Seeing the Big Picture and Taking the Long View – The Development of X-ray Microcalorimeter Spectrometers for Astrophysics

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On behalf of a multitude of scientists, engineers, and students working for more than 4 decades

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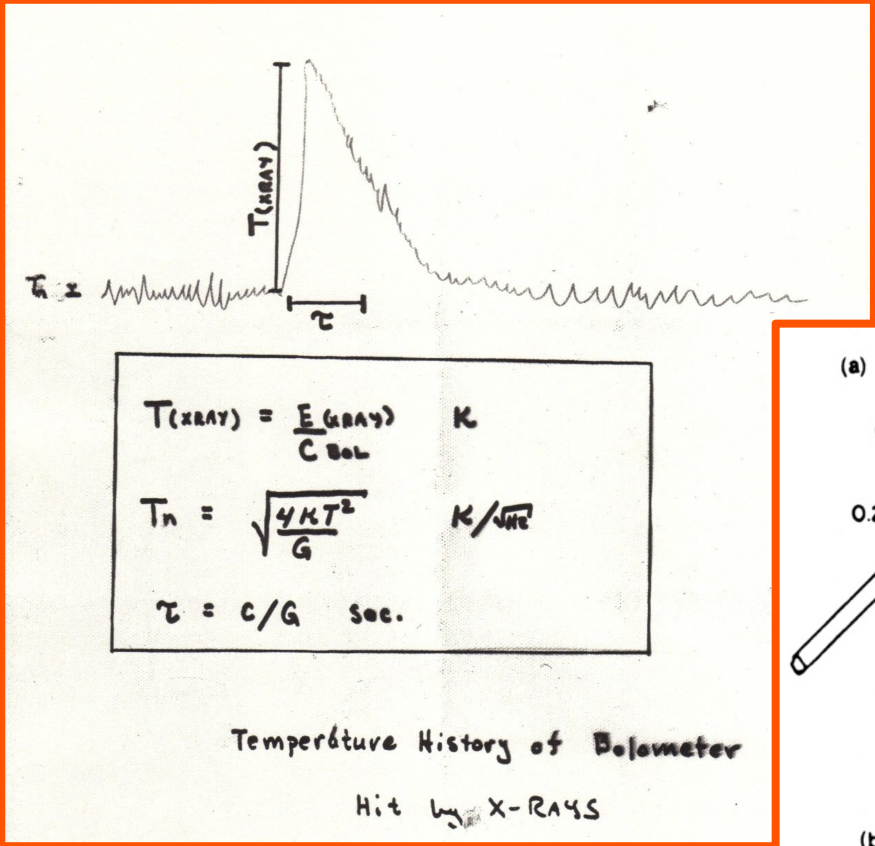
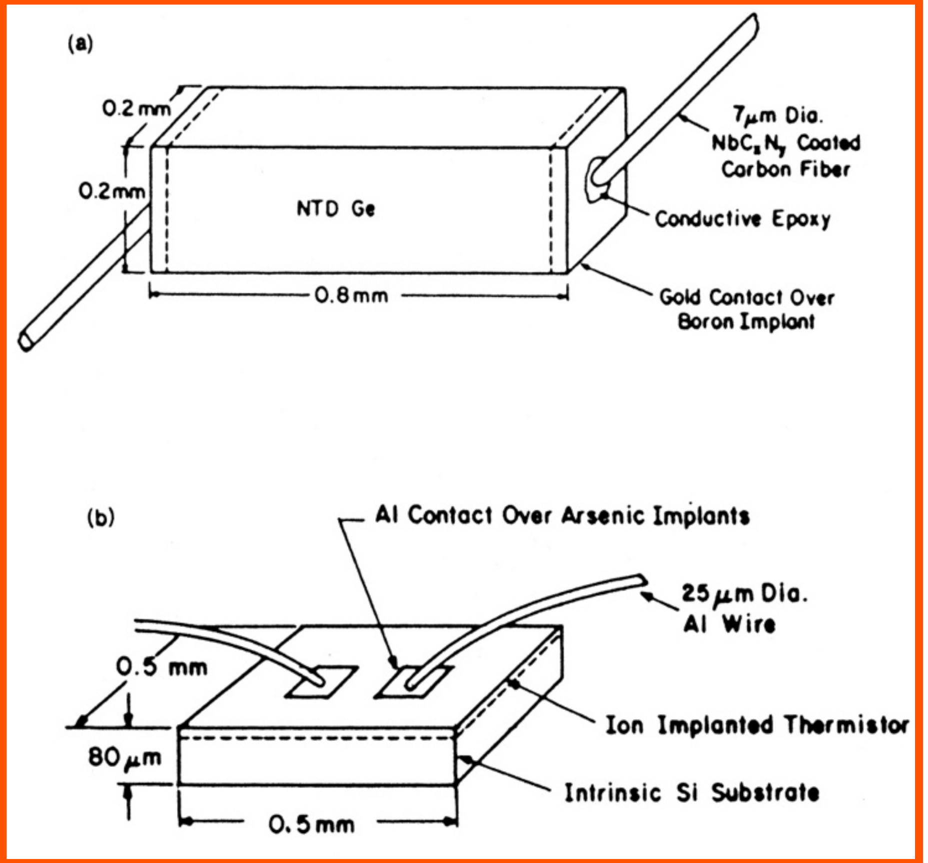
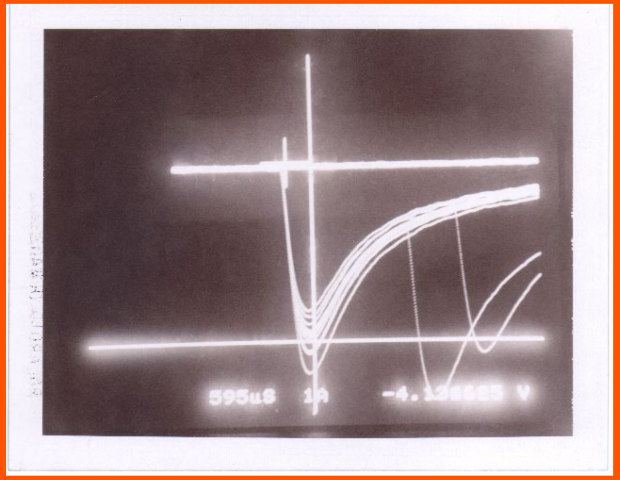
Origin story – the idea for an X-ray microcalorimeter spectrometer

