CMB-CAL @ BICOCCA

TES bolometer non-linearity:

an (incomplete) review

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Motivation for this talk

Personal reason I got interested in TES non-linearity:

- I moved to Japan about 7 years ago. The day I arrived at IPMU I received a message from Tomo Matsumura saying that *S. Takakura et al. JCAP 05 (2017) 008* had just been accepted for publication.
- In the next ~5 years I worked at IPMU on the detector prototypes for LiteBIRD (from UC Berkeley) next to Tomo & many of his students who were developing the HWP for LiteBIRD LFT.
- Non-linearity coupled to HWP synchronous signals (HWPSS) was a natural topic for me to start thinking about.

More practical reason:

- From **Sara Simon** opening talk on Monday: As sensitivity increases so does the impact of systematic effects, hence we need a better calibration.
- I would add: Combination and interplay between different systematic effects makes them even more problematic to handle ⇒ TES non-linearity and HWPSS are a perfect example!

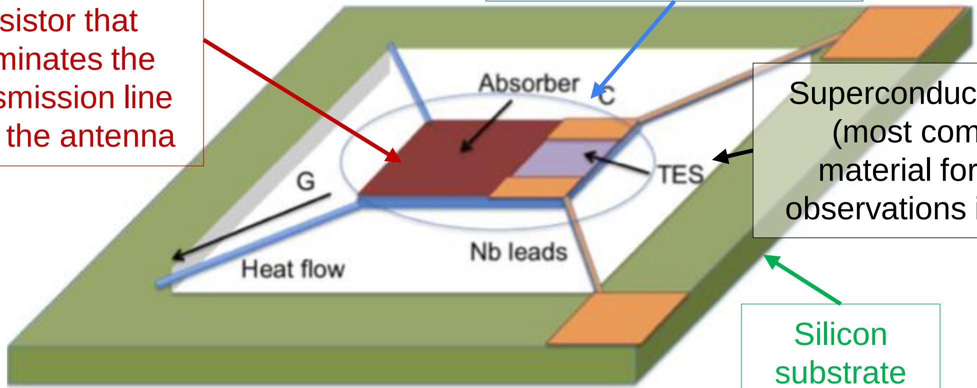
Problems resulting from TES non-linearity:

- Up-conversion of HWP synchronous signals and 1/f noise -> Contamination of polarization data
- Saturation of bright sources
- Effects of non-linearity on gain calibration or polarization angle calibration

Transition-Edge Sensor Bolometers

For antenna-coupled: load resistor that terminates the transmission line from the antenna

TES Island and “legs” Silicon Nitride



Superconducting film (most common material for CMB observations is AlMn)

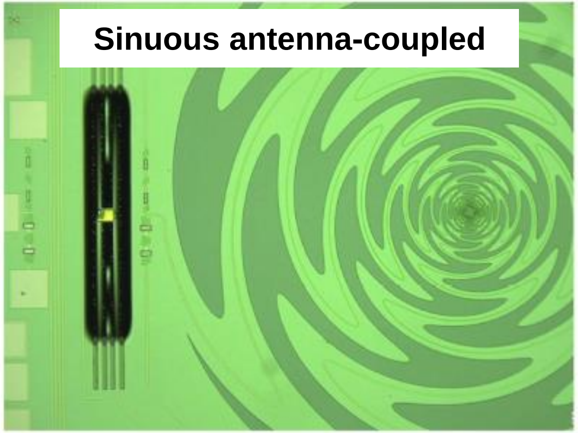
Silicon substrate

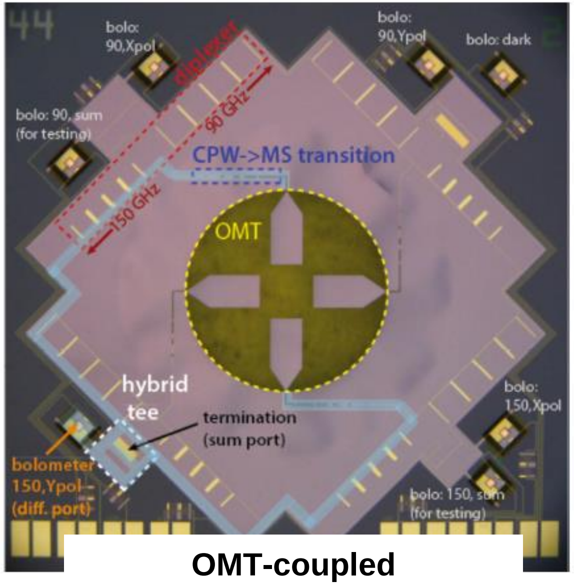
*P. D. Mauskopf 2018 PASP **130** 082001*

From Wikipedia: **Bolometer** is a device for measuring radiant heat by means of a material having a temperature-dependent electrical resistance.

