# RFSoC-based Readout and Characterization Platform Development at SLAC

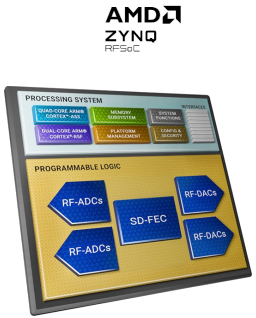
**Chao Liu on behalf of SLAC TID&FPD collaborators**

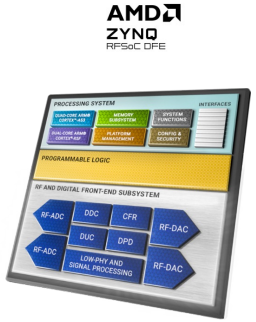
CPAD Workshop, November 2023, SLAC

U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

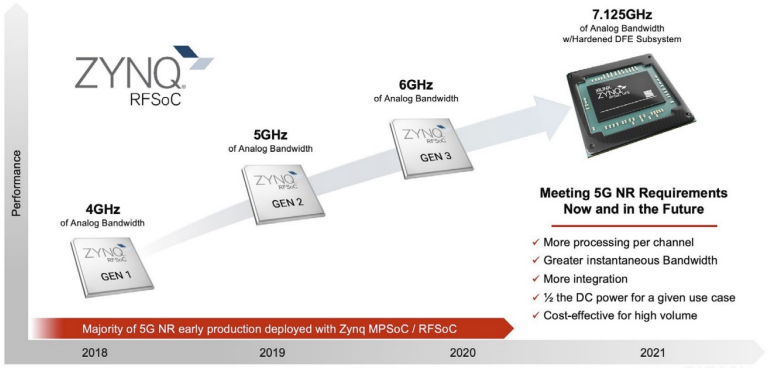
# RFSoC Platforms Supported at SLAC




**RFSoC – one-stop shop for readout:**

- **RF ADCs**
- **RF DACs**
- **PL**
- **PS**



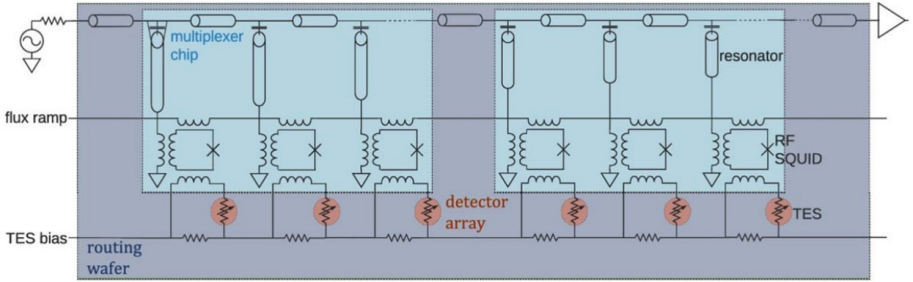

Ref: https://www.xilinx.com/products/silicon-devices/soc/rfsoc.html

## Evaluation Platforms

- **Open-source firmware and software and example projects with commercial evaluation hardware – great for small scale R&D projects**
  https://github.com/slaclab/Simple-ZCU208-Example and other platforms
- **ZCU111 – RFSoC GEN 1 XCZU28DR**
  - 8x 4.096GSPS ADCs and 8x 6.554GSPS DACs
  - Support GEN1 device based hardware
- **ZCU216 – RFSoC GEN 3 XCZU49DR**
  - 16x 2.5GSPS ADCs and 16x 9.85GSPS DACs
  - High channel count applications
- **ZCU208 – RFSoC GEN 3 XCZU48DR**
  - 8x 5GSPS ADCs and 8x 10GSPS DACs
  - High bandwidth applications
- **ZCU670 – RFSoC DFE XCZU67DR**
  - 8x 2.95GSPS ADCs, 2x 5.9GSPS and 8x 10GSPS DACs
  - Applications need higher RF input frequency
- **RFSoC 4x2 Kit – RFSoC GEN 3 XCZU48DR**
  - 4x 5GSPS ADCs, 2x 9.85GSPS DACs
  - Academic applications with low channel count
  - **Low cost and low barriers to entry**

