AAS High Energy Astrophysics Division Meeting

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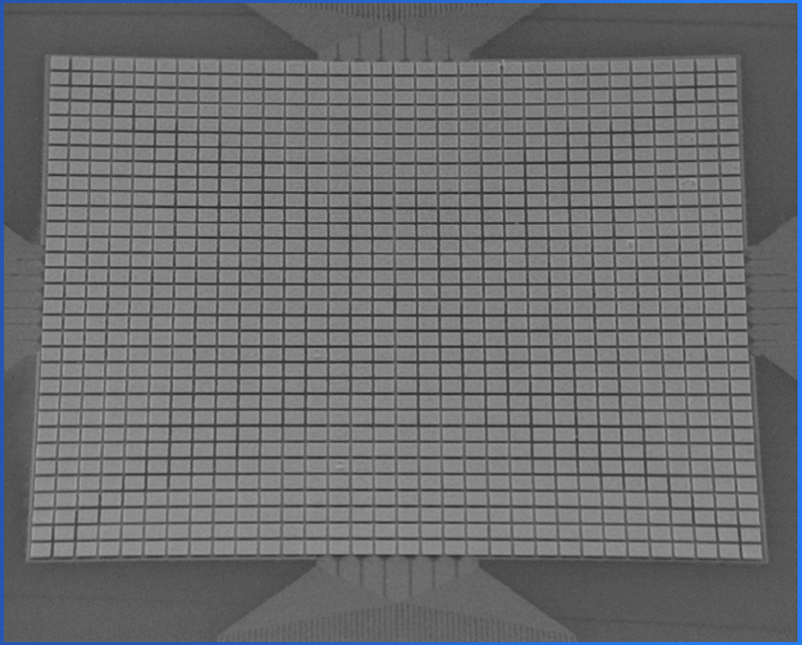
Future development trajectories for imaging x-ray spectrometers based on microcalorimeters



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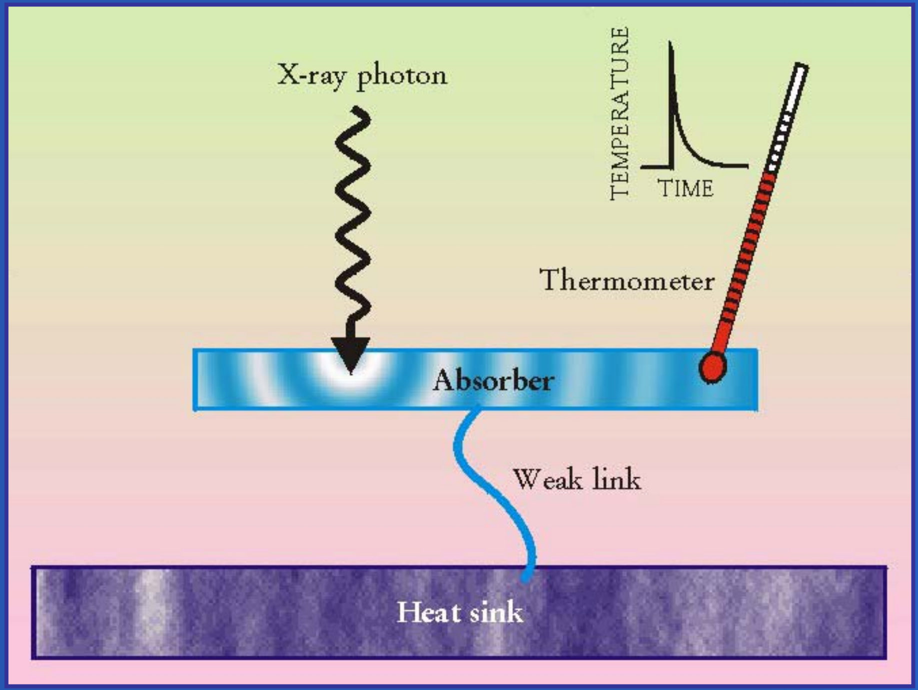
Looking specifically at microcalorimeters (operated at T<0.1 K)

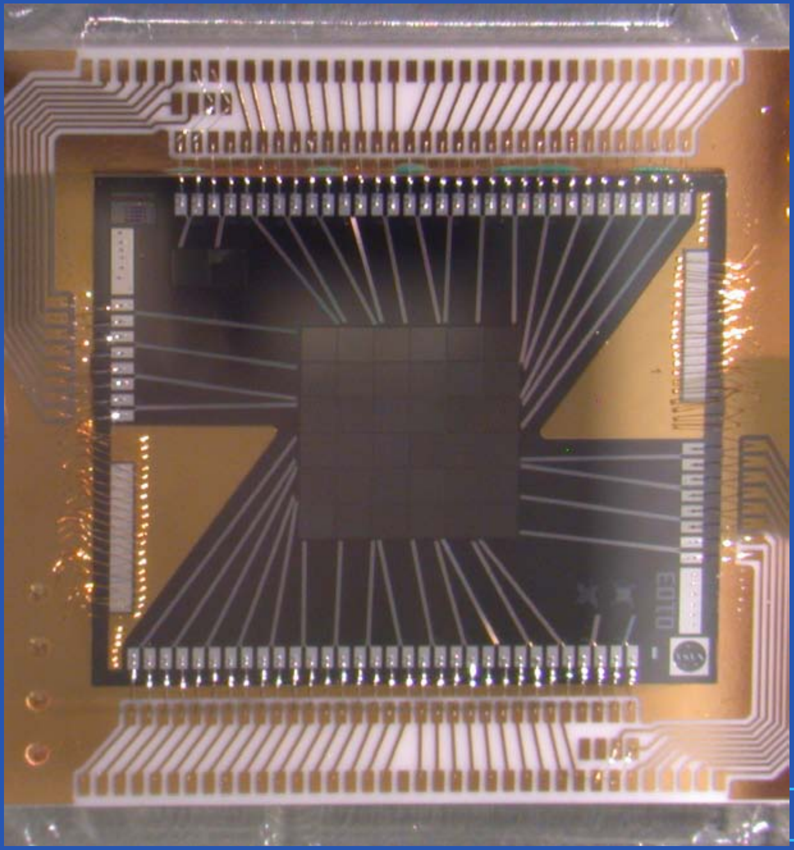


- The leading microcalorimeter thermometer technologies
  - Resistance (semiconductor thermistors and superconductors at their phase transition)
  - Magnetically coupled calorimeters