Currently the most common technology (at least for CMB) consists of antenna coupled bolometers with superconducting thermometers called **Transition Edge Sensors** (TES) and are read out with multiplexed superconducting quantum interference device (SQUID) current amplifiers.

Sinuous antenna-coupled

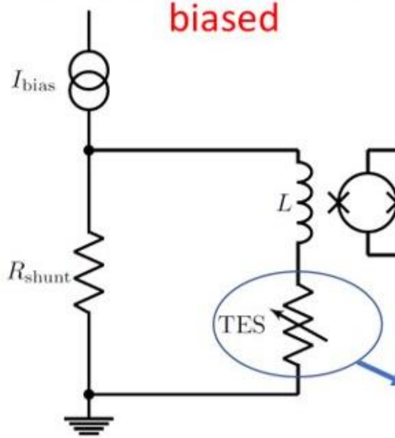




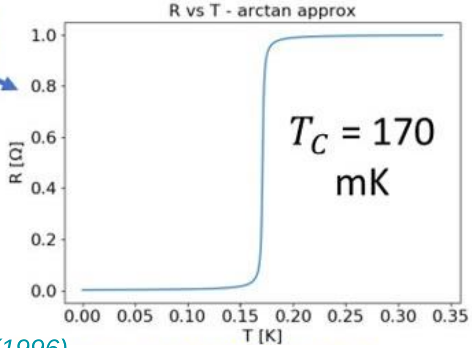
OMT-coupled

Transition-Edge Sensor Bolometers

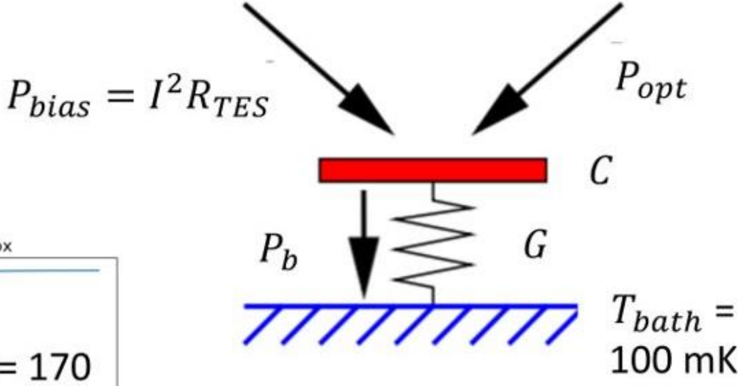
Electrical circuit – DC biased



$$L\frac{dI}{dt} = V - IR_{TES} - IR_{shunt}$$



Thermal circuit

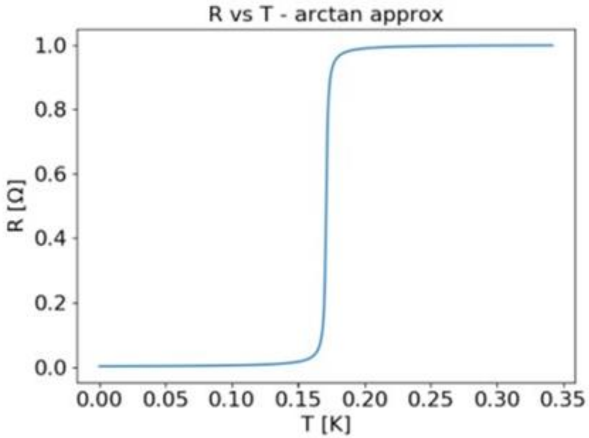


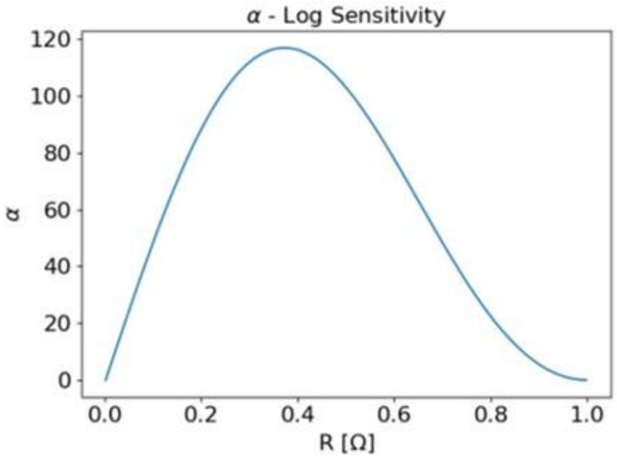
$$C\frac{dT}{dt} = -P_b + I^2R_{TES} + P_{opt}$$

