Performance of a broad-band, high-resolution, TES spectrometer for laboratory and space x-ray astrophysics experiments

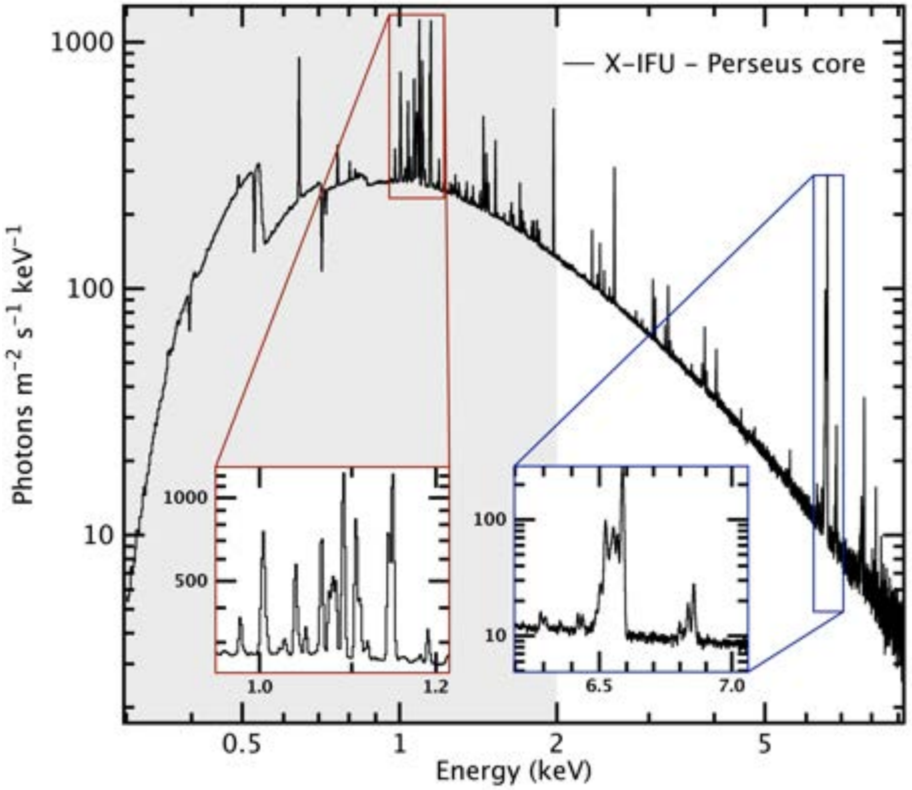
Presented by Stephen J. Smith

NASA Goddard Space Flight Center

Discussion time 16:45-18:00 November 3rd, 2020.

Microcalorimeters for imaging and high-resolution spectroscopy

- ATHENA is European led x-ray observatory due for launch in 2030s.
- ATHENA X-ray Integral Field Unit (X-IFU).
  - 3,168 transition-edge sensors (TES).
  - With 96-column by 34-row time division multiplexed readout (TDM).
  - ΔE_{FWHM} = 2.5 eV at 7 keV.
  - 4.7 arc second pixel pitch with 5 arc minute field of view.



Barret et al. SPIE 2016

Simulated X-IFU spectrum of Perseus galaxy cluster, based on Hitomi SXS observations. The insets show the region around the iron L and K complexes. The wealth of information provided by such a spectrum, that will be measured on sub-arc minute scales enables in depth studies of the physical properties of the hot cluster gas (e.g. temperature, density, turbulence, bulk motion, abundance, . . .).

Microcalorimeters for imaging and high-resolution spectroscopy

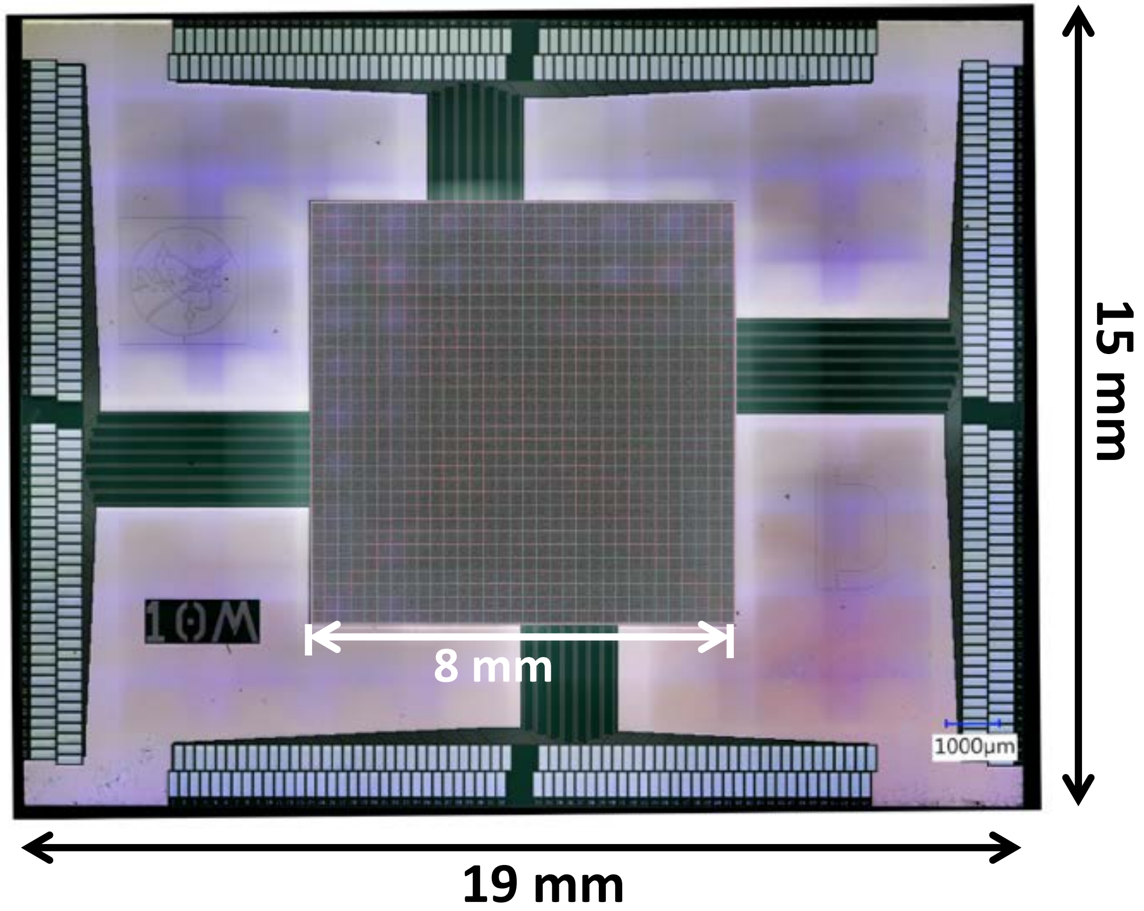
- Parallel effort to develop a 250-pixel instrument for laboratory astrophysics.
- Uses prototype X-IFU technology.

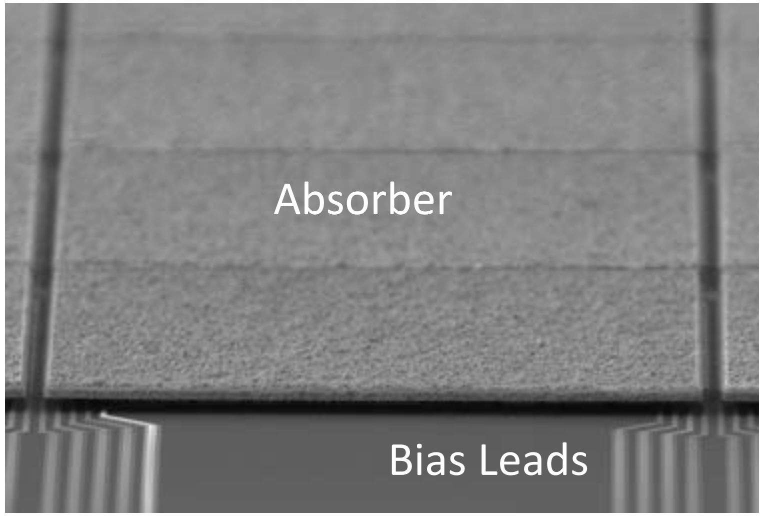
  → Demonstrator for critical X-IFU detector and readout technology.
- Will be deployed at LLNL Electron Beam Ion Trap (EBIT).
- Observe highly ionized plasmas in controlled laboratory conditions.

  → Support x-ray missions by benchmarking and give guidance to atomic models and spectral synthesis codes.
- In this presentation we talk about progress towards completing this instrument and demonstrating the key performance requirements for X-IFU.

