Kent Irwin, NIST

Photon detection with the TES: gamma-rays to the CMB
Technology for a mega-pixel imager

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TES: complex, or flexible?

Separation of the detection and readout functions adds complexity, but allows separate optimization.

Detection flexibility

The TES has the highest energy resolution of any non-dispersive photon detector technology over six orders of magnitude in wavelength (visible photons to gamma rays)

Readout and multiplexing flexibility

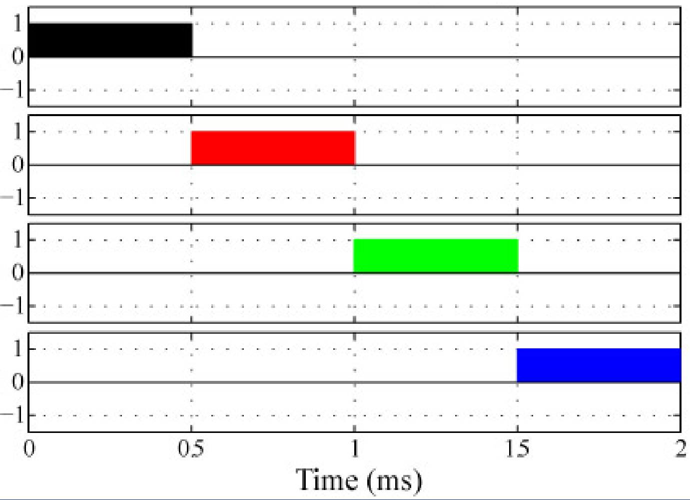
• FDM makes it easier to use communication channels with large bandwidth.

• CDM enables high Shannon efficiency in lower bandwidth channels, with extremely small MUX components and low electronics cost

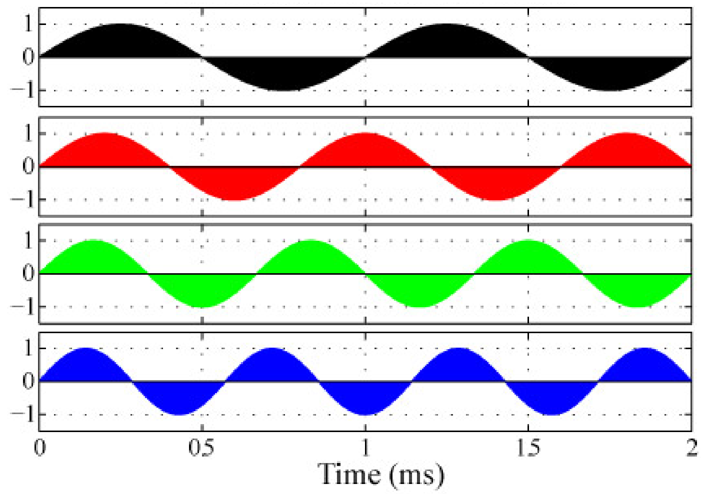
A hybrid modulation function enables both (a la CDMA cell phones) making efficient use of our communication resources

Three modulation functions

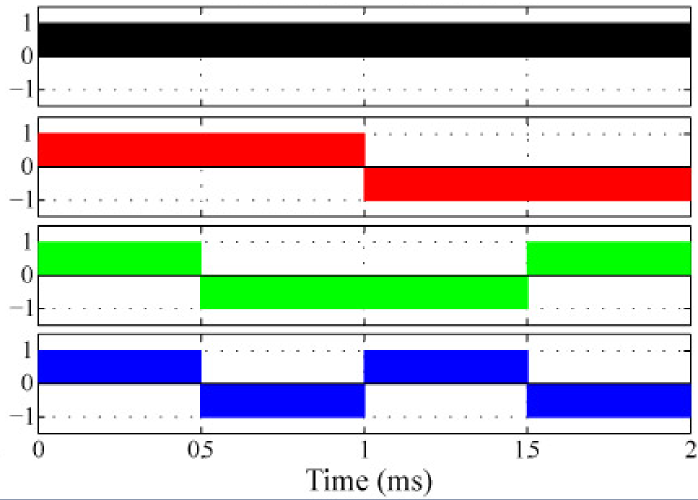
Time-division MUX



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

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Outline

- Shannon-Hartley Theorem and information content
  - How much information is in a TES optical photon detector?
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- Modulation functions for multiplexing
- State of the art in TES photon detectors
  - Optical, X-Ray, Gamma-Ray, CMB (not photon counting)
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Shannon-Hartley Theorem

- 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

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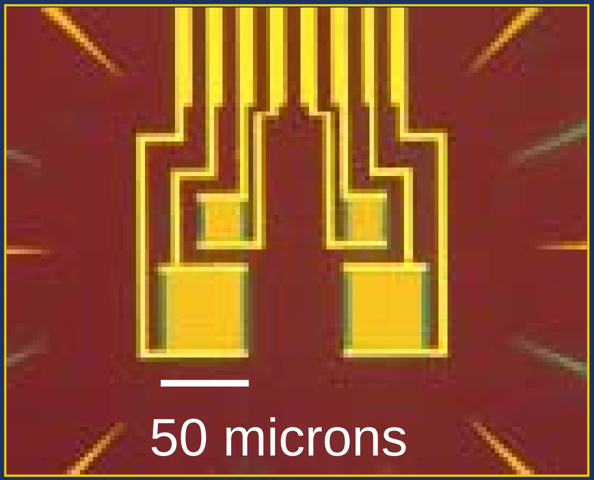
Information content in an optical TES

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



Optical TES detector

$P = 16\ \mathrm{fW}$ Incident photon power (including the sky)

$\mathrm{NEP} = 5\times10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ Photon shot noise

$B = 4\ \mathrm{kHz}$ Bandwidth for a particular scan strategy

$\mathrm{SNR} = 500$ SNR in bandwidth *B*

$C = 72\ \mathrm{kHz}$ Shannon-Hartley bit rate

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Information capacity of cryogenic amplifiers

SQUID

$$\Delta\Phi = \Phi_0$$

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

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

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

HEMT

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

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

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

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

Since our optical photon detector requires ~ 100 KHz, a highly efficient MUX would be able to read out ~10^2 detectors per SQUID, and ~10^6 detectors per HEMT

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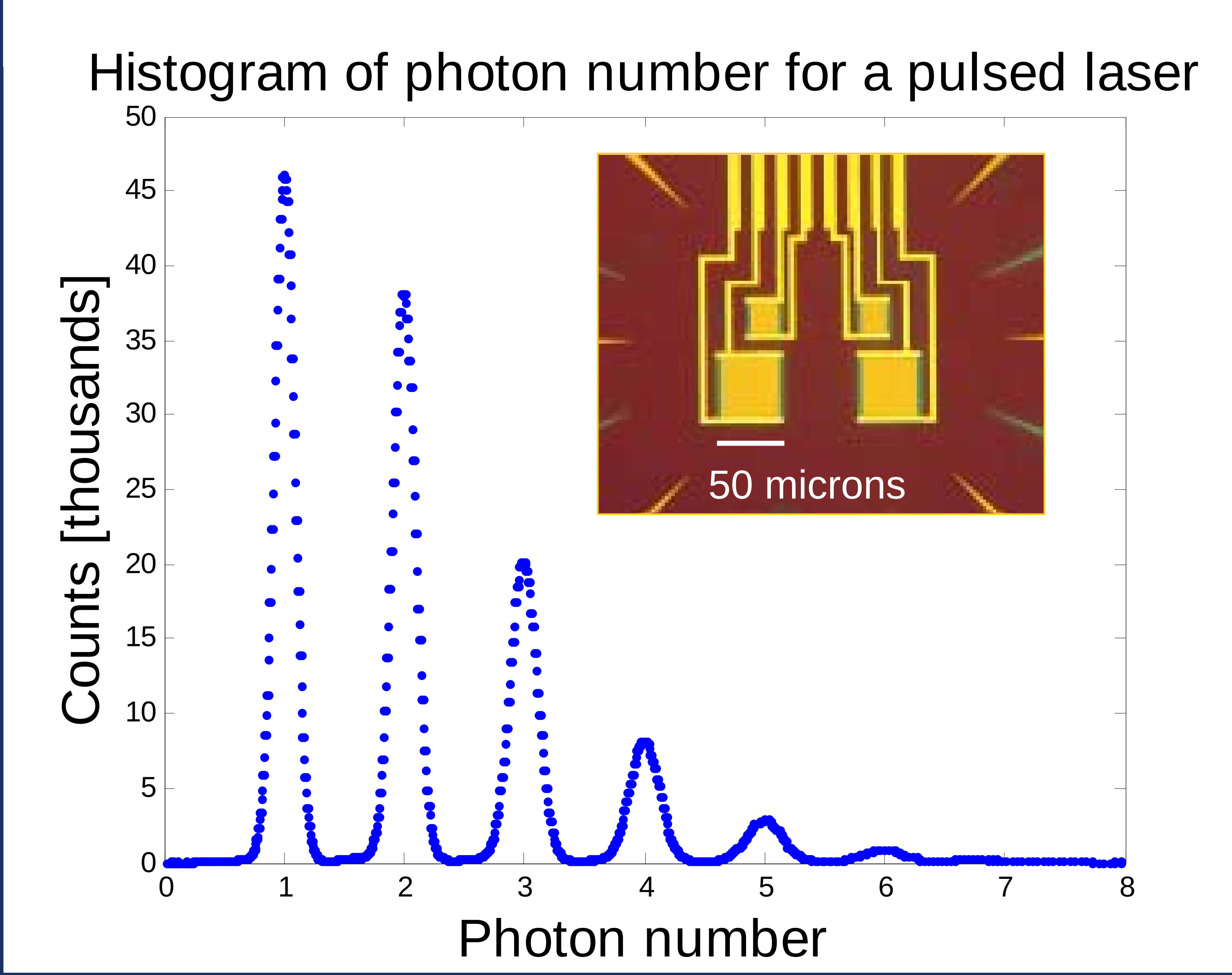
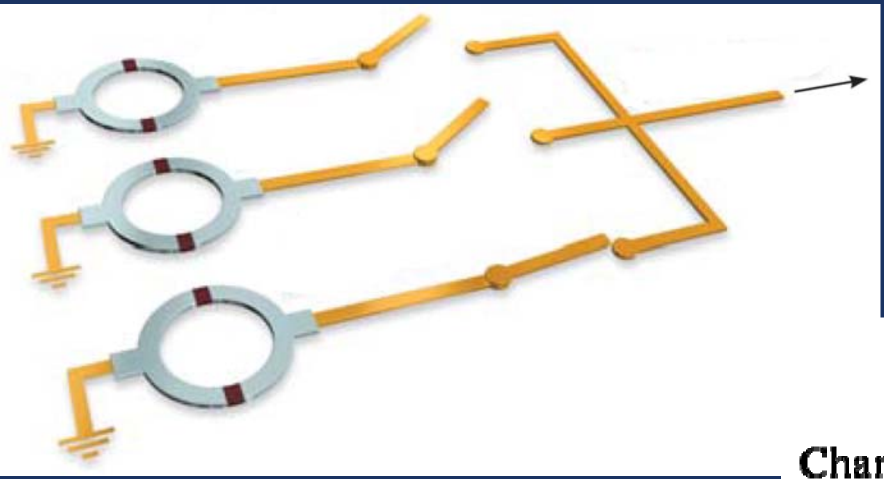
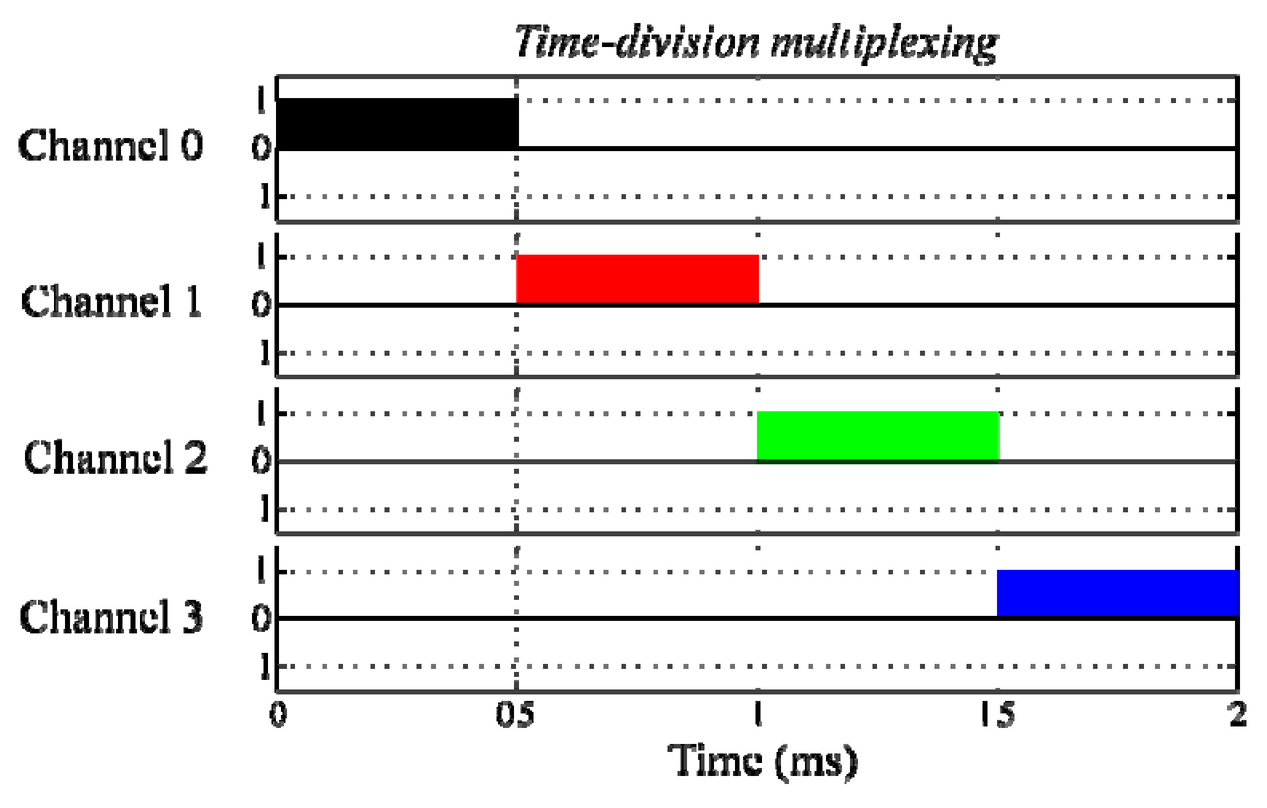
Optical photons: 1550 nm pulsed laser