- idea for thermal measurement of small amounts of energy occurred in several places in the world independently when scientists observed pulses in the readout of low-temperature thermometers and infrared detectors
  - attributed to passing cosmic rays
  - inspired ideas for optimizing such devices for precise energy measurement
- idea to use such signals for X-ray astrophysics conceived at Goddard in 1982 during preparations to propose instruments for AXAF
  - X-ray astronomer R. Mushotzky approached IR group about narrow band-gap semiconductors for possible use as higher resolution X-ray detectors
  - IR astronomer H. Moseley suggested that thermal detection (microcalorimetry) could enable much higher energy resolution

Proposed for AXAF
2 years later







A PROPOSAL FOR AN X-RAY SPECTROSCOPY
INVESTIGATION FOR THE AXAF OBSERVATORY

VOLUME 1: TECHNICAL PROPOSAL

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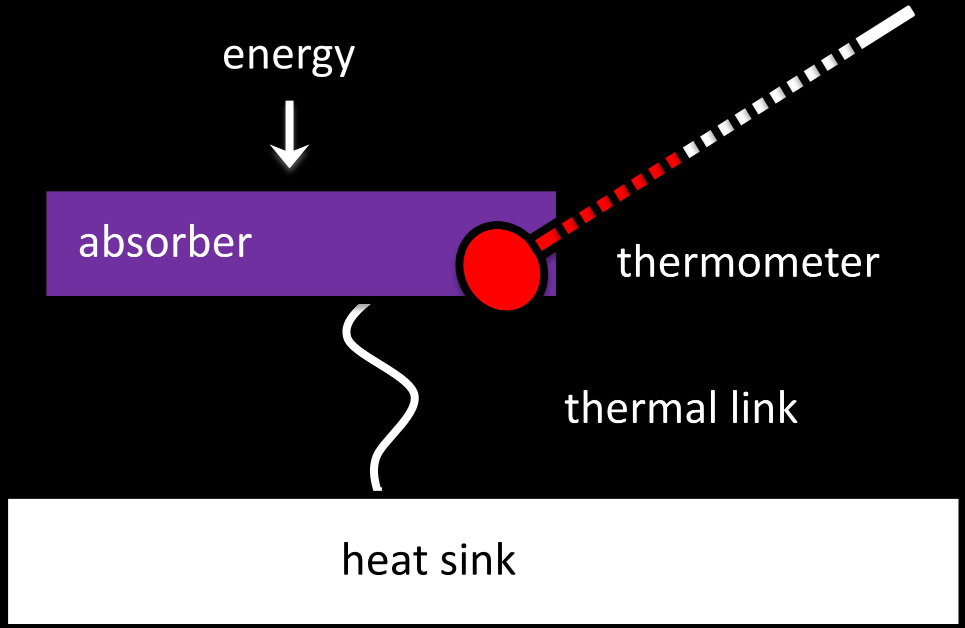
WITH ADDITIONAL COLLABORATORS AT THE GODDARD SPACE
FLIGHT CENTER AND THE UNIVERSITY OF WISCONSIN

