*SOFIA Tele-talk*

# Hunting Magnetic Fields with SOFIA and ALMA:

# The Case of the Masquerading Monster in BYF 73

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arXiv:2301.03618 (*ApJ*, **945**, 34)

# Outline of talk

- *B* field measurements are *hard!* Especially in high-density gas where star formation happens
- A new CN-bright cloud sample could quadruple the number of Zeeman $B_{\mathrm{LOS}}$ strength measurements in high-density gas (Sharpe 2020)
- First cloud examined: BYF 73 with SOFIA+ALMA, continuum *and* spectral lines
- Stokes *I* data already reveal unexpected features in both continuum and lines
- Continuum polarimetric analysis: DCF and HRO methods
- ALMA spectropolarimetry: CN (Zeeman effect via Stokes *V*) and $^{12}$CO (Goldreich-Kylafis effect via Stokes *P*)
- Summary and conclusions

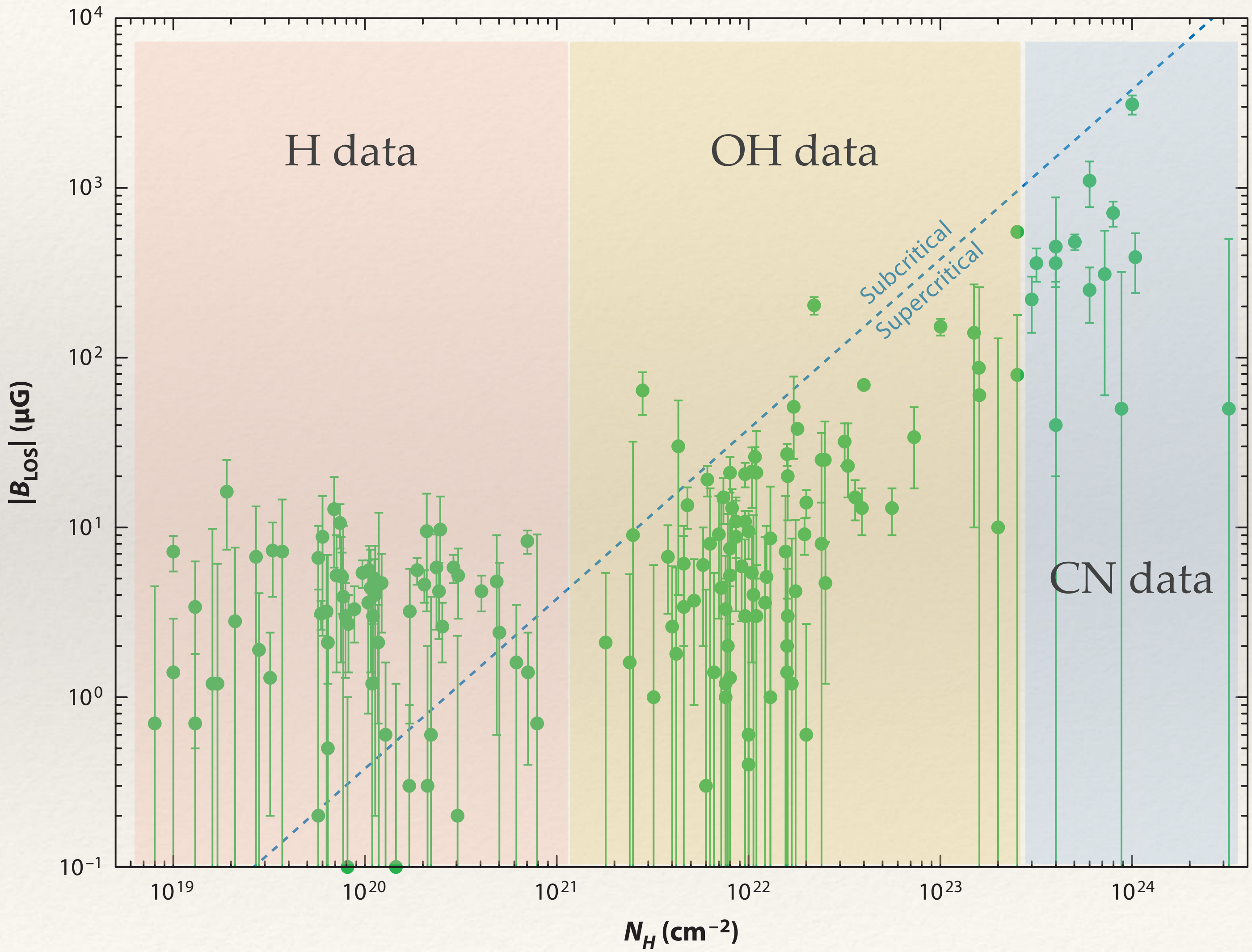
But first…

# Kia Ora, SOFIA


Welcome to Aotearoa

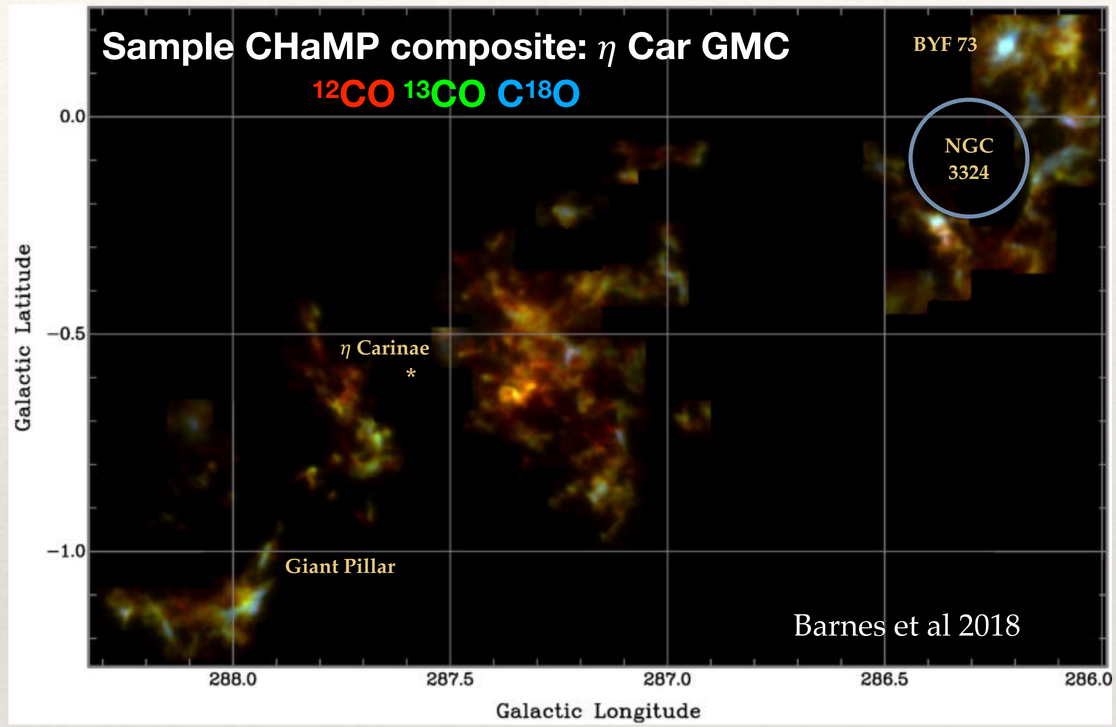
# Motivation: $B_{\text{LOS}}$ results to date

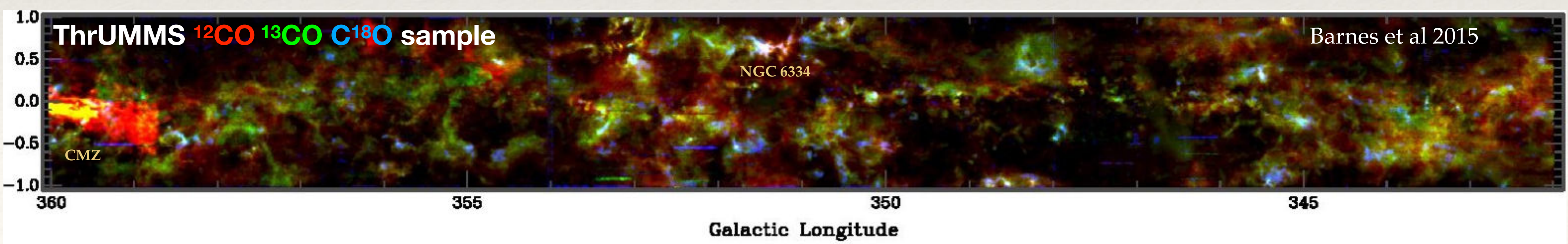
- Review by Crutcher (2012)
- Zeeman effect can be observed in H, OH (low-density gas) and CN (high-density gas)
- Only 14 Zeeman-CN measurements in past 40 years: *really hard!*



# Defining a new CN-bright cloud sample

- CHaMP+ThrUMMS are wide-field, multi-species, pc-resolution cloud surveys over kpc scales
- Sharpe (2020) generated a **complete, uniform catalogue of 45 CN-bright, massive, SF molecular clouds** across 240 deg² of southern MW, ***bright enough to map Zeeman effect with ALMA***
- Use SOFIA+ALMA for polo mapping, with ancillary data on cloud physics from CHaMP, ThrUMMS, HiGAL & other GP surveys

