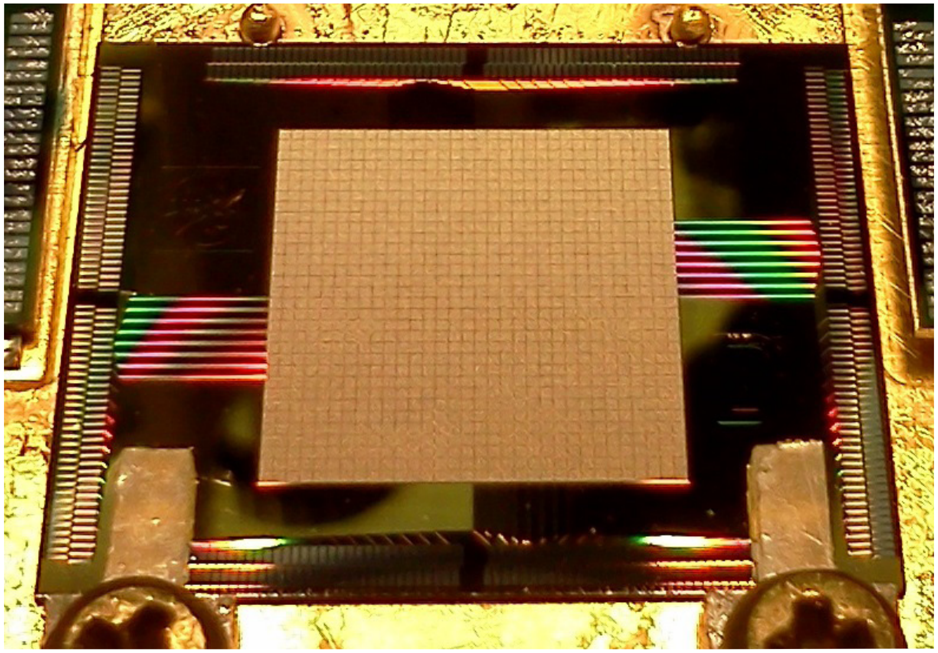
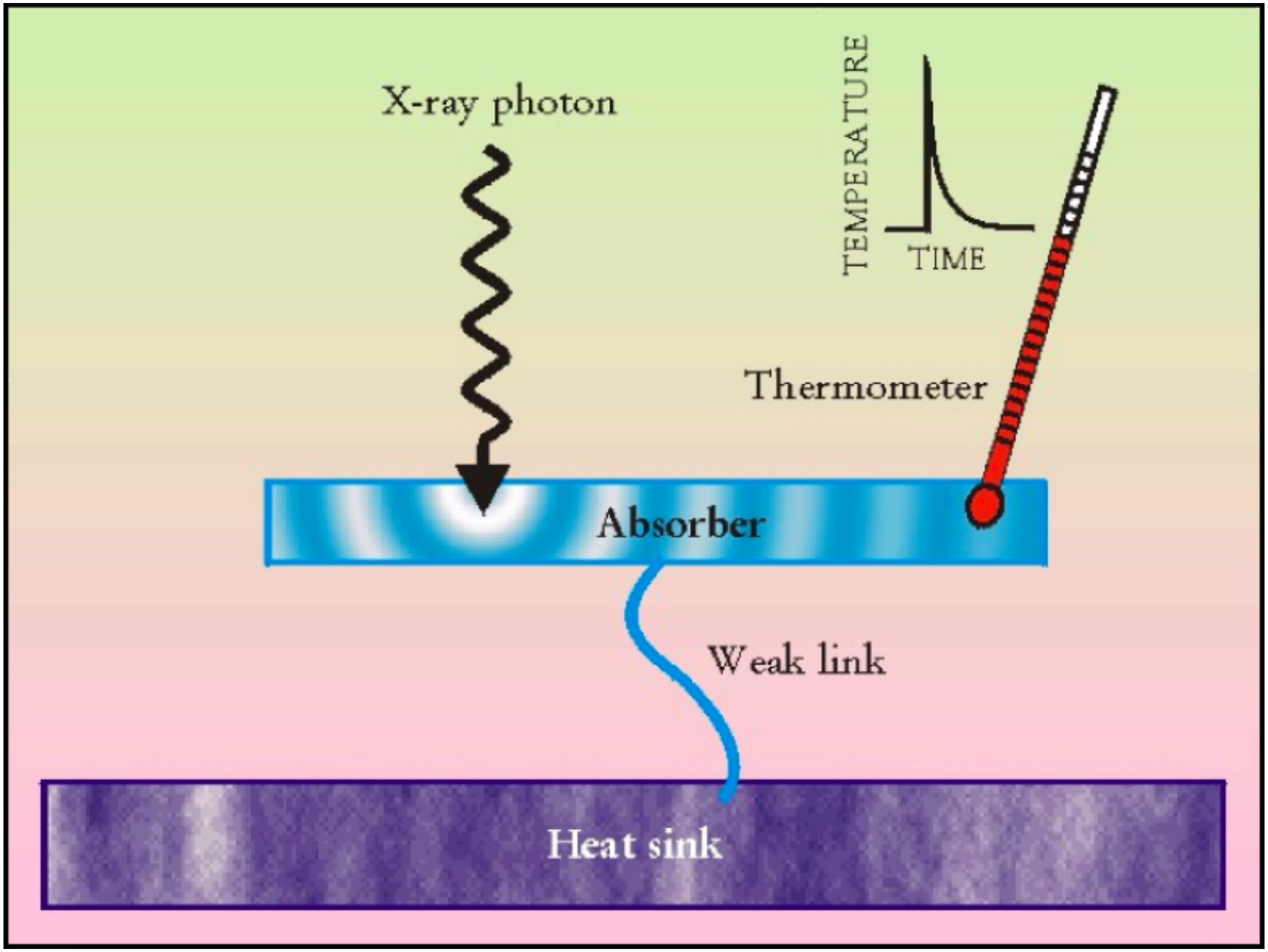
Status of current efforts and future needs in detectors

Simon Bandler: X-ray Astrophysics Laboratory at NASA/GSFC

- Sensor technologies – the good and the bad
- Who's doing what ?
- State-of-the-art performance
- XMS instrument concepts
- Array size limits
- Getting to TRL-6





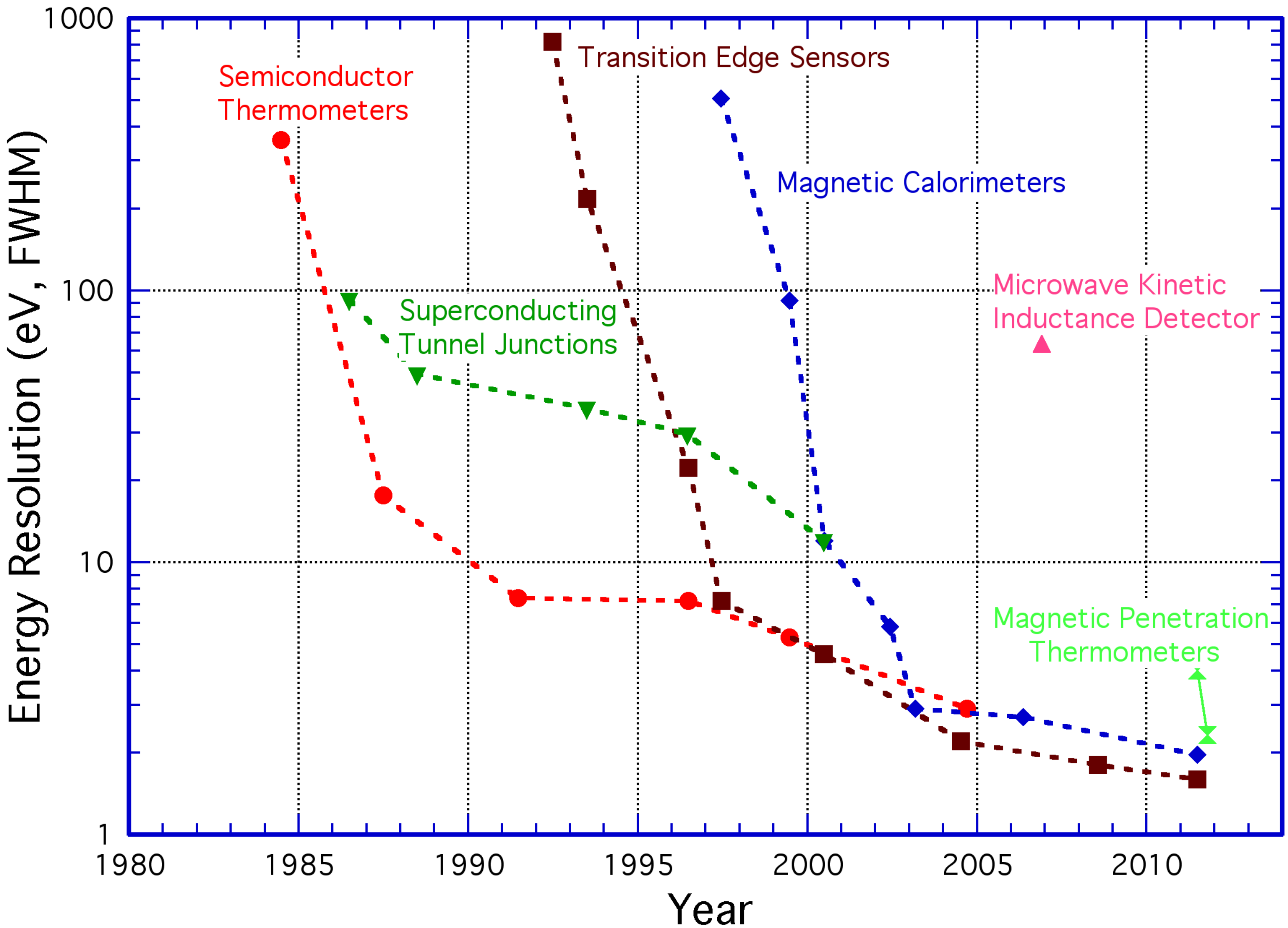
$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

Thermal relaxation time:

$$\tau = \frac{C_{\mathrm{tot}}}{G}$$

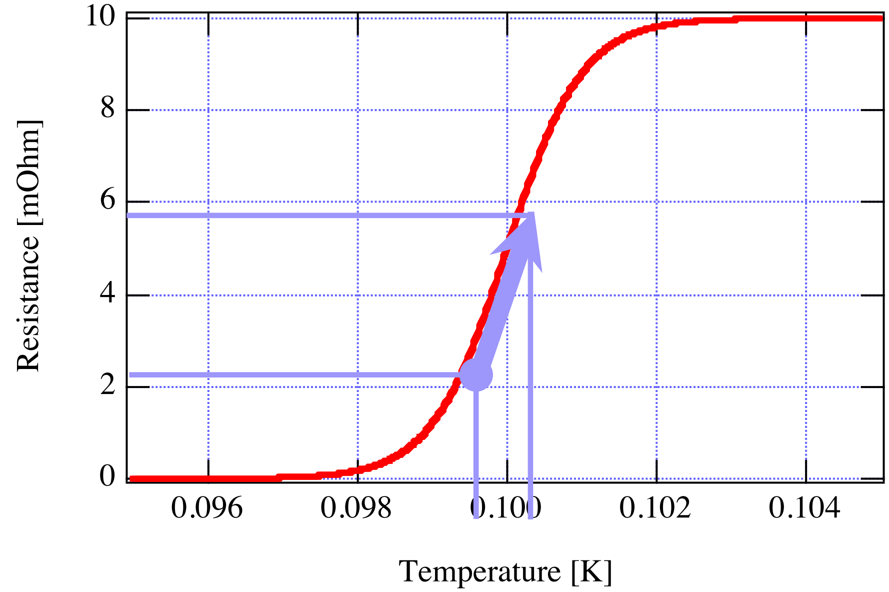
Thermal conductance

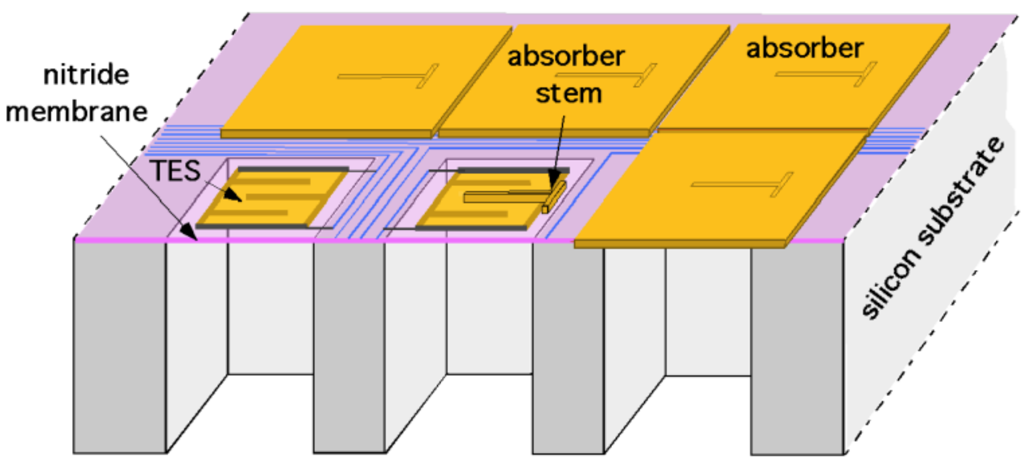
X-ray microcalorimeters capable of 1 eV energy resolution
S.H. Moseley, J.C. Mather, D. McCammon, J. Appl. Phys. 56, 1257 (1984)

