Polarization Modulator Signal Phase Variation: The Simons Observatory Case

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Overview

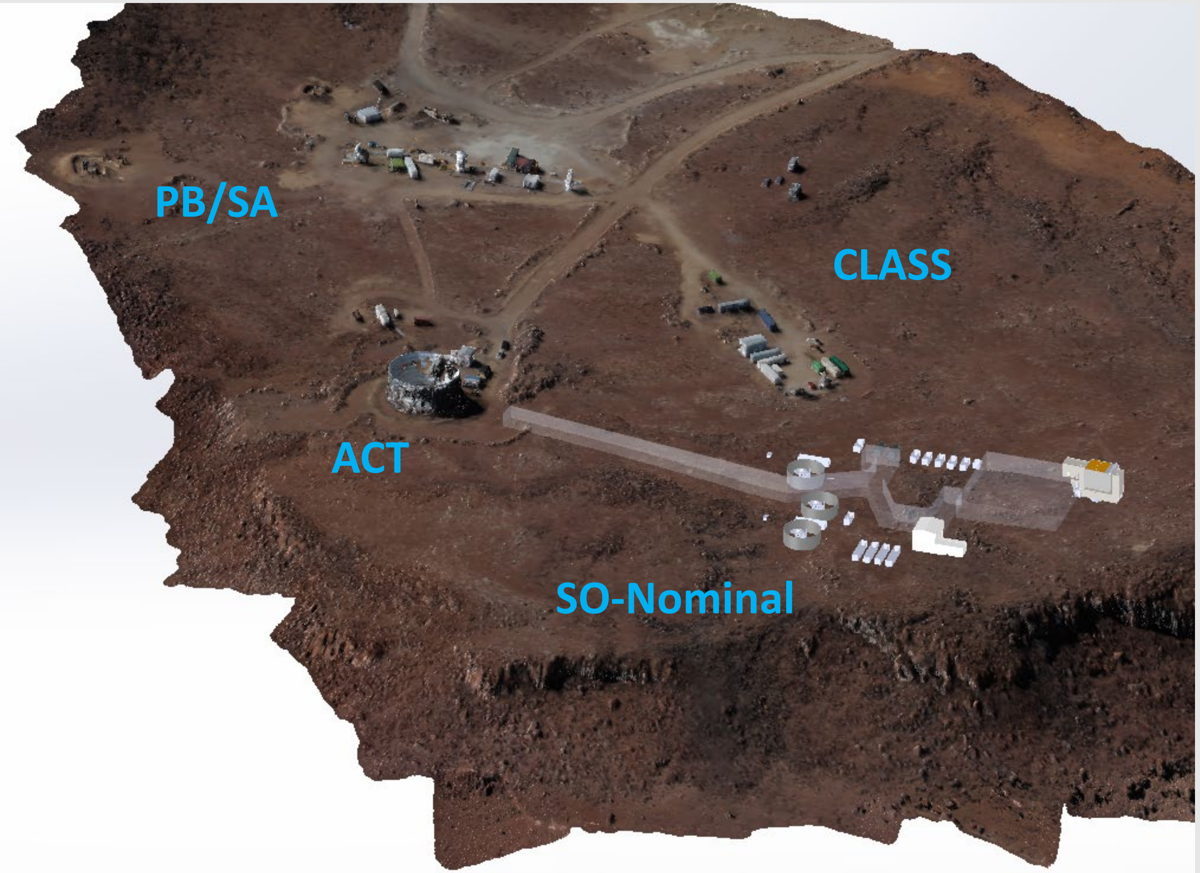
- Simons Observatory/SAT
- Systematic: shifts in effective polarization angle
- Modeling the shift
- Setting requirements

- Mitigations
  - Marginalization
  - Averaging over observing seasons
- Work to come

Intro to SO

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

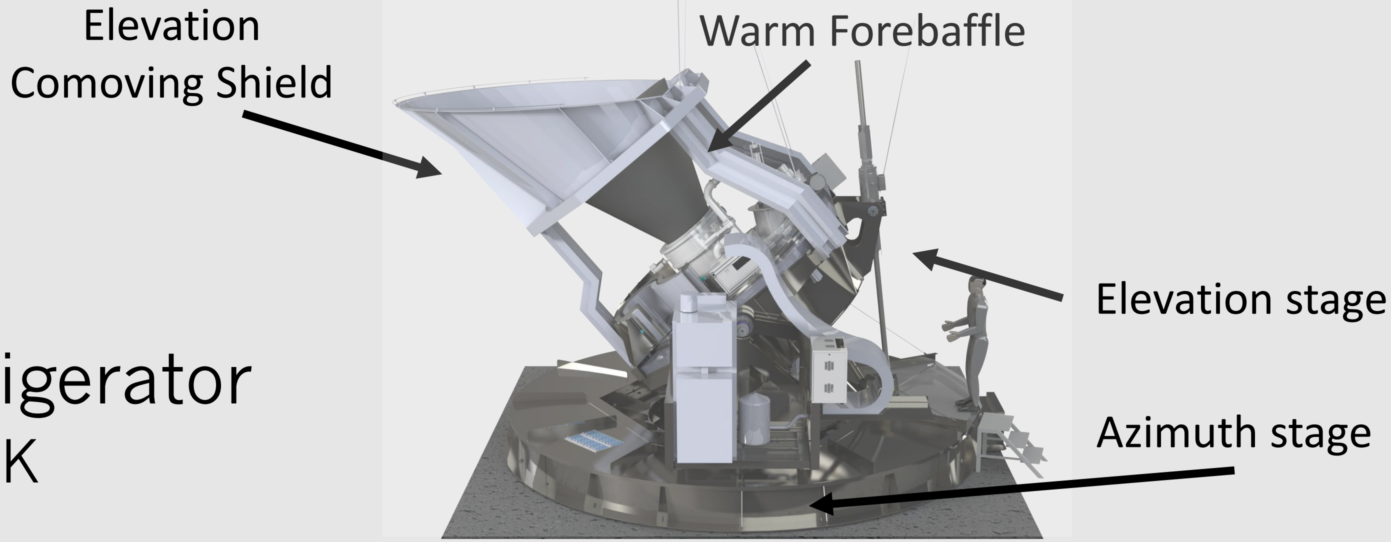


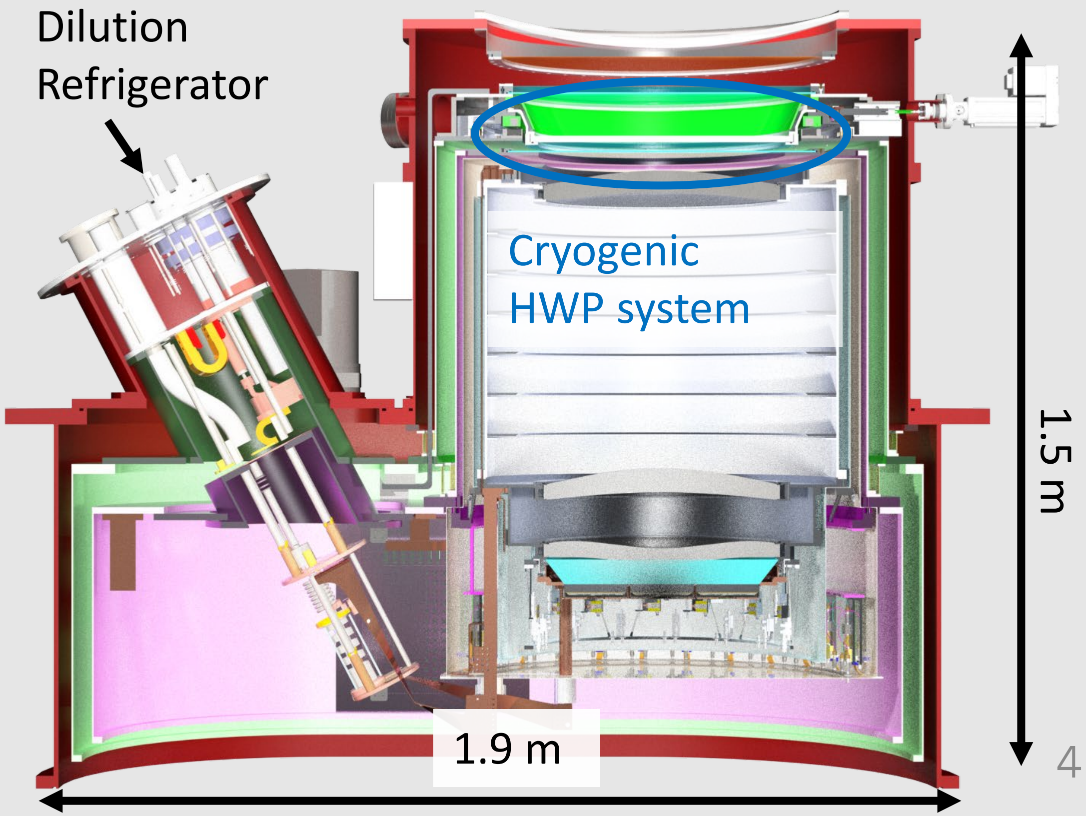
- LAT: Crossed-Dragone, 6m primary aperture
  - 1.3 arcmin resolution @ 150 GHz
- SAT x3: Three-lens refractor, 42 cm aperture
  - 17 arcmin resolution @ 150 GHz
- Six bands spanning 27 – 280 GHz

