HAWC+ for SOFIA:
Two Years of Flying, and First Science Results

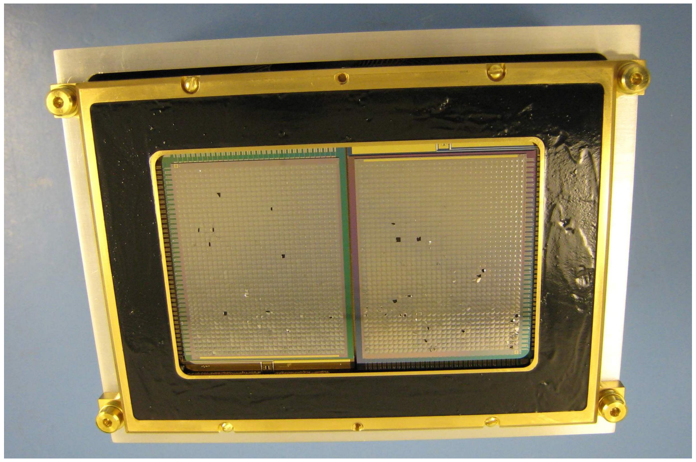
C. Darren Dowell,
HAWC+ instrument and science teams

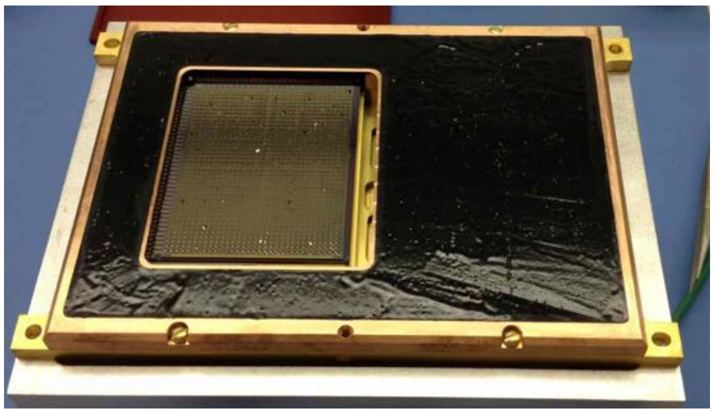
September 12, 2018

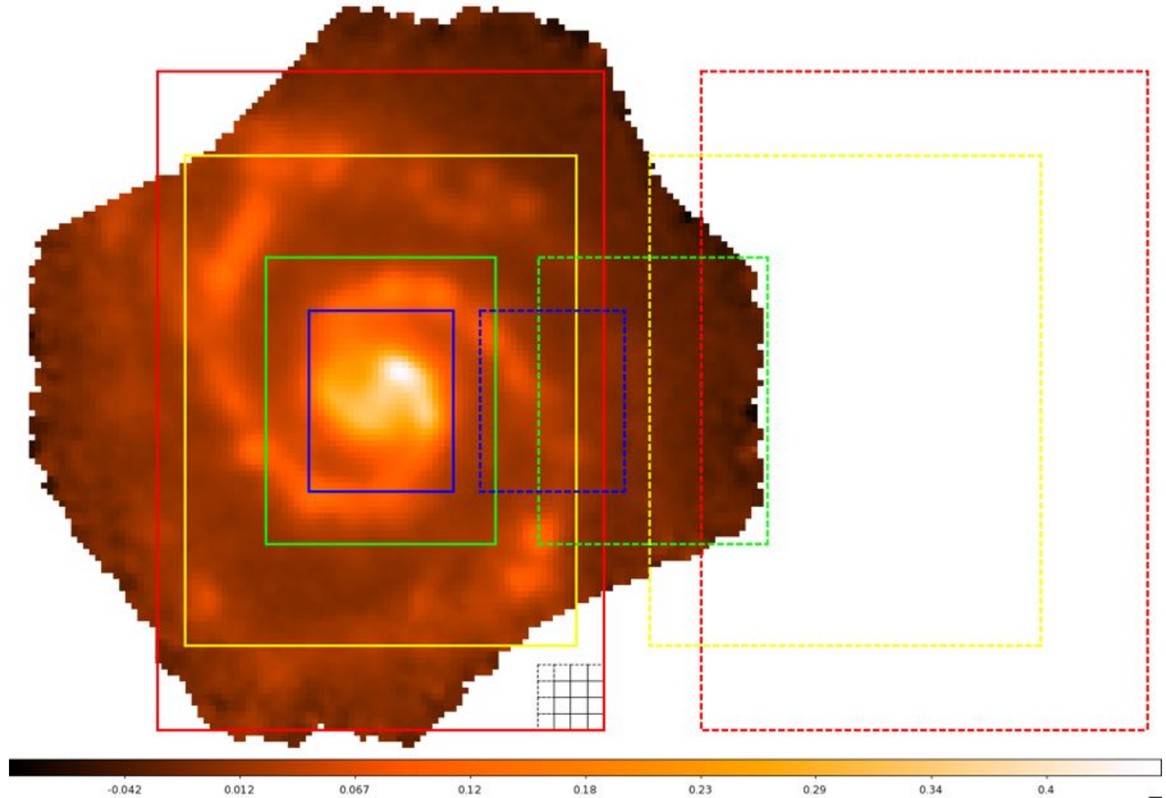
outline

- HAWC+ intro. & update
- GTO programs
- OMC1: magnetic field modeling
- grain alignment
- Galactic Center CNR
- other galaxies

HAWC+ facility far-IR camera/polarimeter for SOFIA

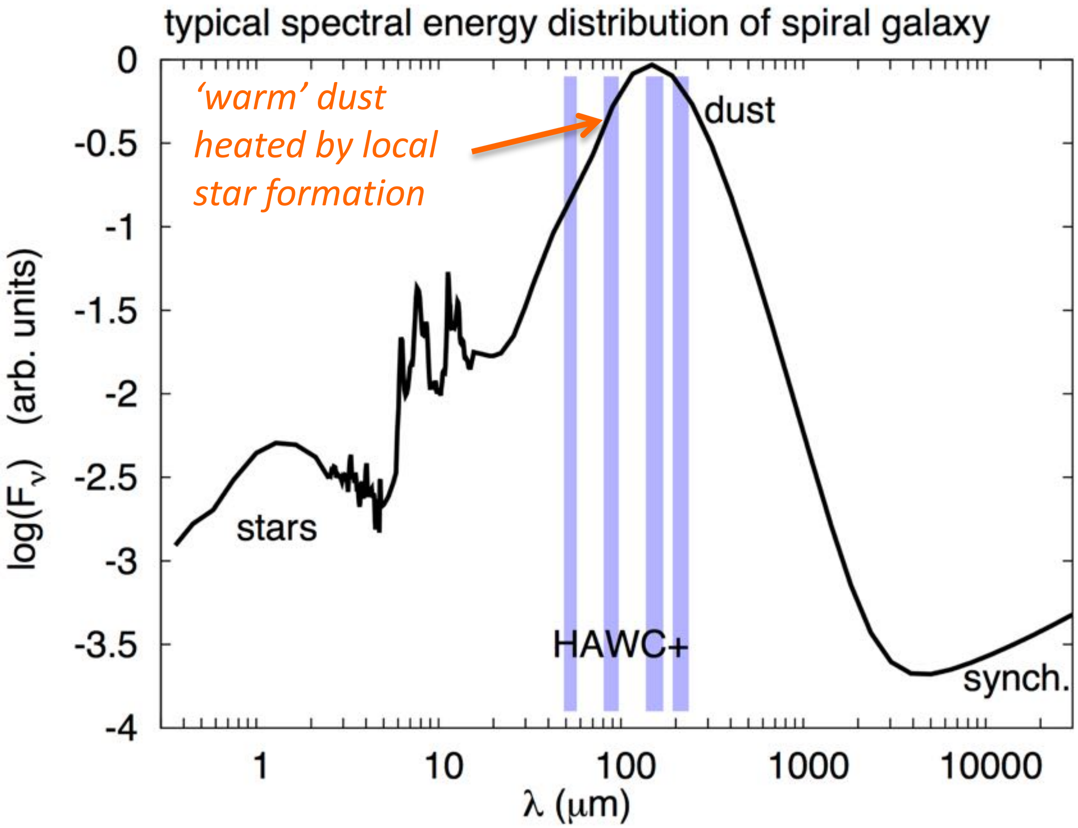




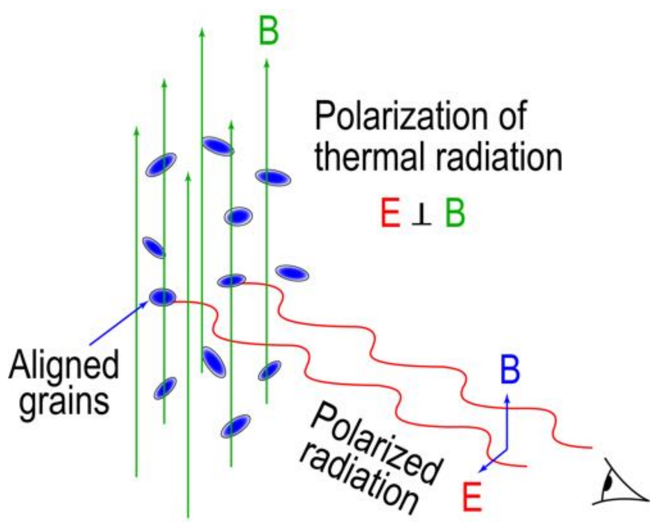


four wavelength bands: 53, 89, 154, 214 μm

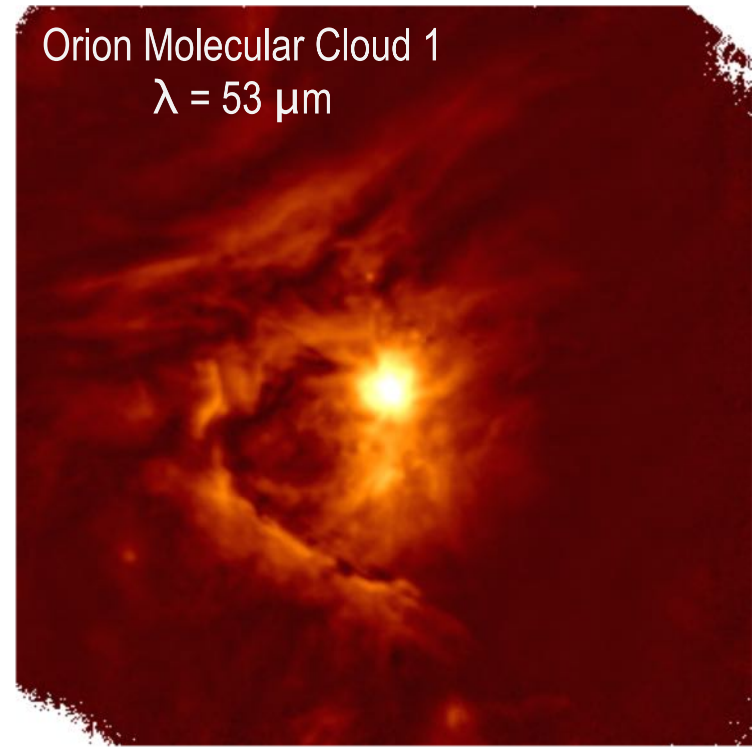
imaging and differential polarimetry with 3@ 32×40 bolometer detector arrays

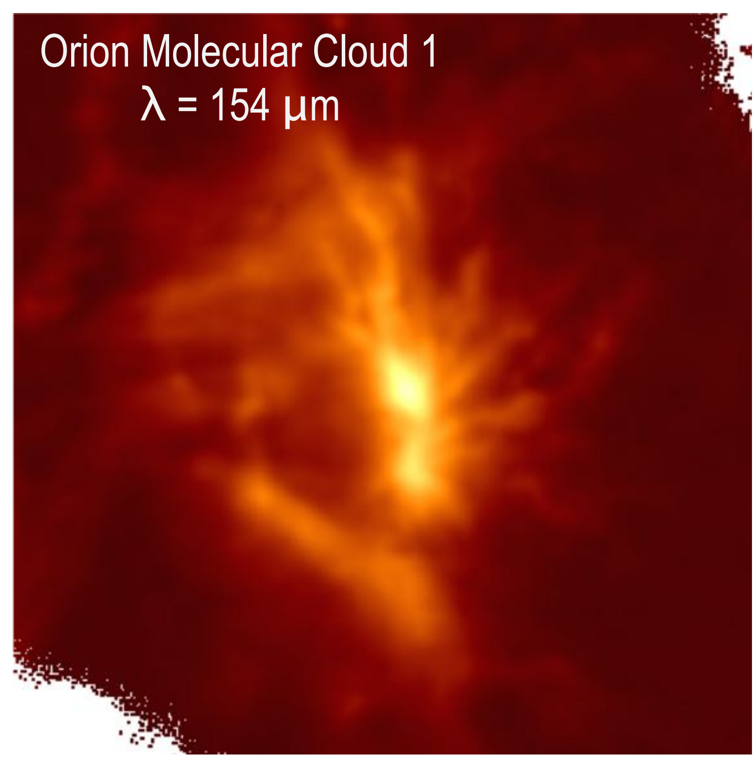


HAWC+ filter bands cover the spectral peak of dust emission.



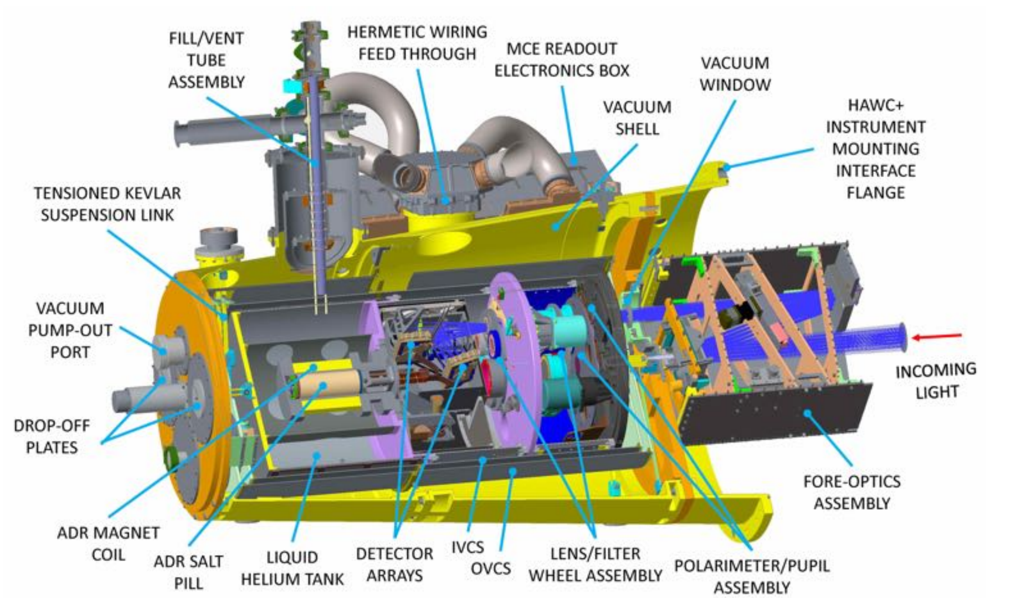
HAWC+ measures the polarization from dust aligned with respect to the magnetic field.

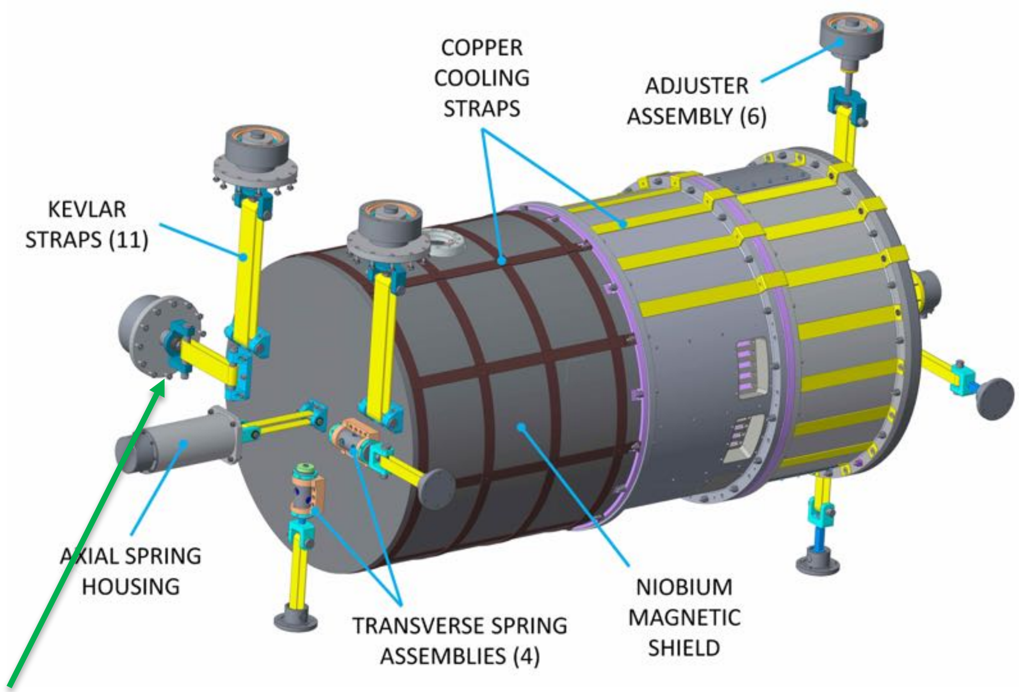




HAWC+ updates

- (Jan. 2017: last HAWC+ tele-talk)
- June – August 2017: further work on instrument internals, improving ADR run time and restoring 4 columns & 2 rows in detector readout
- October – November 2017: 15 full-length flights, ADR lasting through all; lots of data
- April 2018: HAWC+ instrument team completes work on instrument and pipeline; USRA/NASA takes over all responsibility
- July 2018: 8 very successful flights out of New Zealand



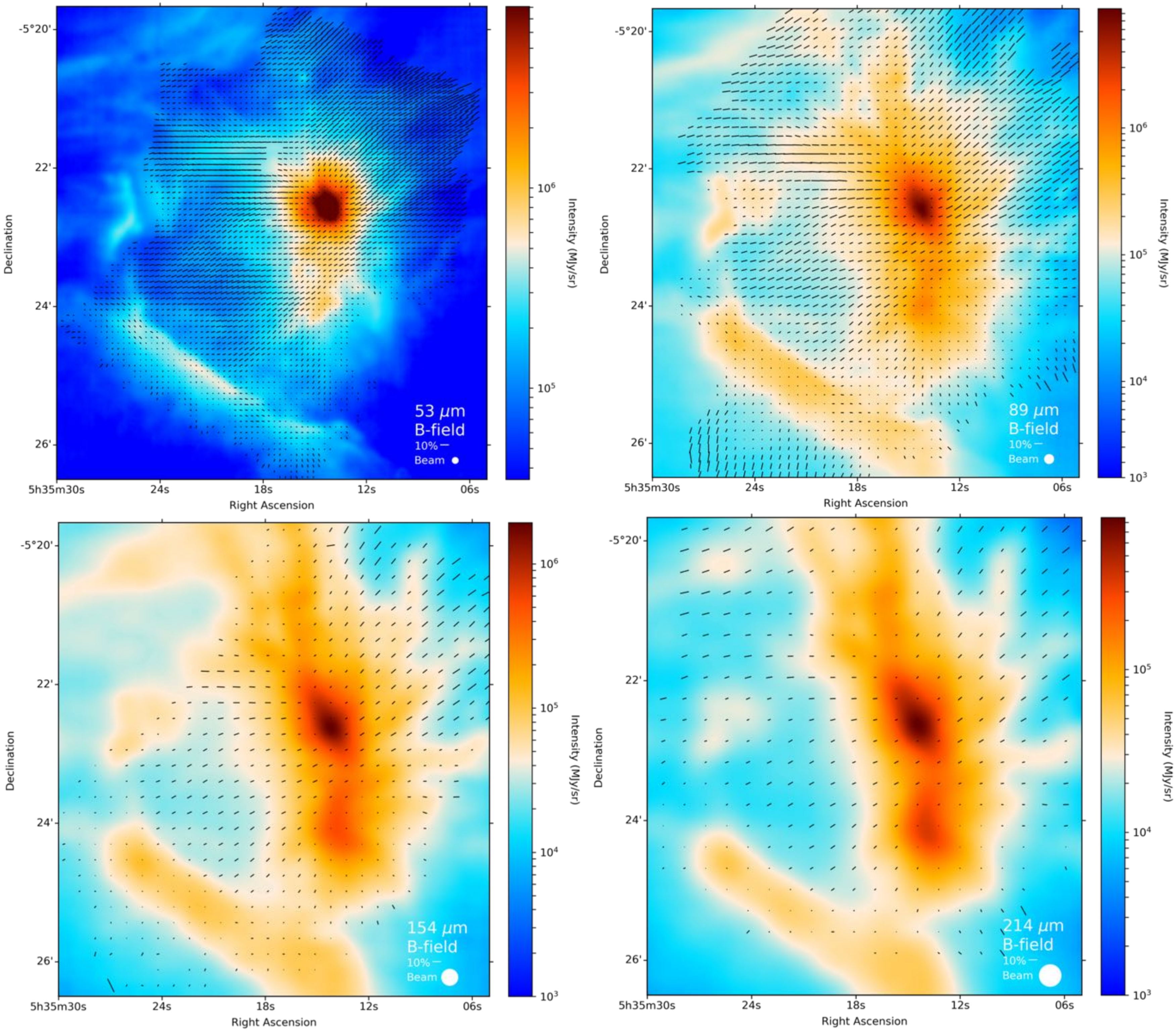


added a disc spring (Belleville washer) stack to each of 6 "hard" straps in summer 2017, for improved vibration isolation

figures from HAWC+ instrument paper (Harper, Runyan, Dowell, Wirth, et al., *Journal of Astronomical Instrumentation*, in press)

