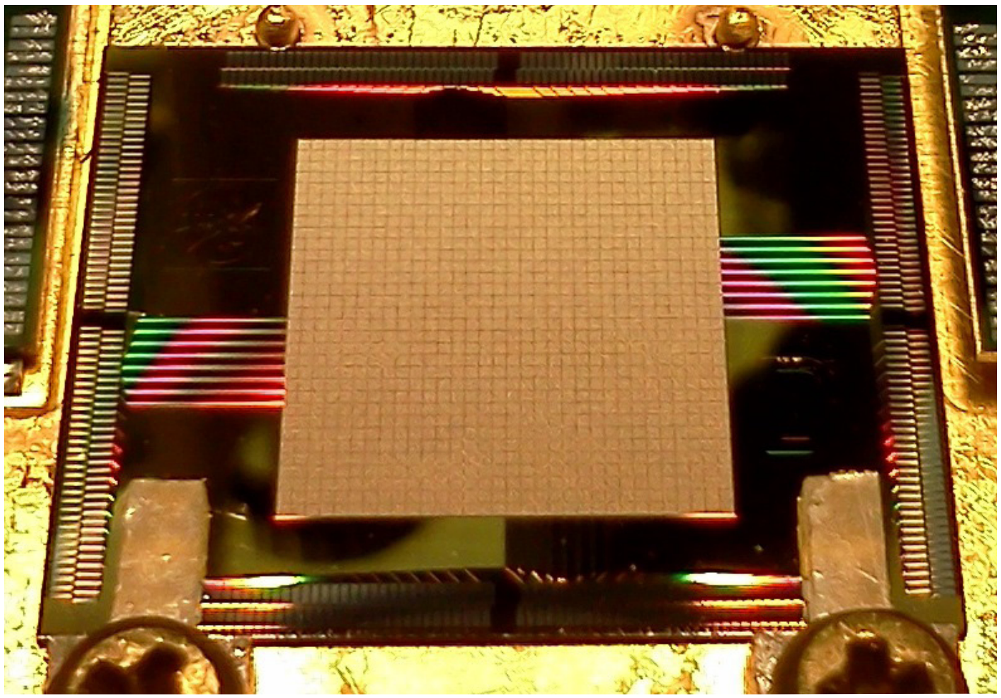
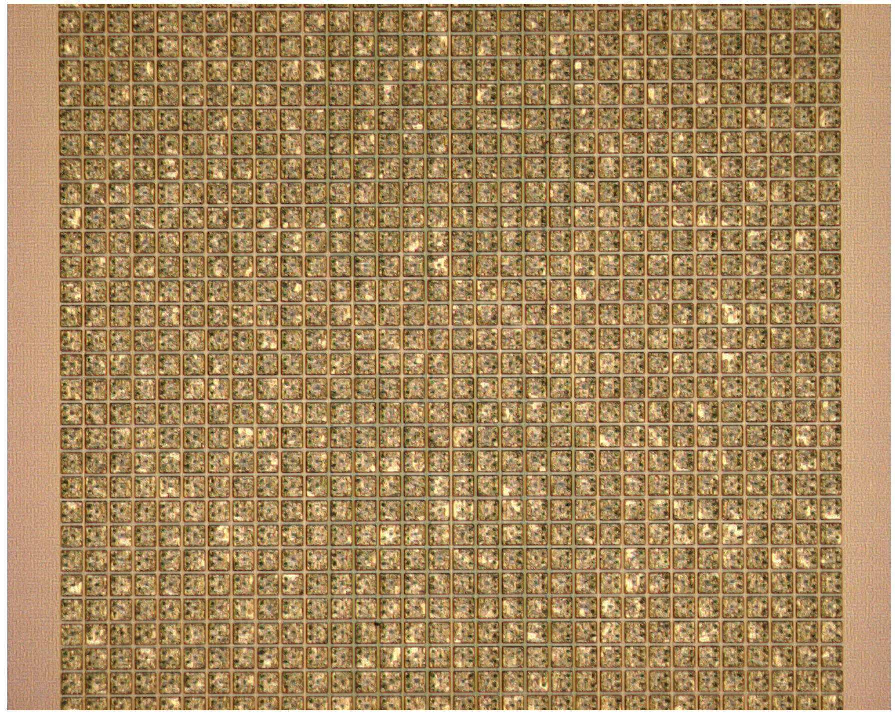
Large-Format High Resolution X-ray Microcalorimeter Arrays

Simon Bandler: University of Maryland – College Park & NASA/GSFC
on behalf of the X-ray microcalorimeter groups at NASA/GSFC & NIST/Boulder



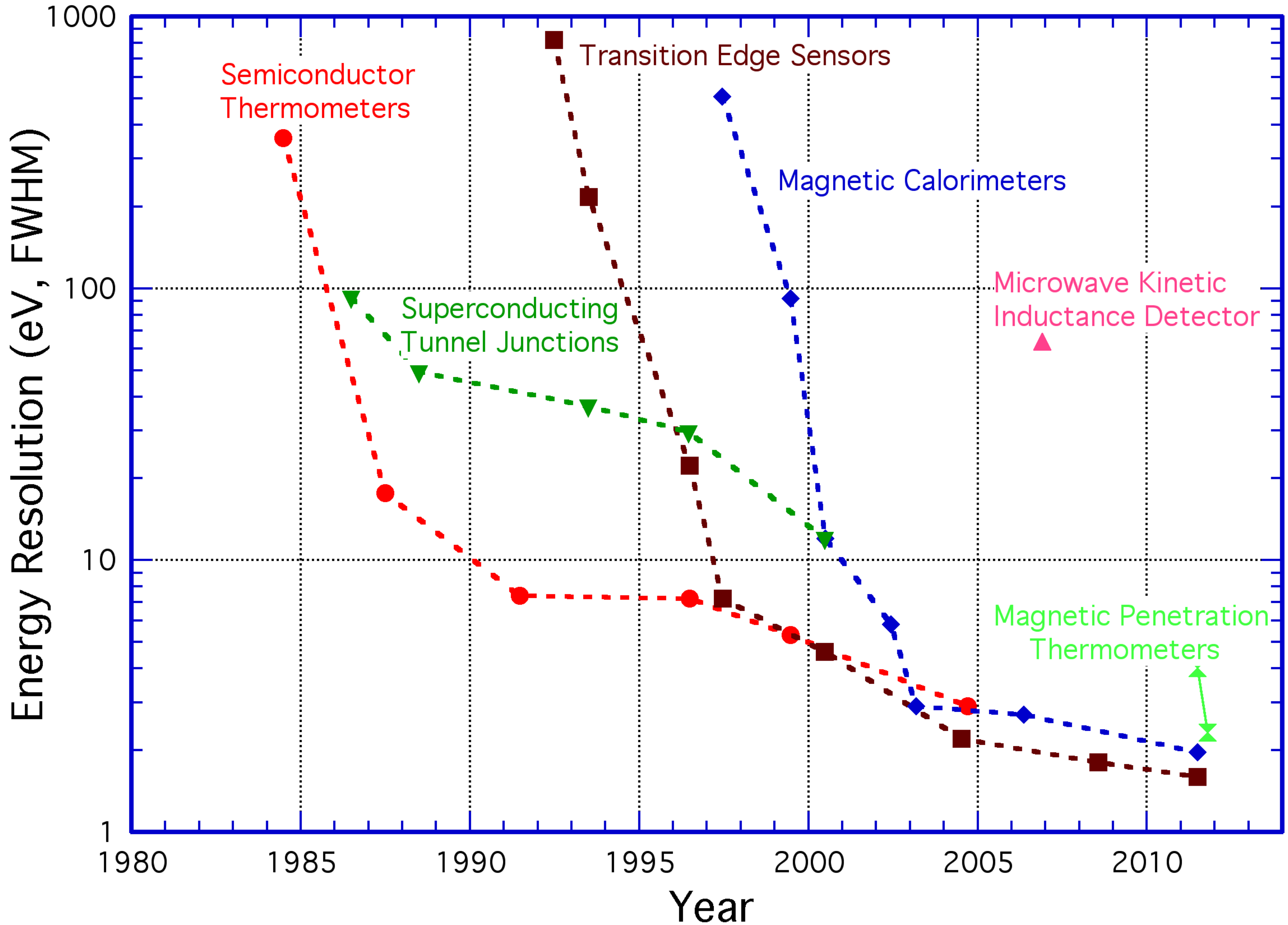


State-of-the-art kilo-pixel arrays of X-ray microcalorimeters (TES-based)

- Left: 1024 pixel array on 300 μm pitch
- Right: 1024 pixel array on 75 μm pitch

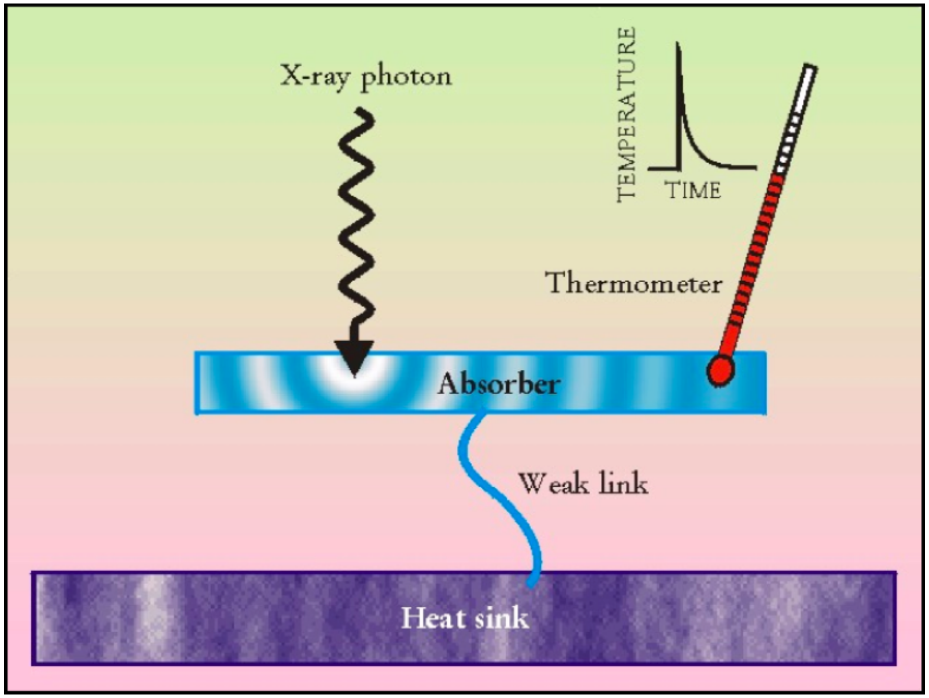
X-ray microcalorimeters capable of 1 eV energy resolution for 6 keV photons:

S.H. Moseley, J.C. Mather, D. McCammon, J. Appl. Phys. 56, 1257 (1984)



Astrophysics Roadmap Town Hall, 2013

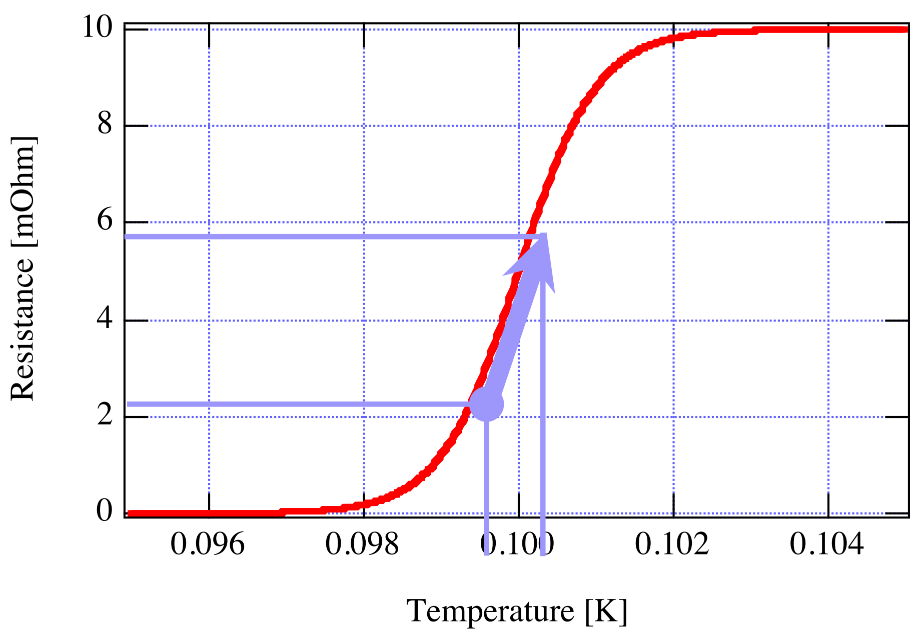
Transition-edge Sensor microcalorimeter basics:



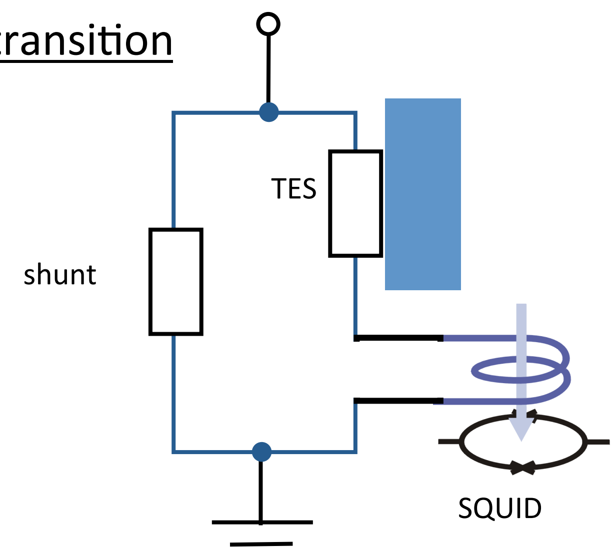
Temperature rise: $\delta T = \frac{E}{C_{\text{tot}}}$

