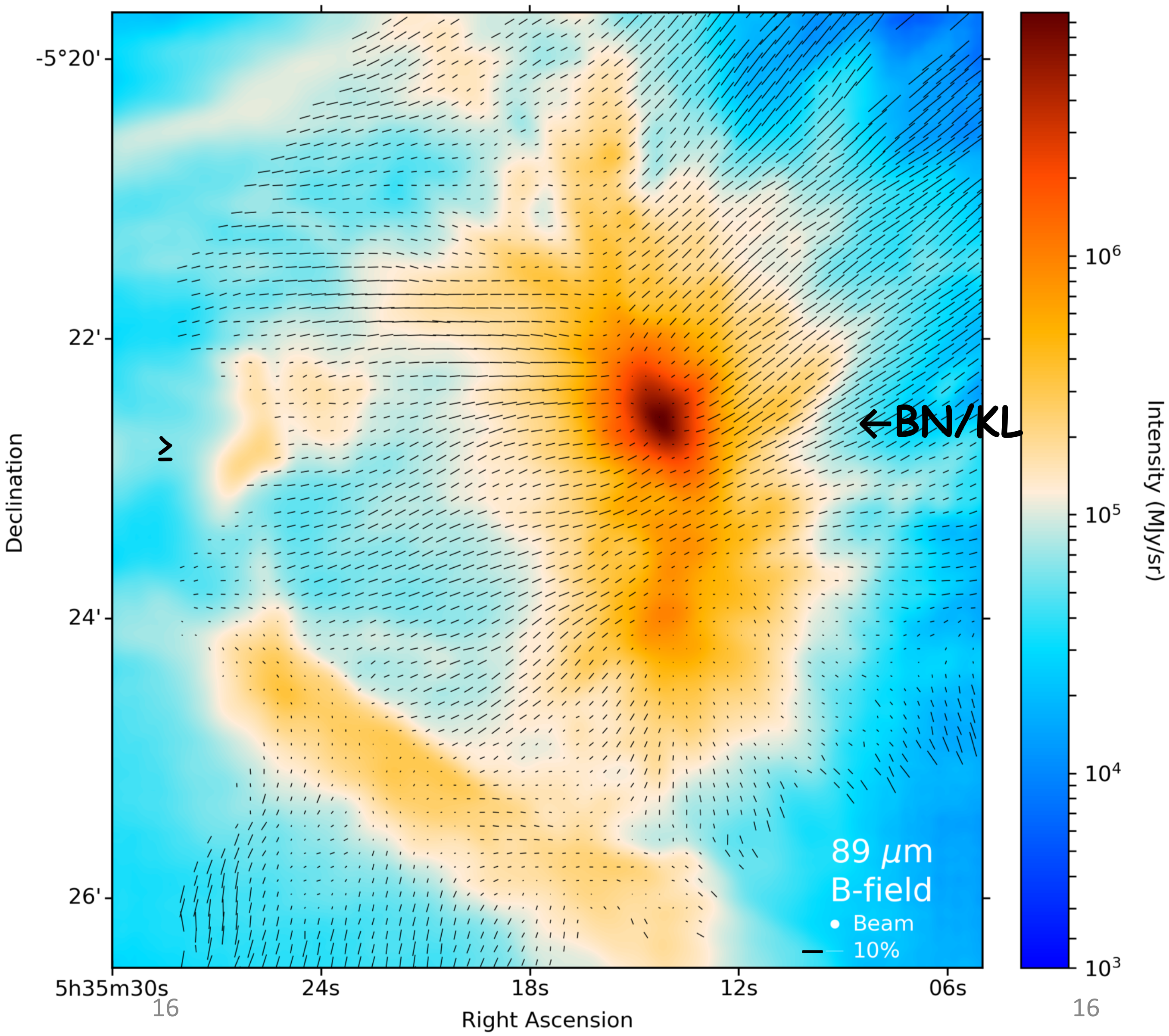
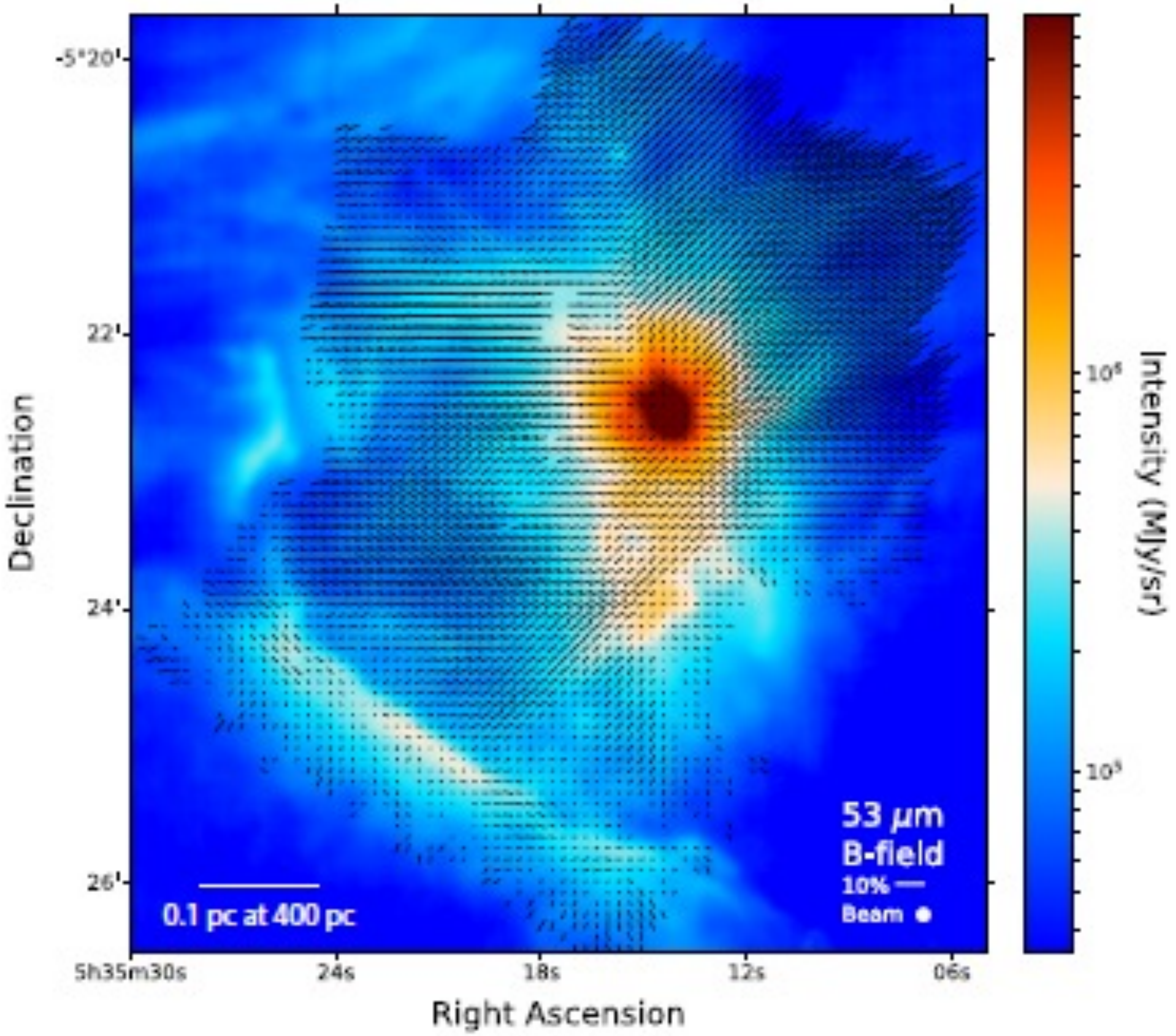
Pattle et al. 2017; 850 μm; 14" beam observation SCUBA2 POL2; field parallel to direction of H_2 outflow from BN/KL region Bally et al. 2017