Sited on Chajnantor plateau in Atacama Desert, Chile @ 5200 m

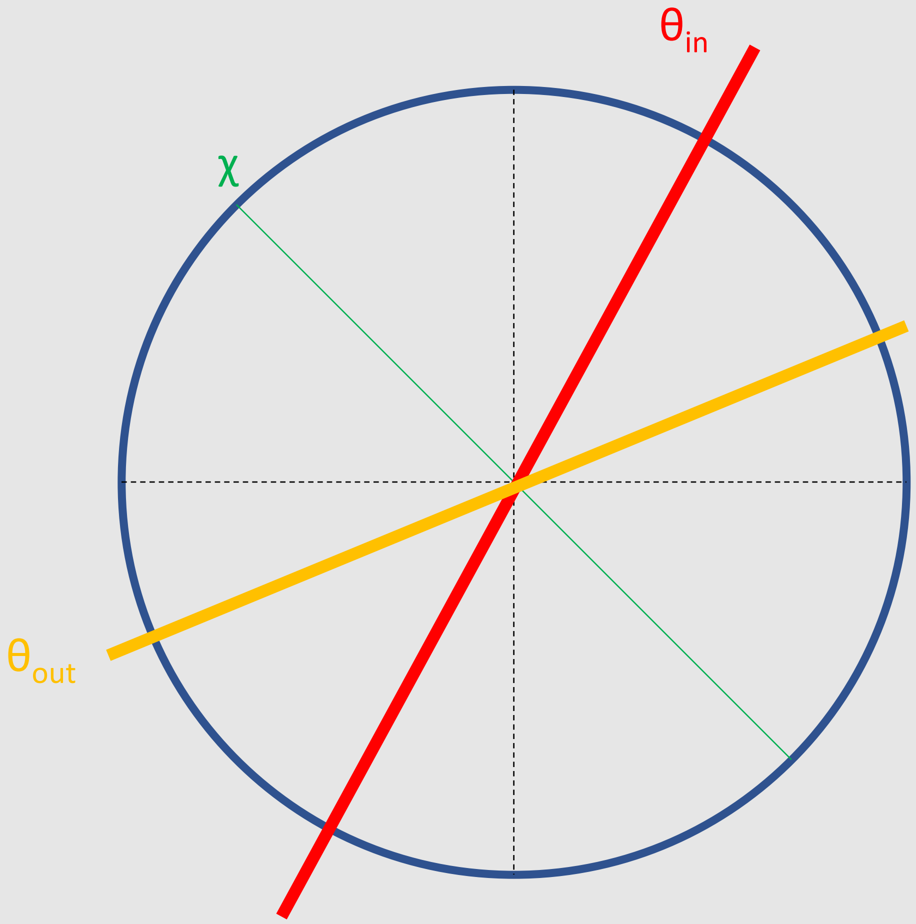
SAT instrument

- 2 PT-420 pulse tubes, Bluefors SD-400 dilution refrigerator
  - Operating temperature: 100 mK
- Three-lens silicon optics + 1 K Lyot stop
- Cryogenic half-wave plate (HWP) + superconducting magnetic bearing
  - see P. Ashton talk: “Instrumentation” session
- Antenna, coupling & detector heritage from Simons Array & ACT
  - Dual polarization, dichroic pixels
  - Transition-edge sensor (TES) bolometers



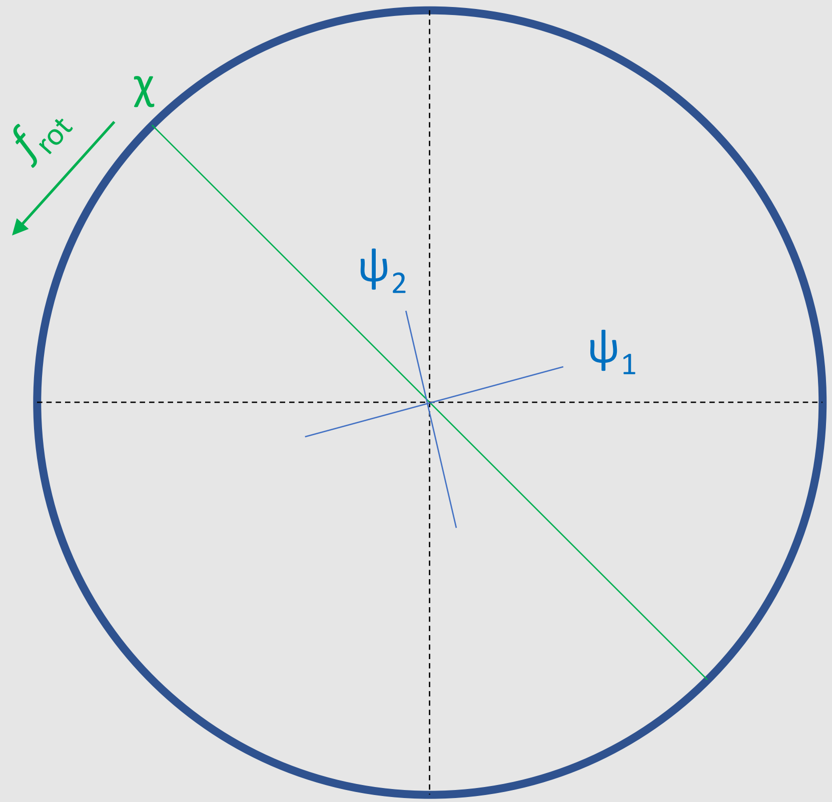


Half-wave plate review



- Birefringent material w/ tuned thickness
  - χ = extraordinary axis (unique index in crystal)
- Ideal HWP response:
  - Incoming linear polarization rotated by $-2\ \theta_{in}$
  - Only at single mm-wave frequency
- Multiple HWPs improves bandwidth (Pancharatnam 1955)
  - Three-stack sapphire design for SO

HWP as polarization modulator



- Constant rotation $f_{rot} = d\chi/2\pi dt$
- Output polarization angle @ 2 f_{rot}
  - Detector records @ 4 f_{rot} – polarimeter senses power
- W/o HWP:

$$d_{raw}(t) = I(t) + Q(t)\cos(2\psi) + U(t)\sin(2\psi)$$

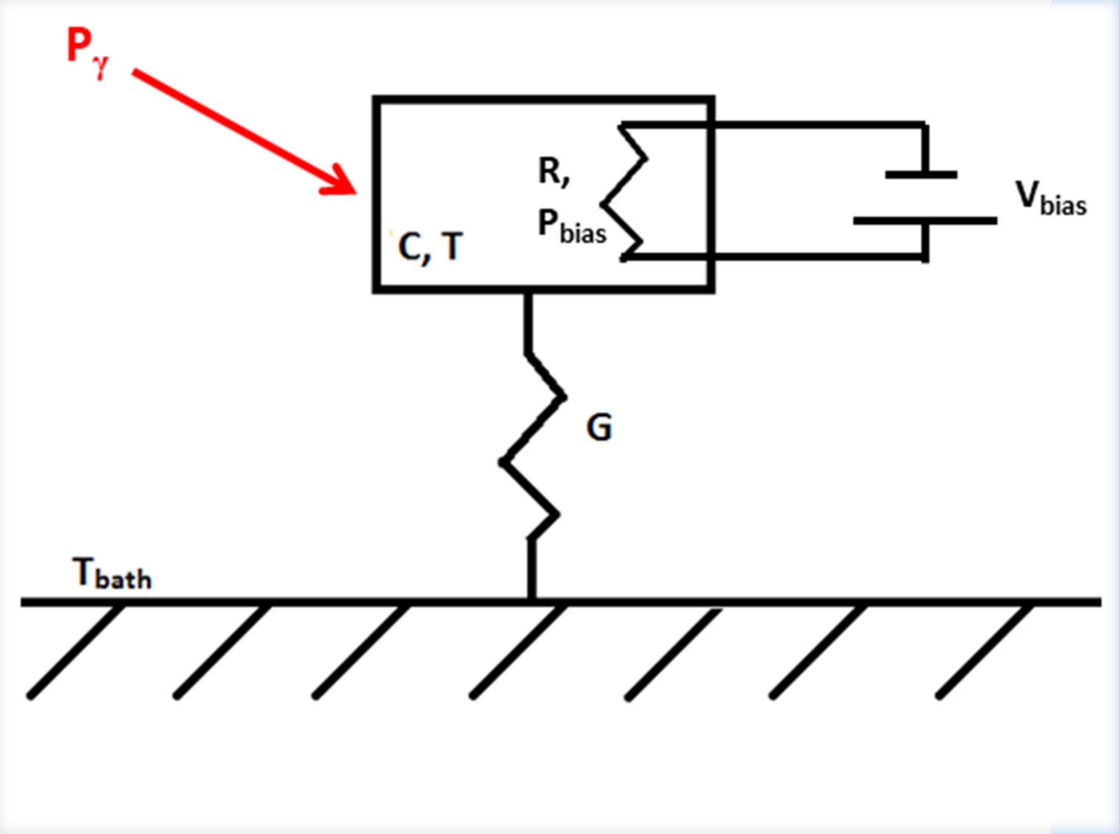
- W/ HWP:

$$d_{mod}(t) = I(t) + Q(t)\cos(2\psi - 4\chi) + U(t)\sin(2\psi - 4\chi)$$

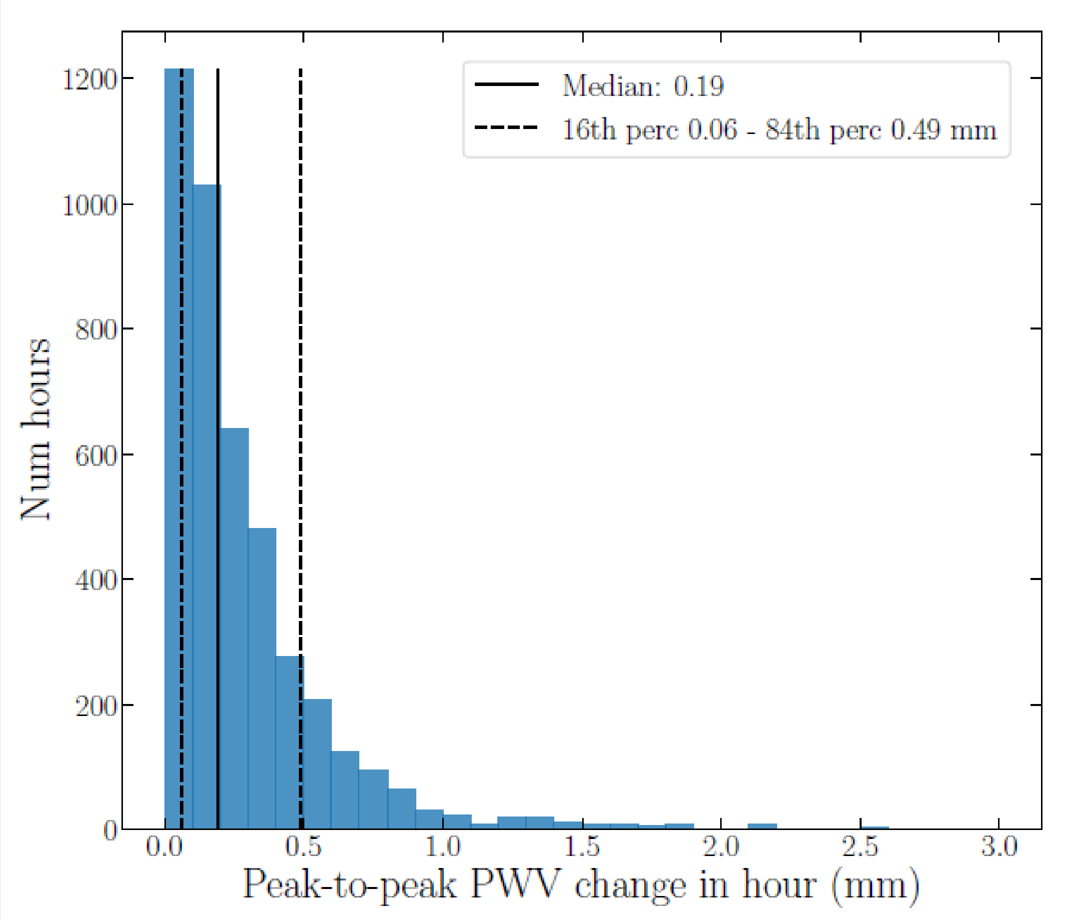
- Polarization signal now lifted above atmospheric f_{knee}

SO detectors: the basics

- TES devices: “relative power”
  - δP → δT → δR → δI
- Bolometer thermal time constant $\tau = C/G$
  - Measure *in situ* $\tau_{eff} < \tau$
- Acts as single-pole filter on TES current signal
  - Response to HWP pol signal has phase $\arctan(4\,(2\pi f_{rot})\,\tau_{eff}) = \arctan(4 f_{rot} / f_{3dB})$
  - f_{3dB} calibration tool: Simon et al. (2014)



Shifts in f_{3dB}

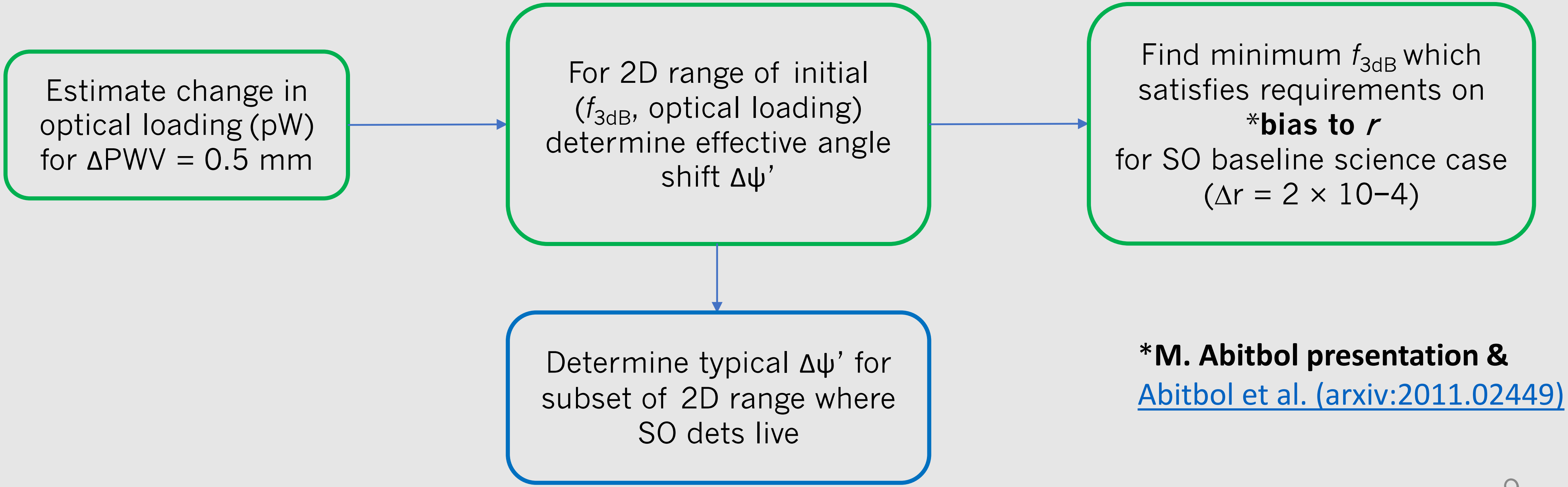


- SO studies f_{3dB} before/after each observing scan
  - Correct for dominant phase
- In between:
  - Changing optical loading changes TES response
- Loading from precipitable water vapor (PWV) in atmosphere
- Study APEX radiometer data over season-long timescale
  - Local to Chajnantor plateau
  - Typical peak-to-peak excursion @ 84th perc: 0.5 mm

Generating requirements by SO frequency band

$\Delta f_{3\mathrm{dB}}$ = change assuming ΔPWV
Size of nonlinearity coefficient roughly consistent with τ_1 in [Takakura et al. POLARBEAR-1]

$$\Delta\psi' = \frac{1}{2}\left(\arctan\left(\frac{f_{\mathrm{sig}}}{f_{3\mathrm{dB}} + \Delta f_{3\mathrm{dB}}}\right) - \arctan\left(\frac{f_{\mathrm{sig}}}{f_{3\mathrm{dB}}}\right)\right)$$



Estimate change in optical loading (pW) for ΔPWV = 0.5 mm

For 2D range of initial ($f_{3\mathrm{dB}}$, optical loading) determine effective angle shift Δψ'

Find minimum $f_{3\mathrm{dB}}$ which satisfies requirements on ***bias to *r***
for SO baseline science case (Δr = 2 × 10−4)

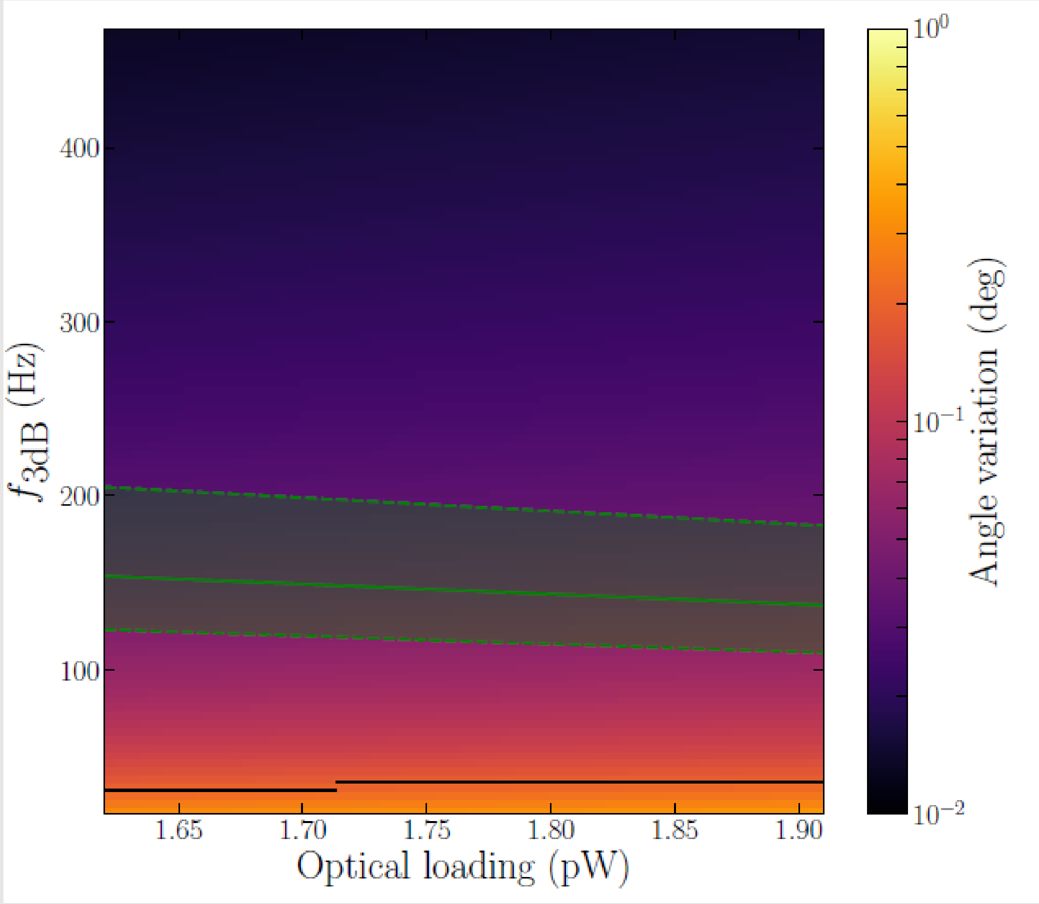
Determine typical Δψ' for subset of 2D range where SO dets live