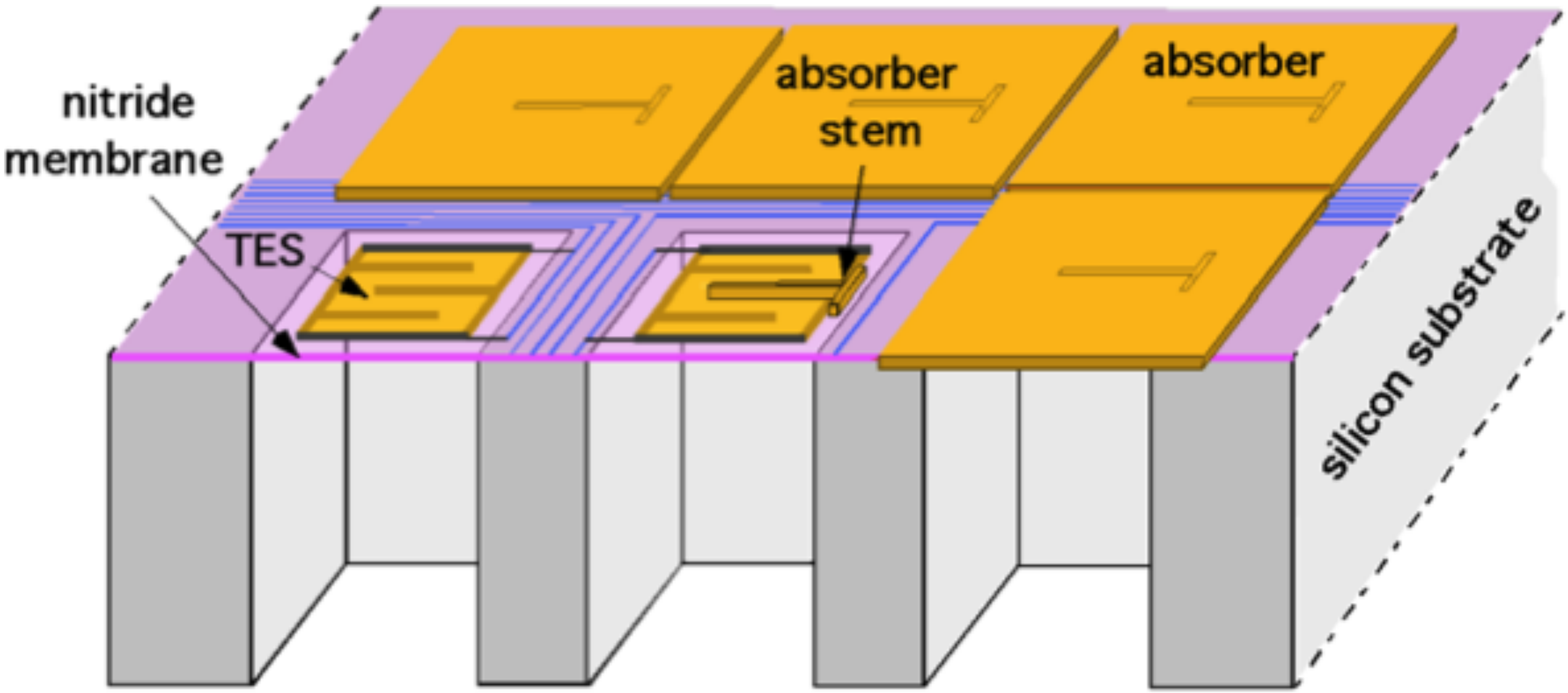
Energy resolution:

$$\Delta E \sim \sqrt{k_{\text{B}} T^2 C}$$



Superconductor voltage-biased in its transition

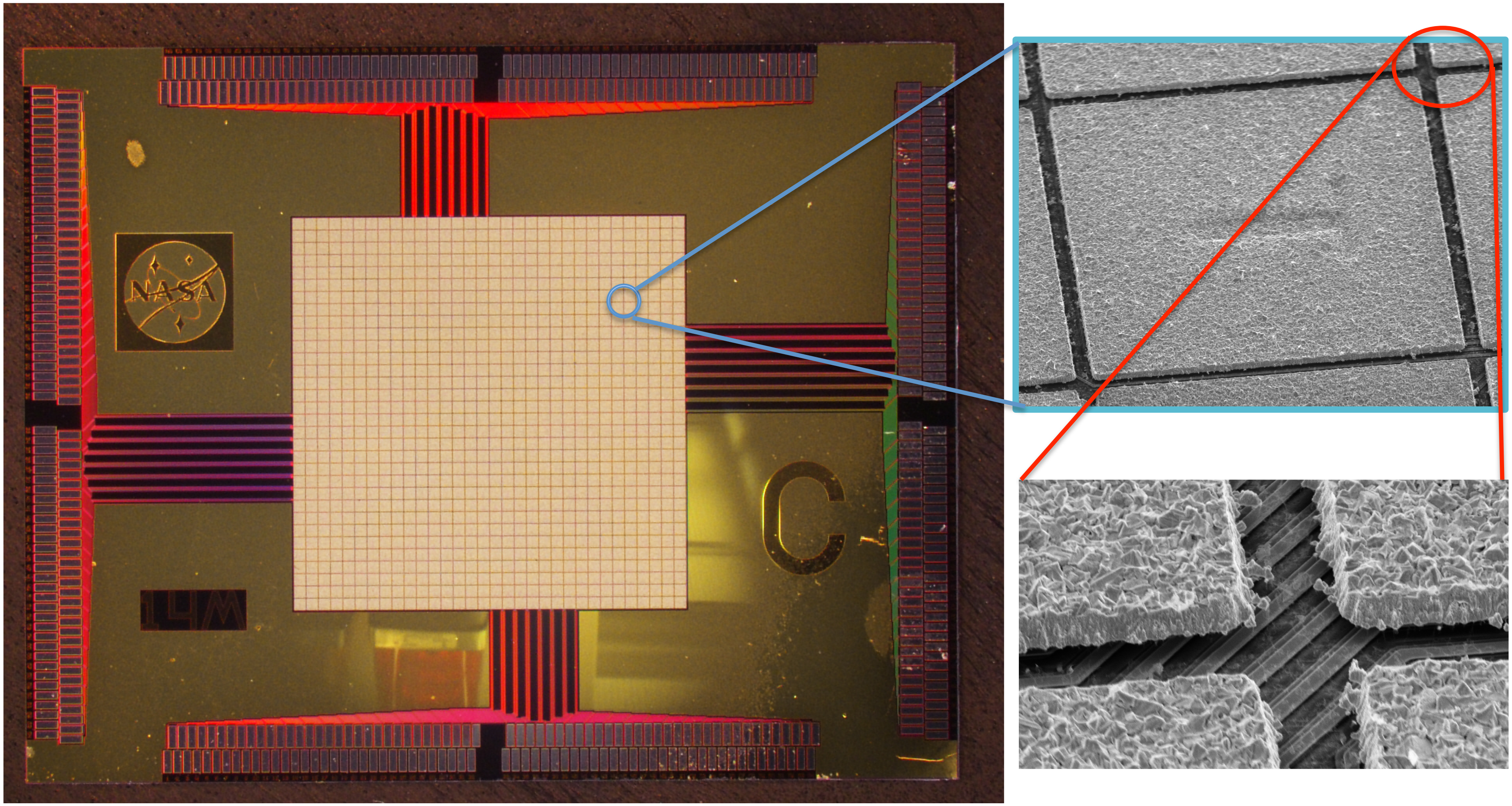




TES: Mo (50 nm) / Au (225 nm)

T_c ~ 0.1 K

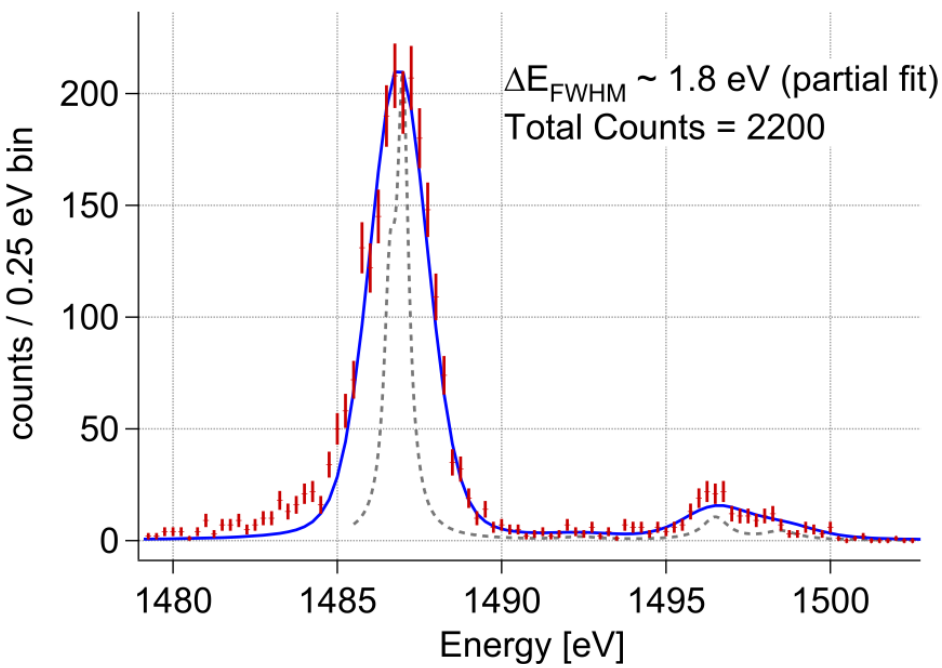
Current state-of-the-art:



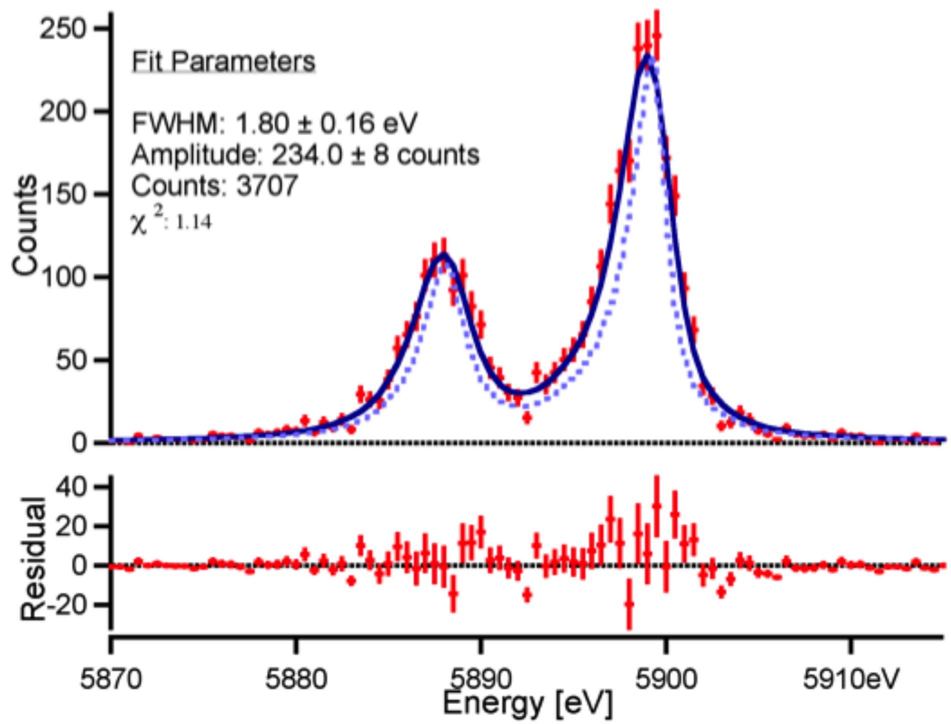
- Photograph and micrograph images of a prototype 32x32 array,
- 300 μm pixels
- Absorbers: Bi (4.2 μm) Au (1.2 μm)

300 μm pixels in 32 x 32 array achieved expected energy resolution at 1.5 keV

Older 250 μm pixels have achieved 1.8 eV FWHM energy resolution at 6 keV:

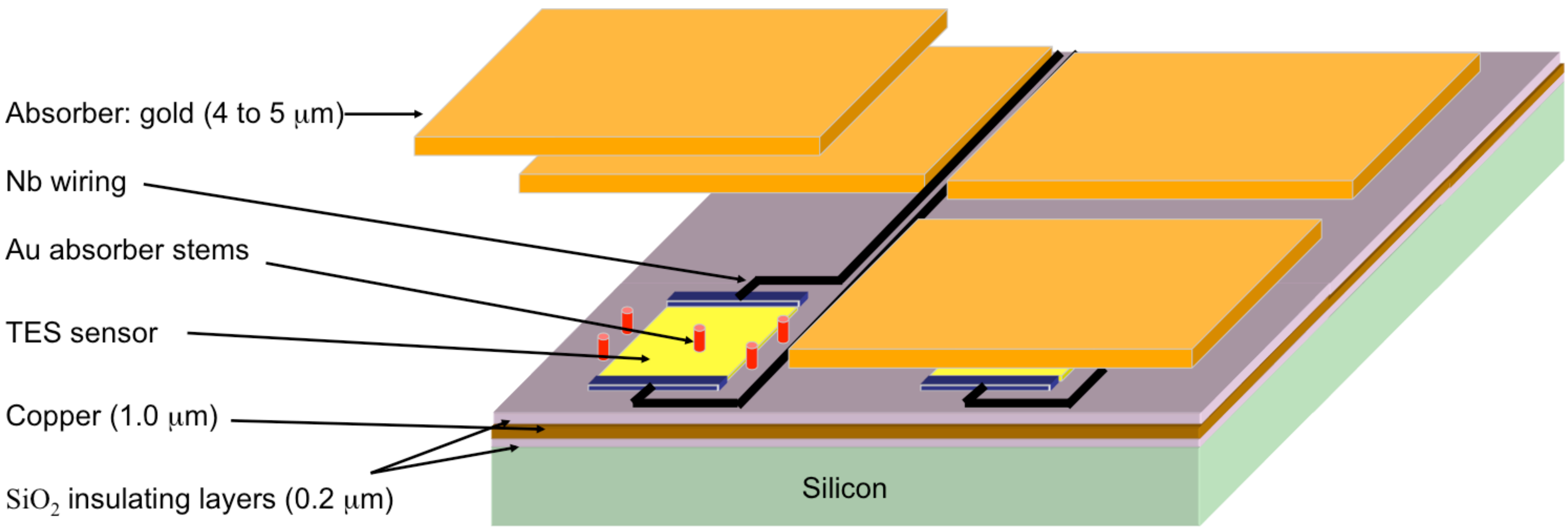


Spectrum from fluorescent 1.5 keV Al Kα X-rays



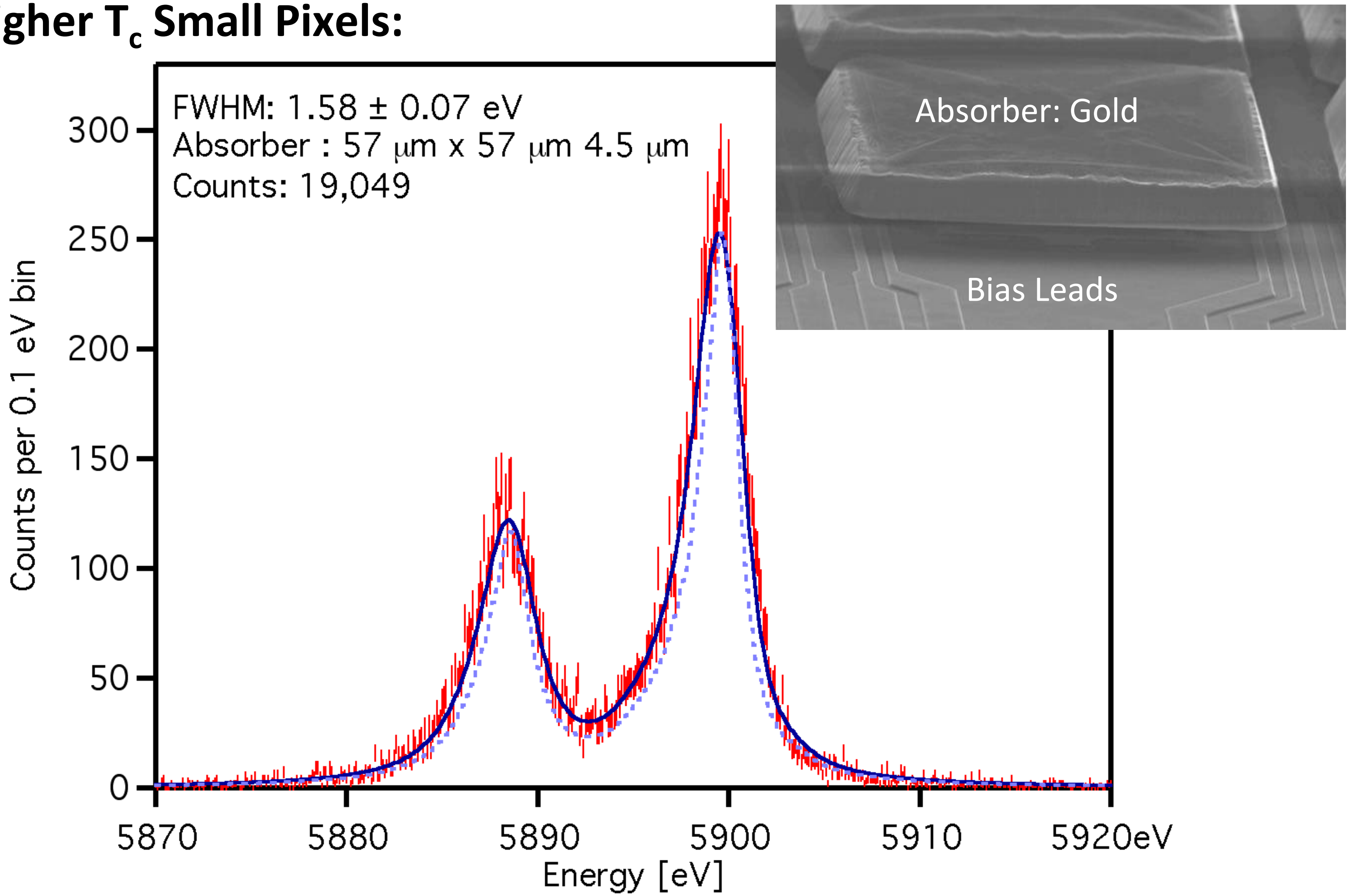
Mn $K\alpha_1$ & $K\alpha_2$ x-rays at 6 keV from an ^{55}Fe internal conversion source

Small Pixel Development



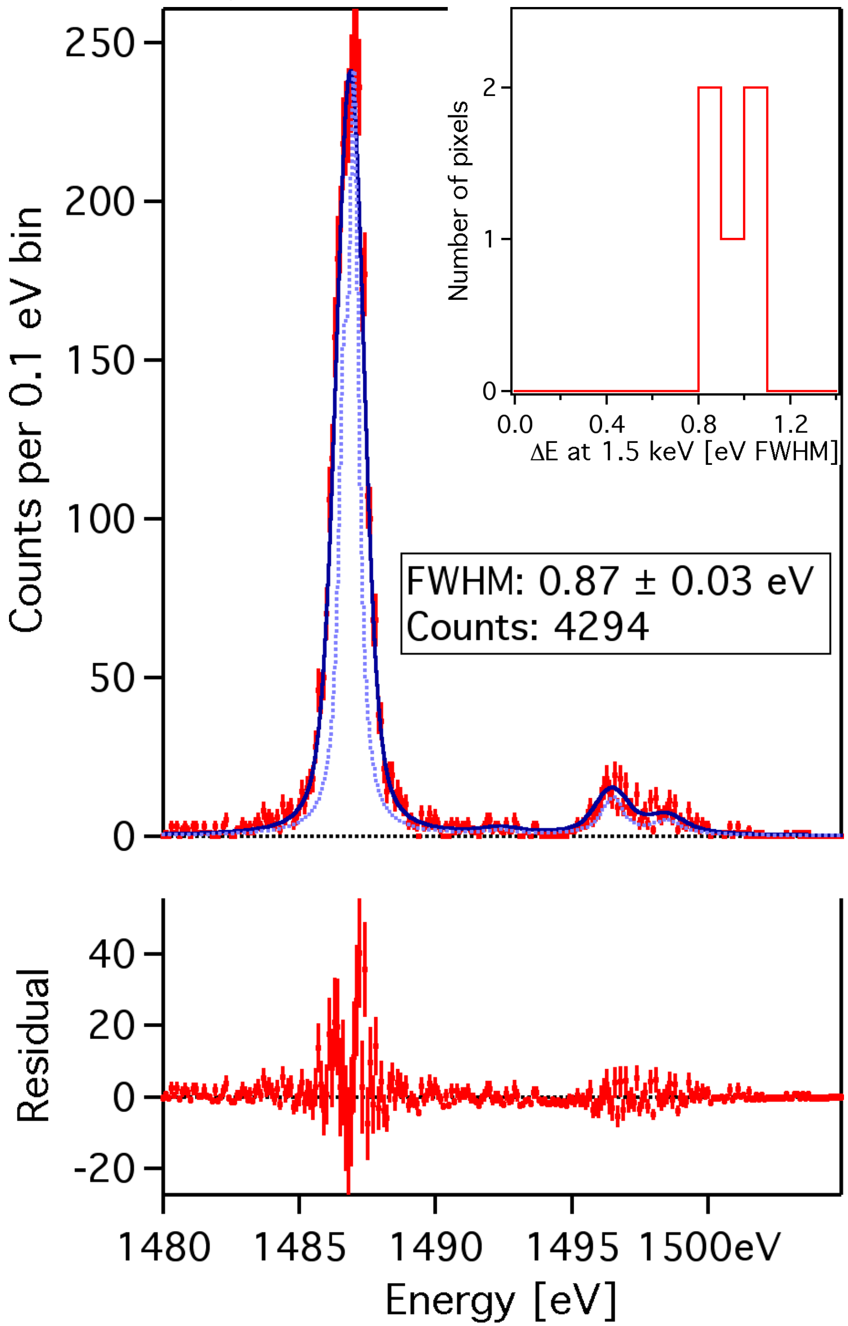
- Small size => low heat capacity => *excellent energy resolution*
- Use of all-gold absorbers (C not too high)
  -> *great for reliable fast thermalization & high fill factor*
- High Count rate capability (~ 1000 cps/pixel) with high T_c versions

Higher T_c Small Pixels:



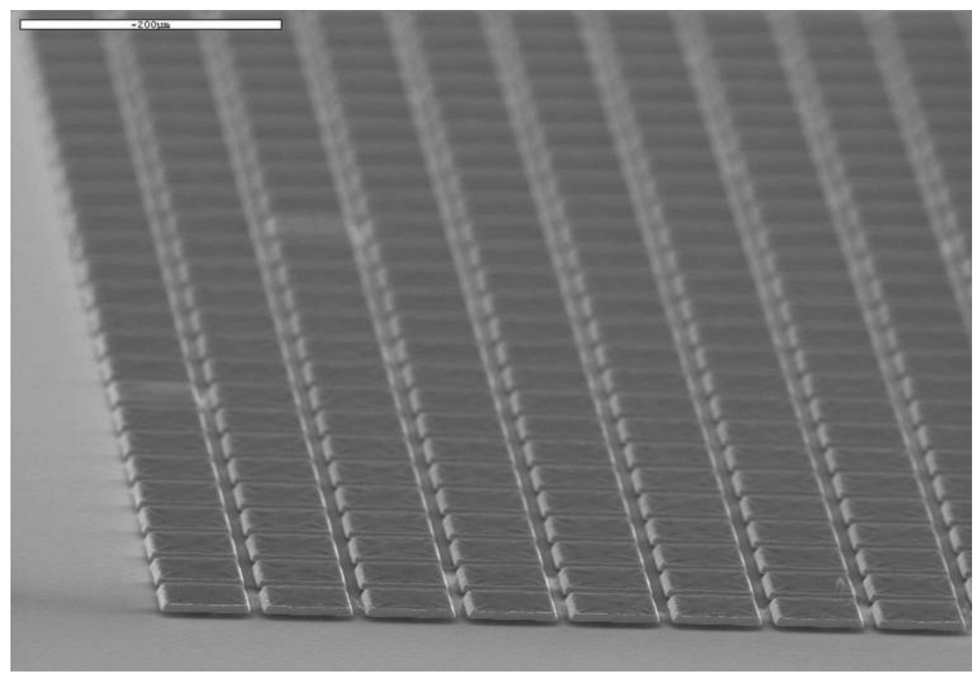
- Best energy resolution detecting 6 keV x-rays with an energy dispersive detector
- High count rate capability
- More demanding read-out requirements

Lower T_c Small Pixels:

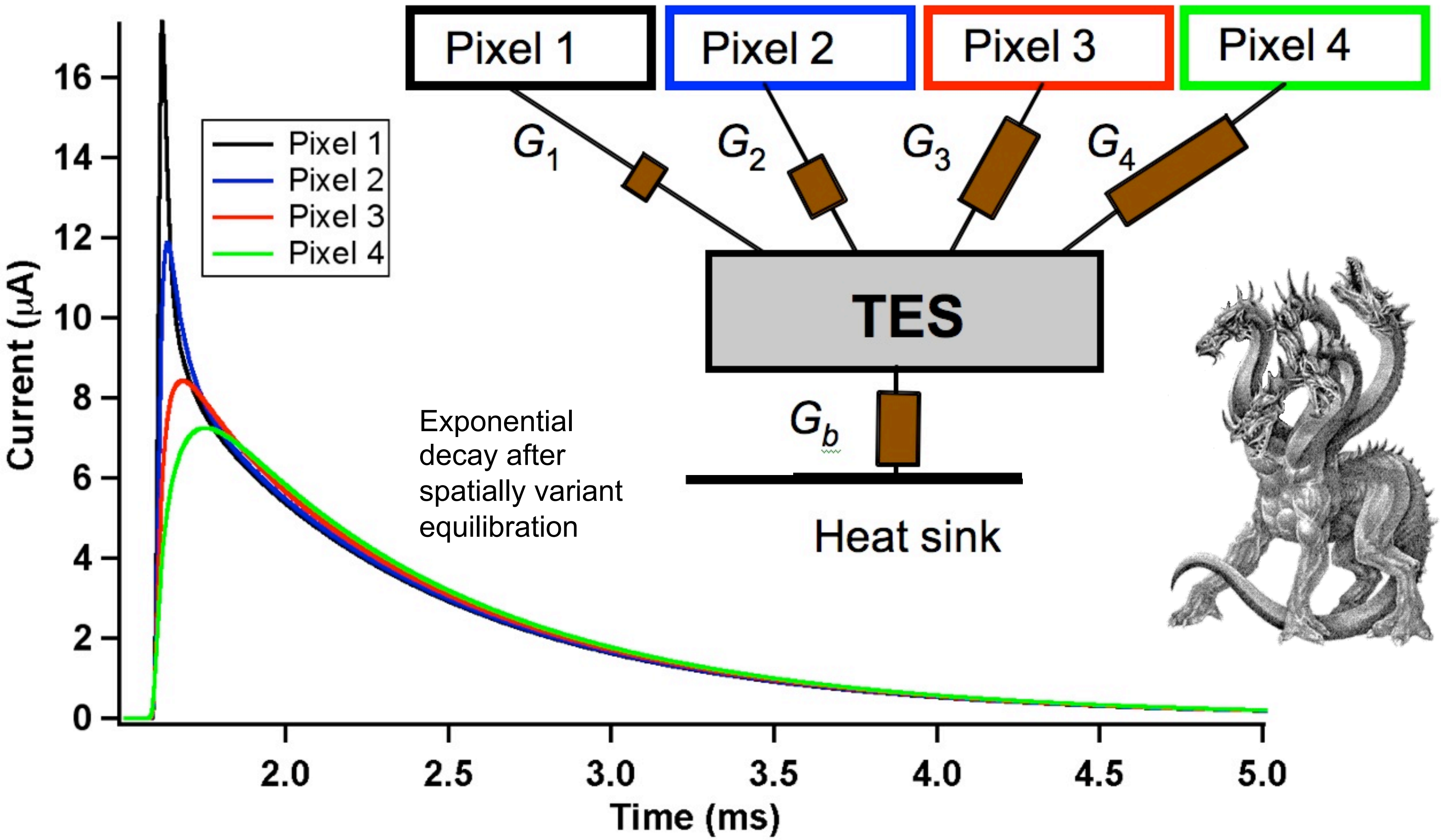


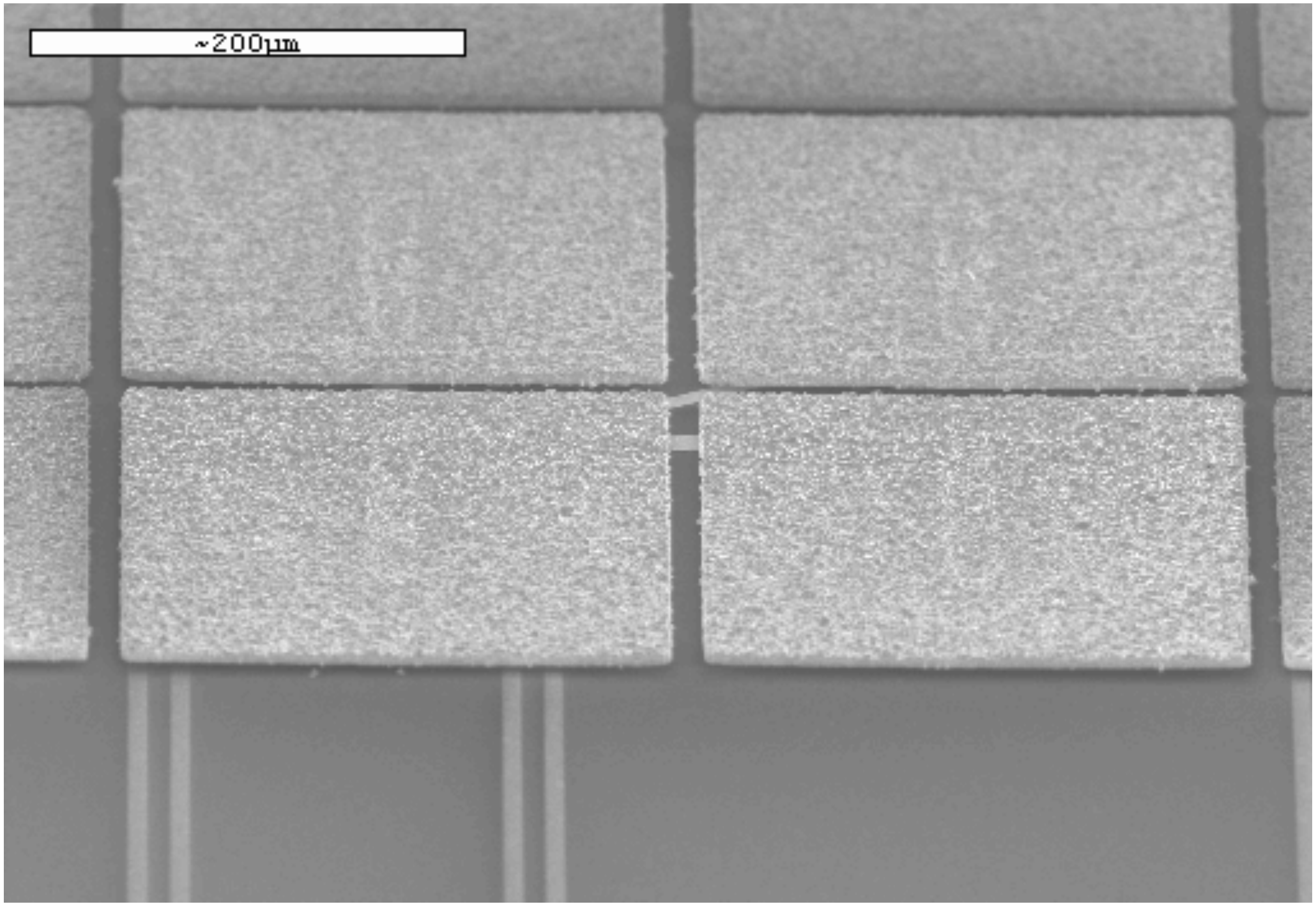
First sub-eV energy resolution result for an X-ray microcalorimeter – at 1.5 keV