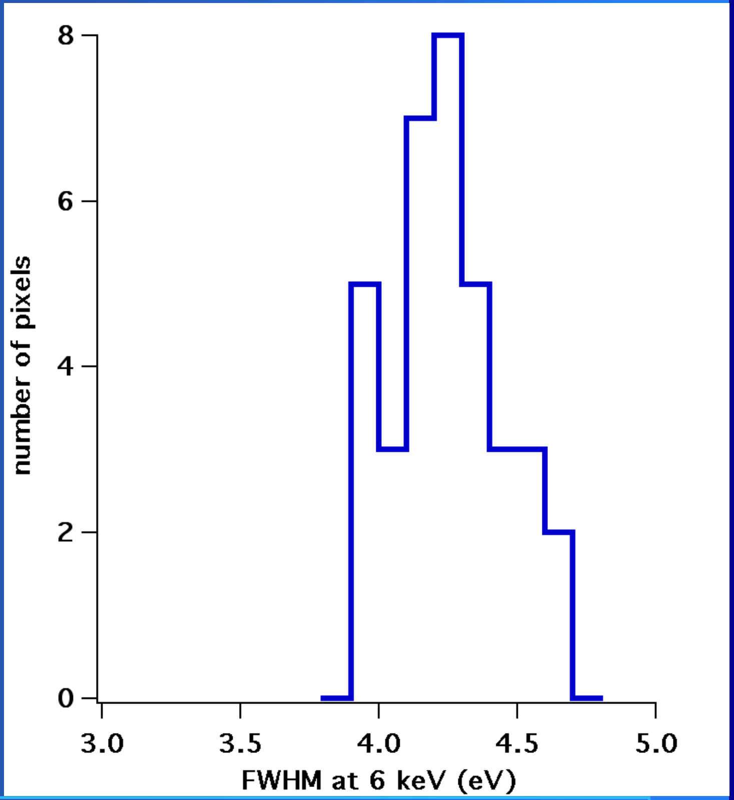
- **What is the state of the art for the leading microcalorimeter sensor and read-out technologies? How far can the limits be pushed?**

Silicon thermistor-based calorimeter array for Astro-H

- Base temperature of 50 mK
- 36 pixels – silicon thermistors on 0.83 mm pitch with HgTe absorbers
- Resolution at 6 keV ranges from 3.6 – 4.6 eV across EM and FM arrays
- Lack of large-scale read-out technology limits arrays to a few hundred pixels
  - Overtaken by TES arrays and SQUID multiplexing
  - Nonetheless, Astro-H is an important pathfinder

