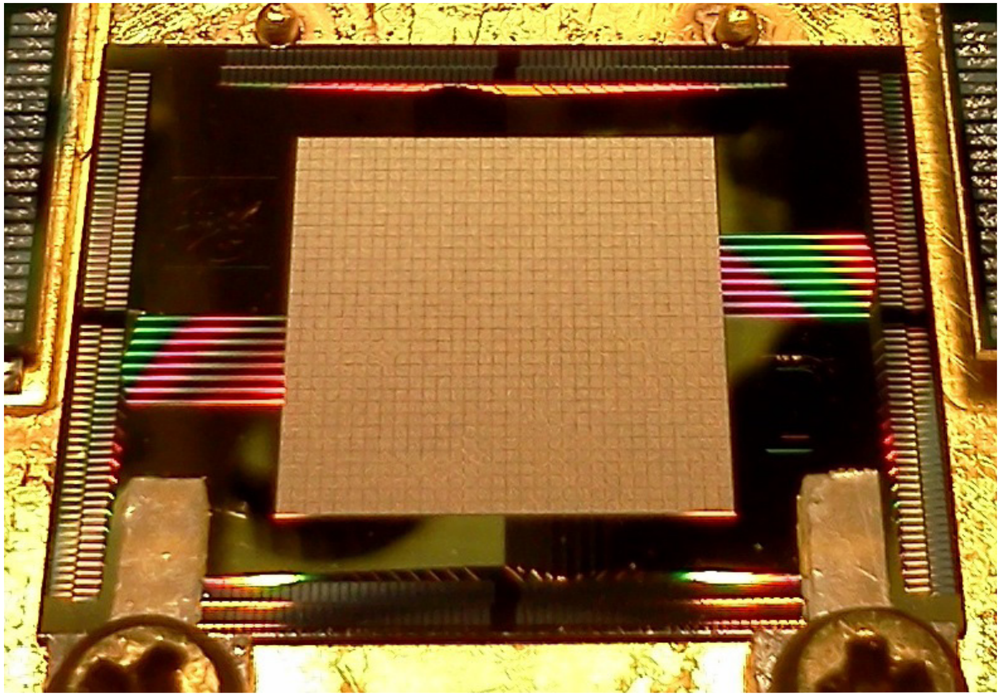
Development of Microcalorimeter Imaging Spectrometers for the X-ray Surveyor Mission

Simon Bandler – X-ray microcalorimeter group at NASA/GSFC



- X-ray detector options
- Transition-edge sensor basic operation
- “Standard” and “small” pixels
  - how small can we go?
- Multi-absorber devices & Hybrids
- Multiplexing
- Filter options

Suggested X-ray Surveyor microcalorimeter requirements from earlier study

- Pixel size: 1”
- Field-of-View: At least 5’ x 5’
- Energy resolution [FWHM]: < 5 eV
- Count rate capability: < 1 count per second per pixel
- For a focal length of optic of 10 m, 1” corresponds to 50 μm pixels

5’ field-of-view with 1” pixels requires a nominal 300 x 300 array => 90,000 pixels

Two categories of low temperature detectors

<u>Equilibrium:</u>

ΔT prop to $\Delta E/C$ - sensor is in thermal equilibrium
Resolution from: accuracy of measuring T in background of T fluctuations
Low-temperature => minimizing thermodynamic fluctuations & low C

For high energy resolution, T < ~ 0.1 K is required.

<u>Non-equilibrium:</u>

Energy => quantized excitations (E >> kT)
Energy prop. to # of excitations

Low T required to avoid thermally generated excitations

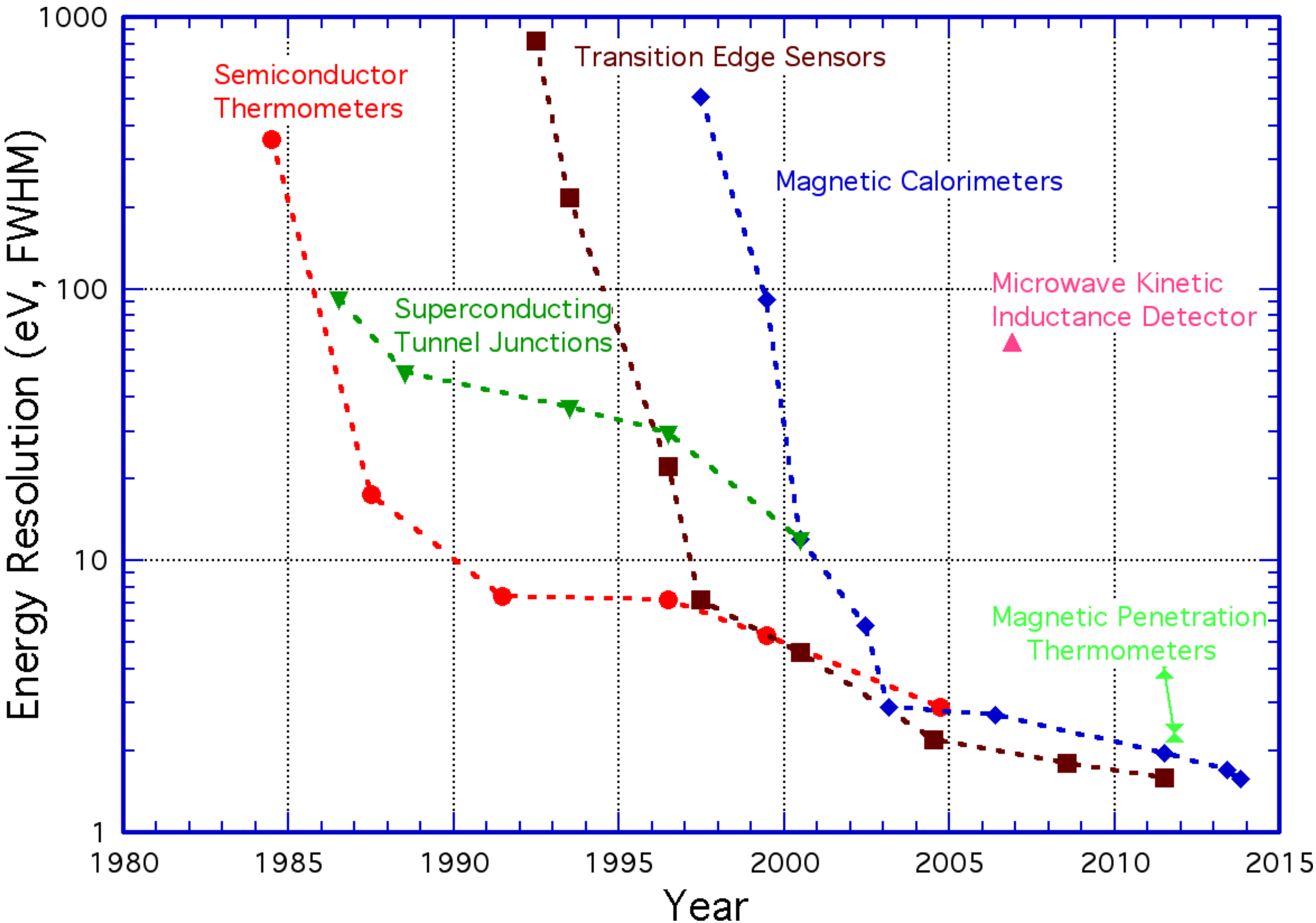
Most successful low-temperature detector technologies:

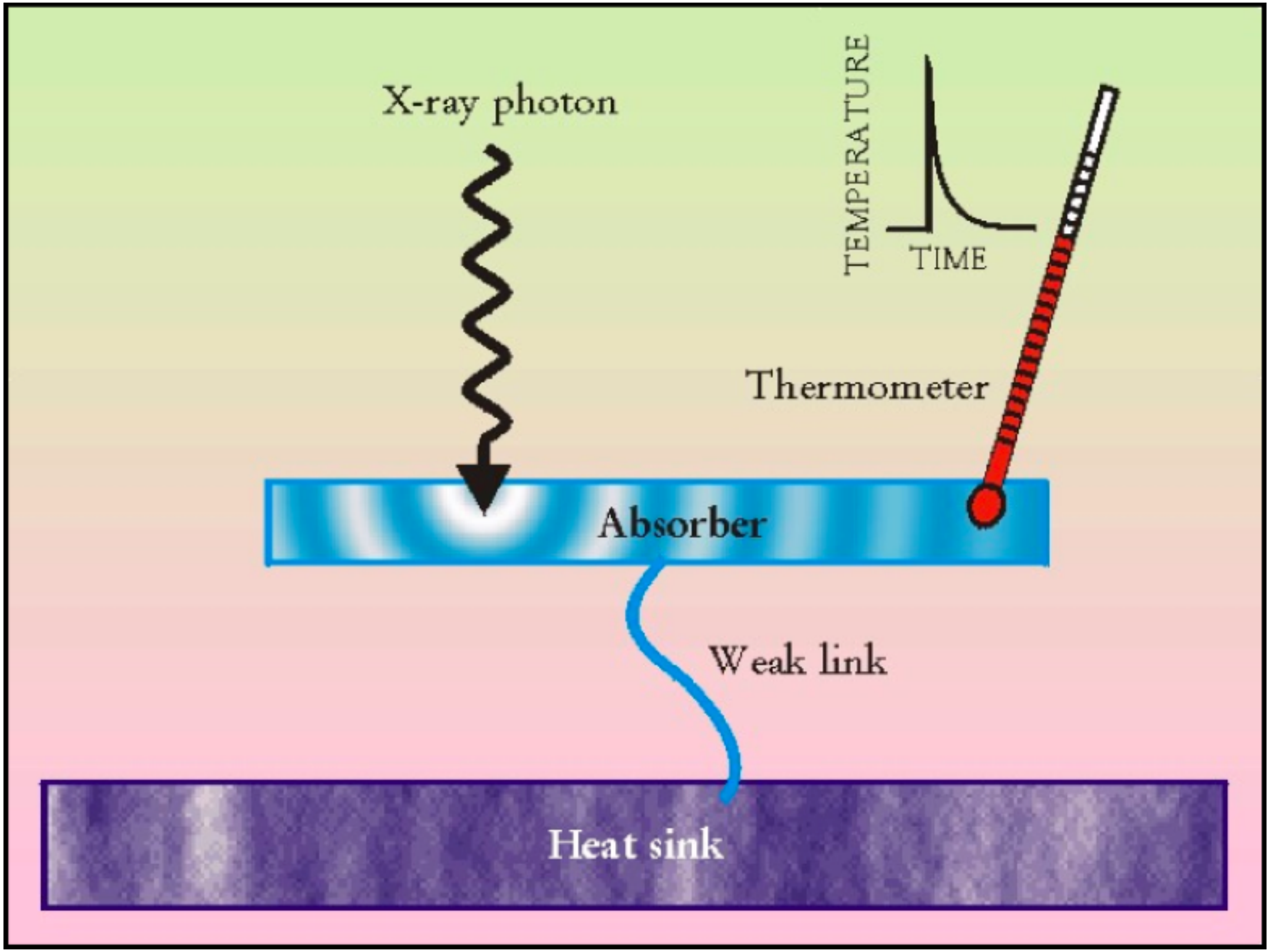
Semiconducting thermistors
Transition Edge Sensors – TES
Metallic Magnetic Calorimeters – MMC
Magnetic Penetration-Depth Thermometers – MPT
} Equilibrium detectors

Superconducting Tunnel Junctions – STJ
Microwave Kinetic Inductance Detectors – MKIDs
} Non-Equilibrium detectors

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

X-ray microcalorimeters capable of 1 eV energy resolution with 6 keV X-rays





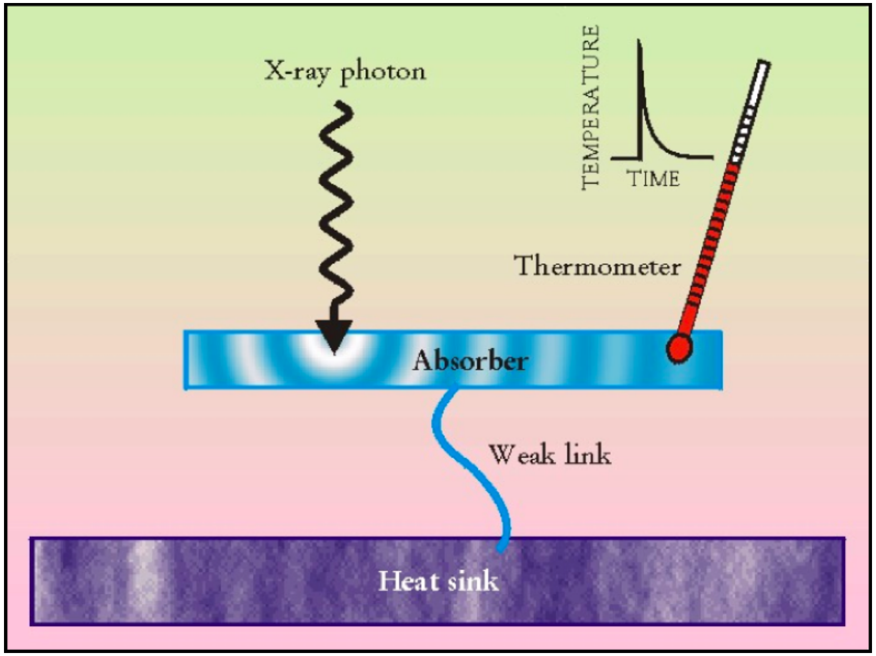
$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

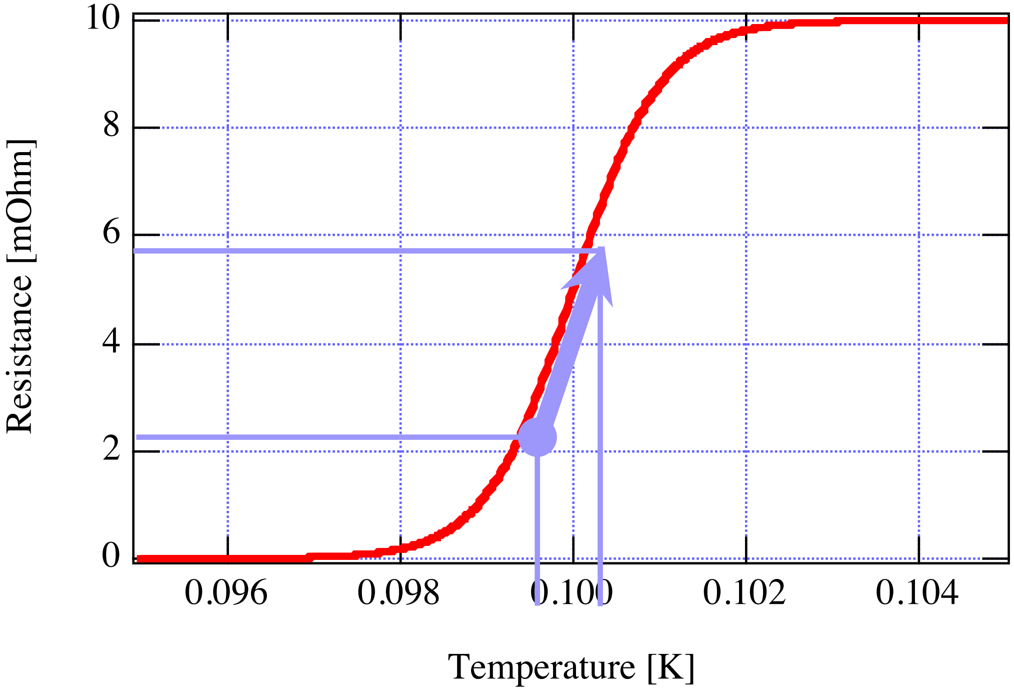
Thermal relaxation time:

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

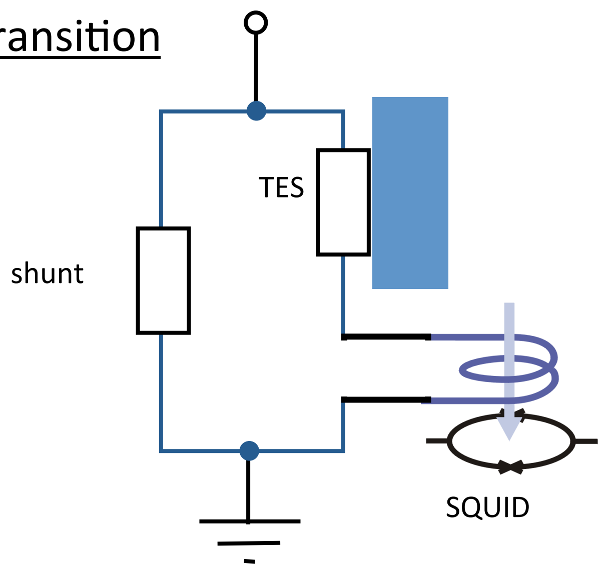
Thermal conductance

Transition-edge Sensor microcalorimeter basics:





Superconductor voltage-biased in its transition



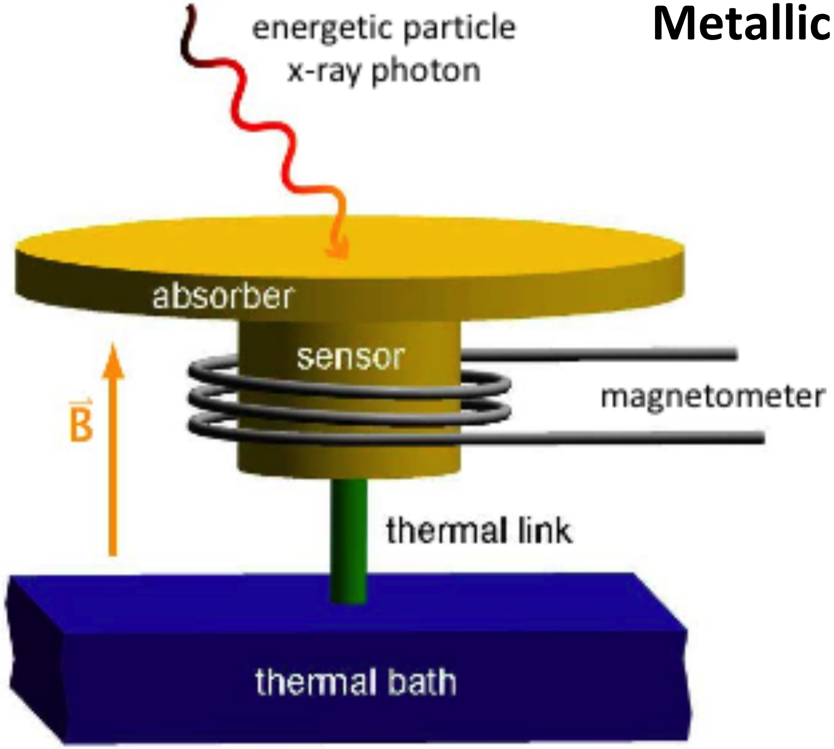
Basic optimization for a linear response:

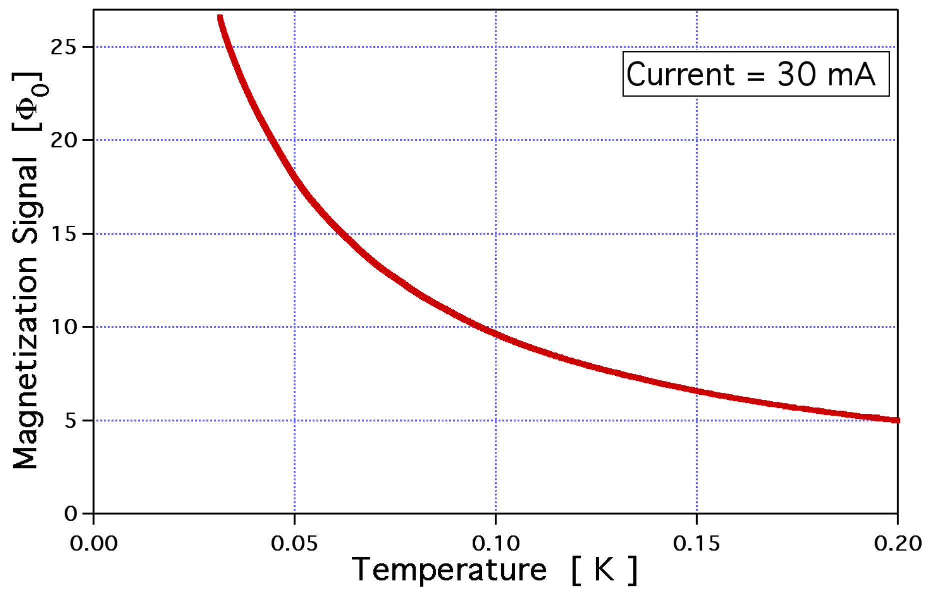
Choose absorber with low C and fast thermalization

C, α such that maximum energy events approach saturation

=> large quasi-linear range of operation

Metallic Magnetic Calorimeters (MMC)





Paramagnetic sensor: Au:Er
(Ag:Er, ...)

