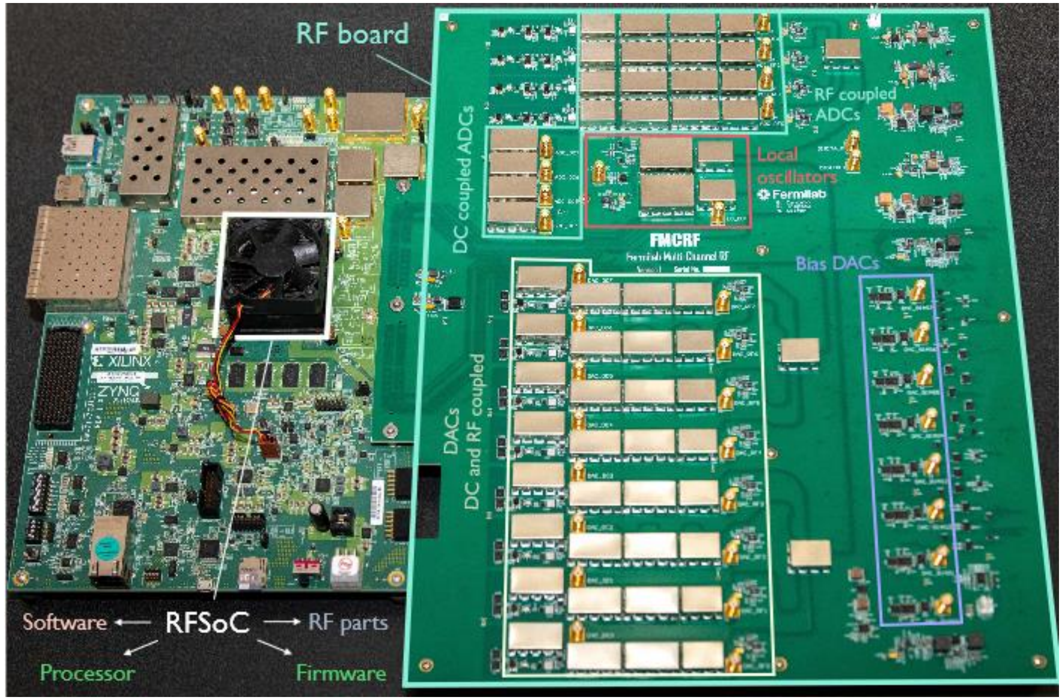
QICK (Quantum Instrumentation Control Kit), Readout and control for qubits and detectors.



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July 18, 2022

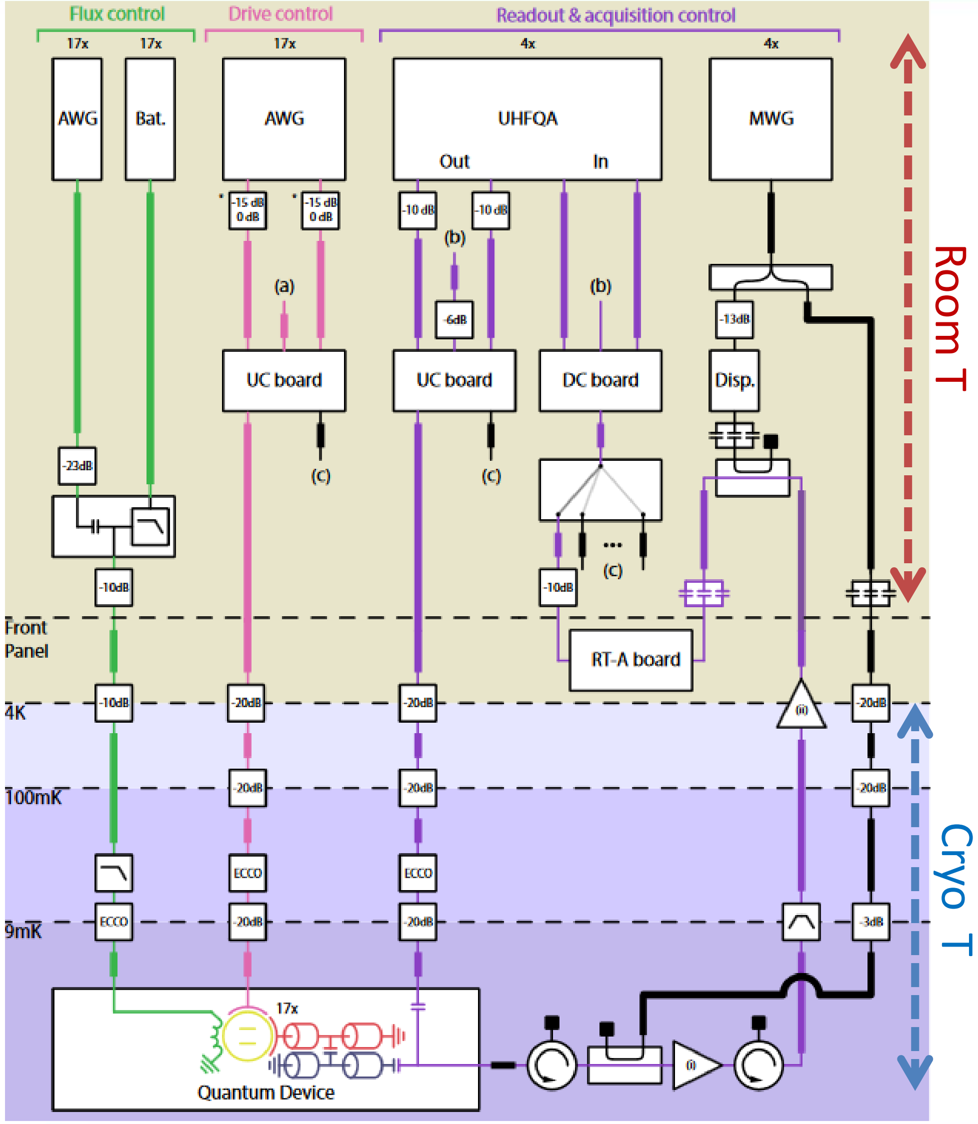
Warm electronics for control, detection, and readout

- This talk focus: detectors and processing elements for high energy physics and quantum information science.
- In particular, detectors for cosmological studies of the CMB, DM and DE.
- Those detectors generate very faint signals. SNR is the main issue.
  - SNR is improved by working at very low T: 10mK-300mK, depending on the technology.
- Quantum detector signals are likely the smallest power of the class.
- Some computing elements (qubits) in quantum information science are technologically similar.
- Some detectors for quantum networks are also technologically similar.
- Technologically speaking they share some physics principles and properties
  - Quantum optics and electrodynamics.
  - Made to operate in superconducting regime.
  - Operated cryogenically below 1K.
  - Independently of the spectrum they are looking at (e.g. microwaves, IR, visible) the detectors translate the signal into an electromagnetic output in the RF spectrum (e.g. 1GHz-20GHz).
  - Many of those detectors and QIS systems need to be exited by DC or RF signals or pulses.

- This work is largely supported by DOE-QSC and DOE-HEP-Detector R&D and projects.

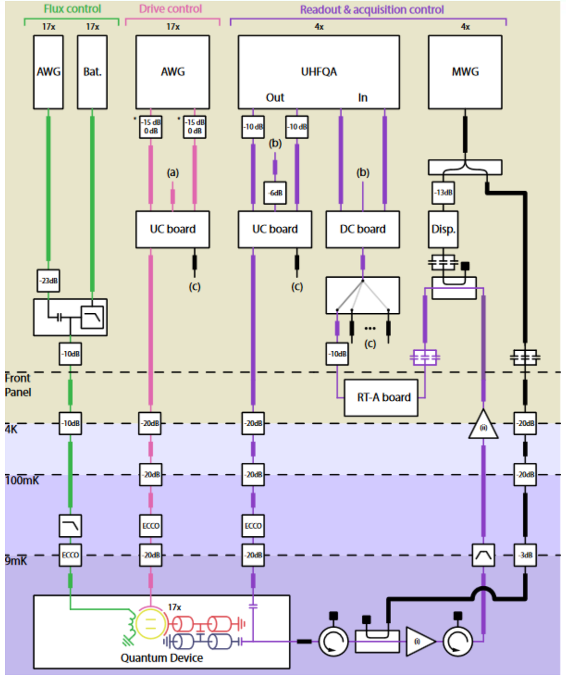
QUANTUM SCIENCE CENTER

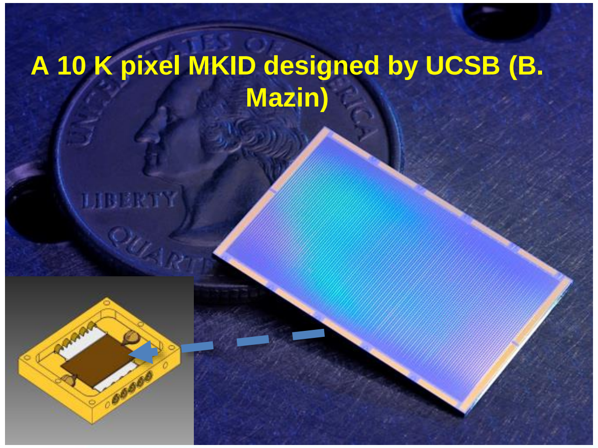
Warm and cold electronics for control, detection, and readout



- To highly suppress thermal photons (noise) the input lines place attenuators at strategic locations at several T stages inside the fridge. 40 to 60 dB typical.
  - That places a requirement of power in the warm electronics for control and readout.
- Since refrigerator lines are expensive and large, it is highly desired to place multiple detectors/qubits on the same input/output lines.
  - The most successful case is the MKID (Microwave Kinetic Inductance Detector) which has proved to place 2000 resonators using frequency multiplexing in the 4-8GHz (B. Mazin lab UCSB).
- Typical excitation/control signals are on the order of -90dBm to -110dBm depending on the technology and material.
- To keep SNR at the output LNAs are required
  - Parametric amplifiers. Sometimes using squeezed params below quantum limit noise.
  - HEMT ~1K noise T.