Prototype X-IFU array design

Kilo-pixel array *(not full X-IFU scale)*
uniform 32x32 array, 15 mm x 19 mm chip



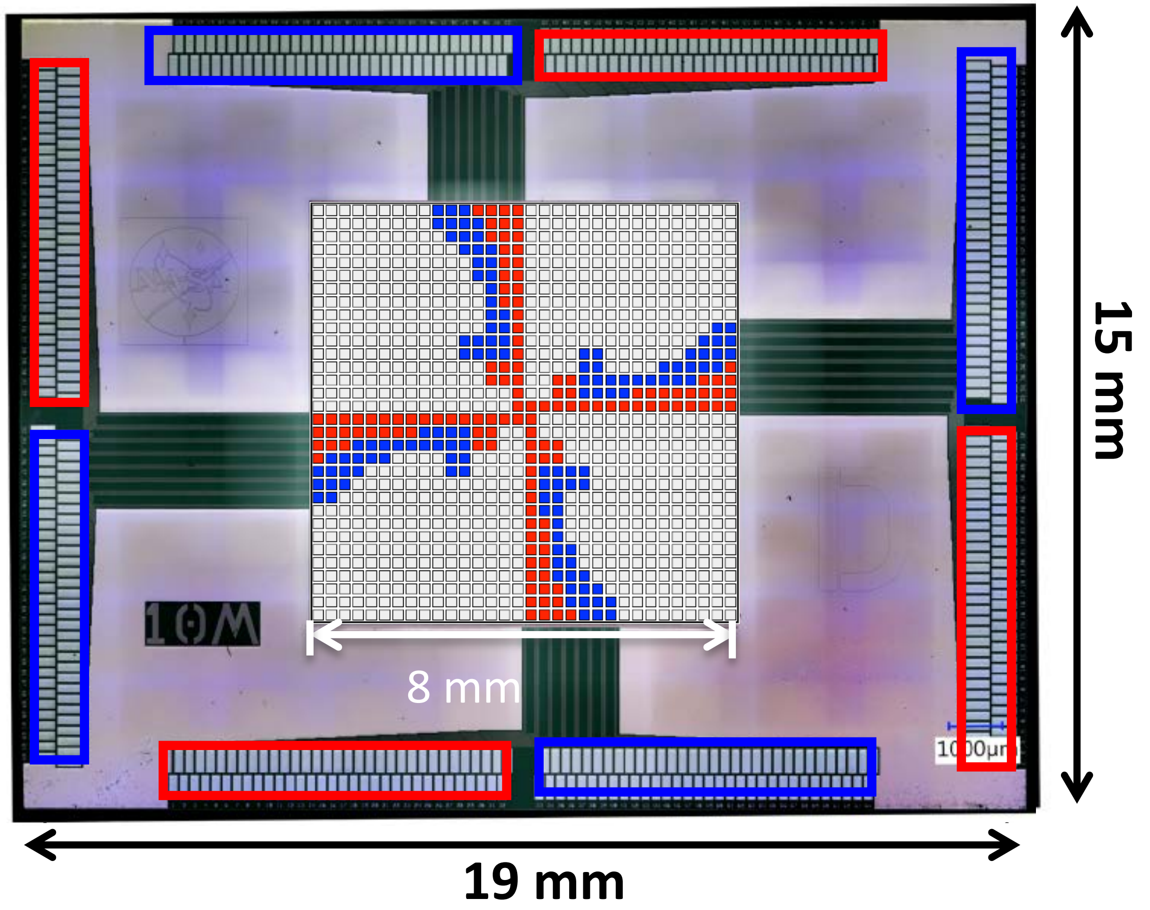


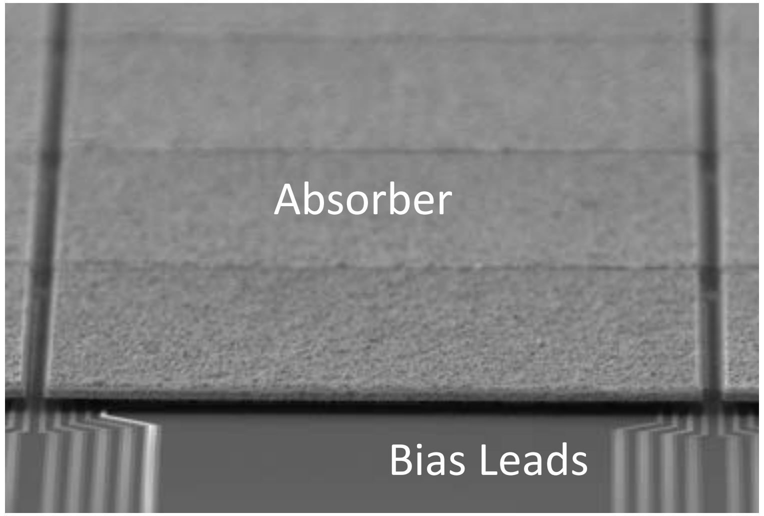
SEM image of absorbers

- 1,024 TESs (3000 required for X-IFU)
- 250 μm pixel pitch.
- All pixels wired within the array.
- 252 pixels connected to wirebond pads.

Prototype X-IFU array design

Kilo-pixel array *(not full X-IFU scale)*
uniform 32x32 array, 15 mm x 19 mm chip





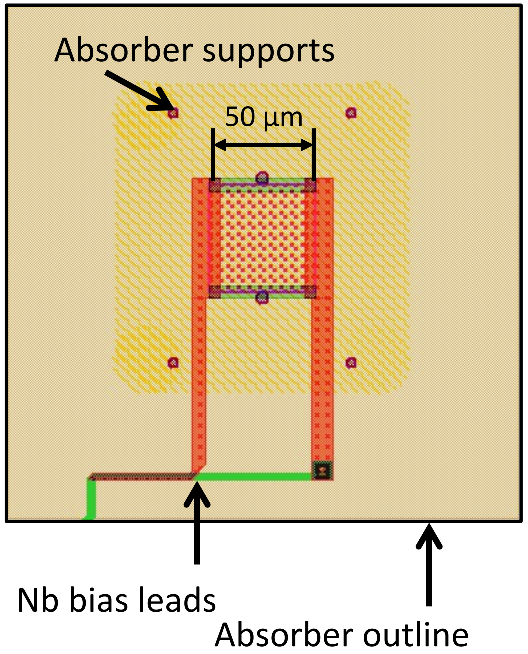
SEM image of absorbers

- Can be readout with 8-column by 32-row TDM.
- Each set of bond-pads is a single readout column.

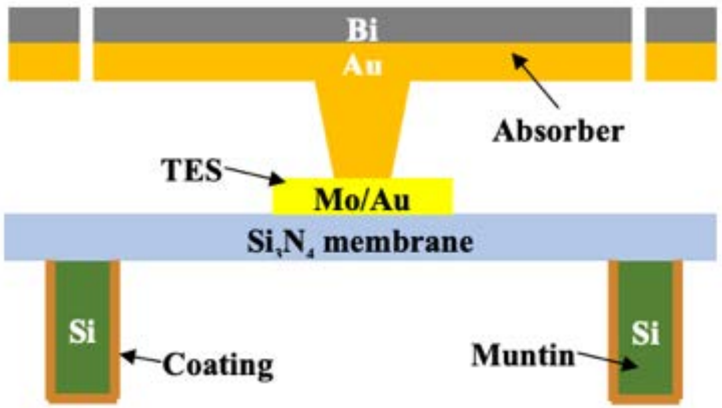
Prototype X-IFU pixel design

- Significant work over past few years to optimize TES design to achieve desired transition properties and detector time constant.
  - Now have smaller TES size (140->50 µm), without normal metal stripes. (Miniussi et al. JLTP 2018, Wakeham et al. JLTP 2018, JAPhys 2019.)

