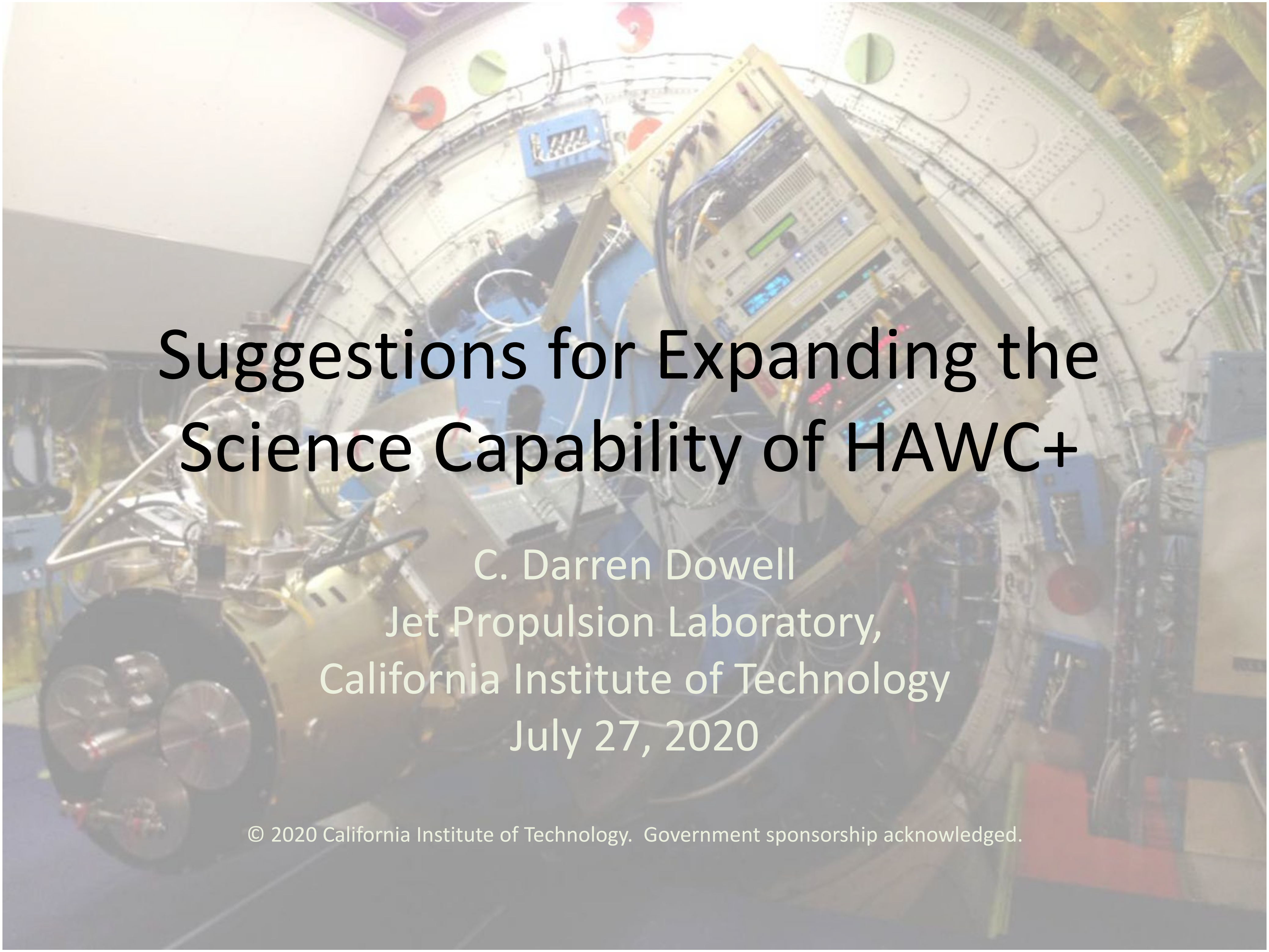


Suggestions for Expanding the Science Capability of HAWC+

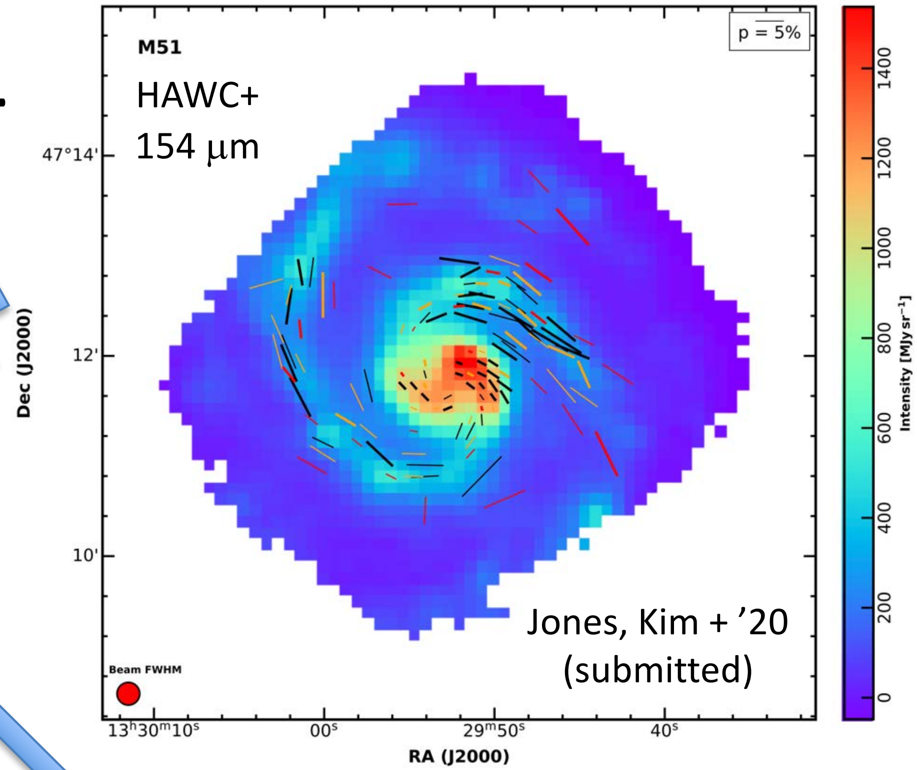
C. Darren Dowell
Jet Propulsion Laboratory,
California Institute of Technology
July 27, 2020

