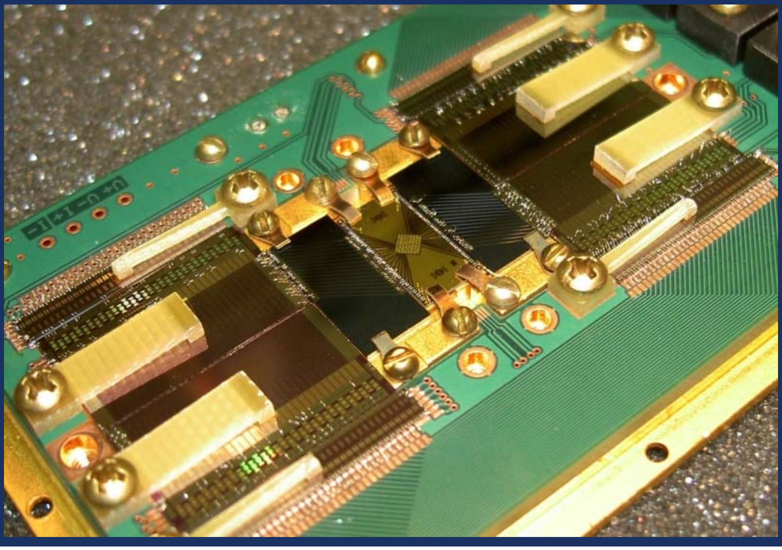
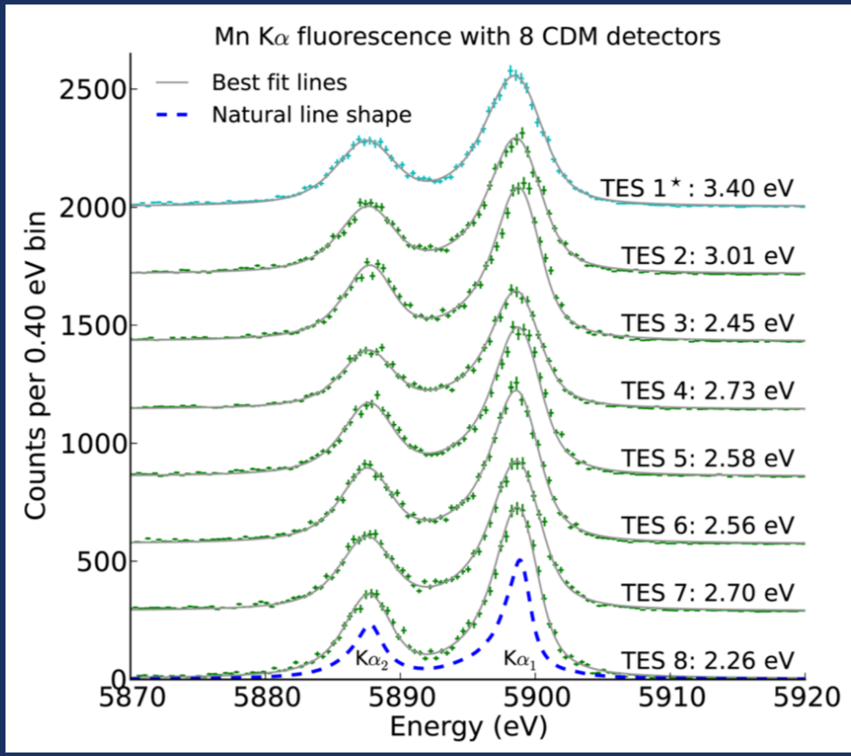
Kent Irwin, NIST

Readout of Large Format Microcalorimeters



Some examples of microcalorimeters

- Transition-edge sensors (TES)
- Magnetically coupled calorimeters (MCC)
- Microwave kinetic inductance detectors (MKID) when run in a thermal mode



Outline: a roadmap for readout

Moore's Law curves for pixel count

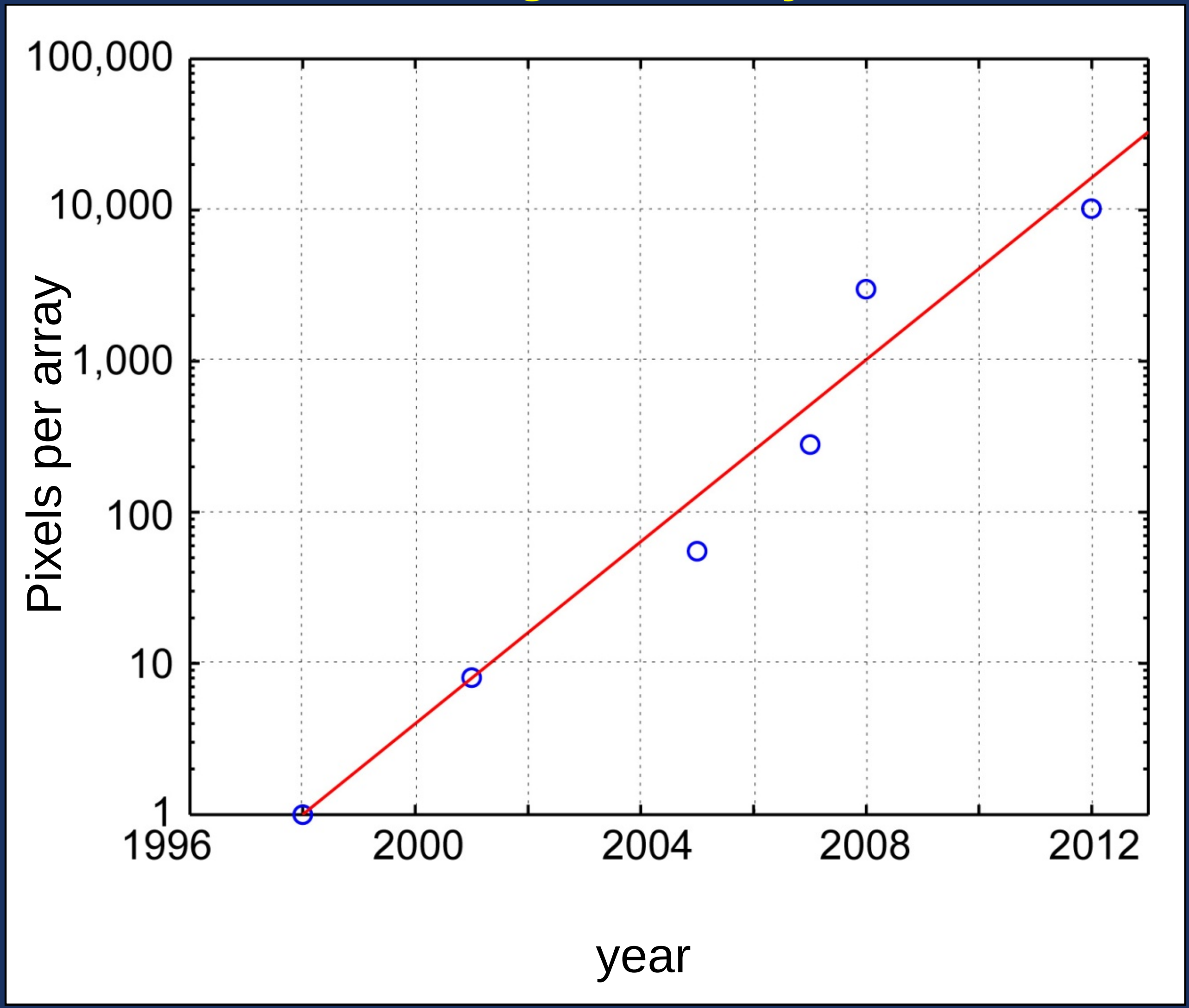
Shannon limits: we are nowhere near them

