Superconducting Sensors:
Classical (Transition-Edge Sensors) and Quantum (RF quantum upconverters)

Kent Irwin, SLAC and Stanford

2020 SLAC Summer Institute

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Introduction – links to other talks in SSI 2020

- Transition-edge sensors (direct detectors)
  - Almost invisibles in the CMB – see Zeesh Ahmed talk
  - Direct Dark Matter Searches – see Jodi Cooley talk
- Quantum coherent superconducting sensors
  - Axions and Axion-like particles - See Gianpaolo Carosi talk

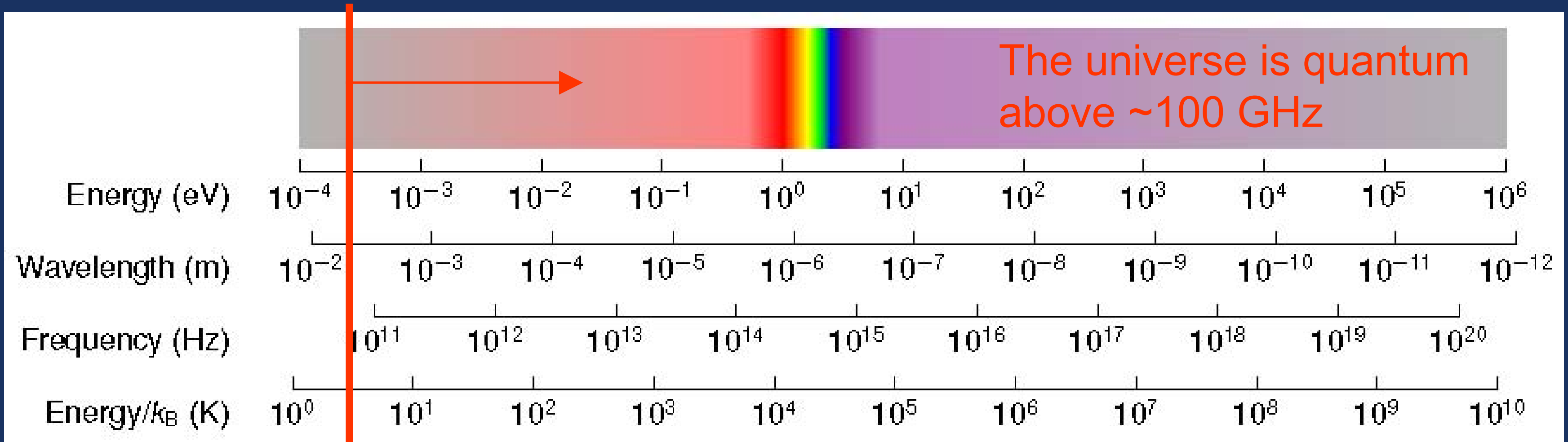
Direct vs. coherent

"Direct" detectors measure the energy or power in an electromagnetic signal, but not the phase.

- e.g. TES, STJ, MKID, nanowire
- No quantum noise (better at short wavelength)

"Coherent" detectors measure both amplitude and phase

- e.g. radio receivers, mixers
- Limited by quantum noise at short wavelengths $\hbar\omega \gg k_B T$
  - 0.5 photon per mode of quantum noise
- Extendable to quantum noise evasion techniques



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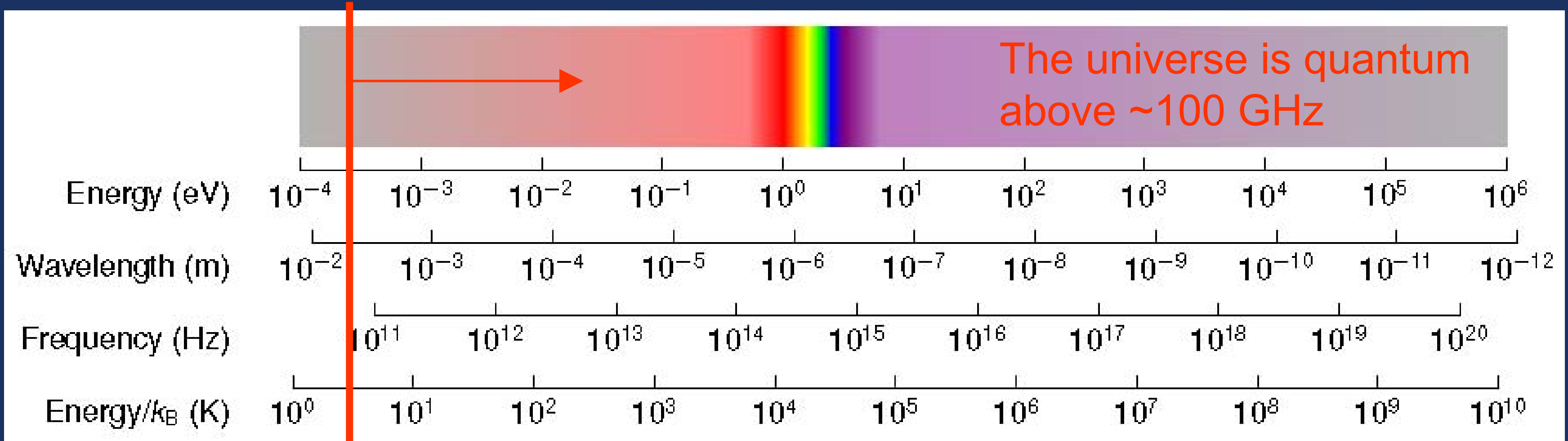


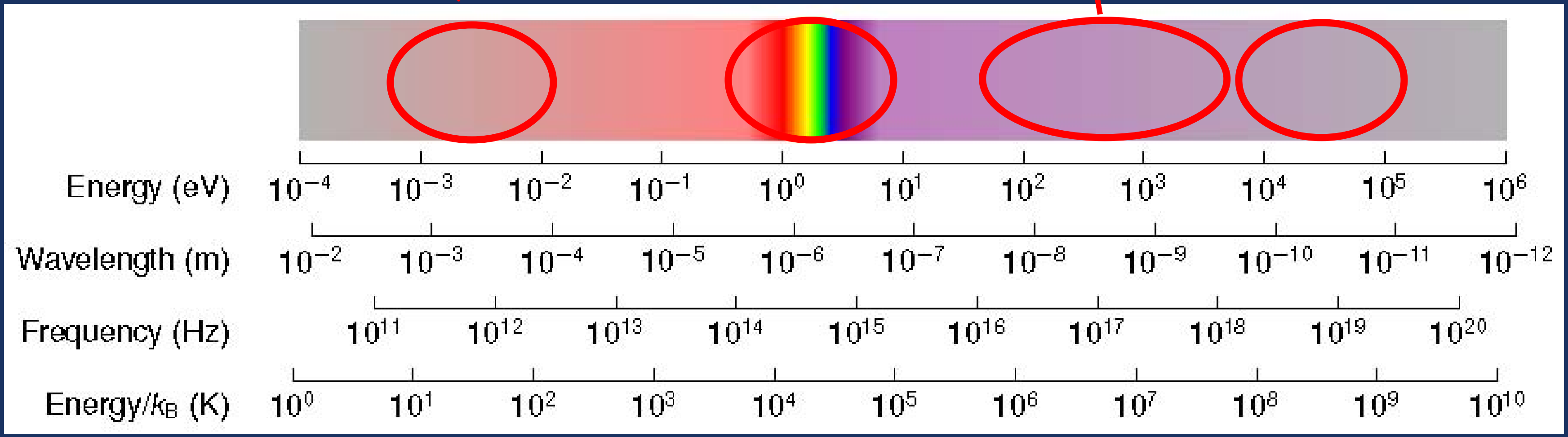
Superconducting sensors across the spectrum

millimeter and submillimeter detectors for cosmology, astronomy

single optical and near-IR photon sensors for quantum information and astronomy

x-ray sensors for astronomy and materials

γ-ray sensors for nuclear materials analysis

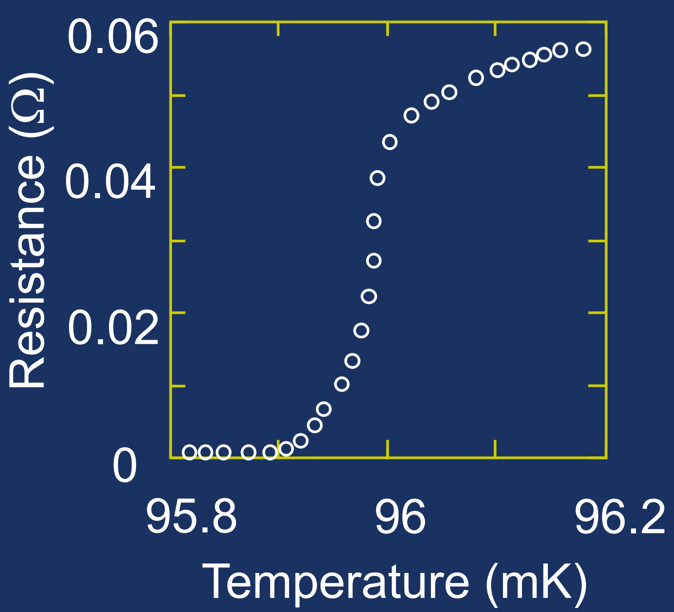


The superconducting transition as a sensor

In 1938, Donald Hatch Andrews invented a thermal sensor based on this transition: the superconducting transition-edge sensor (TES)

He made critical advances on the sensors, optical systems, and cryogenics, but was decades ahead of his time…

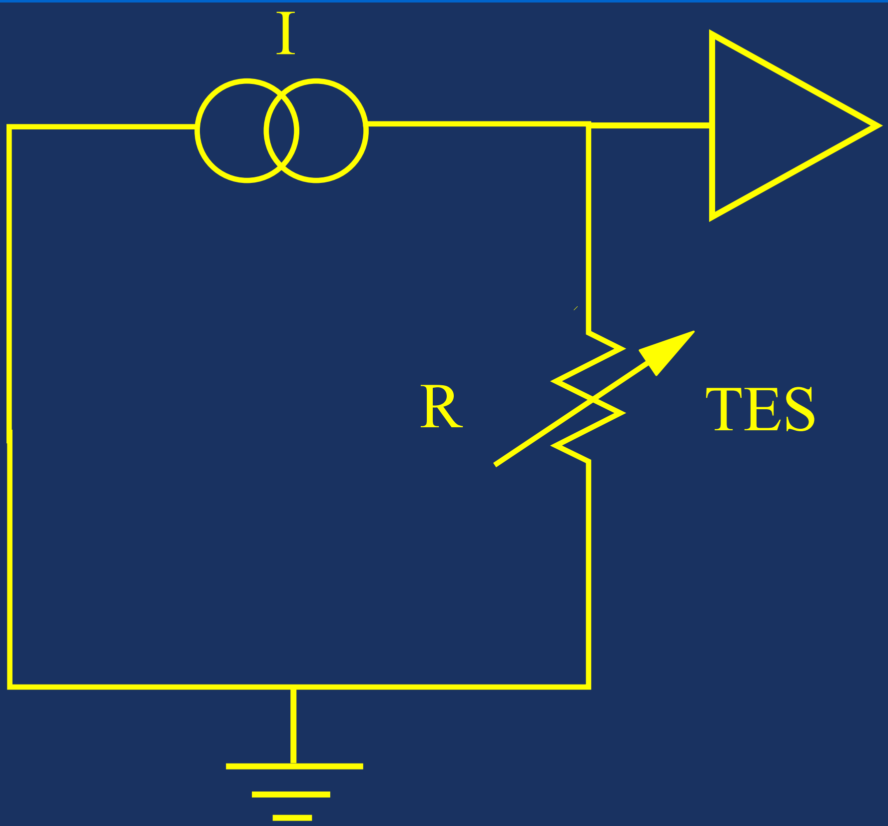
Transition-Edge Thermometer (TES)



D.H. Andrews

A real-time infrared image taken with a TES in 1945

Andrew's sensors were limited by follow-on amplifiers



Andrews current-biased the TES and amplified the voltage across through an audio transformer to a "pulse amplifier."

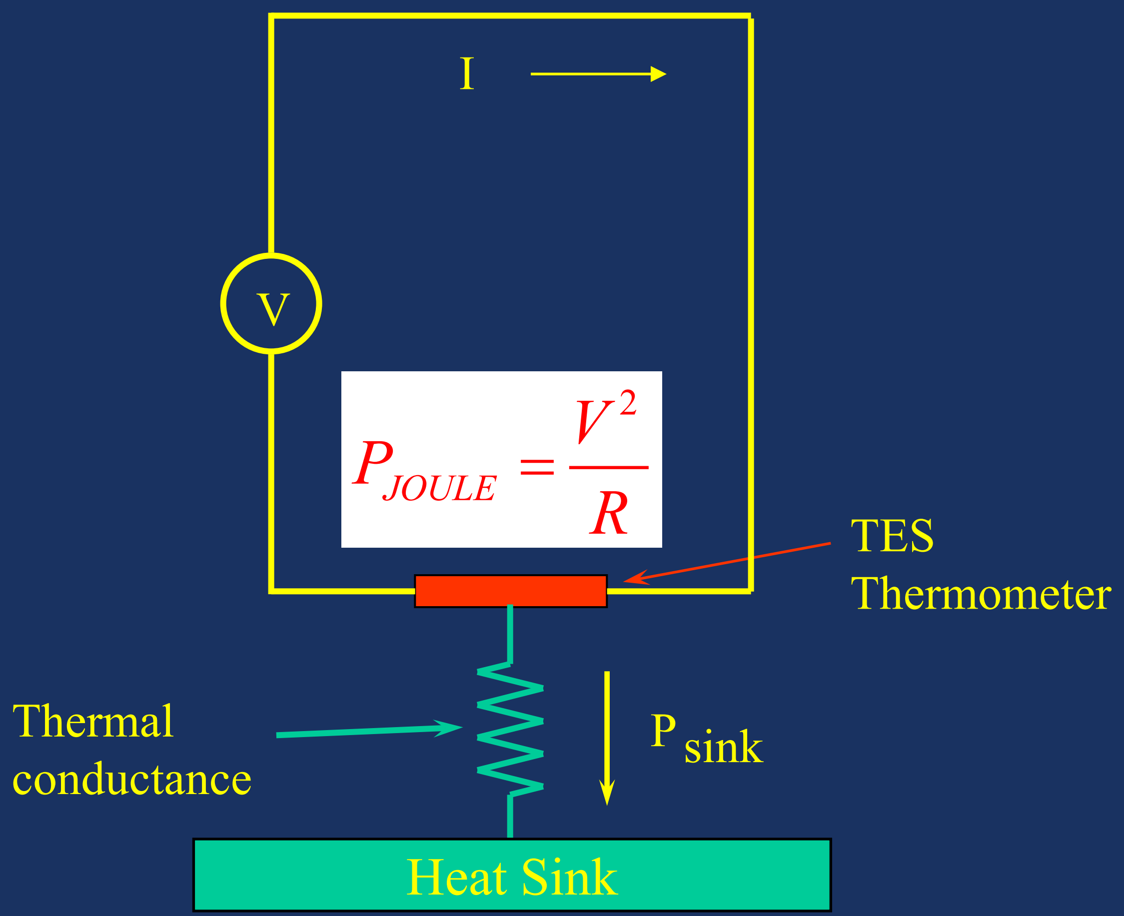
• The sensitivity of Andrews' TES devices was limited by the noise of the follow-on amplifier.
• The temperature over which a TES works is very narrow, and Andrews' devices were thermally unstable: as they heated up, the Joule power dissipation I^2R increased, leading to thermal runaway.

Voltage biased TESs are thermally stable

As the film cools, $R \rightarrow 0$, and Pjoule increases.

Stable equilibrium

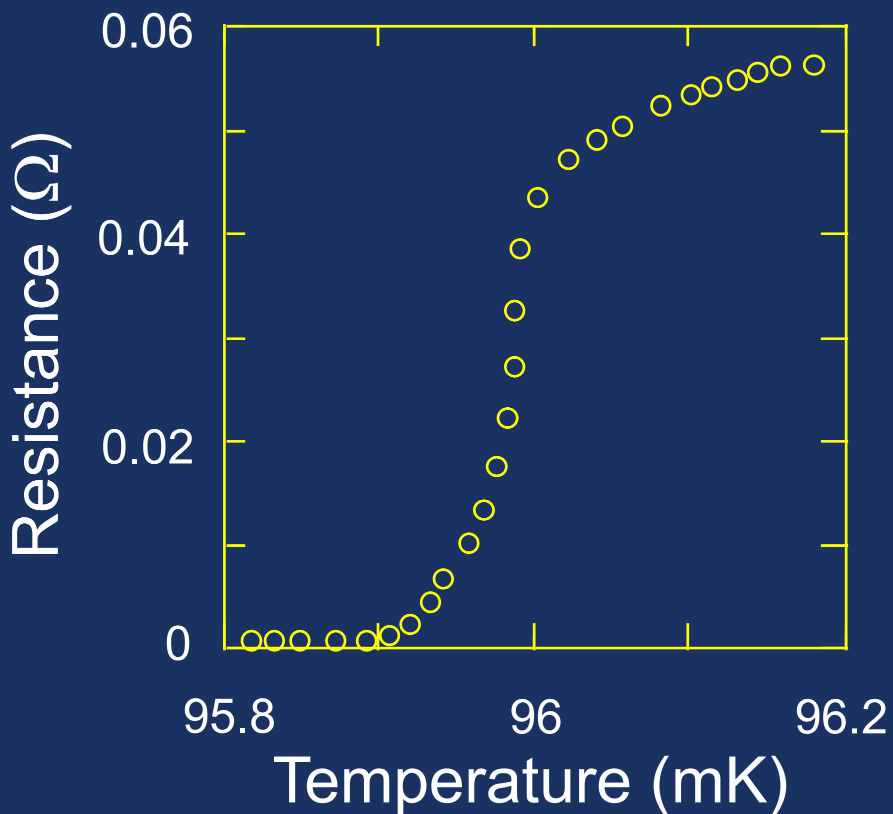
$$\frac{V^2}{R} = P_{SINK}$$



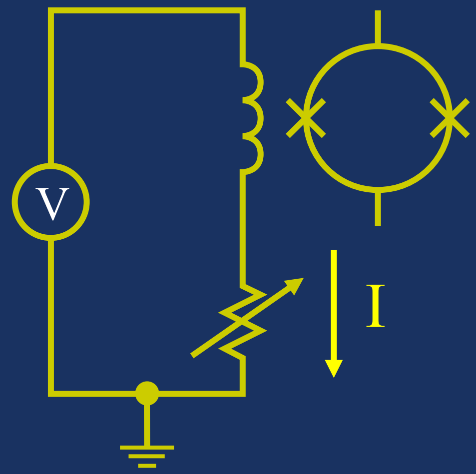
If you cool the heat sink to well below the transition temperature of the TES, the TES will self-heat into its transition.