$$P_b = \frac{G}{nT^{n-1}}(T^n - T^n_{bath})\ \text{with n=4}$$

K. Irwin, Appl. Phys. Lett. 66, 1998–2000 (1995)
A.T. Lee et al. Appl. Phys. Lett. 69, 1801–1803 (1996)
Irwin & Hilton, Transition-edge sensors, 2005

Transition-Edge Sensor Bolometers





- Logarithmic responsivity: $\alpha = \frac{d\,logR}{d\,logT}$
- Loop Gain: $\mathcal{L} = \frac{\alpha P_{bias}}{GT}$
- Thermal time constant: $\tau_{th} = \frac{\tau_0}{\mathcal{L}+1}$ where $\tau_0 = \frac{C}{G}$
- Current responsivity: $S_I = -\frac{1}{V}\cancel{\frac{\mathcal{L}}{\mathcal{L}+1}}\cancel{\frac{1}{1-i\omega\tau_{th}}}$

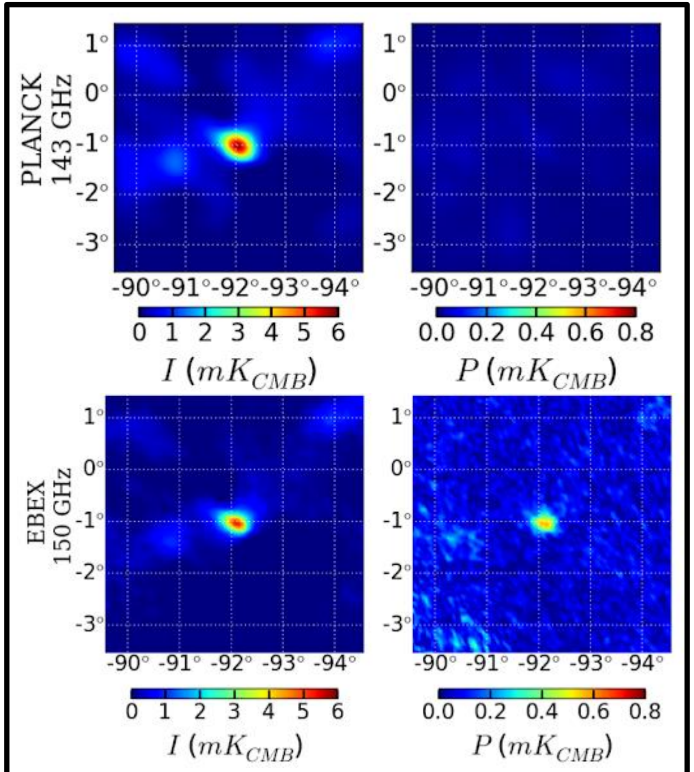
if $\mathcal{L} \gg 1$

if signal is quasi-static $\omega \to 0$

Target: we want to operate detector as deep as possible in the superconducting transition where $\mathcal{L}$ is "large"!

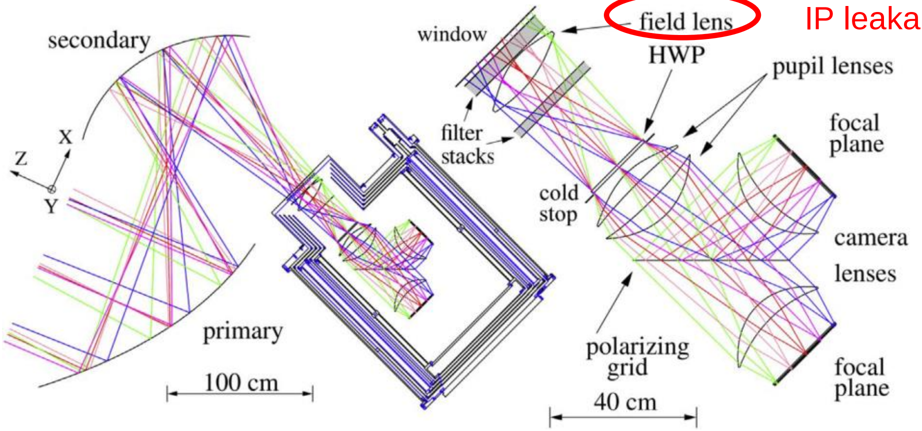
Small-signal approximation
$(\delta P \to 0)$: $\frac{\delta I}{\delta P} = S_I \left[\frac{A}{W}\right]$

