Current and future capabilities of transition-edge sensor microcalorimeters for x-ray beamline science

Douglas Bennett

2018 International Forum on Detectors
for Photon Science
March 13, 2018

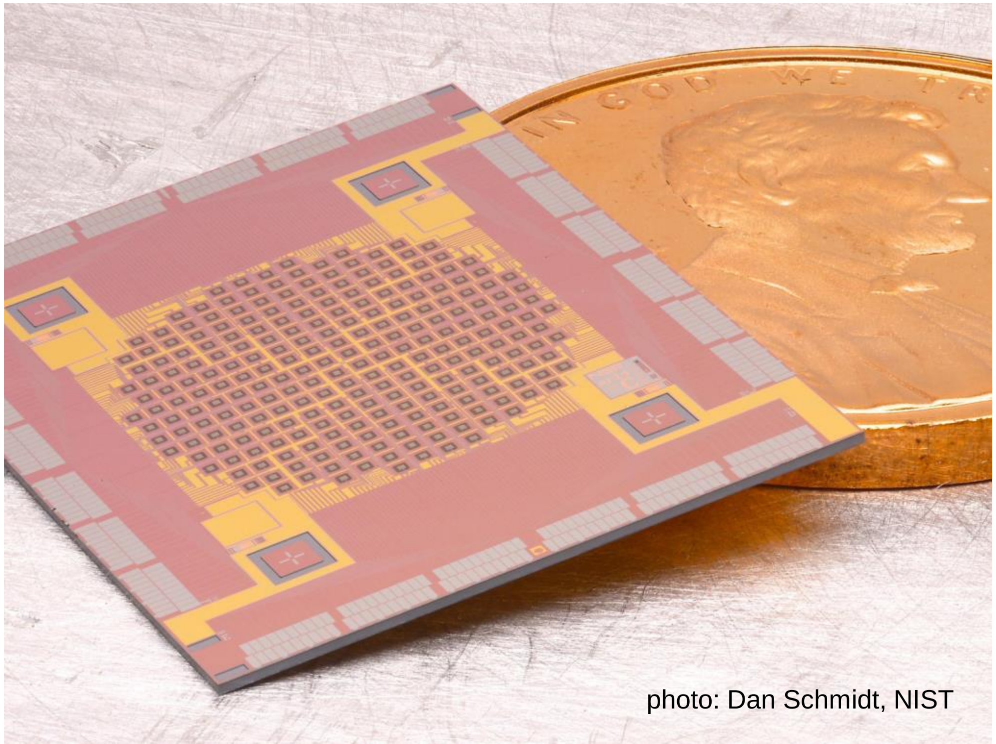

photo: Dan Schmidt, NIST

NIST

Quantum Sensors Group

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Many outside collaborators (always looking for more!)

SLAC
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Argonne National Laboratory
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LCLS
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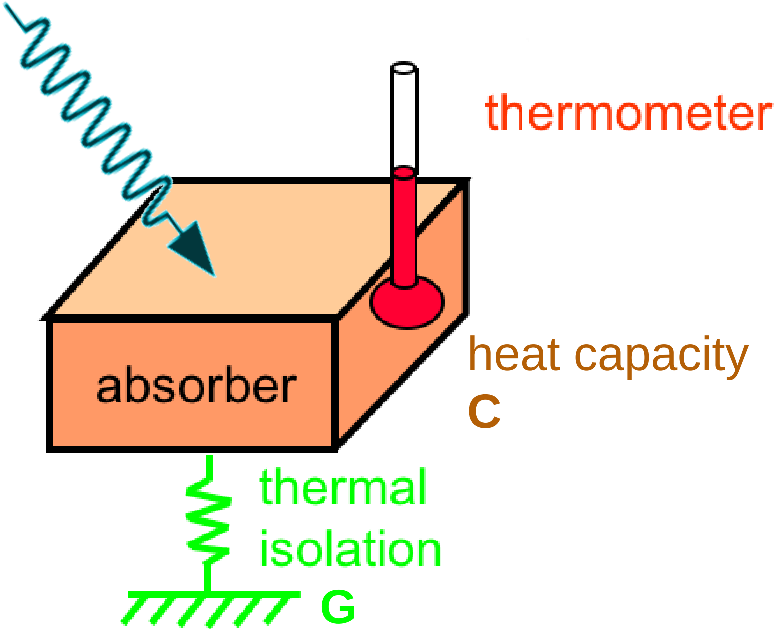
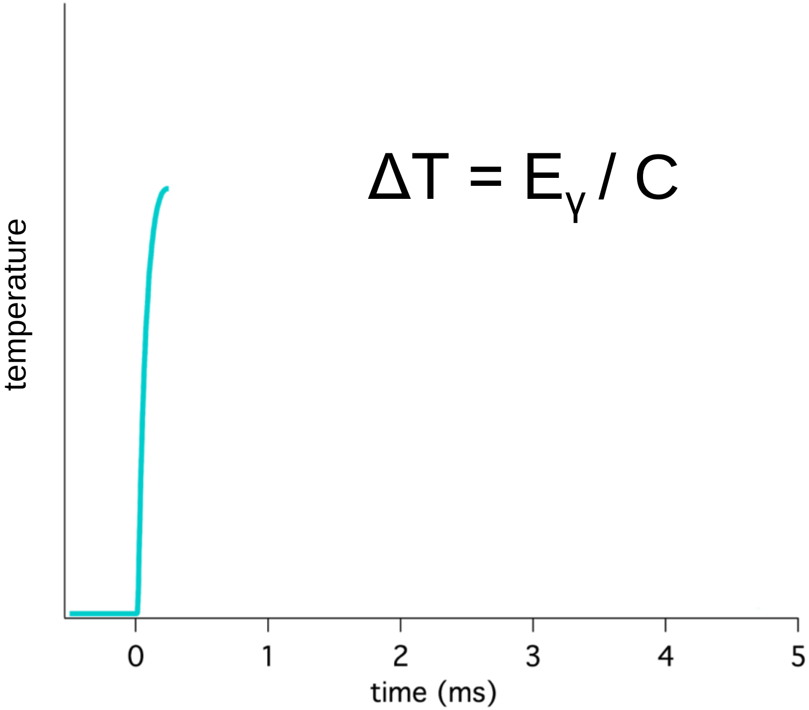
Brookhaven National Laboratory
Lund University
University of Jyväskylä
Lawrence Livermore National Laboratory
Tokyo Metropolitan University
NASA Goddard Space Flight Center
Paul Scherrer Institut PSI
J-PARC
University of Washington
Los Alamos National Laboratory
Università degli Studi di Milano Bicocca

Outline

- What is a TES?
    - How is a TES different from other beamline detectors?
    - Why would I want to use a TES spectrometer?
- Current Status of TES Instruments
    - Instruments deployed to beamlines
    - Examples of photon science with TESs
- Microwave SQUID Multiplexing
    - Why do we need another multiplexing scheme?
    - How does it work?
    - What are the practical limits
- What are the prospects for TES spectrometers?
    - What currently limits arrays size?
    - What are the prospects for larger arrays?
    - Where should we put more effort?

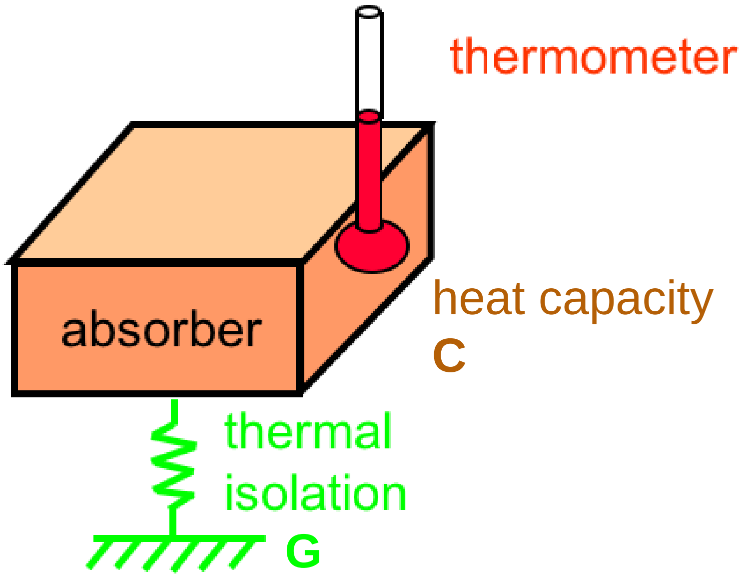
For x-ray science, a TES is used as a **microcalorimeter**

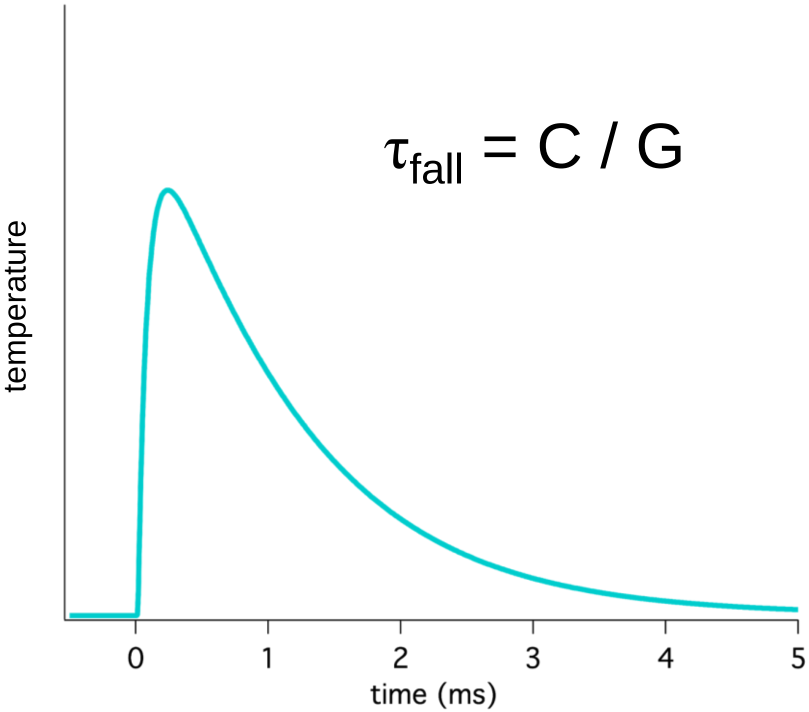




$$\Delta T = E_\gamma / C$$

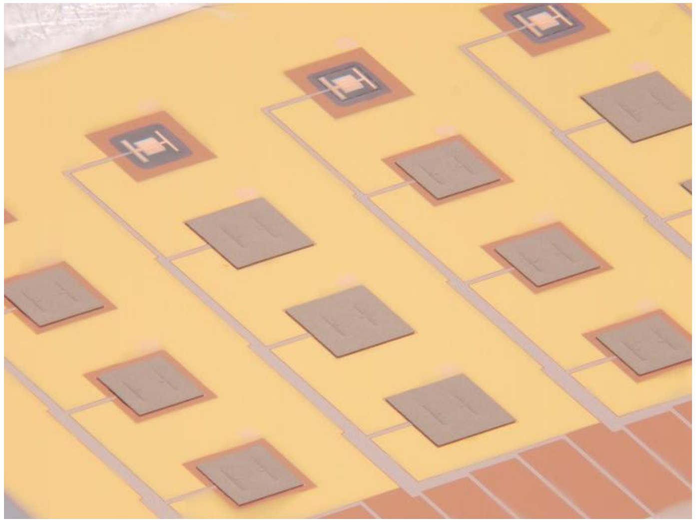
For x-ray science, a TES is used as a **microcalorimeter**



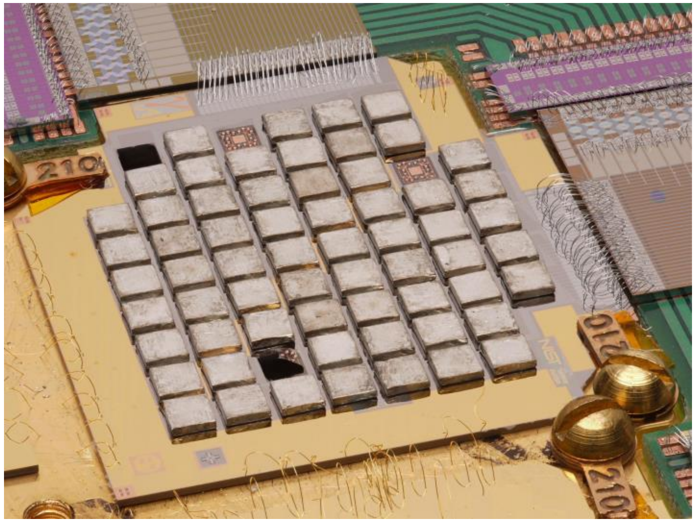


Why use a microcalorimeter?

1. Microcalorimeters are efficient:
   we choose a material with high stopping power for x-rays



X-rays 0.1-20 keV: thin bismuth



Gamma rays >20 keV: bulk tin

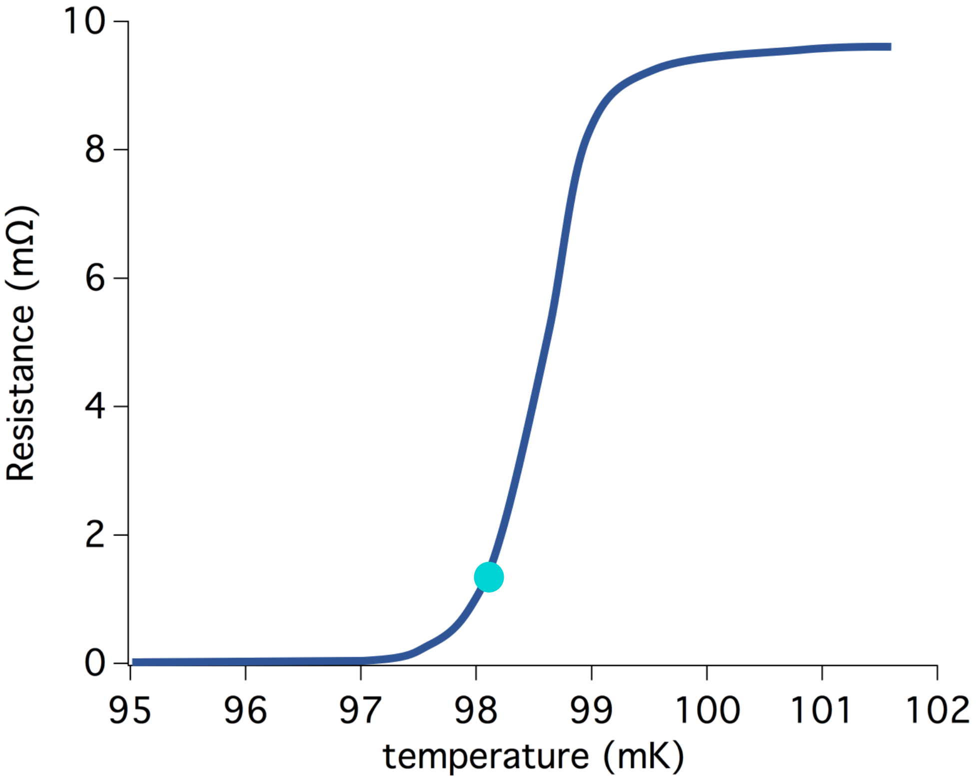
Why use a microcalorimeter?

2. Microcalorimeters can have excellent energy resolution:

$$\Delta E \propto \sqrt{k_b T_0^2 C}$$

No fundamental “physics” limit to resolution
must be kept at cryogenic temperatures (~100 mK)
Temperature changes are μK - mK: need highly sensitive thermometer

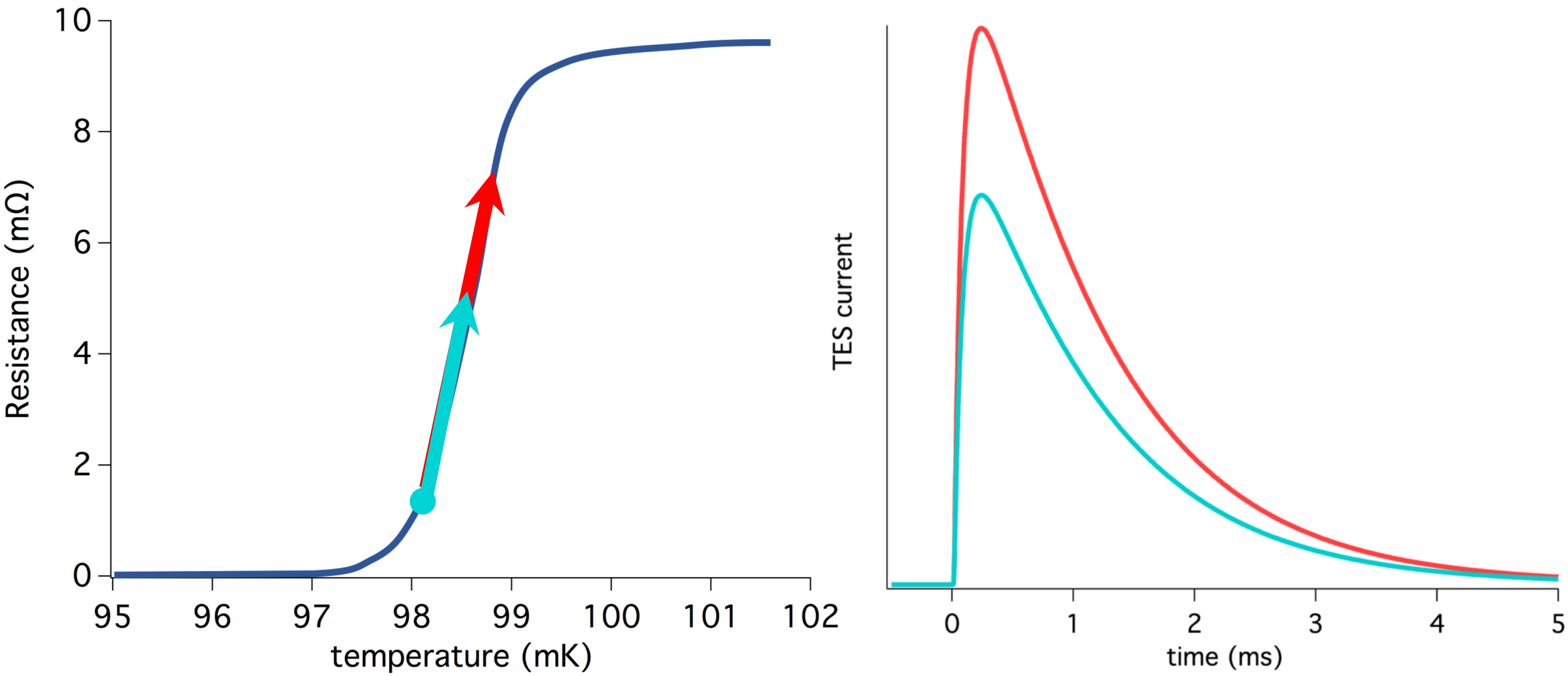
Transition-edge sensor: a superconducting thin film used as a thermometer



