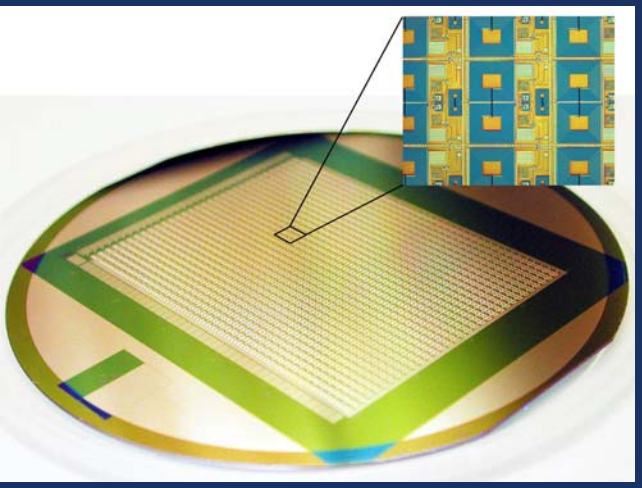
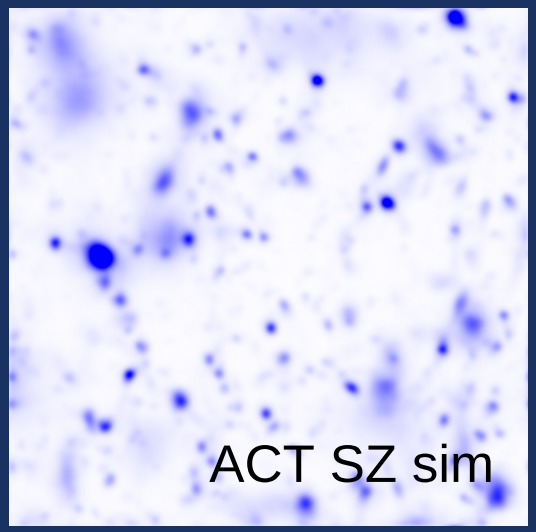
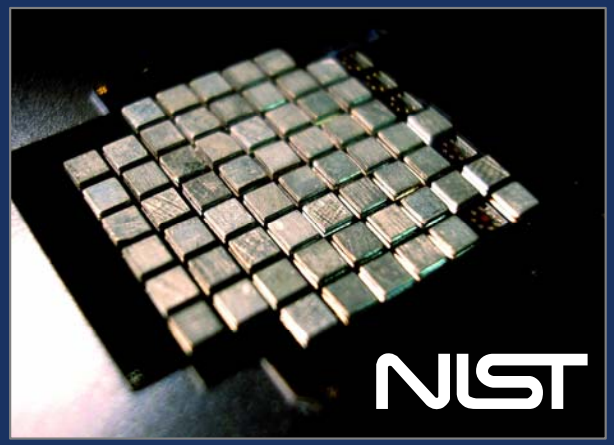
SLAC Advanced Instrumentation Seminar

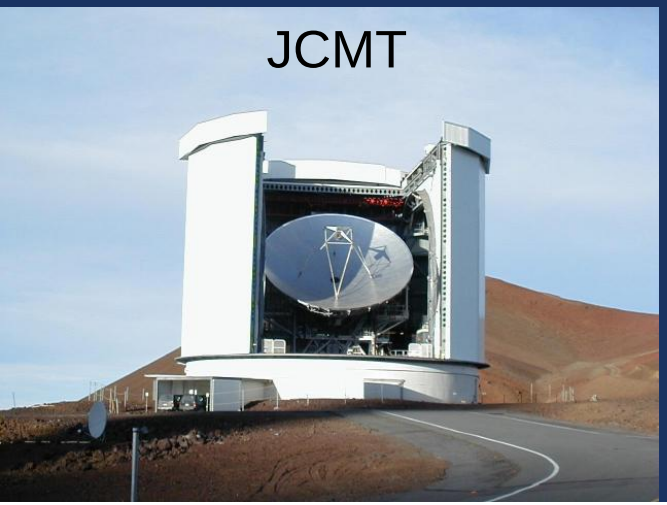
Superconducting detector arrays: from cosmology to nuclear non-proliferation

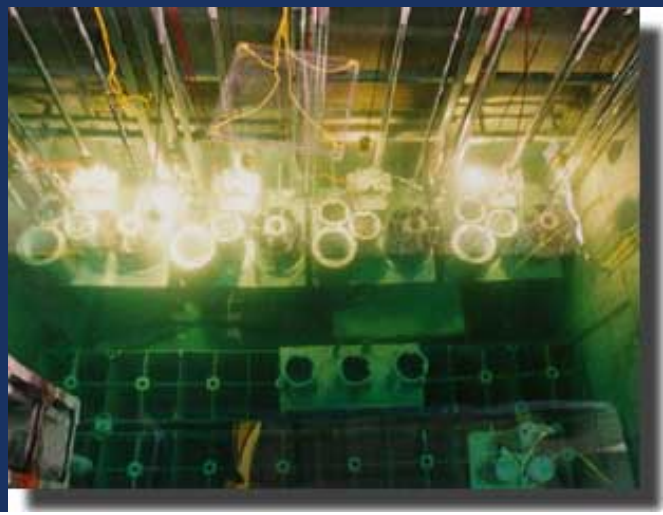
Kent Irwin
NIST











The Quantum Sensors Project at NIST

James Beall
Sherry Cho
Randy Doriese
William Duncan
Lisa Ferreira
Gene Hilton
Kent Irwin
Rob Horansky
Ben Mates
Nathan Miller
Galen O'Neil
Carl Reintsema
Dan Schmidt
Joel Ullom
Leila Vale
Yizi Xu
Ki Won Yoon
Barry Zink

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Outline

- Breakthroughs in superconducting and cryogenic technology are enabling practical large superconducting cameras and spectrometers
  - Superconducting transition-edge sensors
  - Micromachining
  - SQUIDs multiplexers
  - Cryocoolers
- Astronomical and particle physics applications have driven the development of superconducting detector arrays, but a broader variety of fields are being impacted
  - Cosmology
  - X-ray and submm astronomy
  - Quantum information
  - Electron probe materials analysis
  - Security
  - Nuclear materials
  - Particle physics

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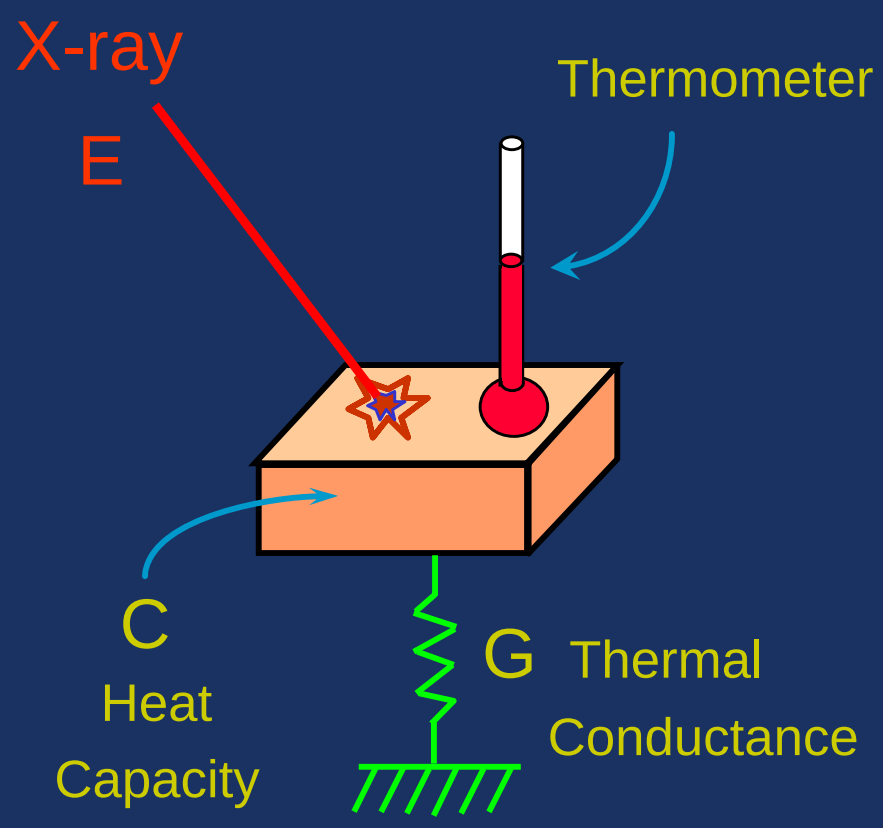
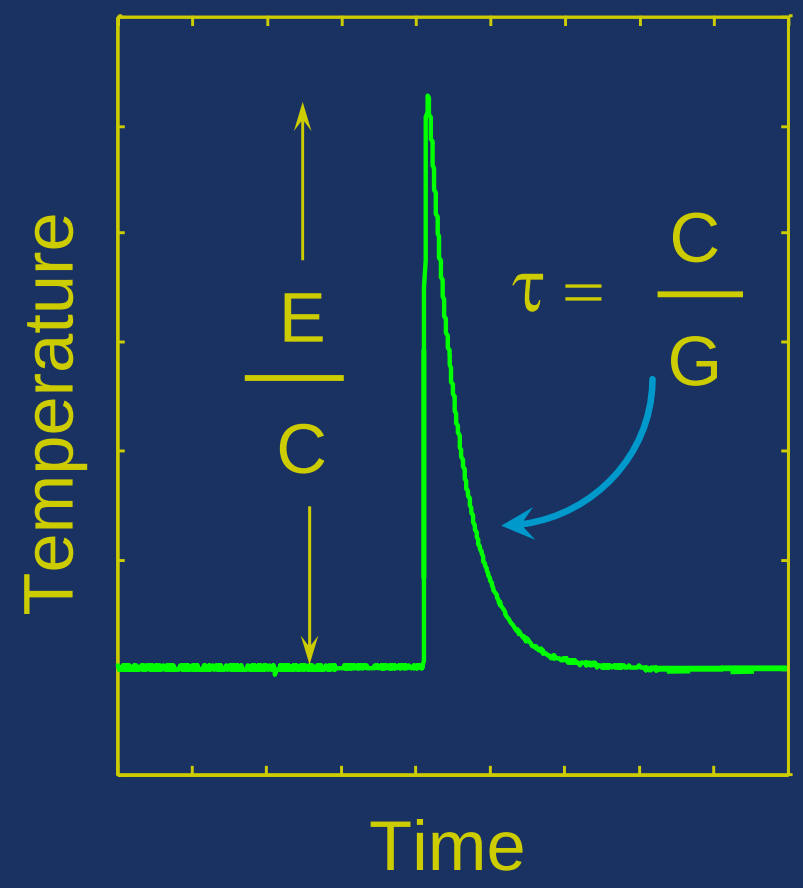
Applications of TES arrays

Cosmology	CMB, submm, x-ray	Dark energy, inflation, neutrino mass…
Astronomy	submm, x-ray, γ-ray	Planet/star/galaxy formation, WHIM, black holes…
Quantum information	optical	Quantum key distribution, computing
Materials analysis	x-ray	Electron-probe materials analysis, synchrotron
Security	THz, γ, neutron	Concealed weapons, Suicide bombers, nuclear smuggling
Nuclear materials	γ-ray, alpha, neutron	Nuclear non-proliferation, forensics
Particle physics	Dark matter, neutrinos	WIMPs, neutrino mass CDMS

Thermal detection





Photon → Heat

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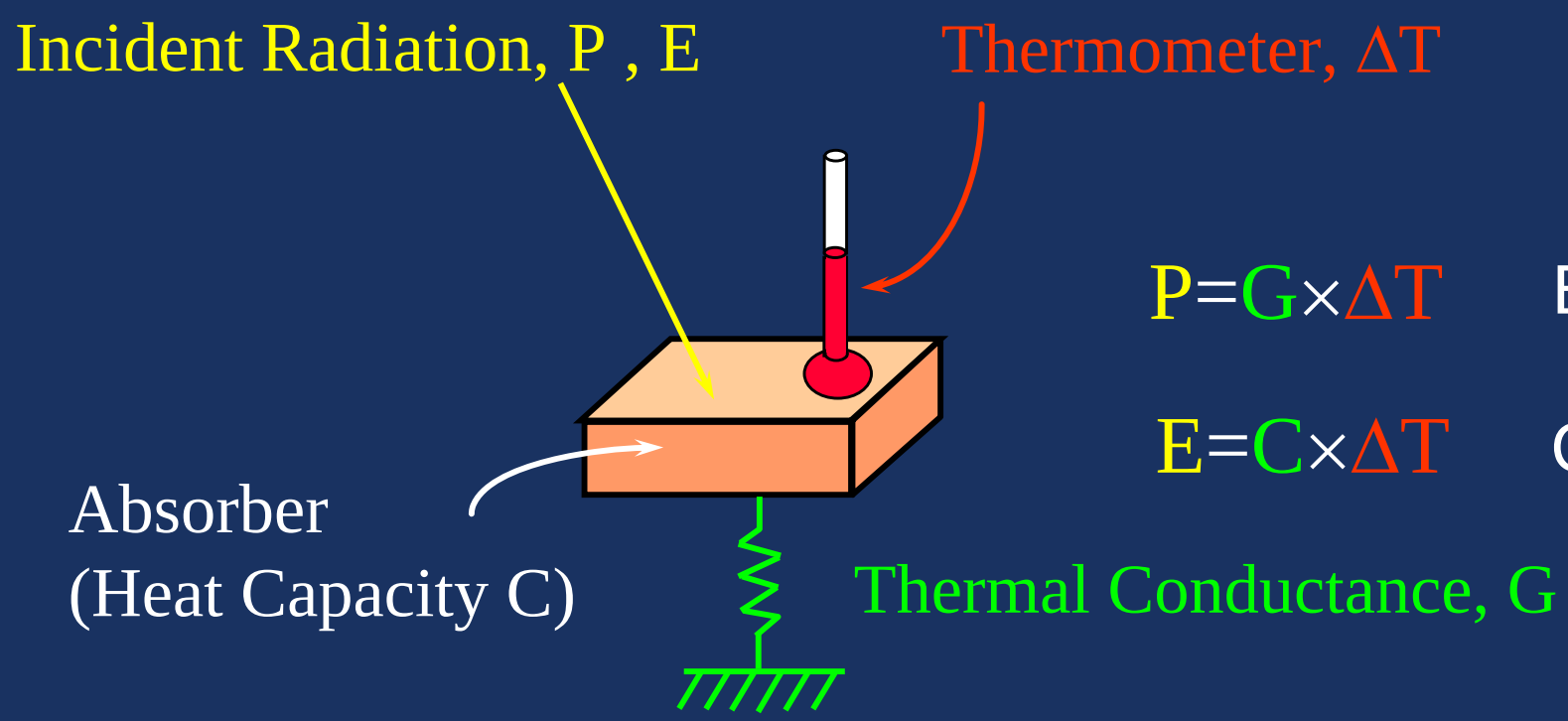
Bolometers and calorimeters



$P = G \times \Delta T$ Bolometer

$E = C \times \Delta T$ Calorimeter

Thermodynamic power noise:	$NEP^2 = 4k_bT^2G$	$(W/\sqrt{Hz})^2$
Energy fluctuations:	$\Delta E_{rms}^2 = k_bT^2C$	$(J)^2$

Operate at low temperatures (T~ 0.1K to 0.3K) where C, G and thermodynamic fluctuations are small.

Response time:	$\tau \propto C/G$	(s)

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X-ray energy resolution

Thermodynamic energy fluctuations

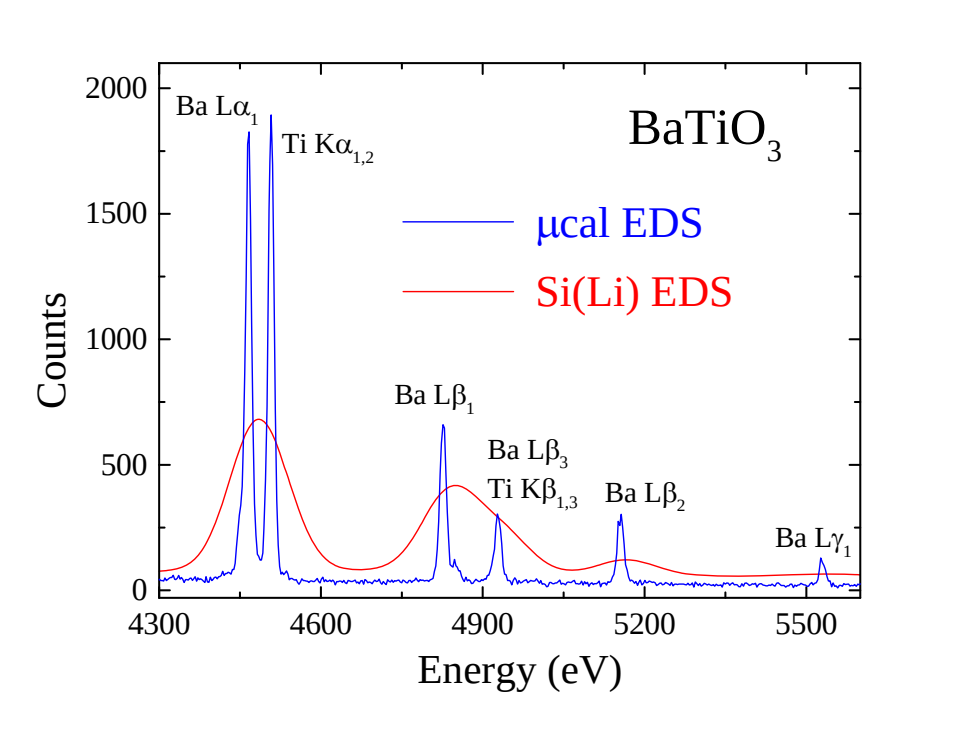
$$\Delta E_{rms} = \sqrt{k_B T C}$$

k_B Boltzmann's constant

T Temperature of operation

C Heat capacity

- The energy resolution can be a bit better than the thermodynamic energy fluctuations.



- At 6 keV, conventional semiconductor detectors have energy resolution as good as about 120 eV
- TES x-ray calorimeters can have energy resolution ~ 2 eV – about 60 times better than SiLi.

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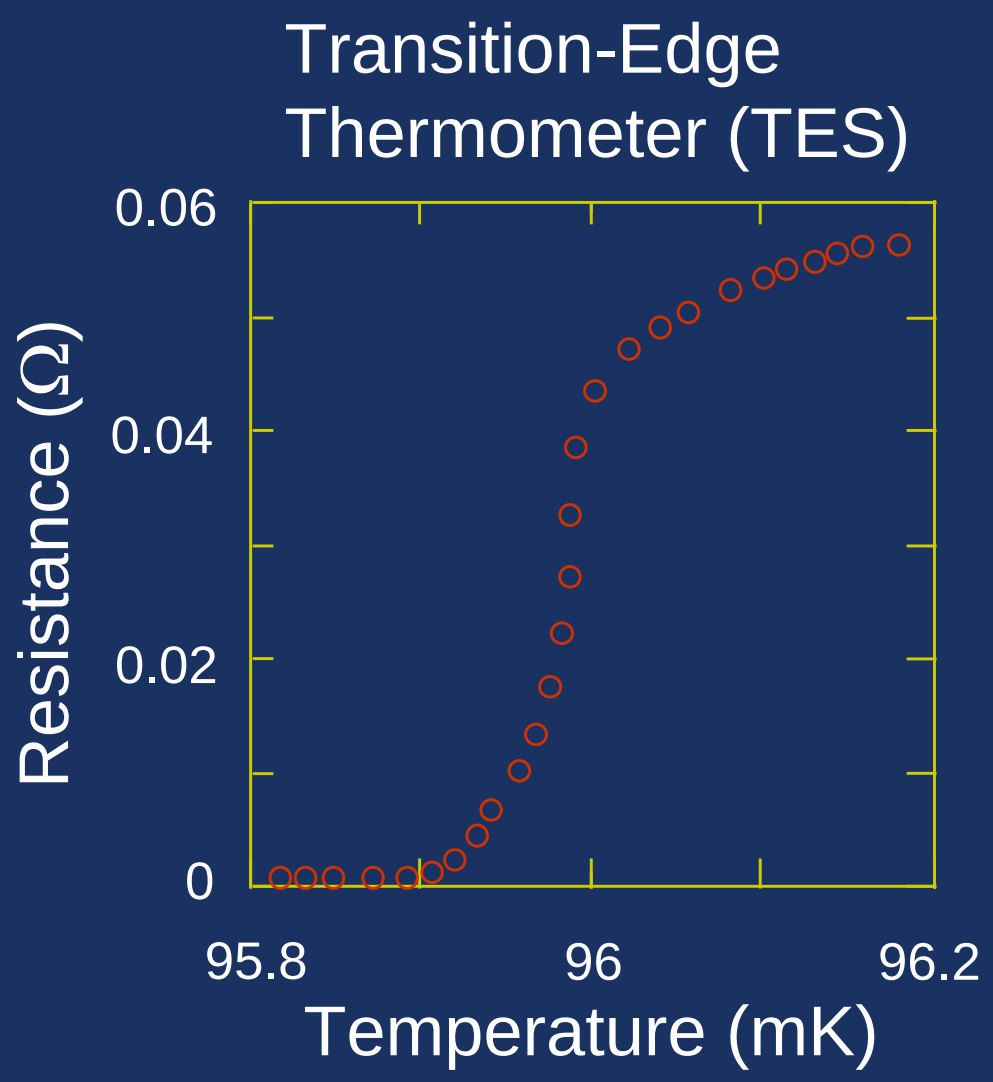
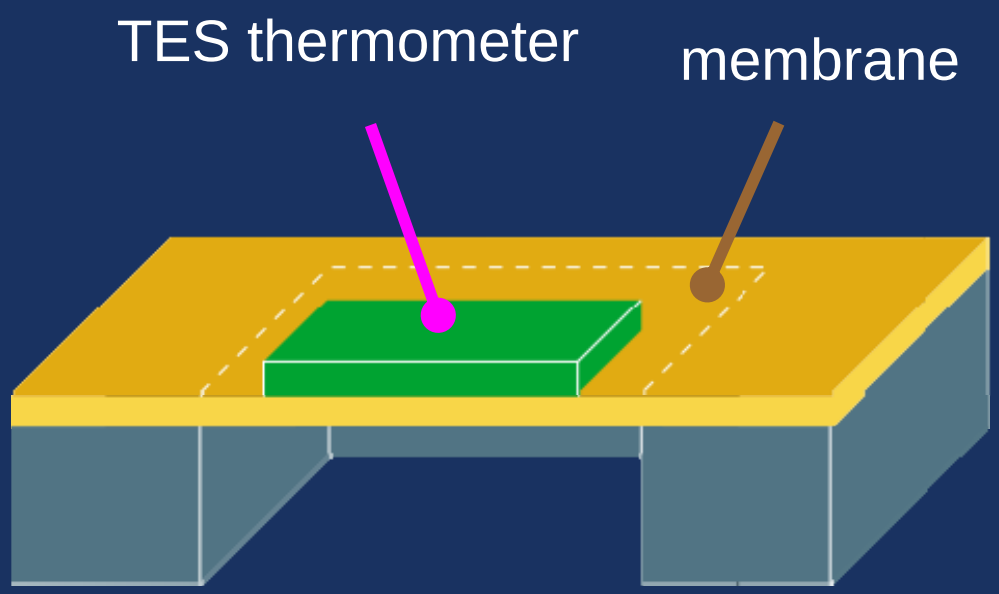
Superconducting Transition-Edge Thermometer





Photon → Heat → Resistance

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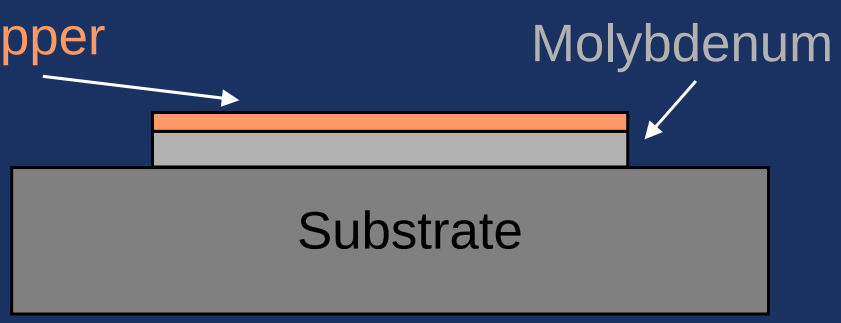
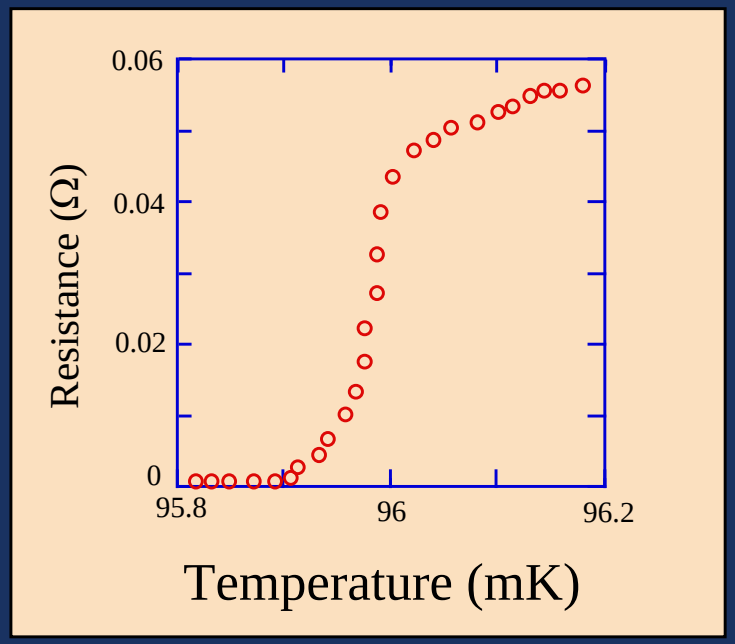
Proximity bilayers

- 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"

- One example system is Mo-Cu

Robust and temperature stable	
Molybdenum	Tc ~ .92 K
Copper	normal





- Sharp
- Reproducible <~ 5 mK
- Tunable
- Robust

Other systems: Ti / Al, Mo / Au, W, Ti, etc.

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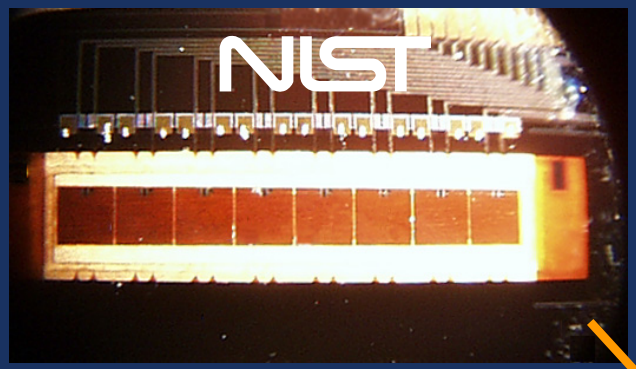
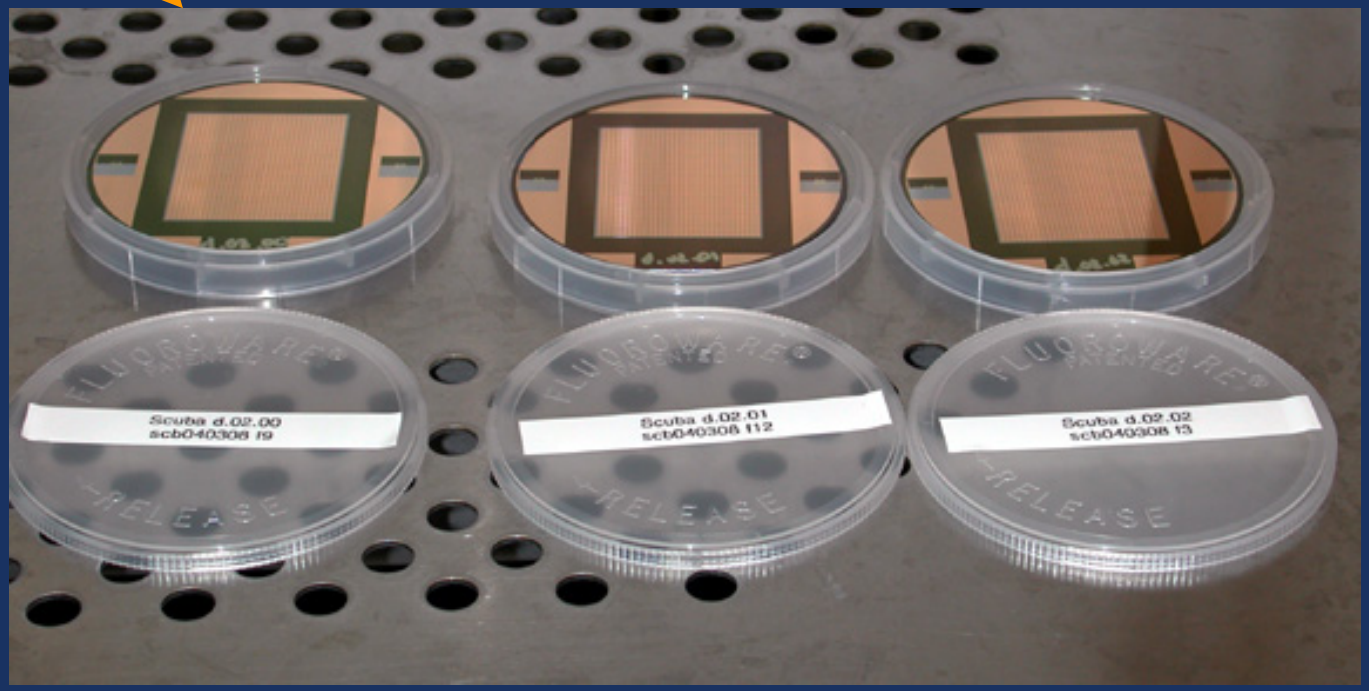
TES arrays

2001 – FIBRE 1



FIBRE 8-pixel bolometer array

2006 – SCUBA-2 subarrays



Three 1,280-pixel TES bolometer subarrays for SCUBA-2; with UK ATC; SMC

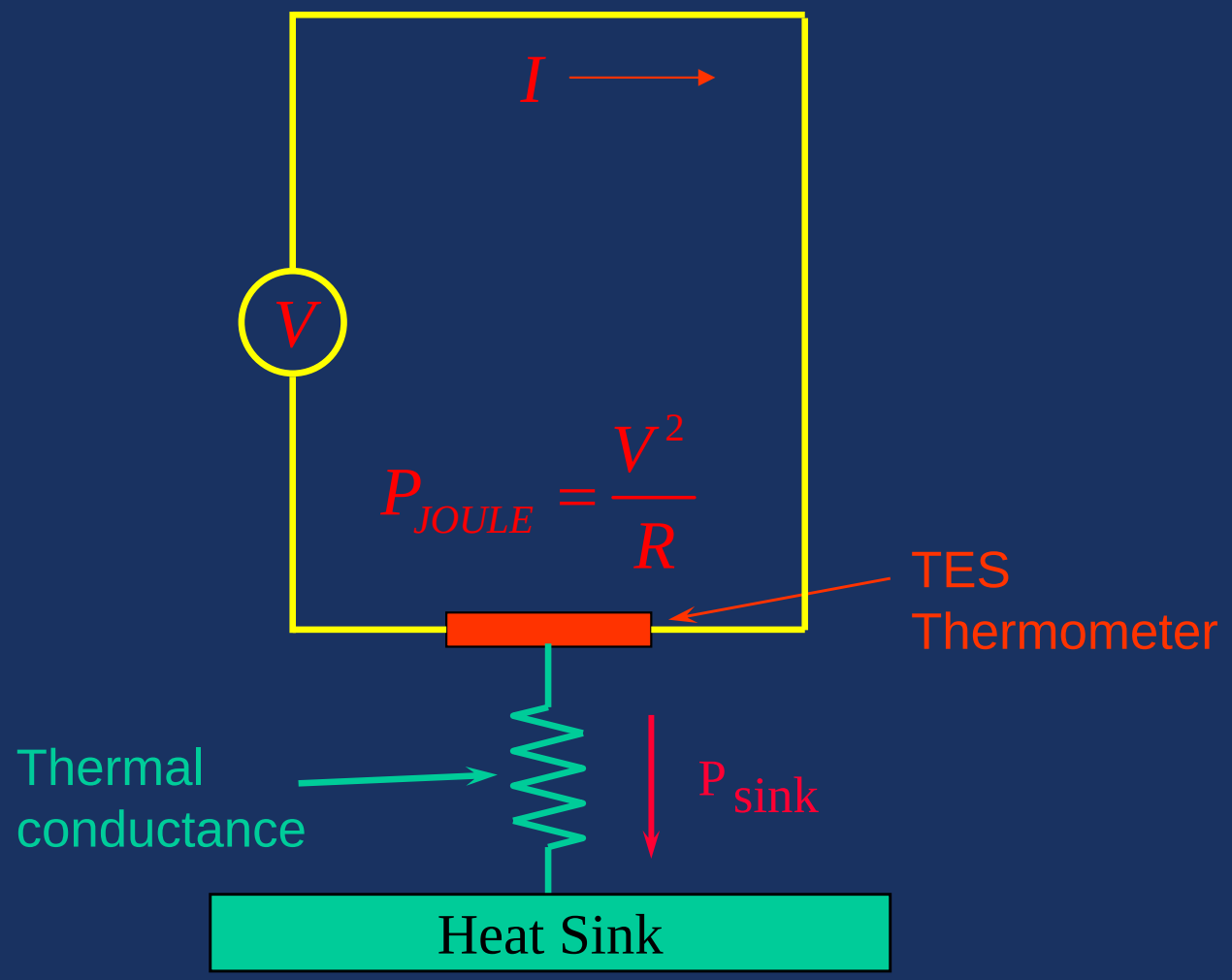
Temperature self-biasing

Temperature self-biasing enables for large TES array applications

As the film cools, $R \rightarrow 0$, and P_{joule} increases.

