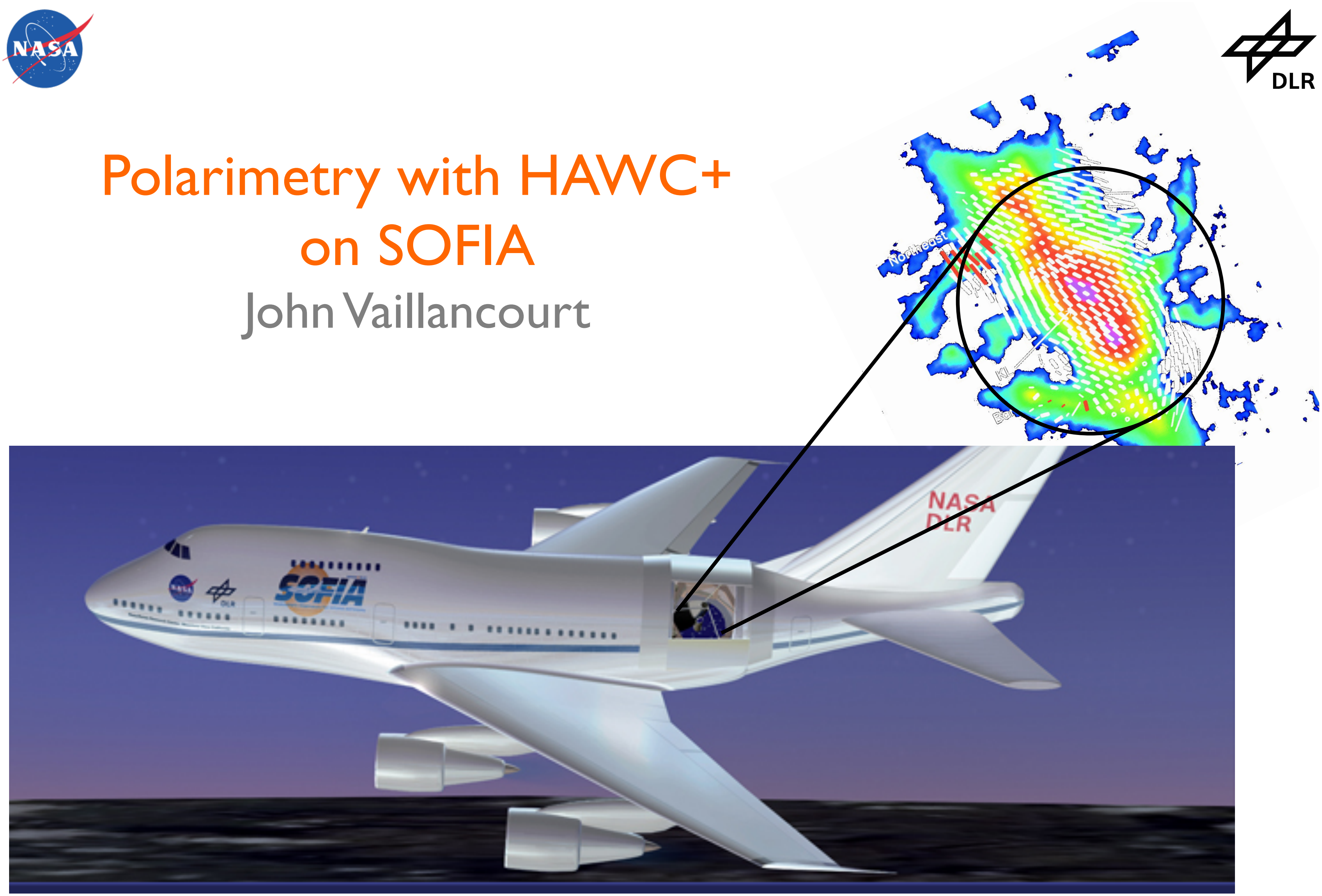
Polarimetry with HAWC+ on SOFIA

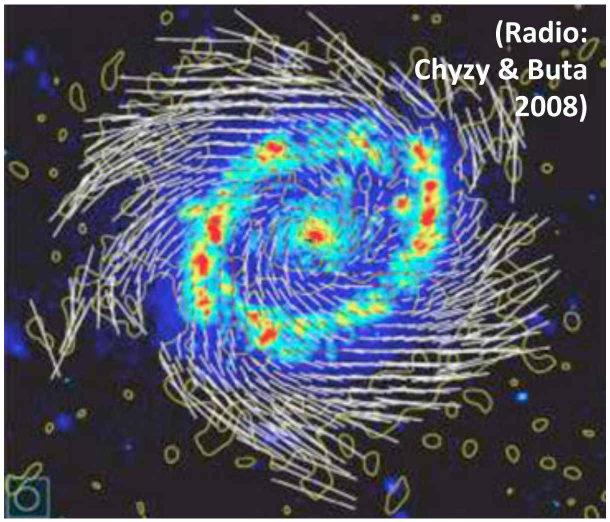
John Vaillancourt

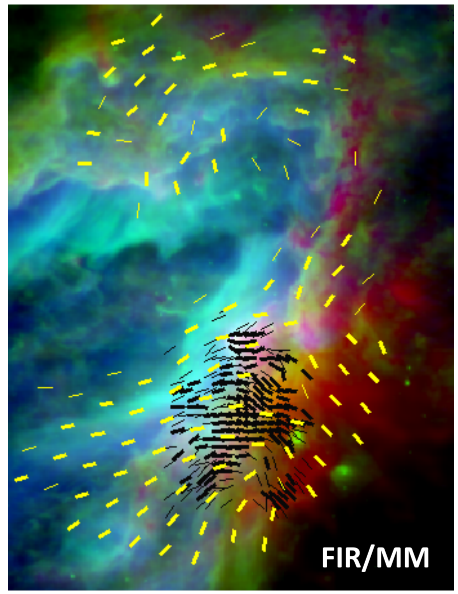


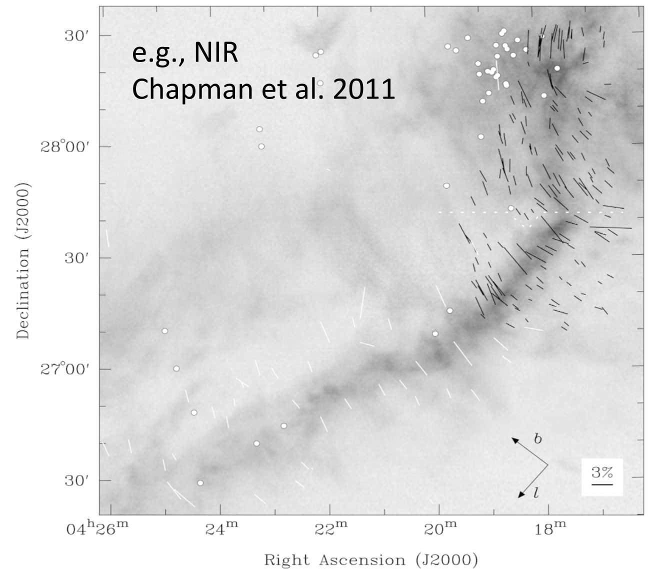
SOFIA Observers Workshop 20+21 May 2015

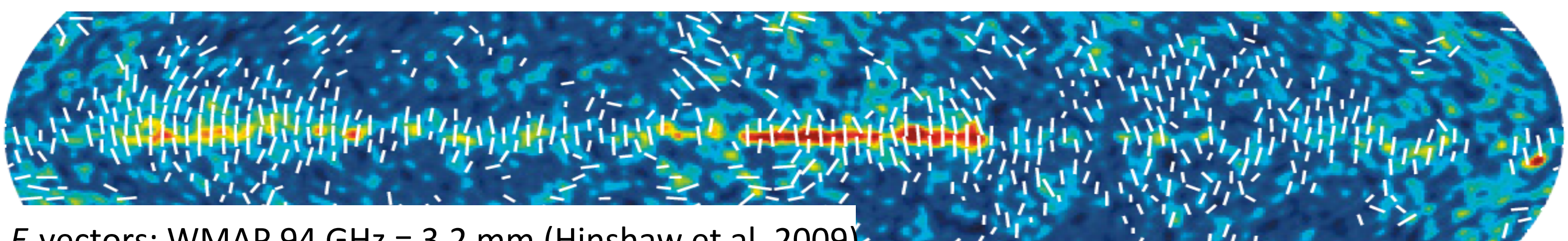
Polarized Light from the ISM

- **Light is polarized** at most wavelengths, from X-ray to Radio.





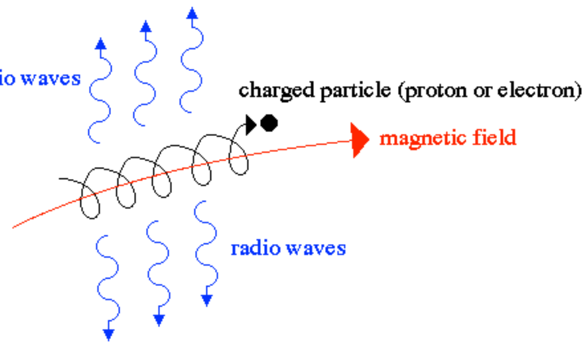


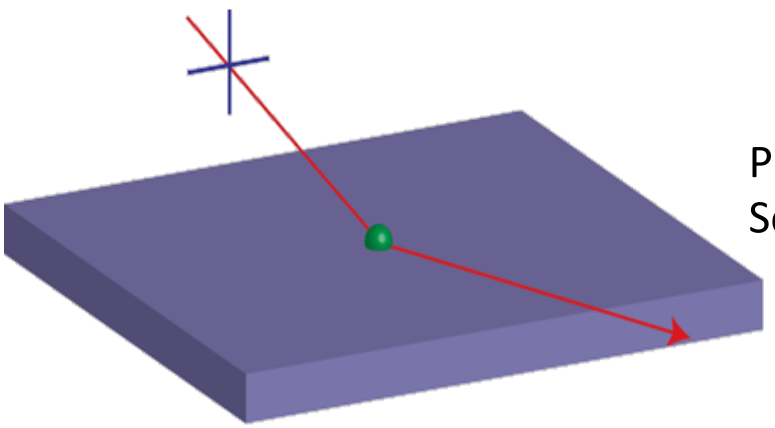


E-vectors: WMAP 94 GHz = 3.2 mm (Hinshaw et al. 2009)