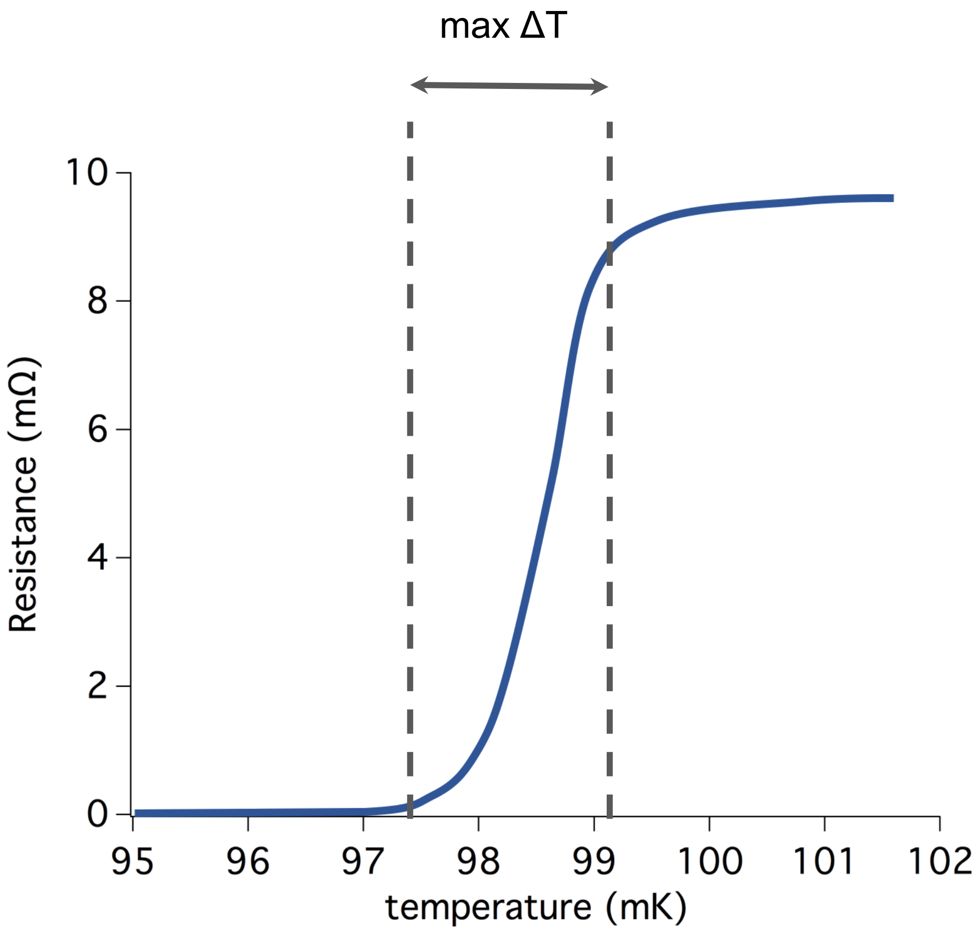
Resistance is a steep function of temperature in the superconducting to normal transition region

Apply a voltage to bias the TES into its transition region

$\Delta R \propto \Delta T$: TES turns temperature pulses into current pulse



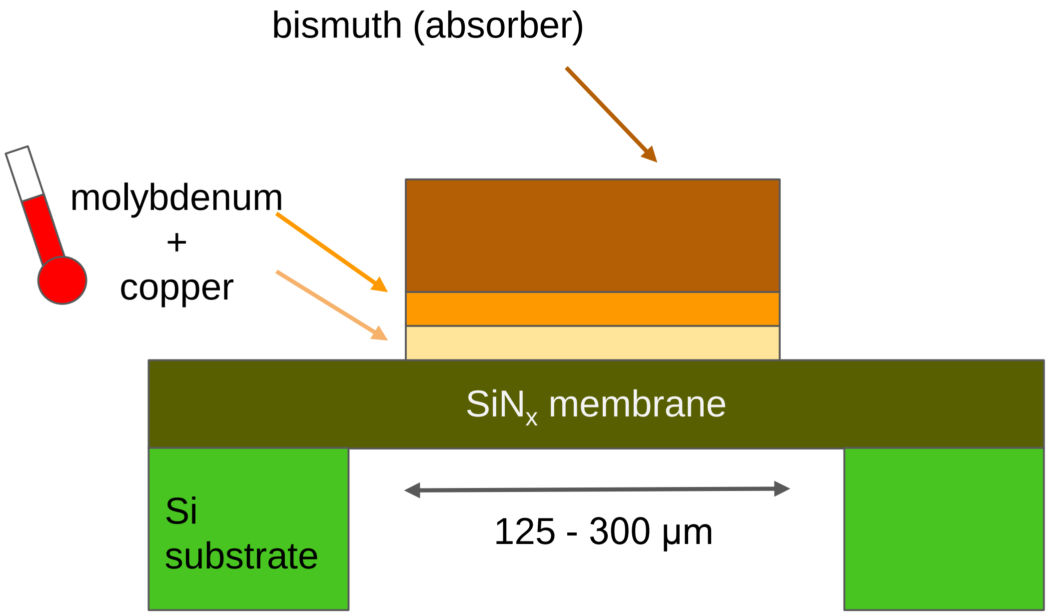
ΔR ∝ ΔT: TES turns temperature pulses into current pulse, until it runs out of the superconducitng transistion



If ΔT > transition width, the TES is no longer sensitive to changes in temperature

⇒ we can tune the TES design to match the desired energy range

How to make a TES



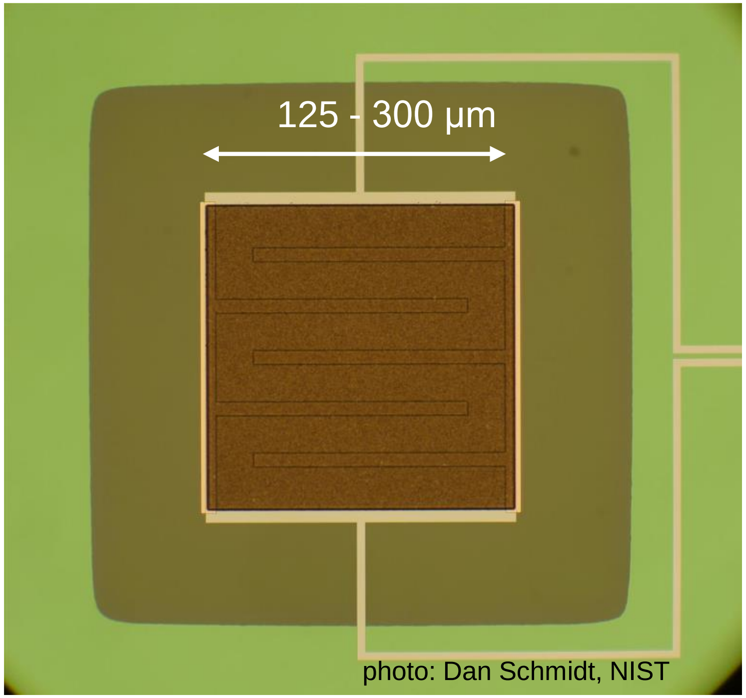
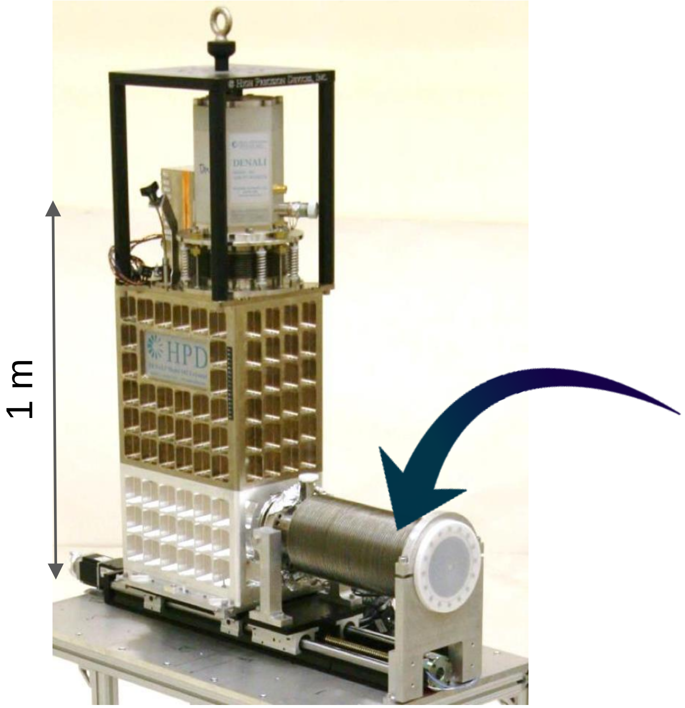
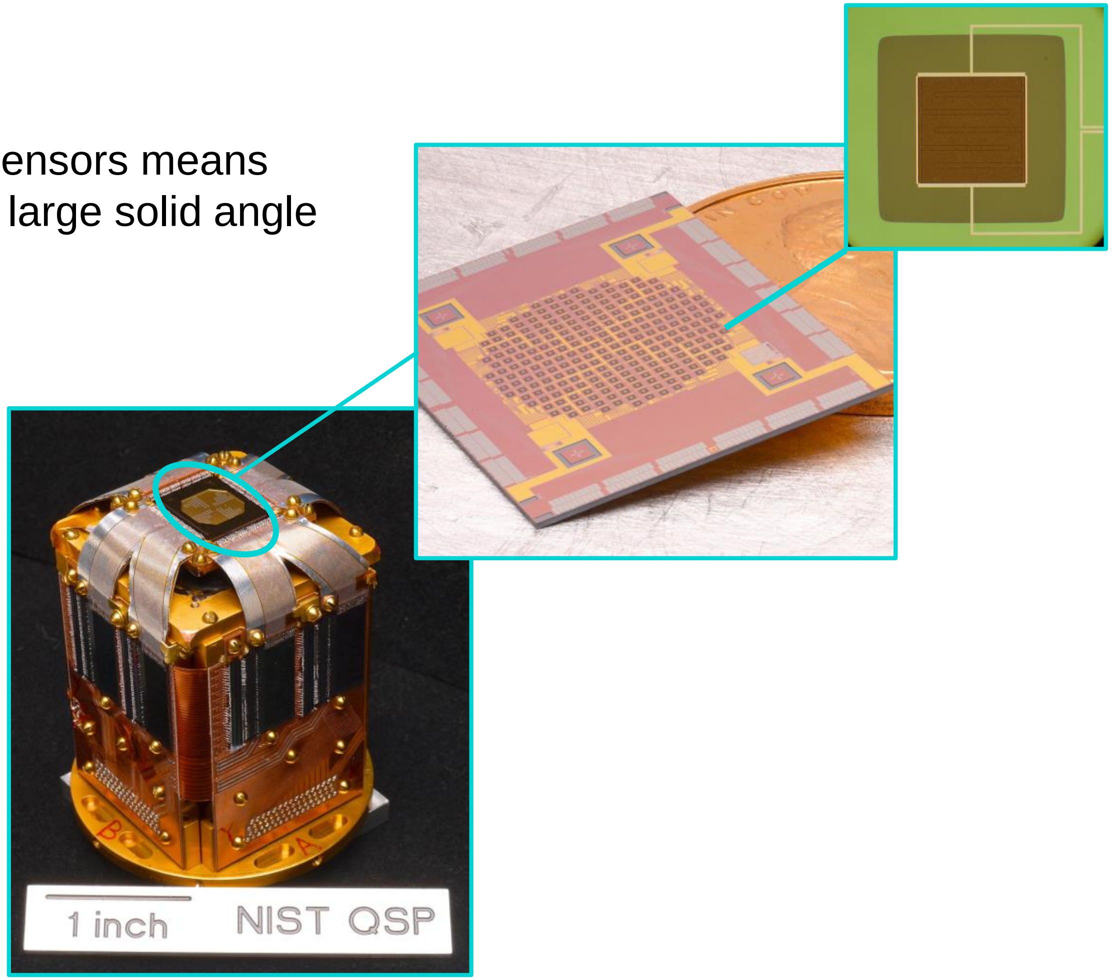


photo: Dan Schmidt, NIST

From a TES pixel to a full spectrometer

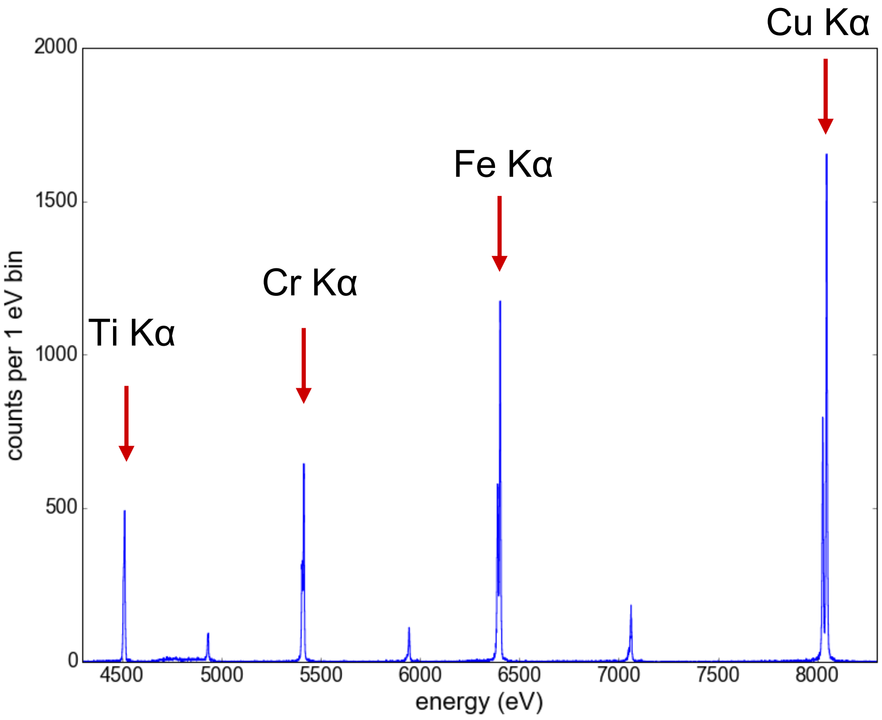
Arrays: more sensors means
more photons, large solid angle

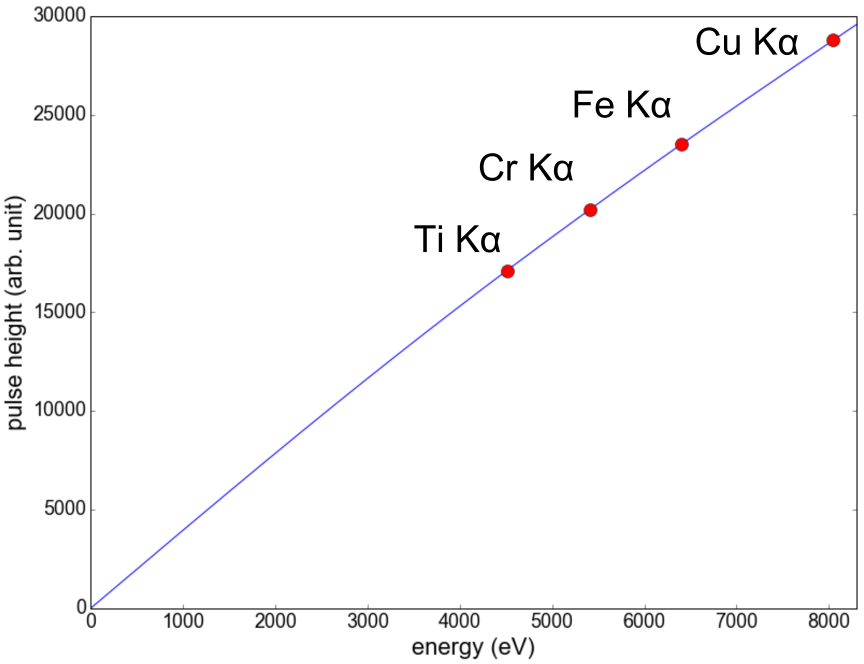




Using a TES array as a spectrometer

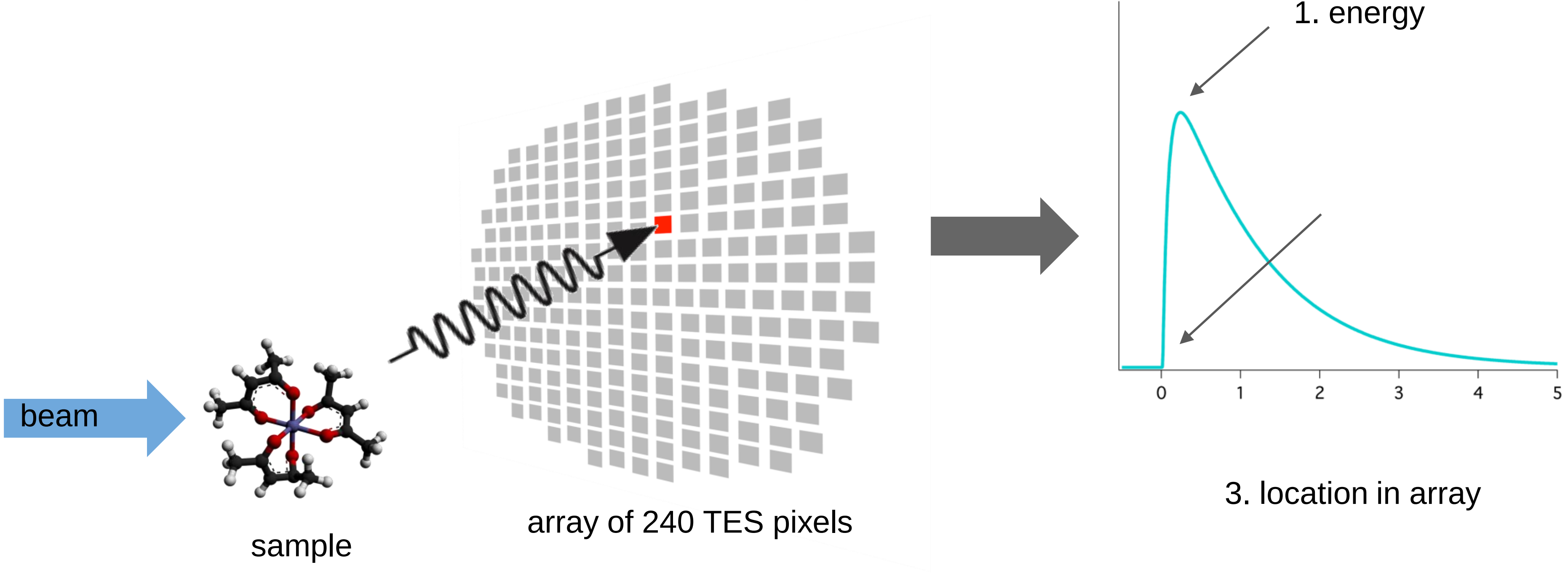
1. Calibration: need to tie pulse height to a known energy, so we measure a series of known energies to make a "ruler"





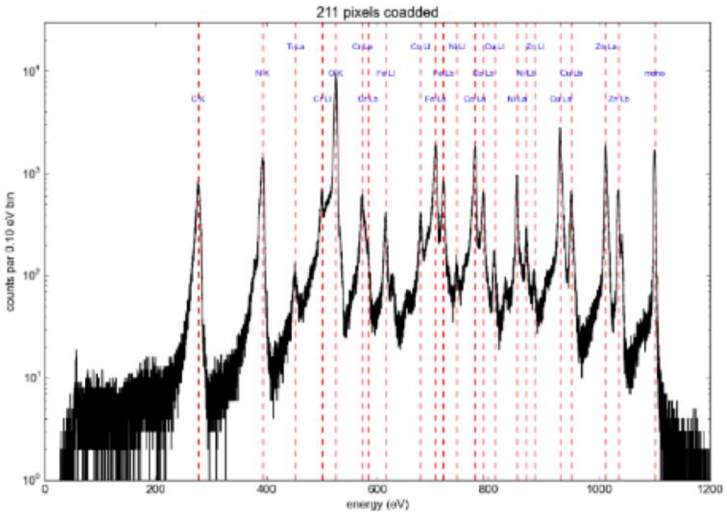
Using a TES array as a spectrometer

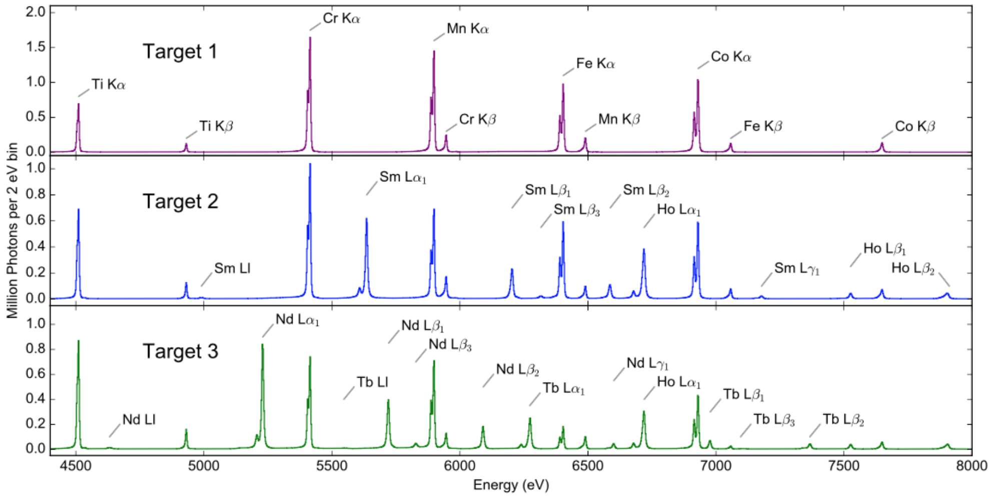
2. Measure signal: when a sensor absorbs an x-ray, you get: energy, arrival time, and location (which pixel in the array)



Why use a TES for photon science?

