Full Instrument Model for the Multiwavelength Sub/millimeter Inductance Camera (MUSIC)

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Caltech, CU-Boulder, JPL, NIST, UC-Santa Barbara, Academia Sinica, UW-Milwaukee, NRL, Goddard

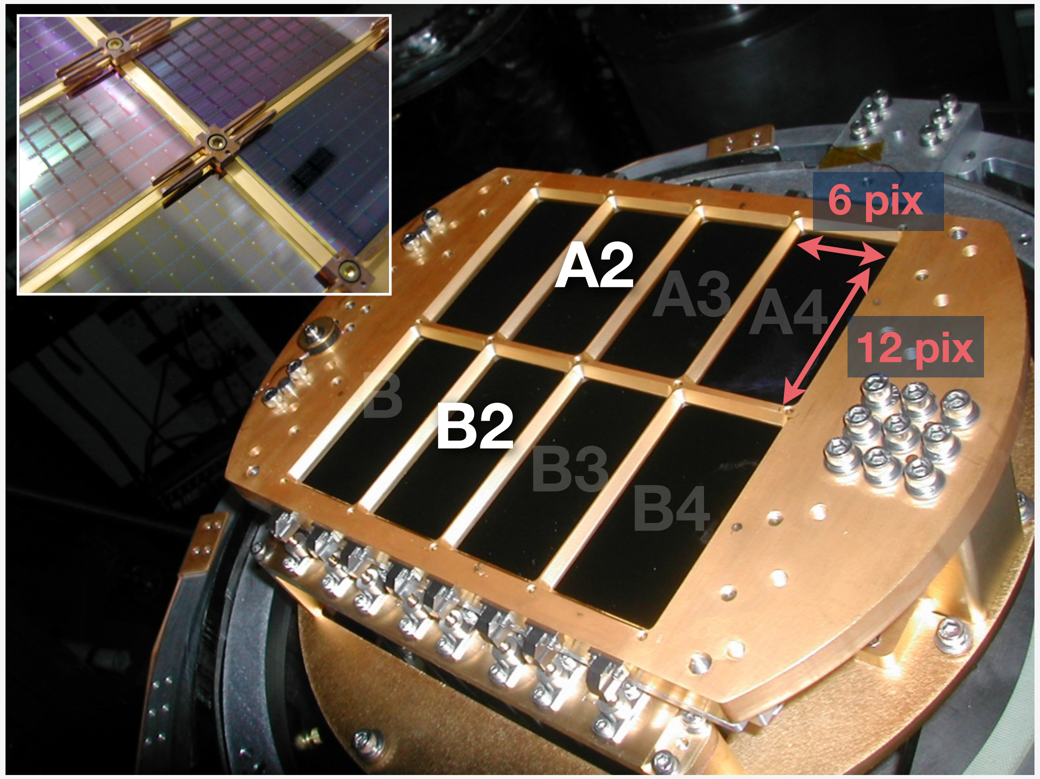
Outline

- Calibration procedure
- Detector parameters
- Compare predicted and measured response to an unresolved astronomical source
- Compare predicted and measured noise

MUSIC

- 576 spatial pixels, simultaneously sensitive to 4 spectral bands

Band	λ [mm]	ν [GHz]	Δν [GHz]	FWHM [“]
0	1.98	150	34	44
1	1.33	230	45	31
2	1.04	290	34	25
3	0.87	350	21	23



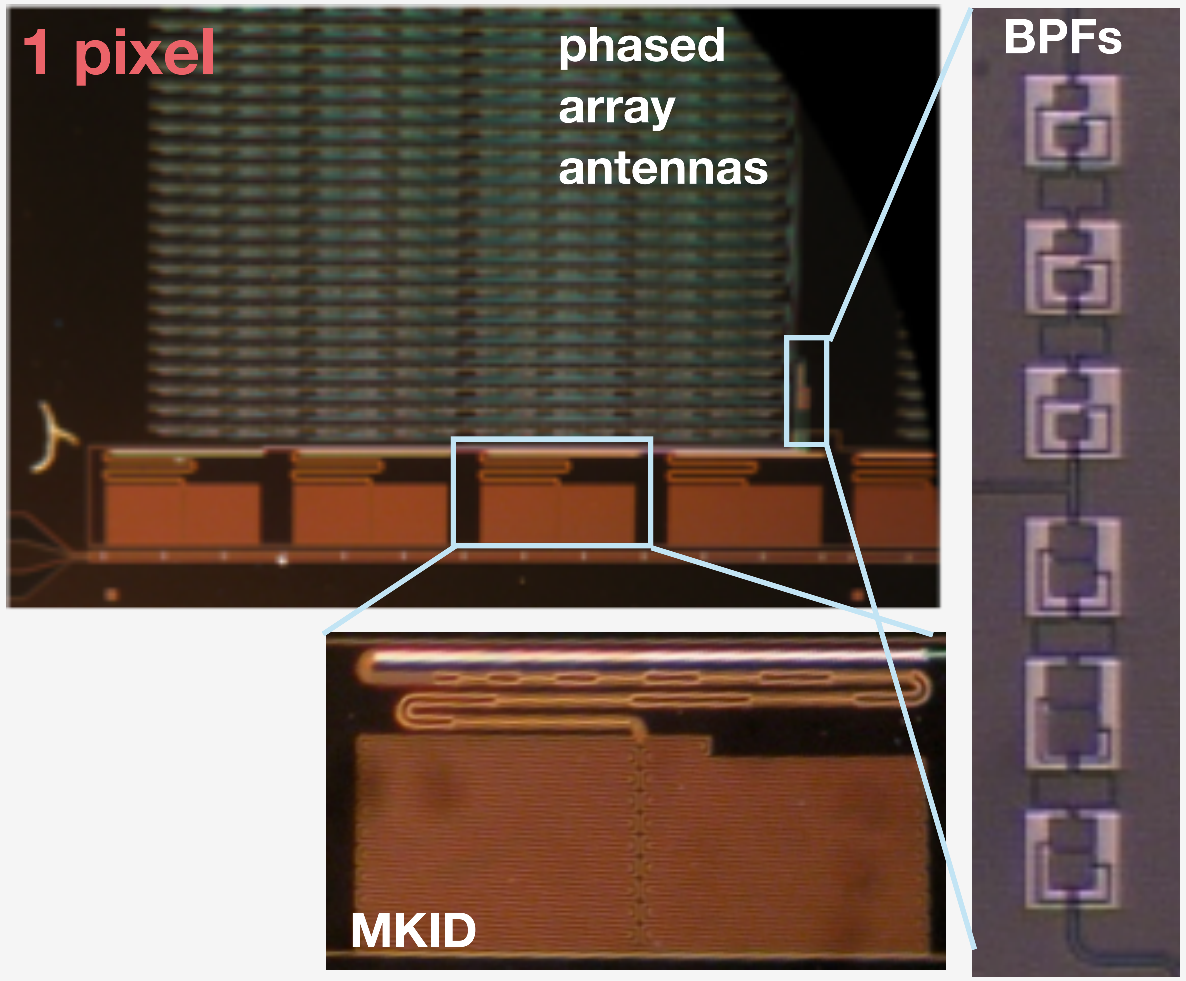
- 14 arc-minute FOV

- Beams formed using phased array of slot-dipole antennas

  Bandpasses defined by on-chip, lumped element filters

  Uses Microwave Kinetic Inductance Detectors (MKIDs)

  ➡ Al-Nb hybrid IDC-CPW operating at 3-4 GHz



- Timeline
  - Commissioned: April 2012
  - Engineering Runs: May 2012, June 2012, October 2012
  - Science Run: August/September 2013 (6 weeks)

Full Instrument Model

Developed model for propagation of signal through our system, from **flux of an astronomical source** to **volts at ADC**.

Constrained with three measurements:

1. Dark Temperature Sweeps

   Measurement of f_{res} and Q_i at multiple array temperatures (230 - 450 mK) with detectors dark.

Use network transmission theory and Mattis-Bardeen theory to relate **resonant frequency / dissipation** to **quasi-particle density.**

$$\delta \frac{1}{Q_i} = \alpha \; \kappa_1 (\omega, T, \Delta_0) \; n_{qp} \qquad \frac{\delta f_{\rm res}}{f_{\rm res}} = \frac{\alpha}{2} \kappa_2 (\omega, T, \Delta_0) \; n_{qp}$$

$$\Rightarrow \alpha, \Delta_0$$

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$$\Rightarrow \alpha, \Delta_0$$

2. Hot / Cold

   Measurement of f_{res} and Q_i at multiple array temperatures with hot (room temperature) and cold (LN2) beam-filling, black-body load at cryostat window.

Use generation-recombination equation to relate **quasi-particle density** to **optical power.**

$$P_{\text{opt}} \propto n_{qp}^2$$

Express as $P_{\text{opt}} = \eta_{\text{opt}} k_B \left(T_{\text{load}} + T_{\text{exc}}\right) \Delta\nu$

$$\Rightarrow \eta_{\text{opt}}, T_{\text{exc}}$$

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Express as $P_{\rm opt} = \eta_{\rm opt} k_B \left(T_{\rm load} + T_{\rm exc}\right) \Delta\nu$

$$\Rightarrow \eta_{\rm opt}, T_{\rm exc}$$

3. Sky Dips

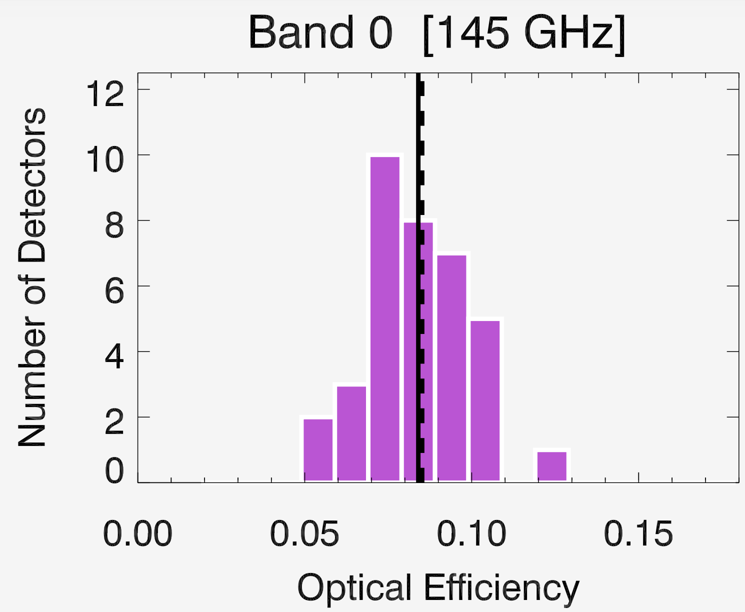
   Measurement of f_{res} and Q_i with telescope looking at blank sky at multiple zenith angles (20 - 70°).