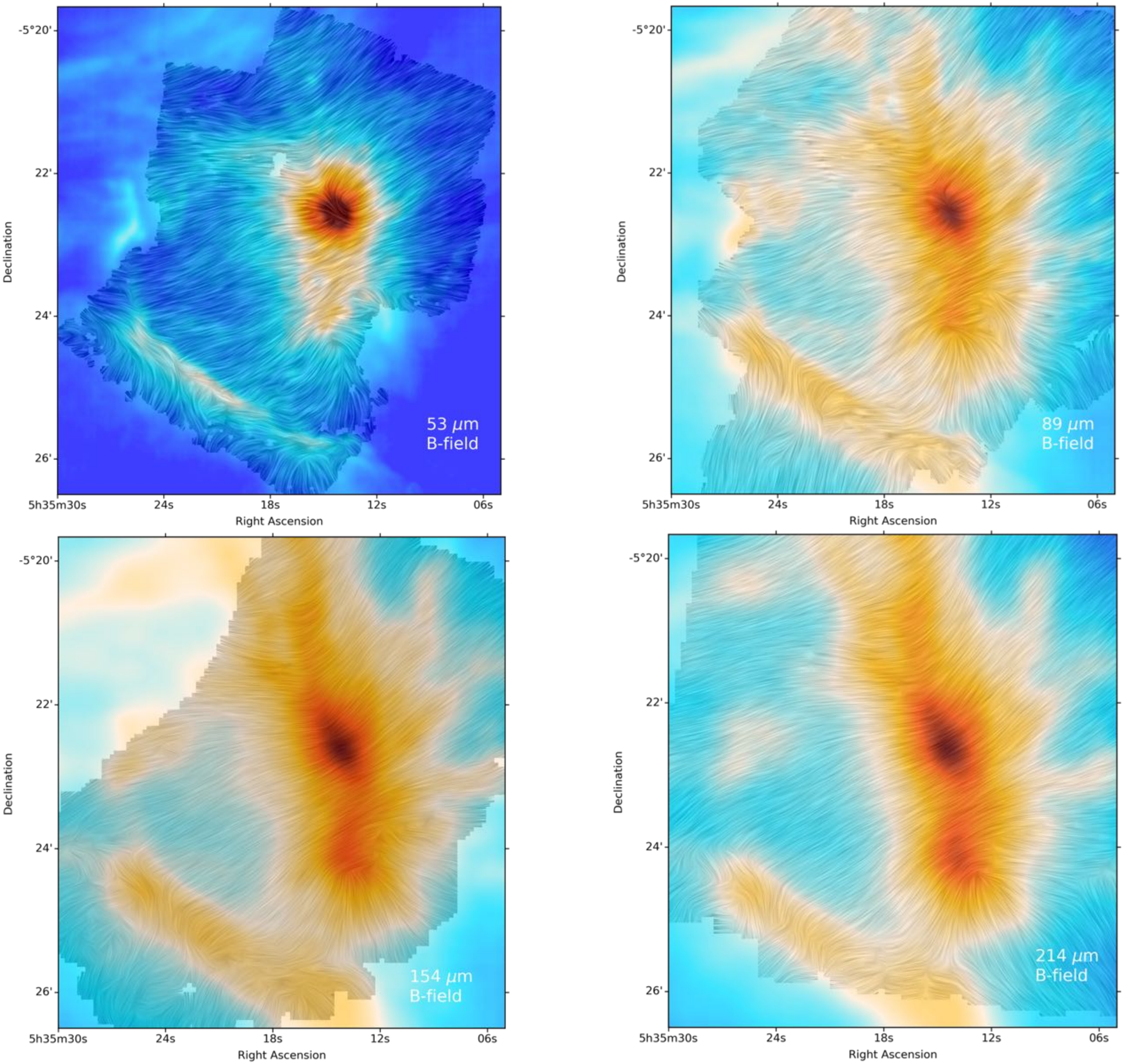
HAWC+ Guaranteed-Time Targets

- *Magnetic field structure and strength in nearby molecular clouds*: W3OH, Orion (OMC1), Vela C, Rho Oph A, M17, NGC 7023, isolated protostars
- *Dust grain alignment*: same targets observed in multiple wavelength bands
- *Magnetic field structure of the Galactic center*: Circum-Nuclear Ring, Sickle, wide field 89 μm survey
- *Degree of polarization and magnetic field structure of resolved IR galaxies*: NGC 253, NGC 891, NGC 1068, M82, M51
- *Far-IR variability on year to decade timescales*: SN1987A, NGC 6334I



Orion Molecular Cloud 1

(Chuss, Guerra, Michail, HAWC+ GTO, in prep.)

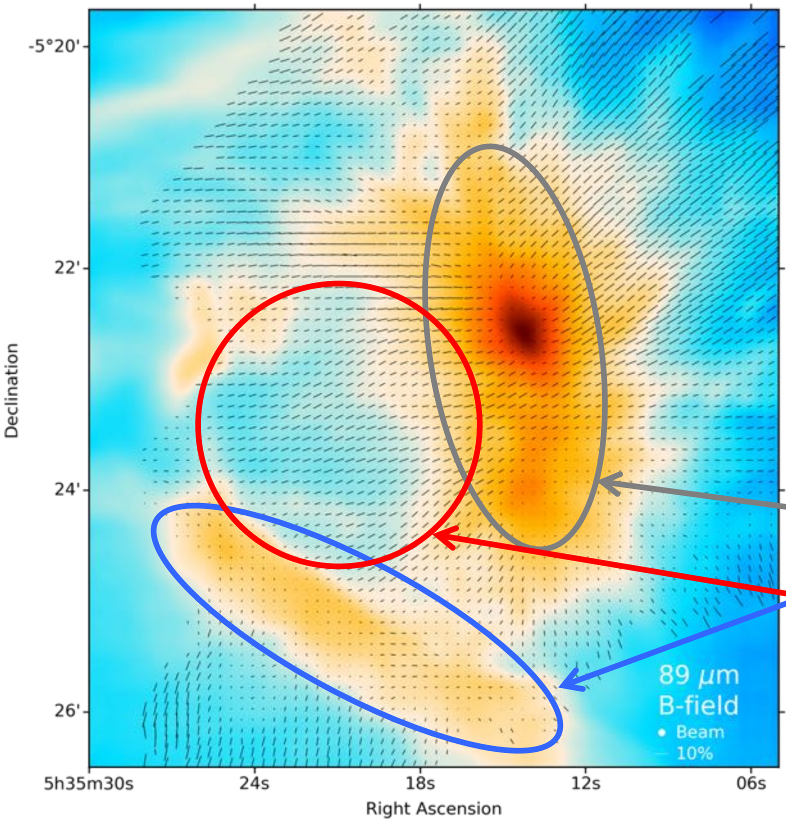


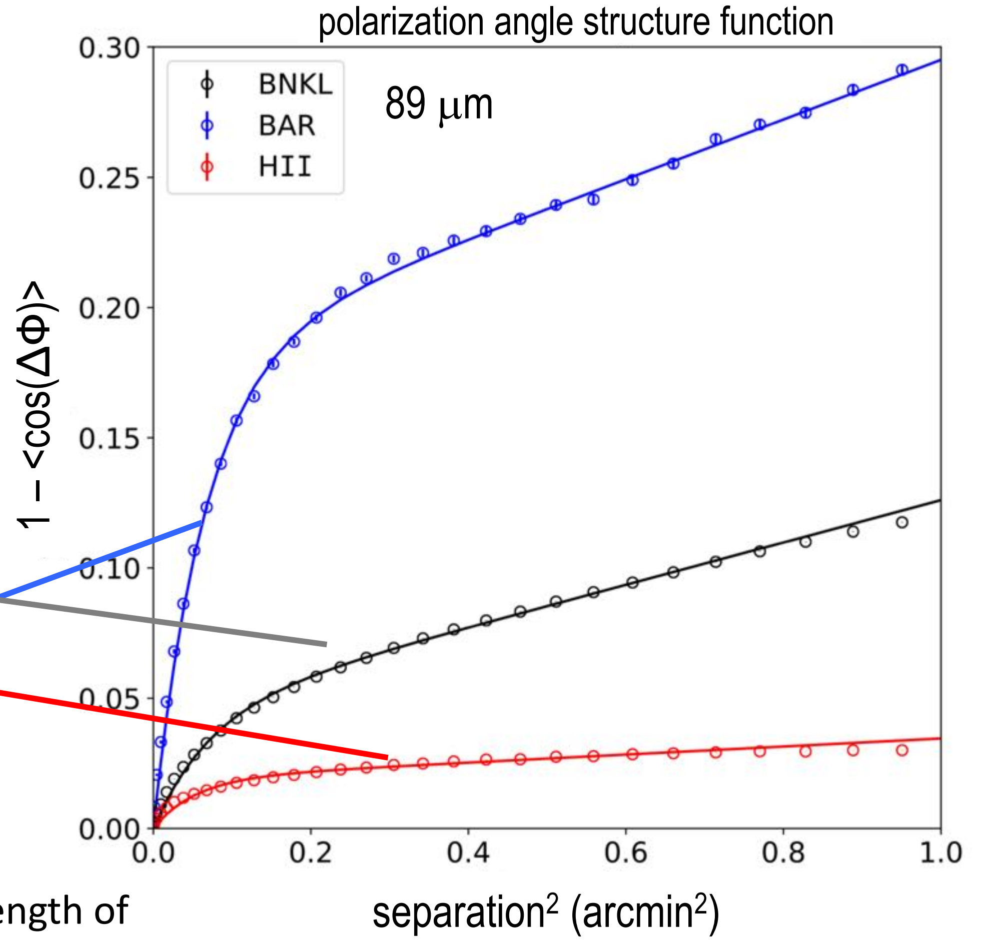
Orion Molecular Cloud 1

(Chuss, Guerra, Michail, HAWC+ GTO, in prep.)

Line Integral Convolution representation of magnetic field direction

Fine-Scale Structure in Magnetic Field





- Dispersion in magnetic field angles is related to strength of field (Davis '51; Chandrasekhar & Fermi '53):

$$\frac{B^2}{4\pi\rho\sigma^2(v)} \approx \frac{1}{(\Delta\phi)^2}$$

  – Need to consider line-of-sight and beam averaging.
- Structure functions are a natural way to separate dispersion from turbulence from slowly-varying ordered field, and to learn about spectrum of turbulence (Hildebrand+ '09; Houde+ '16)

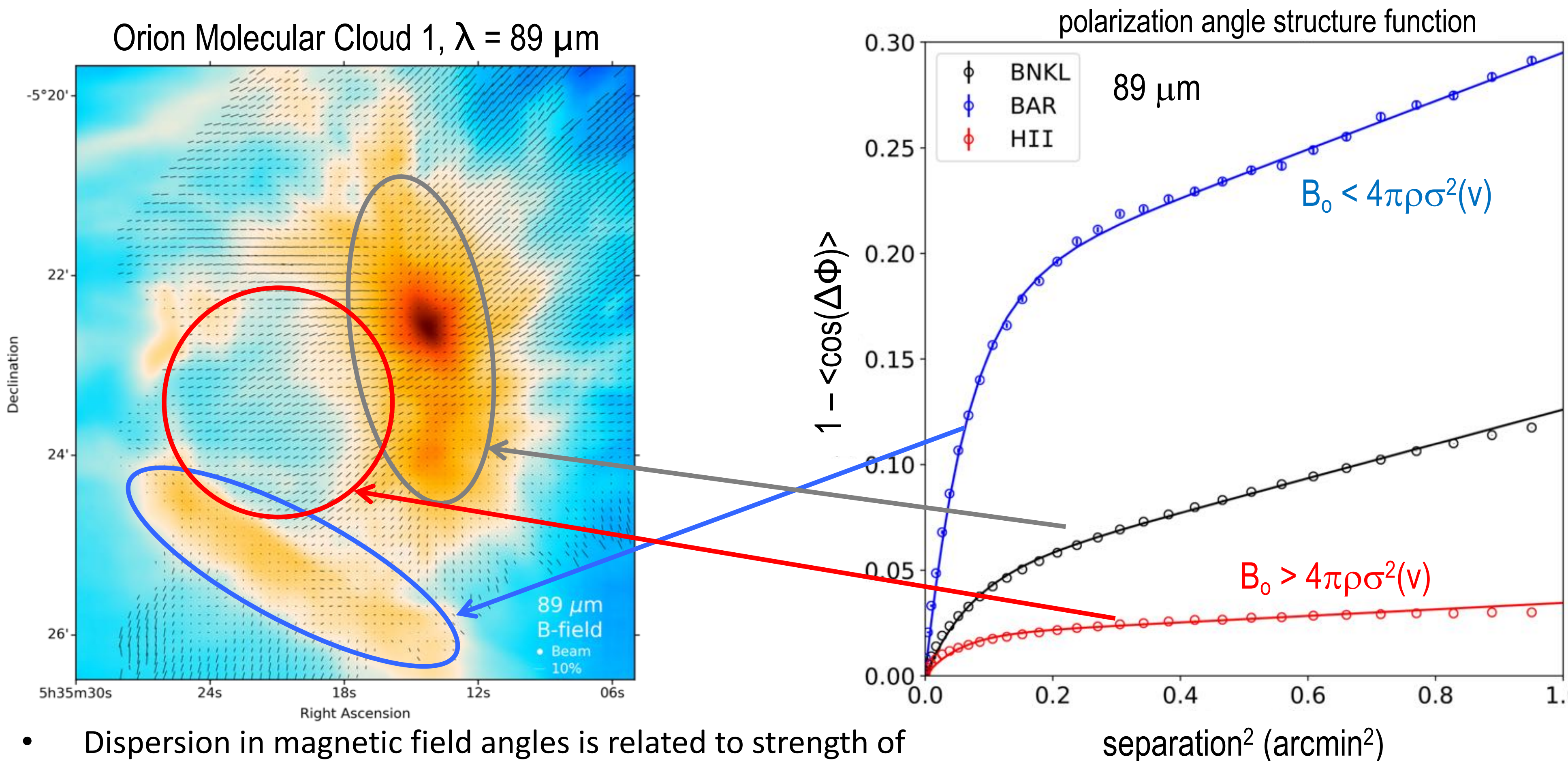
(Chuss, Guerra, Michail, HAWC+ GTO, in prep.)

* *input parameters*: ρ, σ(v), depth of cloud

* *fit parameters*: turbulence correlation length, B_{turb}/B_o, 1 amplitude term for structure in ordered field

* *output*: B_o, # turbulent cells in beam

Fine-Scale Structure in Magnetic Field



- Dispersion in magnetic field angles is related to strength of field (Davis '51; Chandrasekhar & Fermi '53):

$$\frac{B^2}{4\pi\rho\sigma^2(v)} \approx \frac{1}{(\Delta\phi)^2}$$

  - Need to consider line-of-sight and beam averaging.
- Structure functions are a natural way to separate dispersion from turbulence from slowly-varying ordered field, and to learn about spectrum of turbulence (Hildebrand+ '09; Houde+ '16)

(Chuss, Guerra, Michail, HAWC+ GTO, in prep.)

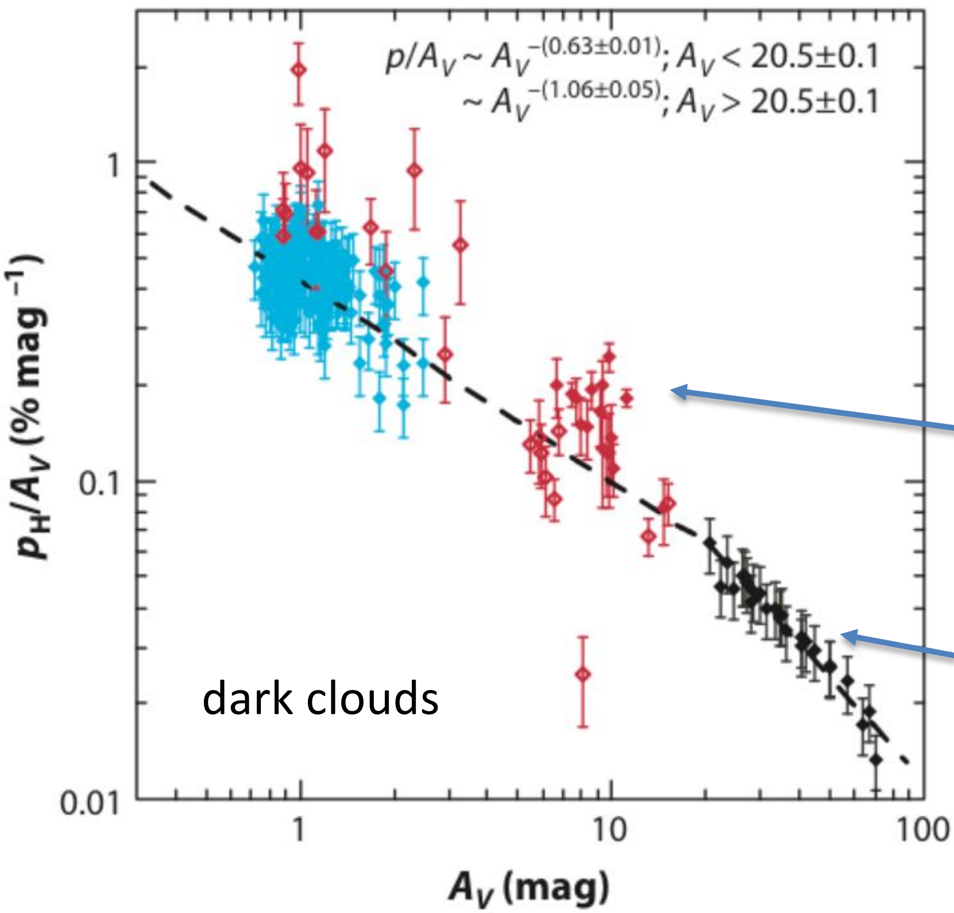
* *input parameters*: ρ, σ(v), depth of cloud

* *fit parameters*: turbulence correlation length, B_{turb}/B_o, 1 amplitude term for structure in ordered field

* *output*: B_o, # turbulent cells in beam

dust grain alignment efficiency

- Our analysis for OMC-1 depends on dust polarization being a reliable tracer of the magnetic field direction.
- In *dark clouds*, at least, the alignment appears to become poor at high extinction.
  - diagnostic: trend in polarization efficiency with column density



- Uniform cloud would produce horizontal line (constant polarizing efficiency of grains).