Voltage-biased TES: inherently stable

Transition-Edge Sensor (TES)



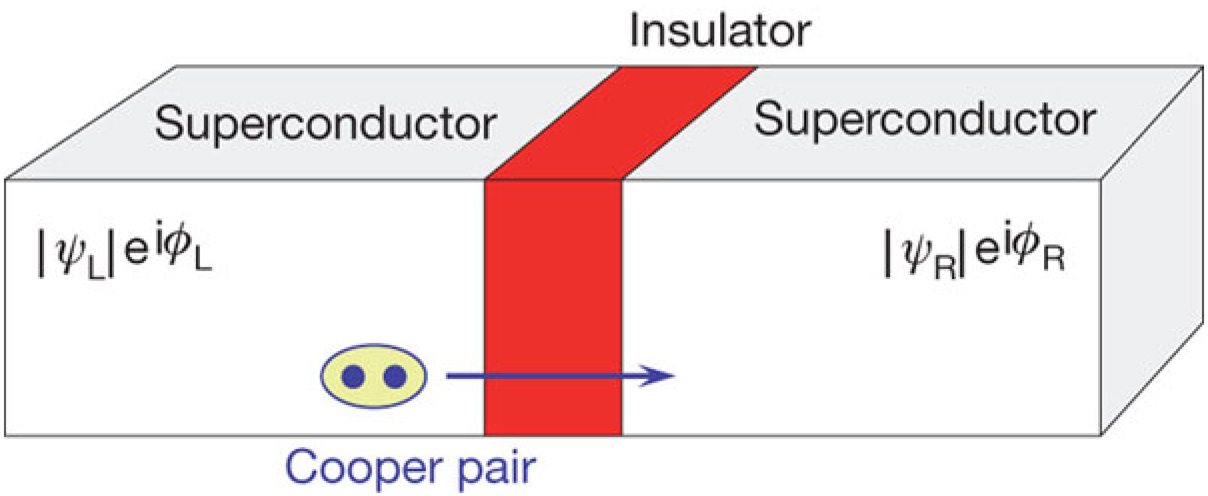
SQUID current amplifier



Photon → Heat → Resistance → Current

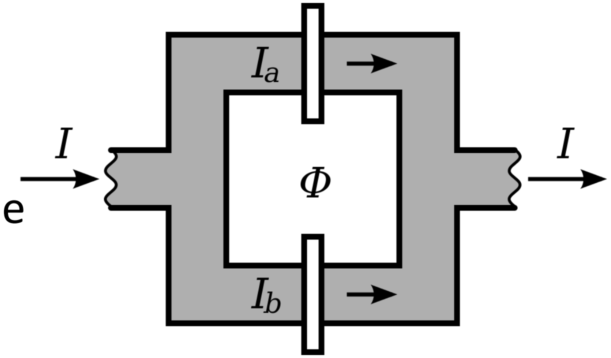
Josephson Junctions

Brian Josephson
Nobel Prize, 1973



$$\boxed{I = I_c \sin(\phi_R - \phi_L)}$$

It gets more interesting when you make a loop:
The magnetic flux modulates the superconducting phase

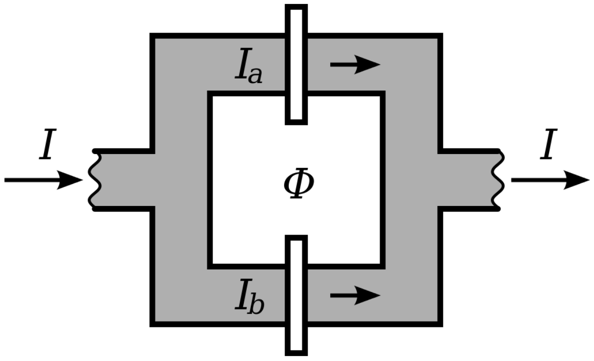


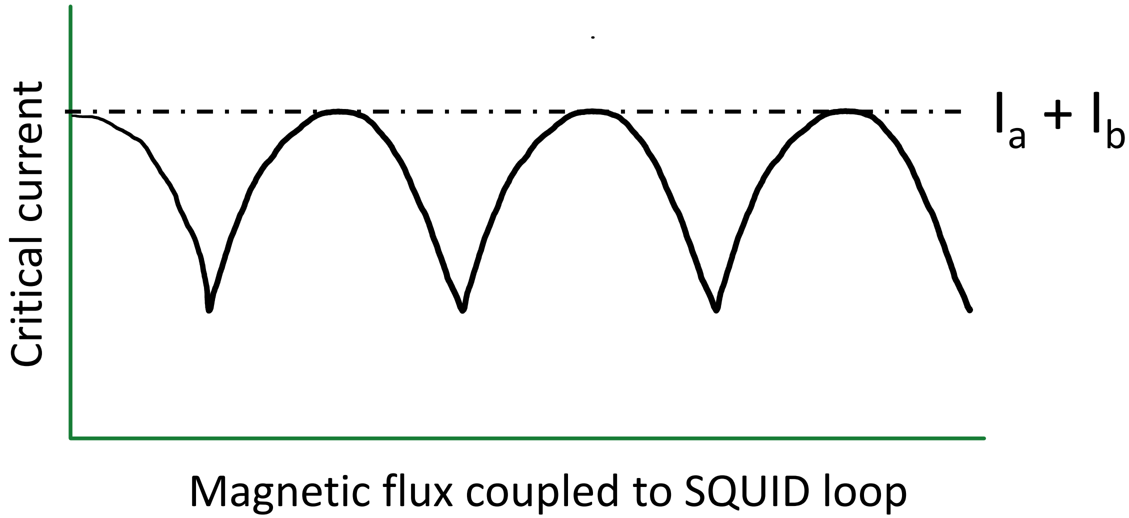
SQUIDs

Superconducting Quantum Interference Device (SQUID)

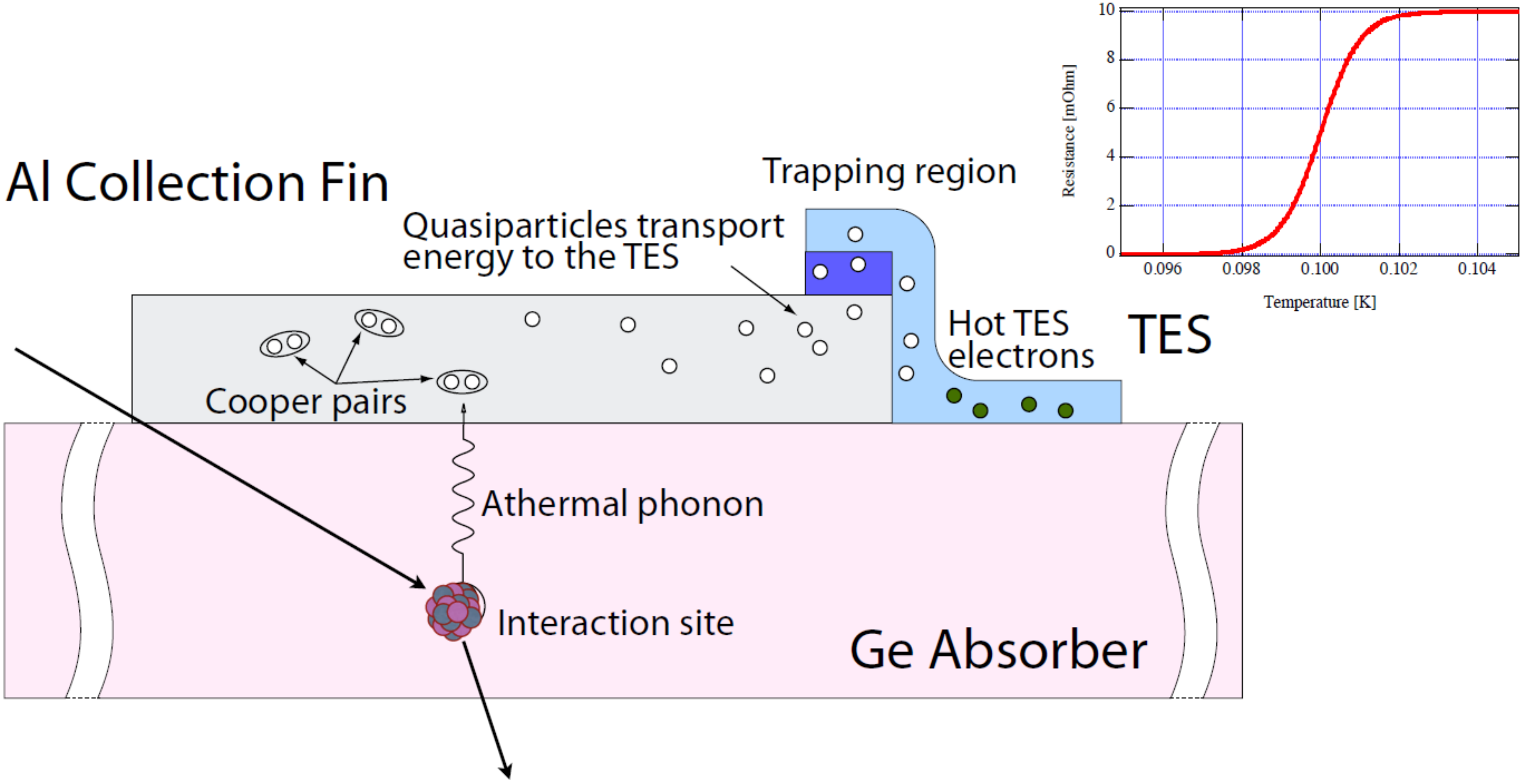
Invented by Arnold Silver, Ford

Quantum interference pattern analogous to a two-slit interferometer





TES heritage: from CDMS

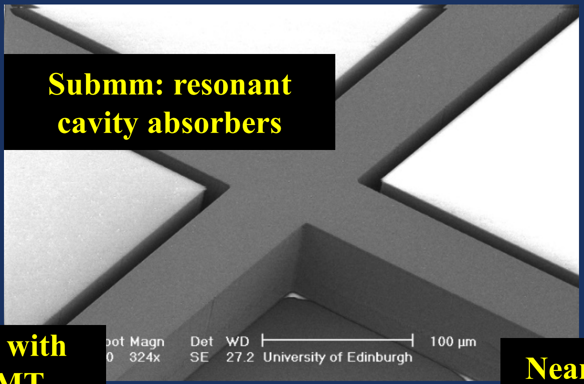


Cryogenic Dark-Matter Search

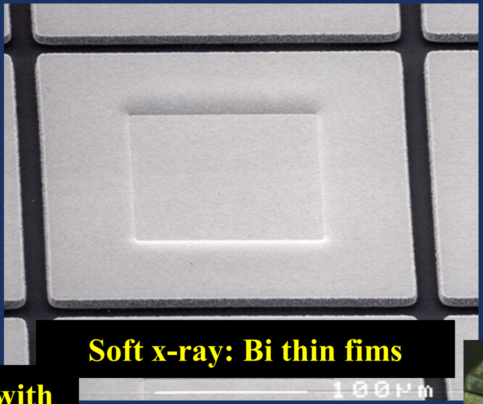
Slide Credit: Blas Cabrera

SQUID-amplified TESs across the spectrum

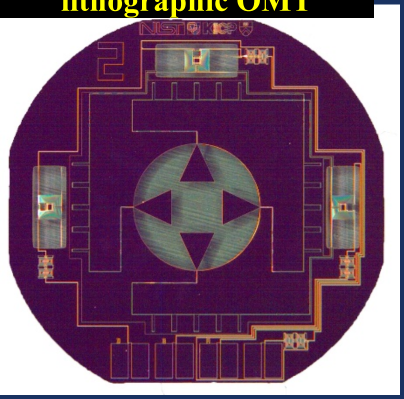
Submm: resonant cavity absorbers



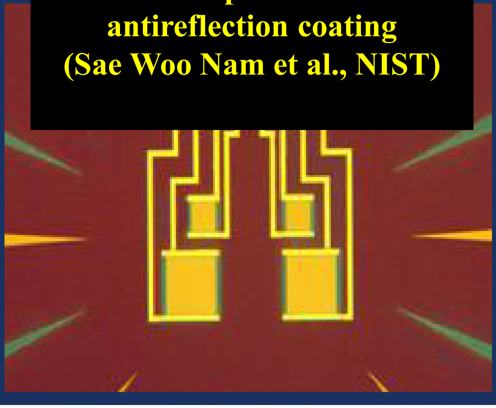
Soft x-ray: Bi thin fims



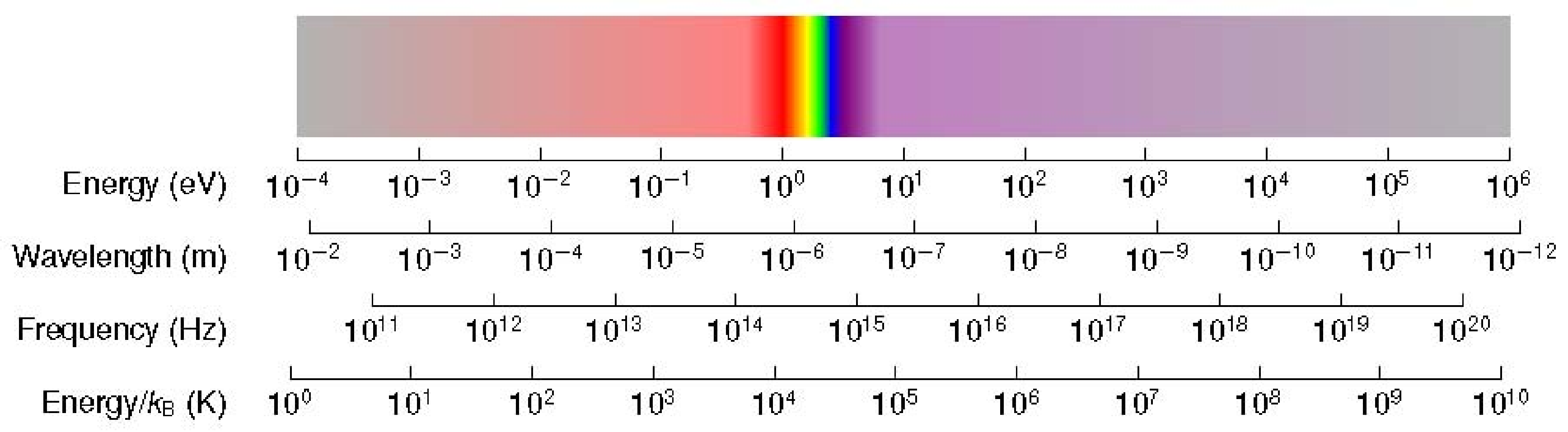
CMB: feedhorns with lithographic OMT



Near IR & optical: TES with antireflection coating (Sae Woo Nam et al., NIST)

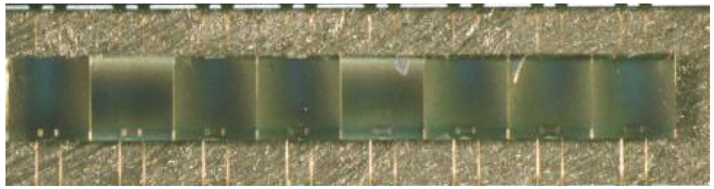


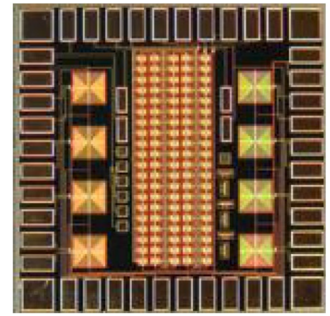
Gamma-ray: thick superconducting foil



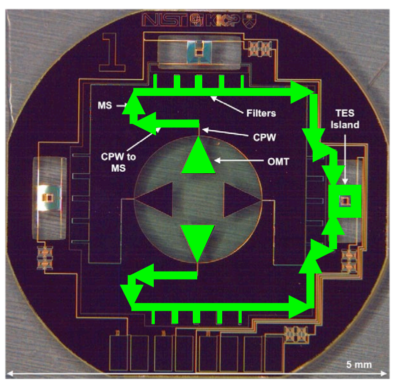
TES bolometers: CMB and submillimeter astronomy

HISTORY



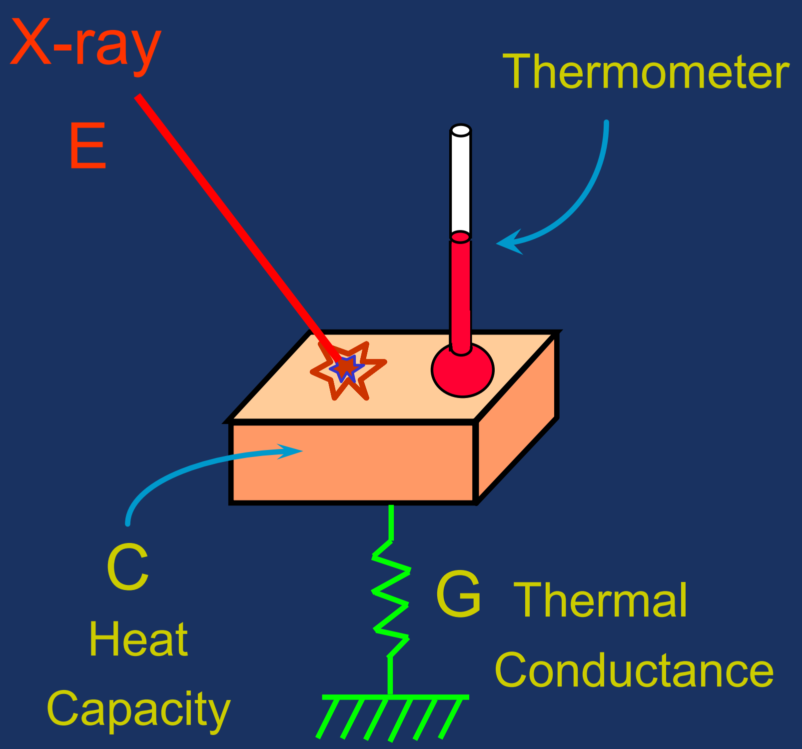


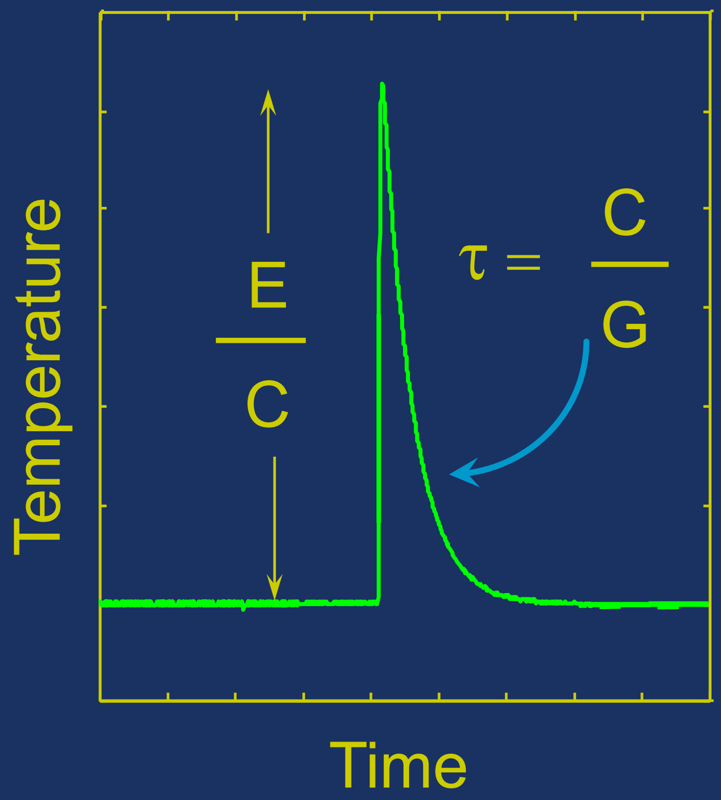
The first TES bolometer array (FIBRE) deployed at Caltech Submillimeter Observatory in 2001. TES (left) and SQUID MUX (right) are shown.



