KEK Seminar
March 11, 2009

X-ray Calorimeter Arrays for Astrophysics

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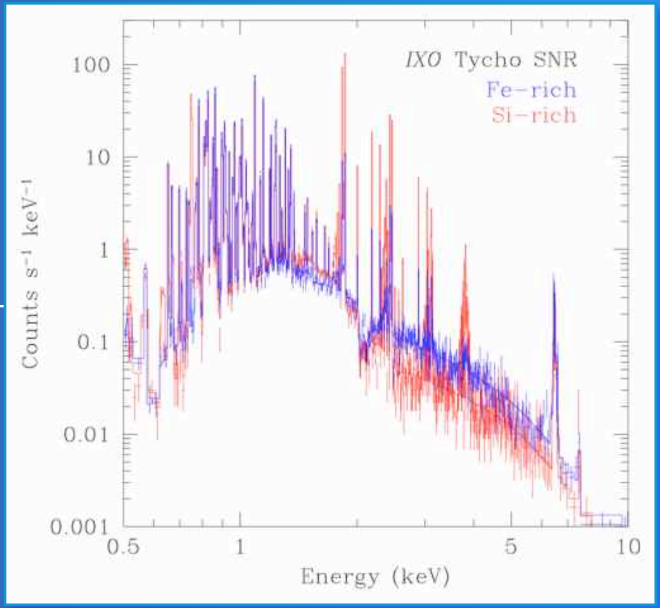
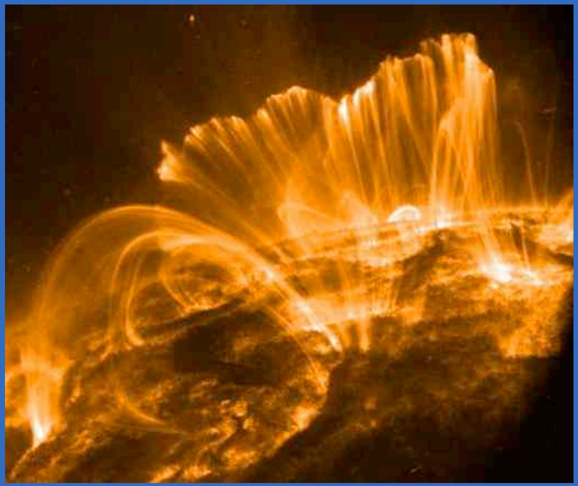


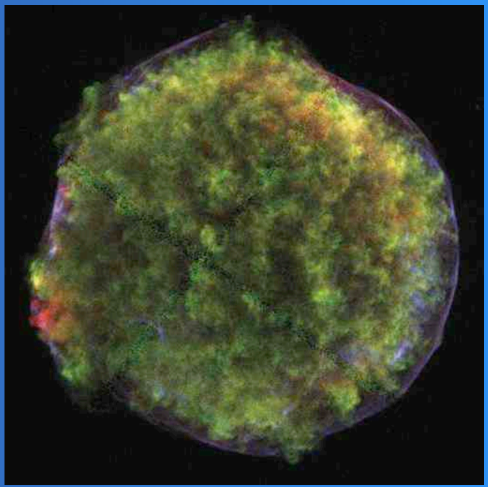
Outline

- high-resolution astrophysical x-ray spectroscopy
- “micro”-calorimeters
  - comparison with other detection schemes, including other low -temperature approaches
  - ideal calorimeters and factors that determine their performance
  - example implementations
- state of the art
  - based on implanted silicon thermistors
  - based on superconducting transition-edge sensors
  - based on magnetic thermometry
- future development and deployment
- other applications

What in the Universe makes x-rays?

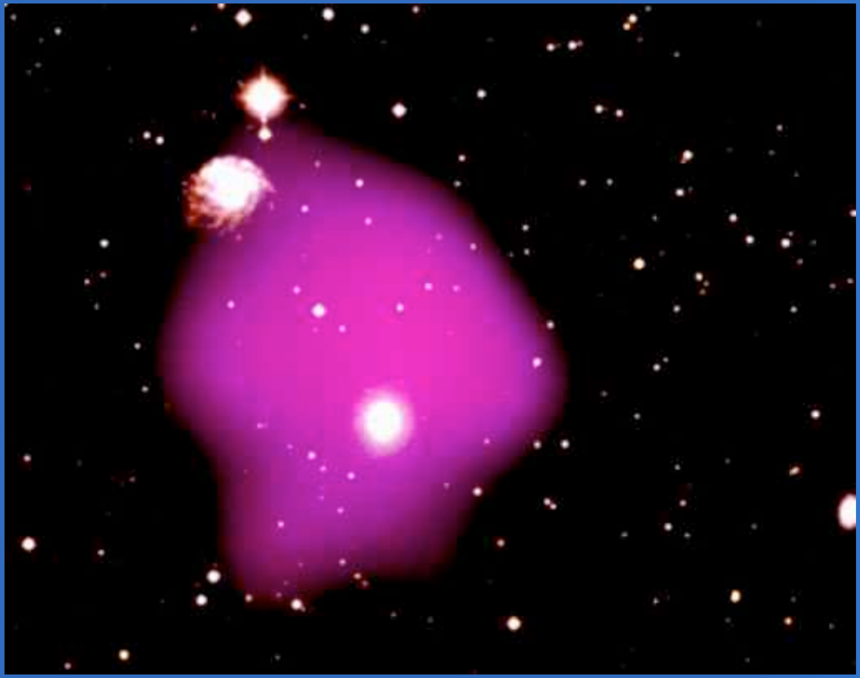
- Gas at temperatures of 1 - 100 million degrees.
  - Remnants of exploded stars
  - Matter falling into black holes and neutron stars
  - Stellar coronae
  - Winds from star-forming galaxies
- Electrons accelerated in strong magnetic fields (~10^{12} - 10^{14} Gauss).
- Electronic transitions in partially ionized atoms of atomic number greater than or equal to 4 (Be).





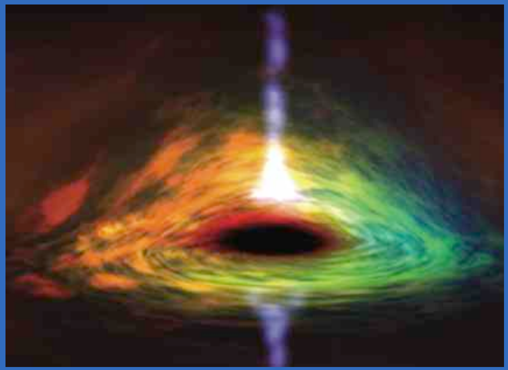
SO?

- That means most of the ordinary matter in the Universe radiates x-rays.
- And this hot ordinary matter can tell us a lot about the extraordinary stuff that's out there, too, because it collects in the gravitational potential wells created by dark matter, and the relaxed gas in clusters of galaxies can be used as a "standard candle" to study dark energy.



X-ray spectroscopy probes four HUGE topics in astrophysics

Black Holes



Cosmic Feedback

- What is the detailed structure of the inner disk around an accreting black hole?
- How prevalent are intermediate-mass black holes?
- Does dark energy evolve with red shift?
- How have massive black holes affected galaxy evolution?
- How do starburst galaxies enrich the intergalactic medium?
- What is the nature of matter that makes neutron stars?
- How do stellar outflows affect planet formation?

Dark Energy & Matter

Life Cycles of Matter

Using X-ray Spectroscopy

- Emission line ratios (e.g. within the He-like triplet) provide density and temperature diagnostics
- Emission and absorption line energies identify ions and determine Doppler shifts
- Line shapes can be used to study effects such as turbulence or the environment of a supermassive black hole
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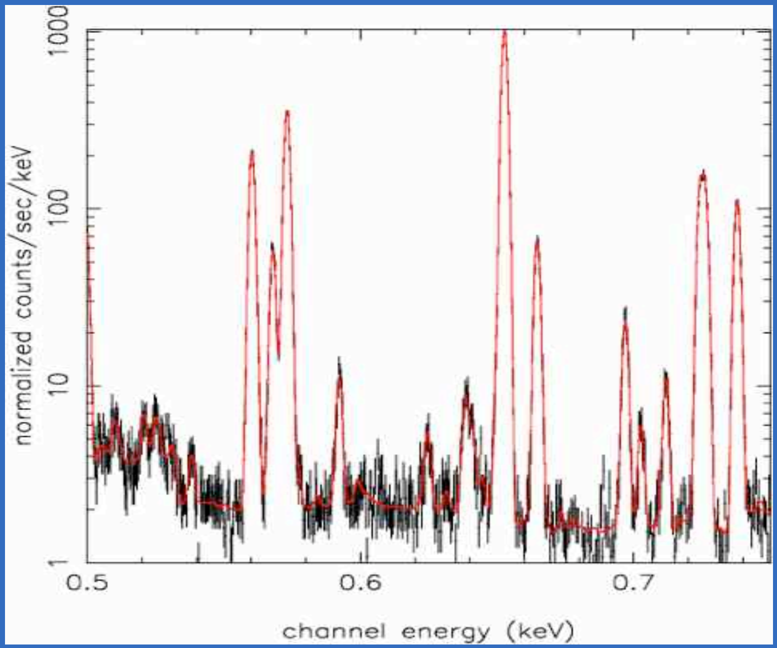
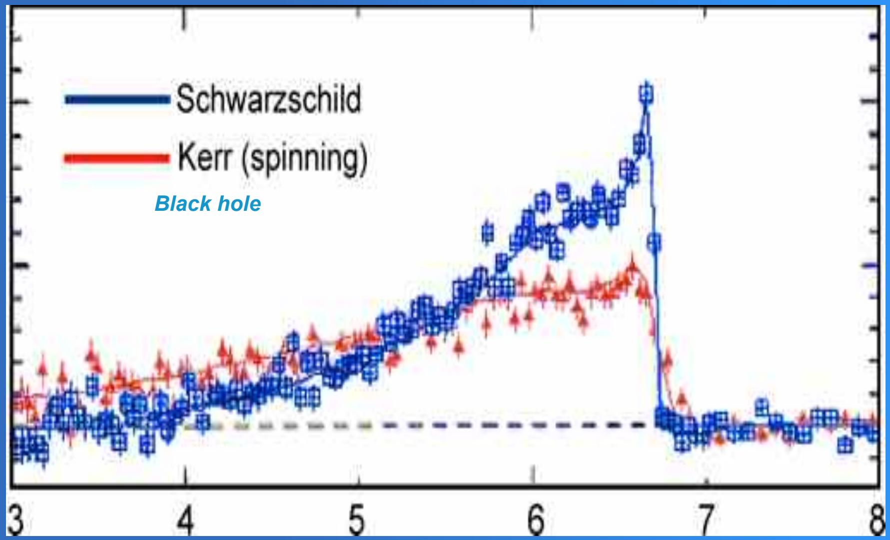




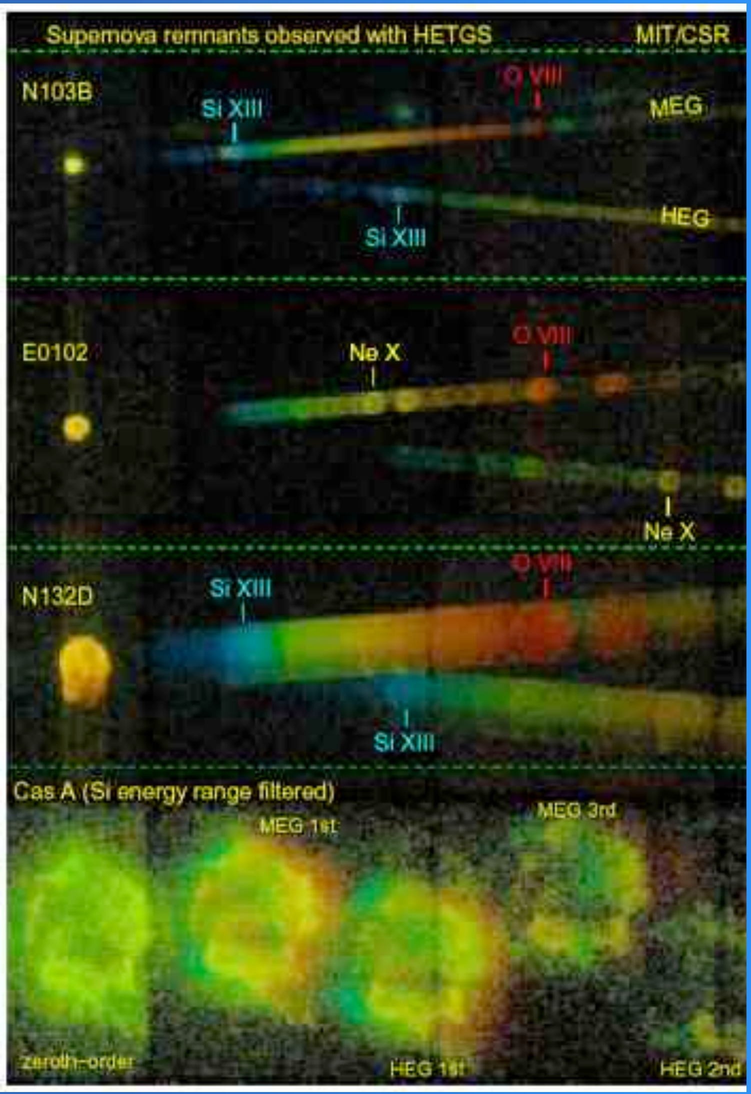
Energy (keV)

Chandra and XMM gratings started a new era in x-ray astronomy, yet…

- Gratings work by dispersing the spectrum across a position sensitive detector, but at the expense of confusion in spectra from spatially extended objects (and much of what we want to observe is spatially extended).

- Gratings have a spectral resolution that is a constant $\Delta\lambda$, thus resolving power degrades with increasing energy. Fe K lines provide clean plasma diagnostics, thus resolving power at 6 keV is needed.

- Thus, we need an imaging, non -dispersive x-ray spectrometer with eV-scale resolution. We need an x-ray camera that can distinguish tens of thousands of x-ray colors.



Non-dispersive spectroscopy – measuring energy directly

Non-equilibrium:

- Absorbed energy goes into quantized excitations.
  - Each excitation has energy much greater than **kT**.
  - These excitations are then counted to determine the energy.
- Since, invariably, some of the energy goes elsewhere, such as into heat, the ultimate energy resolution is determined by the statistics governing the partition of energy between the system of excited states and everything else.
- **This is the operating principle behind most photon and particle detectors.**
- In order to improve the resolution by improving the measurement statistics, a large number of excitation quanta is required.
- This, in turn, requires **low temperature** operation.
  - Superconducting tunnel-junction devices made of small-gap superconductors are based on this principle.

$$dE / E \propto \sqrt{N} / N$$

Non-dispersive spectroscopy – measuring energy directly

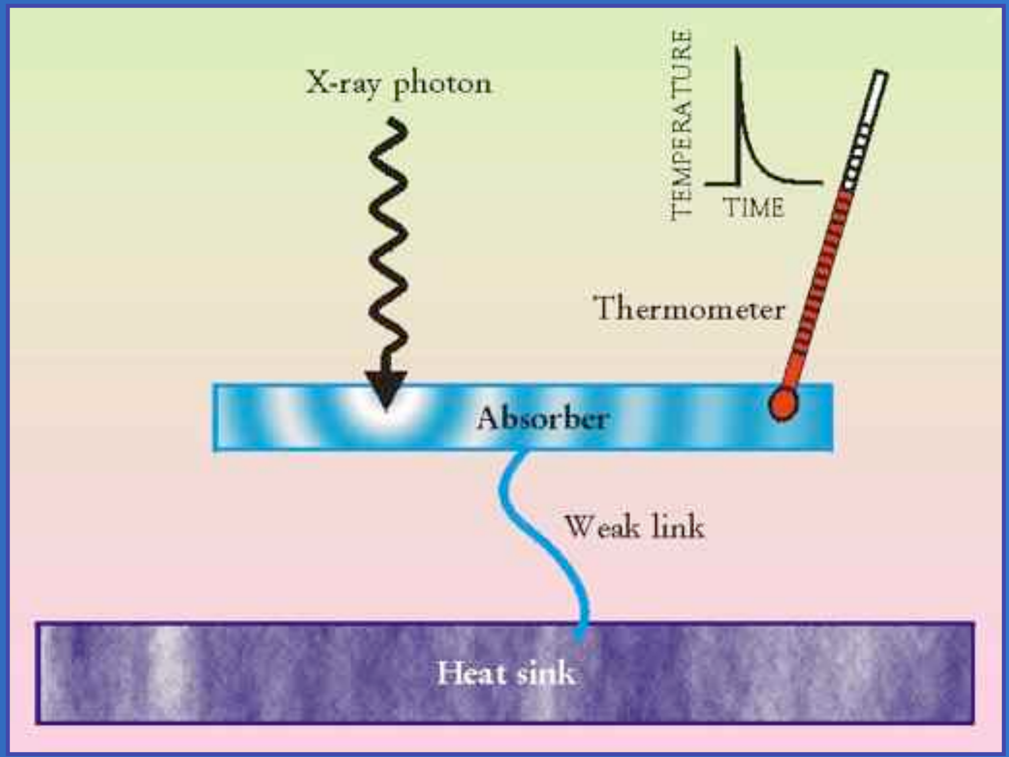
Equilibrium:

- The energy is deposited in an isolated thermal mass and the resulting increase in temperature is measured.
  - At the time of the measurement, all of the deposited energy has become heat and the sensor is in thermal equilibrium.
- The ultimate energy resolution is determined by how well one can measure this change in temperature against a background of thermodynamically unavoidable temperature fluctuations.
- **THIS IS CALORIMETRY***.
  - Among low-temperature detectors, a calorimeter is a device that, at least ideally, determines, through a thermal measurement, all of the energy deposited in it in an impulse. (*I understand that in high-energy physics, a calorimeter is something else, entirely.)
- **Low temperature** operation is required in order to minimize these thermodynamic energy fluctuations.