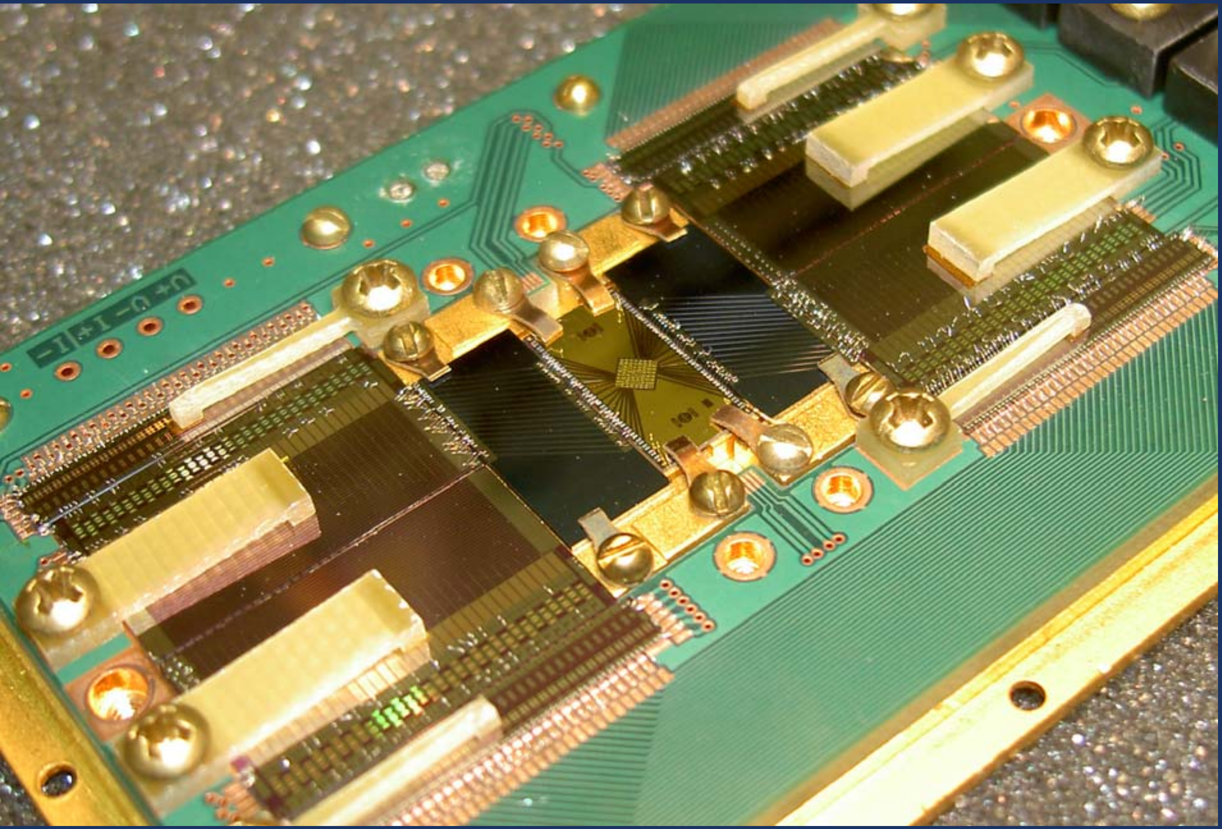
Time-division MUX





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

Soft x-ray: 2x8 time-division MUX



NASA/GSFC 8x8 TES array

NIST TDM MUX

(credit Randy Doriese)

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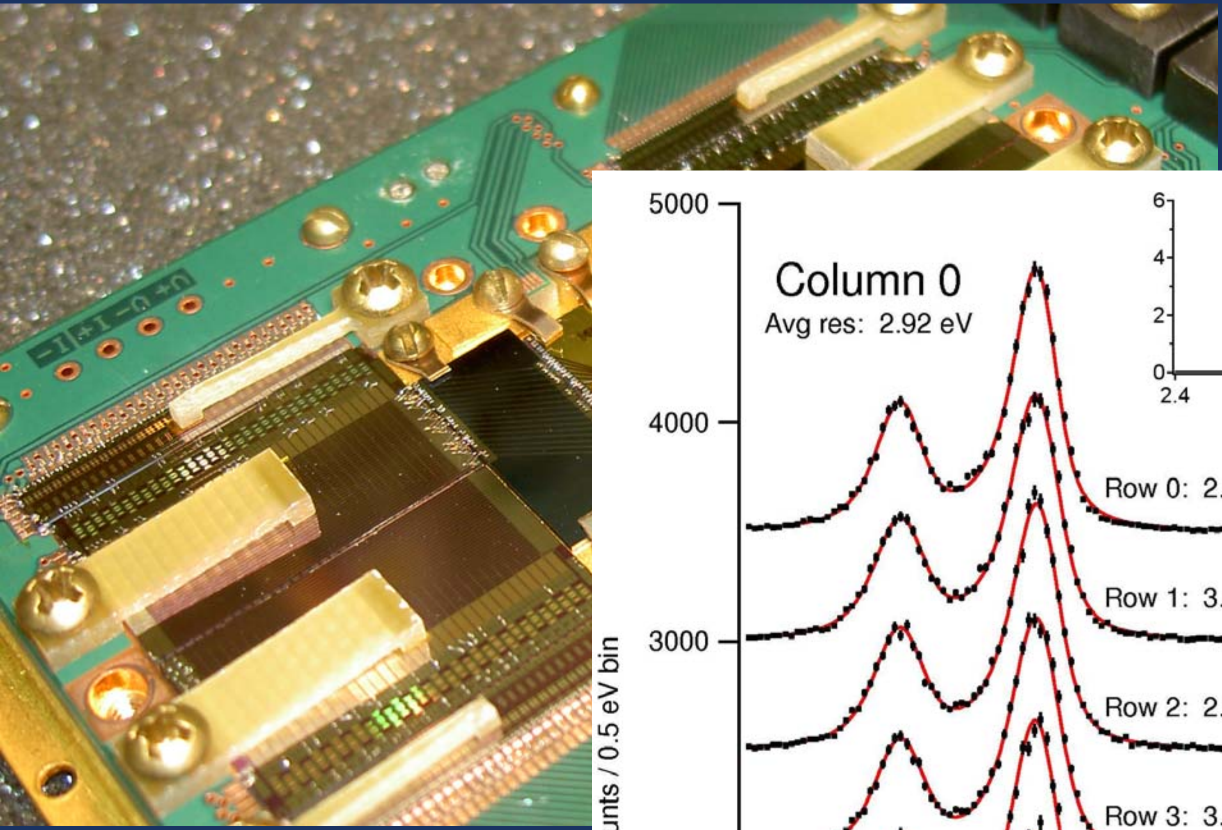
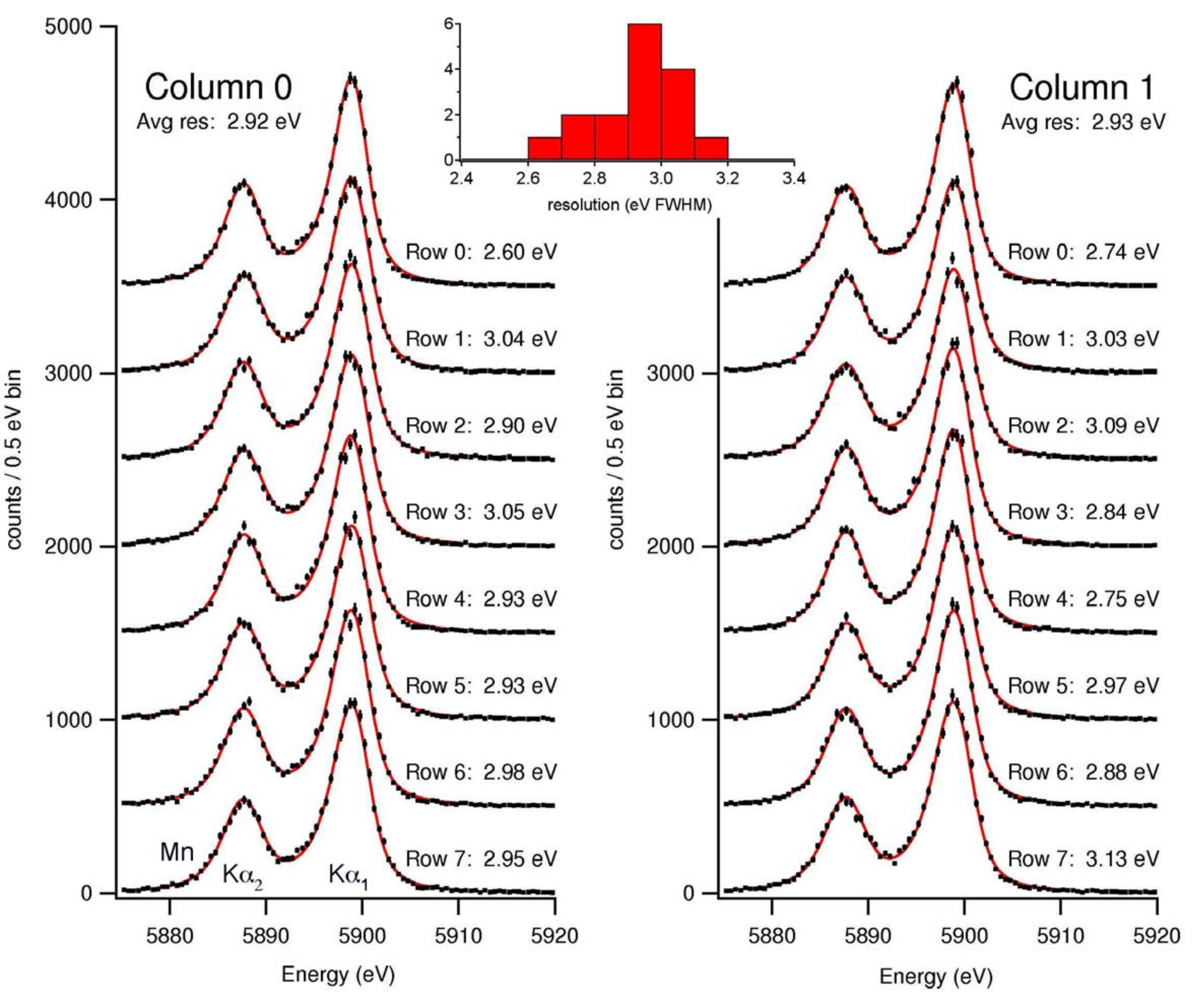
Soft x-ray: 2x8 time-division MUX





