Development of Multi-pixel On-Chip Sepectrometer Array for future CMB missions

SRON SPACE RESEARCH ORGANISATION NETHERLANDS
THz Sensing Group TU Delft

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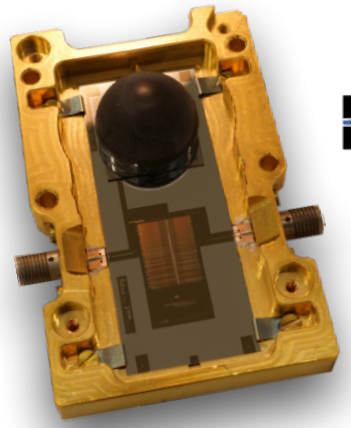
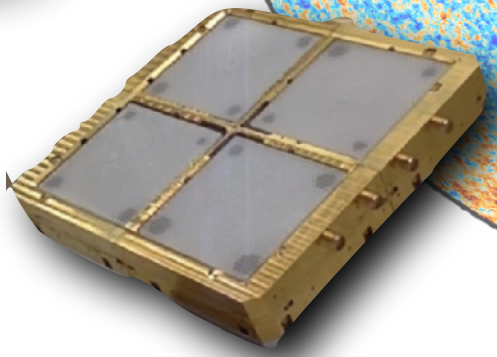
Potential of Integrated Superconducting Spectrometer (ISS)

- *Combining KID Imager + On-chip Filterbank*

How can we use our technology for future astronomy?



DESHIMA



A-MKID

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CMB Sciences

(1) Sunaev-Zeldovich effect (SZE):
Mapping the distribution of hot gas, its temperature, and large-scale velocity flows

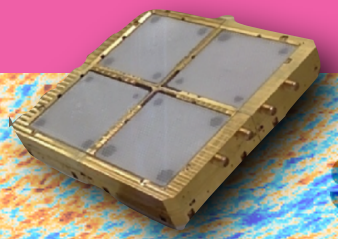
(2) CMB deflections by gravitational lensing:
Mapping the mass distribution in the entire Hubble volume

(3) Primary CMB anisotropies:
Probe for recombination era, and cosmic inflation

(4) Distortion of CMB:
The thermal history of the Universe

Requirement to Focal Plane Detector

- Photon noise limited performance
- Lage format imager (multi-pixel array)
- Polarimetric detection
- Broadband spectrometer



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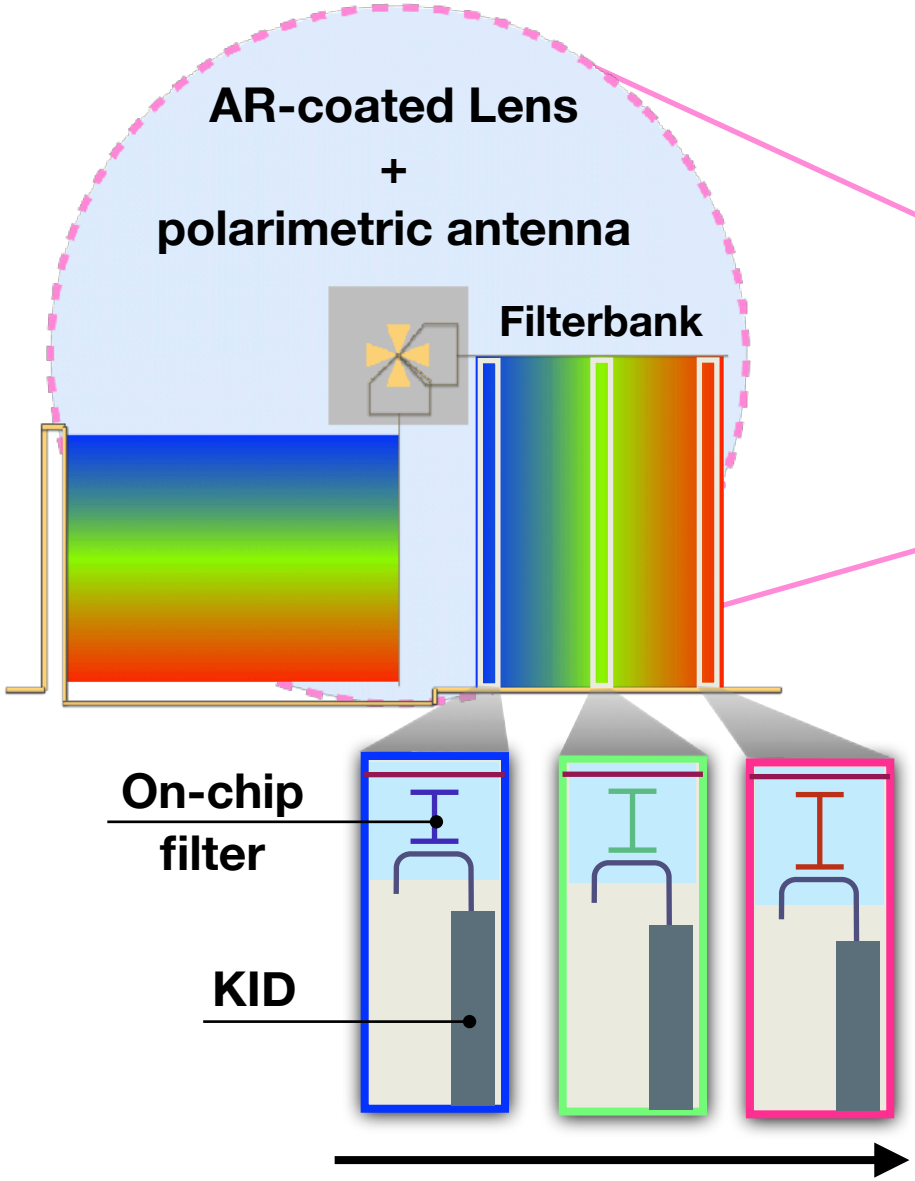
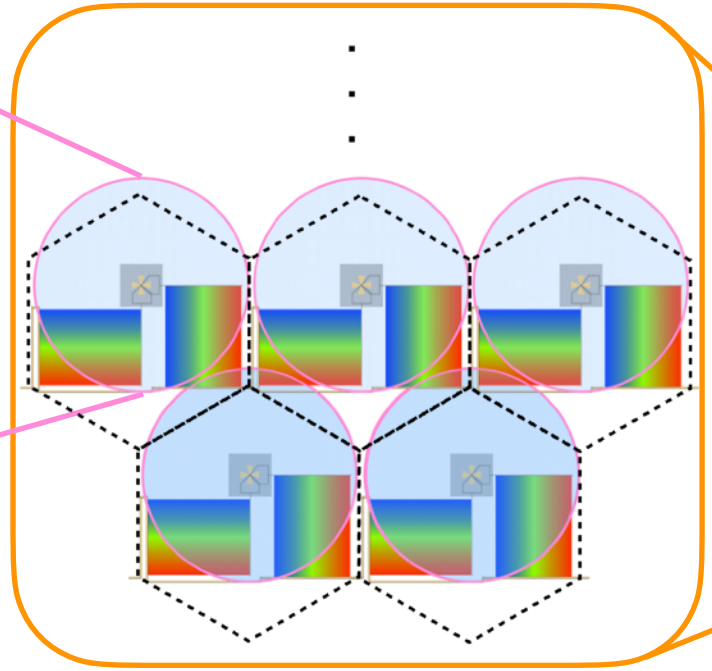
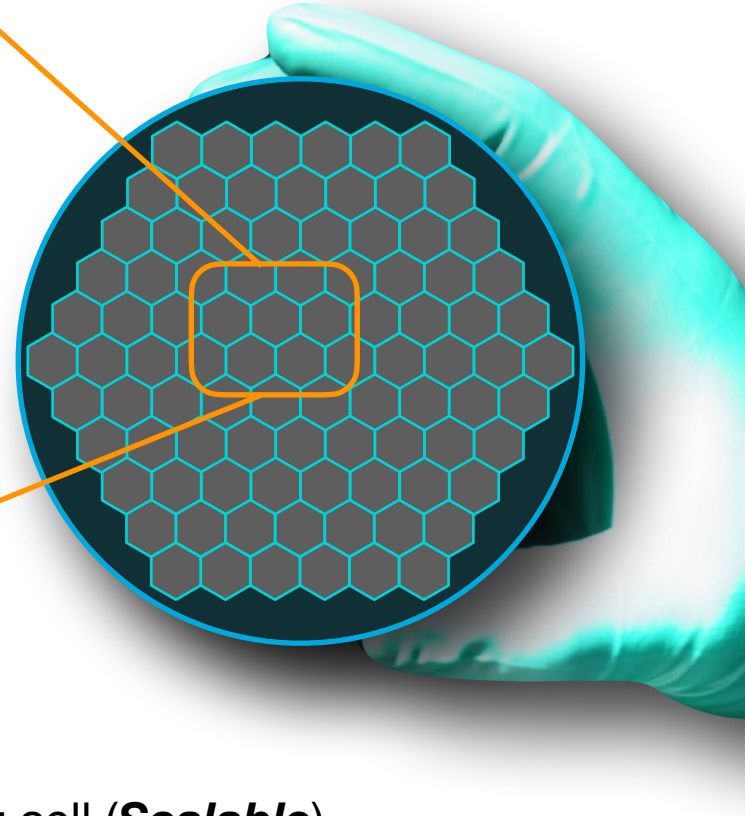
Spectro-polarimetric IFU with KID: Compact and Scalable





Integrated Field Unit (IFU)



- 135 - 270 GHz filterbank
- 22 colors / pixel / pol, R = 20-30
  (c.f. R = 350 for DESHIMA)

- Antenna + Filterbanks fit in a unit cell (***Scalable***)