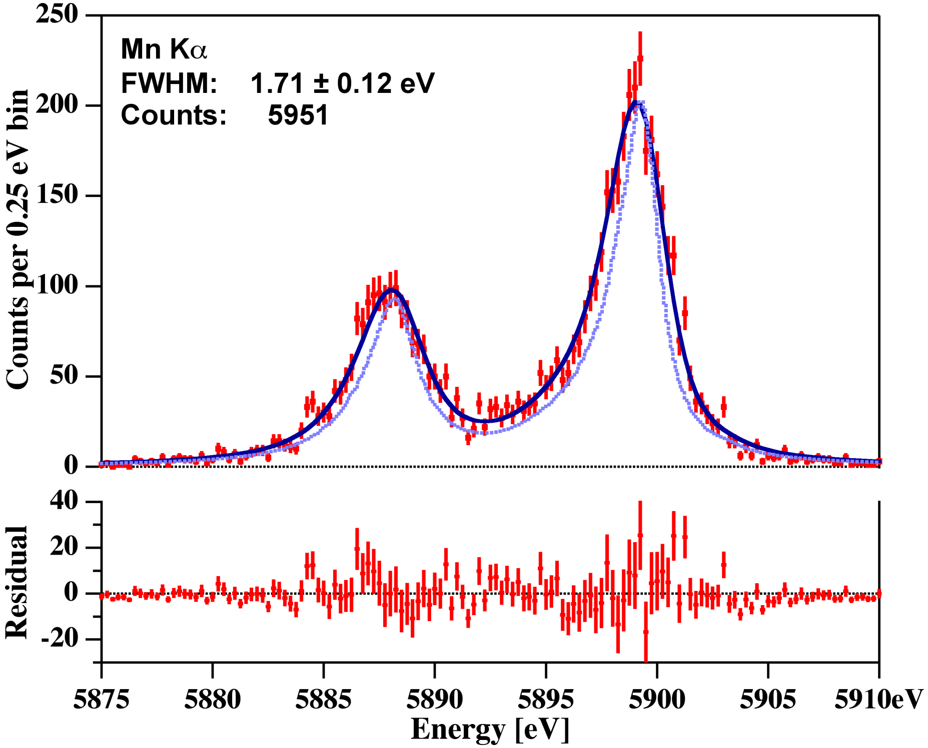
$$M \propto \frac{1}{T}$$

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

- No heat dissipated in the sensor
- No electrical Johnson noise
- Performance properties based upon equilibrium thermodynamics

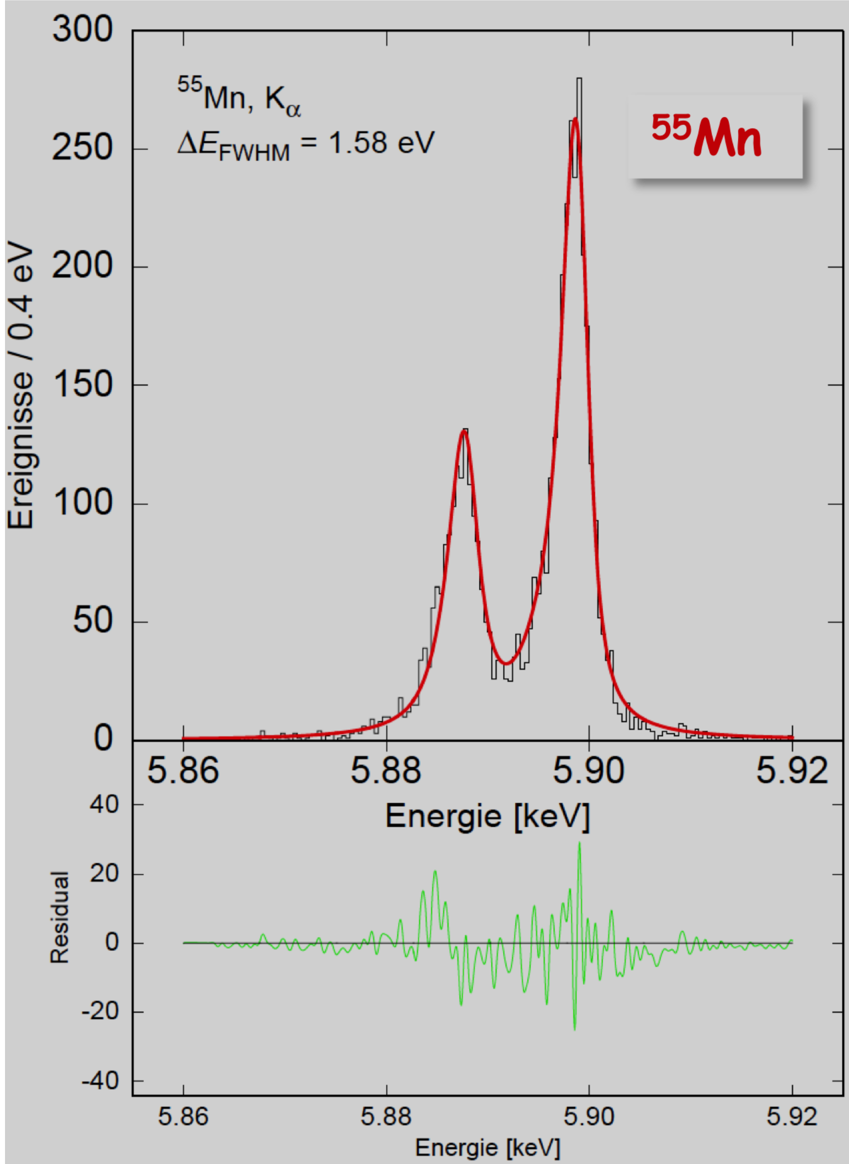
Best MMC results:

NASA/GSFC – meander geometry



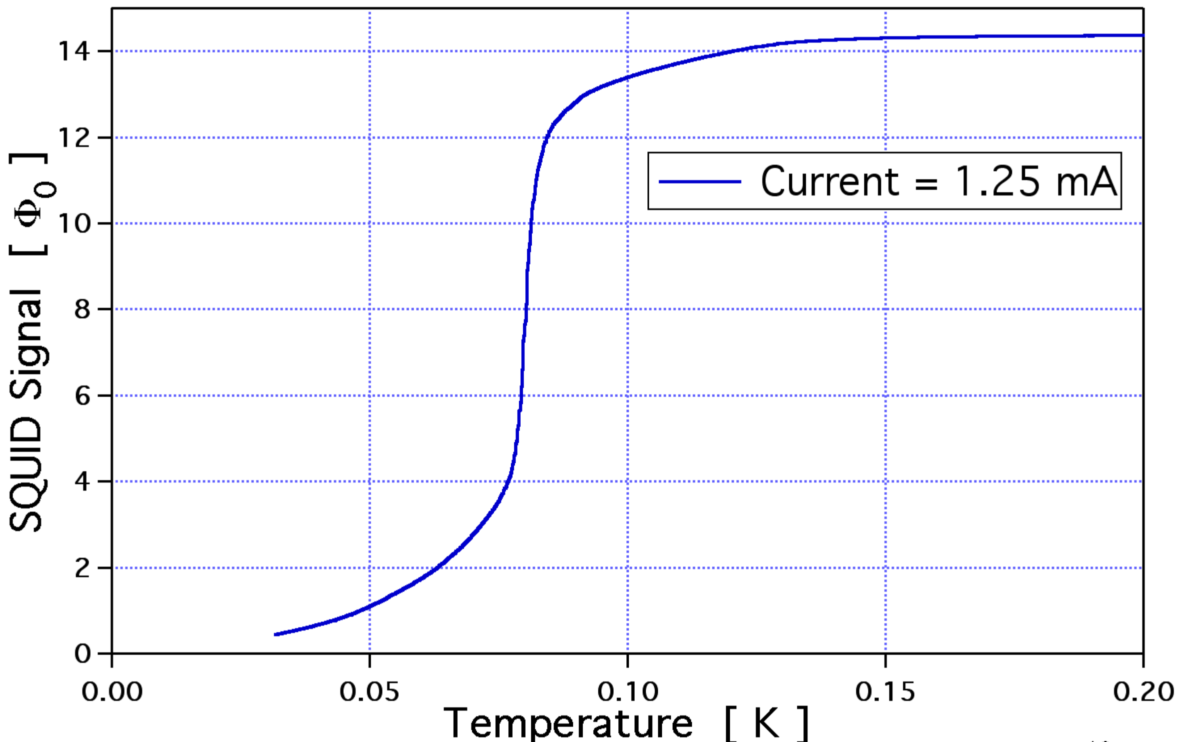
- $T \approx 32$ mK
- $I_f = 35$ mA
- Absorbers 250 x 250 x 3 μm – all gold
- Very linear detector

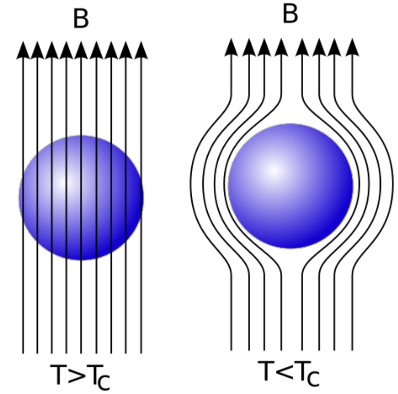
Heidelberg, Germany – sandwich geometry



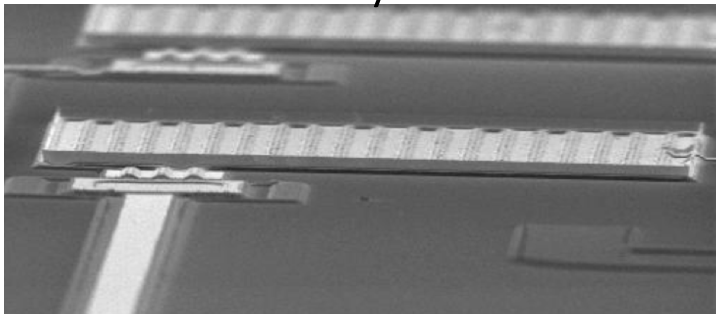
- $T \approx 20$ mK
- Absorbers 250 x 250 x 5 μm – all gold

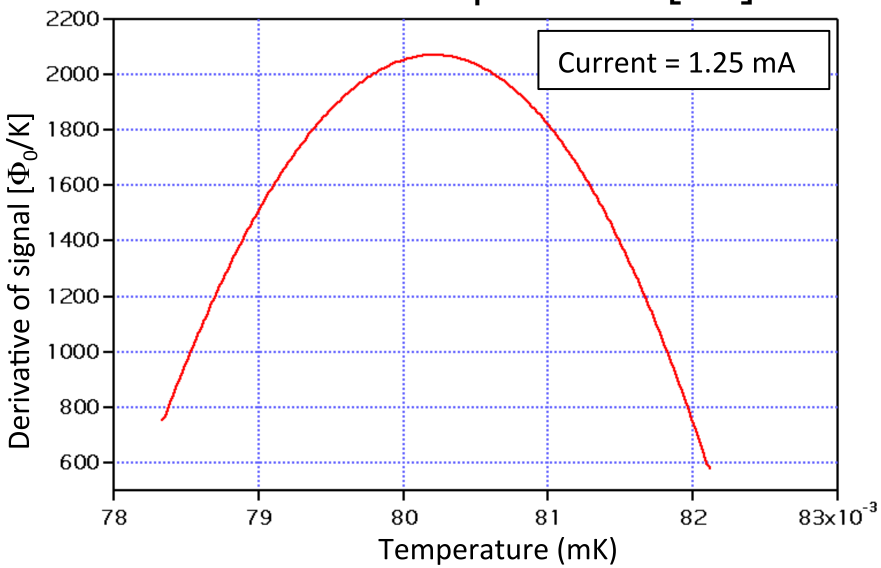
Magnetic Penetration Thermometer (MPT)



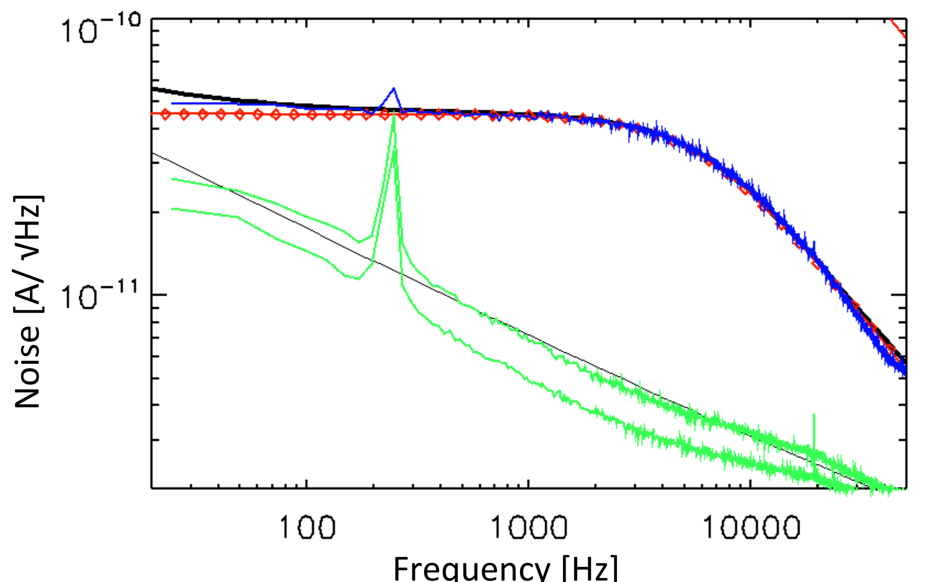


Sensor: MoAu bilayer





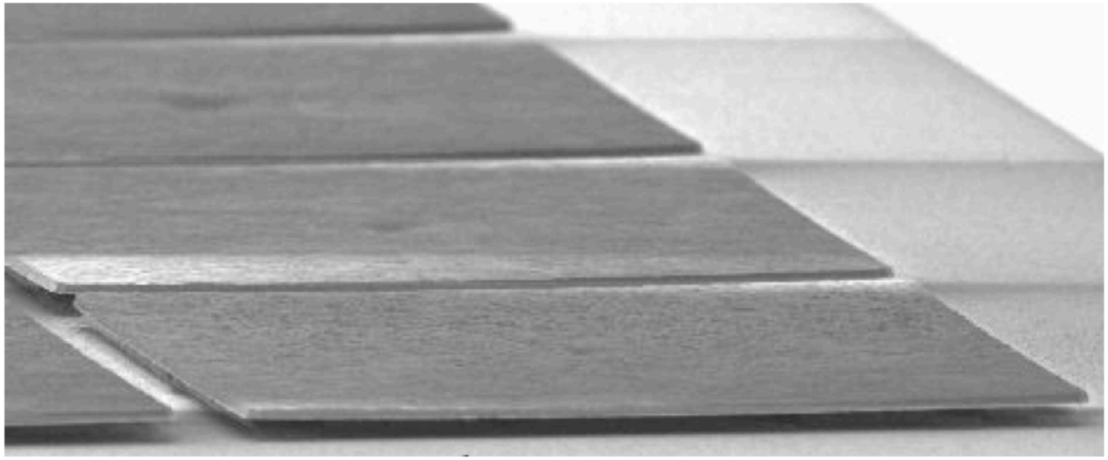
Noise in transition:

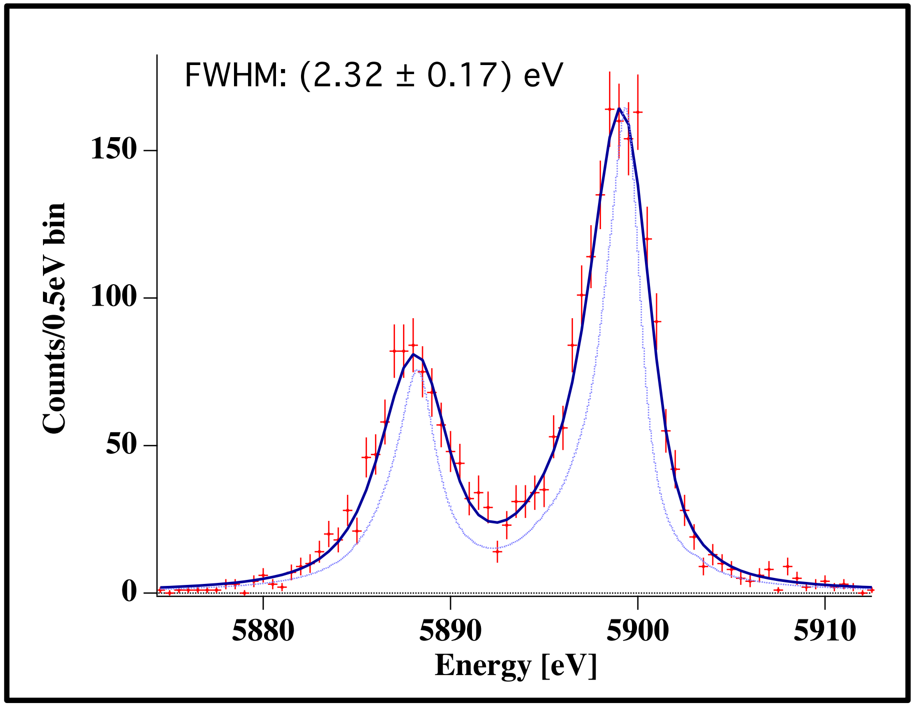


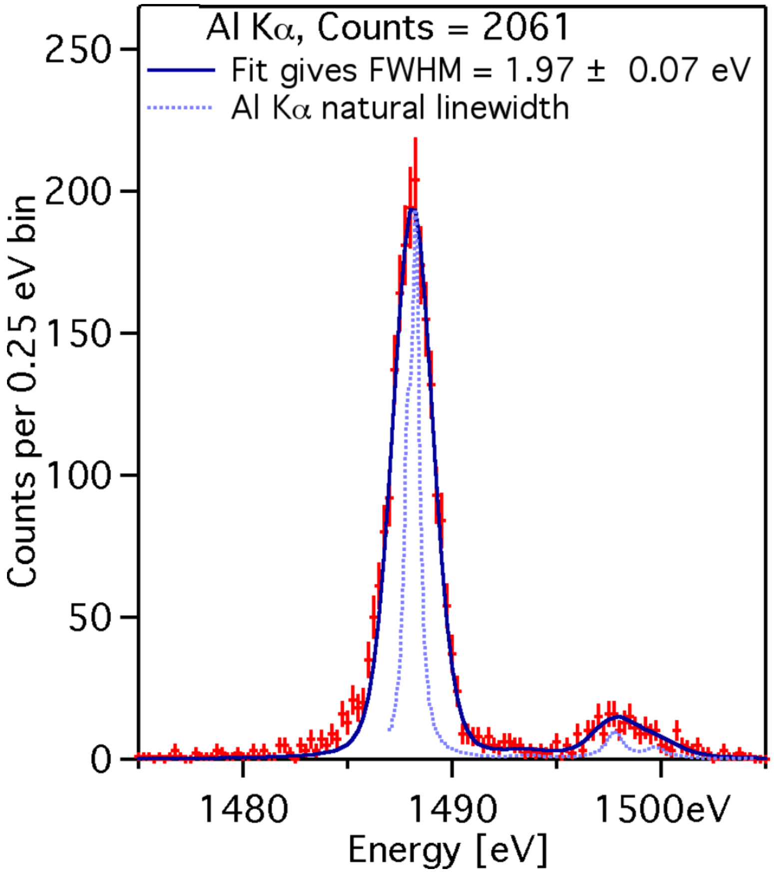
MPT:

C_{abs} = 0.34 pJ/K @ 38 mK

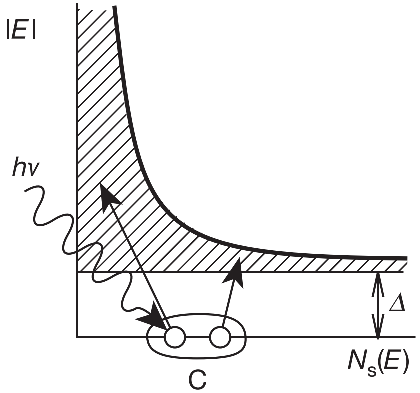
ΔE_{FWHM} = 2.3 eV @ 5.9 keV
= 2.0 eV @ 1.5 keV

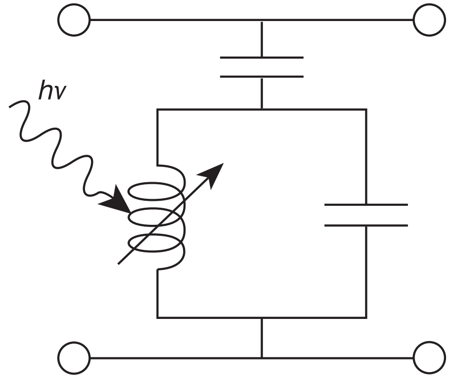


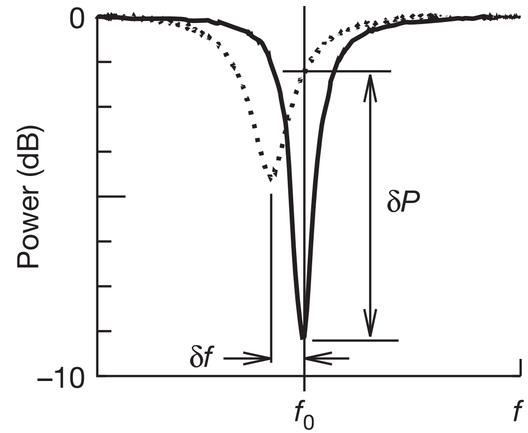




Microwave kinetic inductance devices MKIDs





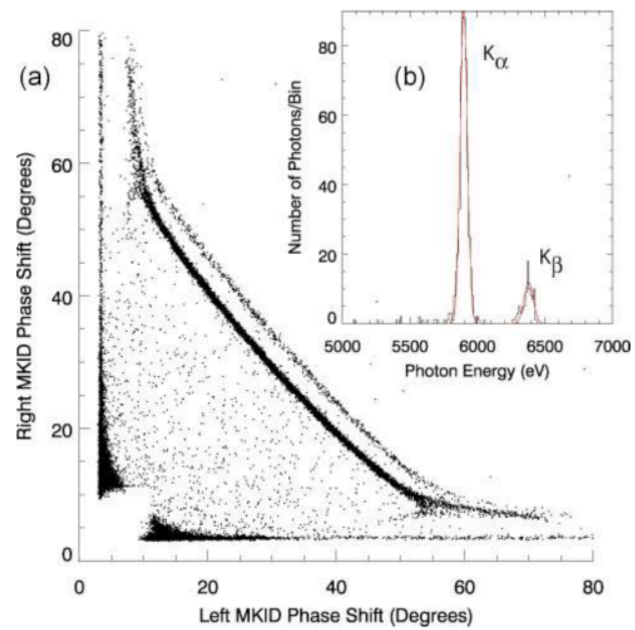


The good:

- Potentially the easiest technology to multiplex with microwave read-out

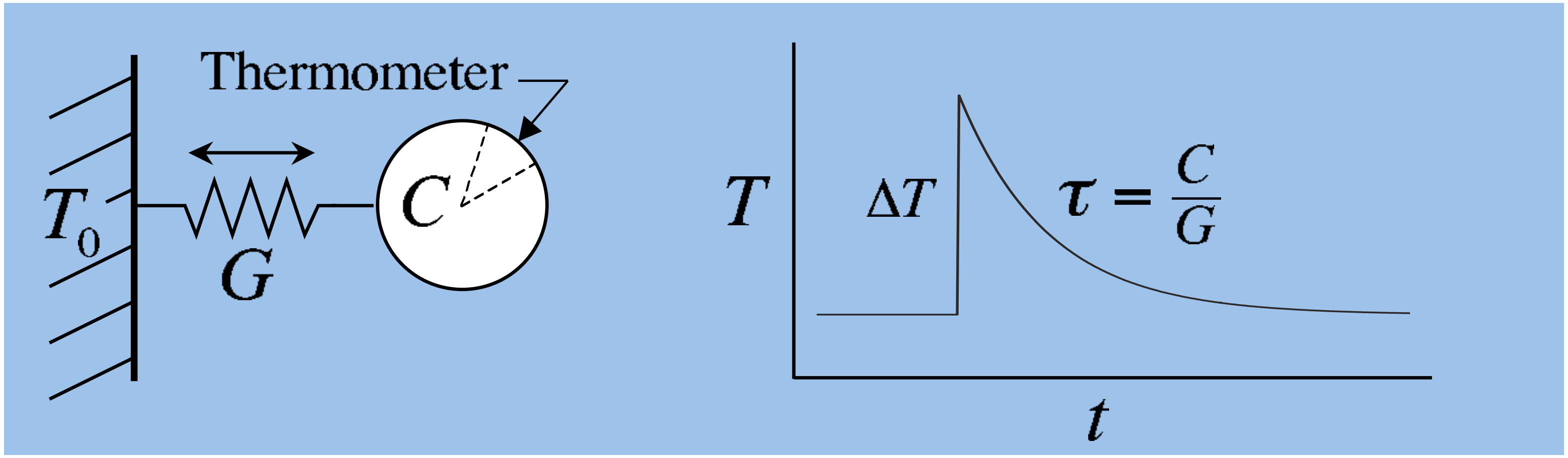
However:

- High energy resolution is very difficult, especially at 6 keV
- Superconducting absorbers are difficult
- Now investigating normal metal absorbers (TKIDs)



Best results achieved using position-sensitive MKIDs ~ 60 eV at 6 keV, (no absorber).

Intrinsic resolution for equilibrium detectors ?

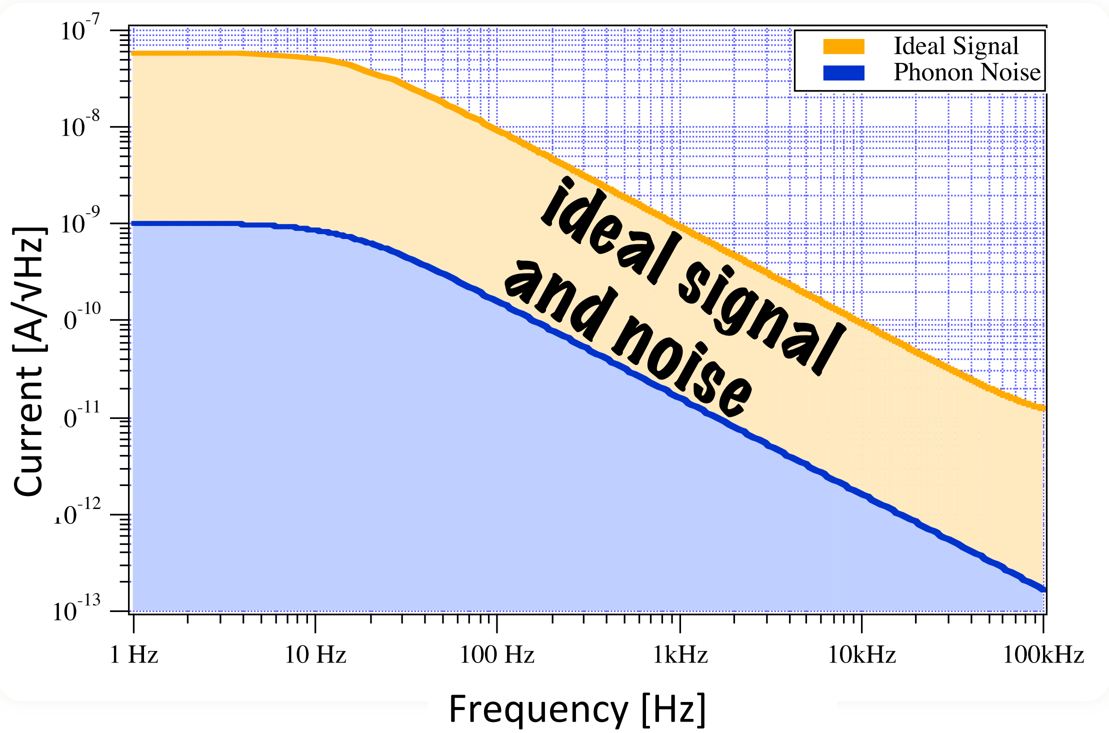


Random transport of energy =>
fluctuations in energy content of C.
Easy to calculate:

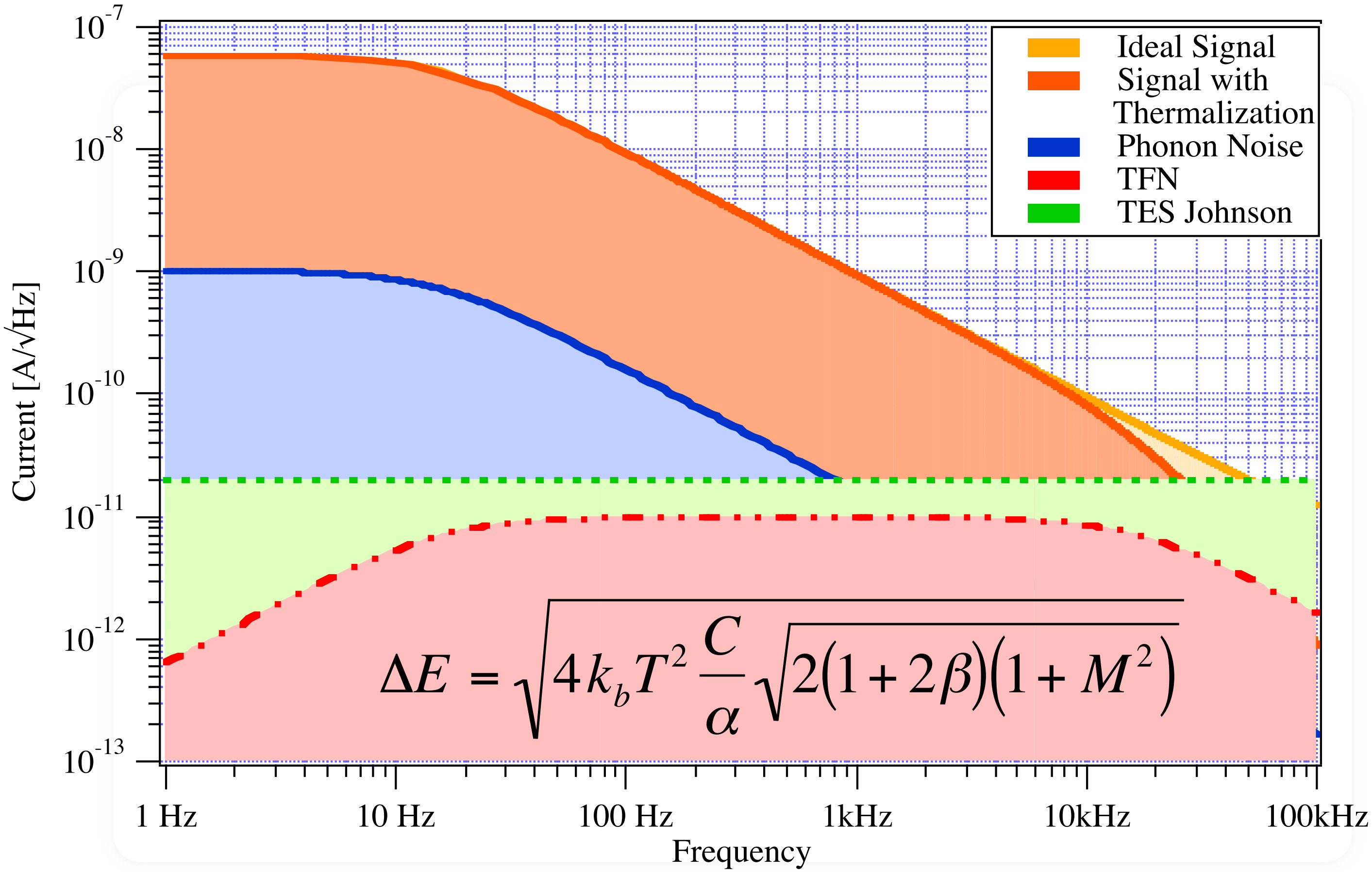
$$\Delta E_{rms} \sim \sqrt{kT^2C}$$

But energy fluctuation is not energy resolution

In absence of bandwidth limit => arb. good energy resolution achievable.



Resolution depends on bandwidth



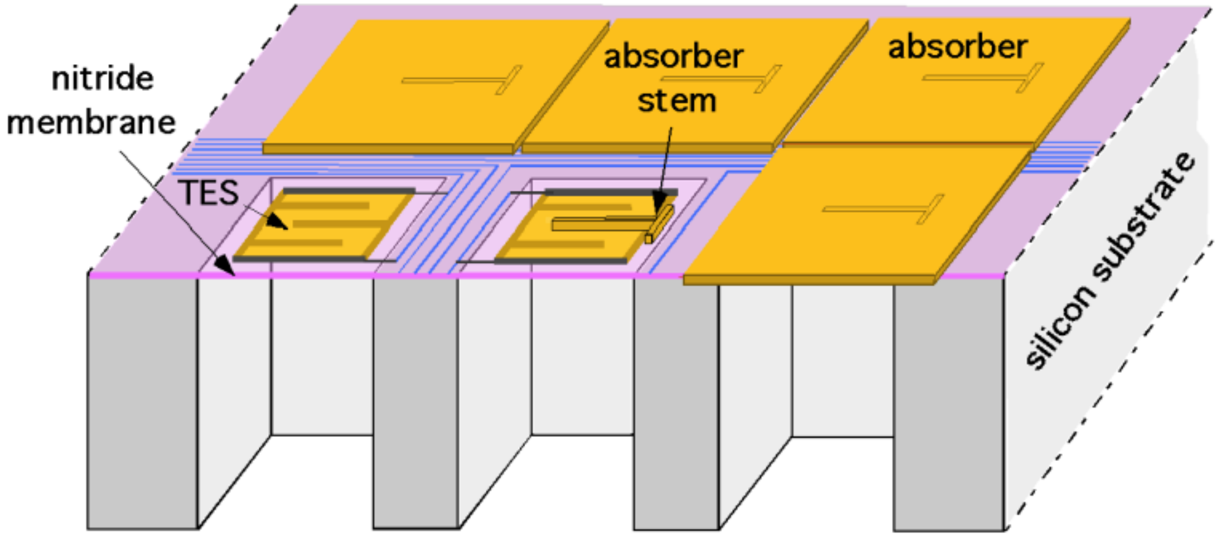
$$\Delta E = \sqrt{4 k_b T^2 \frac{C}{\alpha} \sqrt{2(1+2\beta)(1+M^2)}}$$