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NIST TDM MUX

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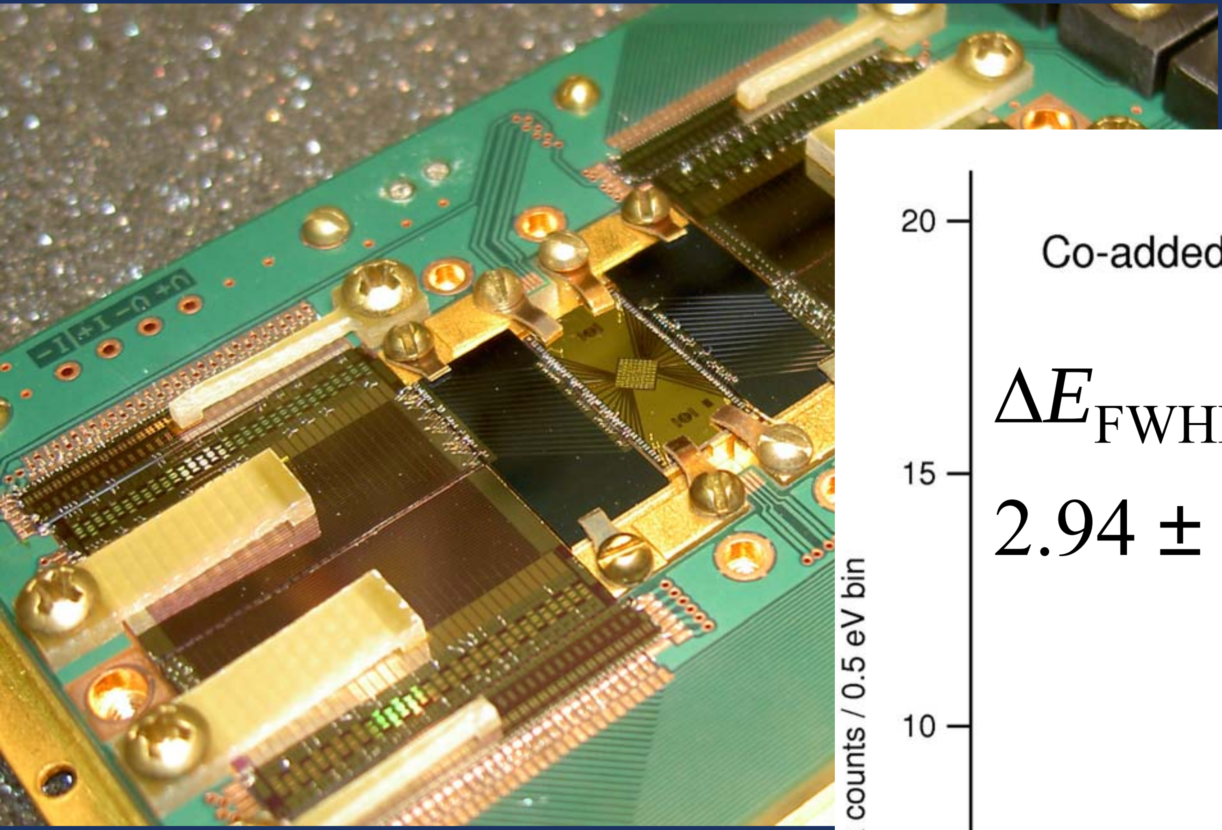
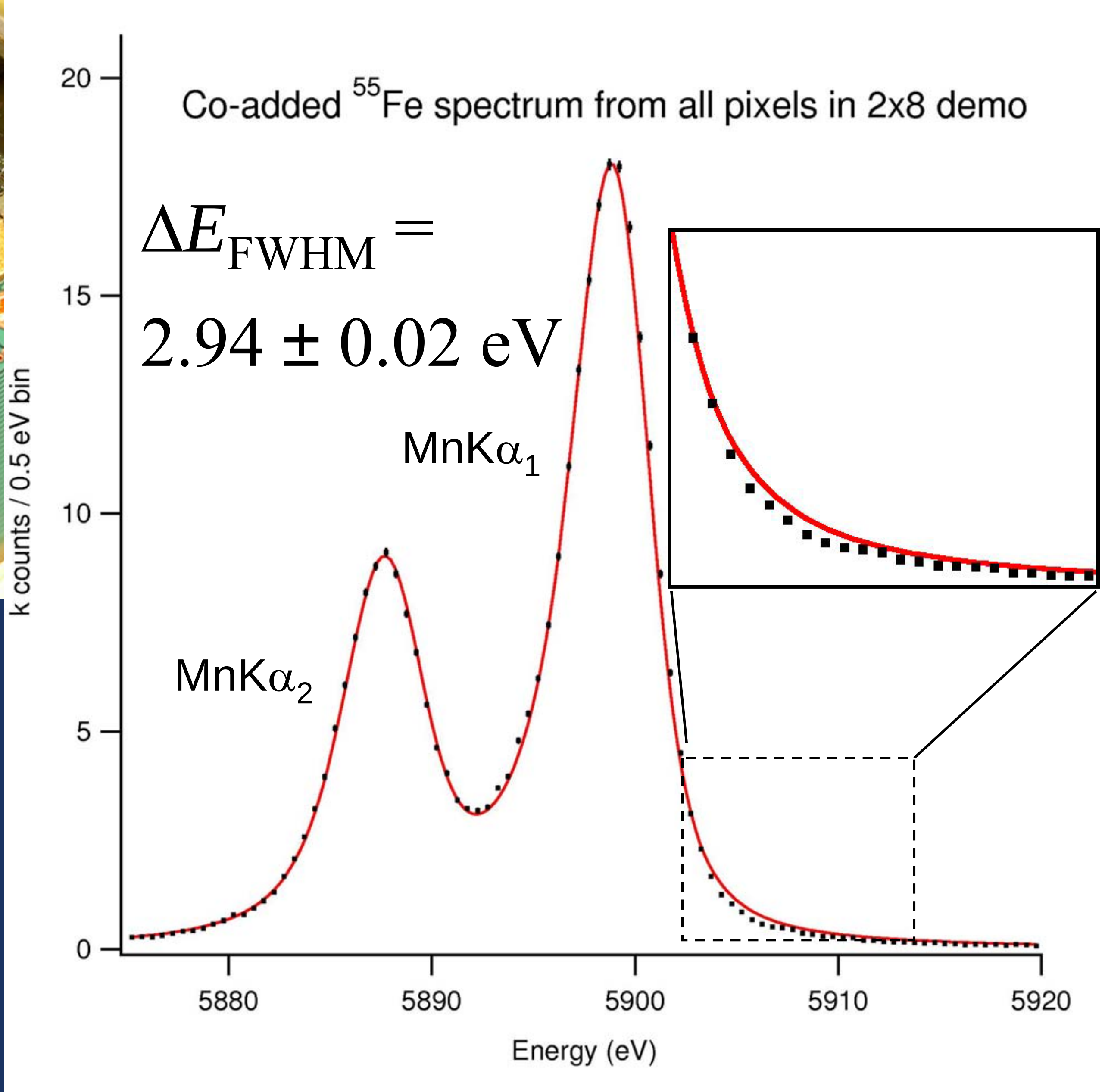


NASA/GSFC 8x8 TES array

NIST TDM MUX

(credit Randy Doriese)



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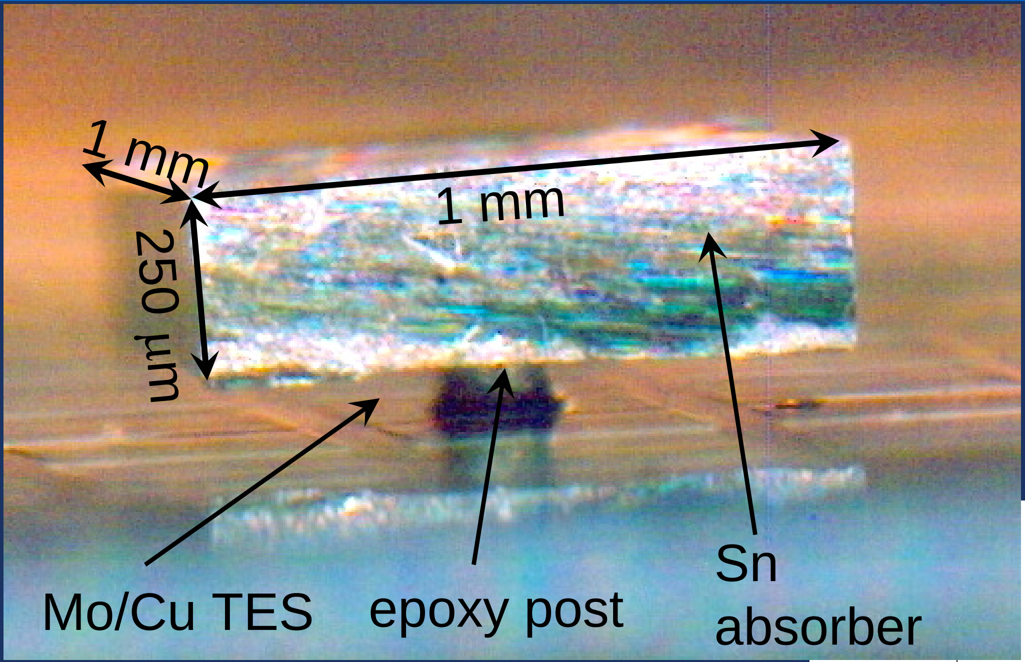
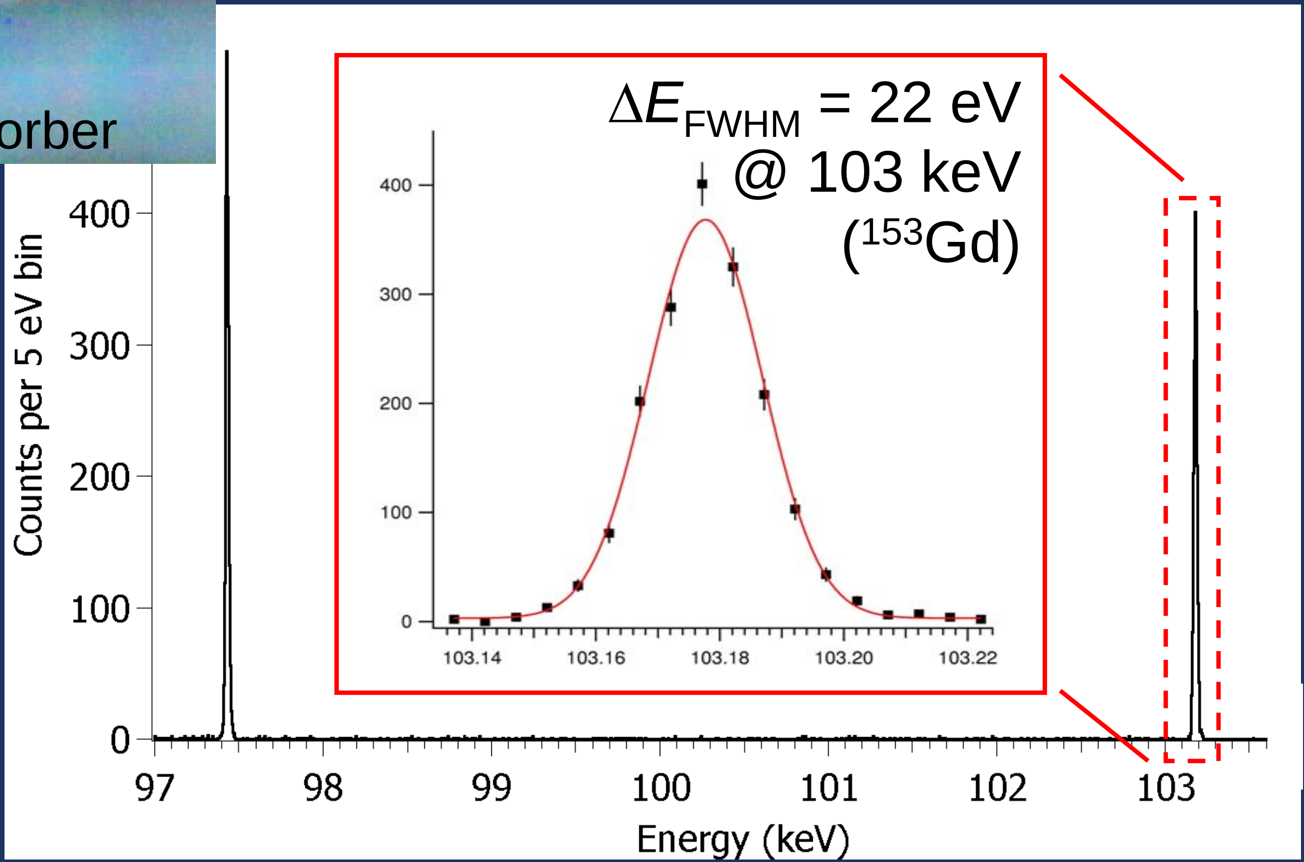
Gamma-ray TES calorimeter