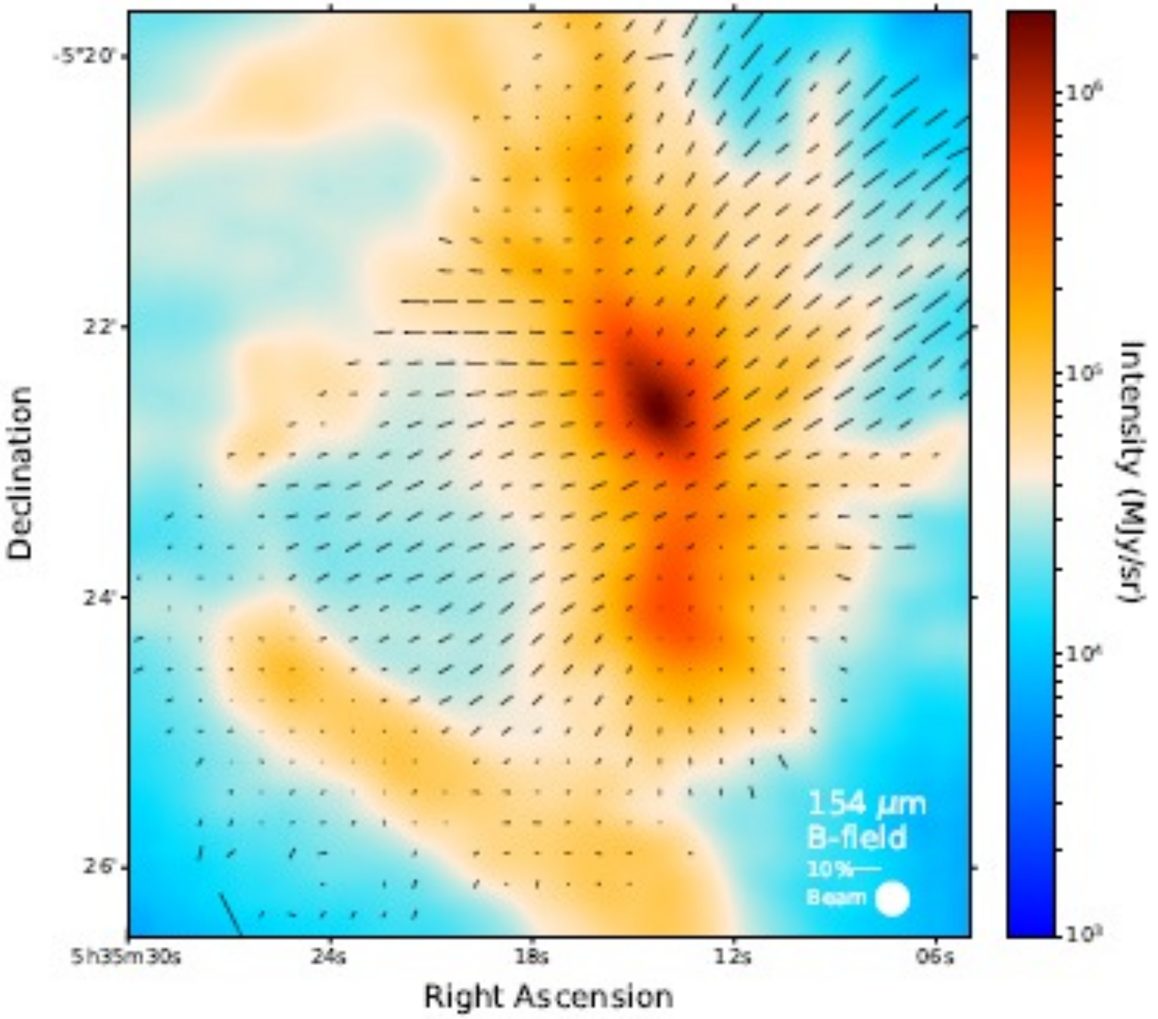


Chuss/HAWC+ arXiv:1810.08233v1 89 μm; 8" res.



