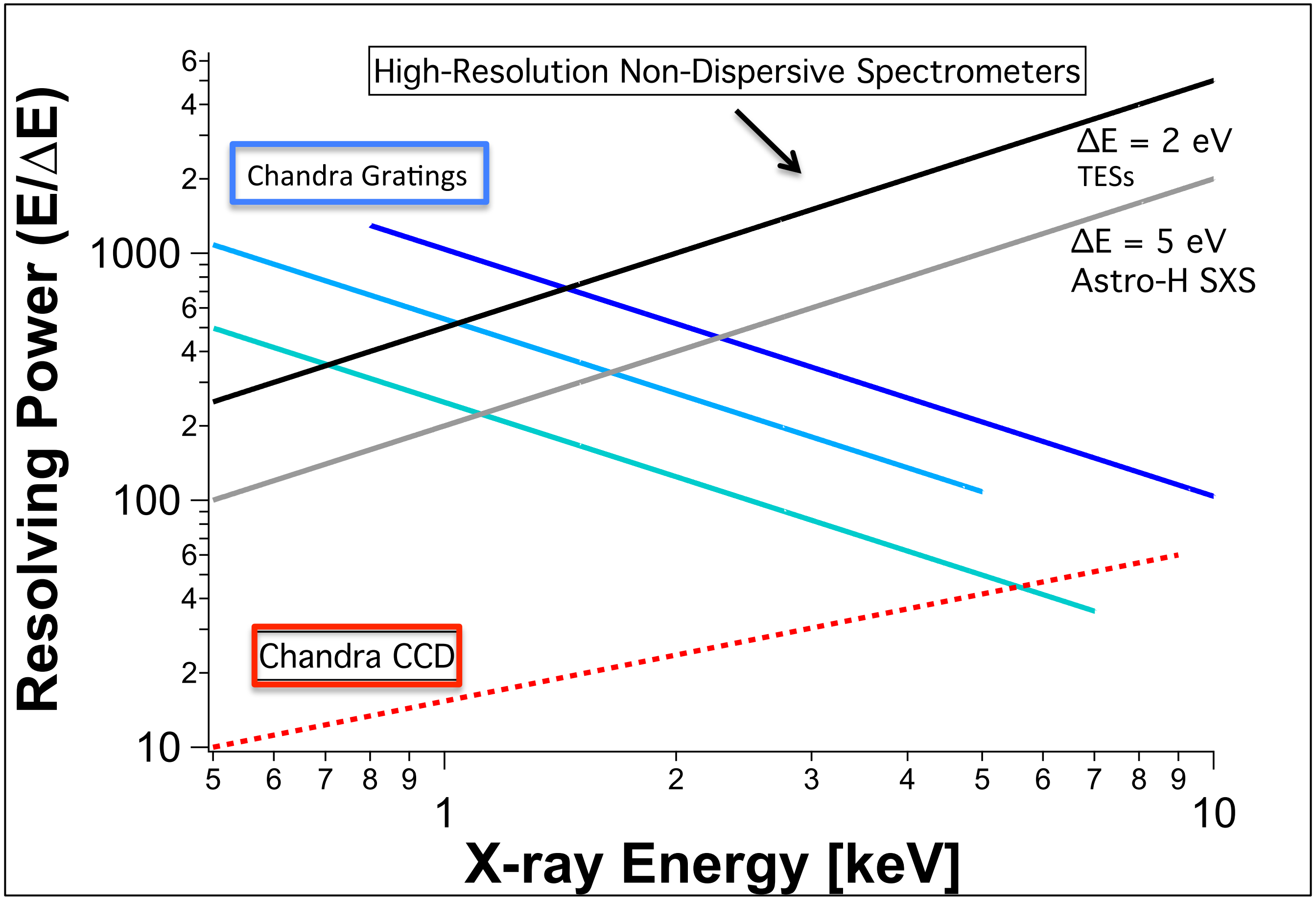
# Microcalorimeters for X-ray Detection

Megan Eckart
NASA/Goddard Space Flight Center

J.S. Adams, S.R. Bandler, K.R. Boyce, J.A. Chervenak, M.P. Chiao,
A. Datesman, F.M. Finkbeiner, R.L. Kelley, C.A. Kilbourne,
M.A. Leutenegger, F.S. Porter, J.E. Sadleir, K. Sakai, S.J. Smith,
G.A. Sneiderman, N. Wakeham, E. Wassell, T. Watanabe, W. Yoon

Plus close collaboration with U. Wisconsin, Stanford/SLAC, NIST/Boulder, Northwestern, Yale

# Power of X-ray Microcalorimeters



Non-Dispersive Imaging Spectroscopy !

- high resolving power at diagnostically rich 6 keV (Fe K-shell)
- spectroscopy of extended sources
- unity QE and photon counting

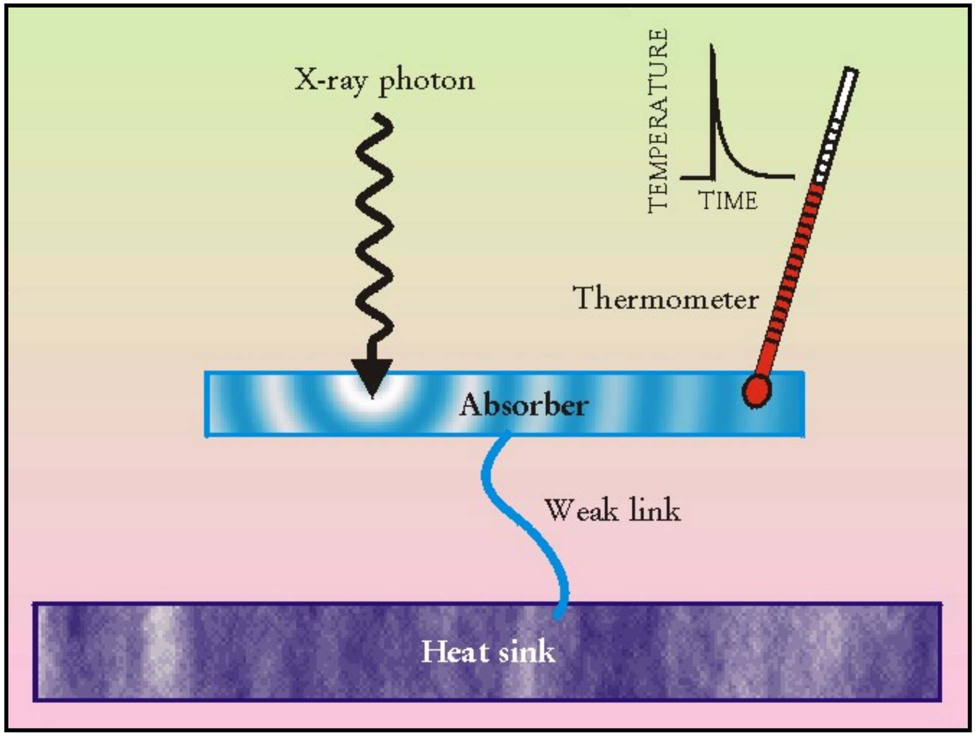
# Outline

- Intro to our X-ray microcalorimeters & sensors
- Two technical challenges
- Reduced heat capacity devices

note: $\Delta E_{FWHM} = 2.355\ \sigma$

# X-ray Microcalorimeter Concept

Non-dispersive spectrometer



**Thermal detection of individual X-ray photons**

- **High spectral resolution**
- **High intrinsic quantum efficiency**

Signal: $\delta T \propto \frac{E}{C_{\text{tot}}}$

Decay: $\tau \propto \frac{C_{\text{tot}}}{G}$

$C_{\text{tot}}$ = total heat capacity

$G$ = thermal conductance

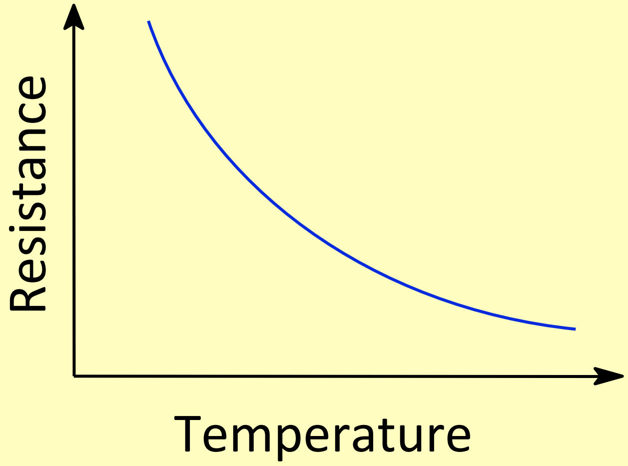
Energy resolution is limited by thermodynamics:

$\Delta E \propto T\,C(T)^{0.5}$

Operate at cryogenic temperatures (~50 mK)