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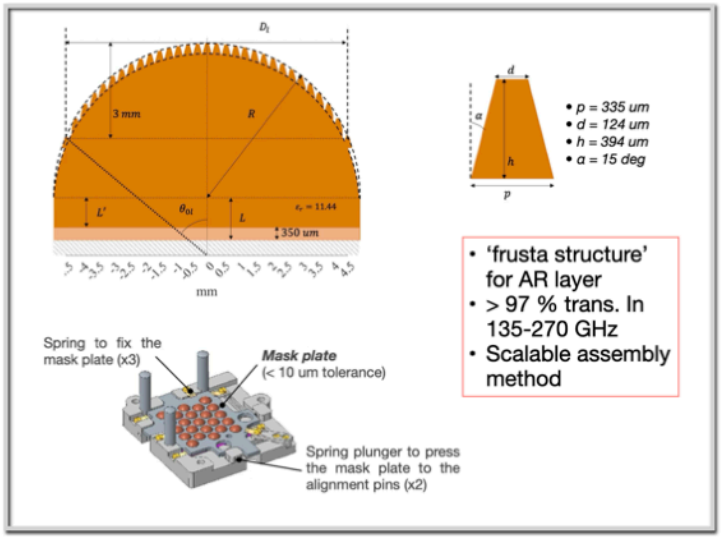
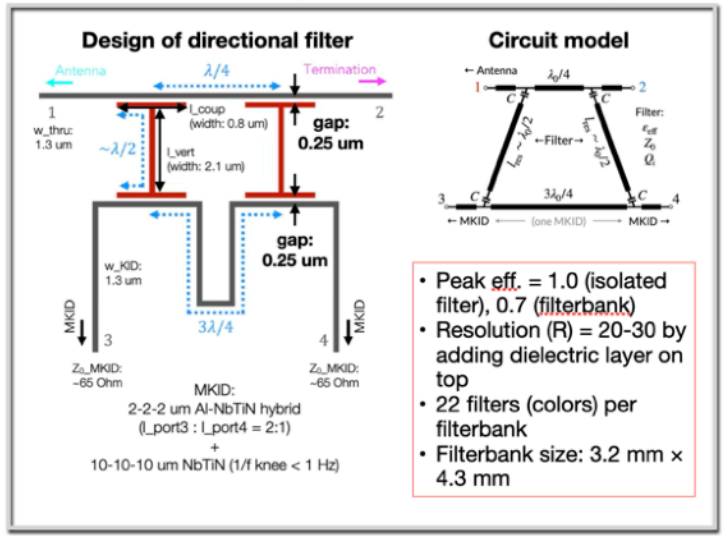
ESA project: Work Packages and Breadboards

WP3: AR-coated Lens Array (Breadboard 1)



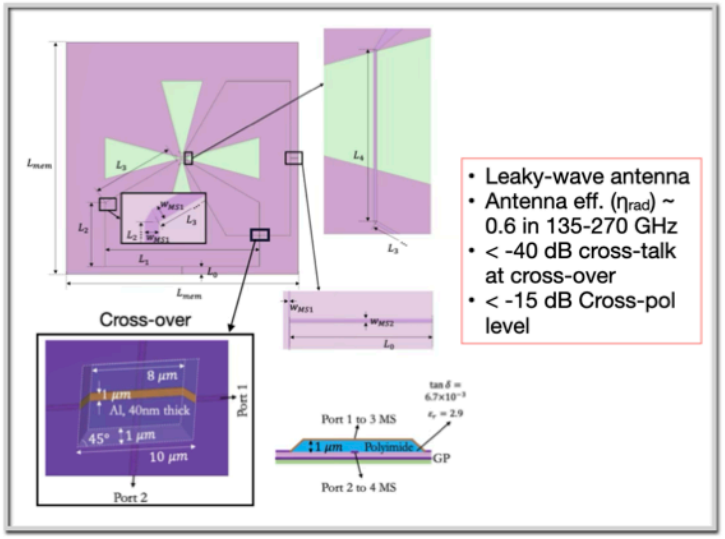
- 'frusta structure' for AR layer
- > 97 % trans. In 135-270 GHz
- Scalable assembly method

WP5: Low-R, High-eff. Filter (Breadboard 3)



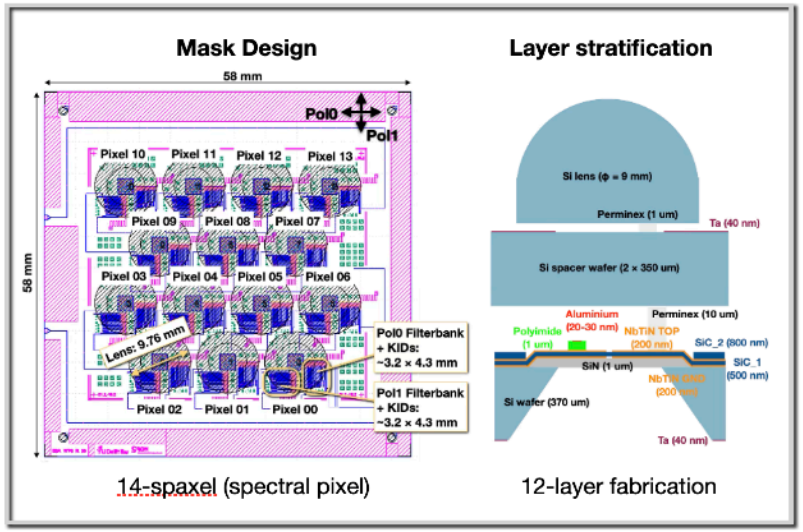
- Peak eff. = 1.0 (isolated filter), 0.7 (filterbank)
- Resolution (R) = 20-30 by adding dielectric layer on top
- 22 filters (colors) per filterbank
- Filterbank size: 3.2 mm × 4.3 mm

WP4: Polarimetic Wideband Antenna (Breadboard 2)



- Leaky-wave antenna
- Antenna eff. (η_{rad}) ~ 0.6 in 135-270 GHz
- < -40 dB cross-talk at cross-over
- < -15 dB Cross-pol level

WP7: Spectro-Polarimetric FPA (Final Demonstrator)



14-spaxel (spectral pixel)

12-layer fabrication

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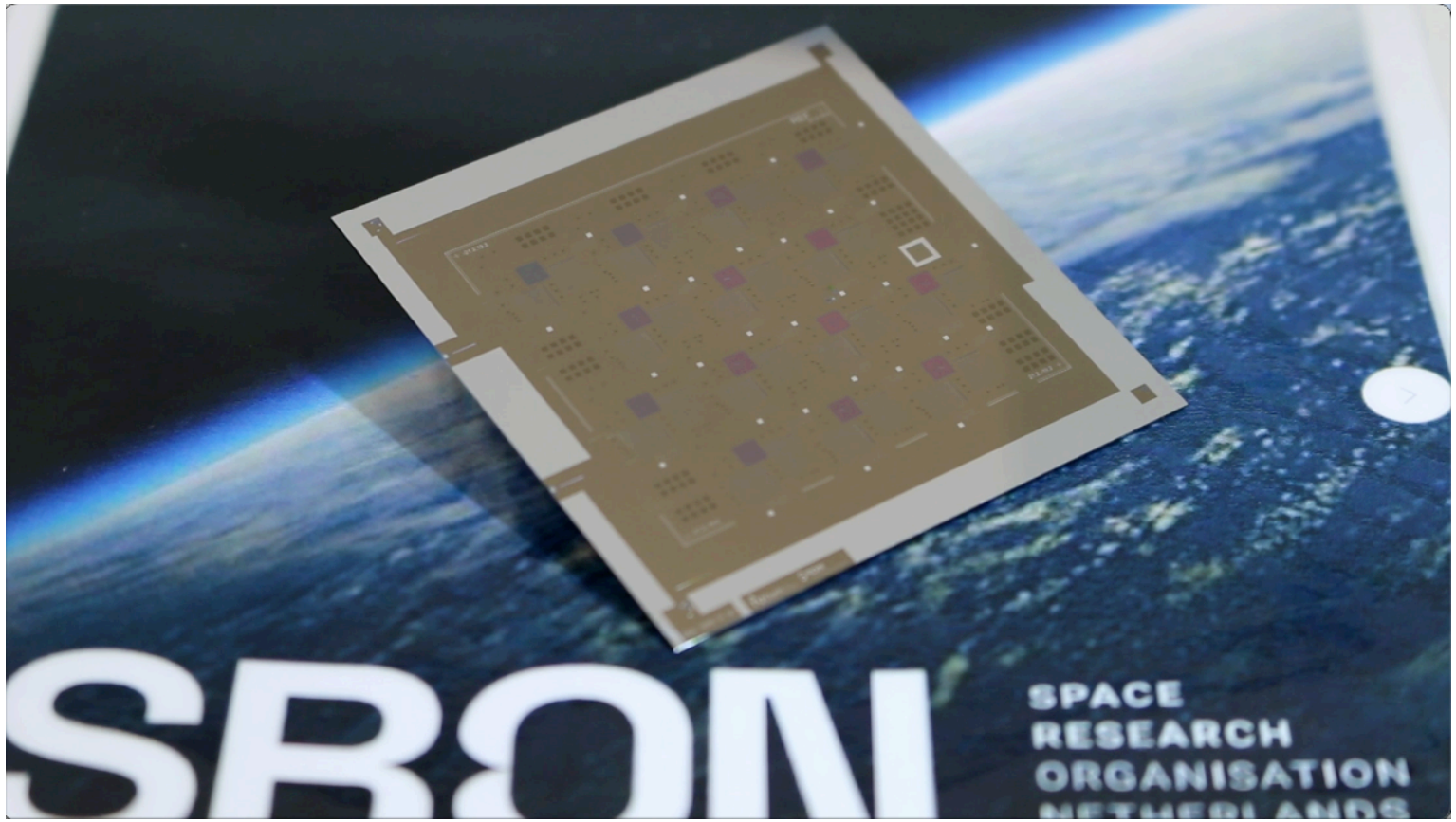
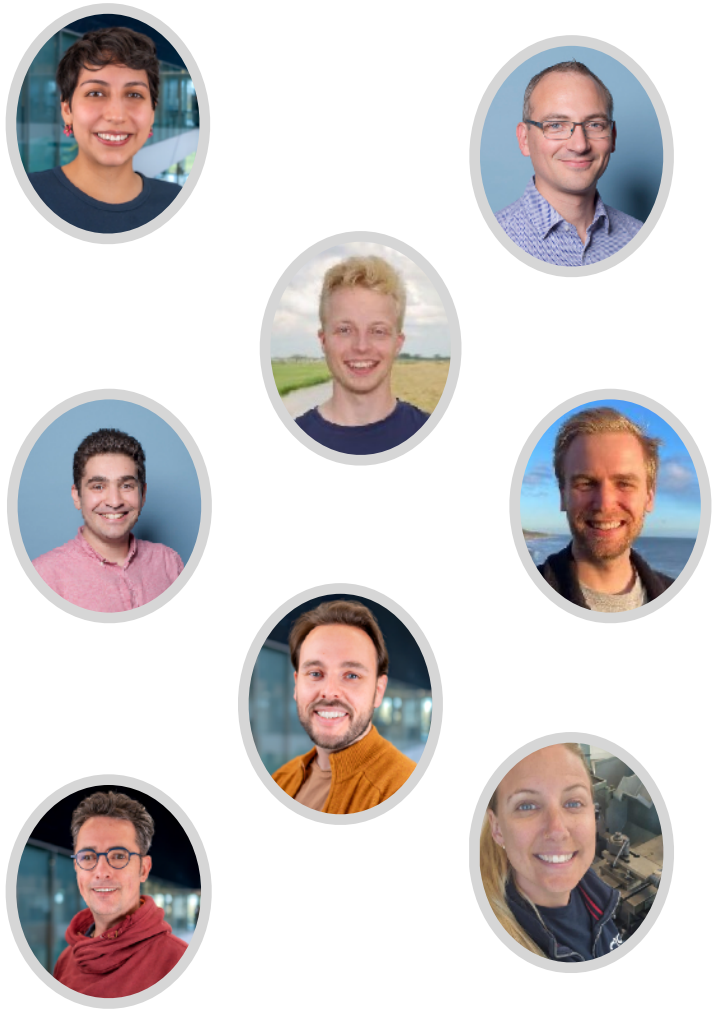
State-of-the-art IFU





