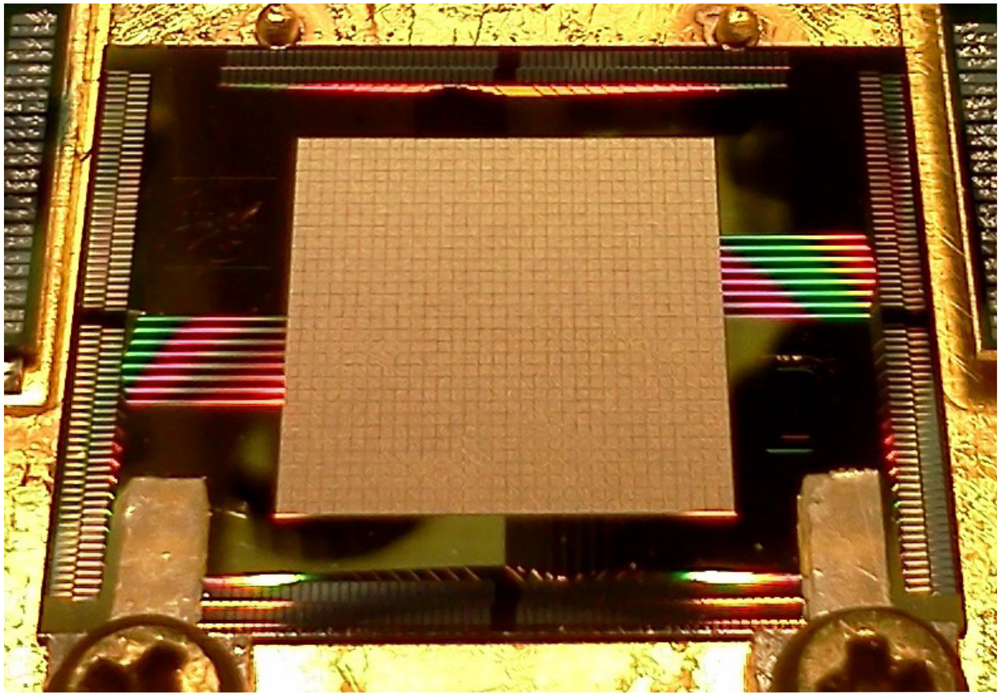
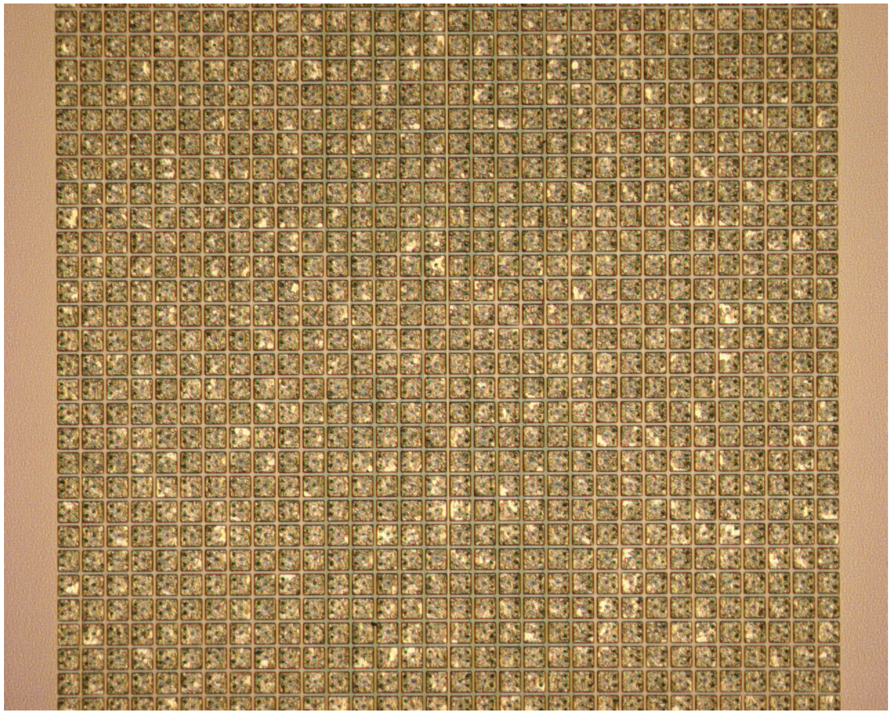
Cryogenic Detectors: Microcalorimeters for X-ray Astrophysics

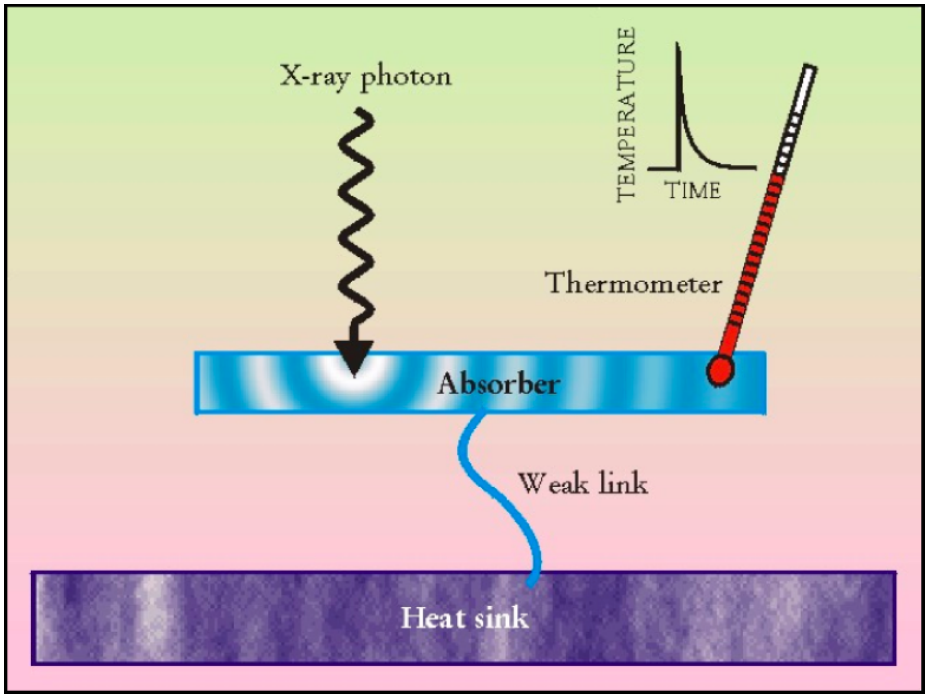
Simon Bandler: University of Maryland – College Park & NASA/GSFC
on behalf of the X-ray microcalorimeter group at NASA/GSFC

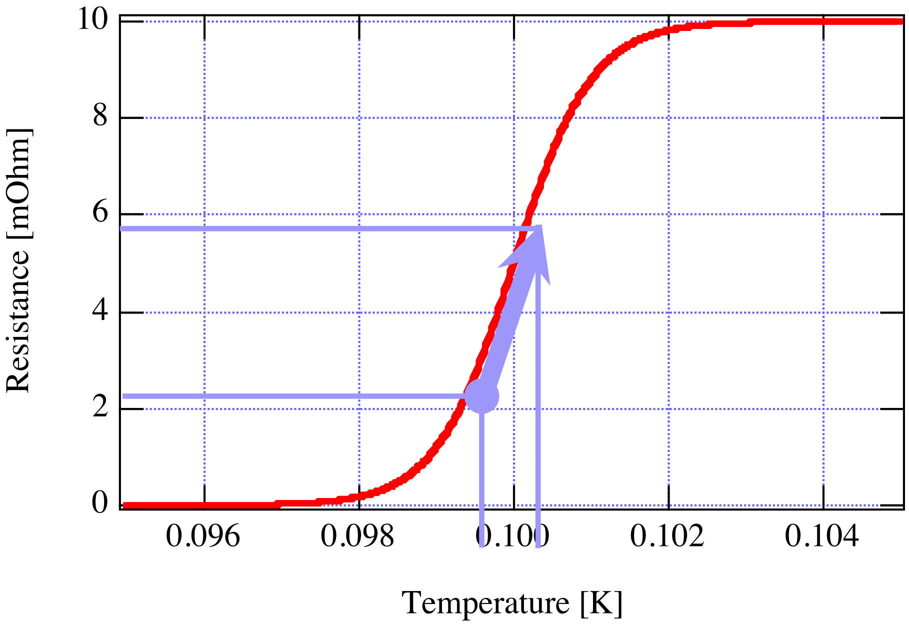




State-of-the-art kilo-pixel arrays of TES-based X-ray microcalorimeters
- Left: 1024 pixel array on 300 μm pitch
- Right: 1024 pixel array on 75 μm pitch

Transition-edge Sensor microcalorimeter basics:





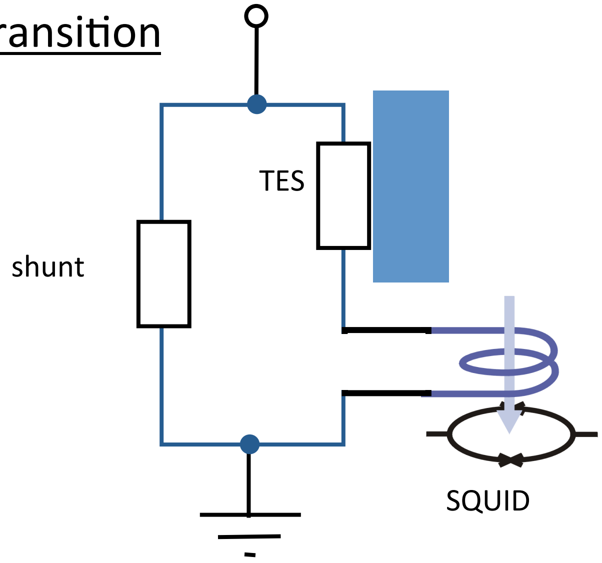
Temperature rise:

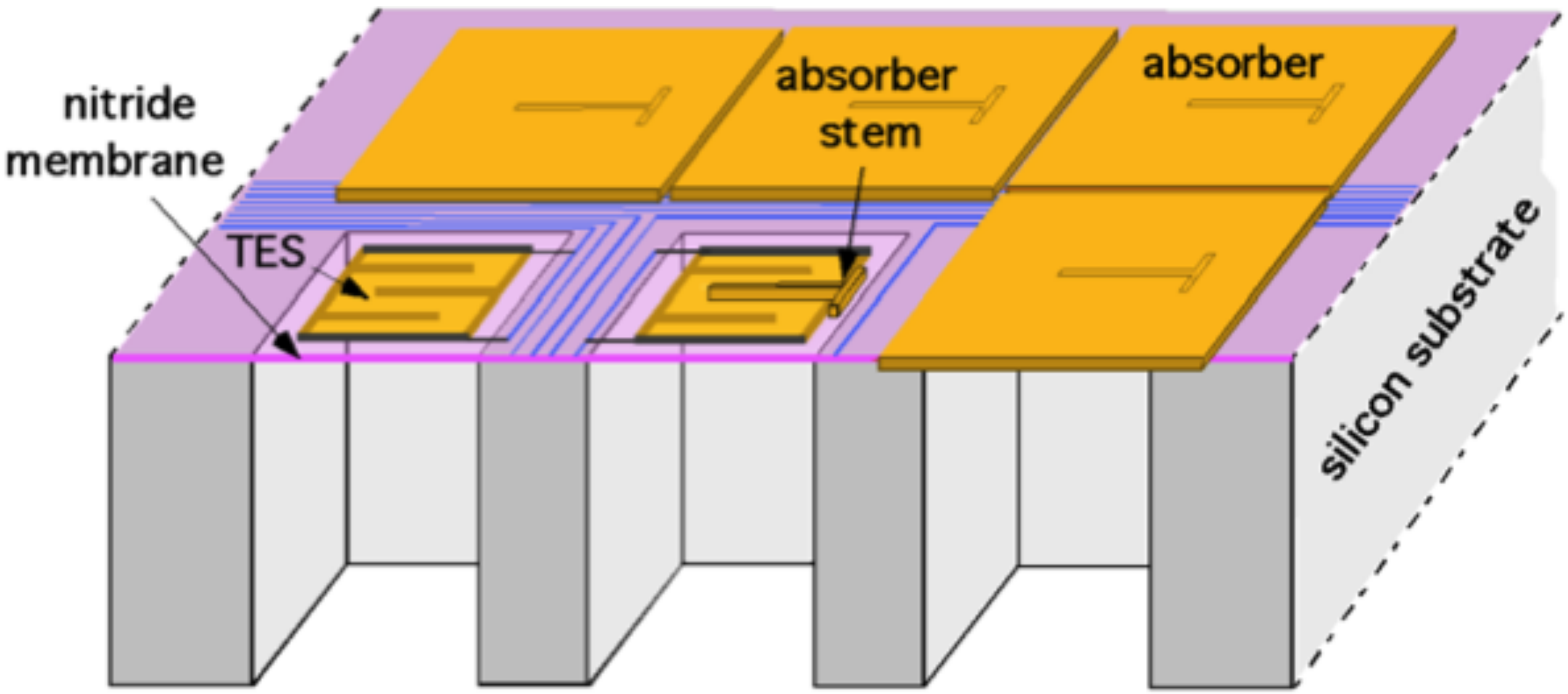
$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

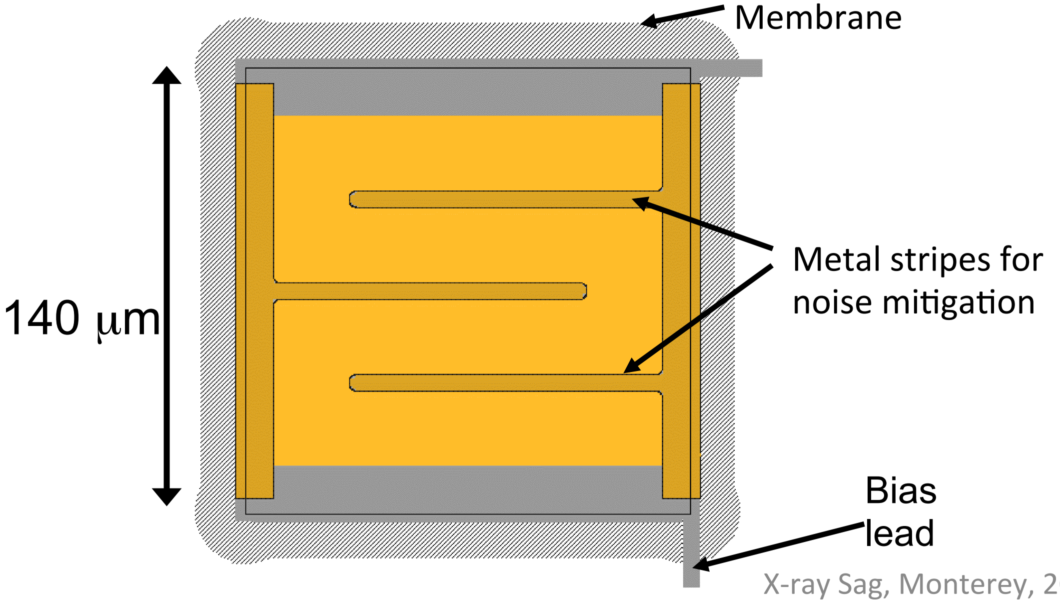
Energy resolution:

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

Superconductor voltage-biased in its transition





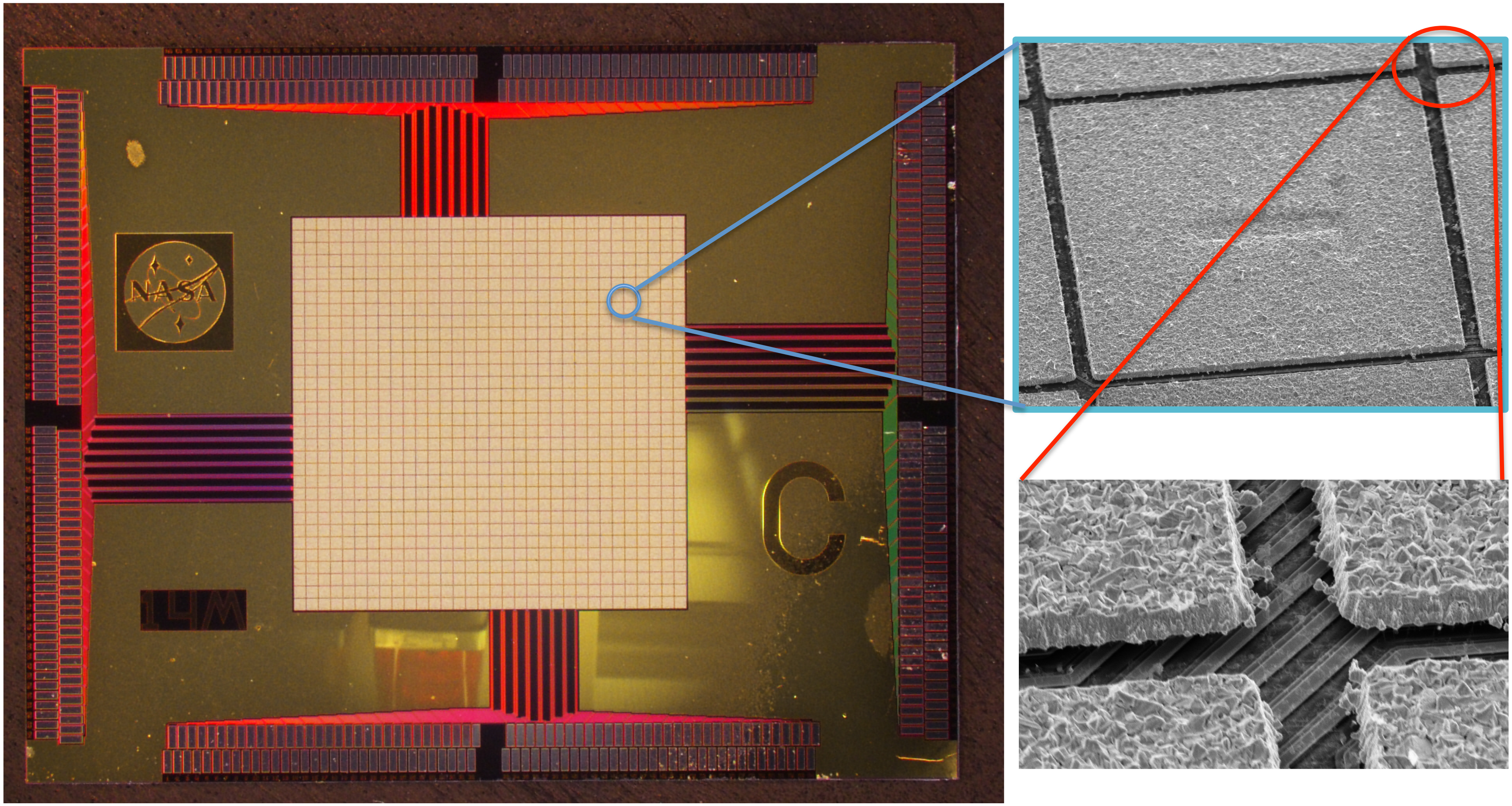


TES: Mo (50 nm) / Au (225 nm)

$T_c \sim 0.1$ K

X-ray Sag, Monterey, 2013

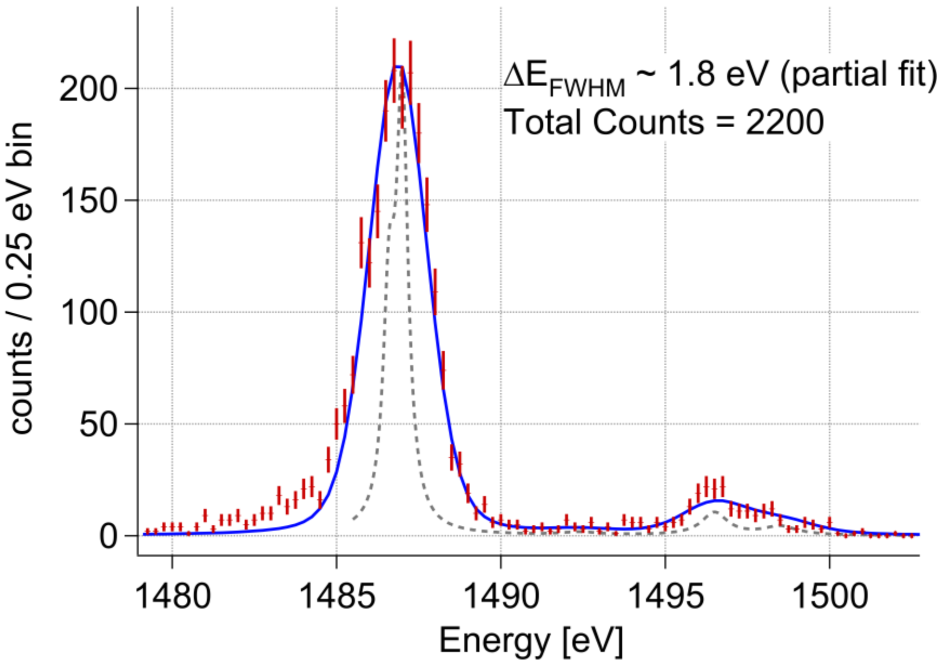
Current state-of-the-art:



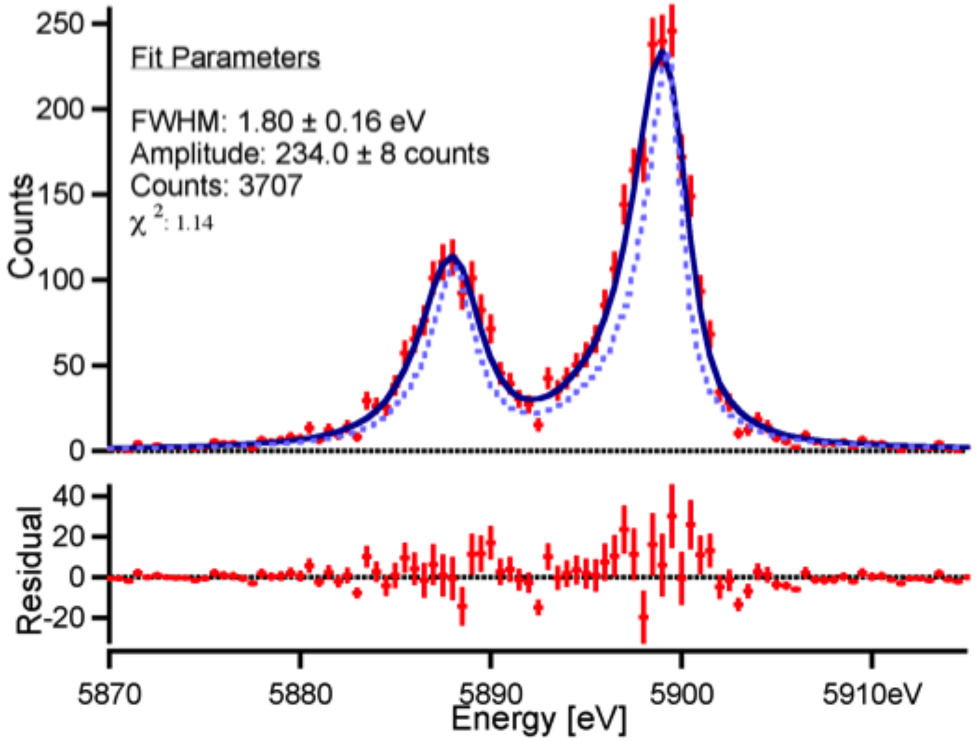
- Photograph and micrograph images of a prototype 32x32 array,
- 300 μm pixels – of standard pixel type for AXSIO
- Absorbers: Bi (4.2 μm) Au (1.2 μm)
- Athena+ to baseline ~ 3600 standard single pixels on 250 μm pitch (5’ FOV)

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:

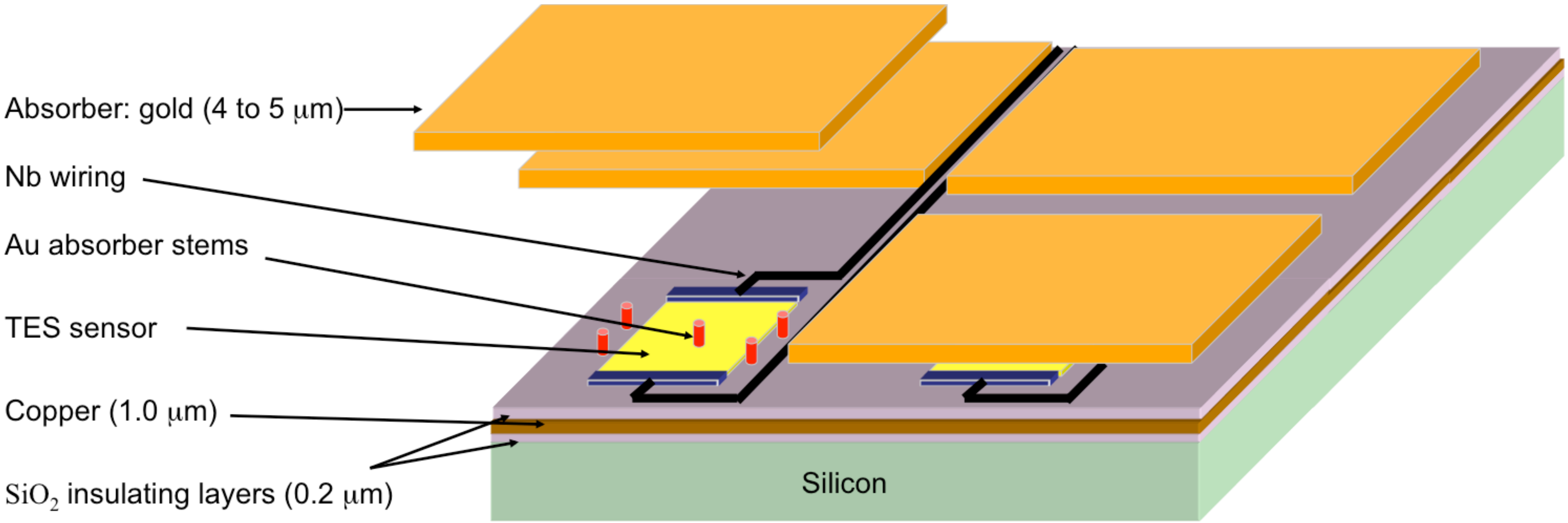


Spectrum from fluorescent 1.5 keV Al Kα X-rays



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

Small Pixel Development



Absorber: gold (4 to 5 μm)

Nb wiring

Au absorber stems

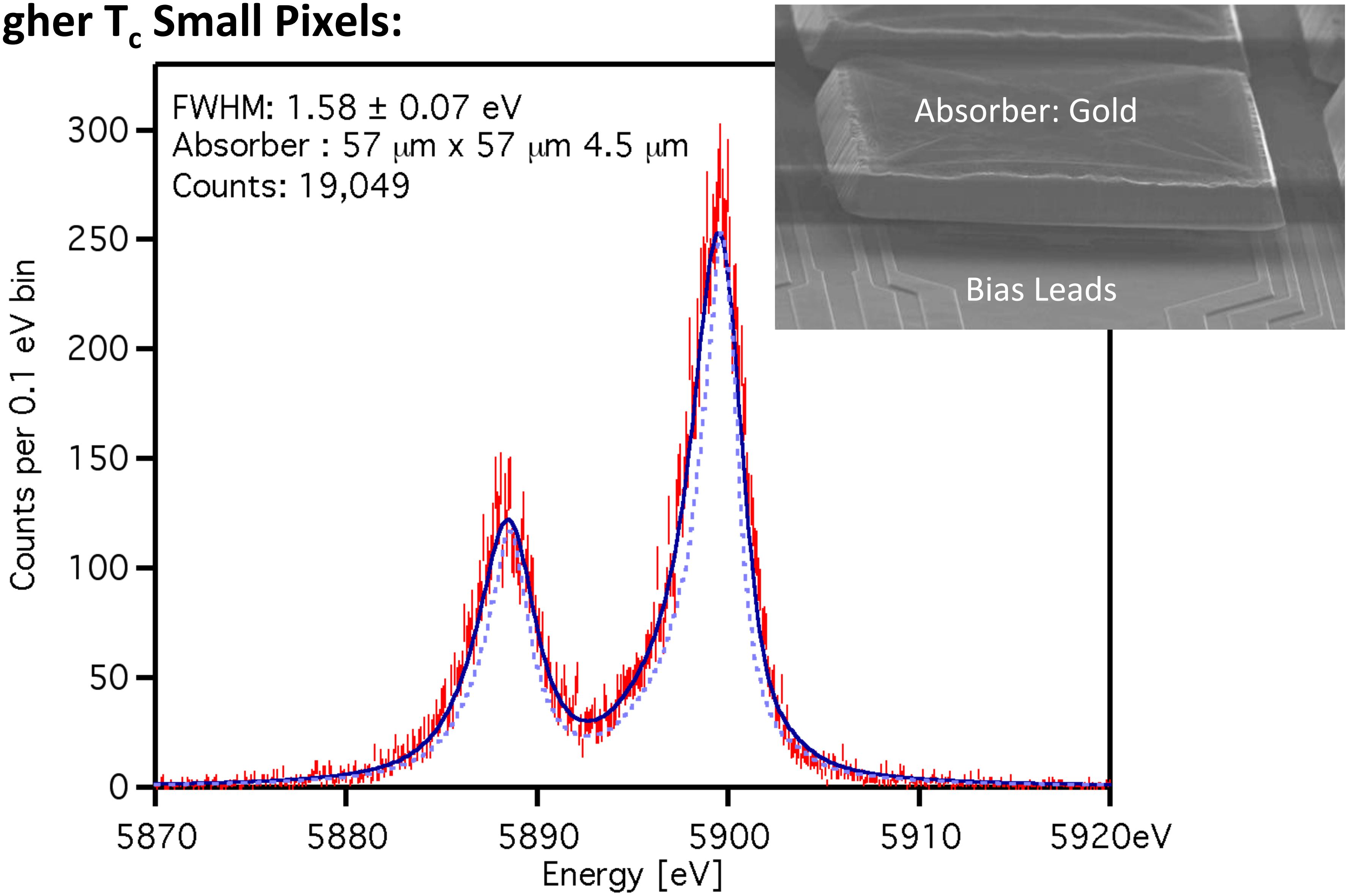
TES sensor

Copper (1.0 μm)

SiO_2 insulating layers (0.2 μm)

- 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 with high T_c versions
- Solid substrate design
  -> great for heat-sinking/low cross-talk
- Low sensitivity to stray power

Higher T_c Small Pixels:

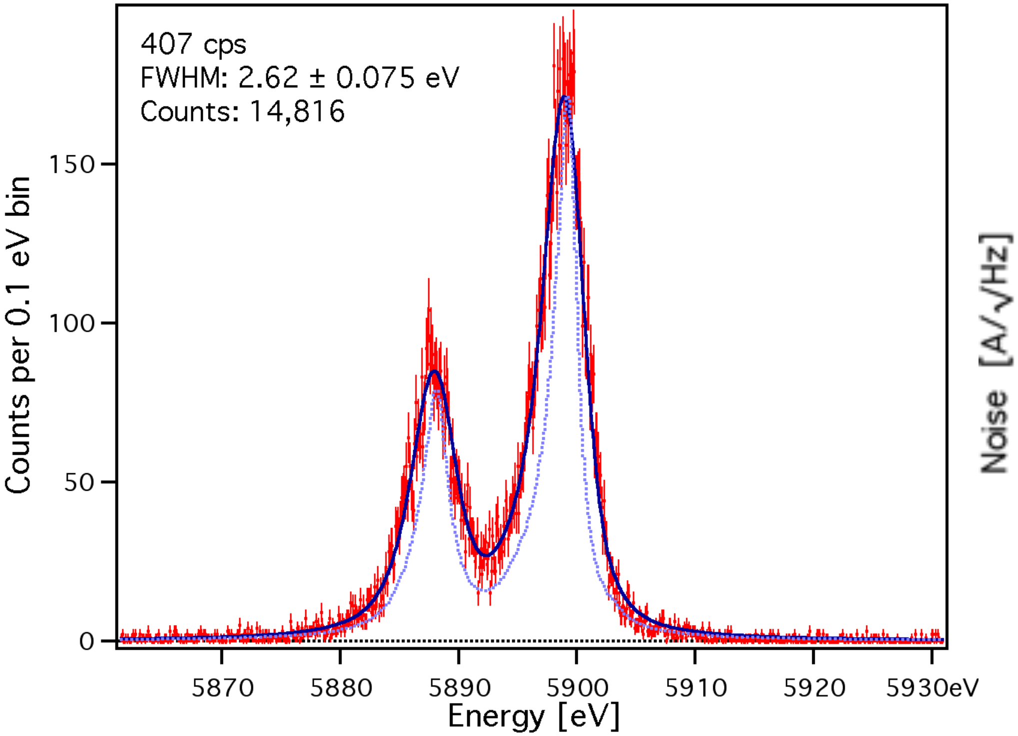


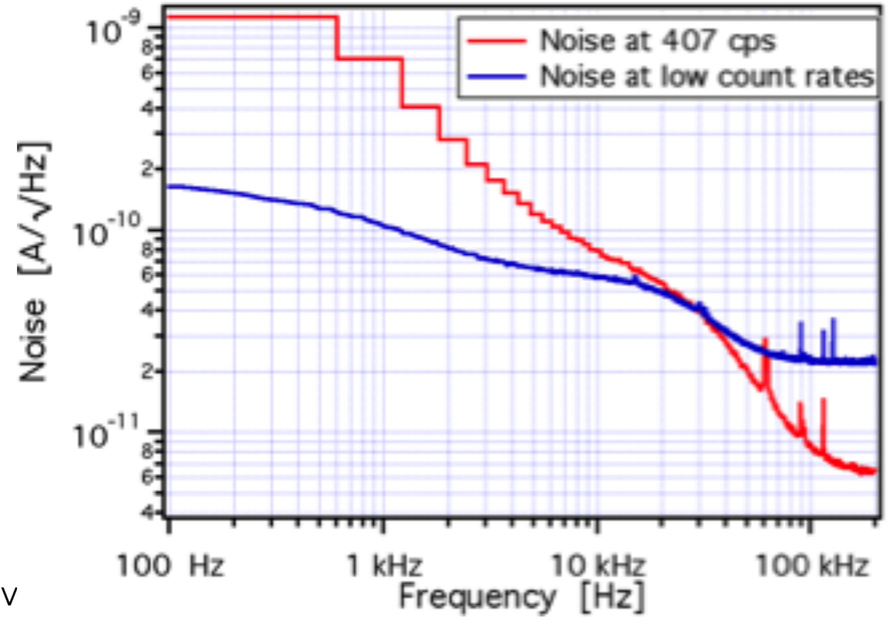
- Best energy resolution detecting 6 keV x-rays with an energy dispersive detector
- High count rate capability
- More demanding read-out requirements

Experimentally verified high count-rate capability:

2.6 eV [FWHM] at 6 keV with ~ 400 cps input count-rate

3.6 eV [FWHM] at 6 keV with ~ 860 cps input count-rate



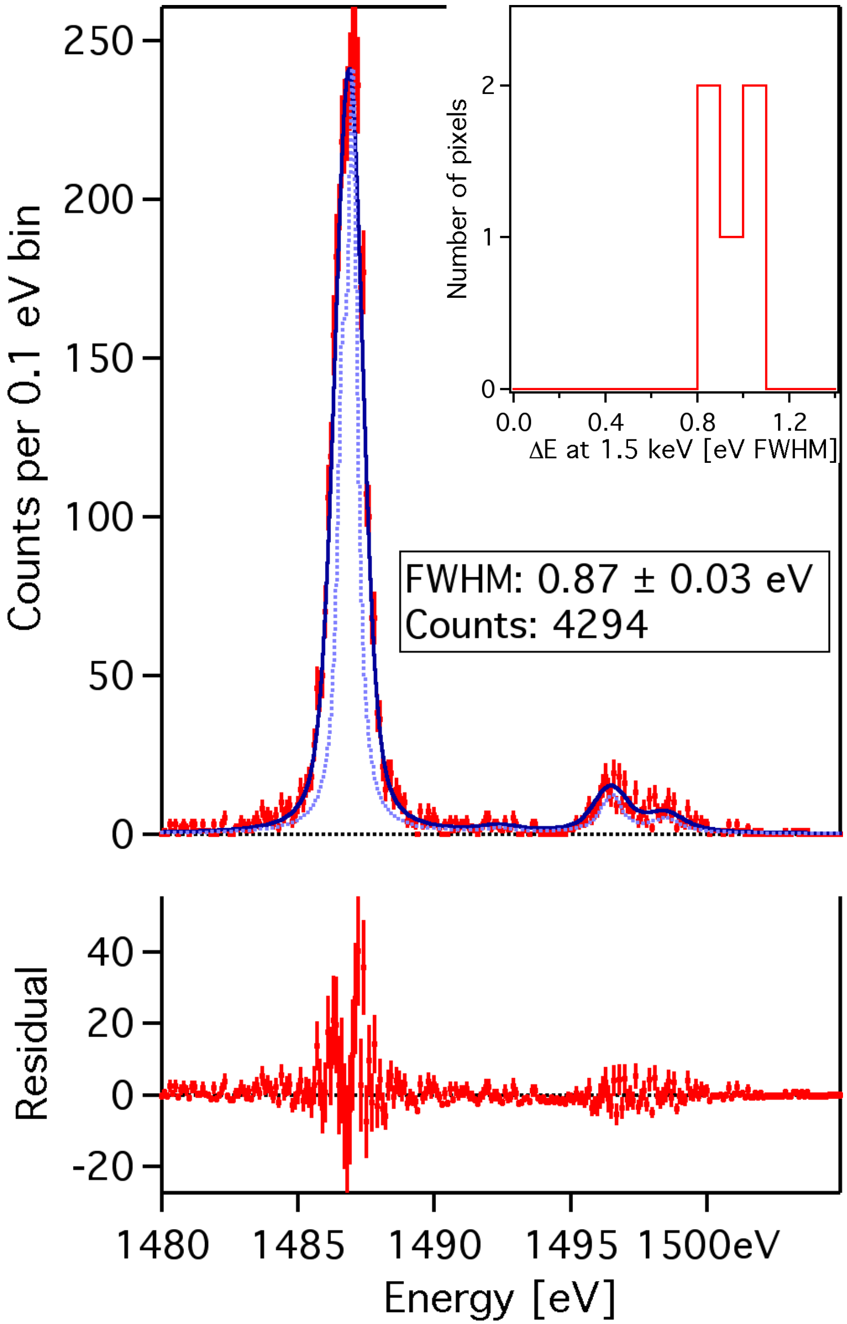


Resolution/throughput analysis ongoing

Some degradation from noise at low frequencies seen

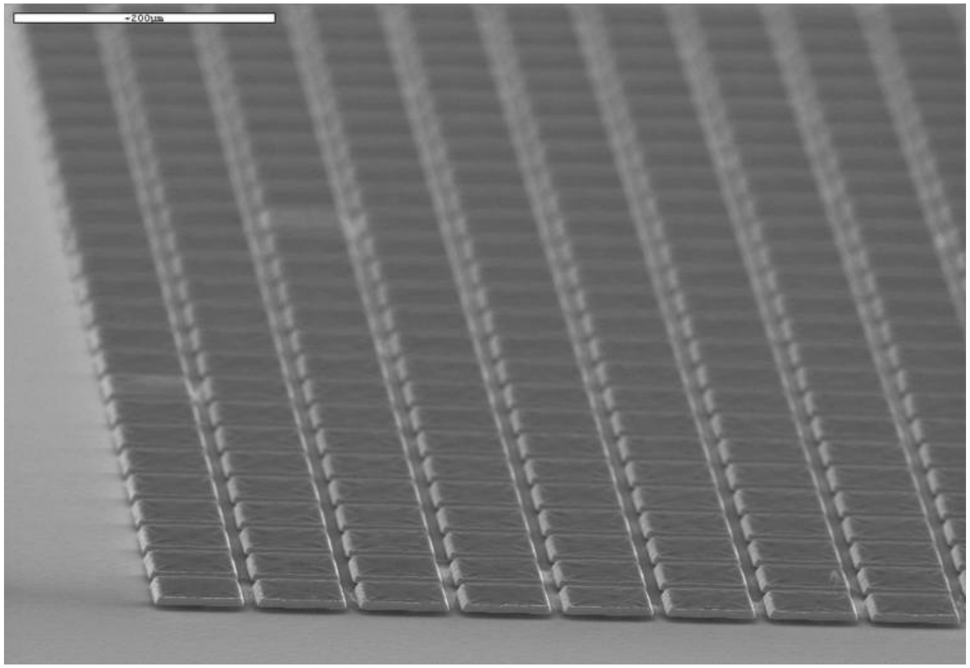
- can be reduced with more chip heat-sinking
- maybe some degradation from cross-talk / source gammas
- astrophysical high count-rate sources
  softer than mono-energetic 6 keV source

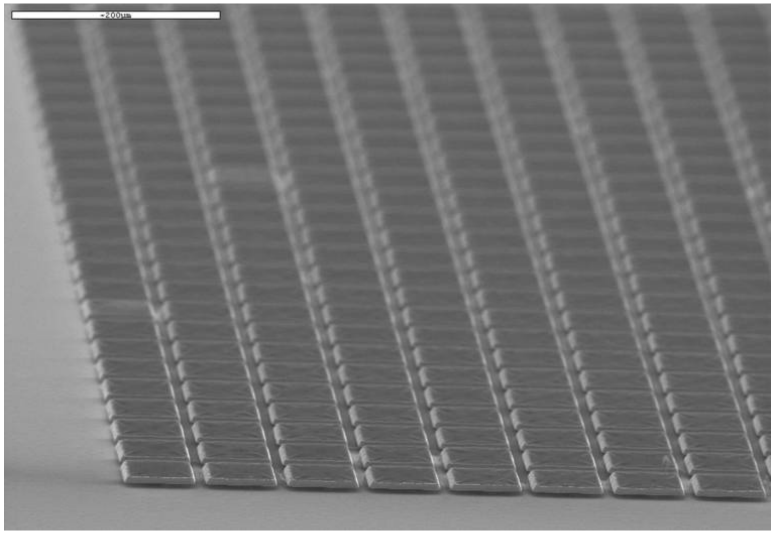
Lower T_c Small Pixels:



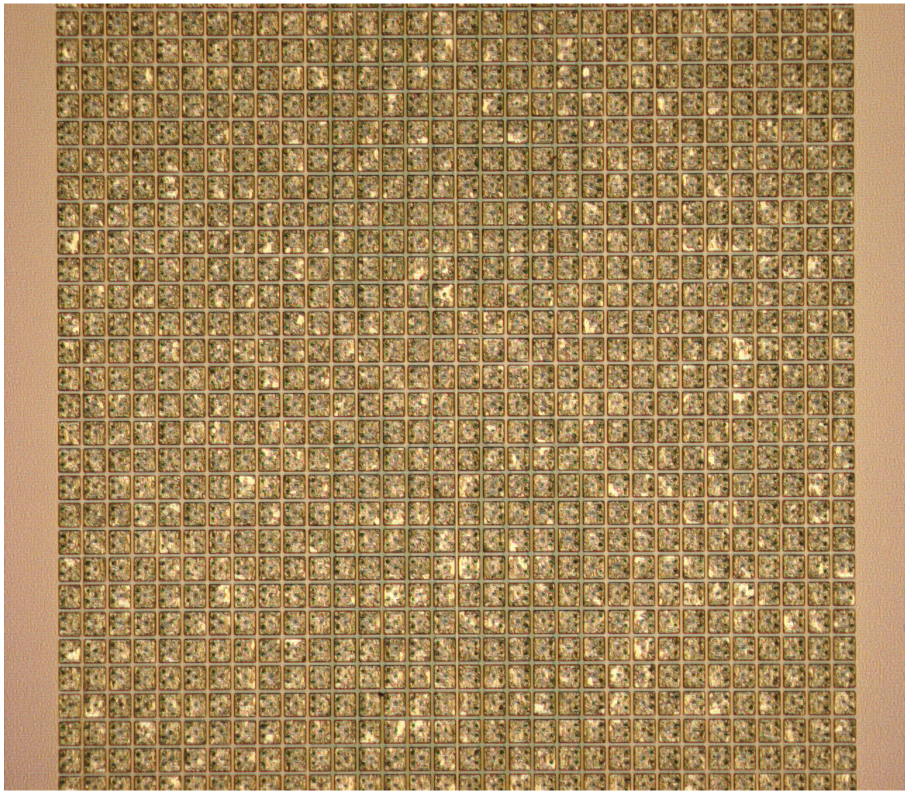
First sub-eV energy resolution result for an X-ray microcalorimeter – at 1.5 keV

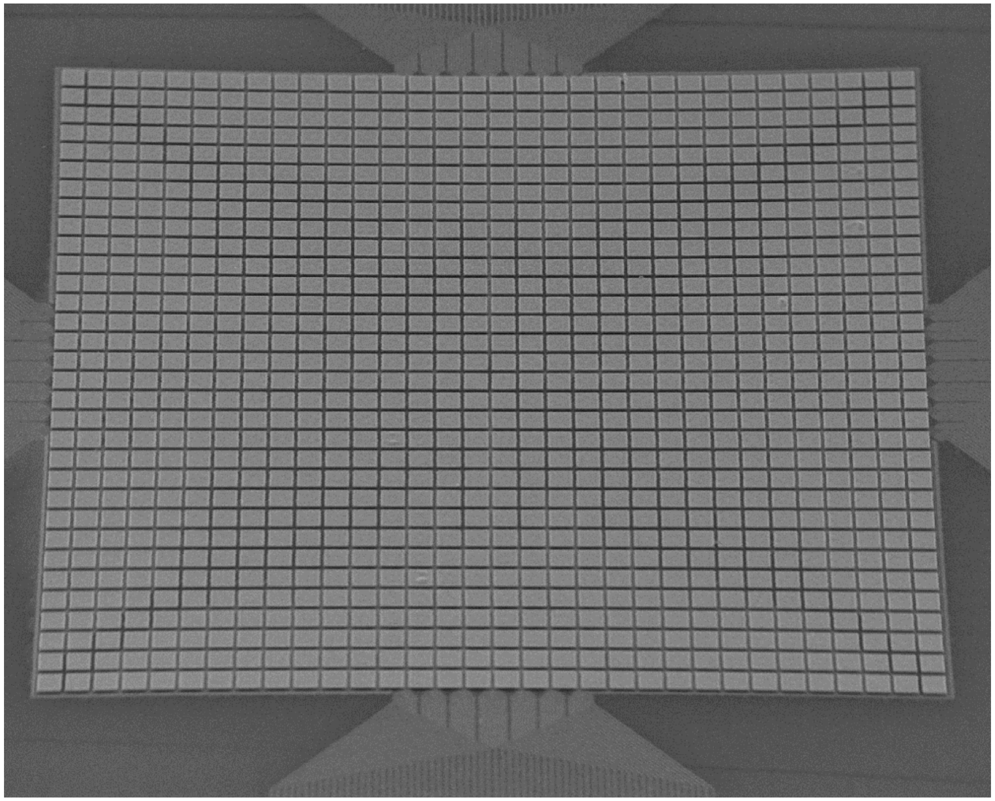
- TES on 75 micron pitch
- Absorber: 65μm x 65μm x 5.0 μm
- Similar signal speeds / count rate capability to standard pixel design
  => similar ability to multiplex this pixel type
  => TRL similar to standard pixel designs
- Athena+ to include 10x10 sub-array of this pixel type – to extend up to ~ 2 keV