ΔE prop. $\sqrt{C}$ prop. L

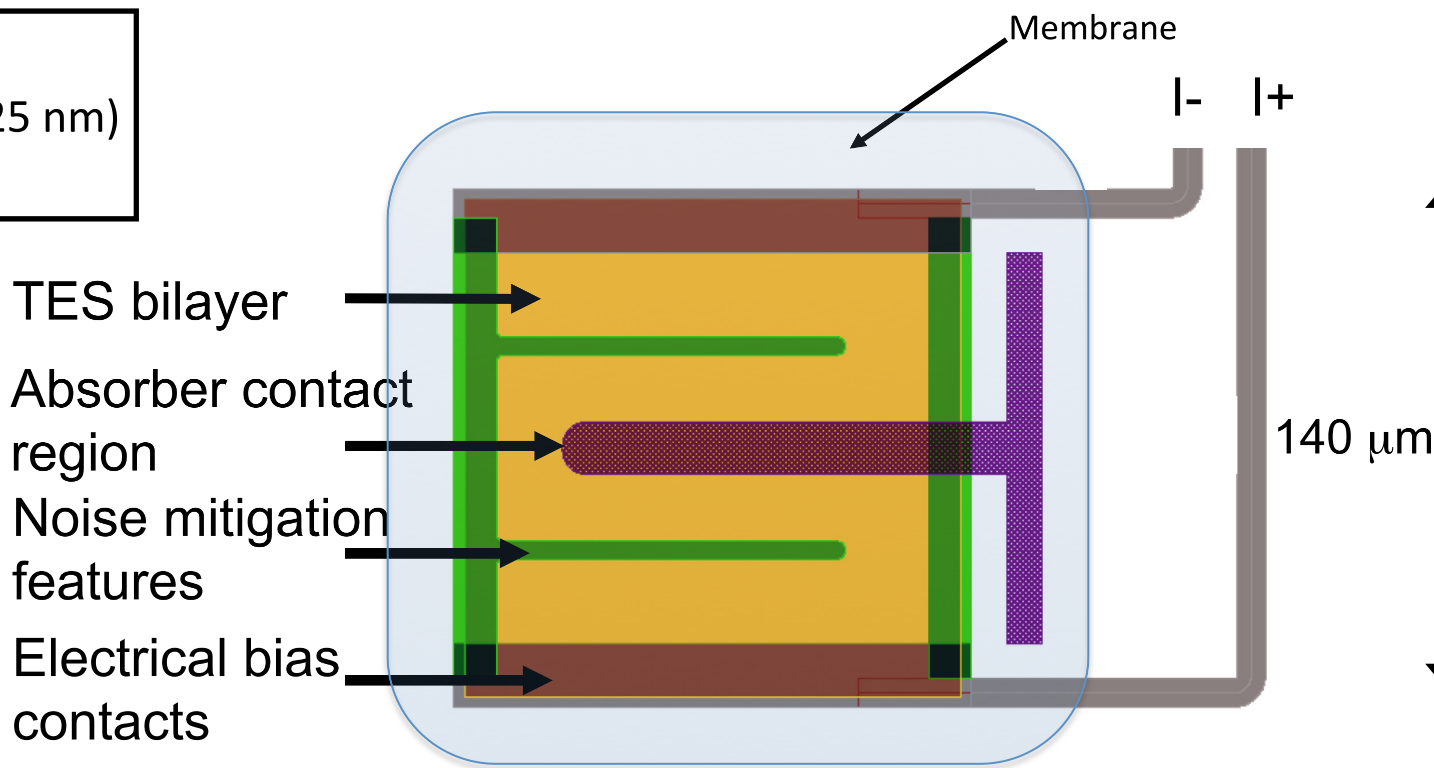
Optimal filtering:

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

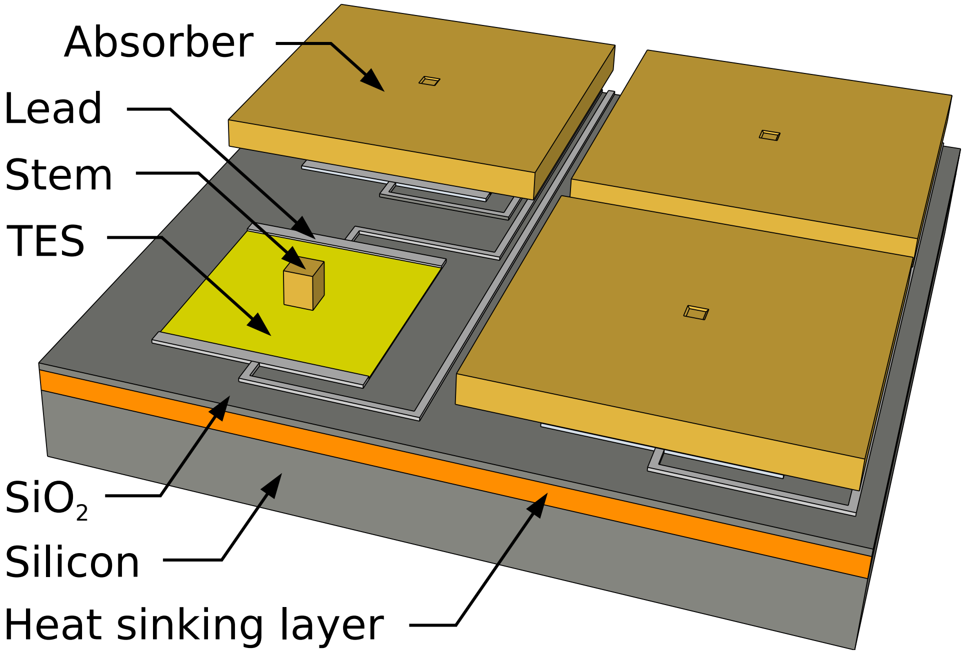
Microcalorimeter array for astrophysics

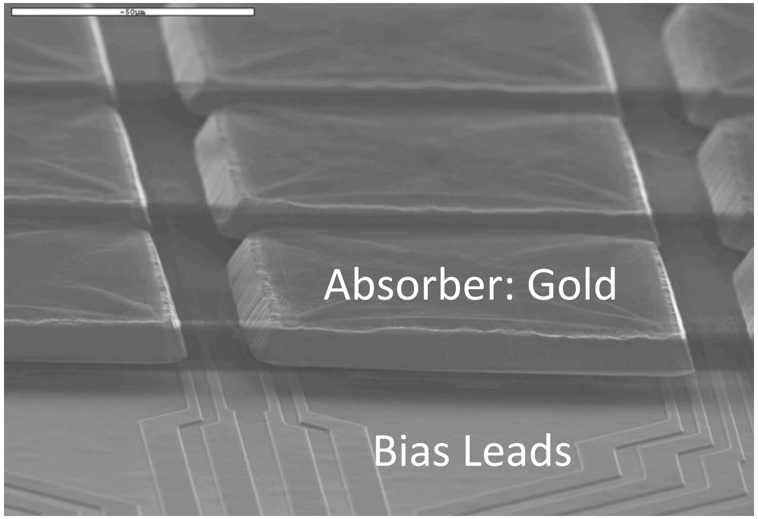


Mo/Au bilayer TES
Mo (45 nm) / Au (225 nm)
T_c ~ 0.1 K

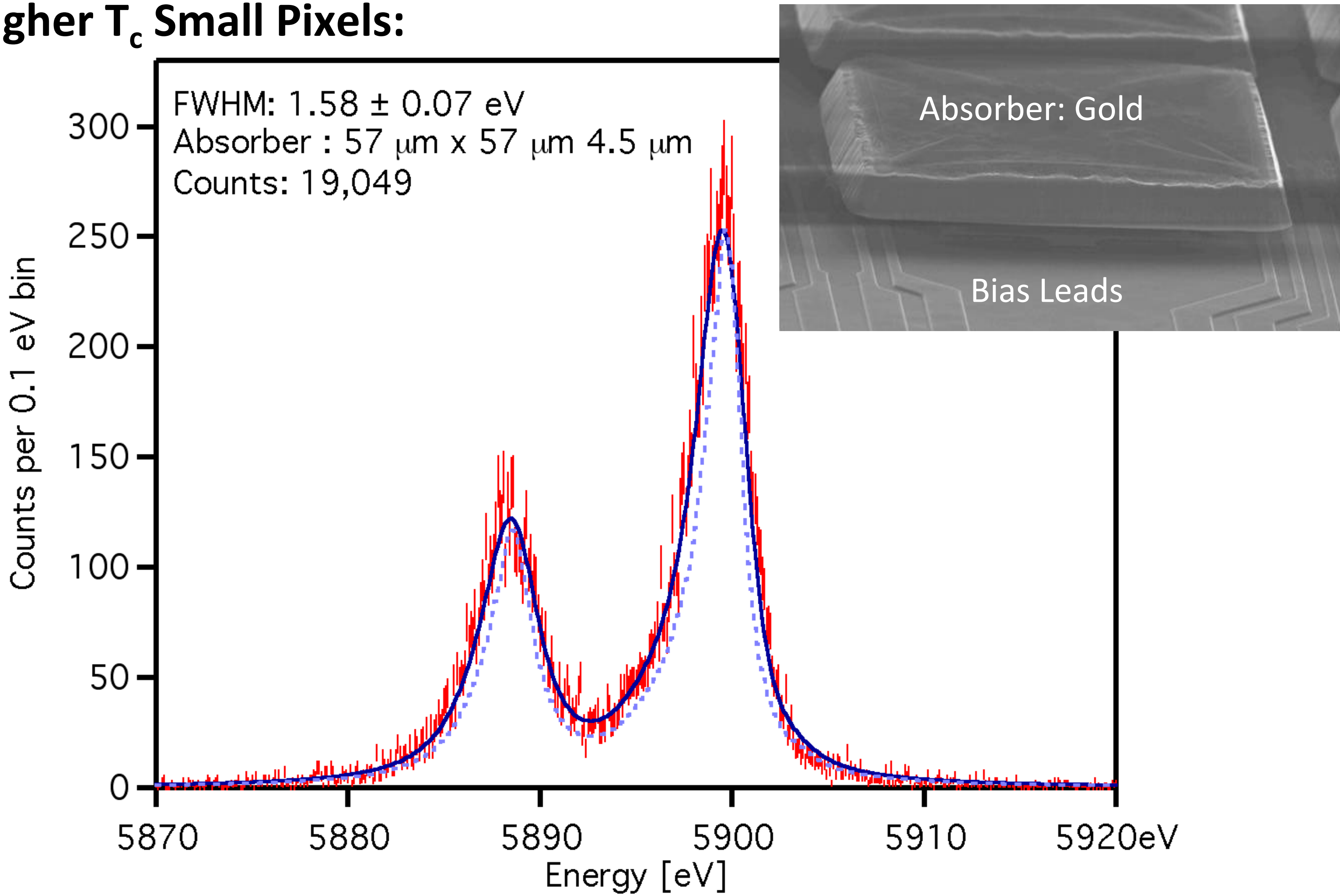


Small-pixel TES microcalorimeter design : on solid substrate





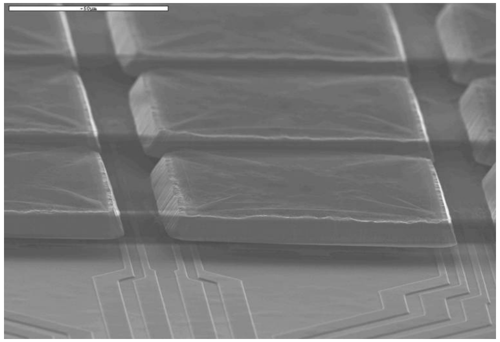
Higher T_c Small Pixels:

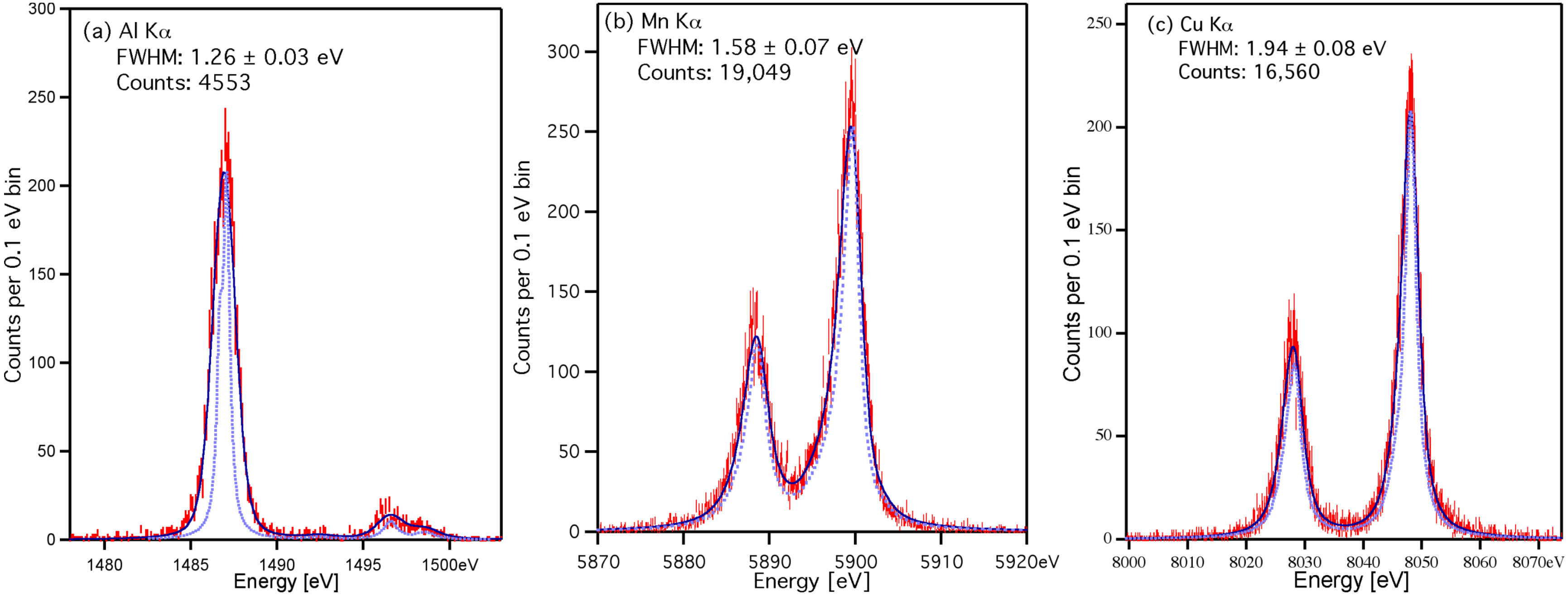


- Best energy resolution detecting 6 keV x-rays (energy dispersive detector)
- High count rate capability
- More demanding read-out requirements

High dynamic range

Gold absorber: 57 μm x 57 μm x 4.5 μm, $T_c \approx$ 90 mK under bias



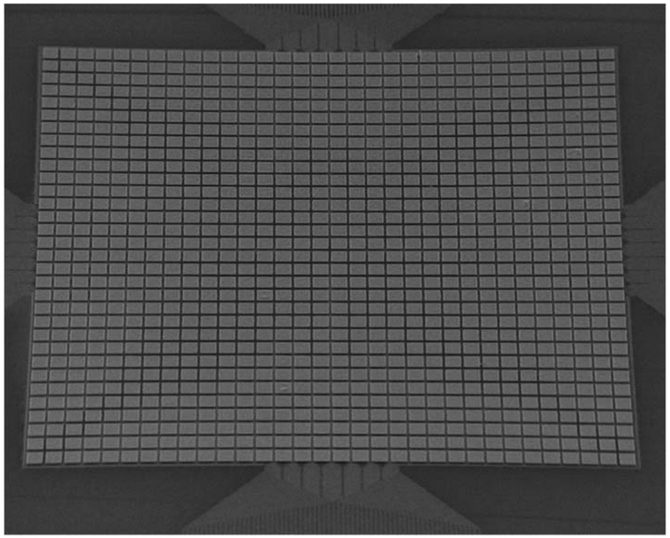


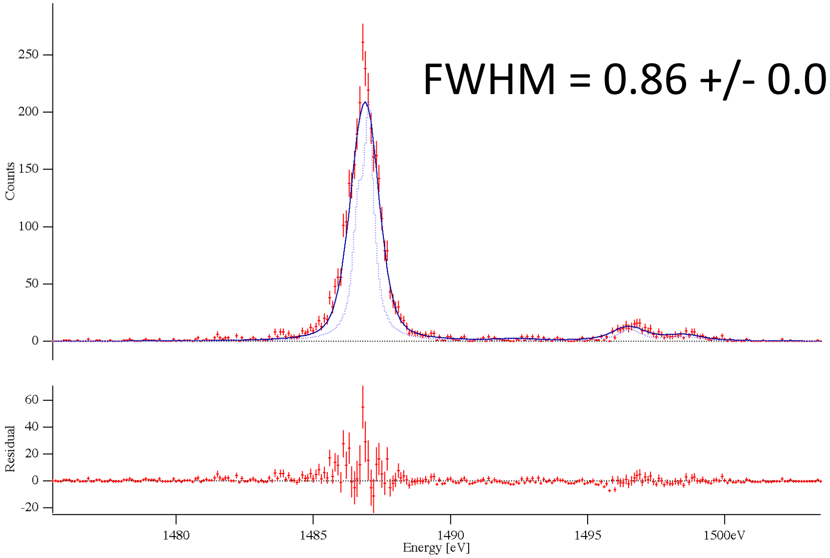
S.J. Smith et al., JLTP 167, 3-4, 168, (2012). (LTD-14)

- Performance of this device is relatively linear.
- All measurements used straight-forward optimal filtering.
- Pulse decay times ~ 200 μs
- *Higher count rate capability*

Intermediate dynamic range

Gold absorber: 65 μm x 65 μm x 5 μm, $T_c \approx$ 80 mK under bias





Pulse decay times ~ 350 μs

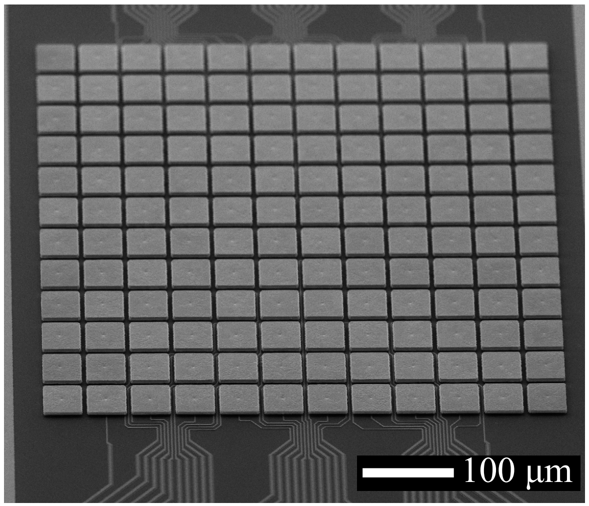
Energy resolution = 0.9 eV [FWHM] at 1.5 keV