14-pixel (~600 KIDs) Spectro-Polarimeter

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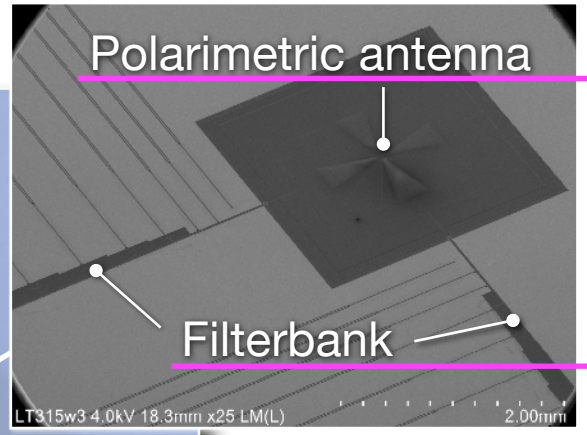
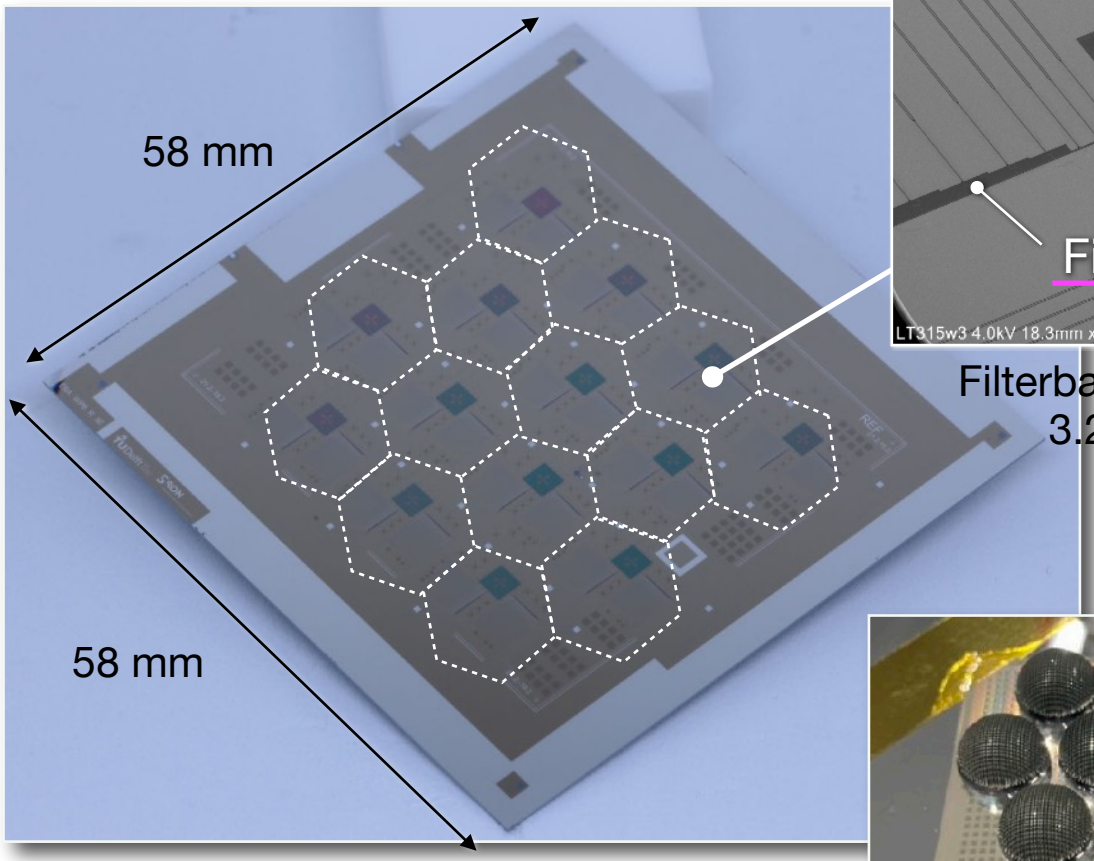
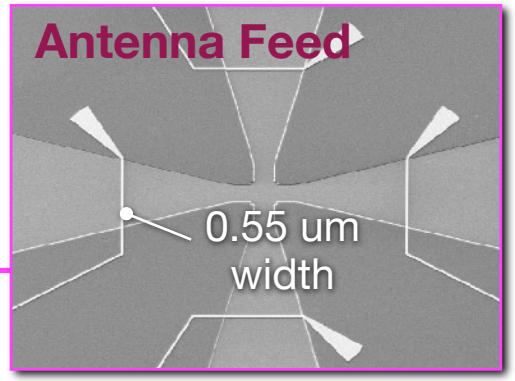
Spectro-Polarimetric IFU