Multiplexing: FDM, TDM, CDM

Bandwidth: MHz or GHz

Moore's law for TES bolometers

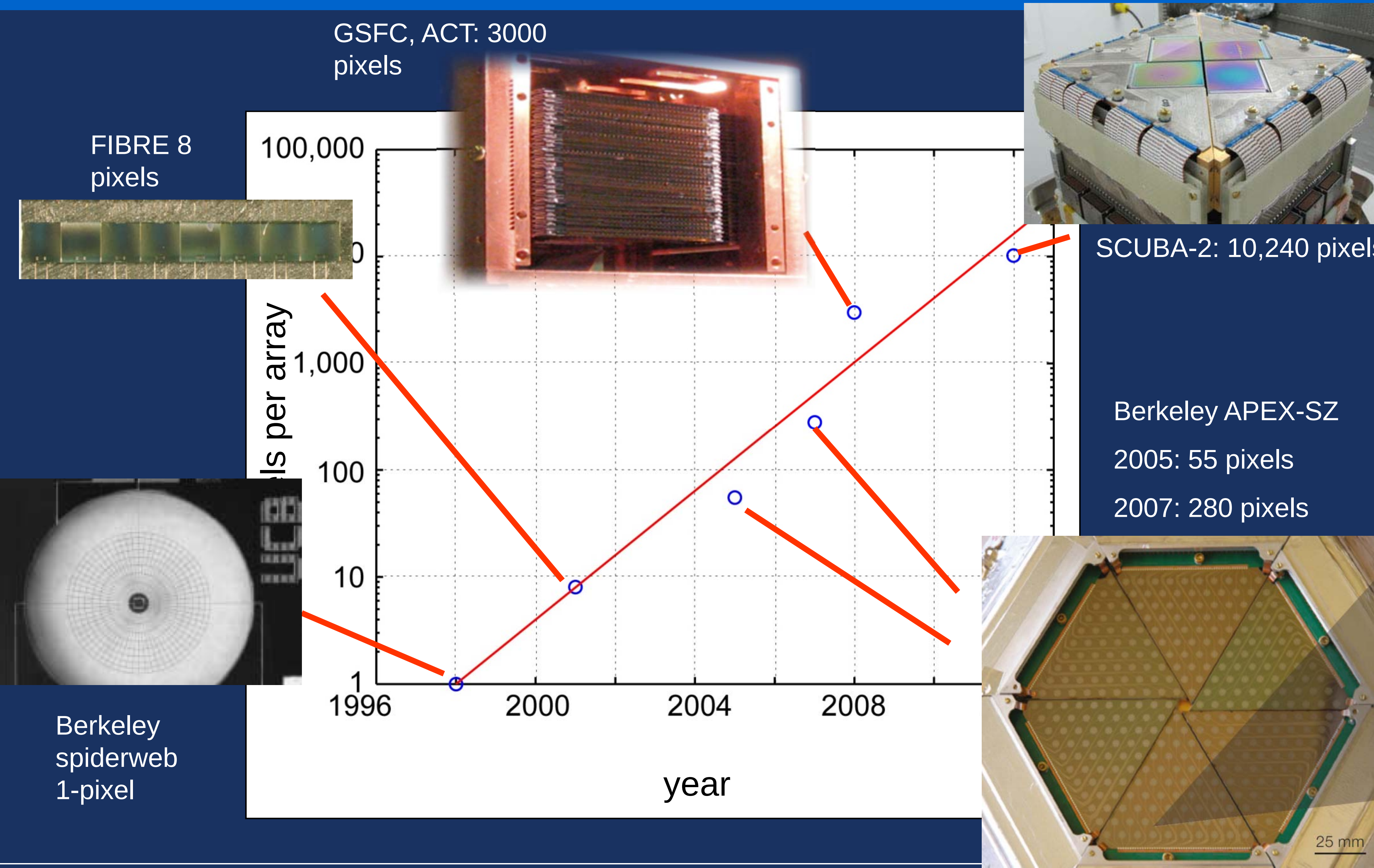
Doubling time: 1 year



Easy: low dynamic range

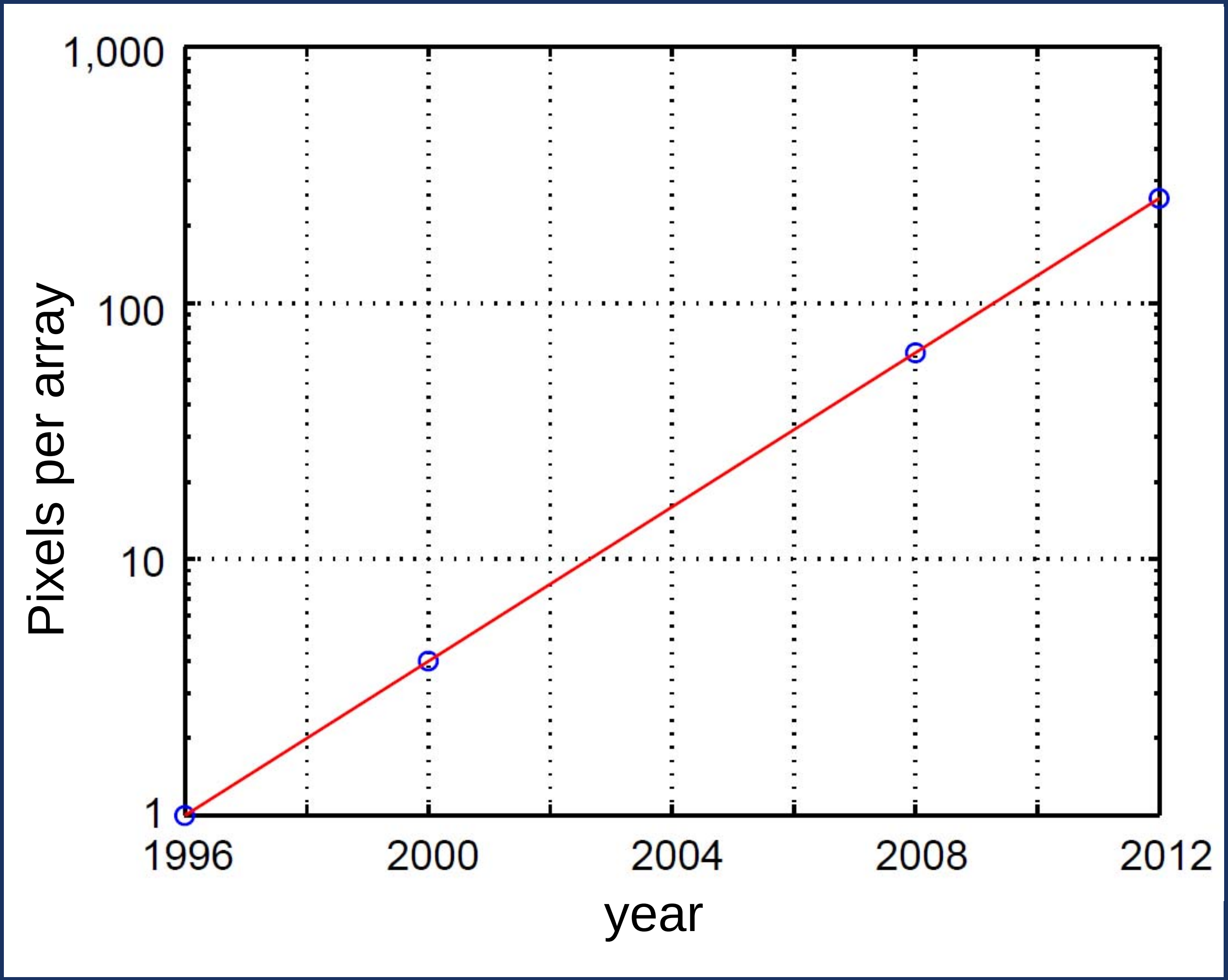
Megapixel by 2020

Moore's law for TES bolometers



Moore's law for instrumented *x-ray* TES calorimeters

Doubling time: 2 years



Much harder because of dynamic range of x-ray events

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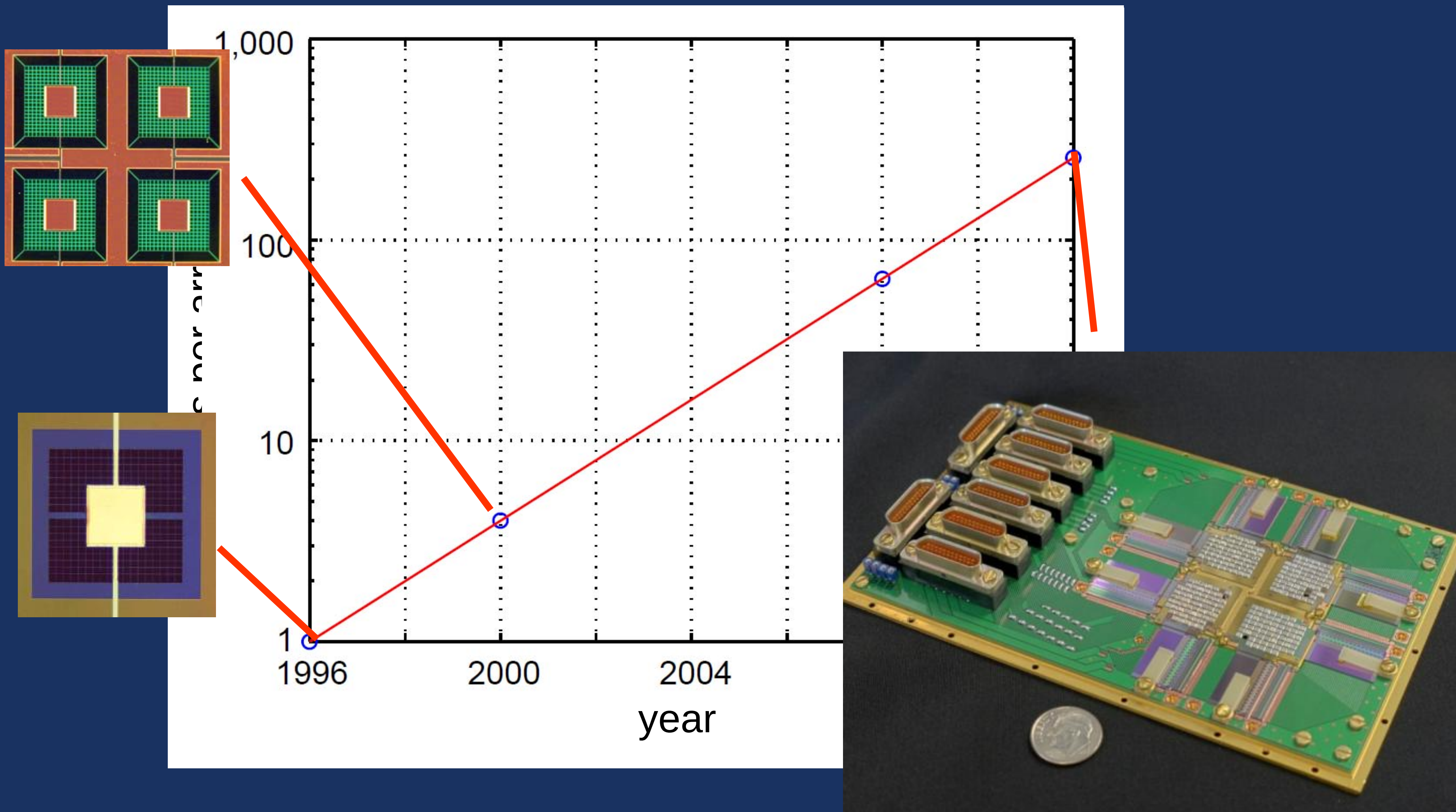
Moore's law for instrumented *x-ray* TES calorimeters



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Moore's law: the next ×1000

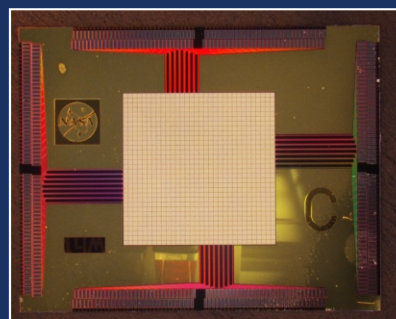
Doubling time: 2 years

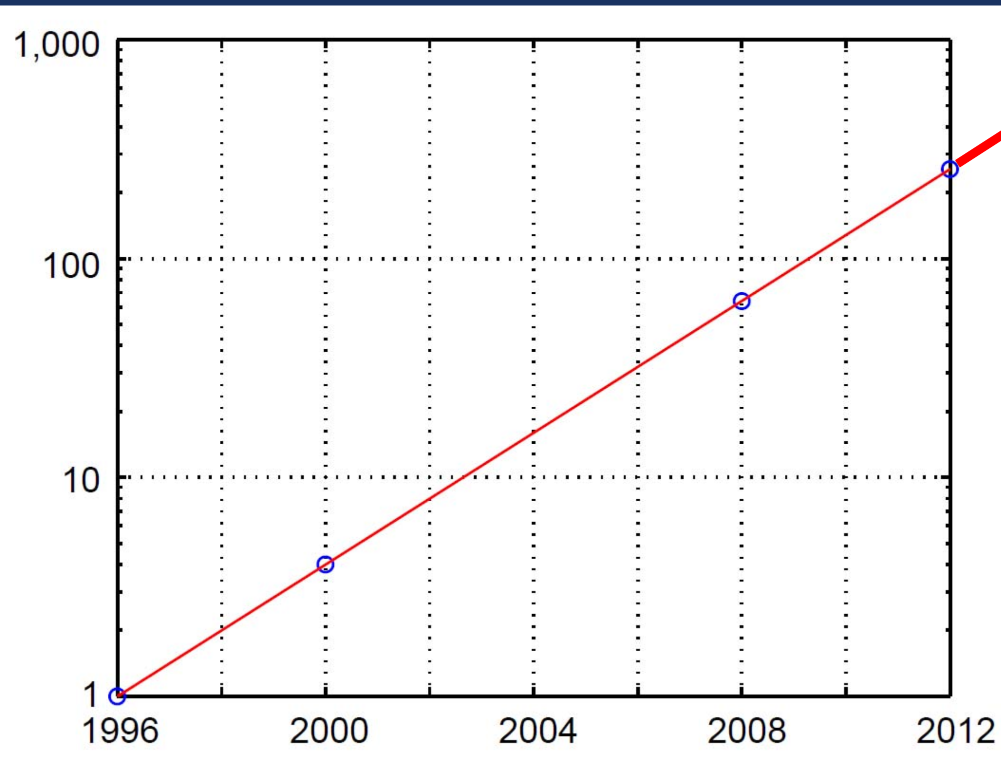
4. TES or MCC with GHz FDM + CDM

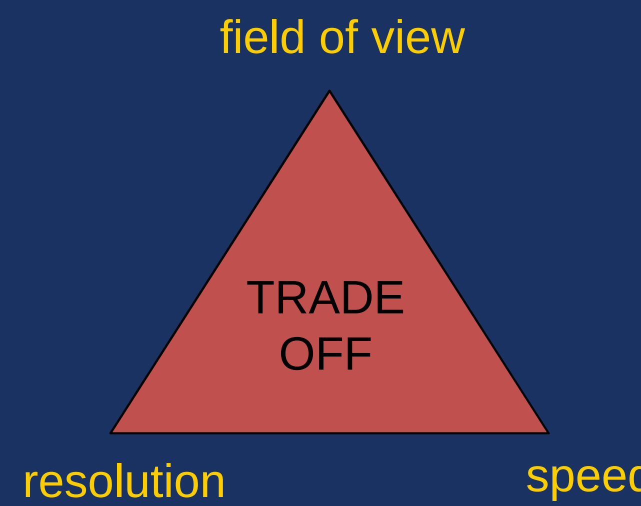
3. TES or MCC or MKID with GHz FDM

2. TES with CDM

1. TES with TDM







What is the limit? How many can we mux?

- 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

Megapixel arrays are possible

SQUID

$$\Delta\Phi = \Phi_0$$

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

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

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

HEMT + coax

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

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

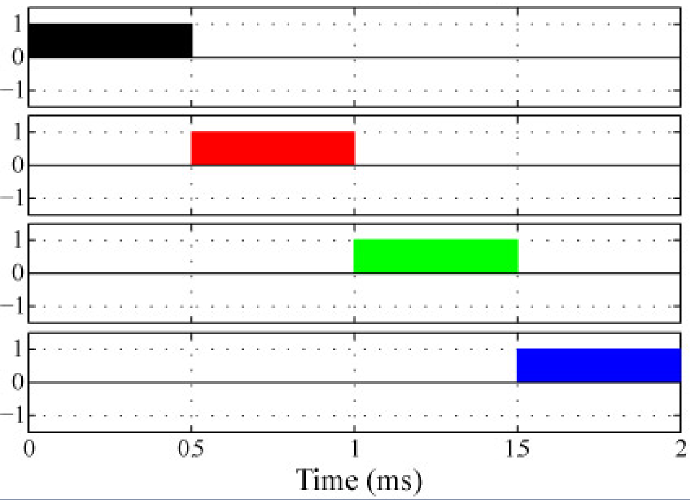
$$B = 10\ \mathrm{GHz}$$

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

With perfect “Shannon efficiency” we could read out hundreds of detectors per MHz SQUID, or millions per HEMT

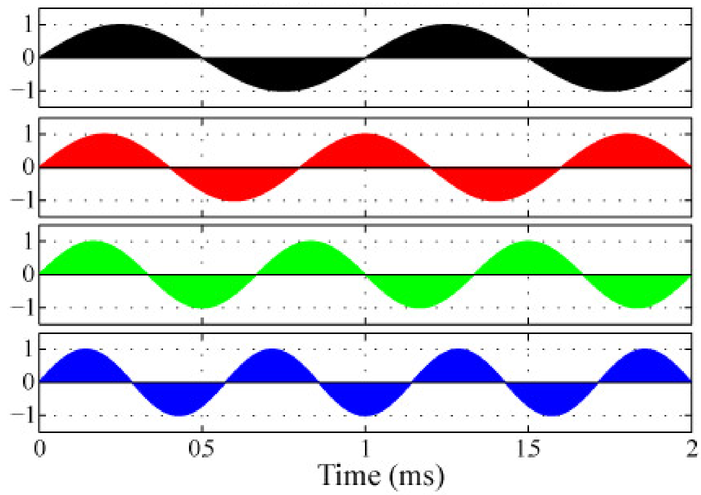
How to mux: three modulation functions

Time-division MUX



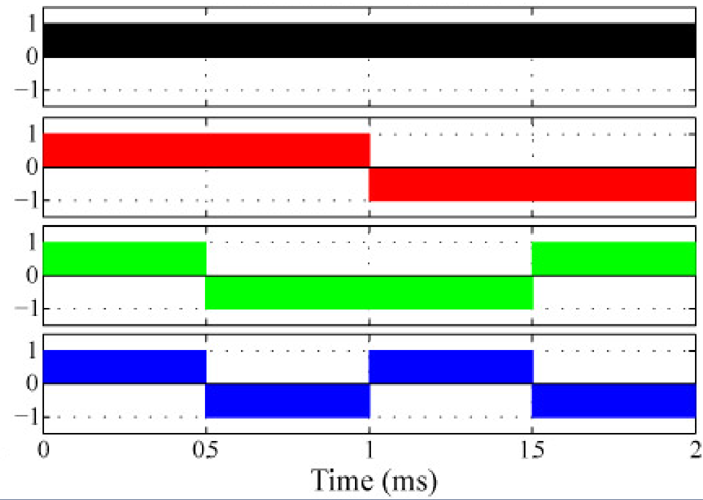
- Define time band by coupling output ‘channel’ to different detectors sequentially.

