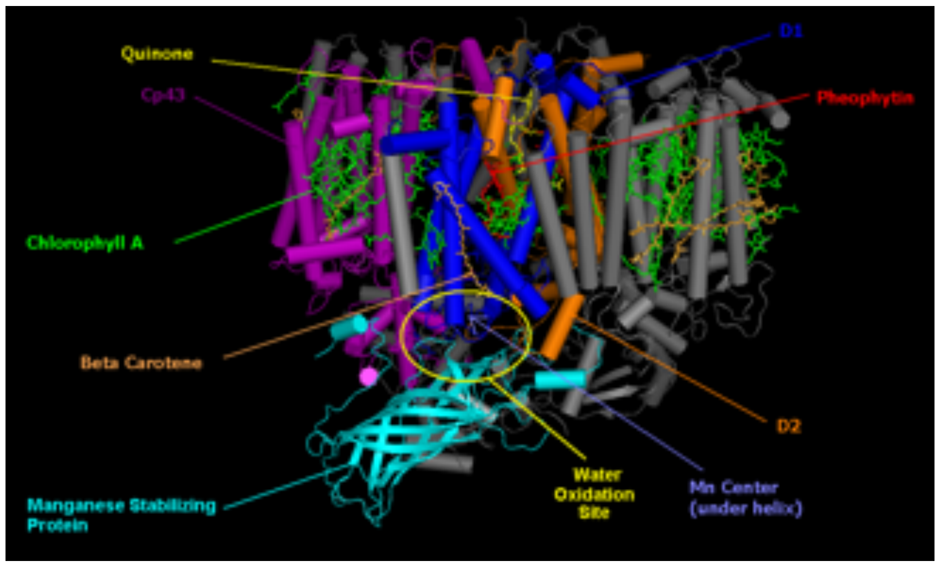
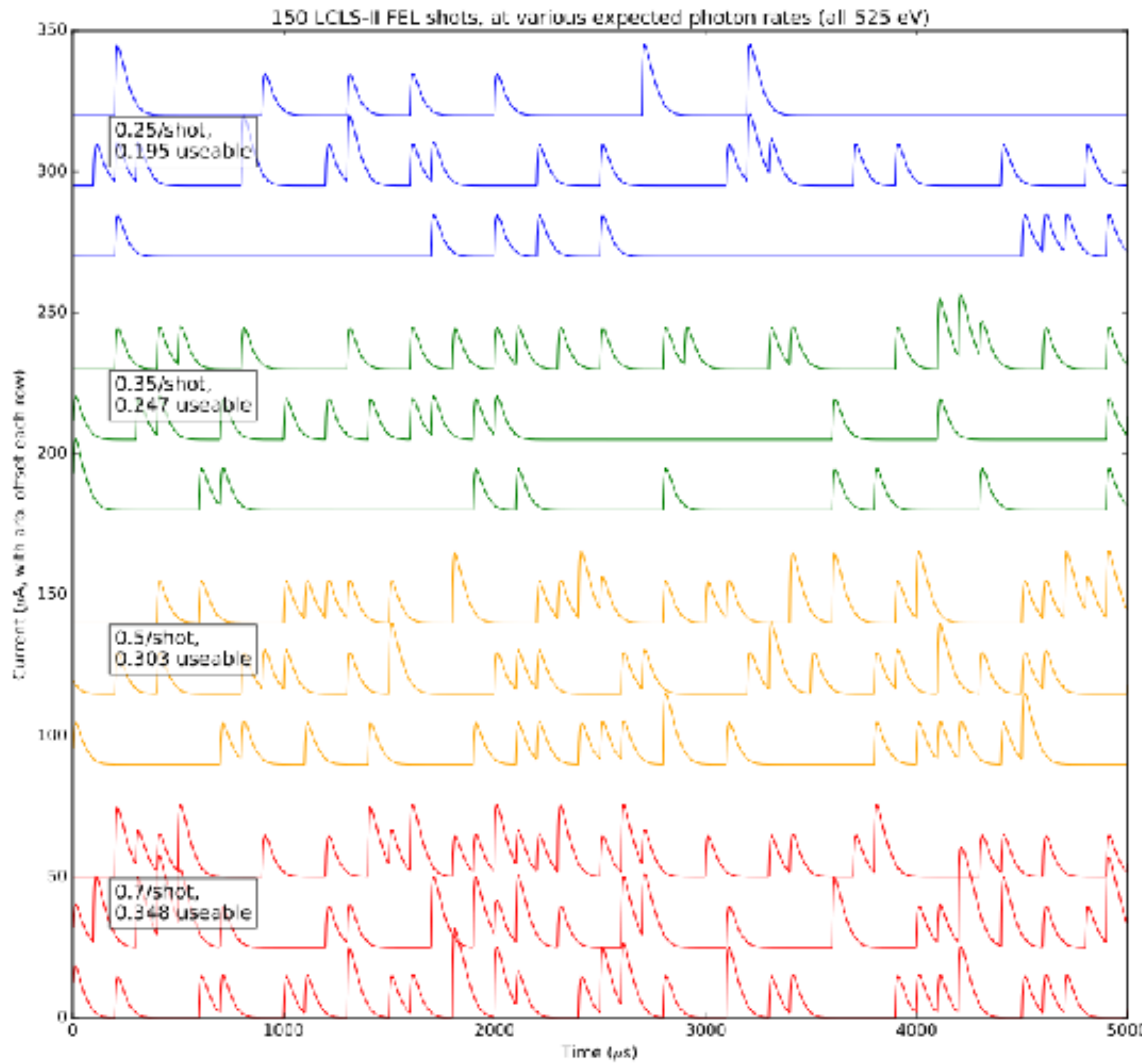
Multiplexing TES Microcalorimeters in the High-Speed Limit



