transition-edge sensors for precision measurements from γ-ray to submm wavelengths

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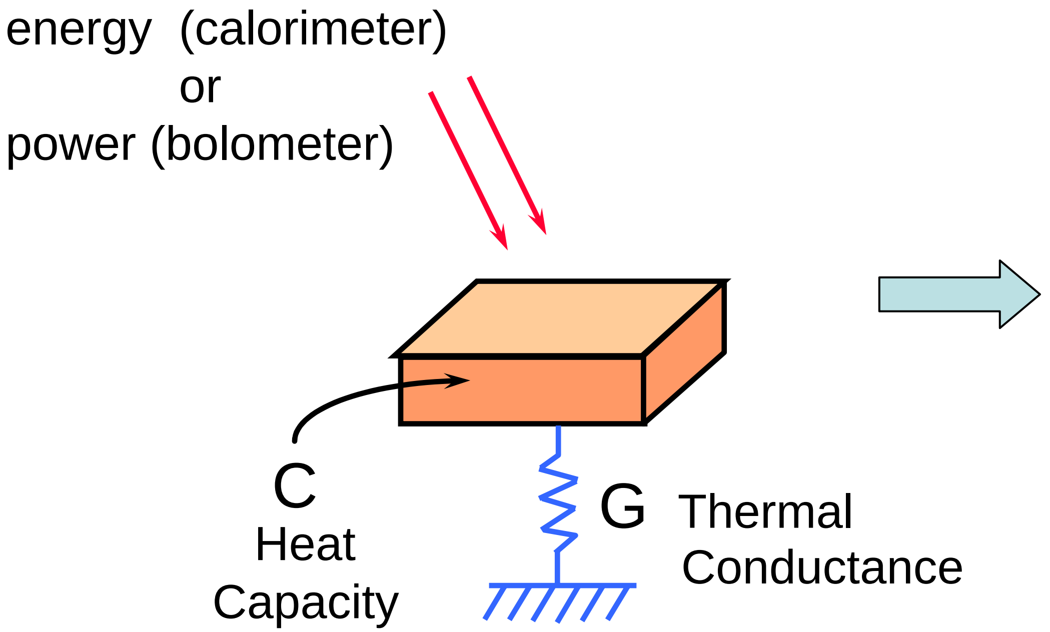
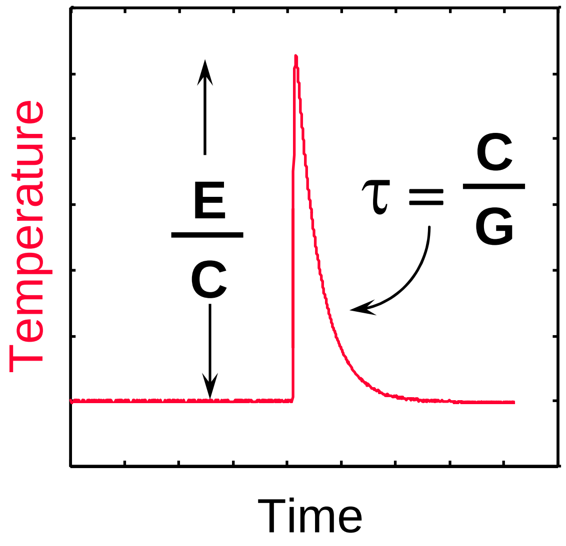
Thermal sensors





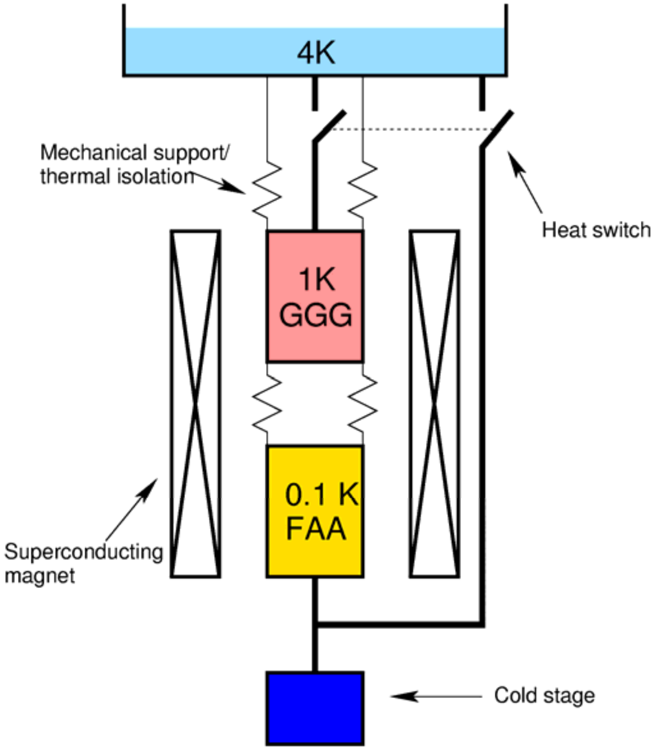
- Noise source: power fluctuations P_N in thermal conductance: $(4k_bT^2G)^{1/2}$ W/Hz$^{1/2}$
- For calorimeters, $\Delta E = P_N * \tau * (\text{bandwidth})^{1/2} \sim (4k_bT^2G)^{1/2} * (C/G)^{1/2} \sim (k_bT^2C)^{1/2}$ J
- So, sensor performance best at low temperatures:

  At 0.1 K, C = 1 pJ/K, G = 1 nW/K reasonable ⇨

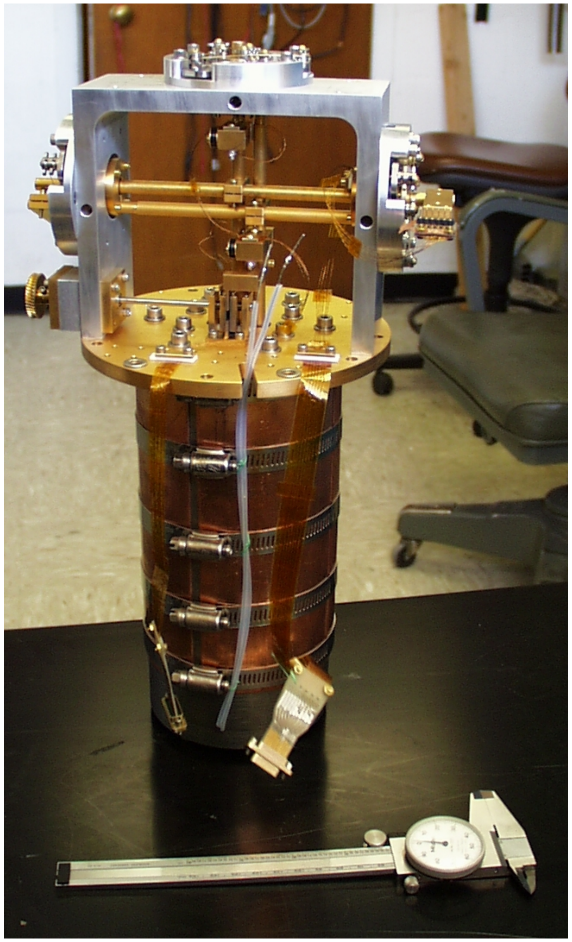
NEP = $2 * 10^{-17}$ W/Hz$^{1/2}$, ΔE = 2 eV

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

Simple 100 mK cryogenics



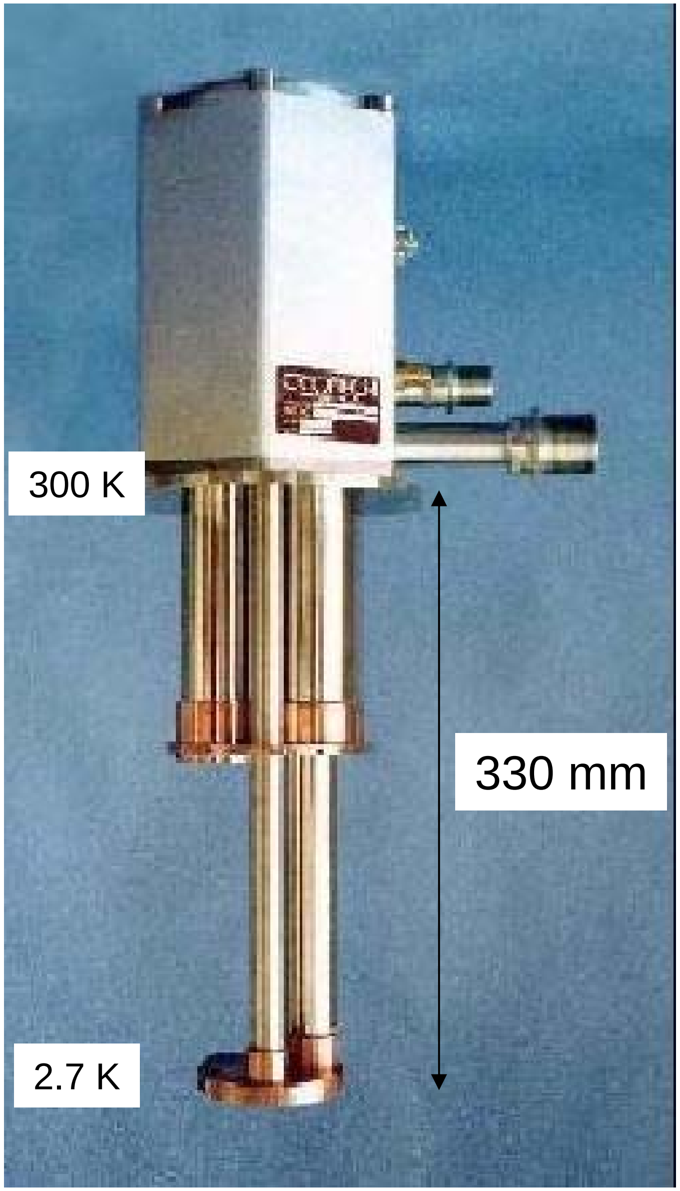
2-stage adiabatic demagnetization refrigerator (ADR)



NIST 2-stage ADR - licensed and now available commercially

ADR and cryogen vessels mounted on SEM

Getting to 4 Kelvin

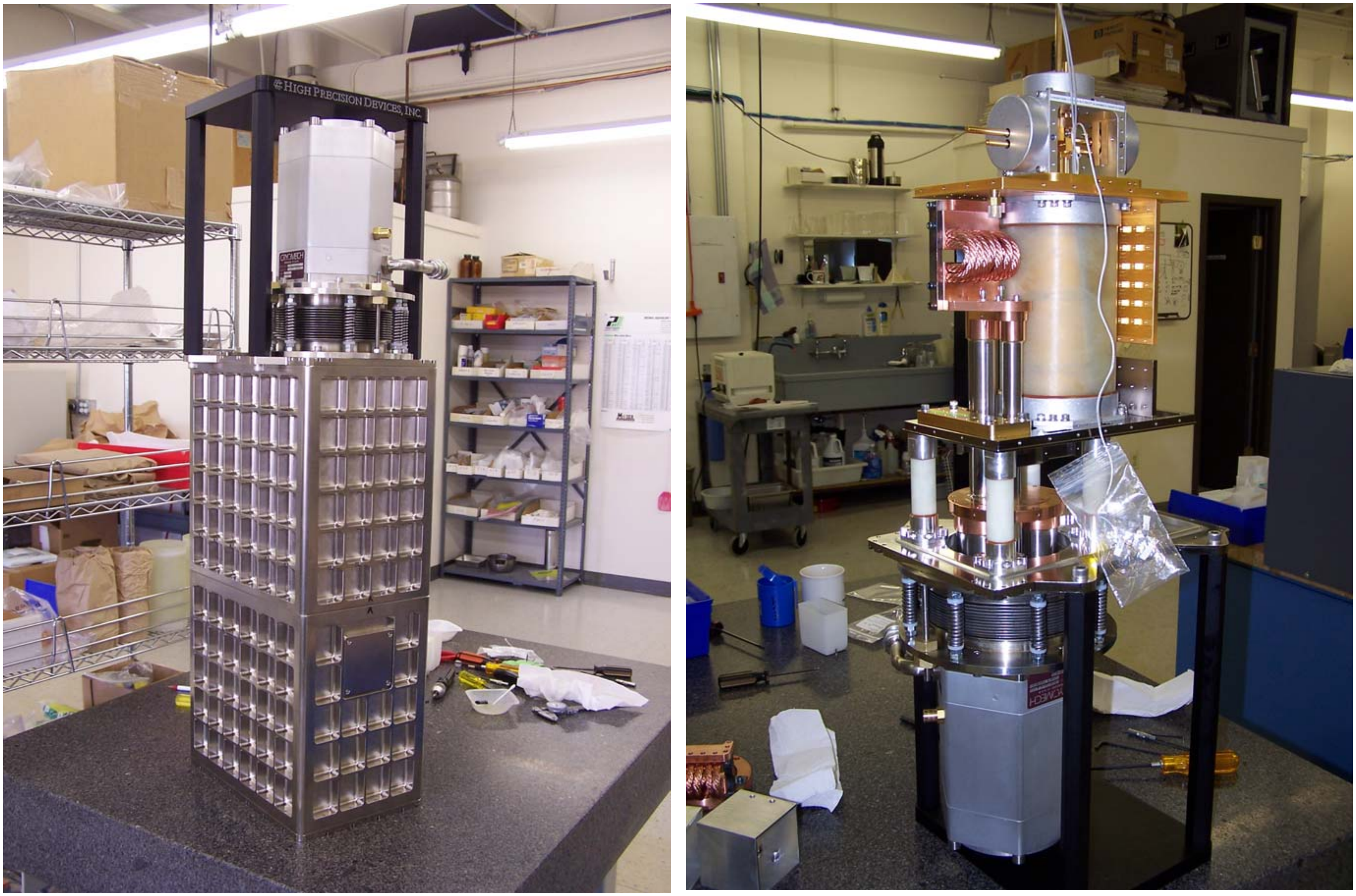


- Traditionally, use LN_2 and LHe
    - expensive (LHe = $5/liter)
    - requires skilled users
    - explosion risk
    - not suitable for field use