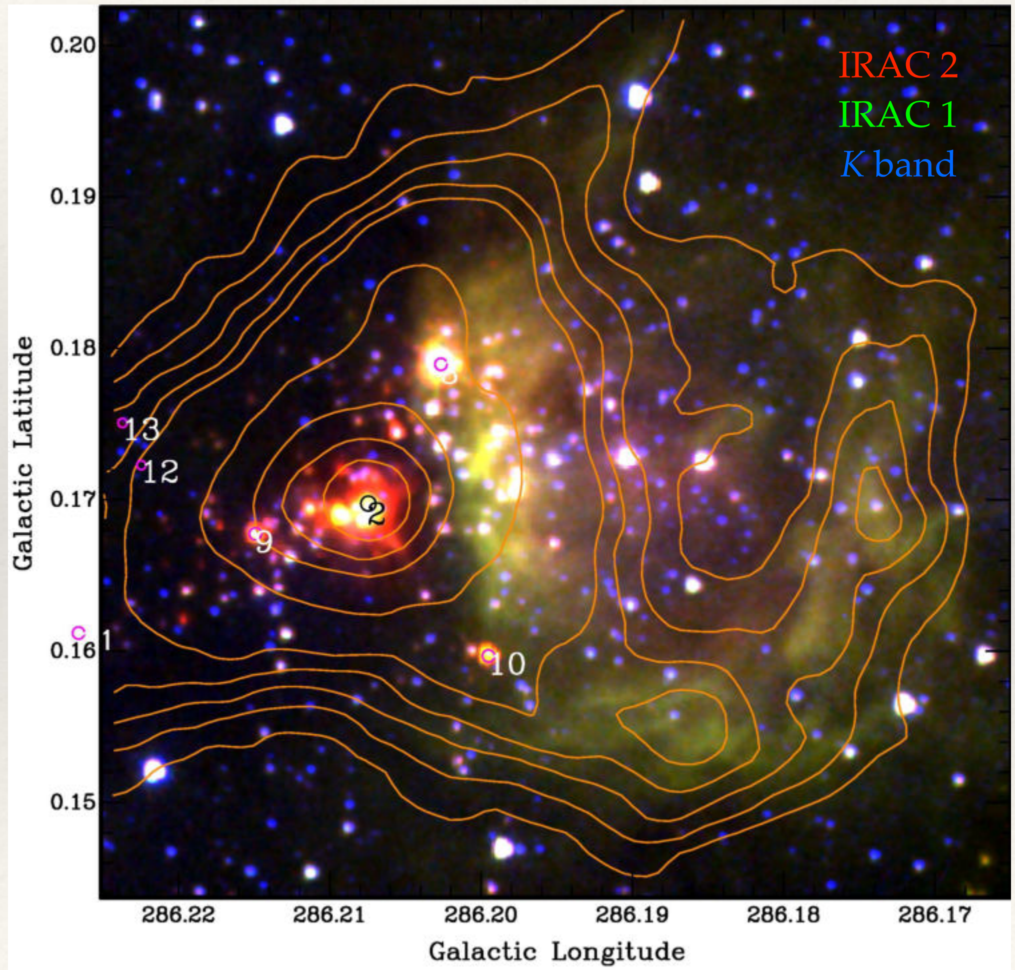


# First cloud: the unusual BYF 73

- From CHaMP (Barnes et al 2010): highest protostellar mass inflow rate known, 0.034 $M_\odot$/yr
- Located at relatively isolated, quiet, western end of $\eta$ Carinae GMC, $d$ = 2.5 kpc
- $2\times10^4$ $M_\odot$, $10^4$ $L_\odot$ clump, centrally-concentrated, small HII region (B1 ✷)
- Prior Gemini + SOFIA data show most NIR ✷s are foreground, only a few MIR ✷s (Pitts et al 2018)
- Most-massive and -embedded is MIR 2: mass ~240 $M_\odot$ , $A_V$ ~ 7000$^m$ from SED fitting, implied dynamical age ~7 kyr

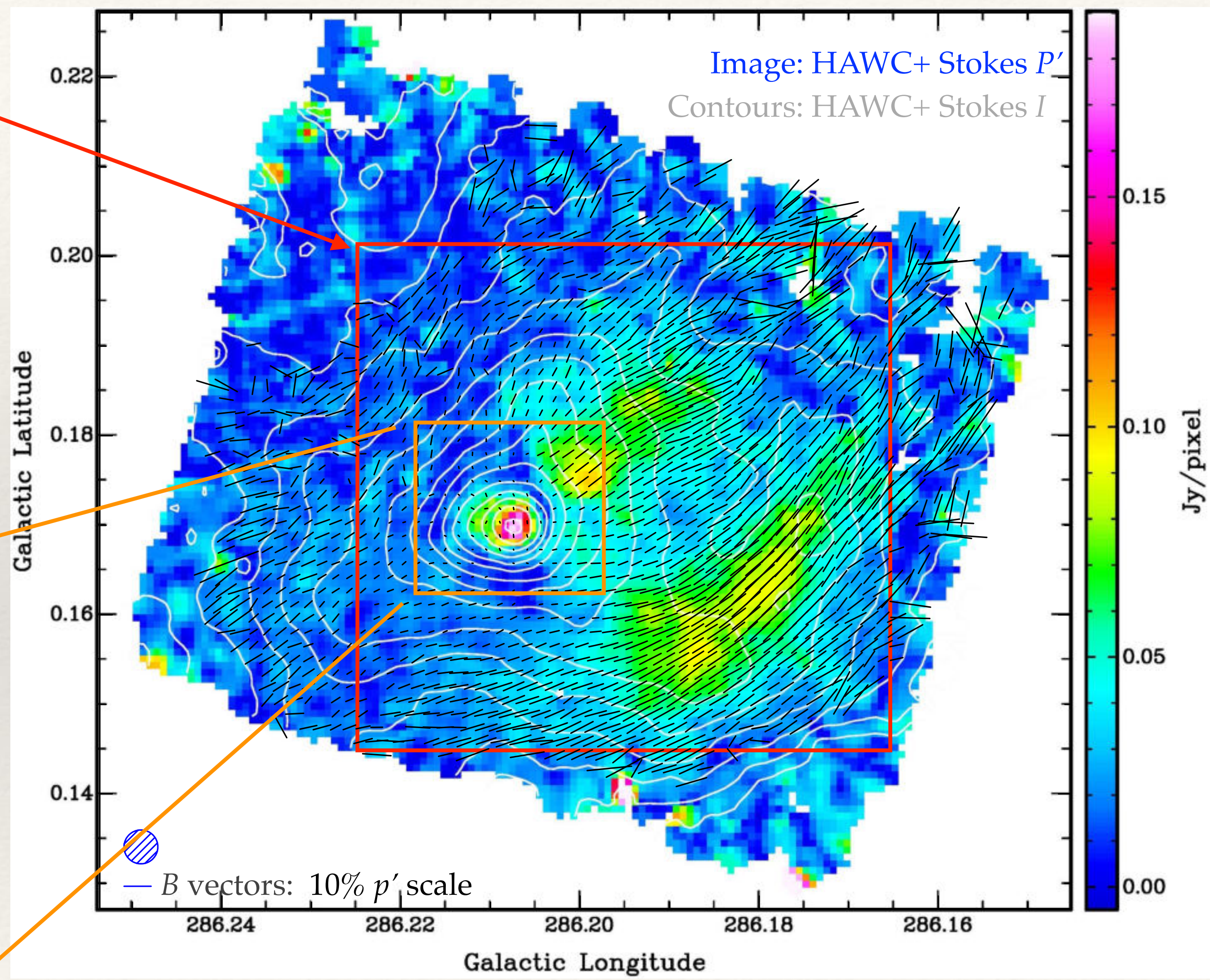
Image: Spitzer-IRAC + AAT
Contours: HAWC+ 154$\mu$m total $I$
Selected MIR ✷s

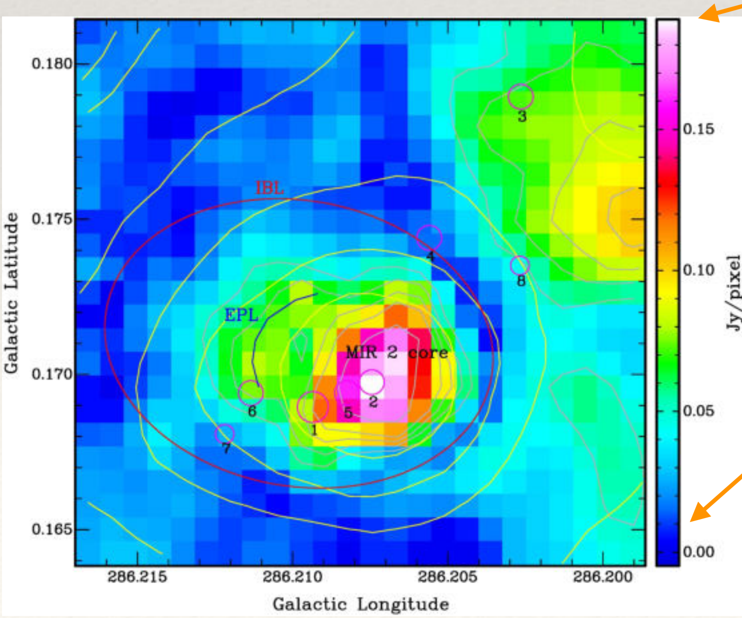


# SOFIA HAWC+ 154μm data: warm dust

Zoom-out from last slide
$p' \sim 10\%$ in HII region

Zoom-in to MIR 2 core:
sharp Boundary Layer with
$B_\perp \sim 0$; $p' \sim 1\%$ in core + eastern polarisation lobe (EPL)




Something very interesting going on!

