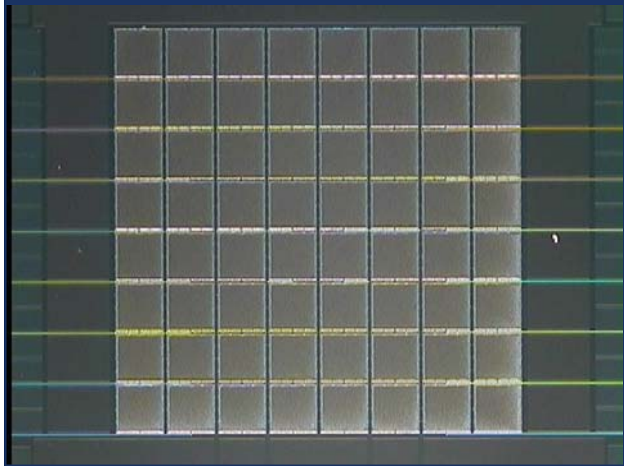
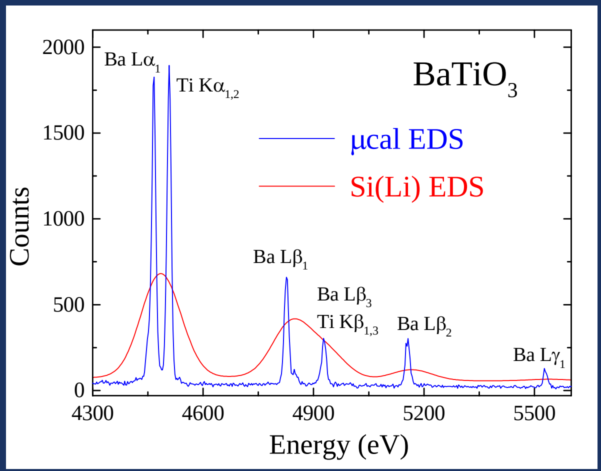
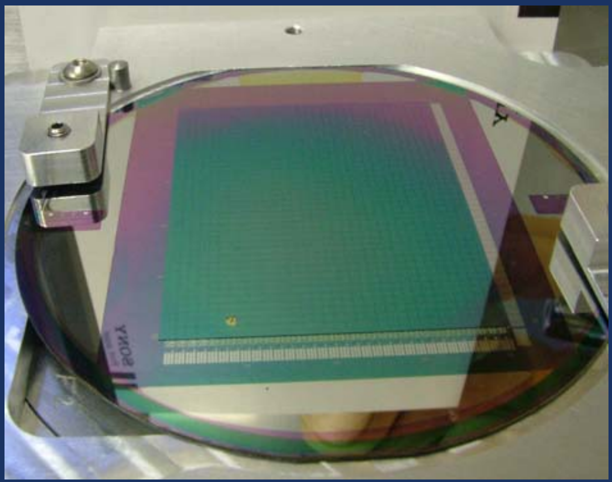
Bolometer Arrays for High-Resolution Spectroscopy



64-pixel x-ray microcalorimeter array



Microcalorimeter x-ray spectrum of BaTiO$_3$



1,280-pixel bump bonded array for THz

Kent Irwin, NIST

Microcalorimeters: no gap, no Fano limit, thermal fluctuations

STJs: a gap much smaller than semiconductors (Friedrich)

- Microcalorimeters and bolometers
- Multiplexed readout
- Soft and hard x-ray results
- Cryogenics
- The future: 4 possible arrays for synchrotron applications
- Emerging microwave readout techniques

NIST staff

NIST Boulder:

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Lisa Ferreira
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Nathan Miller
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Dan Schmidt
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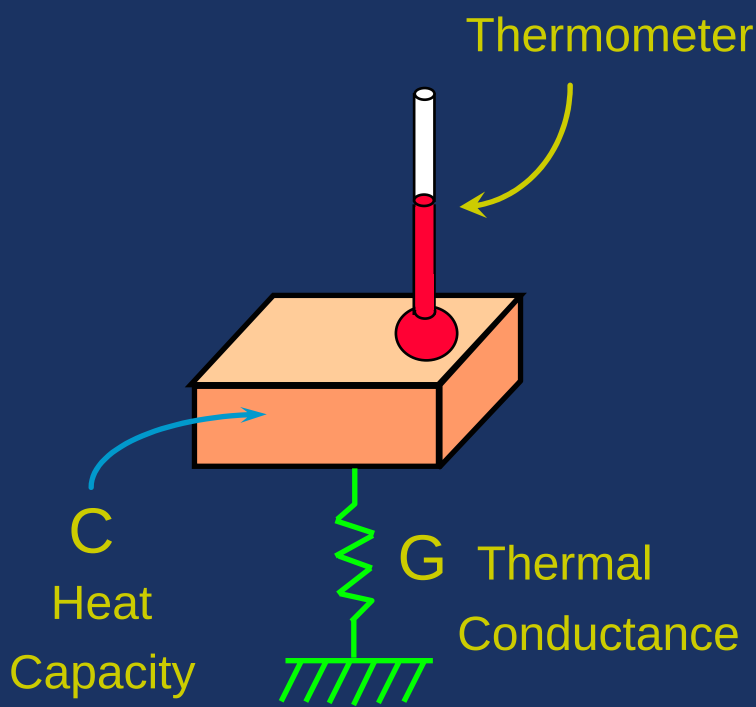
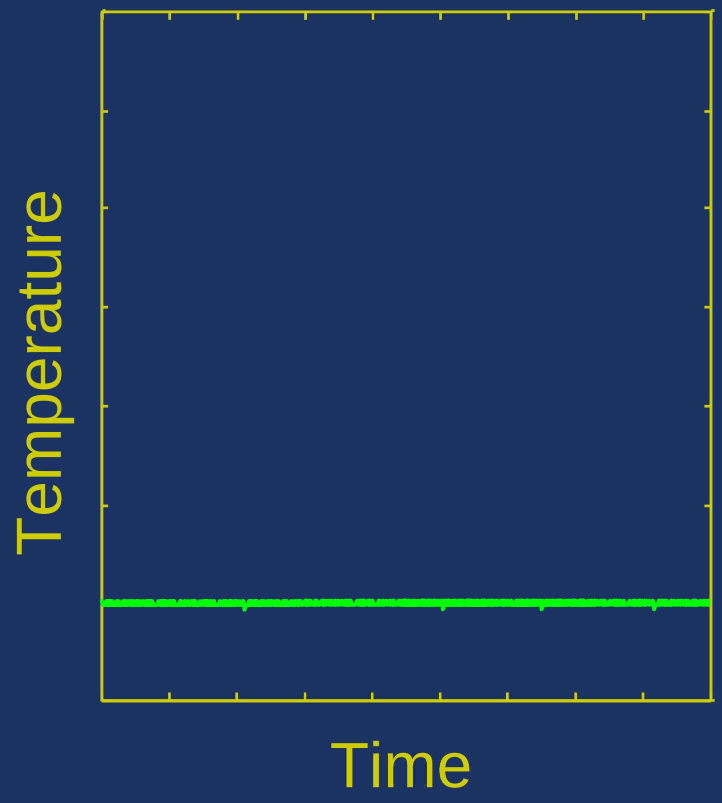
NIST Gaithersburg:

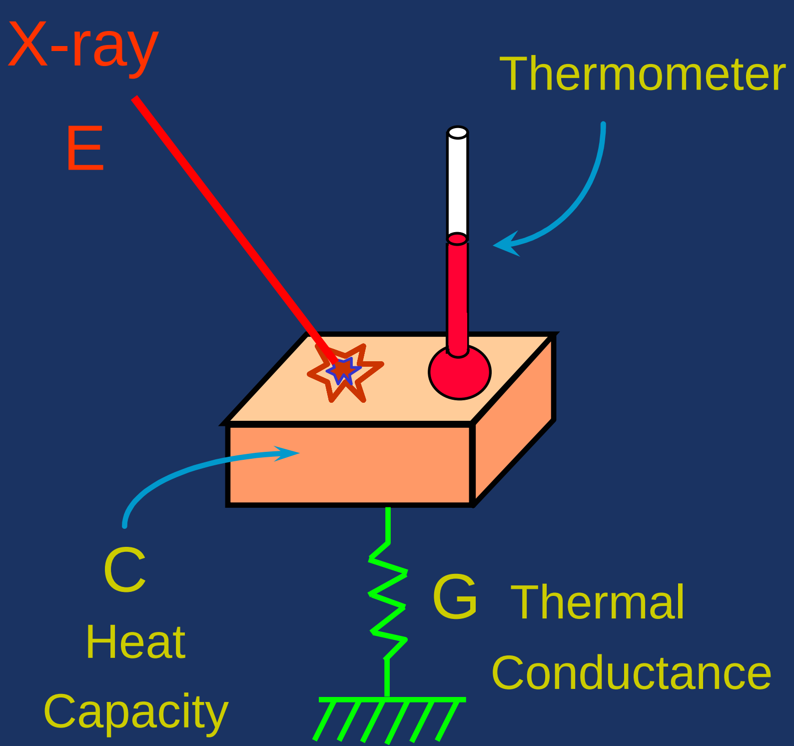
Dale Newbury
Terry Jach
John Small

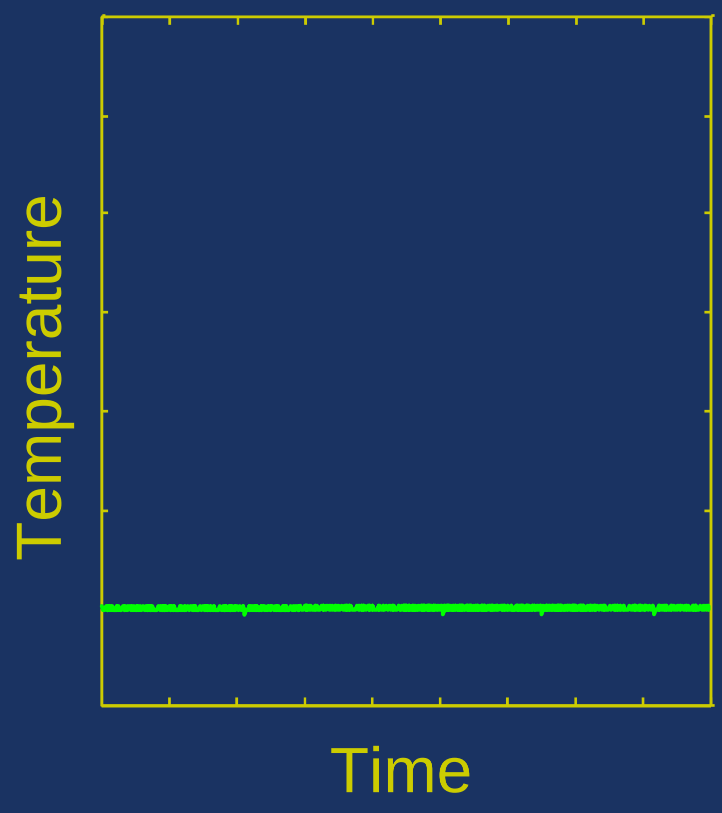
Bolometers / Microcalorimeters





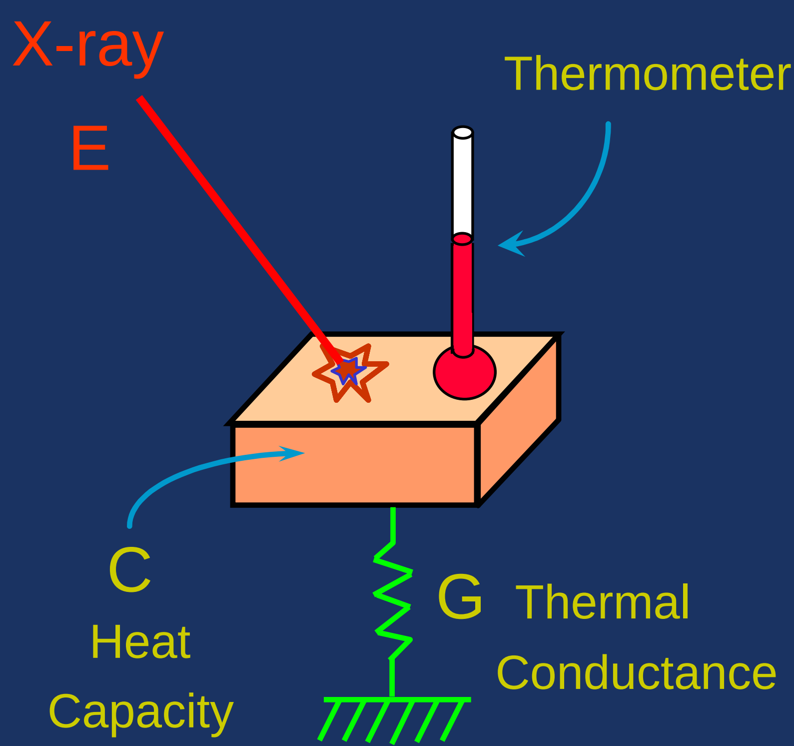
Bolometers / Microcalorimeters

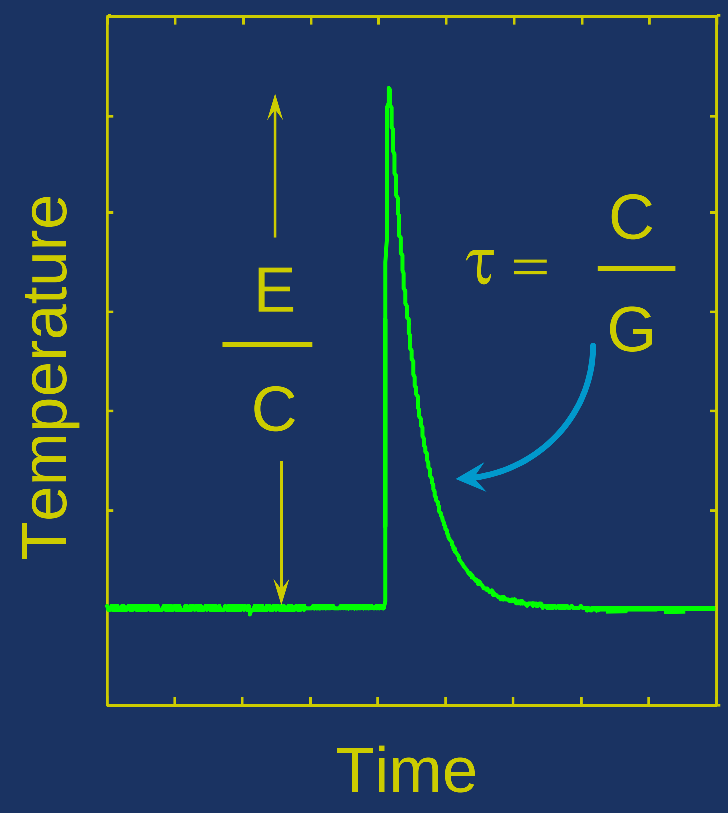




Photon

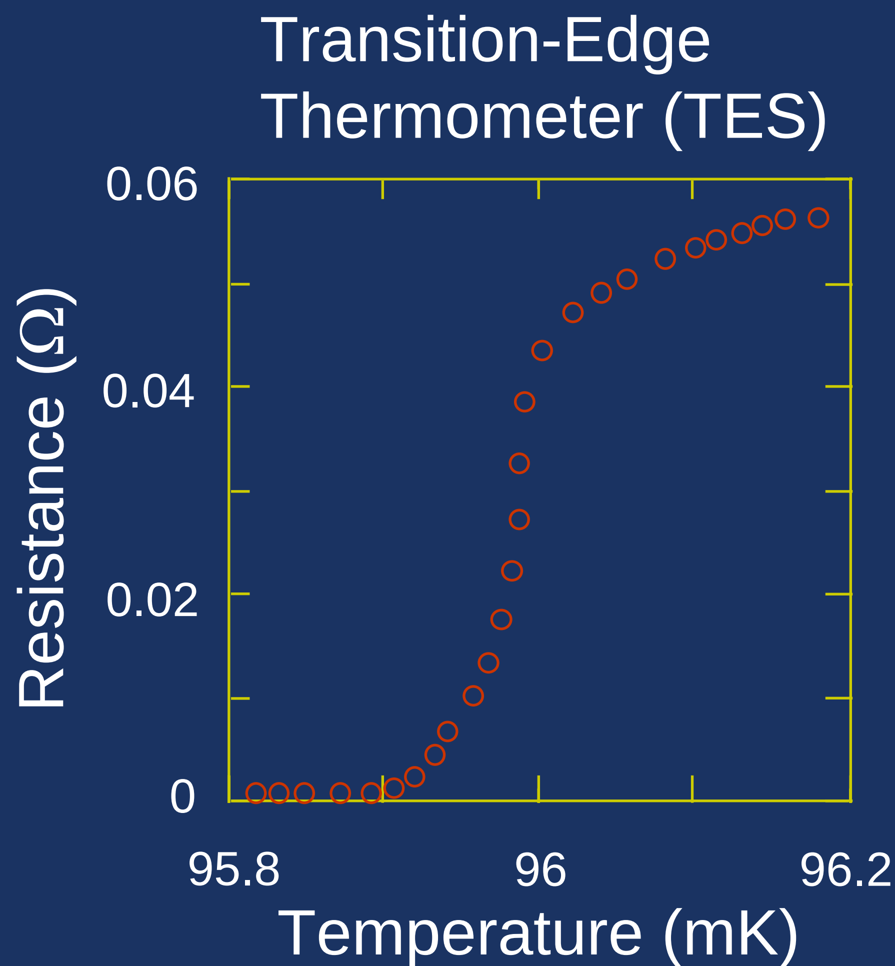
Bolometers / Microcalorimeters





Photon → Heat

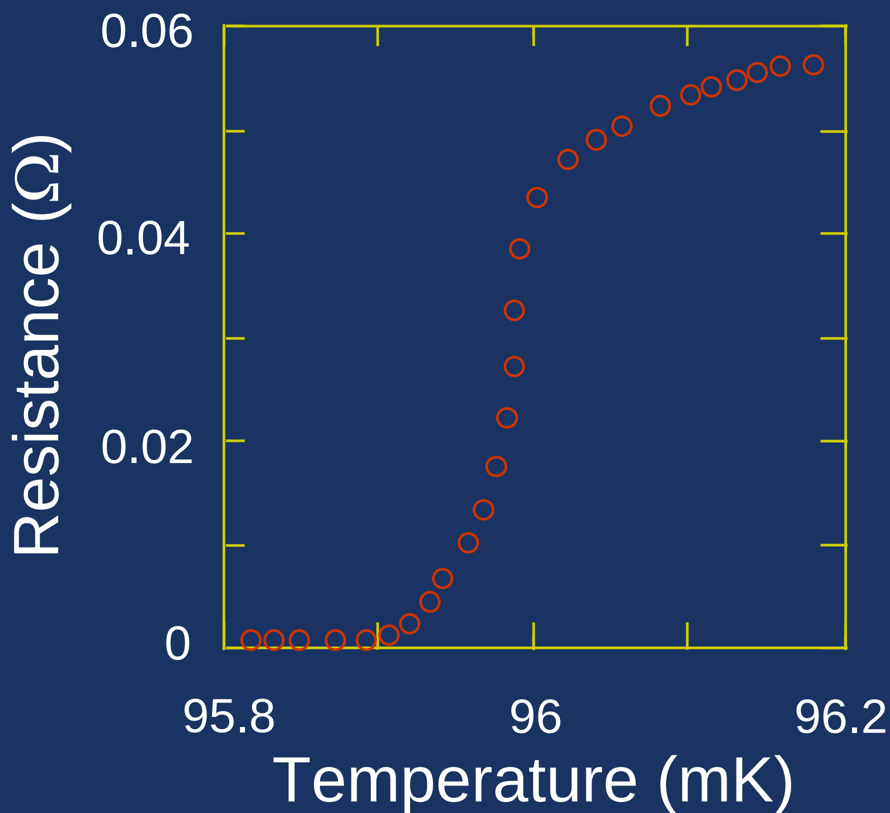
Superconducting Transition-Edge Thermometer



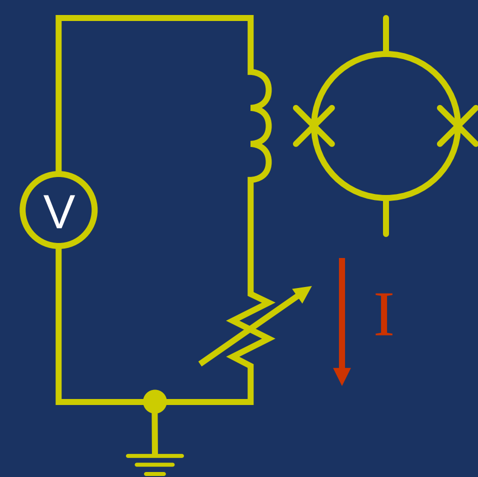
Photon → Heat → Resistance

Superconducting Transition-Edge Thermometer

Transition-Edge Thermometer (TES)

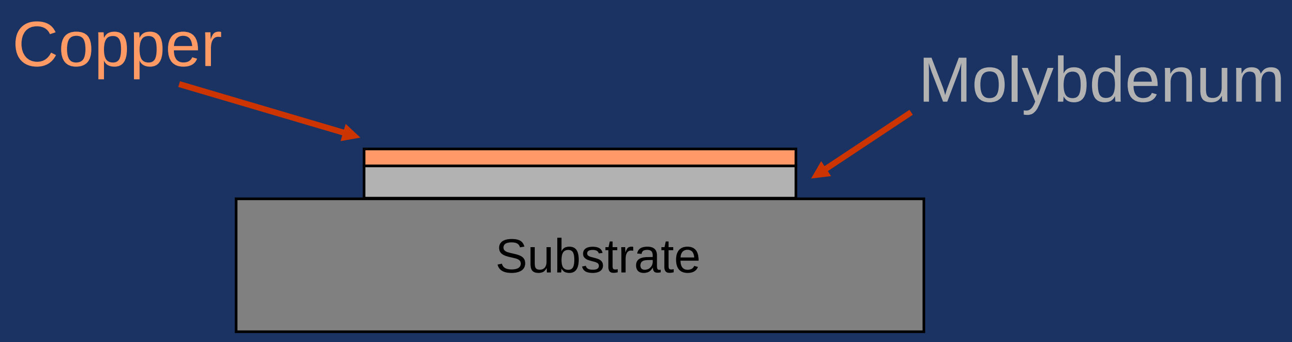


SQUID Current Amplifier



Photon → Heat → Resistance → Current

Molybdenum-Copper Bilayer TES



• A bilayer of a thin superconducting film and a thin normal metal acts as a single superconductor with a tunable T_c - the "proximity effect"

• Molybdenum-copper

Robust and temperature stable

Molybdenum T_c ~ .92 K

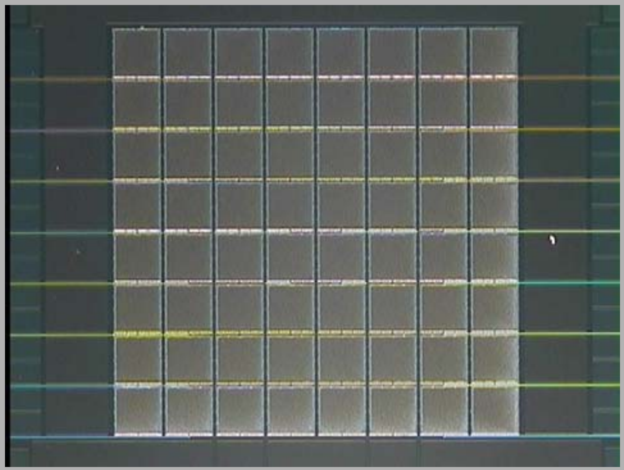
Copper normal

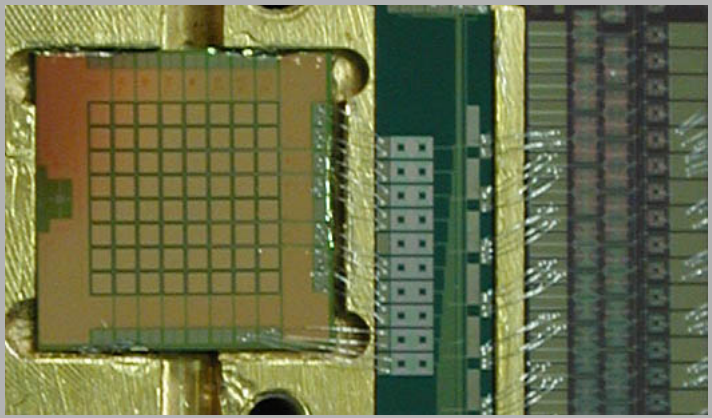
NIST Superconducting Clean Room Facility