***M. Abitbol presentation &**
[Abitbol et al. (arxiv:2011.02449)]

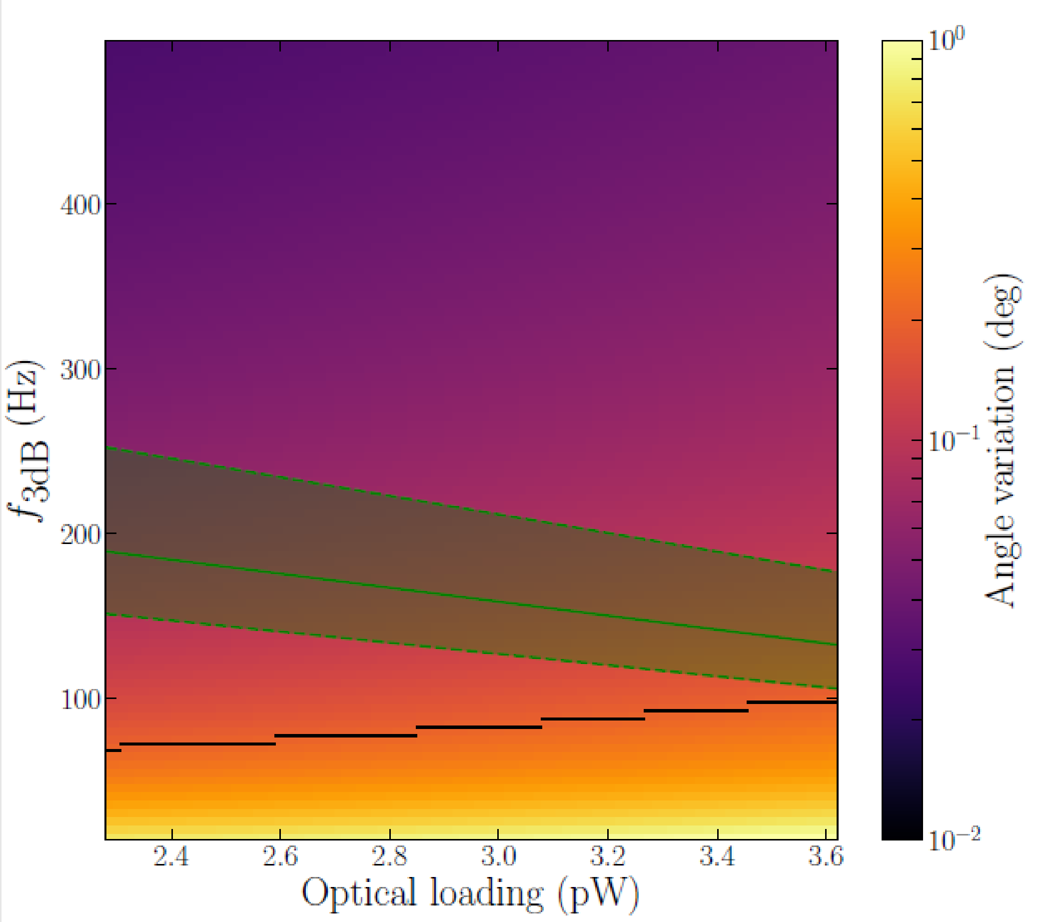
Results: effective polarization angle shift

Black: 0.2 deg

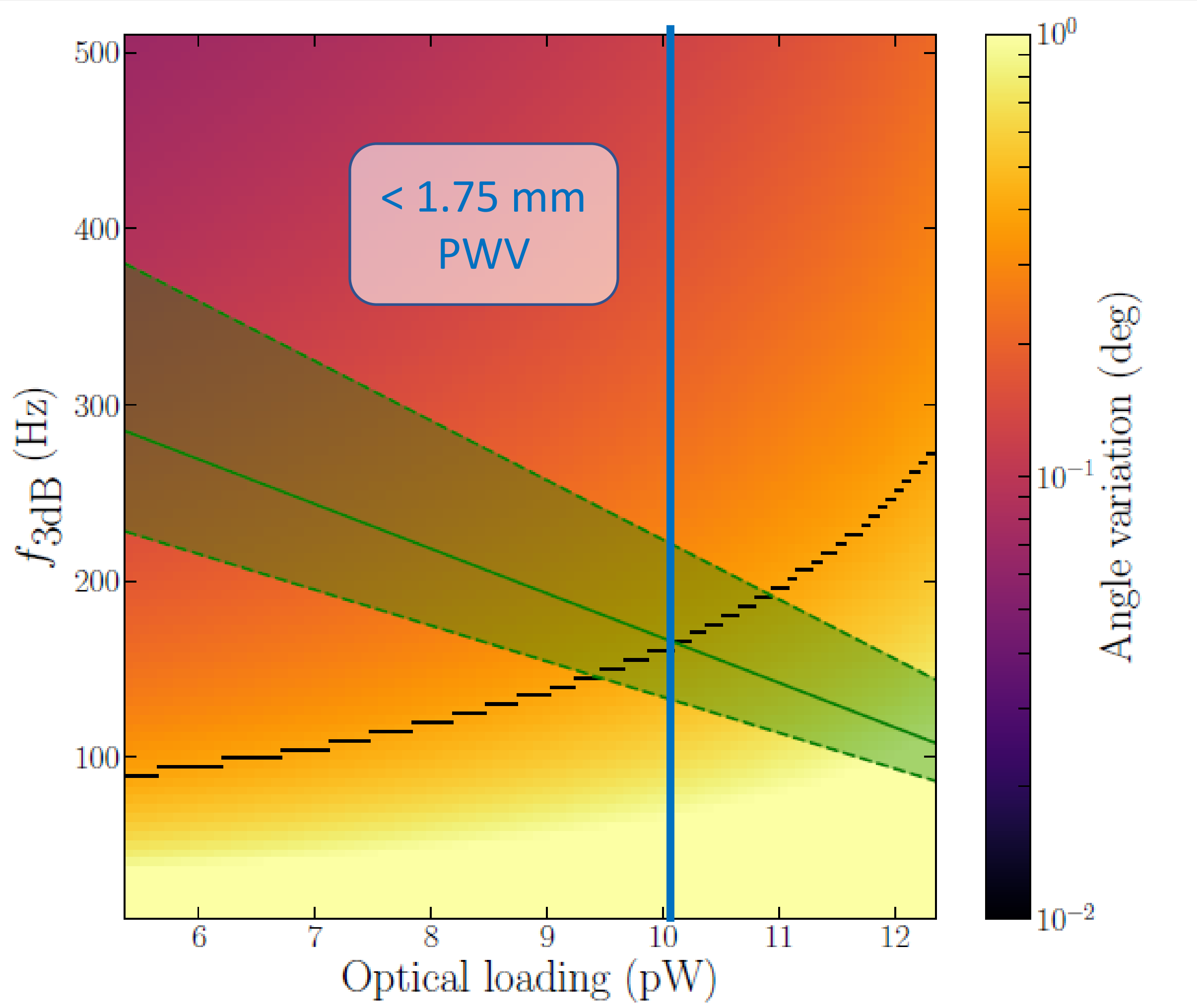
94 GHz Band



148 GHz Band



Difficult band: 225 GHz (dust constraints)