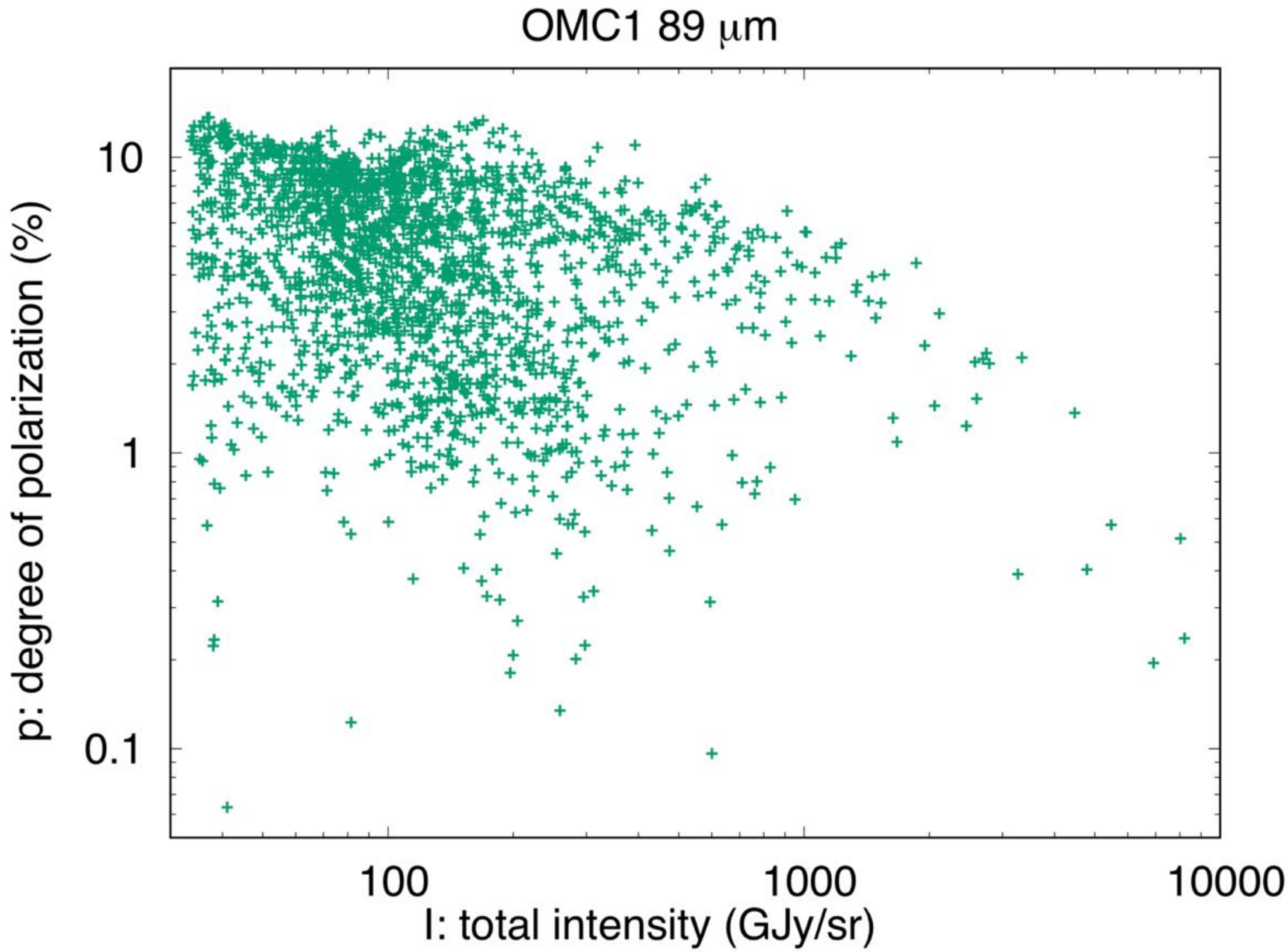
decreasing polarizing efficiency (magnetic field structure? partial loss of grain alignment?)

slope of -1: complete loss of grain alignment (?)

Observations are difficult and few in number.

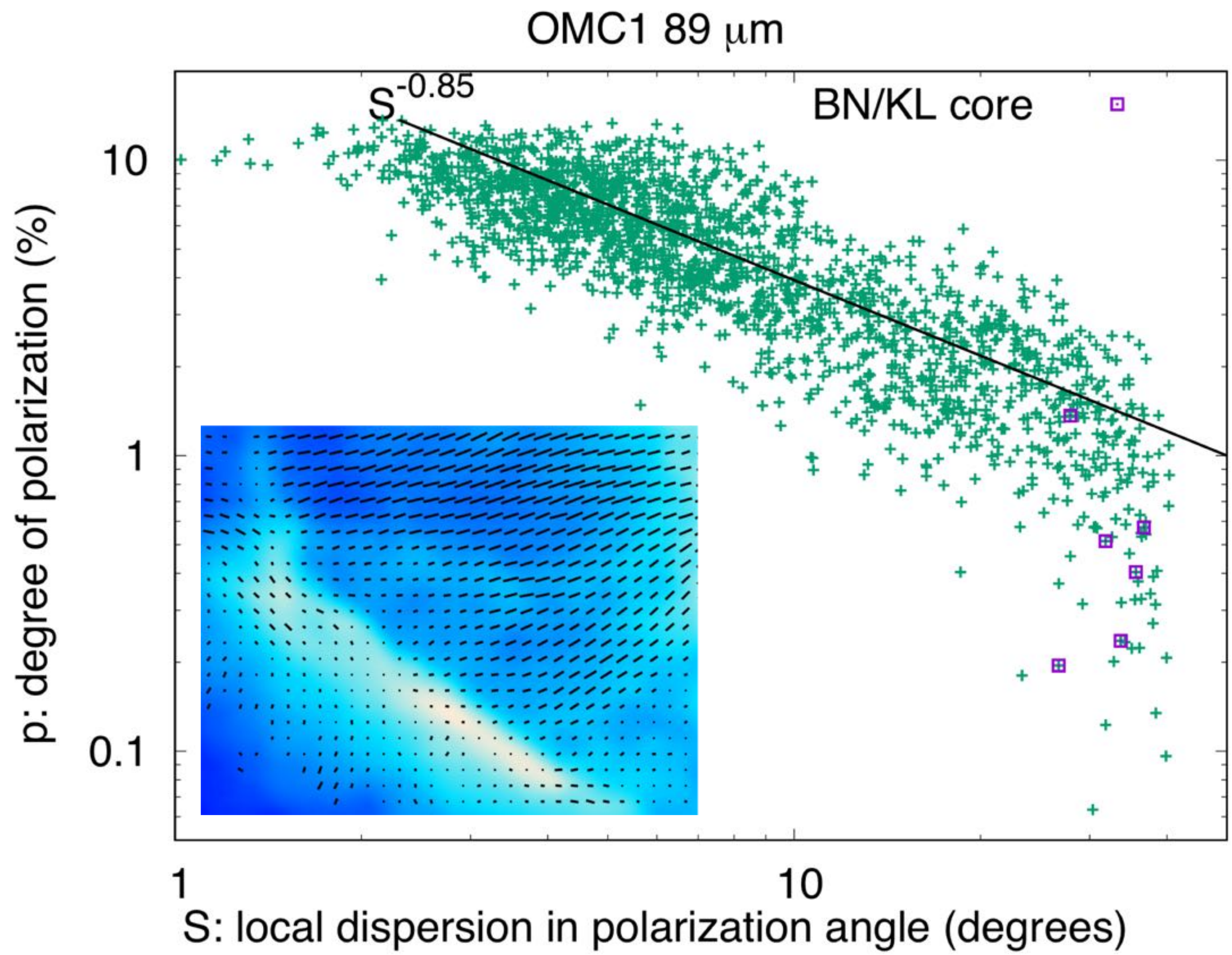
Andersson, Lazarian, & Vaillancourt (2015)

OMC-1: polarization vs. total intensity



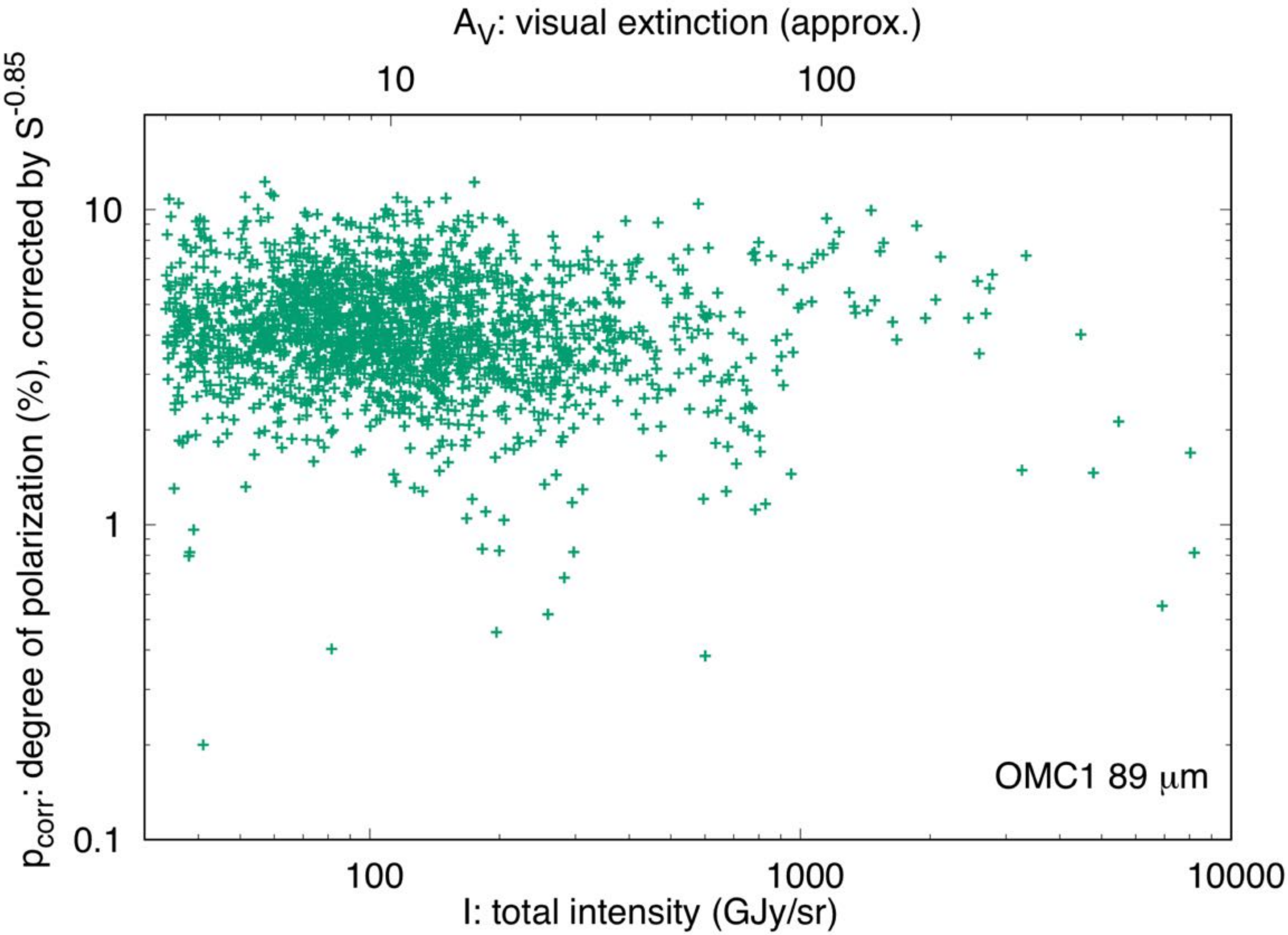
- A mess!
- The trend in both the upper envelope and median is pretty flat.

effects of magnetic field structure on p



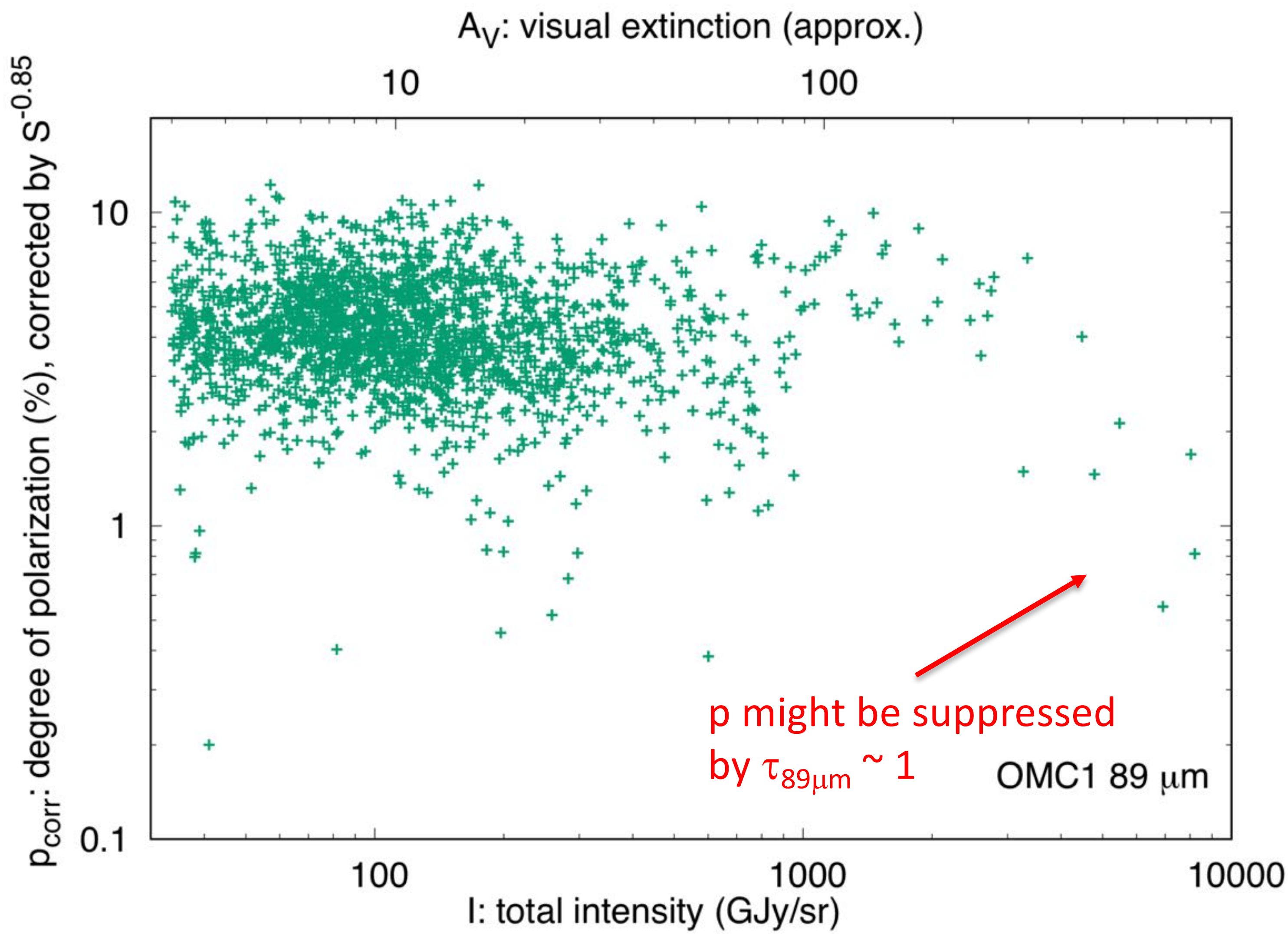
- *Best predictor of p for a line of sight is the dispersion of pol. angles in its vicinity.*
- Expectation is $\mathbf{p \sim S^{-1}}$, for a simple model of magnetic field structure (Planck Collab. '18)
- Following Fissel+ '16, fit trends with both S and I: $\mathbf{p = p_0 (S/\langle S\rangle)^{\alpha} (I/\langle I\rangle)^{\beta}}$

de-trended polarization vs. intensity



- Now that effect of magnetic field structure has been removed, we see nearly uniform grain alignment to $A_V > 200$. Presumably the many stars embedded in OMC-1 are important for this.
- Degree of polarization and polarization angles are both diagnostic of the magnetic field structure.

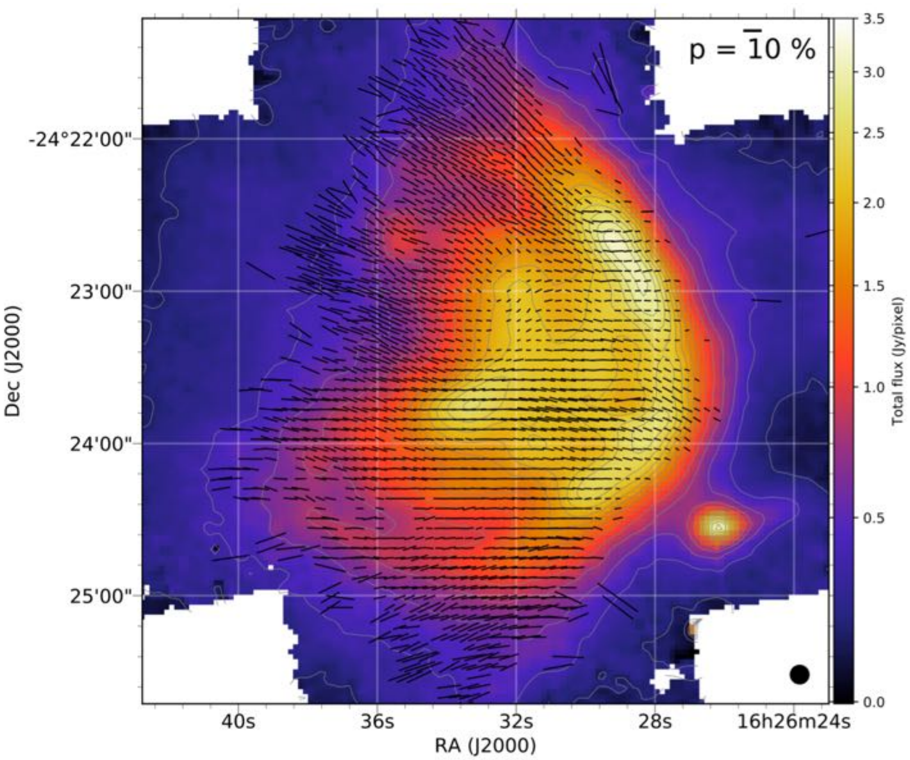
de-trended polarization vs. intensity

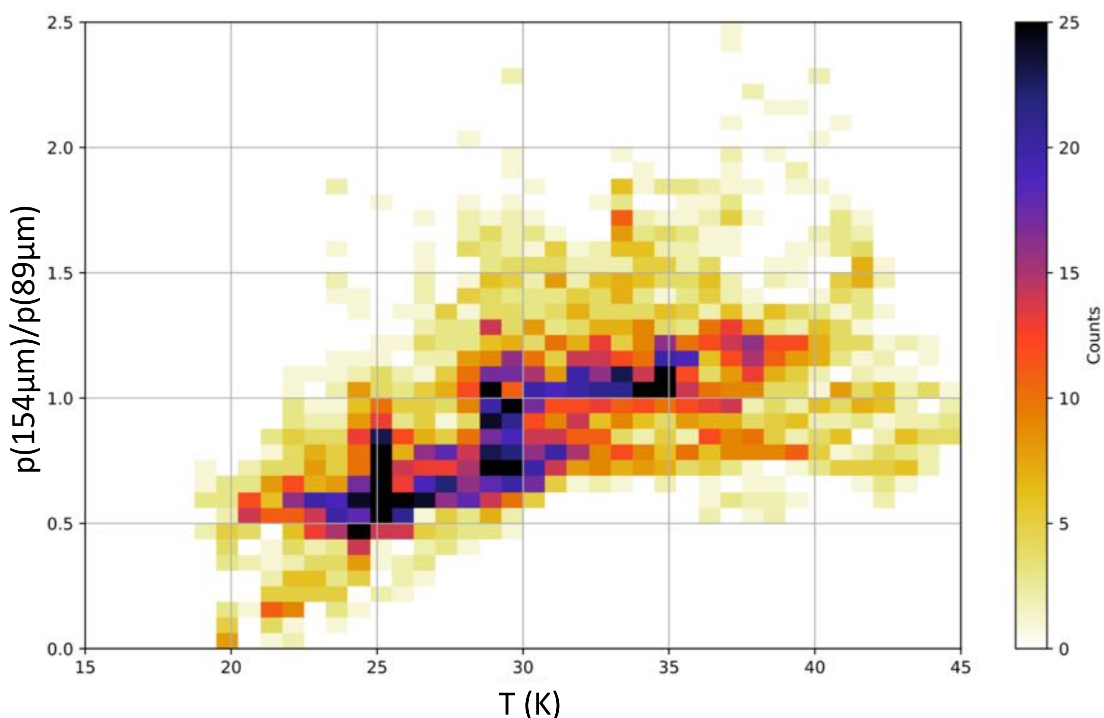


- Now that effect of magnetic field structure has been removed, we see nearly uniform grain alignment to $A_V > 200$. Presumably the many stars embedded in OMC-1 are important for this.
- Degree of polarization and polarization angles are both diagnostic of the magnetic field structure.

