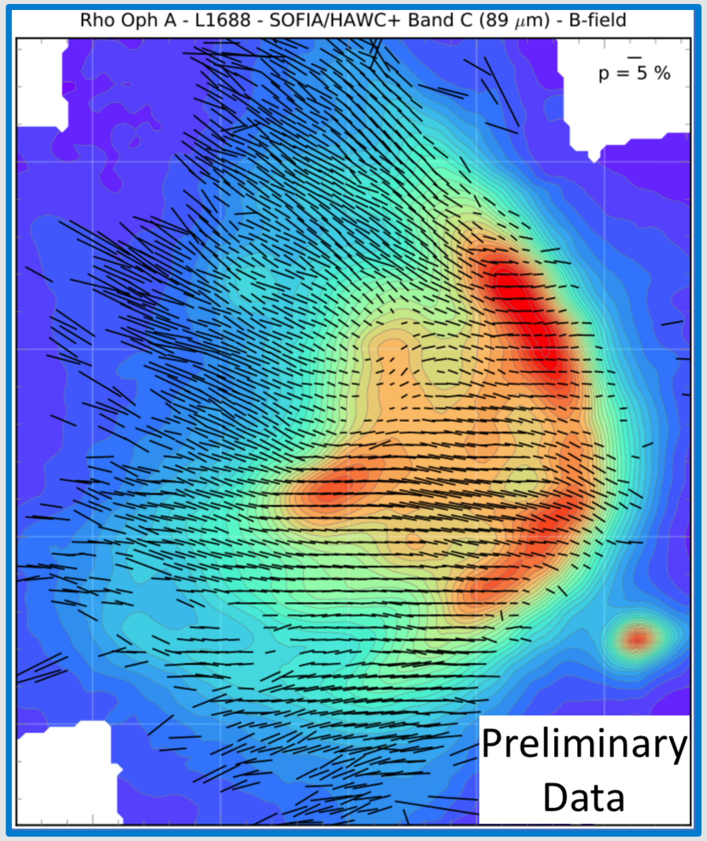
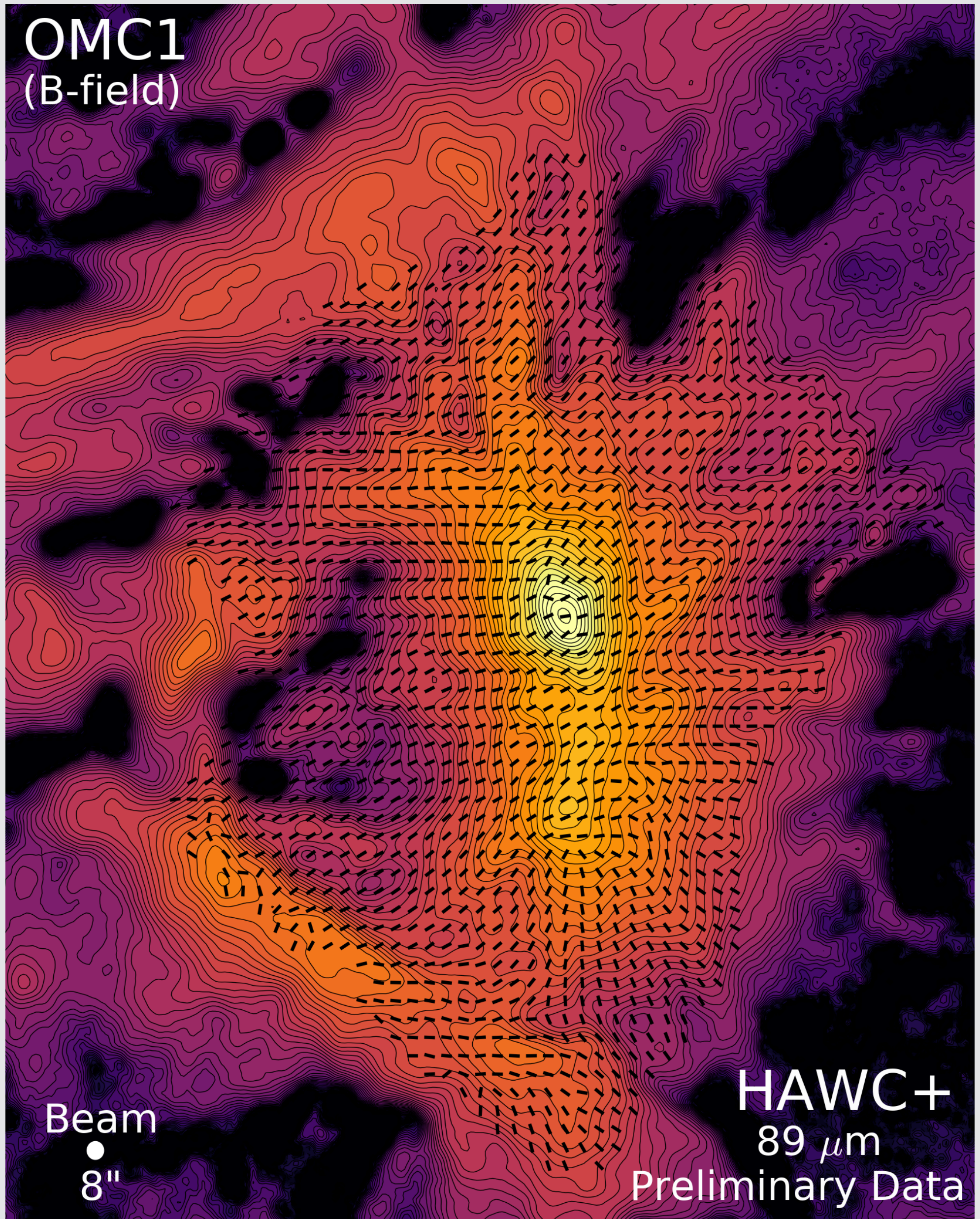
SOFIA INSTRUMENTS

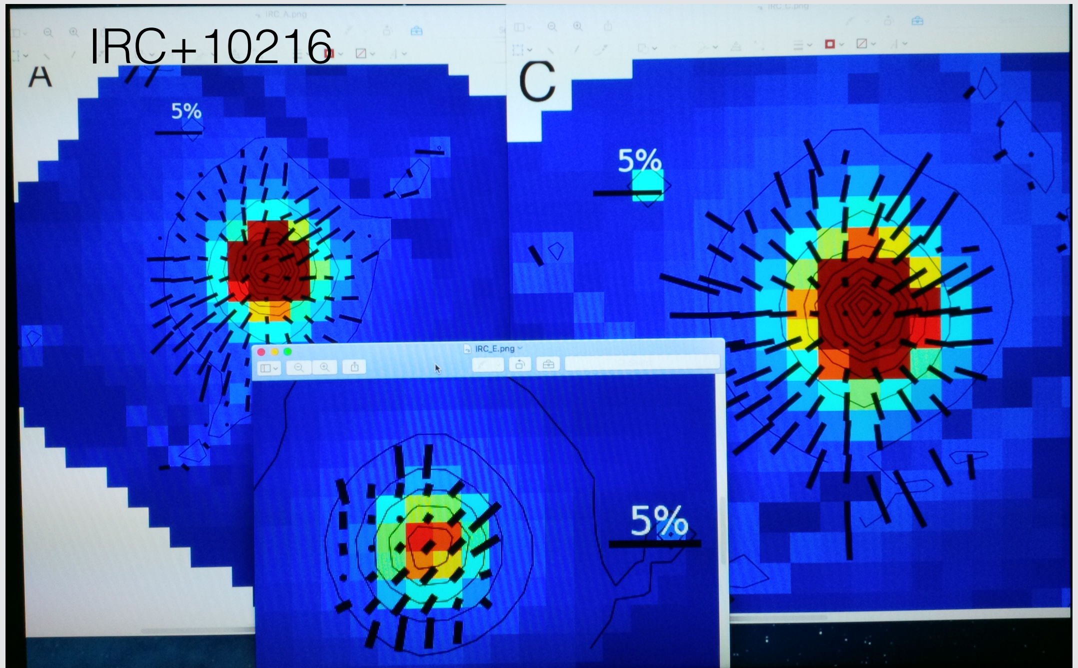
HAWC+

B-G Andersson

(with – lots of - help from Enrique)







Outline

- Polarimetry basics
- Polarization mechanisms
- The HAWC+ instrument
- Preparing HAWC+ observations

Polarimetry Basics

- Polarization is a [pseudo] vector
  - Degenerate on 180° rotation
- Does not add and subtract as scalars ($p_1+p_2 \neq |p_1|+|p_2|$)
- Add and subtract in Stokes parameter space, I, Q, U, V
- HAWC+ is only sensitive to linear polarization, so "assume" V=0
- For [partially] linear polarized light
  - $Q=PI\cos(2\gamma)$; $q=Q/I=p\cos(2\gamma)$
  - $U=PI\sin(2\gamma)$; $q=Q/I=p\sin(2\gamma)$
    - $p=\mathrm{sqrt}(q^2+u^2)$
    - $\gamma=1/2\arctan(u/q)$
- Because $p=\mathrm{sqrt}(q^2+u^2)$, p is positive definite and therefore σ_p is biased at small S/N

Polarimetry Basics II

- Observationally q & u are determined from measurements at 4 angles - or more! At the cost of add. overhead, avoid systematics
- For an arbitrary angle α of the instrument (for HWP)

  $q' = I(\alpha) - I(\alpha+90) / I(\alpha) + I(\alpha+90)$

  $u' = I(\alpha+45) - I(\alpha+135) / I(\alpha+45) + I(\alpha+135)$

- Need to calibrate orientation of instrument (vs. sky), efficiency of the instrument (100%pol ->X% measured) and the instrumental polarization
  - Efficiency is measured in the lab. >85% in all band
  - Position angle is measured E of N, calibrated in lab
  - Mounting is reproducible so calibrate in lab
  - Keep track of parallactic angle
  - Instrumental polarization is measured via sky-dips and on un-polarized sources
- All these corrections are incorporated in the pipeline processing, but the user should know about them

Polarization Mechanisms

- There are [at least] three polarization mechanisms that should be considered when analyzing HAWC+ polarimetry
- Emission from aligned grains
- Synchrotron radiation
- Scattering (off of dust)