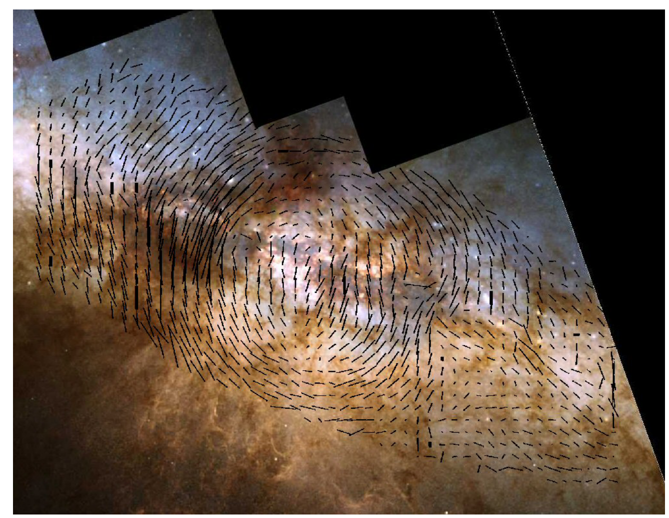
Polarization Mechanisms

Synchrotron Radiation



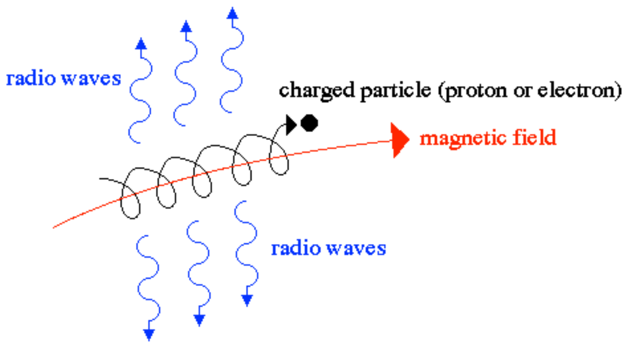


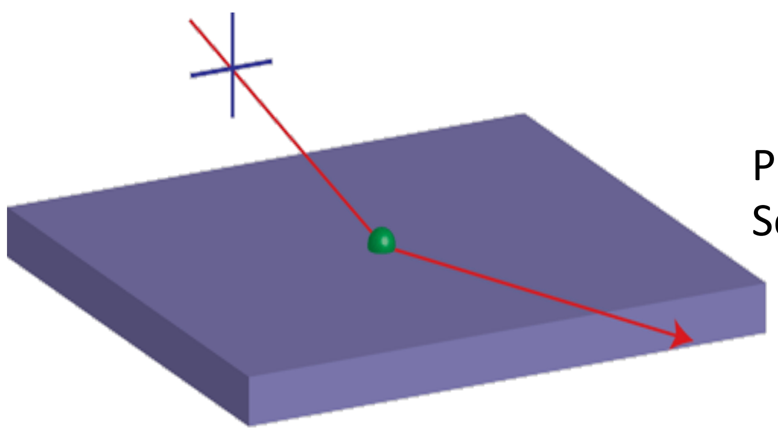
Polarization by Scattering



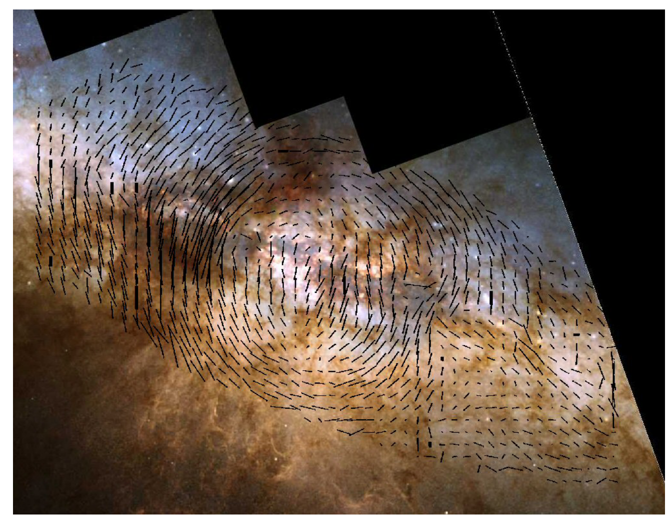
Polarization Mechanisms

Synchrotron Radiation





Polarization by Scattering



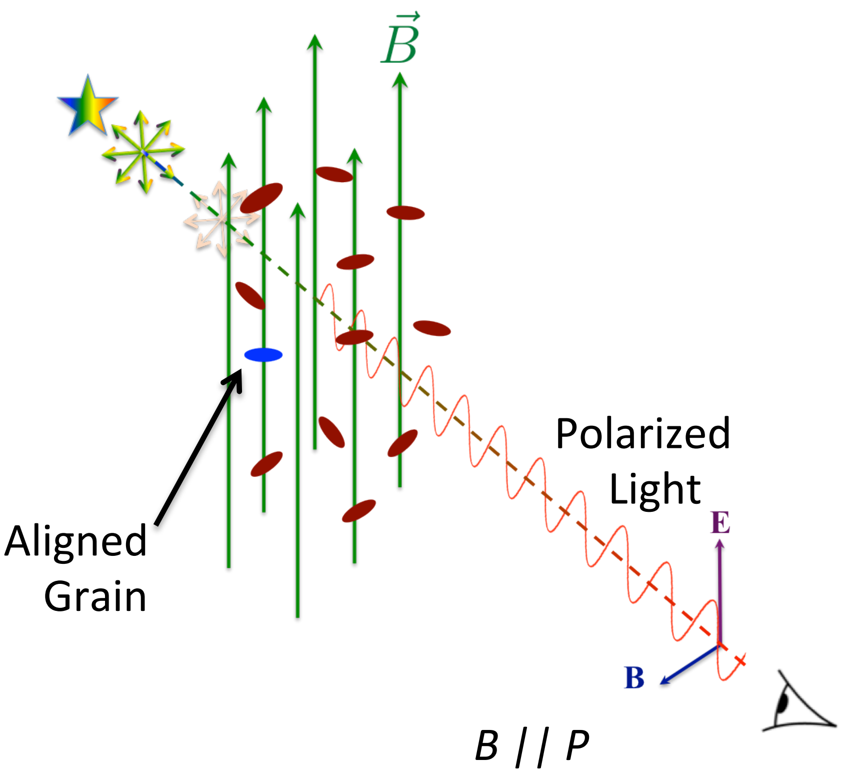
Polarization by Absorption & Emission

Diagrams adapted from A. Goodman: http://cfa-www.harvard.edu/~agoodman/ppiv/

Polarization by Extinction

polarization of background starlight

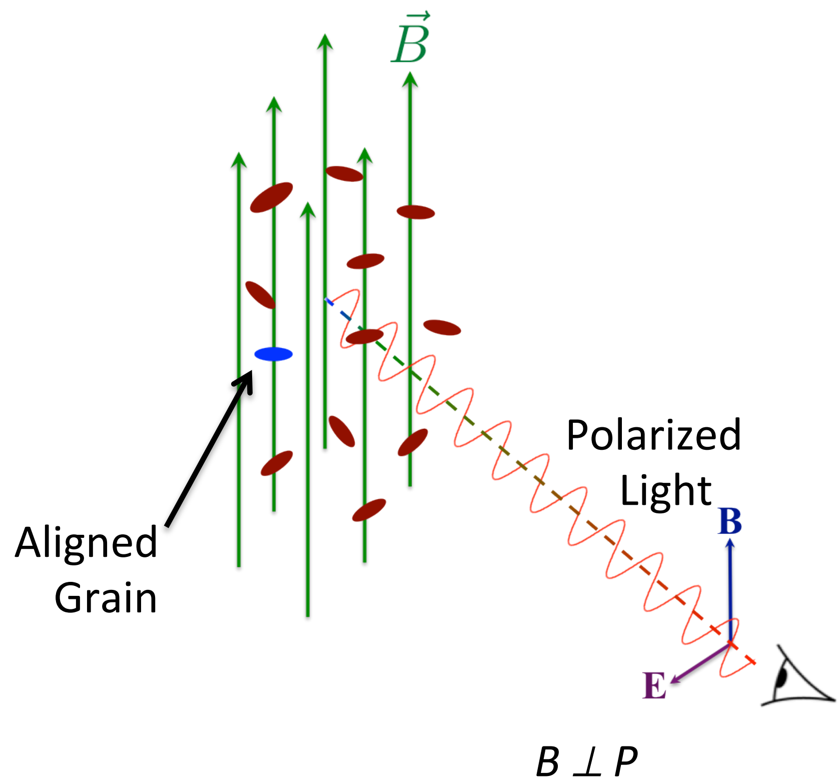
wavelengths ~ NUV – optical – NIR



Polarization by Emission

polarization of thermal emission

wavelengths ~ FIR – mm



Dust & Magnetic Fields

– Why is FIR light from ISM polarized

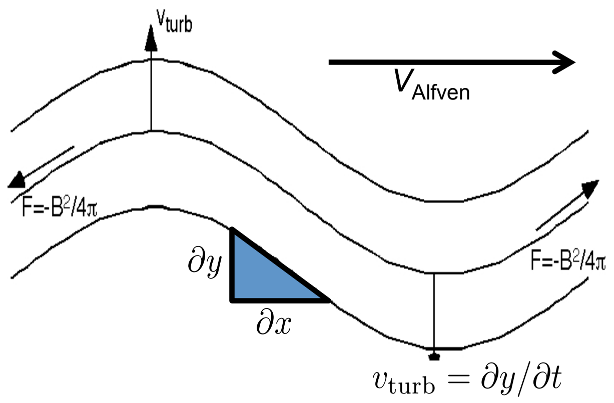
- interstellar dust dust grains are aligned with respect to magnetic field

• Two main goals of FIR polarimetry are:

- constrain the effect of *B*-fields on ISM evolution
- study the physics of dust grains, and interaction with *B*-fields

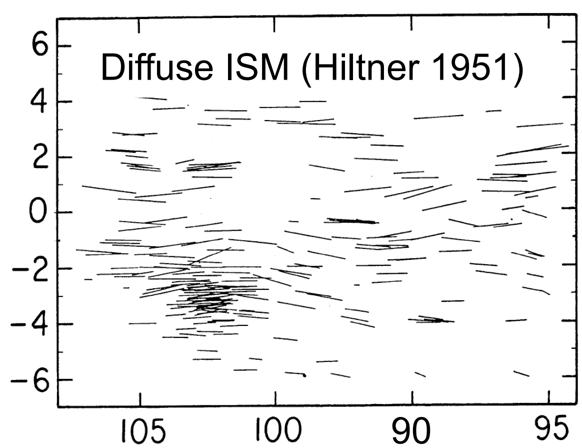
Inferring Field Strength – CF'53

[Davis 1951, Chandrasekhar & Fermi 1953]



$$V_A^2 \left\langle \frac{\partial y}{\partial x} \right\rangle^2 = \left\langle \frac{\partial y}{\partial t} \right\rangle^2$$

