Filamentary Molecular Clouds, Star Formation, and Pristine B-Fields, as seen by SOFIA/HAWC+, Gaia DR2, and Mimir Near-IR Polarimetry

A SOFIA Tele-Talk – September 19, 2018

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NSF/AST14-12269 , USRA SOF_4-0026, & NASA NNX15AE51G gratefully acknowledged

Filamentary Molecular Clouds, Star Formation, and Pristine B-Fields seen by SOFIA/HAWC+, Gaia DR2, and Mimir Near-IR Polarimetry

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much here also appears in our SOFIA Focus Issue paper: Clemens et al. 2018 (accepted; arXiv 1809:05457)

Overall Question: Is the Magnetic Field (B-field) an important player in cloud, dense core, and star formation and evolution?

Specific Questions: Are B-field properties similar in cloud peripheries, dense core envelopes, and star formation regions? Is there a common B-field or is the B-field disrupted?

Laboratory: GF9 Filamentary Dark Cloud, **GF9-2 YSO** (d~200-440 pc)

Lowest luminosity Class 0 YSO – 0.5 $L_\odot$ minimal outflow – very early stage of star formation. **Is its B-field still intact, or is it modified?**

B-field Probes: (1) **Near-IR background starlight polarimetry (BSP) w/ Mimir;** (2) **SOFIA HAWC+ E-Band Polarimetry;** (3) I-band BSP (Poidevin & Bastien ’06); (4) Planck (XIX ’15)

Photometric Probes: (1) WISE (Wright+ ’10); (2) Spitzer/IRAC; (3) IRAS; (4) ISO/ISOPHT

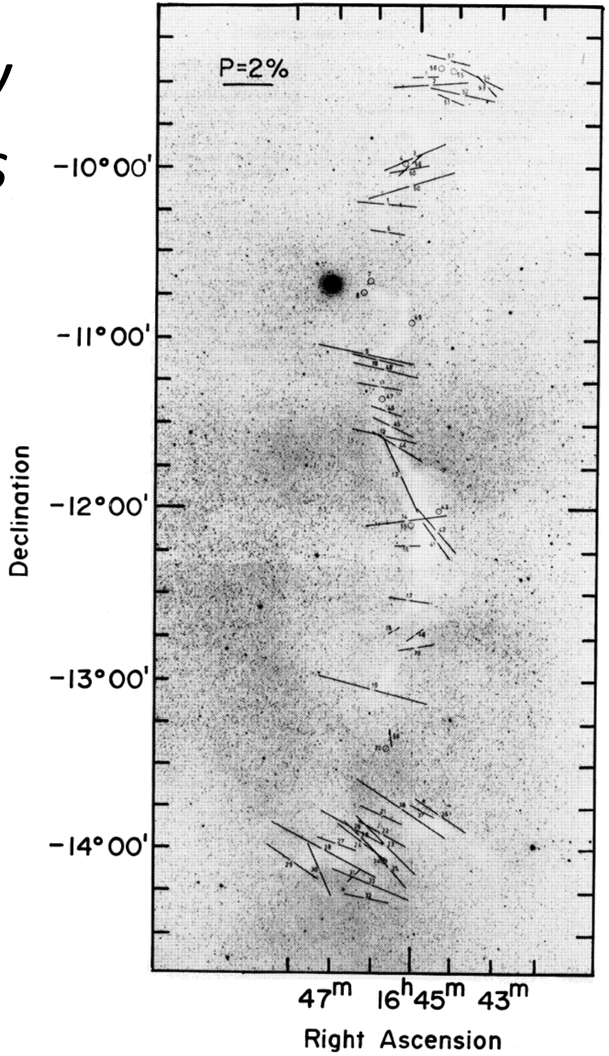
Distances: Gaia (DR2 ‘18)

Boston University Team

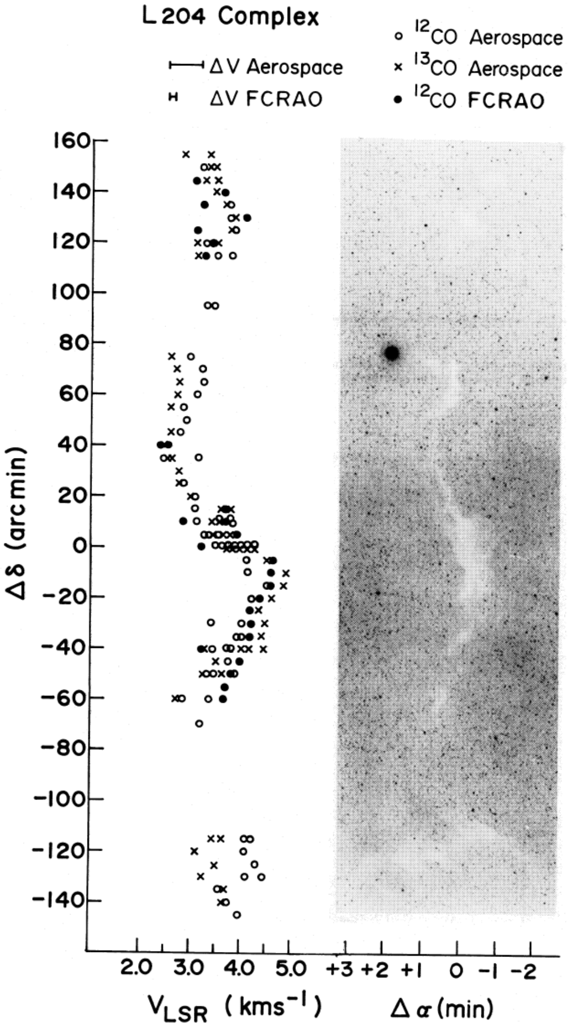
- From left:
  - <u>Catherine Cerny</u>
    - Joined in 2018 Summer – Gaia expert
  - <u>Genevieve Schroeder</u> (U. Rochester)
    - Summer 2017 REU intern
    - Flying on SOFIA tomorrow night and Friday night for HAWC+ observations
  - <u>Jordan Montgomery, now Dr. J.M.</u>
    - At MIT Lincoln Labs, along with Sadia Hoq, John Vaillancourt, Mike Pavel…)
    - Flew on SOFIA 2016 December
  - <u>Sofia Kressy</u>
    - BU Senior Undergrad – lead on Mimir Orion project
  - <u>Adham El-Batal</u>
    - 3rd year grad student
    - Just back from GAIA workshop in Heidelberg
    - Flew on SOFIA 2016 December
  - <u>Dr. Thushara Pillai</u>
    - BU Senior Research Scientist

Filamentary Dark Clouds before they were all the rage… and their B-fields

- **<u>L204</u>** – McCutcheon+'86
  - Optical Palomar Sky Survey Plates
  - Optical starlight polarimetry
    - B-field in plane-of-sky
    - B-field orientation parallel to polarization position angle (PA) of intensity maximum (E-field direction)
    - One star at a time…
  - B-field position angle (BPA) generally perpendicular to filamentary cloud long axis (4˚)

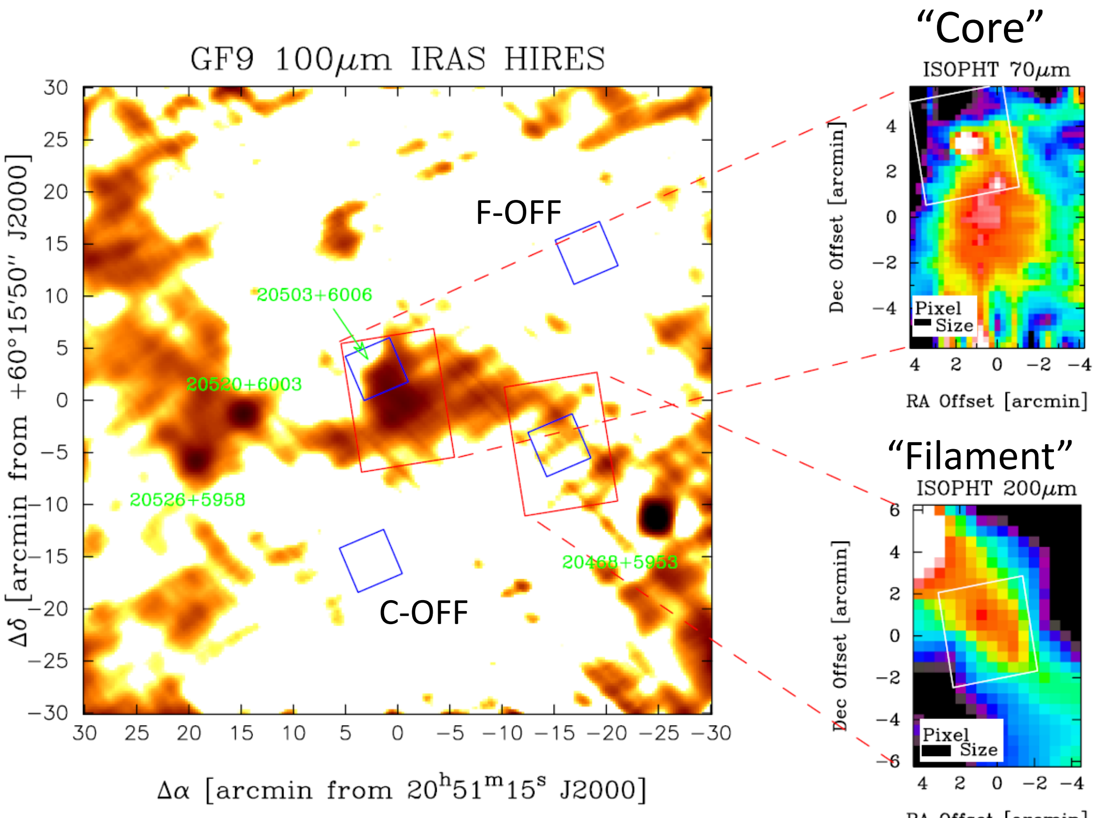


- Strong correlation of cloud location and gas kinematics
  - R.A. and RV (CO)
  - Gas dynamics matter
  - MHD turbulence likely present and bending BPAs on all size scales
    - Support for Davis / Chandrasekhar-Fermi method of obtaining B-field strengths from BPA dispersions, gas dispersions, and gas mass densities