Baseline X-IFU like pixel



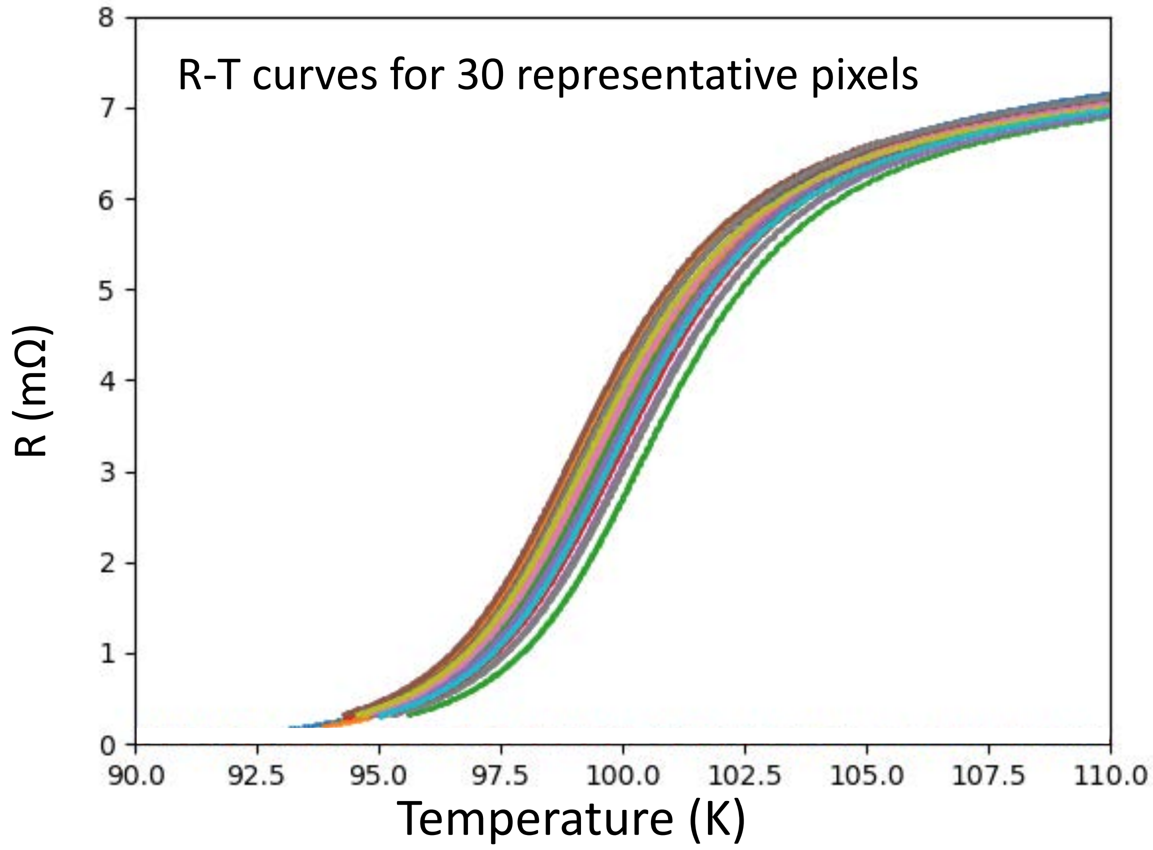
Cross-sectional view

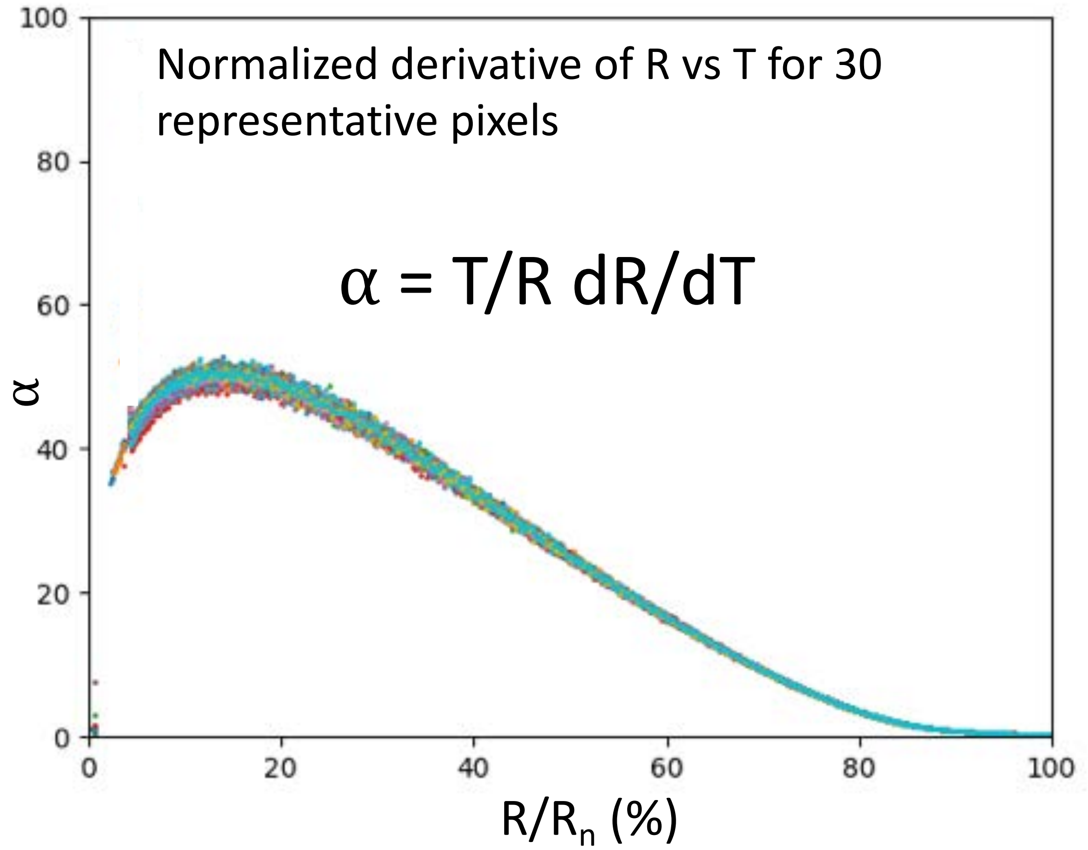


- 50 µm Mo/Au bilayer TES.
- R_n = 8 mΩ.
- C = 0.73 pJ/K.
- G_b = 70 pW/K.
- T_C = 90 mK.
- 800 µs pulse decay time constant.
- 250 µm pixel pitch.
- Au(1.8 µm)/Bi(3.1 µm) absorber.
- 0.5 µm SiN membrane.

Transition shape uniformity

- Pixels now have very uniform transition shapes compared to previous generations that suffered from ‘kinks’
  - ⇒Uniform pulse shapes and noise properties.
  - ⇒Essential for meeting X-IFU resolution and uniformity requirements in large format array.

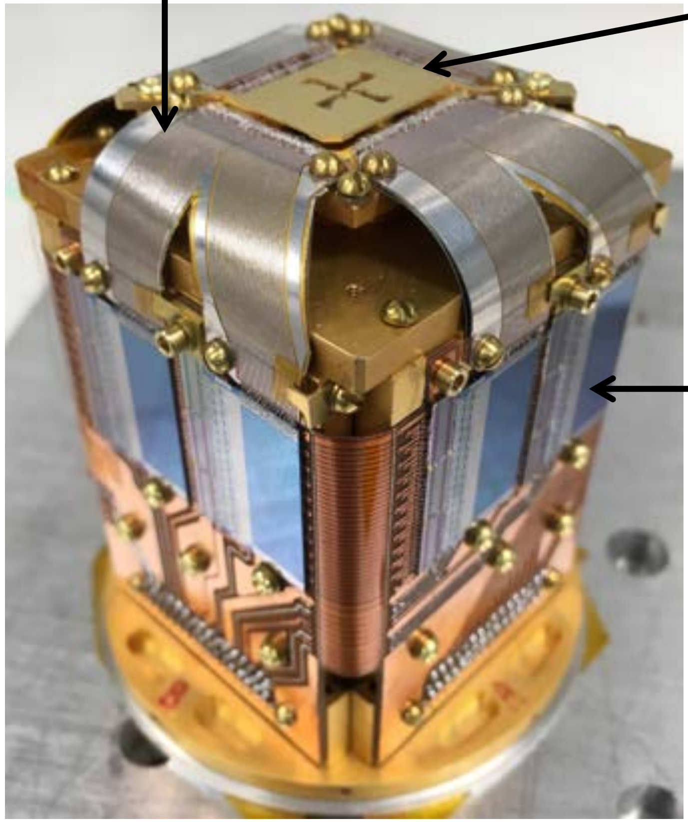


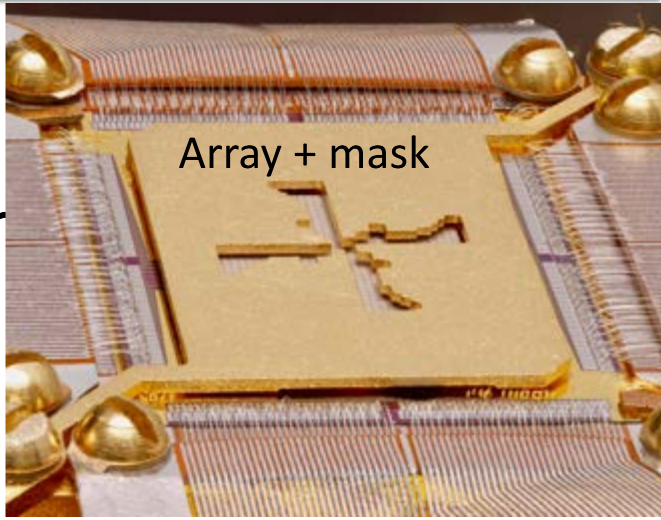


252-pixel detector with Time-Division-Multiplexed Readout

- At 2018 ASC, system was in a mixed 'box of chocolates' configuration of different TDM mux chip designs on different side panels.
- At that time X-IFU baseline was 40-row TDM.
- M_{in} (part of SQ1):
  - Input coupling of TES current to SQ1 flux.
  - Trades input referred read-out noise with dynamic range.
  - Chosen to accommodate pulses up to 12 keV (0.3 A/s 'slew-rate') whilst muxing 40 rows.

Superconducting flex





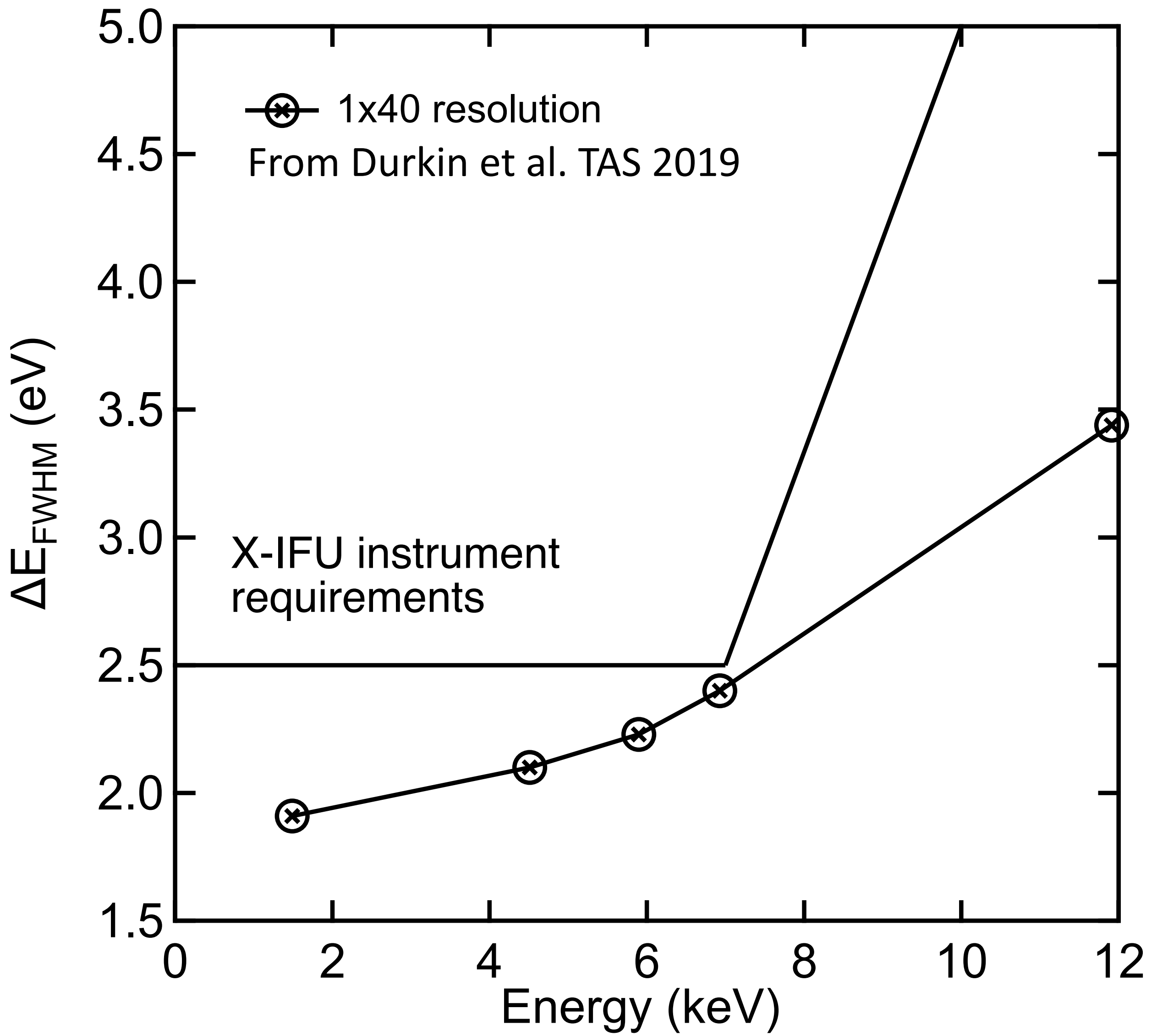
NIST TDM MUX + Shunt/Inductor chips

8-column x 32-row NIST TDM snout package

- R_{shunt} = 75 μΩ
- $L = 0.6L_{crit}$ = 640 nH

2018 results summary

- Simulated 40-row TDM with 32 SQ1s and 32 TESs per column:
  - leave the 32nd row on for 8 extra row periods at the end of each frame.
  - gives same noise and timing as true 40-row TDM.