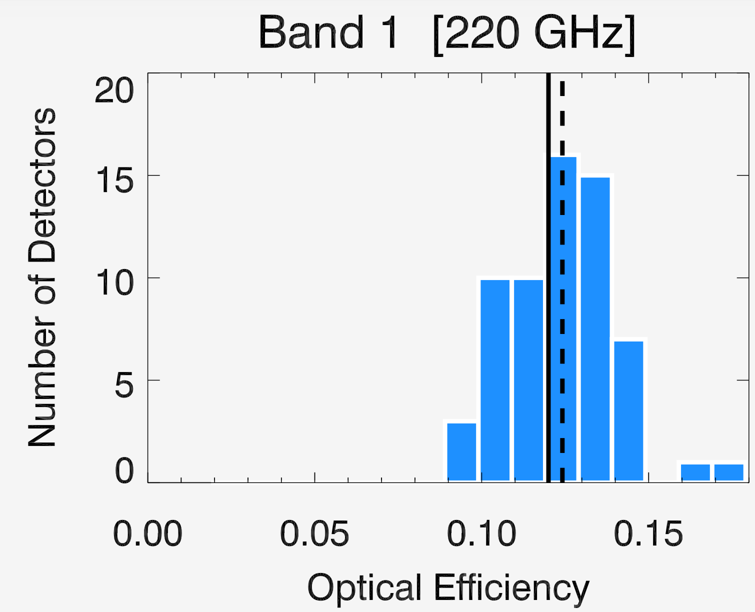
Relates **power at cryostat window** to **power on-sky.**

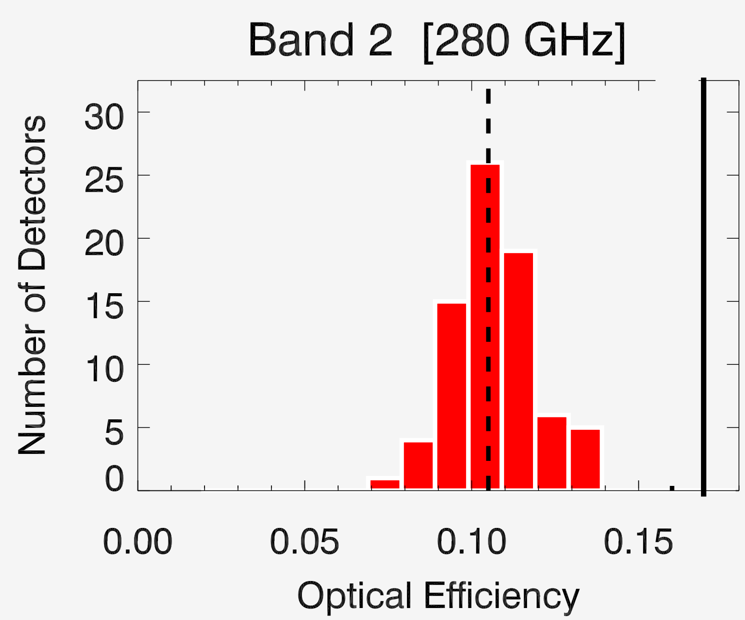
$$T_{\rm load} = f_{\rm spill} \, T_{\rm room} + \left(1 - f_{\rm spill}\right) \left(1 - e^{-\tau \sec {\rm za}}\right) T_{\rm atm}$$

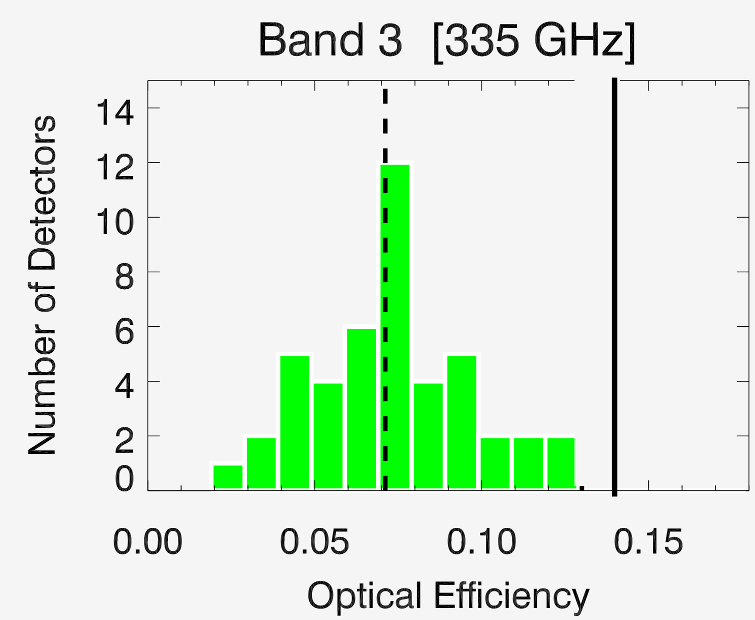
$$\Rightarrow f_{\rm spill}, \tau$$

Optical Efficiency



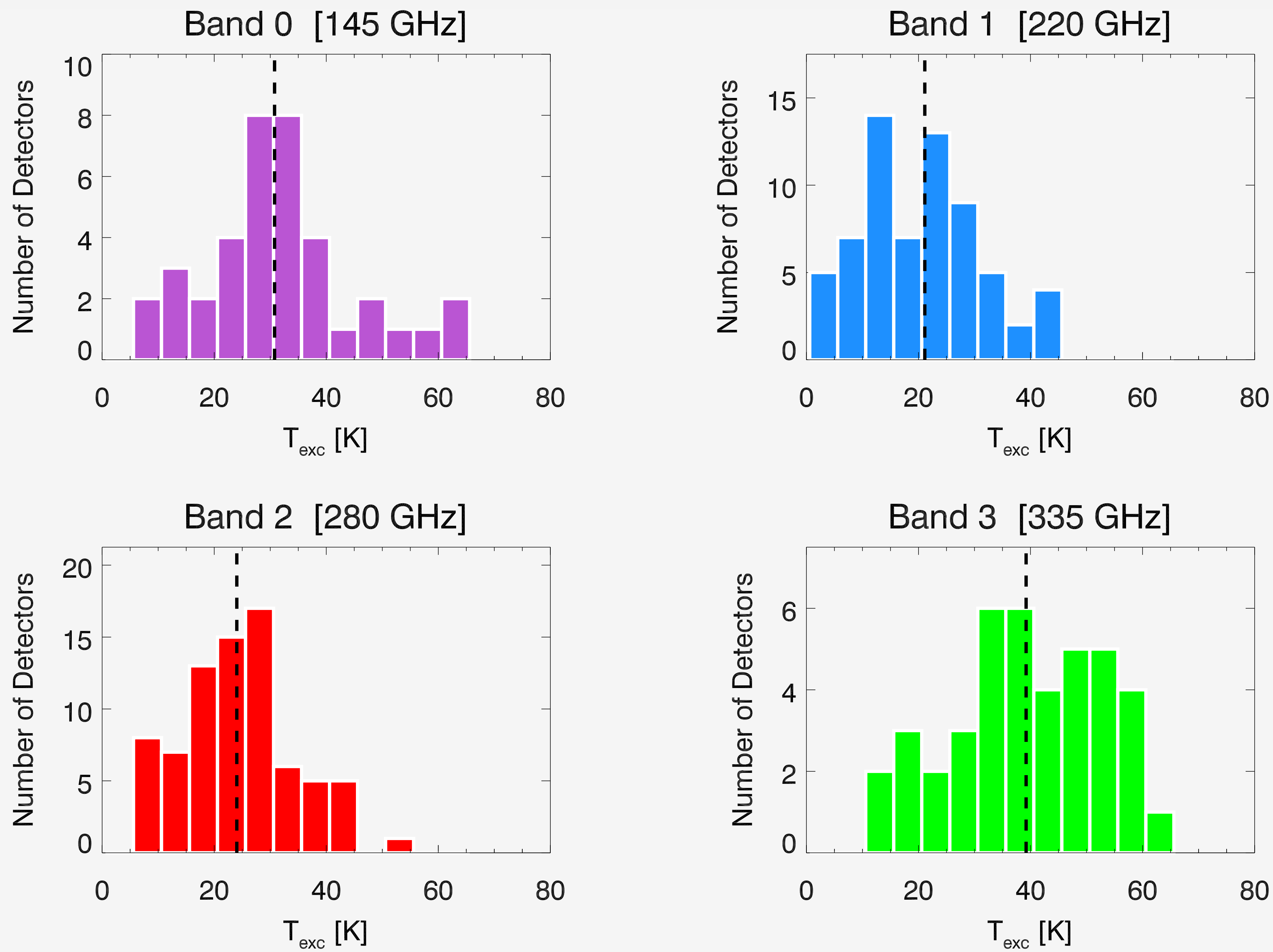






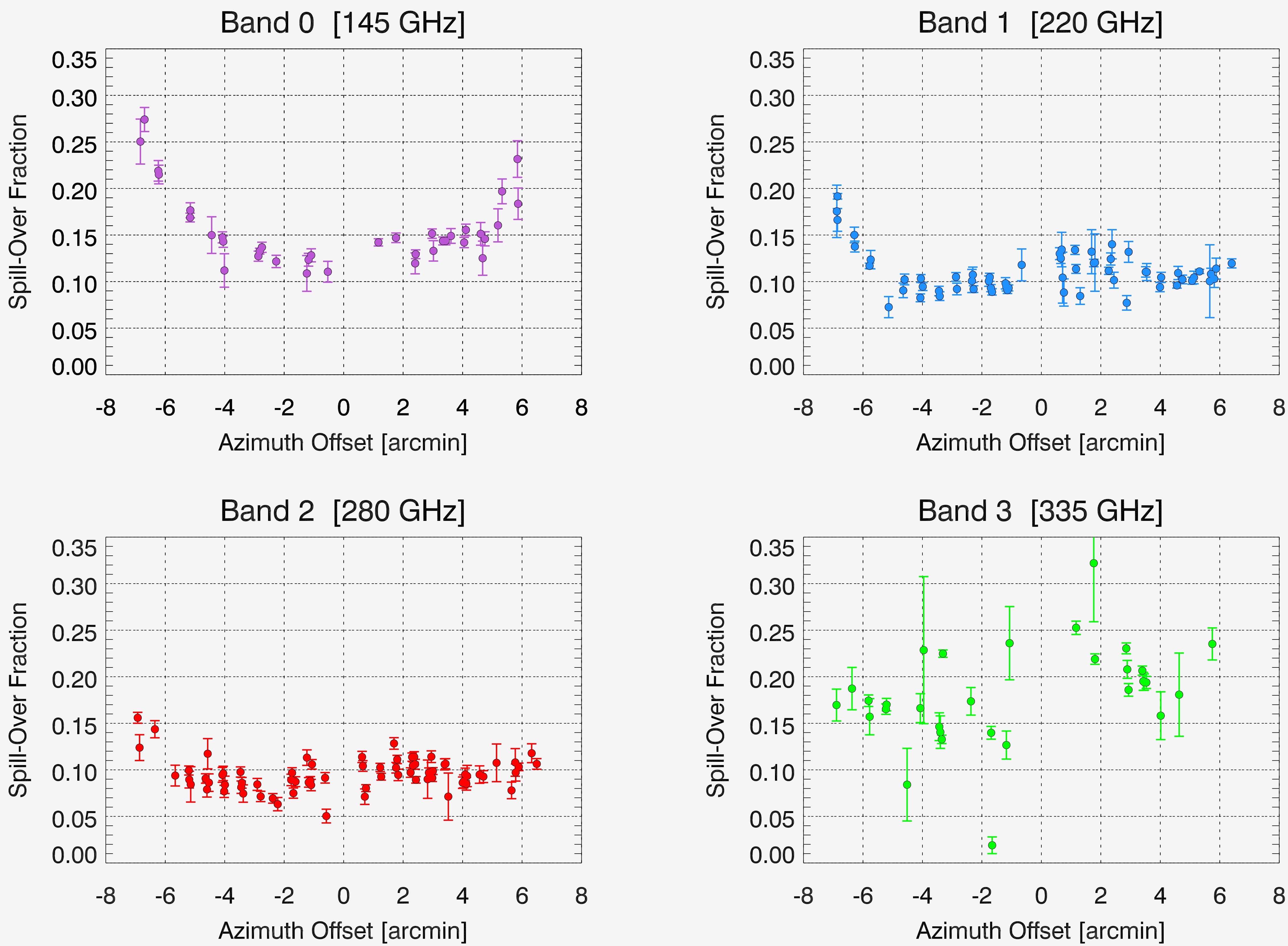
Band	Measured Efficiency	Expected Efficiency
0	0.09 ± 0.02	0.09
1	0.12 ± 0.02	0.13
2	0.11 ± 0.01	0.17
3	0.07 ± 0.02	0.14