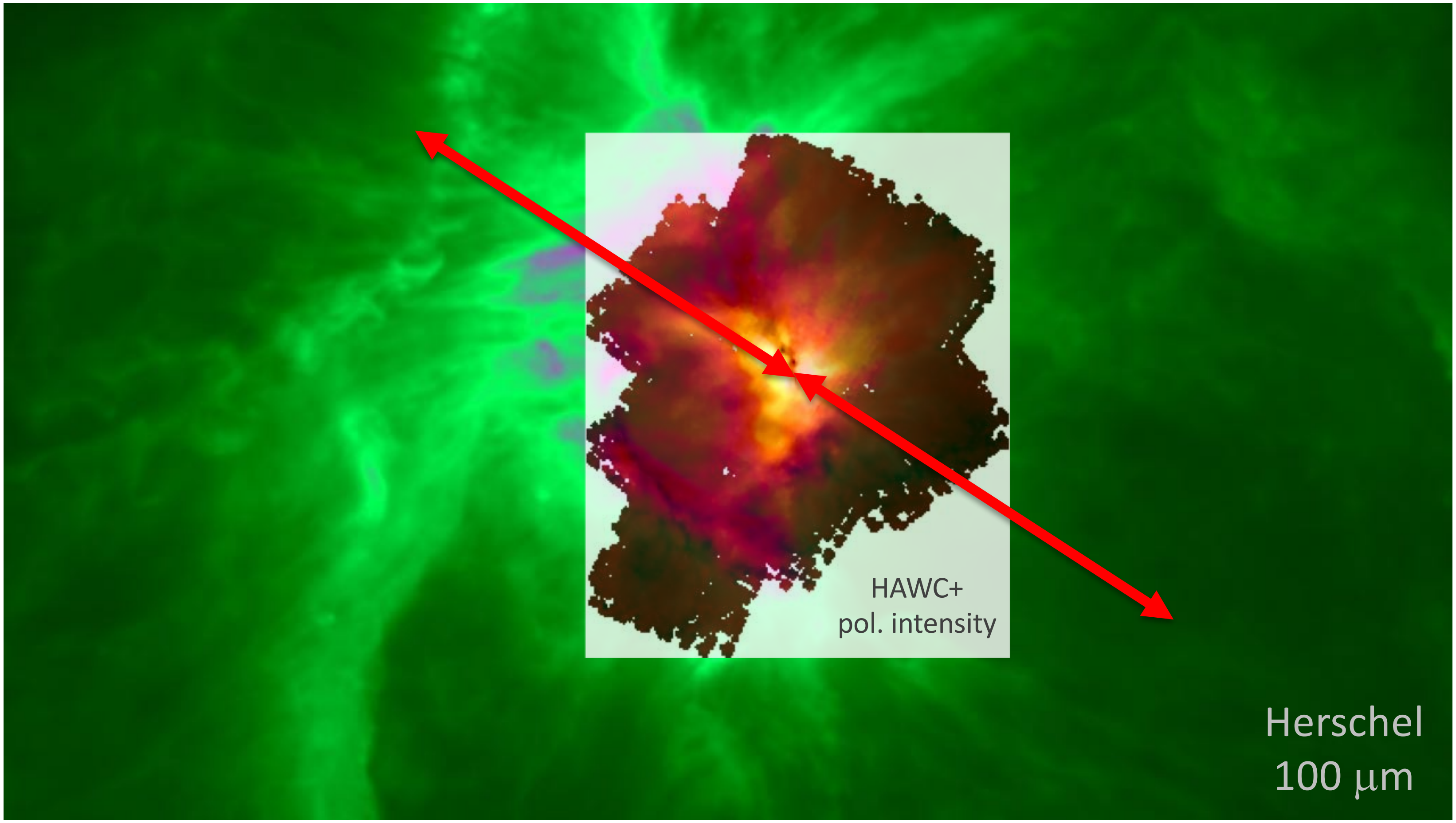
What will HAWC+ see in cold, dark clouds?

- Very little GTO time is invested in T < 20 K dark clouds.
- Insights to grain alignment in such objects more likely to come from GO programs.
- The hint from analysis of Rho Oph A (Santos, HAWC+ GTO, in prep.) is that colder grains produce less far-IR polarization:



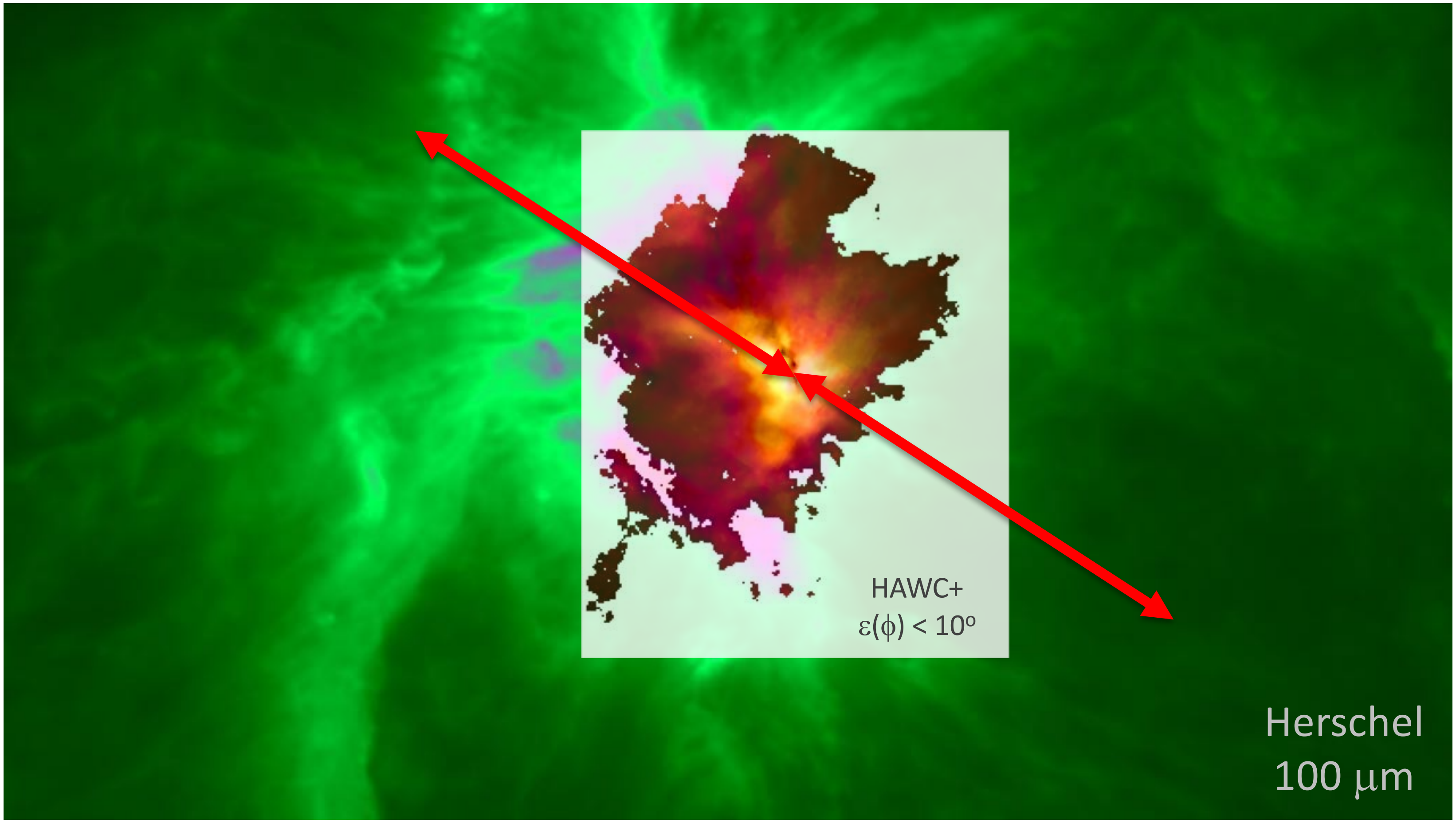


chop reference beams / need for method of large-area mapping

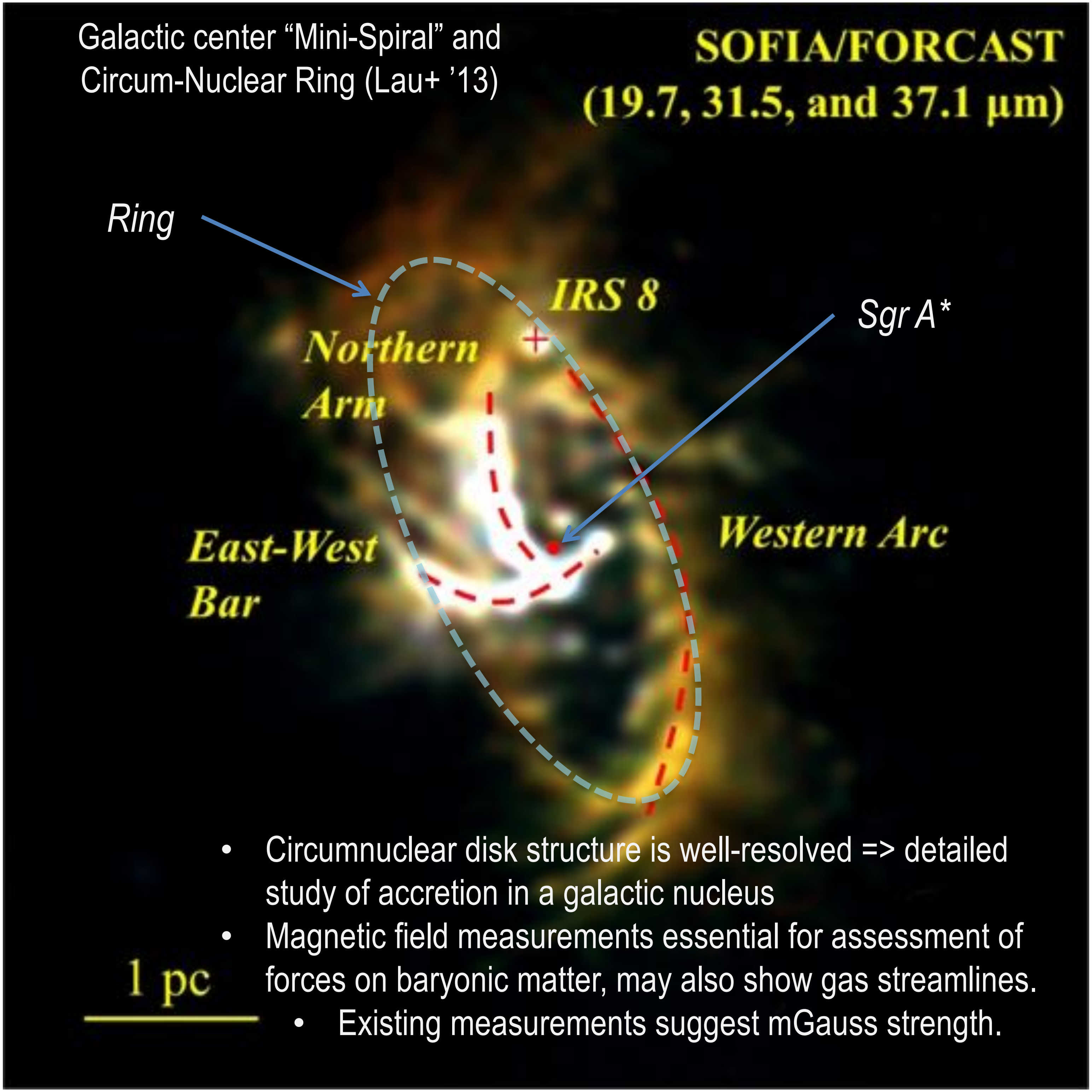


- HAWC+ measures polarization and intensity by chopping (differencing) vs. two reference positions <= 8 arcminutes away.
- Polarization at reference positions is unknown.
  - Systematic uncertainty estimated using Novak+ ‘97, Schleuning ‘98, Dotson+ ’00
- We need a method of mapping large areas with HAWC+ beyond 8 arcminutes.

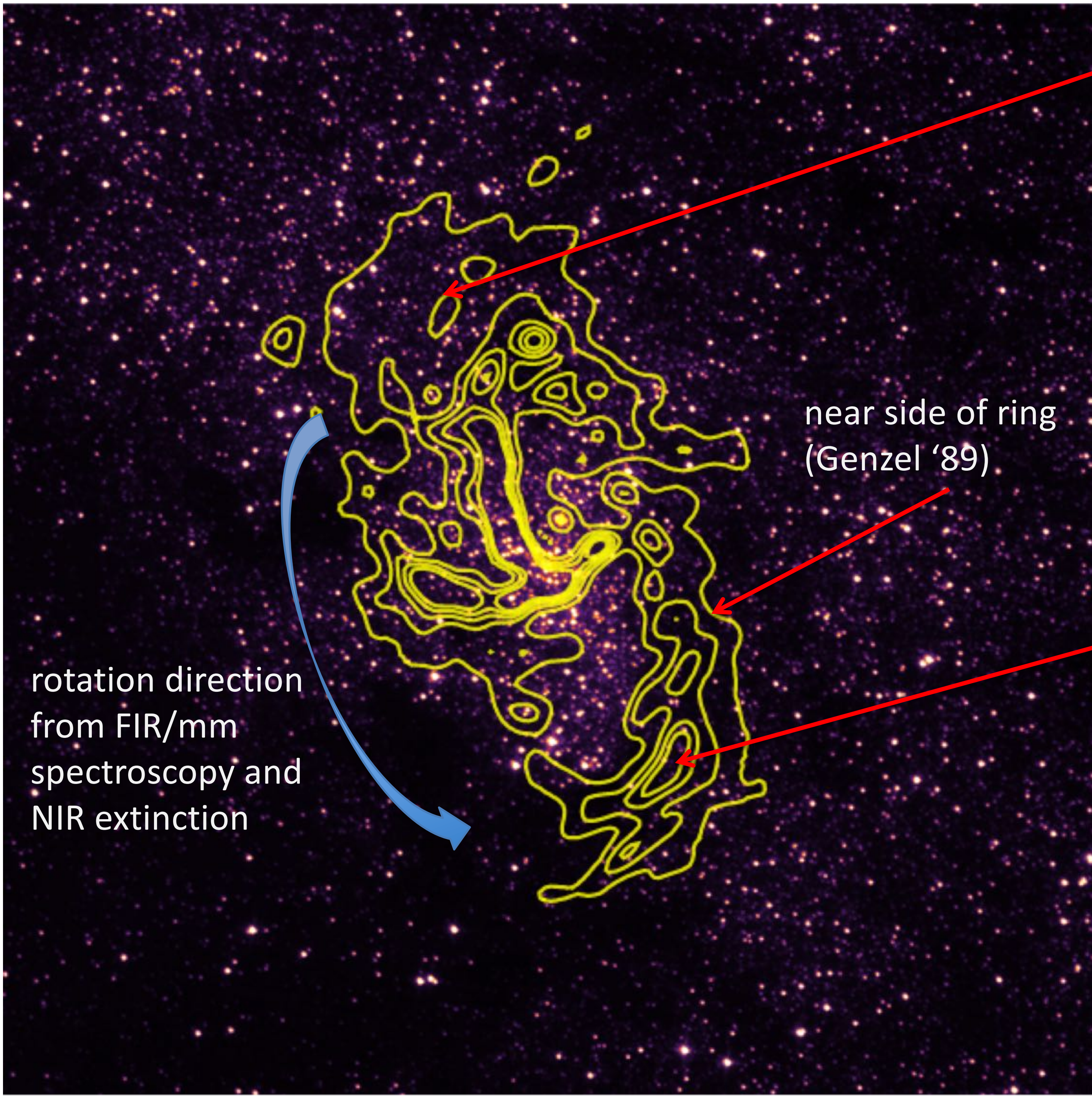
chop reference beams / need for method of large-area mapping

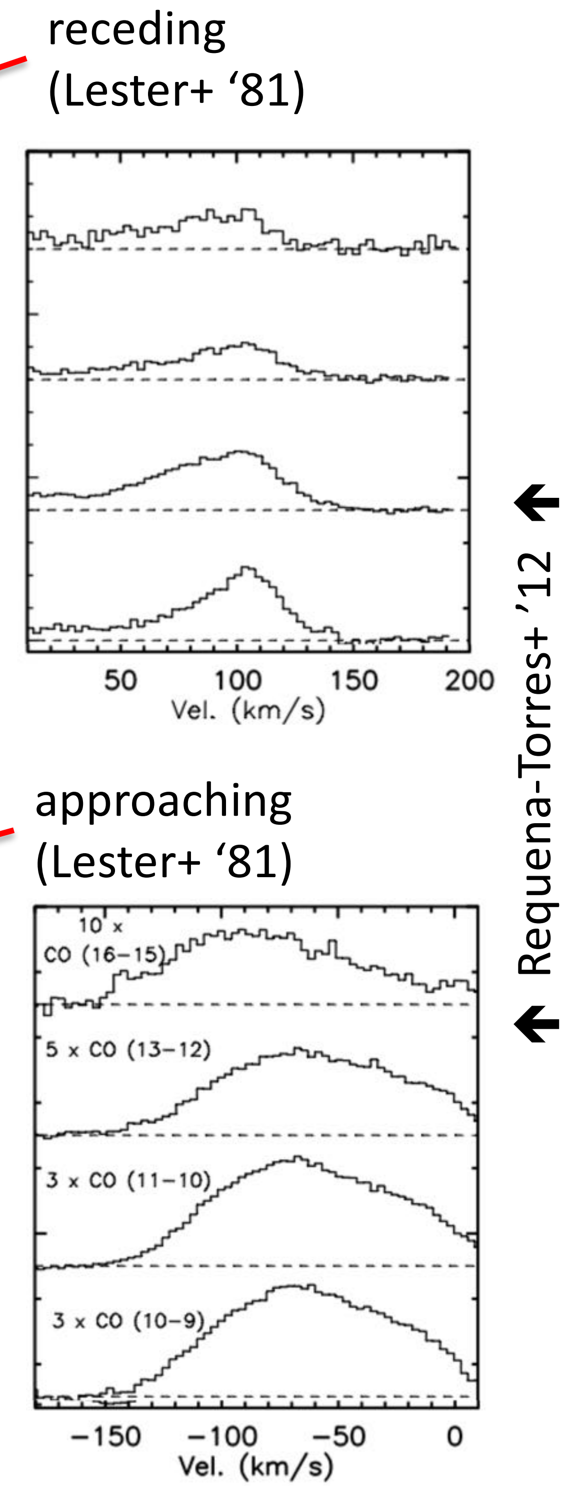


- HAWC+ measures polarization and intensity by chopping (differencing) vs. two reference positions <= 8 arcminutes away.
- Polarization at reference positions is unknown.
  - Systematic uncertainty estimated using Novak+ '97, Schleuning '98, Dotson+ '00
- We need a method of mapping large areas with HAWC+ beyond 8 arcminutes.