Photosystem-II protein



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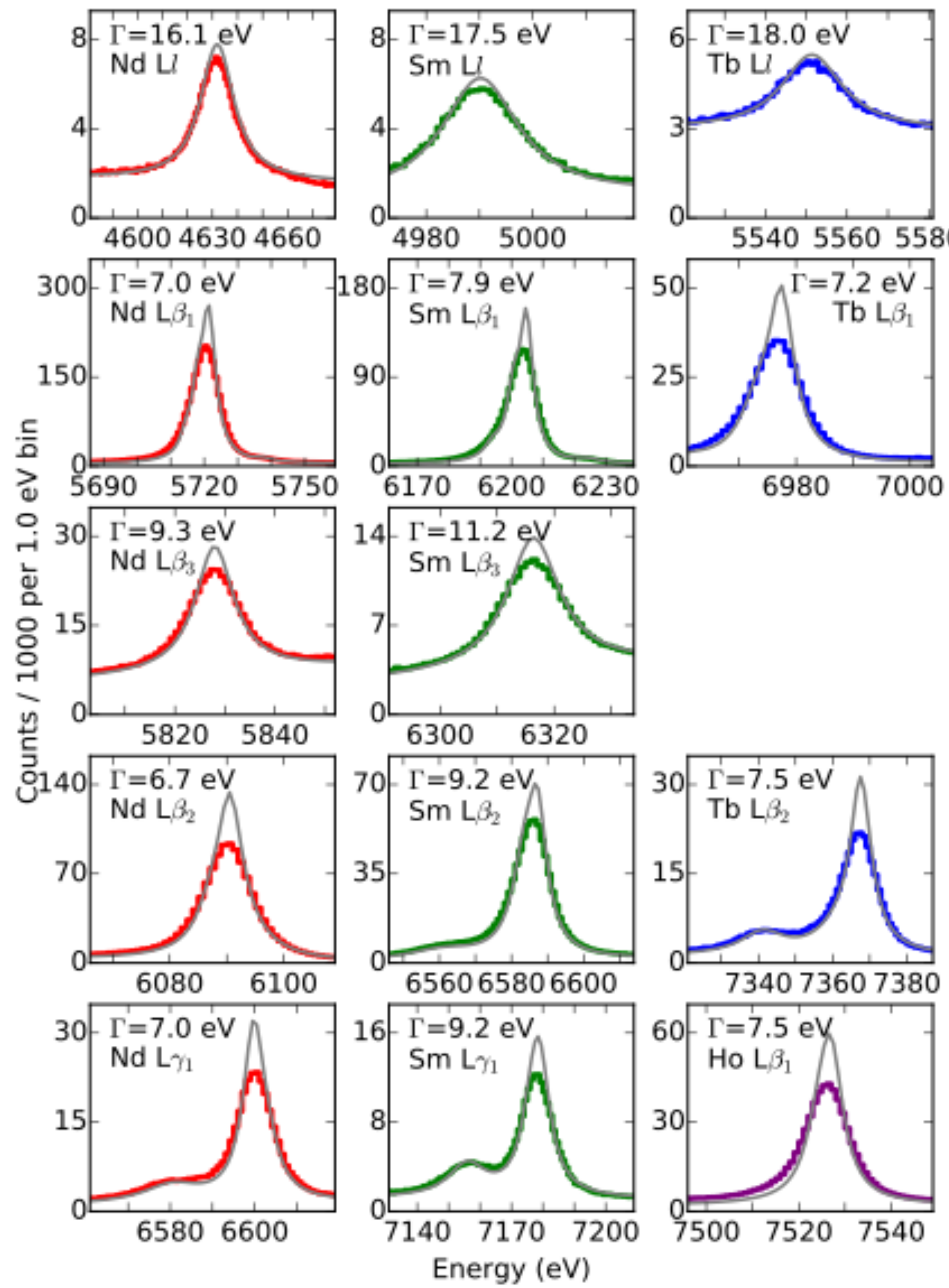