Excess Loading

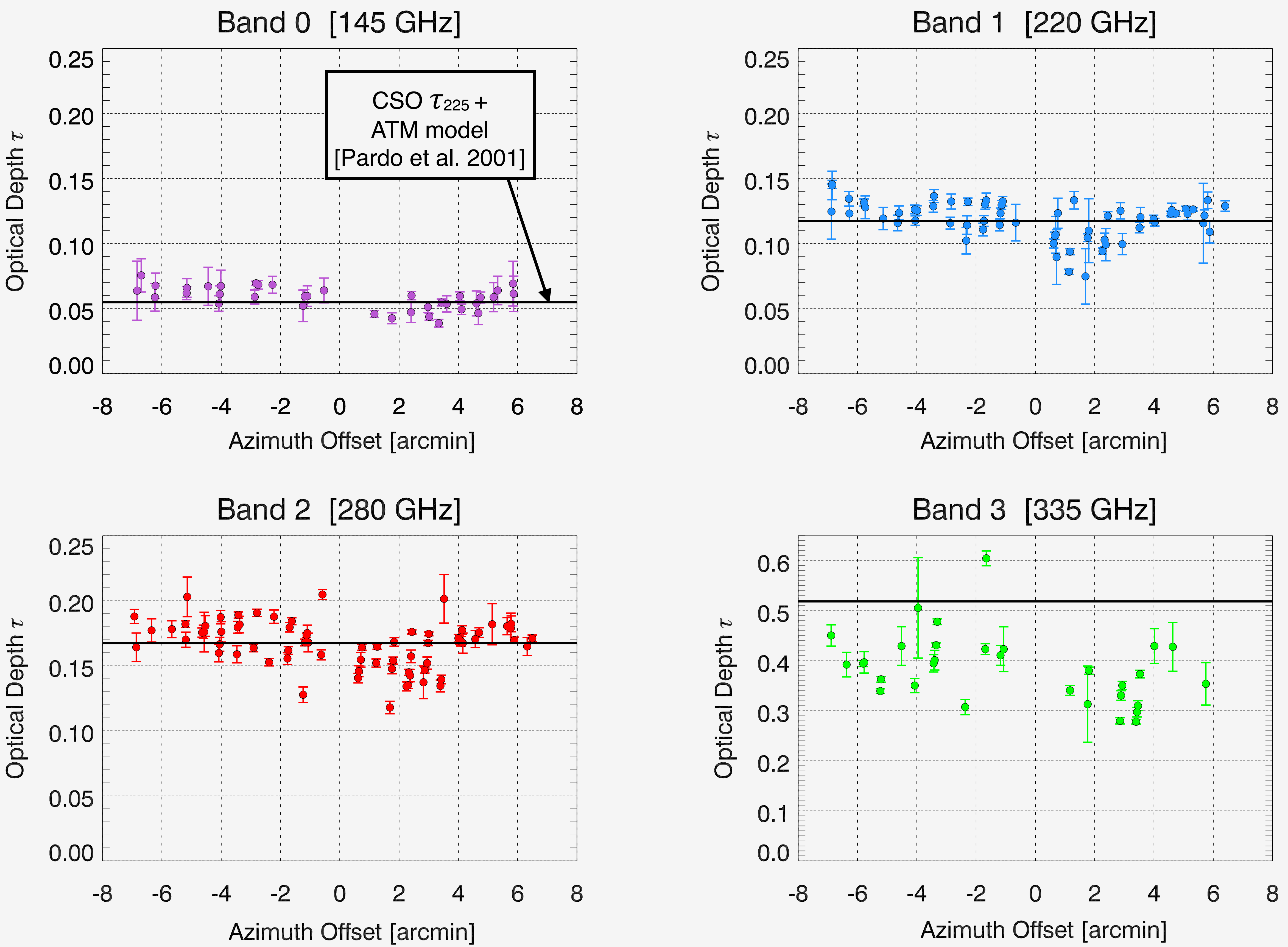


Band	T_{exc}	P_{exc}
0	30 ± 10	1.1 ± 0.5
1	20 ± 10	1.7 ± 1.0
2	25 ± 10	1.2 ± 0.5
3	40 ± 15	1.2 ± 0.7

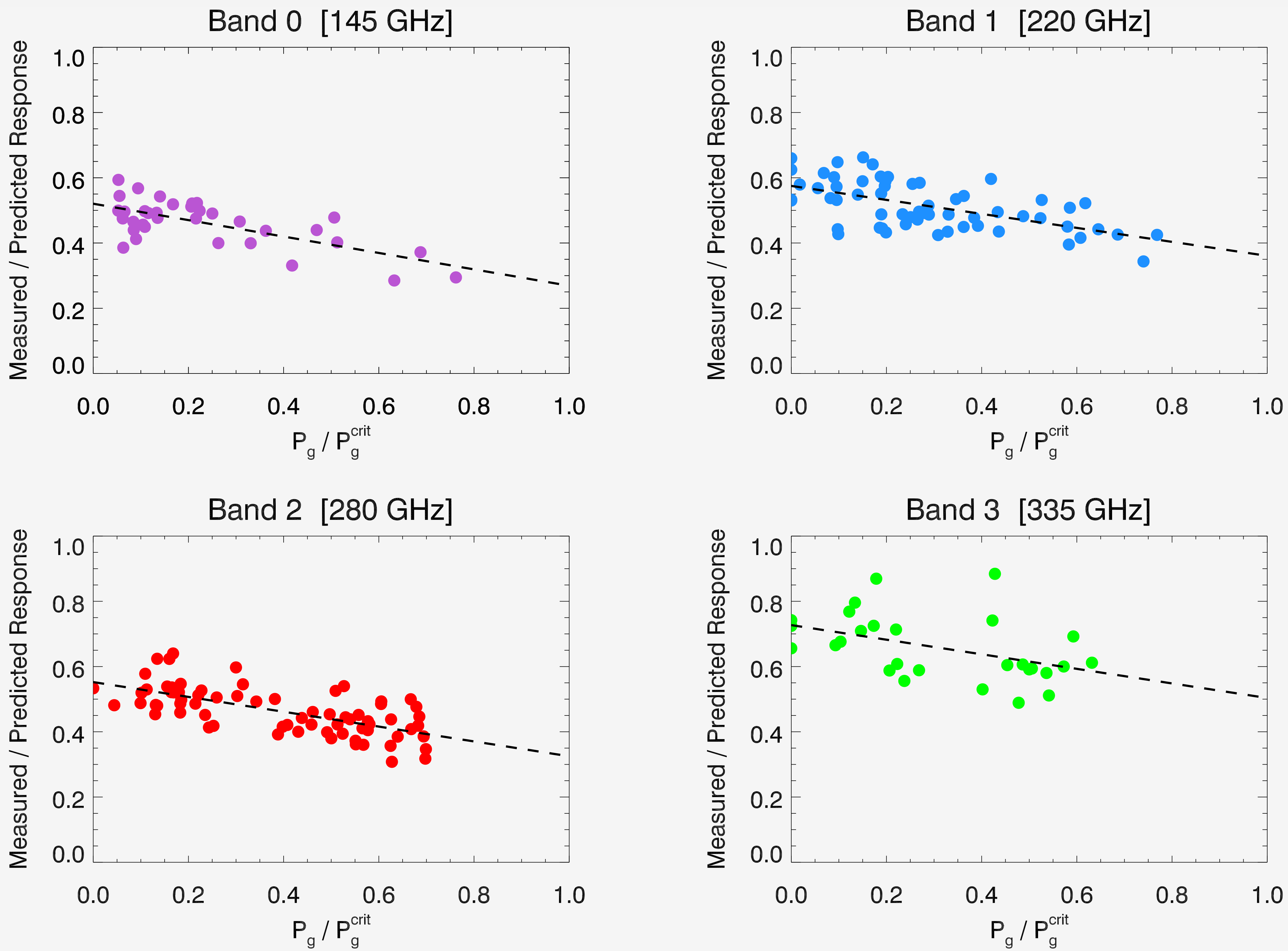
Spill-Over Fraction



Optical Depth



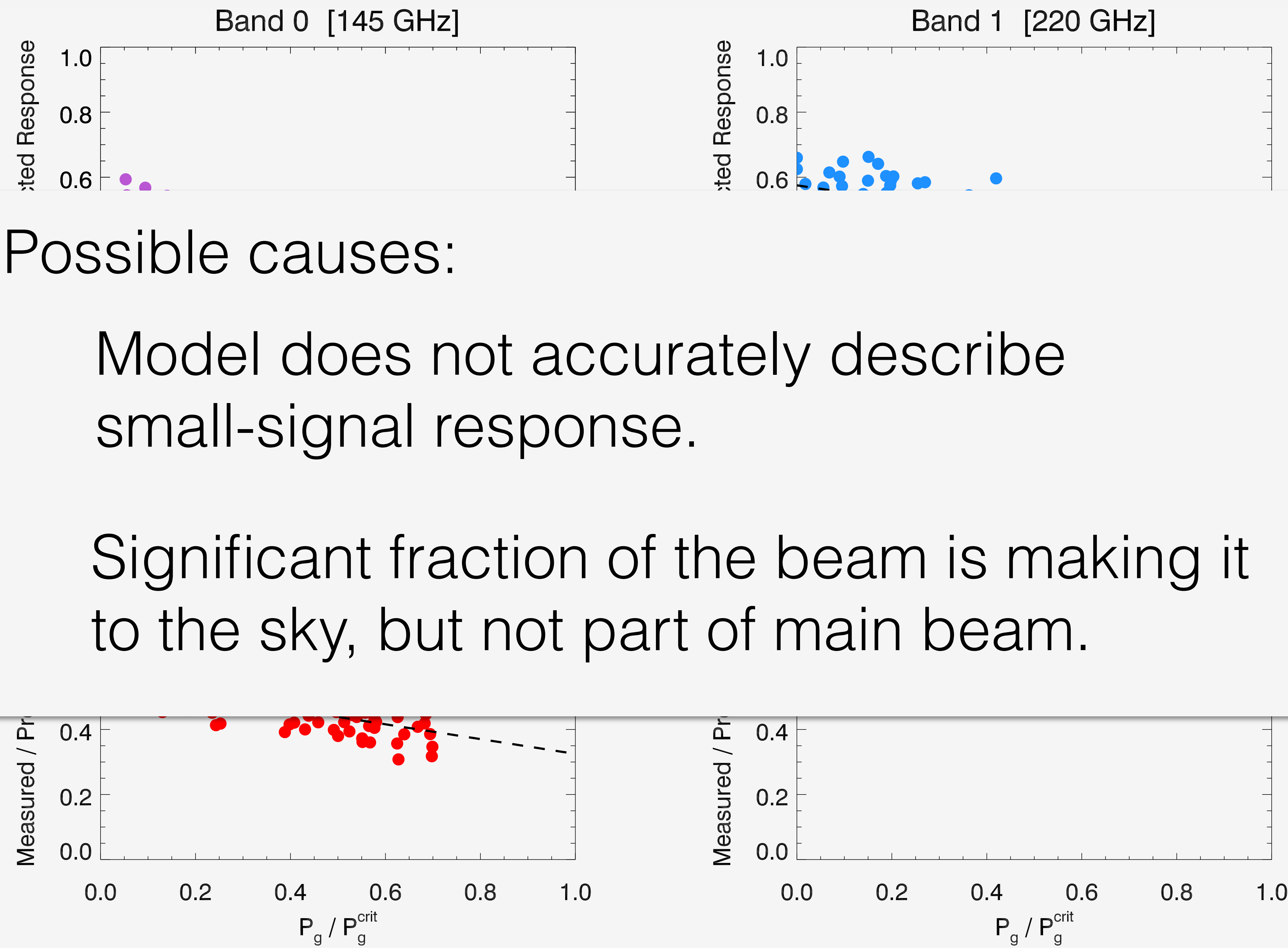
Responsivity: δf/f / Jy



Measured: (Peak height of Uranus source crossing) / (Flux of Uranus)

Predicted: Full instrument model

Responsivity: δf/f / Jy



Possible causes:

Model does not accurately describe small-signal response.