Modern TES array (ACTpol – reference baseline design for CMB-S4)

Thermal photon spectroscopy



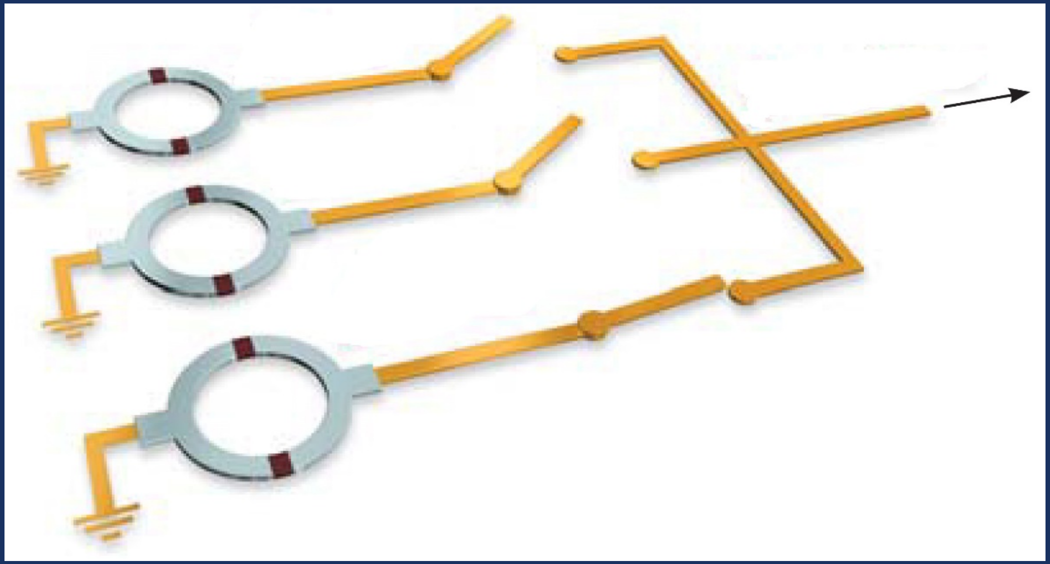


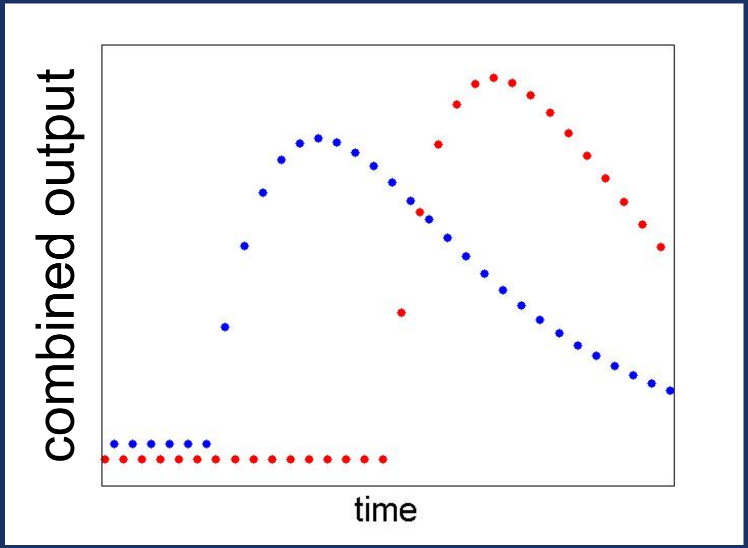
Photon → Heat

Optical, UV, x-ray, gamma-ray

Large TES cameras require multiplexing

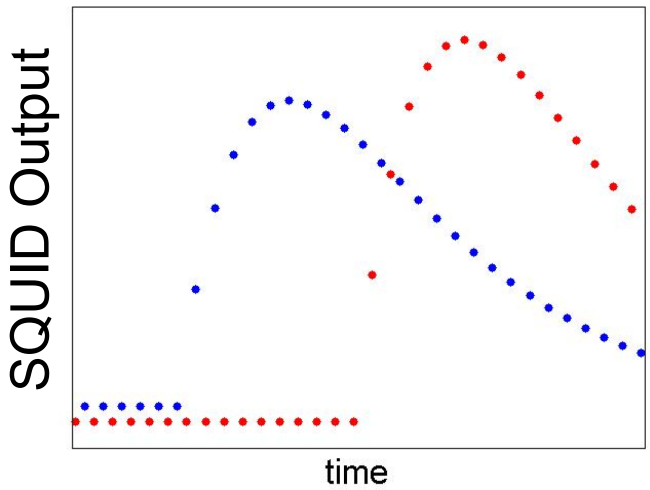
For large TES arrays, multiplexing becomes necessary to minimize complexity and heat load from wires

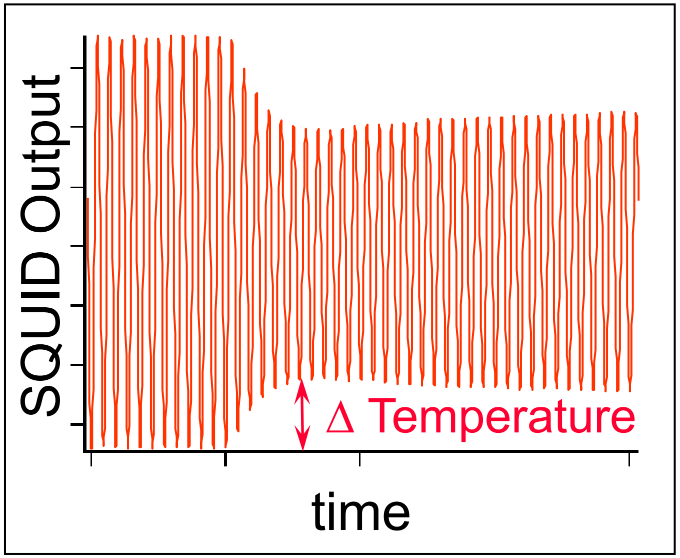




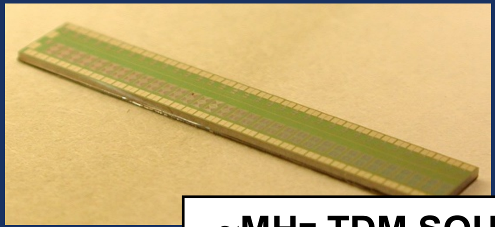
Multiplexing allows many TES detectors to be sampled with one output line

Time and frequency division mux



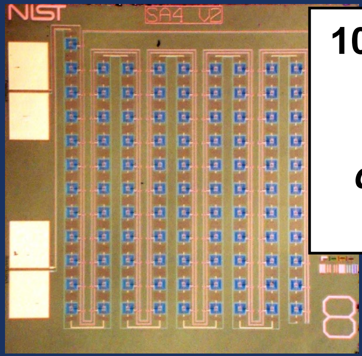


Time division (TDM): different pixels sampled at different times



~MHz TDM SQUID switches

Frequency division (FDM): different pixels operated at different frequencies



100-SQUID series array for *~MHz frequency-domain readout with Berkeley/LBNL*

Same idea, different orthogonal modulation functions

How much information is in a LTD?

- To fully characterize a signal with bandwidth *B*, it must be sampled at the "Nyquist rate"

$$\Delta t_{NYQ} = \frac{1}{2B}$$

The Nyquist-Shannon Sampling Theorem

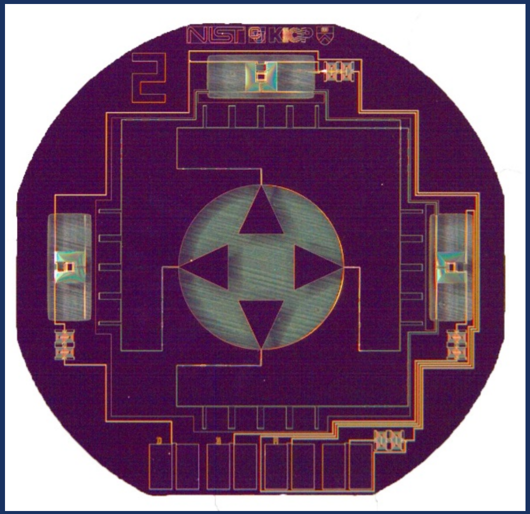
- The number of voltage levels that can be distinguished in each sample is determined by the signal-to-noise ratio. The number of bits of information scales as $\log_2$ of the number of distinguishable voltage levels.
- Taken together, the number of bits per second in an analog communication channel is:

$$C = B\log_2\left(1+(S/N)^2\right)$$

The Shannon-Hartley Theorem

Information content of a typical LTD signal

$$C = B\log_2\left(1+(S/N)^2\right)$$



Example: Ground-based 150 GHz CMB polarimeter

$P = 5\ \mathrm{pW}$ Incident photon power (including the sky)

$\mathrm{NEP}=4\times10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ Photon shot noise

$B = 100\ \mathrm{Hz}$ Bandwidth for a particular scan strategy

$\mathrm{SNR}=1.25\times10^{4}$ SNR in bandwidth *B*

$C = 2.7\ \mathrm{kHz}$ Shannon-Hartley bit rate

Information capacity of cryogenic amplifiers

SQUID

$$\Delta\Phi = \Phi_0$$

$$\Phi_n = 1\,\mu\Phi_0 \Big/ \sqrt{\mathrm{Hz}}$$

$$B = 1\ \mathrm{MHz}$$

$$C = 20\ \mathrm{MHz}$$

HEMT

$$\Delta P \sim -40\ \mathrm{dBm}$$

$$P_n = -90\ \mathrm{dBm}$$

$$B = 10\ \mathrm{GHz}$$

$$C = 175\ \mathrm{GHz}$$

Whereas LTDs typically require a few thousand bits per second per detector.

With a suitable access method (muxing scheme), we should (in principle) be able to read out thousands of detectors per MHz SQUID, or millions per HEMT

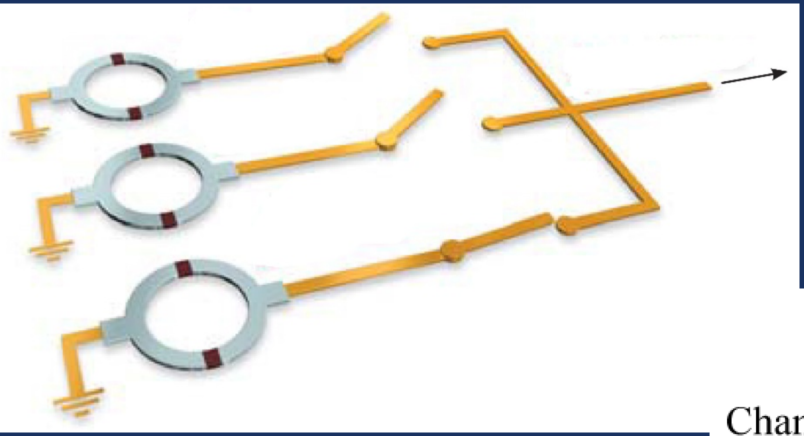
Elements of a MUX access method

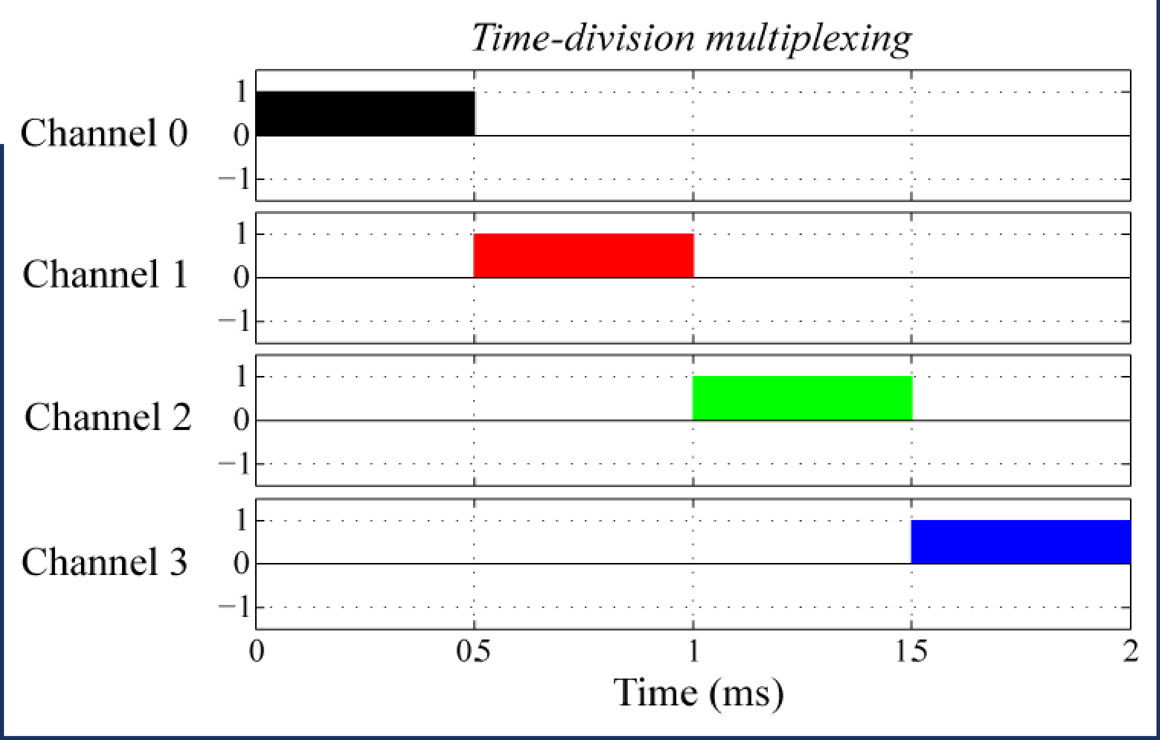
1. The detector bandwidth is limited *before* signal combination
   - Prevents out-of-band signal crosstalk and noise aliasing
   - L/R or RC low-pass filter (TDM and CDM)
   - LC tuned resonance (FDM)
2. Signal channelization

   The information from each LTD is modulated, usually by a set of orthogonal functions
3. Signal combination
   - Direct summation of currents or voltages
   - Capacitive or inductive summation
4. Demultiplexing at room temperature

   Requires complex room-temperature electronics

Time-division MUX

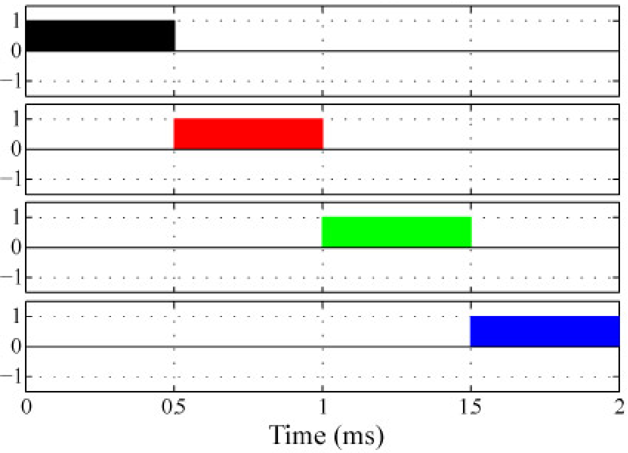




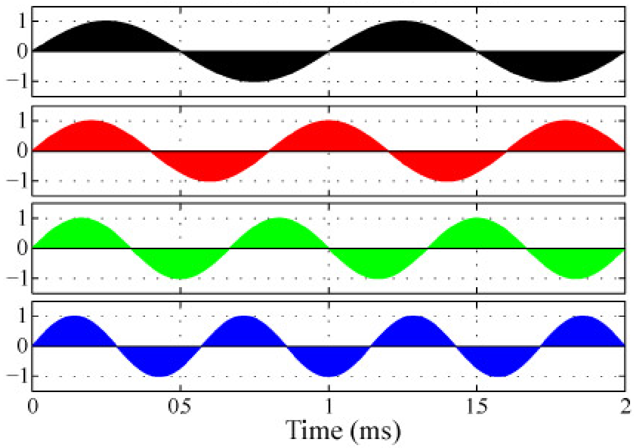
- Define time band by turning SQUIDs on one at a time
- Each detector output is measured 1/N of the time

Three modulation functions

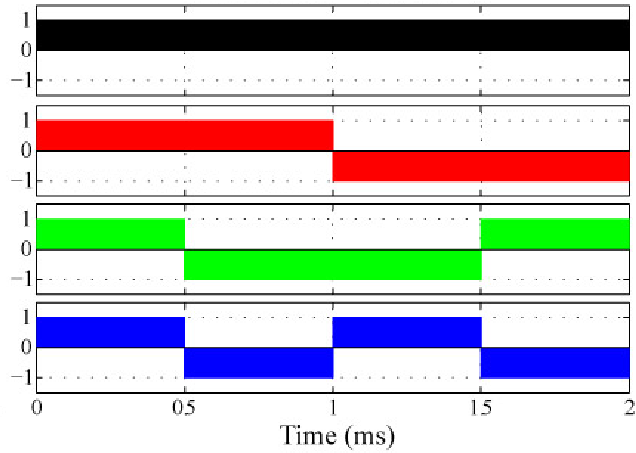
Time-division MUX



Frequency-division MUX



Code-division MUX



- Define time band by coupling output 'channel' to different detectors sequentially.

- Define frequency band with different passive LC circuits

- Define 'code' band by switching the polarity with which each detector couples to the output channel in an orthogonal Walsh pattern

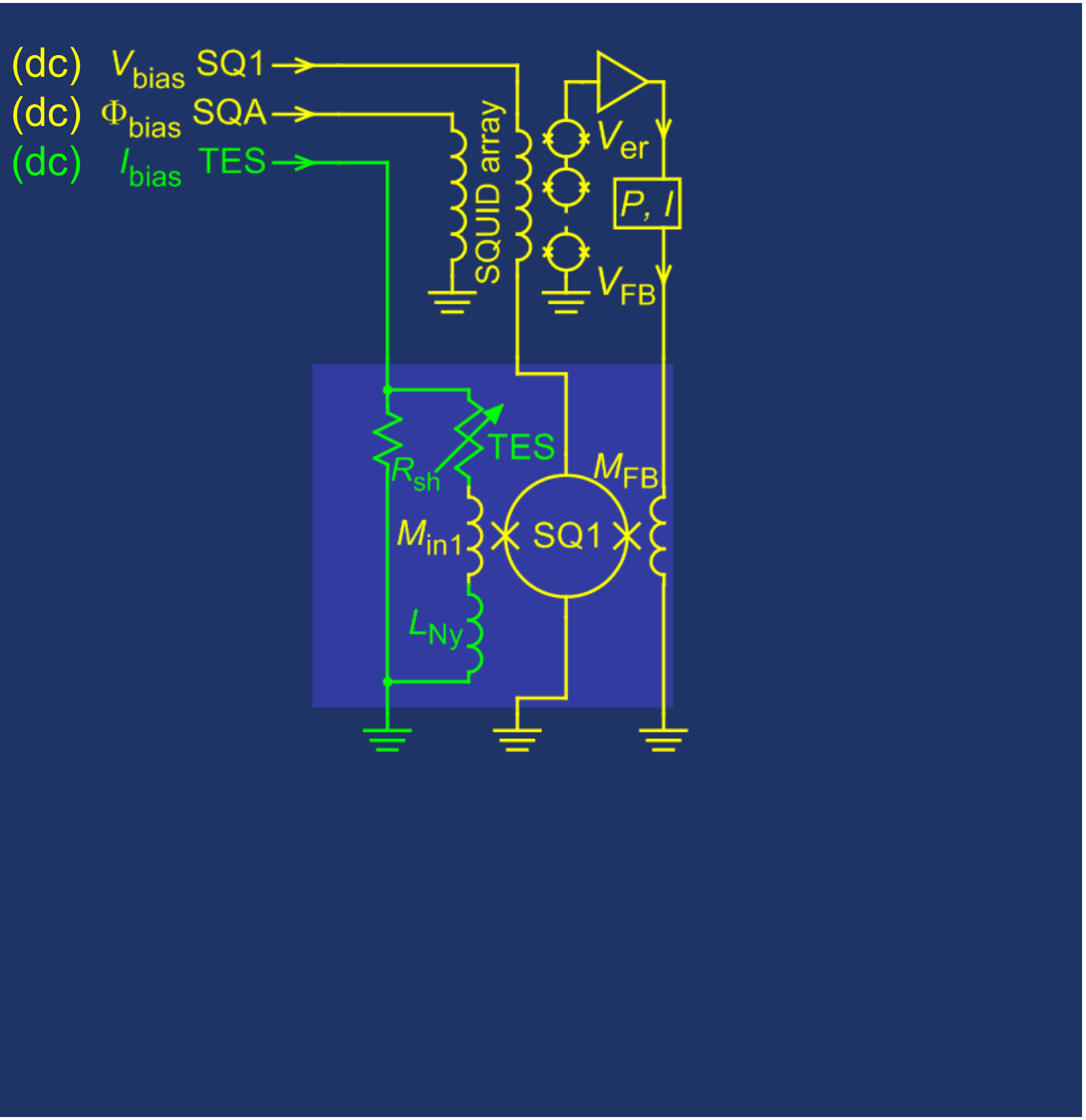
History: multiplexing TESs

- Time-division multiplexing
  - SQUID: Chervenak et al., APL 74, 4043 (1999)

- MHz Frequency-division SQUID multiplexing of TESs
  - Yoon et al., APL 78, 371 (2001)
  - Kiviranta et al., AIP 605, 295 (2002), for x-ray
  - CABBAGE, Miyazaki et al., AIP Conf. Proc. 605, 313 (2002)

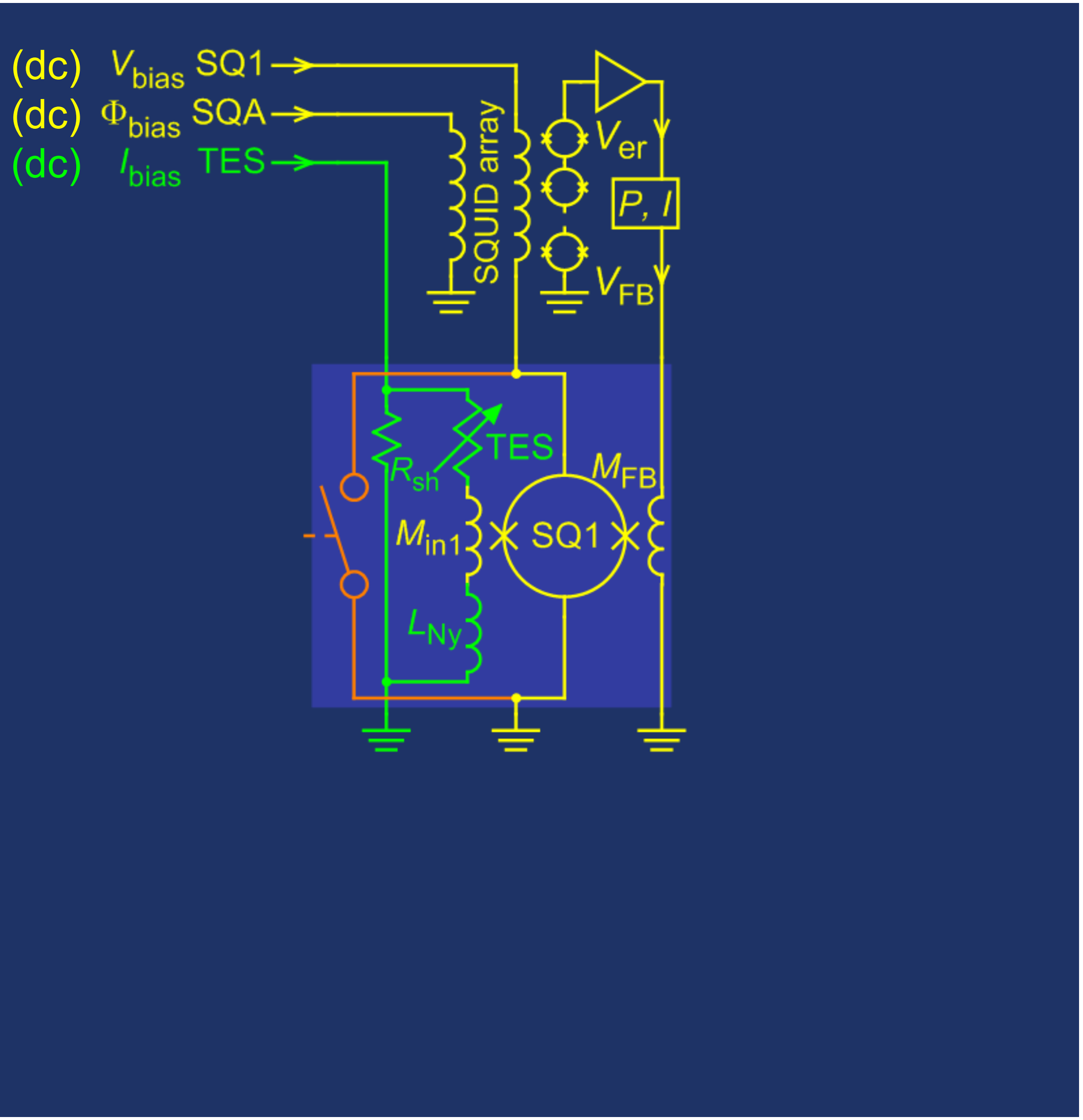
- Microwave resonator FDM readout
  - RFSET: Stevenson et al., APL 80, 3012 (2002)
  - MKIDs: Day et al., Nature 425, 6960 (2003)
  - Microwave SQUID MUX: Irwin et al., APL 85, 2107 (2004)
    Mates et al., APL (2008).