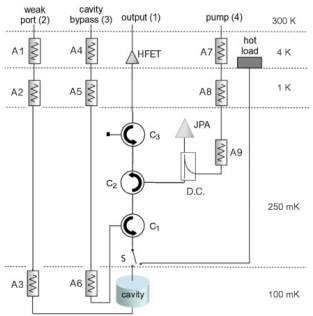
# Science Drives

## Microwave SQUID multiplexing (μMUX) for CMB experiments



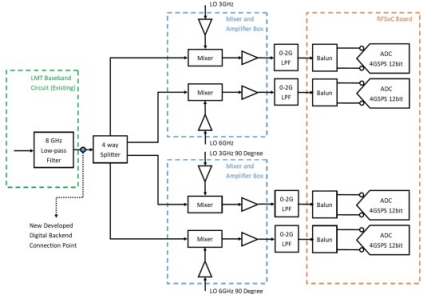

McCarrick et al. https://arxiv.org/abs/2106.14797

## Axion dark matter experiment



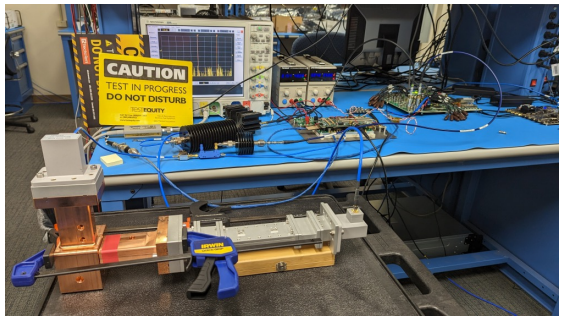

Bartram et al. https://arxiv.org/abs/2010.06183

## Heterodyne-based radio astronomy receivers

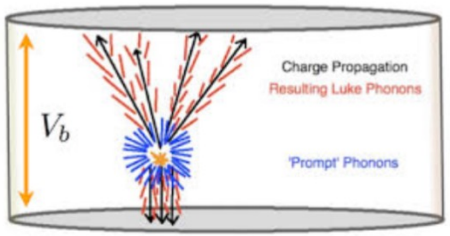


Liu et al. https://ieeexplore.ieee.org/abstract/document/9814190

## LLRF control of Linac




## Quantum Sensing R&D For Dark Matter




Kurinsky @ Aspen23

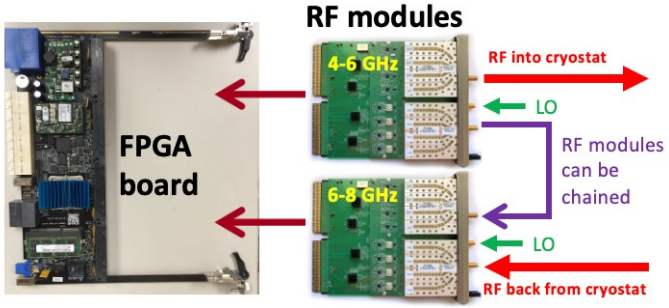
# SMuRF – μMUX at scale for CMB

## SLAC Microresonator Radiofrequency Electronics = *SMuRF*

- Generate and readback up to 3328 RF carriers in 4-8 GHz bandwidth.
- Unique "tone-tracking" ability sets SMuRF apart from other systems
  - Game changer – enables >1000x channel readout/RF line

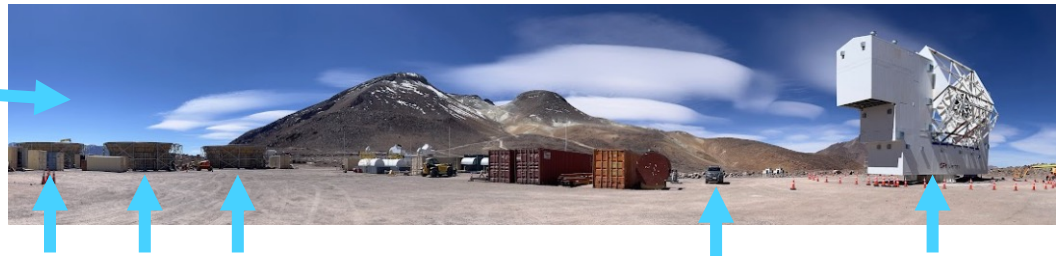
    *C. Yu et al., Rev. Sci. Instrum. 94 (2023)*