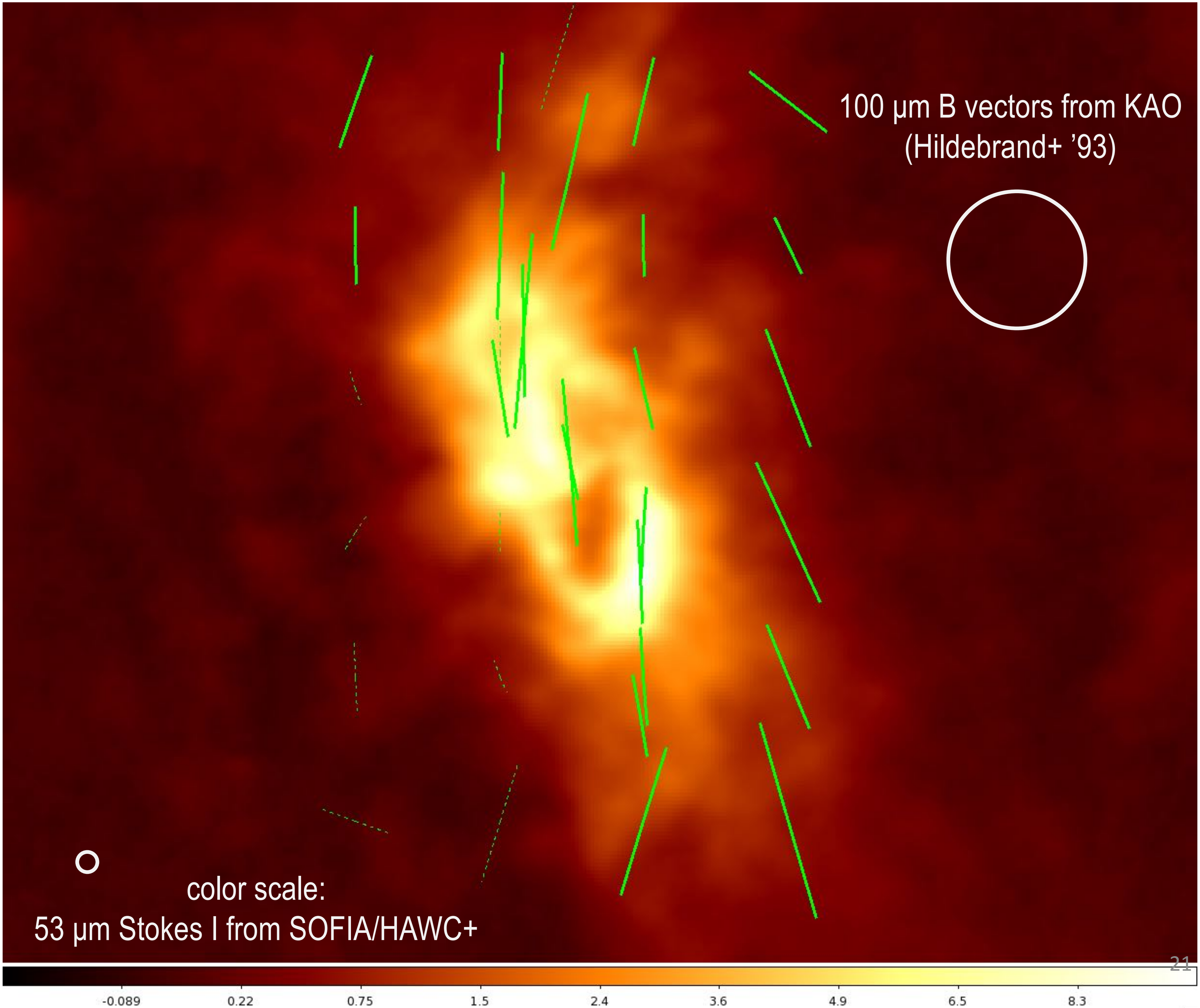


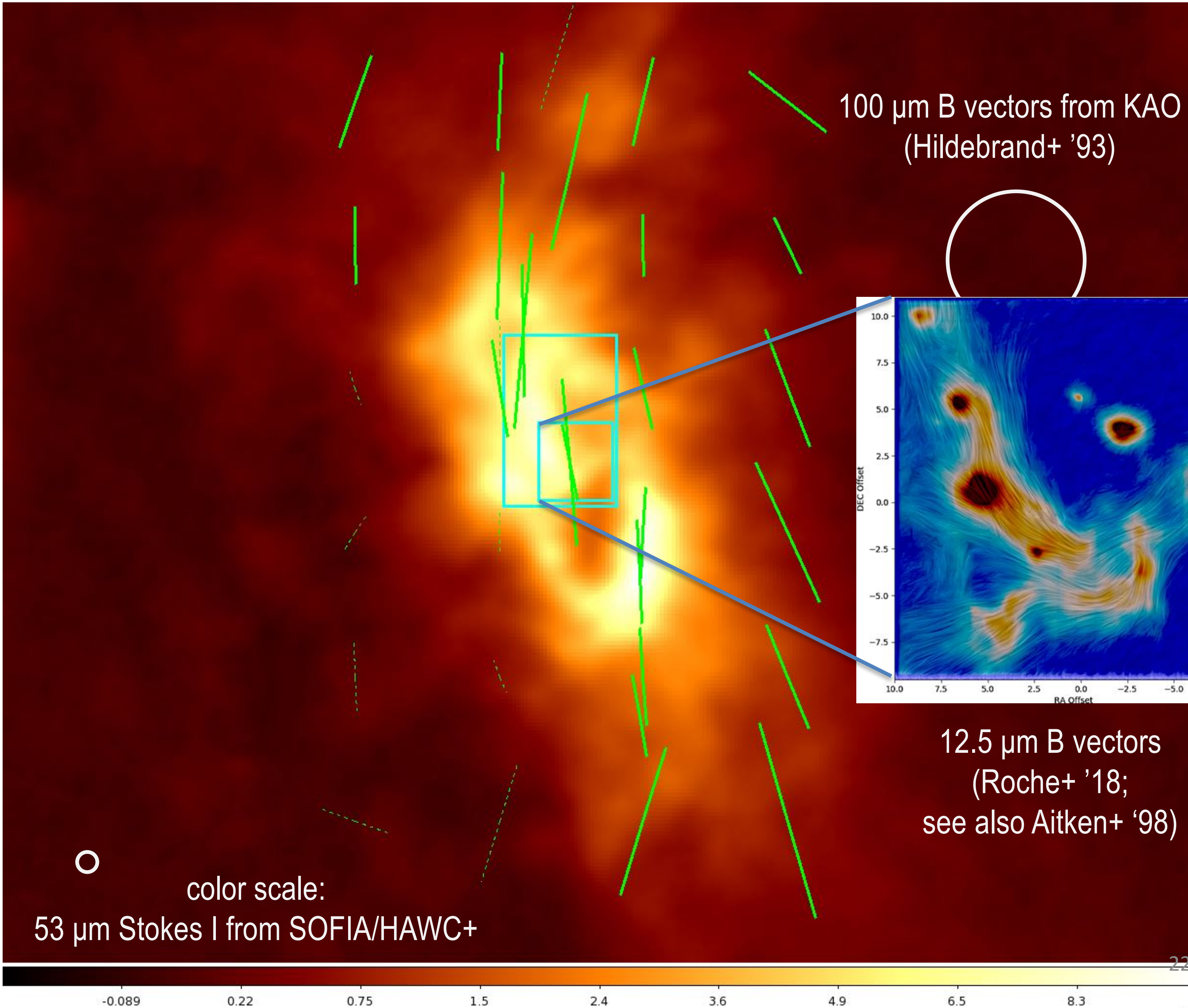
- Circumnuclear disk structure is well-resolved => detailed study of accretion in a galactic nucleus
- Magnetic field measurements essential for assessment of forces on baryonic matter, may also show gas streamlines.
  - Existing measurements suggest mGauss strength.

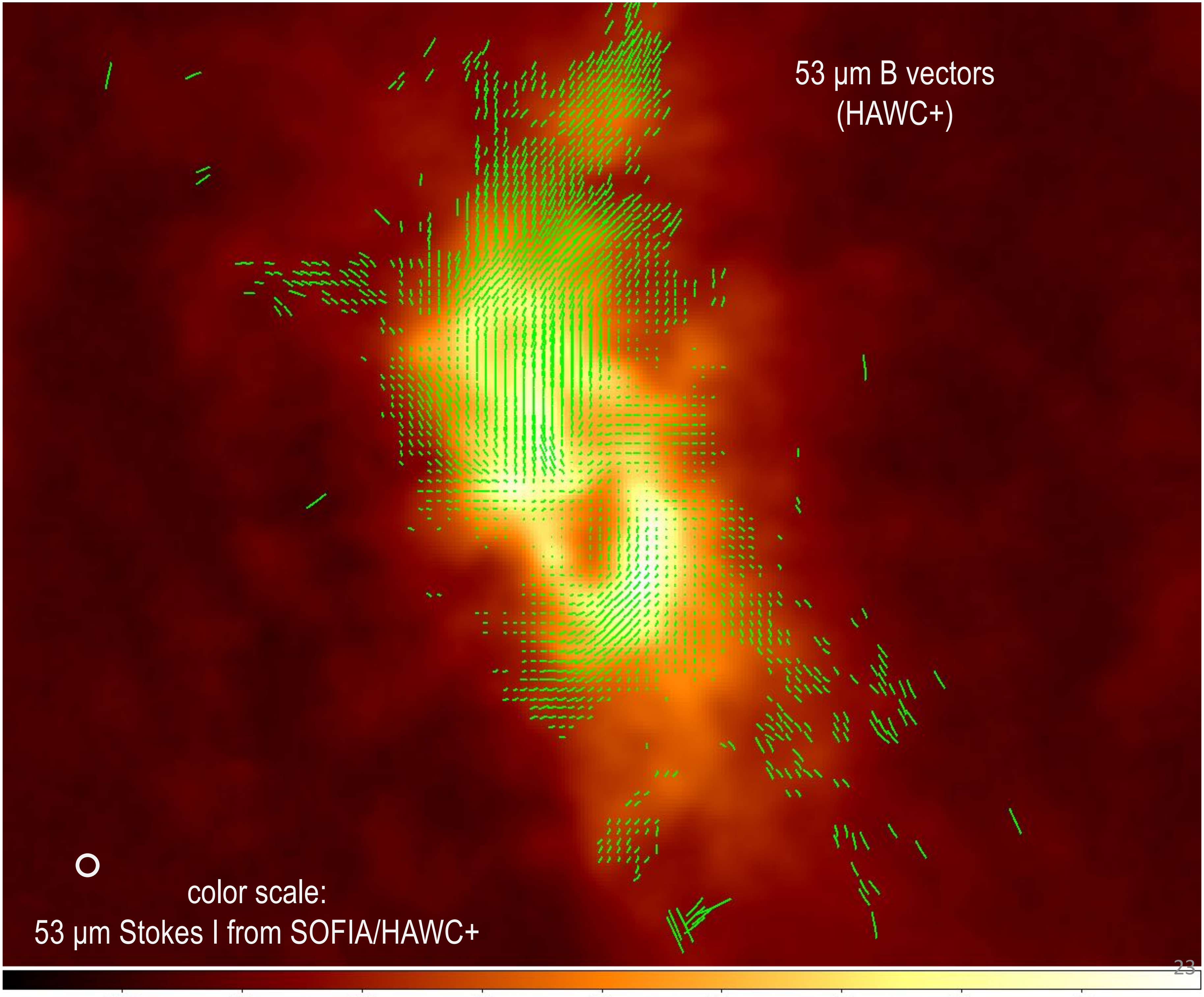




37 µm contours on 1.9 µm HST/NICMOS image


100 μm B vectors from KAO
(Hildebrand+ '93)
color scale:
53 μm Stokes I from SOFIA/HAWC+
-0.089
0.22
0.75
1.5
2.4
3.6
4.9
6.5
8.3


100 μm B vectors from KAO
(Hildebrand+ '93)
12.5 μm B vectors
(Roche+ '18;
see also Aitken+ '98)
color scale:
53 μm Stokes I from SOFIA/HAWC+
DEC Offset
RA Offset
-0.089
0.22
0.75
1.5
2.4
3.6
4.9
6.5
8.3


53 µm B vectors
(HAWC+)
color scale:
53 µm Stokes I from SOFIA/HAWC+
-0.089
0.22
0.75
1.5
2.4
3.6
4.9
6.5
8.3