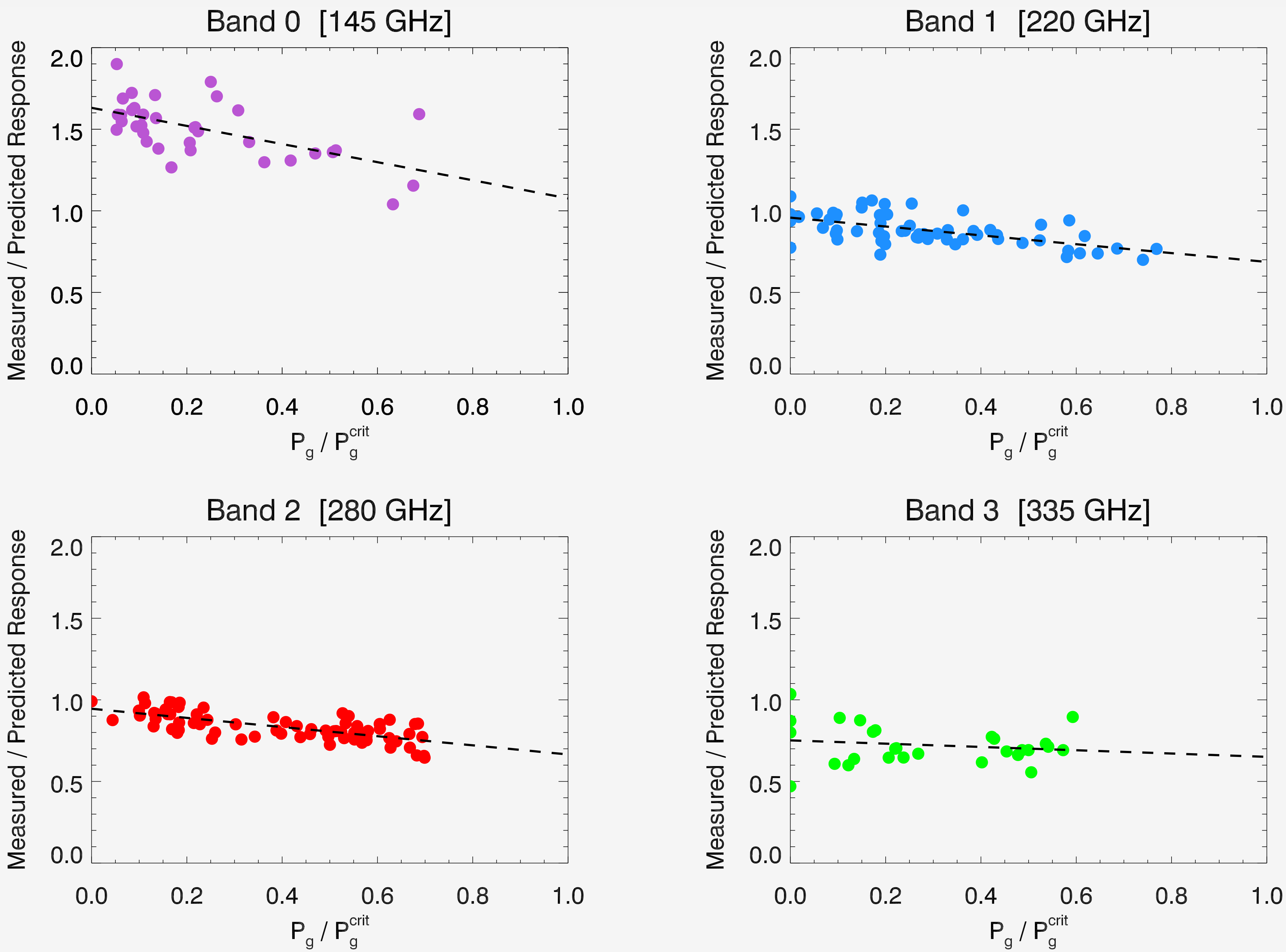
Significant fraction of the beam is making it to the sky, but not part of main beam.

Measured: (Peak height of Uranus source crossing) / (Flux of Uranus)

Predicted: Full instrument model

Responsivity: δf/f / Jy

Recent Results…

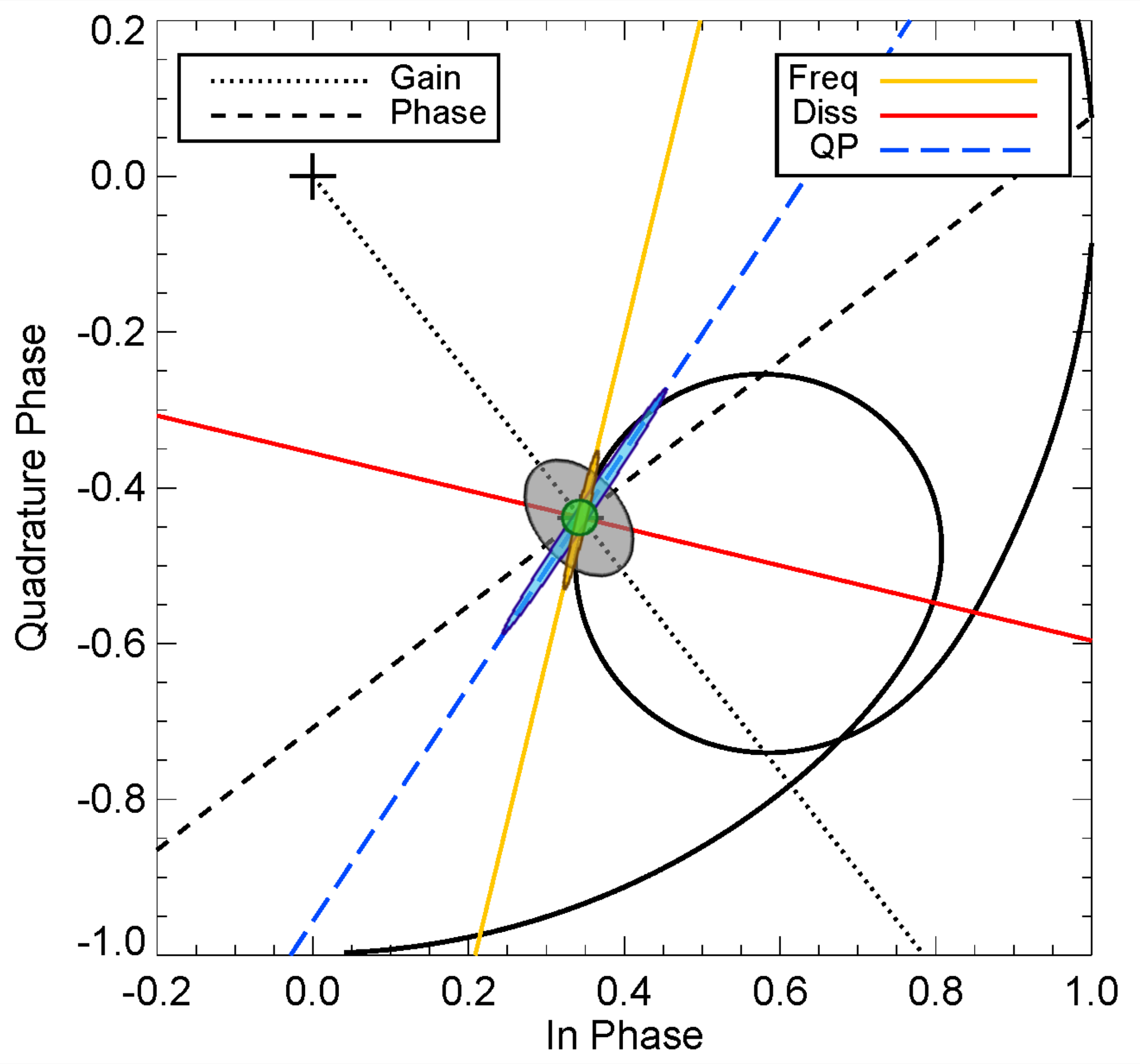


Measured: correlation coefficient between detector timestream and telescope elevation track ⟹ measures response to small changes in air-mass.

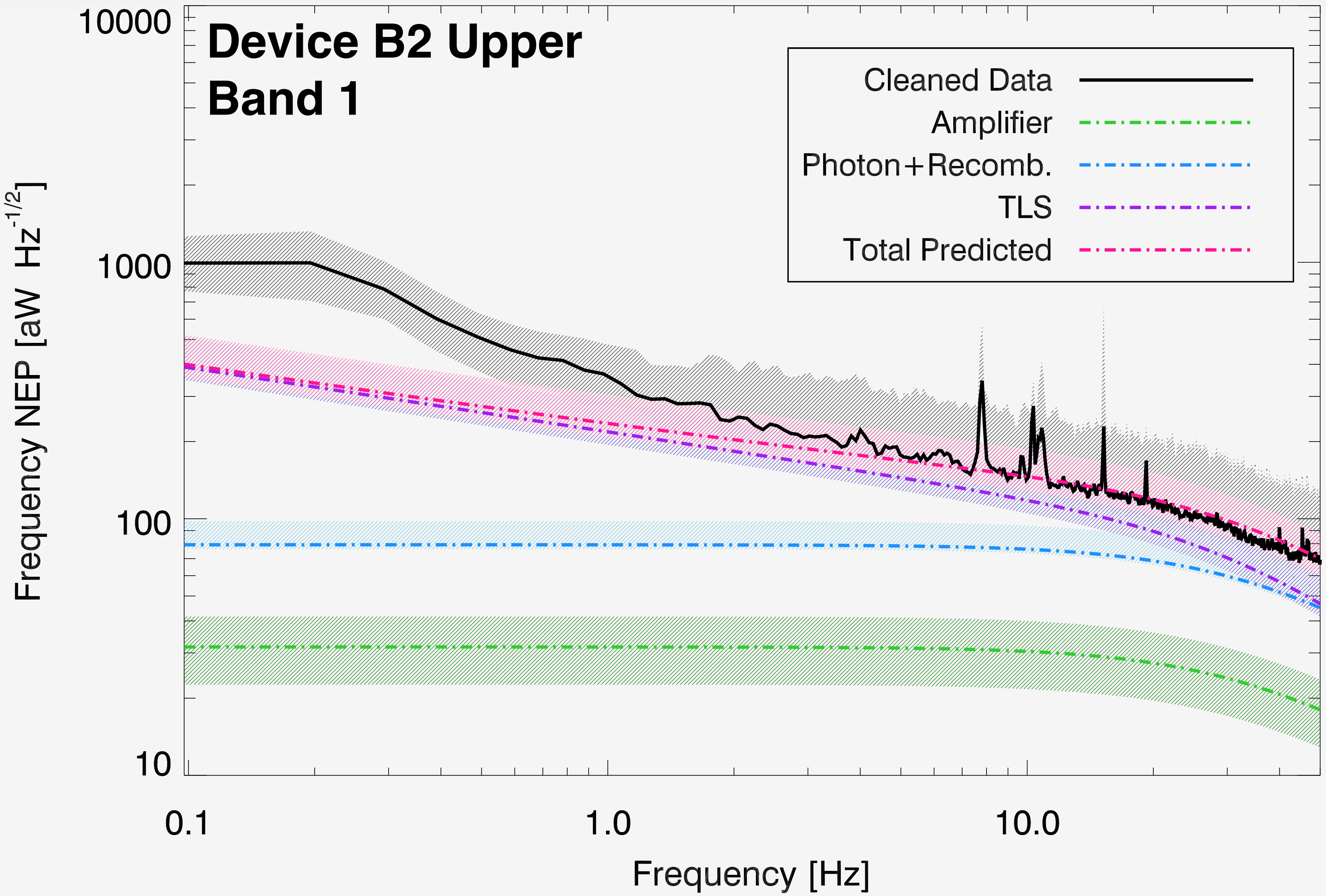
Noise Model

$$\hat{V}(t) = Ae^{i\phi}\left[1 + \delta A + i\delta\phi + \frac{2Q^2}{|S_{21}^{\rm res}|Q_c}\left(\frac{\delta f}{f}\right)_{TLS} e^{-i(\frac{\pi}{2}+\phi_{\rm res})} + \frac{Q^2\beta}{|S_{21}^{\rm res}|Q_c}\delta n_{qp} e^{i(\Psi-\phi_{\rm res})}\right] + \delta w_{\rm hemt}$$

Noise	Direction	PSD	On-Resonance	Off-Resonance	Correlated
HEMT white (Amplifier)	Isotropic	$k_B T_{\rm HEMT}$	✔	✔	
Multiplicative Electronics	Gain/ Phase	$1/f$ and drift	✔	✔	✔
TLS	Freq	$f^{-1/2}$	✔		
Fluctuations in Atmospheric Emission	QP	$f^{-8/3}$	✔		✔
Photon	QP	white	✔		
Generation - Recombination	QP	white	✔		



Noise Equivalent Power (NEP)



Power incident on the MKID from the antenna that gives S/N = 1 in a 1 Hz output bandwidth.