$$\sqrt{\frac{B_0}{4\pi\rho}} = \frac{\sigma(v)}{\sigma(\Phi)}$$



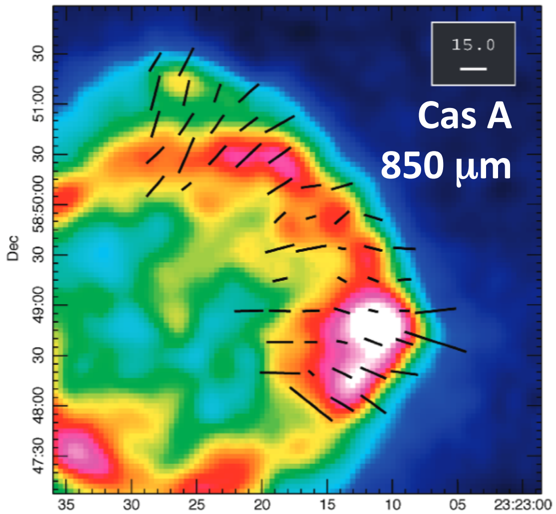
$\sigma(\Phi)$ = angle dispersion

ρ = gas density

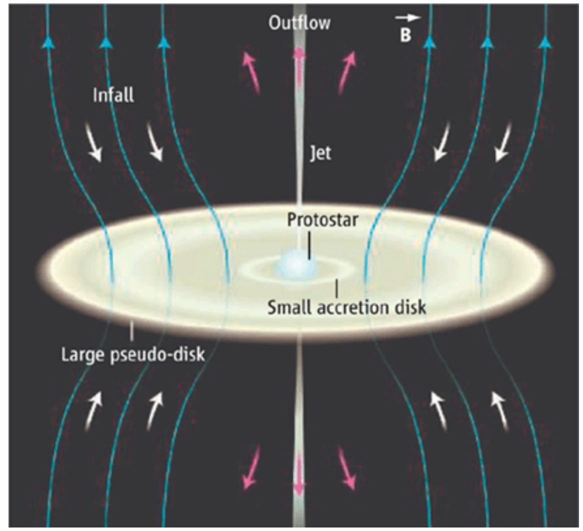
$\sigma(v)$ = velocity dispersion

B_0 ~ few microGauss

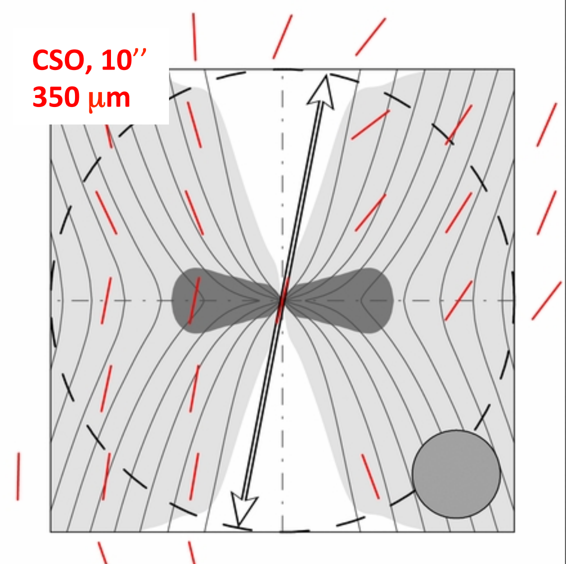
Interstellar Clouds



Dunne et al. 2009, MNRAS, 394, 1307



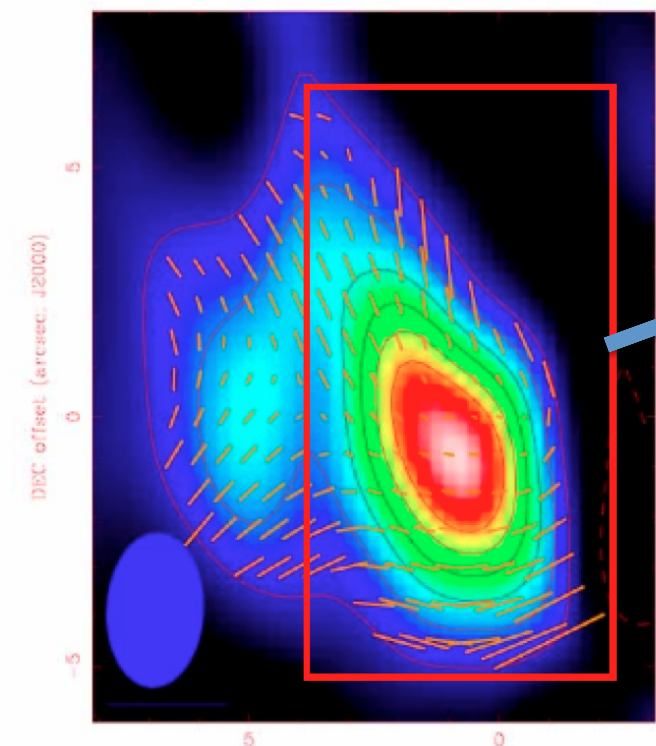
Shu et al. 1987, ARA&A, 25, 23
Galli & Shu. 1993, ApJ, 417, 220
Galli & Shu. 1993, ApJ, 417, 243
Fiedler & Mouschovias. 1993, ApJ, 415, 680
Crutcher 2006, Science, 313, 771



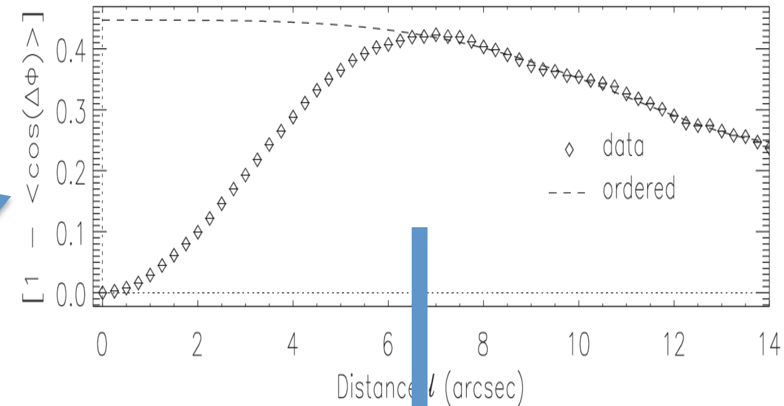
Chapman et al. 2013, ApJ, 770, 151
Davidson et al. 2011, ApJ, 732, 97
Allen et al. 2003, ApJ, 599, 363

- Magnetic Fields in the ISM
  - Do they regulate shape, collapse, flows?
  - What are relative energy/pressure contributions from components: *gravity, thermal, magnetic, turbulent*
  - Supernova remnants. Polarization at 850 μm has significant contributions from both dust and synchrotron.

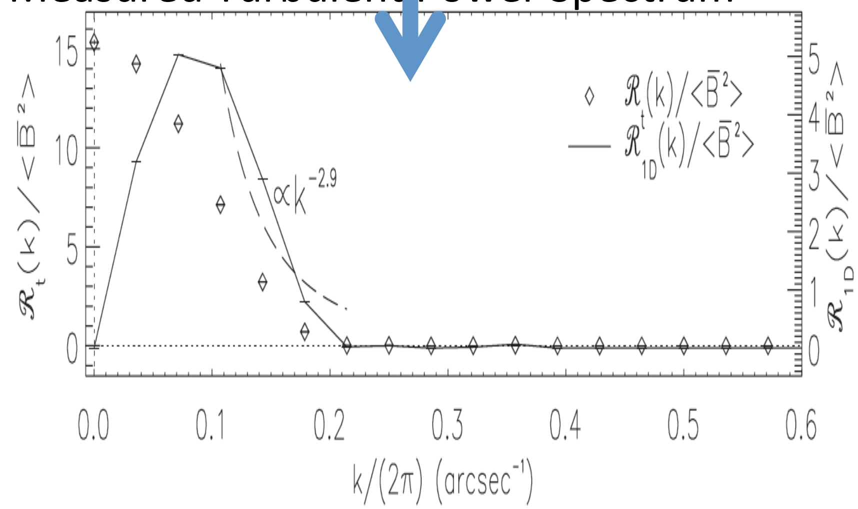
Turbulence in the ISM



Angular Dispersion

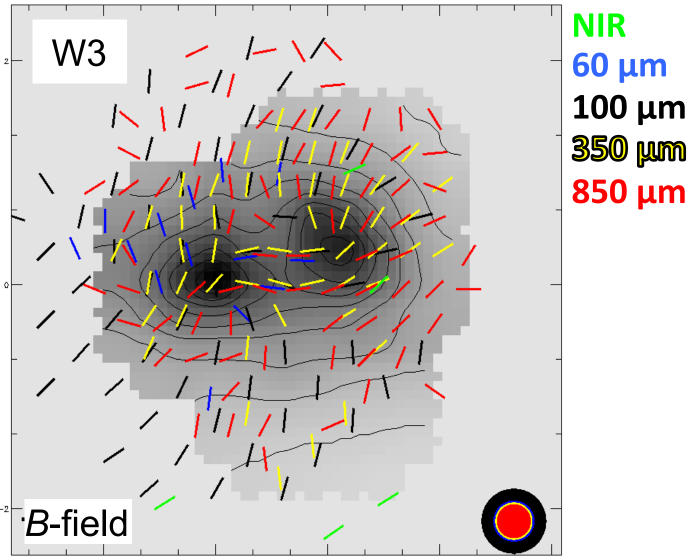


Measured Turbulent Power Spectrum

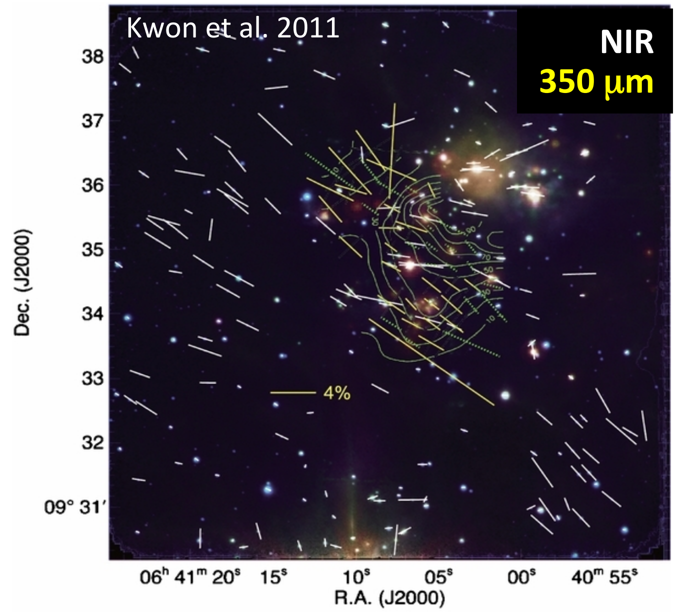


- Measure angle dispersion, apply CF analysis (Houde et al. 2011, ApJ, 733, 109 and refs. therein)

Multi-wavelength Polarimetry



Schleuning et al. 2000; Dotson et al. 2010

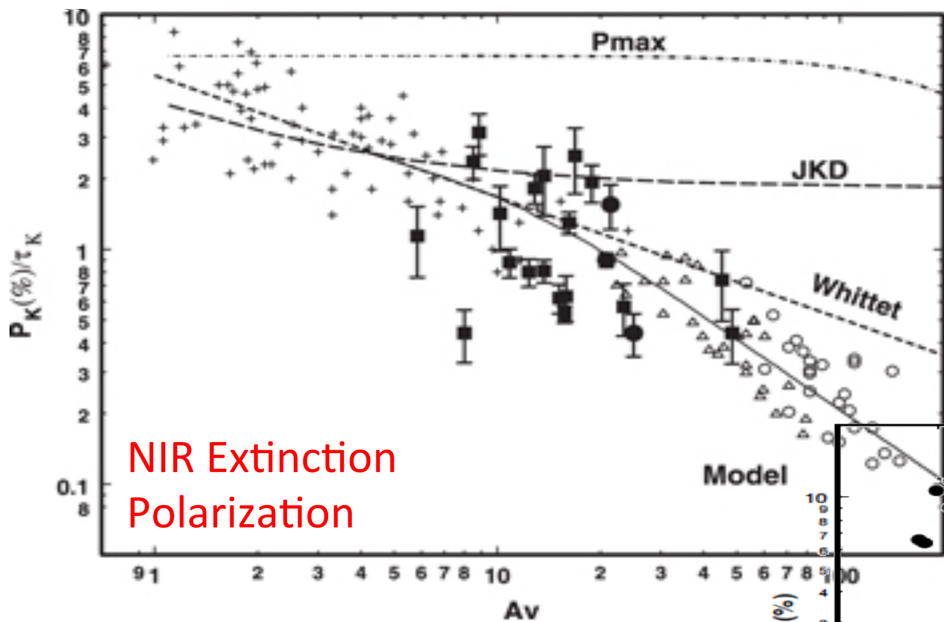


- Different wavelengths trace different types of dust and hence different regions of clouds.
  - Optical data traces diffuse ISM, FIR/MM traces denser parts of cloud and cores. Do they yield same B-field orientation? How does existence of cloud alter mean Galactic field?
  - Short FIR wavelengths trace dust and B-field close to warm cores
  - Long FIR wavelengths trace dust and B-field in cooler cloud edges