Choosing equilibrium or non-equilibrium scheme

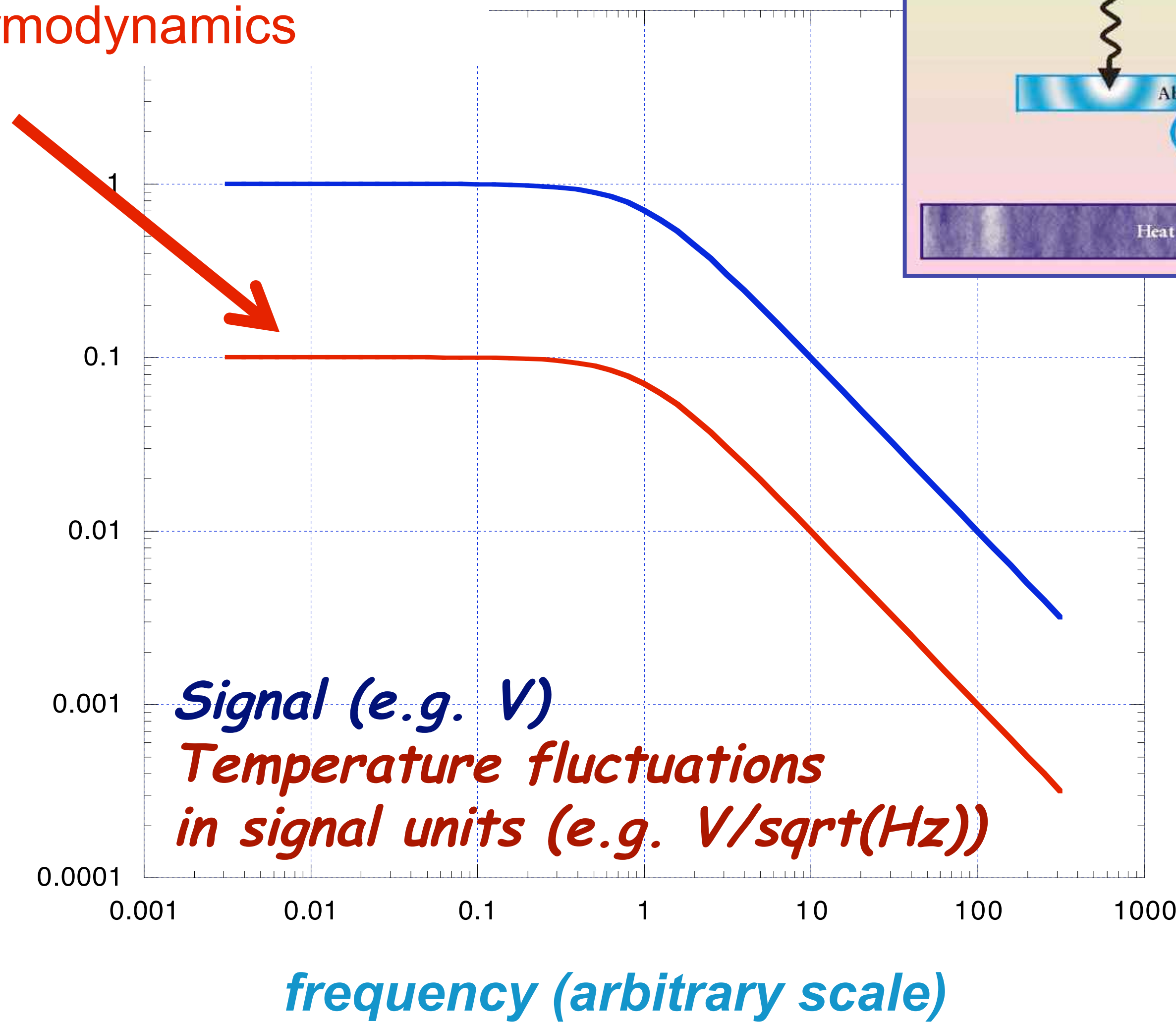
- speed vs. resolving power (very generally)
  - detectors based on non-equilbrium scheme can be made faster before sacrificing resolving power
  - detectors based on equilibrium scheme can achieve the best energy resolution at a given temperature in a small (low heat capacity) device, especially at higher energies
- world astrophysics community planning several satellites that will place non-dispersive x-ray spectrometers behind focusing x-ray optics; each one is based on a calorimeter array.
  - based on laboratory demonstrations of x-ray calorimeters, in a variety of implementations

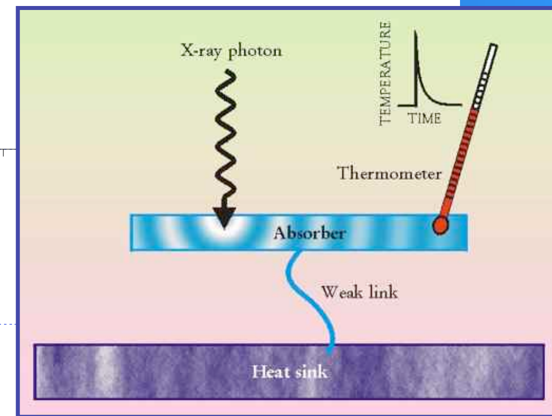
Microcalorimeter basics

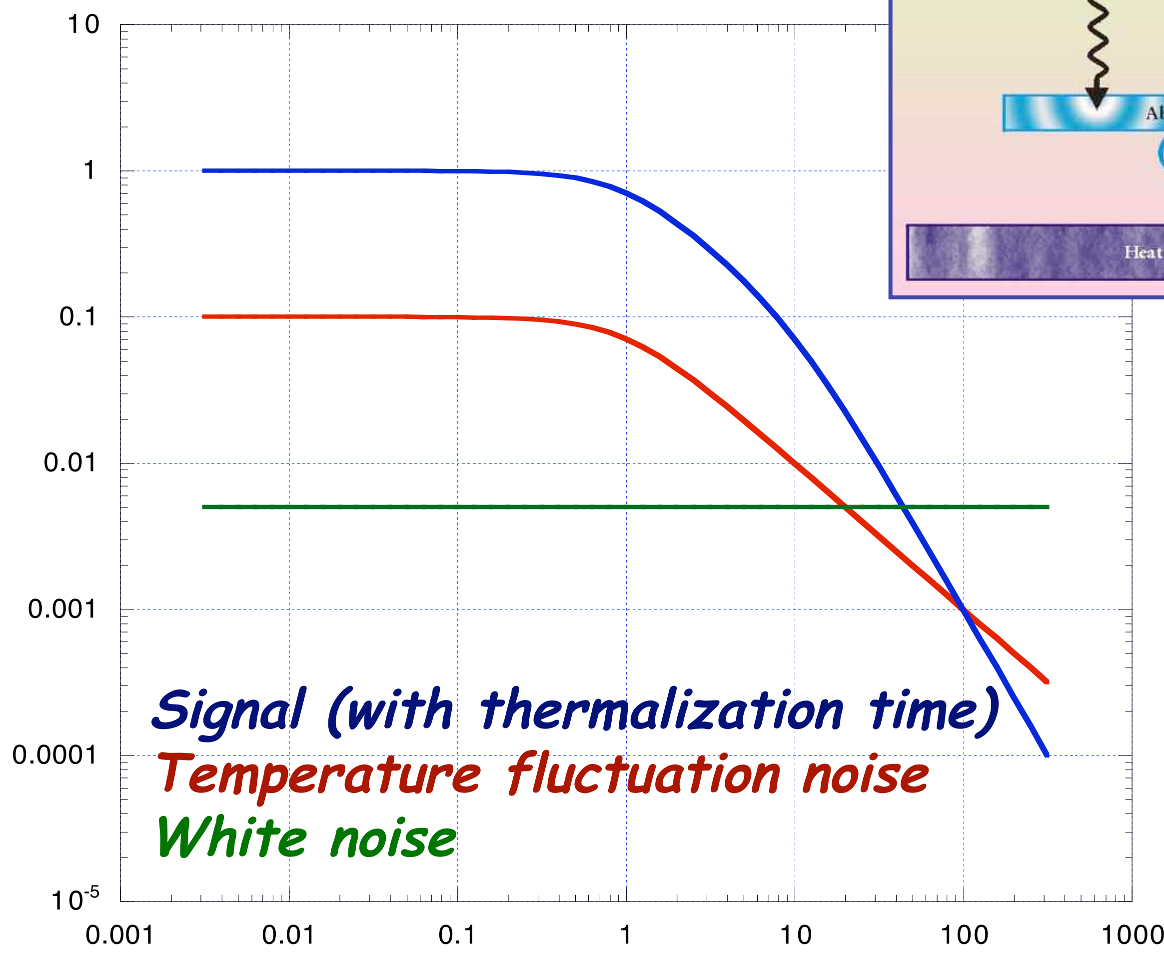


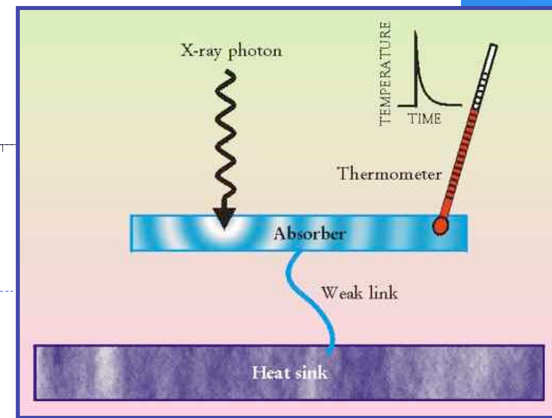
- Thermometers can be based on: resistance, capacitance, inductance, paramagnetism, electron tunneling, thermoelectric effect
- Because the dominant noise term has the same power spectrum as the signal, the measurement accuracy is set by the bandwidth of measurement, which is typically set by other noise terms that dominate at high frequencies and by the detector response (see next slides…)

due to movement of energy across the weak thermal link – from thermodynamics









frequency (arbitrary scale)

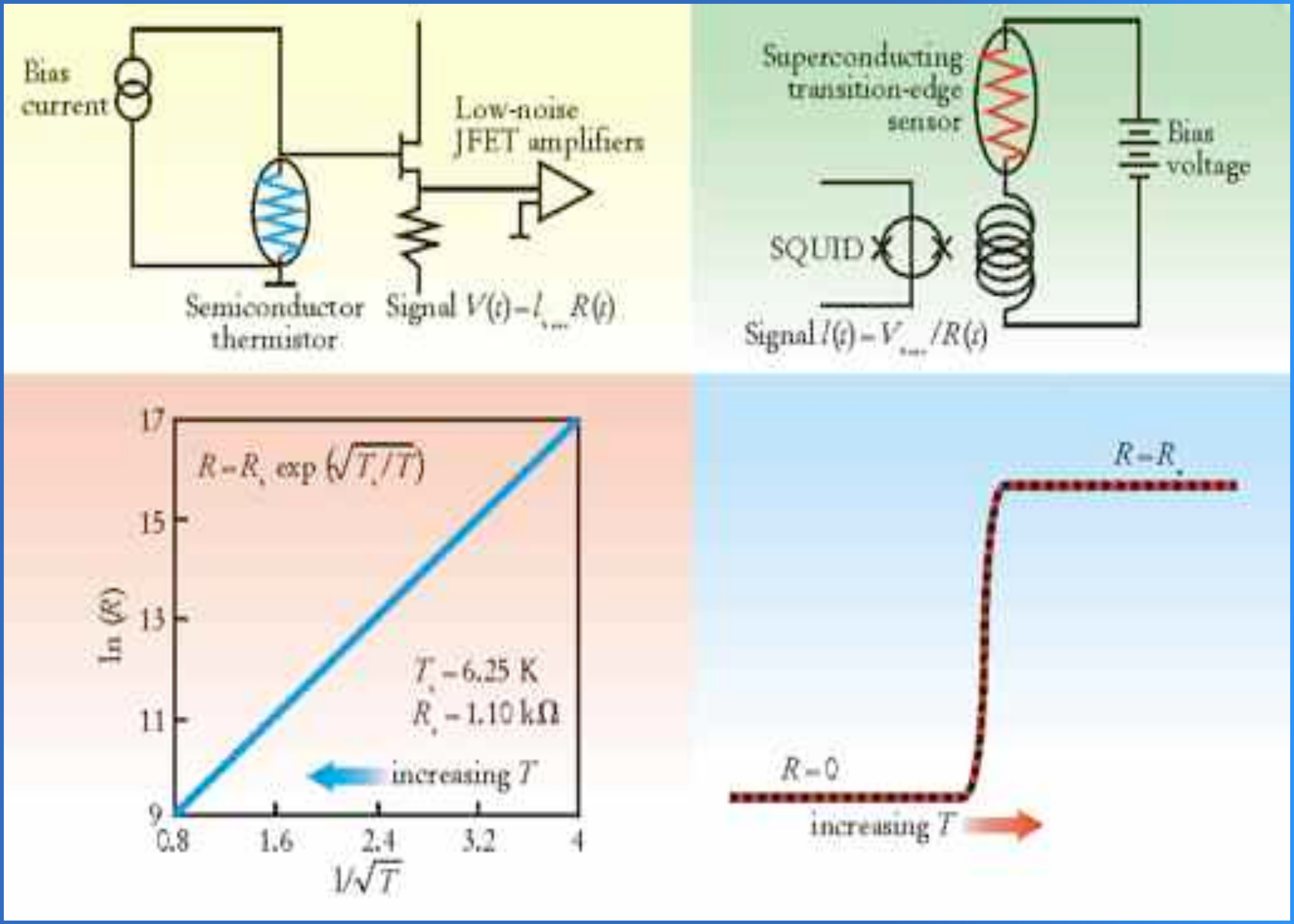
Calculating expected energy resolution

- A fundamental limit on the energy resolution can be calculated for cases in which the thermal fluctuation noise is the dominant noise term at low frequencies, and the noise term that sets the bandwidth is also intrinsic to the detector (thus above amplifier or environmental noise terms).
- For an ideal **resistive** thermometer, the following scaling holds as long as the sensitivity is high enough that thermal noise dominates Johnson noise at low frequencies.
  - α = dlog(R)/dlog(T)

$$dE \propto T\sqrt{C/|\alpha|}$$

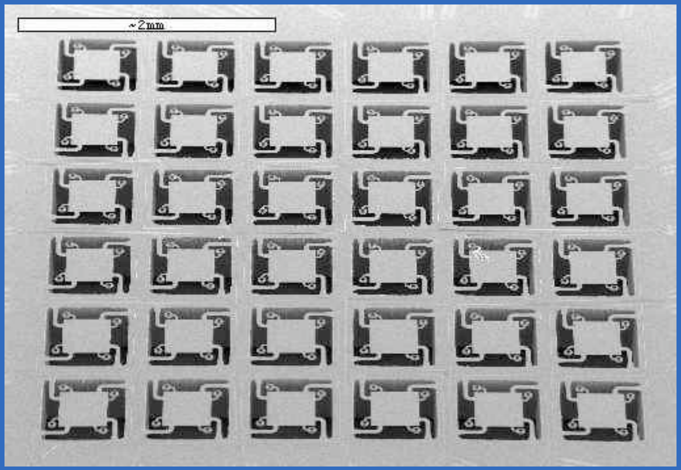
- Because the signal of a thermistor is fundamentally a resistance change, but is read as a voltage or current, resolution depends on the bias power. Increasing the bias increases the sensitivity, but also heats the device. Thus, there is an optimal bias.
- To set the scale: for eV-scale energy resolution, and T in the range 60 - 100 mK, need C ~ 0.1 pJ/K for α = 10. C can be increased to 1 pJ/K if α = 100. These values are readily achieved in designs for astronomical calorimeters.