Each TES pixel in an array is an independent, broadband energy-dispersive spectrometer



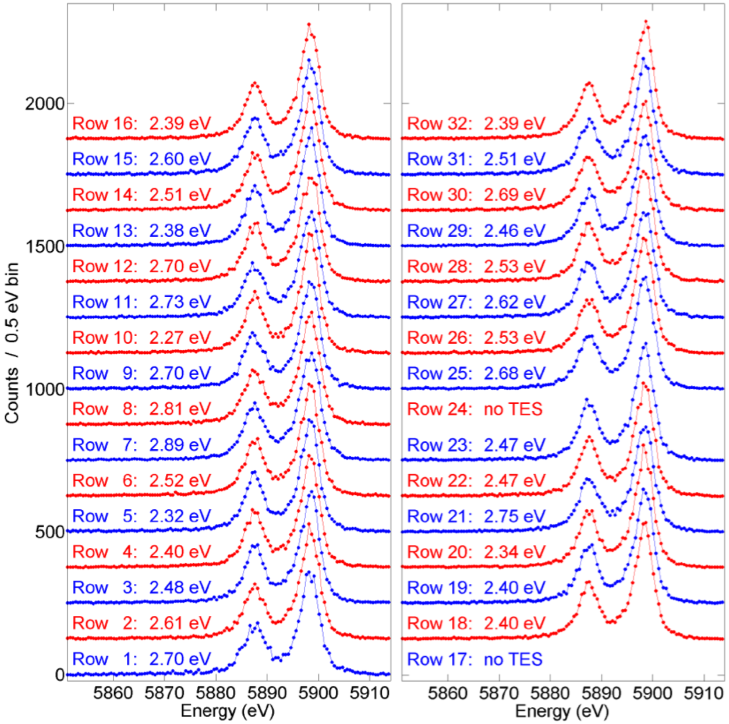


low-E TES array measuring 0-1.2 keV emission lines simultaneously

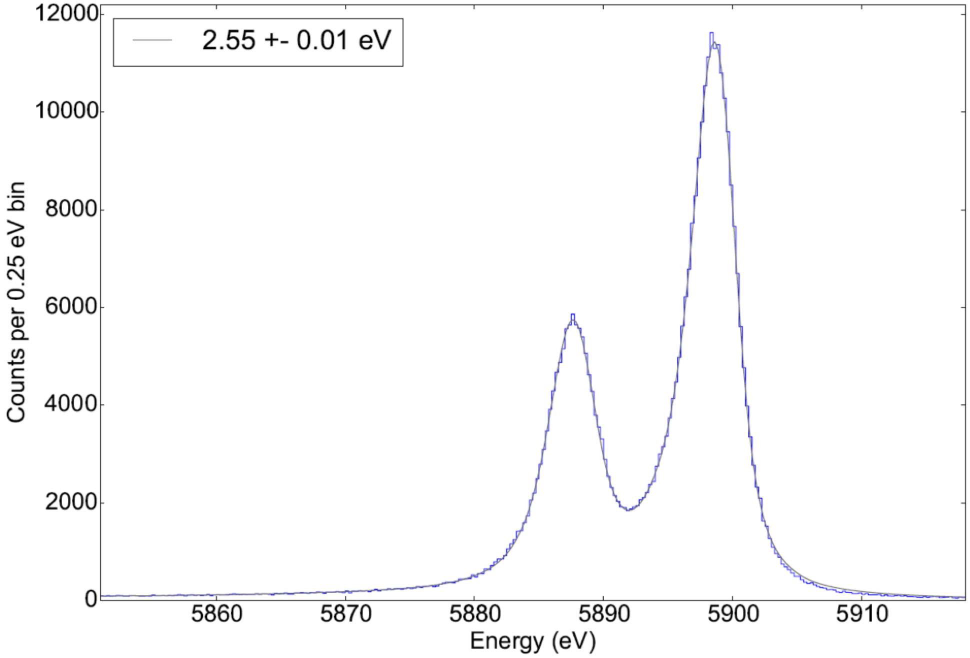
high-E array measuring 4.5 - 8 keV emission lines simultaneously

Why use a TES for photon science?

A large array of TESs makes a versatile area detector:
sum signal for statistics, or use the pixels individually



Mn Kα, sum of 30 TES pixels

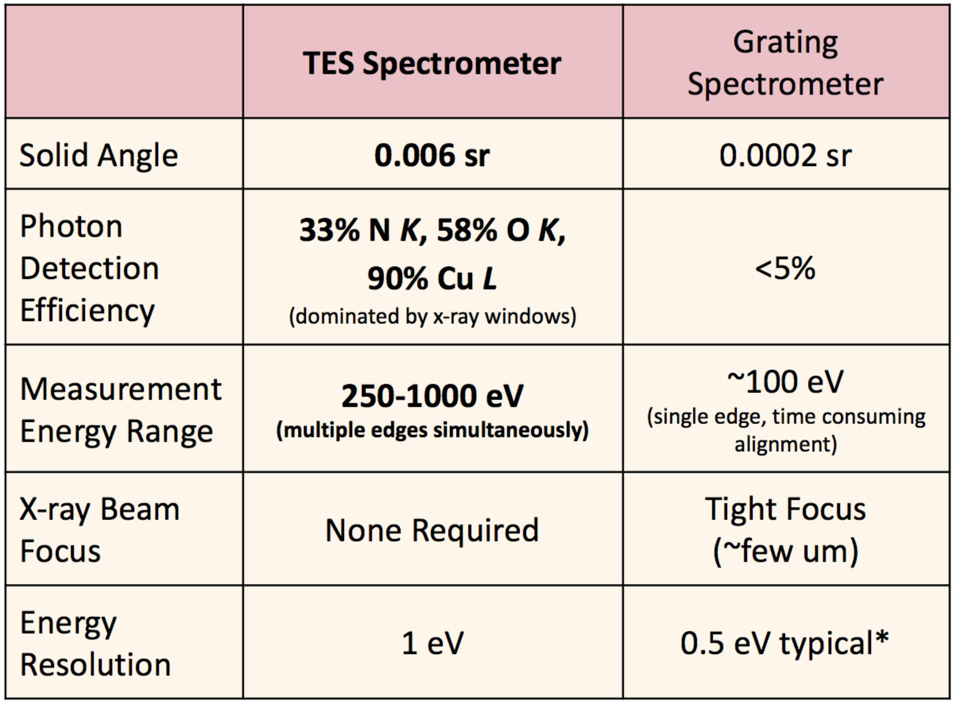


Why use a TES for photon science?

TES throughput can be 100x higher than wavelength-dispersive instruments

TES energy resolution is 10-100x better than typical energy dispersive detectors

Enables:
lower concentrations, dilute solutions, lower doses, etc.

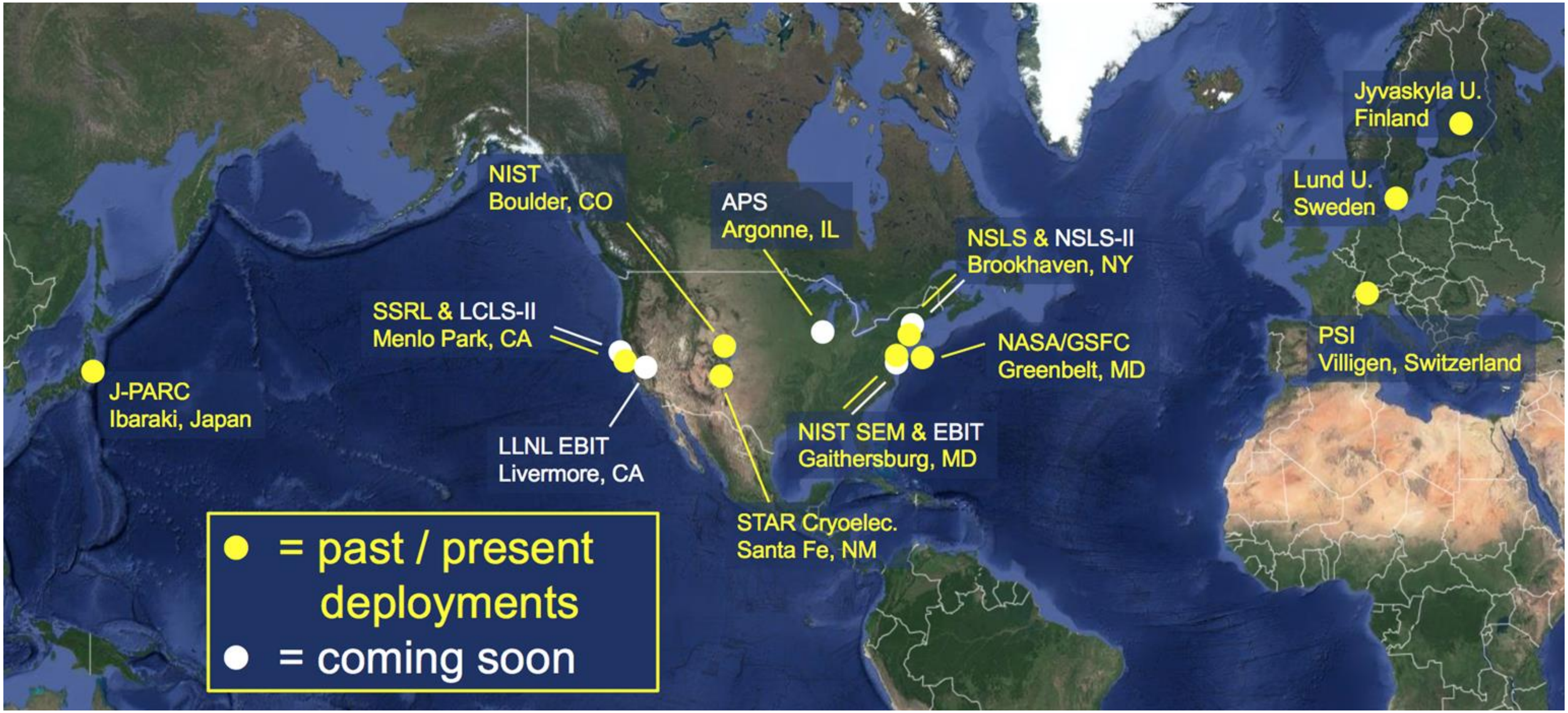


	TES Spectrometer	Grating Spectrometer
Solid Angle	**0.006 sr**	0.0002 sr
Photon Detection Efficiency	**33% N *K*, 58% O *K*, 90% Cu *L*** (dominated by x-ray windows)	<5%
Measurement Energy Range	**250-1000 eV** **(multiple edges simultaneously)**	~100 eV (single edge, time consuming alignment)
X-ray Beam Focus	None Required	Tight Focus (~few um)
Energy Resolution	1 eV	0.5 eV typical*

*Can be better, but with lower efficiency and smaller solid angle

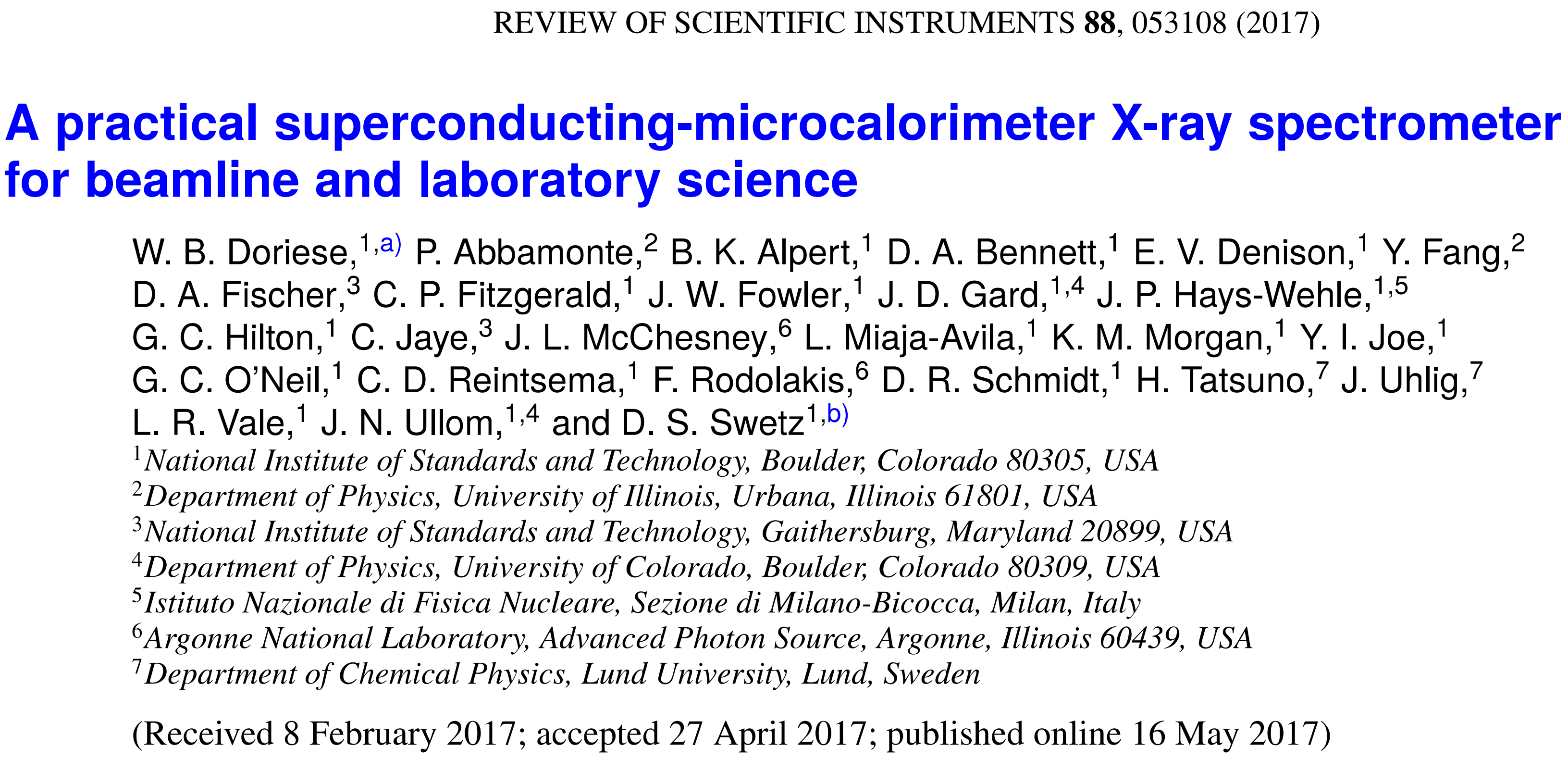
Example: 240 pixel TES spectrometer, 16-crystal von Hamos at LCLS (Alonso-Mori et al, 2012)
Uhlig et. al., Journal of Synchrotron Radiation, 22 (3), 766 (2015)

TES spectrometers are doing science around the world



Doriese et al, Rev. Sci. Instr. 88, 053108 (2017)

For more details see:



REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 053108 (2017)

A practical superconducting-microcalorimeter X-ray spectrometer for beamline and laboratory science

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Examples of photon science with TESs

- XES
    - NSLS U7A - Explosive compounds at NSLS
    - NIST laser facility -Time-resolved work on iron tris bipy
- XAS
    - NSLS U7A - In fluorescence mode PFY-XAS
    - NIST laser facility - in transmission mode – time resolved studies of ferrioxalate
- RIXS
    - SSRL 10-1 - See talk next session by Sang Jun Lee
- RSXS
    - APS BL 29ID – high-Tc superconductors
    - Demonstration planed for SSRL 13-3

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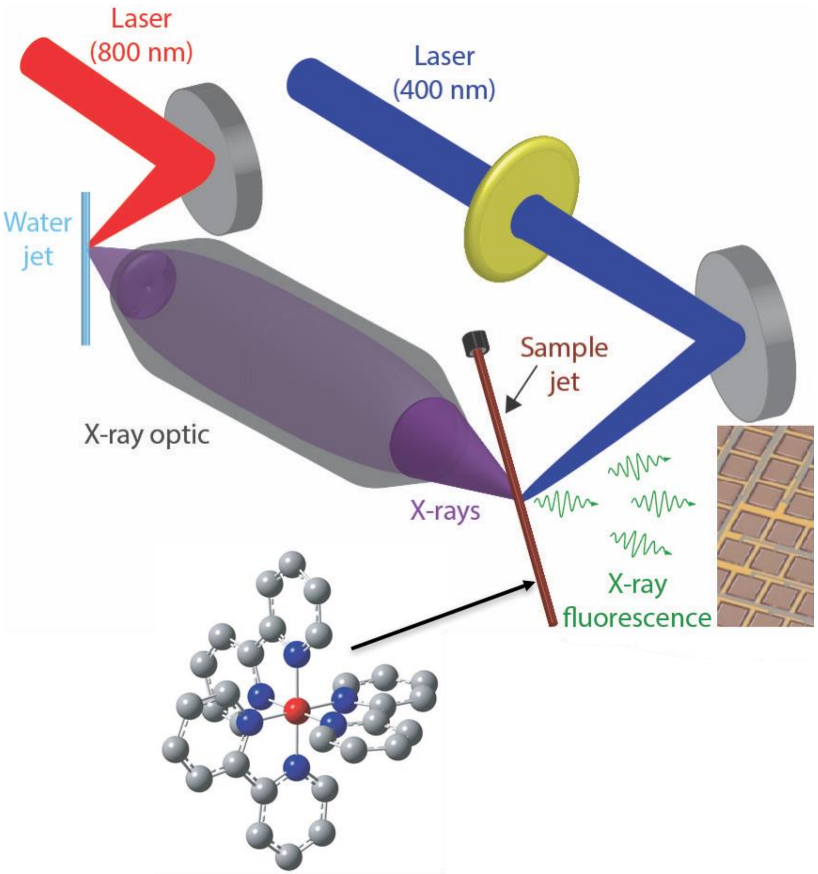
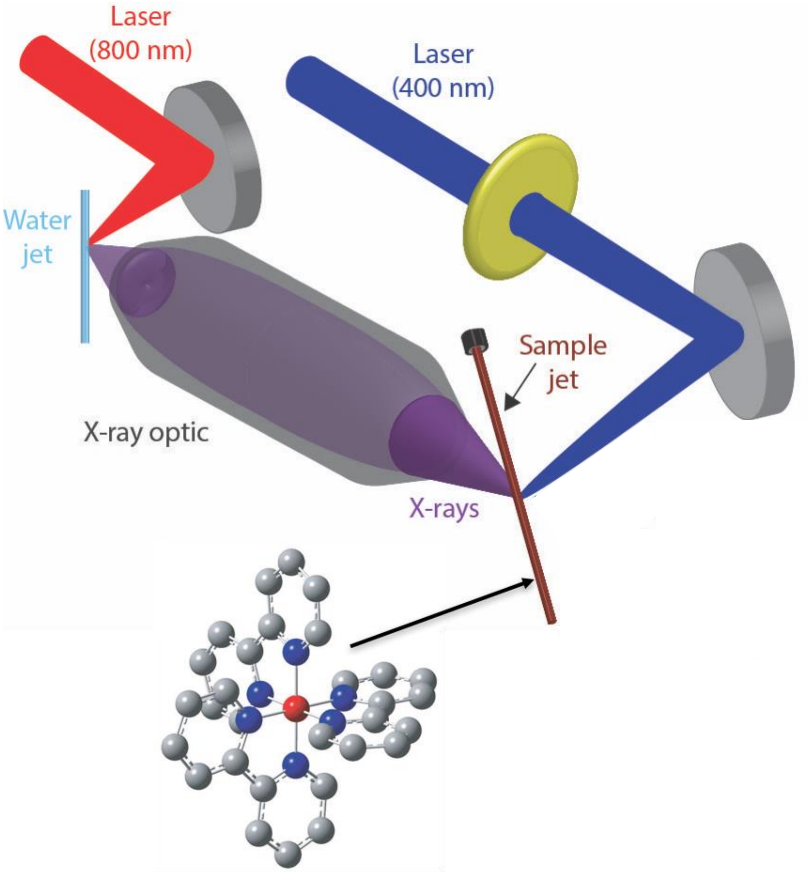
water jet plasma source:
~10^6 photons/sec at output focus
L. Miaja-Avila *et al*, Struc. Dyn. 2, 024301 (2015)