Warm and cold electronics for control, detection, and readout




A 10 K pixel MKID designed by UCSB (B. Mazin)

- The warm electronics for control and readout requires signal generators, sometimes AWGs (Arbitrary Waveform Generators) with continuous or pulsed signals.
- Frequency multiplexing of continues RF signals of up to several thousand tones are used.
  - The excitation frequency comb must be clean of harmonics and spurs.
  - Typical specifications are: 100dBc/sqrt(Hz), SFDR>70dB.
  - Individual power control for every frequency tone.
  - Individual frequency control for every frequency tone with a resolution of a fraction of the detector BW (e.g. resolution of <1KHz for a typical 100KHz KID).
- Frequency and time domain multiplexing of band limited signals
  - Required for quantum control.
- DC coupled control up to 1GHz of BW
  - Some systems require few KHz ramps.
- DC biasing, up to 20 bits.

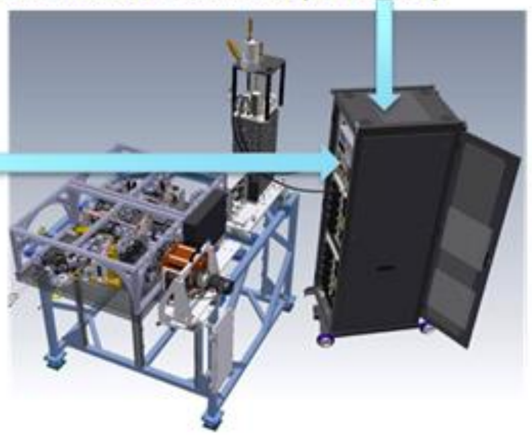
- What is the best architecture and technology to solve the problem with high performance and in the most cost-effective way?

2015 fMESSI: 1Kpixel control and readout board by Fermilab-UCSB

7 years ago!

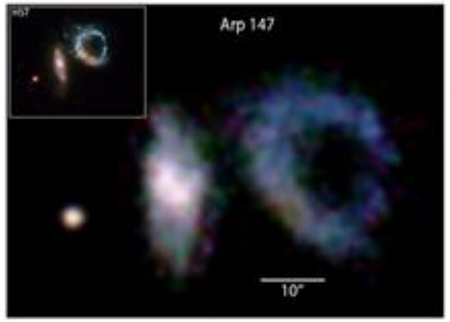
fMESSI 2016-2020

MEC: 20K MKID system operating at 8m telescope at Subaru since 2018 using FNAL Gen2 fMESSI electronics (20 boards)



- Single RF output/input in 4-8 GHz
- MEC required 20 fMESSI for 20Kpixel camera.
- FPGA technology plays a big role the design of complex signal generation and readout functions:
- Digital signal processing galore!
  - Digital up/down converters.
  - Polyphase filter banks.
  - Digital filters.
  - Channelizers (for synthesis and analysis).
  - Optimal control.

DARKNESS at Palomar 2016



Previous, related work
20K MKID pixel camera (MEC) at 8m Subaru telescope (2018).
https://web.physics.ucsb.edu/~bmazin/projects/mec.html

10K MKID pixel camera DARKNESS at Palomar (2015)
Both instruments in collaboration with Ben Mazin's Lab (UCSB)
https://web.physics.ucsb.edu/~bmazin/projects/darkness.html

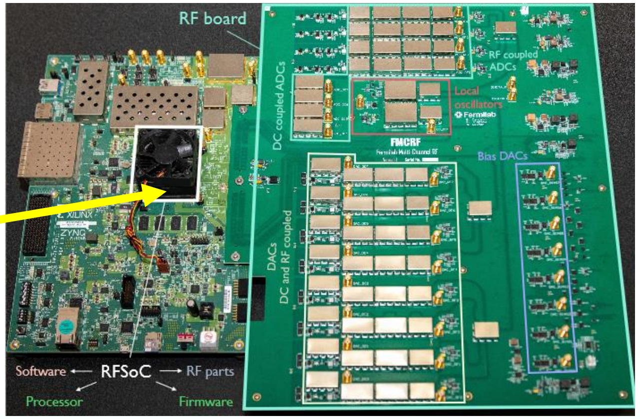
2021 QICK1: integrated control and readout for detectors and QIS

- A fully integrated readout and control system for QIS, quantum networks and superconducting detectors.
  - No extra room temperature hardware needed.
- Increased performance: RF control up to 10GHz. DC coupled control up to 2GHz. 1ppm resolution in bias channels. 2ps resolution in timing measurements.
  - 16 x 14-bit DAC outputs in DC to 10 GHz. I-Q done in digital => you only need half the number of outputs
- Frequency multiplexing of up to 8K channels per board.
- Frequency multiplexed control and readout up to 16 qubits per output/input.
- The cost of the system is $20K including the digital FPGA board and RF custom board.

Qubit control is still full of off-the-shelf expensive equipment. HEP can help a lot (and that is what we did with QICK)

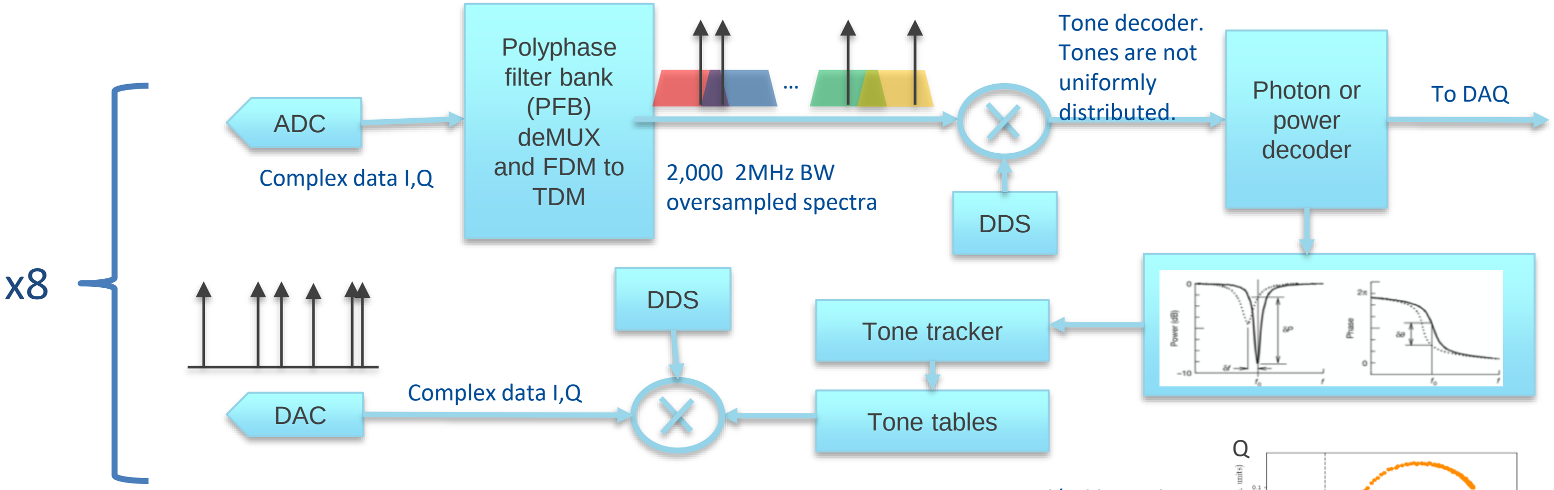
Replaces ~$1M, full rack, off-the-shelf → **with $20K, single pair of boards**

RFSoc
FPGA



QICK for detectors: CMB, dark matter, dark energy, quantum network, gravitational wave detectors

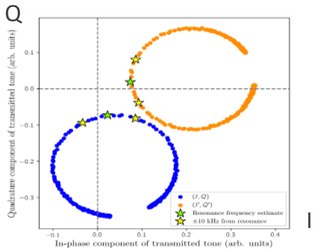
- **8K channels on a single XCU28DR FPGA, cost $2/channel including the cost of RF warm electronics.**

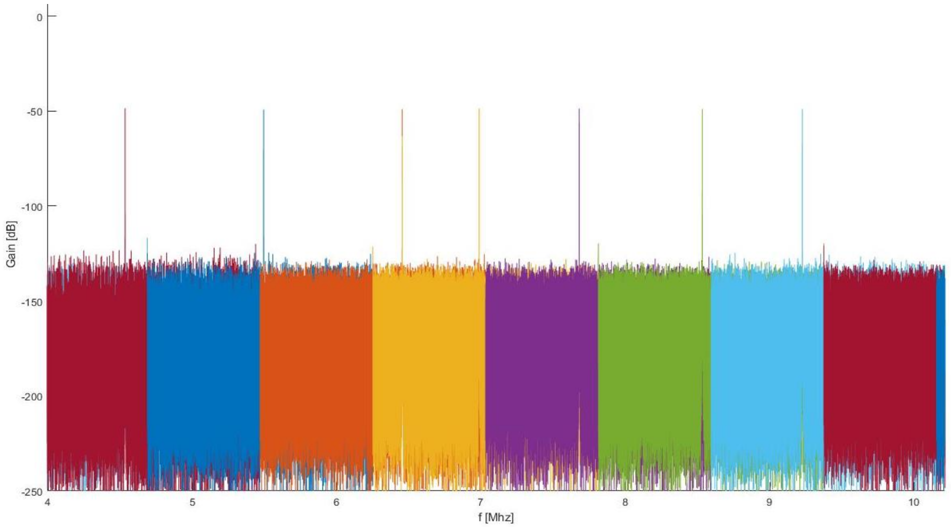


- Total input: 2GHz per feedline.
- 1000 channels, 2MHz (typical) separation.
- Channel frequency fine adjustment using DDS.
- Channel output measures power or single photons.
- Output/input powers adjustable.
- Fast digital up/down conversion.