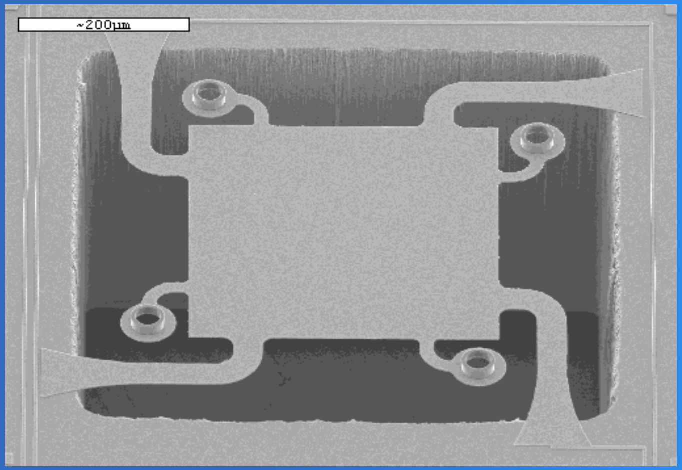
Resistive thermometers



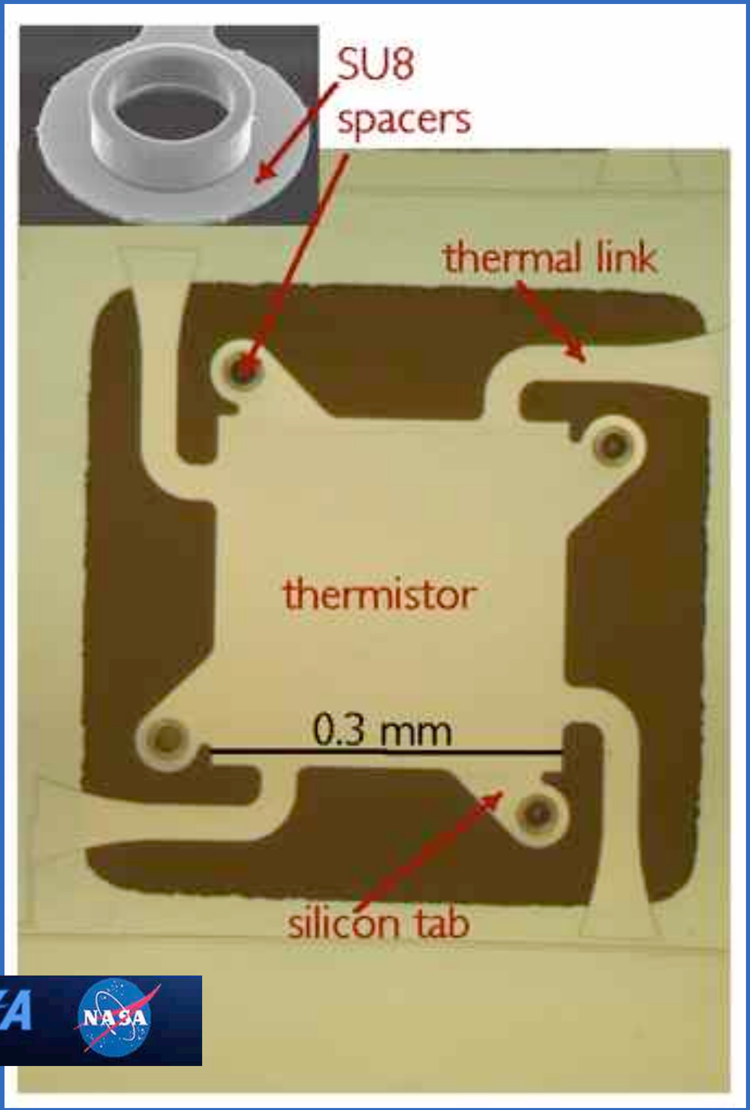
Silicon thermistor-based microcalorimeters

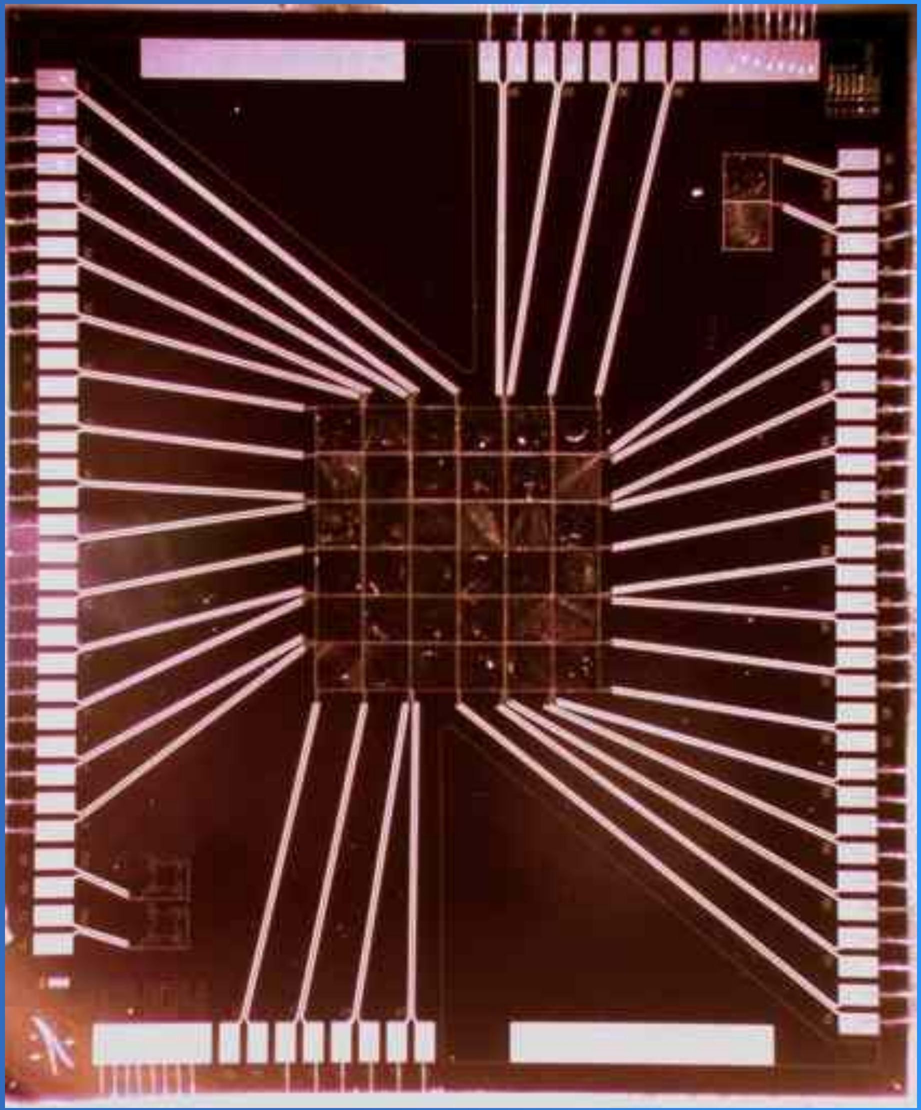
- Thermistors are ion-implanted (P, B) and annealed
- IC and MEMS techniques are well established for Si
- Arrays are fabricated at a high level of integration
  - Presently the x-ray absorber material (HgTe) is still attached in a separate step
  - Separate absorbers are needed for high fill factor, increased quantum efficiency, and because the silicon of the thermistor does not thermalize well
    - energy trapped in long-lived states



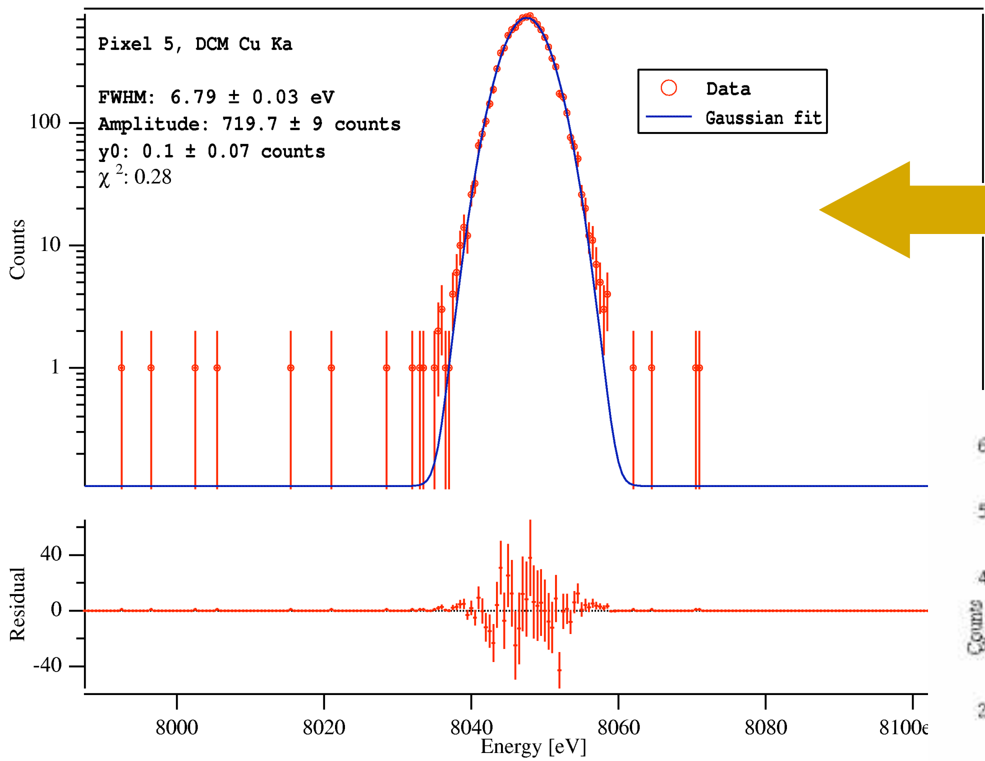


Silicon-thermistor calorimeter array of すざく/XRS *(launched 2005)*

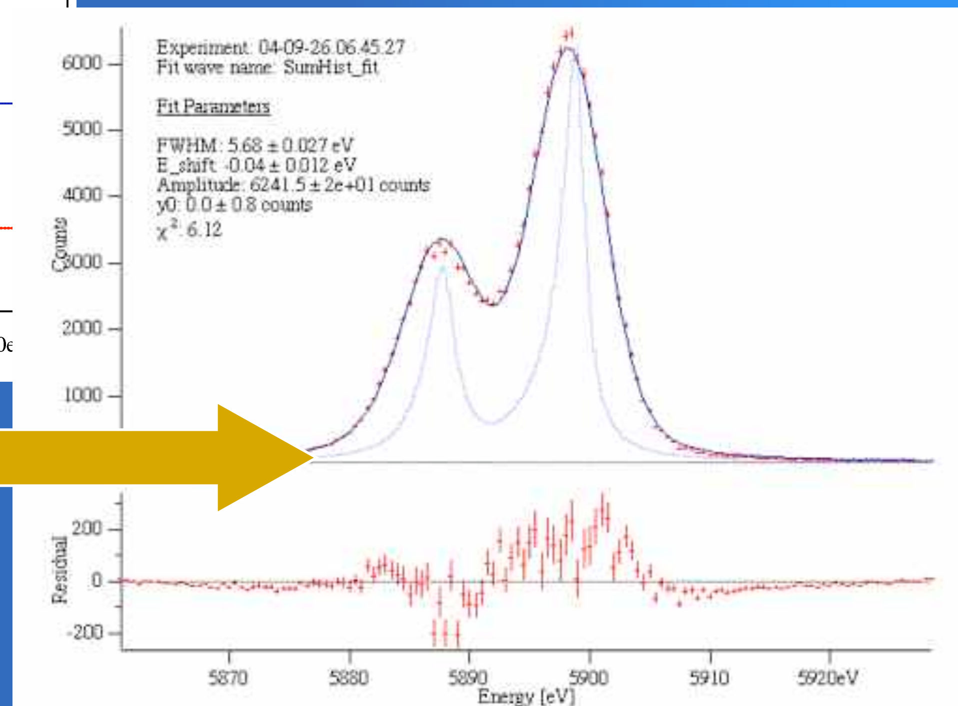




Suspended thermistors sit over individual wells in the silicon frame. HgTe absorbers were attached manually, one at a time. The heat sink was controlled at 60 mK; the thermistors ran at ~75 mK.



No deviation from Gaussian down to better than 1% of peak

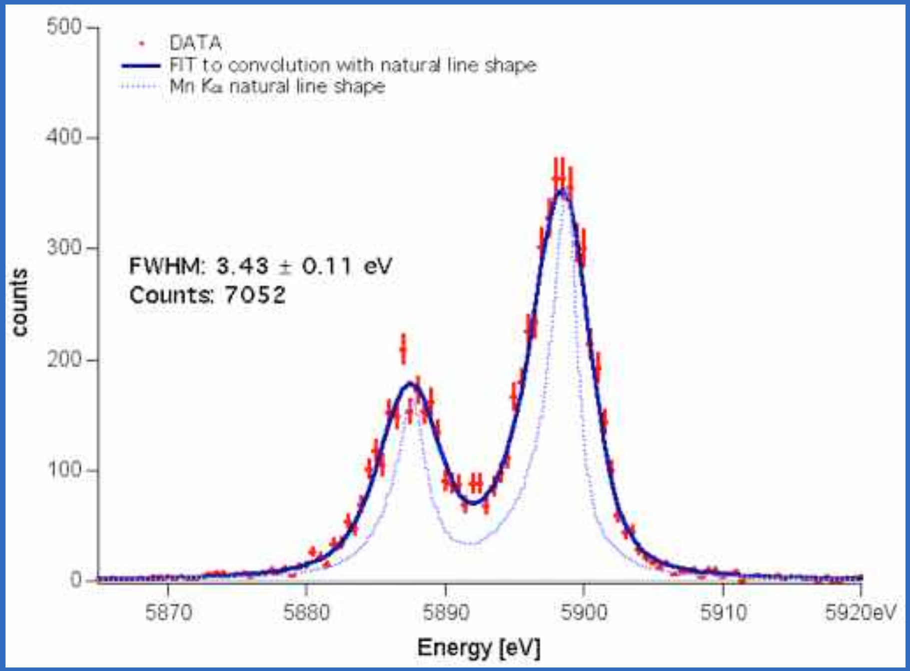


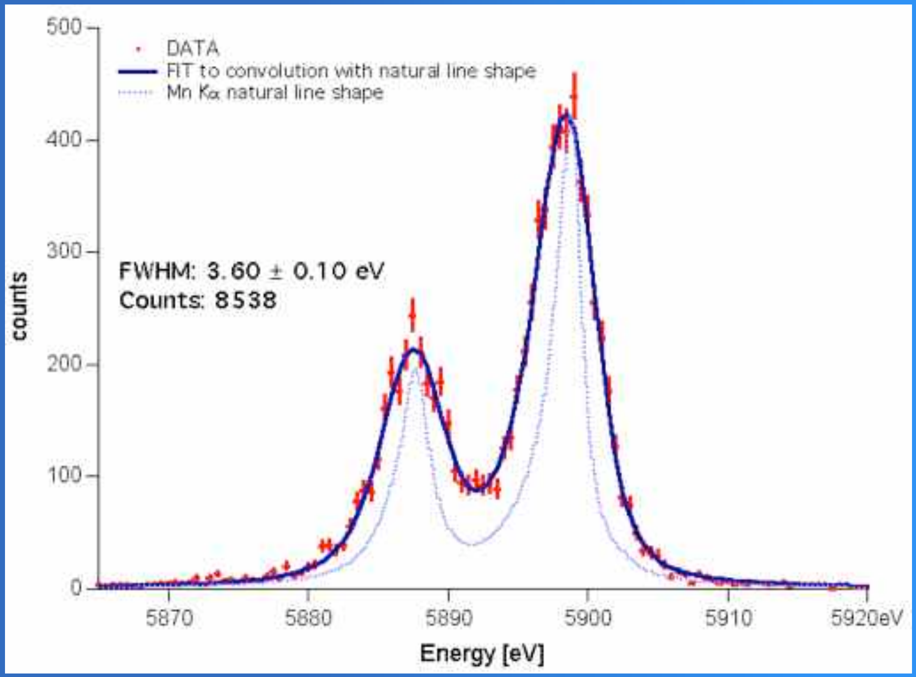
29 hours of data – Co-added XRS array: 5.68 eV ± 0.03 eV at 6 keV

4 arrays completed and tested, resolution 5.3 - 6.5 eV FWHM with 1-2 outliers per array. In-orbit performance of XRS on Suzaku: 7 eV. *(Regretably, instrument was not able make any astrophysical measurements due to premature loss of liquid helium.)*

