

SPECTRA

SMuRF and SPECTRA

scalable readout for superconducting & quantum sensors from the CMB to rare-event searches



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U.S. DEPARTMENT of ENERGY

SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Outline

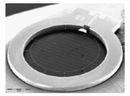


SPECTRA

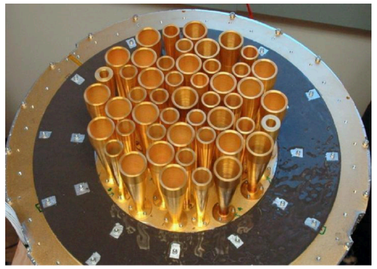
- How CMB broke through the scaling barrier
  - μMUX: Microwave multiplexing
  - SMuRF: SLAC Microresonator RF Electronics & Tone tracking
- Recent extensions beyond μMUX-CMB-TES: MKIDs, X-ray microcalorimeters, qubit-based sensors for dark matter and rare events.
- SPECTRA: Scalable Platform for Experiment Control,Tone-tracking, and RF Acquisition
- Cryo-ASICs: Move some RF complexity to cryogenic temperatures

The scaling challenge for CMB of the 2020s and 30s

How to read out O(100,000) sensors

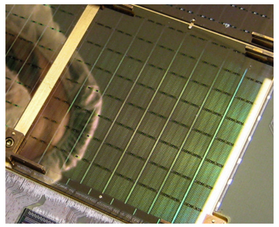


Gen-1: Hand assembly
O(1) sensor module

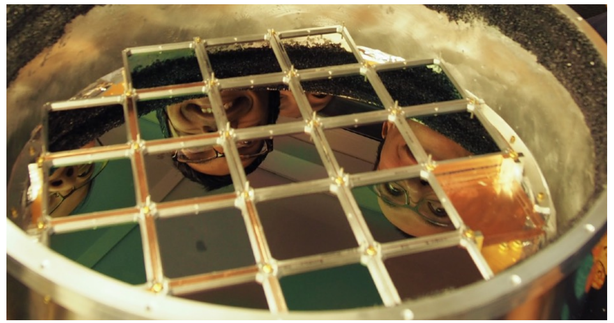


O(100)-pixel cameras
Pixel-density limited

75 mm

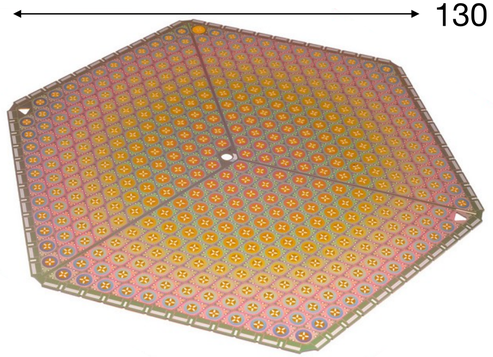


Gen-2: Monochromatic Arrays
O(100) sensor module

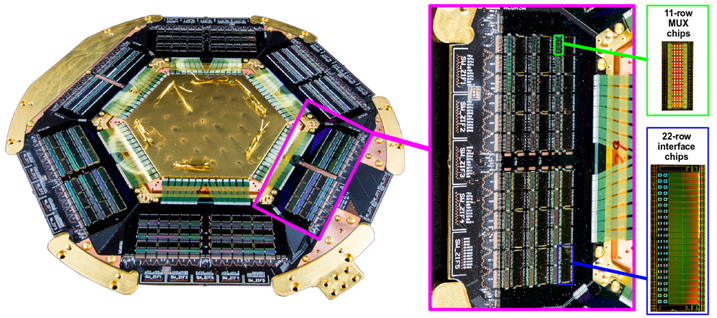


O(1000)-pixel cameras
Pixel-density limited

130 mm



Gen-3: Multi-color Arrays
O(1000) sensor module



O(10^3-10^4)-pixel cameras
Readout-density limited

?

Gen-4: Massively-multiplexed TES era
O(10^5)-pixel cameras

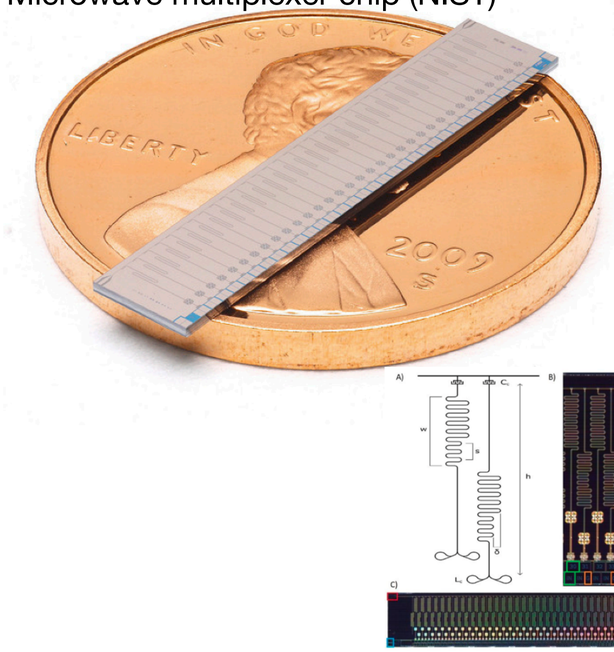
Challenges for every generation of sensitivity advancement

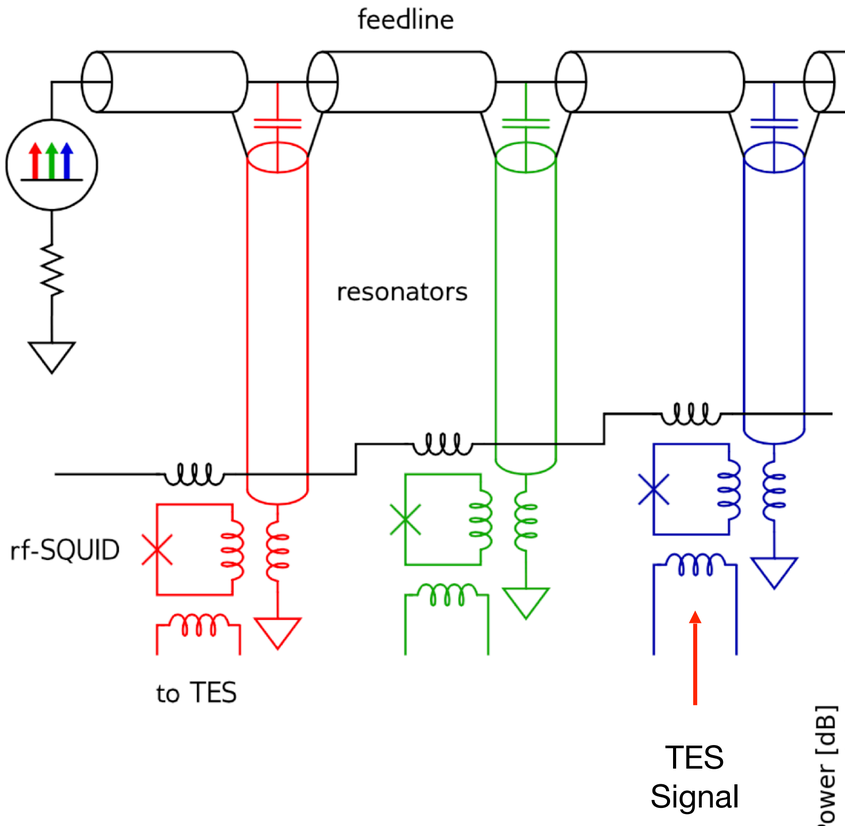
Pictures from BICEP, ACT, NIST

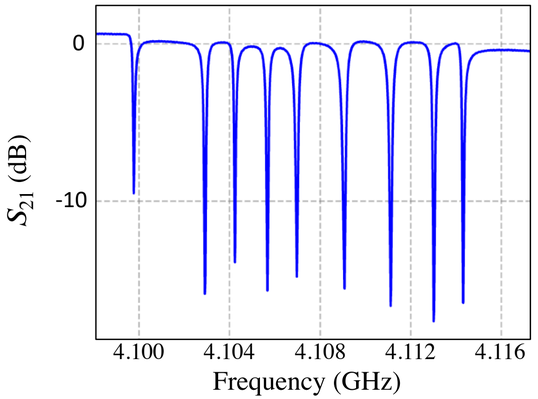
Microwave Multiplexing of TES bolometers

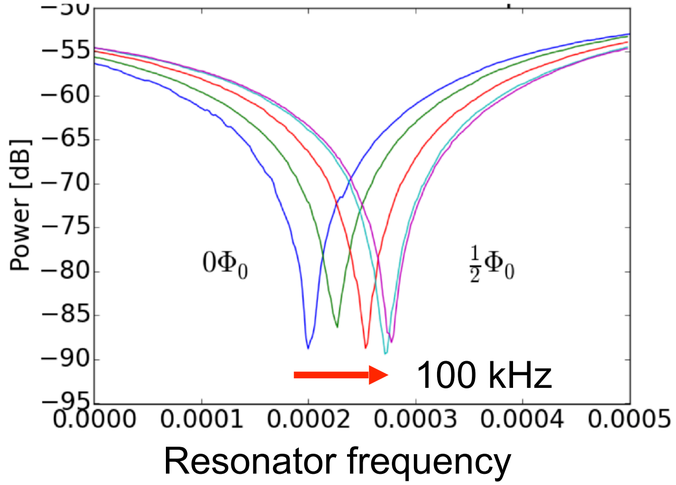
"FM Radio readout"

Microwave multiplexer chip (NIST)









- TES current → flux into rf-SQUID through input transformer
- Flux modulates the SQUID inductance
- SQUID loads a high-Q microwave resonator → resonance shifts
- Probe with microwave tone on a common feedline; demultiplex by frequency. *Flux ramp to linearize response.*
- ~1000 channels per coax pair, two coaxes, one HEMT

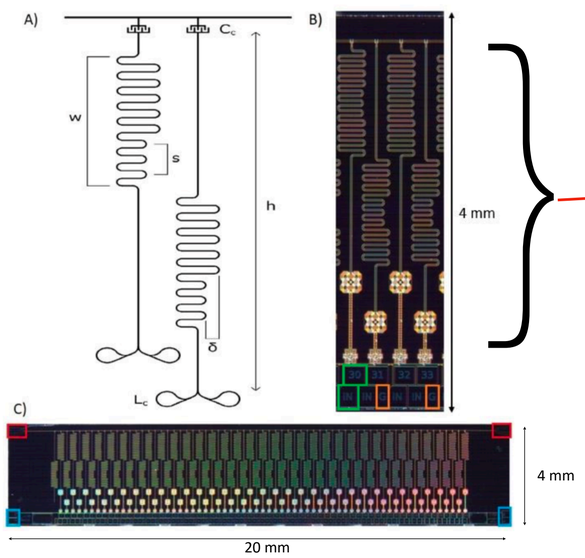
Irwin & Lehnert, APL 85, 2107 (2004)
J.A.B. Mates PhD Dissertation (2011)
Dober et al., APL 118, 062601