Each SQUID is coupled to one TES



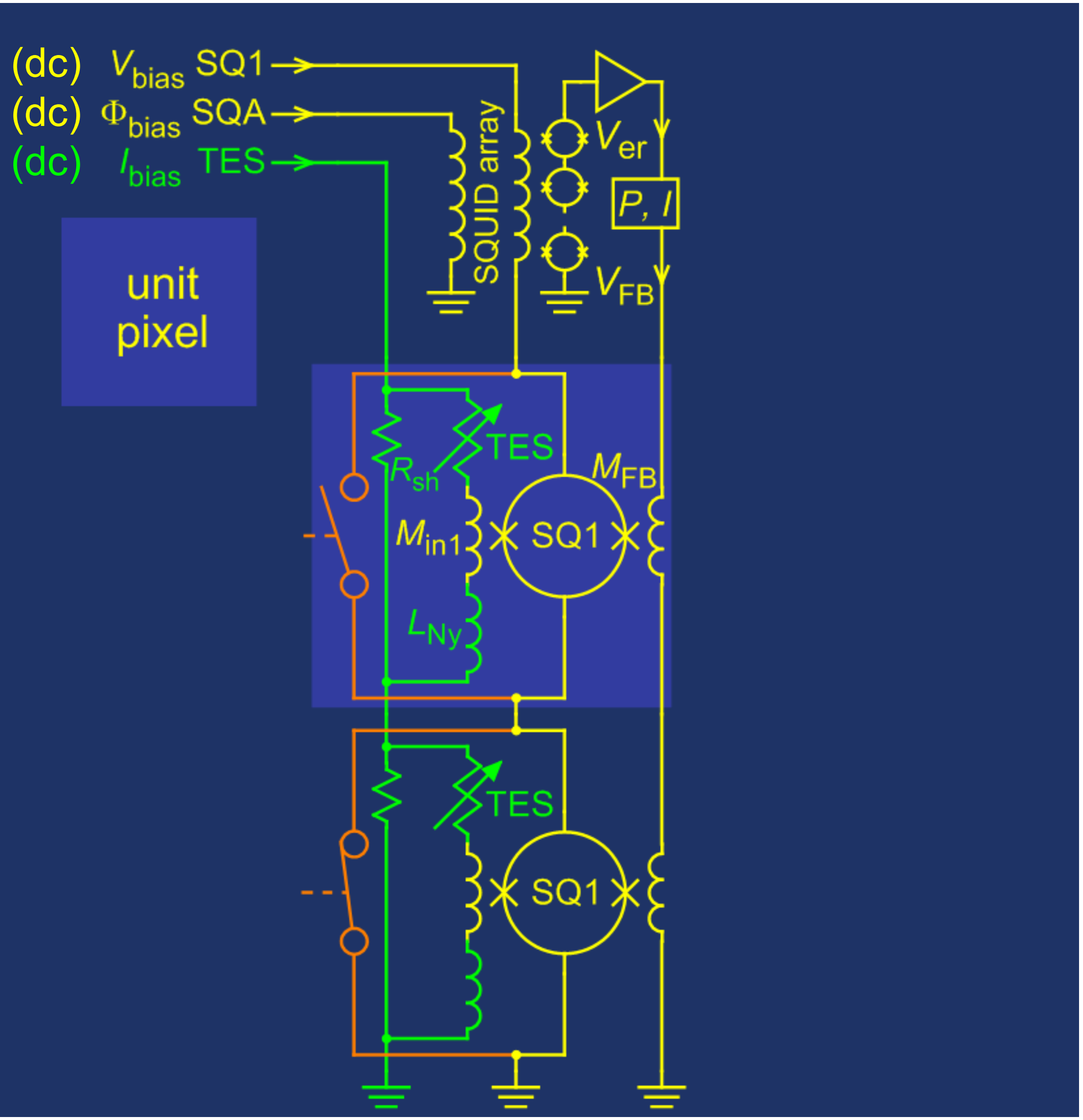
- TES is dc-biased
- Each TES coupled to dc SQ1

Superconducting switch turns SQUID on



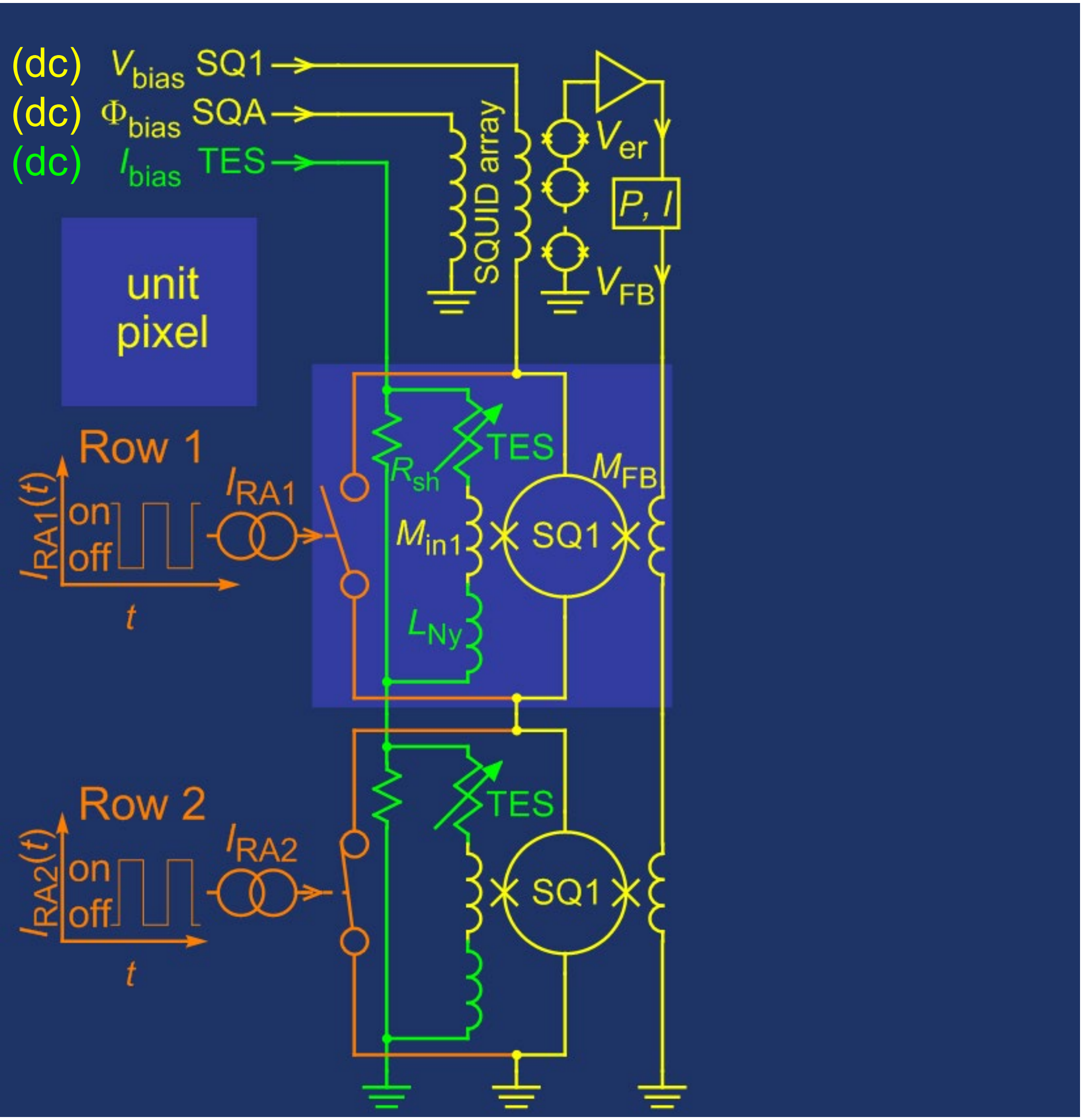
- TES is dc-biased
- Each TES coupled to dc SQ1
- SC switch turns SQ1 on/off

SQUIDs in column wired in series



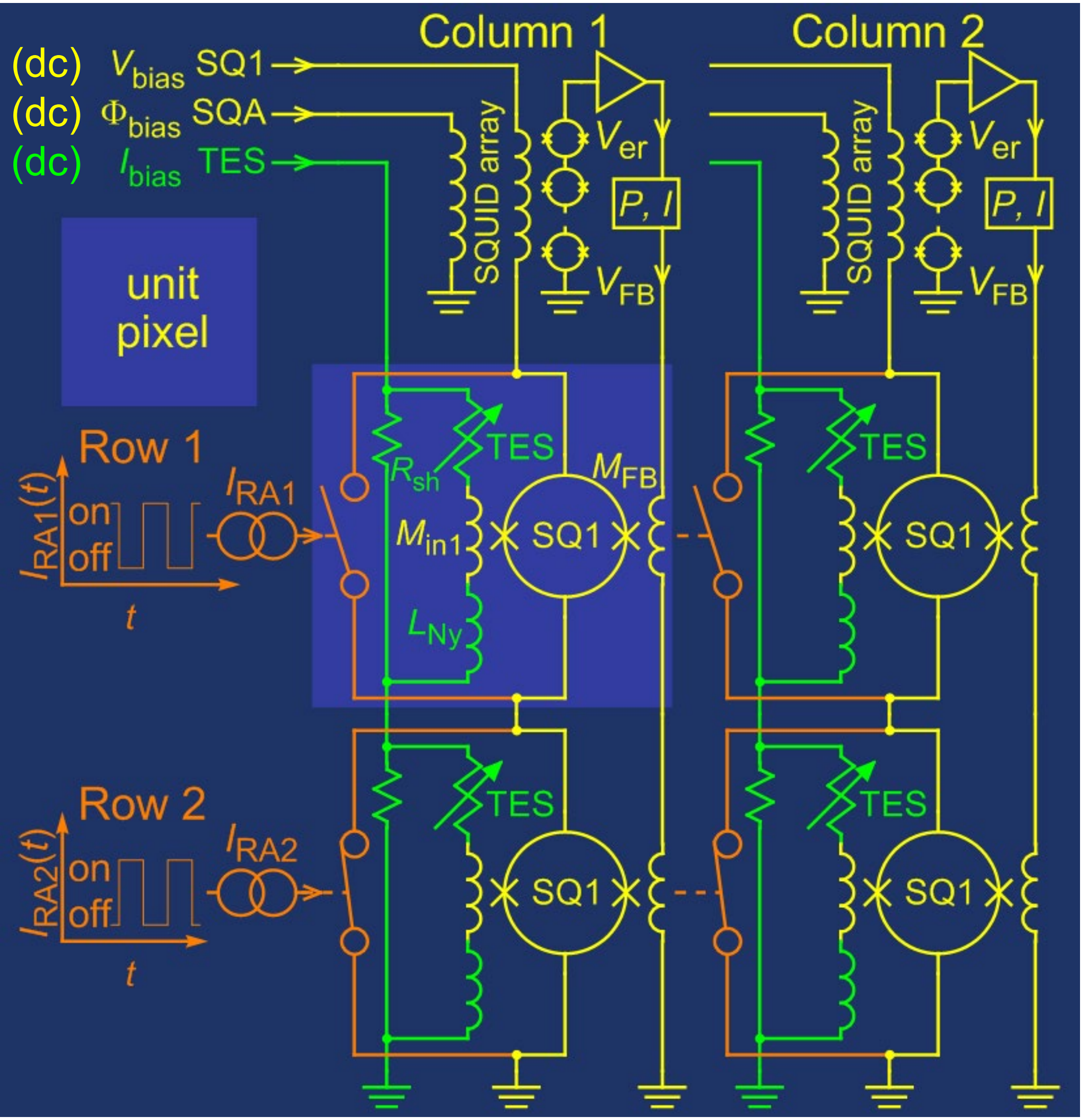
- TES is dc-biased
- Each TES coupled to dc SQ1
- SC switch turns SQ1 on/off

Rows turned on one at a time



- TES is dc-biased
- Each TES coupled to dc SQ1
- SC switch turns SQ1 on/off
- Rows of SQ1s turned on sequentially
- Each SQ1 in flux-locked loop

Columns read out in parallel



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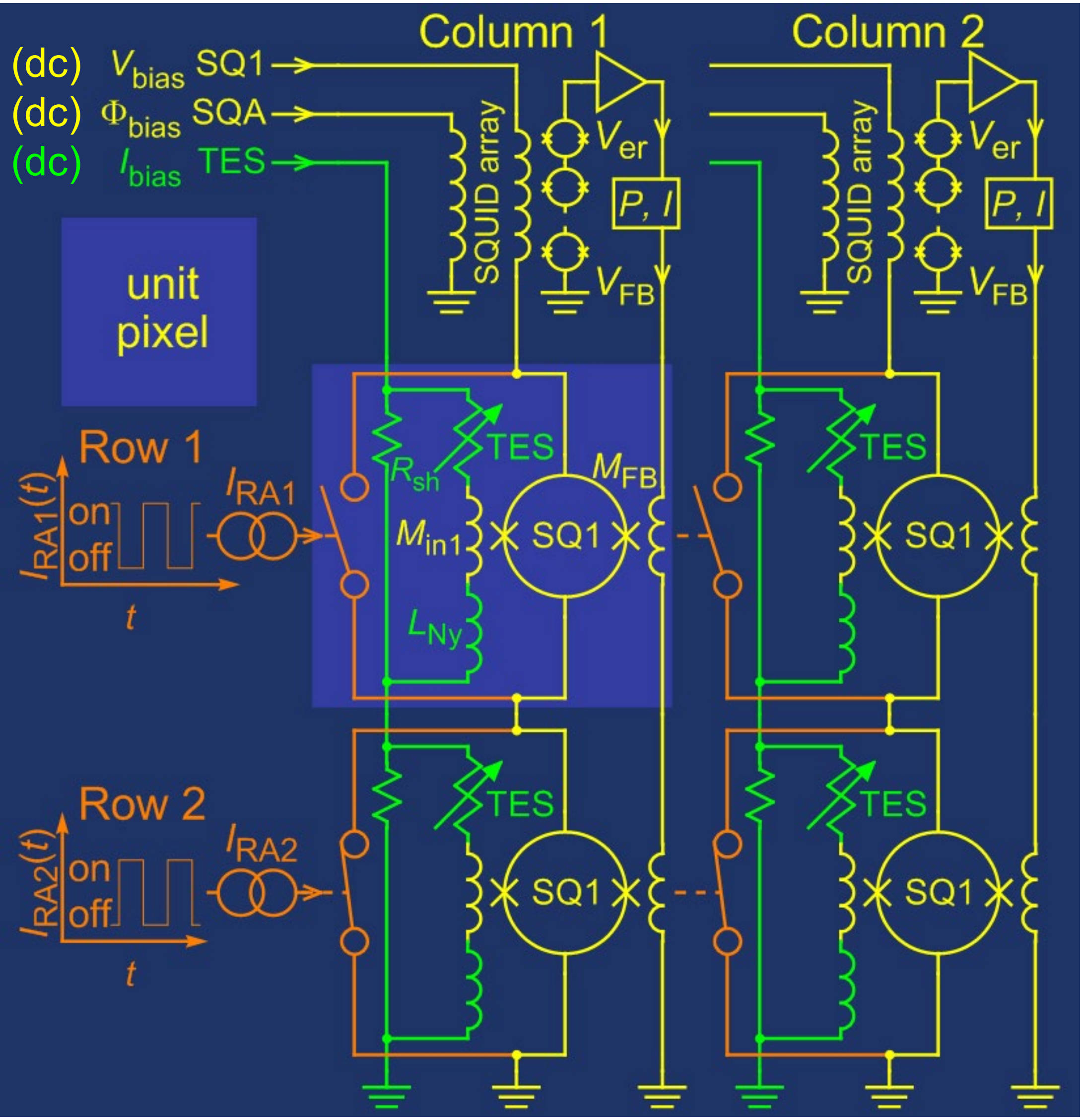
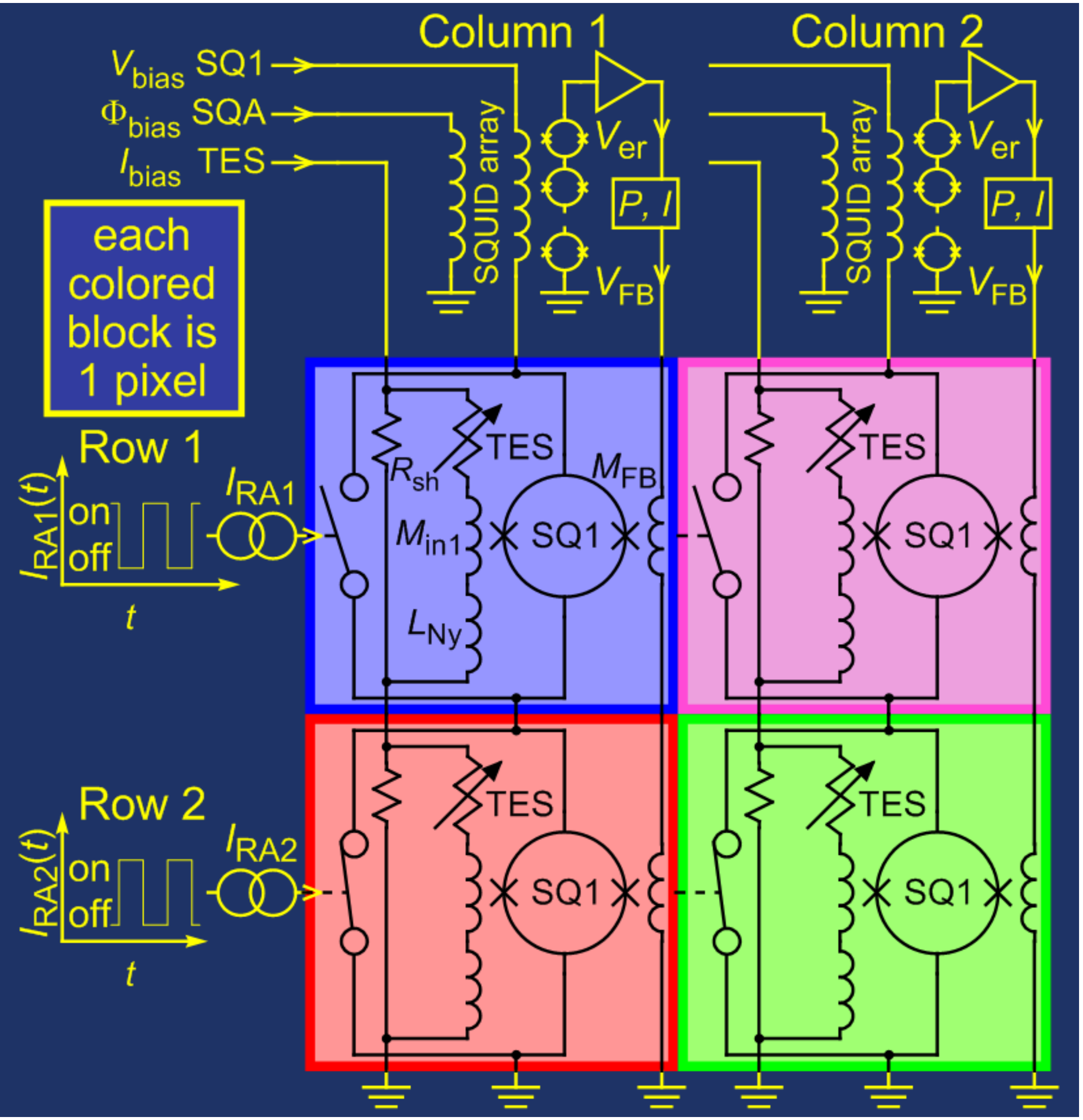
N rows x M column array