Amplifier	Determined from white noise floor of nearby off-resonance carriers.
Photon+ Recombination	Calculated from optical loading P_{opt} predicted by model and the band center and band width measured with FTS.
TLS	Calibrated from noise data collected at multiple readout powers with detectors dark.

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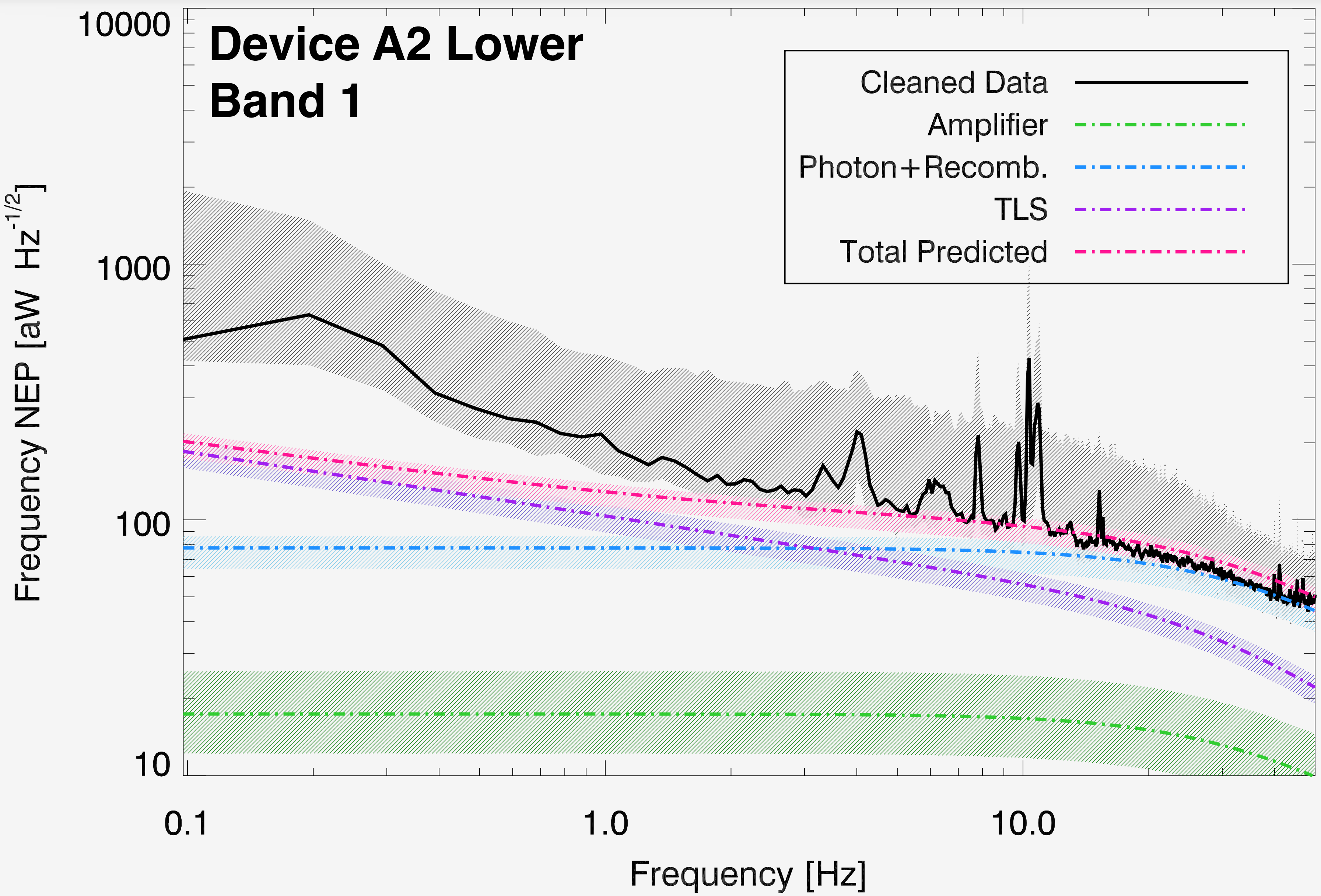

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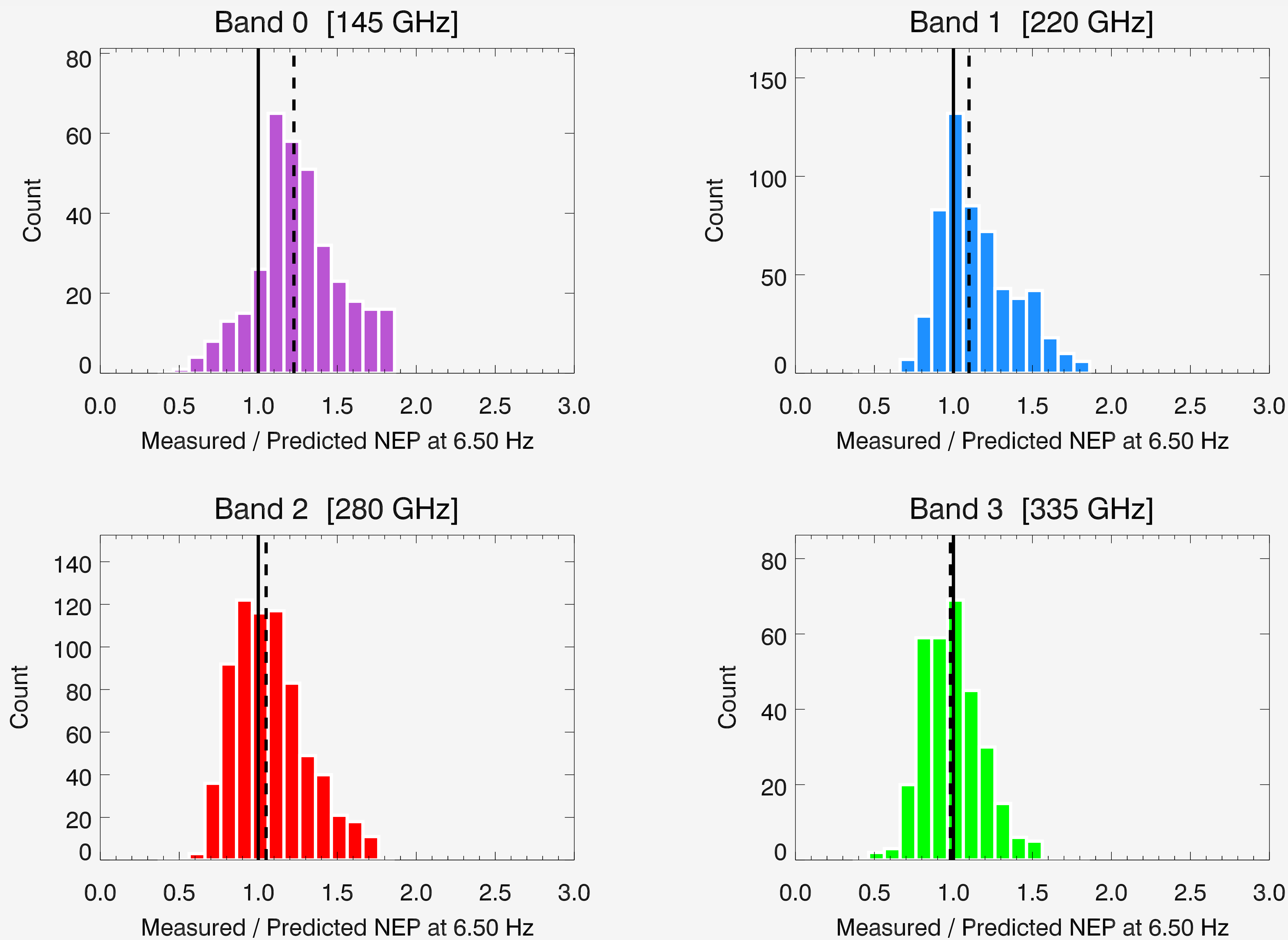
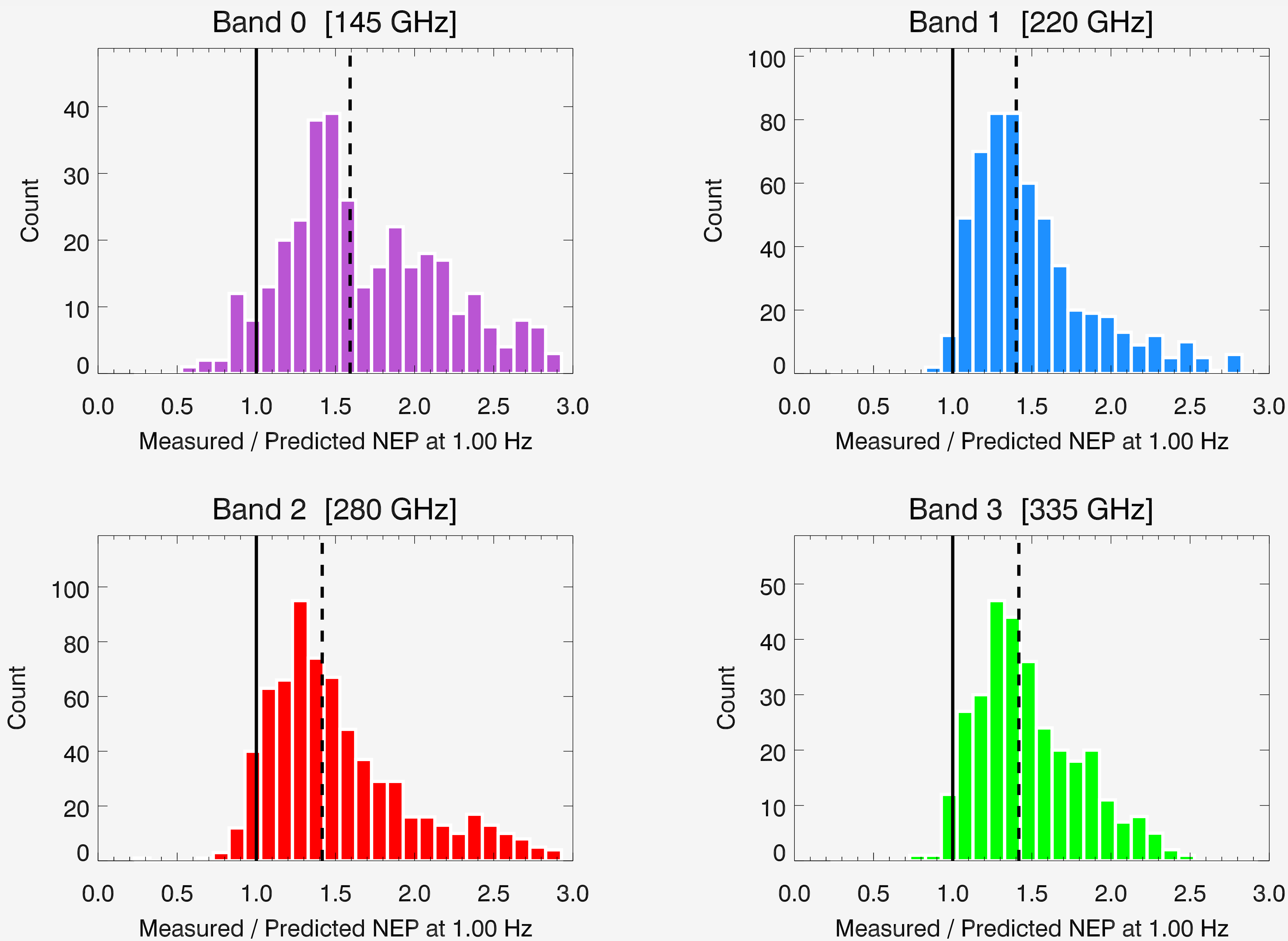
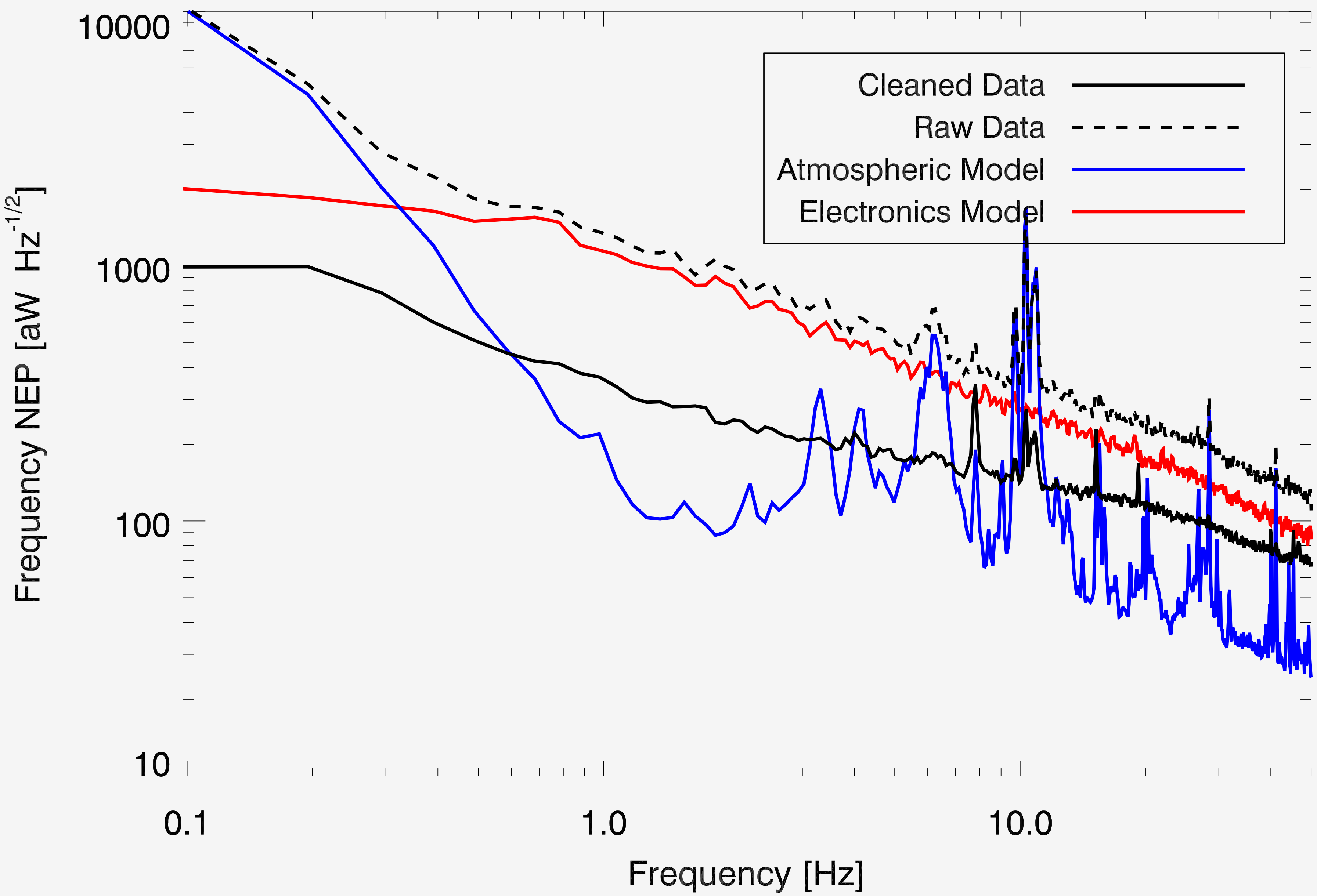
Predicted vs Measured (6.5 Hz)