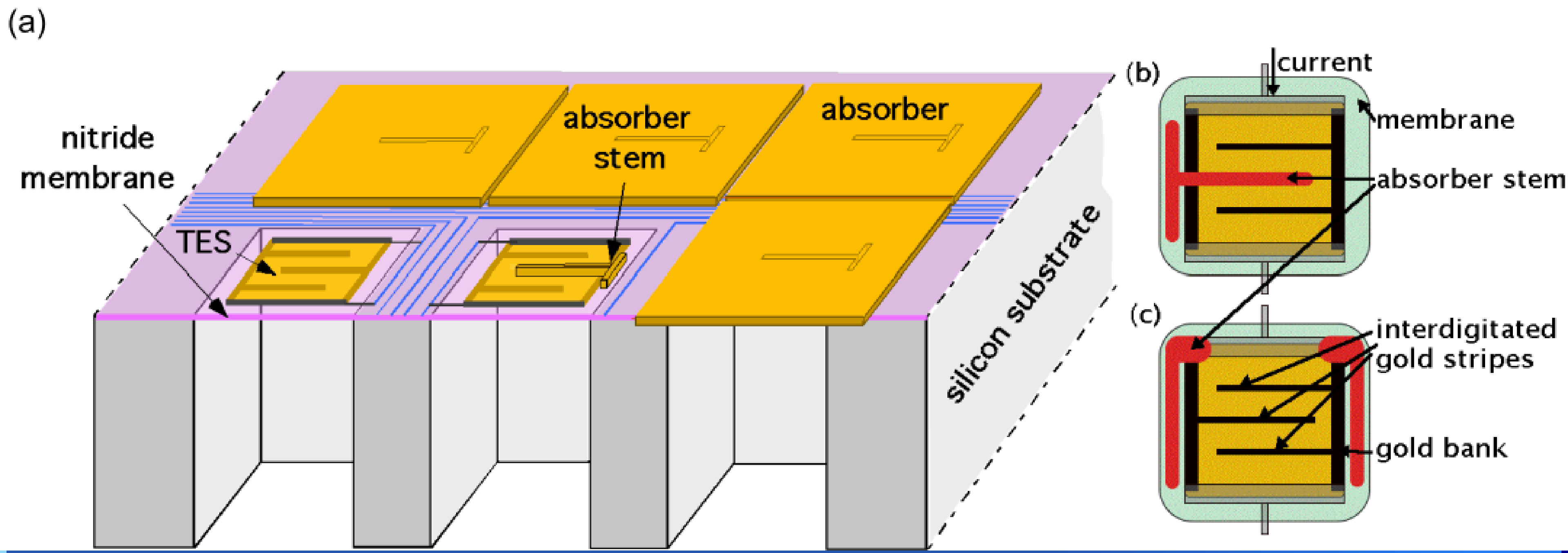


SXS FM candidate array



Transition-edge sensors (TES) – basic pixels

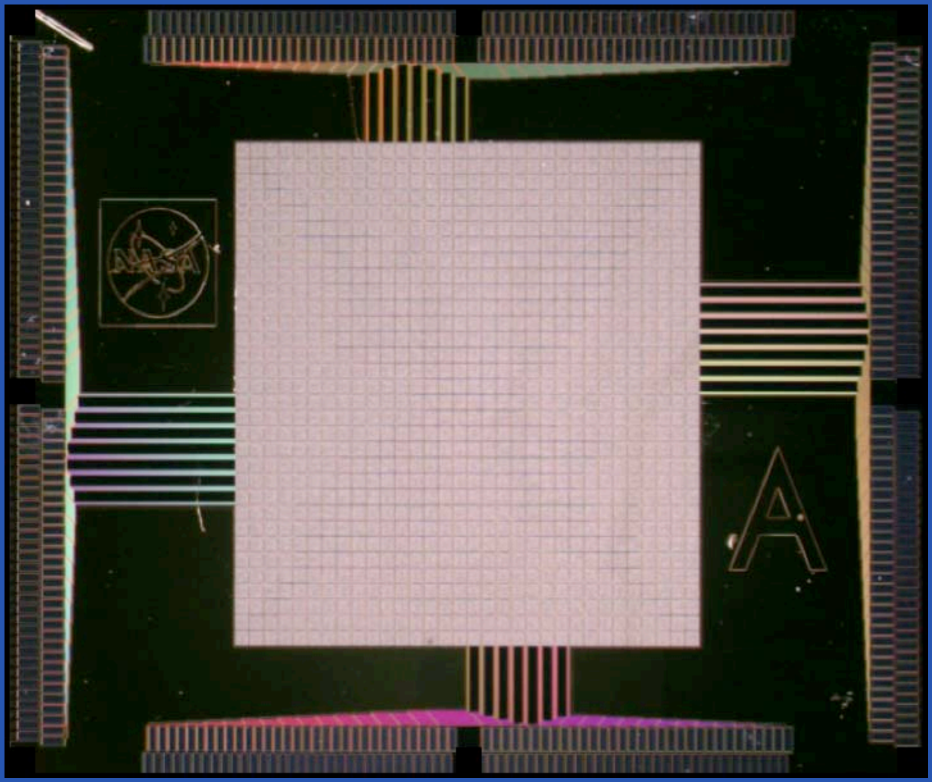
- The temperature and current dependence of the transition from the zero-resistance to normal-resistance state is used for thermometry
- Consist of thermometer (with superconducting leads and normal-metal features), x-ray absorber, and controlled link to heat sink

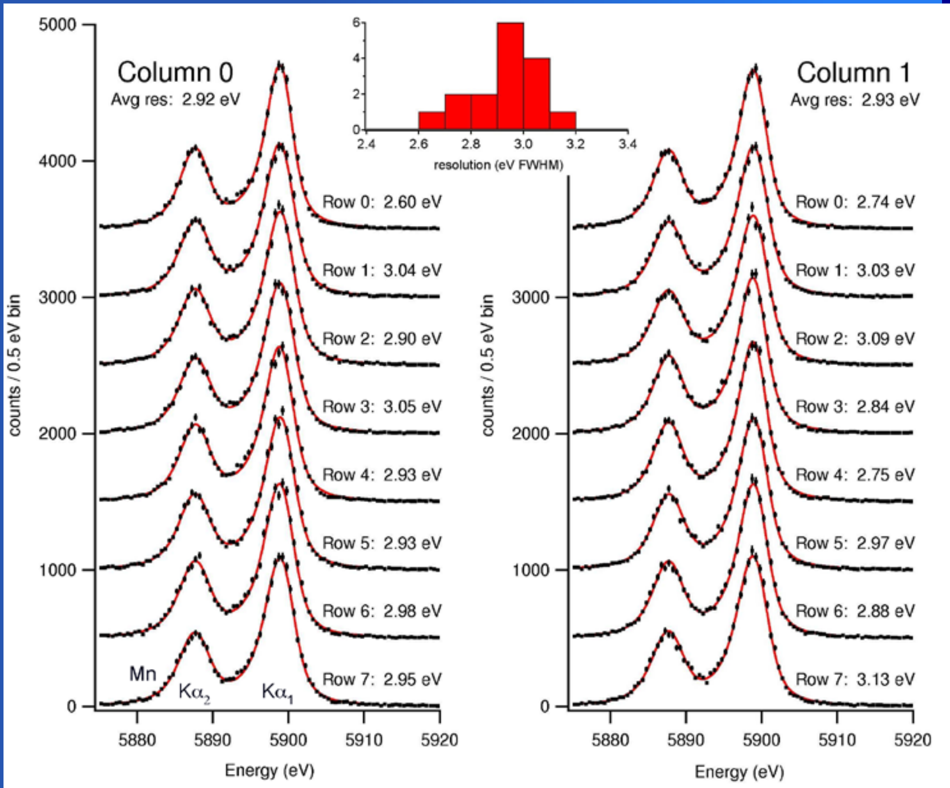


- Pixel pitch ➔ thermometer size ➔ transition properties and whether membrane needed for thermal link
  - "small" TES thermometers < 0.05 mm; "standard" ~ 0.14 mm

"Standard" TES pixels –XMS baseline of IXO, Athena, etc.

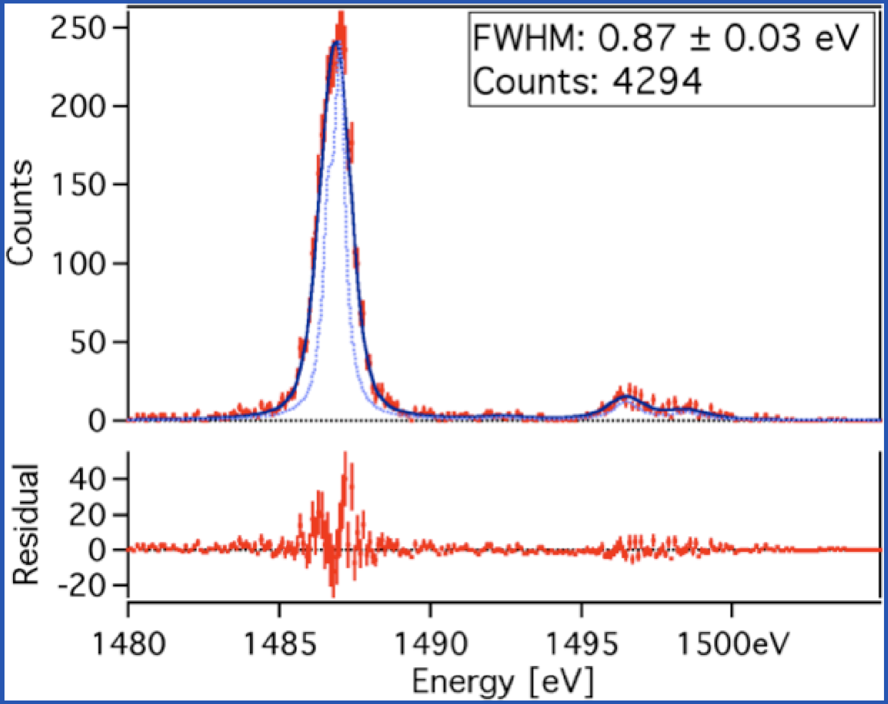
- XMS reference design based on GSFC TES design
  - Membrane-isolated Mo/Au TES with T_c ~ 90 mK, (base temperature at 50 mK)
  - Electroplated Bi/Au absorbers, 0.25 – 0.30 mm pitch
  - 1.8 eV resolution demonstrated, 2 – 3 eV routine in this design
  - Multiplexed SQUID read-out close to requirements for few-thousand pixel array
  - 32x32 arrays with microstrip leads successfully fabricated