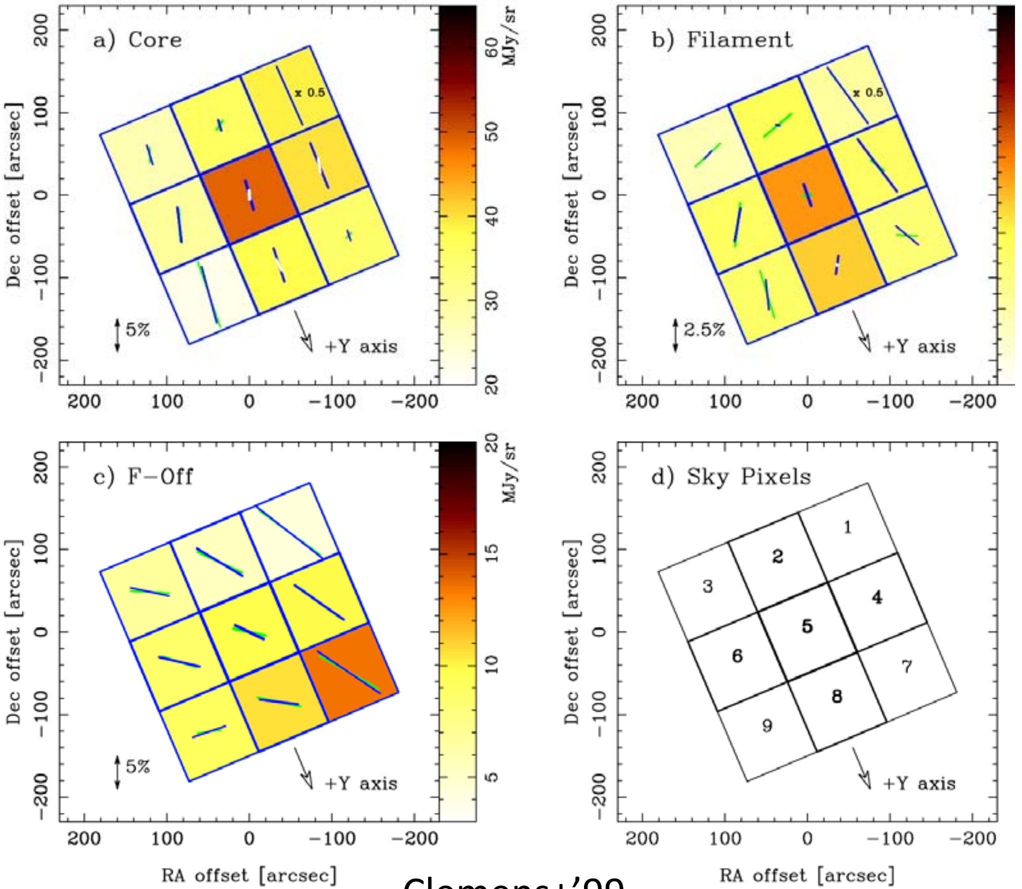
Globular Filaments, IRAS, and ISO

- Catalog of filamentary dark clouds (from POSS) exhibiting "globules" along their lengths (Schneider & Elmegreen '79; GF#s)
  - Likely sites of current or future star formation
  - Prescient study!
- We selected one, Northern, isolated GF (#9) for CO mapping, *Infrared Astronomical Satellite* (*IRAS*), *Infrared Space Observatory* (*ISO*, an ESA mission):
  - FIR photometric mapping **[red rectangles]**
  - FIR polarimetry (160 μm) **[blue squares]**



FIR Polarimetry from Space: ISOPHT

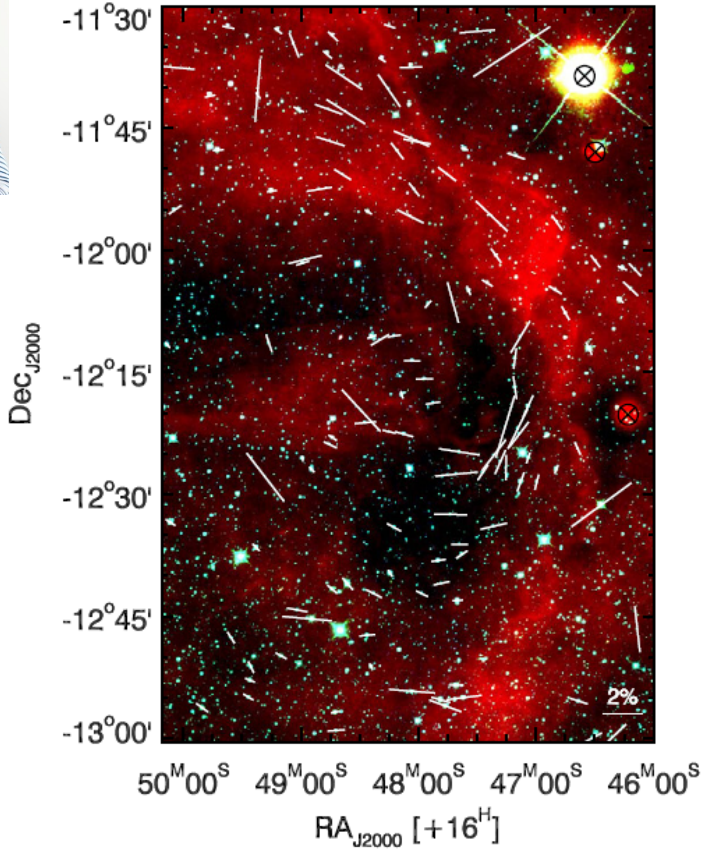
- ISOPHT FIR "array" was 2x2 pixels
- Three, fixed-angle wire grids in a filter wheel
  - 0, 60, 120 deg
  - Integrate in one, move to next, repeat
- No chopping or nodding; only slow pointing changes
- Cycled among the 4 zones, putting each pixel of the array on the center of each zone, so 4 cycles
  - Yields four 3x3 pixel maps
- Pre-*Planck*, so difficult calibration
- Differenced intensities against position with weakest signal ("C-OFF")
- Corrected using best estimates of instrumental polarization for each pixel
- Shortly after GF9 observations, *ISO* ran out of helium coolant, mission ended…



Clemens+'99

Two Decades Pass…

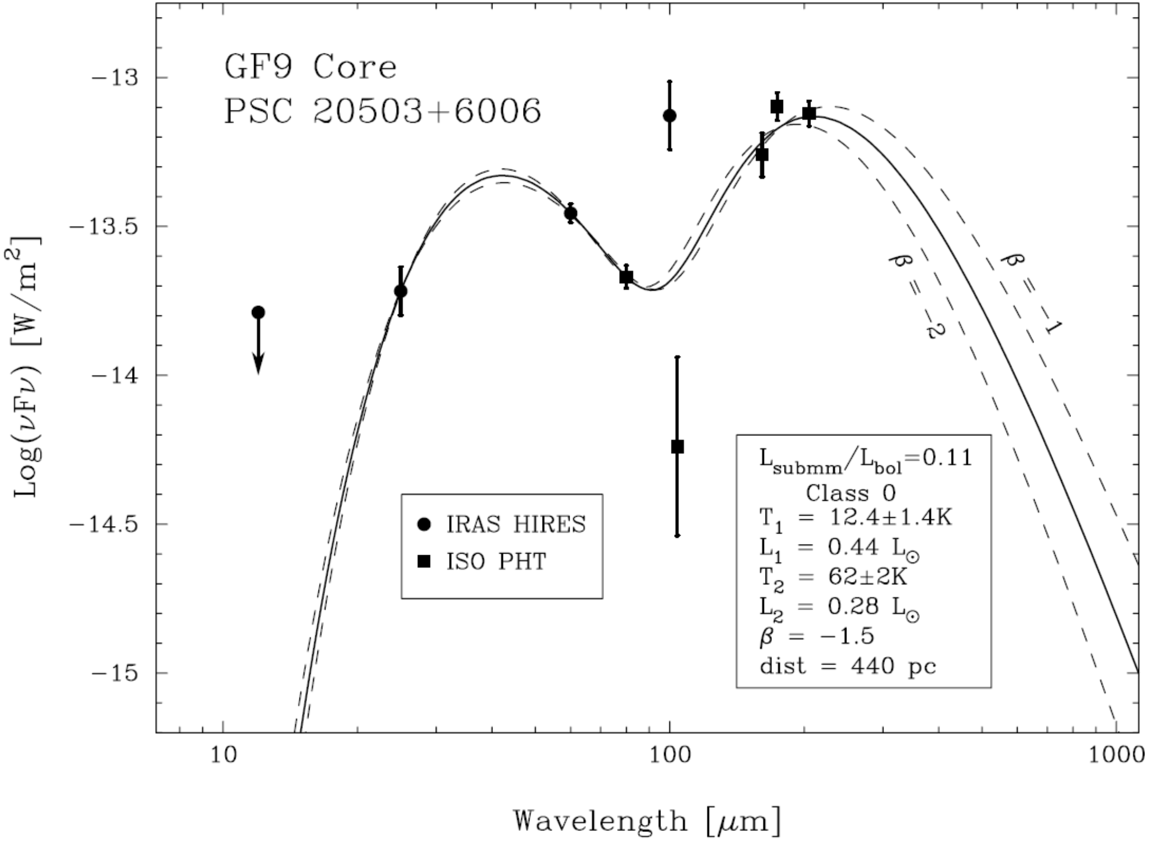
- Tried to move toward more access to FIR polarimetry
  - Proposed SMEX mission(s): PIREX, M4
  - Proposed SOFIA 2nd Generation Instrument: IMPP
- Instead…
  - Built ground-based NIR imaging polarimeter
    - Mimir (Clemens+'07)
    - Use it to survey Galactic plane and other friends (like L204, GF9)
- <u>Others</u>:
  - Optical polarimetry of the GF9 region (Poidevin & Bastien '06)
  - Limited NIR polarimetry of ISO-mapped GF9 Core and Filament regions (Jones '03)
  - **<u>NIR BPAs don't agree with the ISO FIR pol. ones</u>**



Portion of L204 ("Cloud 3") as seen by Wise (RGB) and Mimir H-band polar. (white vectors) Cashman & Clemens '14