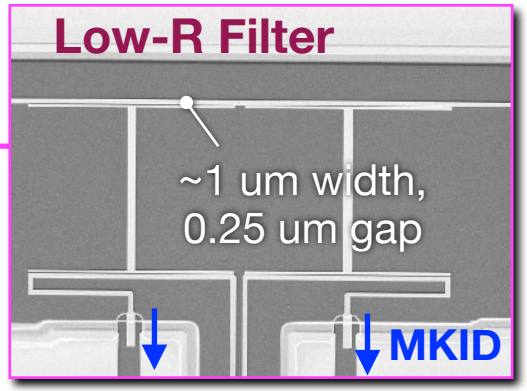
Membrane around antenna:
1.8 × 1.8 mm

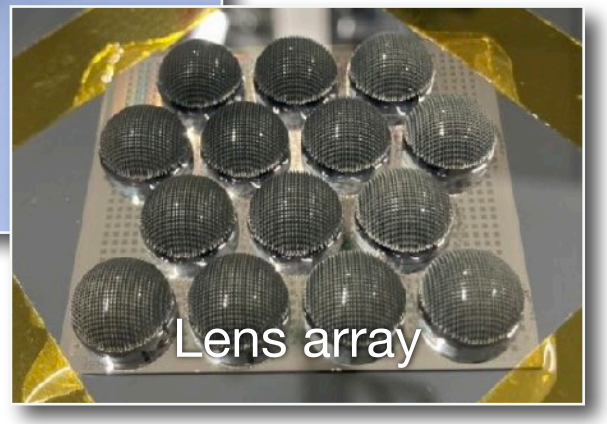




Filterbank + KIDs area:
3.2 × 4.3 mm







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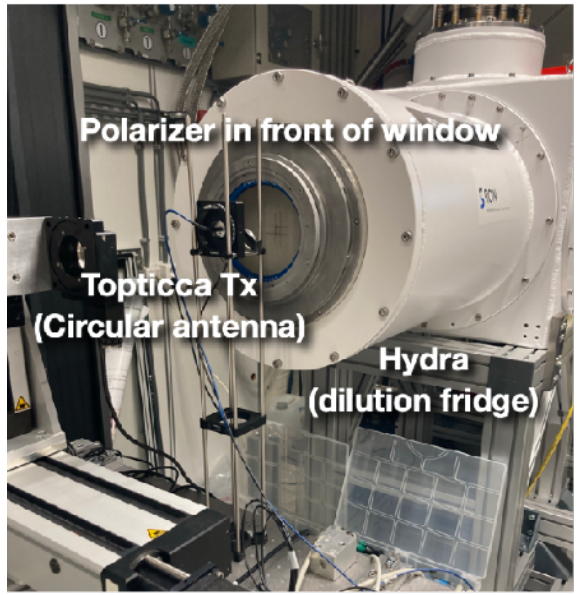
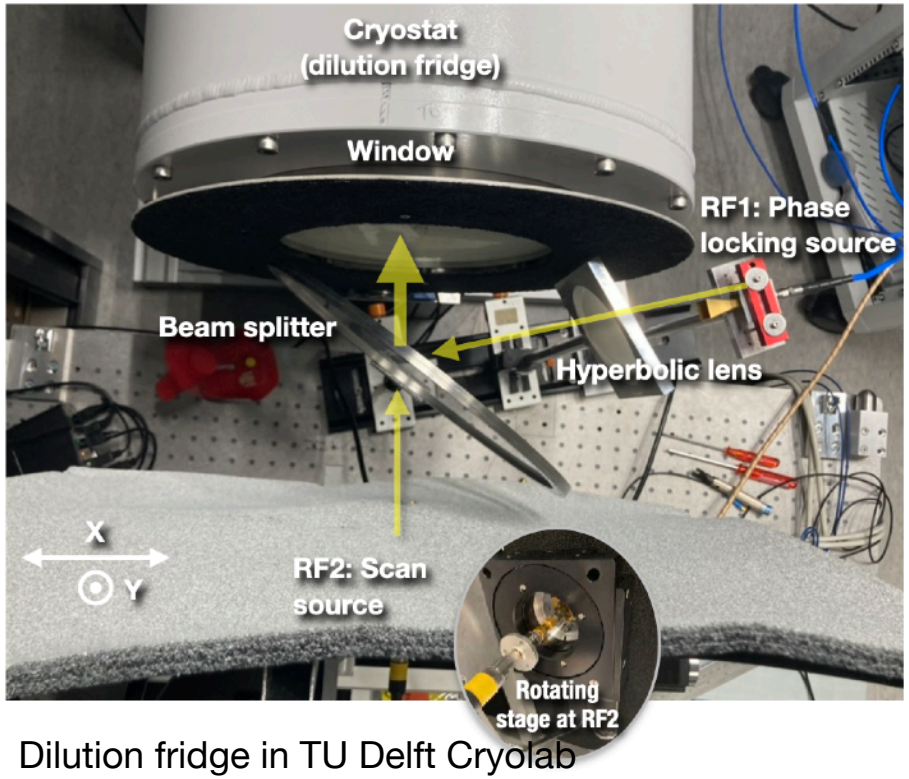
Performance Evaluation: Measurement setups

- **THz frequency sweep measurement**



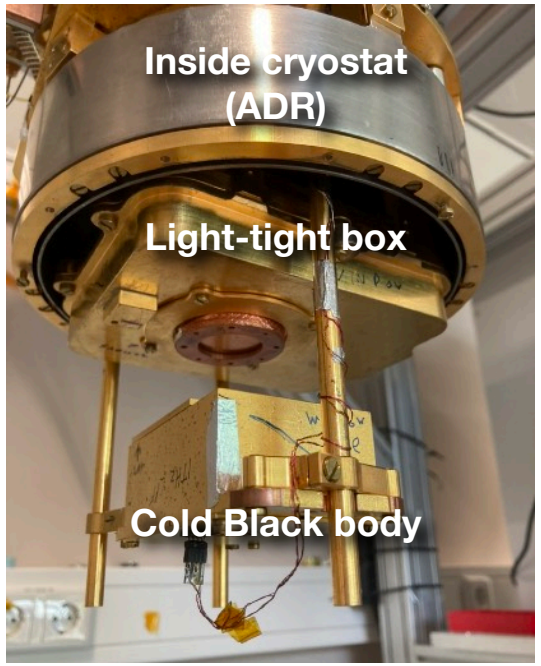
Dilution fridge in TU Delft Cryolab

- **Phase & amplitude beam pattern measurement**



Dilution fridge in TU Delft Cryolab

- **Optical sensitivity measurement**



ADR in SRON Leiden

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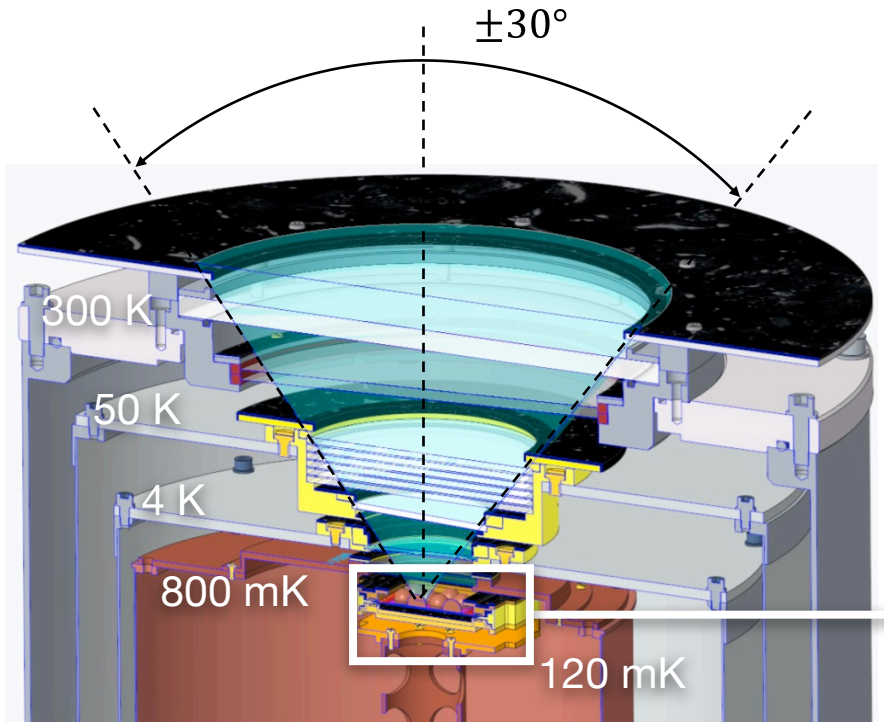
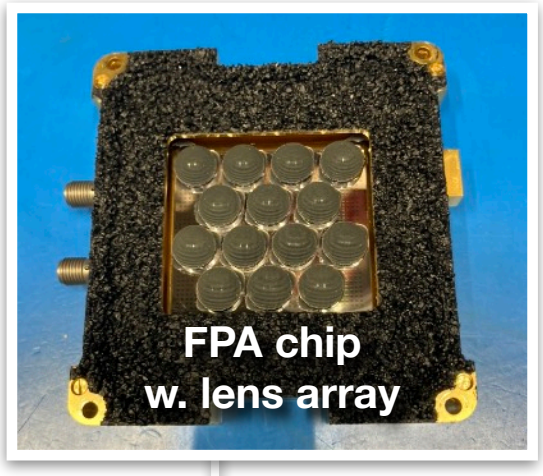
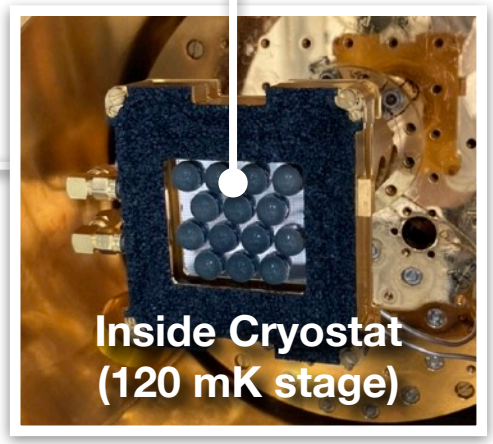
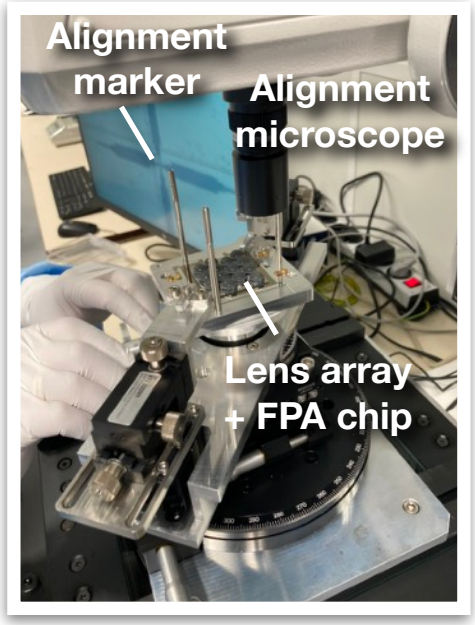
Performance of Spectro-Polarimetric FPA







All pixels are visible from outside thanks to the large aperture



Mount lens array with alignment tool (alignment accuracy: 10-20 um)