Co-designed CMB detector package

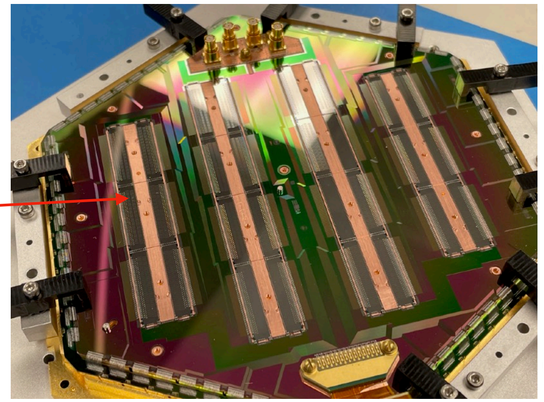
The Gen-4 1800-sensor CMB detector module

McCarrick, H. et al. ApJ 922, 38 (2021)

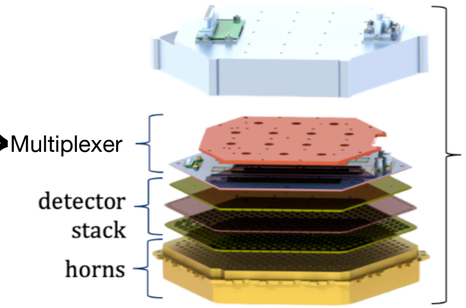
Collaborated with NIST to shrink microwave multiplexer for massive multiplexing

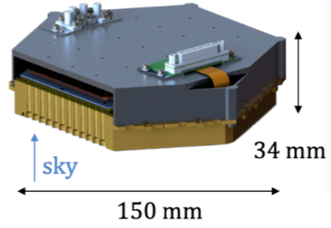


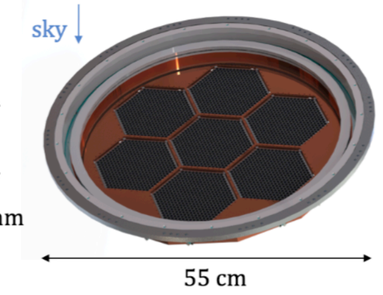
Dober, B. et al. APL 118, 062601 (2021)



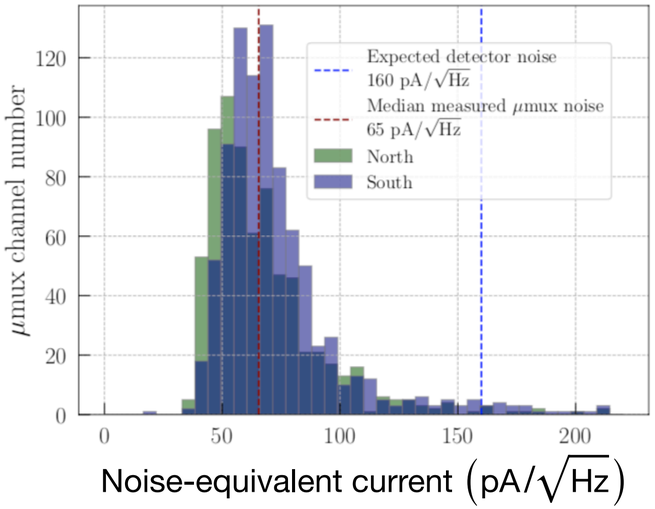
Collaborated with NIST, Princeton, UCSD, U. Michigan and *Simons Observatory* for design of new compact “tiling" detector module

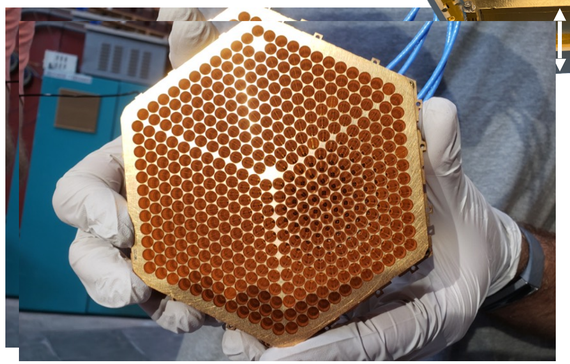




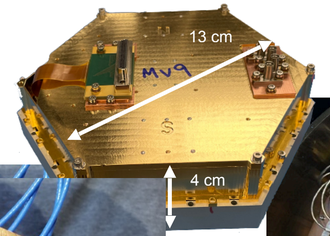


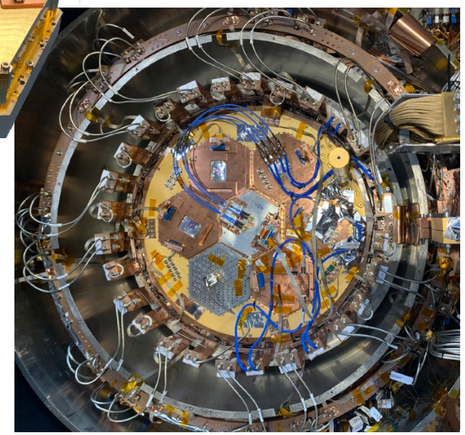
Constructed noise model and demonstrated suitability for Gen-4





Detector module





A Detector module installed in a Simons Observatory camera

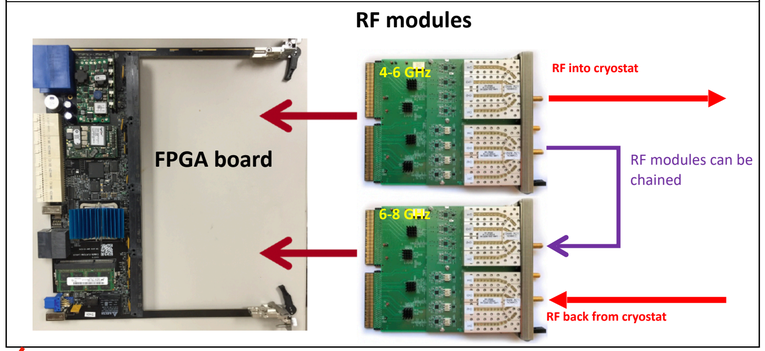
Max Silva-Feaver, Erin Healy, Heather McCarrick, Shawn Henderson, Cyndia Yu

SMuRF: SLAC Microresonator Radio Frequency Electronics

Manipulating thousands of superconducting resonators



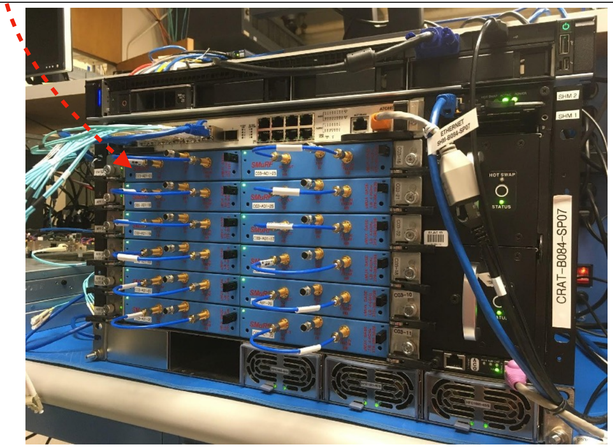
One SMuRF readout board can manipulate 3328 resonators



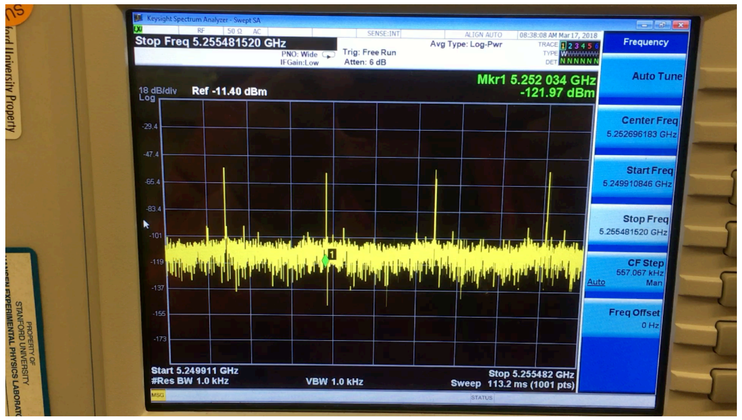
Tone-tracking: Enable a feedback loop to run *independently on each resonator* faster than recorded sky signals.

Feedforward: Enable fast signal modulation on top of feedback for better instrument noise control

ATCA Crate of 6x SMuRFs, 20k channels



4-resonator tone-tracking demonstration



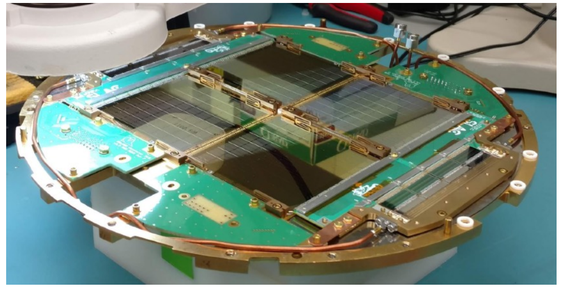
μMUX+ SMuRF enabled scale up from ~60 to ~1000 TES signal multiplexing for CMB

Yu et al., Rev. Sci. Instrum. 94, 014712 (2023)
Henderson et al., Proc. SPIE 10708, 1070819 (2018)

SMuRF deployed at scale for CMB

From ~500 to ~100,000 channels (2018-2026)