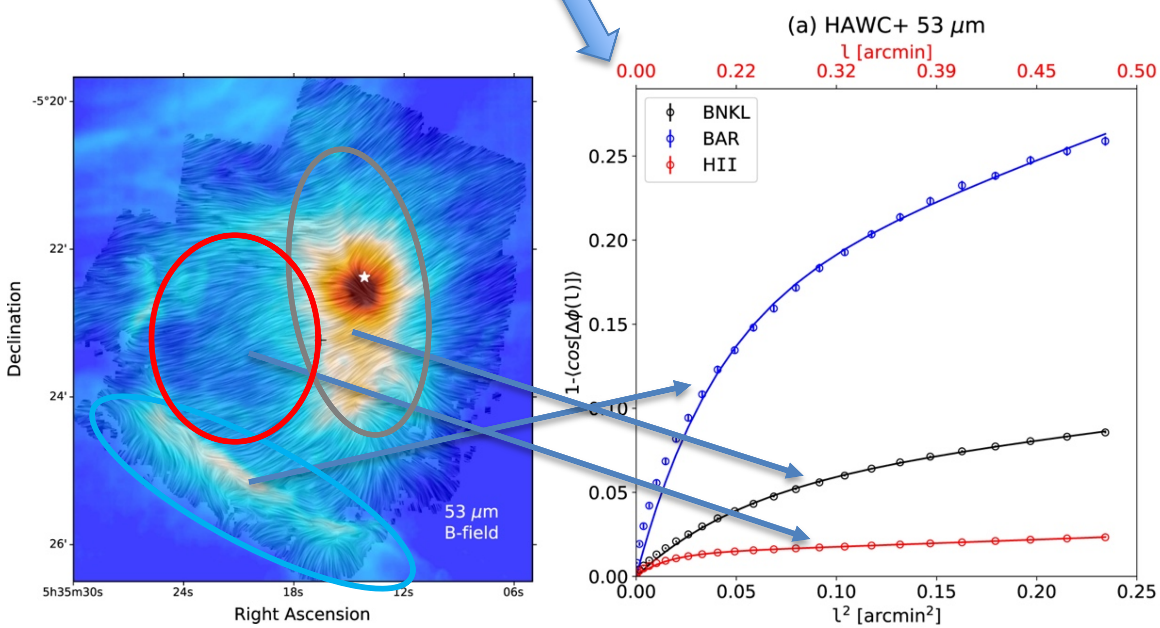
Outline

- brief introduction to HAWC+
- upgrade wish list
- requirements & optical constraints for upgraded detectors
- suitable far-IR detectors
- need for a large-area polarization mapping mode
- polarized atomic lines

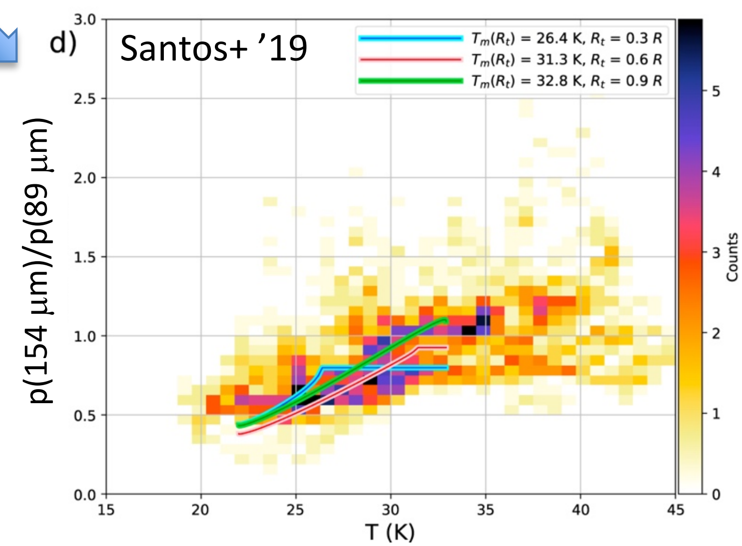
Key Features of HAWC+

- **sensitivity at photon noise limit**
- **wide field**
- **wavelength range (50 – 220 μm)**
- **polarization accuracy (~0.3%):**





Chuss+ '19



evidence optically-shielded grains less efficient at producing polarization

HAWC+ Upgrade Wish List

HAWC+ Upgrade Paths

- Minor upgrades (~12-18 months)
  - Narrow-band filters
    - Enables new science
  - Cryo tuning/new observing modes
    - Sensitivity and overhead improvements
  - 4th array
    - Increase mapping speed and FOV
- Major upgrades (2-3 years)
  - 4 new arrays
  - BLAST-TNG kinetic inductance detector arrays

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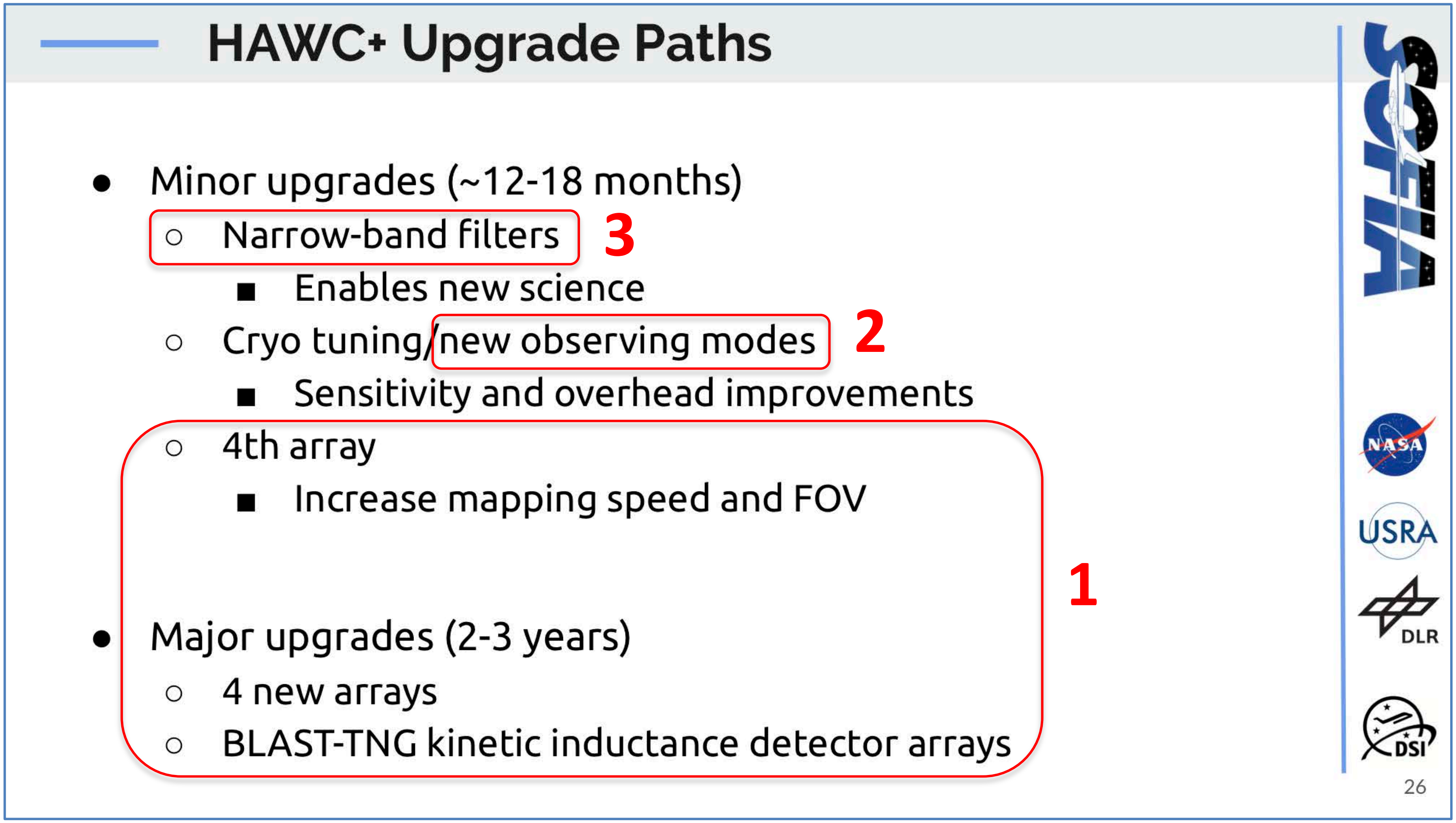
HAWC+ Upgrade Wish List