Stable equilibrium

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



If you cool the heat sink to well below the transition temperature of a voltage-biased TES, the TES will self-heat into its transition (electrothermal feedback).

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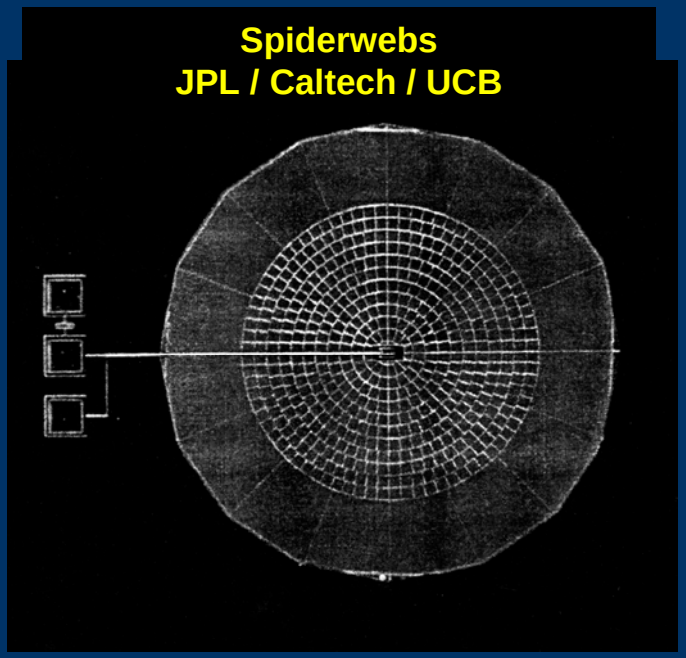
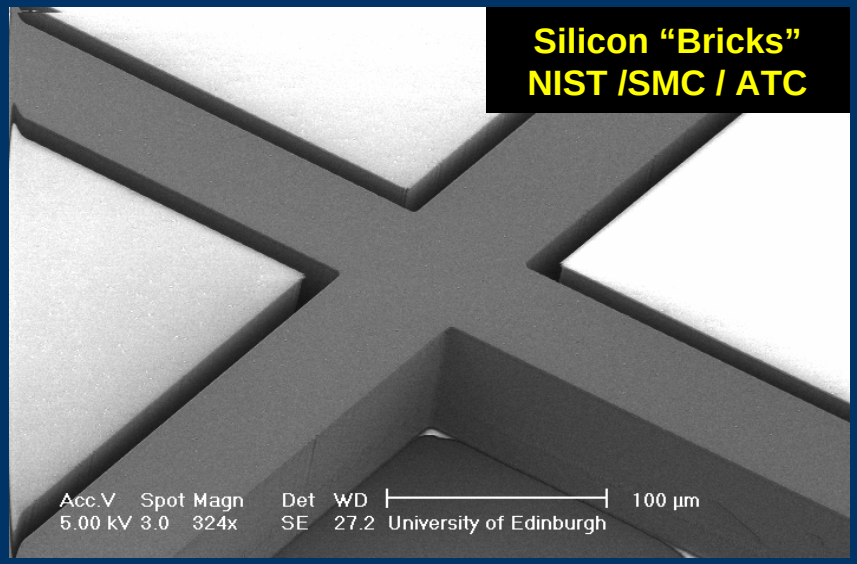
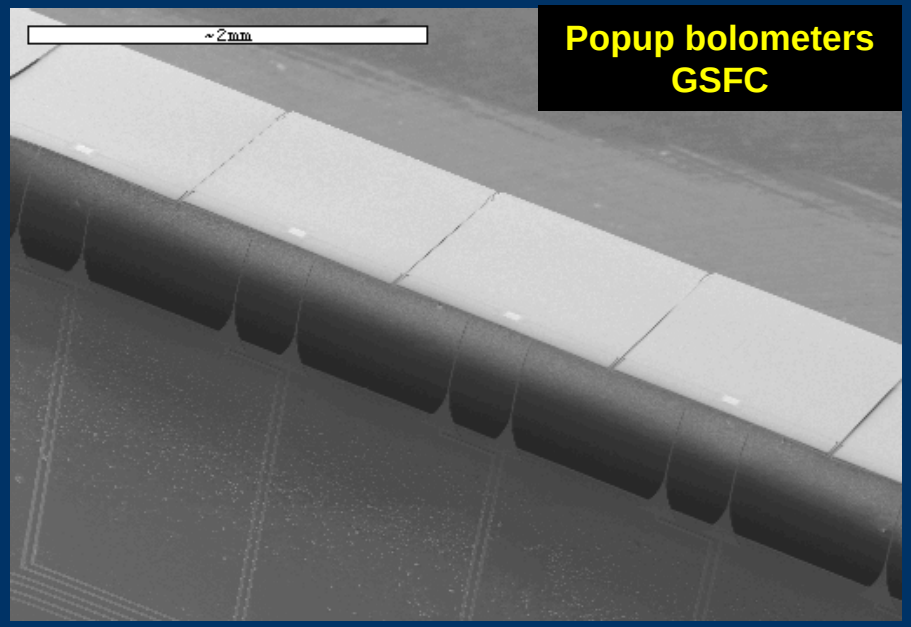
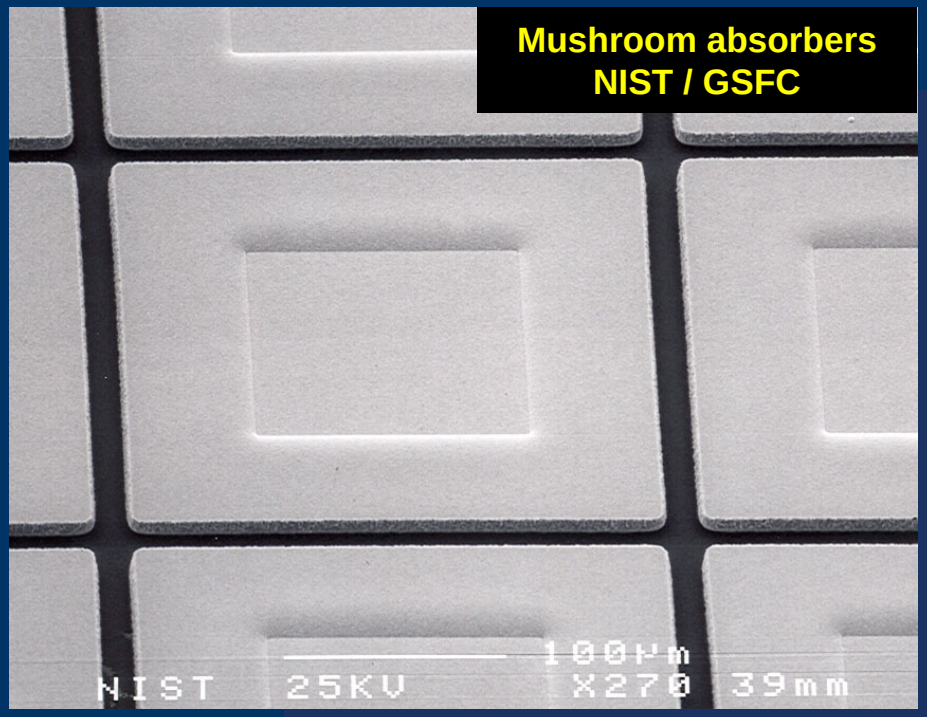
Micromachining

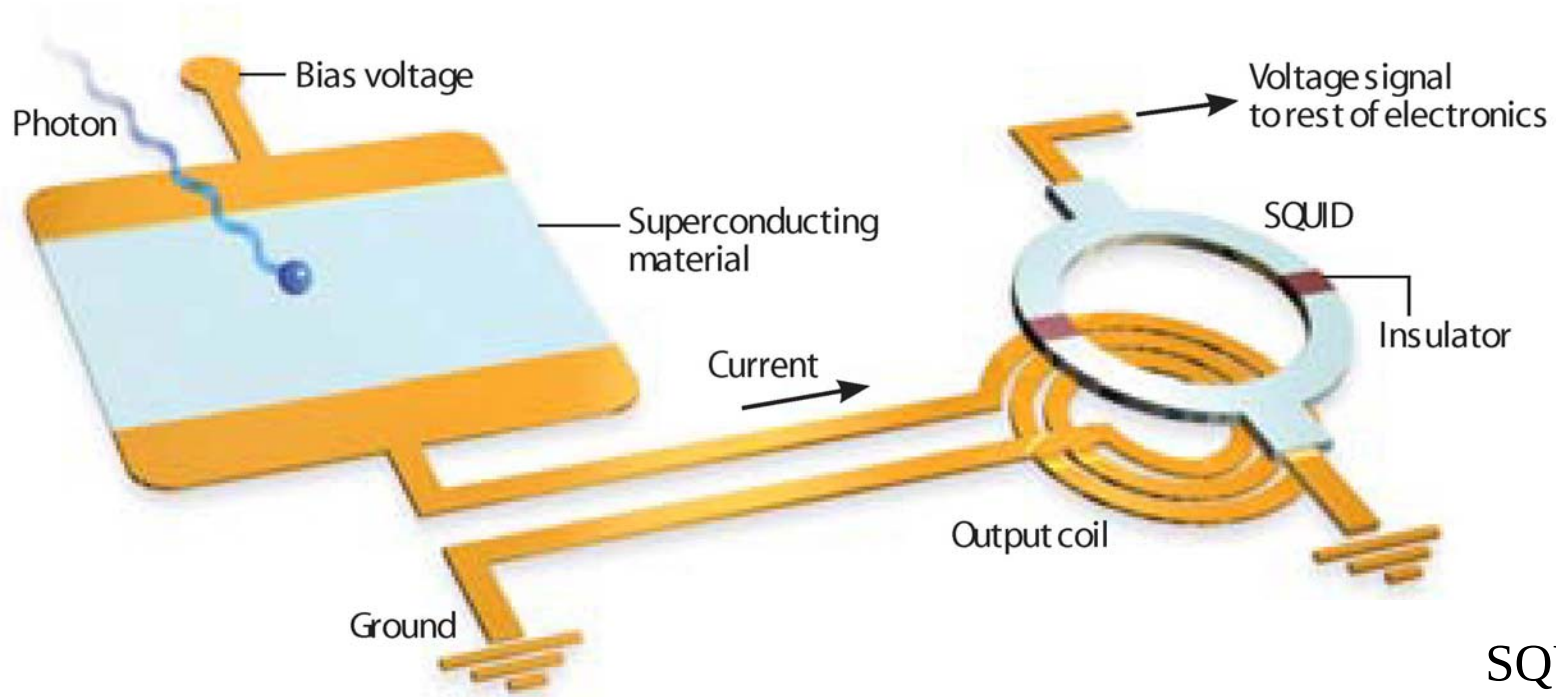




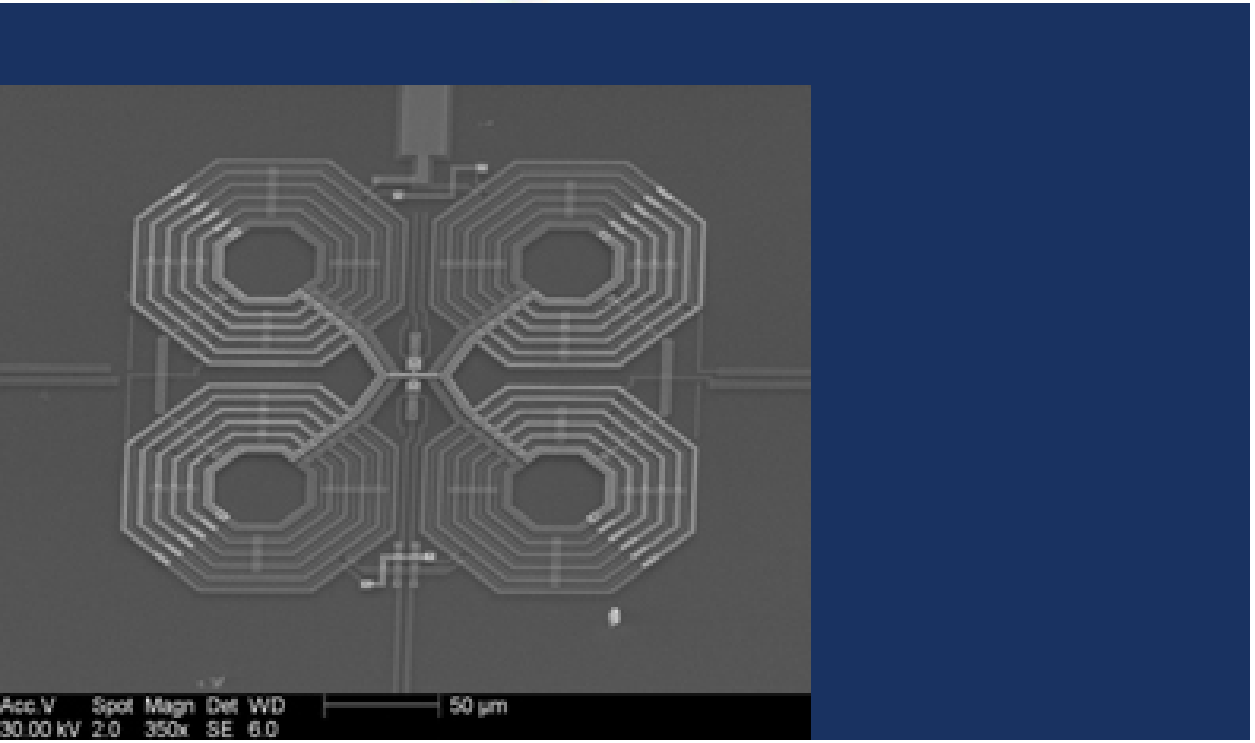




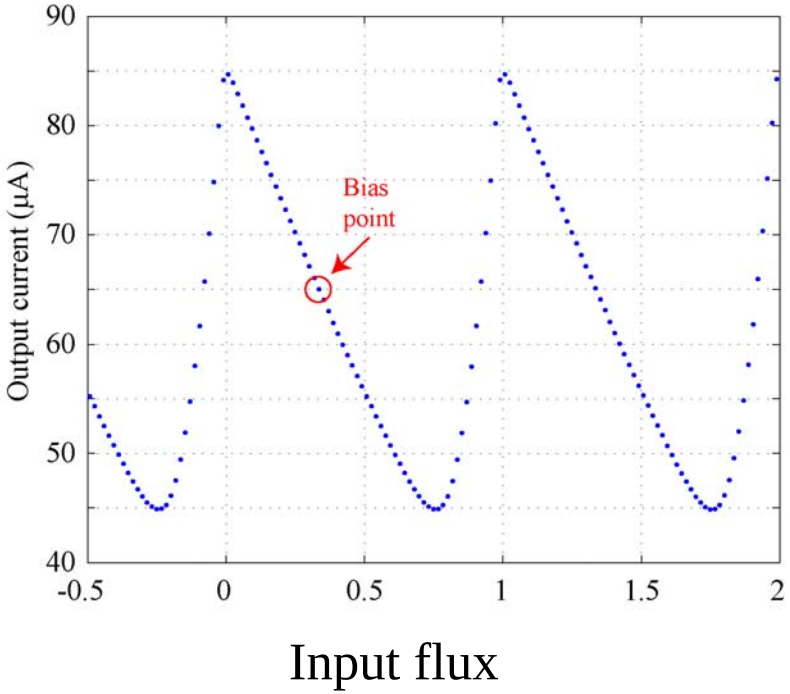
SQUID readout



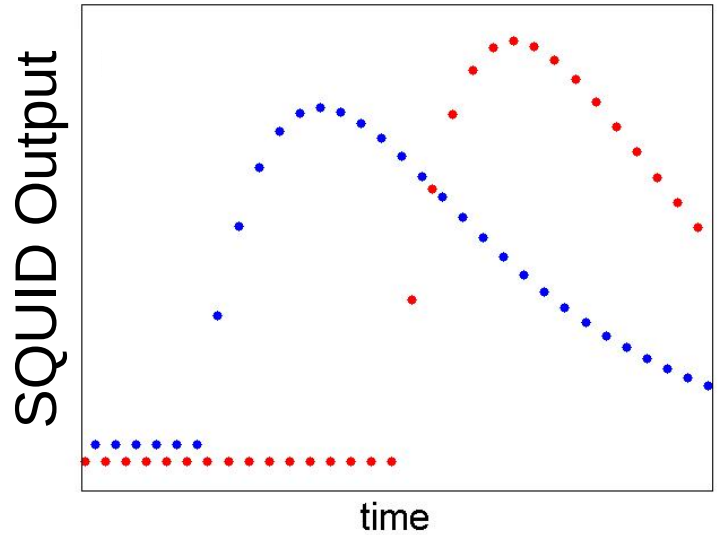
SQUID power: ~ nW per 'on' channel – operate at base temperature

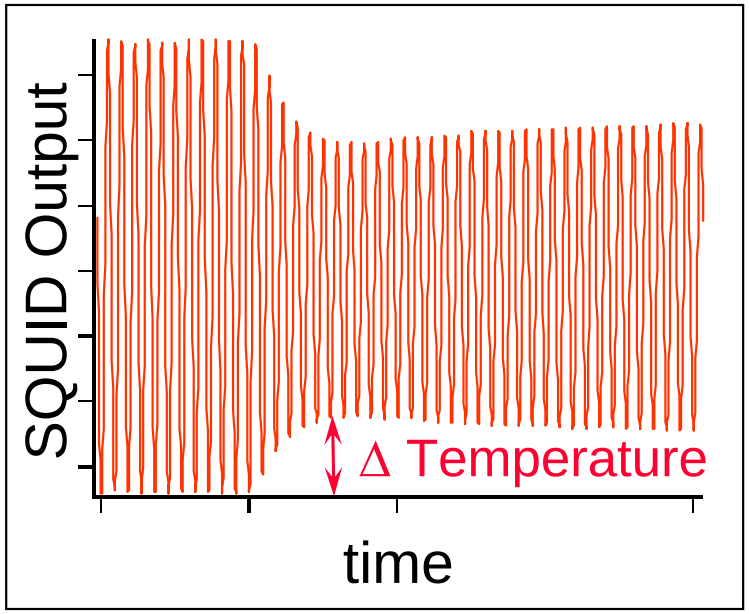


SQUID response

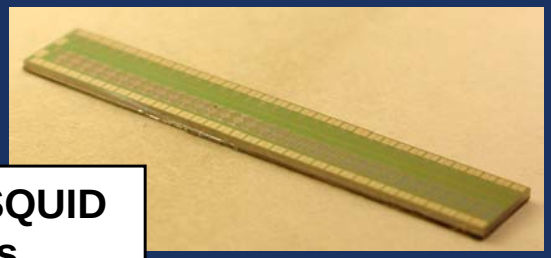


Multiplexing basis sets



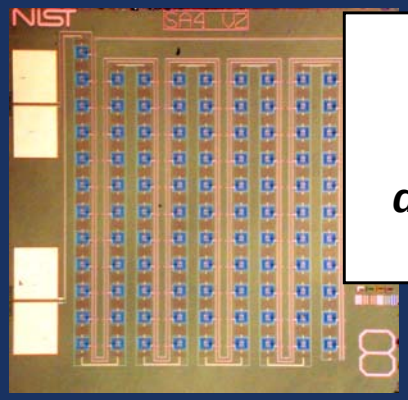


Time division (TDM): different pixels at different times

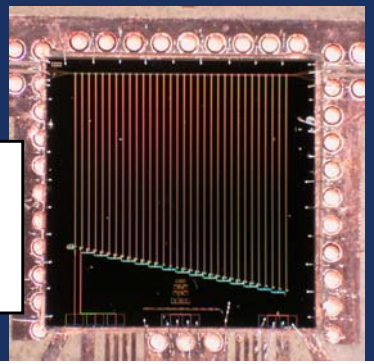


~MHz TDM SQUID switches

Frequency division (FDM): different pixels at different frequencies



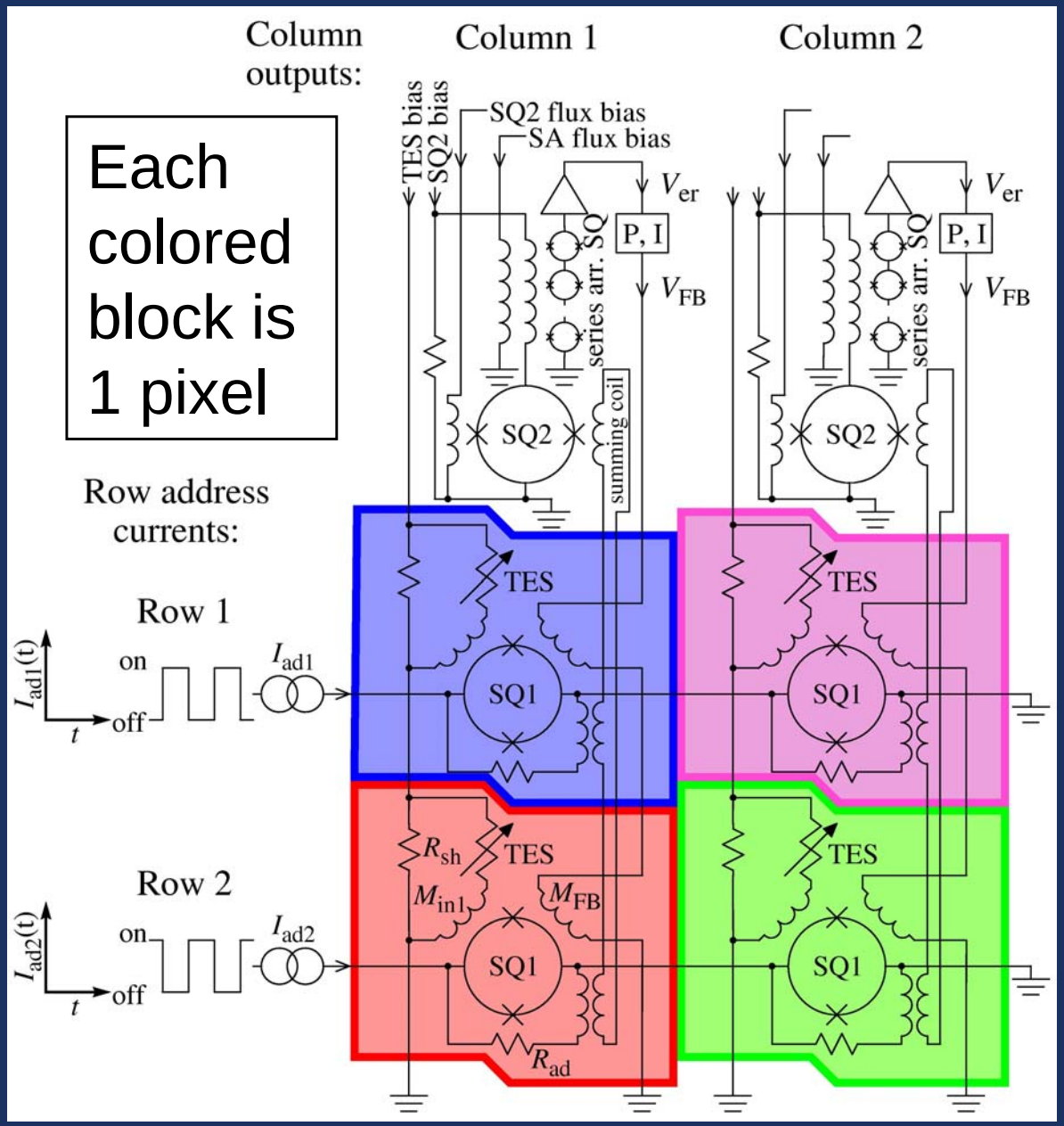
100-SQUID series array for *~MHz frequency-domain readout with Berkeley/LBNL*



Dissipationless rf SQUID multiplexer ~4-8 GHz

Same idea, different orthogonal basis set

Analog time-division multiplexing



- 2 x 2 array is shown as example of *N*-row by *M*-column array

- TDM operation:
  - each TES coupled to its own SQ1
  - TESs stay on all the time
  - rows of SQ1s turned on and off sequentially
  - SQUIDs are nonlinear amplifiers, so use digital FB

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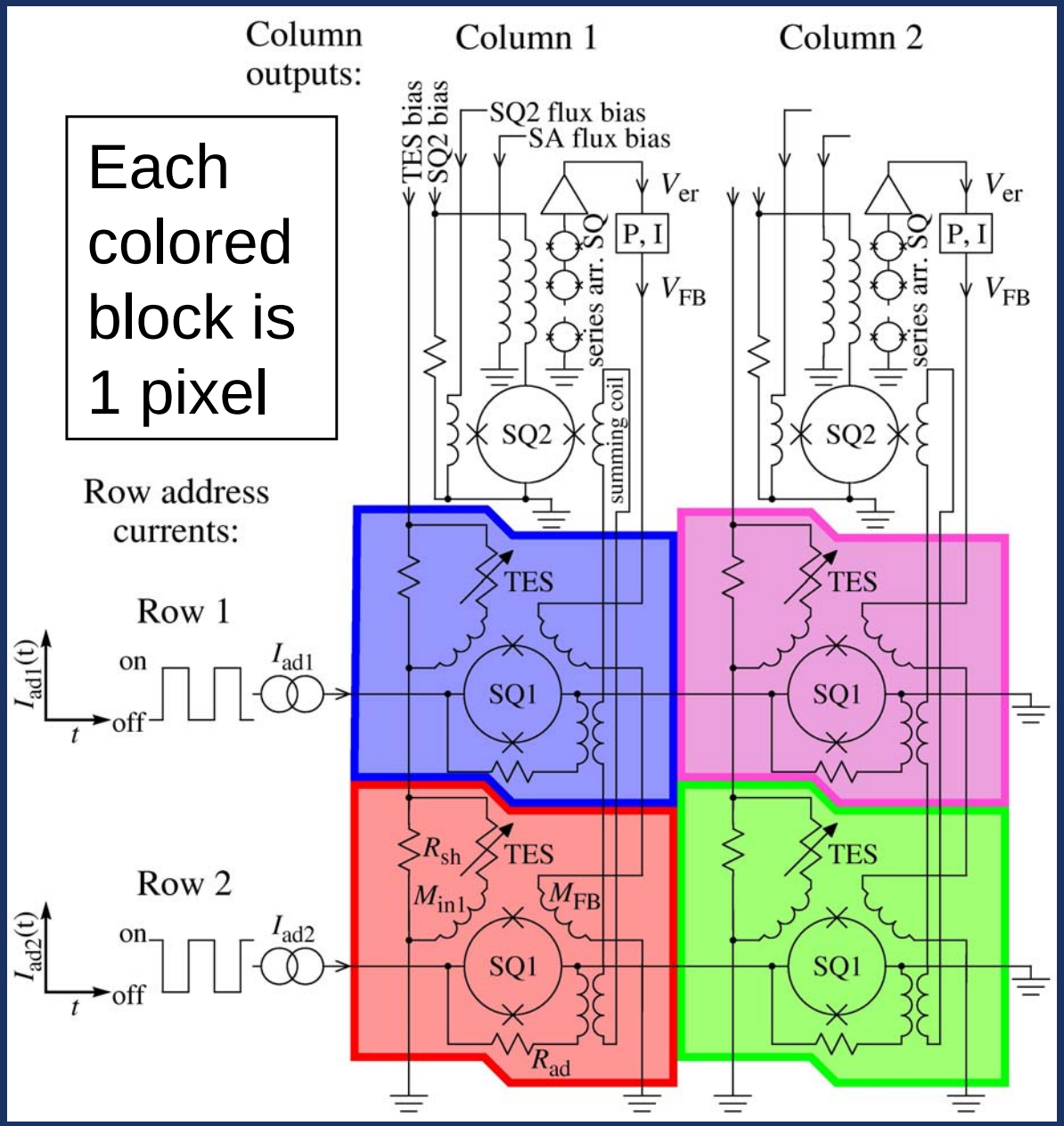
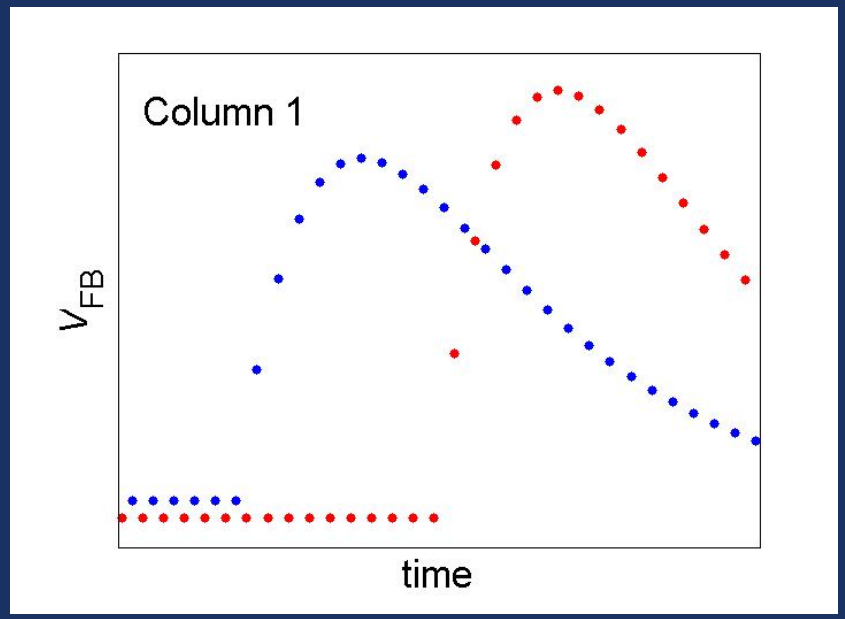
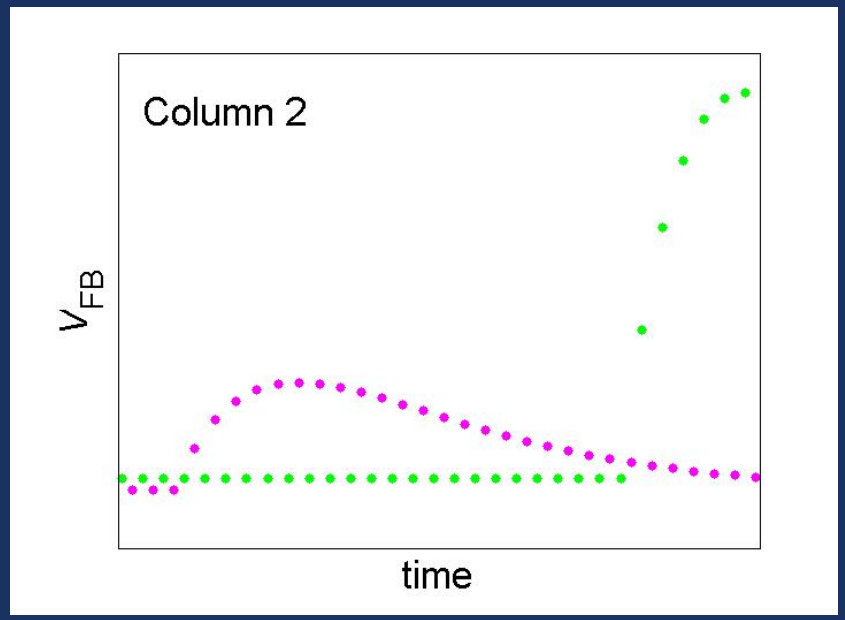
Analog time-division multiplexing