Rotated/calibrated resonator

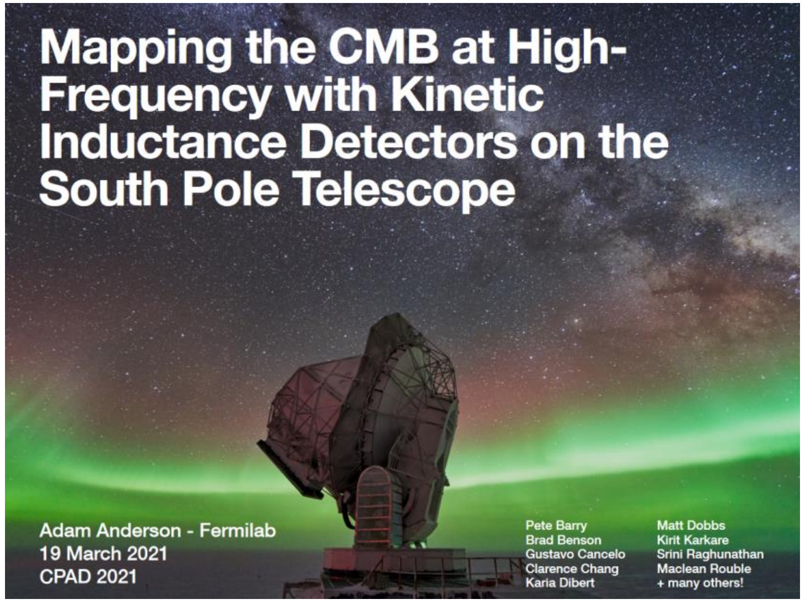
Unrotated/uncalibrated resonator

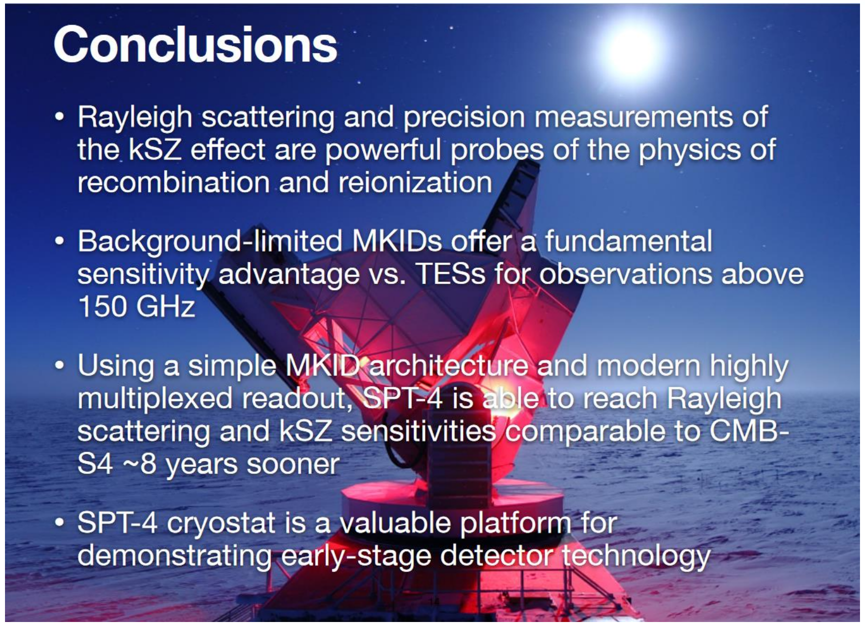




1000 channels
Per RF feedline decoded with better than 80dB channel separation.

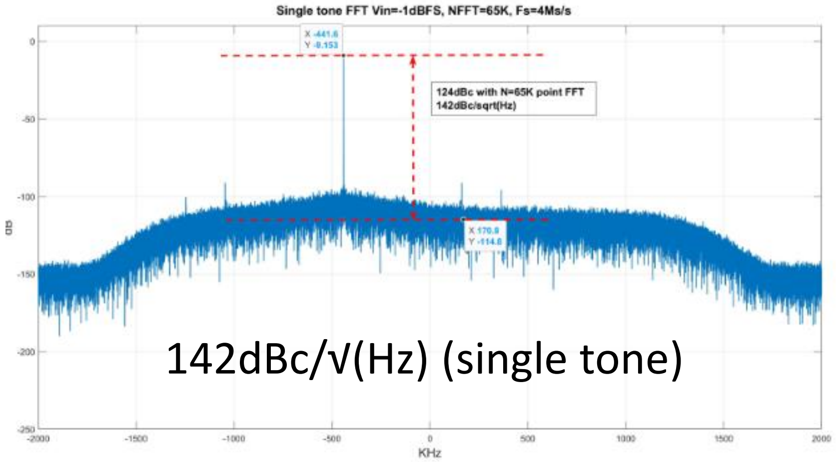
QICK for detectors: CMB, dark matter, dark energy, quantum network, gravitational wave detectors



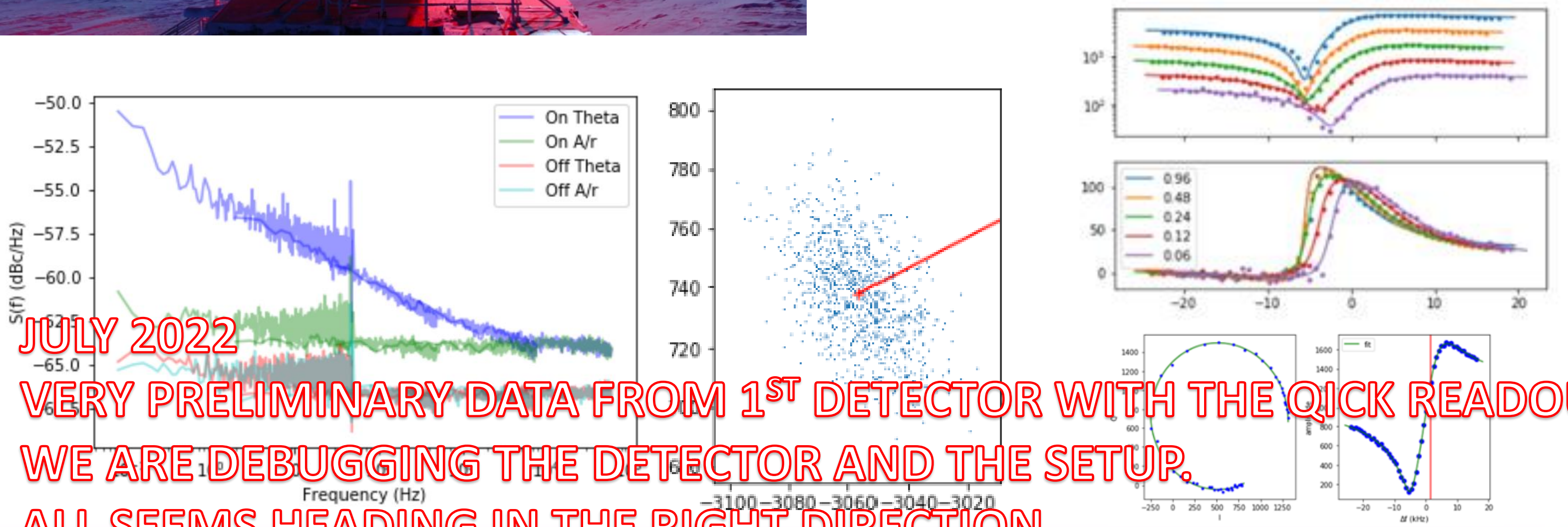


Adam Anderson (FNAL) et al., SPT collab.

- **MKIDs offer SPT upgrade a unique opportunity to improve science, even reaching Rayleigh scattering and kSZ sensitivities comparable to CMB-4**
- **More detectors per area.**
- **Low res. Spectroscopy.**



142dBc/√(Hz) (single tone)



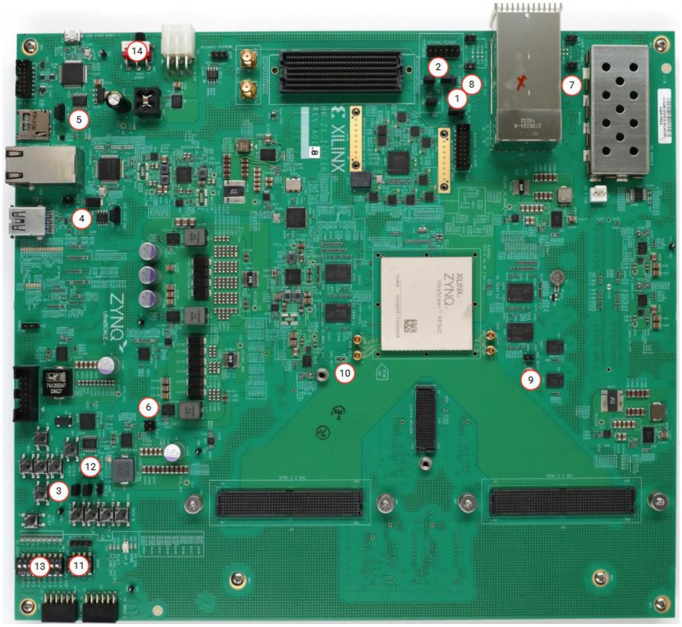
JULY 2022

VERY PRELIMINARY DATA FROM 1ST DETECTOR WITH THE QICK READOUT

WE ARE DEBUGGING THE DETECTOR AND THE SETUP.