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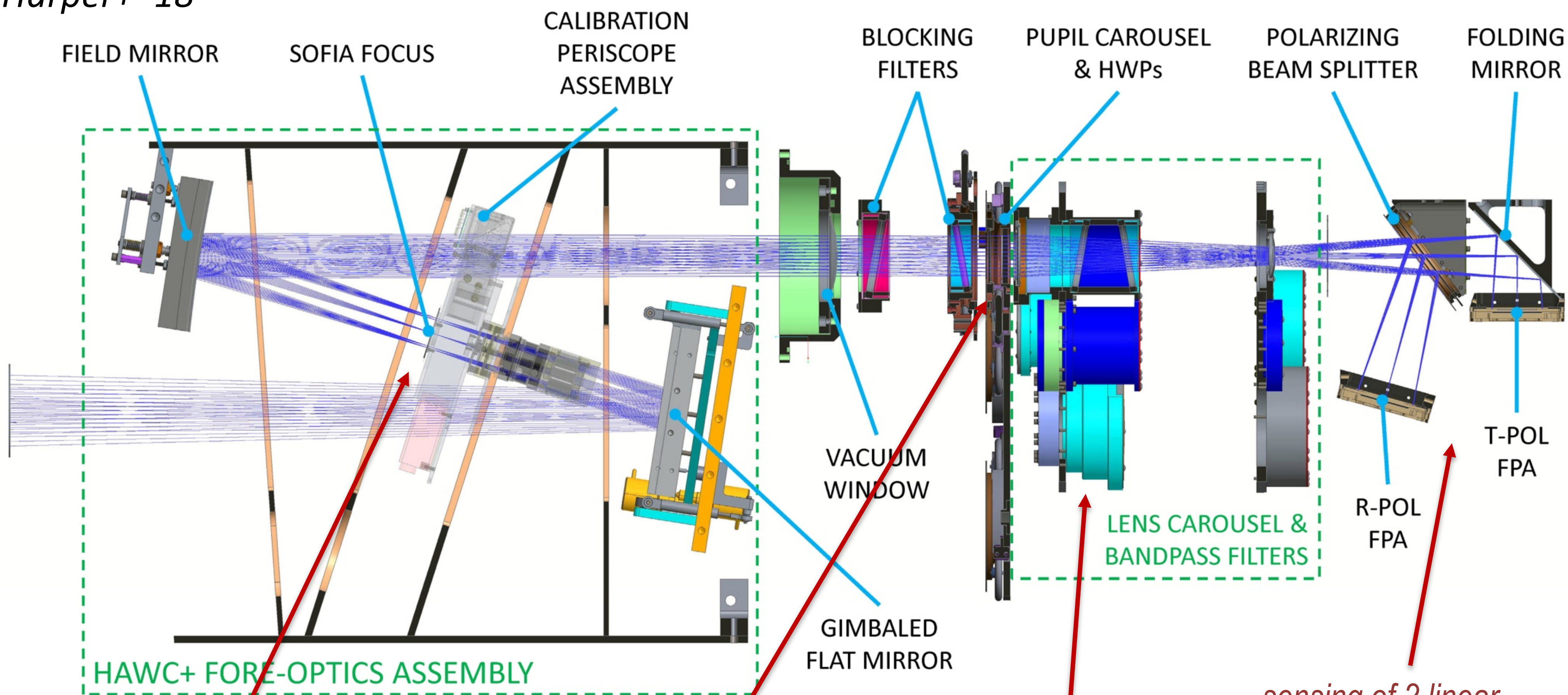
HAWC+ Optics

Harper+ '18



- Fore-optics assembly is near focus and restricts field beyond ~8.5 arcminutes.

- Polarization is modulated with 1 of 4 half-wave plates at pupil: Stokes (Q,U) in short time; consistency checks.
- Optics near pupil support full SOFIA field of view.

- *5 sets of lenses & filters*
- *Magnification sets 0.5 λ/D to 1 mm.*
- *May need to grow with detector arrays.*

- sensing of 2 linear polarizations with polarizer + 2 detector arrays
- Existing polarizer limits field to ~85 x 60 mm.

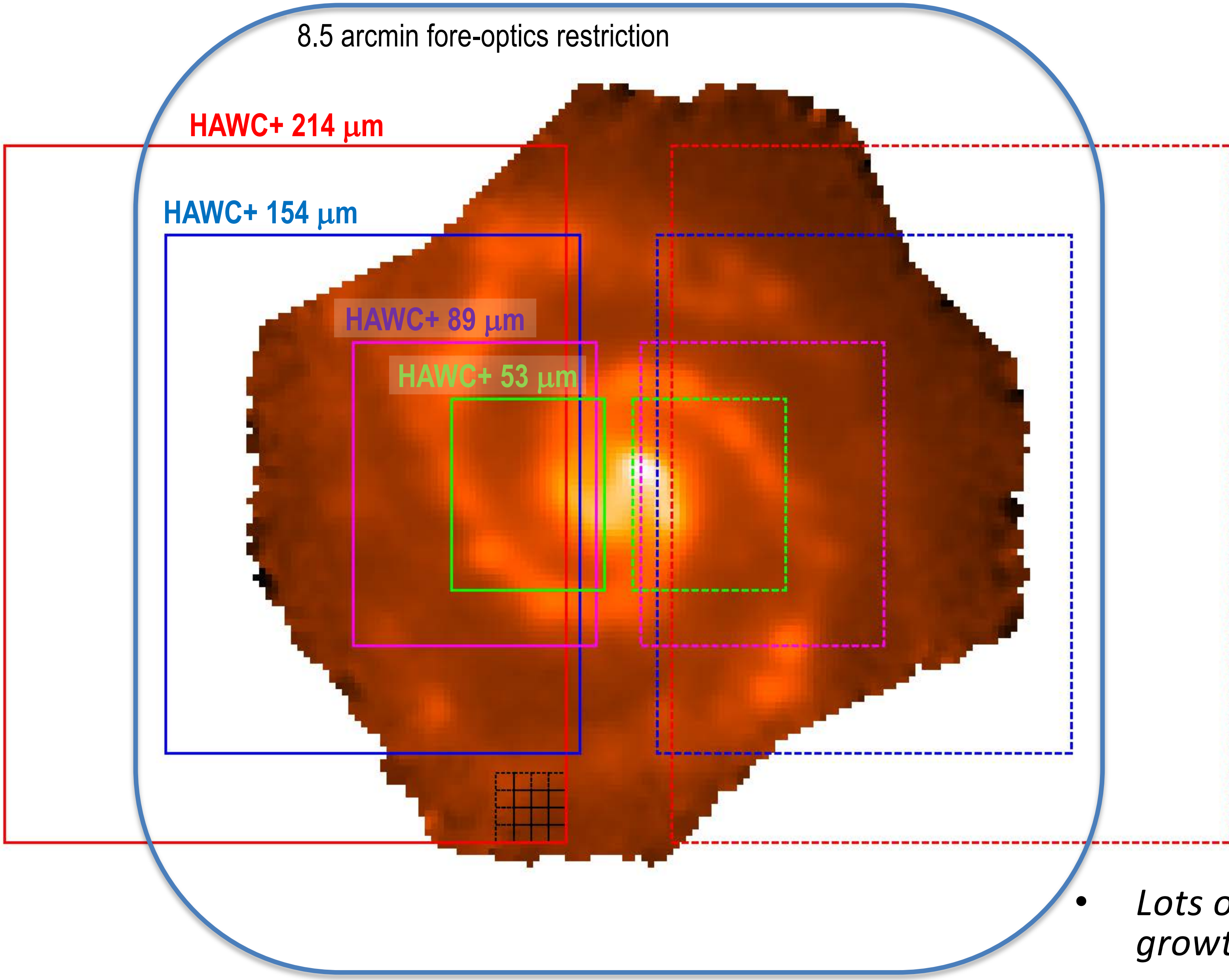
Detector Performance Requirements for Upgraded HAWC+

assuming 50% Q.E.