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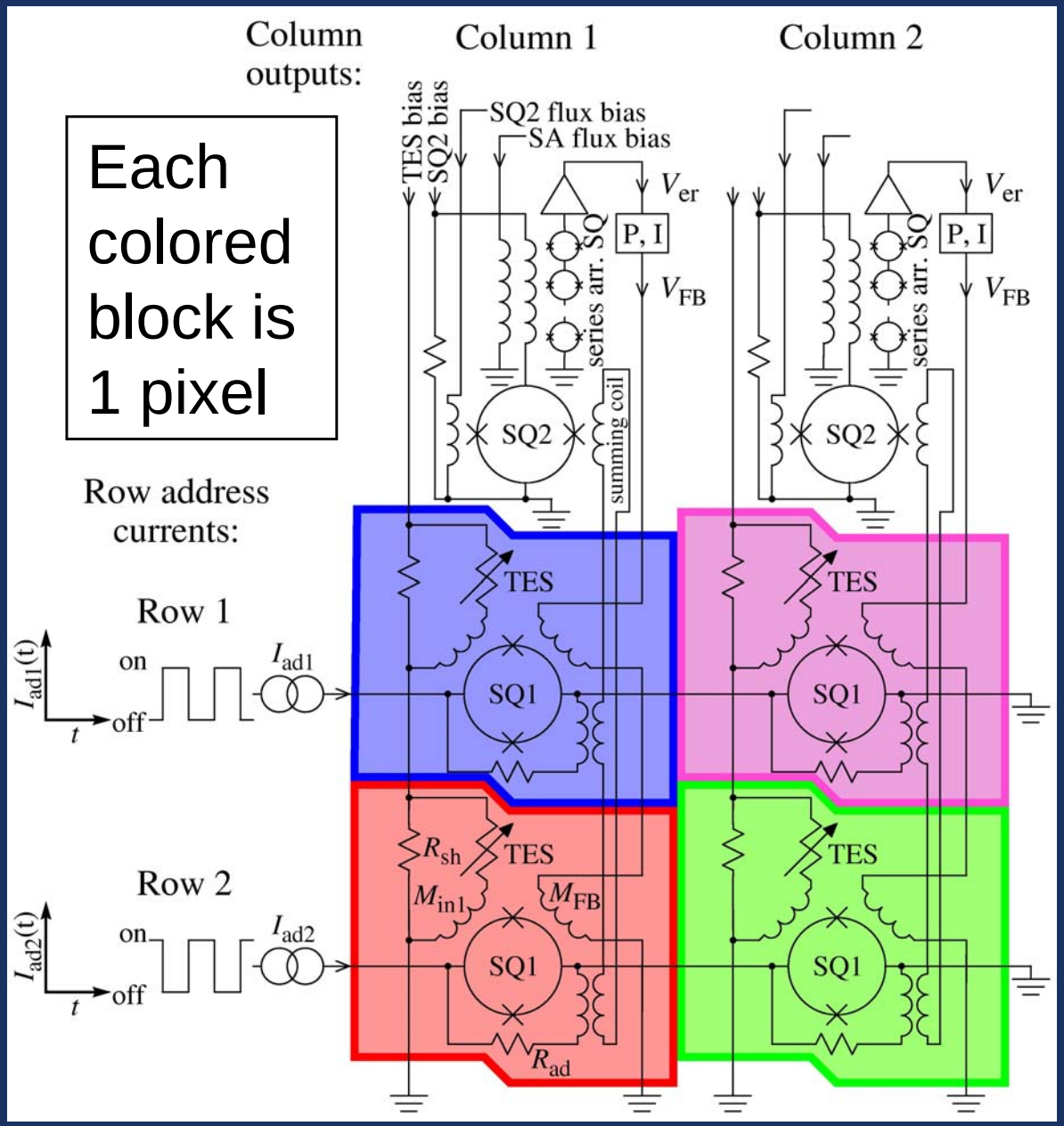
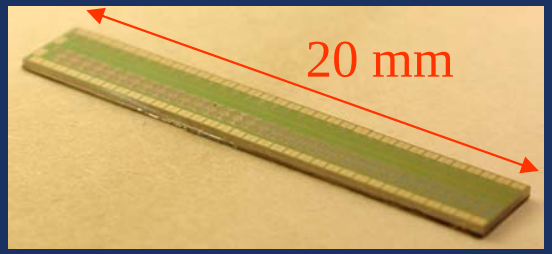
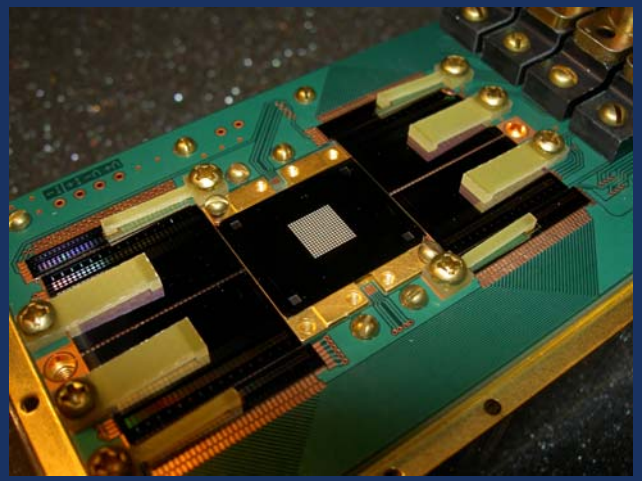
Analog time-division multiplexing



Each colored block is 1 pixel





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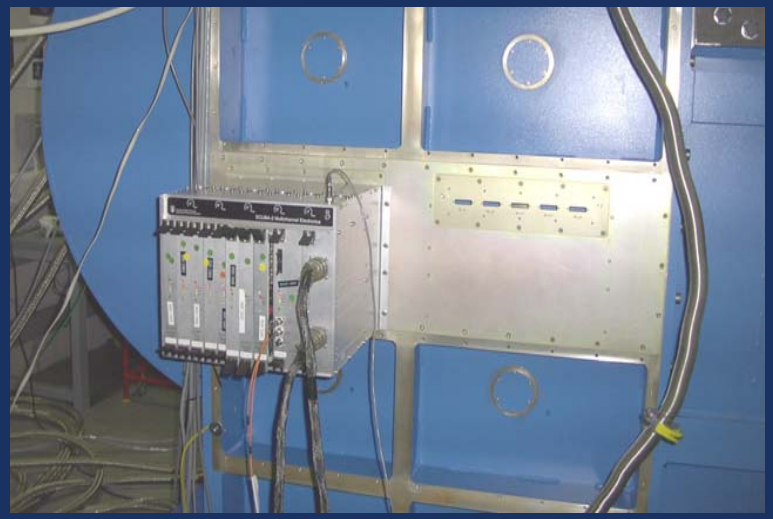
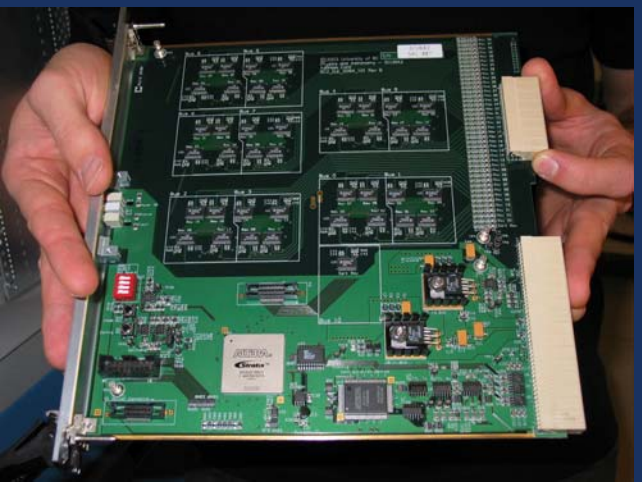
UBC Room-temperature electronics

- Electronics
  - MCE from UBC – 8 columns per mux card, fully supported system, 10 person years of FPGA firmware development
  - NIST/UBC MUX used for SCUBA-2, ACT, SPIDER, BICEP-2, SPUD, ClOVER, ZEUS…



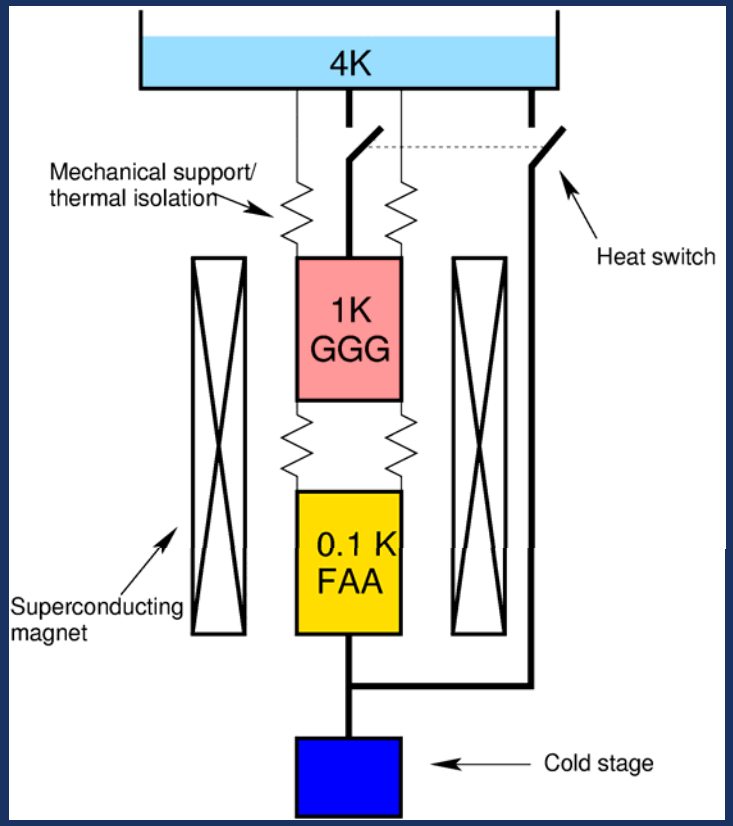
One crate controls 1,280 pixels

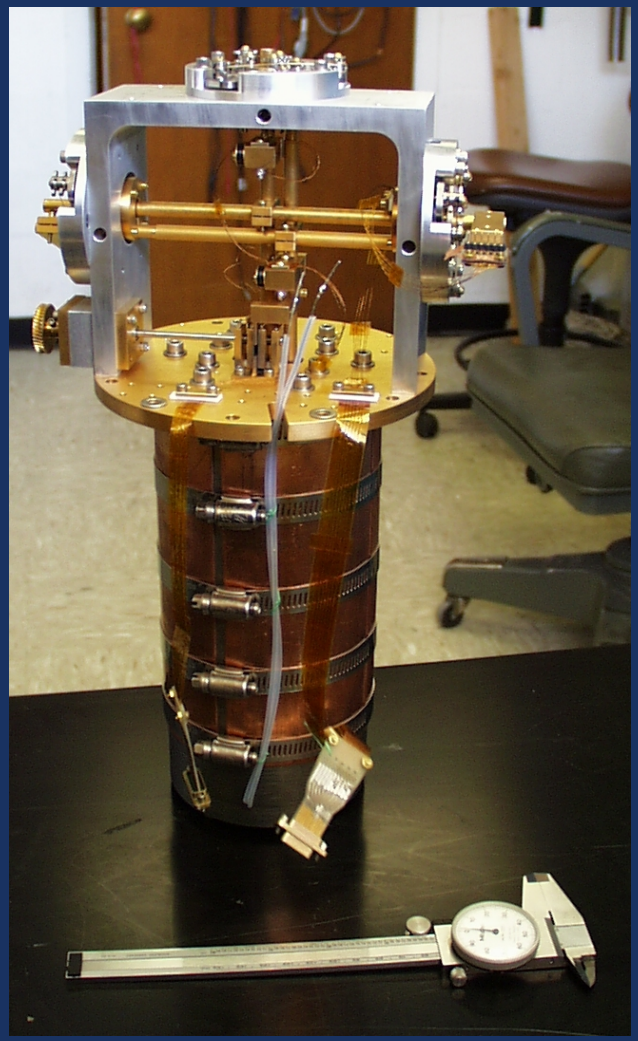


Canadian SCUBA-2 Consortium

NIST National Institute of Standards and Technology

4K - 100 mK cryogenics





2-stage adiabatic demagnetization refrigerator (ADR)

- Cryocooler: no liquid cryogens
- Push button operation from room temperature to 50 mK
- Each magnet cycle gets you to ~ 45 mK and ~ 7 days < 100 mK
- NIST-designed cryostat and insert; now commercially available

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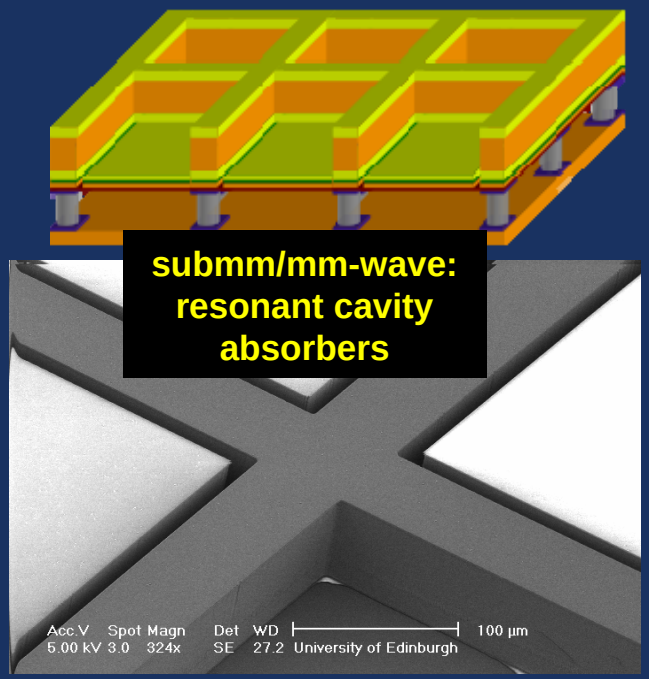
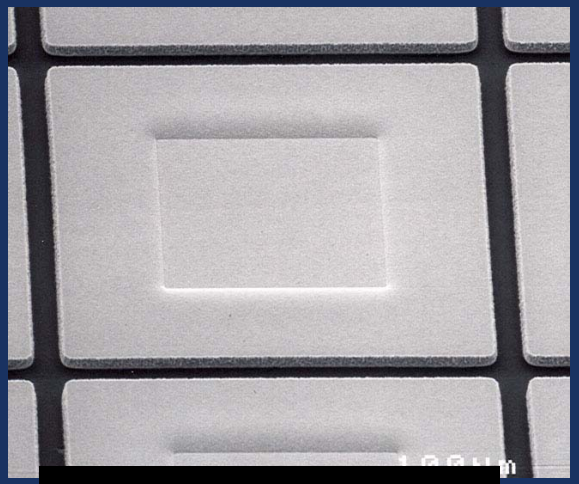
Absorbers for the electromagnetic spectrum + beyond



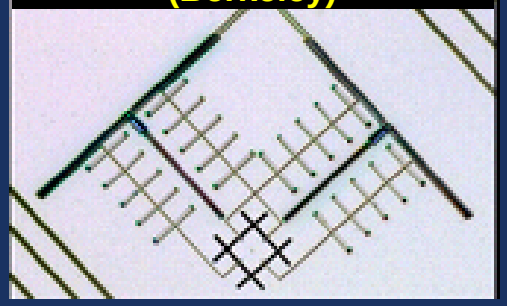
submm/mm-wave: resonant cavity absorbers

Near IR & optical: TES with antireflection coating (Nam / NIST / Stanford)

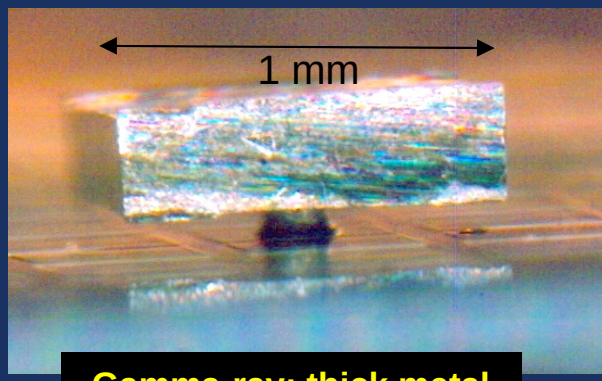


Soft x-ray: thick Bi "mushroom" absorber

submm/mm-wave: antennas (Berkeley)



Dark matter: thick Si or Ge crystals



Gamma-ray: thick metal foil

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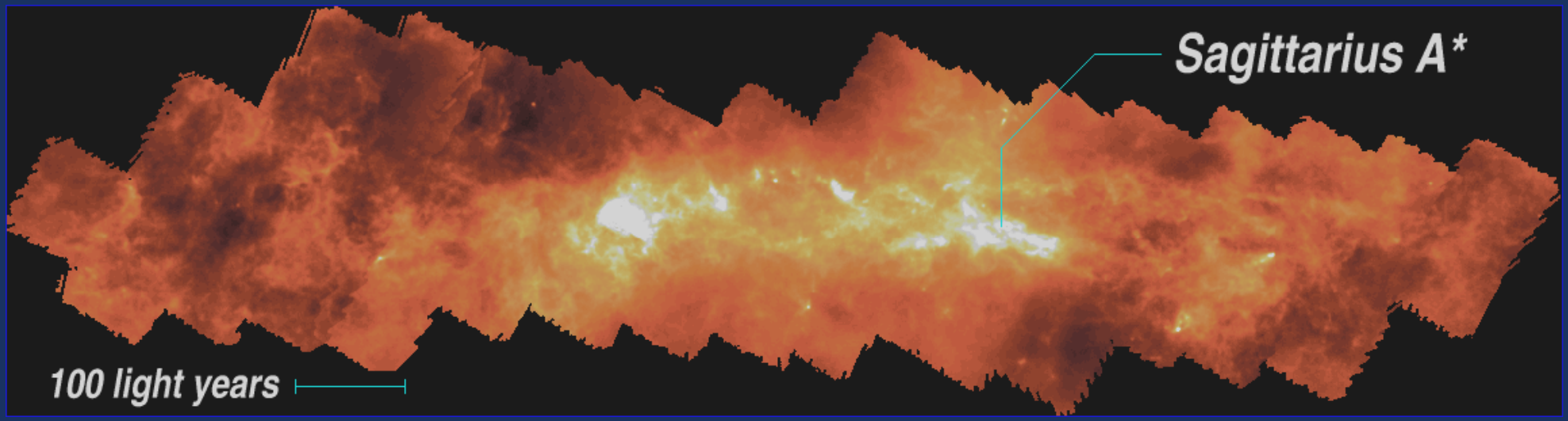
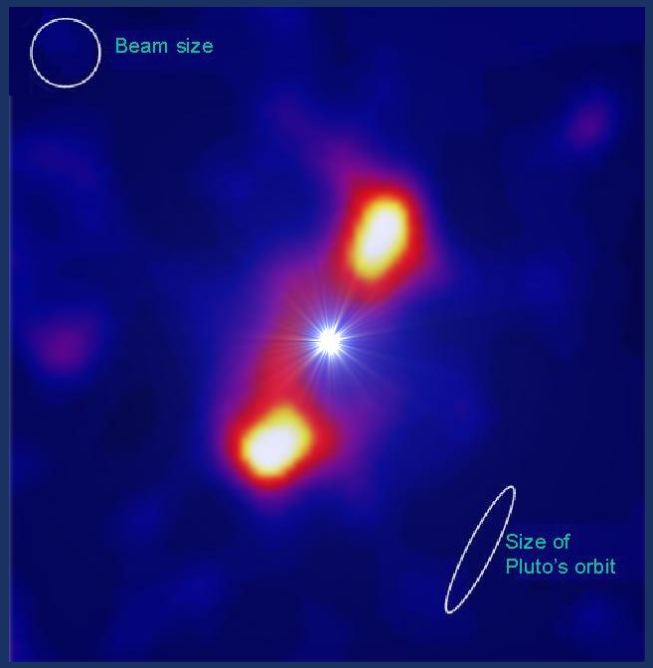
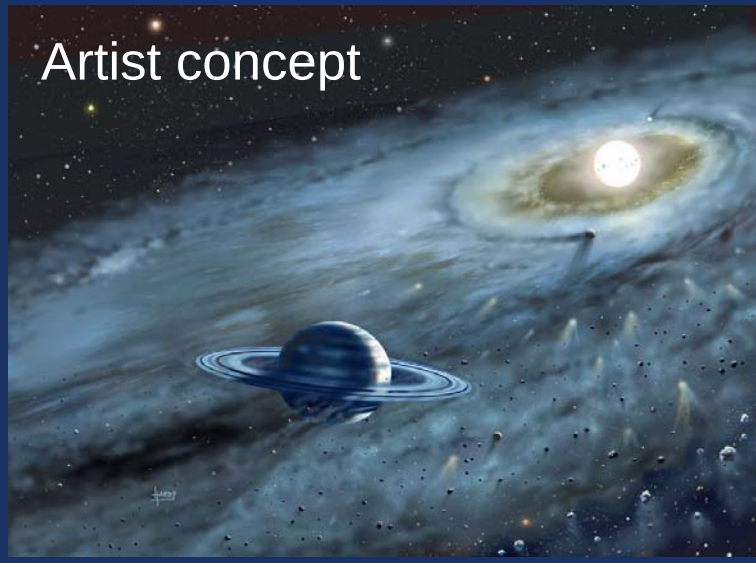
Submm astronomy: SCUBA-1



Survey of the galactic center

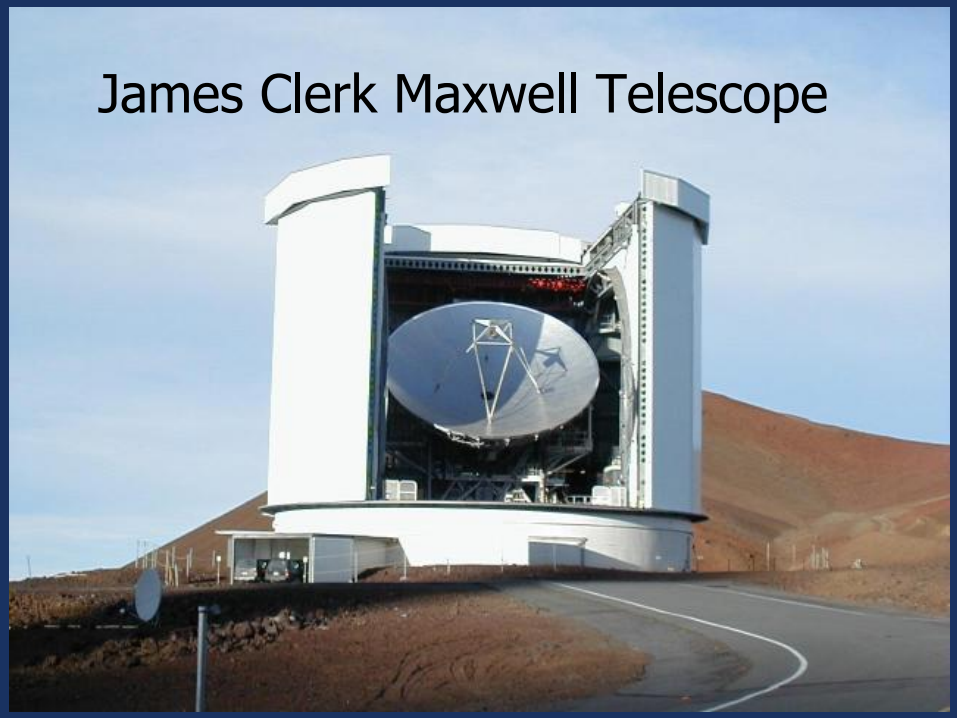




Detection of a gas giant around Fomalhaut

Submm astronomy: SCUBA-2

- A collaboration of the UK, Canada, Raytheon, and NIST
- SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the James Clerk Maxwell Telescope *real soon*.



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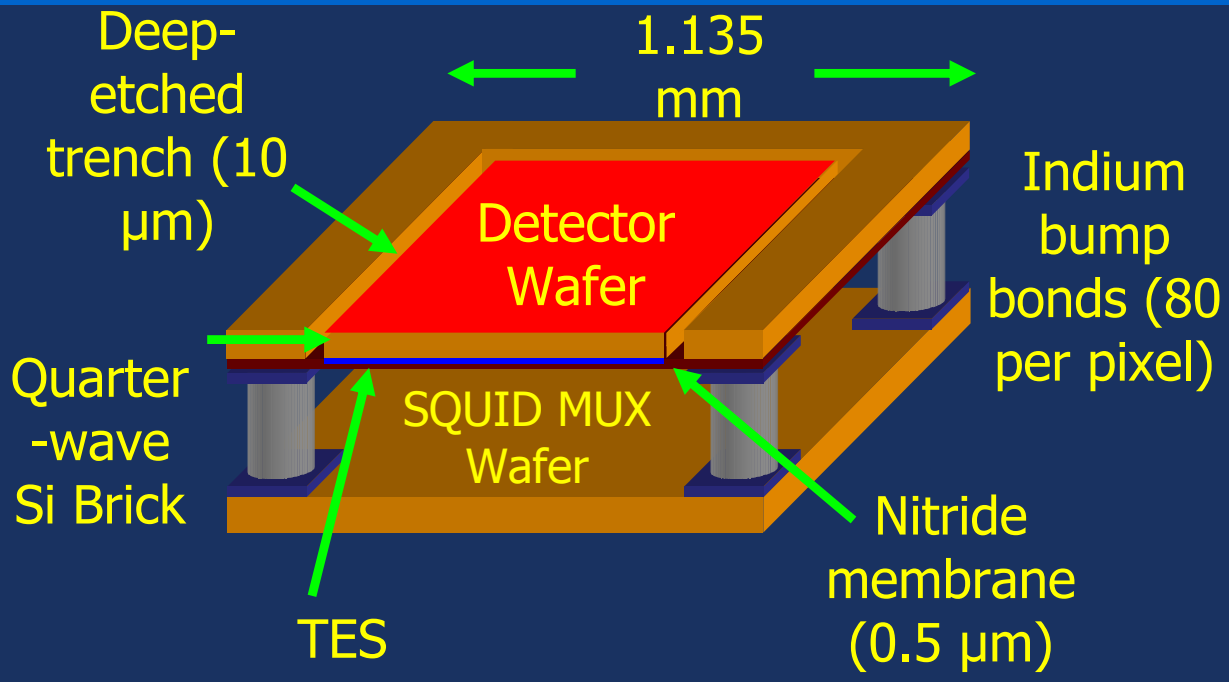
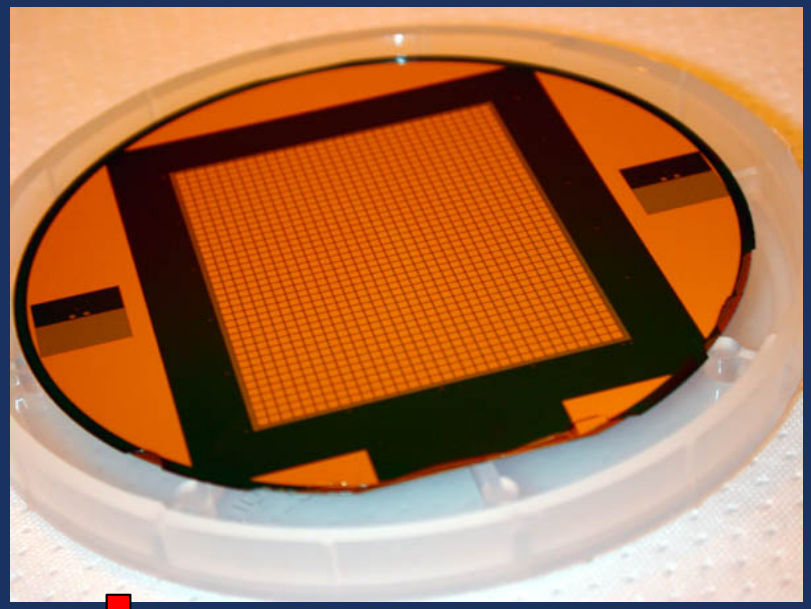
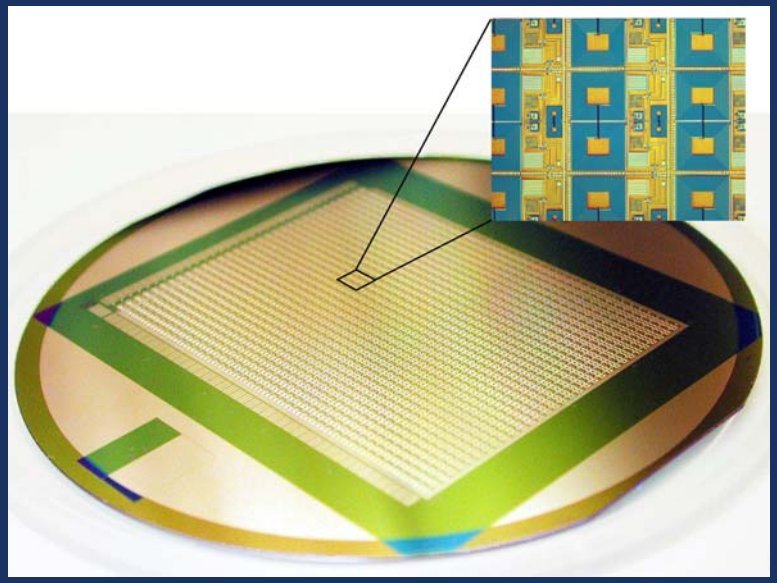
Submm astronomy: SCUBA-2