Why do I worry about non-linearity then? [EBEX data]



EBEX data: *J. Didier et al 2019 ApJ 876 54*

From the paper abstract: …The data show **polarization fractions larger than 10%, while less than 3% were expected from instrumental polarization**. We give evidence that the excess polarization is due to **detector nonlinearity** in the presence of a continuously rotating HWP. The **nonlinearity couples intensity signals to polarization**. We develop a map-based method to remove the excess polarization. Applying this method to the 150 (250) GHz band data, we find that 81% (92%) of the excess polarization was removed.



Primary source of IP leakage

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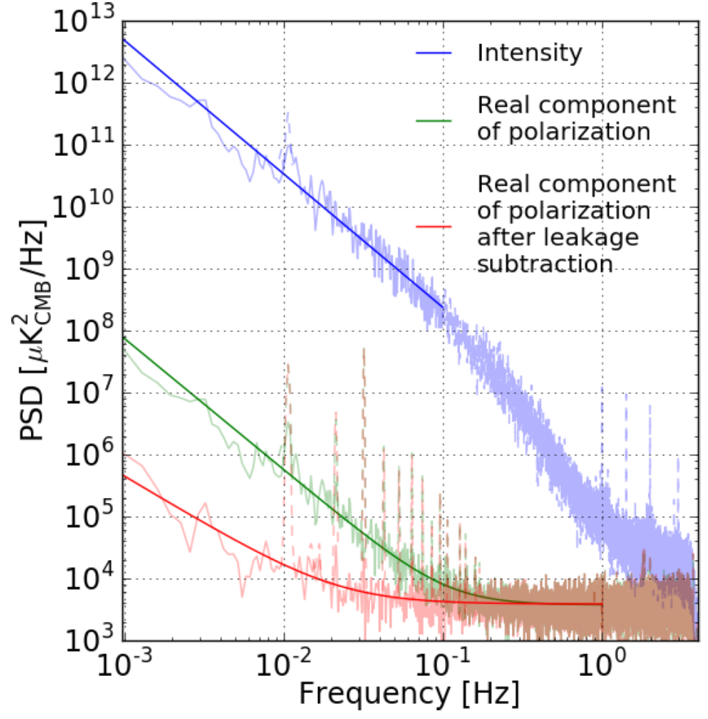
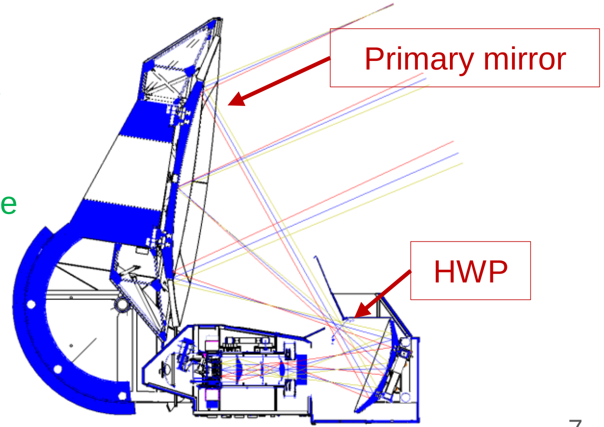
Why do I worry about non-linearity then? [PB data]



POLARBEAR data: [S. Takakura et al. JCAP 05 (2017) 008]()

From the paper abstract: …We find that the ***I→P* leakage is larger than the expectation** from the physical properties of our primary mirror, resulting in a **1/f knee of 100 mHz**. The excess leakage could be due to imperfections in the detector system, i.e. **detector non-linearity in the responsivity and time-constant**. We demonstrate, however, that by subtracting the leakage correlated with the intensity signal, the 1/f noise knee frequency is reduced to 32 mHz (ℓ ~ 39 for our scan strategy), which is very promising to probe the primordial B-mode signal.