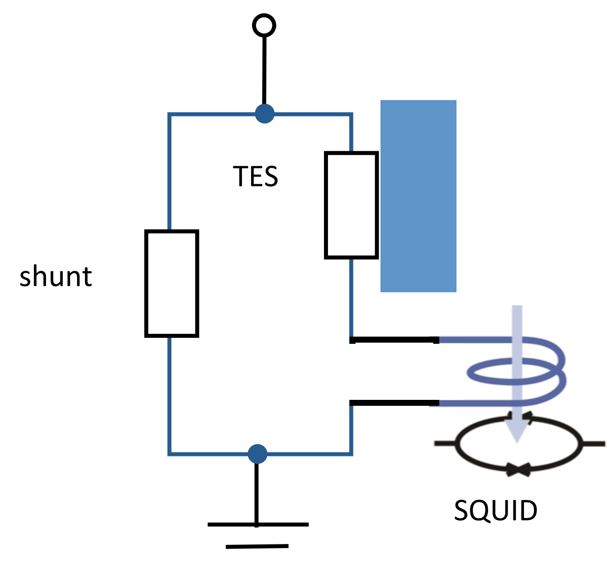


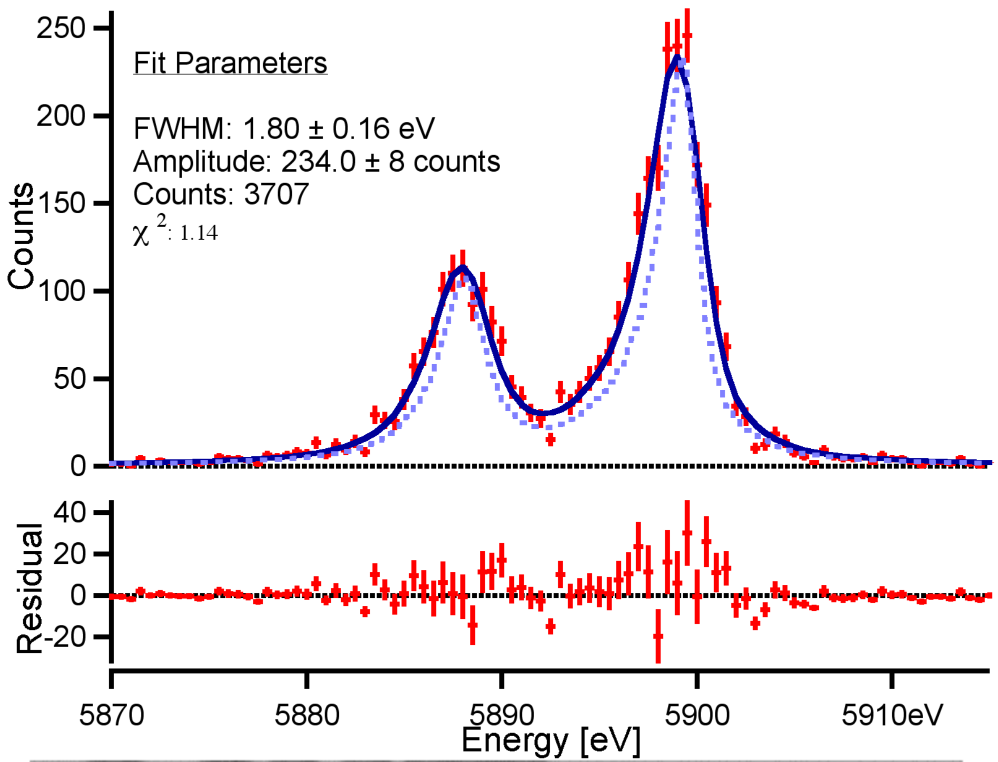
Transition-edge Sensors

- Superconductor biased in its transition
- Low resistance allows read out with SQUIDs
- $T_c = 0.1$ K
- Overhanging absorbers are several microns thick







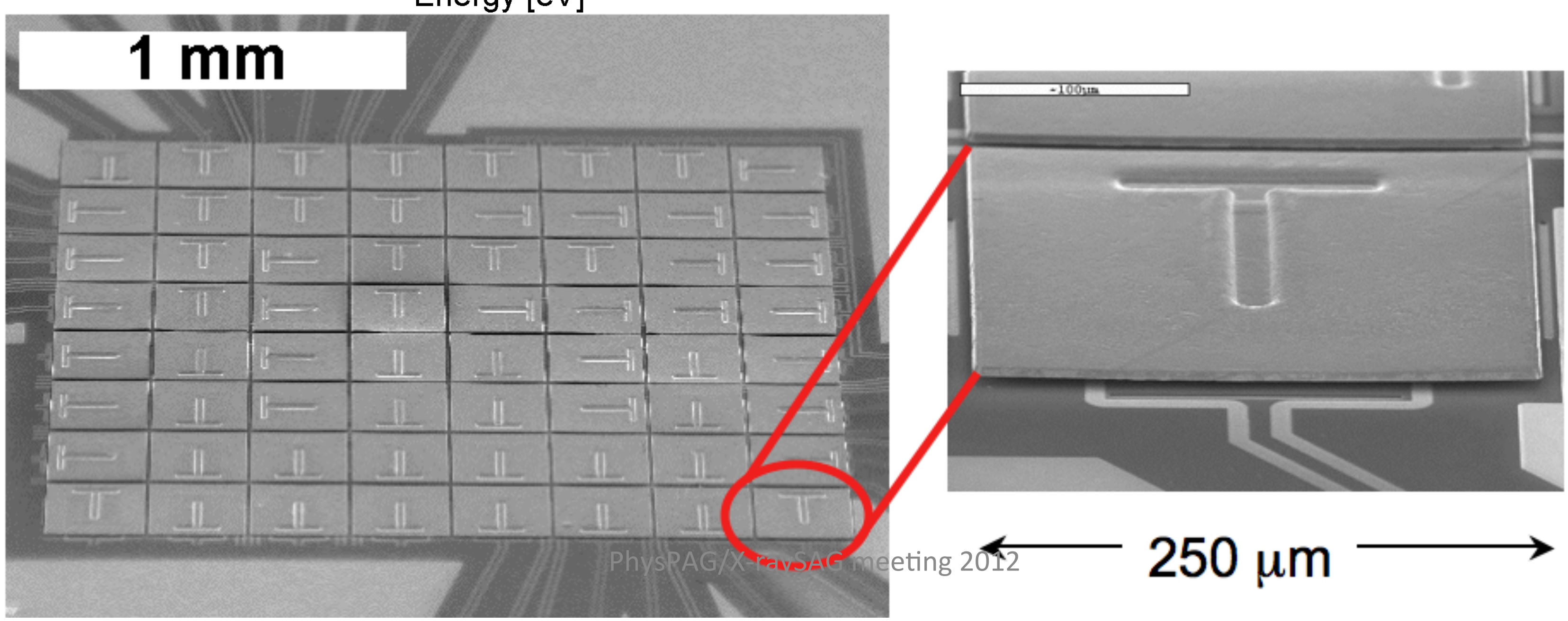


- Mn Kα_1 & Kα_2 x-rays at 6 keV from an ^{55}Fe internal conversion source
- Instrumental broadening consistent with a gaussian response with 1.8 eV resolution FWHM

Array absorbers :

