CPAD INSTRUMENTATION FRONTIER WORKSHOP 2019
University of Wisconsin-Madison

Fermilab

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Readout and control of superconducting detectors

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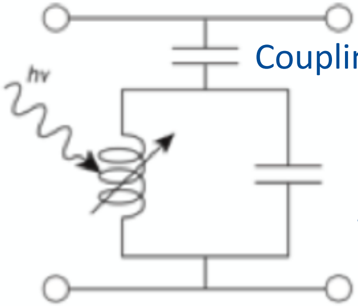
Some examples of superconducting detectors in astrophysics and astronomy

- TES-SQUIDs: B. Cabrera (Stanford), K. Irwin and NIST, Caltech, JPL, ANL, LBNL, etc.
  - Dark matter: CDMS, SuperCDMS.
  - CMB 1st, 2nd, 3rd generation of experiments.
  - Now applications from IR-Optical-Xray.
- MKIDs: Zmudzinas (Caltech), B. Mazin (UCSB), E. Shirokoff (UC).
  - Astronomy: Exoplanets, NIKA2.
  - Dark Energy: Large survey low resolution spectroscopy (future) .
  - Applications from IR-Optical-Xray
- SNSPD: D. Semenov (Moscow), R. Hadfield (Glasgow), U Rochester.
  - Quantum photonics. High resolution photon timing ~10ps. Q. Communications.
- 3D Superconducting qubits (Yale, UCSB, Google, IBM, UC, etc)
  - Dark matter: Axion detection, ADMX?

- **So far, all superconducting detectors are controlled and readout by non superconducting electronics between 4K and 300K.**
  - The field of superconducting readout electronics is progressing but won’t be able to replace warm electronics in the next decade. The consumer market of electronics is still based on 300K devices.
- **This talk addresses the similarities (and differences) of highly multiplexed readouts for systems that use, typically, a portion of the RF spectrum (e.g. 4GHz to 8GHz).**

MKIDs are RF resonators

A microwave or optical photon deposits energy on the inductor breaking Cooper pairs into electrons

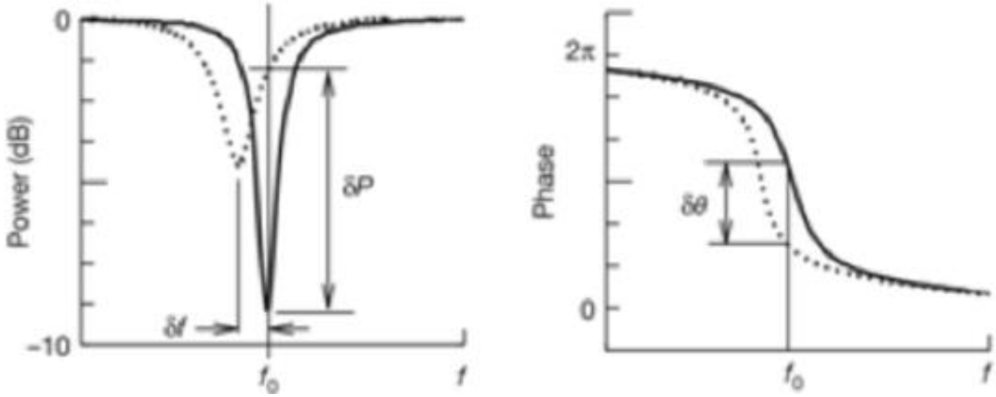


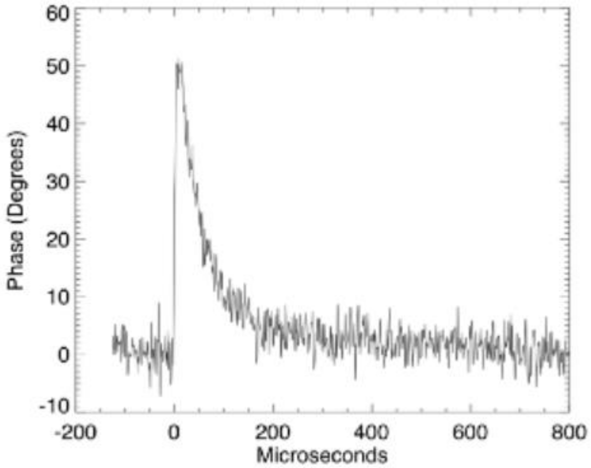
RF transmission line

Coupling capacitor

LC resonator capacitively coupled to the RF line

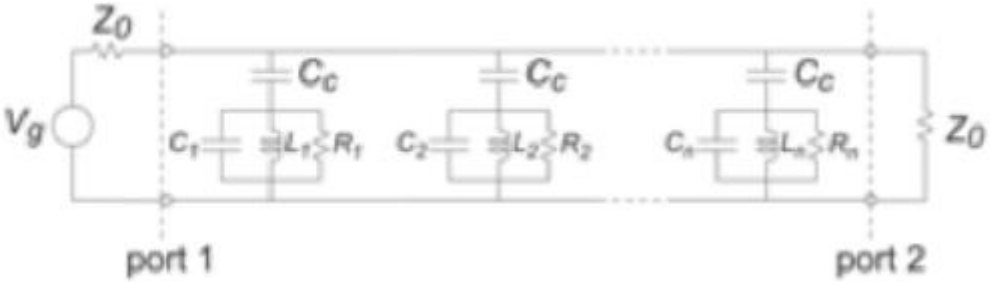
The LC resonator has a large Q ~ 30K.
The photon generates electrons and add a resistor in parallel to LC.
The Q lowers, the resonance shifts to the left (amplitude and phase).
The electrons go back to Cooper pairs in 100 usec time.



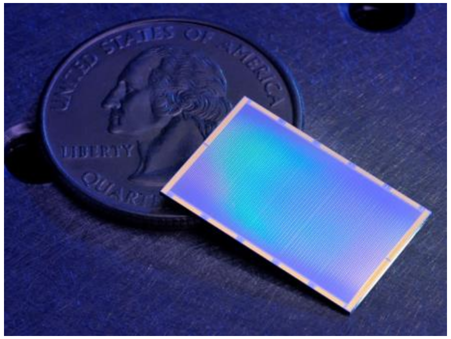


- The superconducting part of the inductance is the kinetic inductance and used for detection. The capacitors can be used for frequency placement and coupling (loaded Q).
- Typical bandwidth ~ 250KHz