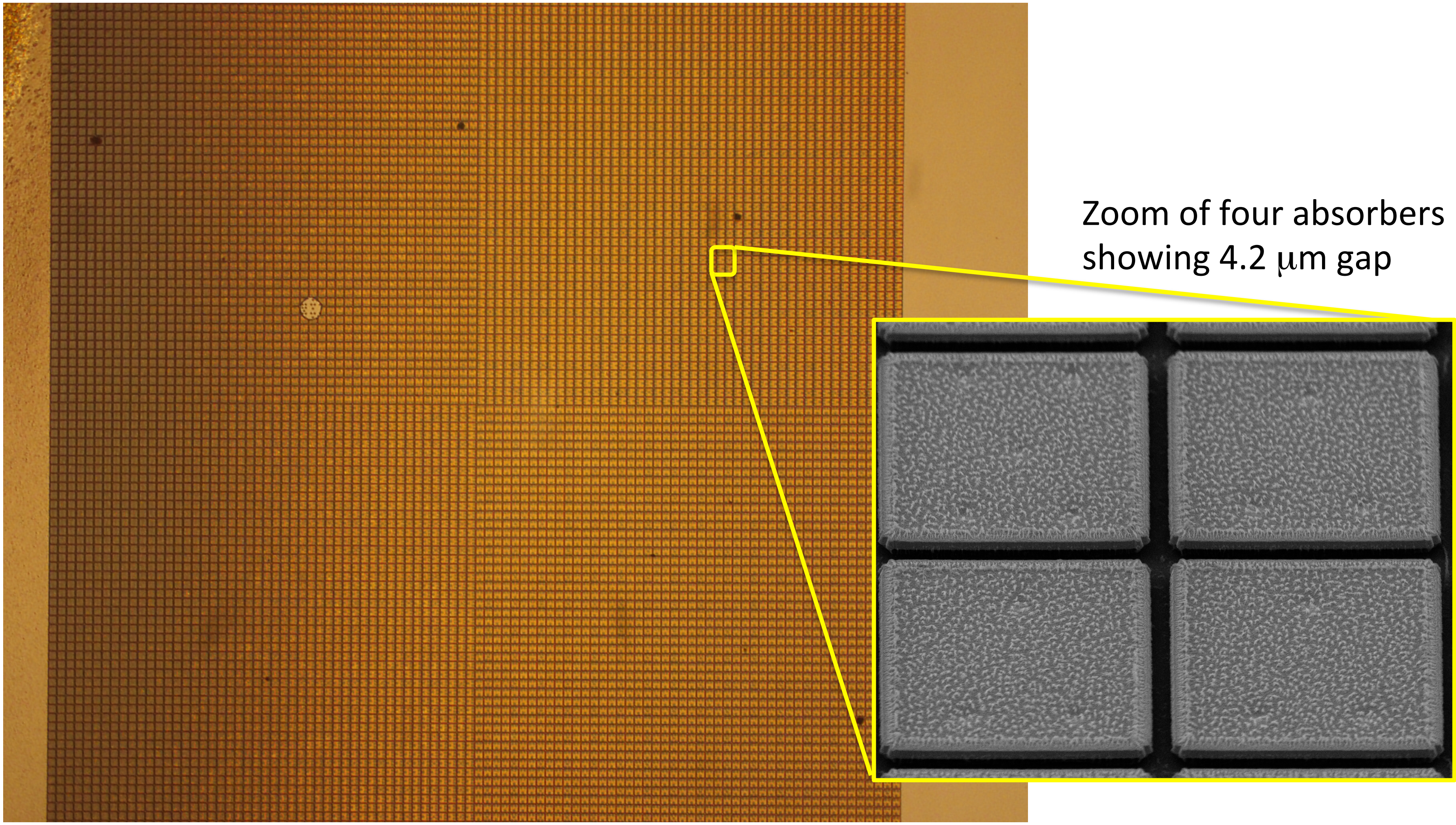


- 32x32 arrays of small pixels
- TES on 75 μm pitch
- Compact stripline wiring on 4 μm pitch
- Gold absorbers : 65μm x 65 μm x 5.0 μm





Absorber fabrication progress – higher filling fraction

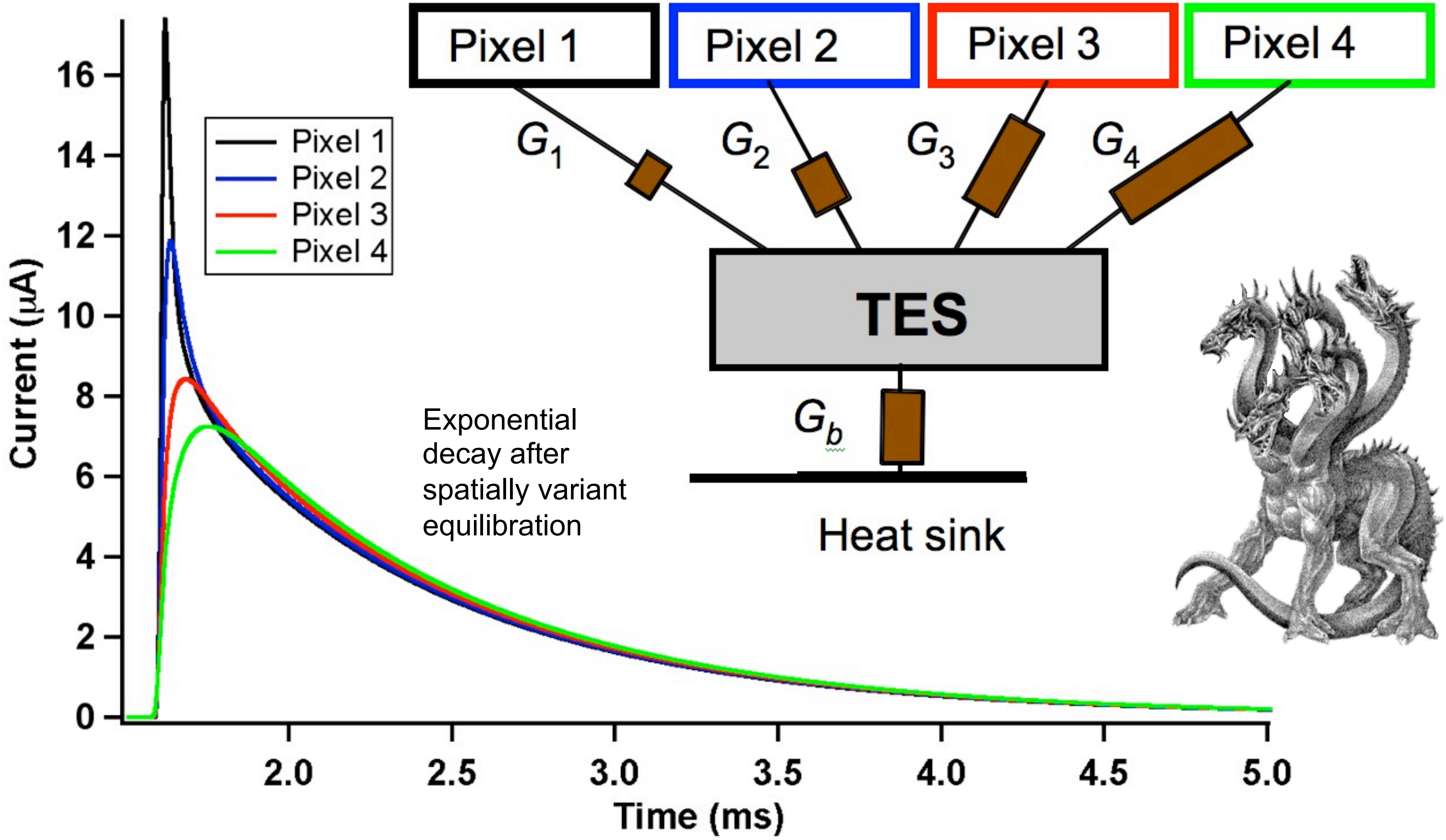


Zoom of four absorbers
showing 4.2 μm gap

- Prototype absorber array with 9216 absorbers (75 micron pitch)
- 4-5 micron gap achieved between absorbers (previously 10-11 microns)

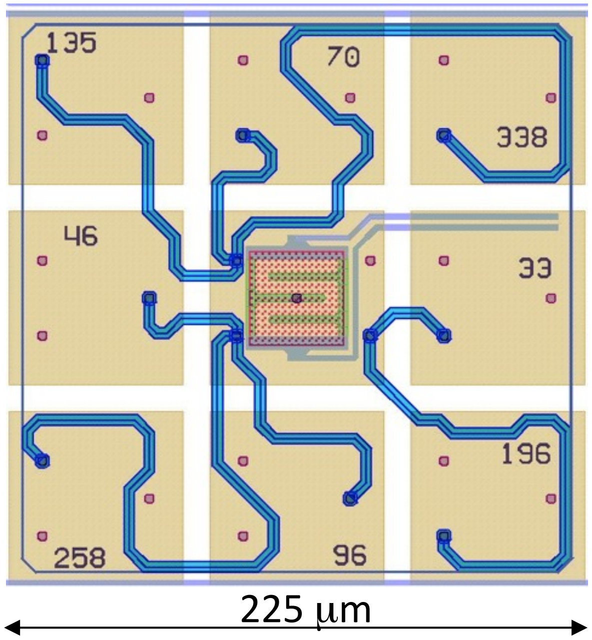
Multi Absorber TES “Hydras” - 1 TES, 4 absorbers

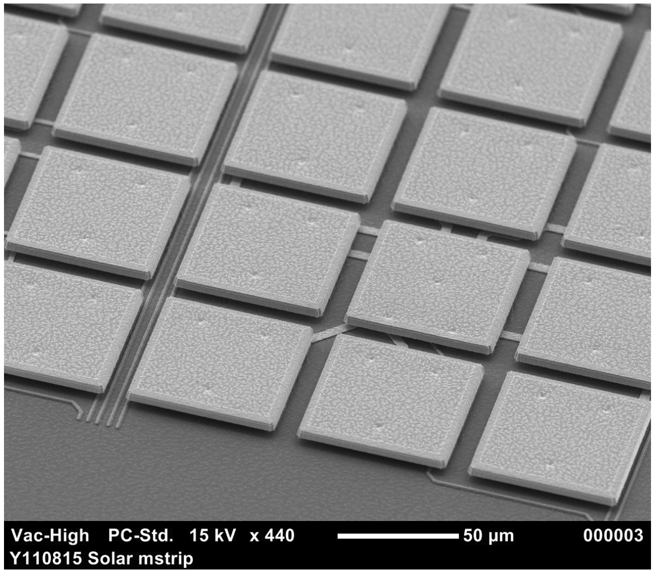
– increase field of view for a fixed number of read-out channels



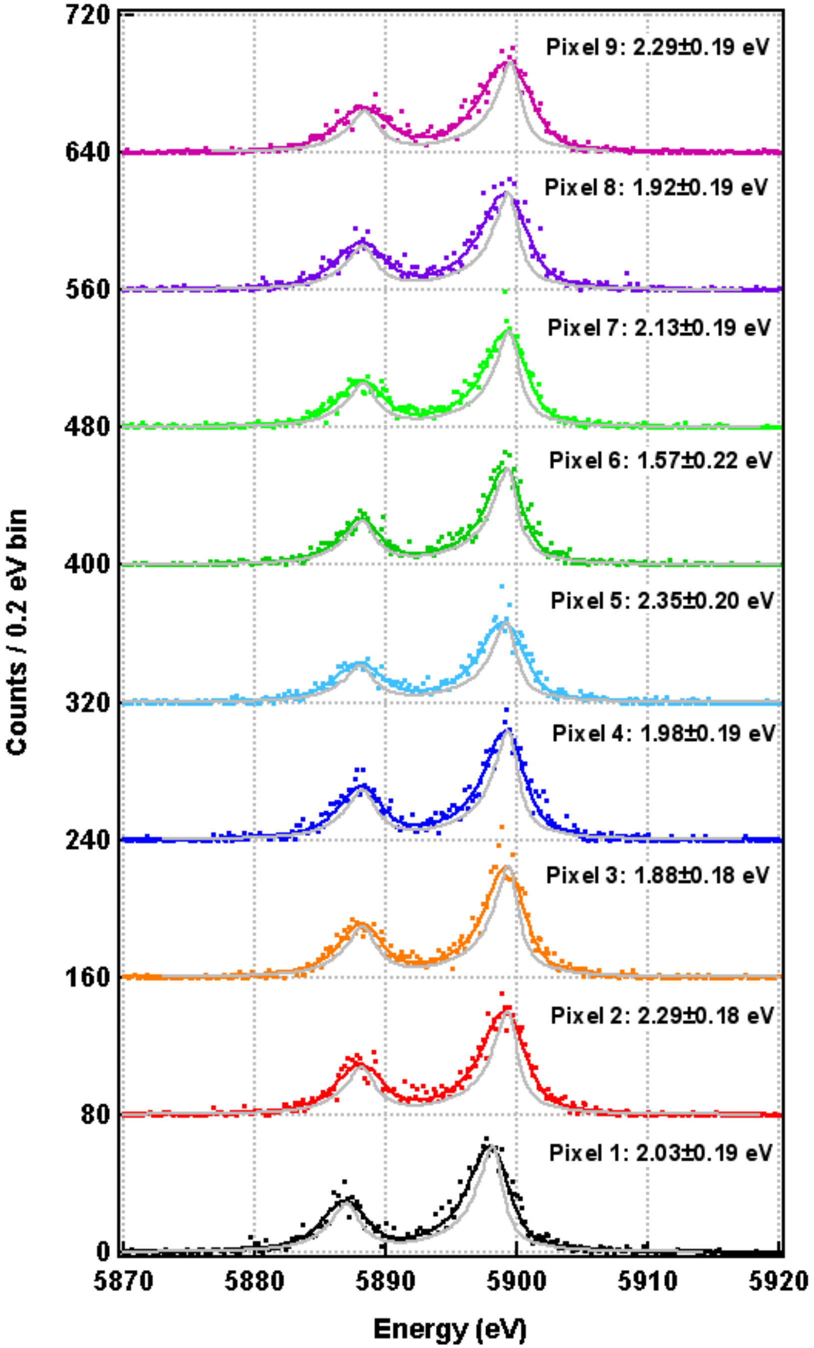
Exponential decay after spatially variant equilibration

