Continuous Half-wave Plate Modulators

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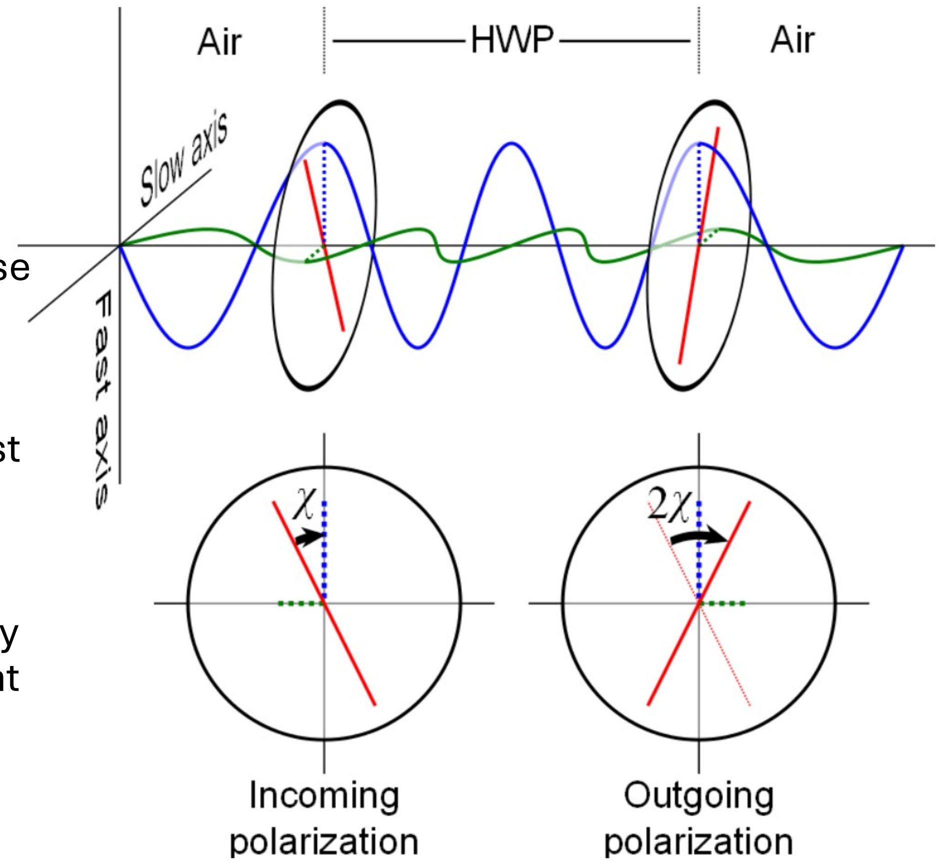
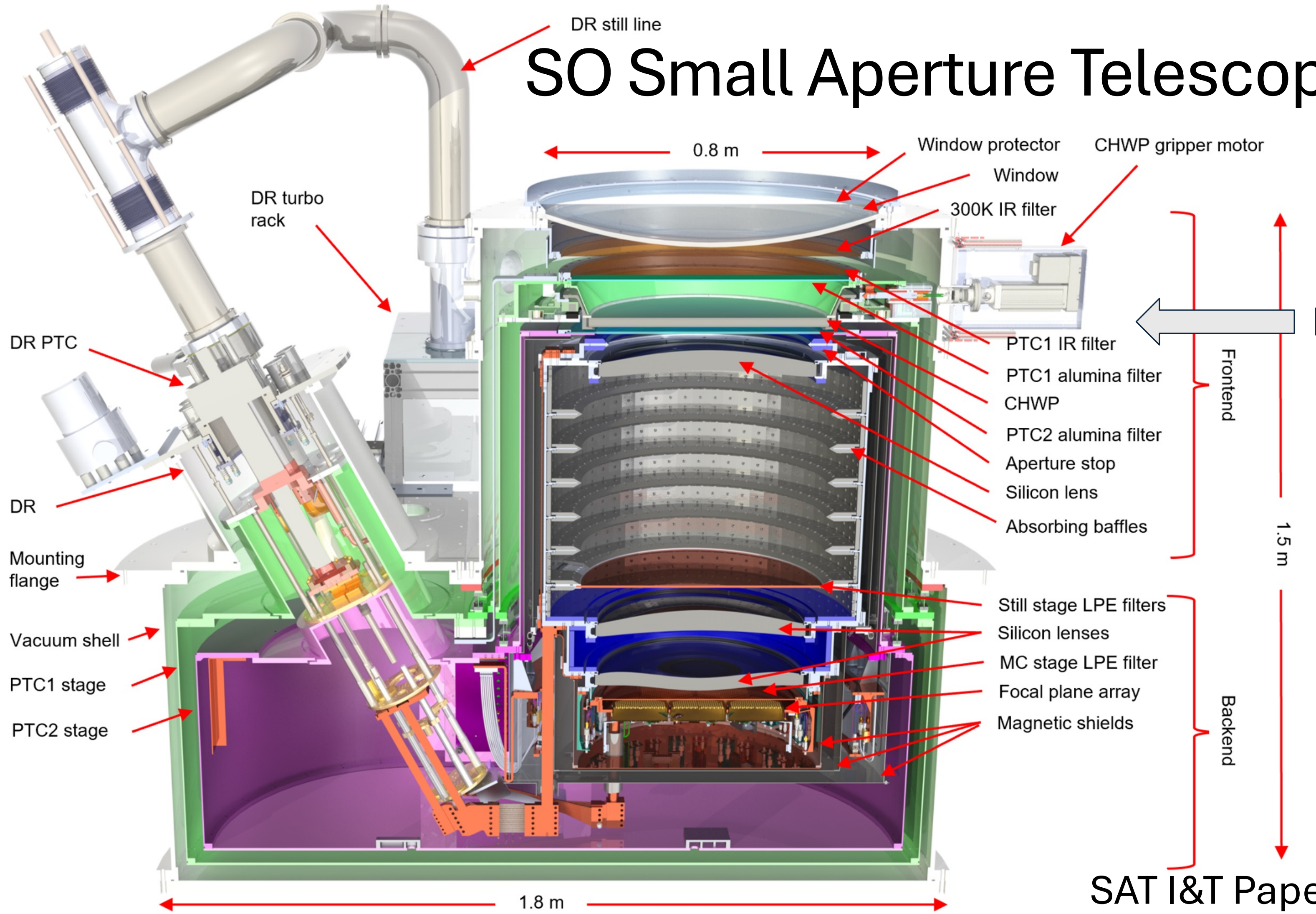
7/31/24