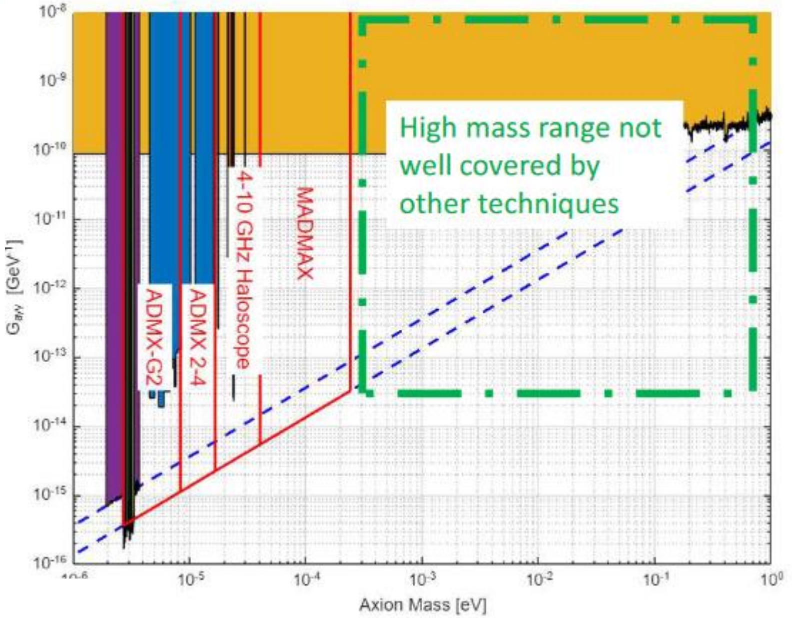
ALL SEEMS HEADING IN THE RIGHT DIRECTION.

QICK2 for detectors: CMB, dark matter, dark energy, quantum network, gravitational wave detectors



- We have developed QICK2, based on the ZCU216 from Xilinx. Compatible with ZCU208.
- MKIDs: 8K channel/board.
- It does not require external analog mixers.
- It covers a spectrum of up to 10GHz with I-Q tones generated in the digital domain.
- This is the default for QIS systems we are working with at U.Chicago (D. Schuster's lab), Princeton (A. Houck's lab), Pittsburgh (Hatlab).
- We are working on a companion RF board that includes amplifiers, filters and step power attenuators.
- For 8K channels the cost is $2/KID.
- $1M for 500K channels.

QICK for detectors: High Mass Axion Searches, BREAD project



BREAD Collaboration

Broadband Reflector Experiment for Axion Detection (BREAD)

Pete Barry, Clarence Chang, Juliang Li *Argonne National Laboratory*

Gianpaolo Carosi, *Lawrence Livermore National Laboratory*

Kristin Dona, Jesse Liu, David Miller, *University of Chicago*

Daniel Bowring, Aaron Chou, Mohamed Hassan, Stefan Knirck, Noah Kurinsky, Andrew Sonnenschein, *Fermilab*

Rakshya Khatiwada, *Fermilab and Illinois Institute of Technology*

Sae Woo Nam, *National Institute of Standards and Technology*

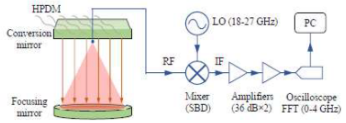
Omid Noroozian, *NASA Goddard Space Flight Center*

Three Types of Experiment

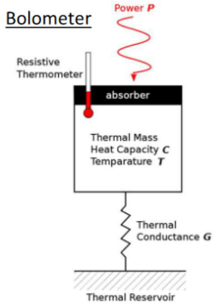
1. Heterodyne detection
   - Downconvert signal frequency by mixing with a local oscillator.
   - Excellent for measuring narrow spectral features.
   - Ultimate sensitivity governed by Standard Quantum Limit (SQL)

     $T_{noise} = hf/K_b$
2. Bolometer
   - Absorb optical power on a "black" surface & measure temperature.
   - Intrinsically broadband- single device may cover decades of wavelength.
   - No intrinsic frequency resolution.
   - Not subject to Standard Quantum Limit.
   - Detection of 10^{-25} W KSVZ axion signal within one year requires Noise Equivalent Power (NEP) $\sim 10^{-22} W/\sqrt{Hz}$. Two orders of magnitude beyond state-of-art.
3. Photon counting
   - Simple counting experiment similar to WIMP searches.
   - Background rate as low as ~1 event/day needed to cover mass range up to 0.1 eV.
   - This is beyond current capability, but photon counting technology is evolving rapidly, driven by quantum information science applications.

Heterodyne detection



Bolometer



Three type of experiments:

Broadband antenna 2-20GHz. Readout requires a fine resolution FFT averaged for a long time until a signal is detected.

Photon counting using SNSPDs.

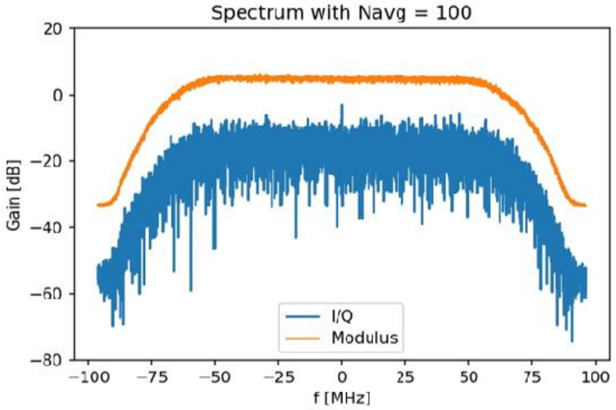
QICK1 used for the antenna readout.

QICK2 for SNSPD control and readout.

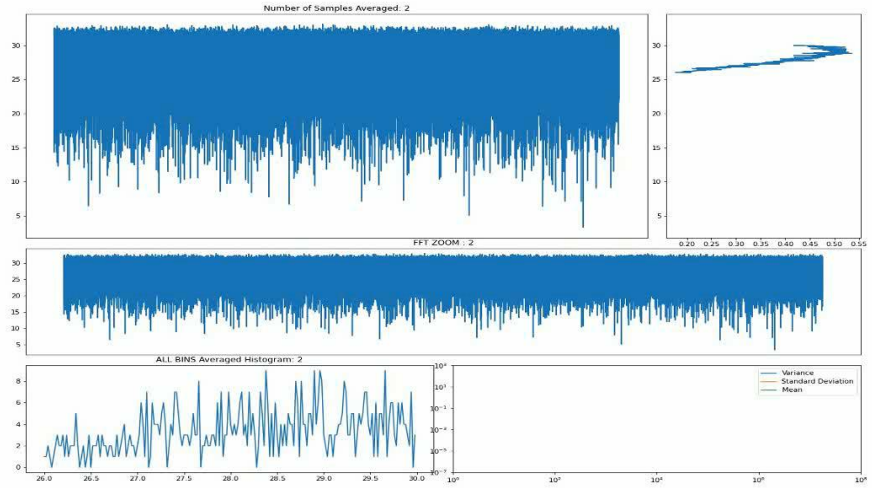
QICK1 for control and readout of Quantum Capacitor Detectors.

QICK for detectors: High Mass Axion Searches, BREAD project

Broad-band spectrum analyzer



- 500K point FFT every 60usec.
- FFTs are averaged on the FPGA.
- Number of averages is very large (up to days, if needed).
- The analog RF band is preselected by analog hardware.
- Zooming on a slammel spectrum allows for very fine frequency resolution.

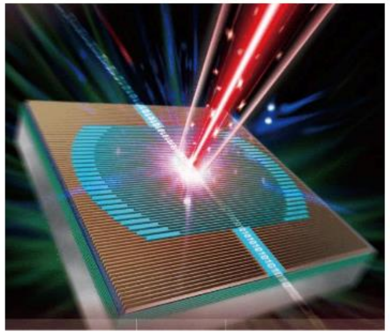


Lab test with an Agilent noise source

QICK2 for detectors: SNSPDs (Fermilab, INQNET C. Peña. et al., JPL M. Shaw et al., NIST, Caltech M. Spiropulu et al.)

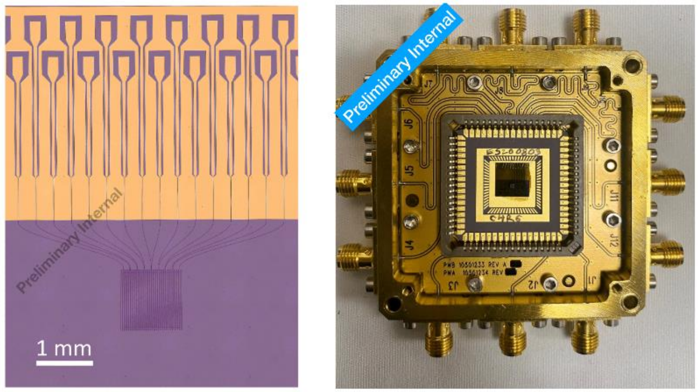
Quantum Sensor: SNSPDs

Superconducting Nanowire Single Photon Detectors



- Sensitive to **0.1eV photons**
- **>90% system efficiency**
- Low **dark count** rate **1e-5Hz**
- Record **time resolution ~3ps**