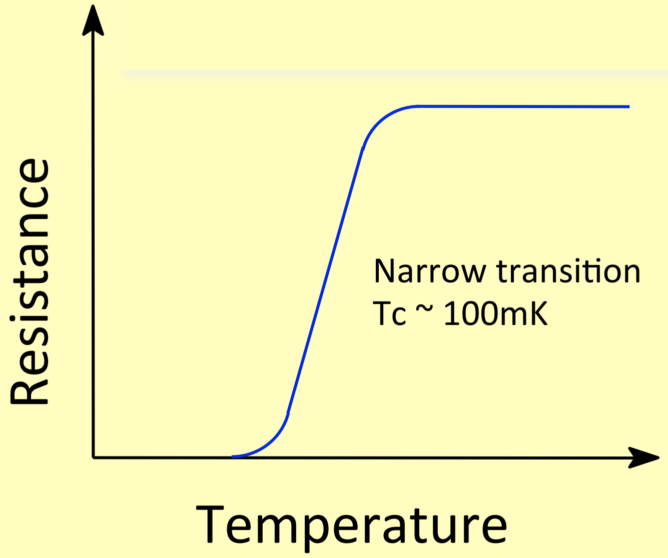
Several sensor approaches:

Semiconductor Thermometer
(Doped Ge or Si)



Approach used for:
XQC Sounding Rocket
Astro-H Soft X-ray Spectrometer (SXS)

Superconducting Transition Edge
Sensor (TES) Thermometer

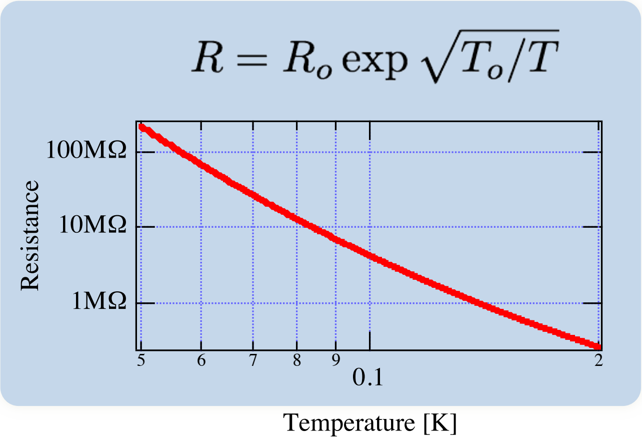


Large Arrays, Best E/ΔE

Also, magnetic calorimeters.

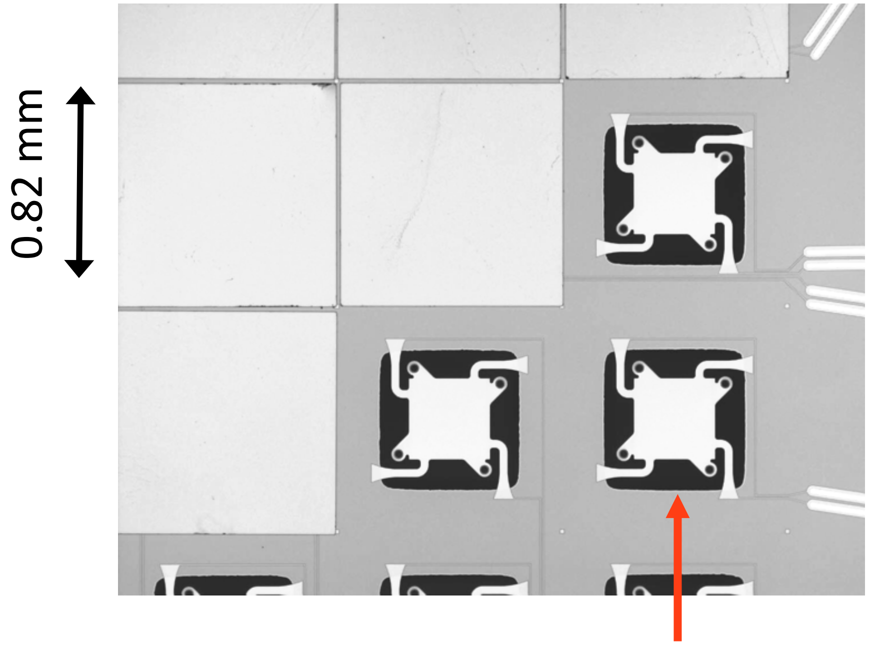
# Semiconductor Thermistors

- Ion-implanted Si
  (or Neutron Transmutation Doped Ge)
- High resistance,
  read out with JFET

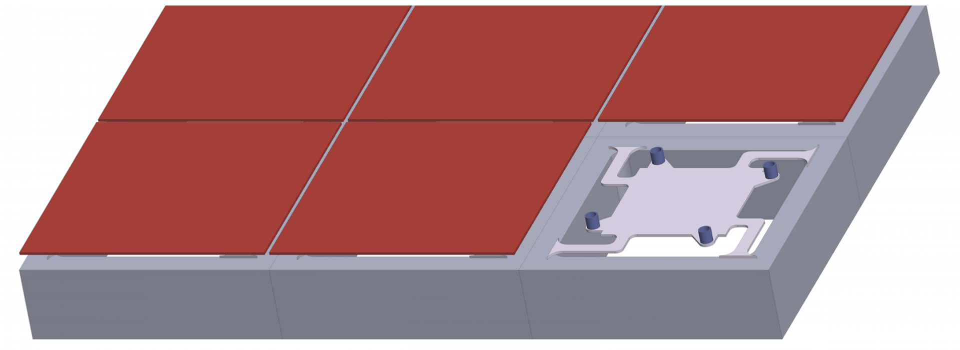

$$R = R_o \exp \sqrt{T_o/T}$$

$\Delta E_{FWHM}$ ~ 4 eV (R~1500 at 6 keV)