$$\frac{E}{\Delta E_{FWHM}} \sim 4800!$$



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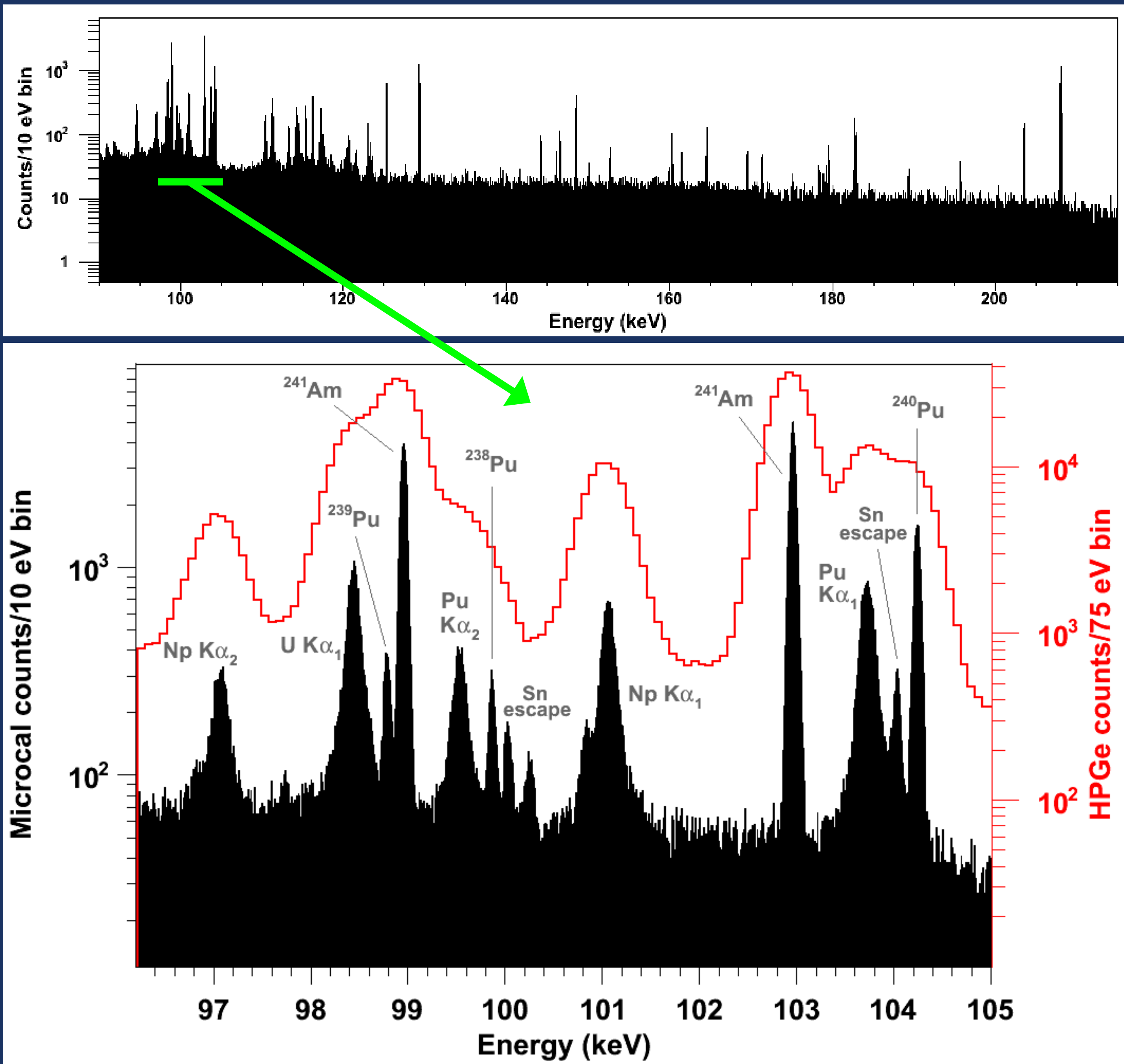
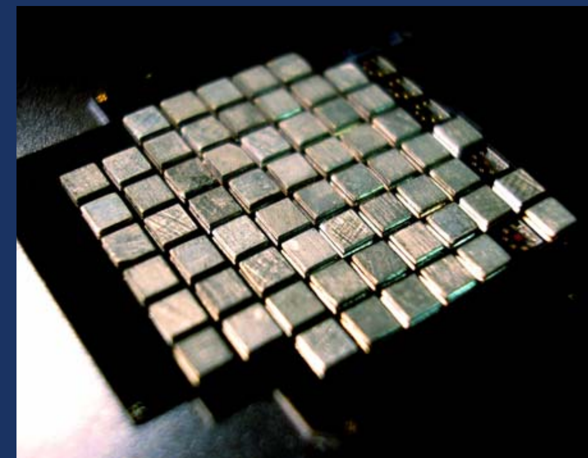
Plutonium isotopic analysis

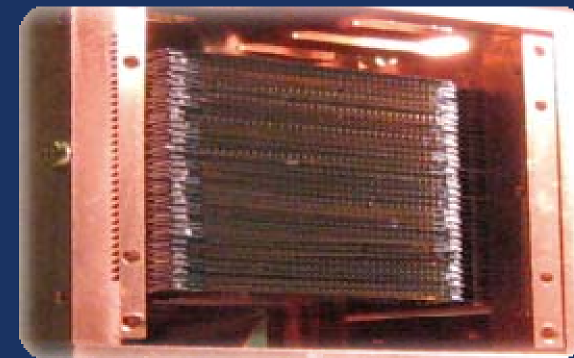




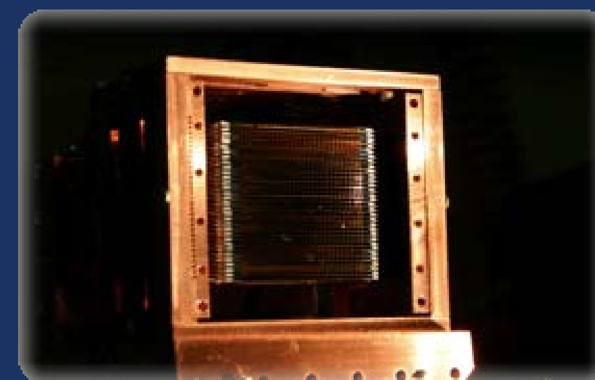
- 66 pixel array: 256 now in the field
- LANL/NIST

CMB: Atacama Cosmology Telescope

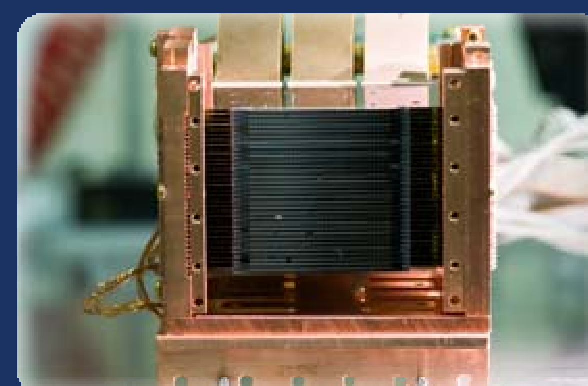
148 GHz



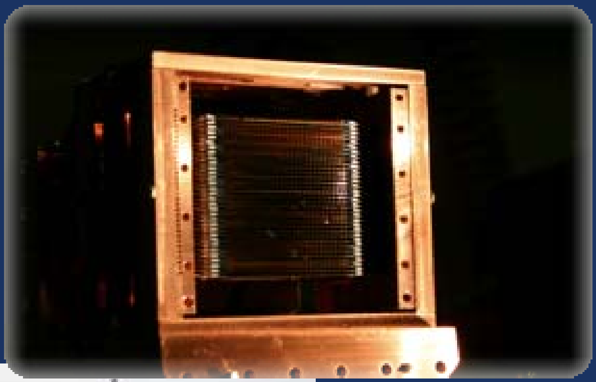
218 GHz



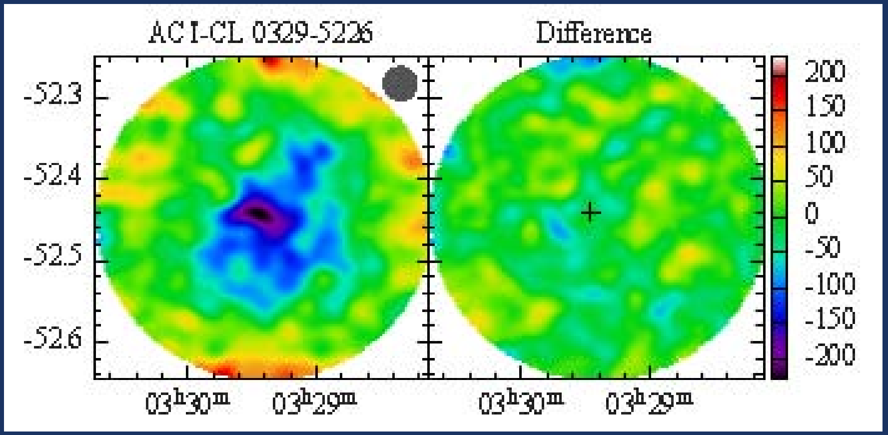
277 GHz



The Atacama Cosmology Telescope - SZ



3,000 TES pixels
on the sky



SZ cluster

Collaboration:

Cardiff, Columbia, CUNY, Haverford, NASA/GSFC, NIST

Penn, Princeton, Rutgers, Univ. de Catolica, UMASS, Univ of Toronto

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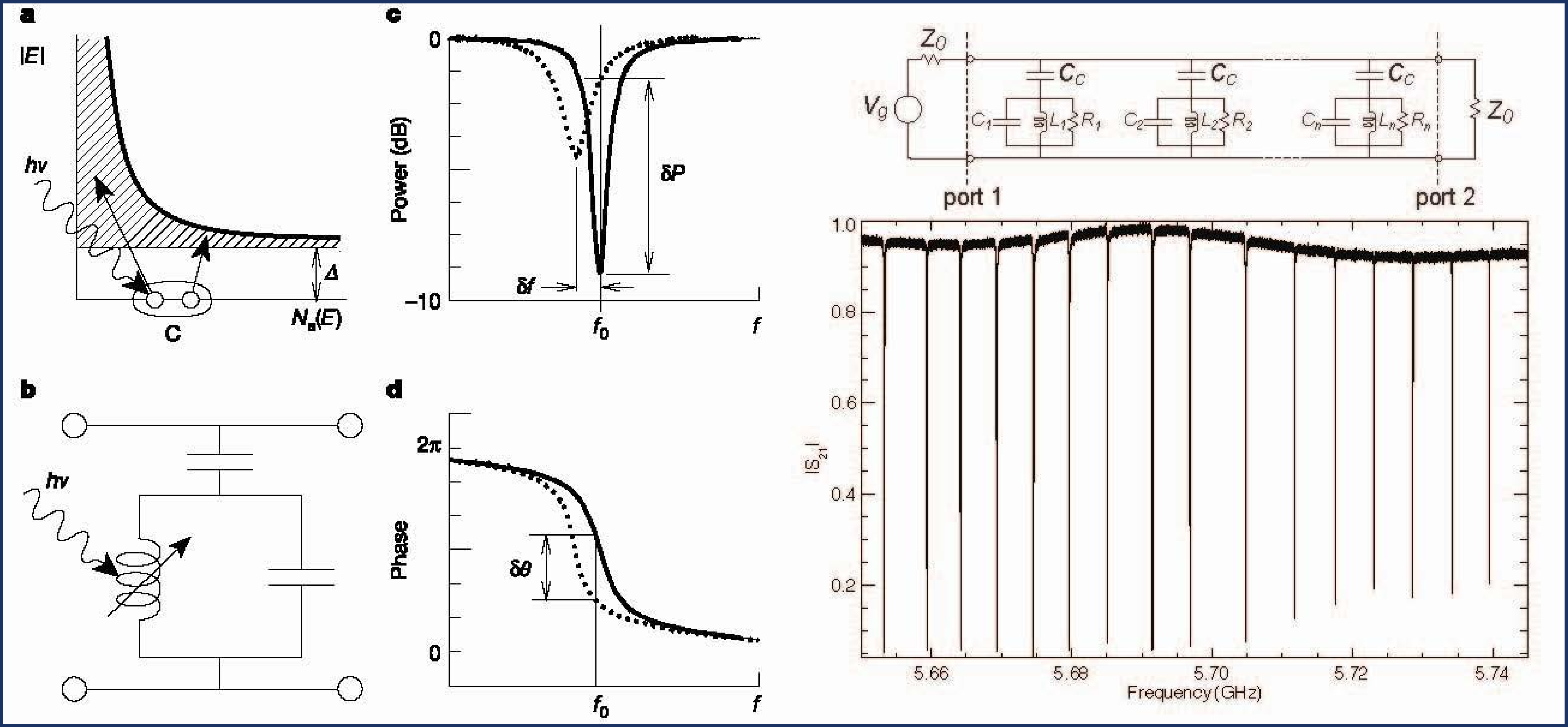
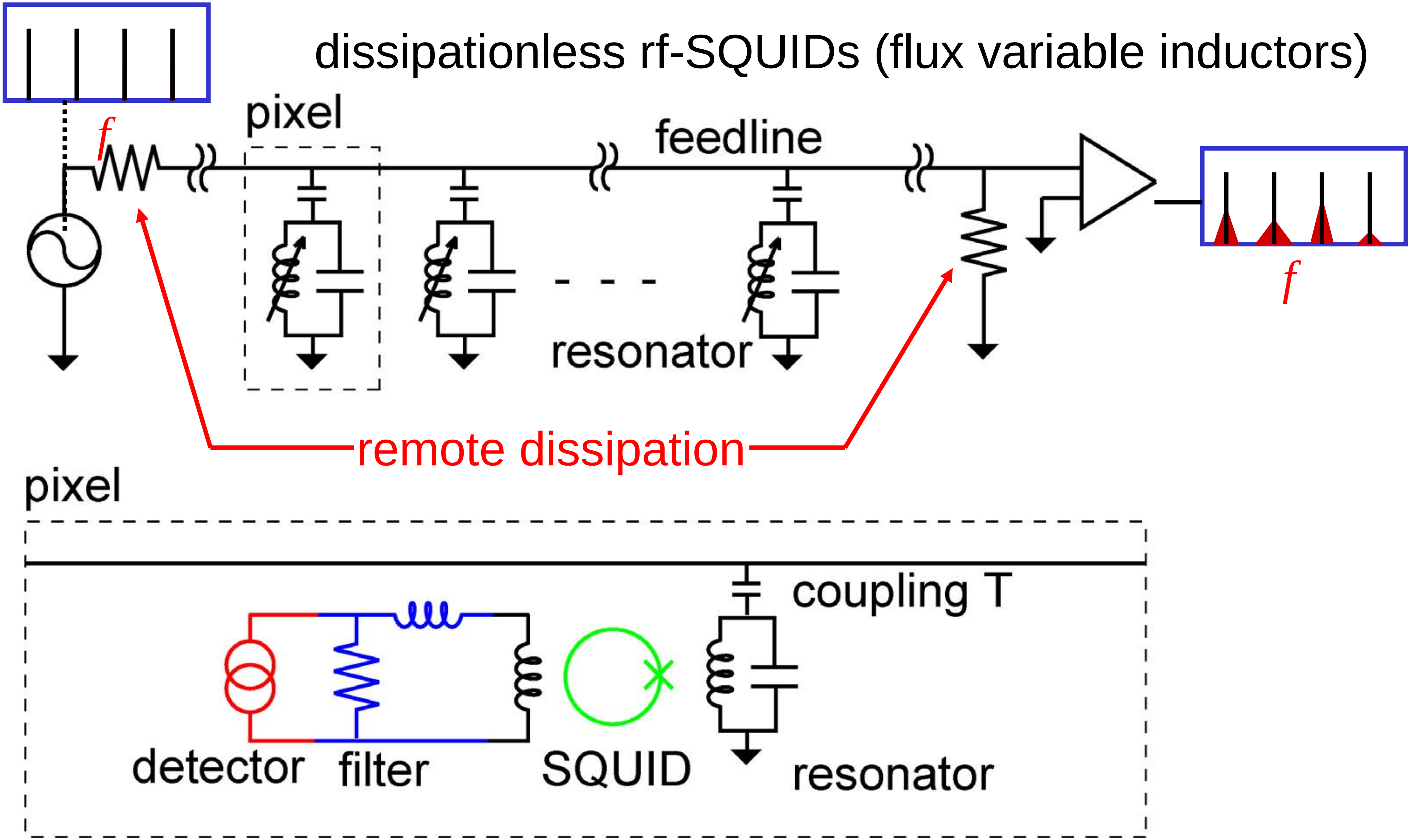
GHz FDM: MKIDs



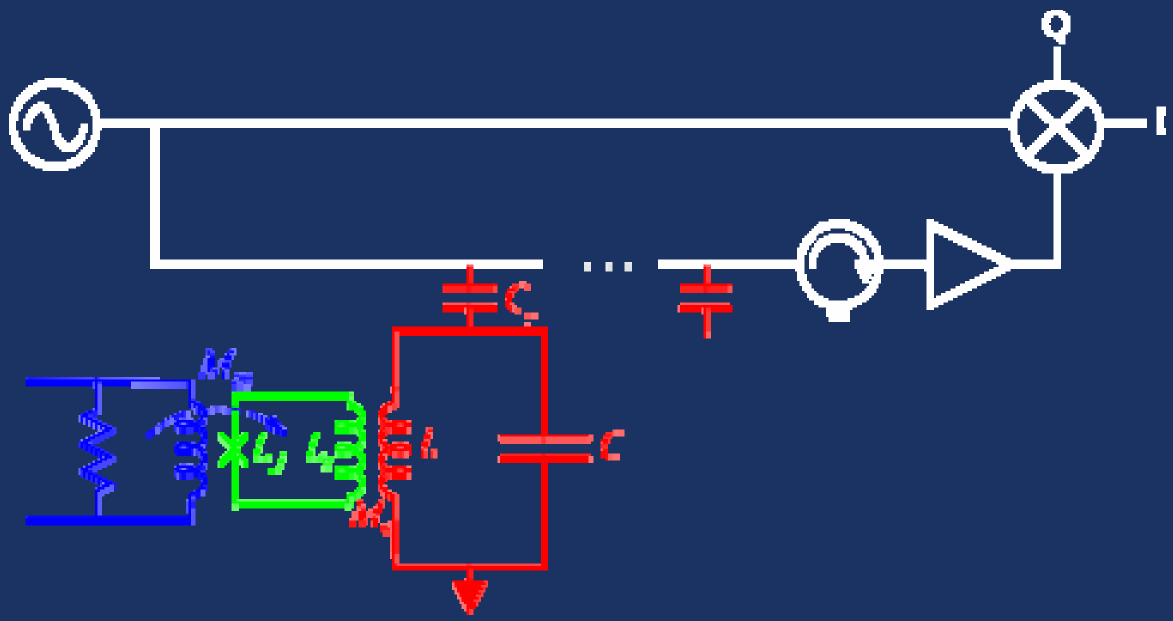
Already well described by B. Mazin

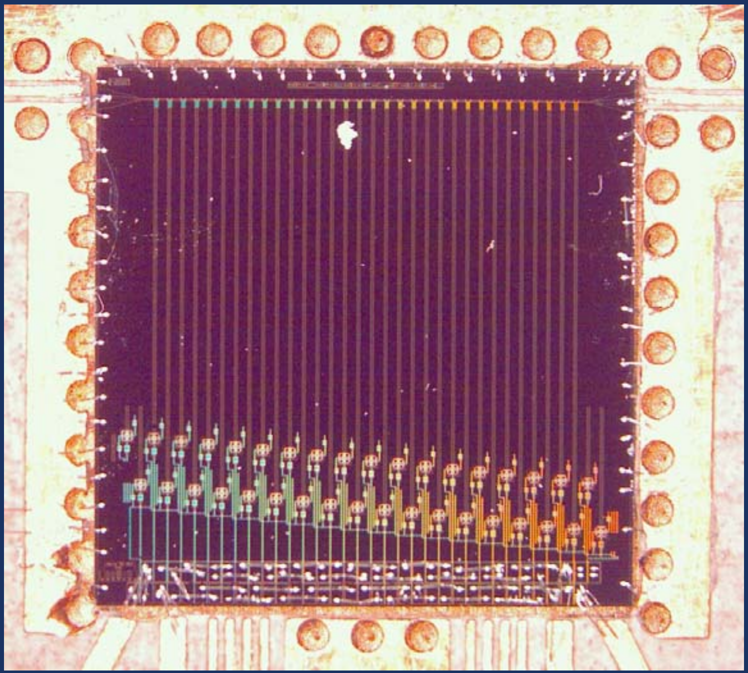
GHz FDM of TESs



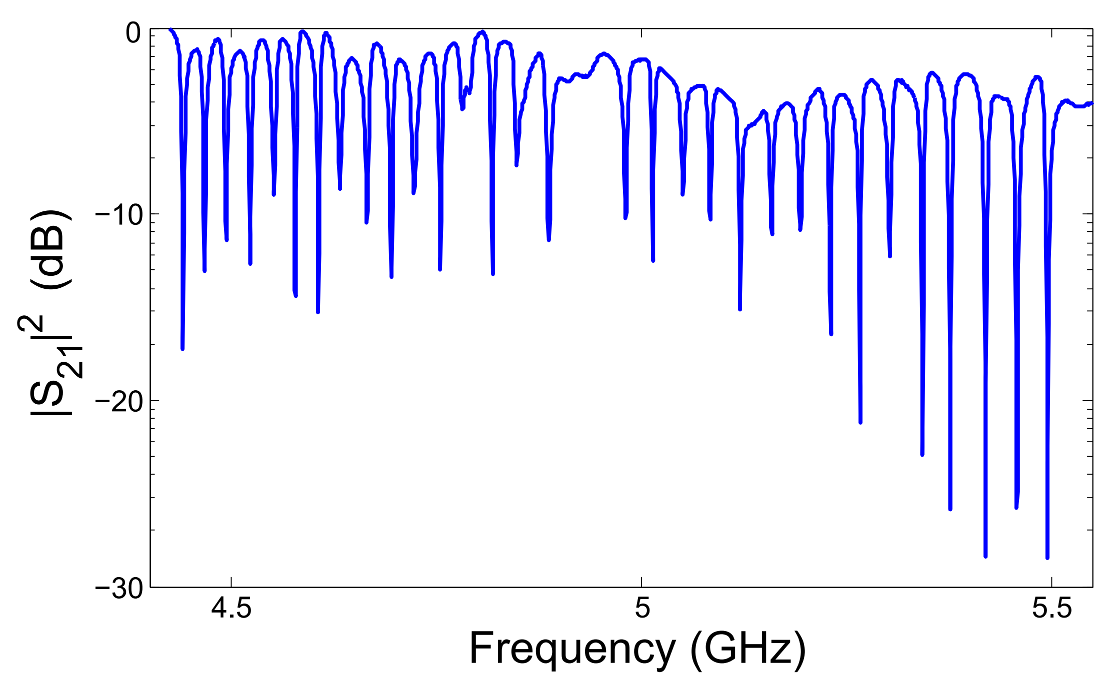
A Josephson junction is required to provide noise matching between TES and HEMT

GHz FDM: microwave SQUIDs





- dissipationless, reactive SQUIDs
- no feedback (modulated)
- ~ pW power dissipation per resonator
- Use electronics from readout consortium