- More recently, mechanical cryocoolers: perform thermodynamic cycle on sealed working gas (He)
    - push-button operation
    - only consumable = electricity
    - some vibration signature

pulse tube cryocooler

NIST-designed cryogen-free 100 mK refrigerator

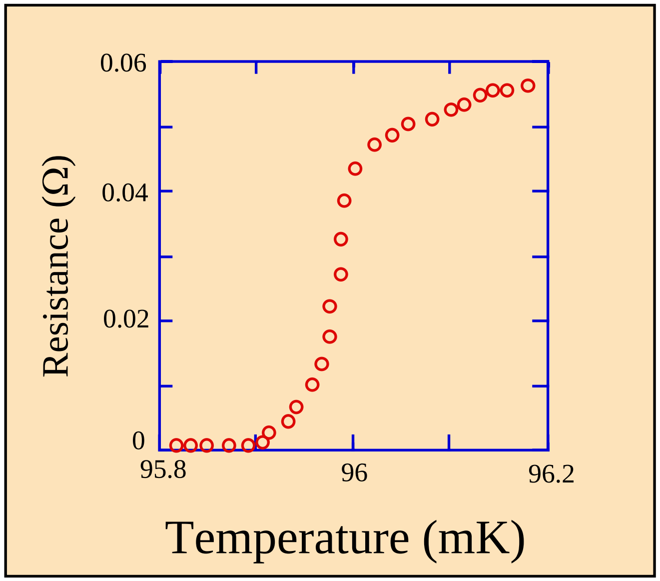


Superconducting Transition-Edge Sensor (TES) thermometer

- Transition-Edge Sensor (TES) = thin-film biased in superconducting-normal transition

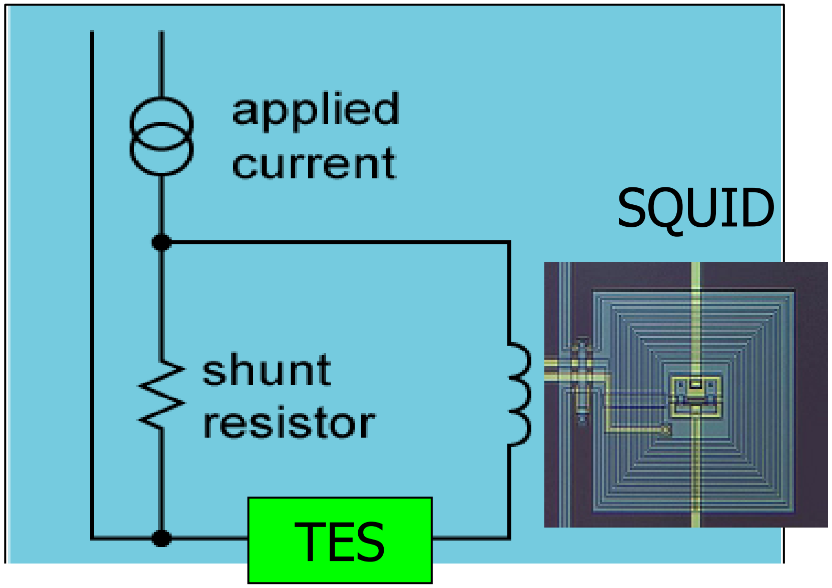
- Use strong dR/dT in transition as thermometer

- Historically, the TES was *too sensitive*: difficult to temperature bias, and low count rate. This was fixed by the introduction of voltage biasing and electrothermal feedback.



Electrical circuit and negative electrothermal feedback

electrical circuit



TES is voltage biased

$$P_{bias} = \frac{V^2}{R}$$

deposited energy increases T & R

→

1. decrease in current to SQUID = signal
2. reduction in bias power accelerates return to T_o

electrothermal feedback provides improved stability and speed

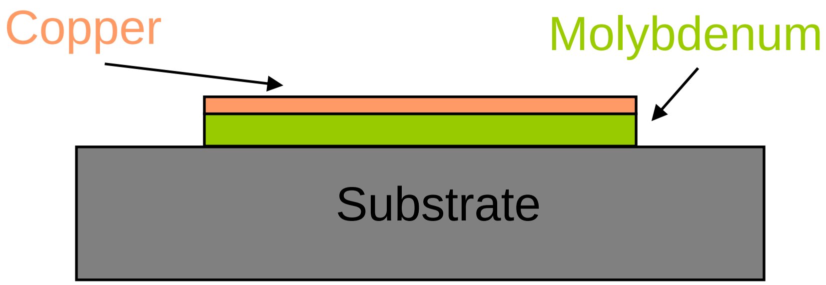
Implementation of TES: Mo-Cu bilayer

- molybdenum-copper:

  robust and temperature stable

Molybdenum	$T_c \sim .92$ K
Copper	normal

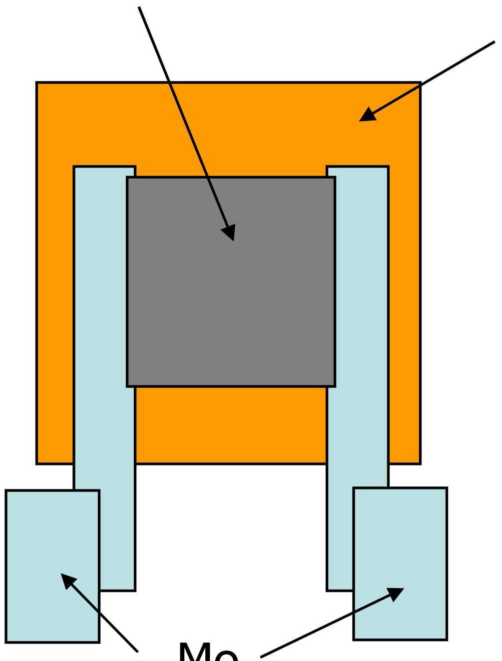
- a bilayer of a superconducting and a normal film acts as a single superconductor with a tunable T_c via the proximity effect



- Sharp
- Tunable
- Robust

TES microcalorimeter schematic

top view

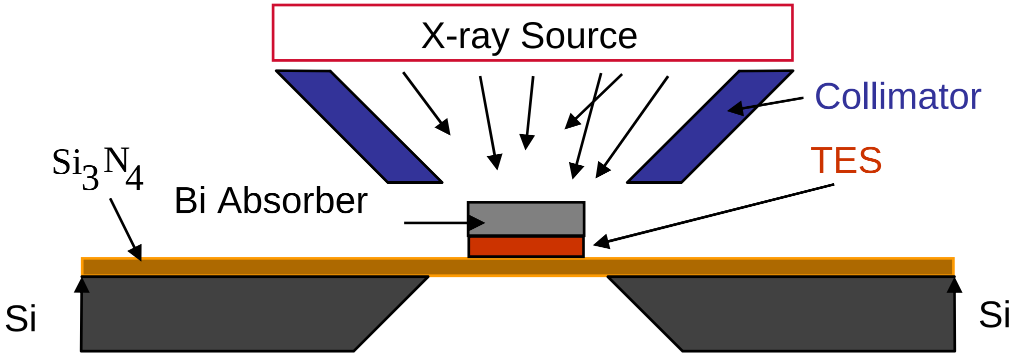


TES and absorber
400 μm x 400 μm

Si_3N_4
Membrane

Mo
Contacts

side view



X-ray Source

Collimator

TES

Si_3N_4

Bi Absorber

Si

Si

X-ray application #1: materials analysis

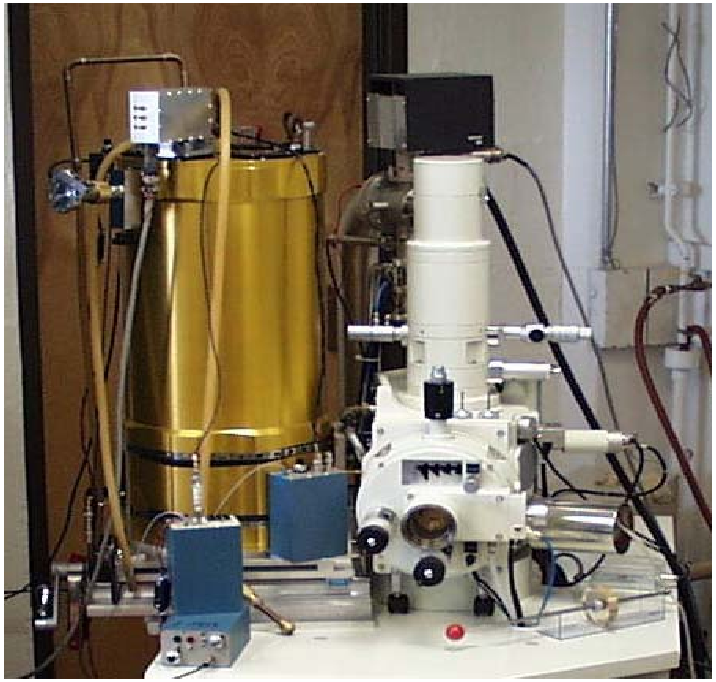
- x-ray spectroscopy is a powerful tool for materials analysis
- commonly performed on scanning electron microscopes (SEMs) and at synchrotrons
- existing technologies:
  - semiconductor EDS
    - ubiquitous
    - large collecting areas and count rates
    - but resolution ~ 100 eV

  - WDS
    - high resolution
    - but smaller collecting area & broad-band operation complicated