Improved silicon thermistor-based calorimeter array for Astro-H

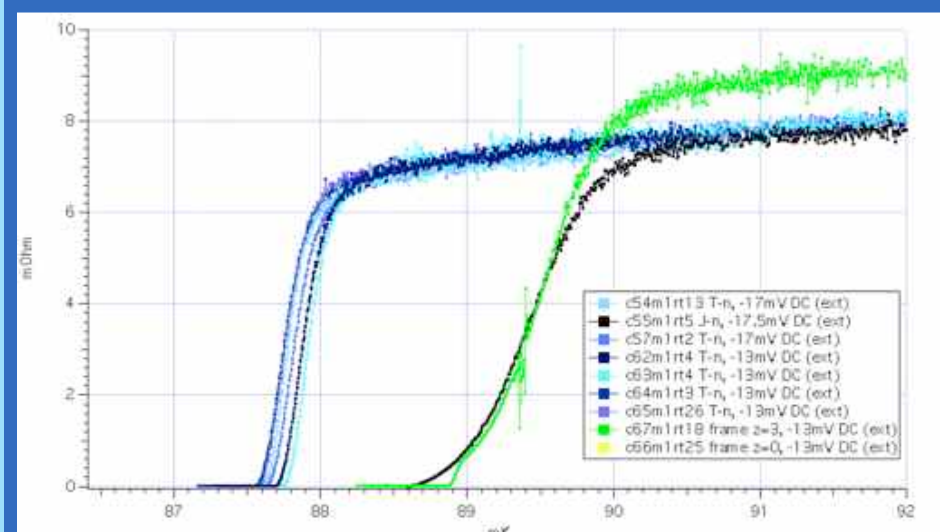
- HgCdTe from EPIR thermalizes well, but has substantially lower specific heat
- Instrument designed for lower base temperature (50 mK)
- Better energy resolution despite larger pixel size (increased area by factor of 1.7) realized in the laboratory
- Demonstration of feasibility of improved heatsinking suggests improved resolution can be maintained in orbit
- Designing an 8x8 array

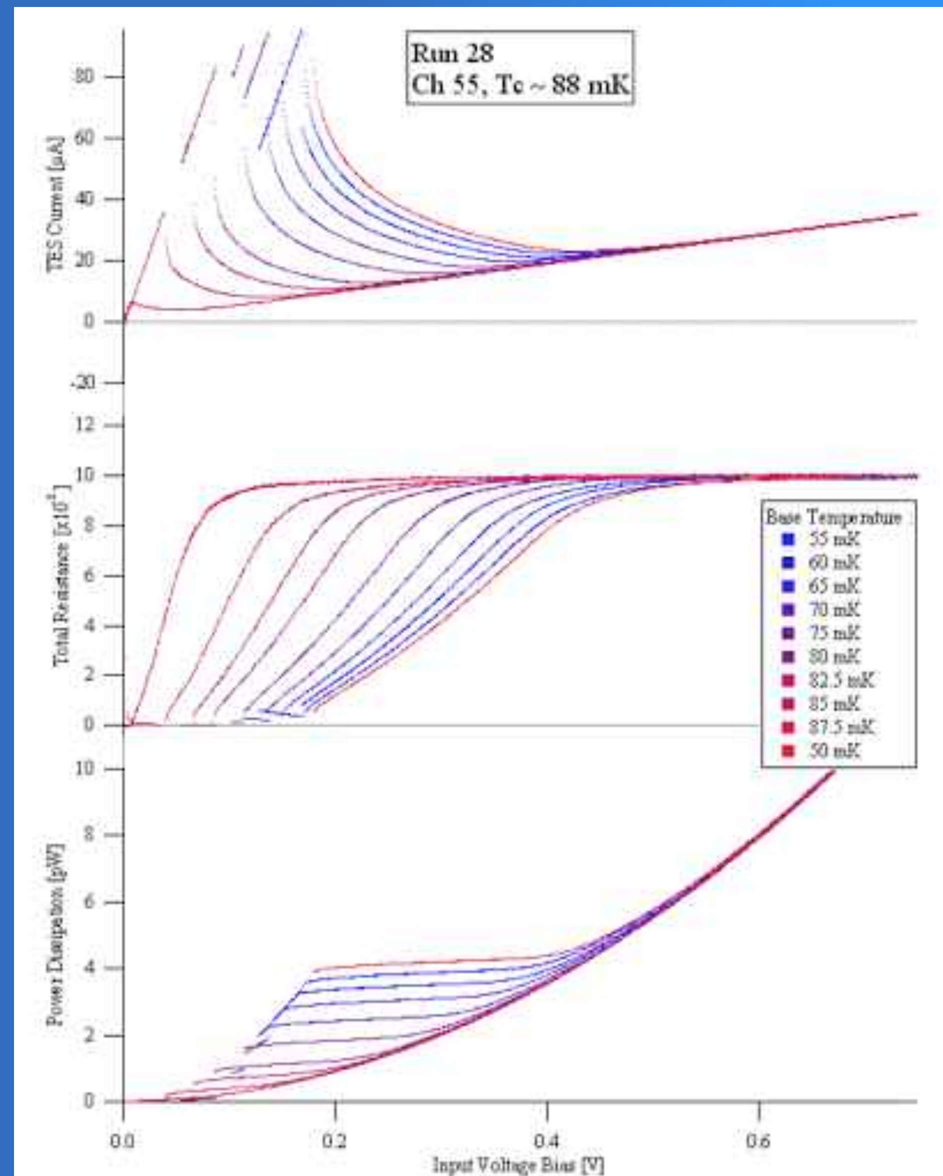




Superconducting transition-edge sensors (TES)

- Stable operation in the transition via electrothermal feedback (changes in temperature cause change in resistance and a change in Joule power that opposes the change in temperature)
- Use proximity-effect bilayers for $T_c \sim 0.1$ K
  - E.g. Mo/Cu and Mo/Au





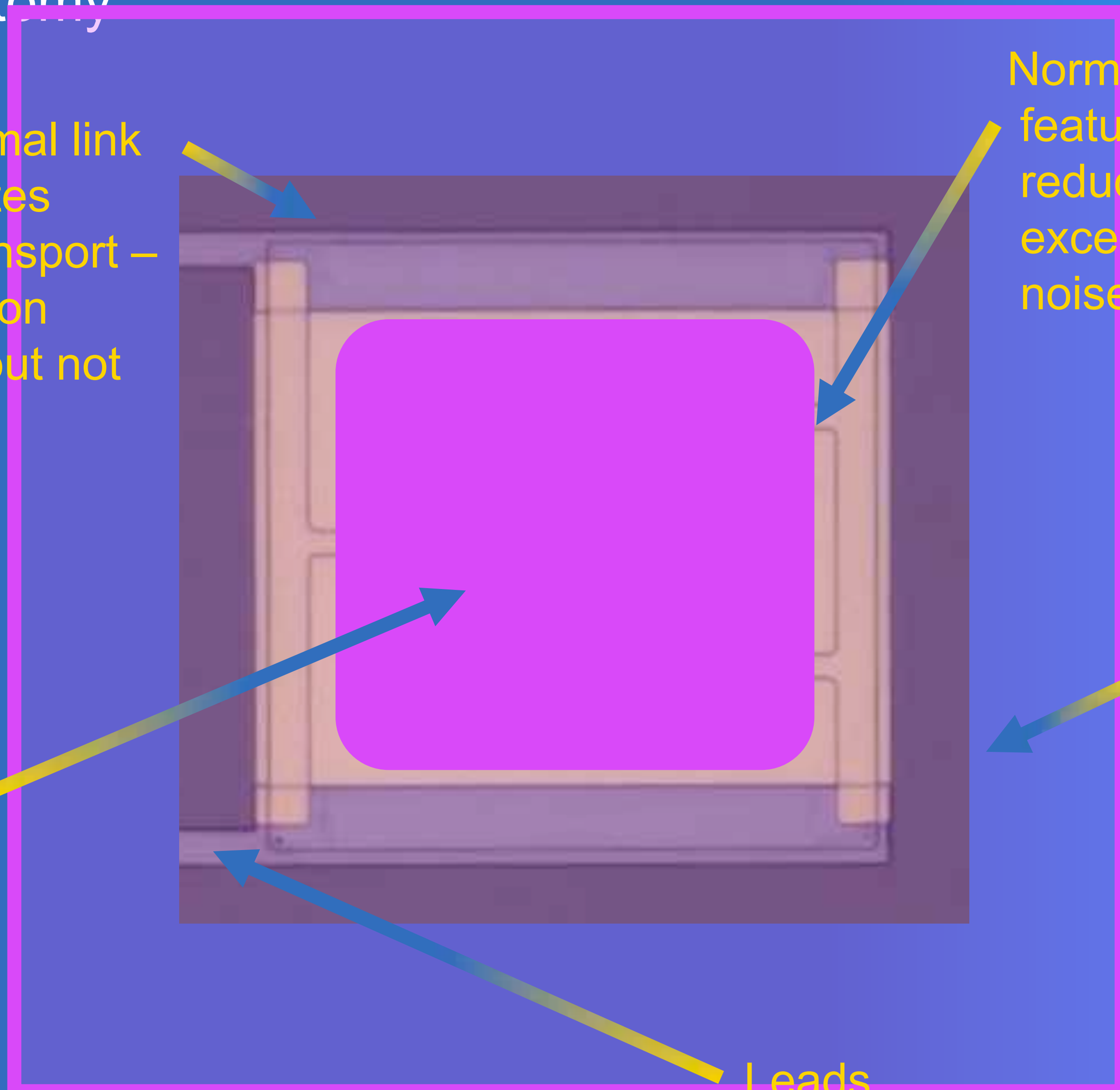
TES vs. Thermistor (Part 1)

- $|\alpha| < 10$ vs. $\alpha > 100$
- Increasing α increases the measurement bandwidth, improving resolution, except, this α is only good over a small temperature range.
- We need to increase C to stay within the linear regime. So we choose C to match the maximum energy. $C = E/dT \sim \alpha E/T$

$$dE \propto T\sqrt{C/\alpha} \propto \sqrt{TE_{\max}}$$

- For measurement of low energy quanta, full advantage of the higher sensitivity can be made.
- For x-rays, TES's require larger heat capacities than the heat capacities of useful thermistor x-ray calorimeters, which have been designed to meet quantum-efficiency and resolution requirements. By a quirk of nature, TES's require heat capacities that are larger by about the same factor that α is larger. Thus, TES's and thermistors are capable of delivering about the same energy resolution.
- But, the larger budget for C allows considerable design flexibility! We can choose materials (LIKE GOLD!) that thermalize well and can be deposited as part of the detector fabrication.

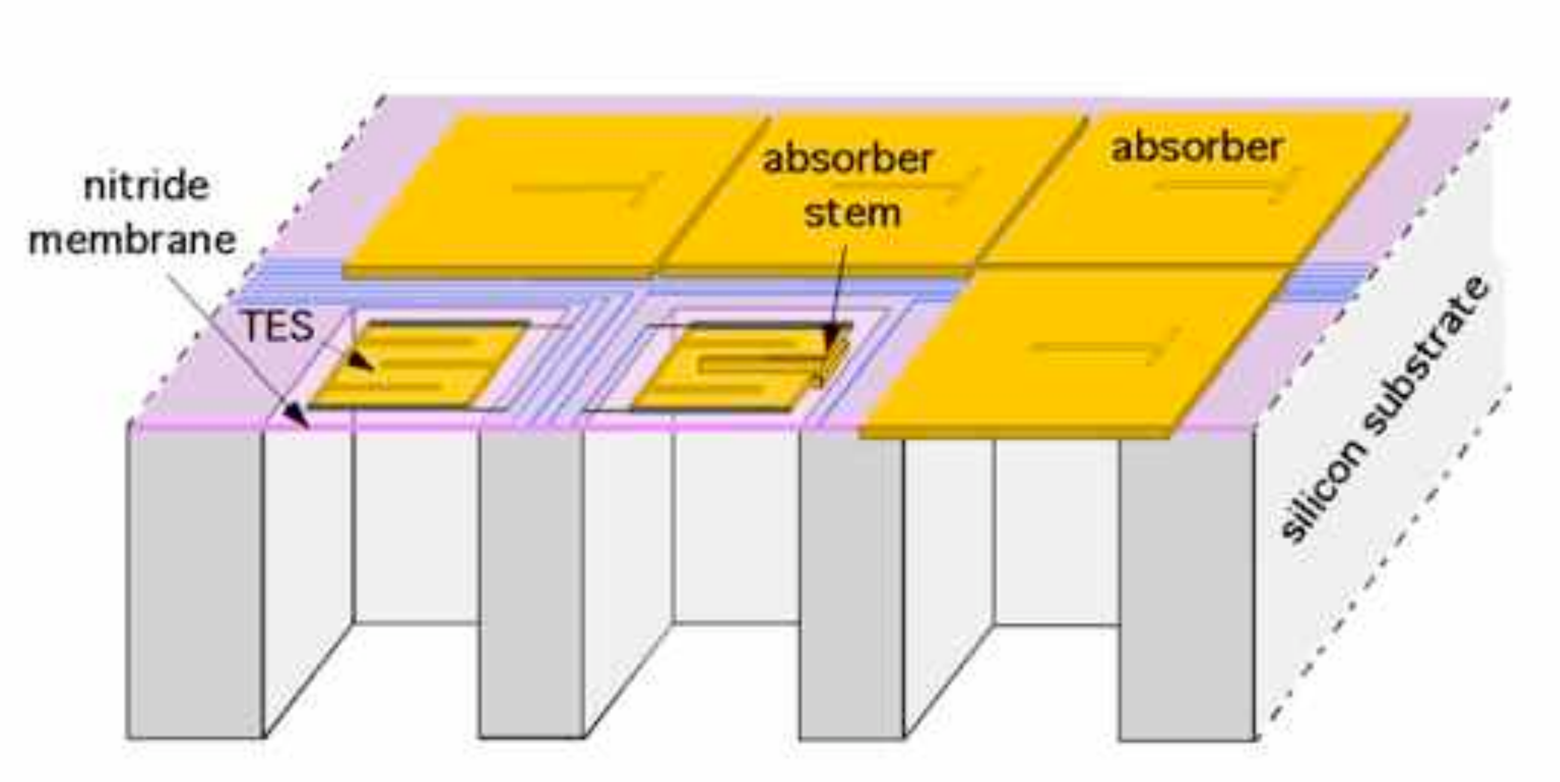
TES Anatomy

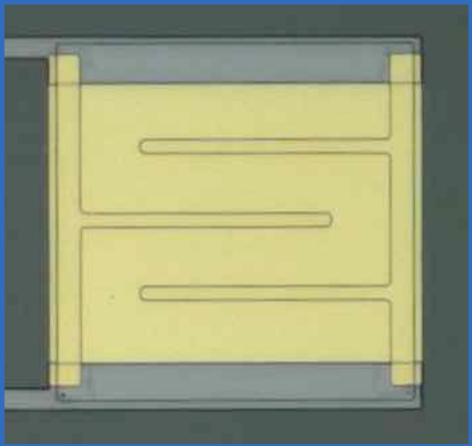

Nitride thermal link demonstrates ballistic transport – G depends on perimeter but not on extent
Normal metal features to reduce excess white noise
Silicon at 50 mK
Sensor
Leads

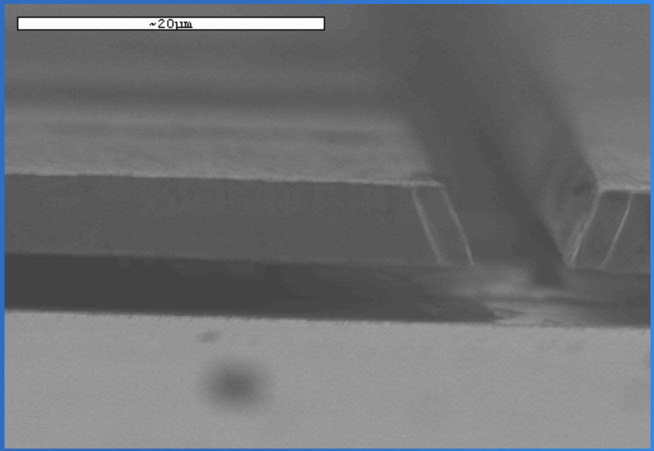
Design of reliable absorber contacts

- Touch in regions that are already normal
- Constrain contacts so that current will not be shunted through a high -conductivity absorber (high conductivity needed for uniform thermal response across absorber)
- Provide additional contacts outside the TES for mechanical stability.