- 2700 sq ft class 100 dedicated superconducting integrated circuit / MEMS space
- I-line 5x lithography
- Niobium trilayer system
- Mo-Cu TES bilayer system
- ECR PECVD deposition
- Bosch “deep” RIE
- XeF_2 etch system
- E-beam lithography
- Reticle generation
- Sputter deposition (x2)
- LPCVD (x2)
- Thermal oxide / diffusion (x2)
- Thermal deposition (x2)
- RIE (x2)
- Plasma etching
- Ion mill etching

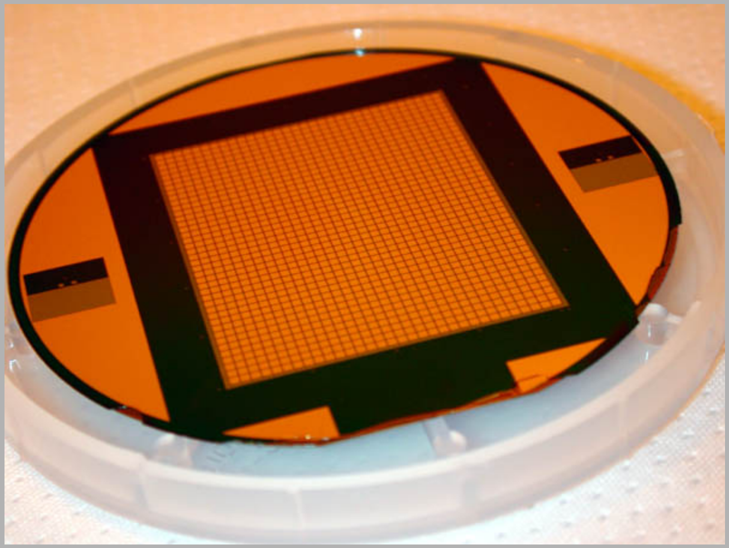
TES Fabrication

64-pixel microcalorimeter array



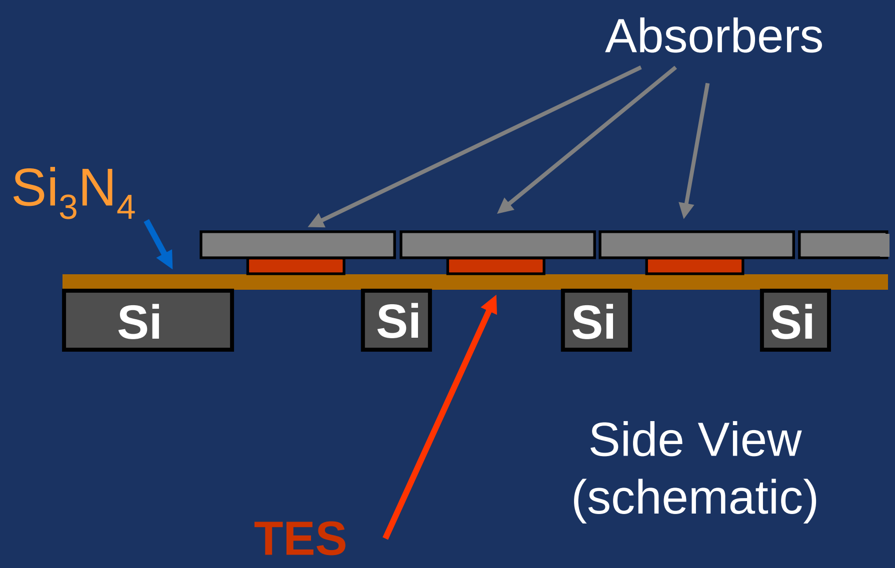


1,280-pixel SCUBA-2 subarray

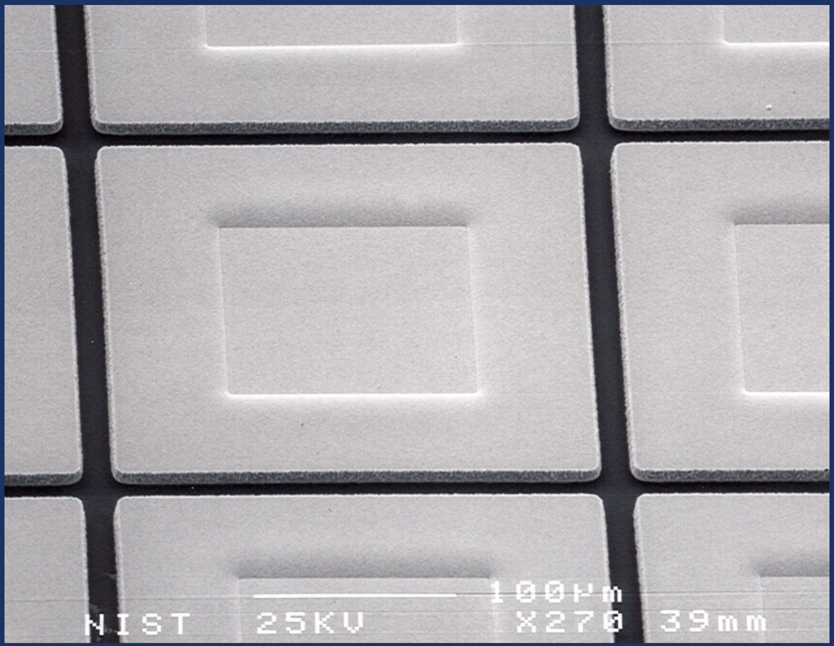


TES + soft x-ray absorbers

Side View
(SEM)



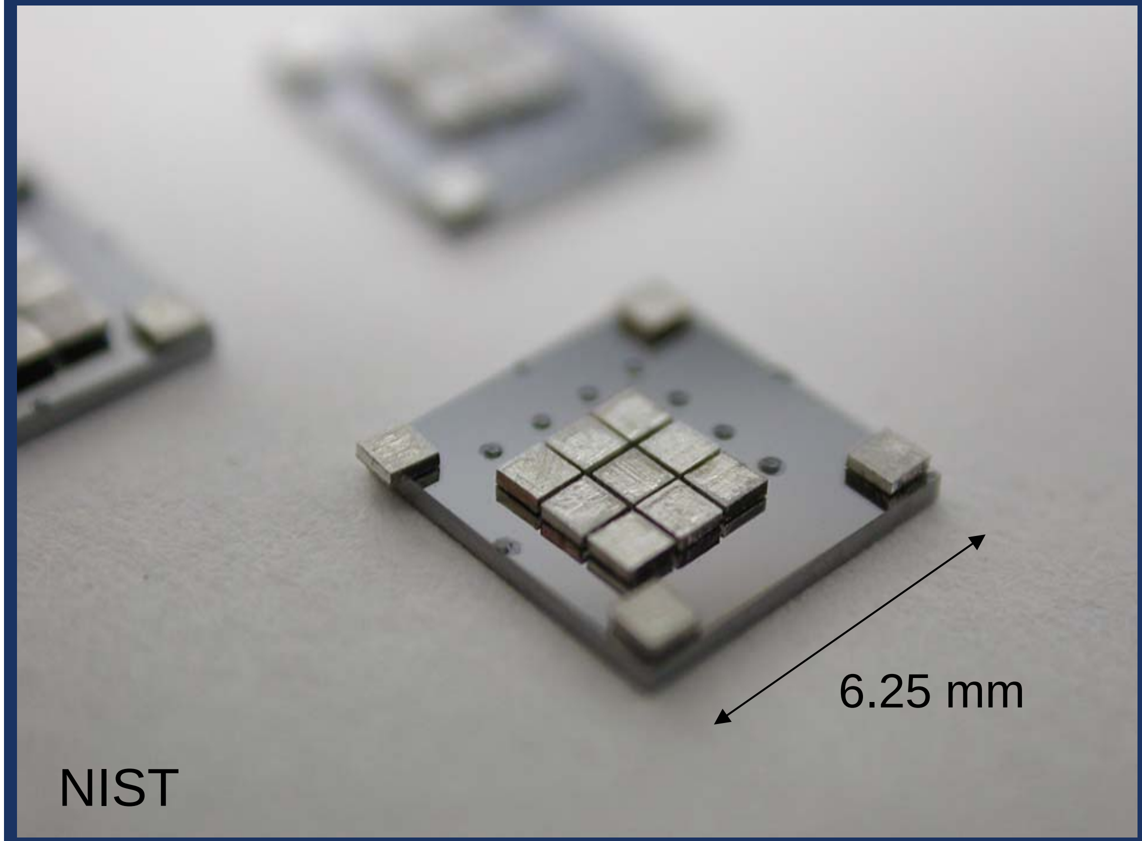
Side View
(schematic)

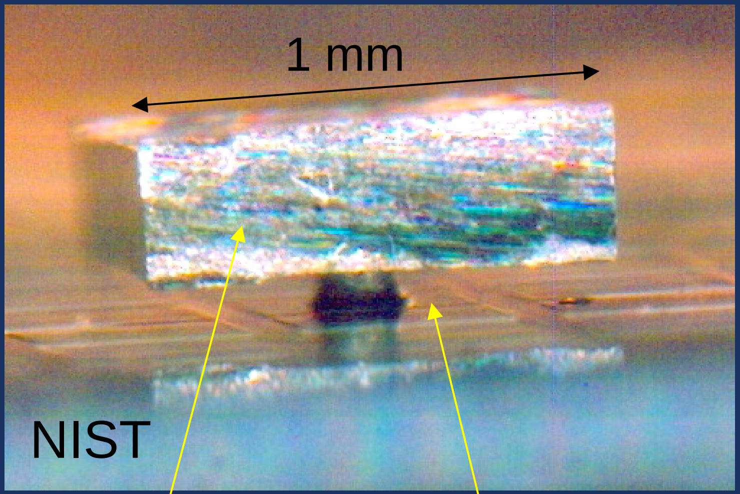


250 μm pixels
6.7 μm thick Bismuth

Top View
(SEM)

TES + hard x-ray / γ-ray absorbers





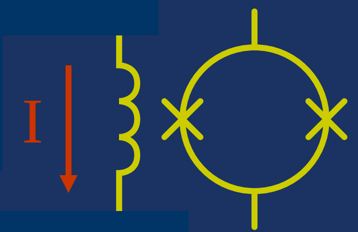
1 mm pixels
250 µm thick Tin

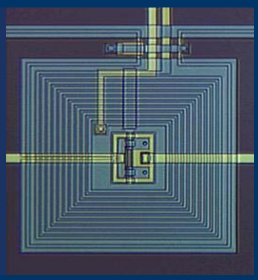
Prior work at LLNL:

e.g. T. Miyazaki et al., *IEEE Trans. App. Super.*, **13** 630 (2003)

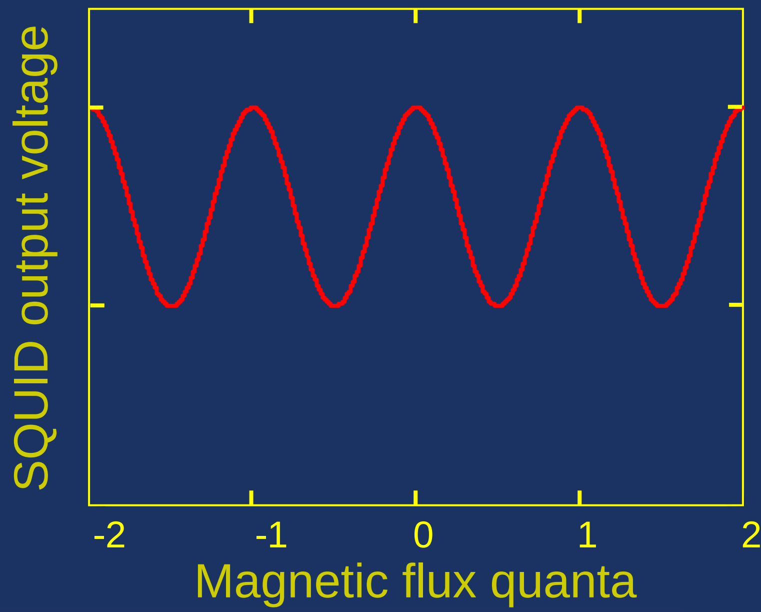
SQUIDs

SQUID Current Amplifier





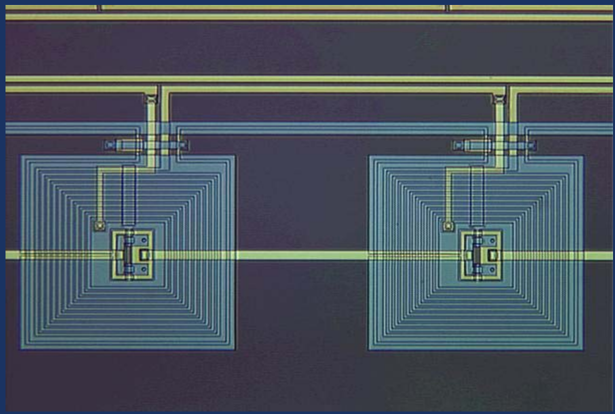
- Superconducting Quantum Interference Devices
- The most sensitive devices for the measurement of magnetic fields.
- SQUIDs operate by quantum interference between two Josephson tunnel junctions
- The output voltage is a periodic function of the applied magnetic flux.



