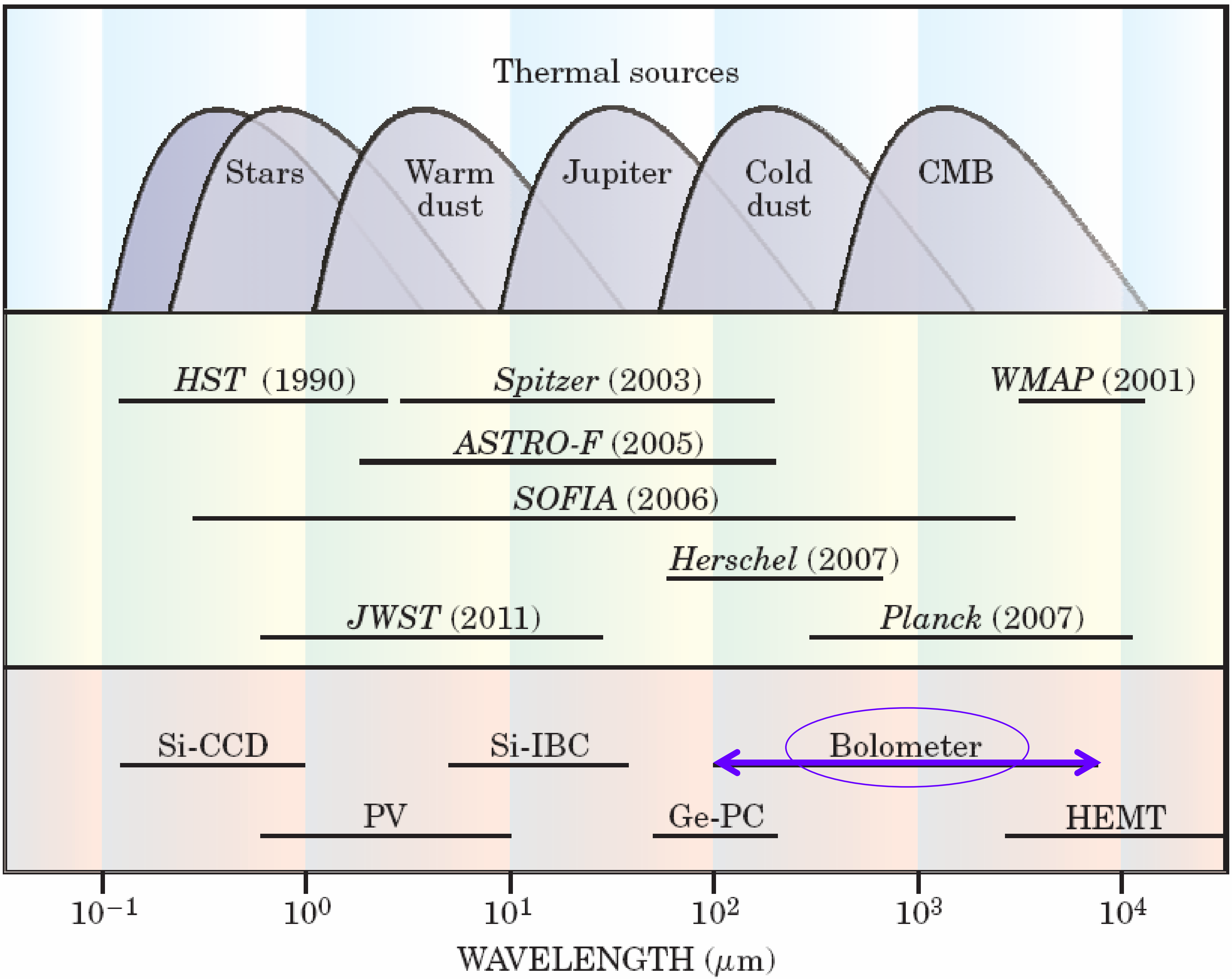
Bolometers and Readout

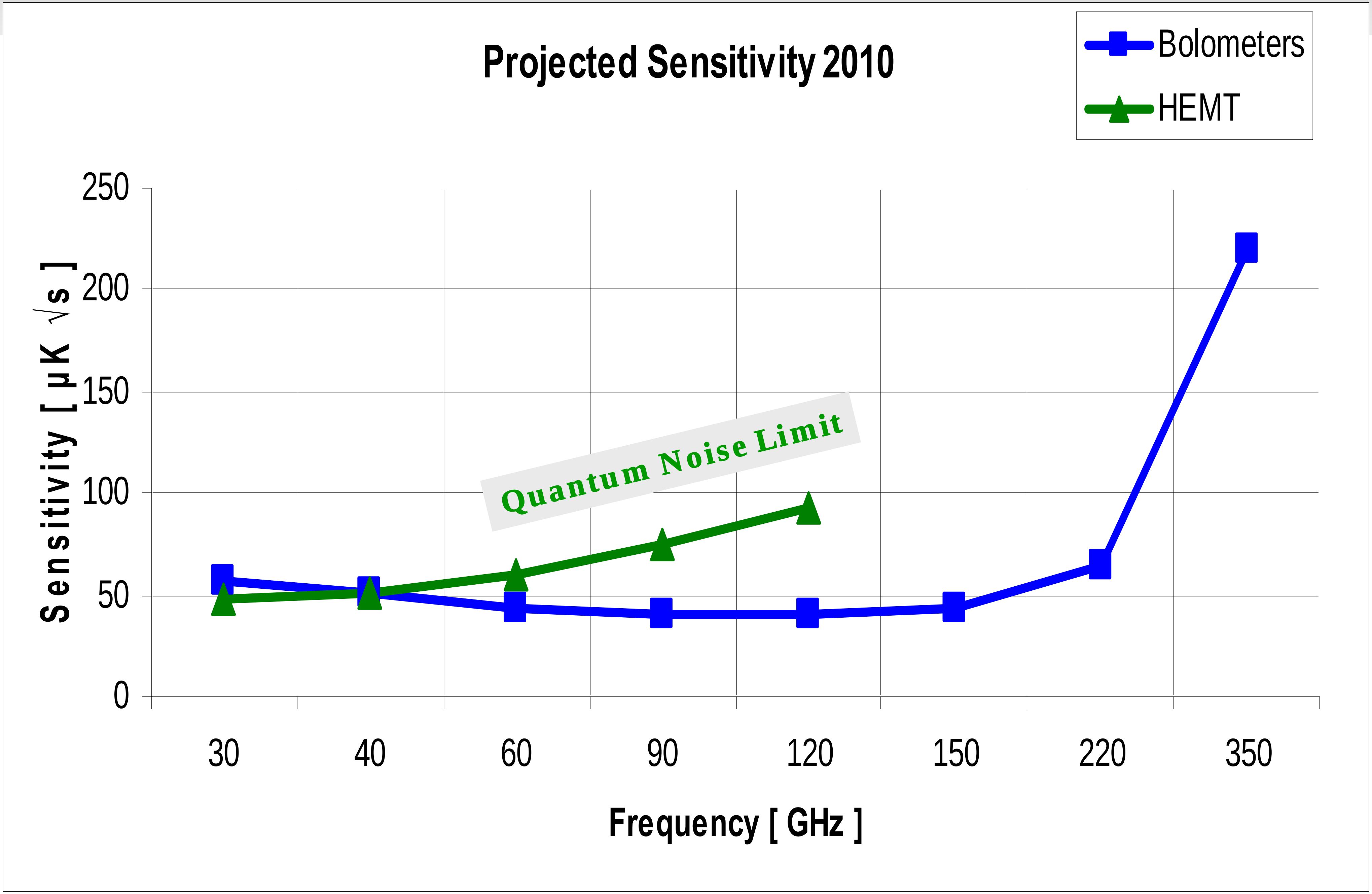
McGill CMB Workshop 2008

Matt Dobbs

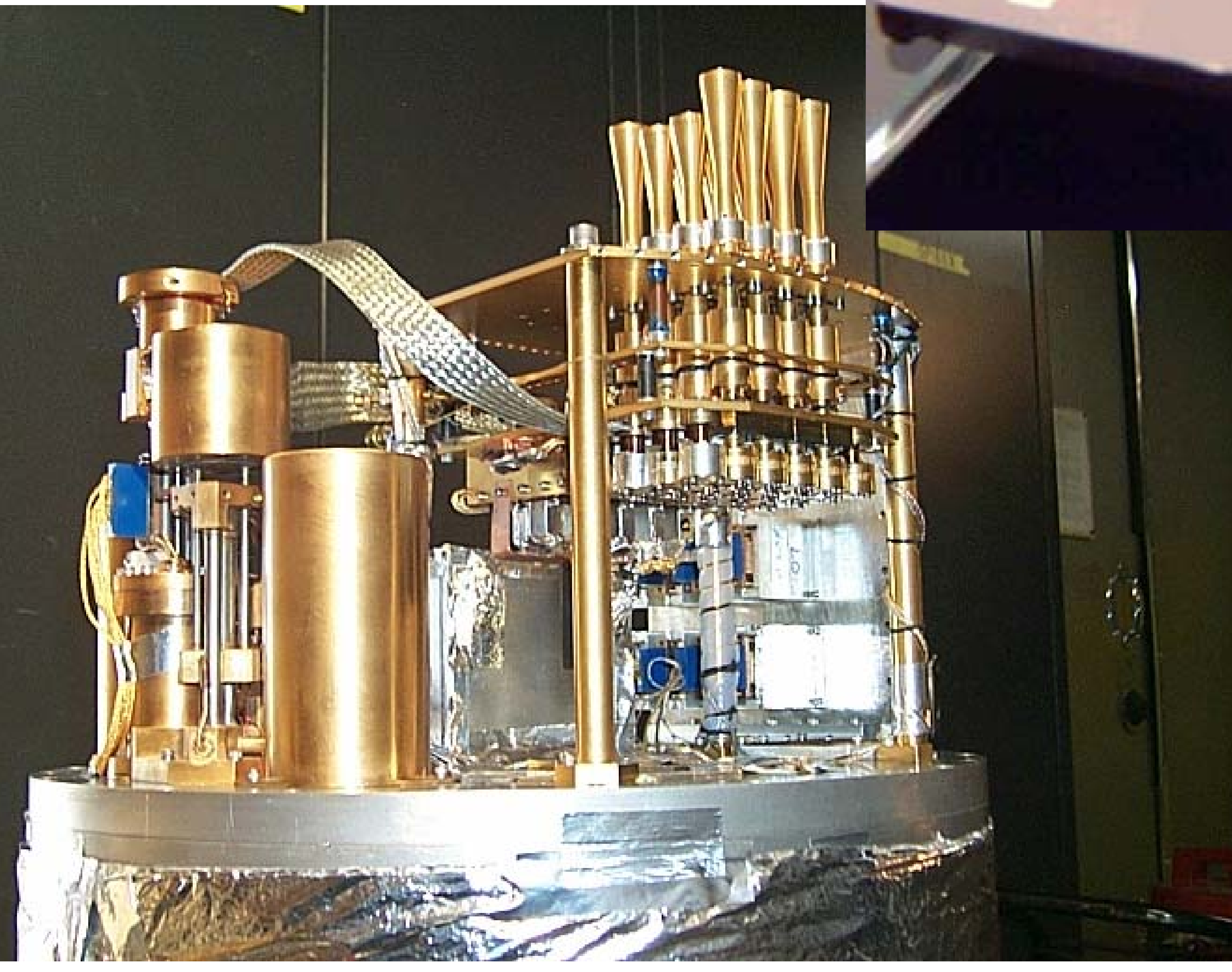


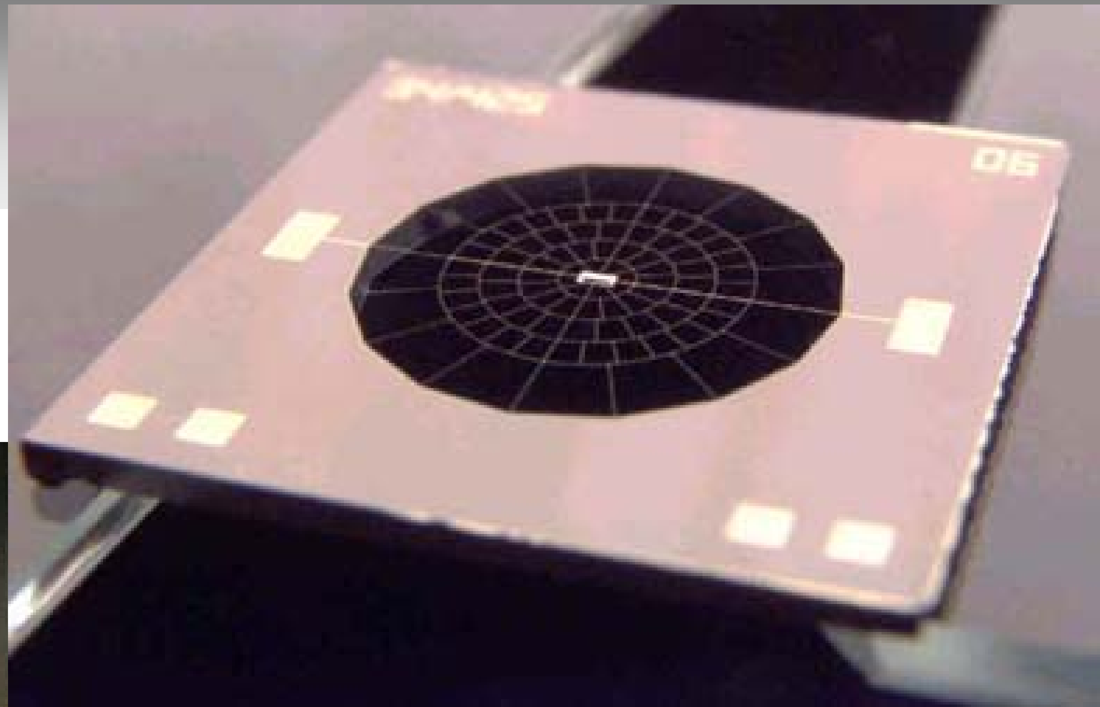
Plot: Richars & McCreight, Physics Today 2005.