HWP Modulation

- A HWP has "fast" and "slow" optical axes
- The thickness is chosen so there is a 180 deg. phase shift of two orthogonal polarizations
- Therefore, the polarization is flipped around the fast axis.
- The polarization rotates at 2x the rotation frequency of the HWP and the signal is therefore modulated at 4x the rotation frequency



SO Small Aperture Telescope Cryostats



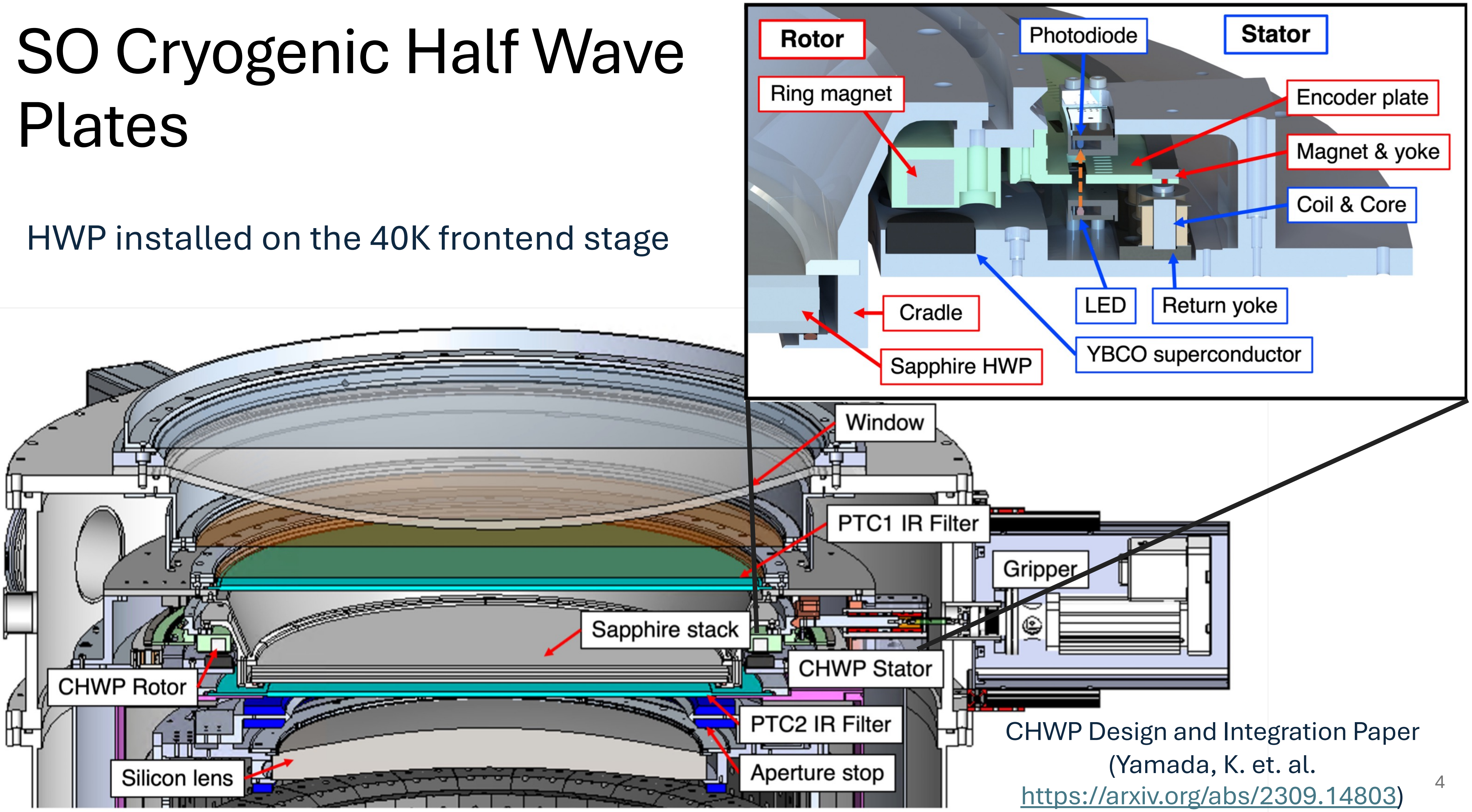
HWP on 40K stage

SAT I&T Paper (Galitzki et. al.