$[Fe(2,2'\text{-bipyridine})_3]^{2+}$

Time-resolved x-ray spectroscopy on a table-top at NIST



$[Fe(2,2'\text{-bipyridine})_3]^{2+}$

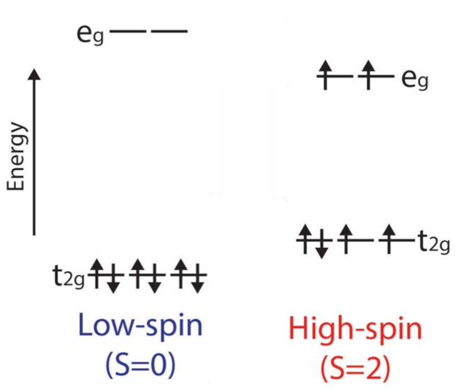
Optical pump duration: 50 fs - 1.3 ps
X-ray probe energy: 1.5 - 15 keV
Probe beam diameter: 70 μm

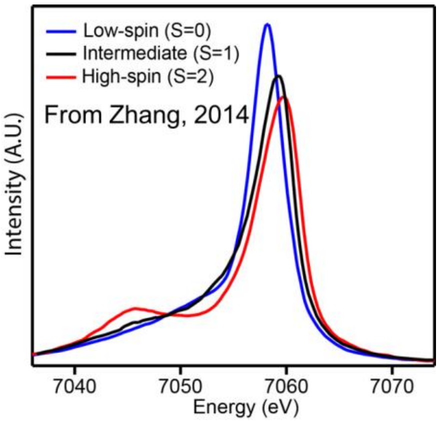
overall time resolution: **1.7 - 2.6 ps**

water jet plasma source:
~10^6 photons/sec at output focus
L. Miaja-Avila *et al*, Struc. Dyn. 2, 024301 (2015)

Time-resolved x-ray spectroscopy on a table-top at NIST

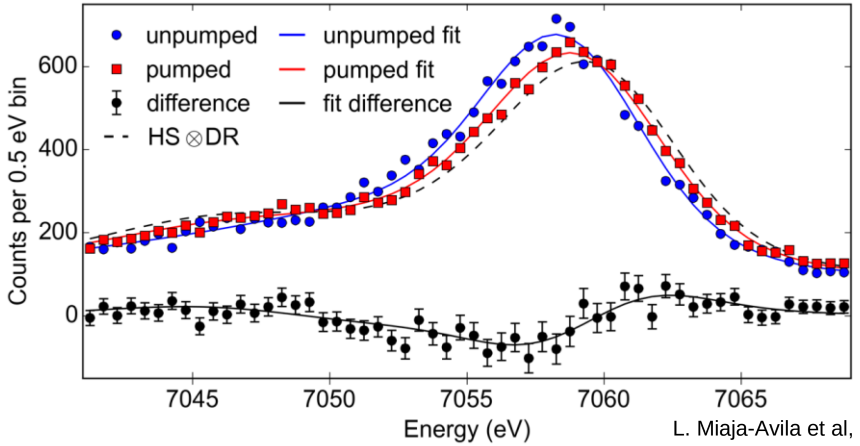
Measure lifetime of high-spin state in Iron-tris bipyridine:





Static XES of Fe compounds in different spin states shows spectral differences in Kβ emission

Data taken at NIST with TES spectrometer
Time delay = 3 ps



L. Miaja-Avila et al,
Phys Rev X (2016)

Spin state of sample is determined by fitting to linear combinations of literature curves for varying pump/probe time delays

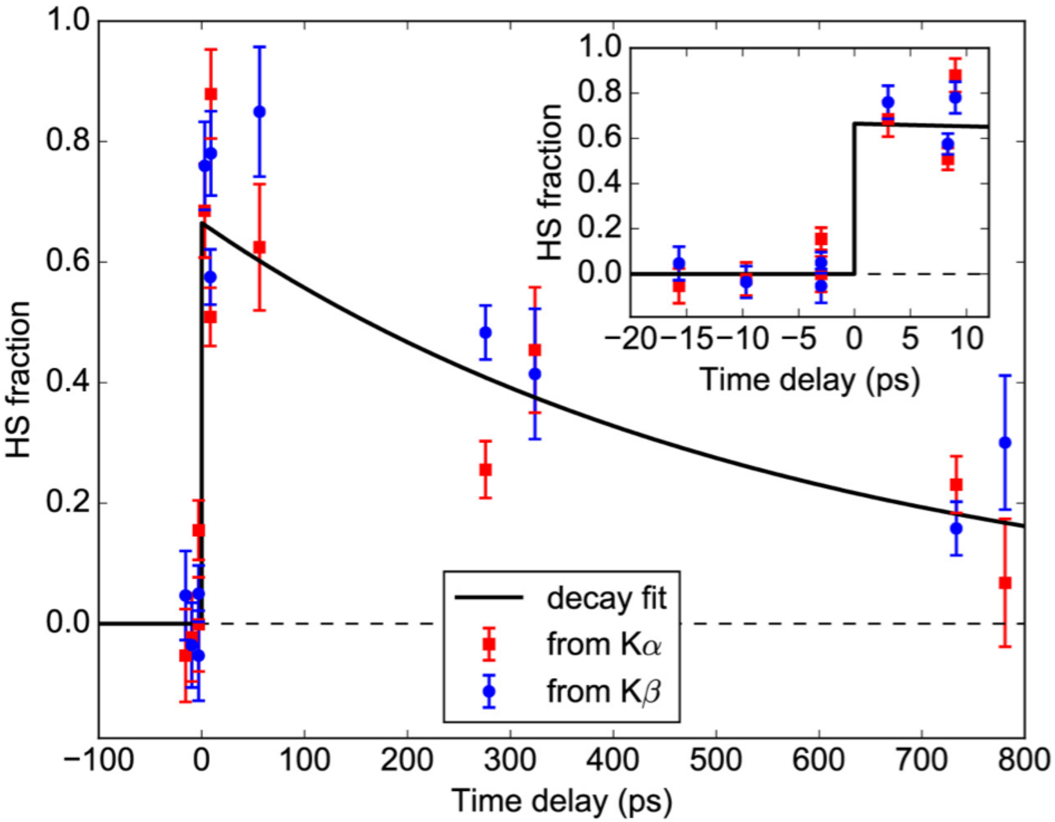
Time-resolved x-ray spectroscopy on a table-top at NIST

High-spin state lifetime = 566 ± 100 ps
L. Miaja-Avila et al, Phys Rev X (2016)

Agrees with synchrotron measurement (Haldrup *et al,* 2012), which required 10^4 more photons

Time resolution < 6 ps,
10x better than synchrotron

Measure Kα, Kβ, simultaneously



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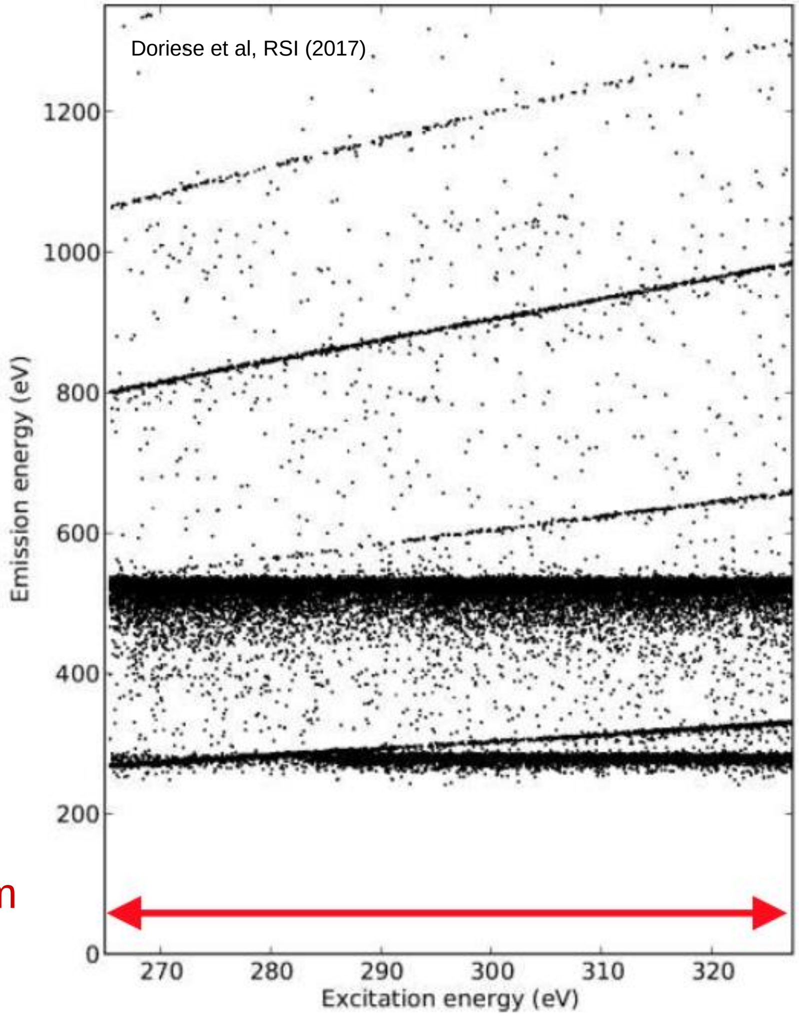
Commissioned late 2011
240-pixel TES array
ΔE ~ 2.5 eV
Will return to NSLS-II in summer 2018

PFY-XAS at NSLS U7A

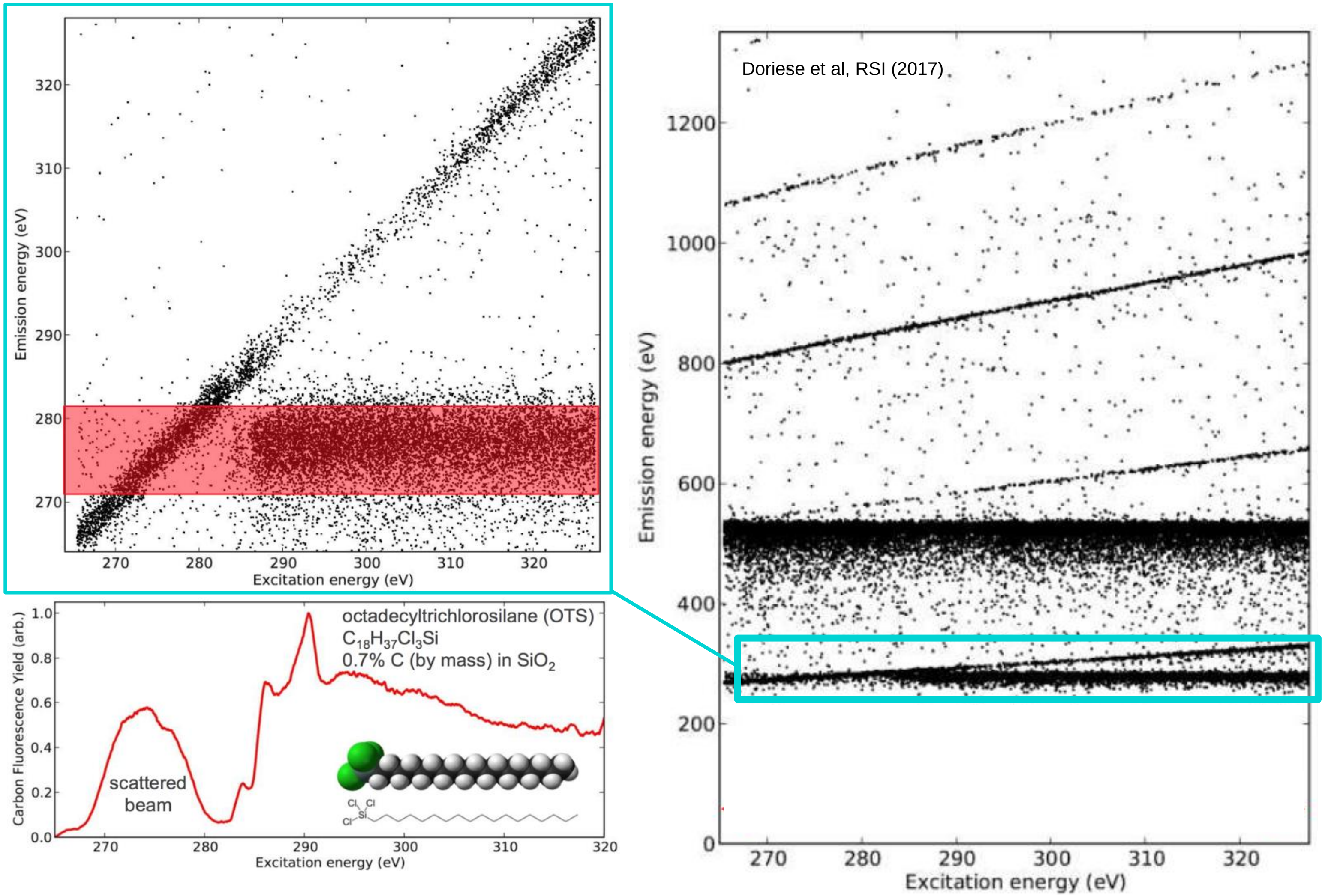
Carbon-edge absorption spectroscopy: octadecyltrichlorosilane (OTS) 0.7% C by mass in porous microparticulate SiO2

Emission collected simultaneously from 200 eV to 1400 eV by TES array

Beamline monochromator scanned from 265 eV to 327 eV (across C edge)


Doriese et al, RSI (2017)

PFY-XAS at NSLS U7A



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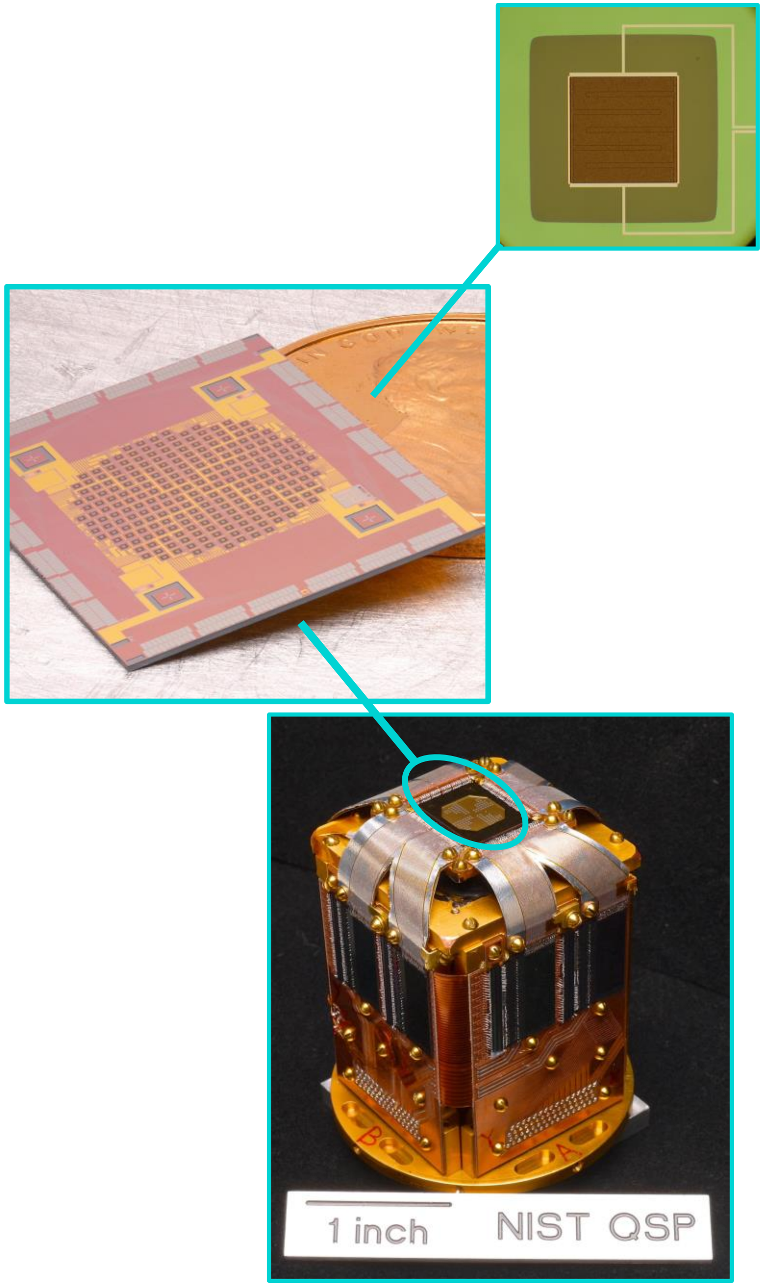
240 TES pixels
~1.5 eV energy resolution

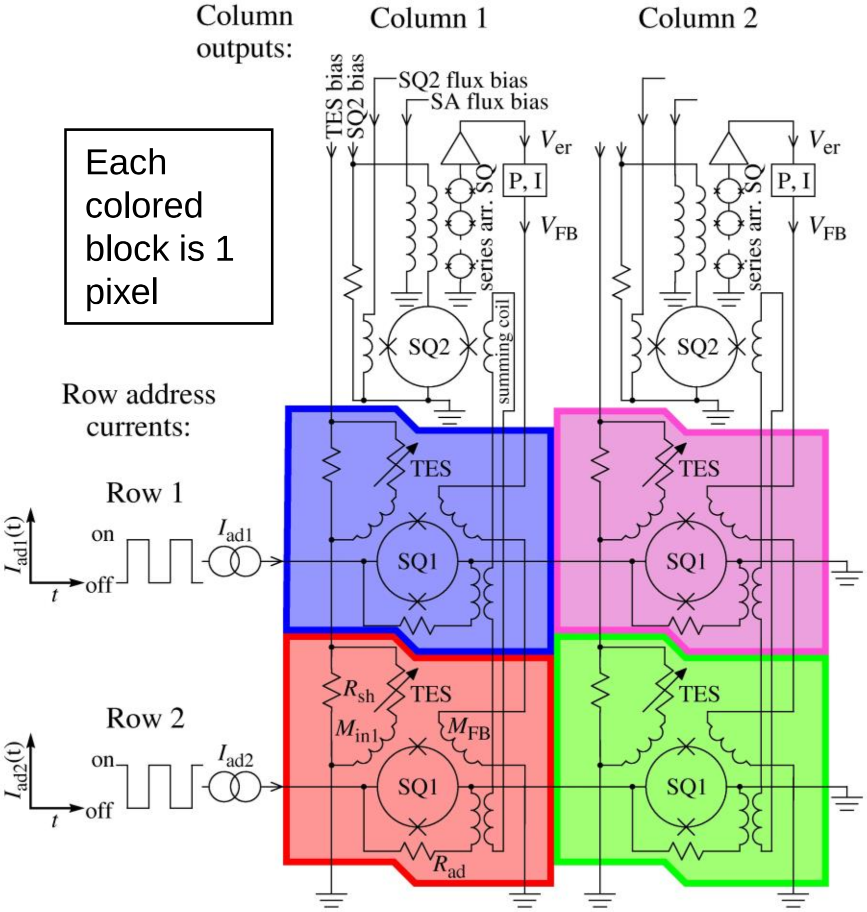
Why use a TES for photon science?