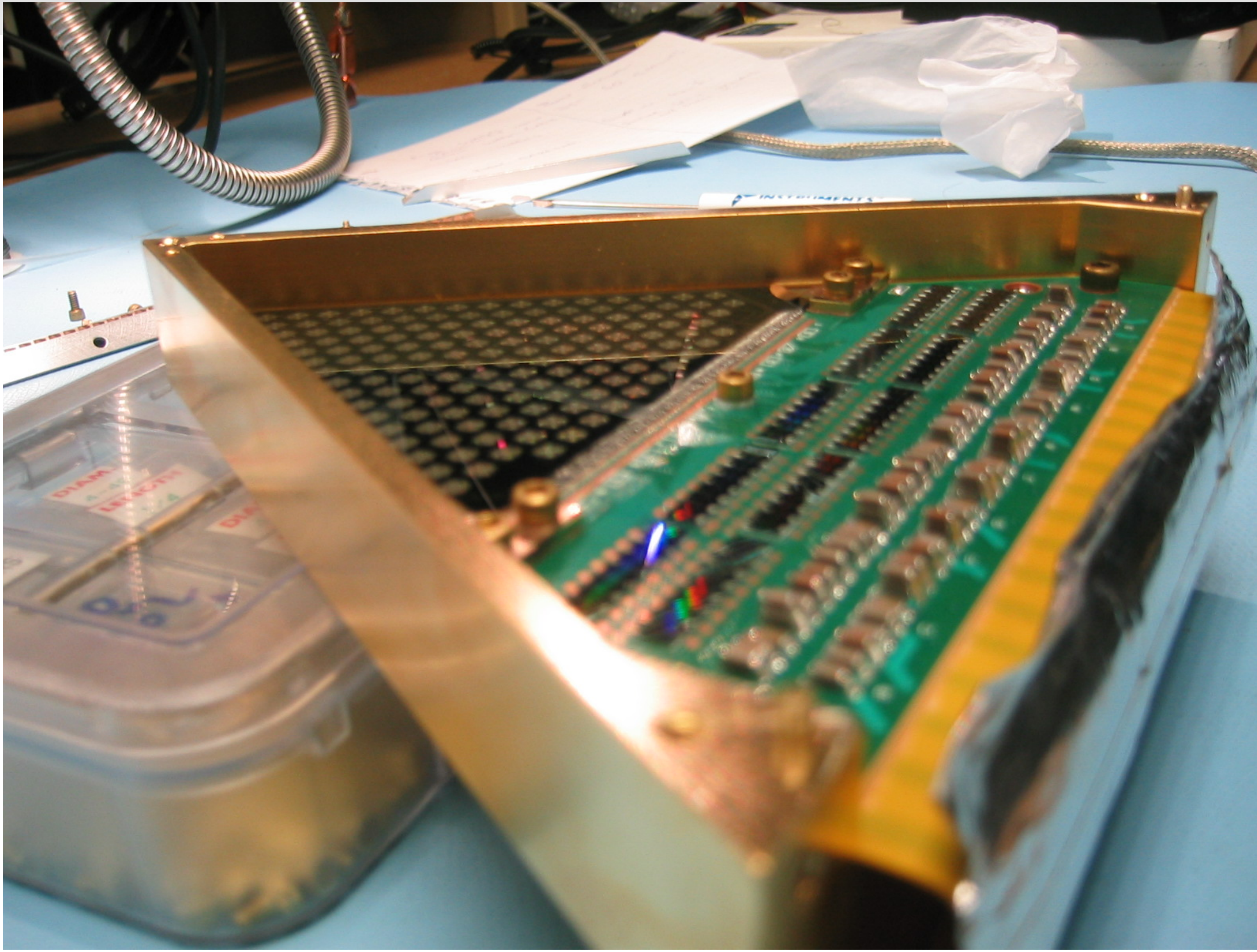
Coherent Amplification vs. Bolometers

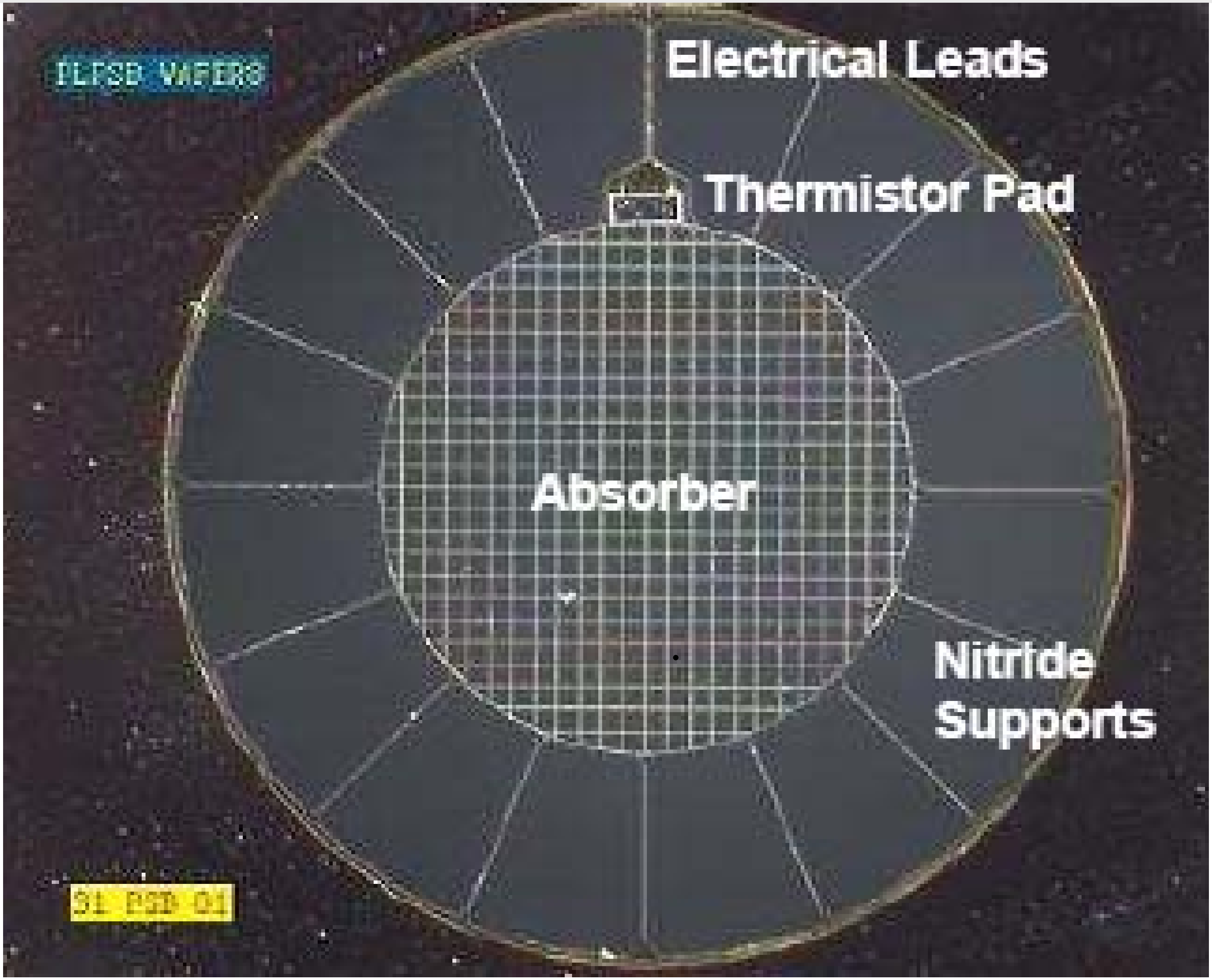


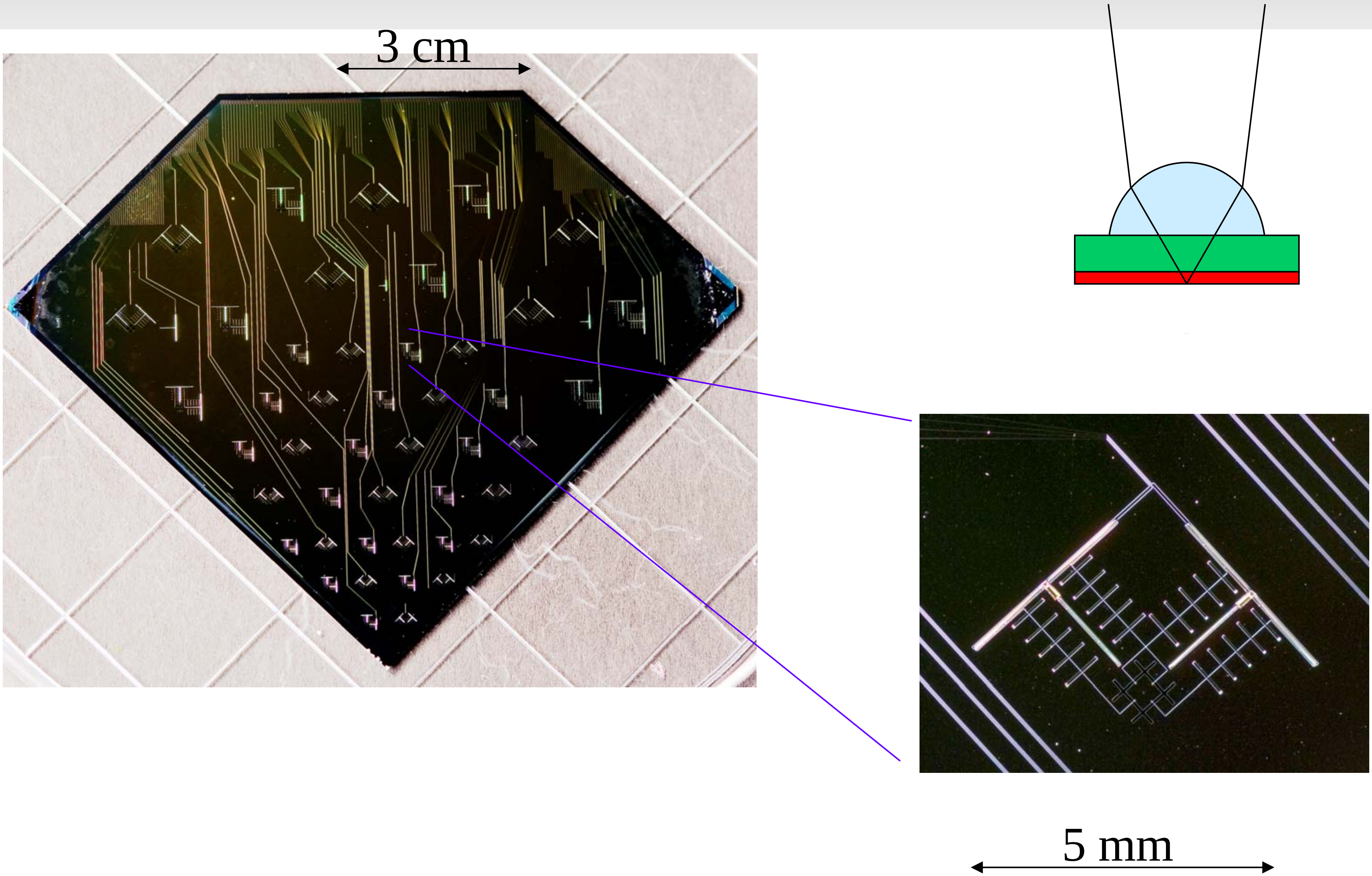
Source: Weiss DOE/NSF/NASA CMB Taskforce, Table 7.2





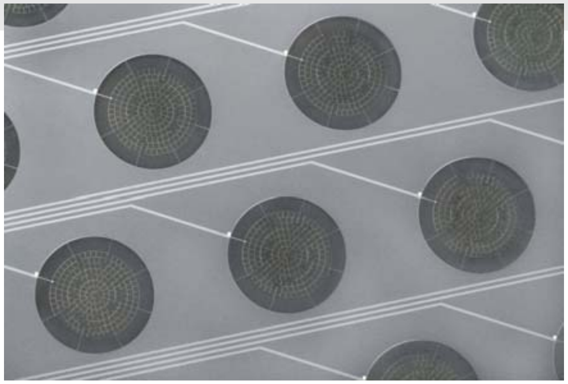


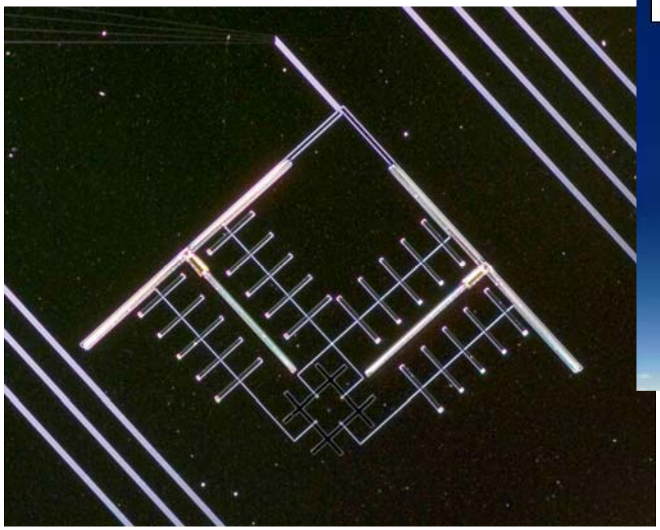

Electrical Leads
Thermistor Pad
Absorber
Nitride
Supports

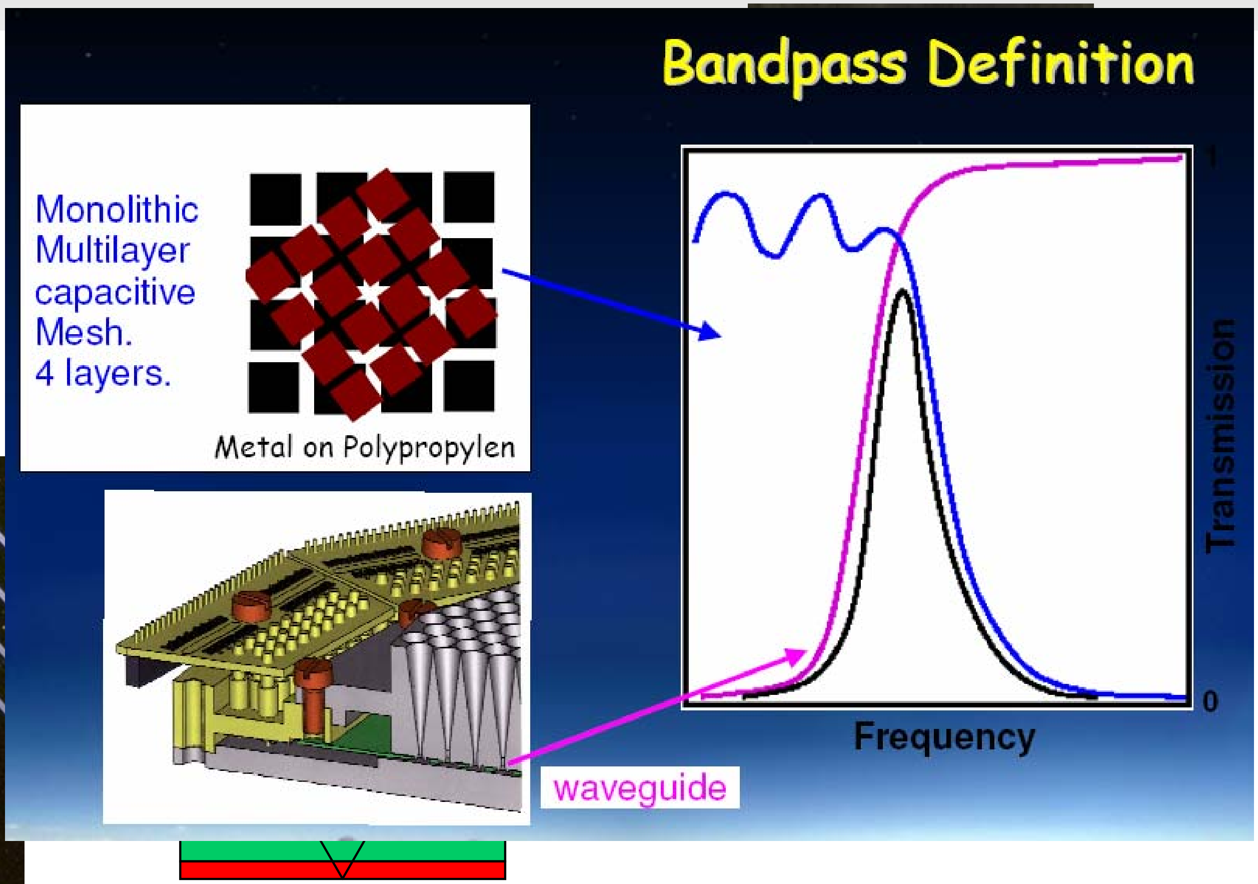

3 cm
5 mm

(http://theory2.phys.cwru.edu/~pete/GravitationalLens/GravitationalLens.html)