- TES on 75 micron pitch
- Absorber: 65μm x 65μm x 5.0 μm
- Similar signal speeds / count rate capability to standard pixel design



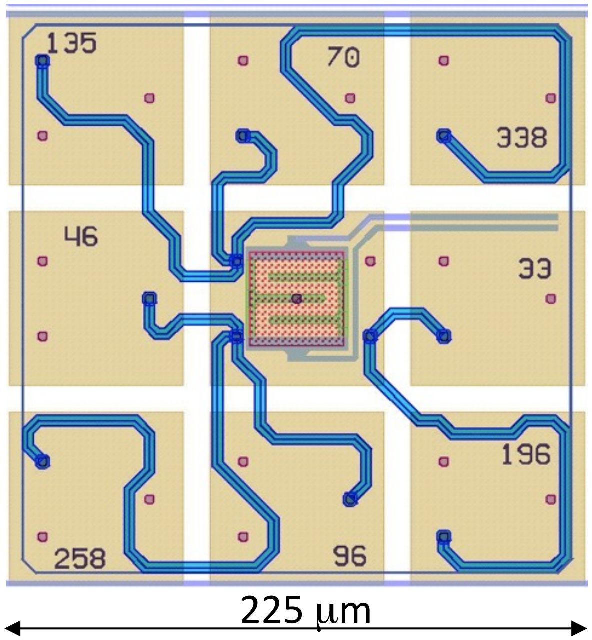
Multi Absorber TES "Hydras" - 1 TES, 4 absorbers
– increase field of view for a fixed number of read-out channels

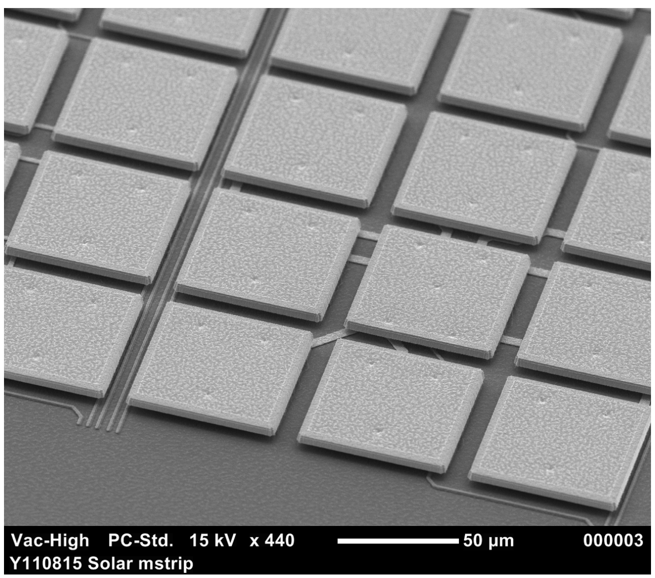




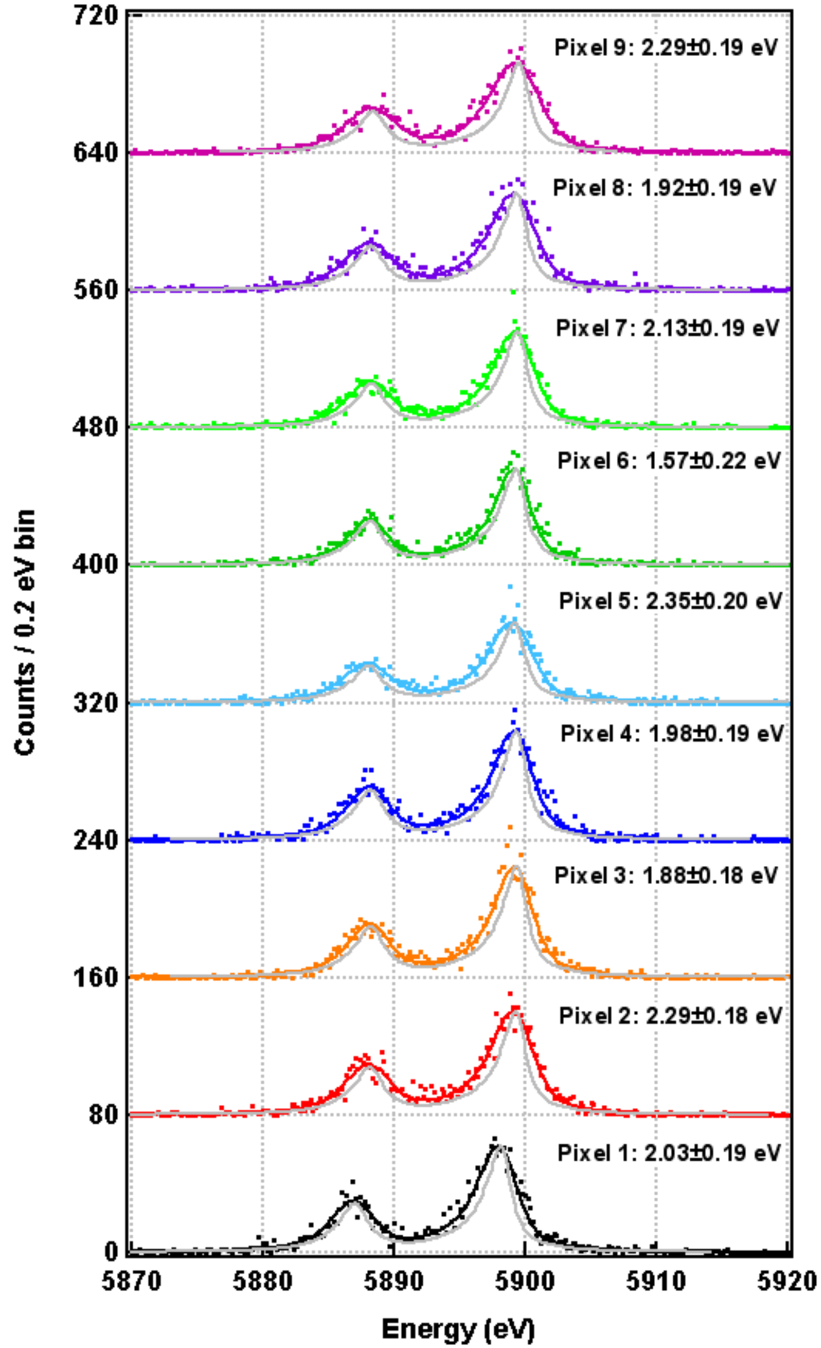
2x2 Hydras with 250 µm absorbers:
E < 6 eV FWHM

Hydras with 3x3 array of 65 μm absorbers, 5.0 μm thick

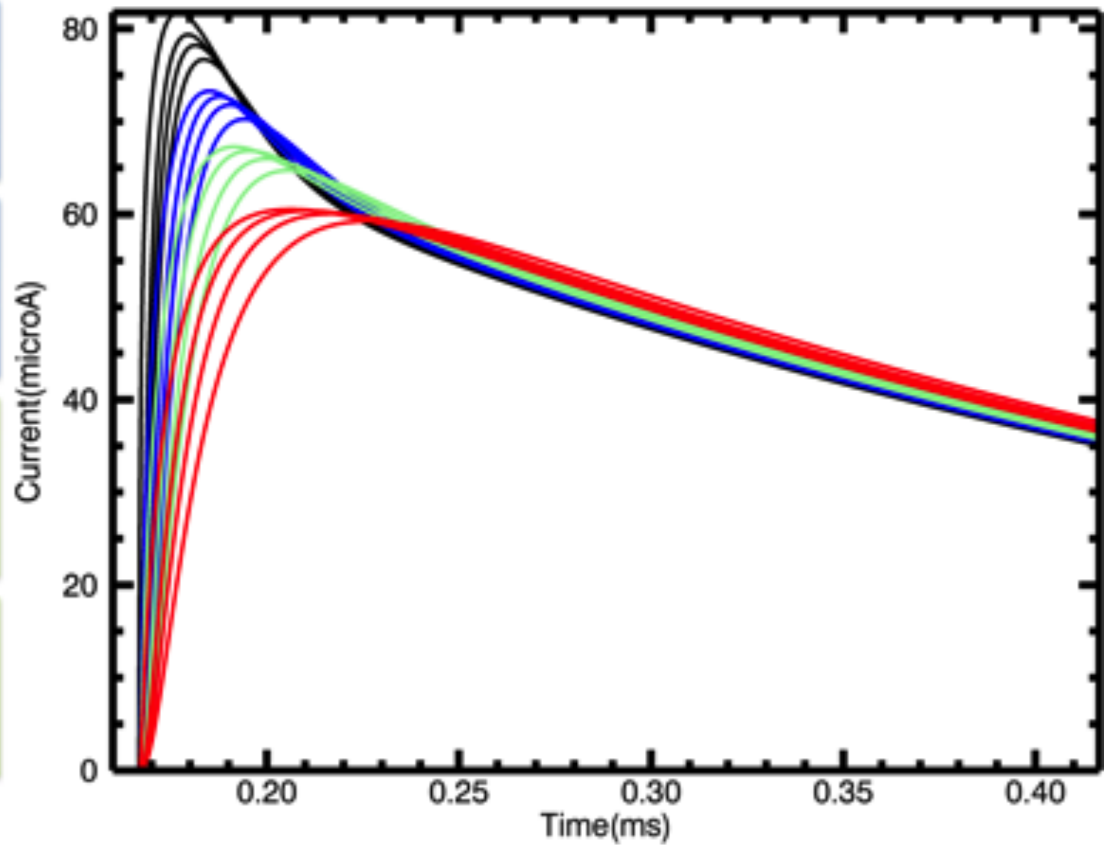




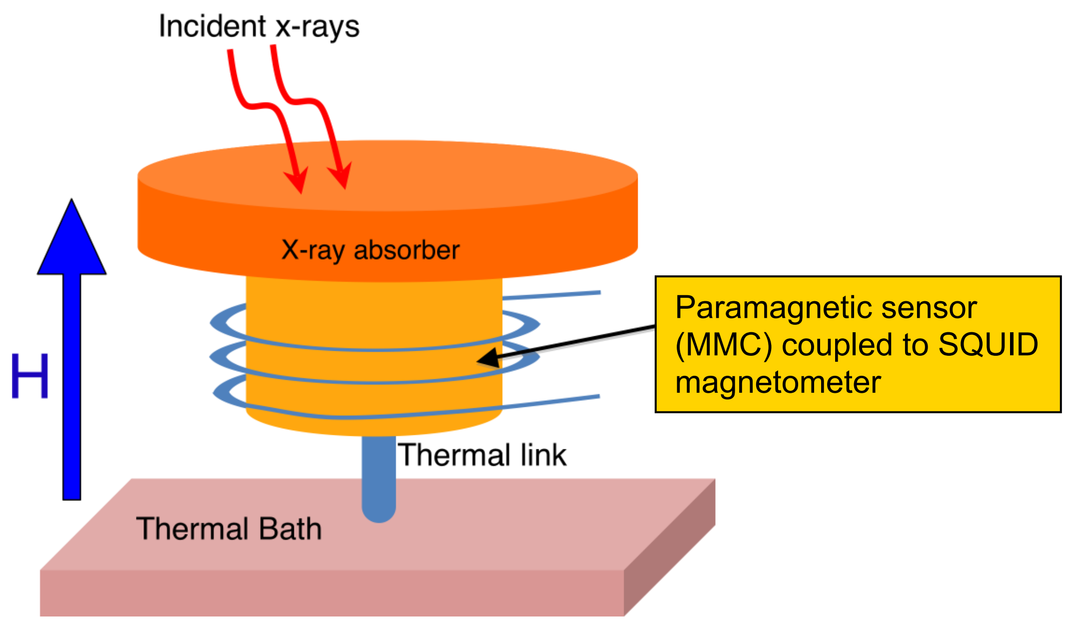
ΔE_{rms} = 2.4 eV (FWHM) at 6 keV, Mn-Kα



Future hydra designs for high-spatial resolution, large FOV mission concepts:



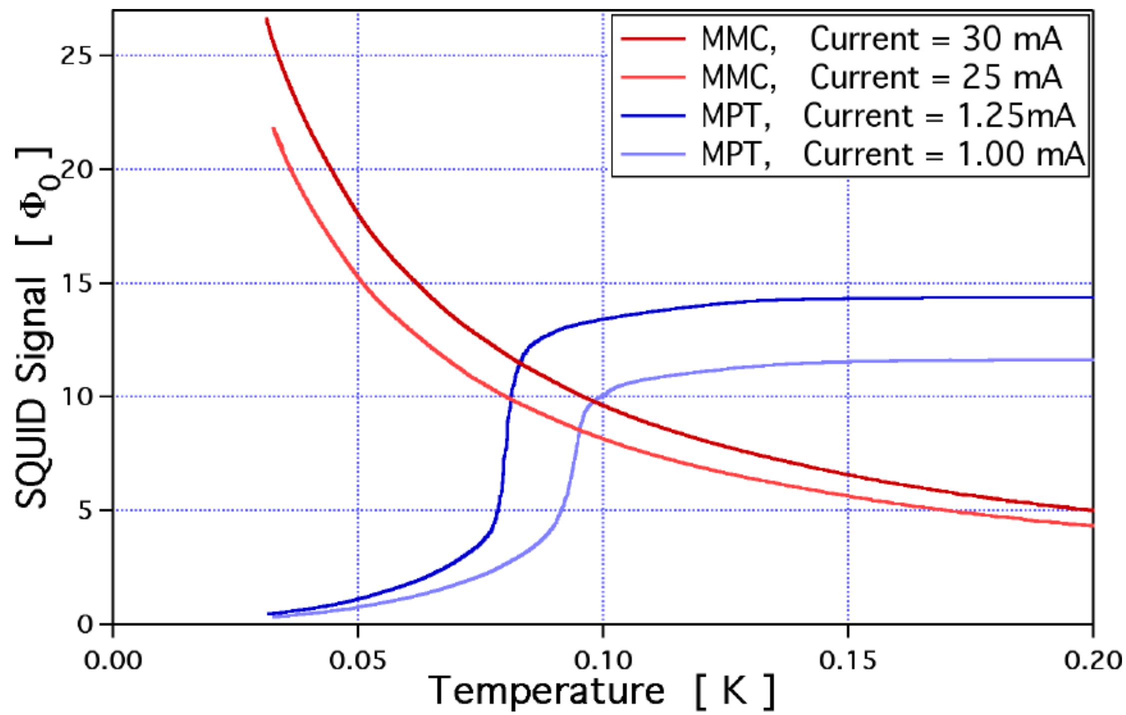
Magnetic Calorimeters (MMC) & Magnetic Penetration Thermometer (MPT) Microcalorimeters

