Dark TESs and Dark SQUIDs

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with inputs from Sara Simon and Brad Benson (FNAL)

Wed 3/10/2021 Detectors: Parallel
CMB-S4 remote meeting March 2021

Definitions

- **<u>dark SQUID (DS)</u>**:
  - extra MUX channel to monitor drifts in the readout
    - mostly for magnetic pickup, occasionally readout crosstalk

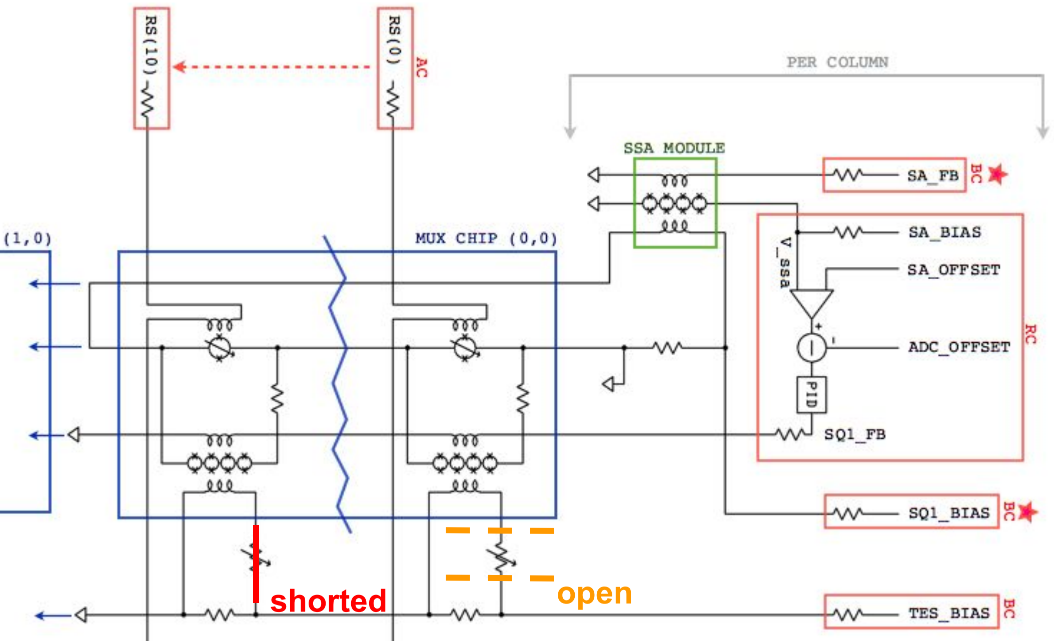
- **<u>dark TES (DT)</u>**, list of historical/possible implementations:
  - complete horn/OMT/TES assembly, the horn gets taped over [“<u>taped horn</u>”]
    - equivalent to a normal OMT+TES with no horn in front of it [“no horn”]
  - complete TES island, but feedline from OMT/antenna is cut [“<u>cut feedline</u>”]
  - no termination resistor on the island [“<u>no resistor</u>”] (legs can act as a mm-wave slot antenna)

- can *you* think of a dark that is not captured above?

- general consensus is to have them, but details matter
  - number per wafer
  - exact location
  - biasing / P_{sat}^{darks} adjustment

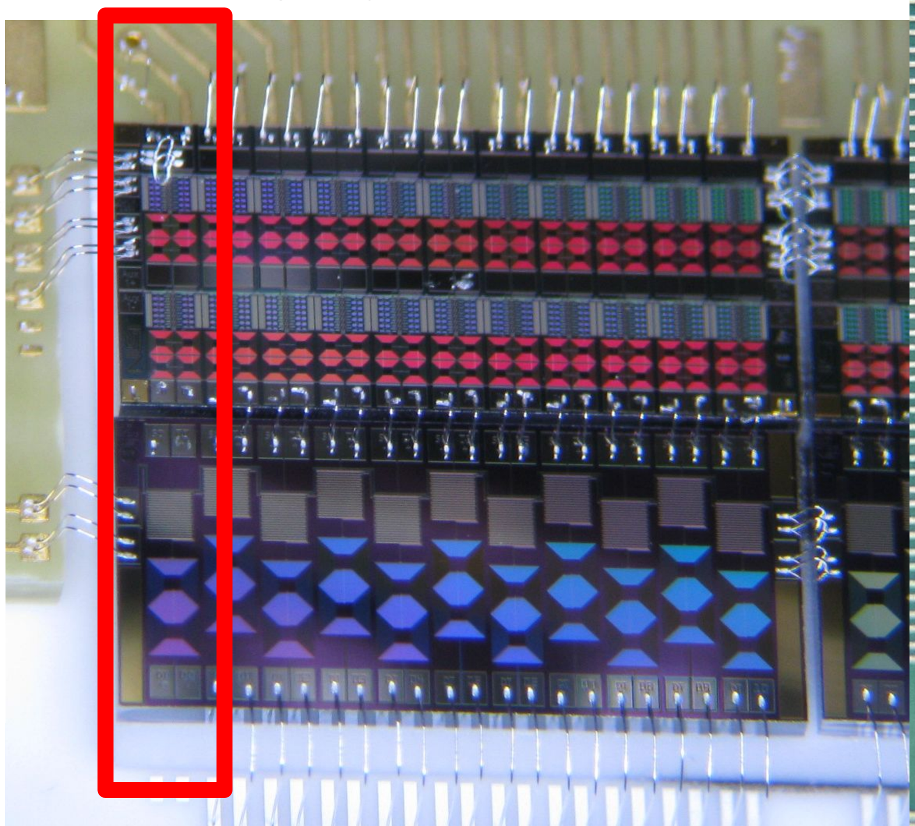
Dark SQUIDs in BICEP/Keck/SPIDER

- a Row-Select line must still be assigned to them
- totally independent from TES bias lines
- mostly for **magnetic pickup diagnostics**
- also useful for readout crosstalk
- (soft) recommendation: 1 DS per MUX column