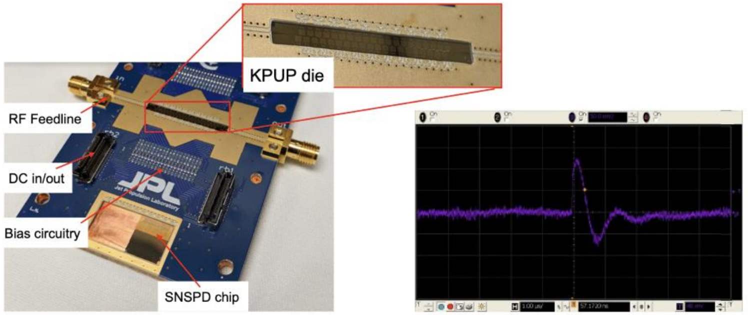
DM Search: Scintillation+SNSPD



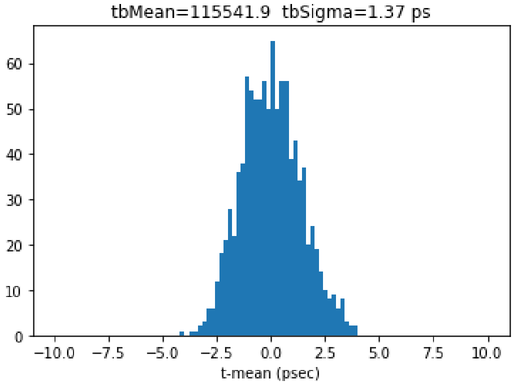
1x1 mm² sensor — 8channel   1x1 mm² sensor package

Next Generation SNSPD — Large Areas

Achieving large area SNSPD will open up new HEP applications

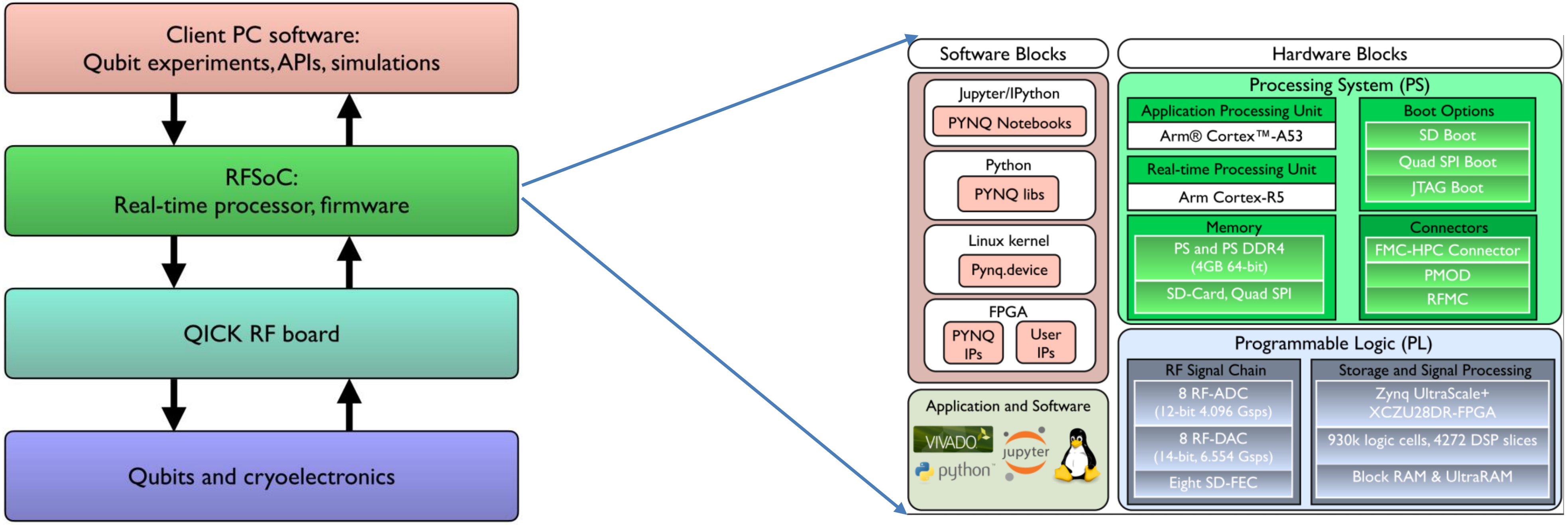


- **SNSPD measurements at FNAL-SCD**
- **QICK fast timing measurements for quantum networks: < 2ps resolution**
  - Already triggering and reading photon entanglement experiments (Cristian Peña, et al)
  - JPL (Matt Shaw's group will use QICK).
- **QICK to read single SNSPDs and SNSPD arrays for DM and gravitational waves.**
  - We have a multichannel prototype for single SNSPD (time precision measurement)
  - GQuEST recently approved.

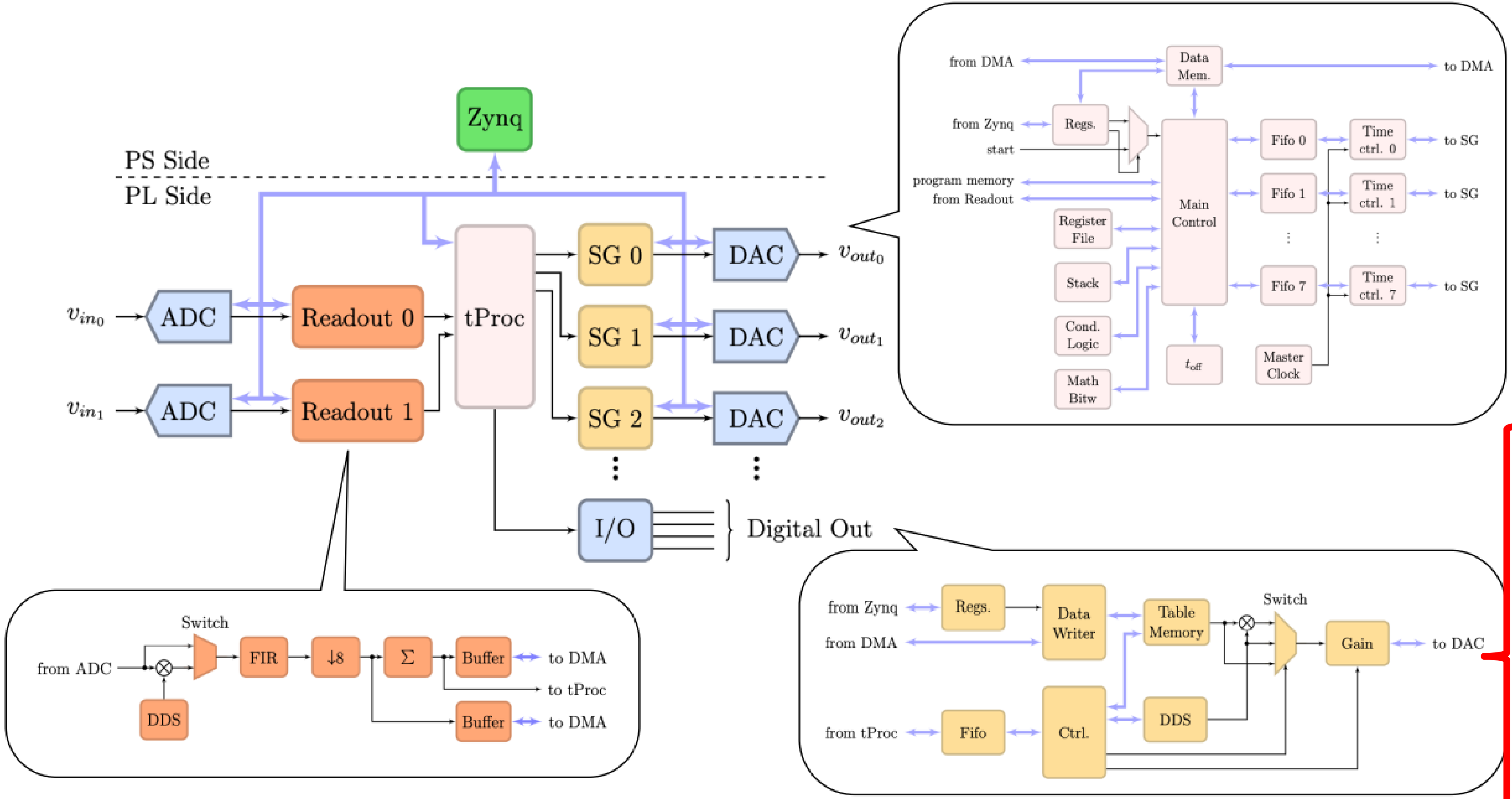


QICK Software for QIS (similar model can work for detectors)

- **Quantum programs are developed in python using the PYNQ environment and Jupyter notebooks.**
- **Quantum programs run on Linux in the RFSoC FPGA 4 core processor.**
  - QICK is kerberized and on the network.
- **All critical functions are executed in the programmable logic.**
- **In progress: Software layers to make QICK a backend for Qiskit and Braket. OpenQasm3**