Polarization vs. Density

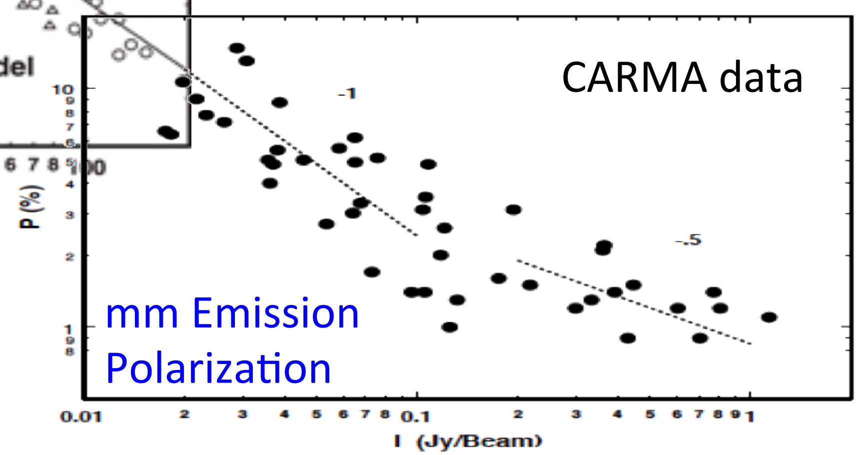
- Comparison across density regimes requires use of different wavelengths tracing different dust.
- SMA/CARMA/ALMA will resolve out extended structure. Single dish instruments needed to make connection.

Jones et al. 2014

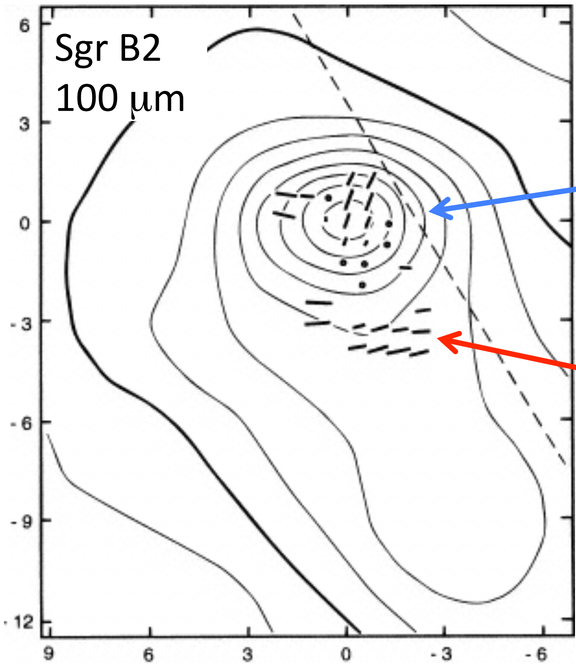


Compilation courtesy Terry Jones

Jones et al. 2015



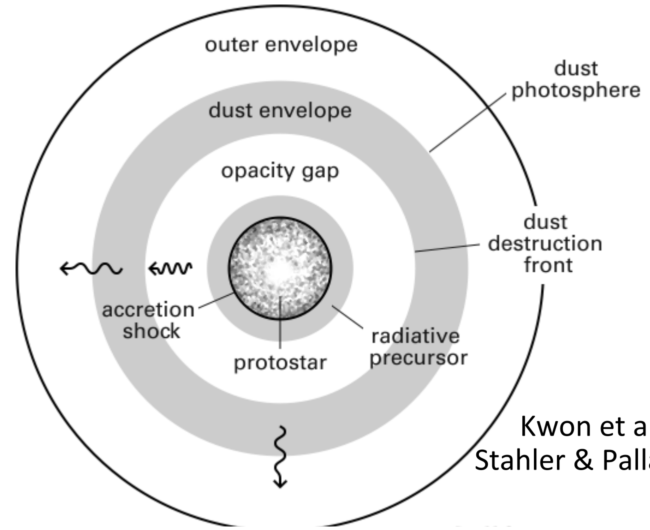
Multiple Pol'n Mechanisms



Polarization by absorption

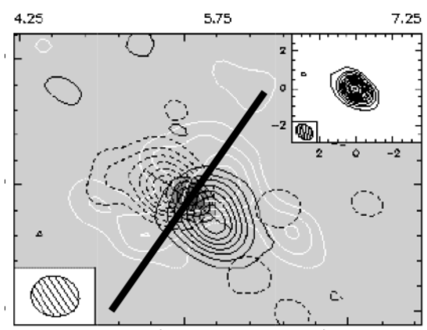
Polarization by emission

Dowell (1997), Novak et al. (1997)



Kwon et al. 2009
Stahler & Palla 2004

GM Aur



850 μm
Tamura et al. (1999)

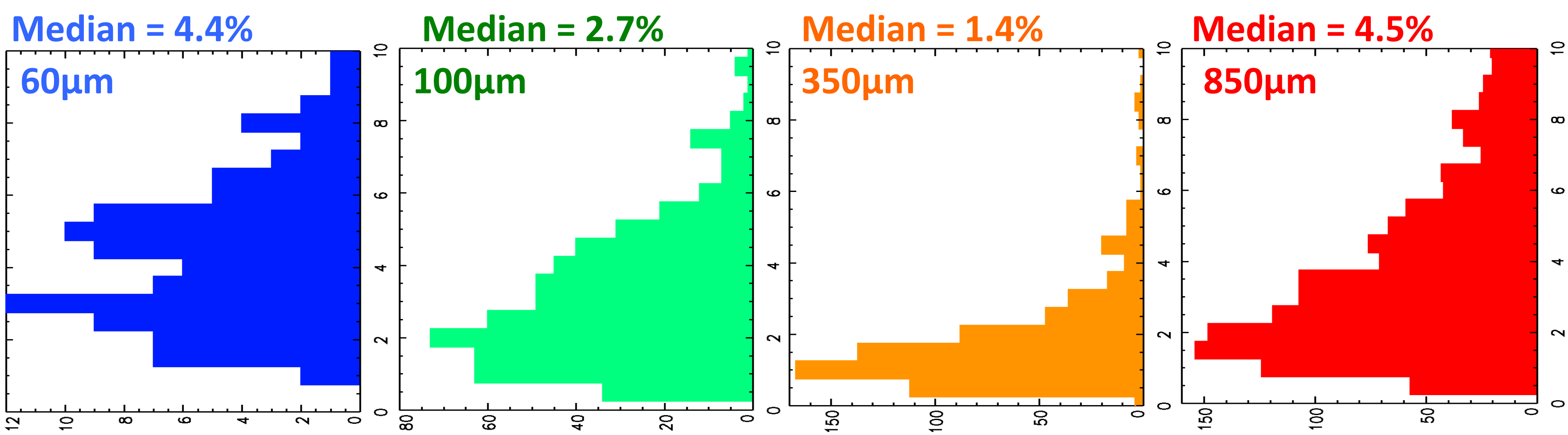
Polarization by scattering ??

Where in cloud is light polarized? Where in cloud is polarization tracing the magnetic field. These questions require multi-wavelength data to answer.

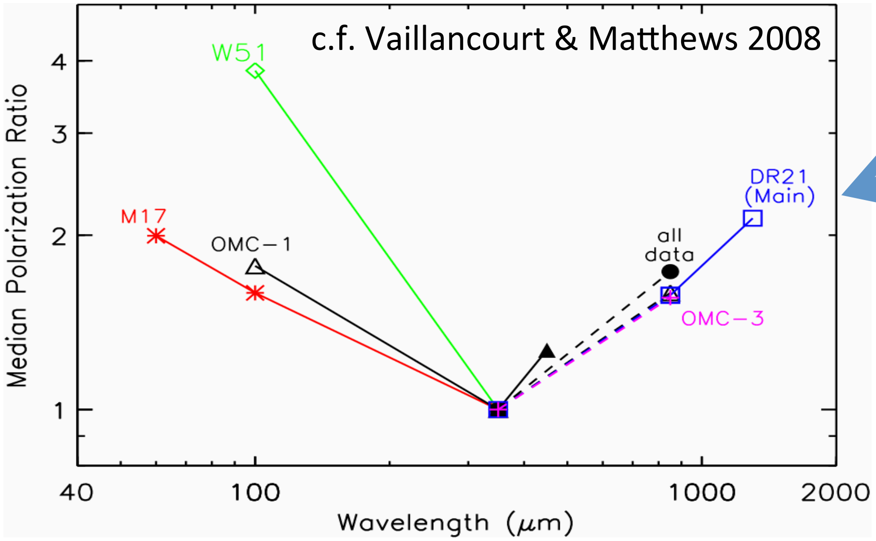
Polarization Spectra

- Histograms off all previous measurements at single-dish telescopes at 60 – 850 µm

Dotson+ 2000, ApJS, 128, 335
Dotson+ 2010, ApJS, 186, 406
Matthews+ 2009, ApJS, 182, 143