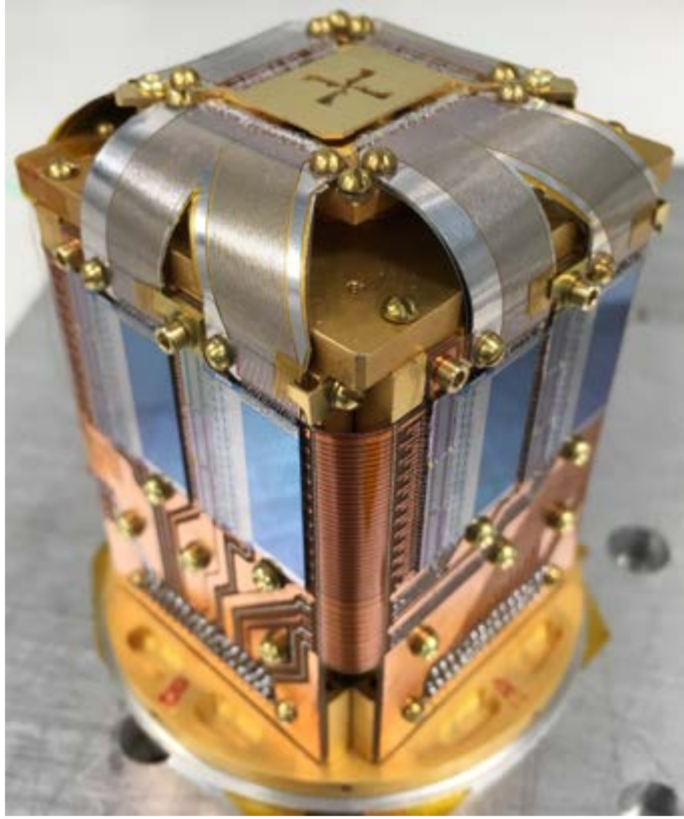
Developments since 2018

- System now in uniform configuration (identical mux chips) for testing all 8 columns.
  - X-IFU was moving toward a mux factor closer to 32, so we ran system with natural 32 rows instead of pseudo-muxing extra rows.

- Readout noise in "40-row" TDM experiments:
  - readout noise was **25.6 pA/√Hz** (ref'd to TES) in "40-row" experiments.
  - scales by $\sqrt{N_{rows}}$. For N_{rows} = 32: scaling noise by √(32/40) => 22.9 pA/√Hz.

- Improved dynamic behavior => reduced TDM readout noise and various sources of cross-talk.
  - **See Malcolm Durkin's talk for optimization details: Wk2EOr5A-01**.
  - Noise in new 32-row TDM experiments: **20.2 pA/√Hz**.

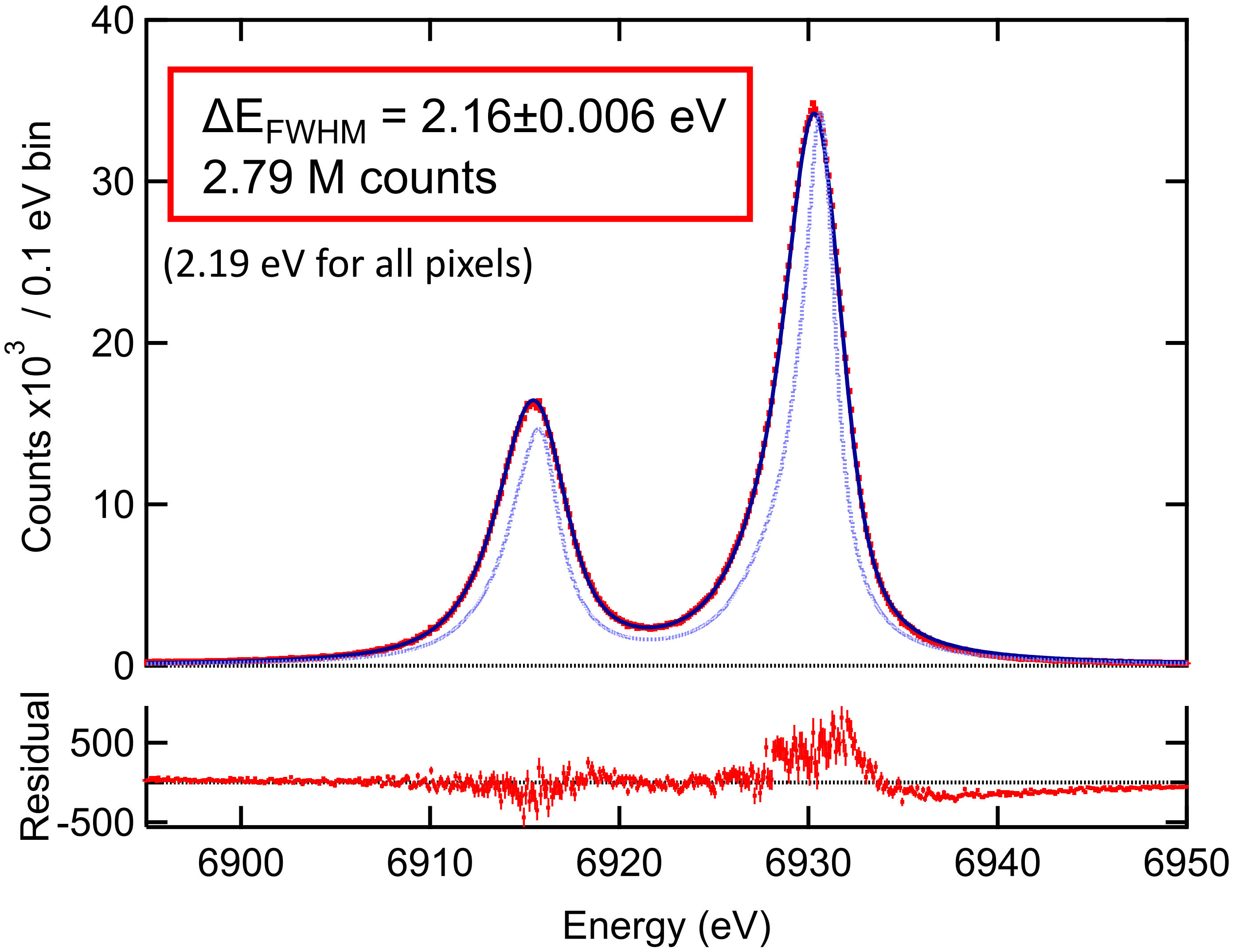
- Improved understanding of optimum TES bias-point:
  - "40-row" experiments: TES bias point ~ **11 – 12% R_n**
  - better performance; still within slew-rate requirements: ~ **10% R_n**



8x32 Results: Co-Kα

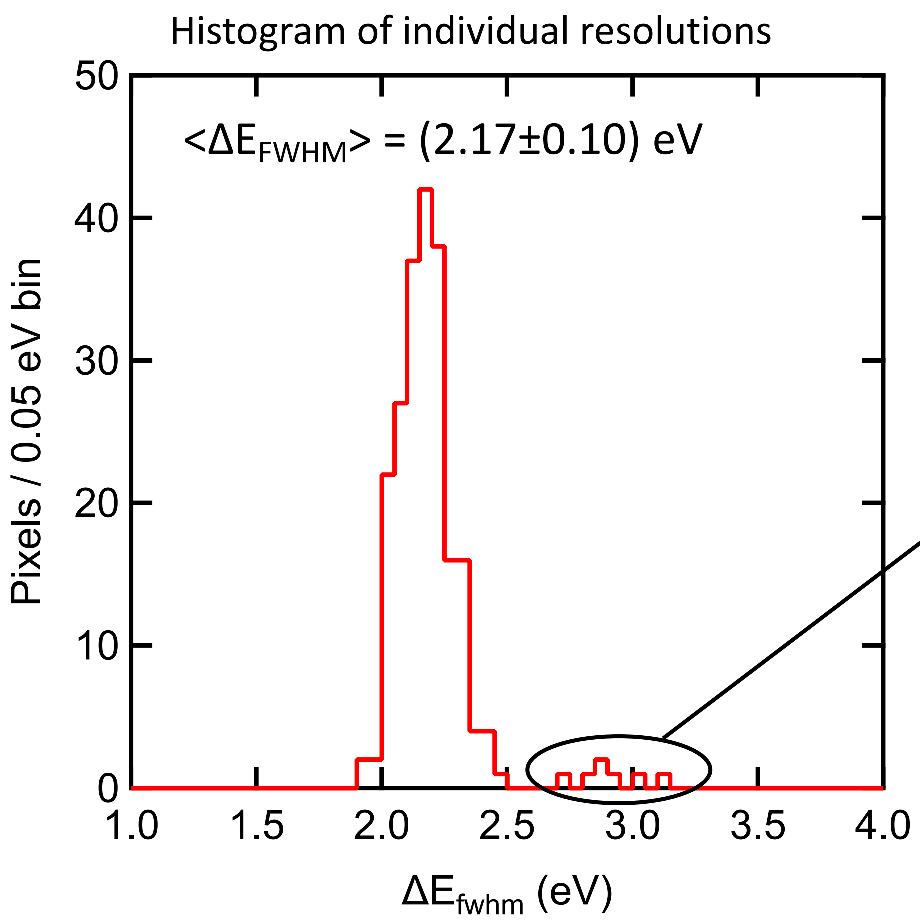
- Available yield was 218 pixels out of 252 (combination of open and shorted TES bias and 1 open SQ1 row address line)
- ~ 10 k counts/pixel in Co-Kα complex.
- 0.25 cps/pixel (5% of events removed for pile-up and targeted cross-talk cuts).

