The HAWC Upgrade Investigation

C. Darren Dowell (JPL/Caltech)
& Johannes Staguhn (JHU, NASA-GSFC)
2012 November 28

Outline

- project background and team
- primary motivation: measurement of interstellar magnetic fields
- upgrade implementation
  - new detector from Goddard
  - polarimeter (JPL)
  - performance and schedule
- a future upgrade path: fine-structure line imaging

Project History

- HAWC facility far-IR continuum camera: SOFIA first generation instrument (U. Chicago, P.I. Al Harper)
  - 12×32 detector array
  - 4 continuum (R = 5) bands: 53, 89, 155, 216 μm
  - Pre-Ship Review passed in July 2012
- Two SOFIA Second Generation Instrument investigations proposed upgrades to HAWC, submitted Oct. 2011:
  - JPL: single-beam polarimeter, polarimetry science investigation
  - JHU/Goddard: much bigger detector arrays, dual-beam polarimeter, R = 300 fine-structure-line filters, broad science investigation
- Following selection, merging, and negotiation process, funded HAWC upgrade ("HAWC+") consists of:
  - major detector upgrade
  - linear polarimeter and polarimetry science investigation
  - project management and instrument integration & test at JPL
  - start in January 2013
  - any R = 300 imaging postponed beyond first-light

HAWC+ Instrument Upgrade Team

JPL


Darren Dowell


Louise Hamlin

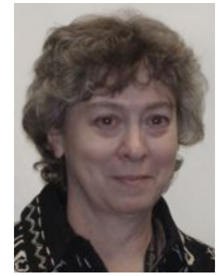

Marc Runyan

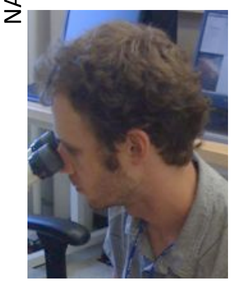
NASA-GSFC, JHU


Johannes Staguhn


Dominic Benford

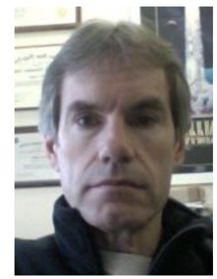

Leroy Sparr


Christine Jhabvala


Elmer Sharp


Attila Kovacs


Dave Chuss


Troy Ames


Steve Maher, SSAI


Kent Irwin, NIST

University of Chicago


Al Harper


Jesse Wirth


Marc Berthoud

Northwestern U.

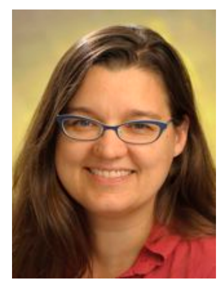

Giles Novak


Nicholas Chapman

USRA


John Vaillancourt


Eric Sandberg


Jessie Dotson, NASA-Ames


Leslie Looney U. Illinois

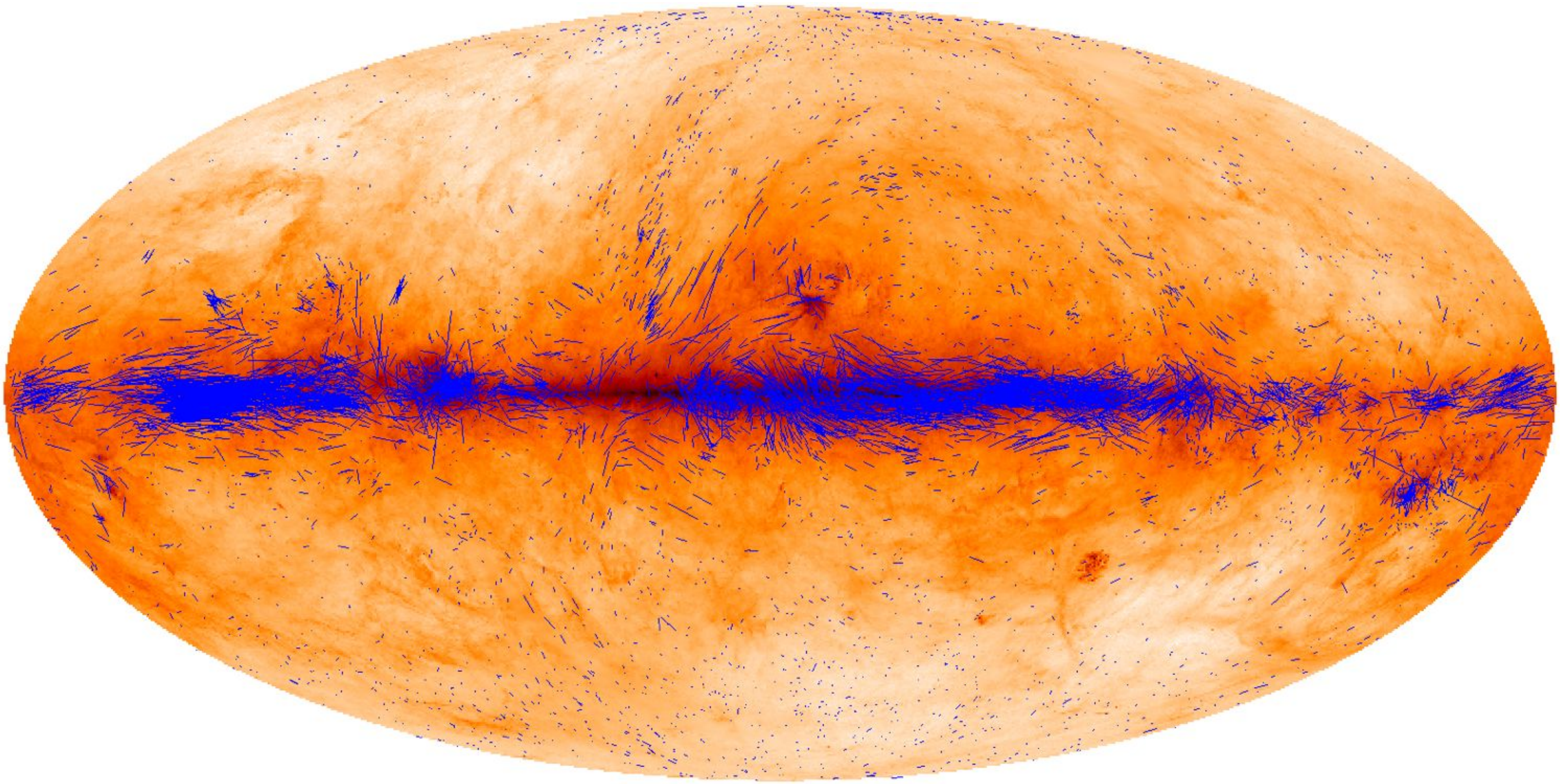
Briefly, HAWC+ is:

- far-infrared camera:
  - R = 5 bands: λ = 53, **63**, 89, 155, 216 μm
  - imager with 64×40 detector pixels
- dual-beam polarimeter:
  - all continuum bands
  - two polarizations detected simultaneously and independently with two 64×40 detector arrays
- 20-hour polarimetry science investigation
- facility instrument ("HAWC"), available 2015

Dust polarimetry reveals the Galactic magnetic field on large and small scales

- increasing misalignment of field with respect to Galaxy at higher densities (cloud formation, or feedback from star formation?)
- Still, magnetic field is energetically important in clouds.
  – Corroborated by Zeeman measurements.
- Polarimetry analysis is becoming statistical and quantitative.

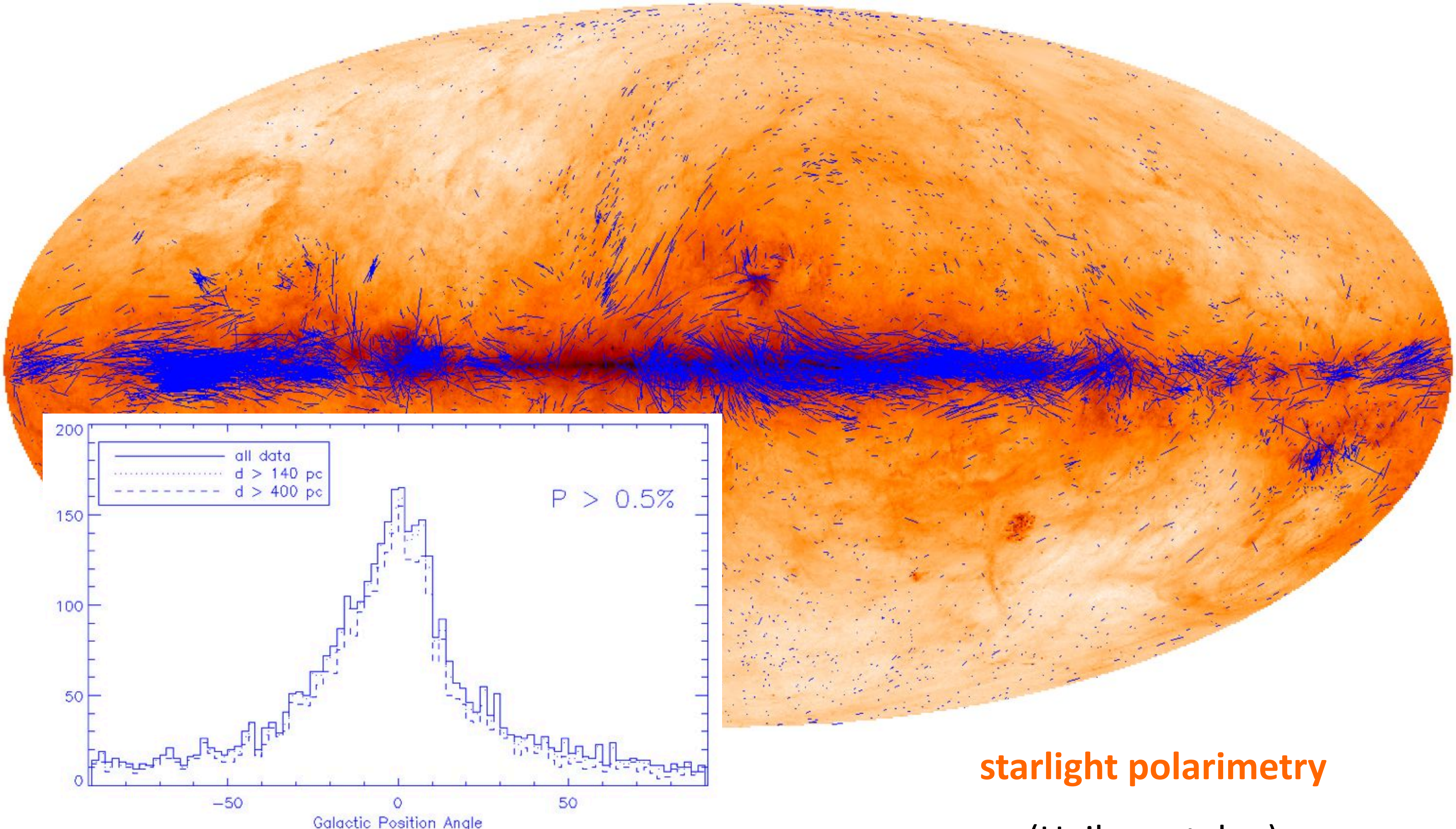
Galactic Field in $A_V \approx 1$ Medium



starlight polarimetry

(Heiles catalog)

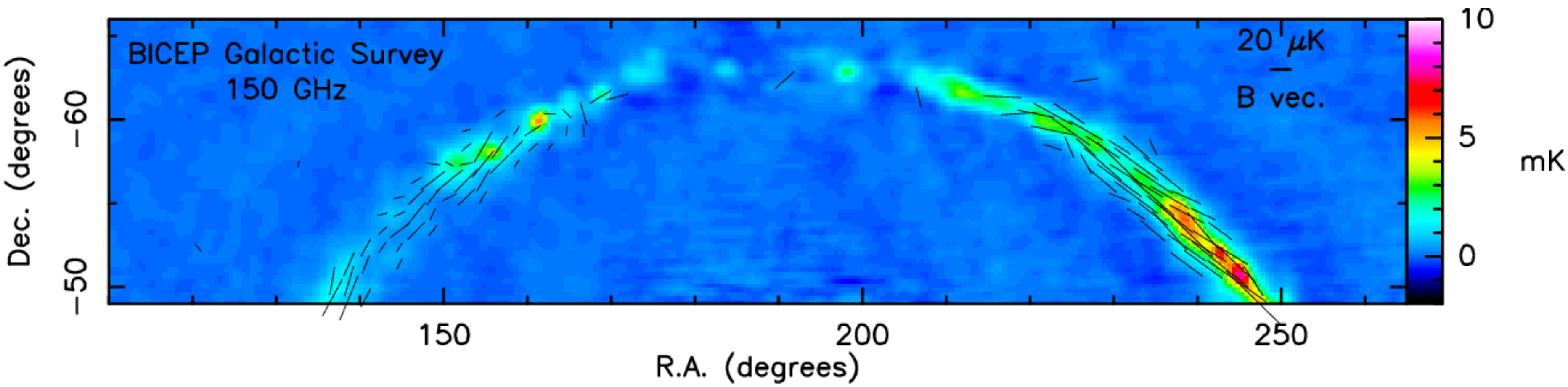
Galactic Field in $A_V \approx 1$ Medium



starlight polarimetry

(Heiles catalog)

Galactic Field in $A_V \approx 10$ Medium



BICEP: southern sky at λ = 2 mm, 1° resolution

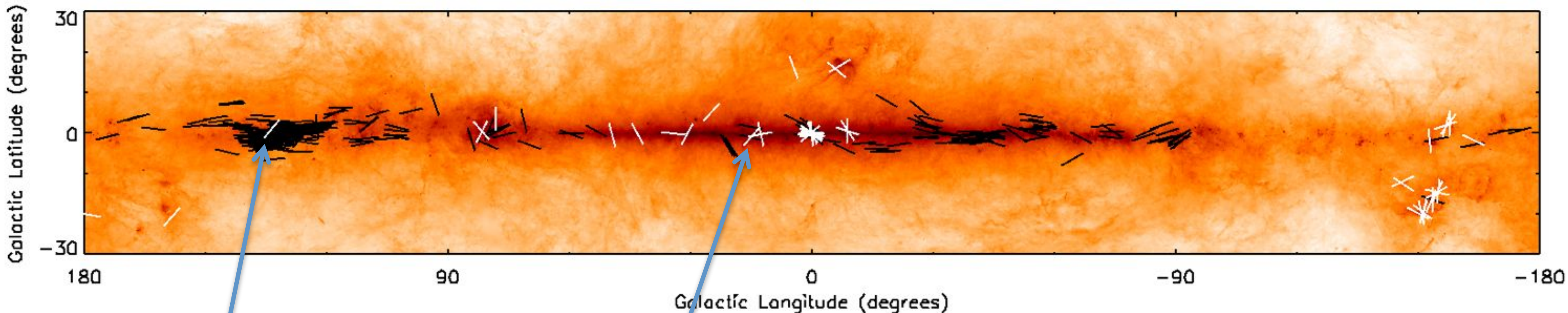
(Bierman et al., 2011)

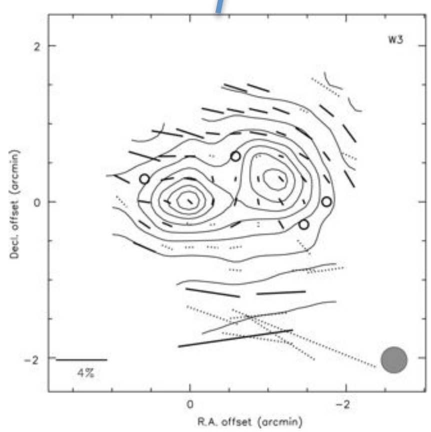
(See also: Benoit et al. 2004 – Archeops
Li et al. 2006 – SPARO
WMAP dust component
Culverhouse et al. 2010 – QUaD)