Predicted vs Measured (1.0 Hz)



Noise Removal



Electronics Construct template for gain and phase fluctuations using nearby off-resonance carriers.

Atmospheric Construct common mode template for the fluctuations in atmospheric emission (separately for each band). Iteratively re-calculate the coefficients that scale template to the individual detectors using temporal frequencies 10-100 mHz.

Noise Summary

Median from a sample of 11 observations representative of the observing conditions during our August/September 2013 run (Median PWV 1.3 mm)

Detector Loading

Band	T_{exc}	T_{spill}	T_{sky}	T_{load} [K]	P_{opt} [pW]
0	30	45	10	**85**	**3.3**
1	20	30	20	**70**	**5.5**
2	25	30	25	**80**	**3.9**
3	40	55	70	**165**	**4.9**

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NEP at 6.50 Hz [aW $\text{Hz}^{-1/2}$]

	Predicted						Measured	
Band	Amplifier	GR	Shot	Bose	TLS	Total	Total	Ratio
0	20	26	26	34	85	**100**	**130**	1.3
1	22	36	42	56	90	**125**	**150**	1.1
2	13	30	40	52	75	**110**	**115**	1.1
3	17	32	46	70	85	**130**	**125**	1.0

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Measured at 1.00 Hz

Band	NEP [aW $Hz^{-1/2}$]	NET [mK $s^{1/2}$]	NEFD [mJy $s^{1/2}$]
0	250	14	500
1	270	6	230
2	225	10	400
3	245	24	1220

Summary

- We have a model that describes both the response and noise in the MUSIC MKIDs.

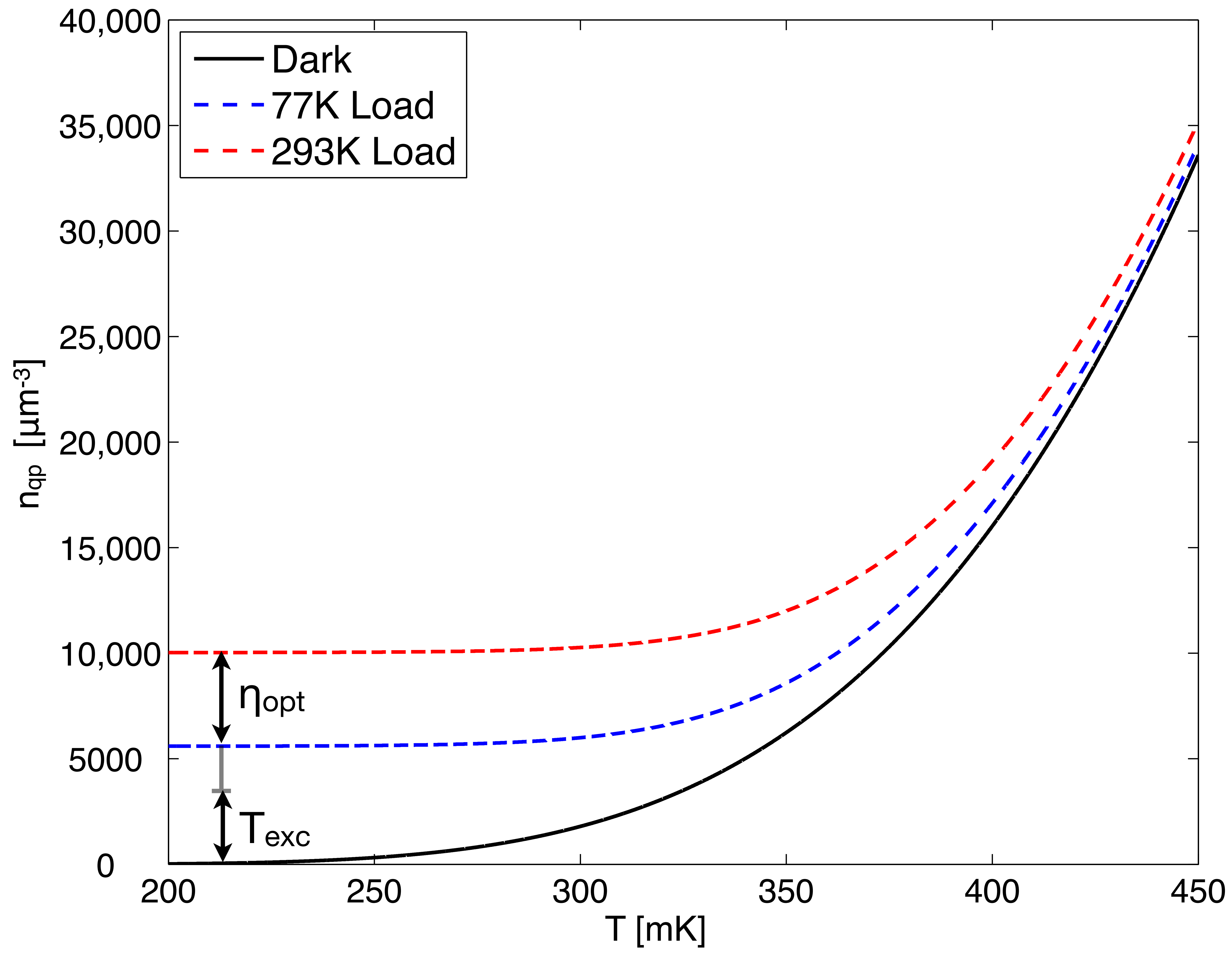
- There are two unexplained sources of loss in our system:
  - Measured optical efficiency drops off relative to expected in the two highest frequency observing bands.
  - Measured response to unresolved astronomical source (e.g. planets) 40% lower than beam filling calibrators (e.g. atmosphere), independent of band.
    - Suspect optics rather than unaccounted MKID physics.

- Understand noise at high frequencies (> a few Hz): sum of TLS, photon+GR, and amplifier white noise.

- Excess noise at low frequencies due in part to residual atmospheric and (possibly) electronics noise. Could improve with better subtraction algorithms.

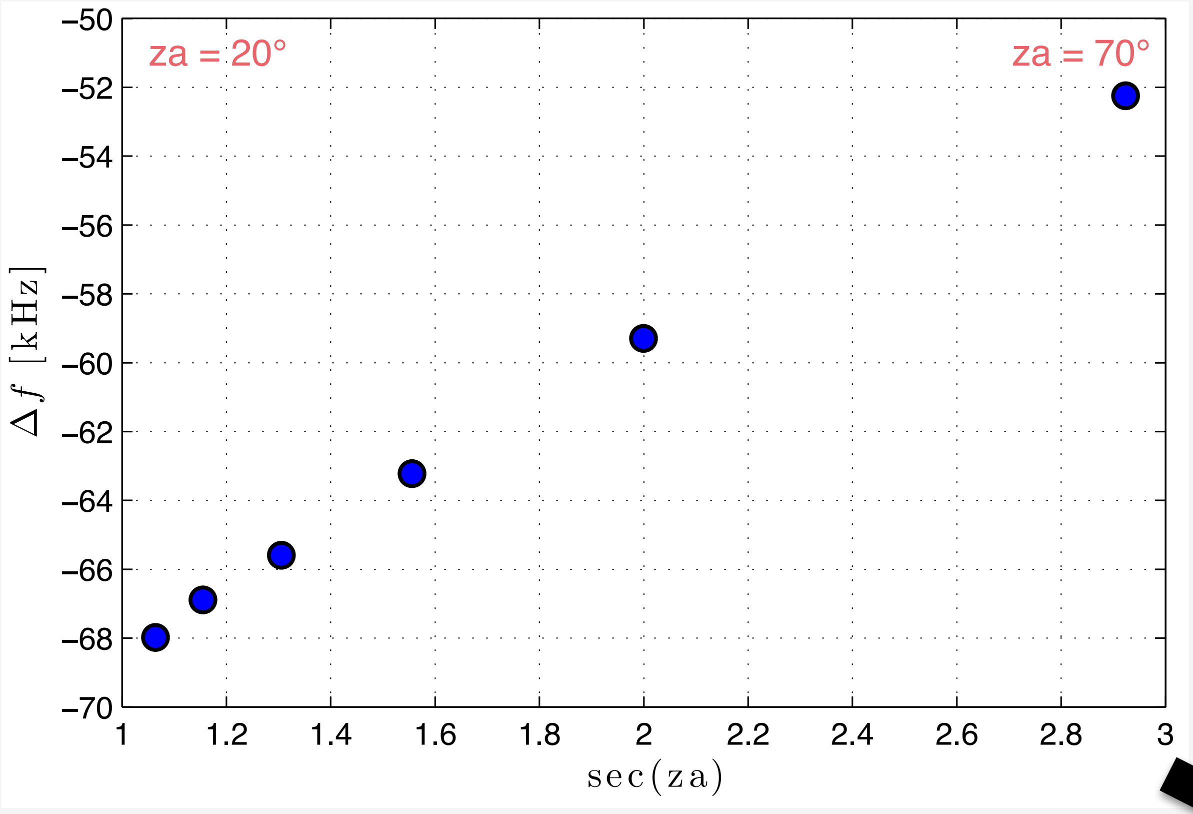
Additional Slides

Hot / Cold



Dark
77K Load
293K Load
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5000
0
n_{qp} [μm-3]
η_{opt}
T_{exc}
200
250
300
350
400
450
T [mK]