Frequency-division MUX



- Define frequency band with different passive LC circuits

Code-division MUX



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

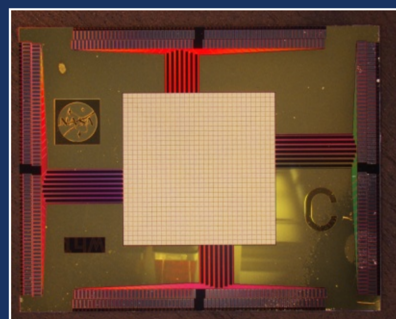
Moore's law: the next ×1000

Doubling time: 2 years

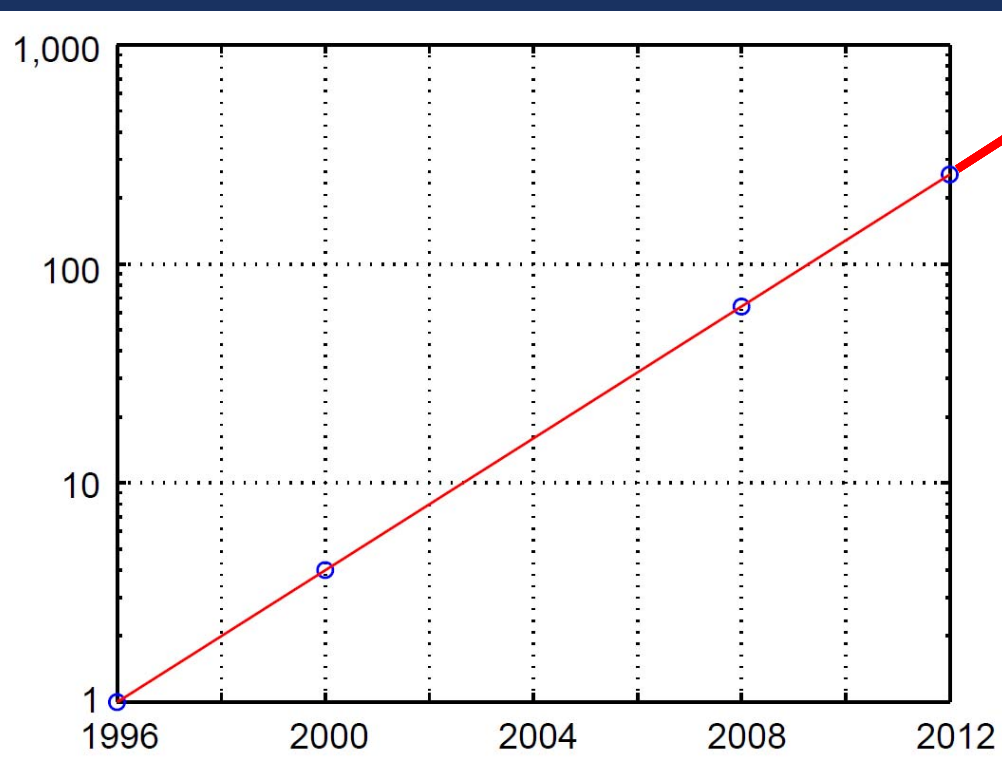
4. TES or MCC with GHz FDM + CDM

3. TES or MCC or MKID with GHz FDM

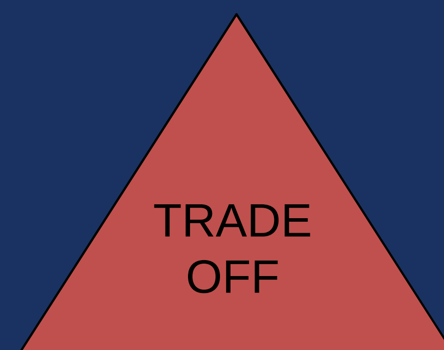
2. TES with CDM



1. TES with TDM



field of view



resolution

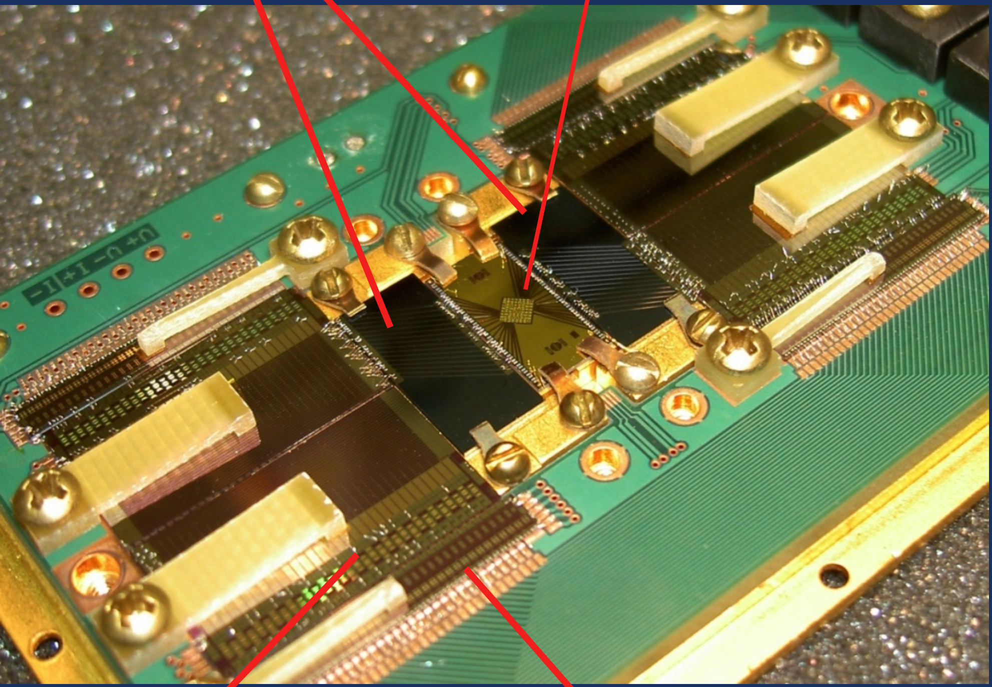
speed

TDM of XMS baseline

GSFC 8 x 8 array
NIST SQUID MUX readout

Interface chips

Calorimeter array

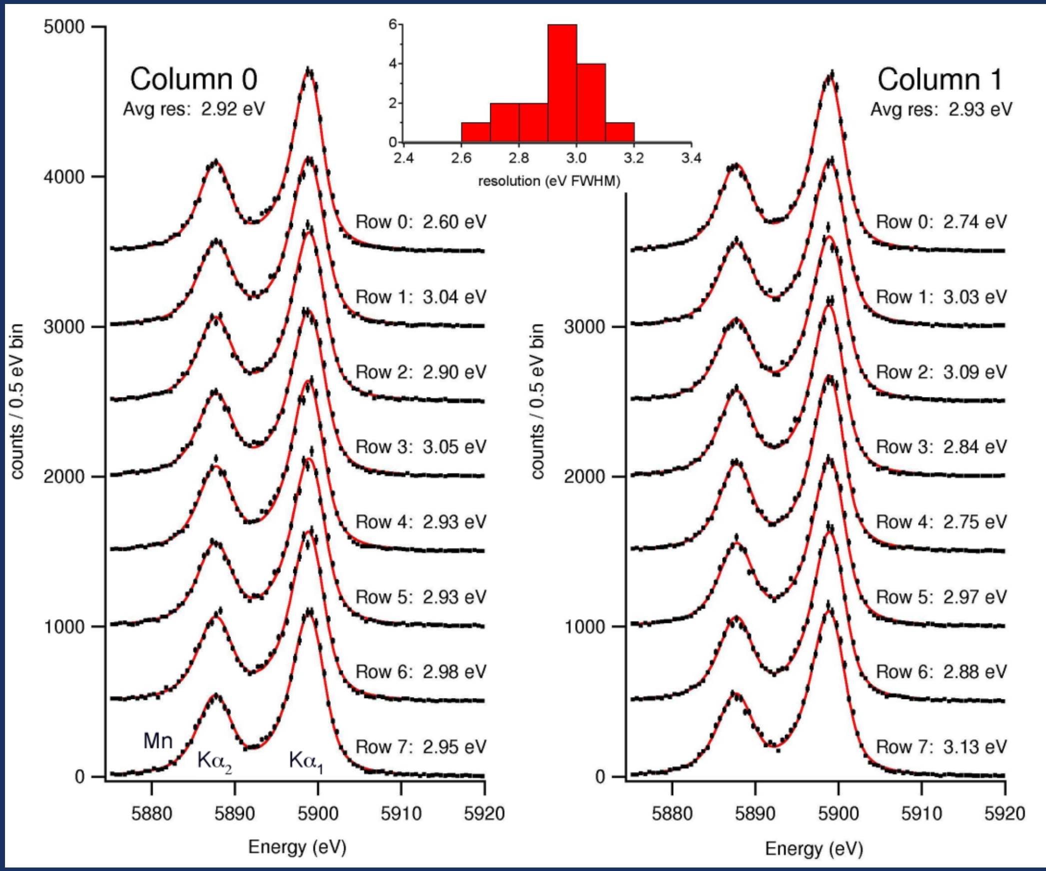


Anti-alias filters +
TES bias resistors

SQUID
multiplexers

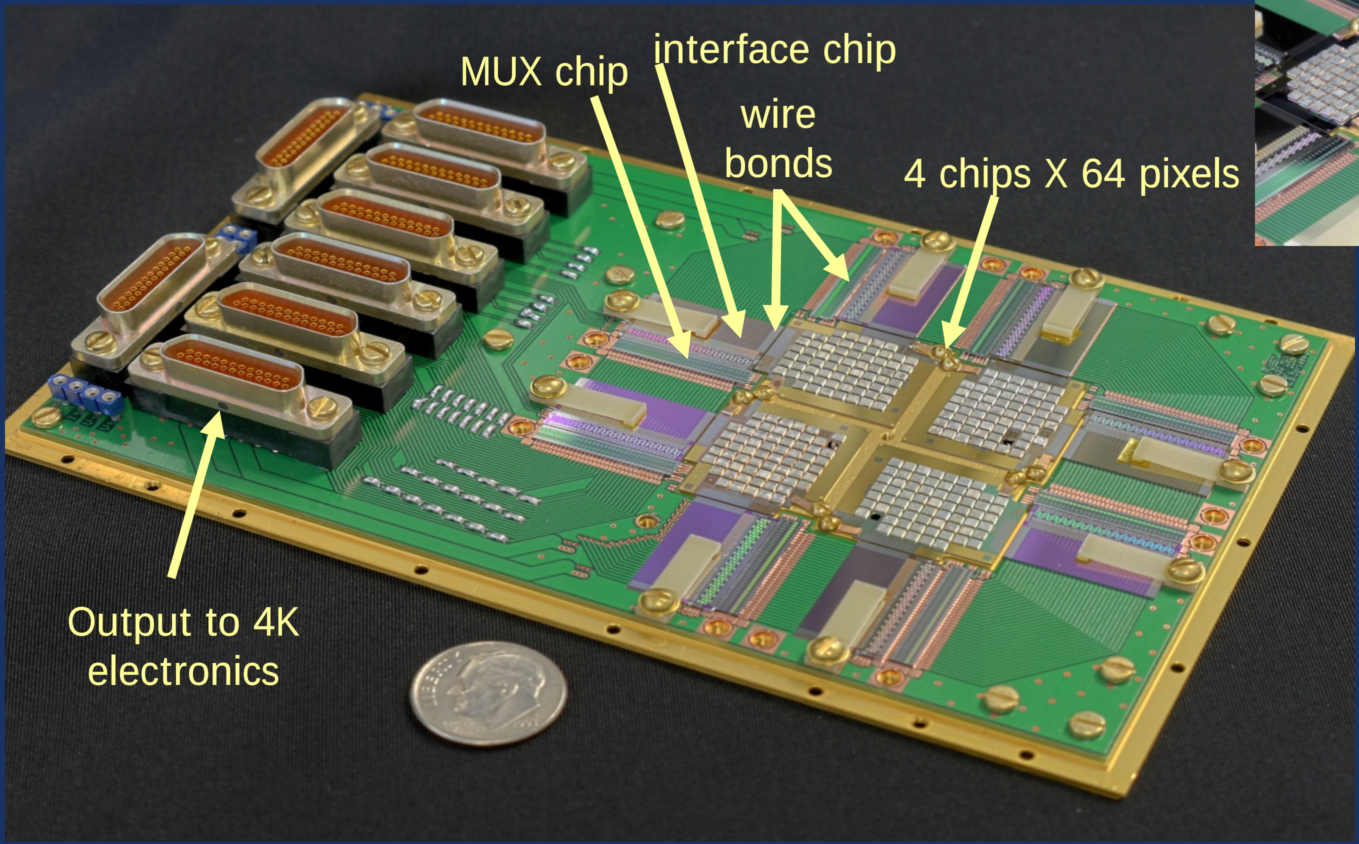