Not shown 214 mm – v1. preprint 10-18-18





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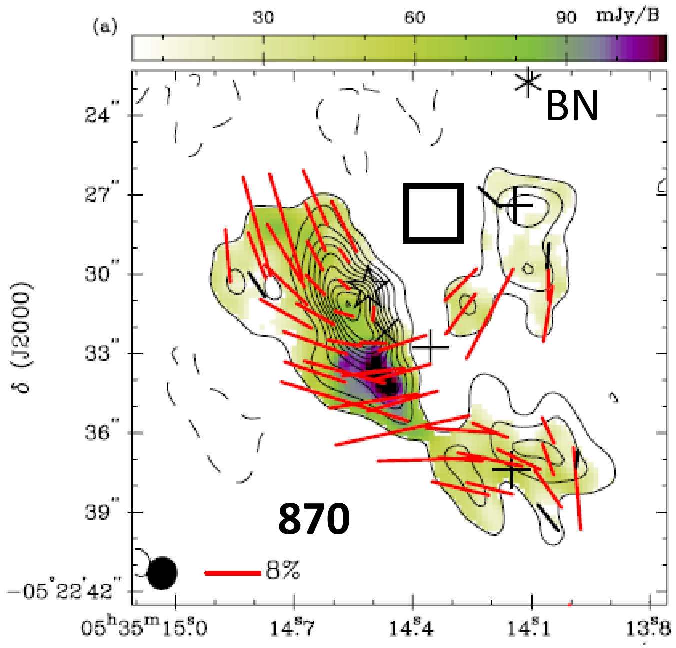
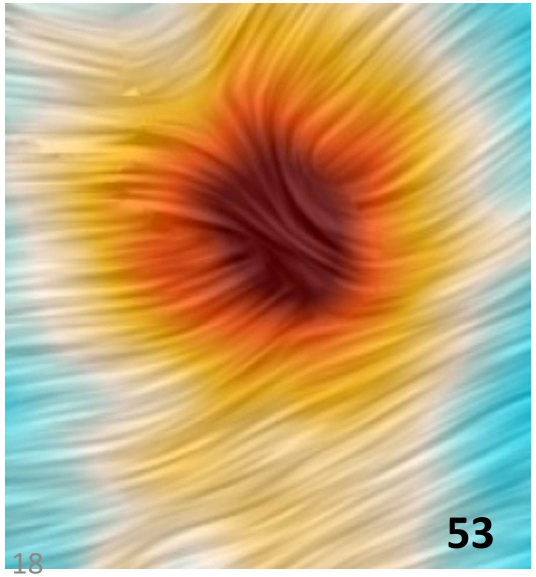
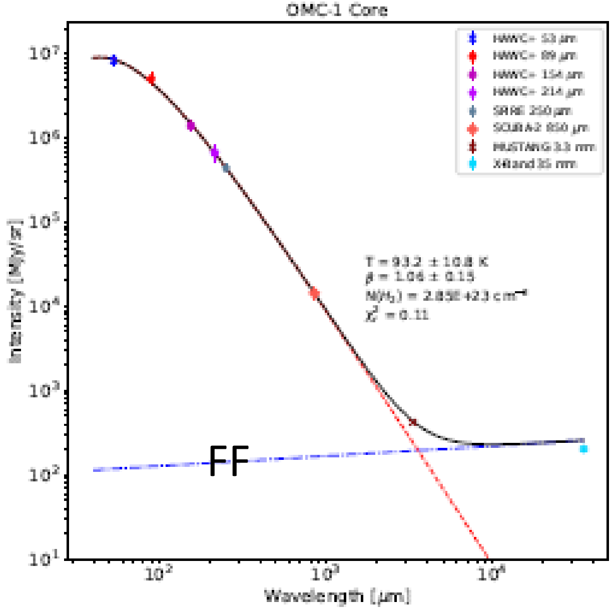
OMC1 Polarization Results

- Similarities in FIR/submm results – with differences in detail
  - The 53um filter is just on the short λ side of the SED for the Bar, and just on the long λ side for the OMC1 core, and the 155um filter is on the long side for both. HAWC+ samples the warm and cold dust, the submm-mm samples the colder dust (and free-free emission)
- In diffuse cloud, field perpendicular to the Integral Filament, with hourglass pinching at all long wavelengths→magnetically regulated cloud collapse