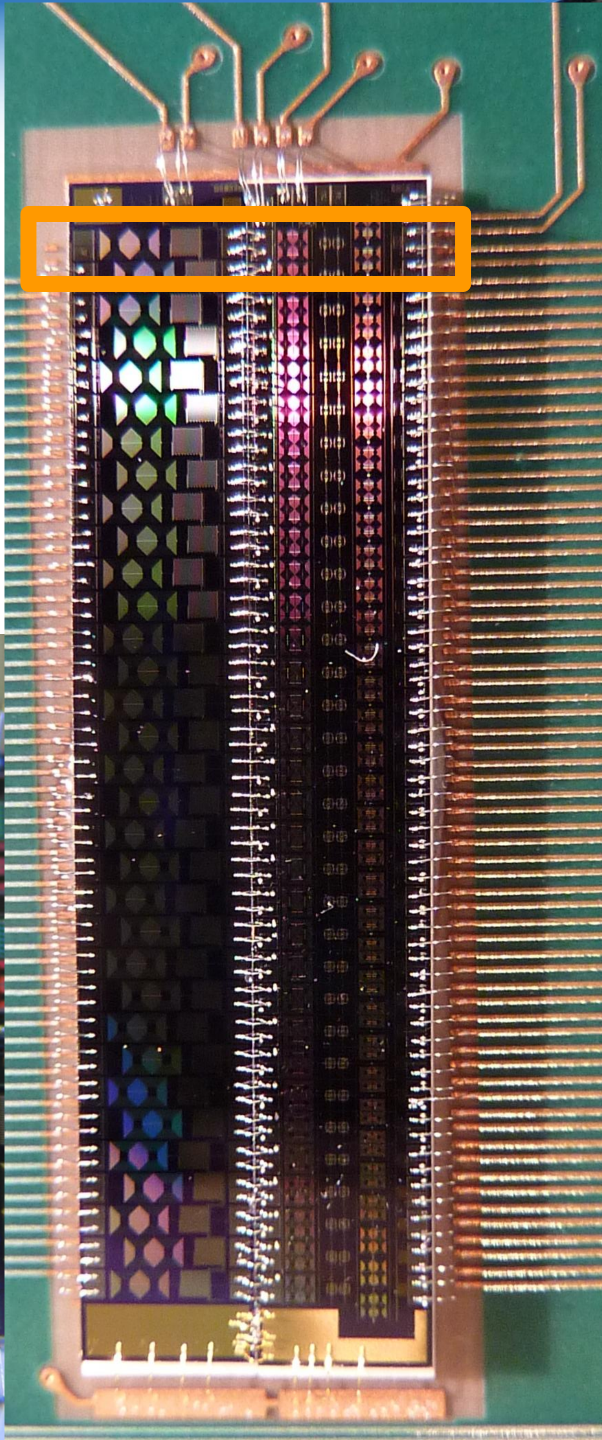


MUX11d schematic

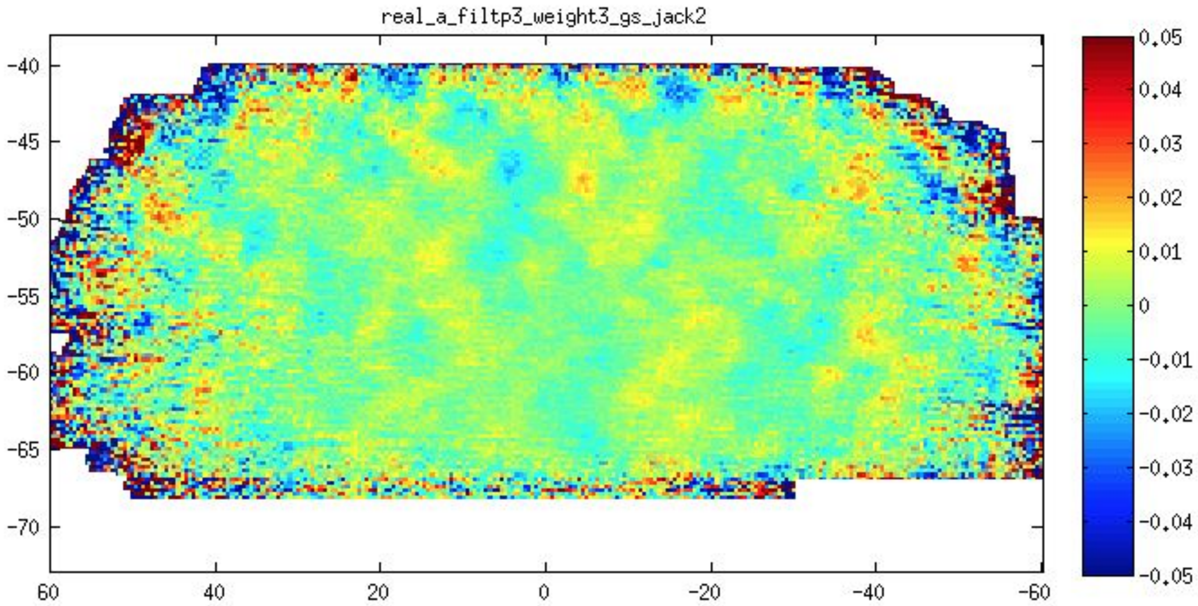
BICEP3
“shorted”
MUX11d



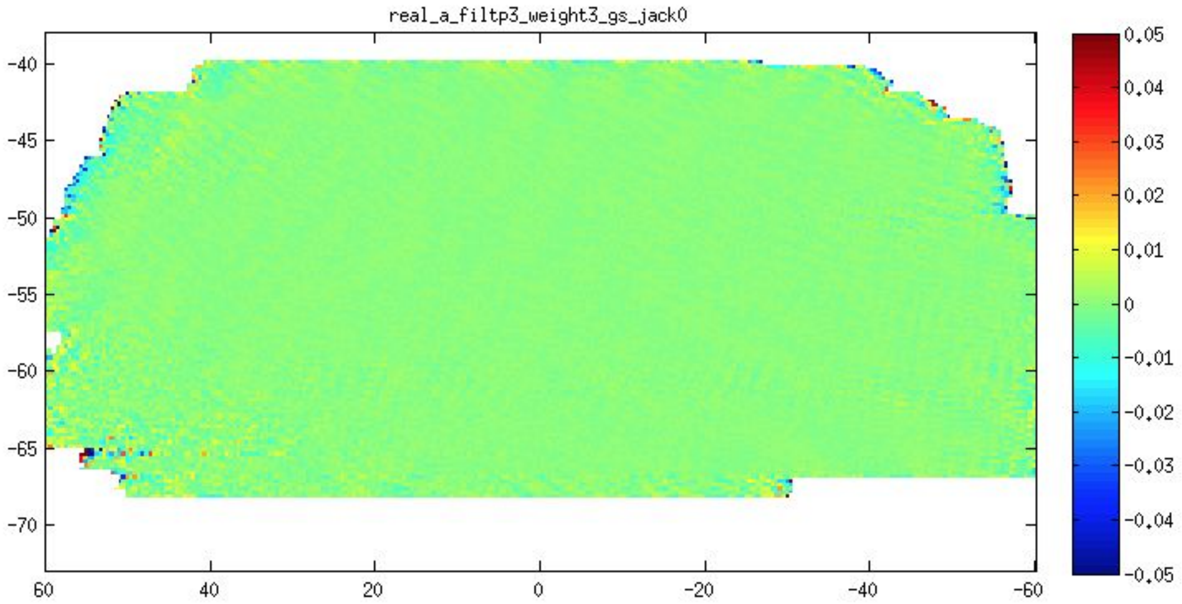
BICEP2/Keck
left “open”
MUX09



BICEP3 maps, 3rd order polynomial + ground subtraction



CMB U scan-dir jack



Dark Squids

With proper calibration, dark SQUIDs can inform how much of the ground-subtracted component is due to magnetic pickup

Credits: Hui / BICEP3

Dark TES in BICEP/Keck SATs

- very important for: **optical, thermal, electrical diagnostics**
- never actually used for the high-level science analyses
- same TES bias line as light detectors, choice is made to make sure either are in transition, depending on loading
- location: wafer corners or off to the side for 30/40 GHz