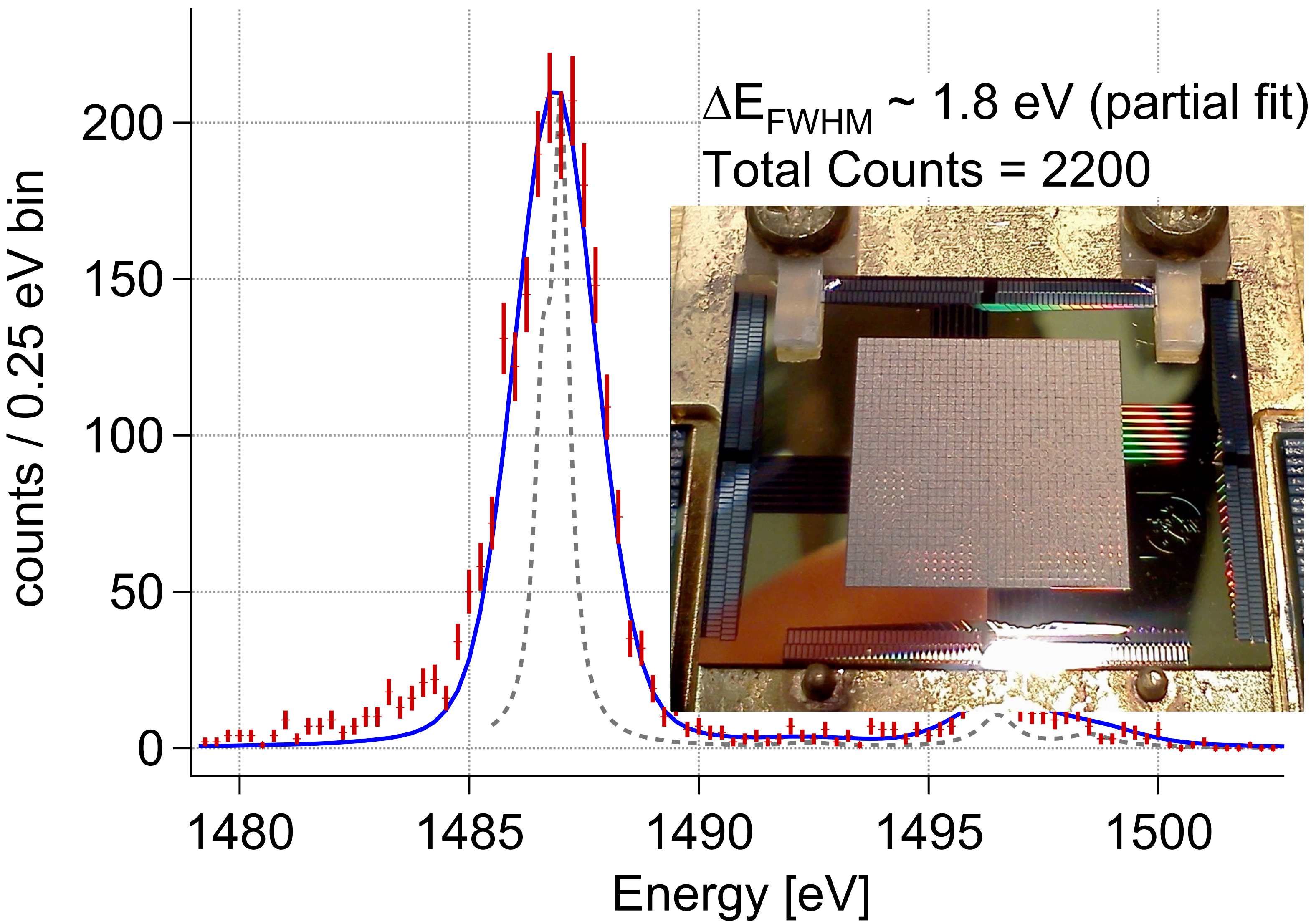
240 µm x 240 µm

0.7 µm Au & 6 µm Bi



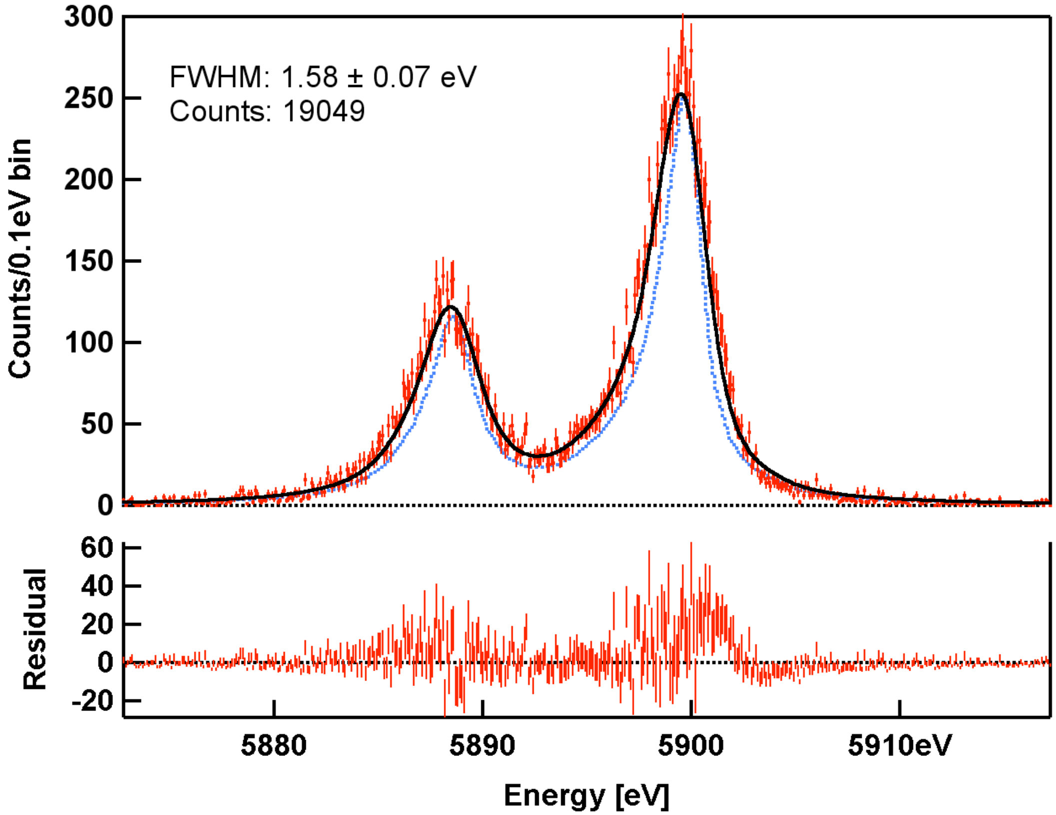
Current state-of-the-art

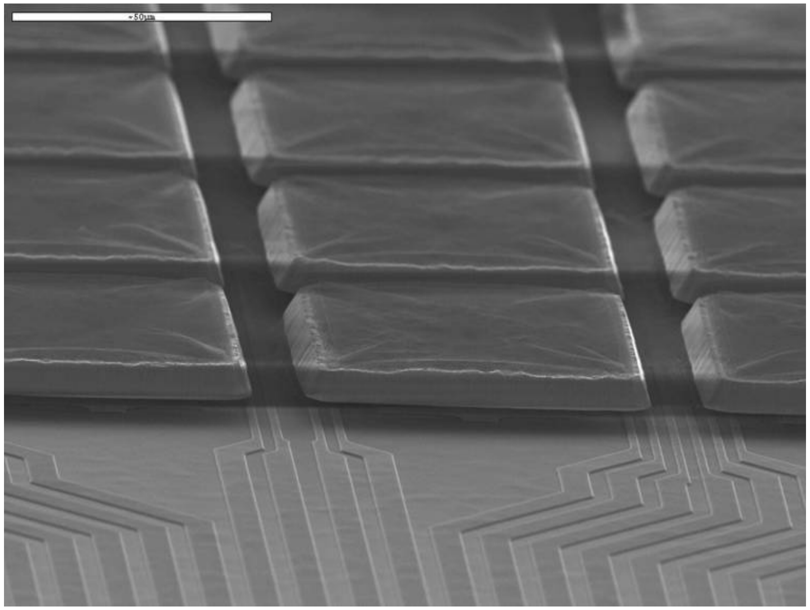
32 x 32 array with
300 micron pixels



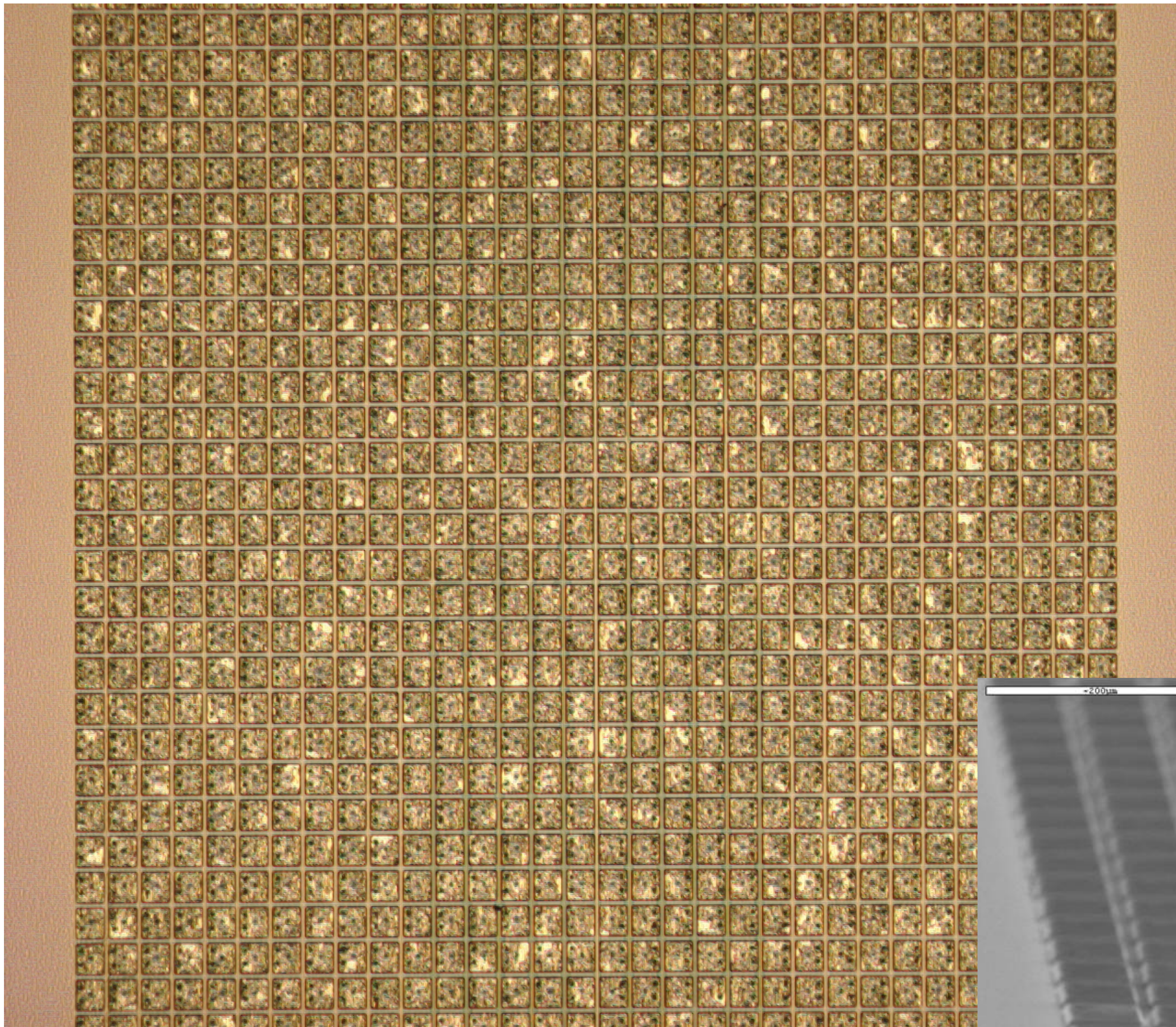
TES – smaller pixels

- *Suited to shorter focal lengths and/or higher spatial resolution*
- *Fantastic microcalorimeter energy resolution*
- *Use of all-gold absorbers* - great for reliable fast thermalization
- *Solid substrate design* - great for heat-sinking/low cross-talk
- *Use of multiple designs on a single silicon chip*
  - no variation in back-etching / fabrication
  - less complex focal plane assembly design
- *Through choice of T_c, can be optimized for speed or resolution.*



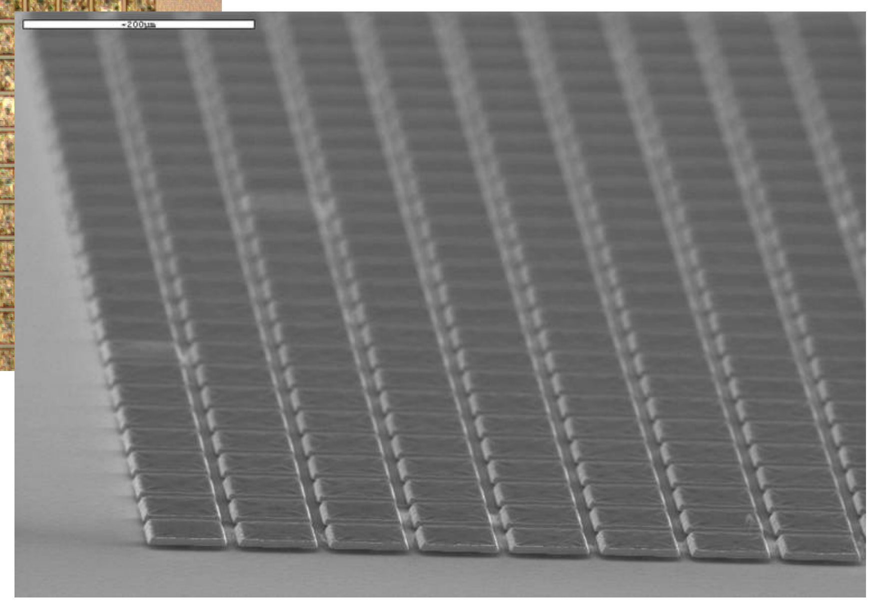


57 μm pixel with 30 μs time constant

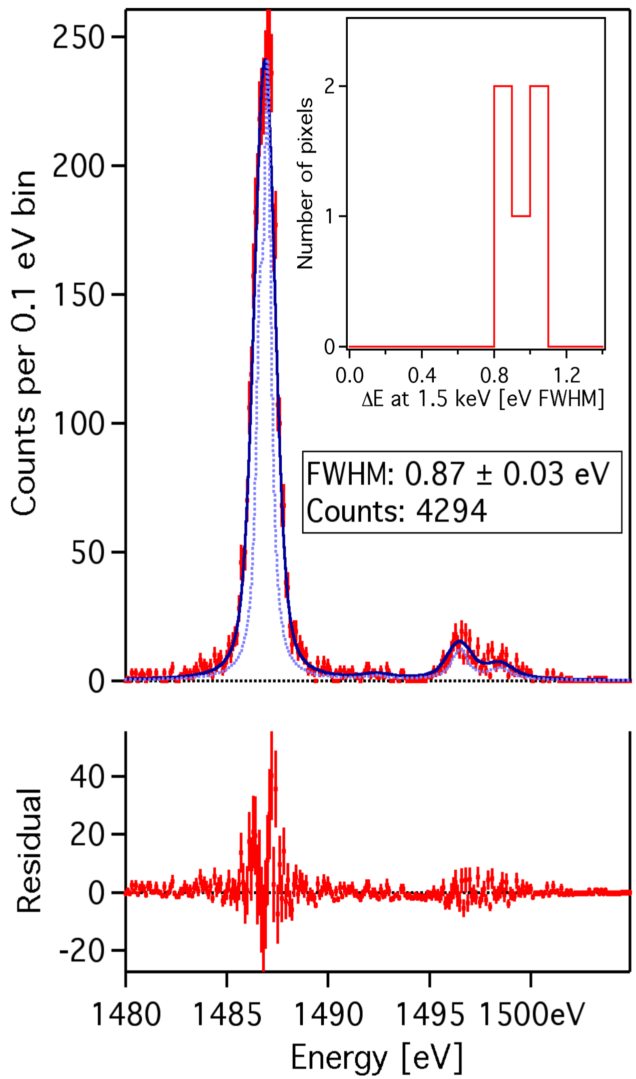


Motivated by solar physics applications:

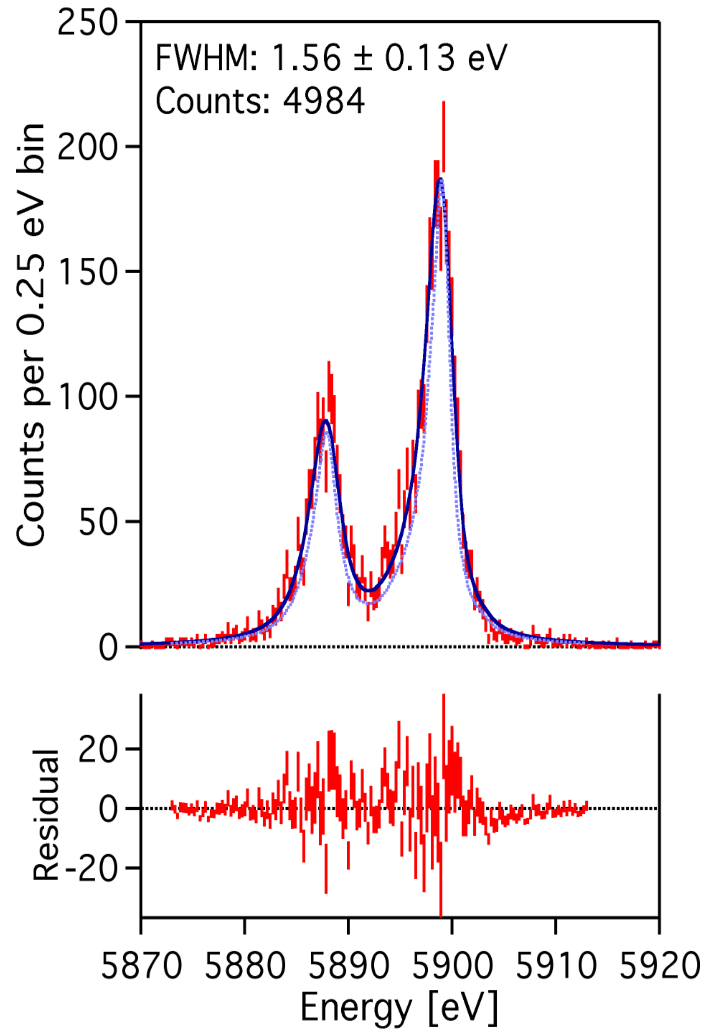
- 32x32 arrays
- TES on 75 μm pitch
- Absorber gold: 65μm x 65 μm x 4.0 μm



ΔE ~ 0.9 eV (FWHM) at 1.5 keV (Al-K)



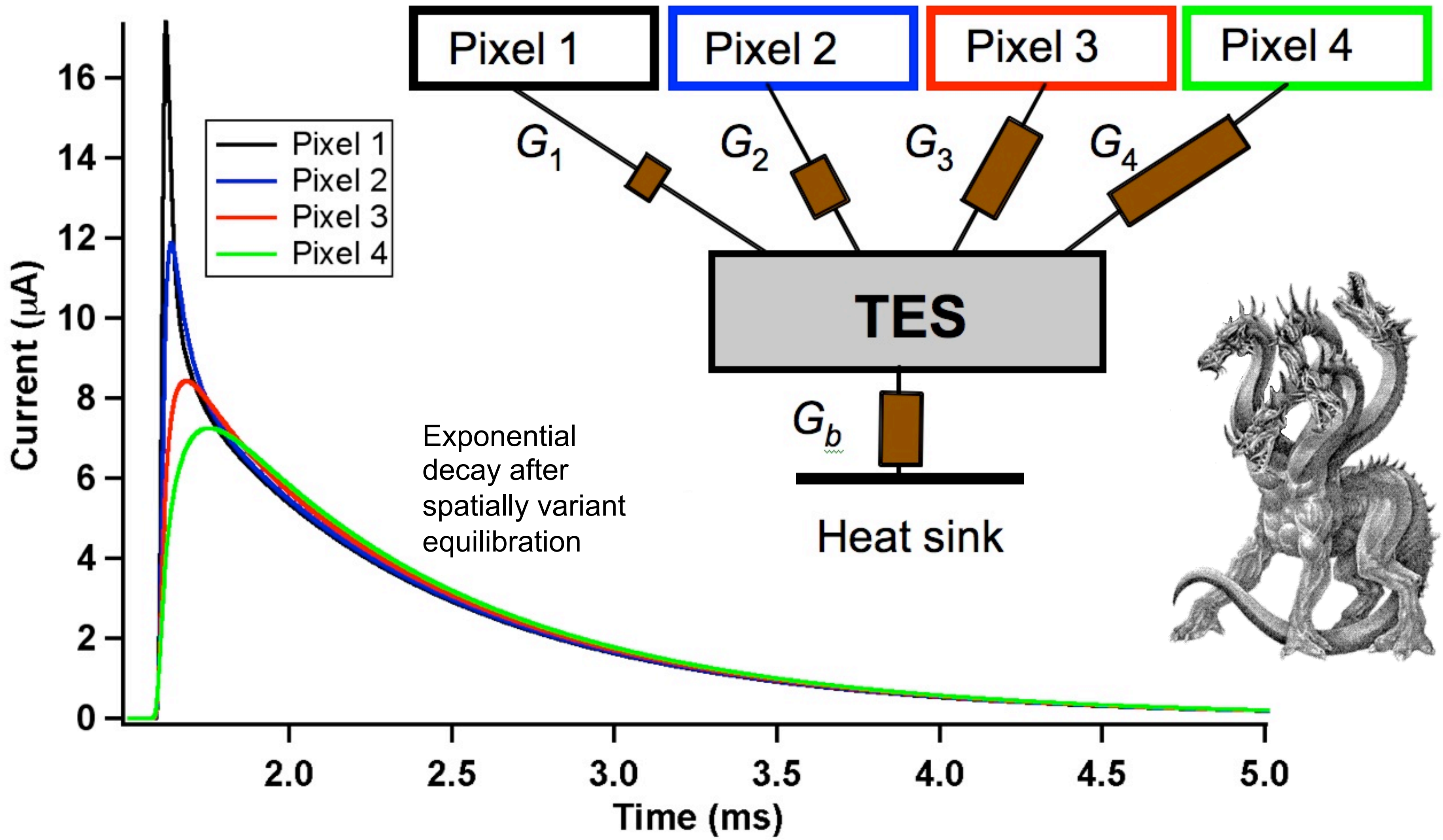
ΔE ~ 1.6 eV (FWHM) at 6 keV (Mn-K)



- Surpasses previous best at 1.5 keV
- Low T_c pixel results match best resolution at 6 keV (utilizing non-stationary noise analysis)
- Count rate capability of a few 10's per second

Multi Absorber TES "Hydras" - 1 TES, 4 absorbers

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



S.J. Smith et al., Proc. SPIE, 2008.