MKIDs can be frequency multiplexed

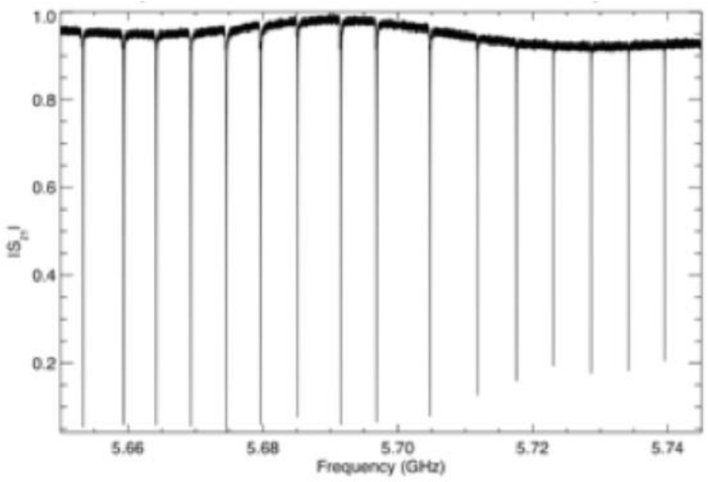


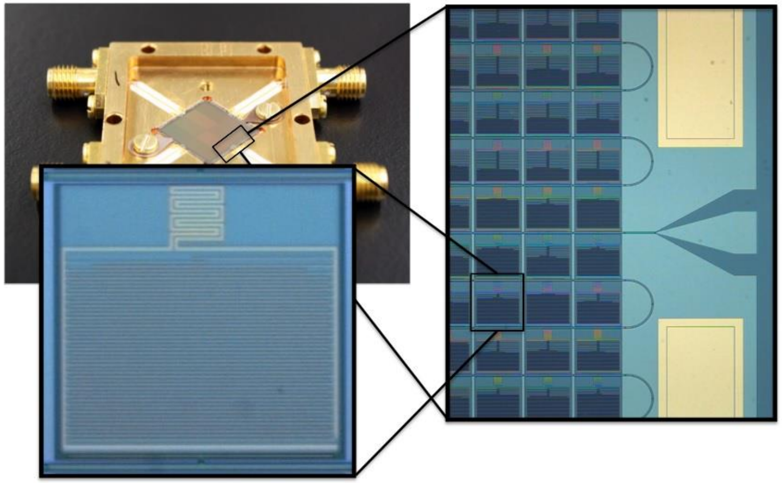
- A typical detector may have 2K MKIDs separated by 2MHz on a single RF line.



10,000 pixels Mazin et al. (UCSB)

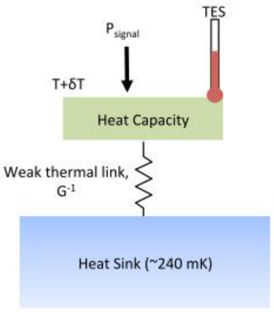
A frequency scan made by a VNA instrument of the S21 amplitude

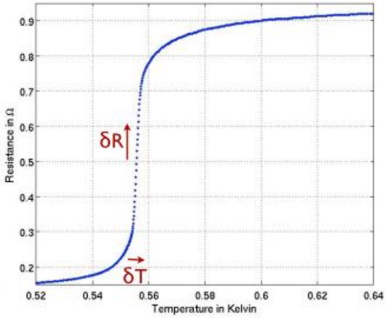




Different size capacitors define the resonant frequency

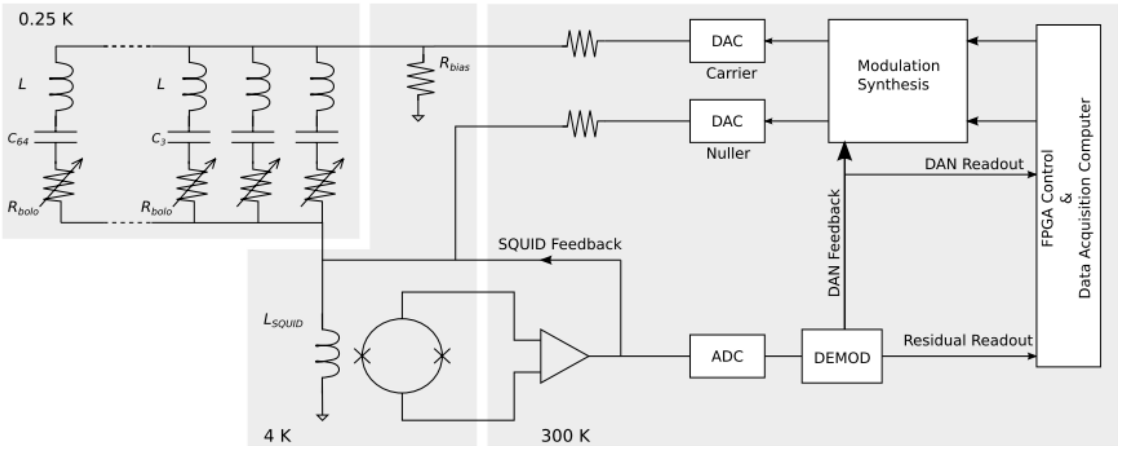
TES-SQUIDs

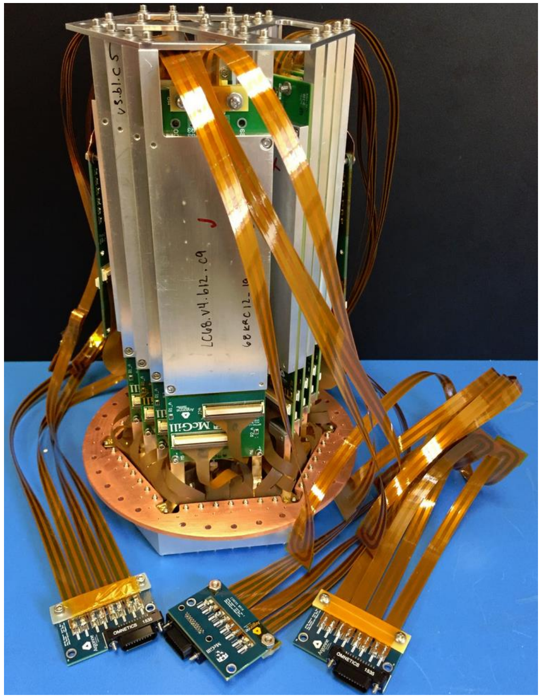




- TES is a bolometer coupled to a SQUID with feedback to keep it operating at the middle of the high slopped temperature transition.
  - They are low noise.
  - Used on the sky for many years and many telescopes.
  - Technology of choice for CMB-S4 (main frequencies).

FDM architecture of SPT3





Issues:

TES couple to a very nonlinear device, the SQUID.

Very large arrays (>100K channels) pose a readout interconnection challenge.

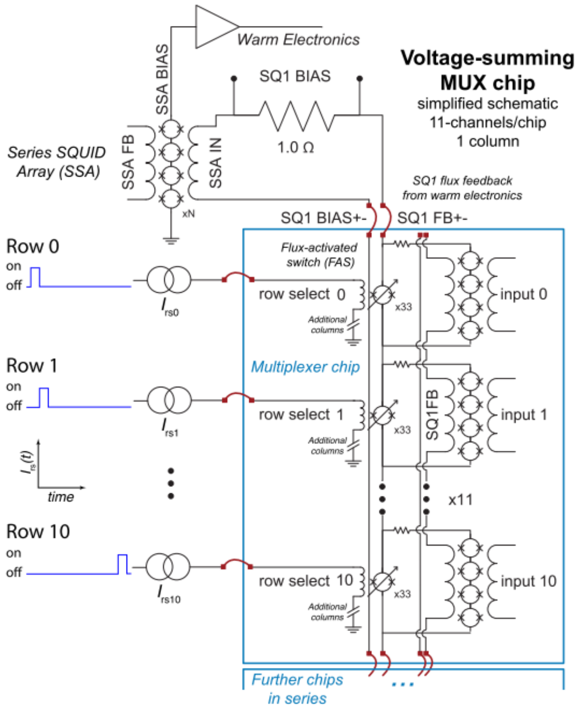
Experiments that need >100K superconducting detectors

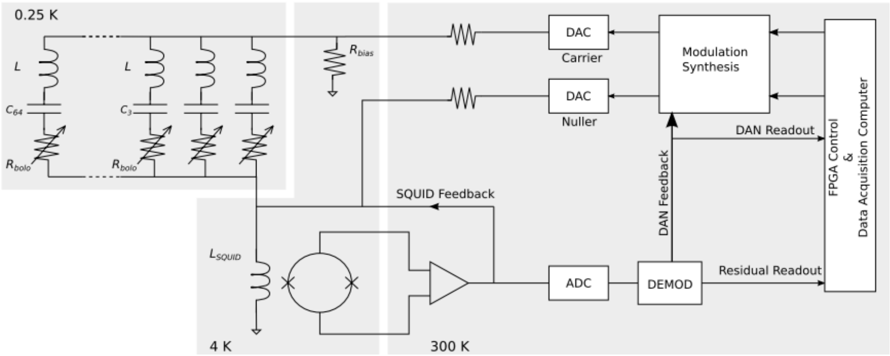
- 3 Large Aperture Telescopes
- 18 Small Aperture Telescopes
- 2 sites: South pole, Atacama.
- 8 frequencies of observation.
- ~500,000 channels.
- Amazing science: Inflation, light relics, galaxy clusters, gamma-ray burst, neutrinos, &more.
- Down selection of detectors, readout, to be done in 2021.