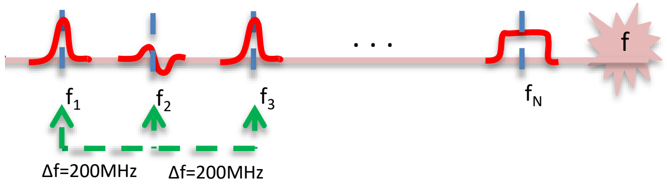


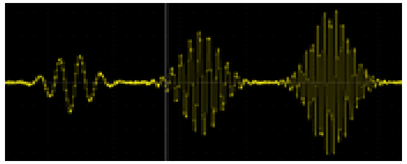
The QICK firmware for QIS



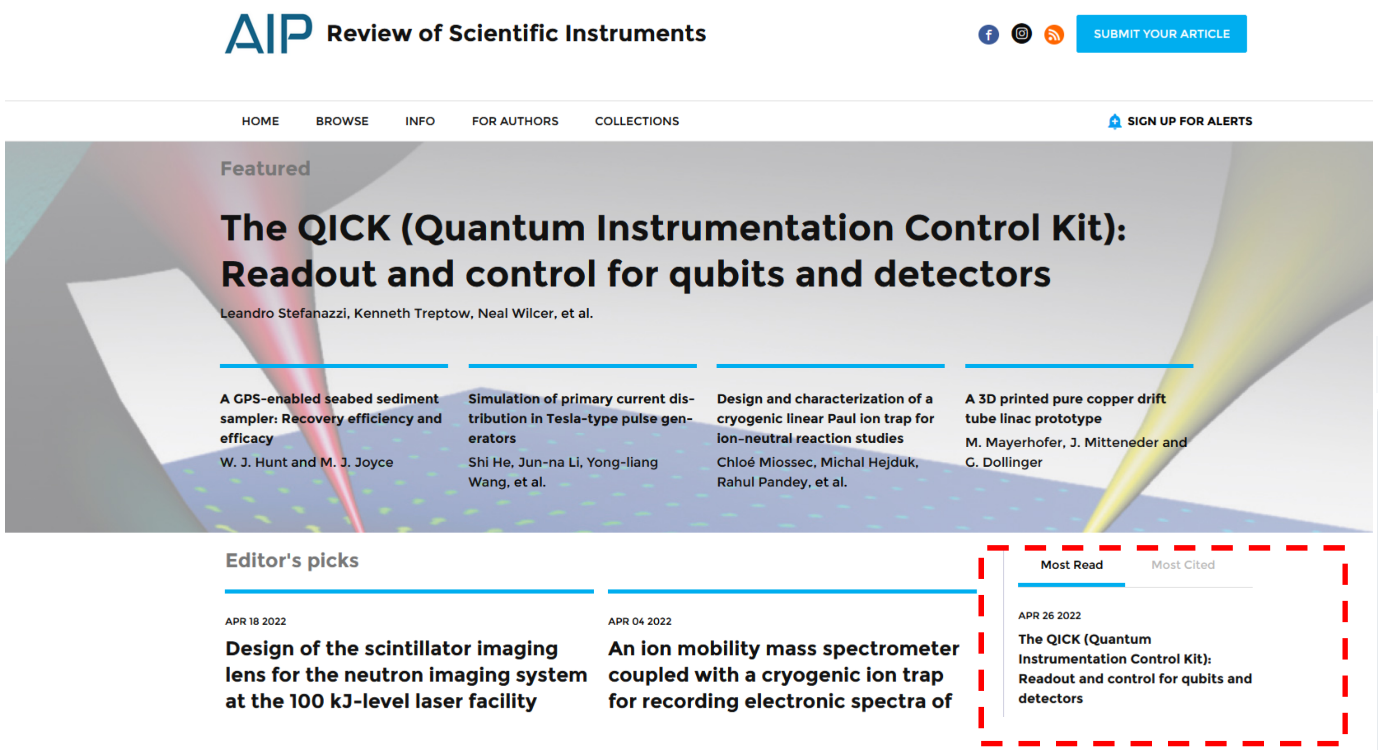
Highly configurable to accommodate qubit types and number of channels

Frequency and time multiplexing available on every DAC (and ADC)



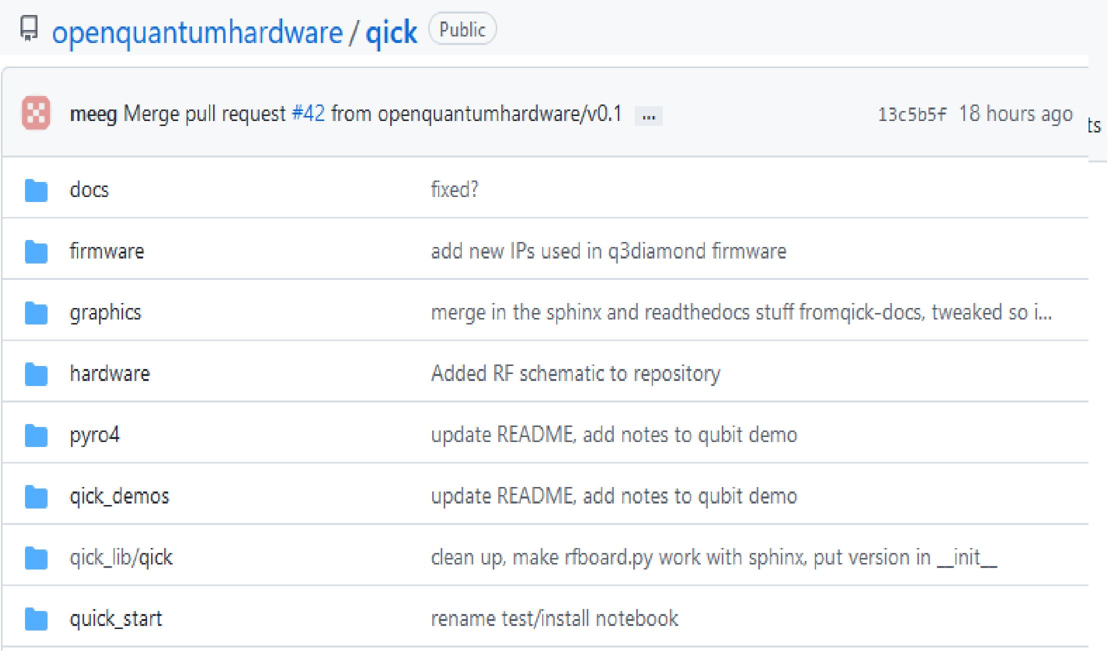


QICK paper made the cover of AIP RSI



Research Details

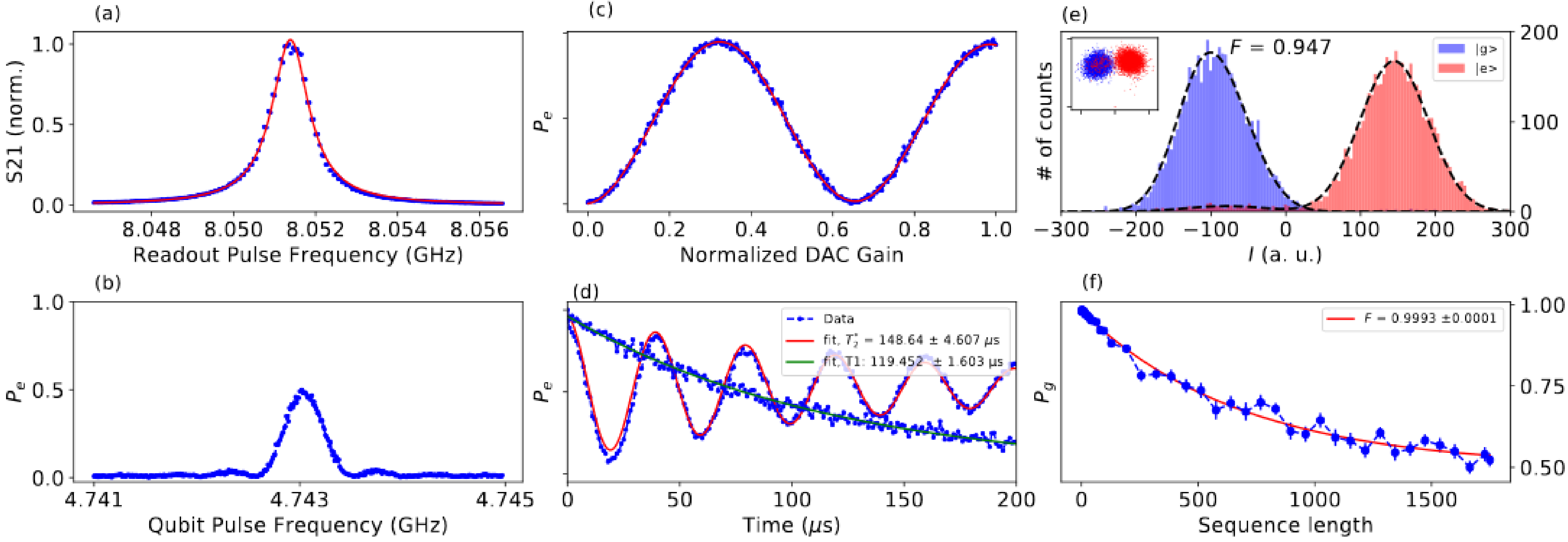
– We outline state of the art methods in the paper The QICK (Quantum Instrumentation Control Kit): Readout and control for qubits and detectors. arXiv:2110.00557. Published in Research of Scientific Instruments. https://doi.org/10.1063/5.0076249



- We opened our work to the scientific community.

https://github.com/openquantumhardware/qick

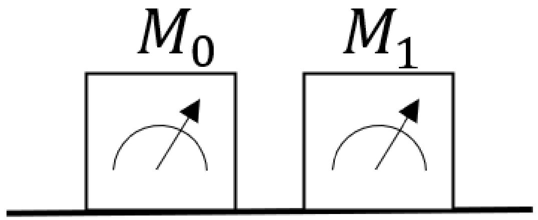
QICK: single qubit measurement at David Schuster's lab, U.C (prepared by Ankur Agrawal).