Basic parts of an X-ray microcalorimeter



1) collector of the incident radiation
   - absorbs individual X-ray photons and thermalizes them
2) sensitive thermometer
   - semiconductor thermistor
   - superconducting transition-edge sensor (TES)
   - paramagnetic thermometers
   - other concepts
3) thermal link to low-temperature heat sink

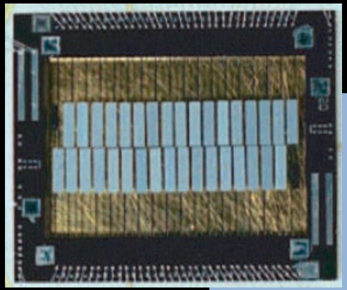
- basic concept can be tailored to mission requirements

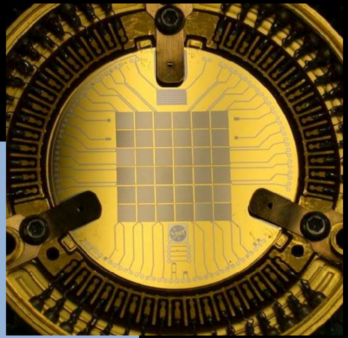
- The ultimate energy resolution is determined by how well one can measure this change in temperature against a background of temperature fluctuations.
- Low-temperature (< 0.1 K) operation is required to minimize these thermodynamic energy fluctuations and to reduce the heat capacity.

Stories of successful infusion are rarely (never?) linear

- note AXAF as initial driver for X-ray calorimeter development
  - microcalorimeter spectrometer was initially selected for AXAF, then AXAF-S when split into separate imaging and spectroscopy missions, but only AXAF-I proceeded (becoming Chandra)
- flight opportunities are rare
  - most mission concepts don’t become actual missions
- flight opportunities don’t always work out as planned
  - infusion of X-ray microcalorimeter technology into a successful orbiting observatory was a particularly unlucky case
    - 3 failed missions, for causes unrelated to each other or the sensor technology, before the successful Resolve instrument on the JAXA XRISM satellite.

X-ray Quantum Calorimeter Mission History



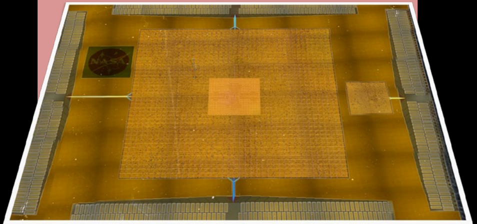


XQC
sounding rocket
7x (1995-2022)

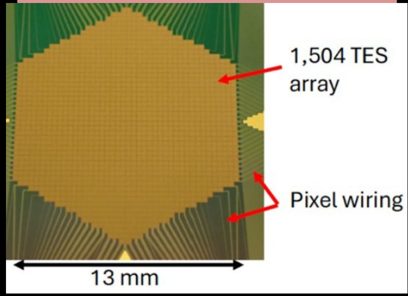
laboratory
astrophysics
x-ray
spectrometers
(continuous)