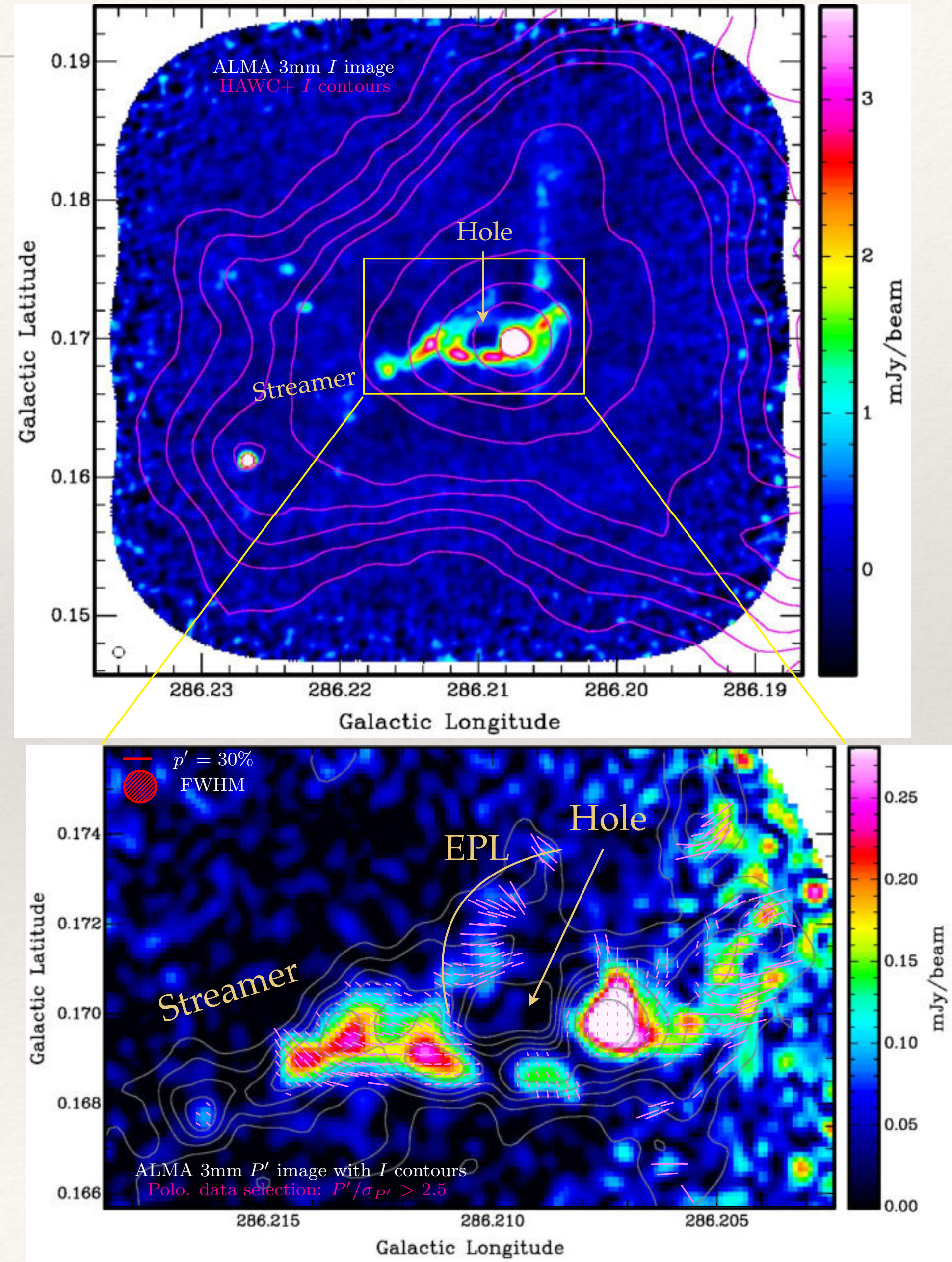
# ALMA 3mm continuum data: cold dust

*Zoom back out:*

Image: ALMA *I*-continuum mosaic
Contours: HAWC+ *I*-continuum
→ Very few 3mm ✷s (mainly MIR 2), plus a massive "Streamer" and a "Hole"

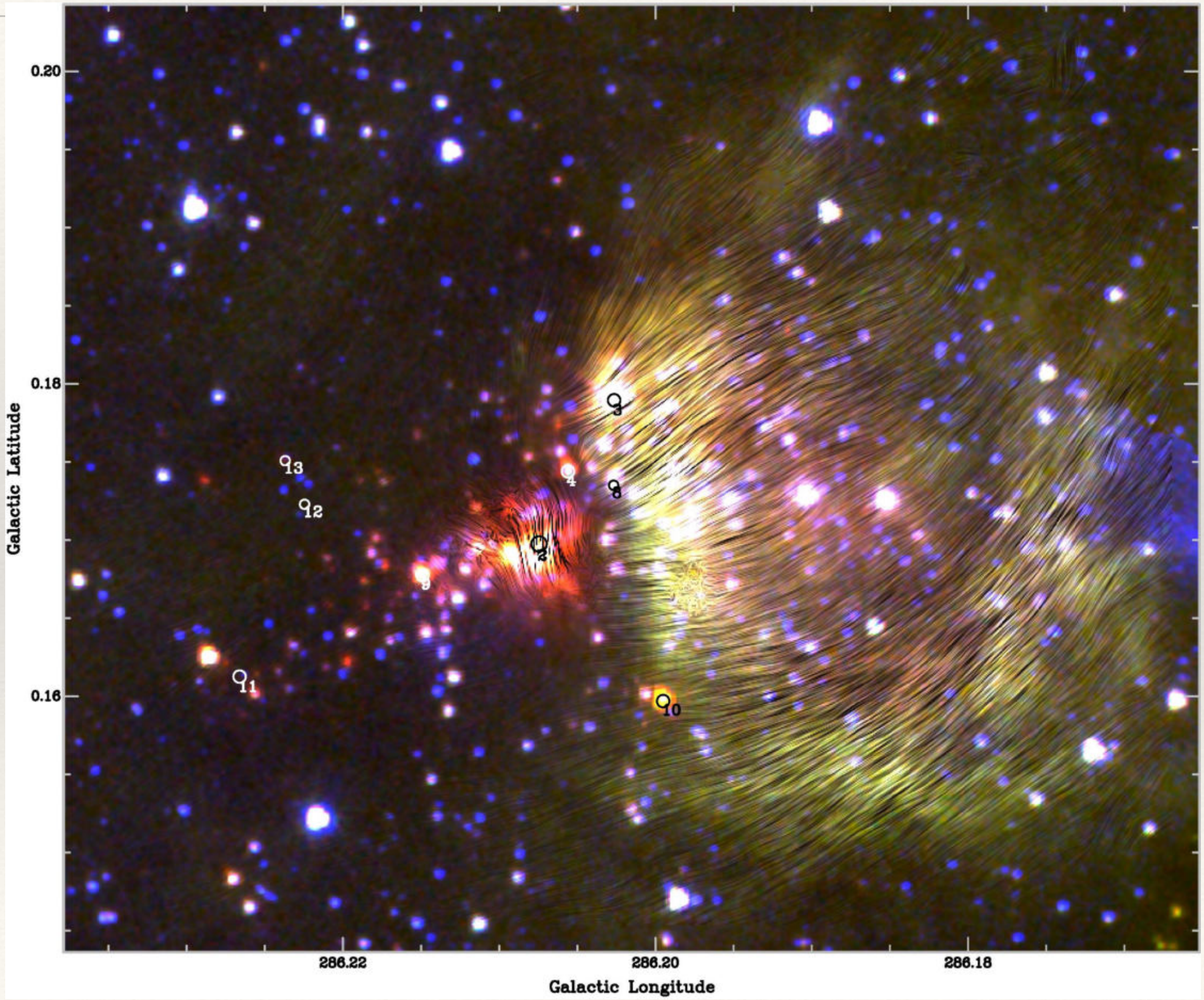
*Zoom back in:*

Image: ALMA single polo field, $P'$ flux
Contours: ALMA *I* mosaic
*B* vectors: 30% $p'$ scale (TL corner)
Polo data selection: $P'/\sigma_{P'} > 2.5$, every 2nd pixel
→ Limited polarised emission



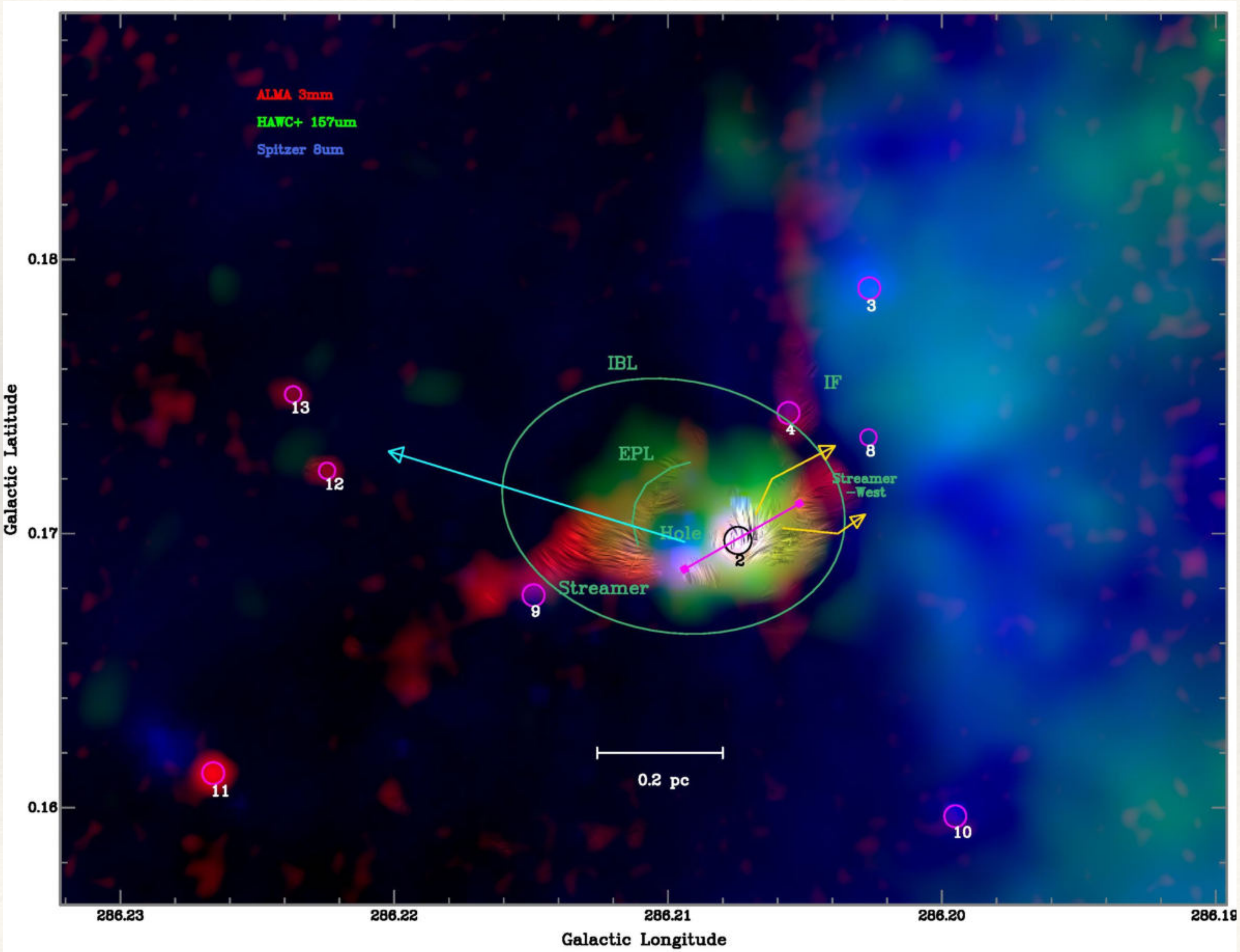
# NIR-FIR composite with LIC

- Background = same IRAC 2 IRAC 1 *K* band from earlier
- Overlaid LIC pattern from HAWC+ 154$\mu$m Stokes $P'$
- Numbered protostars from Gemini MIR and ALMA