**SMuRF readout for 1x 2000 TES CMB wafer**




**An integrated 6x SMuRF system – readout for >20,000 TESs**

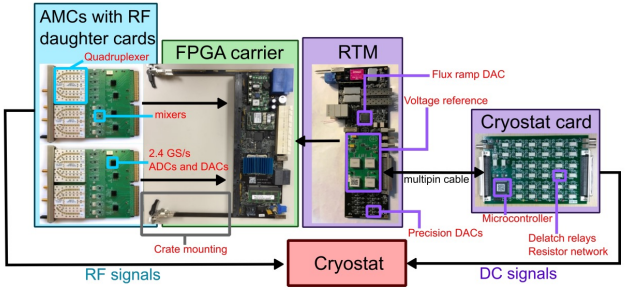

**48x SMuRF systems deploying now on Simons Observatory in Chile**



# SMuRF Electronics and SMuRF-RFSoC

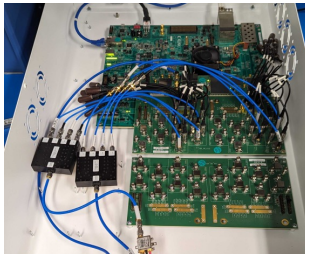
SLAC

**SLAC Microresonator RF (SMuRF) Electronics**

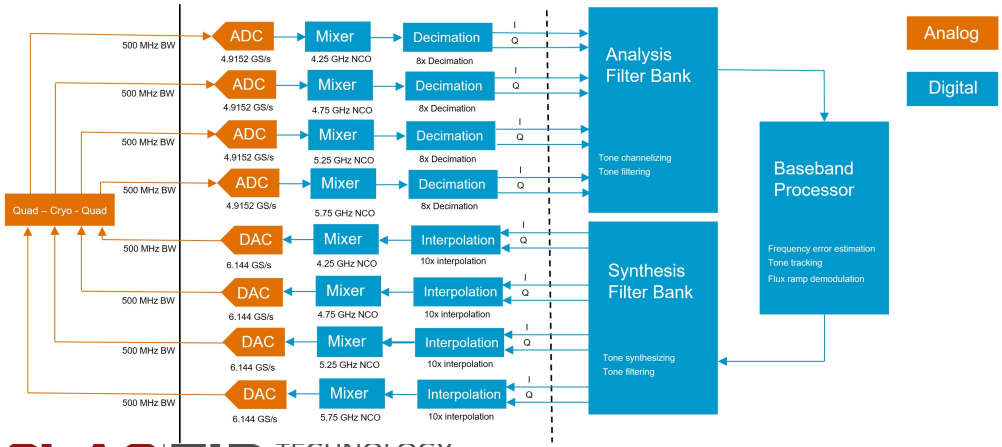



Yu et al. https://arxiv.org/pdf/2208.10523

**SMuRF-RFSoC**



**SMuRF-RFSoC System Block Diagram**




## Readout System Summary

- **SMuRF electronics**
  - Analog mixers
  - Discrete data converters with JESD interface
- **SMuRF-RFSoC - upgrade path for SMuRF**
  - Integrated ADCs and DACs datapath
  - **NO JESD interface**
  - **NO analog mixer needed for 4-6 GHz**
  - **Lower cost and barriers of entry**
- **μmux firmware as example**
  - SMuRF firmware ported to RFSoC platform
  - Firmware and software are just scaled down or modified versions for other application
  - Performance characterization widely applicable

# Motivation for Characterization

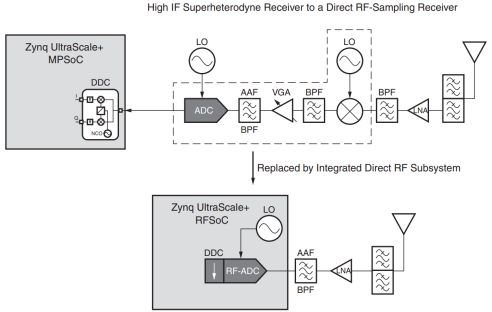
## Higher order Nyquist zone / Direct RF sampling

- Reduced complexity of RF front end
  - DAC generating RF signal at 2nd Nyquist zone
  - ADC direct sampled and aliased image as signal
- Reduced analog impairments: matching and LO leakage
- **Compact size, low cost and low barriers of entry**
- **Does performance meet HEP requirements???**

## Key performance parameters

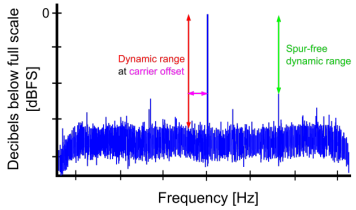
- Spurious Free Dynamic Range (SFDR) – the overall dynamic range for measurement
- Intermodulation distortion – intermod-products can land on other resonators on same RF line
- RF dynamic range – measured at a specific offset of the carrier frequency and requirement for μMUX is -100 dBc/Hz at 30 kHz offset to achieve the high channel density