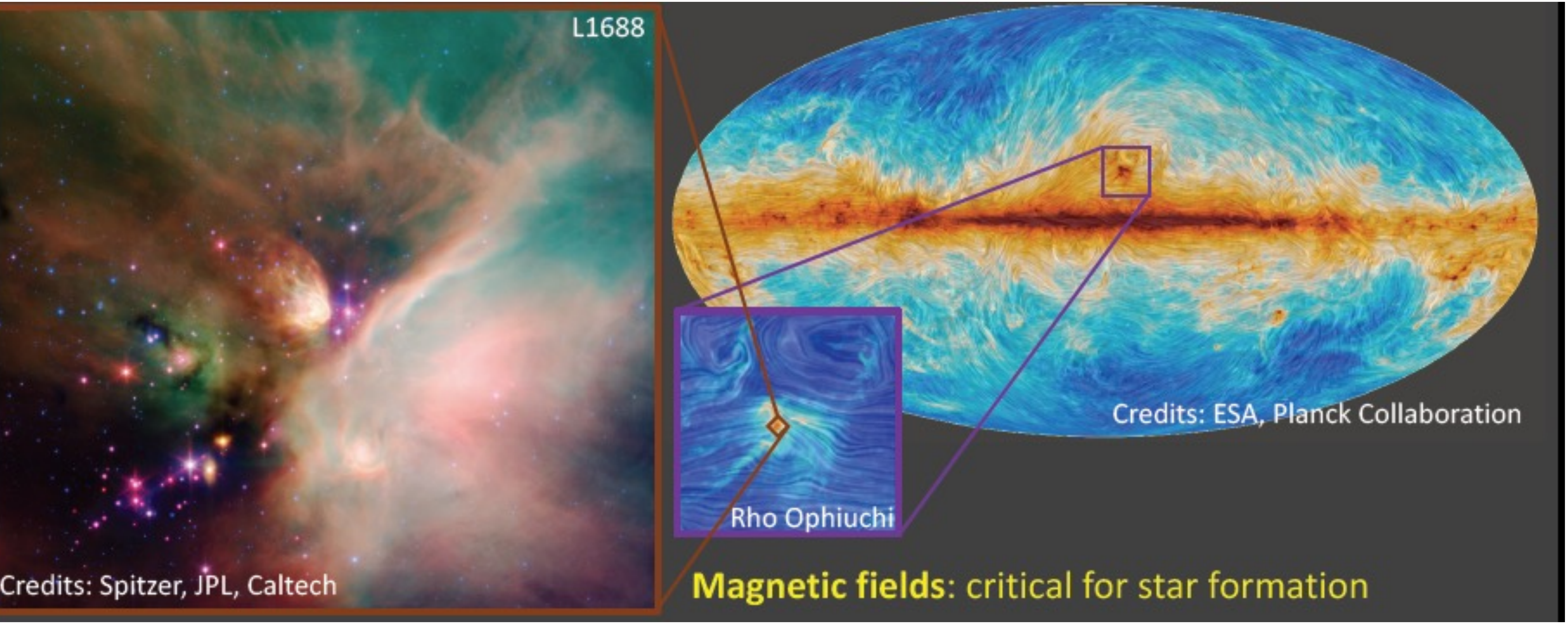


- At 53 and 89 mm, there is component parallel to highest density region of ISF at BN/KL, different at longer λ
- BN/KL region 1" resolution Tang et al. 2010 870 μm upper right shows B || at less dense end, perpendicular to filament at KL





Rho Oph


L1688
Credits: Spitzer, JPL, Caltech
Rho Ophiuchi