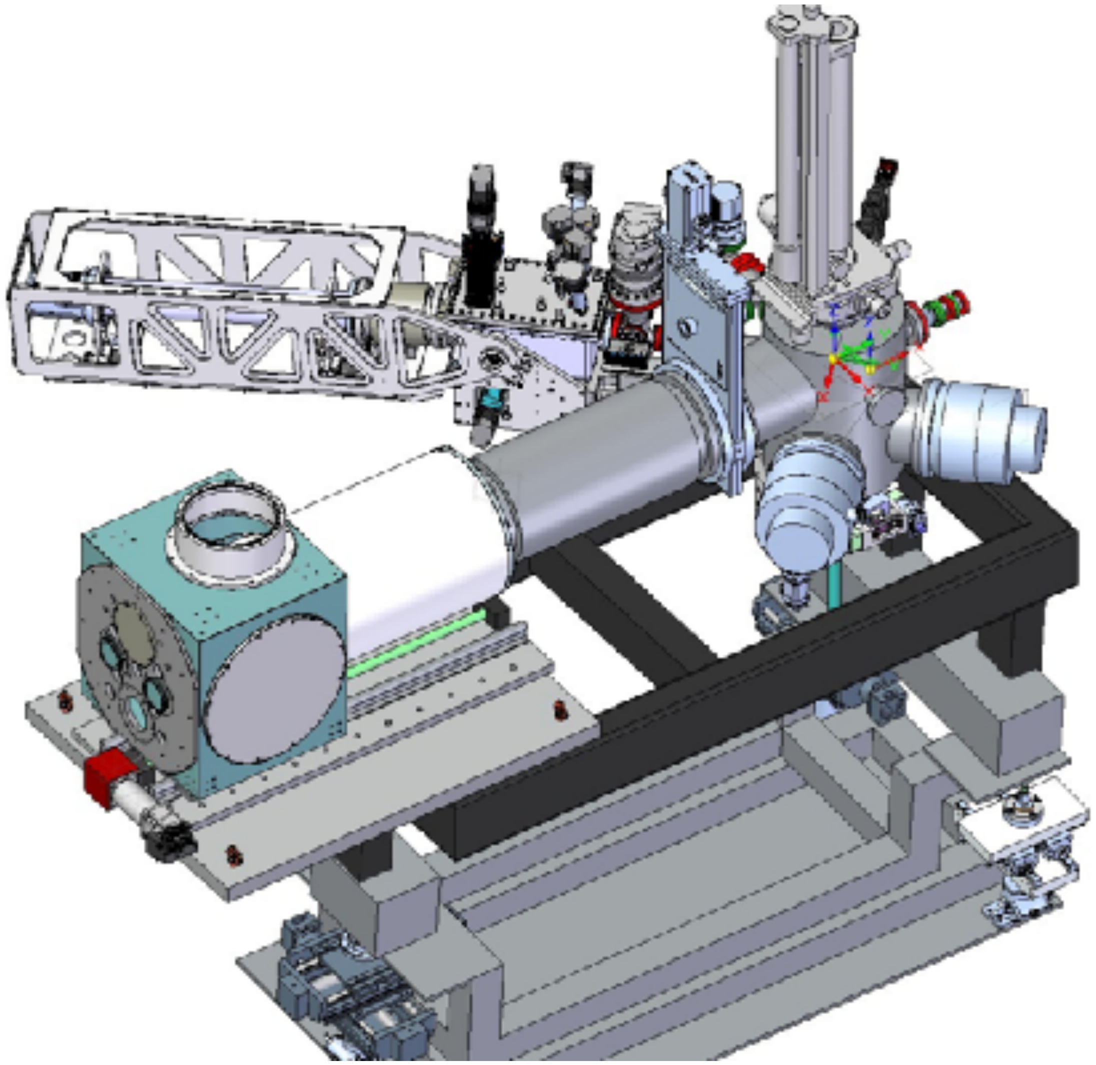
A recent success: X-ray fluorescence metrology