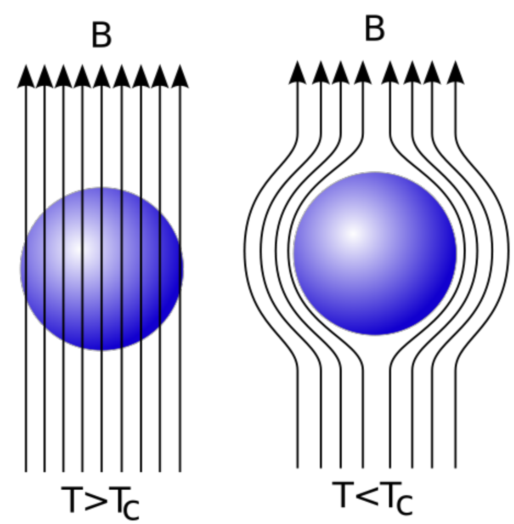


$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{\delta E}{C}$$

Paramagnetic sensor: Au:Er

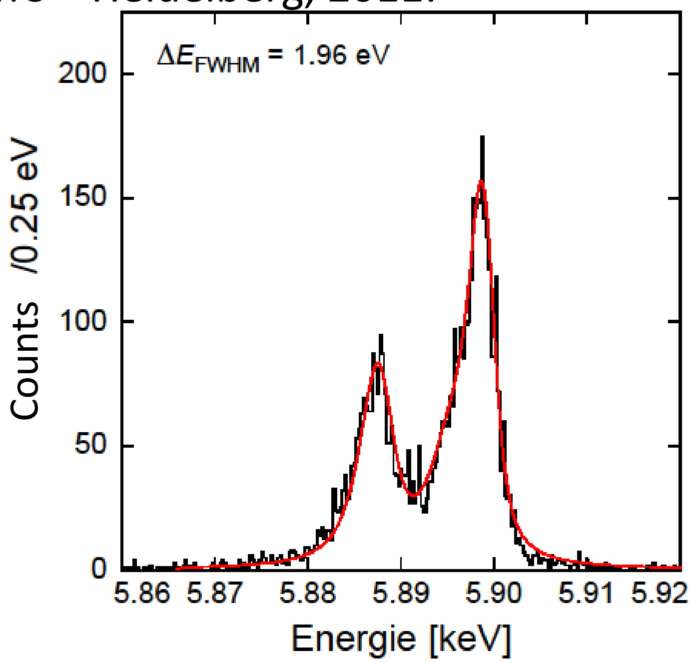
$$M \propto \frac{1}{T}$$



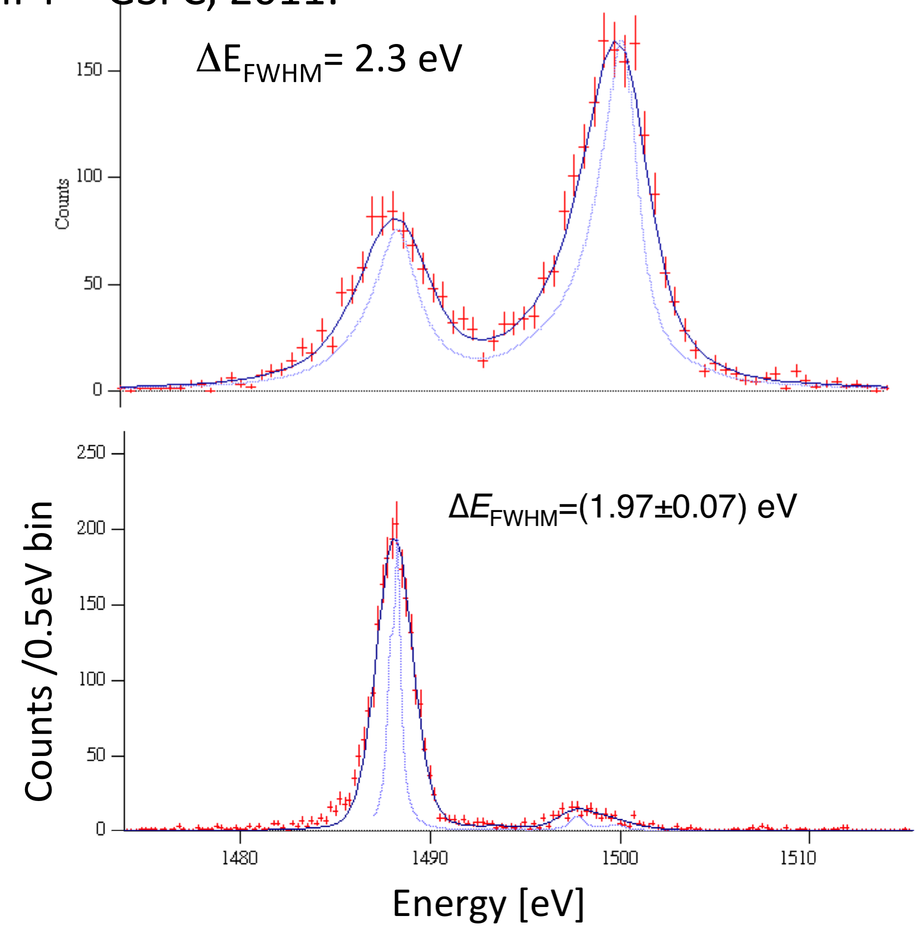


Best magnetically coupled calorimeter results at 6 keV:

MMC – Heidelberg, 2011:



MPT – GSFC, 2011:



MMC / MPT

The good:

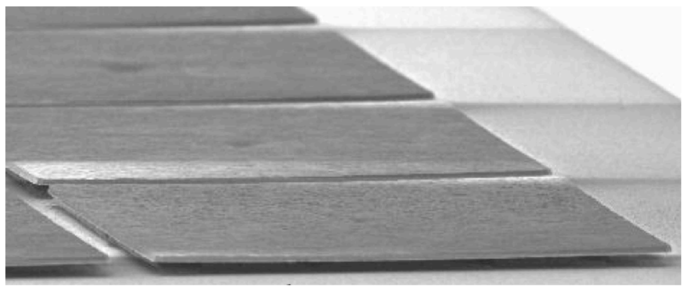
- Potential for the very highest energy resolution

  (no Johnson noise)

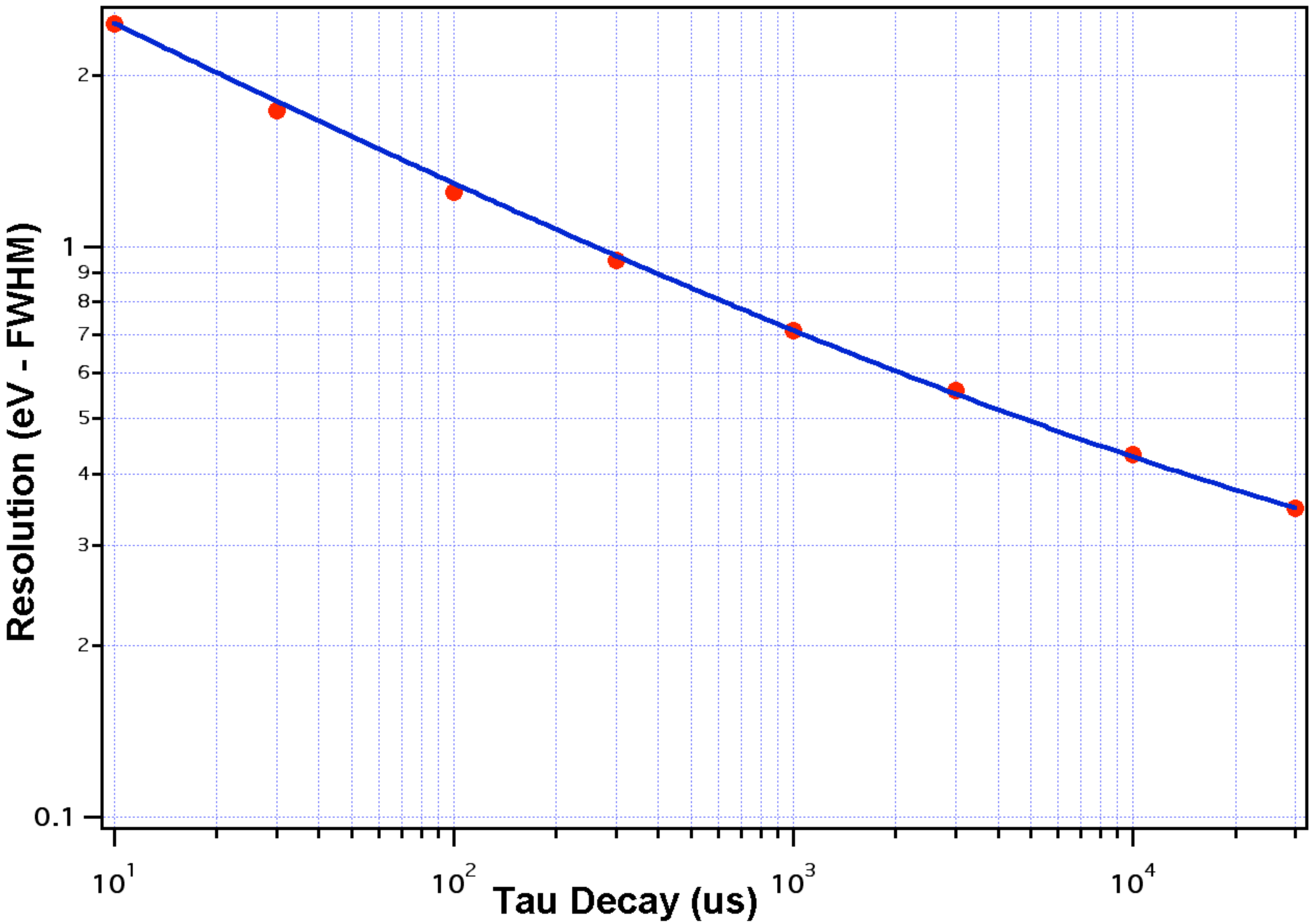
- Non-dissipative nature => larger array sizes might be possible

The bad:

- Hardest to technology to read out and multiplex with a non microwave read-out scheme



250 μm absorb., 2.8 μm thick Au, supported on single 3.5 μm stems



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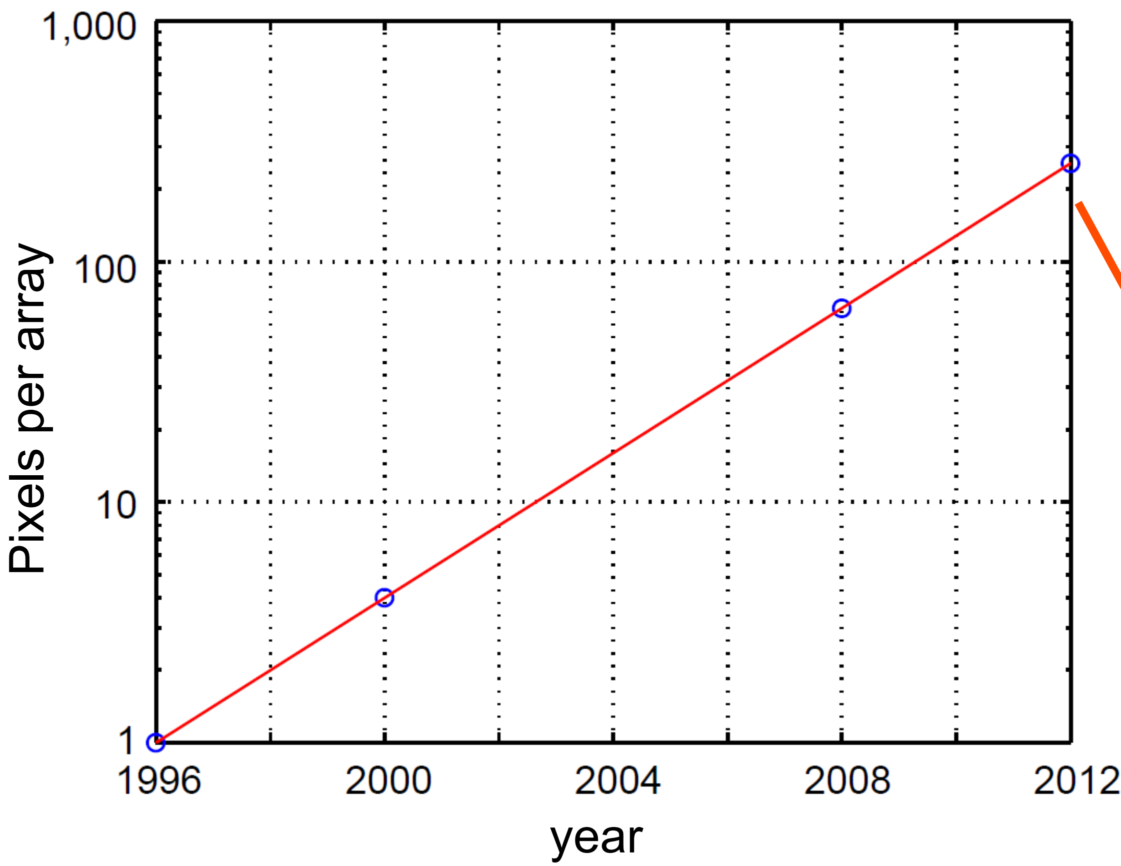
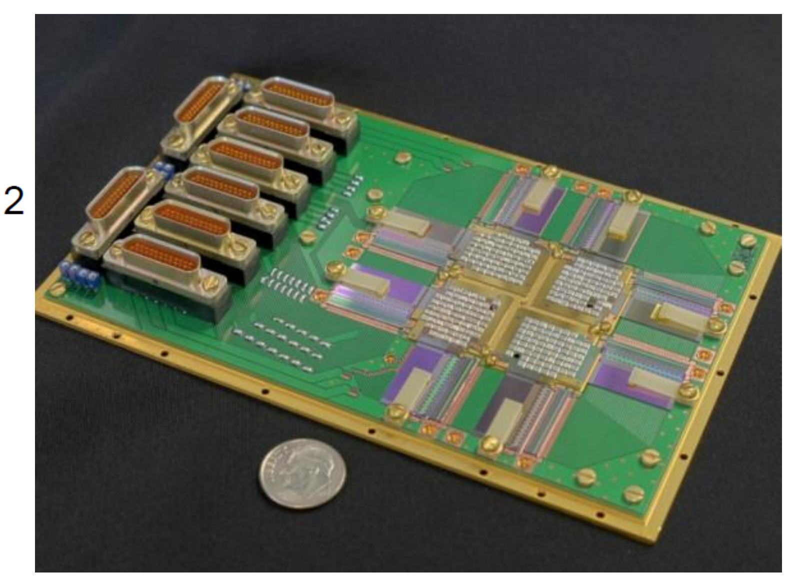
Moore's law for instrumented TES calorimeters

