NASA/Goddard Space Flight Center
Greenbelt, Maryland

The X-ray Microcalorimeter Spectrometer for Constellation-X

Richard L. Kelley

NASA/Goddard Space Flight Center

Integrated Product Team for X-Ray Microcalorimeter Instrument

NASA/Goddard Space Flight Center

TES development:	Caroline Kilbourne
Continuous ADR:	Peter Shirron
Cryocooler:	Paul Whitehouse

National Institute of Standards & Technology

TES & readout development:	Kent Irwin

Harvard/Smithsonian Astrophysical Observatory

Ge-based microcalorimeters	Eric Silver

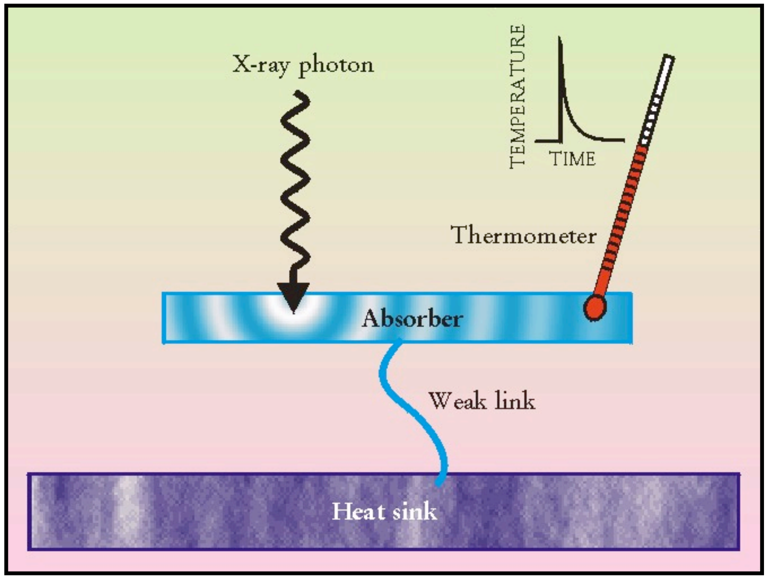
- IPT organization structure no longer in effect as of late 2005.
  - Rick Shafer (NASA/Goddard) named as XMS Instrument Scientist to provide independent support to Project.
- Con-X and LISA Technology Assessment requested by NASA management in late 2005; I will present the XMS input to that assessment today.

XMS Top-Level Requirements

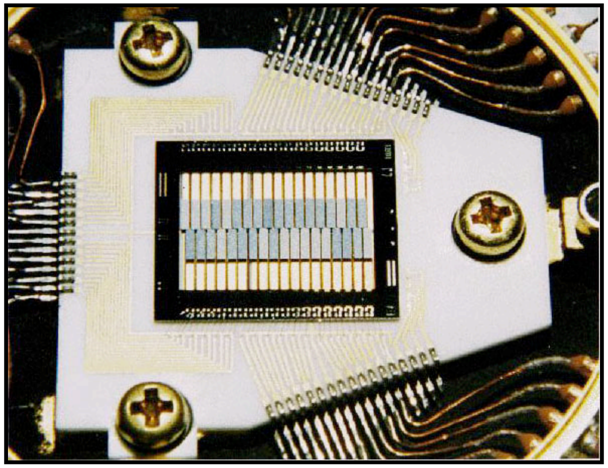
XMS Performance Requirement		Trace to Top-Level Mission Requirements
Bandpass	0.6 – 10 keV	TLRD
Spectral resolving power ($E/\Delta E$)	1500 at 6 keV	TLRD
Angular resolution	5 arcsec	Oversample SXT PSF by a factor of 3
Field of view	2.5 arcmin	TLRD
Derived Detector Requirements		**Derivation**
Pixel size	242 μm	Meets TLRD beam sampling requirement
Number of pixels	32 x 32	Gives 2.7 arcmin FOV vs. 2.5 arcmin requirement
Energy resolution	4 eV at 6 keV; 2 eV at 1 keV	Gives $E/\Delta E$ = 1500 at 6 keV
Intrinsic quantum efficiency	95%	Flowdown to meet effective area req.
Filling Factor	95%	Flowdown to meet effective area req.
Detector speed	<300 μsec pulse decay time constant	Supports bright source counting rate req.
Time resolution	10 μsec	Allocation to meet absolute timing req.
Derived Instrument Requirements		**Derivation**
Mass	147 kg	Current engineering estimate
Power (watts)	80/146 (min/max) 150/200 (BOL/EOL)	For analog, digital, CADR control electronics Cryocooler electronics
Data rate (avg/peak)	7.2/640 kbps	Average source rate plus 840 bps H/K data Peak rate from bright sources limit

X-Ray Microcalorimeters

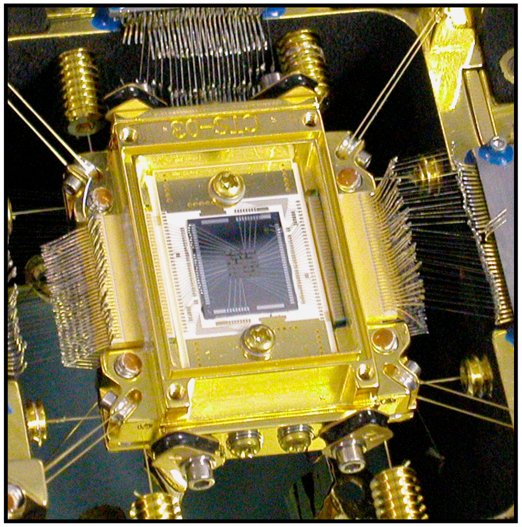
- X-ray microcalorimeter: thermal detection of individual X-ray photons
  - High spectral resolution
  - ΔE very nearly constant with E
  - High intrinsic quantum efficiency
  - Non-dispersive — spectral resolution not affected by source angular size



Arrays have been developed for a sounding rocket payload and an orbiting observatory

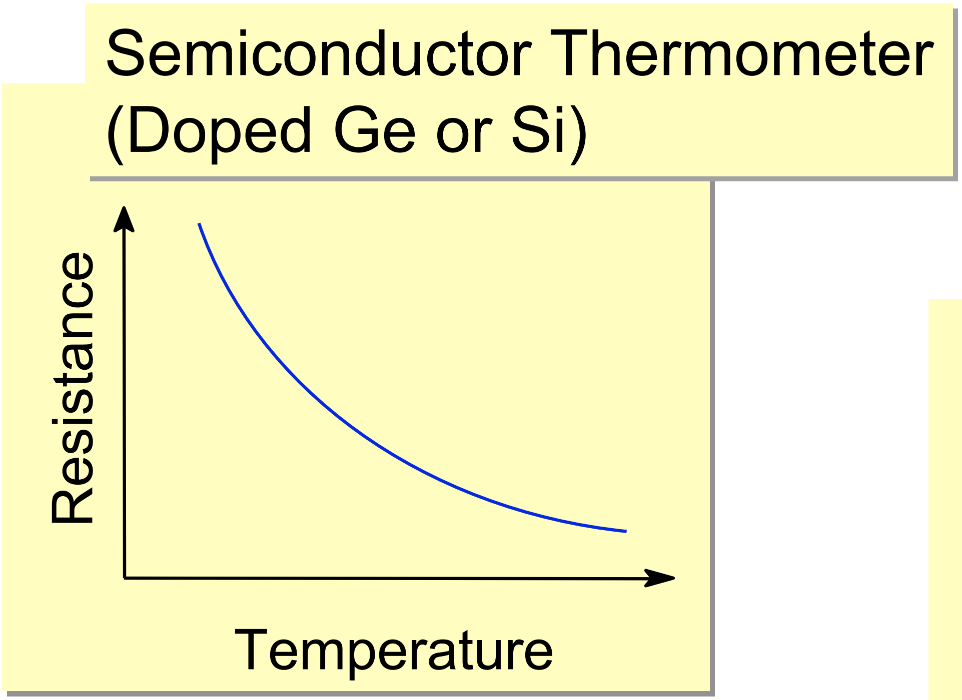


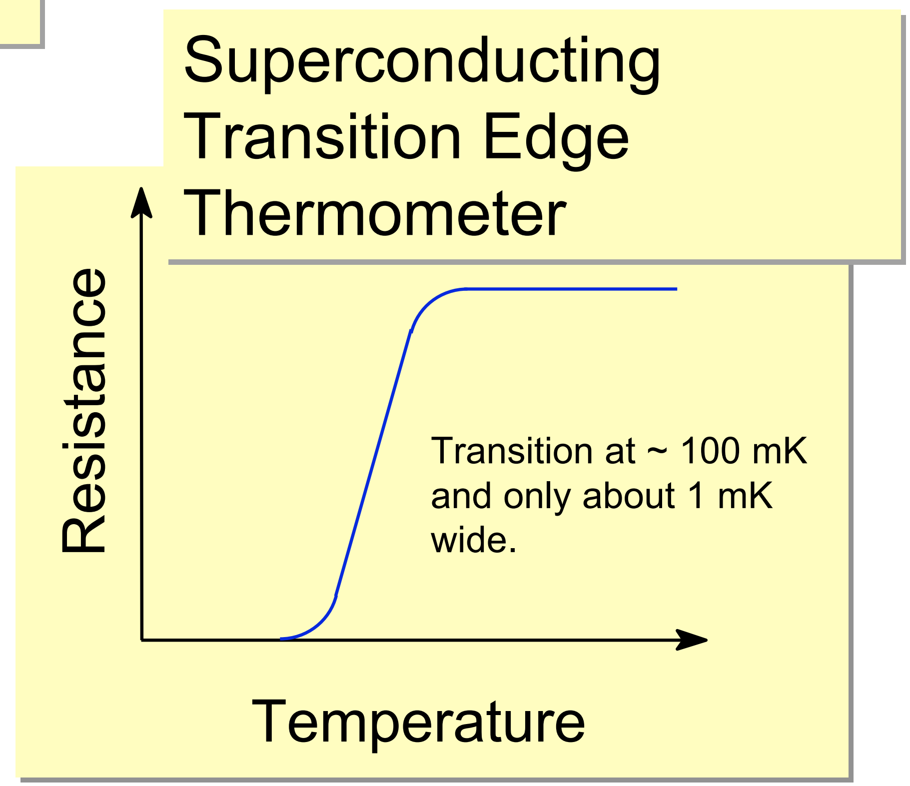
XQC



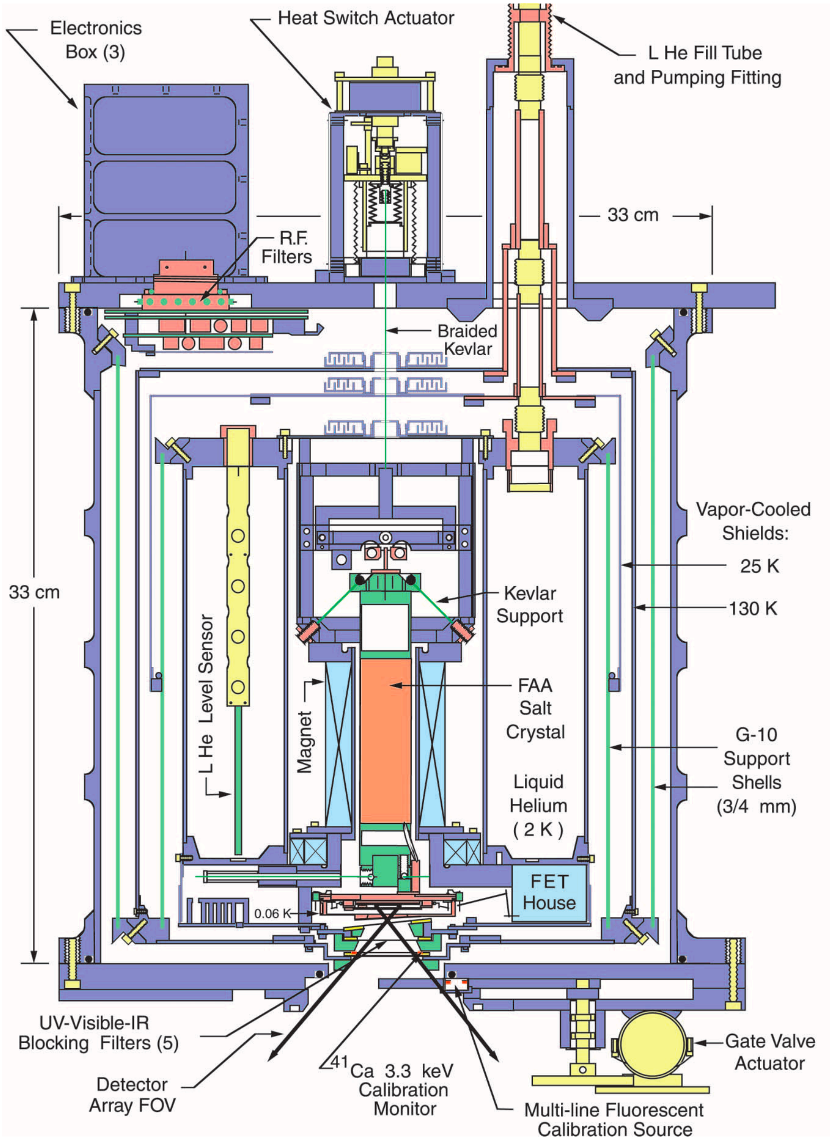
Astro-E2/XRS
****TRL9****

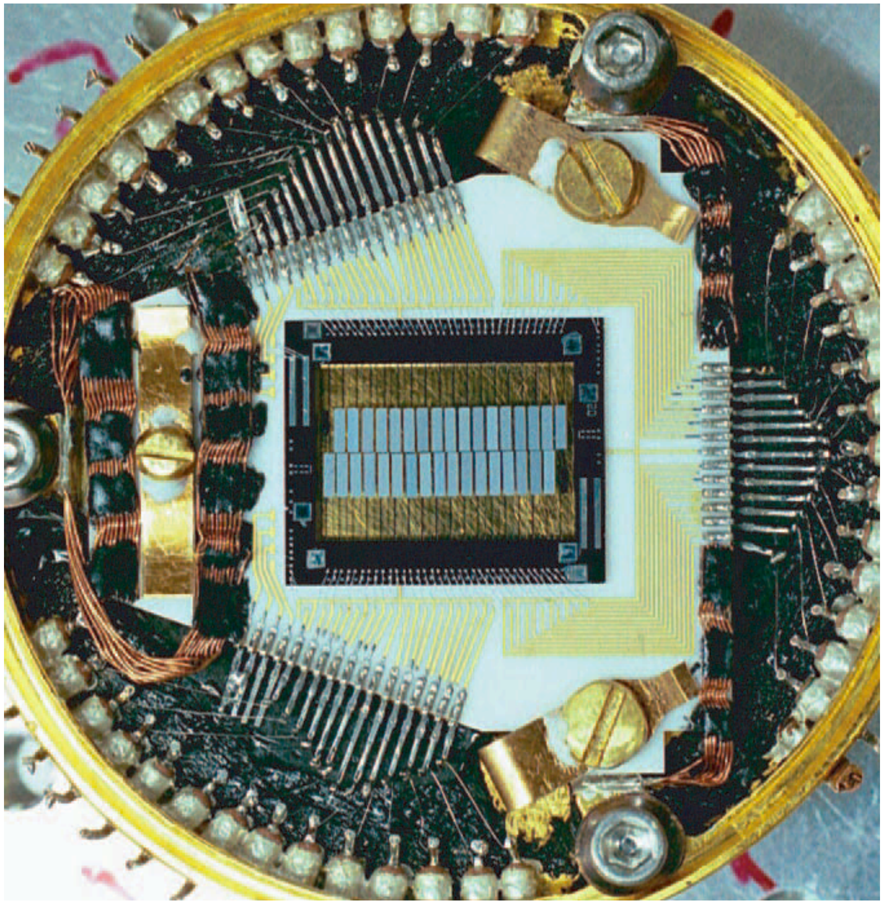
Greatest heritage using *d*R/*d*T as the thermometer





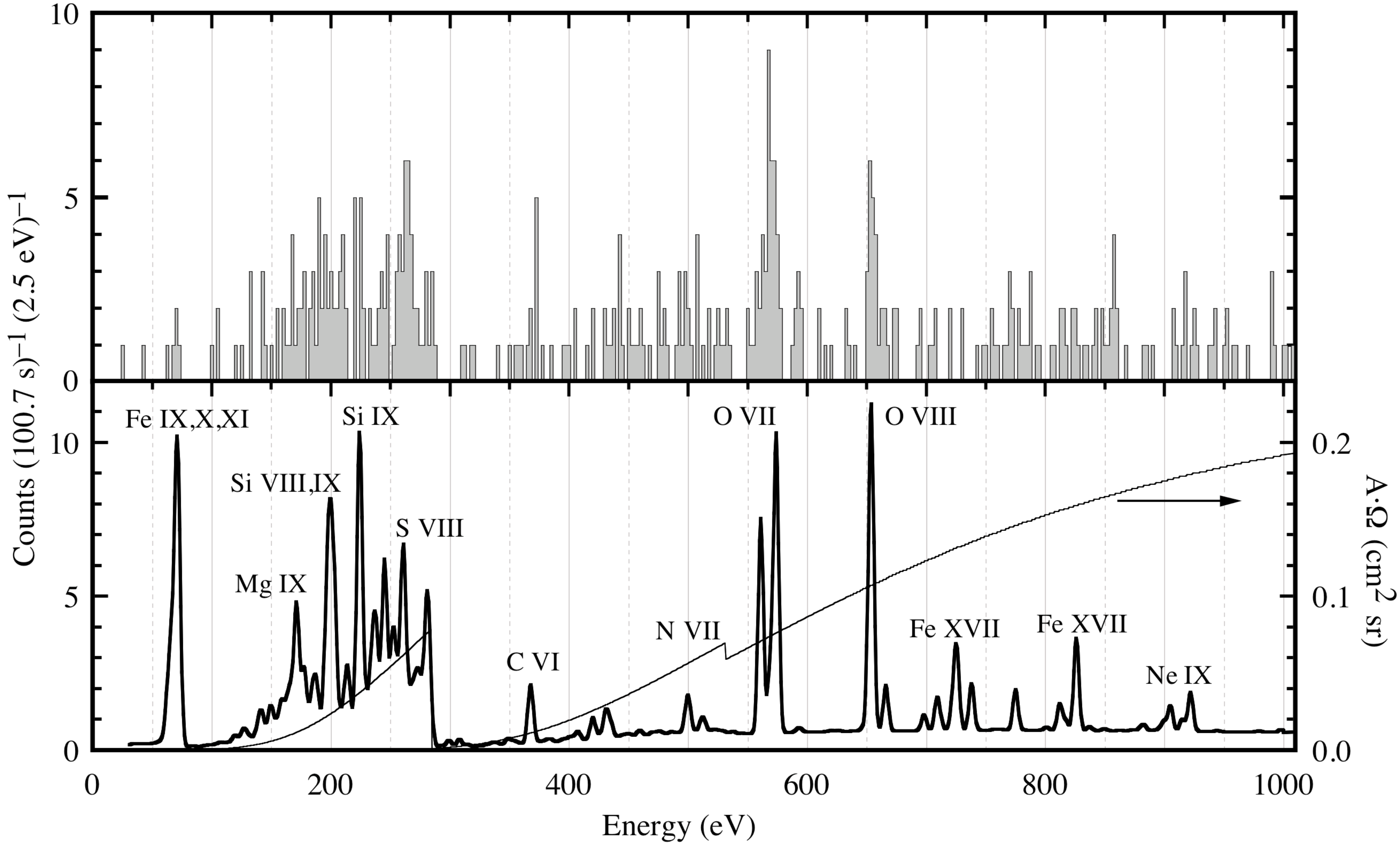
First x-ray microcalorimeter in space - XQC Instrument





36 pixel ion-implanted Si x-ray microcalorimeter. Collaboration between Goddard and the University of Wisconsin

Spectrum of Diffuse X-Ray Background in 5 minutes



McCammon et al. 2002

Constellation X
The Constellation X-ray Mission

Improved Energy Resolution and Uniformity - Astro-E2

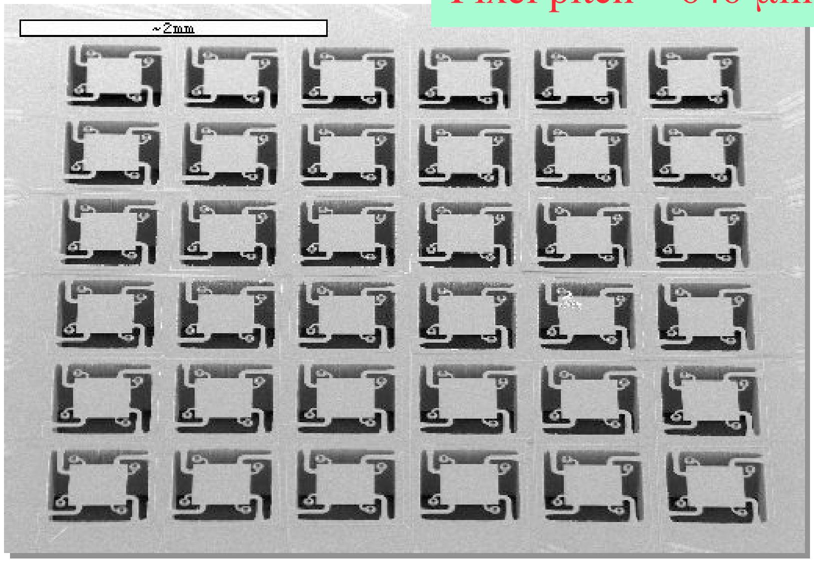
Ion-implanted Si using Silicon-On-Insulator wafers

- Buried oxide layer provides diffusion barrier ⇒ deeper, more uniform implant profiles. No more 1/f noise.