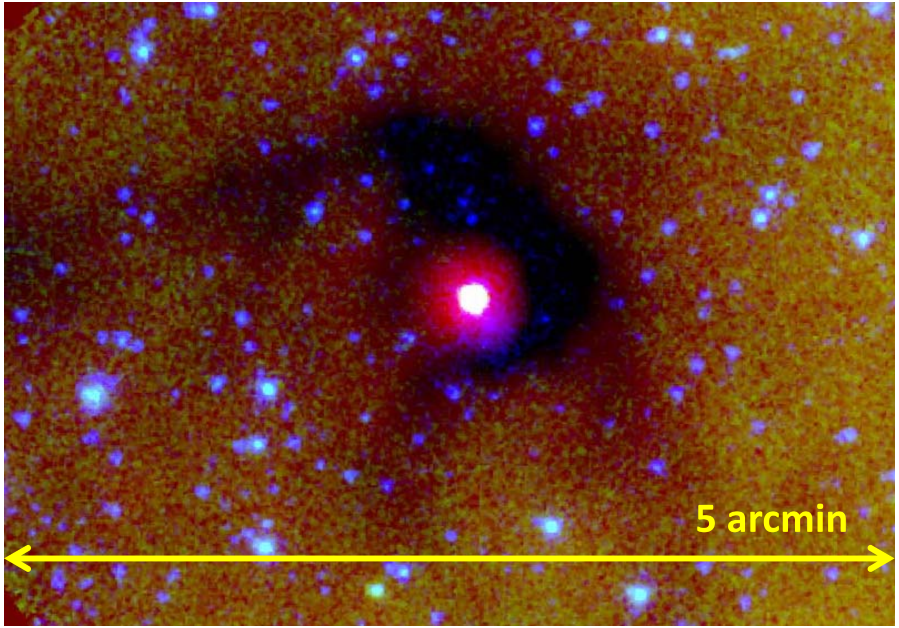
GF9 does have active star formation

- Four IRAS Point sources
- One at the Core zone
- IRAS 20503+6006 (aka GF 9-2, L1082 C, or LM 351)
  - Class 0 YSO (quite young, though MIR/FIR visible)
  - $L_{YSO} \sim 0.3\text{-}0.5\ L_\odot$
  - Outflow sought since ’96 (Bontemps+), found in ’14 (Furuya+)



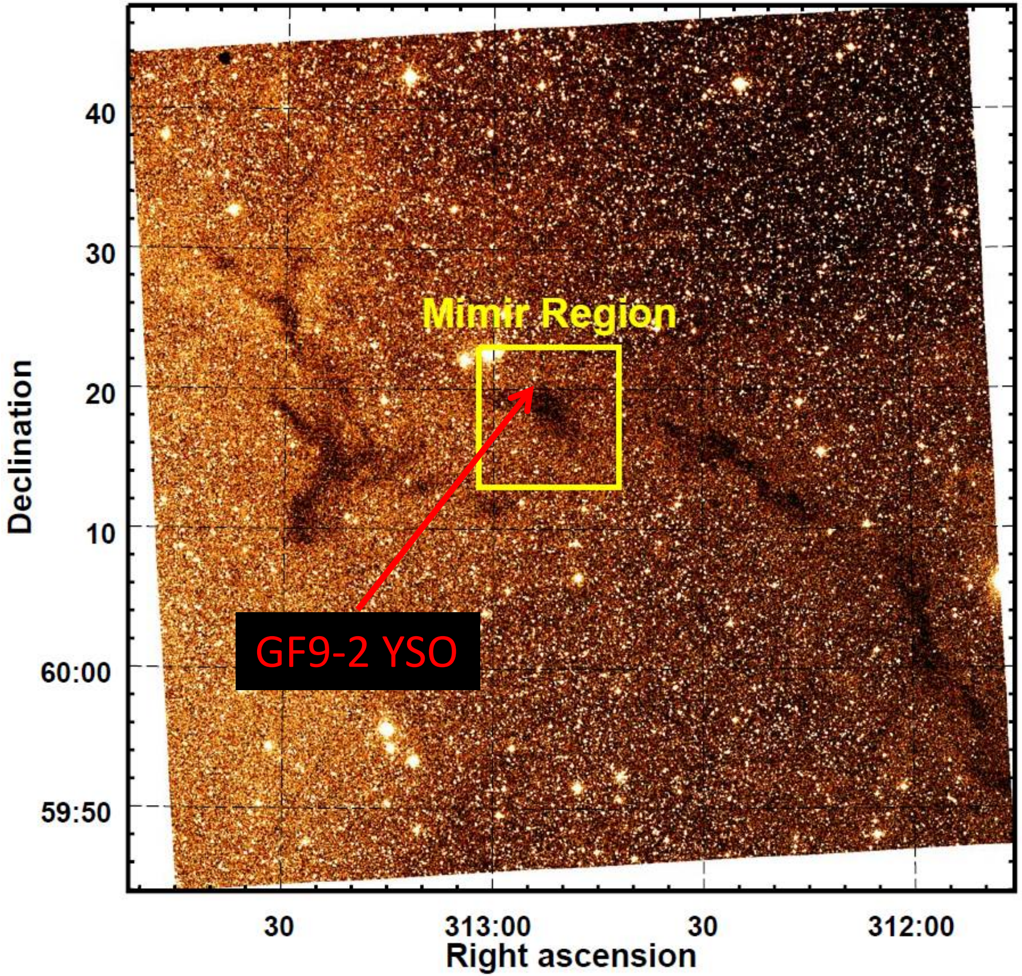
Low-Mass, Young, YSO – maybe B-field not (yet) disrupted?

- Most B-field studies look at the most luminous objects
  - Fastest, most likely to generate findings
  - But, biased toward <u>super-bright</u>, massive cloud cores with cluster-mode, high-mass star formation
  - Poor little B-fields likely shredded, stomped on, or tangled, if not already super-strong
- Wimpy little GF9-2 could be an ideal place to sniff for what the B-fields look like before all the damage takes place



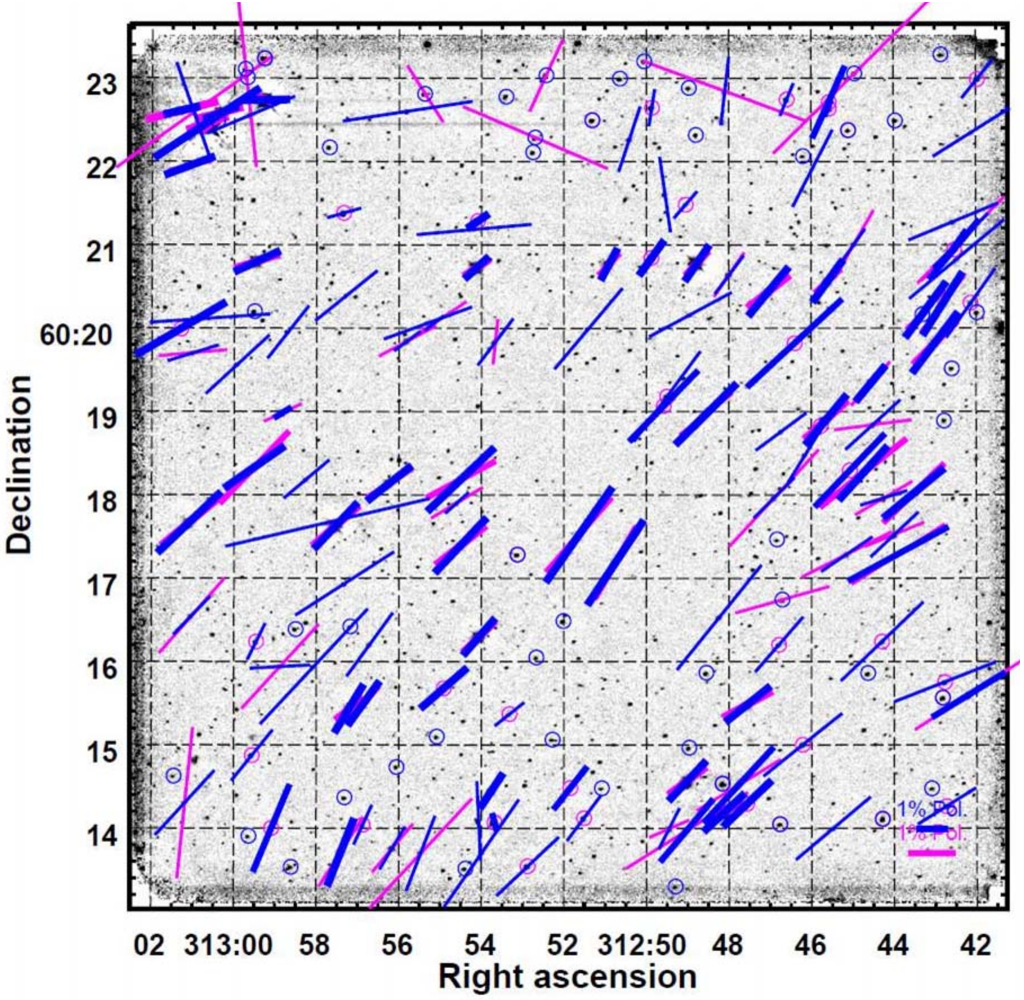
GF9-2 as seen by *WISE* B3 (12μm – red), *Spitzer* IRAC B4 (8μm – green) and *Spitzer* IRAC B2 (4.6μm blue)

GF9 Dark Cloud in Optical DPOSS



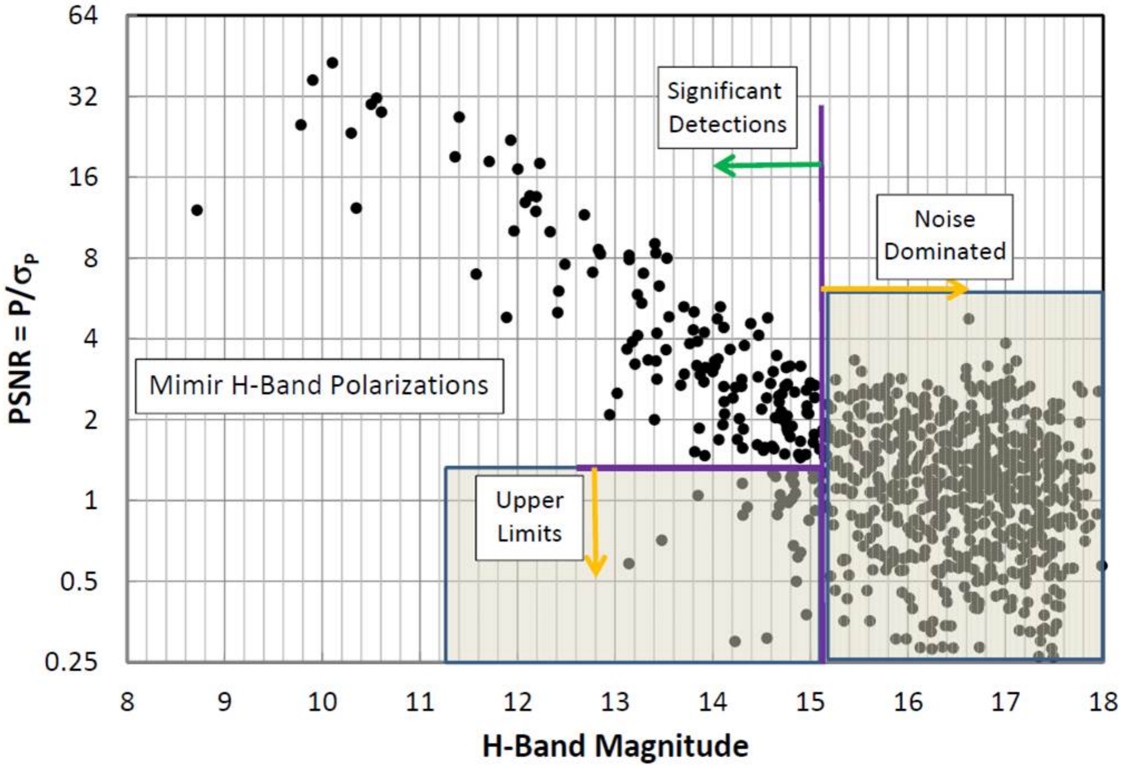
- Used Mimir NIR imaging polarimeter (Clemens+'07) on 1.8m Perkins telescope of Lowell Observatory.
- FOV = 10x10 arcmin at 1024x1024 pixels at 0.6"/pixel.
- H (1.6μm) and K (2.2μm) stellar polarimetry.