Too much power coupling, not measurable…

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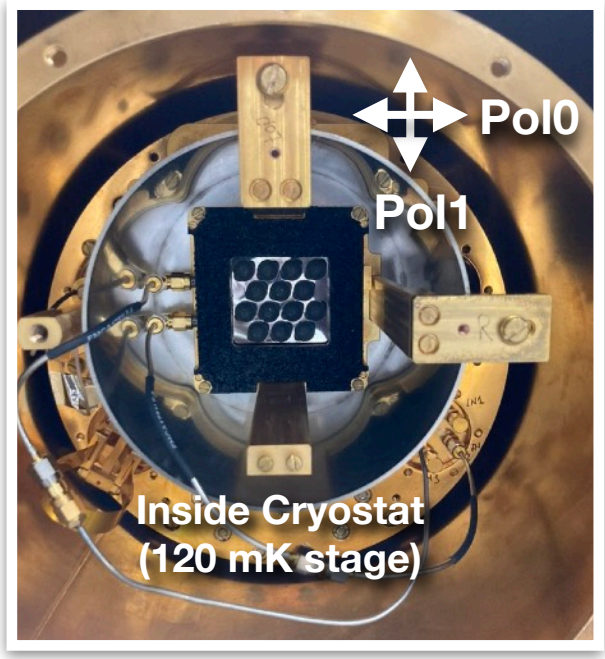
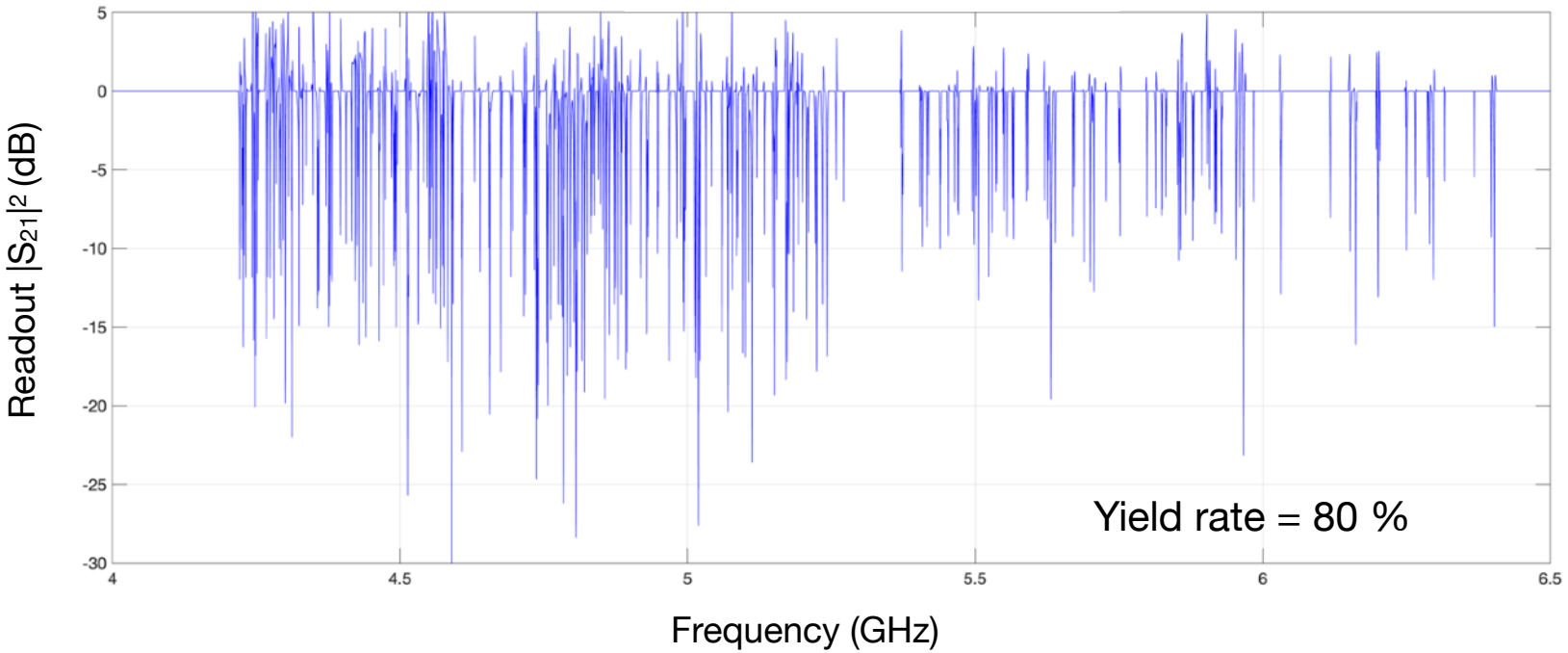
Performance of Spectro-Polarimetric FPA



Put ~100 mm away from the cold aperture



- ***Not optimal position (away from window)***, but all pixels are still visible from outside
- Only THz sweep measurement is valid, but still possible to map KID frequency to pixel-filter information thanks to the implemented encoding

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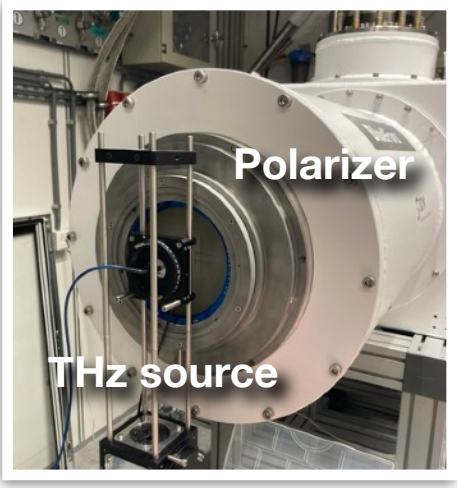
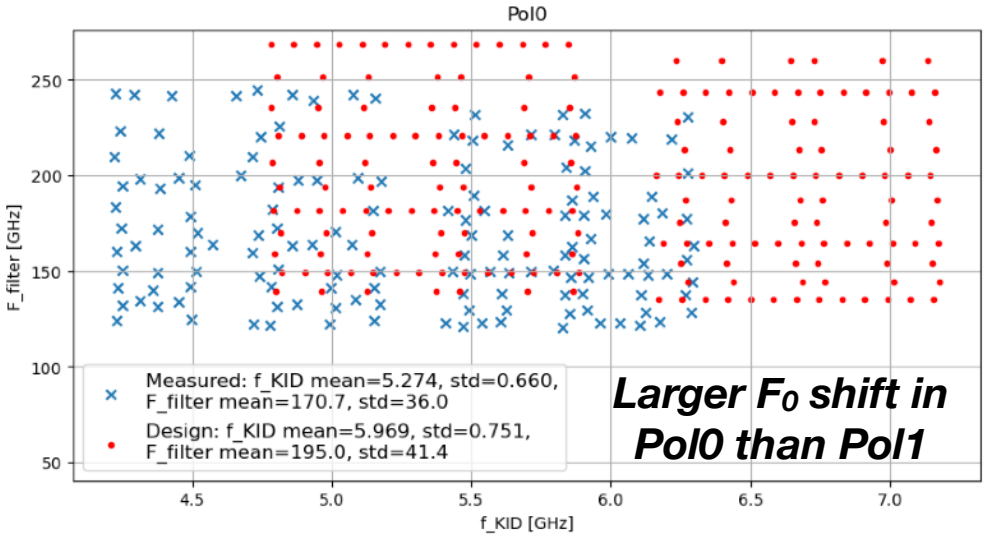
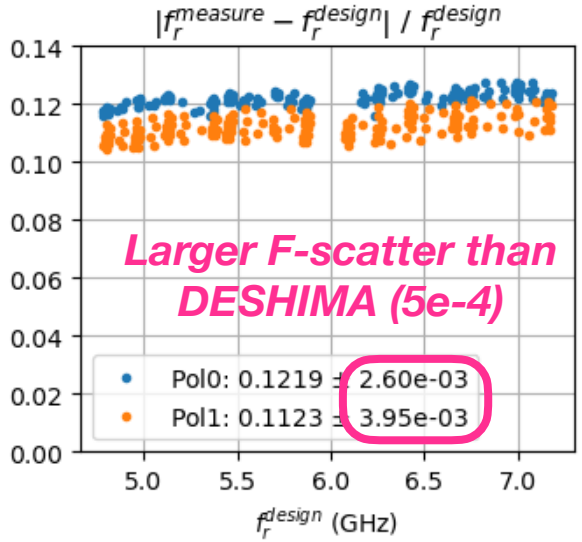
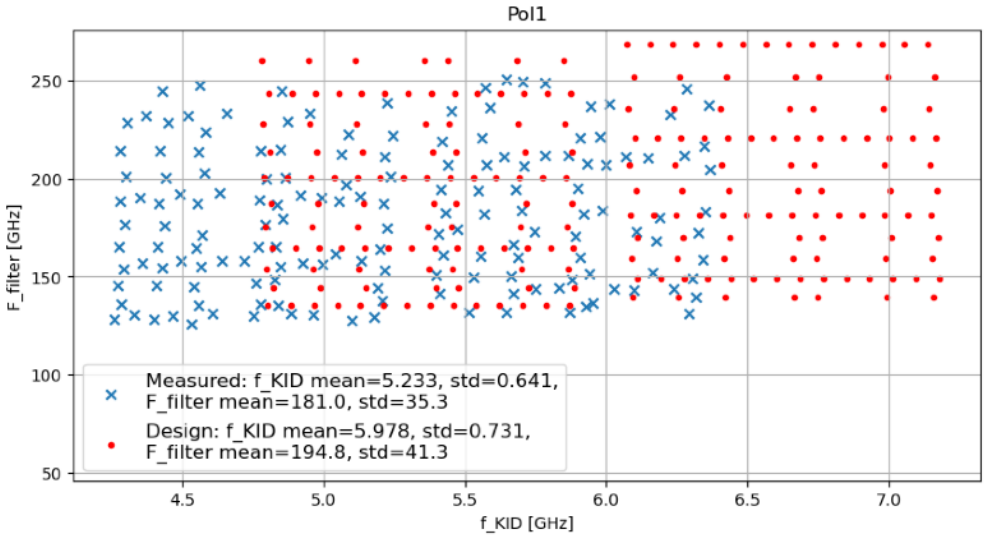
THz sweep experiment & KID correspondence: Pol0, Pol1