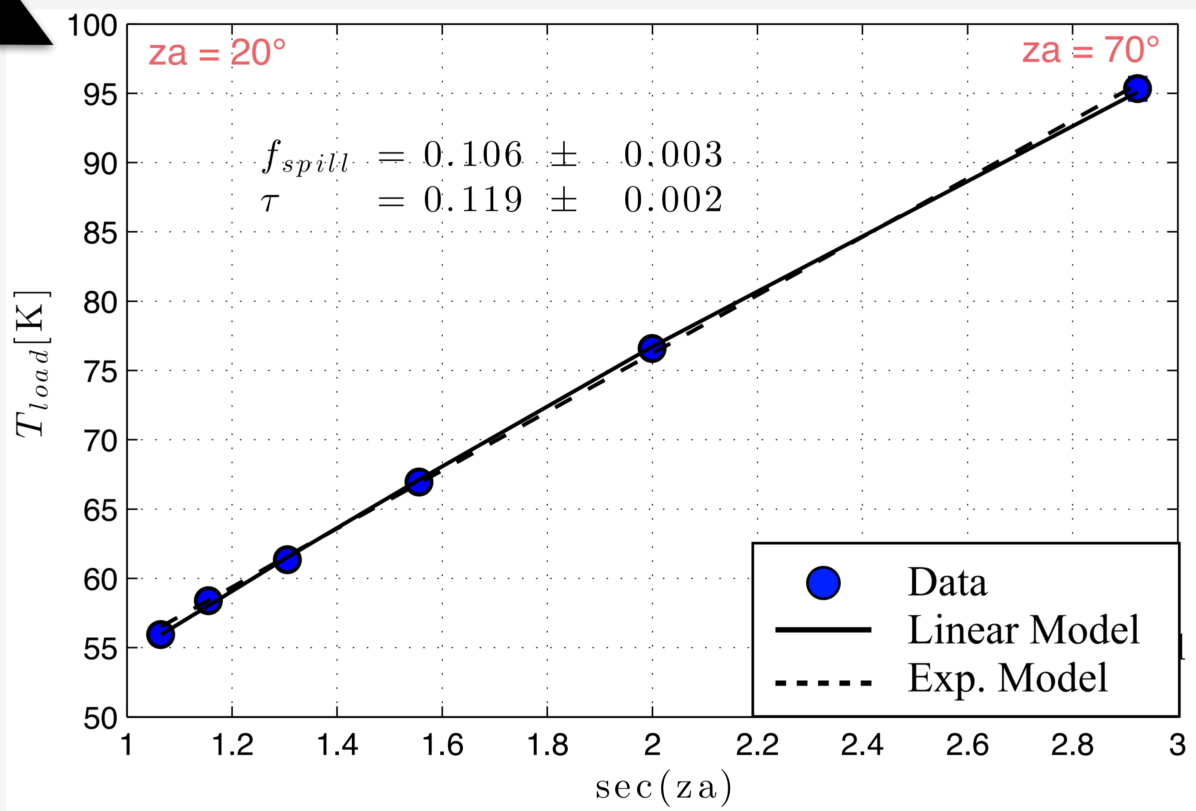
Sky Dips



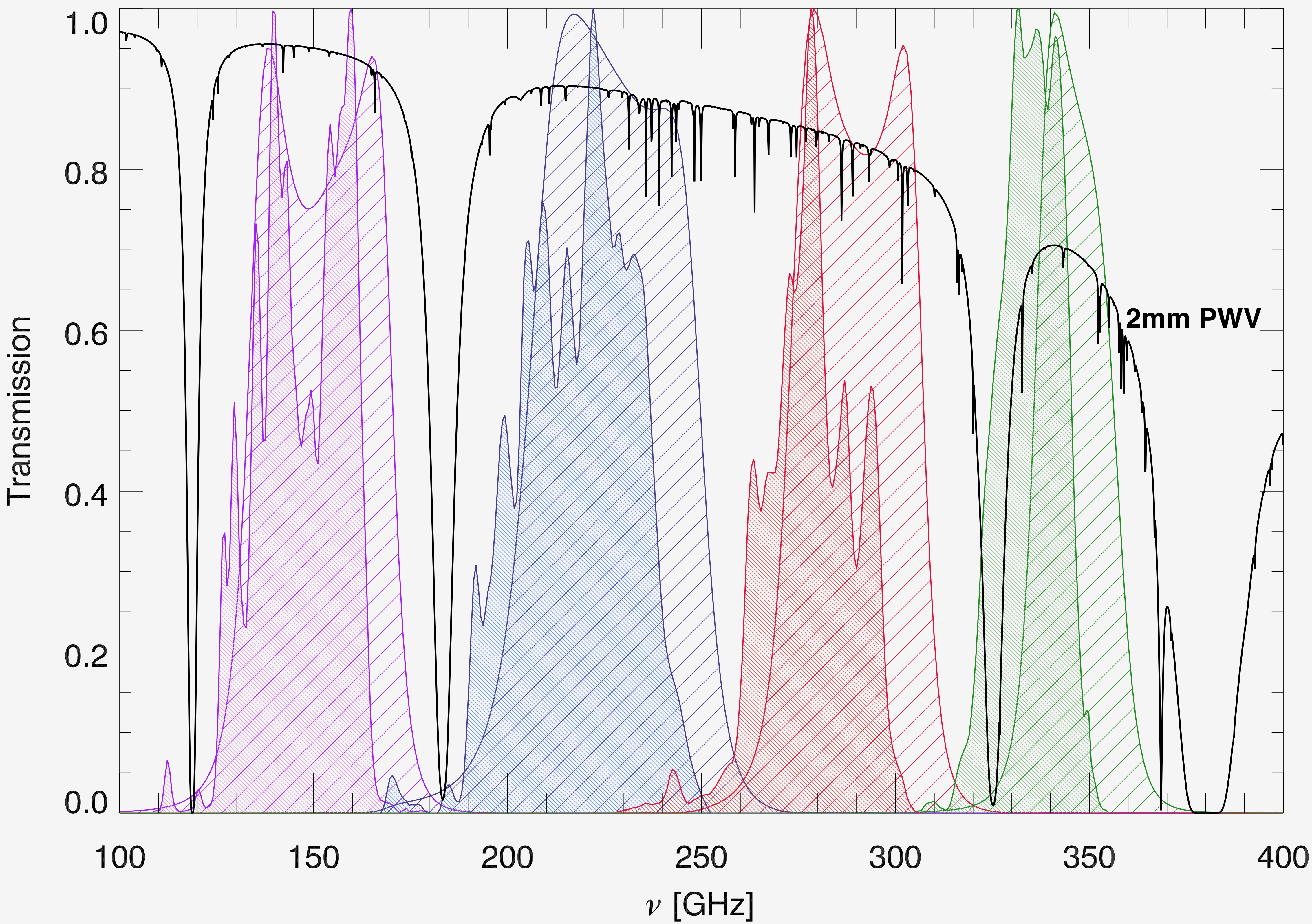
$$
\begin{aligned}
T_{\text{load}} &= f_{\text{spill}}\, T_{\text{room}} + (1 - f_{\text{spill}})\left(1 - e^{-\tau \sec \text{za}}\right) T_{\text{atm}} \\
&\approx f_{\text{spill}}\, T_{\text{room}} + (1 - f_{\text{spill}})\, T_{\text{atm}} \tau \sec \text{za}
\end{aligned}
$$

where $T_{\text{atm}} = 250\ \text{mK}$

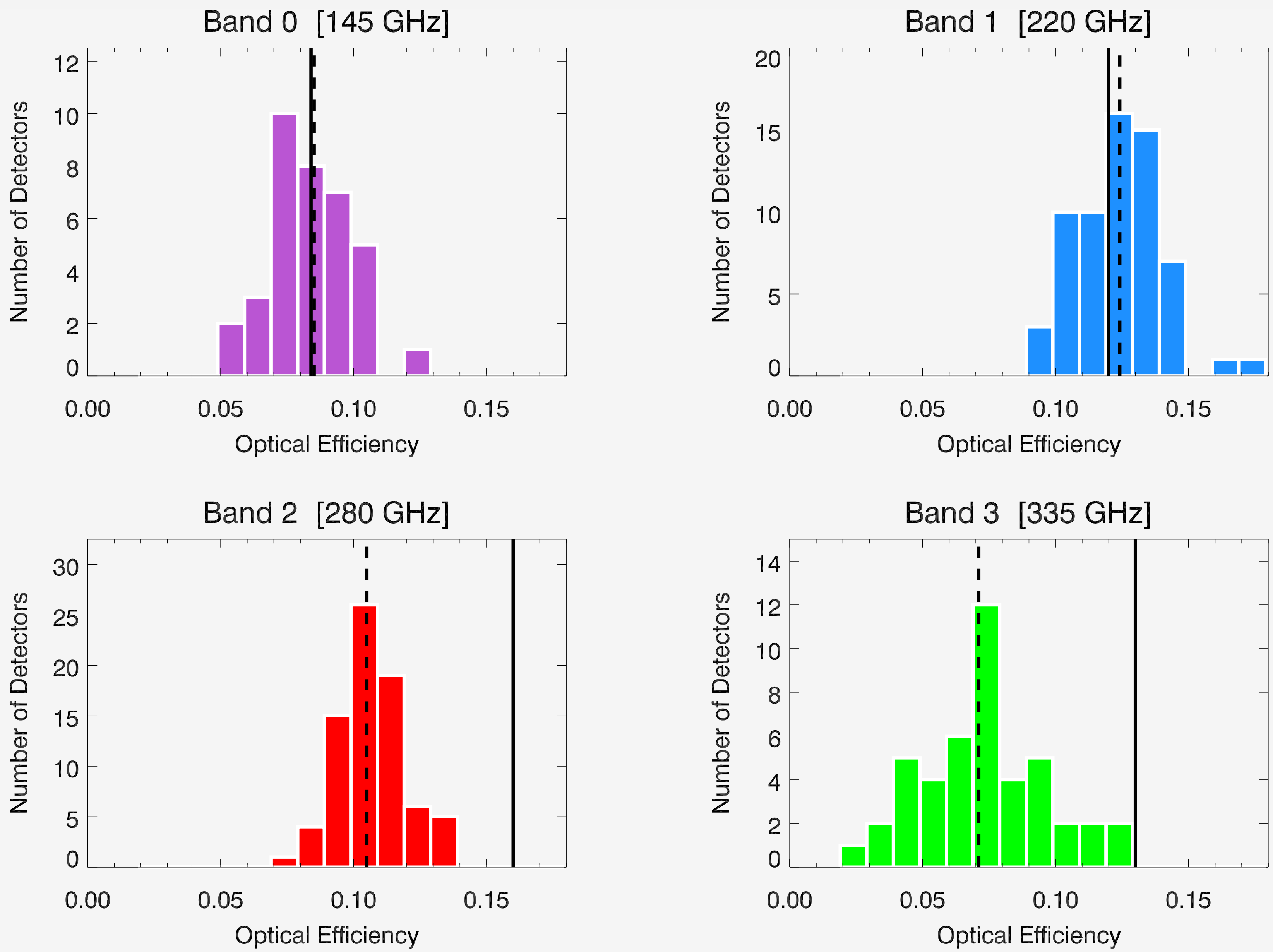
Hot / Cold Parameters



FTS Spectra


1.0
0.8
0.6
0.4
0.2
0.0
Transmission
100
150
200
250
300
350
400
ν [GHz]
2mm PWV

Expected Efficiency



Band	λ [mm]	Expected Efficiency							Measured Efficiency
		Phonon	Microstrip	Antenna	Lyot Stop	Filters	Mirrors	Total	
0	1.98	0.66	0.88	0.74	0.28	0.74	0.94	0.084	0.09 ± 0.02
1	1.33	0.58	0.83	0.7	0.51	0.76	0.94	0.12	0.12 ± 0.02
2	1.04	0.58	0.79	0.78	0.68	0.69	0.93	0.16	0.11 ± 0.01
3	0.87	0.58	0.75	0.71	0.76	0.61	0.91	0.13	0.07 ± 0.02

TLS Noise

Noroozian et al. (2009) measured amplitude of TLS noise for a nearly identical interdigitated capacitor geometry.