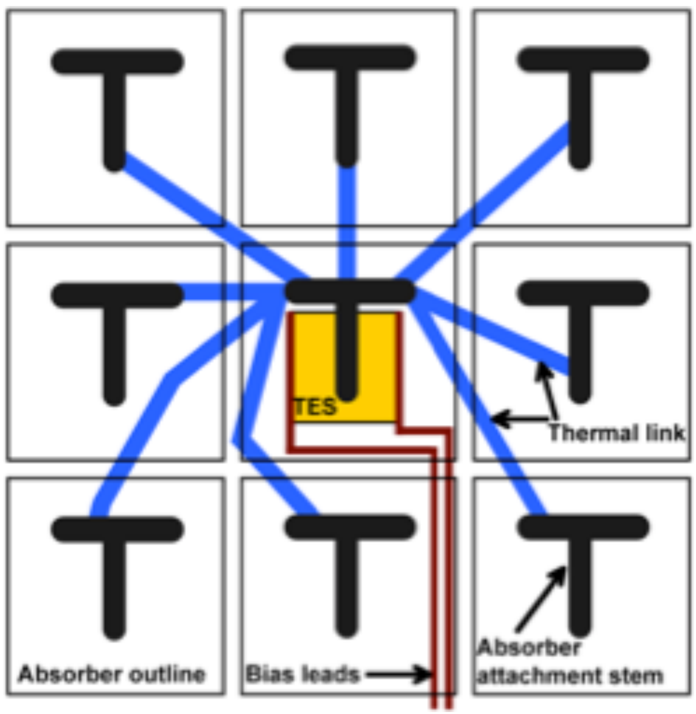
Small Hydra Detectors

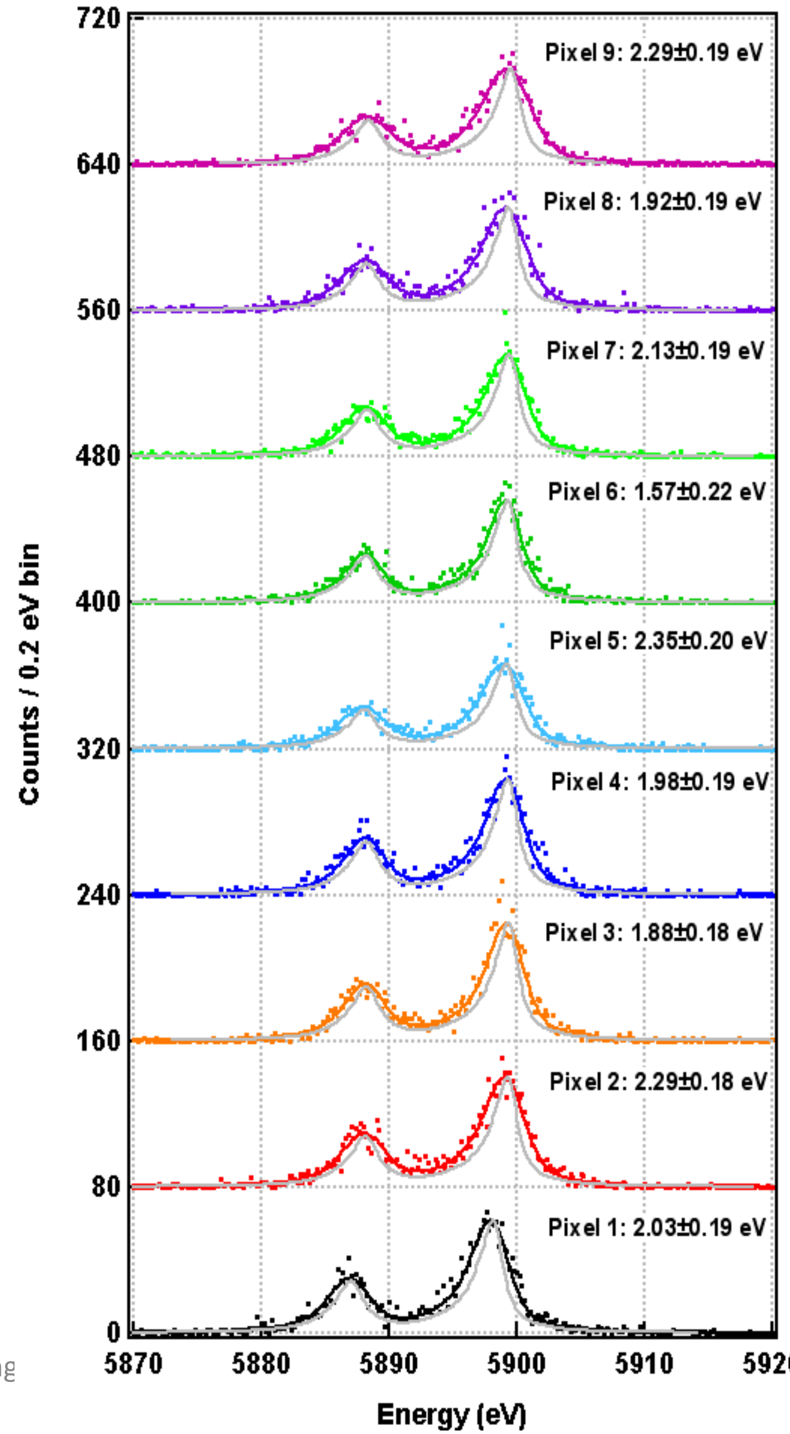
- Close-packed 2x2 and 3x3 Hydras tested
- n absorbers => $\Delta E_{Hydra} \sim n^{1/2}\ \Delta E_{Single\ Pixel}$

  $\Delta E_{Single\ Pixel} \sim 0.7$ eV

  $n = 4$, $\Delta E_{Hydra} \sim 1.4$ eV

  $n = 9$, $\Delta E_{Hydra} \sim 2.1$ eV
- 3x3 array of 65 μm absorbers, 5.0 μm thick.
- 2.2 eV - rms (FWHM) resolution at 6 keV !





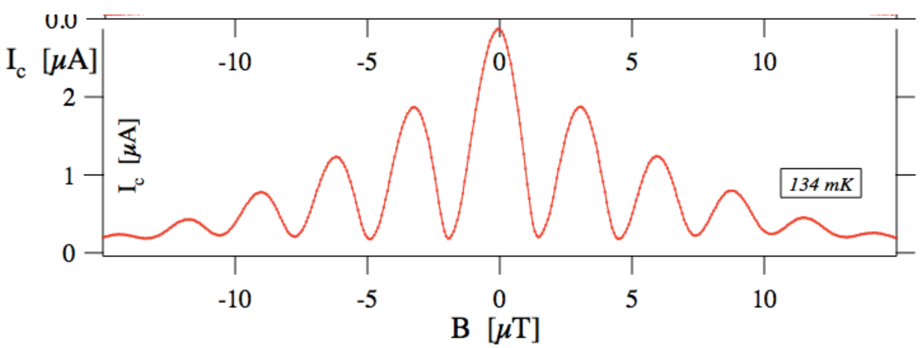
TES

The good:

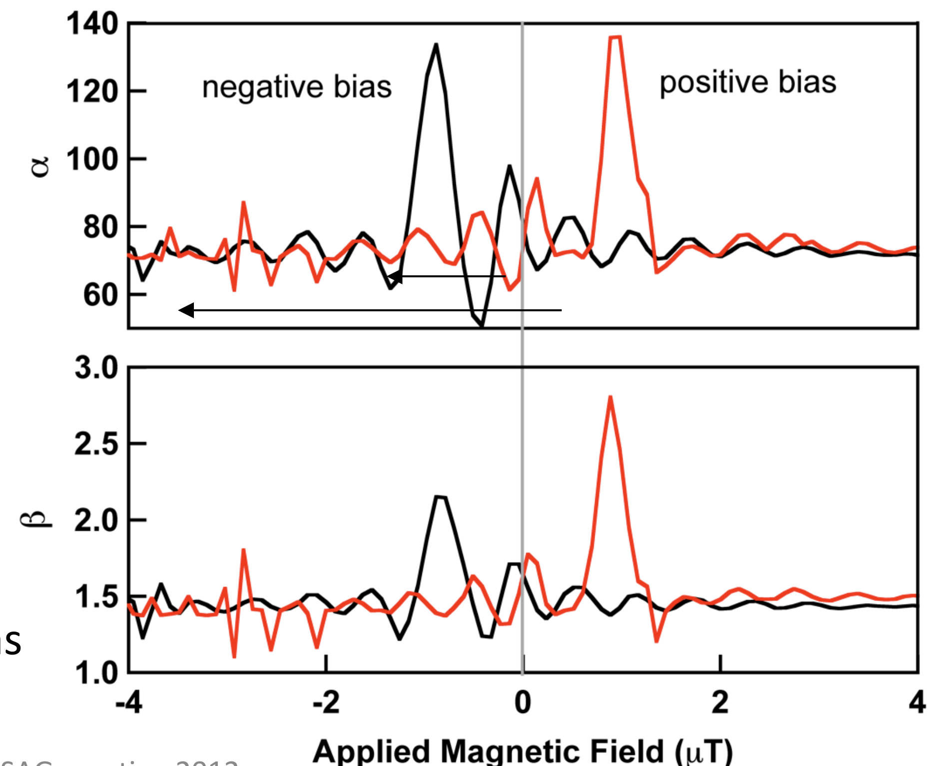
- Best documented energy resolution performance
- Highly multiplexable read-out (more later)
- Highest TRL of all technologies with kilo-pixel potential
- Large variety of pixel sizes possible

The bad:

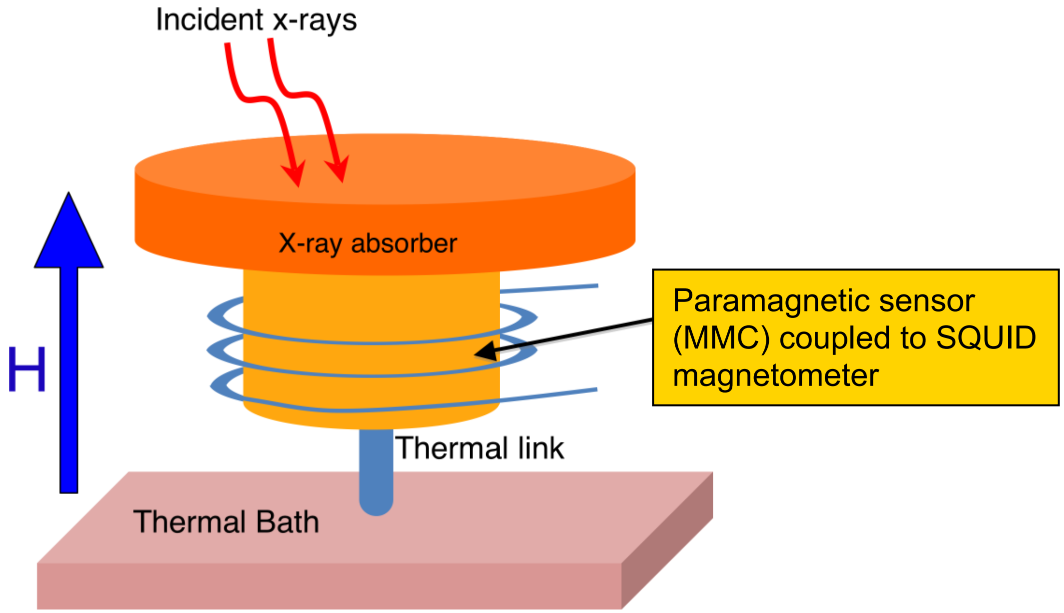
- Superconducting leads attached to TES produce long-range S-N-S junction
  - Very interesting physics – *J.E. Sadleir et al., PRL **104 4** (2010) 0470032010, Phys. Rev. B. 84 (2011) 184502*
  - But high sensitivity to magnetic fields - > some non-uniformity and design complications



Junction-like Fraunhofer pattern in Ic(B)
=> Variations in signal size and noise under bias



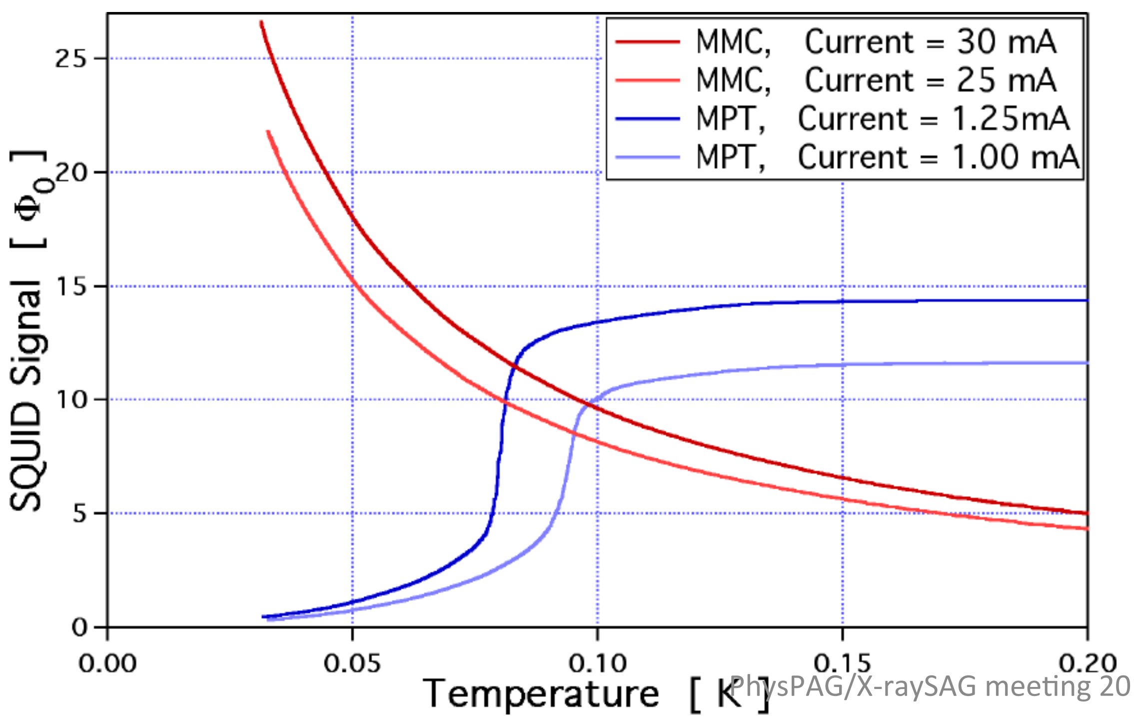
Magnetic Calorimeters (MMC) & Magnetic Penetration Thermometer (MPT) Microcalorimeters