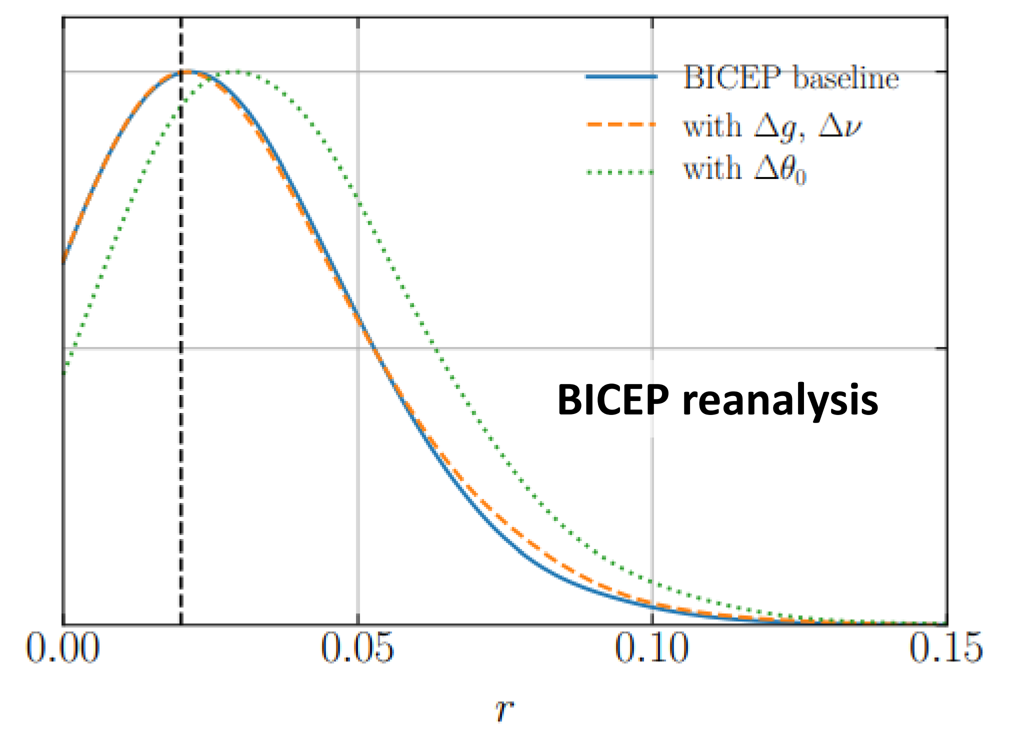


Black: 0.4 deg

Mitigating factors

- Self-calibration of detector polarization angle ψ
  - Marginalize over ψ uncertainty
- Consider average over many hours of observing in 1 sky map
- Can model time constant drift
  - Time-dependent detector ψ exists in mapmaking for parallactic angles

SO case:
Successful self-calibration (using *EB* = 0)
w/o and w/ foreground EB marginaliztion



Δg, *Δv*: bandpass gain & bandcenter
$\Delta\vartheta_0$ = map-level polarization angle shift

Mitigating factors

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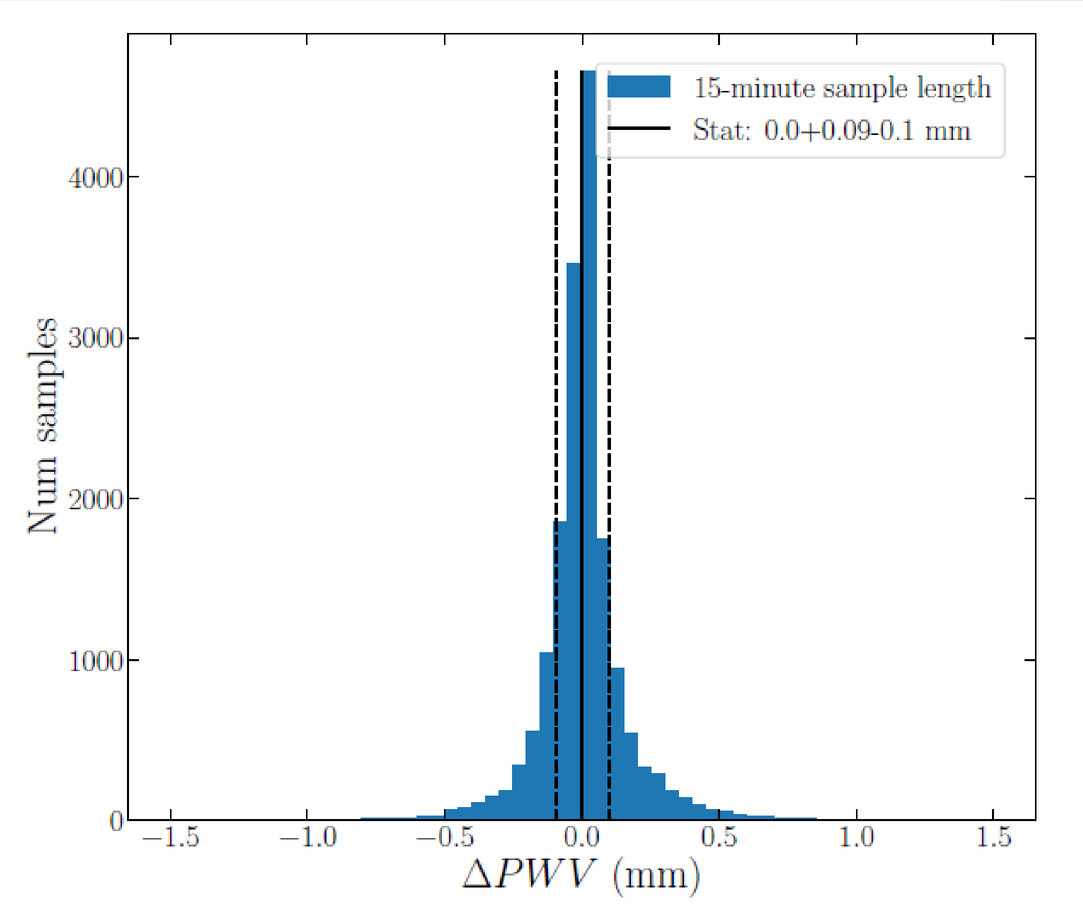
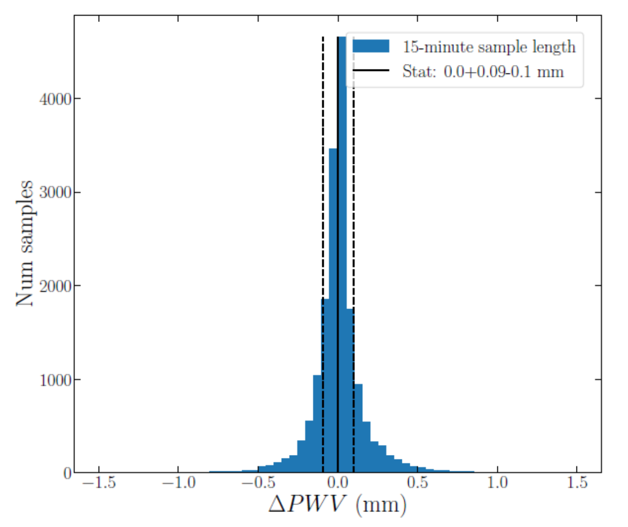


Change in PWV from start of hour every 15 min

~4000 hours

Observation averaging

- W/ averaging:
  - Systematic becomes “polarization angle jitter”
- Reduced polarization efficiency per detector
  - Can be calibrated in final comparison w/ Planck
- Possible spurious B-modes
  - Further study on array uniformity, f_{3dB} calibration needed



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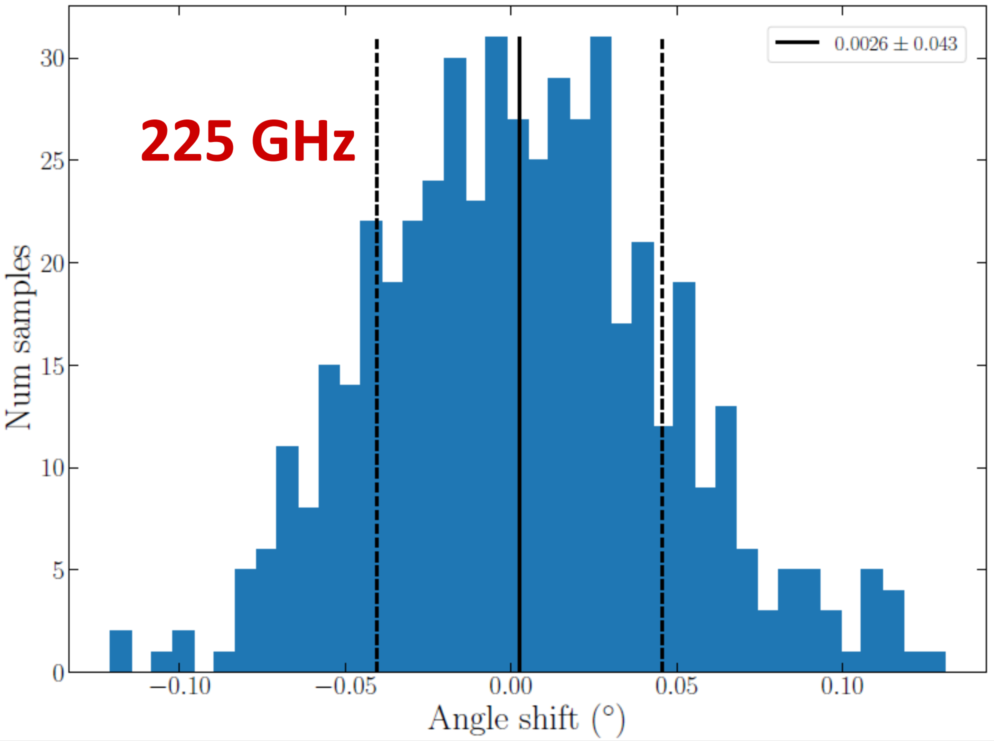