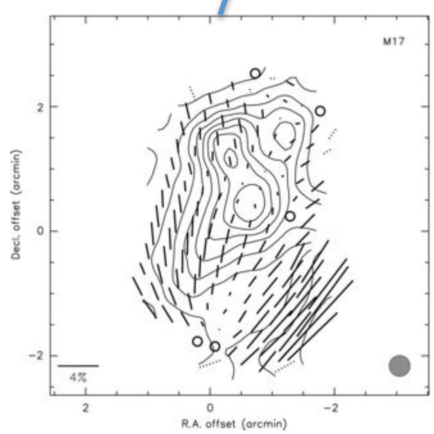
Planck data are coming…

Galactic Field in $A_V \approx 100$ Medium

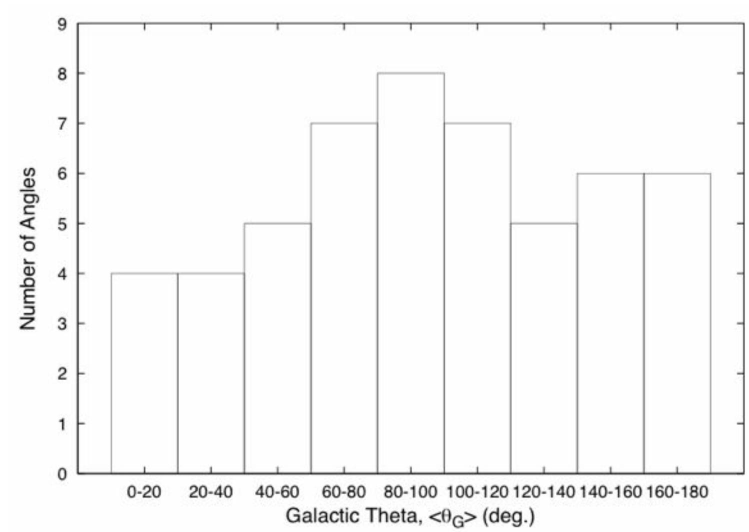
FIR-bright cloud cores (white vectors): no B angle correlation with Gal. plane







I. Stephens et al. (2010)



B-fields may strongly influence star formation

-- *mechanical support by strong B-fields may explain the low overall efficiency of the star forming process*

(e.g., Shu et al. '87; Mouschovias & Ciolek '99; Basu & Ciolek '04)

-- *B-fields may solve the "angular momentum problem"*

(e.g., Allen et al. '03, Shu et al. '04)

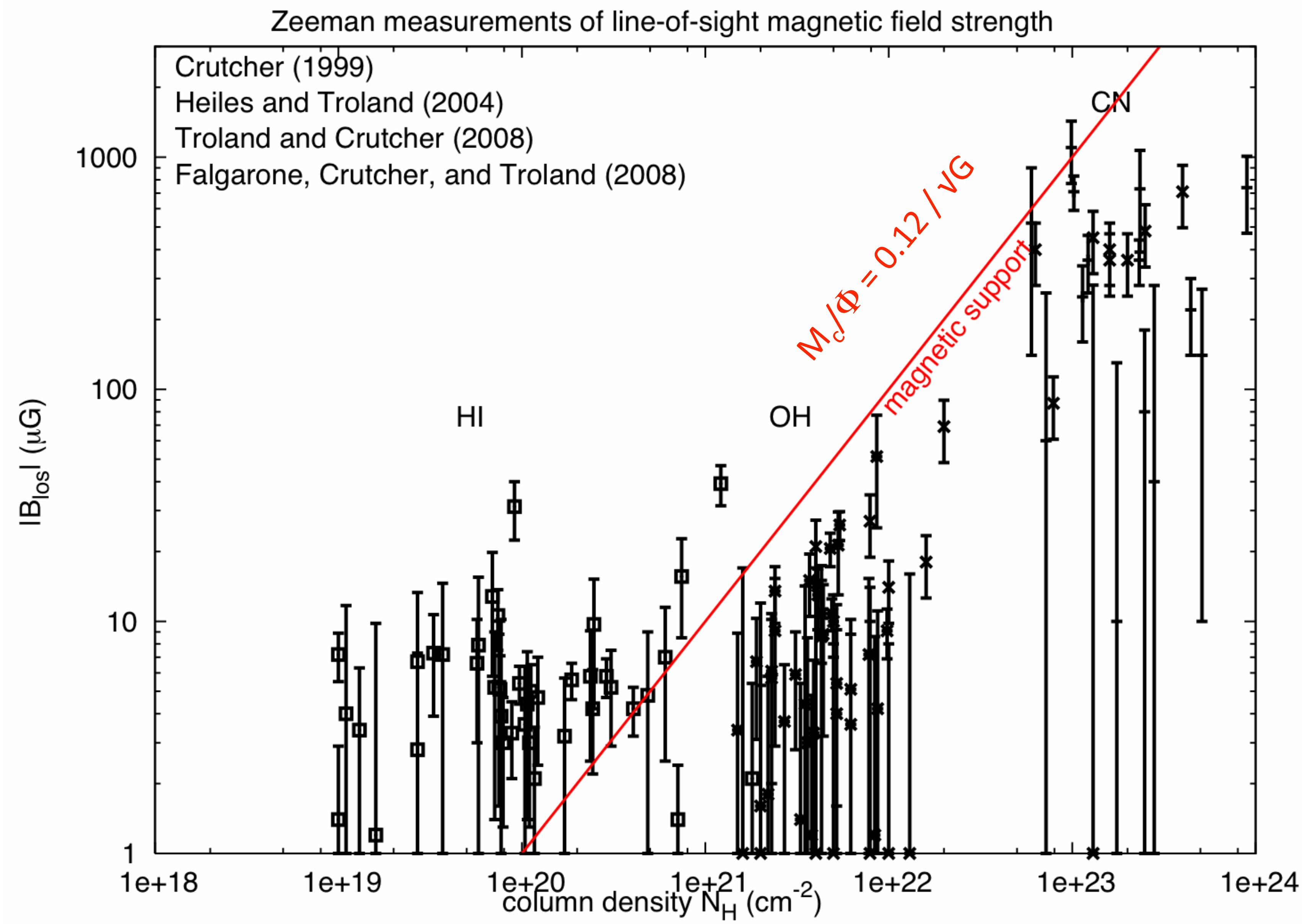
-- *"…supersonic turbulent flows rather than static magnetic fields control star formation."* … Mac Low & Klessen 2004

(see also, e.g., Hartmann et al. `01; Elmegreen & Scalo `04)

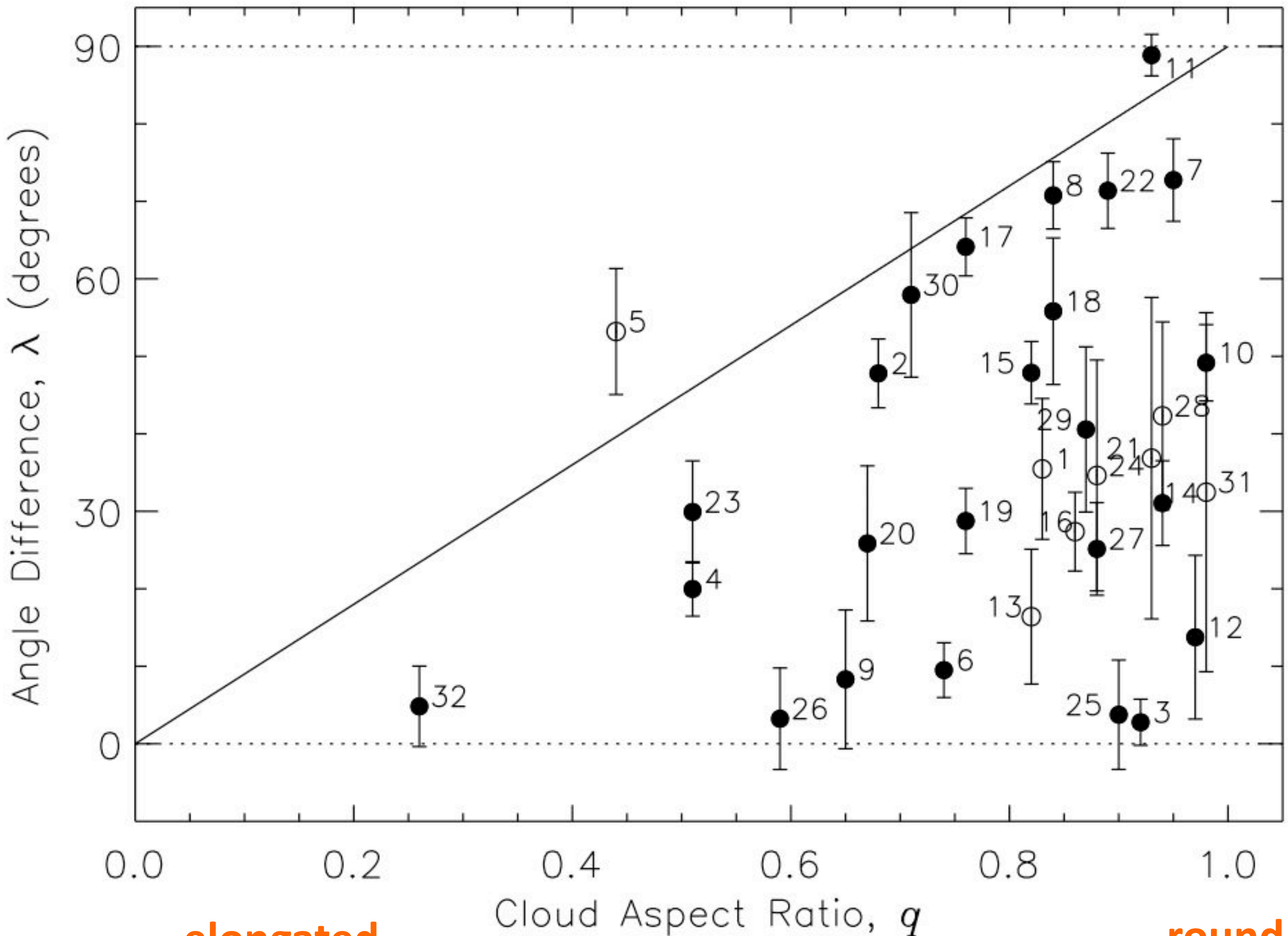
-- *Zeeman molecular line observations provide for direct measurement of magnetic field strength*

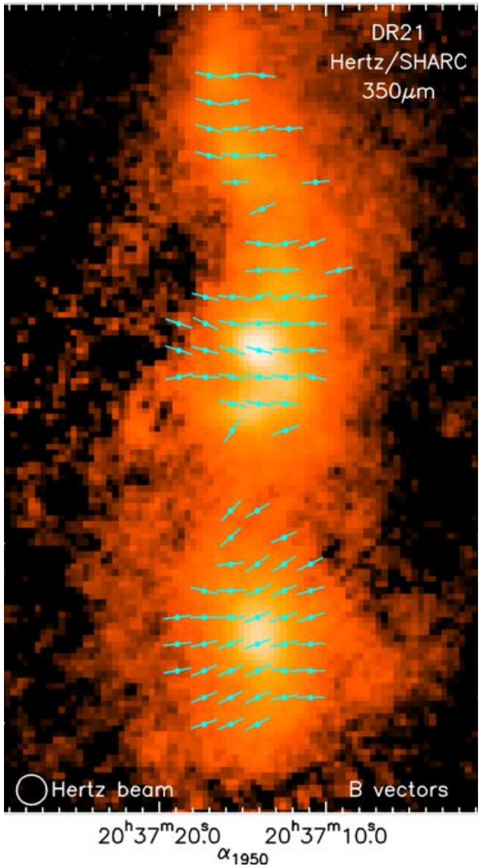
(e.g., Crutcher '99; Bourke et al. '01)

B vs. column density (Zeeman)



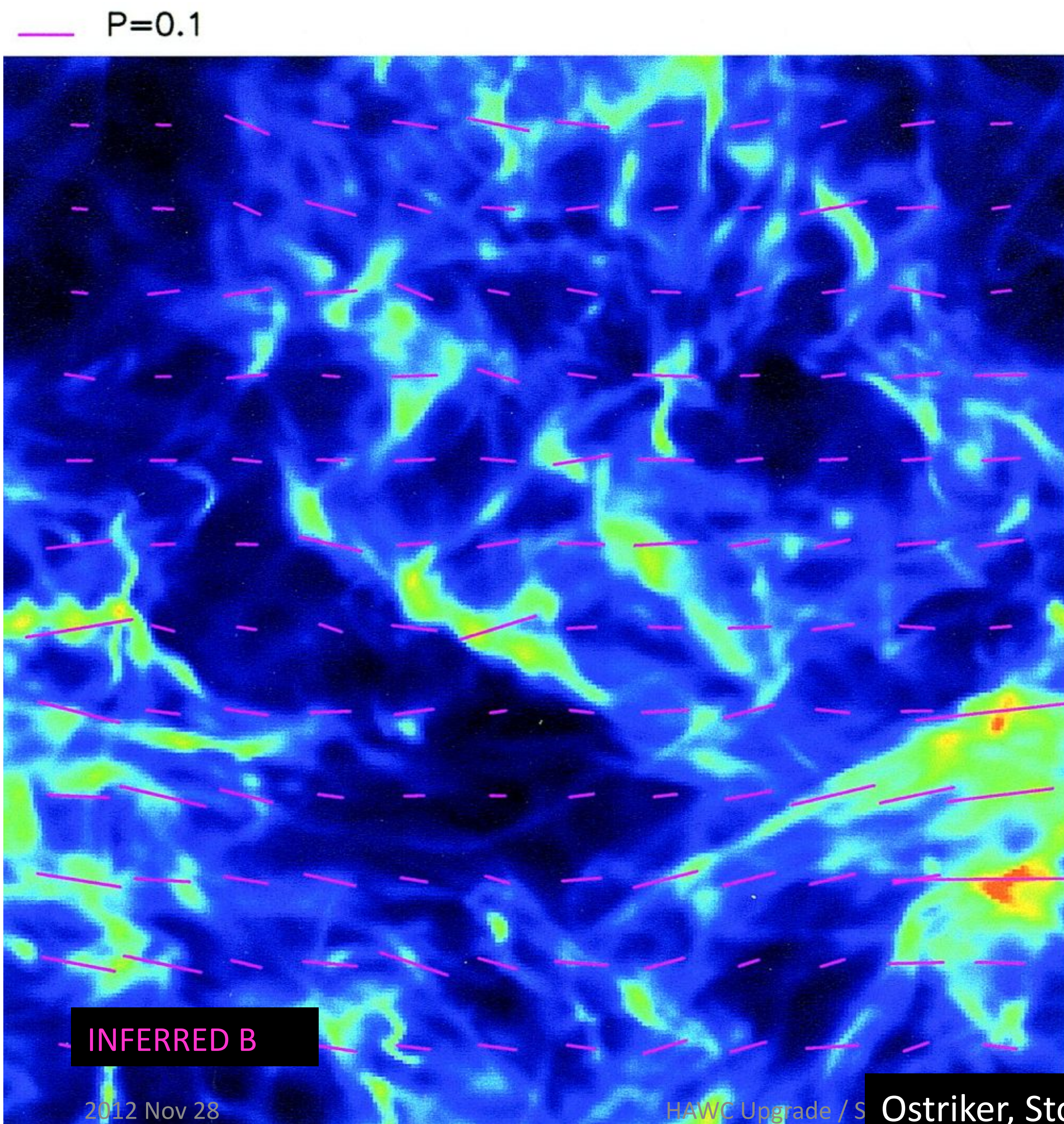
Magnetic field is preferentially along short axis of dense GMC cloud cores.