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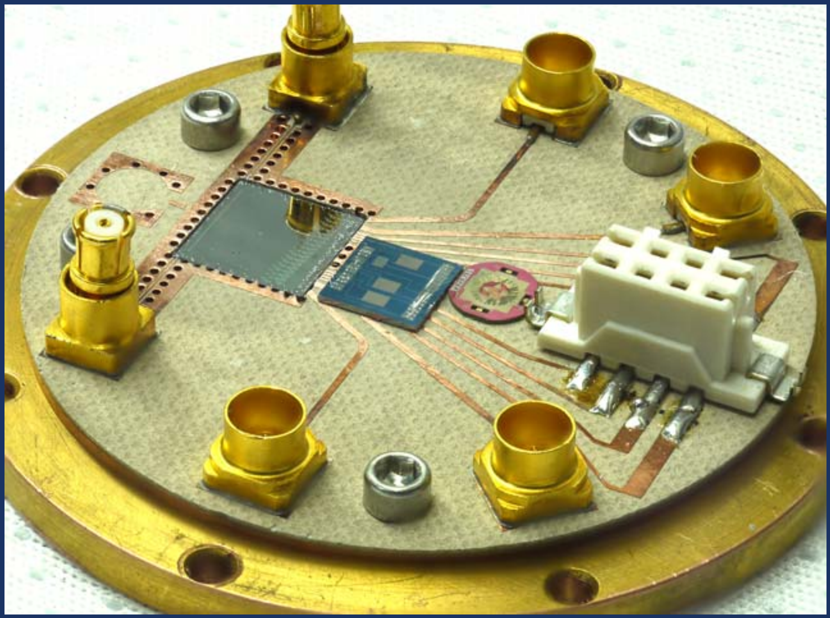
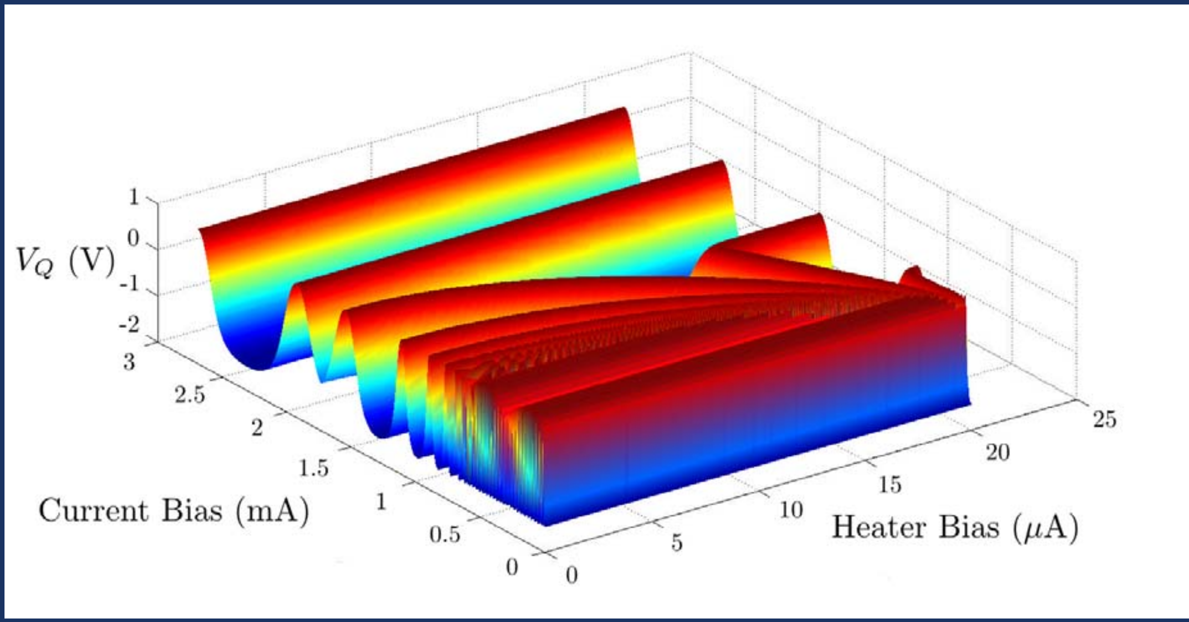
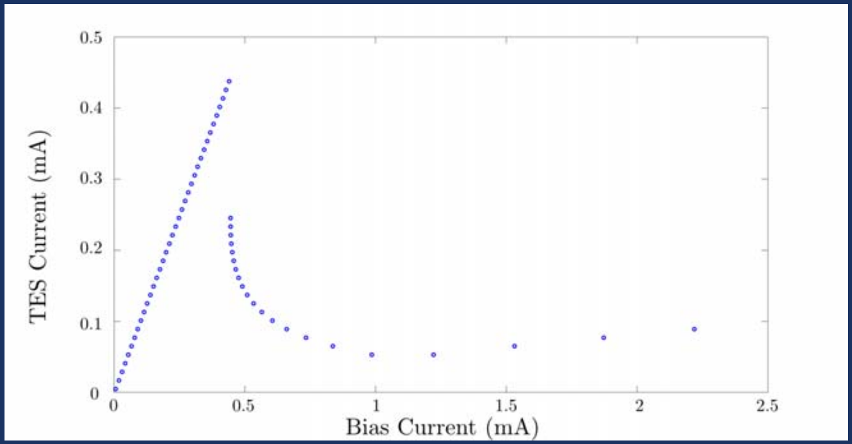
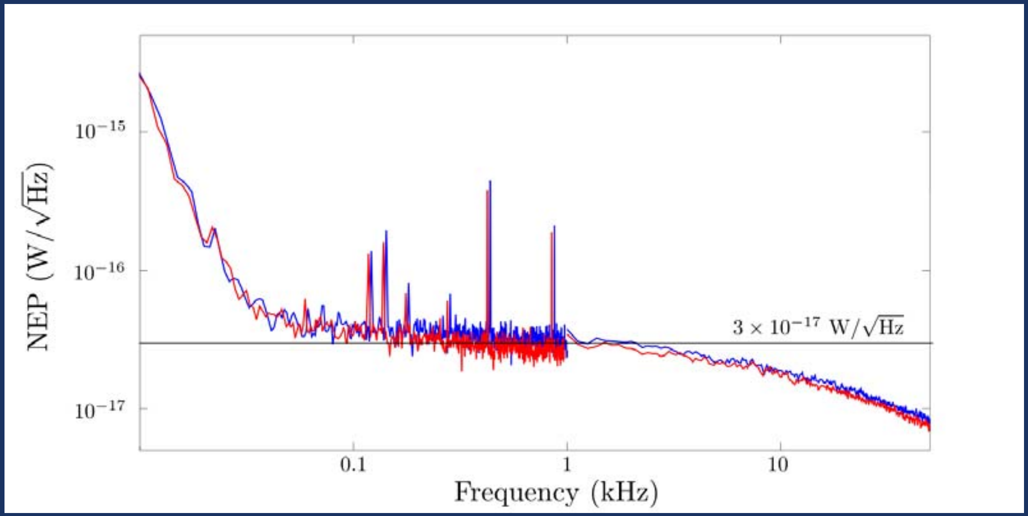
CMB polarimeter measured with MSQUID









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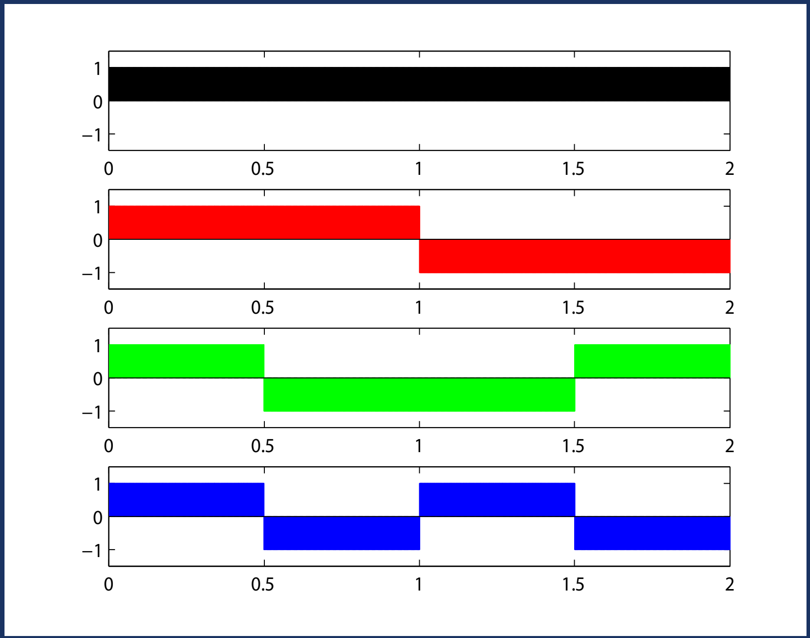
Walsh Code Division Multiplexing



- Every detector pixel is on all of the time
- One SQUID for many detectors
- Polarity of coupling to the SQUID switches between +1 and -1 in orthogonal pattern (Walsh matrix)

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}^{-1} = \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$

- Original signals recovered by multiplying by inverse Walsh matrix.

Additional benefit: SQUID 1/f noise and common-mode rf pickup is removed in all but the first pixel

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Flux-actuated switch

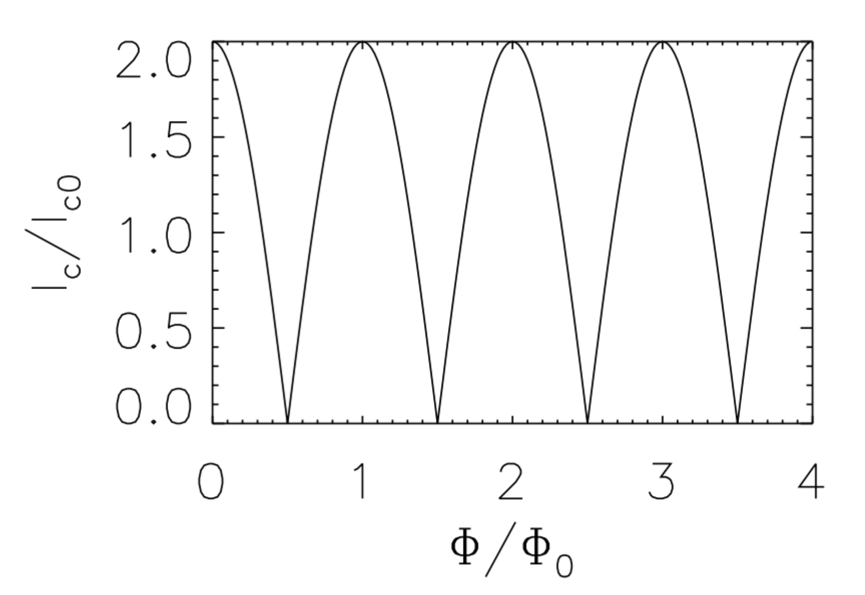
When biased at

$\Phi=\Phi_0/2+n\Phi_0$

the critical current of a low inductance (low beta_L) SQUID is close to zero. High ‘off’ resistance (a few ohms).

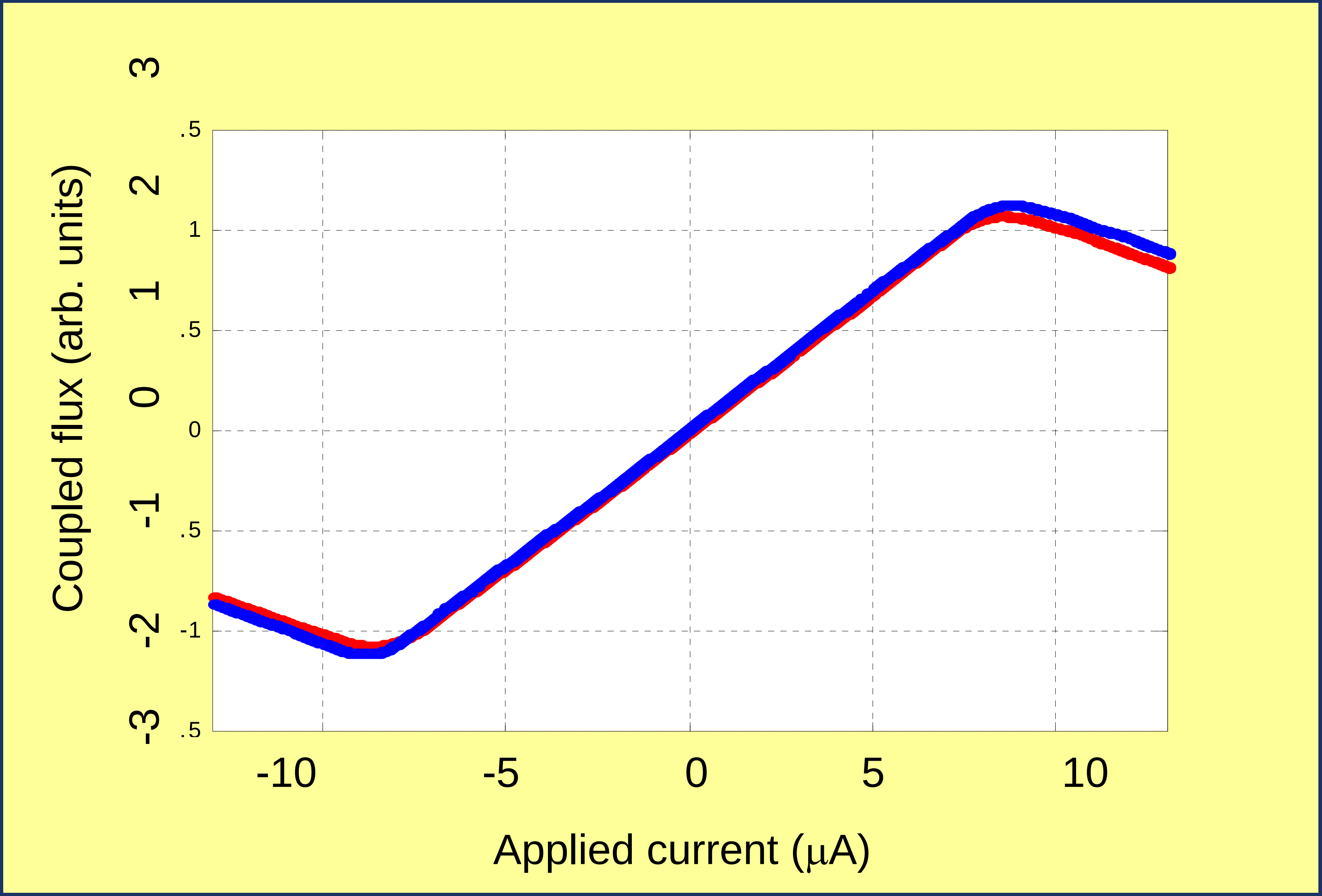
$$I_c \approx 2I_{c0}\left|\cos\left(\pi\Phi/\Phi_0\right)\right|$$