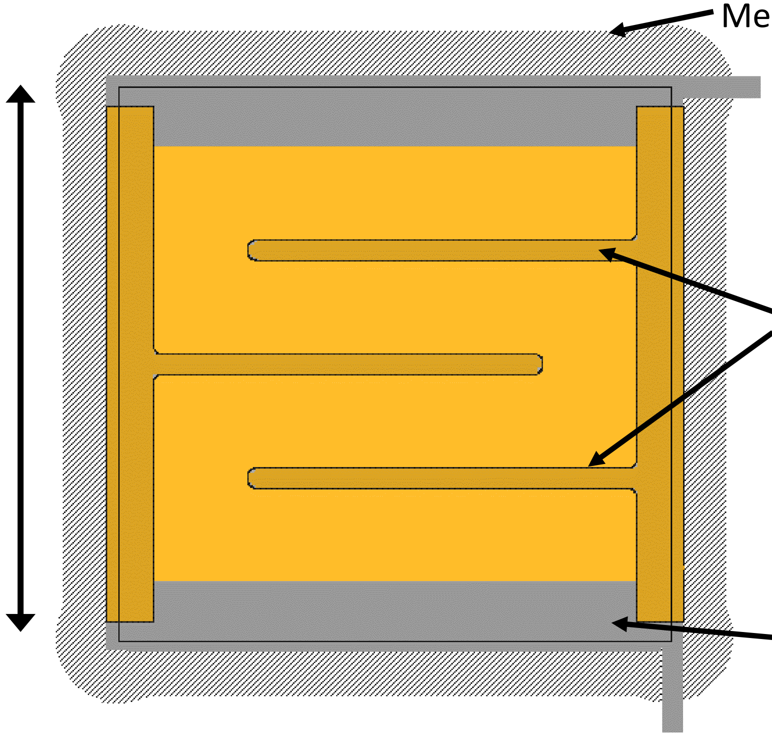
arrays of ~36 pixels



Si thermistor



# Mo/Au bilayer TES



Membrane

140 μm

Interdigitated metal stripes for noise mitigation

Bias lead

Mo (45 nm) / Au (225 nm);
$T_c$ = 0.1 K

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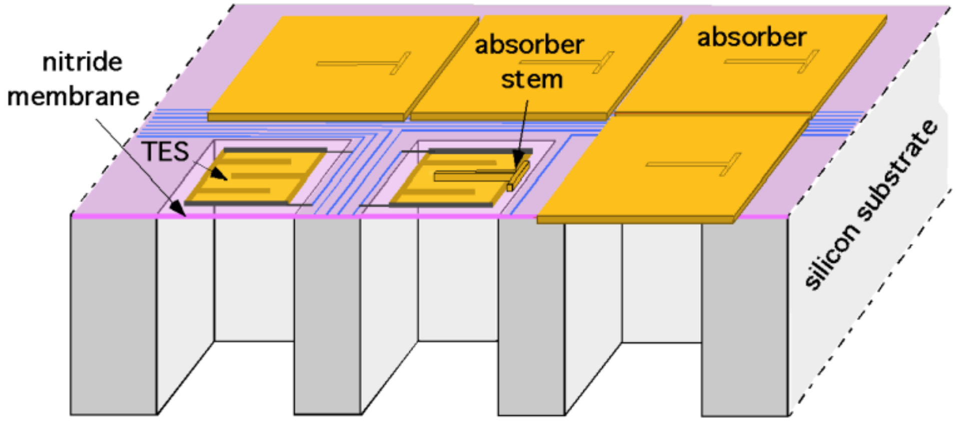
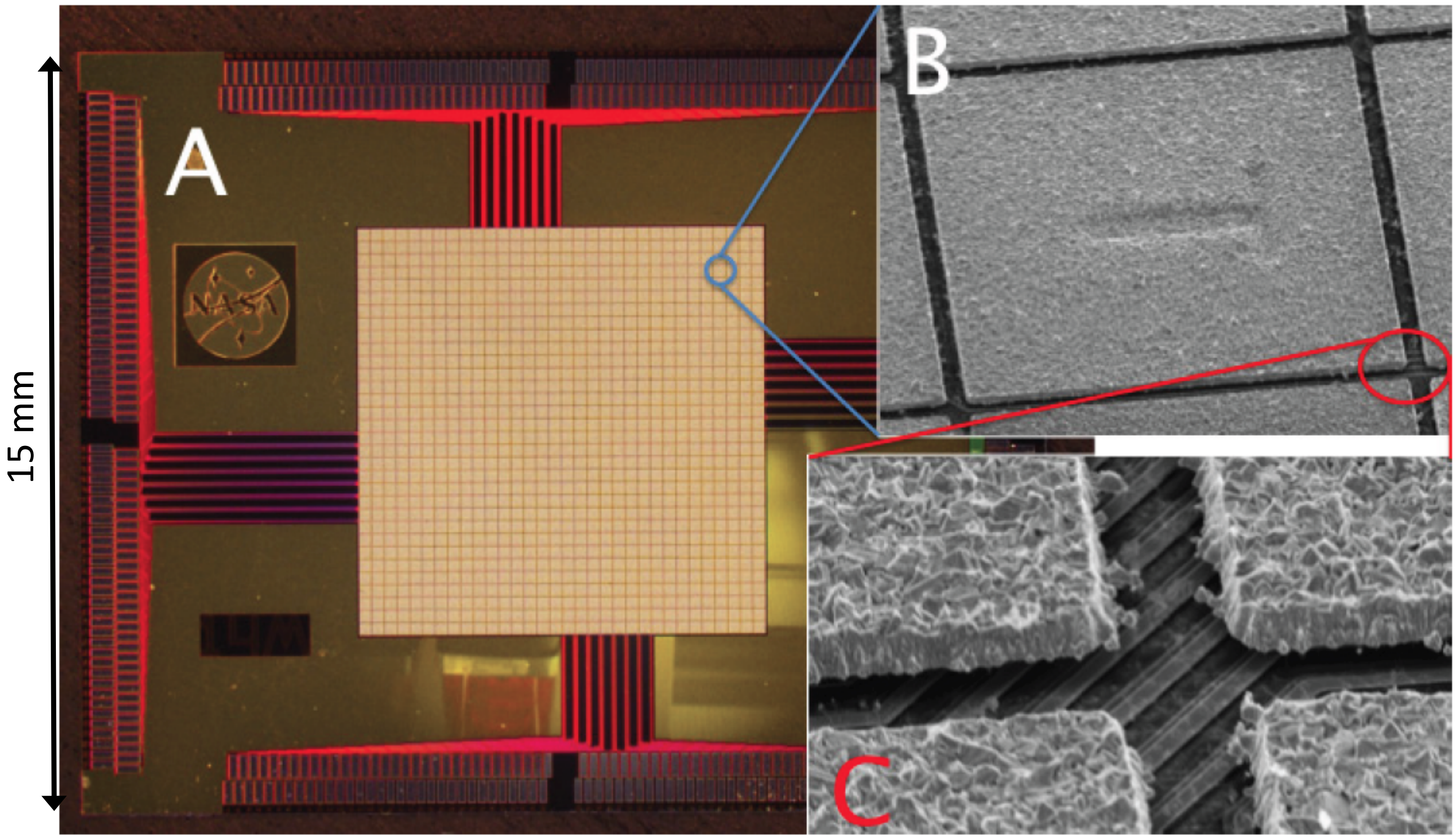


microcalorimeter array
(0.1 –12 keV, $\Delta E_{FWHM}$~2 eV)

- Si removed beneath pixels to leave TES sitting on SiN membrane
- overhanging absorbers are several microns thick (made of Au or Au/Bi), to provide high QE and appropriate C;
even thicker absorbers used for high-energy x-ray or gamma-ray detectors

# Recent TES X-ray Microcalorimeter Array Development:



# Energy Resolution and Device Optimization

$\Delta E \propto T\,(C/\alpha)^{0.5}$ $\alpha = \frac{\partial \ln(R)}{\partial \ln(T)}$ $\beta = \frac{\partial \ln(R)}{\partial \ln(I)}$

- $\Delta E$ is independent of $E$ in small temperature excursion around $T_c$
- Optimize detector design for best resolution with a certain $E_{max}$
  - make heat capacity as small as possible and $\alpha$ as high as possible without saturating detector, taking into account noise scaling

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$\Delta E \propto (T\,E_{max})^{0.5}$ $E_{max} \propto C\,T/\alpha$

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

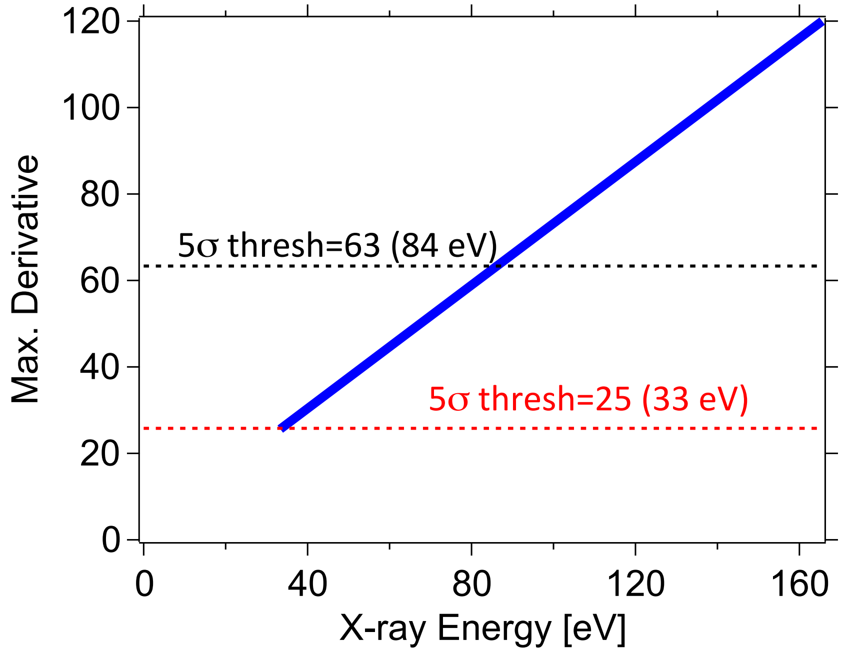
→ For our TESs

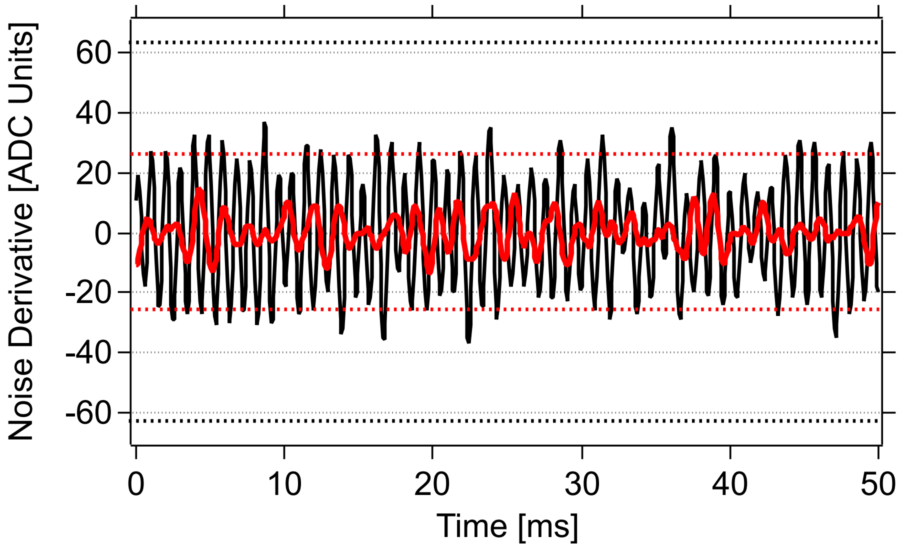
β scales with α

$M^2$ depends on α
high α (>100) → high $M^2$

- Use matched "optimal" filter for standard event processing for best $\Delta E$
  - alternative analysis approaches are in development for non-linear devices and high count-rate applications