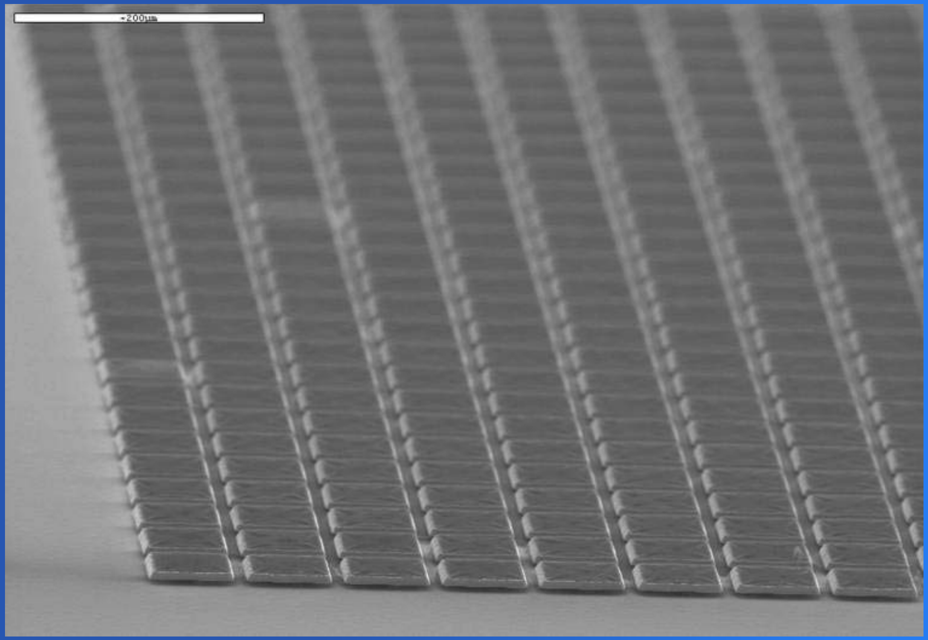




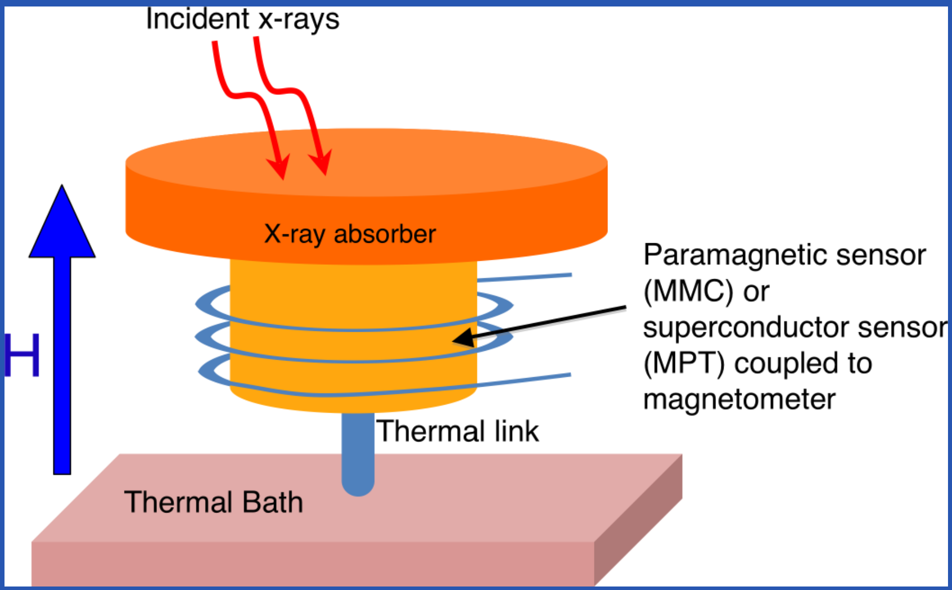
“Small” TES pixels

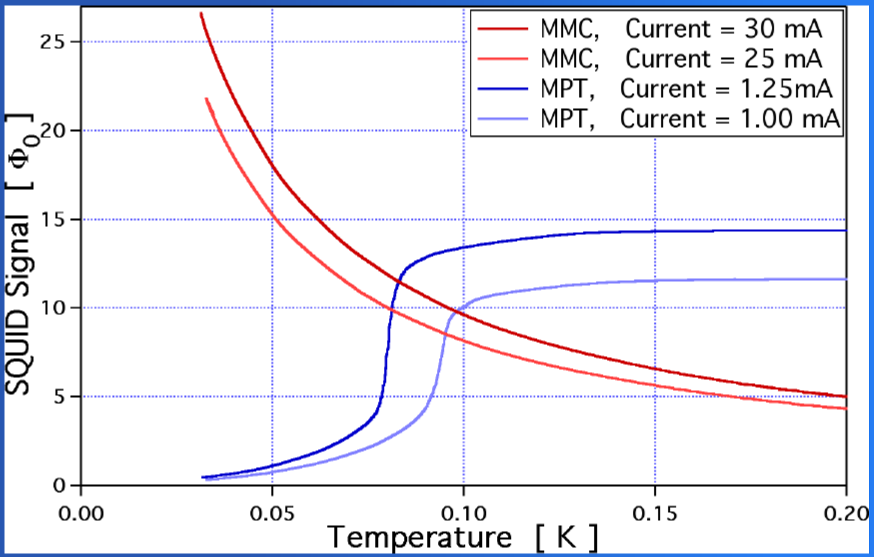
- Small pixels suited to shorter focal lengths and/or higher spatial resolution
- In small TES devices, T_c depends sensitively on current – extends linear operating range of pixels
- Don’t need membrane isolation; small size limits coupling to solid substrate
  - Heat sinking of solid substrate minimizes thermal crosstalk
- Through choice of T_c, can be optimized for speed (0.03 ms fall time) or resolution (0.9 eV FWHM) (GSFC devices).