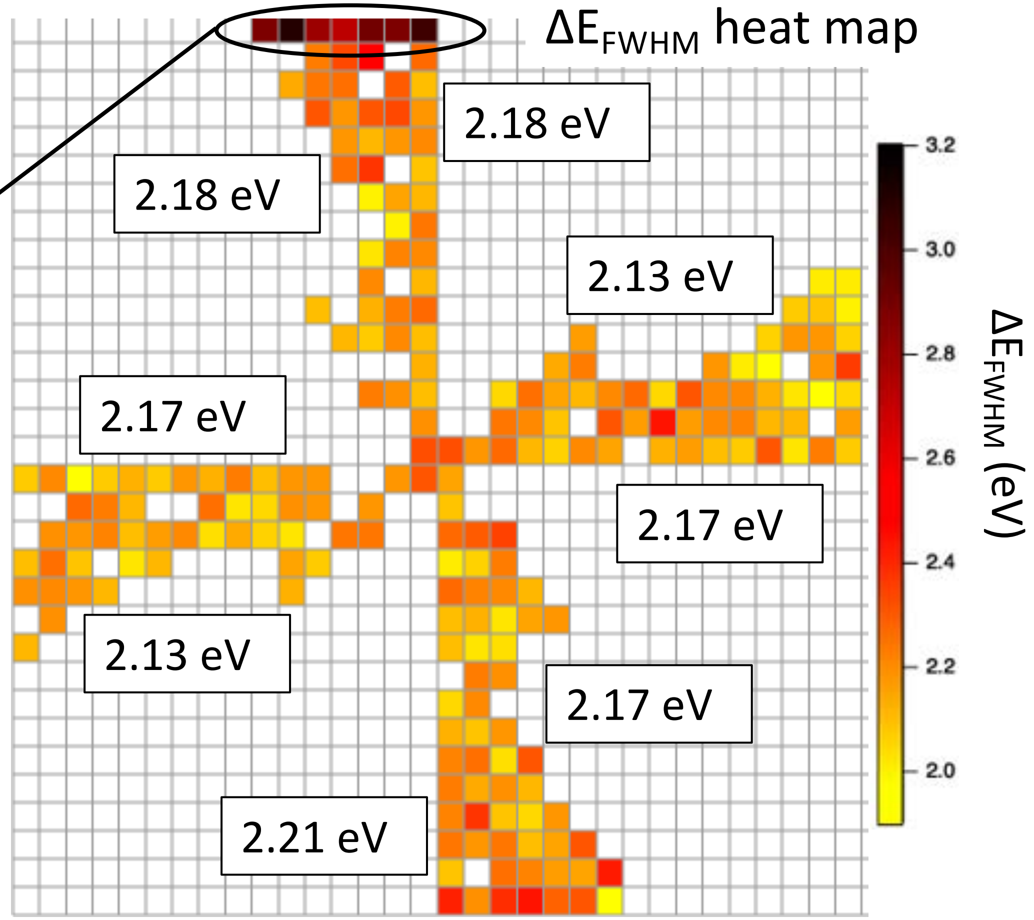
Coadded energy histogram for all pixels excluding subset of outliers.



8x32 Results: Co-Kα

- Except for top row of pixels in array, there is very uniform performance.
  - Issues with absorbers causing excess ΔE broadening in that row of pixels.
- Distribution of individual Δ*E* dominated by statistics.

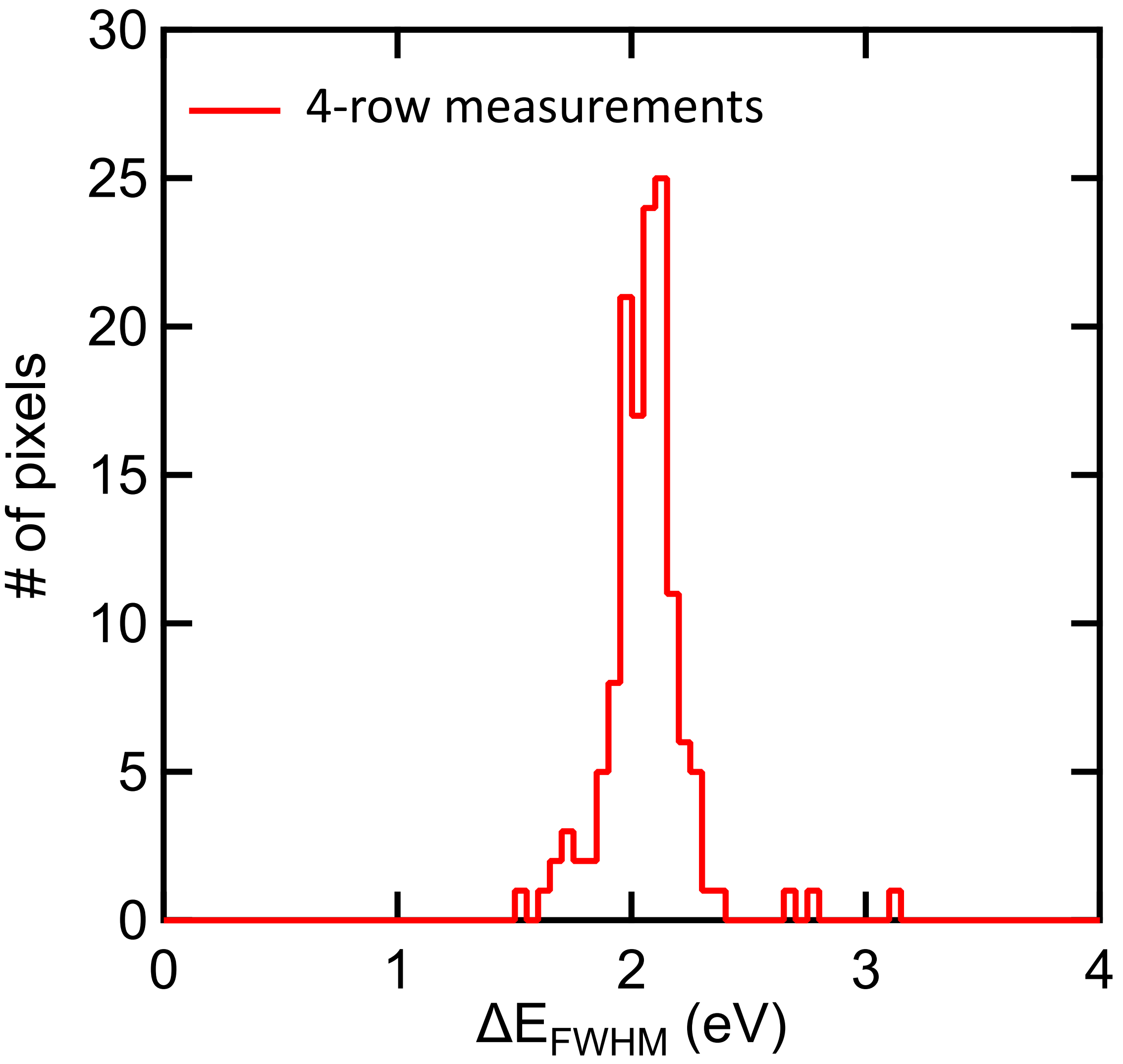




Intrinsic pixel resolution at 7 keV

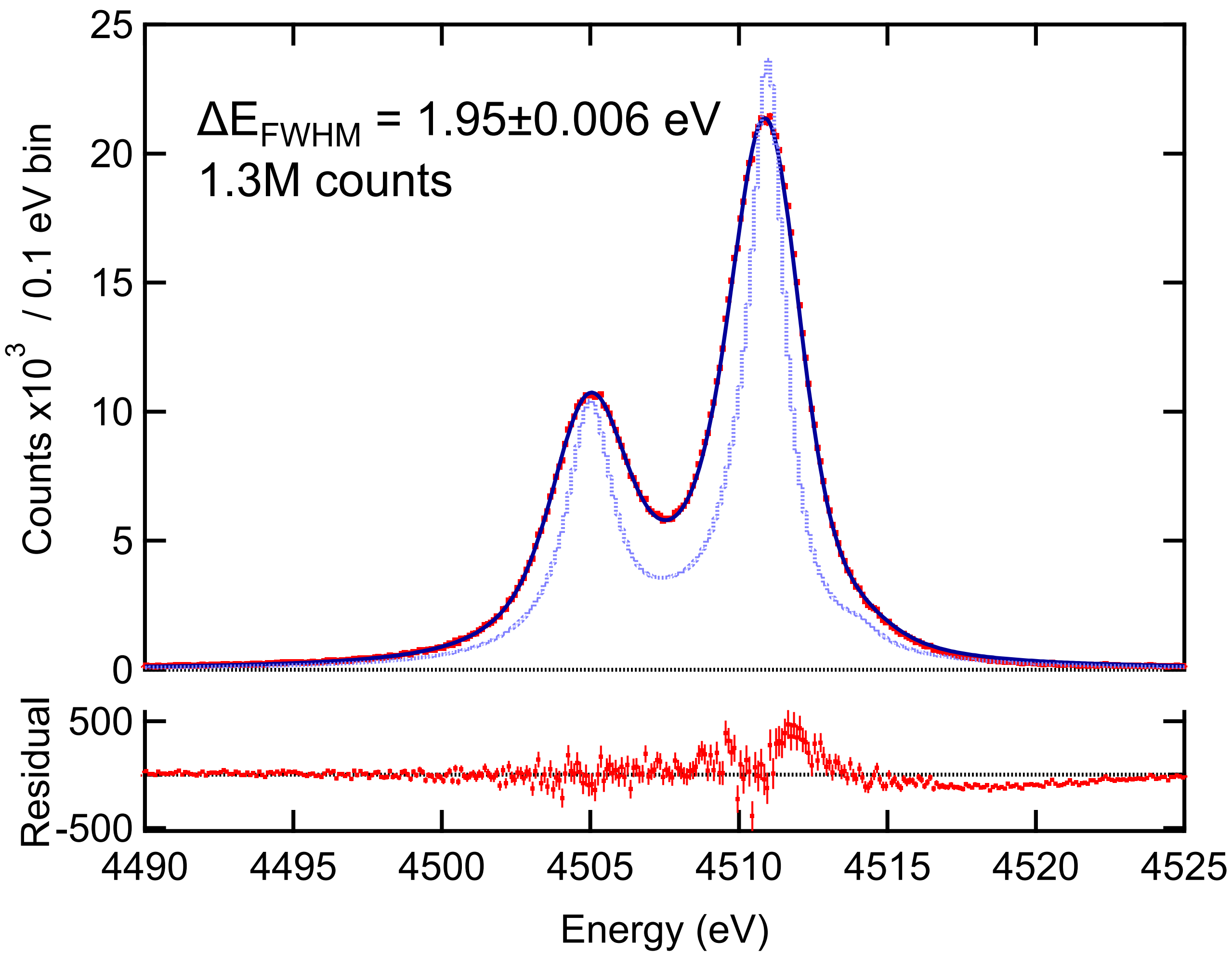
- Series of low mux factor measurements (N_{row} = 4) allows assessment of pixel resolution in limit of low readout noise.
  - 8-10 pA/√(Hz)