silicon thermistor
TES

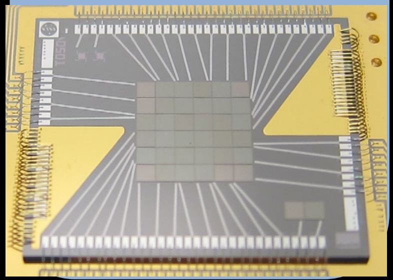
future:
X-ray flagship



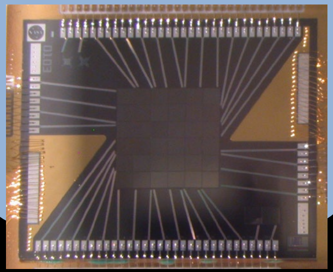
future:
*new*Athena



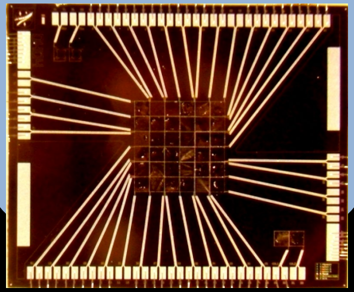
**XRISM
(2023)**



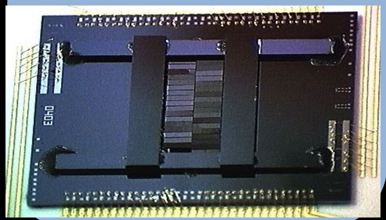
Astro-H
(*Hitomi*) (2016)



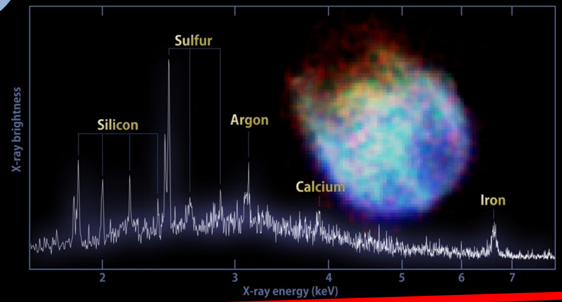
Astro-E2
(*Suzaku*) (2005)



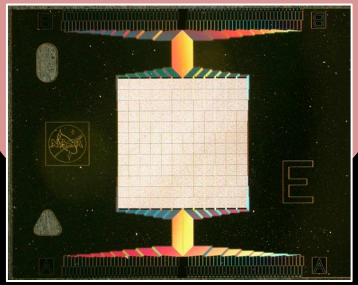
devel. 80s, 90s for
AXAF/AXAF-S
Astro-E (2000)