- Microcalorimeters
    - Good energy resolution – resolving powers in the thousands at 100 mK
    - Broad energy coverage – usually an order of magnitude in energy
    - Low background noise
- Pixelated arrays of TES microcalorimeters
    - High collecting area for weak signals
    - High photon throughput for strong signals

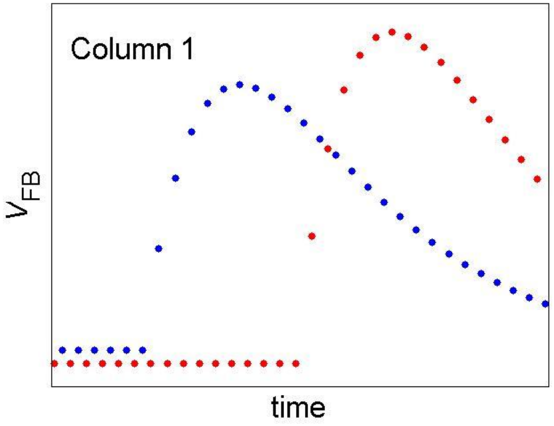


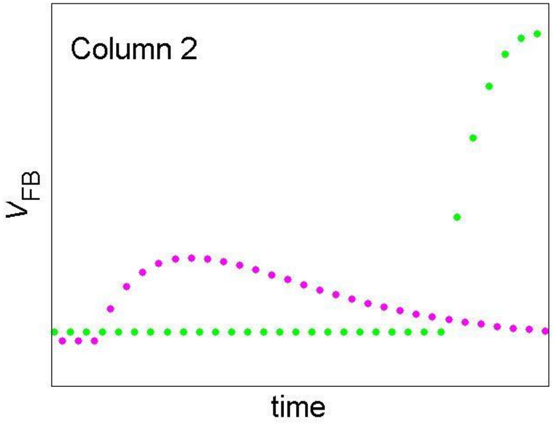
TES readout in currently deployed x-ray spectrometers

Time-Division SQUID Multiplexing Architecture



Each colored block is 1 pixel





How much further can we take TDM?

Building a 960 pixel demo for the X-IFU instrument on the Athena satellite mission

Flexible interconnects to move TES signals around the corner to MUX chips

Readout 24 columns by 40 rows

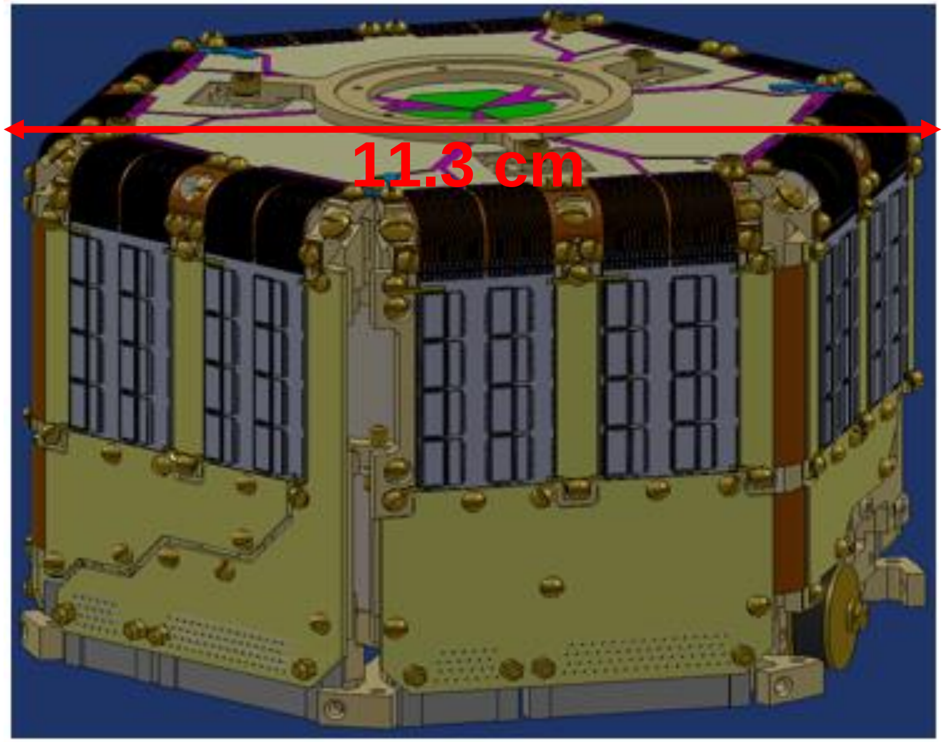
Size determined by space needed to wire bound to flexible interconnects

X-IFU planned to have ≈4000 TESs

Plan to use bump bonding to shrink size needed to make connections

Main difficulties for bigger arrays:

1. **heat load**
2. **packaging**
3. **bandwidth!**



It is all about the bandwidth

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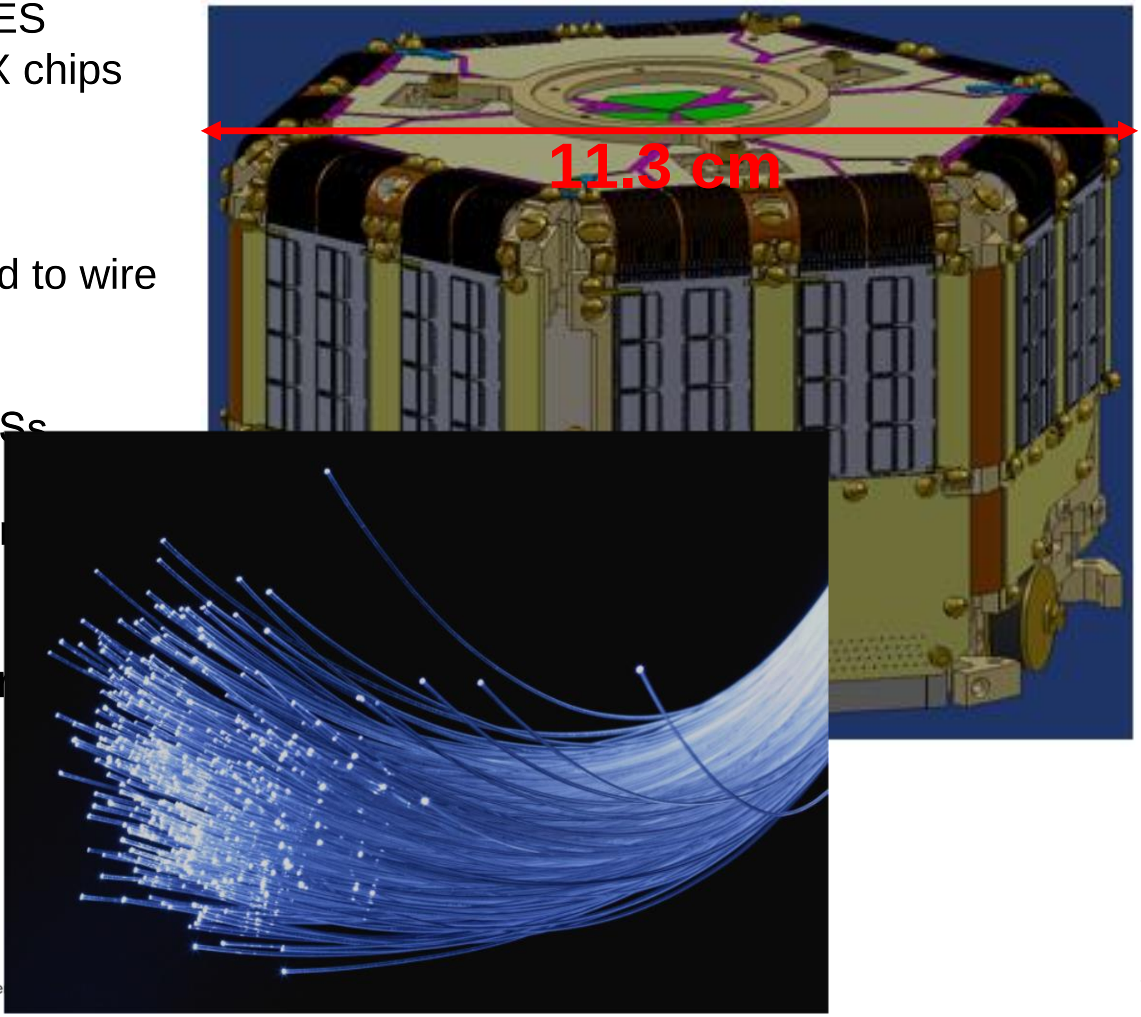
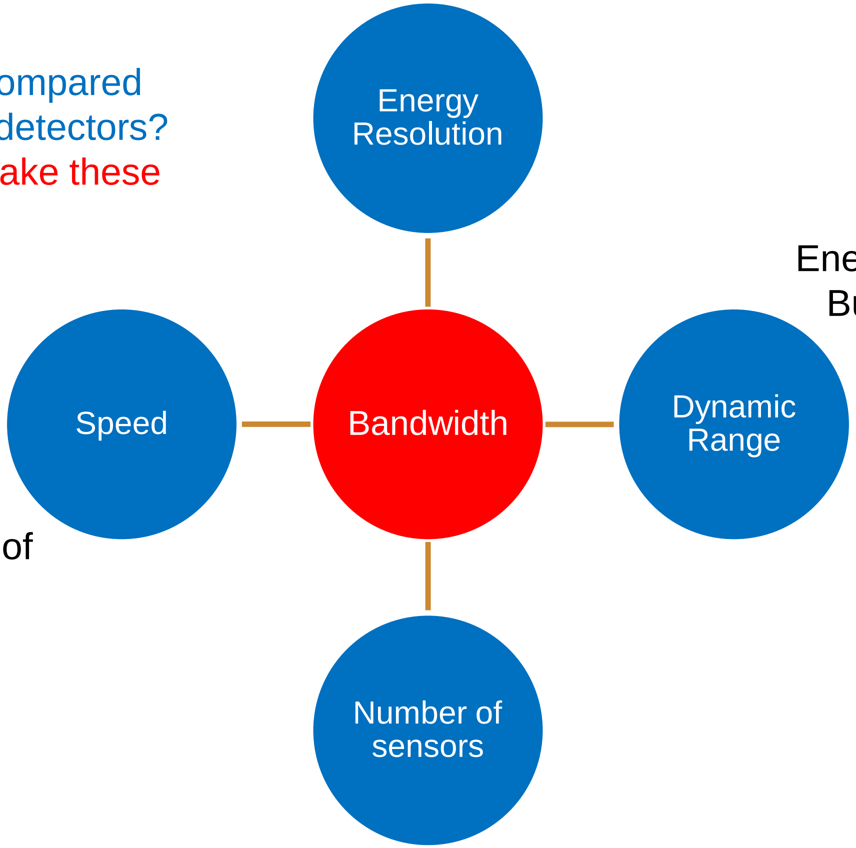


Bandwidth Tradeoffs: It’s all about the bandwidth

Why we focus on TESs compared to other low temperature detectors?
Answer: Its flexibility to make these tradeoffs!

Resolution can be improved by reducing T and C
but readout noise must go down

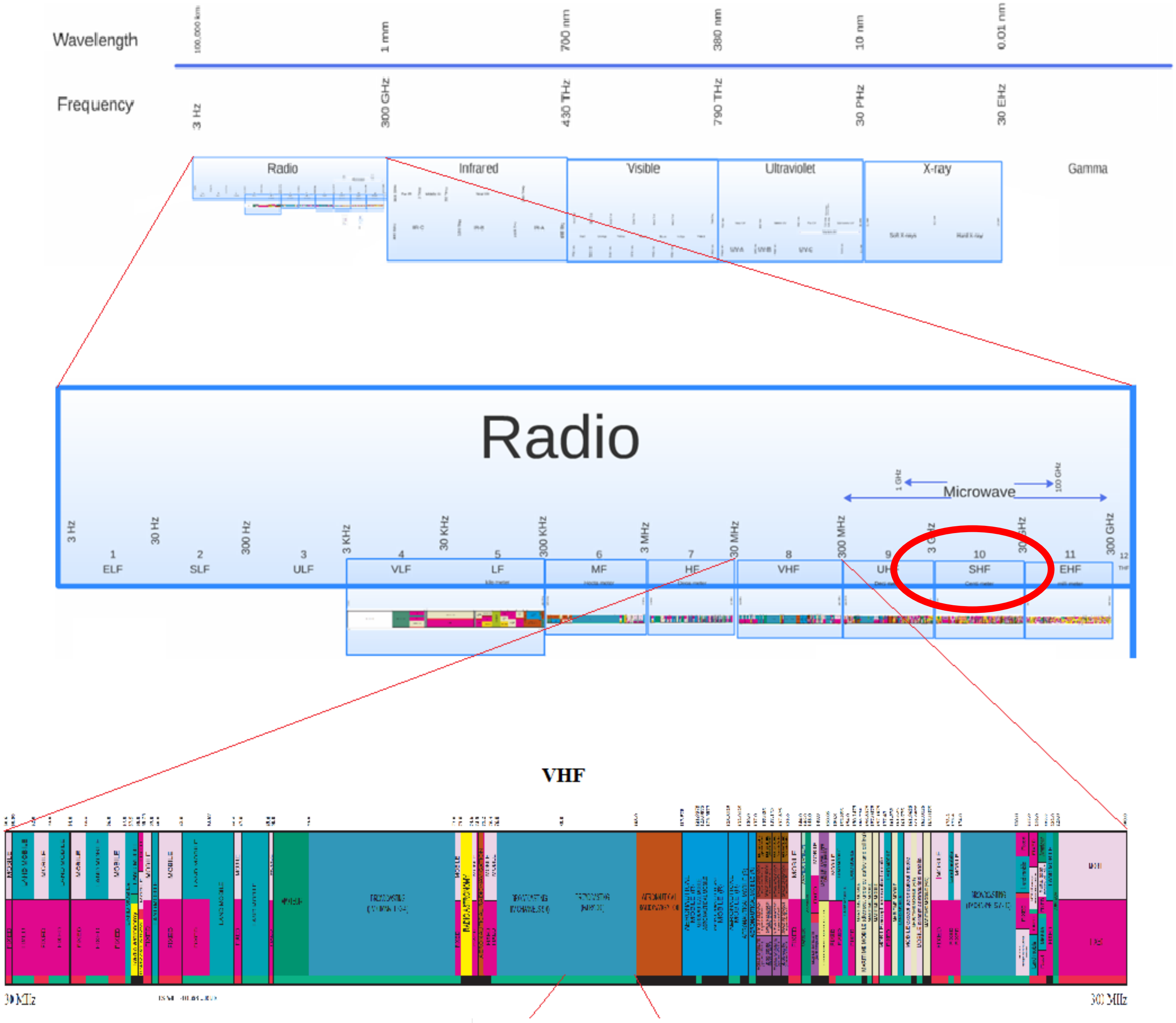


Energy range can be increased
But pulses get harder to track

TESs times constants of
10 µs are achievable

More sensors could be packed
on the same wires

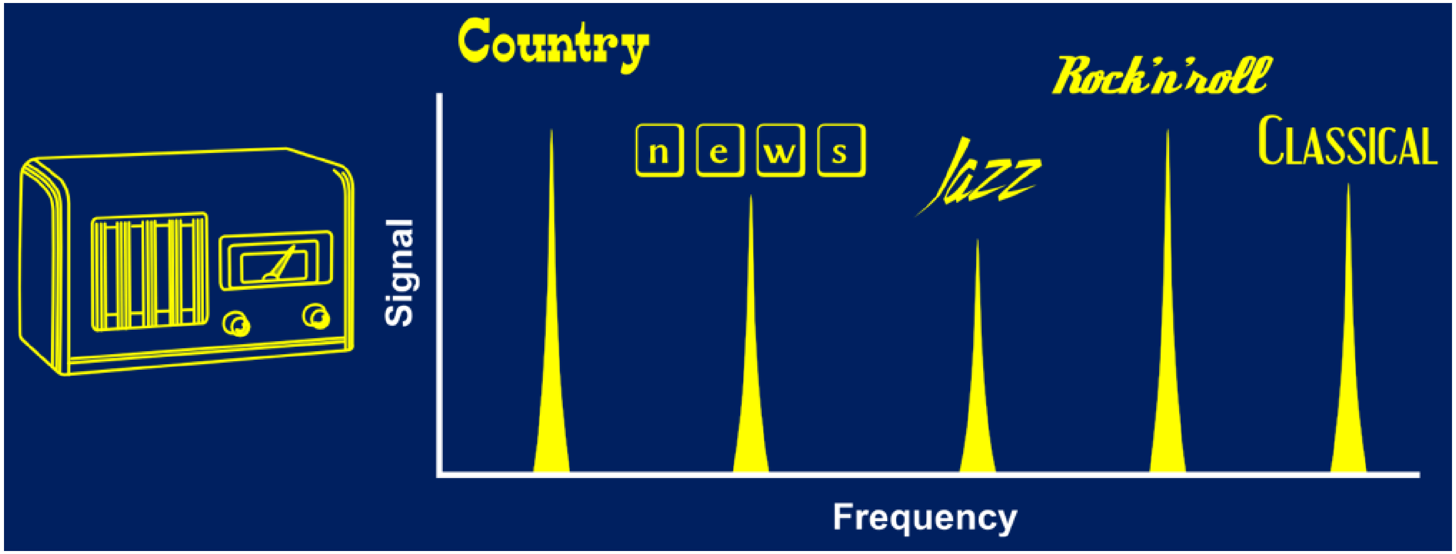
It is all about the analog bandwidth!



