Enabling large arrays of transition-edge sensors with multiplexed microwave readout

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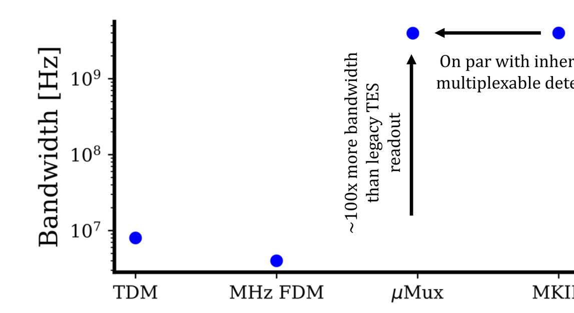
CPAD 2024

Microwave SQUID multiplexing

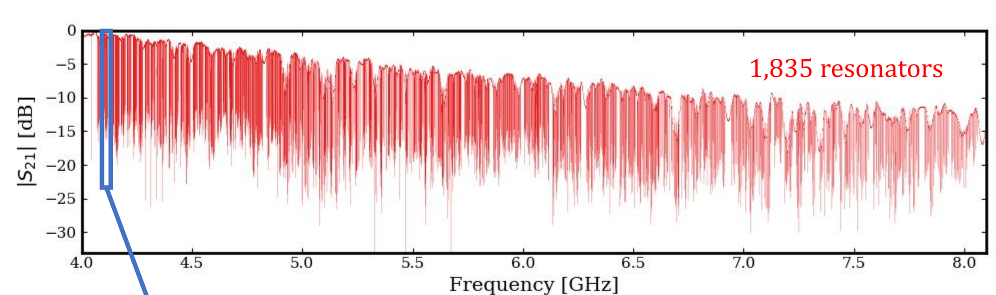
- Microwave SQUID multiplexing (µmux) enables highly scalable readout of TESs and MMCs leveraging advances in superconducting microresonator arrays
- Now ~20 years since first publication, seeing broad adoption for many applications including detection of mm-waves [1], optical photons [2], x-rays [3], gamma rays [4], and β decays [5]
- Here, we showcase two areas of development relevant for HEP applications

Why µmux?

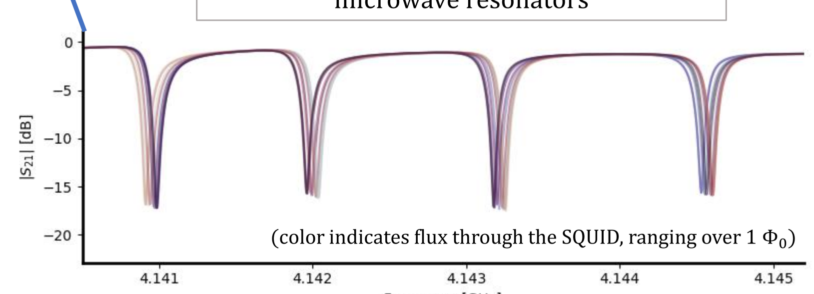
- Access to several GHz of bandwidth allows for very large multiplexing factors
- Ability to separate detector and readout design, as MKIDs are not as sensitive as TESs in many regimes