**Heterodyne to direct RF-sampling**



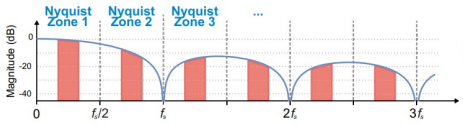

Ref: https://docs.xilinx.com/v/u/en-US/wp489-rfsampling-solutions

**SFDR and RF dynamic range**

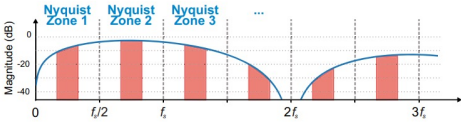



Yu et al. https://arxiv.org/pdf/2208.10523

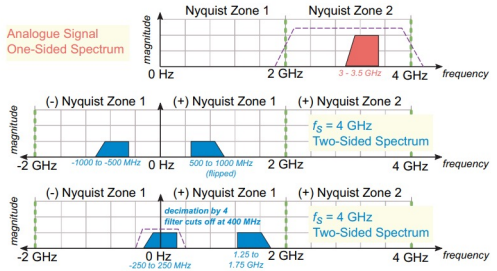
**DAC in Zero-order Hold Mode**




**DAC in Mixed Mode**



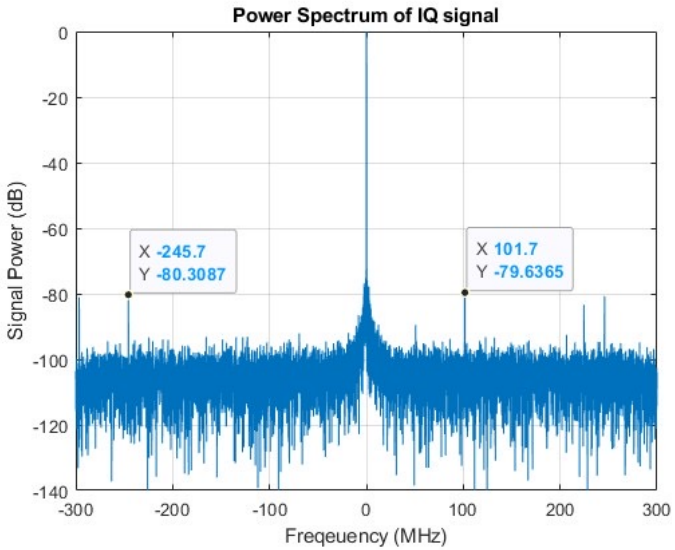

**ADC in Higher order Nyquist zone sampling mode**



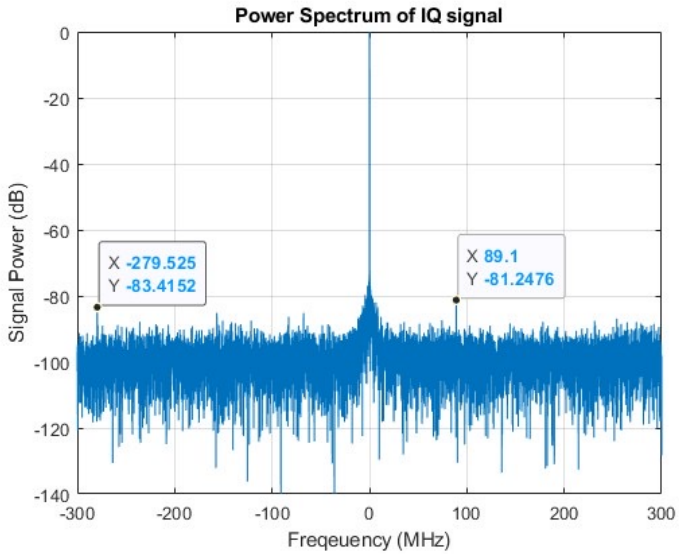

Ref: https://www.rfsocbook.com/

# Single Tone Test Results of Direct RF Sampling

Spectrum of RF signal at 4.25 GHz
DAC: 2nd order Nyquist zone
ADC: 2nd order Nyquist zone




Spectrum of RF signal at 5.25 GHz
DAC: 2nd order Nyquist zone
ADC: 3rd order Nyquist zone

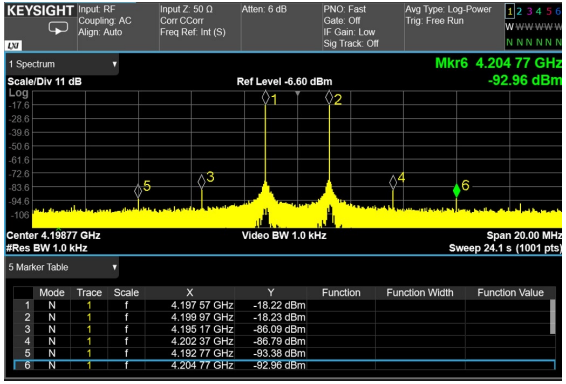



## Test Summary

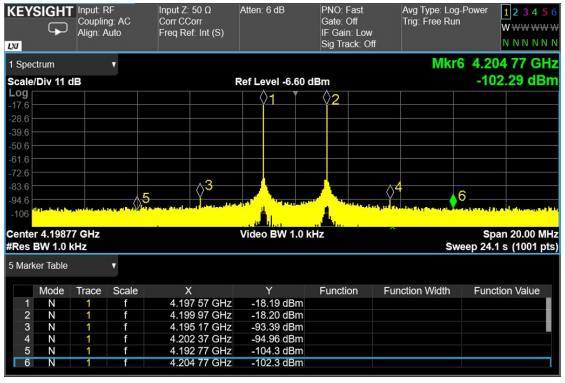
- DAC-ADC loop-back
- SFDR measured
  - 79.6 dB at 4.25 GHz
  - 81.2 dB at 5.25 GHz
- SFDR in Xilinx datasheet with CW power at –10 dBFS
  - 75 dB at 4.9 GHz
  - 74 dB at 5.9 GHz
- **Performance at higher order Nyquist zones meet requirements**

# Inter-modulation Performance Test in 2nd Nyquist Zone

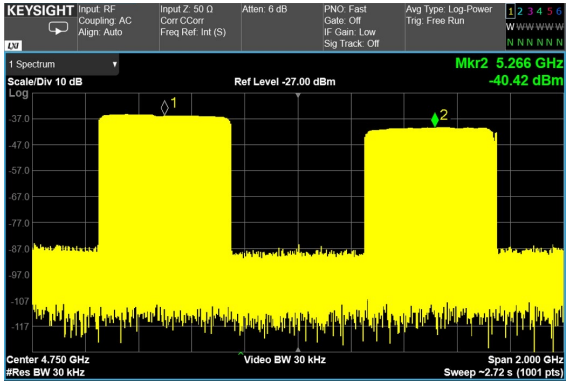
**DAC Two Tone Test in SNR Optimized Mode**




**DAC Two Tone Test in High Linearity Mode**




**DAC Two Band Test in High Linearity Mode**



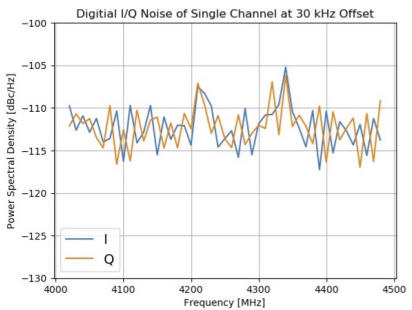

## Test Summary

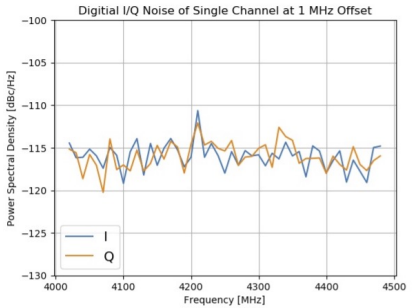
- RFSoC DACs have two modes use different mechanism to select the unit current cells for decoding – the SNR optimized mode and high linearity mode. The **high linearity mode offers 8 dB better IMD performance** than SNR optimized mode.
- The two RF bands directly generated by the integrated DAC have a **low level of intermodulation products and leakage to other bands in high linearity mode**.