https://arxiv.org/abs/2405.05

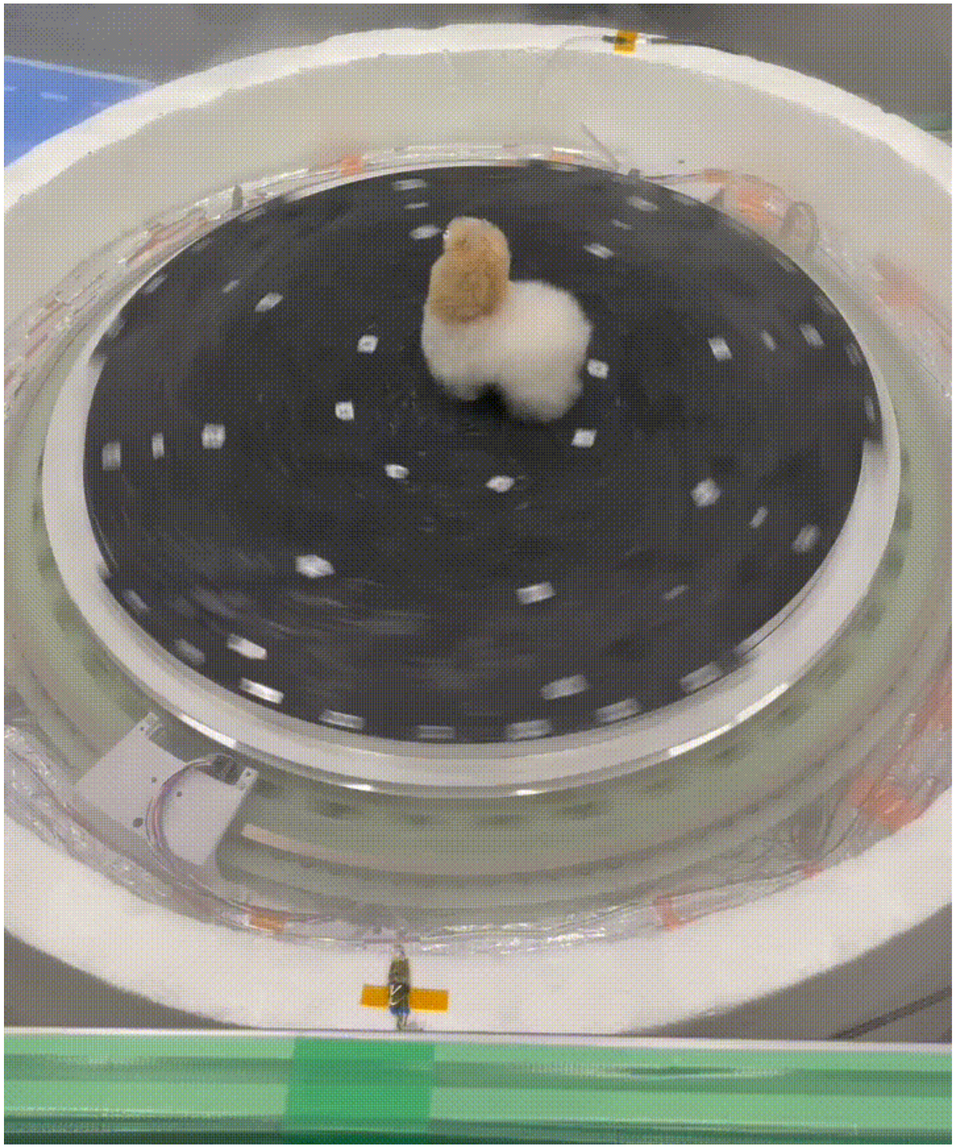
SO Cryogenic Half Wave Plates

HWP installed on the 40K frontend stage

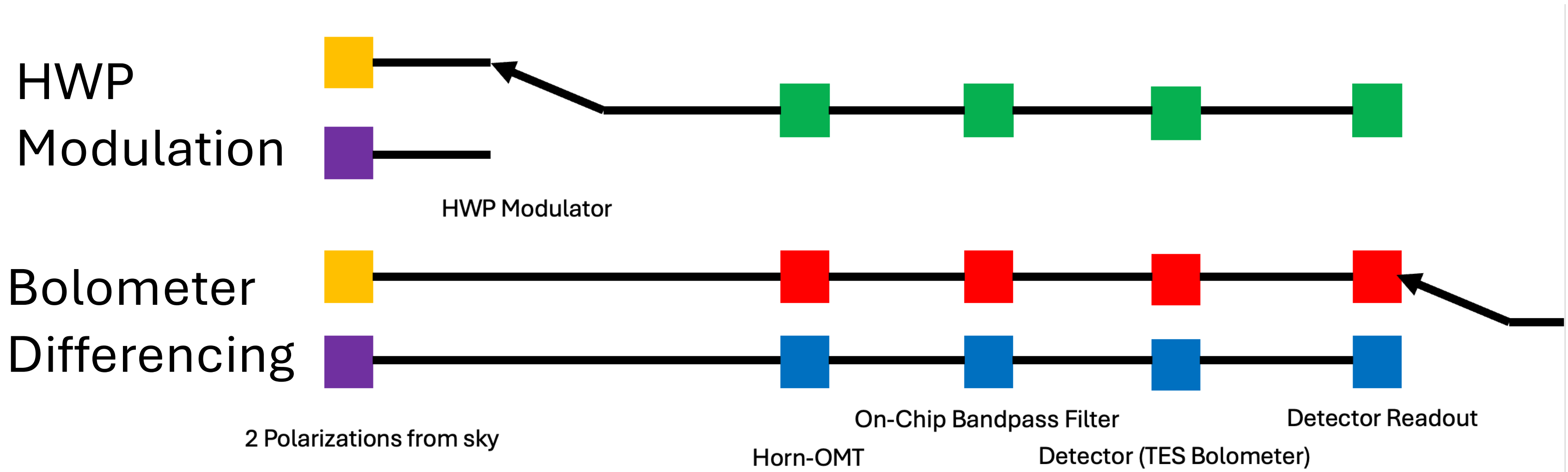


CHWP Design and Integration Paper (Yamada, K. et. al. https://arxiv.org/abs/2309.14803)