- Tested 128 pixels:
  - < ΔE_{FWHM} > = 2.03±0.14 eV (excluding pixels with absorber issues).
  - Suggests N_{row} = 32 muxed penalty contributes ~ 0.13 eV.

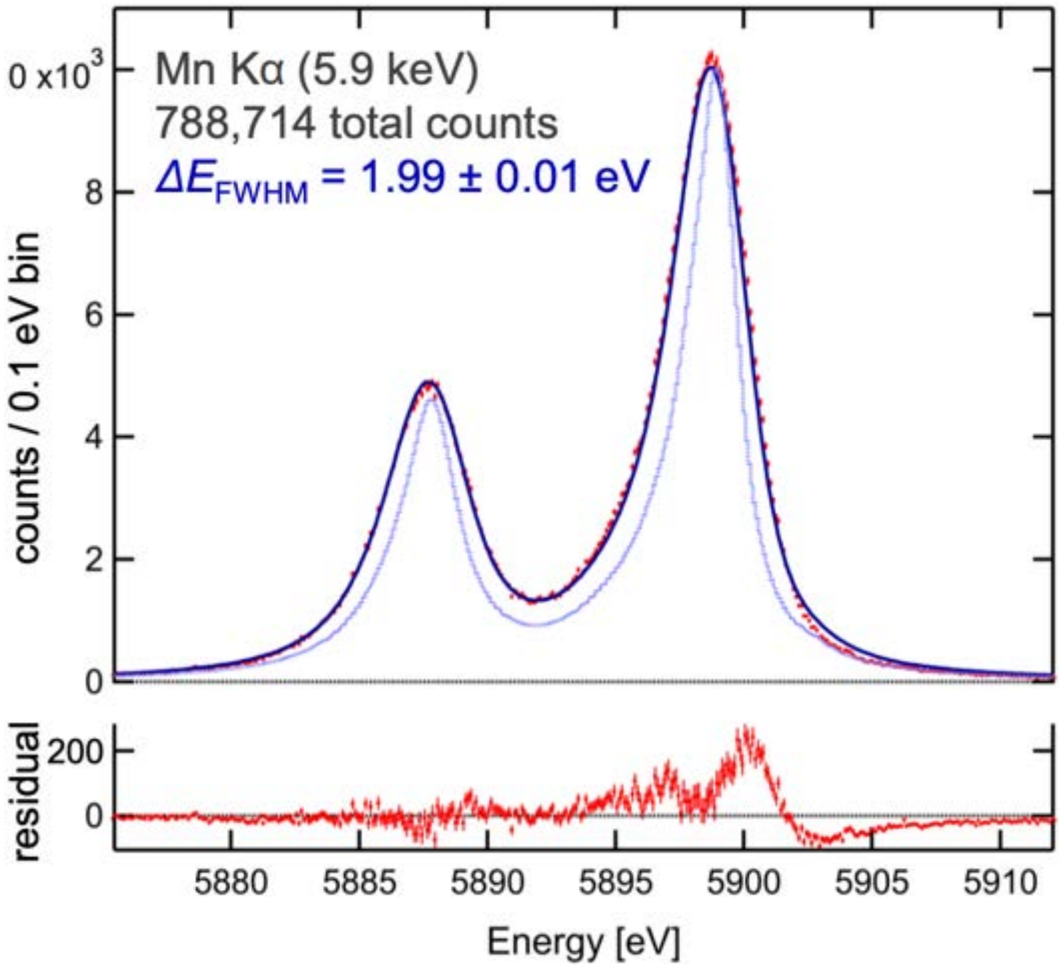


8x32 Results: Ti-Kα and Mn-Kα

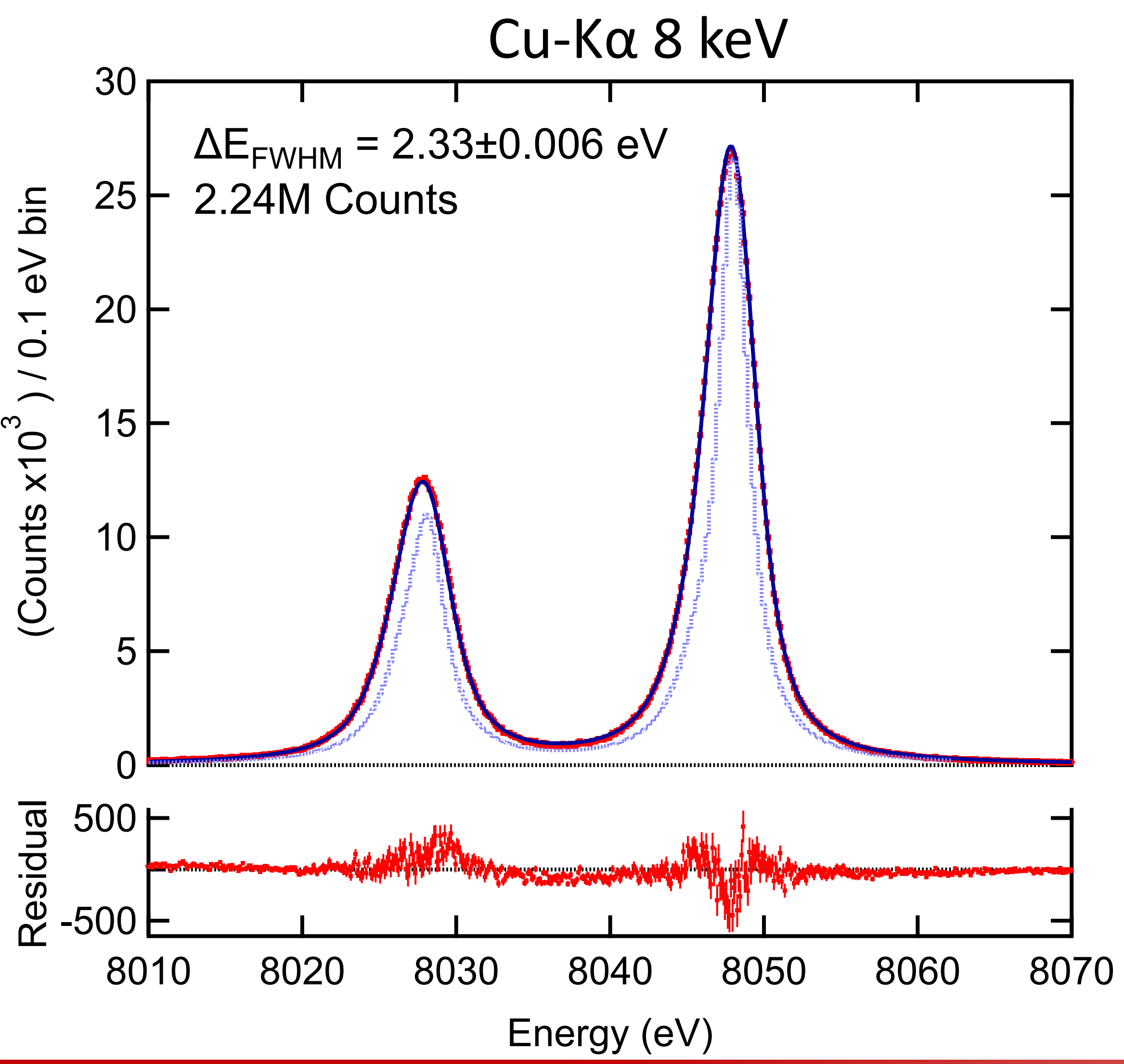
Ti-Kα 4.5 keV

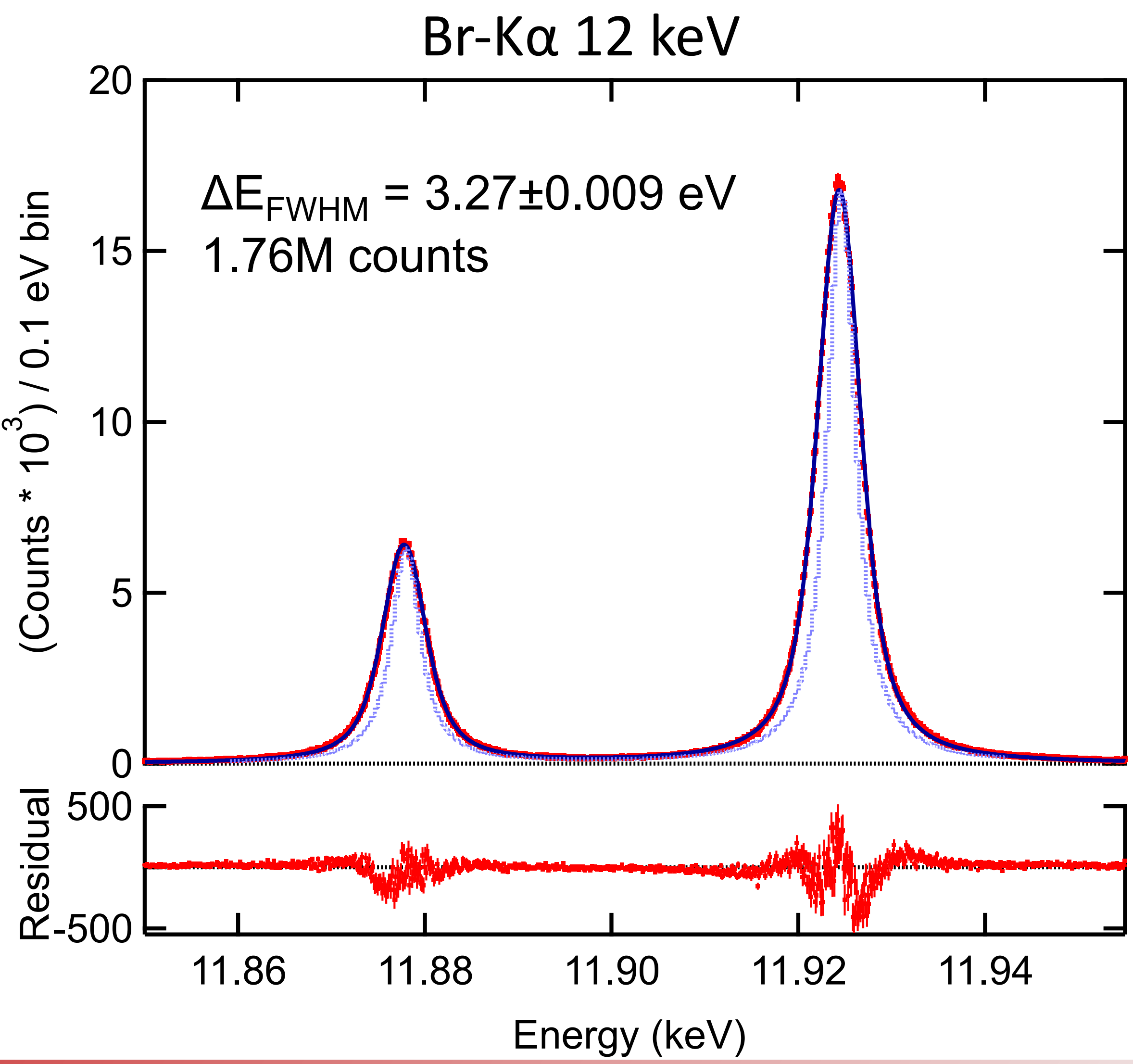


Mn-Kα 5.9 keV



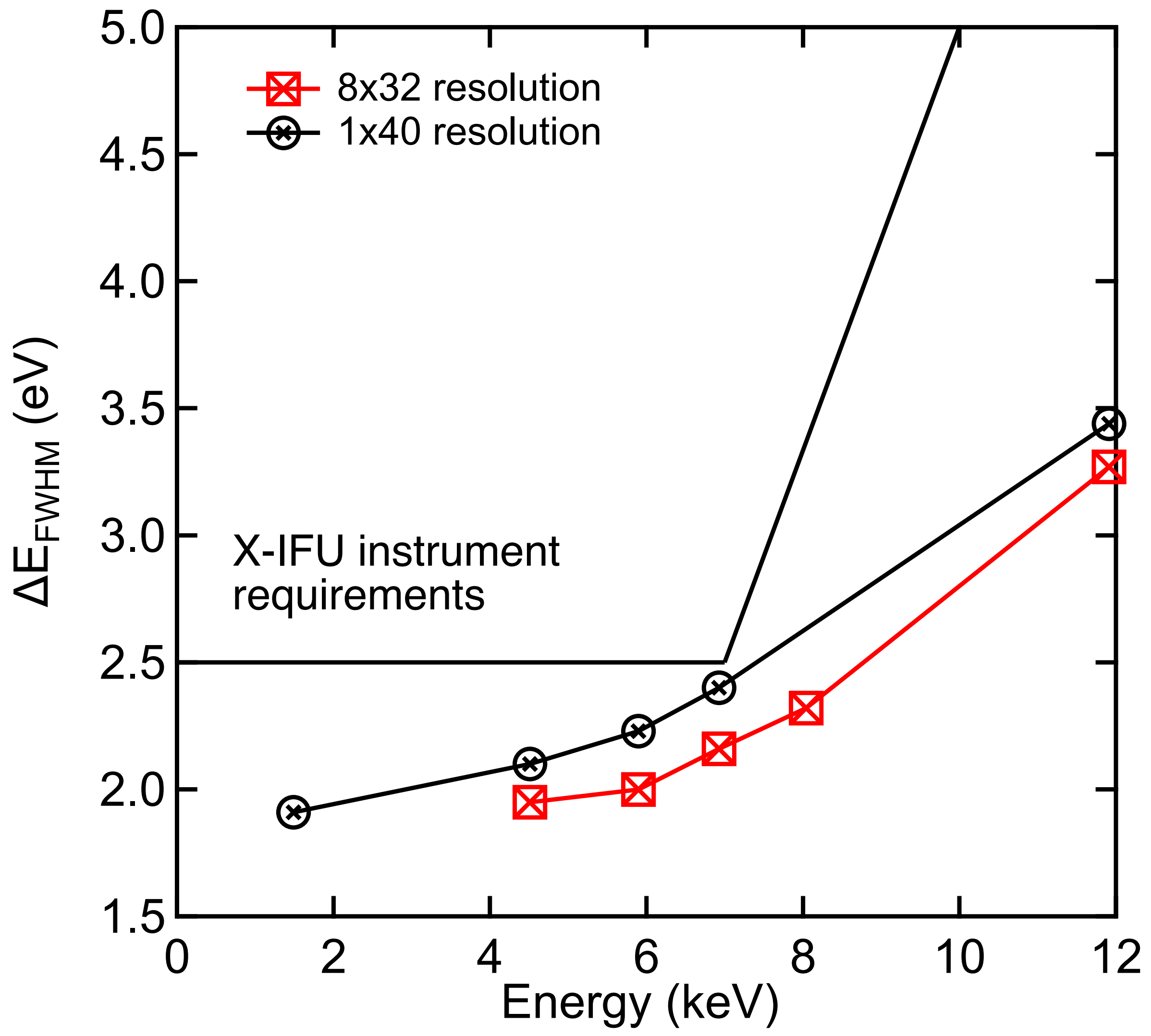