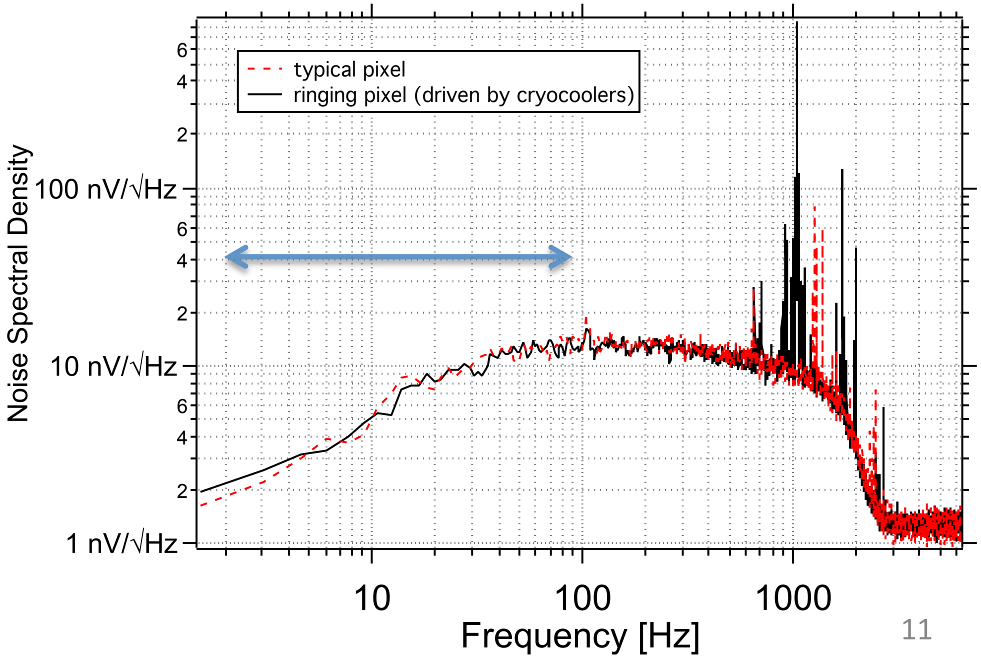
# Energy Threshold (example, using $\Delta E_{FWHM}$ ~4 eV silicon thermistor SXS array)





High-frequency noise can have large effect on trigger threshold, but little impact on energy resolution.

Low instrument collecting area at low energy so not a driving requirement; we trigger as low as possible to reduce background and avoid contamination/pile-up.



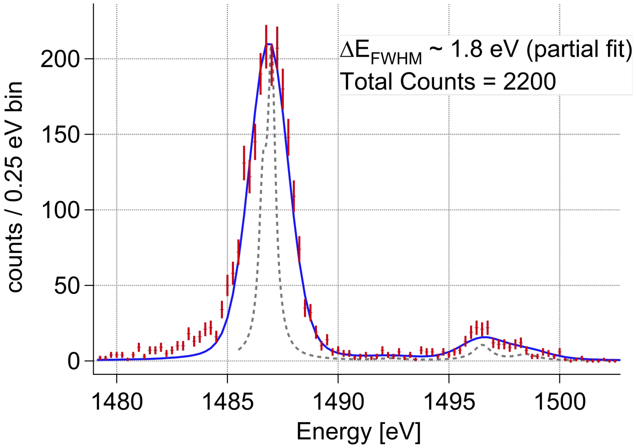
# Technical Challenges (1)

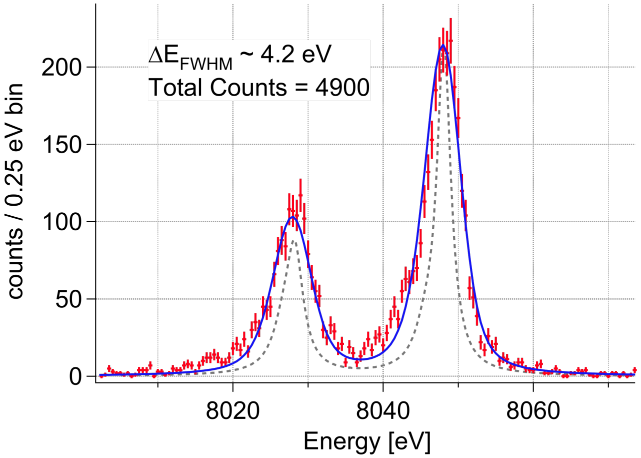
## Thermalization

# Insufficient thermalization can lead to degraded resolution and/or distorted line shape.

- want rapid energy downconversion following photon absorption, where device thermalization is complete prior to sensor response (measuring a single ΔT)

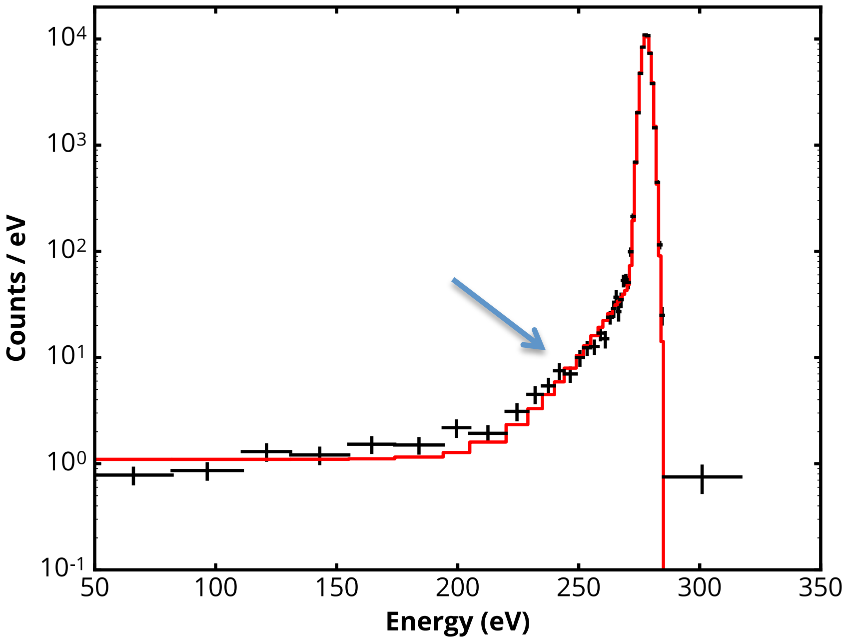
- If thermalization is not rapid or complete or there are other energy loss mechanisms, signal size can depend on absorption position, degrading resolution and distorting line shape
  - <u>silicon thermistor devices</u>: use separate absorber to avoid absorbing in Si, controlled/reproducible absorber attachment process
  - <u>TES devices</u>: use separate absorber; Au layer in absorbers for thermalization, electroplated Bi for stopping power
  - <u>solid substrate TES devices (no membrane isolation)</u>: make absorber attachment stems w/ small area to minimize athermal phonon loss to substrate



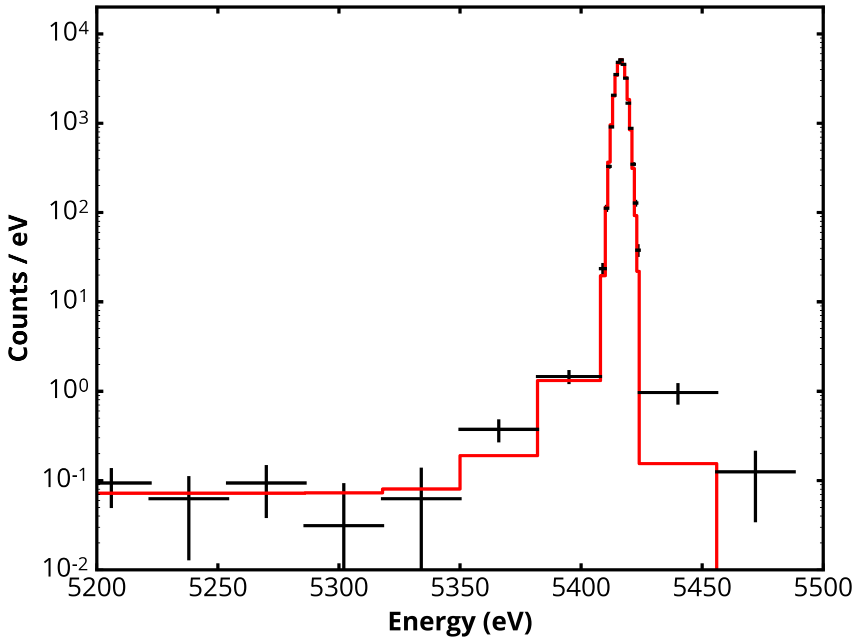


# Example of Surface Effects (energy loss)

- Small exponential tail related to photons absorbed near surface of HgTe absorbers (Astro-H SXS detectors)



~2% at 270 eV



<0.1% at 5410 eV

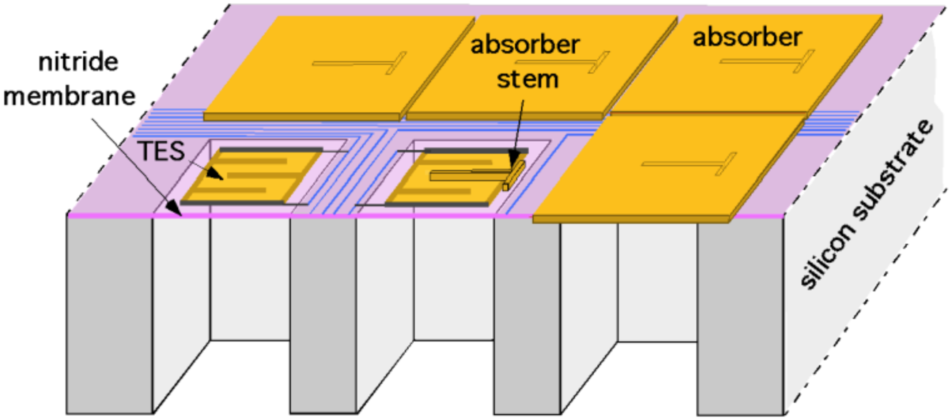
- Tail measured from 0.3 keV – 8 keV. Fraction of counts in tail drops with energy in manner consistent with decreasing fraction of photons absorbed near surface.