2 x 2 array is shown as example of *N*-row x *M*-column array

N rows x M column array



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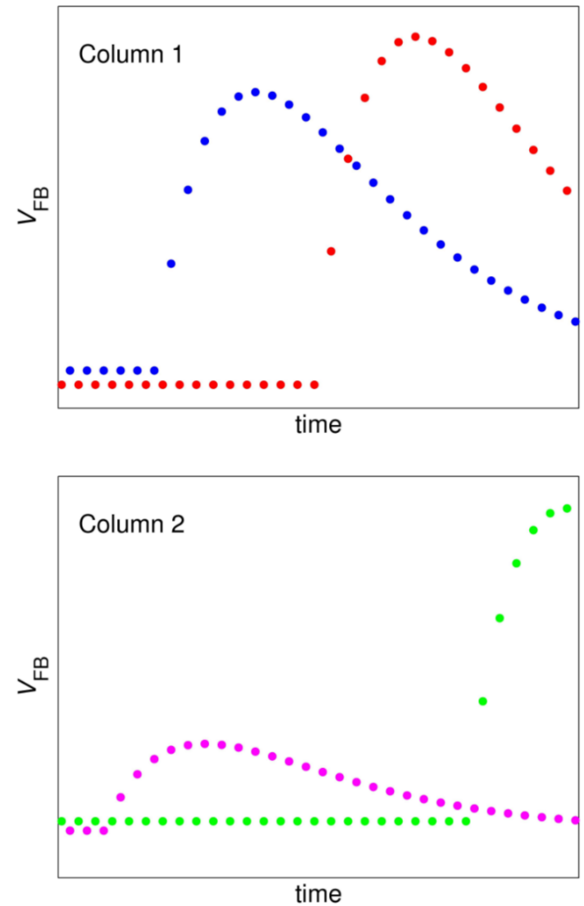
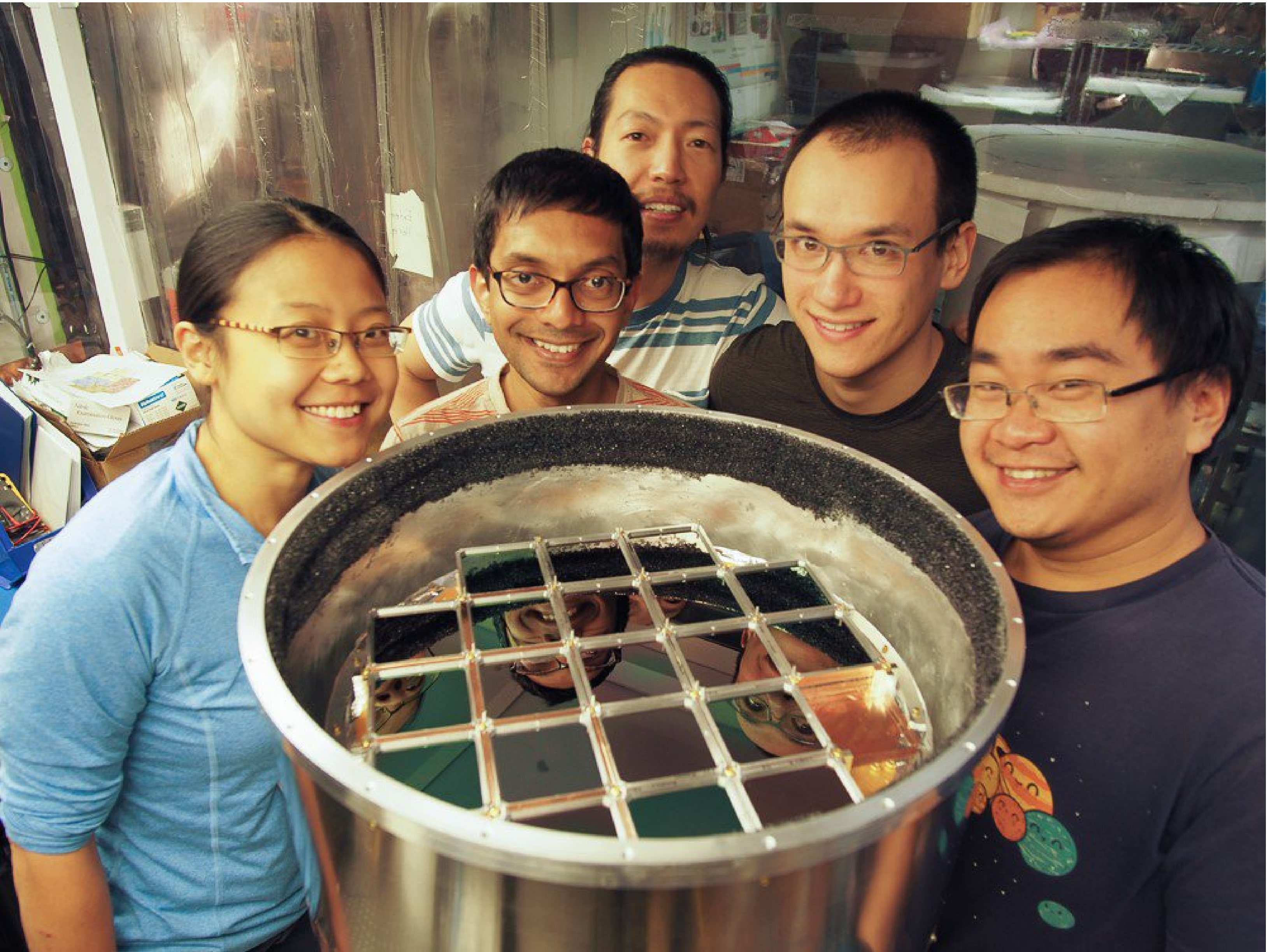
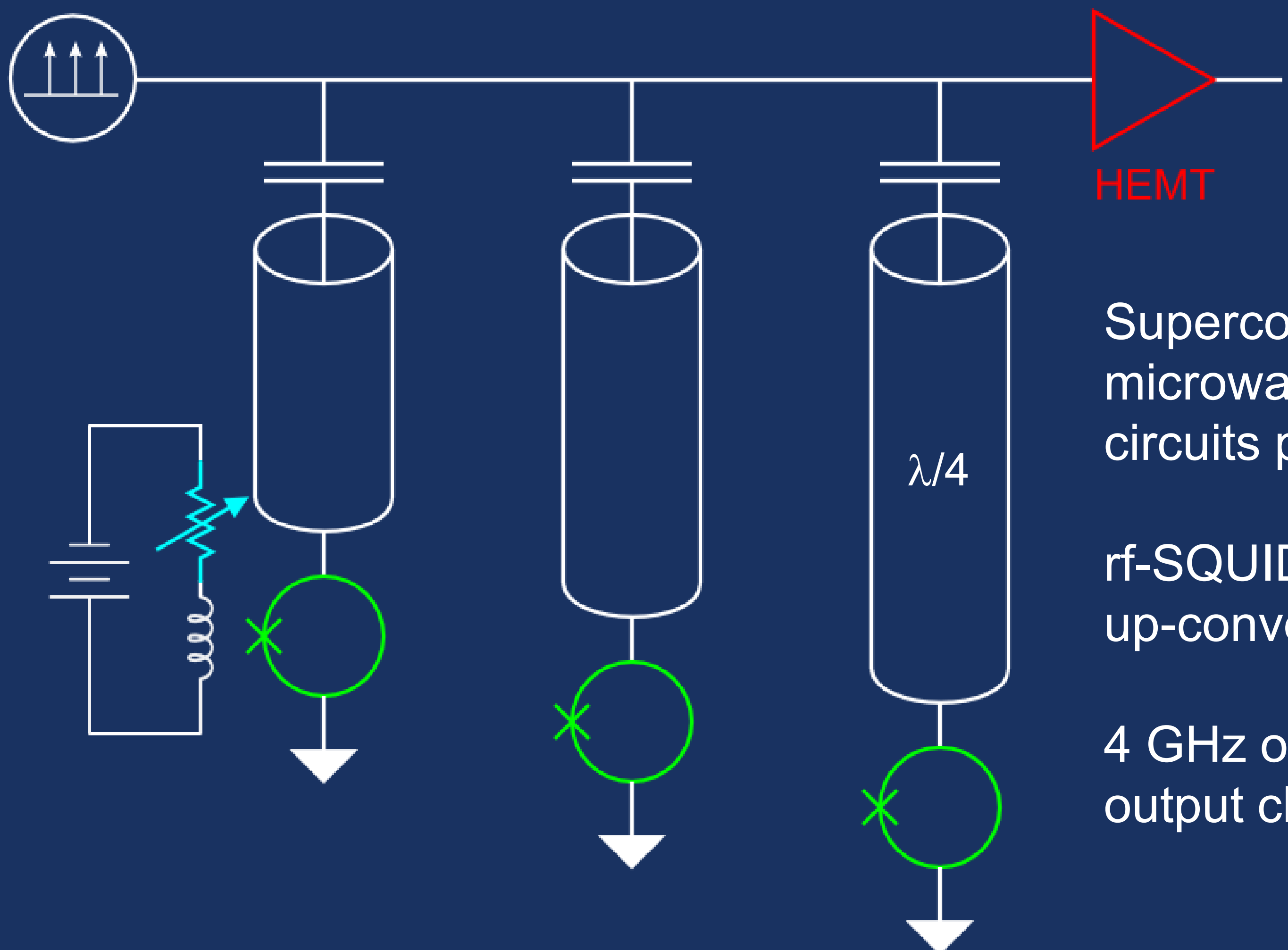


BICEP-3: thousands of TES per tile with TDM MUX



Nonlinear Josephson dynamics: microwave SQUID MUX

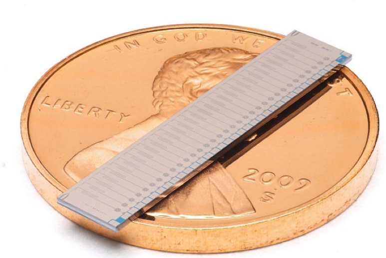


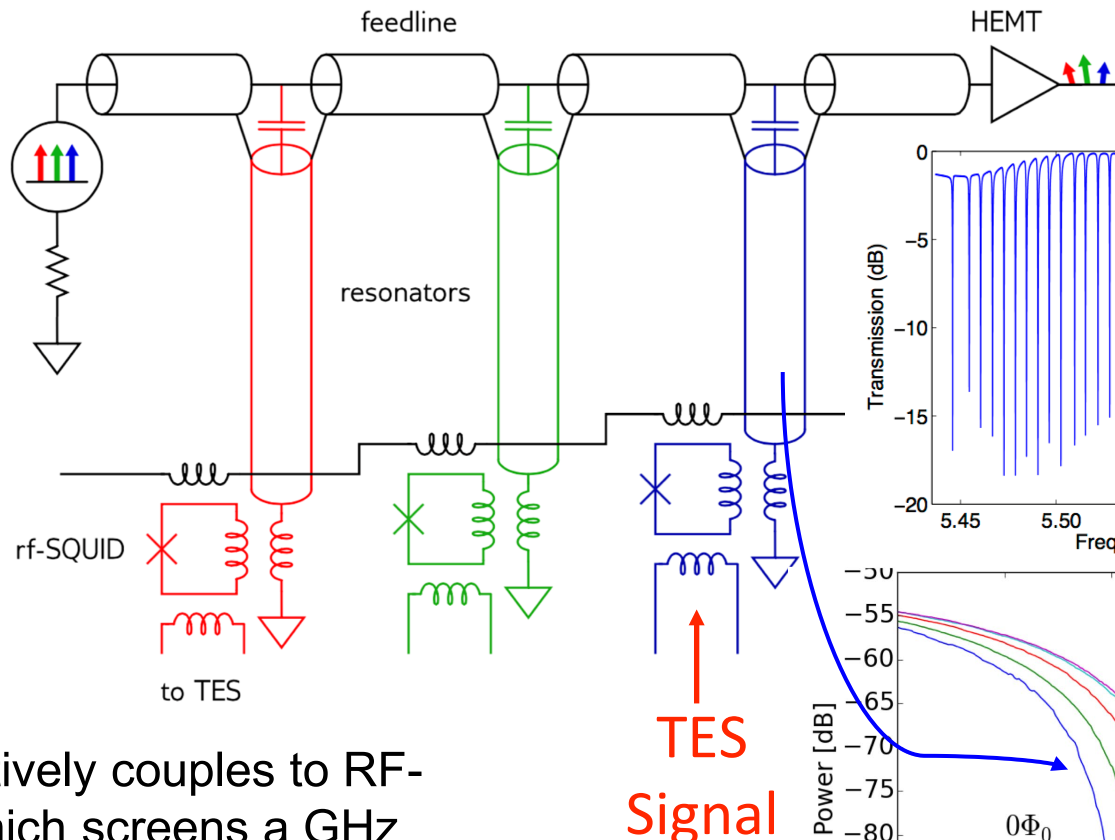
Superconducting microwave resonant circuits partition 4-8 GHz.

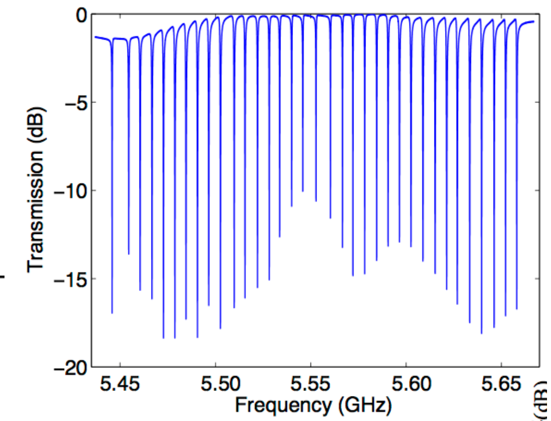
rf-SQUIDs amplify and up-convert TES signals.

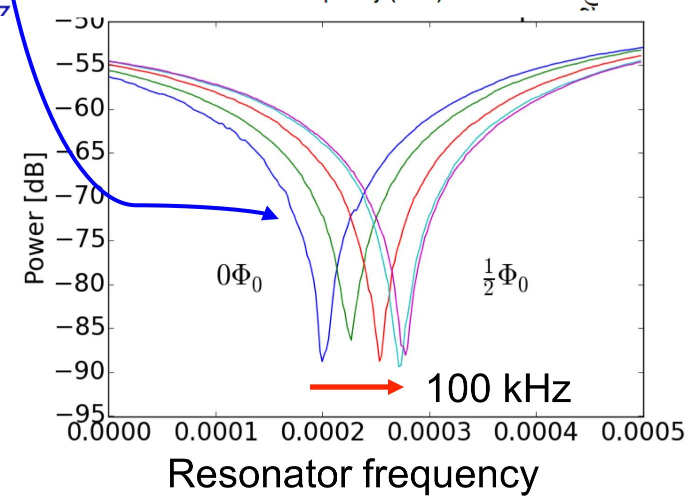
4 GHz of bandwidth per output channel.

uMUX 101









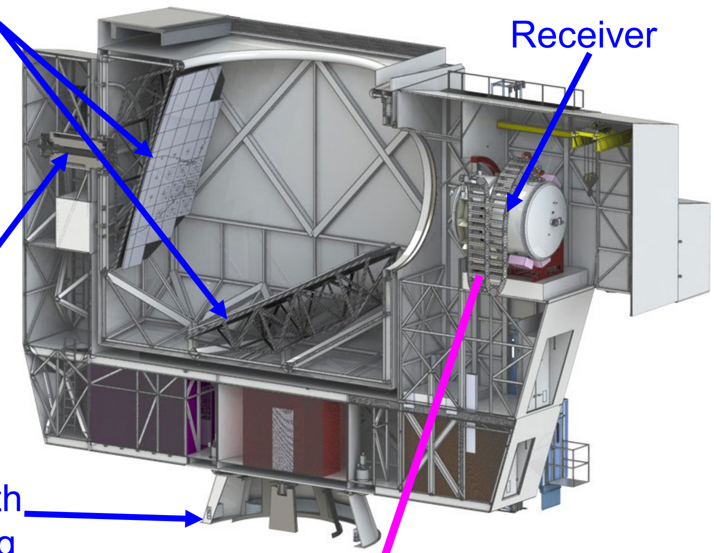
- TES inductively couples to RF-SQUID, which screens a GHz resonator
- TES signal changes inductance, causes resonance frequency shift. But nonlinear

Slide credit: Zeeshan Ahmed

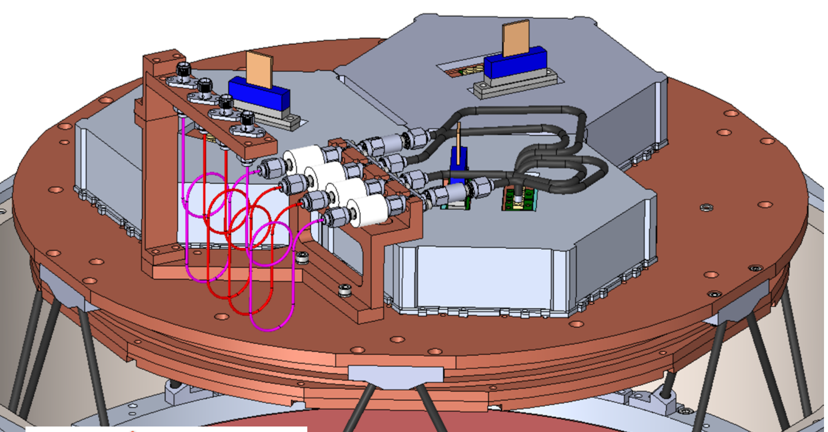
Irwin & Lehnert,
Appl. Phys. Lett. 85, 2107 (2004)

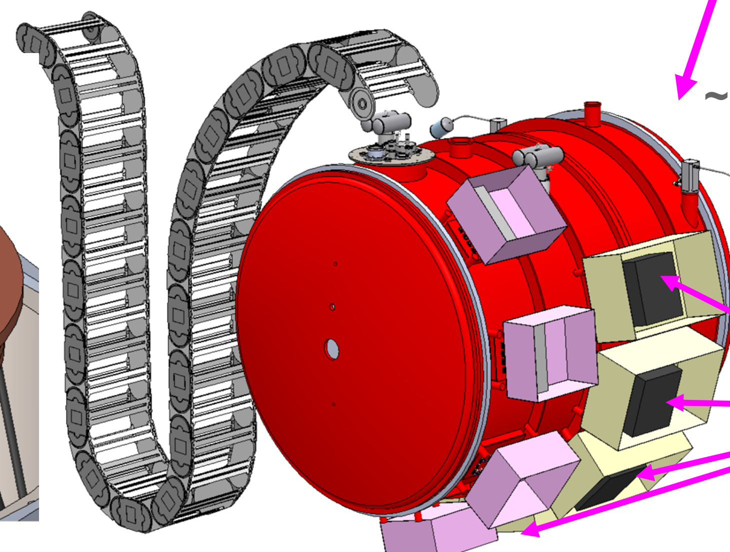
Simons Observatory uMUX (1)