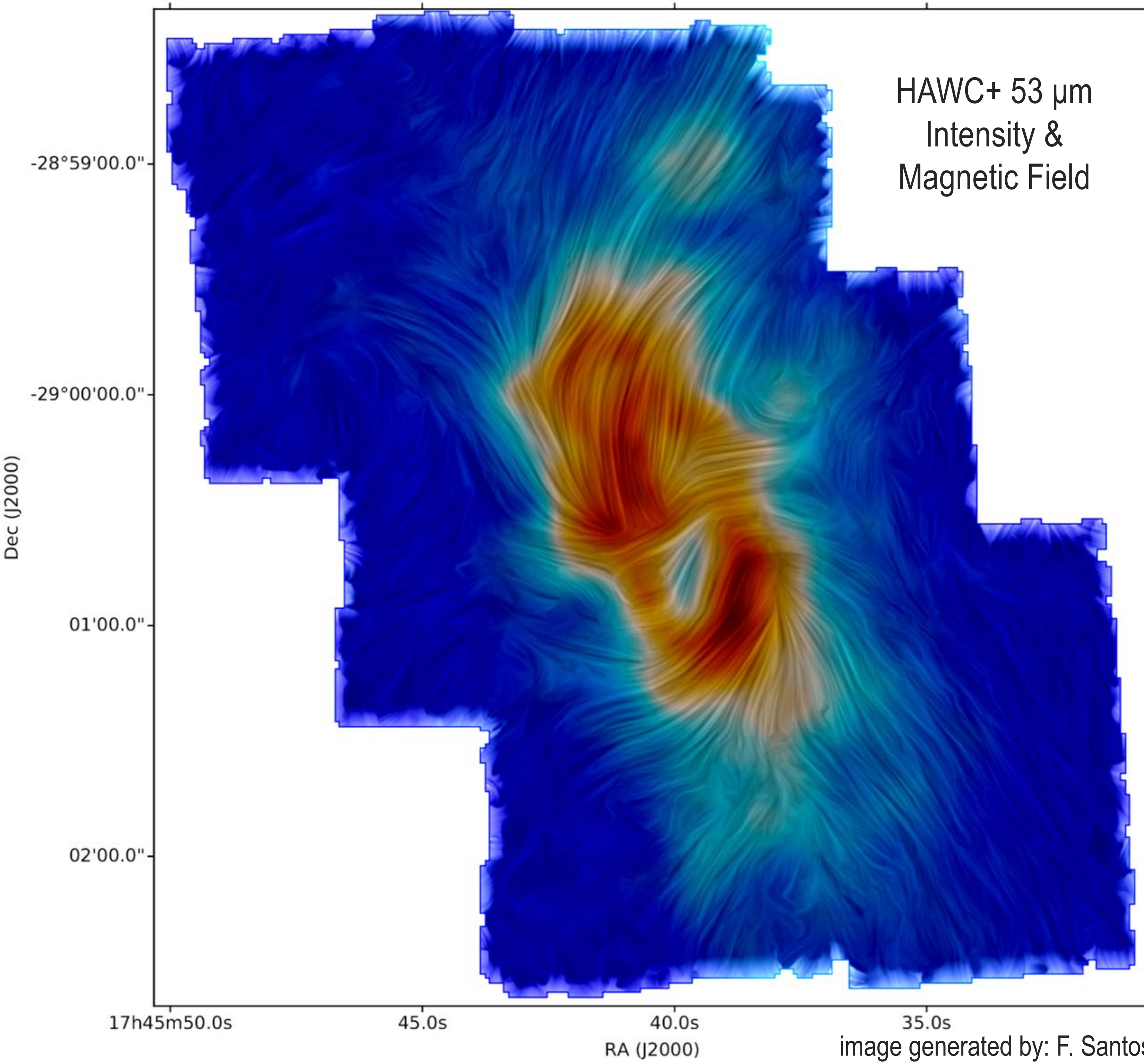


image generated by: F. Santos

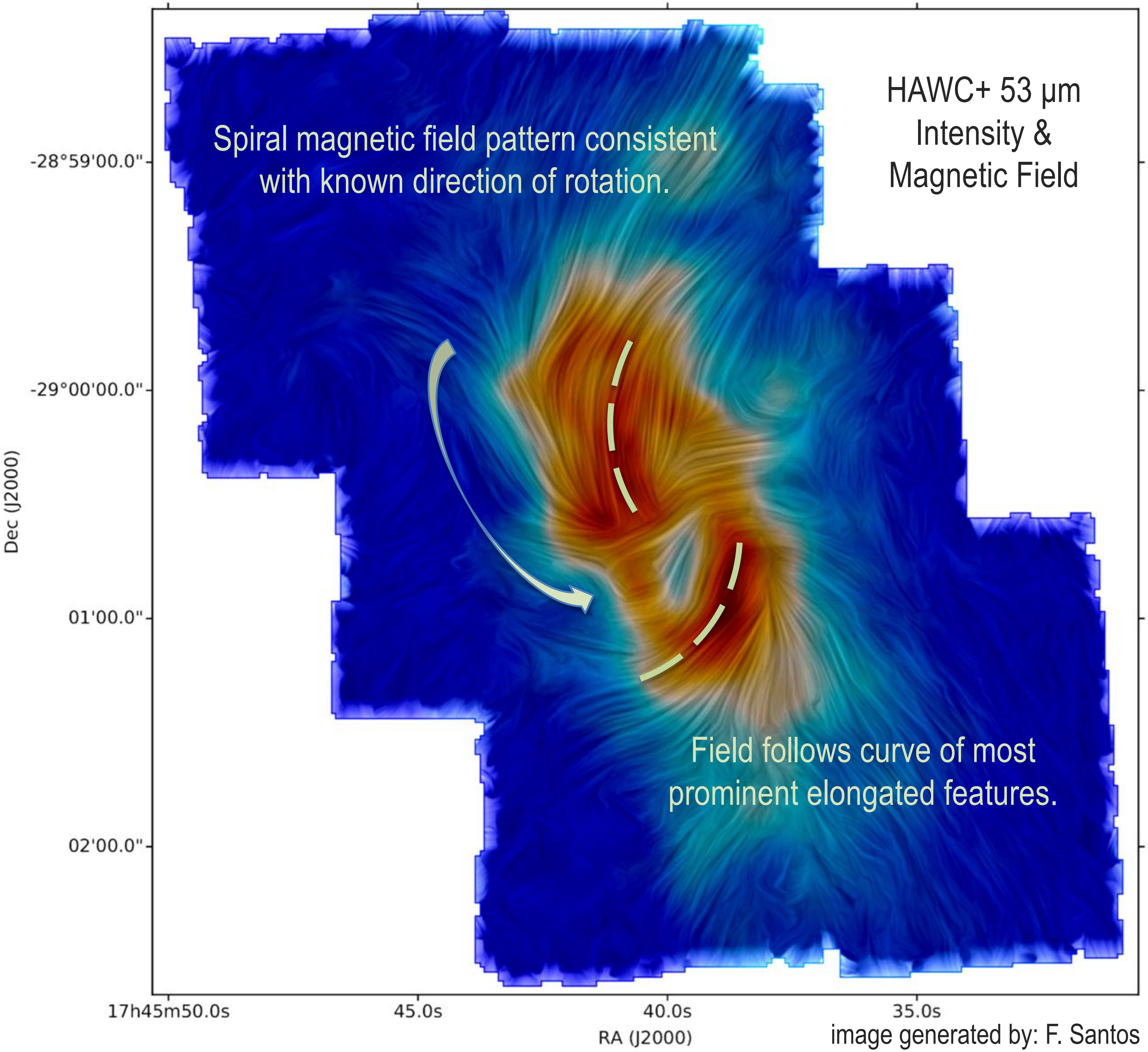
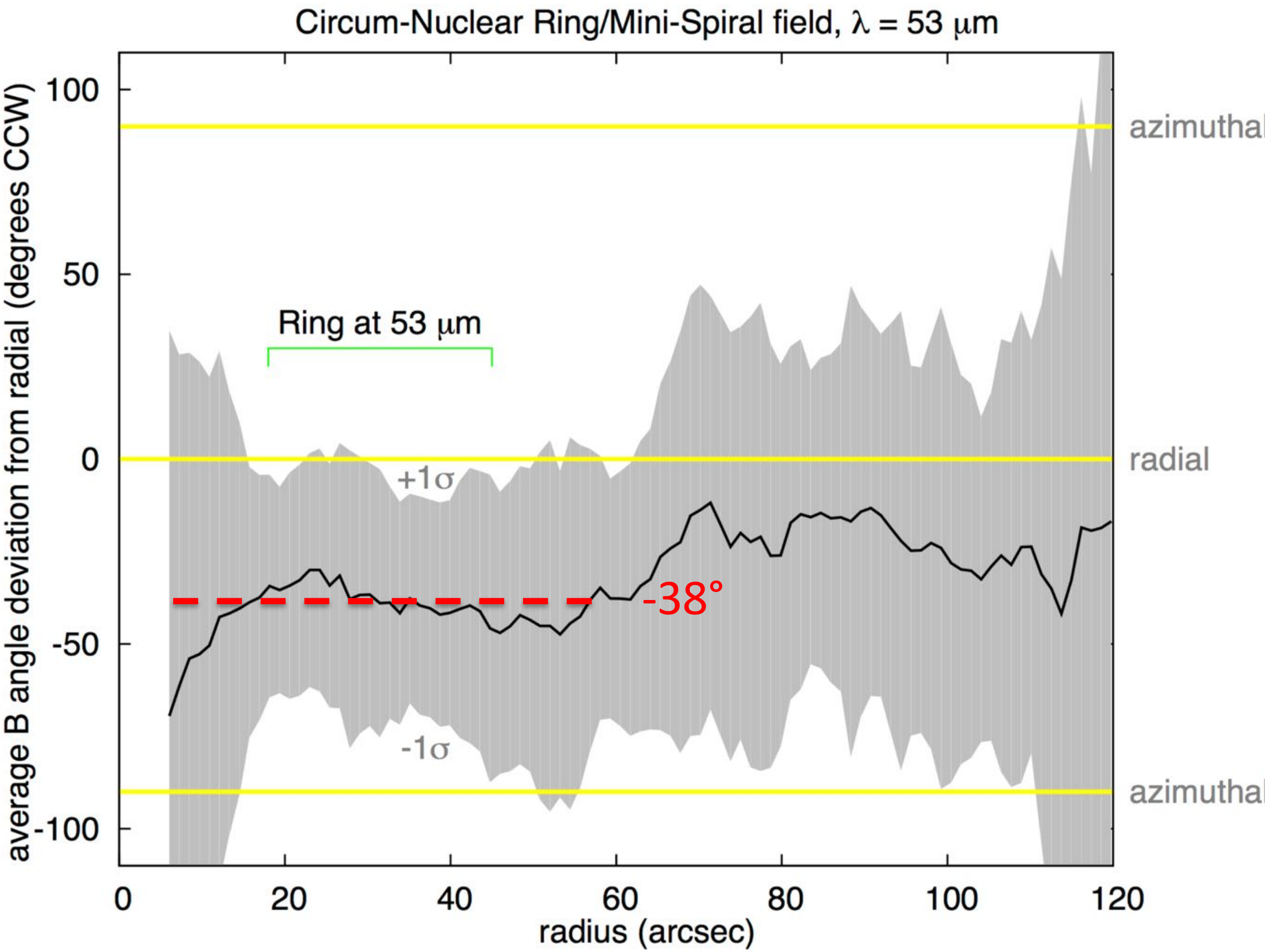
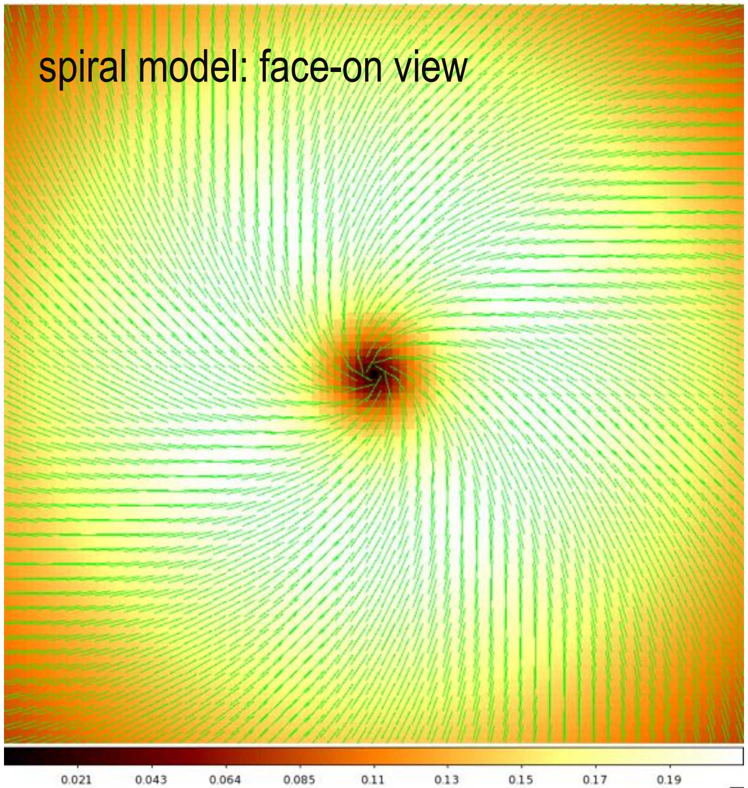


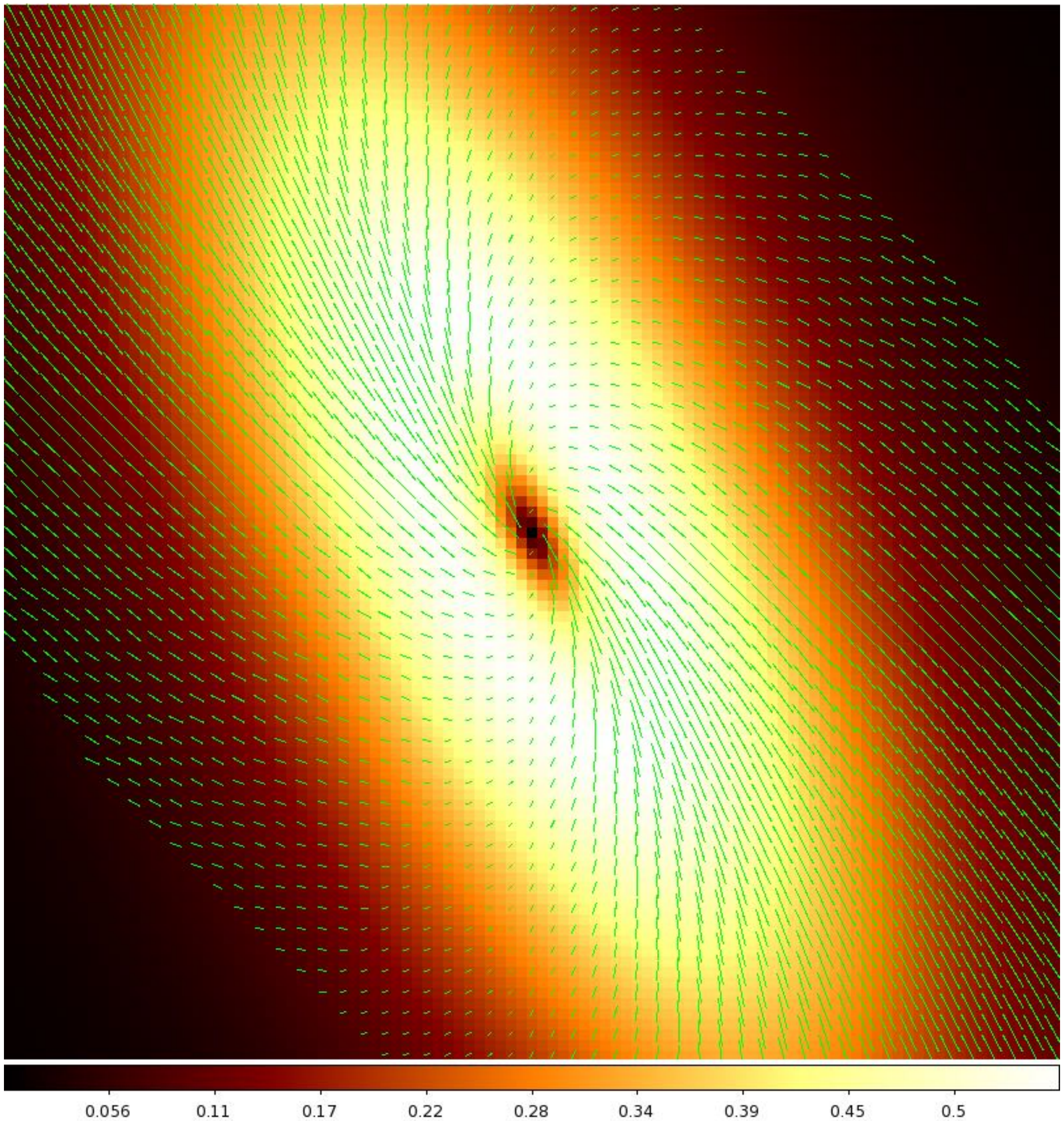
image generated by: F. Santos

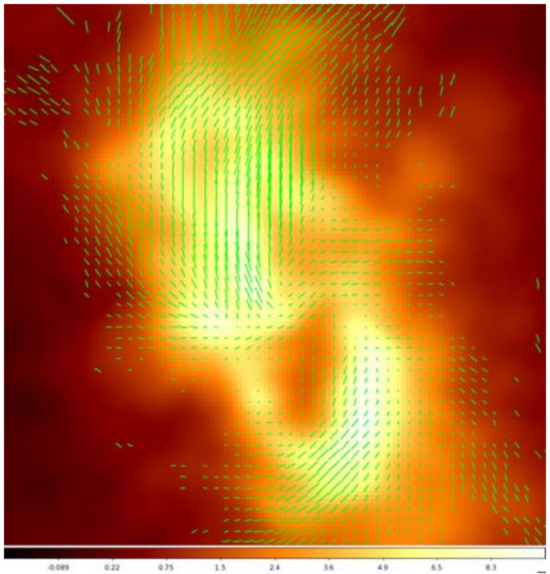


- Spiral pattern evident in 53 μm magnetic field data to at least 60 arcsec (2.5 pc) radius.

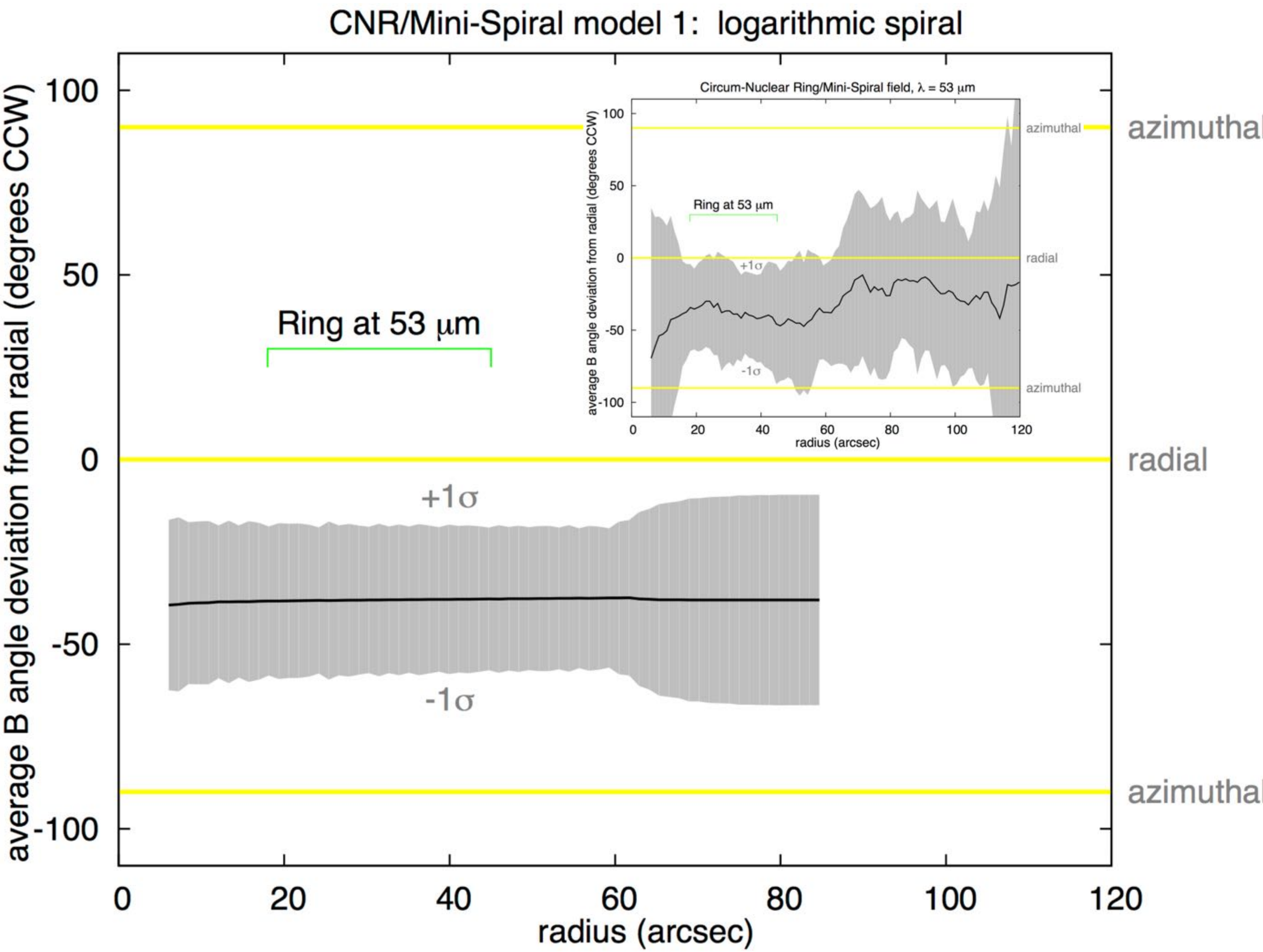
simple model for region: logarithmic spiral field



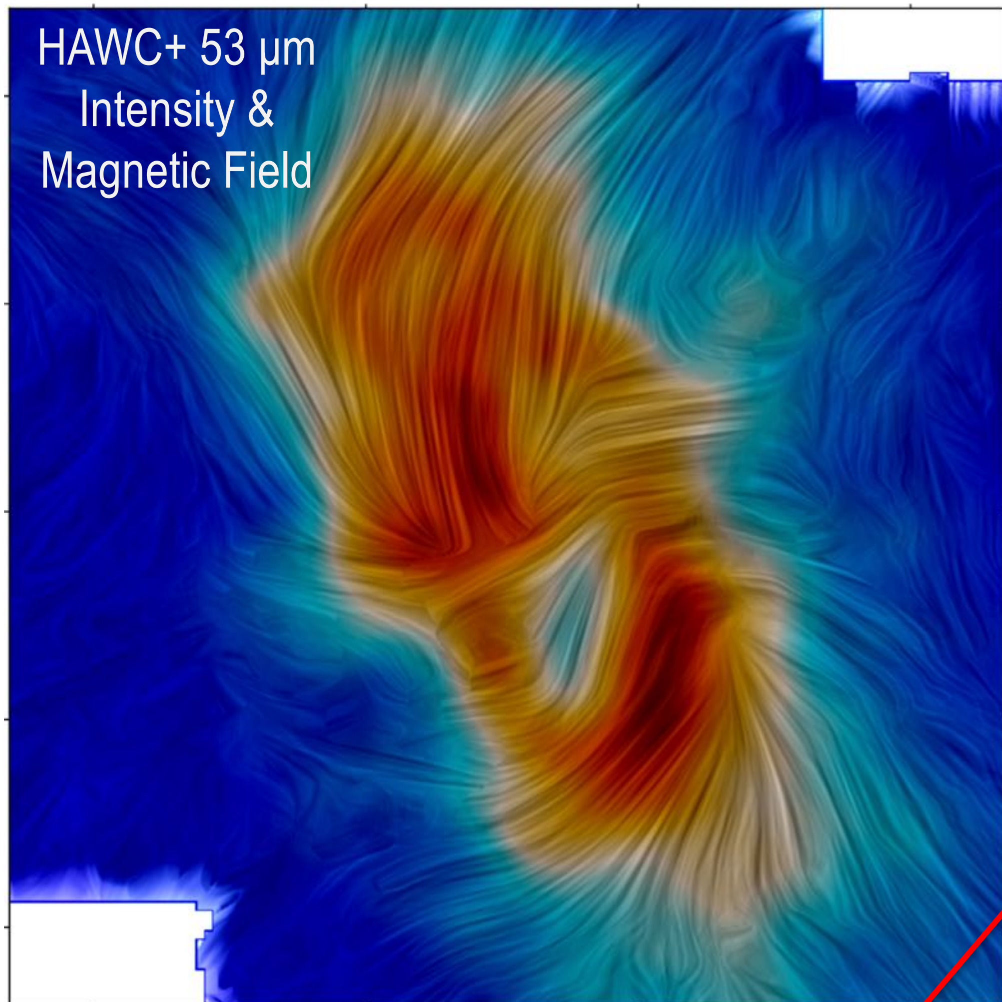


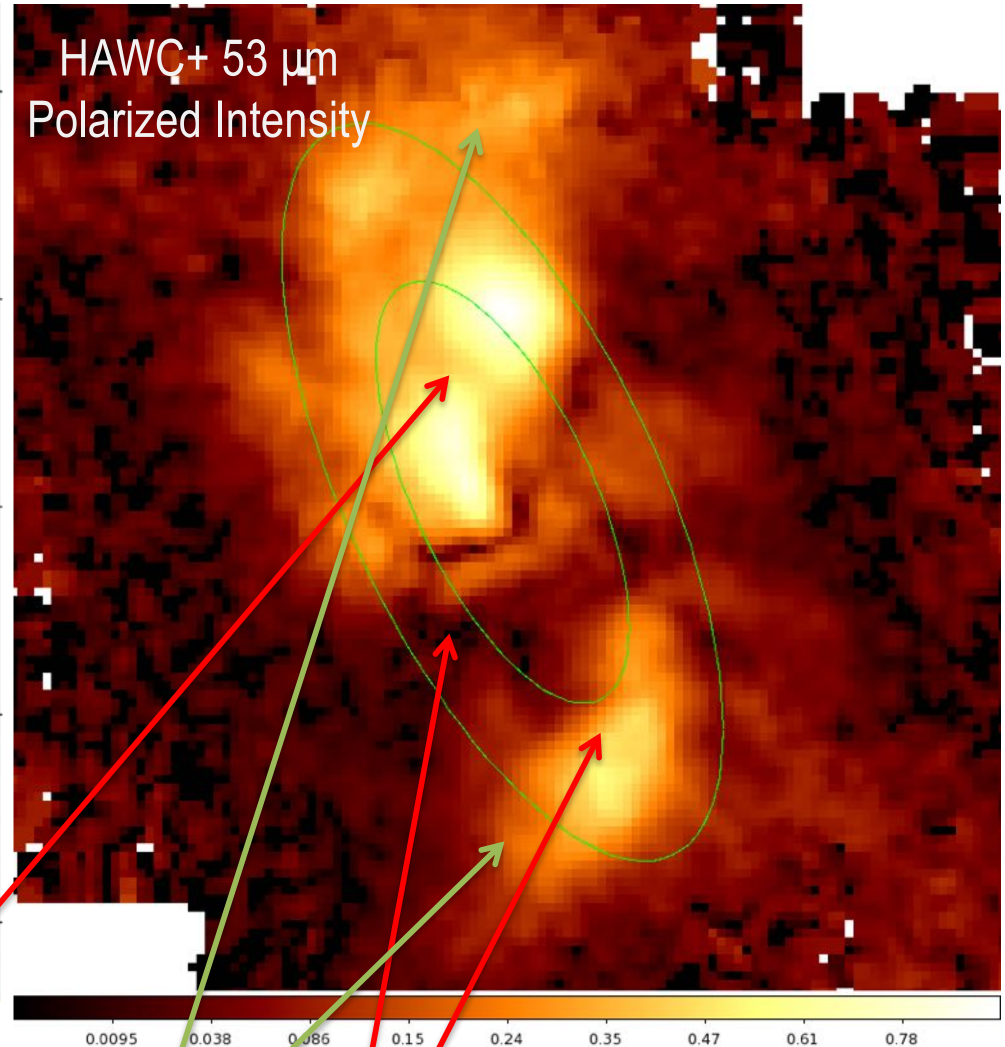


- Initial purpose: characteristic pitch angle of spiral for inner 5 pc
- Model: wedge-shaped disk with $e^{-r/r0}$ distribution of dust emission, inclined 67°; **magnetic field twisted 28° from radial direction**.