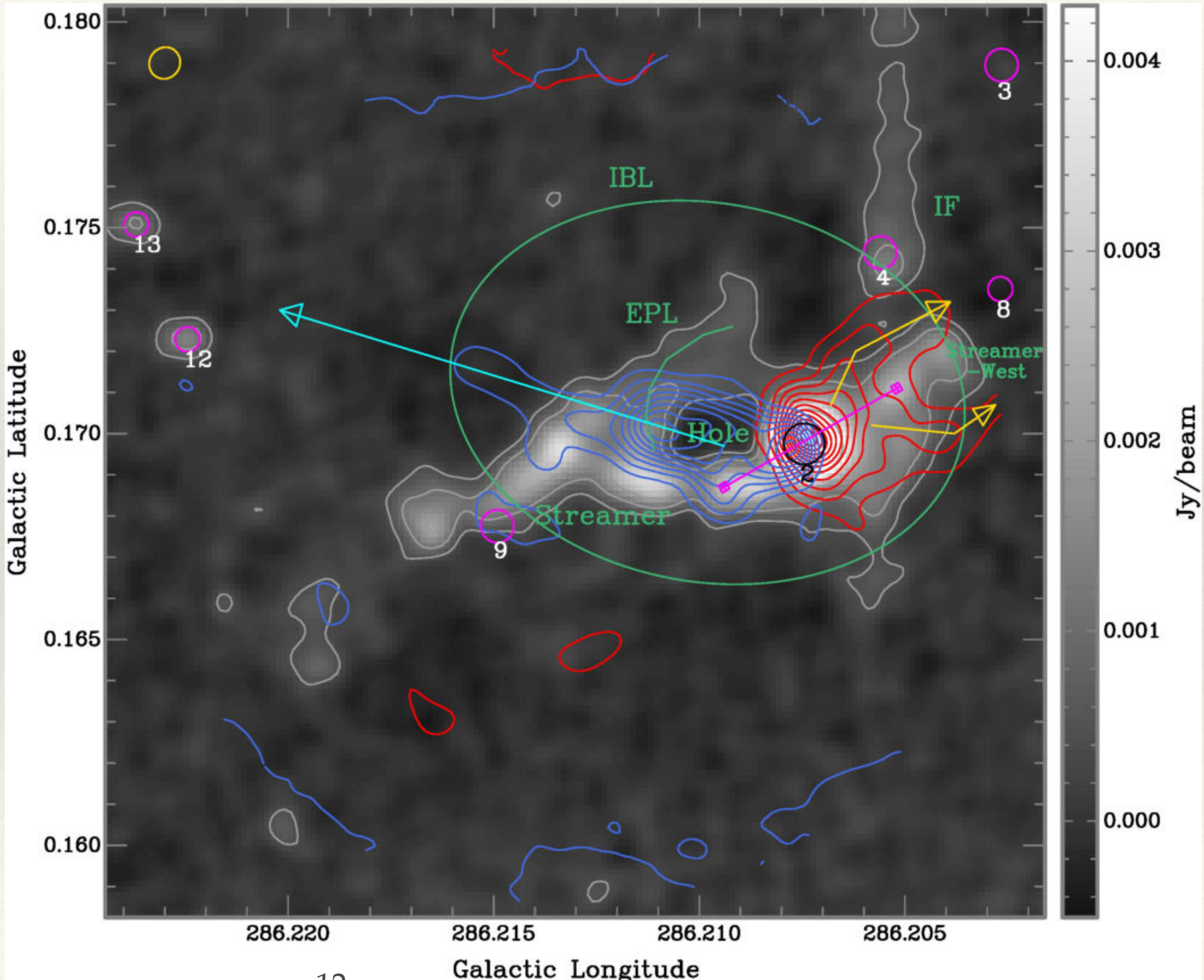
# MIR-FIR-3mm-LIC composite

- Background = ALMA HAWC+ IRAC 4
- Overlaid LIC pattern from ALMA 3mm continuum



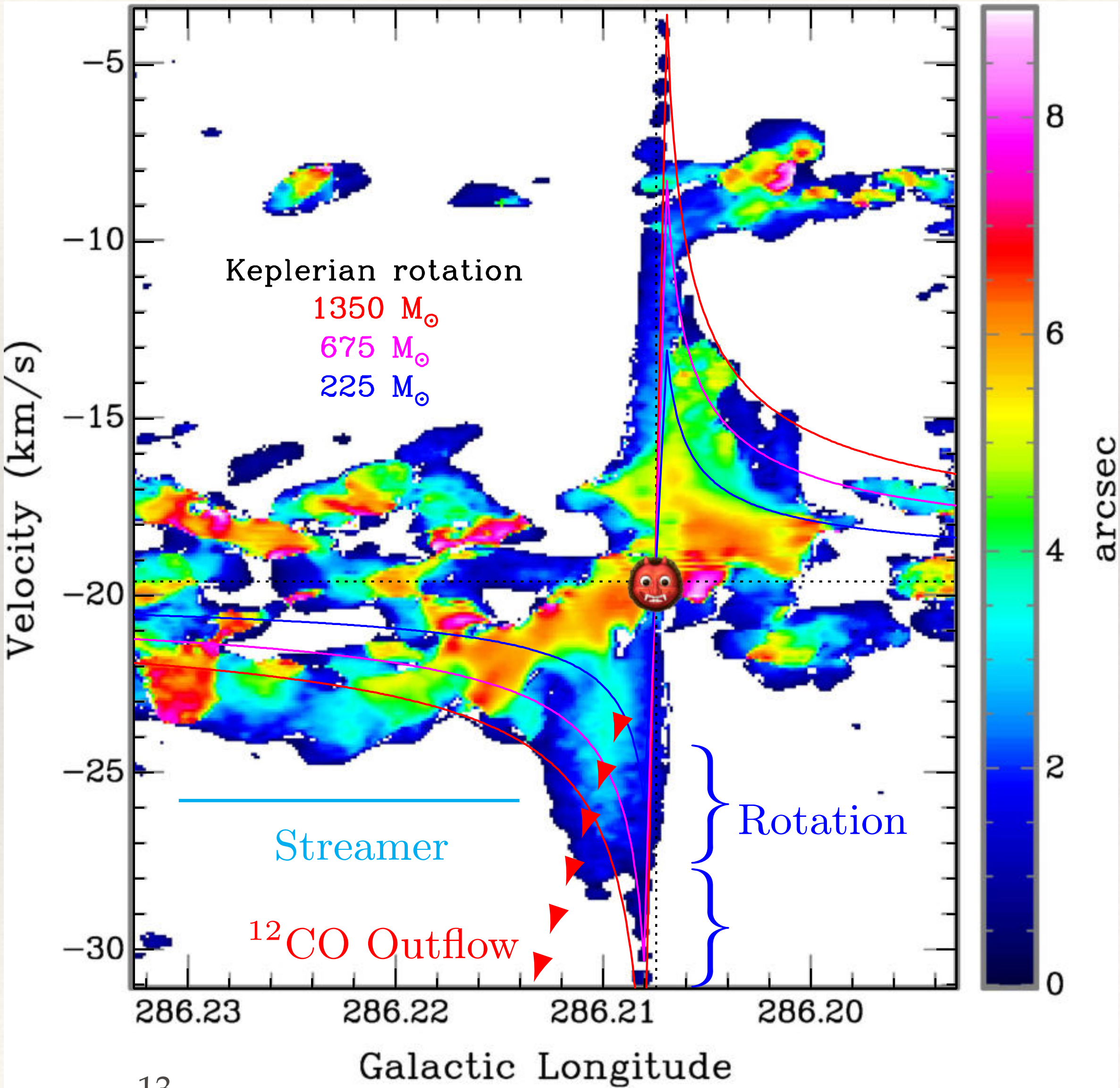
# ALMA spectroscopy

- $^{12}$CO line wings: a powerful, distorted bipolar outflow from MIR 2
- The EPL seems to be a "splash" effect of the deflection of the blue wing away from the outflow axis by the massive Streamer. The red wing is also deflected
- The *B* field points radially to MIR 2 through the EPL, mostly along the Streamer, and along MIR 2's outflow axis



# But wait, there's more!

- $^{13}CO$ line shows Streamer, outflow, and…
- ***Keplerian rotation*** (1350 M☉) or ***free infall*** (950 M☉) !!!
- MIR 2 may be 4–6x more massive (& older) than previously thought— a masquerading monster 👹
- Mass not in SED: where is it hiding? => Significant grain growth in protostellar core?
- Grav. PE release of infall may provide 33% of luminosity