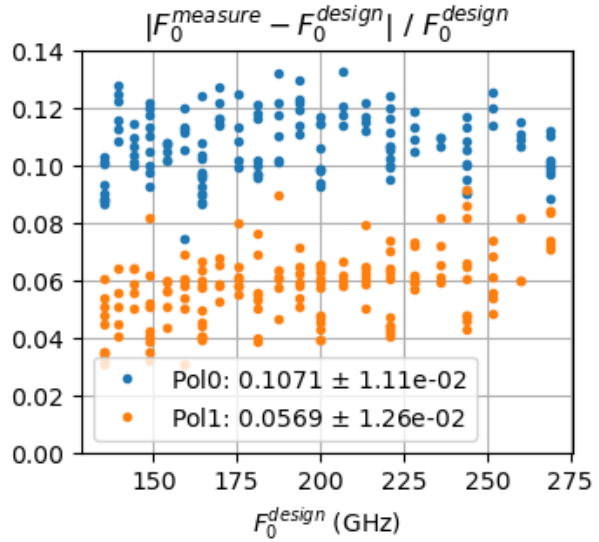


THz sweep with Polarizer in front of window

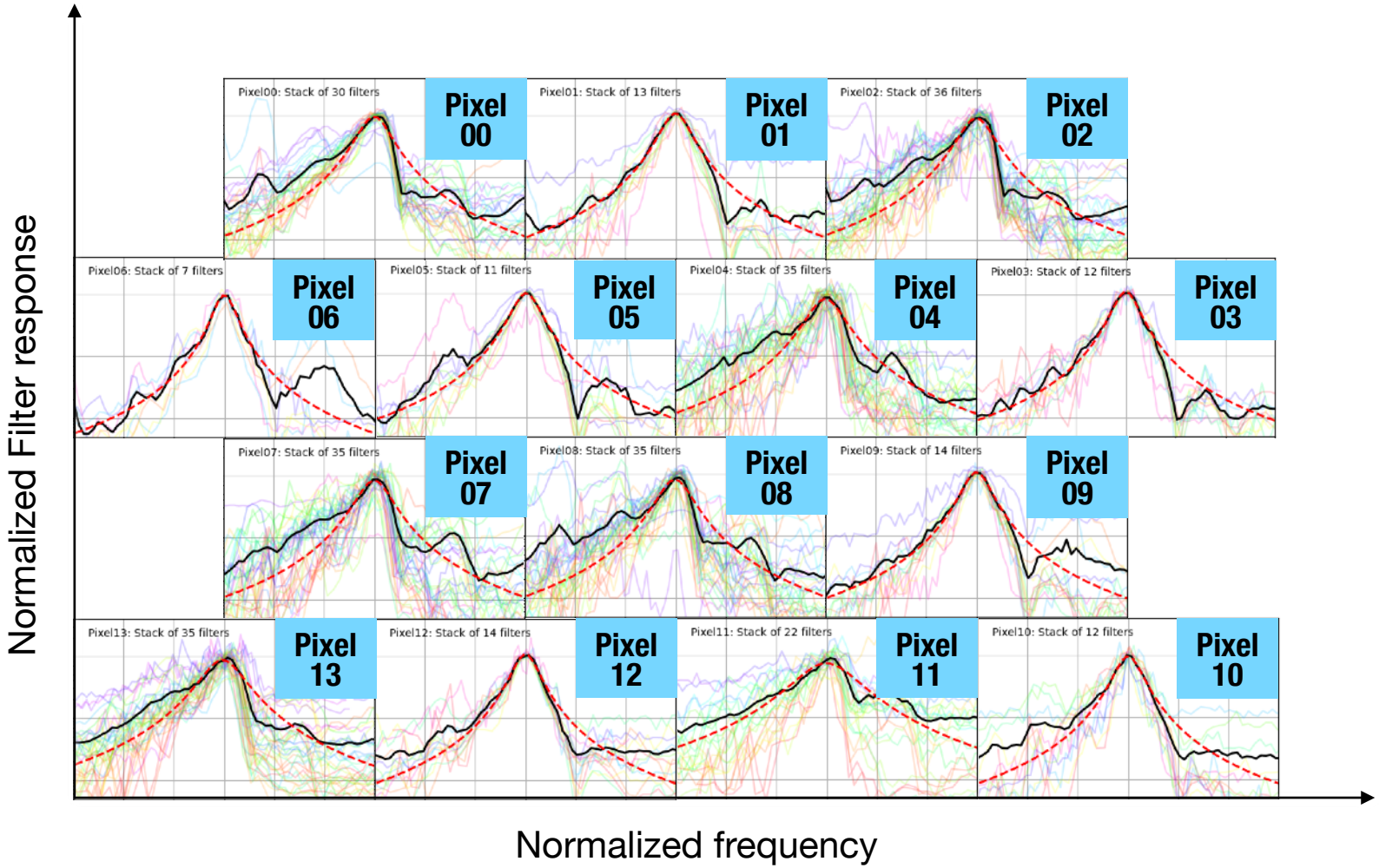








Performance of Spectro-Polarimetric FPA



Averaged filter response: Yield rate = 80 %, R = 20

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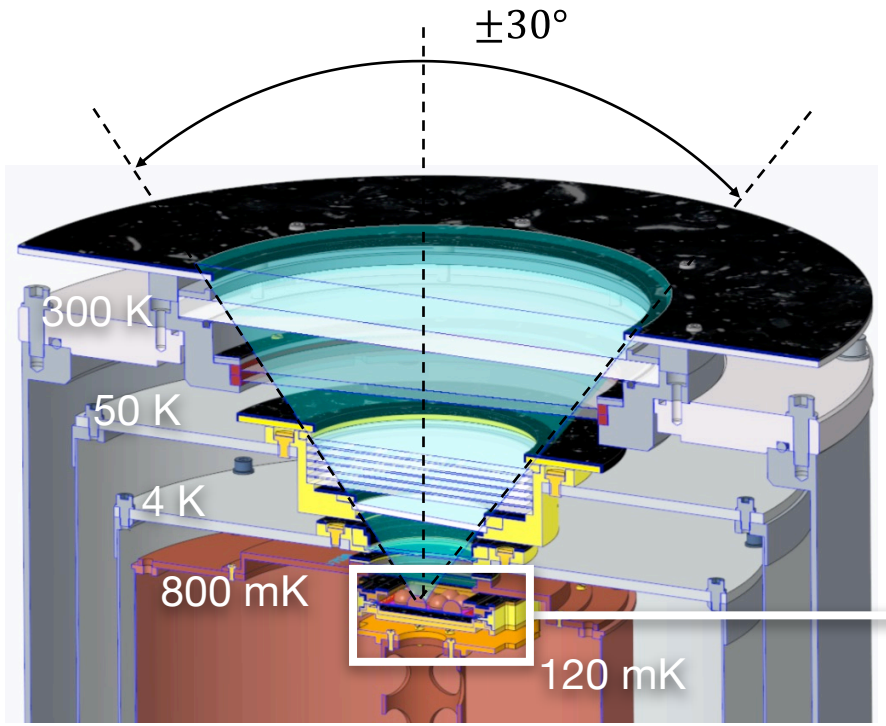
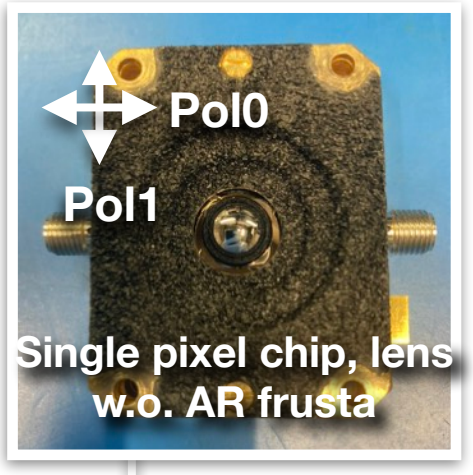
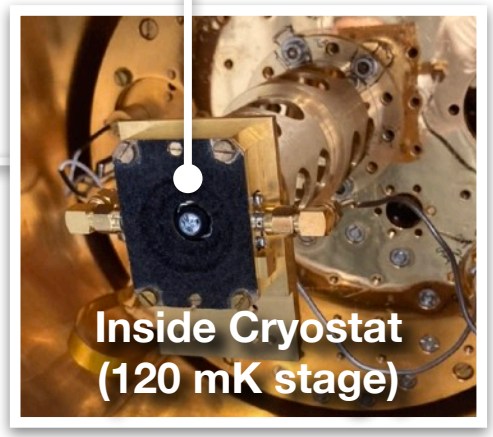
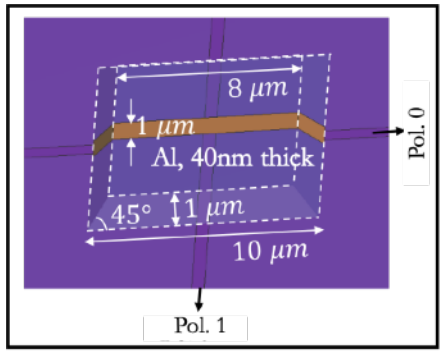
Performance of Single Spaxel Chip (from same wafer with FPA chip)

- ***Use single spaxel for full characterization (filter characteristics, beam pattern and optical efficiency measurement)***









< Cross-over >
- Pol0 has Aluminium section
- Pol1 goes under Polyimide

- Copy of one spaxel from FPA
- Polarimetric antenna
- 22 filters/pol (directional filter)
- No AR frusta on lens