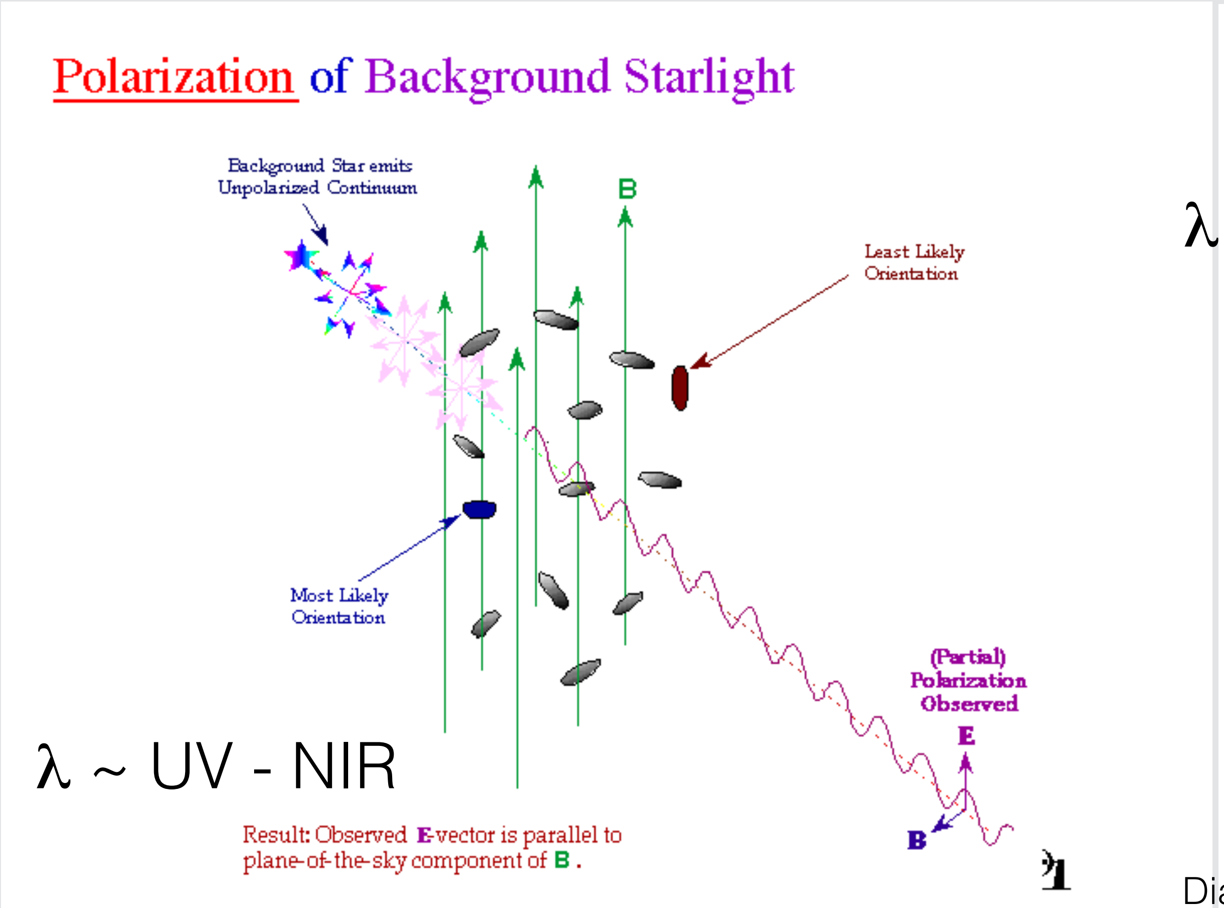
Other effects (aligned atoms, Zeeman, etc.) are possible but because HAWC+ is broad-band and not sensitive to circular polarization, not discussed here.

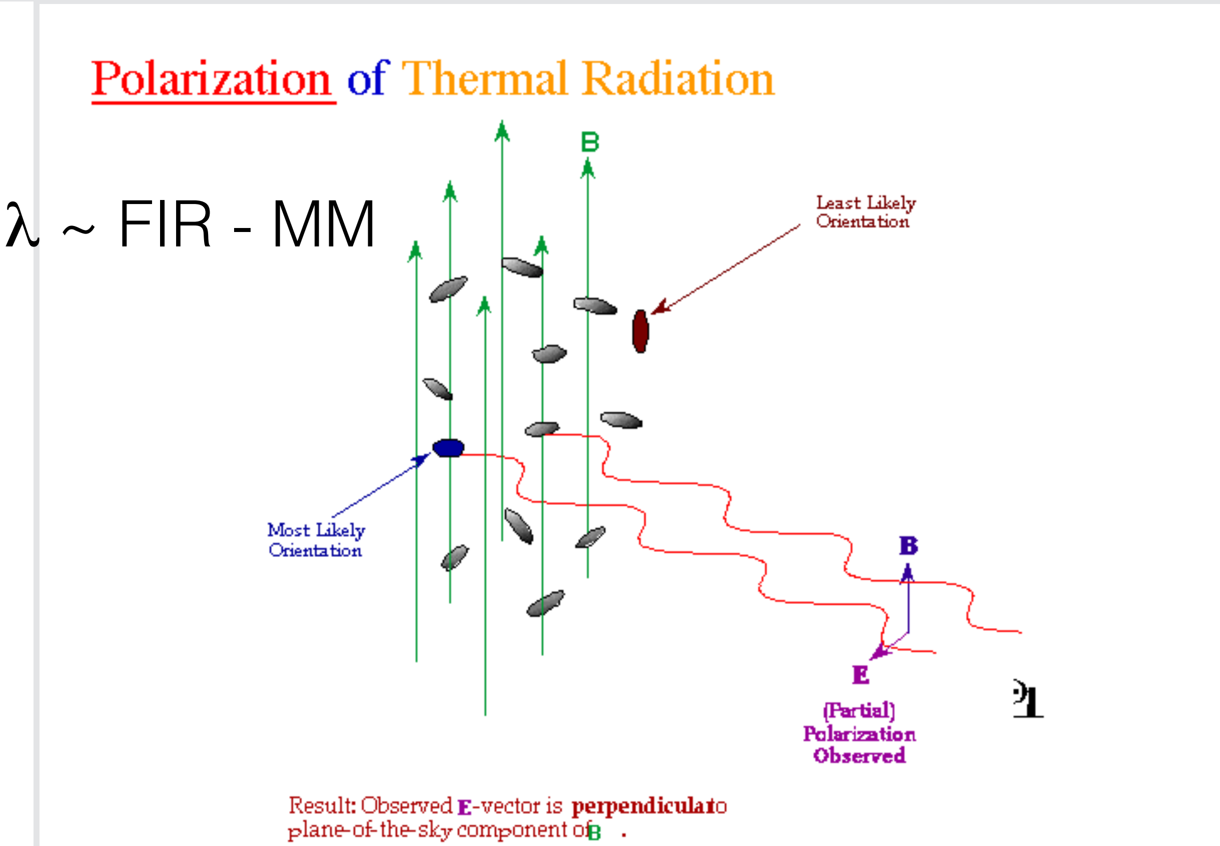
For grain alignment see

Andersson, Lazarian & Vaillancourt, 2015, ARA&A, 53, 501

Polarization by aligned dust grains

Dichroic Extinction Polarization | *Polarization by Dichroic Emission*





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

- Alignment is due to the interaction of the dust grains with radiation.
  - Requires $\lambda < 2a$
  - For paramagnetic grains (Silicates) the alignment is [usually] along the magnetic field (B-RAT)
  - For very strong, anisotropic, radiation the alignment can become along the radiation field direction (k-RAT)
- Disalignment (for “classical” grains) dominated by gas-grain collisions

Polarization by aligned dust grains

- Alignment is due to the interaction of the dust grains with radiation.
  - $\lambda < 2a$
- Alignment more efficient in strong radiation (and not uniform along a line of sight) – e.g. next to embedded YSOs
- For dense, starless cores, the alignment should fail beyond $A_V \approx 20$ mag (Alves et al. 2013; Jones et al 2014; Andersson et al. 2015)
- Carbon grains are not expected to be aligned with the magnetic field

Note that since O/NIR polarization is due to extinction, but FIR polarization is due to emission

$$p_{ext} = -\tau p_{emit}$$

(where the minus sign, by convention, signifies a 90° rotation)

For optically thin emission, $I = T(1-e^{-\tau}) \approx T\tau$ and, if T=constant,

$$p_{ext} \sim -I p_{emit}$$

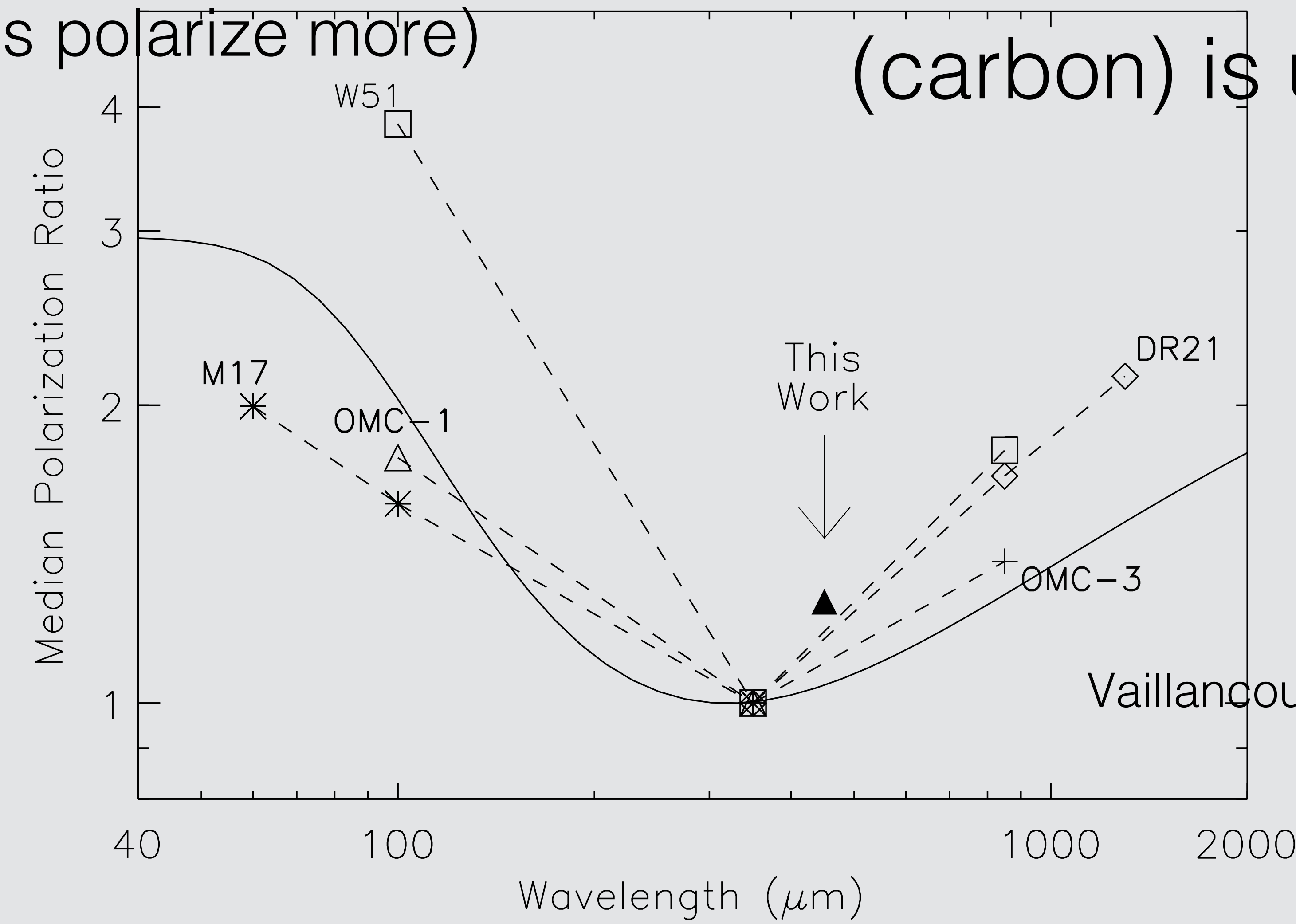
So the polarized flux (at FIR) is equivalent to the polarization at O/NIR

Polarization by aligned HAWC+

- HAWC+ covers the peak of the [large] dust emission
- The HAWC+ “Polarization spectrum” could tell us about source structures and dust composition
- Vaillancourt et al (2008) & Draine & Fraisse (2009)
- But Fissel et al. don’t see it – need more data at <200mm