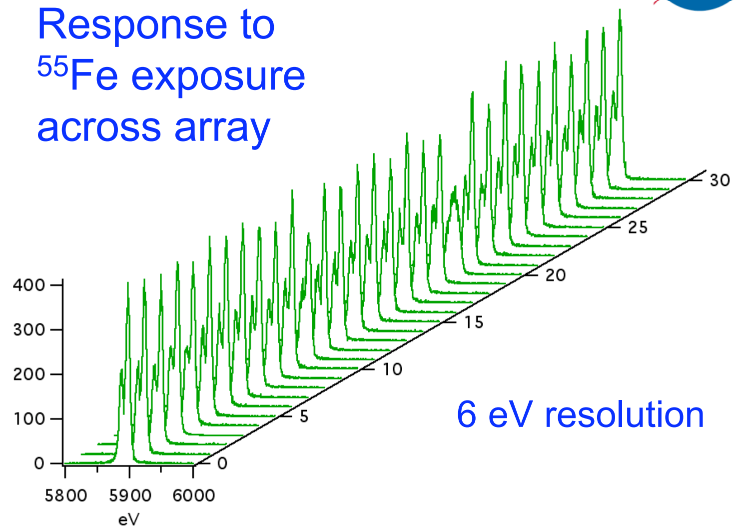
The absorber tabs and polymer "cups" produced very controlled absorber thermal and mechanical attachment.

This led to a much higher degree of energy resolution uniformity and extremely gaussian line spread functions.

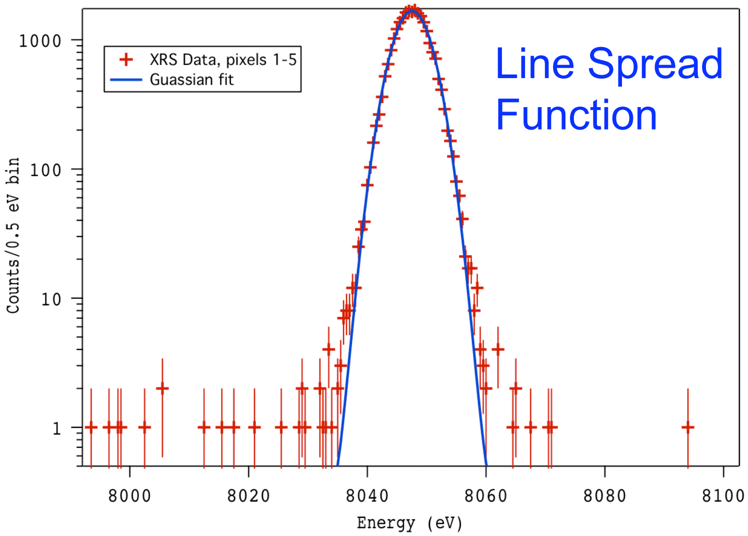
Pixel pitch = 640 μm



Response to ^{55}Fe exposure across array



6 eV resolution



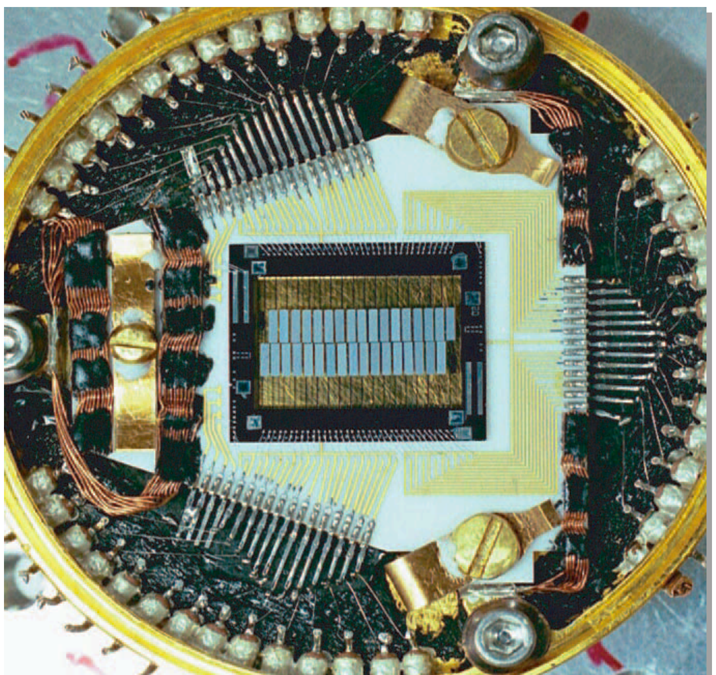
Line Spread Function

X-Ray Microcalorimeter for Sub-orbital Science

First Generation Microcalorimeter Array:

± Designed for study of the diffuse X-ray background below ~ 1 keV

± Pixels are 0.5 x 2 mm



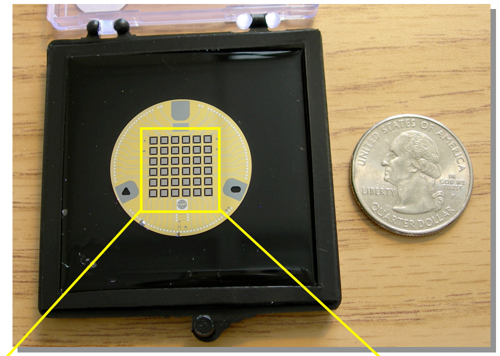
GSFC

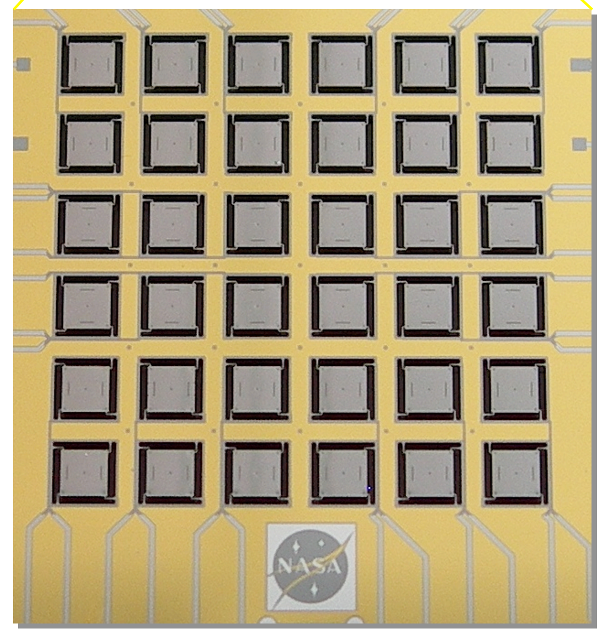
New Microcalorimeter array:

± Design uses XRS technology

± 2 x 2 mm pixels

± ~ 6 eV resolution, but has 4 times the A-Ω





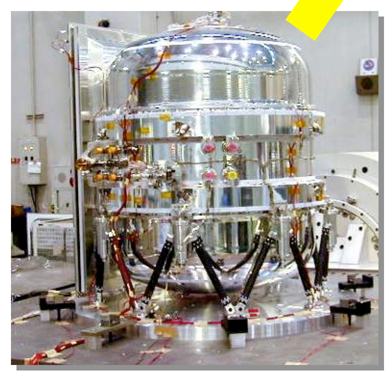
Array prior to attaching absorbers

Suzaku (Astro-E2)/XRS

New technology demonstrated in space:

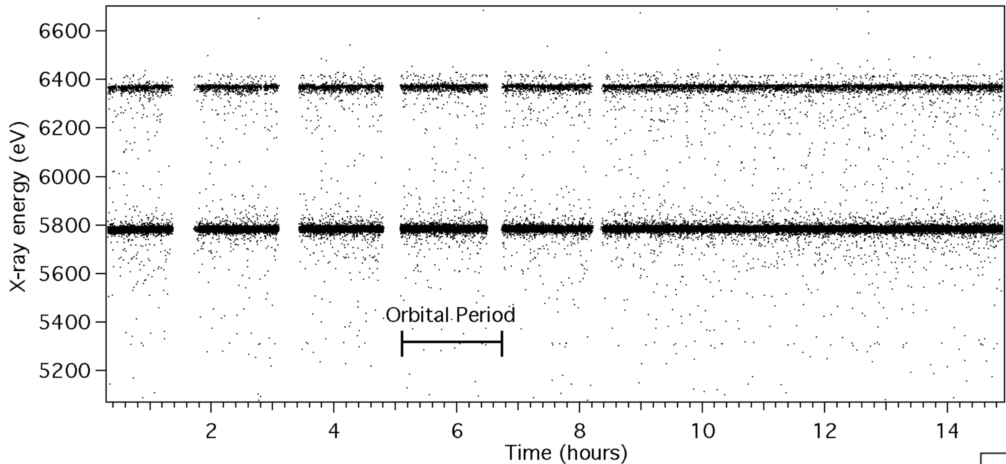
32-channel X-ray microcalorimeter array based on ion-implanted Si with HgTe absorbers.

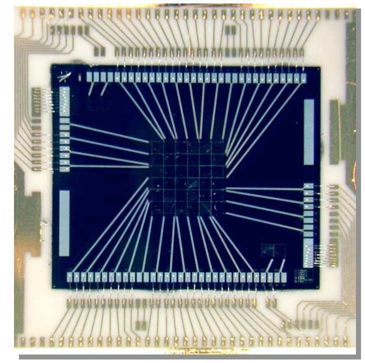
- Energy resolution performance demonstrated (include. DSP electronics)
- Low-temperature anticoincidence detector demonstrated
- Low temperature technology (adiabatic magnetic refrigerator) maintains 60 mK and < 10 μK rms for ~ 36 hours/cycle
- Stirling-cycle cooler operates properly

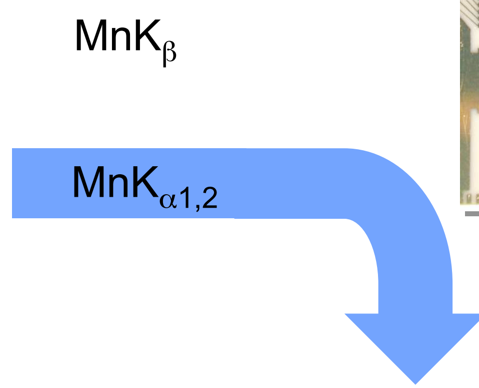


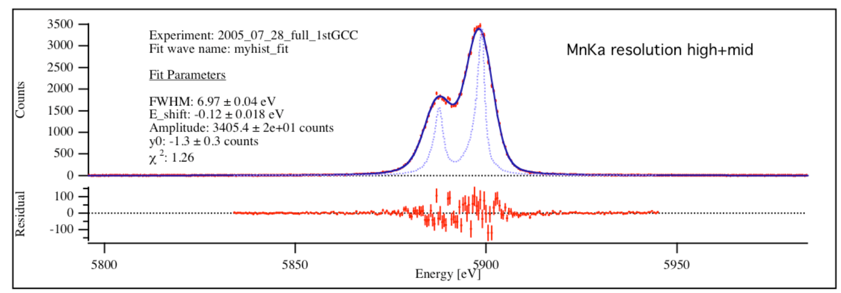
ISAS JAXA Japan Aerospace Exploration Agency NASA

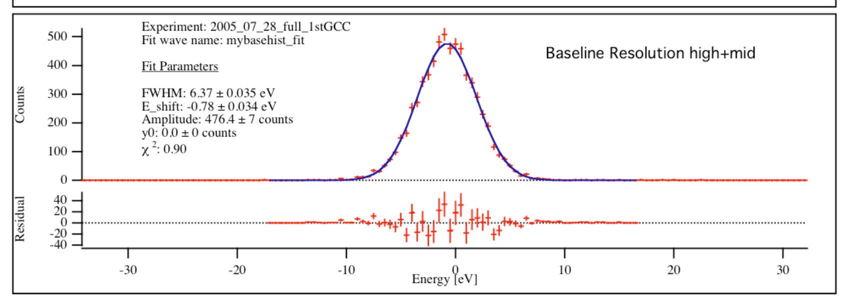
XRS In-flight Performance











Gain is very stable:

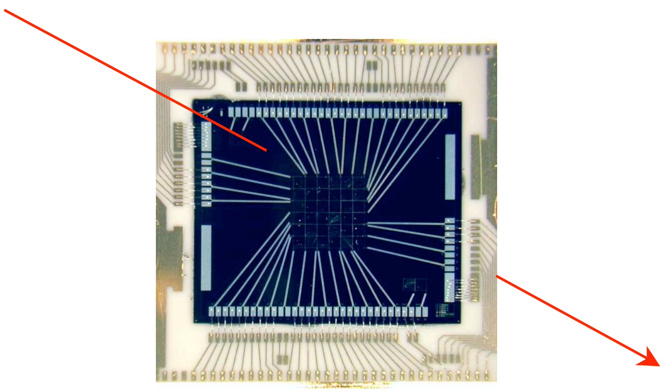
- No heating from SAA passage or day/night effects
- No particle activation
- Energy resolution of 7 eV (FWHM).

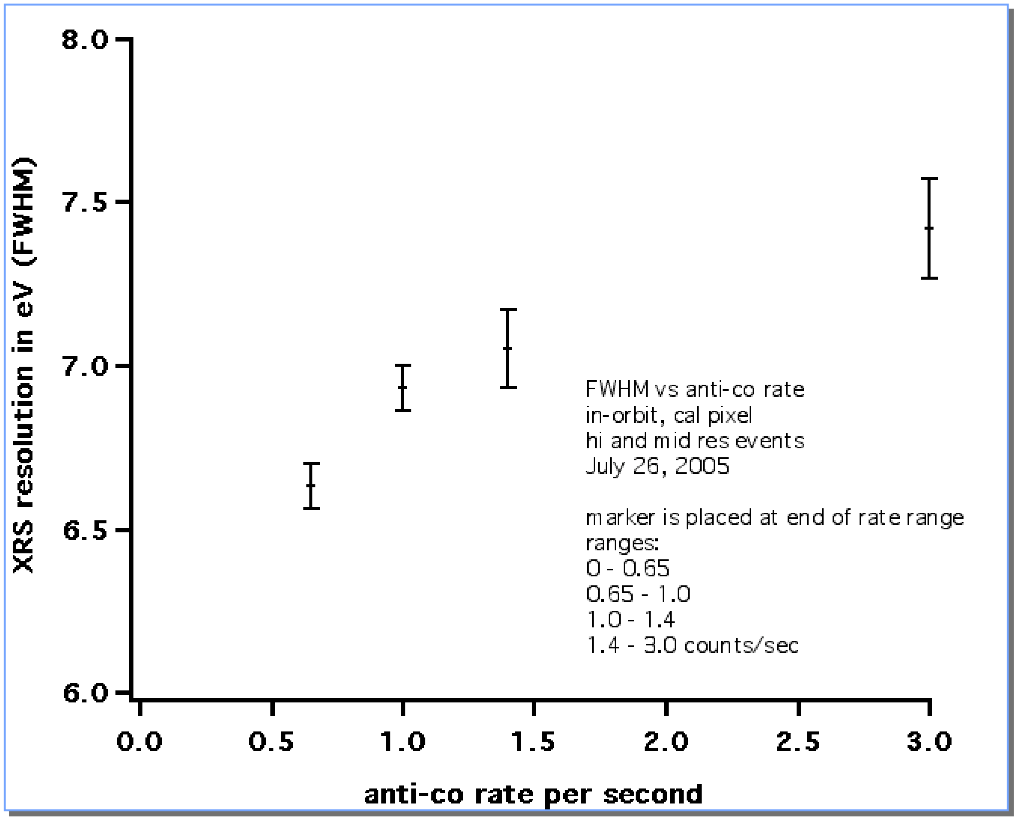
Other pixels give same performance using Filter Wheel cal source.

Energy Resolution vs. Anti-coincidence Rate

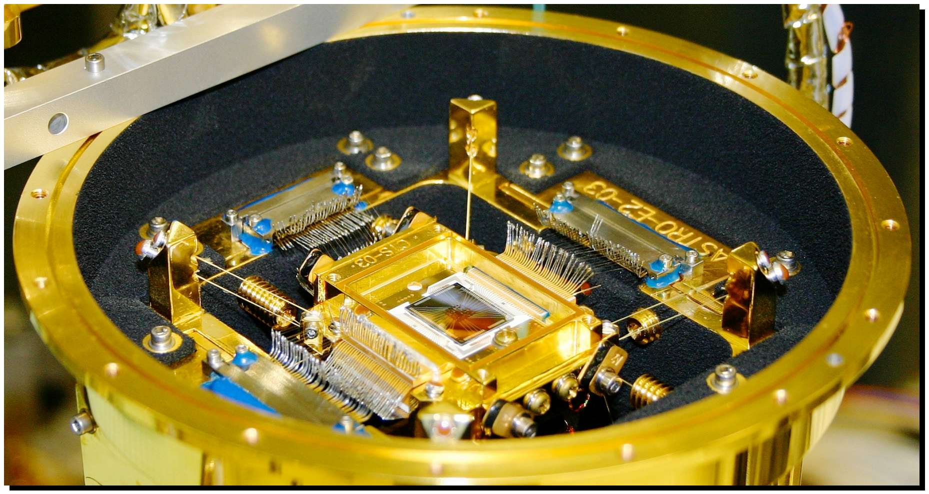
Extrapolated energy resolution at ~ 0 BG rate is consistent with pre-launch calibrations.

Correlation with Anti-co rate is likely due to sub-trigger pulses induced by cosmic rays as they pass through the frame of the array.

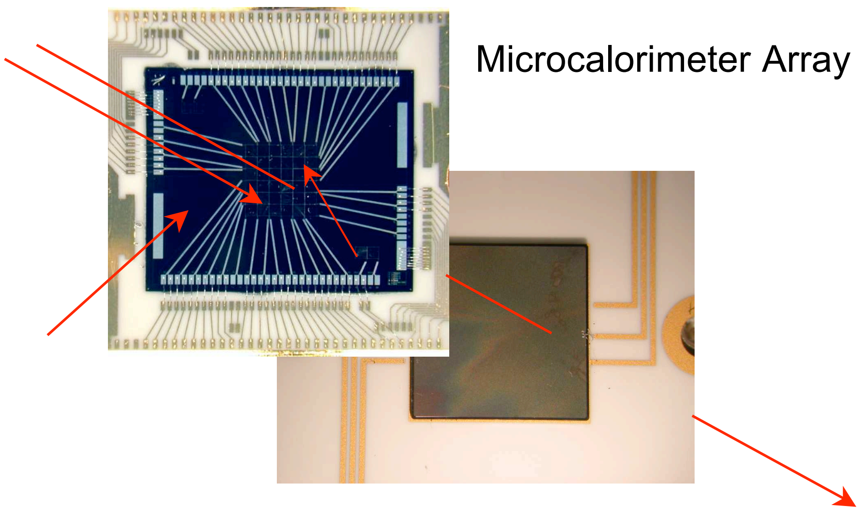




XRS In-flight Background



- Primary cosmic rays
- Secondary particles produced by cosmic rays interacting in the surrounding structure
- Events produced from direct interaction and with the inert frame around the sensors
- Escape electrons within array



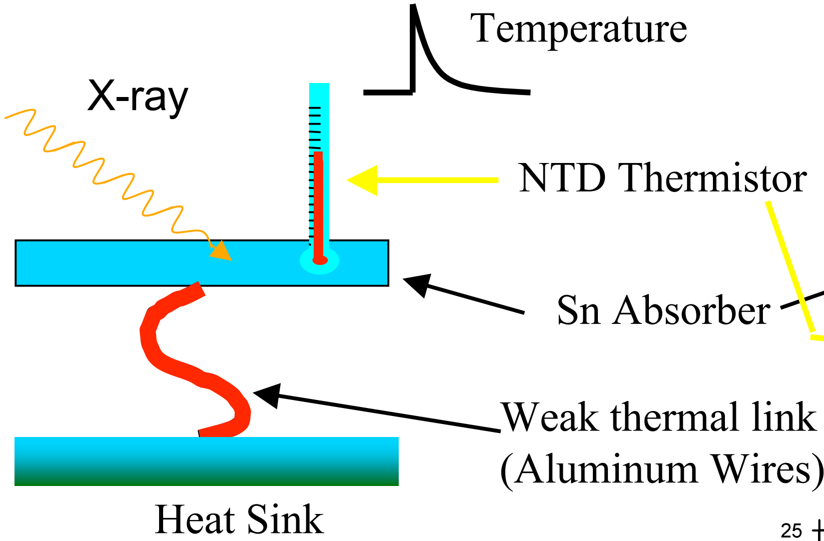
Microcalorimeter Array

Antocoincidence Detector

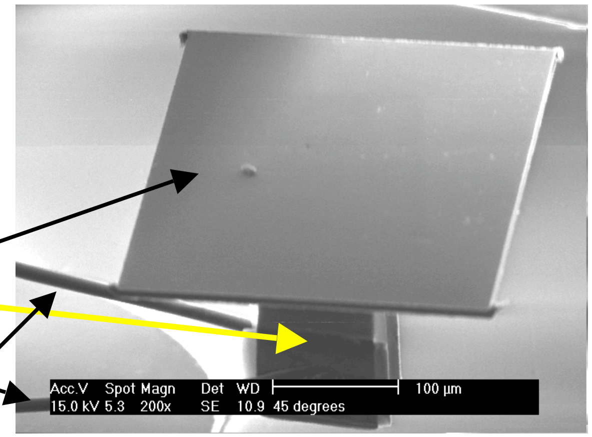
Using anticoincidence detector combined with multi-pixel frame events, and accepting only coefficient of magnetic rigidity cut-off > 6 GeV/c, residual *in-flight* BG is:

2.7×10^{-3} cps/cm^2/keV (100 eV - 12 keV)

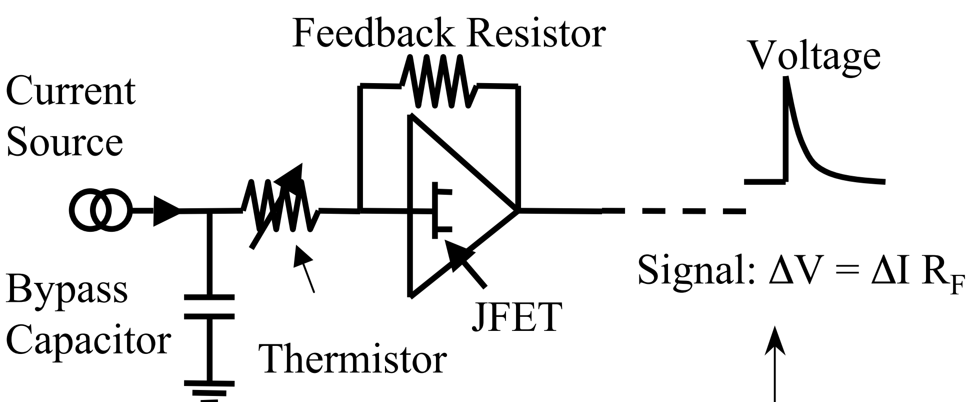
NTD-Ge Microcalorimeter Technology



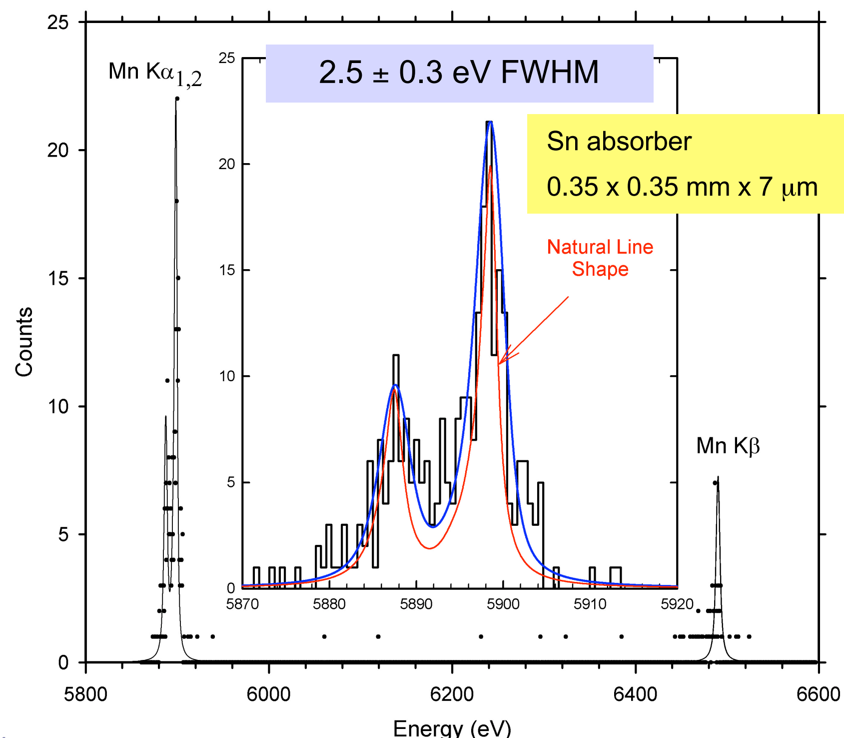
SEM micrograph of single pixel NTD-Ge microcalorimeter with Sn absorber



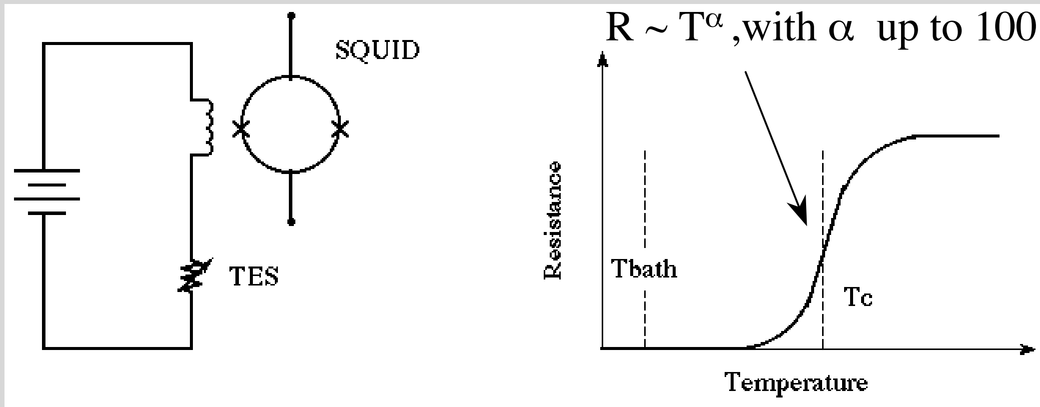
SAO



V constant, ΔR → $\Delta I = -\frac{V}{R^2}\frac{dR}{dT}\Delta T$



Superconducting Transition Edge Thermometer



$$P = \frac{V^2}{R}$$

$$\frac{dP}{dT} = -\frac{V^2}{R^2}\frac{dR}{dT} \Rightarrow \text{stable}$$

Extreme Electro-thermal Feedback
(Irwin, App. Phys. Lett., 1995)

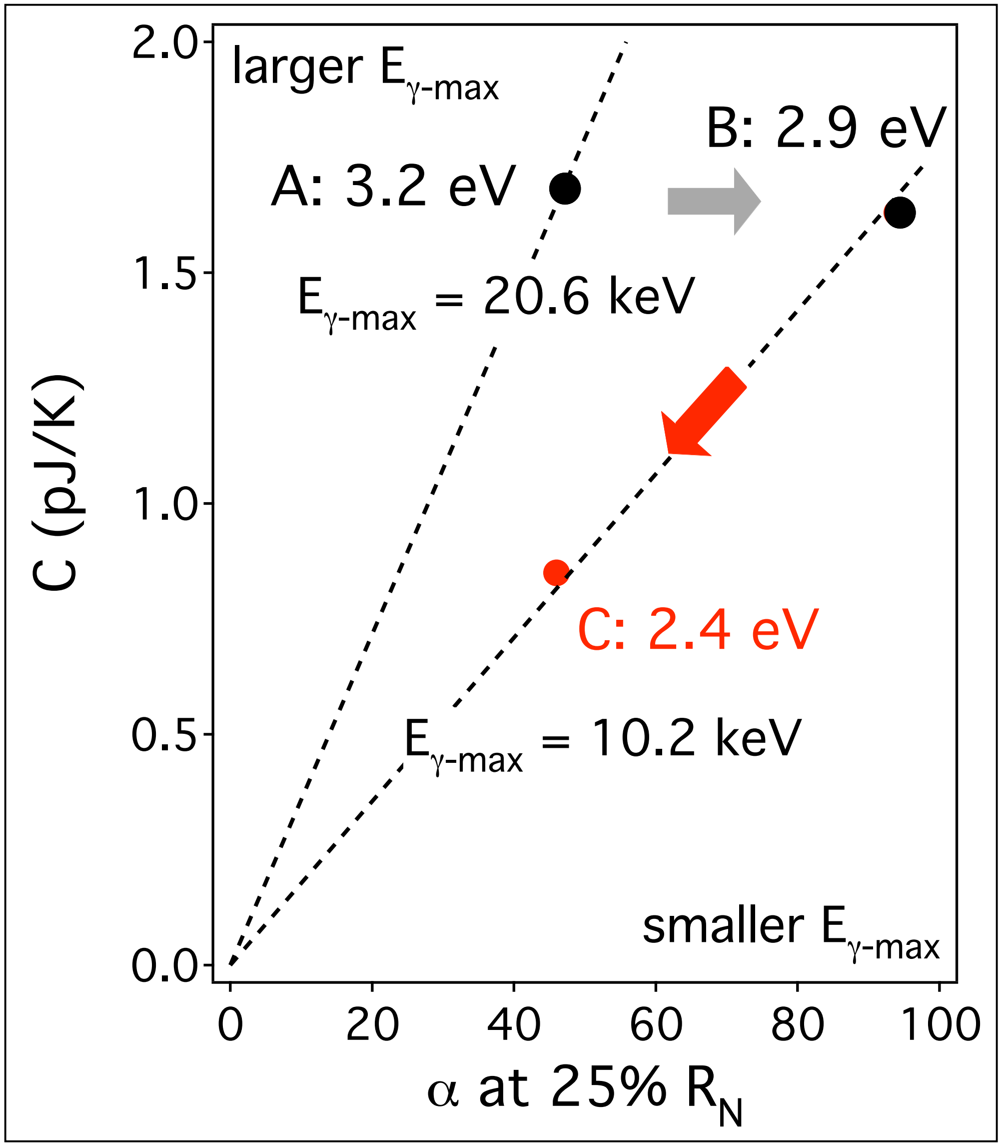
$$\Delta E = 2.35\xi\sqrt{kT^2C} \quad \text{where} \quad \xi \cong 2.4/\sqrt{\alpha}$$

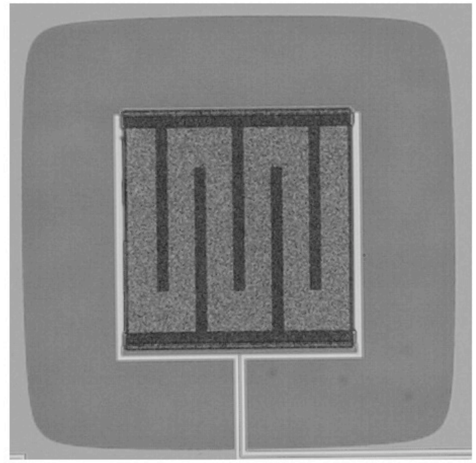
$\Delta E \sim \sqrt{(C/\alpha)} \Rightarrow$ high resolution with higher acceptable heat capacity

$$\tau_{eff} \cong \tau\frac{n}{\alpha} \quad where \quad \tau = \frac{C}{G}$$

$\Rightarrow$ potentially much faster pulse response.

