Workshop on X-ray Mission Architectural Concepts

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Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission – Options, Status, and Roadmap

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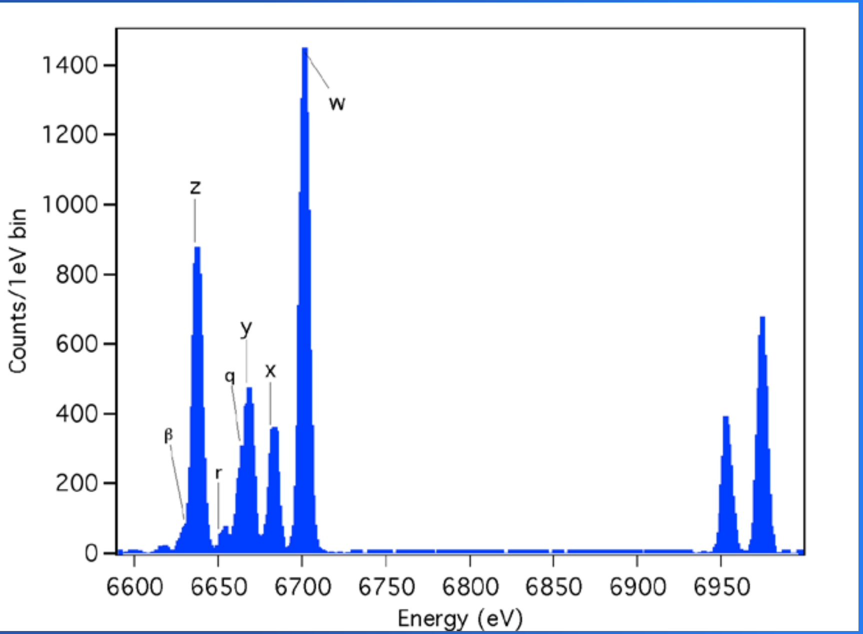


Outline

- Why high-resolution detectors are low-temperature detectors
- Leading technologies
- Multiplexed read-out
- Technology roadmap

High-resolution imaging spectroscopy requires low-temperature detectors

Non-equilibrium:

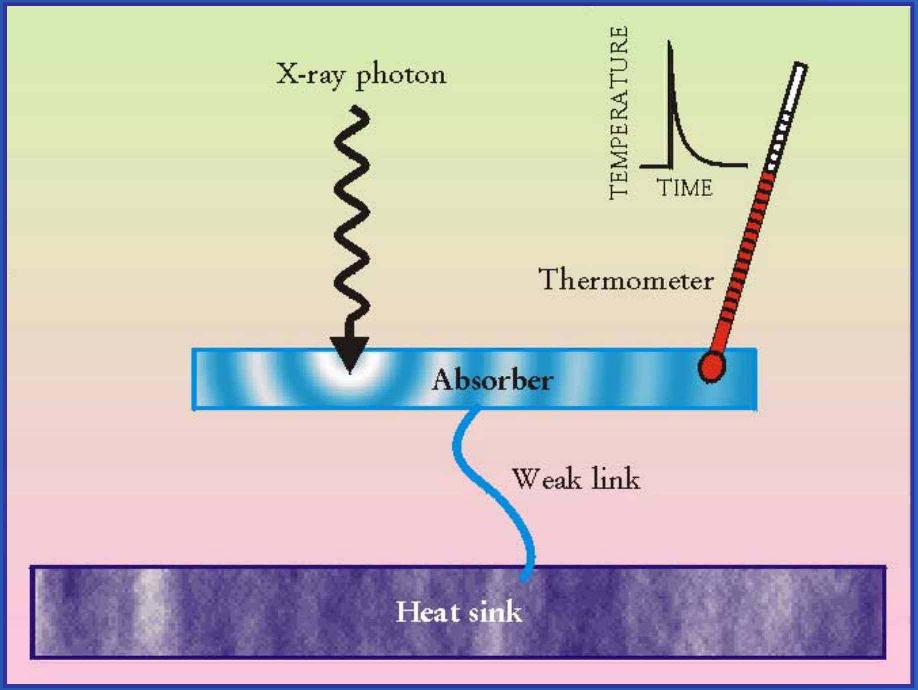
- Energy creates quantized excitations ($E >> kT$)
- Number of excitations proportional to E
- Fano-limited resolution
- *Low temperature* required to avoid thermally generated excitations

Equilibrium:

- Sensor is in thermal equilibrium – ΔT proportional to $\Delta E/C$
- Resolution from accuracy of measuring ΔT on background of T fluctuations
- *Low-temperature* needed to minimize thermal fluctuations and lower C