- Rotating HWP to suppress 1/f noise
- However residual 1/f noise after demodulation is visible
- Even after leakage subtraction some 1/f residual is visible



Primary mirror

HWP

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TES non-linearity

$$d'(t) = [1 + \boldsymbol{s'_I d(t)}]\, d(t - \boldsymbol{\tau' d(t)})$$

At second order we find the non-linear components of the responsivity and time constant that depend from the input d(t)

Responsivity has been calibrated

TES non-linearity

$$d(t) = I(t) + \varepsilon\, Re\left\{[Q(t) + iU(t)]e^{-i4\omega_{hwp}t}e^{-i2\theta_{det}}\right\} + N(t)$$

Even in this “simple” case non-linearity can generate spurious signals that can be mistaken for polarization:

I -> P leakage: product up-converts sky intensity to the polarization science band

If noise contains 1/f component the product up-converts the 1/f noise to the science band

$$d'(t) = [1 + \boxed{\boldsymbol{s'_I d(t)}]d(t - \boldsymbol{\tau' d(t)}})$$

At second order we find the non-linear components of the responsivity and time constant that depend from the input d(t)

Responsivity has been calibrated

TES non-linearity

$$d(t) = I(t) + \varepsilon\, Re\left\{[Q(t) + iU(t)]e^{-i4\omega_{hwp}t}e^{-i2\theta_{det}}\right\} + N(t) + \ \ldots$$

Stationary HWPSS

Scan modulated HWPSS

$$\ldots + \sum_{n=1}^{\infty} \tfrac{1}{2}[A_n + A'_n I(t)]e^{-in\omega_{hwp}t} + \tfrac{1}{2}[A_n^* + A_n'^* I(t)]e^{-in\omega_{hwp}t}$$

$$d'(t) = [1 + \boldsymbol{s'_I d(t)}]d(t - \boldsymbol{\tau' d(t)})$$

At second order we find the non-linear components of the responsivity and time constant that depend from the input d(t)

Responsivity has been calibrated

The situation gets even messier if the rotating HWP adds synchronous signals (HWPSS) which originate from

1. Instrumental polarization from the optical components before the HWP
2. Non-idealities of the HWP Mueller matrix

Which component dominates really depends on the specific instrument configuration. Know your instrument!!!

TES non-linearity

$$d(t) = I(t) + \varepsilon\, Re\left\{[Q(t) + iU(t)]e^{-i4\omega_{hwp}t}e^{-i2\theta_{det}}\right\} + N(t) + \;\dots$$

Stationary HWPSS

Scan modulated HWPSS

$$\dots + \sum_{n=1}^{\infty} \tfrac{1}{2}[A_n + A'_n I(t)]e^{-in\omega_{hwp}t} + \tfrac{1}{2}[A_n^* + A_n'^* I(t)]e^{-in\omega_{hwp}t}$$

Conversion of sky intensity signal to polarization.

Due to non-idealities in the optics that create spurious polarization. In both analysis this is the dominant term in the time-stream.

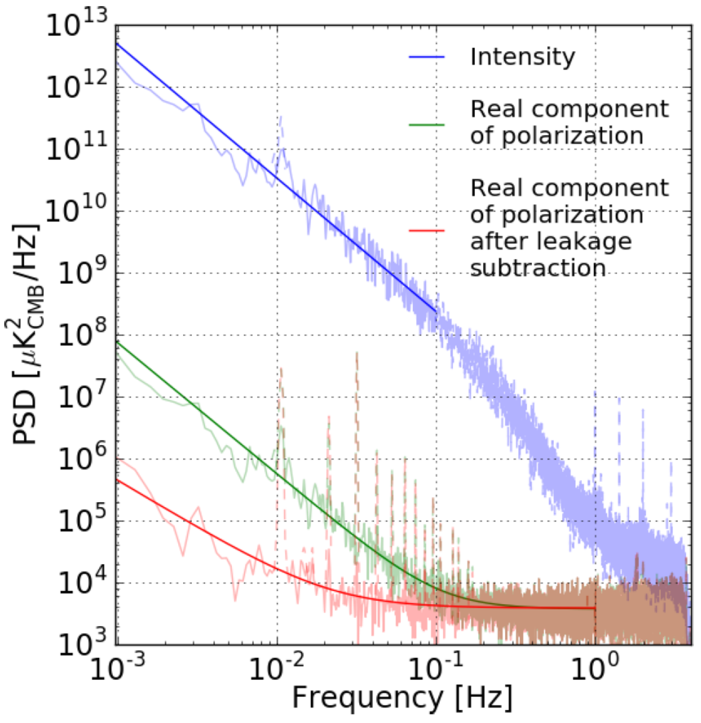
$$d'(t) = [1 + \boldsymbol{s'_I d(t)}]d(t - \boldsymbol{\tau' d(t)})$$

While the stationary HWPSS is dominant, it is “easy” to remove by filtering (harmonics $n \neq 4$) or fitting the amplitude and removing.