- Studied line shape and exact line energy of 22 fluorescence lines from 4 lanthanide metals.
- Consistent with all ***modern*** measurements, but made serious improvements in uncertainty on several lines with only legacy measurements.
- Established TES microcals as a tool for x-ray metrology at the sub-eV level.

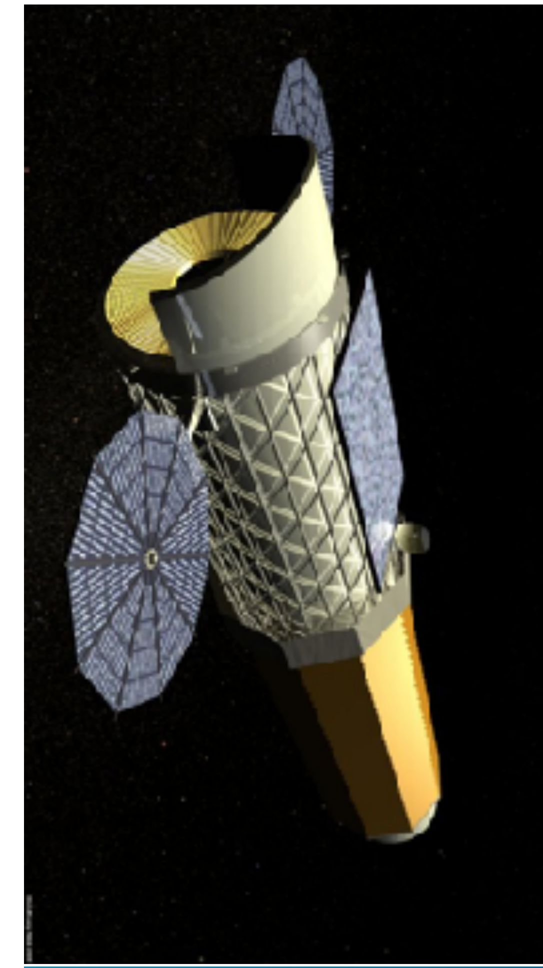
- 2013 measurement with ~100 TESs.
- 12.8 us samples = 39 kHz bandwidth each.
- 160 chan -> 6.3 MHz total bandwidth.