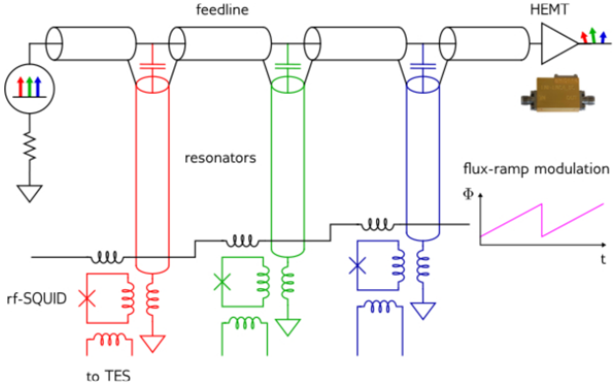
- Possible readout methods:
  - Time domain multiplexing.
  - Frequency domain multiplexing.
  - RF Frequency domain multiplexing.

FDM architecture of SPT3

TDM architecture of Biceps





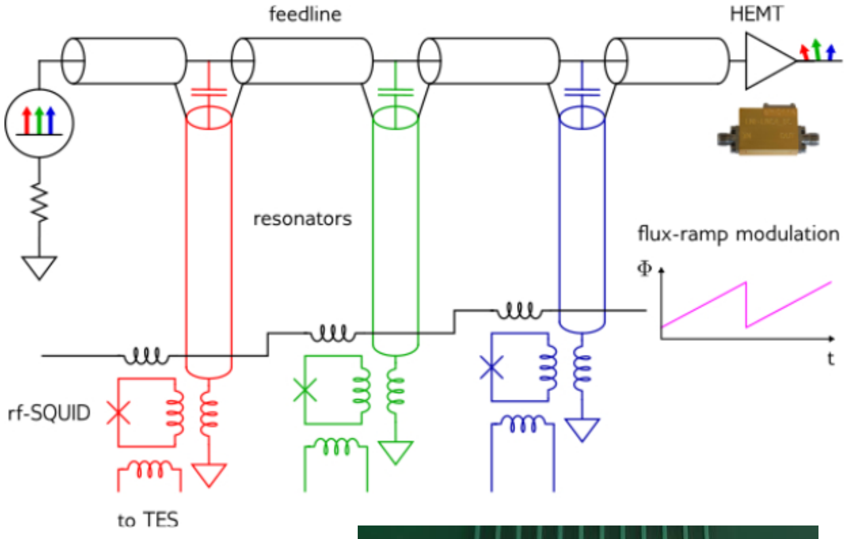


uMUX: RF multiplexed architecture: Simons Obs.

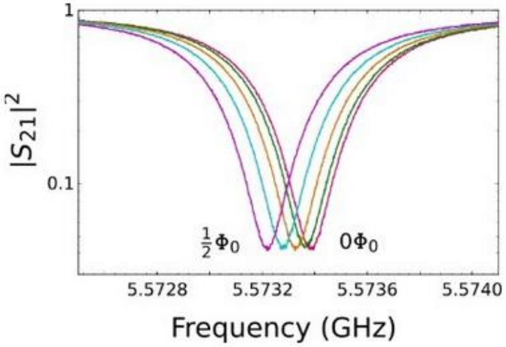
- Readout alternatives:
  - FDM and TDM (time domain multiplexing): require a large number of interconnections with the warm electronics. Dedicated cold electronics and ASICs.
  - uMUX: solves the interconnection problem with the help of a dedicated RF MUX device (K. Irwin, B. Mates).

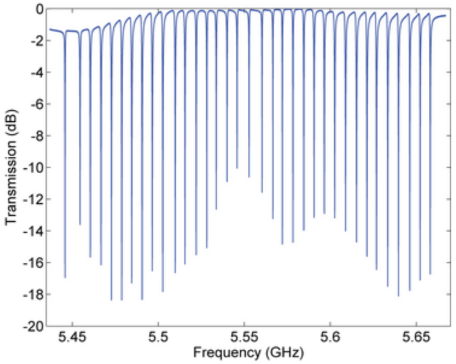
uMUX electronics

- The resonators remain at fixed frequency and can reach high channel multiplexing > 2000.
- 4GHz – 8GHz RF band OK.

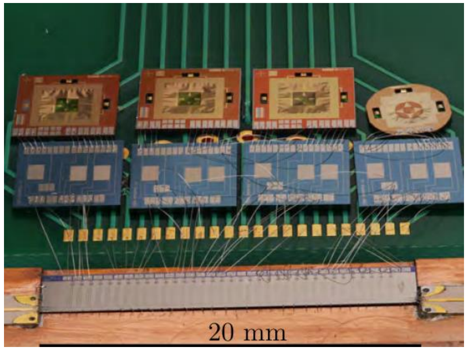


Very similar to MKIDs S_{21}



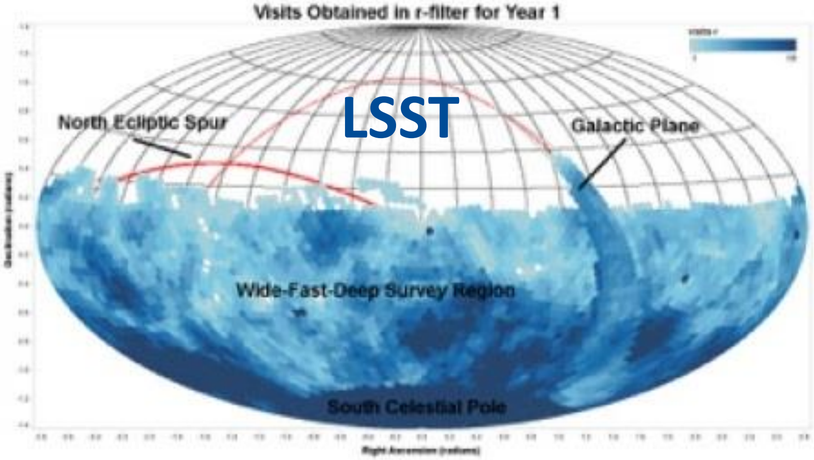


B. Mates, 2011 (NIST)

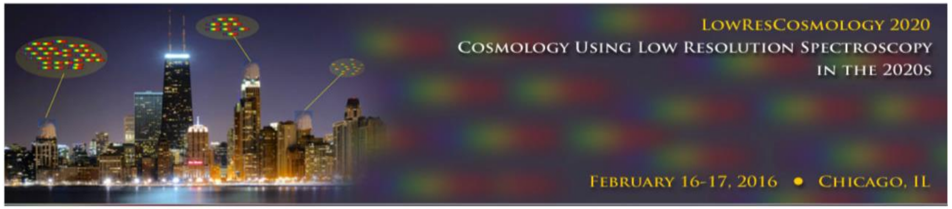


- Still some problems remain:
  - Channel frequency separation is non uniform. Some channels will overlap with neighbor channels and will be non usable.
  - SQUID nonlinearity: requires a ramped flux bias to extract a “linearized” signal.
  - Multiplexing 2000 channels (or even less) on a single RF line makes the LNA (HEMT) work near saturation and in the nonlinear region: Problem is solved by “tone tracking” where the S21 power of each tone is minimized to avoid overpowering the HEMT.