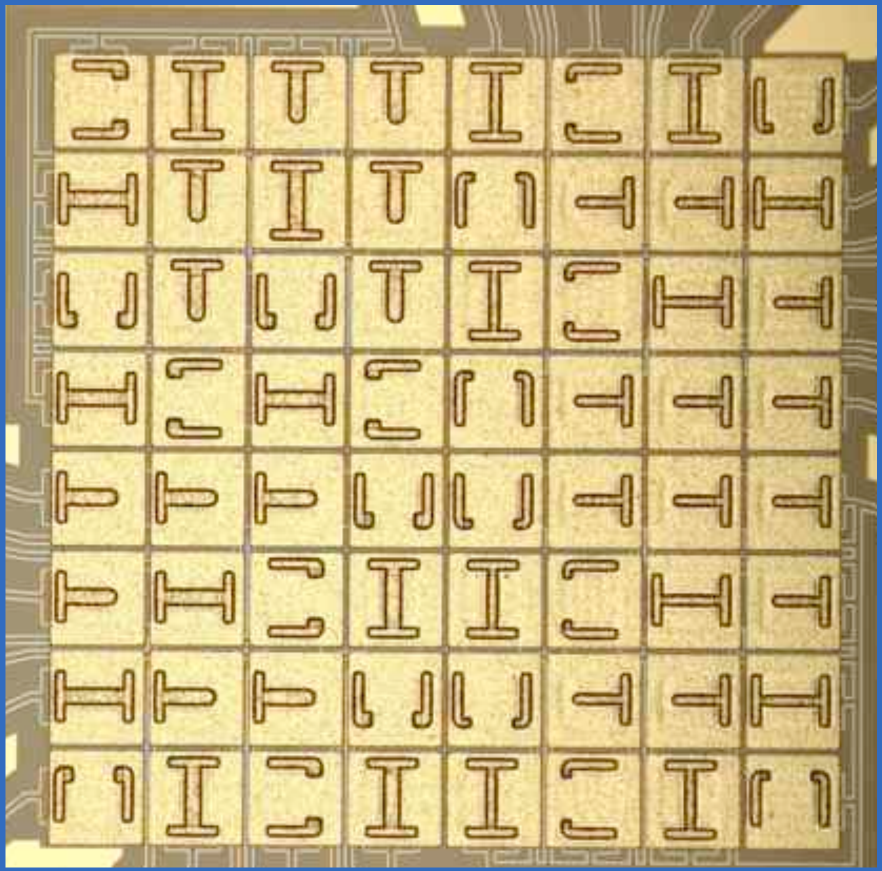
Robust array construction







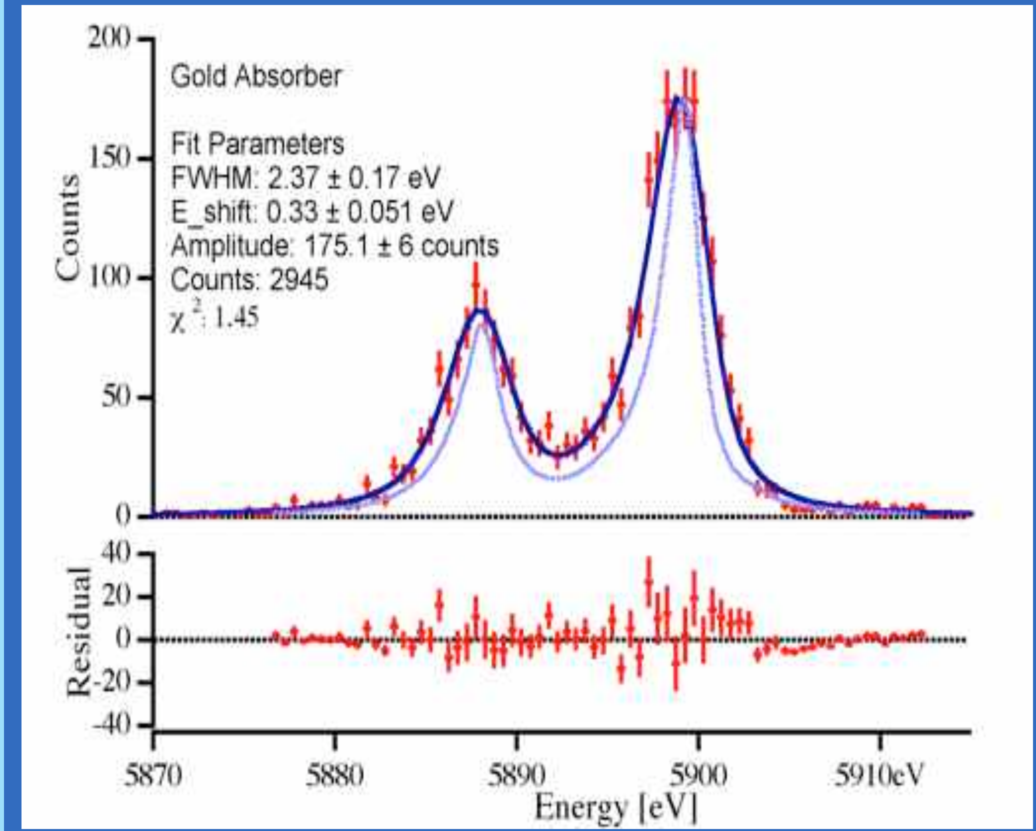
Earlier test arrays using electroplated Au and Au/Bi absorbers

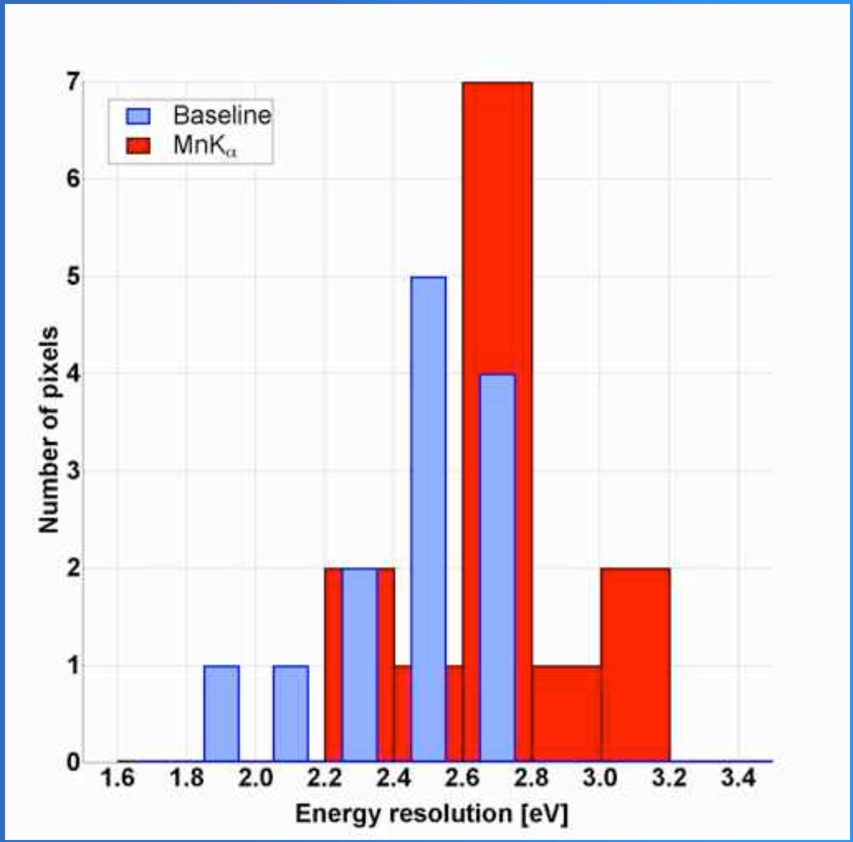


- Evaluated different geometries for the absorber contact area
  - Engineered to neither shunt current through the absorber nor change the properties of the TES
- Robust process
  - Routinely produce arrays of devices with better than 3 eV resolution at 6 keV
- $dT_c \sim \pm 0.1$ mK for devices of the same geometries
- T_c offsets between pixels of different types made common biasing (to reduce number of wires) impractical.

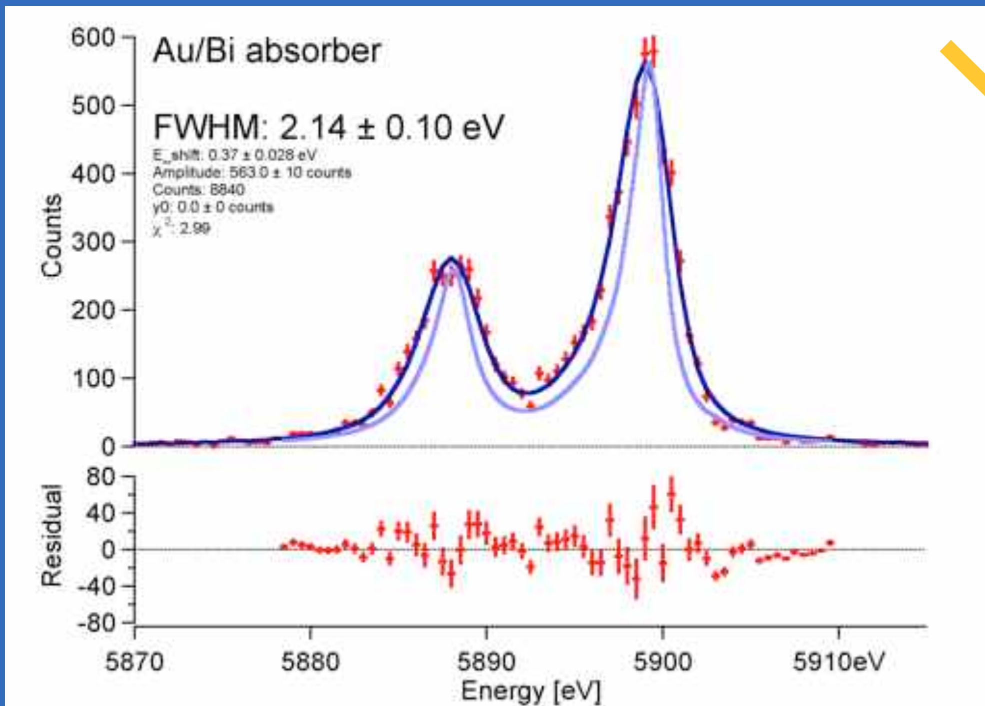
Resolution with Au absorbers

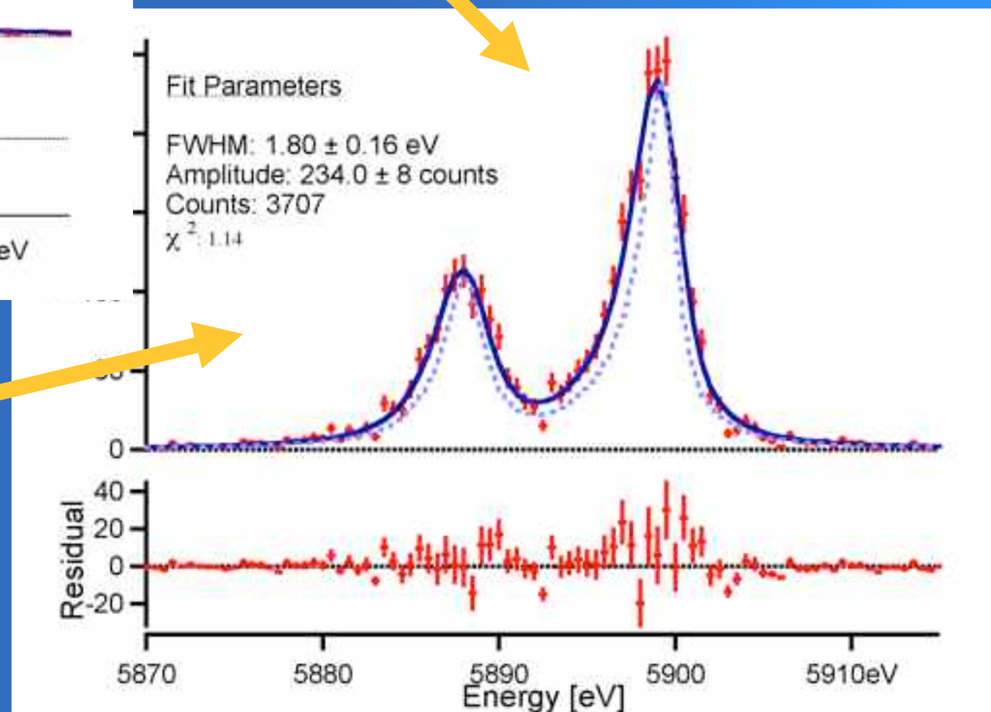
- 13 pixels ("T" and "J" design) on 3 arrays have demonstrated resolution better than 3.2 eV FWHM at 6 keV. (Bias point of each pixel not optimized.)
- Differences between results of different acquisitions on same pixel seen, due to combination of statistics and interference from activity in the lab





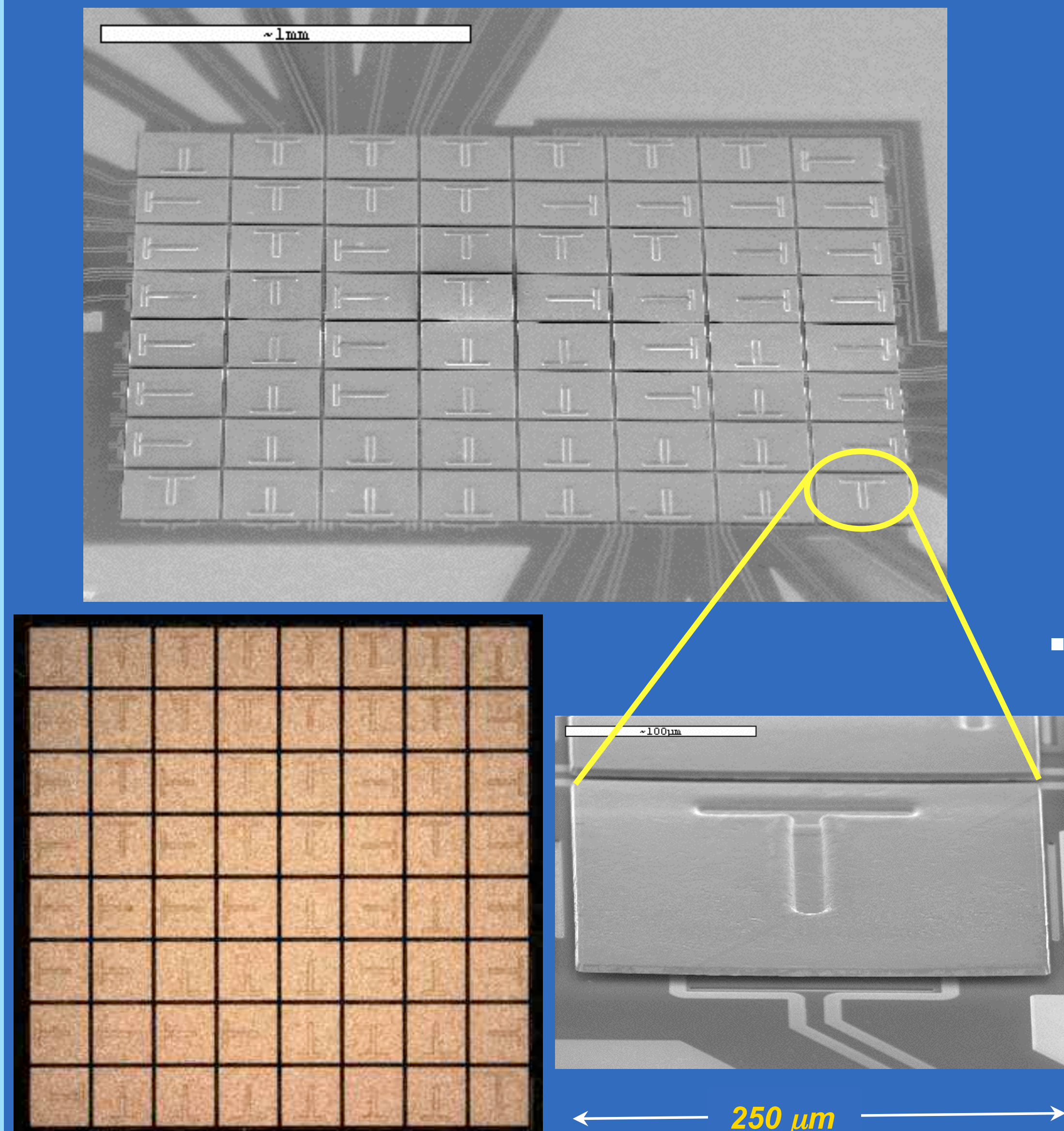
Au/Bi Absorbers (~ 1 μm Au, 4 μm Bi)





We made data cuts based on the DC level of the signal channel prior to a pulse, which is representative of the TES temperature just before the x-ray is absorbed. Such a cut removes sensitivity to slight variations in the TES bias point that may be due to any of a number of systems issues. Thus, 1.8 eV should represent the intrinsic resolution of this detector, for which we measured 2.1-eV resolution without the data cuts.