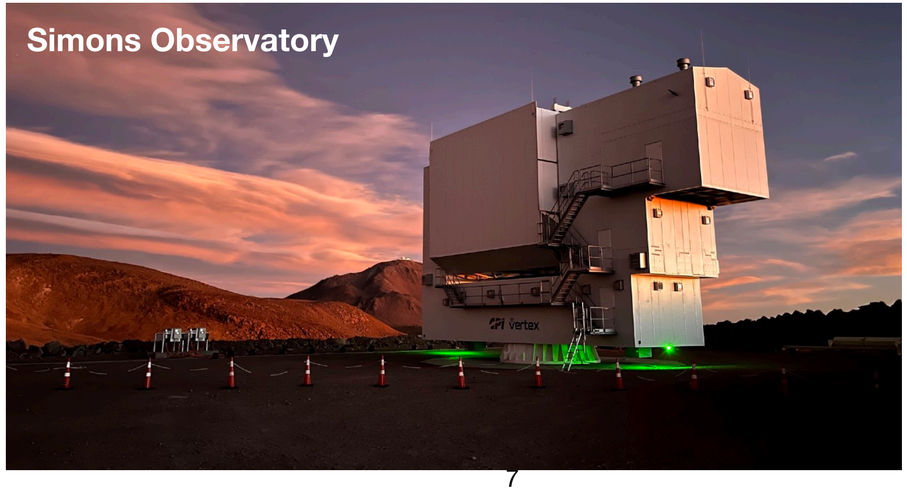
500 channel uMUX Demo
at Keck (Jan 2019)



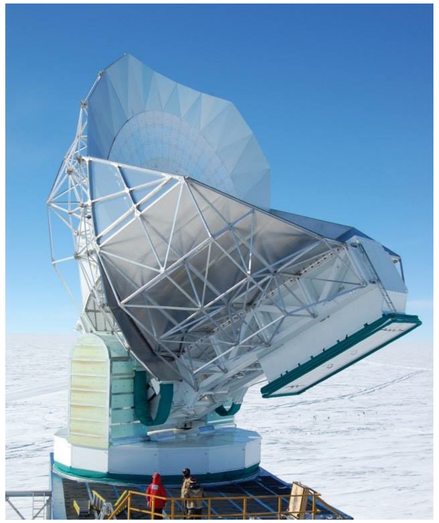


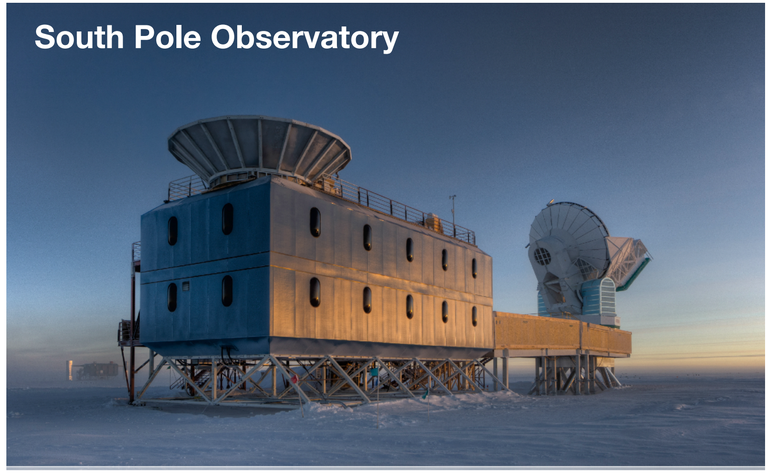
60,000 channels in the SO Large Aperture Telescope (Jan 2026)