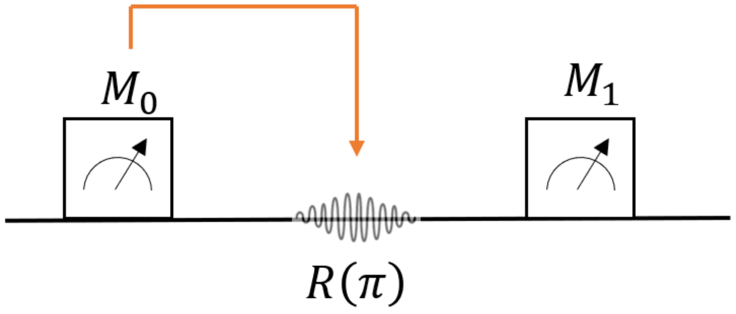


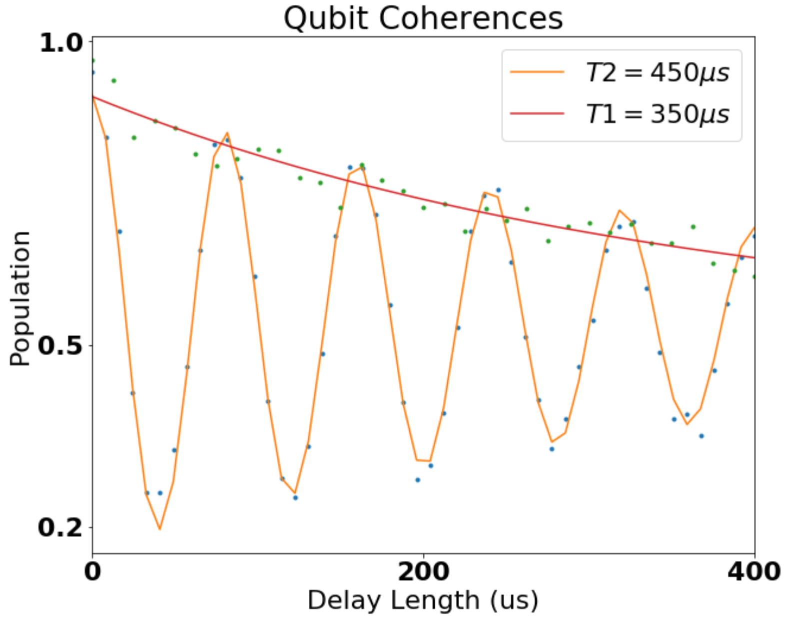
QICK performance measurements using a transmon qubit dispersively coupled to a readout cavity.
(a) and(b) Qubit spectroscopy measurements.(c) Qubit Rabi oscillations. (d) T1 and T2measurements (of 119µs and 148µs, respectively). (e) Single shot measurements of a qubit prepared in ground and excited states showing 94.7% fidelity.(f) Randomized benchmarking protocol. Average gate fidelity is Favg=99.93%±0.01% which approaches the estimated coherence-limited gate fidelity of Flim=99.96%.

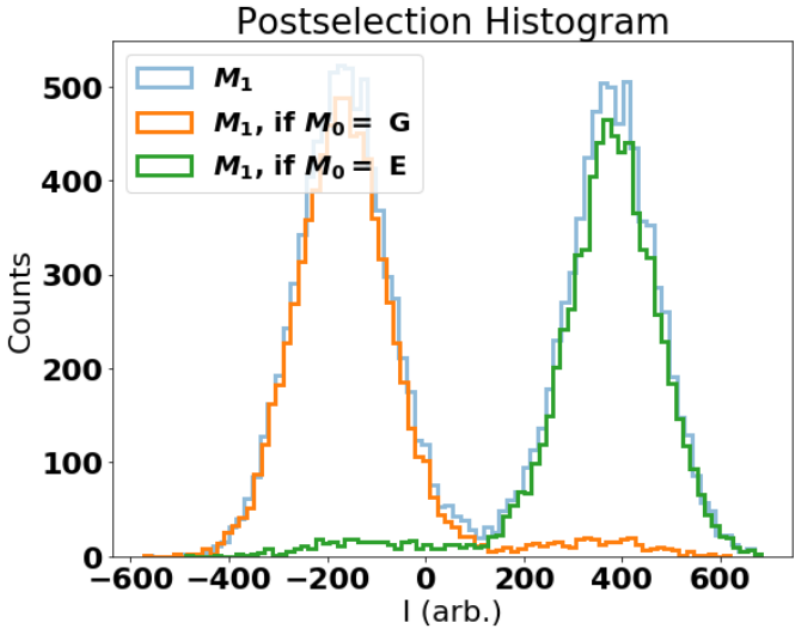
Fluxonium sample measured with RfSoc. (prepared by David Schuster)

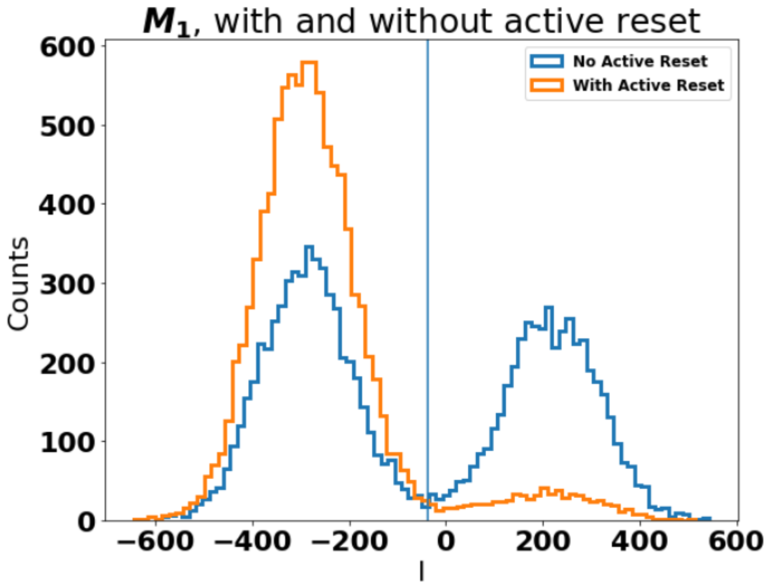
Readout length: 16μs
Readout fidelity: 96.3%
Feedback latency: ~200ns
Qubit Coherence:
T_2=450μs, T_1=350μs





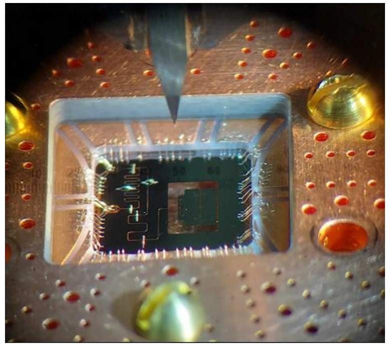


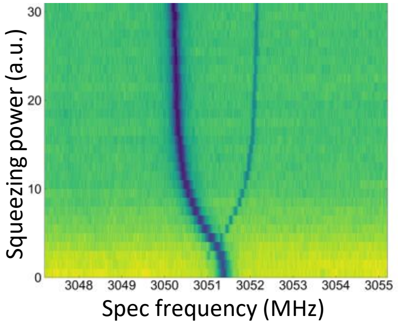




(prepared by Sara Sussman)

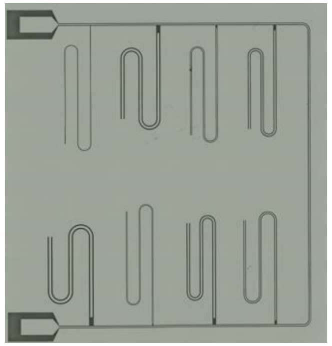
2D tantalum Kerr-Cat qubit

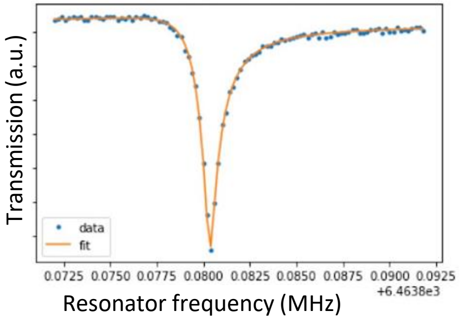




Phase-coherent squeezing drive for noise-biased cat states

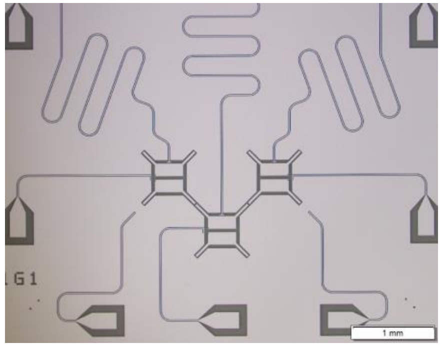
High-Q tantalum resonators

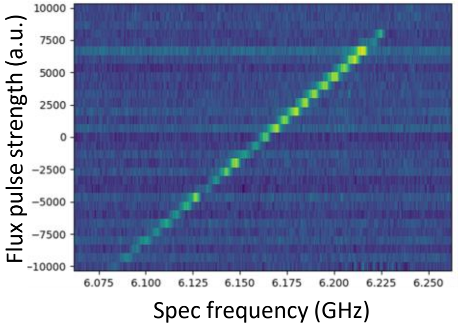




MUX'd readout
Fitted Qs > 15 million

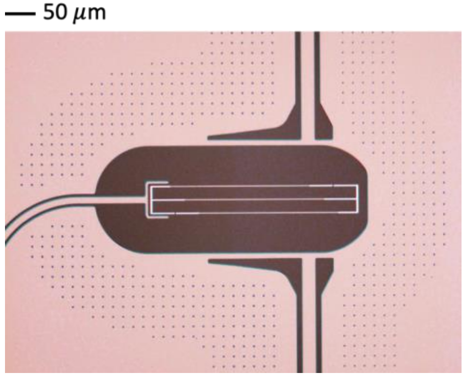
Tunable transmon lattice for quantum simulation