MKID as a tool for Dark Energy



- The DES and LSST will produce unprecedented imaging data. An MKIDs based low spectrograph surveying >1B galaxies reaching to NIR would be of great help.
- MKIDs have been recognized by P5 as a technology that could dramatically leverage investments.

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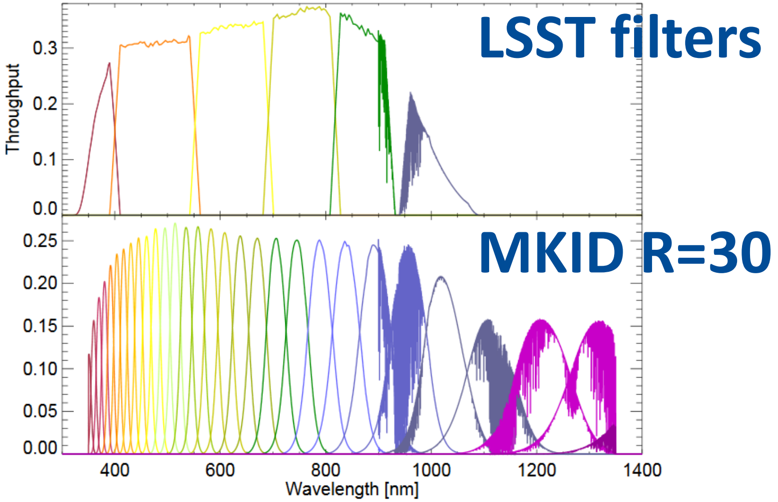
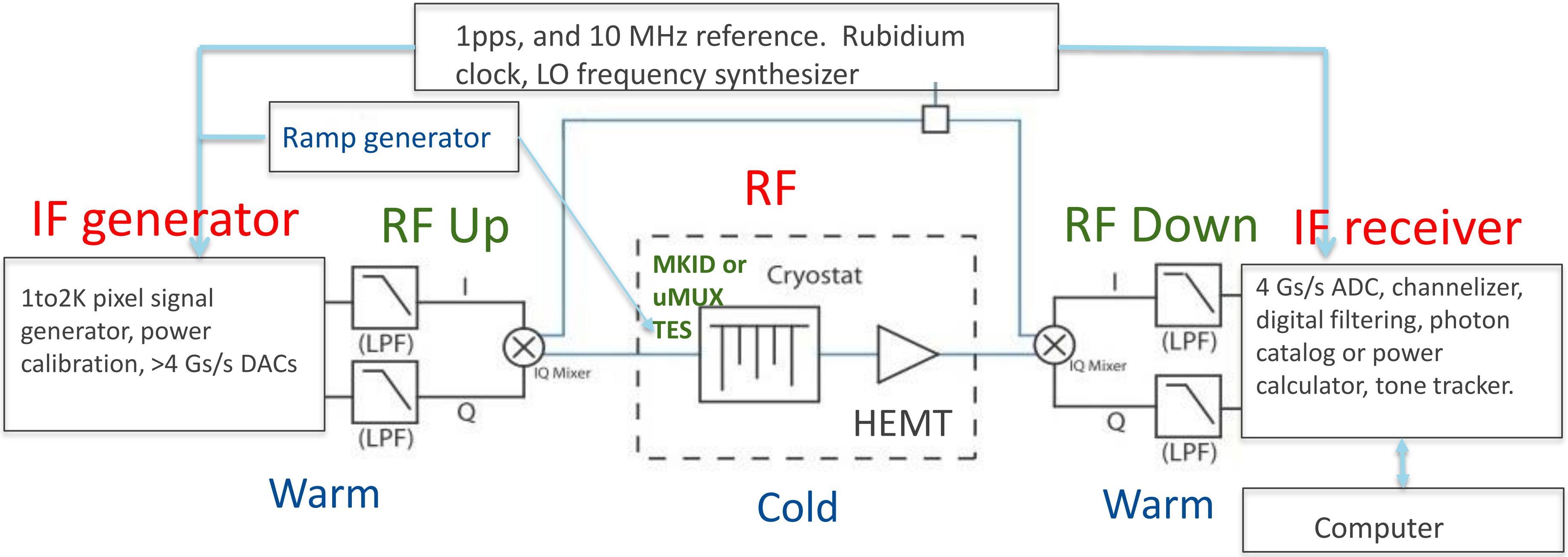


Improvements in BAO FOM.
MKIDs detectors need to improve in spectral resolution and uniformity.