TES Optimization for High Spectral Resolution





400 μm

$\alpha = 45$

C = 0.9 pJ/K

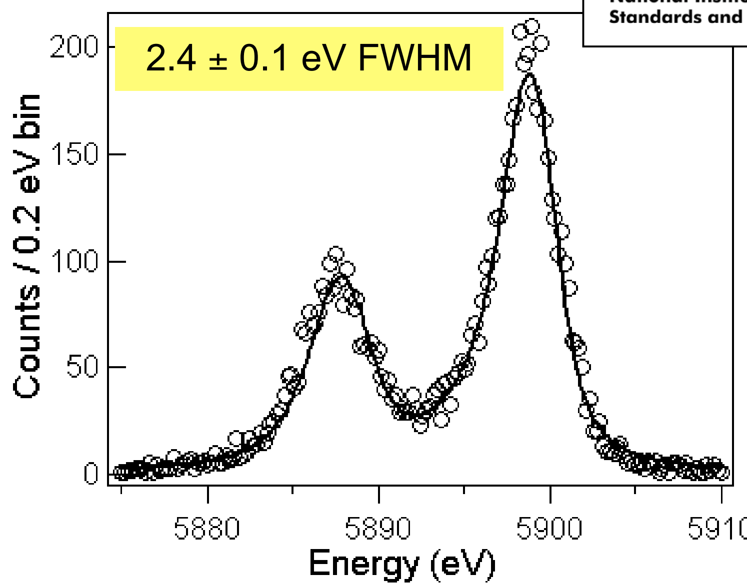
M = 1.2-1.4

Excess noise factor

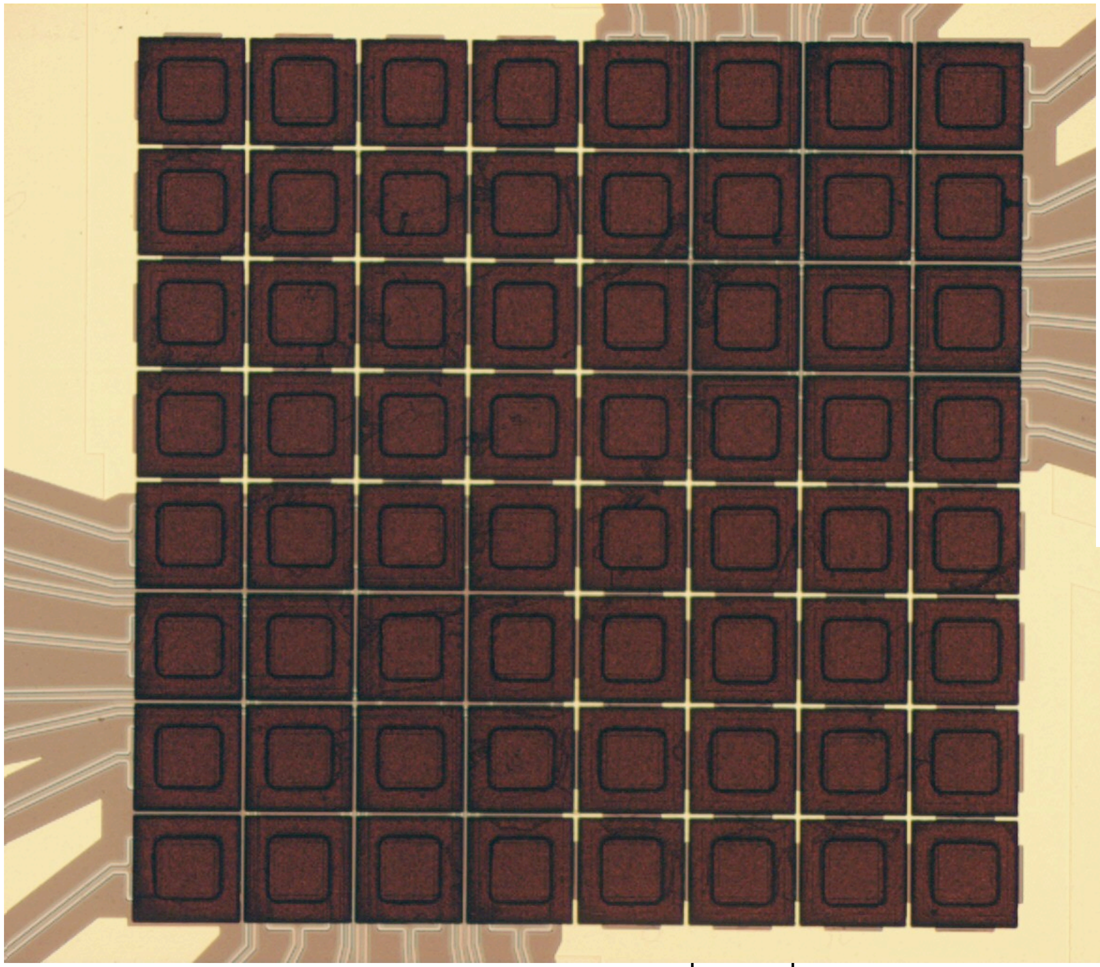
1.5 μm Bi

261 μs

National Institute of Standards and Technology



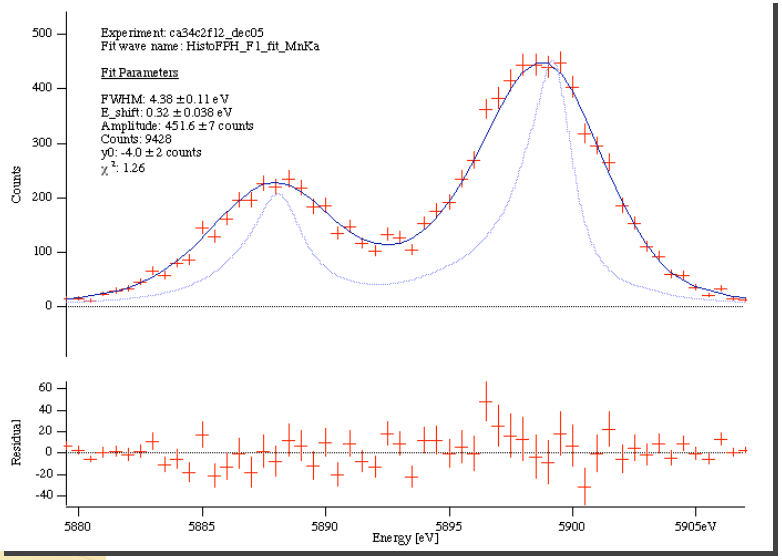
High-density arrays

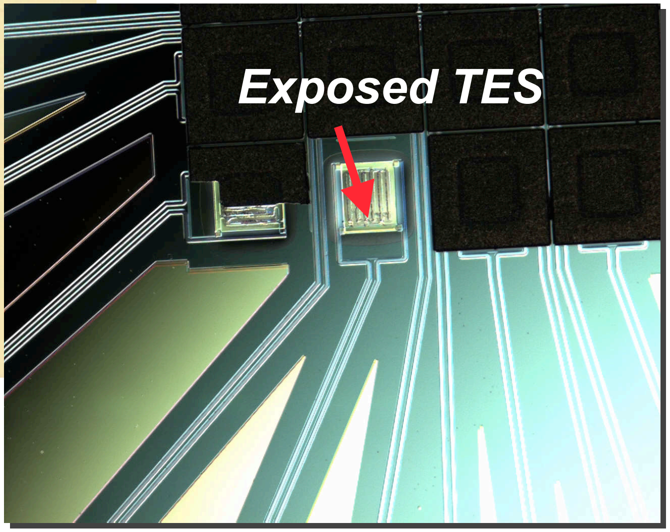


Array with Bi/Cu absorbers
DRIE process

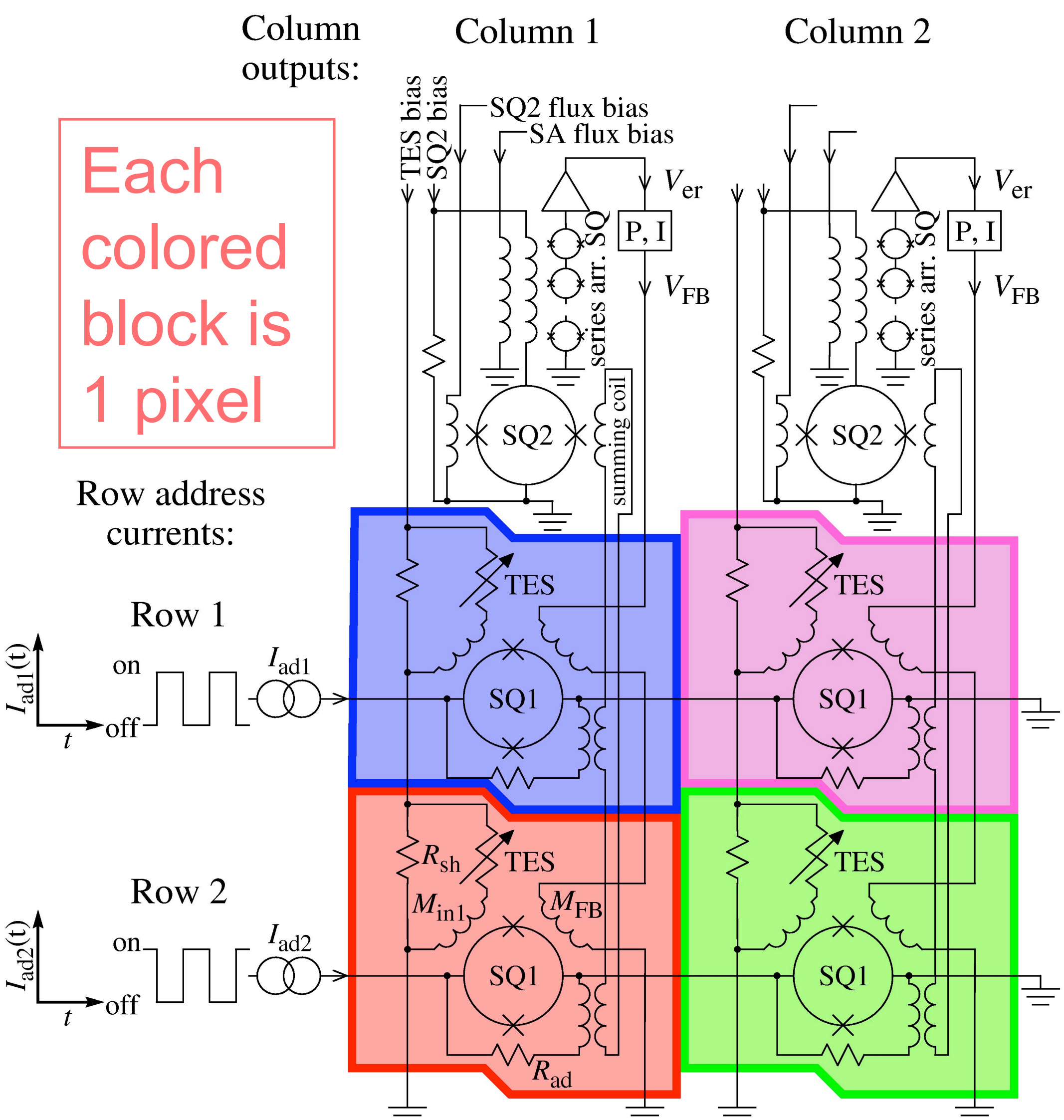
0.25 mm

4.4 eV ± 0.1 eV FWHM





Read-out concept – Multiplexed SQUID* current amplifiers

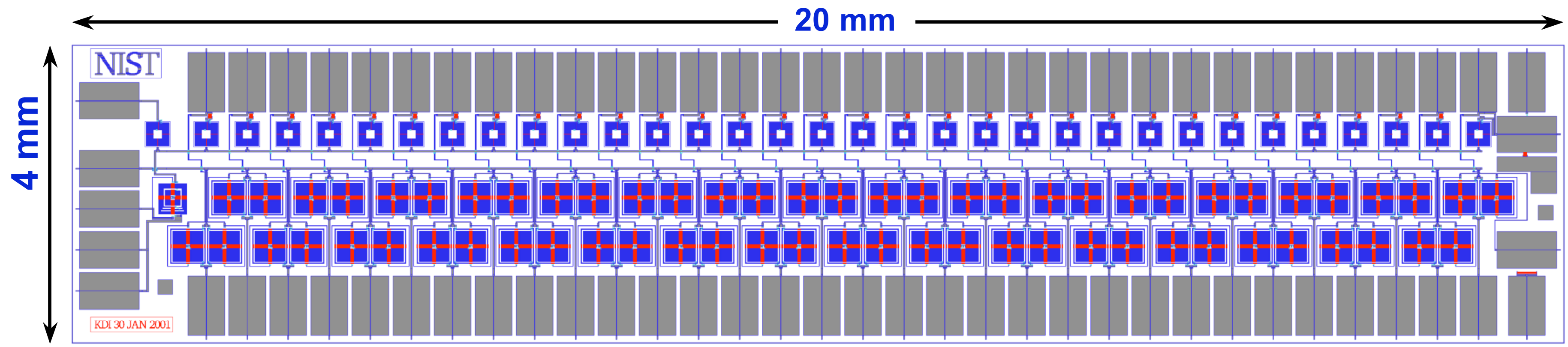


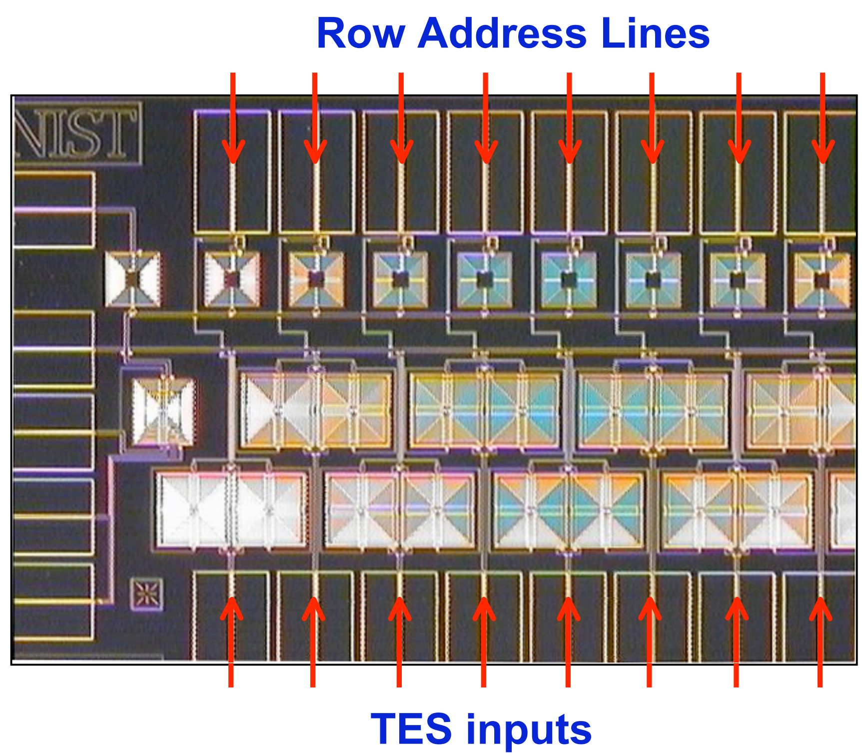
- 2 x 2 array is shown as example of *N*-row by *M*-column array
- operation:
  - each TES coupled to its own low-power input SQUID operated at 50 mK
  - TESs stay on all the time
  - rows of input SQUIDs turned on and off sequentially
  - wait for transients to settle, sample TES signal, move on
  - SQUIDs are nonlinear amplifiers, so use digital feedback to linearize
  - Error signal sampled and required feedback voltage stored for next visit to that pixel
  - Output from each column: interleaved data stream of pixels that is passed to processors that perform demultiplexing, triggering, and processing functions
- Large scale multiplexing minimizes the number of wires and the heat loads at the cold stages

NIST
National Institute of Standards and Technology

**superconducting quantum interference device*

Multiplexed SQUID Readout — Implementation

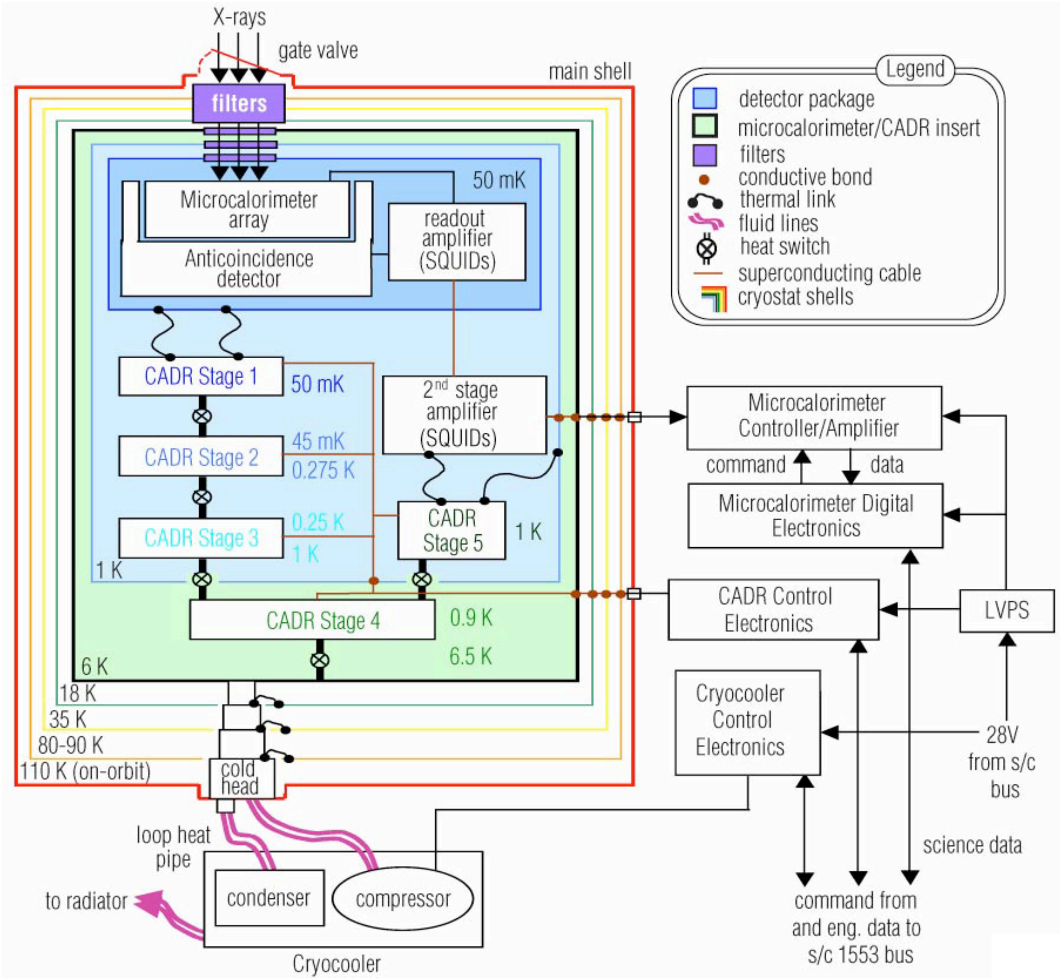


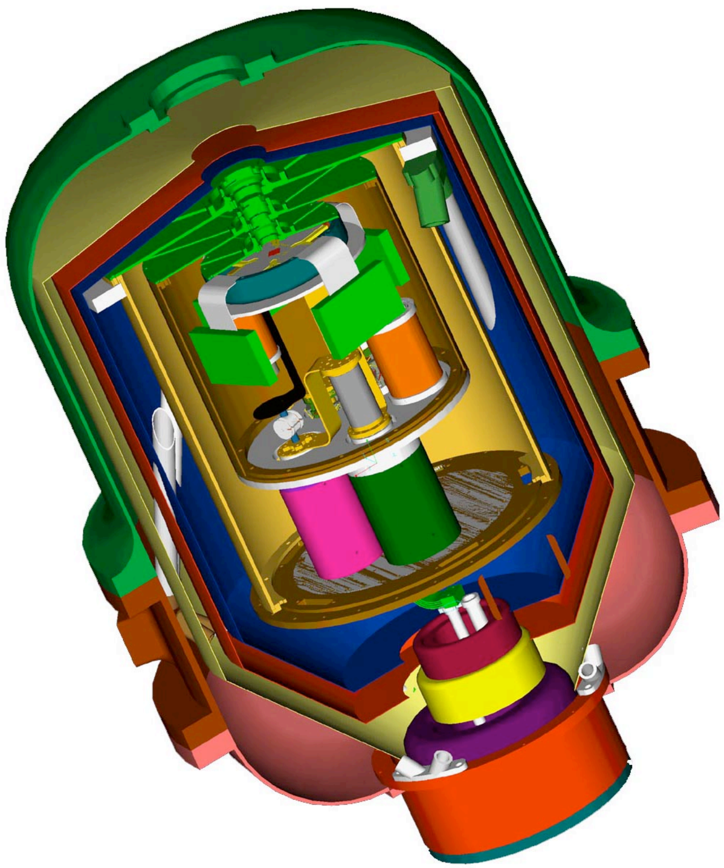


- 1 x 32 input SQUIDs per chip
- One column of 32 x 32 array
- Dissipated Power ≈ 4 nW
- Less than 1 μW for 32x32 array

NIST
National Institute of Standards and Technology

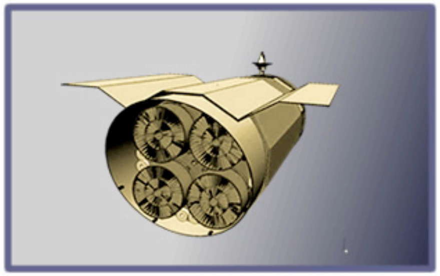
Instrument Block Diagram and Conceptual Implementation for TES X-Ray Microcalorimeter Spectrometer (XMS)

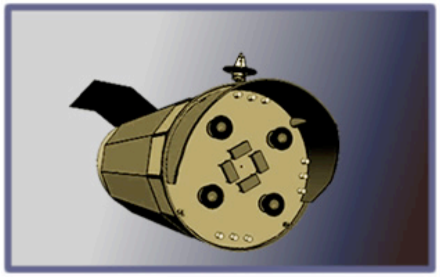


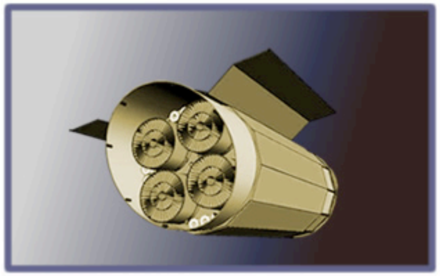


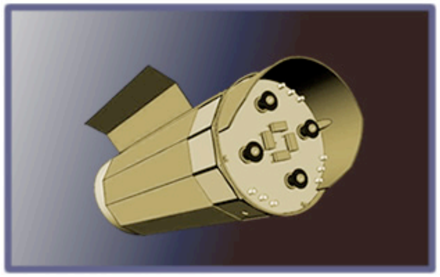
Size ~ 50 x 75 cm
Mass ~ 150 kg, including electronics

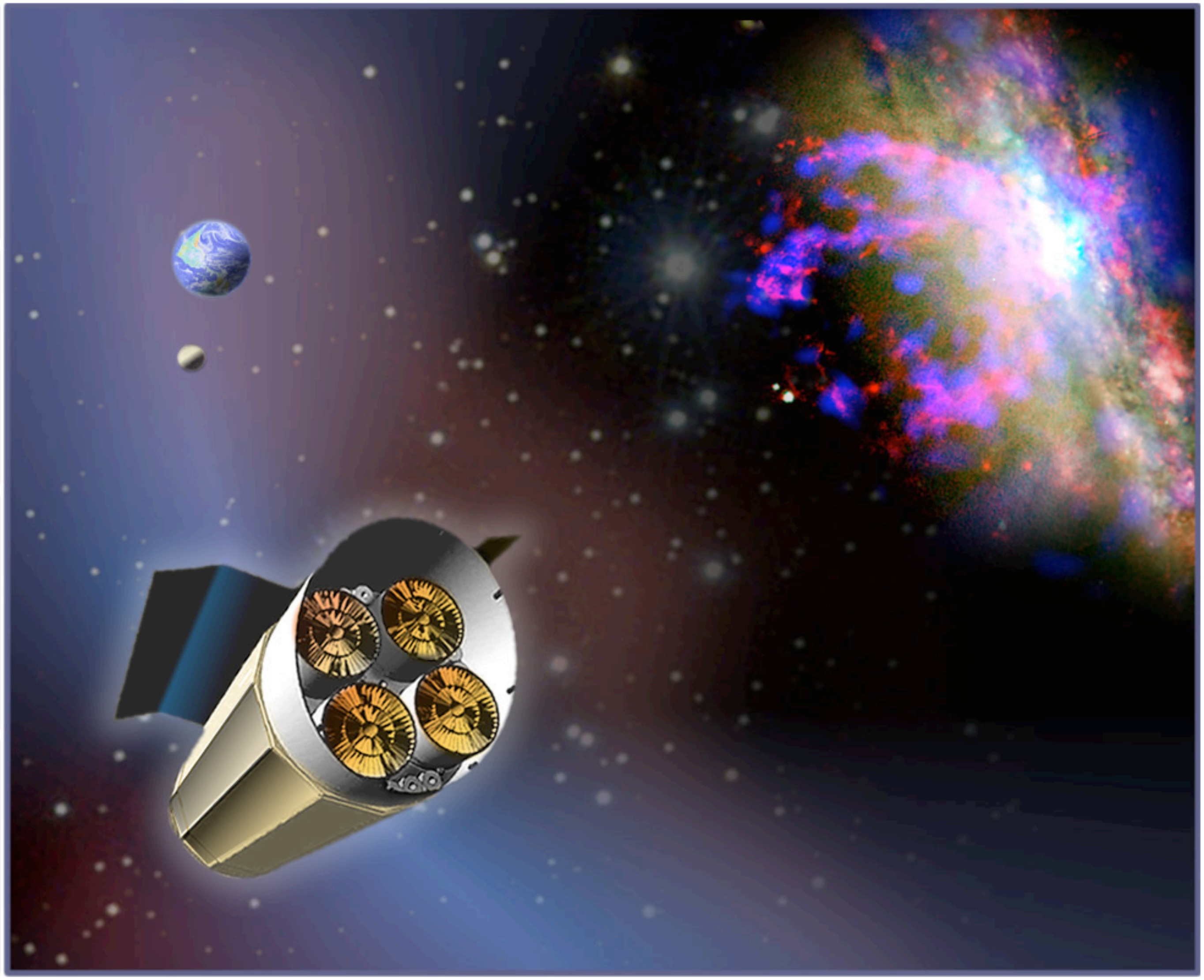
Four XMS Modules



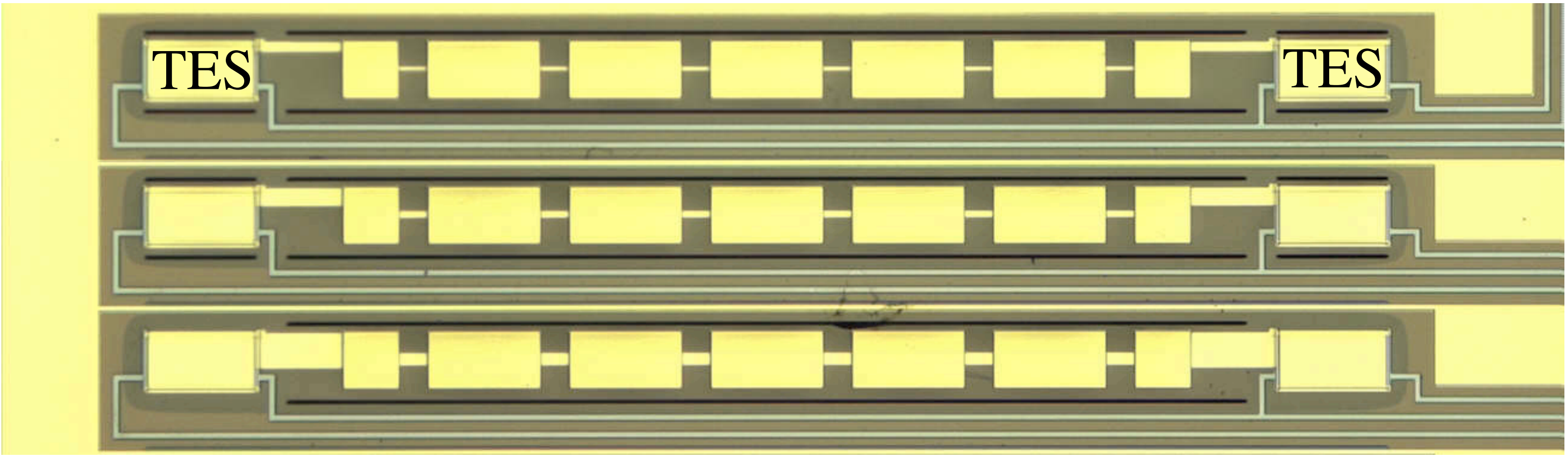


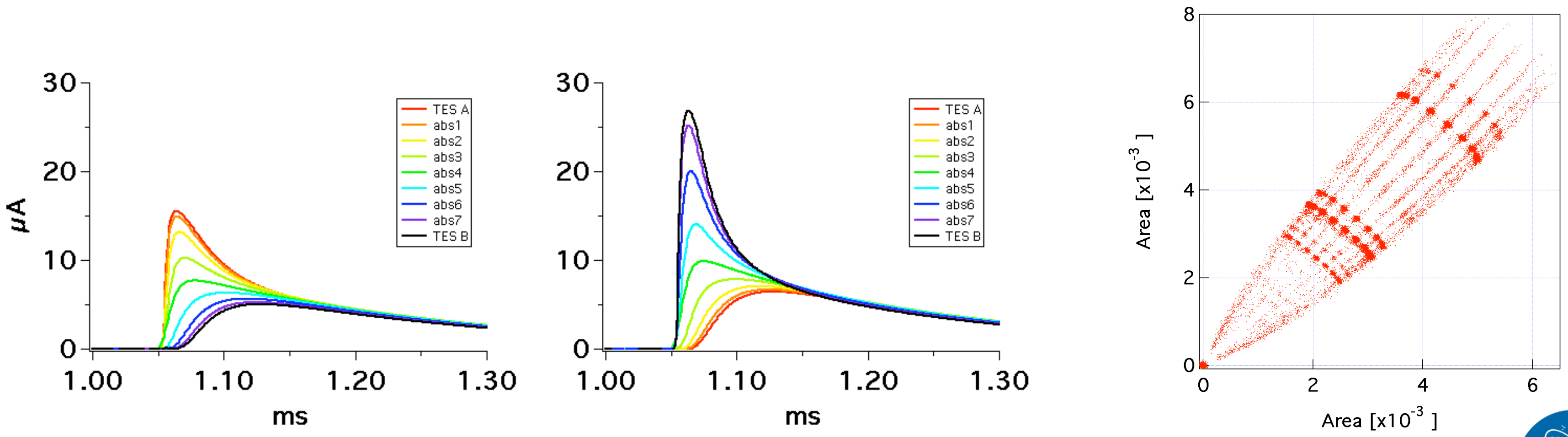






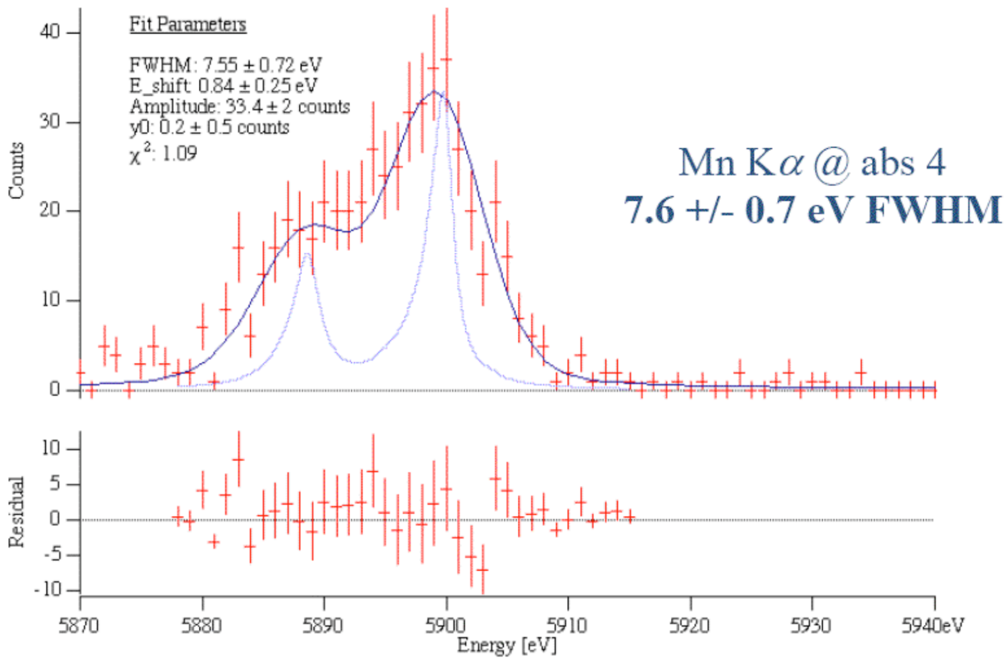
Extended FOV - Position-Sensitive TES ("PoST")