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

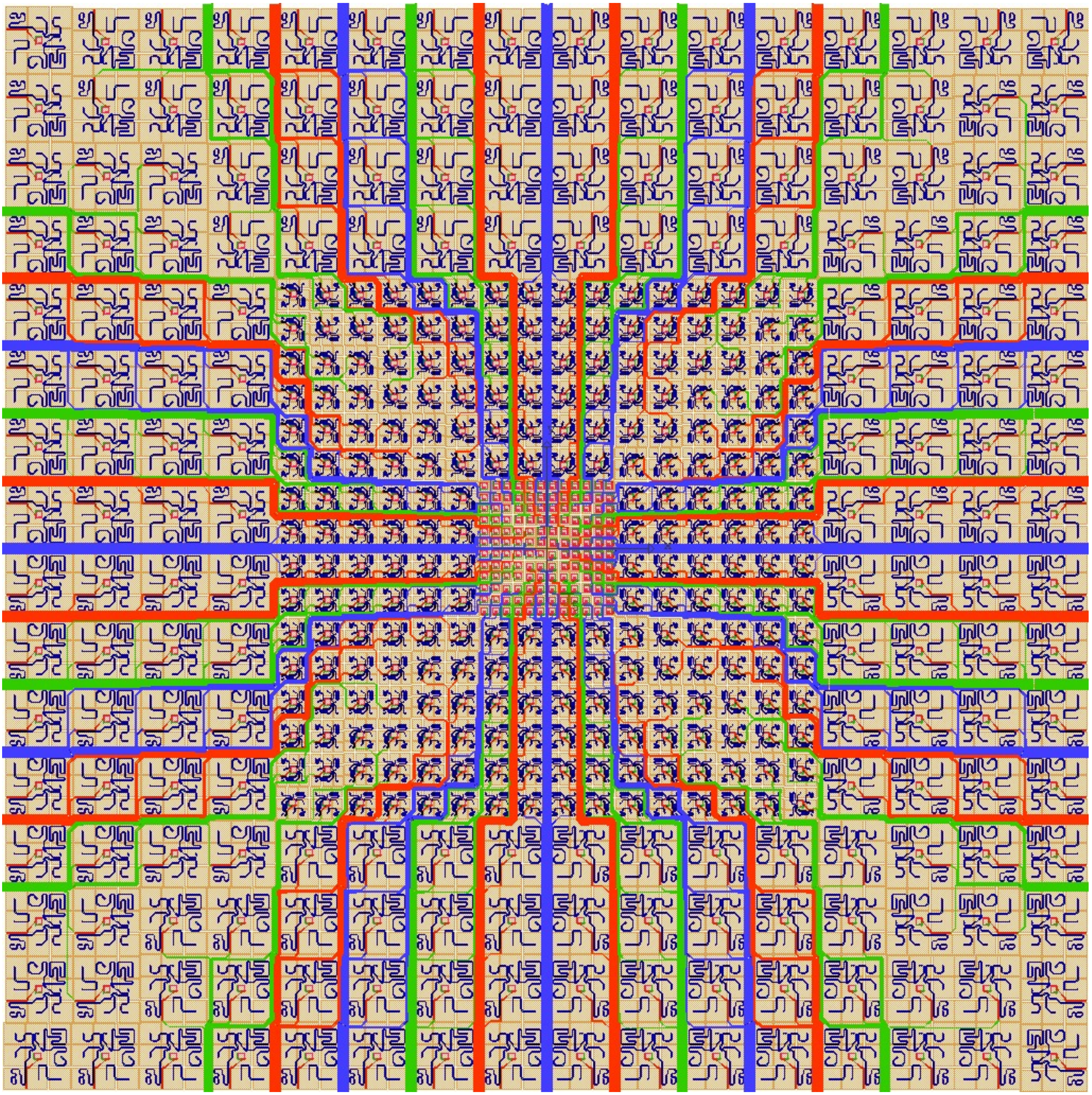




ΔE_{rms} = 2.4 eV (FWHM) at 6 keV, Mn-Kα



Three-tiered array design:



Center: 12x12 array

- 50 μm, single absorber

2nd tier – 48x48 array

- 50 μm, 9 absorber Hydra

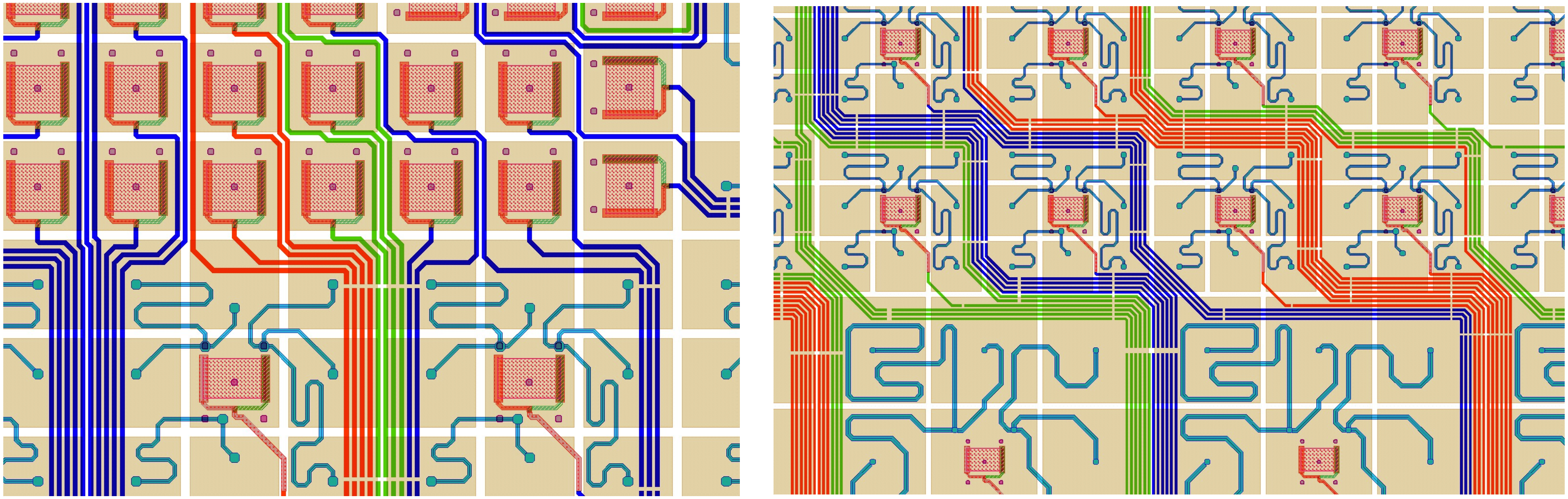
3rd tier – 48x48 array

- 100 μm, 9 absorber Hydra

TES count: 576

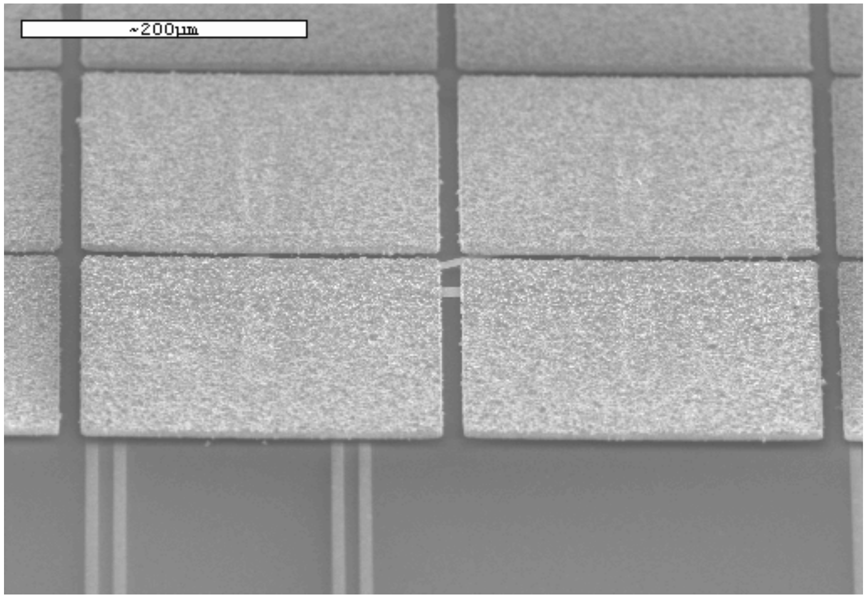
Pixel count: 4032
over 4.8 mm square

Wiring density and routing:

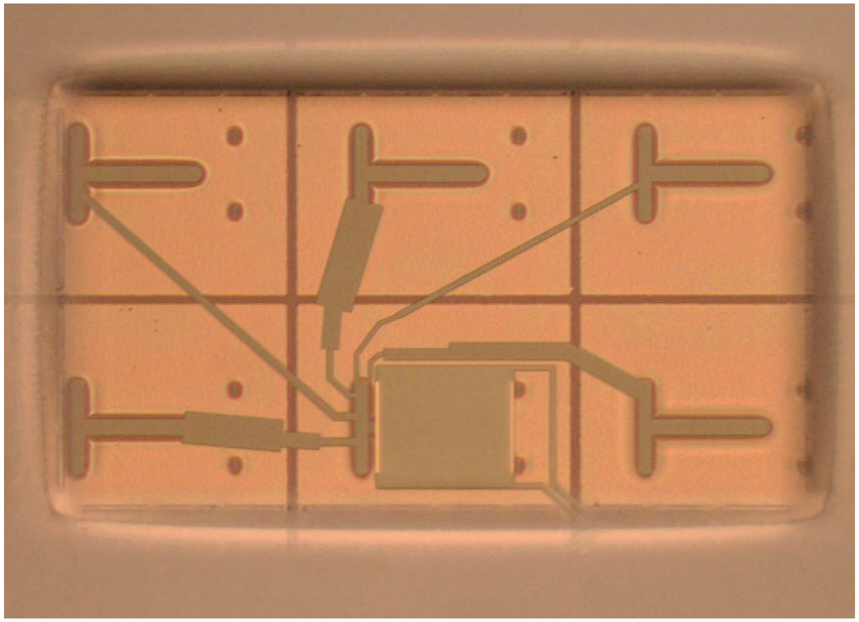


- Stripline wire pitch: 4 μm
- Interface between single pixel and 9-Hydra arrays causes complications in wire routing

AXSIO outer array – at least 4 absorbers per TES



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



- 2x3 Hydras
- Image from rear surface
  (looking through membrane)
- 300 μm absorbers
- Resolution: 5.4 eV to 7.8 eV

AXSIO concept / “N-Cal” concept – streamlined TES number

Main array – single silicon carrier chip:

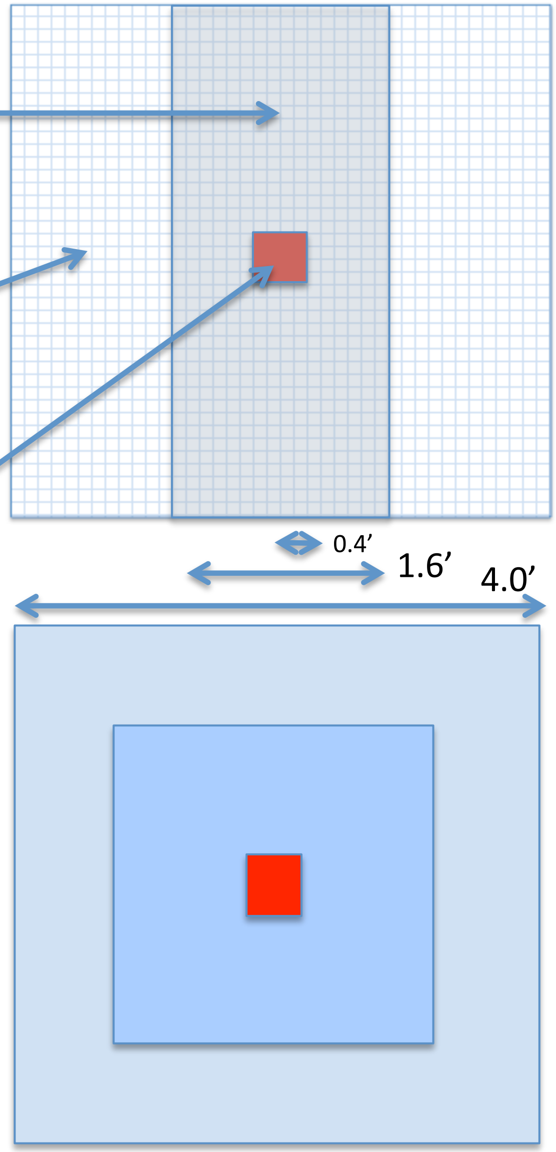
- 40 x 40 pixels, hole in middle: 4 x 4 pixels
- Pixels: 6” each, 300 μm, 4.0 arcmin FOV
- Shaded region:
  - 16x40 – single pixels
  - < 3 eV resolution (FWHM)
  - 50 cps capability, 80% throughput
  - 624 TESs
- Outer envelope – 2x2 Hydra
  - < 6 eV resolution (FWHM)
  - 10 cps per pixel capability 80% throughput
  - 240 TESs   (6x40 each side)

Point source array (PSA):

- 16 x 16 pixels, 1.5” each, 75 μm
- 24 arcsec FOV
- 2 eV resolution (FWHM)
- 80% event throughput at 300 cps/pixel
- 256 TESs

