# Tech investment in low-temperature detectors

“It has become standard to achieve order-of-magnitude or more increases in capability with each generation of missions, and exciting science breakthroughs have resulted from this. The only way to advance the next capability without an exponential increase in mission cost is to find transformational new technological solutions...

Examples of truly revolutionary technologies essential to existing and upcoming astrophysics missions that have been largely or entirely supported by NASA are X-ray imaging mirrors, **X-ray microcalorimeters, and large arrays of submillimeter detectors**.”

*Astro-2010*

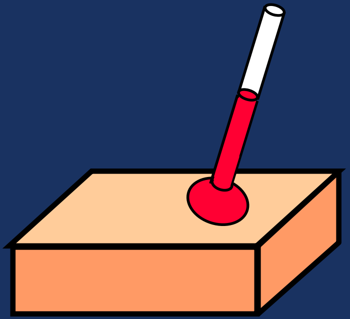
# Points

- From a technology investment perspective, low-temperature detectors (LTDs) for long wavelength and x-ray / $\gamma$-ray should be considered together.
- Single pixel LTDs are almost as good as they need to be / can be (background limited for FIR/submm/CMB, <2 eV FWHM at 6 keV).
- Arrays of LTDs are getting bigger with a Moore's Law doubling of ~20 months. State of the art for submm is 10,000 pixels, for x-ray is 256 pixels.
- There is a technical path towards megapixel arrays with manageable wiring – in the early 2020's (FIR/submm) and late 2020's (x-ray)

# Low-temperature detectors (LTDs)

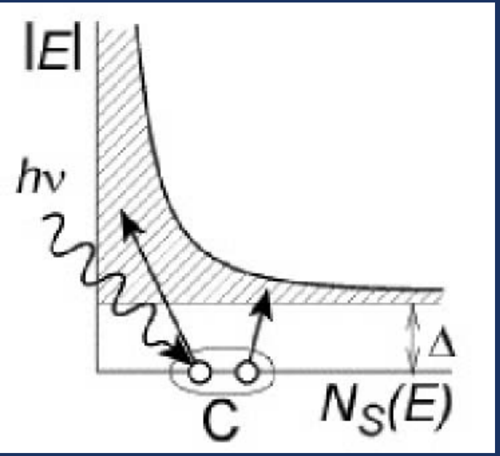
Equilibrium (thermal)

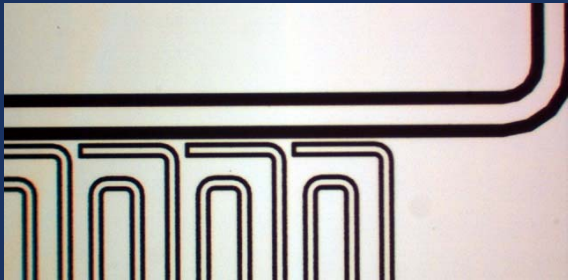
- Semiconductor thermistor (NTD, Si)
- Transition-edge sensor (TES)
- Magnetic calorimeter (mag cal)



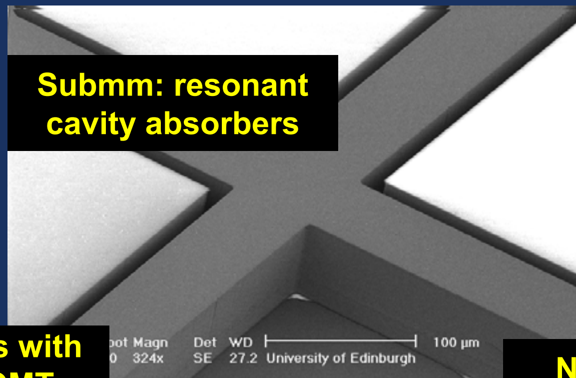
Non-equilibrium (pair breaking)

- Microwave Kinetic Inductance Detector (MKID)