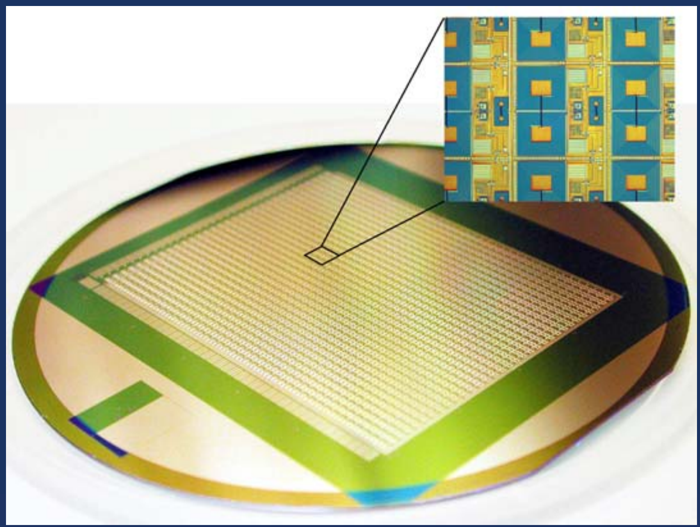
SQUID Fabrication

- $Nb/Al/Al_2O_3/Nb$ trilayer technology
- Low temperature (30 C) ECR PECVD SiO_2
- Two wiring and dielectric levels
- PdAu shunt and damping resistors
- 10 lithography levels

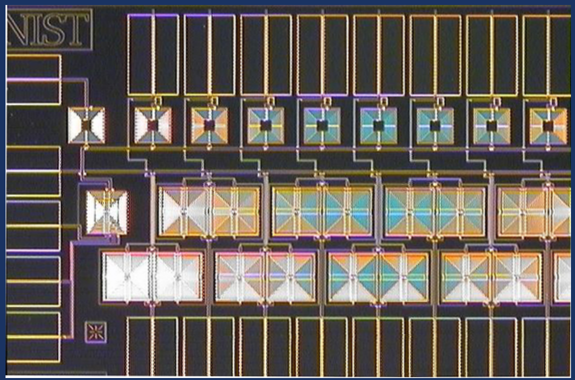
100-SQUID Series Array for the Cryogenic Dark Matter Search