8x32 Results: Cu-Kα and Br-Kα





8x32 Resolution Summary

- Lower noise / optimized set point enabled improved broad-band resolution compared to 40-row measurements.



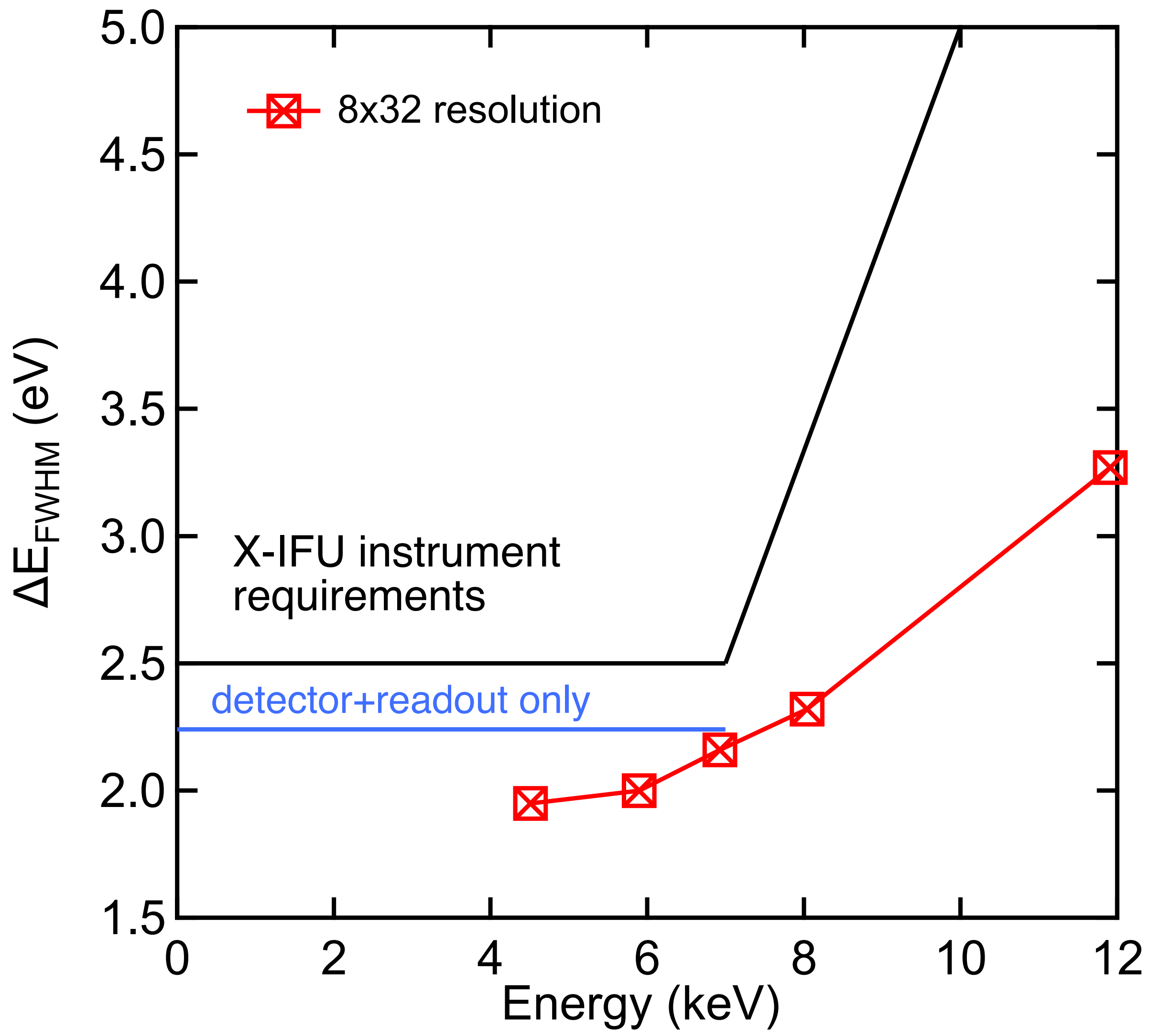
8x32 Resolution Summary

- To allow for margin and many additional noise sources, we need the detector and readout to achieve < 2.24 eV at 7 keV.