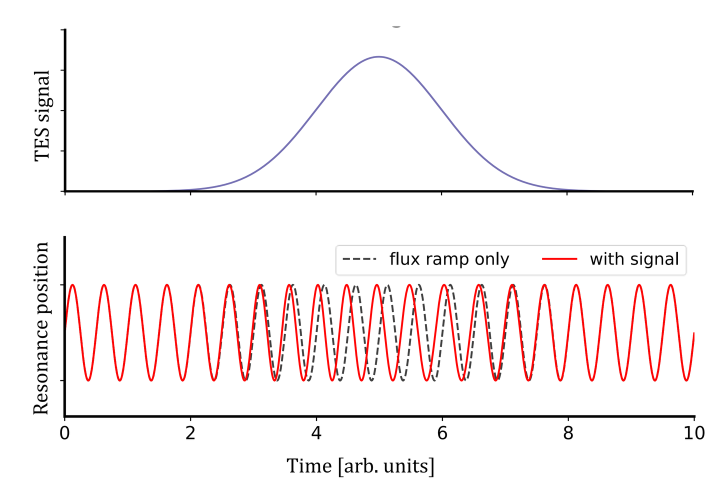
Operation principle



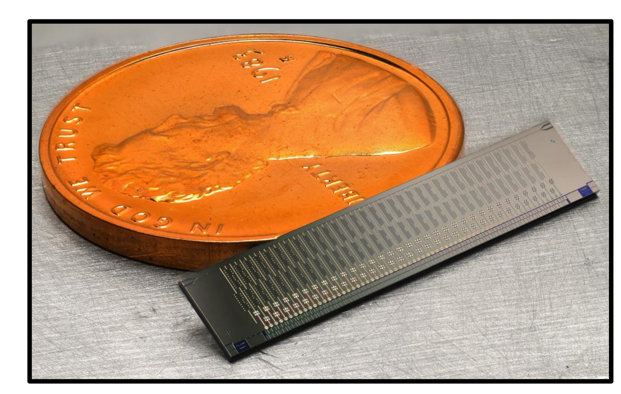
Detectors are channelized with unique microwave resonators



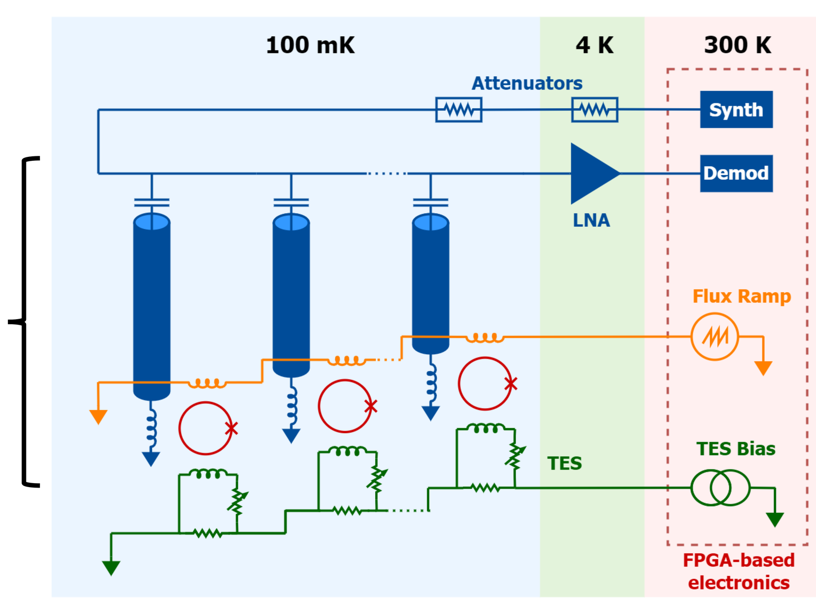
Both the detector signal and a fast "flux ramp" modulate each resonator position via a SQUID



The detector signal is encoded in the phase of resulting modulation



Resonators and SQUIDs may be co-fabricated on the same chip



A software defined radio system tracks the resonator positions in time through voltage [6] or frequency [7] readout. TES bias and flux ramp lines are shared

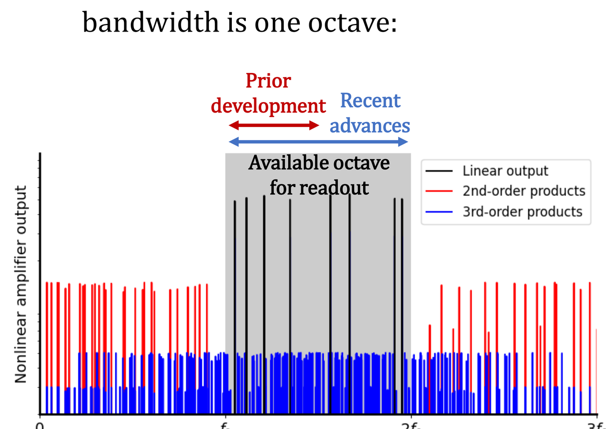
mm-wave bolometer readout

- Development so far for low-bandwidth detectors has focused on TES bolometers for ~100 GHz cosmic microwave background measurements
- First large-scale use in the Simons Observatory – 60,000 channels operating now with 910 channels per multiplexer, distributed across the 4-6 GHz readout band [1]
- There are near-term plans to build another 60,000 across 2 experiments [8,9] and many longer-term possibilities
- Recent work described here advances µmux readiness capabilities for future instruments

The Simons Observatory telescopes (image: G. Coppi)

Development direction: increased readout bandwidth

Fundamental limit on available bandwidth is one octave:



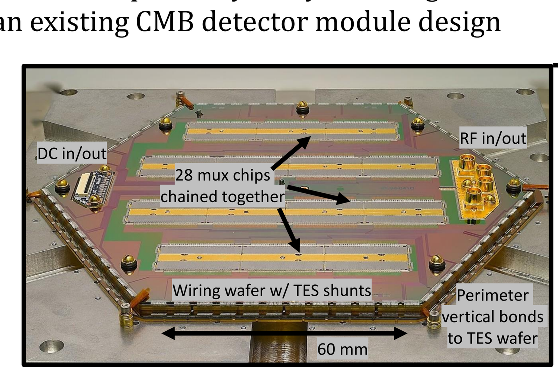
Toy model with just 8 channels

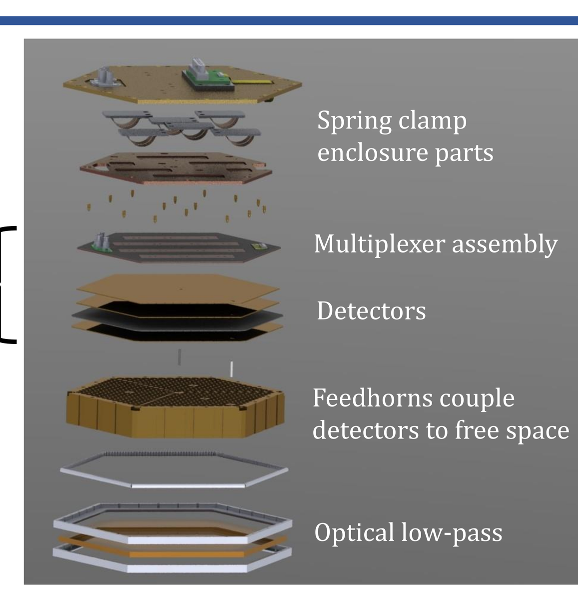
	Simons Observatory	Recent advances
Readout band	4 - 6 GHz	4 - 8 GHz
Multiplexing factor	910	1,820
# of readout lines per 150 mm TES wafer	2	1

Outcomes of this work:
- Doubled the multiplexing factor, halving required cables + amplifiers
- Kept average channel density the same
- Conveniently matched readout units to 150mm detector modules based on 6" TES wafer fab

Physical implementation

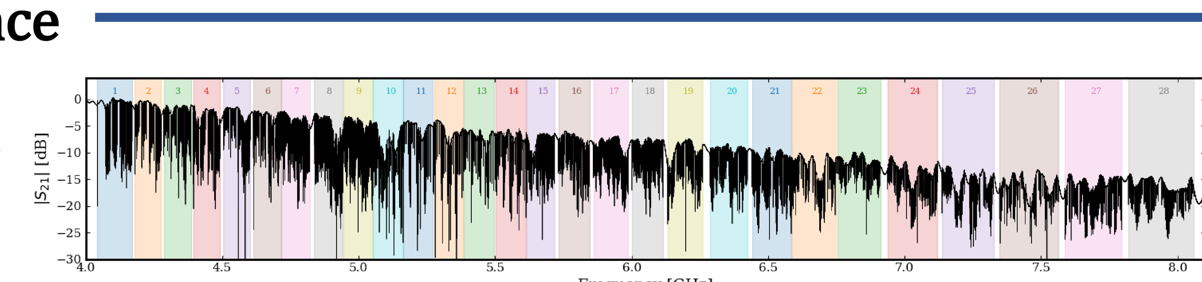
- Updated chip design which avoids parasitic microwave resonance near readout band and optimizes for noise and crosstalk performance across full 4-8 GHz band [10]
- Demonstrated a 1820-channel multiplexer by daisy-chaining the two RF and flux ramp lines in an existing CMB detector module design
- Connections:
  - 1 coax in
  - 1 coax out
  - 13 twisted pairs for TES bias lines and flux ramp



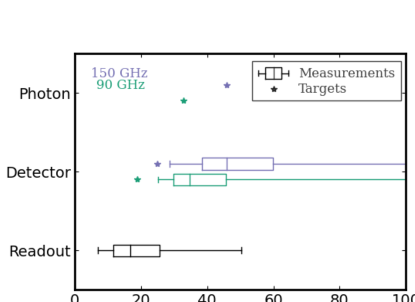


Performance

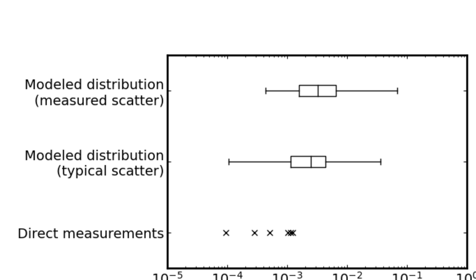
~78% TES IV curve yield for demo assembly [10] (expect ~84% with high-throughput assembly as in [11])