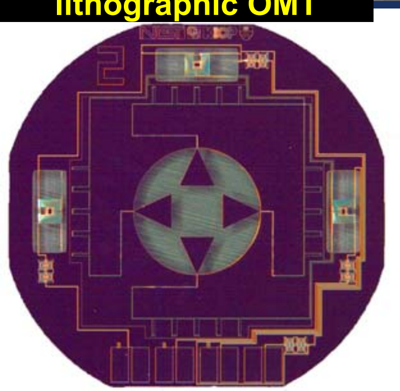



# LTD's span the electromagnetic spectrum




Submm: resonant cavity absorbers

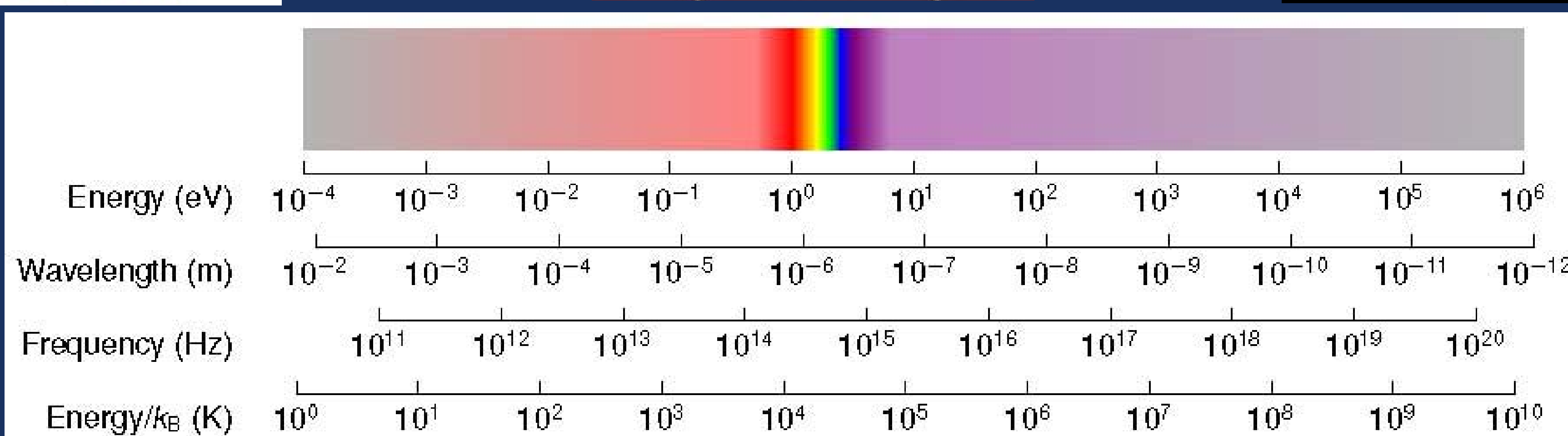
Soft x-ray: Bi thin fims



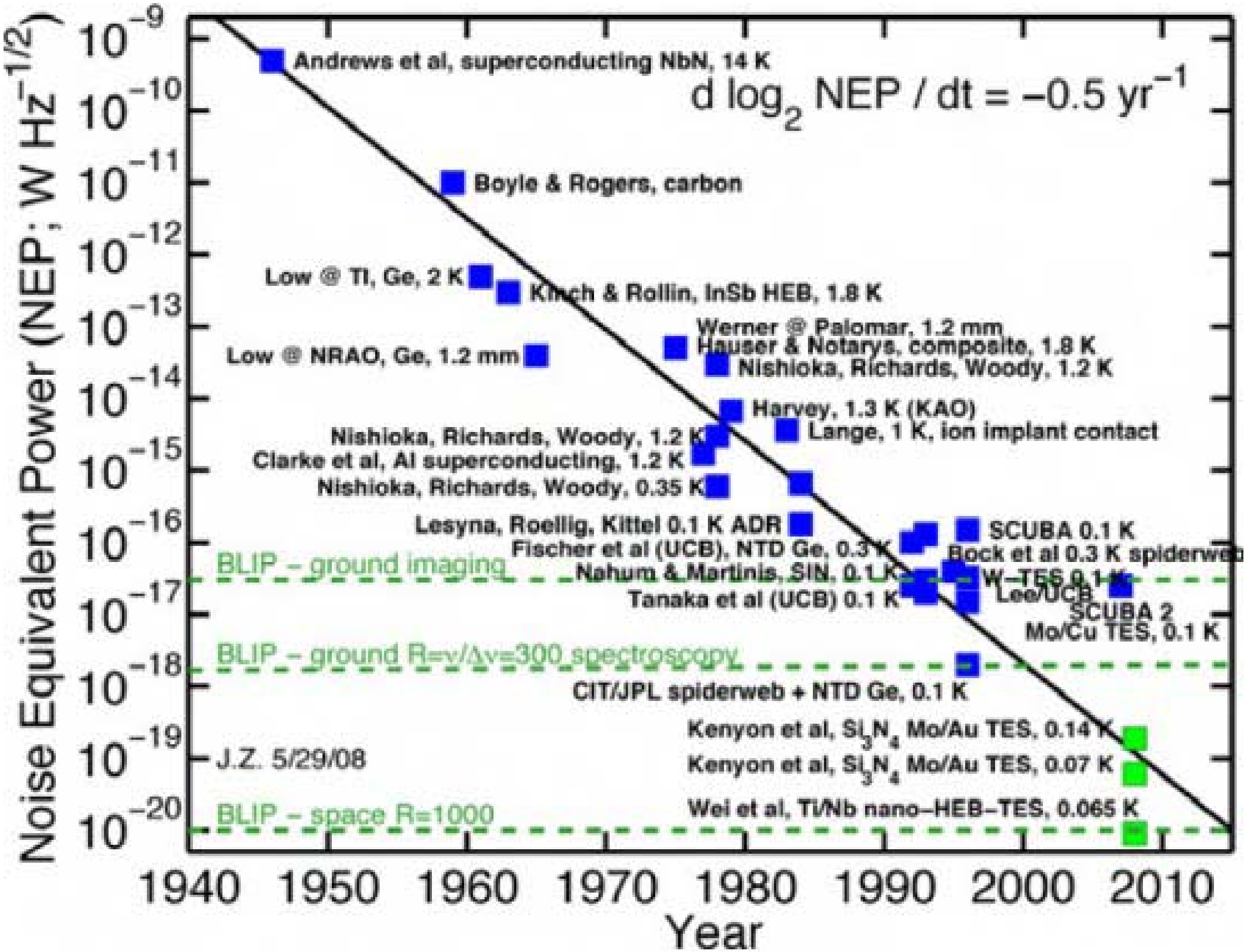
CMB: feedhorns with lithographic OMT

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

Gamma-ray: thick superconducting foil

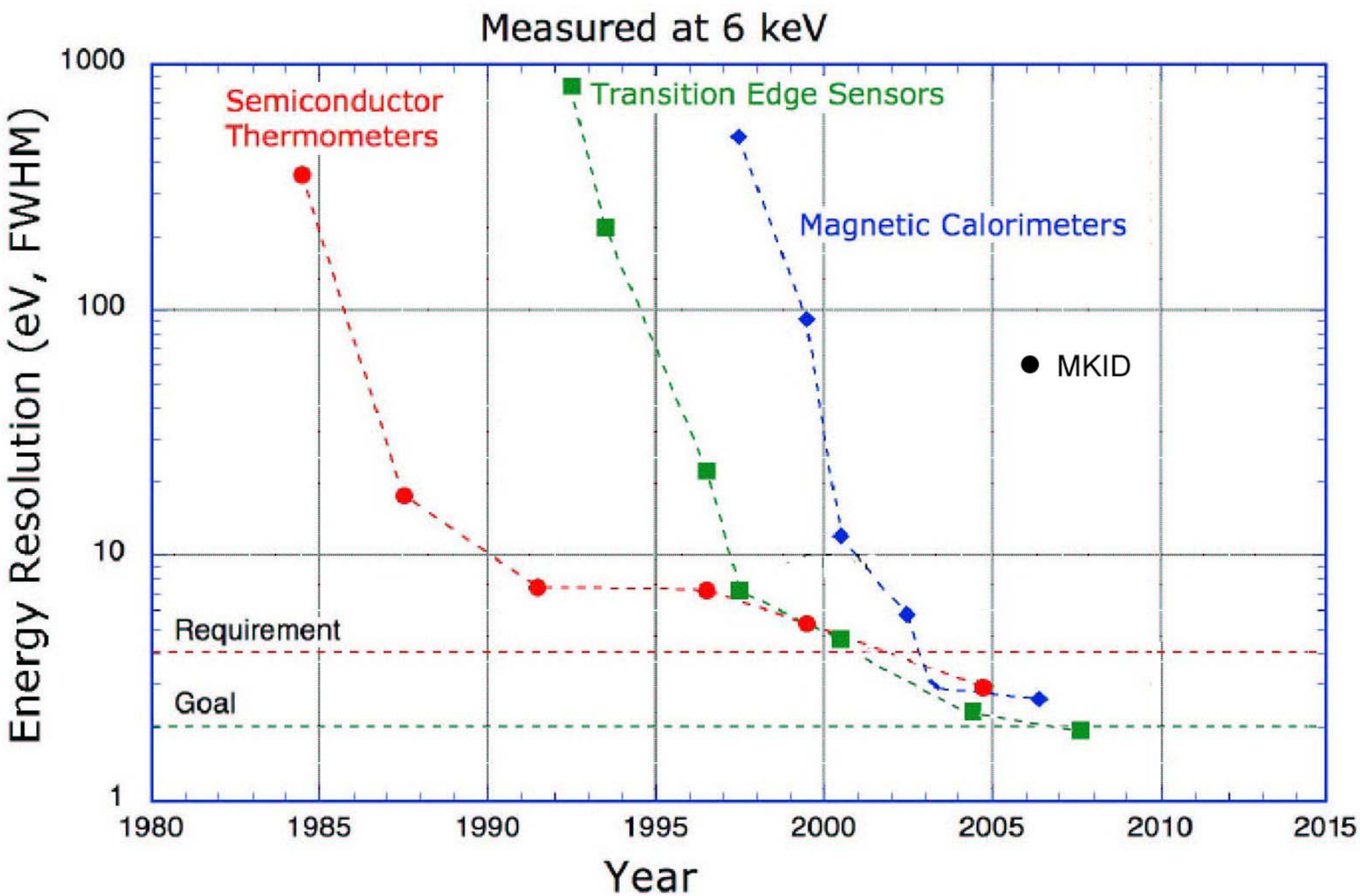


# Single bolometers reach their limits



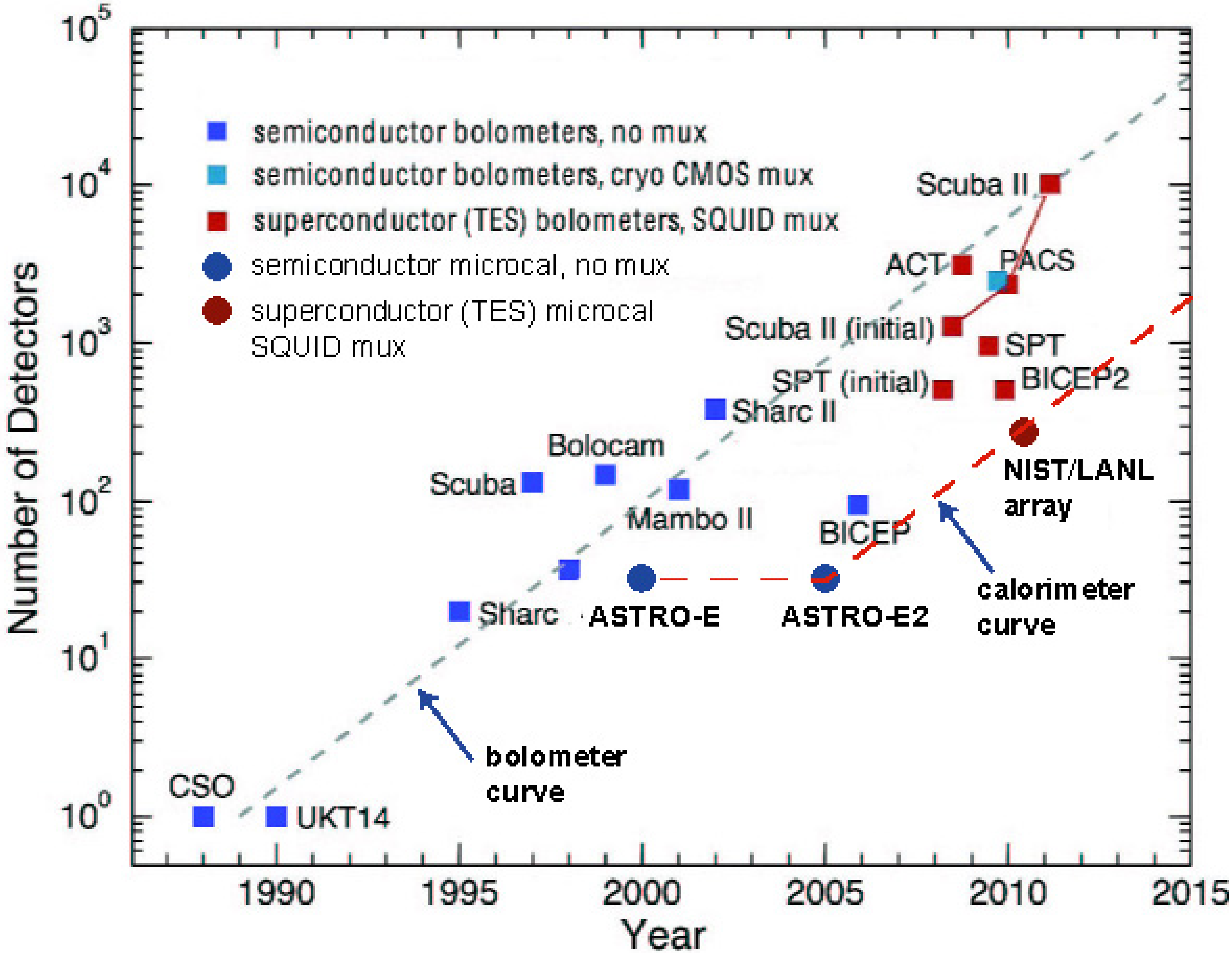