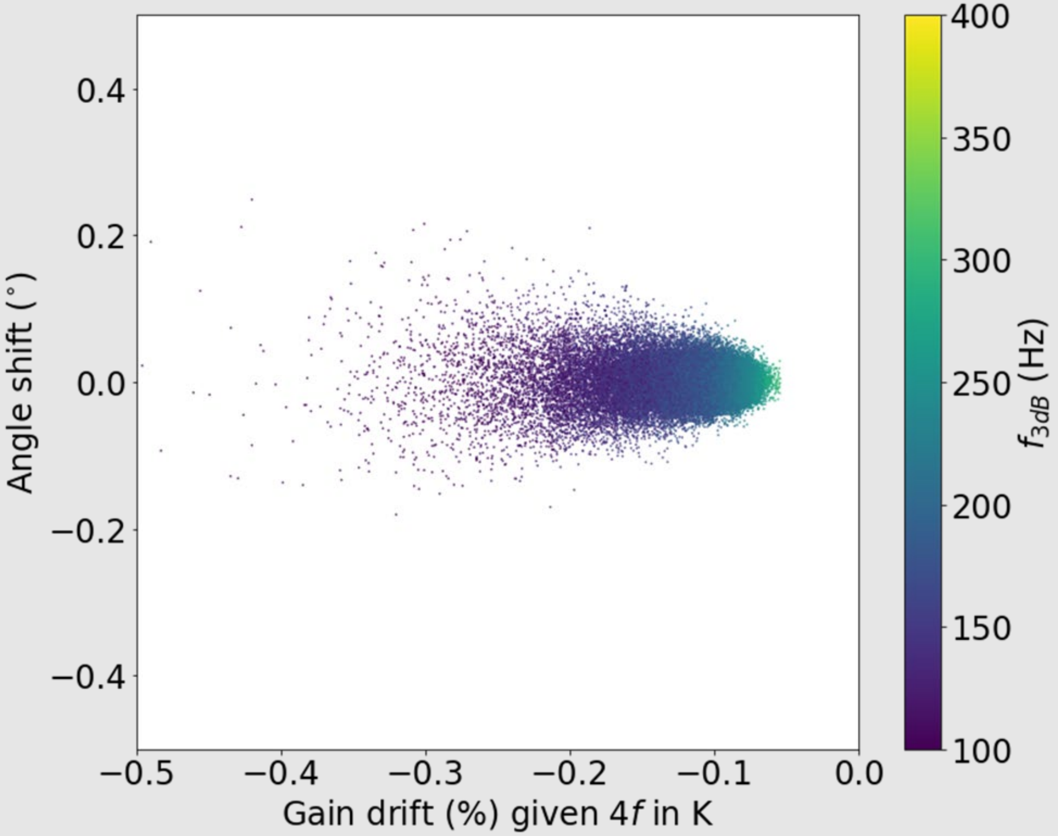
500 random draws of ΔPWV Gaussian

σ = 0.1 mm

Initial PWV = 1.5 mm

Future studies

148 GHz Band



- Per-detector averaging over seasons
  - Randomized optical loading/ bolometer parameters
  - Miscalibration
- Requirements on SAT time constant calibration error
- Inclusion of effect in ongoing SO systematic studies (time-domain simulations)

Summary

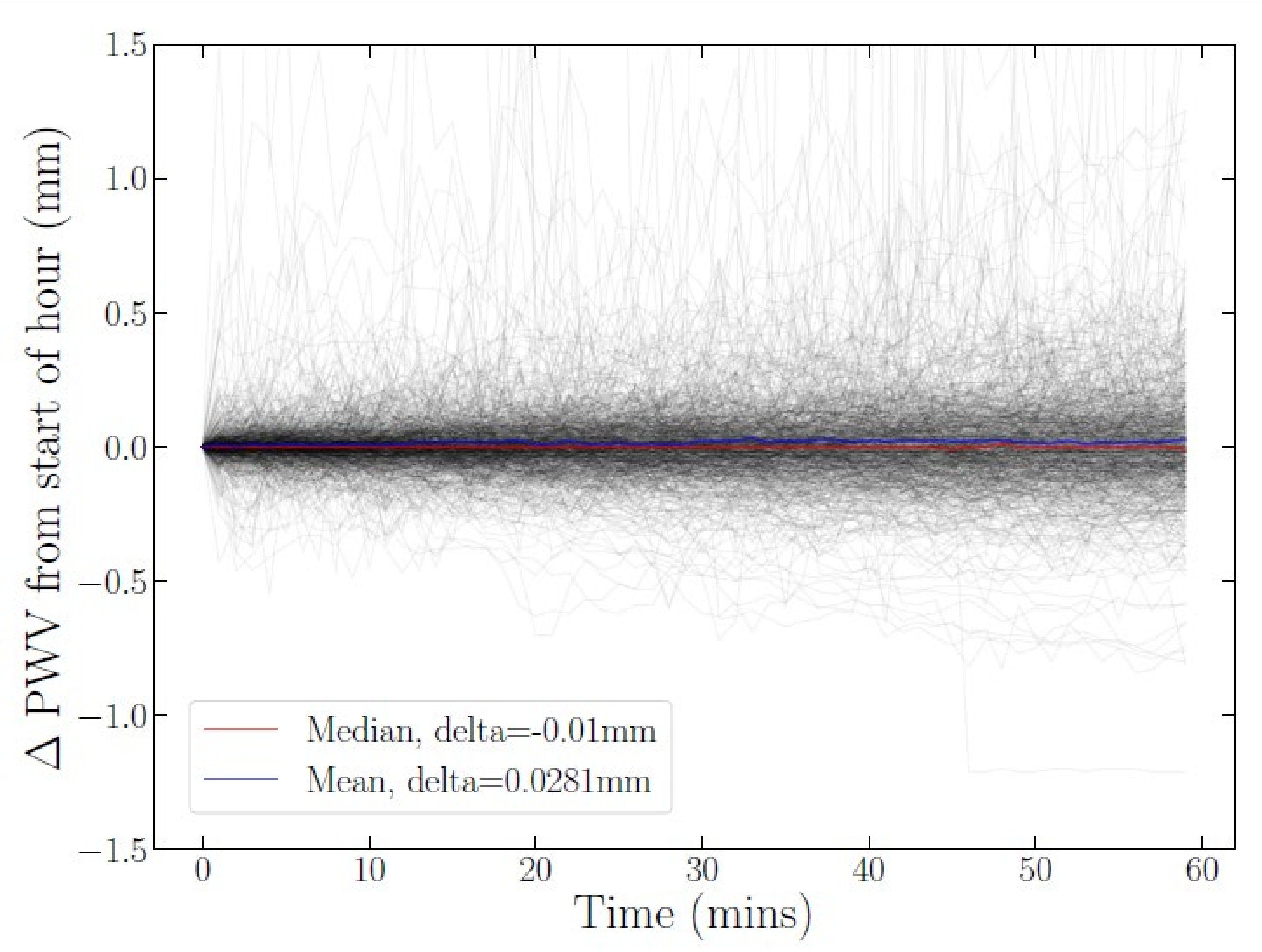
- SO SAT features rotating half-wave plate
  - Detector $f_{3\text{dB}}$ shift → effective polarization angle shift
- SO TES $f_{3\text{dB}}$ targets meet requirements in conservative study
  - In nearly all optical loading conditions
- Various mitigations also exist
  - SO will self-calibrate using EB nulling & marginalize over miscalibrations
  - Stochastic ΔPWV will average down over multiple observations

- Effect will be studied further in SO systematics simulation suite

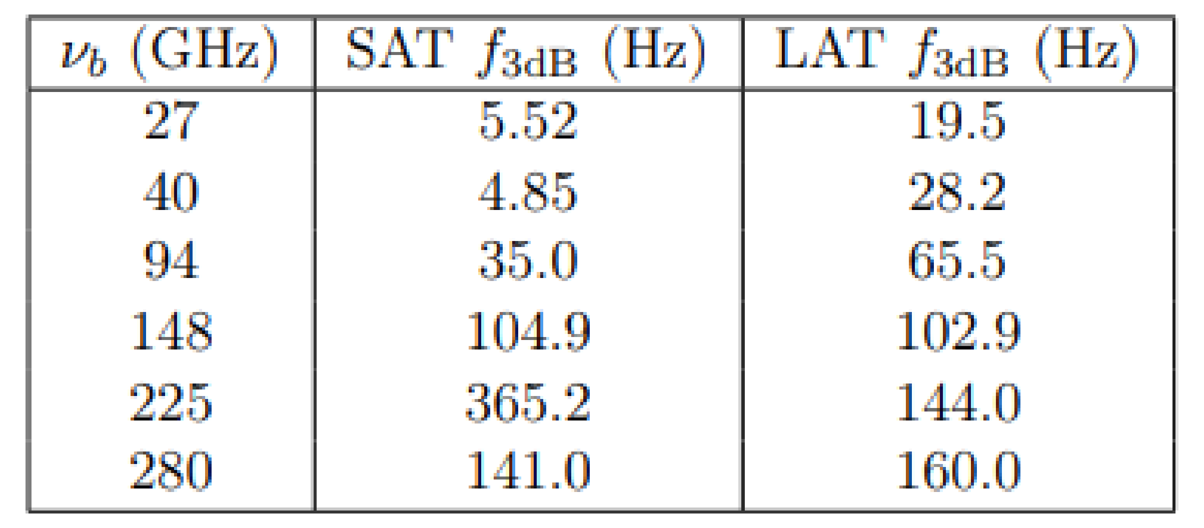
Thank you!