# Loopback RF Dynamic Range Measurements

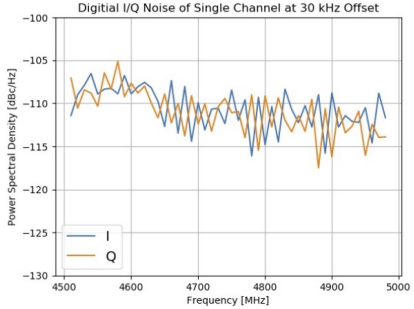
**RF dynamic range measured at all 4 500MHz bands is mostly below -110 dBc/Hz**

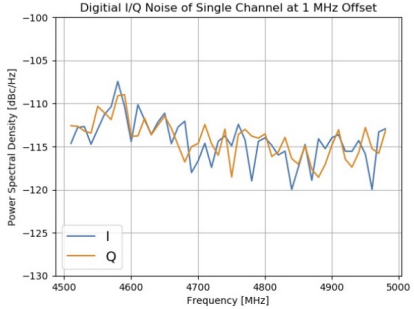
4 – 4.5 GHz Amplifier and Quadraplexer



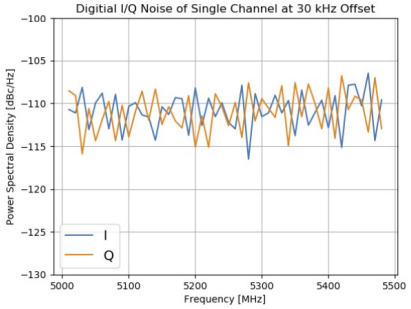



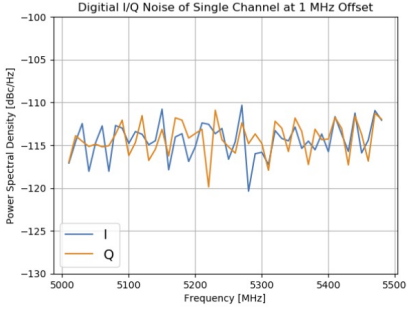

4.5 – 5 GHz Amplifier and Quadraplexer



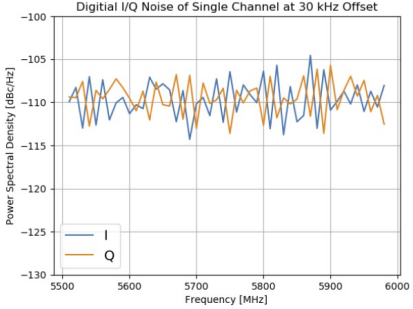



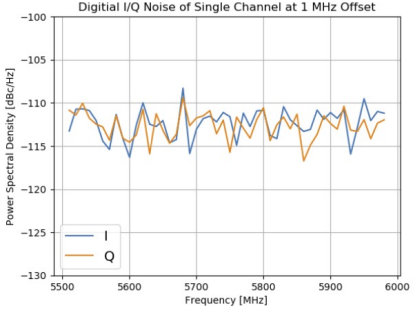

5 – 5.5 GHz Amplifier and Quadraplexer



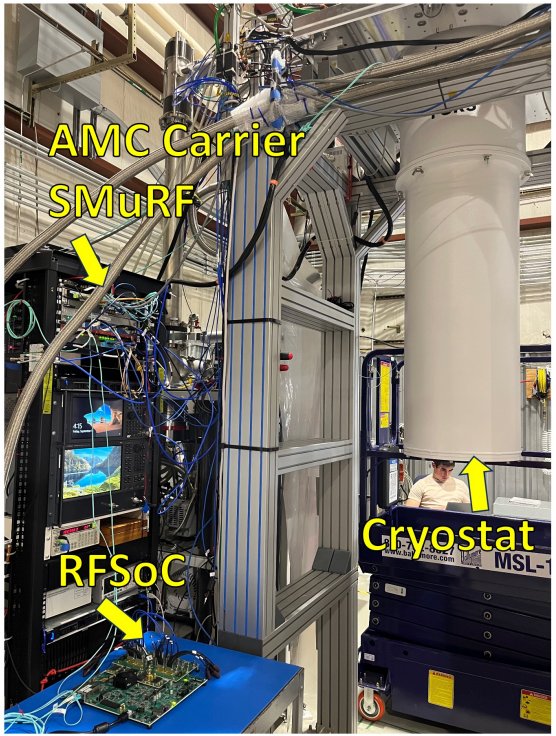



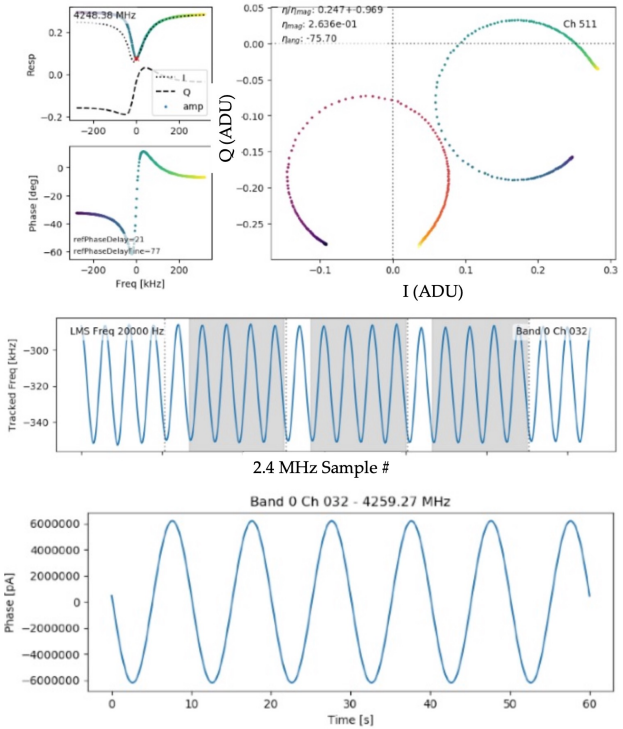