Credit: J. Zmuidzinas

# Single x-ray calorimeters reach their limits

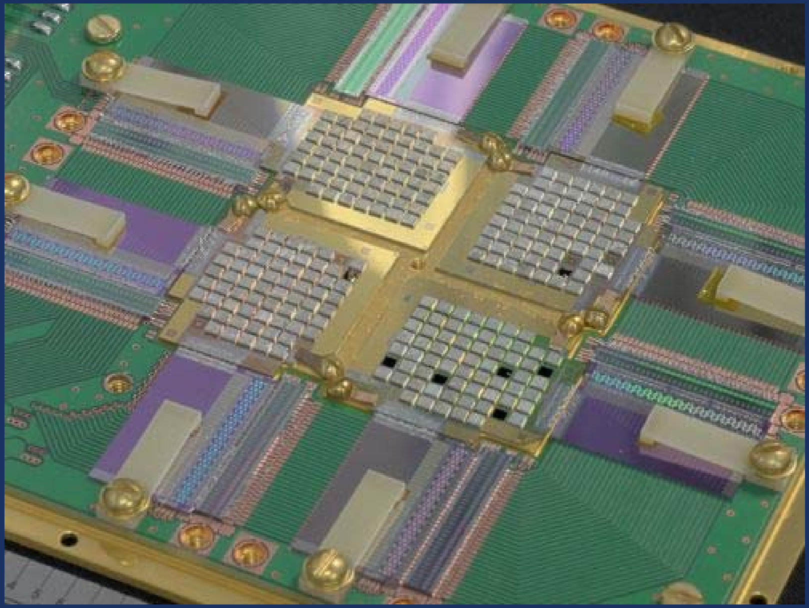



Credit: R. Kelley +

# LTD Array Moore's Law: ~20 months doubling



# State of the art for x-ray

Soft x-ray lab instrument: 160 pixels, 3.1 eV FWHM at 6 keV

also Micro-X sounding rocket, 121 pixels, to fly soon

NIST/LANL array

Hard x-ray / $\gamma$ : 256 pixels

80 eV FWHM at 100 keV

# LTDs can scale to megapixel arrays

Shannon noisy channel coding theorem:

Information content of a transmission line

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

Typical LTD information content

$$C_{LTD} \sim 1 \text{ kbps}$$

HEMT amplifier information content

$$C_{HEMT} \sim 100 \text{ Gbps}$$

LTD multiplexer scaling, as projected today...

| Array scale | MUX technique |
|---|---|
| 10 kpixel | MHz SQUID MUX |
| 100 kpixel | GHz resonator (MKID, uwave SQUID) |
| 1 Mpixel | Hybrid (e.g. Code-division + GHz resonator) |