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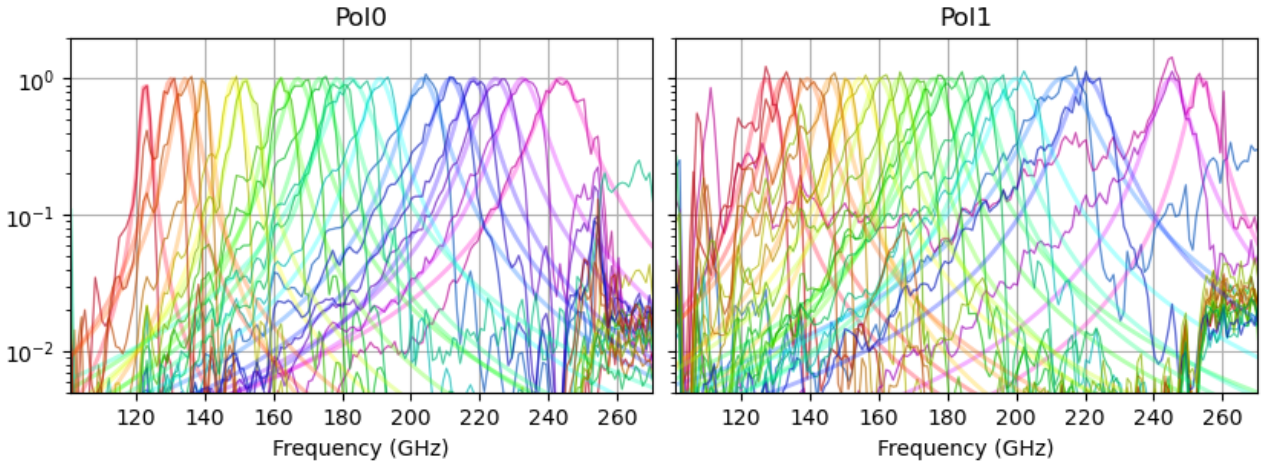
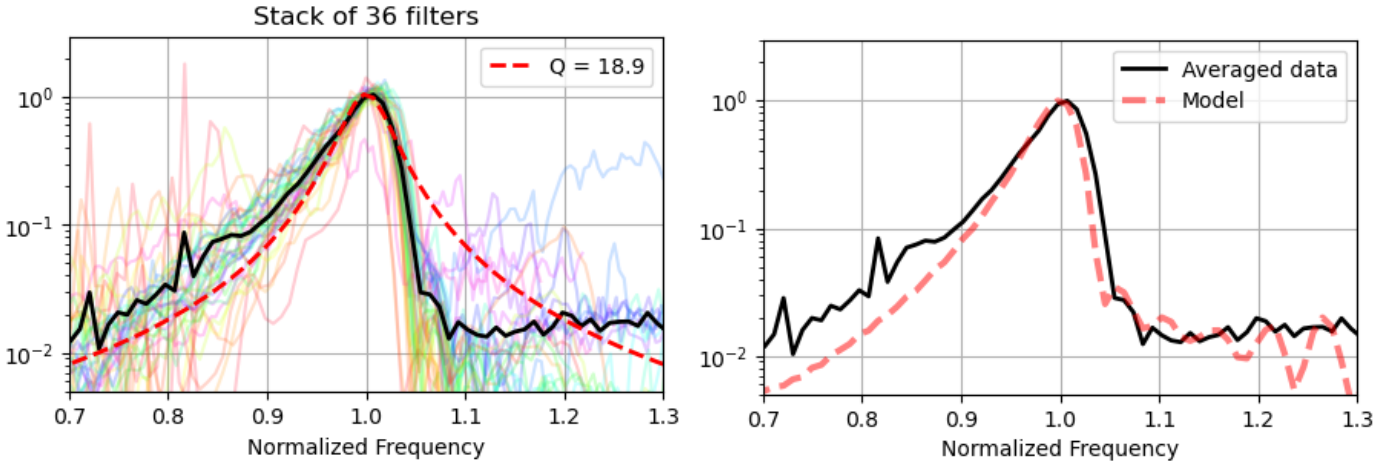
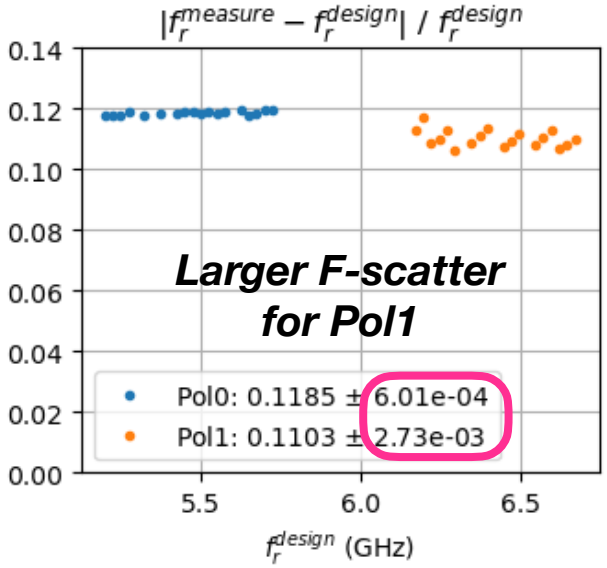
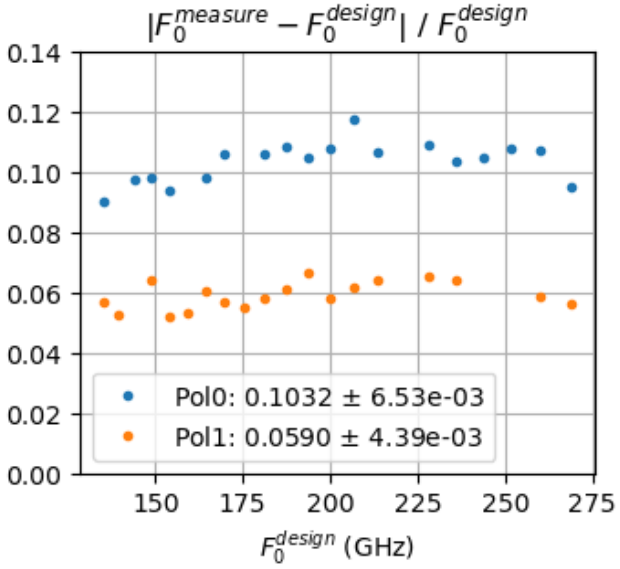
Performance of Single Spaxel Chip: Filter characteristics





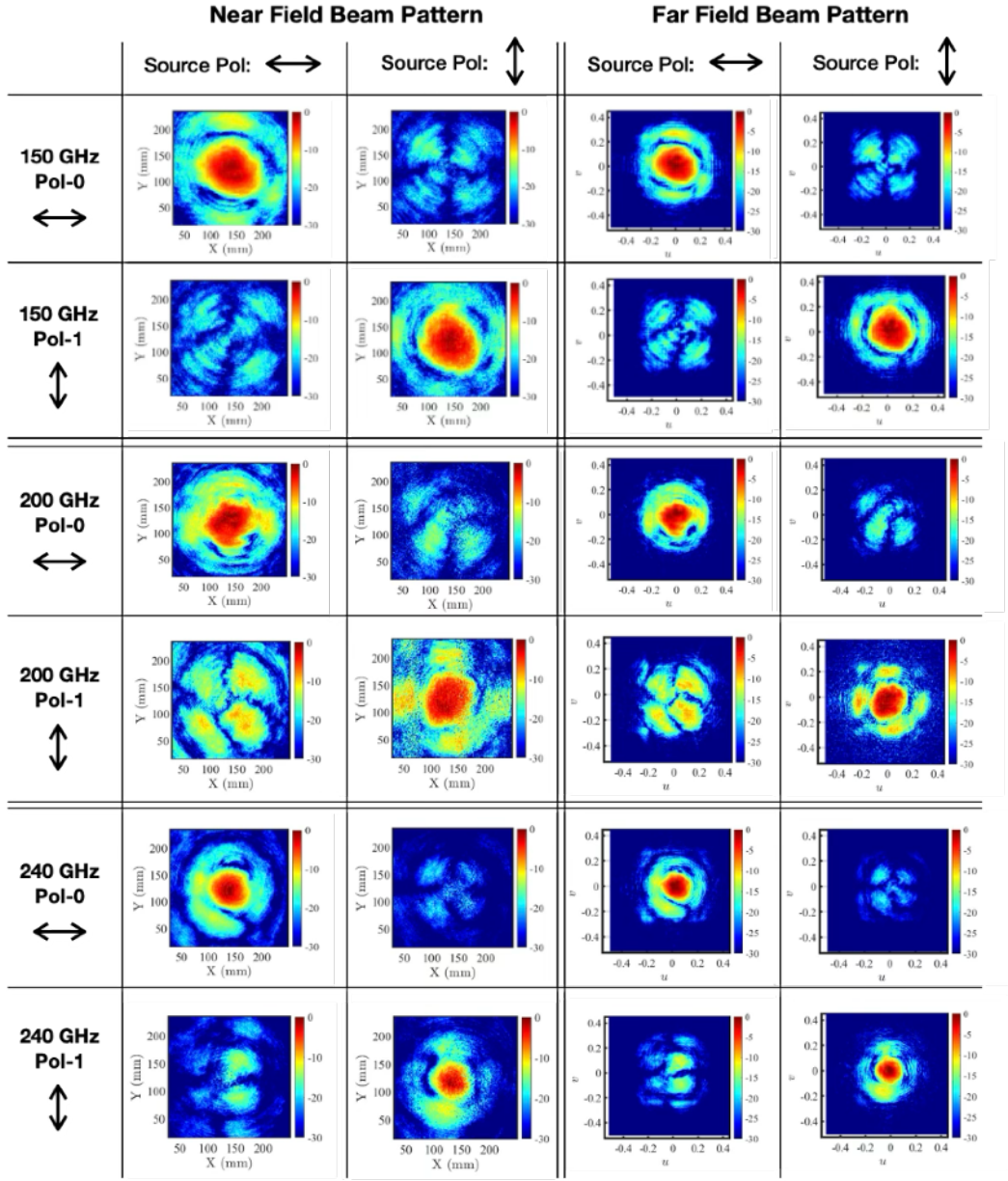




- 36 / 44 filters (~82 % yield rate), R ~ 20
- Systematic difference b.w. filter frequency of Pol0 and Po1 ***(Larger F_0 shift for Pol0)***

Performance of Single Spaxel Chip: Beam pattern

	Pol0	Pol1
141.0 GHz	◯	◯
150.4 GHz	◯	◯
159.8 GHz	-	◯
169.2 GHz	◯	◯
178.6 GHz	-	◯
188.0 GHz	-	◯
197.4 GHz	-	◯
206.8 GHz	◯	-
216.2 GHz	◯	-
225.6 GHz	◯	◯
235.0 GHz	◯	-
244.4 GHz	◯	◯