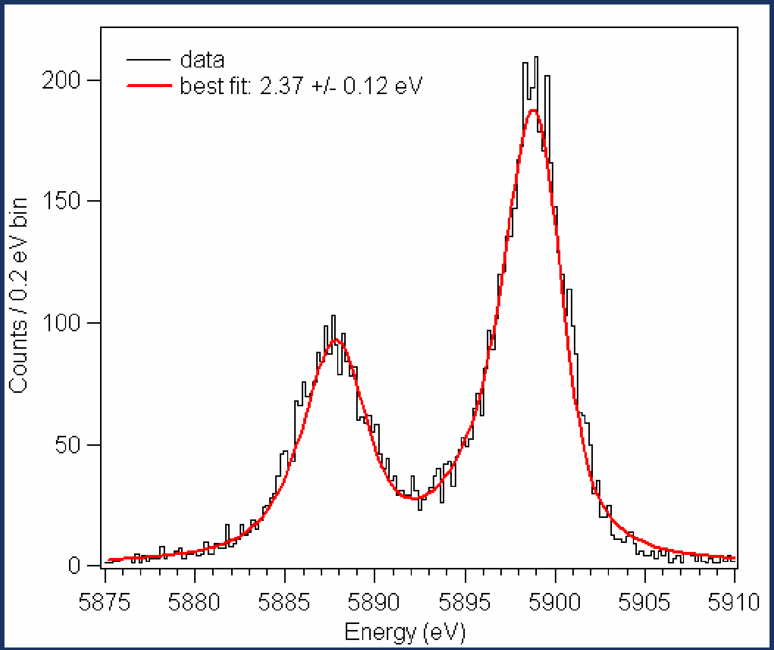
1,280-pixel MUX Array for SCUBA-2



1 × 32 MUX Array

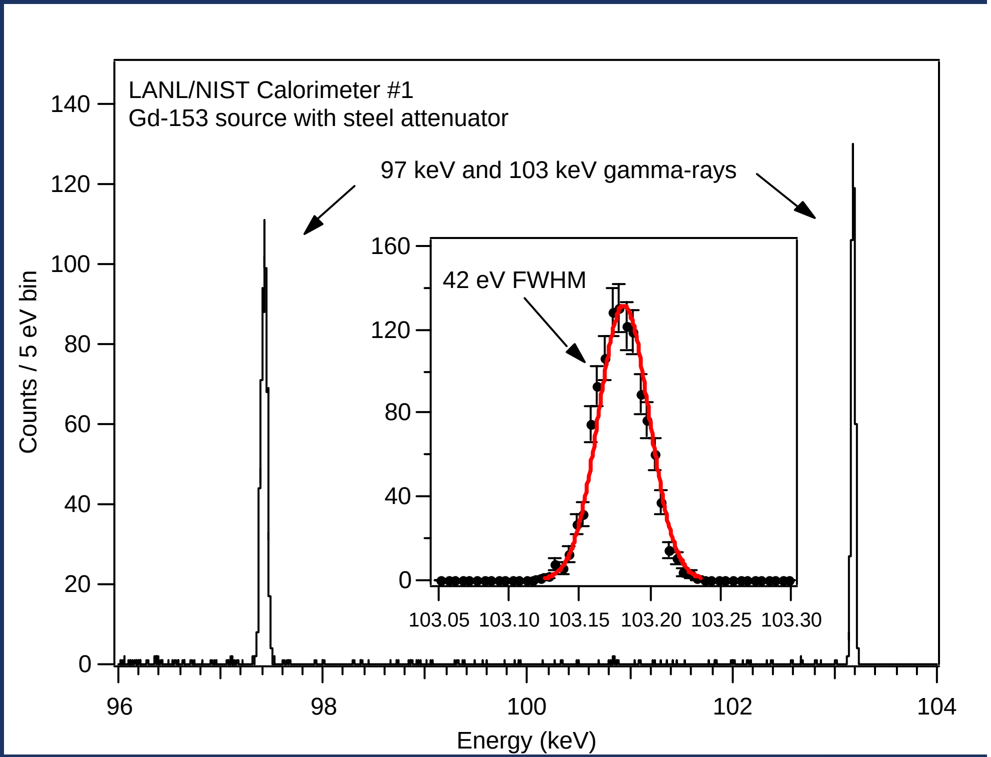


Bolometric energy resolution



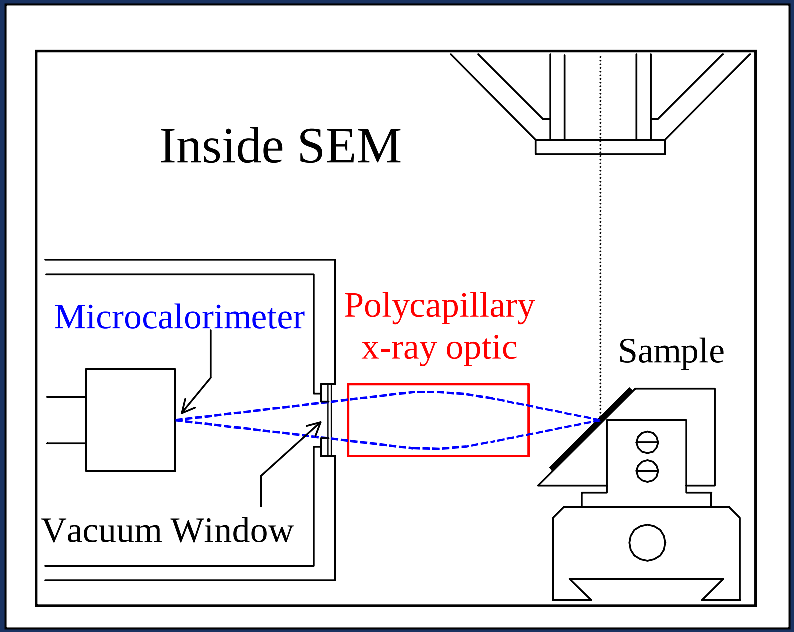
2.4 eV at 5.9 keV Mn Kα

42 eV at 103 keV



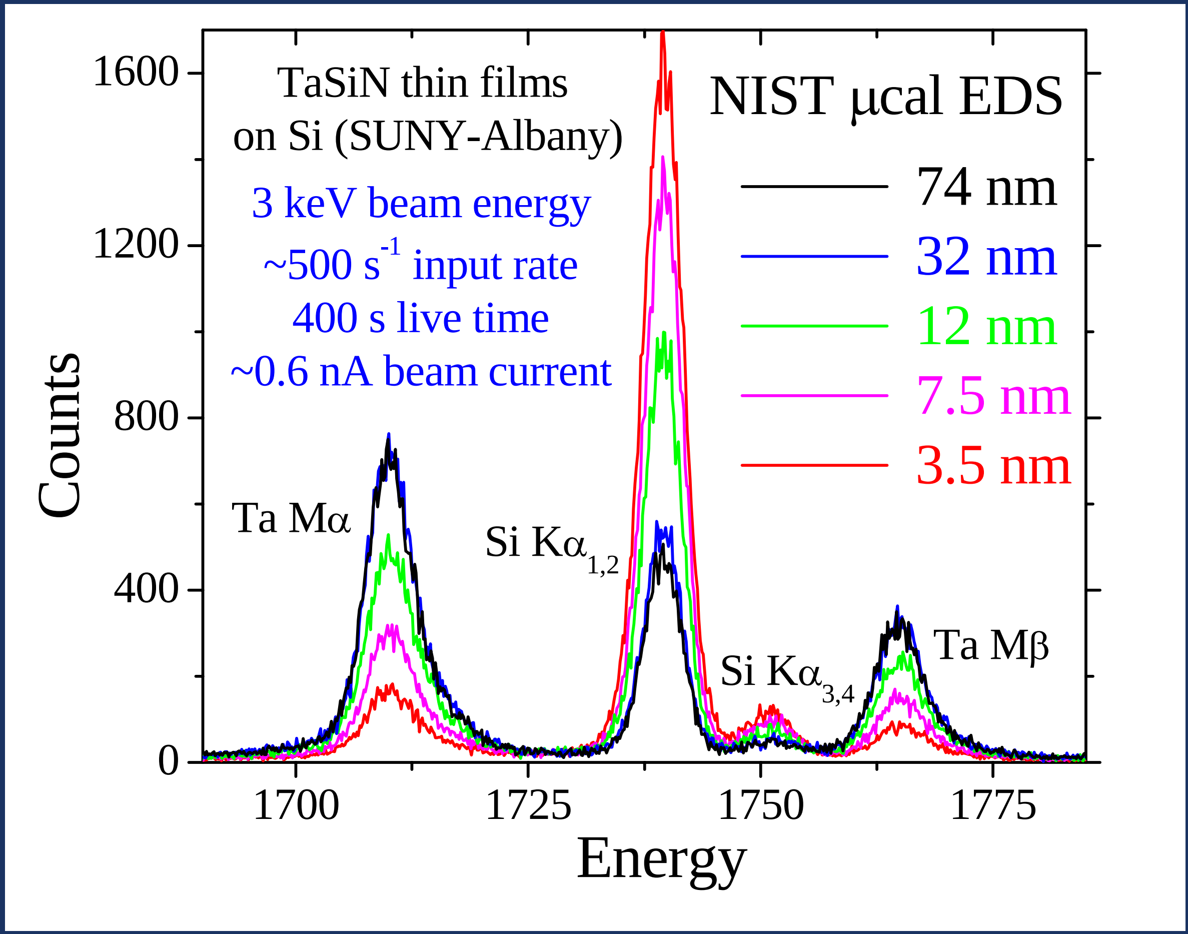
Should be able to do
< 1 eV at < 1 keV

Microanalysis system on SEM



Thin-Film Analysis

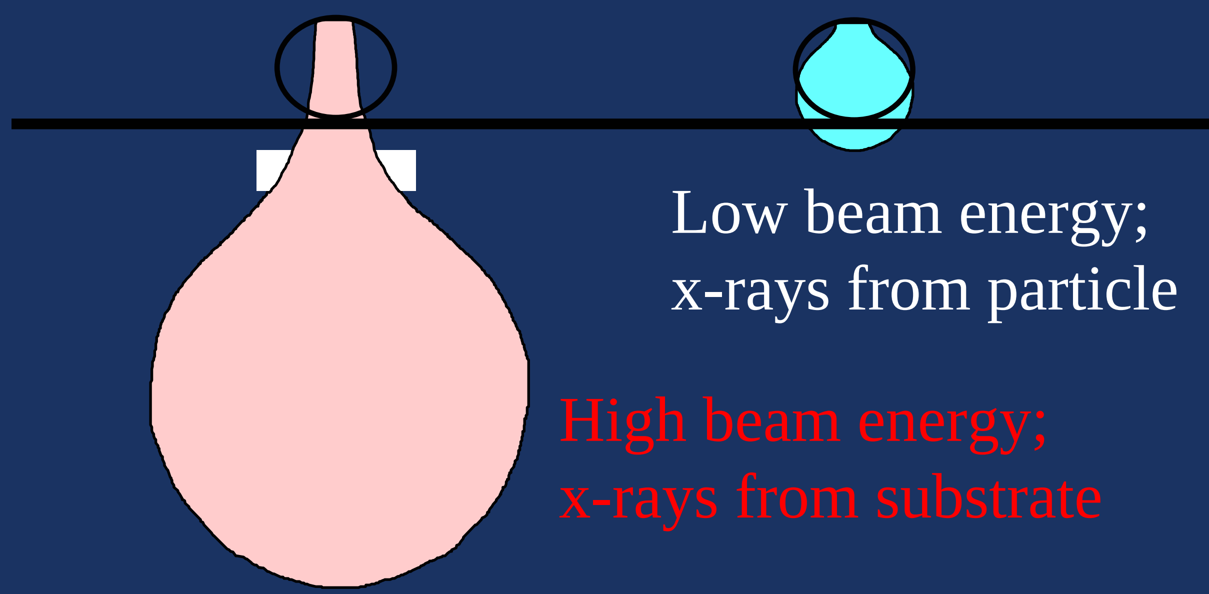
The high energy resolution of the microcalorimeter also provides a high peak-to-background ratio, allowing better thin film & trace element analysis



Ref. Geer et. al.

Nanoscale Particle Analysis

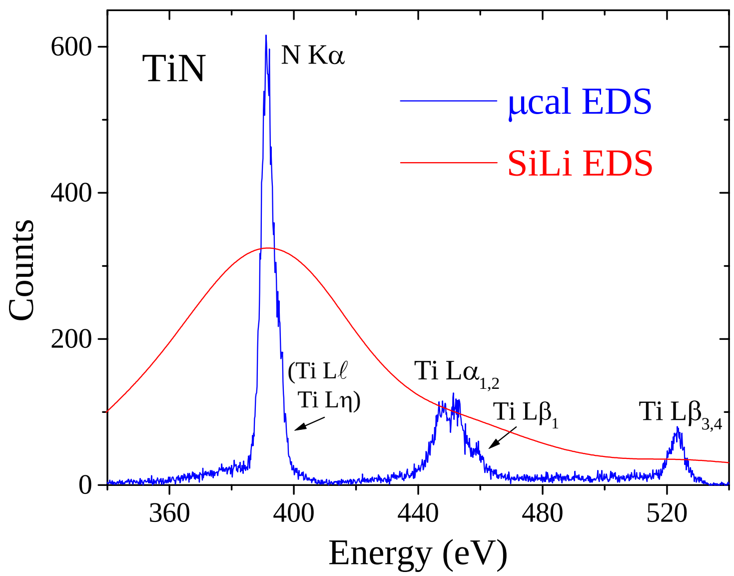
- Contaminant particles in semiconductor processing lower yield
- Low beam energies to localize x-ray production in ~60 nm particle
- High energy resolution to resolve overlapping x-ray lines

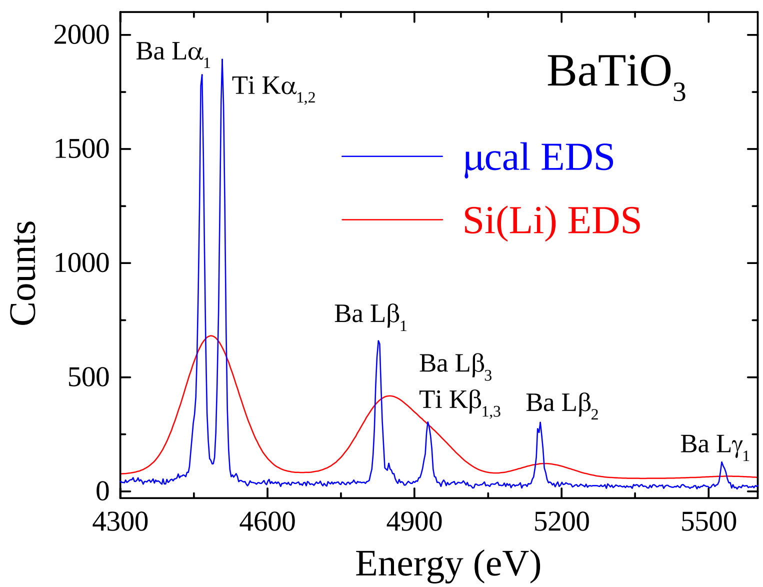


Low beam energy;
x-rays from particle

High beam energy;
x-rays from substrate

Resolving peak overlaps

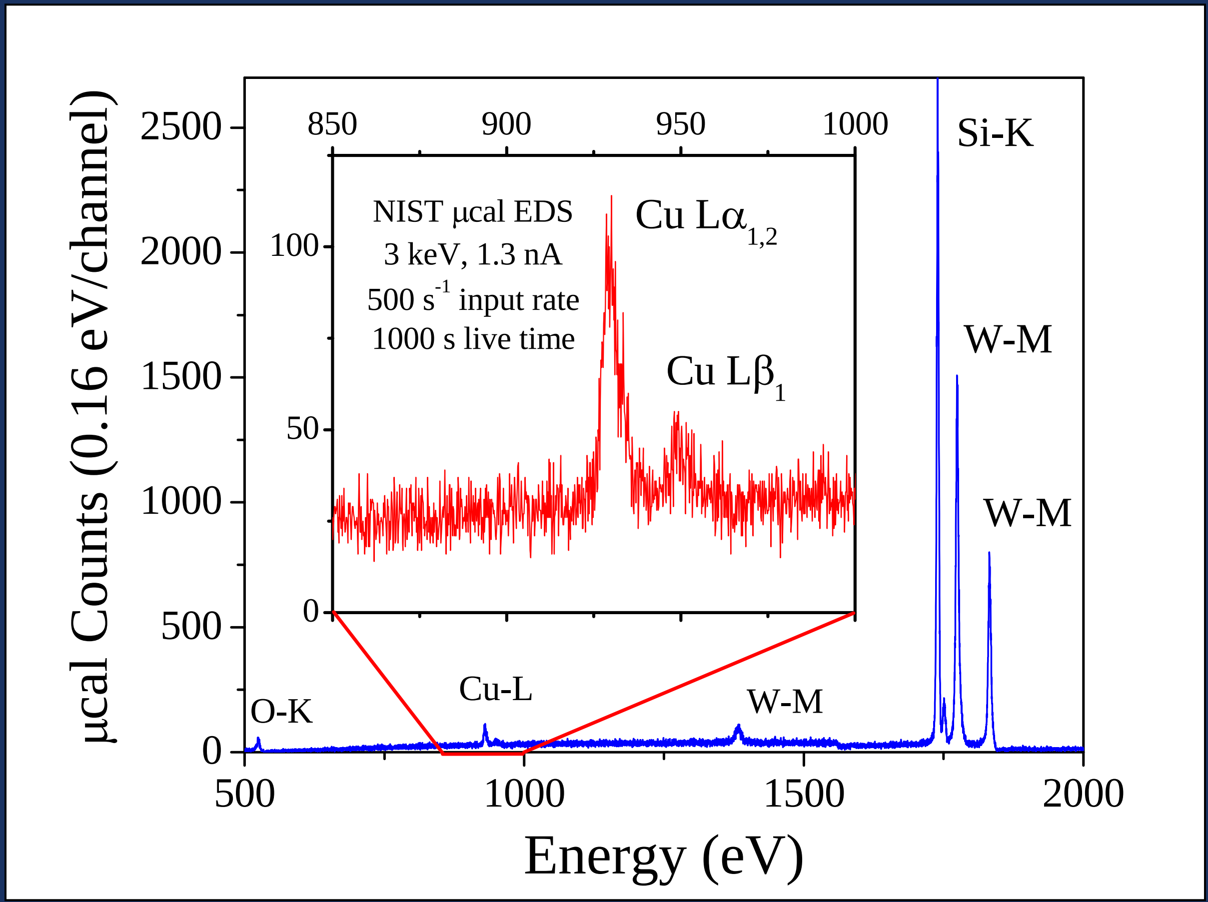




Trace-Element Analysis

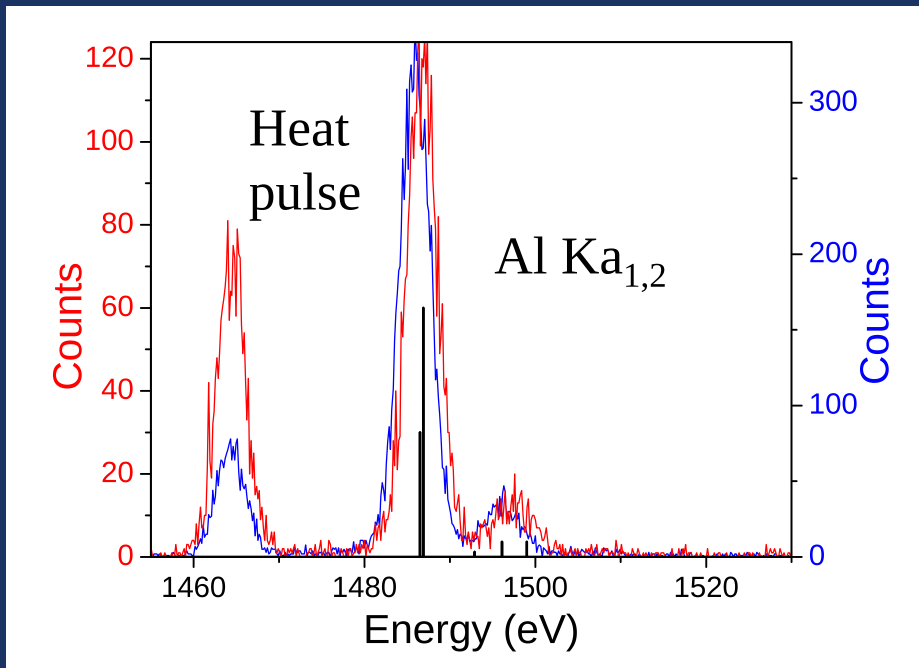
The high energy resolution of the microcalorimeter also provides a high peak-to-background ratio, allowing better thin film & trace element analysis