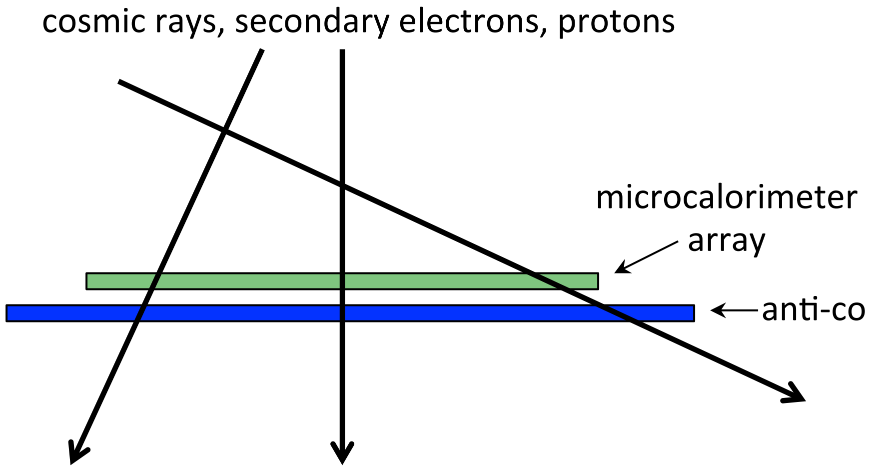
Total = 1120 TESs

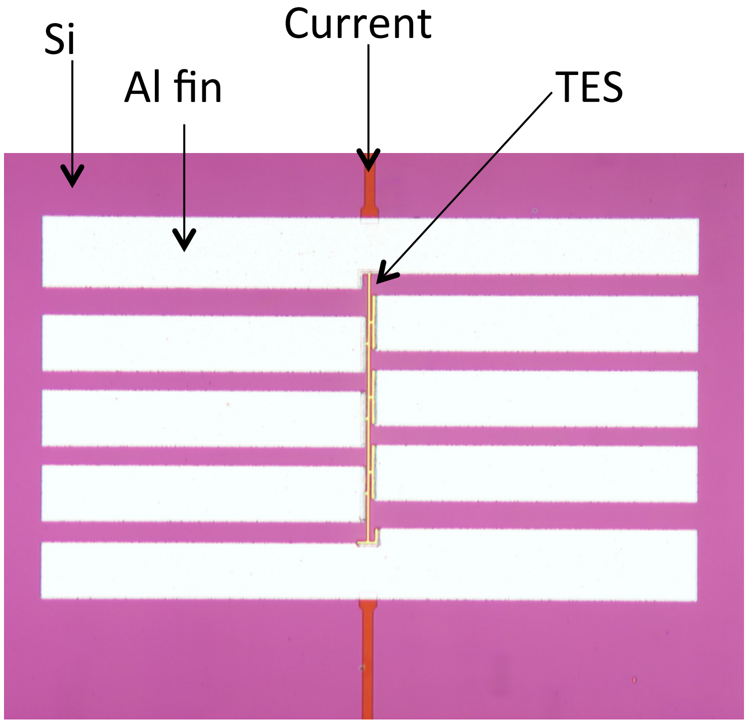
XMS Array Concept



Anti-Coincidence Detector

Needed to reject background interactions



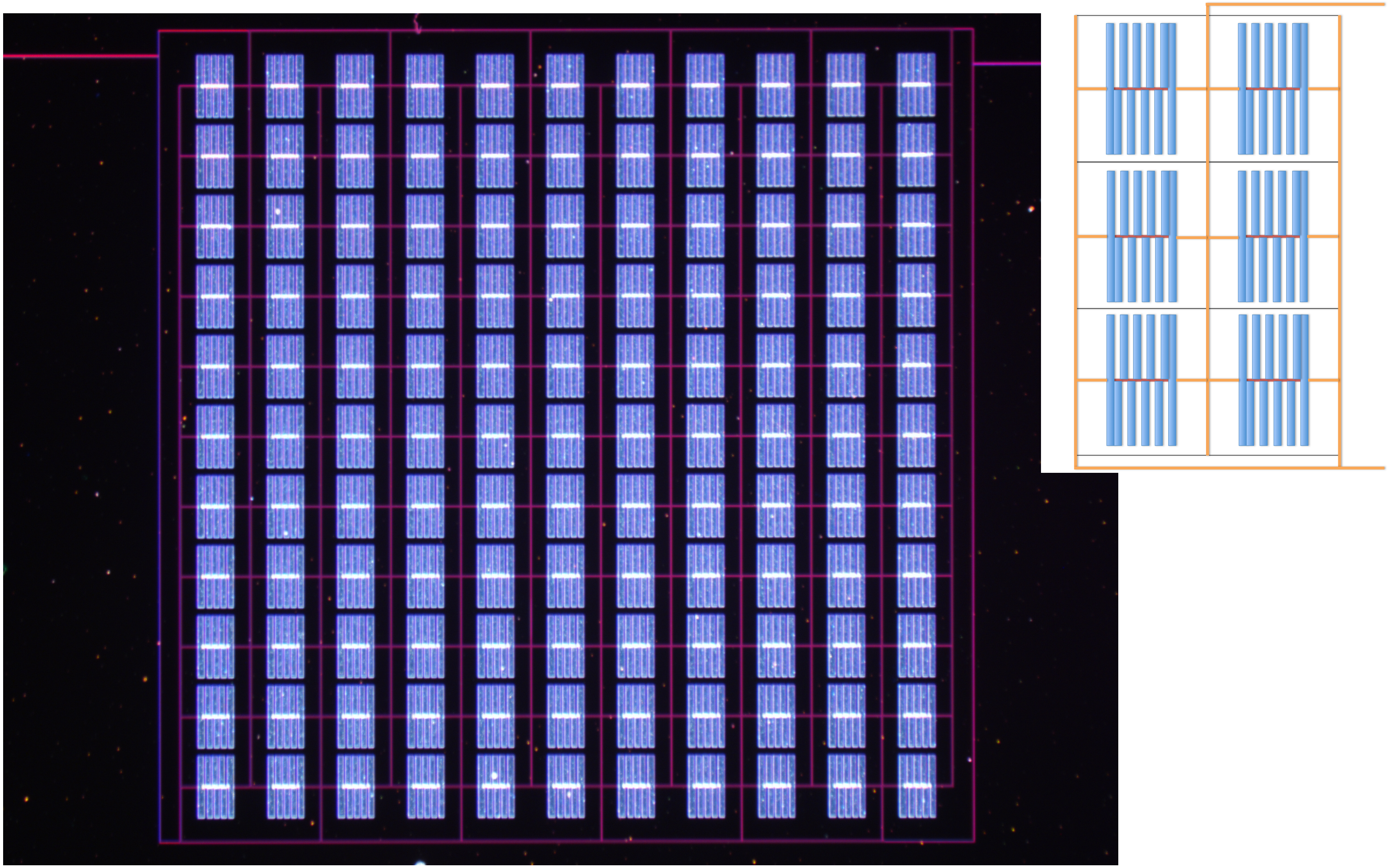


- TES: 250 μm x 2 μm
- Each TES connected to 10 (Al) phonon collection fins 300 μm x 50 μm.
- Interaction in silicon anti-co crystal

  -> ballistic phonons

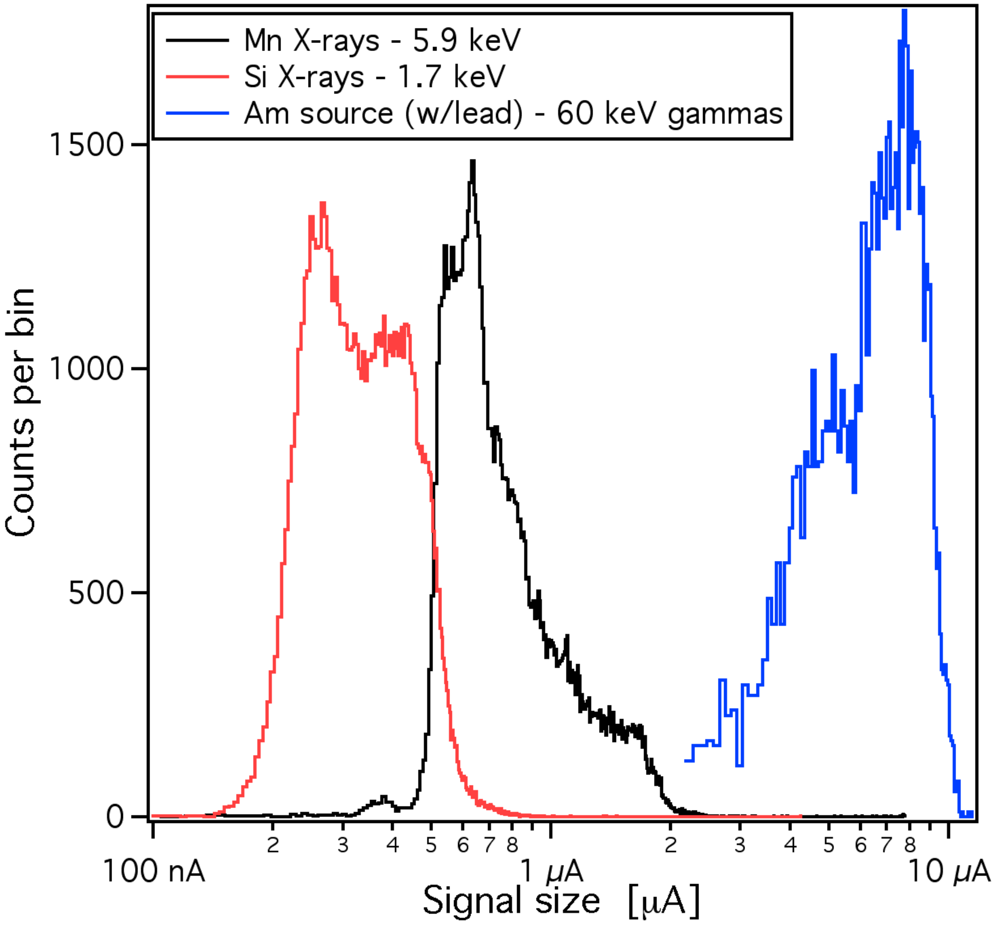
  -> breaking cooper pairs in fins on surface

  -> diffusion to TES to produce signal
- Technology approach based on dark matter detector.



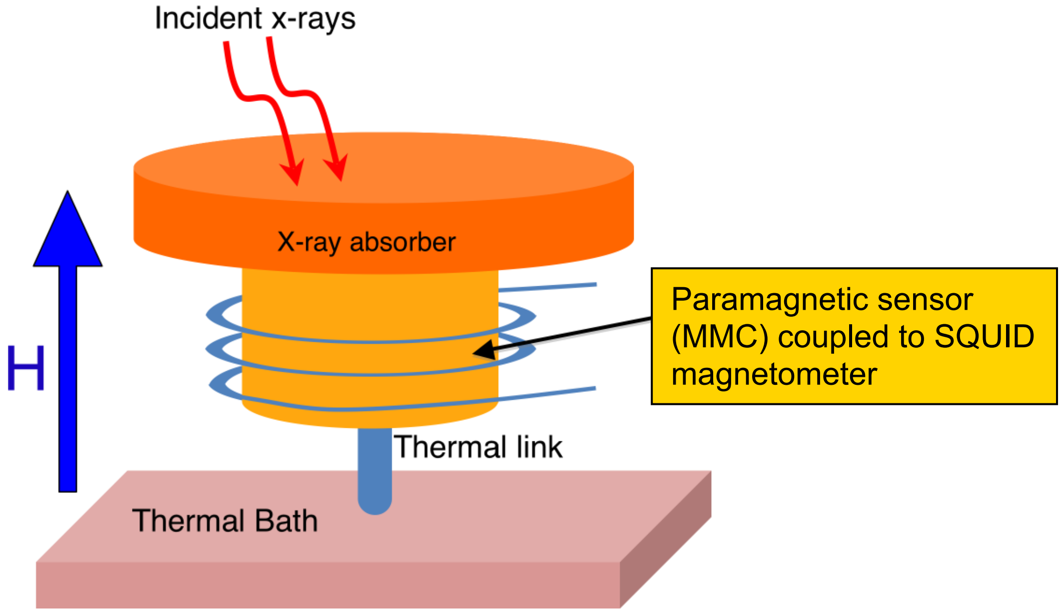
- 121 TESs on 11x11 grid, each 250 μm x 2 μm, each
- Connected in parallel to a single SQUID readout.
- Chip 1.5 cm x 1.9 cm x 0.3 mm

- Successful fabrication and operation.
- Signal decay times < 50 μs.
- Sensitivity threshold below 1 keV
  - well below level of minimum ionizing particles (~120 keV).



X-ray Sag, Monterey, 2013

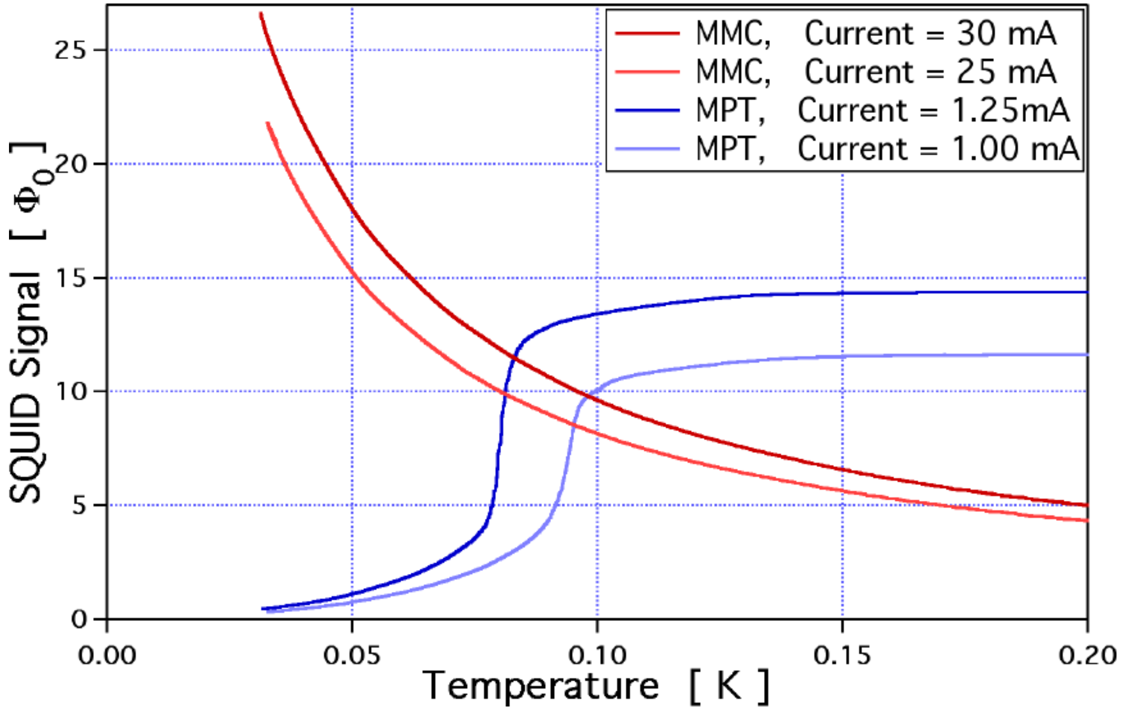
Magnetic Calorimeters (MMC) & Magnetic Penetration Thermometer (MPT) Microcalorimeters