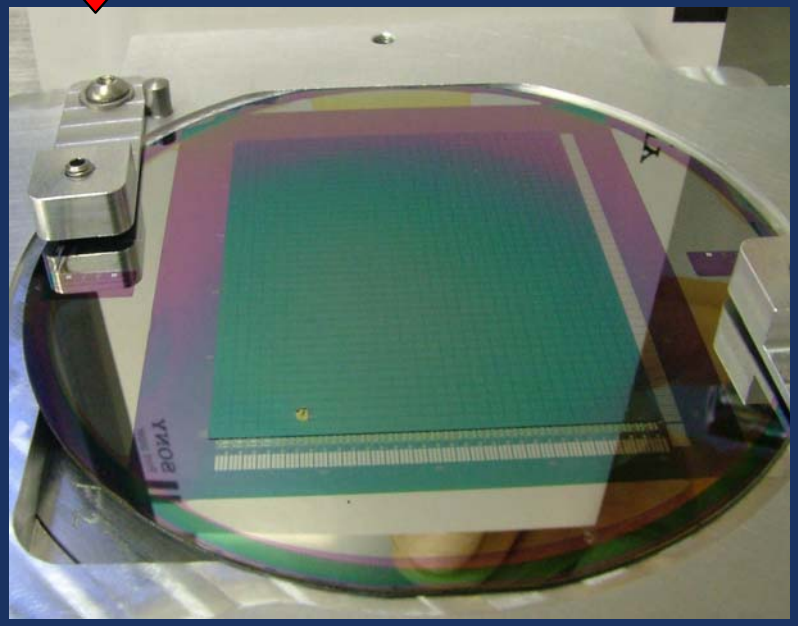
1,280-pixel TES bolometer



1,280-pixel SQUID Multiplexer

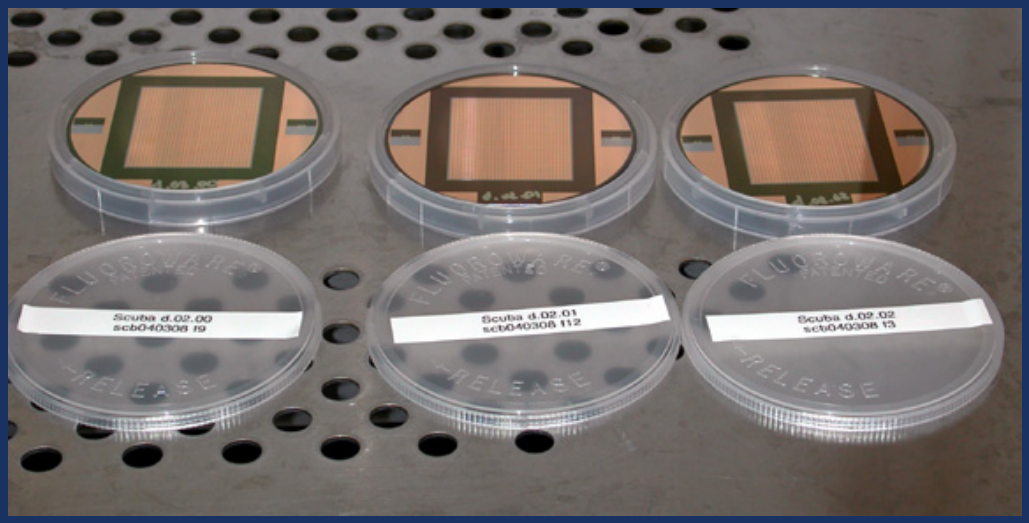


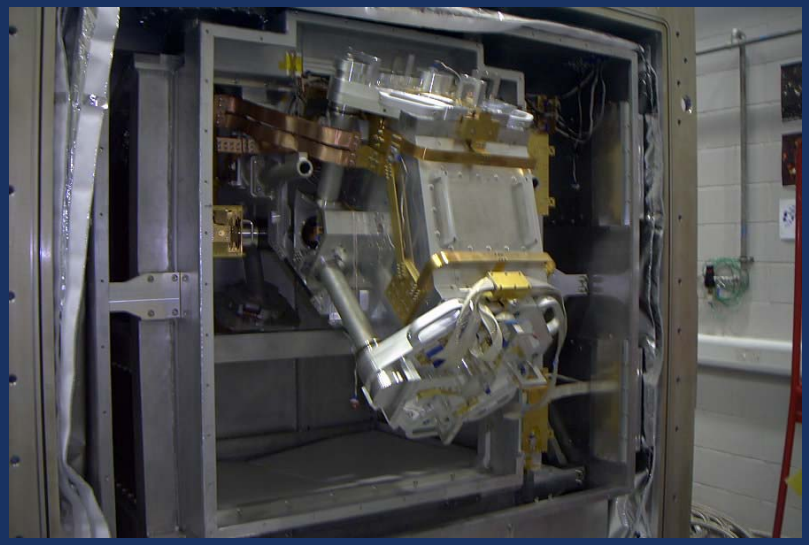
bump-bonded subarray (TES+MUX)

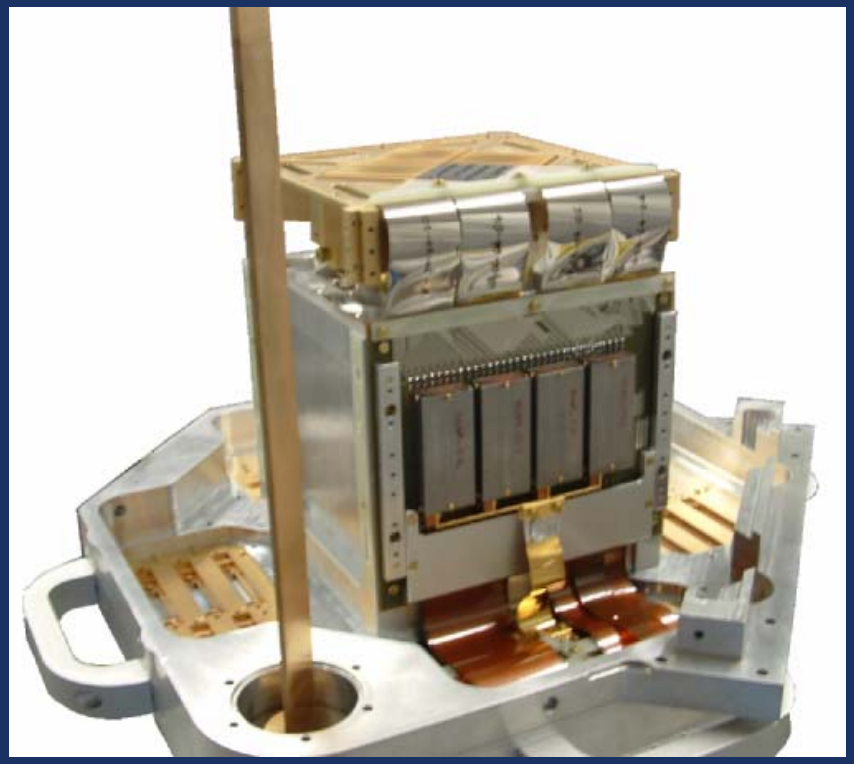


NIST

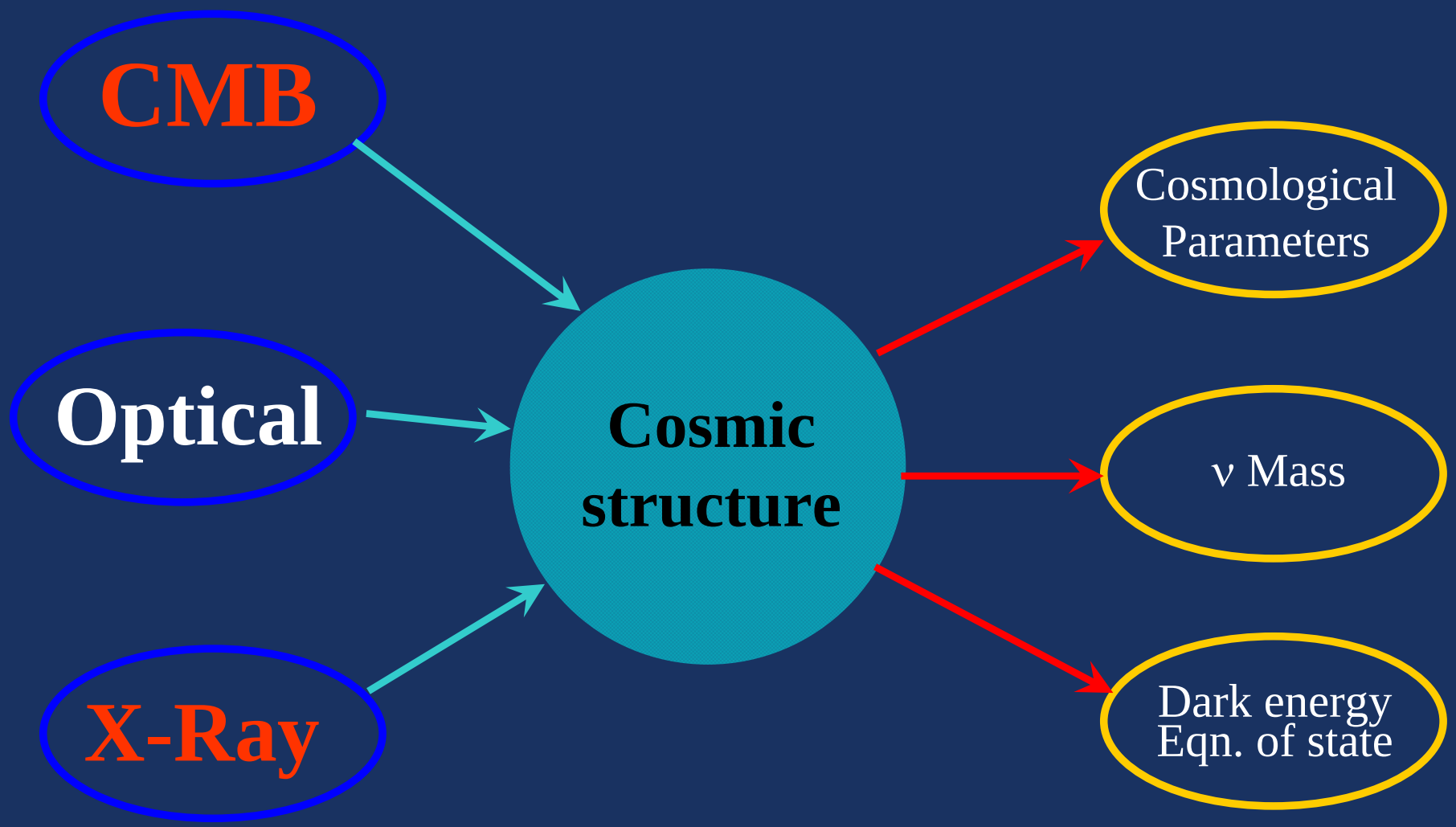
THz/submm astronomy: SCUBA-2





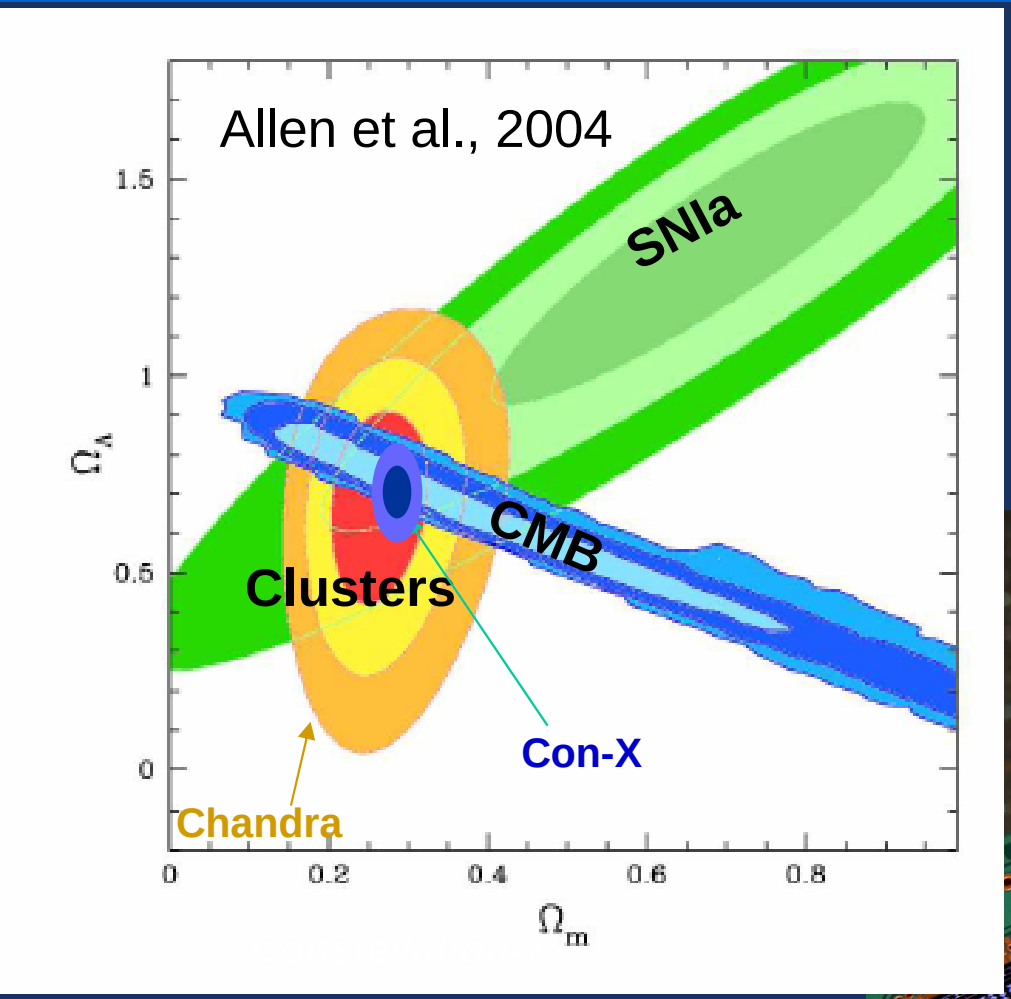


Cosmology by the coordinated study of cosmic structure



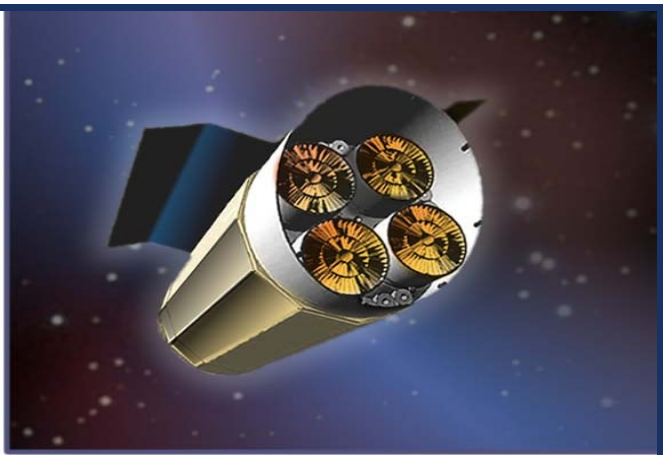
NIST

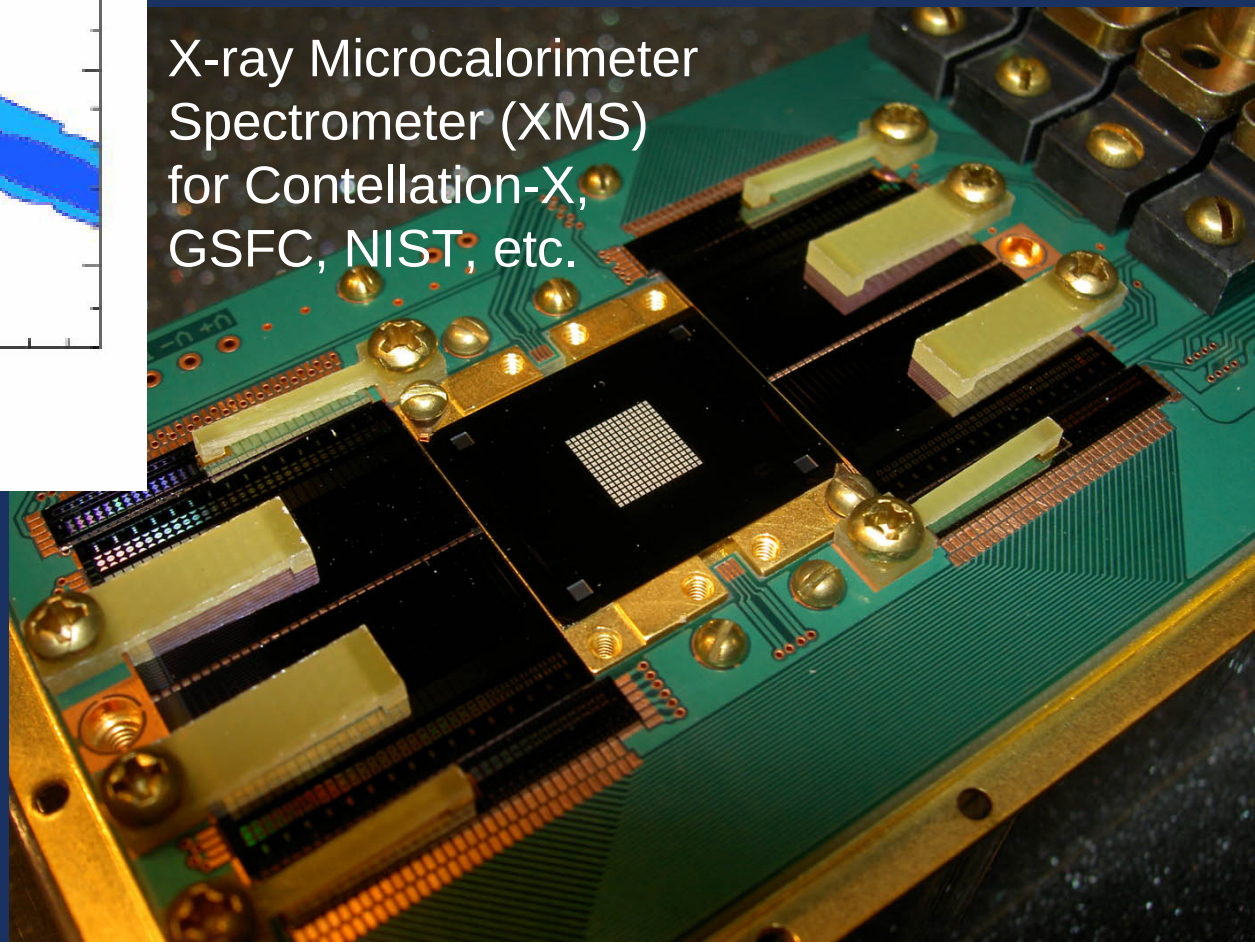
X-rays and & WHIM cosmology



Most of the normal, baryonic matter in clusters lies in the hot X-ray emitting gas (10^6 - 10^8 K)

Probe of total mass of galaxy cluster – constrains cosmological



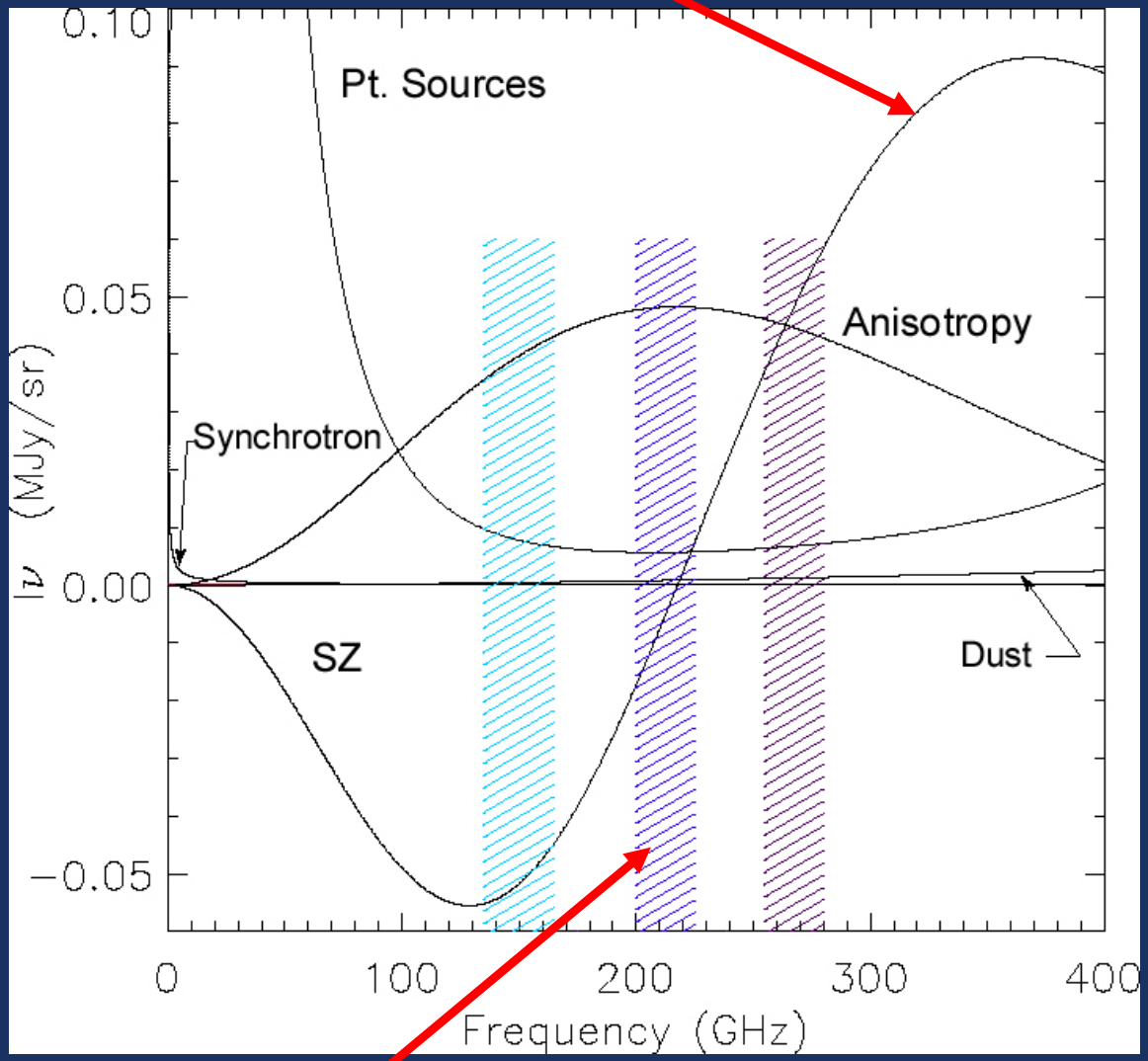


X-ray Microcalorimeter Spectrometer (XMS) for Contellation-X, GSFC, NIST, etc.

CMB: SZ Signature

Hot electron gas imposes a unique spectral signature

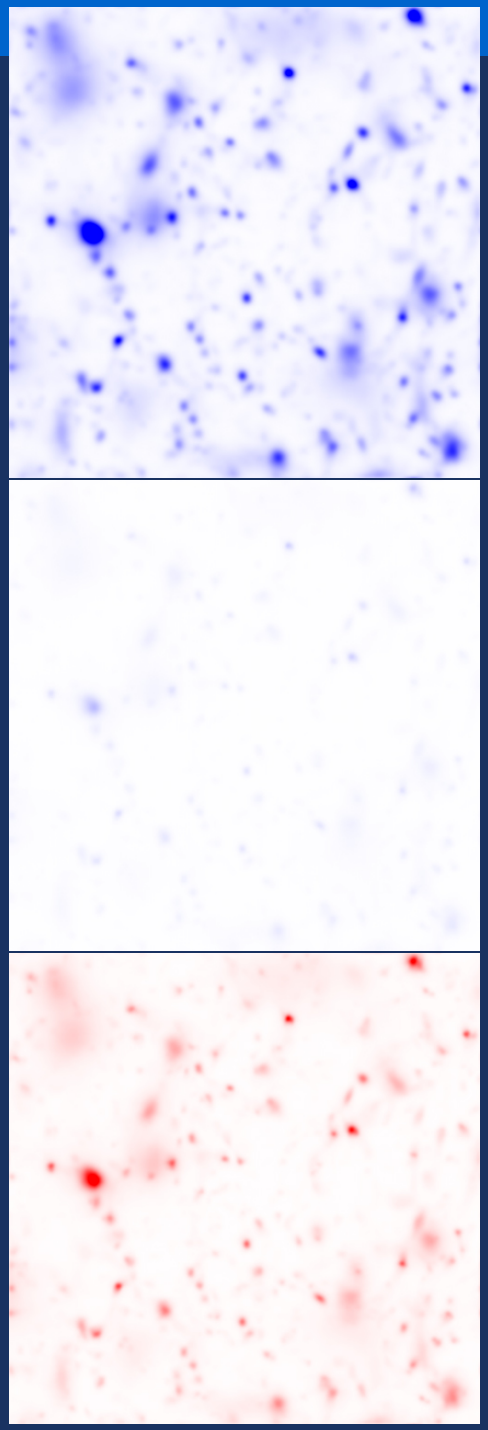
Z-independent cluster surveys



145 GHz decrement

220 GHz null

270 GHz increment



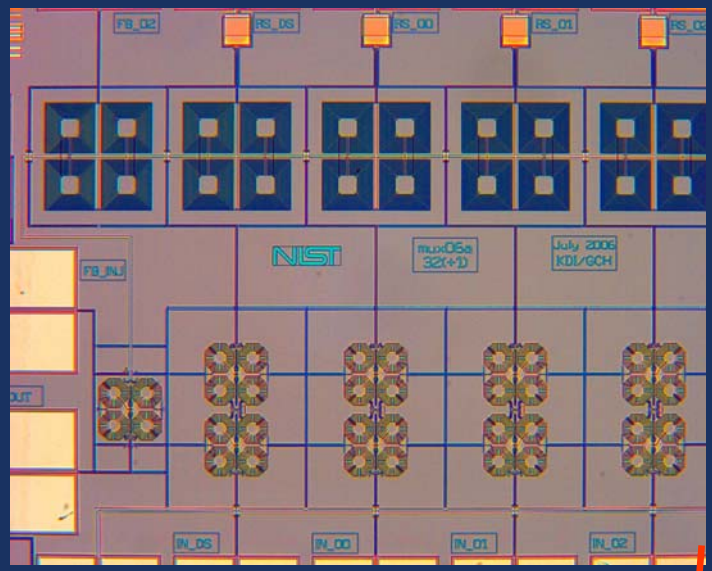
1.4°x 1.4°

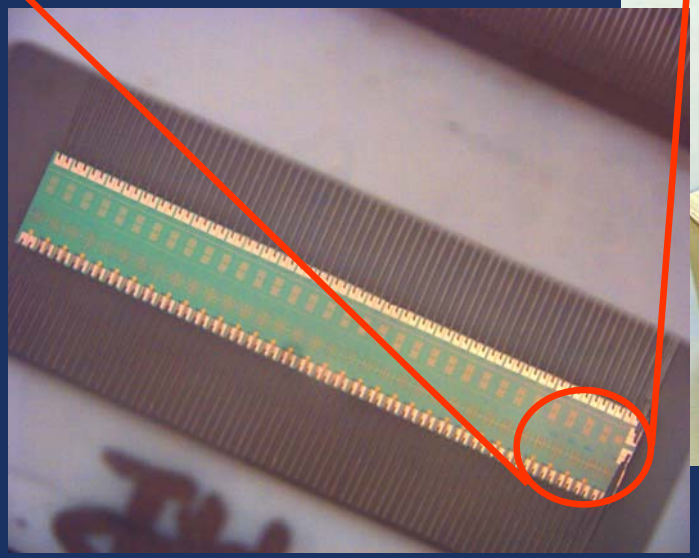
NO SZ Contribution in Central Band

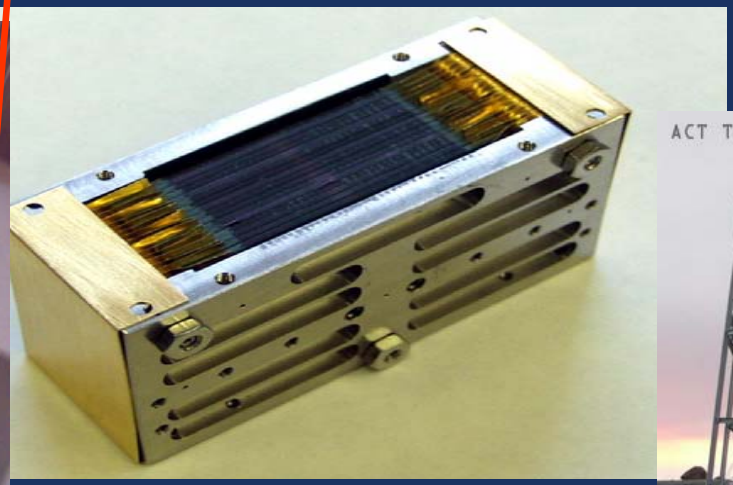
NIST

Devlin, ACT collaboration

The Atacama Cosmology Telescope - SZ







3,000 TES pixels
(256 shown)

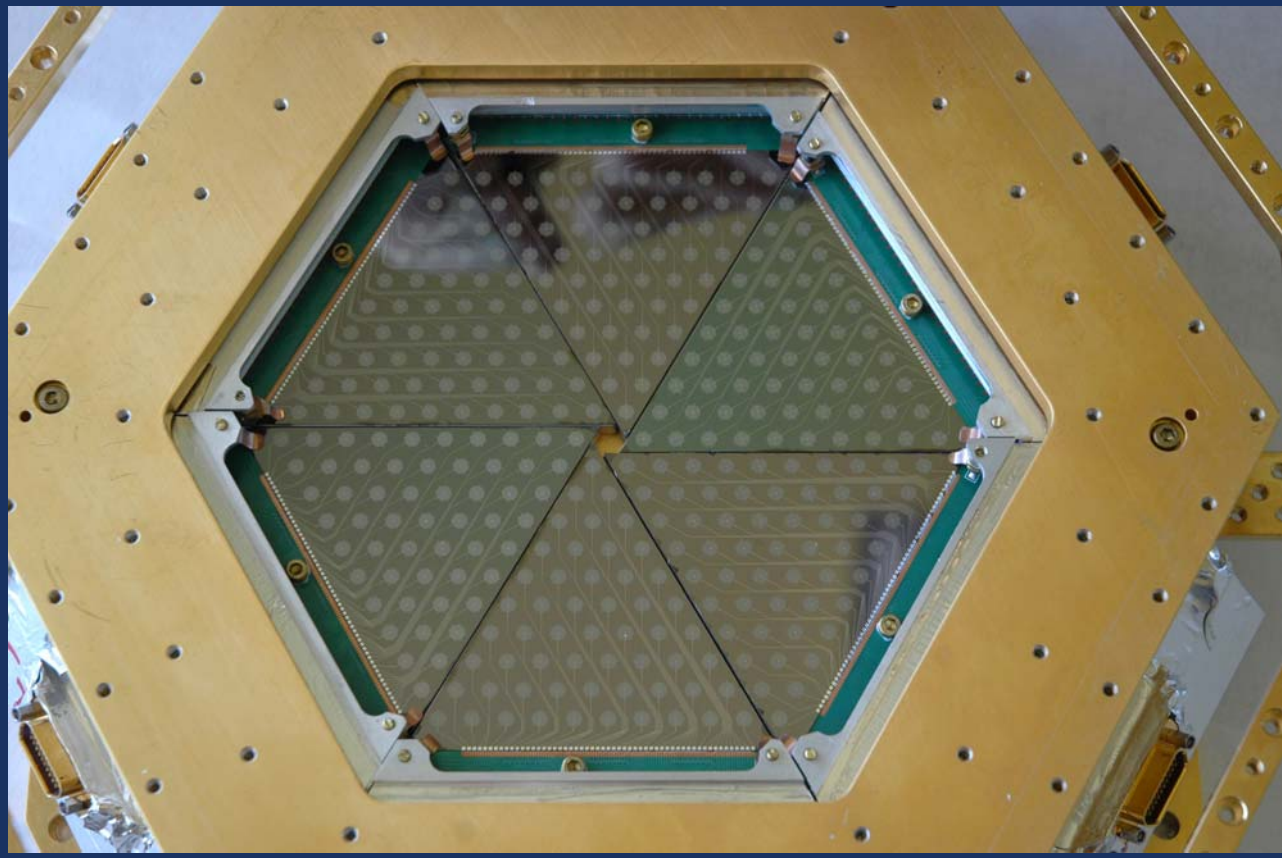
Collaboration:

Cardiff, Columbia, CUNY, Haverford, NASA/GSFC, NIST, Penn, Princeton, Rutgers, Univ. de Catolica, UMASS, Univ of Toronto

South Pole Telescope and APEX-SZ

APEX-SZ, 320 pixels

SPT, 960 pixels

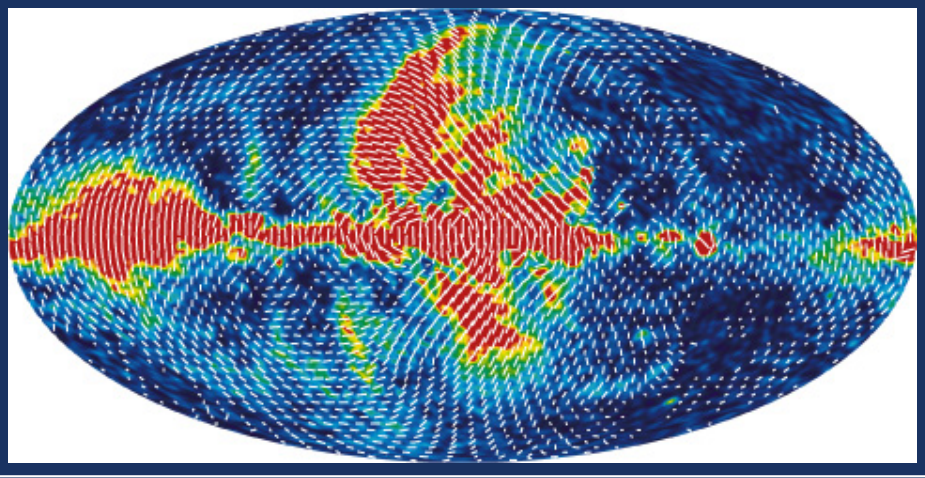


Berkeley, Chicago, etc.