- Possible trapping states due to altered band structure near surface (first tens of A)?

# Technical Challenges (2)

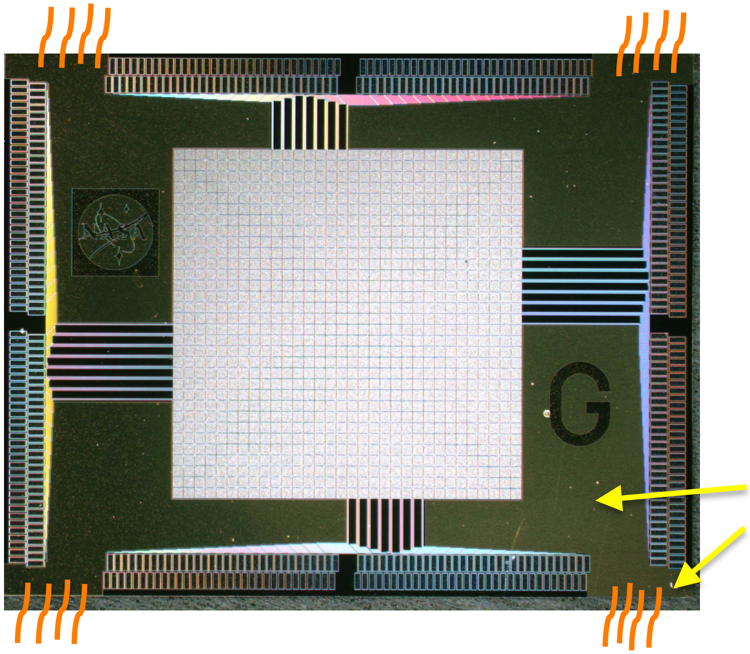
## Heatsinking

# Heatsinking



1) Effective $T_b$ change caused by TES bias power

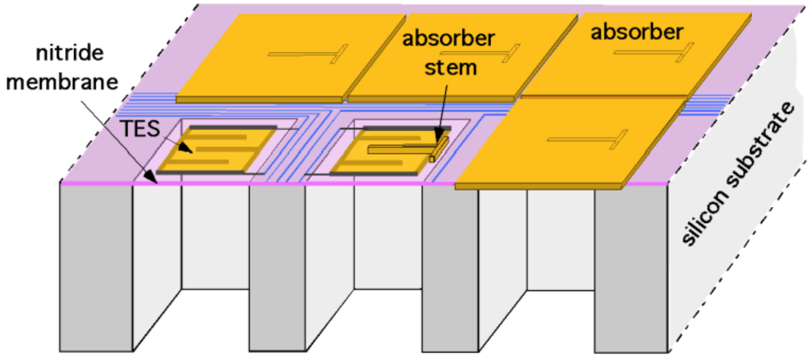
2) pixel-to-pixel crosstalk
   – need good heatsinking to accommodate high x-ray fluxes



thick Au layer

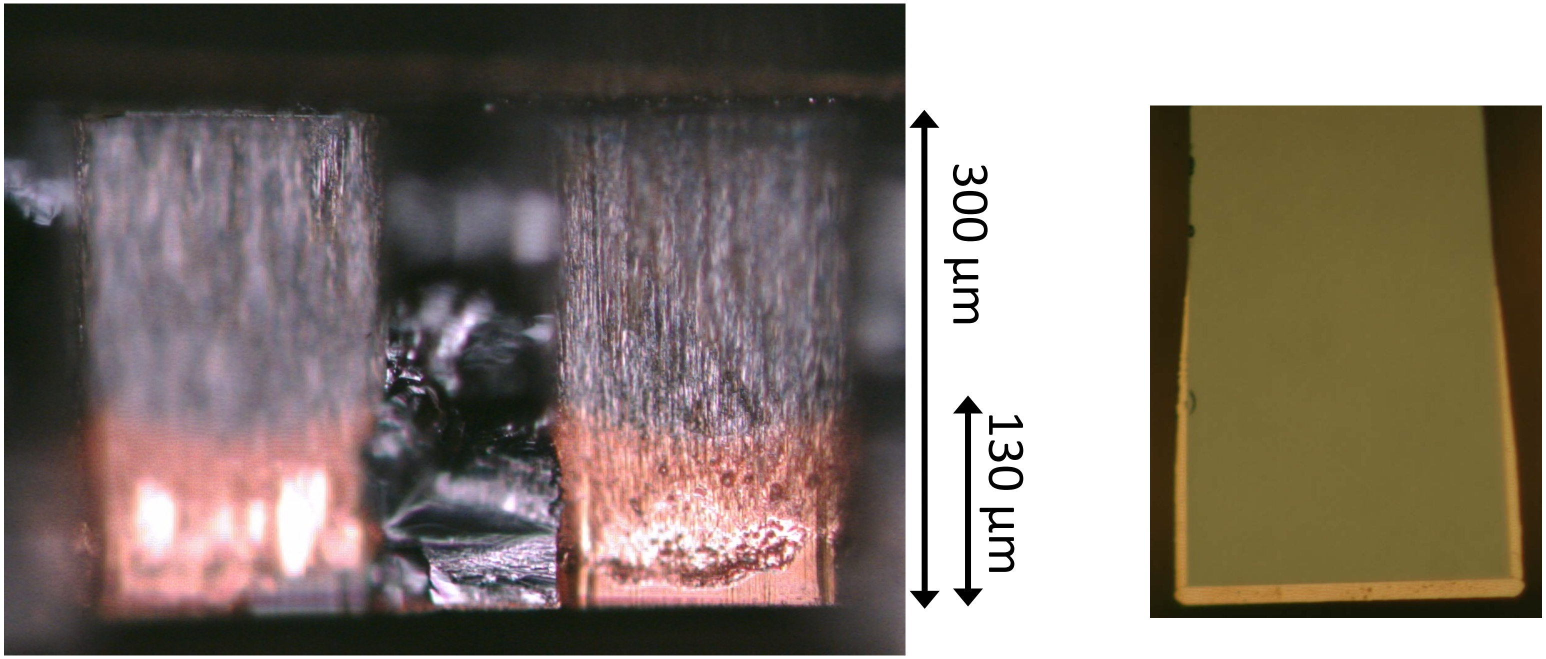
connect to heat sink with Au bonds

## Improve heatsinking: Coat sidewalls of wells with thick Cu



- steep angle deposition from back
- rotating jig to deposit on all four sidewalls