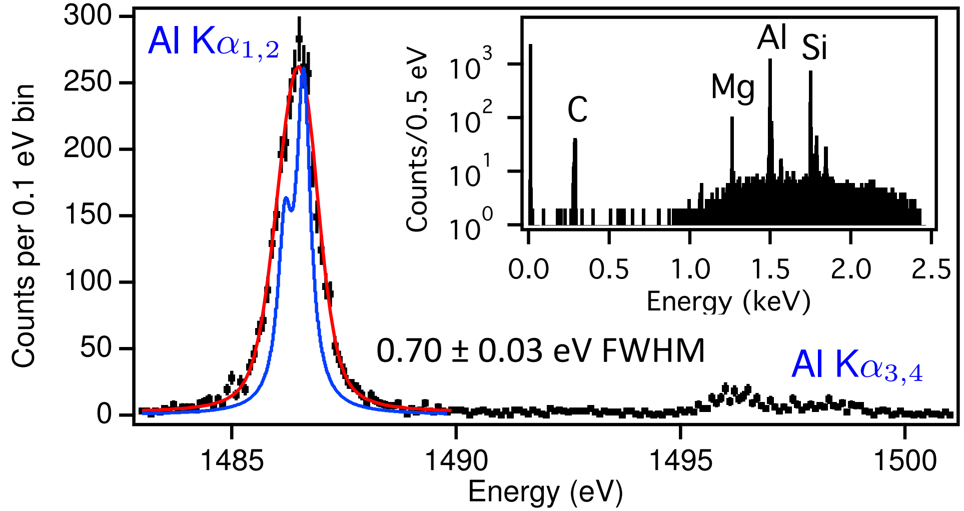
= 3.2 eV [FWHM] at 5.9 keV using traditional optimal filtering

= 1.6 eV [FWHM] at 5.9 keV using PCA

Low Dynamic Range

Gold absorber: 45 μm x 45 μm x 4.2 μm, $T_c \approx 60$ mK under bias





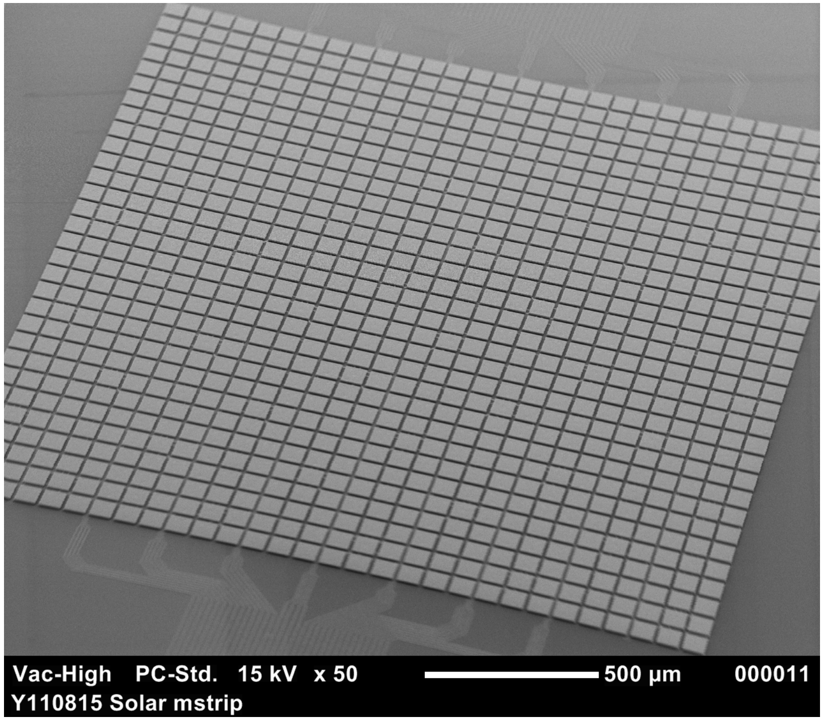
Energy resolution = 0.70 eV [FWHM] at 1.5 keV

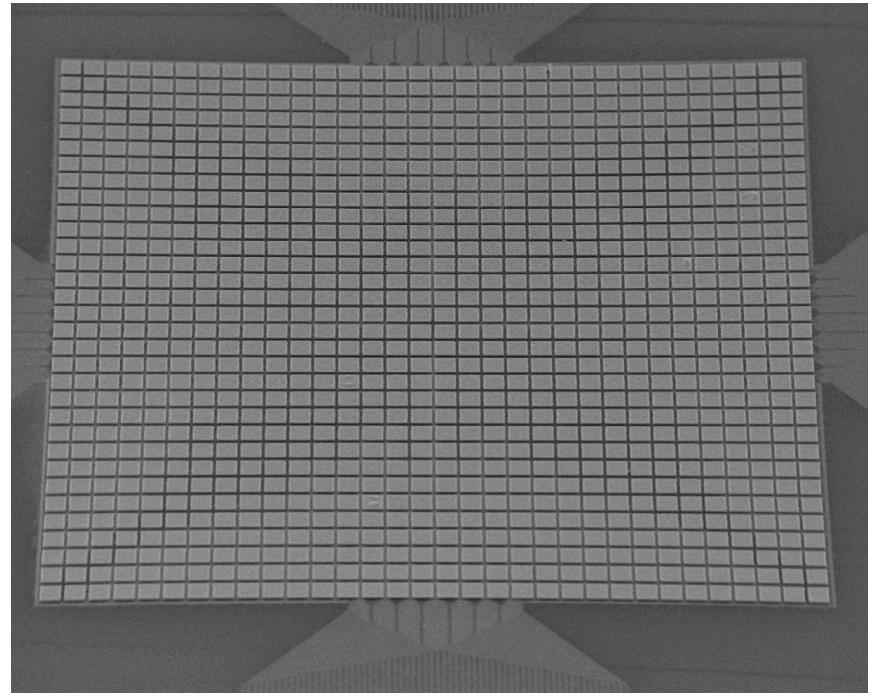
Best achievable theoretically energy resolution at low energies: 0.5 eV

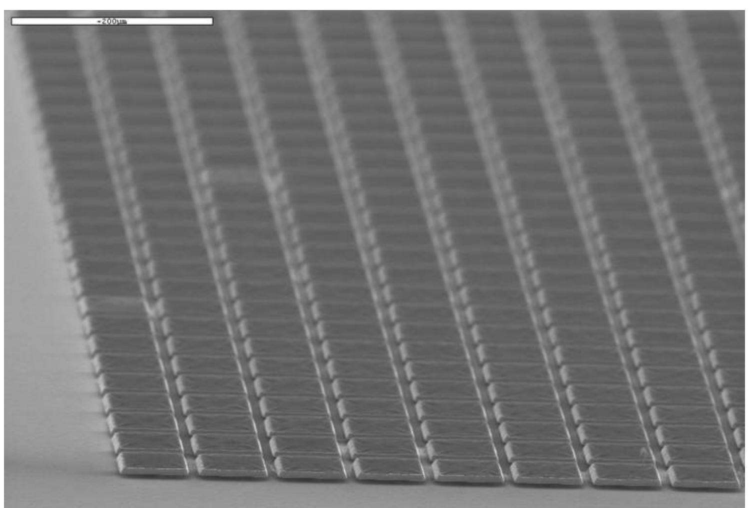
Decay time ~ 1.2 ms

S.-J. Lee et al., Appl. Phys. Lett. **107**, 223503 (2015)

Large-format small-pixel arrays: 32x32 arrays fully wired

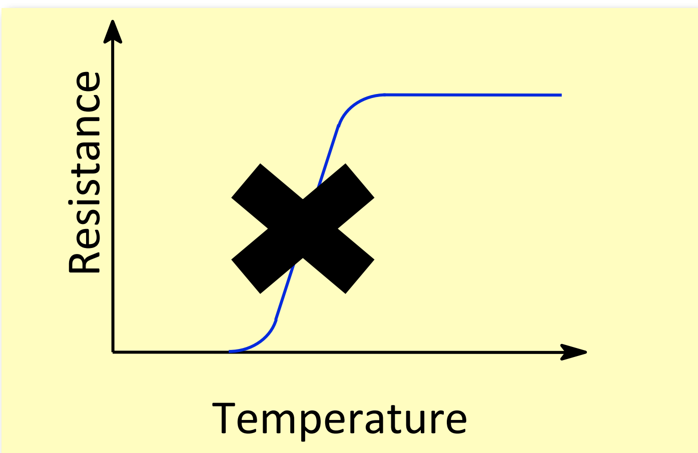


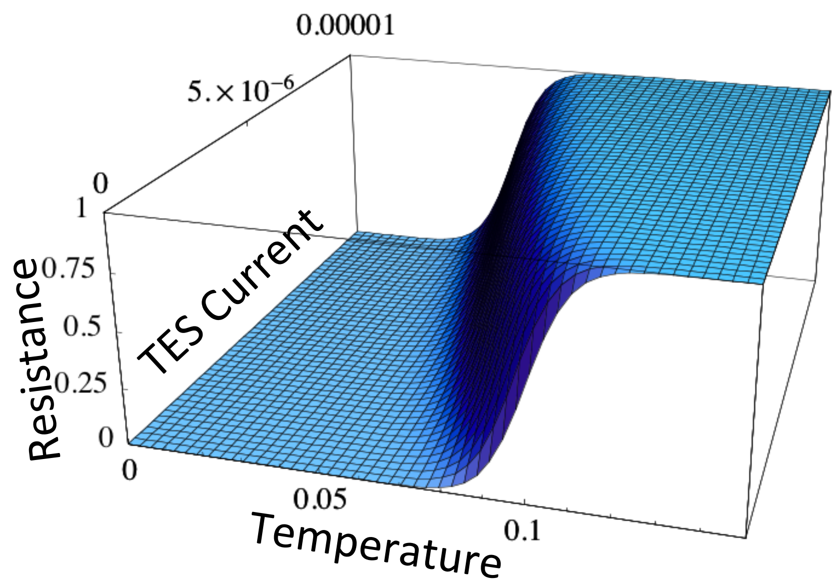




<u>Fully wired</u>
Pixels on a 75 μm pitch
Microstrip pitch = 4 μm

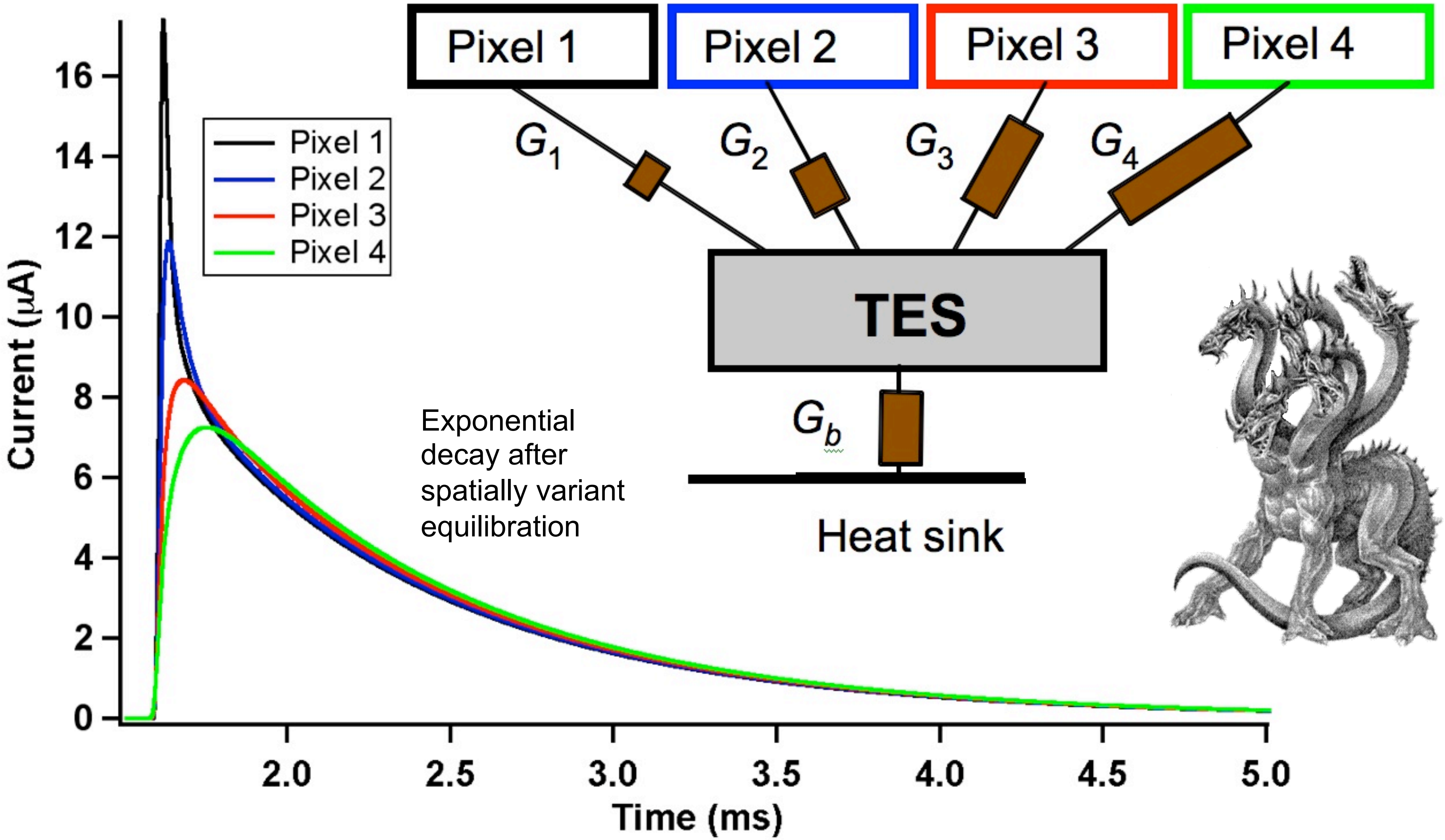
Highly current dependent transition:





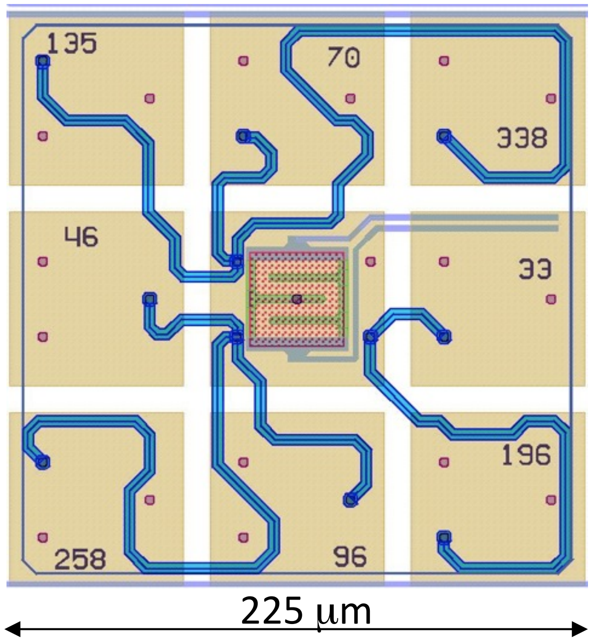
Multi Absorber TES "Hydras" - 1 TES, 4 absorbers

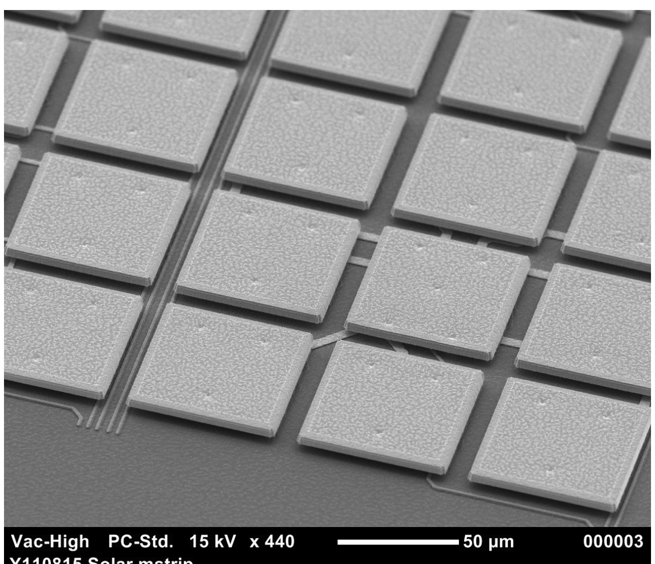
– increase field of view for a fixed number of read-out channels