(NIST SQUIDs)

Future: TES CMB polarimeters for cosmology

- Signature of primordial gravitational waves
- CMB polarimetry microlensing: “cosmic shear”
  - Probe of expansion history of universe with different systematics



WMAP EE mode (HEMTs)

Polarization-sensitive TES provide excellent sensivity
– need good systematic control

Balloons: SPIDER, EBEX

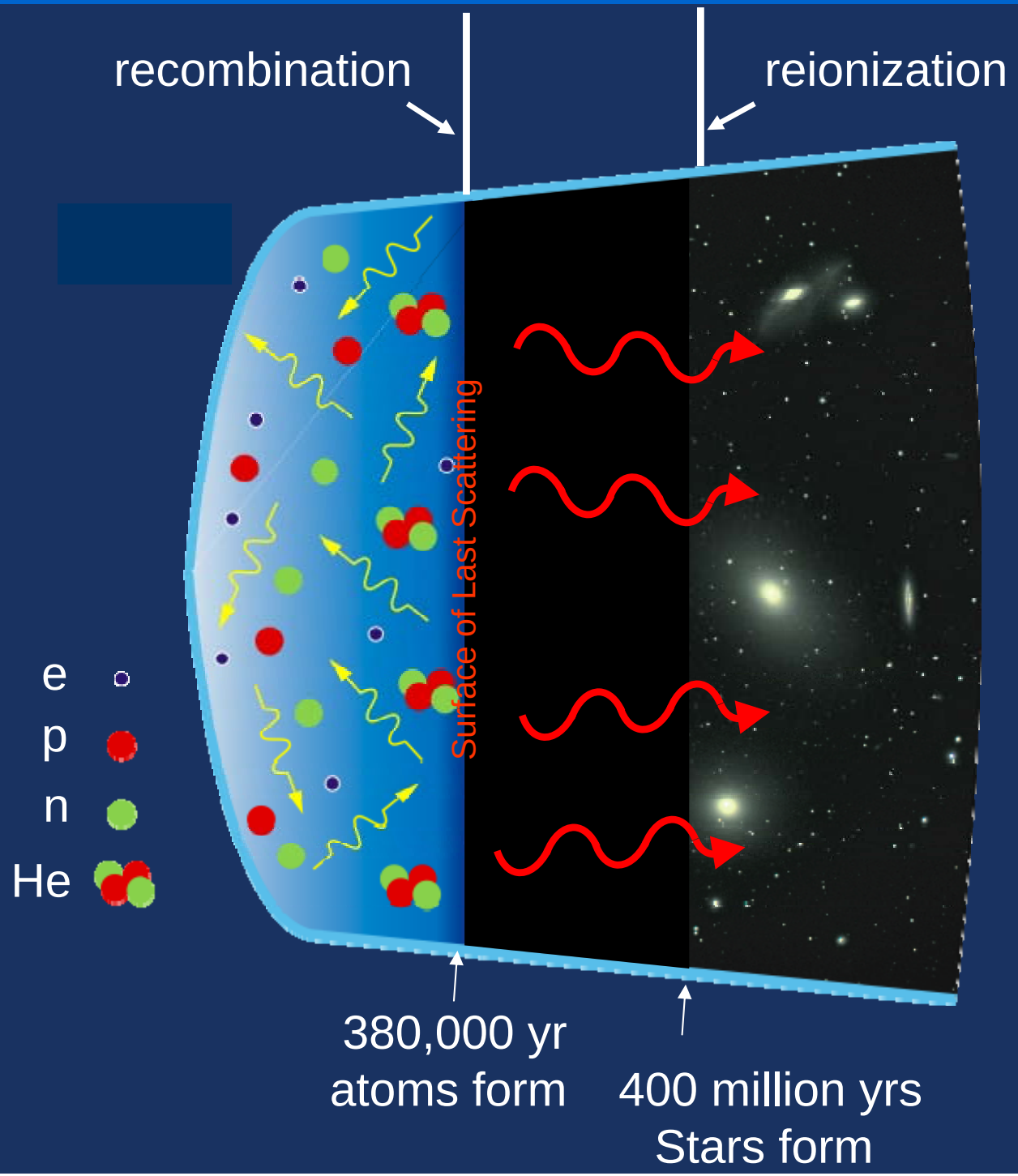
Ground-based: BICEP-2, SPUD, CIOVER, SPT, ACT, …

NIST

CMB polarimetry and primordial gravity waves

The universe is opaque to photons before 380,000 years: but not to gravitational waves and neutrinos

- Detection of the cosmic gravity wave (CGB) background would probe the inflationary era (10^{-35} s?)
- Direct probe of inflation vs. cyclic / ekpyrotic models



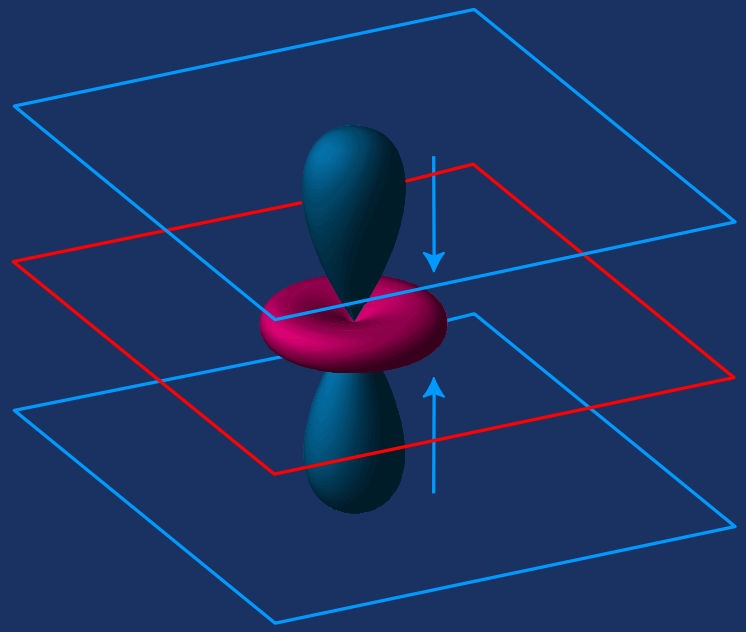
NIST

Density-Wave vs. Gravity-Wave Anisotropies

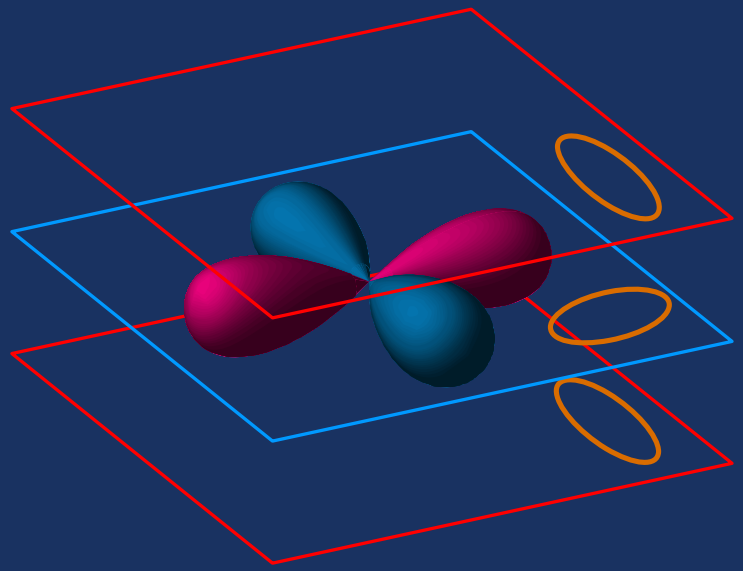
Two different types of anisotropies:

1. Decompose the temperature and gravitational wave distribution at the surface of last scattering into a superposition of plane waves
2. The two types of waves will produce quadropole temperature anisotropies with different spin
3. Integrate the light from all directions scattering off towards the observer
4. The characteristic anisotropies of gravitational waves result in polarization with a curl-like symmetry (BB)

Density-wave anisotropy



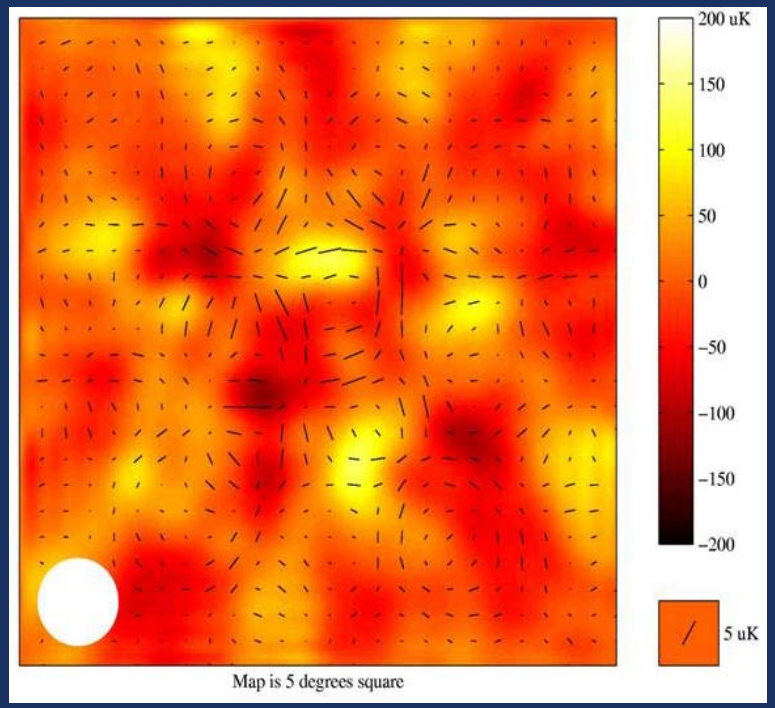
Gravitational-wave anisotropy



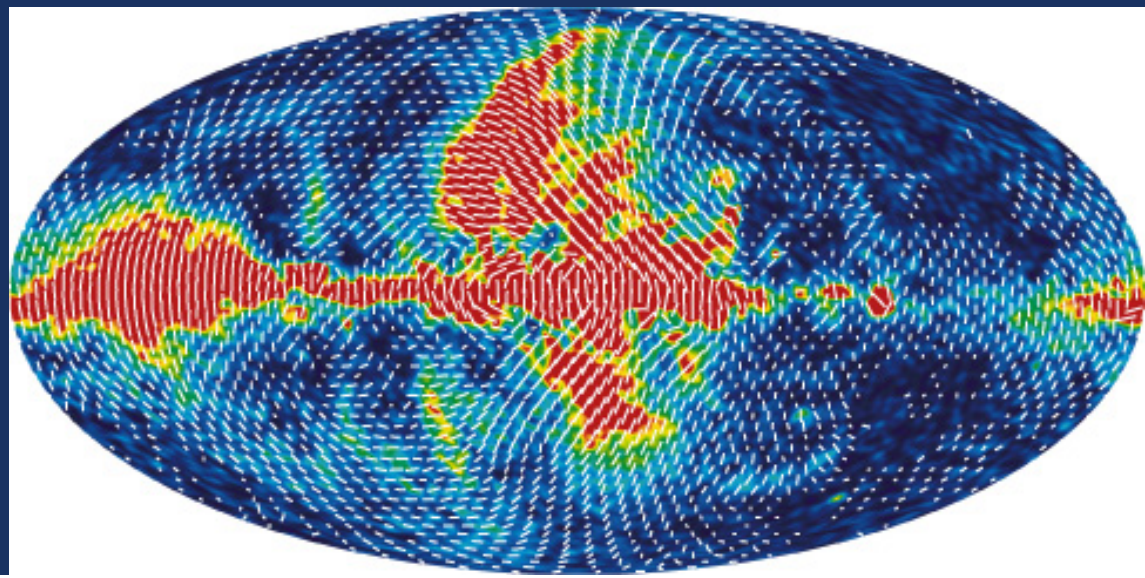
Credit: Wayne Hu, Chicago

CMB polarization so far (no gravity waves)

DASI: EE polarization of the CMB; small angular scale



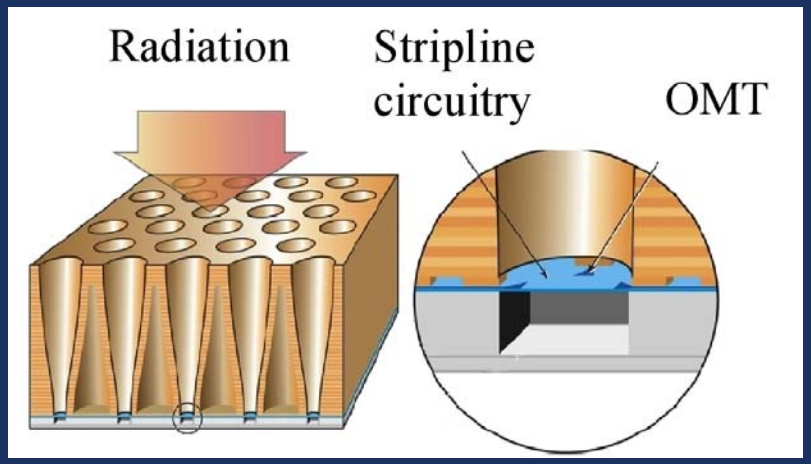
WMAP: EE polarization of the CMB; large angular scale



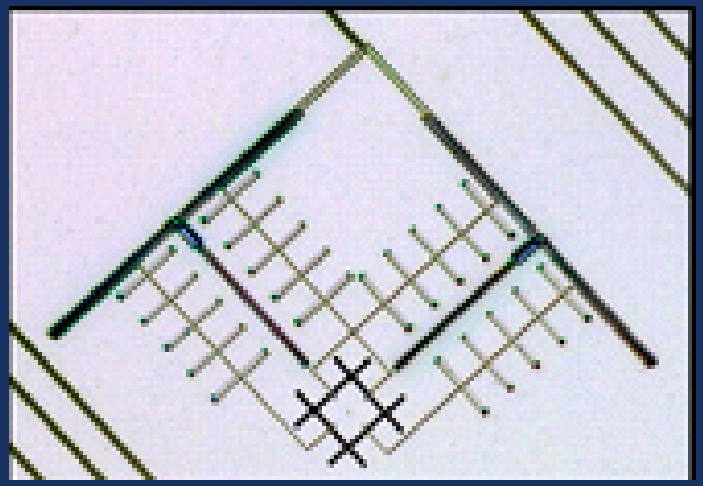
NIST

TES polarimeter arrays

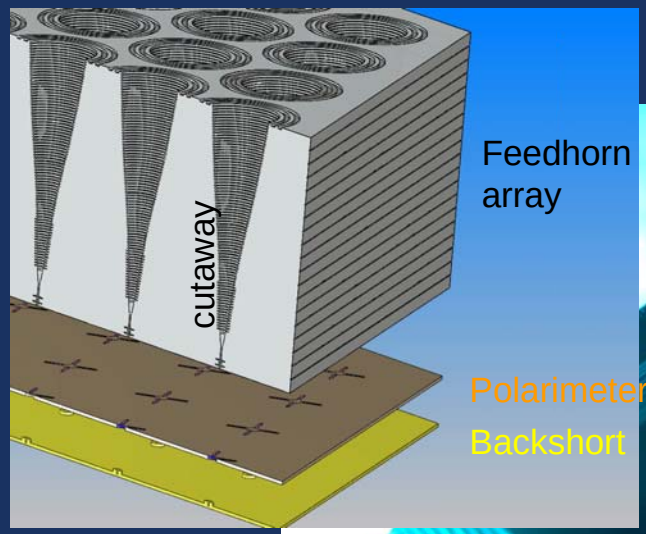
GSFC: metal platelet feedhorns

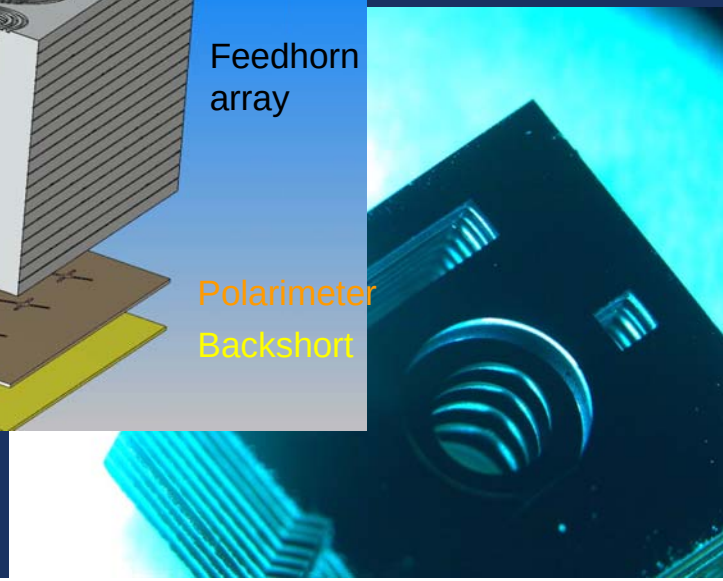


Berkeley: planar antennas

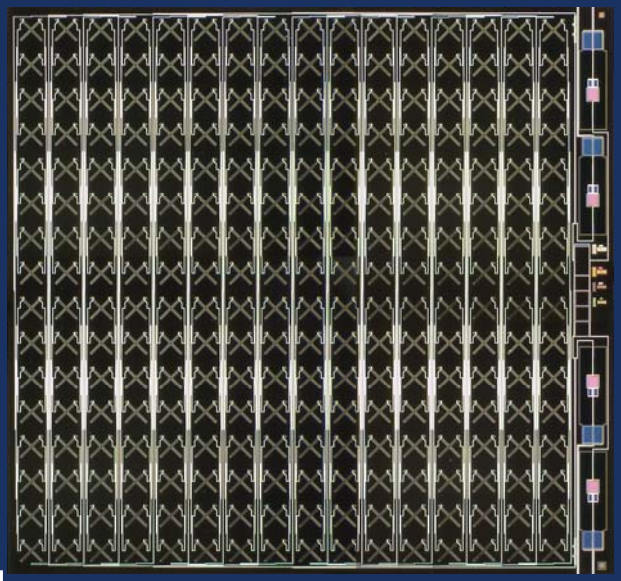


NIST: silicon micromachined corrugated feeds





JPL/Caltech: beam-synthesized antennas



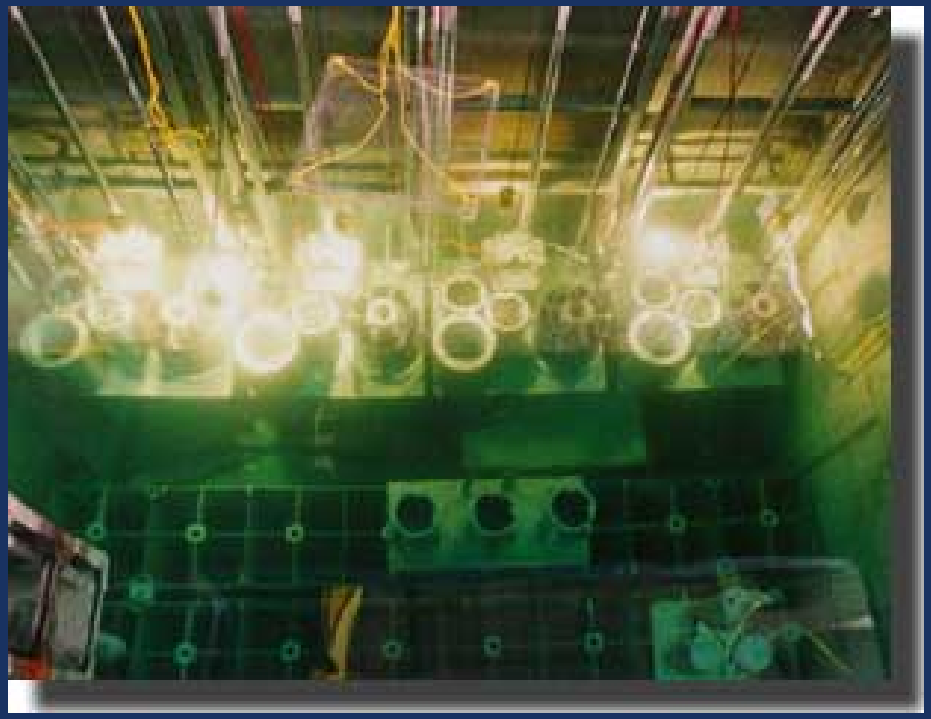
NIST

Gamma-ray: nuclear non-proliferation

About 96 % (>600 tons) of the all the Pu under International safeguards is in spent fuel.
Is it all where it is supposed to be?
Is any of it missing?

Current IAEA Methods

- **γ spectroscopy**
- **Gross neutron**
- **Calorimetry**
- **Computer models**
- ***Operator's reactor history***
- ***Limited* destructive analysis**
- **Containment and surveillance**



Spent fuel in North Korean cooling pond

NIST

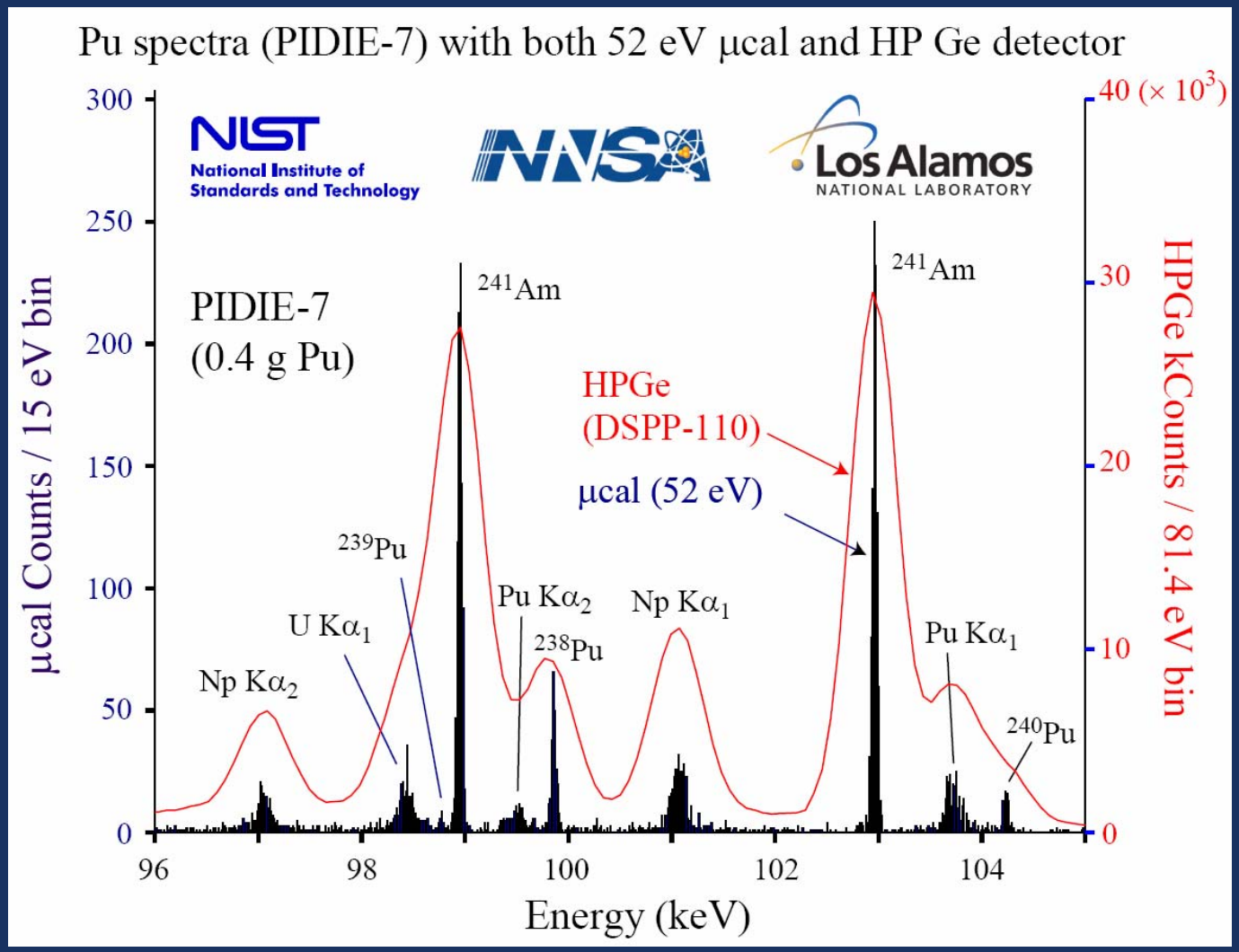
Nuclear materials assay

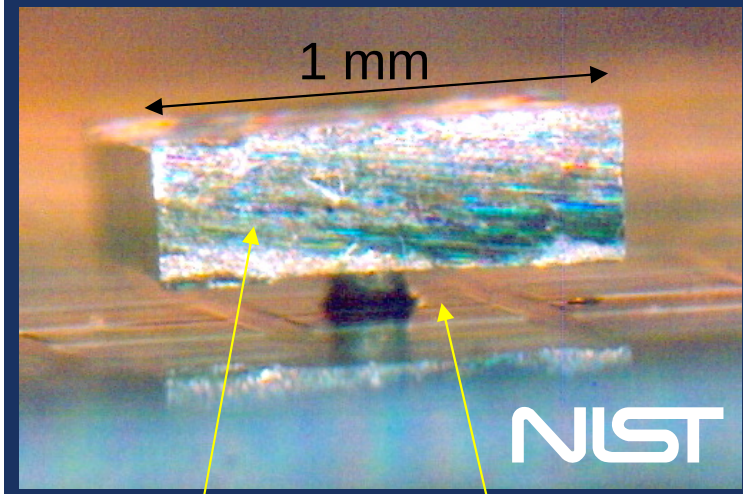
- Nuclear materials (various isotopes of U, Pu, etc.) emit characteristic γ rays and X rays around 100 keV.
- Industry-standard 100 keV spectrometer is HPGe:
  - best ΔE ~ 500 eV (can't resolve some important lines)
  - active collecting area ~ a few cm^2
  - max count rate ~ 50 kHz
- Arrays of TES microcalorimeters promise much better energy resolution, comparable collecting area and count rate.