elongated **round**

Tassis, et al. (2009)



Ostriker, Stone, & Gammie (2001)

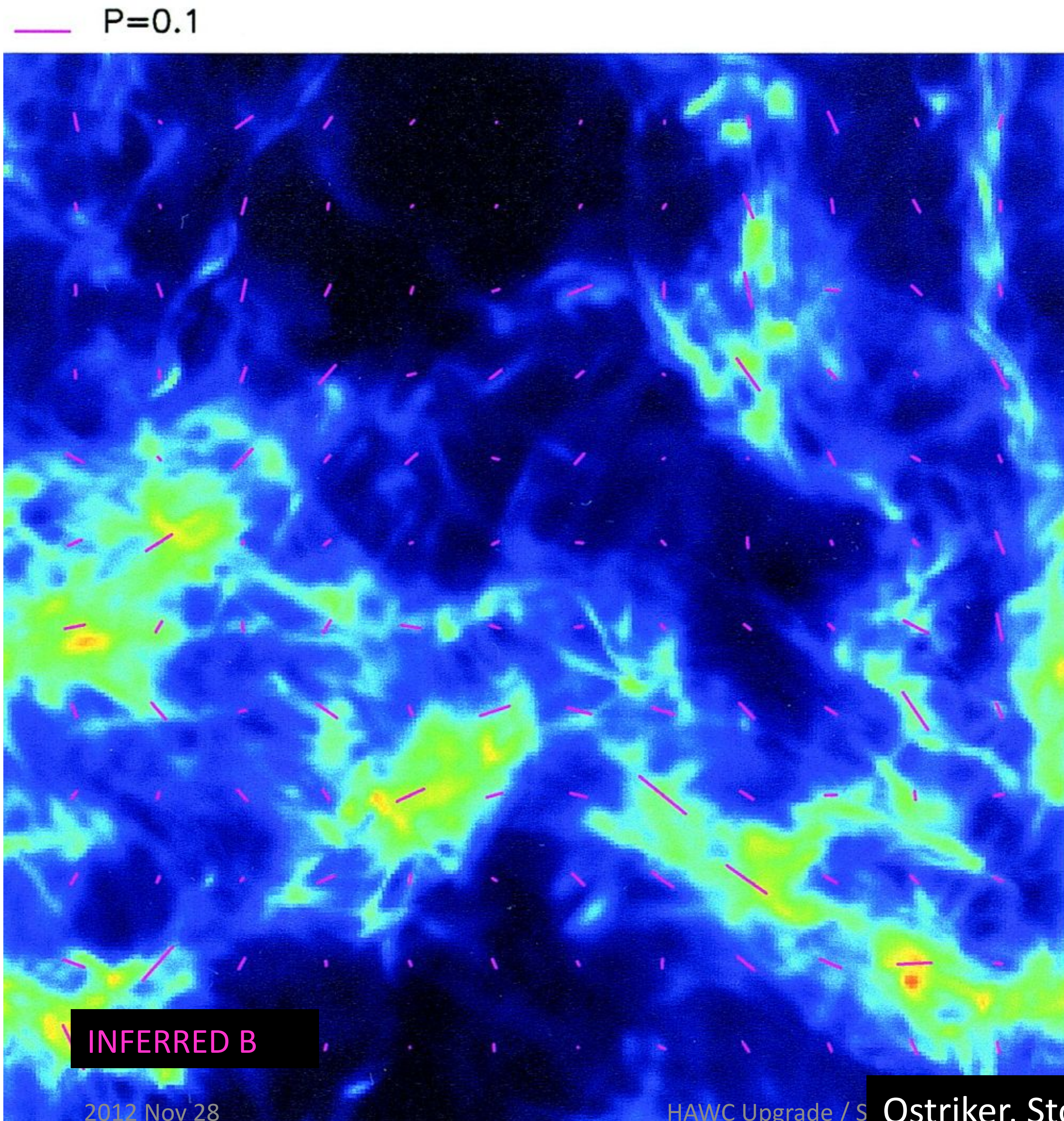
simulated GMC

3-dimensional simulation of magnetohydro-dynamic (MHD) turbulence;

- compressible
- high Mach #
- incl. self-gravity
- isothermal

strong B-field

σ_ϕ = 9.6°



simulated GMC

weak B-field

σ_ϕ = 45.3°

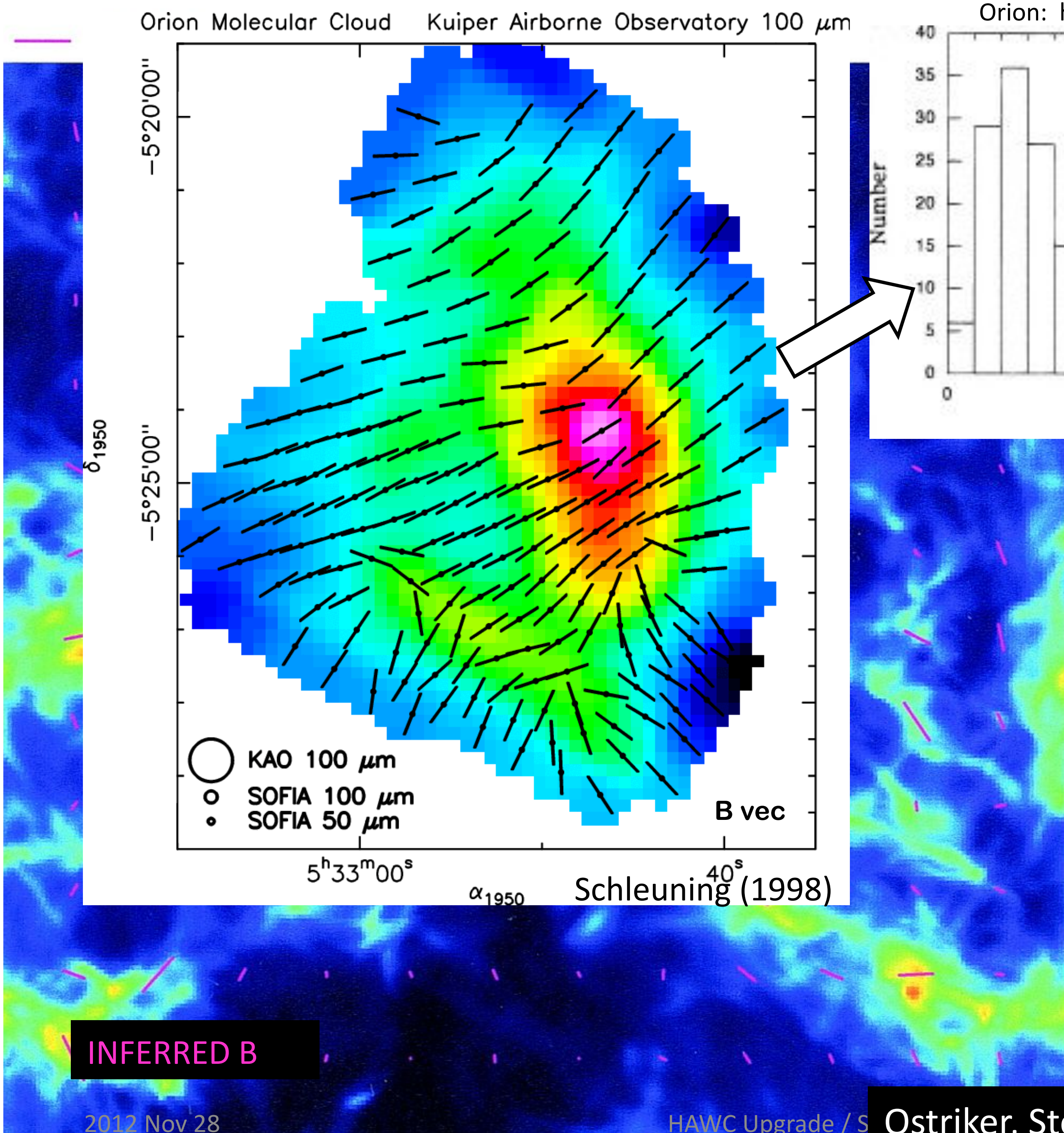
can determine |B|

from σ_ϕ :

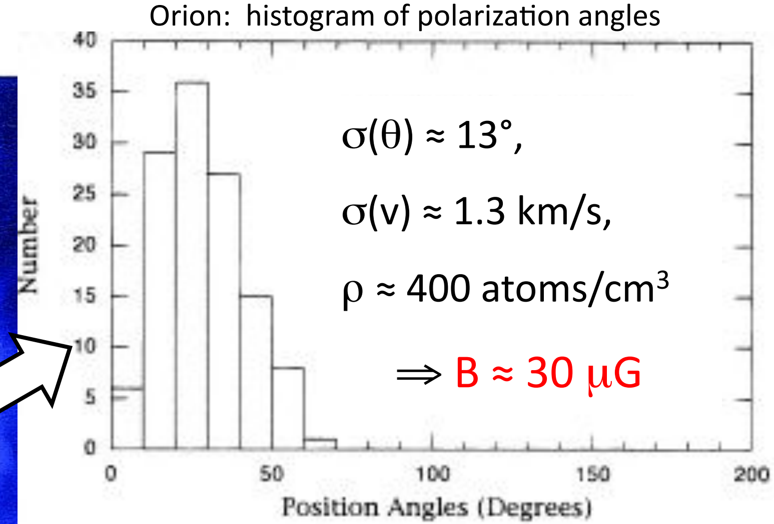
$|B| = k\rho^{1/2}\sigma_v/\sigma_\phi$

(Chandrasekhar & Fermi 1951)

Ostriker, Stone, & Gammie (2001)



Schleuning (1998)



$\sigma(\theta) \approx 13°$,

$\sigma(v) \approx 1.3$ km/s,

$\rho \approx 400$ atoms/cm^3

$\Rightarrow$ B $\approx$ 30 μG

can determine |B| from σ_ϕ :

$$|B| = k\rho^{1/2}\sigma_v/\sigma_\phi$$

(Chandrasekhar & Fermi 1951)

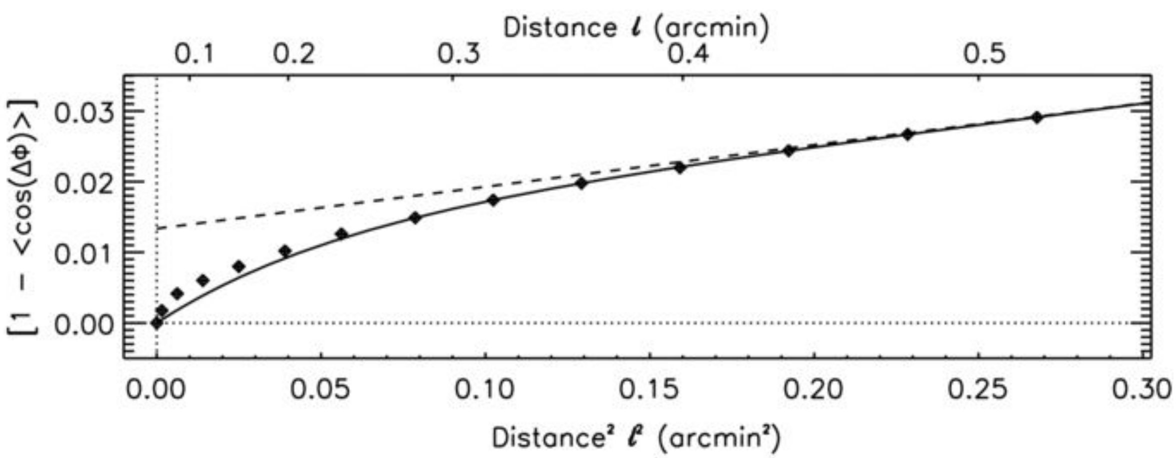
Ostriker, Stone, & Gammie (2001)

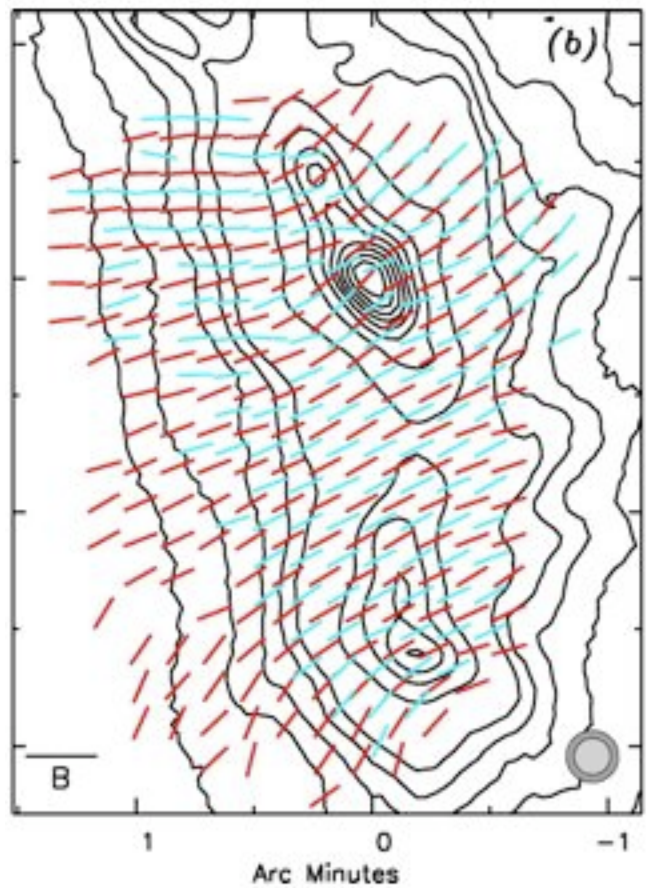
Use of polarization angle structure functions to study power spectrum of magnetized turbulence