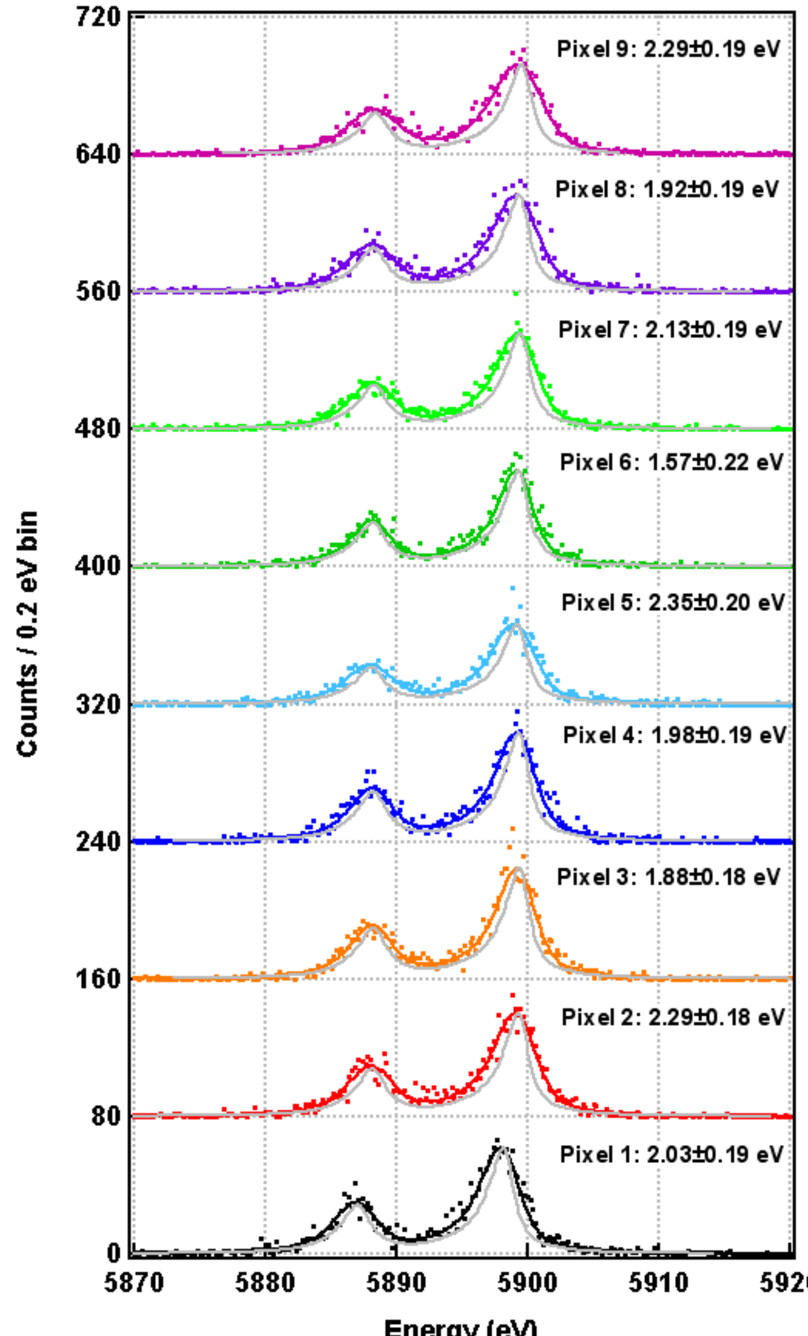
Also works with MCCs

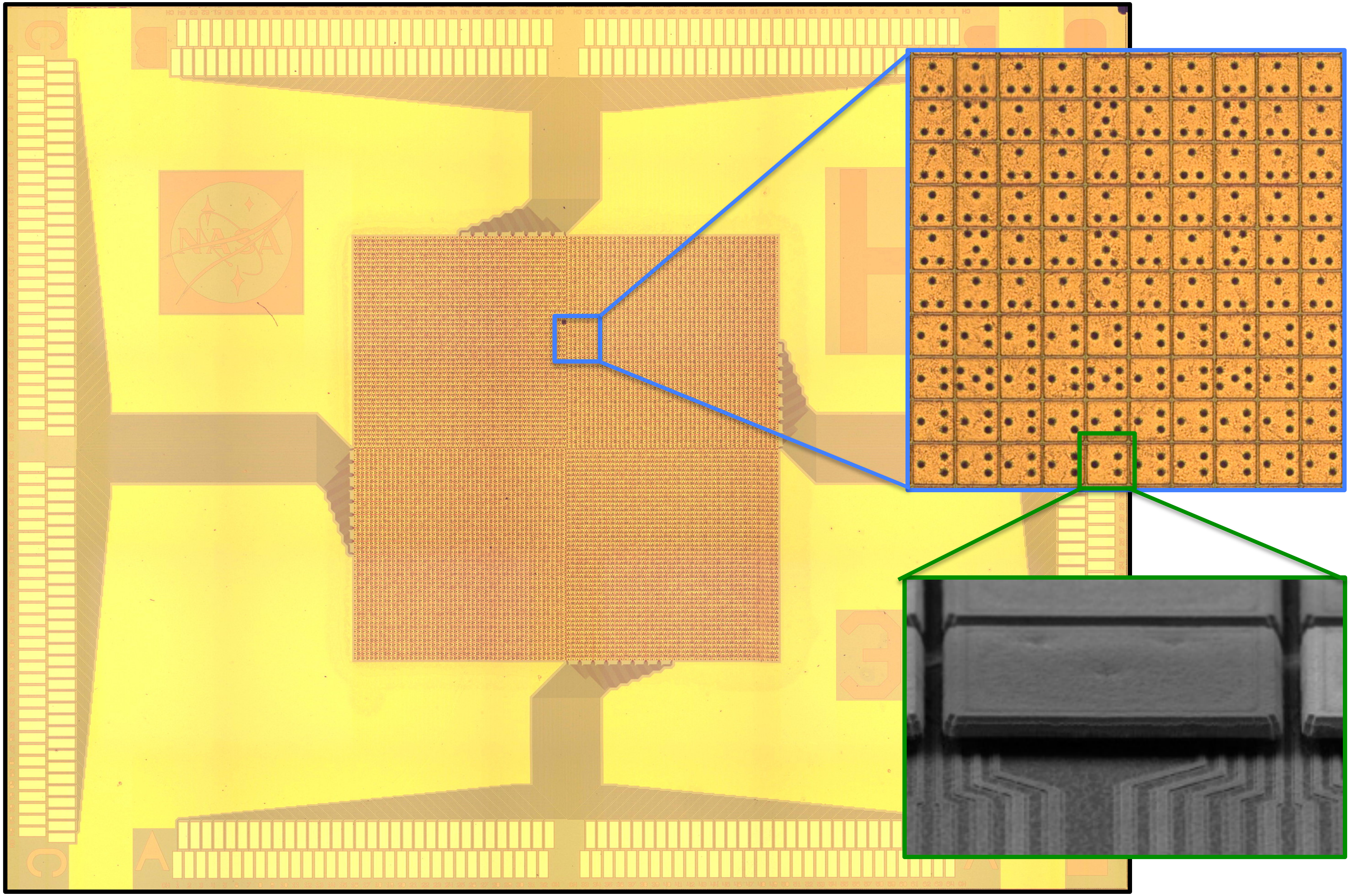
Hydras with 3x3 array of 65 µm absorbers, 5.0 µm thick





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

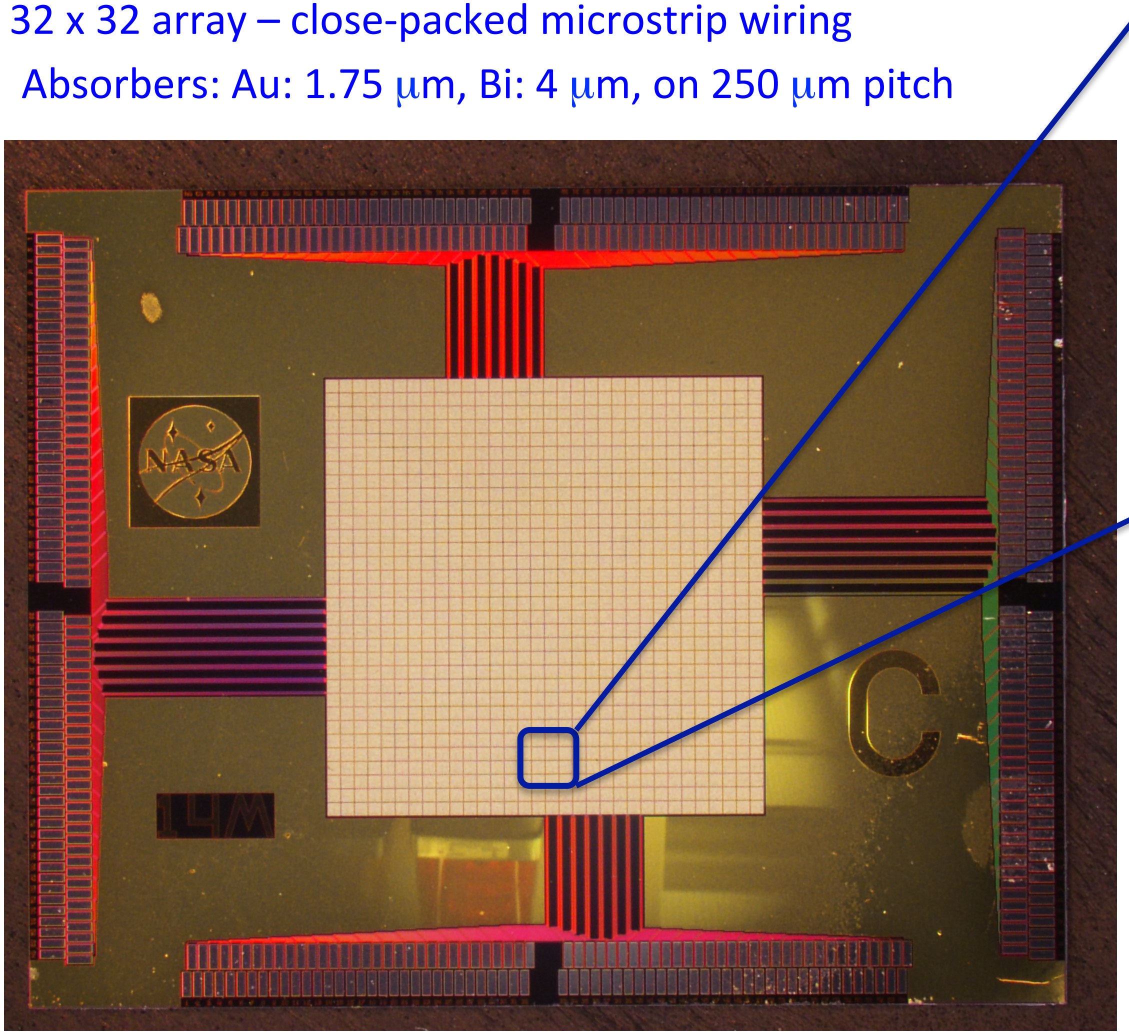


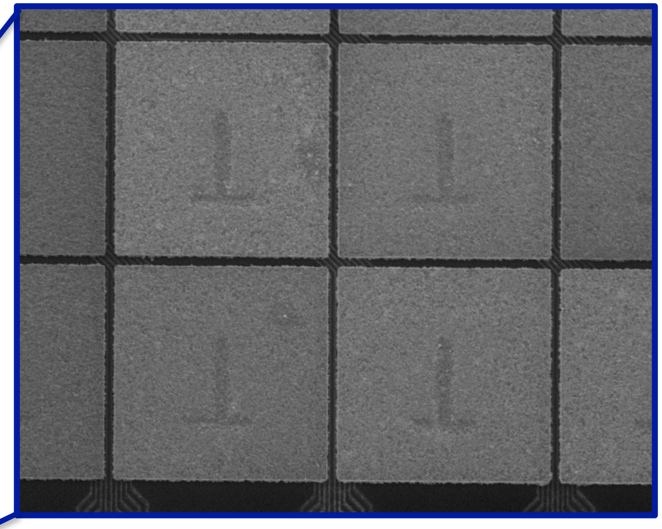


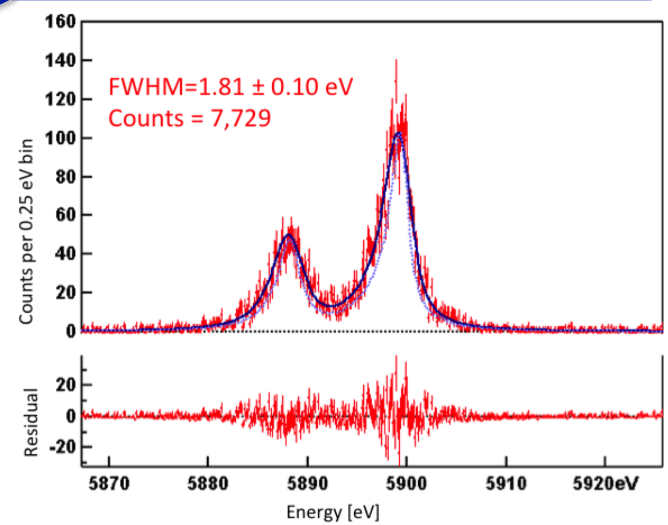
96x96 array (9216 pixels) - fully wired within array – absorbers on 75 μm pitch
- 32x32 array of 3x3 Hydras

Demonstration model (DM) kilo-pixel arrays
- being fabricated and tested

- 32 x 32 array – close-packed microstrip wiring
- Absorbers: Au: 1.75 μm, Bi: 4 μm, on 250 μm pitch



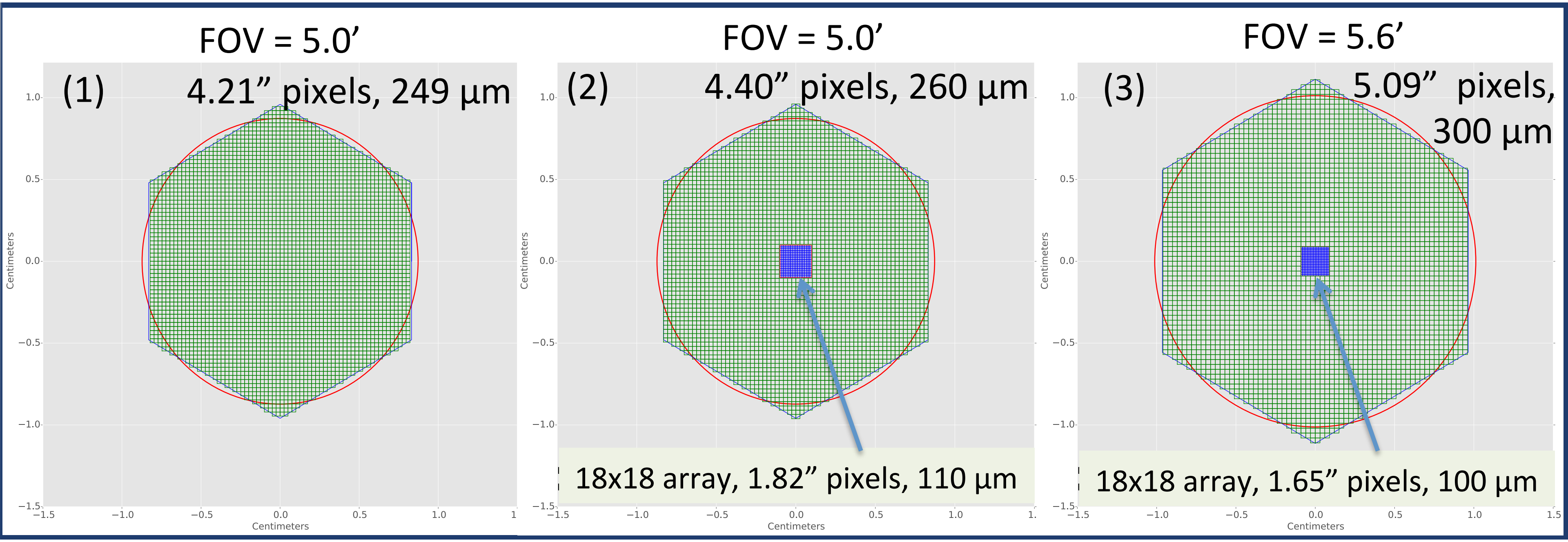




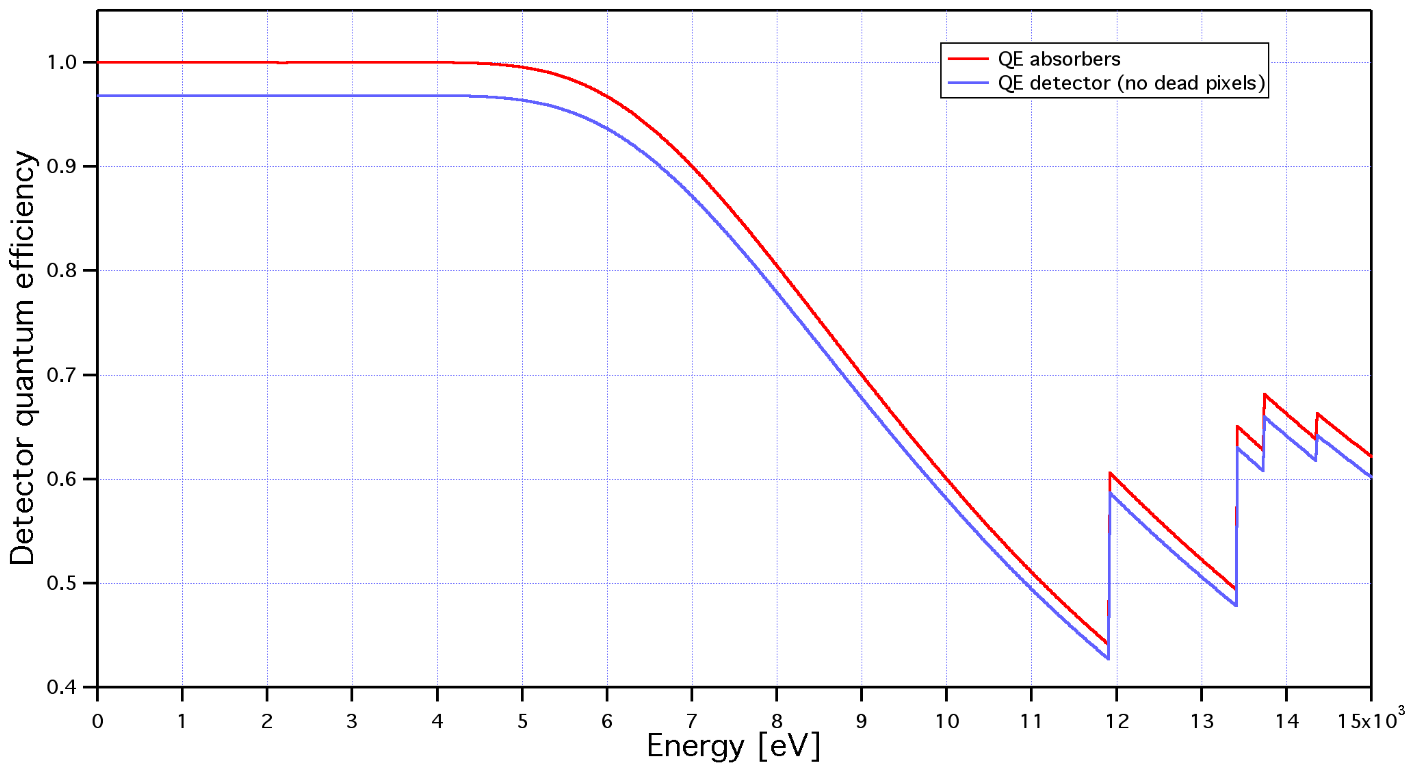
Athena X-IFU array configurations under study

ATHENA X-ray Integral Field Unit

- Athena: three different detector configurations currently under study:



Quantum efficiency versus energy
Example: Athena – X-IFU



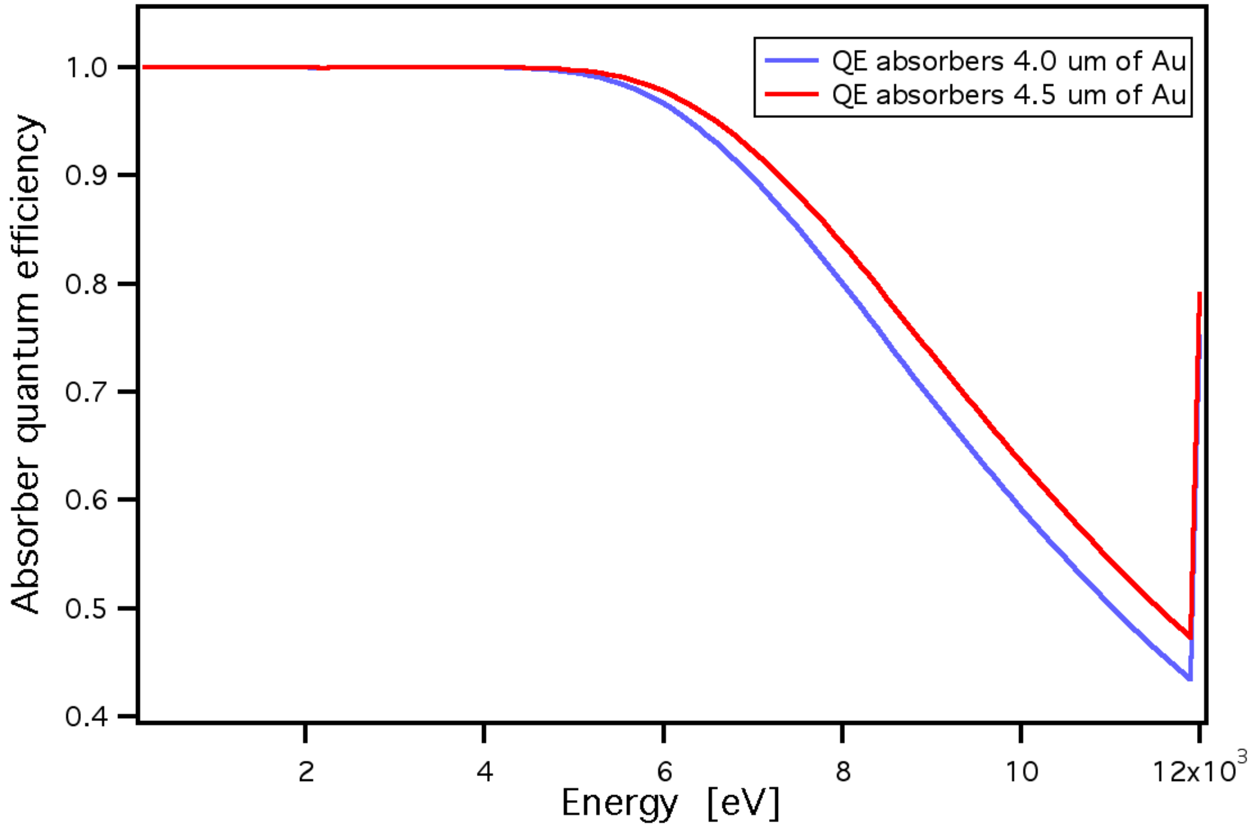
Absorber: 1.7 um Au, 4.2 um Bi

90% QE at 7 keV

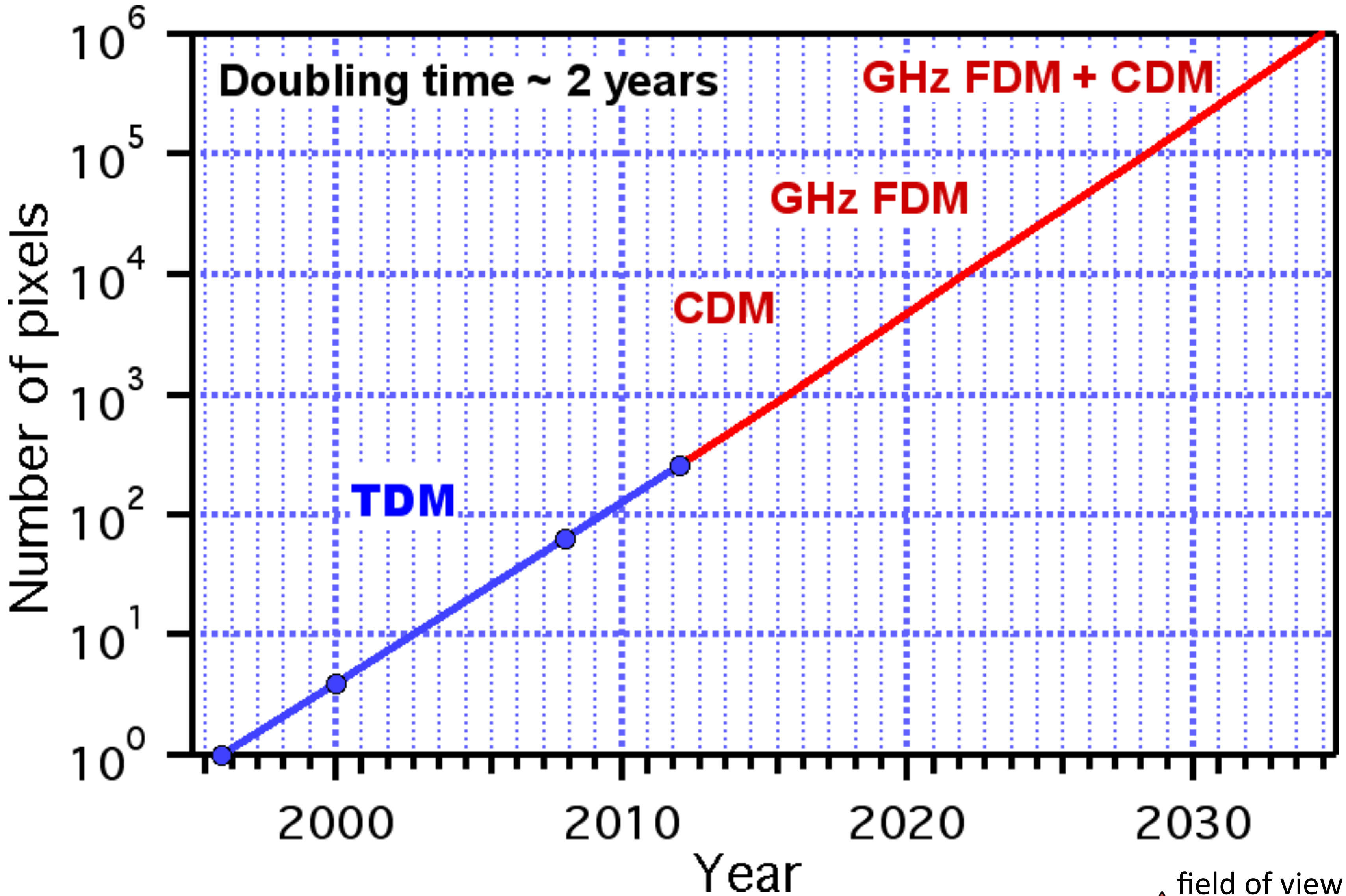
Area filling factor assumed here is 96.8% (4 um gaps)

=> Detector QE = 0.968 * Absorber QE

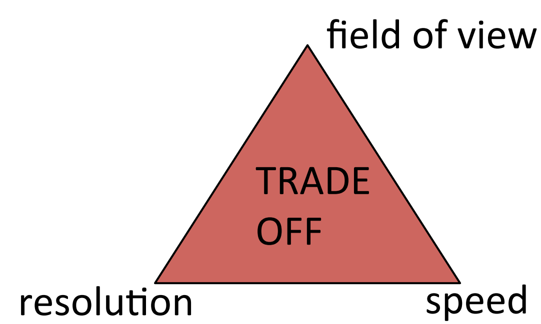
X-ray Surveyor QE verses energy



4 um gaps on 50 um pitch => area fill-factor = 85%



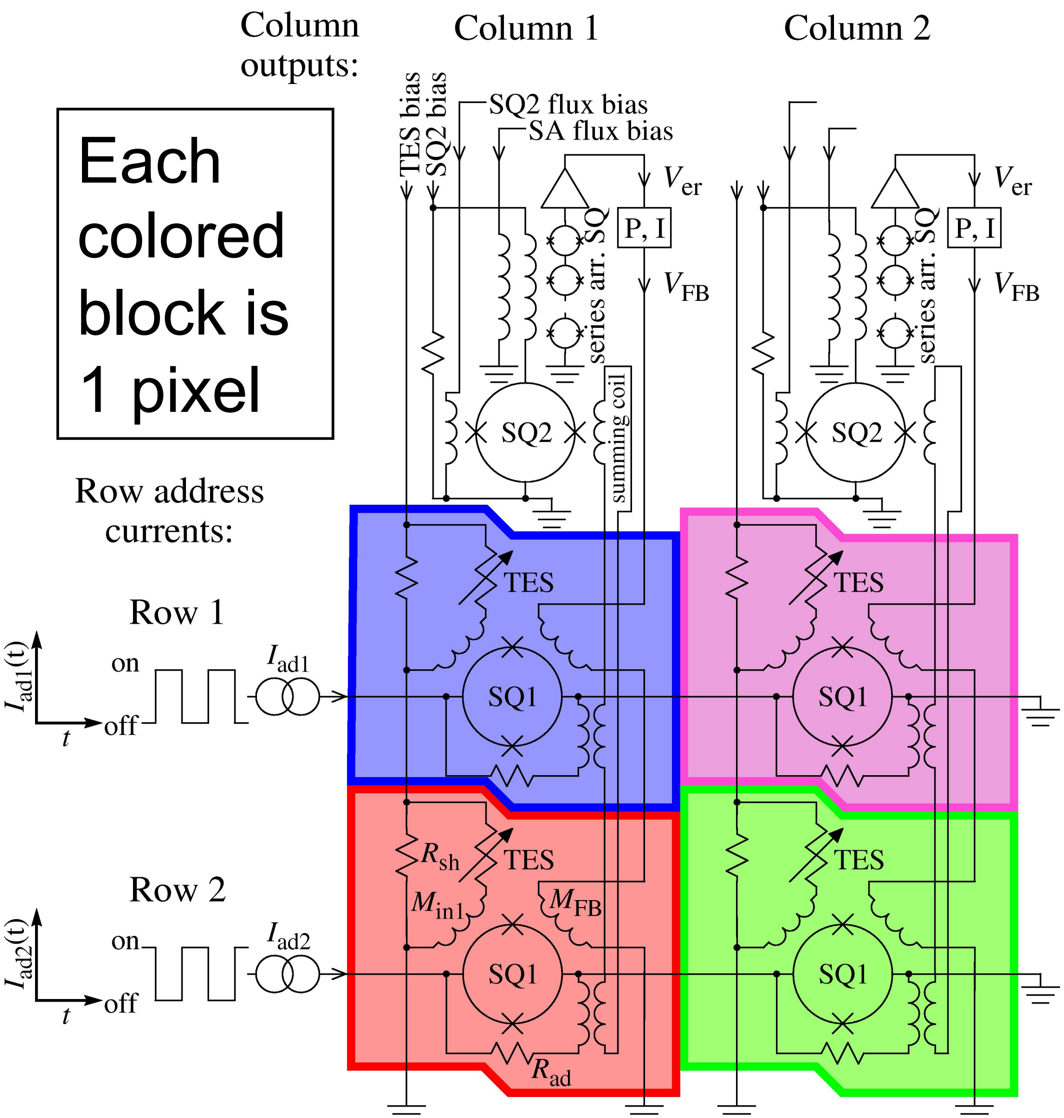
Doubling time ~ 2 years
GHz FDM + CDM
GHz FDM
CDM
TDM
Number of pixels
10^0
10^1
10^2
10^3
10^4
10^5
10^6
2000
2010
2020
2030
Year

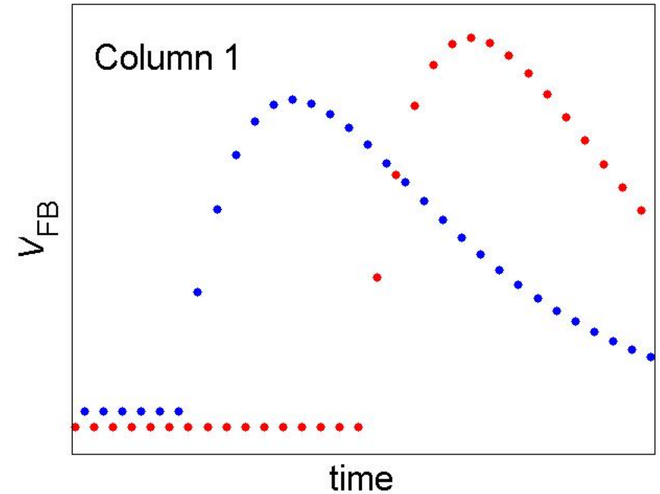


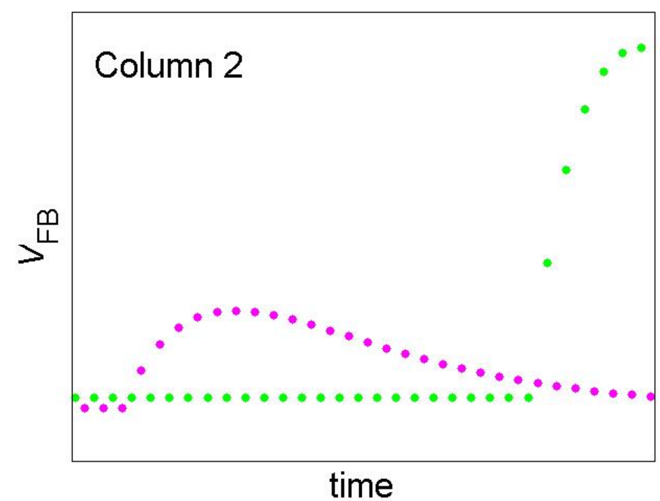
field of view
TRADE
OFF
resolution
speed

Time-division multiplexing (TDM)

- Individual TES pixels are coupled (via each pixel's SQUID) to a single amplifier
- Multiplexed by sequential switching between SQUIDs

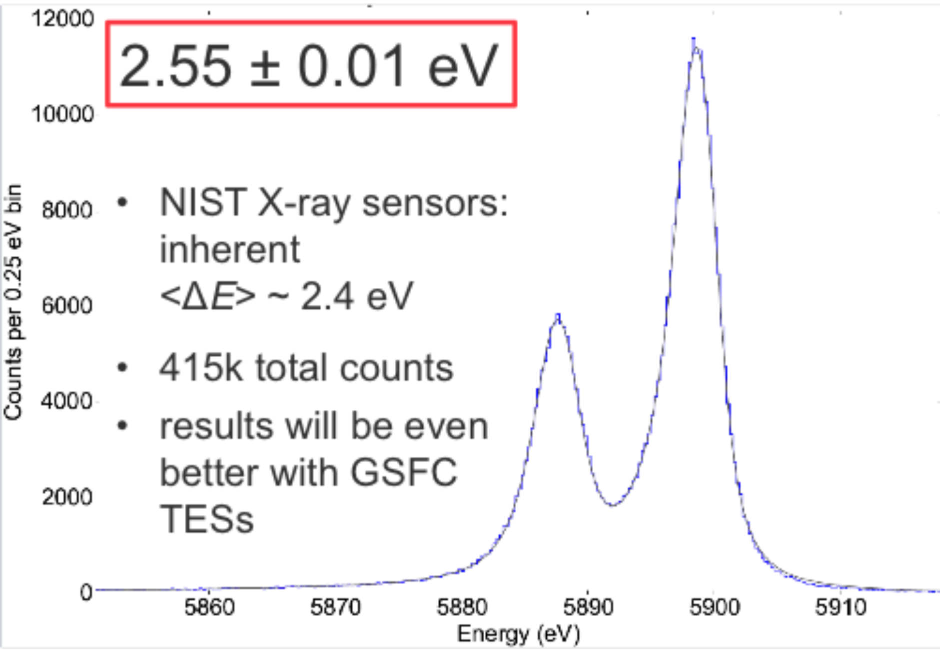


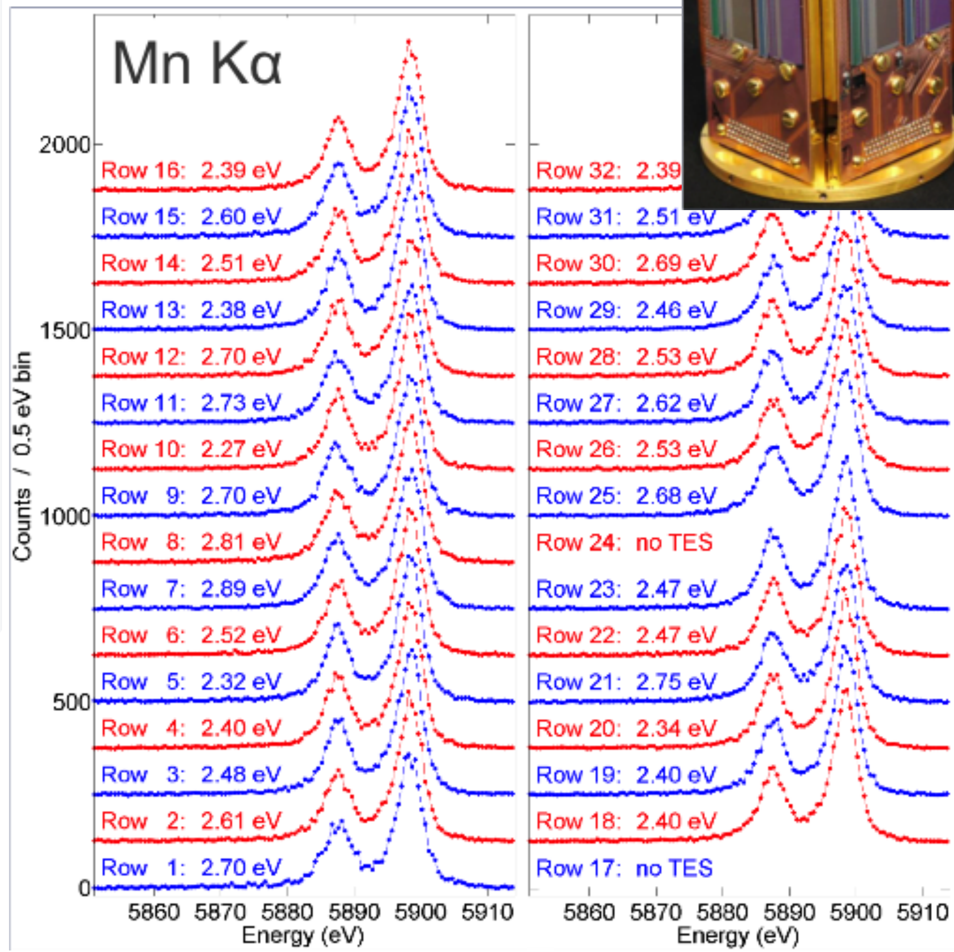




Time division multiplexing

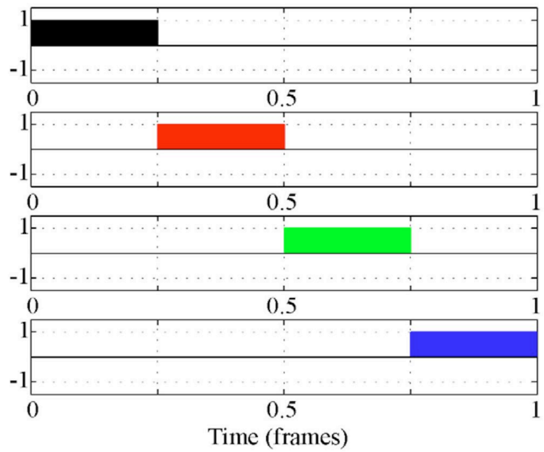
IFU
ATHENA X-ray Integral Field Unit



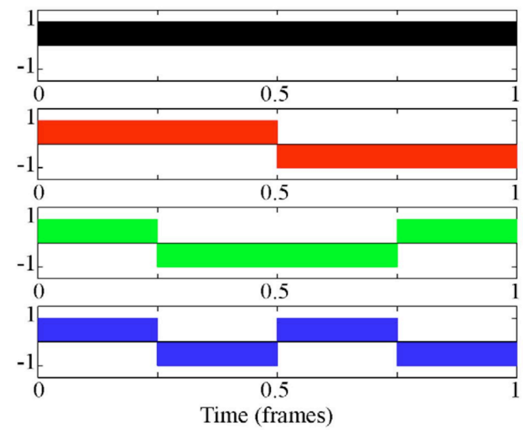


- Combined spectrum: 32-row TDM
- T_{row} = 160 ns (much faster!)
- Almost no energy resolution degradation from multiplexing