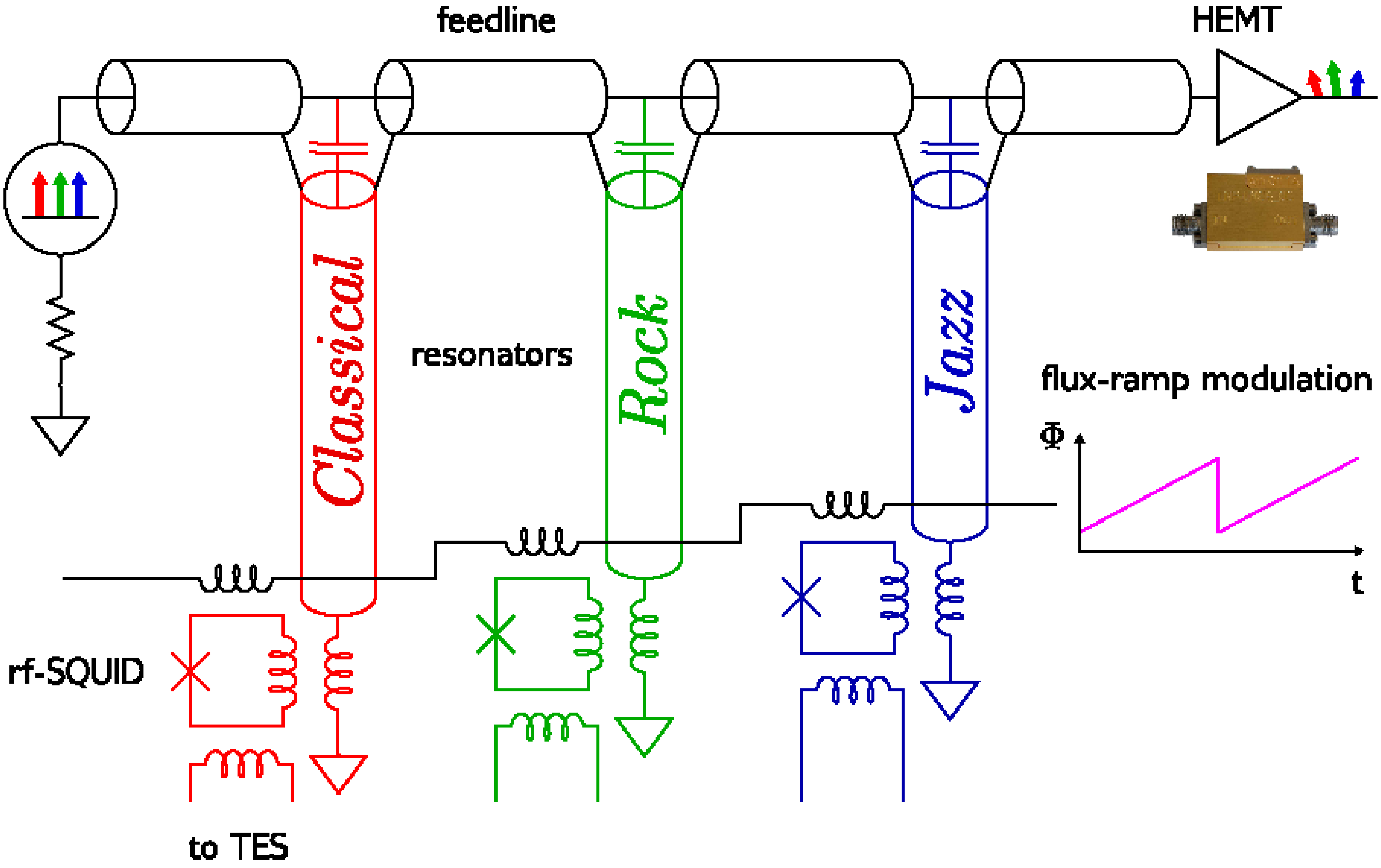
From Wikimedia Commons, the free media repository

Cartoon picture of microwave readout

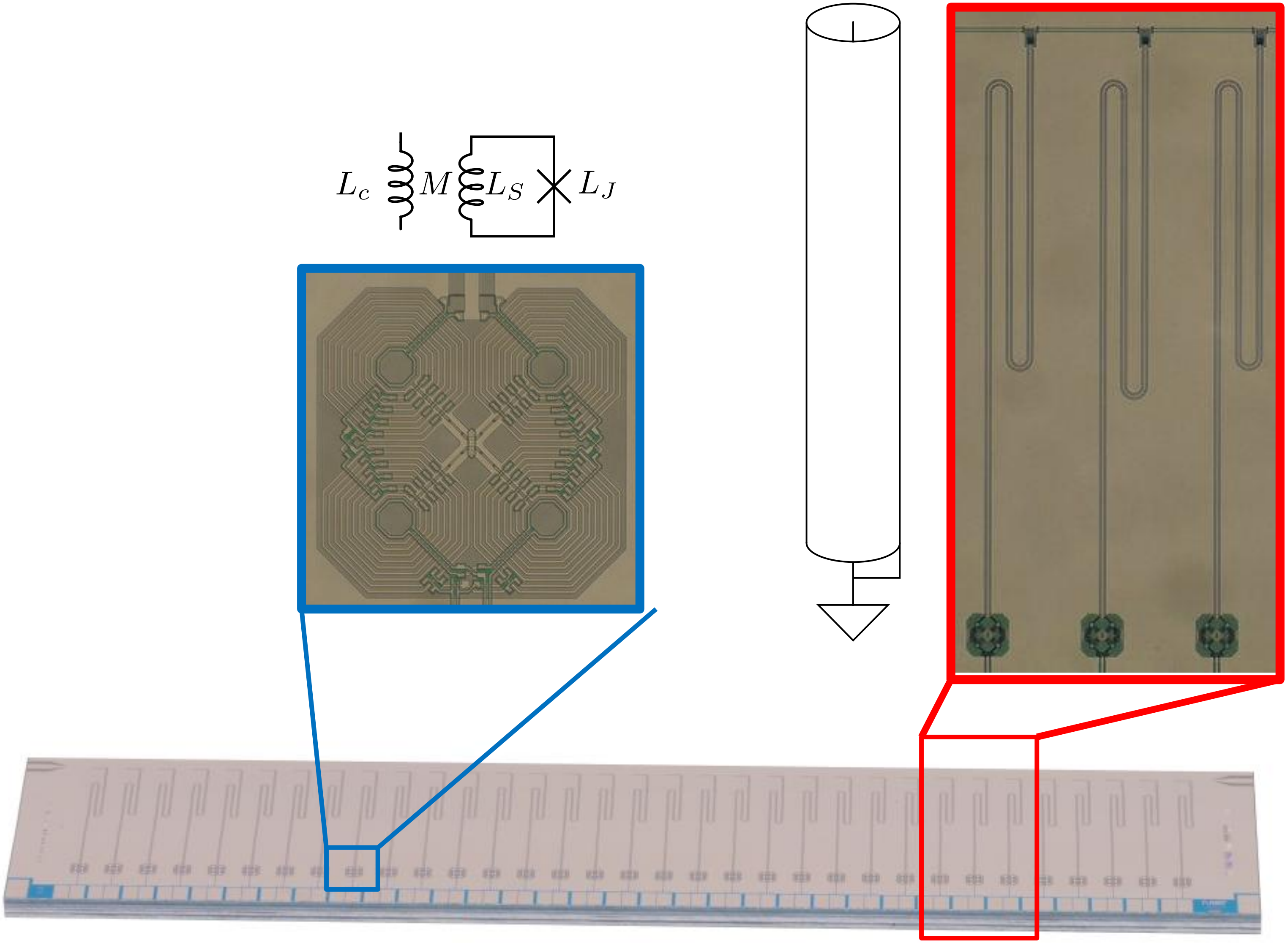
- Each sensor is a radio station. An amplifier with enough bandwidth can measure all of them, at once.
- Sensor response is encoded in the modulation of a carrier tone similar to AM and FM



Microwave SQUID multiplexing: readout for next generation instruments

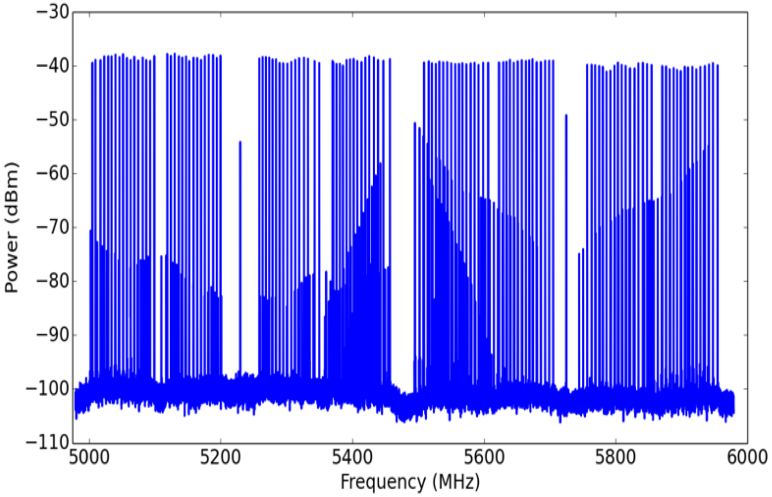


Microwave SQUID multiplexing: readout for next generation instruments

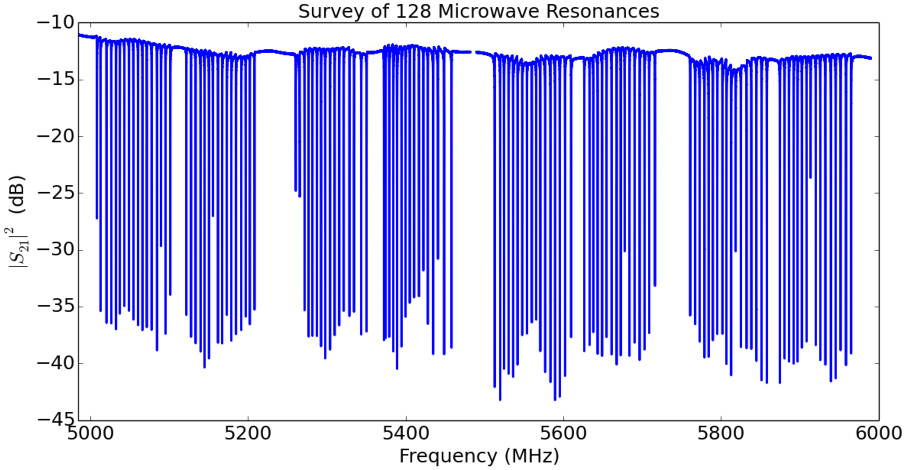


End-to-end demonstration of microwave readout

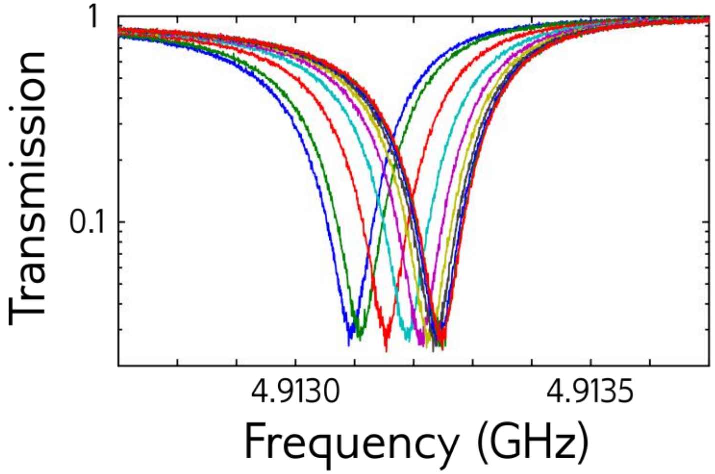
128 synthesized tones



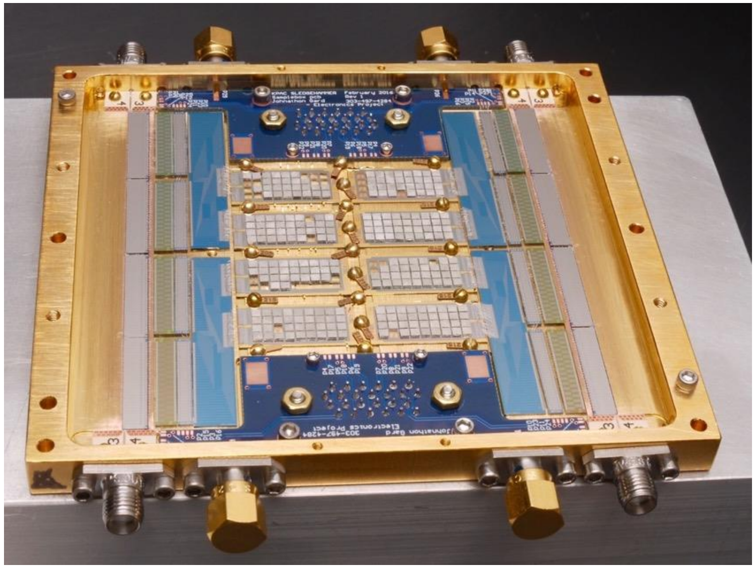
128 resonators



RF-SQUID response

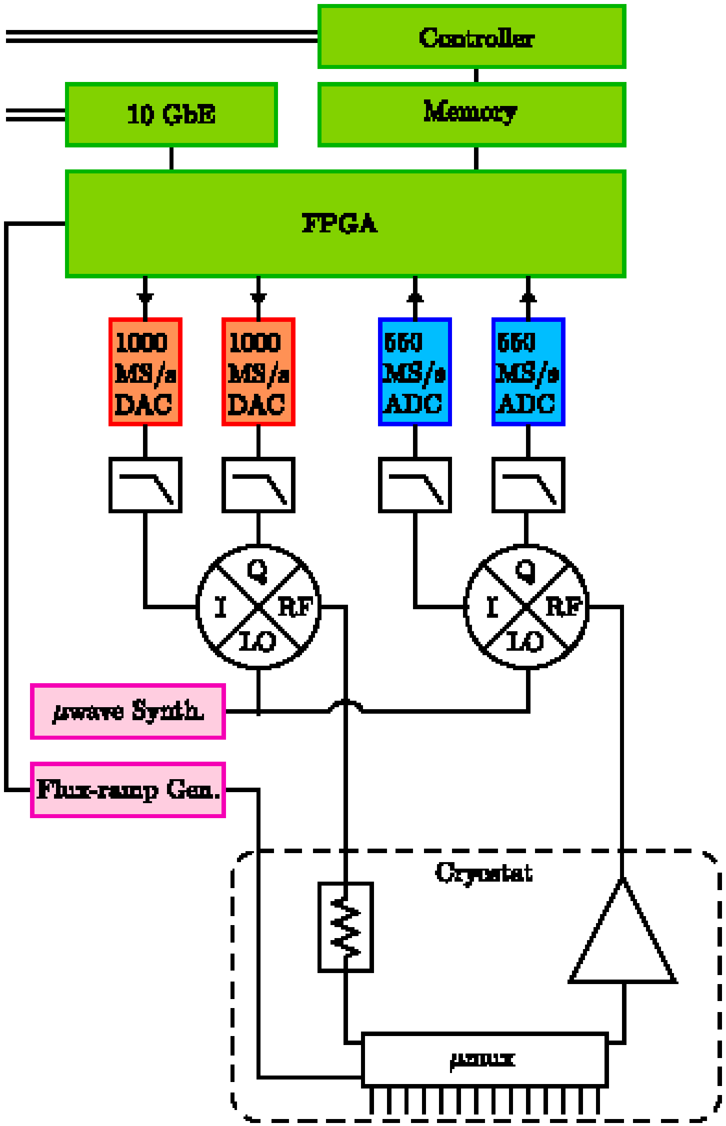


package with γ-ray sensors



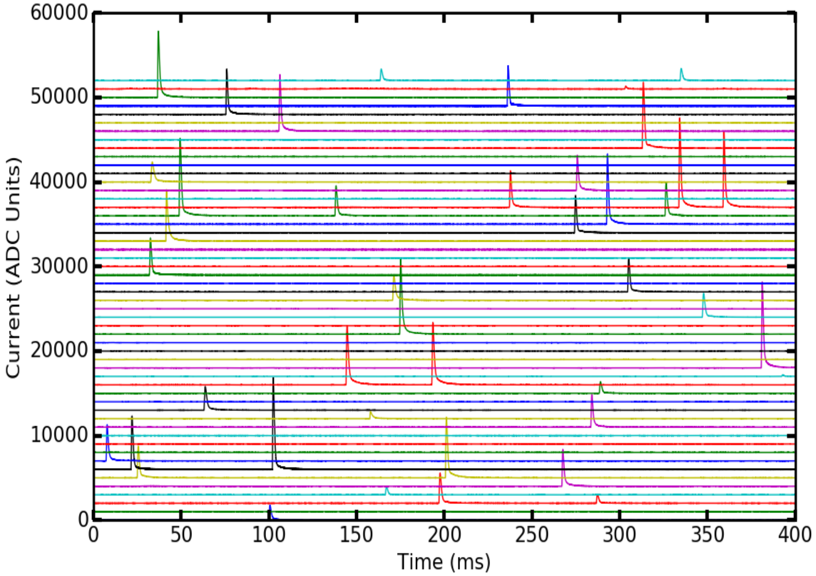
Readout Electronics for microwave SQUID multiplexing

- Generate carriers at baseband using a DAC
- Mix carriers up to resonator frequencies
- Multiplexer translates the sensor signal into a phase modulation of the microwave carrier
- Mix carriers back down to the baseband frequencies
- Digitize the signals using ADCs
- Separate carriers in firmware
- Demodulate phase modulation in firmware
- Send time stream from each channel to a computer for triggering and data processing

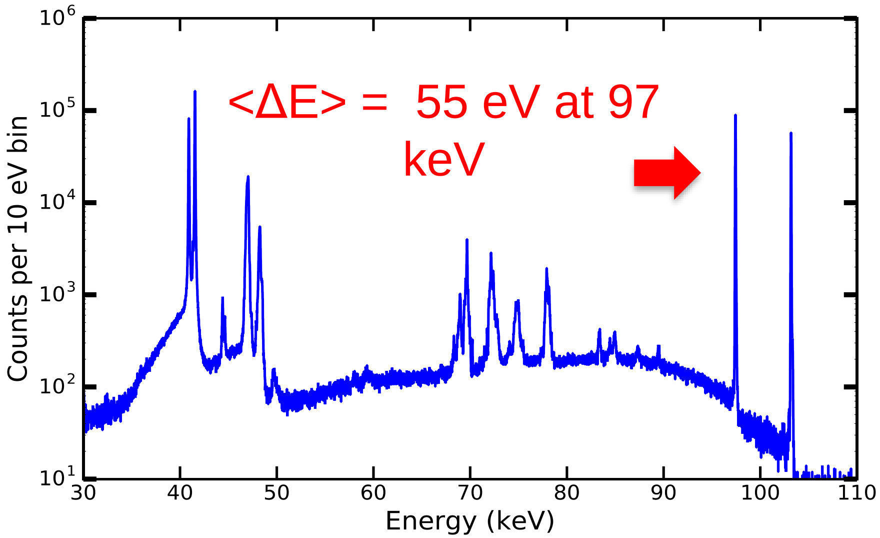


End-to-end demonstrations of microwave readout

some sensor data streams



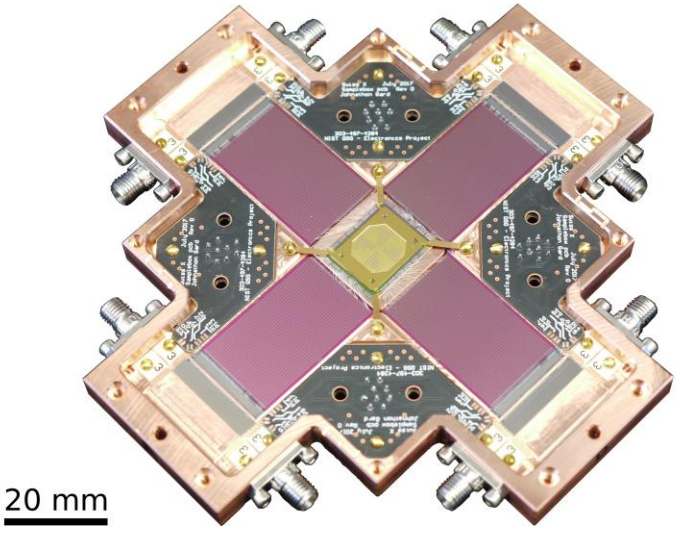
coadded spectra from ~100 sensors

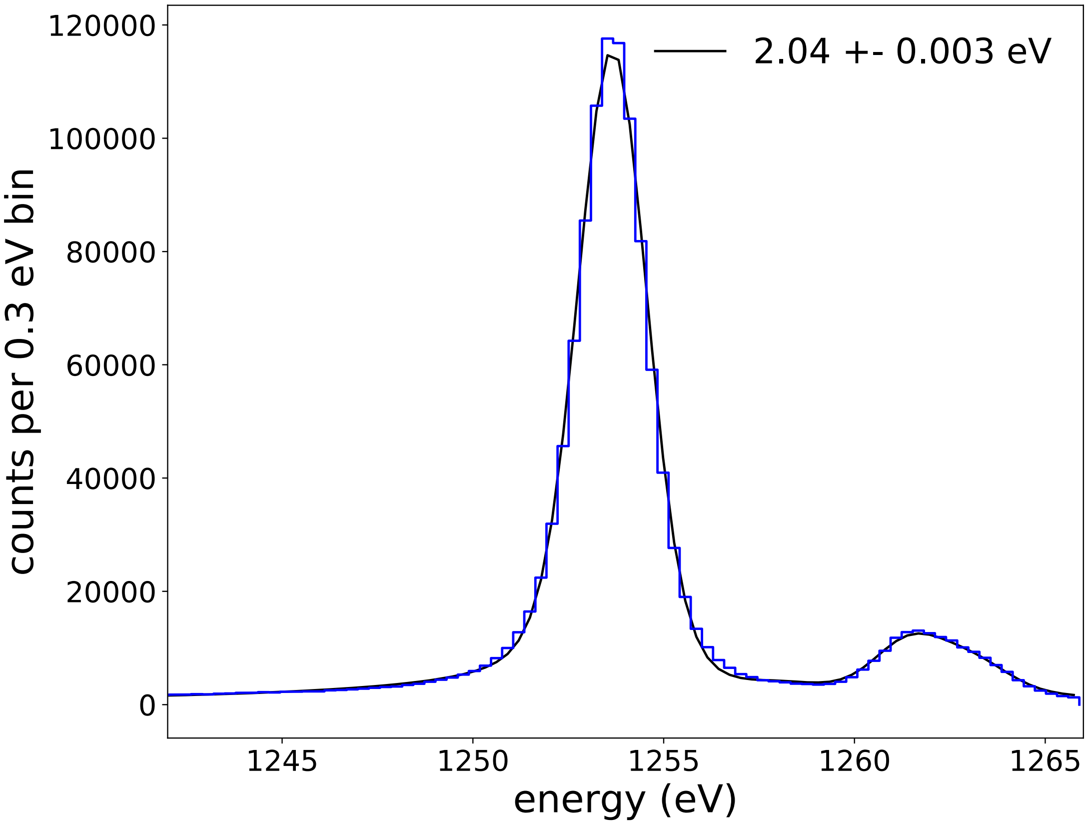


- 1 GHz of controlled bandwidth per output channel, **100x more than previous readout technologies**
- undegraded readout of ~100 γ-ray sensors per cable