Inductive thermometers – using temperature dependence of paramagnetism or magnetic penetration of a superconductor





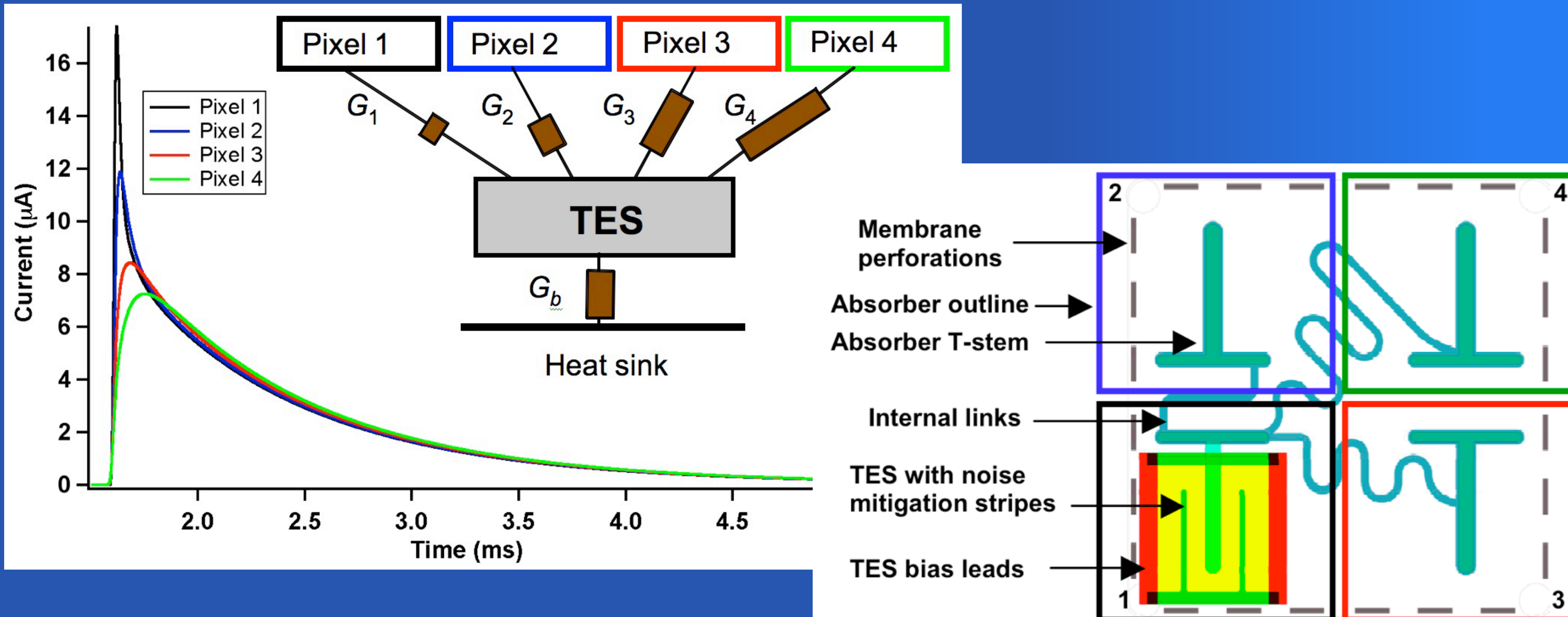
- Arrays of Nb meanders with layer of magnetic material (Au:Er) or a low-Tc superconductor (Mo/Au), with high-fill-factor absorbers as with TES.
  - change of magnetization measured as change of inductance
- The Heidelberg group has achieved just better than 2.0 eV resolution at 6 keV with a Au:Er metallic magnetic calorimeter (MMC).
- GSFC group has obtained 2.3 eV resolution with Mo/Au magnetic penetration thermometer (MPT).

Magnetically coupled calorimeters (MCC) compared with TES

- MCCs are intrinsically dissipationless
  – very large-format focal-plane arrays
- MCC sensor material is electrically isolated
  – can be directly connected to metallic heat sink – simplifying reduction of thermal crosstalk
- Dissipation in TES calorimeters allows electrothermal feedback
  – stabilizes operating temperature, relaxing temperature stability required at heat sink
- TES read-out allows easy signal filtering, greatly simplifying multiplexing.