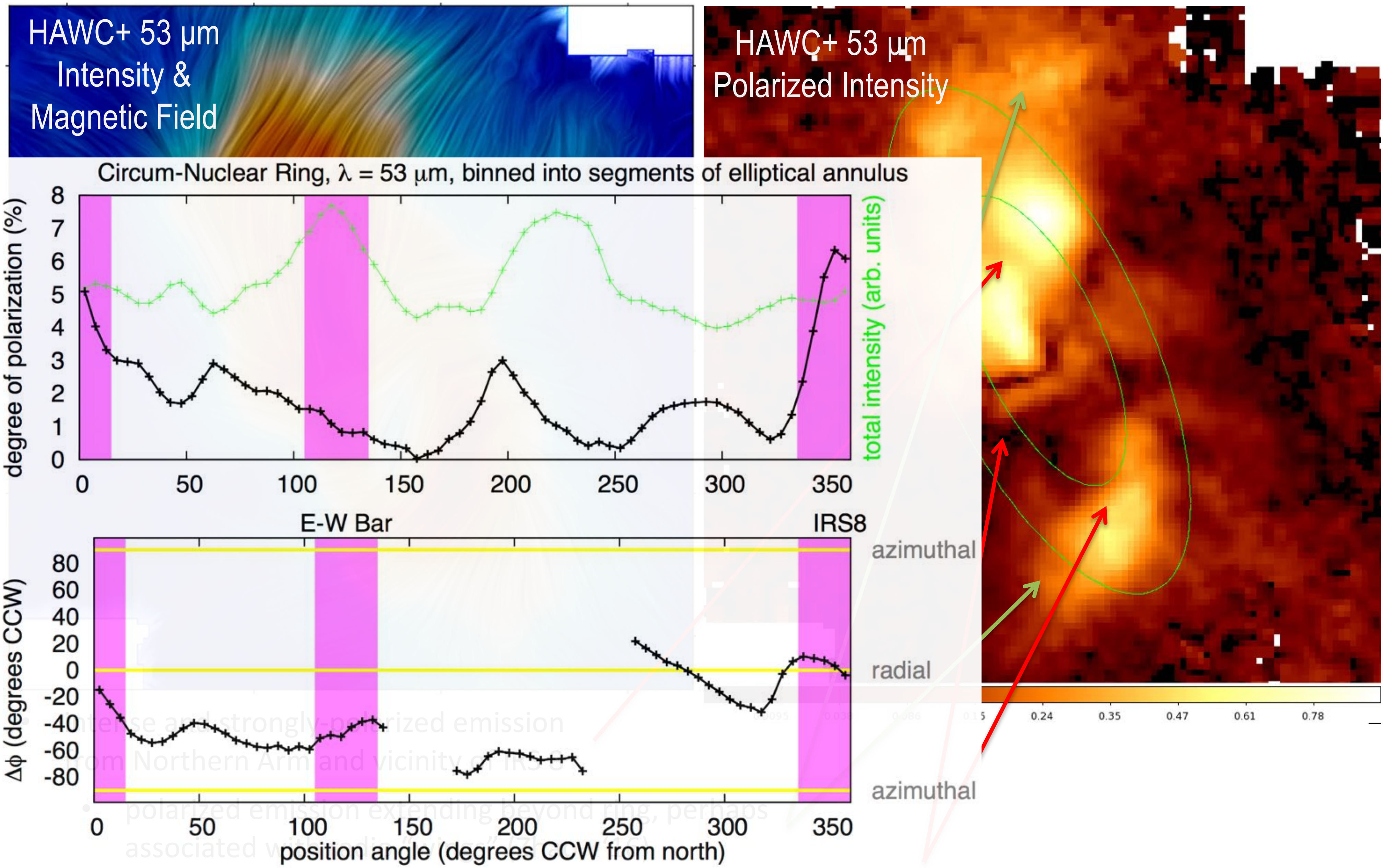
- In broad terms, model gives approximately the right average pitch angle.
- Does not match detailed structure, however.





- intense and strongly-polarized emission from Northern Arm and vicinity of IRS 8
  - polarized emission extending beyond ring, perhaps associated with radio "wings" (Zhao+ '16)
- **contrast between moderate polarization at N&S ends and low polarization at E&W sides.**

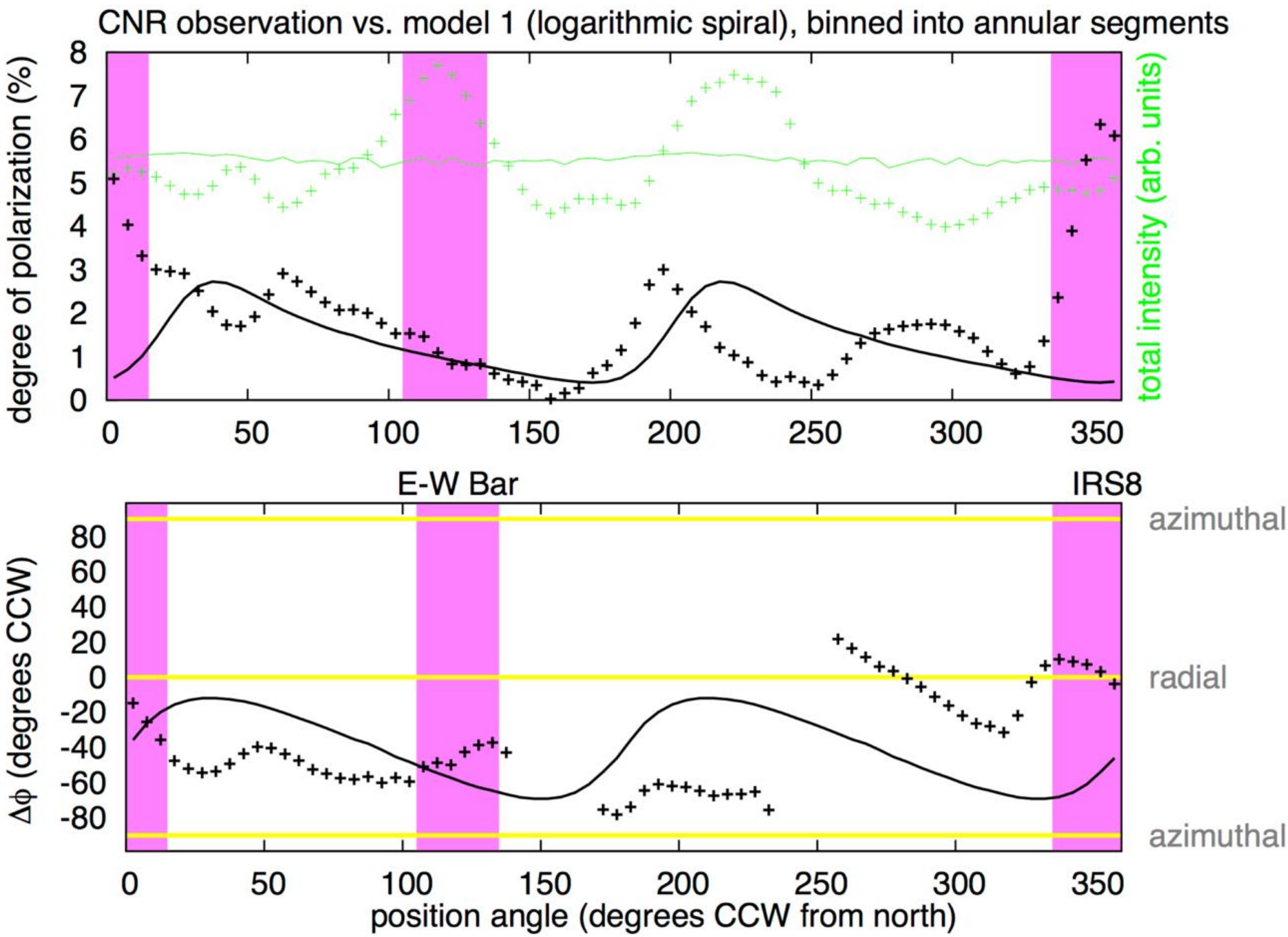
> Can this be explained by field inclination ($p \approx p_0 \cos^2 i$)?



- **contrast between moderate polarization at N&S ends and low polarization at E&W sides.**

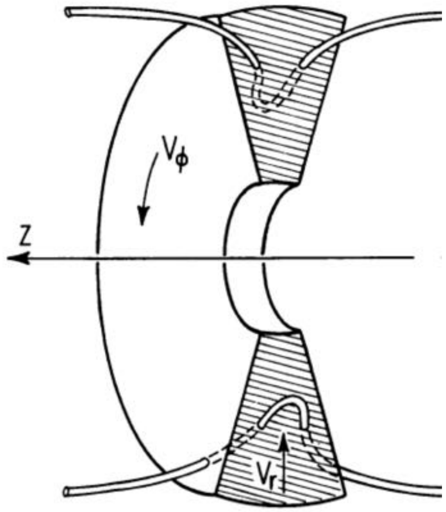
> Can this be explained by field inclination ($p \approx p_0 \cos^2 i$)?

logarithmic spiral model vs. observation

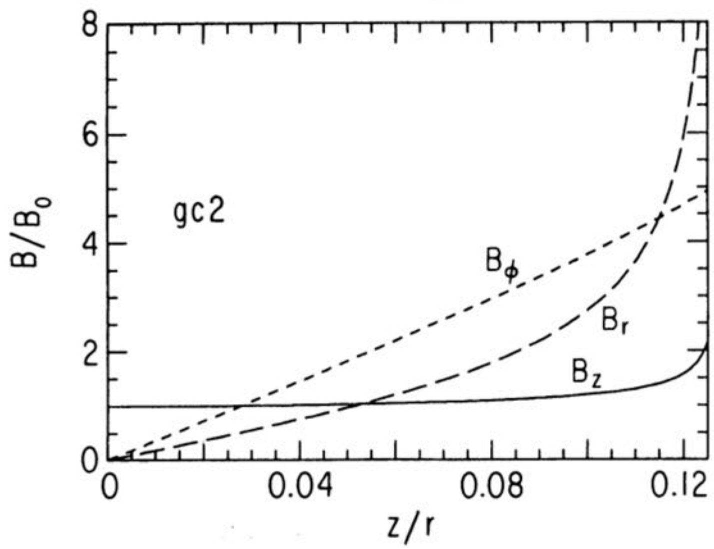


- Although some general trends may be captured by model, detailed structure is not.

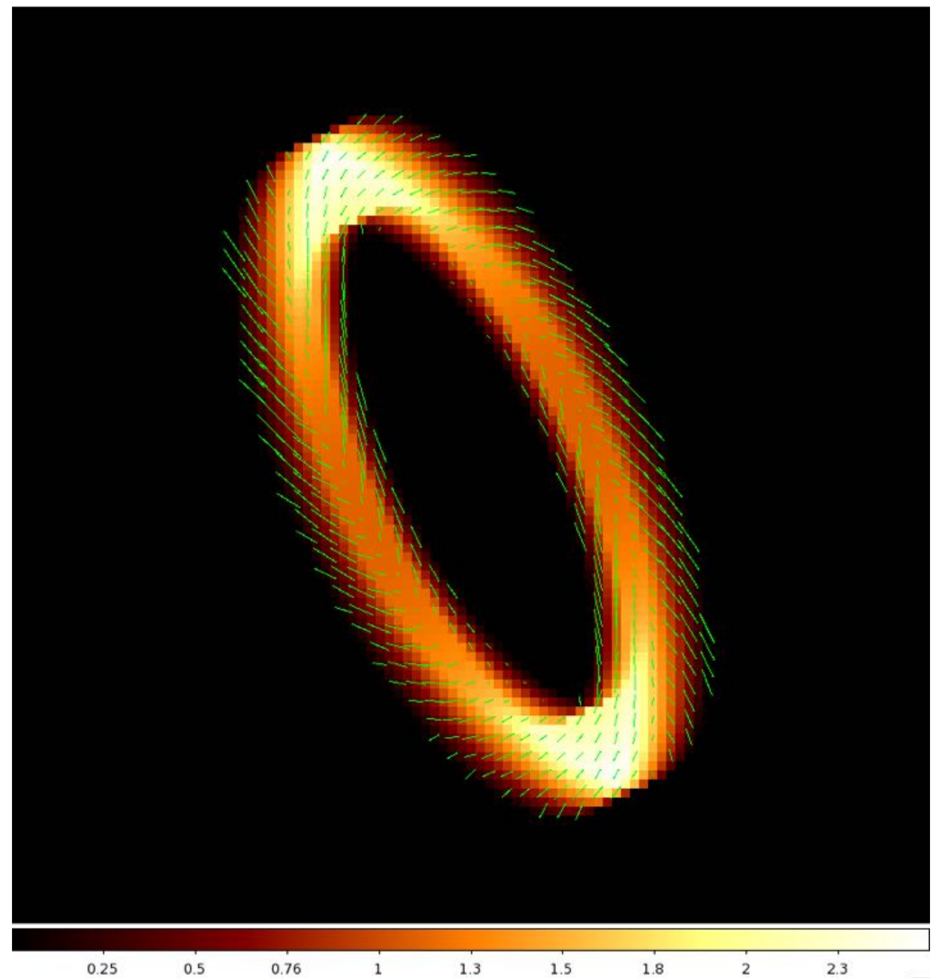
disk with 3D self-similar magnetic field



a
AXIALLY SYMMETRIC FIELD

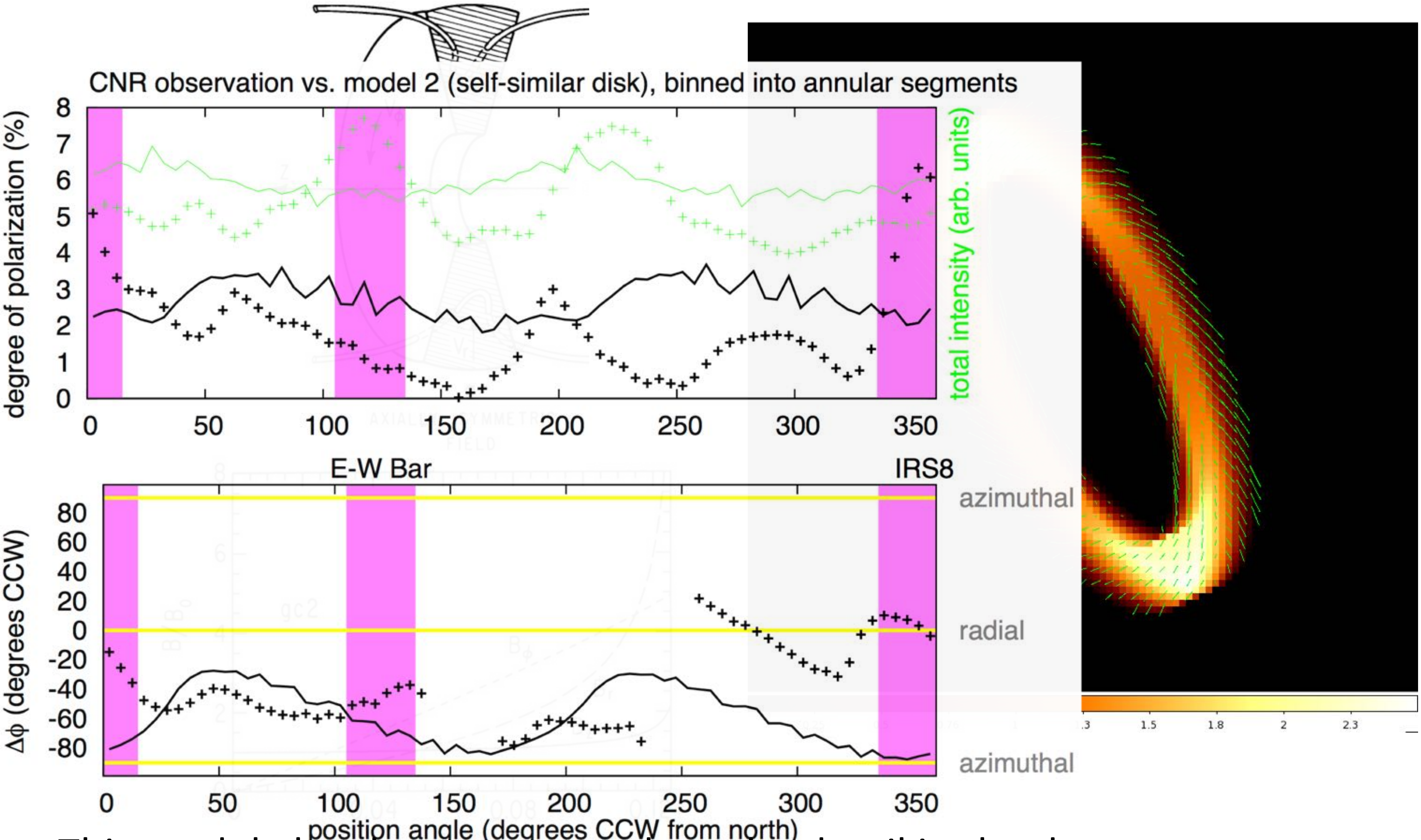


field model “gc2” from Wardle & Königl ‘90 set, preferred (and modified) by Hildebrand+ ‘93