SO Superconducting HWP rotator

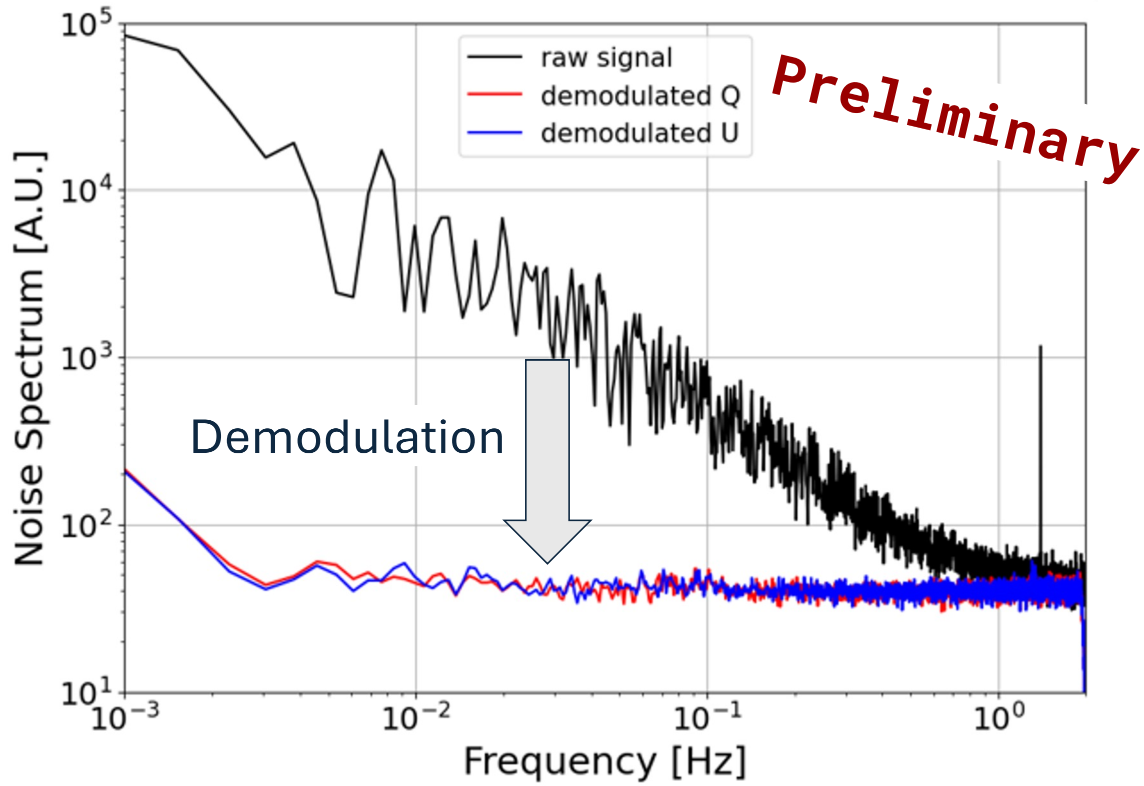


Polarization Differencing: HWP and Bolometer Differencing



- Both Techniques can work well and have been demonstrated
  - Detailed systematic error estimates based on measured instrument models
  - SO will demonstrate HWP systematic error performance at lower noise levels than previous HWP experiments
- Current experience: HWP modulation is better at rejecting atmospheric fluctuations
  - Possible reasons:
    - For differencing, a difference in bandpass shape for paired detectors will result in different gain for CMB and atmosphere, the HWP modulation uses the same bandpass filter for both polarizations
    - HWP modulation requires high gain stability due to HWP synchronous signal and differencing requires high differential gain stability

Atmospheric Rejection in SO SAT Data



Noise spectra from ~100 detectors with no additional filtering post-demodulation. Spectrum is white until very low frequencies.

Galaxy Maps

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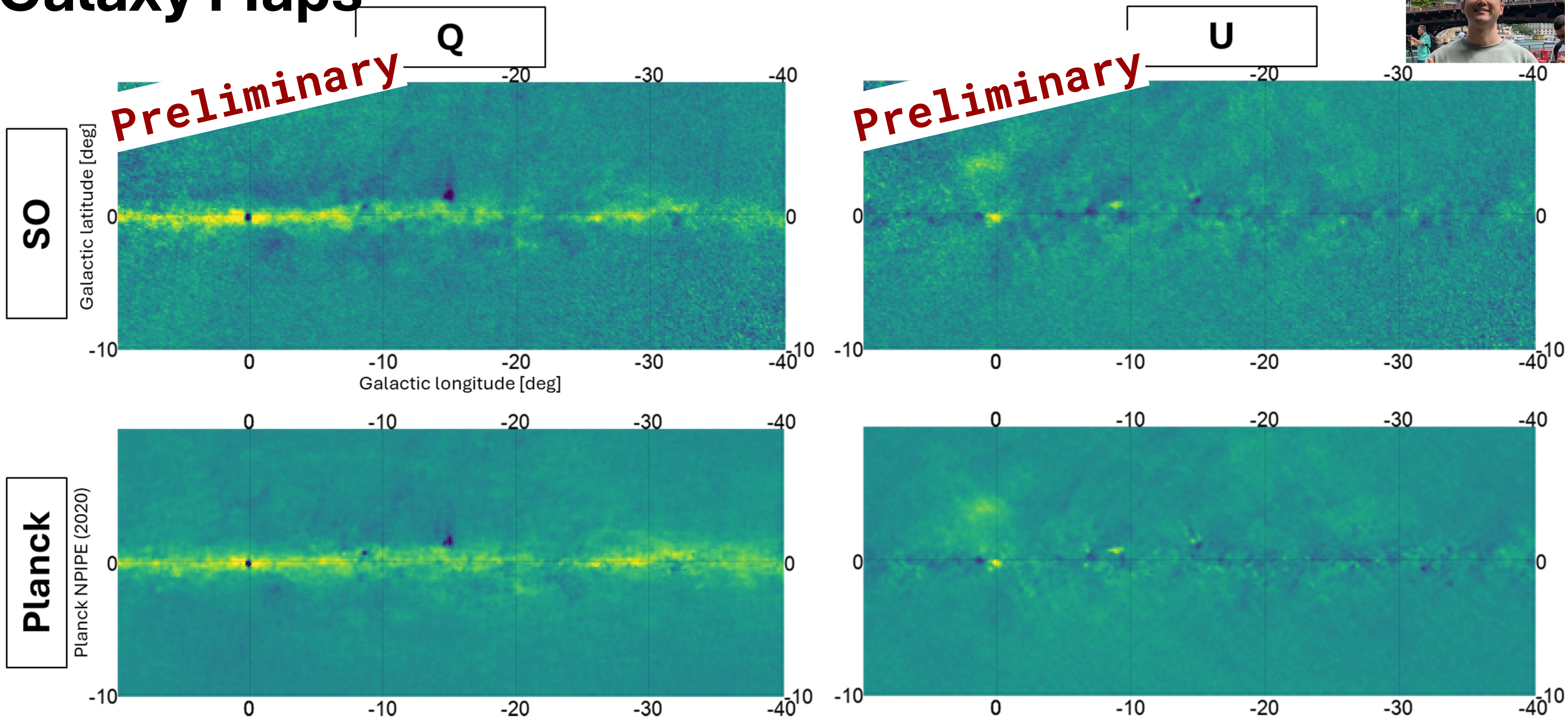