** For eV-scale resolution, $T < \sim 0.1$ K is required. **

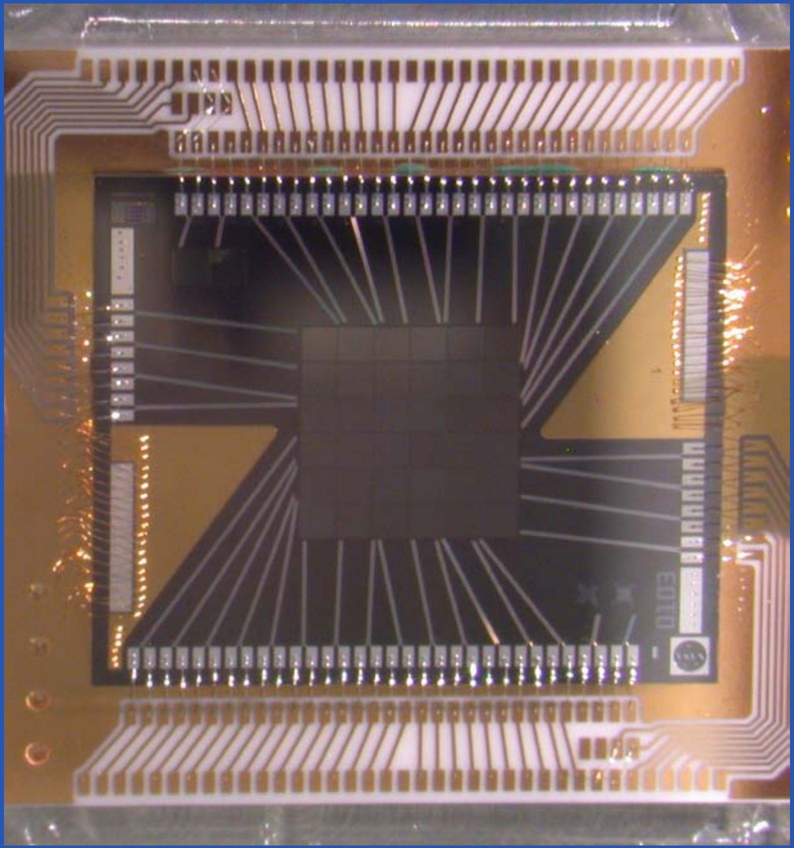
Highest resolution demonstrated with equilibrium devices (microcalorimeters)



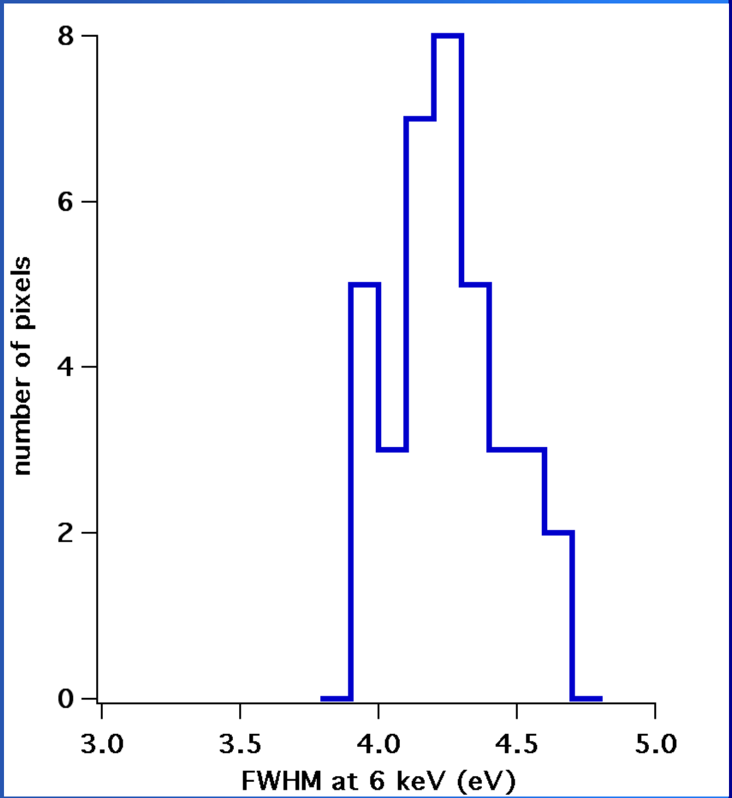
- Thermometers can be based on: resistance, capacitance, inductance, paramagnetism, magnetic penetration, electron tunneling …
- The leading technologies:
  - Resistance (semiconductor thermistors and resistive transition of superconductors)
  - Magnetically coupled calorimeters

Silicon thermistor-based calorimeter array for Astro-H

- Base temperature of 50 mK
- 36 pixels – silicon thermistors on 0.83 mm pitch with HgTe absorbers
- Resolution at 6 keV ranges from 3.6 – 4.6 eV across EM and FM arrays
- Lack of large-scale read-out technology limits arrays to a few hundred pixels
  - Further investment warranted if technique for multiplexing is demonstrated