XRISM Resolve's Recipe for Supernova Remnant N132D

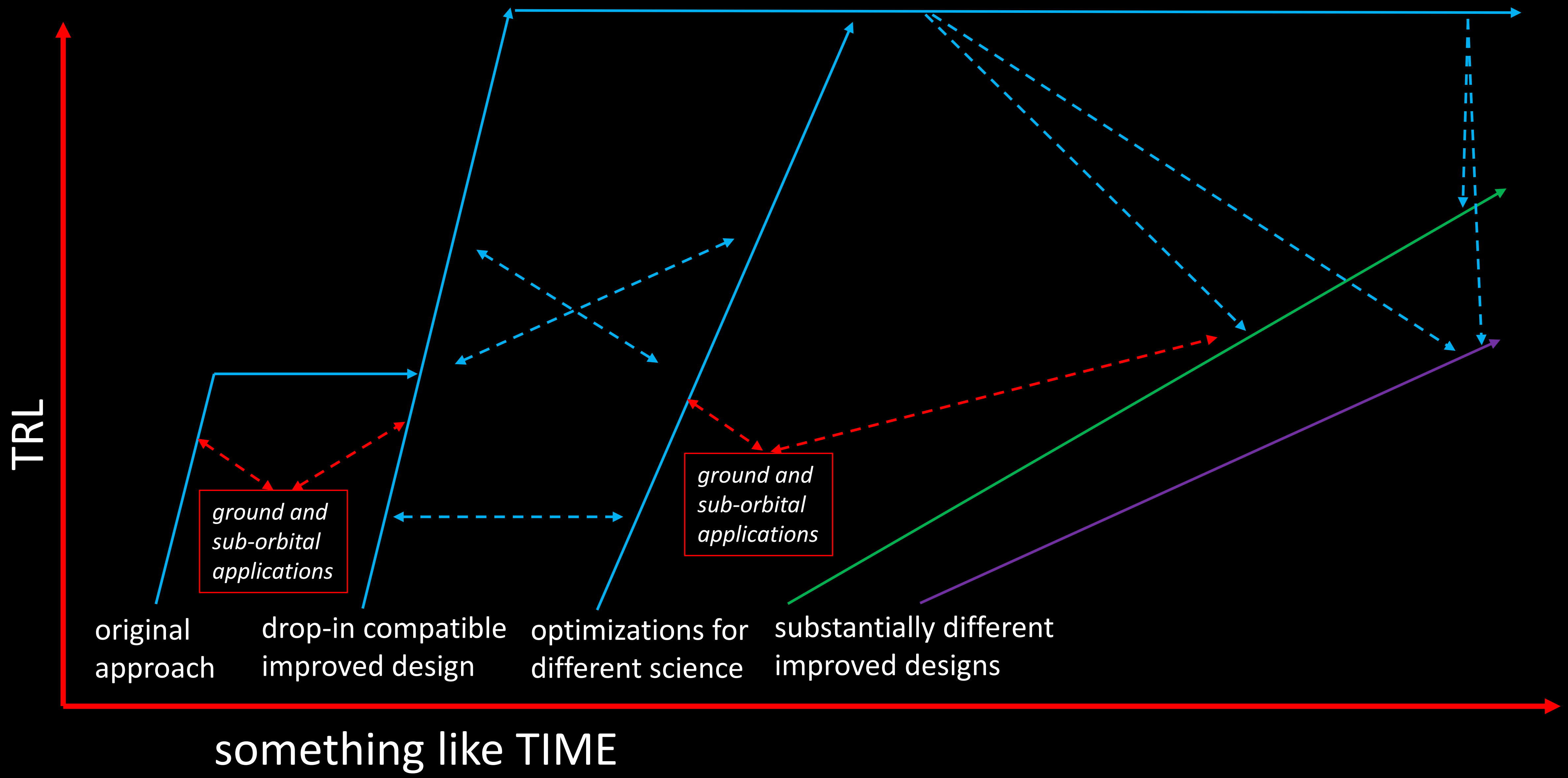


micro-X
sounding rocket
2x (2018, 2022)