Galaxy center maps in comparison to Planck demonstrate instrument performance and larger scale recovery.

POLARBEAR-1

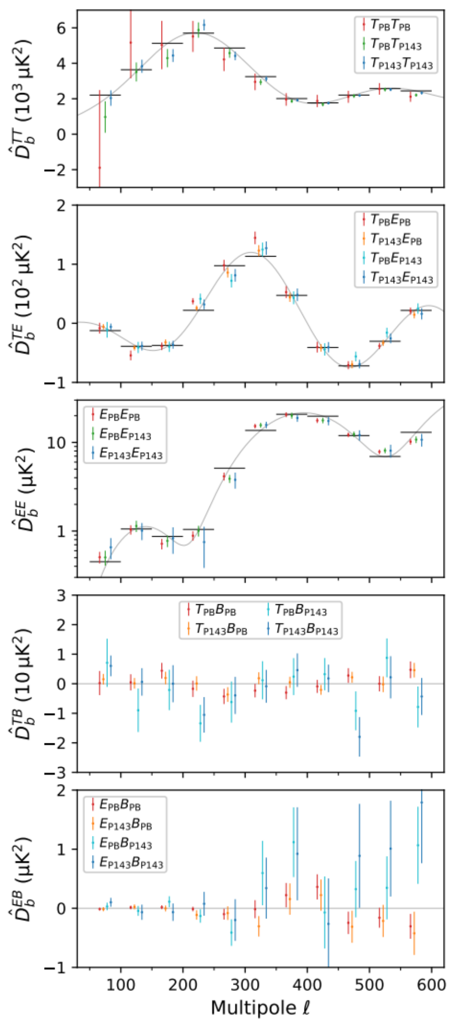


Table 3. Null Test Total χ^2 PTE Values

	EE	*EB*	*BB*
Null test summed over ℓ bins			
First half versus second half	0.6%	67.8%	84.0%
Rising versus middle and setting	1.2%	7.4%	2.2%
Middle versus rising and setting	10.0%	54.2%	78.4%
Setting versus rising and middle	78.6%	50.8%	76.6%
Left-going versus right-going subscans	0.4%	54.2%	4.8%
High-gain versus low-gain CESs	15.6%	82.4%	81.8%
High PWV versus low PWV	30.6%	47.6%	74.8%
Common-mode Q knee frequency	64.2%	88.4%	36.0%
Common-mode U knee frequency	67.0%	65.0%	17.6%
Mean temperature leakage by bolometer	62.8%	24.6%	50.4%
$2f$ amplitude by bolometer	60.6%	65.0%	16.6%
$4f$ amplitude by bolometer	59.6%	90.0%	30.4%
Q versus U pixels	84.0%	8.2%	17.0%
Sun above or below the horizon	9.8%	56.6%	57.4%
Moon above or below the horizon	88.8%	14.0%	50.2%
Top half versus bottom half	84.8%	97.8%	41.0%
Left half versus right half	85.0%	2.0%	94.8%
Top versus bottom bolometers	50.2%	71.6%	47.6%
ℓ bin summed over null tests			
$50 \le \ell \le 100$	7.4%	87.0%	37.4%
$100 < \ell \le 150$	53.4%	74.8%	49.4%
$150 < \ell \le 200$	97.6%	59.2%	25.8%
$200 < \ell \le 250$	95.4%	17.4%	5.4%
$250 < \ell \le 300$	85.4%	73.6%	33.6%
$300 < \ell \le 350$	12.2%	70.0%	97.6%
$350 < \ell \le 400$	0.0%	83.8%	85.0%
$400 < \ell \le 450$	25.8%	10.6%	11.2%
$450 < \ell \le 500$	58.6%	2.2%	15.4%
$500 < \ell \le 550$	70.8%	99.4%	53.0%
$550 < \ell \le 600$	0.2%	17.4%	89.6%