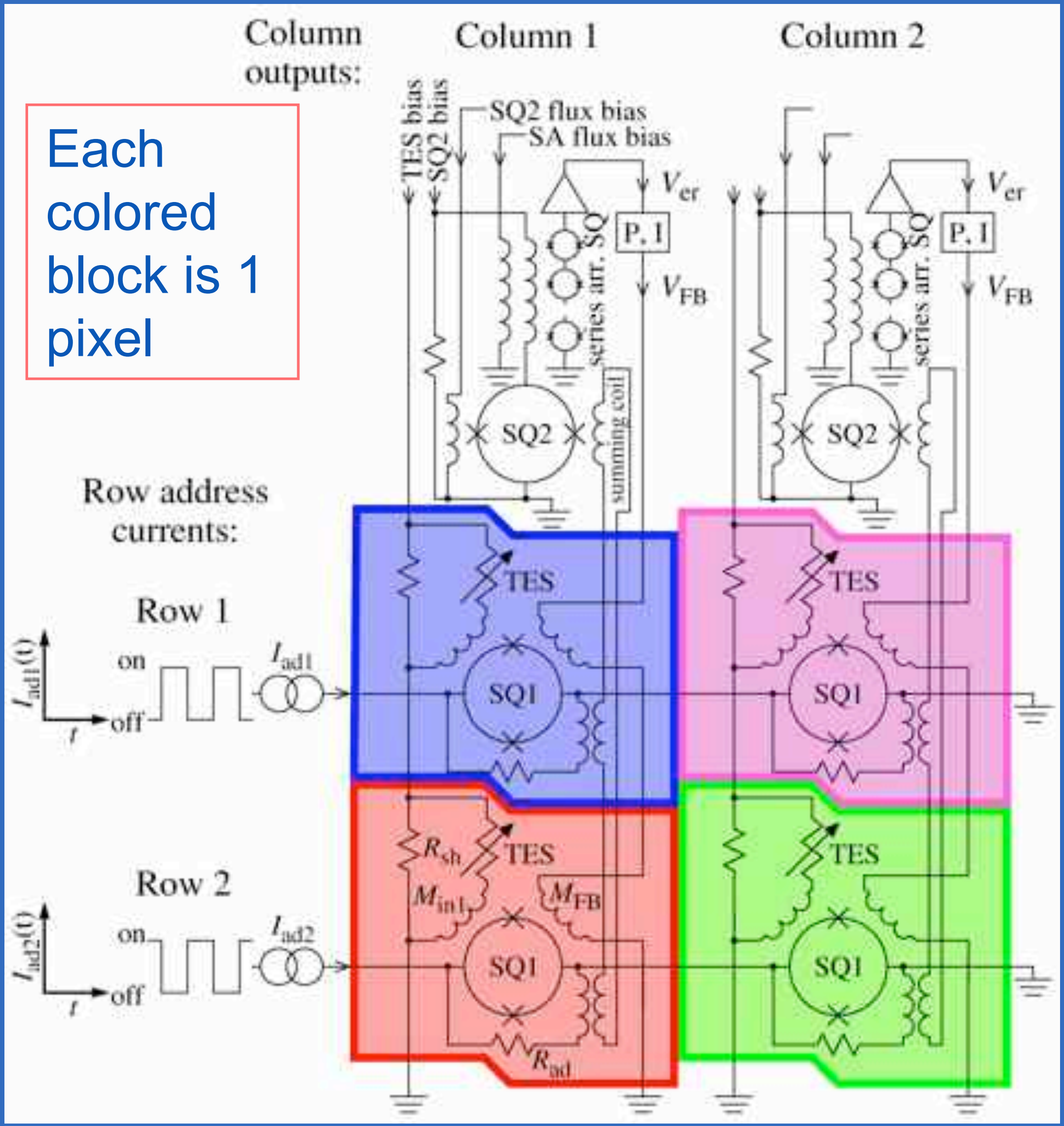
Uniform array



- Choice of absorber contact
  - No significant difference in best resolution achieved in “J” and “T”.
  - “T” design requires expanding the membrane on one side of the TES (whereas “J” requires it on both sides), thus leaving more of the thick silicon between pixels

- Choice of absorber composition
  - Can use Au/Bi composition to trade-off heat capacity and thermalization
  - Both layers electroplated
  - 2.5 μm Au / 3 μm Bi chosen for uniform arrays used for array -scale read-out demonstration

Array-scale read-out using NIST time-division multiplexing *(Irwin, Doriese)*



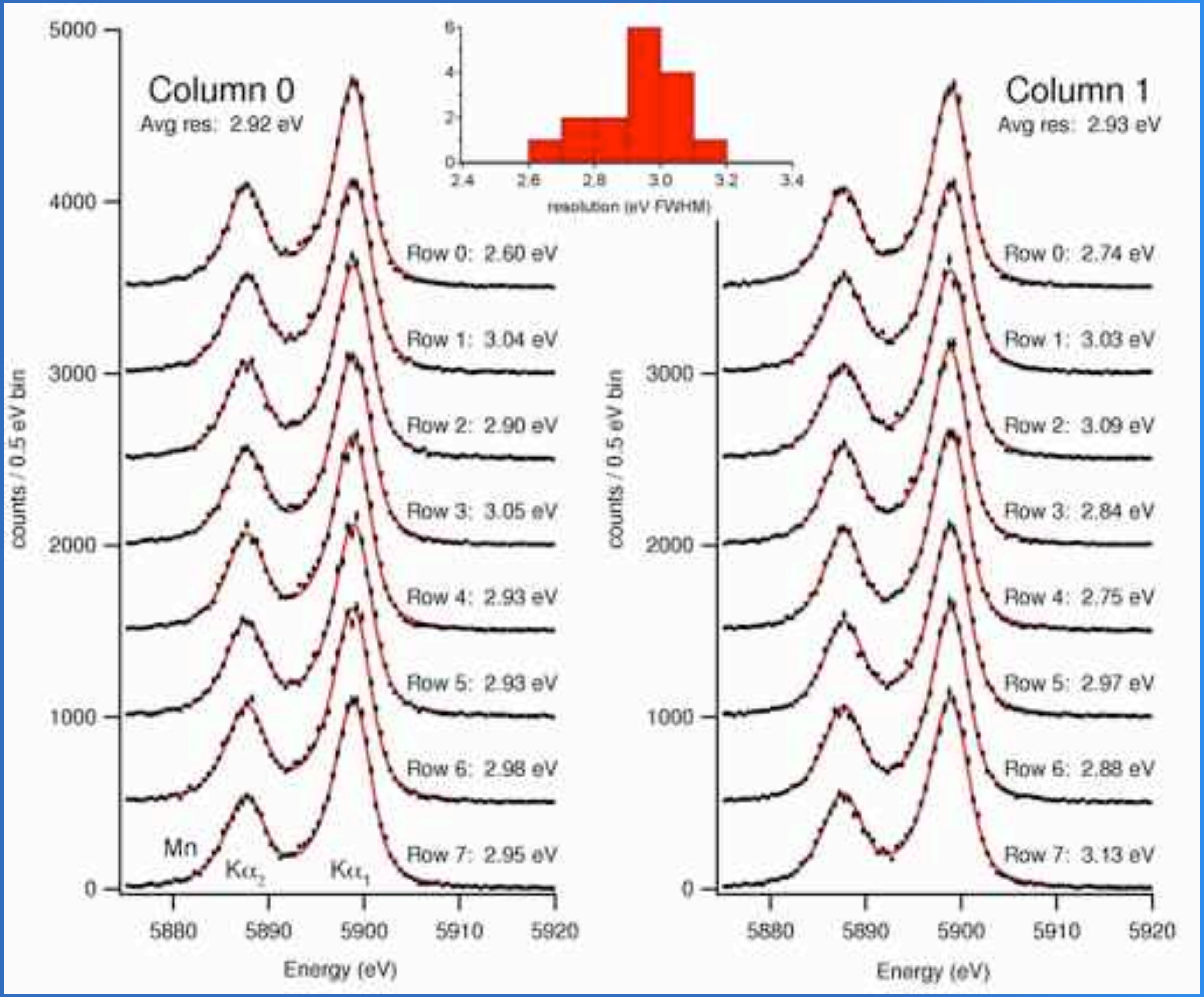
Each colored block is 1 pixel

- 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
  - wait for transients to settle, sample I_{TES}, move on
  - SQUIDs are nonlinear amplifiers, so use digital feedback
  - V_{er} sampled, V_{FB} stored for next visit to pixel
  - each column: interleaved data stream of pixels

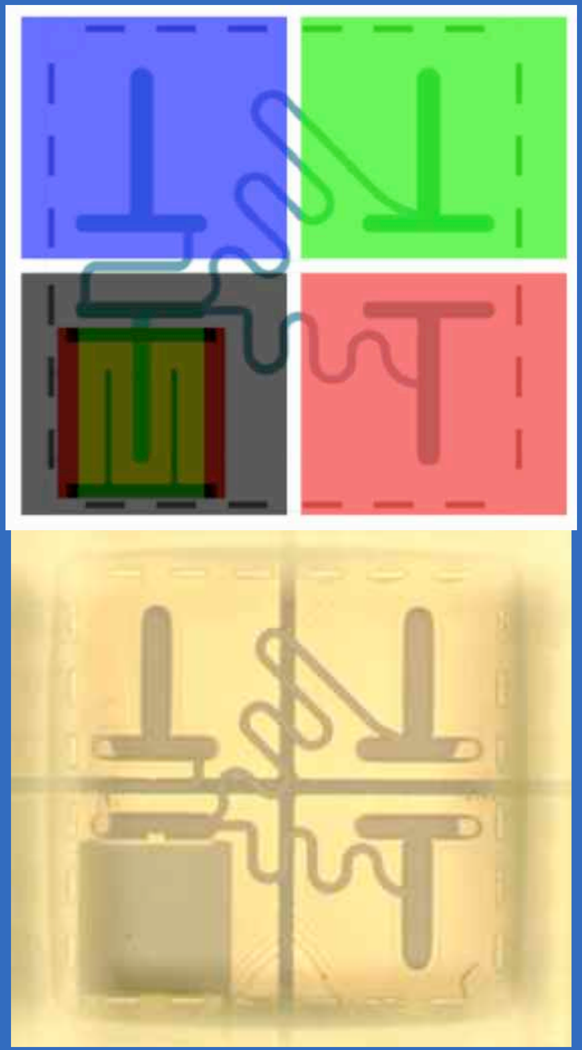
Why multiplex?
Multiplexing advantage for 32 x 32 array (1024 pixels):

- Not multiplexed:
  - 7 wire pairs per pixel
  - 7168 pairs total
  - 1024 electronics channels and FB loops
- Multiplexed:
  - 1 pair per row
  - 6 pairs per column
  - 224 pairs total
  - More manageable electronics
  - Lower heat load on cryogenic stages

Demonstration of 2x8 multiplexing of high-resolution TES pixels

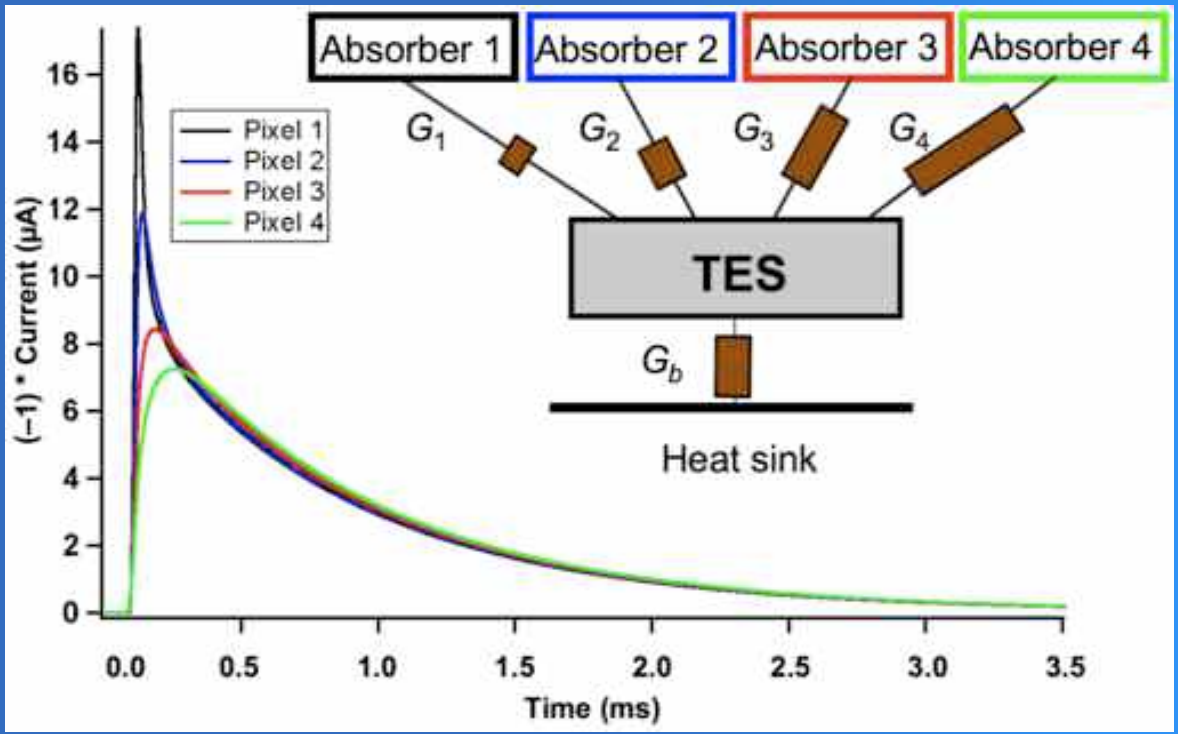


Single-TES, multi-absorber devices



view from back through nitride membrane

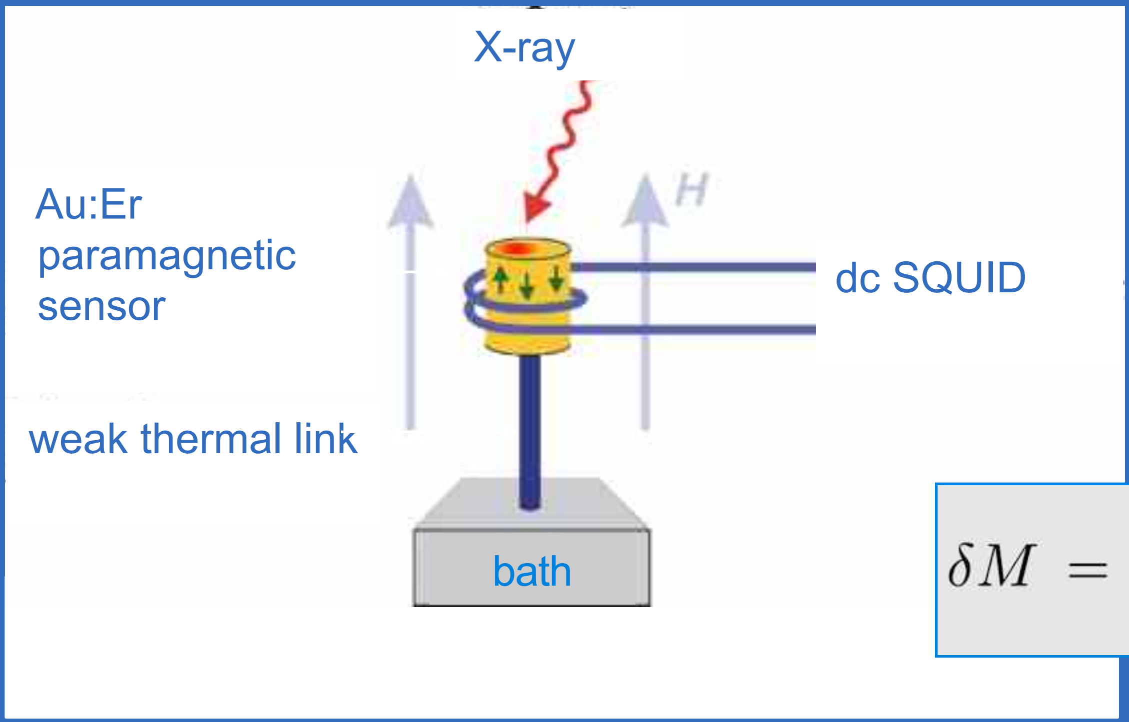
- 4 or more absorbers connected to single TES through different thermal links; absorber is identified by pulse shape
- achieved 6 eV resolution at 6 keV in a 4-pixel device