for $\beta_L = 2I_{c0}L/\Phi_0 << 1$

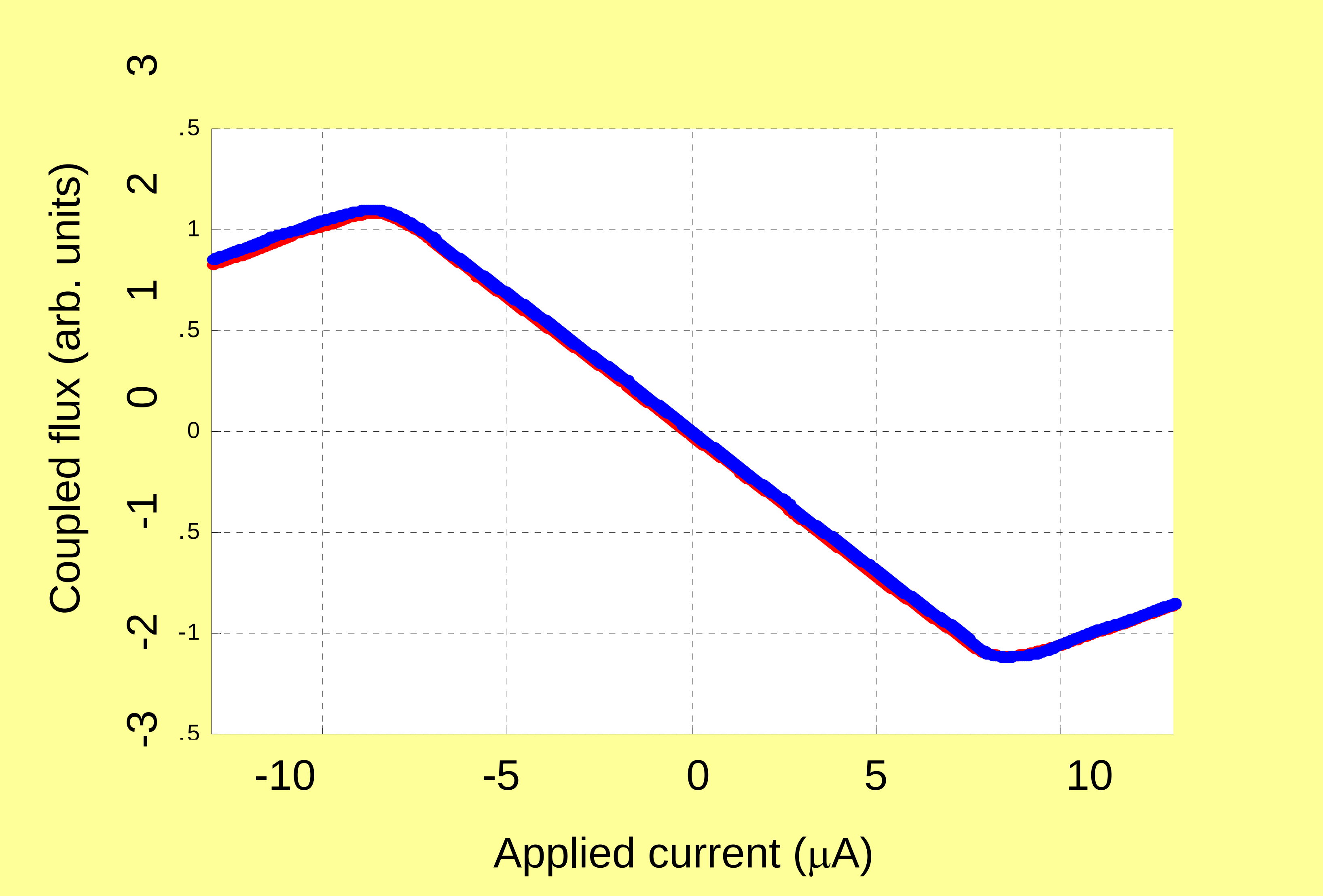


Ref. Beyer, Drung

Switch 0 Φ_0

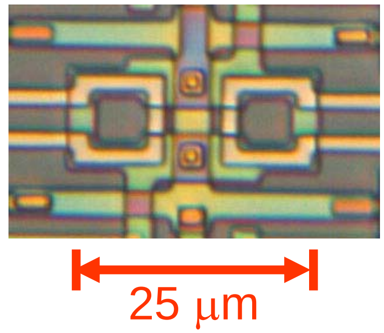


Switch 0.5 Φ_0

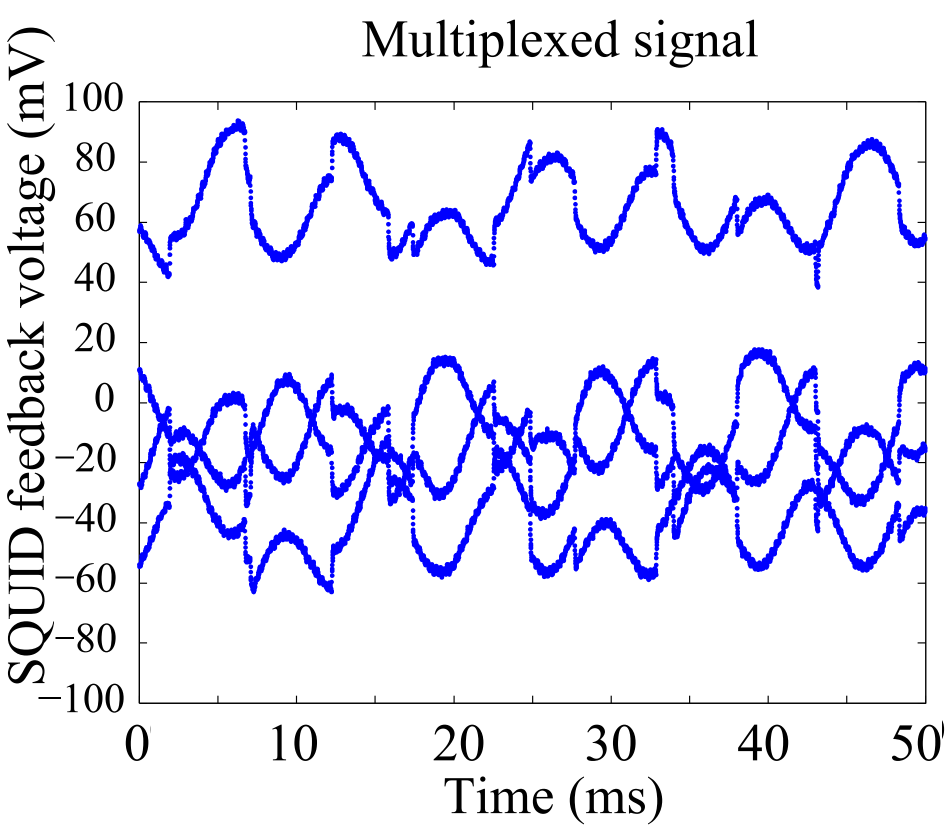


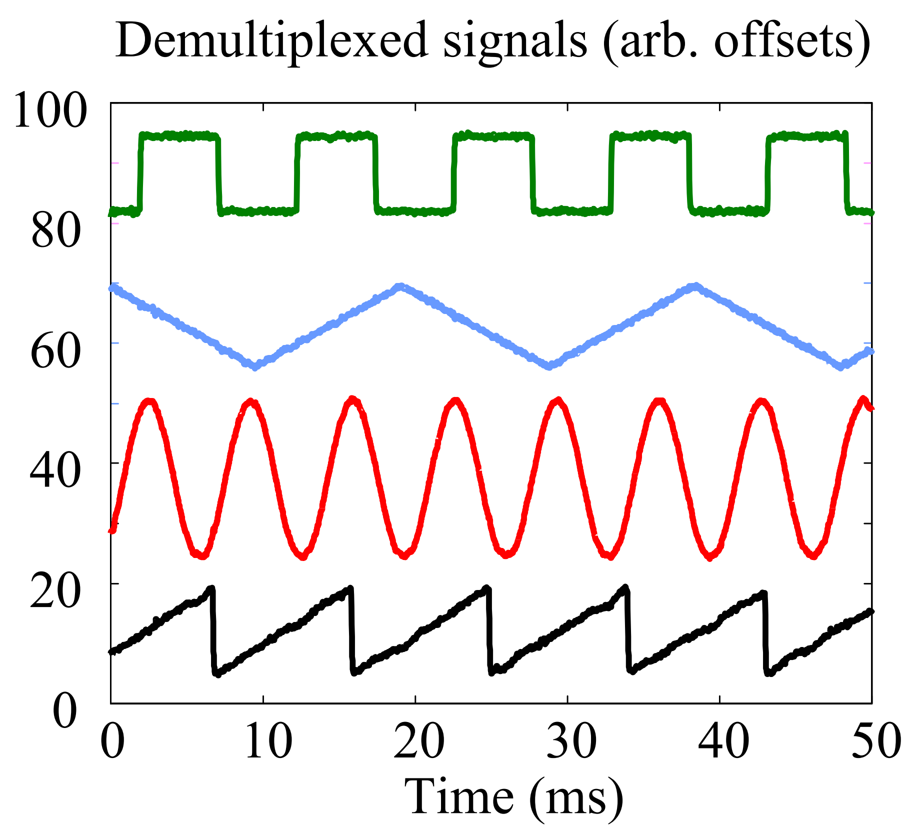
1x4 Code-division demonstration

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$



$$\frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$

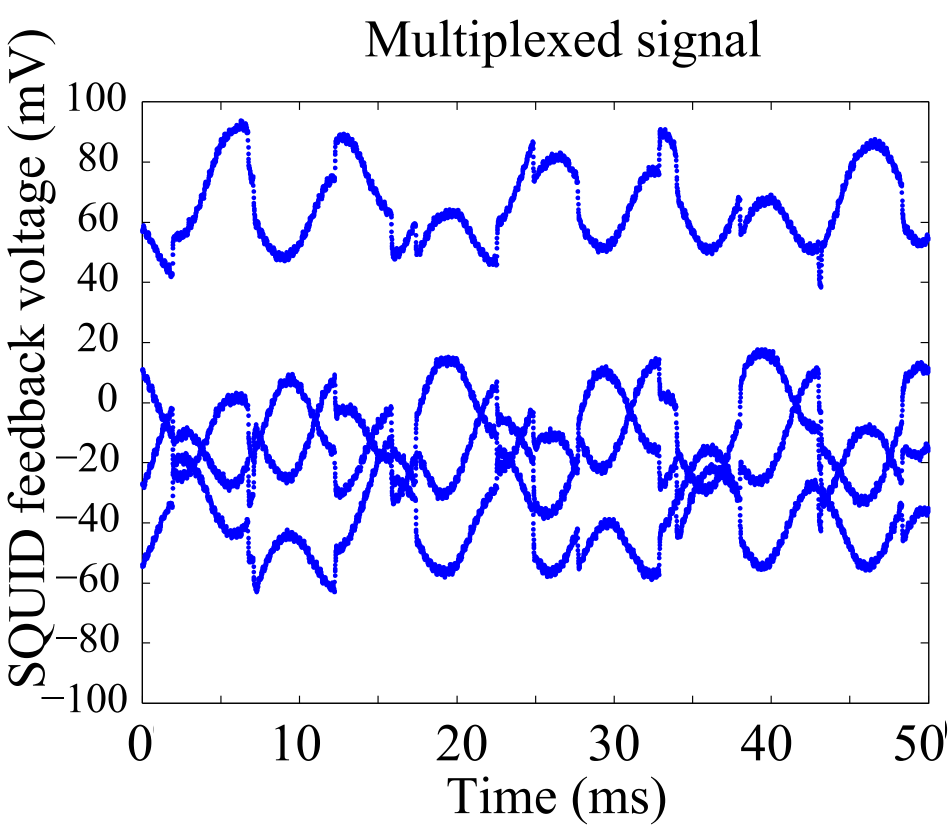


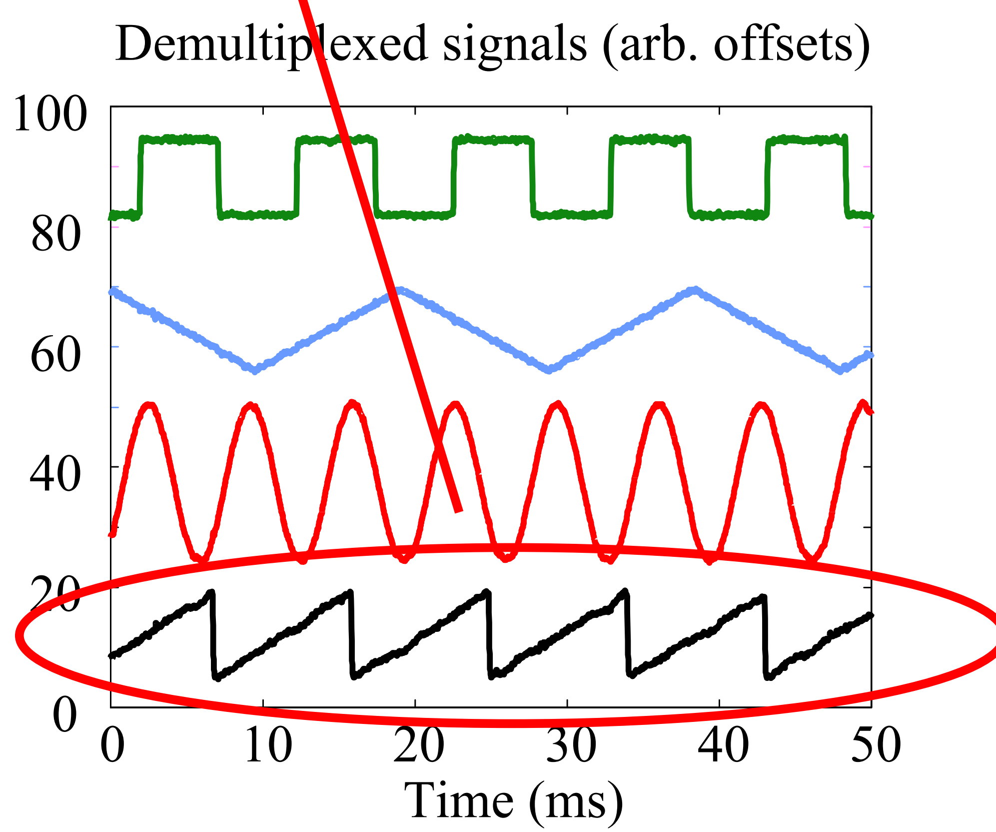


1x4 Code-division demonstration

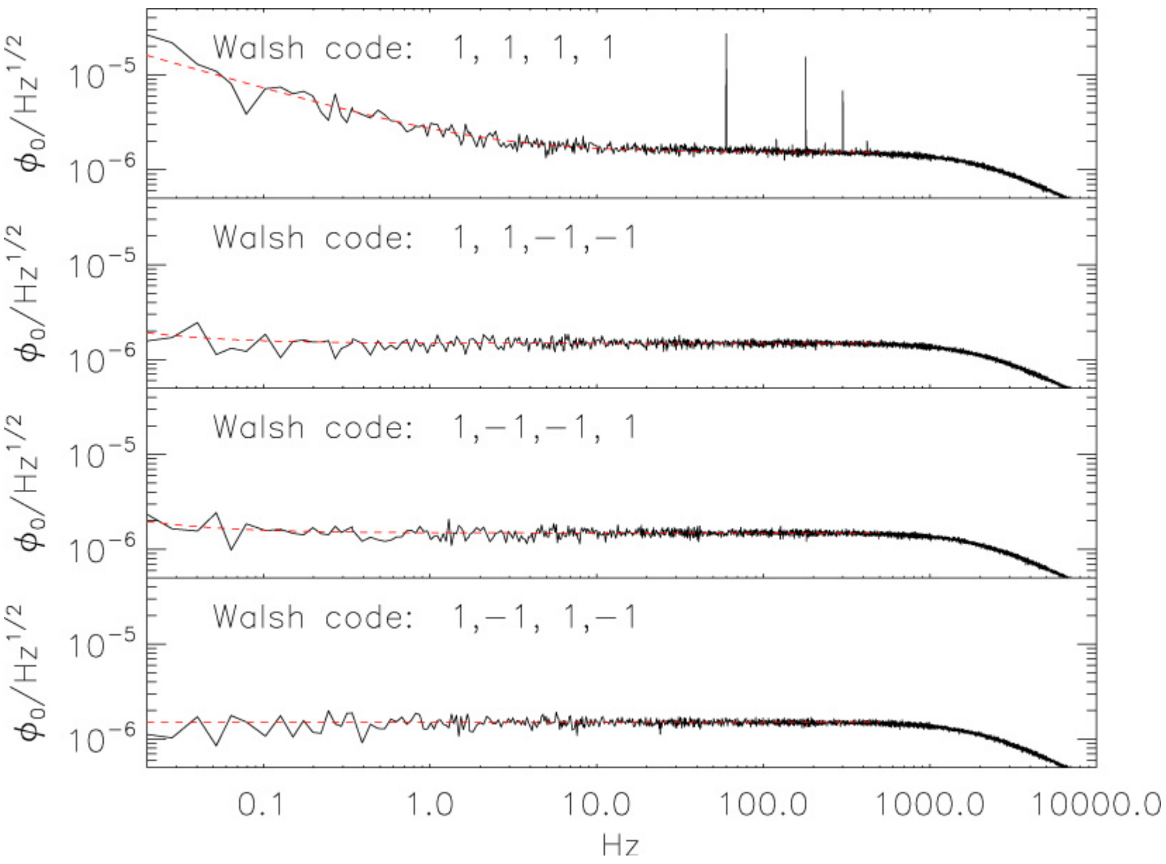
$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$

First basis set is more susceptible to 1/f and pickup since it is not differenced





CDM noise performance



Achieve the expected flux noise white level

The modulation eliminates low-frequency noise

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Shannon Efficiency

- How efficiently are we using our communication resources now?
- Is there room for improvement?

Information content of analog channel $C = B\log_2\left(1+(S/N)^2\right)$

Shannon efficiency: $SE = \frac{NC_{\text{det}}}{C_I}$, assume $C_{\text{det}} = 2.7\text{kHz for CMB pixel}$

	Bandwidth	N	SE
TDM (CMB)	~1 MHz	40	0.5%
FDM (CMB)	~1 MHz	8	0.1%
MKID camera tile	~400 MHz	144	.004%

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Lots of room for improvement

Towards a megapixel array