Efforts at LANL / NIST and LLNL

NIST

TES Pu spectrum measured at LANL



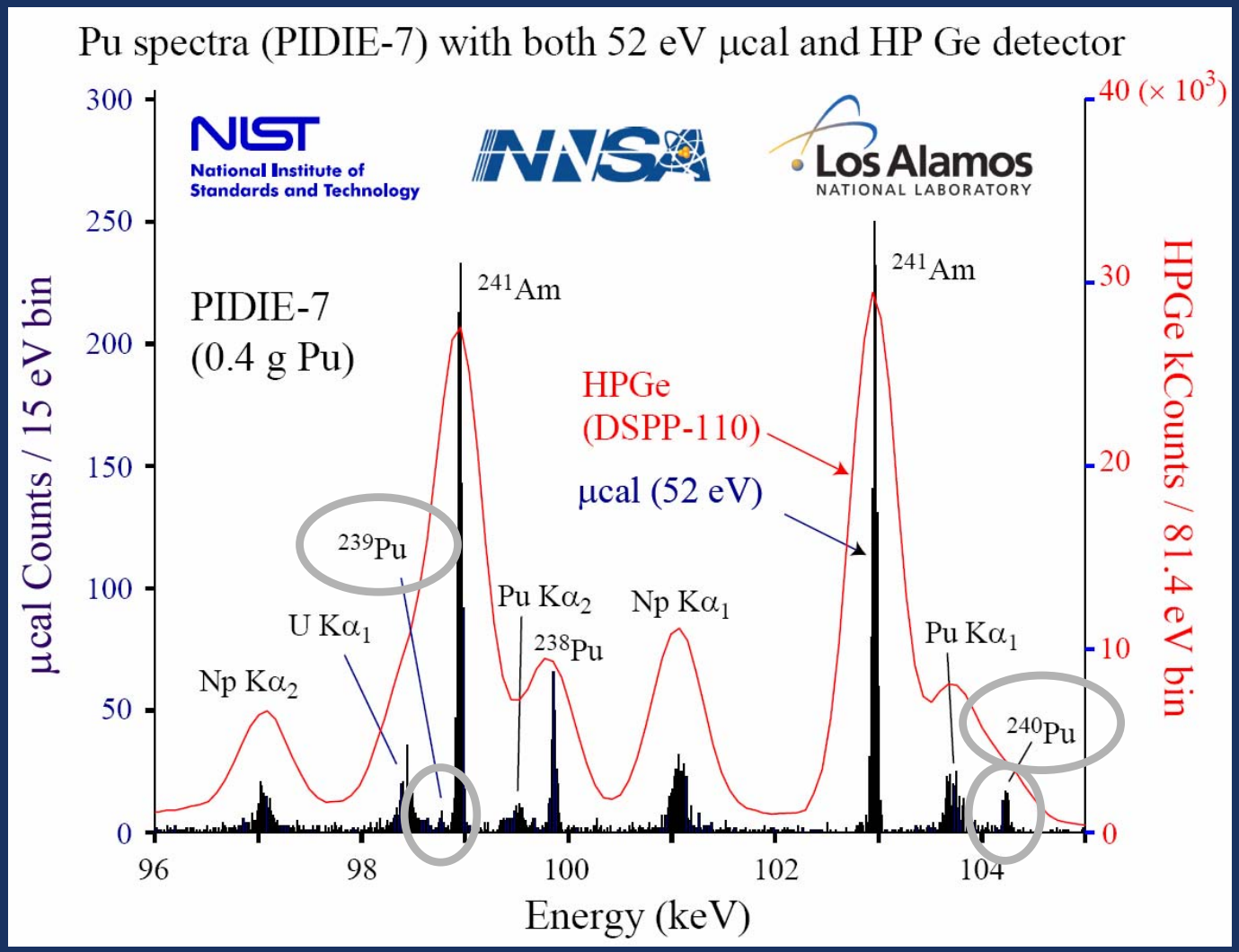


Sn absorber

Mo/Cu TES

NIST

TES Pu spectrum measured at LANL

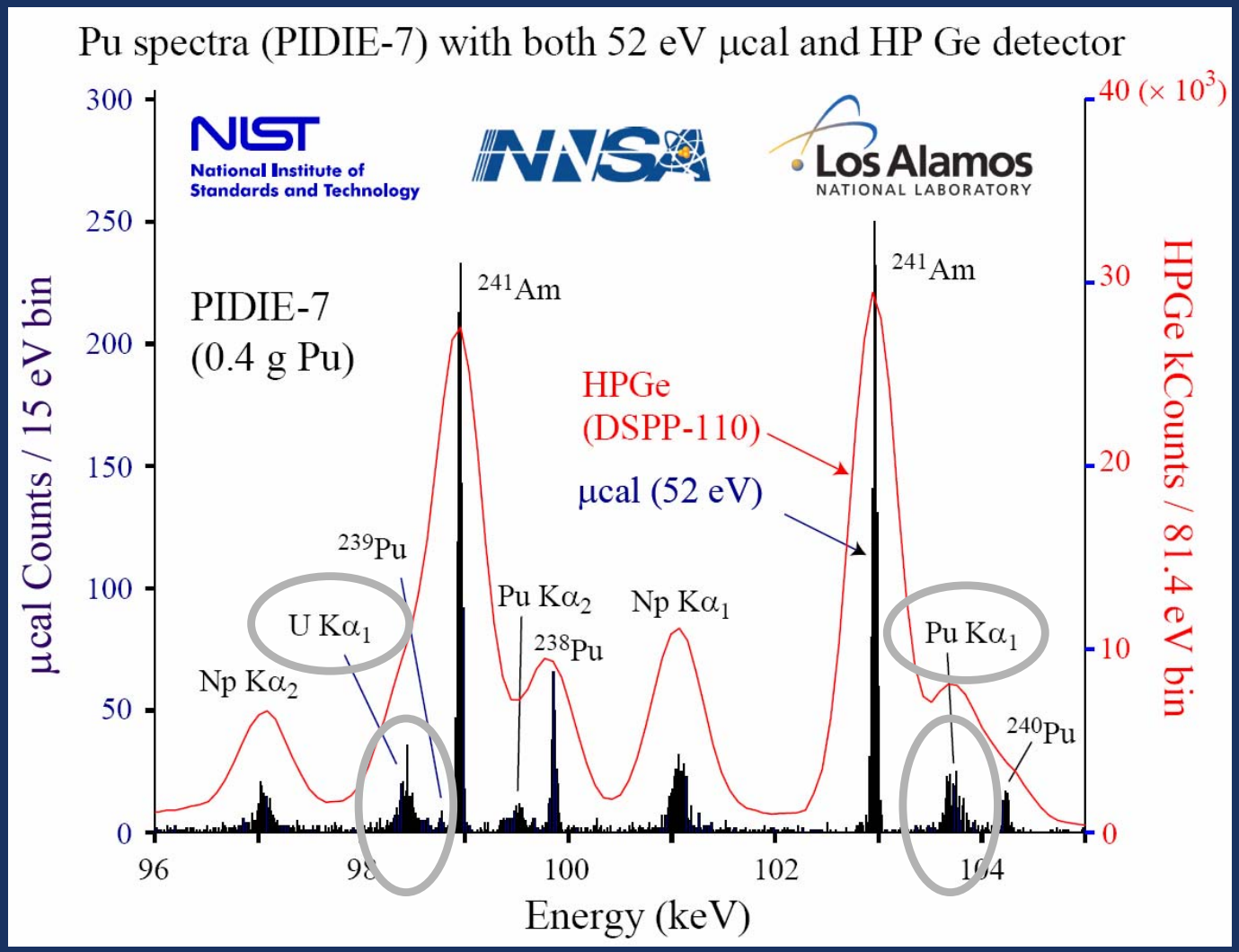


Key measurements:

- Pu isotopes
  ^{239}Pu : ^{240}Pu γ ray
  (^{239}Pu = weapon)

NIST

TES Pu spectrum measured at LANL



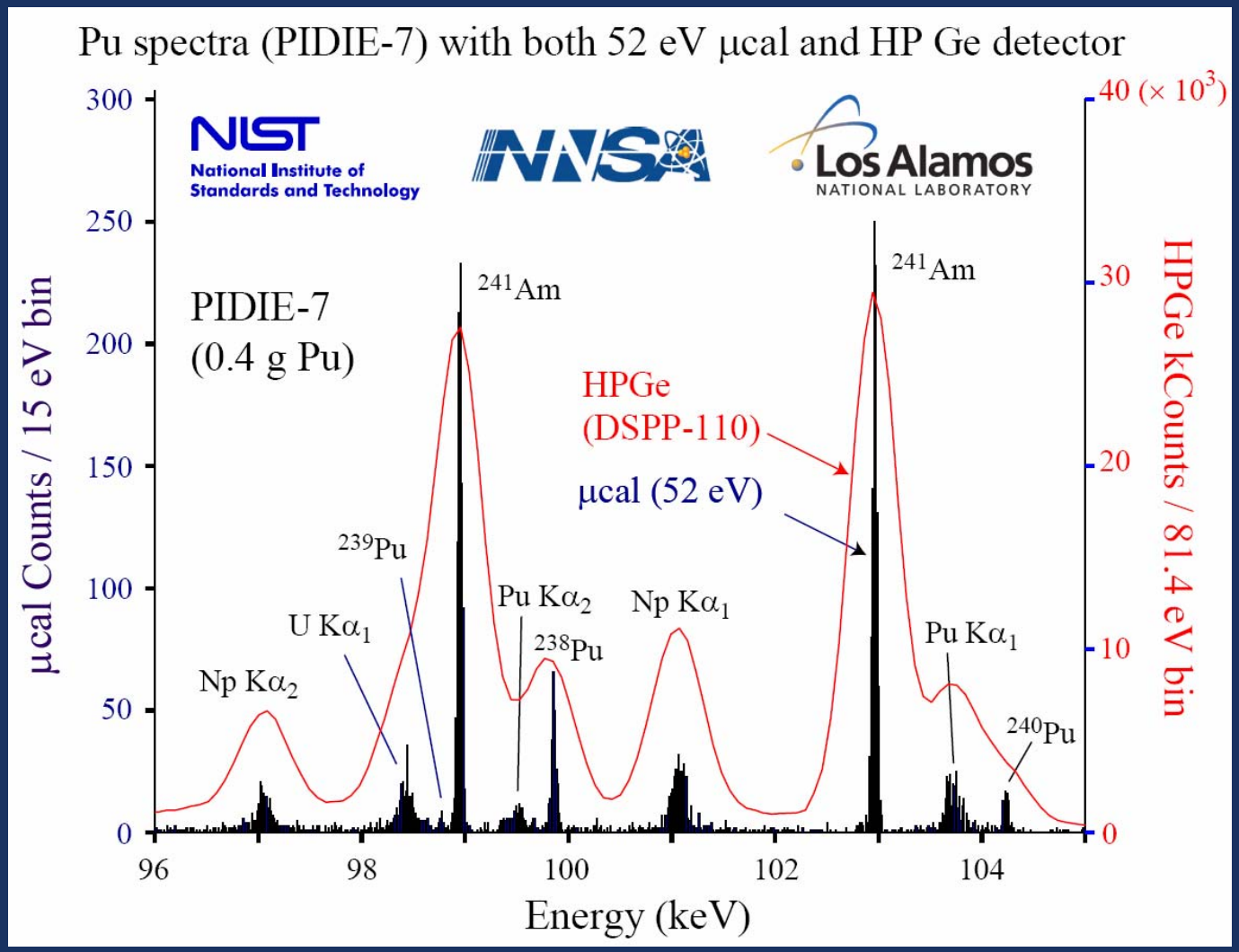
Key measurements:

- Pu isotopes
  ^{239}Pu : ^{240}Pu γ ray
  (^{239}Pu = weapon)

- spent reactor fuel
  (<u>different spectrum</u>):
  Pu Ka_1 : U Ka_1
  x-ray fluorescence ratio
  (learn total Pu content
  without knowing
  reactor history)

NIST

TES Pu spectrum measured at LANL



Key measurements:

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  (^{239}Pu = weapon)

- spent reactor fuel
  (<u>different spectrum</u>):
  Pu Ka_1 : U Ka_1
  x-ray fluorescence ratio
  (learn total Pu content without knowing reactor history)

Need TES arrays:
HPGe: t = 15 minutes
ucal: t = 7 hours

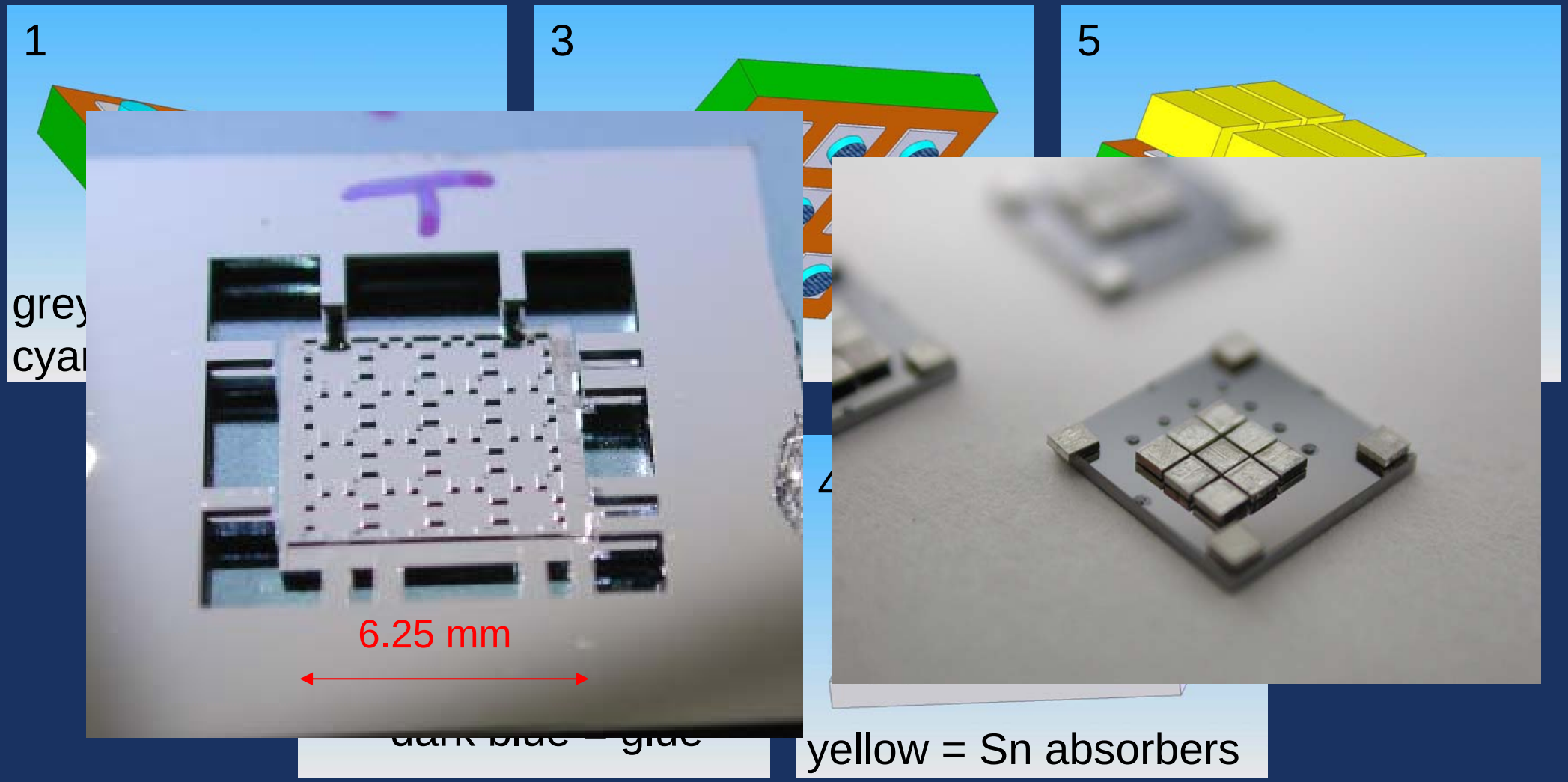
NIST

Batch fabrication of TES γ-ray arrays

std. Mo/Cu TES process;
add lithographed epoxy posts

stamp-print glue
onto epoxy posts

glue on absorbers
to complete array

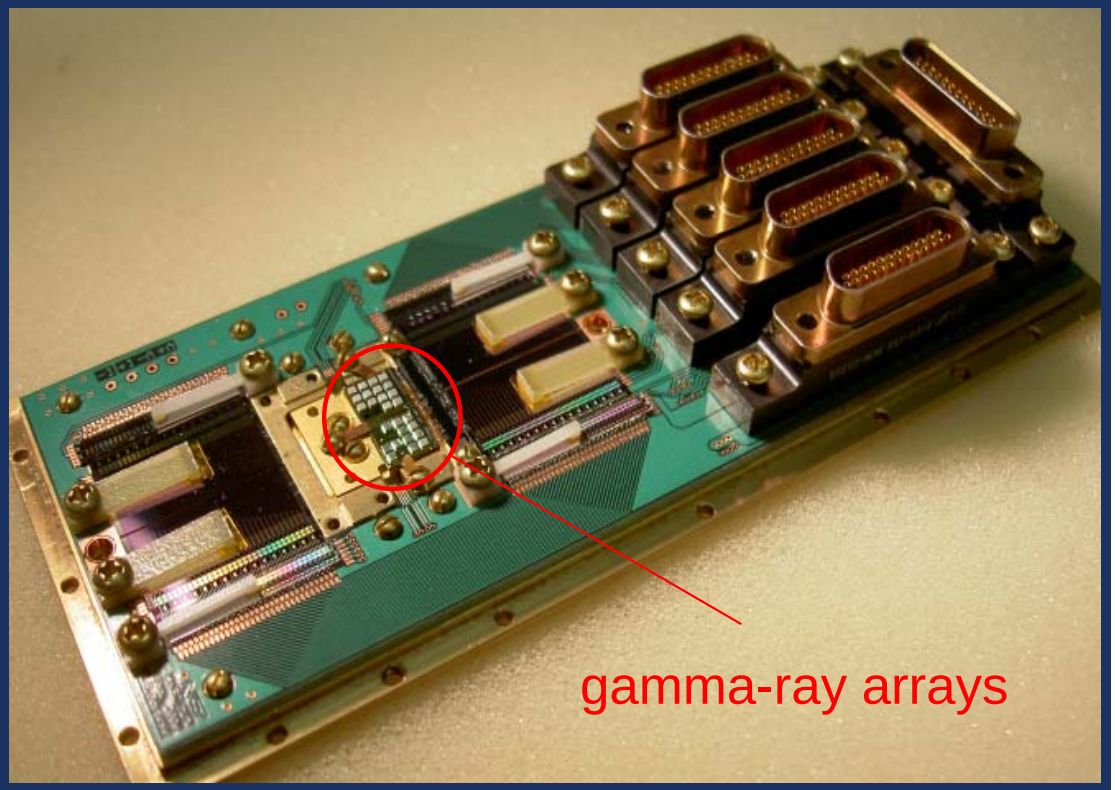


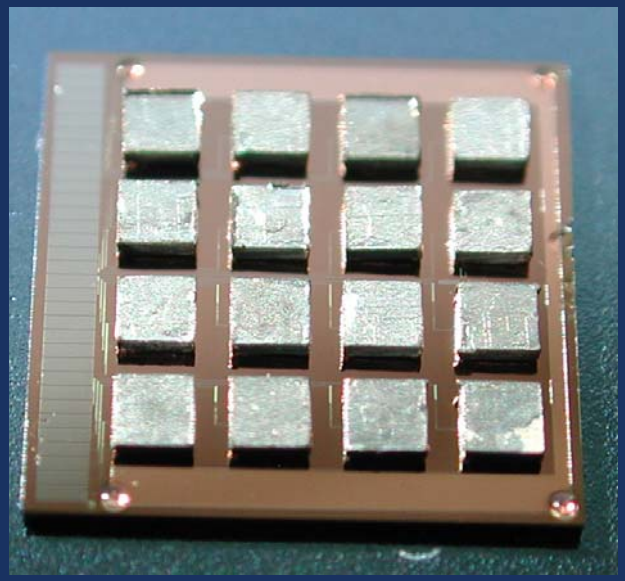
spin-coat another
Si wafer w/ glue

micro-machined “egg crate”
containing Sn absorbers

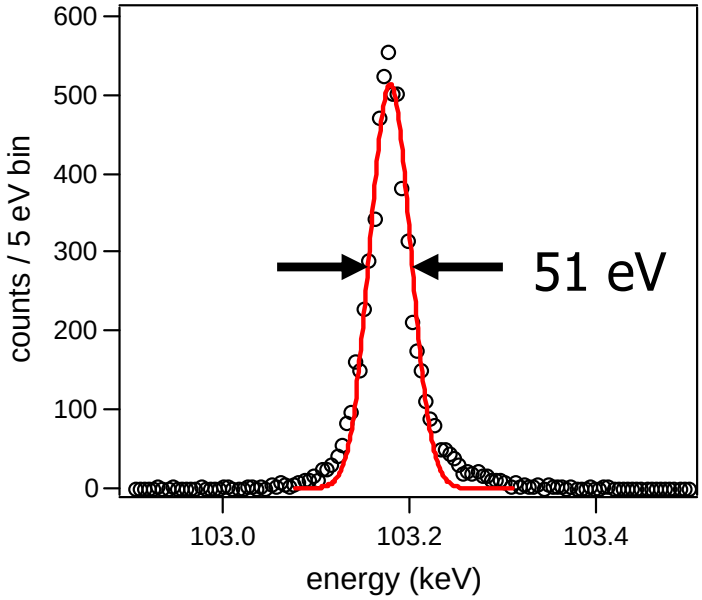
NIST

NIST/LANL 1st generation γ-ray arrays

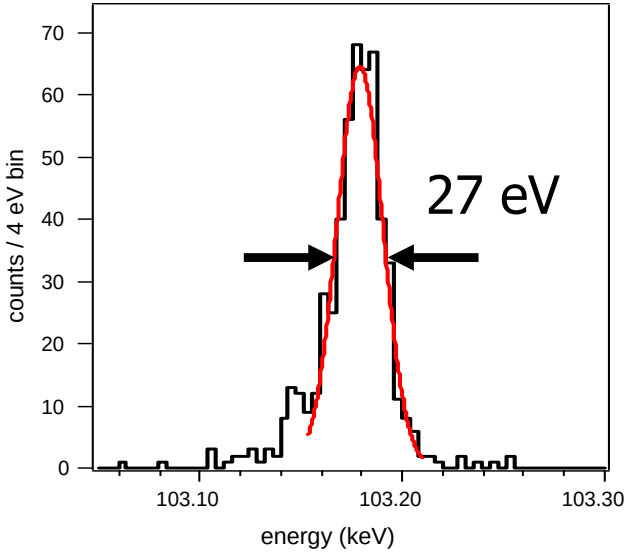




MUXed spectrum of ^{153}Gd γ-ray source
13 coadded pixels

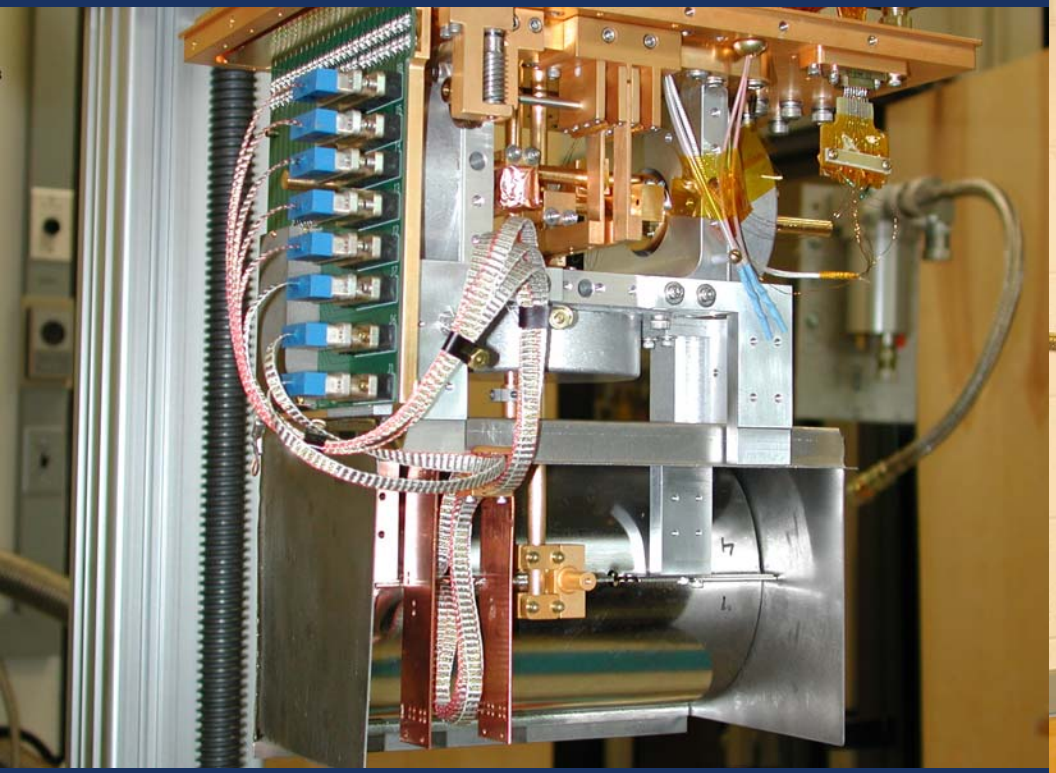


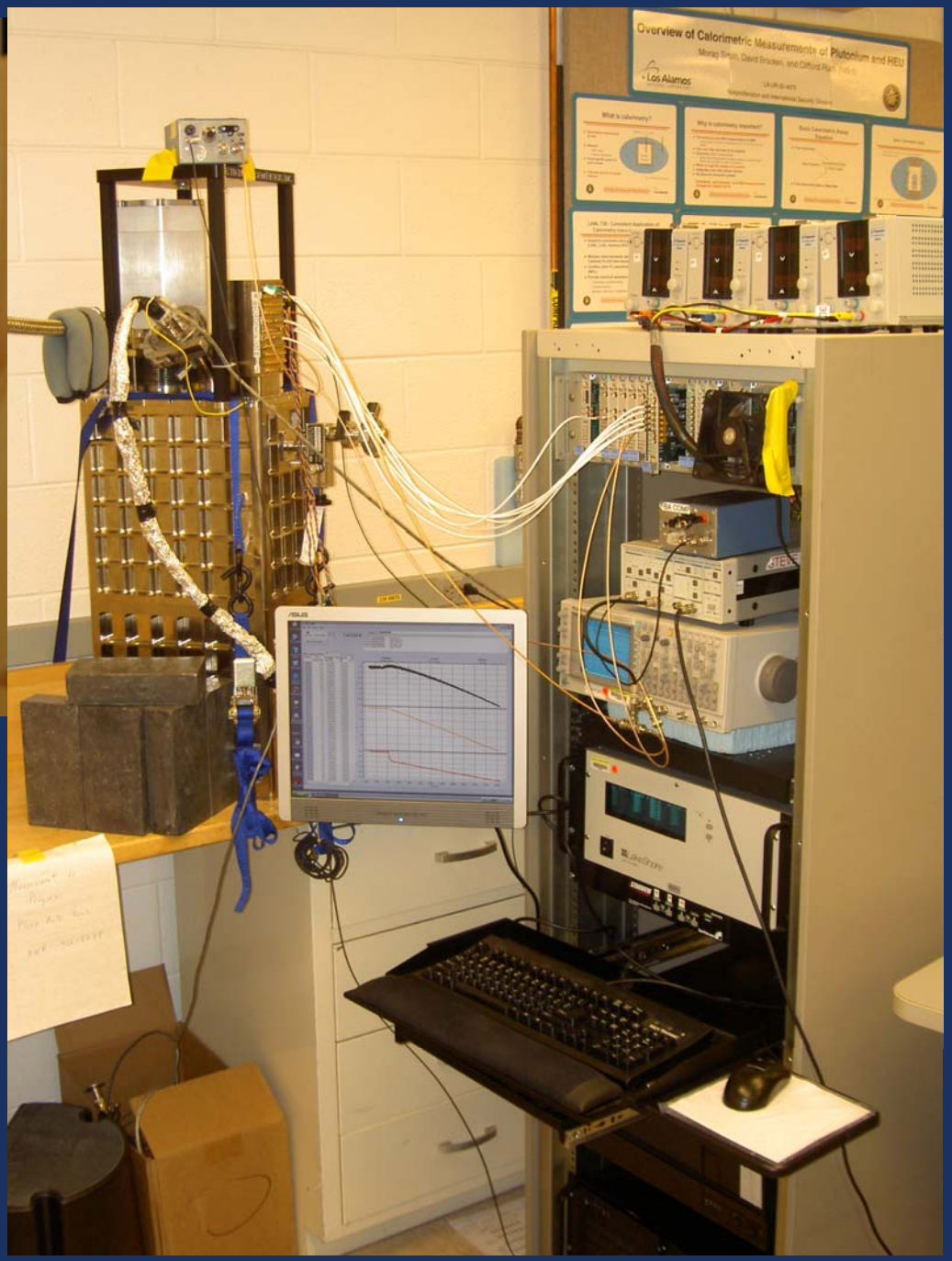
Best pixel

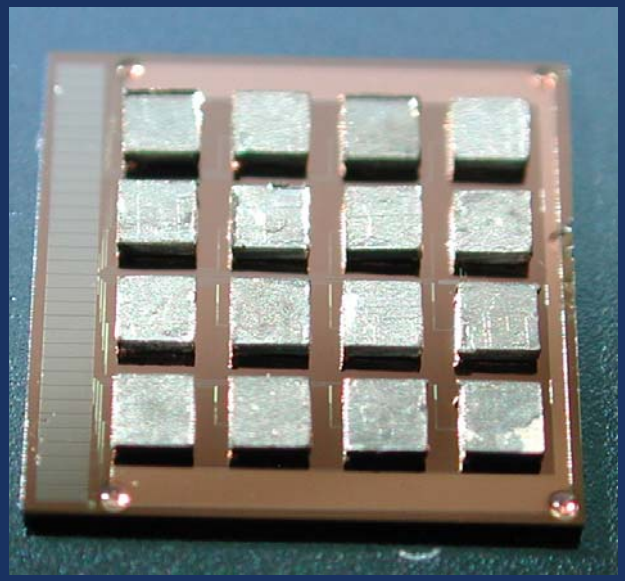


NIST

14-pixel γ-ray array system delivered to LANL

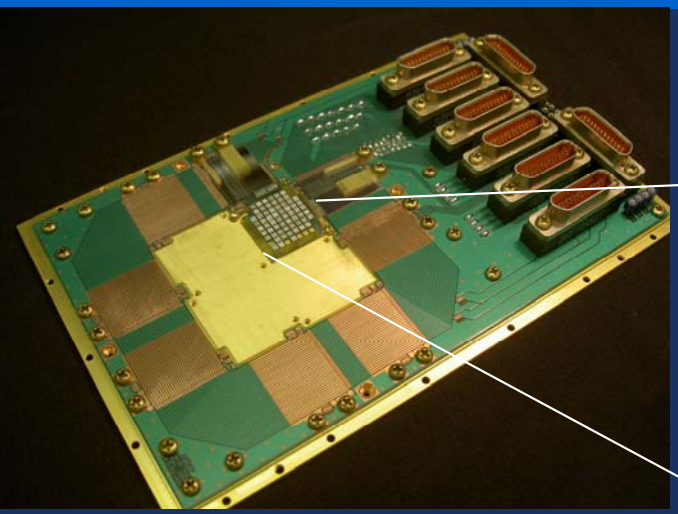


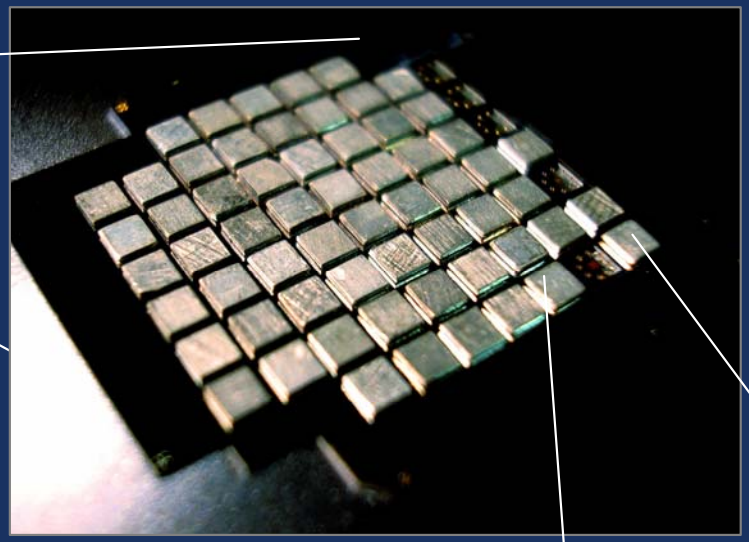




NIST

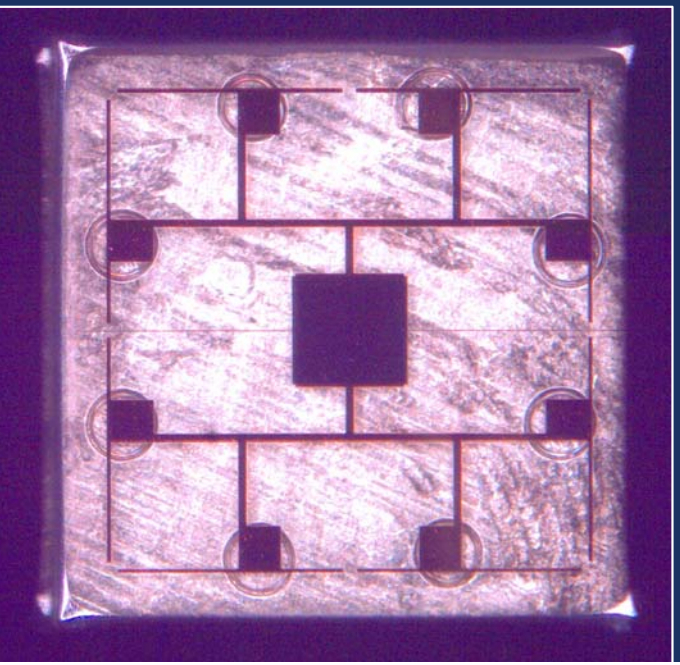
2nd-generation γ-ray arrays

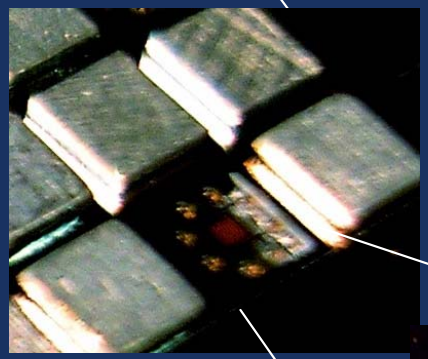




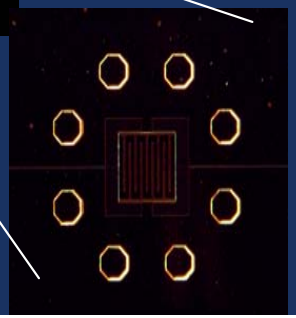
Four 66-pixel array chips

Pixel from underneath





1.5 mm

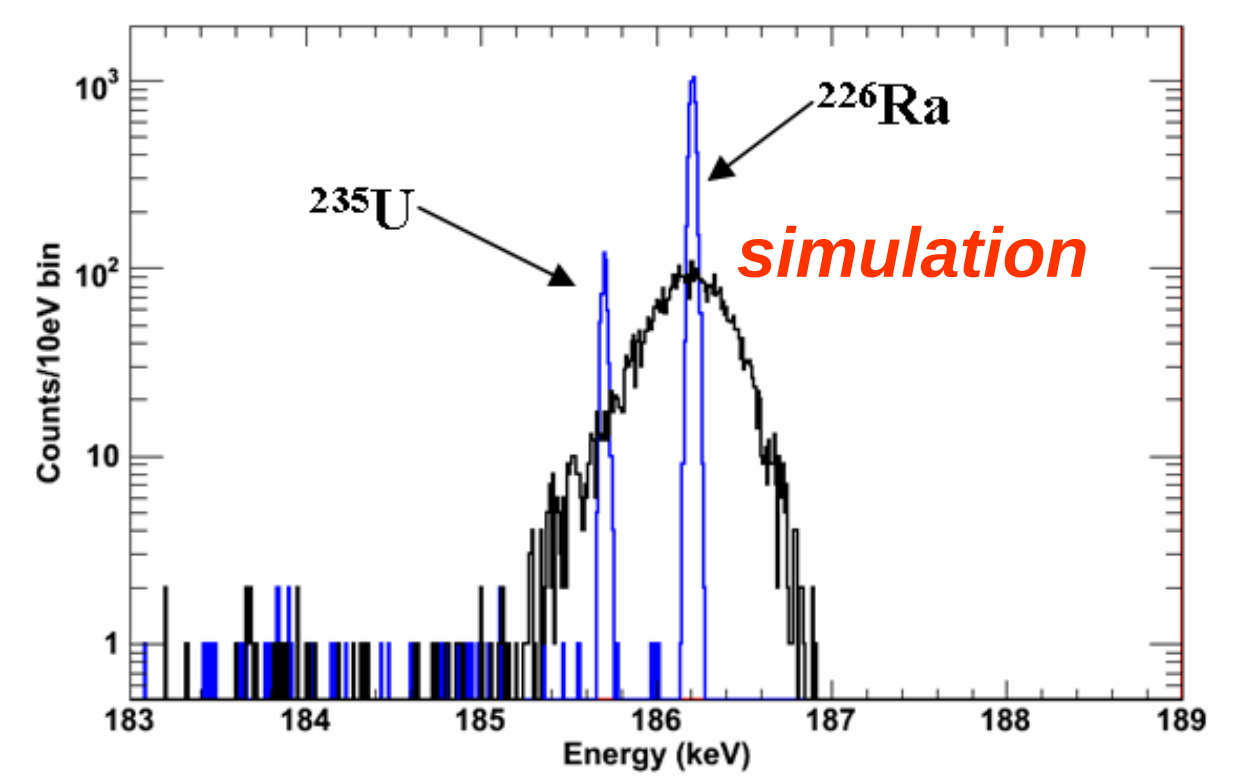


absorber removed

NIST/LANL

Discrimination of ^{235}U from ^{226}Ra

"The Kitty Litter Problem"