2 x 8 mux readout of 8x8 array

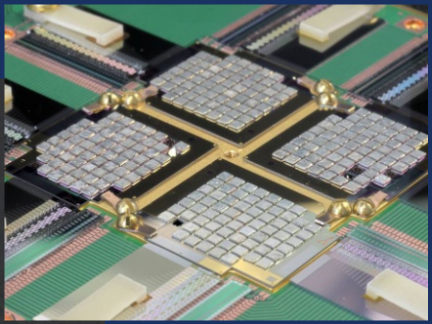
ΔE_{FWHM}= 2.9 eV



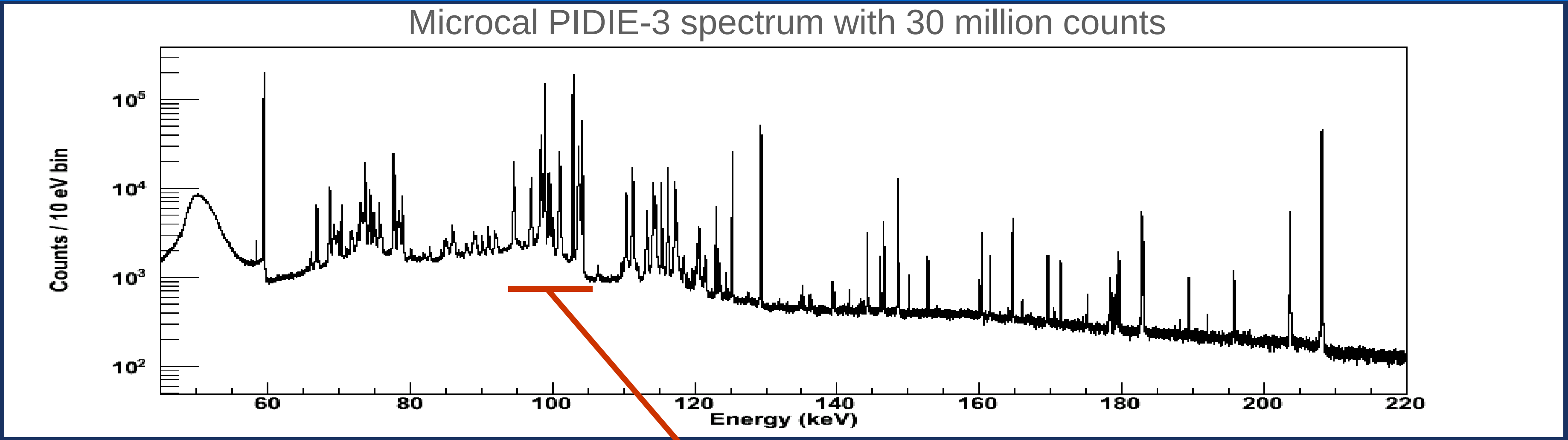
Largest instrumented microcalorimeter: 256 pixel hard x-ray array

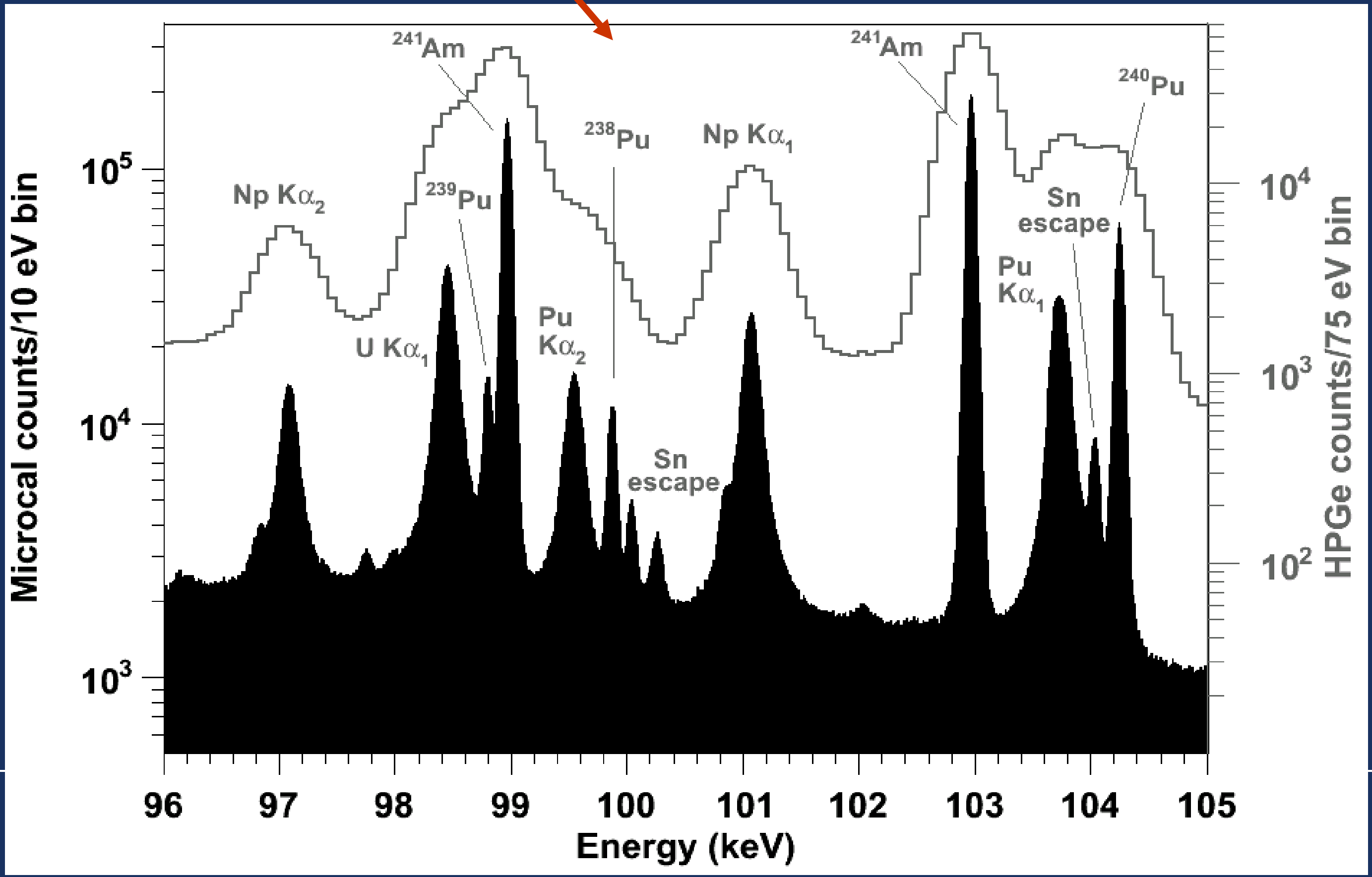
- 8x32 readout architecture
- total collection area = 576 mm^2 (planar HPGE ~200-1000 mm^2)



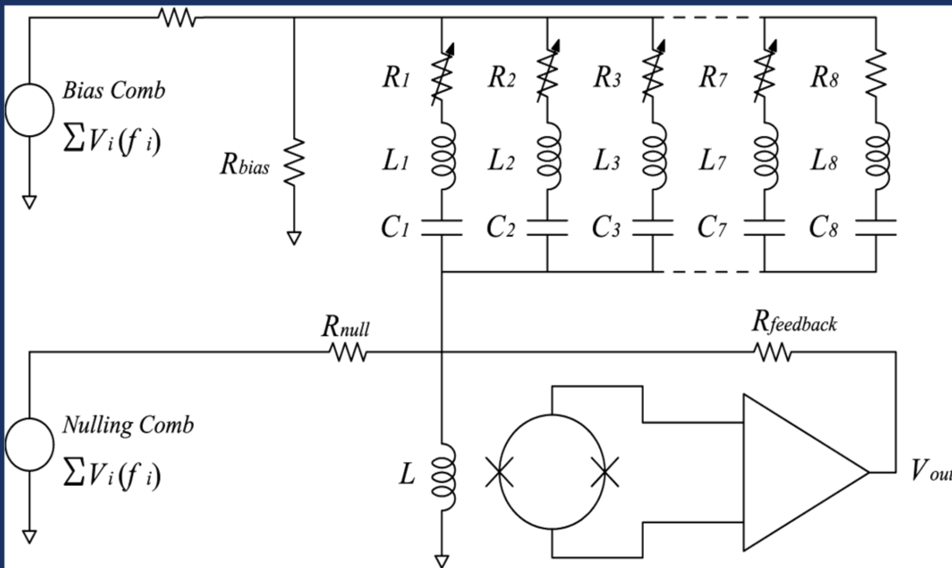


Hard x-ray array: mixed nuclear isotope spectrum





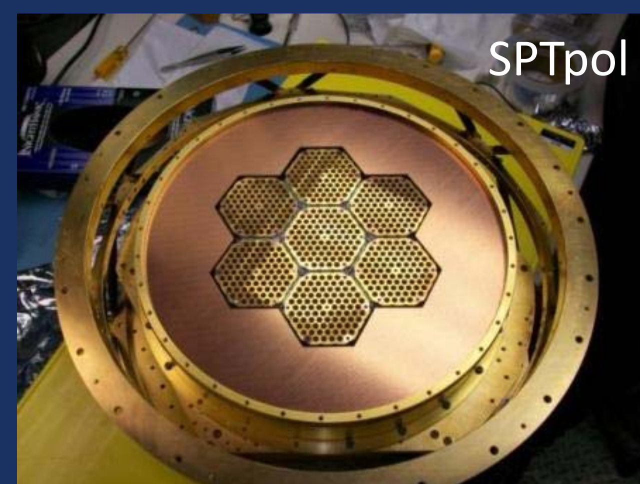
FDM with bias modulation: *bolometers, not (yet) calorimeters*



SRON, ESA, Japan:
SAFARI instrument for SPICA

But, AC-modulating TES calorimeters is observed to degrade energy resolution significantly

Fielded experiments using FDM: Berkeley, LBNL, McGill electronics, NIST SQUIDs & inductors