End-to-end demonstrations of microwave readout

- 100 channel x-ray demonstration
- Used an old TES array that had an “experimental” pixel design with an intrinsic resolution of 2eV FWHM
- All 100 channels readout with 2 coax and 2 twisted pairs
- Achieved resolution of 2 eV consistent with non-multiplexed resolution





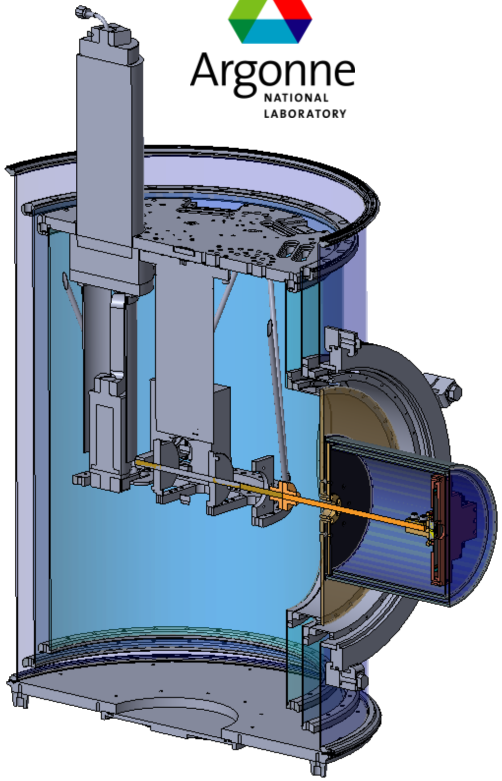
Readout Electronics Under Development

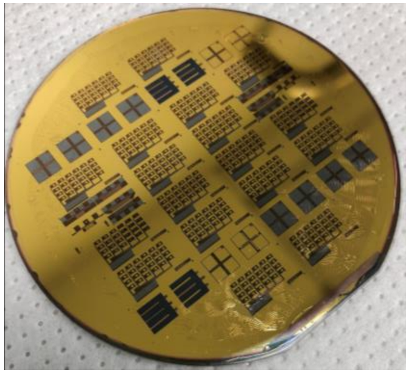
- ROACH2
  - Open source platform developed by CASPER, a consortium of radio astronomers
  - DAC and ADCs developed in collaboration with MKID community
  - Used in our microwave MUX demos and those of our collaborators
  - Fermilab has built a new DAC/ADC board with more bandwidth for MKIDS – Could provide 4 times more readout bandwidth for TESs
- SMURF Electronics
  - Under development at SLAC for both bolometer for CMB measurements and for microcalorimeters for TES instrument for LCLS-II
  - Based on ATCA crate, standardized SLAC architecture
- Commercial Platforms
  - Hardware has significant overlap with industries doing software defined radio and modern radar applications using fast DACs and ADCs interfaced to cutting-edge FPGAs
  - Leverages larger industry efforts to push ADCs to higher speeds at high bit depth
  - NIST currently developing firmware on platform from Abaco with 8 DACs and ADCs at 1 GS/s

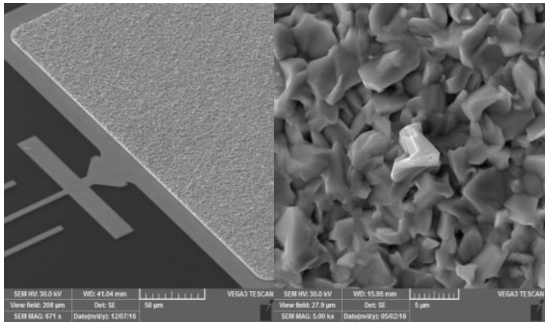
APS hard X-ray TES spectrometer

Argonne NATIONAL LABORATORY

- Design and fabrication of two 100-pixel arrays for X-ray photons between 2-20 keV:
  - One for high energy resolution: < 10 eV at low count rate ~ 100 counts/s per pixel.
  - One for high count rate with moderate energy resolution: ~ 20 eV, aimed to explor the tradeoff between speed and resolution.
  - Ultimate goals: pilot XAFS and XES experiments.
- Mo/Cu TESs:
  - Low resistivity (square R ~ 10 mOhm), compatible with Microwave MUX SQUID readout chips developed at NIST: one set for high resolution (~ 300 KHz resonators) one set for high speed (3 MHz resonators).
  - T_C~ 100 mK, with the possibility of aiming to lower T_C for improved energy resolution thanks to the very low temperatures reachable by the cryostat.
  - Electroplated Bi/Au absorbers for high stopping power at low added heat capacity (i.e. high energy resolution).
- Helium-3 backed, single stage ADR (Adiabatic Demagnetization Refrigerator)
  - Base temperature < 30 mK.
  - >200 hour no-load regulation at 100 mK.
  - 12 inches port with short snout.



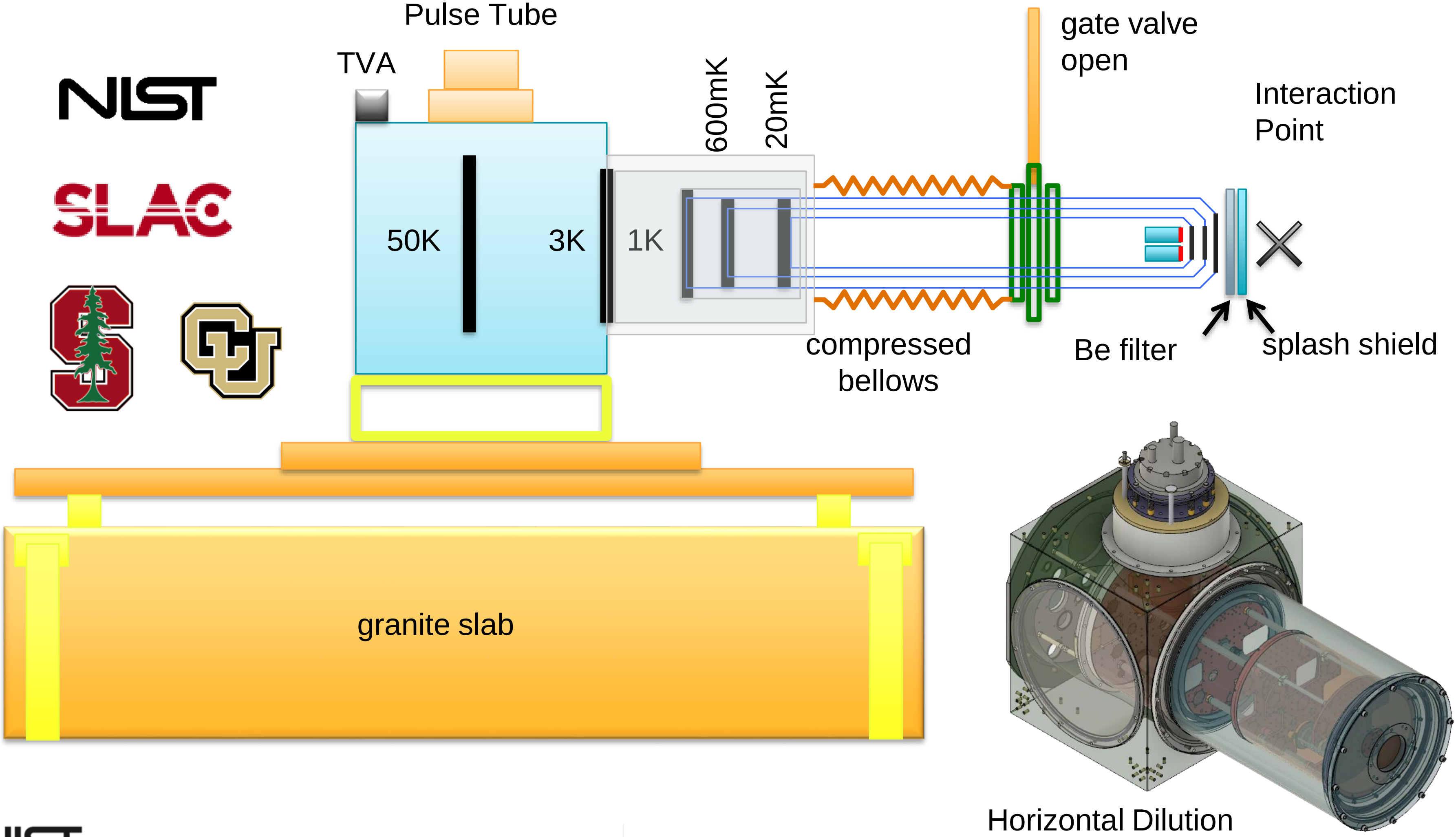




Plans for upcoming instruments using μMUX

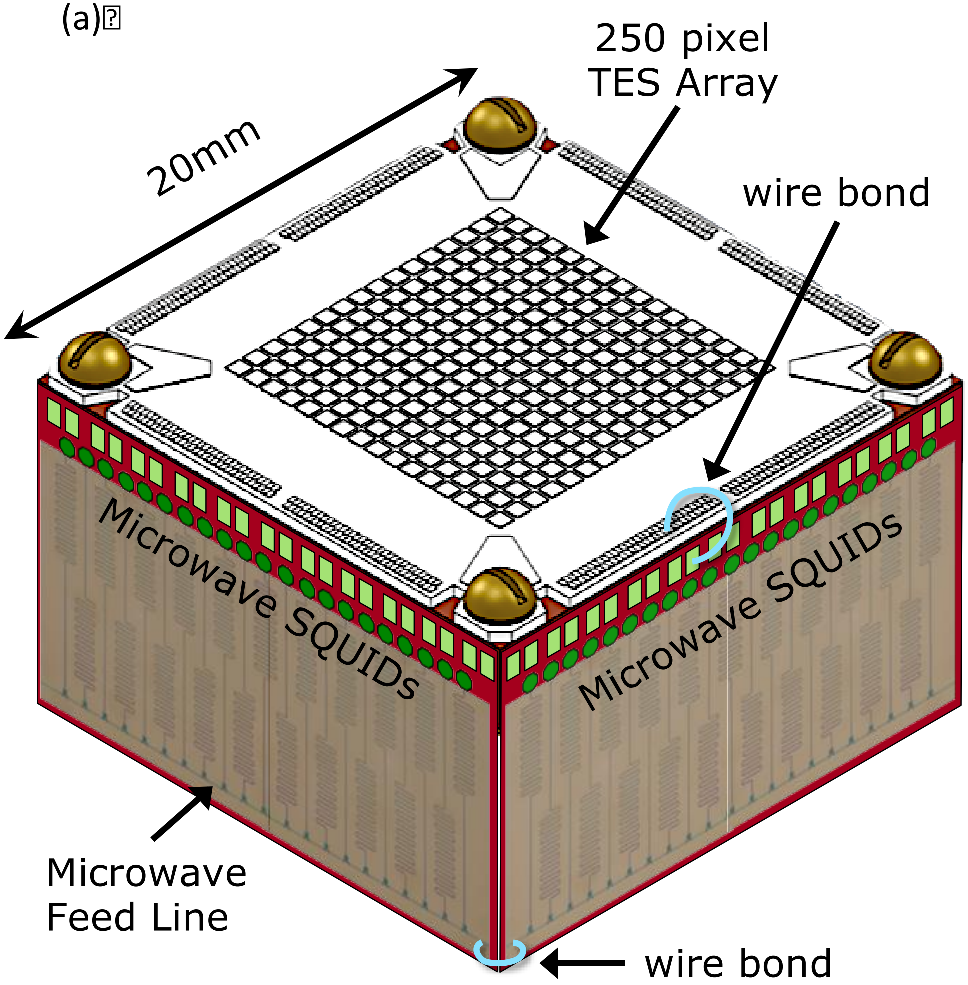
TES Spectrometer for LCLS-II

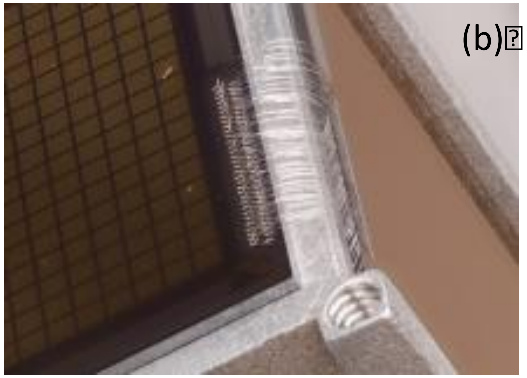
1,000 pixel array at 0.5 eV resolution, upgradable to 10,000 pixels



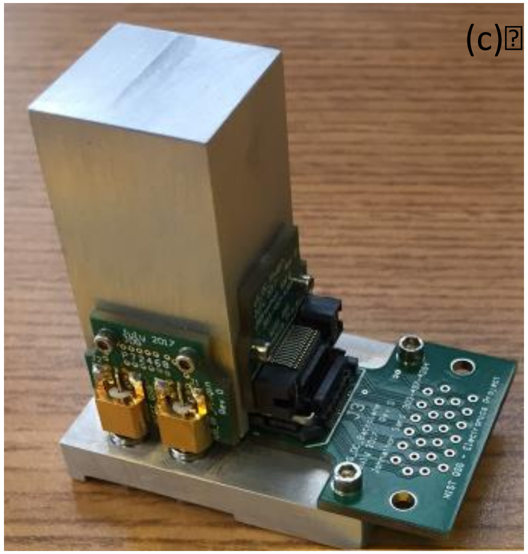
Horizontal Dilution Refrigerator

Microsnouts for near term kilopixel arrays





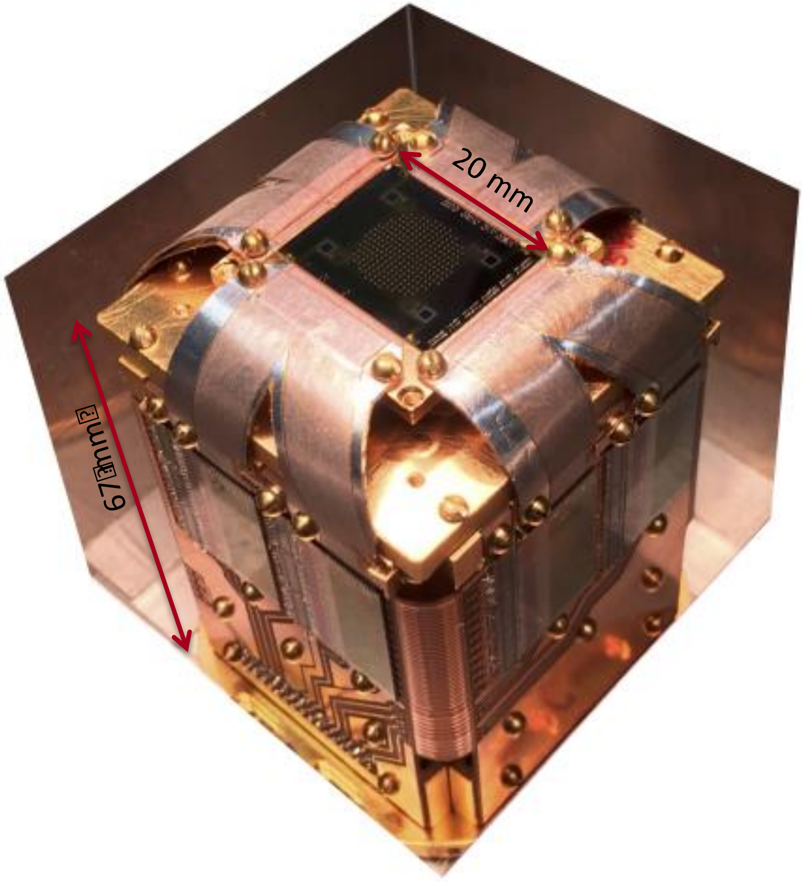
3D wirebonding



connector miniaturization

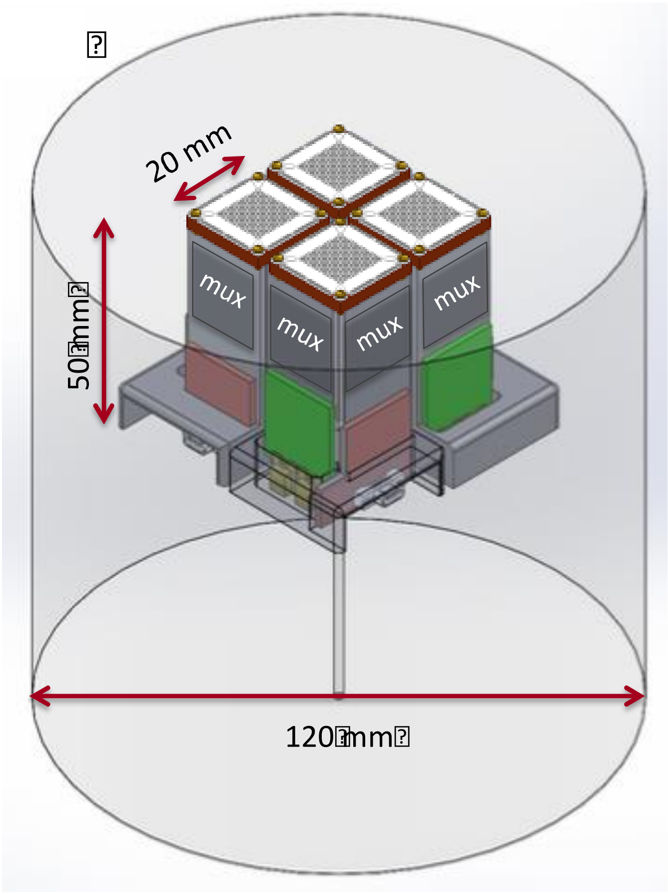
Microsnouts for near term kilopixel arrays

TDM “snout”