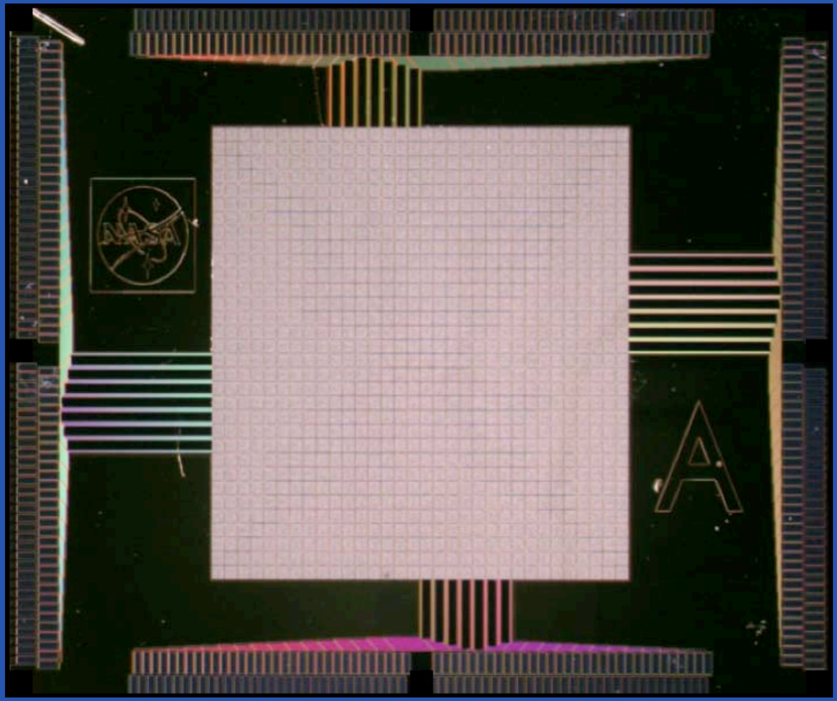


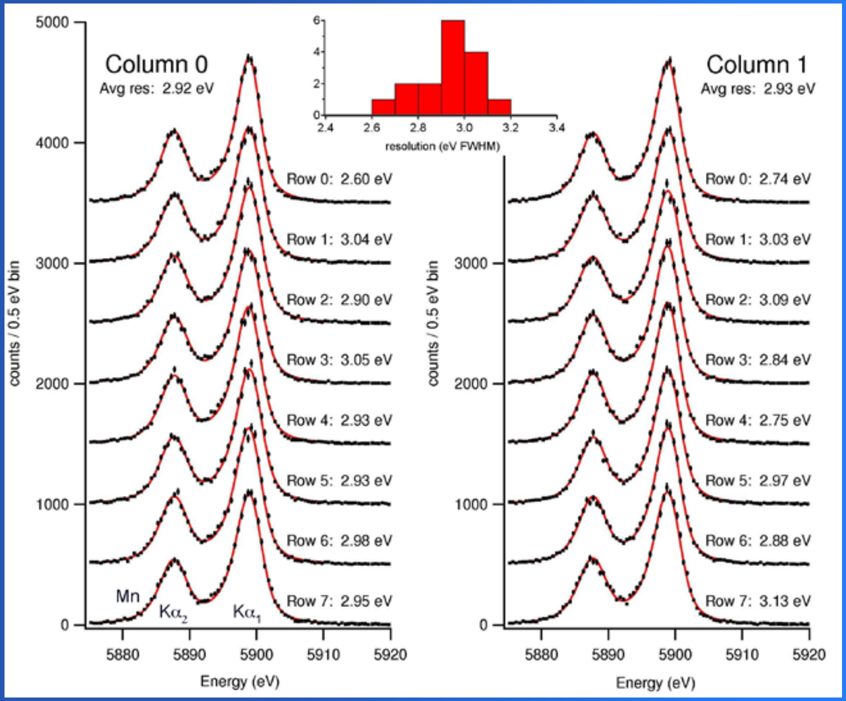
SXS FM candidate array



Transition-edge sensors (TES) – IXO/XMS baseline

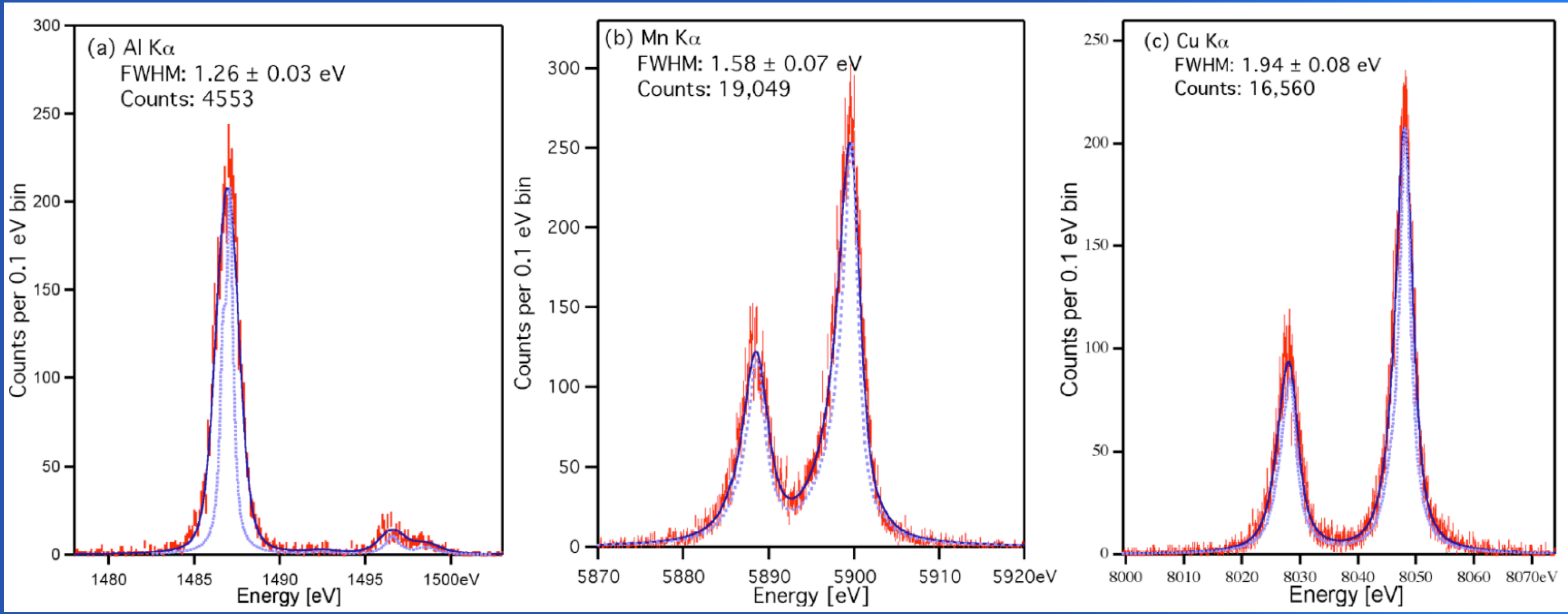
- Temperature and current dependence of the transition from the zero-resistance to normal-resistance state used for thermometry
- XMS reference design based on GSFC TES design
  - Membrane-isolated Mo/Au TES with T_c ~ 90 mK, (base temperature at 50 mK)
  - Electroplated Bi/Au absorbers, 0.25 – 0.30 mm pitch
  - 1.8 eV resolution demonstrated, 2 – 3 eV routine in this design
  - Multiplexed SQUID read-out close to requirements for few-thousand pixel array
  - 32x32 arrays with microstrip leads successfully fabricated