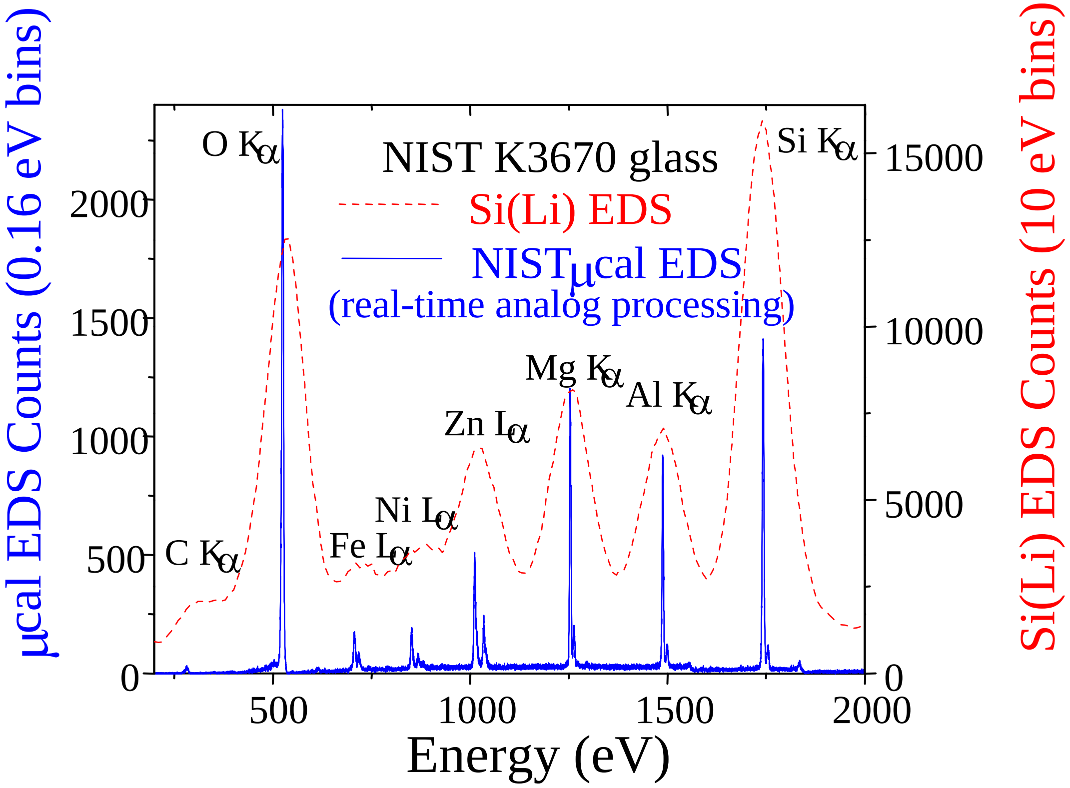
- cryogenic microcalorimeters combine advantages of EDS and WDS:
  - broad-band (500 eV - 10 keV easy)
  - high resolution (few eV)
  - moderate collecting area

Microcalorimeters for materials analysis

adiabatic demagnetization refrigerator & microcalorimeter mounted on SEM: units at Boulder & Gaithersburg



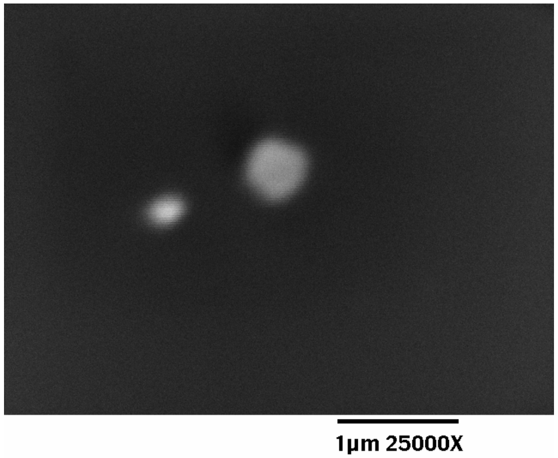
microcalorimeter and Si(Li) spectra of reference glass



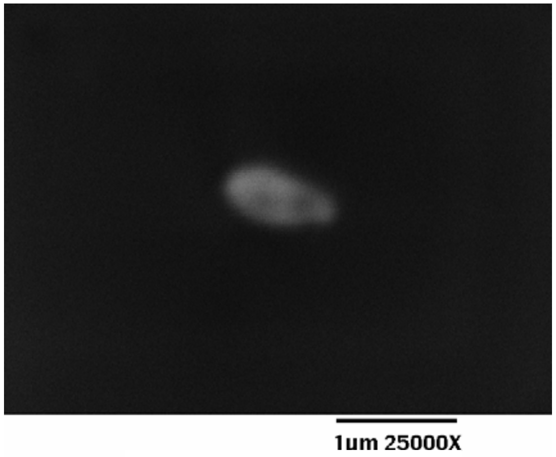
Nanoparticle analysis with microcalorimeters

industrially important problem: particles

spatial images

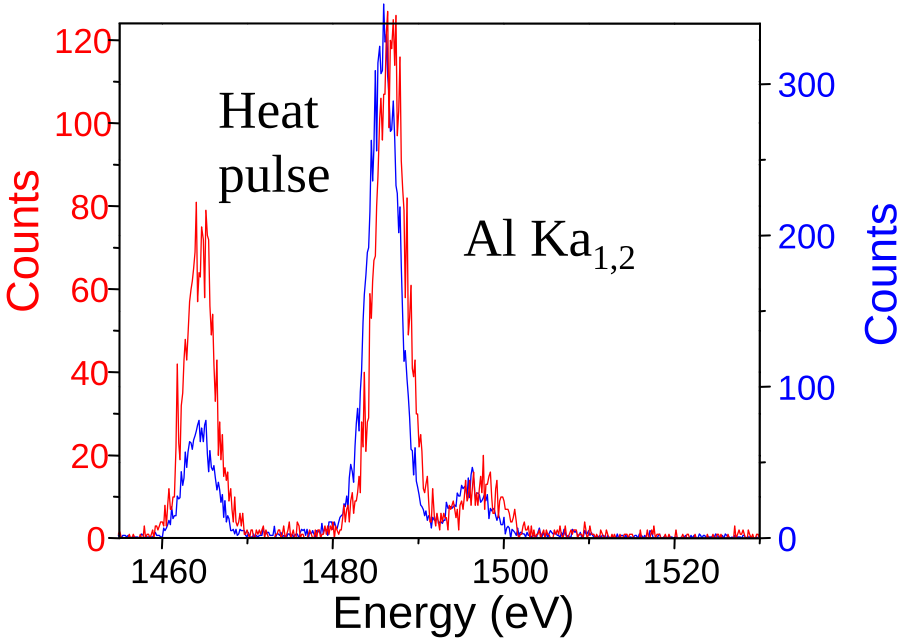


Al oxide particle



Al particle

x-ray spectra



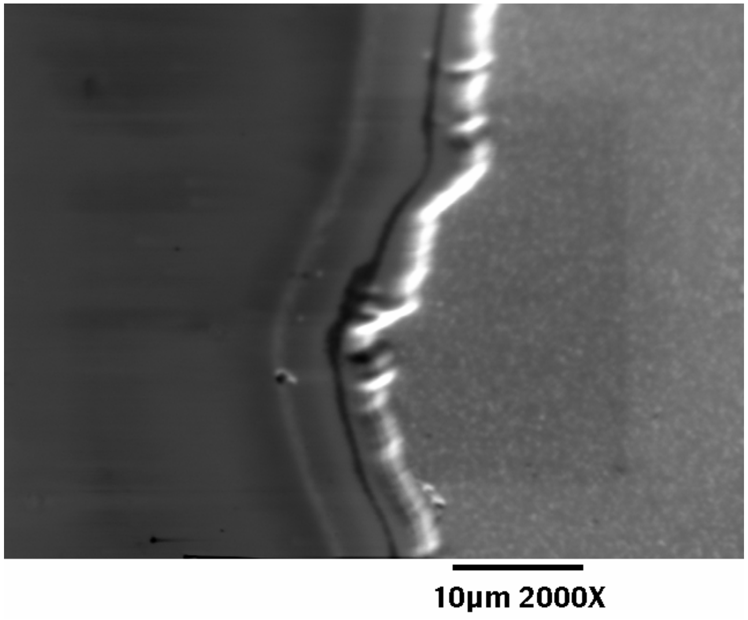
- Al K lines clearly isolated from Si
- Chemical bonding state causes small (< 1 eV) shifts in Al K line position

⇒ distinguish Al from AlOx !

Particle samples provided by
Alan Diebold (SEMATECH)

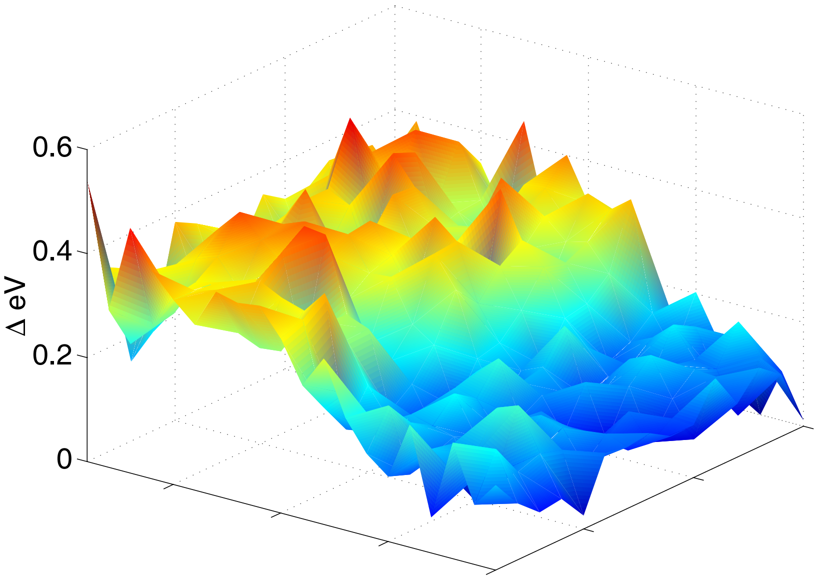
Chemical shift map in SEM

spatial image



Al oxide Al

microcalorimeter measurement of Al K peak energy

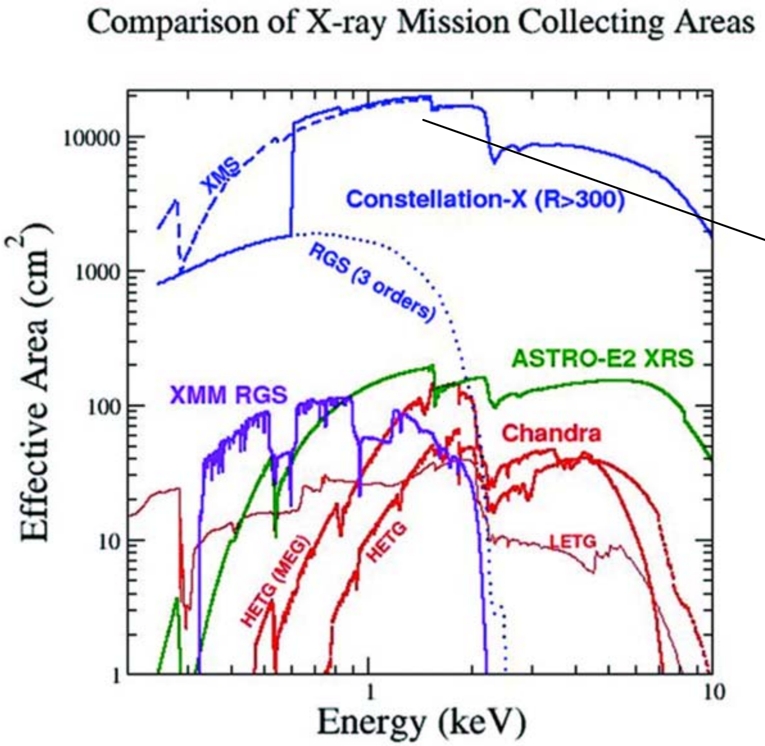


Al oxide Al

credit: Nam and Wollman (NIST)

X-ray application #2: astronomy

- The universe is filled with hot objects that radiate at x-ray wavelengths:
  supernovae remnants, active galactic nuclei, black hole accretion disks, etc.
- Constellation-X is NASA’s next planned x-ray satellite (2015 ?)
- TES microcalorimeters are well suited for x-ray astrophysics:
  broad-band, high spectral resolution, and high quantum efficiency
- NIST is collaborating with NASA GSFC to build a 1,000 TES array & SQUID readout.