- Large scale deployment of uMUX
  - Nearly 40x RF signal chains in LATR alone
- Targeting MUX factor of 2000x (4000x in SMuRF firmware) per RF coax.
- Hardware being built now



3x 6” wafer modules (UFMs) per Optics tube



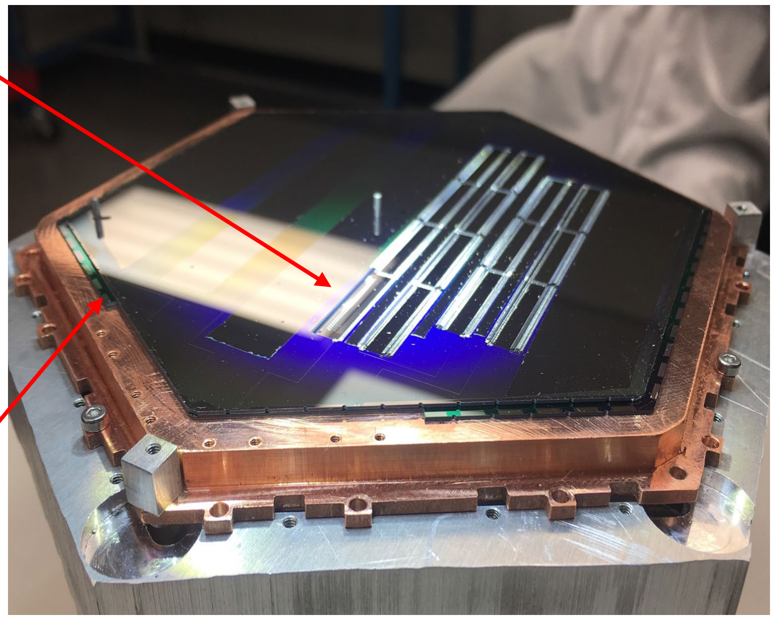


Slide credit: Zeeshan Ahmed

Simons Observatory uMUX development (2)

Readout Array

28 mux chips
64 channels each
1792 MUX factor



all DC wiring, including 12 TES biases

6”

Focal Plane Package

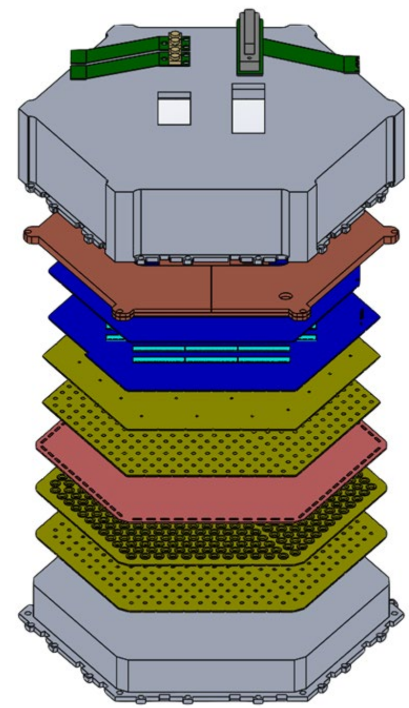
(shown for horns, also compatible with lenslets)

mechanical, thermal & magnetic shielding

umux & readout

detectors & coupling

horns



6”

Readout components are integrated directly behind the detector array and occupy the same footprint

KIPAC

Slide credit: Zeeshan Ahmed

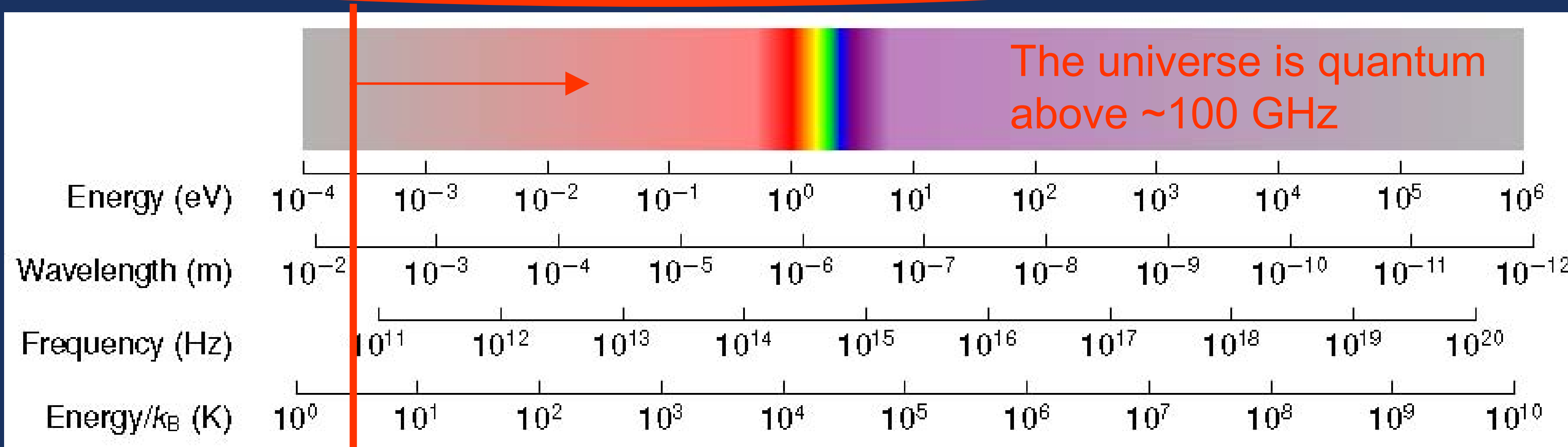
Direct vs. coherent

"Direct" detectors measure the energy or power in an electromagnetic signal, but not the phase.

- e.g. TES, STJ, MKID, nanowire
- No quantum noise (better at short wavelength)

"Coherent" detectors measure both amplitude and phase

- e.g. radio receivers, mixers
- Limited by quantum noise at short wavelengths $\hbar\omega \gg k_B T$
  - 0.5 photon per mode of quantum noise
- Extendable to quantum noise evasion techniques



Quantum 2.0: coherent quantum measurement

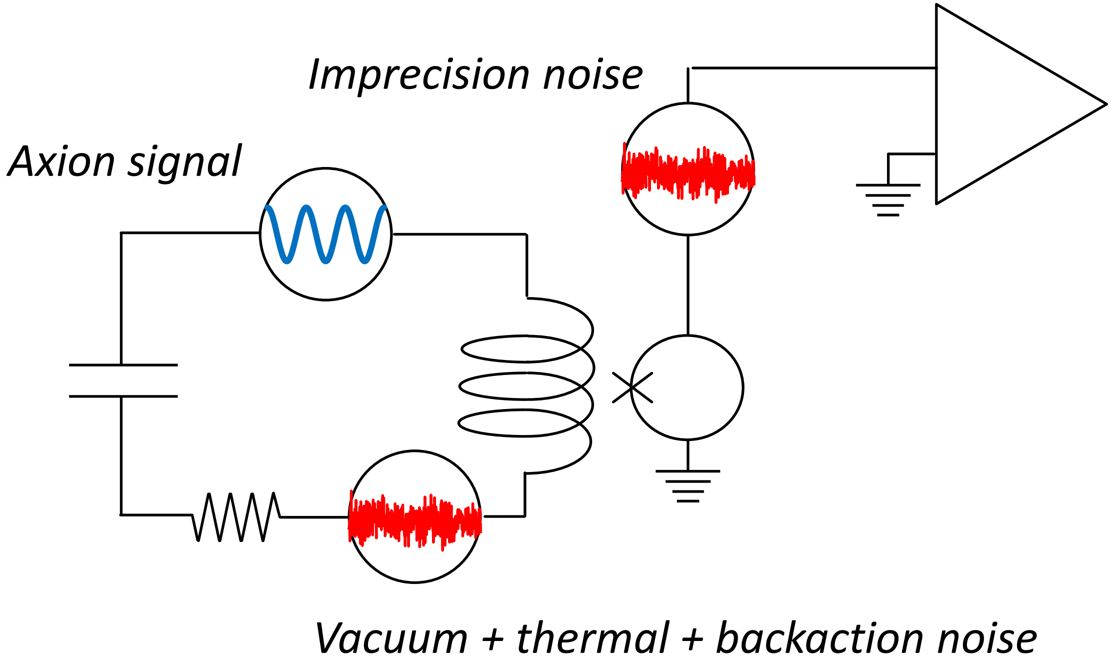
The quantum revolution is bringing new tools that will broadly impact sensing and particle physics

- Evasion of “quantum limits” that apply to classical circuits
  - Vacuum noise, backaction, spin projection noise…
  - Uses quantum protocols including single-mode squeezing, spin squeezing, backaction evasion, quantum non-demolition photon counting

- Control and manipulation of coherent quantum states
  - Superconducting qubit phase
  - Nuclear spins
  - Superconducting phase in other Josephson devices

    (Parametric amplifiers, quantum upconverters, Josephson PMTs)

Fundamental noise sources



1. **Thermal Noise:** set by the resonator's thermal occupation.
2. **Vacuum Noise:** required by quantum mechanics.
3. **Amplifier Noise:** composed of *imprecision* and *backaction* noise, and subject to a Standard Quantum Limit.

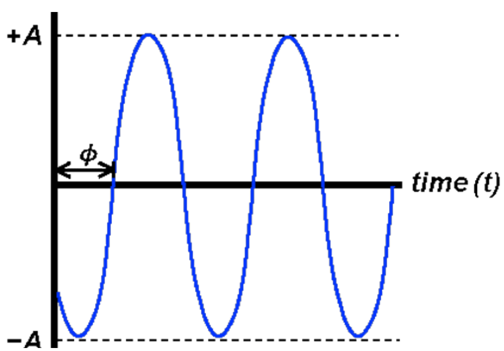
Heisenberg and the Standard Quantum Limit (SQL)

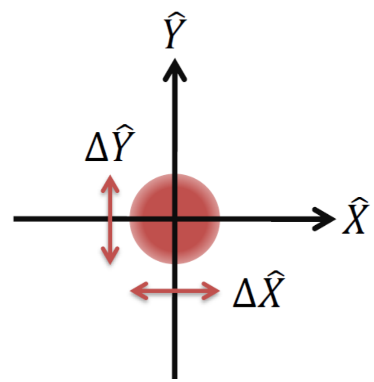
- Heisenberg tells us that you can't know the position and momentum of a particle perfectly at the same time:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

- Heisenberg also tells us that you can't know both the amplitude (A) and phase (ϕ) of an electromagnetic signal in an LC resonator perfectly at the same time.

$$A\cos(\omega t + \phi) = X\cos(\omega t) + Y\sin(\omega t)$$





$$\boxed{\Delta X \Delta Y \geq \frac{\hbar\omega}{2}}$$

- A Quantum 1.0 (classical) sensor measures both amplitude and phase with equal sensitivity, limited by the Standard Quantum Limit of $\hbar\omega/2$ (a "half a photon")
- An additional $\hbar\omega/2$ is added by amplification

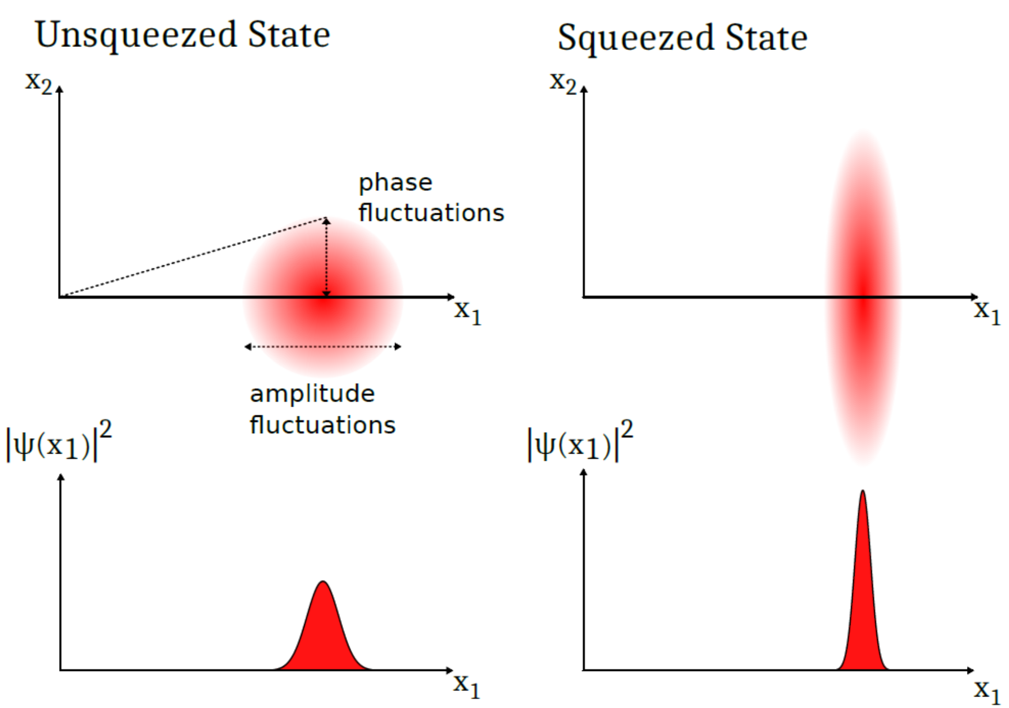
What if I don't care about phase???

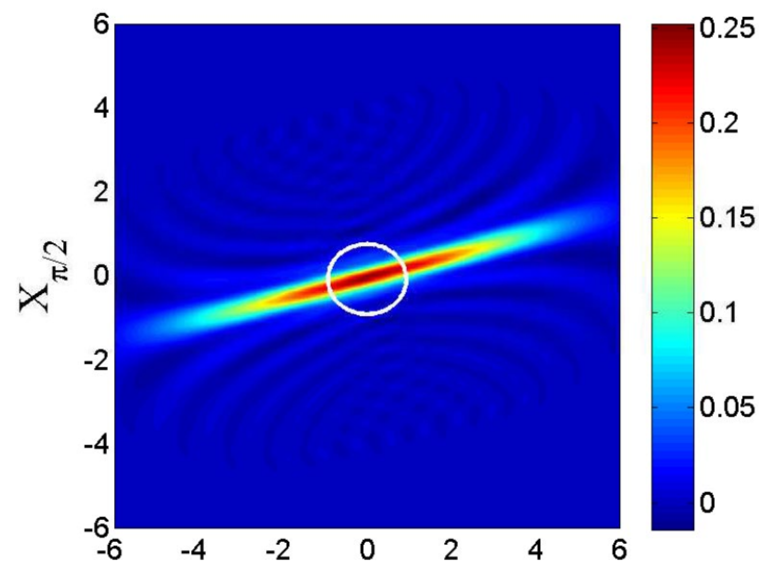
See review: Clerk et al, RMP **82**, 1155 (2010)

Quantum 2.0: Evade the SQL for better measurement

What if I don’t care about phase???

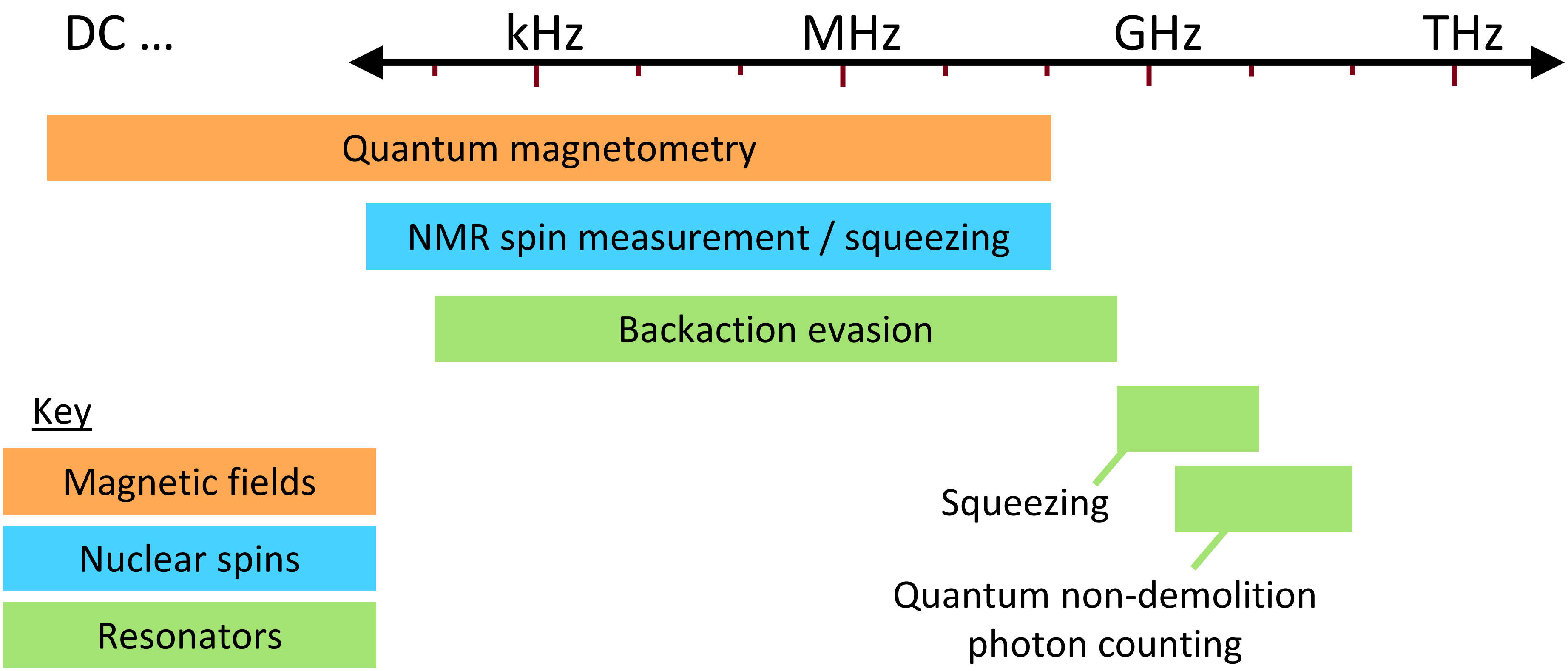
Squeeze the uncertainty into phase, and measure amplitude better than the Standard Quantum Limit!





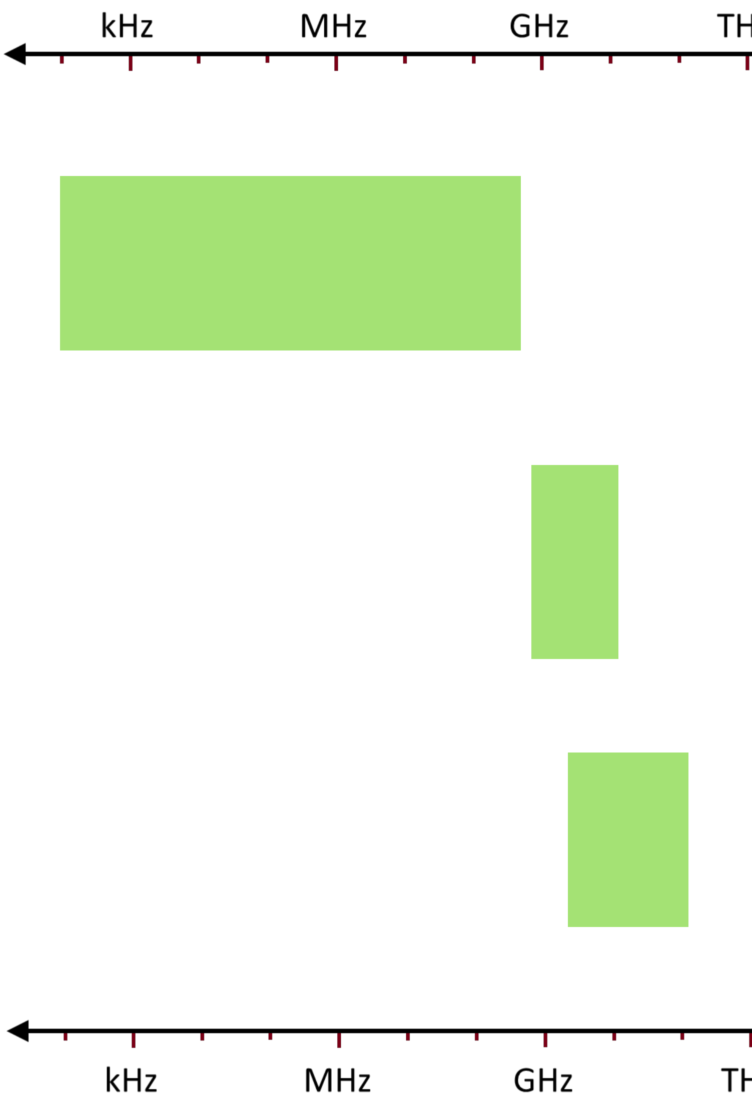
Mallet et al. *Phys. Rev. Lett.* **106**, 220502 (2011)

Quantum 2.0 in electromagnetism

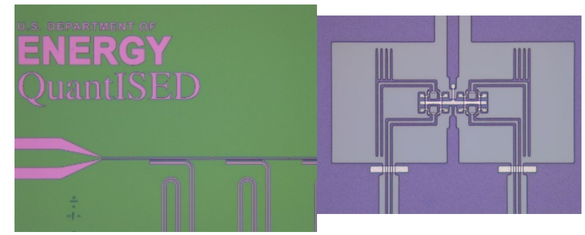


- Superconducting quantum sensors can be *provably superior* to classical sensors in practical use from DC to THz.
- Enhanced sensitivity by exploitation of quantum correlations, including squeezing, entanglement, backaction evasion.