Hotter dust (close to embedded sources polarize more)

Hotter co-mixed dust (carbon) is unaligned



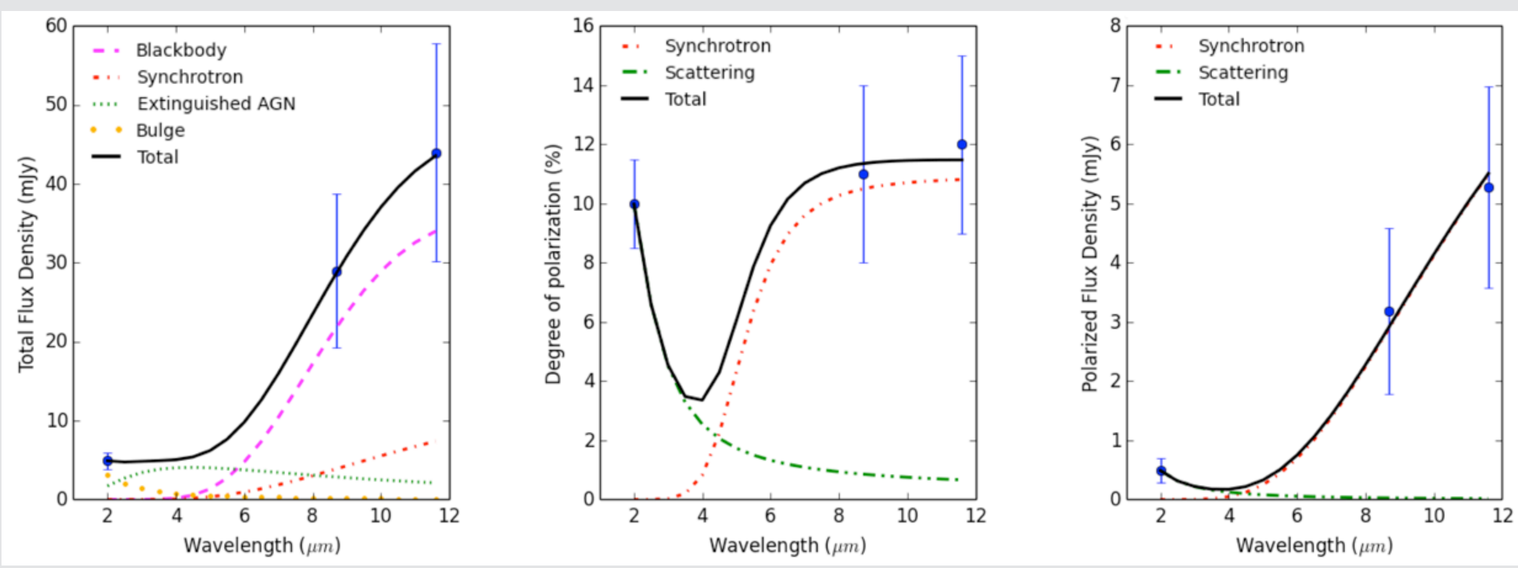
Vaillancourt et al. (2008)

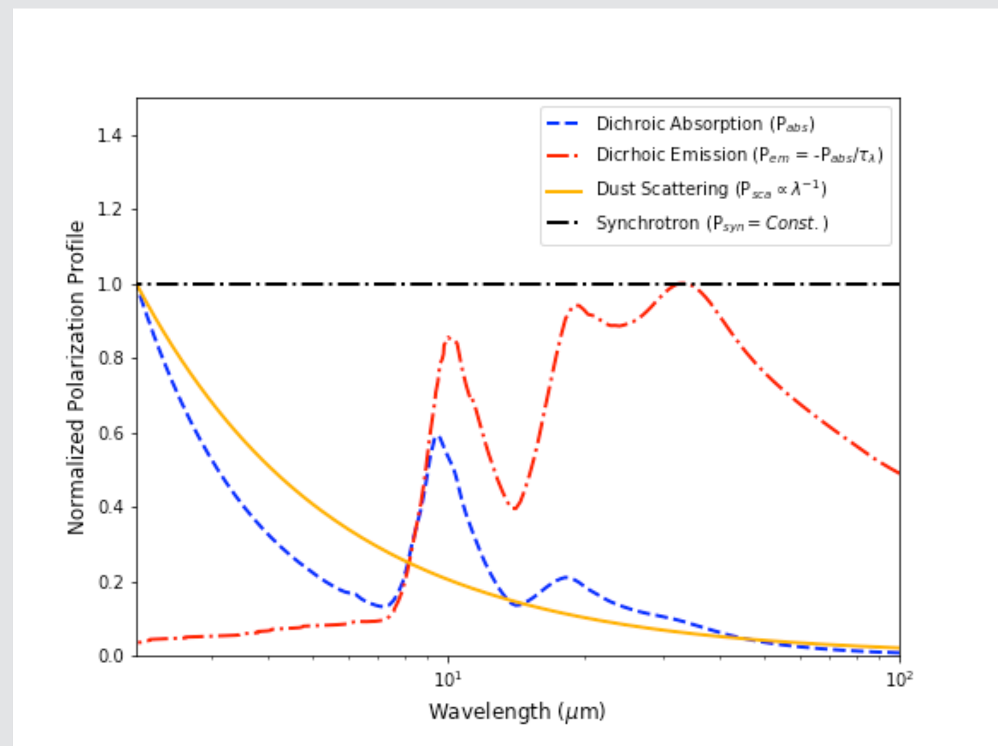
Polarization From Synchrotron Radiation

- From relativistic electrons orbiting magnetic field lines
- Spectrum falls with frequency. To be a concern in the FIR, electrons have to be very high energy

  The polarization and polarized flux depend on the opacity of the source in a complicated way

- Proposed for AGNs due to small-scale (pc-scale) jets
- Highly intrinsically polarized

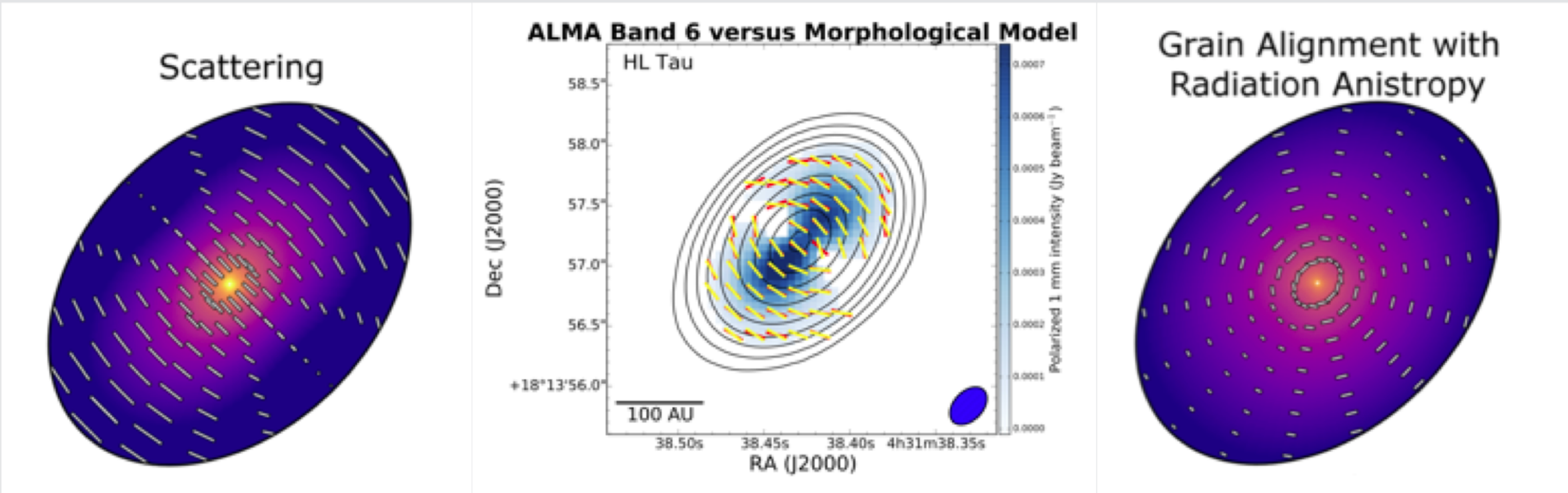


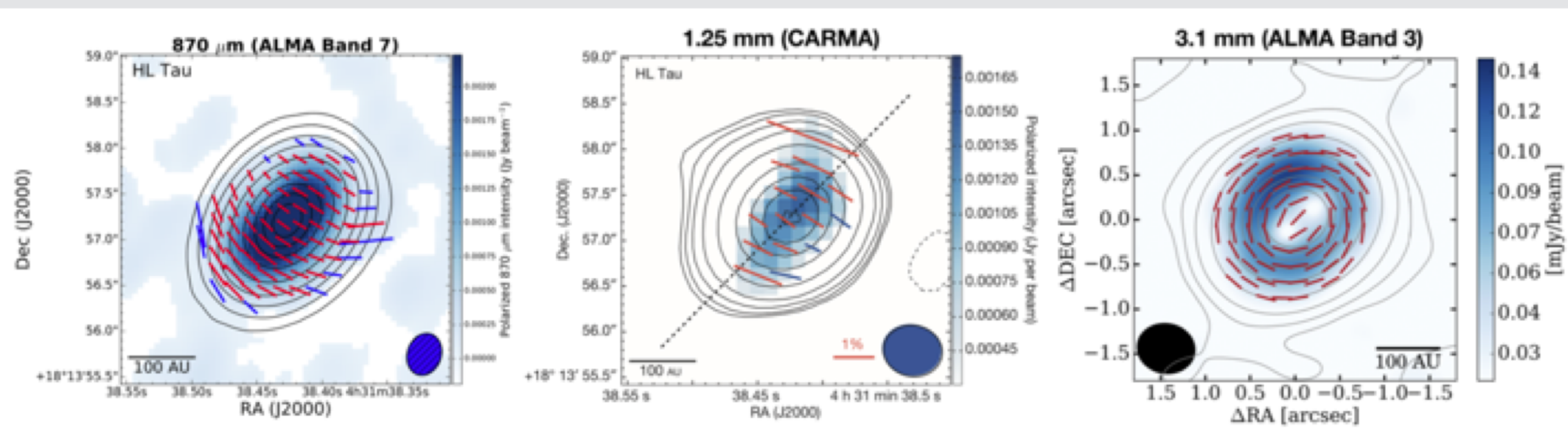


Polarization From Scattering

- Scattering off of polarizable dust will give rise to "Rayleigh scattering"
- In the [diffuse] ISM the grains range from (<) 0.010 – 0.3 μm
  - Only affects the blue (UV) polarization (e.g. Matsumura et al. 2011; Andersson et al. 2013)
- In regions where significant grain growth occurs next to a bright source "Rayleigh scattering" can affect much longer wavelengths
- Looney and collaborators (Kataoka et al. 2017; Stephens et al. 2017) have shown that mm-wave polarimetry can be due to dust scattering