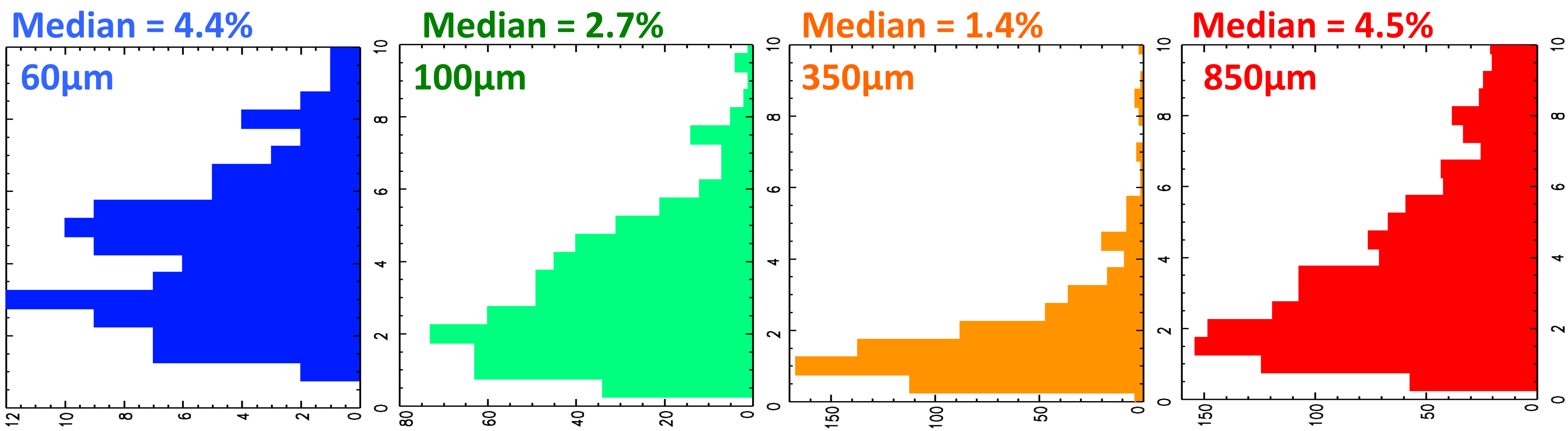


Polarization Spectra

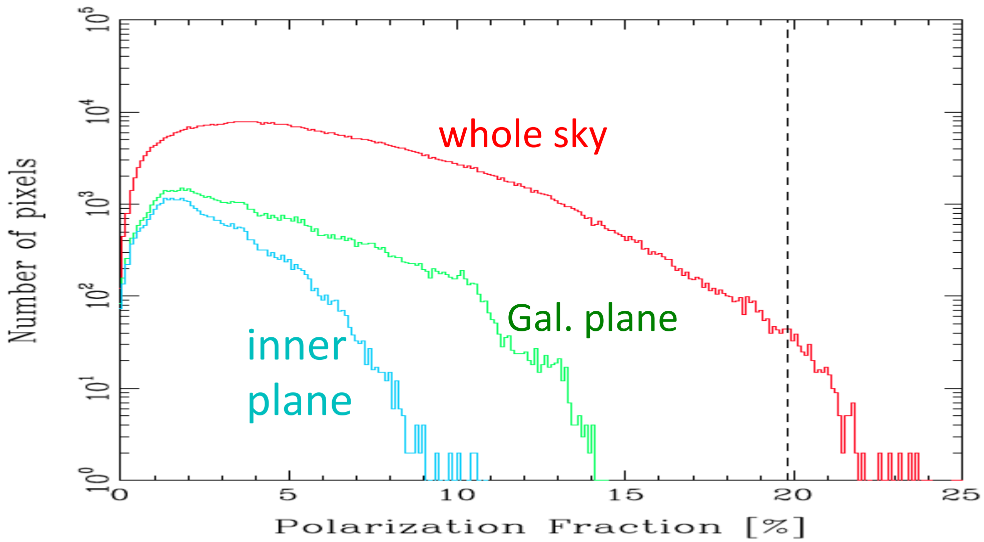


- Even in the same parts of a cloud, polarization changes with wavelength.

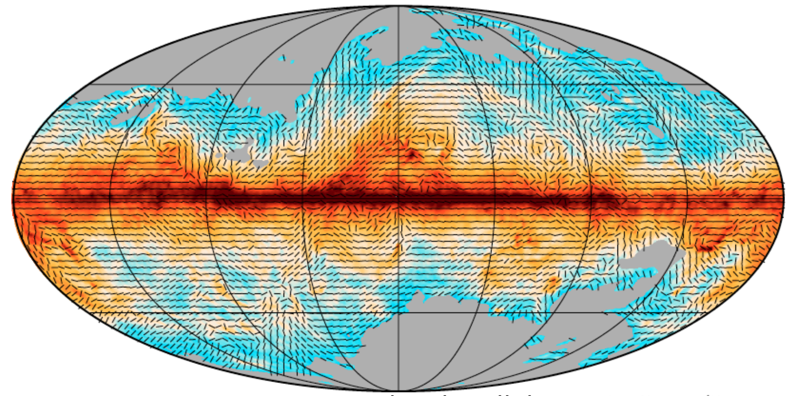
Dotson+ 2000, ApJS, 128, 335
Dotson+ 2010, ApJS, 186, 406
Matthews+ 2009, ApJS, 182, 143



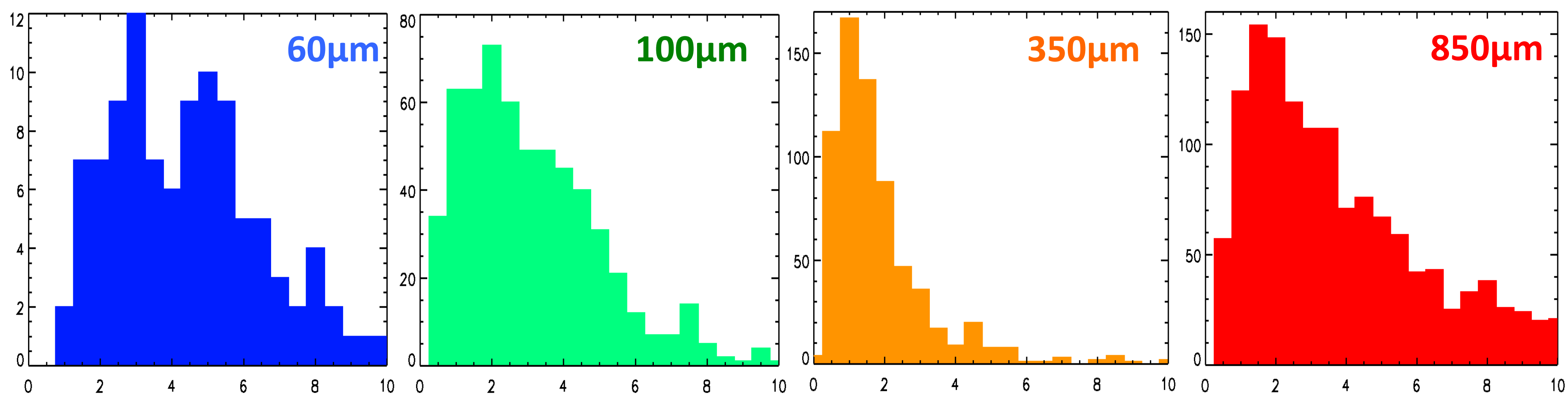
Polarization Spectra



- Planck all-sky histogram at 850 µm, 1-degree resolution

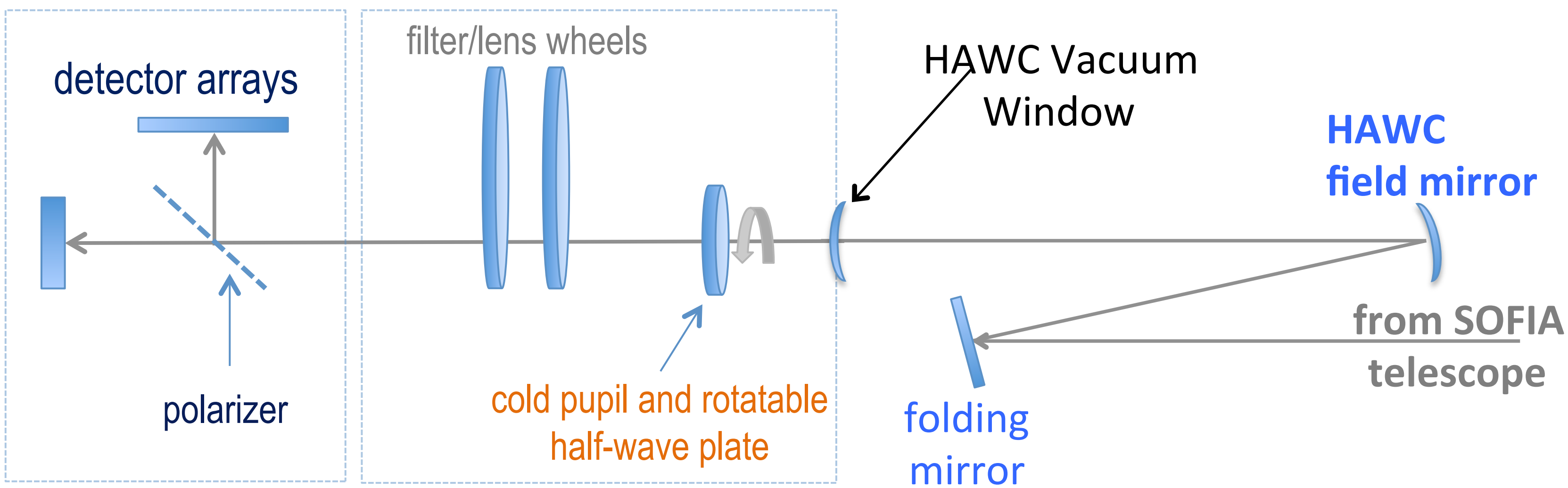


Planck Collaboration XIX 2015

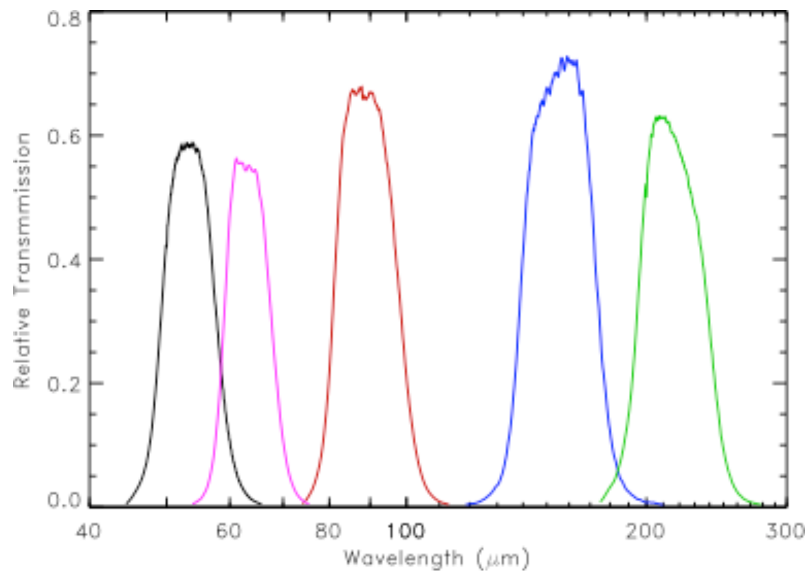


What is HAWC+ ?

- Two detector arrays (64×40 pixels) simultaneously measure both components of linear polarization. Components are ***Reflected*** and ***Transmitted*** off a polarizing wire grid.
- Five different passbands from 50 – 250 µm. Each passband is diffraction limited with a plate scale that Nyquist samples the beams
- Rotatable half-wave plates are used to rotate plane of polarization. HWPs are matched to each passband.