# Davis-Chandrasekhar-Fermi analysis

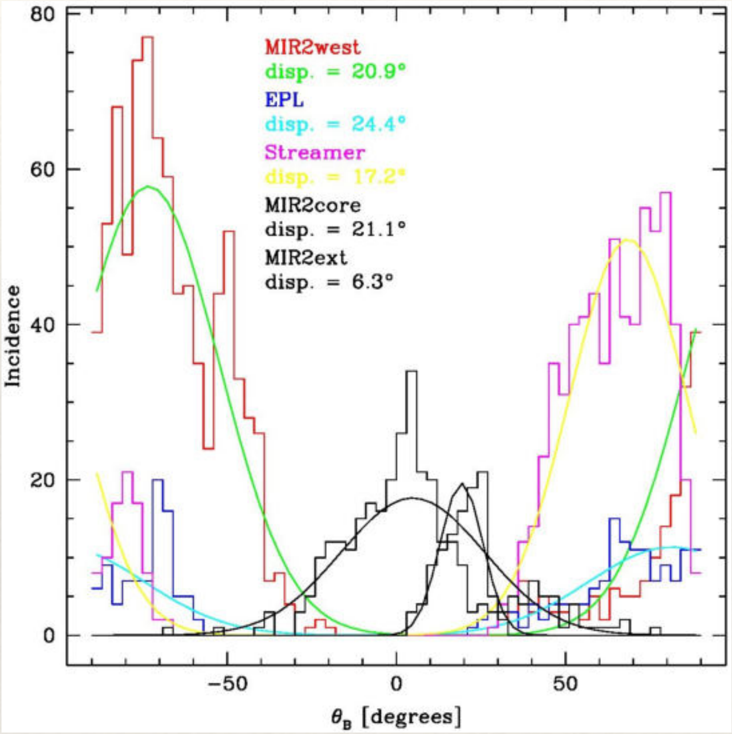
- **For MHD wave in a turbulent medium,**

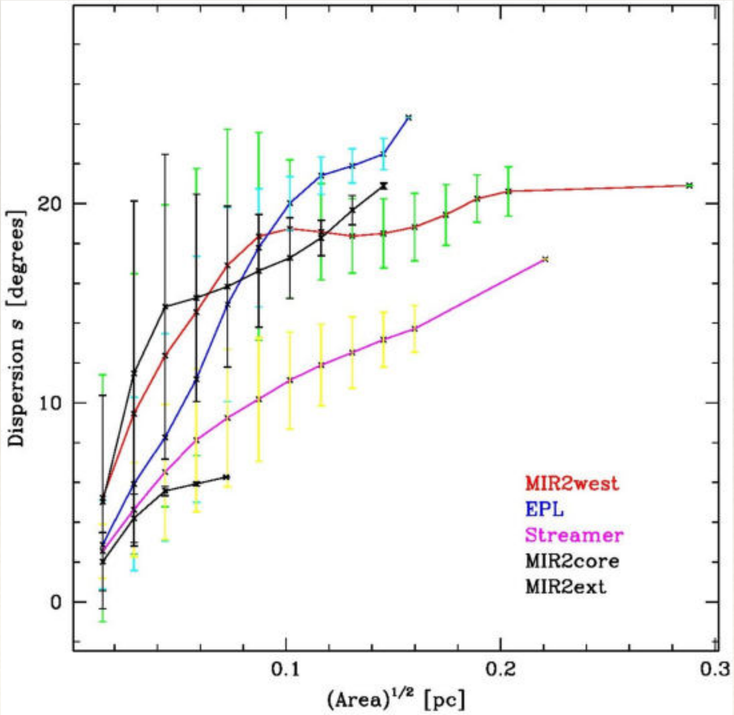
$$B_{\perp,\mathrm{DCF}} \propto \sqrt{n}\,\Delta V / s$$

where $n$ = gas density, $\Delta V$ = velocity FWHM, $s$ = dispersion in $\theta_B$ on scale of $B$ coherence

- Also, structures contain ~a few coherence lengths, so $B_{\perp,\mathrm{DCF}} = B_{\perp,\mathrm{random}} \sim 0.3 \times B_{\perp,\mathrm{ordered}}$

ALMA continuum $\theta_B$ statistics by feature



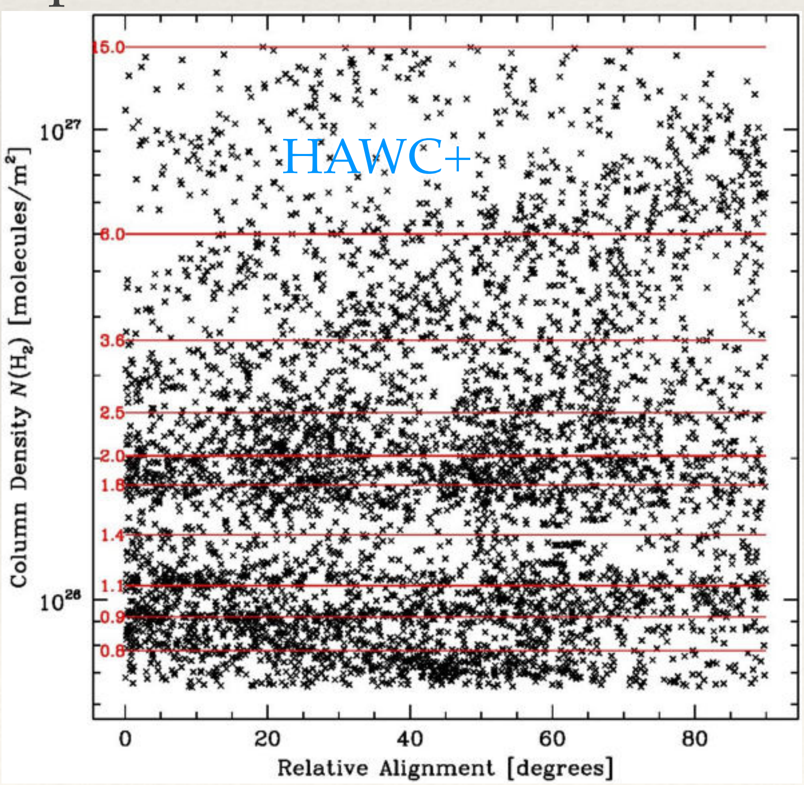



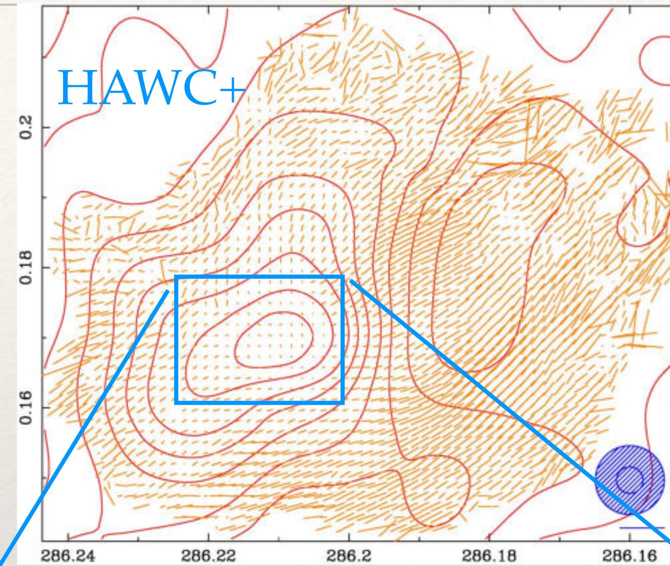

SI alert!
1 nT =
10 $\mu$G

- In Streamer, $B_{\perp,\mathrm{DCF}} \approx$ 45nT $(s/10°)^{-1}$
- In EPL, $B_{\perp,\mathrm{DCF}} \approx$ 22nT $(s/10°)^{-1}$
- In MIR 2, $B_{\perp,\mathrm{DCF}} \approx$ 140nT $(s/10°)^{-1}$

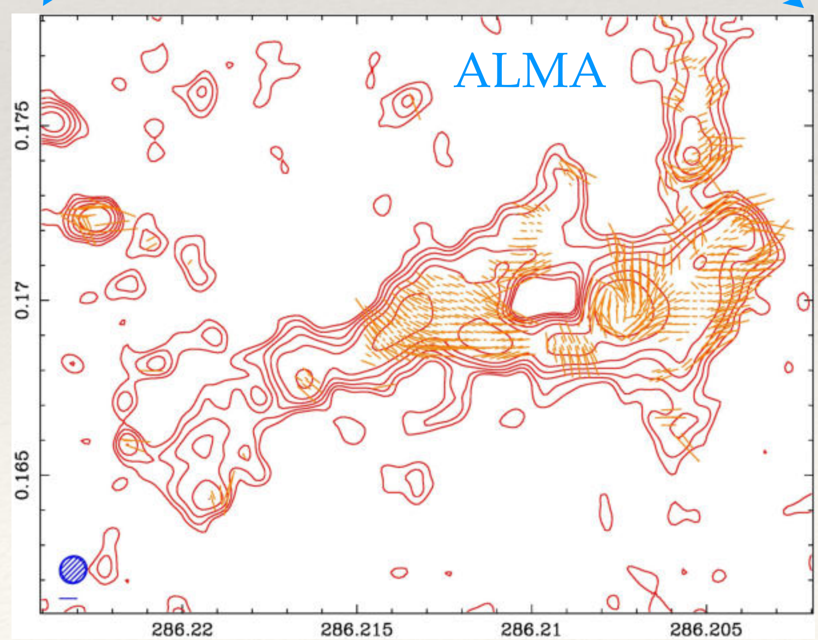
# Histogram of Relative Orientations

- Quantify where transition to criticality occurs by comparing *B* field orientation $\theta_B$ to column density gradient $\nabla N$
- Compile RA statistics in each *N* bin