0.7 wt. % Cu measured in WSi_2 thin film

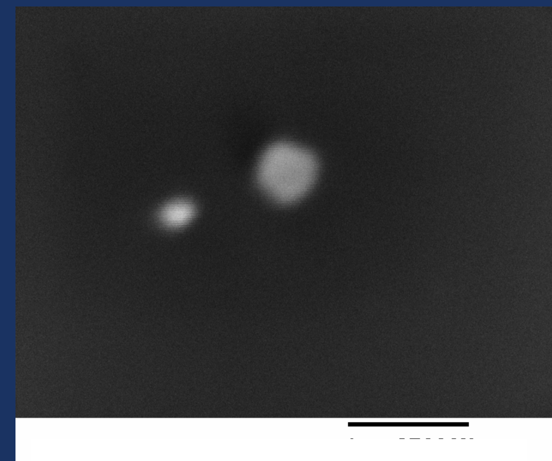


Collaboration with Vartuli and Stevie (Lucent)

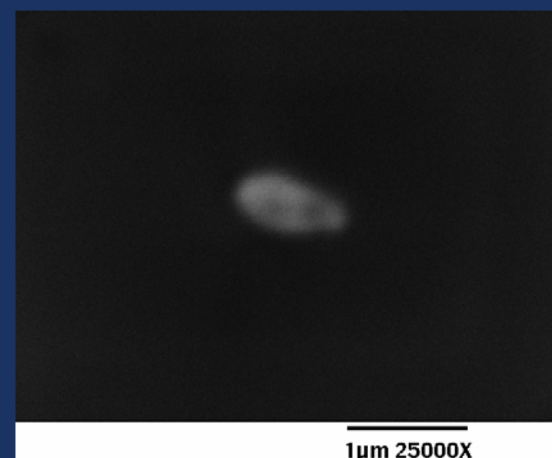
Chemical shift analysis



- Chemical bonding state causes small (< 1 eV) shifts in x-ray line position
- Industrially important problem: Al particles on oxide substrates.



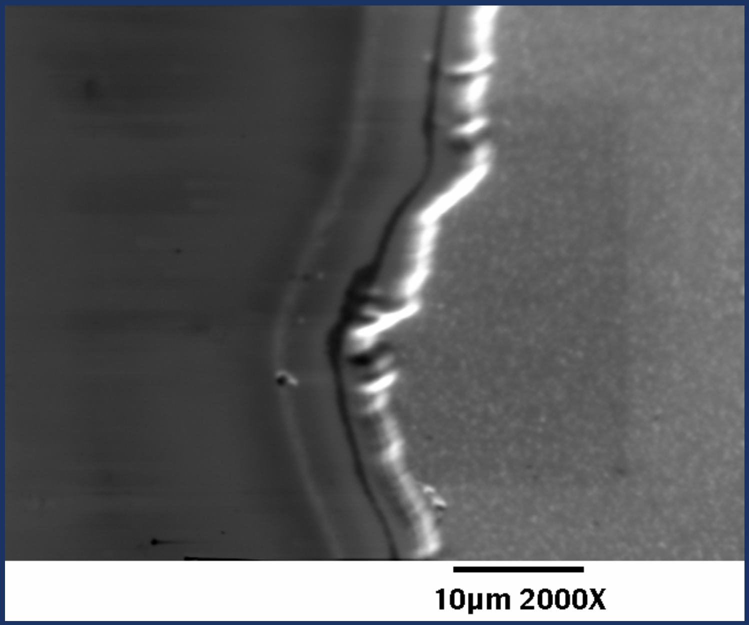
Al oxide particle



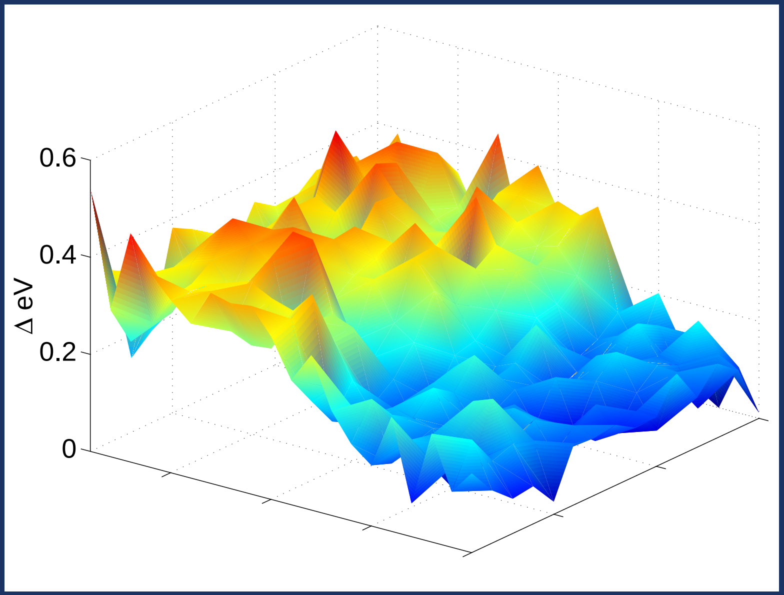
Al particle

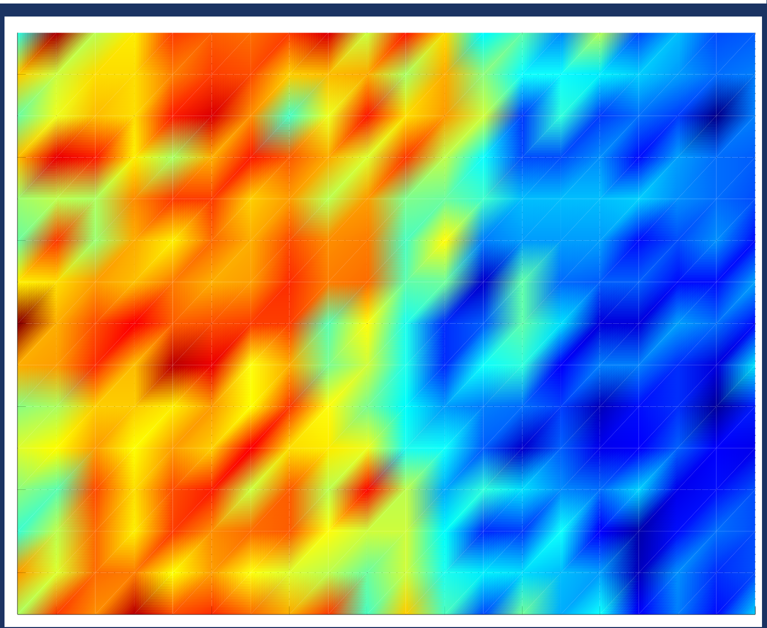
Particle samples provided by
Alain Diebold (SEMATECH)

Chemical shift map



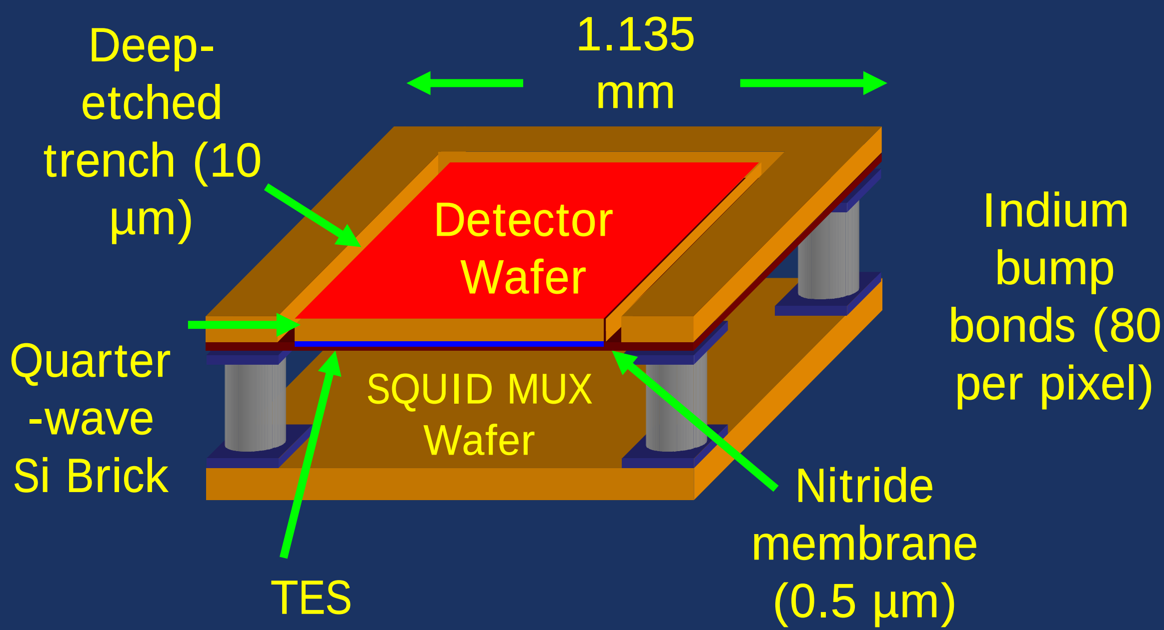
Al oxide Al



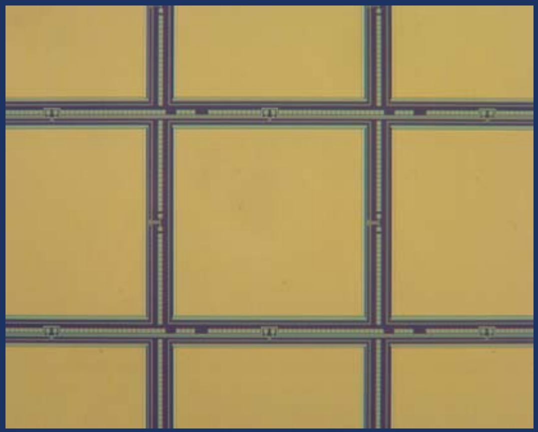


Multiplexed THz bolometer array: SCUBA-2

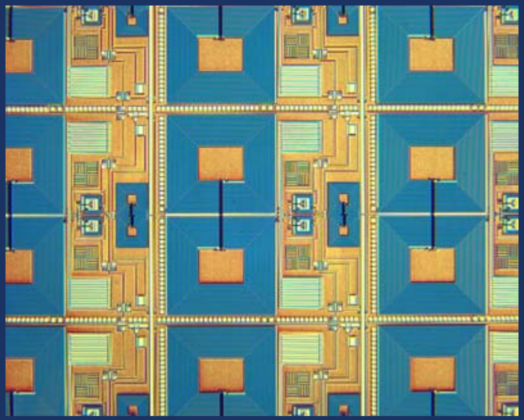
A superconducting pixel detector?