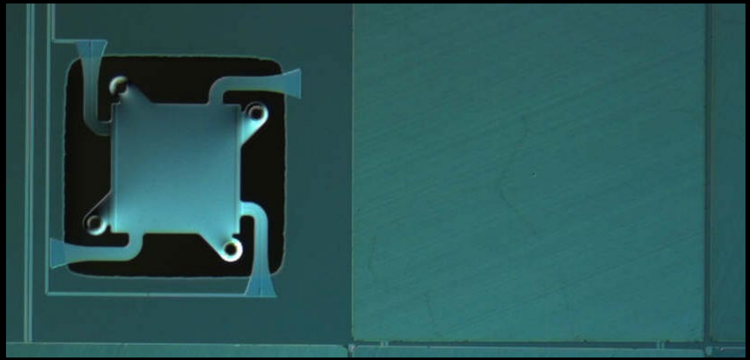


**IDEA!
(1982)**

Technology-development web



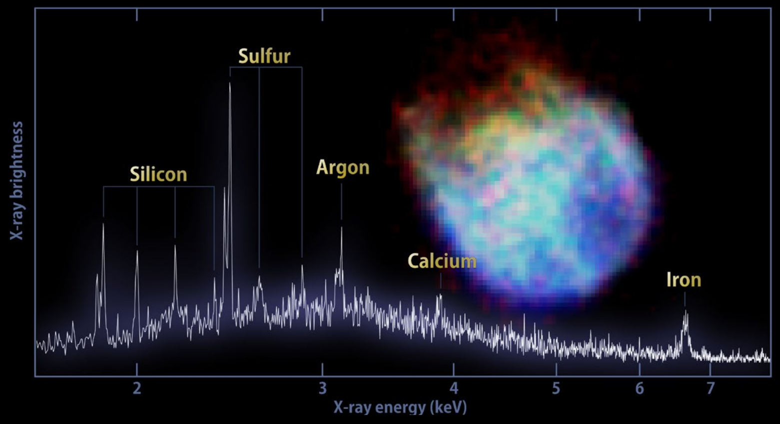
Thermistor case study



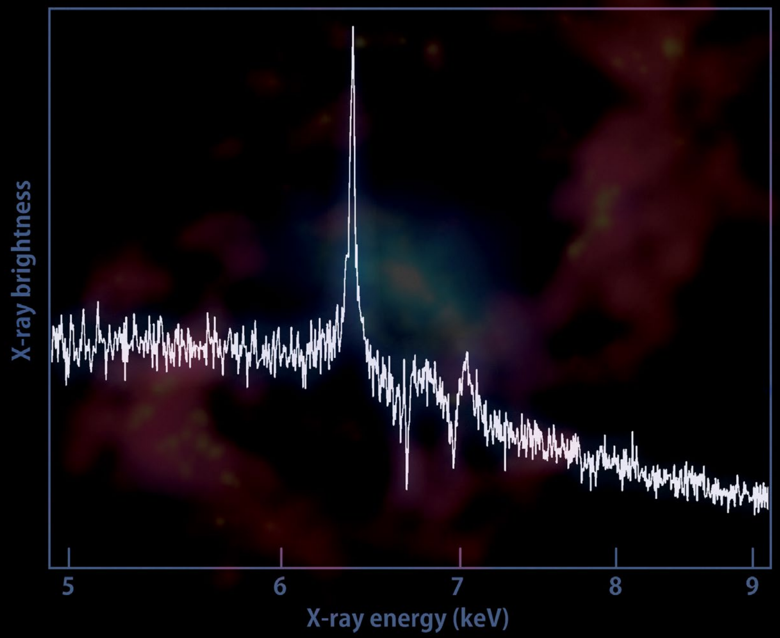
- Ion-implanted Si thermistors and HgTe absorbers
  - basic approach from Astro-E through XRISM
- between Astro-E and Astro-E2, switched to a silicon-on-insulator (SOI) based process (two-year ROSS-2000 award)
  - reduced the 1/f noise of the thermistors by going from shallow implants to deep implants confined in SOI device layer
  - SOI combined with deep reactive ion etching made robust square arrays possible
  - incorporation of lithographically patterned absorber stand-offs resulted in reproducible connection between absorber and thermistor
- between Astro-E2 and Astro-H, industry partner EPIR, via SBIR award, was able to reduce the specific heat of the HgTe
- From Astro-E through Astro-H, the energy resolution for X-rays of energy around 6 keV improved from 11 eV, to 5.5 eV, to 4 eV. No changes to the array design were made between Astro-H and XRISM.

INFUSION! XRISM/Resolve

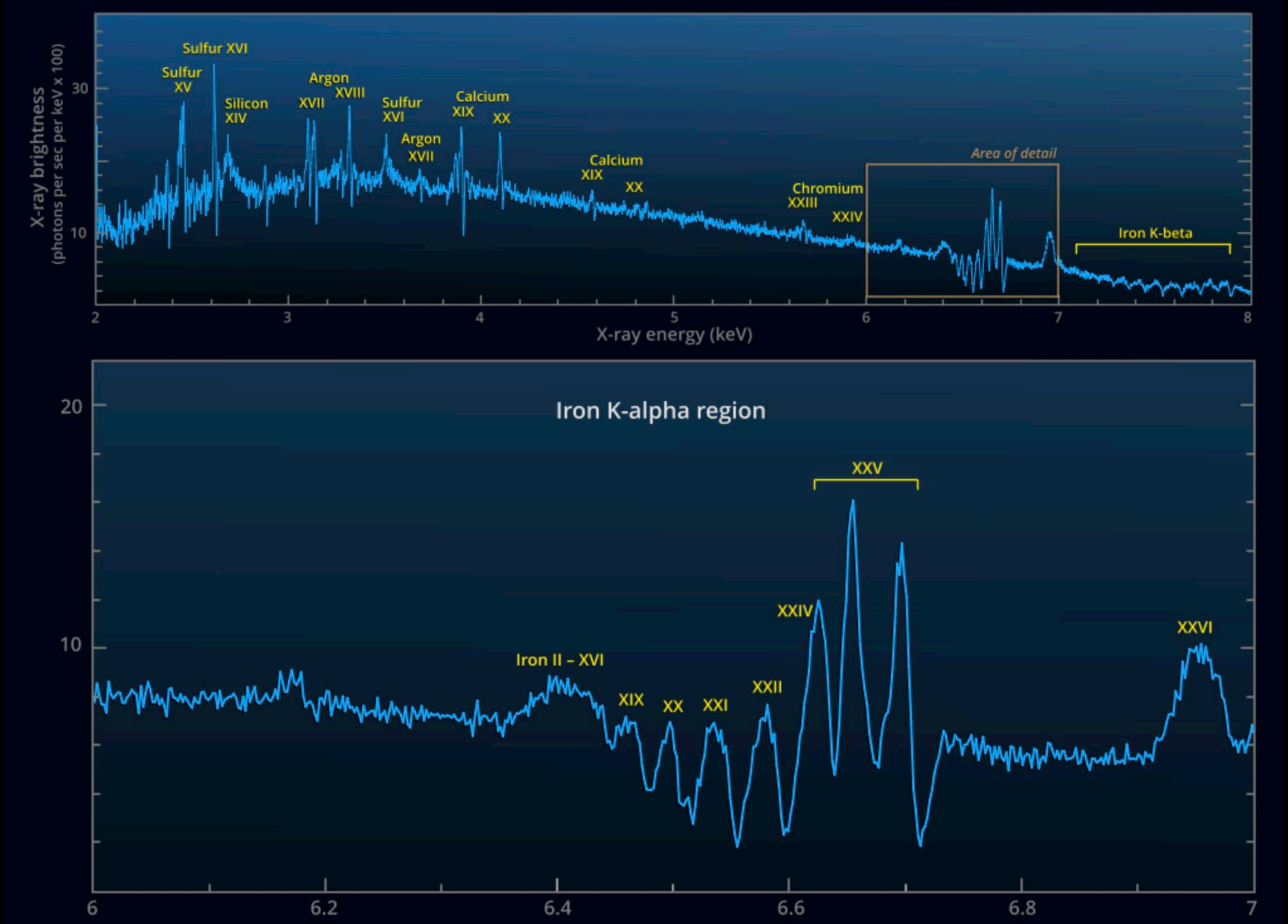
XRISM Resolve's Recipe for Supernova Remnant N132D