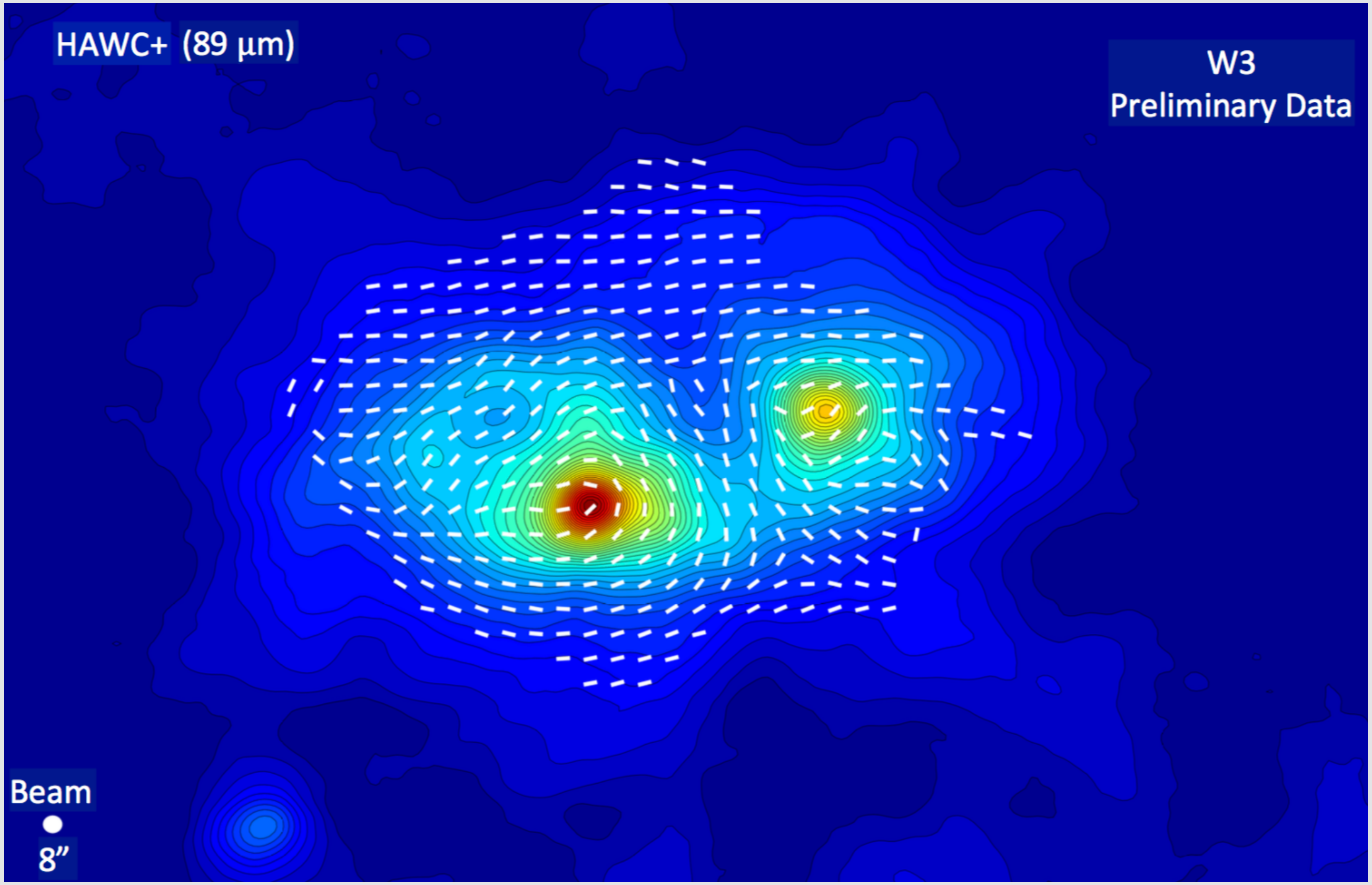
Polarization From Scattering
- The case of HL Tau (Looney et al.)





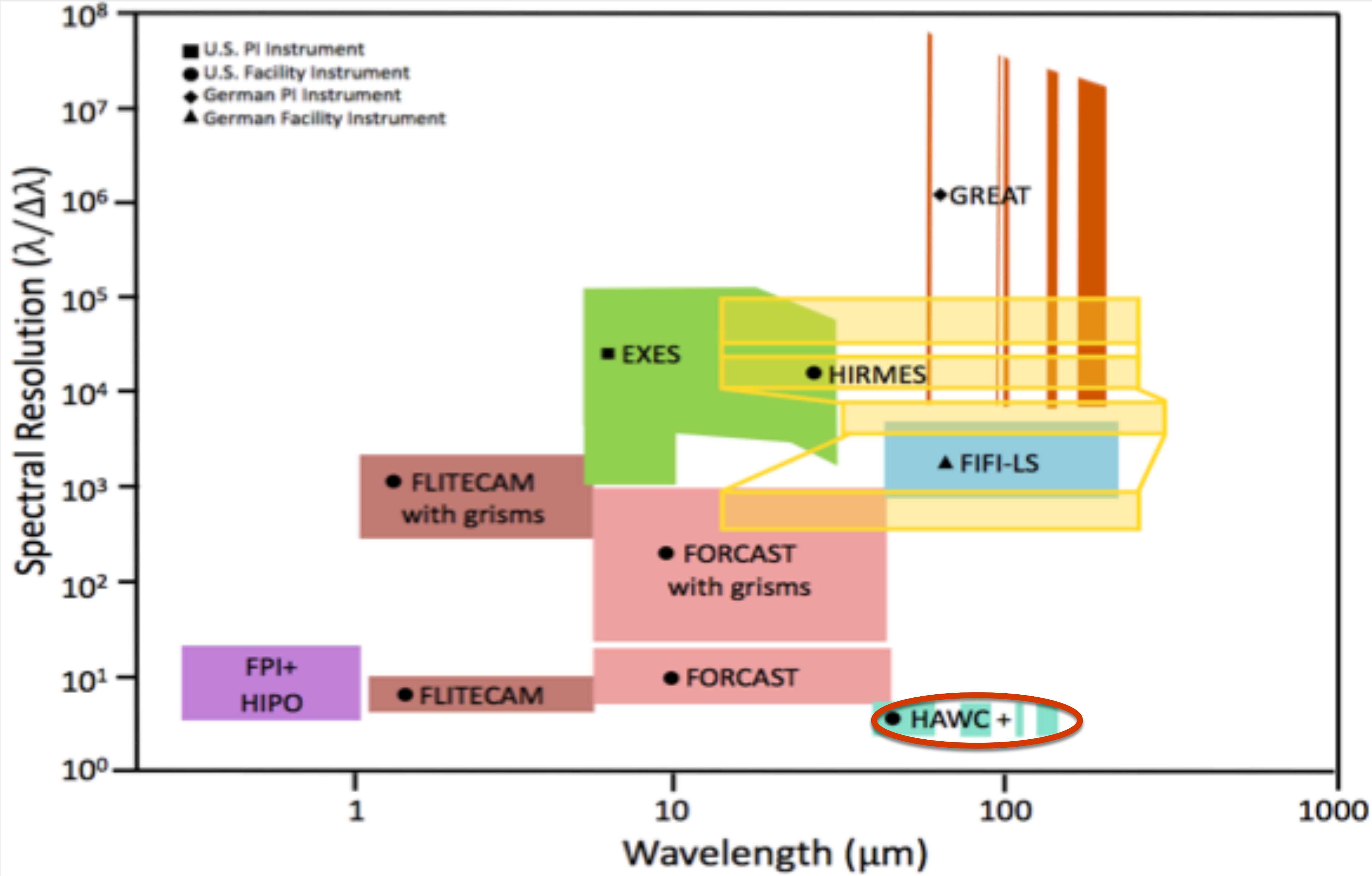
Kataoka et al. (2017); Stephens et al. (2017)

Imaging and Polarimetry HAWC+



Imaging and polarimetry map of W3 at 89 µm (Preliminary data)

HAWC+



U.S. PI Instrument
U.S. Facility Instrument
German PI Instrument
German Facility Instrument
Spectral Resolution (λ/Δλ)
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
GREAT
EXES
HIRMES
FIFI-LS
FLITECAM with grisms
FORCAST with grisms
FPI+ HIPO
FLITECAM
FORCAST
HAWC +
1
10
100
1000
Wavelength (μm)

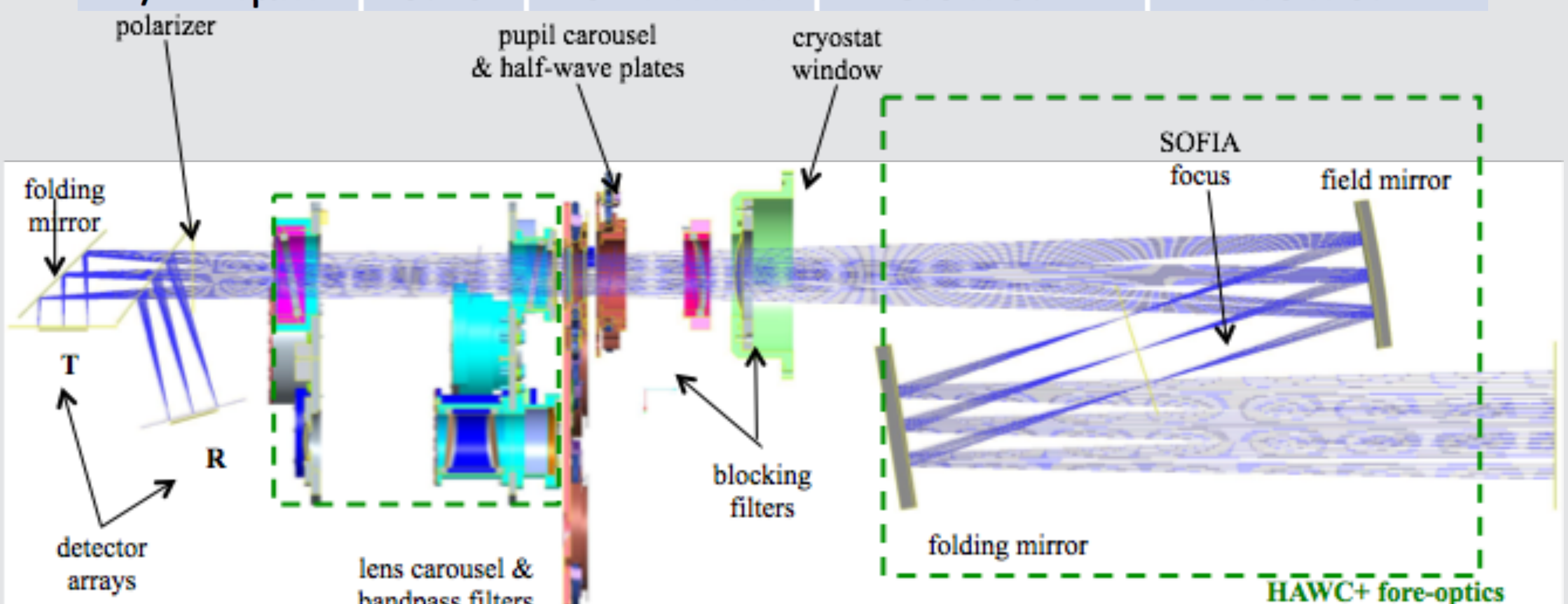
HAWC+

- HAWC+ is a Half-Wave Plate (HWP) and wire-grid polarimeter
  - HWP are bifringent elements that rotate the plane of polarization of the incoming light
- Two simultaneous orthogonal linear polarizations sensed (R & T)
  - Rotating the HWP allows the four required angles to be probed (α = 0, 22.5, 45 & 67.5)
  - This has to be done fast enough that variations in the background doesn't overwhelm the polarization signal
  - Therefore (currently) polarization measurements can only be done in chop-nod mode
- The detectors are superconducting transition-edge sensor (TES) thermometers on membranes with a wide-band absorber coating.
- Cooled to an operating temperature of ~0.2 K in flight, by an Adiabatic Demagnetization Refrigerator (ADR)
  - The hold time of the HAWC+ ADR has now been extended to >10h