- remove DRIE passivant before deposition to ensure good Si/Cu conductance

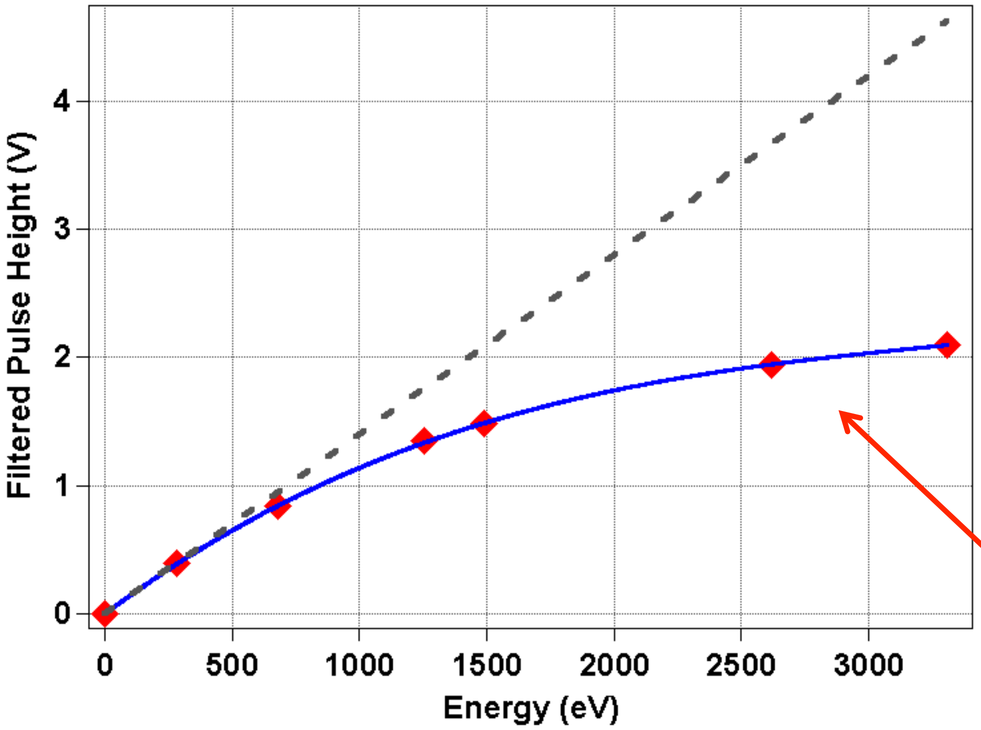


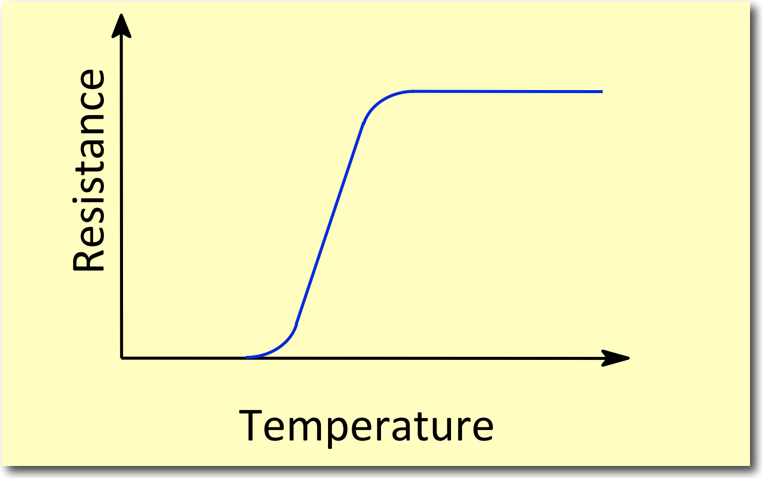
40% coating of sidewalls on this wafer (80% currently possible)
3.5 micron thick

# Reduced Heat Capacity Devices (1)

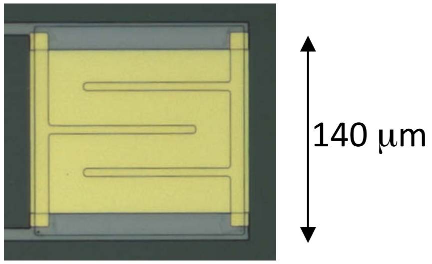
## X-ray TES Microcalorimeters

## Typical low-C response in soft X-ray band:





low heat-capacity “bare” TES



**Heat capacity *C* ~ 0.1 pJ/K (x10 smaller than standard design)**

$$\Delta E \propto T\, C^{0.5}$$

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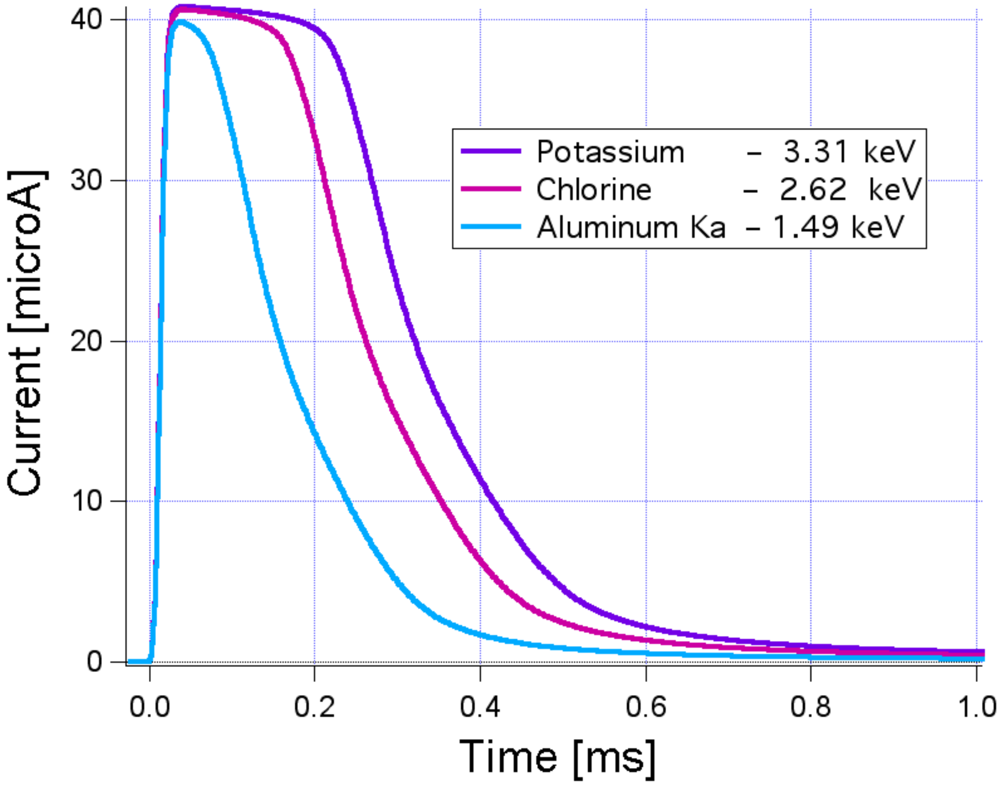

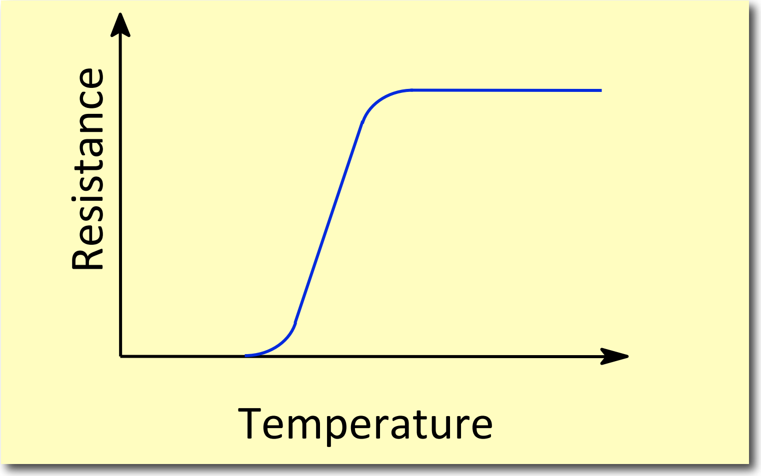

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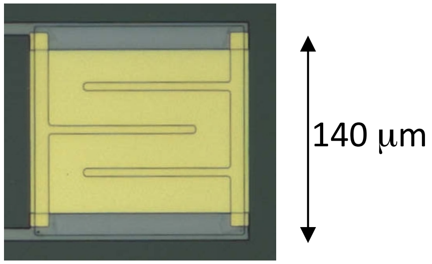

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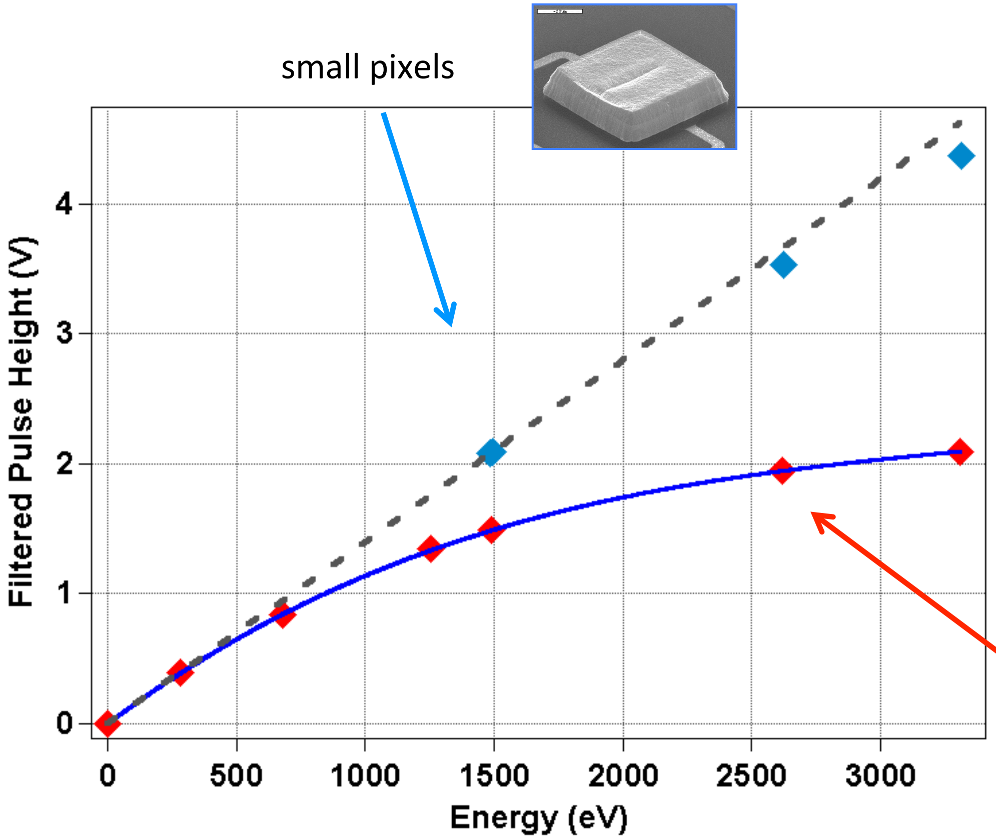
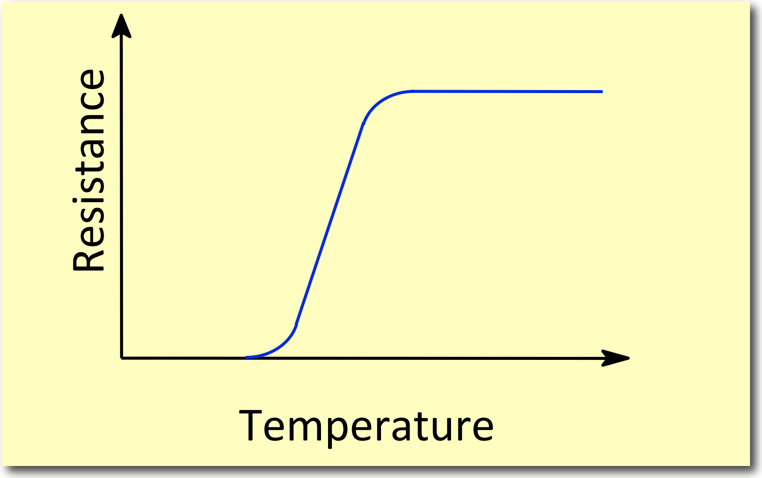
# New operating regime for X-ray TESs – soft saturation:





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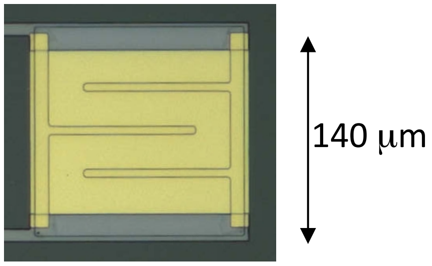

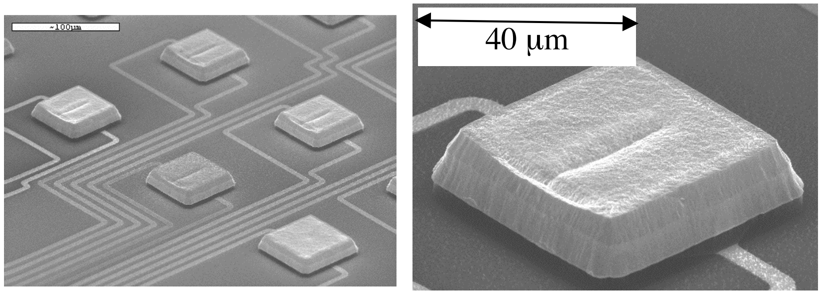

miniaturized pixel: 35 μm TES, 57 μm x 57 μm x 4.5 μm absorber

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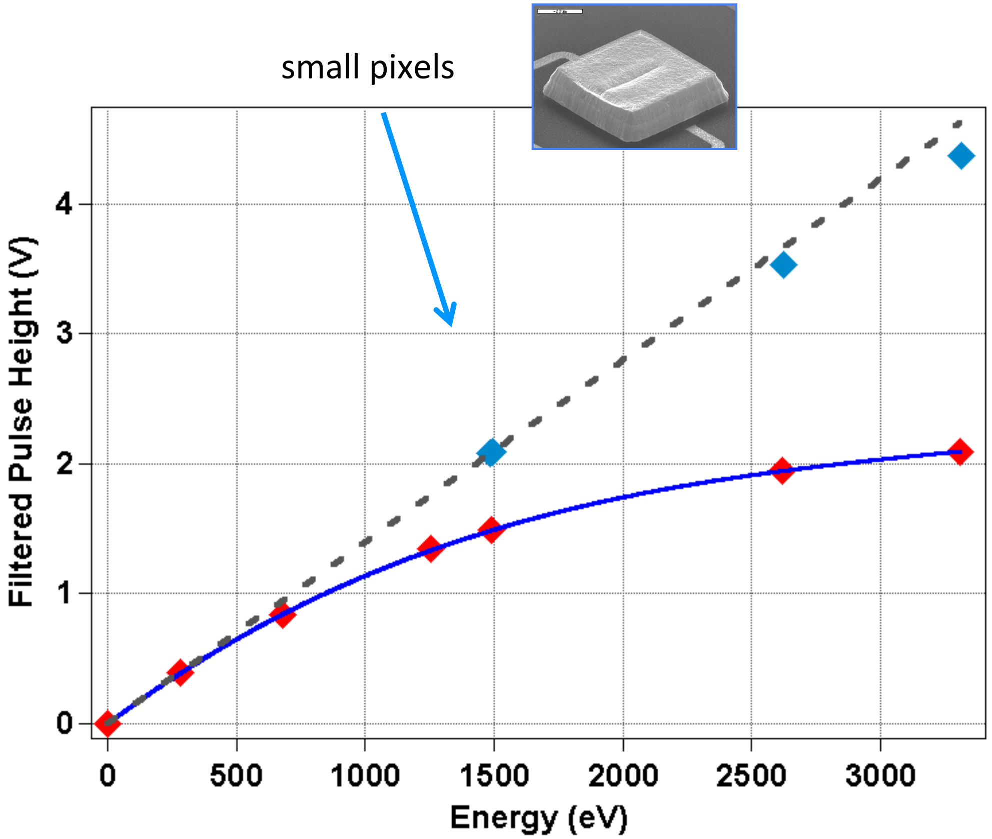
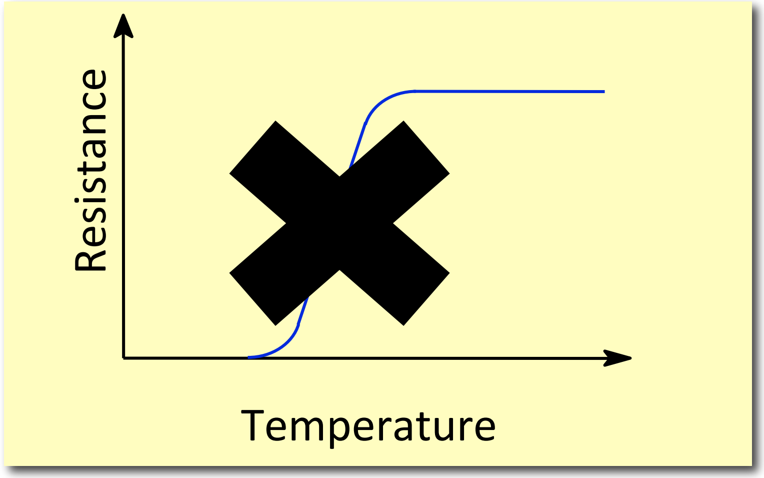
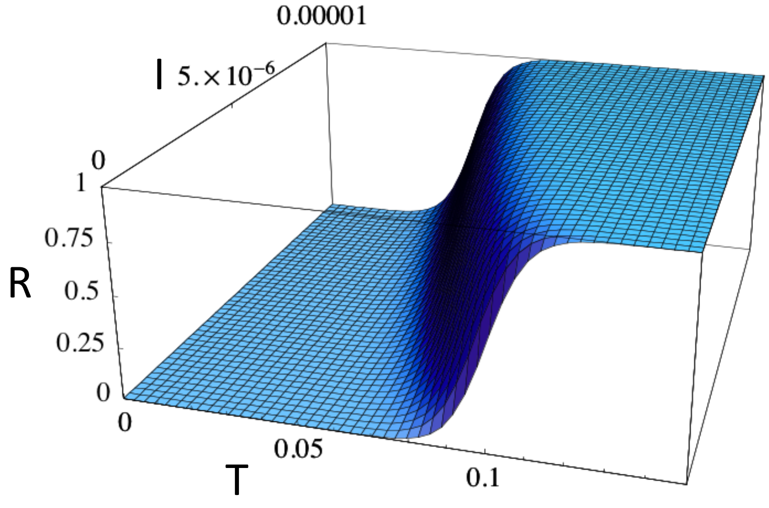






R-I-T Surface

highly current dependent transition

enabled good energy resolution over extended energy range, and $\Delta E_{FWHM}$ = 0.72 eV at 1.5 keV