Hildebrand et al. '09; Houde et al. '09, '11

angle $\Phi(\mathbf{x})$

$$\Delta\Phi(\ell) \equiv \Phi(\mathbf{x}) - \Phi(\mathbf{x}+\ell)$$



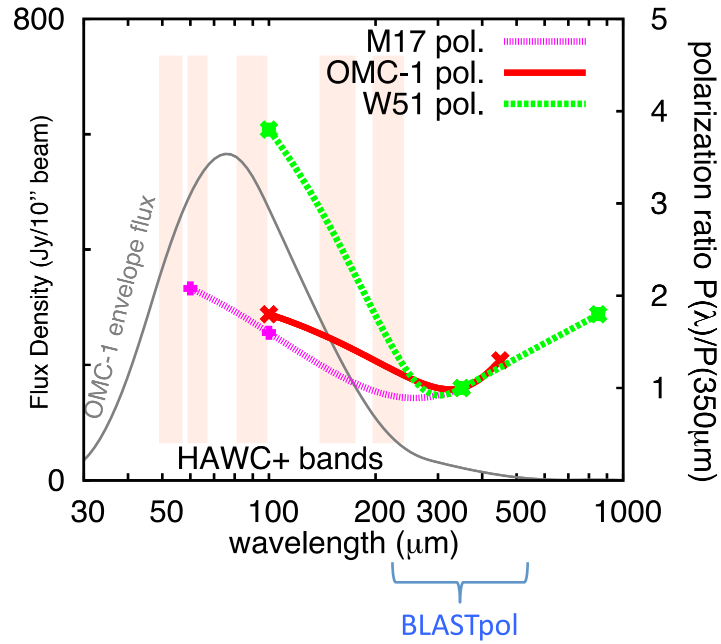


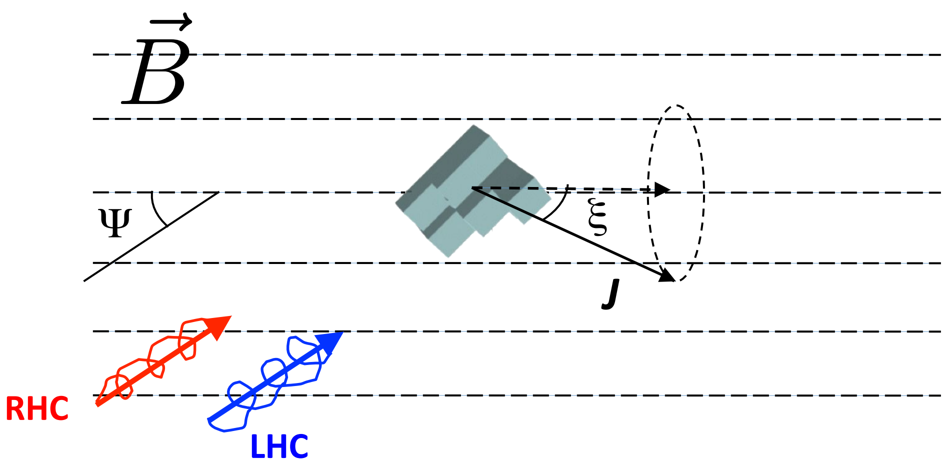
- *characteristic eddy size: ~10 mpc*
- *magnetic field strength: ~0.8 mG*

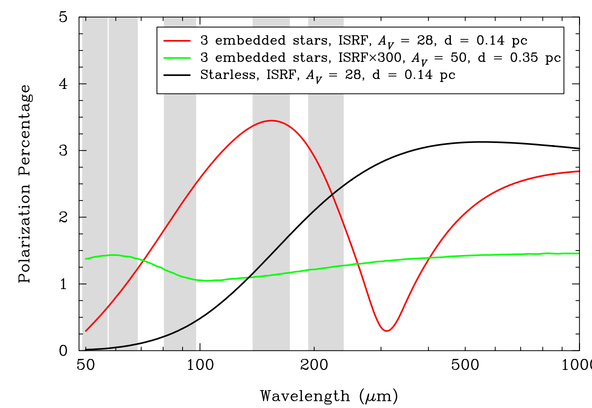
SCTF next week: Martin Houde

Dust Grain Alignment

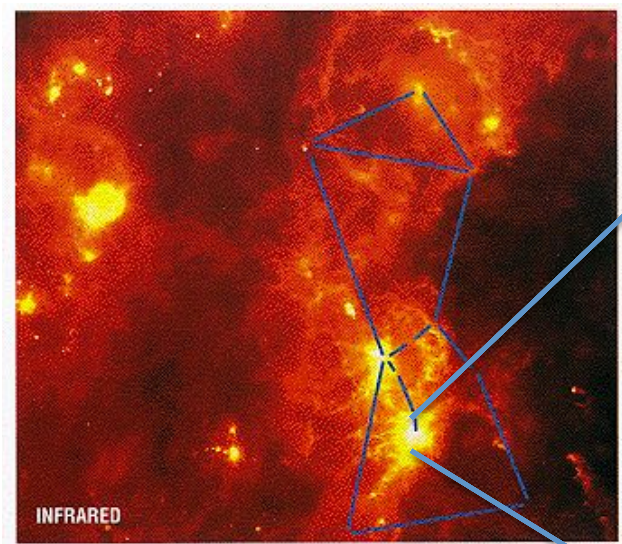
- Dust grain alignment is an unsolved problem of astrophysics.
- Alignment is with respect to magnetic field: Larmor precession ($t \approx 10^6$ s) washes out alignment with respect to any other direction. (Martin 1971)
- Radiative alignment, requiring asymmetric grains and an asymmetric radiation field, is currently the leading theory (A. Lazarian and collaborators).
  – Test #1: Does the degree of grain alignment depend on the strength of the radiation field?
  – Test #2: Is there spectral evidence for better alignment of large grains?
- (See Vaillancourt talk on SCTF, Oct. 2012, for more details.)

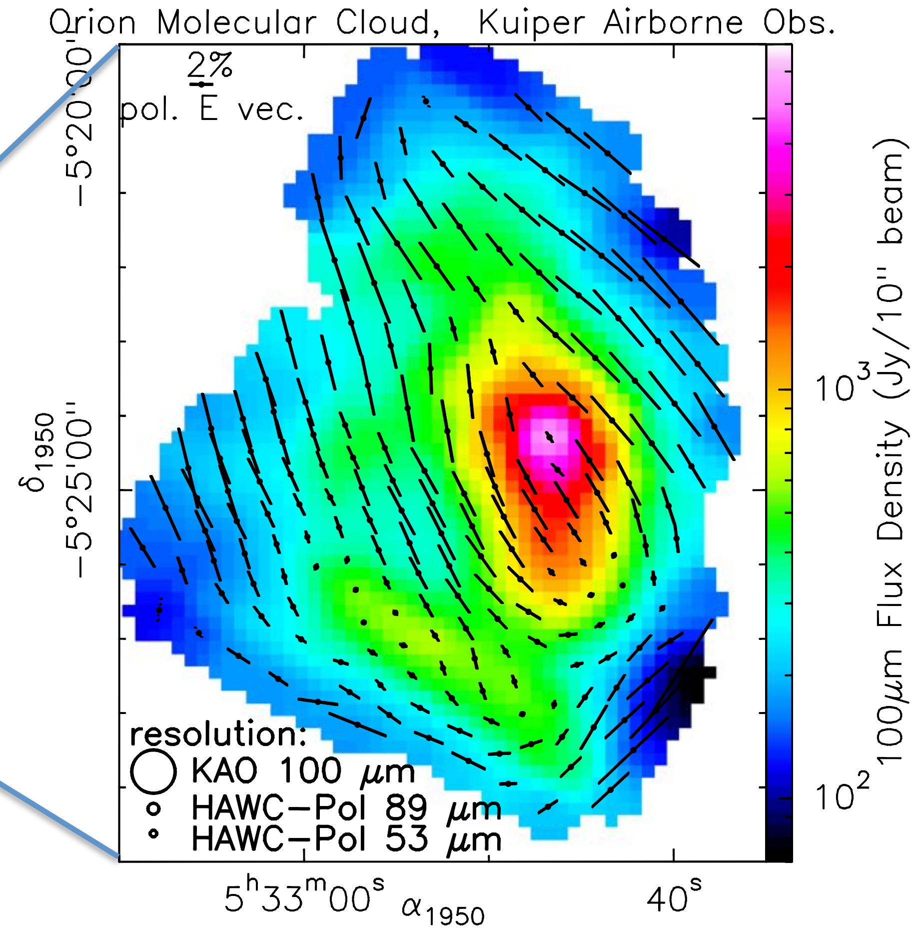






HAWC+/SOFIA Science Goals



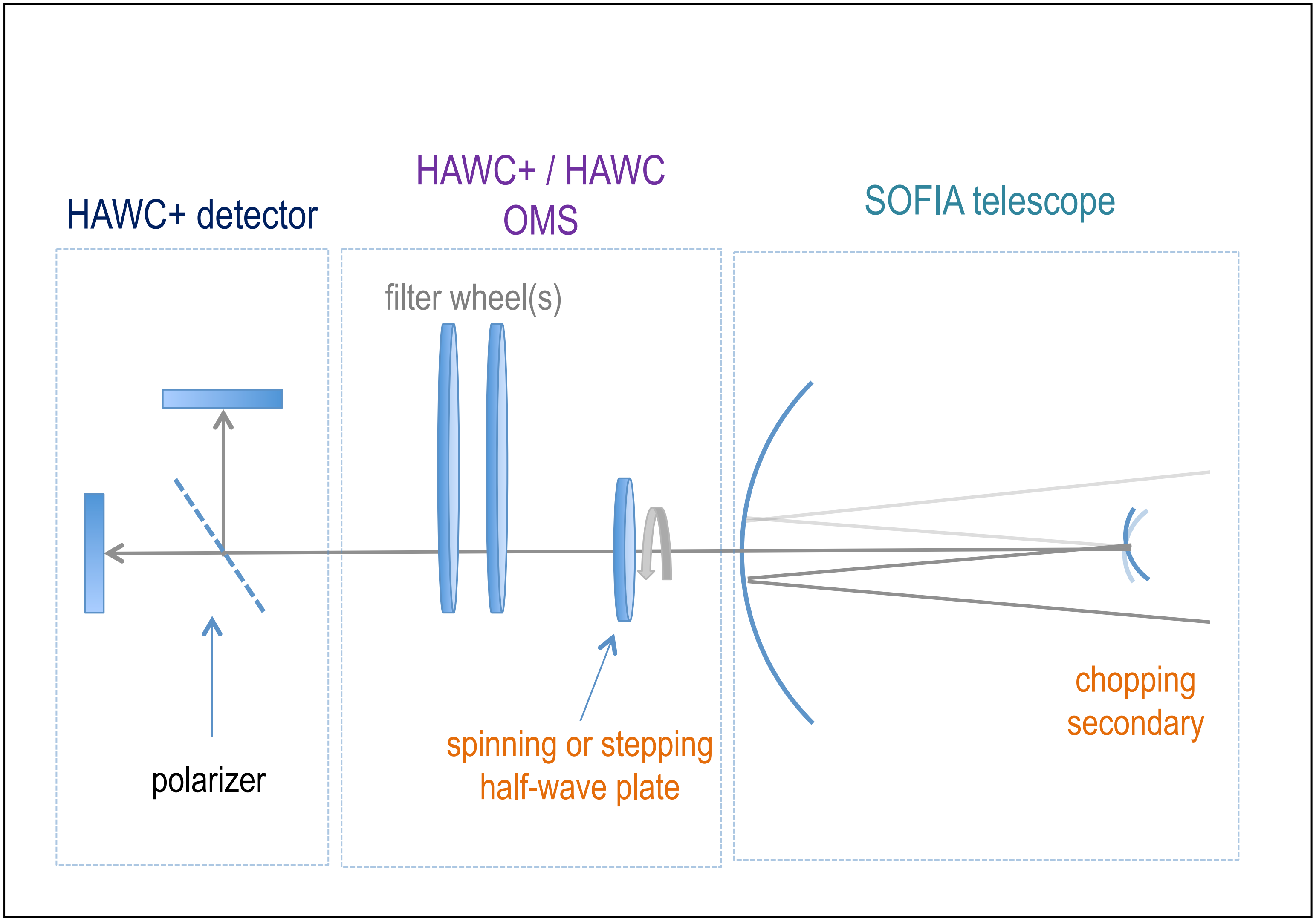


- Compared to previous facilities (polarimetry):
  - 8 × more sensitive to extended emission (can reach $A_V \approx 1$)
  - 50× more sensitive to point sources
  - 10× better areal resolution
  - 20× as many imaging elements
  - 5 wavelength bands instead of 1

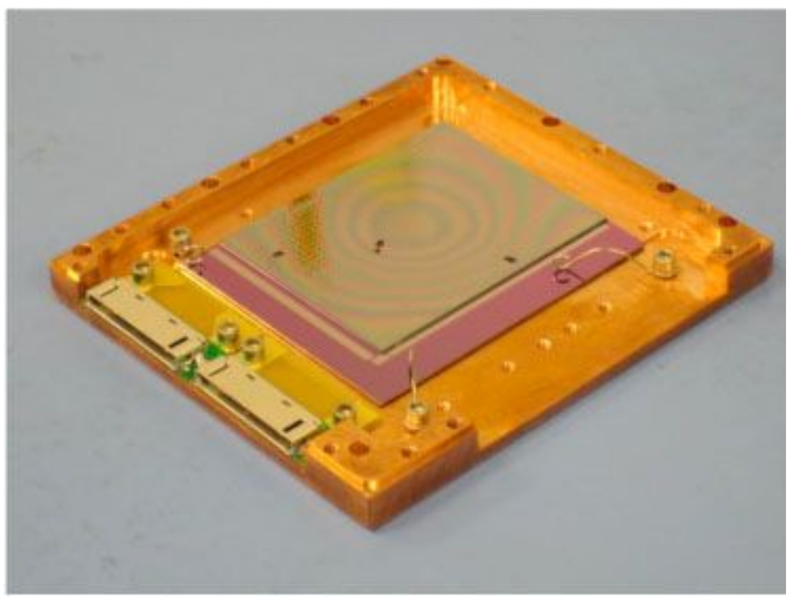
- tests of (ordered) magnetic field models
- statistical estimation of field strength (Chadrasekhar-Fermi)
- tests of grain alignment theory (Radiative Torque alignment)