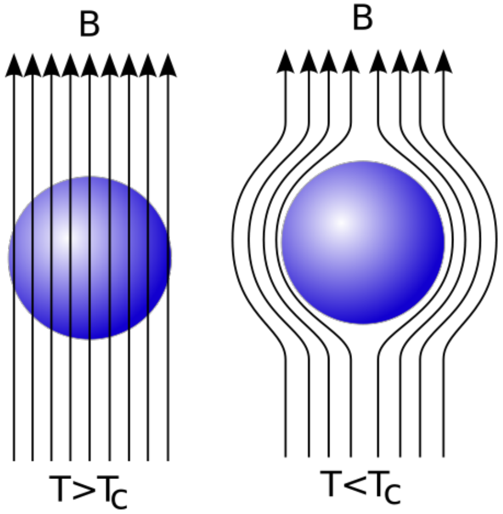


$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{\delta E}{C}$$

Paramagnetic sensor: Au:Er

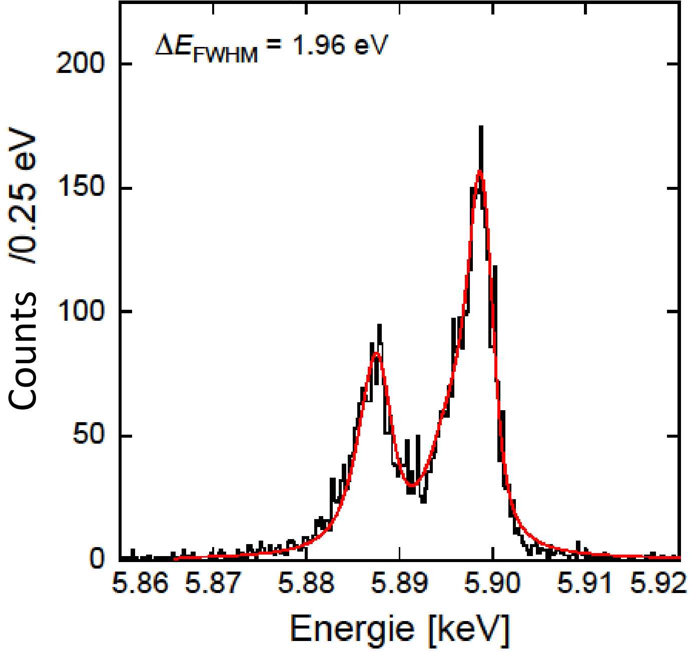
$$M \propto \frac{1}{T}$$



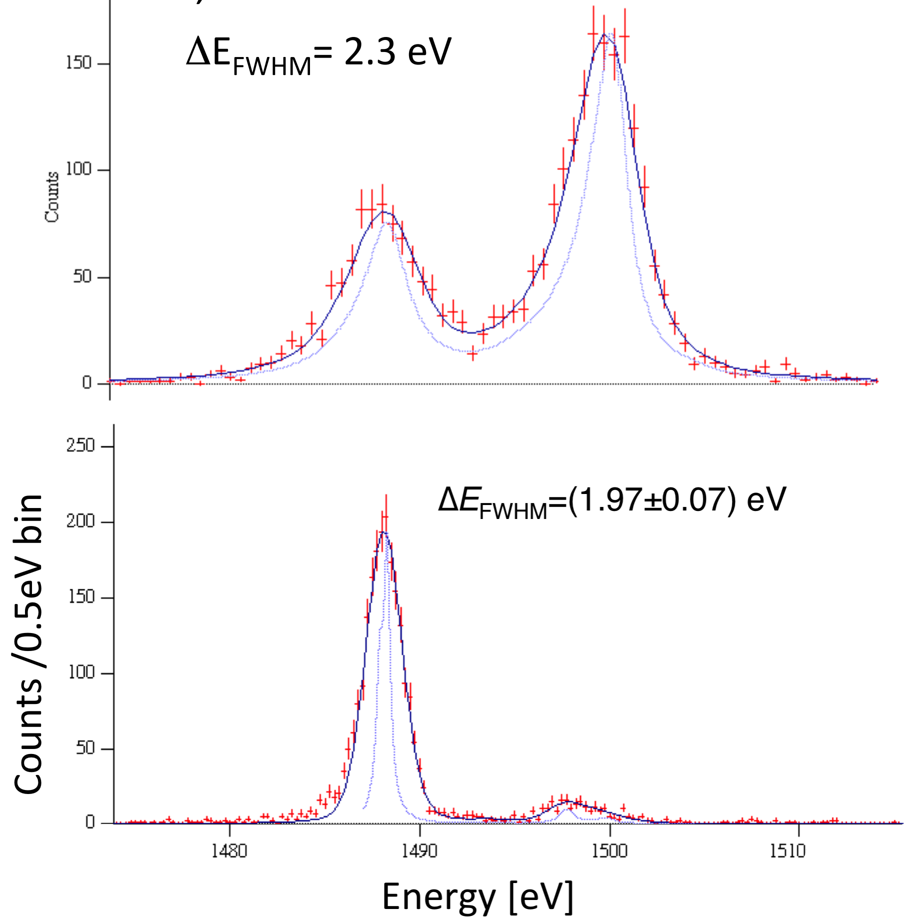


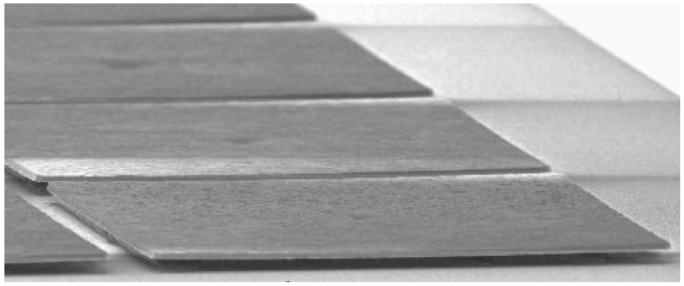
Best magnetically coupled calorimeter results at 6 keV:

MMC – Heidelberg, 2011:



MPT – GSFC, 2011:





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

MMC / MPT

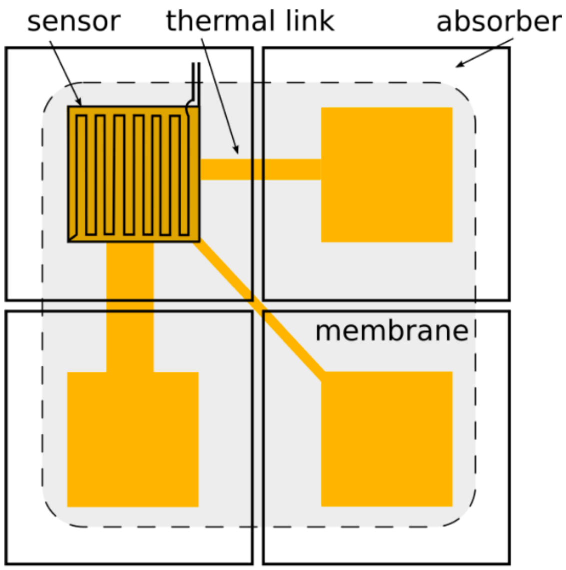
The good:

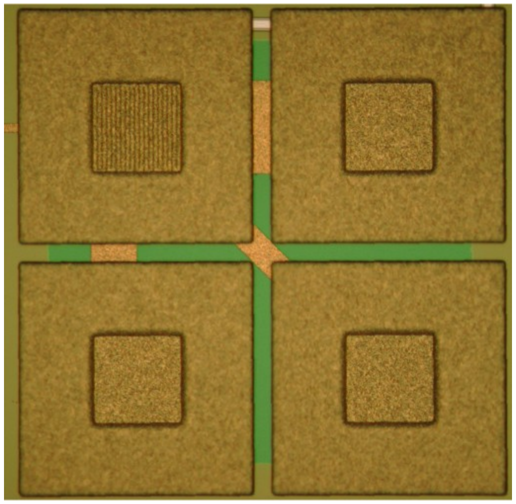
- Potential for the very highest energy resolution (no Johnson noise)
- Non-dissipative nature => larger array sizes might be possible
- Can be directly connected to metallic heat sink
  - reduction of thermal crosstalk

The bad:

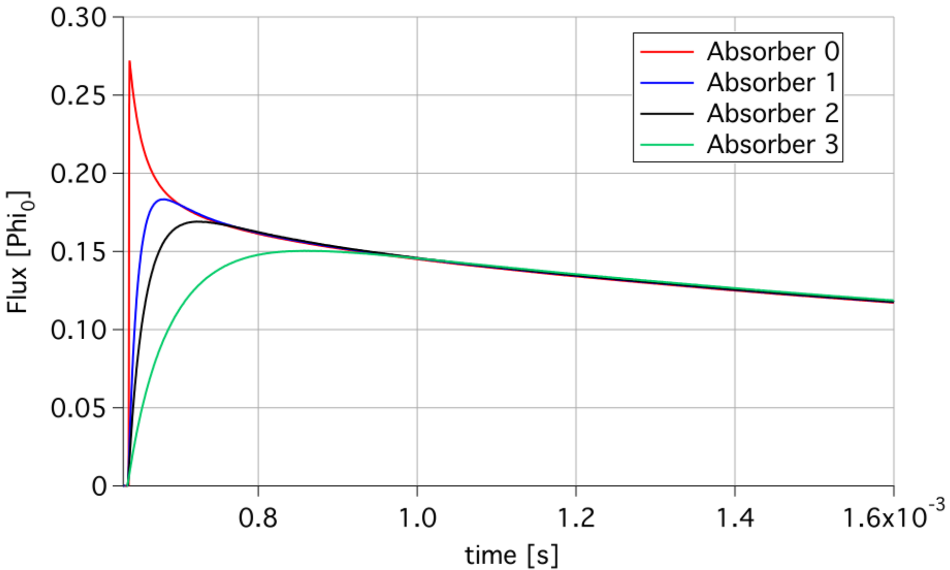
- Hardest to technology to read out and multiplex with a non microwave read-out scheme

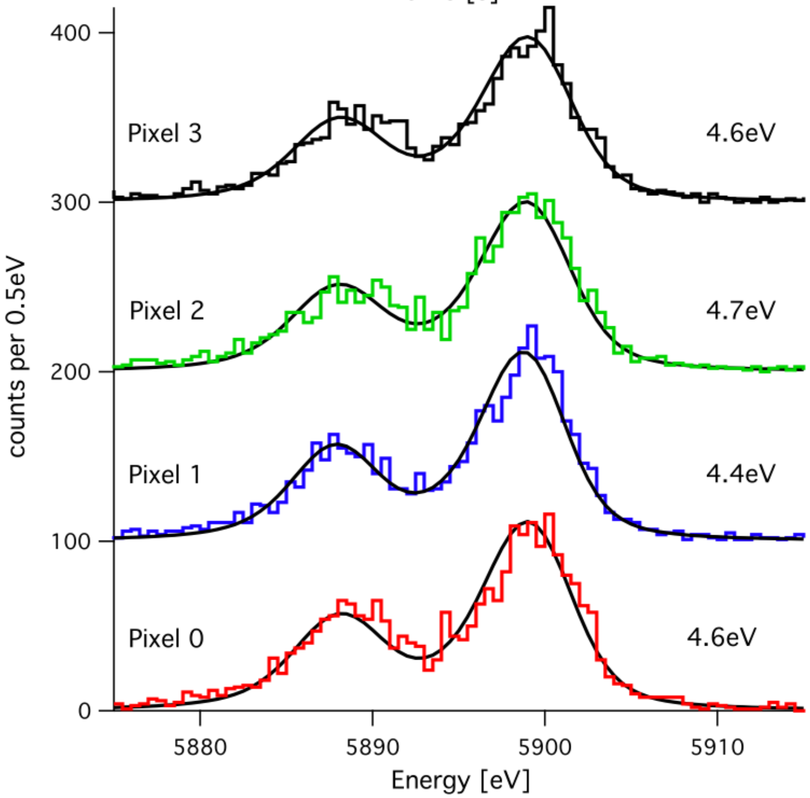
MagCal Hydras:



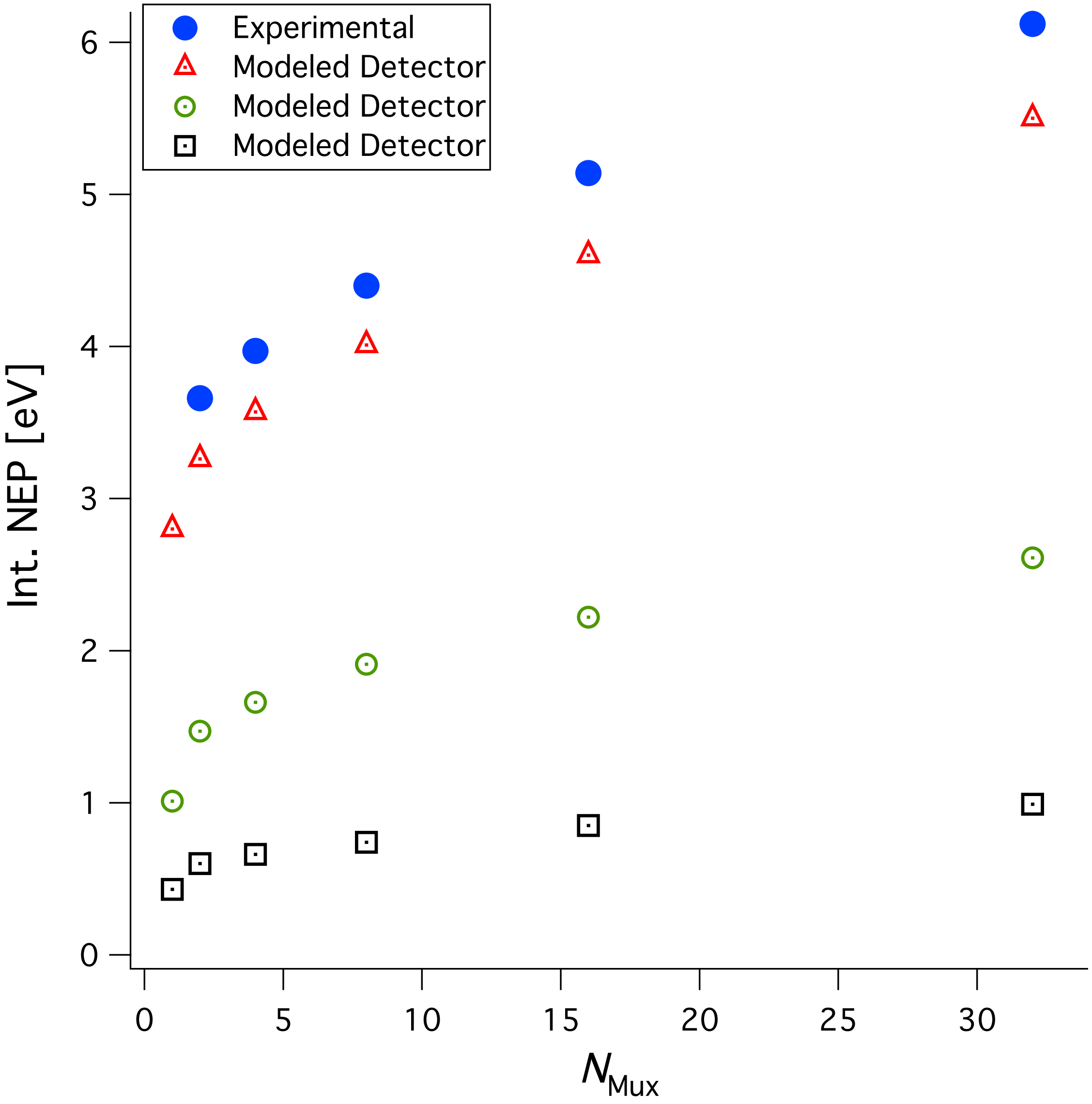


Best resolution for any Hydra detector of “standard-size” at 6 keV (GSFC)



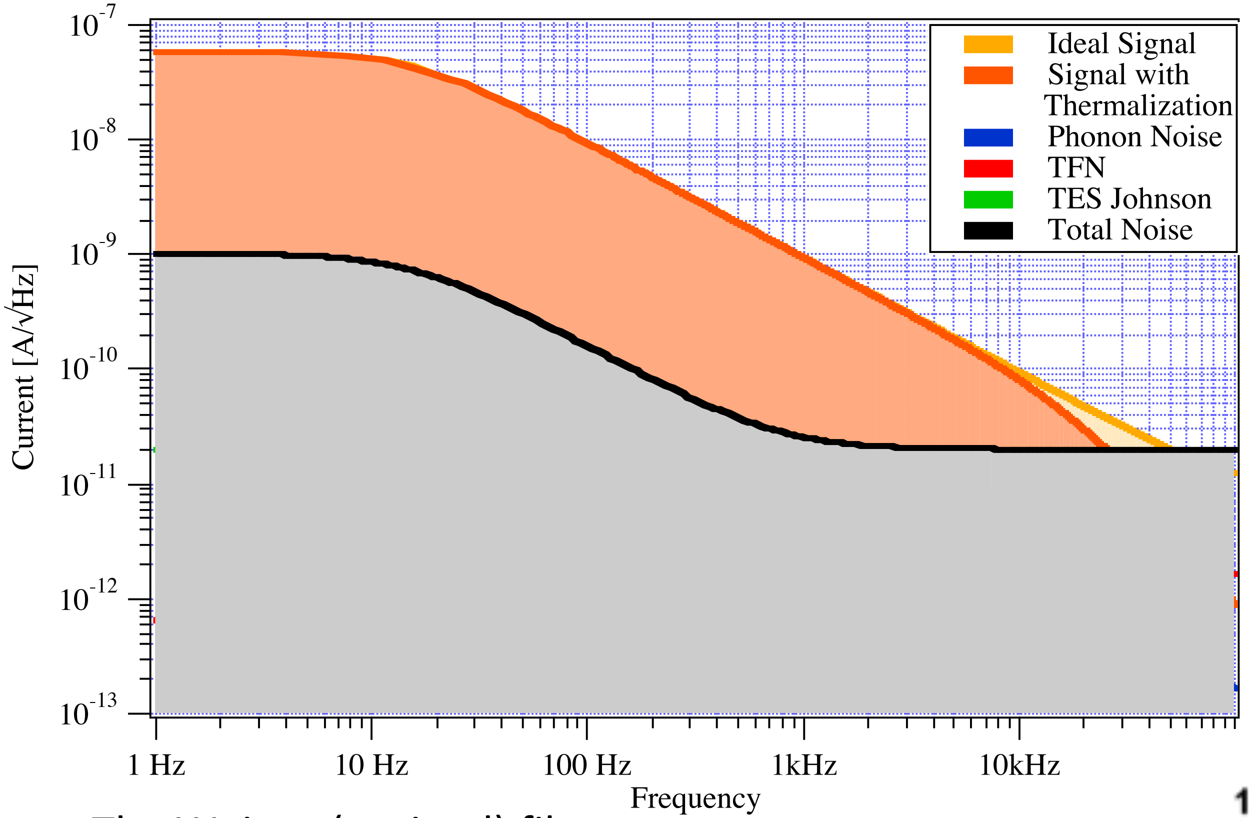


MCC time division multiplexing now demonstrated:

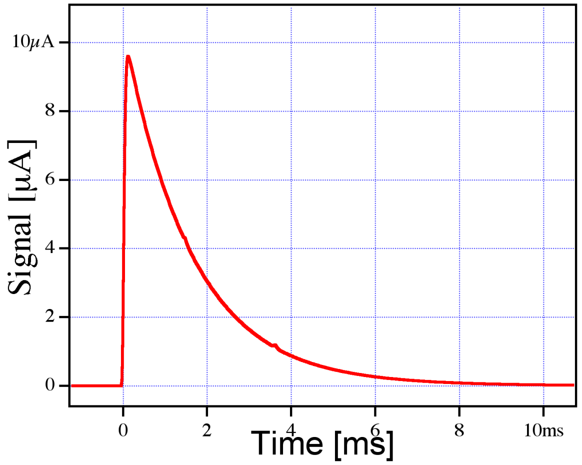


X-ray Sag, Monterey, 2013

Signal processing techniques

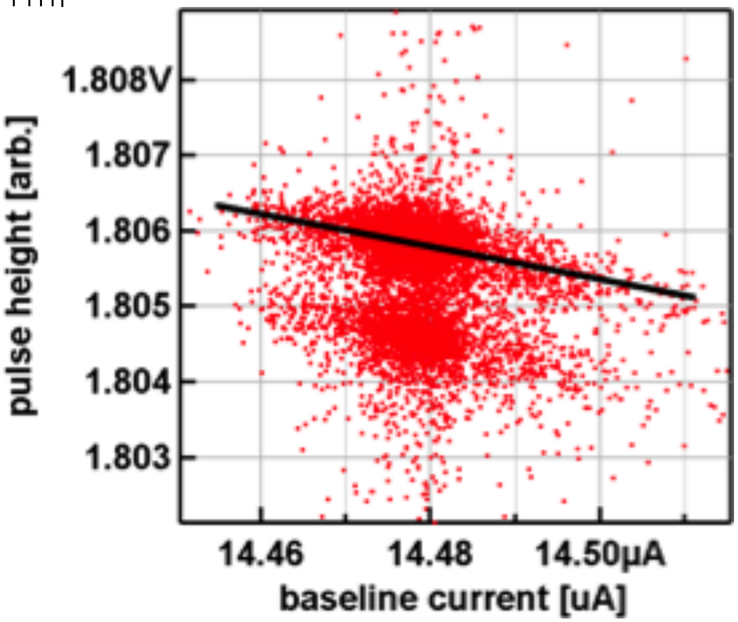


- The Weiner (optimal) filter assumes:
  - Stationary noise (not changing through pulse)
  - Linear response (pulse shape same for all energies)
- Correct for correlations of filtered pulse height with:
  - Pulse arrival time (trigger jitter)
  - DC TES current level (“baseline”) – (temperature)
  - Drifts in time

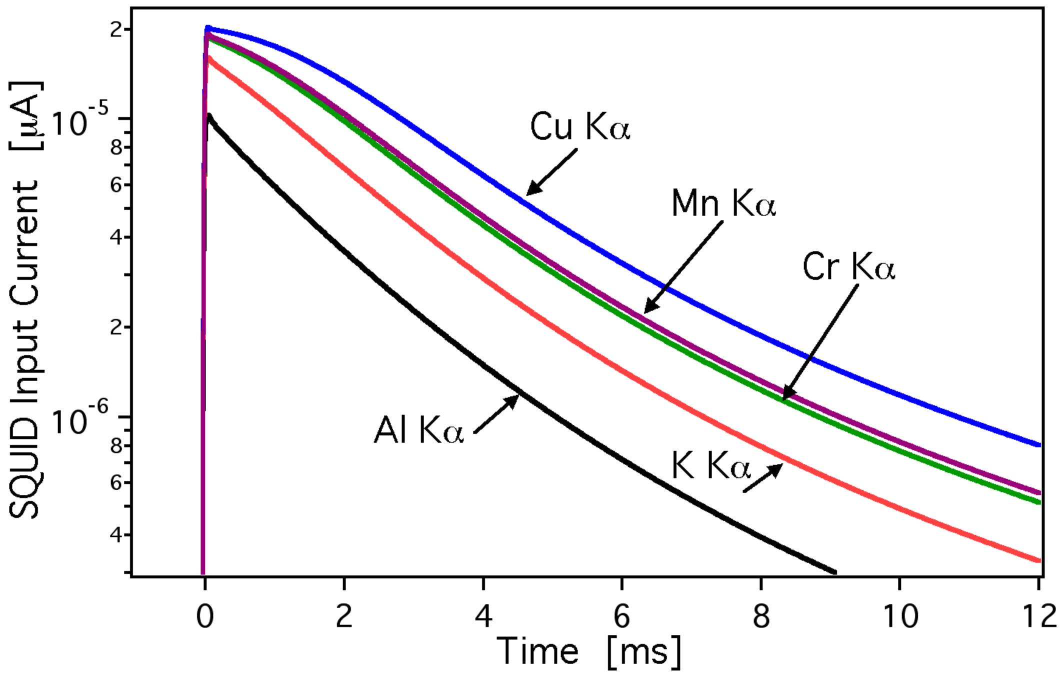


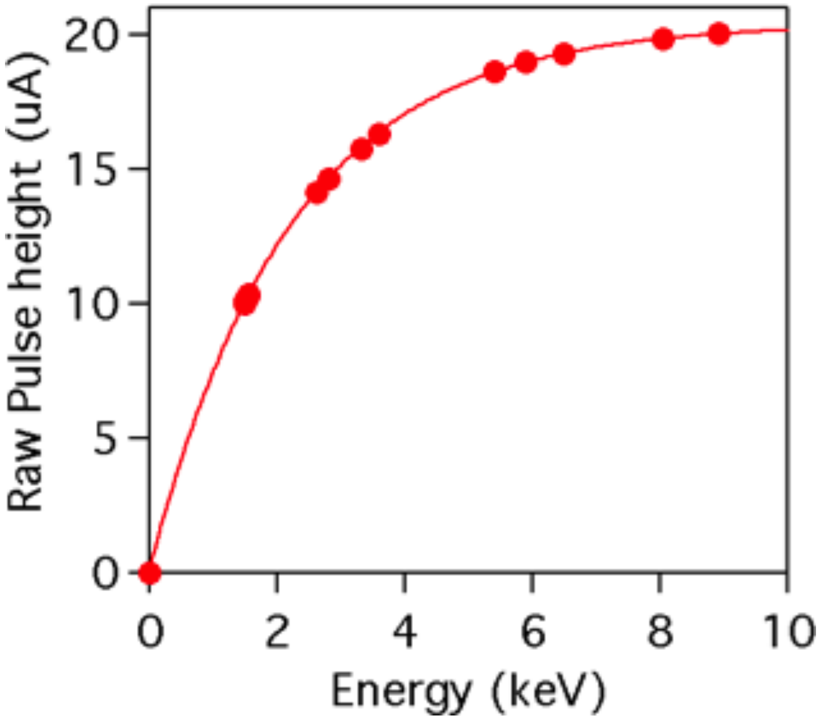
Optimal filtering:

$$\Delta E_{rms} = \left(\int_0^\infty \frac{4\left|S(f)\right|^2}{\left\langle \left|N(f)\right|^2 \right\rangle} df \right)^{-1/2}$$



Signal processing techniques

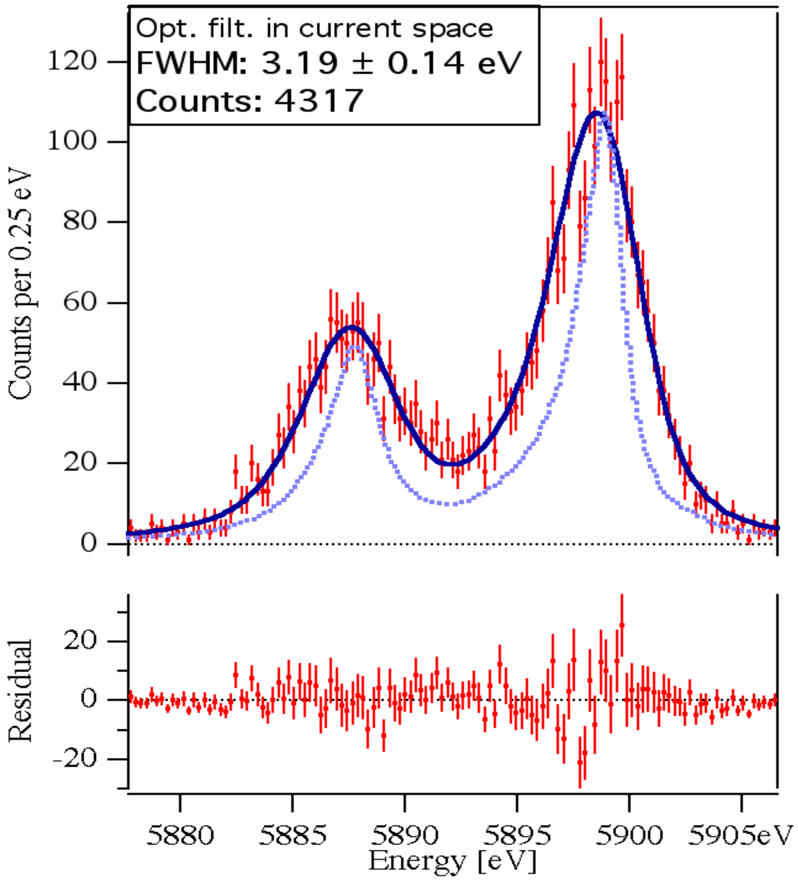




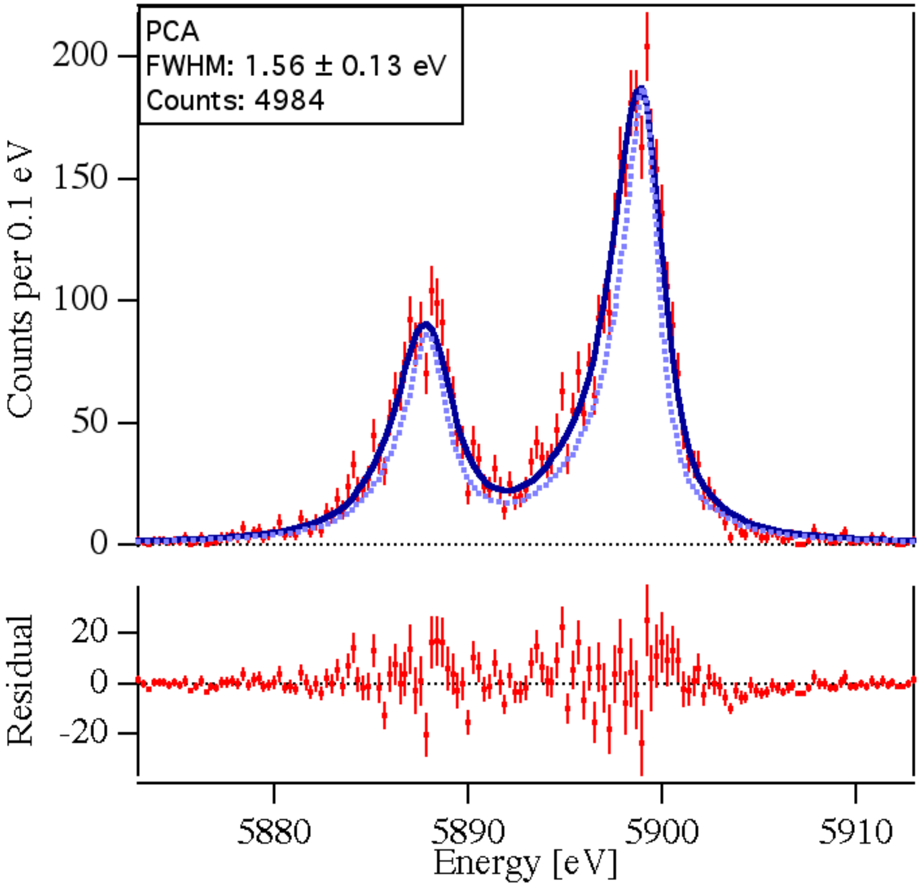
- Non-linear gain curve
  - Non-linear transition curve
  - Non-linear read-out circuit

    => Pulse shape changes with energy
- Non-Stationary Noise

Optimal filter in current space: 3.2 eV



Principal component analysis: 1.6 eV

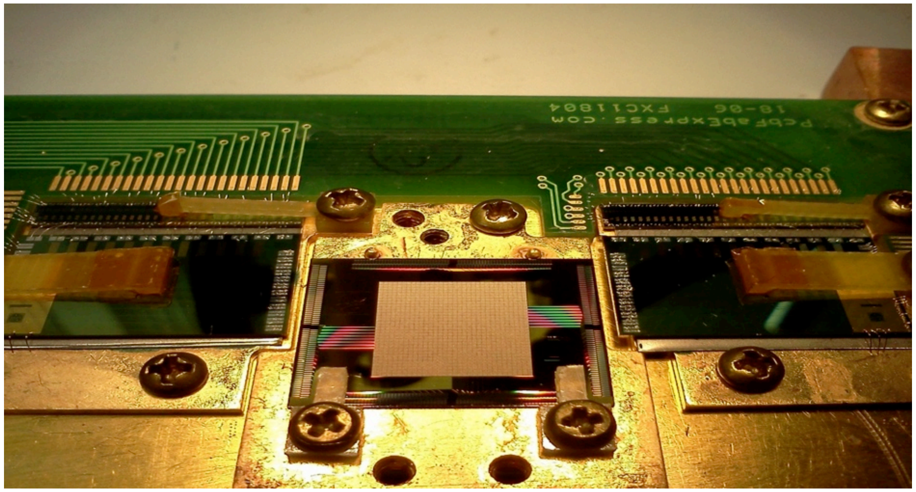


Conclusions

- Developing/optimizing a variety of pixel designs for future microcalorimeter array types
  - Ground-breaking performance; steady, consistent progress
  - Moving towards larger arrays

- Strong teams of X-ray Microcalorimeter technologists supported in the US
  - Strong scientific teams built by Rich Kelley, Caroline Kilbourne, Kent Irwin, Scott Porter and many others
  - Consistently lead the world in majority of the key areas
  - Responsive to new opportunities to work with X-ray scientists throughout the US
  - Embrace opportunities for international collaboration, as desired by X-ray community

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
NASA/Goddard Space Flight Center
Close collaboration & support from *NIST/Boulder*



Let's build a mission !