- For X-IFU need 34 TDM rows:
  - With reoptimized M_{in}, predicted to improve readout noise from 20.2 → 17.7 pA/√Hz.

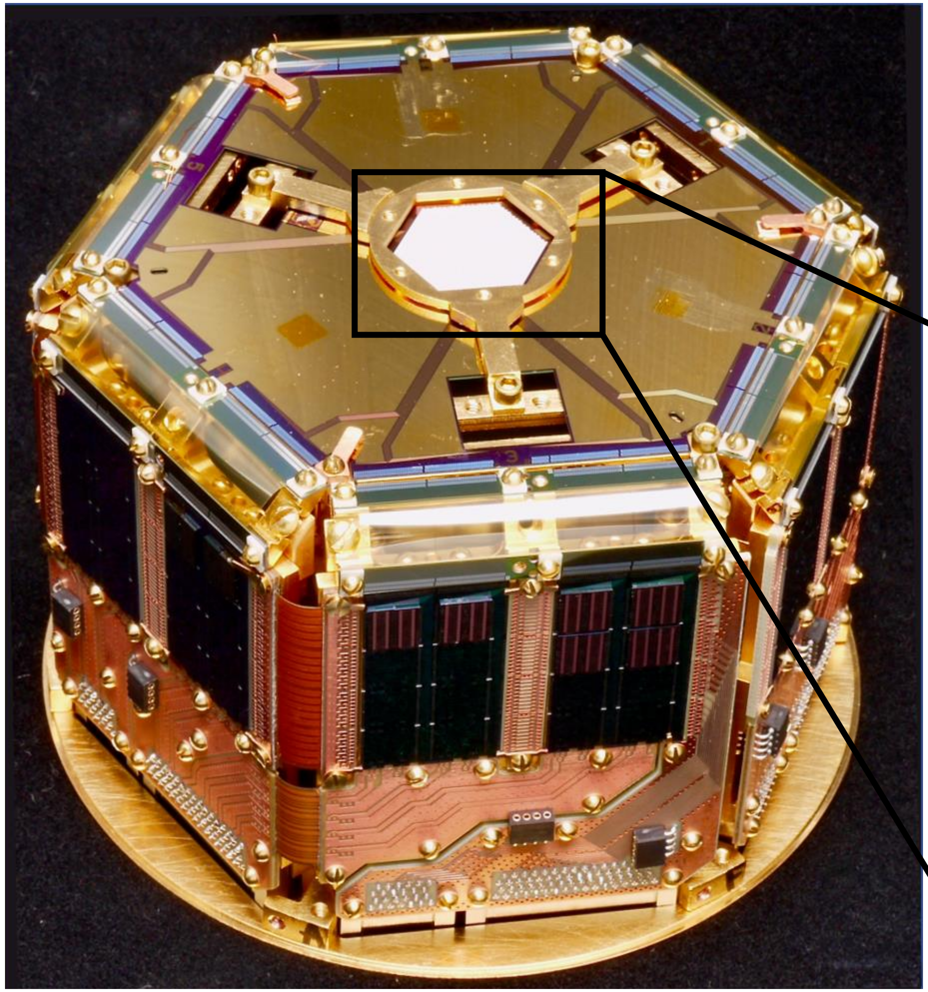
  ⇒ Expect further improvements in ΔE_{FWHM}.

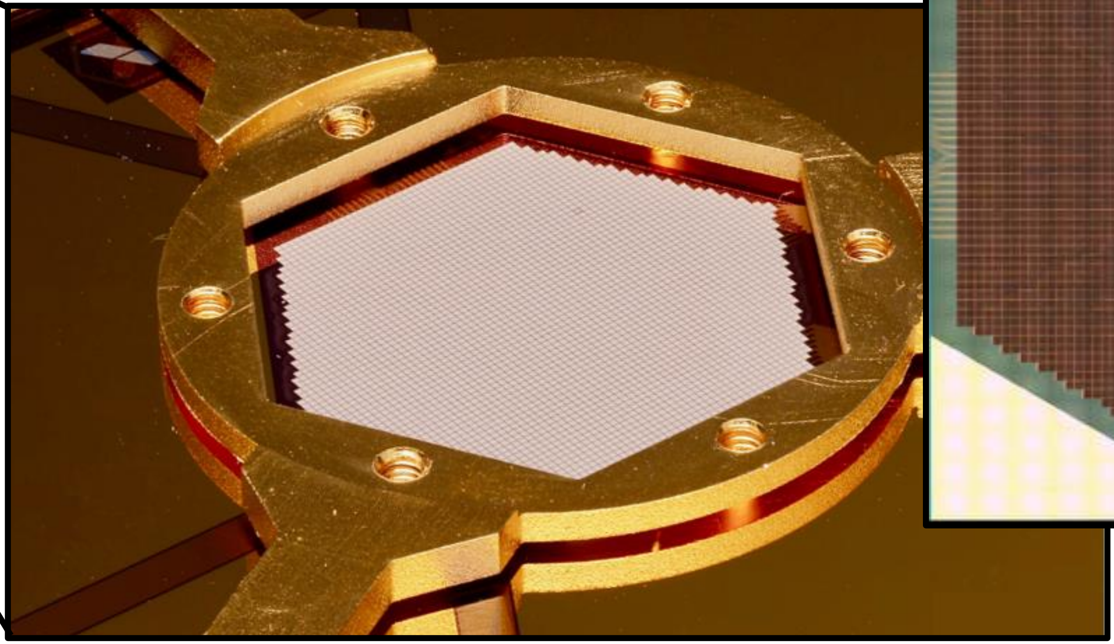
  ⇒ M_{in} maybe adjusted depending upon final margin requirements.

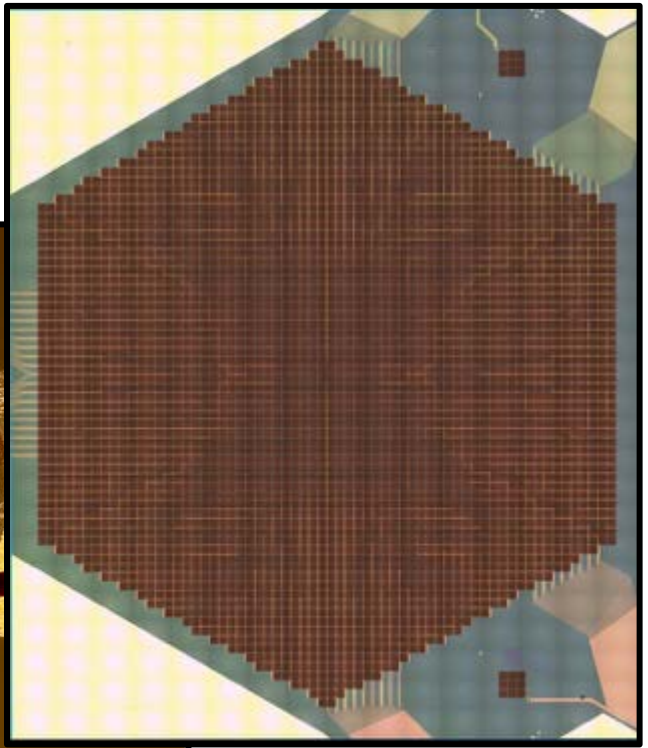


First prototype full-scale X-IFU array

- Prototype full scale arrays (> 3,000 pixels) now fabricated and being tested.
- 90 mm hexagonal chip.
- First devices have 960 pixels connected to bond-pads.
- Later generations will allow testing all pixels.







Summary

- Combined detector and readout optimization has now led to exquisite resolution and uniformity in prototype X-IFU kilo-pixel array.
  - Demonstrates technology can meet stringent Athena X-IFU performance requirements, with further performance improvements still possible.
- This instrument will now be finished, calibrated and delivered to LLNL EBIT for lab astrophysics experiments.
- Now focusing on demonstrating performance in full scale arrays needed for X-IFU.

Contributors

- **NASA GSFC**: Joseph S. Adams, Simon R. Bandler, Sophie Beaumont, James A. Chervenak, Fred M. Finkbeiner, Ruslan Hummatov, Richard L. Kelley, Caroline A. Kilbourne, Maurice A. Leutenegger, Antoine R. Miniussi, Frederick S. Porter, John E. Sadleir, Kazuhiro Sakai, Chintan D. Shah, Nicholas A. Wakeham, Edward J. Wassell, Michael C. Witthoeft
- **NIST**: Edward V. Denison, William B. Doriese, Malcolm Durkin, Joseph W. Fowler, Gene C. Hilton, Carl D. Reintsema, Daniel S. Swetz, Joel N. Ullom, Leila R. Vale
- **Stanford**: Kent D. Irwin
- **LLNL**: Peter Beiersdorfer, Greg V. Brown, Megan E. Eckart, Natalie Hell, Tom Lockard, Ed W. Magee