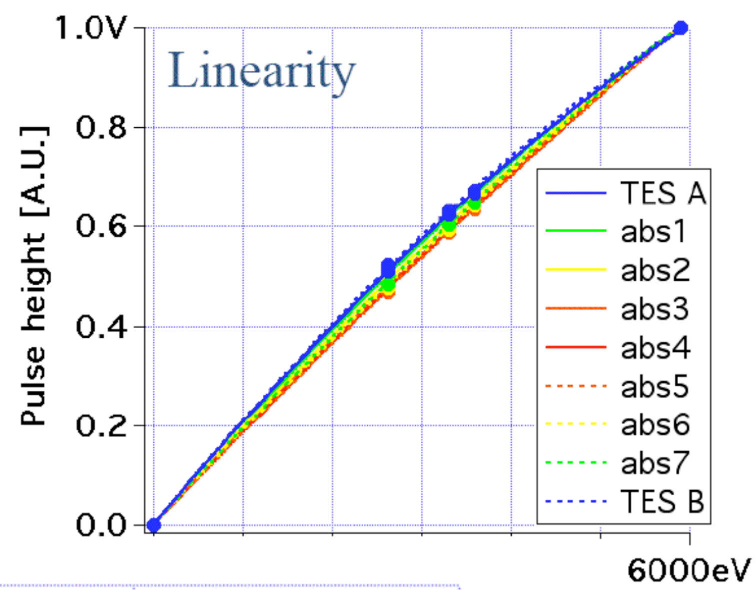


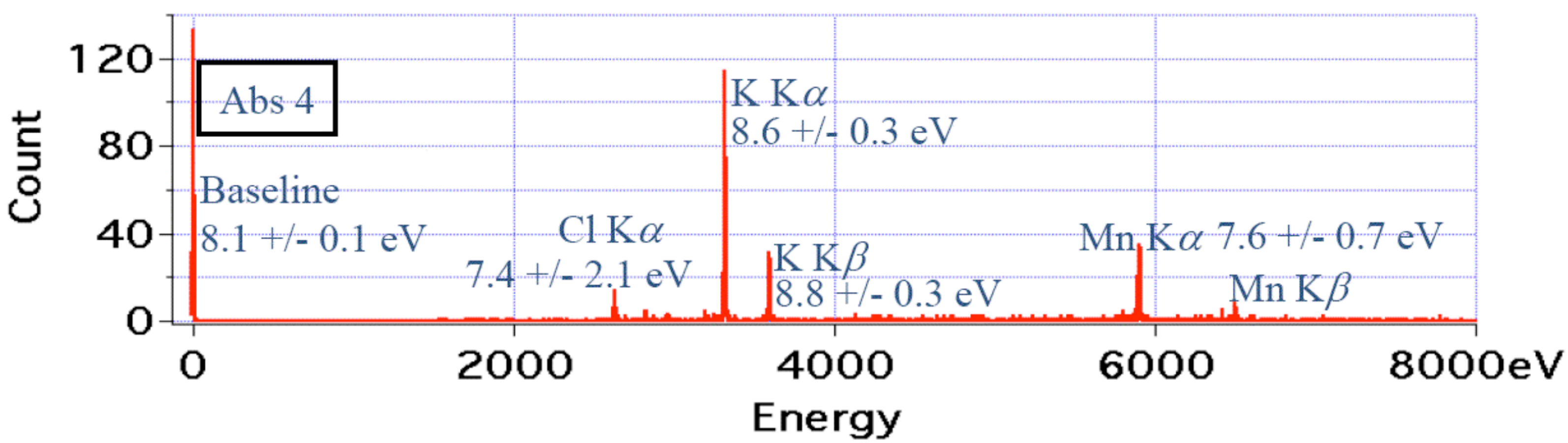


Thermal diffusion gives rise to different pulse responses and hence position; summing signals gives x-ray energy. "PoST" provides path to larger fields of view without significantly increasing electronics.

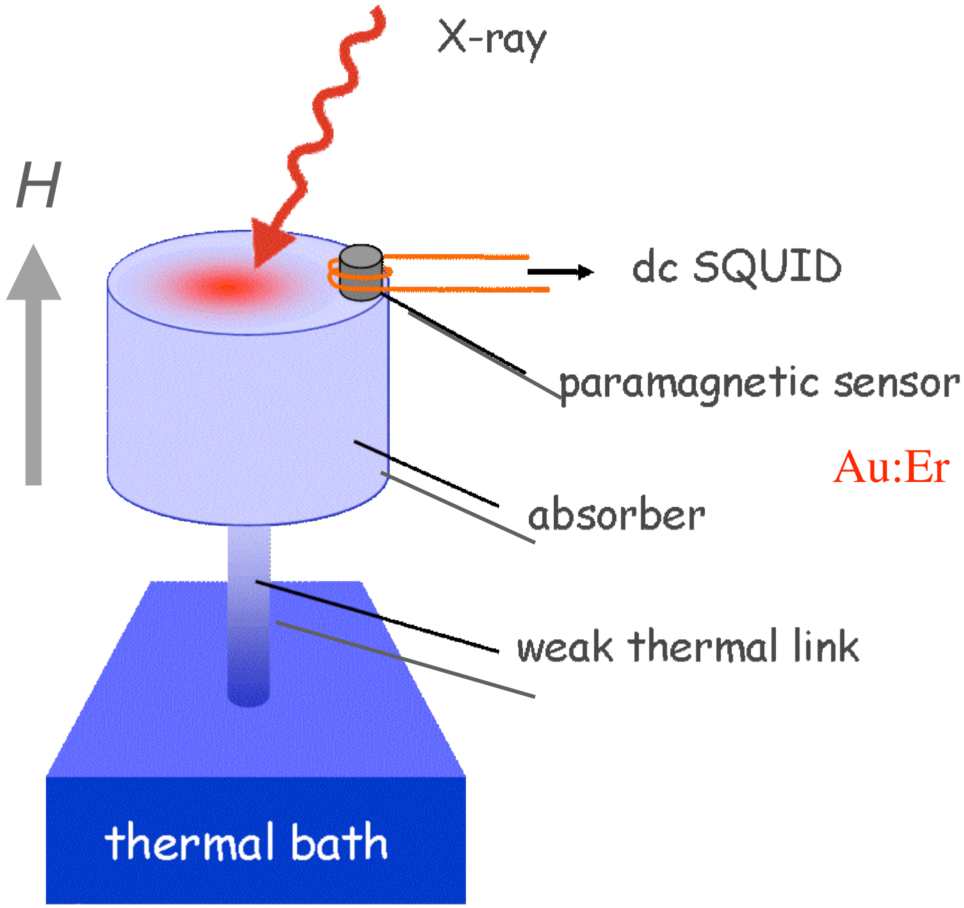
Best PoST Resolution so far:



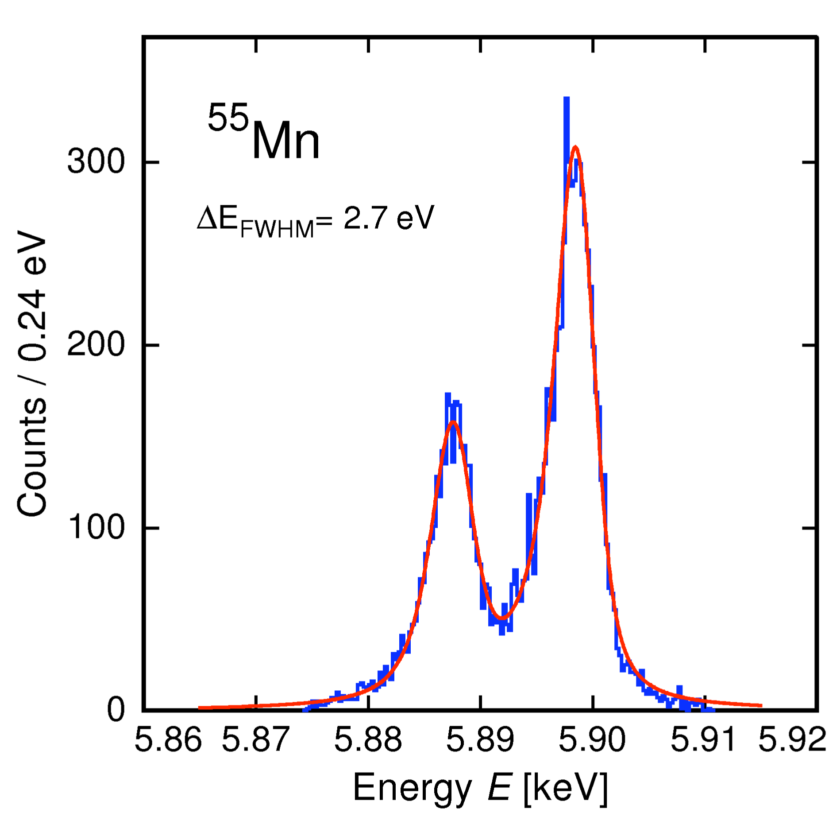




Metallic Magnetic Calorimeter



Heidelberg Group
A. Fleischmann et al. 2006



Magnetic Calorimeters - Large Investigation Team

Magnetic calorimeters are currently *not* being funded by Con-X project, but have demonstrated great potential:

- High spectral resolution
- Amenable to large array fabrication
- Uses SQUID technology being developed for TES arrays

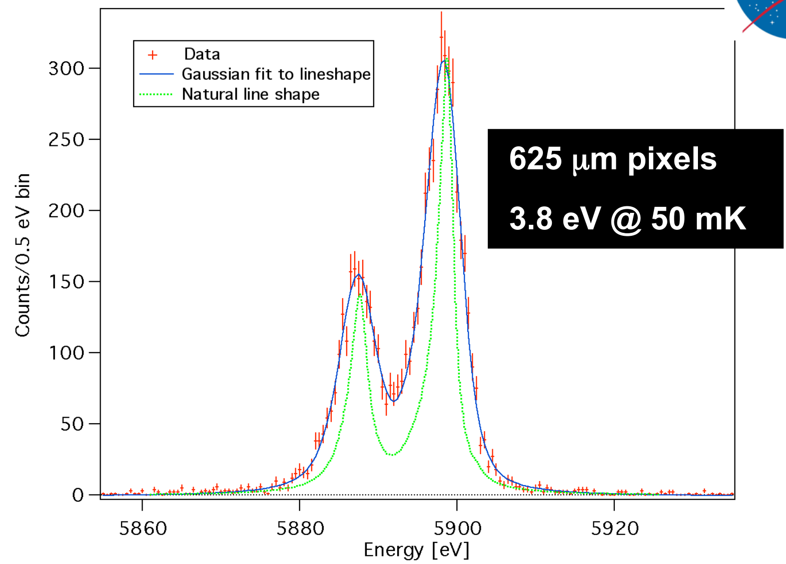
Large “consortium” at work:

Brown University
University of Heidelberg, Germany
IPHT, Jena, Germany
PTB, Berlin, Germany
SAO
Goddard
NIST

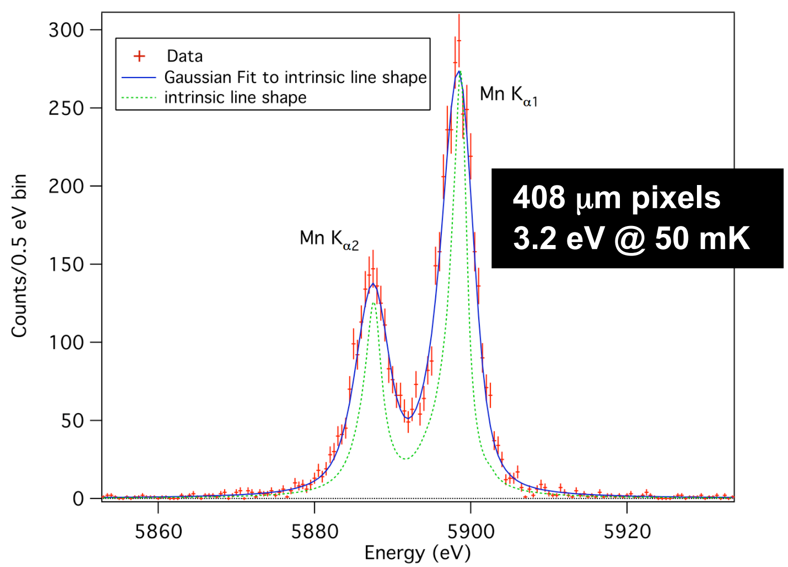
State of the art for ion-implanted Si w/HgTe absorber

¬ Lower temperature ⇒ e.g., 50 mK

¬ Lower heat capacity ⇒ smaller absorbers



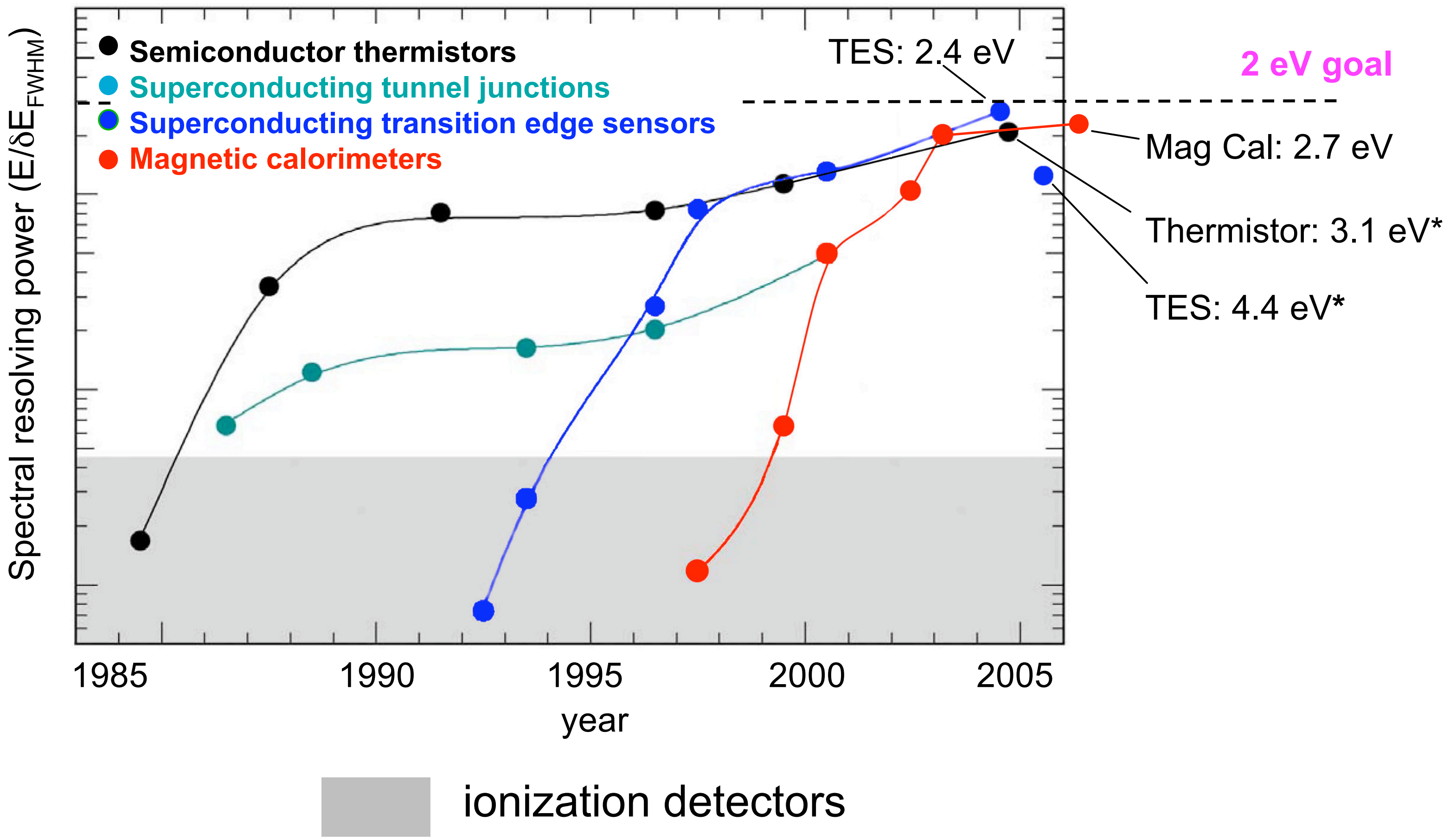
Obtained **3.8 eV FWHM at 6 keV** with XRS-sized pixels operated at 50 mK (625 μm x 625 μm x 8.8 μm HgTe absorber.)



Obtained **3.2 eV FWHM at 6 keV** at 50 mK with 408 μm x 408 μm x 8.8 μm HgTe absorber.

Modeling predicts 2.5 eV; appear to be limited by thermal fluctuations of x-rays absorbed in array frame.