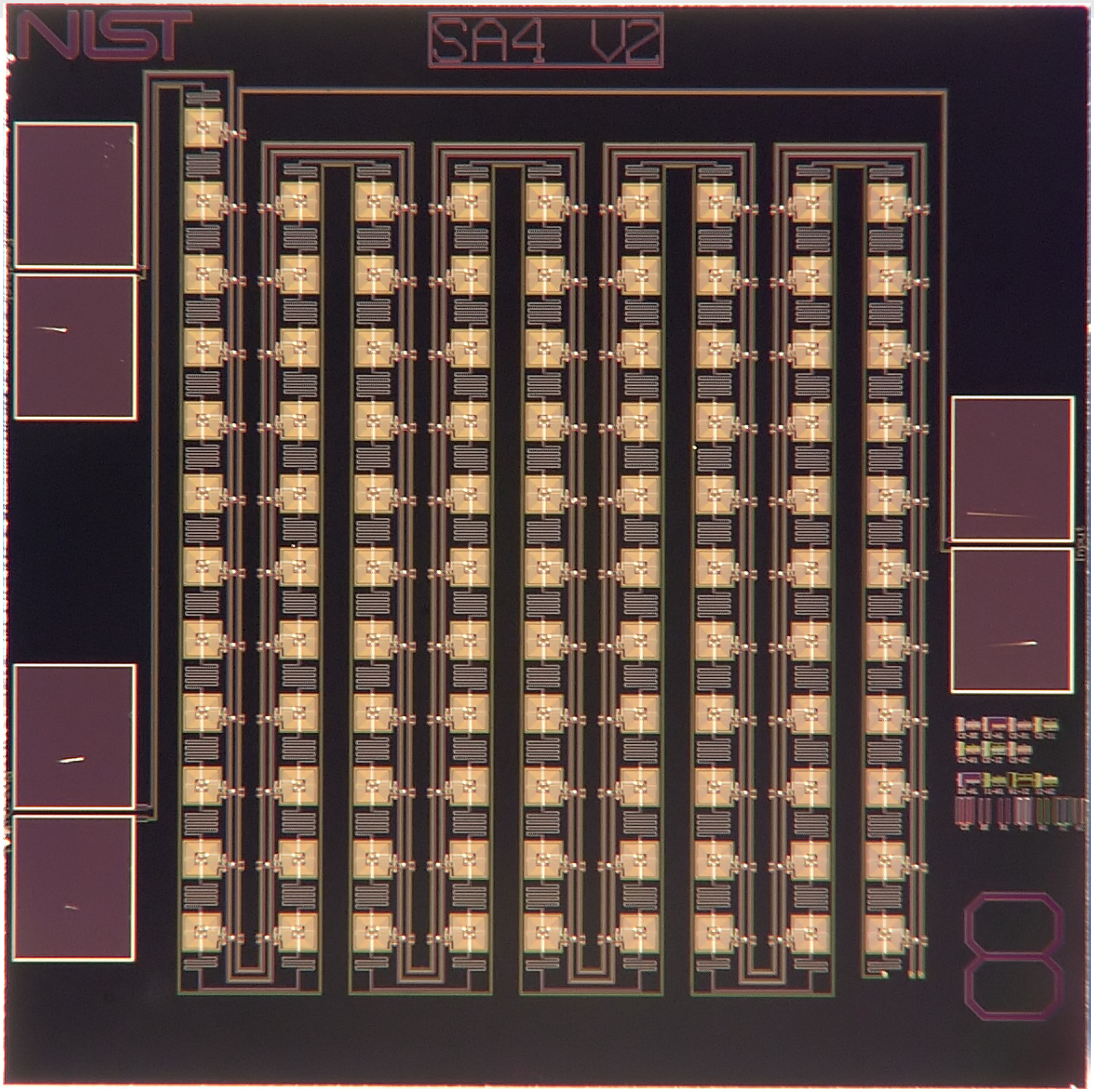
Coupling

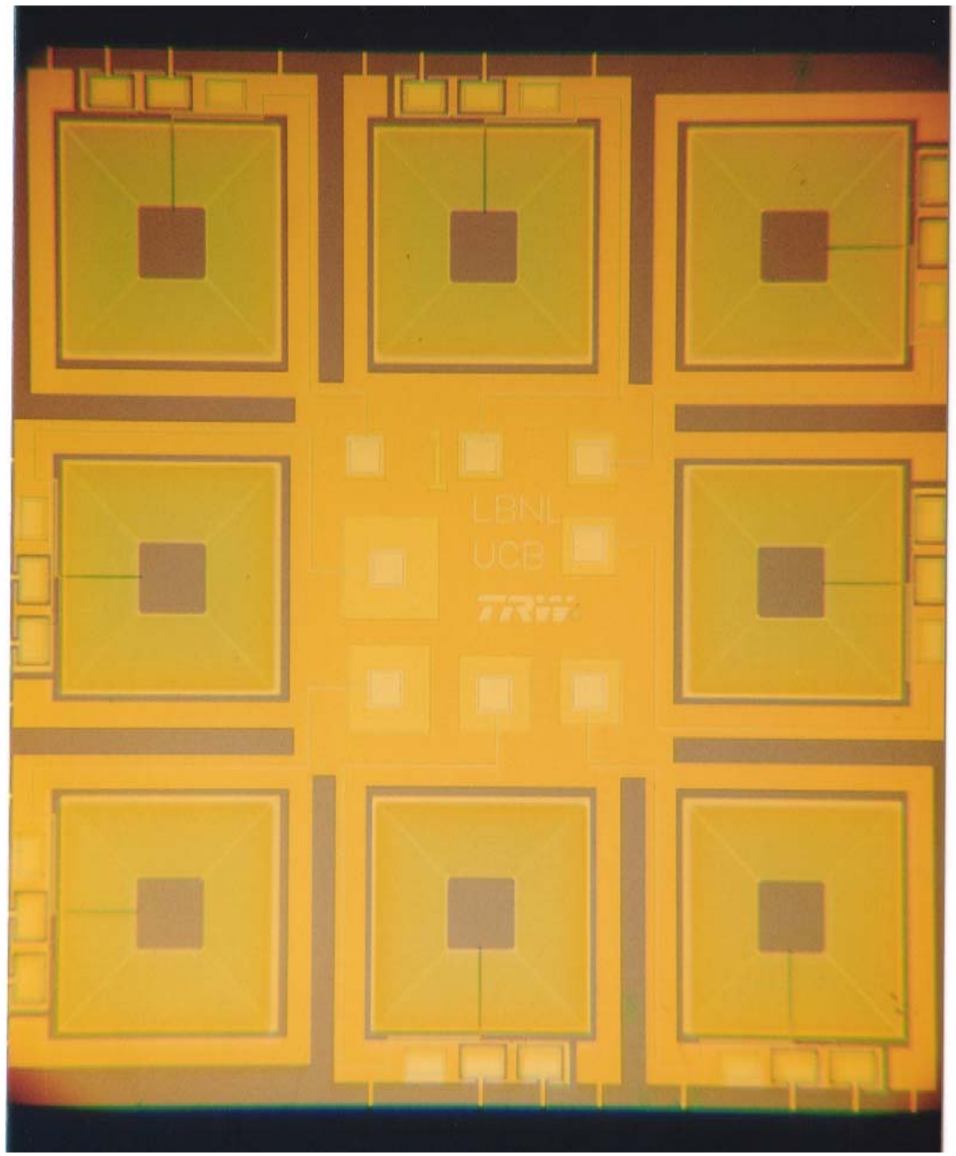




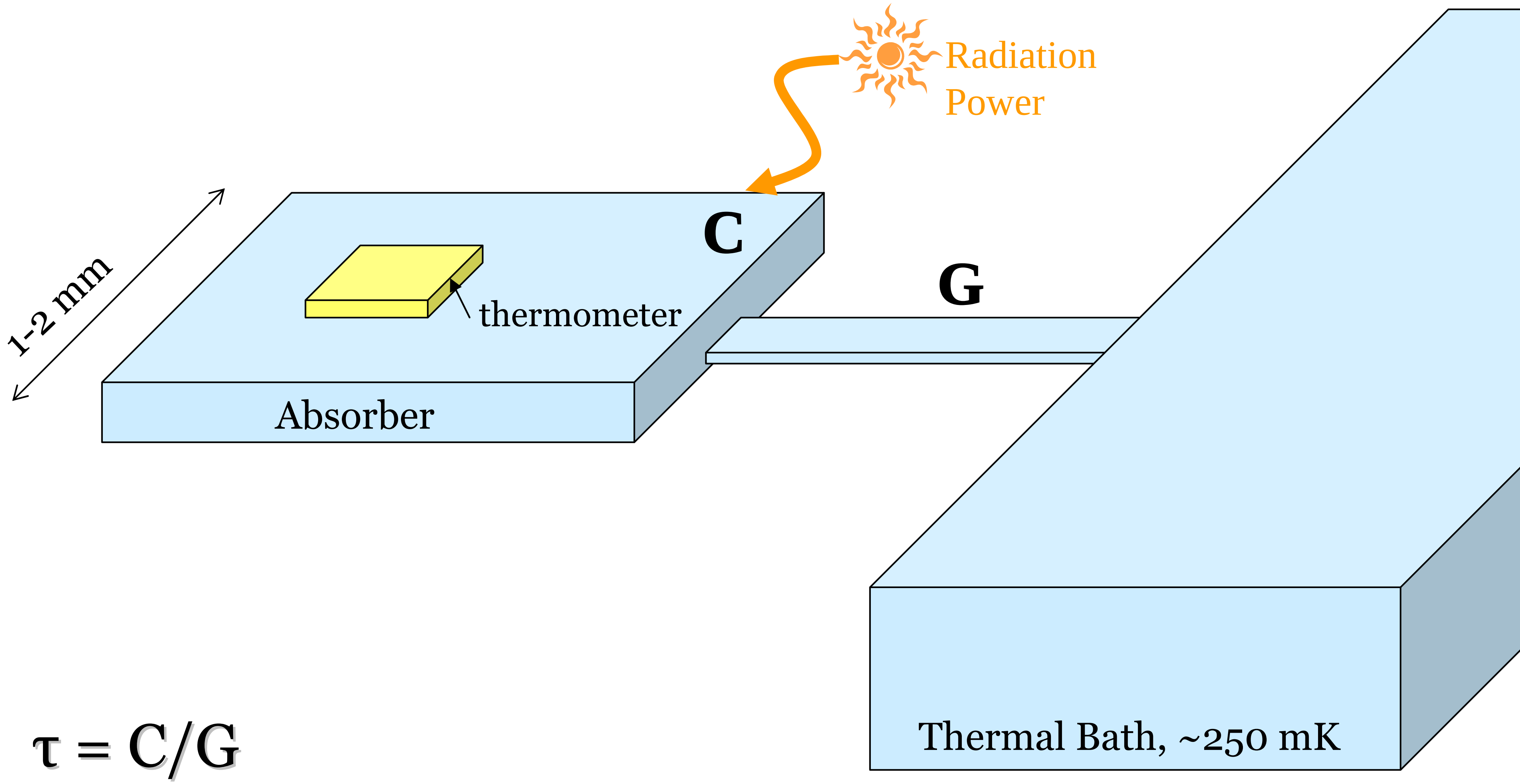


Bandpass Definition
Monolithic
Multilayer
capacitive
Mesh.
4 layers.
Metal on Polypropylen
Transmission
1
0
Frequency
waveguide


NIST
SA4 V2
8


LBNL
UCB
TRW

Basic Bolometer



$\tau = C/G$

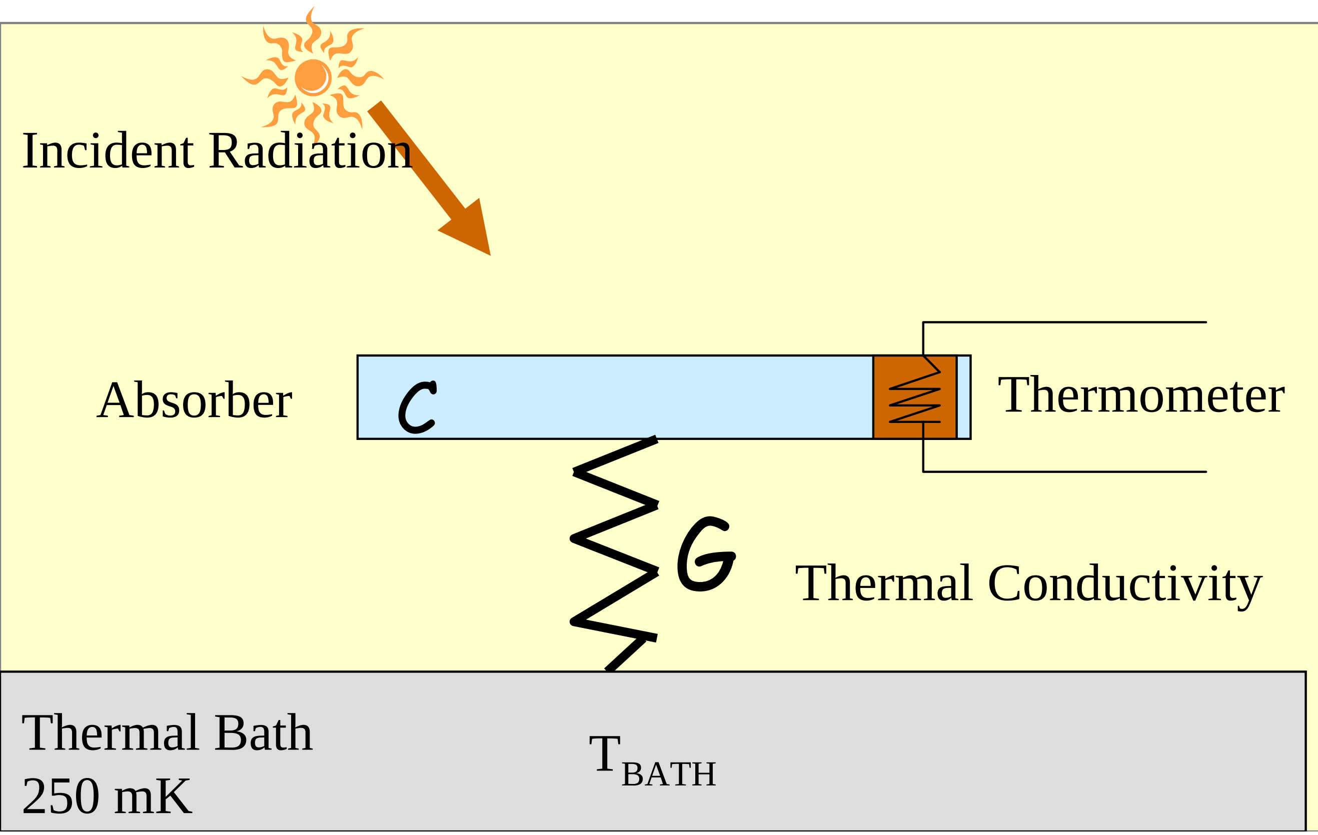
TES Bolometers

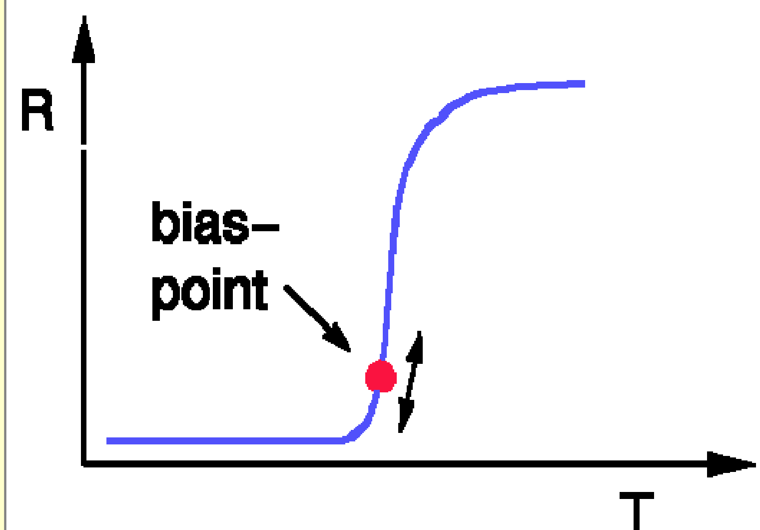
- Low impedance, ~ 0.5 Ω
- Low noise, 20 pA/√Hz → ~ 50 aW/√Hz
- Voltage Bias in Electro-thermal feedback
  - Fast, linear response and higher sensitivity

$$P_{bias} = V_{bias}^2 / R$$

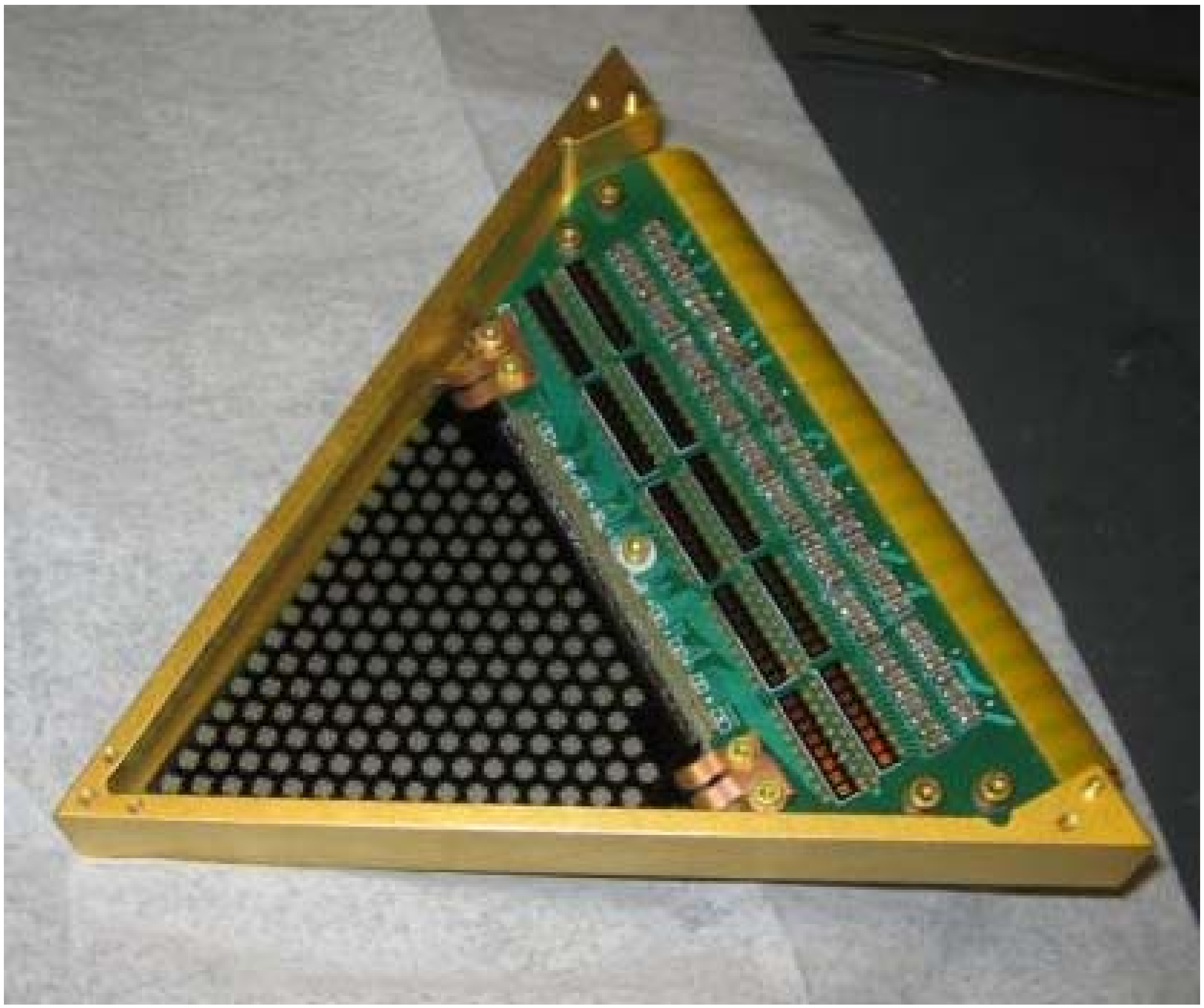
$$P_{Total} = P_{Radiation} + \frac{V^2}{R_{bolo}}$$

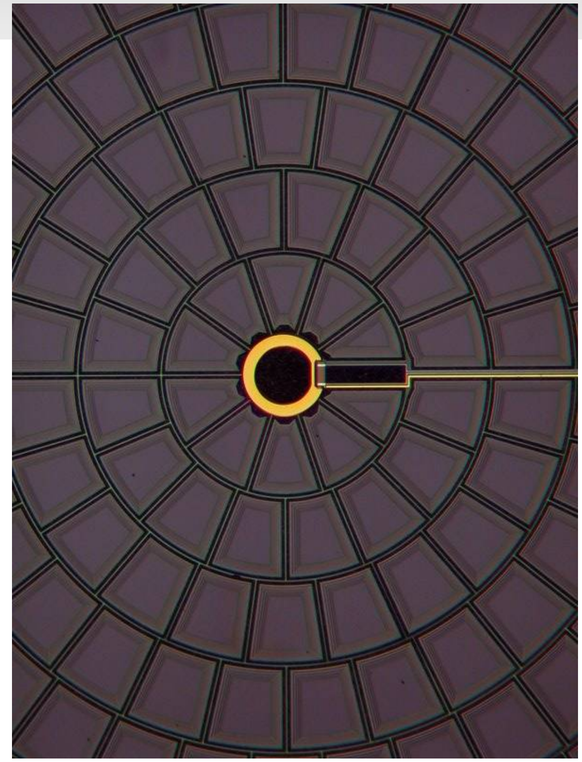
$$P_{Total} = P_{Radiation} + P_{Electrical} = CONST$$

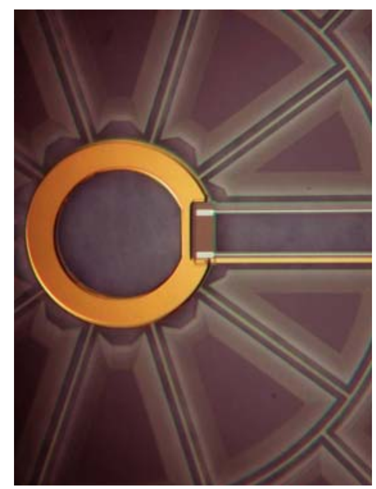




SPT Spyderweb Bolos







(Holzapfel and Lee, UC Berkeley)

Bolometer Responsivity

- The sensor's current response to a change in optical power is called the current responsivity, SI

$$\boxed{S_I = \frac{\partial I}{\partial P_{Optical}} = -\frac{1}{V_{bias}} \frac{\ell}{\ell+1} \frac{1}{1+i\omega\tau}} \qquad S_I \to 1/V_{bias}$$

- For strong electrothermal feedback, the loop gain ℓ is large (typically 10-100) and the low-frequency response S_I is independent of the signal power and the heat sink temperature.

$$\ell = \alpha P_{Optical} / (GT)$$

$$G = dP / dT$$

- α is a measure of the steepness of the superconducting transition and is the differential thermal conductance.