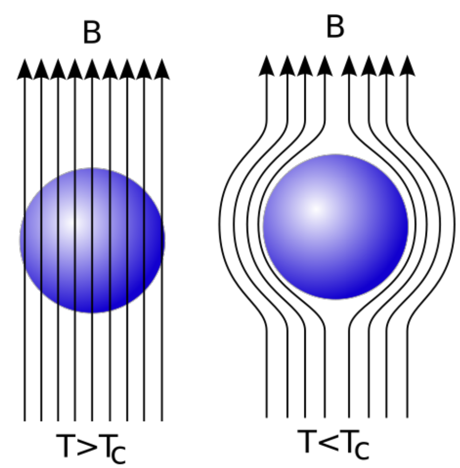


Paramagnetic sensor: Au:Er

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

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

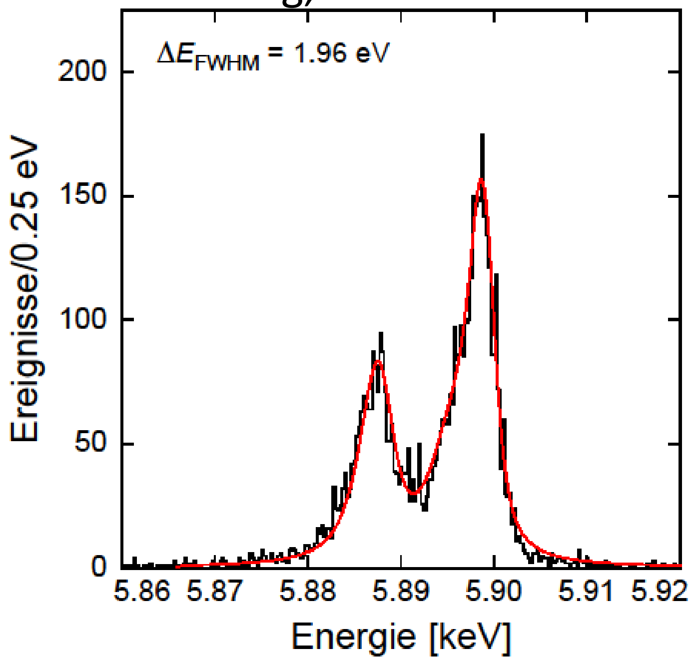




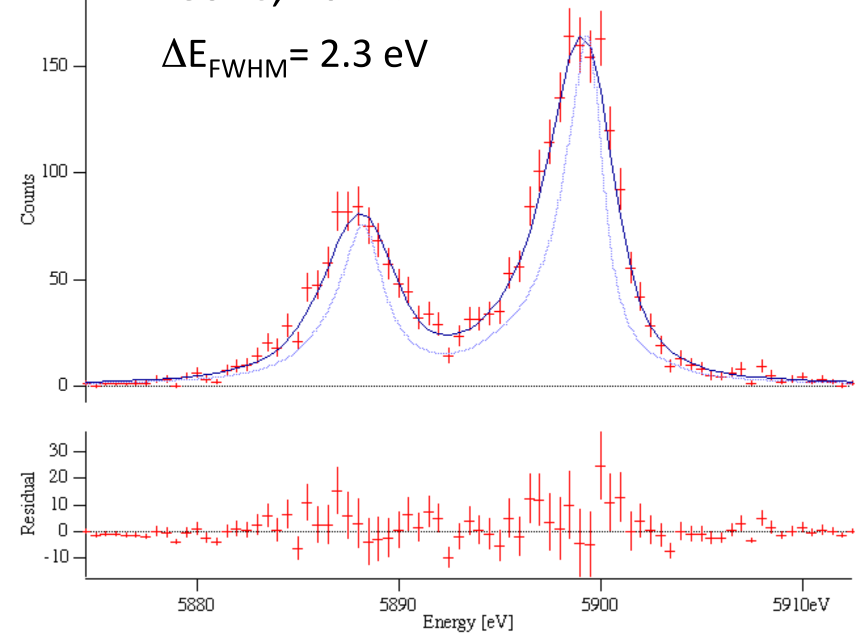
no heat dissipated in the sensor
no galvanic contact to the sensor

Best magnetically coupled calorimeter results at 6 keV:

MMC – Heidelberg, 2011:



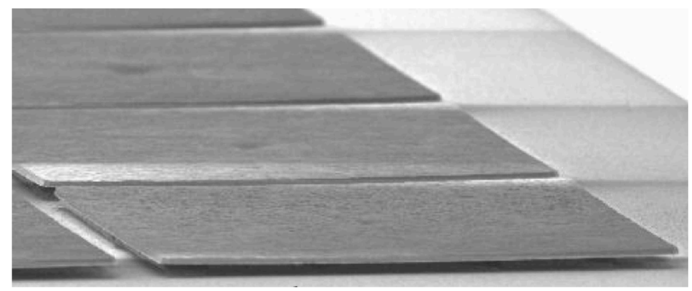
MPT – GSFC, 2011:



MMC / MPT

The good:

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

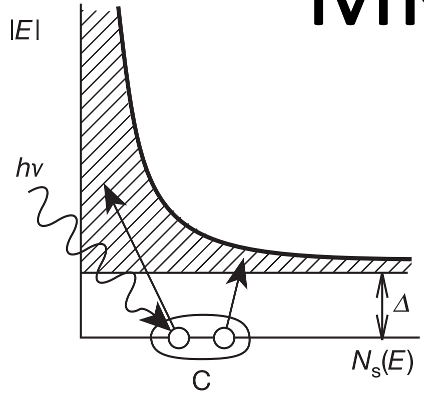


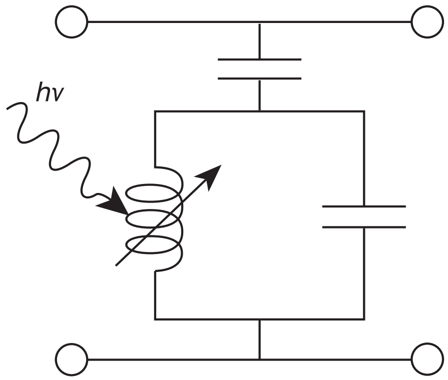
250 μm absorb., 2.8 μm thick Au, supported on single 3.5 μm stems

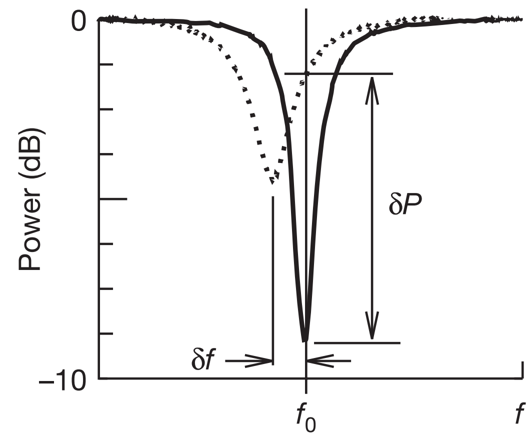
The bad:

- Hardest to technology to read out and multiplex

MKIDs





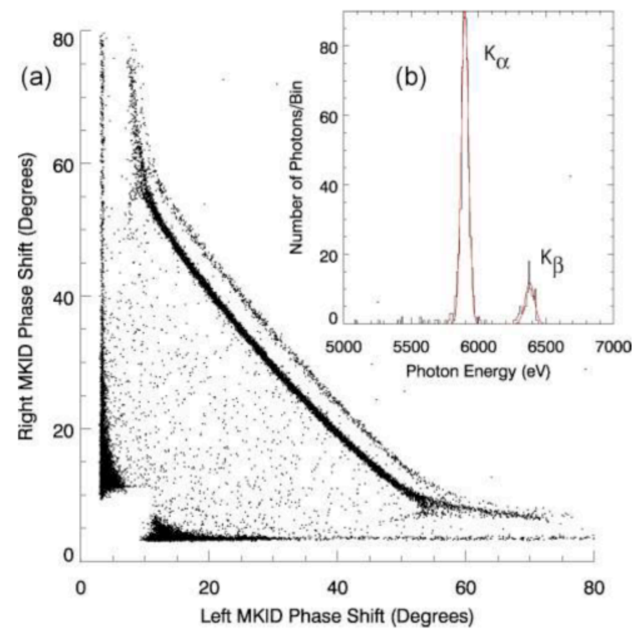


The good:

- Potentially the easiest technology to multiplex with microwave read-out
- Investment taking place in infrared bolometer community (JPL)

The bad:

- High energy resolution is very difficult, especially at 6 keV
- Read-out needs development of parametric amplifiers
- Read-out electronics a long way from being flight qualified – no near-term alternative
- Superconducting absorbers are difficult



Best results achieved using position-sensitive MKIDs ~ 60 eV at 6 keV.

Ongoing programs:

ROSES-APRA supported basic research programs:

- GSFC TES development (Kilbourne)
- NIST SQUID read-out and detector development (Irwin)
- Brown/UMD/GSFC MMC/MPT development (Bandler)
- Santa Barbara (supported by JPL) – MKID (Mazin)
- Wisconsin/GSFC - rocket application, XQC, filters - soft x-rays (McCammon)
- MIT/GSFC/NIST - rocket development, uX, - focused x-rays (Figueroa)

IXO directed funding, ROSES-SAT funding ?

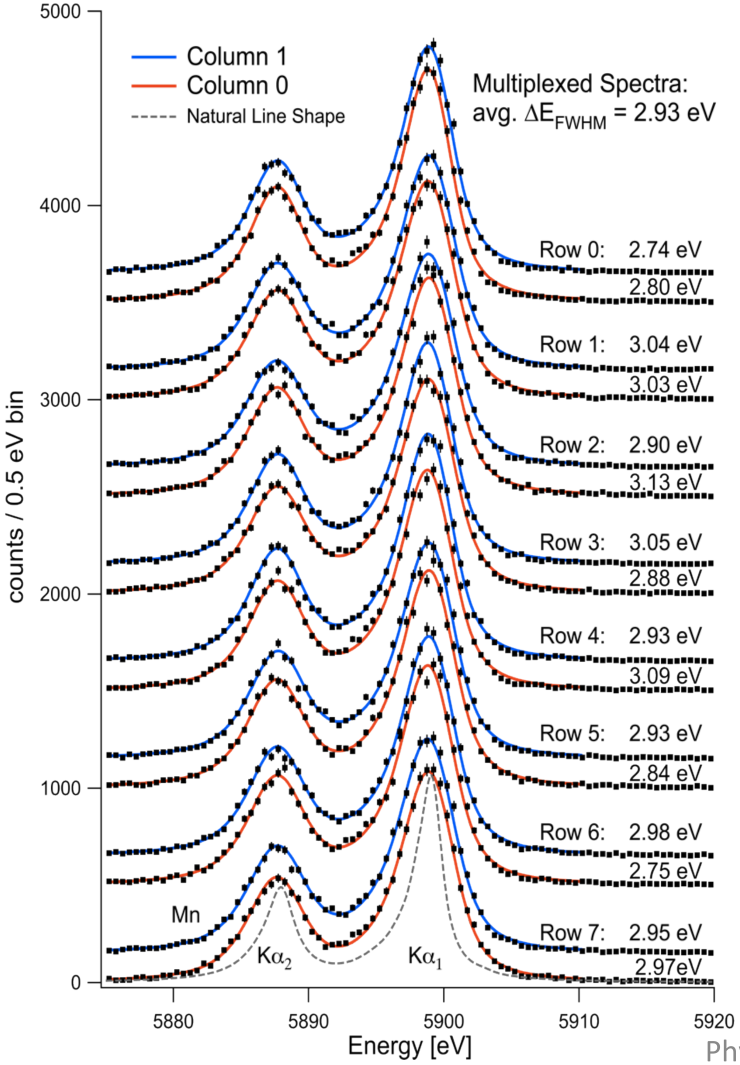
- GSFC / NIST (Kilbourne / Irwin) - reaching higher TRL with new technologies

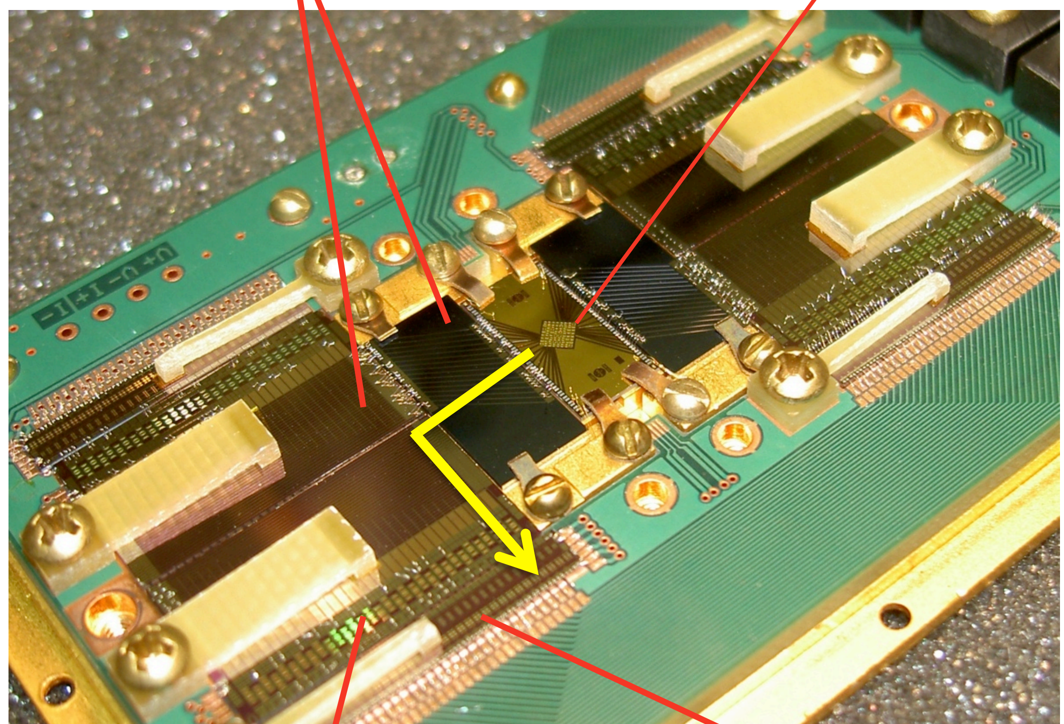
Very difficult / almost impossible for new small groups to work independently of large facilities. Encourage new University Scientists working together with larger labs. on specific tasks.