HAWC+ builds on HAWC

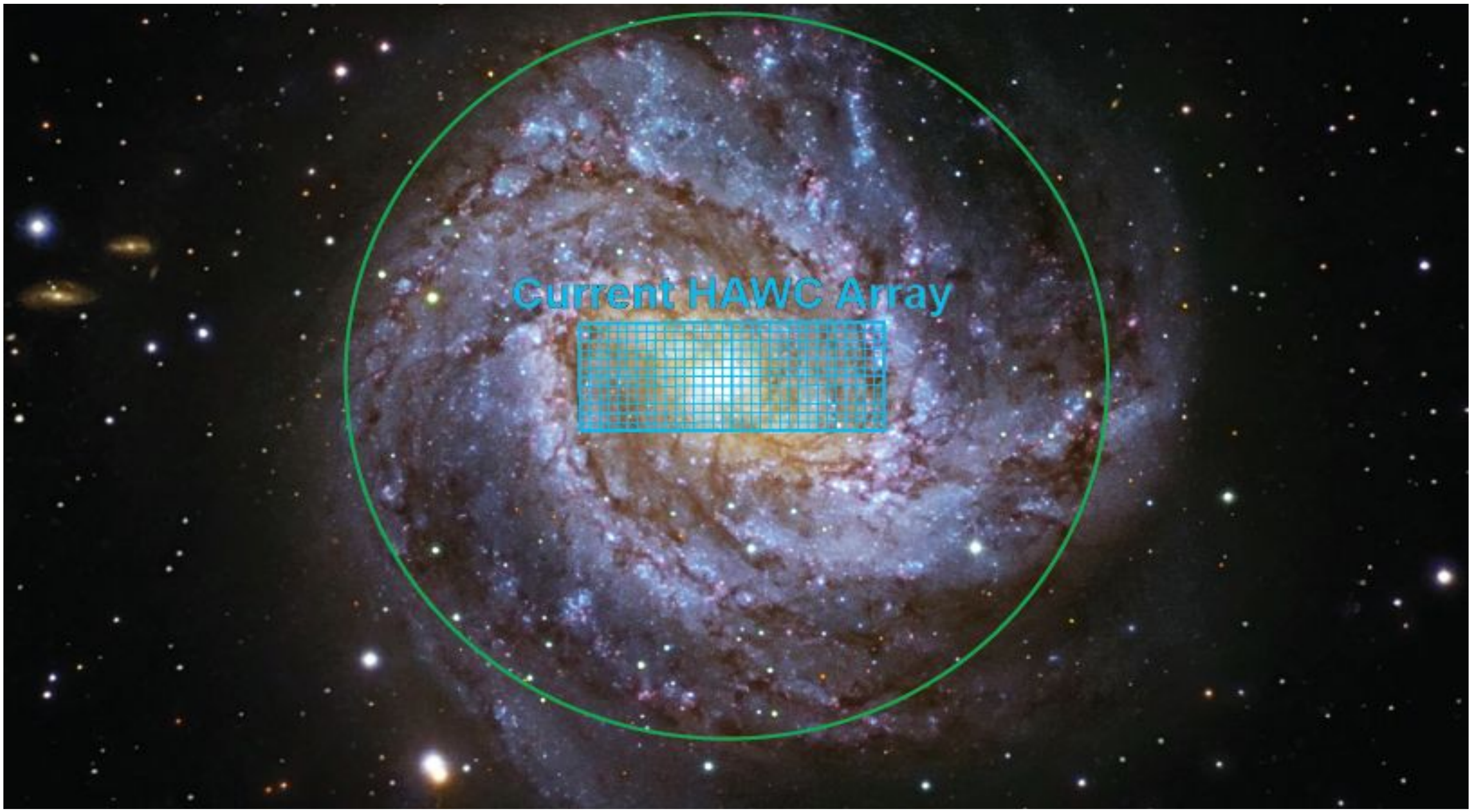
HAWC+ schematic optical path



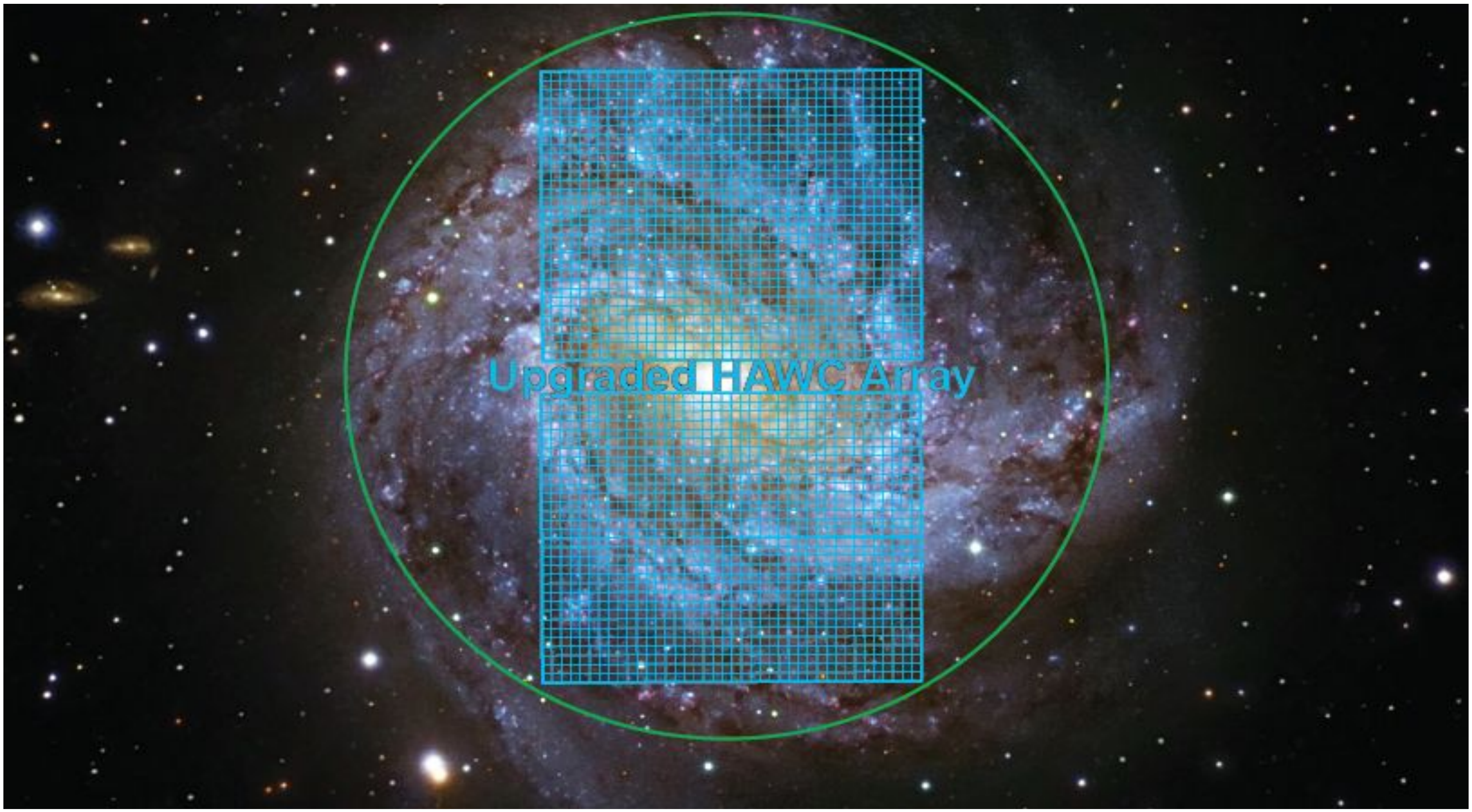
Hybridized, Kilopixel, Backshort-Under-Grid (BUG) Bolometer Arrays with Superconducting Through Wafer Vias for Far Infrared Imaging and Polarimetry



HAWC on SOFIA: 12×32



HAWC+ on SOFIA: 64×40



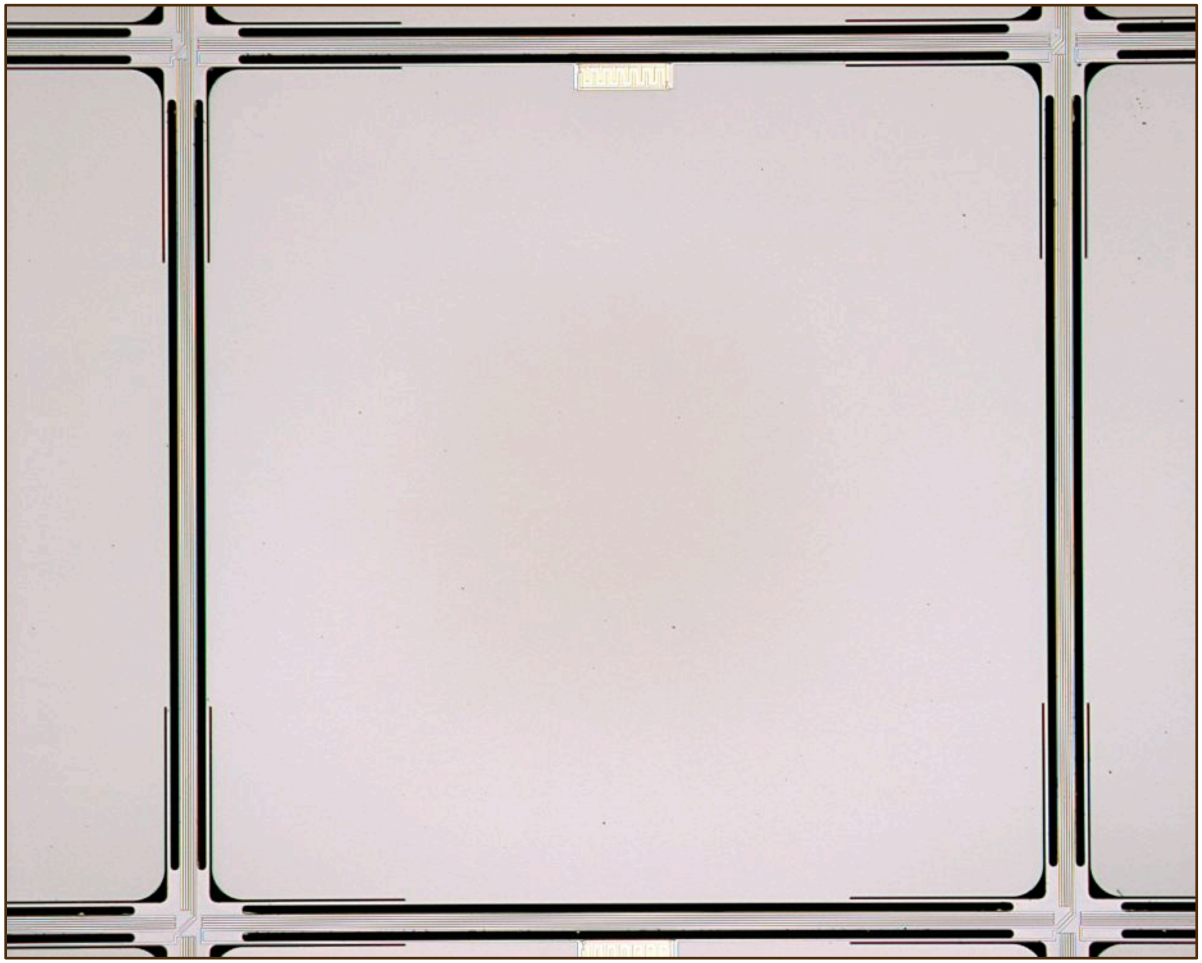
HAWC+ Requirements

- Array format 2×(32×40), with dark pixels; two array mosaics needed for flight
- Each array must be sensitive over the full HAWC+ wavelength range (50-230μm)
- Detectors saturate at >60 pW
- Time constant <<17 ms
- Detector NEP < 8×10^{-17} W/√Hz @ 1 Hz

Key Features

- Superconducting transition edge sensor on leg-isolated membrane bolometers.
- Filled array absorbers with tuned resonant cavities per pixel – enables effective designs
- Hybridized to SQUID TDM multiplexer beneath bolometer –high-performance
- Assembled into package with integral RF, thermal, and bandpass filters; connectorized for modularity

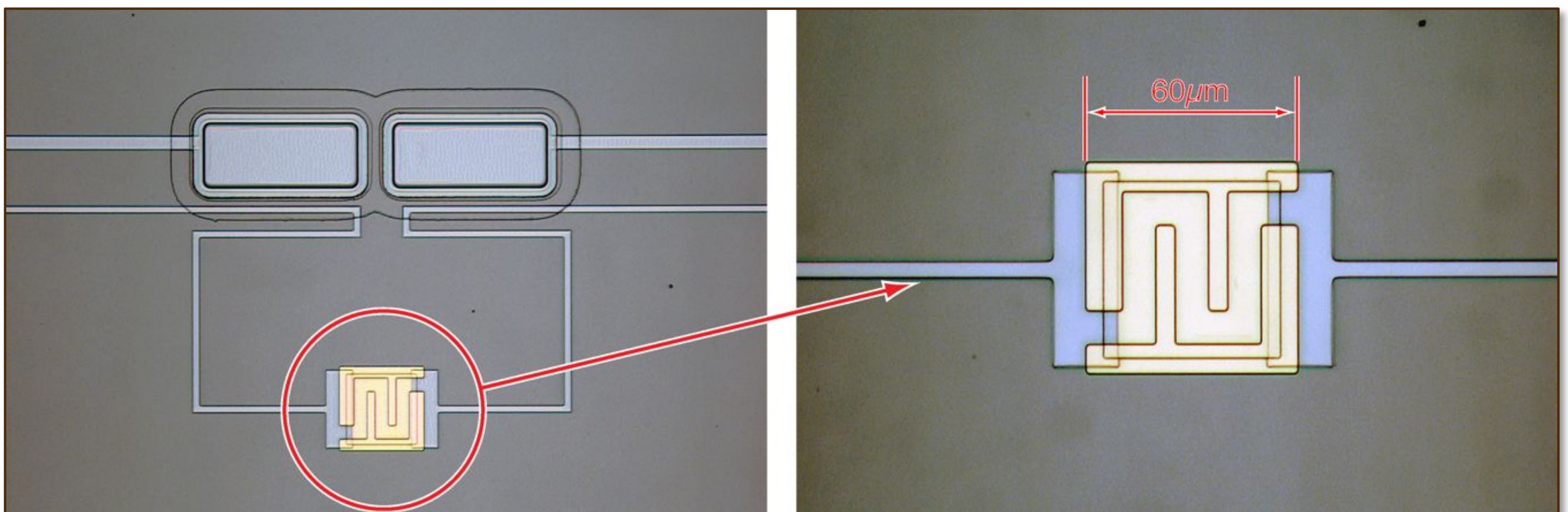
8-leg (GISMO-like) Design



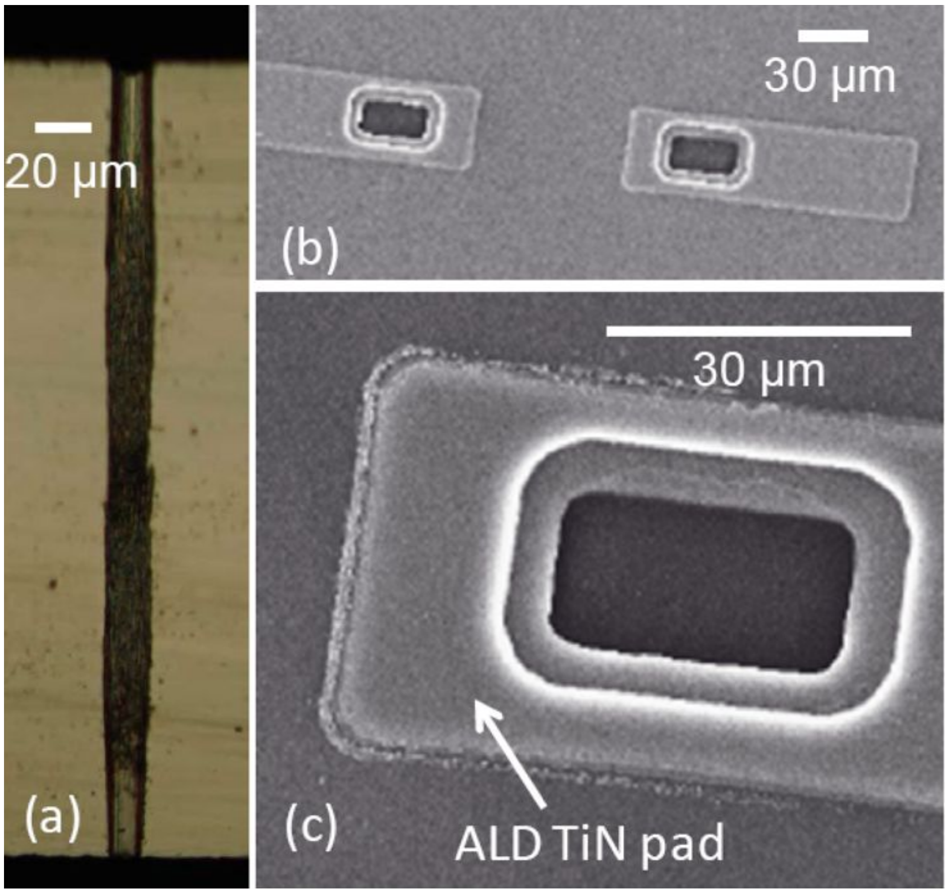
- Designed for 1.135mm pitch
- Geometric filling factor ~95%
- Fabricated on 1.4μm single crystal silicon on insulator
- Back fully removed by DRIE

Transition Edge Sensor Design

- Mo/Au bilayers on SOI wafers
- Small TES tied to wrap-around vias
- Normal metal bars suppress α-noise