Doubling time: 2 years



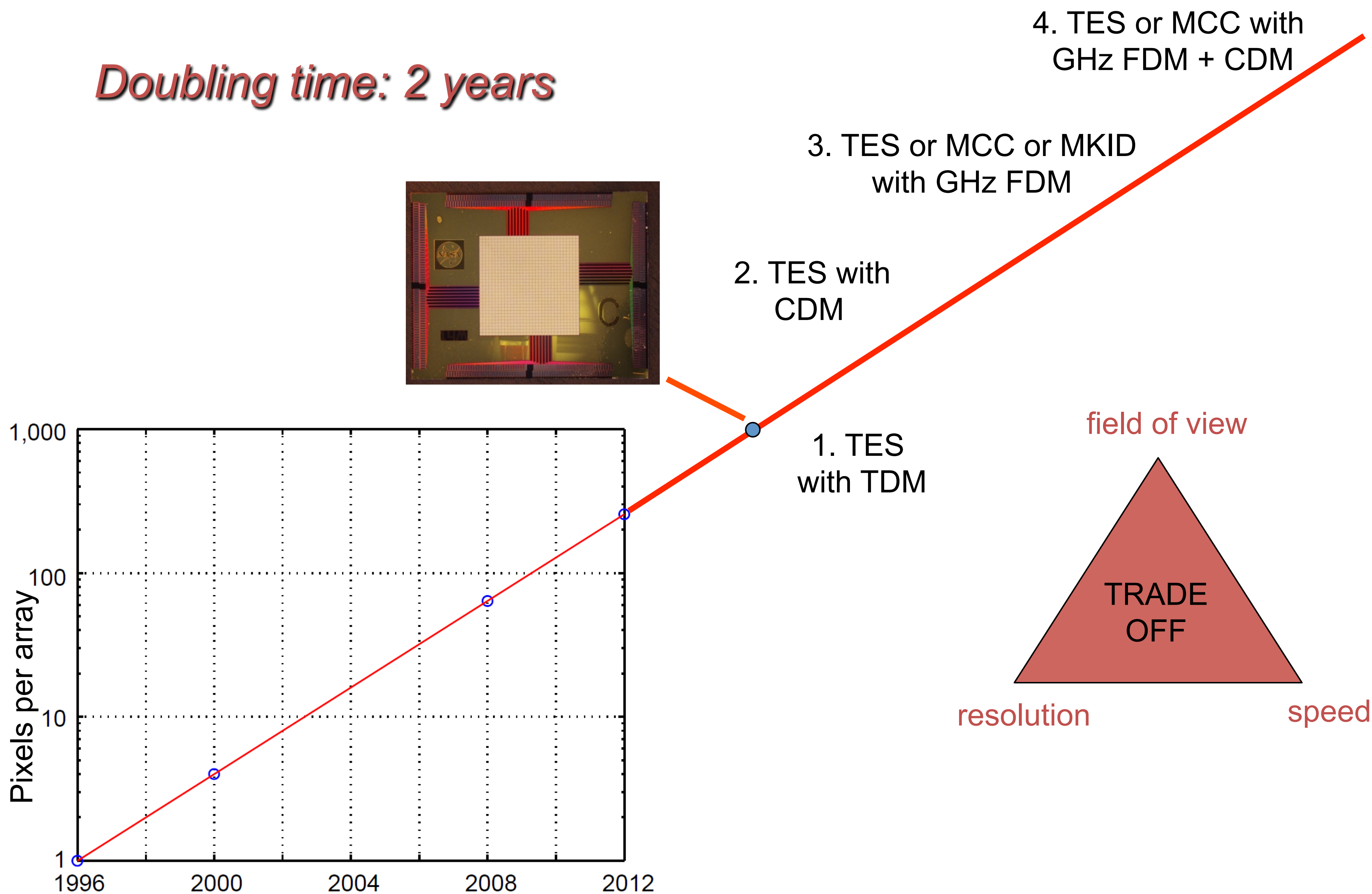
Harder multiplex than TES bolometers because of dynamic range of x-ray events



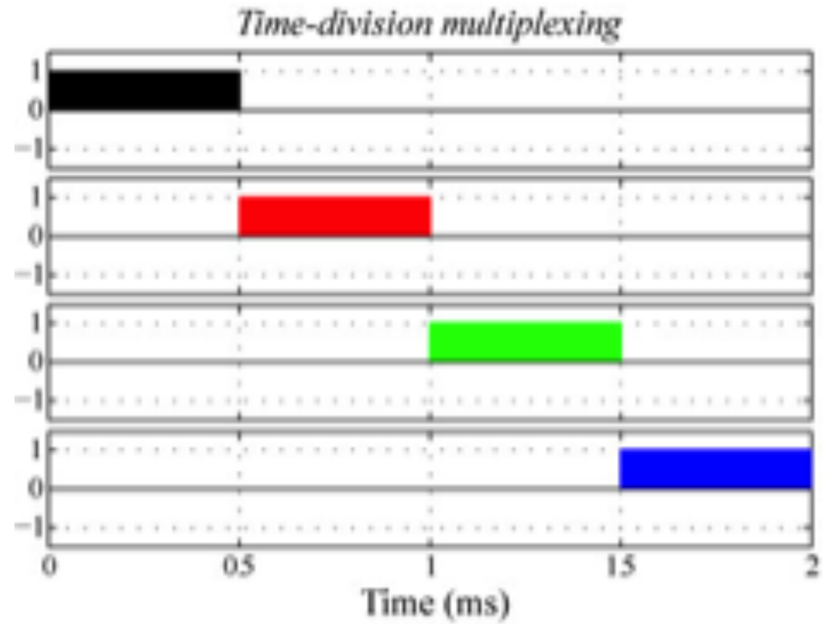
Largest instrumented microcalorimeter: 256 pixel hard x-ray array (NIST)

- 8x32 readout architecture

Moore's law: The 30,000 feet view …….