High resolution α spectroscopy

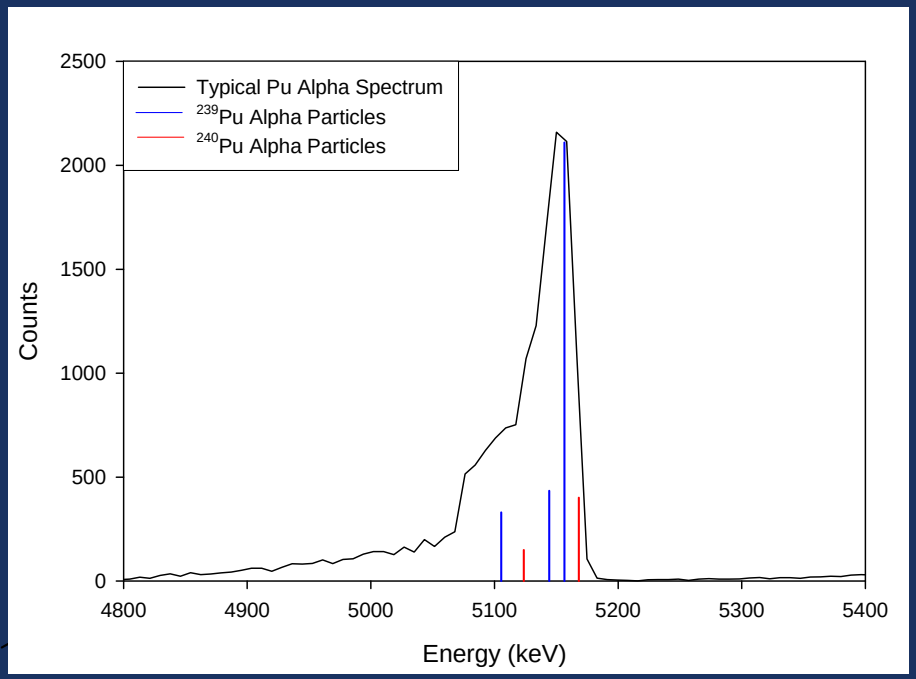
Alpha spectroscopy is a powerful tool for low level actinide measurements (μg – pg)

Approximately 3,000 samples analyzed per year at LANL for the IAEA and others

Poor resolution of conventional alpha spectroscopy (10-30 keV) is a problem:

- Can't split $^{239}Pu/^{240}Pu$ → drives use of slow and expensive mass spec
- Elemental overlaps → slow and expensive wet chemistry to separate

typical alpha samples



typical alpha spectrum

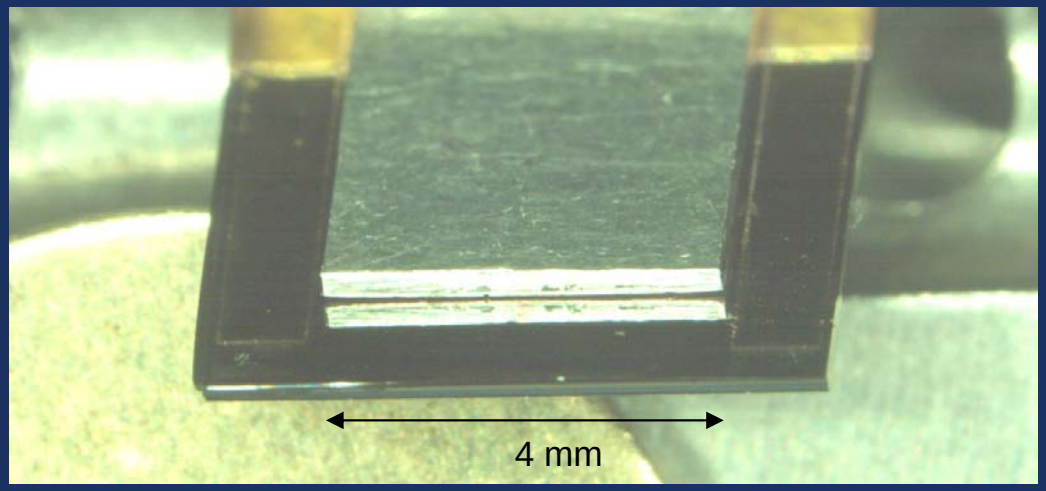
NIST

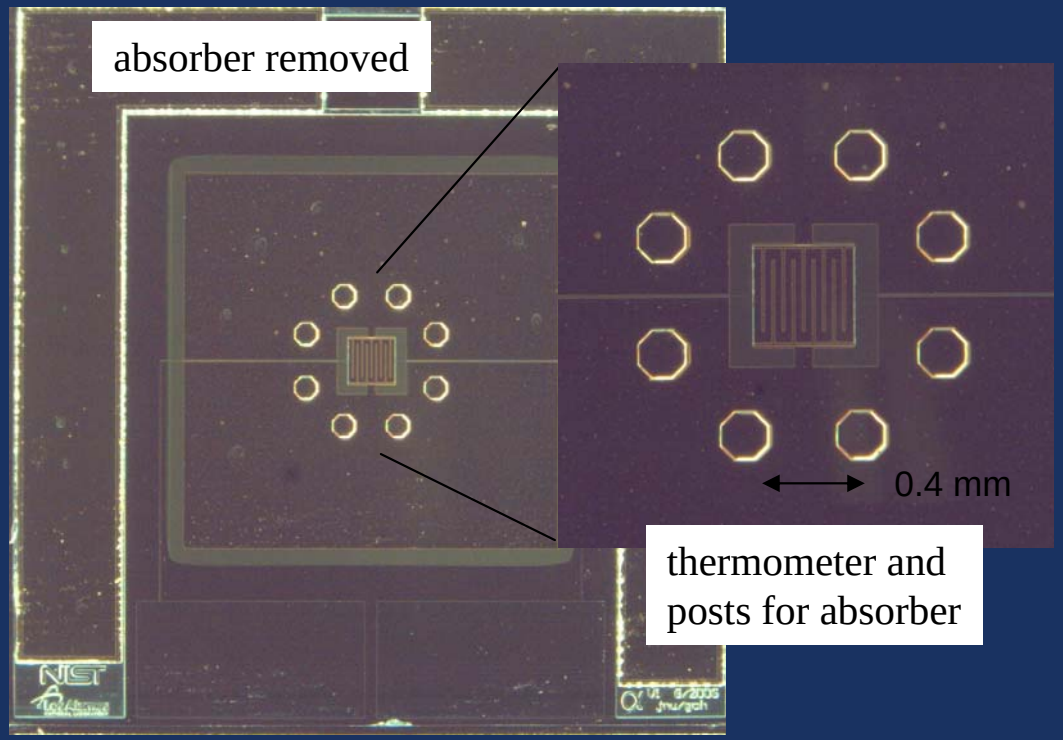
High resolution α spectroscopy

Pu sources and mounting hardware

electroplated mixtures of Pu isotopes below 2 nCi (Boulder limit)

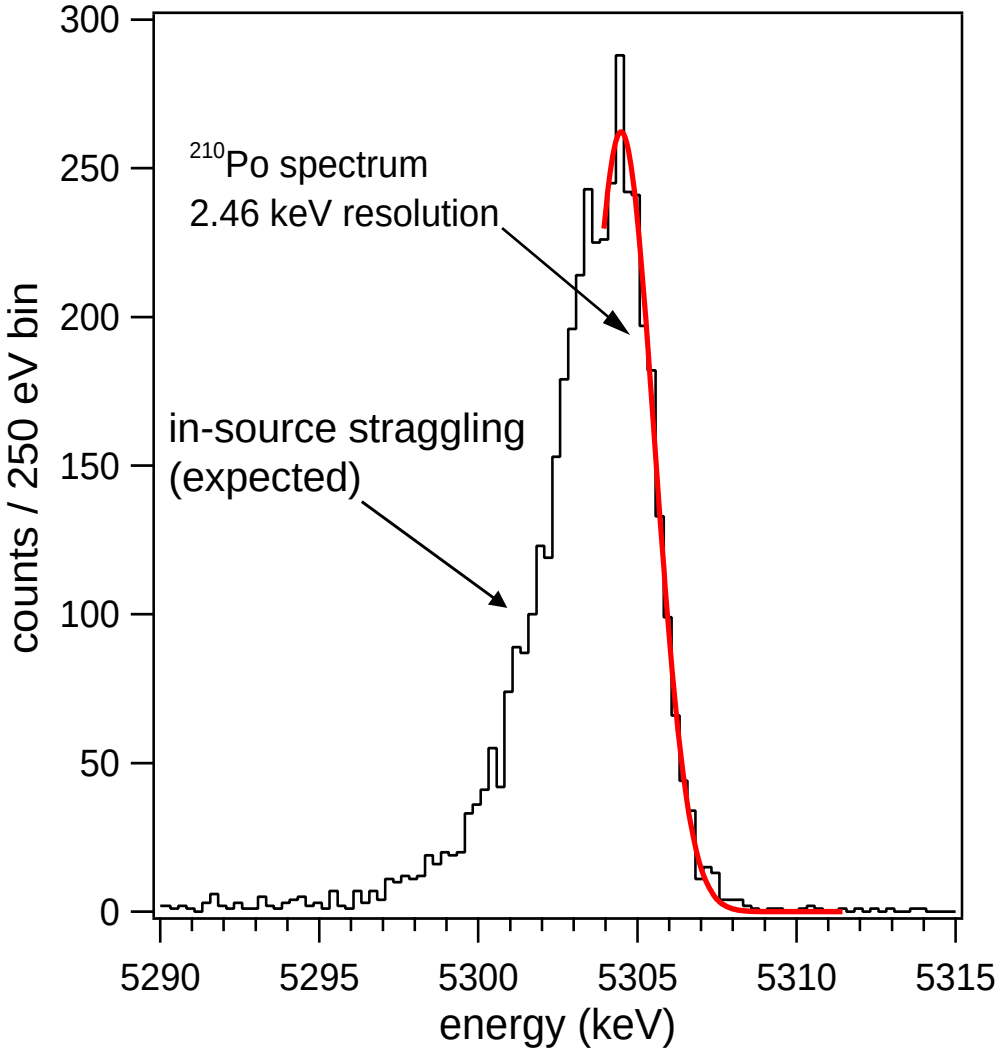
Completed sensors

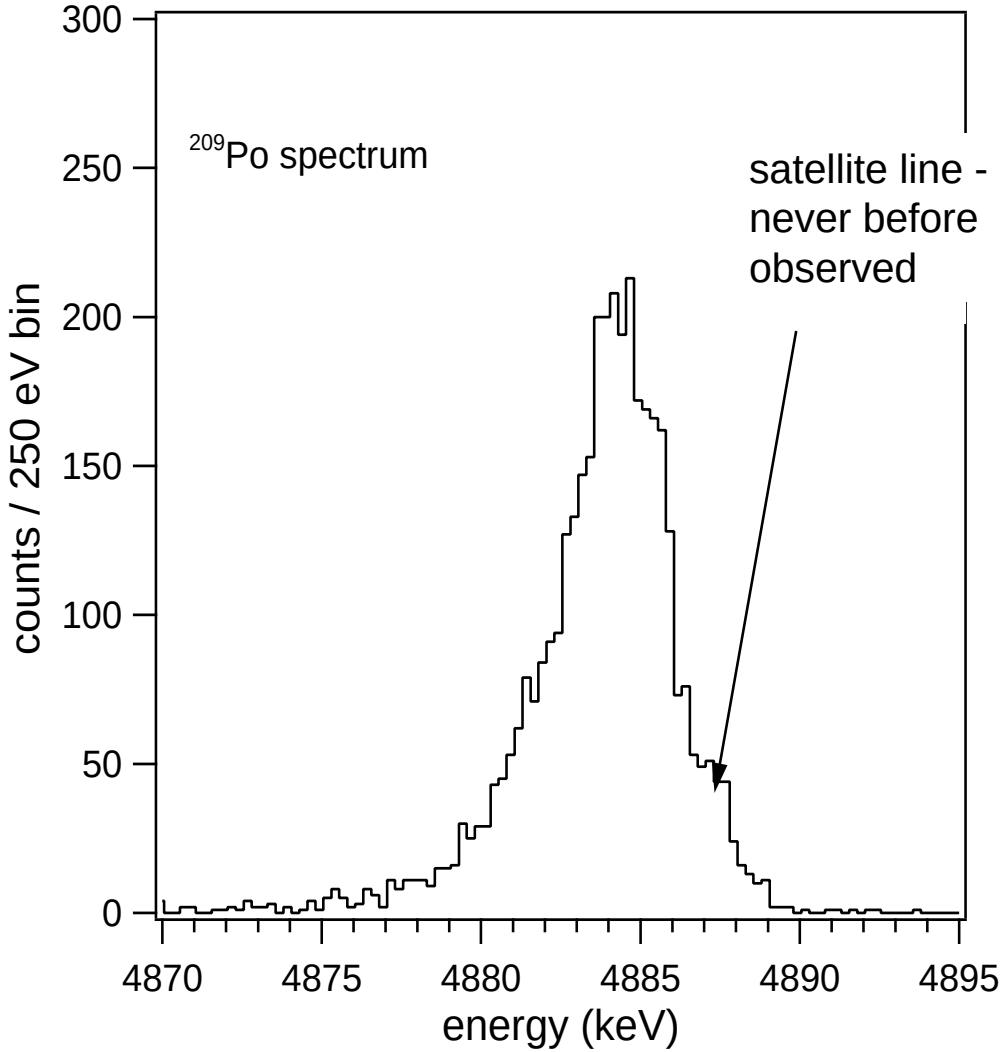




NIST

Alpha spectroscopy of $^{209}Po/^{210}Po$





world-record resolution: 2.46 keV at 5.3 MeV

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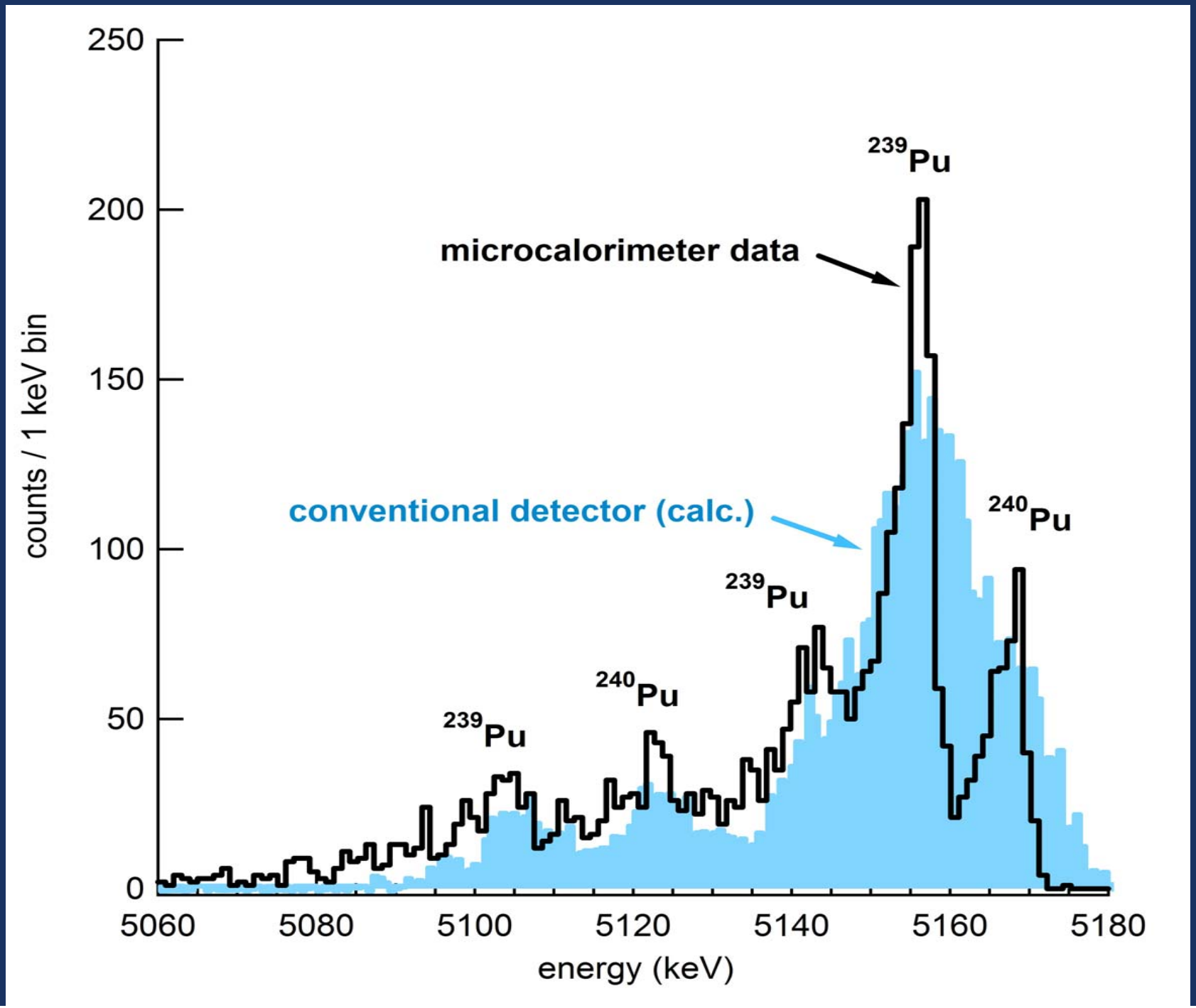
First splitting of $^{239}Pu/^{240}Pu$ α lines



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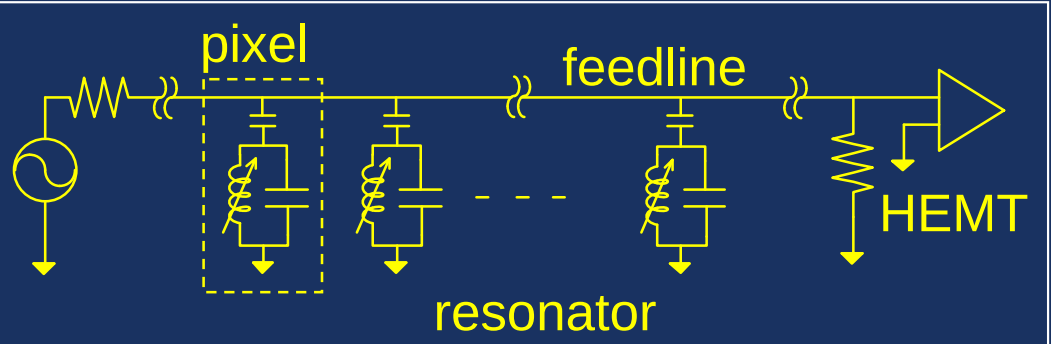
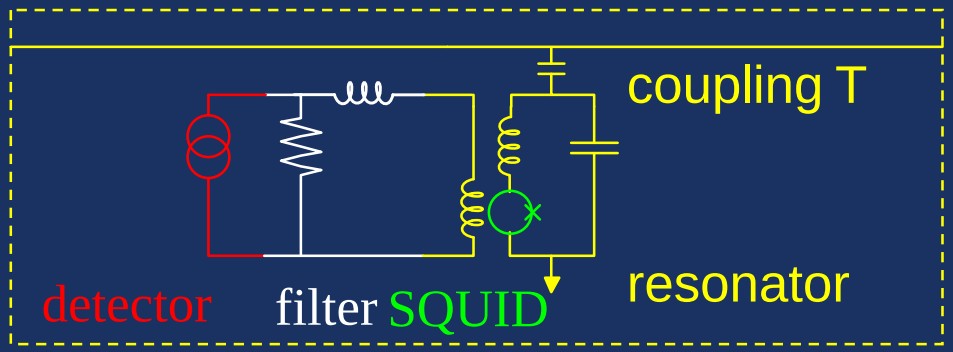
Applications of TES arrays

Cosmology	CMB, submm, x-ray	Dark energy, inflation, neutrino mass…
Astronomy	submm, x-ray, γ-ray	Planet/star/galaxy formation, WHIM, black holes…
Quantum information	optical	Quantum key distribution, computing
Materials analysis	x-ray	Electron-probe materials analysis, synchrotron
Security	THz, γ, neutron	Concealed weapons, Suicide bombers, nuclear smuggling
Nuclear materials	γ-ray, alpha, neutron	Nuclear non-proliferation, forensics
Particle physics	Dark matter, neutrinos	WIMPs, neutrino mass CDMS

Microwave SQUID multiplexer

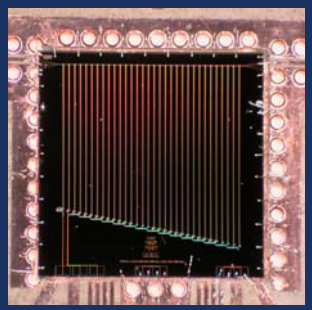


pixel variety #1



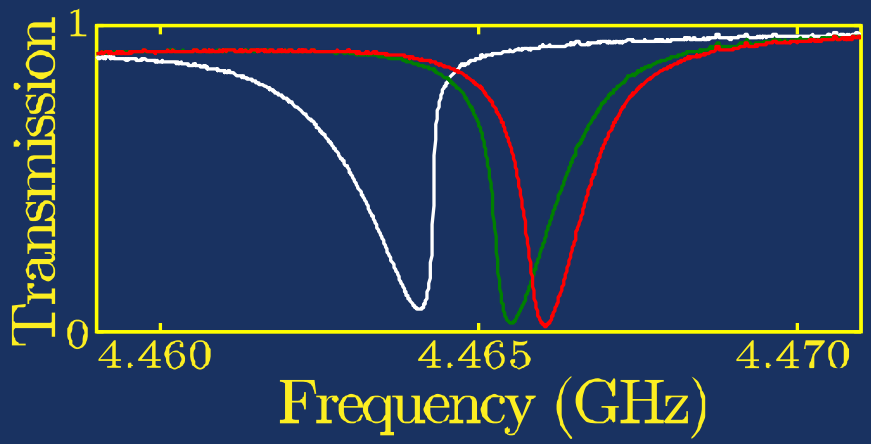
rf-SQUIDs (flux variable inductors)

- unshunted + non-hysteretic
- dissipationless
- CPW resonators similar to MKIDs, P. Day *et al*, Nature (2003)
- Junctions tune microwave resonances



Chip with one feedline; 32 dissipationless SQUIDs

Measured resonance at 3 flux values



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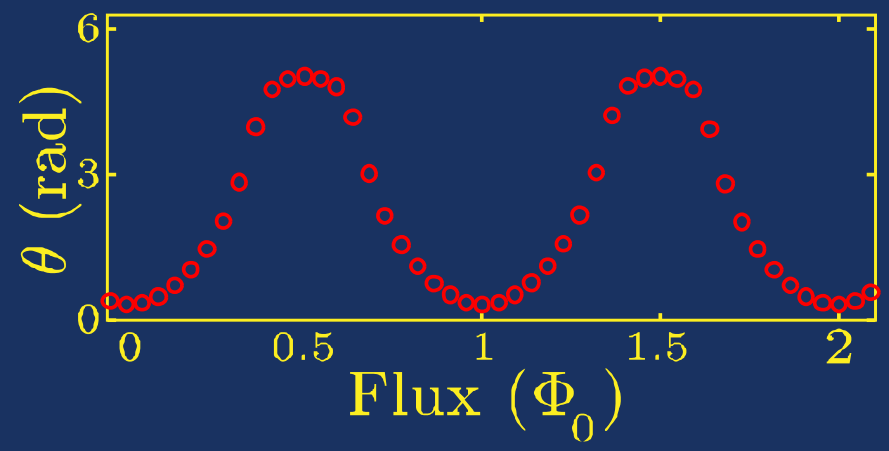
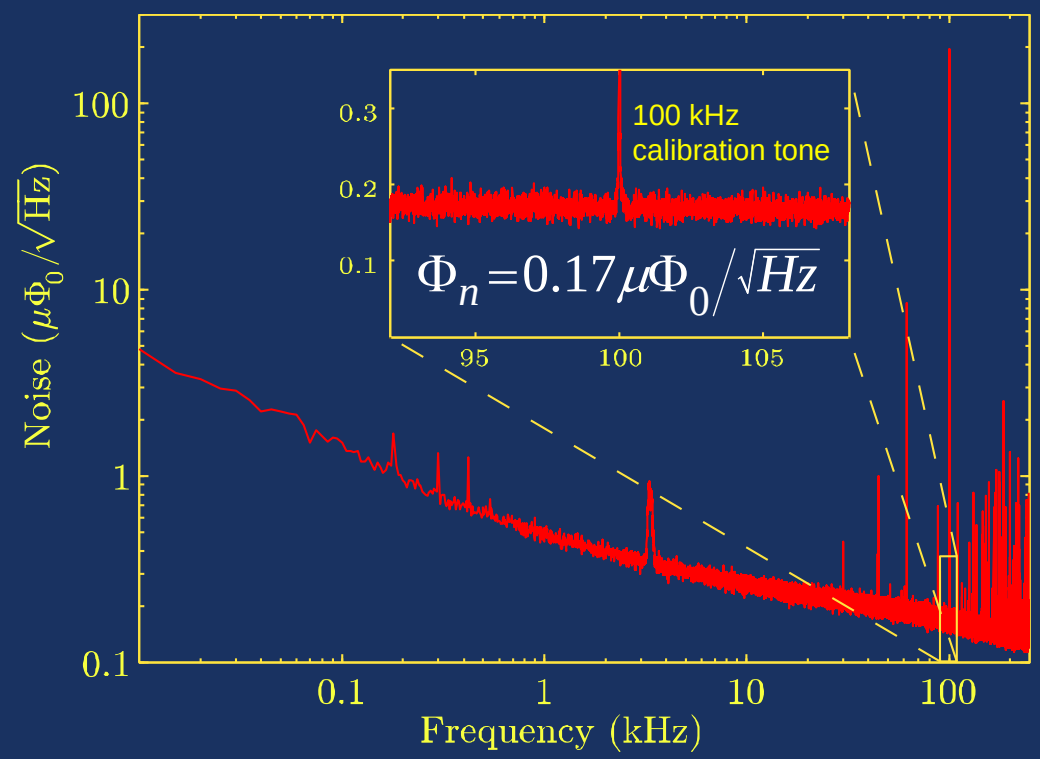
Results

Initial prototypes work well

- 32 resonators on feedline
- Q = 4,000-20,000 at 5 GHz
- Resonator accuracy compatible with > 1,000 SQUIDs per HEMT
- Parasitic power loss (in dielectric) ~ 5 pW
- Stable operation
- Noise dominated by dielectric: $\Phi_n = 0.17\mu\Phi_0/\sqrt{Hz}$ at 100 kHz
- Input low-pass filters block microwaves from detector
- Now working coupling to TESs

Transmitted phase as a function of flux





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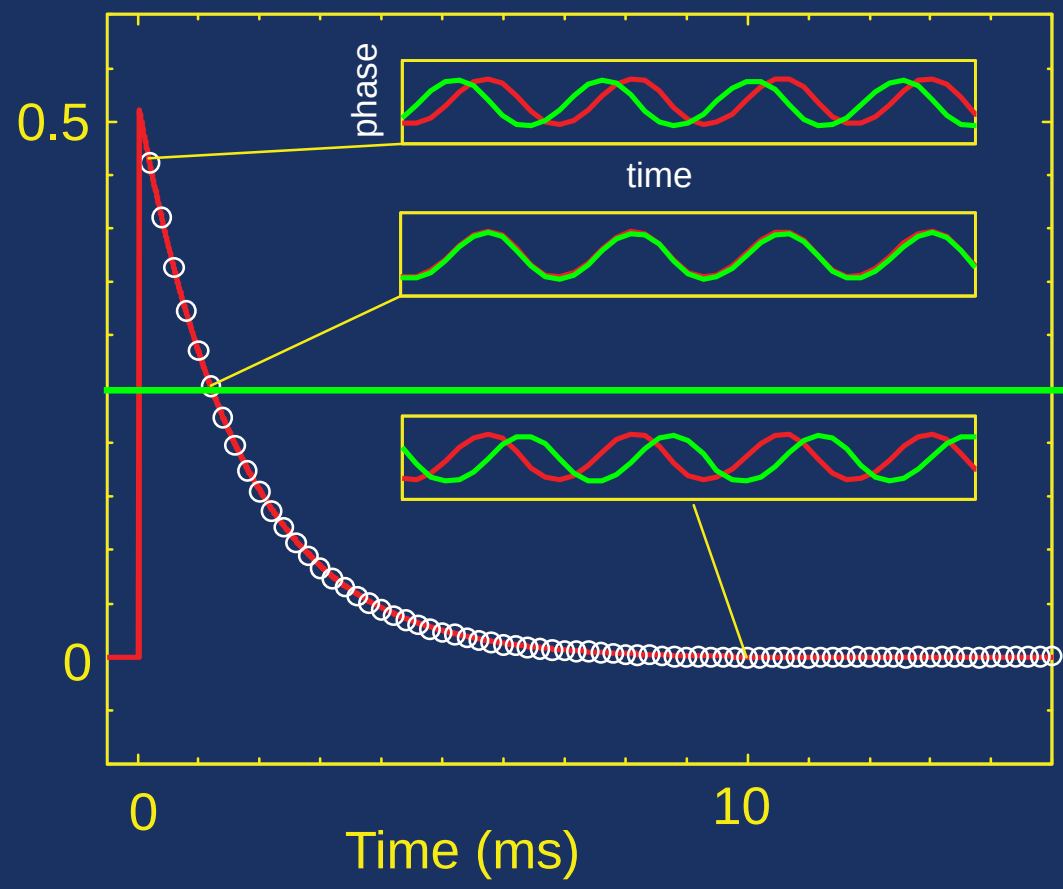
Flux-ramp modulation

Microwave MUX SQUIDs operate open loop (no feedback, but flux modulated)