- Background Image = deep K-band (2.2μm)
- Blue vectors = H-band (1.6μm) polarization
  - 1% references at bottom right
- Purple vectors = K-band polarization
- Lots of stars, wide range of fractional polarizations
- Stars avoid the IR-dark, optical-dark region
- Can't do NIR polarimetry beyond about A_V~20-30 mag
- PAs (B-Field) look quite uniform
- Jones '03 NIR polarization PAs deviant; Poidevin & Bastien '06 optical PAs consistent with new NIR
- What about FIR, though?

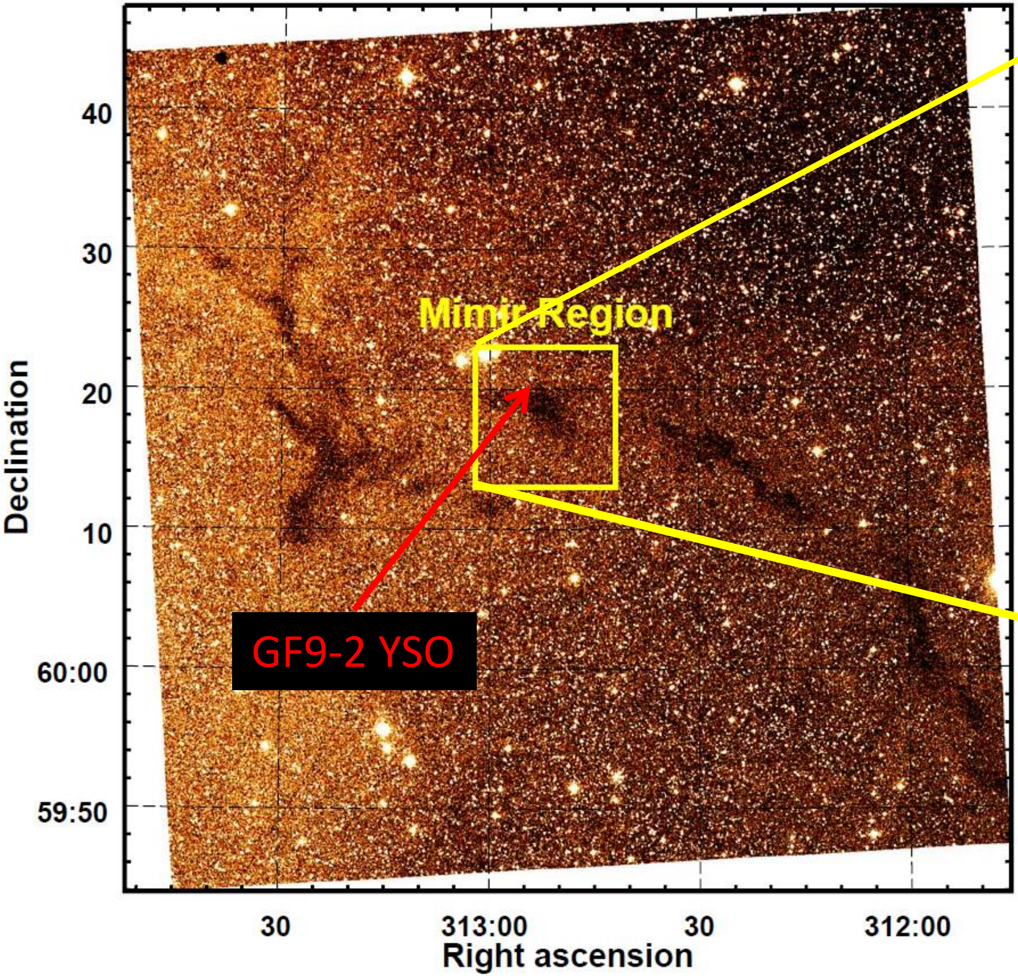


Mimir Polarimetry in H, K bands: 860 stars, but which ones are useful?

- Selecting stars for B-field mapping using Polarization Signal-to-Noise (PSNR)
- High PSNR for bright stars
- Merges into PSNR~1 due to Rice distribution
- Study of 'False positives' (Clemens &Montgomery '18, in prep.)
- Select H-stars down to 15.1 mag



Oh, my, Gaia! DR2… Wow! Virtually every NIR pol. star has a distance!



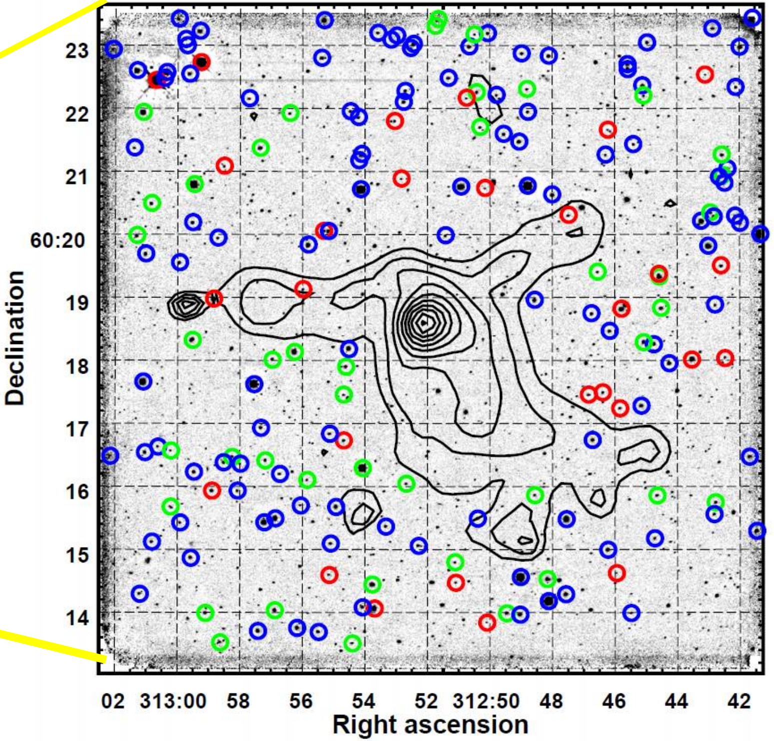
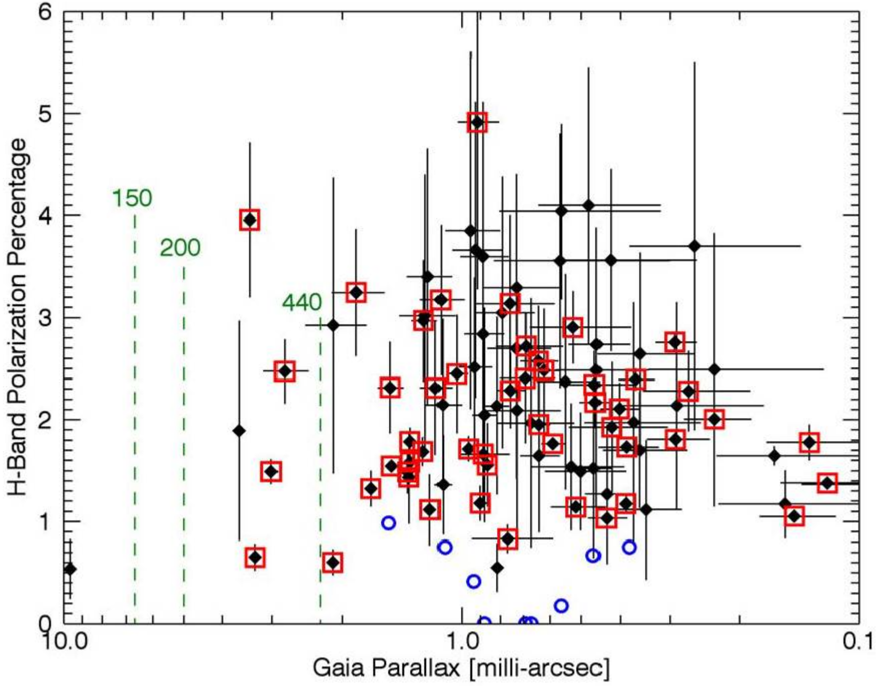
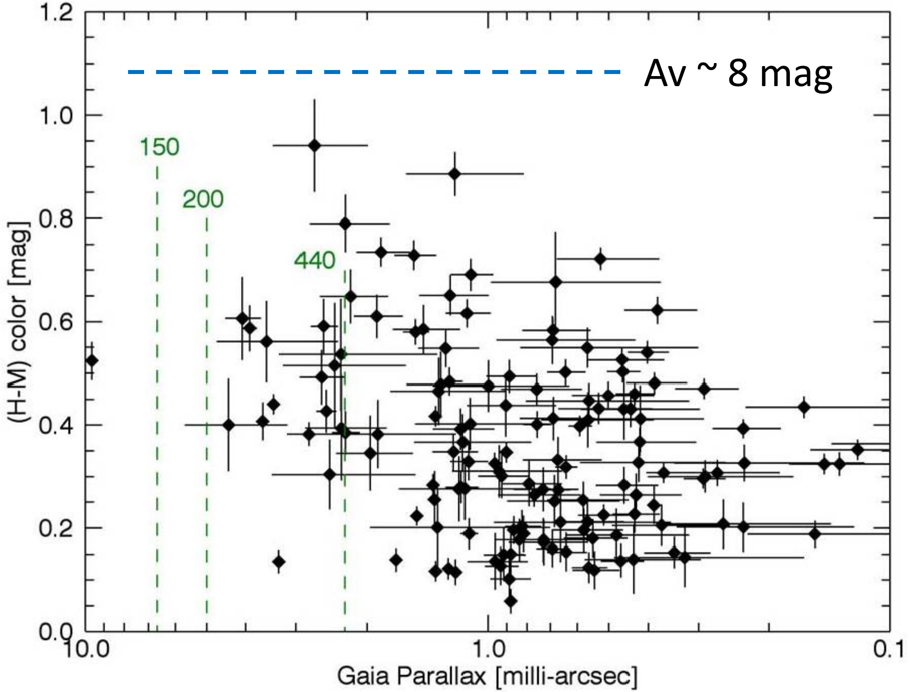