# Reduced Heat Capacity Devices (2)

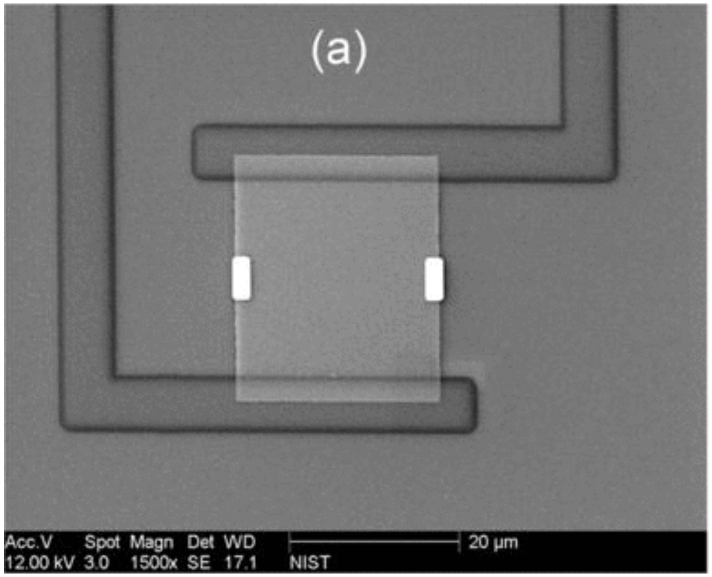
## Optical TES Microcalorimeters

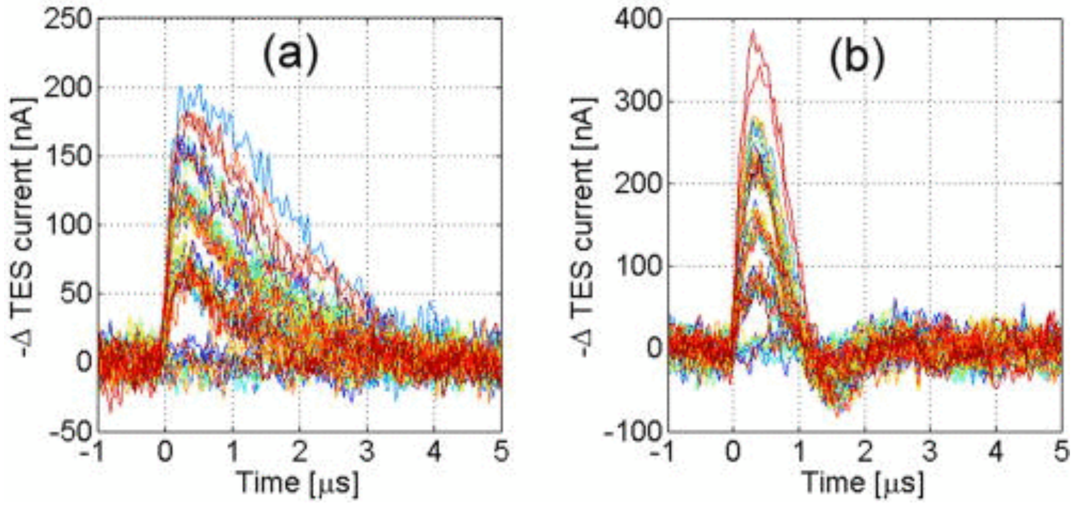
# Optical TES Microcalorimeters

Stanford (Cabrera et al.), NIST/Boulder (Nam, Lita et al.)

## Example of NIST/Boulder optical devices:

- W-TES with Al leads (also explored Hf-TES)
- device Tc tuned to ~150mK
- 25 x 25 µm$^2$
- Detecting photons of 0.6 eV (2 µm) – 3 eV (400 nm)
- push to get high QE, low timing jitter, faster decay times

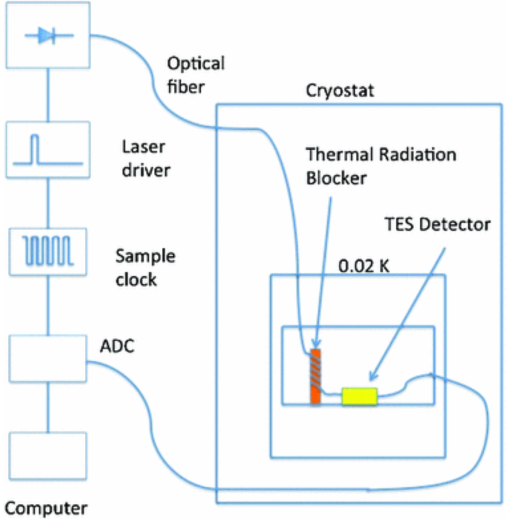


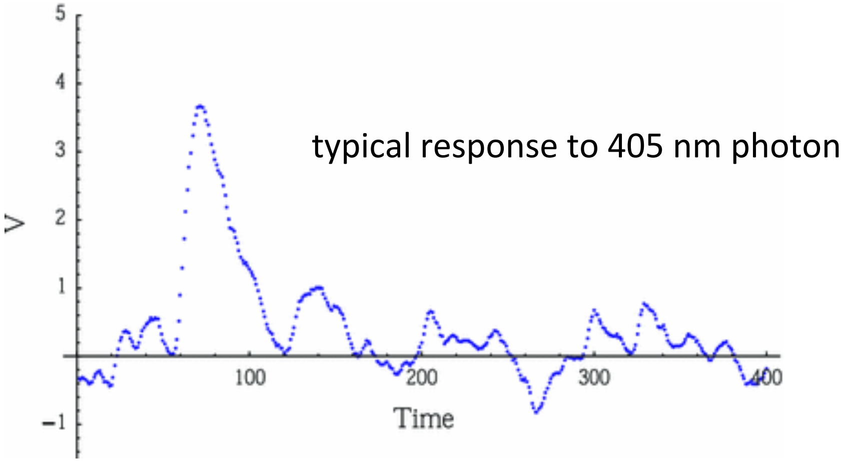


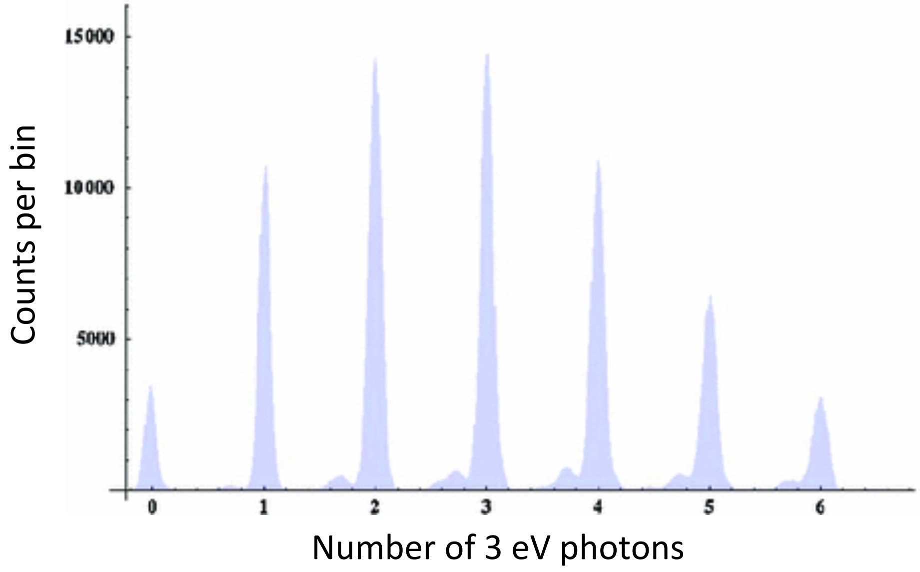
B. Calkins, A. Lita, A. Fox, and S. W. Nam. *APL* (2011).

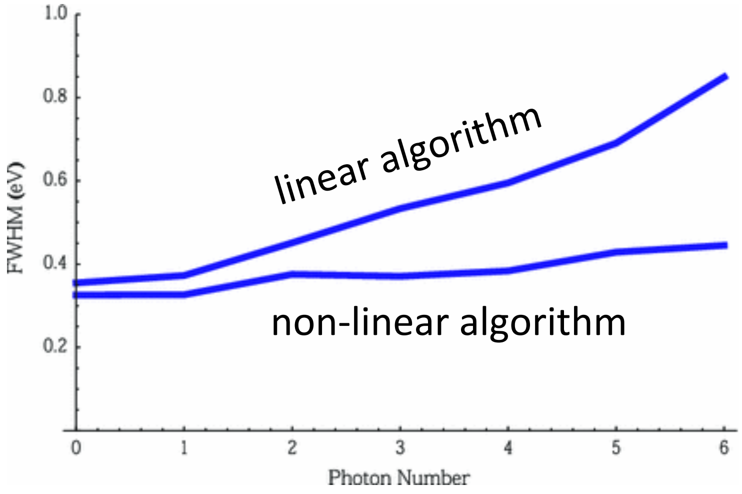
# Optical TES Microcalorimeters – with advanced pulse processing

retaining energy resolving power beyond linear range









D.J. Fixsen, S.H. Moseley, T. Gerrits, A.E. Lita, S.W. Nam. *J. Low Temp. Phys.* (2014)

Lower energy optimization thoughts:

smaller C:
how: smaller device volume, different materials
cautions: often means smaller collecting area; in case of smaller TESs, proximity from leads can raise $T_c$ and change transition shape

lower operating T:
how: can tune sensor operating temperature – bilayer thicknesses (Mo/Au, Mo/Cu) or crystal structure (W)
cautions: only gain like sqrt(T), requires lower heatsink temperature

increase $\alpha$:
how: not straightforward, change normal metal features on TESs, …
cautions: we observe excess noise ($M^2$ term) with high $\alpha$

advanced pulse processing techniques: retain device performance into saturated regime
cautions: calibration needs increase significantly