$E/\delta E$ at 6 keV



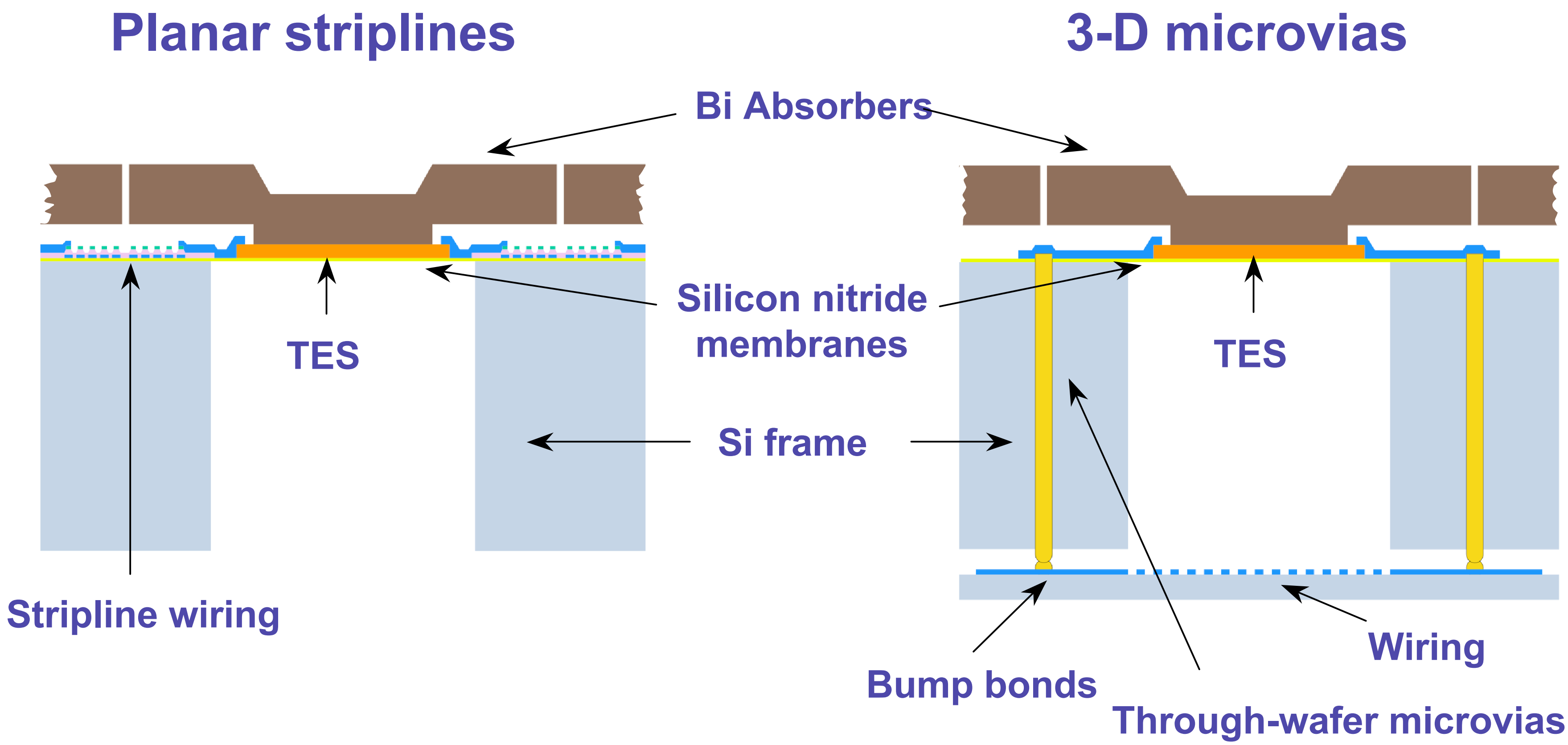
* Meet Con-X requirements for quantum efficiency

Constellation X
The Constellation X-ray Mission

Array and System Issues

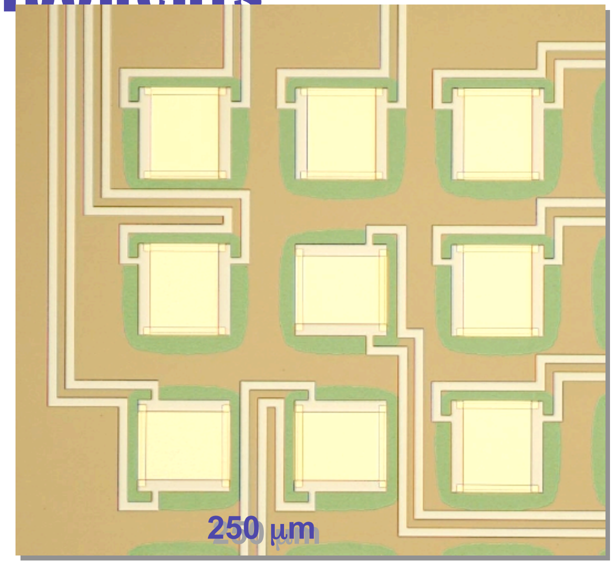
- Achieving large-scale energy resolution uniformity
- Achieving high fabrication yield
- Good mechanical characteristics for handling, thermal cycling and launch
- Heat sinking of array
  - Immunity from cosmic ray heating
  - Minimal effects from bias power with large number of pixels
- Signal leads: large number of pixels ⇒ high density interconnects
- Cross talk (electrical and thermal)
- Radiation hardness
- Minimal dewar heat loads
- Readout system robustness
- Room-temperature electronics design

High Density Interconnects for 32x32 Arrays

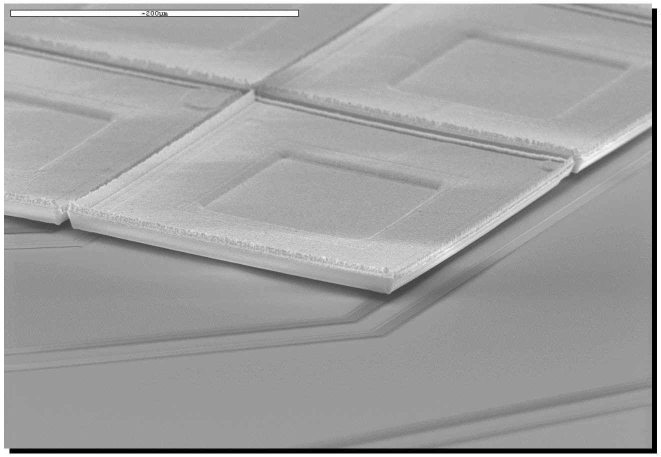


(Not to scale)

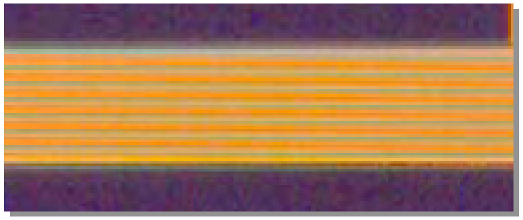
Array Components



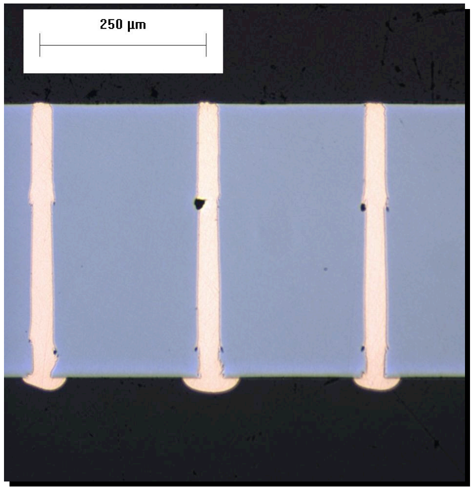
Array of identical TES sensors shown without absorbers



Integral, overhanging Bi absorbers

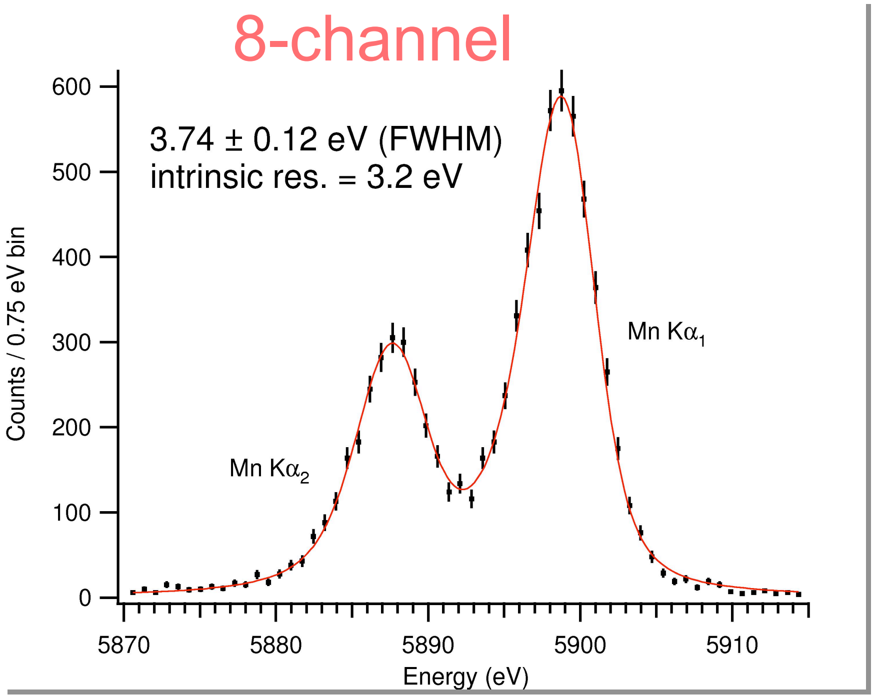


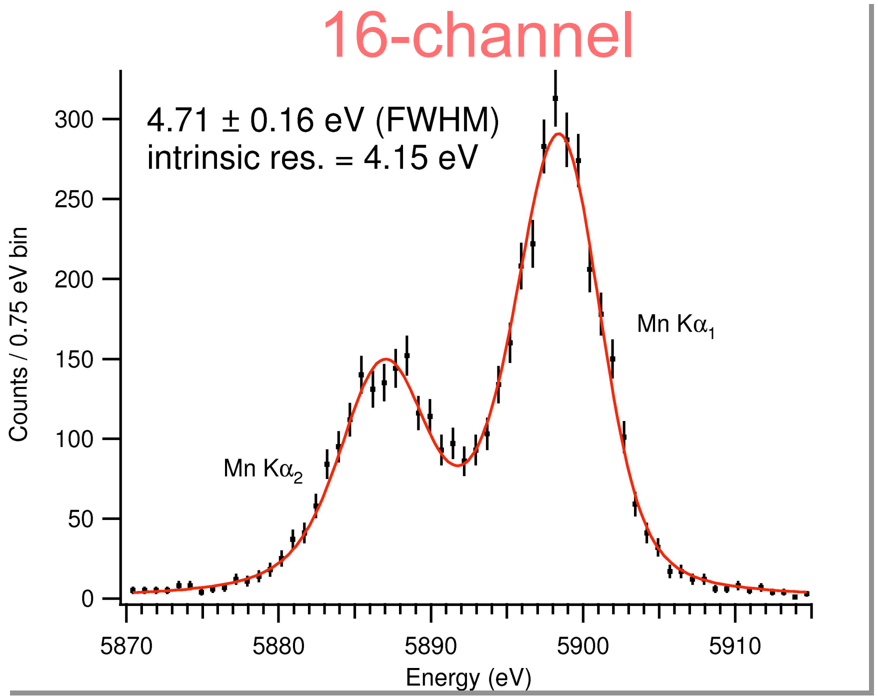
Array of 15 fine-line stripline pairs



Cu micro-vias in Si (25 x 425 microns)

SQUID multiplexing



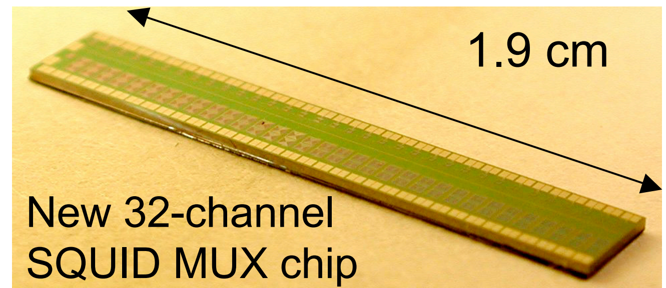


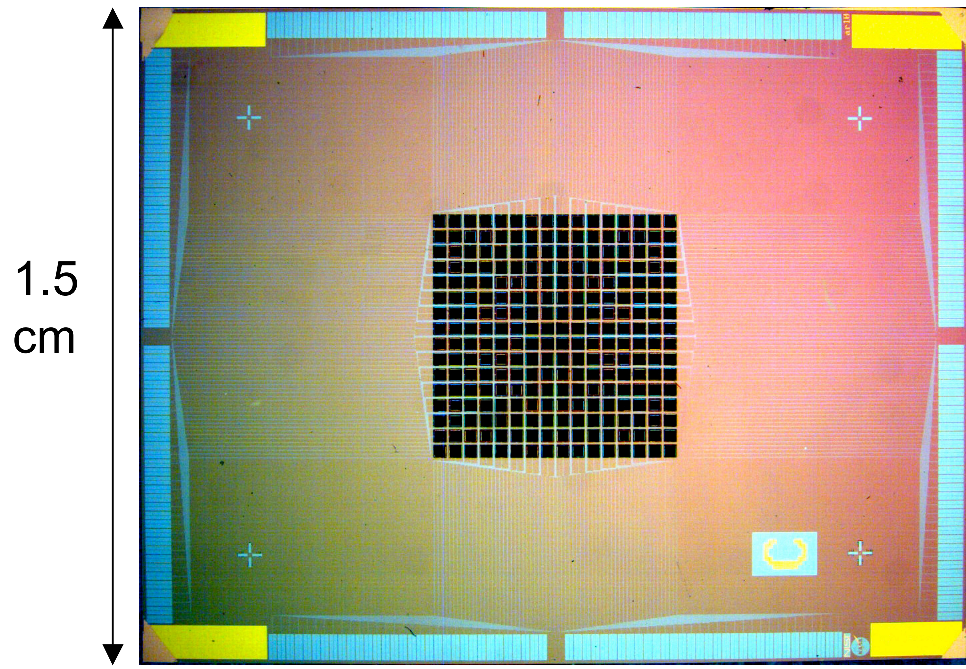
- **each plot contains data for 1 detector**
- **only 4 wired TESs, so rows are cycled more often than feedback**
- **(true test of multiplexer without 8 or 16 detectors)**
- **Coupling to input SQUID *NOT* optimized (thus nonlinearity dominates degradation)**
- **Only cuts are for pulse pileup**
- **Degradation understood in terms of model**
- **Improvements needed to MUX 32 channels at the Con-X specifications are understood**

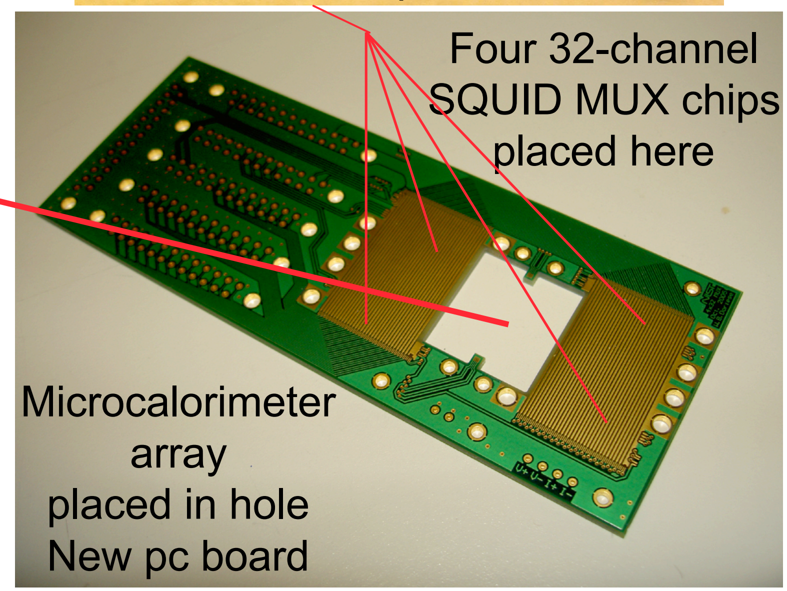
NIST
National Institute of Standards and Technology

The next step in scaling: 4 × 32

- 16 × 16 calorimeter array (1/4 the size of a Con-X baseline array)
- 4 new 32-channel MUX chips (we will MUX half of the array this time around)
- Room-temperature electronics revision to double the bandwidth
- **We will not yet have the full Con-X performance, but we're closing in on it**







NIST National Institute of Standards and Technology

New 256-pixel calorimeter array

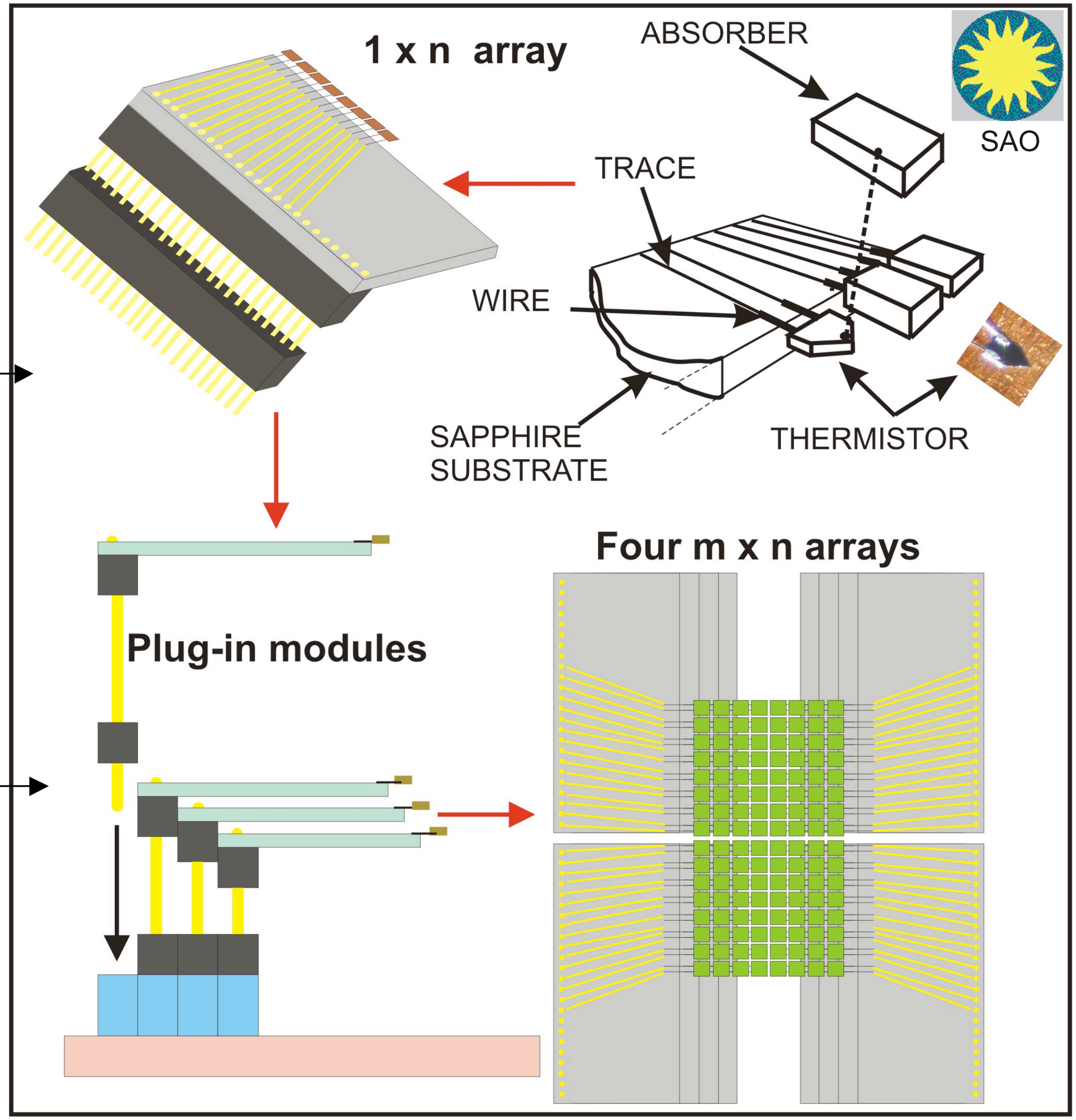
XMS Detector System Technology Roadmap - Major Milestones

Element	State-of-the-Art: XRS	Detector: Current Best	MUX: Current Best	Pre-prototype TRL4	Prototype TRL5	Engineering Test Unit TRL6
Array Size	32	8x8		8 x 8	32 x 32	32 x 32
Simultaneous channels	32	1	8 channels 4 pixels	16	96	1024
Component technologies		TES, superconducting leads, absorbers	TES, superconducting leads, absorbers, MUX	TES, superconducting leads, absorbers, MUX	Pre-PT components + array heatsinking and high density interconnects, detector stage, faster MUX, signal electronics	Integration with ETU ADR, cryocooler and electronics
MUX Scale			1 x 8	2 x 8	3 x 32 goal	32 x 32
MUX Speed (open loop bandwidth)			1.5 MHz	3.5 MHz	12 MHz	12 MHz
Pixel Size	0.64 mm	0.25 mm	0.4 mm	0.25 mm	0.25 mm	0.25 mm
System Noise				< 2 eV	< 1 eV	< 1 eV
Energy Resolution	4.8 eV @ 6 keV, 50 mK (3.8 @ 6 keV with matched load)	4.4 eV @ 6 keV in flight-like, 2.4 eV @ 6 keV in non-flight	3.7 eV @ 6 keV in field-optimized non-flight pixel	4 eV @ 6 keV	4 eV @ 6 keV 2 eV @ 1 keV	4 eV @ 6 keV 2 eV @ 1 keV
Component qualification					Radiation, Vibration	System Qualification
TRL		3.5	3.8	4	5	6

Construction of NTD Ge Microcalorimeter Arrays

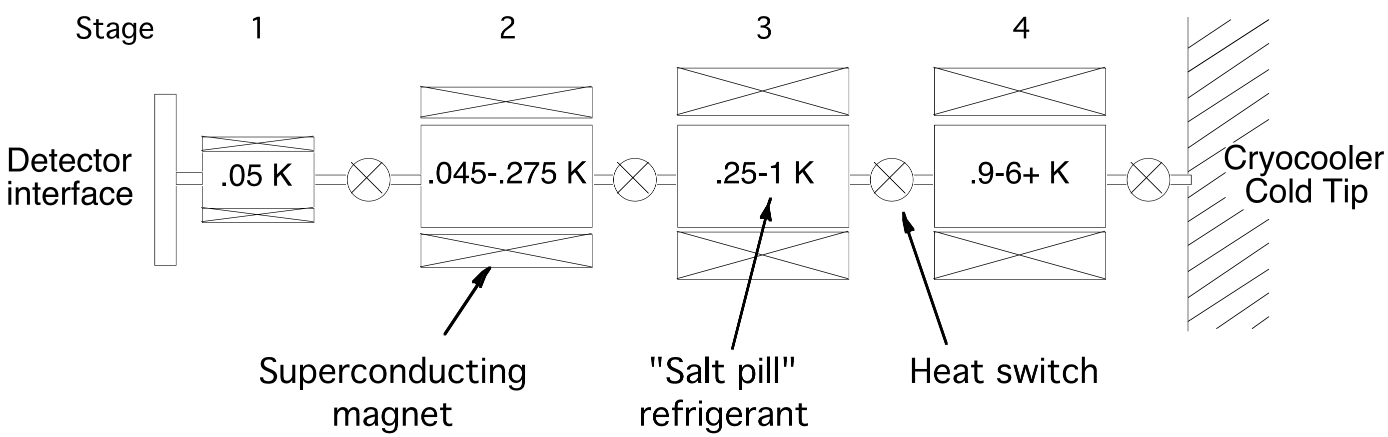
Each linear array module is fitted with a miniature connector attached to the bottom of the sapphire substrate through which the electrical signals are fed .