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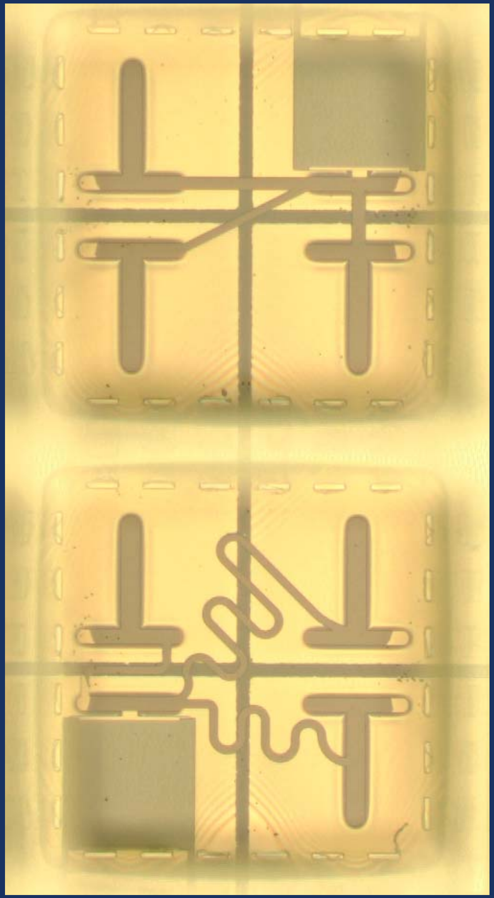
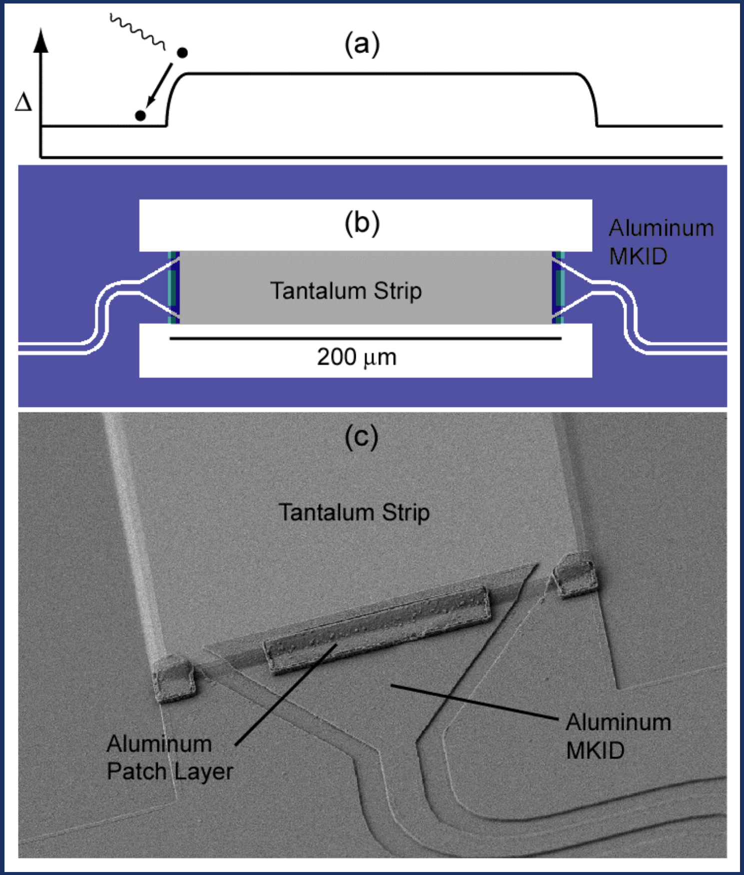
# Diffusive multiplexing

Single sensor, multiple absorber devices



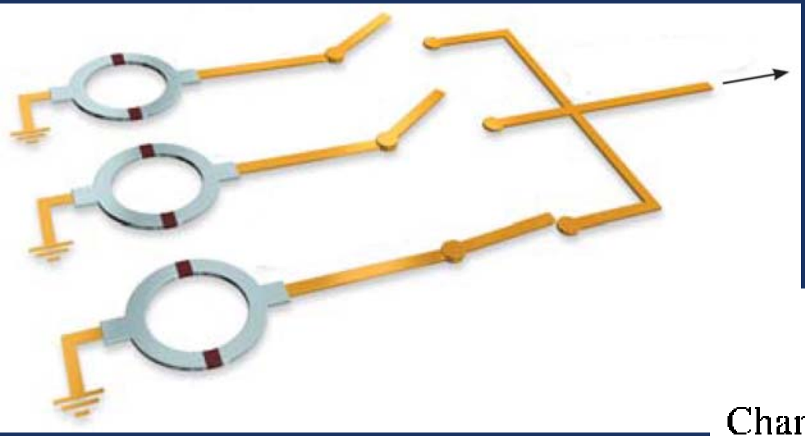
**TES "hydra," view from back through nitride membrane**
**C. Kilbourne**