HAWC+ Optical specifications

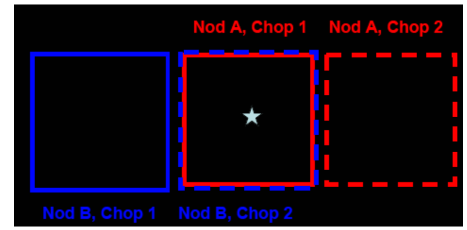


Passbands	A	B	C	D	E
Mean λ (μm)	53	63	89	154	214
Δλ/λ	0.17	0.15	0.19	0.22	0.20
FWHM (arcsec)	4.7	5.8	7.8	14	19
FOV (arcmin)	2.7×1.7	4.2×2.6	4.2×2.6	7.3×4.5	8.0×6.1

HAWC+ Observing Mode

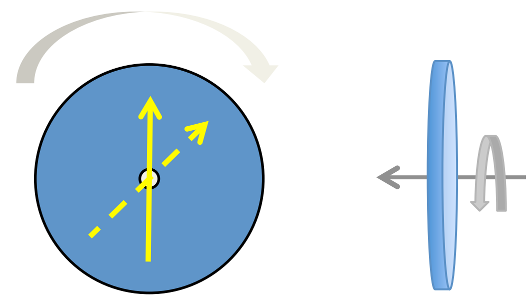
1) Chop-Nod

- Nod parallel to chop, symmetric only
- Chop amp. 2–8 arcmin, freq. 5–20 Hz



2) Rotate Half-waveplate (HWP)

- Step in 4–8 positions/angles (0°-180°)
- Repeat chop-nod sequence at each HWP angle

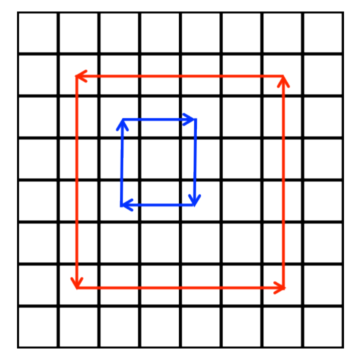


3) Dithering

- Repeat Chop-Nod and HWP sequences at all dither positions

4) Mapping

- Repeat Dither, HWP, and Chop-Nod sequences at all map positions



Polarimetry requires at least 4 separate photometric measurements. (1 chop-nod) × (4 HWP) × (4 dithers) ~ 15–30 minutes minimum observing time.

Sensitivity & Time Estimates

$$\sigma_p = \frac{\sqrt{2}}{\eta_p}\frac{\sigma_I}{I} t^{-1/2} \times 100\%$$

σ_p: polarization uncertainty
I: Total intensity or flux
σ_I: Total intensity or flux uncertainty
η_p: Instrument polarization efficiency
t: total integration time (not per HWP!)

Passbands	A	B	C	D	E
Mean λ (µm)	53	63	89	154	214
MDCPF (% · Jy)	9.0	11	9.4	7.7	6.7
MDCPF with overheads	28	36	30	24	21

← **SITE input for point source**

- MDCPF: **M**inimum **D**etectable **C**ontinuum **P**olarized **F**lux is the quantity $I \cdot \sigma_p$ into a single HAWC beam with for S/N=4 in a 15 minute integration
- "with overheads" is the MDCPF taking into account inefficiences in chopping, nodding, missing/dead detectors, etc.

Sensitivity & Time Estimates

$$\sigma_p = \frac{\sqrt{2}}{\eta_p} \frac{\sigma_I}{I} t^{-1/2} \times 100\%$$

σ_p: polarization uncertainty
I: Total intensity or flux
σ_I: Total intensity or flux uncertainty
η_p: Instrument polarization efficiency
t: total integration time (not per HWP!)

Passbands	A	B	C	D	E
Mean λ (µm)	53	63	89	154	214
NESB (% · Jy · arcsec^{-2})	0.36	0.30	0.14	0.037	0.017
MIfP (MJy / sr)	20,000	17,000	7600	2100	940

← **SITE input for extended source**

- NESB: **N**oise **E**quivalent **S**urface **B**rightness, S/N=4, 15 minutes
- MIfP (**M**inimum **I**ntensity **f**or **P**olarization): This is the minimum surface brightness required if one wishes to measure a polarization uncertainty $\sigma_p = 0.3\%$ in a one-hour integration. The value here includes all overheads.

Sensitivity & Time Estimates

$$\sigma_p = \frac{\sqrt{2}}{\eta_p} \frac{\sigma_I}{I} t^{-1/2} \times 100\%$$

σ_p: polarization uncertainty
I: Total intensity or flux
σ_I: Total intensity or flux uncertainty
η_p: Instrument polarization efficiency
t: total integration time (not per HWP!)

Point source (nominal spatial profile) with spatially integrated brightness 9.4 Jy
Polarization 1.0 Percent

Note: SITE requests both intensity I and polarization p, but only their product is used in the calculation. The returned/entered S/N is p/σ_p.

As usual, time scales inversely as the square of desired uncertainty, in this case the uncertainty on the polarized intensity pI.

$$t = (900\,\mathrm{sec}) \left(\frac{\mathrm{MDCPF}}{4\,\sigma_p\,I} \right)^2$$

Other Uncertainties

- Uncertainty on the polarization angle for $p >\sim 3\sigma_p$

$$\sigma_\phi = \frac{180}{\pi} \frac{\sigma_p}{2p} \quad \text{[degrees]}$$

- Instrument & Telescope polarization
  - subtracted to better than ~0.3%
  - position angle to within 2 degrees

Observation Planning

- HAWC+ has 2 observing configurations
  - TOTAL_INTENSITY: unpolarized mapping (discussed by J. DeBuizer)
  - POLARIZATION: mapping in polarization, discussed here
- C2N (NMC) mode: 2-point chop with matching nod and dithering
  - may include optional mosaic mapping

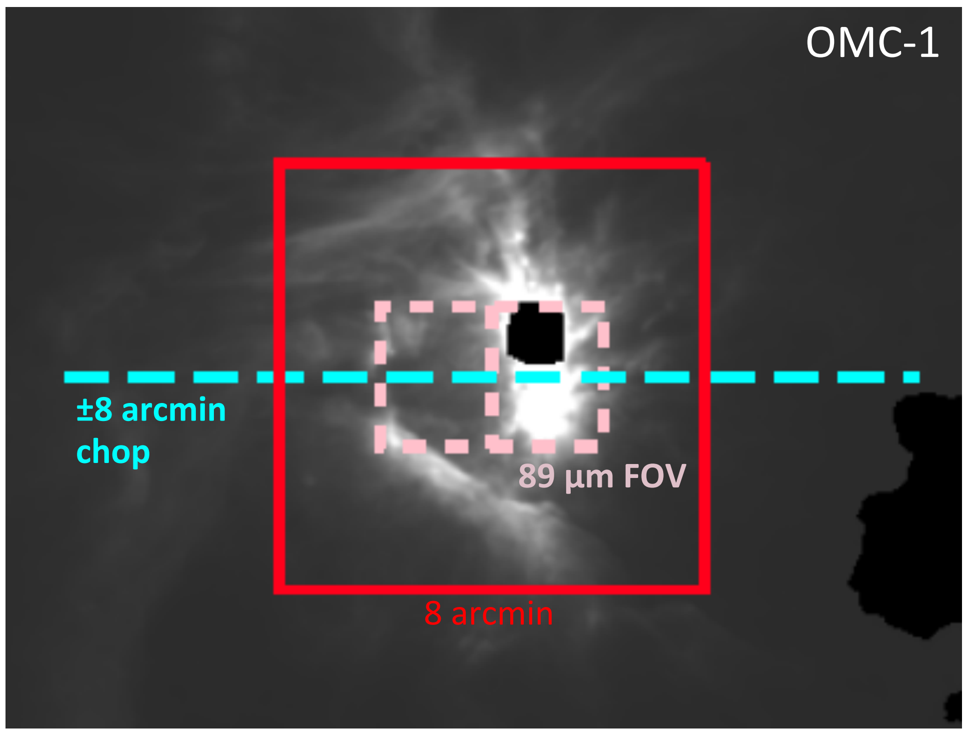
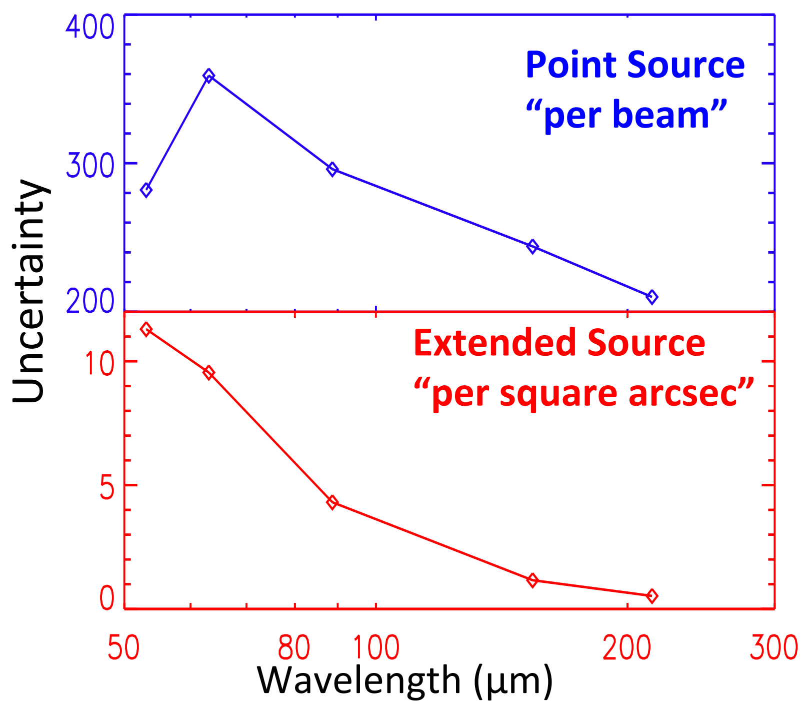
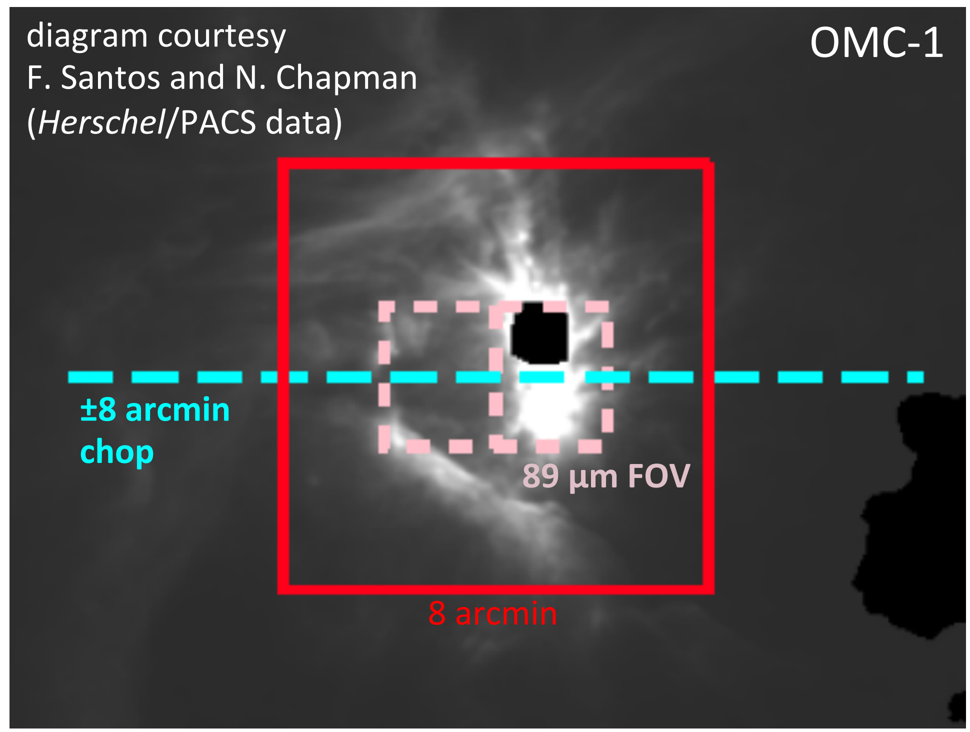


diagram courtesy
F. Santos and N. Chapman
(*Herschel*/PACS data)