Comparison of X-ray Mission Collecting Areas

developing high QE, high fill fraction sensors

x100 increase in effective area:

x20 from mirror

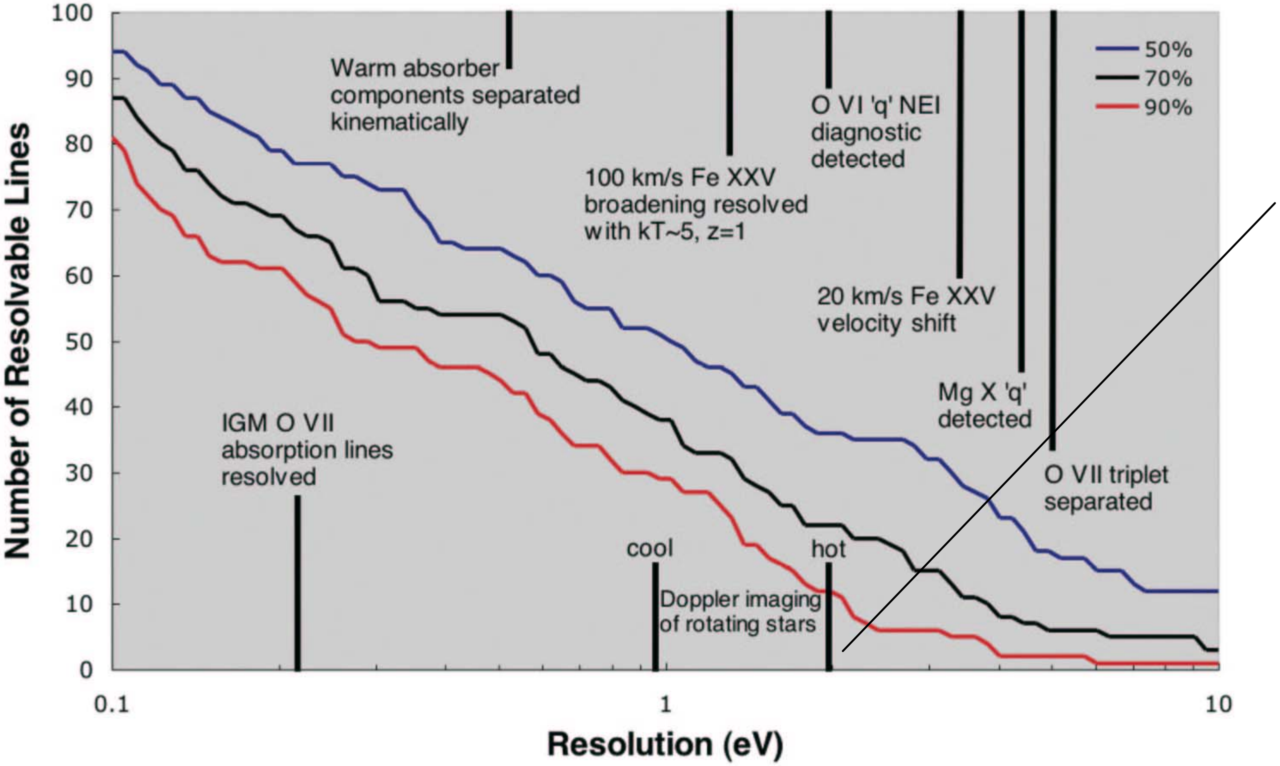
x5 from TES

X-ray application #2: astronomy

science goals for ConX include:

- measure density, temperature, and velocity of plasmas
- observe material orbiting & entering black holes, test GR in strong limit

science return vs detector performance



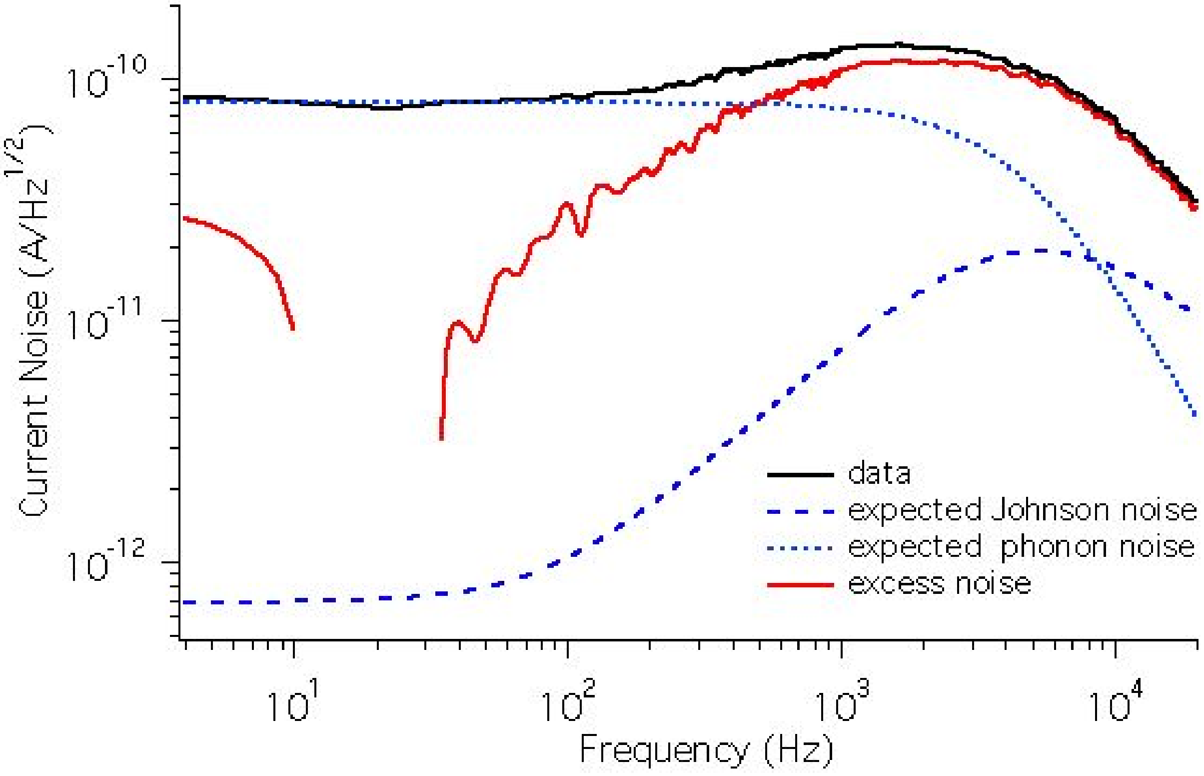
ConX goal:
2 eV resolution

Current research: improving sensor resolution

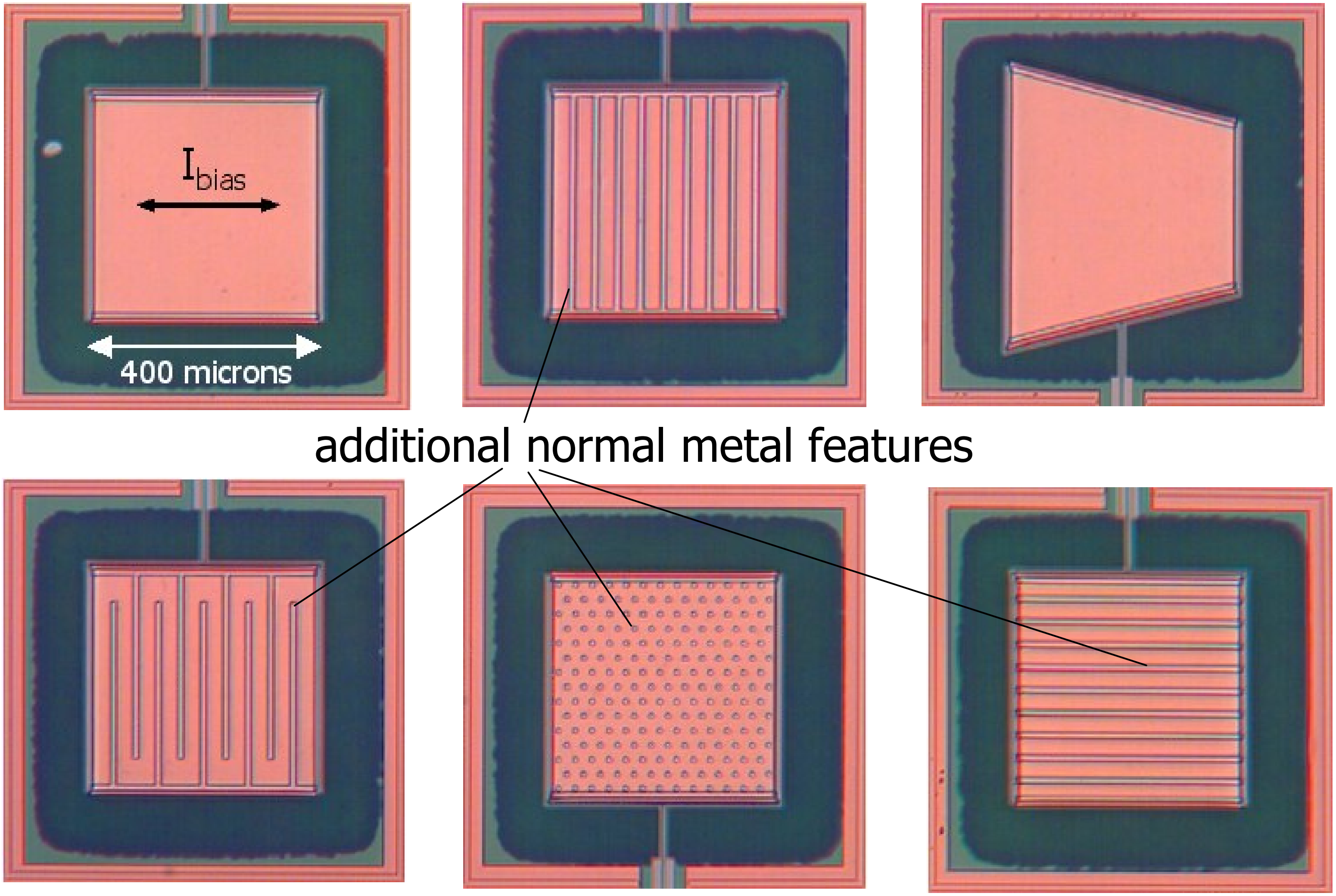
- circa 2004: sensor resolution = 4 - 4.5 eV at 5.9 keV

but

- better resolution predicted theoretically & goal for Constellation-X = 2 eV
- sensors not reaching theoretical resolution limit due to unexplained noise:



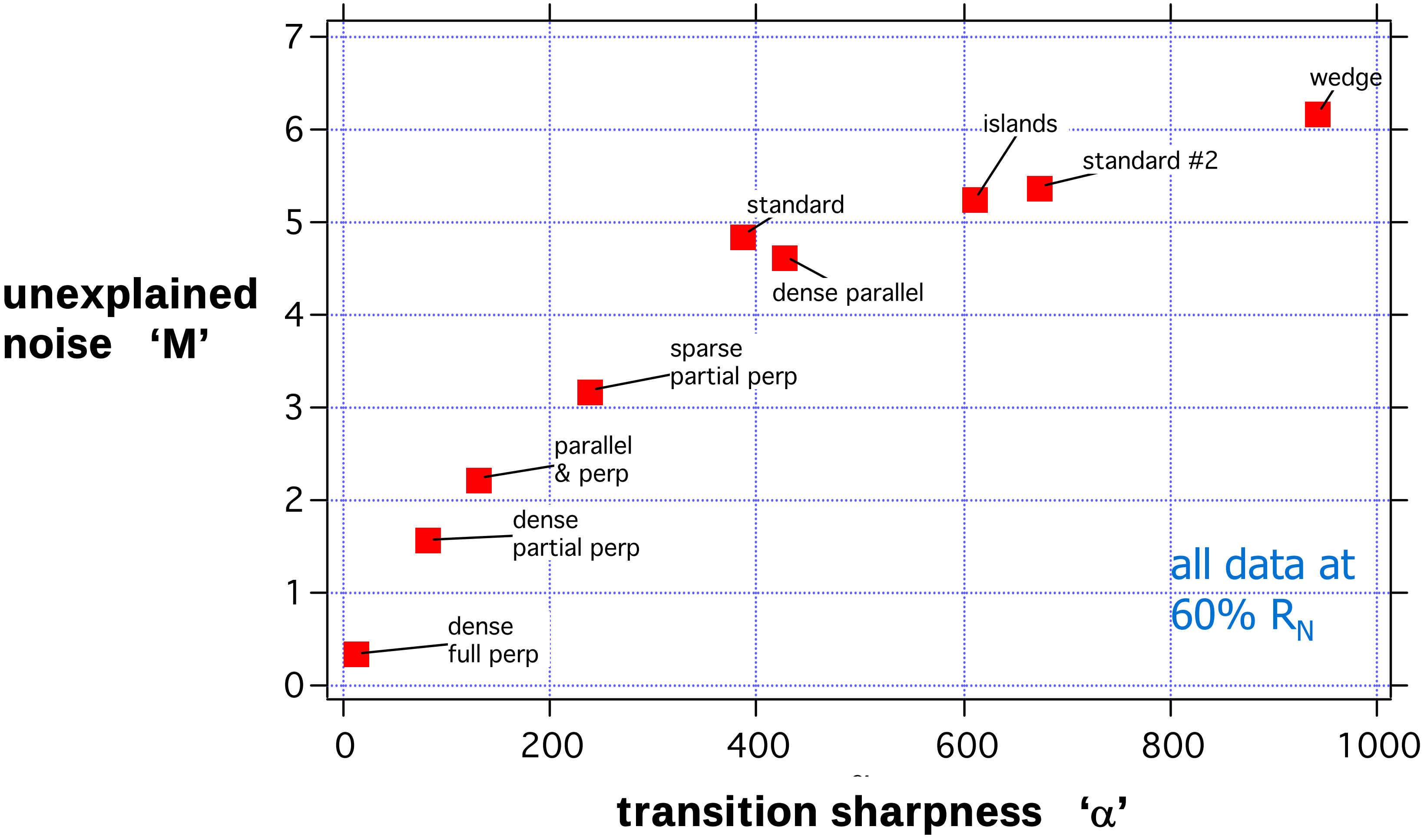
Effects of geometry



additional normal metal features

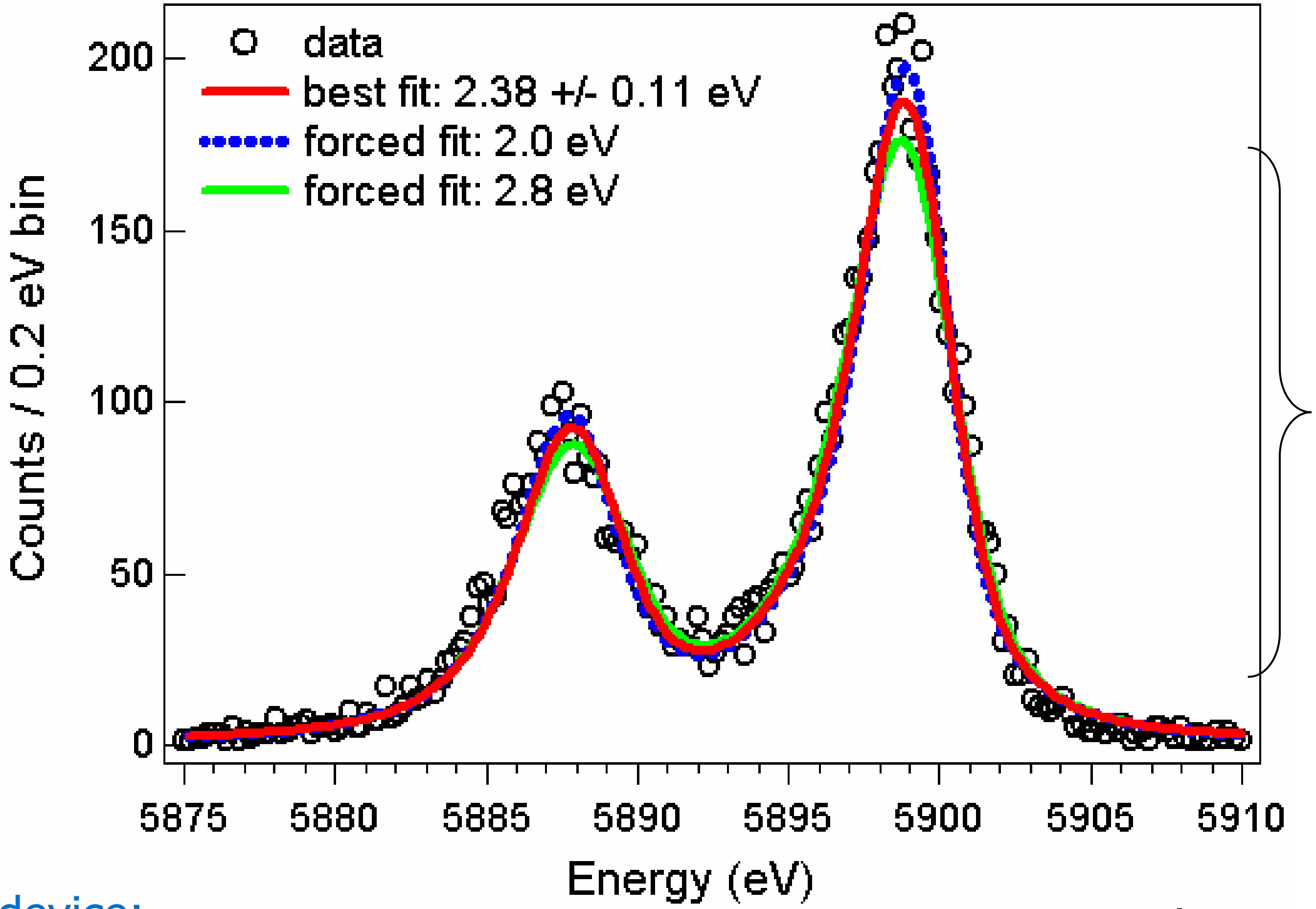
how does noise scale with geometry ?

Noise vs. geometry: unexplained noise and α correlated



- low α designs have little unexplained noise
- perpendicular normal features reduce noise and α

Optimized TES: energy resolution = 2.4 eV FWHM at 5.9 keV



7,754 counts

useful device:

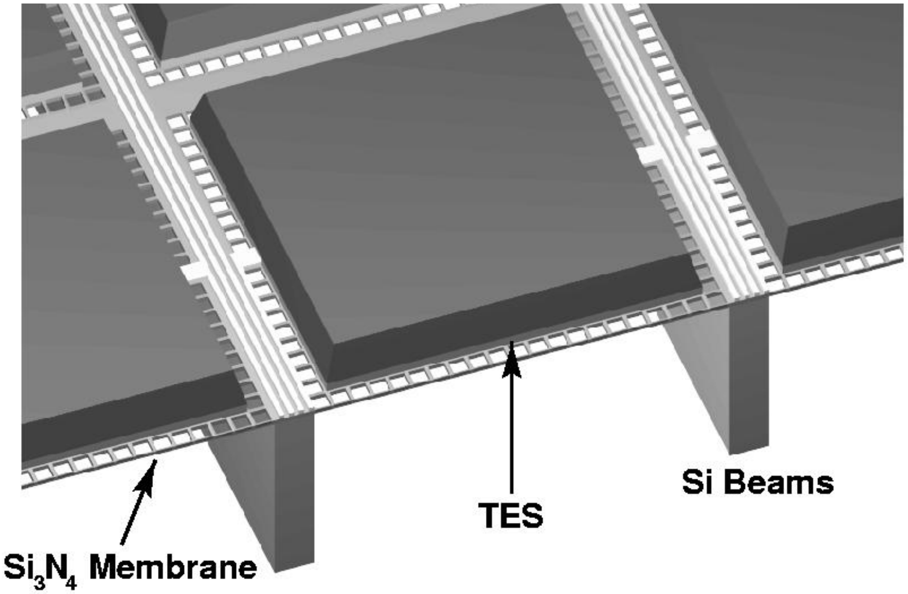
- integrated into close-packed array
- 1.5 μm Bi absorber ⇨ QE ~ 55% at 5.9 keV
- 260 μs decay time

best resolution of any energy-dispersive detector at 6 keV

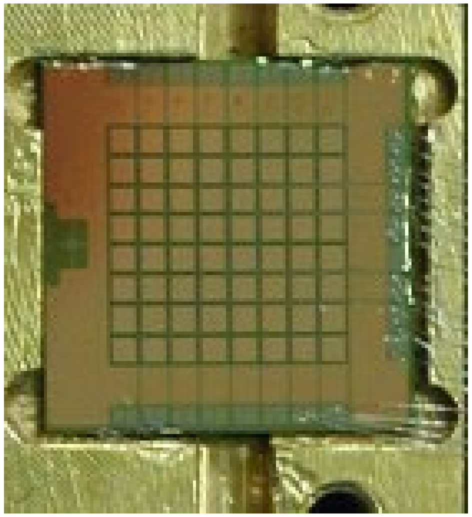
TES arrays

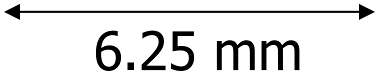
- use deep reactive ion etching (DRIE) to remove substrate beneath pixels & achieve necessary thermal isolation
- use remaining Si beams for wiring, indium bumps, or through-wafer vias

array schematic



64 pixel x-ray array





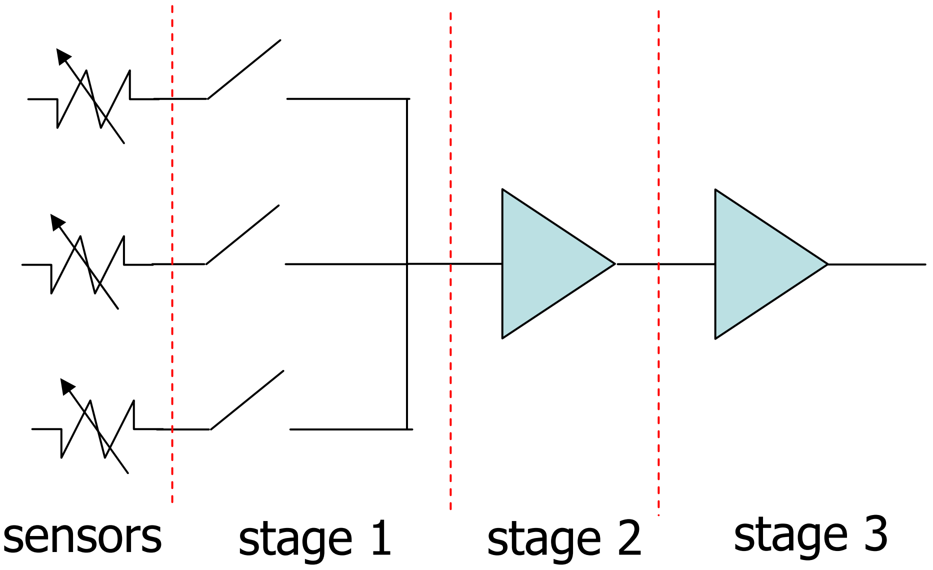
Readout of large sensor arrays

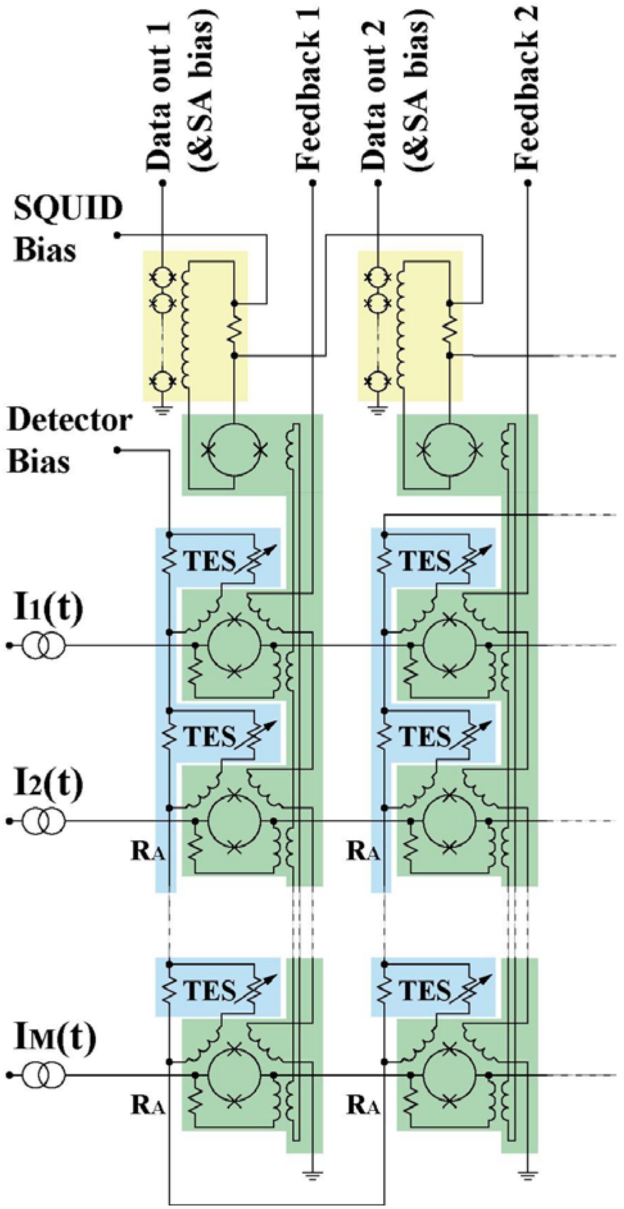
use time-domain SQUID multiplexing:

- 1 amplifier chain/column of sensors
- amplifier chain = 3 SQUID stages
- stages 2 & 3 shared between sensors of column
- each sensor has own squid (stage 1), used as switch

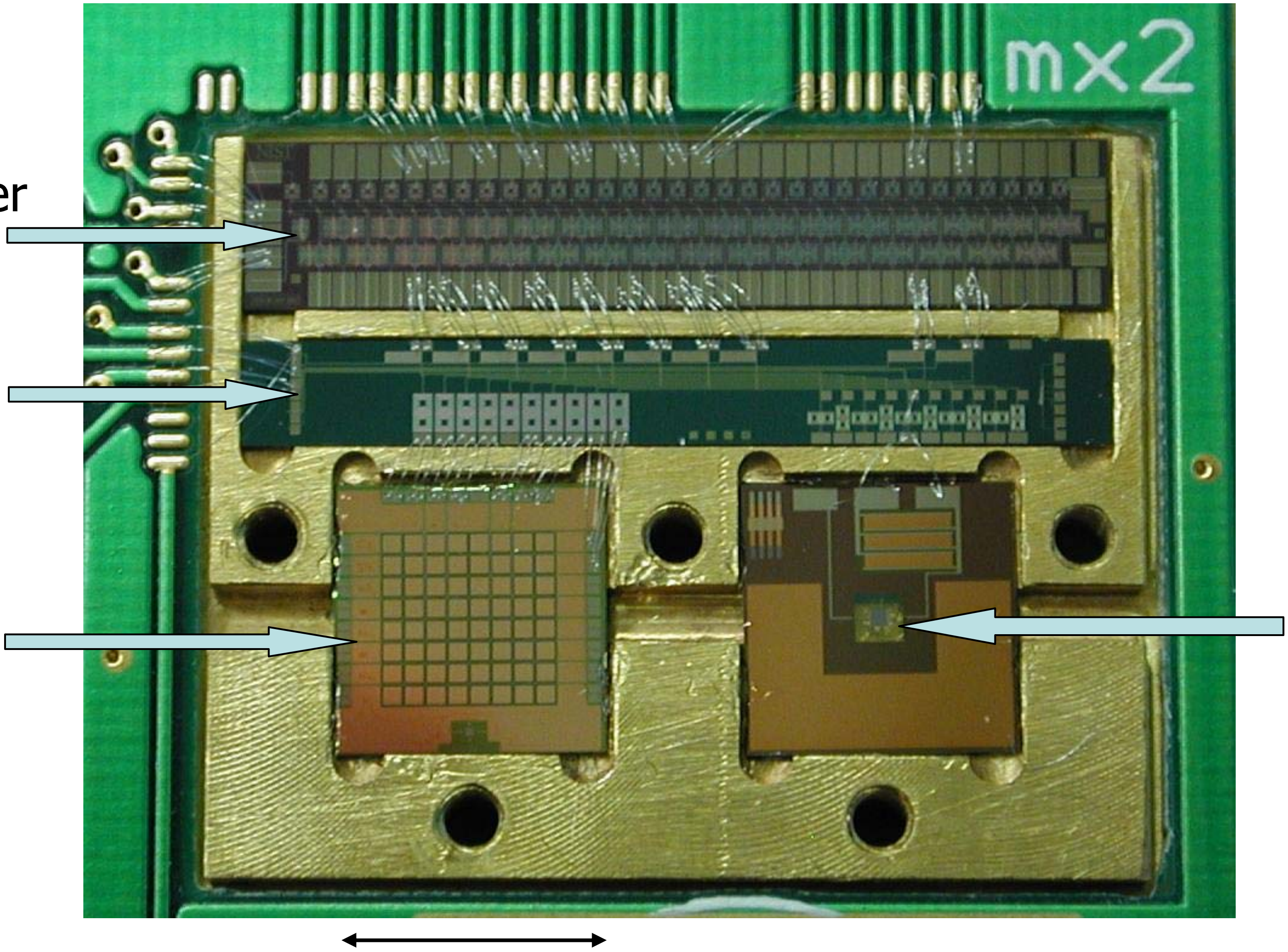
concept

implementation





Multiplexing test setup



multiplexer chip

interface chip

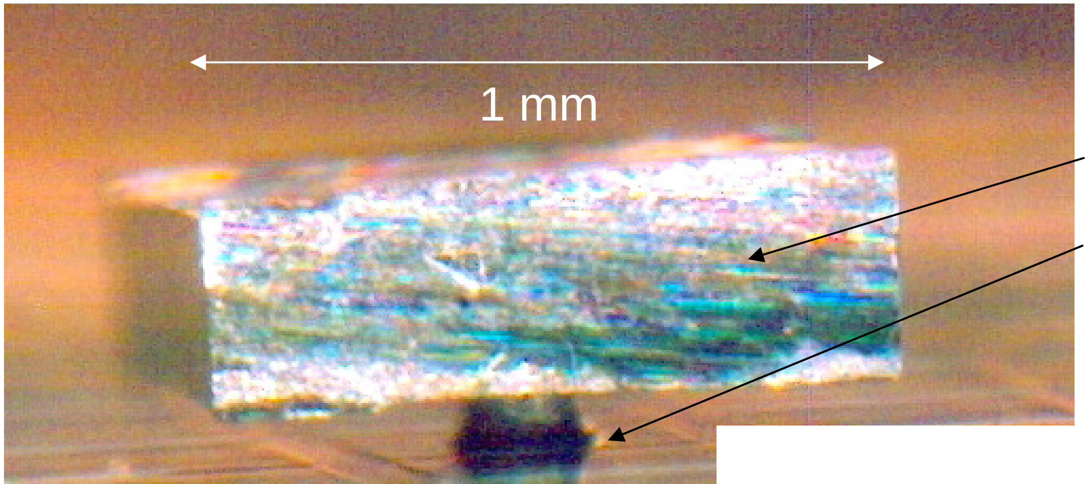
8 x 8 sensor array

individual sensor

6.25 mm

have muxed 16 pixels with 4.7 eV resolution at 6 keV (degraded from 4.2 eV)

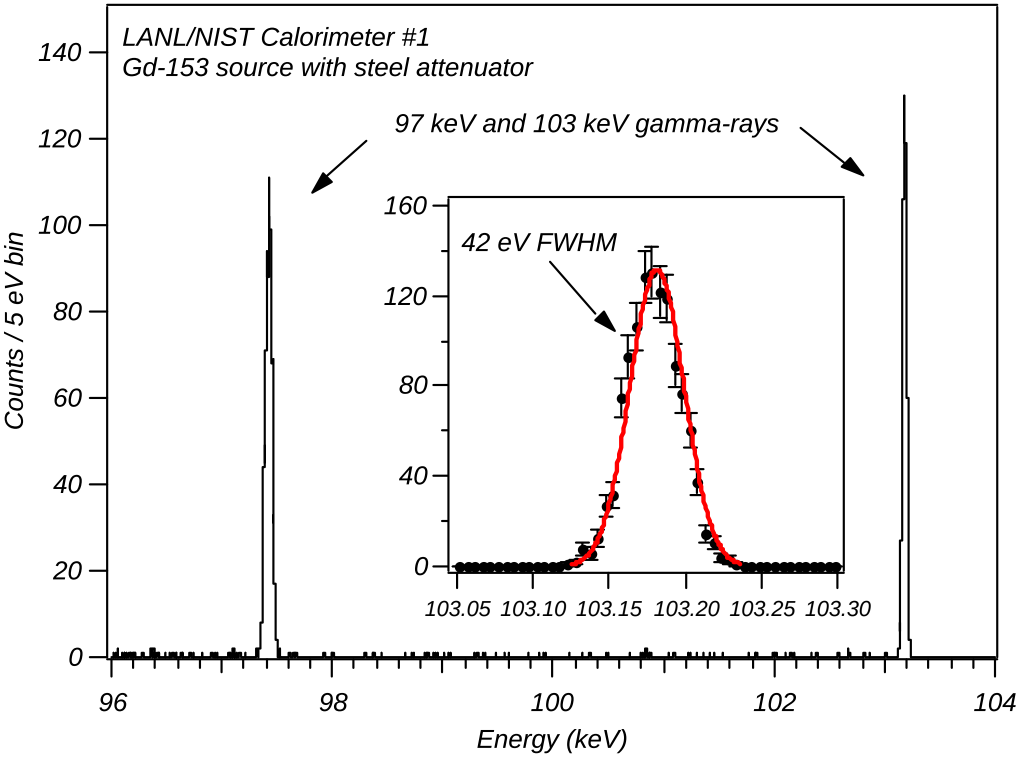
Can TES’s detect γ-rays ? Yes, with bulk absorbers