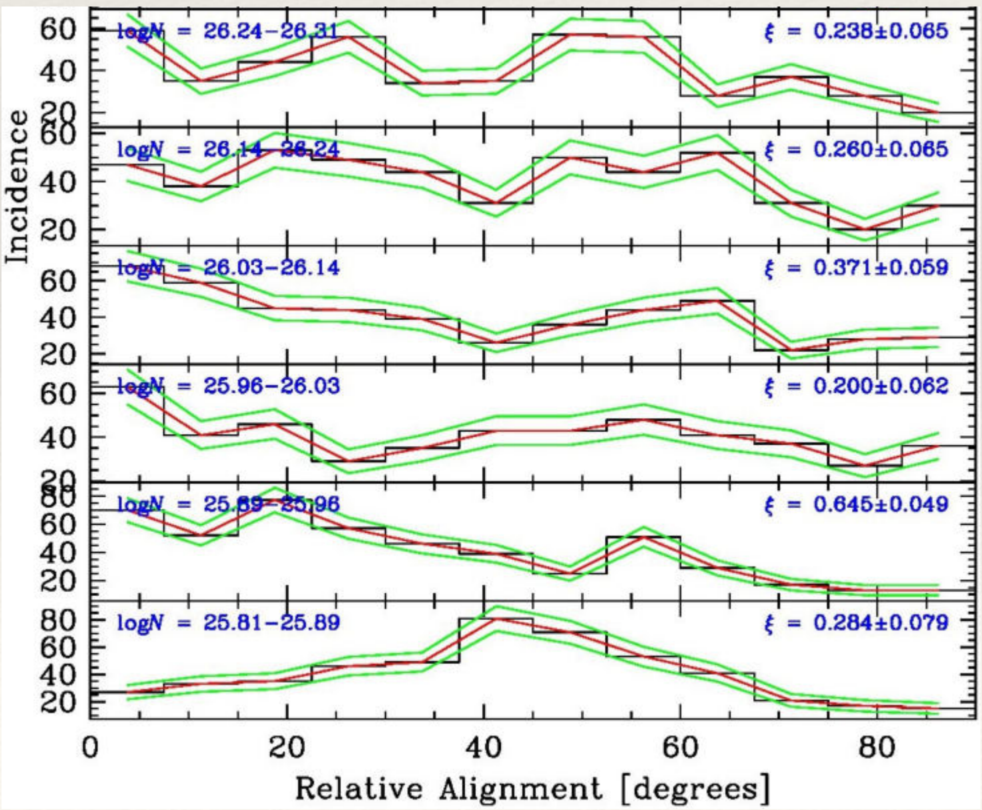

*N* maps from Herschel SED fitting (Pitts et al 2019)



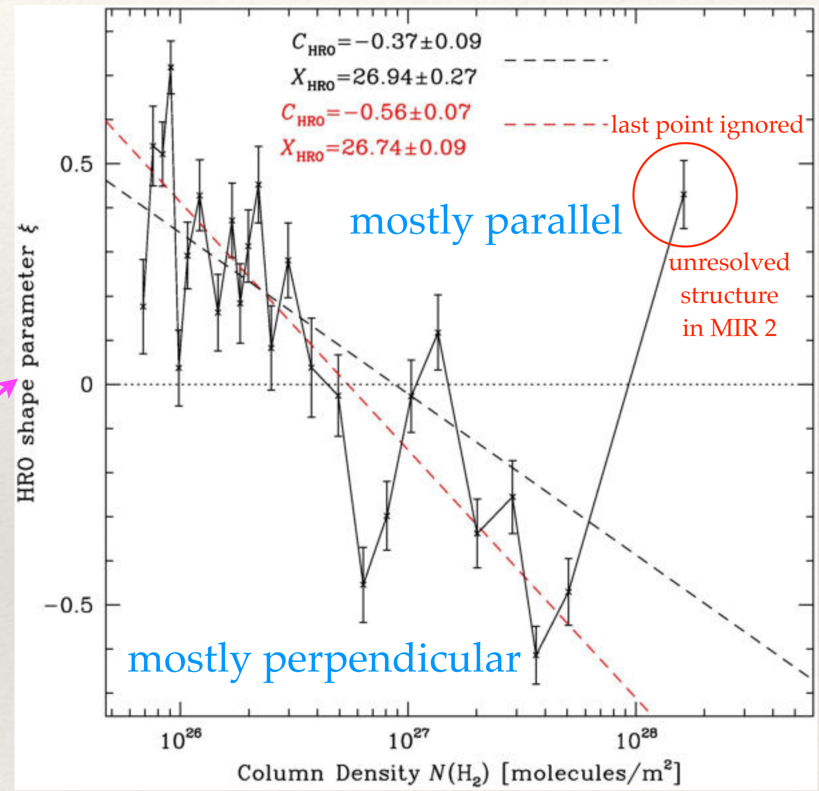
# HRO analysis, cont.

- For each $N$ bin, define "shape parameter" $\xi$ running from –1 (all perpendicular) through 0 (random) to 1 (all parallel) (Soler+2017)

HAWC+ subset




HAWC+ALMA

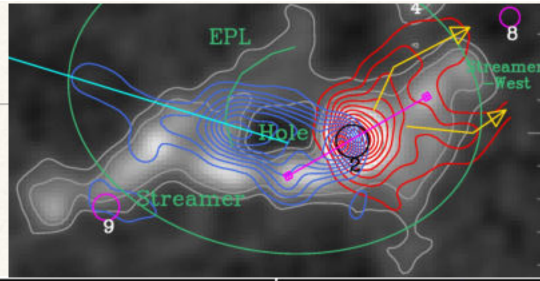



3 orders of magnitude

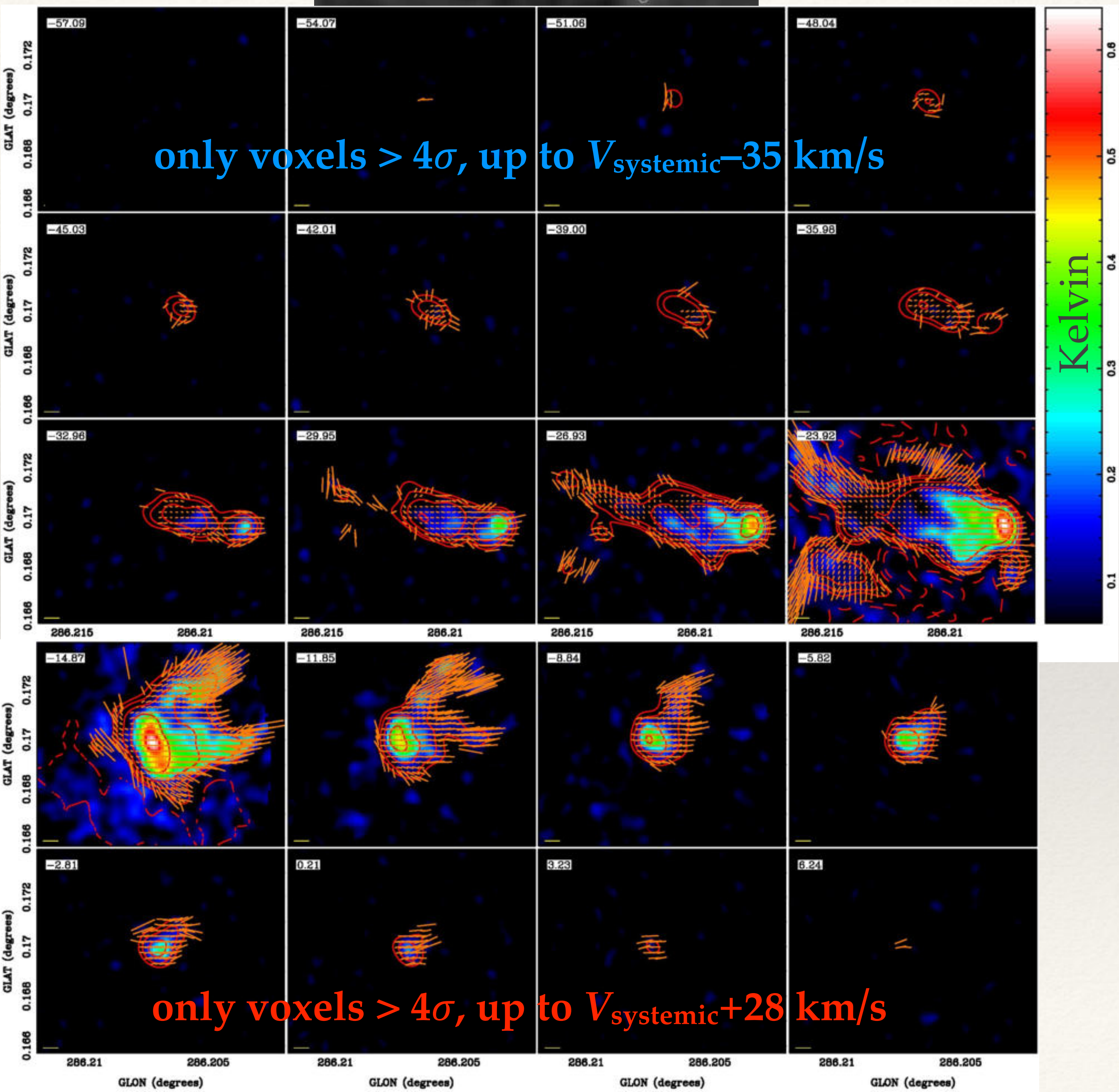
- Then examine trend of $\xi$ with $N$

# HRO Results

- Transition to perpendicularity in BYF 73 occurs at $N = 6.6\pm1 \times 10^{26}$ mol/m$^2$ = 1250 $M_\odot$/pc$^2$, averaged across all HAWC+ALMA polarised emission => most of the Streamer
- If this signifies where $\lambda = (M/\Phi)_{obs}/(M/\Phi)_{crit} = 1$, then the transition is at $B_\perp = 42\pm7$ nT, similar to DCF result for Streamer
- For structures on the scale of a few ALMA beams (eg, the Streamer ~ 0.1pc), this suggests the gas is super- or sub-critical at densities $n_{cr} \gtrless \sim 2\times10^{11}$ m$^{-3}$ => **much higher than typical**
- These values are at the higher end of the Crutcher (2012) ($B$,$n$) diagram, so we are reaching the parameter space we targeted
- But what about ALMA's CN+$^{12}$CO spectropolarimetry…???