TES – smaller pixels

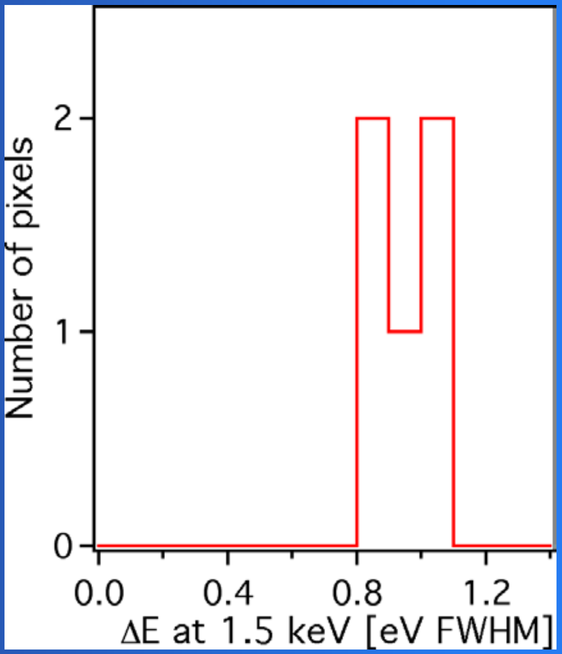
- Small pixels suited to shorter focal lengths and/or higher spatial resolution
- In small TES devices, T_c depends sensitively on current – extends linear operating range of pixels
- Don't need membrane isolation; small size limits coupling to solid substrate
  - Heat sinking of solid substrate minimizes thermal crosstalk
- Through choice of T_c, can be optimized for speed or resolution.