fMESSI DAQ block diagram



1pps, and 10 MHz reference. Rubidium clock, LO frequency synthesizer

Ramp generator

IF generator

1to2K pixel signal generator, power calibration, >4 Gs/s DACs

RF Up

RF

MKID or uMUX TES

Cryostat

HEMT

RF Down

IF receiver

4 Gs/s ADC, channelizer, digital filtering, photon catalog or power calculator, tone tracker.

Computer

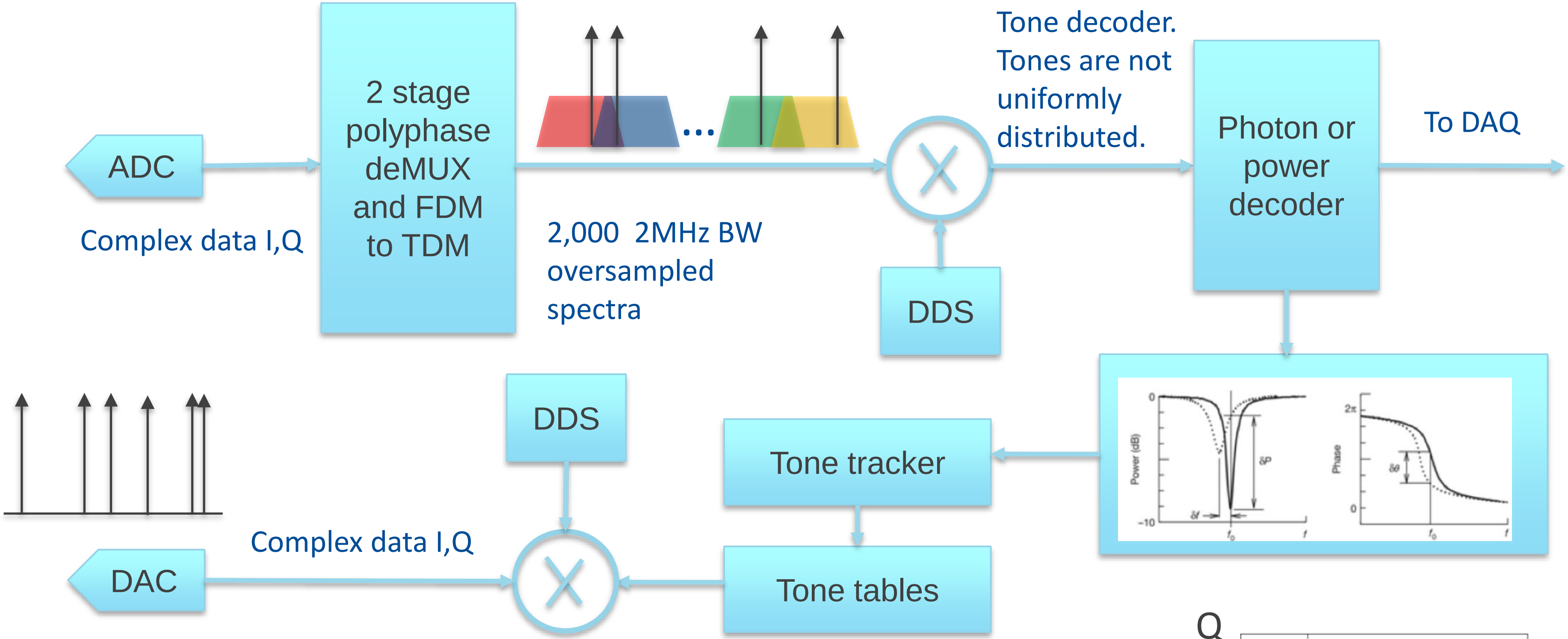
Warm

Cold

Warm

- The IF generator and receiver and reference timing are in the same box.
  - Sophisticated firmware in FPGA, plus full DAQ.
- RF Up/down converters and LO generator share same pc board.
- The RF electronics need to have flexible input and output powers (± 60dB) to accommodate 1 to 2000 tones.
  - The mixers should work at ~ constant power to avoid nonlinearities and bad mixing products.
  - The RF amplifiers should provide close to constant power across the 4-8GHz spectrum.
  - Tones should allow for individual power and phase rotation calibration.
  - Channel crosstalk should be minimized.

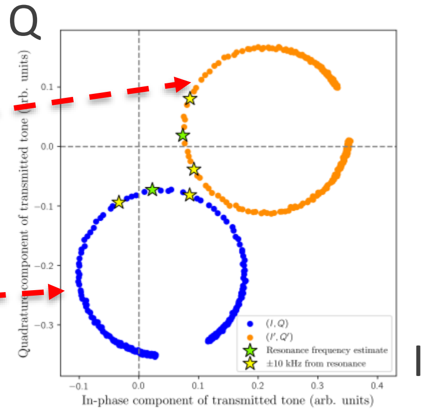
Firmware and software (RF part not shown)



- Software must find resonant frequencies, calibrate powers, rotate I, Q loops, calculate resonator parameters, program Tone tables or DDS.
- Take data and make images.

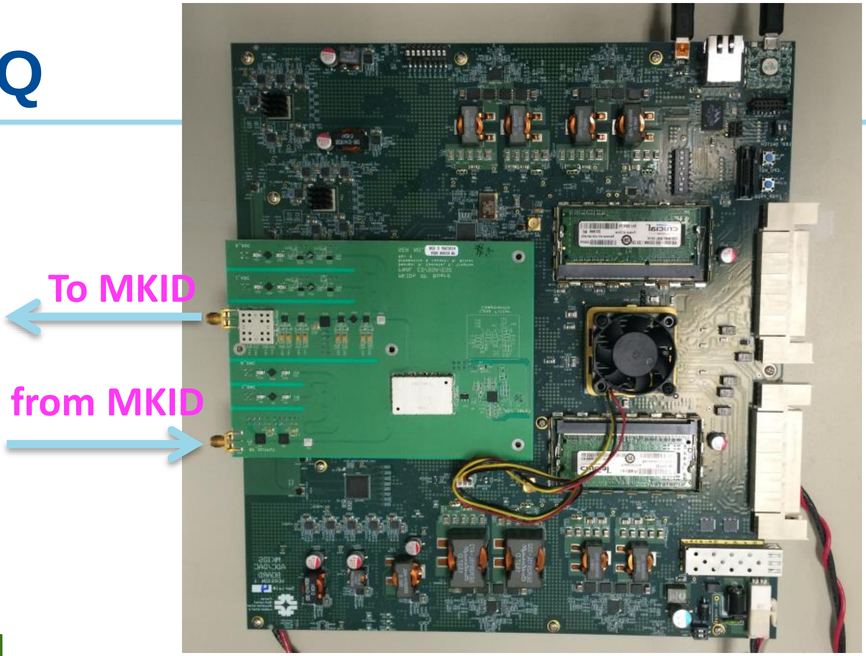
Rotated/calibrated resonator

Unrotated/uncalibrated resonator



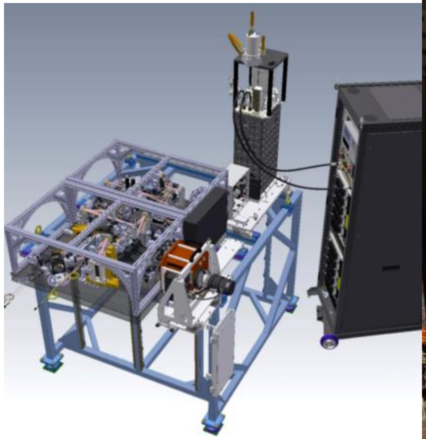
FMESSI DAQ

Designed by Fermilab in 2016.
Production ~100
Still in use



- **fMESSI main features:**
- 1M photons/s per board.
- Noise: 12dB below HEMT.
- <0.1Hz 1/f knee w/o compensation.
- 40 watts of power for the entire board running all ADCs and DACs at max sampling rate.
- Low cost: $6/channel.