Image = Mimir K (2.2 μm) band
Contours = SOFIA/HAWC+ 214μm
Circles = Gaia stars [R: <0.5kpc , G: 0.5-1.0 kpc, B: > 1kpc]

NIR H-Band Polarization Fraction (left) and (H-M) color (right) versus Gaia DR2 Parallaxes





Seeking step-up of P_H at distance of GF9 cloud

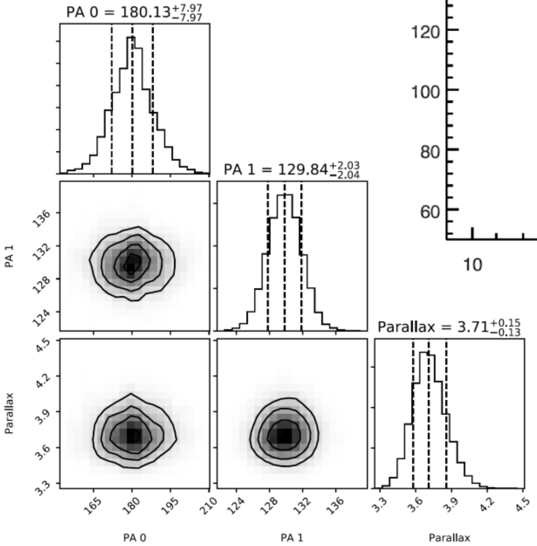
- Insufficient stars closer than ~300 pc to see step
- Polarization stars are nearly all behind cloud
- No rise in P_H with distance -> single dust layer
- Ideal for Background Starlight Pol B-field mapping

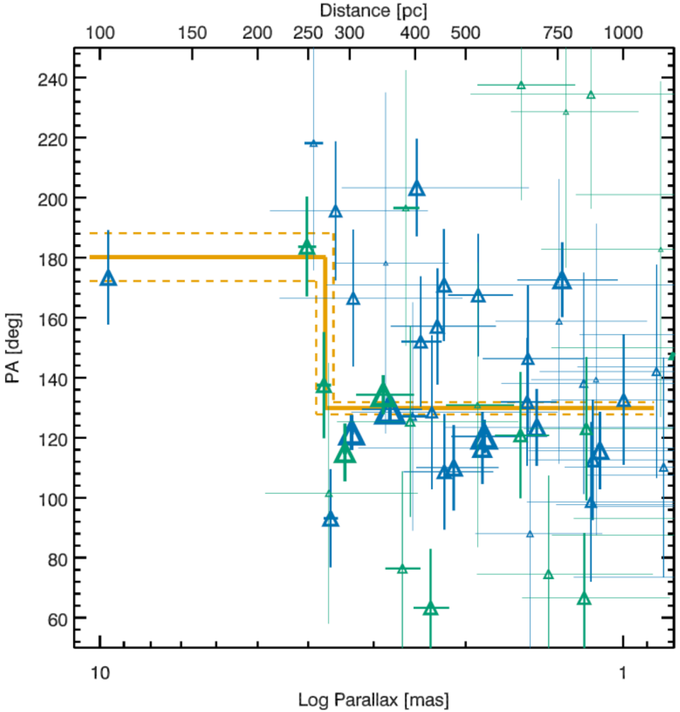
Seeking step-up of (H-M) reddening

- Few stars closer than 250 pc
- Extinction seen for stars as close as 250-300pc
- No rise in extinction with distance, also implies single dust layer

Cheat, look in the "back of the book"

- Need to determine distance to GF9
  - Distances range 150 – 440pc
  - Impacts all astrophysical conclusions
- But, Gaia DR2 distances didn't reveal much jump in P or (H-M)
- What about the **uniform PA**, though?
  - Is there a step into that uniform PA at some distance?
  - PA vs distance plot
- Bayesian Markov Chain Monte Carlo
  - Fit for: PA_{BEFORE}, PA_{AFTER}, transition parallax
  - Clean corner plot
  - **d = 270 ± 10 pc**



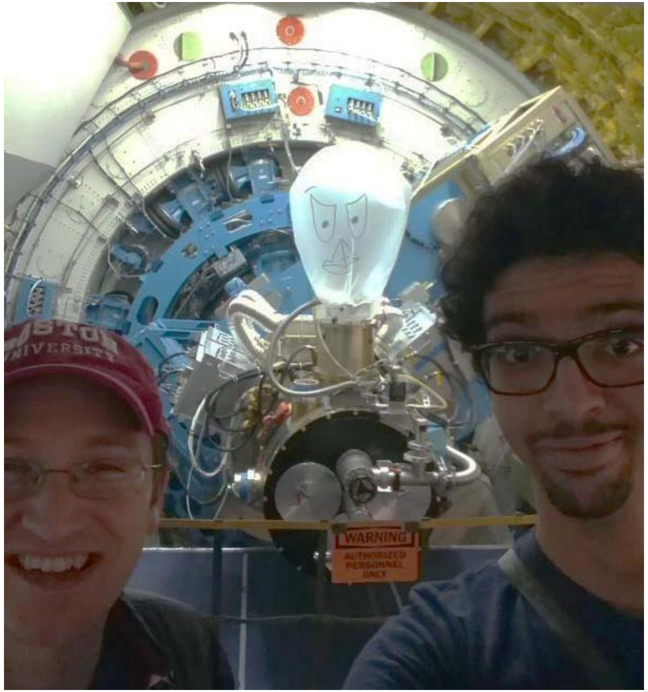


Need FIR polarimetry to probe opaque cloud cores like GF9-2

Two Big Questions:

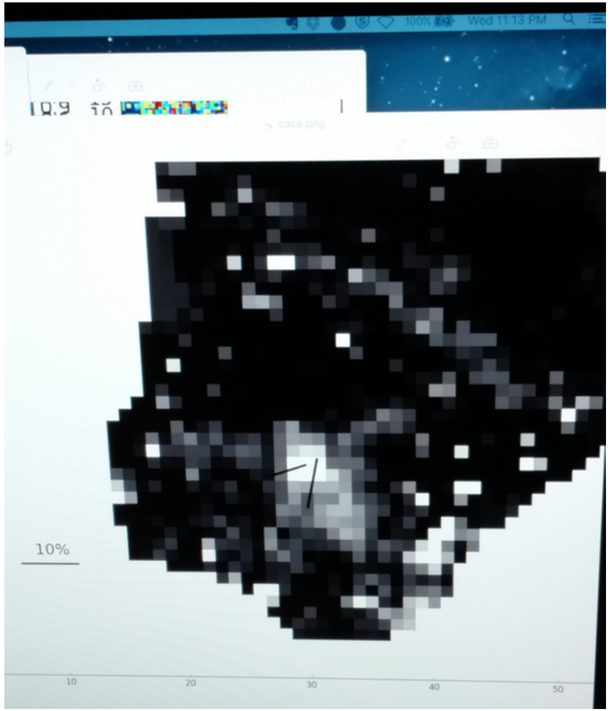
1. Is there PA rotation with wavelength?
   - If so, we are all in deep trouble
   - Signify changes in dust properties and B-field properties with depth into cloud core
2. What is the nature of the B-field where low-mass stars might form in isolation?
   - Must probe into higher A_Vs than NIR can probe
   - Very faint FIR emission, though…

- SOFIA /HAWC+ Cycle 4 Observing
- December 2016 –portions of 2 flights



Jordan Montgomery, HAWC+, Adham El-Batal selfie during SOFIA flight in 2016 Dec.

SOFIA/HAWC+ and post-processing

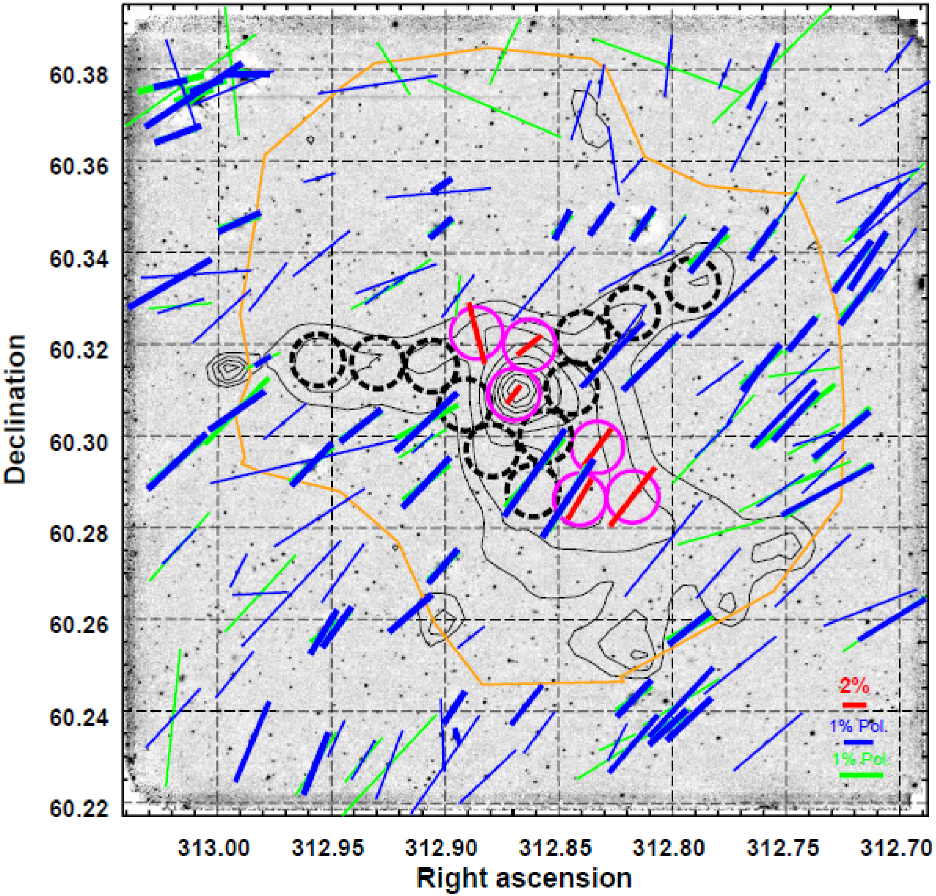


Cell phone pic of GF9-2 total intensity (black & white image) with overlaid polarization vectors (2) obtained surreptitiously in flight…