HAWC+ Specifications

- PI: C. Darren Dowell (JPL)
- Imaging and Polarimetric capabilities

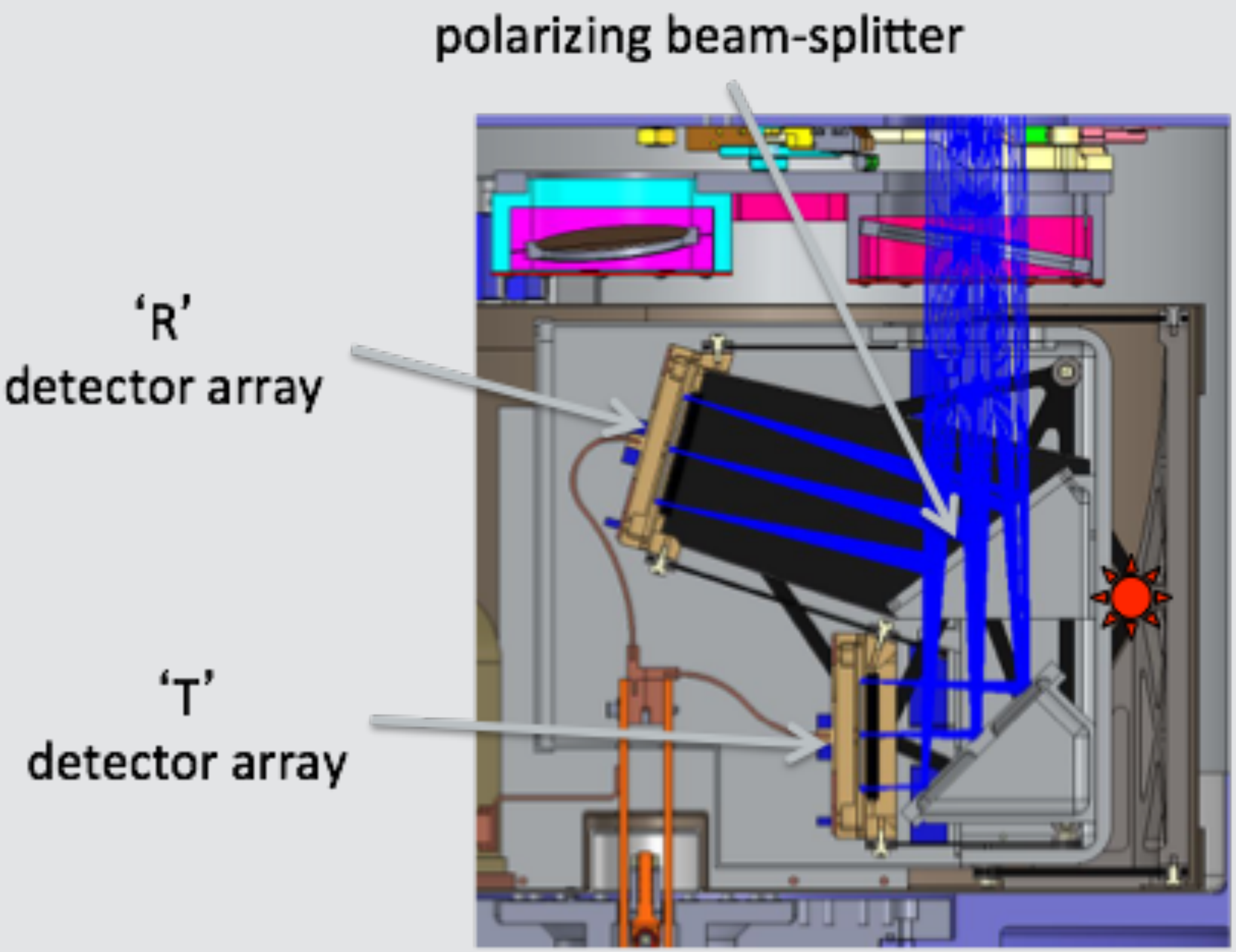
Band / Wavelength	Δλ/λ	Angular Resolution	Total Intensity FOV (arcmin)	Polarization FOV (arcmin)
A / 53 µm	0.17	4.7” FWHM	2.7 x 1.7	1.3 x 1.7
~~B[a] / 63 µm~~	~~0.15~~	~~5.8” FWHM~~	~~4.2 x 2.6~~	~~2.1 x 2.6~~
C / 89 µm	0.19	7.8” FWHM	4.2 x 2.6	2.1 x 2.6
D / 154 µm	0.22	14” FWHM	7.3 x 4.5	3.6 x 4.5
E / 214µm	0.20	19” FWHM	8.0 x 6.1	4.0 x 6.1

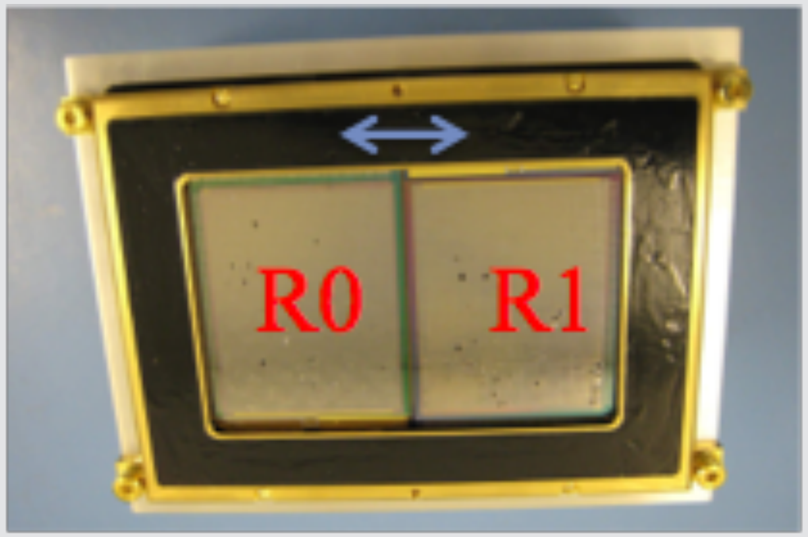


[a] 63µm observations saturate on background flux (too wide a filter) – not offered in Cy 7

HAWC+ Field Of View

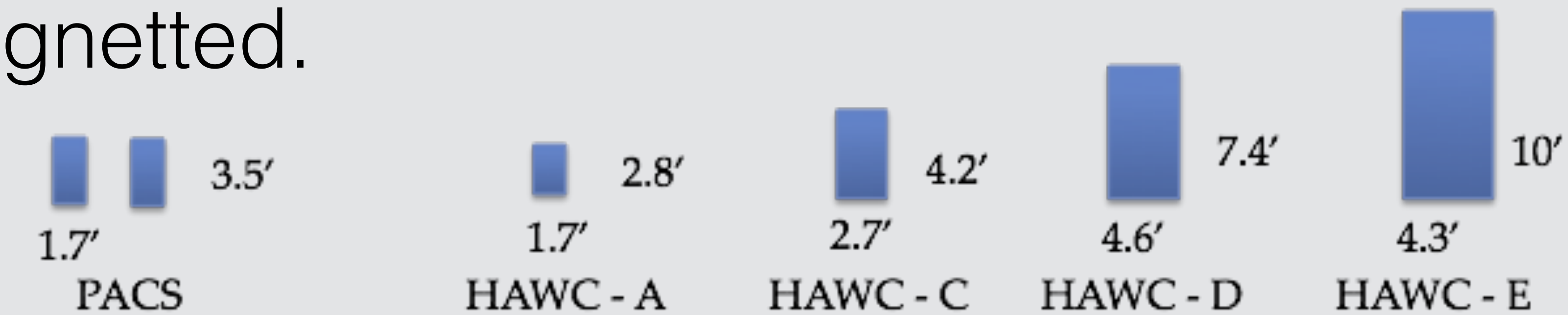
- 3 detectors are available: R0, R1 and T0
- Imaging and Polarimetric capabilities