MEC: 20K MKID system operational at 8m telescope at Subaru

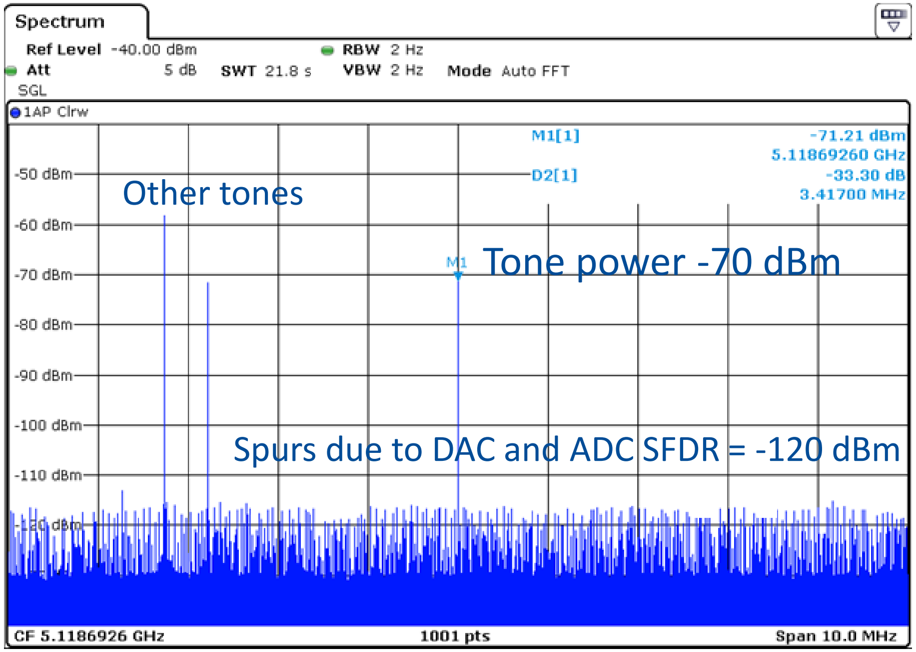


DARKNESS 10Kpixels

Mazin Lab at UCSB
http://mazinlab.org

On-sky, July 23 2016

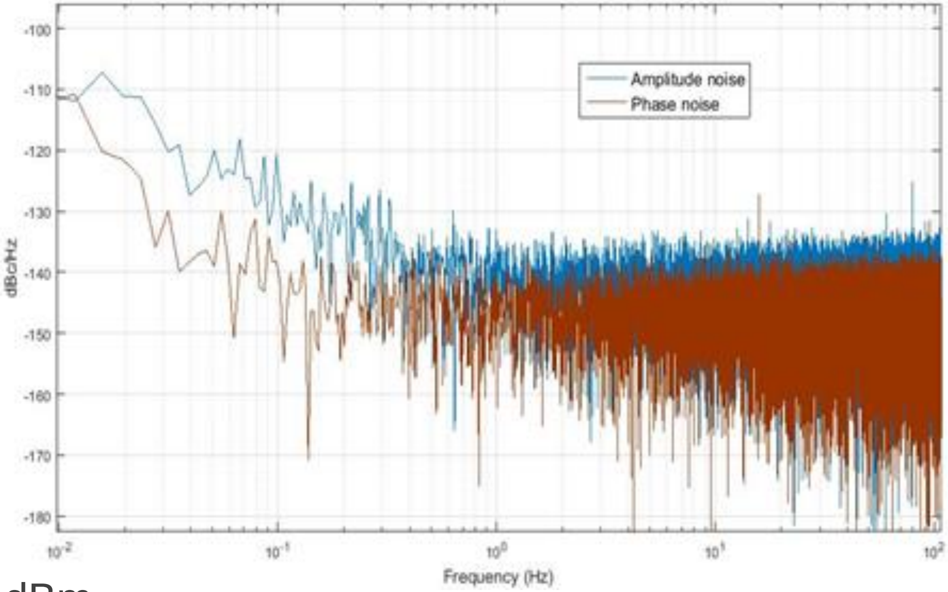
fMESSI performance 1000 tones



Other tones

Tone power -70 dBm

Spurs due to DAC and ADC SFDR = -120 dBm



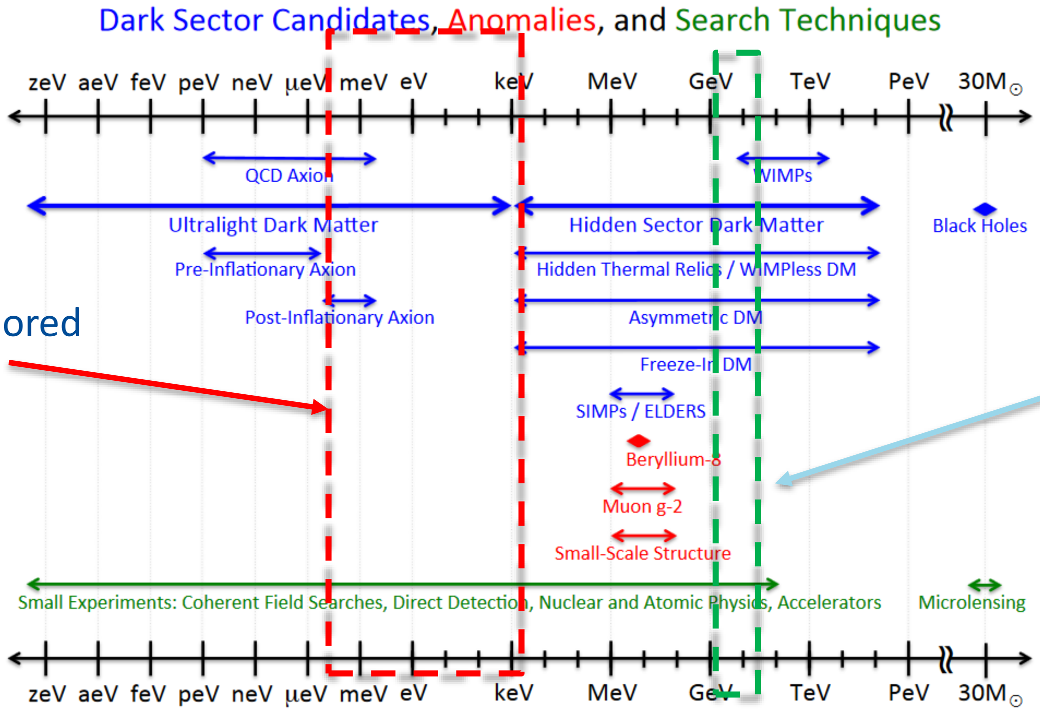
- Noise floor from spurs of 1000 tones at -120 dBm.
- WG noise floor -145 dBm
- That is 2016, things get better now (next slides).

DARKNESS: A Microwave Kinetic Inductance Detector Integral Field Spectrograph for High-Contrast Astronomy
arxiv.org/abs/1803.10420 , DOI: 10.1088/1538-3873/aab5e7

Also SMURF paper (SLAC) arXiv:1809.03689

Superconducting detector for light dark matter search

- Light Dark Matter: searching for low energy WIMPs and Axions.



Can be explored with SCD

Explored or close to be explored down to 10^{-48}?

Axion detectors can make use of superconducting technology developed for QIS.
There is natural synergy between the readout and control electronics for MKIDs, uMUX TES and QIS with superconducting elements.

Superconducting devices for Quantum Computing

- Quantum computing uses quantum-mechanical phenomena such as superposition and entanglement to perform computation.
  - Promise to solve BQP (bounded error quantum probabilistic polynomial) problems exponentially faster than traditional computers.
  - Physical Quantum Computers have not yet achieved Quantum Supremacy.

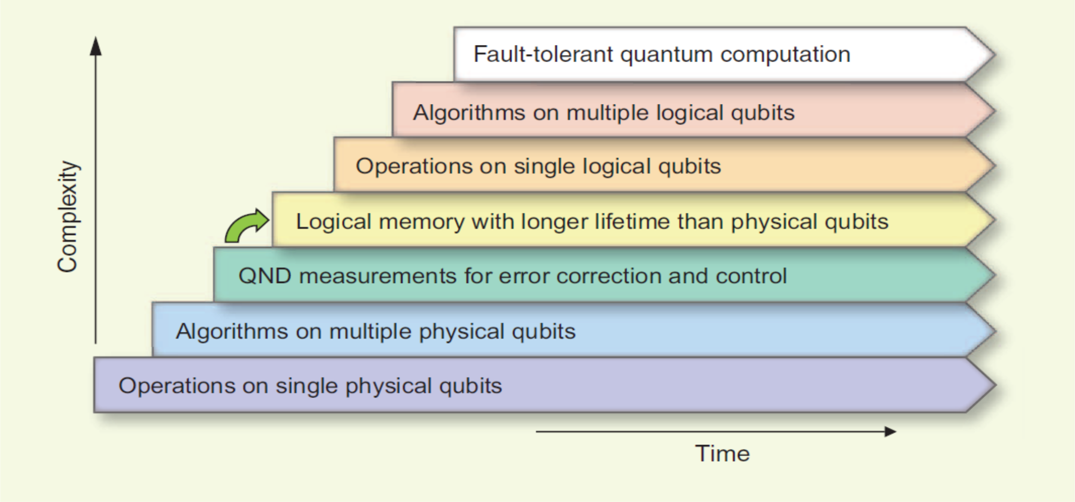


Fig. 1. Seven stages in the development of quantum information processing. Each advancement requires mastery of the preceding stages, but each also represents a continuing task that must be perfected in parallel with the others. Superconducting qubits are the only solid-state implementation at the third stage, and they now aim at reaching the fourth stage (green arrow). In the domain of atomic physics and quantum optics, the third stage had been previously attained by trapped ions and by Rydberg atoms. No implementation has yet reached the fourth stage, where a logical qubit can be stored, via error correction, for a time substantially longer than the decoherence time of its physical qubit components.