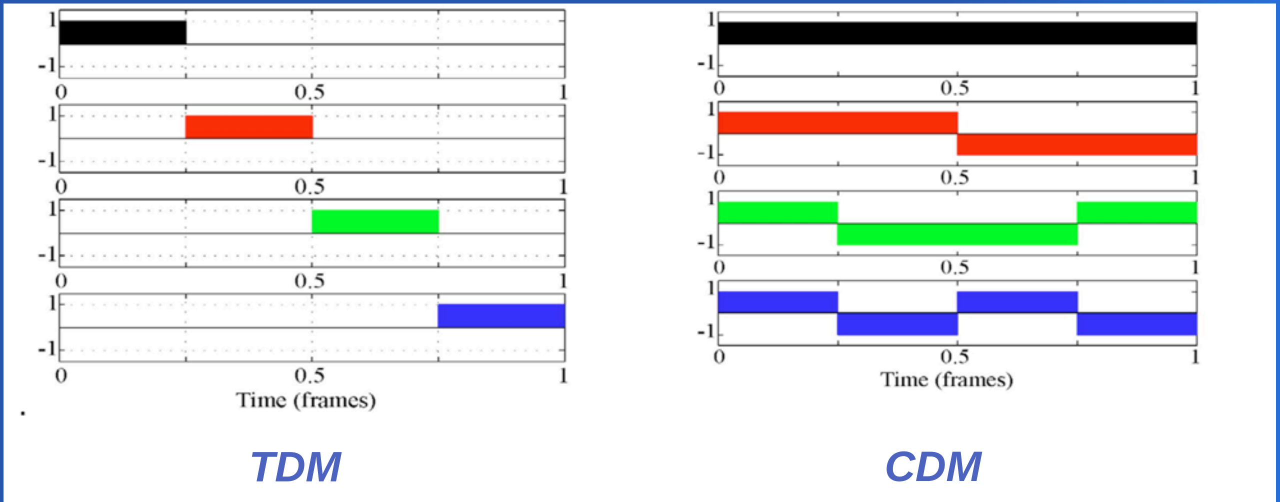
Each has advantages and disadvantages – continued parallel investment in both TES and MCCs is needed.

Using the non-equilibrium signal in equilibrium devices for position discrimination



- Multiple absorbers connected thermally to the same thermometer via different thermal links
- Demonstrated for TESs and MMCs
  - 2.4 eV resolution obtained in 9-pixel TES device with 0.065 mm pixels
- Ideal "hydra" obtains somewhat worse resolution than for one big pixel of the same area due to thermal fluctuations between the absorbers.

Multiplexed TES read out: switched SQUID multiplexing



- XMS reference design included time-division multiplexing (TDM)
  - Individual TES pixels are coupled (via each pixel's SQUID) to a single amplifier
  - Multiplexed by sequential switching between SQUIDs
  - Used in TRL-4 TES read-out demo in 2008 (2.6 – 3.1 eV across 16 mux'd TESs)
- Code Division Multiplexing (CDM) will soon reach TDM TRL level
  - All pixels ON all the time, polarity of coupling is switched
  - CDM has a $\sqrt{N}$ noise advantage over TDM, where N is the multiplexing scale
    - IXO/XMS noise budget was extremely tight – CDM could provide important margin
    - Facilitates faster pixels with larger slew rates by providing the noise margin to allow the coupling of the TES to the in put SQUID to be reduced
- CDM demonstrated: < 3 eV on 16 switched pixels using flux-matrixed CDM

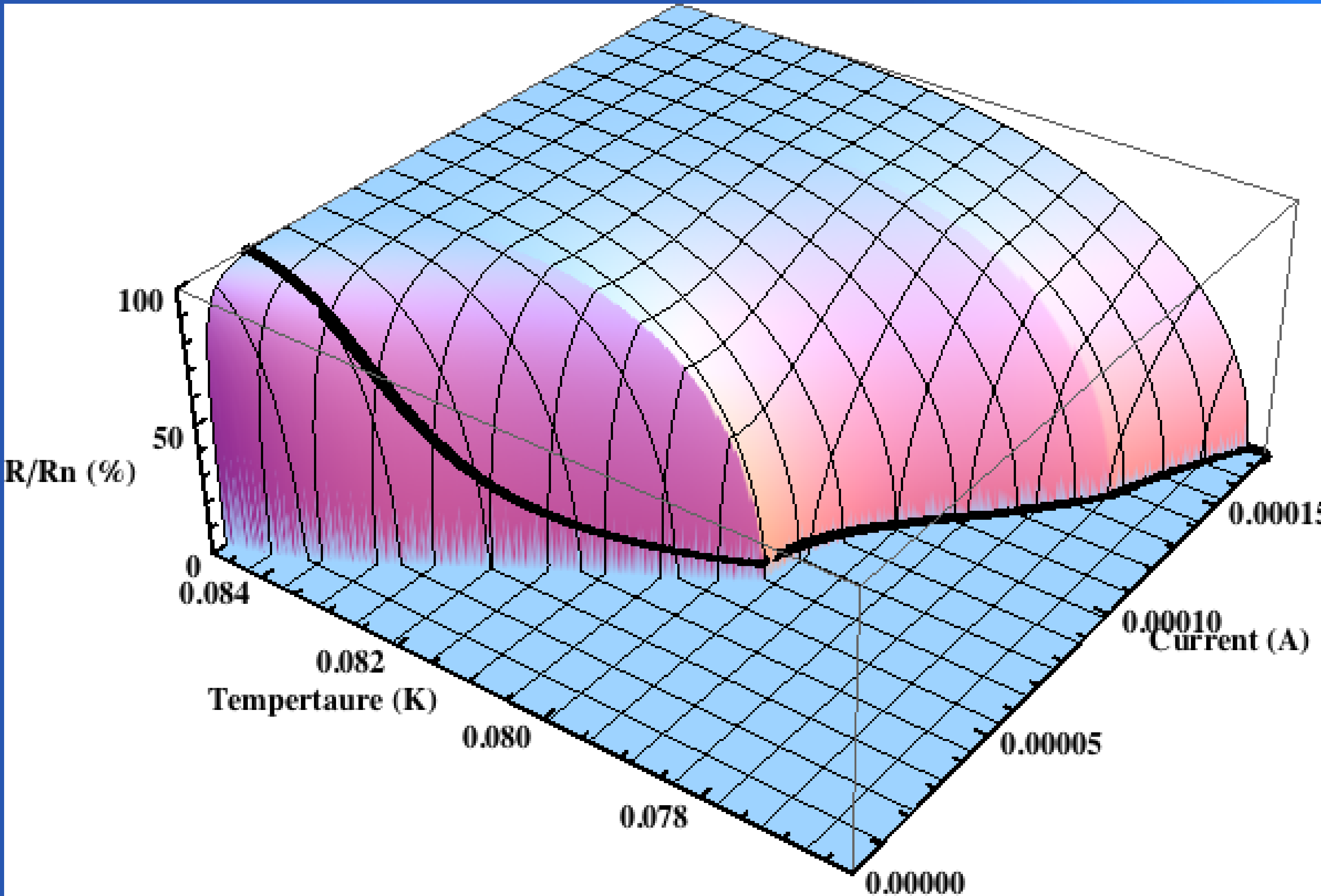
Frequency domain multiplexing (FDM)