Credits: ESA, Planck Collaboration
Magnetic fields: critical for star formation

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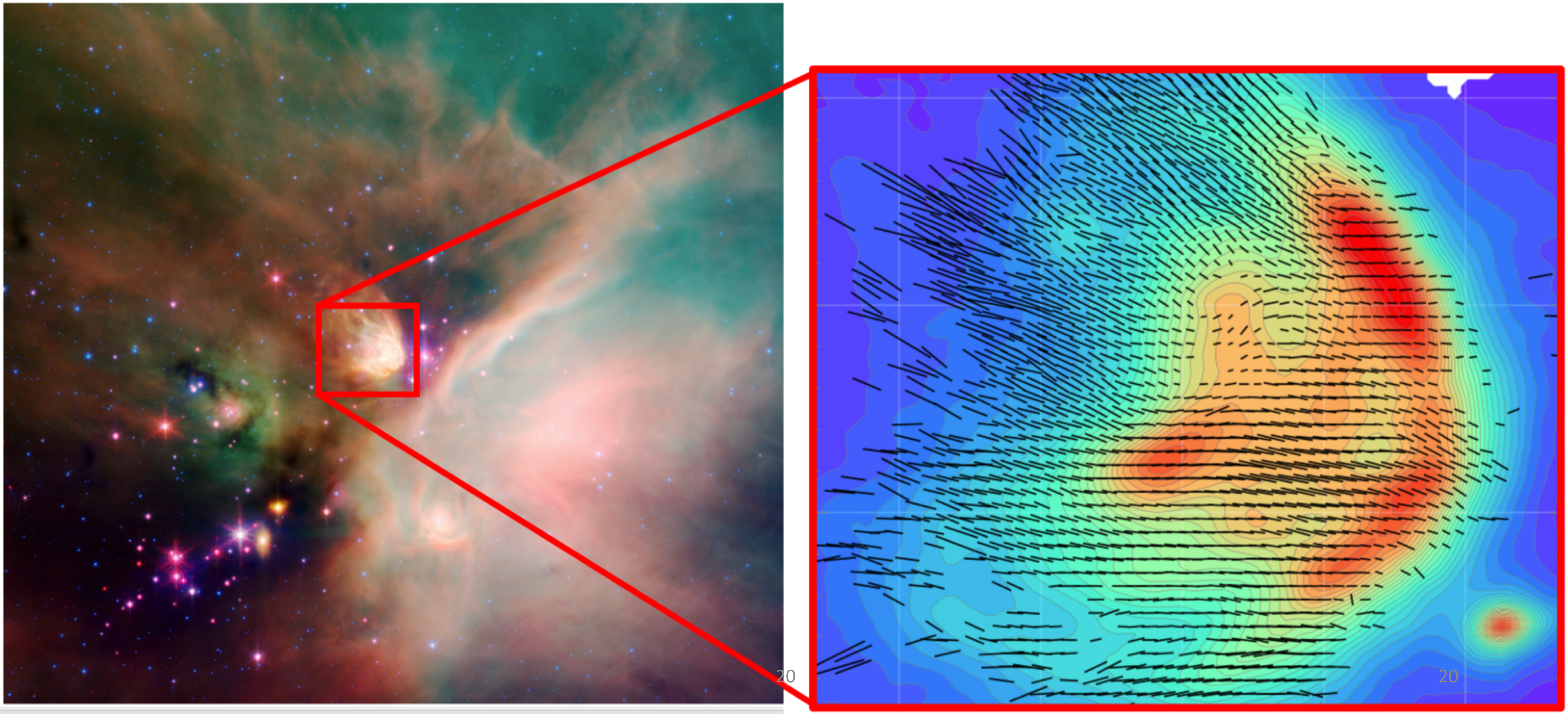
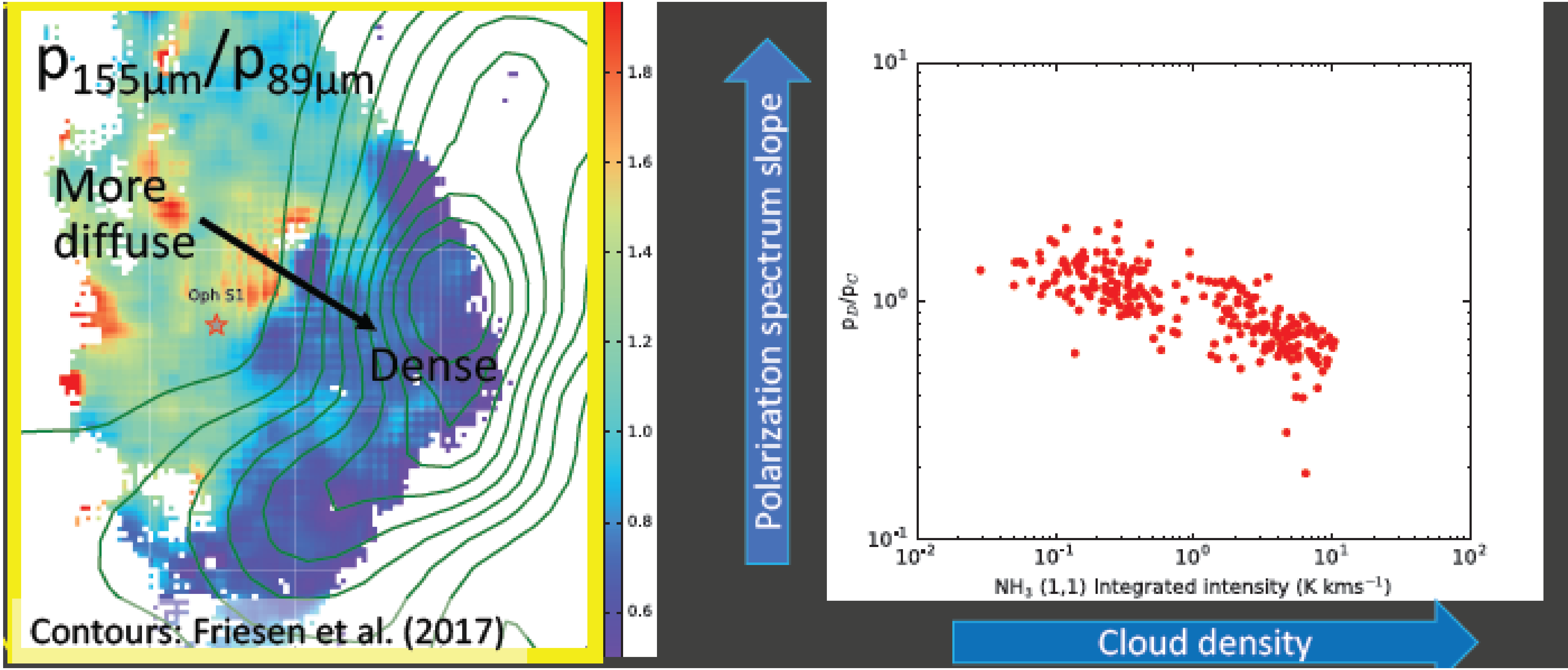
Rho Oph A – Spitzer image, left; Santos/HAWC+ collab., right 89 μm and 8″ Spatial Resolution - B field ~EW through dense core