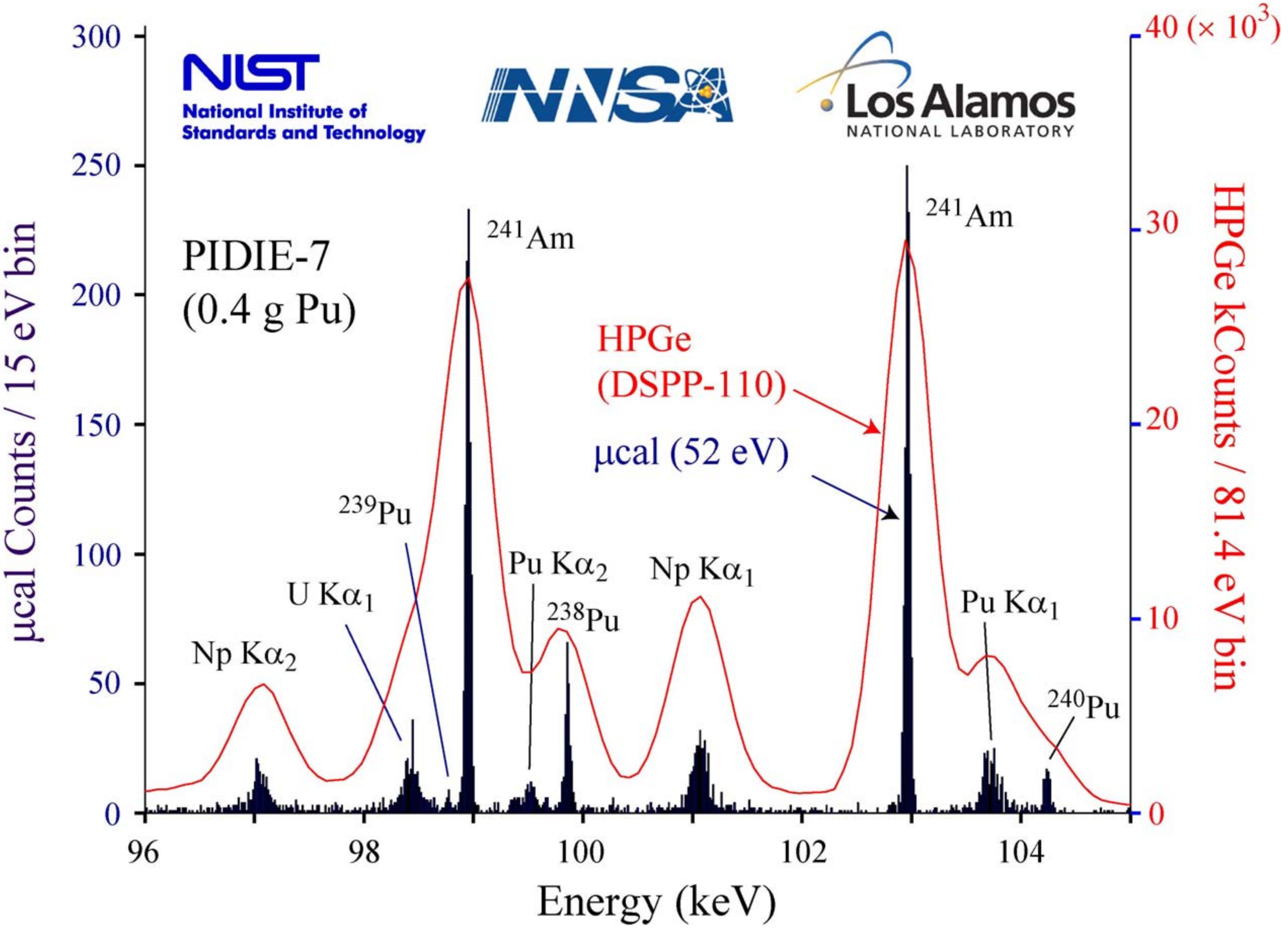
Sn aborber: QE ~25% at 100 keV

Mo/Cu TES

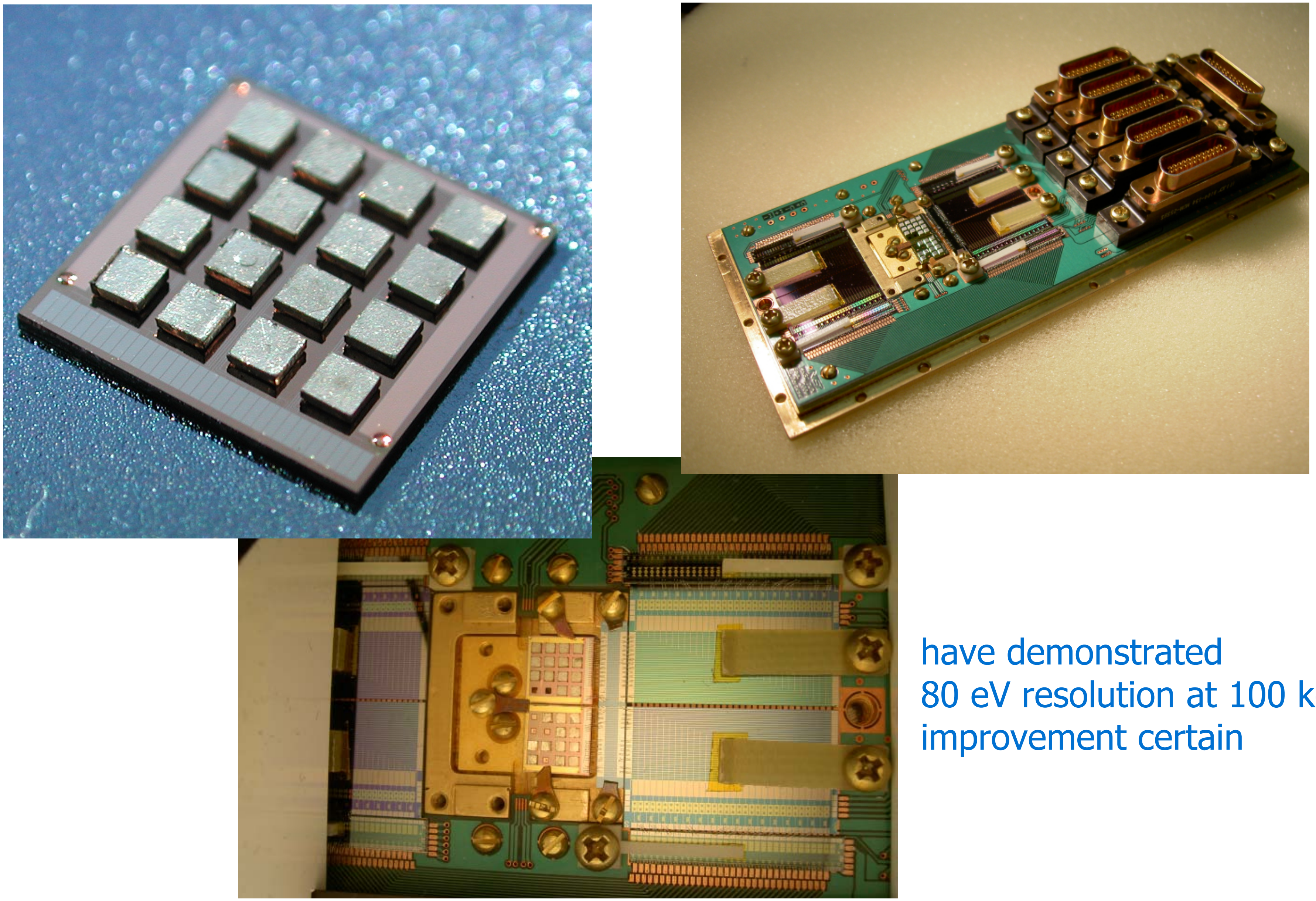
record NIST γ-ray results:
42 eV FWHM at 103 keV



LANL-NIST Pu spectrum: isotopes clearly resolved



Current γ-ray research: multiplexed arrays



have demonstrated
80 eV resolution at 100 keV
improvement certain

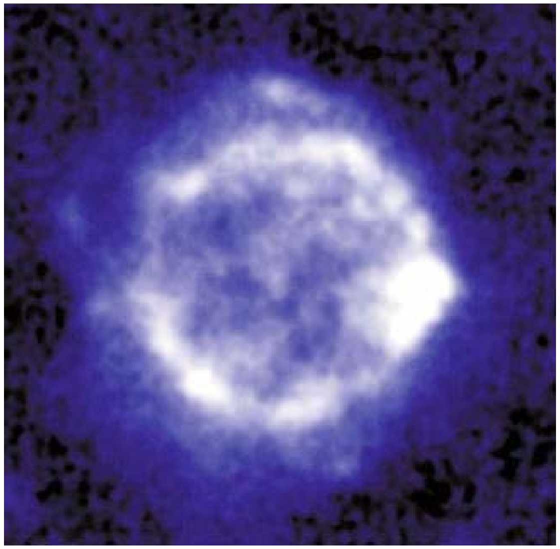
SCUBA 2 - TES sensors for submm astronomy

- The James-Clark Maxwell Telescope (JCMT) is one of the largest sub-millimeter telescopes in the world.

- The primary scientific instrument on the JCMT is the SCUBA bolometer array consisting of ~ 130 pixels. SCUBA is a very successfully, heavily cited instrument.

- NIST is a partner in an international collaboration to build SCUBA-2 which will be 10^2 -10^3 times more powerful than SCUBA.
  (with UK ATC, Edinburgh, Cardiff, Raytheon, Canada …)

JCMT on Mauna Kea



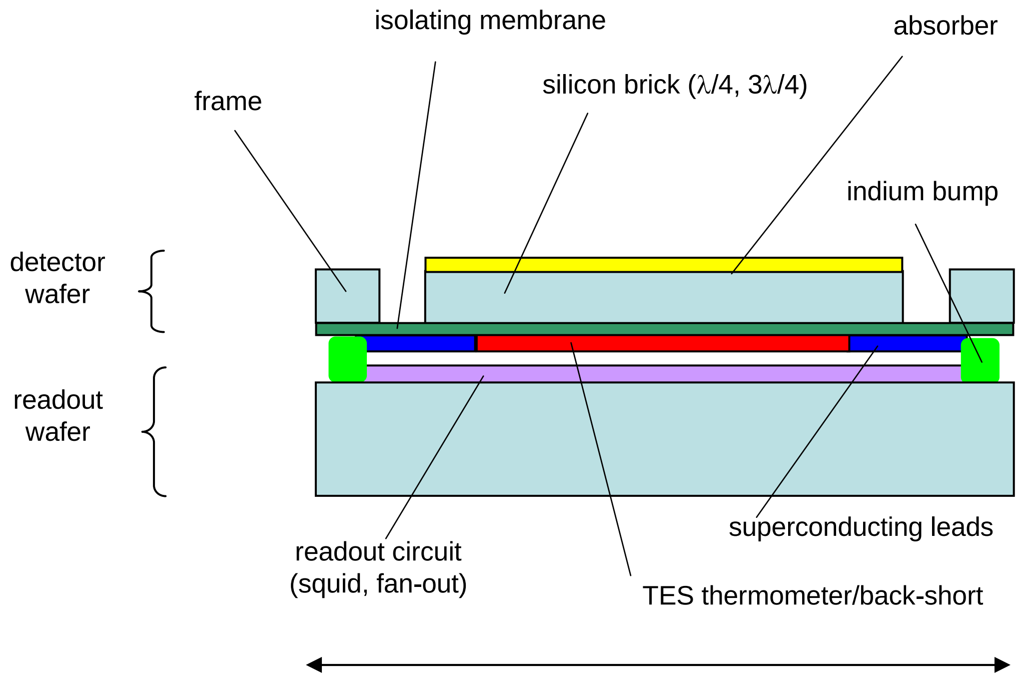
SCUBA image of supernova remnant Cass A *Physics Today*, Oct. 2003

SCUBA 2 - a giant submillimeter camera

- SCUBA 2 will consist of $\sim 10^4$ transition-edge sensor bolometers with multiplexed SQUID readout. This will be one of the largest pieces of superconducting electronics ever made.

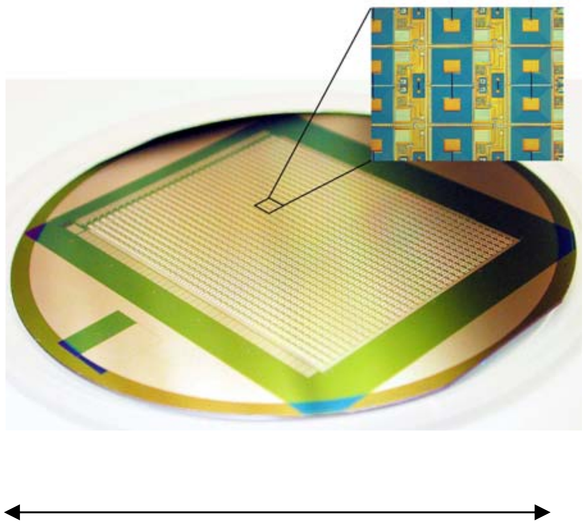
- Present plan: four 3″ wafers with sensors for 850 µm, four 3″ wafers with sensors for 450 µm Each sensor wafer indium bonded to a 3″ multiplexer wafer. Sensor NEP $\sim 3 \times 10^{-17}$ W/Hz$^{1/2}$ at 850 µm and $\sim 7 \times 10^{-17}$ W/Hz$^{1/2}$ at 450 µm.

schematic of one sensor & multiplexer channel



1 mm

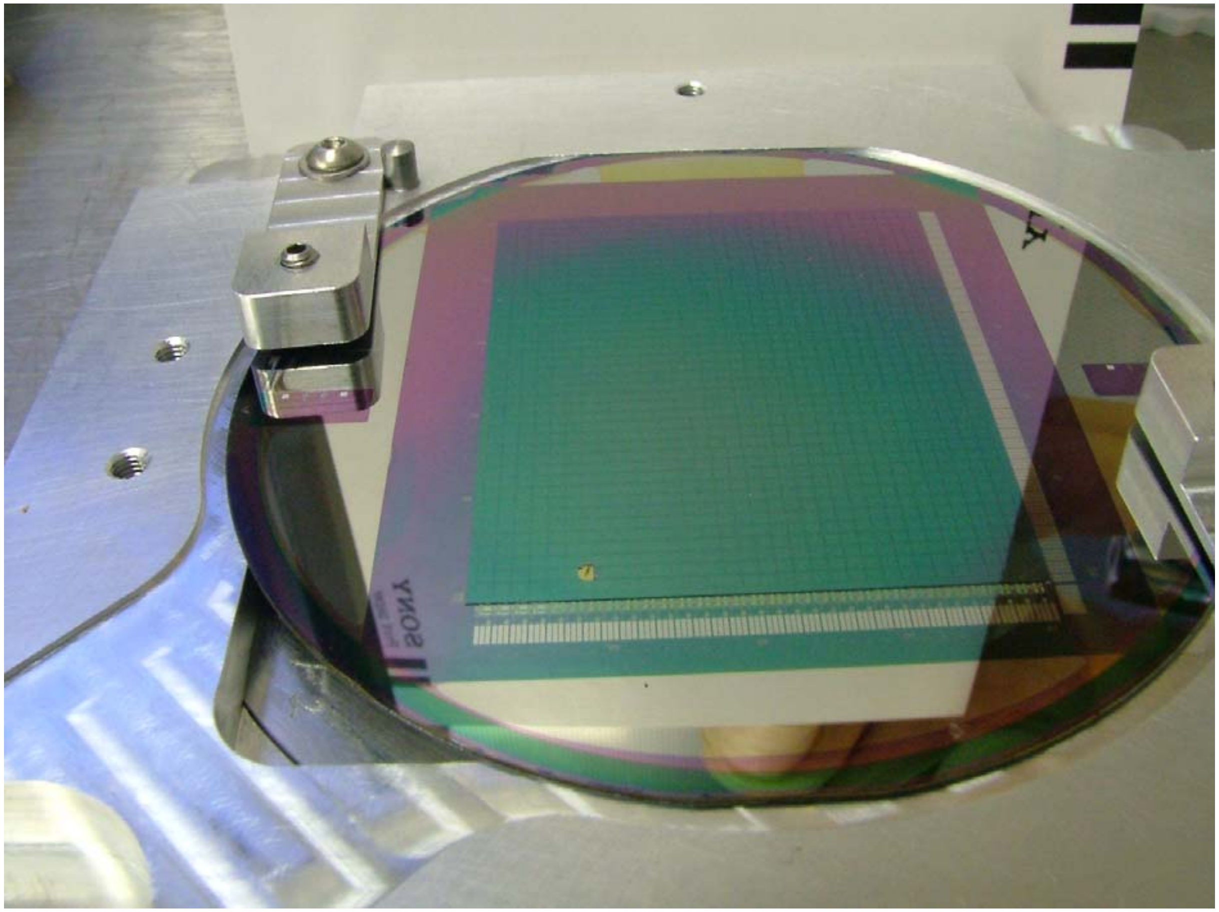
full-wafer SQUID multiplexer:
1312 channels