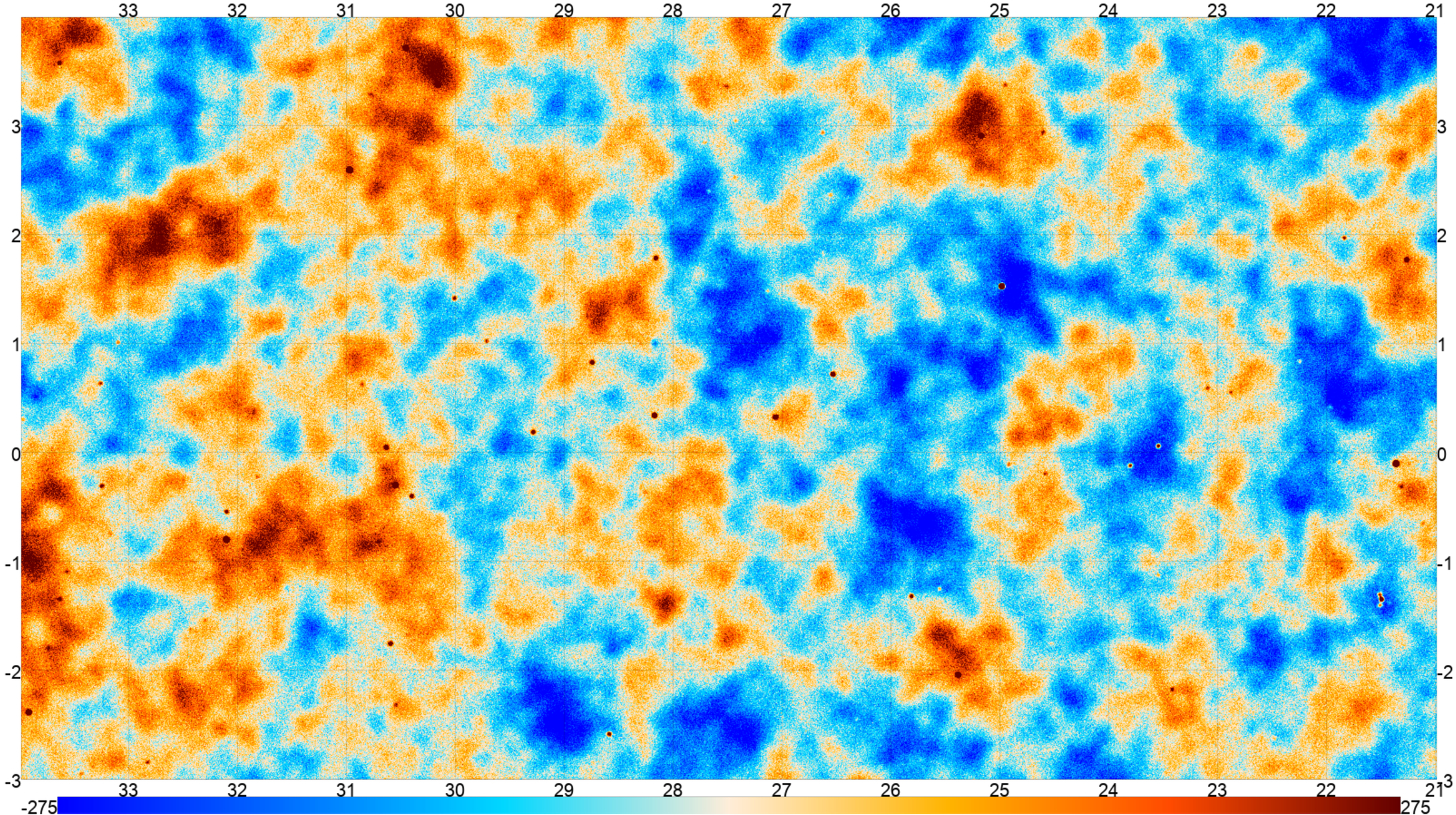


+25,000 channels planned in SPT

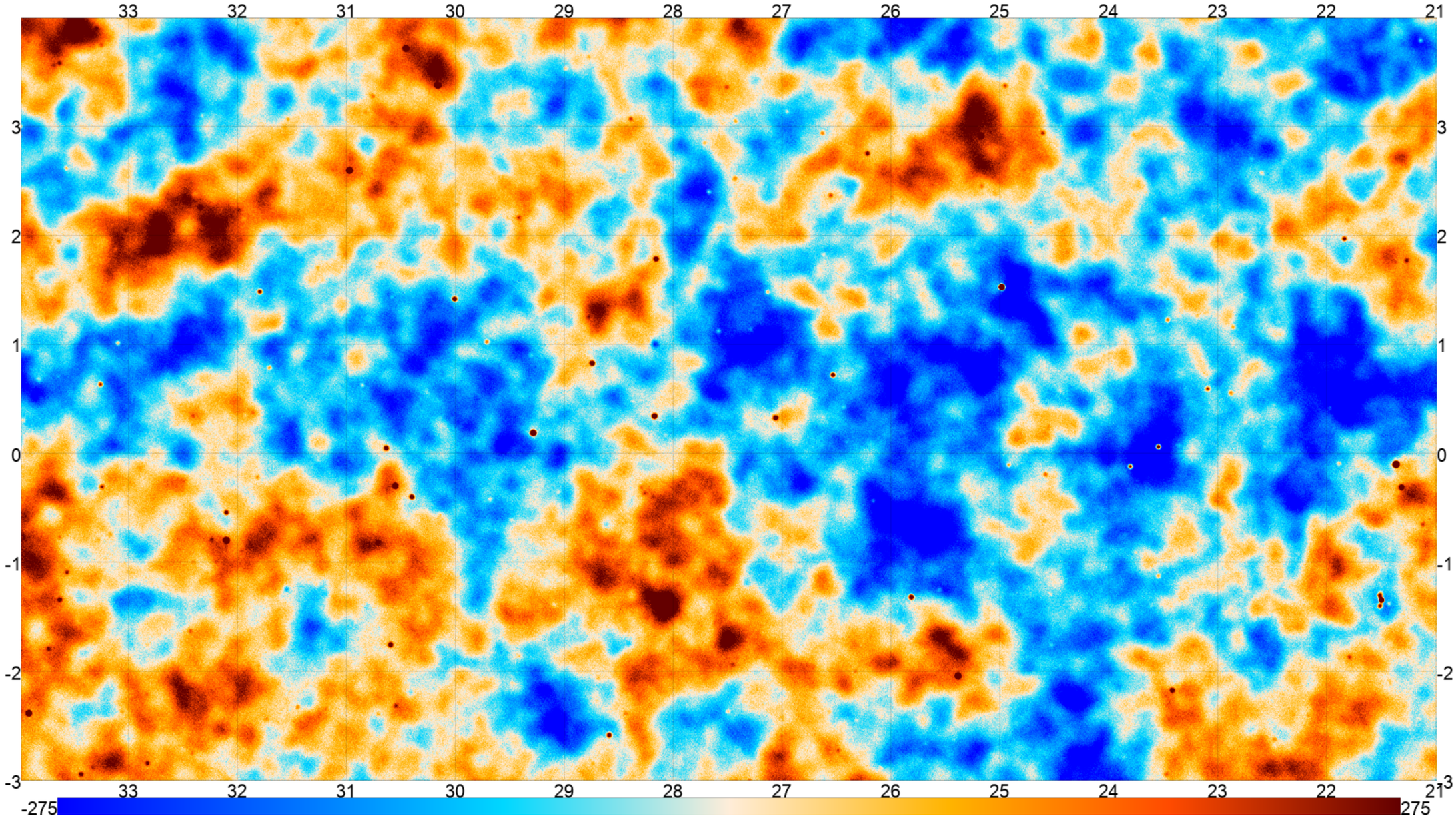




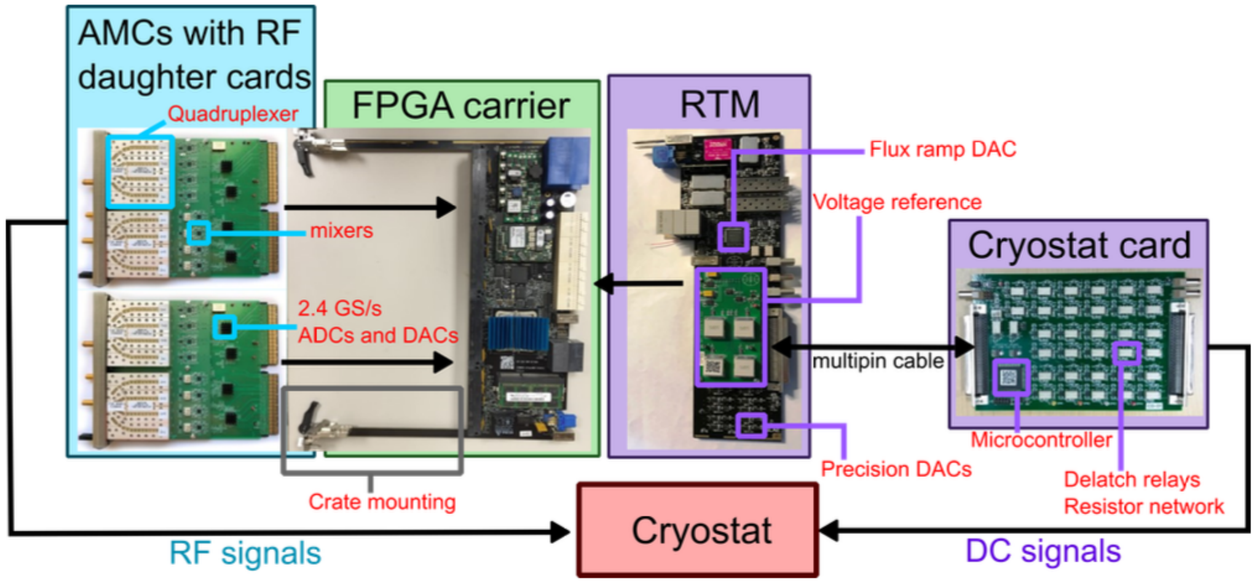
ACT+Planck DR6 90 GHz (5 year integration)



Simons Observatory LAT 90 GHz (~180 hour integration)



SMuRF Hardware

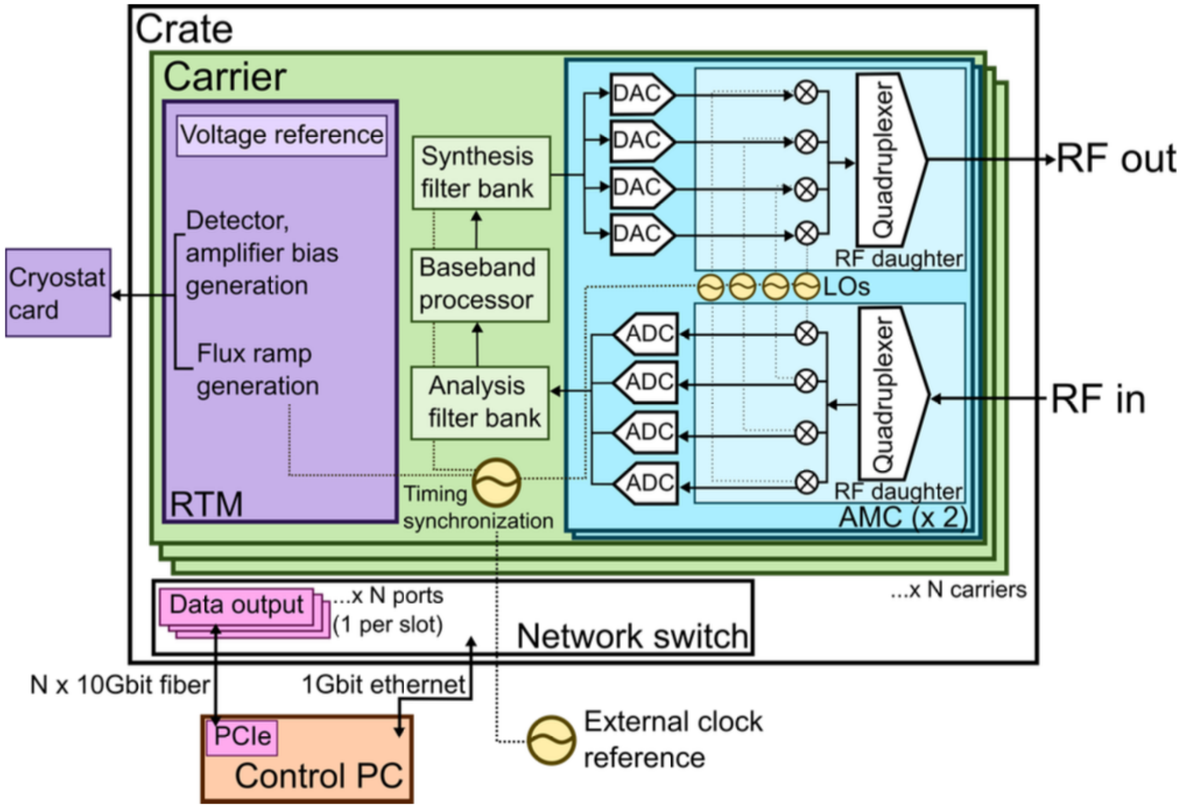


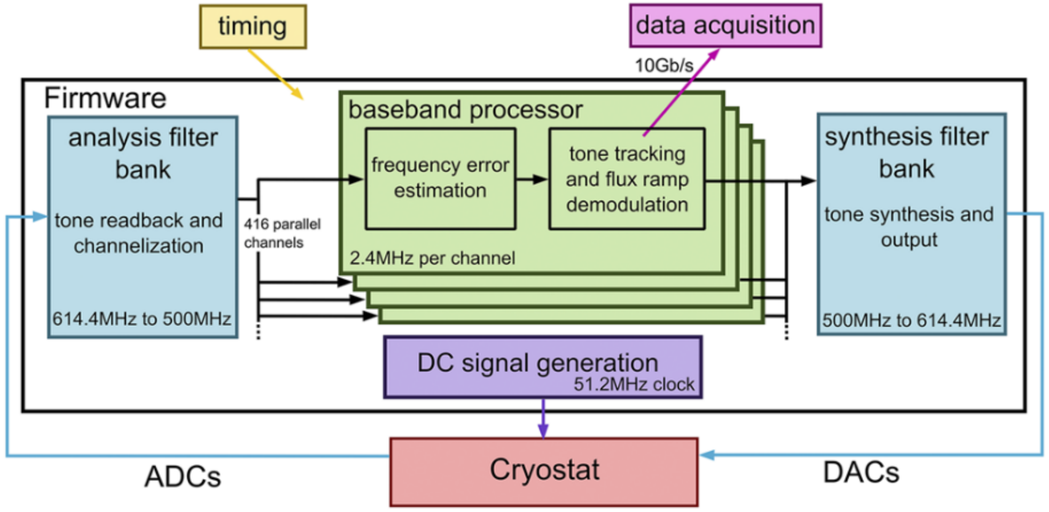
- Custom ATCA carrier board with *FPGA* (Xilinx Kintex UltraScale+ KU15P).
- *Discrete high-speed ADCs and DACs*, 4 GHz bandwidth in 8x 500 MHz bands on Advanced Mezzanine Cards (AMC). Cavity filters for 500MHz sub-band isolation. Up/Down mix with LO
- Low frequency (DC to few MHz) signals like TES biases, flux ramp, amplifier biases provided by Rear Transition Module (RTM). Signal conditioning on cryostat card
- Network/fiber connections to DAQ/control

Yu et al., Rev. Sci. Instrum. 94, 014712 (2023)

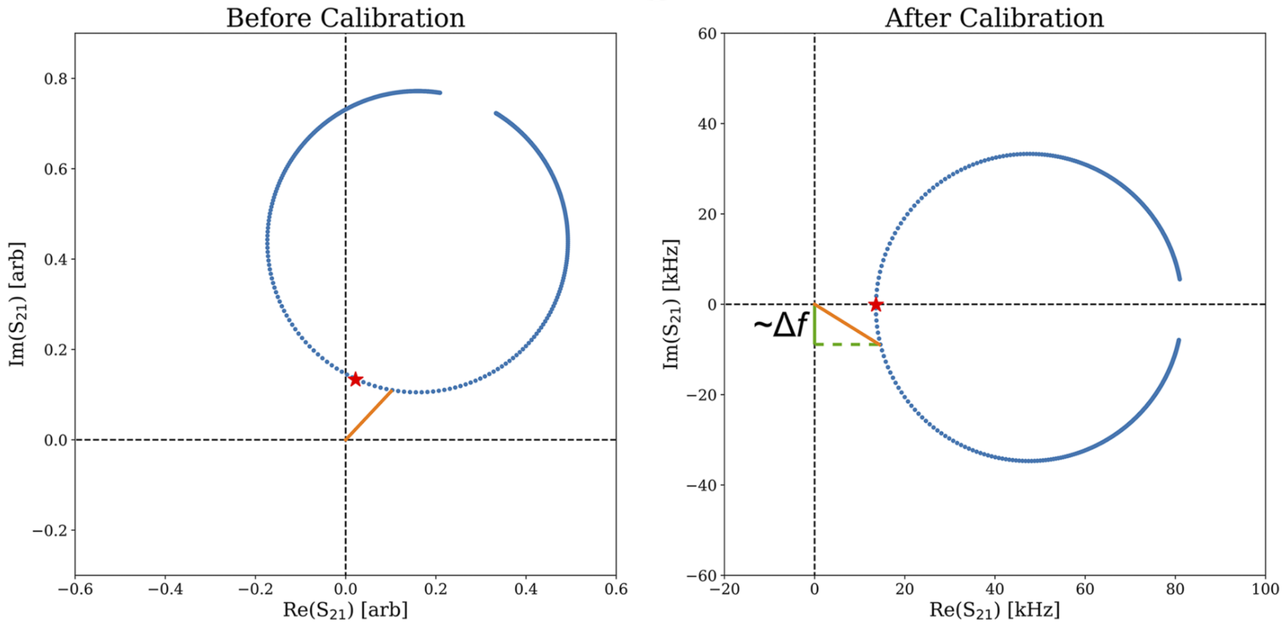
SMuRF Capability

- 4–8 GHz implementation, up to 3328 channels per RF line when low-bandwidth, high-channel count (~1.2 MHz channelization).
- *Polyphase filter banks* for RF tone synthesis and readback and a baseband processor for per-channel computations.
- *Closed-loop tone tracking on FPGA*: each tone follows its resonator minimum up to flux ramp bandwidth. (Next slide)
- Configurability for external reference, timing synchronization
- *Software-defined*: configure per-channel BW, gain, ramp parameters