Future needs: more TESs and higher speed



- All require 1000+ sensors.
- All need peak and fall times below 200 μs (for LCLS-II, *much* less)
- Need careful control of cross-talk.



LCLS-II

Free-electron laser light source

Poster PE-67: Dale Li

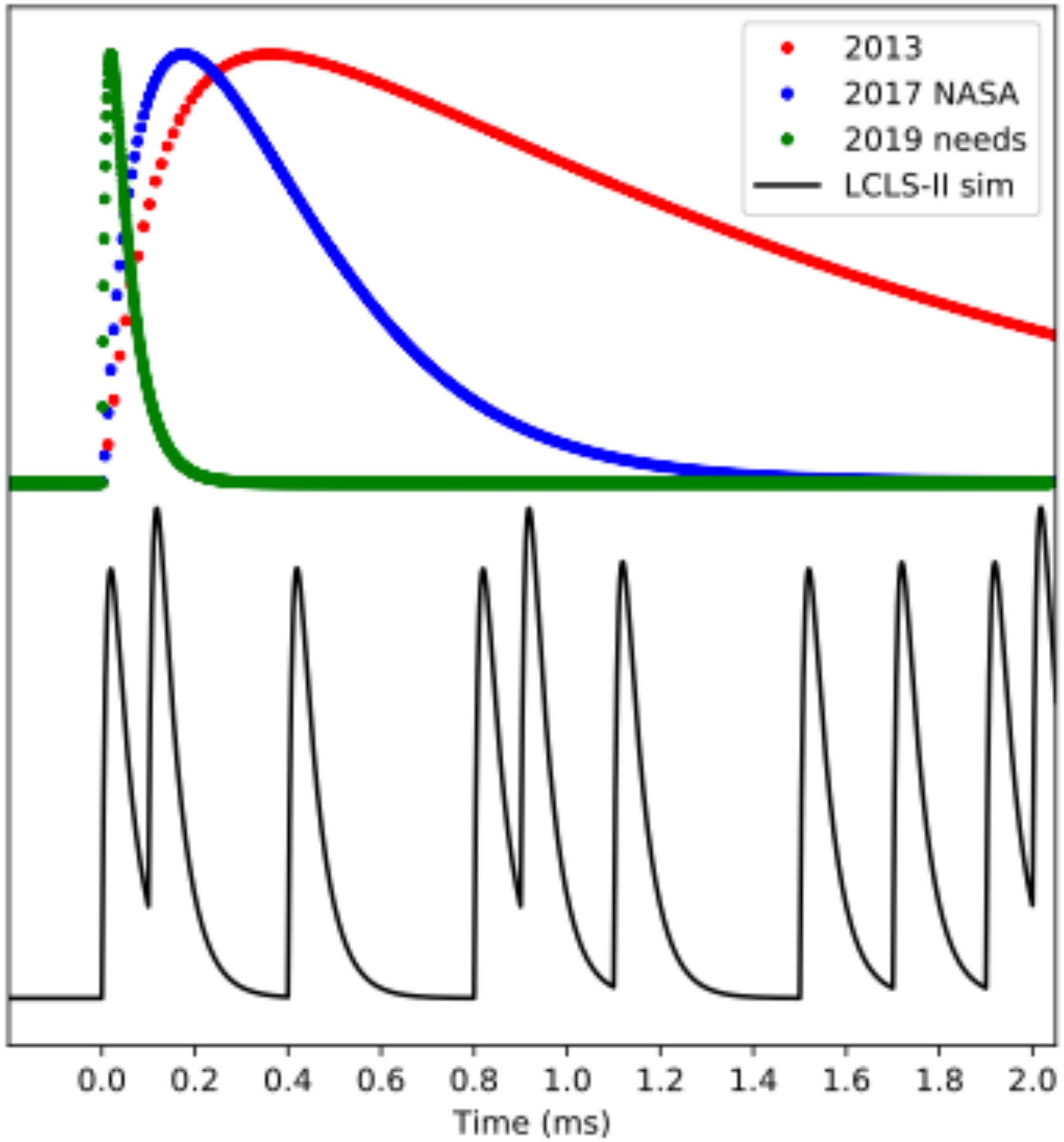
HOLMES

Neutrino mass by
Ho electron-capture

X-IFU
ATHENA X-ray Integral Field Unit

X-ray space
telescope

The need for speed



For comparison, TES x-ray pulses from:

- 2013 metrology measurement
- 2017 NASA array for EBIT
- Future array for LCLS-II and similar