- Our initial "data products" were cell phone pix…
- Soooooo much happier to see rapid turn-around of HAWC+ data through the commissioned pipeline!
- For GF9-2, the total intensity ("Stokes I") image and SNR are fine and reveal dust columns identical to those seen by *WISE* & *Spitzer*
- But, Stokes U and Q images have very low SNR
    - No Polarization detection at the detector pixel native resolution
    - Must "post-process" to trade angular resolution for SNR
    - Convolve with gaussian, using inverse variance weighting of the pixel-based U and Q values
    - Recover better U and Q, for selected "pointings" of "synthetic beams" (Clemens+'14 for SCUPOL)

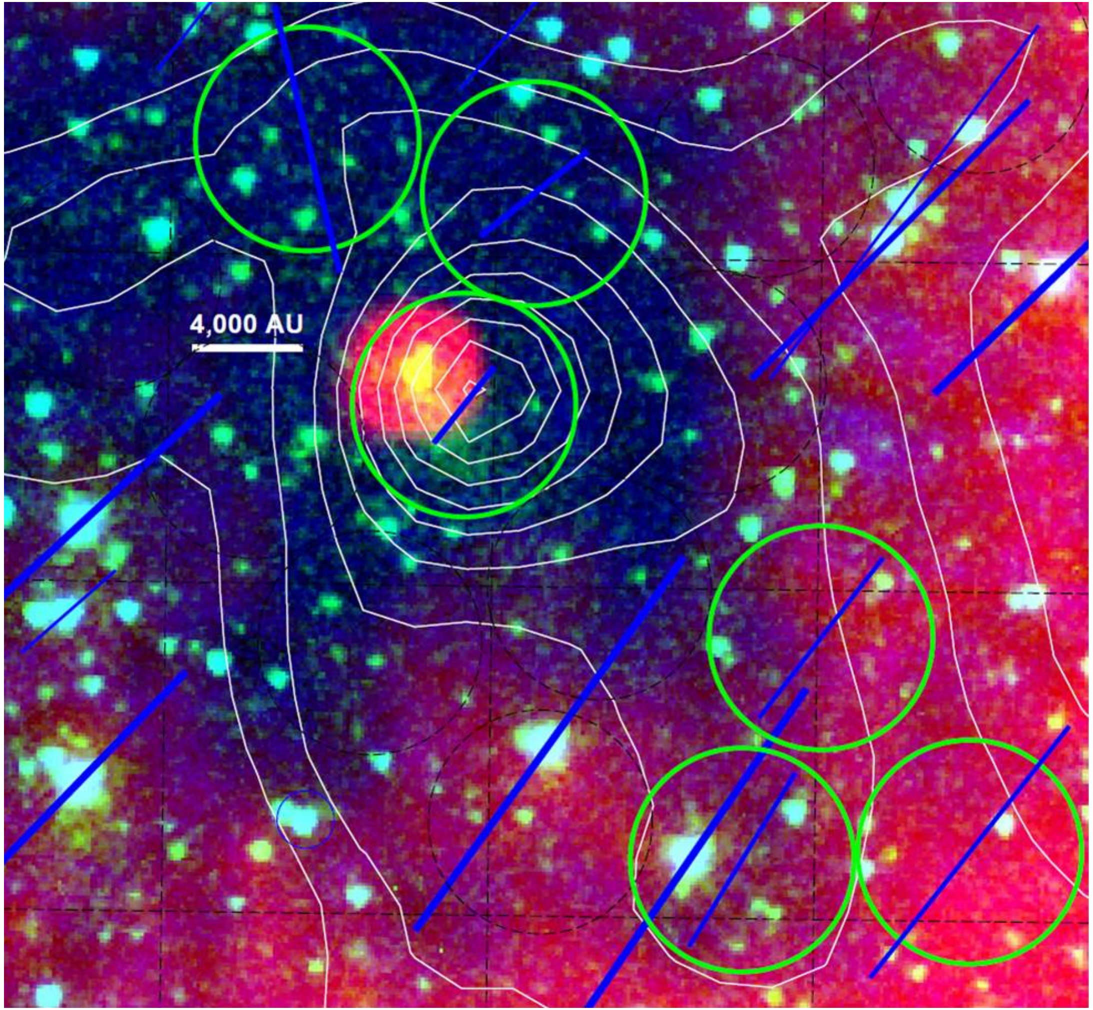
Follow the Flux…

- Select synthetic beam **placements** that:
  1. Are centered on the brightest Stokes I emission (thin contours in the figure)
  2. Are offset from each other so as to be independent samples (the circles don't cross)
- Select synthetic beam **sizes** so that:
  1. Maximize the number of synthetic beams with good PSNR
  2. Don't give away too much angular resolution
- Tried a range of gaussian sizes, found best at **4 HAWC+ pixels FWHM**
  - 6 beams with PSNR > 1.6 (σ_{PA} < 18°); 11 not detected

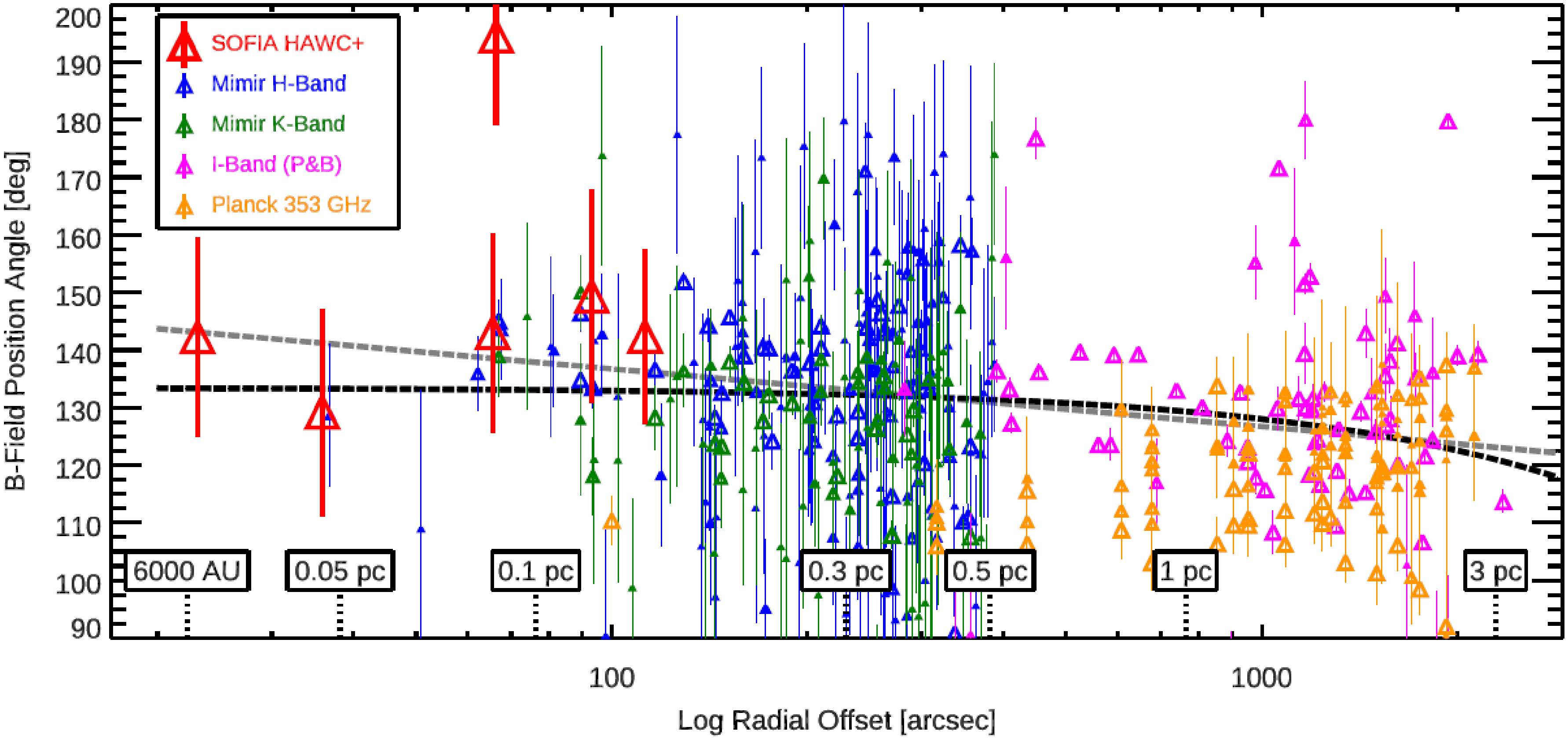


Zoom – *WISE*, *Spitzer*, Mimir, HAWC+

- 5 of 6 SOFIA/HAWC+ synthetic beam BPAs agree closely with NIR H-band BPAs
  - Like, really closely…
  - The NE beam shows a BPA that is perpendicular to the others
  - None of the beams along the East or West arm yielded FIR pol detections
- Q1: How does BPA vary with offset from YSO?
- Q2: How does BPA vary with λ?