Santos/HAWC+ collab.



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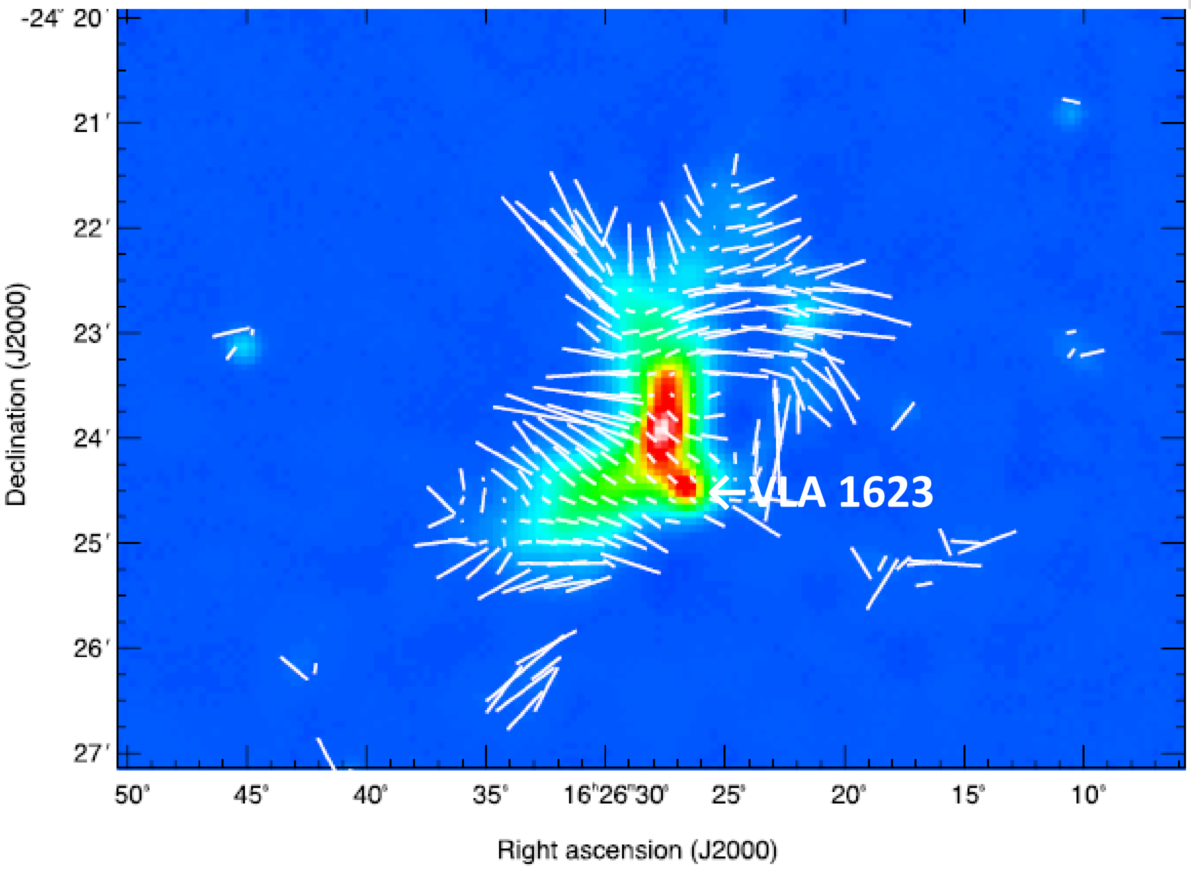
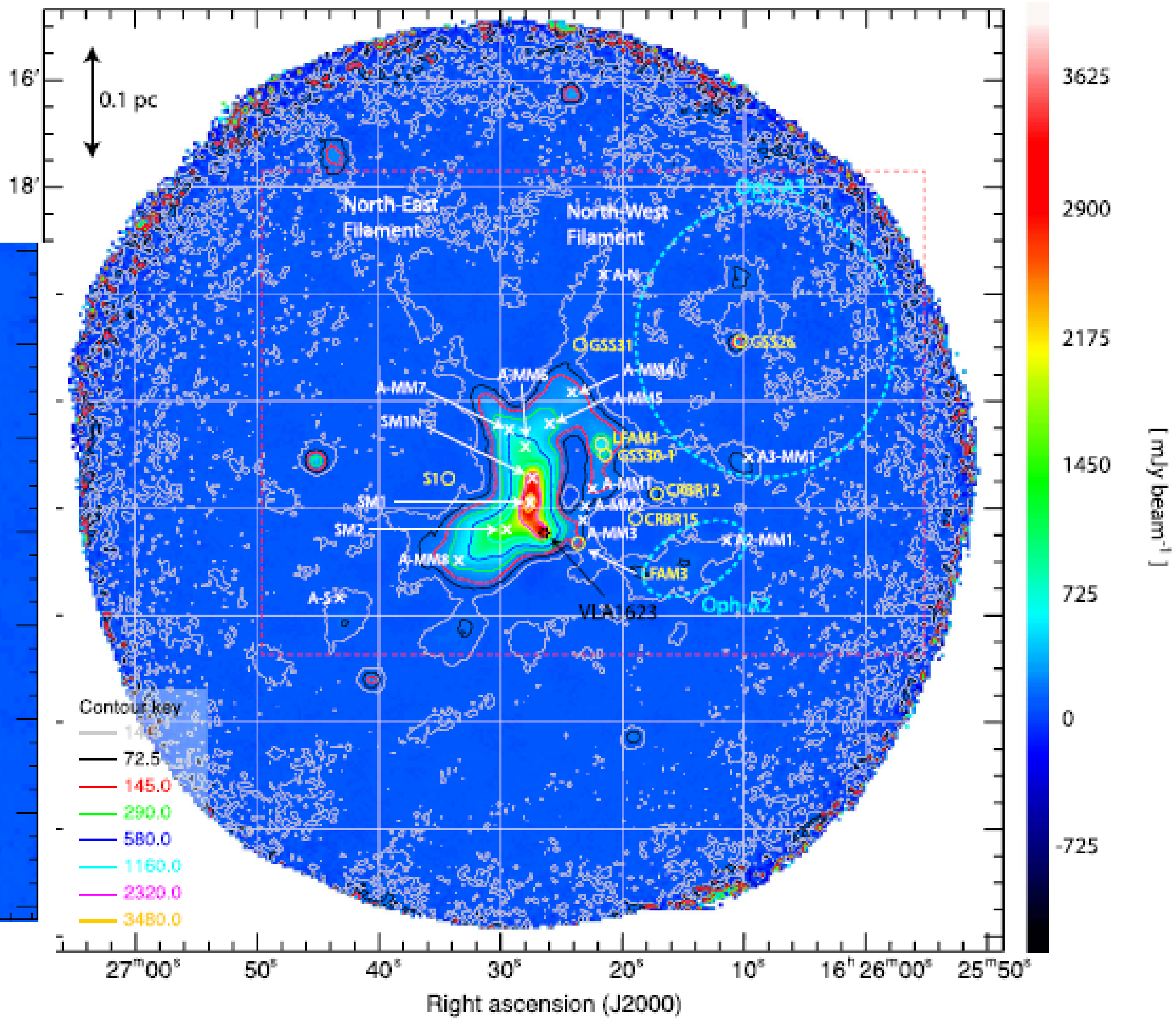
Kwon et al. ApJ May 20 2018
First look BISTRO 850 μm imaging polarimetry ρ Oph-A core 14" spatial resolution