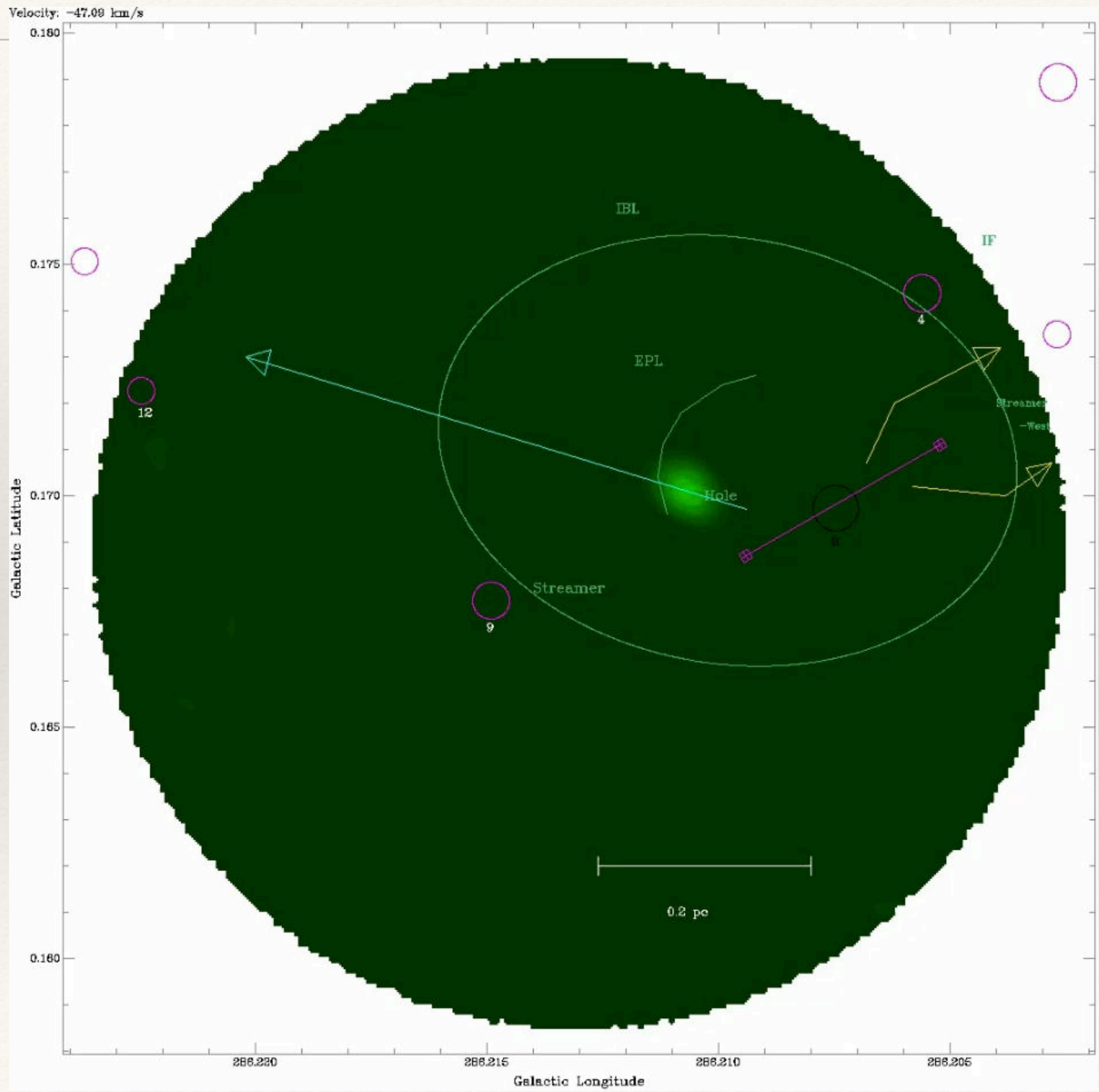

# GK effect in $^{12}$CO



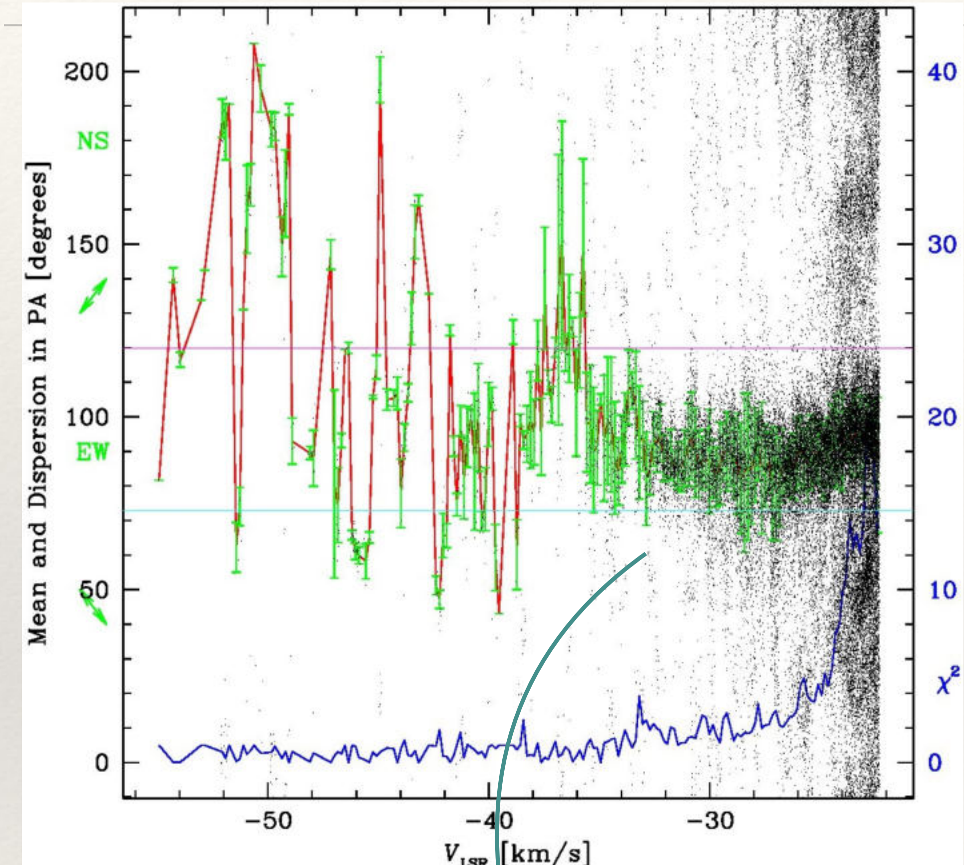

- Line core is almost completely opaque from –24 to –17 km / s
- Goldreich-Kylafis effect produces strongly polarised emission (up to 24%) in moderate opacity line wings (eg, Girart+2004, Cortes+2005)
- Blue wing $p'$ vectors "closed"
- Red wing $p'$ vectors "open"

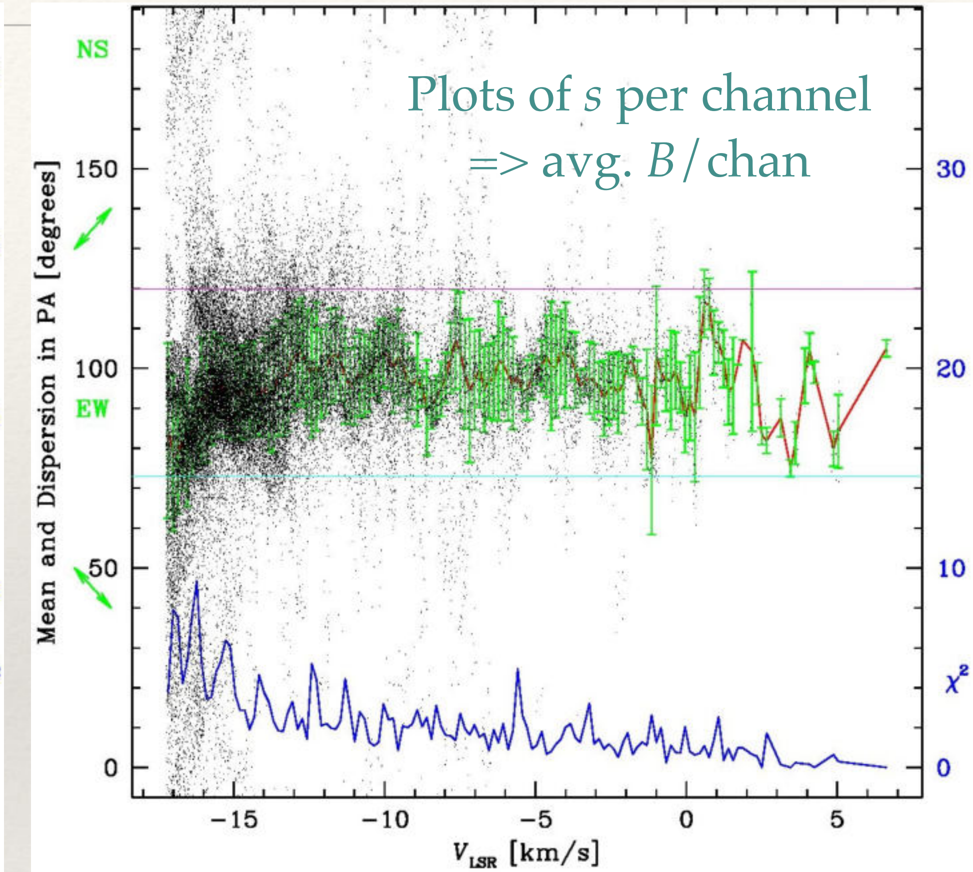
# First ever spectropolarimetric movie in $^{12}CO$

- This is a whopping GK signal!
- Background: ALMA $^{12}CO$ line wings Stokes *I* (line core is almost opaque from –24 km/s to –17 km/s)
- Overlaid LIC pattern from ALMA $^{12}CO$ line wings' Stokes *P'*



# Spectroscopic DCF analysis




- Unexpected bonus! Can perform DCF analysis ($B \sim \sqrt{n}\,\Delta V/s$) per channel via $I_{CO}$ –> $N_{CO}$ conversion laws (Barnes+2018, Pitts+Barnes 2021):

$$n_{\rm ch} = \frac{N_0}{D}\ \frac{(I_{^{12}{\rm CO}}{\rm d}V/{\rm K\,km\,s^{-1}})^p}{10^{[-10\log^2(T_d/T_0)+\log X_0]}}$$