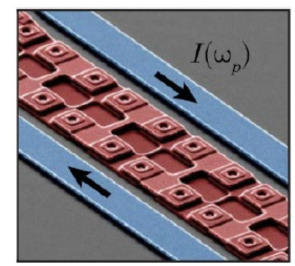
Quantum 2.0 in electromagnetic resonators



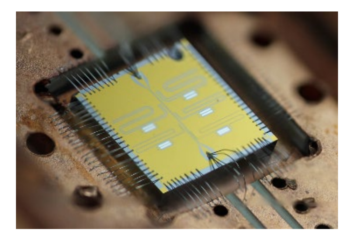
1. Below 300 MHz – *radio-frequency quantum upconverter (RQU)*
2. From ~300 MHz to ~10 GHz, squeezing with *Josephson parametric amplifiers (JPAs)*
3. Above ~ GHz, Quantum Non-Demolition photon counting - *qubits*.



Quantum upconverters, Irwin group / Stanford



JPA, Lehnert / JILA



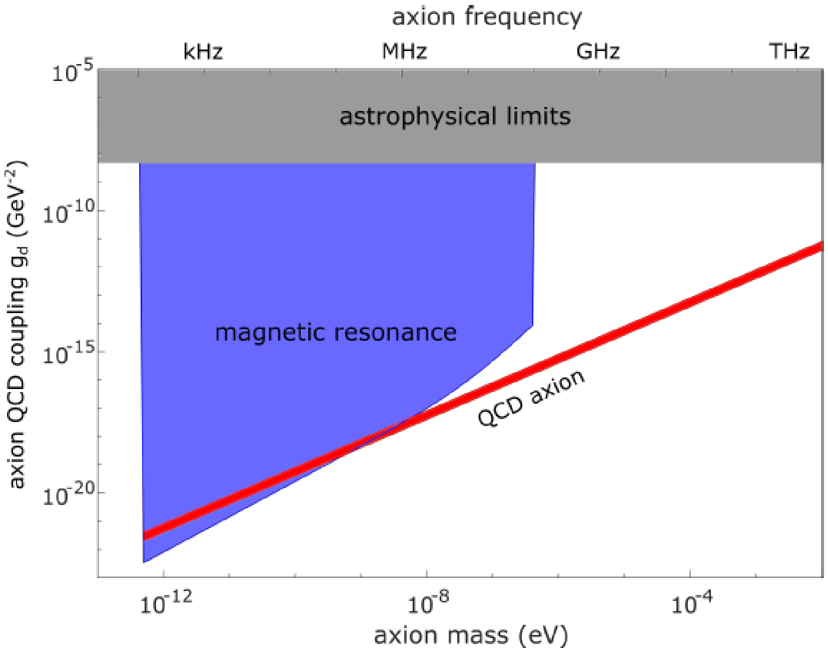
Qubits, Siddiqi / UCB

QCD Axion Detection

DOE DM *Basic Research Needs Report* (2019) lays out 3 main techniques to cover QCD axion:

NMR, Lumped Elements, and Microwave Cavities

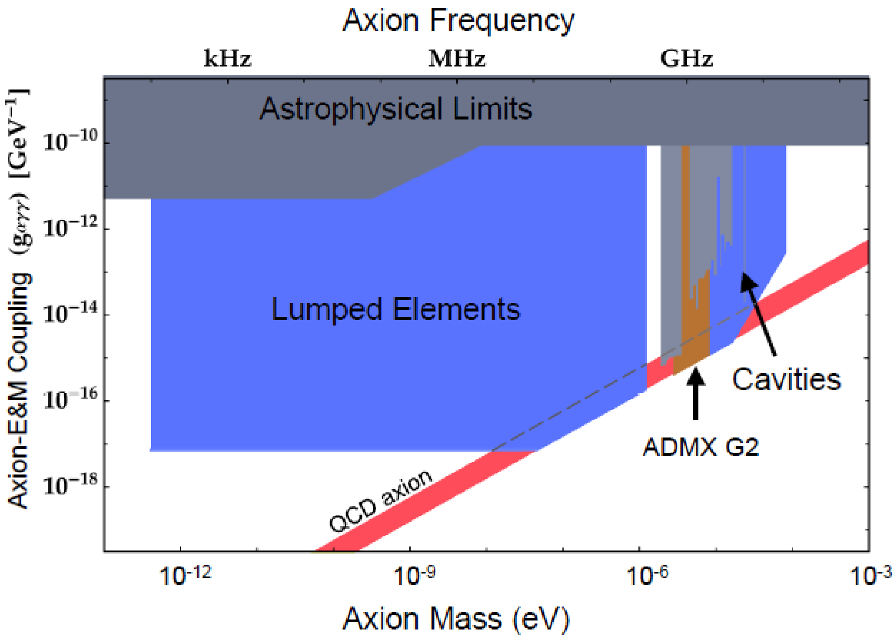
nuclear coupling



CASPEr

significant overlap/collaboration with DM Radio

electromagnetic coupling



ADMX, HAYSTAC,…

LC Circuit, ABRACADABRA, DM Radio

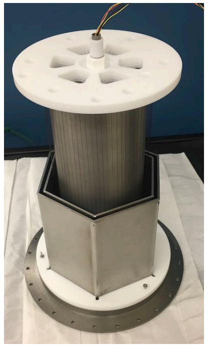
Slide credit: Peter Graham

DM Radio Experiment Family

DM Radio Pathfinder

Status: In testing / operation

- 0.67 L, no magnet
- Q~200,000 now
- 4 K
- Hidden photon science
- DC SQUID



DM Radio-Quantum
DM Radio-50L

Status: In construction

- ~0.5 T, 50 L magnet
- Dilution refrigerator
- ALP science
- Platform for quantum sensors

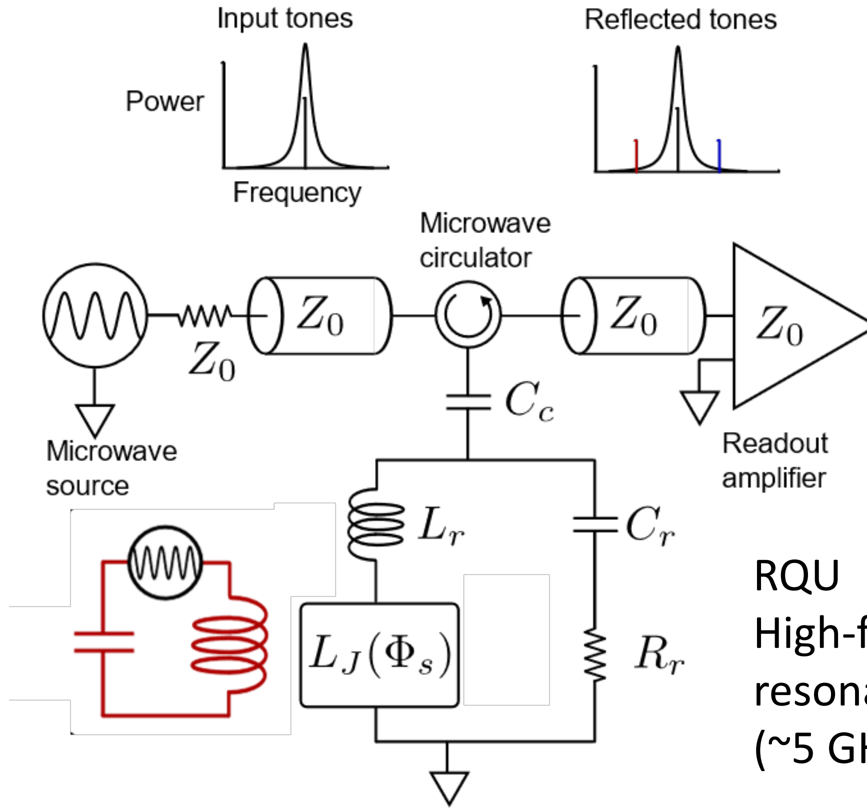
Dark Matter Radio Cubic Meter (DMRadio-m^3)

Status: R&D funded under DOE Dark Matter New Initiatives call

- Brings together both DM Radio and ABRACADABRA teams
- QCD axion over 5 MHz – 200 MHz (20neV-0.8 μeV)
- ~4T, ~m^3 magnet
- Dilution refrigerator

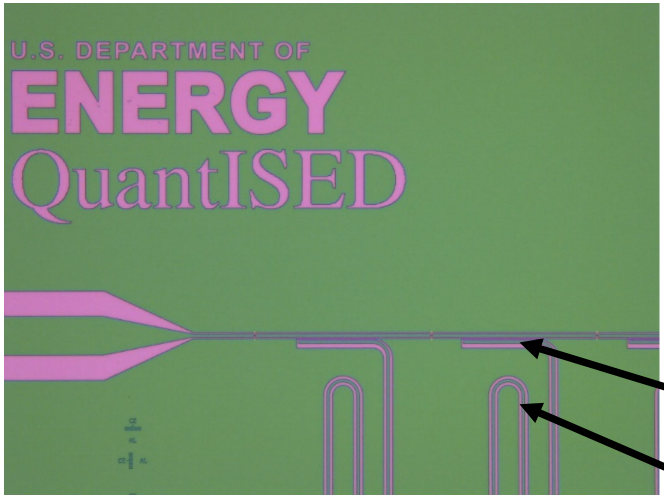
RF Quantum Upconverters

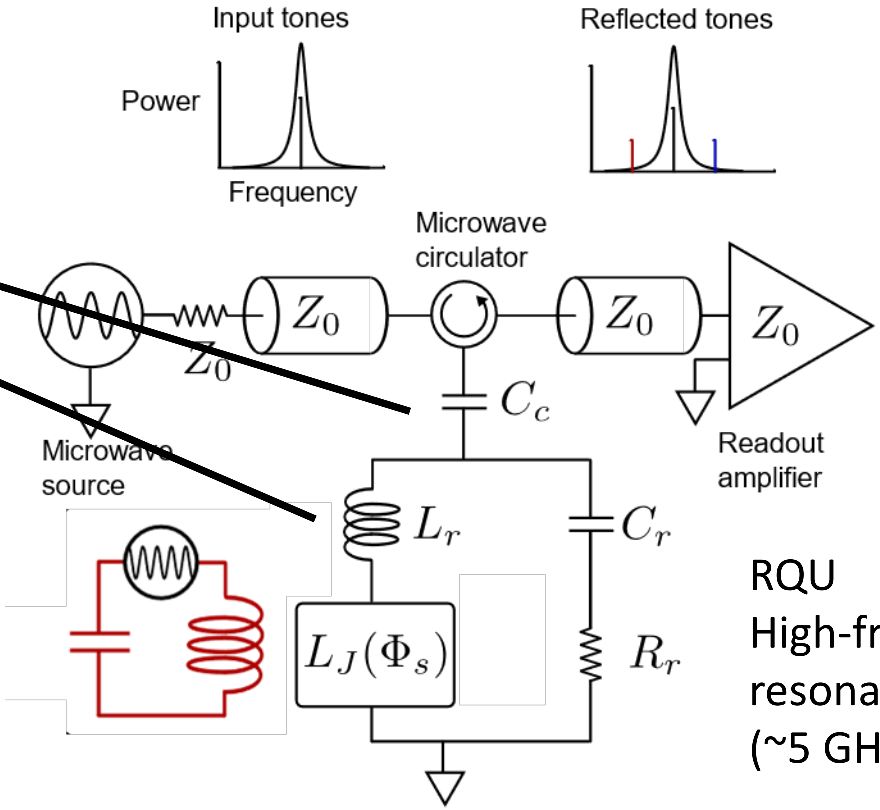
- Electromagnetic sub-μeV axion searches presently use dc SQUIDs in frequency range kHz – 100 MHz.
- The best dc SQUIDs in this frequency range, coupled to macroscopic resonant circuits, are 20 times worse than the SQL, and they couple loss to the resonant circuit.
- A dissipationless sensor is needed that can achieve SQL, and conduct phase-sensitive operations like backaction evasion with electromagnetic signals at audio-RF frequencies.



RQU
High-frequency resonator
(~5 GHz)

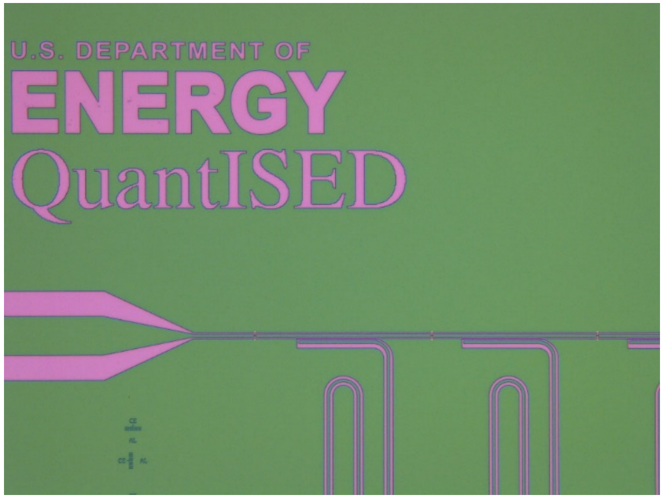
RF Quantum Upconverters

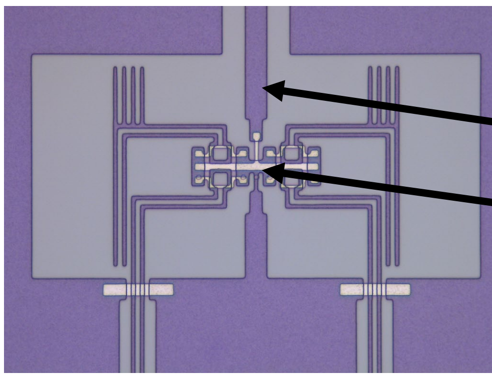


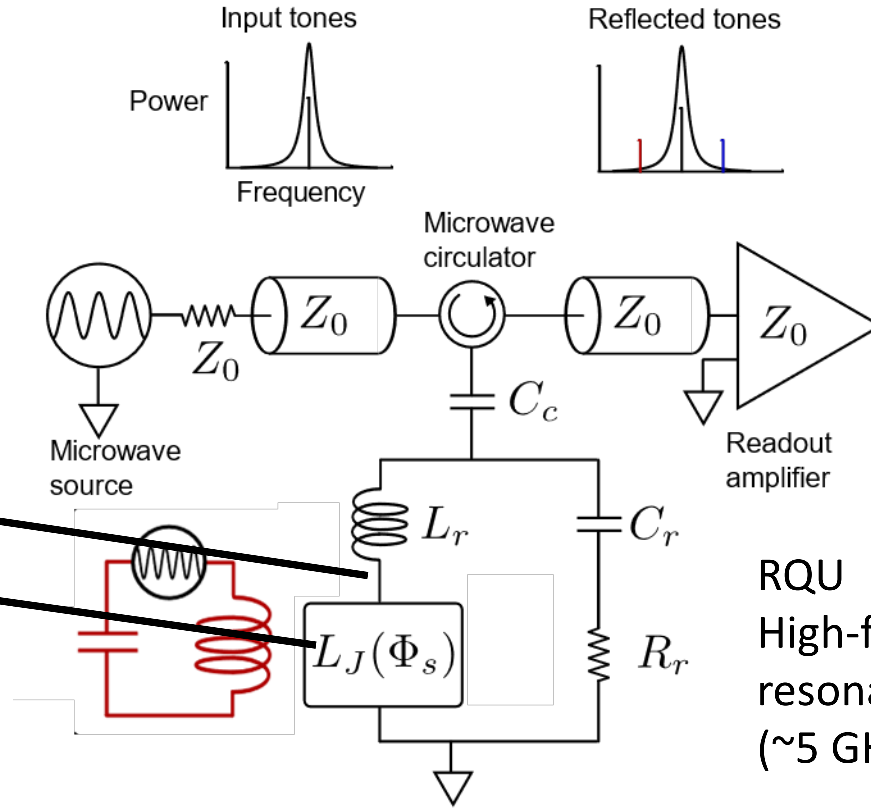


RQU
High-frequency
resonator
(~5 GHz)

RF Quantum Upconverters

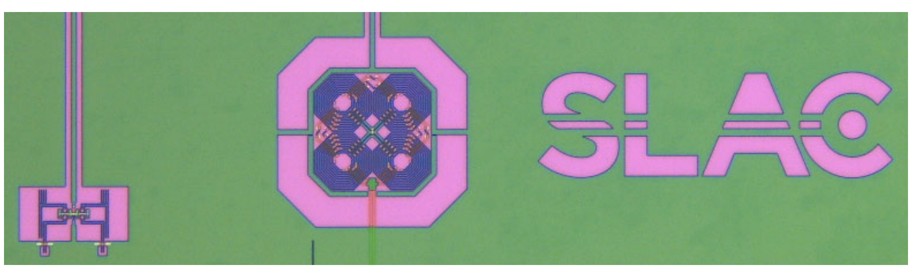




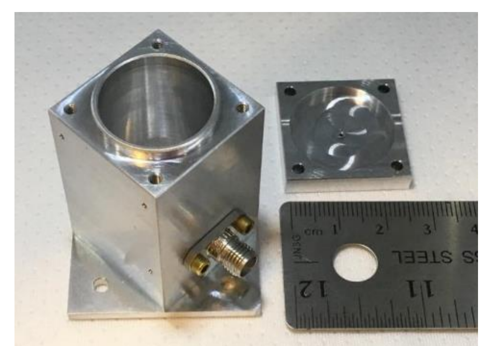


Lithographic resonator RQUs:

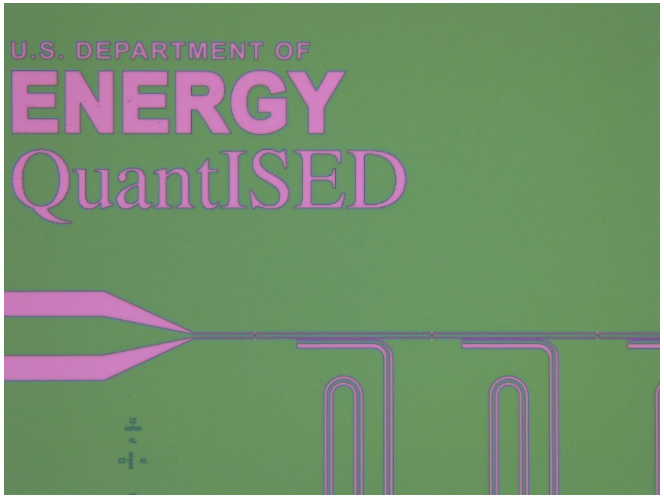
3-junction RQU 1-junction RQU

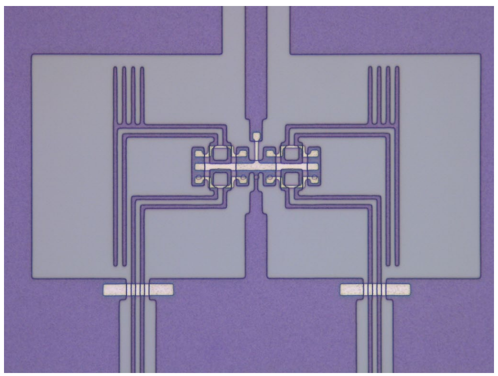


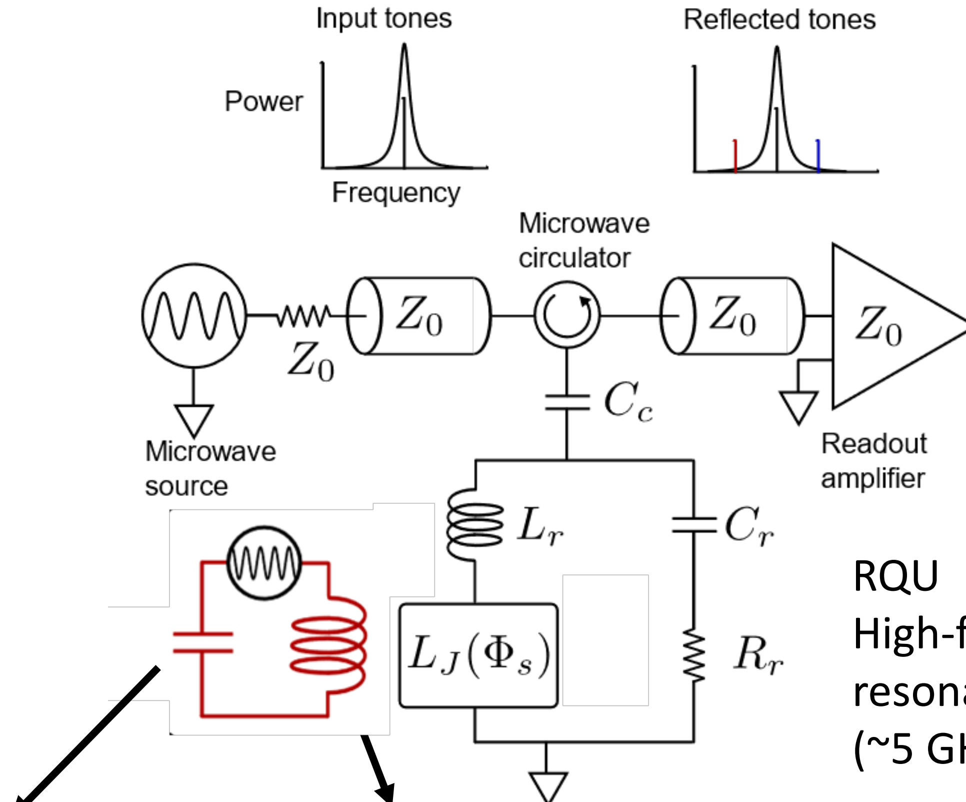
Cavity resonator RQUs:



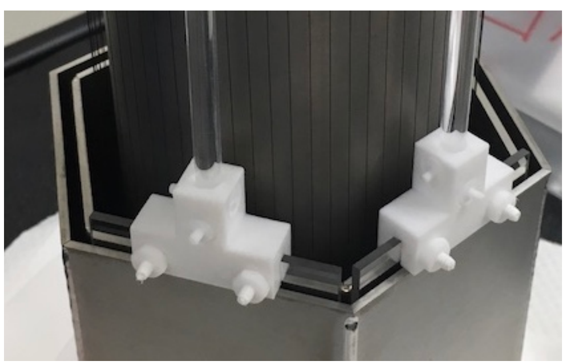
RF Quantum Upconverters

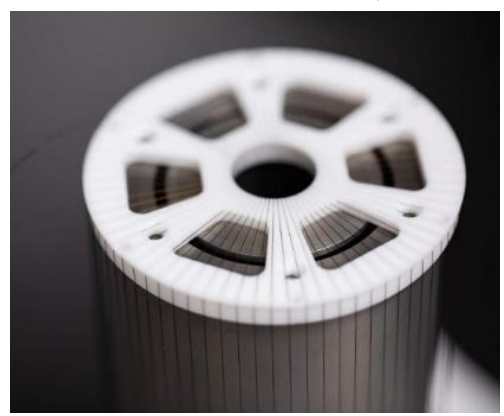






RQU
High-frequency resonator
(~5 GHz)

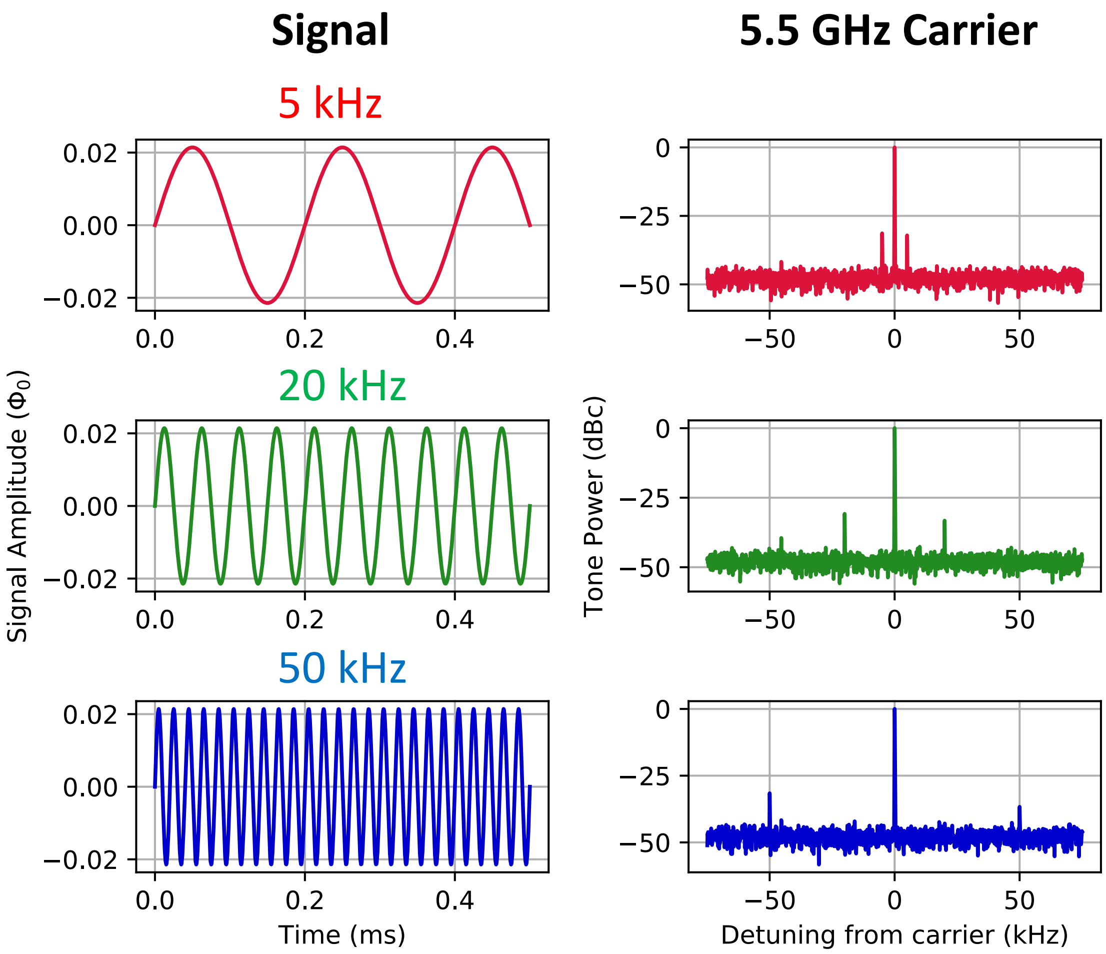




DM Radio Pathfinder
Low-frequency resonator
(~MHz)

Data illustrating RF Upconversion

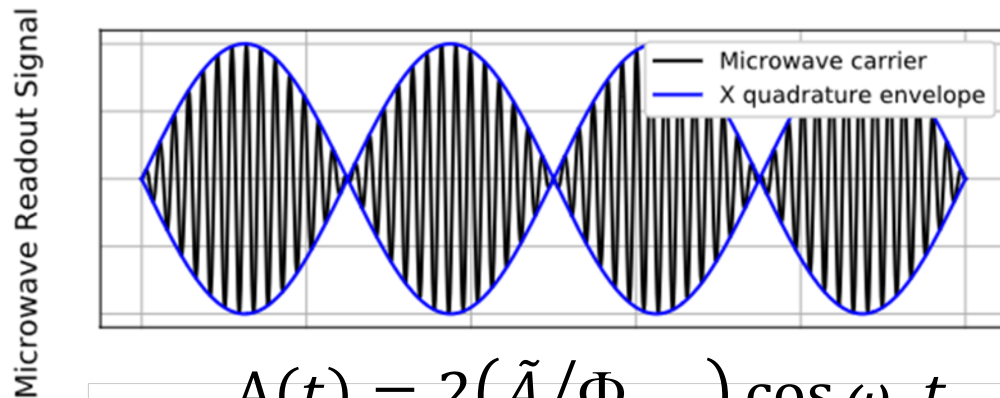
- Data illustrating upconversion in single-junction RQUs
- Single-junction RQU excited on resonance
- The signal information is upconverted to symmetric sidebands on the microwave carrier tone.



Phase-Sensitive Upconversion

If the carrier tone is amplitude modulated in phase with the X-quadrature of the input signal, phase-sensitive amplification of only the X-quadrature is achieved.

Microwave carrier



$$\mathrm{A}(t) = 2\left(\tilde{A}/\Phi_{zpt}\right)\cos\omega_a t$$

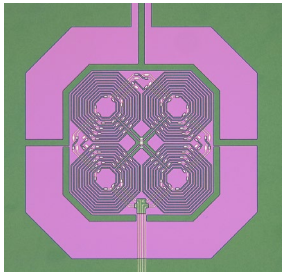
Clerk, *New Journ. Phys.* **10,** 095010 (2008).

$$\widehat{\mathrm{H}} = \hbar\omega_a\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \hbar\omega_b\left(\hat{b}^\dagger\hat{b} + 1/2\right) + \widehat{\mathrm{H}}_{\mathrm{INT}}$$

$$\widehat{\mathrm{H}}_{\mathrm{INT}} = -\hbar A\hat{F}\widehat{\Phi} = -\sqrt{2}\hbar\tilde{A}\hat{F}\left[\widehat{\mathrm{X}}(1 + \cos(2\omega_a t)) + \widehat{\mathrm{Y}}\sin(2\omega_a t)\right]$$

If the carrier tone is amplitude modulated in phase with the X-quadrature of the input signal, phase-sensitive upconversion of only the X-quadrature is achieved.

Phase-Sensitive Upconversion Data

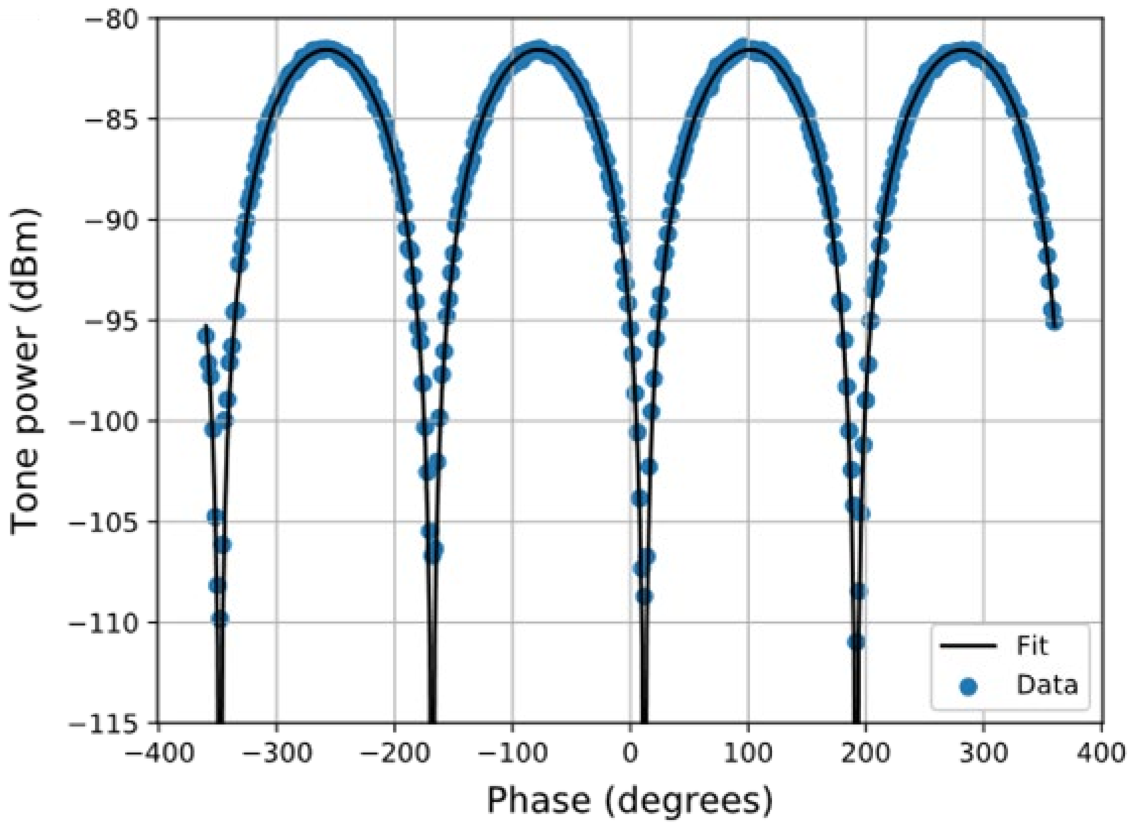


Single-junction RQU

Input: 50 kHz flux signal into single-junction RQU

Carrier: 5.5 GHz sinewave amplitude modulated at 50 KHz

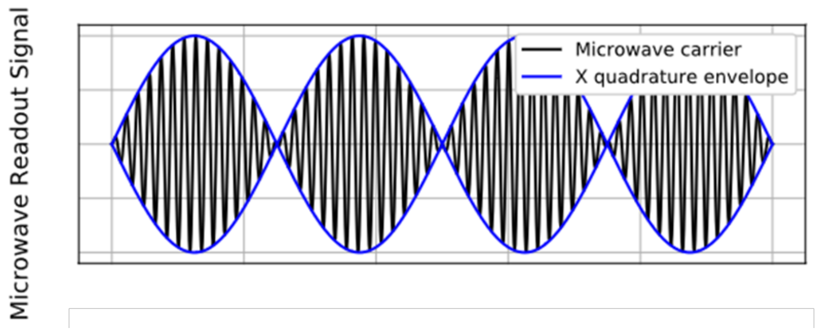
Measure: output tone power as a function of phase shift between input sinewave and AM modulation



$\boxed{\text{29.6 dB of phase-sensitive gain contrast}}$

- Necessary step towards full backaction evasion

Full Backaction Evasion



Carrier tone modulated to measure only X quadrature

- A backaction signal from the microwave resonator only does work on an LC resonator quadrature, on average, if it is 90 degrees out of phase.
- In this limit, if only the $\hat{\mathrm{X}}$ quadrature is measured, the backaction is injected preferentially into the $\hat{\mathrm{Y}}$ quadrature (which is not measured) - BAE
- If the Q of the microwave resonator is high enough (the “good cavity” limit), the sidebands are fully resolved

$$S_X(\omega) = \frac{\gamma}{(\omega-\omega_a)^2+(\gamma/2)^2}\left[1/2+n_{\mathrm{th}}+n_{\mathrm{leak}}\right]+S_{\mathrm{IMP-X}}(\omega)$$

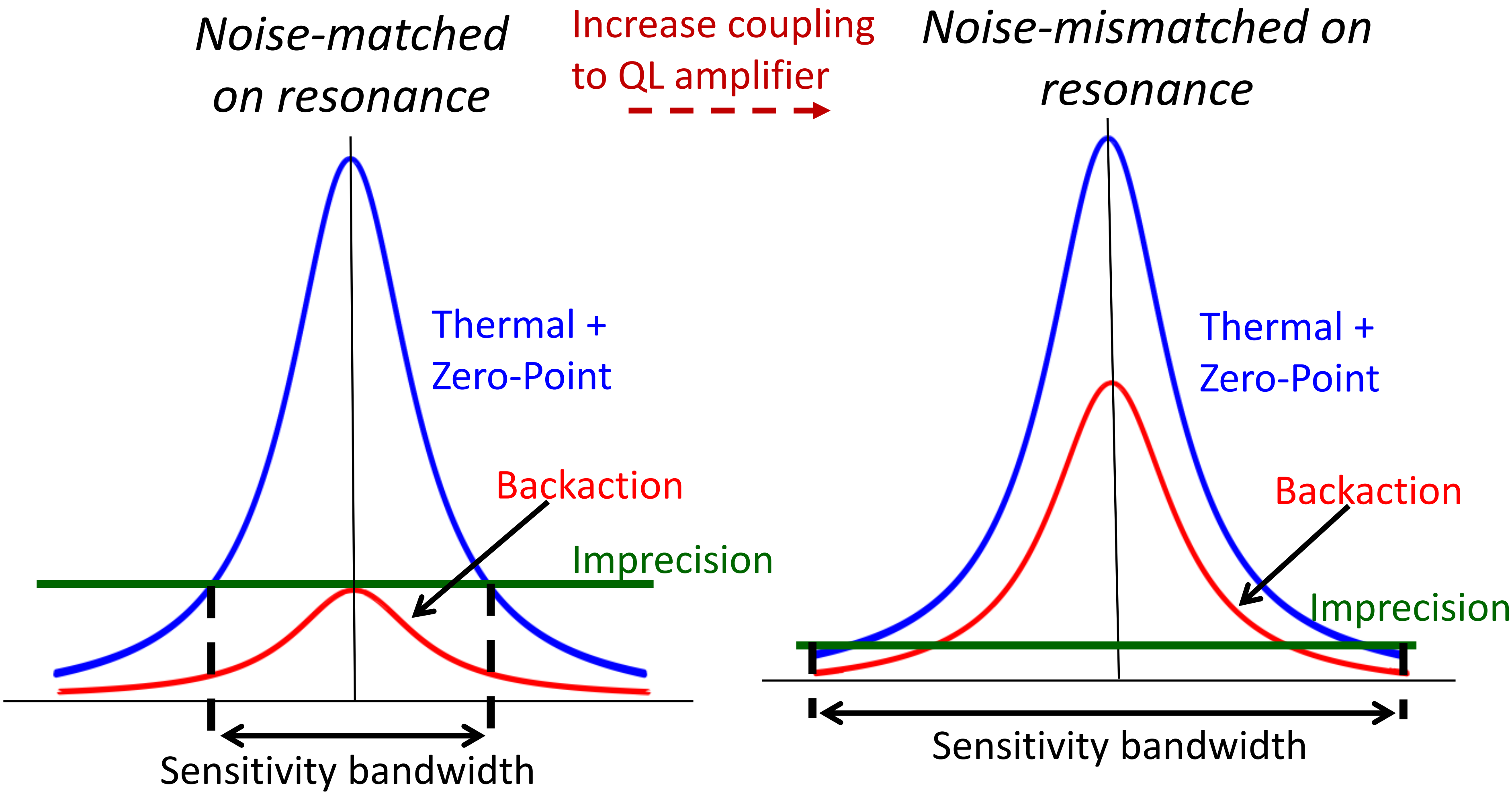
Microwave resonator linewidth

$$n_{\mathrm{leak}} = \frac{n_{\mathrm{BA}}}{32}\left(\frac{\kappa}{\omega_a}\right)^2$$

$$S_Y(\omega) = \frac{\gamma}{(\omega-\omega_a)^2+(\gamma/2)^2}\left[1/2+n_{\mathrm{th}}+n_{\mathrm{BA}}+n_{\mathrm{leak}}\right]+S_{\mathrm{IMP-Y}}(\omega)$$

Braginsky, Vorontsov, and Thorne. *Science* **209,** 547 (1980).
AA Clerk, F. Marquardt, and K. Jacobs, *New Journ. Phys.* **10,** 095010 (2008).

Quantum Backaction



- Increased coupling: reduced imprecision, increased backaction

Summary

- Superconducting sensors have matured, with broad applications across science.
- Transition-edge sensors now are having strong impact on high-energy physics
  - Almost invisibles in the CMB – see Zeesh Ahmed talk
  - Direct Dark Matter Searches – see Jodi Cooley talk
- Quantum coherent superconducting sensors poised to have strong impact on axion searches
  - See Gianpaolo Carosi talk


STOP