Peak times: 400, 180, 20 μs

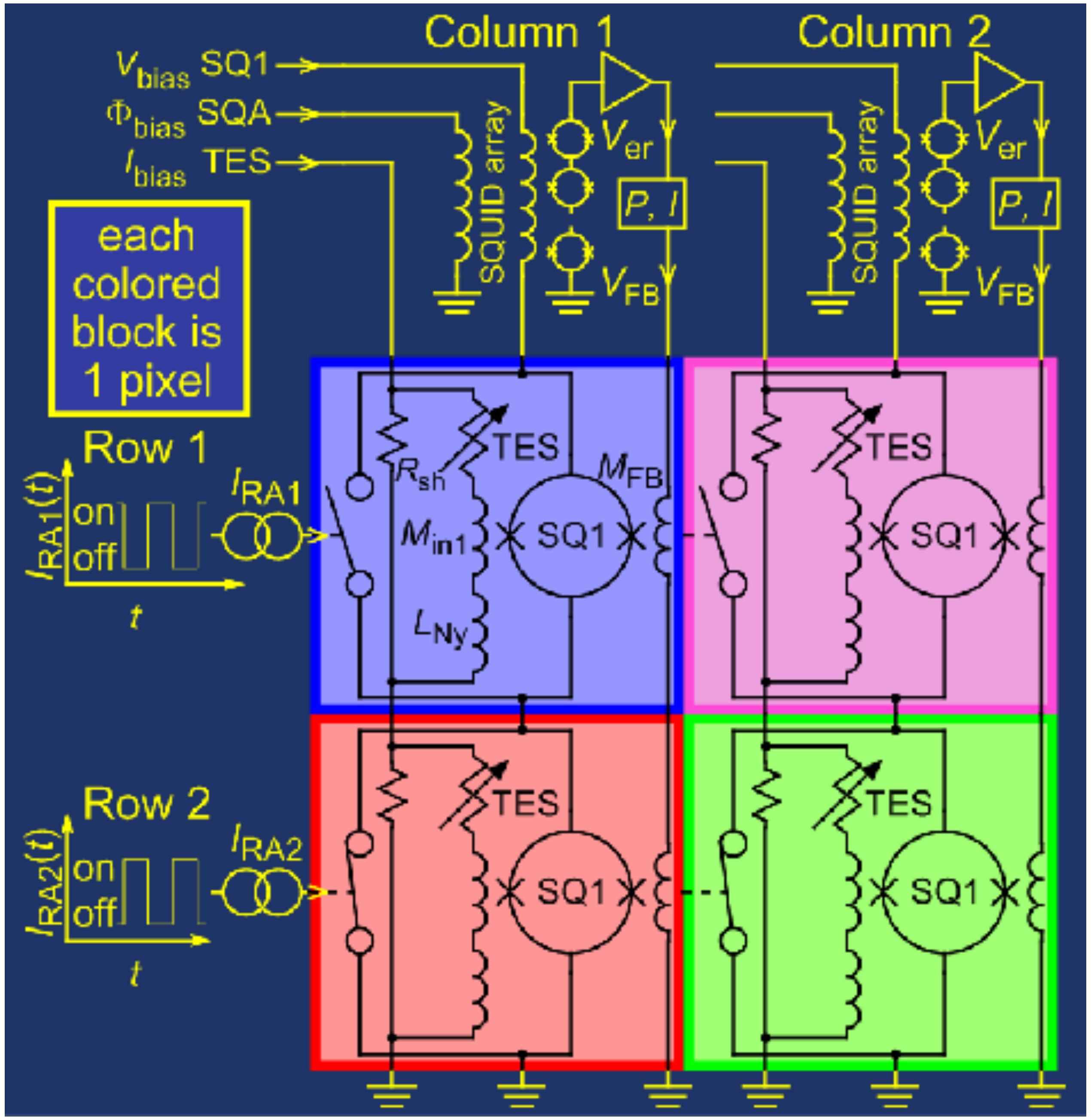
Simulated data for LCLS-II at 0.5 photons per 10,000 Hz shot

Poster PB-25: Brad Alpert

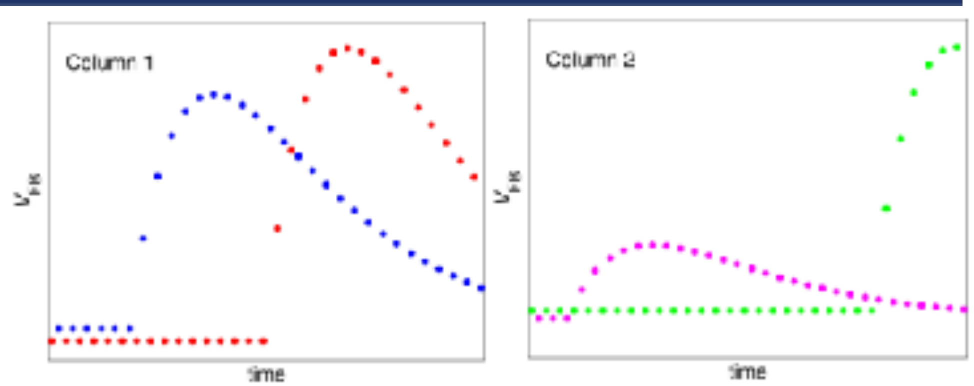
Outline: fast readout for everyone

1. Motivation: more and faster sensors.
2. Time-Division Multiplexing: achievements and limits.
3. Microwave-SQUID Multiplexing: in rapid development.