TES bolometer pixels



SQUID MUX pixels

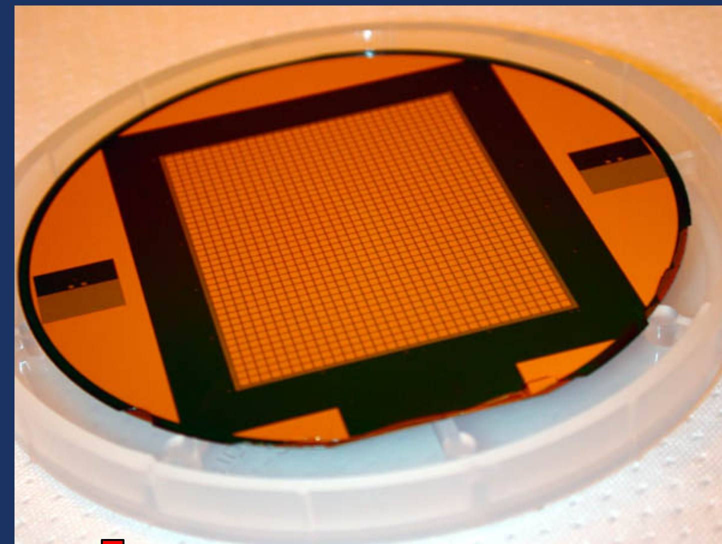


SCUBA-2

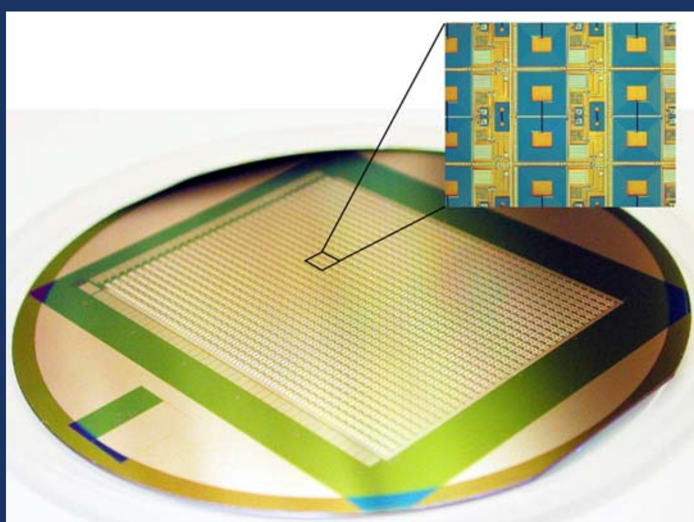
COMMON-USER SUBMILLIMETRE BOLOMETER ARRAY - 2
SCUBA2

- A collaboration of the UK, Canada, and NIST
- SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the

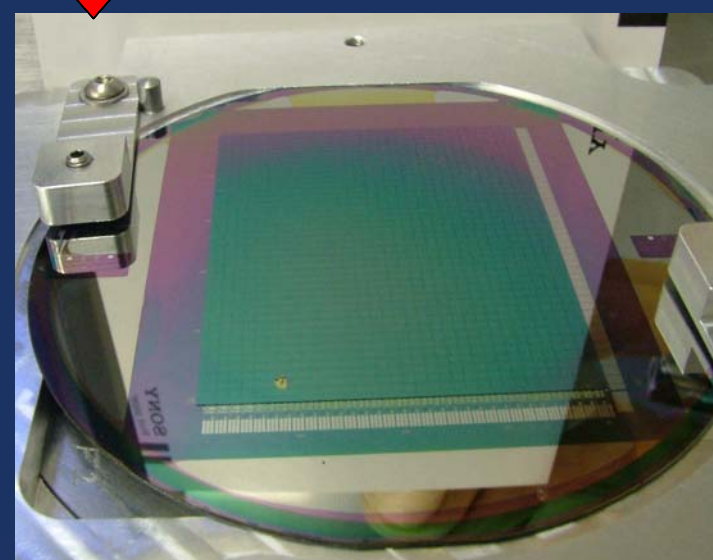
1,280-pixel TES bolometer



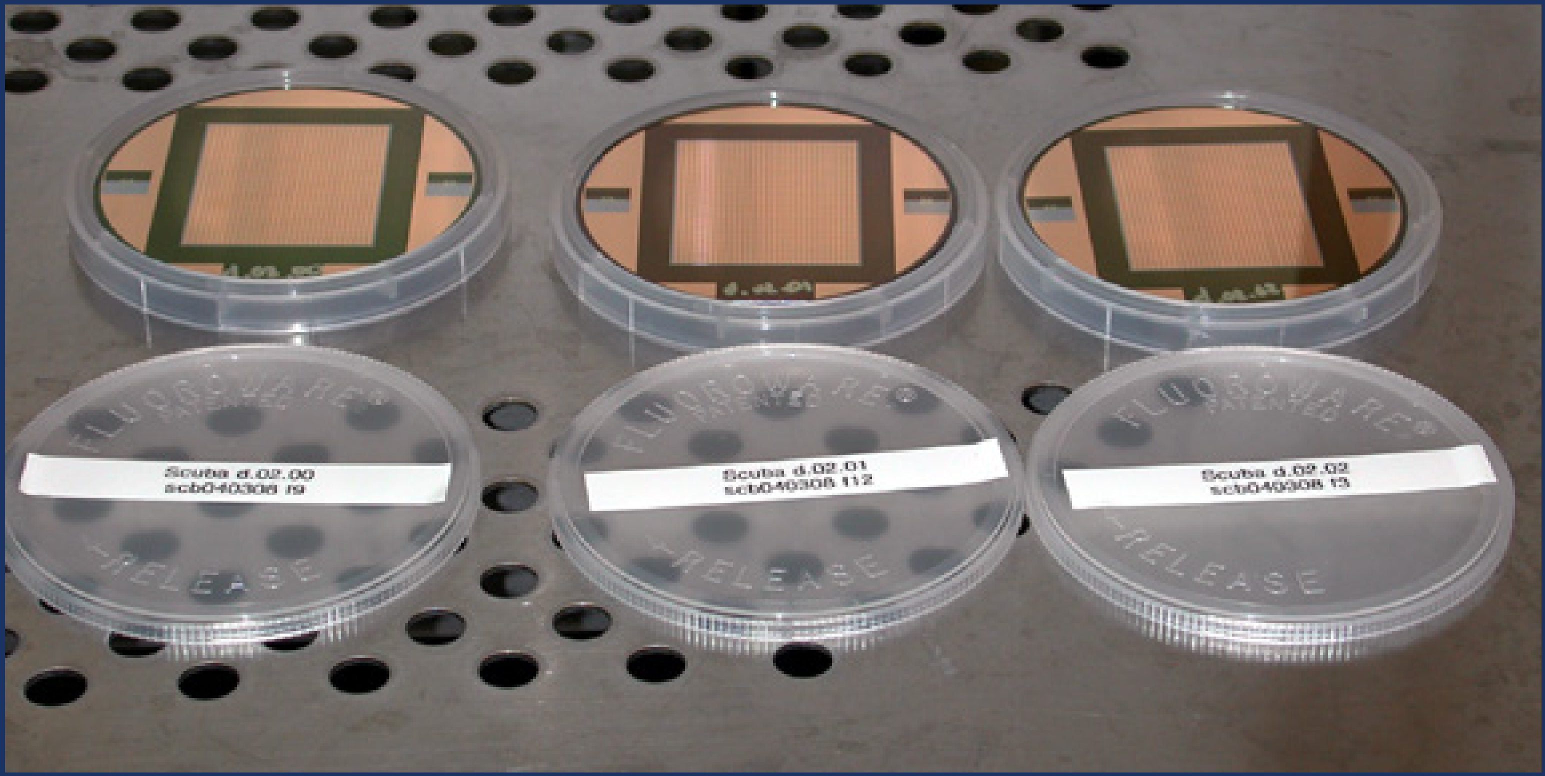
1,280-pixel SQUID Multiplexer



bump-bonded subarray (TES+MUX)