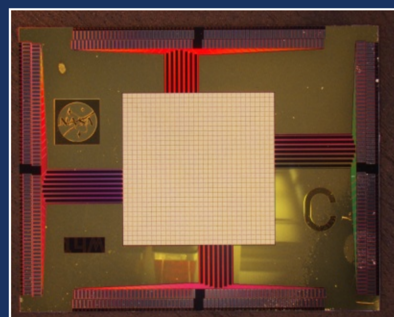
Moore's law: the next ×1000

Doubling time: 2 years

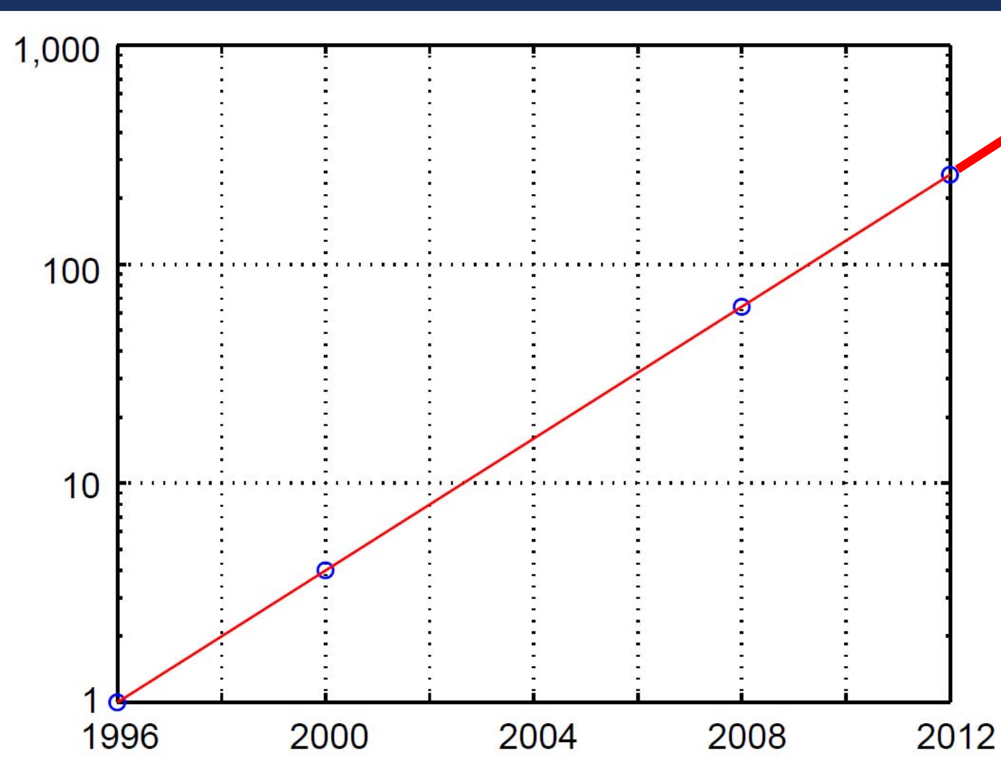
4. TES or MCC with GHz FDM + CDM

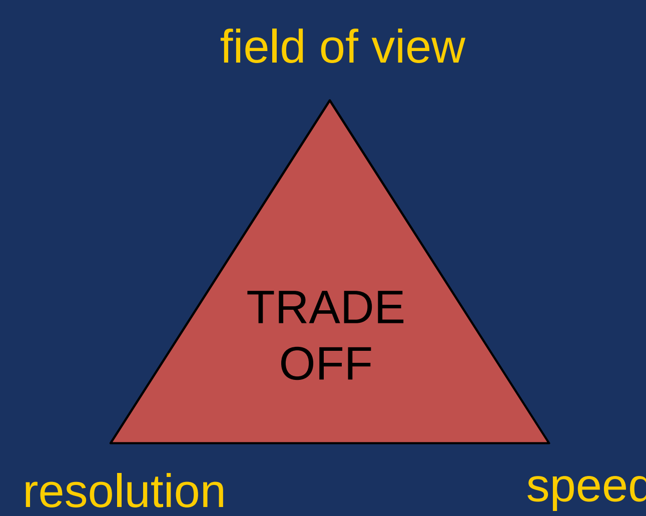
3. TES or MCC or MKID with GHz FDM

2. TES with CDM

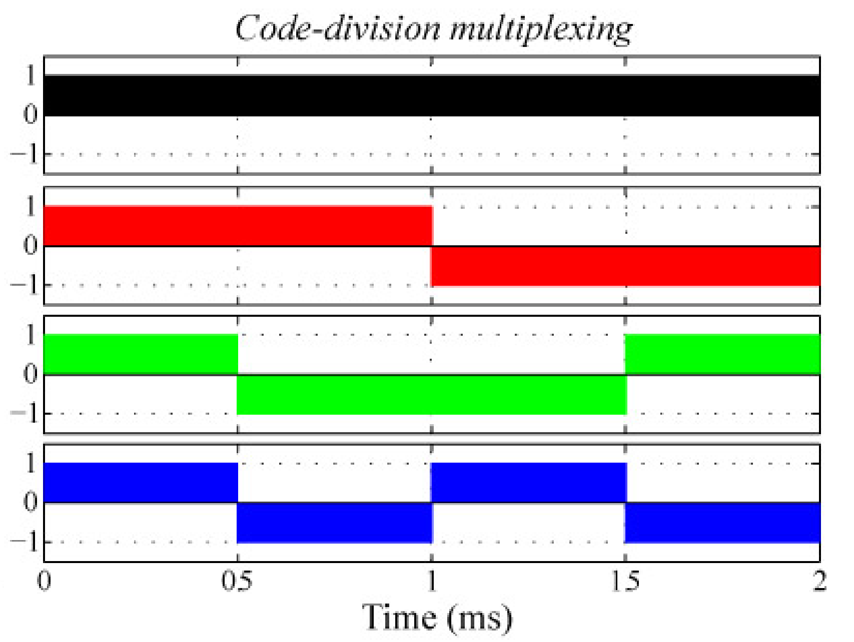


1. TES with TDM





CDM: better dynamic range, energy resolution than TDM



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

- Every detector pixel is on all of the time
- Polarity of coupling to the output switches between +1 and -1 in orthogonal pattern (Walsh matrix)
- Original signals recovered by multiplying by inverse Walsh matrix.
- Does not have “multiplex disadvantage” that exists for TDM multiplexing

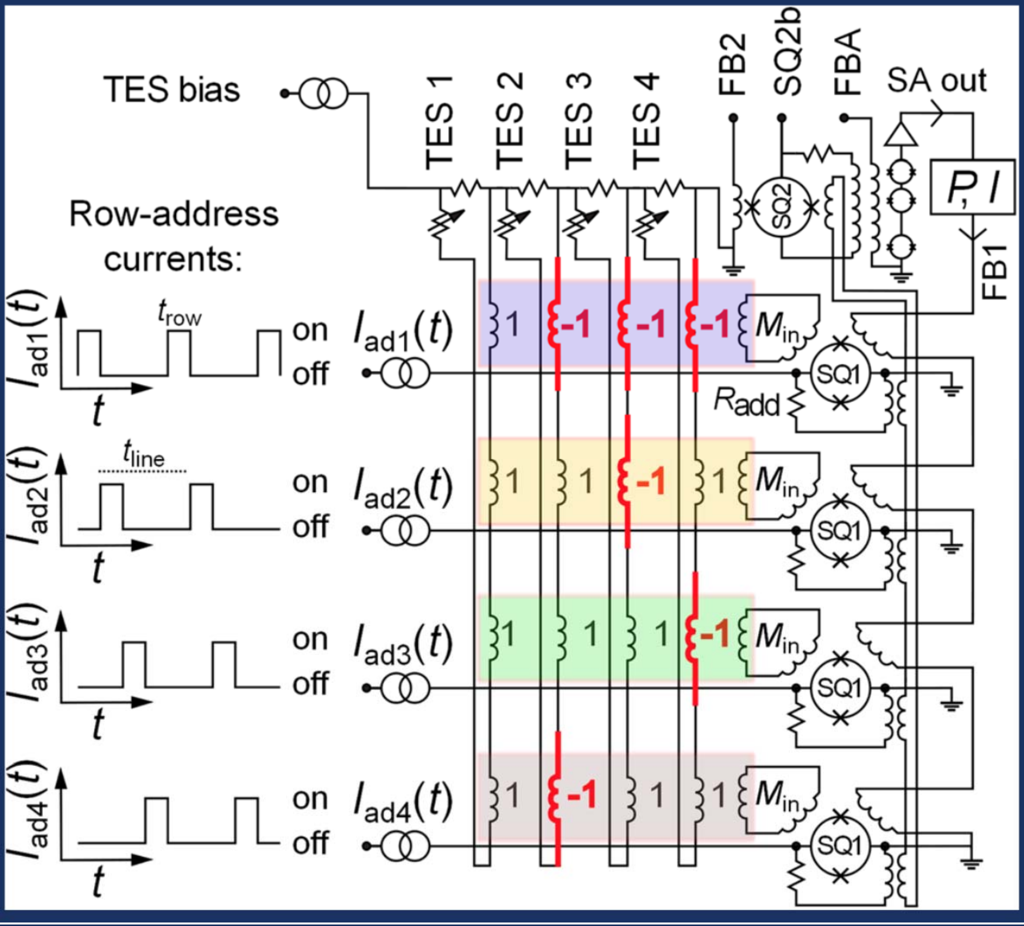
Additional benefit: SQUID 1/f noise and common-mode rf pickup is removed in all but the first (non-switching) row

CDM: excellent performance demonstrated

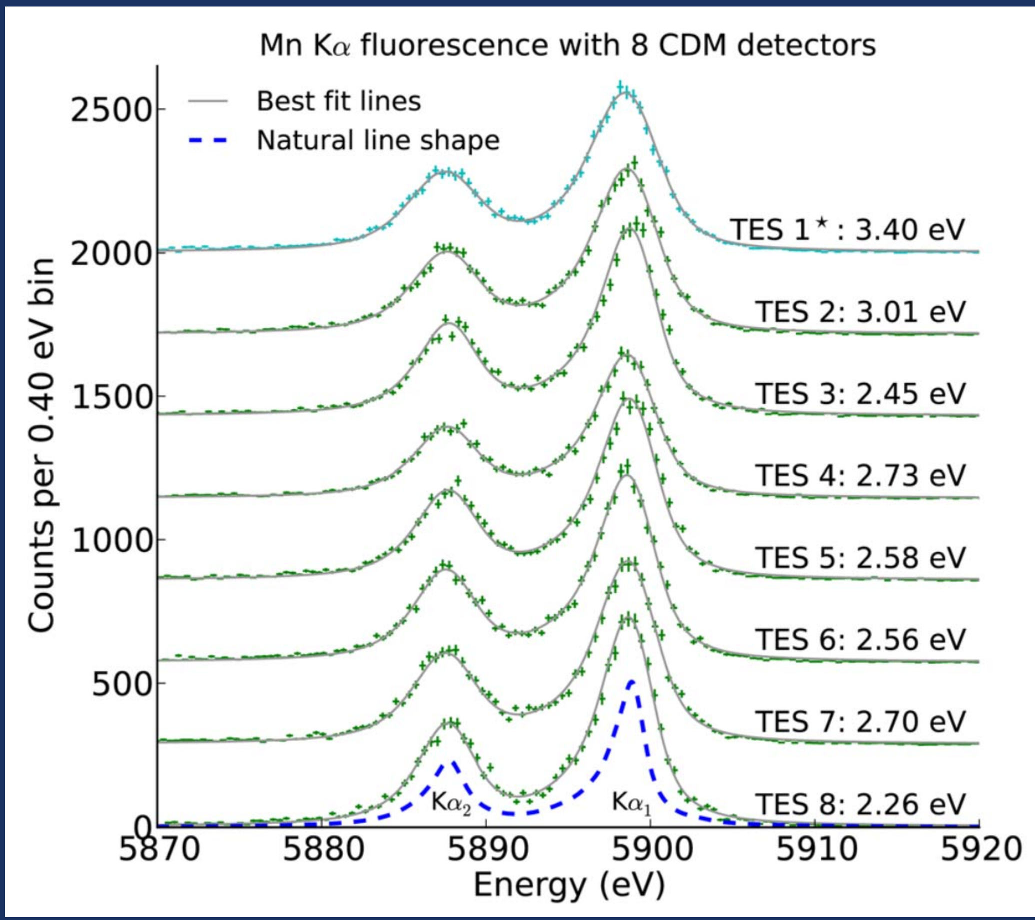
CDM chips are drop-in compatible with existing 32-row TDM systems, with the same wiring and readout electronics, but have higher performance.