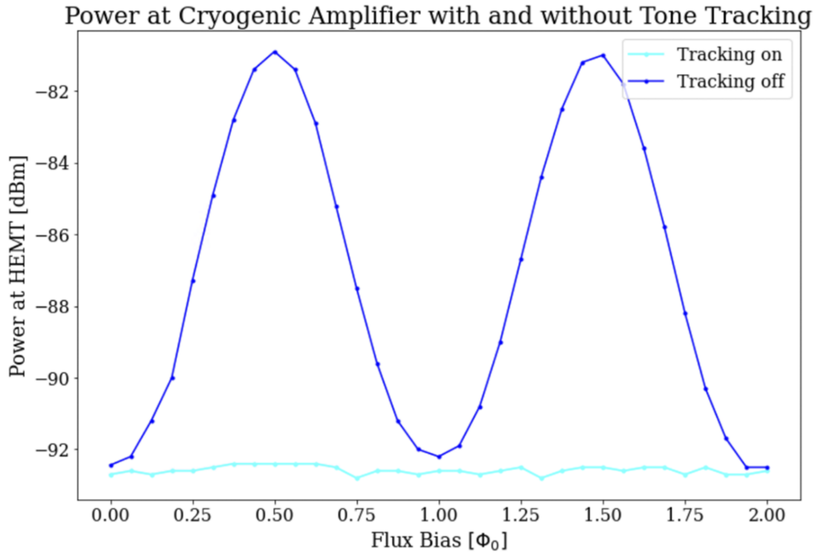
SMuRF Tone tracking

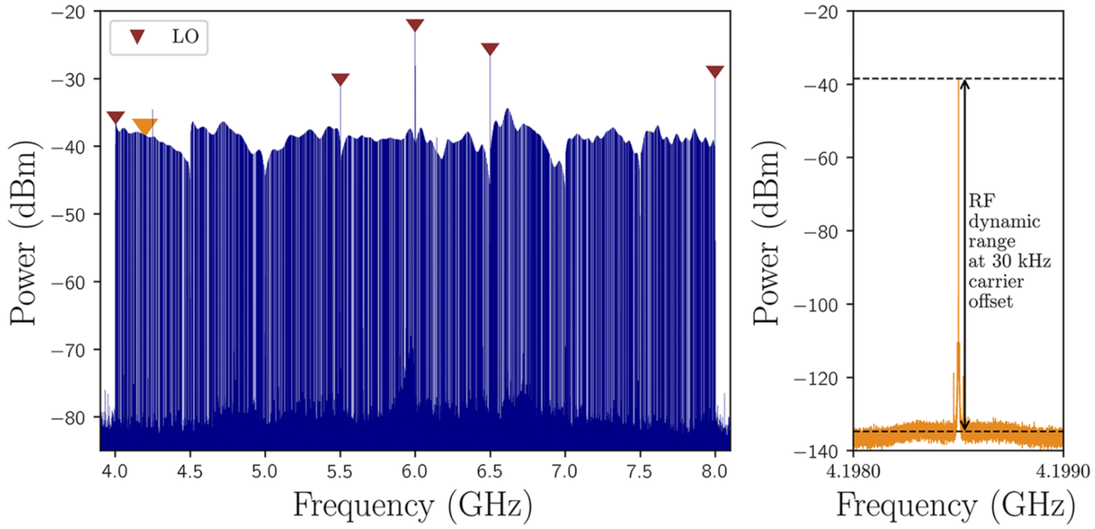


- *Estimate Frequency error*: A per-resonator η rotates/scales the resonance circle so small shifts project onto one quadrature: $\eta \equiv \dfrac{2\Delta f}{(I_+ - I_-) + i(Q_+ - Q_-)}, \qquad \widehat{\Delta f} \equiv \mathrm{Im}\left[S_{21}(\Delta f) \cdot \eta\right].$
- *Closed-loop feedback:* Stochastic gradient descent on $|\Delta\hat{f}|$ at 2.4 MHz updates the DDS tone, fitting M=3 harmonics of the flux ramp: $\vec{\alpha}[n+1] = \vec{\alpha}[n] + \mu\ \widehat{\Delta f}\,[n]\,\vec{h}[n]^{\mathsf{T}}$ where $\vec{h}[n] = \begin{pmatrix} \sin_1[n] & \cos_1[n] & \cdots & \sin_N[n] & \cos_N[n] & 1 \end{pmatrix}$

Yu et al., Rev. Sci. Instrum. 94, 014712 (2023)

SMuRF Tone tracking



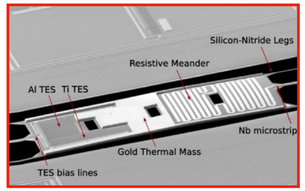


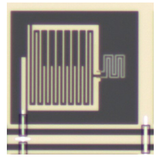
- **Suppresses intermodulation and spurious tones** to better than –100 dBc/Hz at 30 kHz offset, demonstrated for 2000 simultaneous tones.
- Allows tighter tone packing and higher multiplexing density per RF line.
- The prior math trick and tone tracking at high bandwidth improve multiplexing from **O(10)** to **O(1000)** !

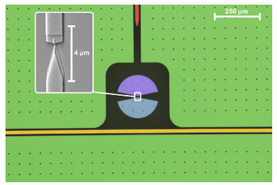
Yu et al., Rev. Sci. Instrum. 94, 014712 (2023)

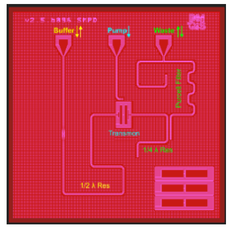
Extending to other operational regimes

Mode	Channels	Per-ch BW	Sensors
A. High MUX, low BW (legacy SMuRF)	1000–2000/ line	~kHz	μMUX+TES (CMB/LIM)
B. Low MUX, high BW (pulse readout)	10s–100s	MHz	μMUX+TES calorimeters, KIDs, KICS
C. CW dispersive monitoring	10s–100s	MHz CW	SQUATs, QPDs, cCPT, transmon-as-detector
D. Pulse-driven control + readout	1–10s	MHz pulses	SMPDs, transmon SPDs, fluxonium





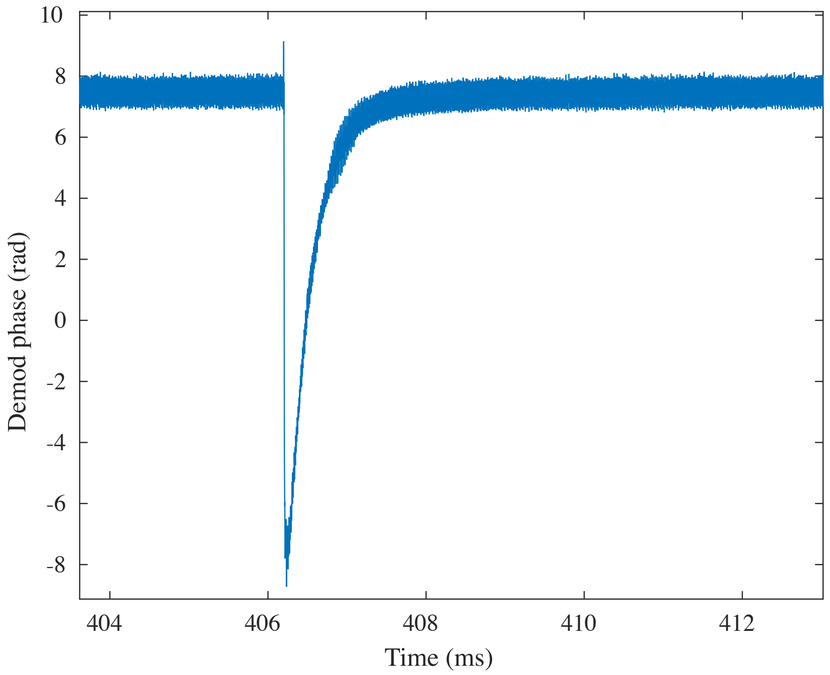




X-ray TES microcalorimeters

Mode B: High bandwidth demo at NIST

- μMUX + TES X-ray microcalorimeters at NIST, July 2019
- Wider 9.6 MHz PFB bins for fast-pulse applications
- ~100 kHz per-channel readout bandwidth
- CW X-ray tube source, mean energy ~3 keV
- Demonstrates Mode B (low MUX, high BW) on the legacy SMuRF

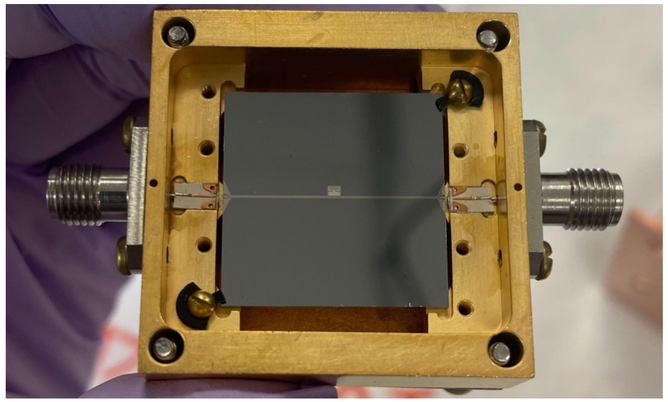


Measurement by Joe Frisch, Mitch D'Ewart, Shawn Henderson, Doug Bennett, Ben Mates, John Gard