	Band A 53 μm	Band B 62 μm	Band C 89 μm	Band D 154 μm	Band E 214 μm
pixel angular size on sky (responsive area)	$(2.2'')^2$ (0.5 λ/D)	$(3.5'')^2$	$(3.5'')^2$ (0.5 λ/D)	$(6.1'')^2$ (0.5 λ/D)	$(8.3'')^2$ (0.5 λ/D)
pixel physical size (existing optics)	$(1.0\ \mathrm{mm})^2$				
quantum efficiency	≥ 50%				
NEP (½ of typical flight photon noise, single pol.)	$\leq 3\times10^{-16}$ W $\mathrm{Hz}^{-1/2}$		$\leq 3\times10^{-16}$ W $\mathrm{Hz}^{-1/2}$	$\leq 2\times10^{-16}$ W $\mathrm{Hz}^{-1/2}$	$\leq 1\times10^{-16}$ W $\mathrm{Hz}^{-1/2}$
background power (typical flight, single pol.)	50 pW		60 pW	60 pW	30 pW
saturation power (lab operation, single pol.)	≥ 100 pW		≥ 120 pW	≥ 110 pW	≥ 70 pW
number of operating detectors	≥ 1850 × improvement factor				

- Operating temperature can be 0.17 K or higher with existing ADR cooler.
- Also worth considering: larger pixel angular size, with corresponding higher saturation power and NEP and lower minimum pixel count.

HAWC+ Field of View



- *Lots of room for detector growth at 53 & 89 μm!*

HAWC+ Constraints on Field of View

U. Chicago (S. Wang)
optical designs for HAWC

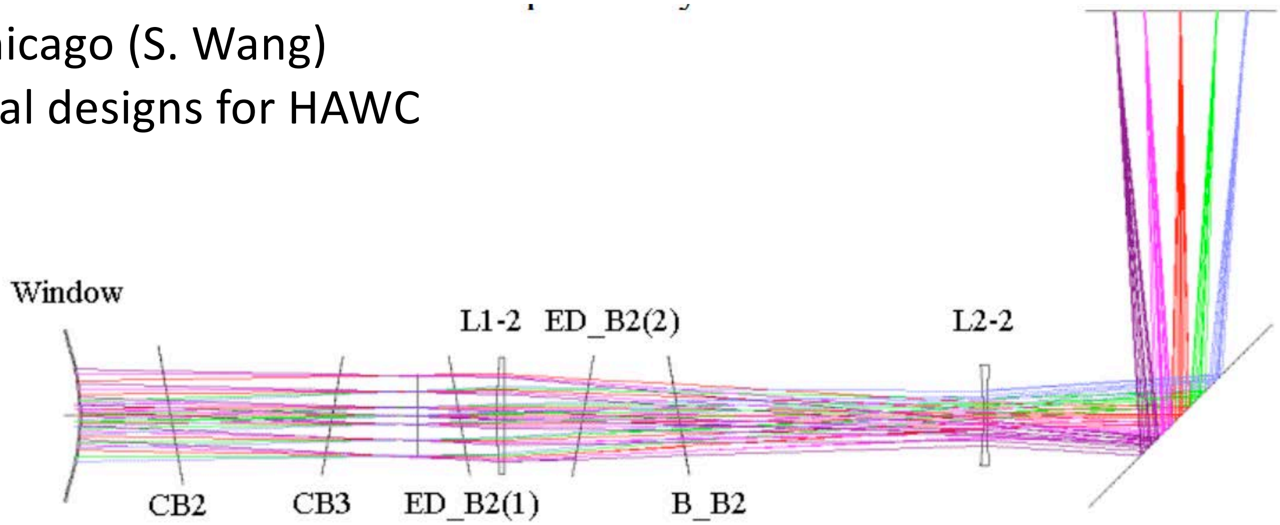


Figure 4. HAWC 89 μm Cold Optical Layout.

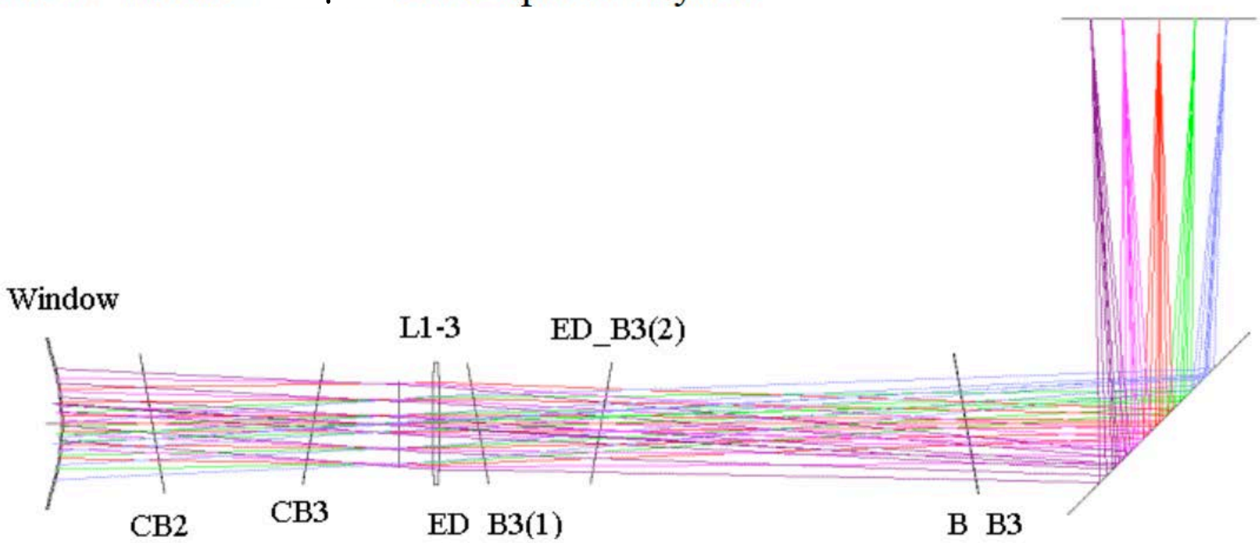
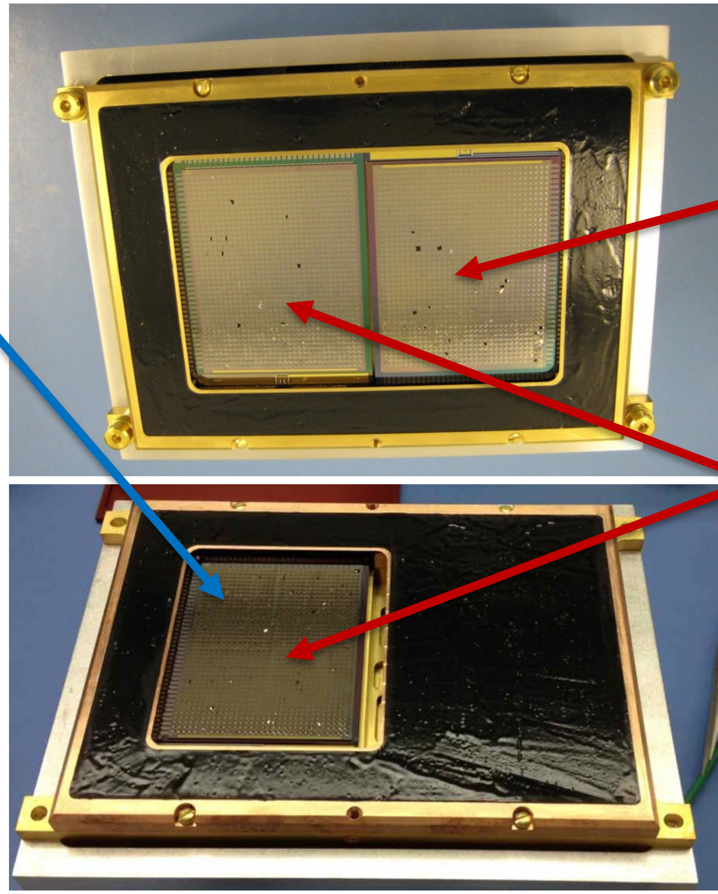


Figure 5. HAWC 154 μm Cold Optical Layout.