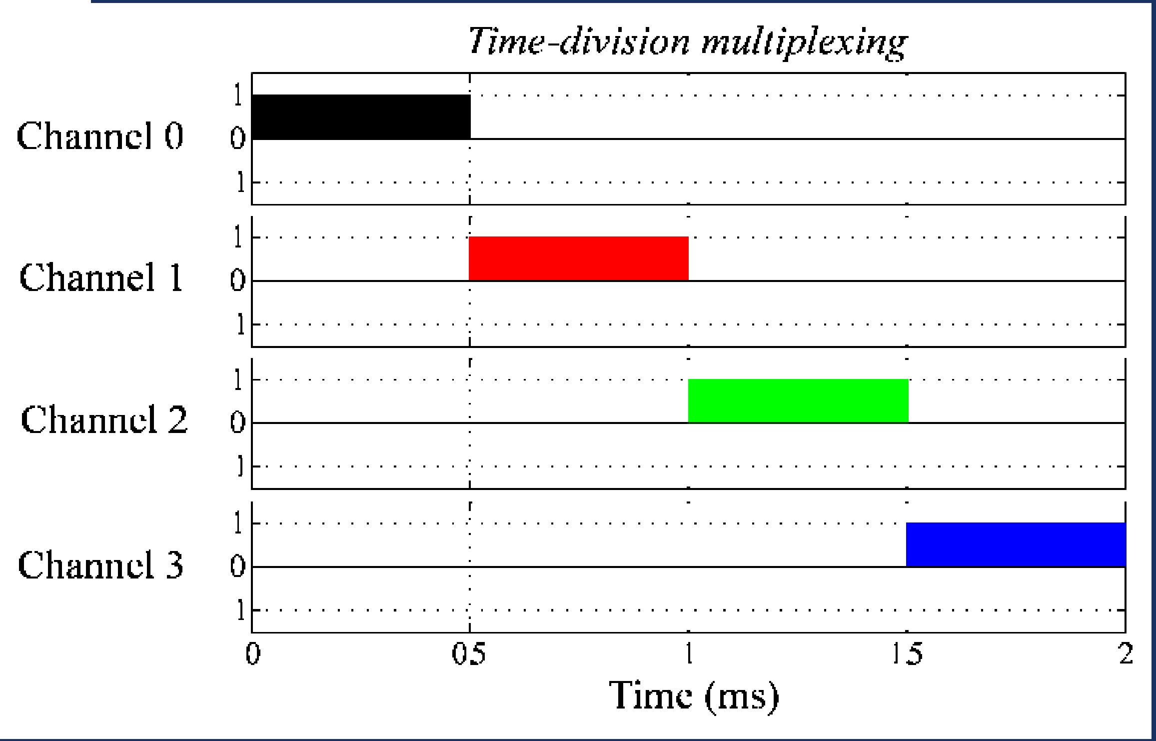
Single absorbers, multiple sensors




**MKID strip detector**
**B. Mazin**

# Time-division MUX

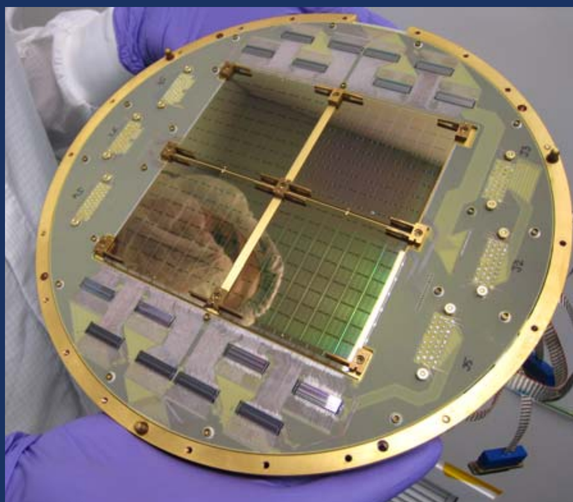




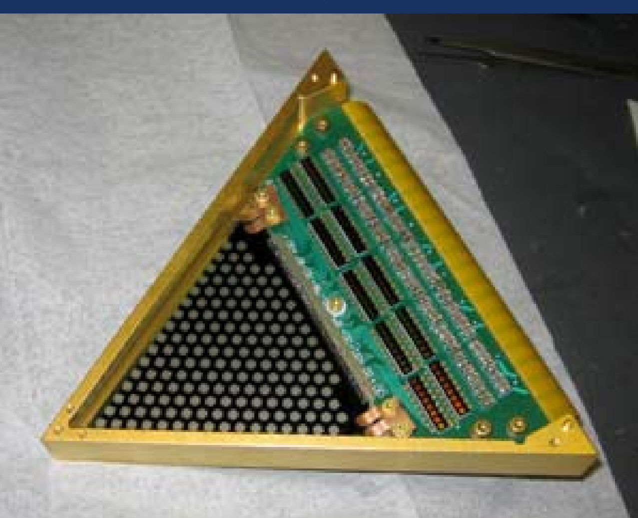

- Define time band by turning SQUIDs on one at a time
- Each detector output is measured 1/N of the time