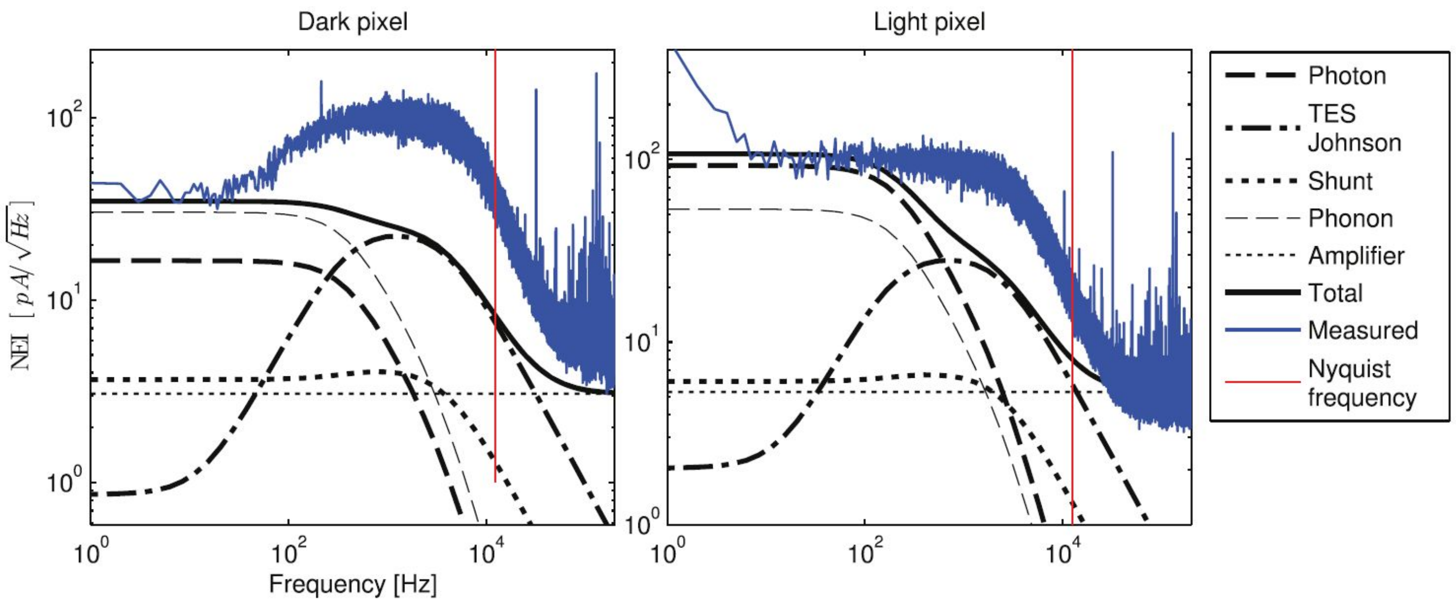
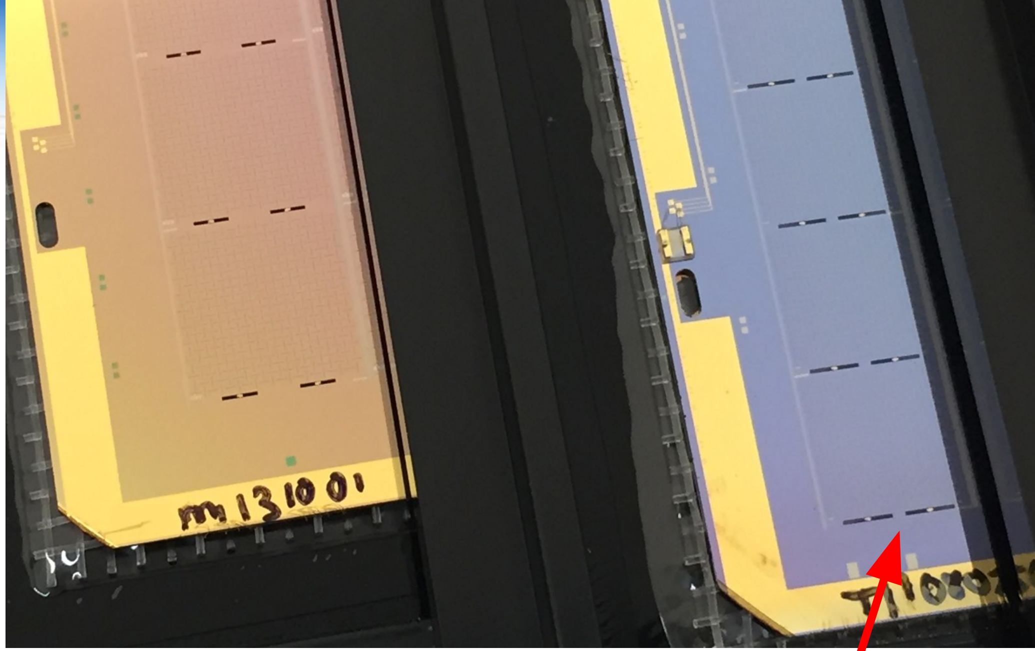
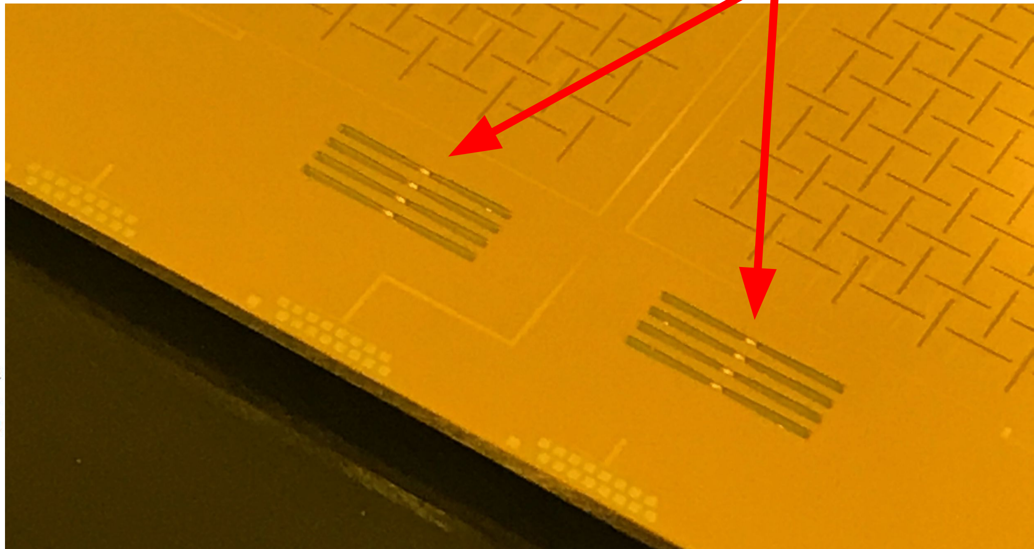


Figure 21. Measured and modeled noise for a individual detectors in the *Keck Array*. The red line indicates the Nyquist frequency for the multiplexing rate. Left is a "dark" pixel, with antenna disconnected showing noise stability down into our science band of a few Hz. There is still 0.05 pW photon loading on these dark detectors. Right is an optically active "light" detector. The $1/f$ knee at 7 Hz in the measured spectra is from atmospheric fluctuations, absent in the dark detector traces. In