Multiplexed read out: switched SQUID multiplexing



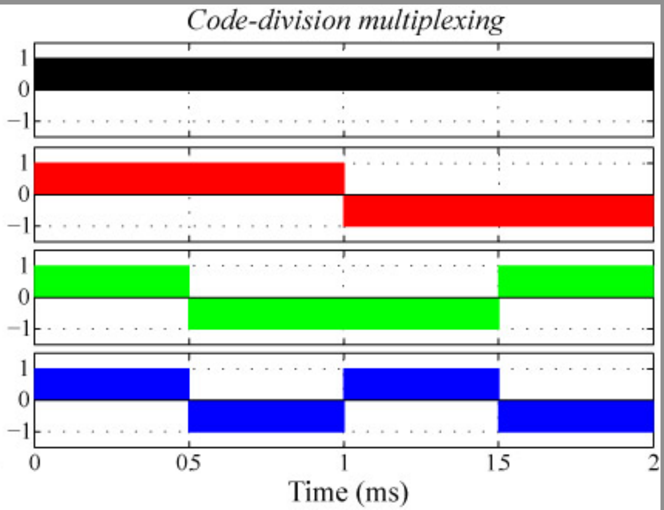
TDM



CDM

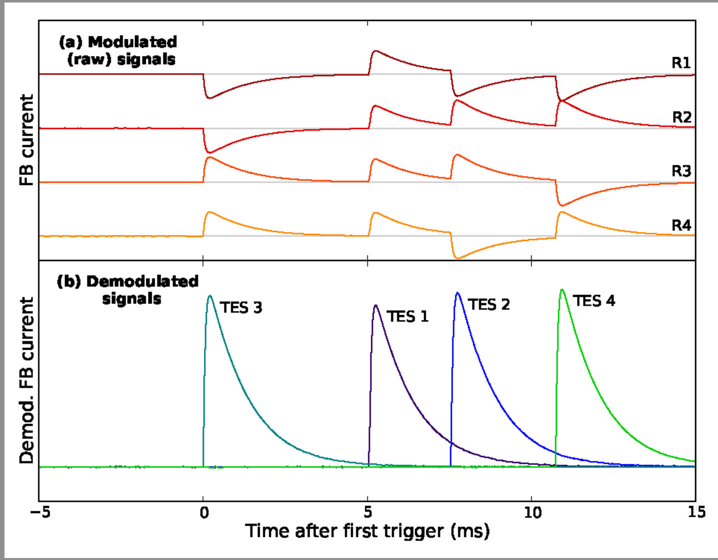
- Code Division Multiplexing (CDM) will soon reach TDM TRL level
  - All pixels ON all the time, polarity of coupling is switched
  - CDM has a sqrt(N) SQUID noise advantage over TDM, where N is the multiplexing scale
  - Define Walsh code by modulating polarity of detector coupling

Walsh code-division multiplexing



$$W_{ij} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$

$$W_{ij}^{-1} = \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{pmatrix}$$



$$\gamma_i = \sum_j W_{ij} d_j$$

$$d_i = \sum_j W_{ij}^{-1} \gamma_j$$

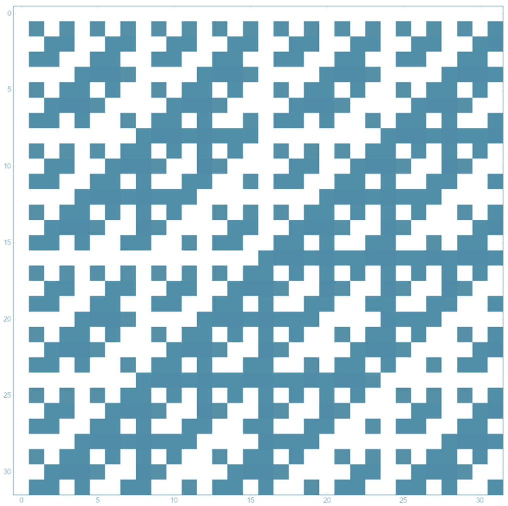
d_j is the vector of detector signals
W_{ij} is the orthogonal Walsh matrix
γ_j is the vector of multiplexed signals
Multiplying by inverse Walsh recovers signals

- MUX factor must be a multiple of four
- One non-modulated channel will be more sensitive to interfering signals
- Additional mathematical subtleties worked out in KD Irwin et al., SUST 23, 034004 (2010).

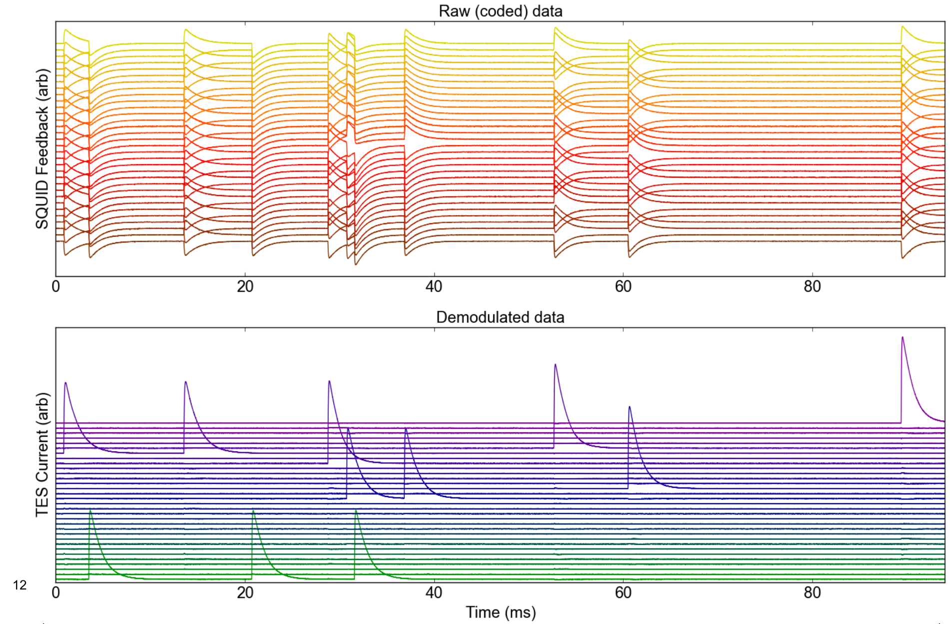
Code-Division Multiplexing

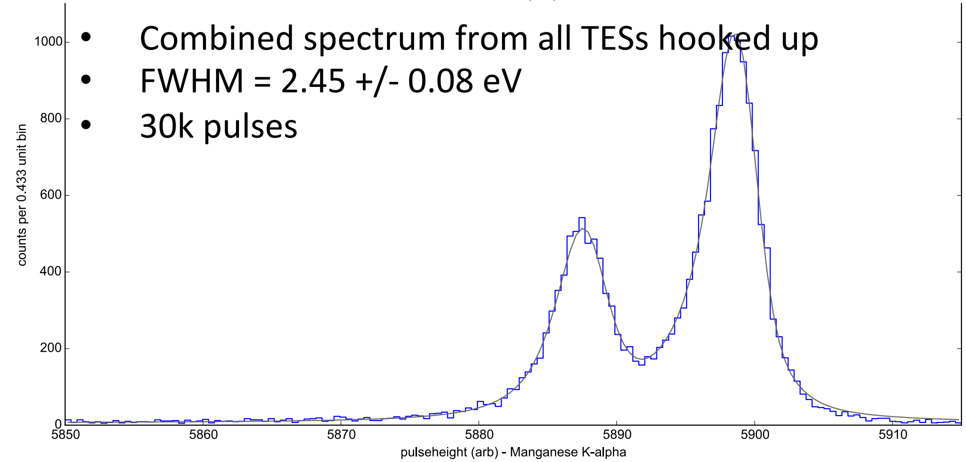
New CDM result:

- FWHM = 2.45 +/- 0.08 eV
  (TESs on 16 of 32 rows)
- 30k pulses
- No energy resolution degradation from read-out
- Now also 2.77 eV in 30 sensors (excluding unmodulated channel).



Modulation matrix



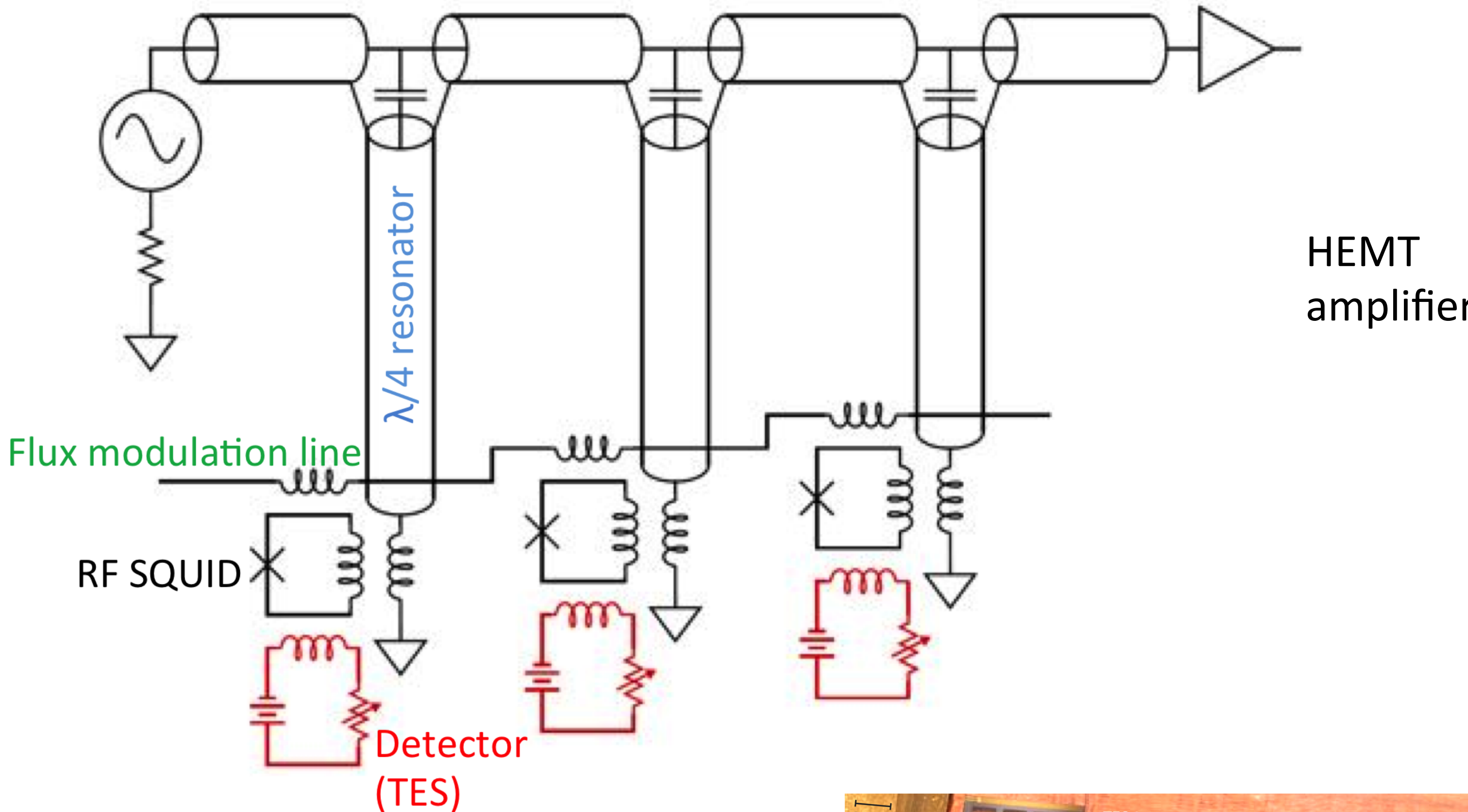


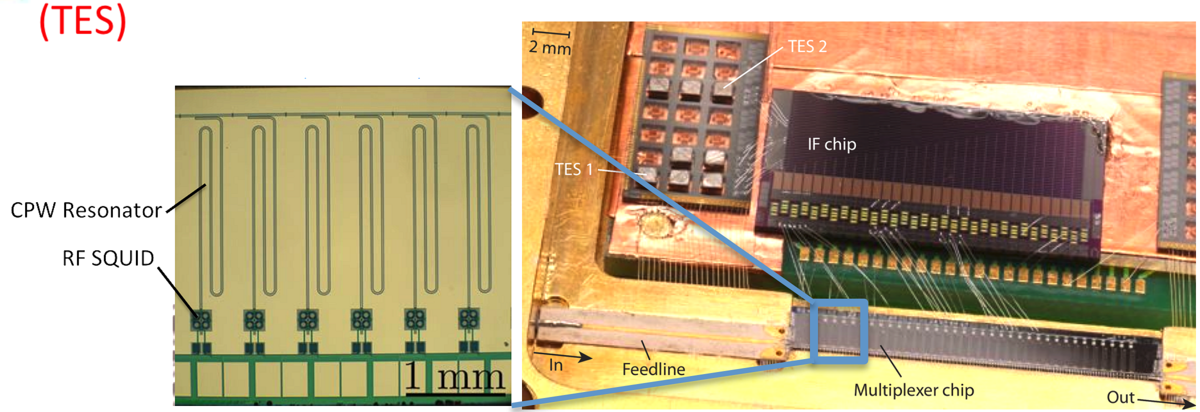
TDM/CDM more X-ray Surveyor?

- If we assume "Hydra" approach, with ~ ~25 absorbers per TES

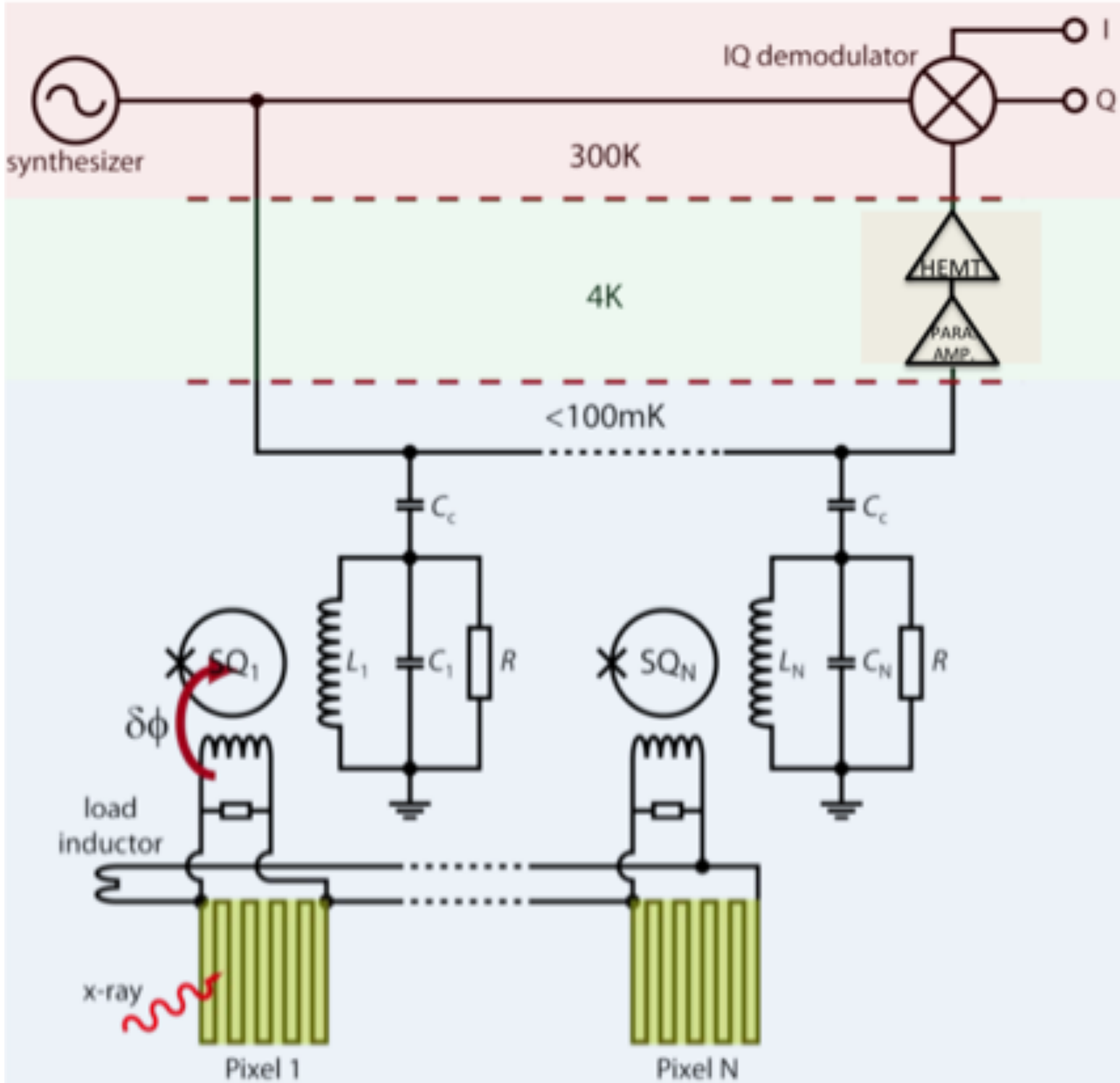
=> the number of sensors needed to be read out (~3600) is the same as is currently proposed for the X-ray Integral Field Unit instrument on Athena (~3840)

Microwave (GHz) SQUID Resonators





Magnetic calorimeters with microwave SQUID read-out



Conclusions:

Basic initial approach: use position-sensitive thermal microcalorimeter, “Hydras”.
These have ~ 25 absorbers attached to each thermal sensor

Sensor: Either a transition-edge sensor (TES) or a magnetically coupled calorimeter (MCC)
With 5x5 array of absorbers attached to each sensor, 90k pixels read out with 60 x 60 array of thermal sensors

Read-out of pixels uses conventional time-domain multiplexing (TDM) or code domain multiplexing (CDM), or alternatively a microwave based multiplexing read-out.

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