International X-ray Observatory (~2020)

- Reference design for IXO XMS instrument includes a >3000-pixel array using superconducting transition-edge sensor (TES) microcalorimeters with multiplexed SQUID readout (40x40 core with 2.5 eV resolution, surrounded by multi-absorber devices)
  - we've begun testing a 32x32 array at GSFC now
- **TES vs. thermistor (part 2):** Despite the in-flight proof of silicon -thermistor technology and its planned used for Astro-H,TES technology is necessary for larger arrays of higher-resolution elements for the following principal reasons:
  - the already demonstrated capability of SQUIDs to be multiplexed
  - the higher heat capacity, and thus greater design flexibility, afforded by their higher sensitivity
  - already demonstrated superior resolution (though just barely)
  - the ability to optimize for high resolution at somewhat faster speeds

Another promising approach
– the metallic magnetic calorimeter (MMC)



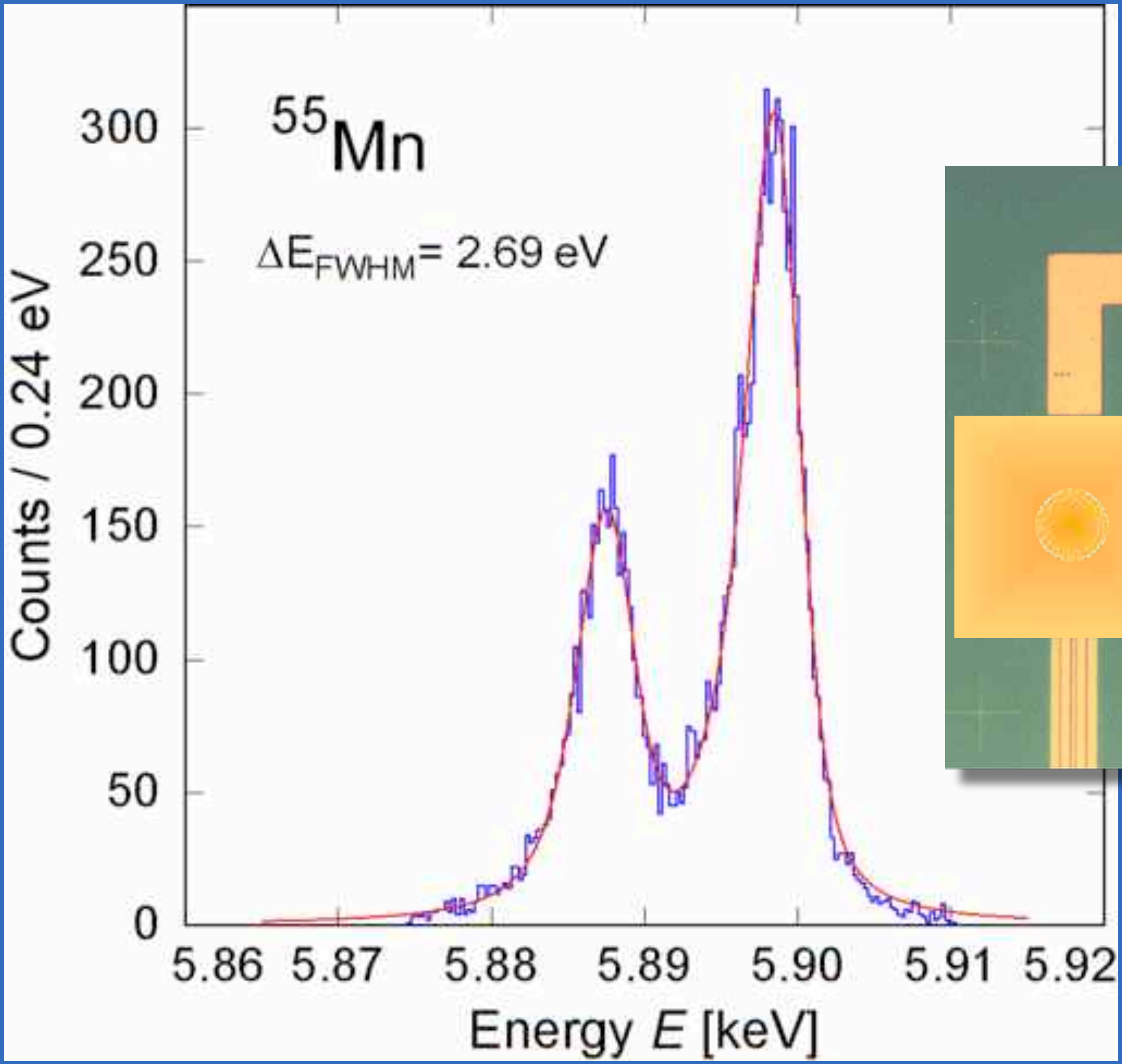
international MMC collaboration
led by S. Bandler (GSFC)
includes Brown, Heidelberg,
NIST/Boulder and PTB/Berlin

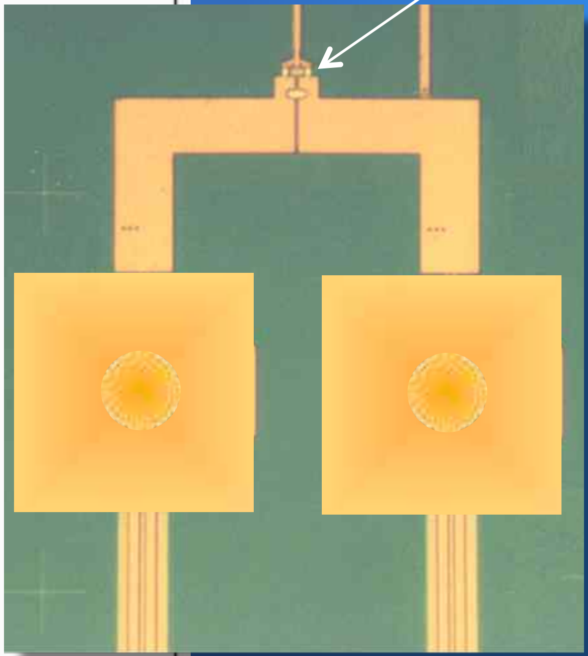
$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

- No heat dissipated
  - real advantage over resistive calorimeters for large arrays
  - pixels in TES arrays presented dissipated 4 – 8 pW each
- Sub-eV resolution possible at 6 keV

Best single-pixel MMC resolution - hand constructed in Heidelberg

(definitely in the same league as best Si-thermistor and TES-based devices)





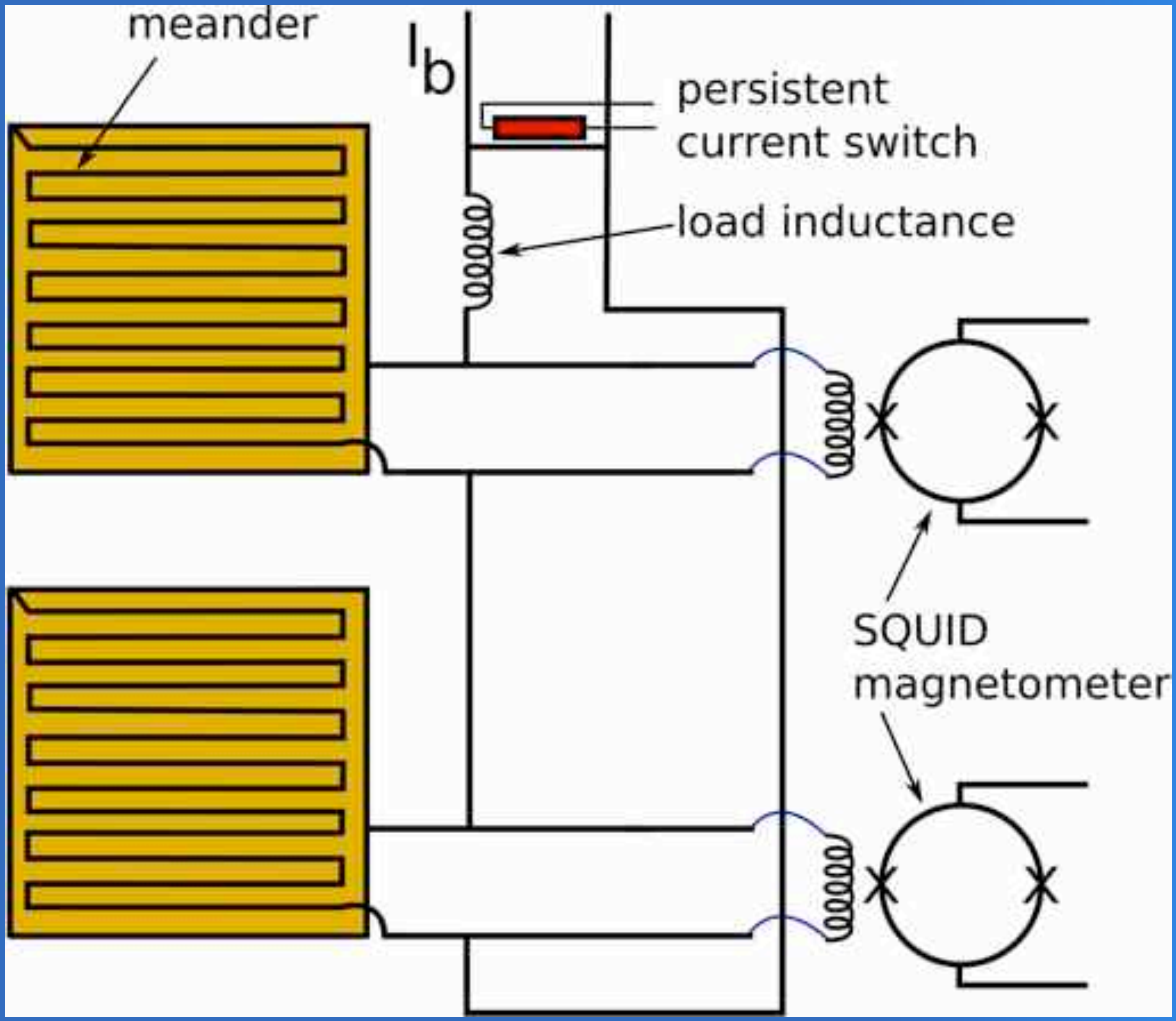
Au absorbers spot-welded within pickup coils:

180 μm x 180 μm x 5 μm

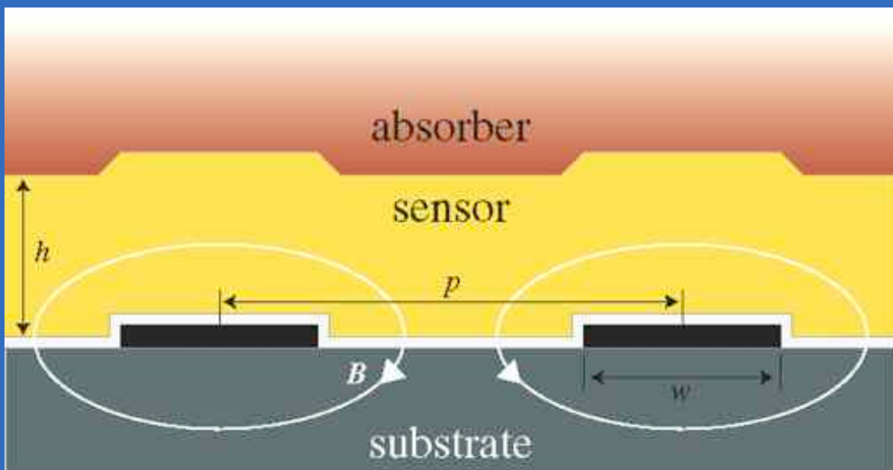
MMC arrays

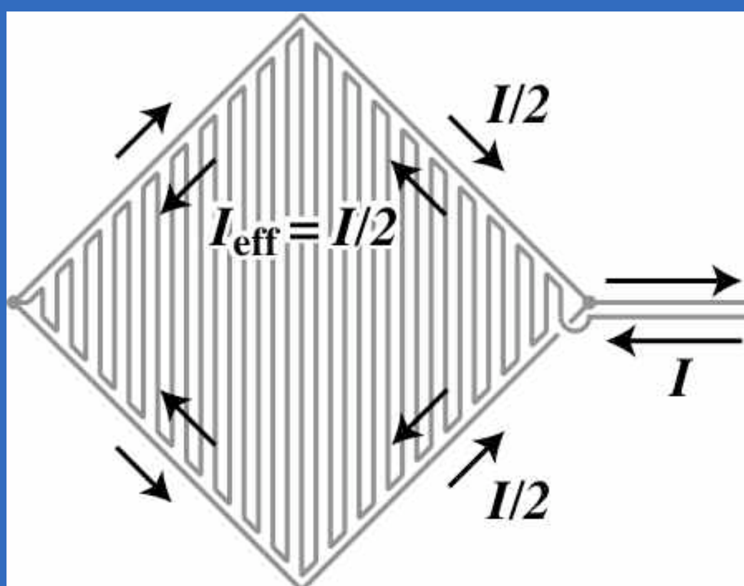
- magnetic-thermometer-in-SQUID approach cannot easily be extended to arrays
  - yield higher if SQUIDs and sensors fabricated separately
  - magnetic crosstalk a problem for close packed arrays
  - design requires a magnetic field applied to the sensor material at each pixel
- for close-packed arrays, meander geometries are more promsing
  - arrays of superconducting Nb meanders onto each of which a layer of magnetic material (Au:Er) is deposited
  - when a current passes through the meander, a magnetic field is produced in the magnetic material. No additional applied field required.
  - when an x-ray is absorbed, the heating changes the magnetic permeability, and, thus, the inductance of the meander
  - meanders placed in parallel with input coils of read-out SQUIDs, thus a change in inductance of the meander changes the current both through the meander and through the input coil of the SQUID