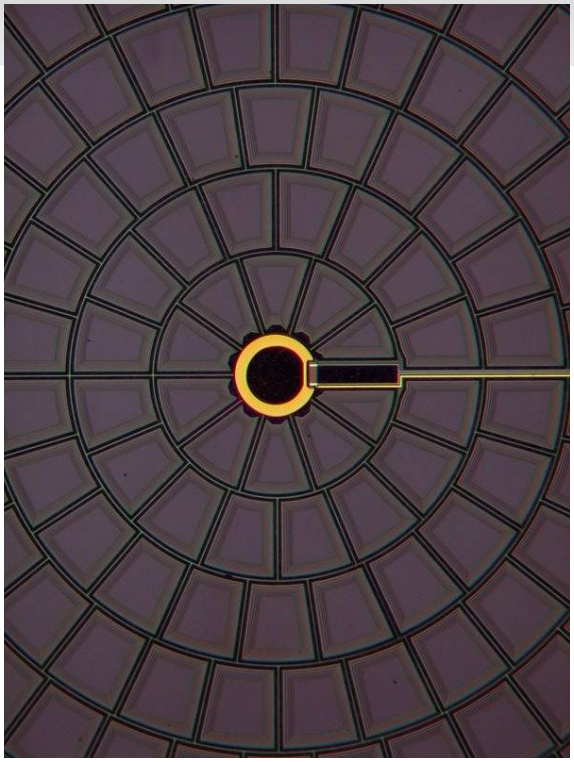
$$\alpha = (T / R) dR / dT$$

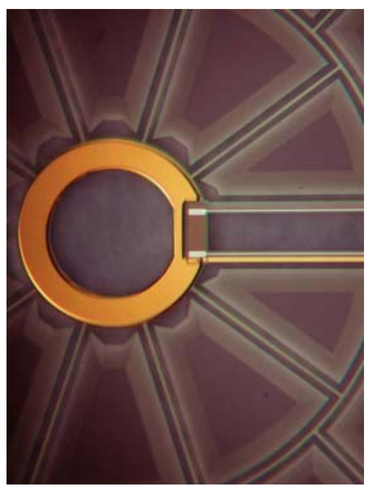
- The sensor's open loop intrinsic time constant τ_o, is decreased by the loop gain .

$$\tau_0 = C / G$$

$$\boxed{\tau = \tau_0 / \ell}$$

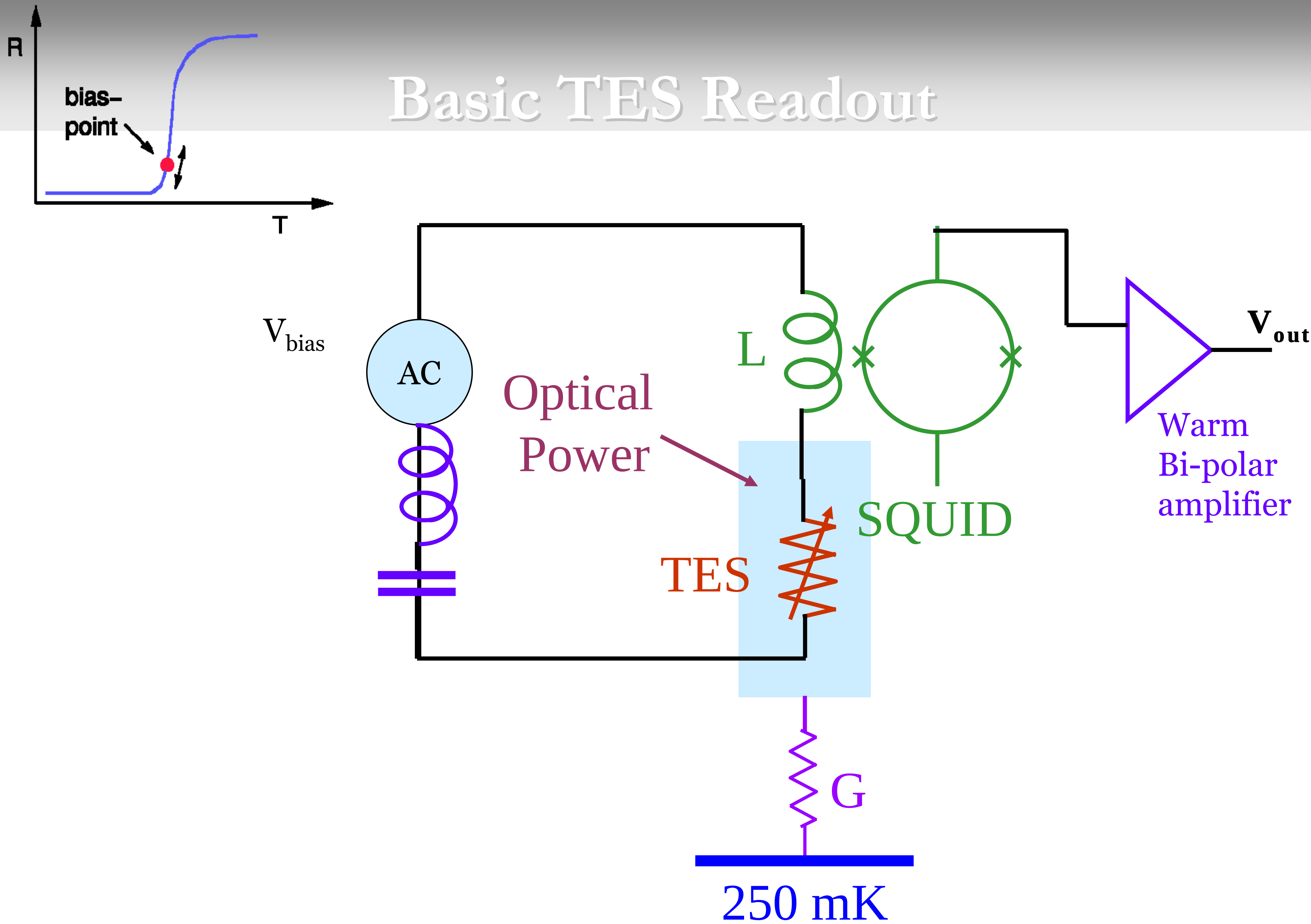
Time Constants and Decoupling





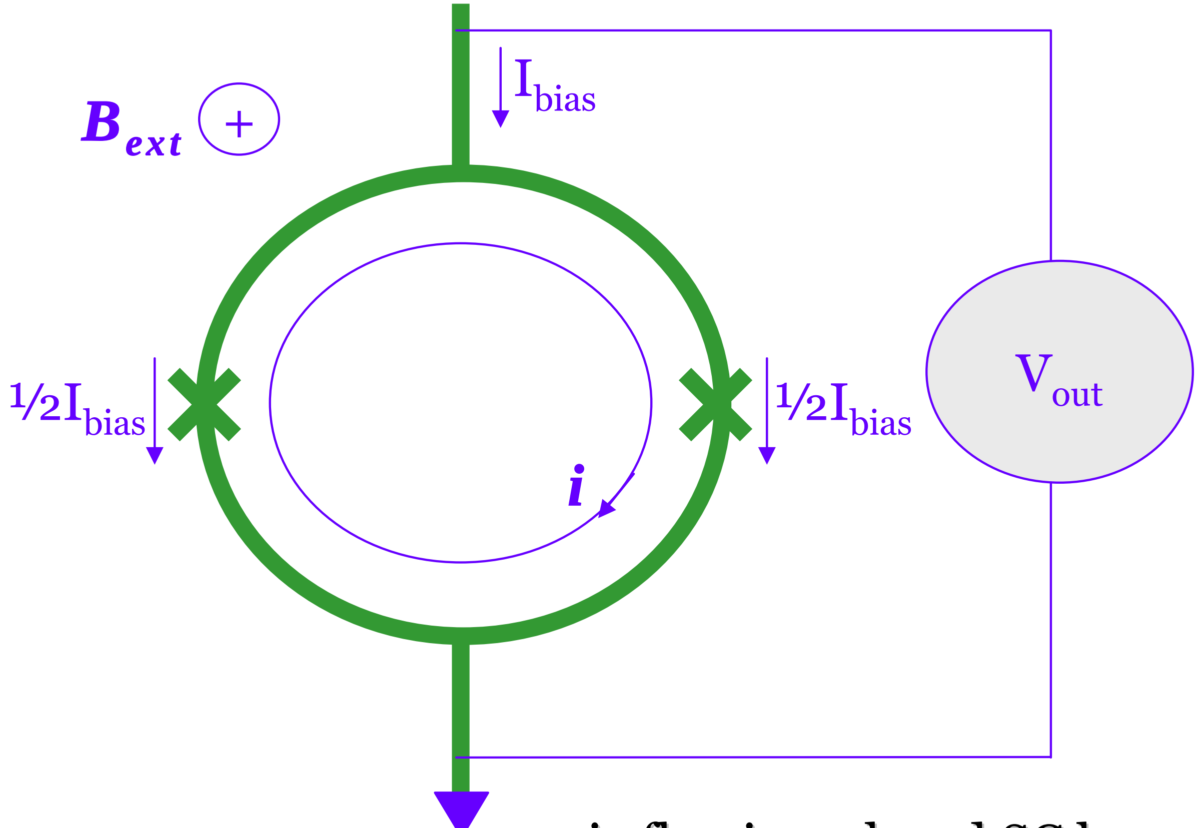
TES Detector Readout

Basic TES Readout

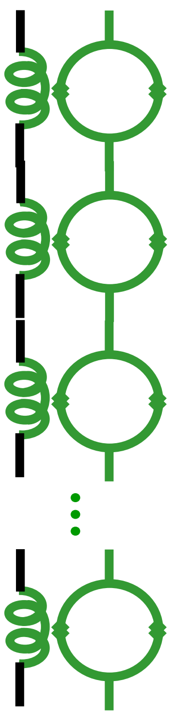


DC SQUID

- ultra-sensitive Magnetometer, 3 fT/√Hz
- transistor of the cryogenic world?



transimpedance
I→V device



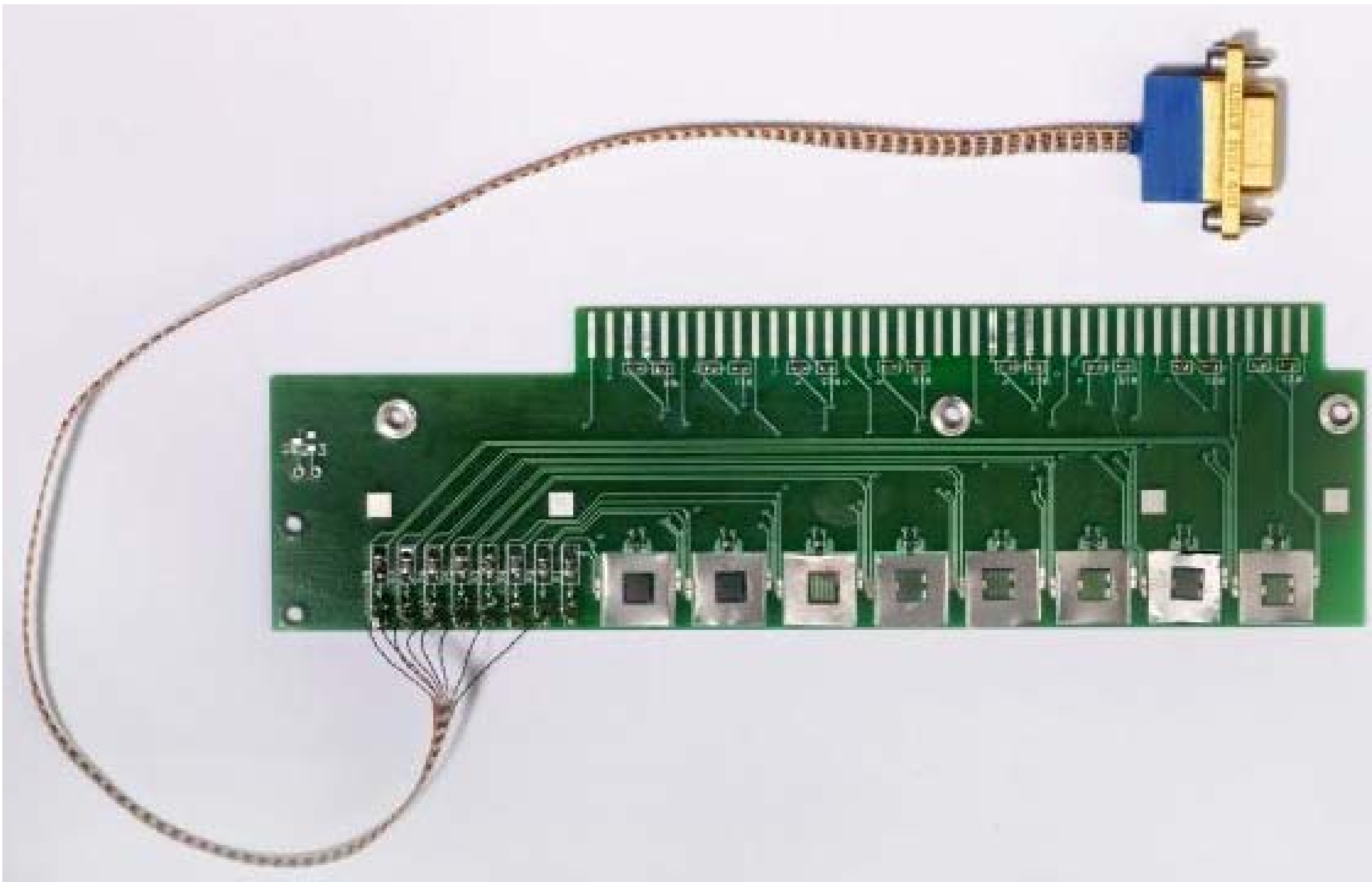
series array SQUID

• magnetic flux in a closed SC loop is quantized in units of the flux quantum

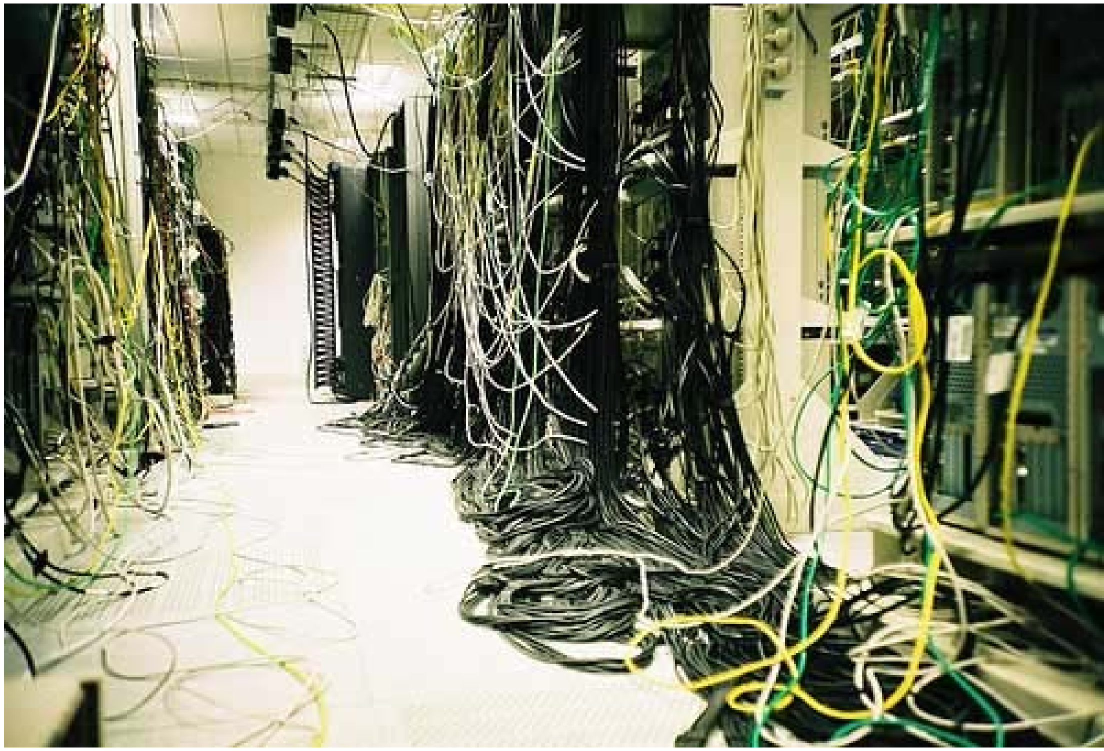
Φo =h/2e =2.07x10-15 Wb.