Manufacturability



We are fabricating eight 1,280-pixel THz arrays for SCUBA-2

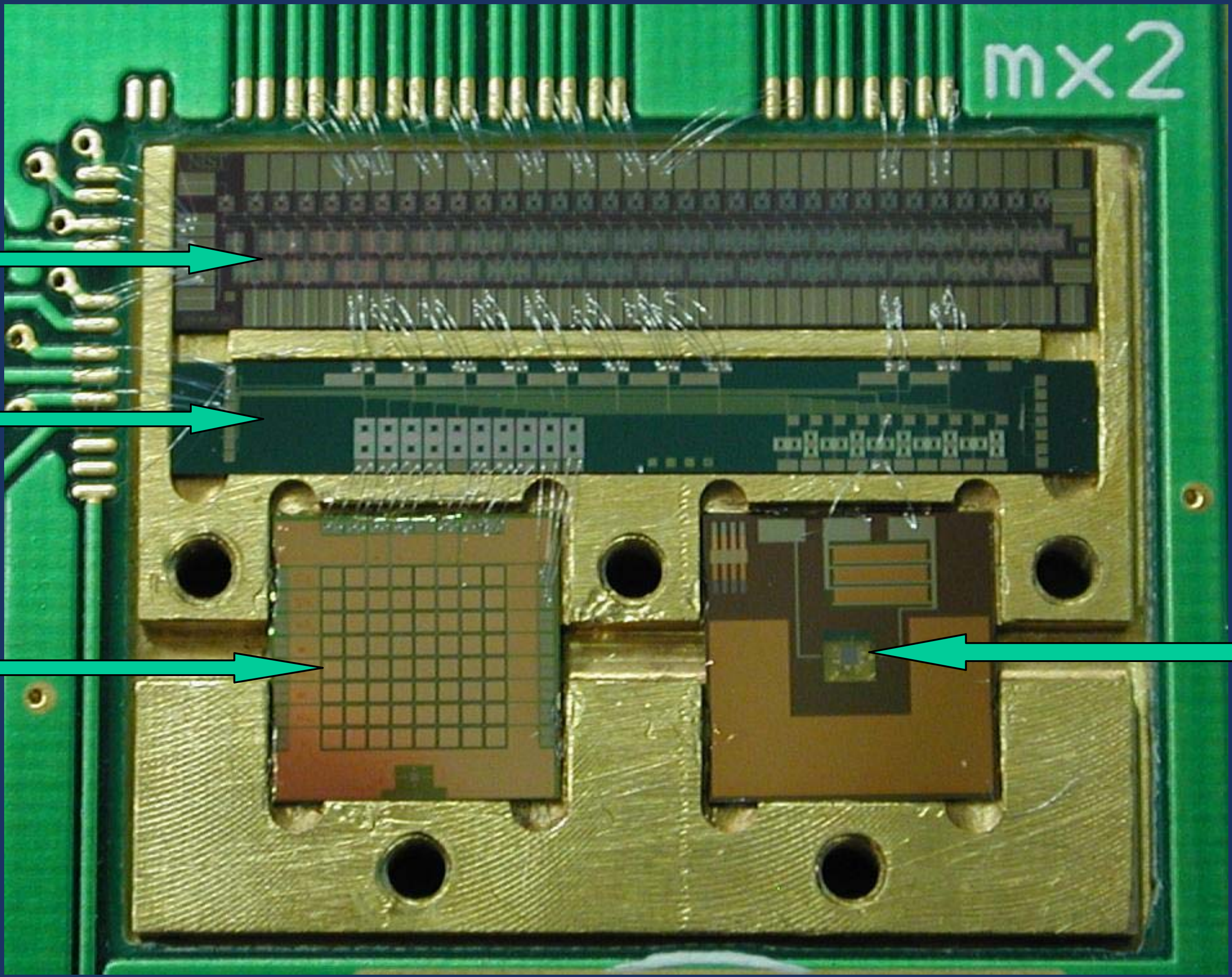
Multiplexed x-ray arrays

32-channel MUX chip

interface chip

8 x 8 sensor array

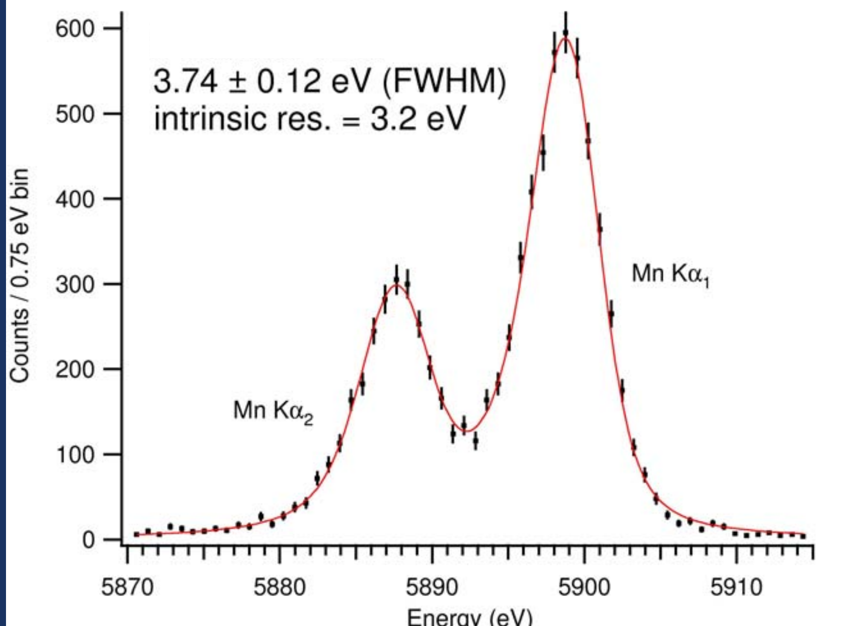
individual sensor



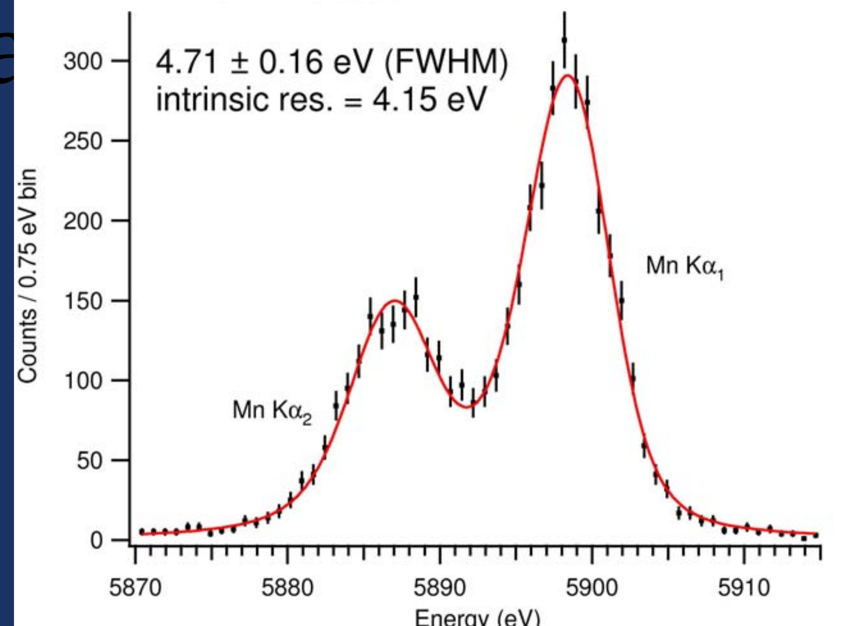
6.25 mm

Multiplexed x-ray calorimeter results

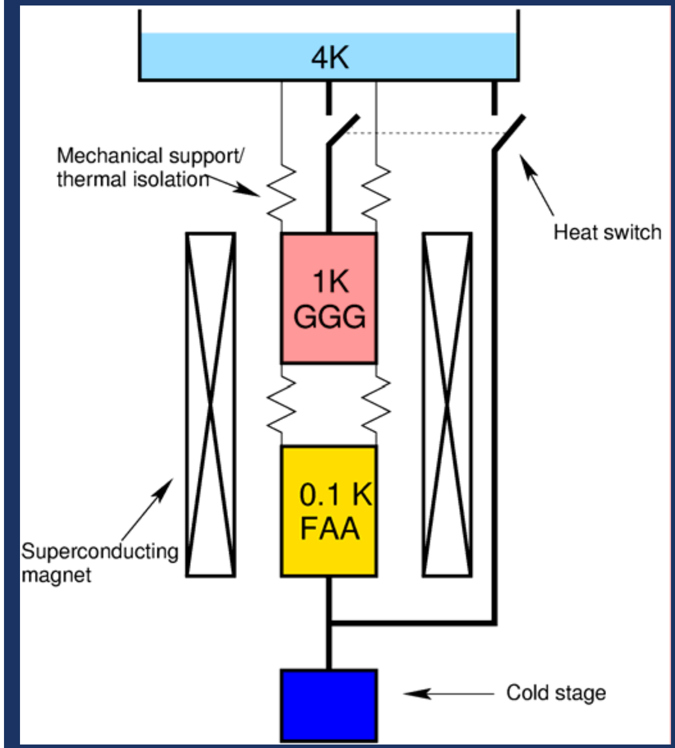
8-channel TDM



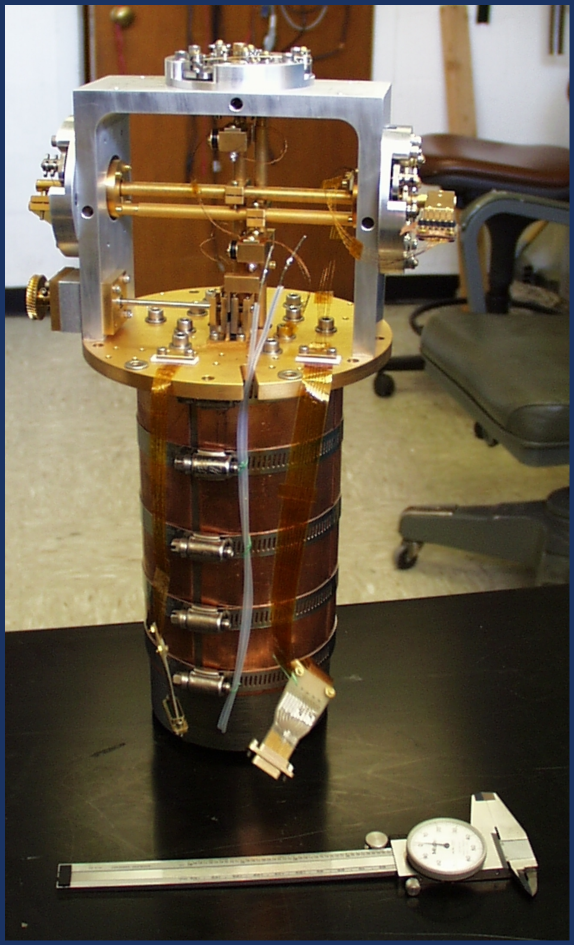
16-channel TDM



100 mK cryogenics



2-stage adiabatic demagnetization refrigerator (ADR)

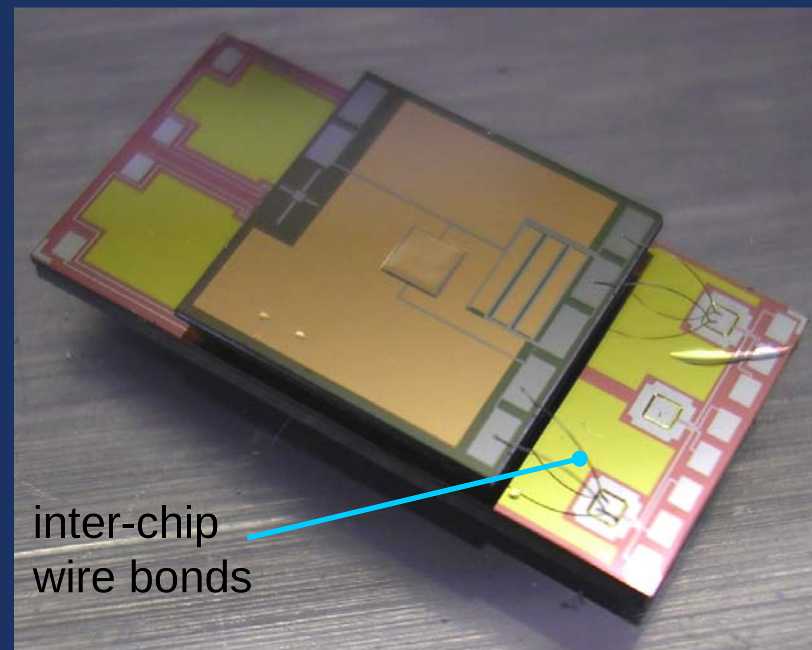


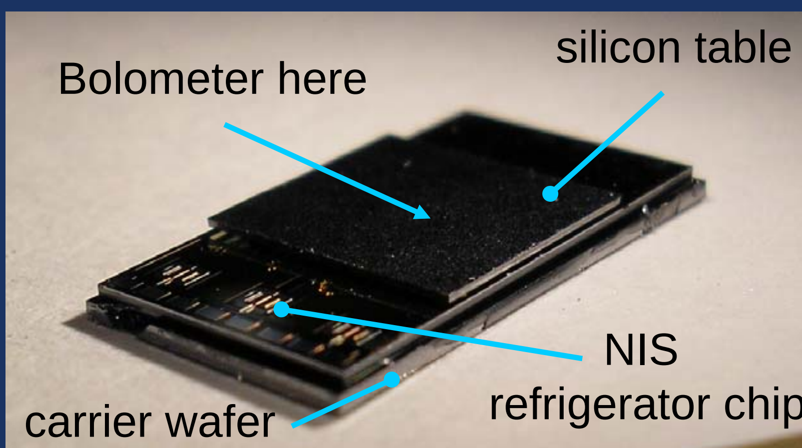
ADR and cryogen vessels mounted on SEM

Currently assembling a compact, cryogen-free ADR system compatible with modern SEMs

Each magnet cycle gets you to ~ 55 mK and ~ 24 hours < 100 mK

NIS full chip cooling

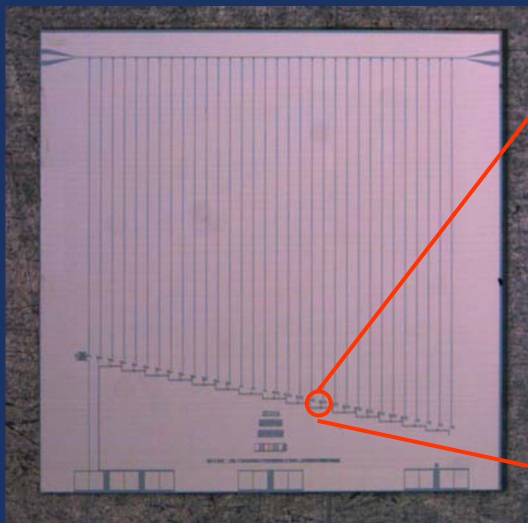




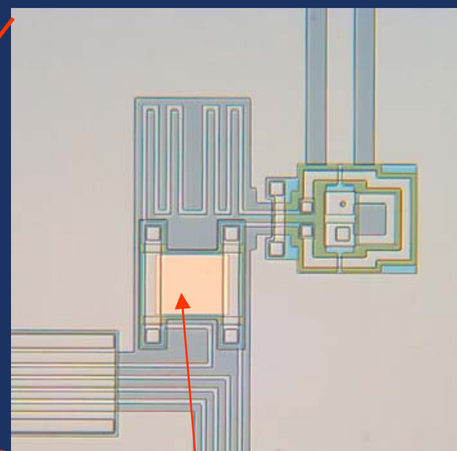
- Like a superconducting Peltier cooling
- Allows ADR temperatures from a cheap, robust, commercial He-3 refrigerator (~ 20 k$)

Microwave SQUID multiplexers

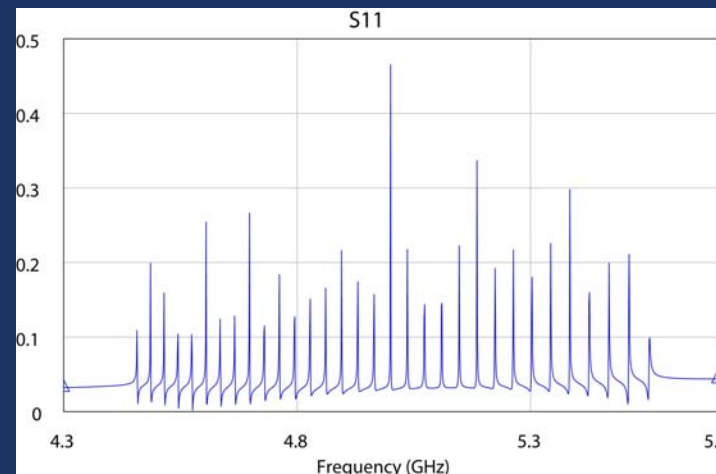
Chip with 32 microwave SQUIDs



Closeup of one SQUID



Model of response of 32 SQUIDs (data to follow)



Resistor simulates TES

- Many SQUIDs / bolometers coupled to high-Q resonators
- Possible future pathway to much larger arrays – 100,000+ pixels
- Scalable to >10,000 pixels in one output channel with large per-pixel bandwidth
- One output cable + one HEMT amplifier for thousands of pixels

Development possible over 5-10 years

All pixels 250 μm in size…

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	0.1 – 10 keV	5 eV	100,000	100 MHz	5 - 10 years

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