O'Brient+, 2015 10.1088/0004-637X/812/2/176

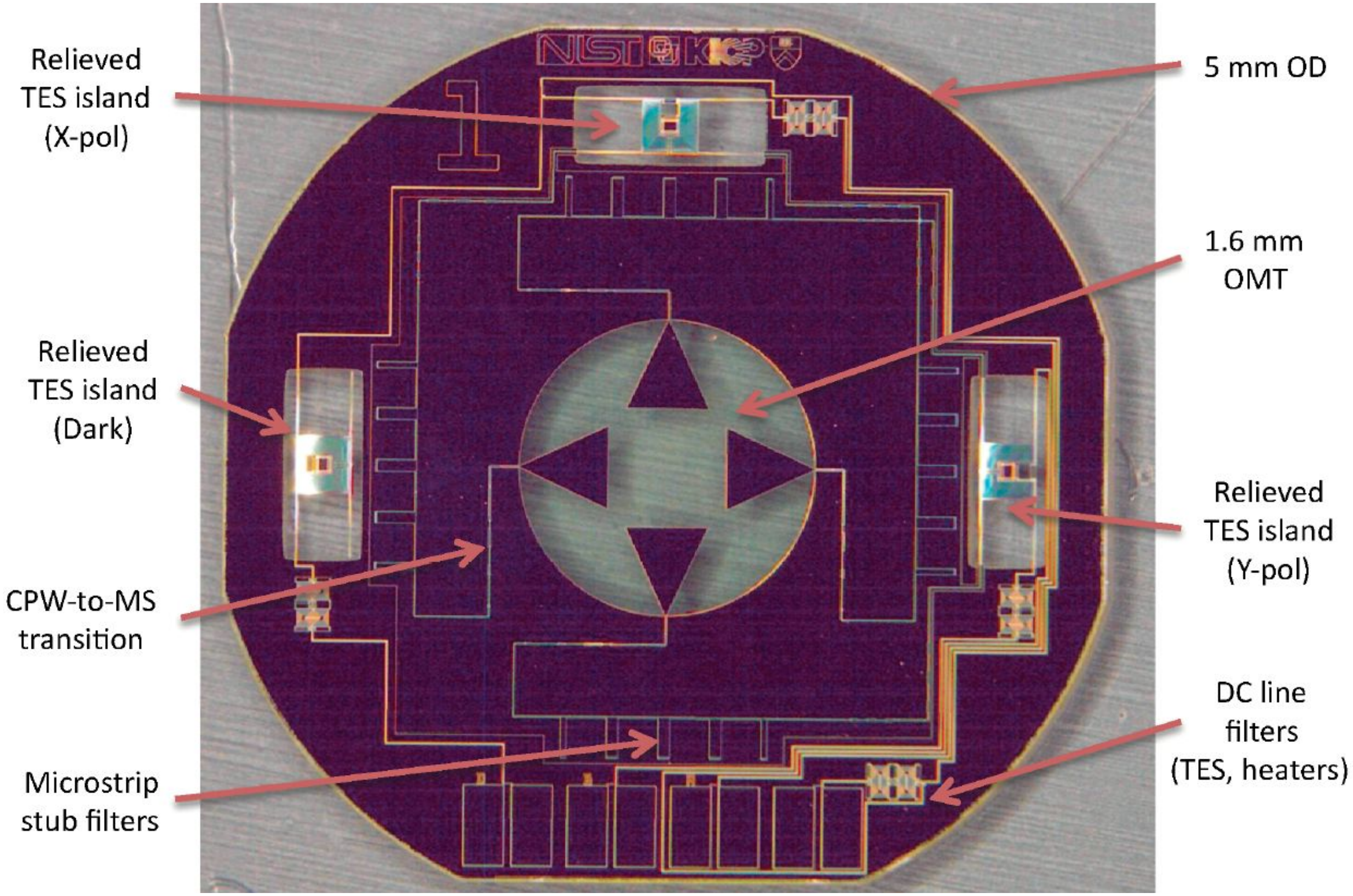
- BICEP2/Keck/BICEP3: "cut feedline" type
- BICEP Array 30/40 GHz no antenna, off to the side



Dark TES in S3 LATs

- Sara Simon: “ACT has used dark “cut feedline” TESes (in combination with thermometry) to separate thermal drifts from the atmosphere, which comes into play in both the cuts and calibration (e.g. flat-fielding). A rough estimate from ACT said that ~1% of the good data would have been cut without darks. The most important thing is to have good spatial coverage across the array [...]. We haven't used [the dark TES] as much on AdvACT as we did on ACTPol, but that might change with the analysis of the 27/39 GHz array.”

- Brad Benson: “we haven’t used a dark bolometer in any SPT science analysis or observation or map cuts, they have been used as a diagnostic during various stages in the detector development, e.g. assessing on-TES island pickup or optical cross-talk between detectors [...] during detector development phases, pre-production or earlier, and could be replicated with dedicated one-off tests or taping over some feedhorns. [Also used for] diagnosing various noise issues.”
    - SPT-SZ had “taped horn”
    - SPT-Pol had “cut feedline”
    - SPT-3G has both “cut feedline” and “no-resistor”



Yoon+, 2009 10.1063/1.3292392
“cut feedline” type

CMB-S4

Dark TES in CMB-S4

merely a diagnostic tool, or wanted during science observations?

- number:
  - SATs: a few (yielded) per wafer should be enough for diagnostics
  - LATs: can/should it be different than the above?
- biasing:
  - design the dark P_{sat} lower than the optical P_{sat}, by just the right amount
    - would they be equally representative of the light TESs in all situations of interest? E.g. instrument loading of unknown origin? Must know dark/light P_{sat} in advance
  - separate bias lines for the darks - this sounds like a huge headache for readout
  - different shunt resistor darks [JPF]
    - drawbacks: different gains, introduces dependence between wafers and Nyquist chip, but it could be tuned to get the darks reliably on transition alongside the lights
- location:
  - on-chip “cut feedline” *[not-really dark]*
    - sensitive to on-TES island pickup or optical cross-talk above waveguide cutoff
  - off to the side or “no resistor” *[really dark]* less sensitive to on-TES island pickup or optical cross-talk
    - but still sensitive to thermal, microphonics, electrical cross-talk
  - optically-sensitive area: “taped horns” *[not-really dark]* can be temporary
    - sensitive to stray photons above waveguide cutoff that can bounce around behind the horn array

Conclusions

- people agree that we should have both dark SQUIDs and some form of dark TES

- readout perspective: 1 out of 11 MUX channels is being currently set aside for "darks"
  - 1 module/wafer: 64 rows x 5 columns x 6 RO boxes = 1,920 channels
  - up to 120 channels available for darks (all types), which is obviously a lot
  - RO plan is likely to change, but included here to spur discussion

- proposed nomenclature:
  - DS
  - DT-taped-horn (or DT-no-horn)
  - DT-cut-feedline (DT-CF)
  - DT-no-resistor (DT-NR)

- One potential plan
  - 1 DS per MUX column (= 30 per 1,920-channel module); can easily be ½ or ⅓
  - a few DT-CF per wafer with adjusted P_{sat}
  - a few DR-NR per wafer with adjusted P_{sat}
  - plan on DT-TH just during initial development and testing (as opposed to permanent DT-NH)

Back-up slides

Dark TES in ACT

- From Sara Simon

“ACT has used dark TESes (in combination with thermometry) to separate thermal drifts from the atmosphere, which comes into play in both the cuts and calibration (e.g. flat-fielding). A rough estimate from ACT said that ~1% of the good data would have been cut without darks. The most important thing is to have good spatial coverage across the array, so that would dictate how many you need and where you want them.