ΔE_{FWHM}= 2.58 eV FWHM at 5.9 keV (unswitched pixel excluded)

Circuit (flux coupled CDM):



Promising first results from 1x8 CDM demonstration:



NIST

Moore's law: the next ×1000

Doubling time: 2 years

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3. TES or MCC or MKID with GHz FDM

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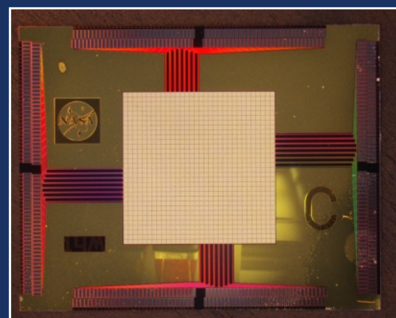
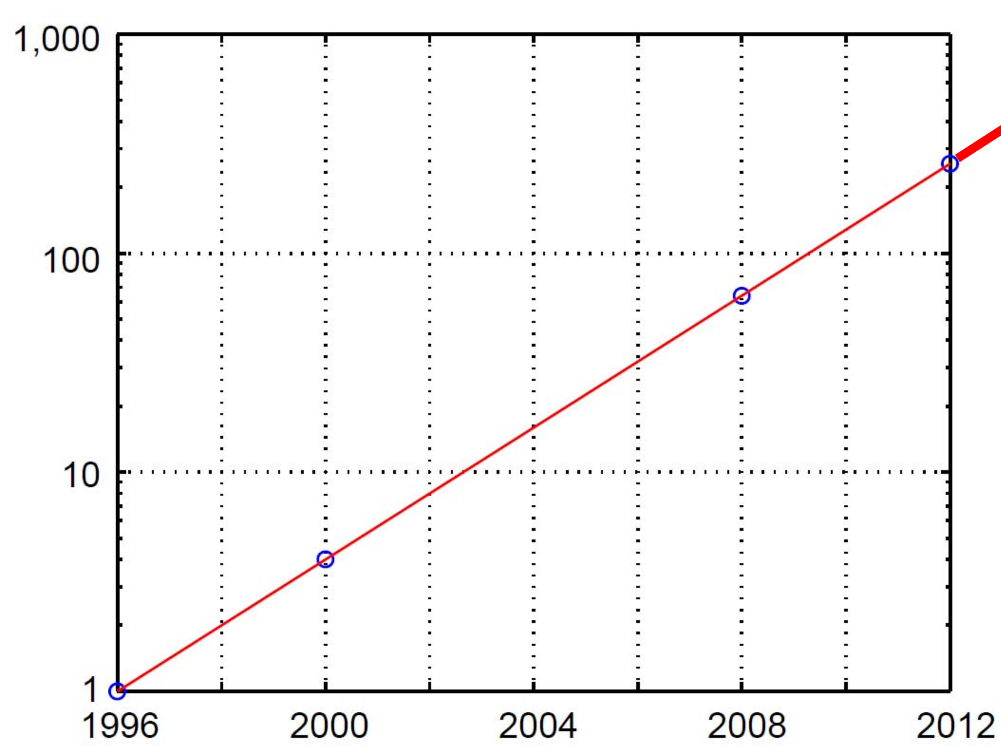
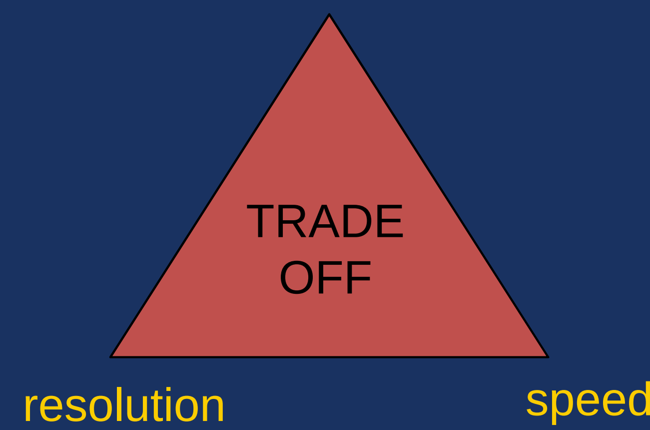
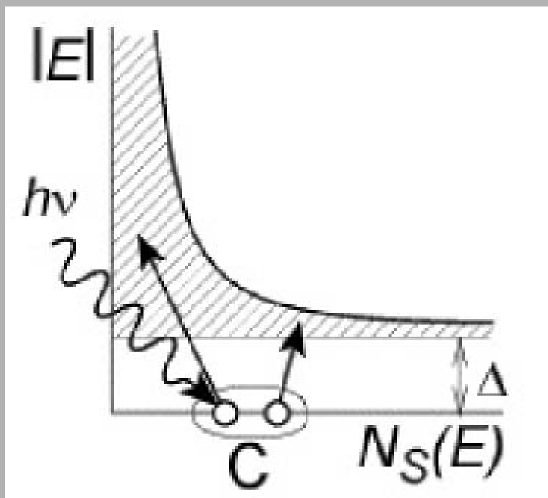


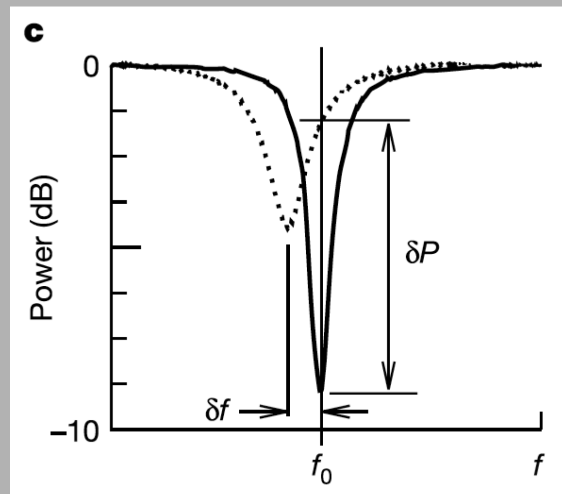




GHz FDM multiplexing convergence

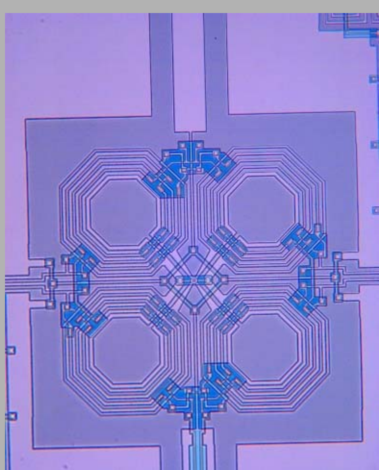
Microwave kinetic inductance detectors (MKIDs): detector is resonator

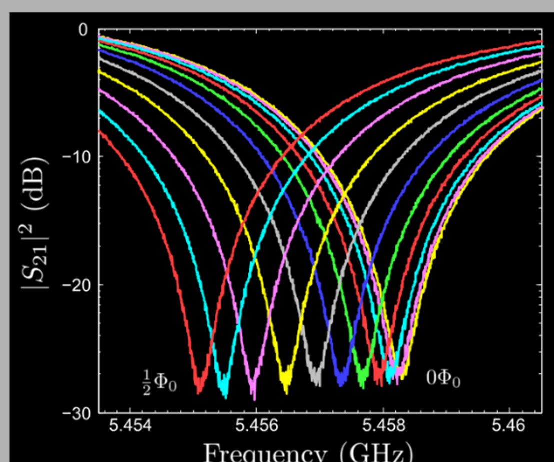




- Single pixel x-ray performance needs to be demonstrated
- P. Day, Nature (2003)

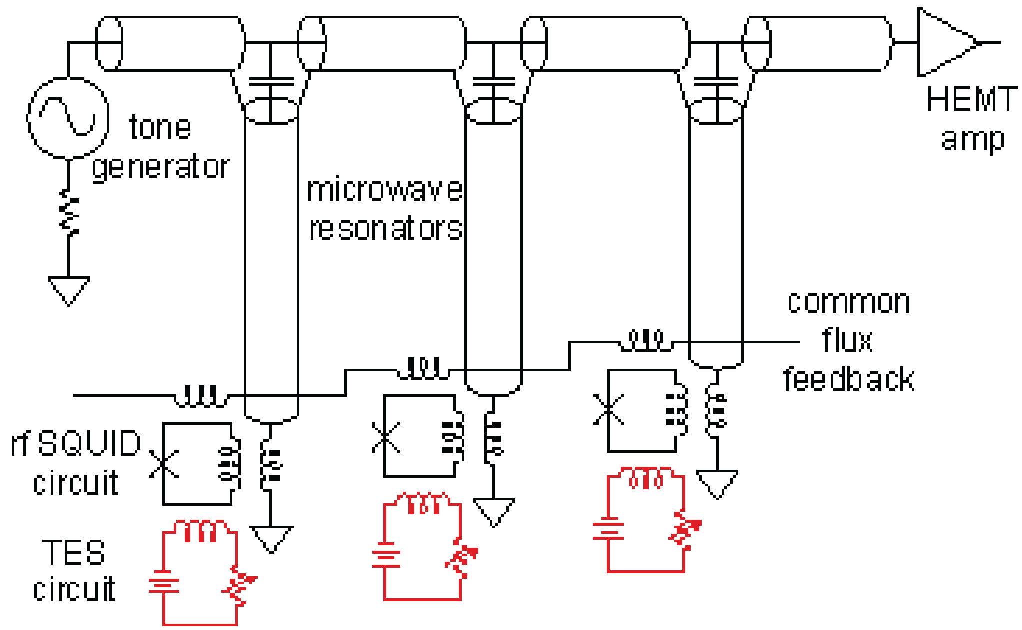
TES detectors or MMCs coupled to microwave resonators





- Dissipationless SQUID in each resonator
- B. Mates, Appl. Phys. Lett. (2008)

GHz resonators for TES / MCC microcalorimeters



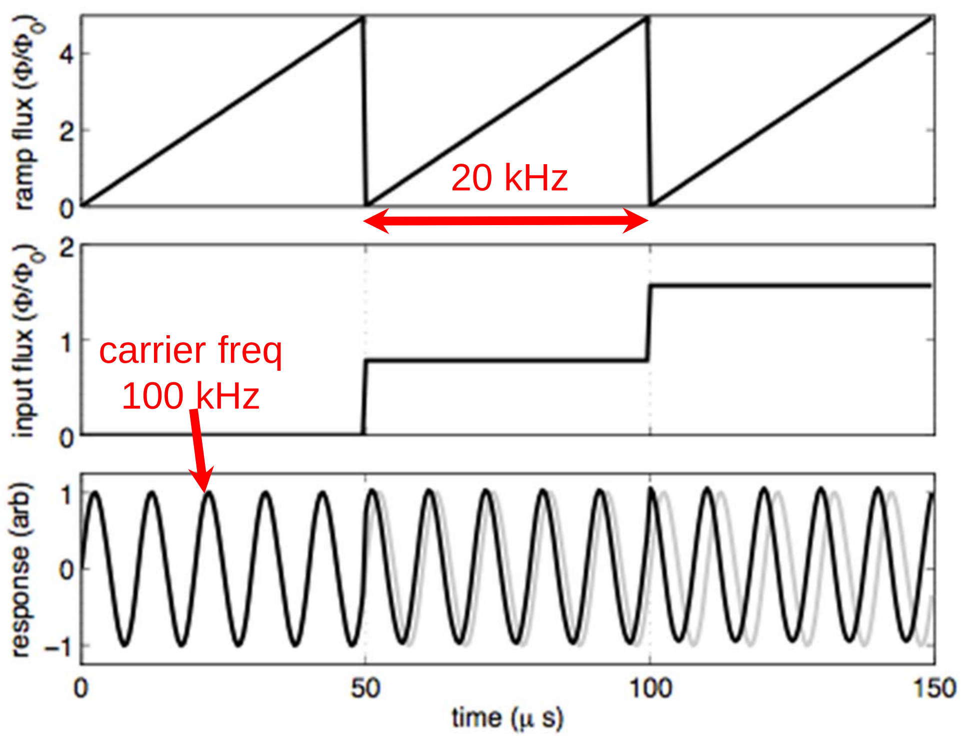
Array has:
2 coaxes (1 input + 1 output, like MKIDs)

2 low-frequency lines (1 dc bias, 1 flux ramp)