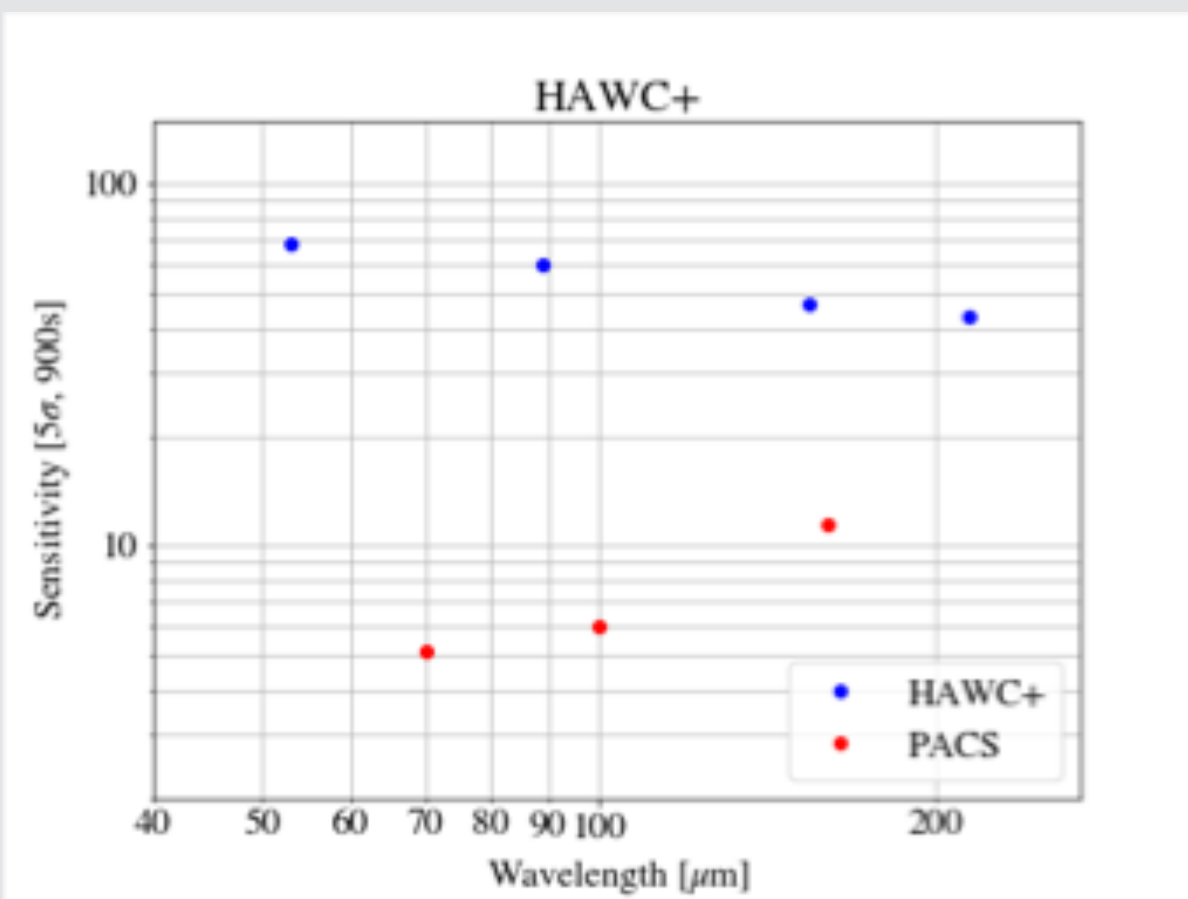


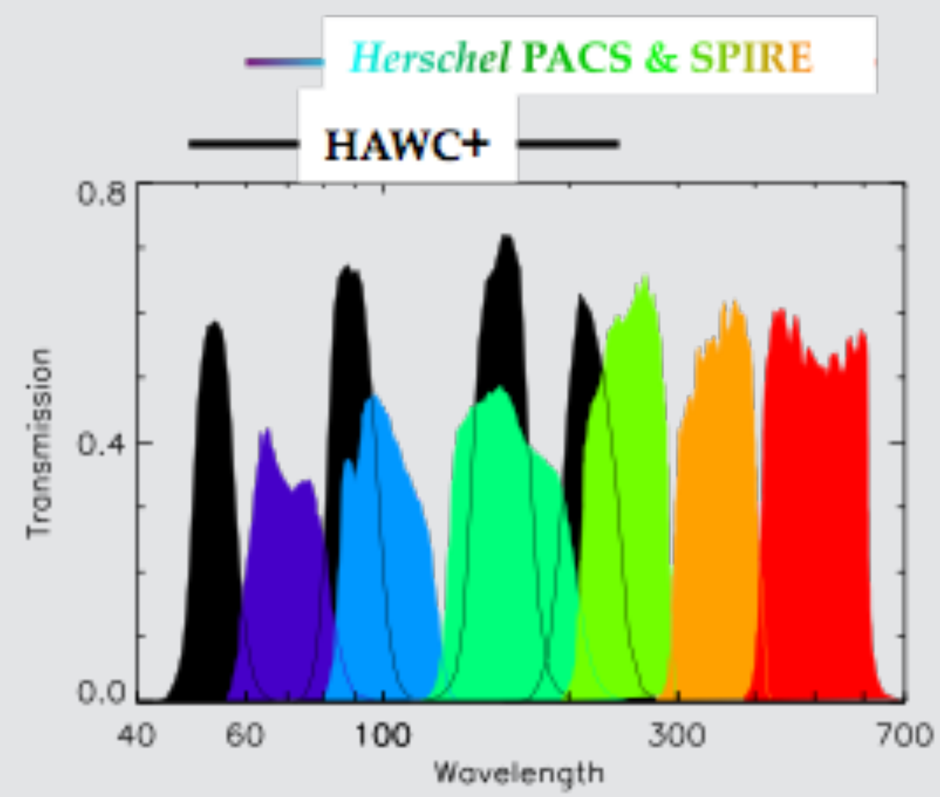


HAWC+ Sensitivities

- HAWC+ total power is less sensitive than PACS, considering that HAWC+ bands are narrower than HERSCHEL's.
- On the other side, the HAWC+ FOV is wider than PACS at long wavelengths. Note that the FOV of Band E (214 μm) is partially vignetted.







HAWC+ Instrumental Polarization

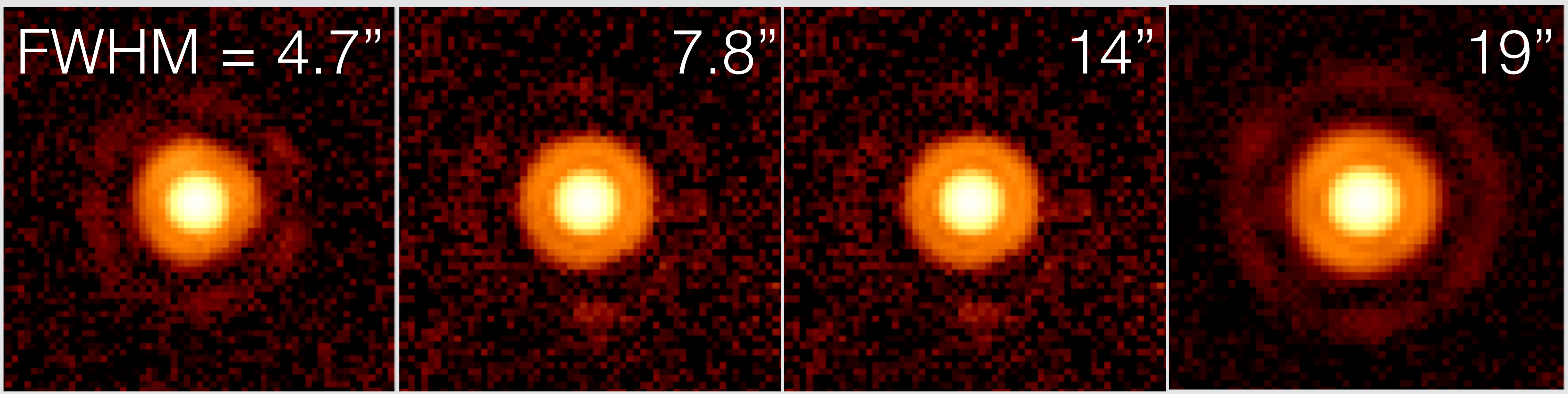
- HAWC+ instrumental polarization (IP) has been measure and is small and stable
- The IP is mainly cause by the tertiary mirror of SOFIA with the position angle of polarization perpendicular to the tertiary mirror direction.

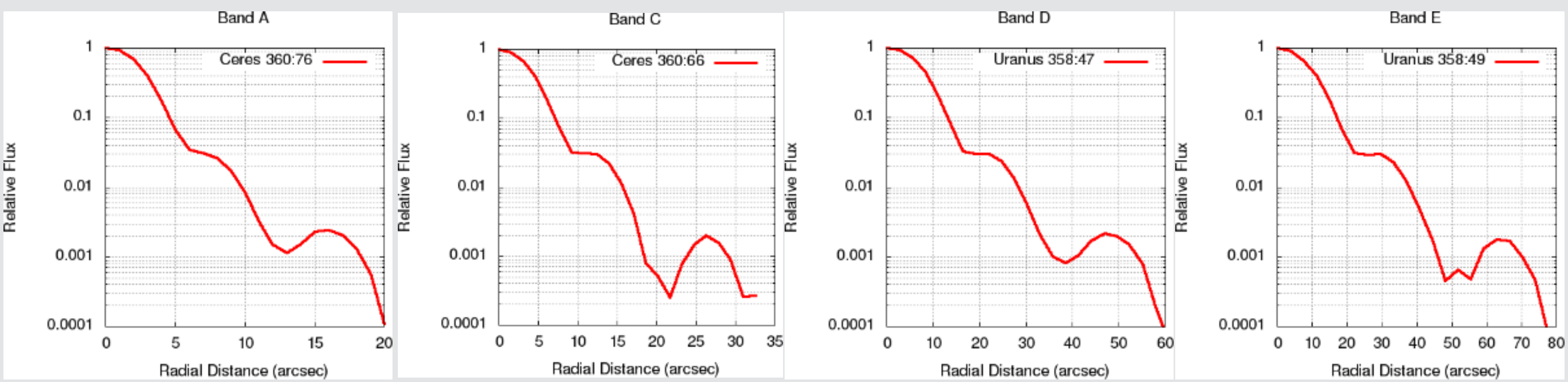
	Band A	Band C	Band D	Band E	σ(q,u)
q	-0.0154	-0.0151	0.0028	-0.0129	<0.003
u	-0.0030	0.0090	0.0191	0.0111	<0.003
IP [%]	1.6	1.8	1.9	1.7	

- IP reproducibility is ~0.3-0.8%
- IP variations over the FOV is also ~0.3-0.8%
- Hence: A (calibrated) measured polarization of <0.8% is consistent with an un-polarized source
- Note that the formal uncertainties of the IP (above) are less than the variations, so unlikely that we can improve IP subtraction significantly

HAWC+ PSF

- HAWC+/SOFIA is diffraction limited at all wavelengths.



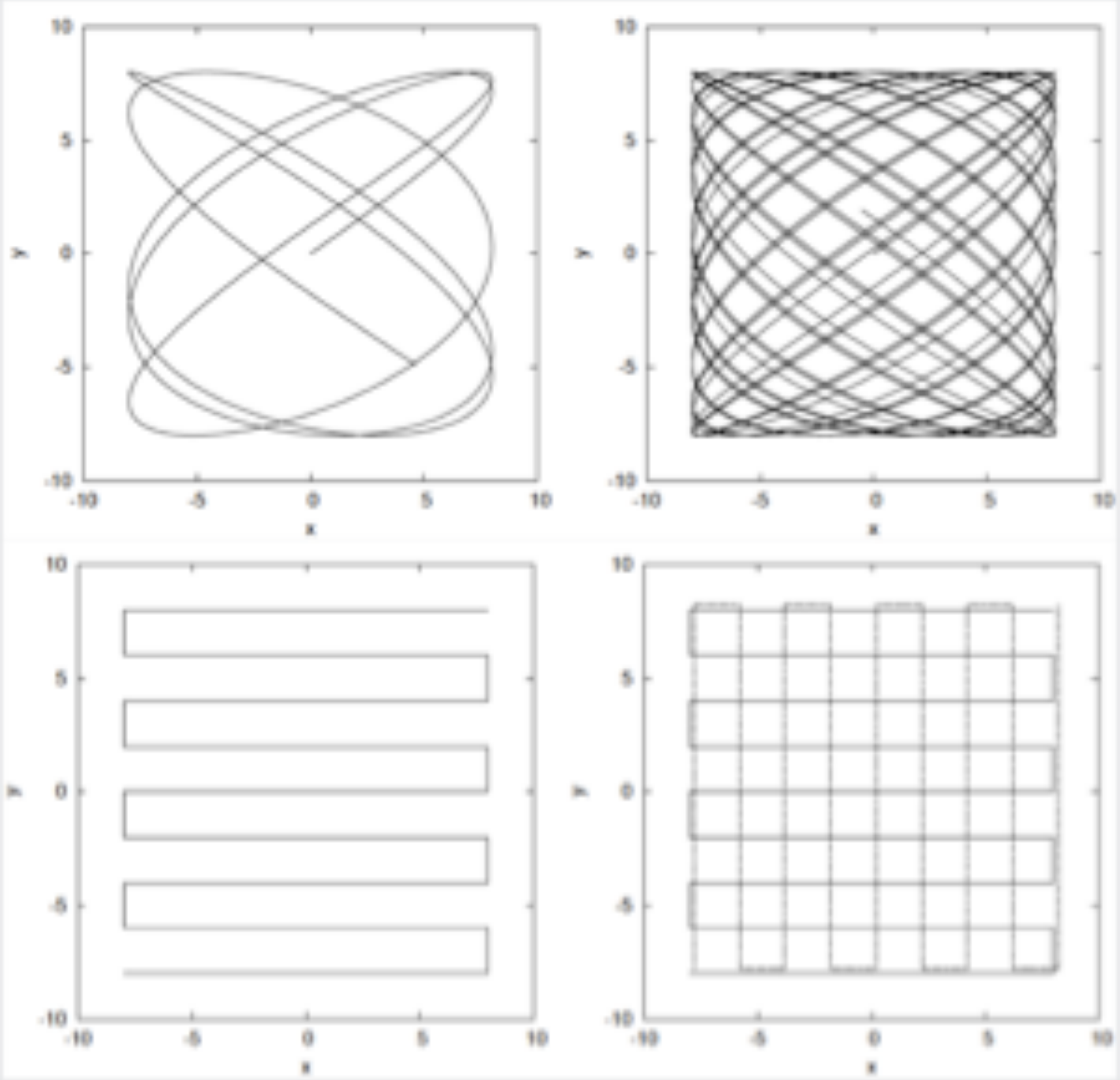


HAWC+ Lissajous & Rasters

- Polarimetry can (currently) only be done in Chop-nod mode.
- Total Intensity scan mapping is used with two available patterns:

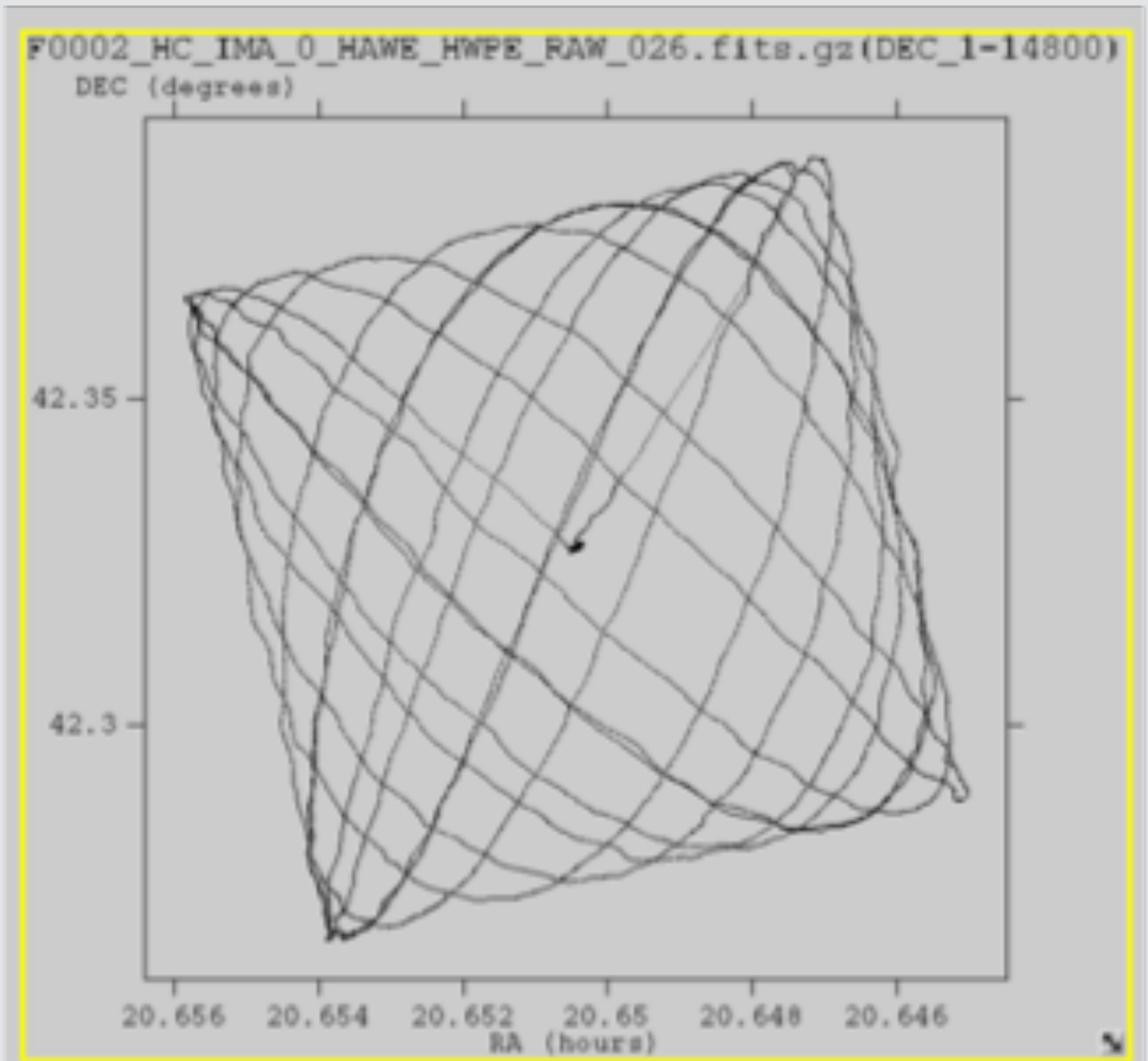
    - Lissajous for small fields. Use this mode for fields comparable to the FOV of HAWC+

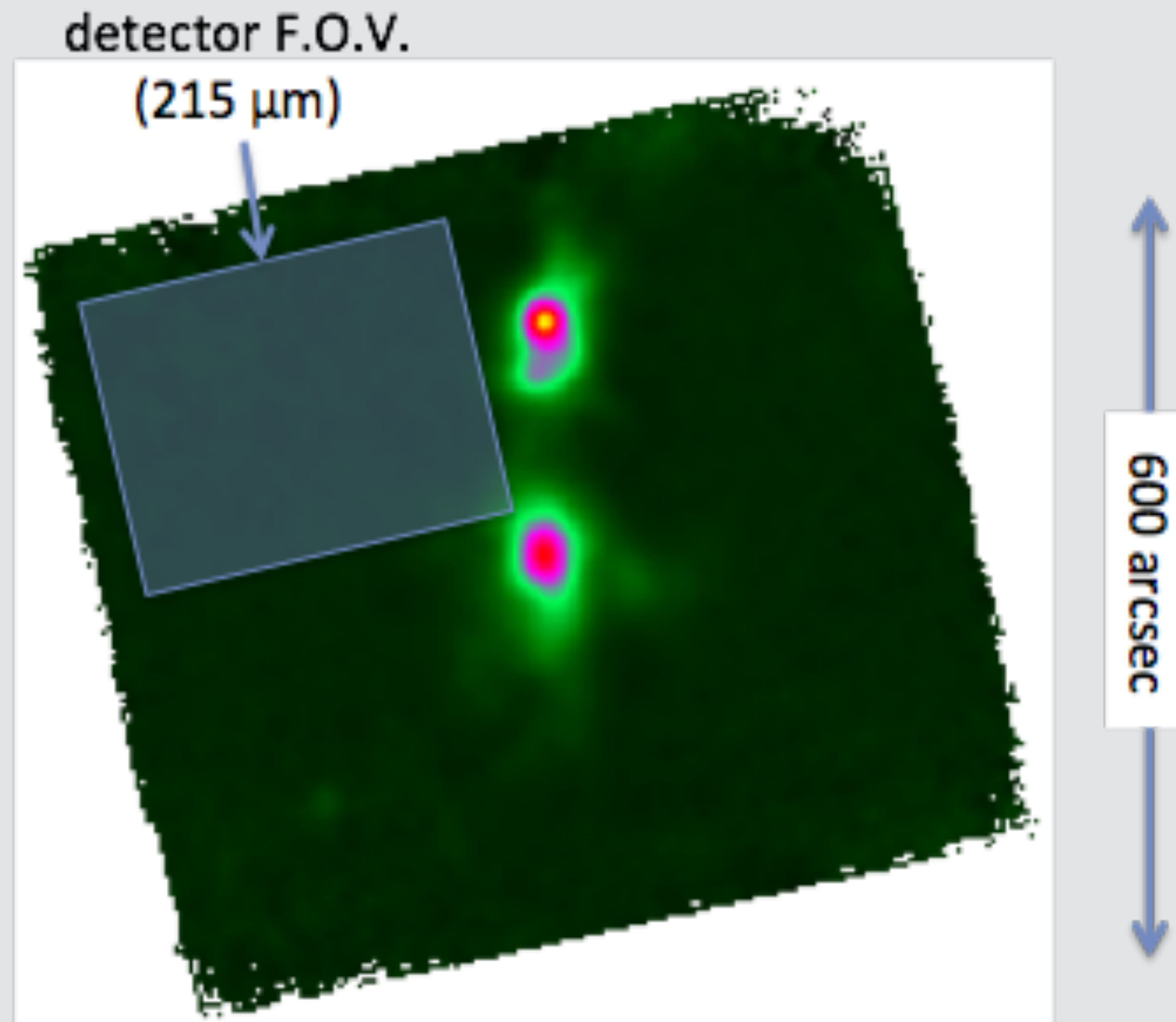
    - Rasters to map large fields.



- In both cases, two scans are required to avoid stripping.
- To obtain an absolute flux calibration, part of the map should include regions with no extended flux.