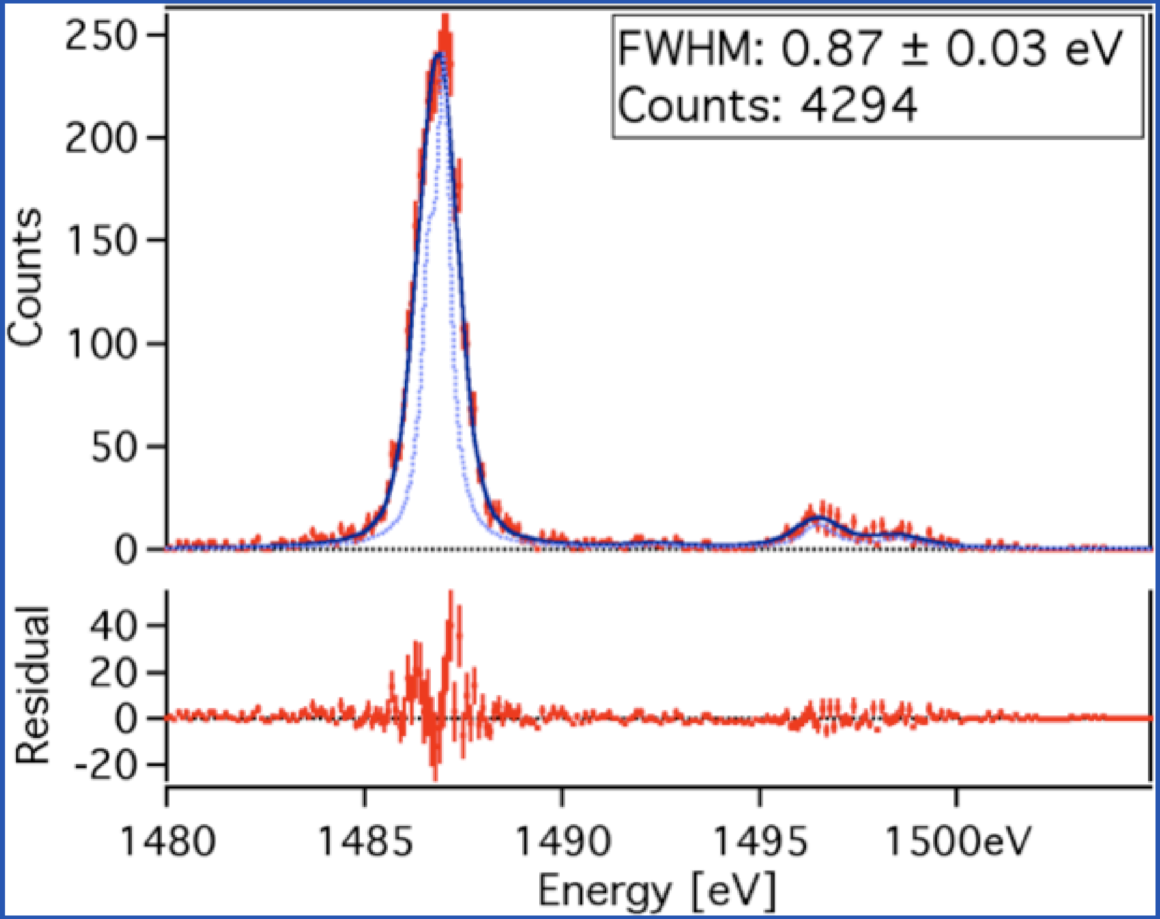


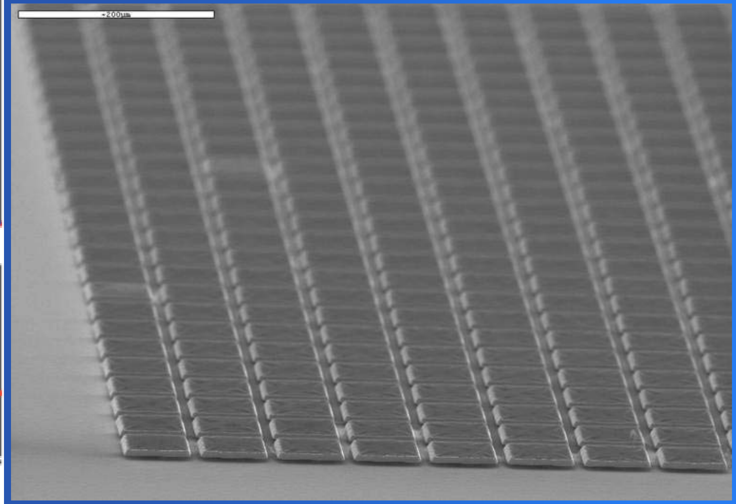
0.057 mm pixel with 0.03 ms time constant

TES – sub-eV resolution

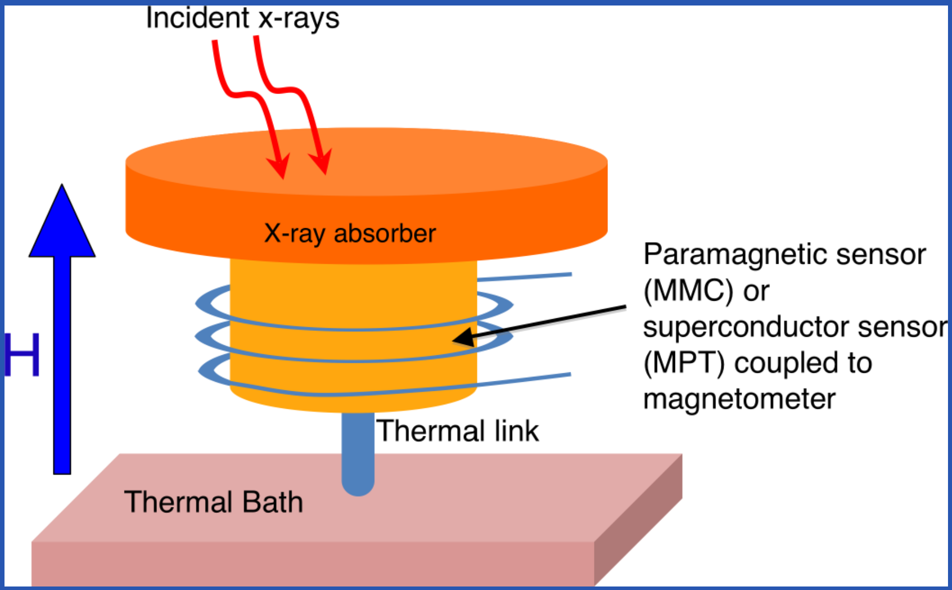
- TES on 0.075 mm pitch
- Au absorber: 0.065 mm x 0.065 mm x 0.0045 mm
- Design uses relatively slow pixels (1.6 ms decay times)

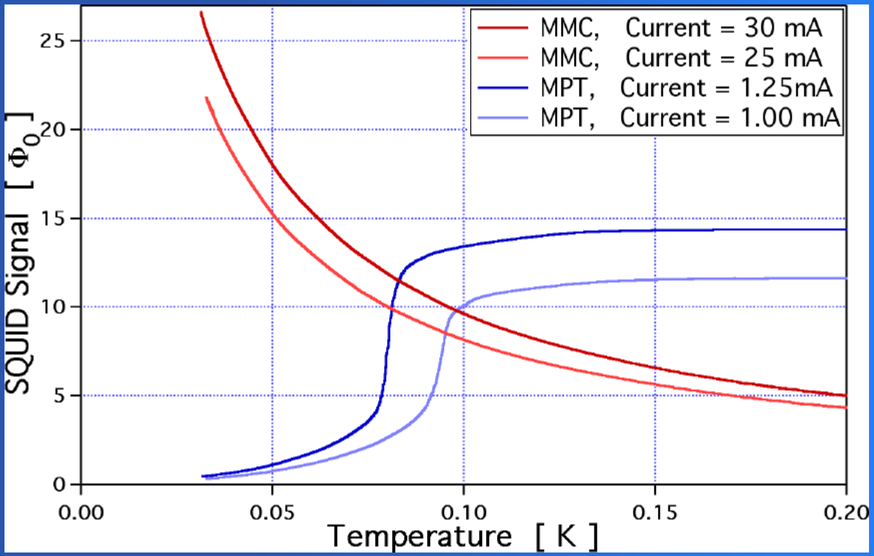






Inductive thermometers – using temperature dependence of paramagnetism or magnetic penetration of a superconductor