- One common “flux ramp” wire for all SQUIDs
- 10 kHz sawtooth current on flux ramp wire with 10 Φ_0 amplitude $\rightarrow$ SQUID response modulated at 100 kHz, above dielectric noise
- Detector signal recovered from phase of modulation

Should be possible to operate >1,000 SQUIDs with two coax cables (input & output), one HEMT, and one flux-ramp wire

Data: recovery of exponential input signal with flux-ramp modulation



Red: input flux

Green: reference baseline

White: signal measured from phase

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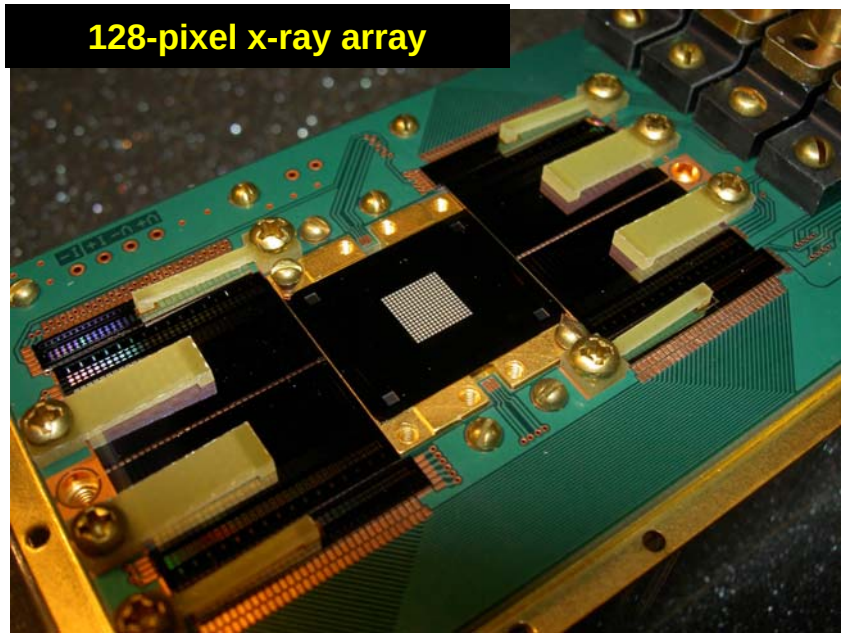
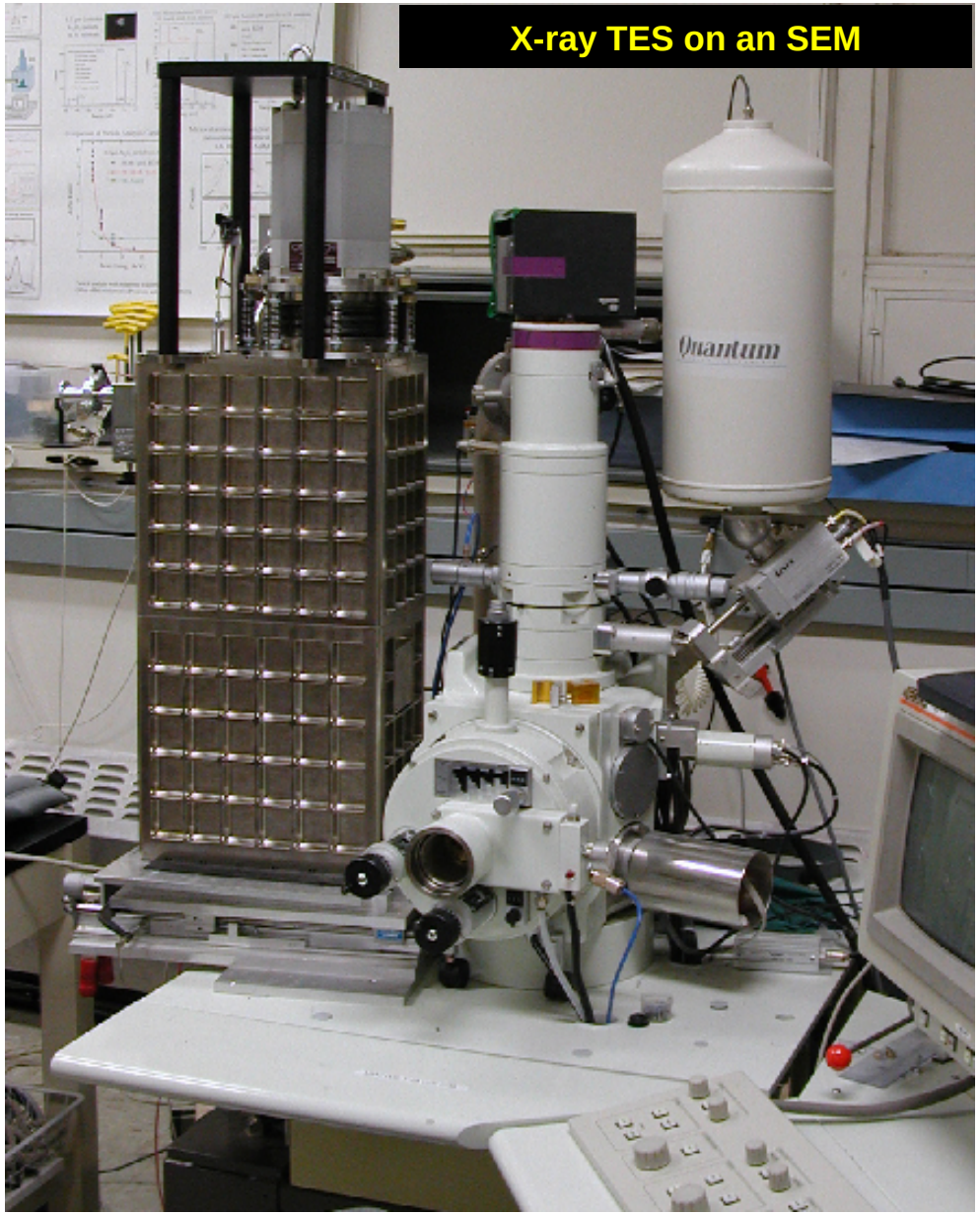
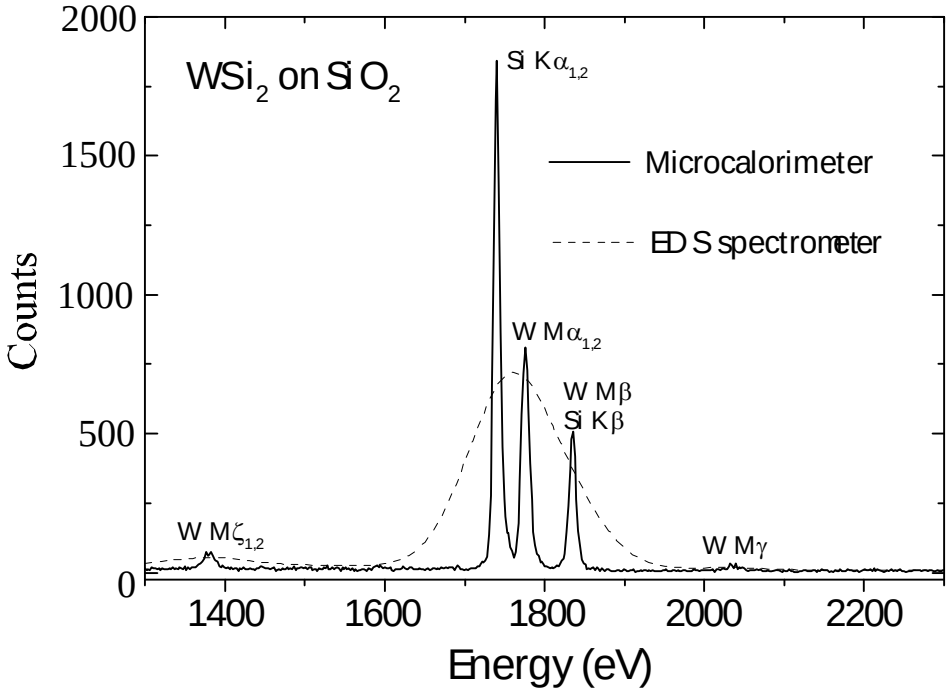
Electron-probe materials analysis

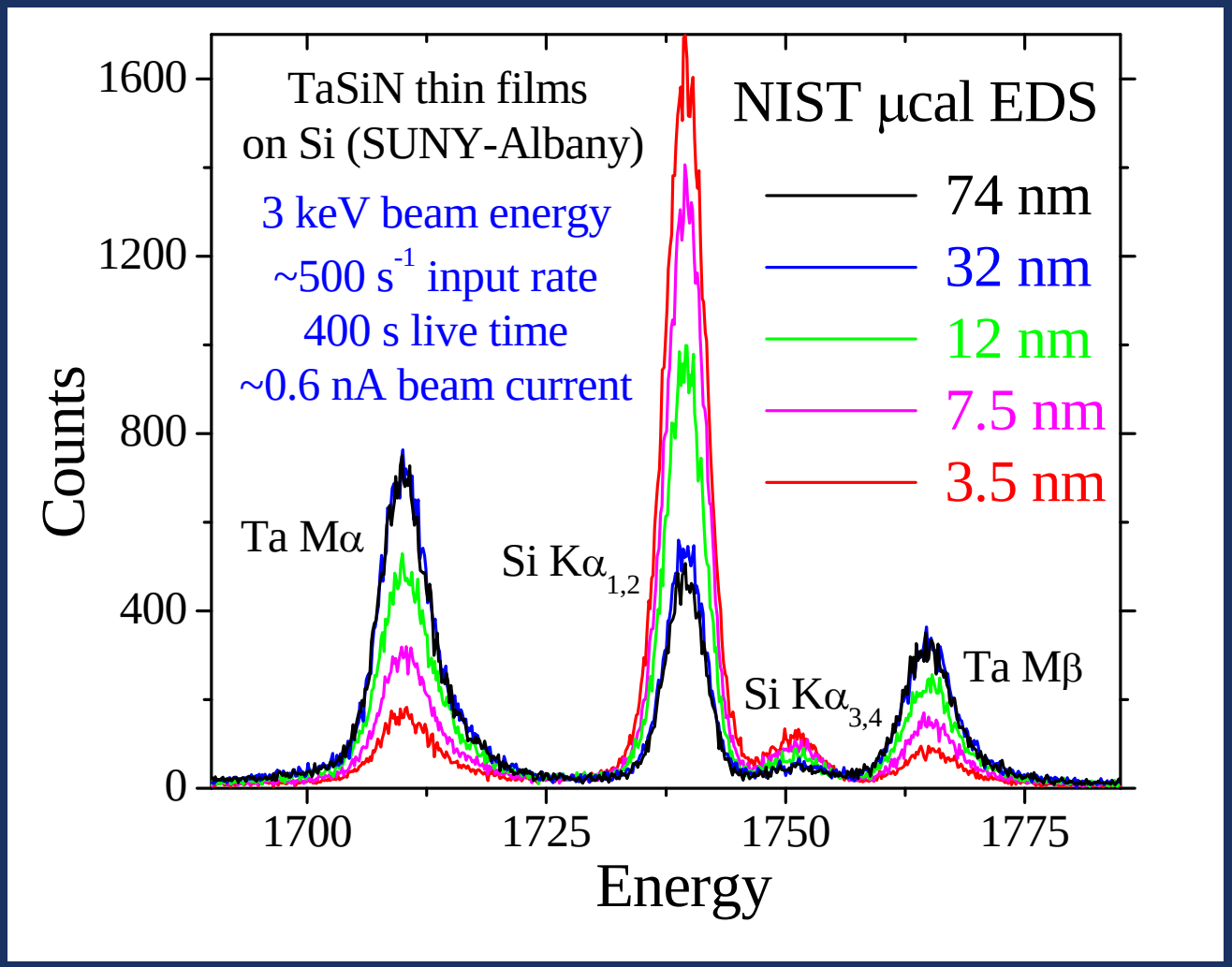






Thin-Film Analysis

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.

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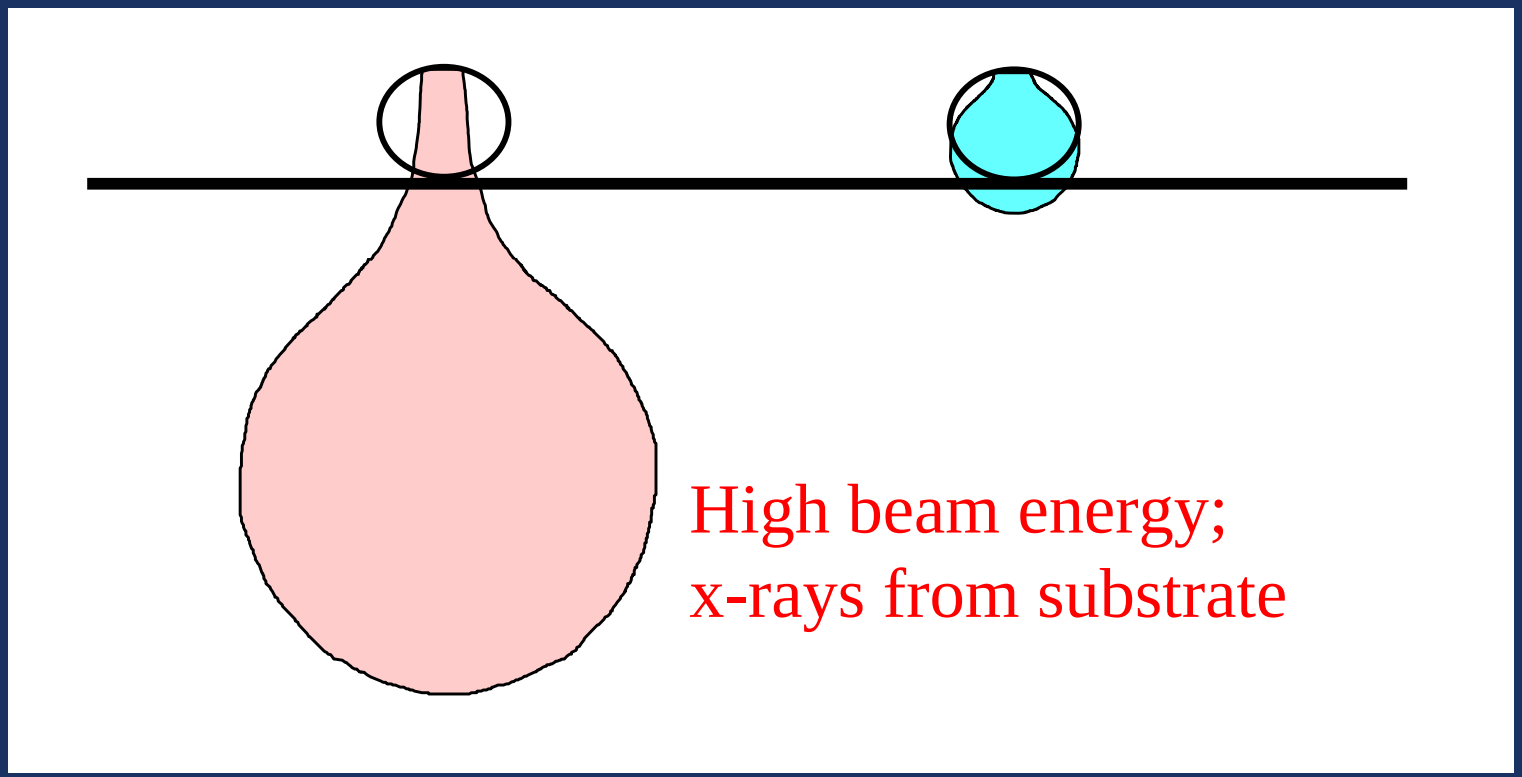
Nanoscale Particle Analysis

- 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



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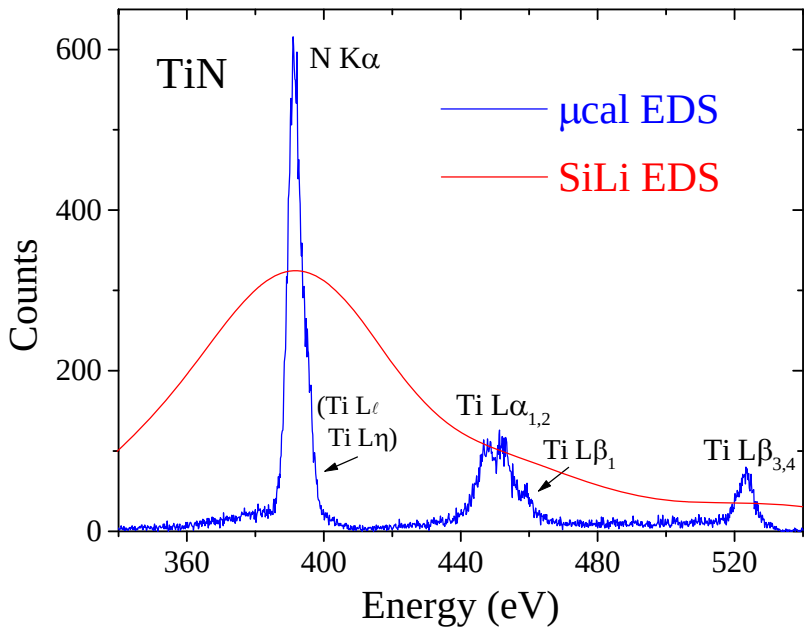
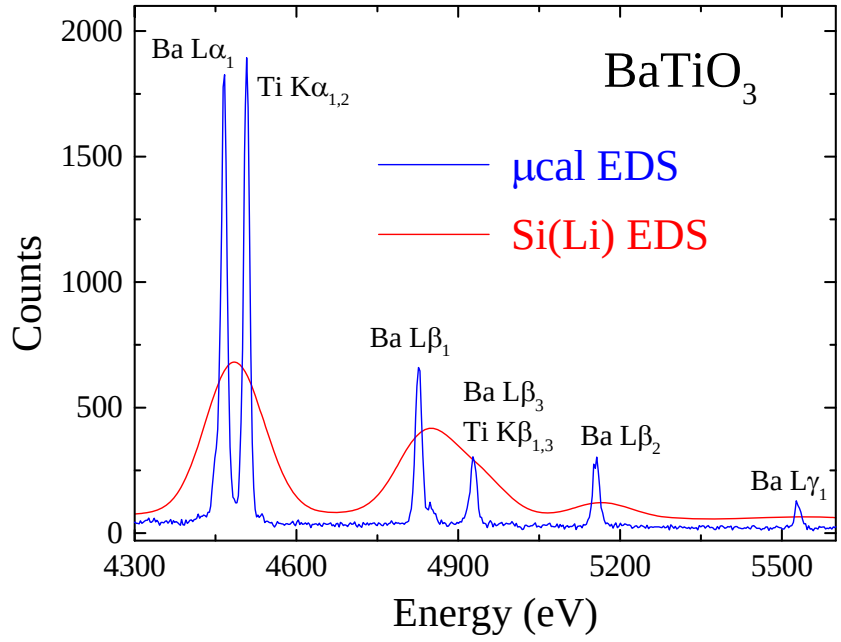
Resolving peak overlaps

The need for low-energy analysis of small particles means that many peaks are overlapping when measured with SiLi

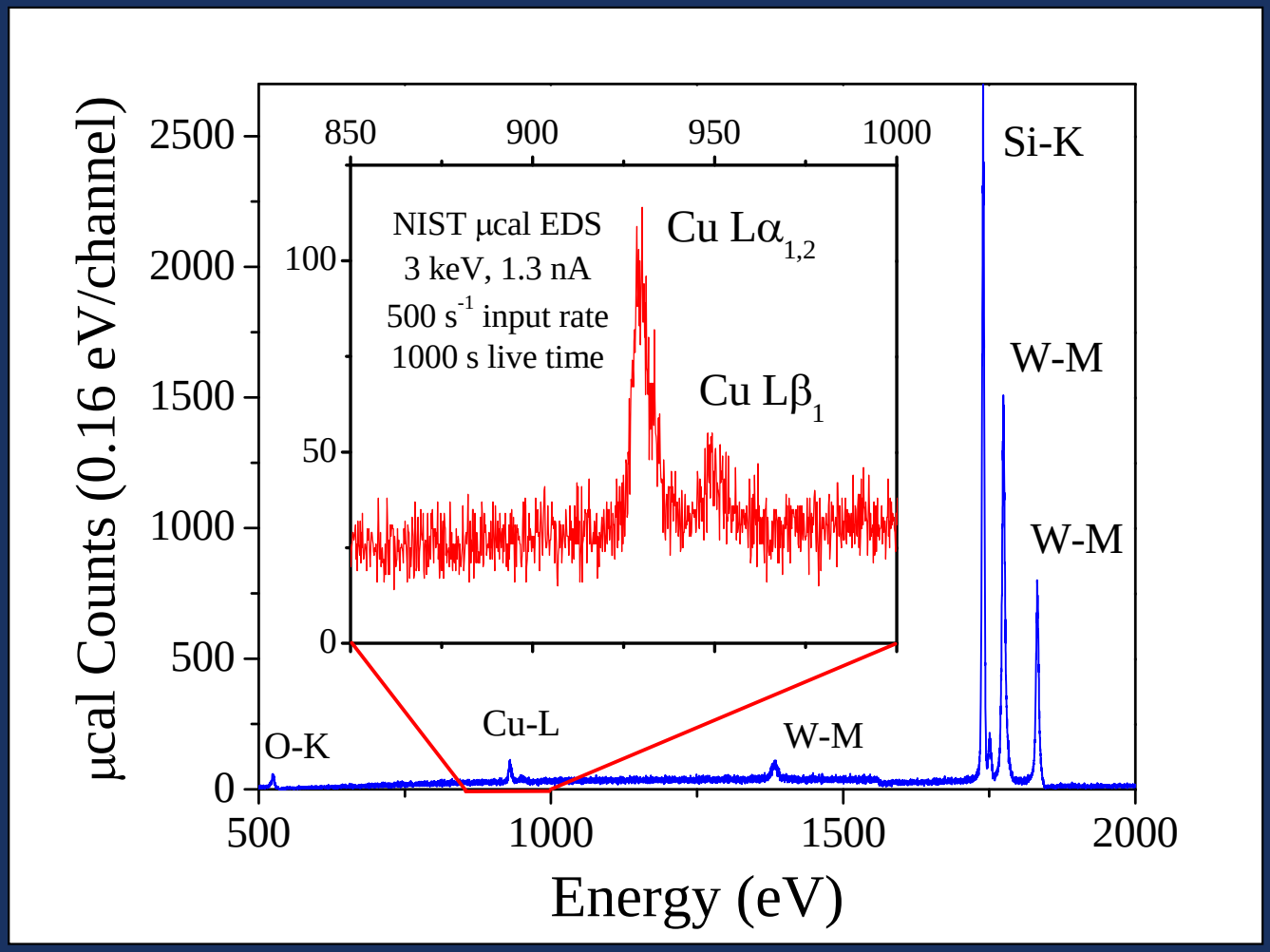




Trace-Element Analysis

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)

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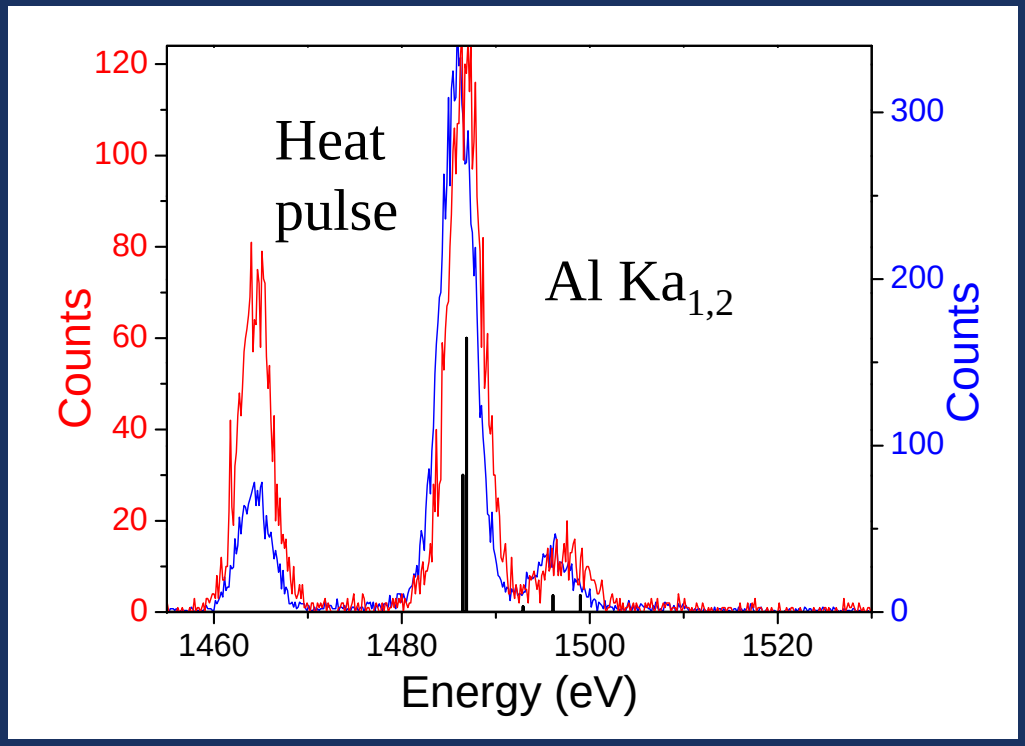
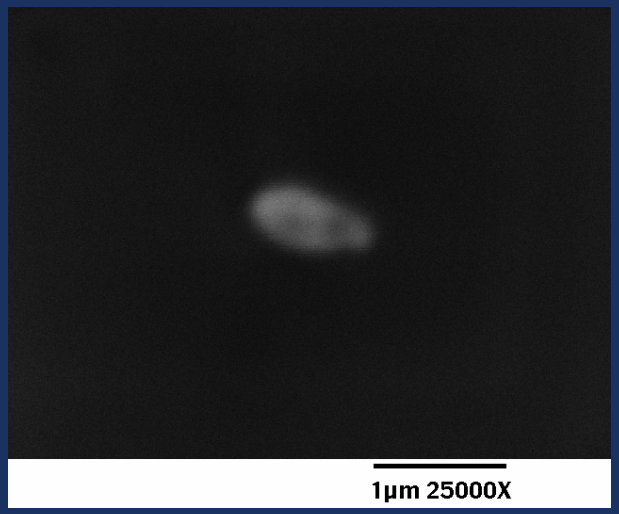
Chemical shift analysis



Al oxide particle



Al particle

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

Particle samples provided by
Alain Diebold (SEMATECH)

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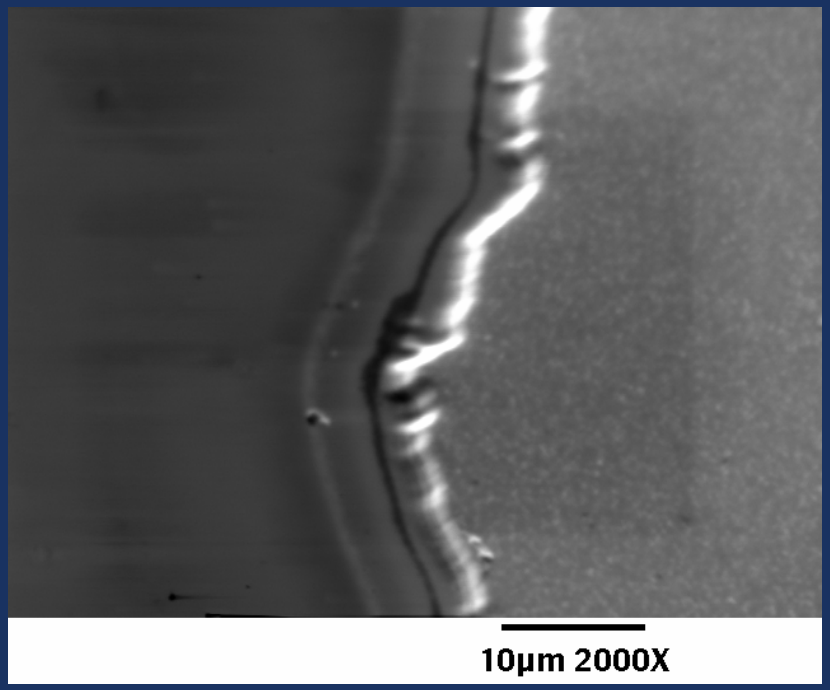
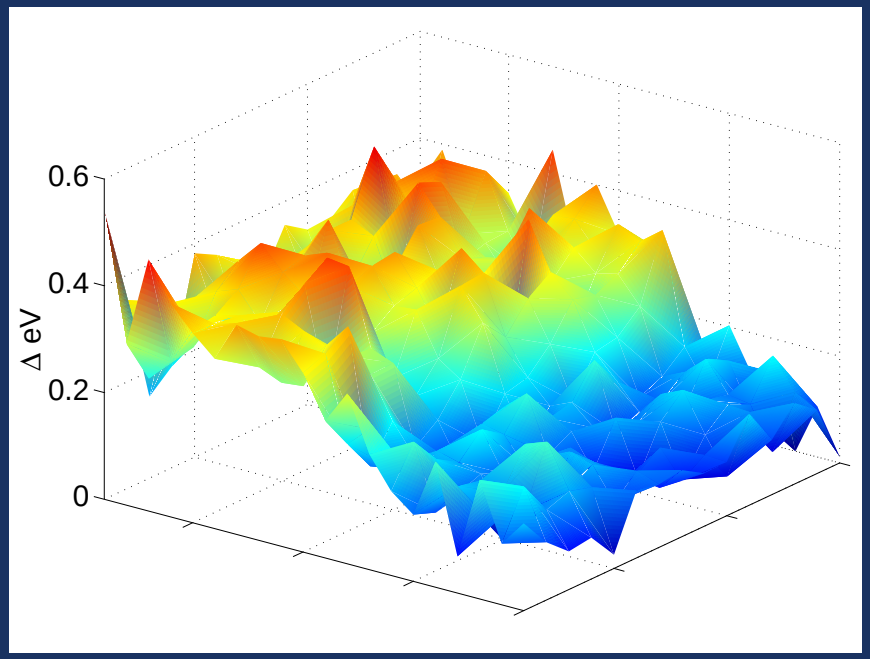
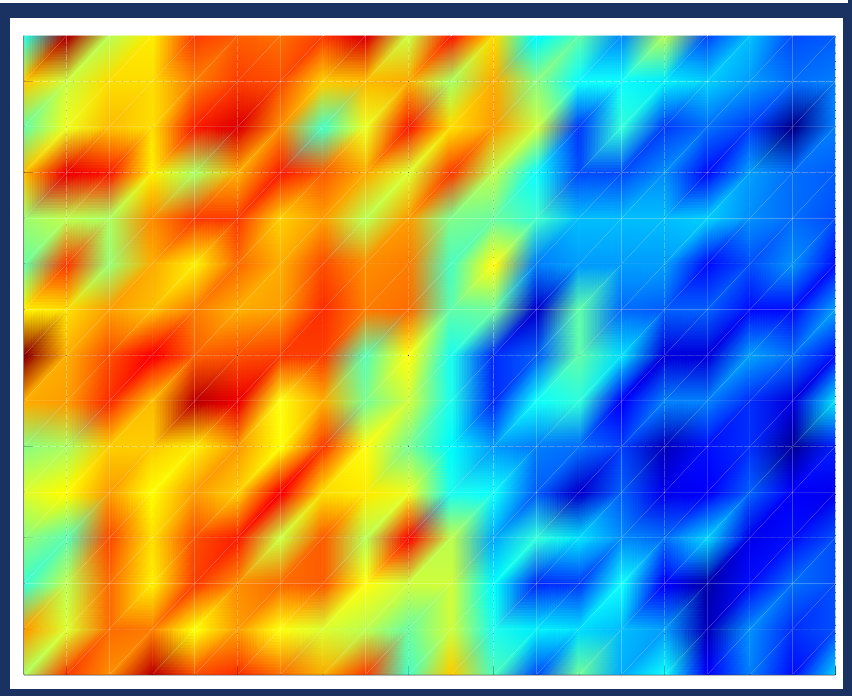
Chemical shift map



Al oxide Al





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