Each module is inserted into a mating connector mounted into a *quadrant base*. A two-dimensional array can be built up from a series of these stacked linear arrays. constructed in this way also



Continuous Adiabatic Demagnetization Refrigerator (CADR) Concept and Requirements

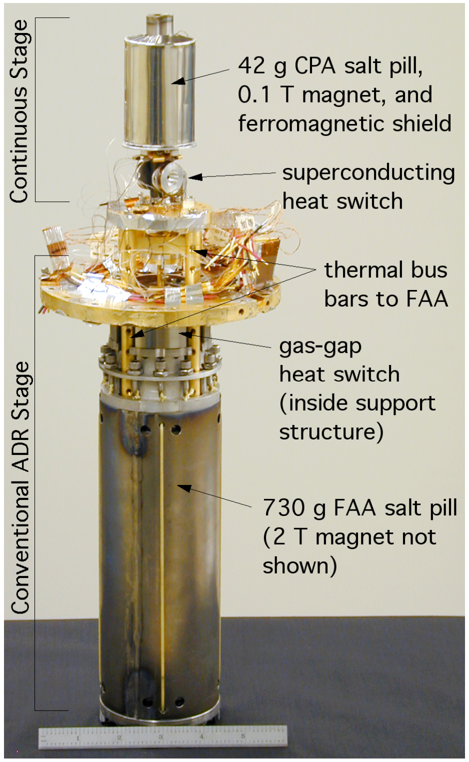
Cooling Stage	Temperature	Cooling Power	Temperature Stability	Heat Rejection Temperature
Detectors, 1st stage SQUIDs	50 mK	5 μW	2 μK rms	6 K
2nd stage SQUIDs	1 K (TBR)	230 μW	TBD	



- Operation
  - First stage regulates load at desired temperature
  - Upper stages cascade heat to the cryocooler
- Additional stage will provide continuous 1 K

CADR Demonstration Units

2-stage (9/00-12/00)



Heat transfer at 50 mK

3-stage CADR (6/01-12/01)

First demo of continuous cooling

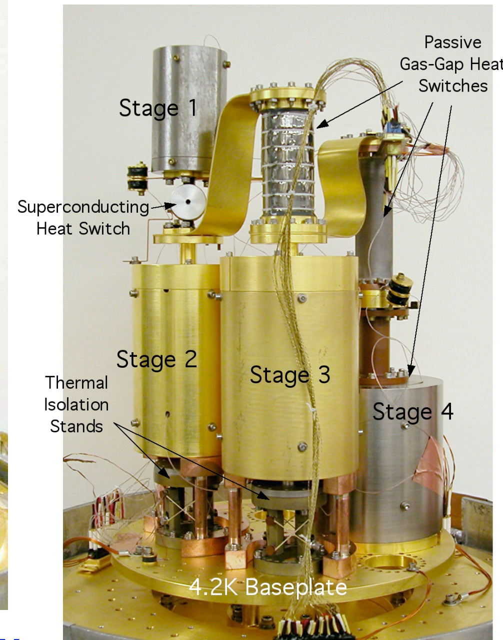
- ♣ 35-100 mK operation
- ♣ 1.3 K helium bath

4-stage CADR (7/02-5/03)

Demonstrates functionality needed for Con-X

- ♣ High cooling power
- ♣ High efficiency
- ♣ High heat rejection (4.2K)

4-stage CADR (5/03-present)



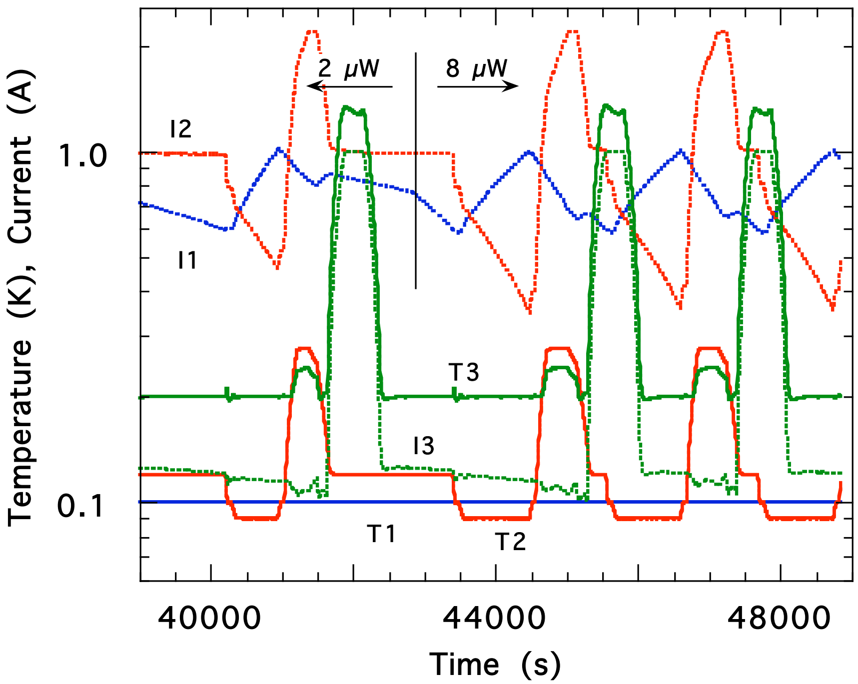
Demonstrates all components needed for Con-X

- ♣ Low mass

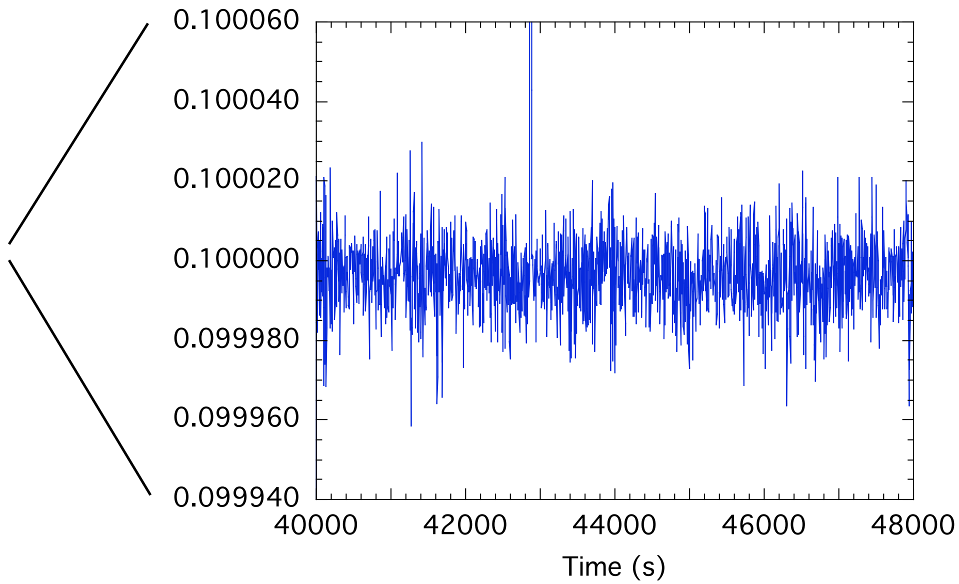
CADR Performance

- Control is fully automated
  - Including initial cool down

T (K)	Cooling Power (μW)
0.10	32
0.09	27
0.08	22
0.07	17
0.06	11
0.05	6



8 μK rms stability limited by readout electronics



Technology Development Remaining

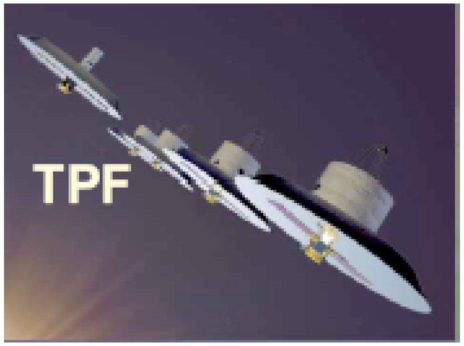
- Develop improved refrigerants to further reduce size and mass
- Develop low current magnets that operate at ~6 K
  - Magnets must operate at the cryocooler's base temperature, 4-6 K
  - Currently funding development of Nb_3Sn wire (T_c=18 K)
    - Prototype magnet achieved 3 T at 8 Amps at 10 K; Goal is <5 A
- Electronics
  - Temperature stability is highly dependent on control and temperature readout electronics
  - Working with Lakeshore Cryotronics Inc. (SBIR Phase II) to develop controller
    - 1st test scheduled for Nov. 28, 2005 at GSFC
- Currently assembling a 4-stage CADR in a dewar with a 4 K cryocooler
  - Conduct tests with x-ray microcalorimeters to verify end-to-end performance
  - Will include continuous 1 K stage for SQUID amplifiers
- Suspension systems and ruggedization

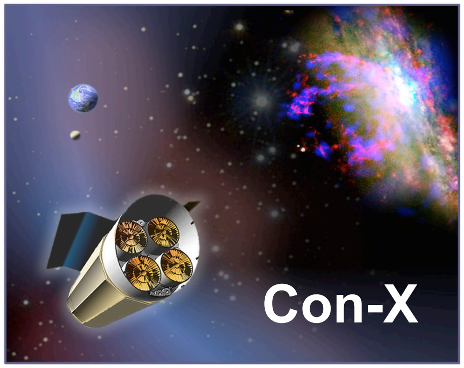
CADR Technology Roadmap

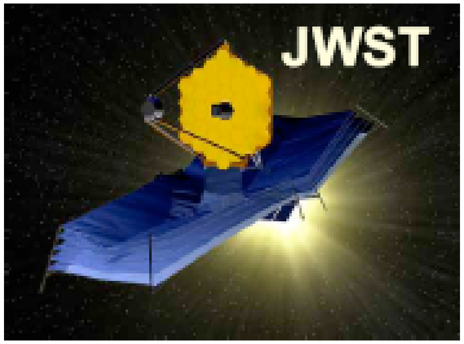
Element	3-stage CADR	4-stage CADR	4-stage CADR	4-stage CADR	50 mK & 1 K CADR	Breadboard
Number of stages	3	4	4	4	5	5
Heat rejection temperature	1.3 K	4.2 K	4.2 K	4-5 K	6 K	6 K
Operating temperatures	60 mK	50 mK	50 mK	50 mK	50 mK/1 K	50 mK/1 K
Cooling power at 50 mK		6 μW	6 μW	> 6 μW	> 6 μW	> 5 μW
Cooling power of "1K" stage					> 0.3 mW	> 0.23 mW
Temperature stability		8 μK rms at 100 mK	8 μK rms at 100 mK	8 μK rms at 50 mK	2 μK rms at 50 mK	2 μK rms above 1 Hz
Mass	18 kg	20 kg	8 kg	8 kg	10 kg	10 kg
Technology goal			High-T stage	Cryocooler, Electronics	6 K magnets, Test with x-ray detectors, Electronics	Environmental testing
Time frame	FY01	FY02	FY03	FY06	FY07	FY08
TRL	3	3.3	3.7	4	5	6

Cryocooler Development

- Cryocooler development needed for next generation space-based observatories
  - 4-6 K/18 K two-stage cooling
  - Remote cold heads (on deployable structures)
  - Minimal generated noise (EMI and vibration)
- Solution was the Advanced Cryocooler Technology Development Program (ACTDP)
- ACTDP requirements driven by three missions
  - James Webb Space Telescope
  - Terrestrial Planet Finder
  - Constellation-X
- Program designed to provide proven Development Model (DM) coolers in 2006

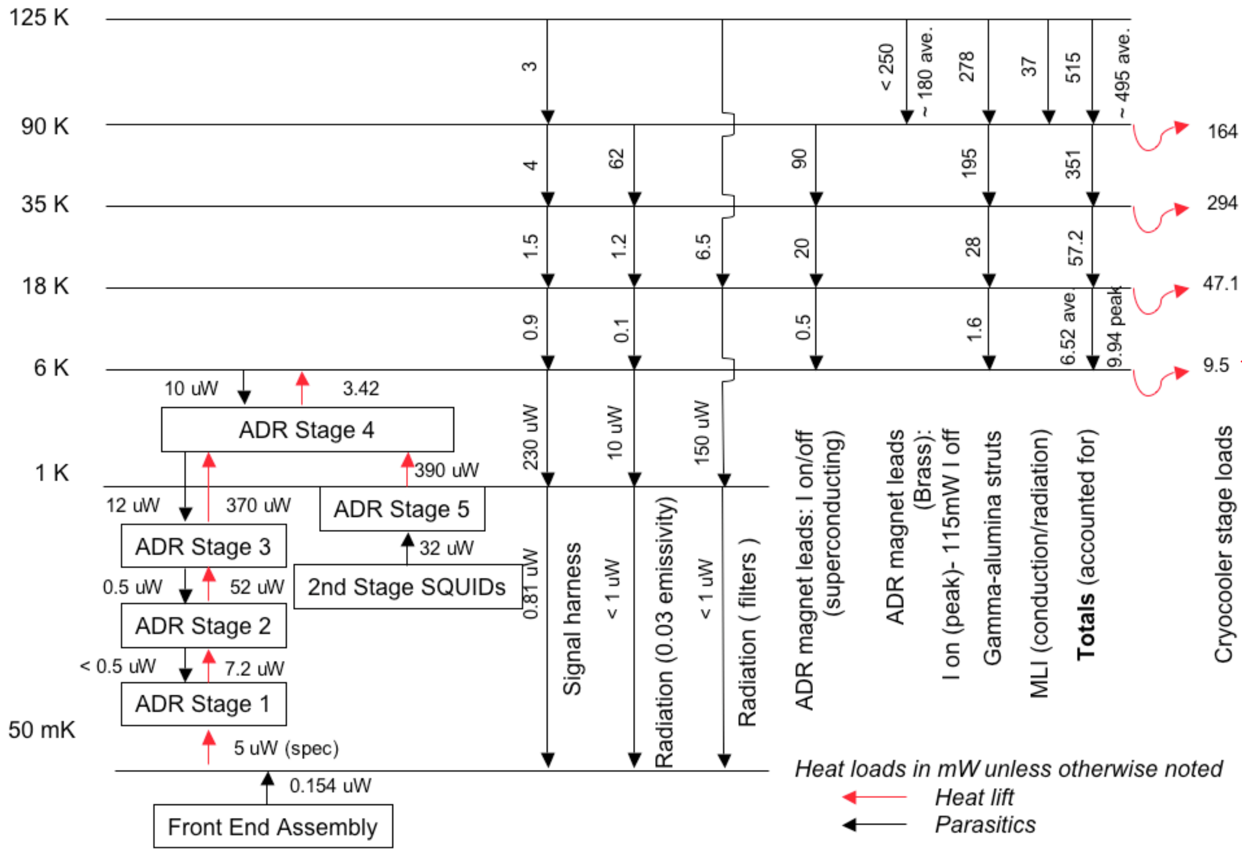






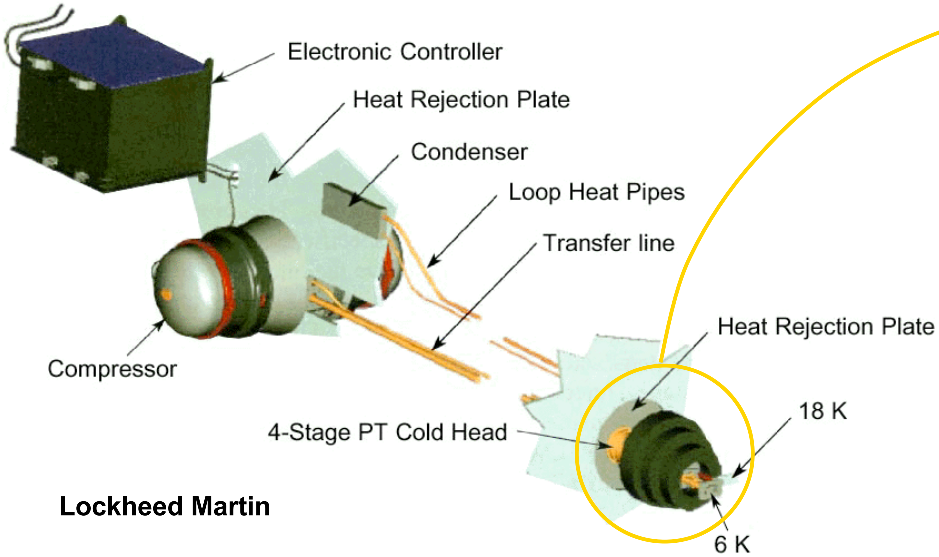
Technology Requirements

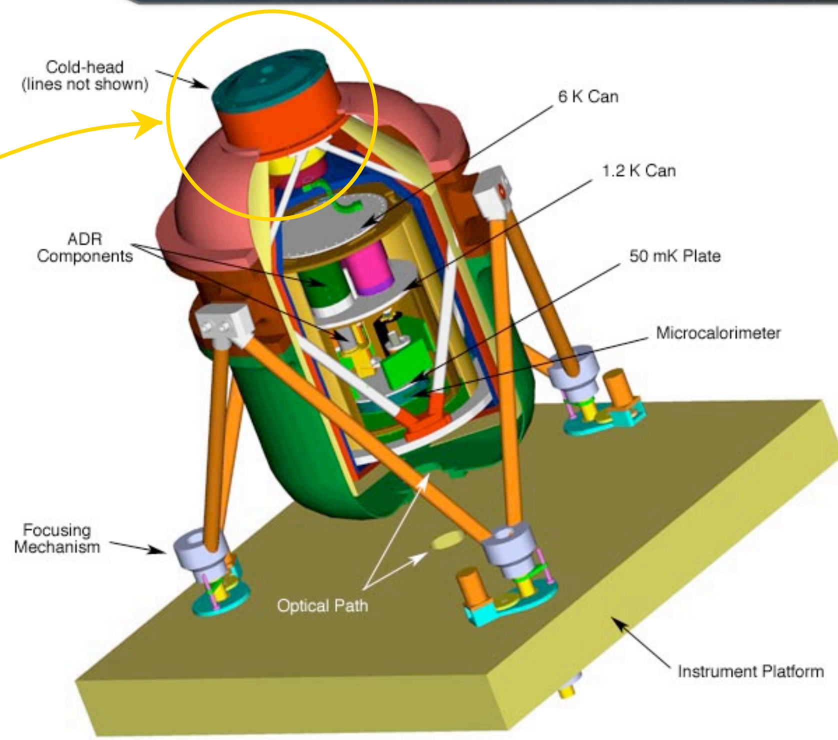
- Cryocooler heat lift requirements derived from Microcalorimeter and ADR requirements
- ACTDP spec developed as a flight spec including vibration, EMI/EMC, contamination &c.