Read-out: Time division multiplexing

GSFC 8 x 8 array
NIST SQUID MUX readout

2 x 8 mux readout of 8x8 array (250 μm pixel)
ΔE_{FWHM}= 2.9 eV





Code division multiplexing (CDM):

Reason: Does not have "multiplex disadvantage" that exists for TDM multiplexing

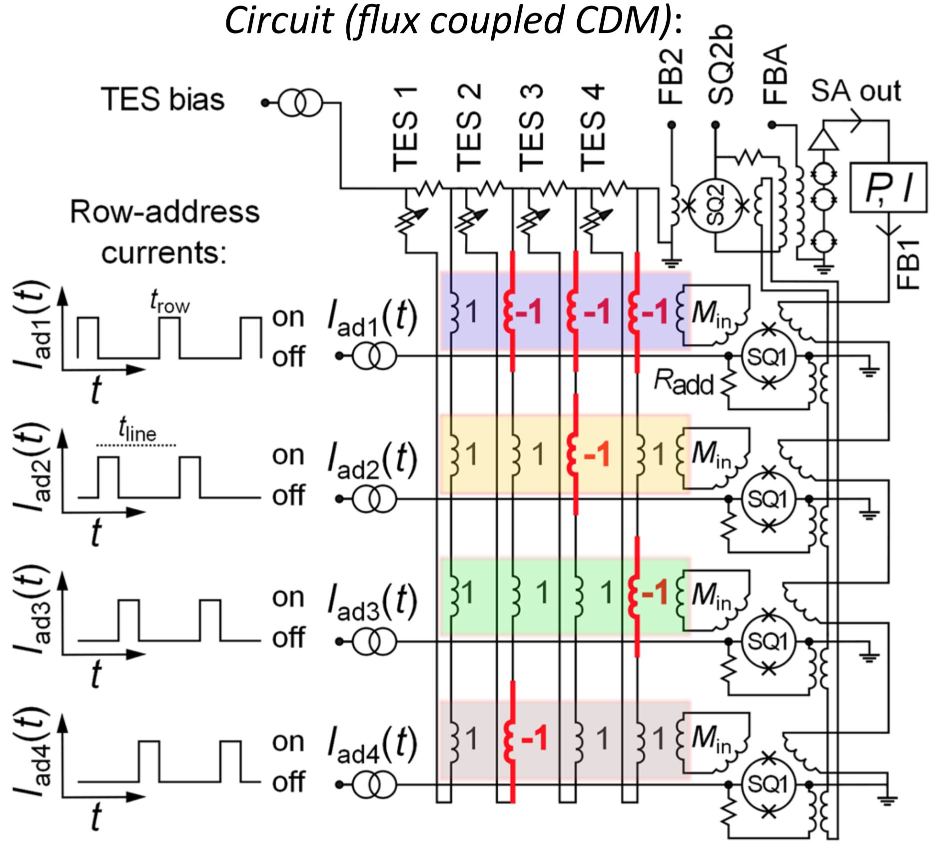
⇒ Better energy resolution / greater engineering margin

How it works:

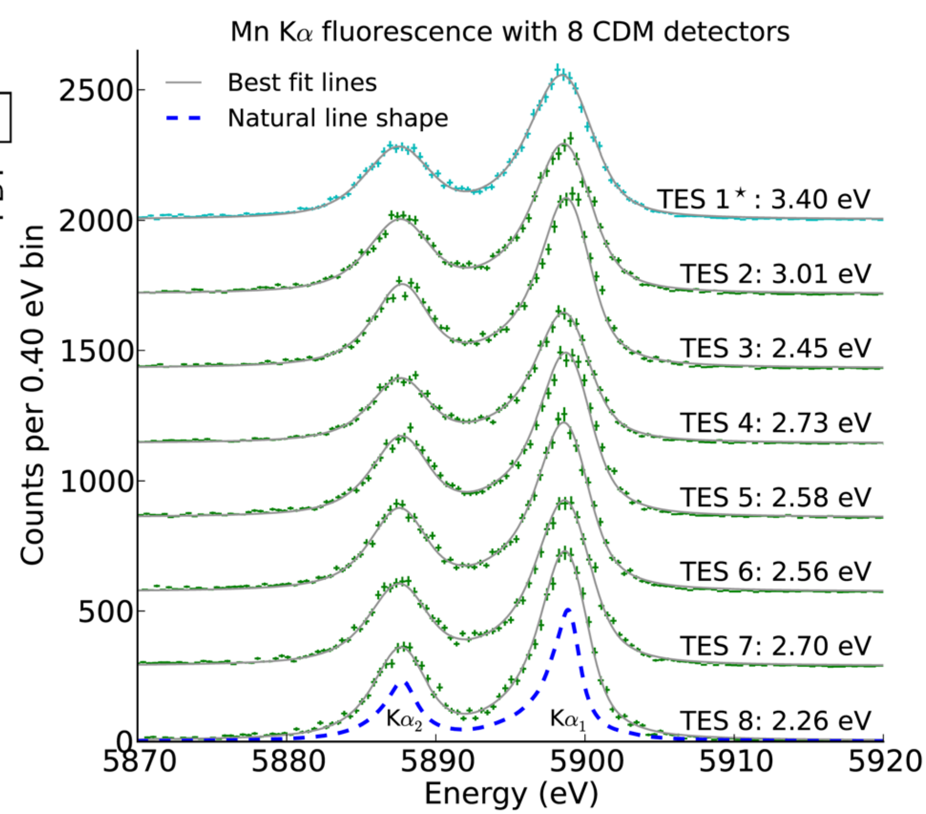
- Every detector pixel is sampled all of the time
- Polarity of coupling to the SQUID switches between +1 and -1 in orthogonal pattern (Walsh matrix)

CDM chips are drop-in compatible with existing 32-row TDM systems but have higher performance.

Circuit (flux coupled CDM):

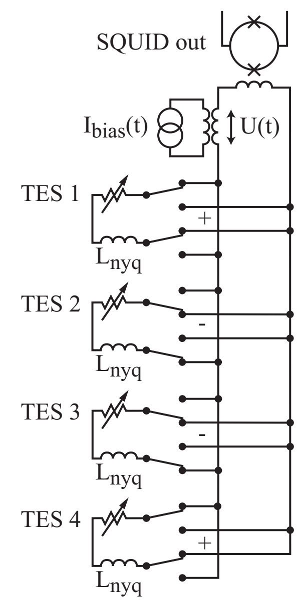


Promising first results from 1x8 CDM demonstration:



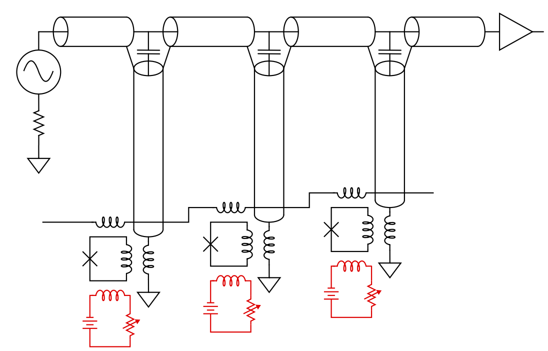
Stiehl et al (2012)

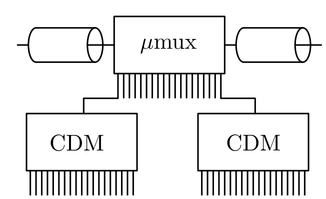
Future Multiplexed Read-out Technologies



1. Current steering CDM
   - Large number of pixels per amplifier
   - Fewer wires
   - Could lead to 3-D geometries => greater multiplexing
   - Being developed first for bolometer applications which require lower currents (easier)

2. Microwave readout
   - Longer term
   - Again being spear-headed by research for bolometer applications (easier)
   - Can be integrated with CDM concepts
   - Deciding when it is most efficient to begin a parallel effort for microcalorimeters is key
     - Many similar technical hurdles
     - Some differences, depending upon technology
       – MKIDs vs TESs vs MCCs
   - Need for flight qualified electronics and components is tricky
     - Rapidly advancing field





Reference design array layout (IXO/XMS)

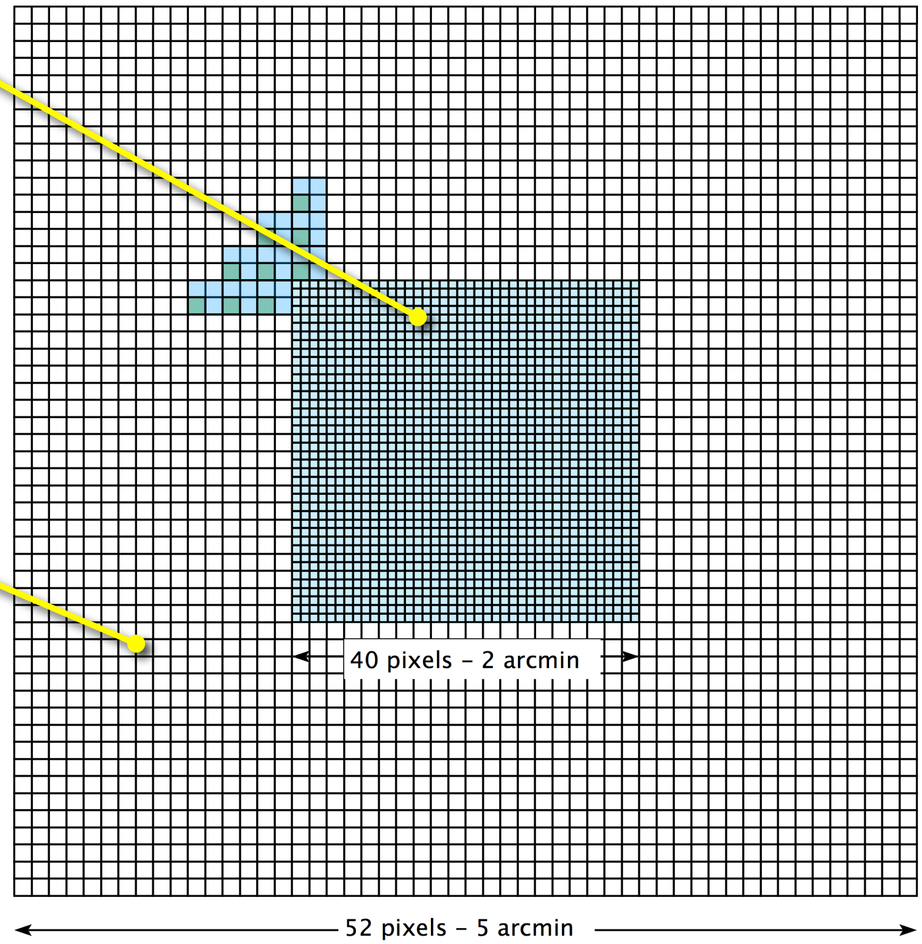
INTERNATIONAL X-RAY OBSERVATORY

Central, core array:

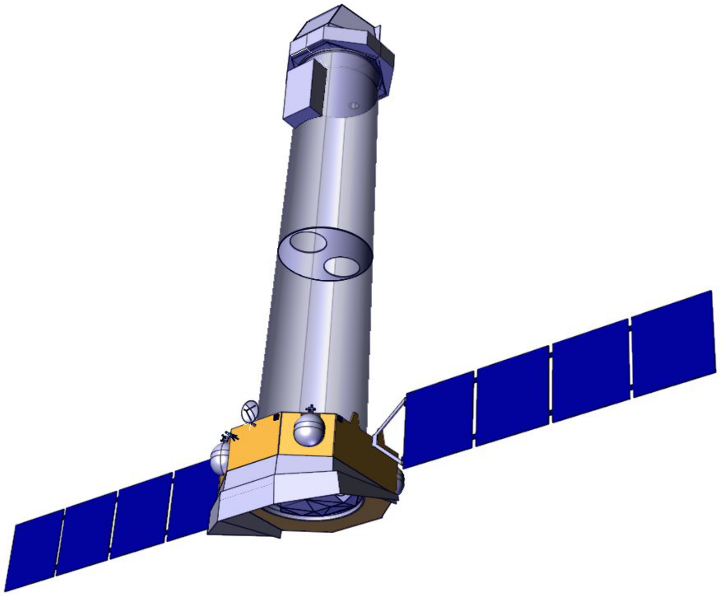
- 40x40 array of Individual TES
  – one absorber/TES
- 2 arcmin FOV
- 2.5 eV resolution (FWHM)
- < 300 μsec time constant

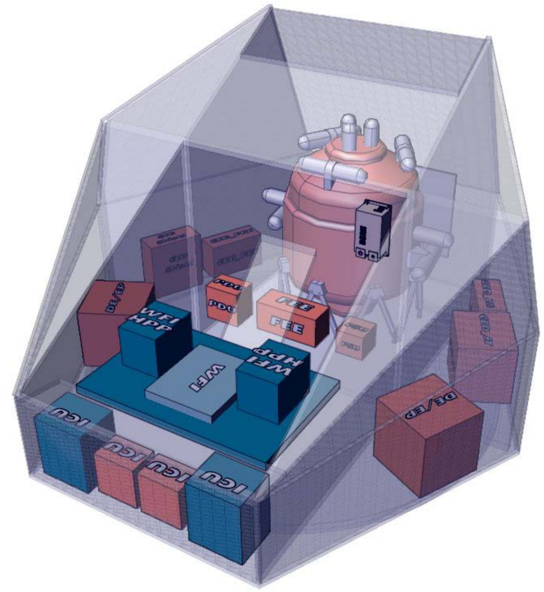
Outer, extended array

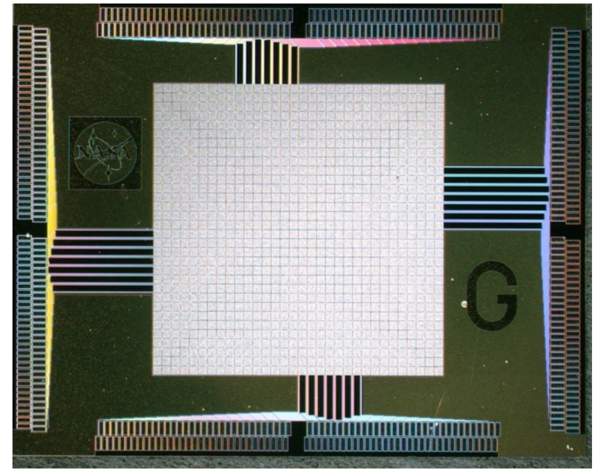
- 4 absorbers/TES
- Extends array to 52 x 52 pixels for a total of 2176 readout channels
- 5.0 arcmin FOV
- < 10 eV resolution
- ~ 2 msec time constant



Athena:

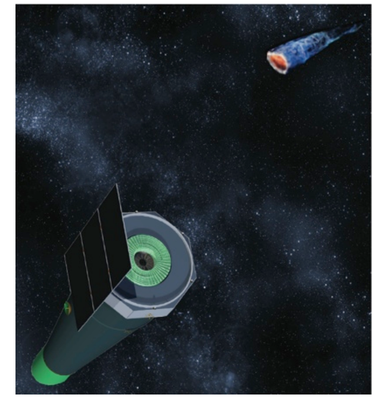






Parameter	Old	New	reason
Energy resolution	2.5 eV	3.0 eV	3.0 has been demonstrated on 2 x 8 array
Array size	40 x 40	32 x 32	32 x 32 arrays have been produced (although there is no technical reason the array cannot be larger)
FoV	2 arcmin	2.4 arcmin	Due to shorter focal length, outer array of 5 arcmin dropped
Pixel size	300 μm	250 μm	Good resolution has been demonstrated for 250 μm pixels, due to lower C there is more margin in the error budget
Number of TESs Number of pixels	2176 3904	1028 1028	32 x 32 + 4 anti-co signals, reduces harness significantly as well as heat loads in cryostat, no re-design of cryostat (yet)
pixels per channel	32	16	Relaxes cross talk and reduces MUX speed requirements
Regeneration time	< 10 hr	< 3 hr	Regeneration cannot be done during periods when XMS is not in focus, 3 hr feasible for current design