FLUX RAMP

SIGNAL

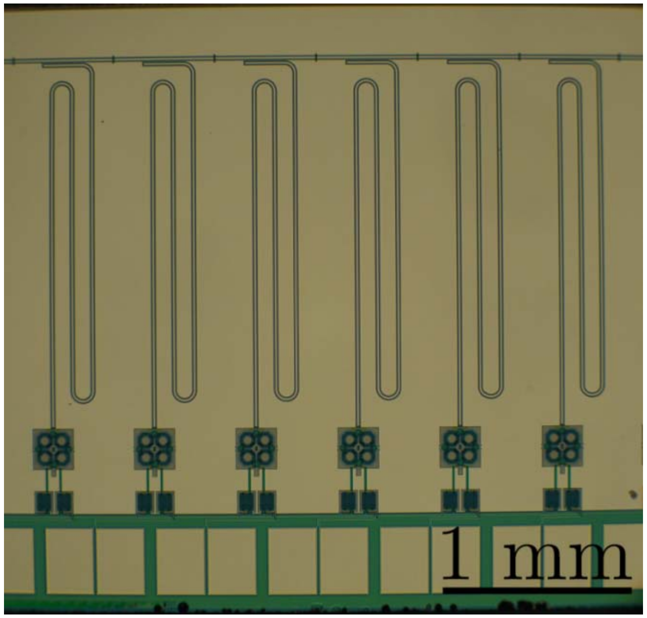
Output

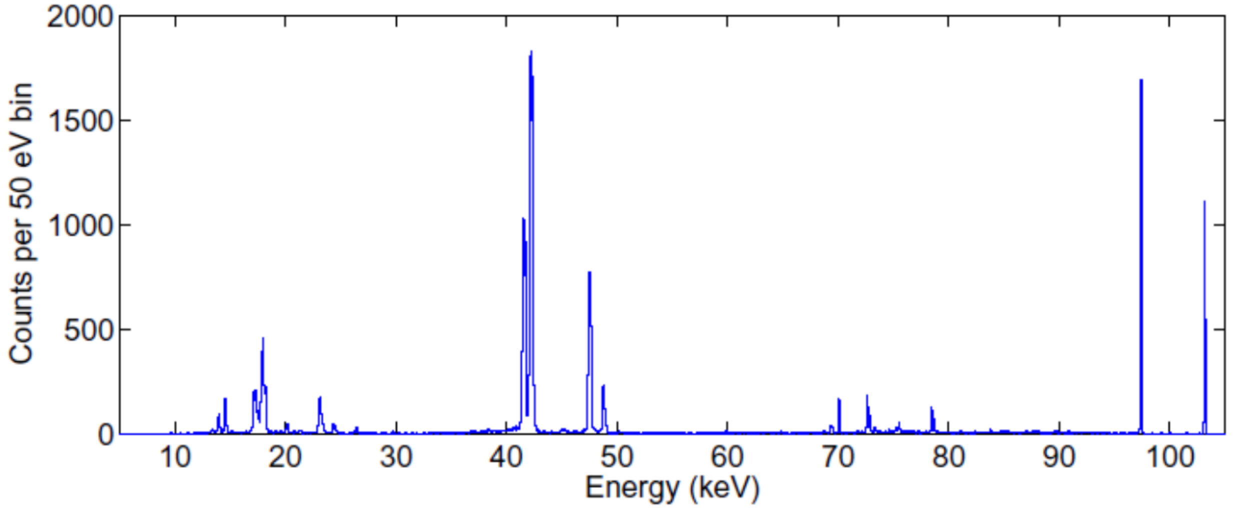


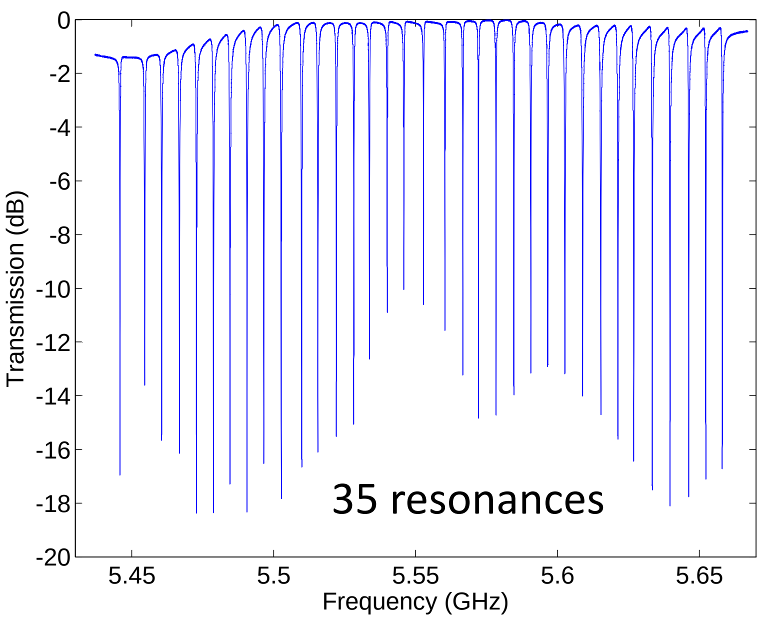
2013

NIST

First GHz FDM x-ray demonstration with high spectral resolution

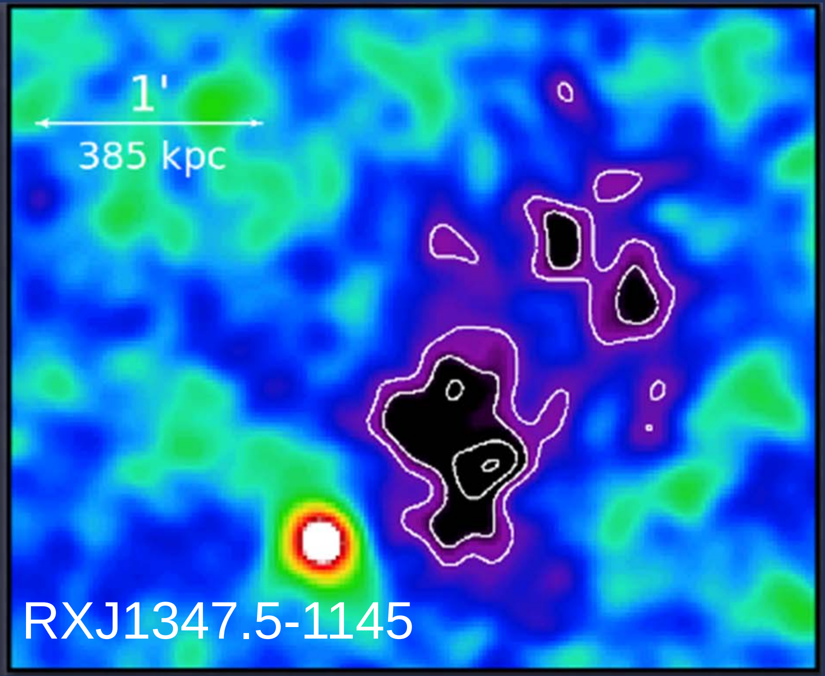


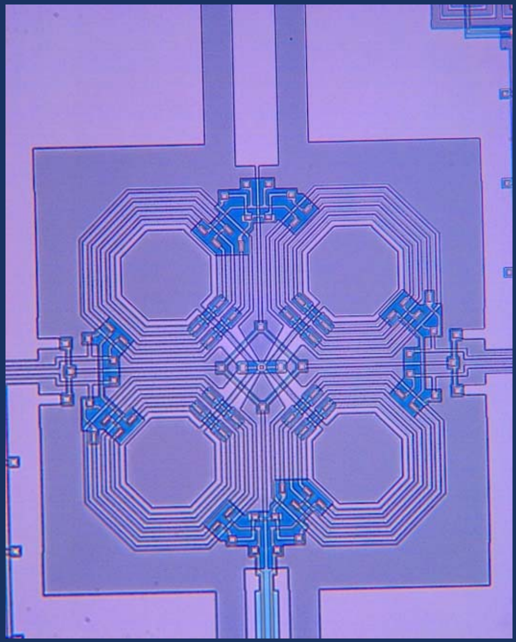




- Spectrum of Gd-153 with TES hard x-ray calorimeters
- At 100 keV, energy resolution ($E/\Delta E_{FWHM}$~1500) very close to the unmultiplexed value
- Two pixels demonstration conducted with rack-mount hardware; large-format electronics compatible with x-ray dynamic range pending

First GHz multiplexed TES bolometer on the sky: MUSTANG 2





- MUltiplexed SQUID TES Array at Ninety GHz
- High-resolution (9”) Sunyaev-Zel’dovich follow up at 90 GHz
- 100 m Green Bank Telescope
- 383 feedhorn (1.9 fλ) TESs
- Read out with ROACH + ARCONS/MUSIC

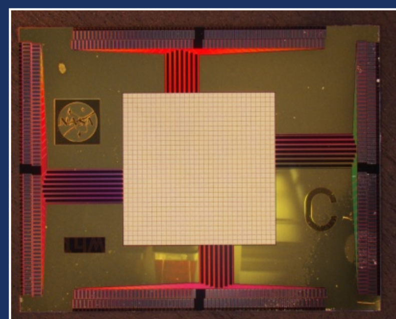
Doubling time: 2 years

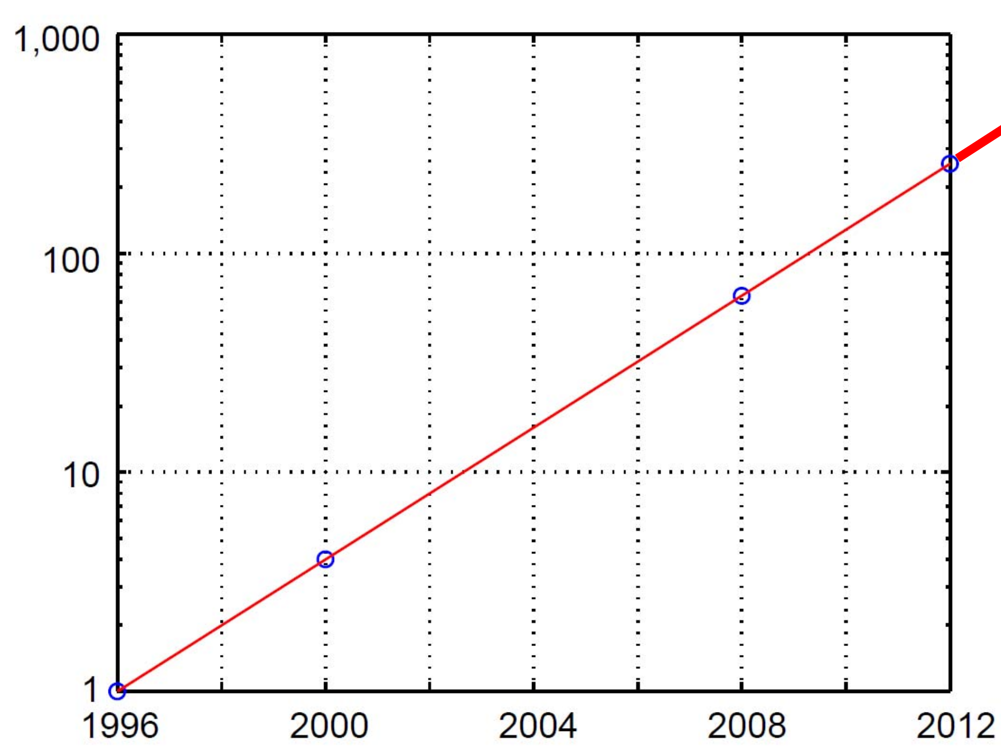
4. TES or MCC with GHz FDM + CDM

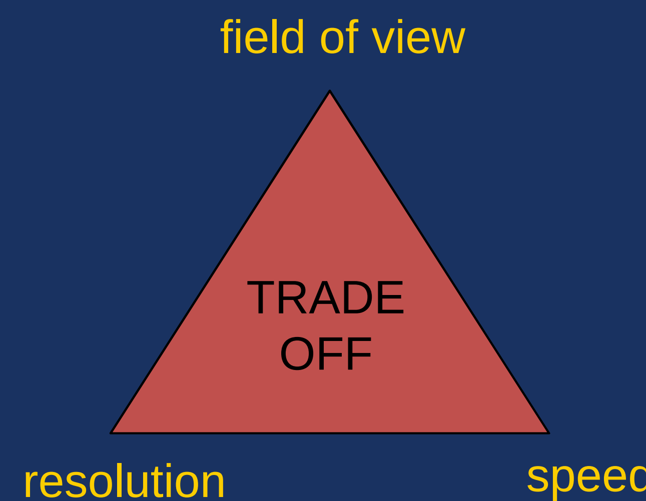
3. TES or MCC or MKID with GHz FDM

2. TES with CDM

1. TES with TDM



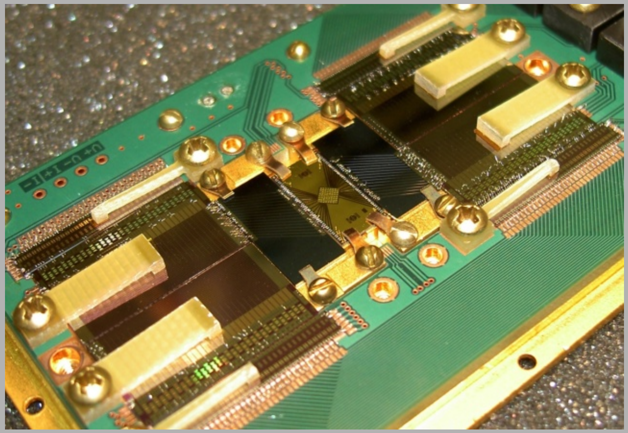




Three tiers of array scale

MHz mux

(TDM, FDM, CDM TES)

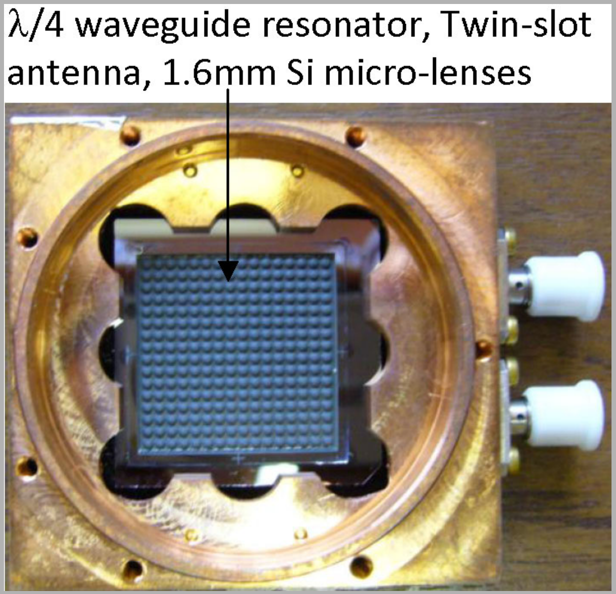


XMS x-ray prototype

- High Shannon efficiency
- MHz bandwidth / channel
- ~10^4 pixels

GHz mux

(MKID, TES)