• Josephson tunneling

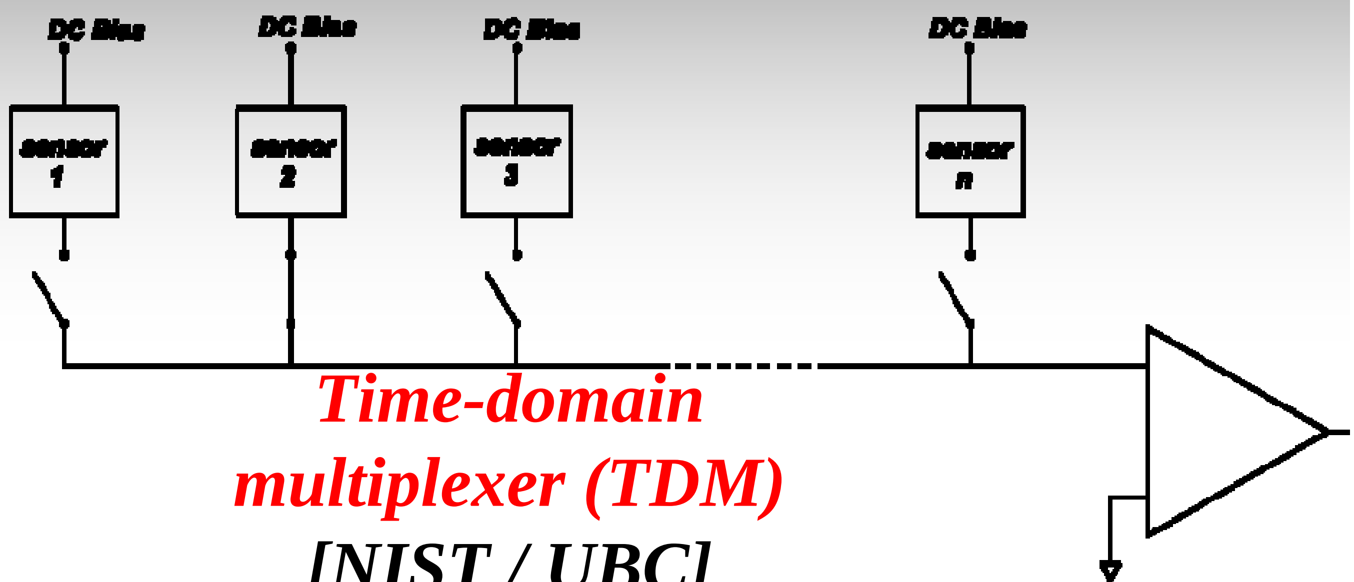
SQUID Pre-amplfiers

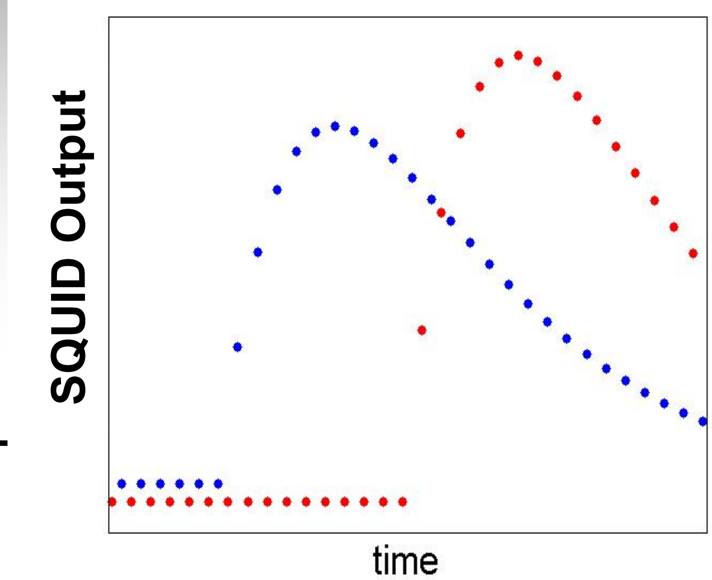


- Kilopixel → 4000 cryogenic wires
- Heat load
- Cost
- Cold complexity

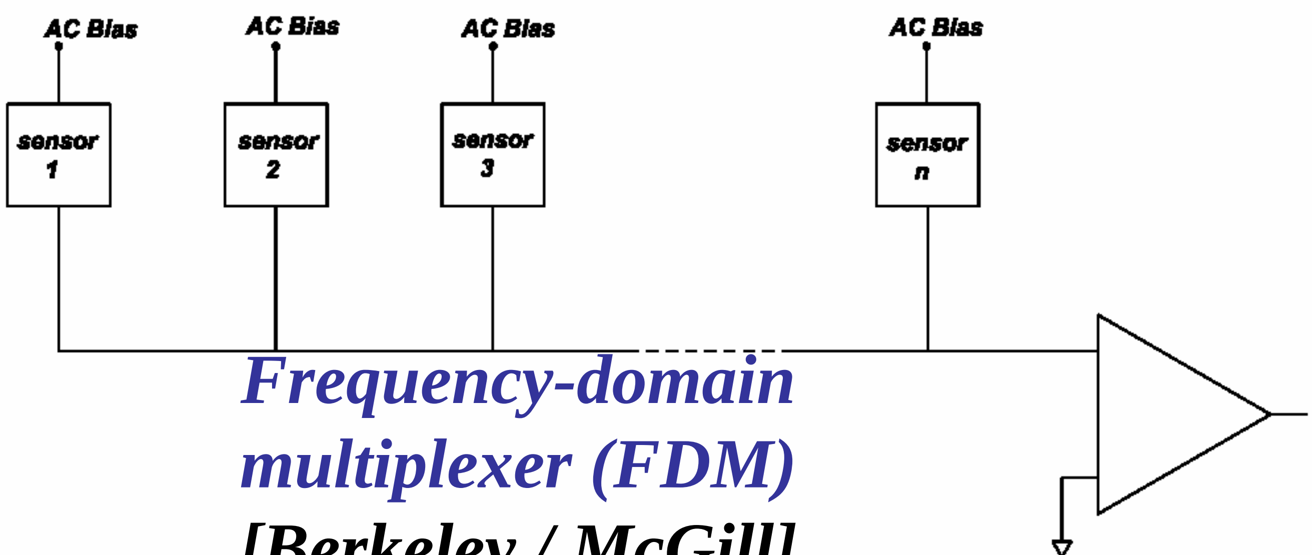


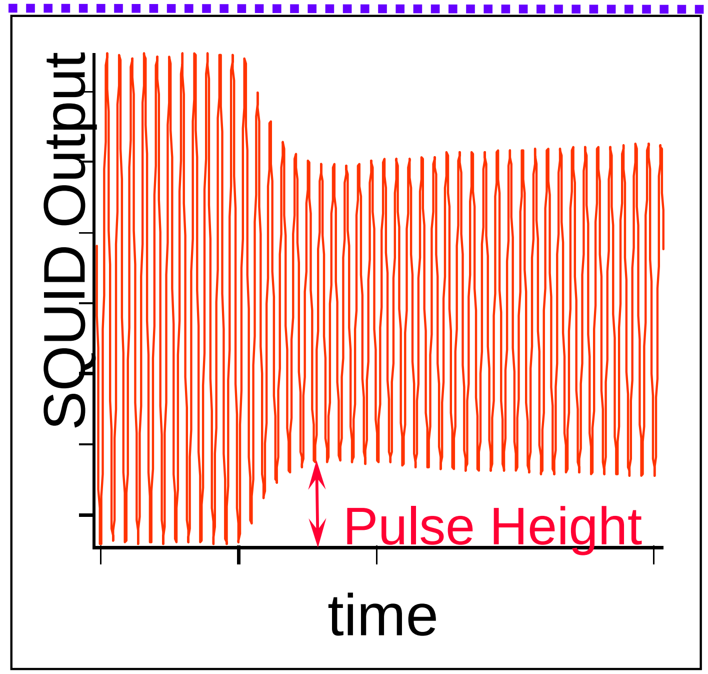
Multiplexing





Time-domain multiplexer (TDM)
[NIST / UBC]





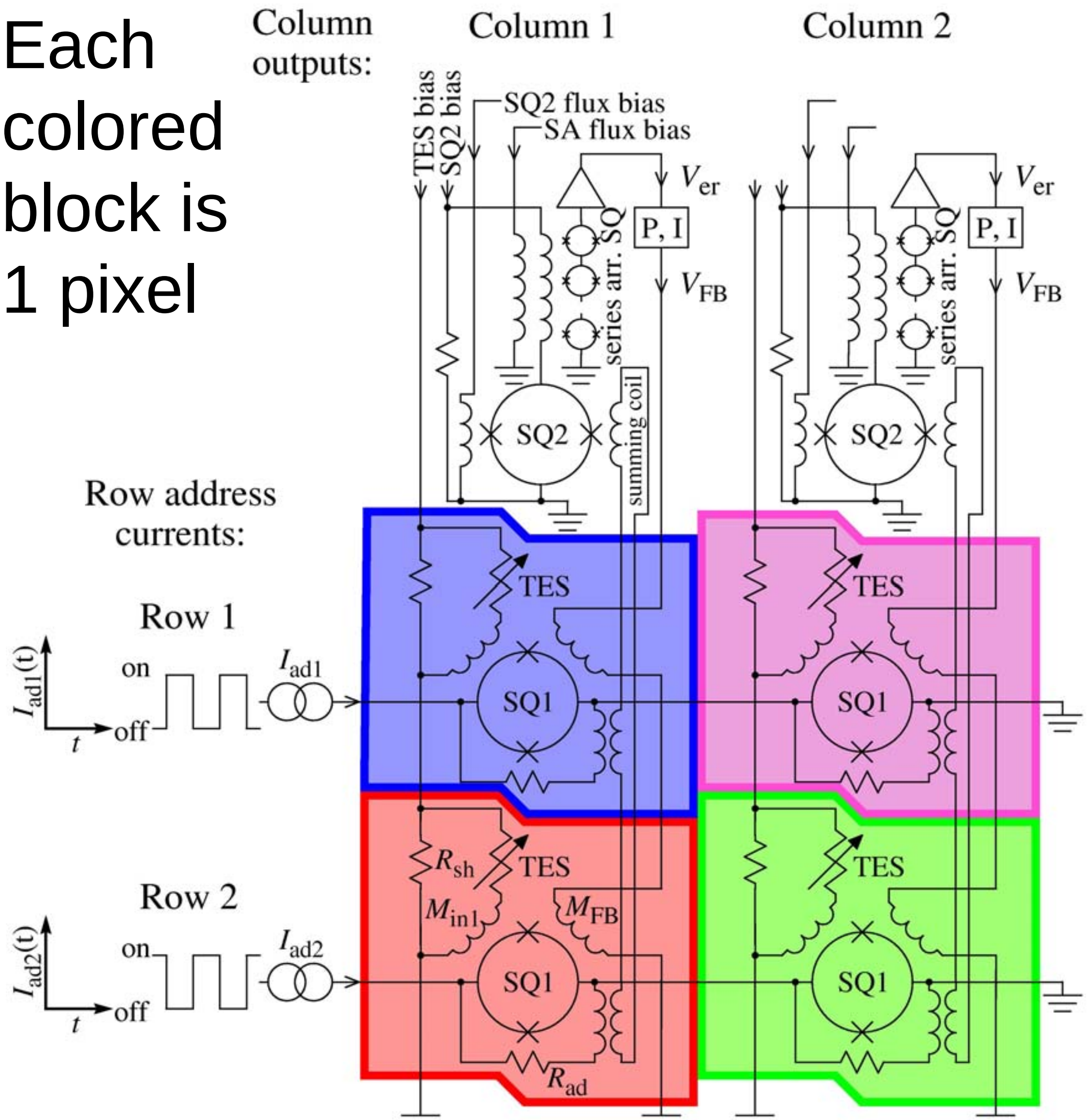
Frequency-domain multiplexer (FDM)
[Berkeley / McGill]

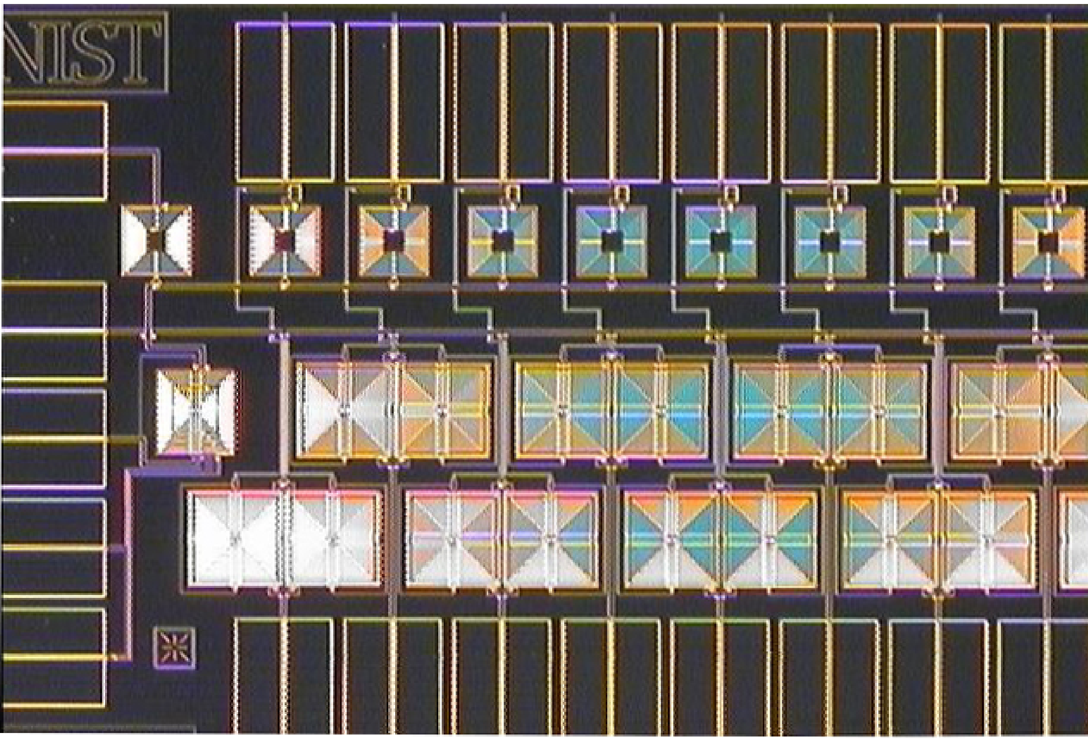
Time Domain Multiplexing

Kent Irwin, NIST

- a SQUID is connected to each bolometer pixel at the base temperature – acts as a switch which selects a row of detectors
- series array SQUID preamplifies the signals from a row of detectors to send out warm

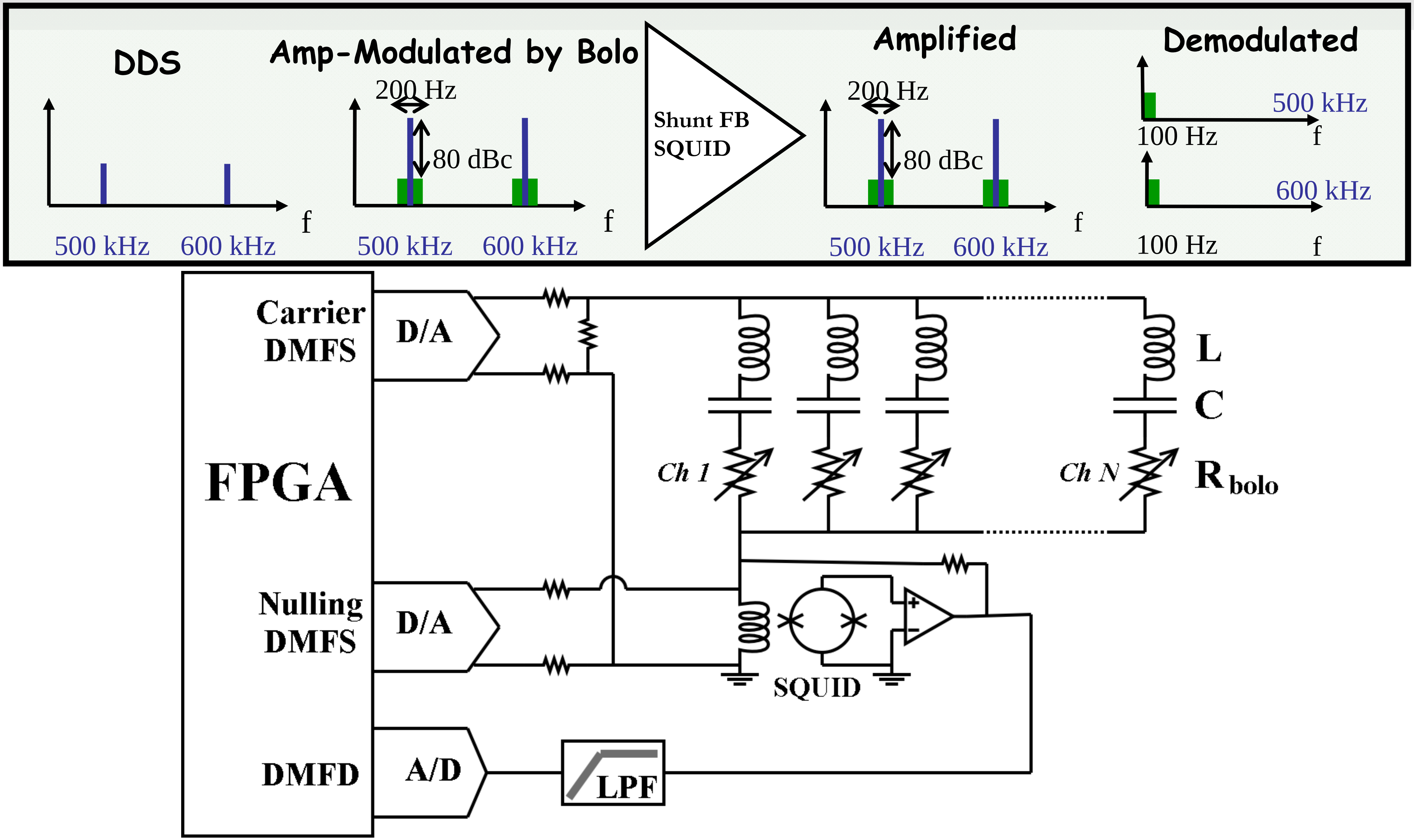
Each colored block is 1 pixel



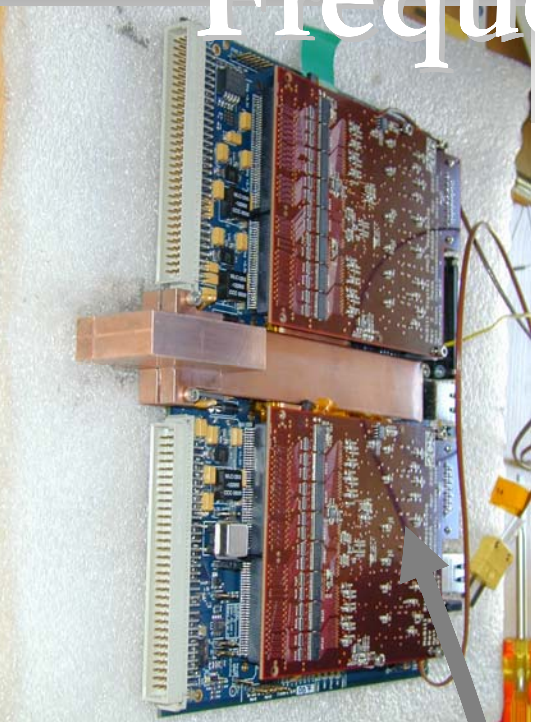


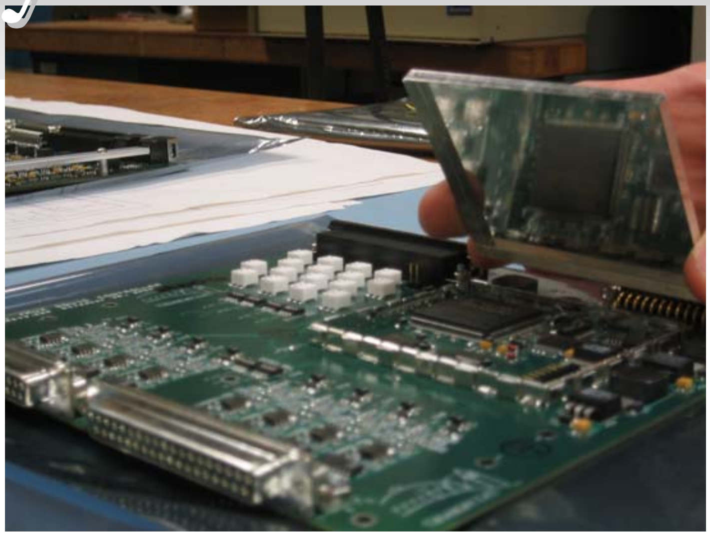
SQUID Integrated Circuit (!!)