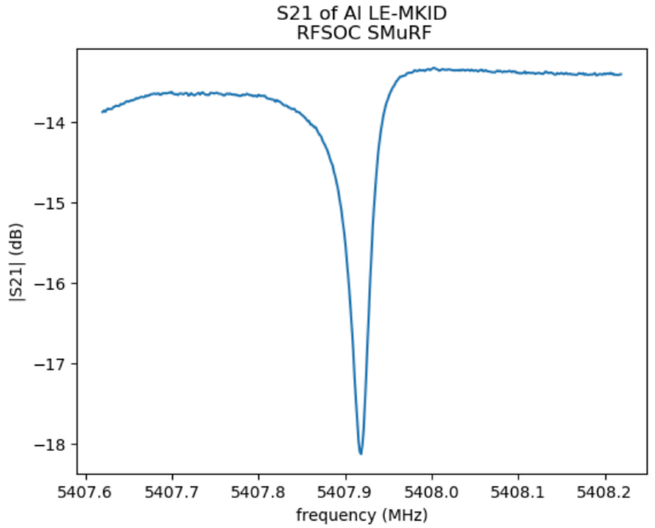
Mates et al., Appl. Phys. Lett. 111, 062601 (2017)

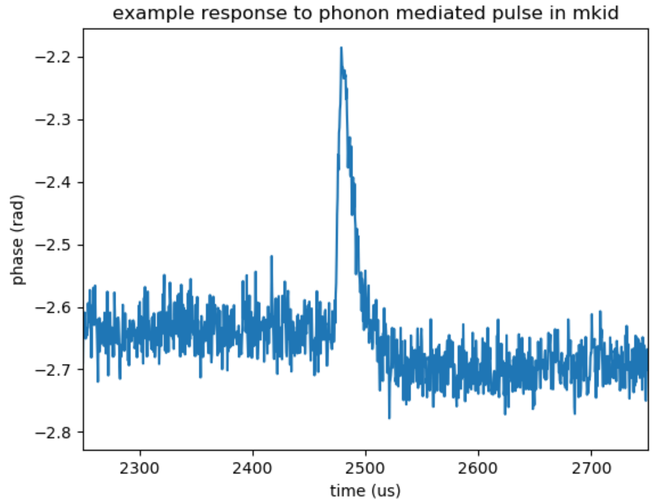
MKIDs

Mode B: High bandwidth pulses in Al lumped-element KID



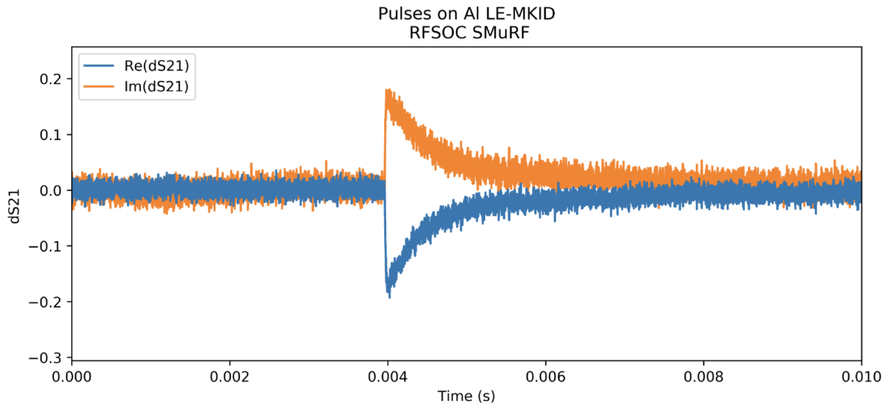
Bruce Bumble and Osmond Wen fab at JPL, March 2023





Measurement by Zoë Smith, Jenny Smith, Chao Liu

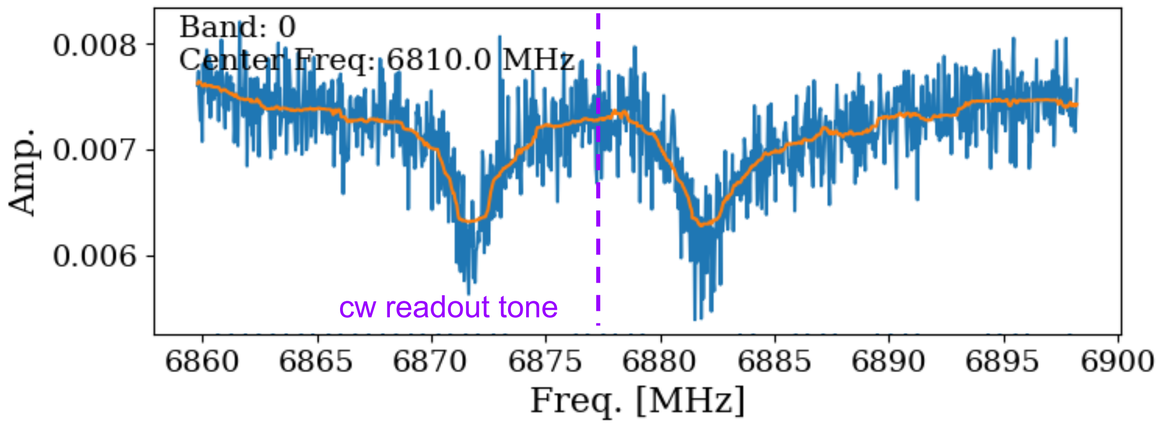
- KID pulse from laser-induced phonons (early 2025)
- SMuRFSoC: S21 frequency comb on Al LE-MKIDs (mid-2025)
- SMuRFSoC: KID pulse with IQ streaming (June 2025)
- Same firmware lineage, validated on a different sensor class

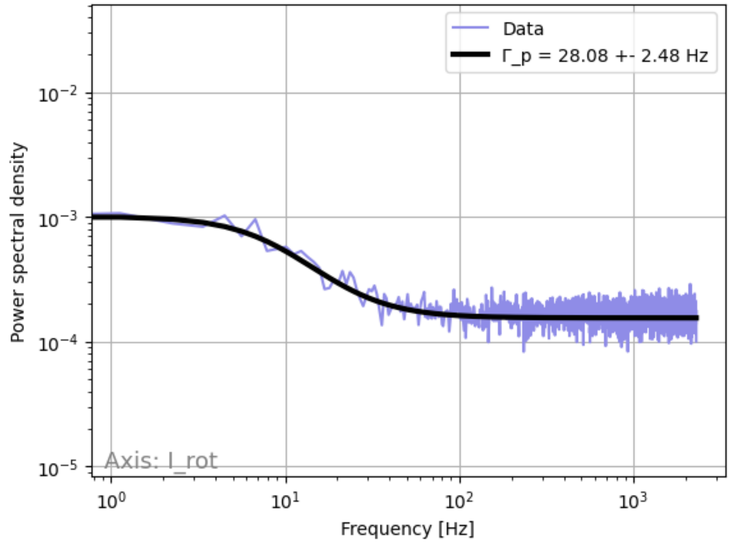


Superconducting Quasiparticle-Amplifying Transmons

Mode C: Single-device CW dispersive readout

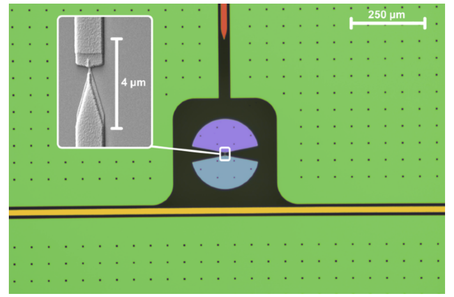
Transmission scan with SMuRF-supplied CW readout tone





PSD with parity-switching rate fit. Note: PSD plot uses VNA characterization data, not SMuRF data; SMuRF role is the CW readout.

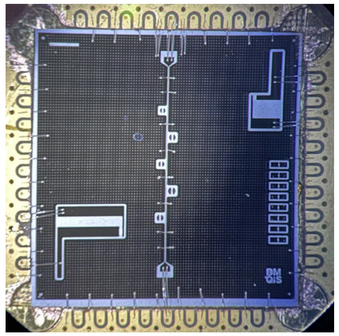
- **SQUATs: charge-coupled transmon whose parity flips on each quasiparticle tunneling event, read out in CW transmission**
- SLAC-fabricated SQUAT device, direct TL-coupled transmon
- SMuRF supplies the CW readout tone
- Parity-switching rate extracted from PSD fit
- Characterization vs. design parameters, drive power, temperature

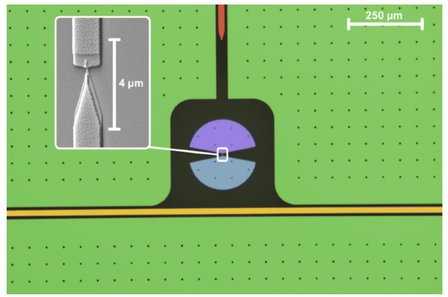


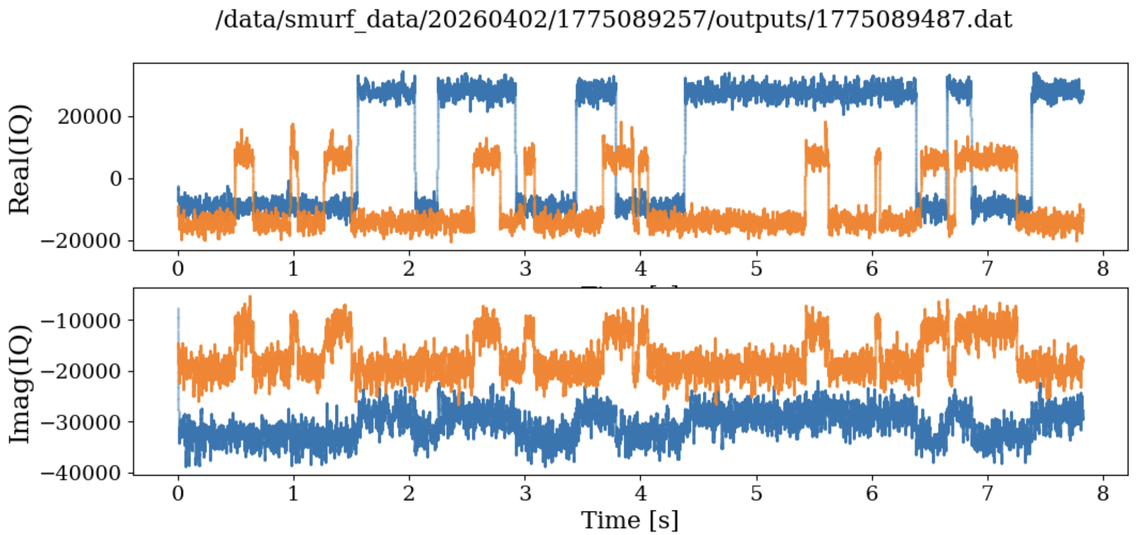
Magoon et al., arXiv:2601.16261

SQUATs

Mode C: First simultaneous multitone SMuRF readout of qubit-based sensors







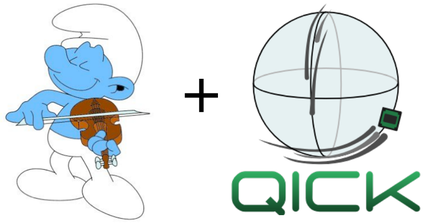
- Two Ta/Al SQUATs spaced ~1 mm on a chip
- Simultaneous multitone streaming, 35 kHz BW per channel
- First step toward correlated-event search and SQUAT arrays for DM
- Mode C demonstrated on real hardware, on real SMuRF data