ACT does not have a stimulator which could conceivably help improve the flat-fielding measurements without darks, but that doesn’t help with the cuts (or in S4 SATs where it would be difficult to use a stimulator due to the optics design).

we haven't used them as much on AdvACT as we did on ACTPol, but that might change with the analysis of the 27/39 GHz array.”

Zhao PhD thesis, 2010
dark TES unit, which only has an inductor unit and a SQUID unit

Essinger-Hileman PhD thesis, 2011 ABS
“dark” TES bolometer which is not optically coupled (not coupled to the OMT)

Crowley PhD thesis, 2018 AdvACT

Li+ 2018 10.1117/12.2313942
There is one dark TES per frequency per pixel to monitor bath temperature variation, 98 of which are connected to the readout system

Li+ 2021 2101.02658v2
Each pixel is composed of an orthomode transducer (OMT) coupled to four TESes, respectively measuring the CMB at two linear polarization and two frequencies. In addition, each pixel has two “dark” TESes that are not coupled to OMT. In total we readout 292 OMT TESes and 98 dark TES

Dark TES in SPT

- From Brad Benson

“we haven’t used a dark bolometer in any SPT science analysis or observation or map cuts, they have been used as a diagnostic during various stages in the detector development, e.g.:

* Assessing on-TES island pickup or optical cross-talk between detectors - Though this has only been during detector development phases, pre-production or earlier, and could be replicated with dedicated one-off tests or taping over some feedhorns.

* Diagnosing various noise issues. In practice, I don't think they’ve actually ended up telling us very much on the sky though. Most recently we did use some number of darks to assess a 1/f noise issue in the 2018 SPT-3G focal plane, that ended up being primarily from microphonic noise, and comparing 1/f noise in optical vs dark detectors were one piece of evidence that we looked at to build the case that it was microphonic. [...]”

For SPT-SZ, it was a horn-coupled spider web absorber. To create darks pixels, we taped over 4-5 horns per wafer with aluminum tape. Obviously the coupling was very different with these detectors though, because it was a TES in the middle of a spider web absorber

For both SPTol and 3G both, the darks were created same as you, by severing (or really just not depositing) the feedline between the OMT / antenna to the TES island. The big difference was that SPTpol was basically first-generation NIST OMT coupled detectors, so the pixels and TES were behind a feed horn and waveguide. However, we expected the TES’es to have some pickup through a similar mechanism as BK and SPT-3G, from the TES island etching effectively looks like a slot dipole antenna. And as you know, there are some ways you can change the geometry of that TES island etch to make slot dipole be outside the observing band.

So for a horn-coupled system, the waveguide kills anything below the lower band-edge, but light above that cutoff that doesn’t couple to the detectors can bounce around behind the horn array, propagate through the Silicon wafers, and potentially get coupled to neighboring pixels or TESes. This is one of the reasons you see the elaborate moats of CF110 / MF110 in the interface wafers for the horn-coupled design, there is of course some amount of mm-wave power bouncing around back there. So above the waveguide cutoff, I'm not sure the dark pickup is very different between the horn-coupled OMT vs lenslet-coupled or planar array architecture. Above the waveguide cutoff, light not efficiently absorbed by the antenna can bounce around or prograde in the detector / interface wafers and get terminated on other pixels antennas or the TES.

However, for both SPTpol and SPT-3G, we effectively just treat this as a small level of dark pickup as something that we calibrate out, through some combination of FTS measurements, beam-maps, leakage beam / cross-polarization, deprojection, etc. The darks pixels are used during detector development to help put upper limits on the dark pickup of the pixels, understand instrumental noise, basically to make sure we haven't completely screwed up the design, but in practice once we deploy, we are basically just using in-field calibrations and on-sky measurements of the “optical” detectors, the darks are never used.

Henning's thesis (2014, SPTPol with OMTs + horns)

- Each 150 GHz module also has four “dark” detectors uncoupled to incident radiation for diagnostic purposes. Light is coupled to the detectors by feed horns
- A prototype SPTpol 150 GHz pixel fabricated at NIST-Boulder is shown in Figure 2.7 (Lorenzo: I already had found this image and put it in my slide 7). [...] A third “dark” TES is sometimes included for characterizing electrothermal properties, calibration tests, and controlling systematics.
- third TES, which is not connected to the OMT and is therefore a “dark” device [...] test for non-OMT coupling power

Everett+ 2019 (SPT-3G with sinuous antennas + lenslets)

- each wafer has six “dark” pixels, where the microstrip from antenna to TES island is disconnected.