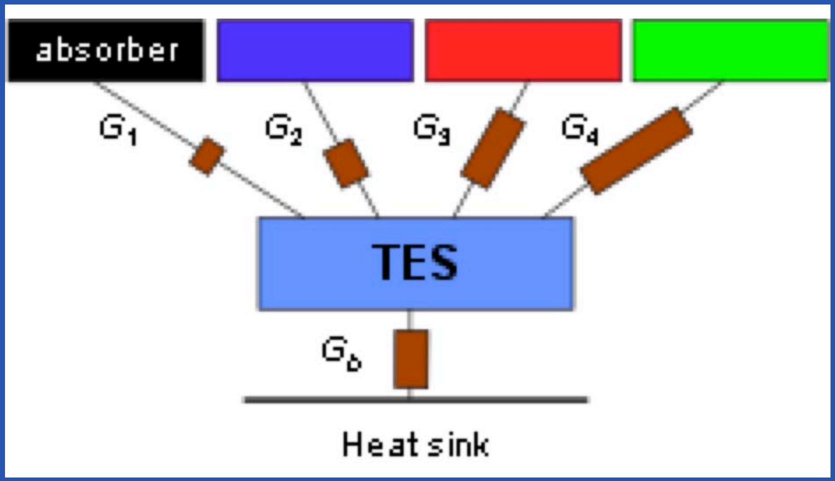
- Arrays of Nb meanders with layer of magnetic material (Au:Er) or a low-Tc superconductor (Mo/Au)
  - change of magnetization measured as change of inductance
- The Heidelberg group has achieved just better than 2.0 eV resolution at 6 keV with a Au:Er metallic magnetic calorimeter (MMC)
- GSFC group recently obtained 2.3 eV resolution with Mo/Au magnetic penetration thermometer (MPT).

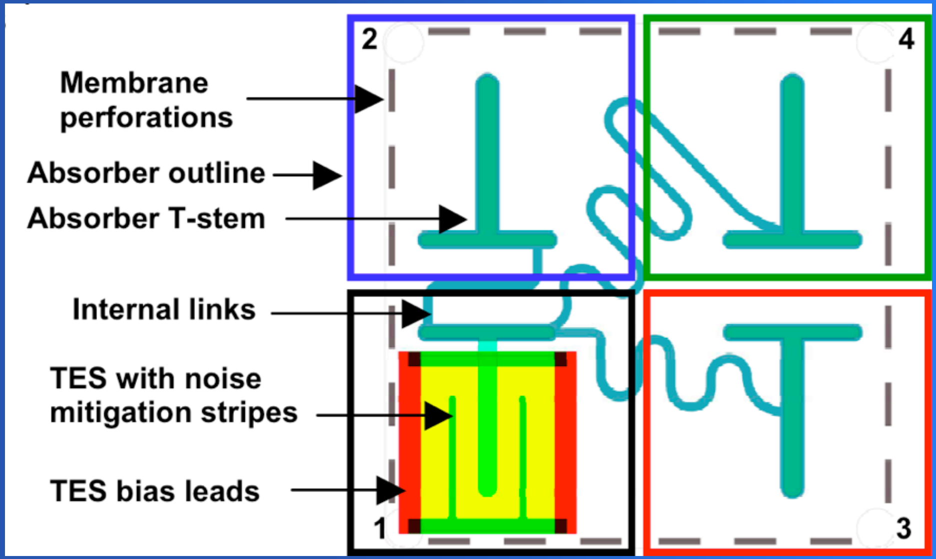
Magnetically coupled calorimeters (MCC) compared with TES

- MCCs are intrinsically dissipationless
  - very large-format focal-plane arrays
- MCC sensor material is electrically isolated
  - can be directly connected to metallic heat sink – simplifying reduction of thermal crosstalk
- Dissipation in TES calorimeters allows electrothermal feedback
  - stabilizes operating temperature, relaxing temperature stability required at heat sink
- TES read-out allows easy signal filtering, simplifying multiplexing.

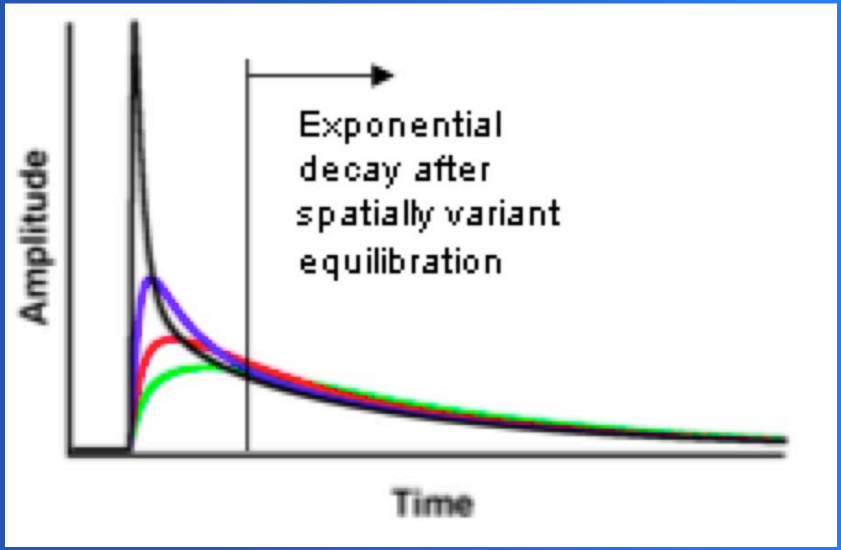
Each has advantages and disadvantages – parallel investment in both TES and MCCs is recommended