Time Division Multiplexing

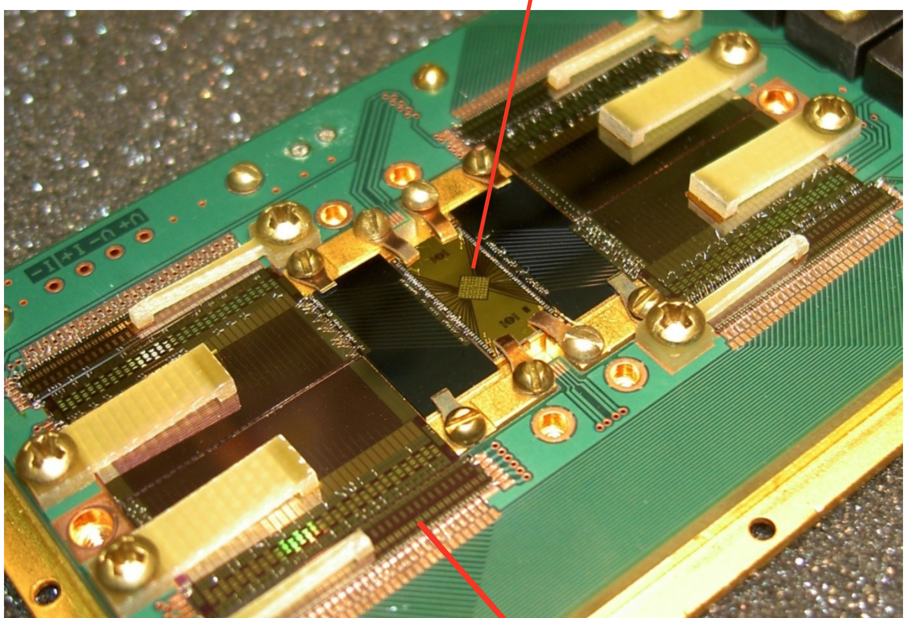


GSFC 8 x 8 array
NIST SQUID MUX readout

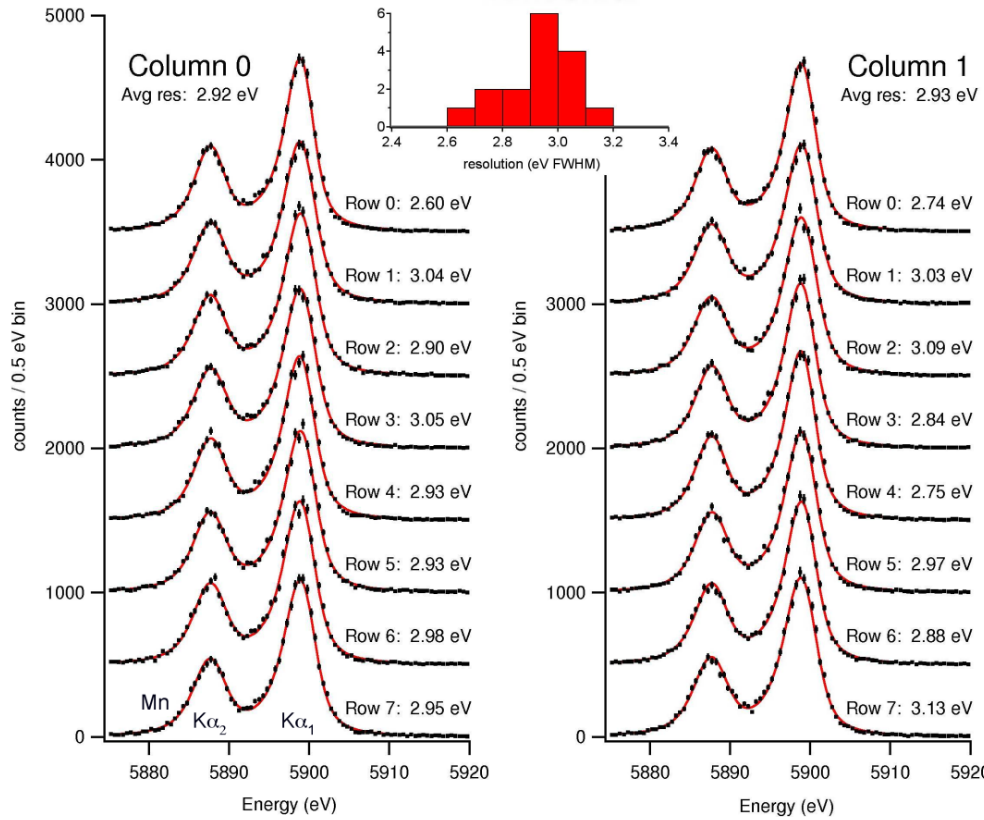
2 x 8 mux readout of 8x8 array

ΔE_{FWHM}= 2.9 eV

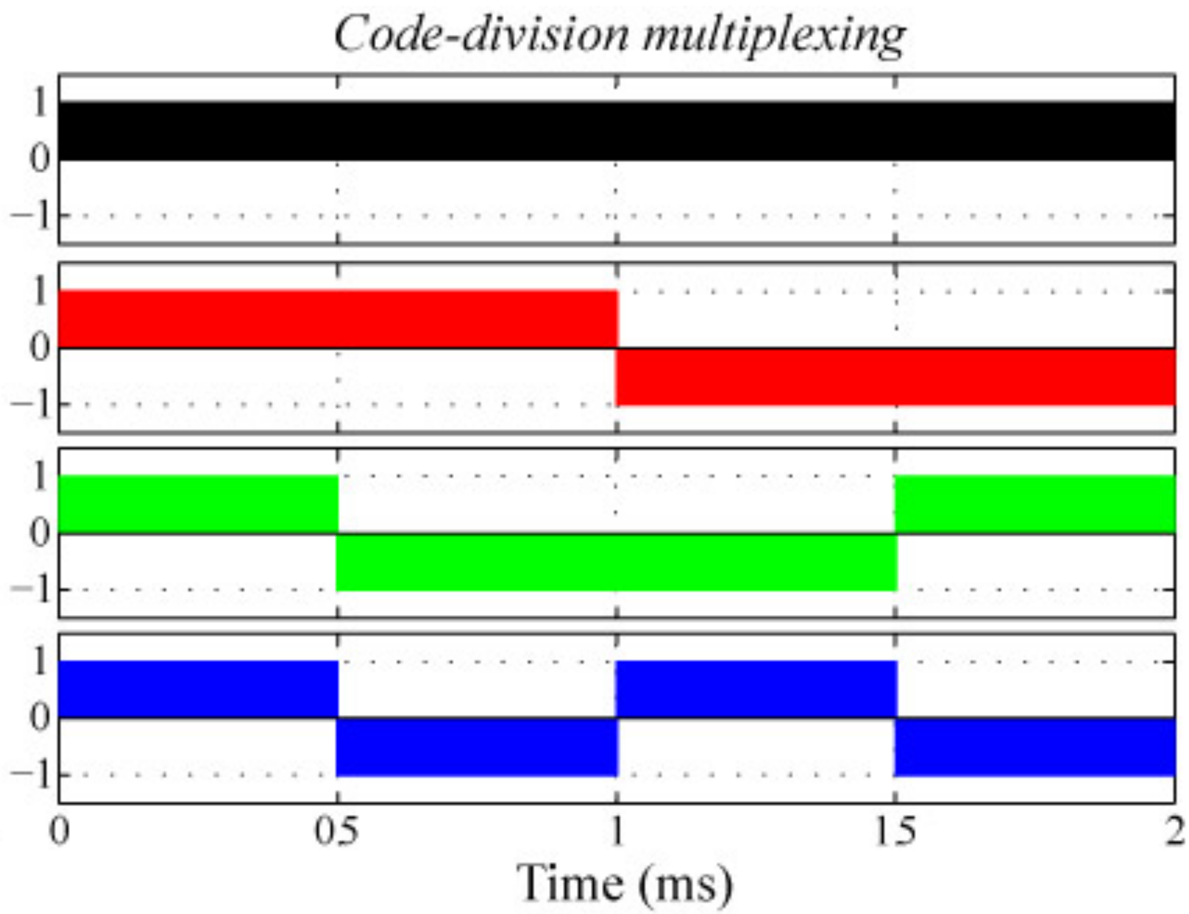
Calorimeter array



SQUID multiplexers



CDM: better dynamic range, energy resolution than TDM

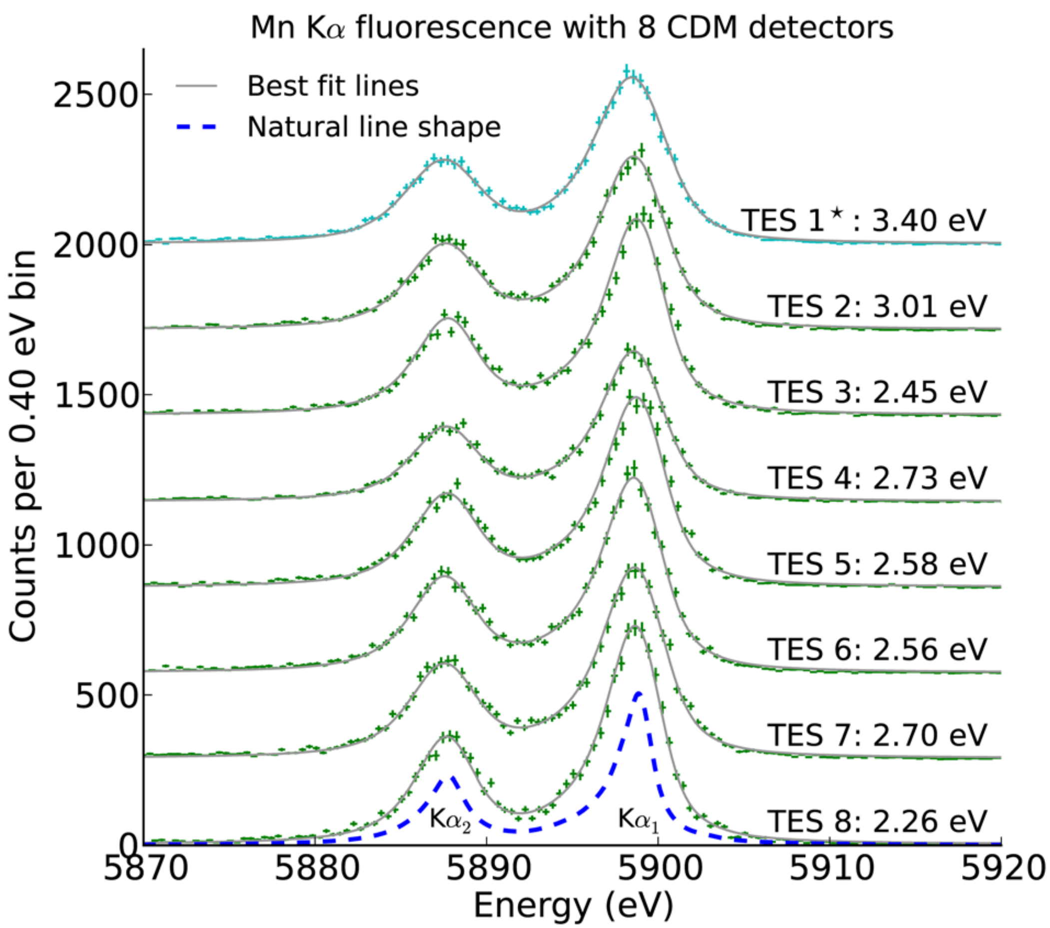


- Every detector pixel is on all of the time
- Does not have "multiplex disadvantage" that exists for TDM multiplexing

CDM: excellent performance demonstrated

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

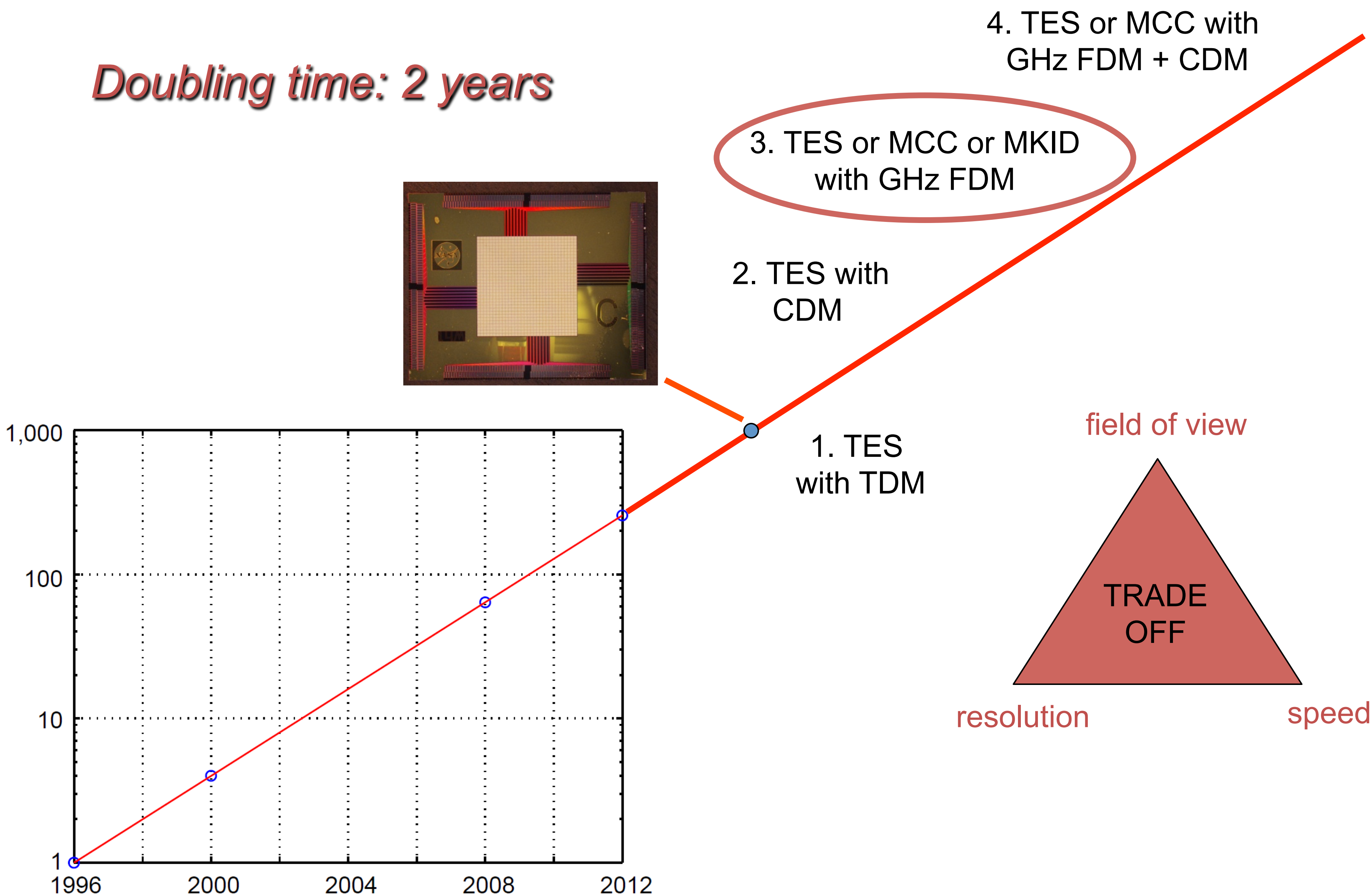
Promising first results from 1x8 CDM demonstration:
Circuit (flux coupled CDM):

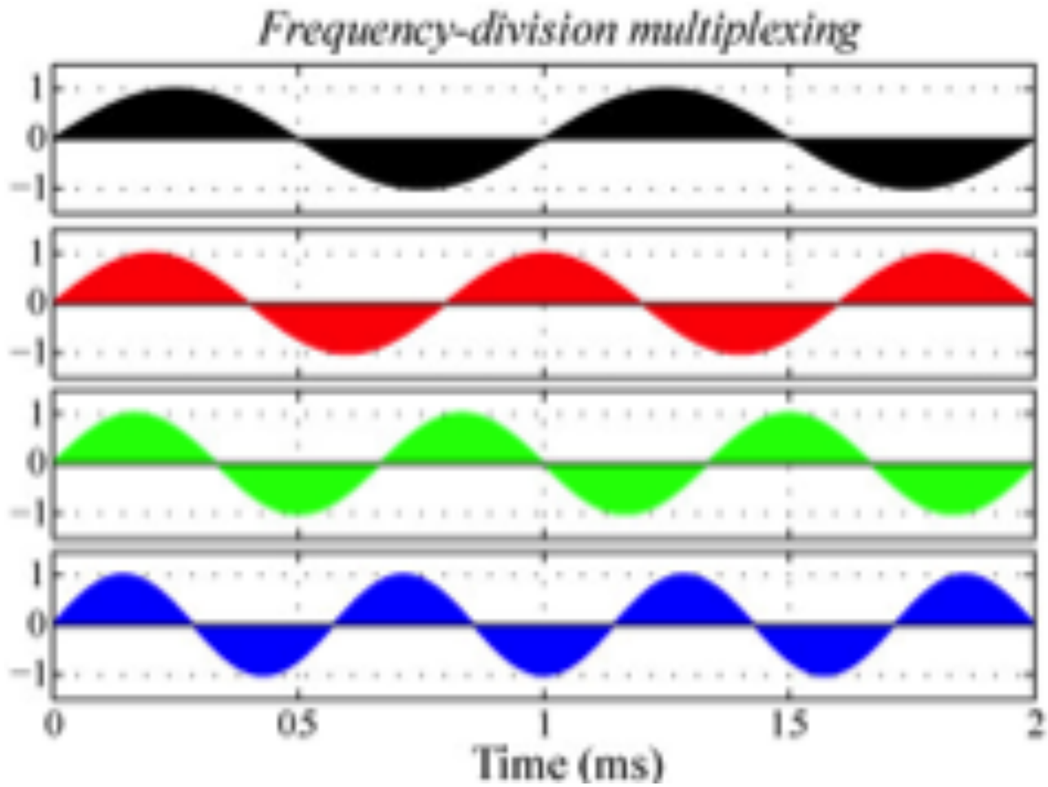


CDM chips - drop-in compatible with existing 32-row TDM systems, with the same wiring and readout electronics, but have higher performance.

Moore's law: the next ×1000

Doubling time: 2 years



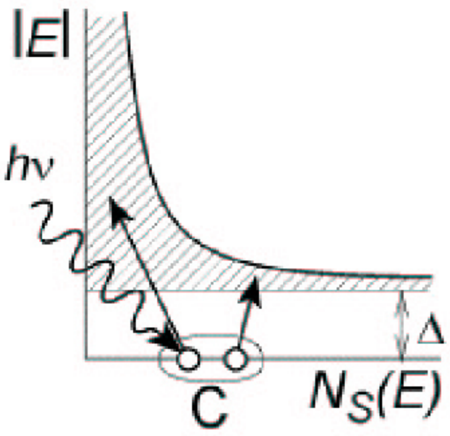


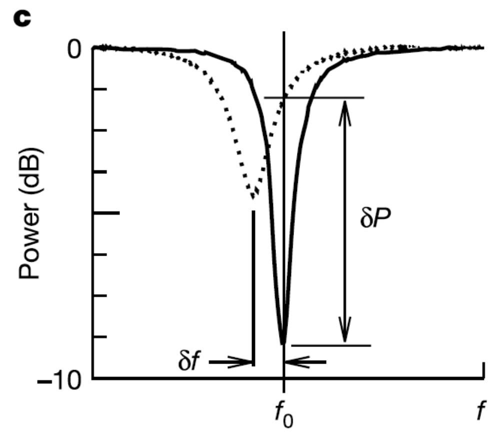
TES bias modulation

- Different TES pixels AC-biased at different frequencies read out by single amplifier
- X-ray pulses seen in amplitude modulation
- Like CDM, no multiplexing disadvantage

GHz FDM multiplexing convergence

Microwave kinetic inductance detectors (MKIDs): detector is resonator

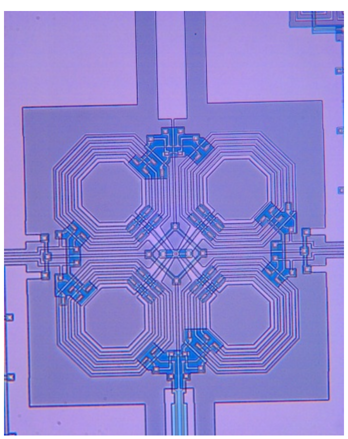


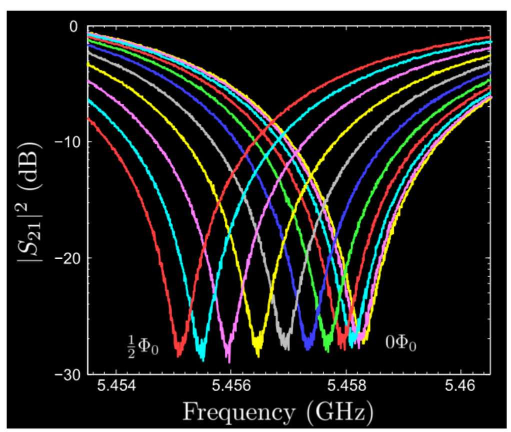


- Single pixel x-ray performance needs to be demonstrated

- P. Day, Nature (2003)

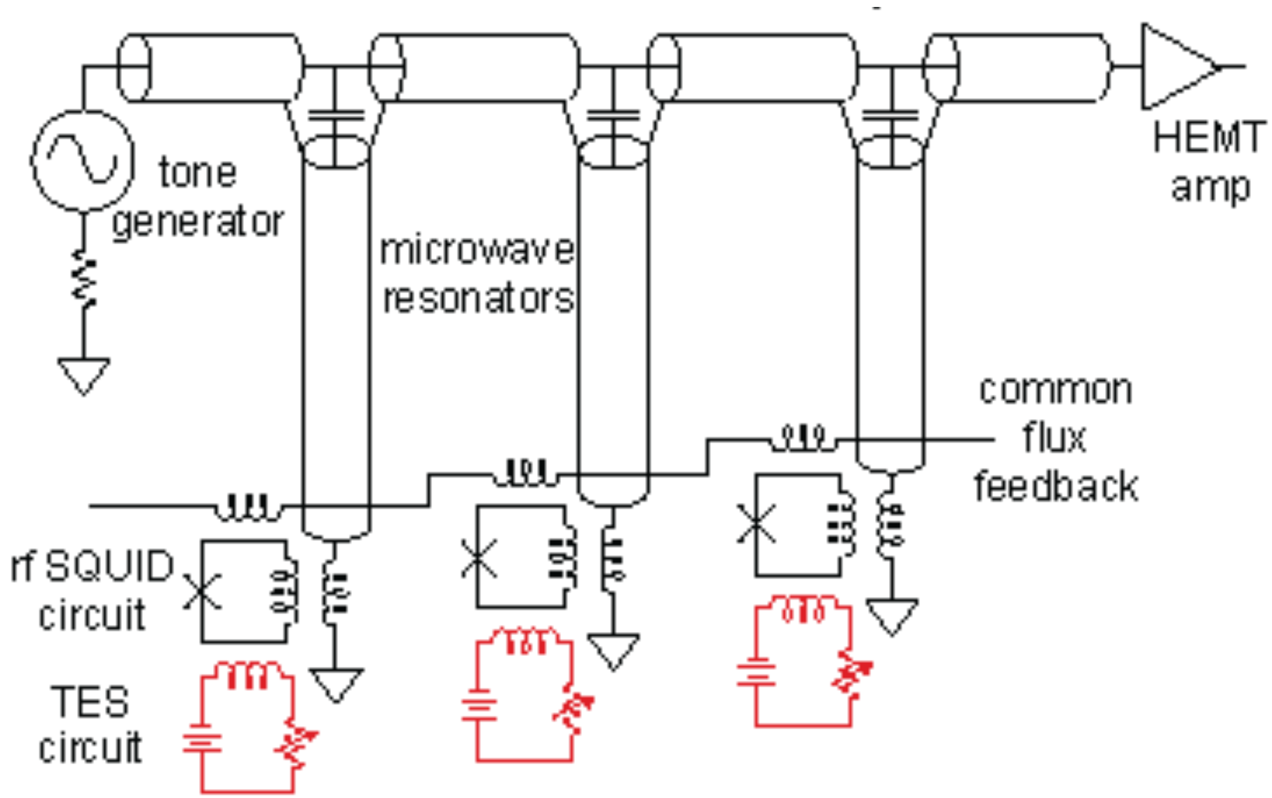
TES detectors or MMCs coupled to microwave resonators