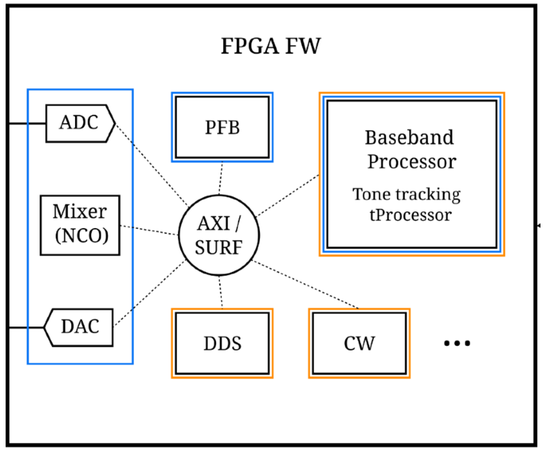
Magoon et al., arXiv:2601.16261

SPECTRA: Scalable Platform for Experiment Control,Tone-tracking, and RF Acquisition

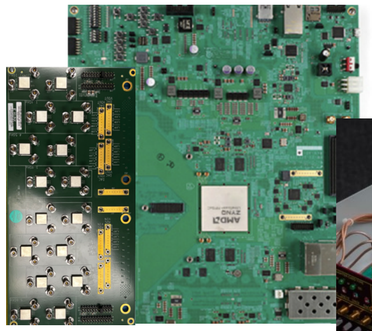
Multi-mode RFSoC readout for the broader sensor community

- *Evolution*: From one firmware regime to four; from custom FPGA to RFSoC; from proprietary to open source.
- *Team*: Collab with Fermilab, U. Chicago and recruiting broad user community across astro/ cosmo, dark matter, rare-event
- *Firmware*: SMuRF tone tracking + QICK pulse controls + modular variants for Modes A/B/C/D
- *Hardware*: RFSoC + RFMC daughter card, deployable on eval boards, QICK box, or SLAC ATCA carrier, depending on scale of application
- Software: open-source, lightweight frontend stack from U. Chicago (Vieregg group)

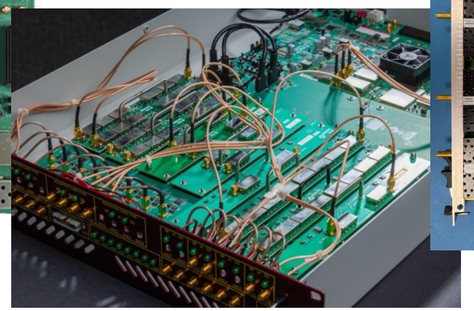




Eval Boards



QICK Boards

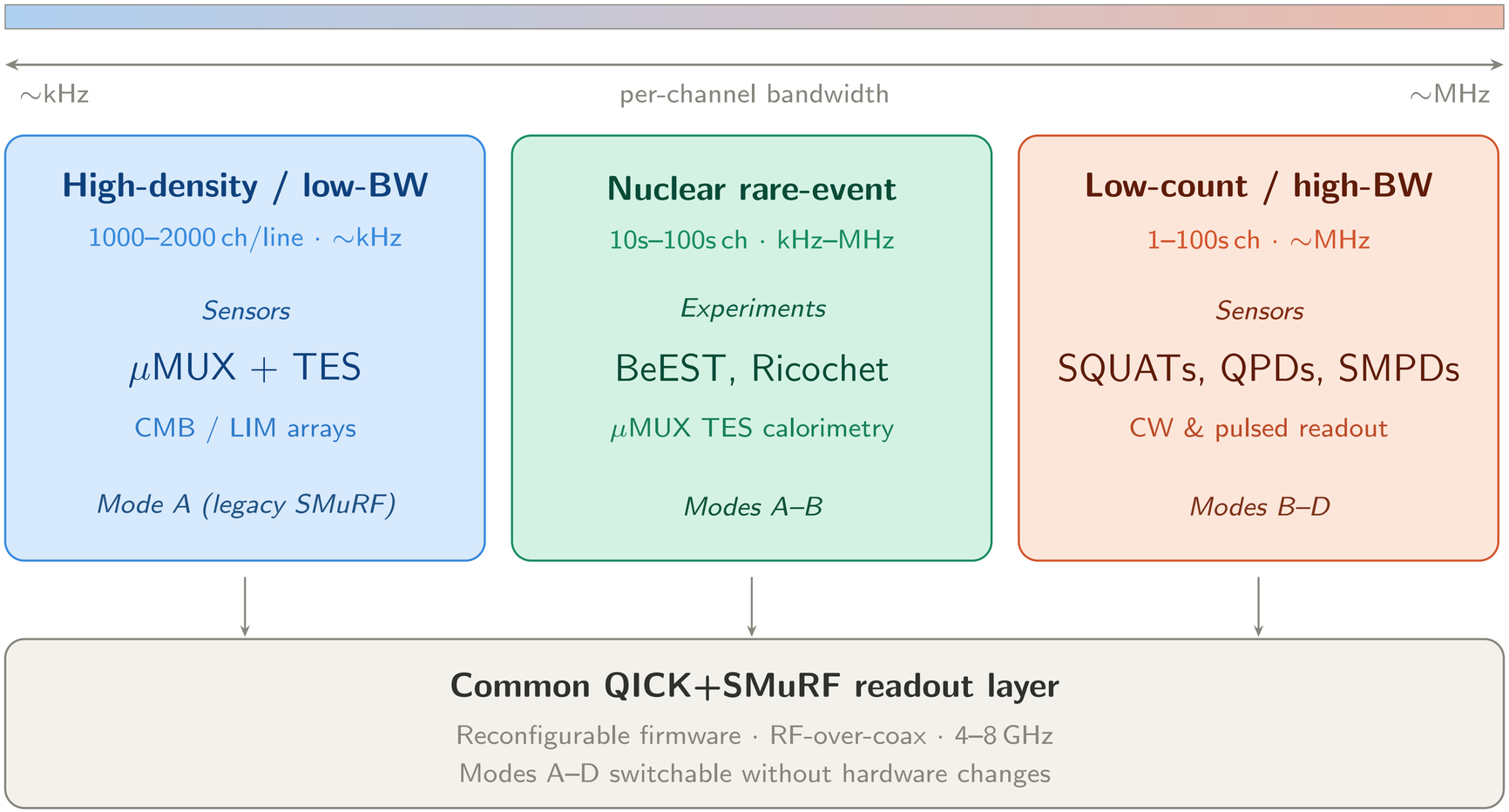


ATCA Carrier



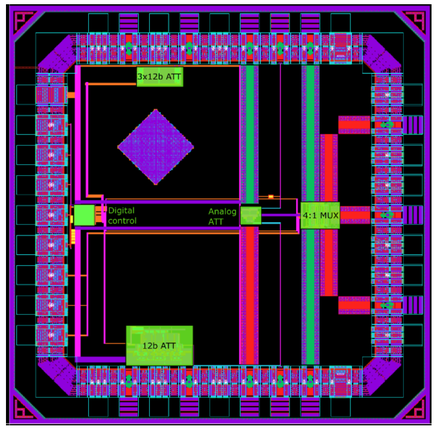
SPECTRA: Scalable Platform for Experiment Control,Tone-tracking, and RF Acquisition

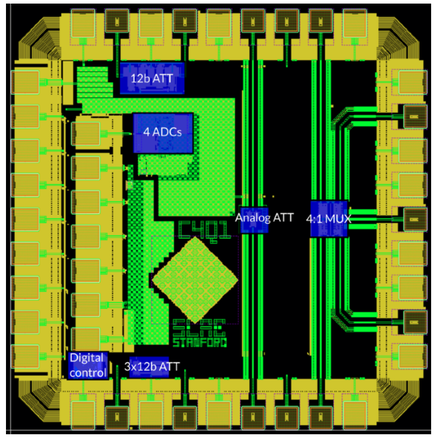
Multi-mode RFSoC readout for the broader sensor community



Cryo-CMOS

for Scalable Quantum Systems and Rare-Event Detection



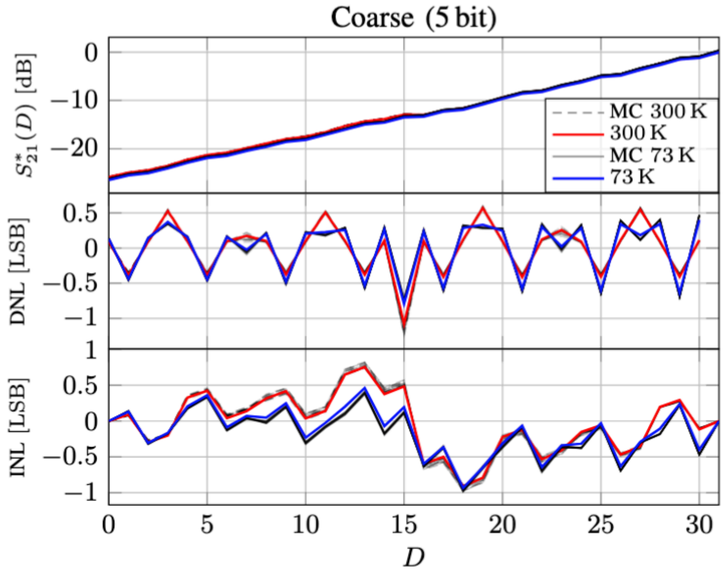


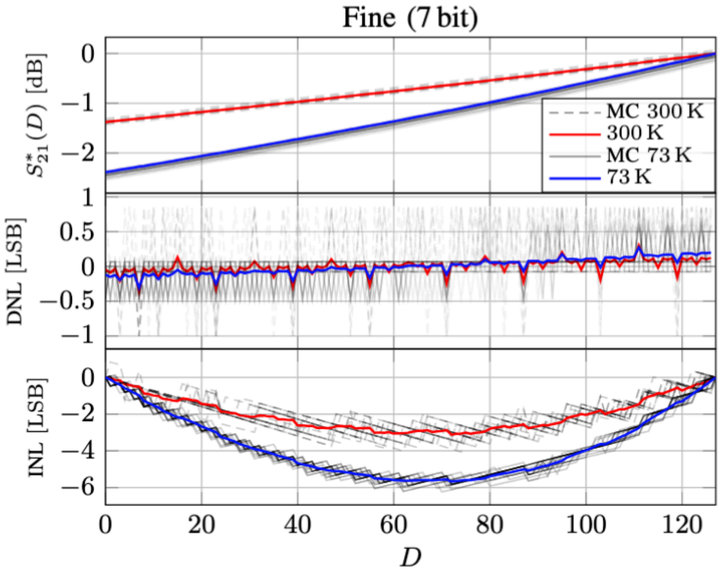
Also working with ASIC team to explore supplemental functionality at low temperature

C4Q1

RF switches & programmable attenuators
Top: GF 22 nm FDSOI
Bot: 28 nm CMOS
ASIC testing at 4 K and below is in progress.