BACKUP

Time trend of 1000 APEX hrs

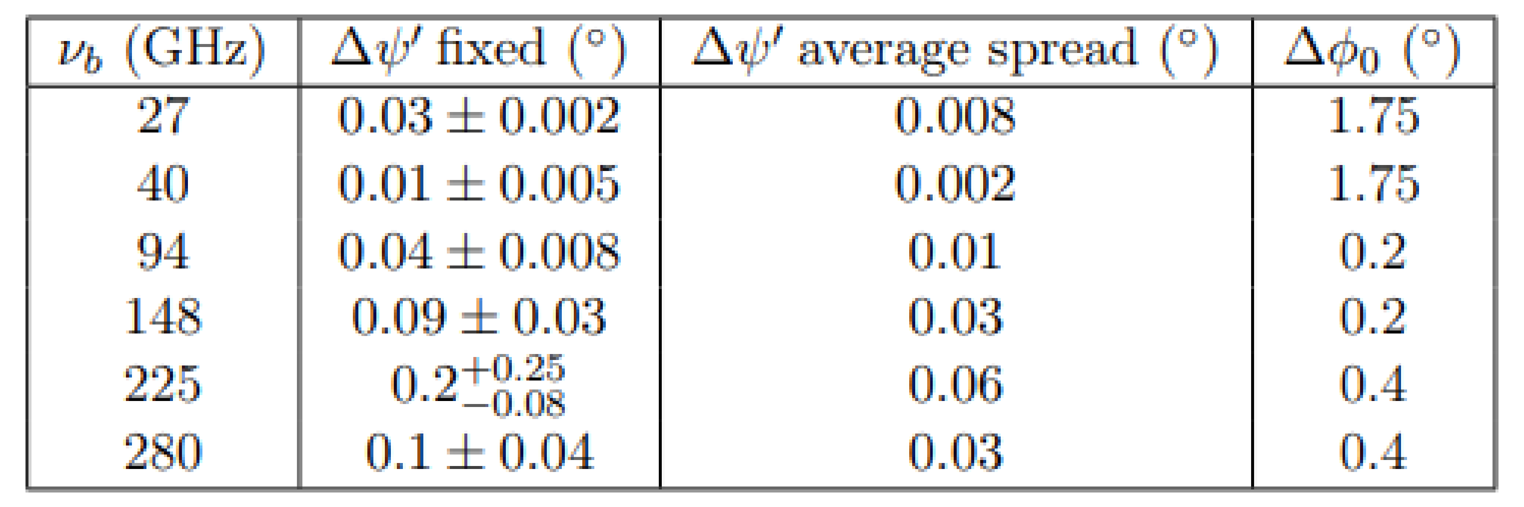


Summary of SAT f_{3dB} requirements



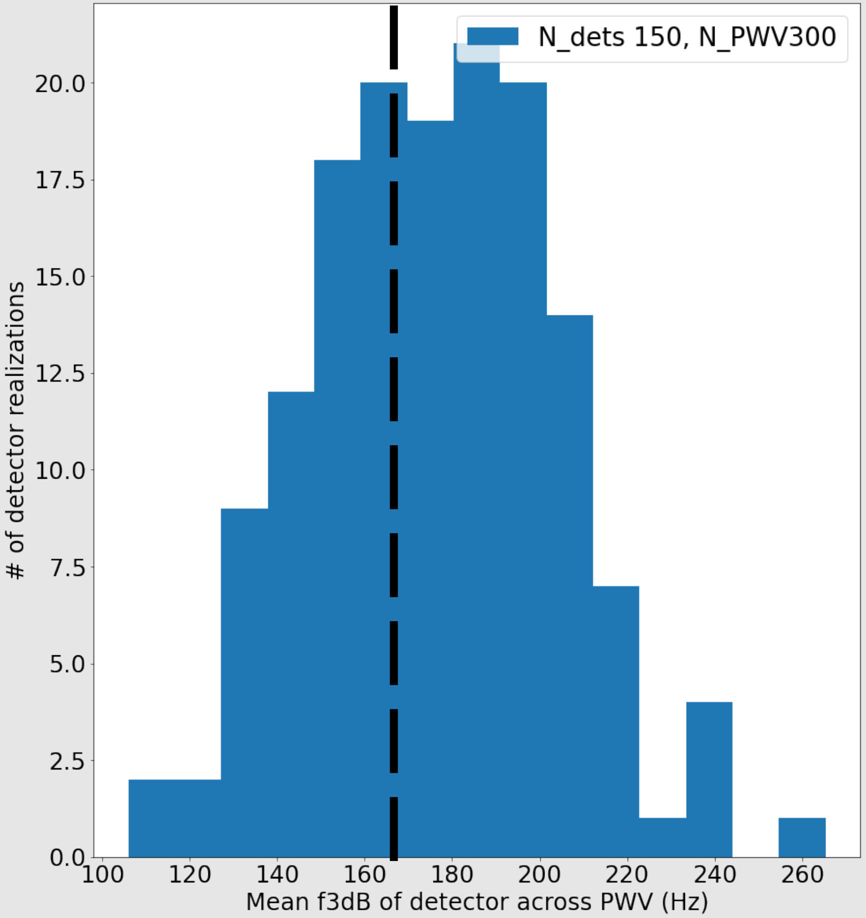
ν_b (GHz)	SAT f_{3dB} (Hz)	LAT f_{3dB} (Hz)
27	5.52	19.5
40	4.85	28.2
94	35.0	65.5
148	104.9	102.9
225	365.2	144.0
280	141.0	160.0