# Compare Energetics

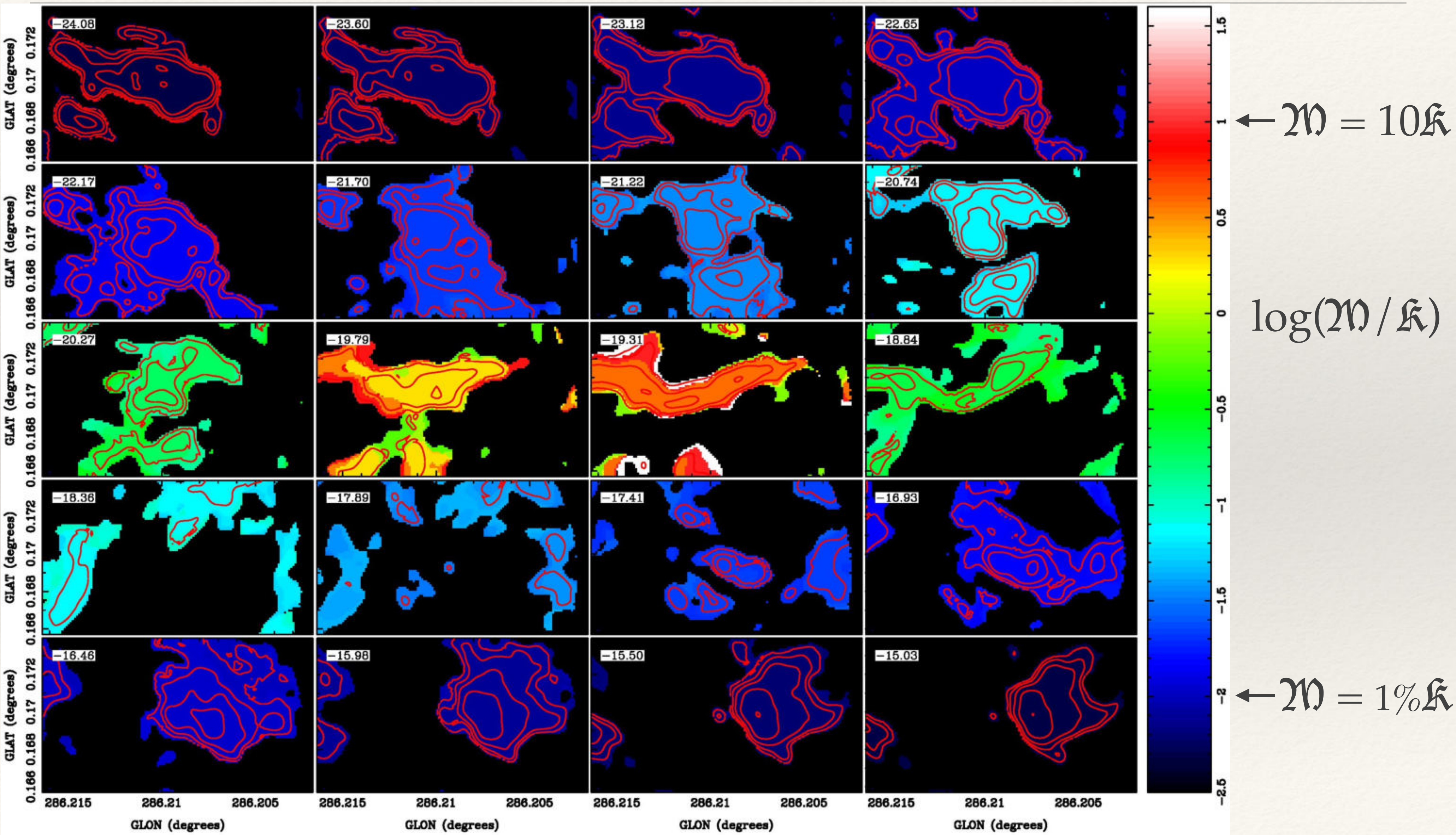
$\psi$ is a $(\Delta V/\mathrm{d}V)$ scaling factor

- So then, $$B_{\perp,\mathrm{DCF,outflow}} \approx 4.5\,\mathrm{nT}\left(\frac{I_{^{12}\mathrm{CO}}\mathrm{d}V}{10\,\mathrm{K\,km\,s^{-1}}}\right)^{p/2}\left(\frac{\psi}{s/7^\circ}\right)$$
- Compare estimate of magnetic energy density $\mathfrak{M} = B^2/2\mu_0$ and kinetic energy density $\mathfrak{K} = {}^1/_2\rho V_{\mathrm{rel}}{}^2$ in outflow:

$$\frac{\mathfrak{M}}{\mathfrak{K}} = 3.8\% \left(\frac{\Delta V/V_{\mathrm{rel}}}{s/7^\circ}\right)^2$$

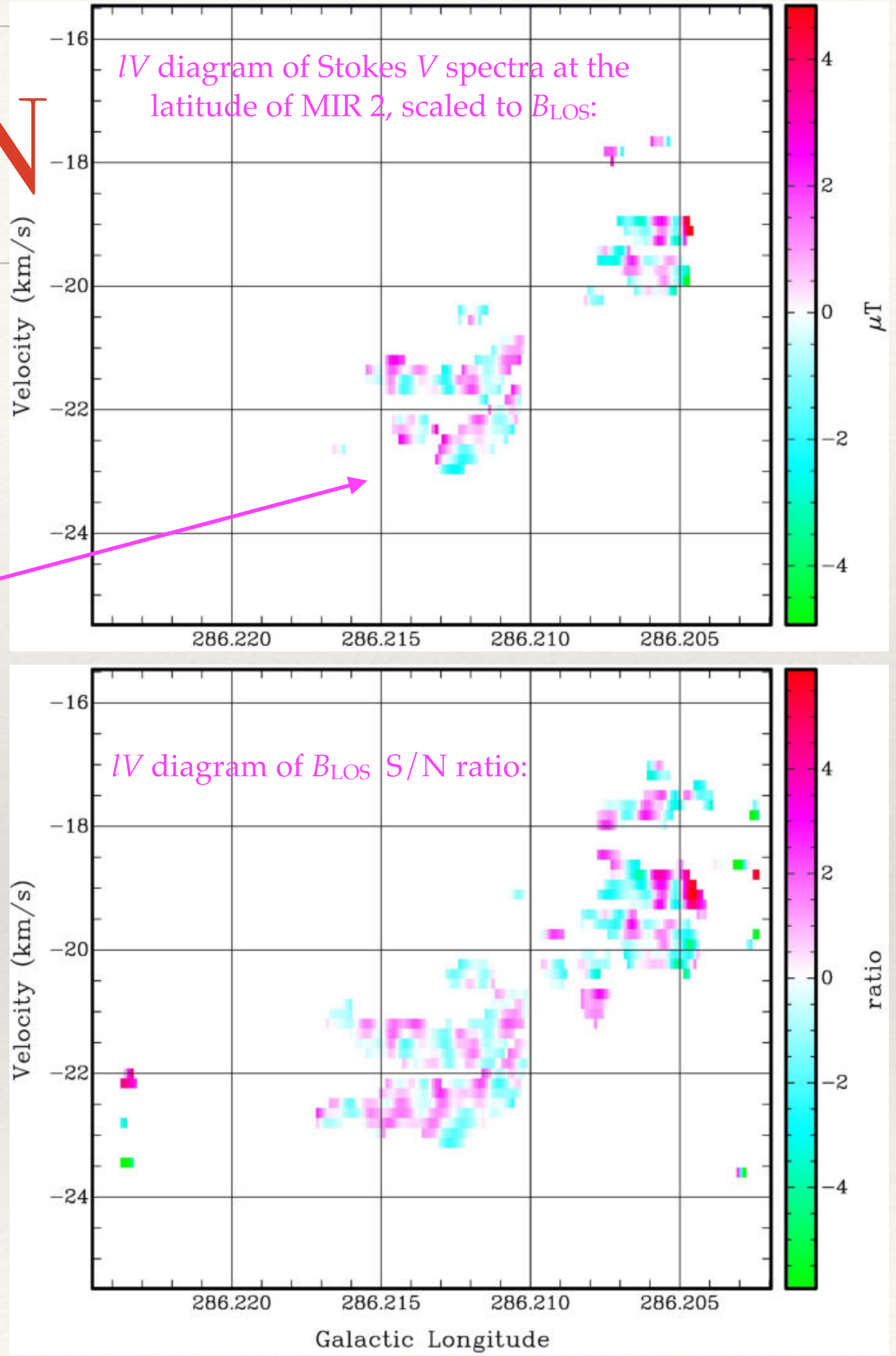
- Map ratio $\mathfrak{M}/\mathfrak{K}$ in outflow: >> 1 near MIR 2
- B field may drive the outflow. Via sudden magnetic reconnection in bipolar loops, anchored in the protostellar disk? See Jiang+2021 CME simulations

# Magneto-centrifugal driving?



# Zeeman effect in CN

- Only way to measure actual $B_{LOS}$ field strength ($\propto$ Stokes $V$), instead of statistically inferring it
- Nope: $V$ spectrum has noise… NBG!
- $I$ spectrum has $\sigma_{rms} = 50$mK, S/N>100/ch: very high quality!
- => $B$ purely in plane of sky? Possible, since outflow ~mostly edge-on
- Oh, well: maybe other ALMA maps will have a $V$ signal…



# Summary

- The new CN-bright cloud list shows a lot of promise for expanding discovery space
- SOFIA+ALMA make a powerful combination to explore *B* fields in star formation
- In BYF 73, the very massive+young protostar MIR 2
  1. Is actually WAY (4–6x) more massive 👹 (950–1350 $M_\odot$) and older (30–40 kyr)
  2. Has a dense-gas environment at the high end of the *n*-*B* criticality scale, $N_{cr} = 6.6\pm1 \times 10^{26} m^{-2} = 1250\ M_\odot\ pc^{-2}$, $n_{cr} = 2\times10^{11} m^{-3}$, $B_\perp = 42\pm7$ nT
  3. Drives a powerful bipolar outflow which is starting to disrupt the massive cloud, fed by a fast infall that could supply much of the cloud's luminosity
  4. The outflow displays a strong Goldreich-Kylafis effect and may be driven by magnetocentrifugal forces
  5. BYF 73 has no detectable Zeeman effect possibly due to the outflow's side-on geometry
- Images+movies at gemelli.spacescience.org/~pbarnes/research/champ/papers/ and arXiv:2301.03618; published in 2023 *ApJ* **945** 34