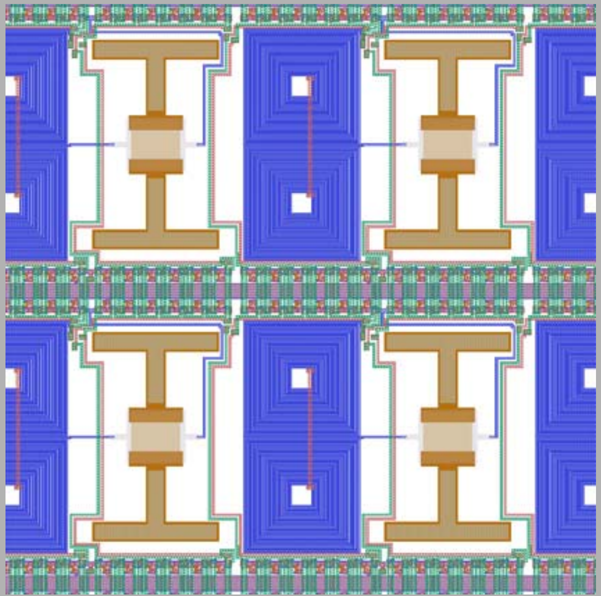


NIKA submm array

- *Low* Shannon efficiency
- GHz bandwidth / channel
- ~10^5 pixels

hybrid GHz mux

(resonator + CDM)

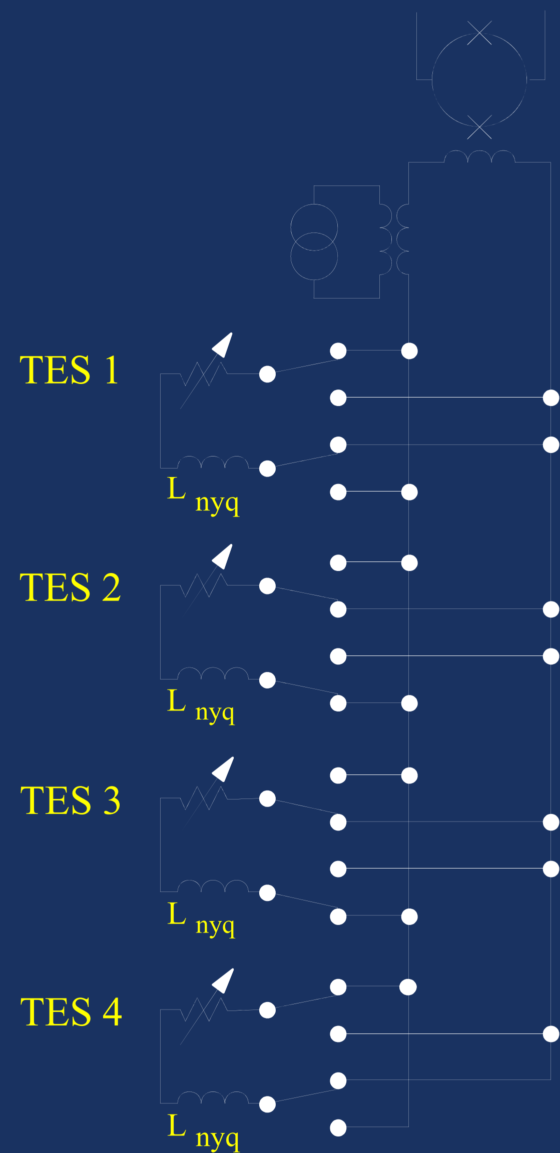


Hybrid design

- High Shannon efficiency
- GHz bandwidth / channel
- ~10^6 pixels

Hybrid circuit: hundreds of detectors per resonator

- Current from all calorimeters is summed in one output resonator
- Polarity with which each calorimeter couples to the output SQUID is switched in Walsh code
- No TES shunt resistors or power
- Compact modulation elements (*much* smaller than resonators / MKIDSs)



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Design for 300 μm hybrid x-ray pixel

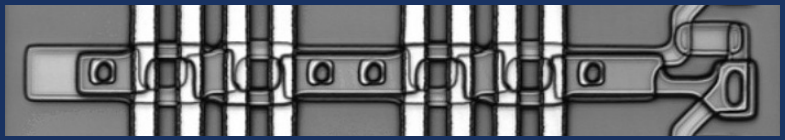


Photo: I-CDM modulator

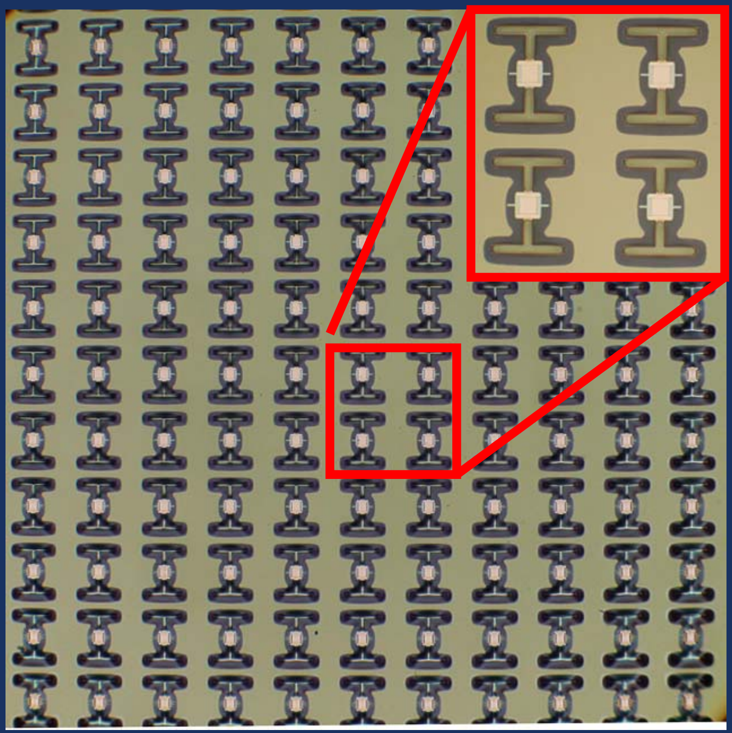
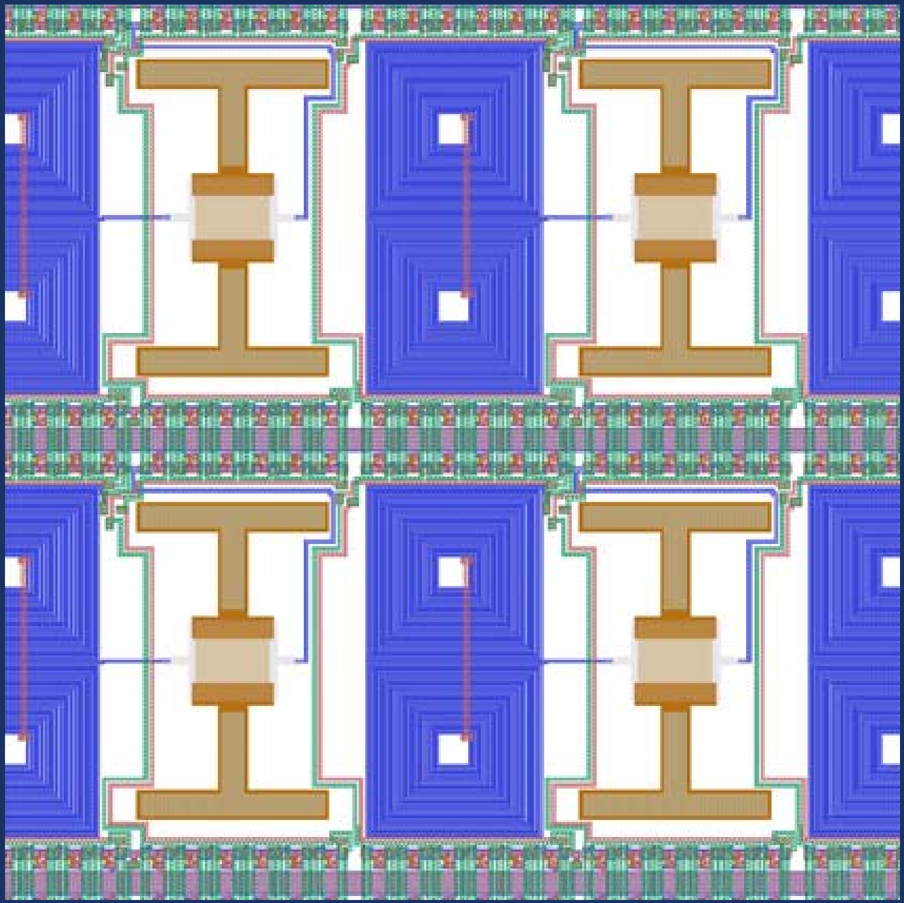
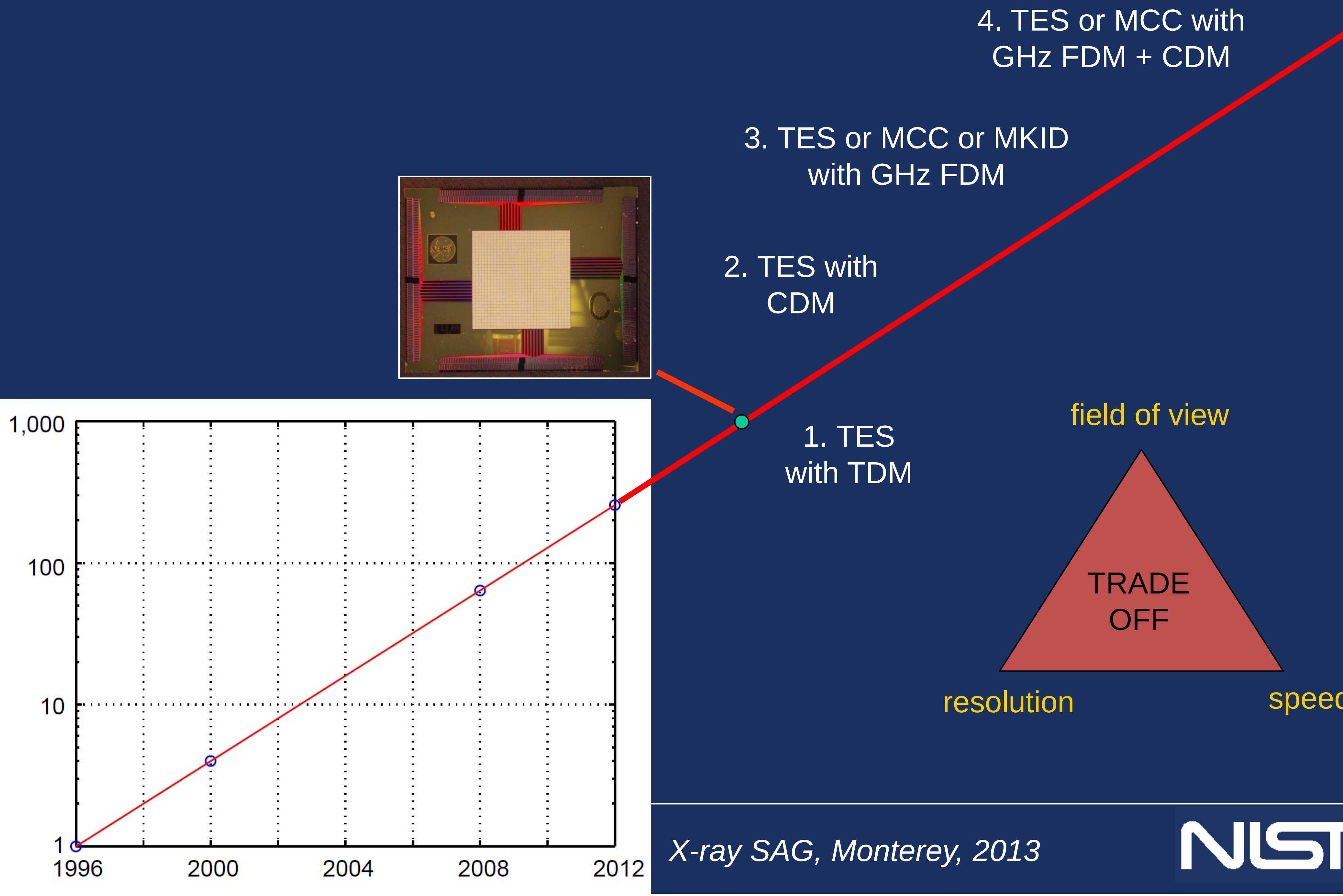


Photo of 32 × 32 array of x-ray calorimeters on 300 μm pitch – D. Schmidt



Lithographic layout of in-focal-plane I-CDM modulators on 300 μm pitch

Moore's law: the next ×1000



NIST