Readout noise sub-dominant to detector and photon noise for ground-based CMB experiment [8]

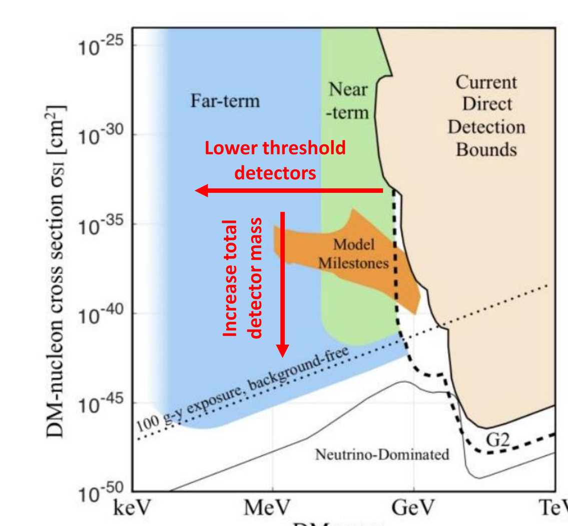


Nearest-neighbor crosstalk typical amplitude of ~0.3% (non-neighbor crosstalk significantly lower) [12]



Athermal phonon detector readout

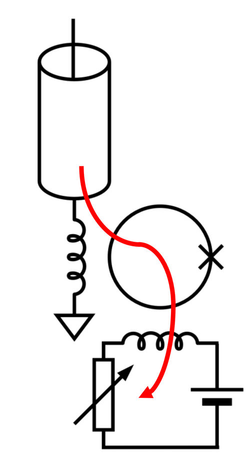
- Most µmux development to date has focused on small (≲mm) and modest power (~pW) sensors
- sub-GeV dark matter searches starting to utilize large (~cm) and low power (~fW) TES sensors which will need significant scaling to reach ultimate targets
- Starting new LDRD-funded research program to develop proof of concept multiplexer compatible with TESSERACT [13] sensors



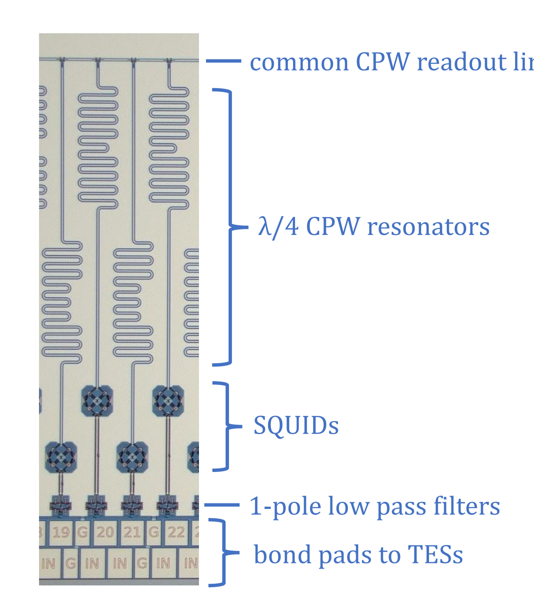
Prospects for future nuclear recoil searches [14]

Key direction: controlling parasitic microwave leakage

- Power from ~GHz resonator readout tone can leak into the TES via the SQUID coupling
- Current paradigm for ~pW detectors utilizes simple 1-pole low pass filter to isolate TES from readout tone
- Long-term target requires ~100x reduction in parasitic loading
- Investigating more optimal filtering paradigms in collaboration with NIST µmux group

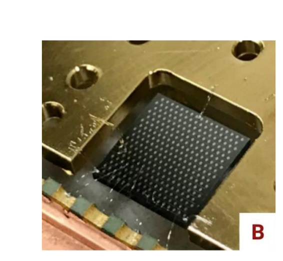


Simplified schematic of microwave leakage path



Current mux chip architecture

- Additional points of attention: fanout to larger sensors, 10 mK SQUID and resonator operation
- Setting up microwave SQUID readout testbed in Berkeley (featuring a new dilution refrigerator!)
- Plan initial multi-channel demo w/ spare TESSERACT-style sensors



Example ~cm² size athermal phonon TES detector [15]

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