HAWC+ TES Detectors and Upgrade Ideas

32×40 "BUG" array:
- Transition-Edge Sensors (300 mK)
- from NASA/GSFC, using SQUID MUX from NIST
- 2 side abut-able
- Designed for 50% absorption through far-IR
- Intricate and clever engineering – worth reading about (e.g., HAWC+ instrument paper, Harper+ '18)



- "R1" has ~50% yield, larger 1/f noise of unknown origin, and no "polarization mate".

- These two arrays ("R0" and "T0") map to same place on the sky, in opposite polarizations.
- Together, ~1850 operating pixels (72% yield)

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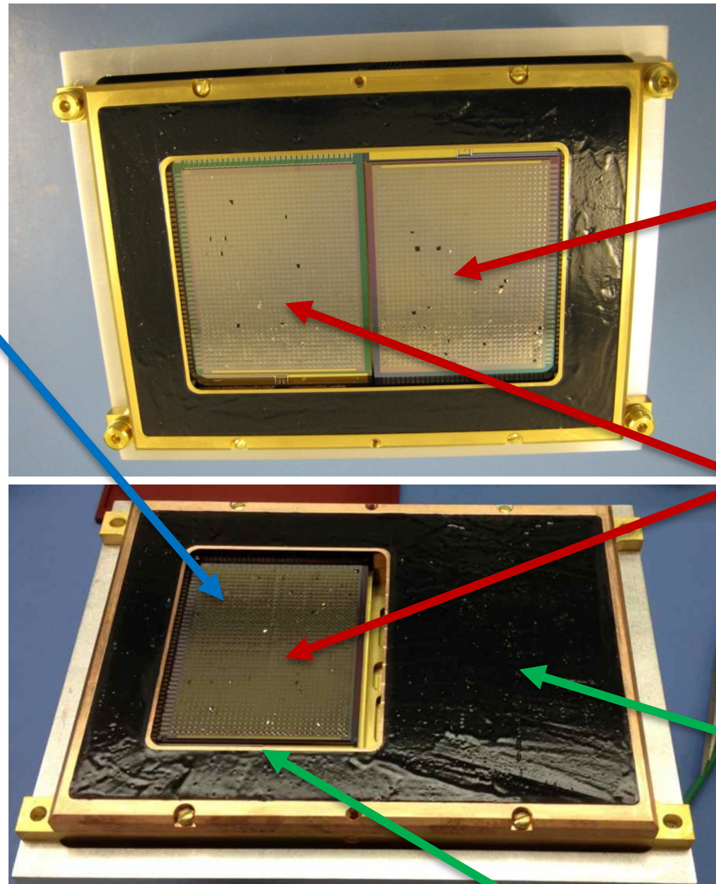


- "R1" has ~50% yield, larger 1/f noise of unknown origin, and no "polarization mate".

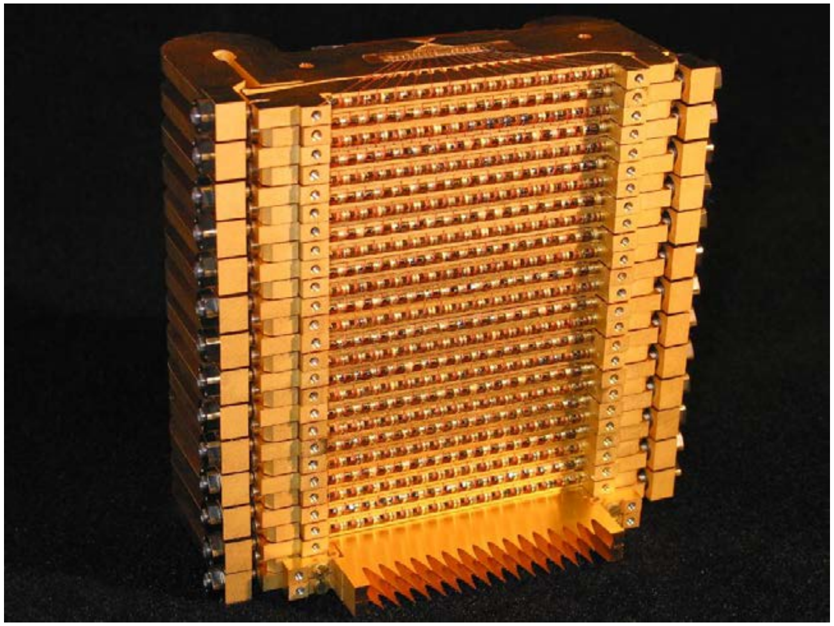
- These two arrays ("R0" and "T0") map to same place on the sky, in opposite polarizations.
- Together, ~1850 operating pixels (72% yield)

- There is space for a 4th array throughout the HAWC+ system. 1064 wires total to detectors!

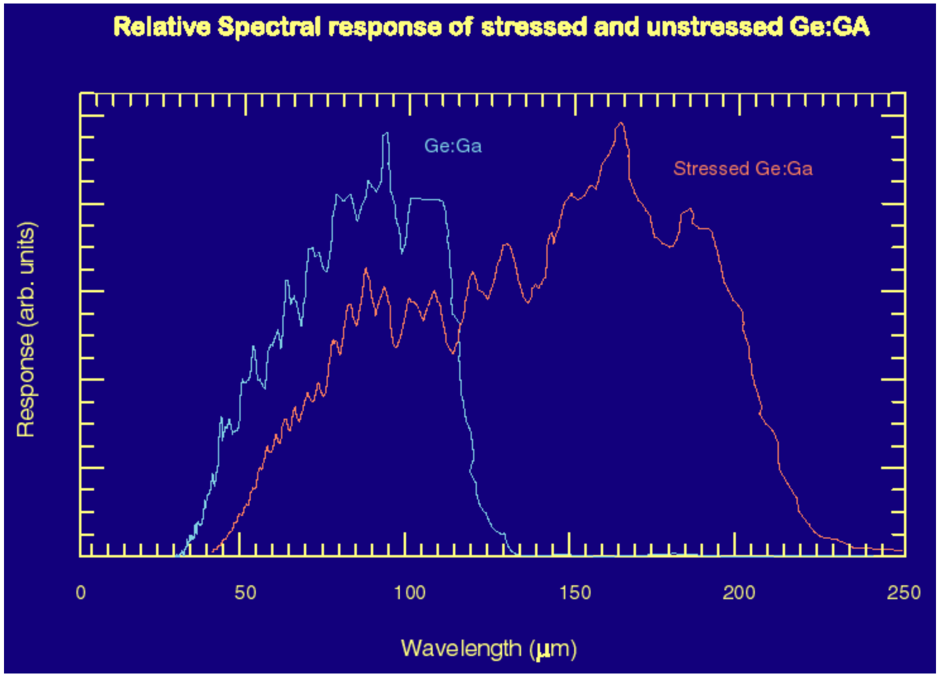
- While you're at it…
The low-level ghost image associated with the edge of the aperture could likely be reduced.