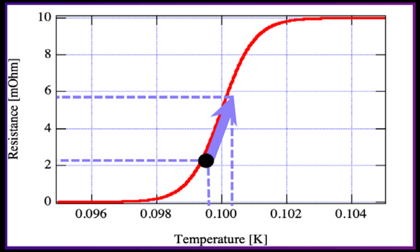
XRISM Resolve Spectrum of NGC 4151



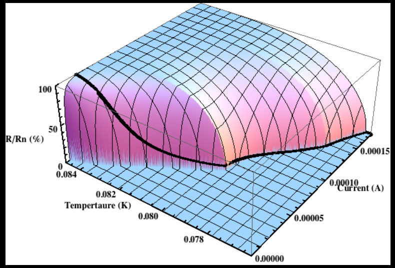
XRISM Resolve Spectrum of Cygnus X-3

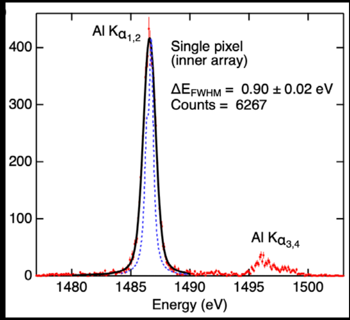


TES case study



- GSFC TES work started in 1996, inspired by K. Irwin's thesis work
- focused on XMS instrument of Constellation-X, then IXO, and eventually, after IXO ranked 4th in Astro-2010 Decadal, on providing the detectors for X-IFU of ESA's Athena mission (now newAthena, 2037), offshoot efforts focused on future Flagship mission or Probe opportunity
- contributions to success
  - emphasis on scaling up early to large arrays
  - longstanding collaboration with NIST to develop compatible sensors and multiplexed readout and to test at the detector-system level as early as feasible
  - development of electroplated Bi/Au absorbers that make contact to the TES only at well defined points
  - developing an understanding TESs as superconducting weak links, not just in isolation, but how they function in the electro-thermal circuit of realistic operation





Technology development in the context (and culture) of managed programs (both flight and in formulation)

- systems demonstrations and TRL assessments always imminent
- emphasis on practical understanding
- collaboration and sharing lessons learned
- contemporaneous ground-based and sub-orbital applications produce science results while also providing lessons in calibration and data processing
- important to learn about technologies with common issues
  - or opposite issues:
    - If your noise is my signal, we can learn from each other!
    - If you need your quasiparticles to have long lifetimes so you can measure their current, but I need them to thermalize quickly, we can use each others reject materials!
- technology development is a web, not a timeline, and successful infusion comes from continuously making the connections.