Metric	Magnitude	Comment
Range of operation	$[0\,\mathrm{GHz}, 10\,\mathrm{GHz}]$	
Insertion loss	$< 2\,\mathrm{dB}$	Critical for the readout side
Switching time	$< 1\,\mu\mathrm{s}$	
Attenuation range	$[3\,\mathrm{dB}, 30\,\mathrm{dB}]$	
Power consumption	$< 1\,\mu\mathrm{W}$	Critical, as low as possible
Z_0	$50\,\Omega$	
Digital control		Dedicated pads for speed





Material from Aldo Perez

Conclusion and Outlook



SPECTRA

- **Legacy SMuRF is mature for μMUX readout** — deployed at the ~100,000-sensor scale on Simons Observatory. Adapts naturally to other low-BW, high-multiplexing applications.
- **The platform is being extended** to support three additional regimes: high-BW pulse reconstruction, CW dispersive monitoring, and pulse-driven qubit control and readout.
- **SPECTRA is the open-source, multi-mode successor** — combining SMuRF's tone tracking with QICK's tProcessor, deployable across eval boards, QICK box, and SLAC ATCA carrier. Development and protos over next ~1-2 years
- **We're expanding the user community — join us.**



SPECTRA

Thanks

For listening.

Materials acknowledgements:

SMuRF, uMUX: Shawn Henderson, Larry Ruckman, Ryan Herbst, Tristan Pinsonneault-Marotte, Zoë Smith, Jenny Smith, Chao Liu, Ben Mates, Doug Bennett, Hannes Hubmayr

SQUATs/cCPTs: Noah Kurinsky, Alex Droster, Hannah Magoon, Jadyn Anczarski, Taj Dyson, Taylor Aralis

QICK: Gustavo Cancelo, Sho Uemura

Cryo-CMOS: Aldo Perez

SPECTRA deployment tiers

Tier	Hardware	Specs	Use case
Eval board	ZCU208 + RFMC daughter	~$2k academic	Beginner, Small lab
QICK box	ZCU216 + QICK RF board	16 RF out / 8 RF in to 10 GHz	Small-scale experiment
SPECTRA ATCA carrier	Custom SLAC RFSoC + RFMC	8 ADC × 5 GSPS, 8 DAC × 9.85 GSPS, 100 W, 60 A VCCINT	Large experiments

Noise budget

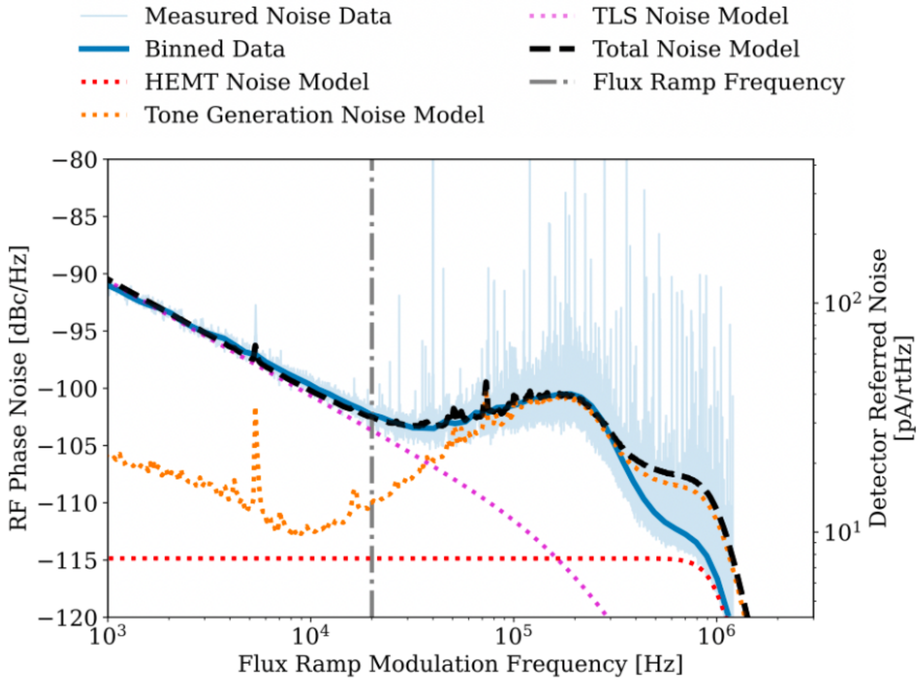
- HEMT-noise dominated readout in single-channel mode (Mates thesis Eq. 2.163):

$$S_\Phi^{\mathrm{HEMT}} \approx \frac{4\,k_B T_N L_J}{\pi\, f_0}$$

- Numerical example:

$$T_N = 6\,\mathrm{K},\ f_0 = 6\,\mathrm{GHz},\ L_J = 60\,\mathrm{pH} \Rightarrow \sqrt{S_\Phi} \approx 0.58\ \mu\Phi_0/\sqrt{\mathrm{Hz}}$$

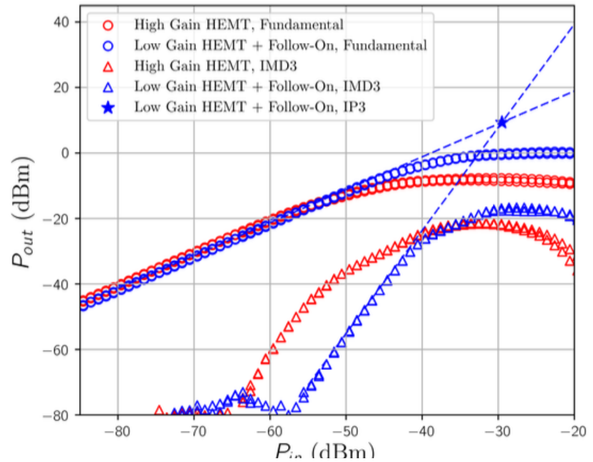
- However, in multi-channel realistic operation, balance TLS and DAC noise
- Junction shot noise typically subdominant in modern designs
- KI-TWPA preamp reduces SQUID flux noise by roughly 2-3× over HEMT-only readout (Malnou 2023). Open-loop demonstration approaches the quantum limit; flux-ramp-modulated noise sits a factor of 2-3 above due to demodulation overhead and system terms (0.45 → 0.20 μΦ_0/√Hz.).

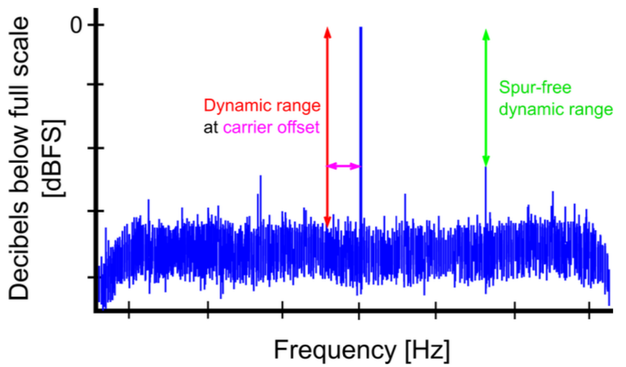


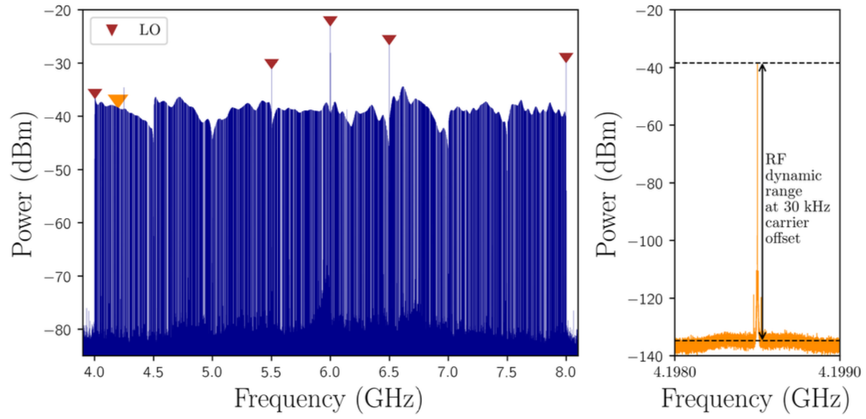
Driving factors

dynamic range, bandwidth, phase noise

- Dynamic range:
  - Linearity scales as N^2 without tracking; ≈ N with tone tracking
  - Tone tracking relaxes amplifier linearity by 30 dB or more
- Per-resonator bandwidth:
  - Need O(1 MHz) per channel to capture 10 kHz flux ramp adequately
  - Sets the ADC sample-rate-to-channel-count tradeoff
- Phase noise:
  - Target around –110 dBc/Hz at 30 kHz offset
  - Sets the per-channel readout-noise floor at the resonator
- Flux-ramp rate ≈ 10 kHz balances aliasing penalty vs TLS noise







Flux-ramp linearization

- Problem: SQUID response is periodic in Φ_0; per-channel feedback would kill multiplexing
- Solution (Mates 2012): apply common sawtooth flux ramp to all SQUIDs
- Each cycle: SQUID produces a near-sinusoidal carrier waveform at ω_m
- TES signal rides as a slow phase shift on this carrier
- Demodulate offline (Mates thesis Eq. 8.1):

$$\varphi = \arctan\left[\frac{\sum_t x_t \sin(\omega_m t)}{\sum_t x_t \cos(\omega_m t)}\right]$$

- **√2 noise penalty is the cost; no cold feedback wires is the benefit**
- Modulation rate ≈ 10 kHz balances aliasing vs TLS noise