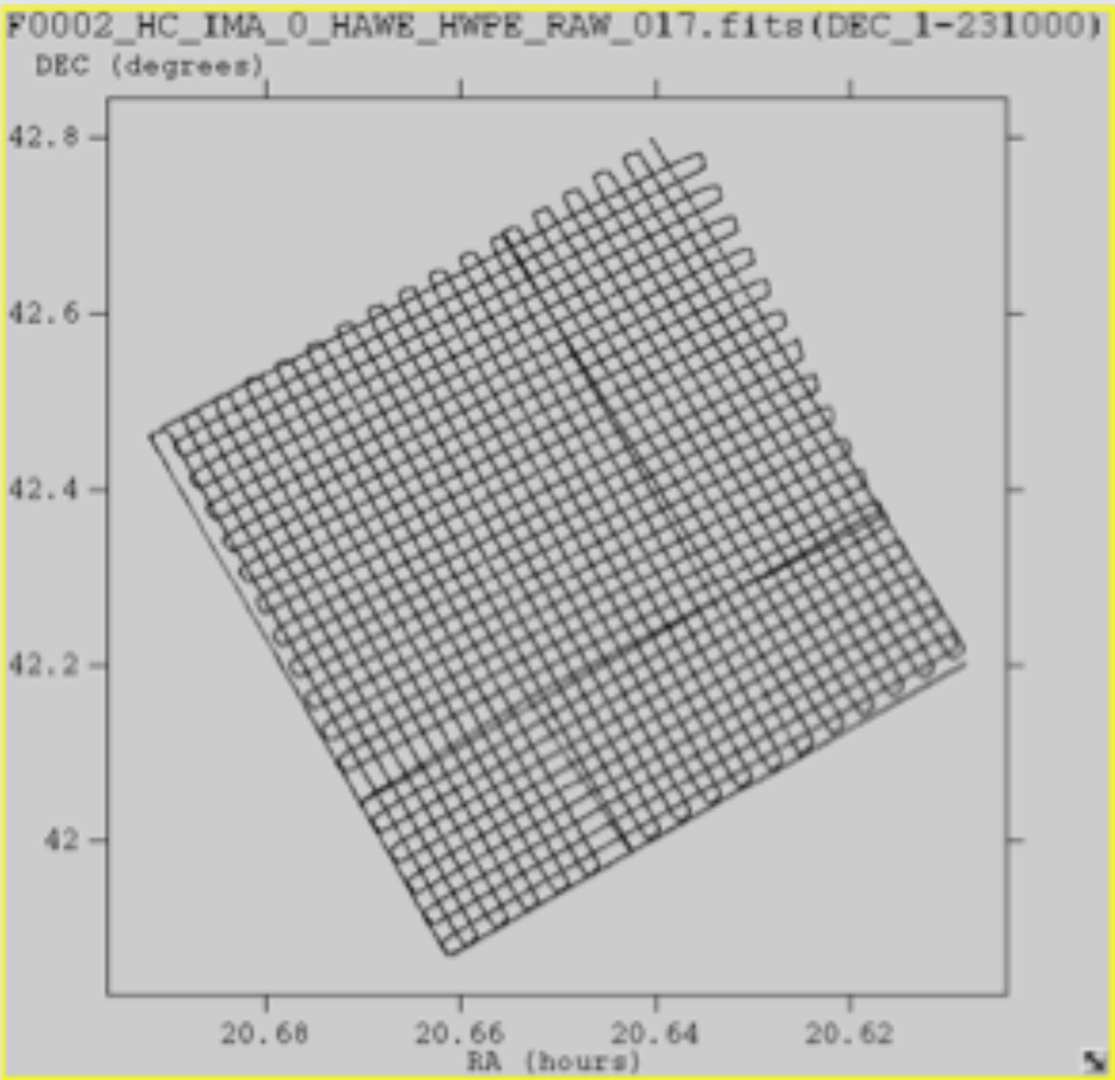
HAWC+ Lissajous

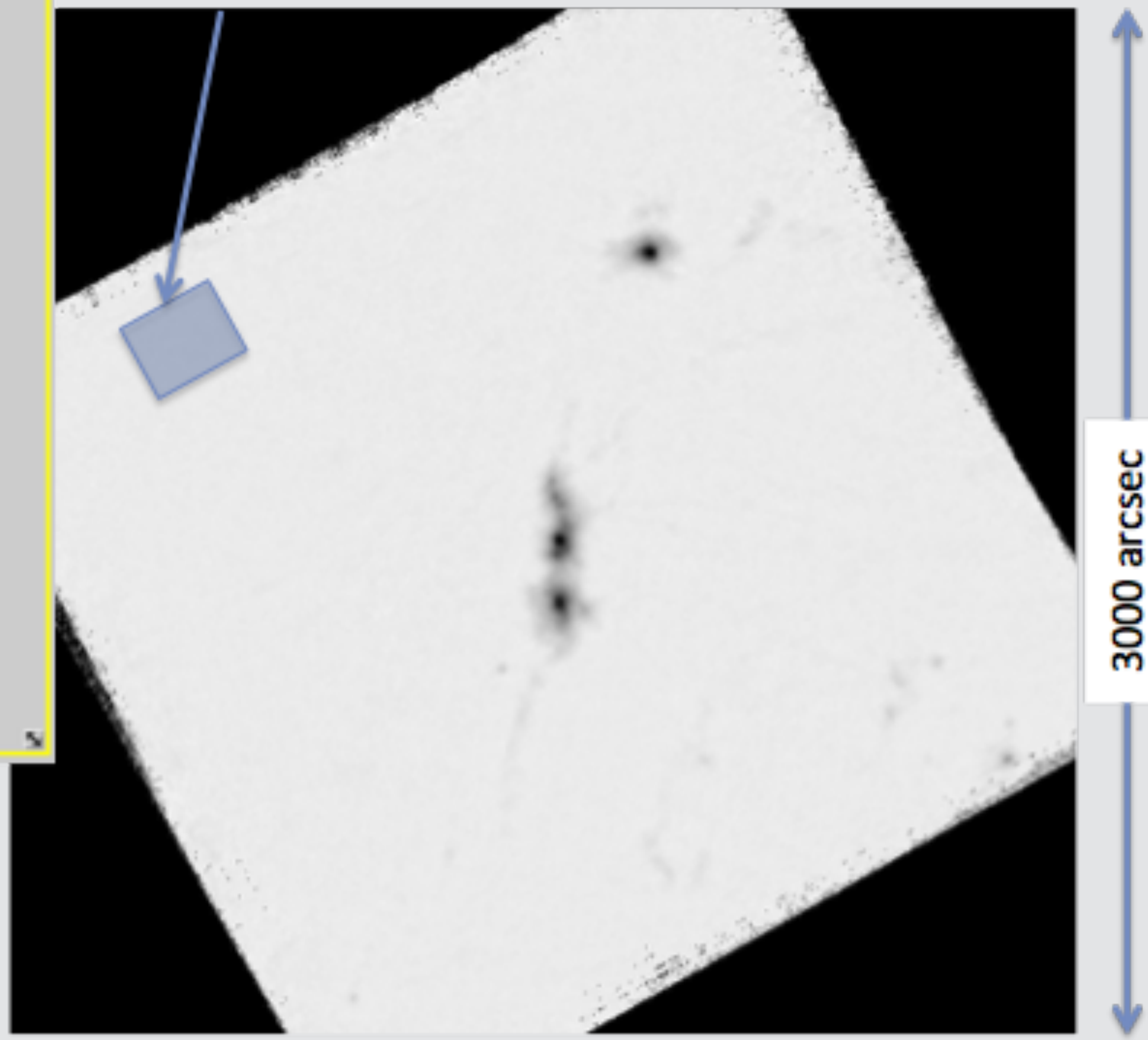




360 arcsec pk-pk, 200 arcsec/sec, 60 sec duration

HAWC+ Raster

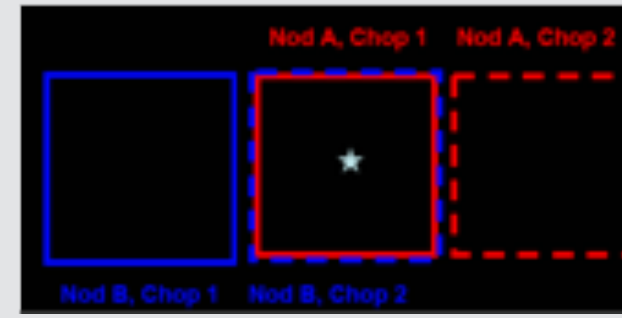




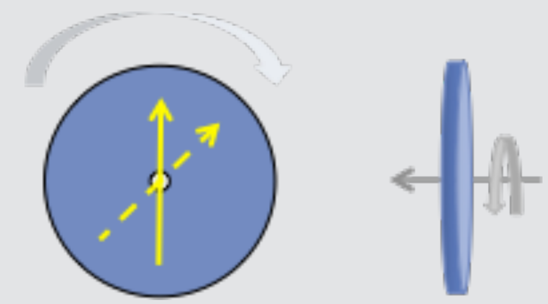
200 arcsec/sec, 19 min. duration
5 pauses to cross-check gyros vs. star tracking

HAWC+ Polarimetry

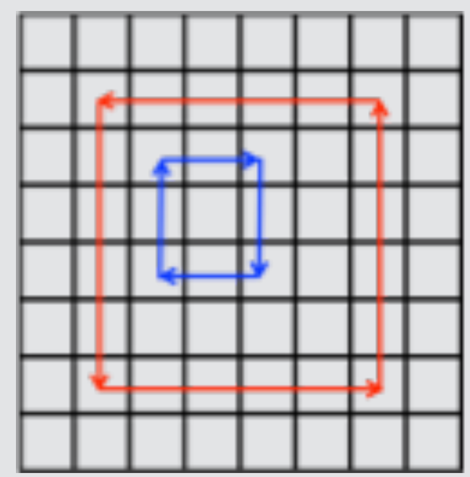
1) Chop-nod:
   - Nod parallel to chop, symmetric only
   - Chop-throw <8 arcmin, Chop-freq. 5-20 Hz



2) Half-WavePlate (HWP) rotation:
   - 4 HWP positions: 0°, 45°, 22.5° and 67.5°
   - Chop-nod at each HWP angle



3) Dithering:
   - 4 dither positions within the FOV



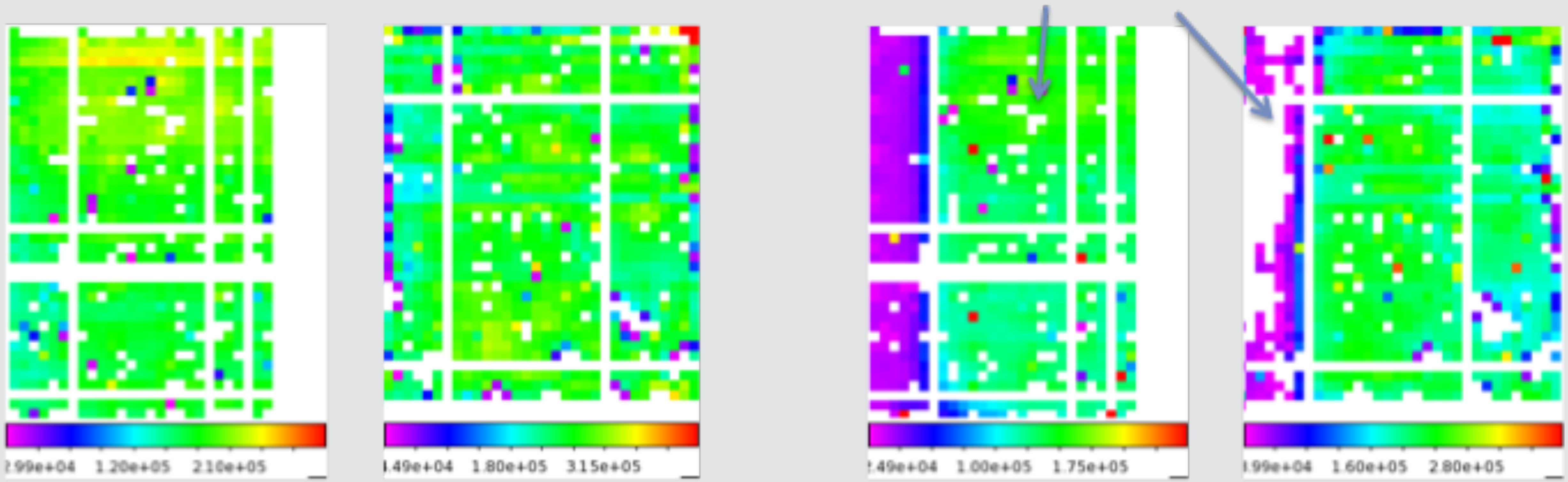
Repeat chop-nod and HWP rotation at each dither position

4) Mosaics:
   - Steps 1 to 3 are repeated for a new sky position
   - Overlap by ~5 pixel
   - Account for rectangular array and no K-mirror

HAWC+ Dithering

- Bad and missing pixels in the detector of HAWC+ require dithering to have images without holes.
- Band E (214 μm): Vertical vignetting on the left and right of the array. Usable FOV ~2’x6’.

Band E vignetting



RO TO

Band A

RO TO

Band E

Preparing HAWC+ observations

- Key instruments/observation parameters:

1) Expected Total flux at desired wavelength
   - [use Herschel or SED modeling]
2) Expected degree of polarization at desired wavelength
   - [use SED modeling or polarization models]
3) Expected polarization accuracy.
   - It depends on your scientific goals
   - Instrumental polarization puts a floor at $p \approx 0.8\%$
4) Establish OFF/Chop positions/Chop .
   - 480" max Chop through
   - Polarized flux is what count
5) Go to ETC and estimate the observing time given your requirements.
6) No K-mirror – mosaics must be "robust"
7) Use USPOT to establish availability of guide stars

HAWC+

- HAWC+ is a imaging polarimeter
  - HWP + Wire grid
  - TES bolometers cooled to 0.2K by ADR
- Covers 53 - 214μm
- Beam sizes 4.7-19”; FOV: 1.3’x1.7’ – 4.0’x6.1’
- Polarimetry done in Chop-Nod mode
- Photometry (imaging) more efficiently done in scan mode
  - Scan-map mode polarimetry is under development