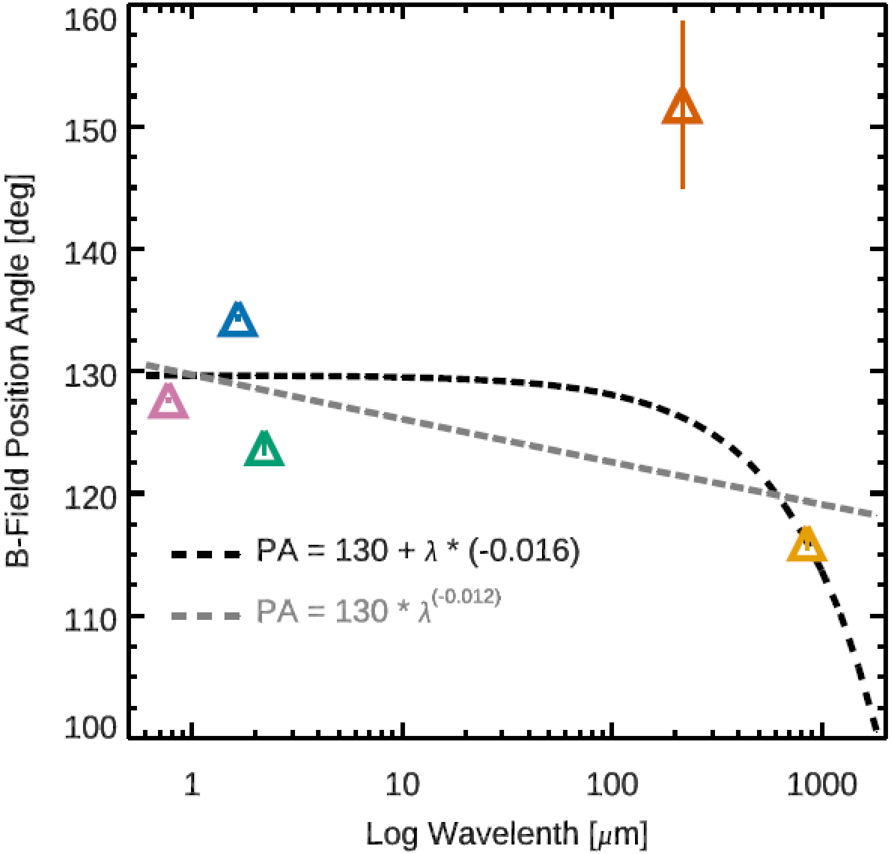
Combining all B-field probes – Plane of Sky Magnetic Field Orientation vs Offset from YSO



- B-field orientation is unchanged from ~3pc to ~6000 AU; No B-field disruption near the YSO
- No strong evidence of B-field orientation change with λ

No BPA change with λ – deep averages

- Inverse variance weighted averages of full data sets by waveband
  - **Optical (P&B '06)**
  - **Mimir H**
  - **Mimir K**
  - **SOFIA/HAWC+ 214μm**
  - **Planck 850μm**
- Linear and power-law fits
- Very little change with wavelength
- SOFIA/HAWC+ point includes all 6 synthetic beams with detections – if the one deviant beam is rejected, the **orange triangle** moves down 10 deg



P(FIR) vs Offset; P/A_V vs A_V

- Tough to tease out of the GF9-2 laboratory
  - FIR emission is faint, few points available for testing
- Synthetic Beam Values
  - YSO position – P'(E-band) = **$1.9 \pm 1.1\%$**
    - $P' = (P_{RAW}^2 - \sigma_P^2)^{0.5}$ = "debiased" estimator
  - Mean of 8 beams offset from YSO $P' = 3.2 \pm 0.9\%$
    - Mean of 5 detection beams P' = **$3.8 \pm 1.1\%$**
  - Polarization "hole"? -> meh…
    - $\Delta P'$ = **$1.9 \pm 1.6\%$**
- Higher Angular Resolution with HAWC+ Bands C, A?
  - GF9-2 is too faint for polarimetry in these bands
- P/A_V vs A_V & grain alignment – TBD
  - But, strong agreement of FIR with NIR/Optical/Planck suggests all sampling common B-field, so alignment can't be horrible

Comparisons with Models

- Hull+'17
  - Simulations with synthetic observations
  - Multi-scale
- GF9-2 observations are most consistent with strong B-field case
  - BPA uniform from 3pc to 6000AU
  - **Last column, top two rows**
- Seems GF9-2 YSO formed in a fairly strong B-field region

The Astrophysical Journal Letters, 842:L9 (10pp), 2017 June 20 Hull et al.

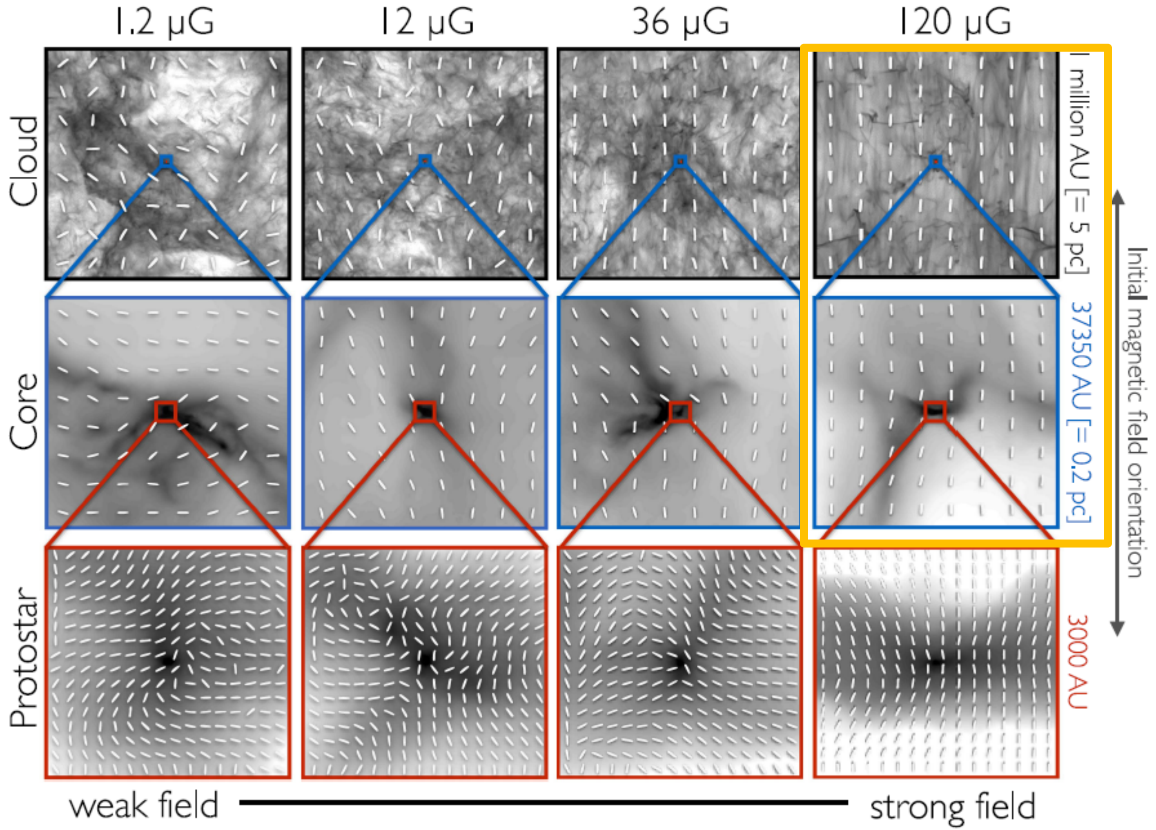
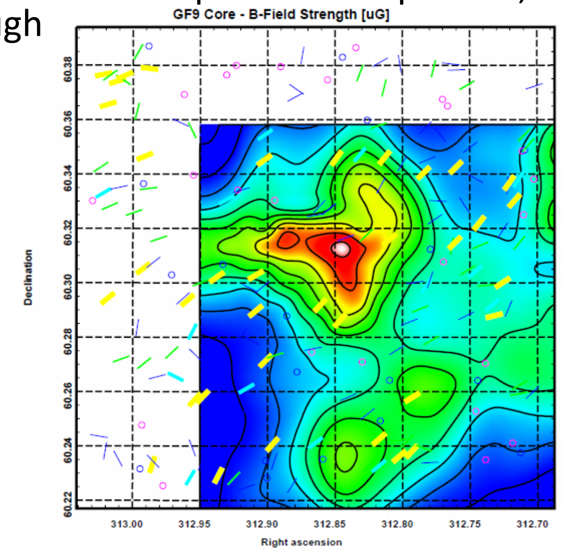


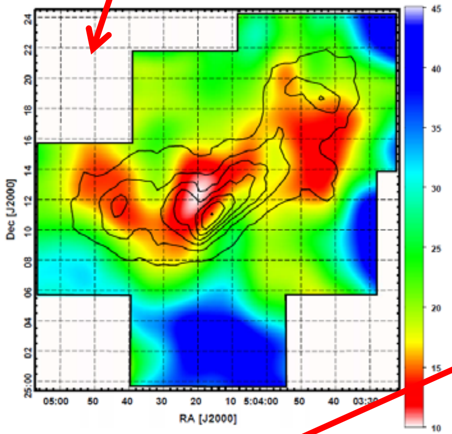
Figure 2. Multi-scale projections of simulated data. Shown are the column densities and the magnetic field orientation of protostellar cores that formed in our AREPO simulations. As indicated, the initial mean magnetic field is oriented in the vertical direction. The initial magnetic field strength increases from the left to the right columns, corresponding to Alfvén Mach numbers $\mathcal{M}_{A,\text{mean-field}} = 35, 3.5, 1.2, 0.35$ (see Table 1). The top row shows the full-scale AREPO simulations, centered on the cores shown in the bottom row. The full simulation boxes are 5.2 pc in extent (cloud scale). The middle row shows zoom-ins between JCMT and CARMA scales (core scale). The bottom row shows zoom-ins of cores at ALMA scales (protostar scale). By allowing the magnetic field orientations and zoom boxes to be toggled on and off, the interactive figure enables the reader to compare more easily the background grayscale column density maps with the foreground magnetic field orientations.

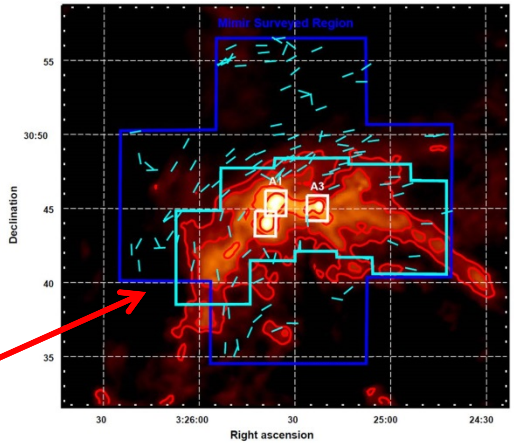
Next Steps, Other Cases

- **GF9-2**
  - Recently obtained ARO CO, ^{13}CO, CS data to augment older FCRAO data (Ciardi+'00) and fully cover the 10x10 arcmin Mimir FOV
  - Estimate gas dispersion, density
  - B-field strength map
  - Too few HAWC+ points to help much, though



- **L1544** – low-mass, pre-stellar dense core
  - Deep Mimir polarimetry (Clemens+'14)
  - Some HAWC+ obs, more on current flight series





- **L1448** – multiple, low-mass YSOs with advanced outflows
  - HAWC+ obs tomorrow night and Friday night
  - Former REU student Genevieve Schroeder will be on-board SOFIA for these observations.

