# Snowmass2021 - Letter of Interest

# *Warm Electronics readout of superconducting microwave resonators*

**Thematic Areas:** (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors

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## Abstract:

Superconducting sensors have become ubiquitous in physics. As the detector count in experiments grow ever larger, reading them all out becomes an ever larger problem. One powerful solution which has developed rapidly is to couple the sensors to unique RF microwave resonators. This LOI discusses ongoing work, which has already demonstrated unparalleled multiplexing factors in hundreds, as well as future work which could enable multiplexing factors in the 10,000s.

Superconducting detectors have provided low noise measurements across multiple subfields of physics. Modern lithographic techniques have lowered the cost and increased the reliability of manufacturing large numbers of sensors. Existing experiments rely on many thousands to tens of thousands these detectors[2–4;6;7;10;13], and future experiments may be built upon hundreds of thousands[1;8;12;16;17]. The large number of sensors increases the integration complexity as well as conductive load between cryogenic stages. This pushes instrument designers to ever higher multiplexing factors. One of the most promising avenues to achieve high multiplexing is to couple a superconducting detector to a high-Q resonator. This has been achieved either by making the resonator a part of the detector itself (KIDs)[15] or by coupling the transition edge sensor (TES) to a resonator via an electrical circuit ($\mu$Mux)[11;14]. Each resonator is fabricated with a unique resonant frequency which identifies the channel. The resonators are coupled to a single microwave transmissions line, allowing hundreds to thousands of channels to be read out on a single RF coaxial cable. Input power onto the sensor shifts the resonator center frequency and shape. Thus input signal is measured by tracking the resonator.

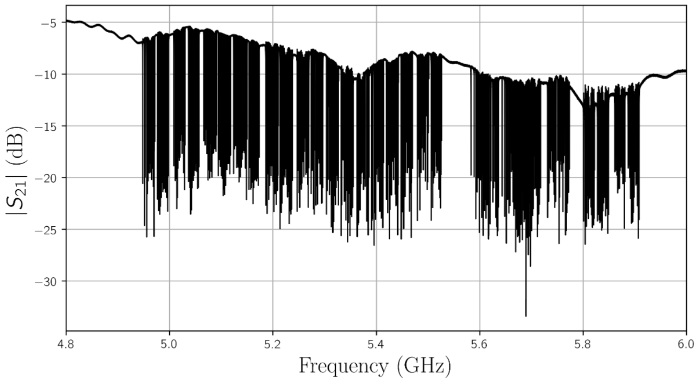

Figure 1: Measured transmission (S21) through the NIST 528-channel microwave SQUID multiplexer at 250 mK from 4.8–6 GHz[9]. Each sensor is coupled to one resonator. Tracking each resonator allows for parallel readout of thousands of channels.

The system can be broken into two parts - the cold and warm system. The cold system is primarily the fabrication of the sensors and resonators The warm system is the electronics that interrogates the resonators. This LOI focuses on the warm system.

A group at SLAC developed the SLAC Microresonator Radio Frequency electrons (SMuRF)[9], shown in Figure 2. SMuRF generates probe tones which interrogate the resonators and then digitizes the response. A unique capability of SMuRF is tone tracking, a fast feedback system which keeps the probe tone on the resonant frequency. This minimizes power through the RF system, and critically lowers the power onto the first cold amplifier. Excess power onto the amplifier drives it nonlinear, which ultimately limits the multiplexing factor. Tone tracking allows SMuRF to multiplex several thousand resonators compared to the $\sim$100 without tone tracking.

The first deployment of SMuRF was at the South Pole on the Keck Array telescope[5]. A TES focal plane that had previously been deployed using a different multiplexing scheme was retrofitted with RF resonators and observed for the 2019 season. This allowed for the comparison of readout performance between $\mu$Mux and the legacy readout system. This same system is currently being deployed on the Simons Observatory but at a much larger scale[7].

There are two development paths under consideration for the SMuRF electronics. The first is to develop a space compatible package on a RF system on a chip (RFSoC). This work is funded an ongoing. This will

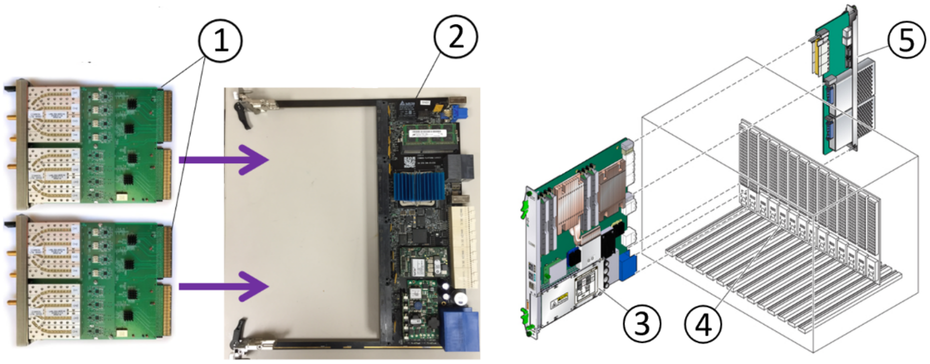

Figure 2: The SMuRF electronics. 1. High and low band RF cards 2. FPGA carrier card 3. A complete SMuRF readout card. One carrier card with two RF cards 4. The commercial ATCA crate. 5. The Rear Transition Module which handles slow (non-RF signals)[9].

unlock microwave resonators as a viable technology for balloon and space missions in the coming years. As an ancillary benefit, the packaging will be smaller than the existing ATCA platform, allowing closer packaging of the warm electronics.

The second development path is the readout of KIDs. The existing SMuRF system has already demonstrated successful readout of KIDs in limited lab demonstrations. With additional development, SMuRF is expected to be able read out 10k-20k KIDs on a single coax line compared to 4000 for TESs via $\mu$Mux. This is largely due to the higher resonator Qs of KIDs, lower excitation power, and possibly not requiring tone tracking.

SMuRF has already deployed the highest multiplexing factor of any superconducting sensors on the Keck Array. It will beat its own record on the Simons Observatory. As the physics community looks to the future, it will need ever higher multiplexing factors in smaller form factors. Ongoing development of SMuRF will answer that call.

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