B field map at 850 μm

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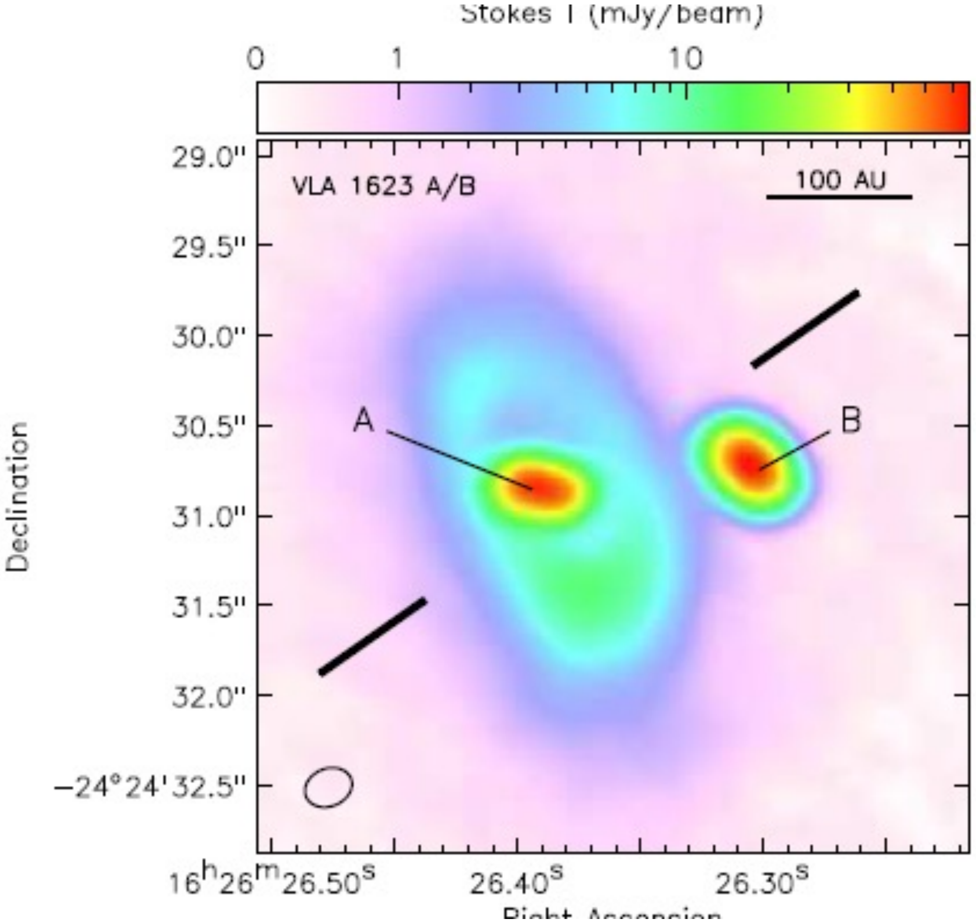
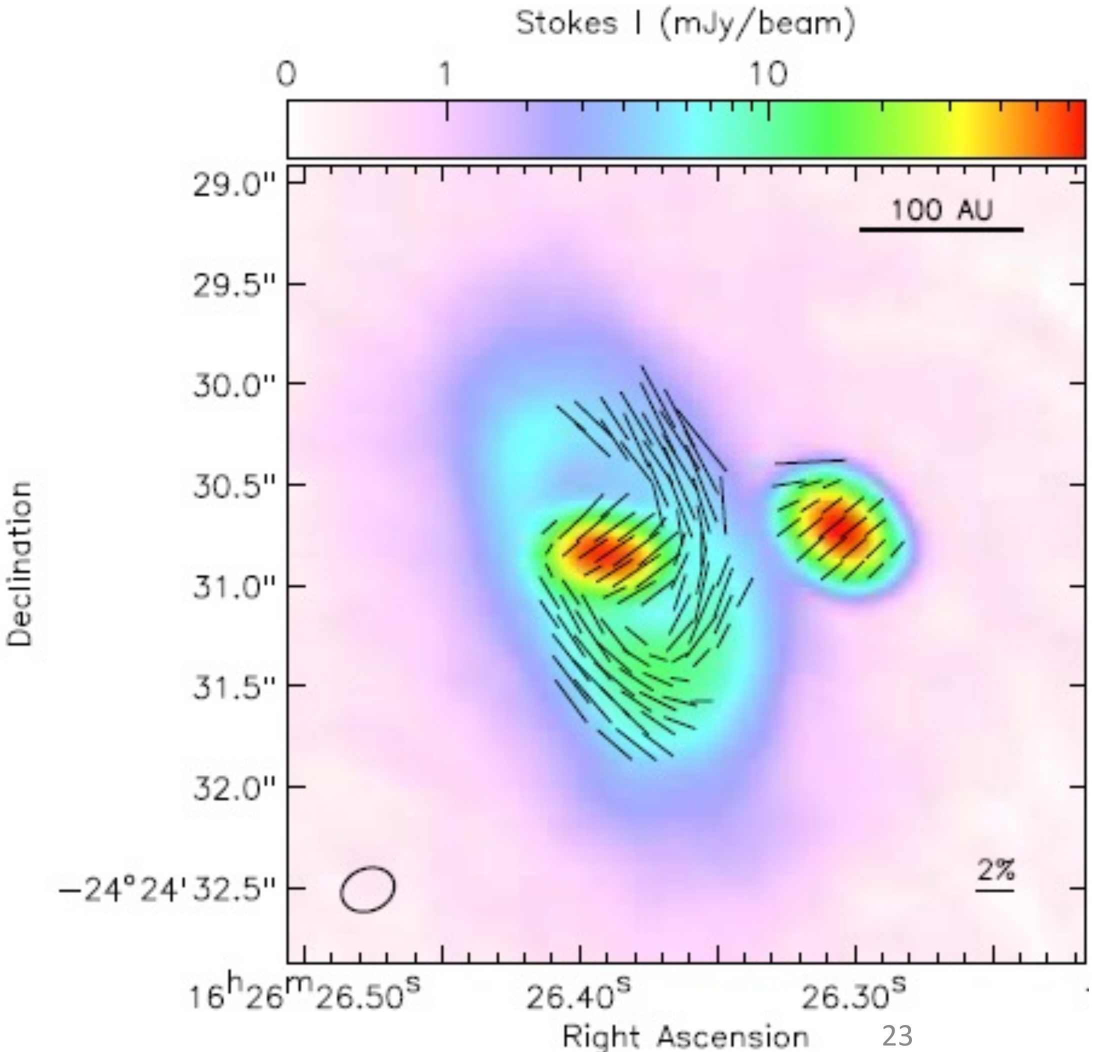
1.3 mm ALMA (Sadavoy et al. 2018)
VLA 1623 class 0 protostars
T ~ 43K



Dust scattering in A ring



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Role of Turbulence in Star Formation?