The scan-modulated HWPSS is found to be the limiting factor. Conclusion of both analysis is that this is due to it coupling to underestimated and poorly understood detector non-linearity.

Both try to use a template of the intensity signal (Takakura et al. in timestream, Didier at al. map based) to remove the leakage, but residuals can be observed in both.

TES non-linearity



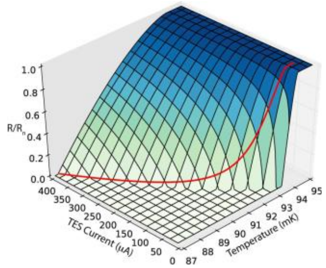
POLARBEAR data: *S. Takakura et al. JCAP 05 (2017) 008*

1. Limited by detector non-linearity model. Poor understanding of the detector R(T, I, B).

$$g_1 \approx -\frac{\eta}{2P_{\rm elec}}\frac{\mathcal{L}}{\mathcal{L}+1}\frac{\mathcal{L}+1+\omega_{\rm mod}^2\tau_0^2}{(\mathcal{L}+1)^2+\omega_{\rm mod}^2\tau_0^2}\boxed{C},$$

C is a factor that depends on the second derivatives of R(T, I, B).

$$\tau_1 \approx \tau_0\frac{\eta}{P_{\rm elec}}\frac{\mathcal{L}^2}{\mathcal{L}+1}\frac{1}{(\mathcal{L}+1)^2+\omega_{\rm mod}^2\tau_0^2}C,$$



TES is not a simple temperature dependent resistance. TES physics is a lot more complicated.
See *D. Bennet et al. LTD 2023*.

2. Both experiments used FDM, where TES is AC biased. Possible that this adds extra complexity to the TES responsivity.
See *J. Van der Kuur et al. 2011*.

3. Detector responsivity may vary due to fluctuations of the focal plane temperature or stability of the readout (possibly 1/f like variations).
This would be present in the intensity timestream. If this is used to subtract the leakage signal this components would end up in the polarization timestream.

Conclusions?

Both analysis come roughly to the same conclusions:

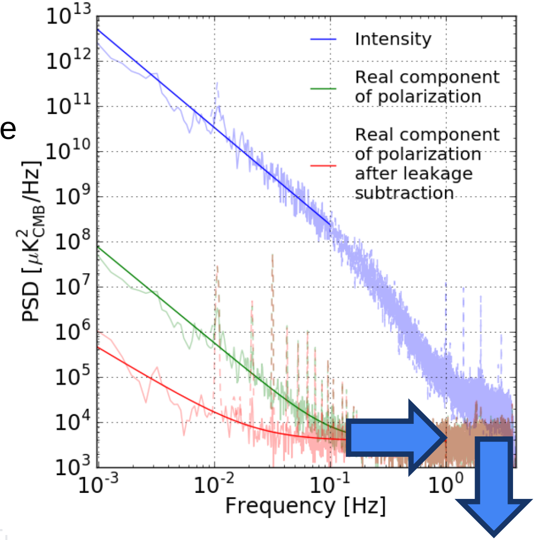
1. Reduction of the HWPSS is necessary to reduce the level of IP leakage and non-linearity that boosts the leakage.
2. Operation of the TES at high loop-gain reduces the leakage level. Indication that detector at high loop gain is more linear.
3. Better TES models are necessary to take into account sources of gain variations and non-linearity.

Next generation experiments are going to be more sensitive, hence systematic effects will be even more limiting for B-mode search.

Give a look at some of the papers me and others have put out recently on detector non-linearity both for modelling it and forecasting it:

- T. Ghigna et al. 2023 -> Modelling non-linear response by solving the differential equations at slide 4 without making a small signal approximation. Code available on github can be found in the paper. **Results are in line with conclusions above!!!**
- T. de Haan 2024 -> Modelling non-linearity due to imperfections in the TES readout like parasitics that spoil the voltage-bias.
- S. Micheli at al. 2024 -> Coupling between Tijmen's model and HWPSS for LiteBIRD to forecast impact on science.

Talk to anyone of us if you are interested in the topic!



As white noise goes down, correlated 1/f components become more dominant. f-knee moves higher in frequency and "obscures" higher multipoles.

Thanks for listening!