5.5 – 6 GHz Amplifier and Quadraplexer



# Full Microwave Multiplexing Readout with RFSoC



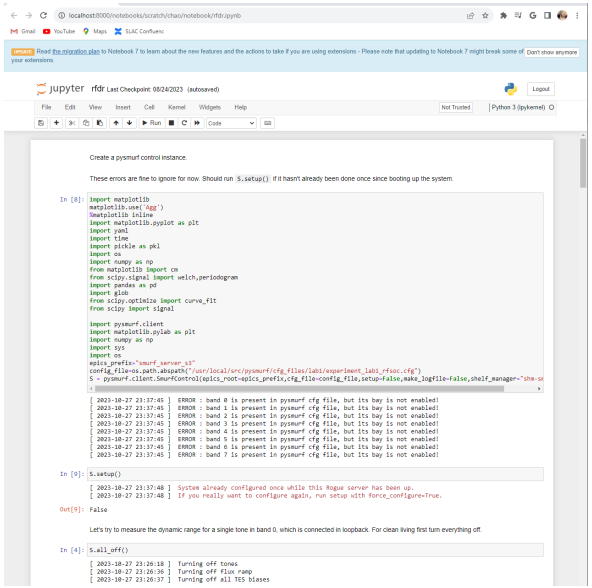




## Test Summary

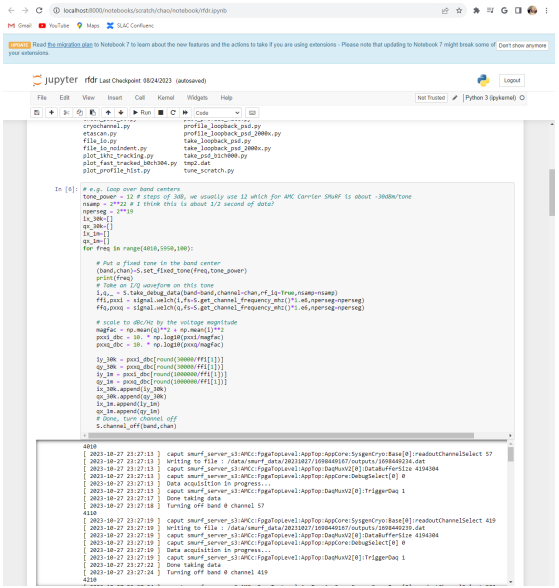
- SMuRF-RFSoC to readout a superconducting sensor in the CMB dilution refrigerator
- **Scan of complex transmission through** a superconducting resonator
- Tracking the modulation of a SQUID-coupled resonator **demonstrates tone tracking**
- Recovered 100 mHz sine-wave signal injected into a transition-edge sensor (TES), **demonstrating the successful readout of TES**.