Using the non-equilibrium signal in equilibrium devices for position discrimination





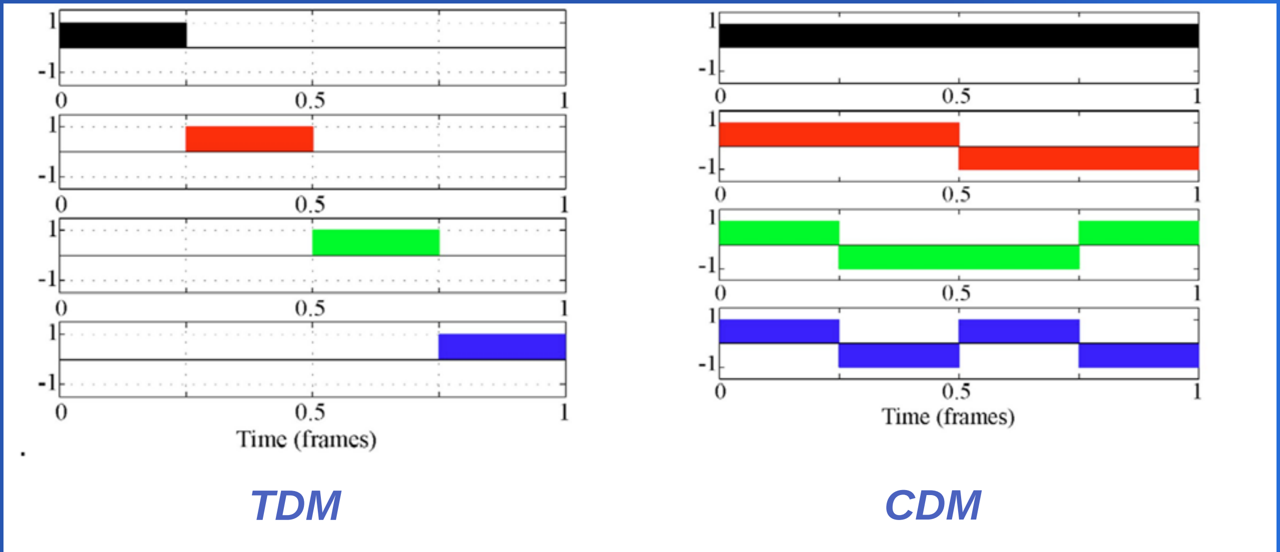
- Multiple absorbers connected thermally to the same thermometer via different thermal links
- Demonstrated for TESs and MMCs
  - 2.6 eV resolution obtained in 9-pixel TES device with 0.065 mm pixels
- Ideal "hydra" obtains somewhat worse resolution than for one big pixel of the same area due to thermal fluctuations between the absorbers



Superconducting Non-equilibrium Detectors

- X-ray energy breaks Cooper pairs in a superconductor into quasiparticles. Microwave kinetic inductance detectors (MKIDs) are one technique for measuring the number of quasiparticles produced.
  - quasiparticles are trapped near sensitive element of a microwave resonator.
  - measure change in kinetic inductance from change in quasiparticle density
- Intrinsic advantages:
  - speed of signal and high multiplexibility of MKIDs
- Intrinsic disadvantages:
  - good energy resolution not demonstrated
  - competitive resolution at 6 keV not even theoretically possible with Nb
- Not best match to IXO science; could be important for other experiments not requiring highest-resolution spectroscopy

Multiplexed read out: switched SQUID multiplexing



- XMS reference design included time-division multiplexing (TDM)
  - Individual TES pixels are coupled (via each pixel's SQUID) to a single amplifier
  - Multiplexed by sequential switching between SQUIDs
  - Used in TRL-4 TES read-out demo in 2008 (2.6 – 3.1 eV across 16 mux'd TESs)
- Code Division Multiplexing (CDM) will soon reach TDM TRL level
  - All pixels ON all the time, polarity of coupling is switched
  - CDM has a sqrt(N) noise advantage over TDM, where N is the multiplexing scale
  - IXO/XMS noise budget extremely tight – CDM could provide important margin
- CDM demonstrated: < 3 eV on 16 switched pixels using flux-matrixed CDM

Frequency domain multiplexing (FDM)

- TES bias modulation
  - Different TES pixels AC-biased at different frequencies read out by single SQUID
  - X-ray pulses seen in amplitude modulation
  - Like CDM, pixels on all the time, imparting a sqrt(N) advantage over TDM
  - However, in identical pixels tested with AC and DC bias, significantly better resolution was obtained in the DC bias case, which may be fundamental
- Microwave multiplexing
  - Pixel electronics form high-Q microwave resonant circuits (GHz scale), hundreds of which can be combined on a single coax
  - For MKIDs the sensor itself is part of the resonator
  - For TESs, MMCs, and MPTs, an unshunted rf SQUID is incorporated into the read out of each pixel, which is in turn coupled to a resonant circuit
  - Likely to be needed for pixel scales > ~10,000

Technology roadmap

- SCOPE
  - Impossible to define a generic technology roadmap for new mission concepts that meet all or some of the original IXO scientific objectives.
  - Thus, we have kept close to the original XMS baseline for the detector system for the projected roadmap and cost, with an allowance for alternate technologies to merge into the flow.
  - Development of many of the alternate technologies is already funded for other applications.
  - **The IXO/XMS roadmap is representative of the roadmaps needed for other LTD-based instruments**