Photoconductors

- (Earlier presentation by J. Pipher, wavelength range to ~40 μm.)
- More challenging at long-wavelength side of HAWC+ range.
  - FIFI-LS long-wavelength array, 25 x 16 pixels:



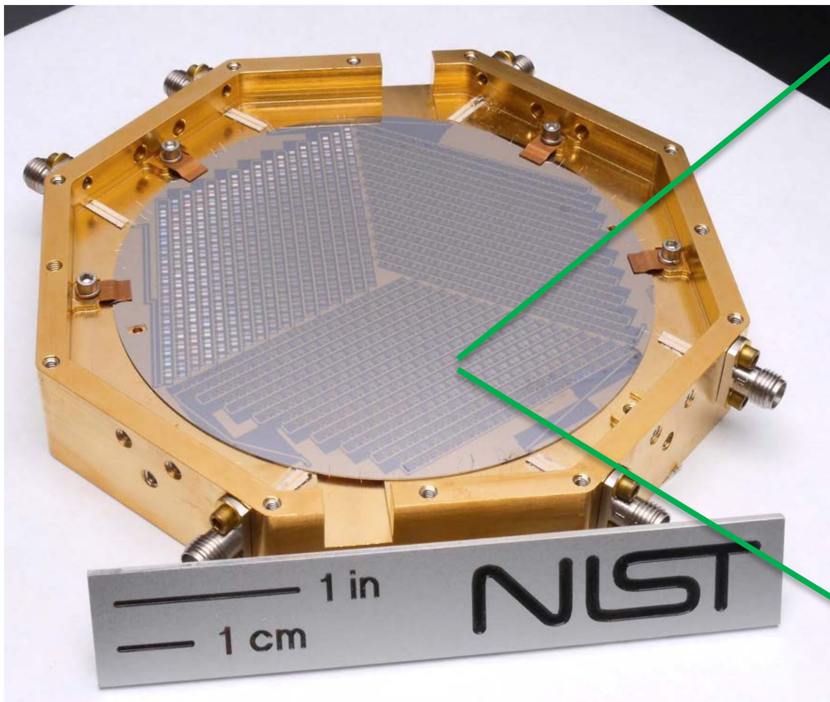
from fifils.mpe.mpg.de



- Perhaps an expert can give status of photoconductors out to 200 μm during the Q&A following this presentation.

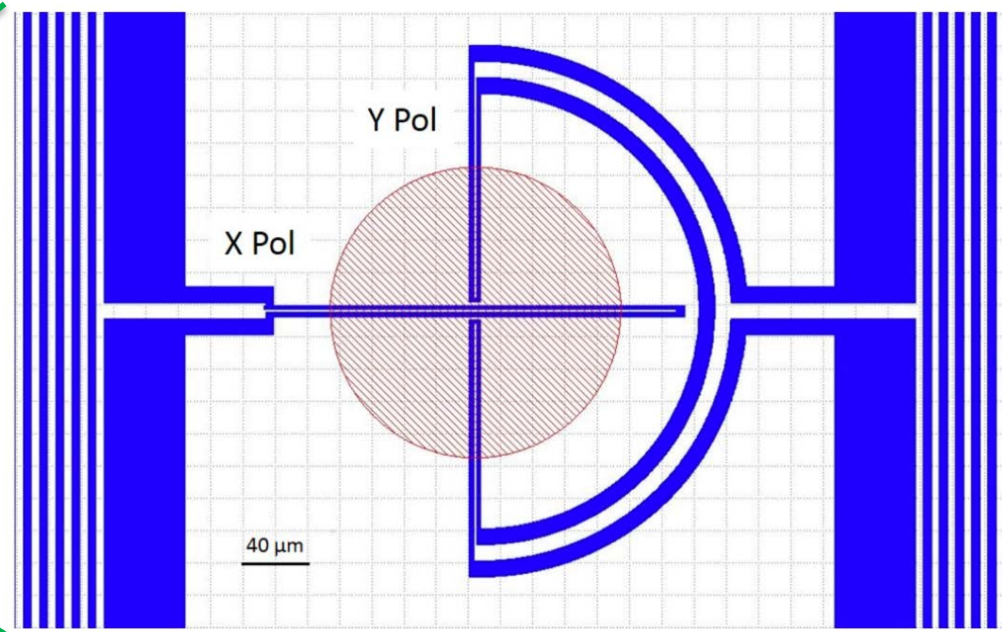
Kinetic Inductance Detectors

- No KID implementation is ready for HAWC+ use, but there are some advantages if detectors requiring development are under consideration:
  - Much lower wire count per array permits *pixel count well beyond HAWC+*.
  - *Dual-polarization sensing in one focal plane is ideal* and has been demonstrated at $\lambda \geq 250$ μm in BLAST-TNG instrument.



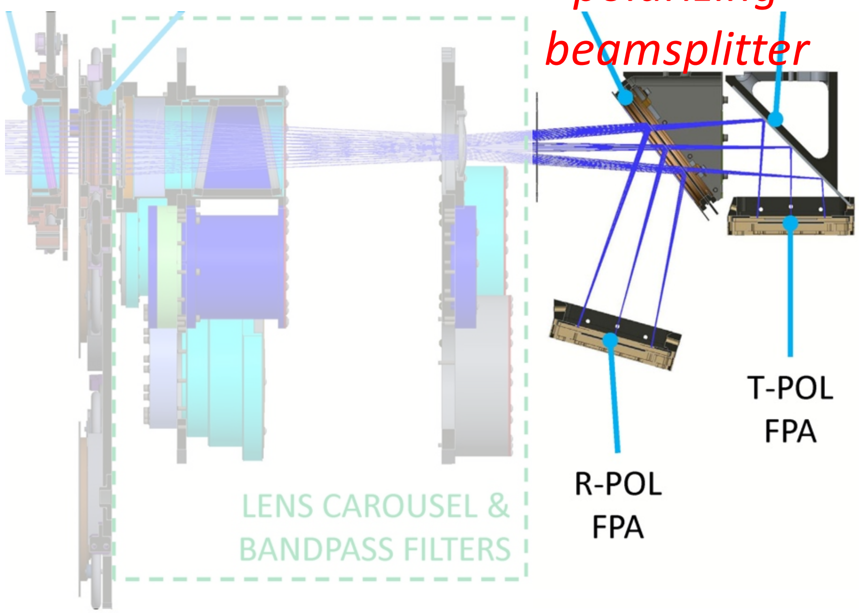
BLAST-TNG 250 μm array, 1836 pixels
(not shown: feedhorn array)

from www.nist.gov/programs-projects/novel-devices



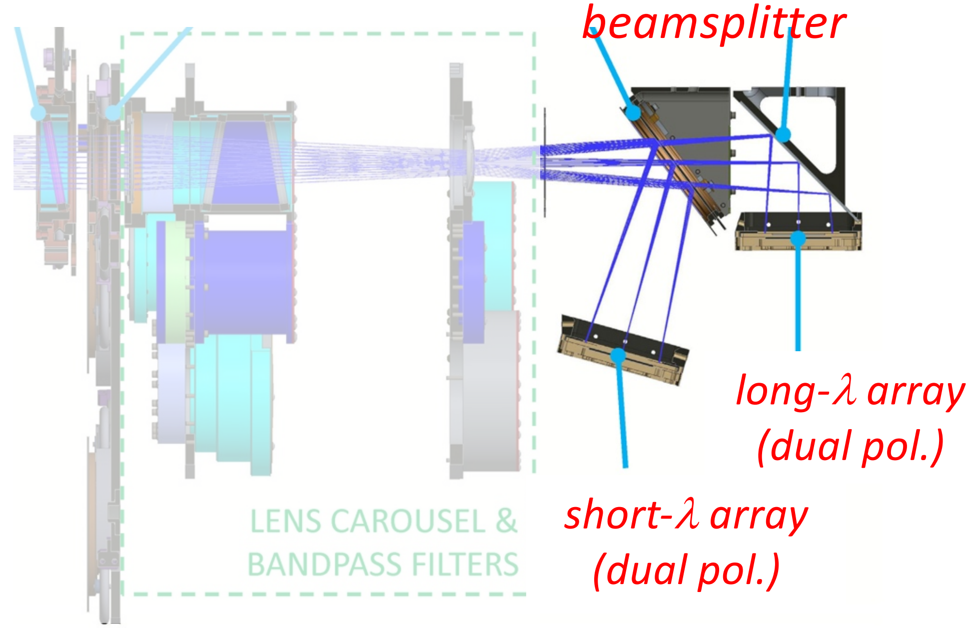
dual-polarization sensing
(Dober+ '16)