- Ell knee = 90

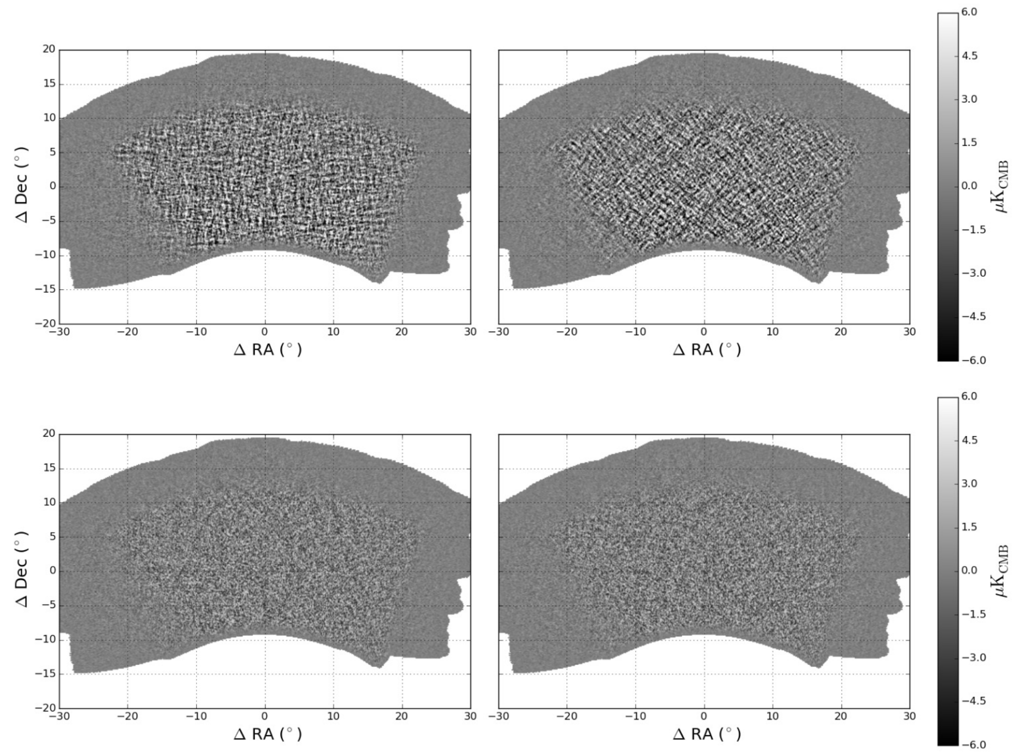
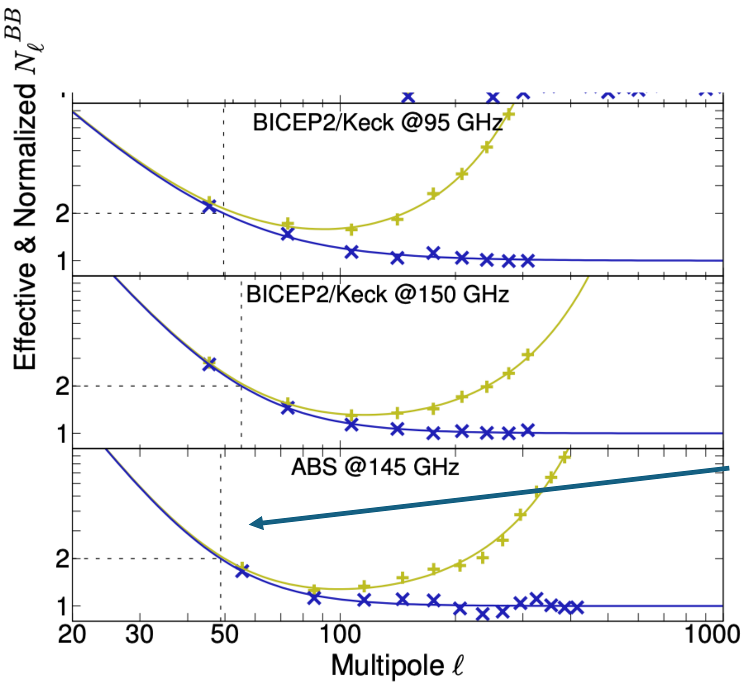