Old dogs  new tricks… 

- **<u>Gaia DR2</u>**
  - Wowzer!
  - Nearly all GF9 Mimir stars have distances now!
- **<u>Bayesian MCMC</u>**
  - Better distances to clouds, cores, YSOs
  - P, PA steps at cloud locations
  - Wait until you see our U, Q versions! (different project…)

- **<u>HAWC+</u>**
  - Wowzer!
  - Seeing where NIR can't
  - Faint, quiescent as well as the usual, bright suspects…
- **<u>Synthetic Beam "Re-Obs"</u>**
  - Trade resolution for SNR to pull out faint polarization signals
  - Pick placements wisely…

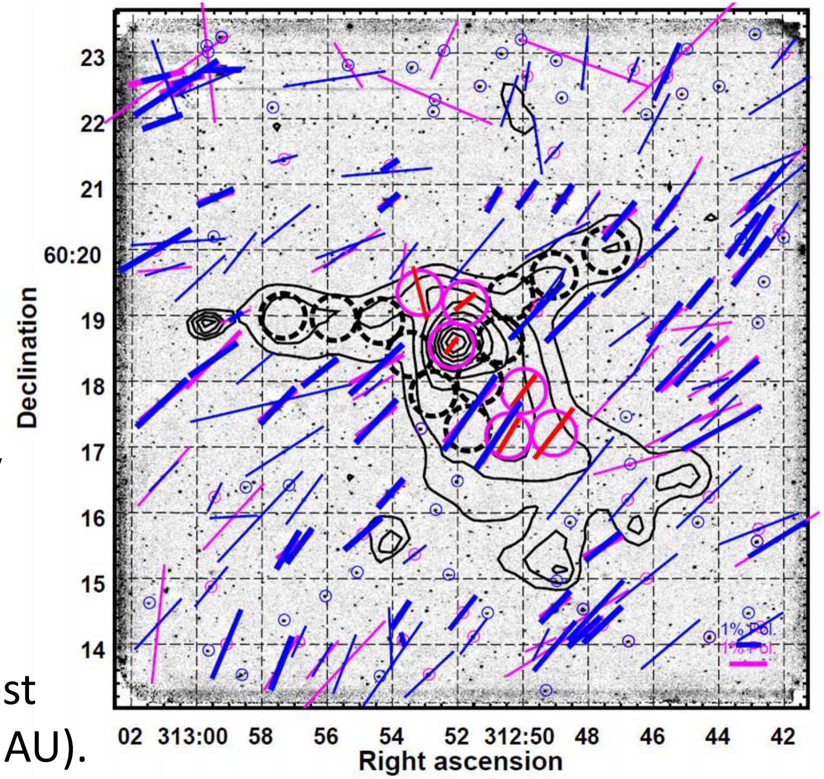
Summary

Big Question – Are B-fields important in clouds->cores->star formation?

Tested here – Are B-fields strongly modified at/for some length scales?

Tools: (1) Near-IR polarimetry in H, K bands w/ Mimir
(2) SOFIA/HAWC+ E-band (214 μm) polarimetry

Laboratory: GF9-2, a very young, low-mass, Class 0 protostar with only a weak outflow



Findings: (1) B-field orientations preserved from largest scales (> 3pc) to smallest probed (~6000 AU).

(2) No evidence for B-field orientation change with wavelength.

(3) Distance to GF9 cloud/core/YSO is 270 ± 10pc (thanks Gaia DR2!)

(4) Mimir NIR + SOFIA HAWC+ FIR polarimetry = powerful combination for elucidating B-field properties in core, star formation

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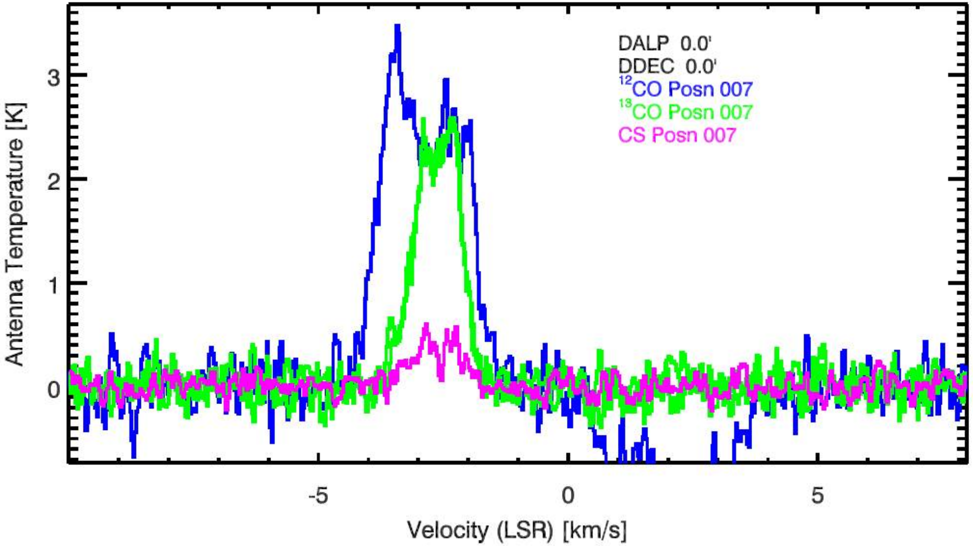
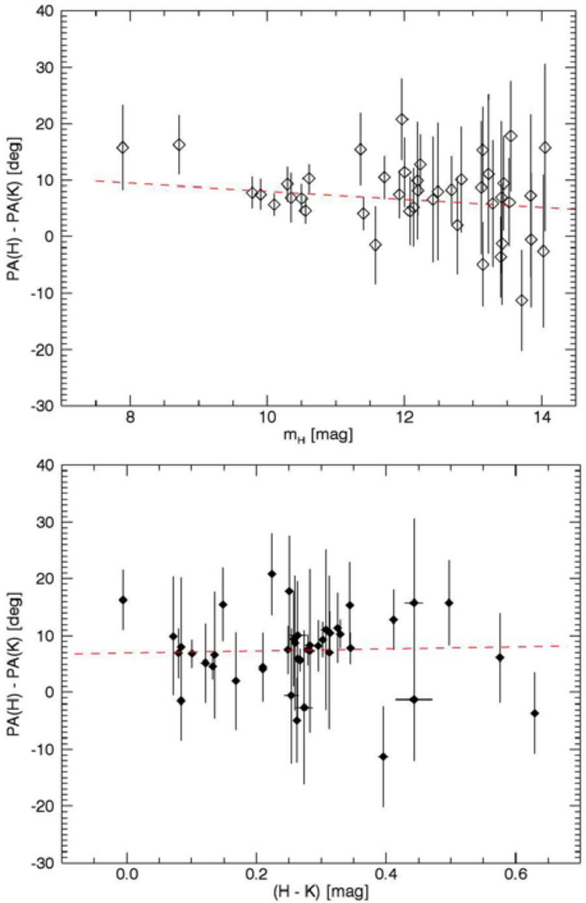
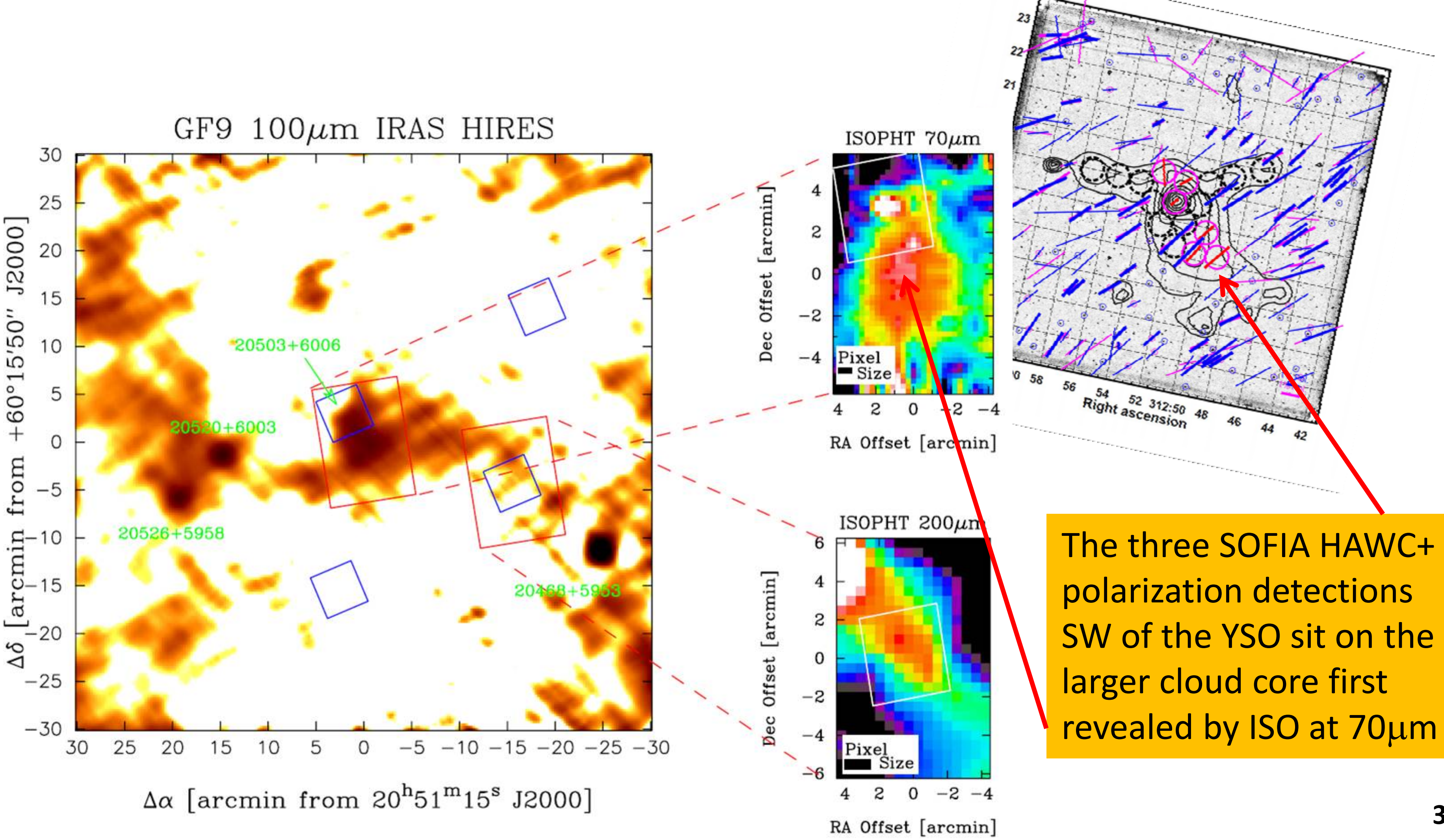


Arizona Radio Observatory radio spectral lines observed in 2017 toward the GF9-2 YSO position. Note self-absorptions and asymmetries



H to K polarization position angle differences vs mH (upper) and (H-K) lower – no significant trends



The three SOFIA HAWC+ polarization detections SW of the YSO sit on the larger cloud core first revealed by ISO at 70μm