Read-out of MMC meander geometry



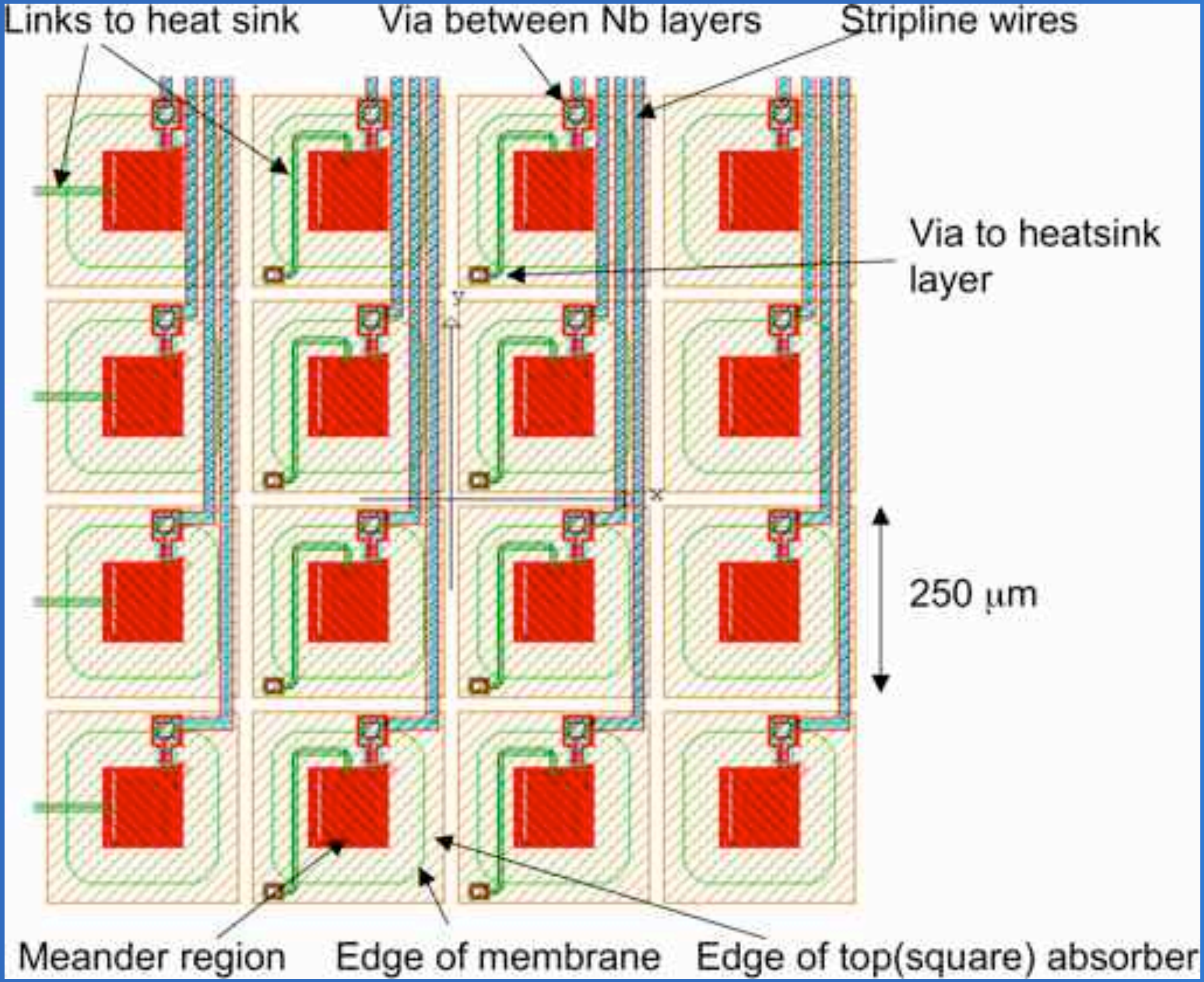
Geometry of MMC pixel with meander





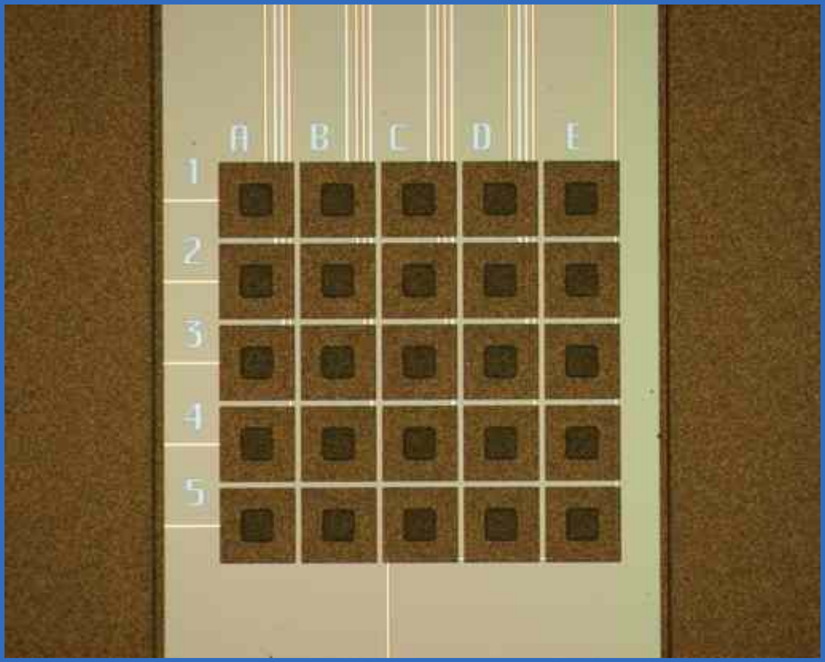
- 2d geometry with high filling-factor
- every part of sensor is in close proximity to a wire that connects to the SQUID pick-up coil
- No external field coils needed
- Negligible magnetic cross-talk between pixels - ~10^{-5}
- Reduced pickup of magnetic Johnson noise
- Thinner films needed - easier to fabricate

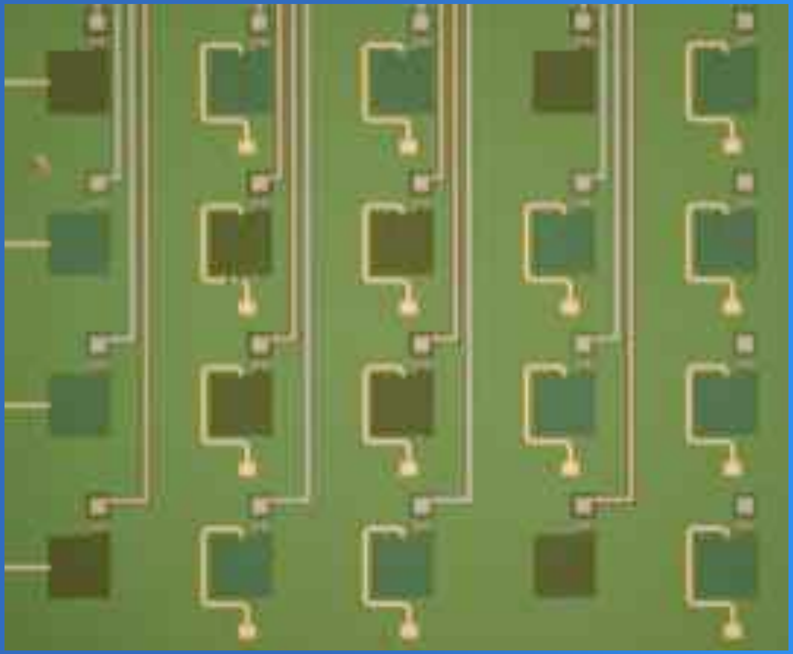
Experimental MMC array layout is similar to TES array

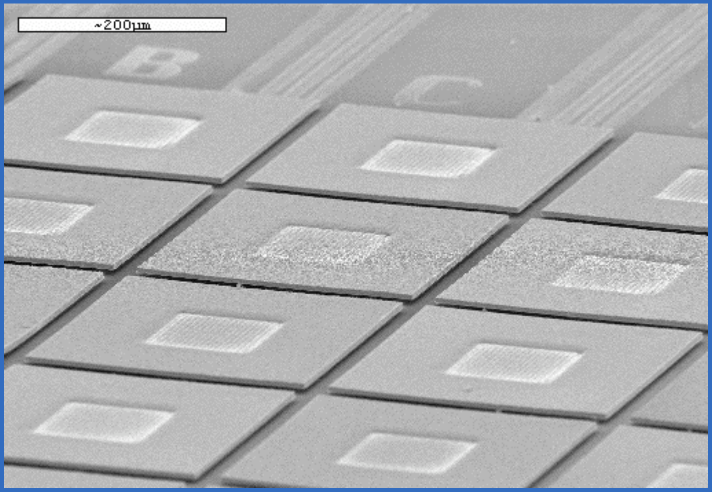


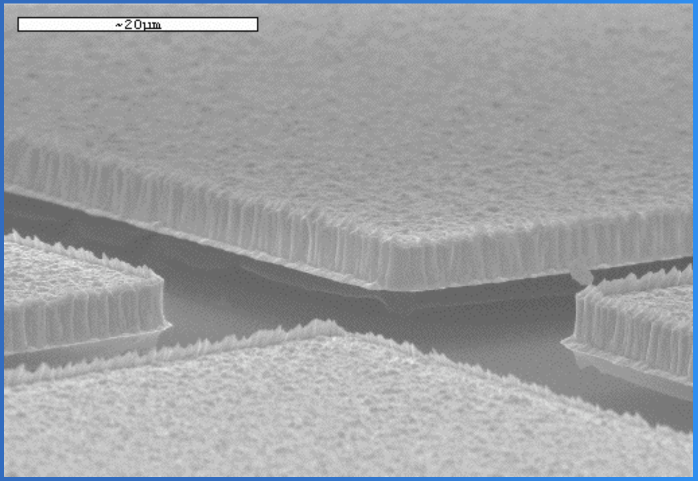
- thermal link is metallic; membrane used to impede loss of energetic phonons prior to thermalization, not as weak link

MMC arrays fabricated at GSFC

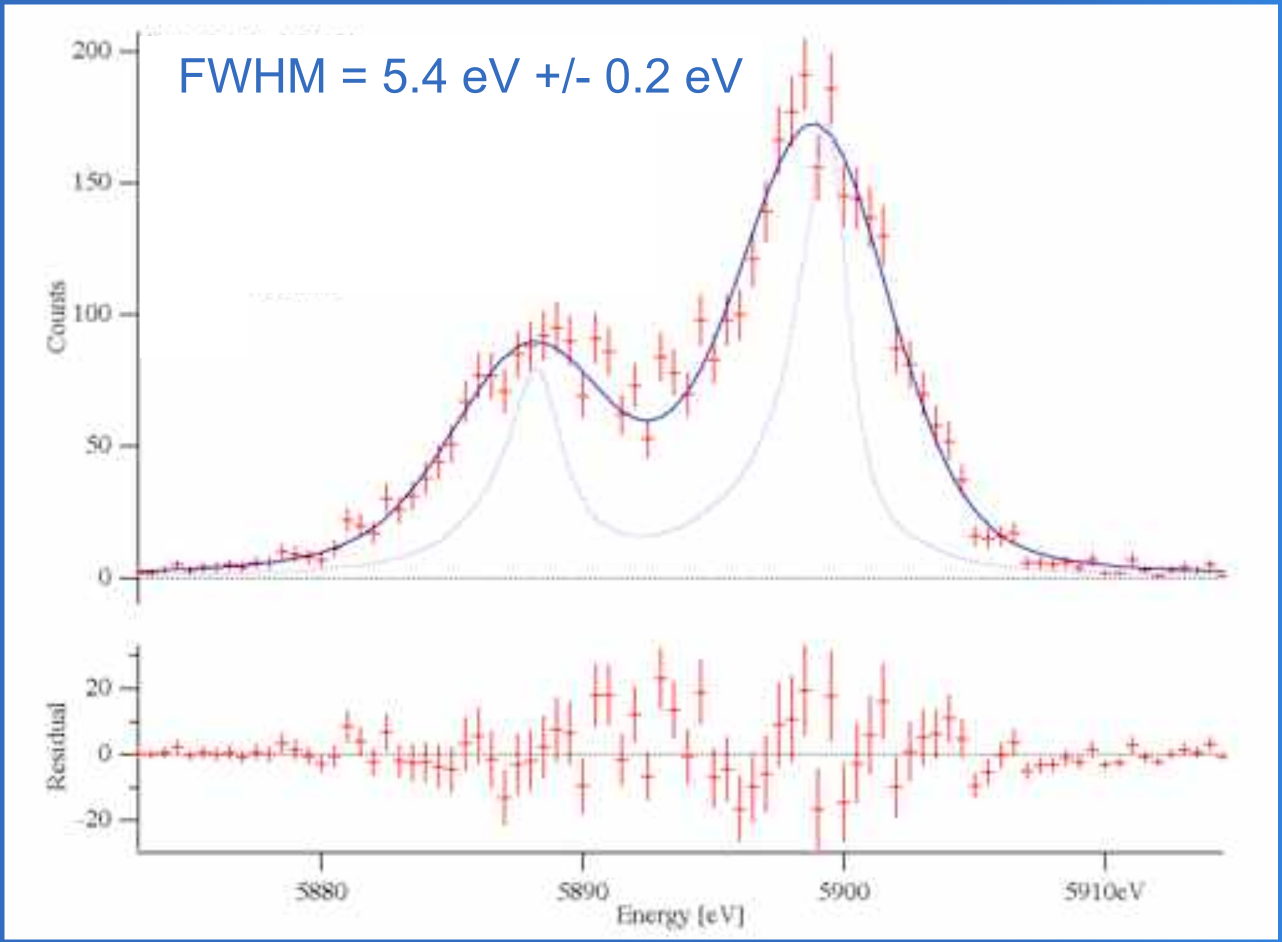








Best results in MMC meander



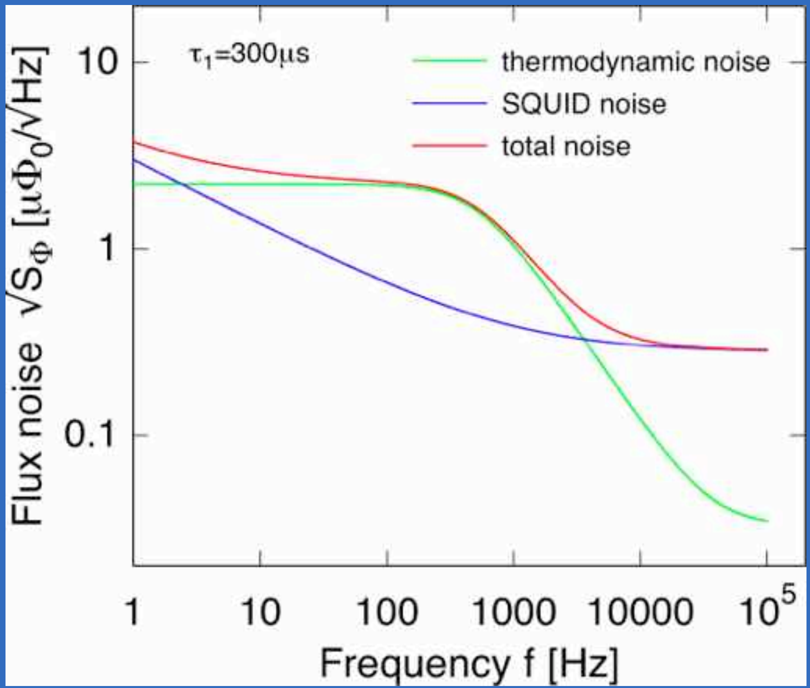
- limited by oxidation of Er, which resulted in lower temperature sensitivity than designed
- can also improve through lowering absorber heat capacity

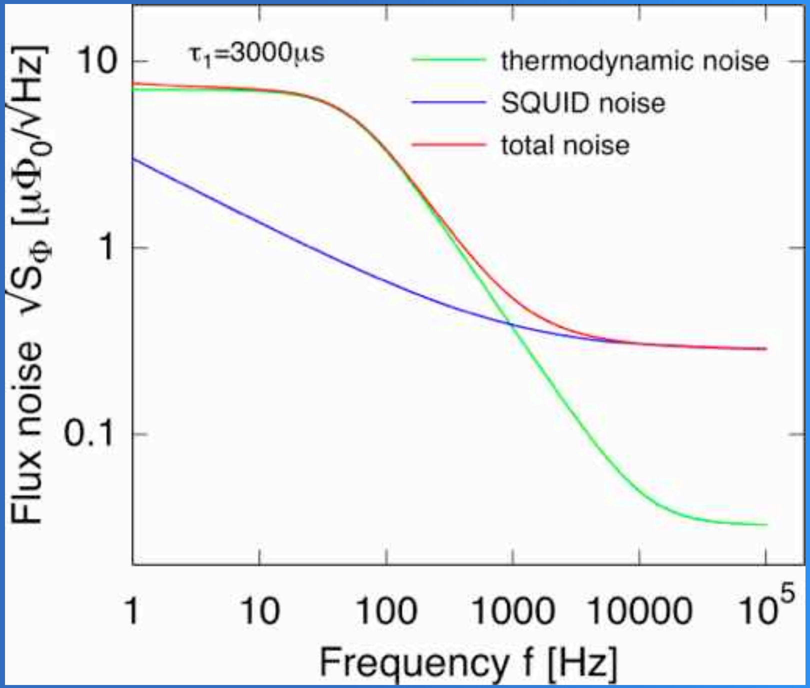
Optimization of MMC pixels – fundamental and practical

- fundamental band-limiting noise in an MMC comes from thermodynamic exchange of energy between the spin and electron systems, leading to:

$$\Delta E_{\mathrm{rms}} = \sqrt{4k_{\mathrm{B}}C_{\mathrm{e}}T^2}\left(\frac{1}{\beta(1-\beta)}\,\frac{\tau_0}{\tau_1}\right)^{1/4} \quad \text{with} \quad \beta = \frac{C_{\mathrm{z}}}{C_{\mathrm{e}}+C_{\mathrm{z}}}$$

- however, for realistic thermometer sensitivities, the SQUID noise is higher than the internal thermal fluctuation noise.





- Nonetheless, for C_{absorber} = 0.2 pJ/K at 40 mK, still predict energy resolution = 0.53 eV (FWHM) for τ_1 = 3 ms (= 0.91 eV (FWHM) for τ_1 = 300 μs)

X-ray calorimeter arrays for astrophysics – scale vs. time

- Astro-H
  - 2013
  - 32 – 64 pixels
  - silicon-thermistors and HgCdTe absorbers
- IXO
  - 2020?
  - kilopixels
  - TES with normal-metal absorbers
- Gen-X
  - 2030?
  - megapixels
  - MMCs?
  - **readouts need to move in step with detector arrays**
- hopefully there will be opportunities for smaller, targeted missions (outside of these observatory class satellites)
  - MIT-led micro-X sounding-rocket payload will have 128 TES channels scheduled for first flight in 2011

Other applications?

- ground-based x-ray spectroscopy
  - arrays not generally needed for imaging, but to increase the area of high -resolution sensor
  - materials analysis
  - plasma physics
    - GSFC has facility calorimeter instrument at LLNL EBIT
- other energy quanta
  - other photon bands
  - particle spectroscopy
  - ….
- versatile concept
  - whether feasible for any given application depends on the requirements of the experiment and practical considerations

GSFC x-ray calorimeter team

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- Regis Brekosky
- Ari-David Brown
- Jay Chervenak
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- Wen-Ting Hsieh
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- Thomas Stevenson

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- MIT: Enectali Figueroa