Figure 4. POLARBEAR Q and U maps (top) and a sample noise realization (bottom) produced using the "signflip" coadd pipeline. The CMB E-mode signal is visible in the real maps as a checkerboard pattern in Q and U. These noise realizations are used to estimate the band power covariance of the the final power spectrum and the noise bias used in the foreground estimation pipeline.

ABS Spectra



Ell knee limited by Az scan range and not 1/f noise

Figure 1. The normalized uncertainties on the C_ℓ^{BB} power spectrum achieved by QUIET (QUIET Collaboration 2011, 2012), BICEP2 and Keck Array (BICEP2 and Keck Array Collaborations 2016), and ABS (Kusaka et al. 2018). The yellow data points are $\Delta C_\ell^{BB}/\sqrt{2/[(2\ell+1)\Delta\ell]} \propto N_\ell^{BB}$; the blue points have the beam divided out and are normalized to unity at high ℓ. Solid lines show the modeled curves with Eq. 1. Dashed horizontal lines indicate the location of $\ell_{\rm knee}$ and are at $\ell \approx 50$ or below.

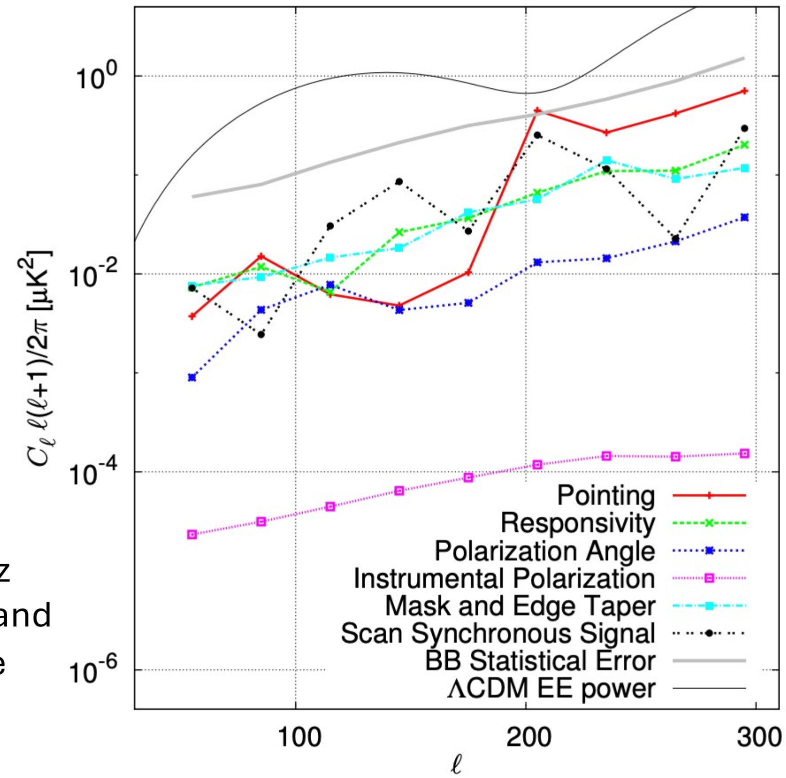


Figure 8: Systematic uceratinty estimates for the BB power spectrum. Within each category, the errors are added in quadrature since the estimates do not have a preferred direction of bias. Except for instrumental polarization and the polarization angle, the estimates are dominated by residual statistical fluctuations and are thus conservative upper limits. The systematic uncertainties are well below the statistical uncertainty for $\ell < 150$.

Studies on systematic errors due to HWP modulation

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Framework for analysis of next generation, polarized CMB data sets in the presence of Galactic foregrounds and systematic effects

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Effect of Instrumental Polarization with a Half-Wave Plate on the B-Mode Signal: Prediction and Correction

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Probing frequency-dependent half-wave plate systematics for CMB experiments with full-sky beam convolution simulations

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Impact of half-wave plate systematics on the measurement of CMB B-mode polarization

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Conclusions

- ABS and POLARBEAR
  - Show strong rejection of atmospheric fluctuations
  - Full set of null tests and estimates of systematic errors
- Simons Observatory
  - Two 90/150 GHz SATs currently observing
  - Preliminary analyses are encouraging
  - Timescale is one to few years for data that is useful for CMB-S4 design process