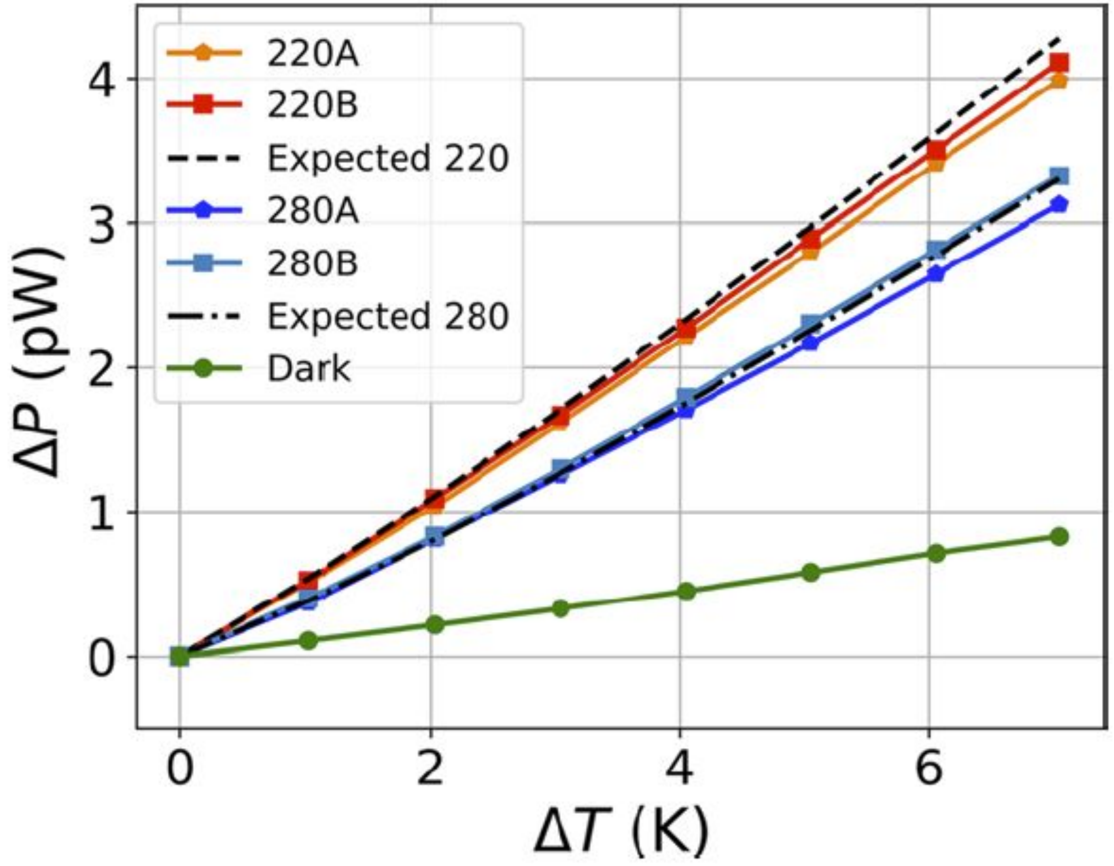
Dutcher's thesis (2020, SPT-3G with sinuous antennas + lenslets)

- Each wafer also houses a number of dark detectors, purposely left unconnected to the pixel antenna to test for non-optical signals

Dark TES in SO 220/280 GHz

Walker+, 2019 [10.1007/s10909-019-02316-1](https://doi.org/10.1007/s10909-019-02316-1)

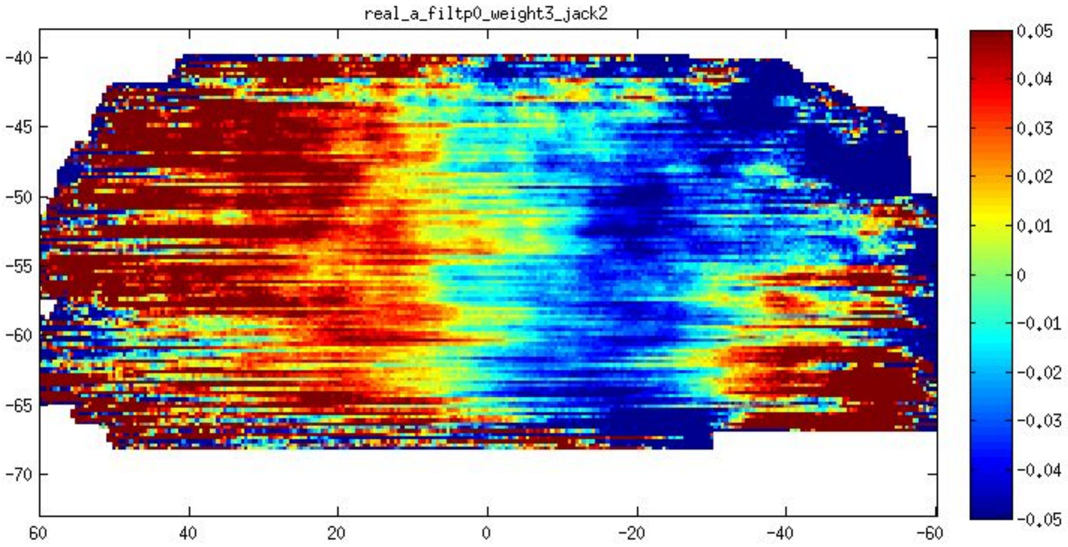
- we include two dark TES bolometers for systematic checks
- Assuming ΔP of dark bolometers accurately monitors the parasitic power radiatively coupled to the optically coupled bolometers, we subtract dark ΔP from optical ΔP to estimate optical efficiency