240 TESs readout with TDM

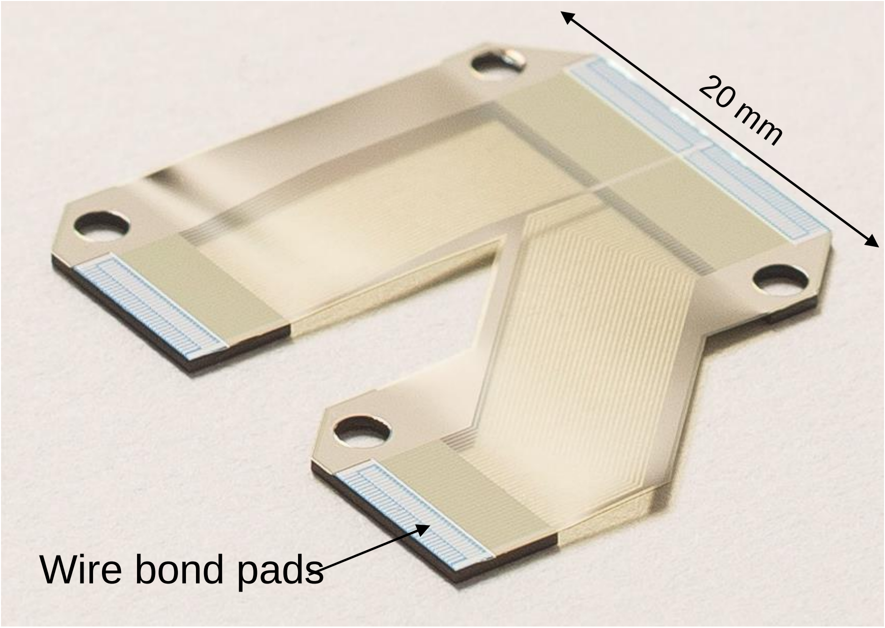
“microsnouts”



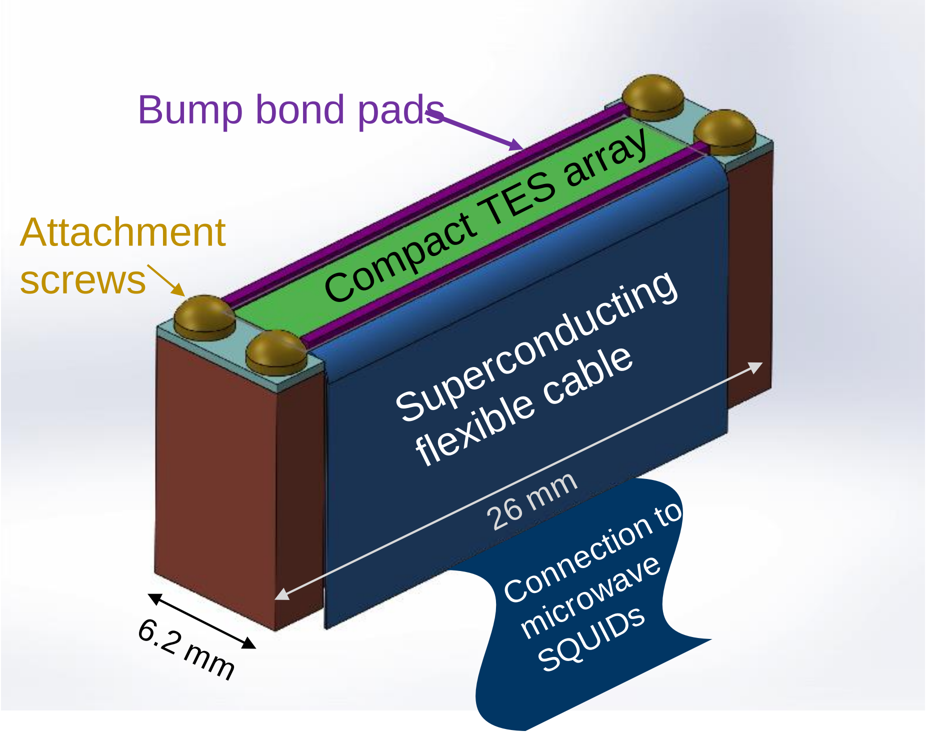
1024 TESs readout with µMUX

How do we get to 10’s of thousands of pixels?

prototype superconducting flexible cable

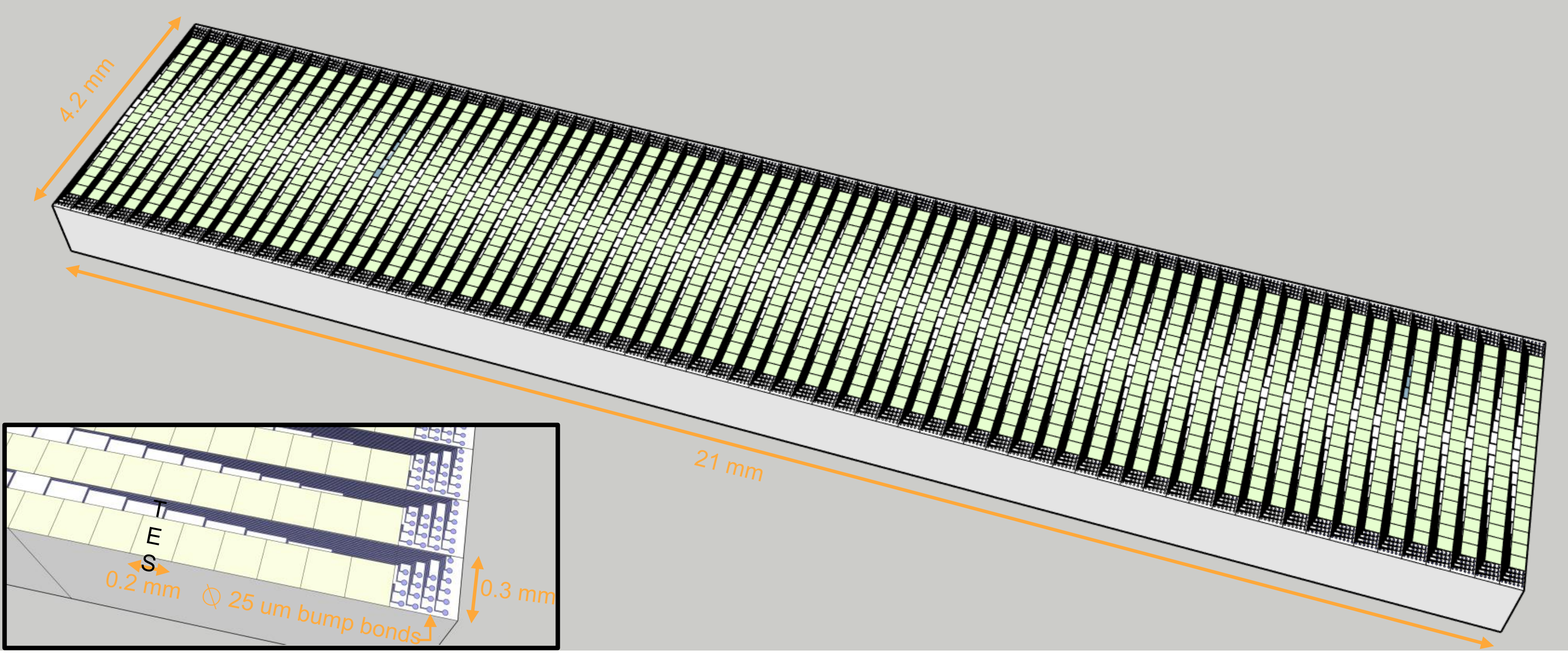


proposed 1260 TES “nan-snout”



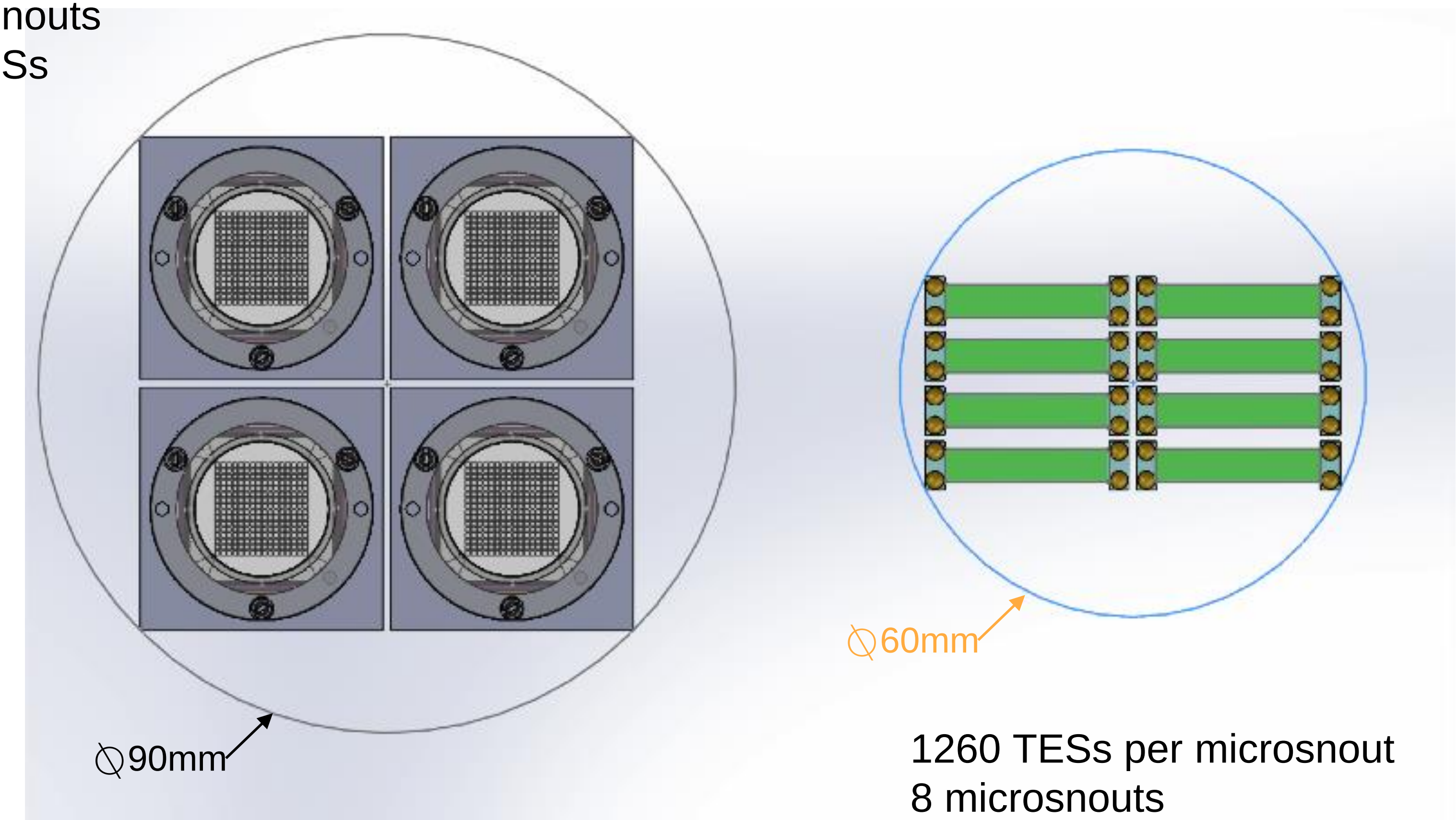
How do we get to 10’s of thousands of pixels?

compact 1260 TES chip with bump bond pads



How do we get to 10’s of thousands of pixels?

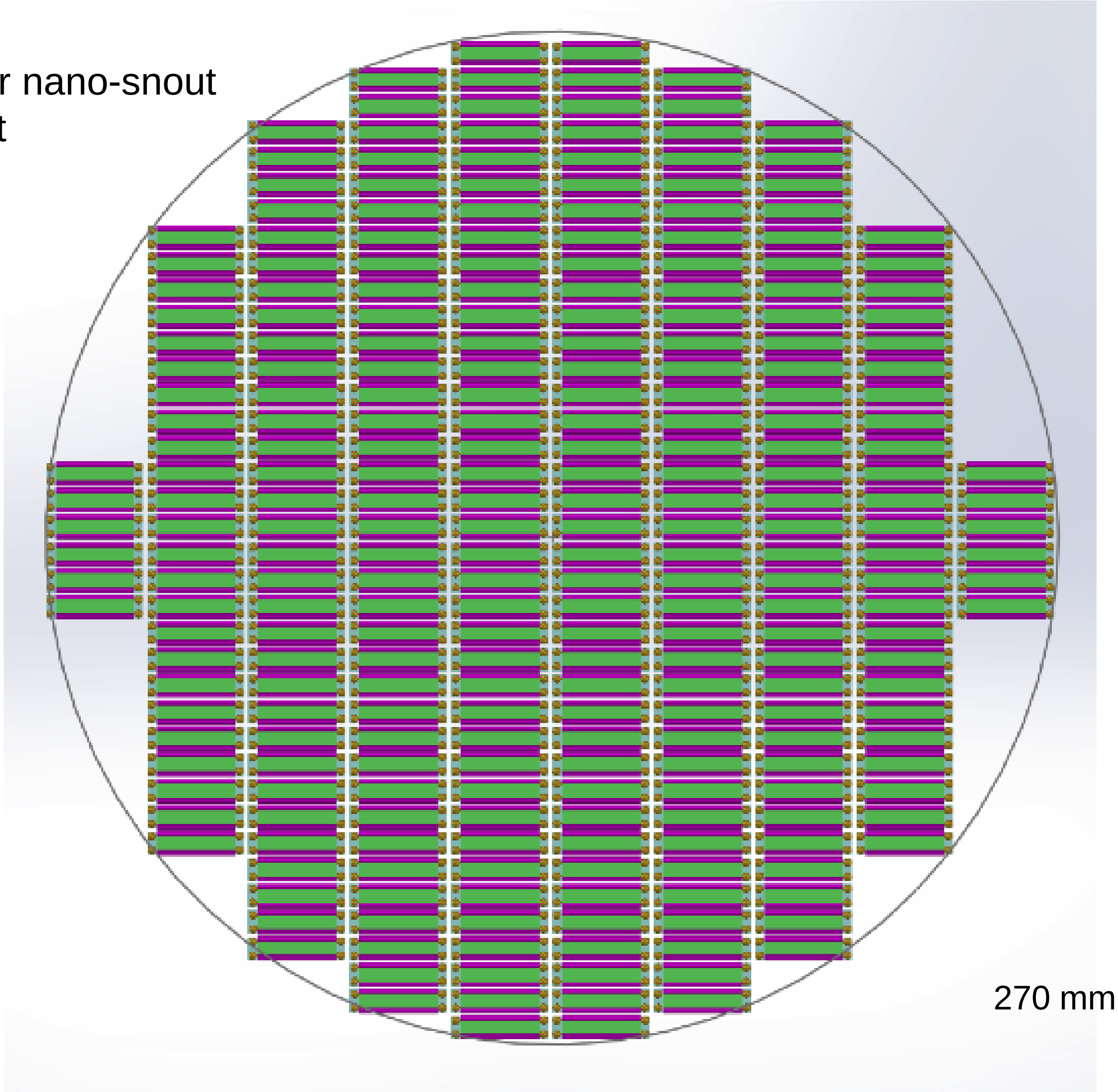
256 TESs per microsnout
4 microsnouts
1024 TESs



1260 TESs per microsnout
8 microsnouts
10,080 TESs

How do we get to 100’s of thousands of pixels?

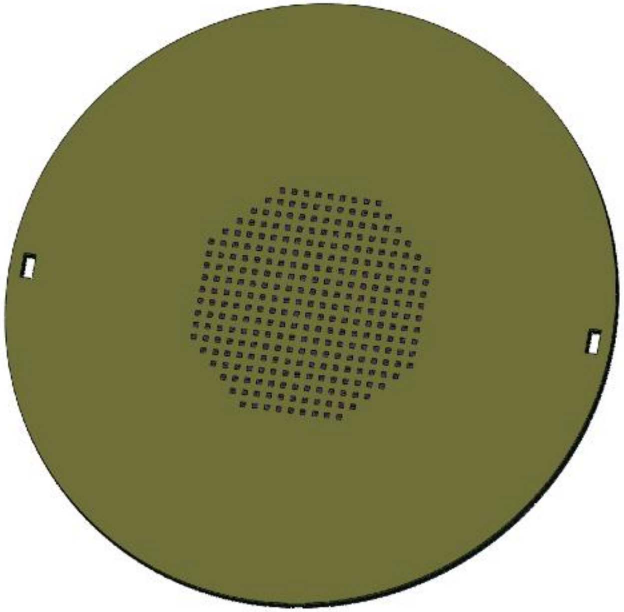
1,260 pixels per nano-snout
272 nano-snout
342,720 pixels

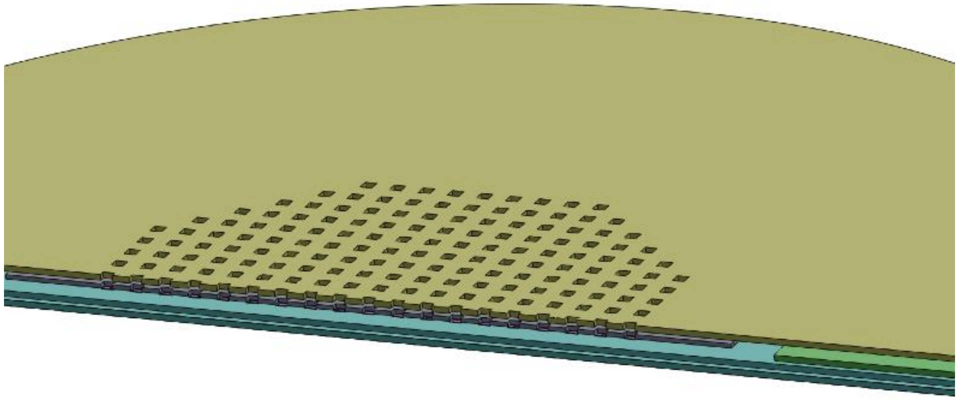


270 mm diameter

How do we get to 100’s of thousands of pixels?

- Utilize wafer scale flip chip bonding
- Micromachine apertures into 6 inch or larger wafer
- Wire routing between readout and TES chips on back side of aperture wafer
- Flip chip bond TES chips and microwave MUX chips to aperture wafer
- Microwave MUX feedline and a few dc connections on outer perimeter of aperture wafer wire bonded to PCB and microwave launch boards





Under-resourced areas of development

- Lack real-time software or firmware
    - Large amounts of data produced very quickly by large arrays
    - Microcalorimeter data is typically analyzed offline
    - Need real time feedback and advanced data pipelines
- Need bigger X-ray windows and filters
    - Commercially available windows (25 mm) and IR filters (17 mm) limit packaging
    - Multiple windows planned for 1,000 pixel LCLS-II, need a better solution for upgrade
- Readout is currently expensive
    - Price per bandwidth likely to be cost driver for larger arrays
    - Prices are coming down with effort
    - Potential to leverage advances from commercial markets, i.e. integrated FPGA and ADCs
- Detector packaging is challenging
    - Wire bonding takes up too much real estate
    - Bump bonded flexible cable likely suitable for ten to hundred thousand pixels
    - Wafer bonding is promising
    - Prospects for in-focal plane readout
        - makes design and fabrication harder
        - could significantly effect yield

What can we reasonably expect in the future?

Predicted scaling for speed and # number of TESs

	Deployed	Under Construction	5 years out	10 years out “prediction”
# of TESs	250	1000	10,000	100,000
Total Area	8 mm^2	32 mm^2	320 mm^2	3,200 mm^2
Time Constant	1 ms	100 µs	100 µs	10 µs
Max Throughput	25 kcps	1 Mcps	10 Mcps	1,000 Mcps
Total Bandwidth	4 GHz	16 GHz	80 GHz	800 GHz
Bandwidth / cable	4 GHz	4 GHz	8 GHz	12 GHz
# cables	2	8	20	134

Typical energy resolution at 100 mK and predicted resolution at 25 mK

Temperature	FWHM @ 1 keV	FWHM @ 6 keV	FWHM@ 200 keV
100 mK	1 eV	2 eV	50 eV
50 mK	0.5 eV	1 eV	25 eV

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Many outside collaborators (always looking for more!)

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Brookhaven National Laboratory
Lund University
University of Jyväskylä
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