NIST/Stanford Time-Division Multiplexing

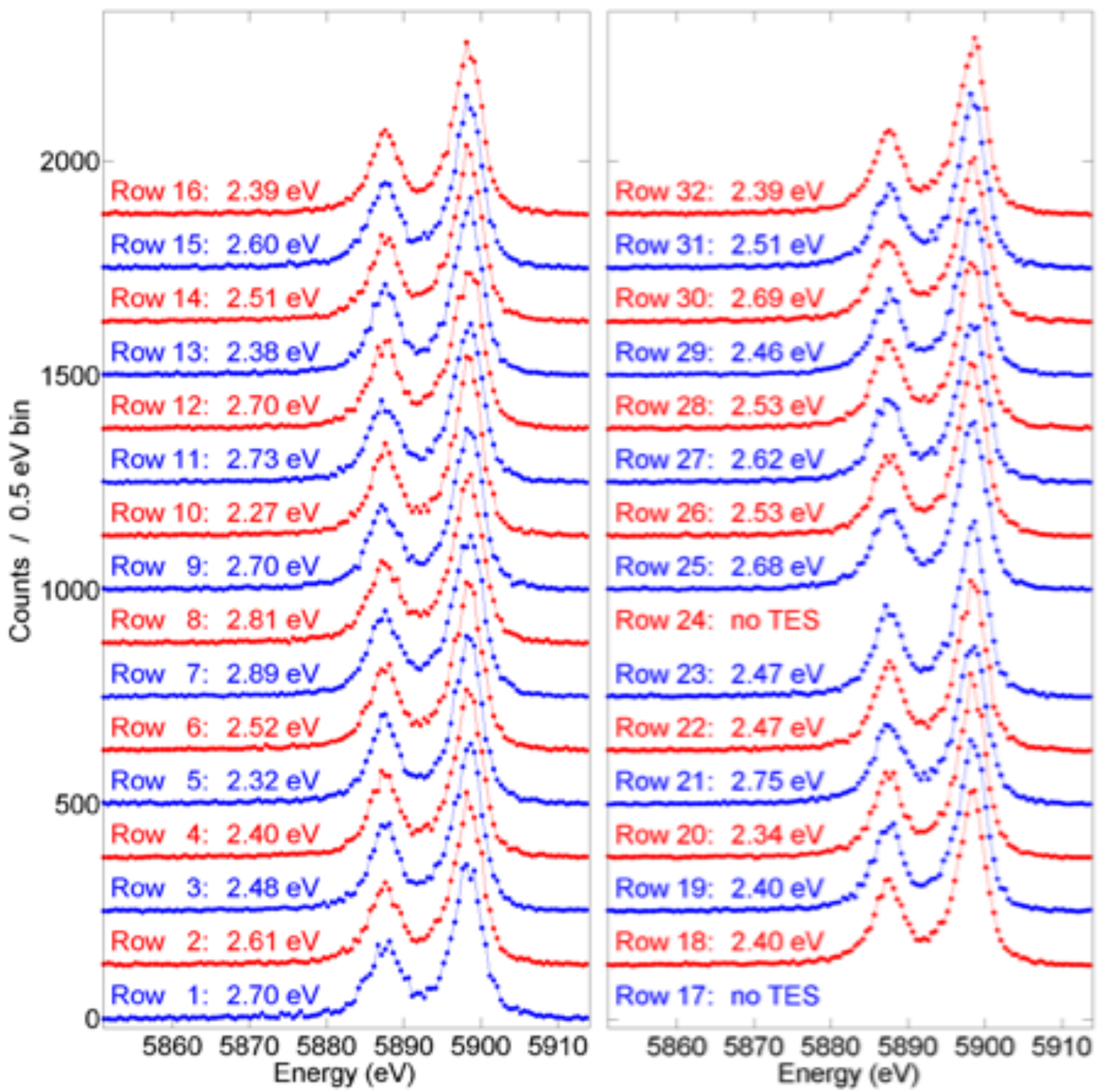


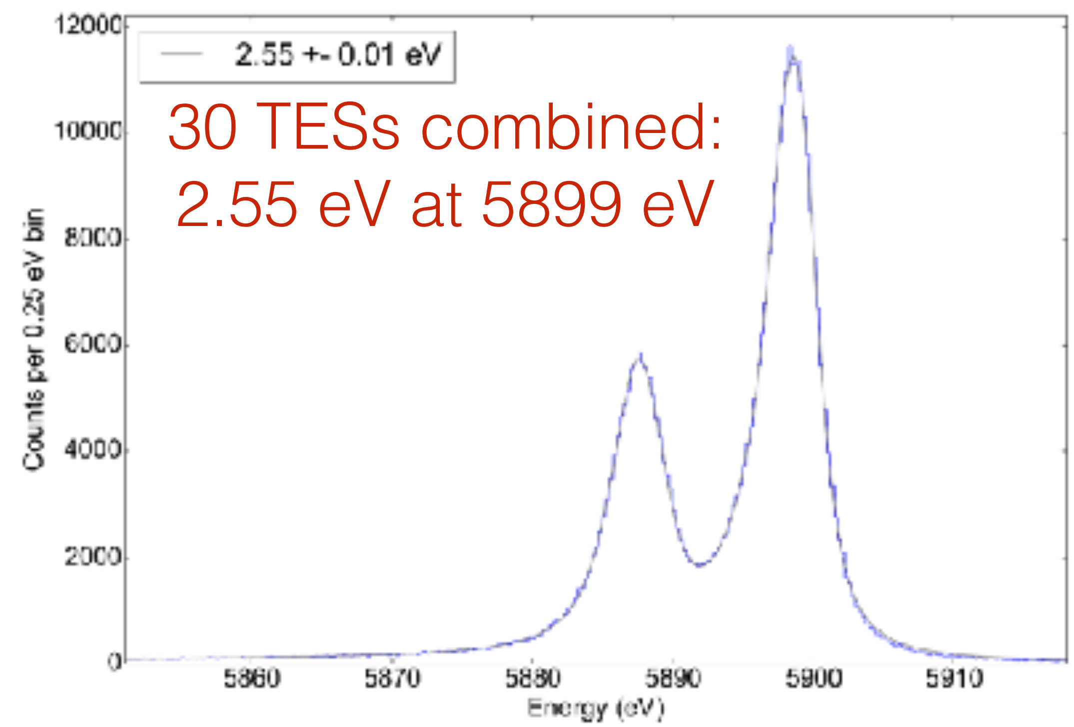
- A time-sharing SQUID-based amplifier.
- Each of several (8+) “columns” reads out several (20-32+) sensors in sequence, then repeats again every ≲ 10 μs.
- TESs are DC-biased; only their read-out circuit is switched on and off.
- Nonlinearity of SQUID amps is mitigated by applying active feedback to SQ1.
- That nulling feedback is the signal.



Poster PB-31: Malcolm Durkin
Talk: Kent Irwin

TDM at the last LTD: 1-column performance





- Detector details: 1.1 ms fall time. Max slew rate 0.21 A/s at 5.9 keV.
- Cross-talk was limiting multi-column arrays.