Observation Planning

- Mosaic Mapping: Consider your key goal
  - Do large maps (> 8 arcmin) really need best possible resolution (5'' @ 2 amin FOV) ?
  - Do maps at multiple wavelengths need exact same coverage?
  - Do all map sub-fields require same integration time?
- Example: 63 µm band has only slightly larger beam than 53 µm band, but better sensitivity and 2.4 times larger FOV



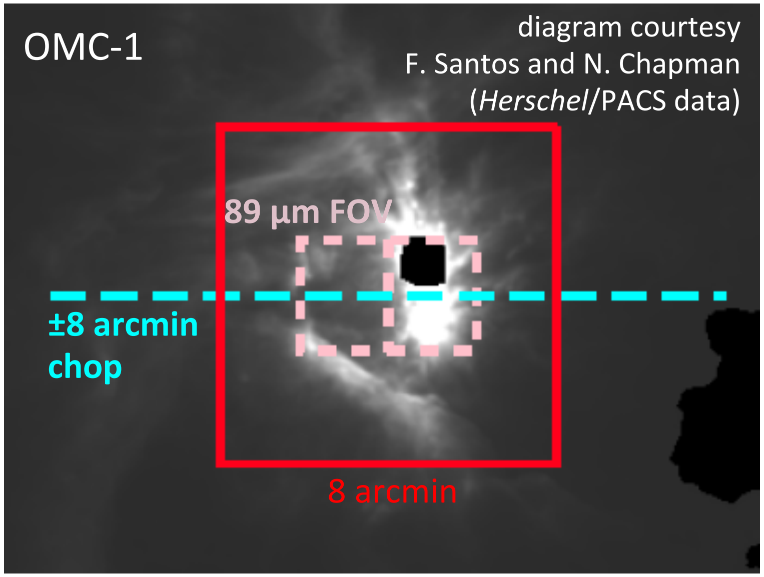


Polarized Reference Beams

- **Beware flux in your reference beams**

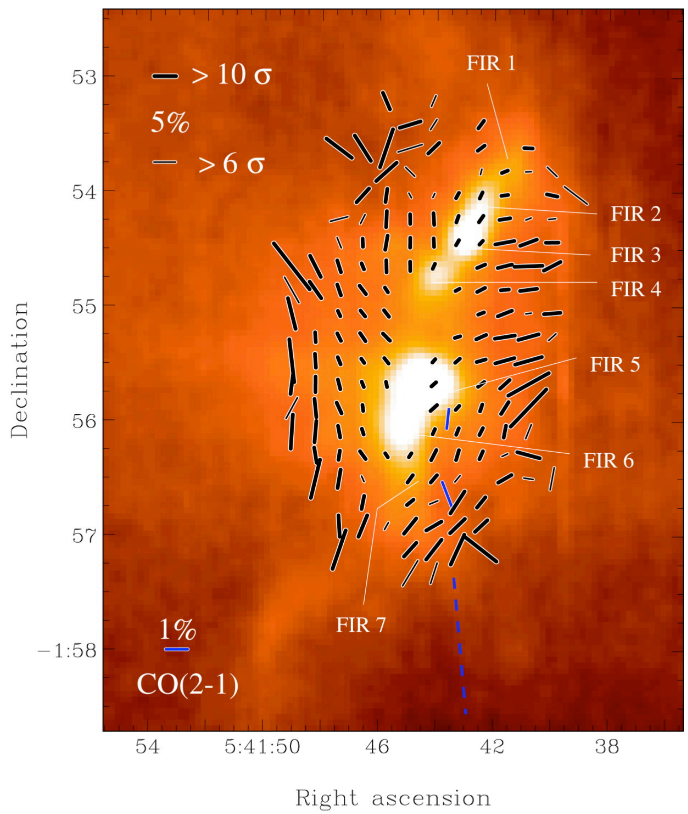
- Total Intensity:
  - even if reference flux cannot be avoided, it always subtracts from source flux
  - There exist many large-scale maps in FIR for planning to avoid reference flux (e.g. IRAS, *Herschel*, *Spitzer*)

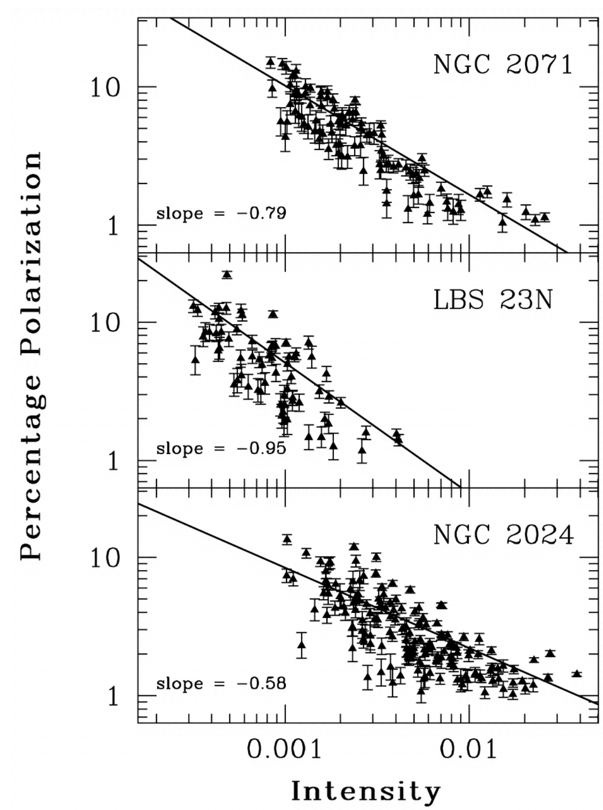
- Polarized Intensity:
  - polarization angle differences between reference and source can lead to subtraction *or addition* (Schleuning+ 1997, PASP, 109, 307; Novak+ 1997, ApJ, 487, 320)
  - No large-scale FIR polarization maps. Maybe some combo. FIR intensity surveys and *Planck* 850 μm data
  - Best solution: find the dimmest total intensity region possible, use larger chop throws, repeat measurement w/ different ref. region



Polarized Reference Beams

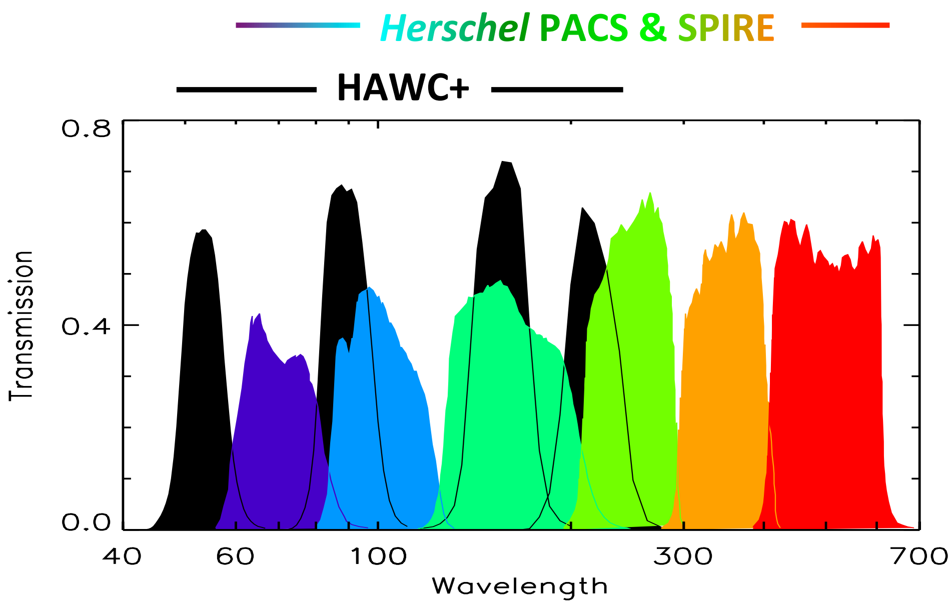
- Polarized Intensity:
  - polarization angle differences between reference and source can lead to subtraction *or addition*
  - Fractional polarization often *increases* as total intensity drops. So no guarantee very dim reference regions are devoid of polarization.

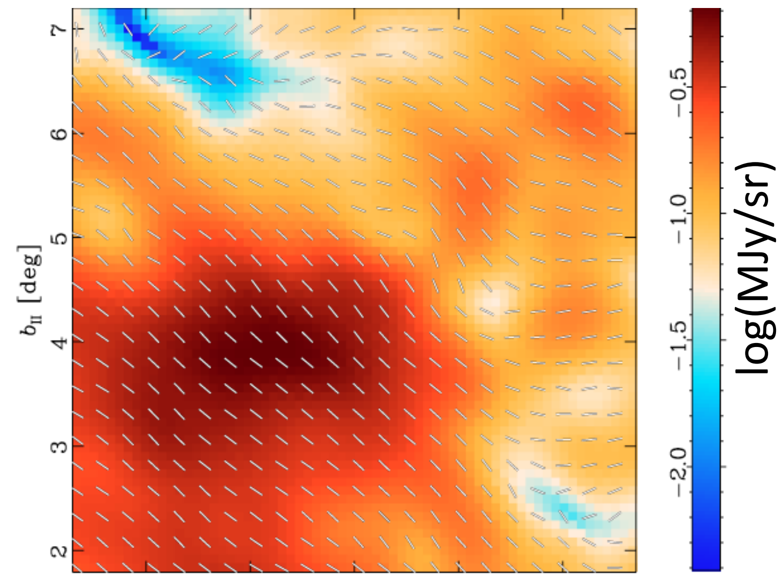




“polarization holes” in regions of high intensity and column density (e.g., Schleuning 1998, Matthews+ 2002)