# A few of the TES arrays in the field

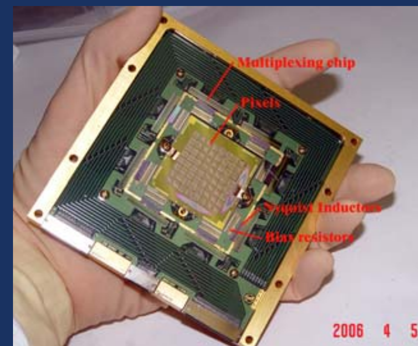
BICEP-2, 512



SPT-SZ, 960

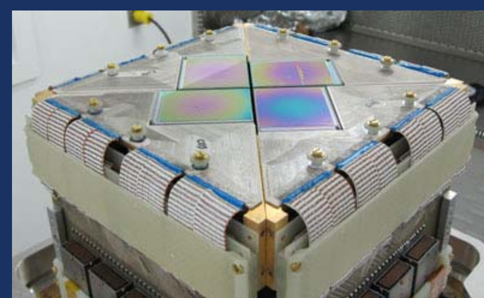


MUSTANG, 64

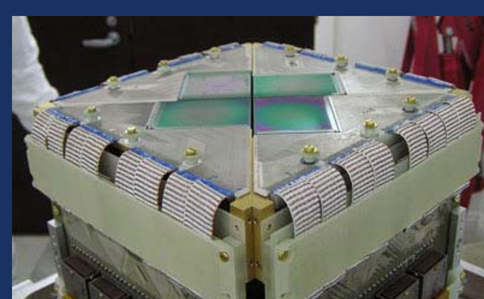



SCUBA-2, 10,000

450 um

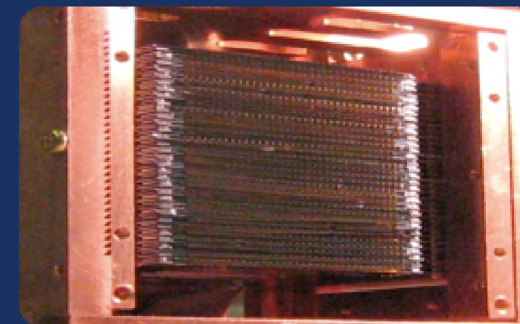


850 um

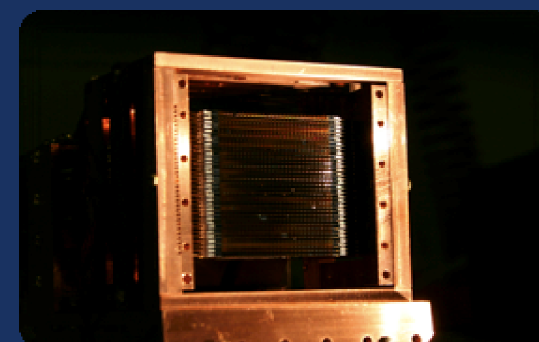


ACT-SZ, 3,000

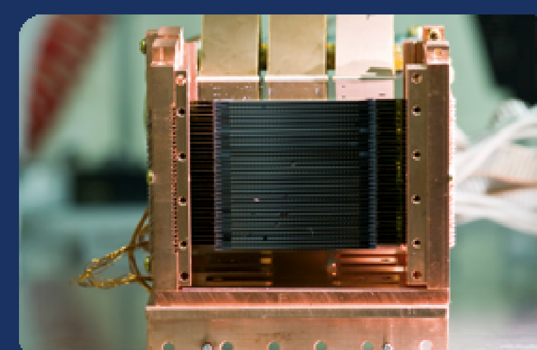
148 GHz



218 GHz



277 GHz



# Conventional NIR detector arrays

32x32

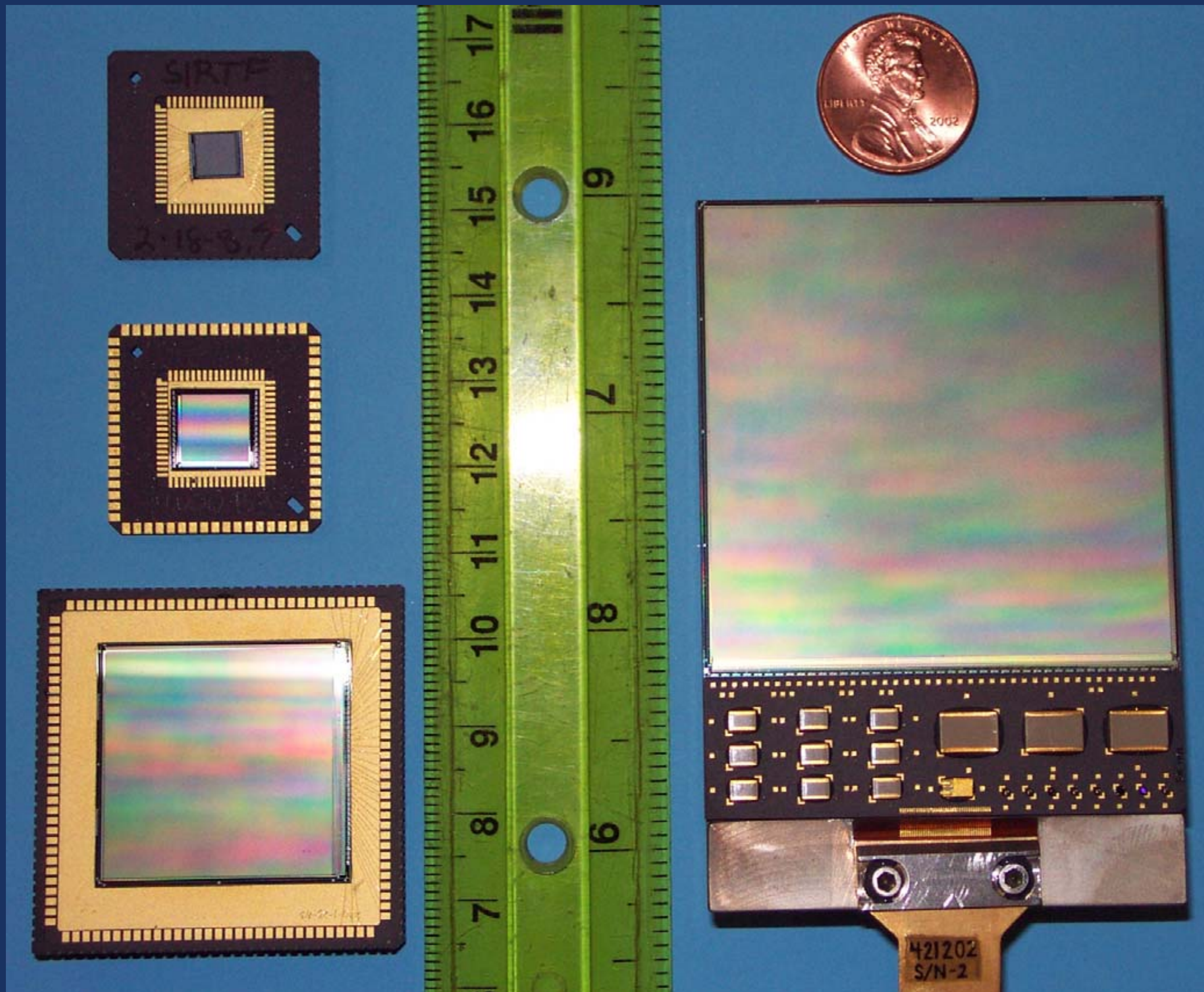
1983

58 x 62

1988

256x256

1998




$2048^2$

2008

Pipher et al.

Courtesy of H. Moseley

# Information capacity of cryogenic amplifiers

SQUID

$$\Delta\Phi = \Phi_0$$

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