First AXSIO XMS Array Concept

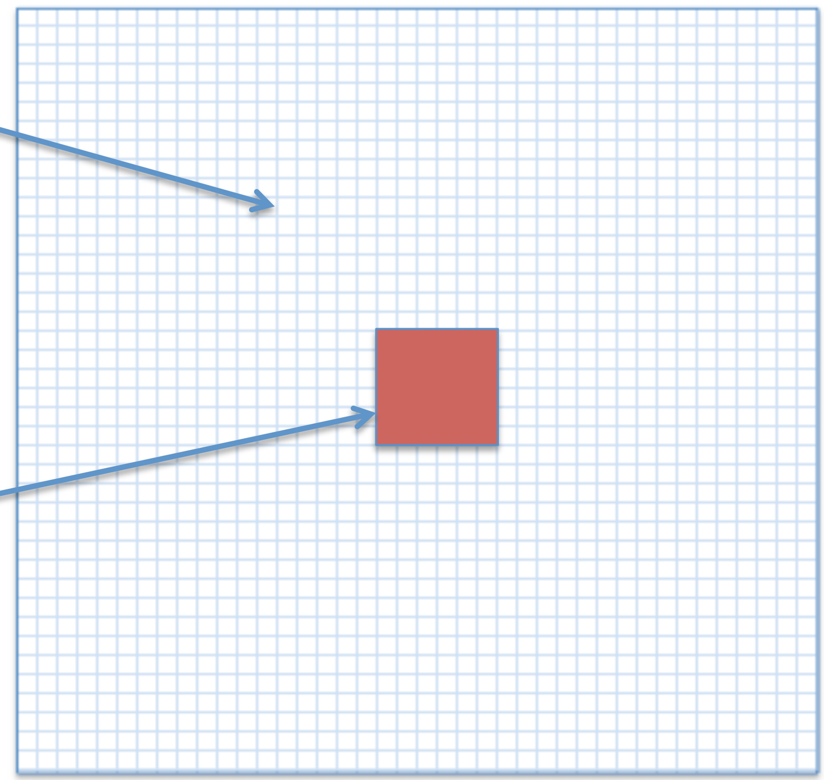


Main array:

- 40 x 40 pixels, 6” each
- 4.0 arcmin FOV
- 300 μm pixels
- 3 eV resolution (FWHM)
- 80% event throughput at 50 cps/pixel

Inner point source array (PSA):

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



2140 TESs (68 readout columns)
Same as IXO

Streamlined (current) AXSIO concept, “N-Cal” concept

Main array – single silicon carrier chip:

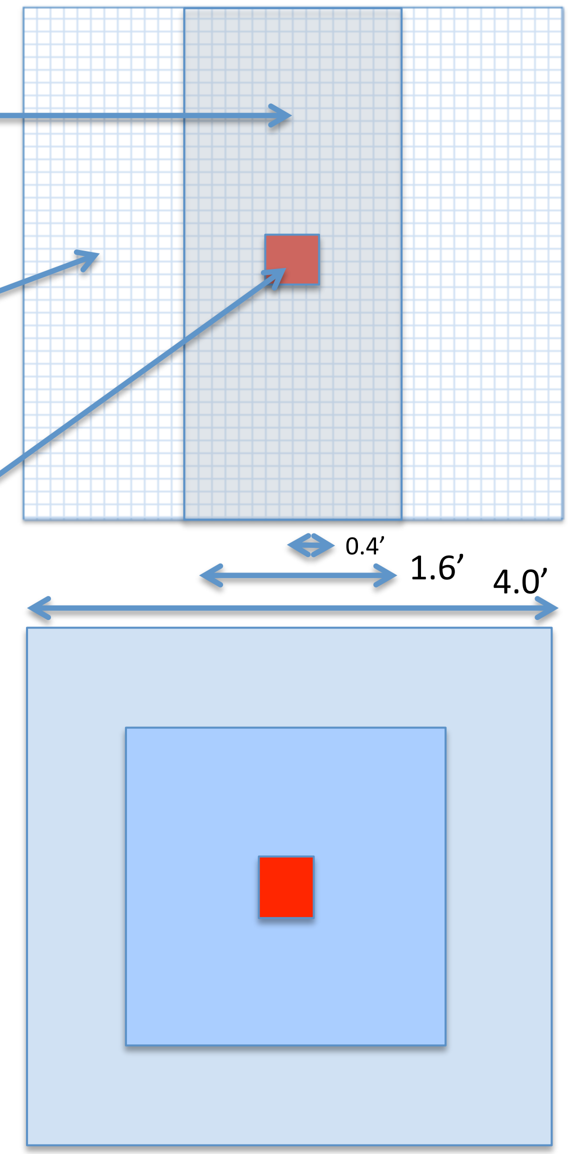
- 40 x 40 pixels, hole in middle: 4 x 4 pixels
- Pixels: 6” each, 300 μm
- 4.0 arcmin FOV
- Shaded region:
  - 16x40 – single pixels
  - < 3 eV resolution (FWHM)
  - 50 cps capability, 80% throughput
  - 624 TESs
- Outer envelope – 4x4 Hydra
  - < 6 eV resolution (FWHM)
  - 10 cps per pixel capability 80% throughput
  - 240 TESs (6x40 each side)

Point source array (PSA):

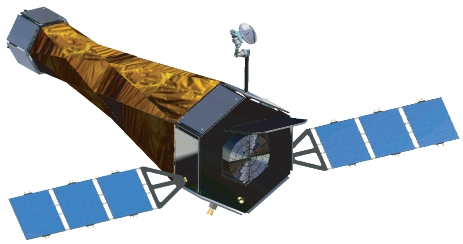
- 16 x 16 pixels, 1.5” each, 75 μm
- 24 arcsec FOV
- 2 eV resolution (FWHM)
- 80% event throughput at 300 cps/pixel
- 256 TESs

Total = 1120 TESs

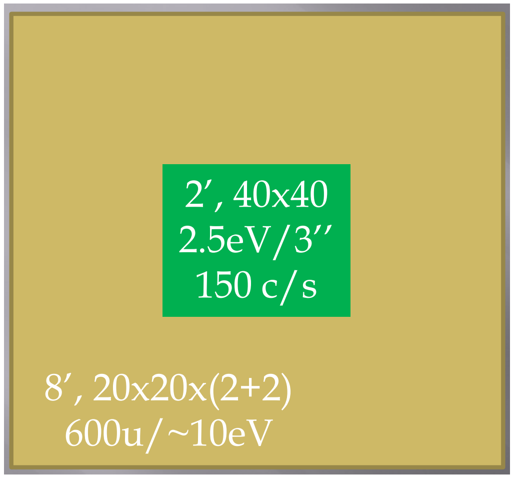
XMS Array Concept

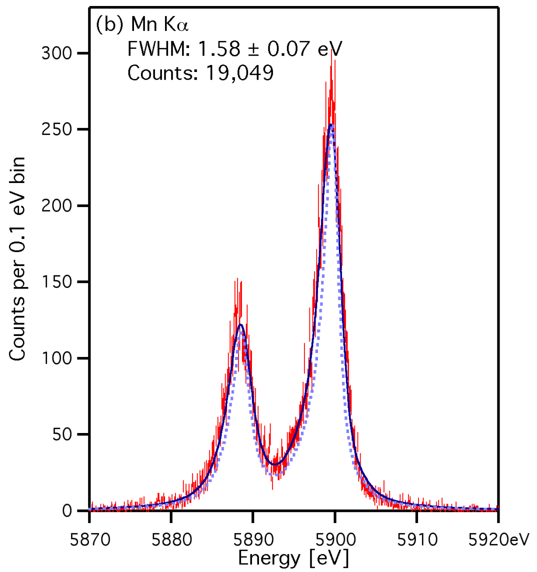


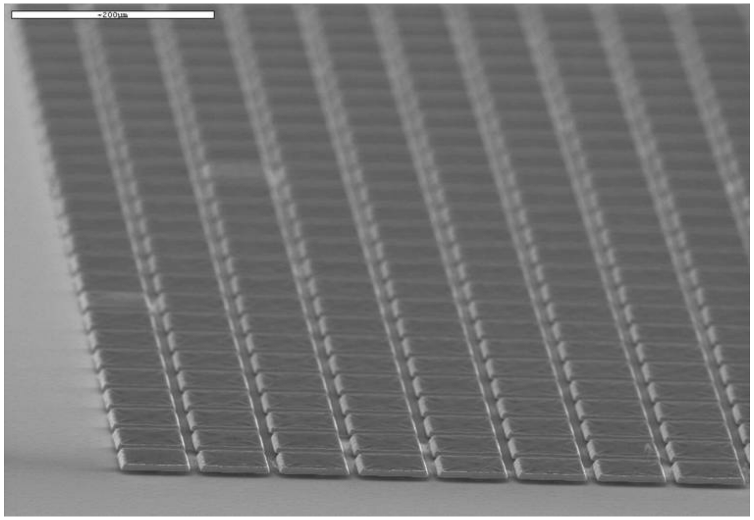
The Extreme Physics Explorer - Mike Garcia et al.



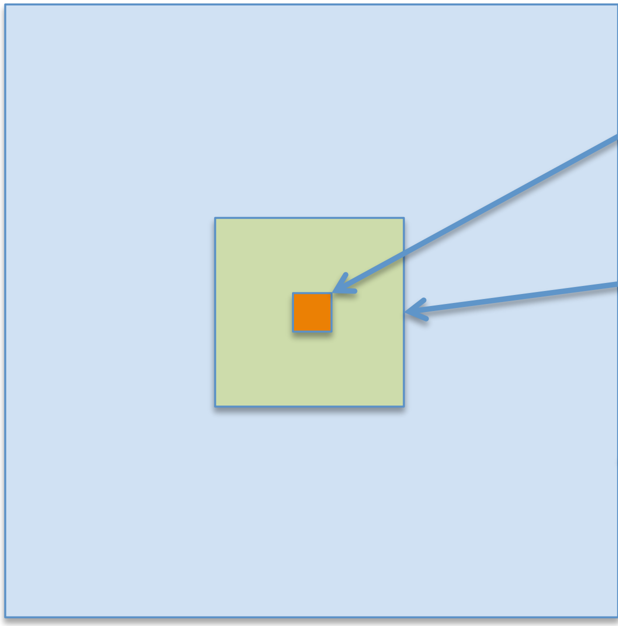
- 10 m focal length (40 m)
- Inner array:
  - 40x40 array of high count-rate pixels (150 cps)
  - Angular resolution ~1′, 2′ FOV
  - 3″ pixels - over-sampling point spread function
  - 150 um pitch, 145 um x 145 um x 4.5 um pixels
  - (or 600 um x 600 um pixels)
  - ΔE< 2.5 eV [FWHM]
- Outer array:
  - 20x20 TESs, each 2x2 Hydra
  - 8′ FOV, 12″ pixels
  - 600 um pitch between absorbers
  - ΔE< 10 eV [FWHM]
  - Old IXO outer array hydra design







"Sahara" - Spectral Analysis with High Angular Resolution Astronomy - *(Mushotzky et al.)*



1.5 eV FWHM requirement, 0.5 eV goal
2.5" single pixels (50 μm)
12x12 array – 30"x30"

~ 1 eV up to 3 keV
~ 4 eV at 6 keV
- data

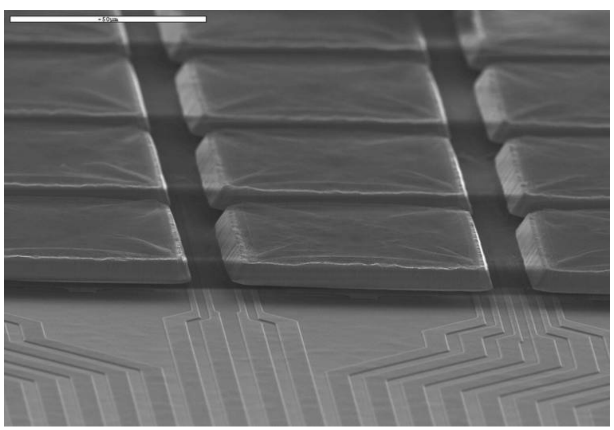
3.0 eV FWHM requirement, 1.5 eV goal
2.5" pixels (50 μm) in 3x3 hydras
20x20 hydra, 60x60 pixels, 2.5'x2.5'

~ 2 eV for all energies up to 7 keV
- estimate

4.0 eV FWHM requirement, 2.0 eV goal
5" pixels (100 μm) in 3x3 hydras
32x32 hydra, 96x96 array – 8'x8'

~ 3 eV for all energies up to 7 keV
- data

Shorter focal length
+ high angular resolution => Small pixels

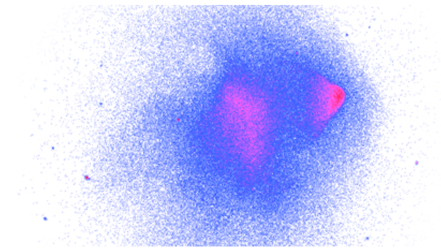


4 m focal length, small pixels
Local length: 4m
Angular resolution: 5"
FOV: 8' x8'

Different design types in different regions on a single wafer substrate

12k pixels, with only 1344 TESs read-out !

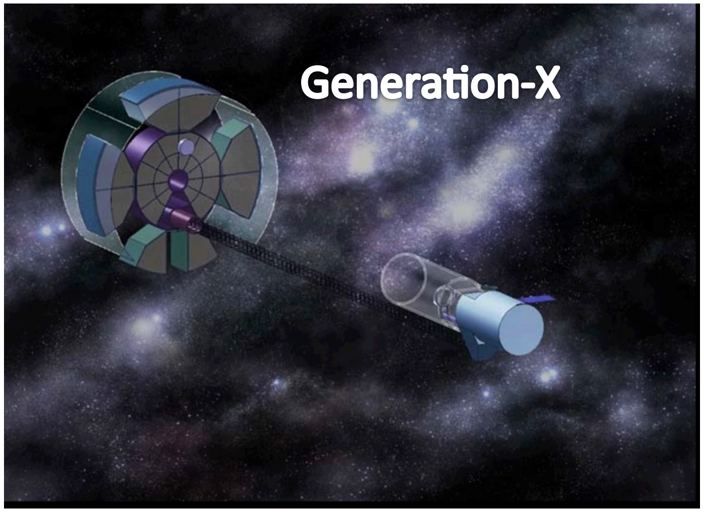
SMART-X
"Square Meter, Arcsecond Resolution X-ray Telescope"



- 2.3 m^2 effective area, 10 m FL, 0.5'' angular resolution X-ray telescope
- 5' FOV, 1'' pixel size microcalorimeter

Microcalorimeter:

- 5' x 5'
- 50 μm (1") pixels - *90k pixels !*
- < 5 eV energy resolution
- 4x4 or 5x5 Hydras
- Max. 20 cps/TES count-rate capability
- Multiplex 64-128 TESs (CDM multiplexing assumed)
- Same number of read-out channels as AXSIO !