an alternative configuration of arrays

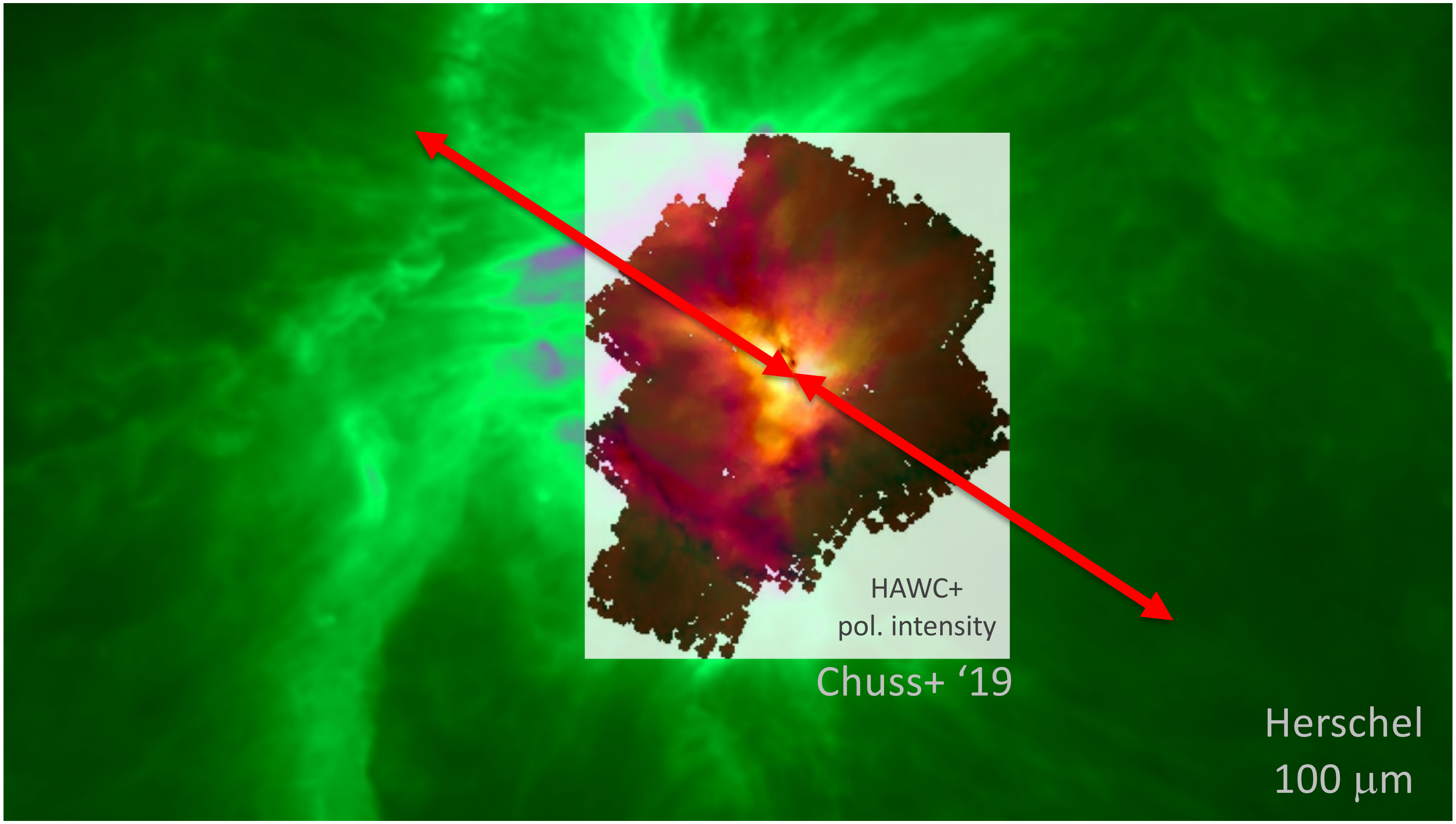


existing HAWC+

alternative

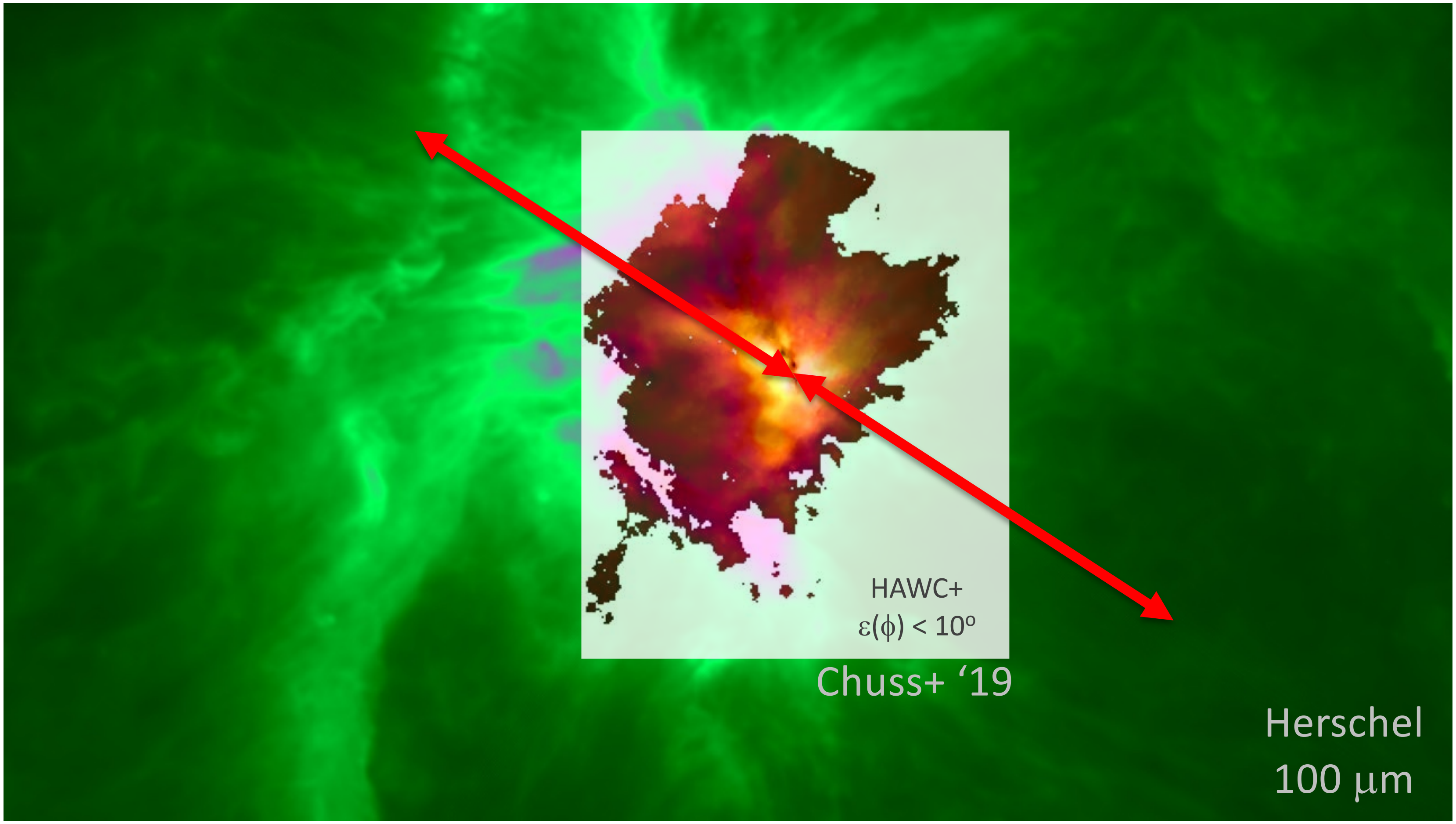


chop reference beams / need for method of large-area mapping



- 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



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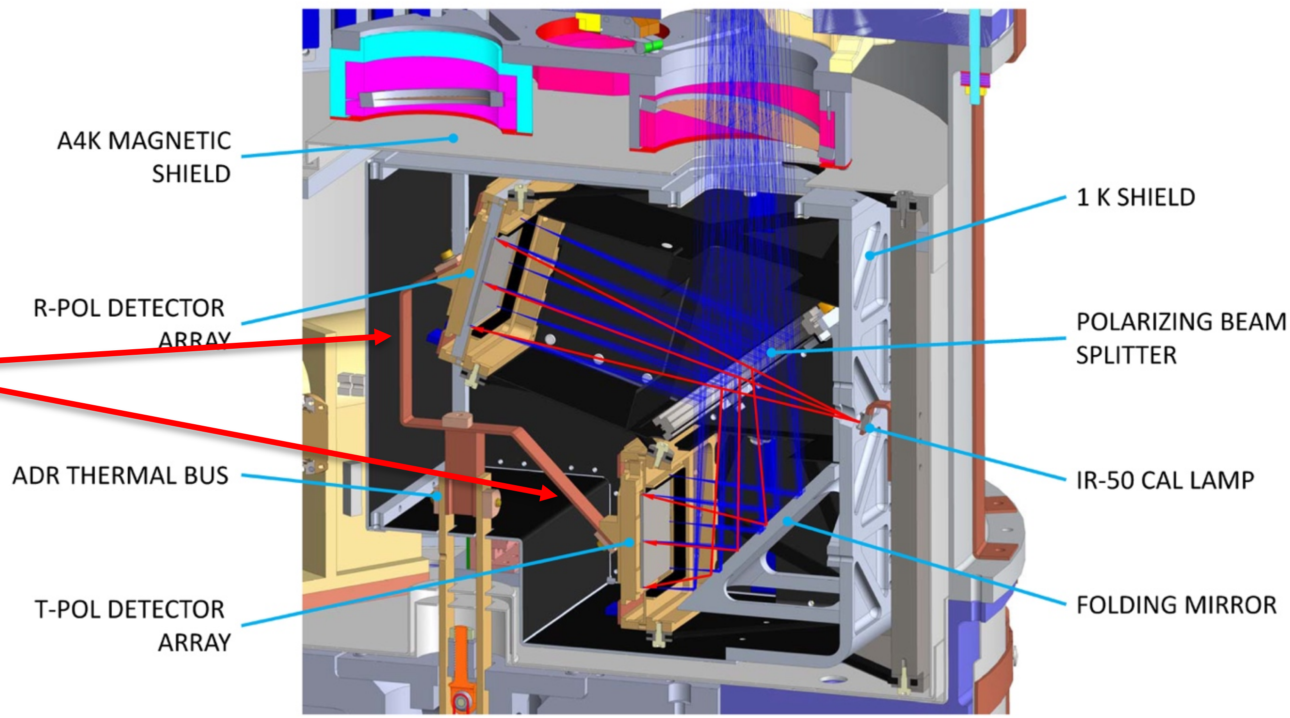
Challenge of Mapping Large Areas

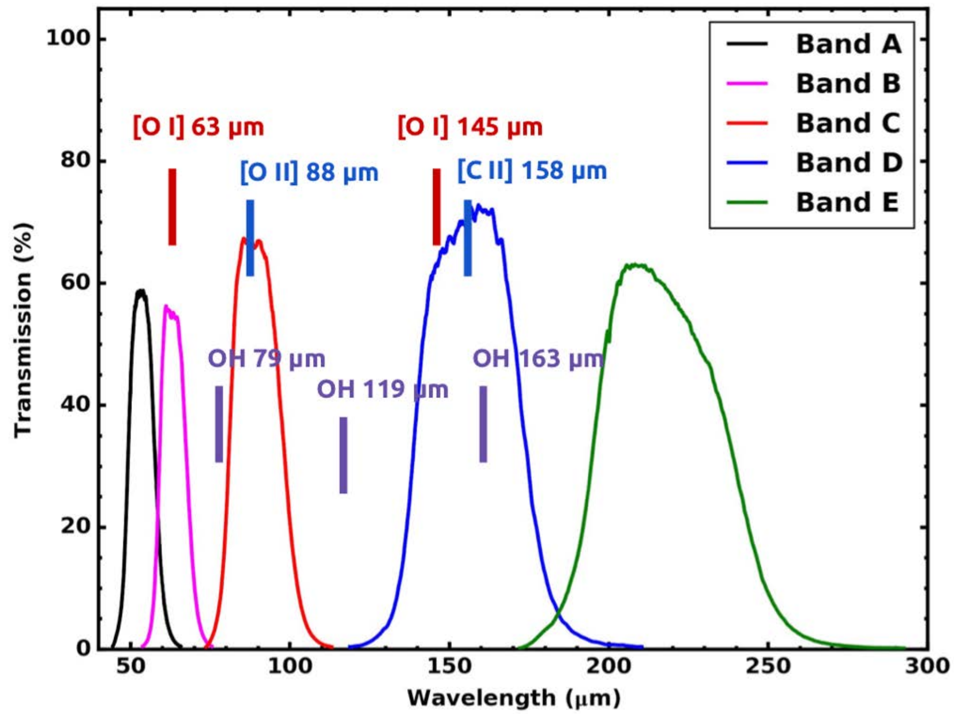
- Sources of signal at the detector:
  - **astrophysical (polarized) intensity**, diminished by variable atmosphere
  - variable atmospheric emission, polarized by tertiary & window
  - response to detector temperature variations, including some uncorrelated between the two arrays
- 10 Hz **chopping** eliminates the thermal response, but mixes points on the sky (albeit in a straightforward way).
  - Could be "bootstrapped" to double or triple the chop.
  - For efficiency in mapping large areas, could replace nodding with scanning.
- **Scan-only mapping** is vulnerable to thermal response and can mix points on the sky in more subtle ways.
  - Challenging to correctly recover the large-scale astrophysical emission.
  - Simulation needed to understand the spatial filtering.



- might help to improve thermal link between the two arrays
- alternative: dual-polarization sensing in one focal plane

Polarized Atomic Lines

- $R \approx 300$ surveys in far-IR fine-structure lines with 1000's of pixels could contribute to overall SOFIA effort to measure these important lines.
  - *Furthermore, lines may be polarized and trace magnetic fields.*
- narrow-band filters: fixed-tuned Fabry-Perot, added to optics carousel
- detector NEP requirement: 3×10^{-17} W Hz$^{-1/2}$
- Continuum subtraction via observations in the $R \approx 5$ filter; needs good relative calibration.



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Conclusions

- At least two appealing paths for detector upgrade:
  - full implementation of HAWC+ TES 4×32×40 design goal beyond the 2×32×40 baseline
  - technology development of far-IR dual-polarization KIDs, especially to field 1000's of pixels at 53 and 89 μm
    - Expansion of field of view may need enlargement of optics.
- Science needs and instrument sensitivity motivate the development of a good large-area mapping mode.