- TES bias modulation
  - Different TES pixels AC-biased at different frequencies read out by single SQUID
  - X-ray pulses seen in amplitude modulation
  - Like CDM, pixels on all the time, imparting a $\sqrt{N}$ advantage over TDM
  - However, in identical pixels tested with AC and DC bias, significantly better resolution was obtained in the DC bias case, which may be fundamental
- Microwave multiplexing
  - Pixel electronics form high-Q microwave resonant circuits (GHz scale), hundreds of which can be combined on a single coax
  - For TESs, MMCs, and MPTs, an unshunted rf SQUID is incorporated into the read out of each pixel, which is in turn coupled to a resonant circuit
  - A successful microwave multiplexing demonstration has recently been completed at NIST on two gamma-ray TES pixels.

Pushing the limits on spectral resolution

- Resolving power for soft x-rays
  - All microcalorimeters are non-linear. If we set dT_{max} as the maximum allowed temperature change, then we need to design the TES so that E_{max} produces dT_{max}. E_{max} scales as C/α, but resolution dE scales as $\sqrt{C/\alpha}$. Thus designing for 0.5 keV instead of 6 keV will not preserve the resolving power achieved at 6 keV. Getting to 0.2 eV resolution at 0.5 keV will not be possible without signal processing techniques (under development) that enable analysis of highly non-linear signals with high resolution. Reducing C by more than a factor of ~10 will need reductions in the TES size as well as the absorber C.
  - In small TES devices, T_c depends sensitively on current – extending the linear operating range of pixels for a given C/α. However, the Johnson noise of a resistor with current dependence fundamentally increases with this current sensitivity, β.
  - Paramagnetic calorimeters also have scaling issues. They are more linear, but their sensitivity scales with the heat capacity of the spin system.

➔ R = 1000 within reach at 0.5 keV, R = 3000 probable, but much higher than that is unlikely.


100
50
R/Rn (%)
0
0.084
0.082
Tempertaure (K)
0.080
0.078
0.00000
0.00005
0.00010
Current (A)
0.00015

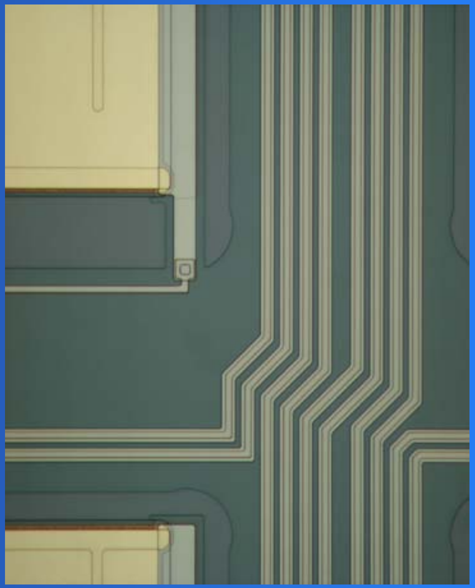
Pushing the limits on counting rate

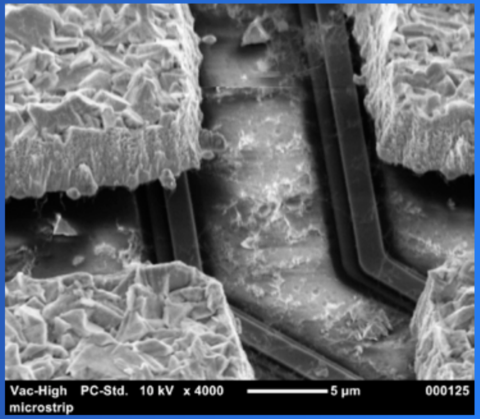
- Limits at the pixel (trade against resolution and array size)
  - Decreasing the thermal time constant of a pixel starts to degrade resolution when it approaches thermalization time scales in the absorber.
  - Increased thermal conductance requires higher bias current with ramifications for the operating point in the transition and for heat sinking.
  - Faster paramagnetic calorimeters fundamentally have worse resolution than slower ones ($\tau^{0.25}$ scaling).
- Limits on the readout (trade against multiplexer scale, array size)
  - The more bandwidth per pixel, the fewer pixels per multiplexer channel.
- Limits on the signal processing
  - Historically, optimal digital filtering used. Long records containing a single pulse are required in order to have sufficient frequency resolution in the optimal filter as well as to avoid pile up; resolution degraded when shorter records used.
  - Recently, new optimizations specifically for high count rates are being developed (e.g. by B. Alpert, NIST).

➔ Expect that 1000/s/pixel rates at > 80% live time will be possible in small sub-arrays with new processing techniques.

Pushing the limits on number of pixels

- Array architecture
  - Limit on bringing out wires between the pixels will be reached at the ~10^4 pixel level (depending on pitch, etc.). Larger arrays will need close integration of the pixels and the multiplexing. NIST is working on integrating CDM with TES arrays.
  - Use of Hydras eases demands on heat-sinking, wiring, and electronics, at the expense of resolution and per-pixel count rate.
- Wiring to room temperature
  - Combining integrated CDM with microwave multiplexing holds the promise of reading out 10^5 sensors (pixel pitch > 0.25 mm) with as few as two coaxes (depending on sensor speed).