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

GHz resonators for TES / MCC microcalorimeters:

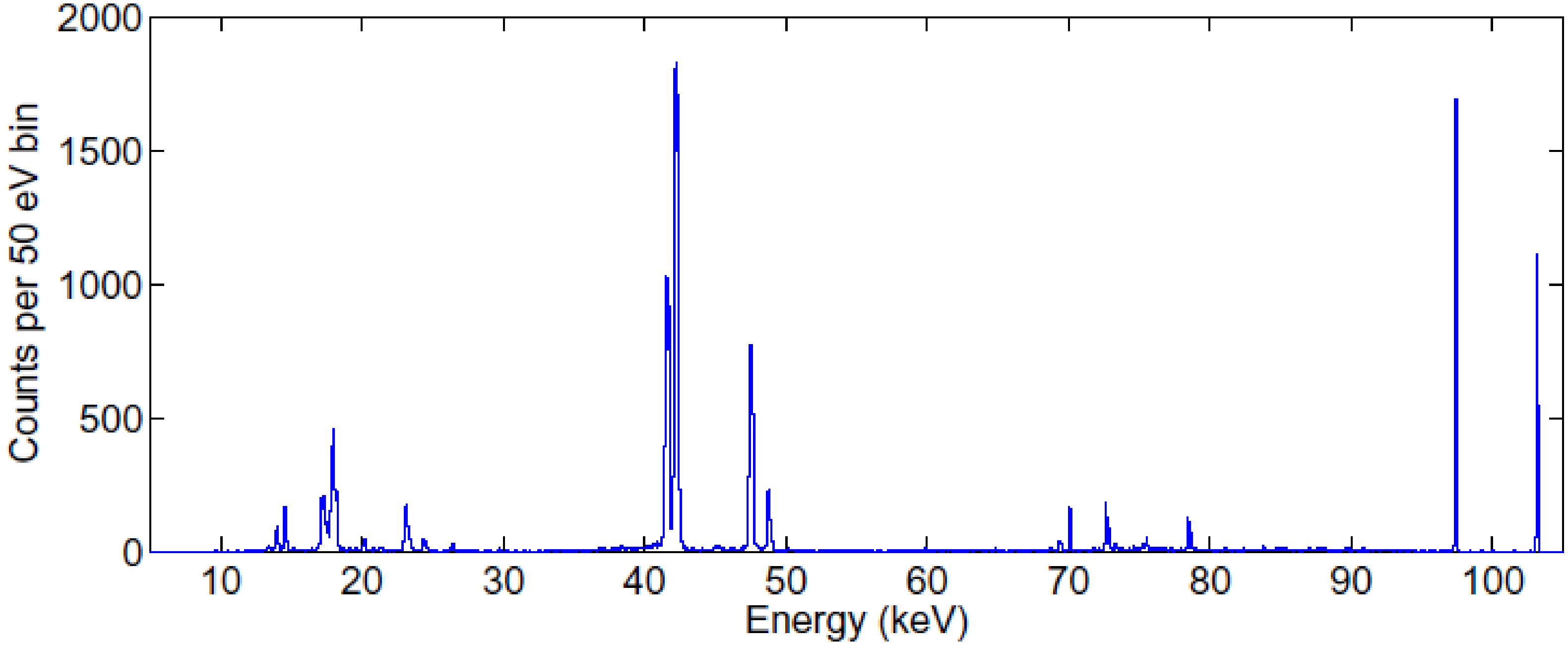


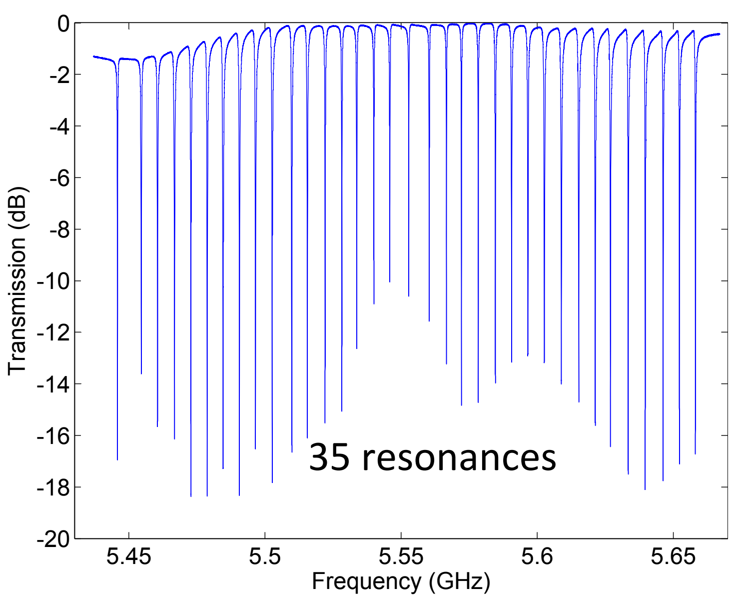
Array has:
2 coaxes (1 input + 1 output, like MKIDs)

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

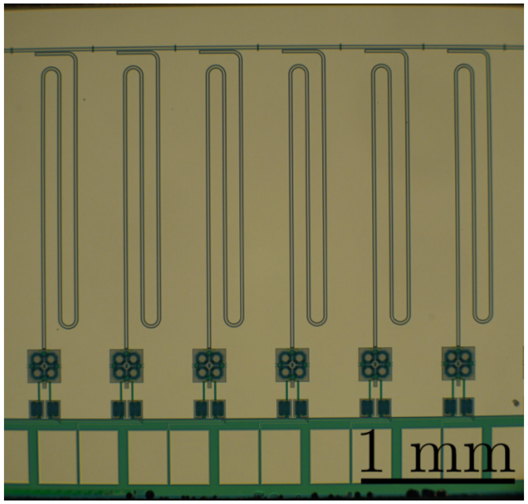
No feedback – (flux ramp modulation provides linear response)

First GHz FDM microcalorimeter demonstration with high spectral resolution:

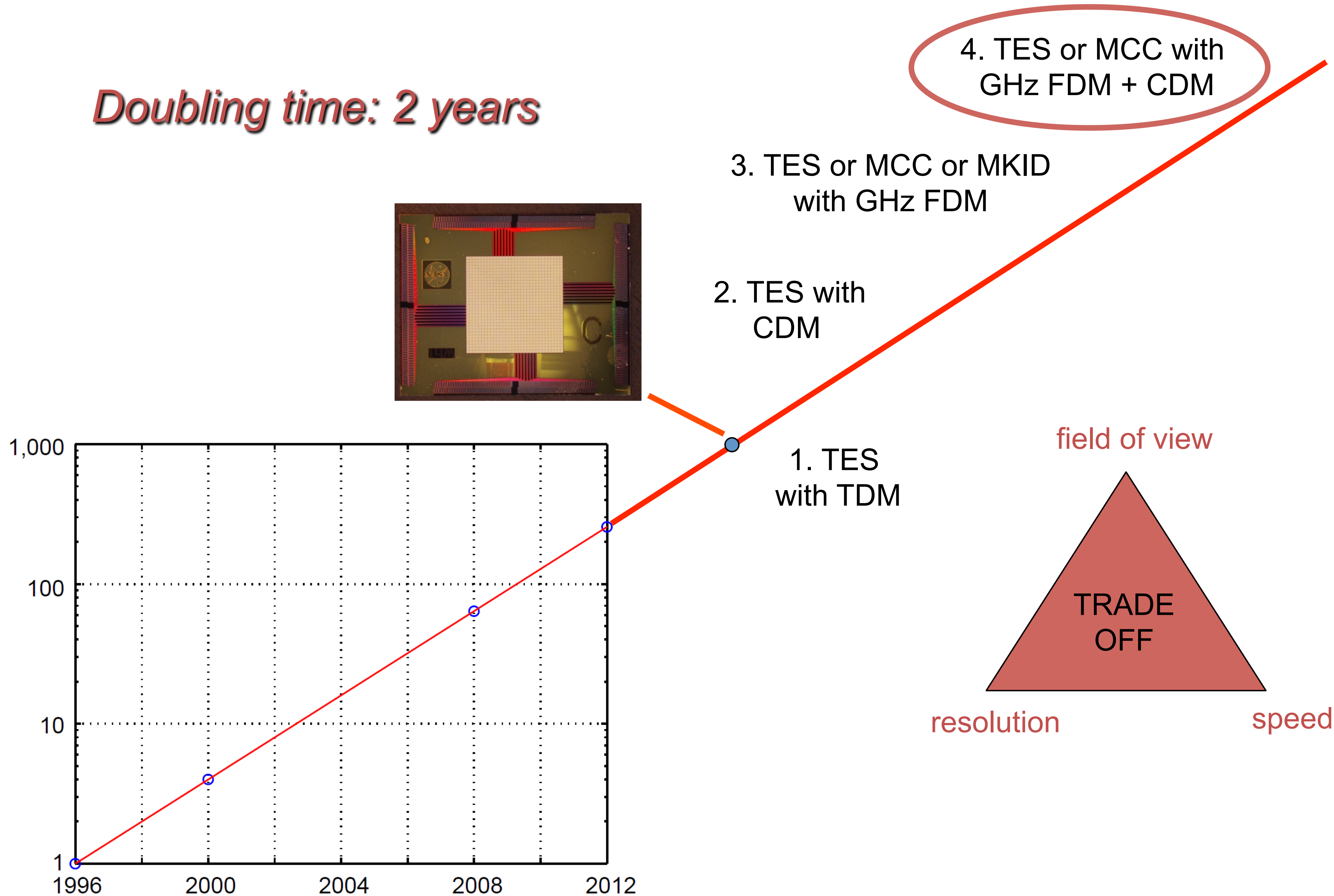




- Spectrum of Gd-153 with TES hard x-ray calorimeters
- At 100 keV, energy resolution ($E/\Delta E_{FWHM}$~1500)
  - very close to the unmultiplexed value 1

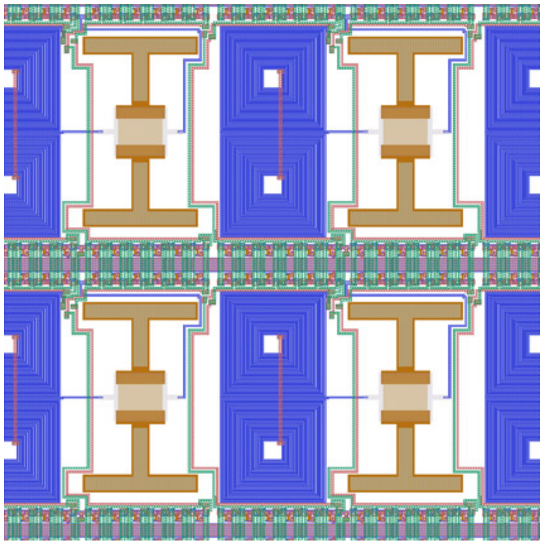


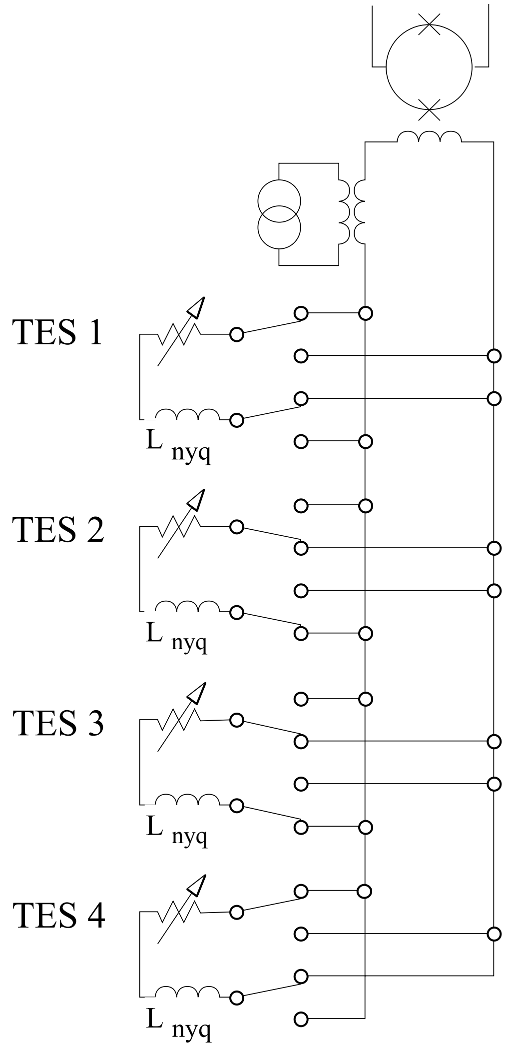
Moore's law: the next ×1000:



Hybrid GHz mux design
(resonator + CDM)

- GHz bandwidth / channel
- ~10^6 pixels

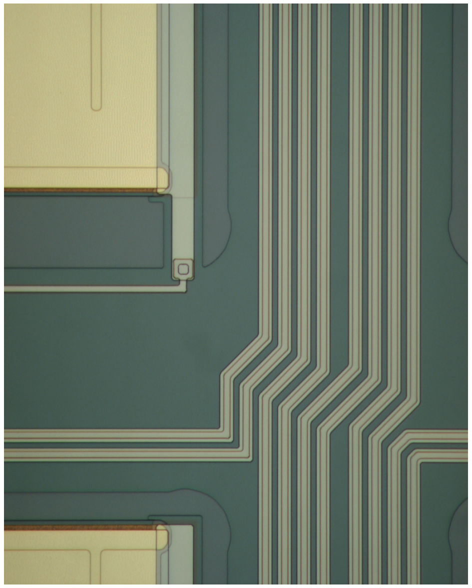




- Current from many calorimeters summed in one output resonator
- Polarity of coupling to output SQUID is switched in Walsh code
- No TES shunt resistors or power
- Compact modulation elements

Pushing limits on number of pixels:

- Array architecture
  - Wires between: Limit ~10^4 – 10^5 pixel level (depending on pitch, use of Hydras etc.).
  - Larger arrays -> close integration of pixels & read-out.
  - Hydras: Eases demands on heat-sinking, wiring, & electronics, (less resolution and per-pixel count rate).
- Wiring to room temperature
  - CDM with microwave multiplexing >10^5 sensors? with as few as two coaxes (depending on sensor speed, pitch).



➔ *Possibly > 10^5 TESs in next 20 years (>10^6 with Hydras), though compromises on count rate may be necessary.*

J.S. Adams, M. Balvin, S.E. Busch, J.A. Chervenak, M.E. Eckart, A. Ewin, F.M. Finkbeiner, R.L. Kelley, C.A. Kilbourne, S.-J. Lee, F.S. Porter, J.-P. Porst, J.E. Sadleir, S.J. Smith, T.R. Stevenson, E.J. Wassell
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