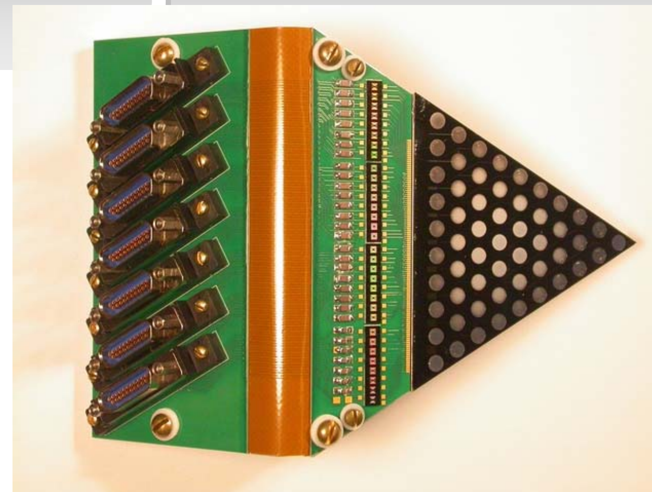
Frequency Domain Multiplexer

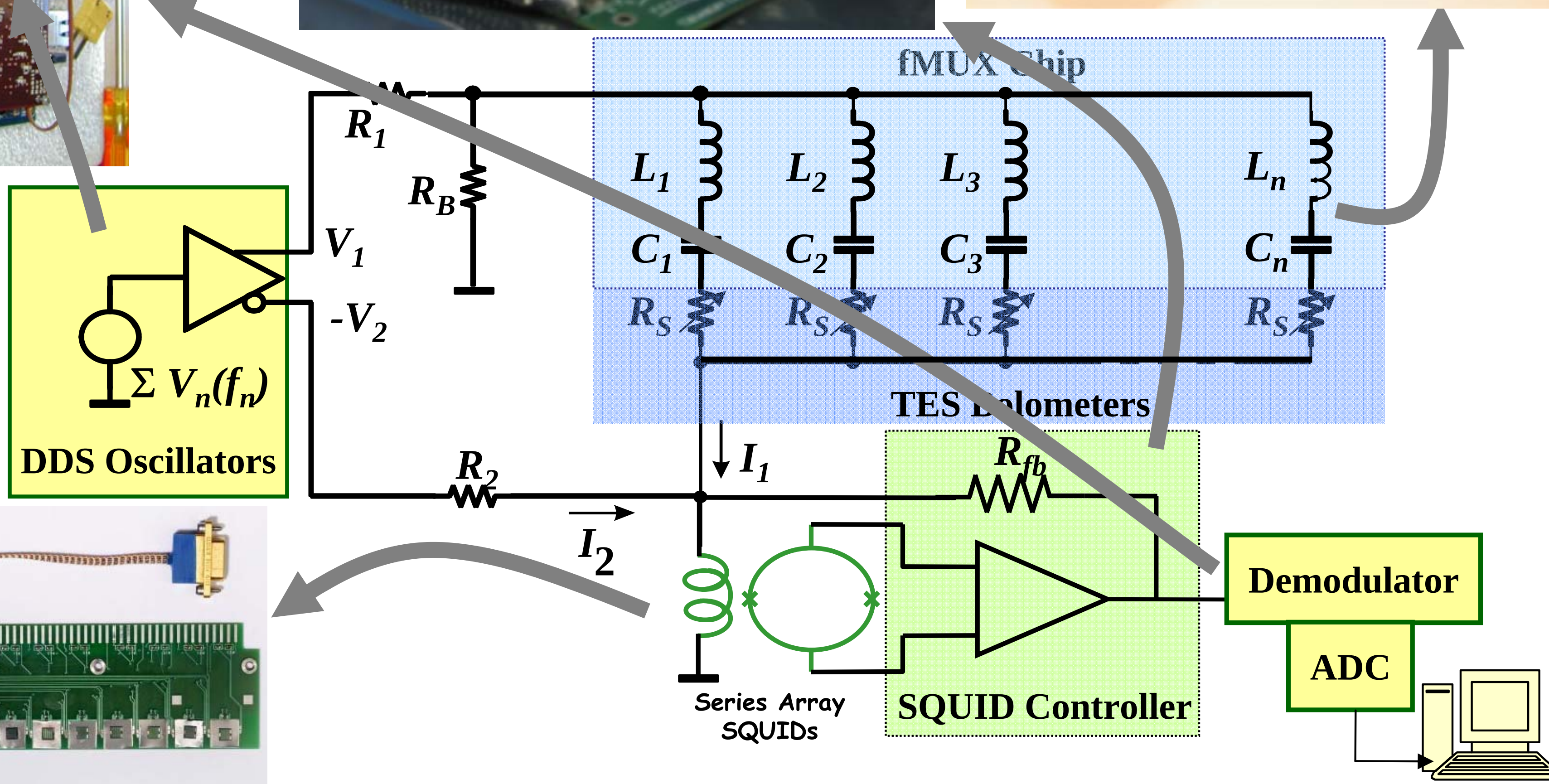


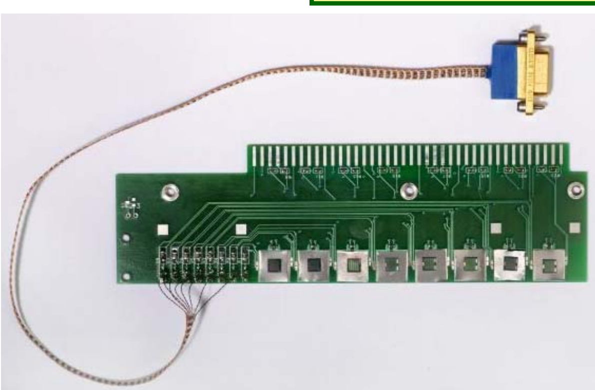
Frequency Domain Multiplexer



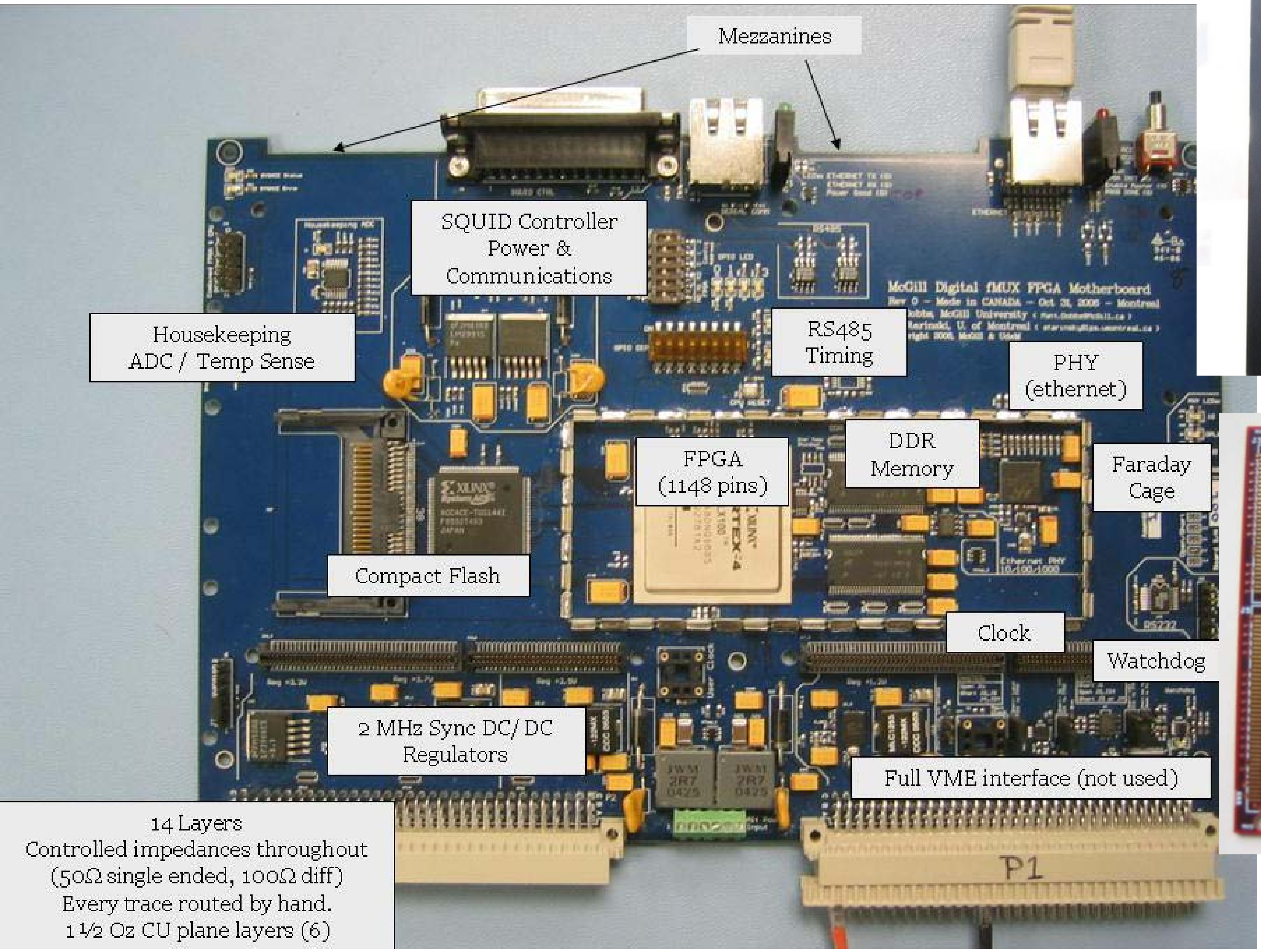


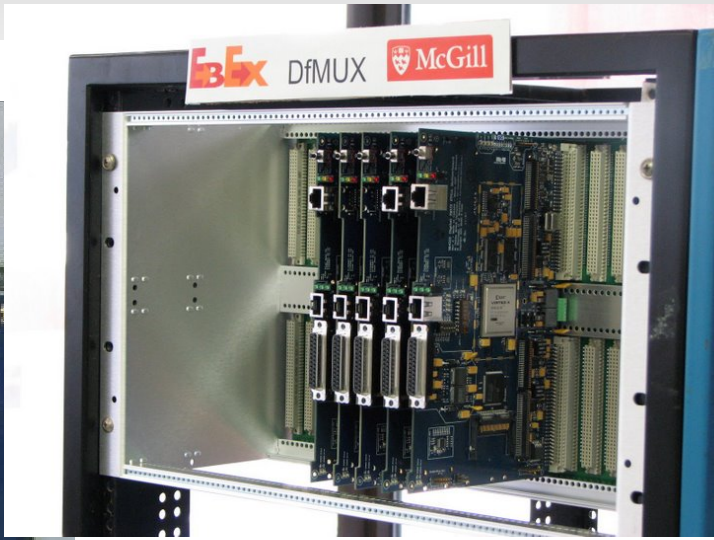


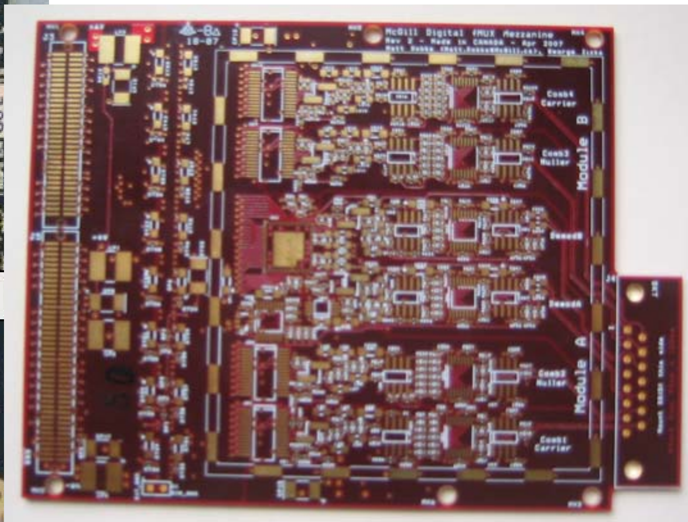




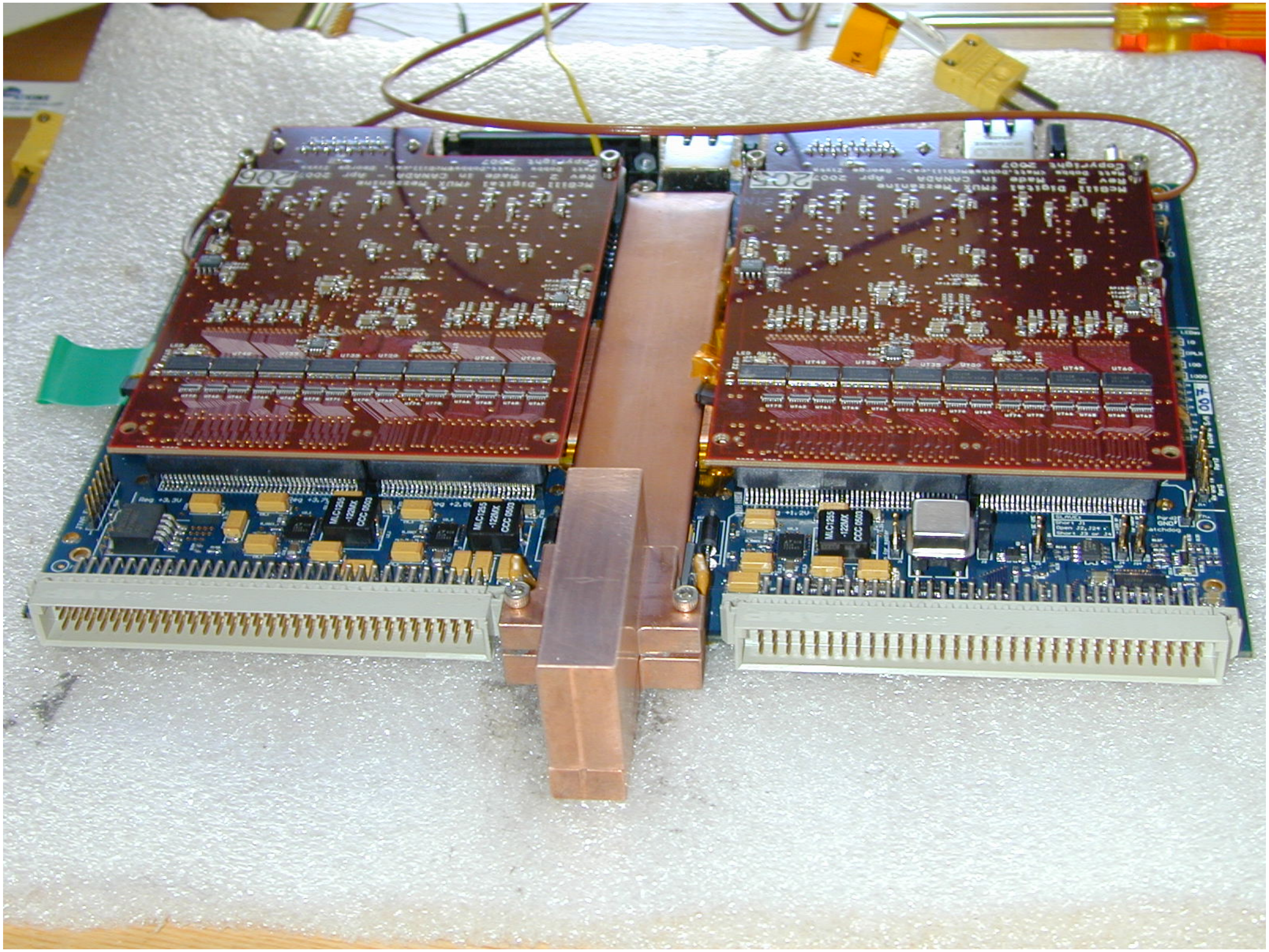
Electronics Anatomy



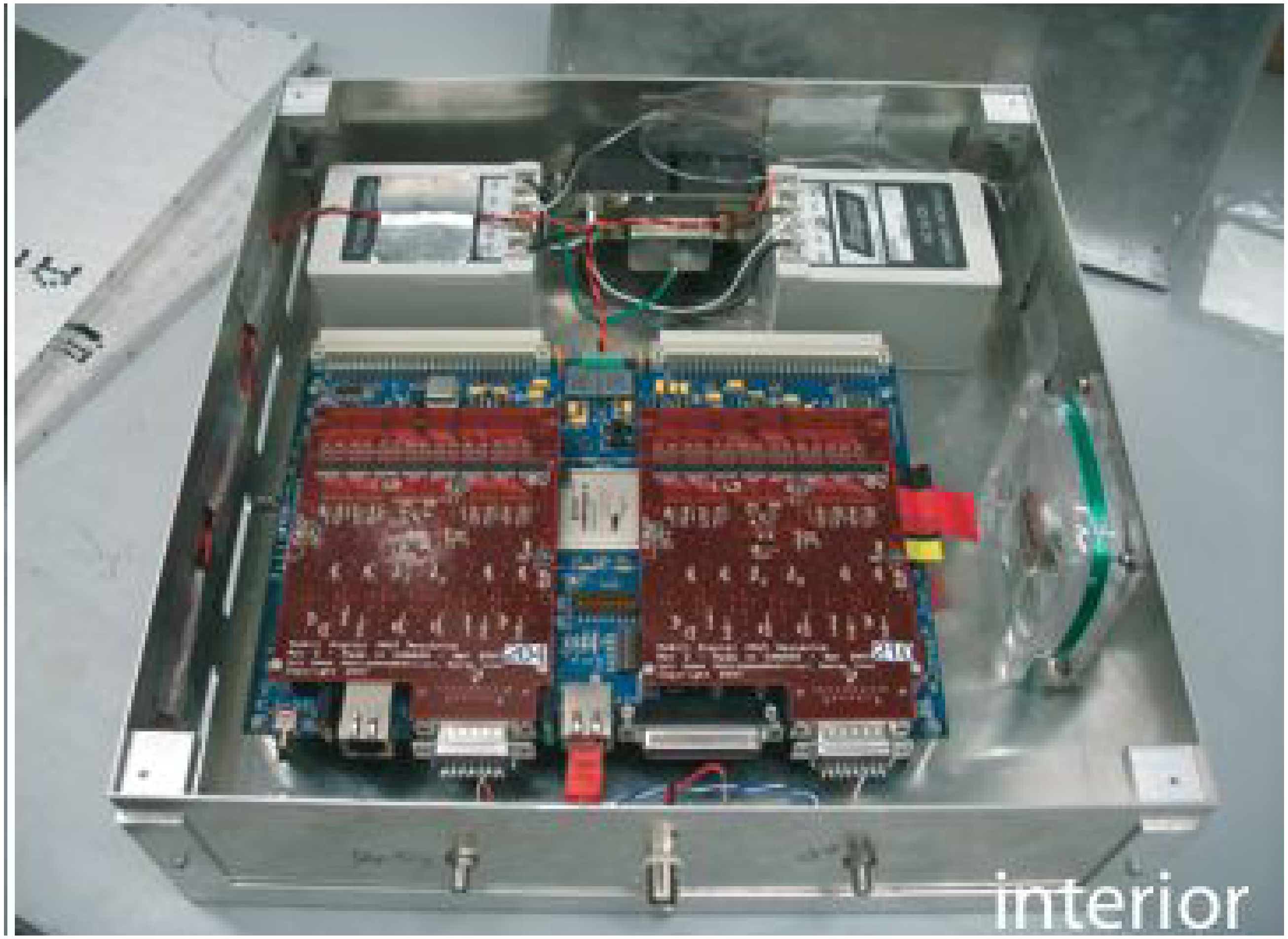




McGill Digital Mux



DfMux Transformed into SPT Holography Correlator

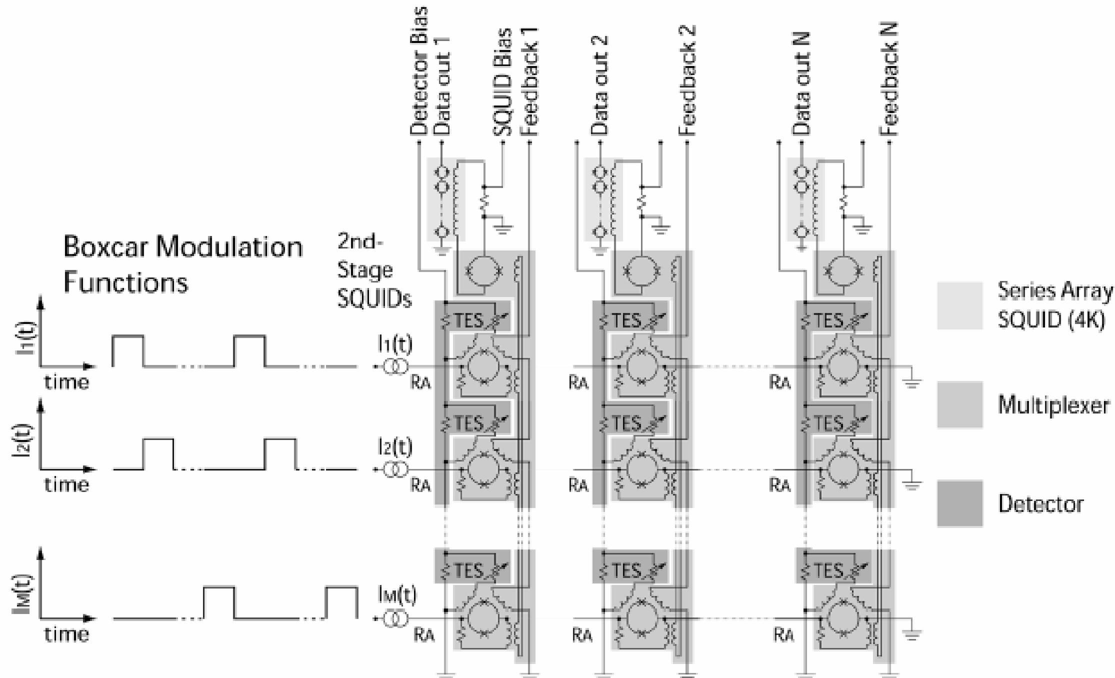


Summary Multiplexing

Two complementary strategies:

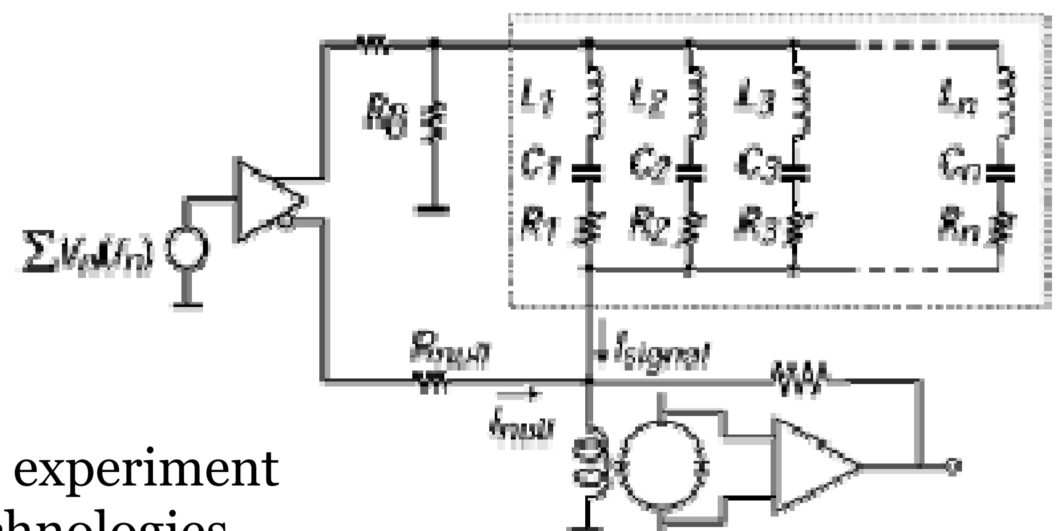
NIST/UBC Time Domain MUX

- ACT, SCUBA2, Clover, Spider,…



Berkeley/McGill Frequency Domain MUX

- Analog system: SPT/APEX
- Digital system: EBEX/Polarbear



Status: ***every*** CMB kilo-pixel bolometer experiment is using TES sensors and one of these technologies.

Noise

Electronic Noise

$$i = \frac{nev}{s}$$

the fluctuations in this current are given by the total differential

$$\langle di \rangle^2 = \left(\frac{ne}{s} \langle dv \rangle \right)^2 + \left(\frac{ev}{s} \langle dn \rangle \right)^2$$

Velocity fluctuations
“Thermal noise”

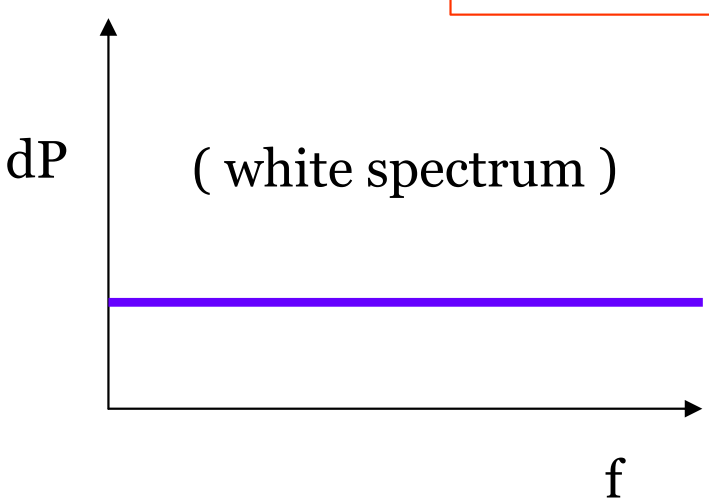
Number fluctuations
“shot noise”

Thermal (Johnson Noise)

$$\langle di \rangle^2 = \left(\frac{ne}{s} \langle dv \rangle \right)^2 + \left(\frac{ev}{s} \langle dn \rangle \right)^2$$

- Thermal noise is described by the low energy (Rayleigh-Jeans limit) of Planck's black body spectrum, where the power per unit bandwidth is constant.

$$\boxed{\frac{dP_n}{df} = 4kT}$$



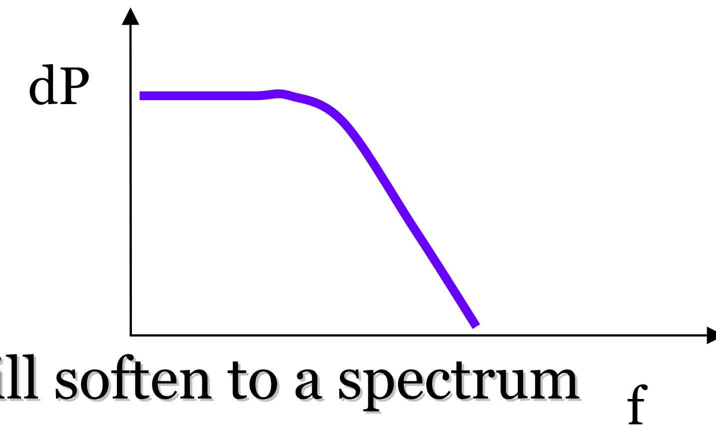
Shot noise occurs anytime electrons are injected independently of one another as in thermionic or semiconductor diodes.

$$\boxed{i_n^{\ 2} = 2eI}$$

Low Frequency Noise

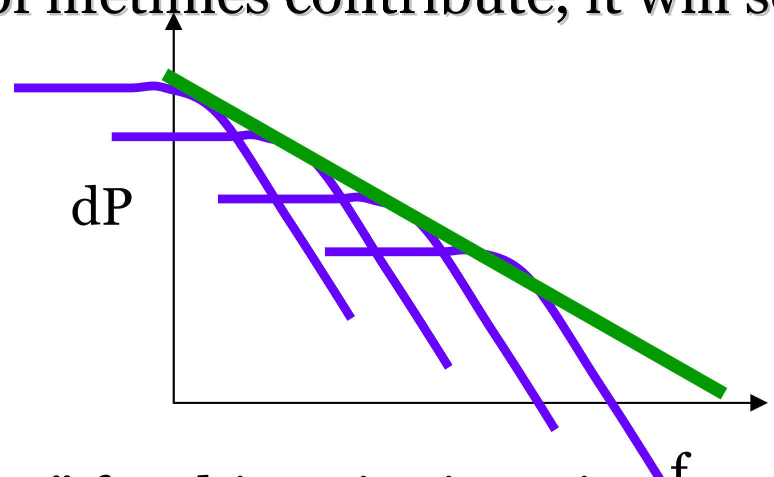
- Number fluctuations can also be caused by carrier trappings.
- Impurities/imperfections in a crystal lattice will trap carriers, and release them after a characteristic lifetime.
- If there is just one lifetime, the spectrum of this noise will be

$$\boxed{\frac{dP_n}{df} \propto \frac{1}{f^2}}$$



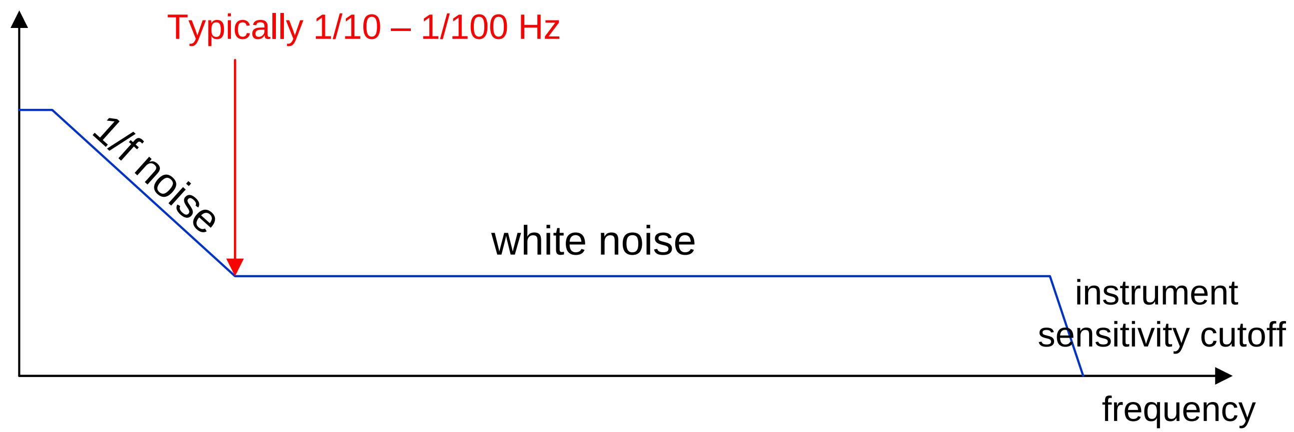
- if an infinite number of lifetimes contribute, it will soften to a spectrum

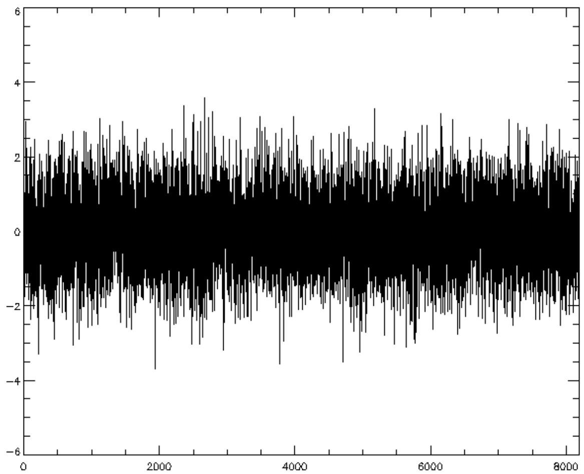
$$\boxed{\frac{dP_n}{df} \propto \frac{1}{f}}$$



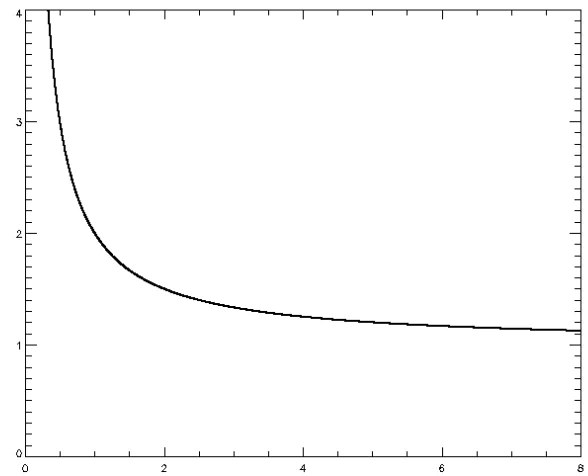
- the low frequency "knee" for this noise is an important parameter, and can be improved by improving the purity of non-ohmic devices.

Noise vs. Frequency



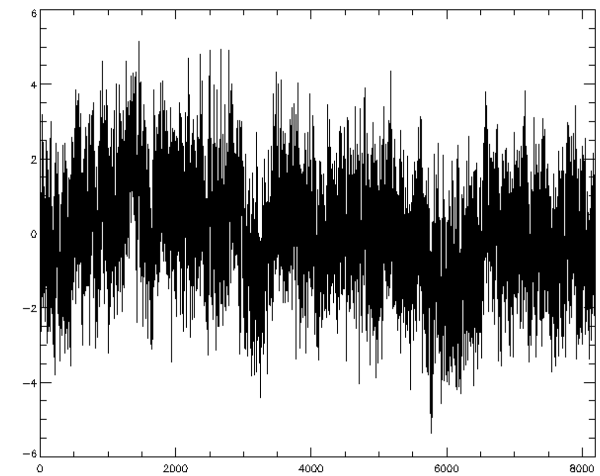


FFT, x



-1

FFT



Noise on the Sky

- Noise equivalent temperature (NET) is defined as the temperature fluctuation required to achieve a signal to noise ratio of 1:1 in a 1 Hz signal bandwidth.
  - NET is defined at a specific location along the optical chain – almost always the sky.
  - and you have to specify what "type" of temperature you're referring it to: usually ΔT_{CMB} or ΔT_{RJ}.

$$NET_{CMB}\left[\mu K \cdot \sqrt{s}\right] = \frac{1}{\eta\sqrt{2}} \left.\frac{dT}{dP}\right|_{T_{CMB}} \times NEP\left[\frac{W}{\sqrt{Hz}}\right]$$

What's up with this?

  - η is the optical efficiency – the fraction of photons remaining after traveling through the optics system

Nyquist and the factor √2

- Silly convention:
  - When we talk about NEP, we use units of W/√Hz
  - When we talk about NET, we use units of μK•√s
    - Since the bandwidth for a 1 second timestream (according to Nyquist theorem) is ½ Hz, there is a factor of √2 difference in addition to the conversion from μK to W.
    - e.g.

$$10\frac{\mu K}{\sqrt{Hz}}\times\frac{1}{\sqrt{2}}=7\,\mu K\cdot\sqrt{s}$$

Bolometer Noise

Several fundamental noise sources

- Photon Noise
- Phonon Noise
- Johnson noise
- 1/f noise

Good Reference: P. Richards, "Bolometers for infrared and millimeter waves", J. Appl. Phys., Vol 76 (1994) 1.

Good bolometer intro:
Richards & McCreight, "Infrared Detectors for Astrophysics", Physics Today (February 2005) P. 41.
(matt has a copy if you want to borrow it).

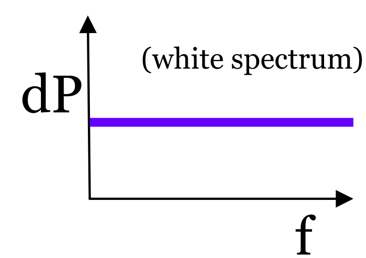
Photon Noise

- Arises because the incident radiation power is quantized… there is a randomness to the arrival times of the photons.
  - These fluctuations follow Poisson statistics
  - average number of photons arriving per second is $N \pm \Delta N = N \pm \sqrt{N}$

2 polarizations

$$NEP = h\nu\sqrt{2N} = \sqrt{2\cdot h\nu\cdot(h\nu\cdot N)} = \sqrt{2\cdot h\nu\cdot P_{Radiation}}$$

$$\boxed{NEP = \sqrt{2h\nu P_{Radiation}}}\left[\frac{W}{\sqrt{Hz}}\right]$$

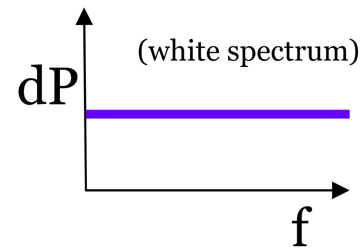


Photon Noise (2)

$$NEP_{photon} = \sqrt{2h\nu P_{Radiation}}$$

- term in the Photon noise that arises because of the correlations (bunching) between the photons. If this were a 100% bunching, it would change the photon

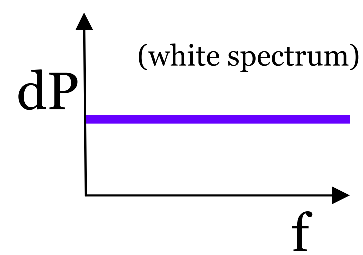
$$NEP_{photon} = \sqrt{\gamma \frac{P_{Radiation}^{2}}{\Delta\nu}} \quad \left[\frac{W}{\sqrt{Hz}}\right]$$



  - $\Delta\nu$ is just the bandwidth – typically 25 – 40 GHz.
  - γ is a fudge factor, typically 0.3, which encapsulates our lack of understanding for this phenomena. ACBAR has measured it – but interpretation of the data relies on us fully believing that all aspects of the noise have been understood.
  - As the bandwidth gets smaller, this noise goes up, as the photons are more the same frequency.
- there is still quite some debate about the correct mathematical form for this.

Phonon Noise

- arises from energy fluctuations in the heat flow across the bolometer.
  - Heat flows at the speed of sound, and can be understood with a "phonon" model, wherein the heat takes on a particle-like behavior.
  - Caused by the quantization of the energy carriers: phonons, electrons



$$\boxed{NEP = \sqrt{4kT^2G}} \quad \left[\frac{W}{\sqrt{Hz}}\right]$$

Johnson Noise + Low Frequency Noise

- Johnson noise is exactly the same as for a resistor

$$\boxed{\frac{dP_n}{df} = 4kT}$$

- its bandwidth is unlimited, so it is normally cut off with a low pass anti-aliasing filter.

- There are many possible sources of low frequency noise in a bolometer (impurities, etc), and coupled in from other sources in the experiment (temperature drifts, etc.). We can't cover them all here.
  - A really good 1/f knee would be at 50 mHz.
  - A typical 1/f knee is about 0.3 – 1 Hz.

Bolometer Noise

TES Device Noise

Example: APEX-SZ

- Johnson Noise — 12 aW/√Hz

$$NEP = \sqrt{4k_B T_{bolo} P_{elec}}$$

- PhoNon Noise — 60 aW/√Hz

$$NEP = \sqrt{4k_B T_{bolo}^2 G}$$

Limits from Mother Nature

- Photon Shot Noise & Correlations — 100 aW/√Hz

$$NEP = \sqrt{2h\nu P_{incident} + \gamma \frac{P_{incident}^2}{\Delta\nu}}$$

(aW = 10^{-18} W)

Sensors are reaching fundamental limits (though we're not there yet for orbital missions). Achieving better signal to noise requires longer integration (forget it) or making many measurements simultaneously (large format arrays).