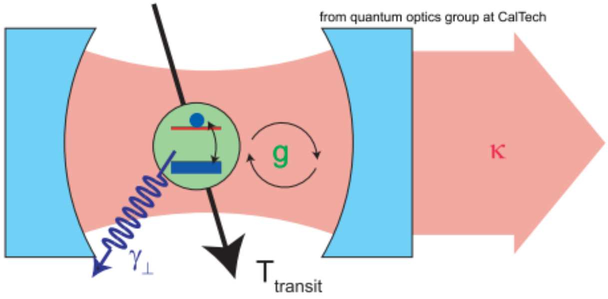
What is a qubit?

- A quantum mechanic quantum bit is the basic unit of quantum information.
- It is quantum mechanic two level system defined by the Jaynes-Cummings Hamiltonian in a 2 dimensional complex Hilbert space.

$$H_{JC} = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \hbar\omega_a\sigma_z + \hbar g_c\left(a^\dagger\sigma^- + a\sigma^+\right)$$

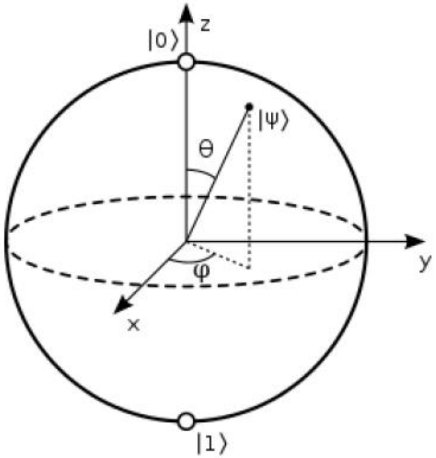
$$\varphi(x,t) = \cos\left(\frac{\theta}{2}\right)\varphi_0(x) + \sin\left(\frac{\theta}{2}\right)\varphi_1(x)e^{i\varnothing}$$

Atom in a cavity

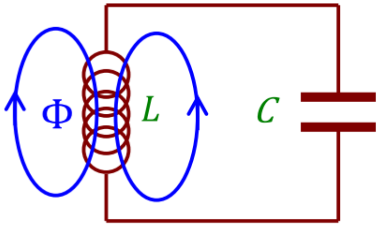

from quantum optics group at CalTech

A general wave function state |φ> is in a superposition of the base states and collapses to |0> or |1> when measured.

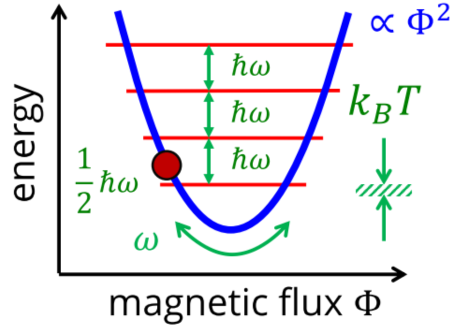
The Block sphere



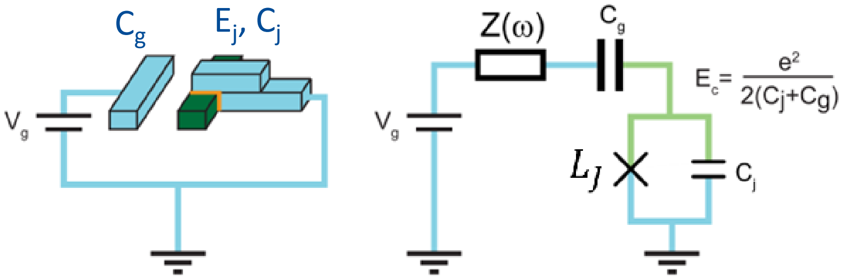
The harmonic oscillator does NOT work, we need an harmonic eigenenergies



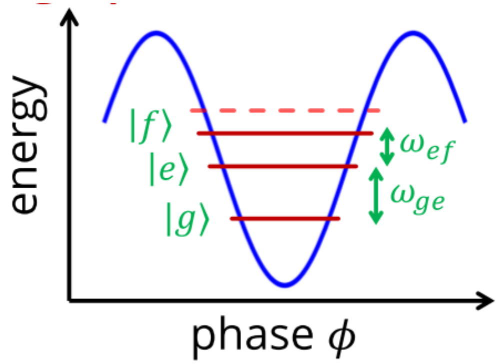
$$\omega = 1/\sqrt{LC}$$



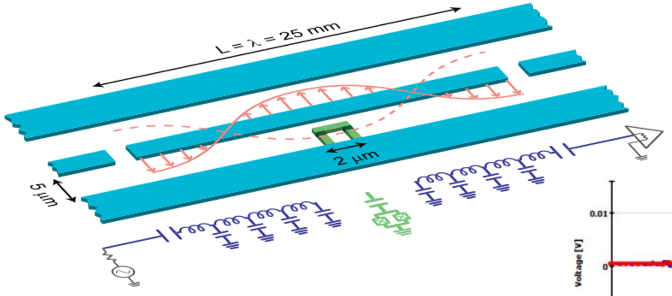
The Cooper pair box, 2D and 3D xmons: RF cavities and TJS

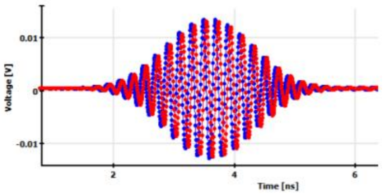


The oscillator’s inductance has been replaced by a nonlinear inductance, a Josephson junction.

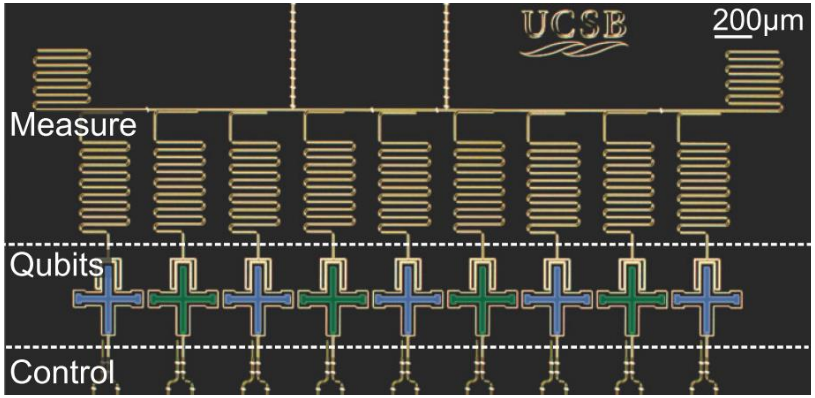


Now the energy levels are not equally spaced. We can control that device using different RF frequencies.



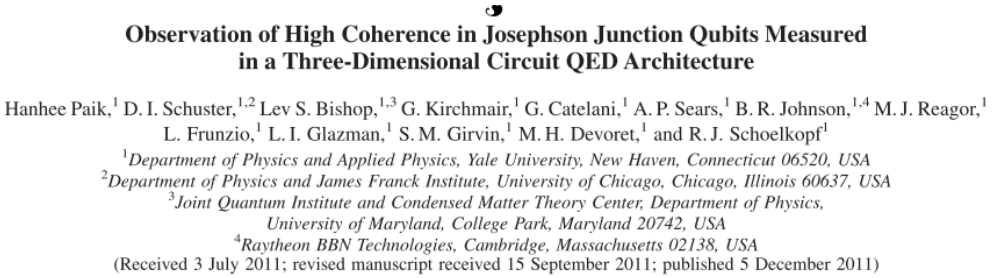


- Controlled by RF pulses.
- Multiplexed readout in 4-8 GHz like MKIDs.