Planning with *Planck* & *Herschel*, caveats



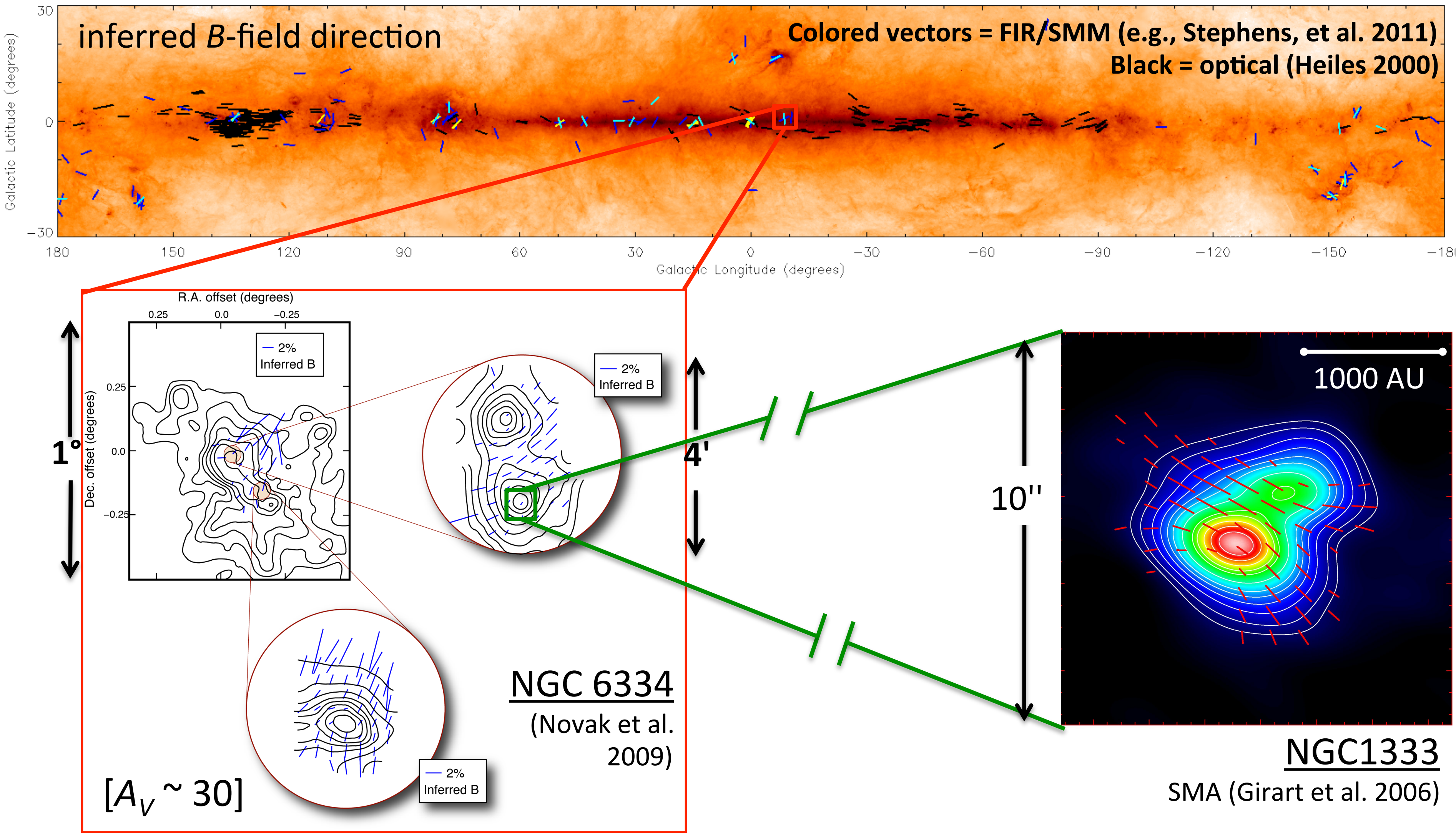


polarized intensity and B-orientation

- HAWC bandwidths are narrow
  - $\lambda/\Delta\lambda \sim 5 - 6$.
- Herschel bandwidths are wider
  - $\lambda/\Delta\lambda \sim 3$.

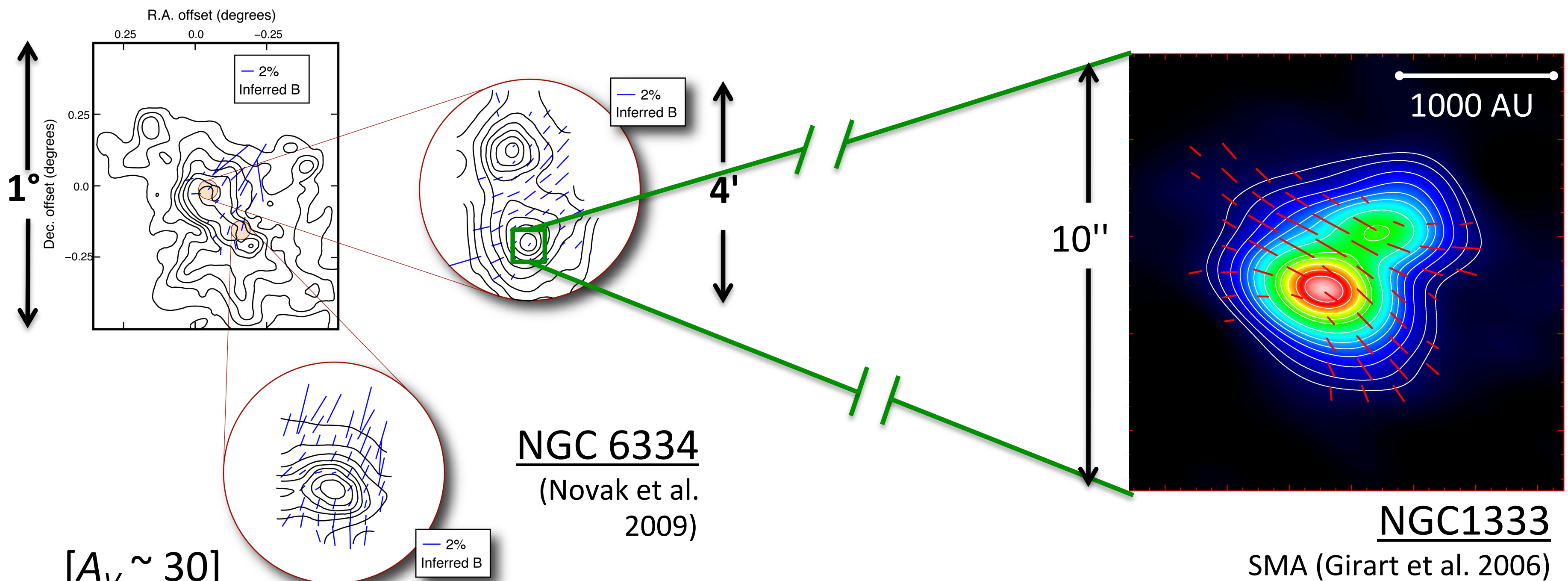
- Planck at 850 µm
  - published data plotted at 1 degree resolution for B-vectors
  - native resolution ~ 5 arcmin
- Herschel bandwidths are wider
  - $\lambda/\Delta\lambda \sim 3$.

SOFIA Probes Intermediate Scales



SOFIA Probes Intermediate Scales

HAWC+ @ 53 µm: 2 arcmin FOV, 5 arsec resolution
HAWC+ @ 214 µm: 7 arcmin FOV, 20 arcsec resolution

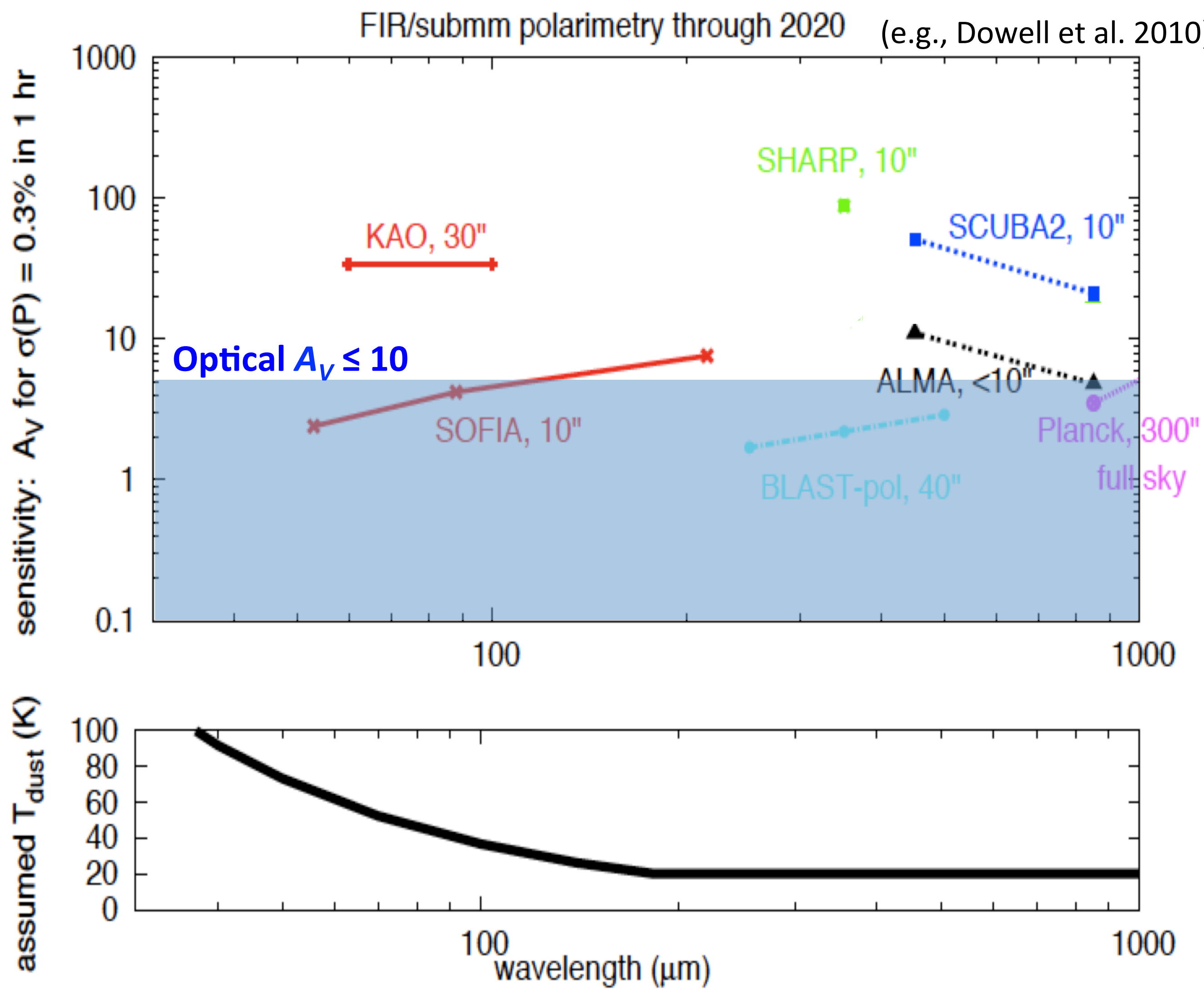


NGC 6334
(Novak et al. 2009)

NGC1333
SMA (Girart et al. 2006)

[A_V ~ 30]

Polarization Across Wavelengths



Further Reading

- HAWC in Molt, On the Way to Becoming SOFIA's Facility Far-IR Camera and Polarimeter: http://www.sofia.usra.edu/Science/SCF/pdf/08-06-14_Dowell.pdf
- Dust and Polarization in the Interstellar Medium: http://www.sofia.usra.edu/Science/SCF/pdf/10-17-12_Vaillancourt.pdf
- The HAWC Upgrade Investigation: http://www.sofia.usra.edu/Science/SCF/pdf/11-28-12_Dowell-Staguhn.pdf
- Polarimetry with SOFIA: http://spirit.as.utexas.edu/~dan/SOFIAteletalk/sofiateletalkarchive/12-16-09_Novak-Dowell.ppt
- Far-infrared polarimetry from the SOFIA: http://www.sofia.usra.edu/Science/instruments/HAWC-SPIEs/2007SPIE.6678.66780D.pdf
- Far-infrared Polarimetry of The Interstellar Medium: http://dx.doi.org/10.1051/eas/1152042
- New Insights into the Physics of Infrared Cirrus: http://www.sofia.usra.edu/Science/science_cases/dowell_v2.pdf
- Magnetic Fields, Turbulence, and Star Formation: http://www.sofia.usra.edu/Science/science_cases/novak_v2.pdf