- photolithographic sensor construction
- readout multiplexing

Excess Noise

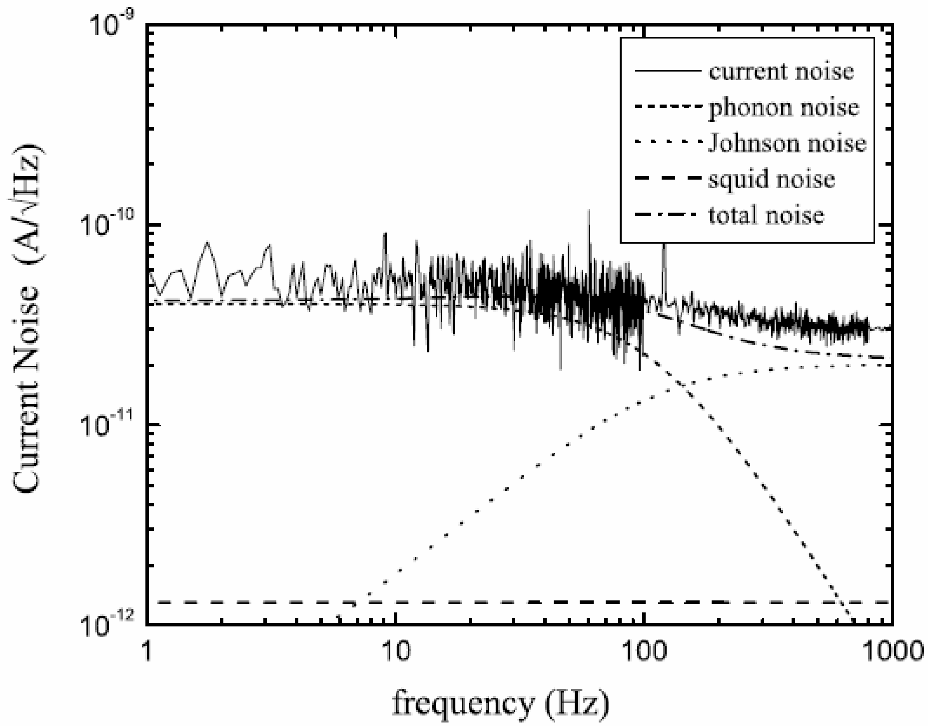
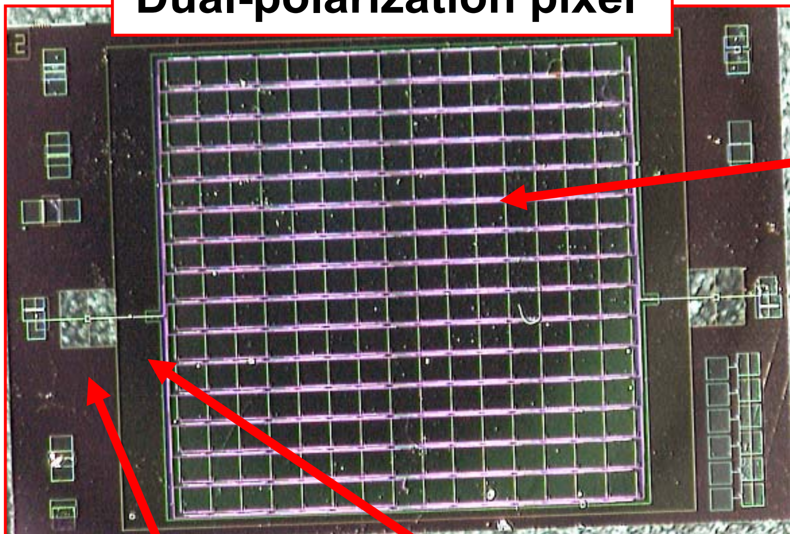


Figure 3: Measured current noise from the single element TES, biased at 0.38 μV. Spectra taken at different frequency bands were combined for better coverage of the range of frequencies. There is slight excess noise at frequencies above ~200 Hz.

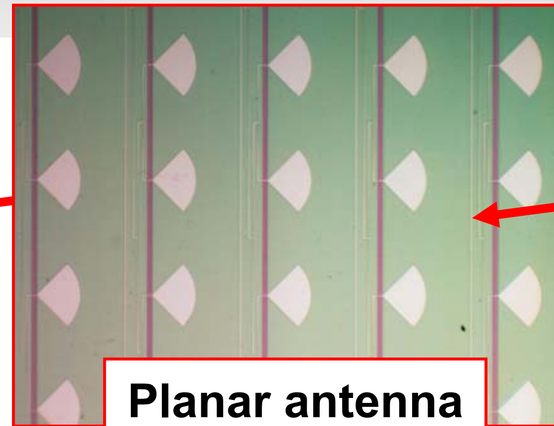
Cynthia Hunt et al., Antenna Coupled Bolometers, (JPL) SPIE 2002

Really Cool Bolometers

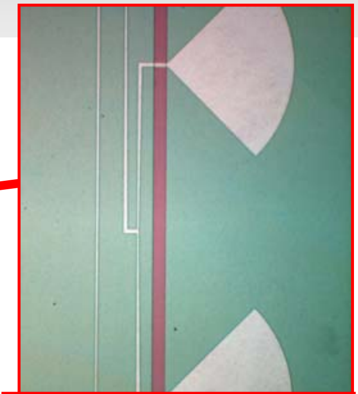
Antenna Coupling Bolometers for Arrays



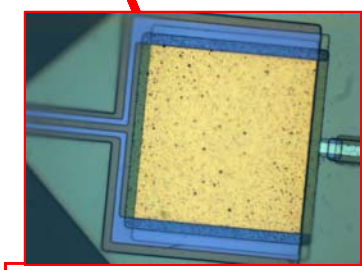
Dual-polarization pixel



Planar antenna

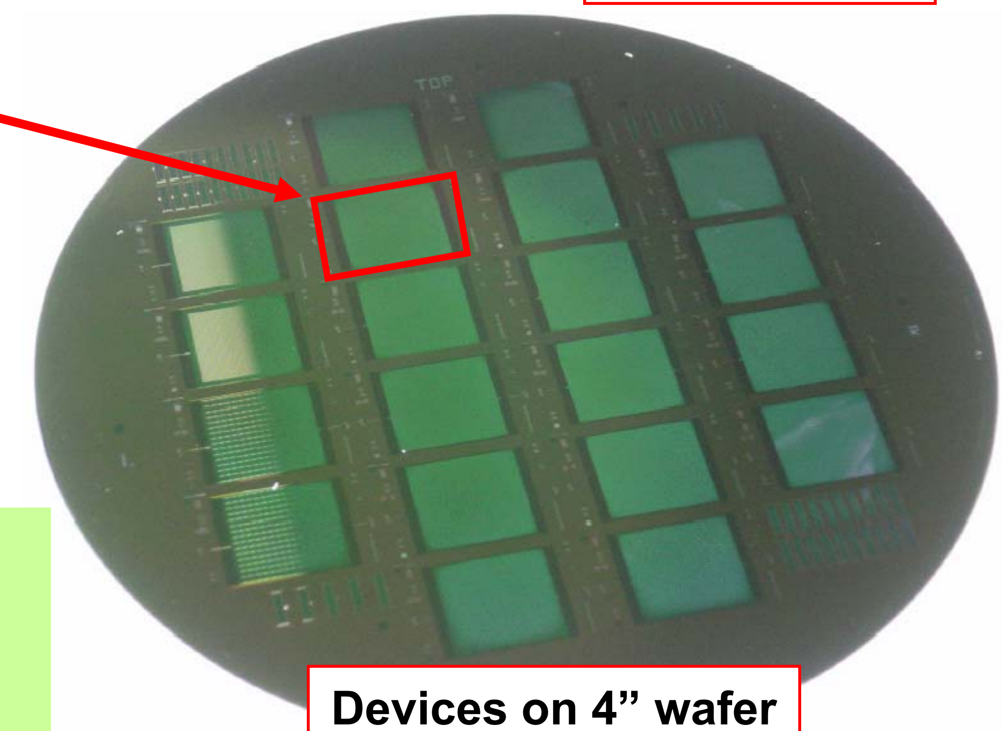


Nb microstrip



TES bolometer

25 % BW filter



Devices on 4” wafer

Jamie Bock / JPL
Andrew Lange / Caltech

Advantages:

- Antennas provide beam collimation
- Small active volumes
- Extendable to low frequencies
- SQUID multiplexed
- Detectors achieve sensitivity requirements

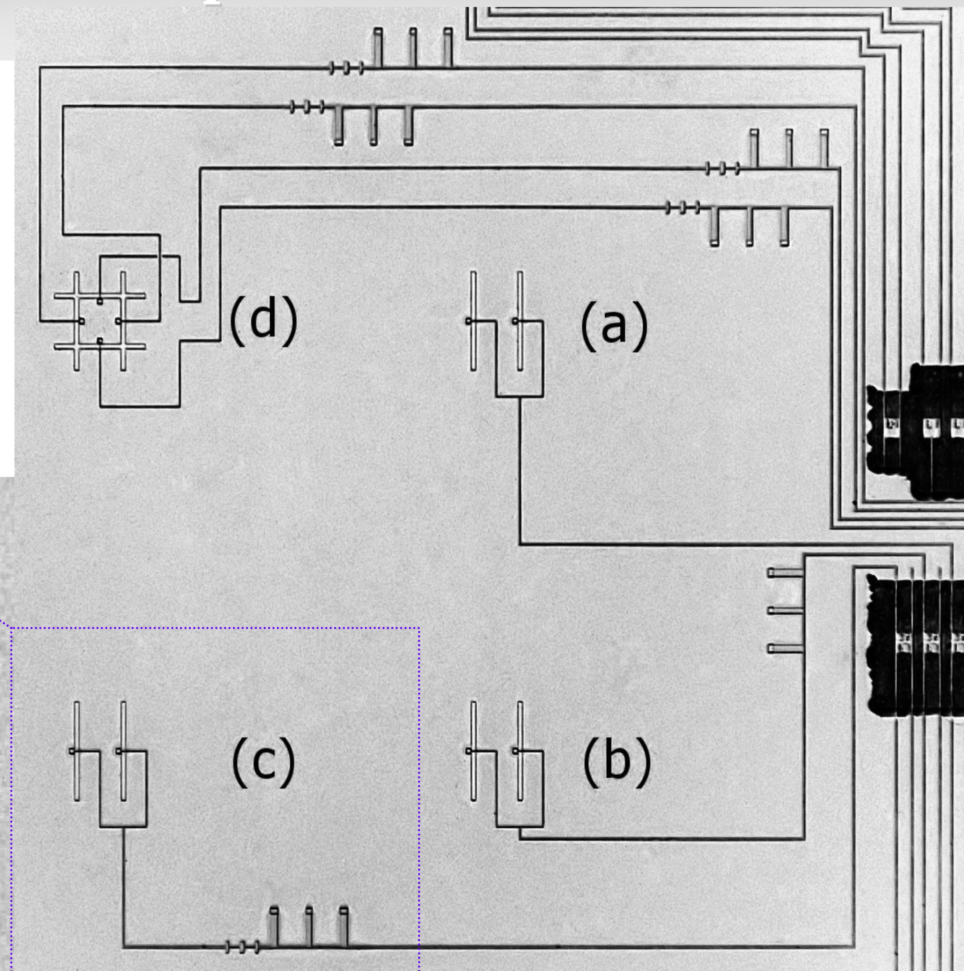
Antenna Coupled Bolometers

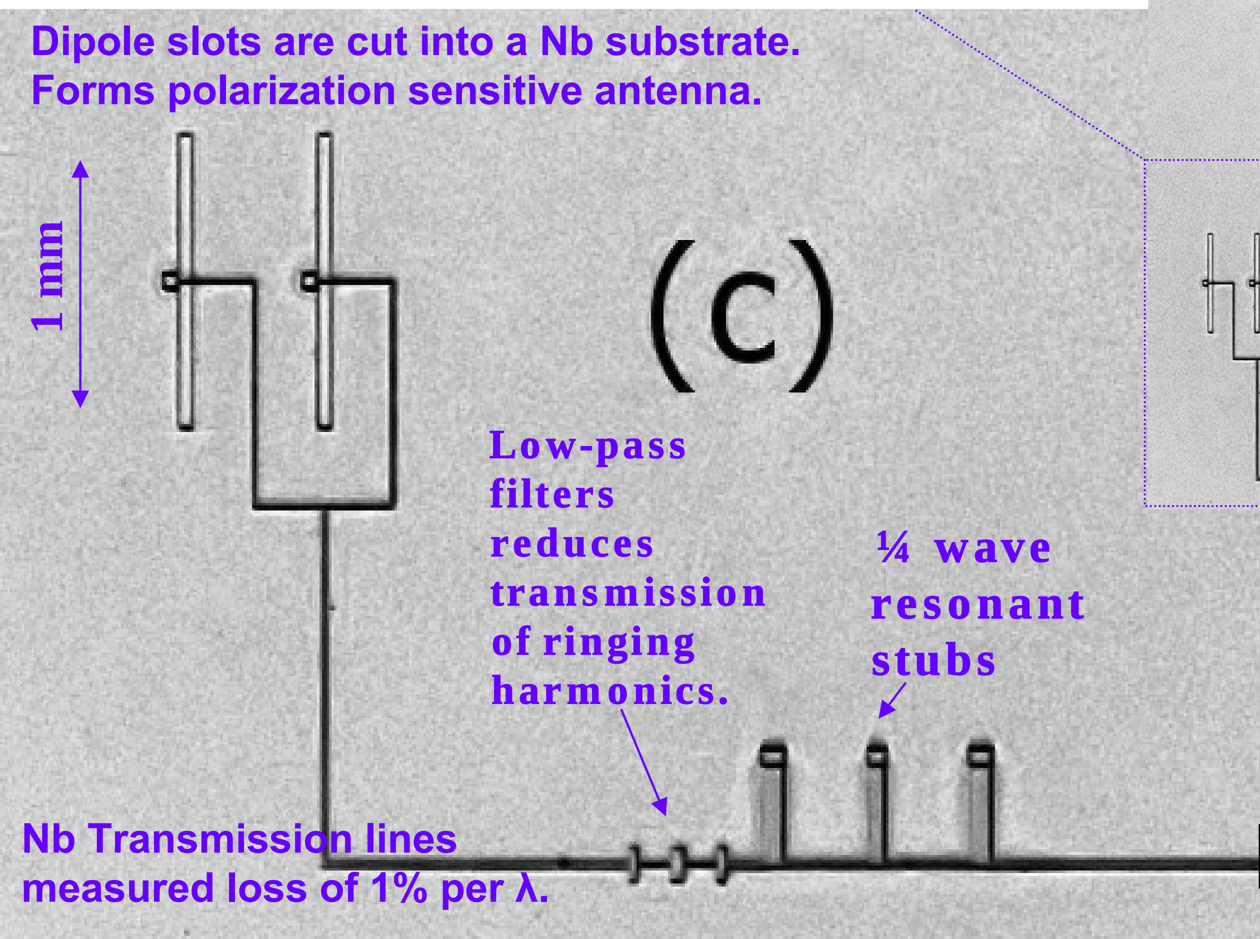
radiometer on a chip

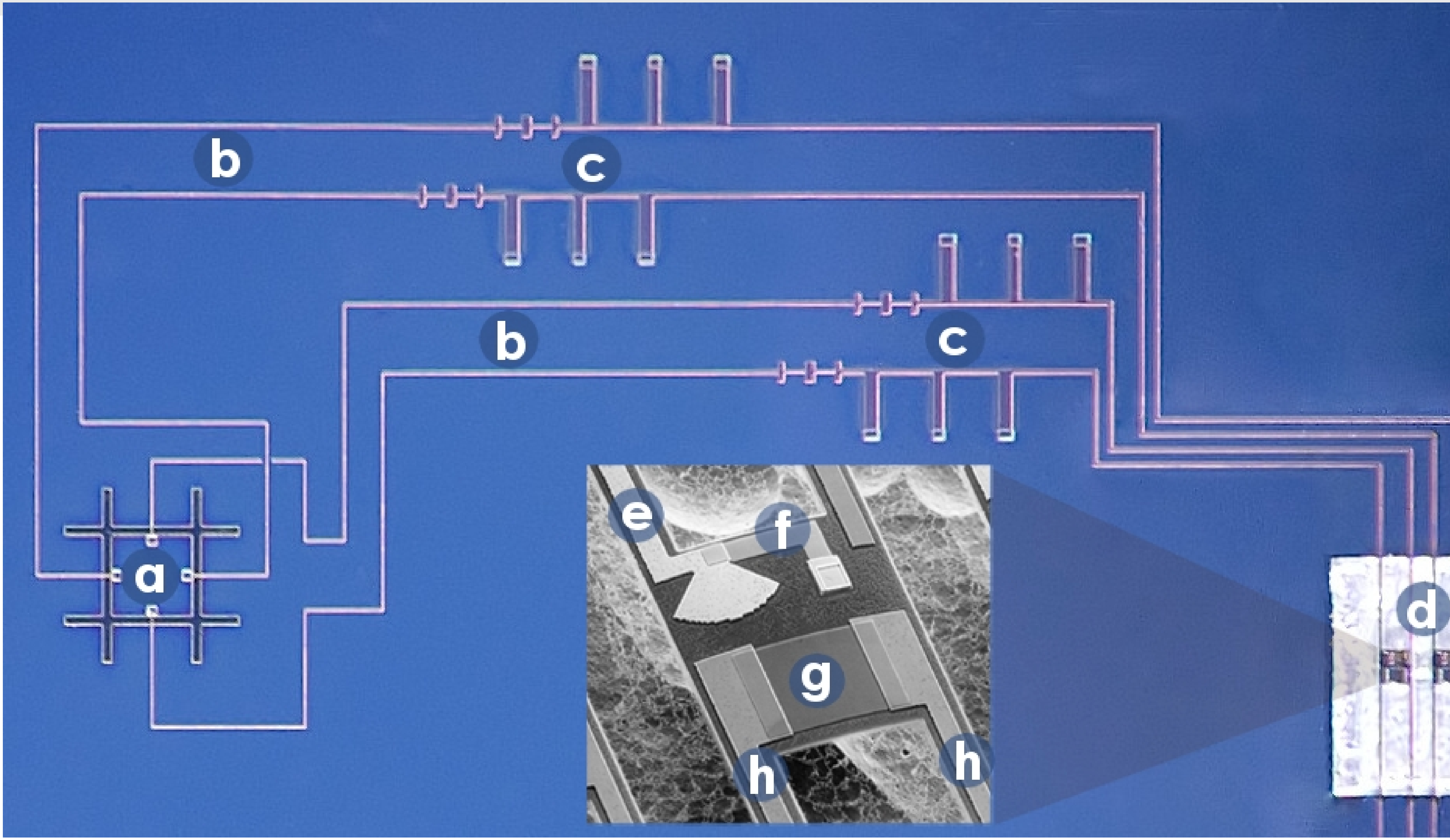
- use multiple bands per pixel → Multicolor

This device: Myers *et. al.*, UC Berkeley, 2004.

Similar device: C.L. Hunt *et al.*, Caltech/JPL, SPIE 2003.







a
b
c
b
c
d
e
f
g
h
h

Summary

- Bolometers are sensitive total power detectors
- TES devices can be mass produced
  - Readout by SQUIDs → multiplexed in time or frequency

- There's a lot of room for fun mm-wave engineering to create the ultimate focal plane.

- Noise.