- Recent paper Nixon and Pringle arXiv:1809.04921 state simulations of late stages of star formation including B fields are less realistic than those which don't include B fields - ???
- Estimating plane of sky magnetic field strength using CF method *can* be in error for situations with high turbulence, or high optical depth at that wavelength, and there are theorists who claim only turbulence affects star formation
- New method introduced in 2017-8 the VGT – velocity gradient technique by Lazarian and collaborators – suggested useful as magnetic field tracer in turbulent regions – turbulence-B coupling???

  "VGT has its foundations in the theory of MHD turbulence which states that the velocity motions of turbulent fluids are anisotropic and the direction of anisotropy is determined by the local direction of the magnetic field" Hsieh et al. 2018

- VGT not yet ready for application – theoretical bounds of techniques still being worked out

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Suggestion: SOFIA Legacy Polarization Survey

- HAWC+ polarization survey of limited portions of the galactic plane would provide an unbiased sample of star forming regions, including low and high mass stars at various evolutionary stages and for a variety of physical conditions
  - Large angular scale polarization vs. intermediate scale immediately available with Planck/SOFIA with comparisons to long wave BISTRO JCMT survey
- If velocity and density information for the regions are lacking, SOFIA upGREAT and for some situations FIFI-LS could be exploited
  - ALMA and/or SMA follow-up of small cores within the filaments
- Turbulent vs. magnetic field dominance and environment in filaments
- Extent to which flows in filaments affect B field direction
- Do RAT grain alignment models for GMCs always fit at HAWC+ wavelengths?

(suggestion made at January AAS – do not know whether some variant on this submitted as Legacy proposal for Cycle 7: Legacy selections November?)

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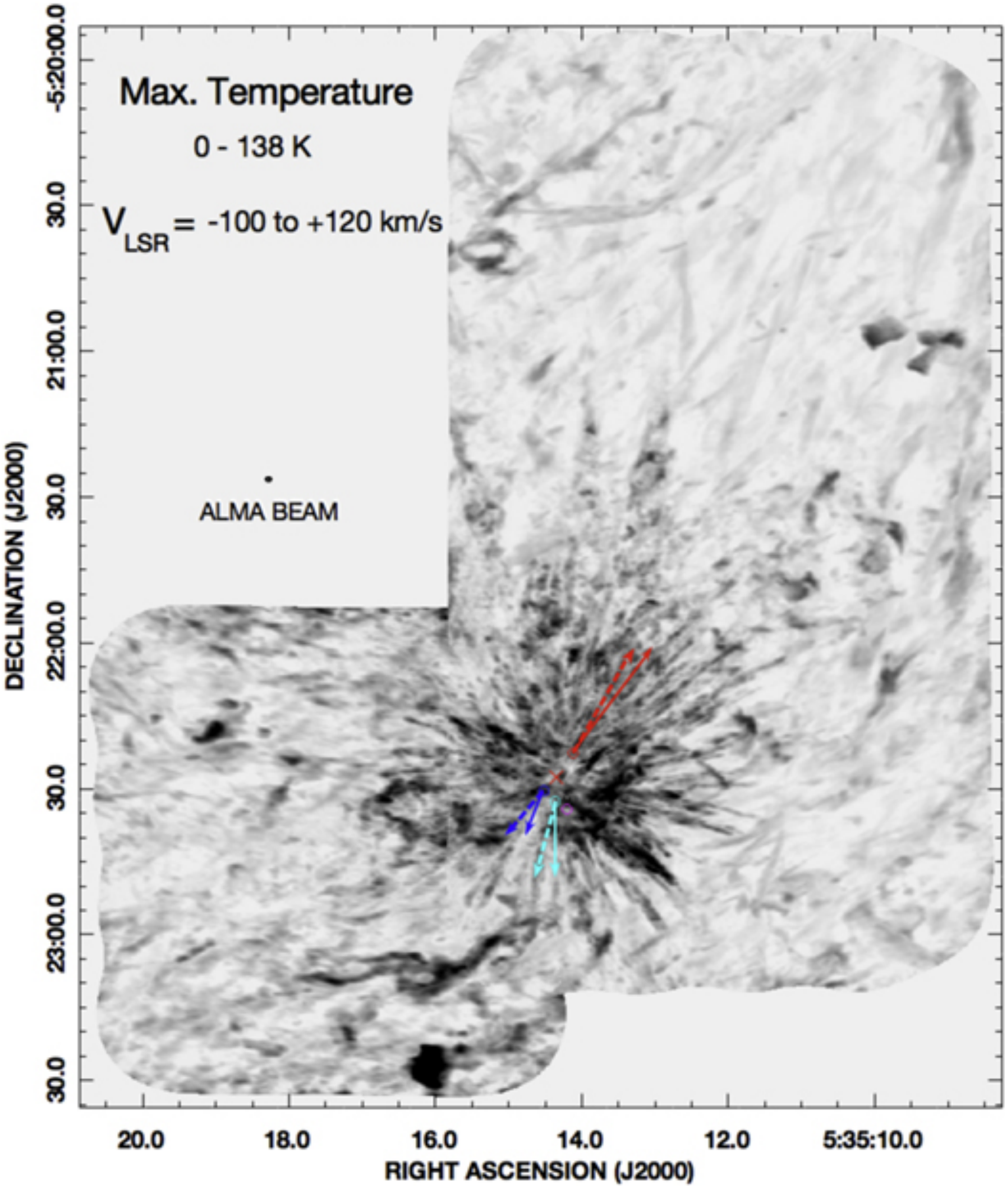

OMC1 an example

1.3 mm ALMA image of CO outflow with proper motions of BN (red), Source I (blue), and Source n (cyan) shown, vector length positions in 2000 years.

Internal structure revealed by ALMA includes velocities of small scale structures

OMC1 well studied – velocities and densities available as well