Through-Wafer Via Array Cell



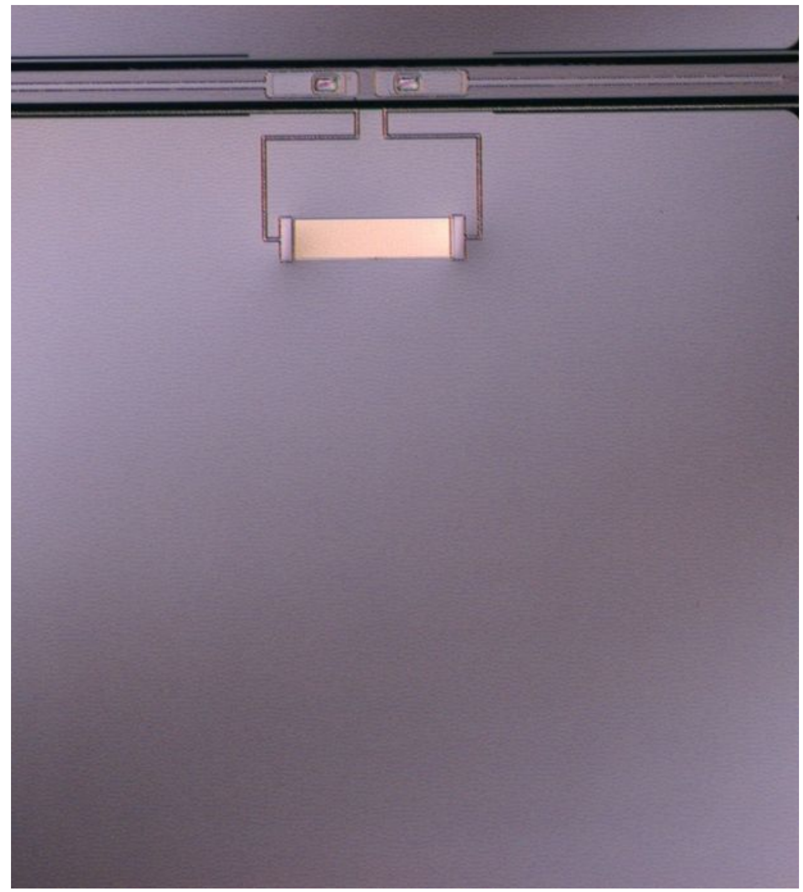
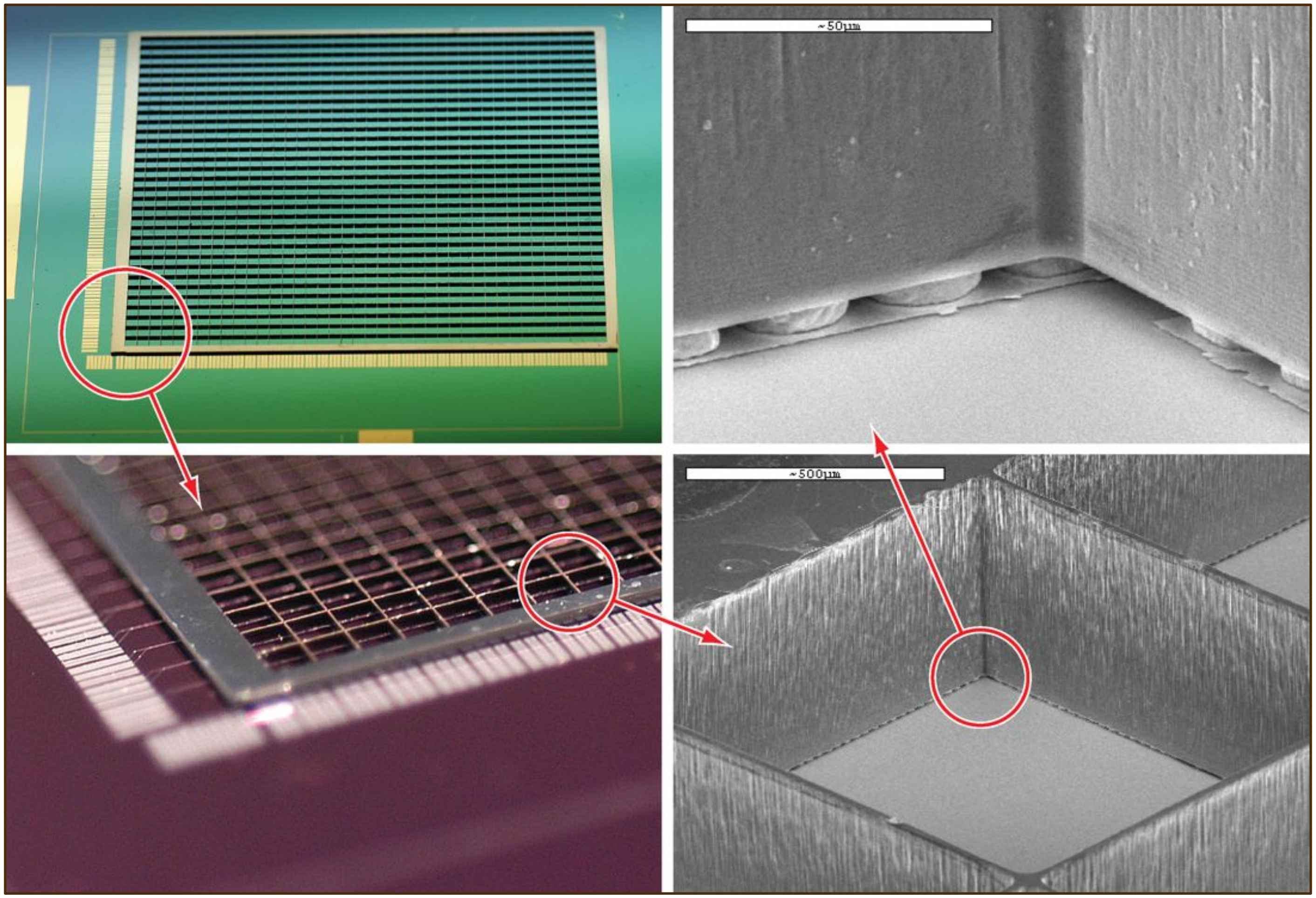
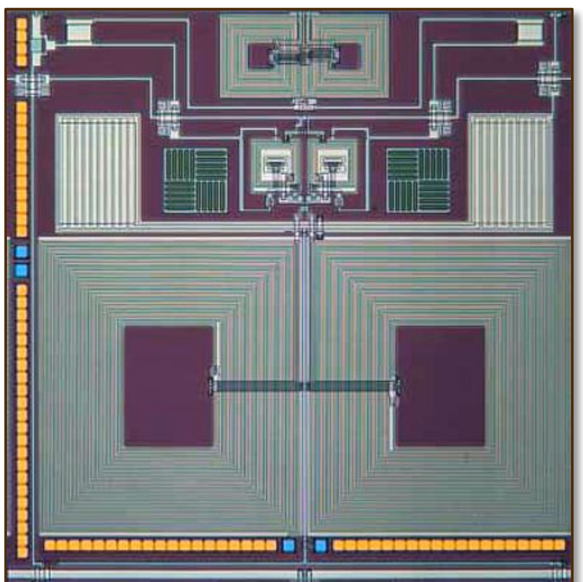


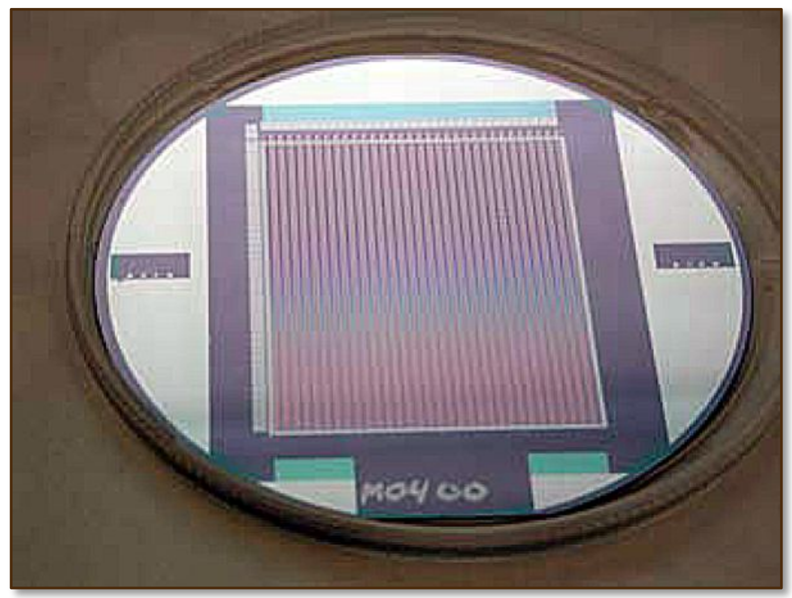
Diagram of Bump Bonding



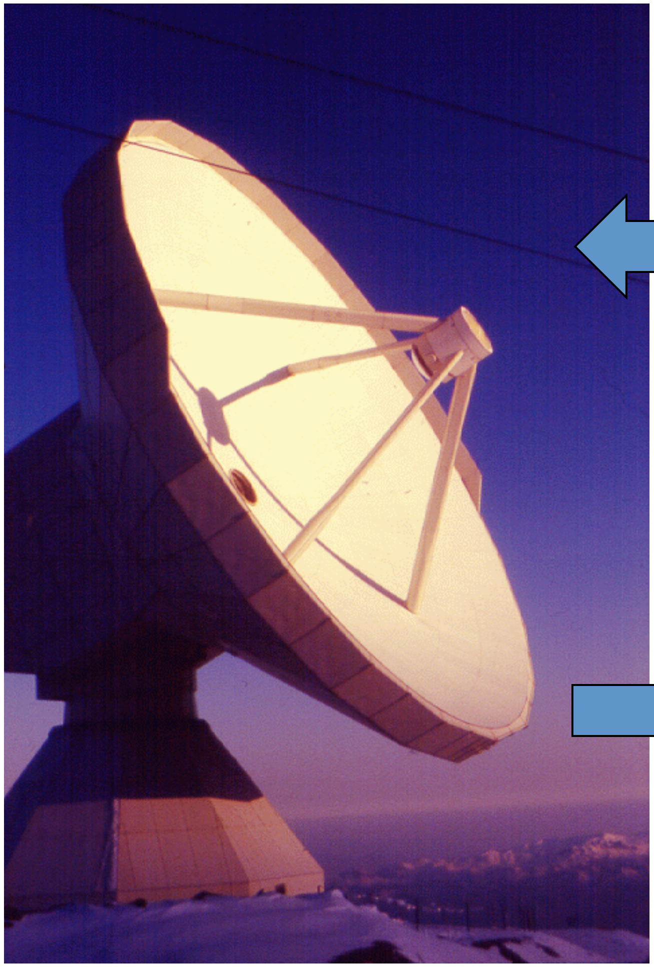
Multiplexer Design

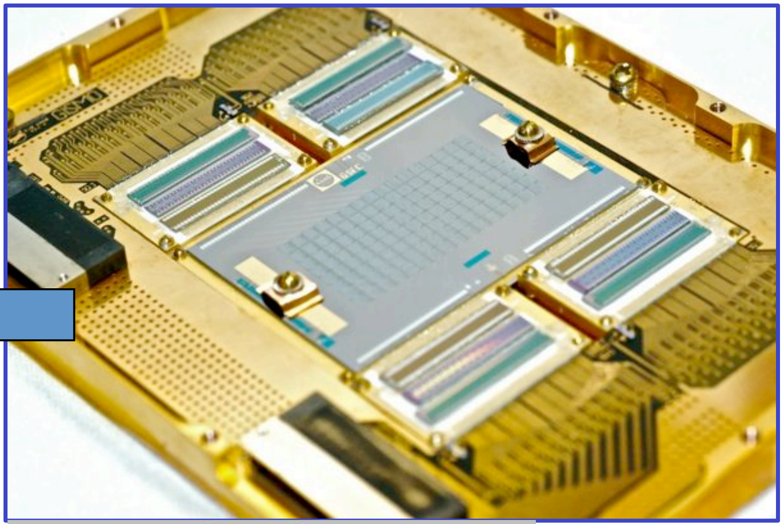
- “Goddard Mux” based on “SCUBA-2 Mux” heritage