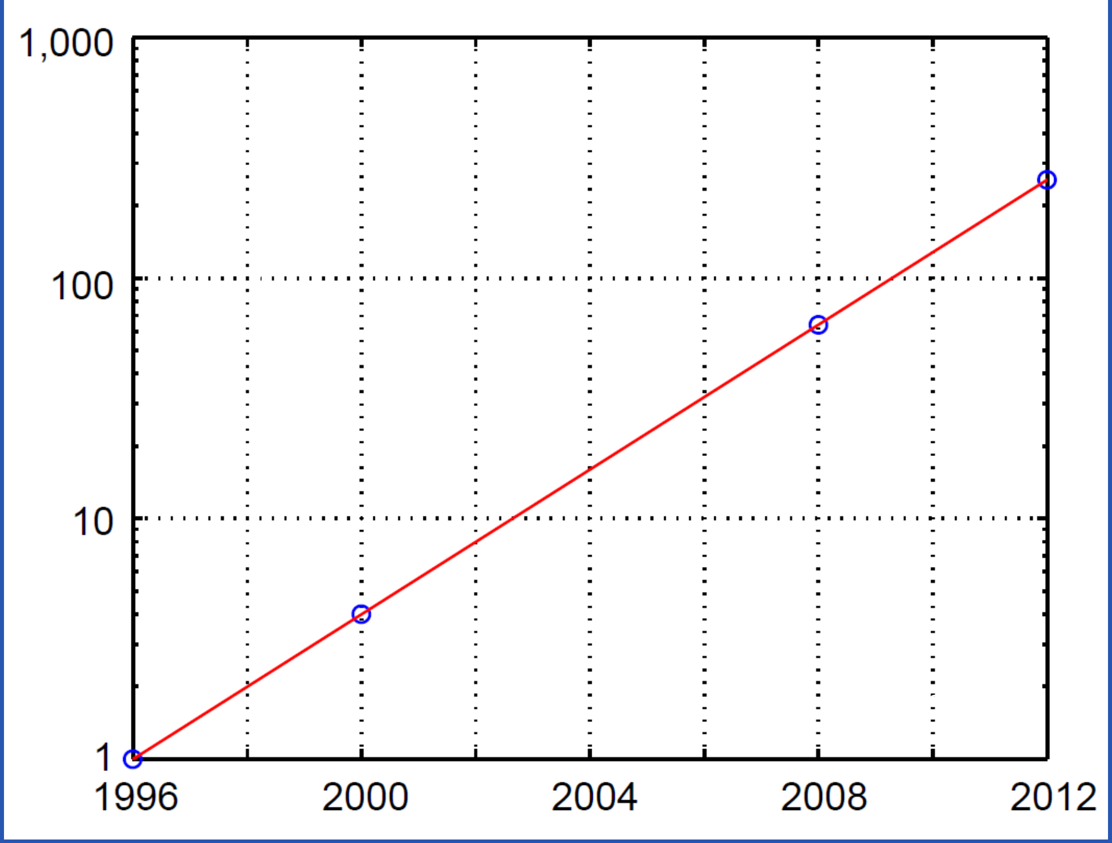




➔ Expect to get to 10^5 TES in the next 20 years (10^6 with Hydras), though compromises on count rate may be necessary.

Moore's Law for instrumented TES microcalorimeter arrays (courtesy of Kent Irwin)

Doubling time: 2 years



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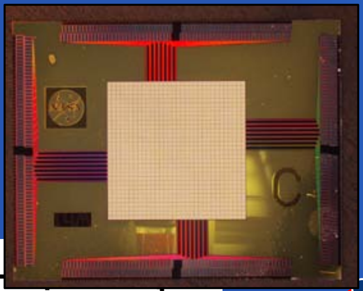

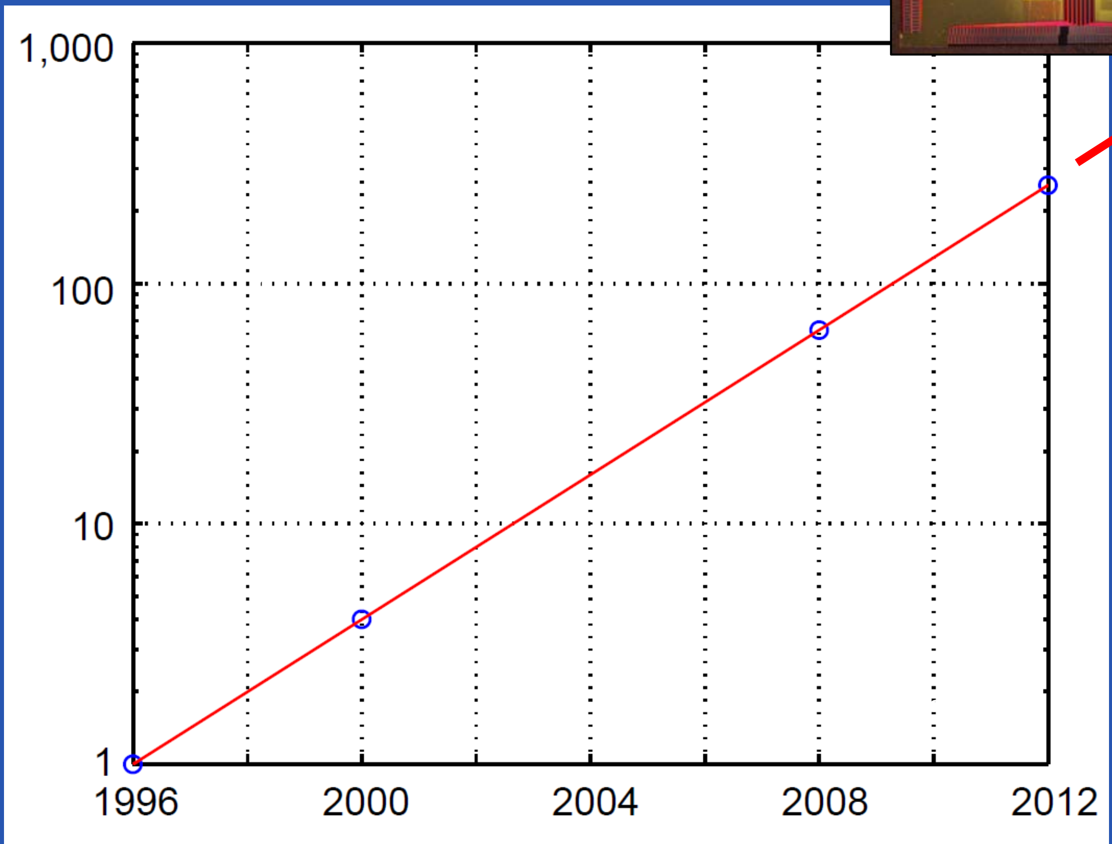

TES with TDM

TES with CDM

TES or MCC with microwave MUX