Observatory with 100 m^2 Effective Area and 0.1” angular resolution

For the 60 m focal length,
0.1” pixels => 30 μm pixels

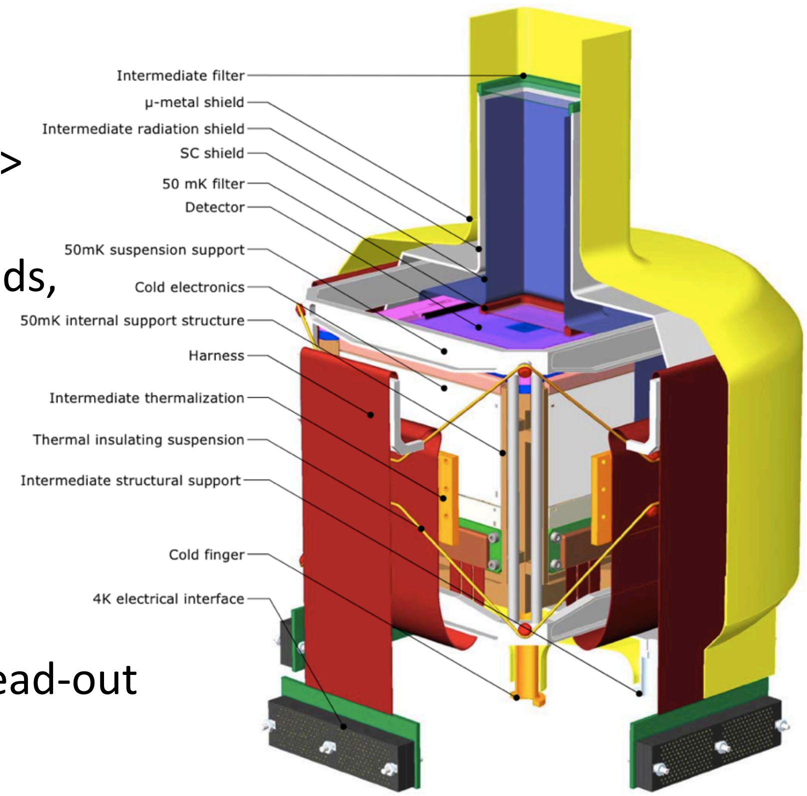
3’x3’ => 1800x1800 array of 0.1” pixels
=> **3.24 x 10^6 pixels**

- 324,000 position sensitive calorimeters
- 3x3, 2x5, 4x4 Hydras (10 absorbers per TES previously assumed)
- Microwave multiplexing of SQUIDs
- 8 HEMT amplifiers
- Just ~ 24 coax cables
- 1265 RF SQUIDs multiplexed on each HEMT amplifier
- Code division multiplexing – 32 TESs per SQUID readout

Distant future ……????

What limits number of pixels?

1. Number of amplifier channels (MUXed read-out) -> electronics cost & power
2. Size / mass of FPA - ability to withstand launch loads, magnetic shielding
3. Easy attachment of pixels within plausible size (wire-bonding) -> bump-bonding etc.
4. Number of stripline wires between pixels
   - in planar geometries (goes as n/4 for nxn array)
5. Complexity of wire routing through connections
6. Thermal management of power from pixels and read-out
7. Use of Hydras etc.
8. Count rate requirement

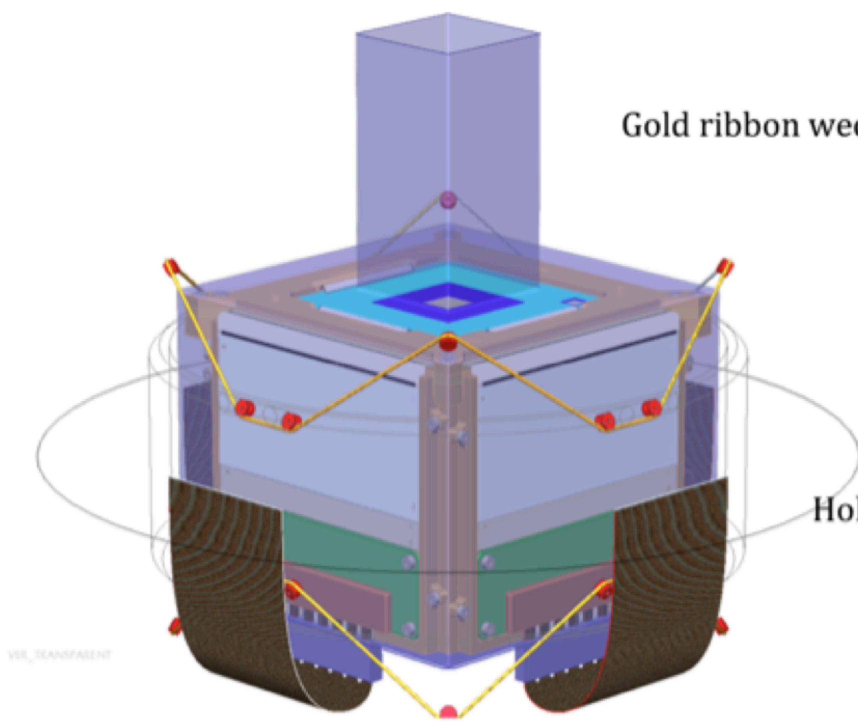


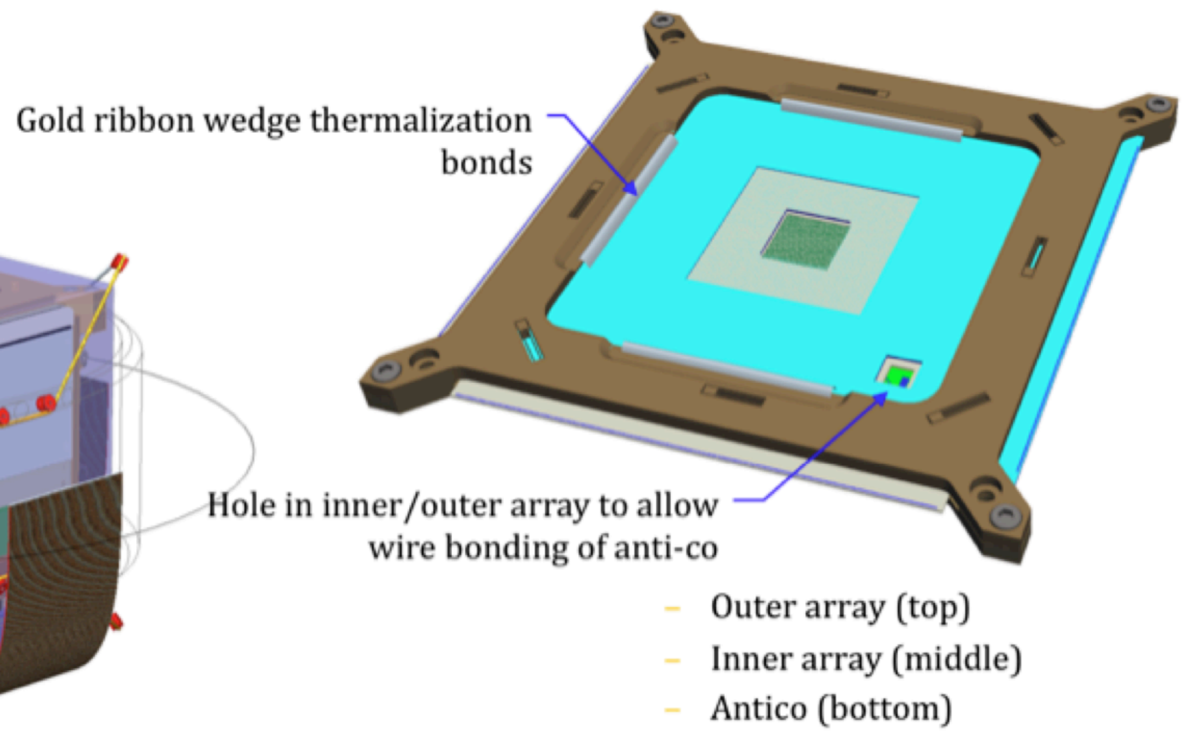
50 mK focal plane assembly

Somewhere between 1k - 100k pixels with technology under development, depending on details of what is required.

TRL6 : Integrated detector system

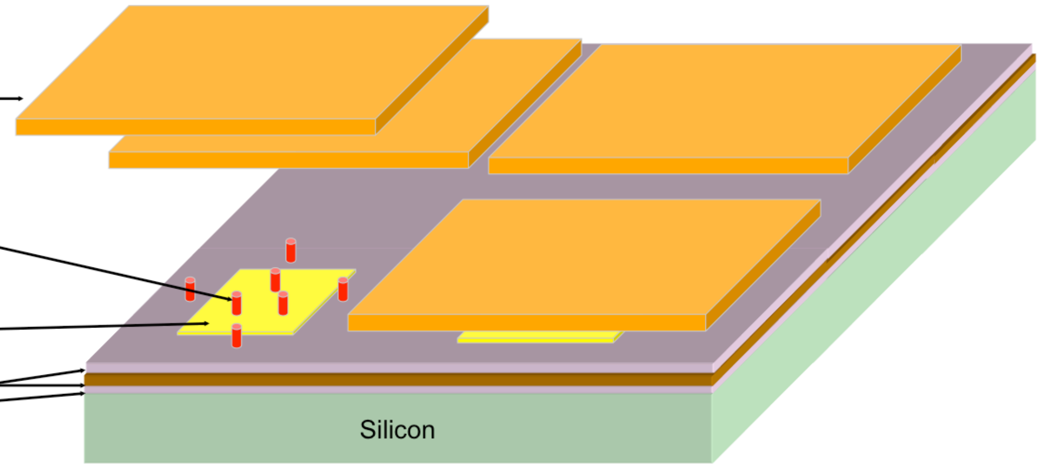
- Multiplexed (6x32) read-out of portion of full composite focal plane array
  - 128 different single-TES pixels in a 40x40 core array
  - 64 multi-absorber TES (256 0.6-mm pixels) of a full-sized outer array
  - Particle-veto integrated into the test set-up
- Electrical and thermal interconnects and staging approach flight-worthy design

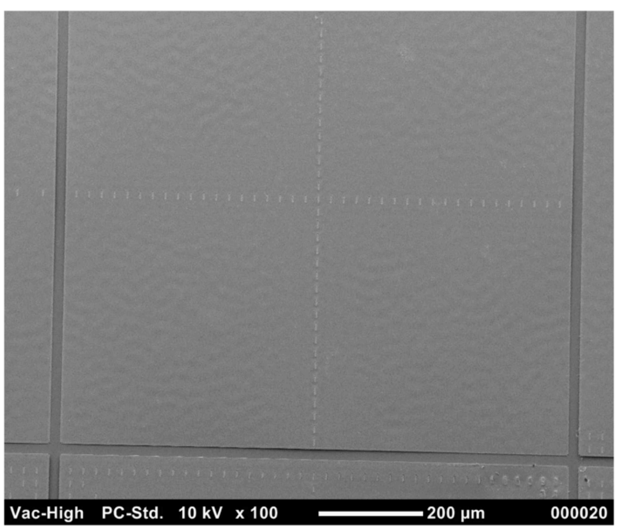


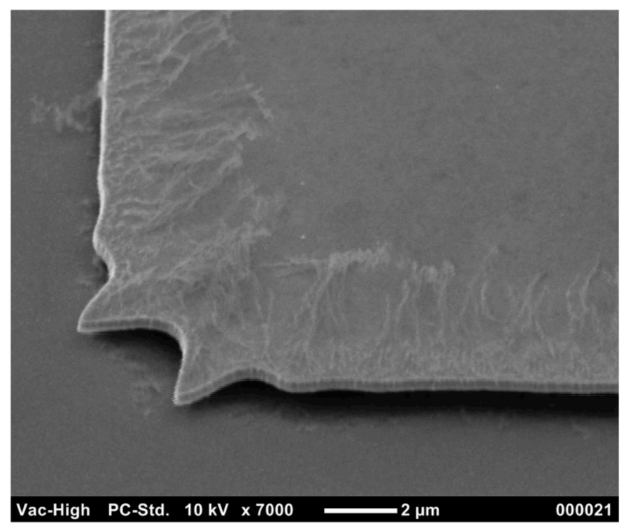


Working towards 1 mm x 1 mm pixels with ~ 1 eV energy resolution up to 1 keV

- XQC
- DIOS
- ORIGIN / Xenia







Getting to TRL-6 vs. new capabilities

Where to put the emphasis - size/ count rate ?

- 250-300 um pixels ?
  - bismuth
  - membranes
- Smaller pixels / Hydras - where calorimeters "work" better ?
- Larger pixels 1mmx1mm and above, ~ 1eV res. – WHIM ?
- Read-out ?
- FPA TRL ?
- Moving towards < 1eV ?
- Highest count-rates ?

What array size should we me aiming for ?

Astro-H 36 pixels => 1k …..or 4k ……… or 10k …….. or 100 k ?

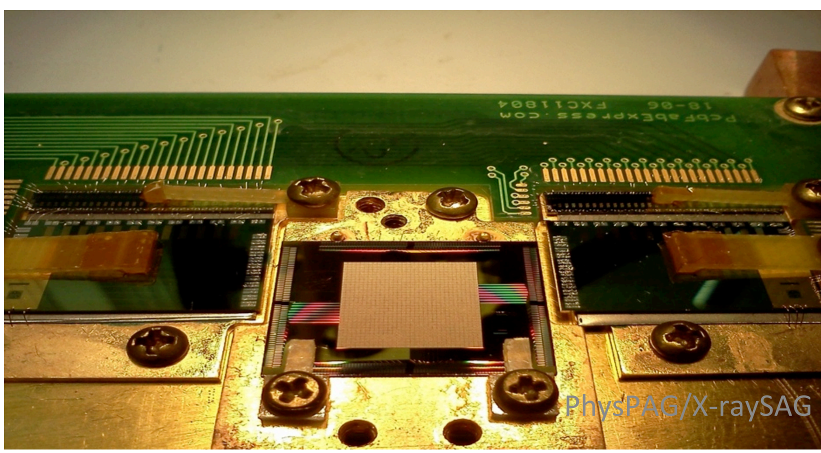
We welcome your feedback on emphasis !

Conclusions

- Developing/optimizing a variety of pixel designs for future microcalorimeter array types
  - Ground-breaking performance; steady, consistent progress
  - New detector ideas regularly developed
  - Increasing TRL of existing technologies
  - Moving towards larger arrays

- Thank you X-ray community
  - Microcalorimeter scientists fortunate to have had consistent funding for a large number of years
  - Has maintained well-defined goals to justify development programs

- 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



Let's build a mission !