# Jupyter Notebook for Prototyping

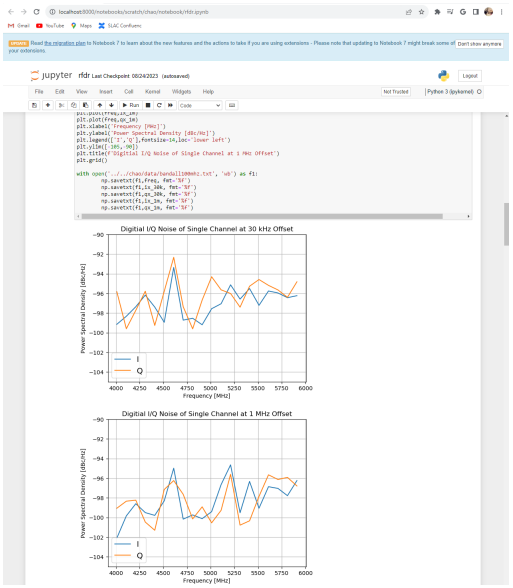
## System Setup



## Measurement and readout scripting and data capturing

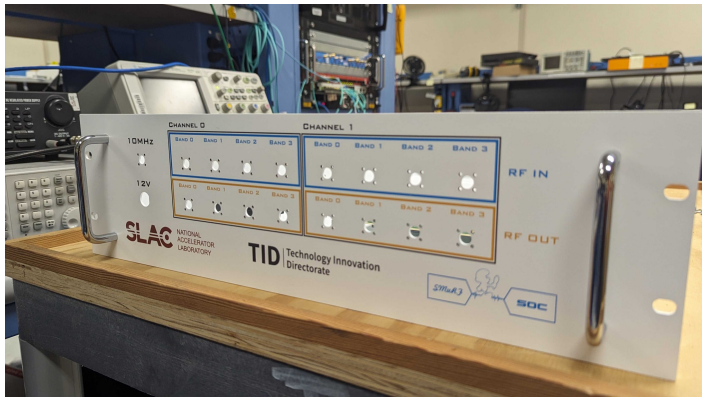


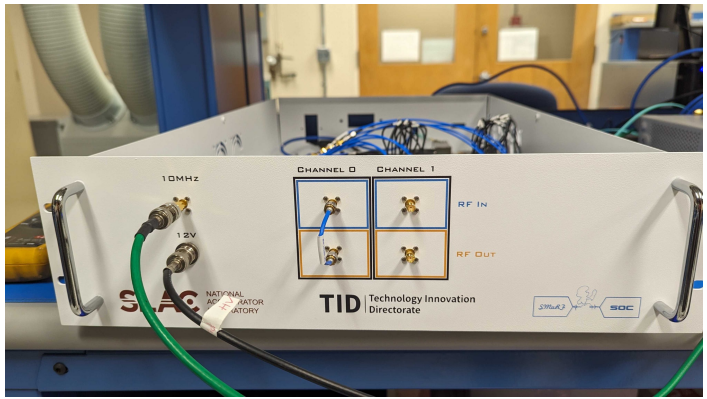
## Data processing and visualization

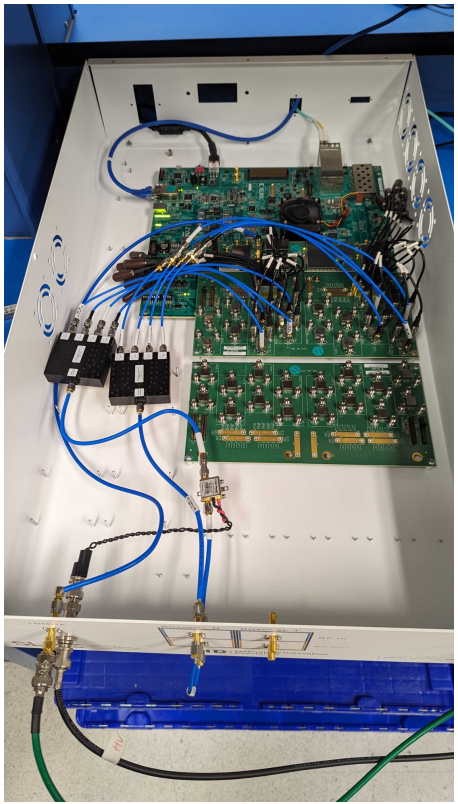



**University and national lab users can prototype rapidly based on example notebook**

# Pizza Box for RFSoC based uMux Readout



**RFSoC Chassis Ideal for Small Scale R&D and university project**

- 3U module for rack mounting
- Flexible circuit connection
- 10 MHz external sync
- PL and PS Ethernet for data stream and remote updating
- Two front panel versions

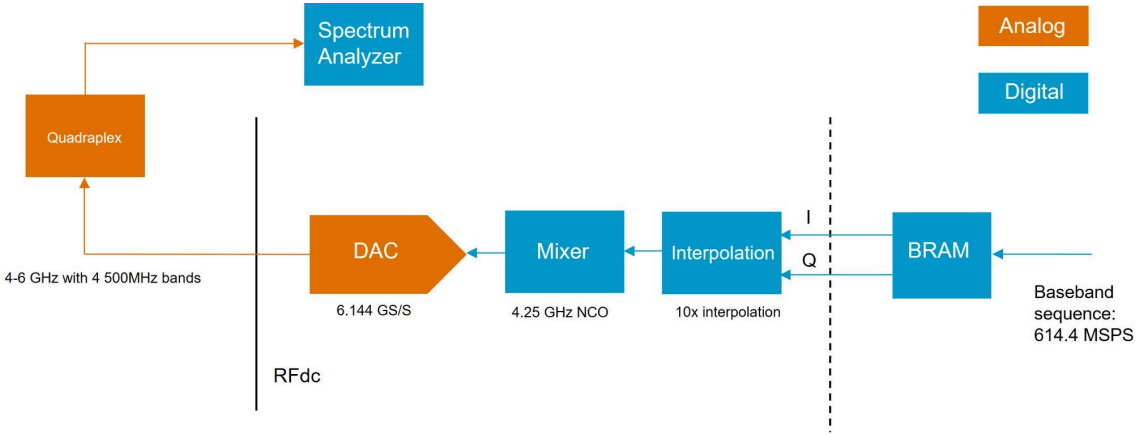
# Conclusions and Future Works

- Direct RF sampling delivered desired performance at higher order Nyquist zones
- Milestones for RFSoC based readout and control system development at SLAC
  - Demonstrating the successful readout of transition-edge sensor for CMB experiment
  - Highly configurable channelizer developed for axion dark matter search
  - LLRF control for Linac demonstrated with extremely low phase noise
- **Commercial hardware and open-source firmware and software enable rapid and low-cost (but extremely powerful) R&D readout system prototyping**
- Highly flexible system implementation with capability of data streaming at multiple stages of readout – essential for CMB and dark matter search experiments
- **Open to collaboration for firmware and software library development**