3 inches

State-of-the-art TES array: 1,280 pixels

TES wafer indium bump bonded to SQUID multiplexer wafer



SQUID fab and TES metallization performed by NIST

SCUBA 2 will consist of 8 of these assemblies

3 inches

Future prospects

x-ray detectors = most challenging: need speed and resolution

Optimization	E	ΔE_{FWHM}	array size	Array count rate	Timescale
Best resolution	0.1 – 10 keV	3 eV	32 × 32	200 kHz	~ 3 years
Best count rate 1 keV	0.1 – 1 keV	6 eV	100 × 100	20 MHz	~ 5 years
Best count rate 10 keV	0.1 – 10 keV	20 eV	100 × 100	5 MHz	~ 5 years
Microwave readout	0.1 – 10 keV	5 eV	100,000	100 MHz	5 - 10 years

Can also make instruments for THz, IR, visible, UV, & γ-ray

Conclusions

- 0.1 K operating temperatures now achievable simply and without liquid cryogens

- performance of individual TES sensors = excellent
  - 2.0 eV FWHM at 1.5 keV
  - 2.4 eV at 5.9 keV
  - 42 eV at 103 keV
  - 1/e response time = 100 μs - 1 ms
  - area = 0.1 - 1 mm^2

- TESs well suited for terrestrial materials analysis (x- and γ-ray) and astronomy (x-ray and submm)

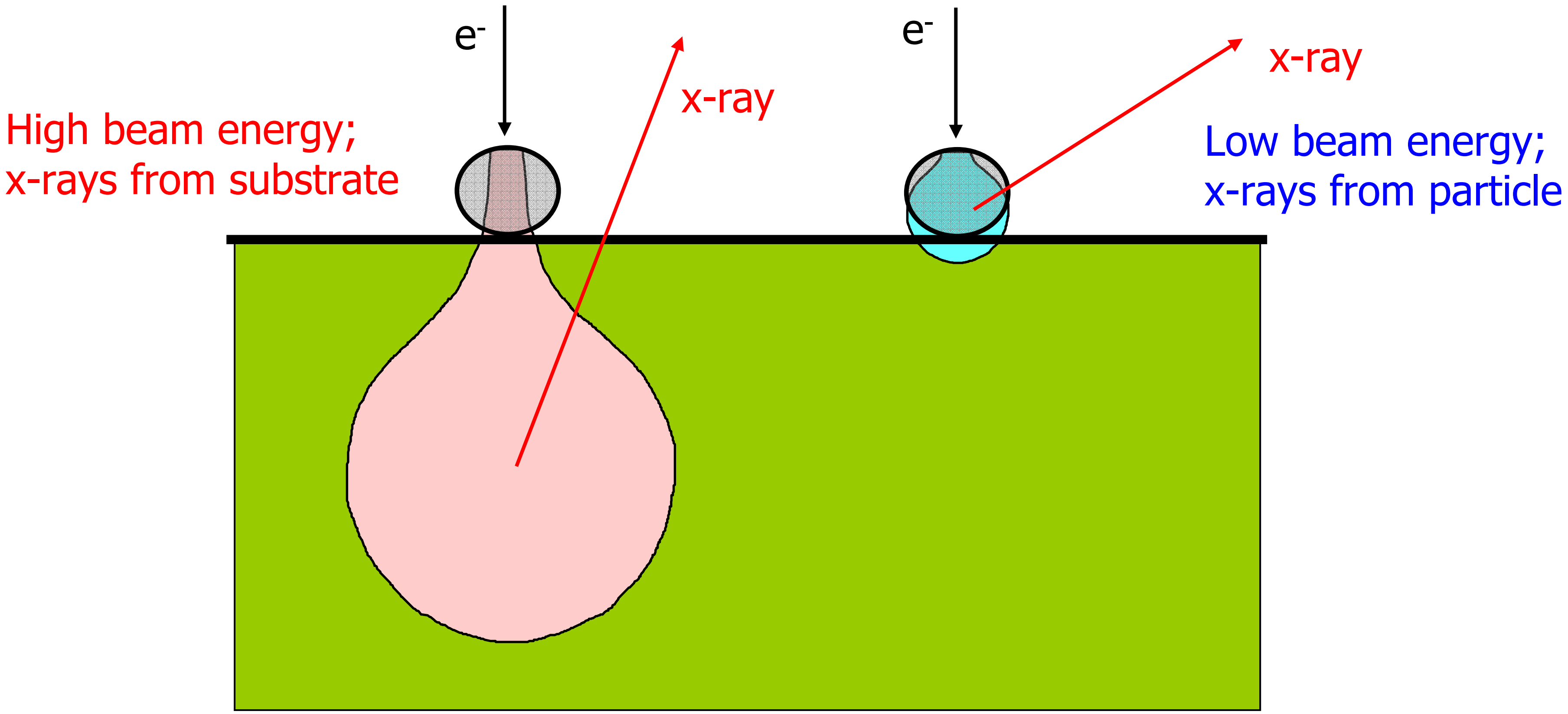
- we are now building and testing arrays of x-ray, γ-ray, and submm TESs

- multiplexing = essential for arrays, time-domain SQUID mux works well

- SCUBA 2 submm camera (10^4 sensors) underway

Nanoscale Analysis with Microcalorimeters

- Low electron beam energies required to probe small or thin samples



- BUT, low energy electrons only excite low energy x-rays ⇨ peak overlap
- Microcalorimeters can easily resolve overlap

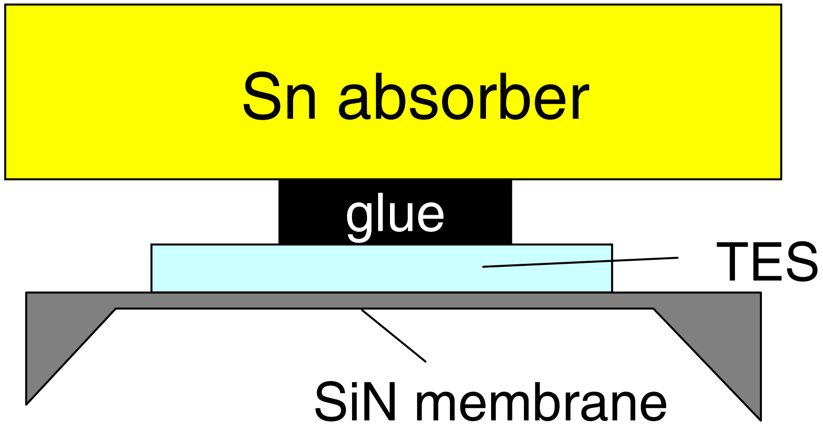
Can TESs measure γ-rays ?

QE of thin-film devices too low (≤ 1%)

BUT, there is a simple solution:

attach a bulk absorber to the TES
γ-ray energy is captured, thermalized in absorber
energy flows from absorber into TES

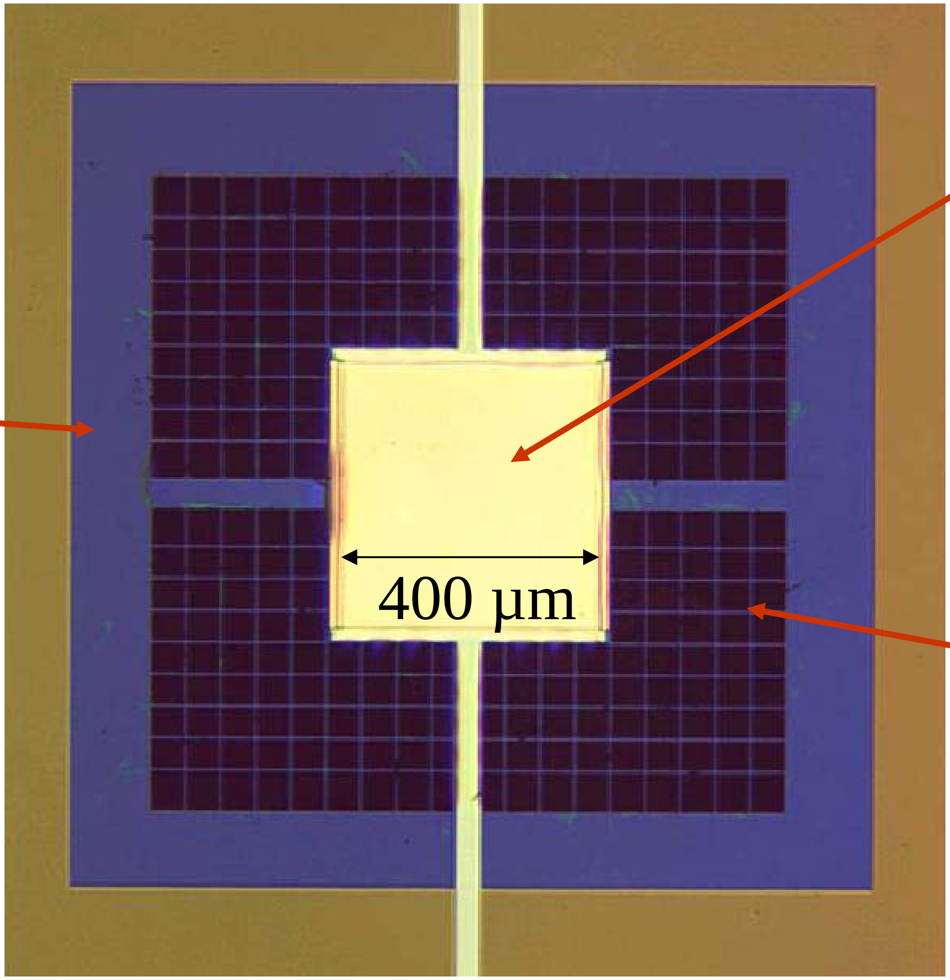
need low C absorber; candidate materials = insulators & superconductors



‘bulk’ Sn:
1 x 1 x 0.25 mm^3
QE = 24% at 100 keV

C_{abs} = 60 keV/mK
C_{TES} = 9 keV/mK
but volume ratio = 1250

TES Microcalorimeter Photo



Si_3N_4

Membrane

Mo-Cu

TES

Empty

Space

ΔE_{FWHM} = 2.0 eV at 1.5 keV

ΔE_{FWHM} = 2.4 eV at 5.9 keV

TES Optimization

$$\Delta E_{FWHM} = 2.35\sqrt{\frac{4k_bT^2C}{\alpha}\sqrt{\frac{n\,(1+M^2)}{2}}}$$

M is excess noise
ratioed to Johnson noise

additional constraint: $E_{saturation} \sim C\,T/\alpha$

empirically, $M \sim 0.2\,\alpha^{1/2}$ ⇨ lower α to lower excess noise

optimal design: reduce C, α, and M, match C/α to target x-ray energy