- Measure multiple frequencies at once thanks to the harmonic mixer sources

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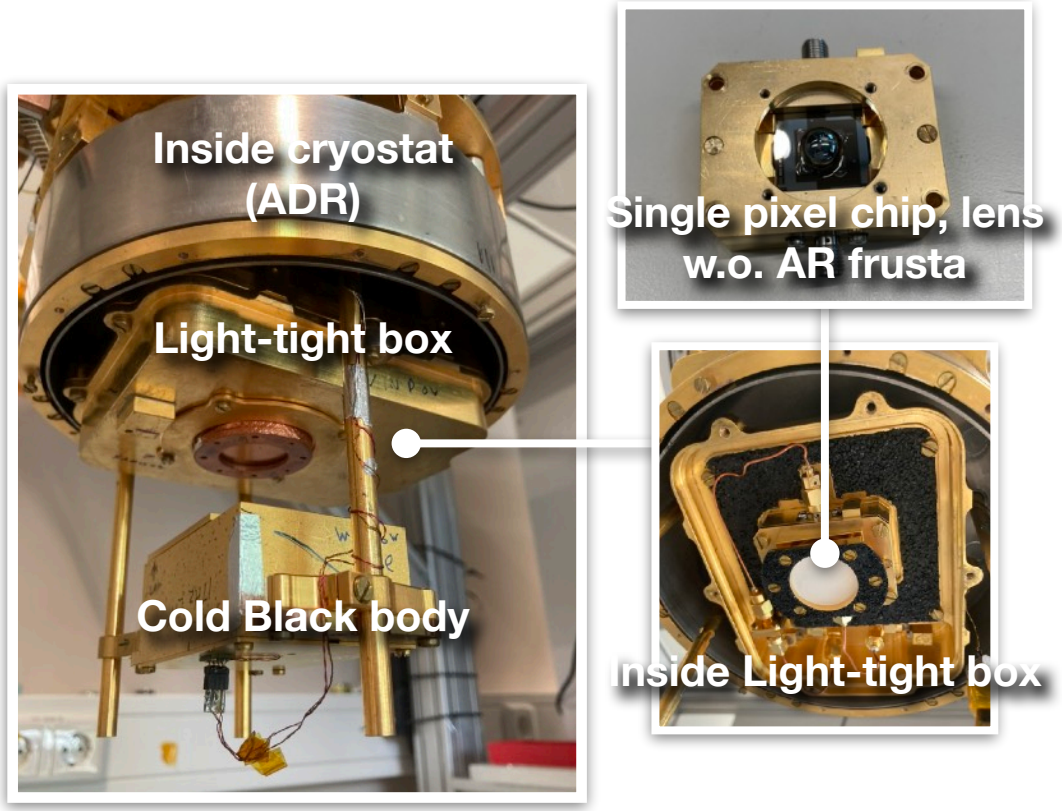
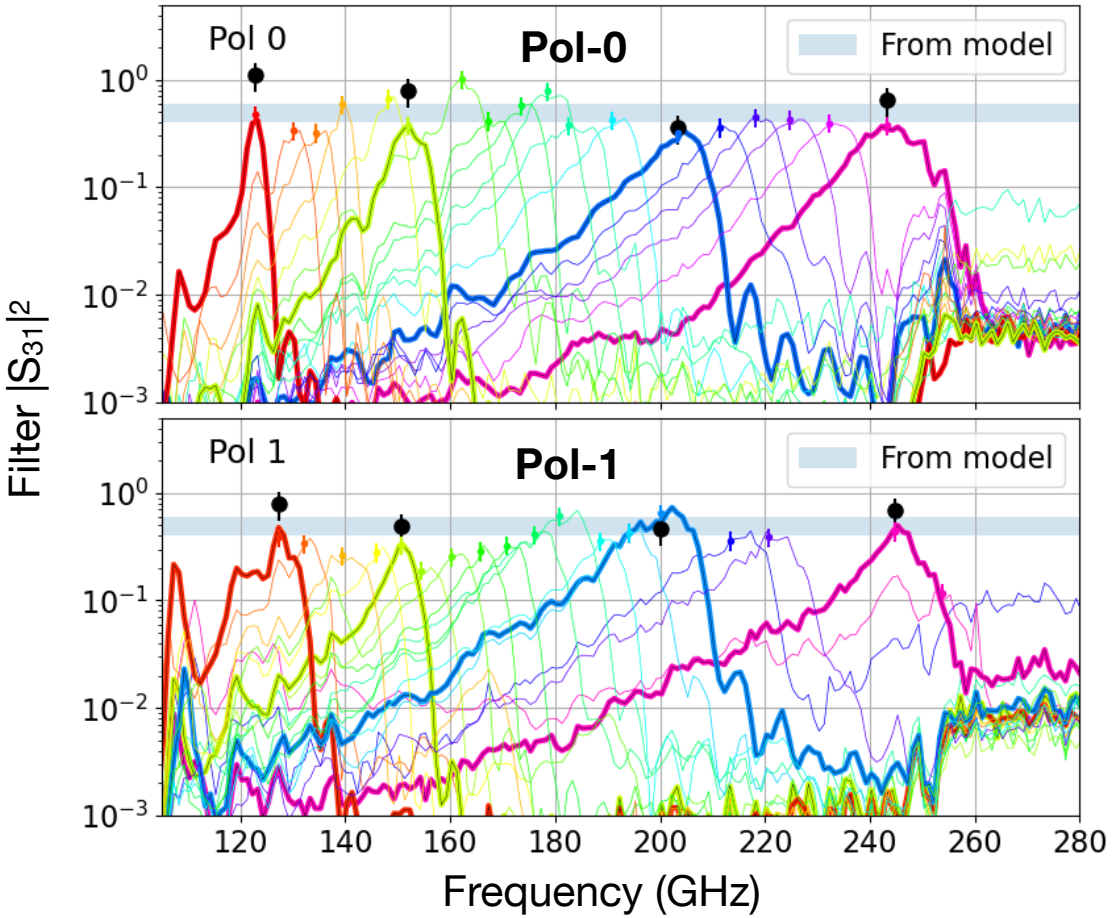
Performance of Single Spaxel Chip: Optical efficiency





- Not all KIDs are measured due to capability of readout system
- Change cold black body temperature (T_{BB}) to measure responsivity ($d\theta/dP$) and noise (S_θ)
- Calculate Noise Equivalent Power (NEP) and optical efficiency

Filter efficiency (filterbank): 0.67 ± 0.22

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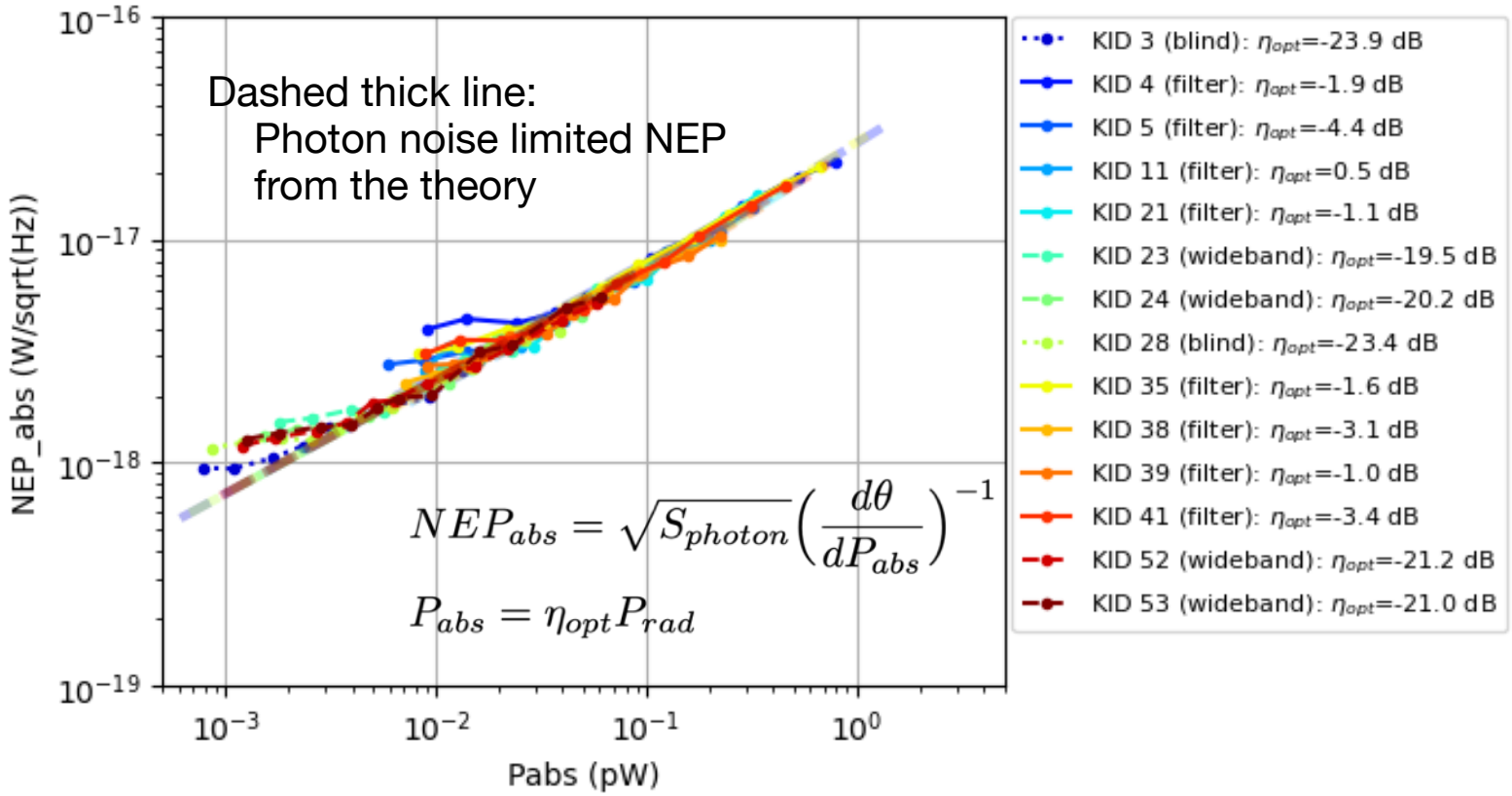
Performance of Single Spaxel Chip: Optical NEP



Photon noise limited sensitivity for optical NEP > 1e-18 (Loading power 1-1000 fW)

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Conclusion and Lesson Learned

- We have developed ***Compact*** and ***Scalable spectro-polarimetric IFU*** using the KID technology for future CMB missions
- Proof of concept of the IFU with single spaxel chip

- <u>Lesson learned (need to improve):</u>
  - KID f_r-scattering
  - 1/f noise
  - Careful design of test-bed (stray-light control)

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