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

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

HEMT

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

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

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

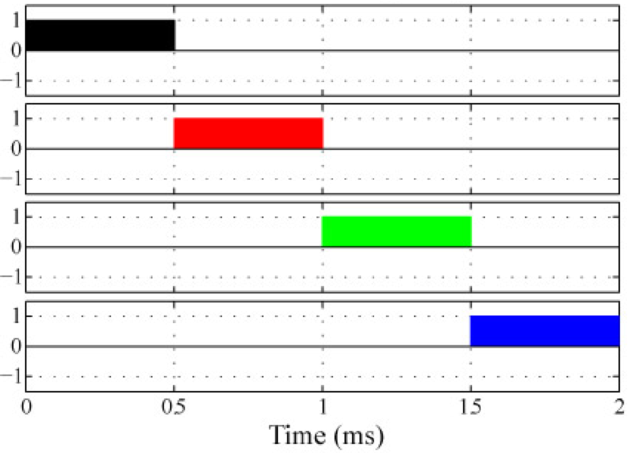
$$C = 175\ \text{GHz}$$

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

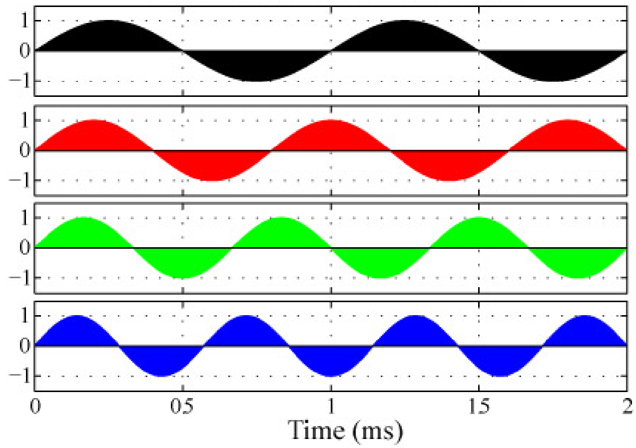
With a suitable access method (muxing scheme), we should (in principle) be able to read out thousands of detectors per MHz SQUID, or millions per HEMT

# Three modulation functions

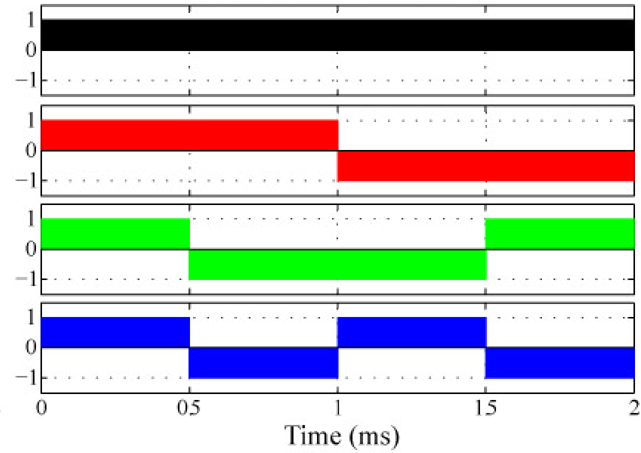
## Time-division MUX




## 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