- We need the information capacity of HEMT + coax
- We need the Shannon efficiency of the SQUID-based approaches

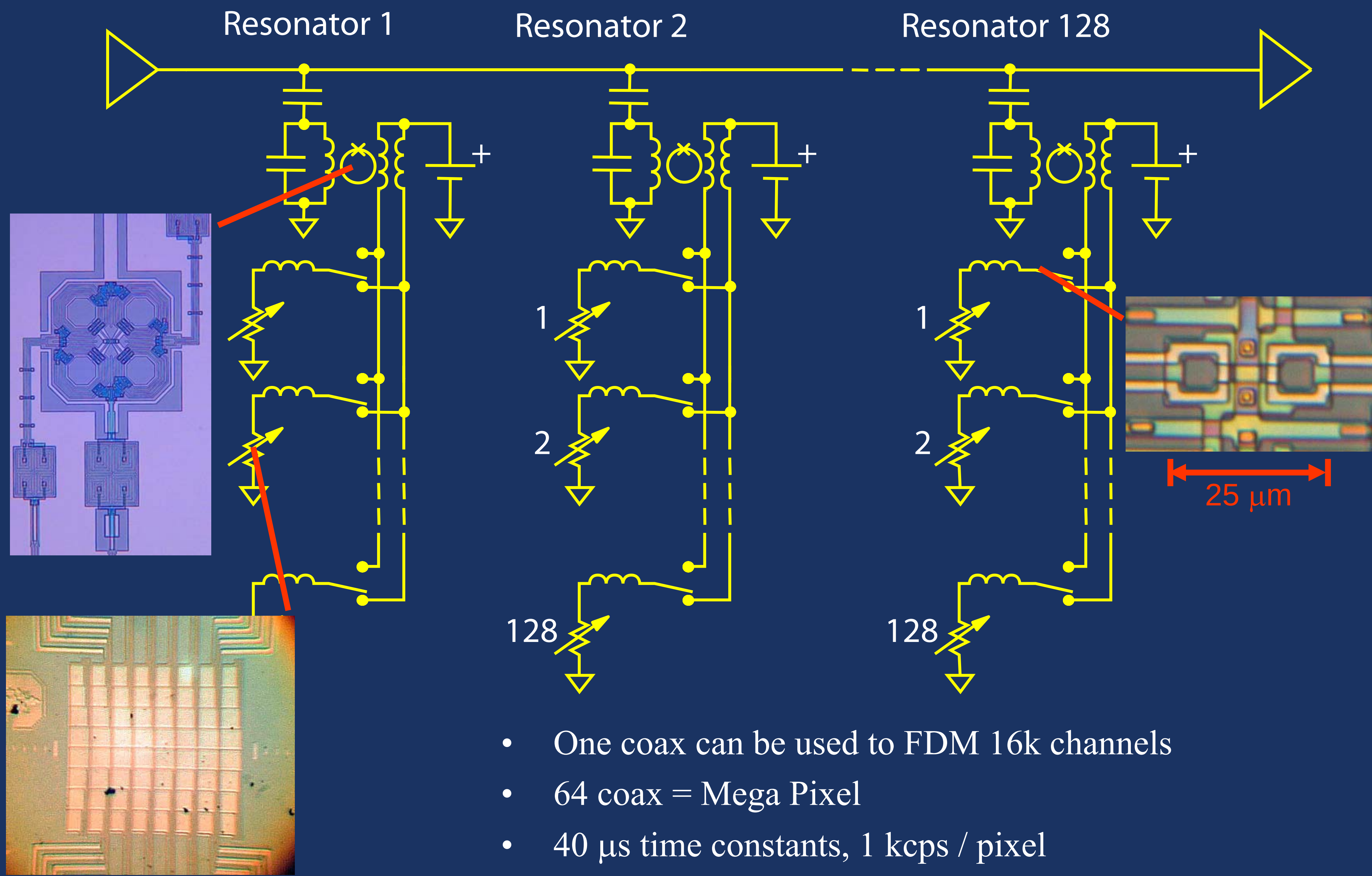
  Go to many more resonators (deal with ~1 MHz variation in resonator position, computational cost)

  Or, implement multiple sensors on a single resonator

	Bandwidth	N	SE
TDM (CMB)	~1 MHz	40	0.5%
FDM (CMB)	~1 MHz	8	0.1%
MKID camera tile	~400 MHz	144	.004%

NIST

Lots of room for improvement



- One coax can be used to FDM 16k channels
- 64 coax = Mega Pixel
- 40 µs time constants, 1 kcps / pixel
- Lenslet array – high fill factor, 70 um pixels

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Putting it all together

1. All components required for the megapixel imager already work with sufficient performance. Power dissipation of the MUX components is sub-fW per pixel. All elements fabricated in one planar circuit on one chip.

2. The CDM switches and resonator readout components use the same layers and fabrication steps. 8 lithography levels required for the full chip, including the TES.

3. Readout consortium electronics has sufficient performance for FDM demultiplexing of the resonators. Cost per channel is already acceptable since 128 pixels are on each resonator.

4. Walsh code demultiplexing is a matrix multiply step that can be done in firmware or software (multiple computers required).

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