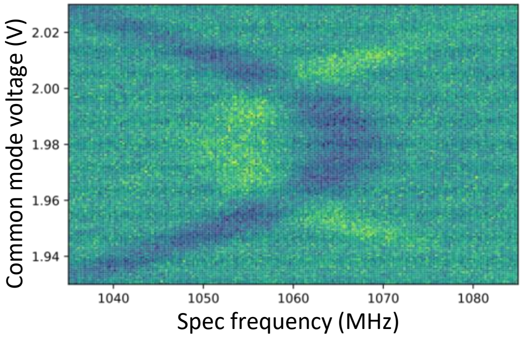




Fast flux pulses to simulate flat band state dynamics

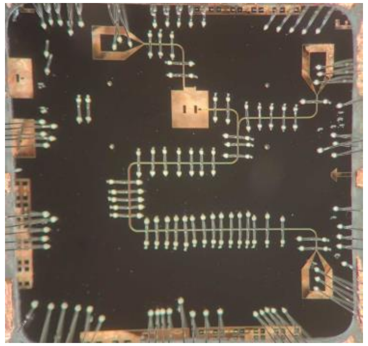
Fluxonium molecule

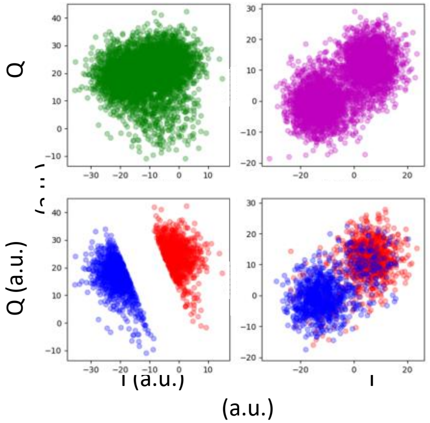




Sensitivity to qubit levels that are protected from noise

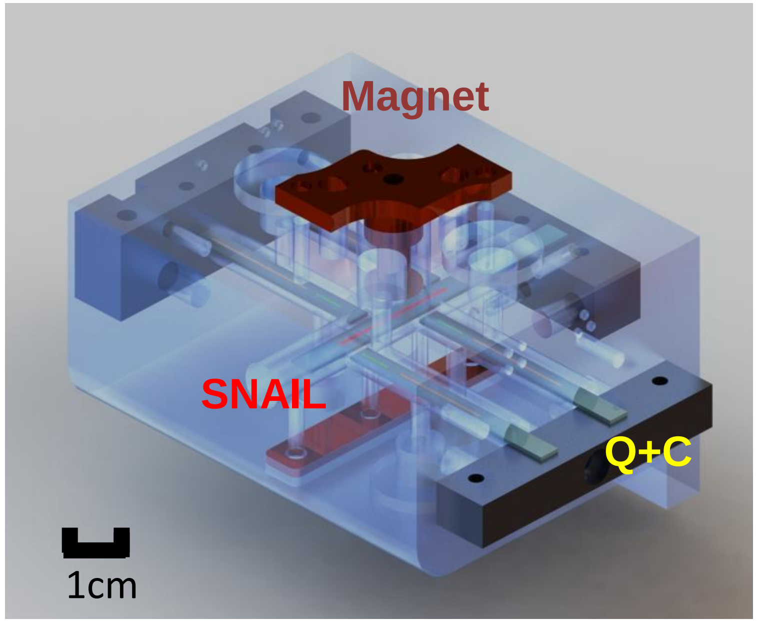
Active control of fluxonium

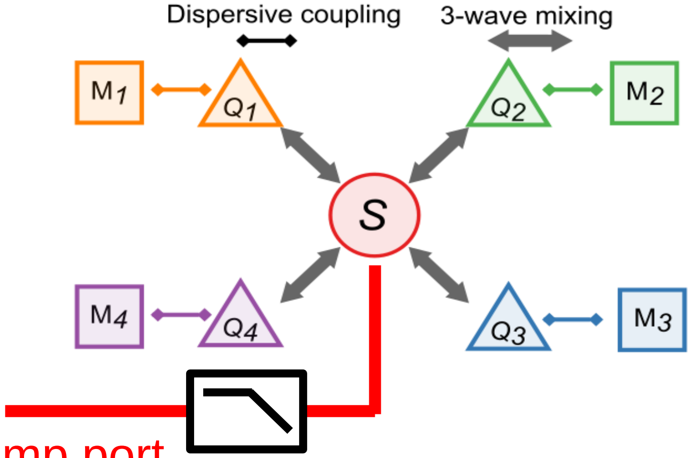


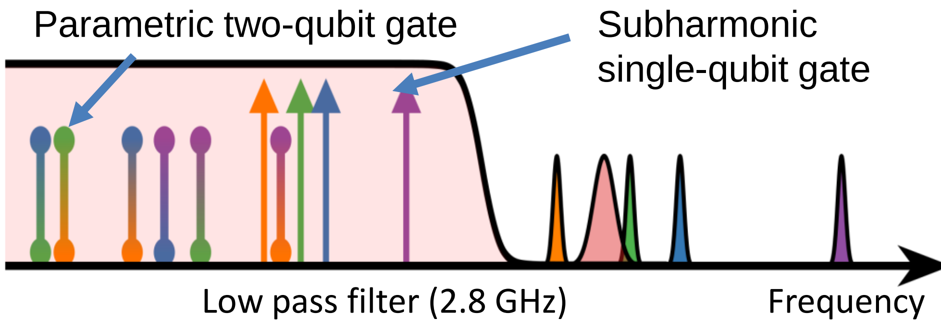


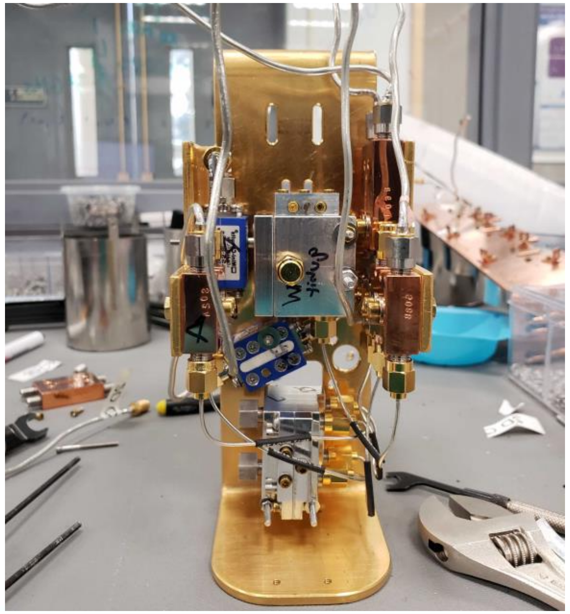
Optimal readout
Post-selection
Active reset

A quantum module with all-to-all gates via parametric control (prepared by Chao Zhou, U. Pittsburg)

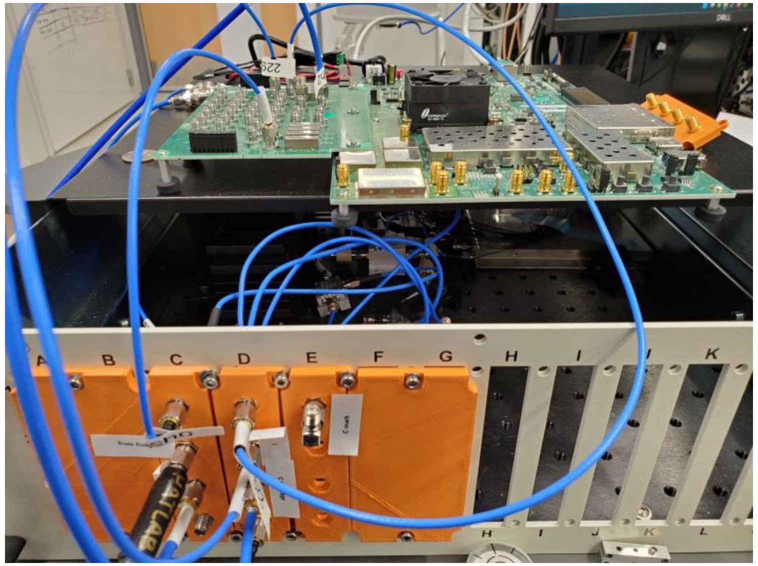








QICK



- Currently at Hatlab, the RFSOC board is set up for single qubit characterization.
- We have used this setup to measure tens of qubits over many cool downs, above is a typical result.
- We got similar results as we have gotten before with Keysight cards, and the high freq DDS has greatly simplified our qubit control circuit.
- More complicated multi-qubit experiments with ZCU216 are working in progress.

QICK team (FNAL group supported by QUANTUM SCIENCE CENTER) and collaborations

- QICK developers, testing, and experiments:
- Fermilab: Ken Treptow, Leo Stefanazzi, Chris Stoughton, Sho Uemura, Neal Wilcer, Martin Di Federico, Silvia Zorzetti, Salvatore Montella, Gustavo Cancelo.
- U. Chicago: David Schuster, Ankur Agrawal, Chunyang Ding, Helin Zhang
- C2QA Princeton: Sara Sussman, Jake Bryon, Jeronimo Martinez, Russell McLellan, Xanthe Croot, Hoang Le, Andrew Houck.
- ANL: Shefali Saxena.
- CNEA, Argentina: Horacio Arnaldi.
- also exchanges with INQNET CONSORTIUM est. 2017 : CALTECH/JPL/FNAL and others including industries with CRADAs and MOUs

- Newer collaborations:
- LBNL AQT: User project approved. Partners: Kasra Nowrouzi, Gang Huang, Neelay Fruitwala, Yilun Xu.
- C2QA Hatlab: Michael Hatridge, Chao Zhou, Mingkang Xia.
- SQMS: Anna Grassellino, Alex Romanenko, and SQMS control team.
- Q-NEXT: Andrew Cleland (UC), Robert Mcdermott, David Awschalom's lab (AMO qubits)
- Nexus: Daniel Bowring et. al.

- Collaborations with industry:
- Amazon AWS: The AWS team is building a software layer to have QICK as a braket backend and on their cloud.
- Other industries have made contact and had a meeting with the team.

Thank you