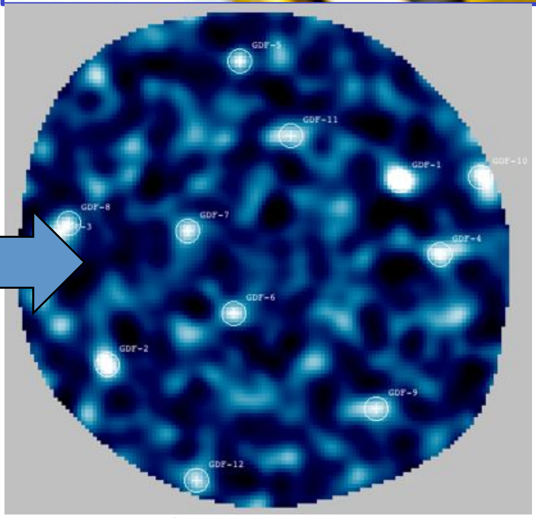


Heritage: GISMO



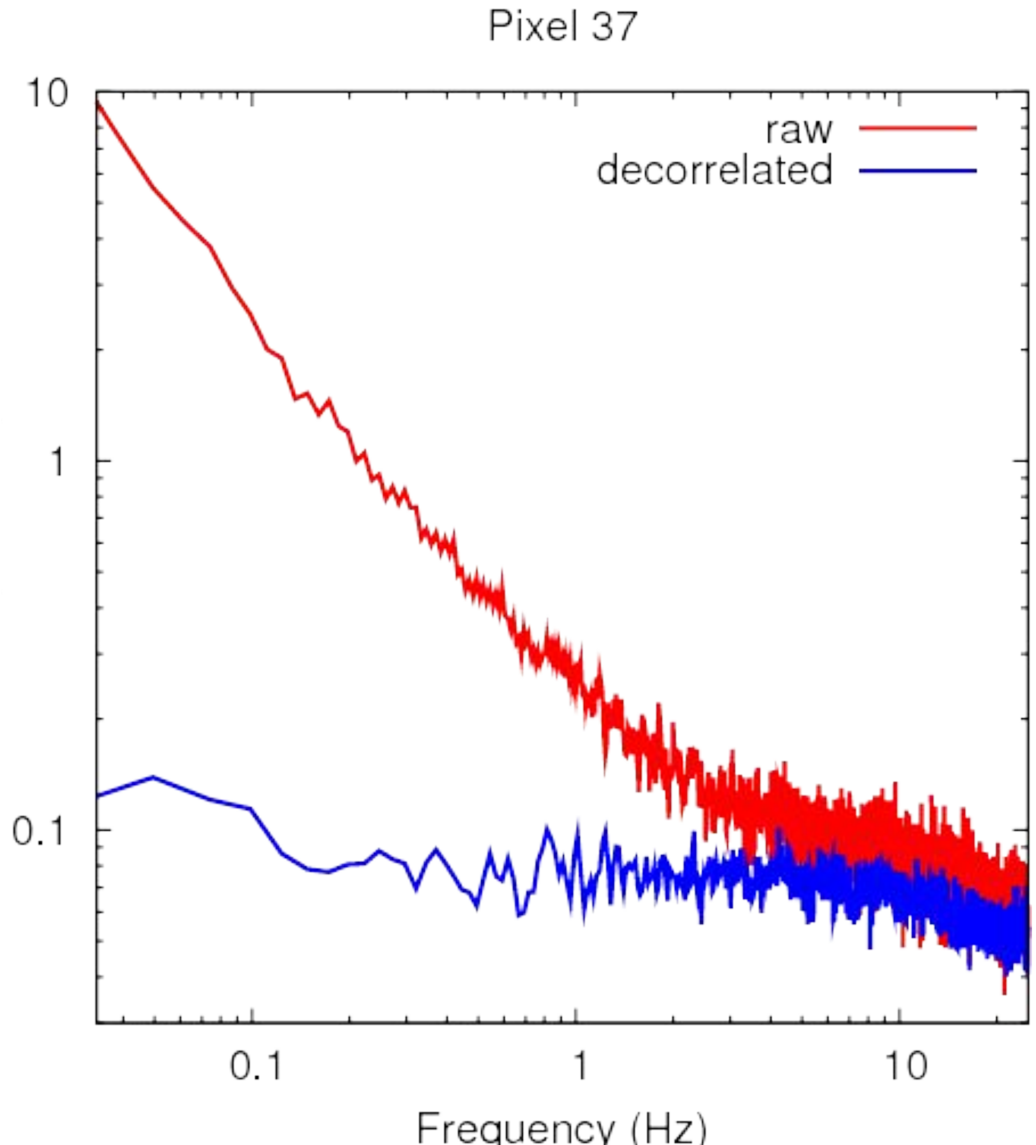


Backshort under Grid (BUG) TES detector array

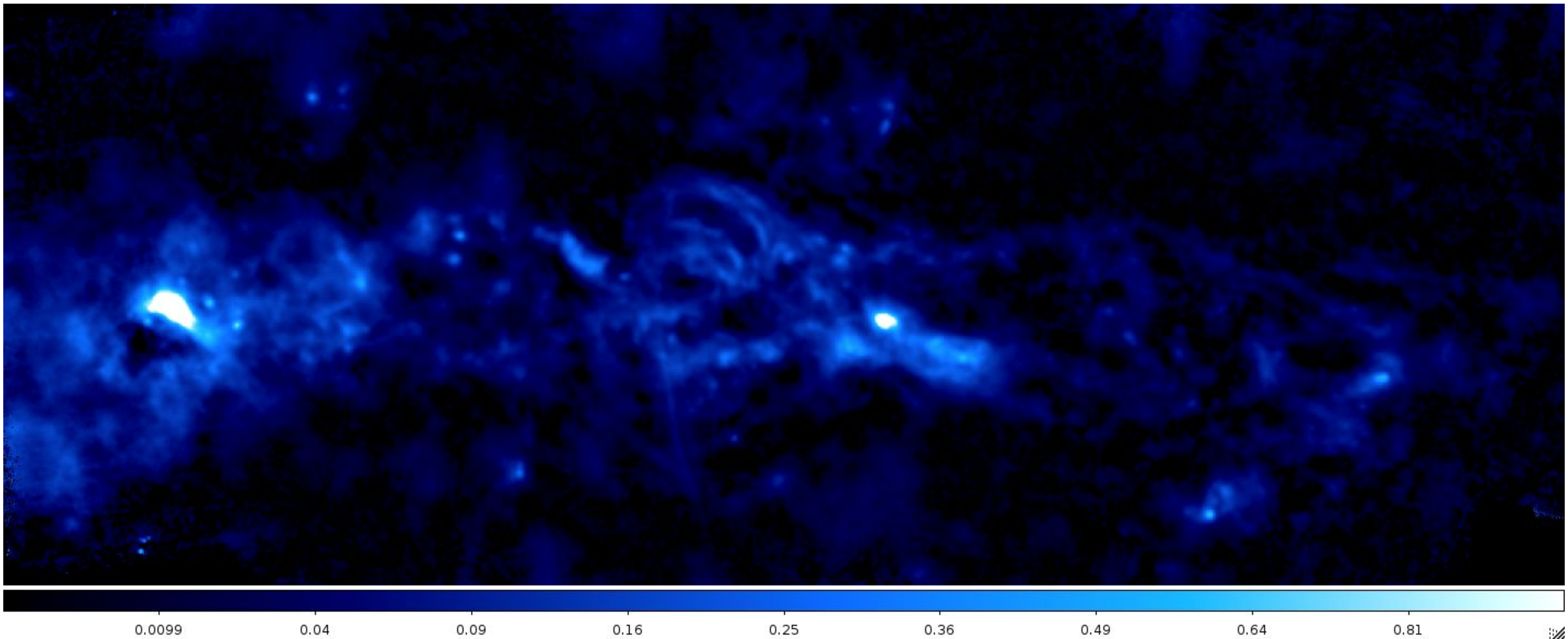


GISMO Deep Field (GDF)

GISMO – Pixel Noise Spectrum on Sky

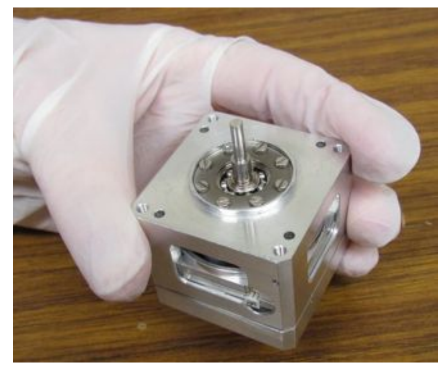


Galactic Center @ 2mm



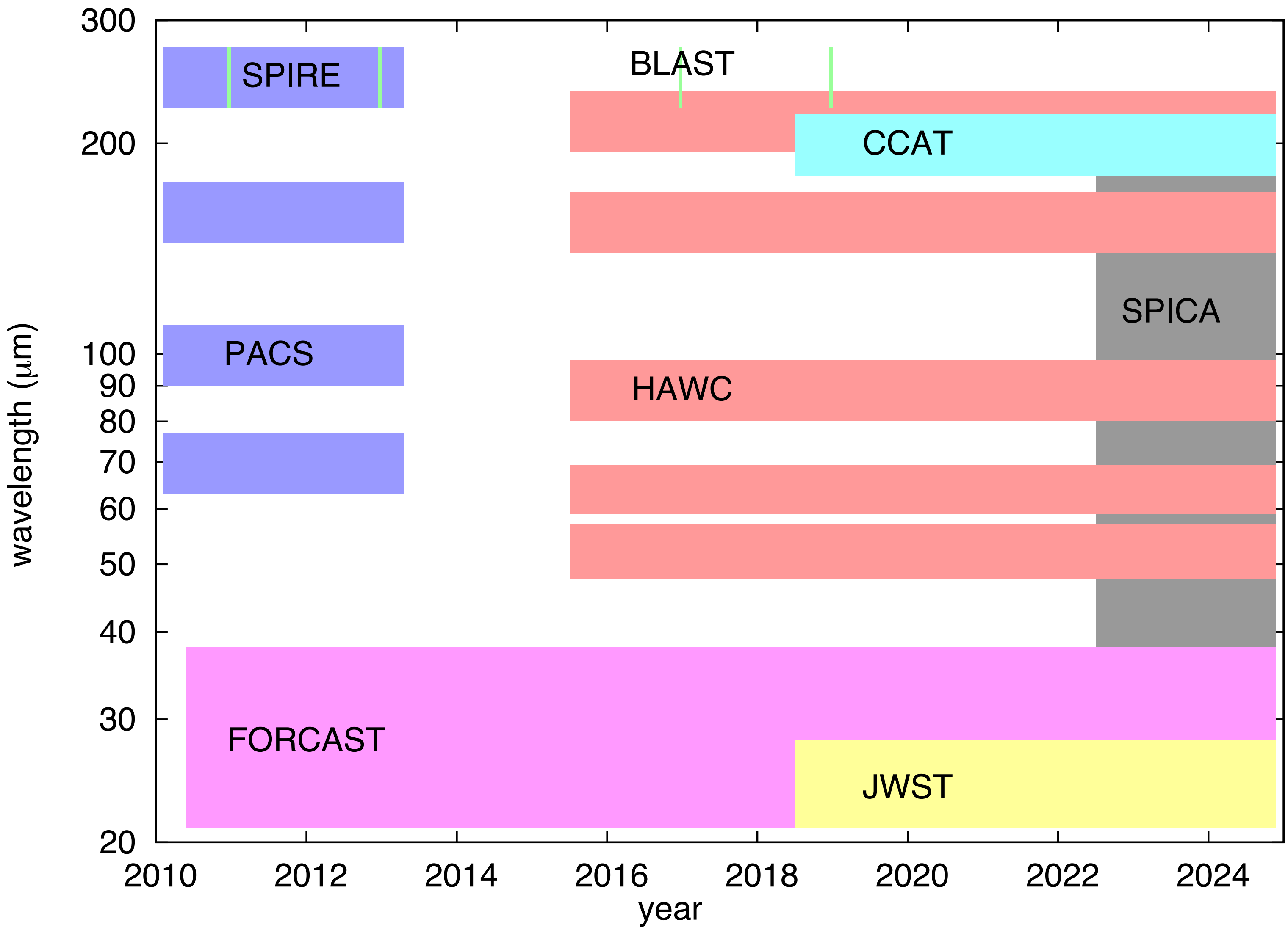
t_int (including pointing measurments): 6.5 hours
NEFD ~ 9 mJy rt(s)
noise in map: 2 - 2.5 mJy
dynamic range >1000

HAWC Upgrade – Polarimeter



- HAWC+ uses four monochromatic quartz half-wave plates in pupil wheel.
- Selected half-wave plate is spun continuously or stepped, driven by a cryogenic motor from U. Illinois.
- Hardware is in advanced state of development at JPL.

HAWC fills a key wavelength gap for many years.



(Shown are imagers with sub-arcminute resolution.)

HAWC+ Performance

Table 1-1. HAWC+ predicted performance for continuum imaging and polarimetry.

Instrument	Instrument Parameter	Band 1	Band 1.5	Band 2	Band 3	Band 4
HAWC and HAWC+	wavelength (μm)	53	63	89	155	216
	angular resolution (arcsec FWHM)	5.4	6.4	9.0	16	22
	imaging NEFD[a] (Jy/beam $s^{1/2}$)	0.87	0.79	0.59	0.60	0.44
HAWC+	field of view (square arcmin)	4.6	11	11	33	59
	min. flux density[b] for σ(P) < 0.3% in 1 hr (Jy/beam)	10	9	7	7	5
	min. surface brightness[b] in 1 beam for σ(P) < 0.3% in 1 hr (MJy/sr)	13,000	8000	3000	1000	400
	min. column density[b] for σ(P) < 0.3% in 1 hr (A_V)	0.9	1.2	1.8	5	4

[a]*Published performance of HAWC (http://www.sofia.usra.edu/Science/instruments/instruments_hawc.html). Noise Equivalent Flux Density gives the flux density detectable with signal-to-noise=1 in a 1 second integration time. Signal-to-noise scales as (flux/NEFD) × (time)$^{1/2}$.*

[b]*Assumes 60% observing efficiency and an instrument such as HAWC+ which simultaneously detects two polarization states. The quantity σ(P) refers to the uncertainty in the measured degree of polarization, expressed as a percentage.*

HAWC GTO Science Programs

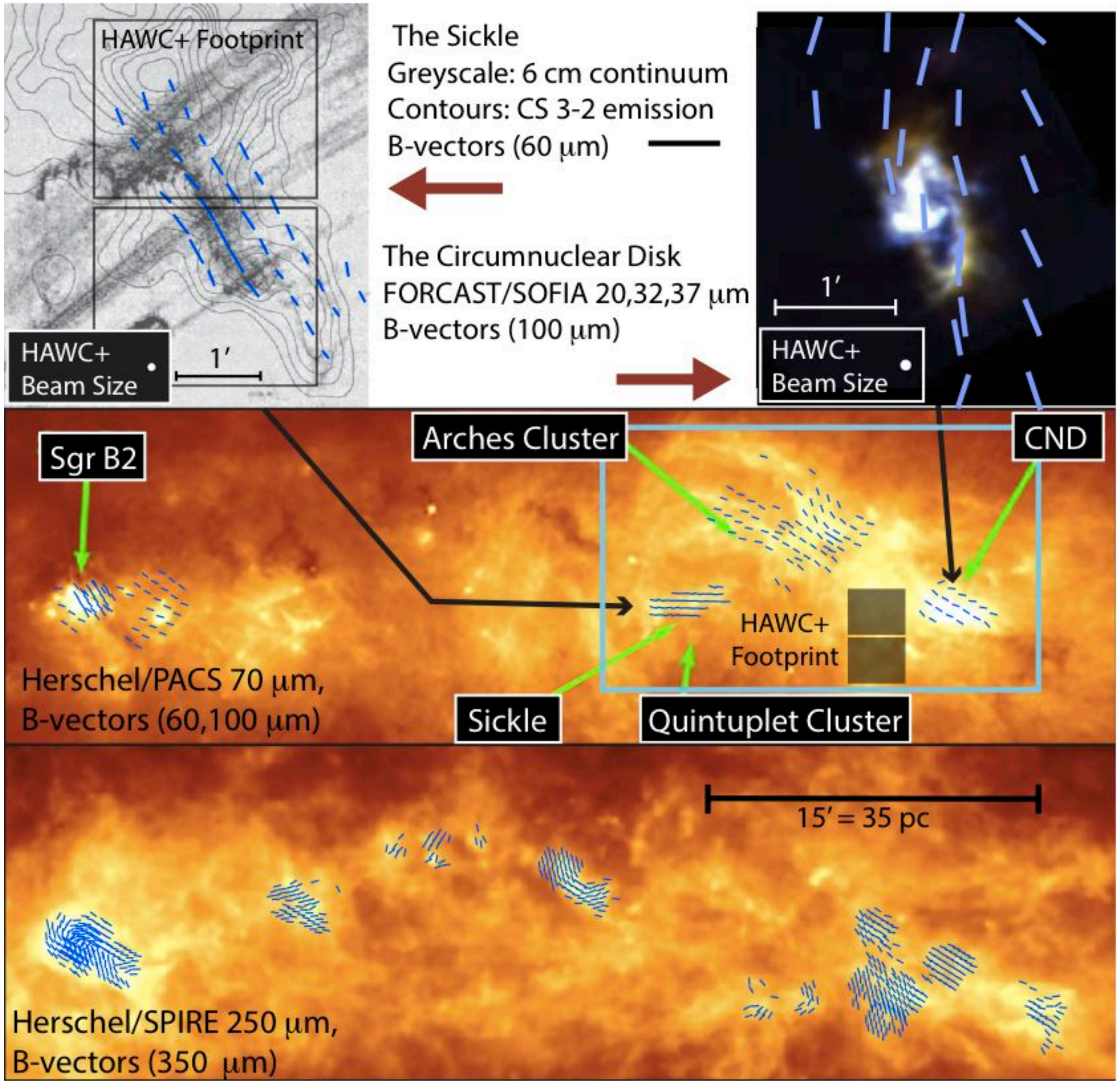
- Multi-disciplinary HAWC+ science team will be collaborating to prioritize objects for observation and then interpret results:
  - **polarimetry, data analysis, and star formation:** P. Ade, D. Benford, M. Berthoud, N. Chapman, D. Chuss, J. Dotson, D. Dowell, S. Hanany, D. Harper, A. Kovacs, G. Novak, P. Goldsmith, T. Henning, R. Hildebrand, M. Houde, T. Jones, J. Staguhn, D. Ward-Thompson, J. Vaillancourt
  - **diagnostics of ISM:** J. Bally, E. Churchwell, R. Crutcher, D. Dale, J. Davidson, E. Dwek, A. Eckart, L. Looney, M. Morris, H. Moseley, E. Schinnerer, K. Sheth, G. Stacey, M. Werner
  - **MHD and grain alignment theory:** A. Lazarian, K. Tassis, B. Whitney, H. Yan, E. Zweibel
- Main themes are:
  - magnetic field strength and structure in Galactic clouds at a variety of evolutionary states
  - magnetic field structure of the Galactic center
  - dust grain alignment and characteristics in clouds, supernova remnants, and circumstellar disks

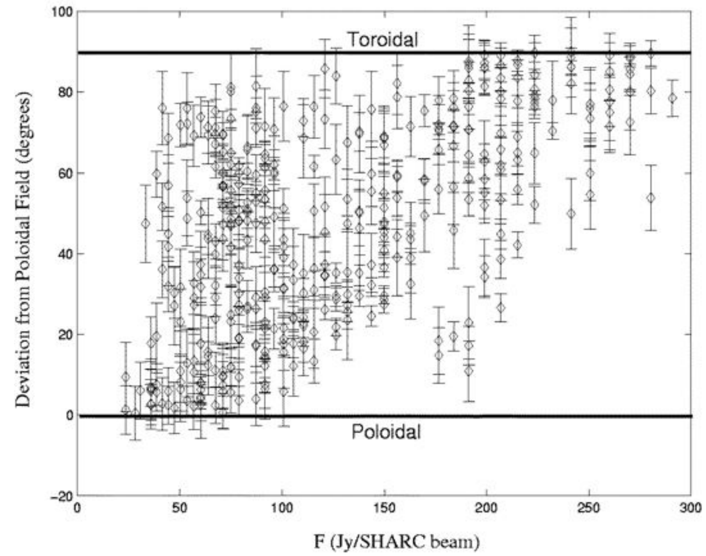
Nearby Galactic Clouds

Vela-C, mapped with Herschel (Hill et al. 2011) – also a target for BLASTpol

- HAWC+ polarimetry has a unique and powerful combination of sensitivity, wavelength coverage, and angular resolution for the study of magnetic fields and grain alignment in Galactic clouds.