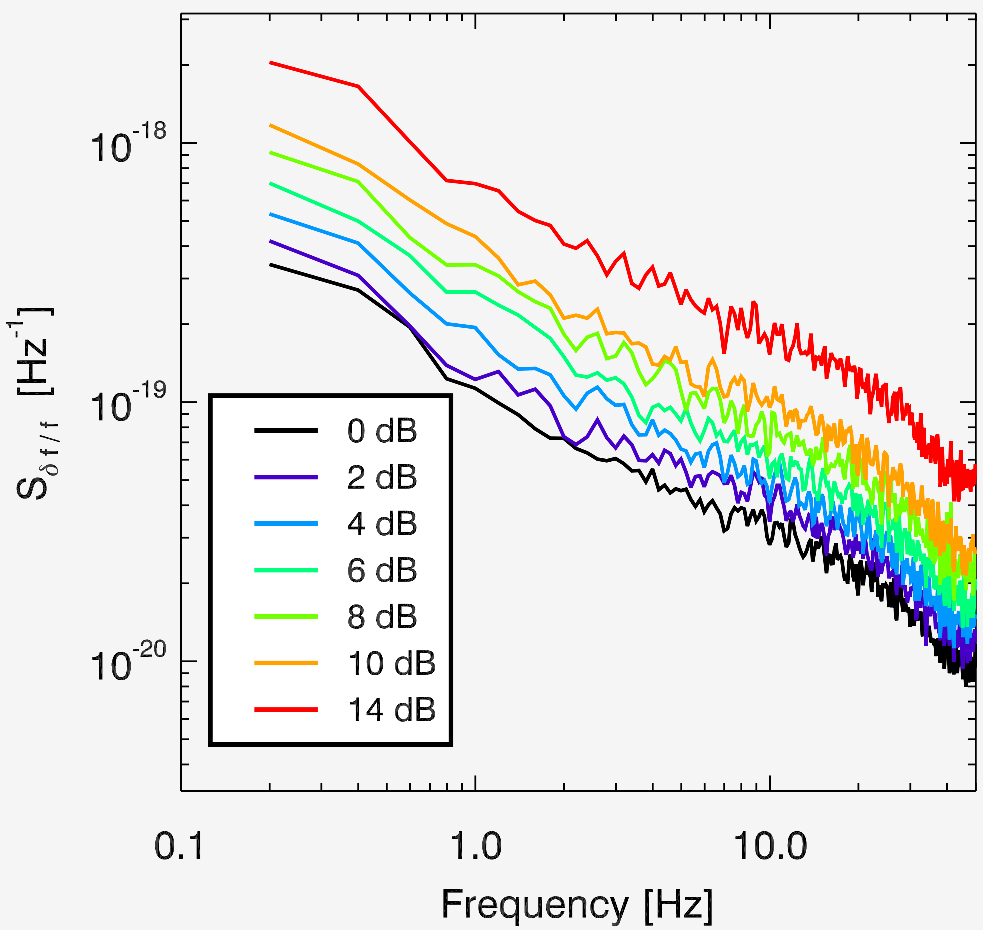
Semi-empirical model predicts PSD of the relative frequency fluctuations scales as

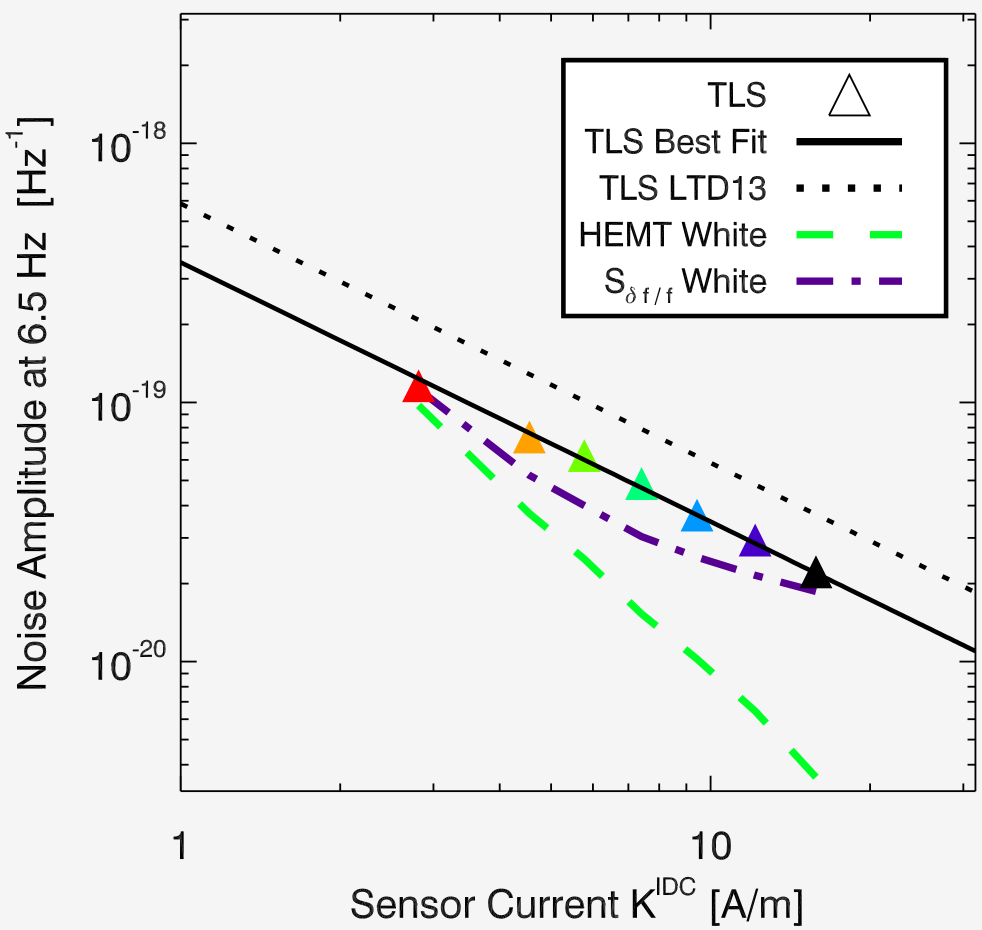
$$S_{\delta f/f} \propto f_{\rm audio}^{-1/2}\ P_{\rm int}^{-1/2}\ T_{\rm bath}^{-1.7}$$

Collected noise data with the detectors **dark**, varying

(1) Microwave readout power (14 dB range)

(2) Array temperature (250 - 450 mK)





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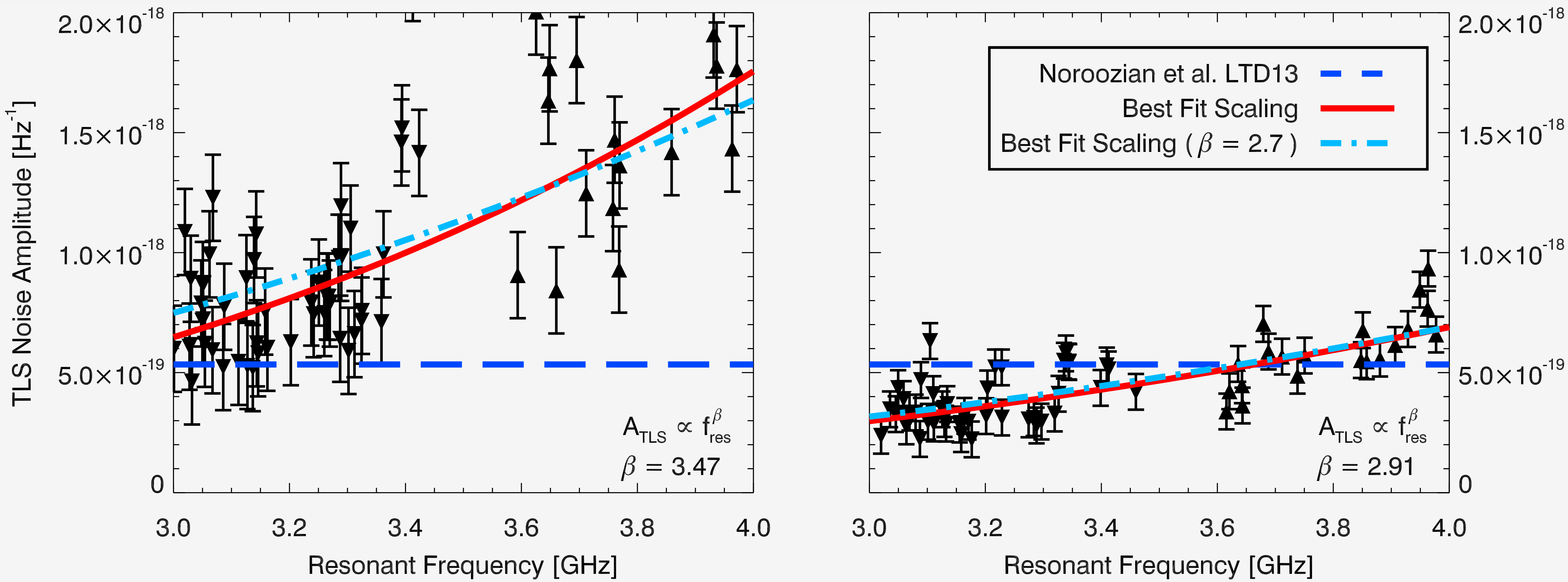
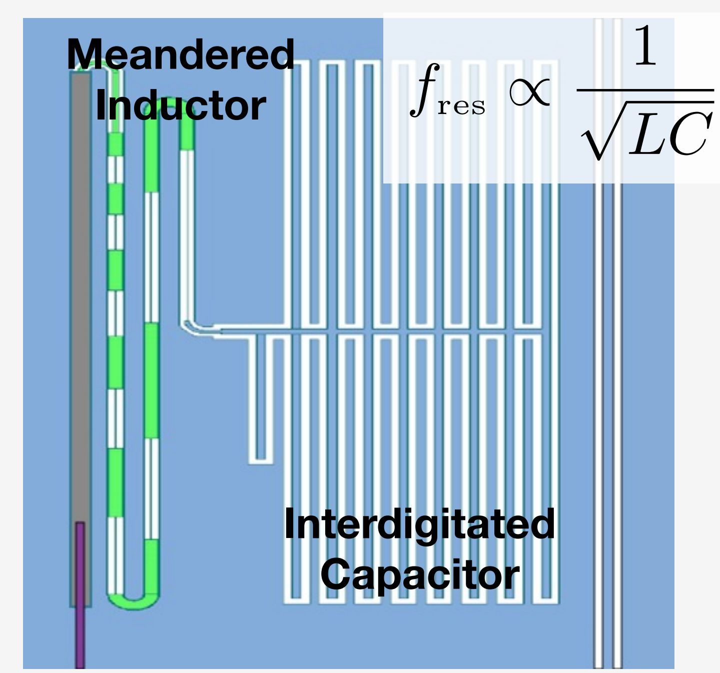


Observe strong dependence between amplitude of the TLS noise and resonant frequency.

Cause:

Varied resonant frequency by decreasing the length/number of fingers of the interdigitated capacitor



TLS are spatially independent fluctuators, noise adds incoherently

$$\Longrightarrow A_{\mathrm{TLS}} \propto \frac{1}{\ell} \propto f_{\mathrm{res}}^{2.7}$$

Across the 6 MUSIC devices $A_{\mathrm{TLS}}^{\mathrm{MUSIC}} / A_{\mathrm{TLS}}^{\mathrm{Noroozian}} = 0.6 - 1.6$