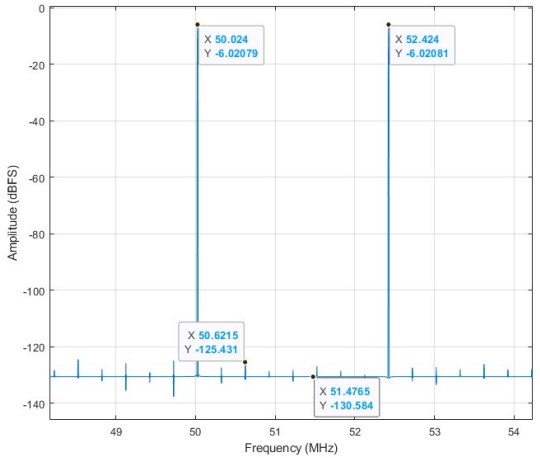
# Backups

# Higher Order Nyquist Zone IMD Evaluation for DACs

## DAC inter-modulation evaluation circuit



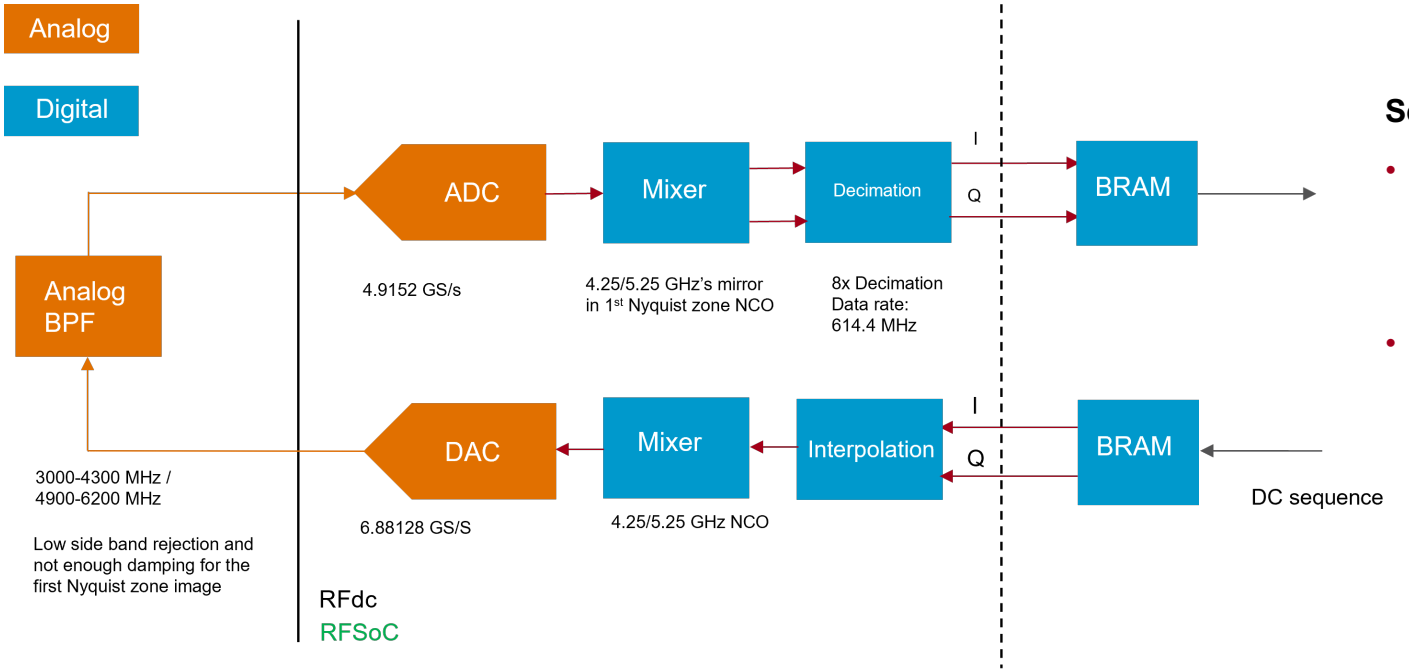

## Two-tone Signal Loaded to DAC




### Motivations

- Intermodulation distortion (IMD) performance for the DAC is critical for frequency division multiplexing with high multiplexing factor
- Exploring the optimum DAC configuration to achieve the best performance with the integrated datapath in RFSoC

# Integrated Datapath Characterization Test Setup




**Setup Summary**

- Single tone test
  - Full loopback
  - Dynamic range
- Comb of tones test
  - Tone power
  - Intermodulation level
  - Phase noise