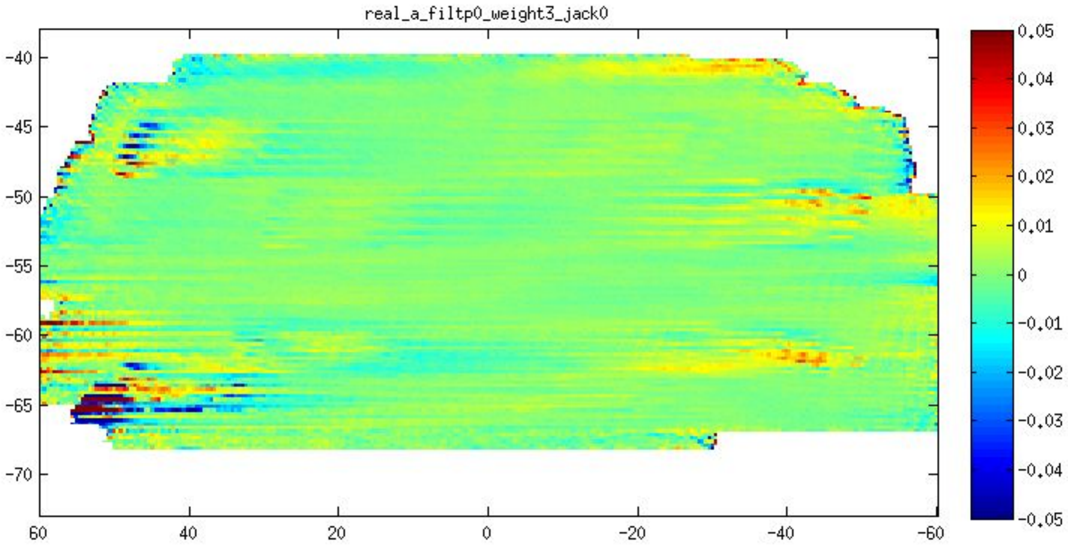
BICEP3 magnetic pickup

- Use dark squid channels to look at magnetic pickup
- Compare that to the light channel, for calibration
- This initial analysis is using 1 deck angle, first 30 tags of data in 2016 B3
- Comparing p0/p3 filters, and with/wo ground subtraction

BICEP3 maps, p0/ no ground subtraction

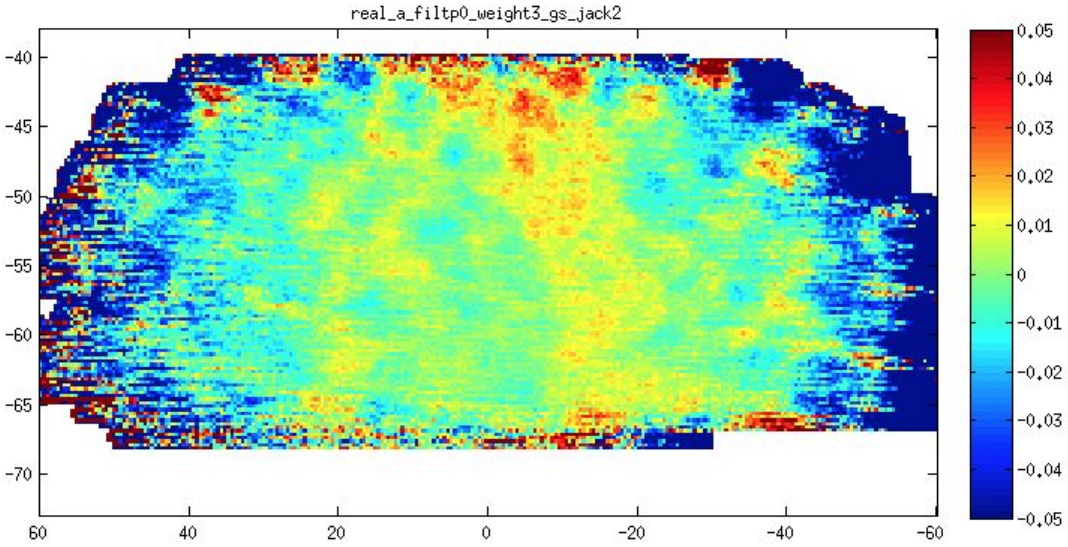


Light scan dir jack

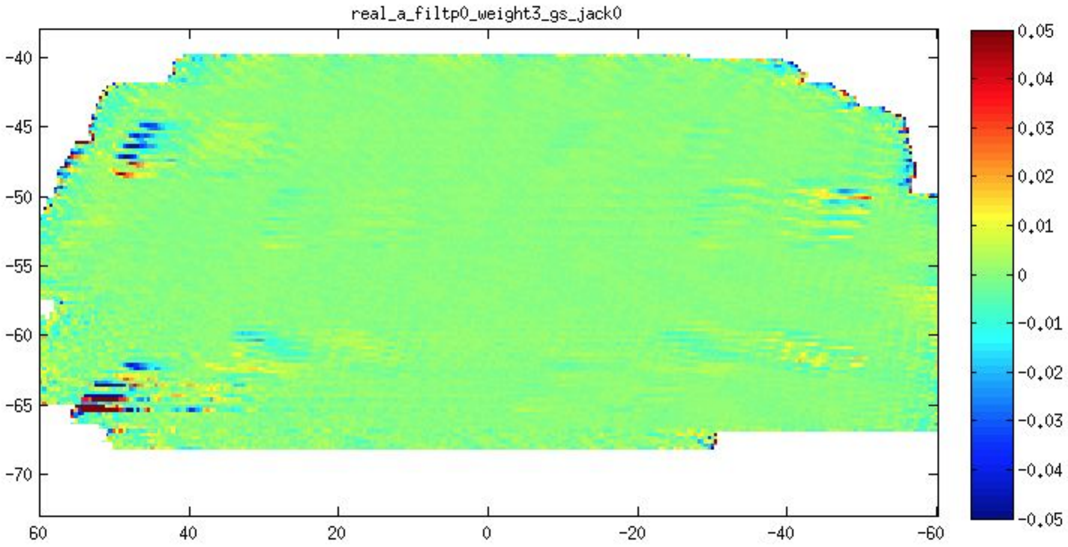


Dark Squids

BICEP3 maps, p0/ ground subtraction



Light scan dir jack



Dark Squids