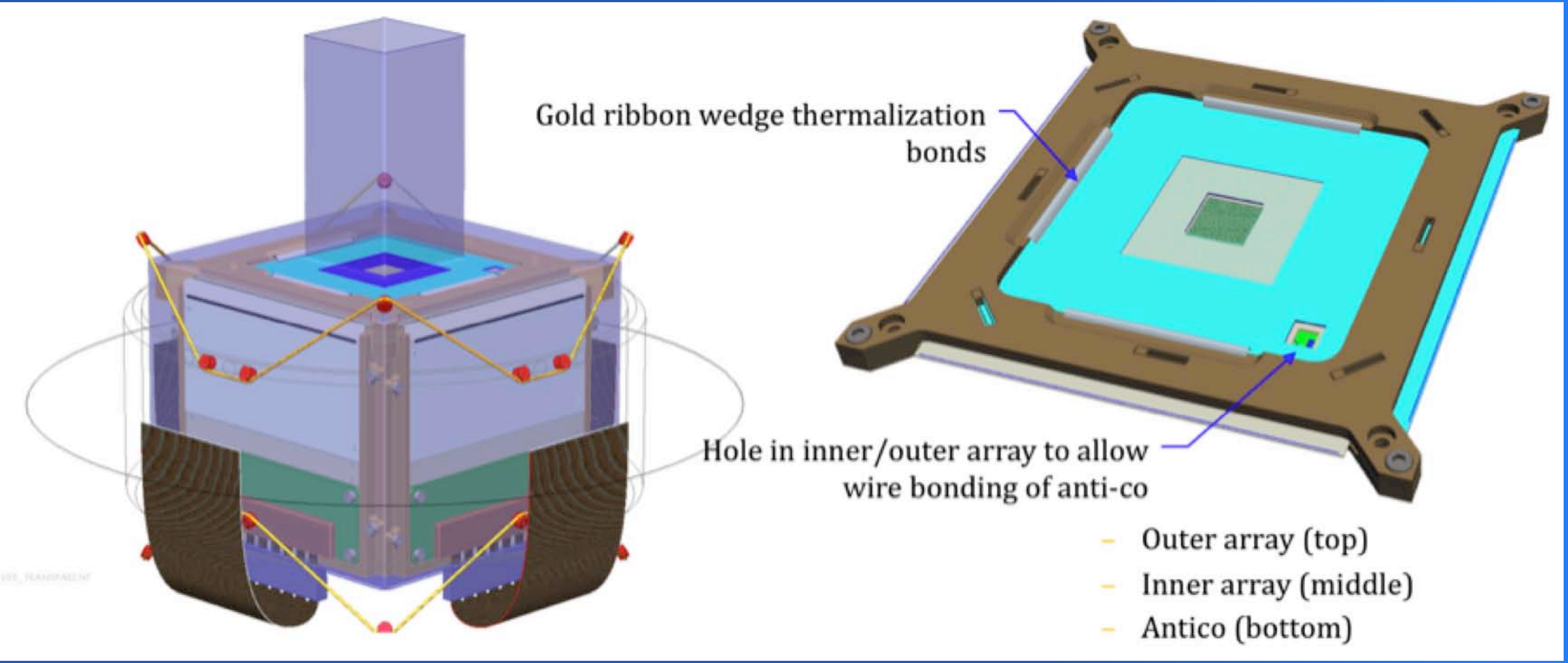
- IXO/XMS TRL 4 reached in 2008
  - The “2x8 demo” of multiplexed read-out of part of a TES array achieved the most fundamental goal of a demonstration of TRL 4 – basic technological components were integrated to establish that they will work together.

IXO/XMS roadmap – representative development path for a multi-component focal plane (from mid-TRL technologies)

- TRL 5 demo of core array
  - Demonstrate multiplexed (3 columns x 32 rows) read-out of 96 different flight-like pixels …
    - work towards an Athena-scaled version (3x16) in progress now (Goddard/NIST)
- TRL 5 demo of outer array
  - Demonstrate multiplexed (2 columns x 32 rows) read-out of 8x8 array of four-absorber devices…
- TRL 5 of particle veto
  - Demonstrate particle veto prototype on scale appropriate for full XMS array…
- integrated detector system TRL 5
  - Demonstrate core array, outer array, and anti-coincidence detector together, though not in a flight-like arrangement.

IXO/XMS roadmap (3)

- integrated detector system TRL 6
  - Multiplexed (6x32) read-out of portion of full composite focal plane array
    - 128 different single-TES pixels in a 40x40 core array
    - 64 multi-absorber TES (256 0.6-mm pixels) of a full-sized outer array
    - Particle-veto integrated into the test set-up.
    - **Electrical and thermal interconnects and staging approach flight-worthy design**



Going forward

- Cost to TRL 6
  - Depends on mission goals and whether funding ramps up quickly or slowly.
  - Range ~$10M to $20M
    - first is for focused development of only the core-array technologies over ~4 years
    - latter is for slower development of something like full IXO/XMS detector system
      - » some investment in technology variations, such as CDM
    - based on historical cost of advancing these technologies through APRA, Con-X development, and other sources.
- Forecast
  - CDM could replace TDM in the roadmap in the next two years
  - In 2-4 years, new TES designs will enable improvements in intrinsic TES resolution
  - By 2017, magnetically coupled calorimeters and microwave multiplexing will be on solid footing, advancing towards mega-pixel arrays.

Development trajectory