J. Martinis (Google, UCSB), A. Cleland (UC)

3D qubits couple xmons with 3D RF cavities



Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture

Hanhee Paik,[1] D. I. Schuster,[1,2] Lev S. Bishop,[1,3] G. Kirchmair,[1] G. Catelani,[1] A. P. Sears,[1] B. R. Johnson,[1,4] M. J. Reagor,[1]
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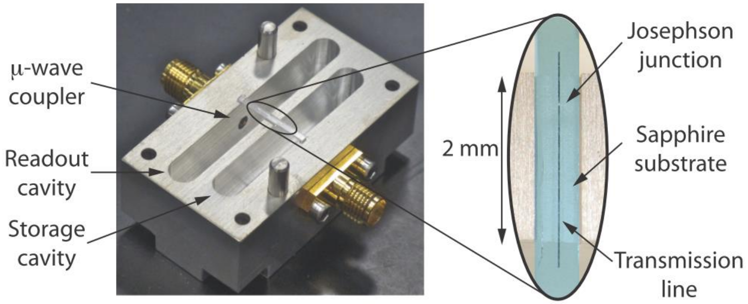
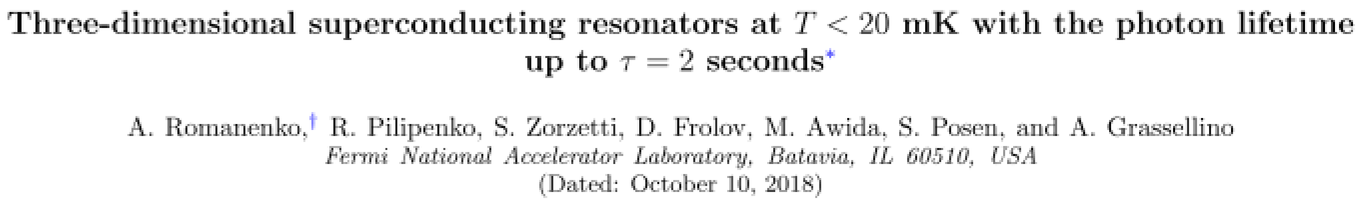
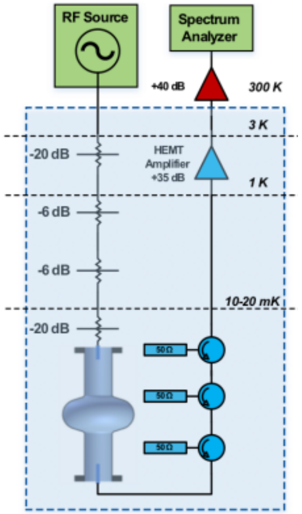
(Received 3 July 2011; revised manuscript received 15 September 2011; published 5 December 2011)

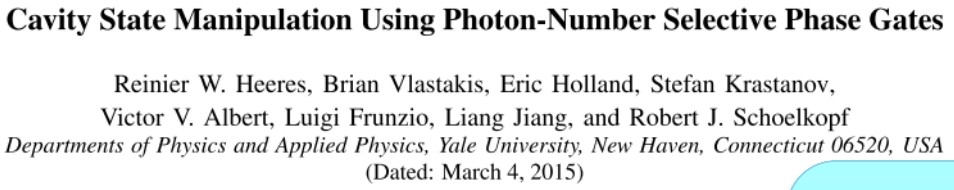




Three-dimensional superconducting resonators at $T < 20$ mK with the photon lifetime up to $\tau = 2$ seconds*

A. Romanenko,† R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, and A. Grassellino
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
(Dated: October 10, 2018)





Cavity State Manipulation Using Photon-Number Selective Phase Gates

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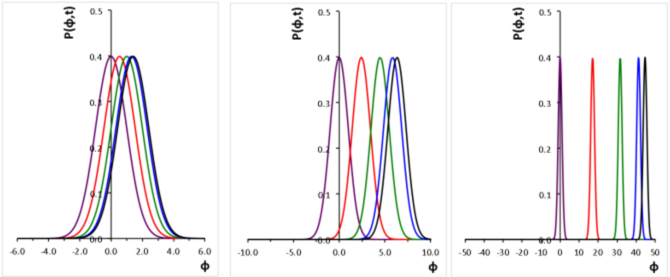
(Dated: March 4, 2015)



HEP is already using all this technology available. Readout and controls is key

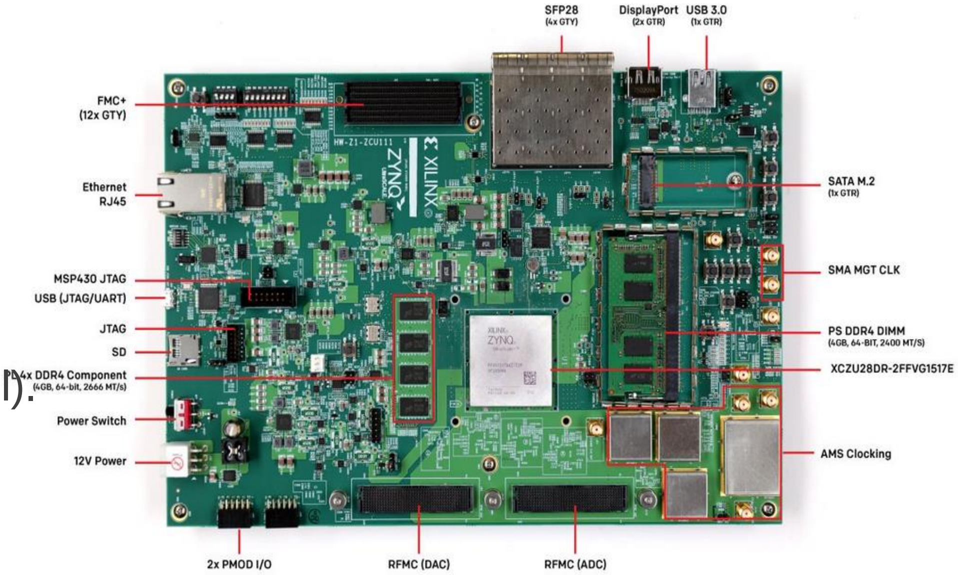
How are we moving forward with multiplexed readout and controls?

- Commercial technology has made a quantum leap in FPGA and analog ADC/DAC integration. Xilinx ZU series integrates:
  - 8 ADCs at 5Gs/s
  - 8 DACs at 10 Gs/s
  - Huge FPGA logic
  - 4 core ARM processor (ready for Linux)
  - lots of peripherals.
- Almost all we need is in a single chip!
- A single FPGA can control and readout

up to 8000 channels (2MHz separation/channel).

- Advantages:
- Cost: $1/channel.
- Power: <10mW/channel.
- Multiplexing factor and DAQ size reduction.

Xilinx ZCU111 evaluation board



How are we moving forward with multiplexed readout and controls?

- The priority is the firmware and the software.
  - Complex FPGAs require sophisticated firmware techniques from firmware experts.
  - Mathematical functions from theory need to be translated into efficient algorithms for FPGAs.
  - Algorithms must use FPGA resources efficiently at >500Mhz of clock.
  - Latency is important in qubit control.

- Hardware developments:
  - For now we use the ZCU111. Projects such as CMB-S4 will require new hardware designs.
  - A multichannel IF/RF hardware is needed.

Fermilab has started a by weekly collaboration meeting with US labs and Univ.
You are welcome to join: Every other Tuesday 11am Central time (please email me at cancelo@fnal.gov to be added to the list) https://fnal.zoom.us/j/470735194

Summary

- Superconducting detectors are being chosen for large experiments approaching millions of channels.
- Although some electronics is moving to <1K and 4K, it is expected that the rapid development of commercial electronics for 300K will lead the way to readout and Control implementations.
- New experiments, in particular for cosmology, will continue to request new hardware firmware and software developments for Readout and Controls.
- Multiplexed Readout and Controls will lead the way for these large size experiments.