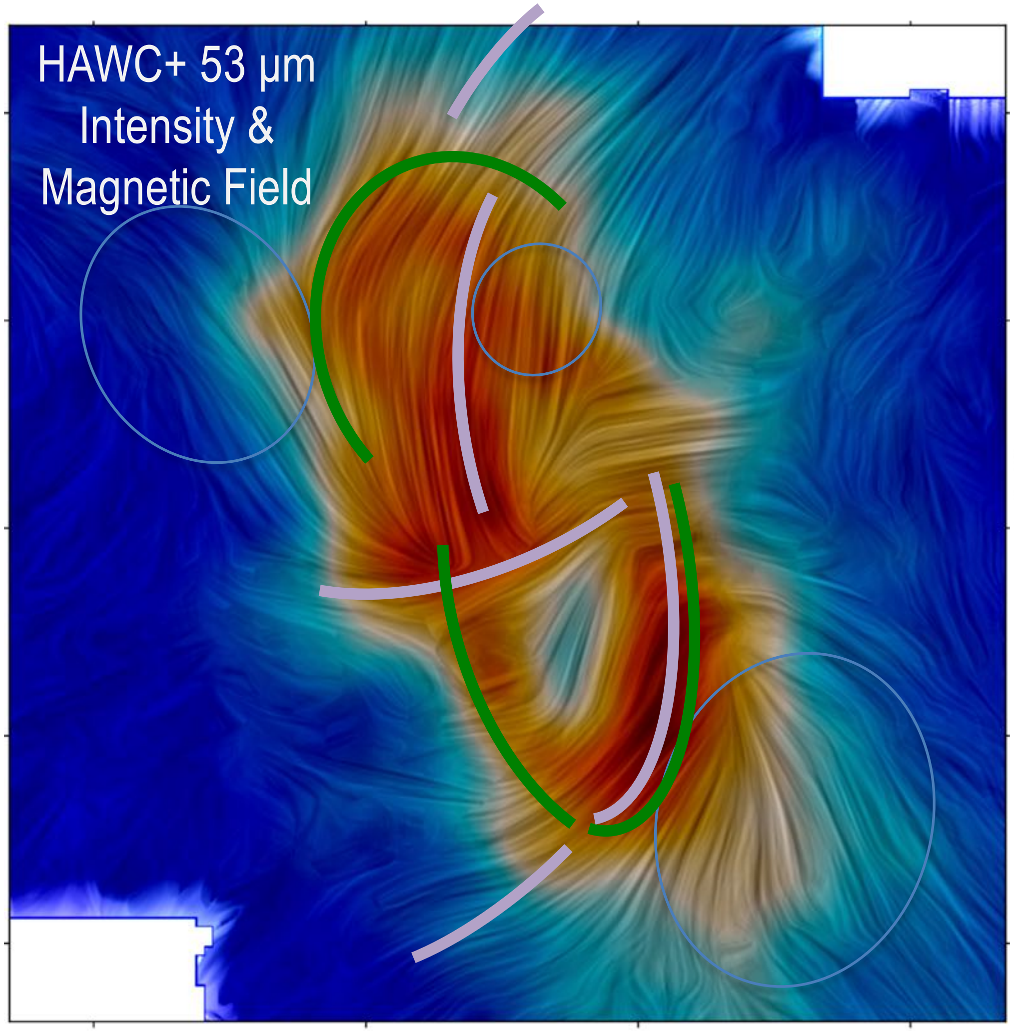


total intensity model based on Lau+ ‘13

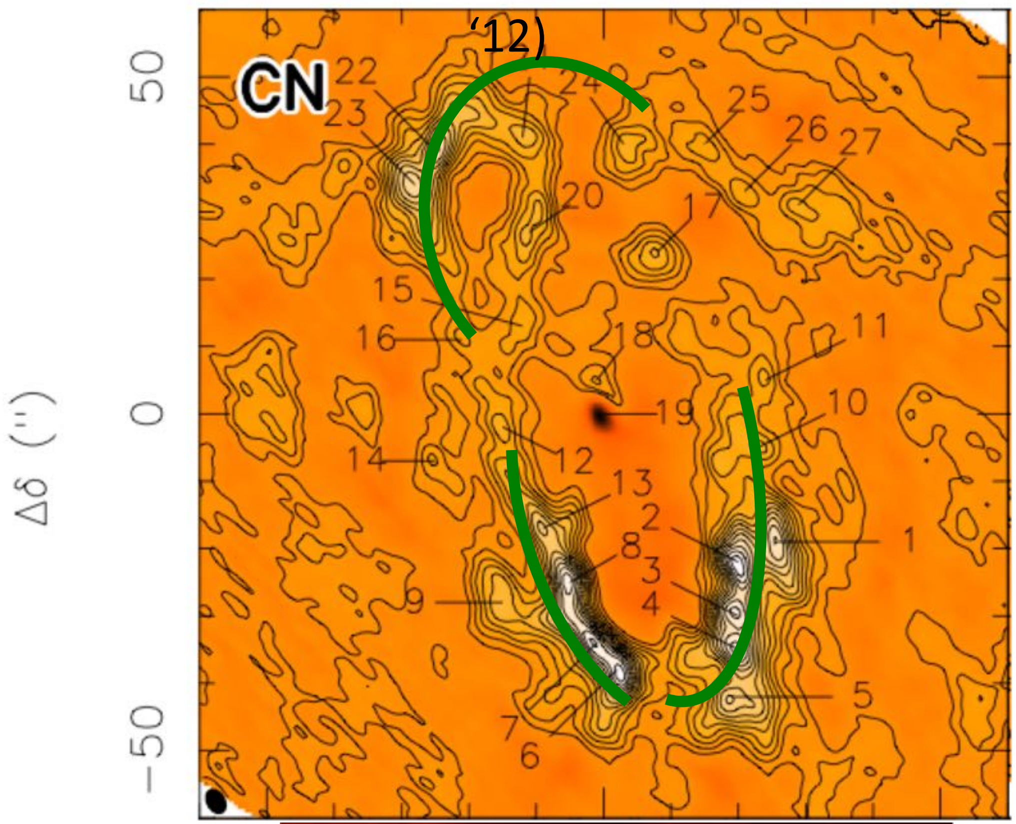
disk with 3D self-similar magnetic field

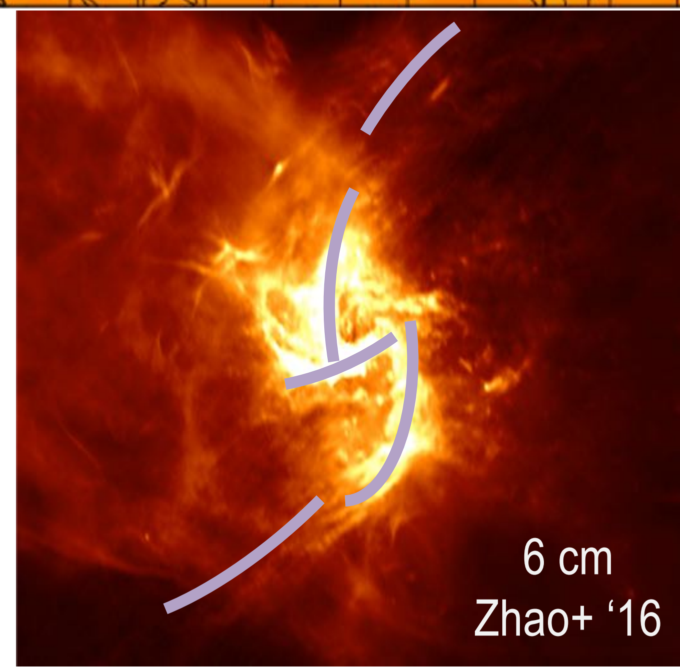


- This model also does not reproduce the detail in the data.
- Ordered disk models have 180° symmetry, unlike the data.



kinematic components in CN (Martín+ '12)



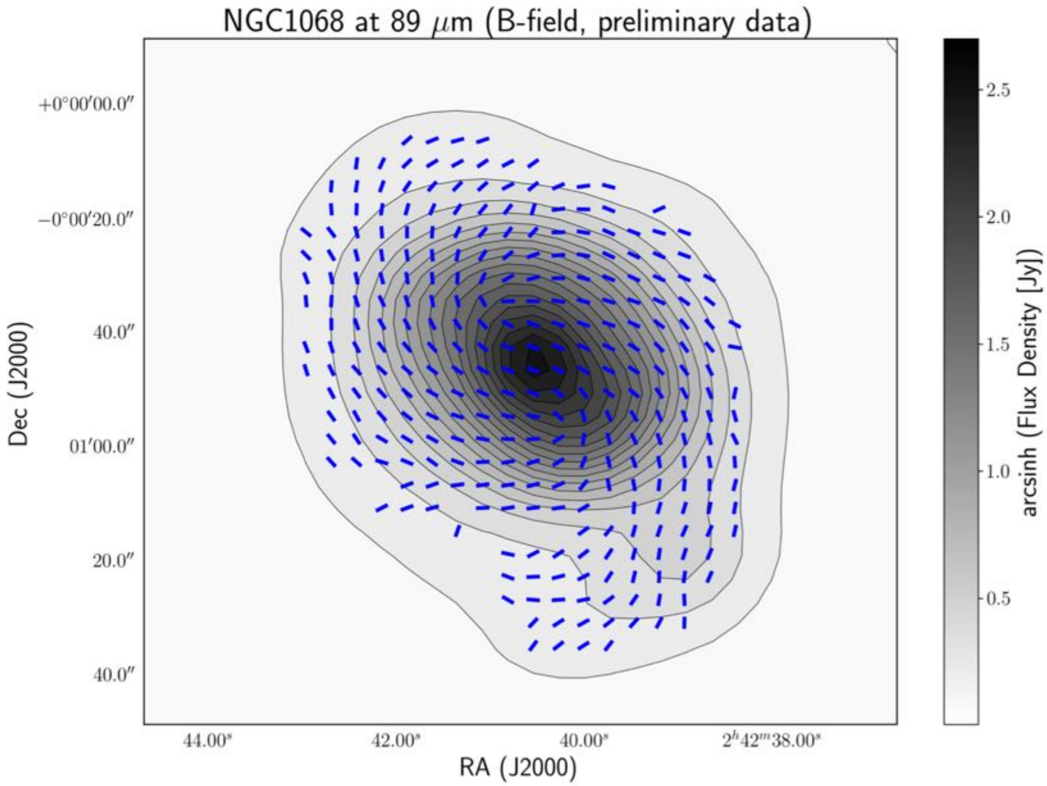


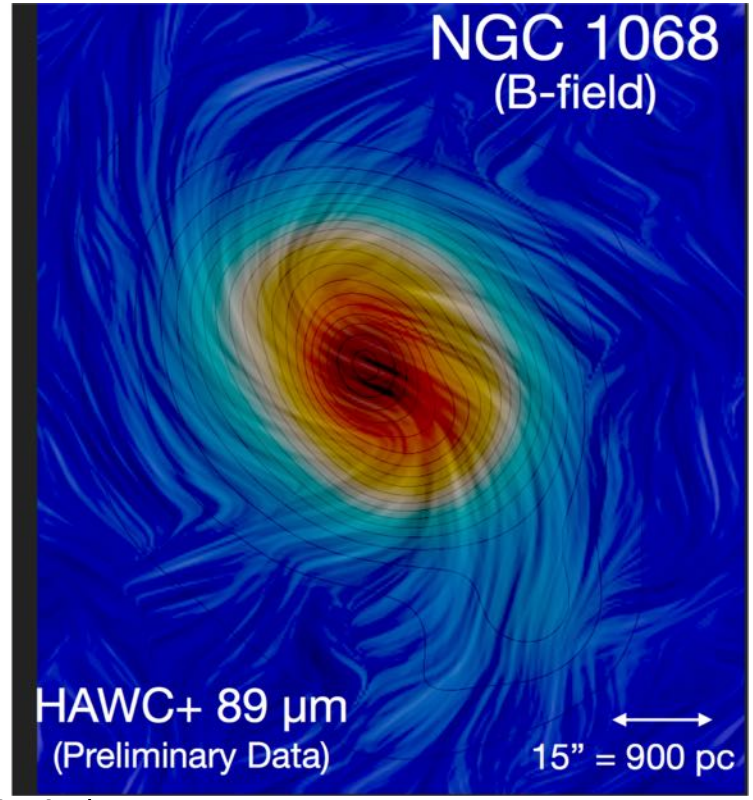
- Five 53 μm intensity and polarization features correspond to radio continuum features, with field parallel to all.
- Three molecular kinematic components correspond to 53 μm intensity features.
  - Two have field roughly following them.
  - One has very low polarization.
- Other suggested intensity/magnetic components in blue.

image credit:
HAWC+ GTO team
FORCAST (Lau+ ‘13)
HST/NICMOS
SOFIA/USRA

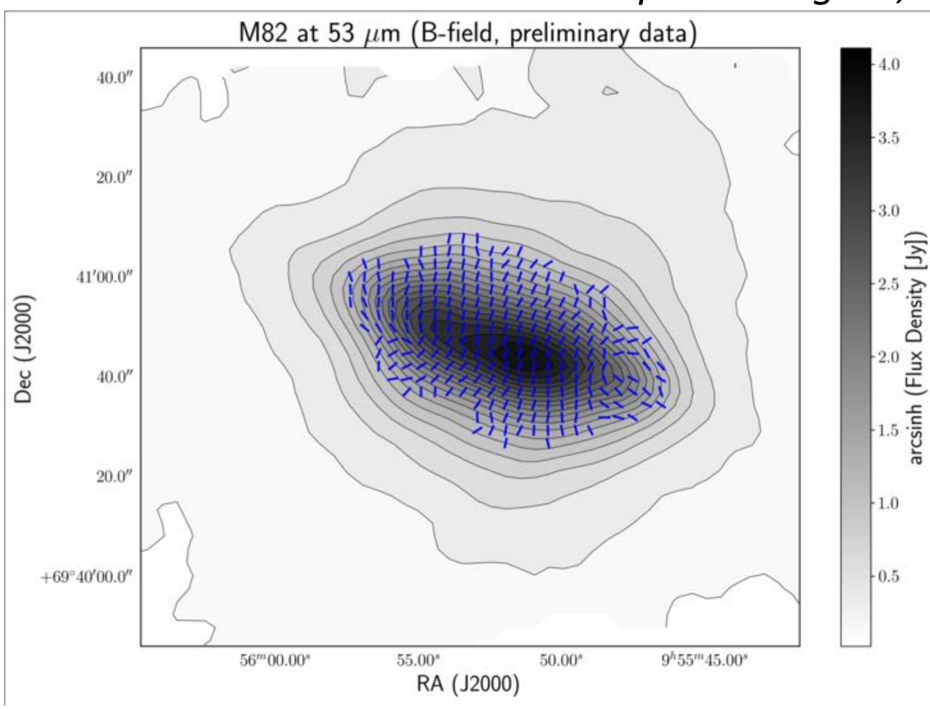
- Within central 2.5 pc radius, magnetic field shows a general spiral pattern with direction more radial than azimuthal.
  - Orientation of spiral is consistent with known ring rotation direction.
- Some aspects of the observations are represented by models, but observations do not show 180° rotational symmetry of ordered disk models.
- In general, field appears to follow elongated structures in this region.

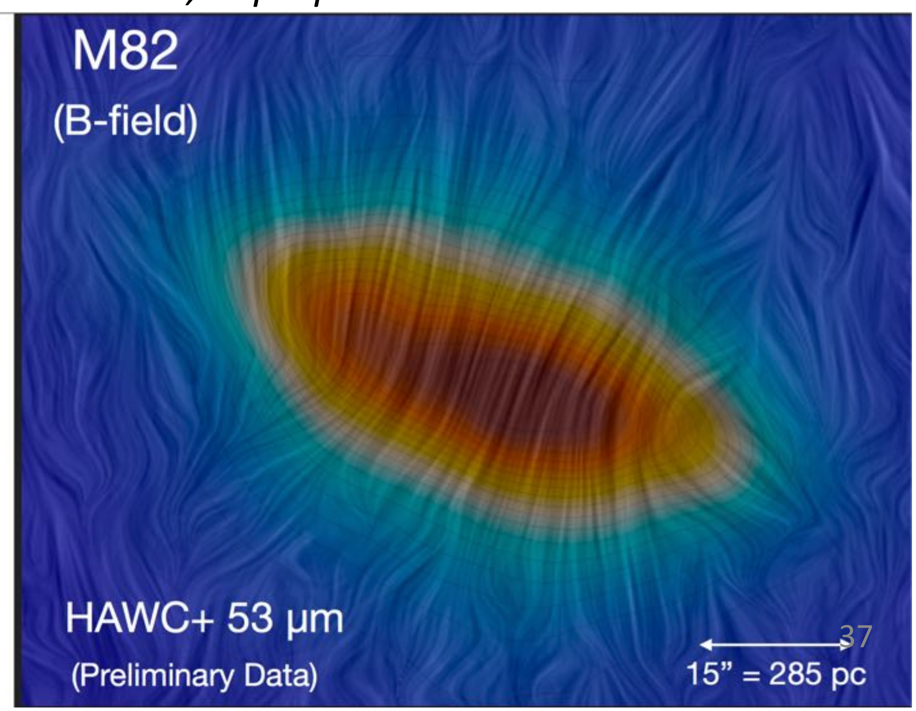
image credit:
HAWC+ GTO team
FORCAST (Lau+ ‘13)
HST/NICMOS
SOFIA/USRA





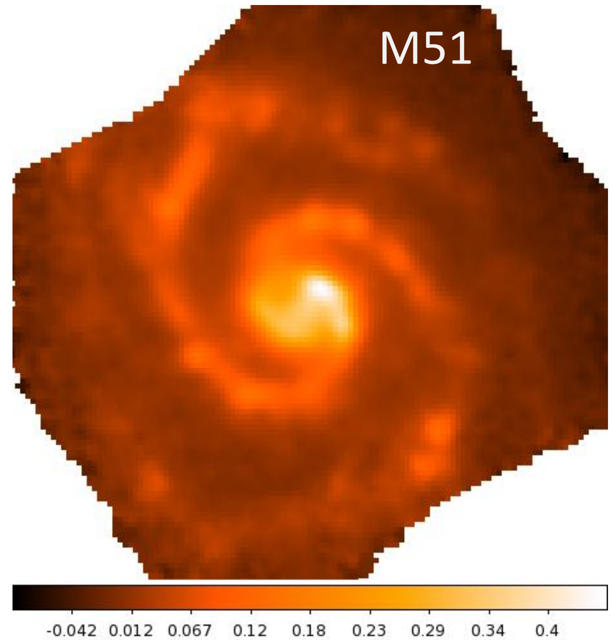
E. Lopez-Rodriguez, HAWC+ GTO, in prep.

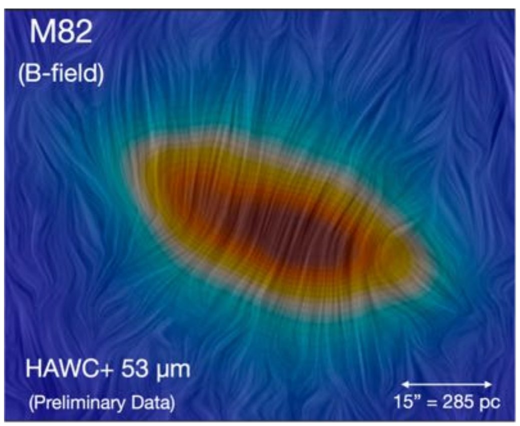


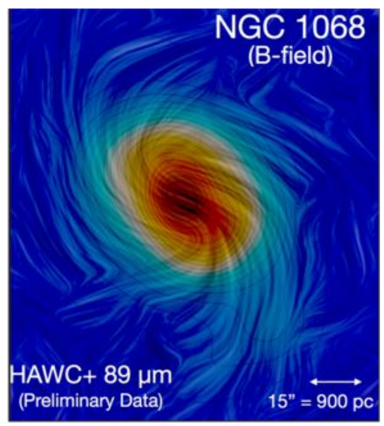


galaxies: measured far-IR polarization

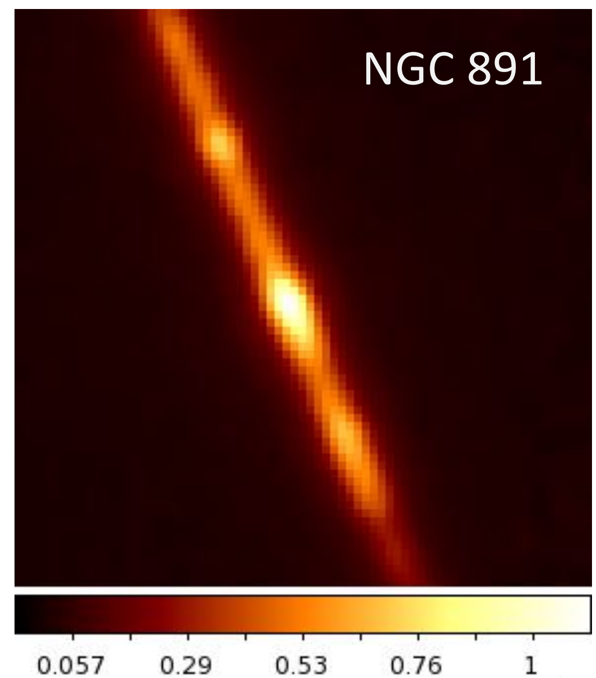
galaxy	structure	degree of pol.
M82	nuclear starburst (ø 0.8 kpc)	2.0 %
NGC 1068	nucleus + bar (ø 0.8 kpc)	0.8 %
"	starburst ring (ø 2 kpc)	1.4 %
NGC 253	nucleus (ø 0.6 kpc)	0.5 %
M51	face-on disk (inner ø 8 kpc)	~2 % (prelim.)
NGC 891	edge-on disk (inner ø 8 kpc)	t.b.d.







- Polarization is 0.5 – 2% on ~0.5 kpc scales
- This is measurable with systematic errors (<= 0.2%) already achieved in several instruments.
- Sensitivity from space (e.g. SPICA, Origins Space Telescope) would permit detailed magnetic field maps of nearby galaxies.



Summary

- HAWC+ is a facility instrument for SOFIA, providing far-infrared continuum imaging and polarization mapping.
- GTO and GO programs to map the magnetic field structure in Galactic clouds, the Galactic Center, and nearby infrared galaxies are underway.
- **https://www.sofia.usra.edu/science/instruments/hawc**