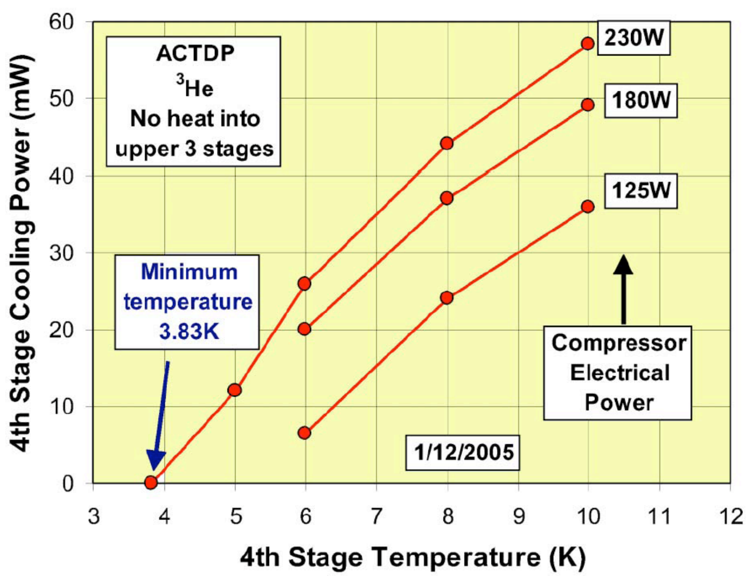


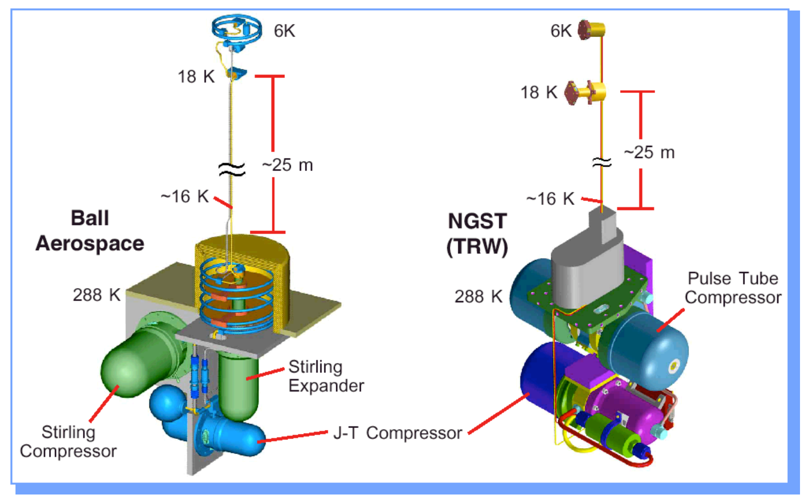
ACTDP Con-X Requirements:
150 mW @ 18 K
20 mW @ 6 K
200 W bus power

Technology Description



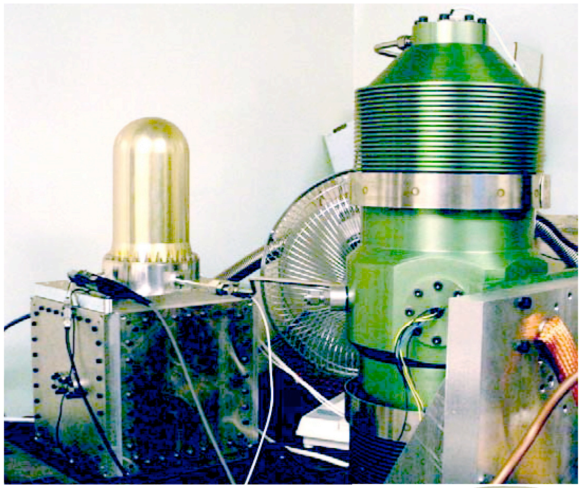




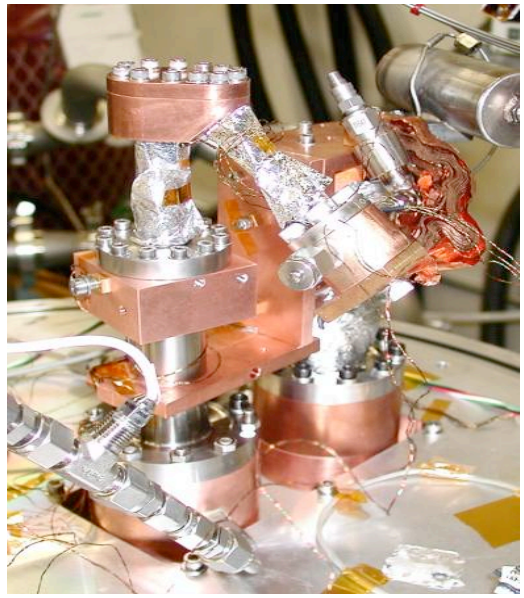


Progress and Status - cont'd

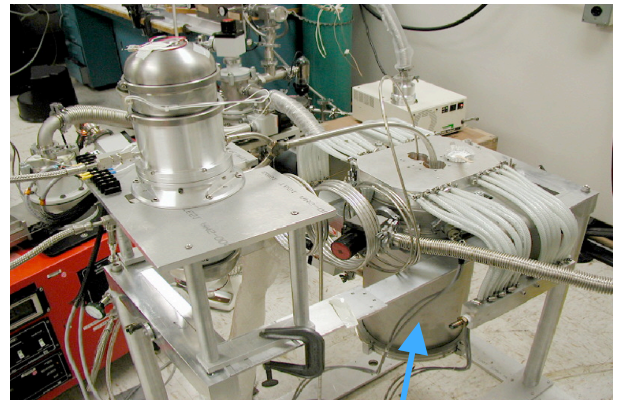
Ball Aerospace
Stirling Precooler
Completed and in test



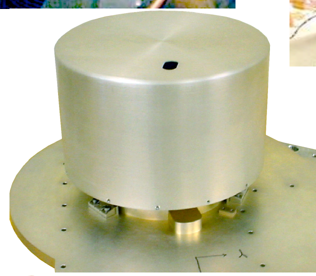
NGST
PT Precooler Testing

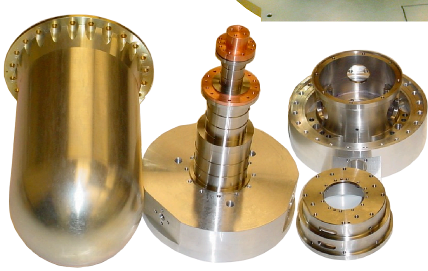


Lockheed
4-Stage PT System
completed and in test

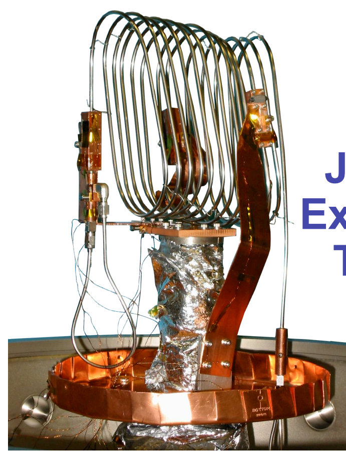


Shake Testing Precooler Cold-head Structure Completed

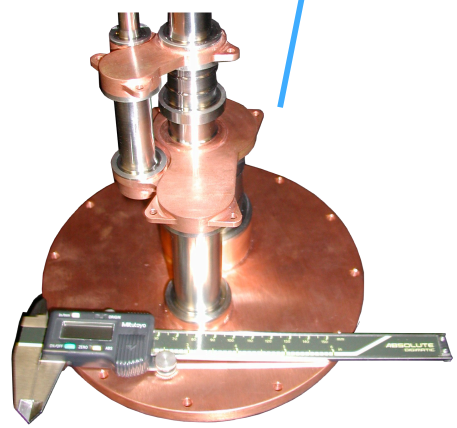




Displacer Parts



J-T Heat Exchanger Testing



4-Stage PT Expander

Status:

- Constellation-X ACTDP reference cryocooler (Lockheed) has met XMS cooling requirements
- All three ACTDP vendors now sizing versions for 60 mW at 6 K
- ACTDP cryocooler technology development program complete.
  - NGST selected to build cryocooler for JWST/Mid-IR Instrument (MIRI)
- Cryocooler technology for Con-X awaiting further instrument definition

Other Technology Issues

Design of 1024-channel (or more) detector assembly.

Signal Processing Electronics - 32 channels of XRS to 32 x 32.

Good ideas; need to actually implement with flight considerations in mind (mass, power, mechanical properties, etc.)

Operating microcalorimeters in cryogen-free dewar systems to begin to assess issues of electromagnetic and vibration interference.

This is just beginning now.

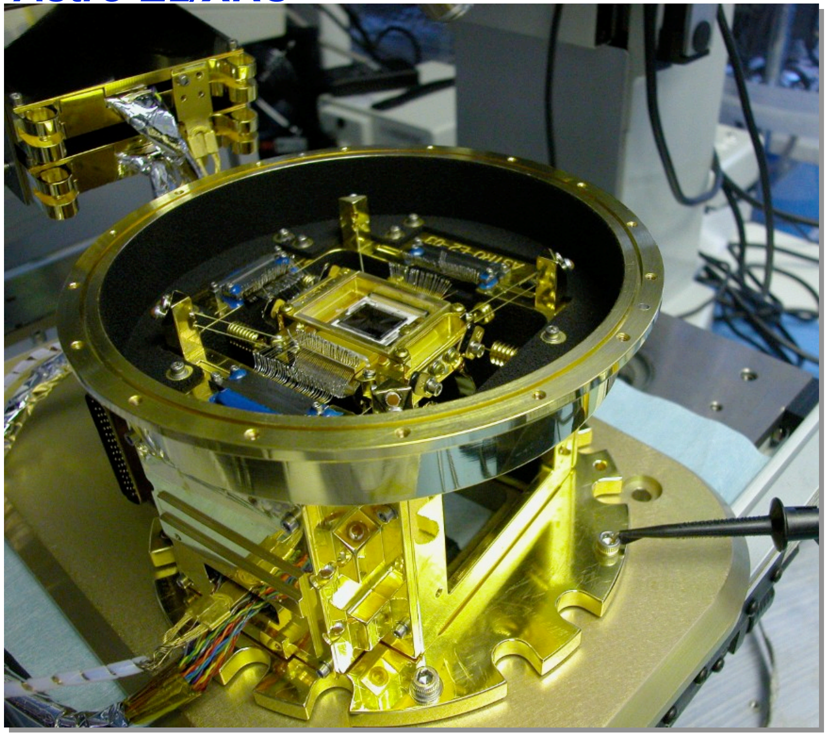
Blocking filters - need thin and “defrostable” with low power

Low-level work at Wisconsin, Luxel Corp. and Goddard has begun but will need substantial support for flight development

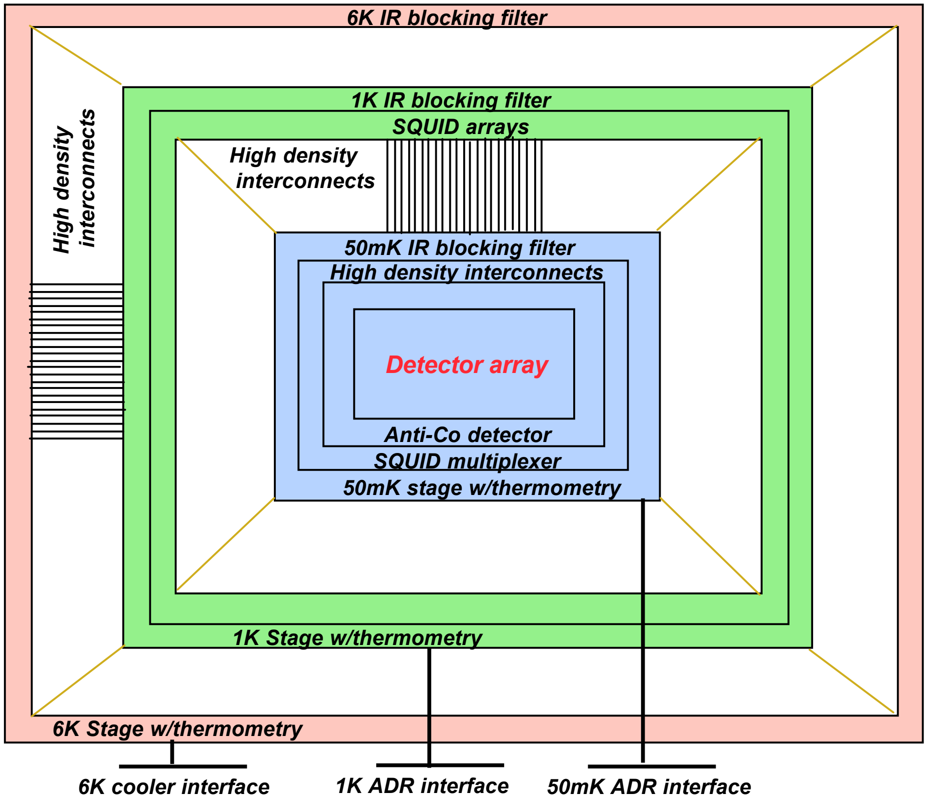
Concept for thermal and electrical staging

- Housing and thermal staging for the detector array, anticoincidence detector and SQUID amplifiers.
- Includes suspension systems, wiring interconnects, high density wiring feedthrus, multiplexers, and SQUID amplifiers.

Astro-E2/XRS



Con-X/XMS



- To be developed to maintain the following at an acceptable level:
  - Thermal stability, thermal gradient across array, and thermal crosstalk
  - Electrical crosstalk, microphonics, magnetic shielding, and susceptibility to interference
  - Conducted and radiative heat loads on all the temperatures stages

Summary and Conclusions

Substantial progress has been made since 1998 on advancing microcalorimeters for high resolution, larger numbers of smaller pixels, and speed.

X-ray microcalorimeters are commonly used in the lab with < 4 eV resolution.

Now have flight heritage with implanted Si, which provides valuable data for all types of x-ray microcalorimeters.

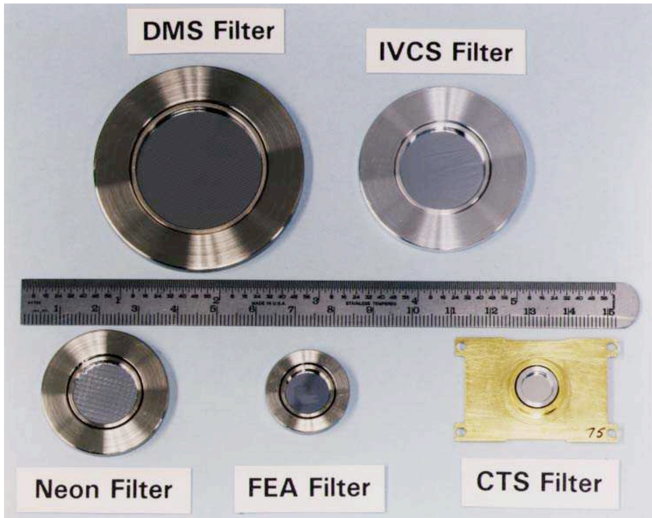
There are multiple paths toward producing a flight-qualified cryogen-free system for low temperature detectors.

More engineering work will be required to determine which approach is best for overall system robustness with acceptable weight and power figures.

The development program for the XMS has led to both breakthroughs and solid optimization work over the last eight years, and the groundwork has been laid to begin the next level of real engineering work toward flight systems.

Supporting Charts

Thin-film Blocking Filters



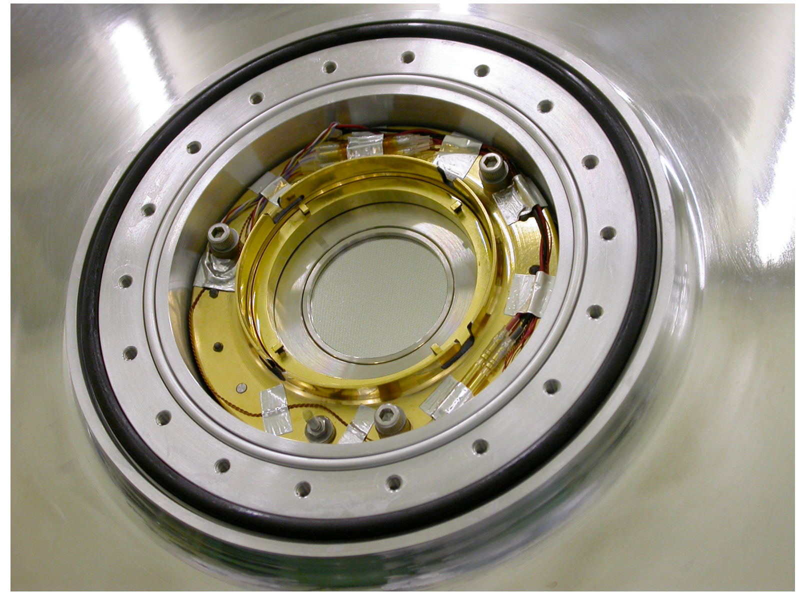


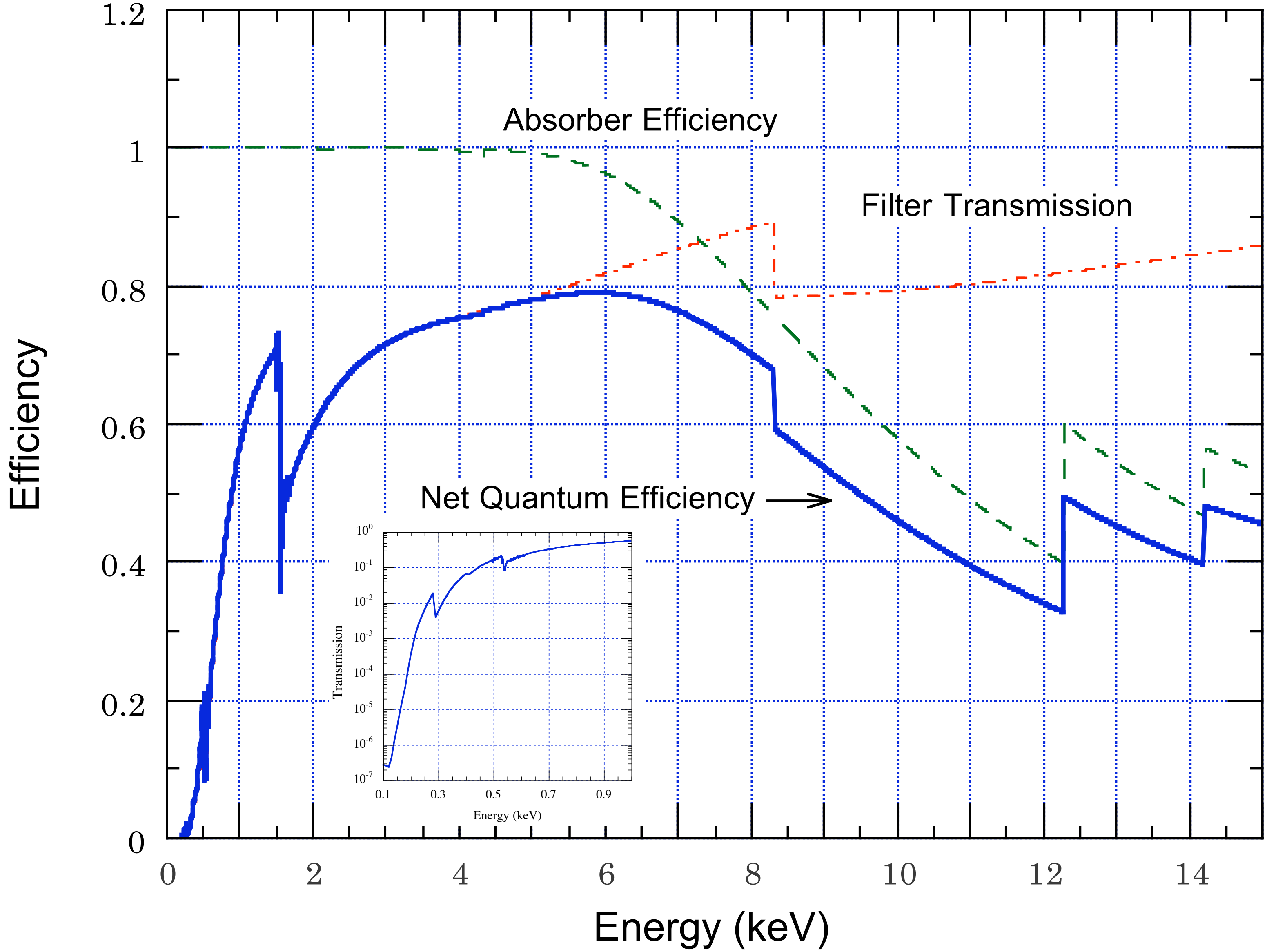
Table 16: Blocking Filter Requirements

In Band Transmittance		Out-of-Band Transmittance	
Energy	Transmittance	Energy	Transmittance
0.5 keV	> 16 %	IR (3-30 μm)	$< 3 \times 10^{-11}$
1.0 keV	> 52 %	10.2 eV (1216 Å)	$< 1 \times 10^{-7}$
6.0 keV	> 70 %	21.2 eV (584 Å)	$< 1 \times 10^{-6}$
10.0 keV	> 70 %	40.8 eV (304 Å)	$< 3 \times 10^{-6}$

Table 17: Properties of the blocking filters

Label/ Serial Number	Luxel Run Number	Pinhole Trans	Nominal Thickness Polyimide	Nominal Thickness Aluminum	Mesh
CTS-FM-05	9328.4	3.80×10^{-4}	737 Å	508 Å	None
FEA-FM-201	9328.4	4.33×10^{-4}	737 Å	508 Å	None
Neon-FM-202	9495.2	3.59×10^{-8}	1023 Å	1088 Å	None
IVCS-FM-204	9495.1	2.69×10^{-8}	1025 Å	1088 Å	None
DMS-FM-201	9498.4	1.31×10^{-5}	1060 Å	802 Å	70 lines/inch Ni (T=78 %)

XRS Filter Transmission & QE



Filters for XMS

Discussed with Luxel Corporation (in 2000) the prospects for fabricating thinner filters for increased transmission at lower energies.

They provided an plausible limit to how thin they think reliable filters could be made, assuming there is some kind of support structure (e.g., a Kevlar mesh). See table.

Larger diameter filters are a potential issue:

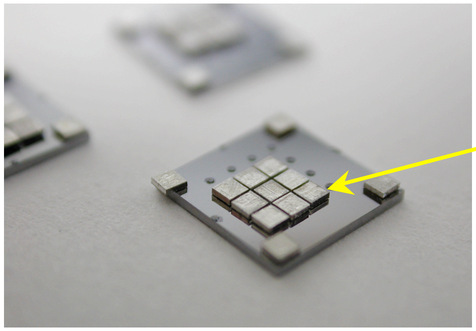
- Larger unsupported area vs. lower mass.
- Need to set up a R&D program as soon as possible.
- The XRS program did this for many years, including cold vibration tests.

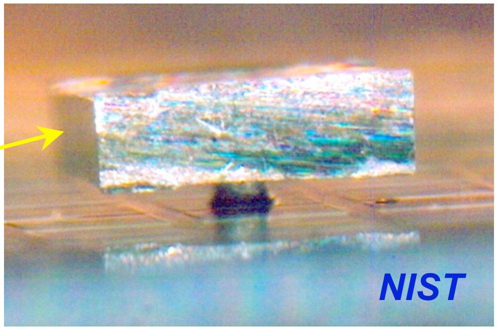
XRS vs. *Possible* XMS filters (total thicknesses)

	Al (Å)	Poly (Å)
XRS	3992	4582
XMS	2100	2800

Large arrays using semiconductor thermometers

Large arrays of ion-implanted can be fabricated. Supporting technologies could make this approach tractable.





Simultaneous absorber attachment

¬ research is ongoing.

Thermal isolation stages integrated with JFET fabrication

¬ has been approached in the past and could be revived.