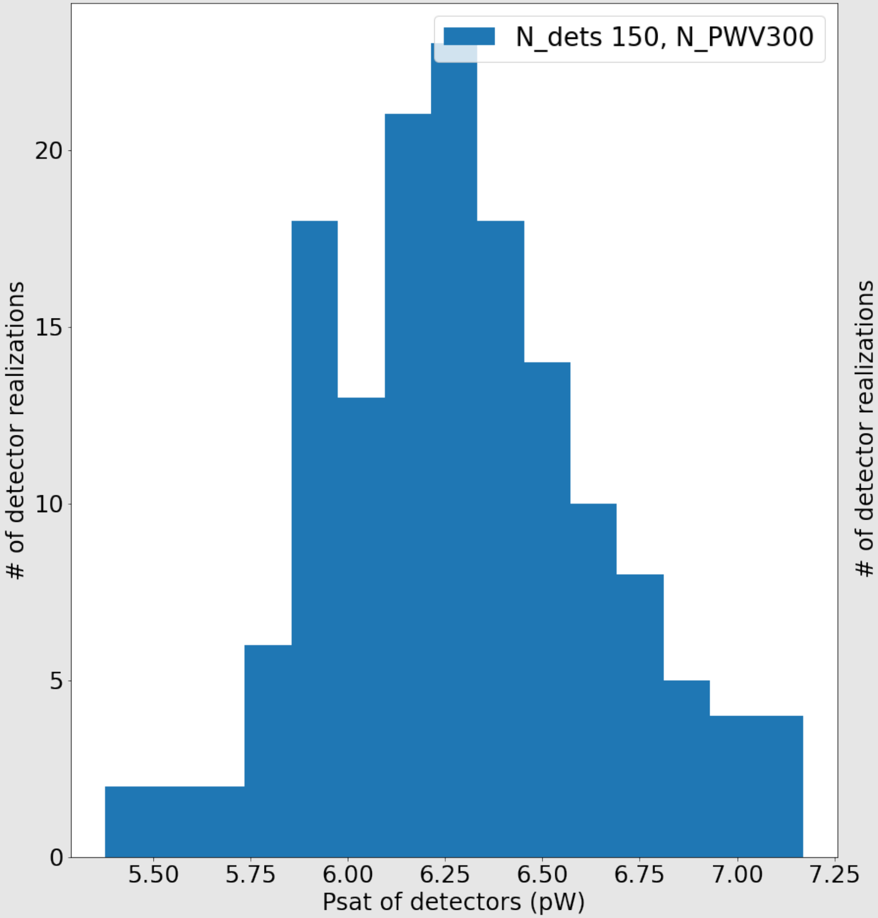
Typical shift values for SO detectors

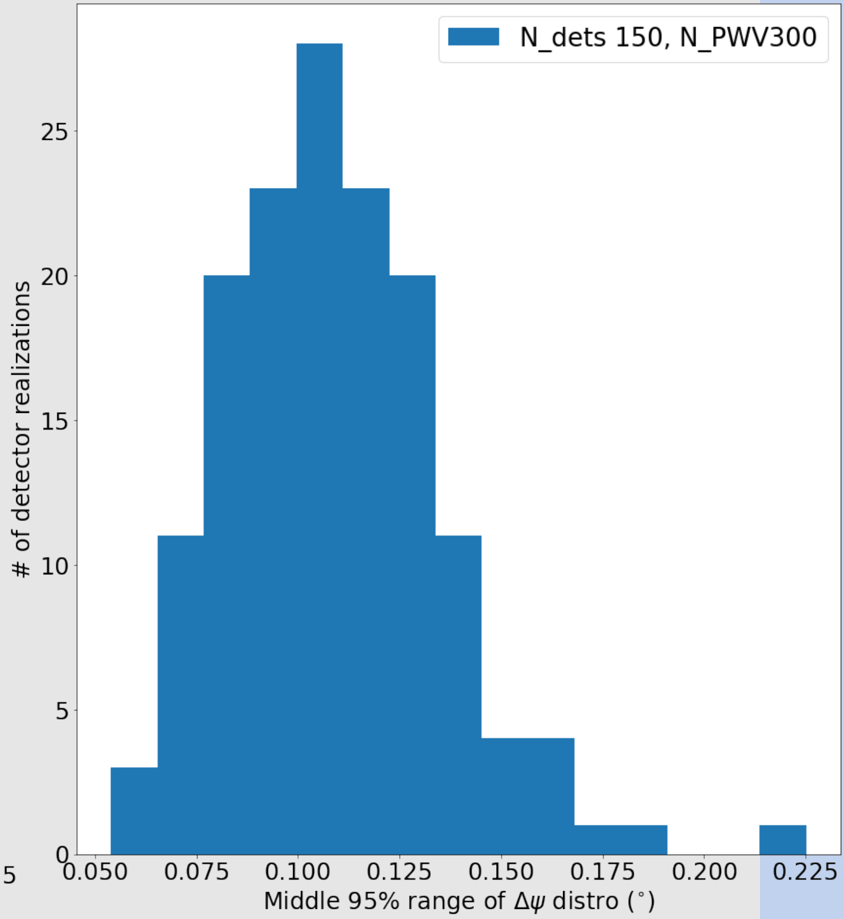


ν_b (GHz)	$\Delta\psi'$ fixed (°)	$\Delta\psi'$ average spread (°)	$\Delta\phi_0$ (°)
27	0.03 ± 0.002	0.008	1.75
40	0.01 ± 0.005	0.002	1.75
94	0.04 ± 0.008	0.01	0.2
148	0.09 ± 0.03	0.03	0.2
225	$0.2^{+0.25}_{-0.08}$	0.06	0.4
280	0.1 ± 0.04	0.03	0.4

148 GHz band: simulation statistics

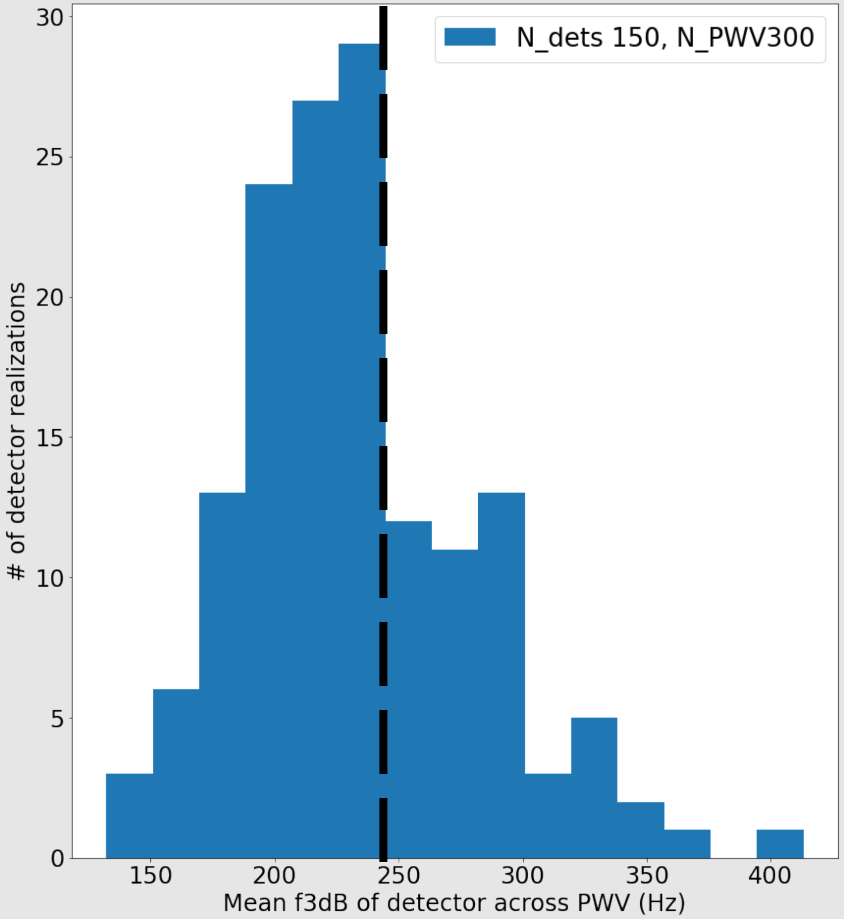


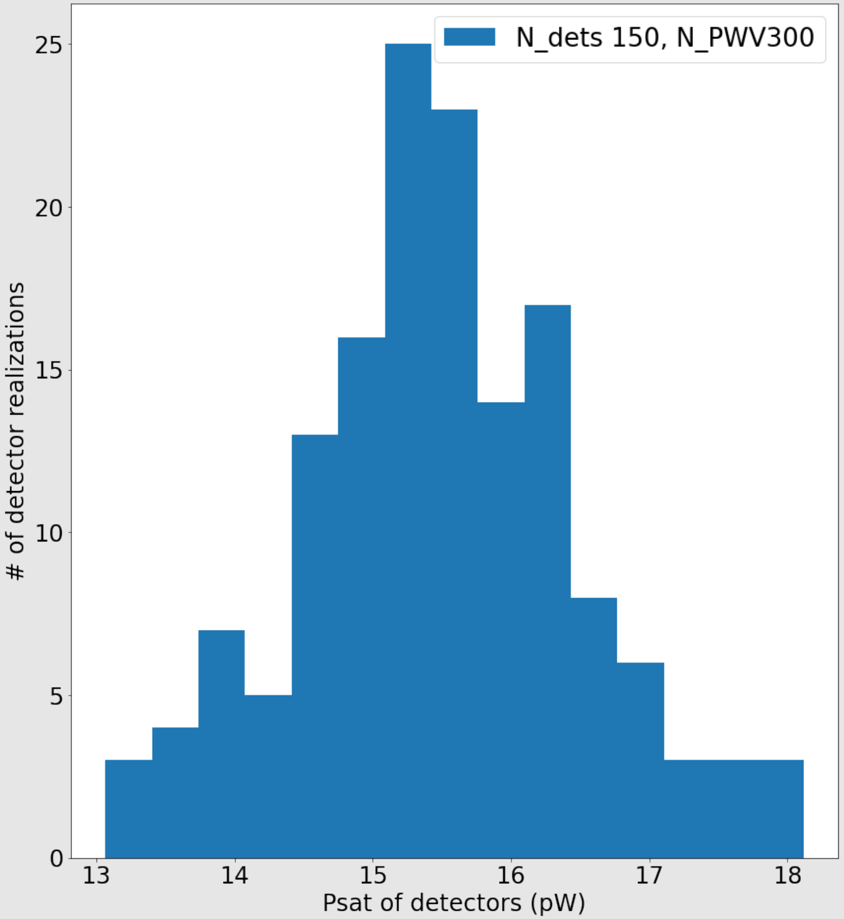


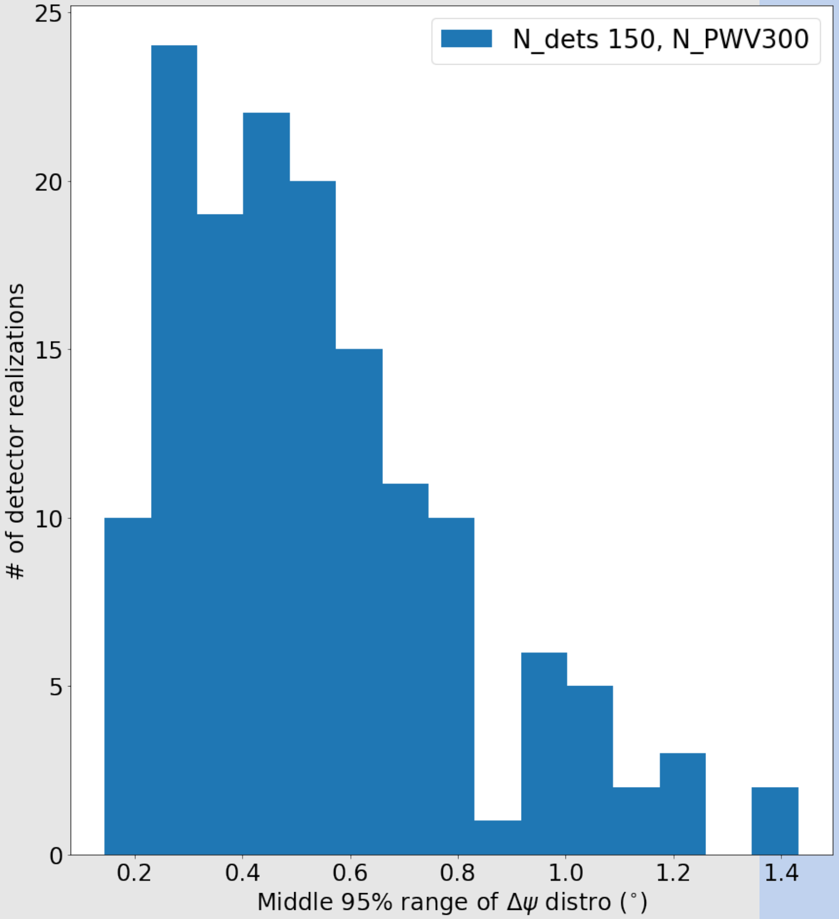


Min LAT f_{3dB}
166 Hz

225 GHz band: simulation statistics







Min LAT f_{3dB}
245 Hz