Galactic Center



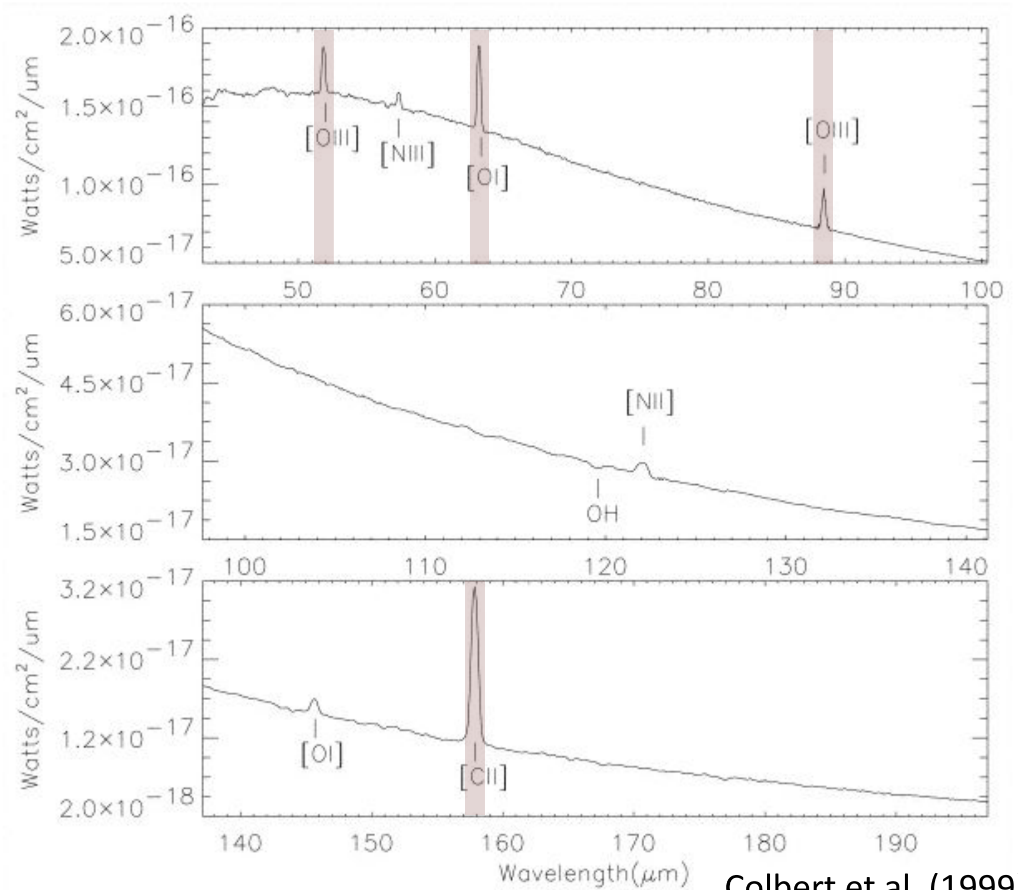


Chuss et al. (2003): CSO and KAO polarization measurements suggest toroidal field in dense material and poloidal in more diffuse, consistent with model of Uchida et al. (1985).

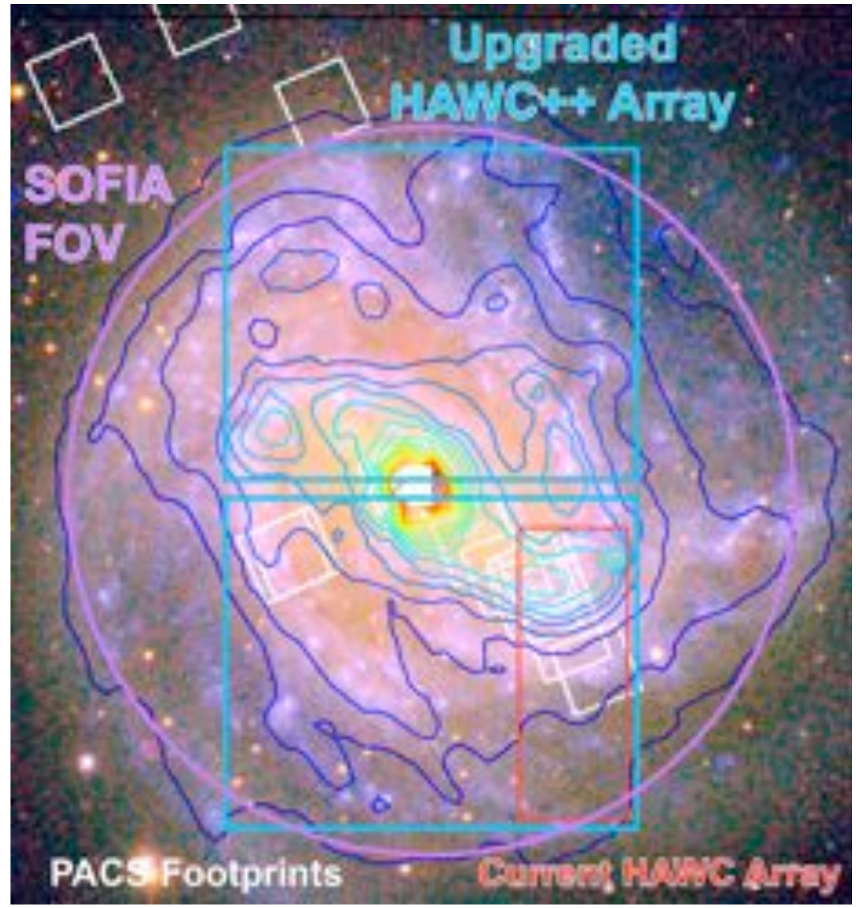
Project Milestones

- According to current schedule:
  - (July 2012: HAWC passed Pre-Ship Review)
  - January 2013: start of upgrade program
  - July 2013: Critical Design Review
  - November 2013: integration and test of HAWC with polarimeter
  - October 2014: integration and test of HAWC with new detector
  - April 2015: delivery to DAOF, followed by commissioning flights

Possible future upgrade: fine-structure line imaging

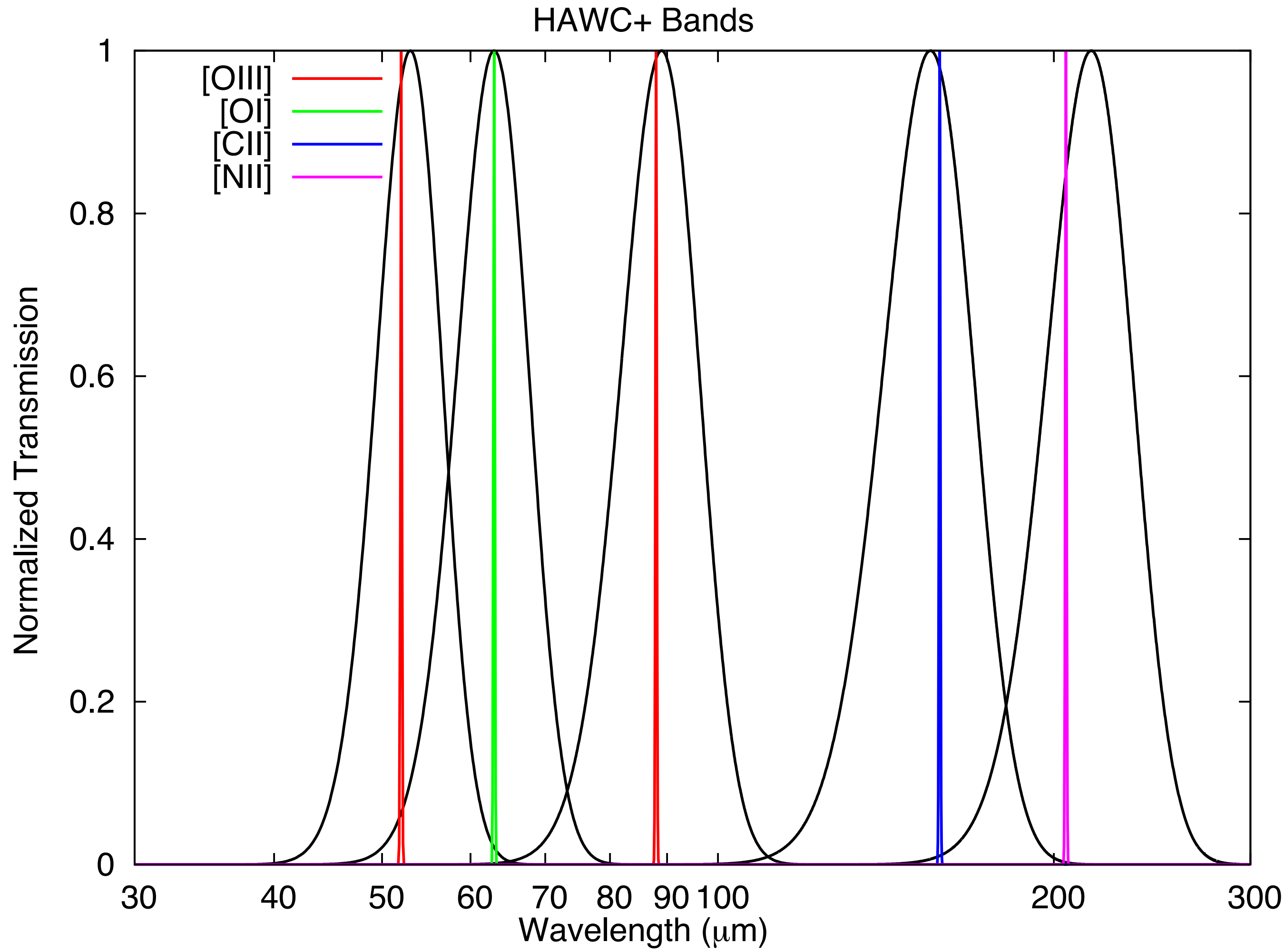


Colbert et al. (1999)



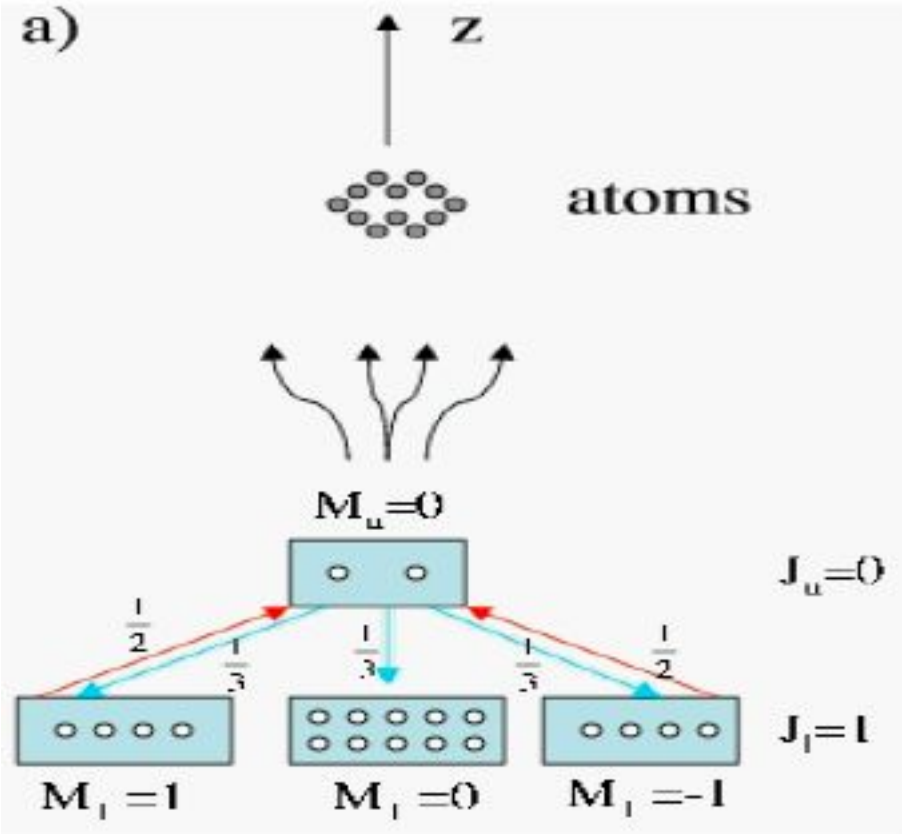
- Due to large detector array in HAWC+, mapping speed for fine structure lines is as good as Herschel.

HAWC+ with fine-structure-line imaging



- 0.5 – 0.9 Jy $s^{0.5}$ sensitivity for continuum imaging and polarimetry
- $3\times10^{-16} – 1\times10^{-15}$ W/m^2 $s^{0.5}$ sensitivity for imaging through R = 300 filters

Fine-Structure-Line Polarization



A toy model to illustrate how a simple two-level atom is aligned by an incident beam of light.

Yan & Lazarian 2006, 2007,2008

•Alignment of atomic gas (i.e. orientation of the angular momentum vector **J**) can be traced by measurement of FS-Line polarization

•Required conditions for FS polarization: atoms/ions embedded in magnetic fields and irradiated by inhomogeneous radiation field.
Consequence: Anisotropic radiation pump the atoms differentially from different magnetic sublevels, resulting in over- or under-populations of the atomic states of various magnetic quantum numbers, **M**

•F-S line excitations dominated by radiative excitation (proof: observations have clearly demonstrated non-LTE distributions of FS line excitations in PDRs)