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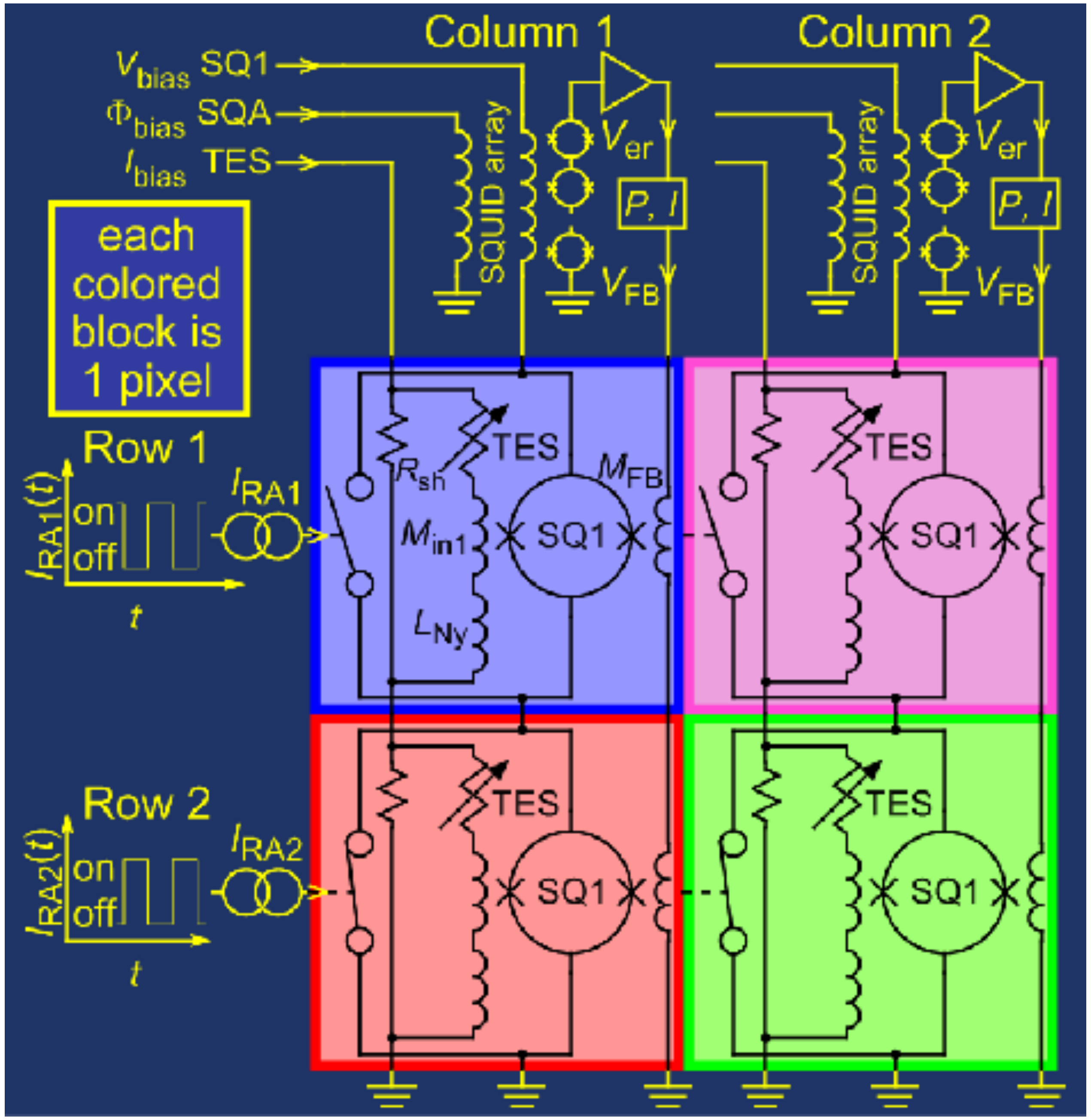
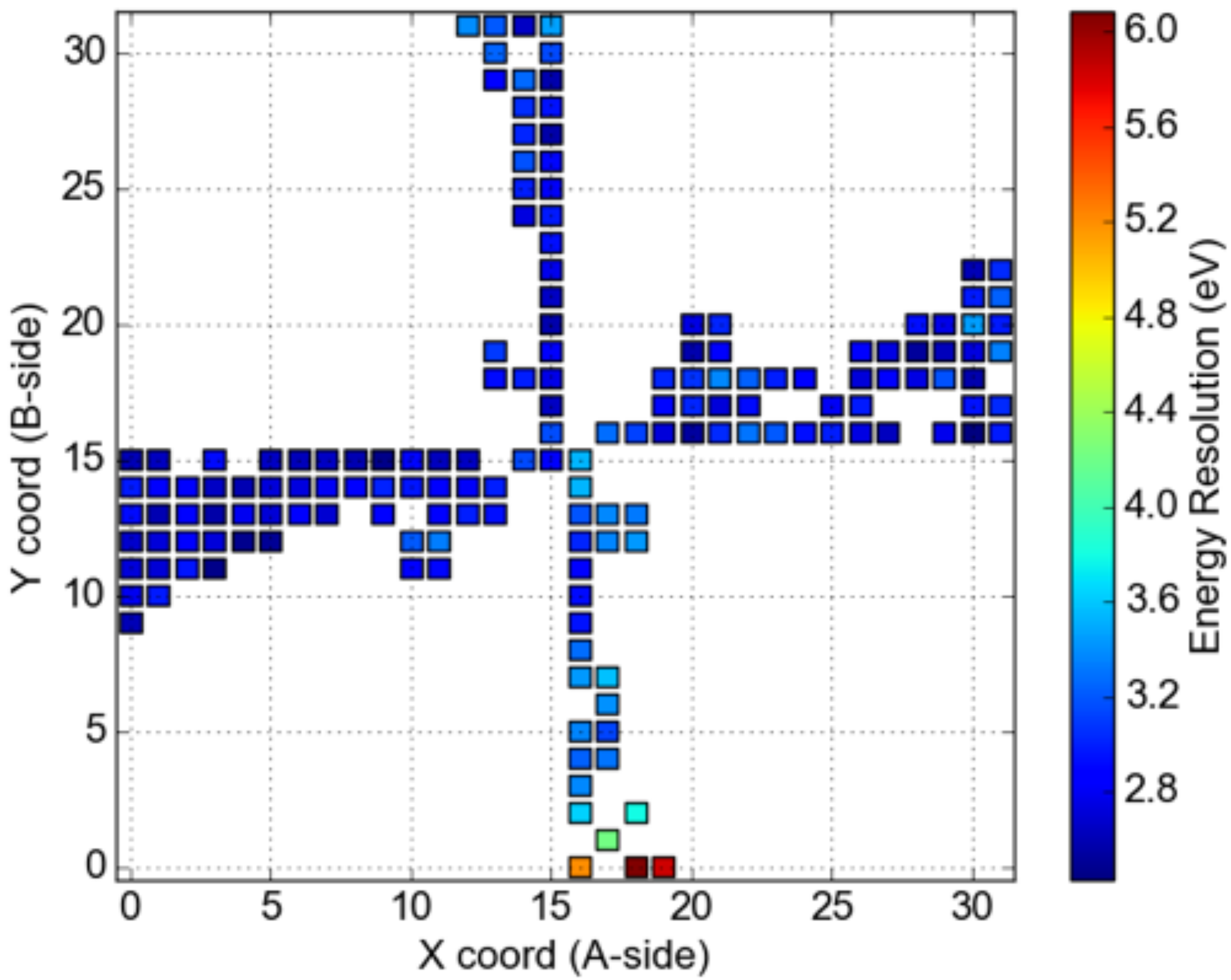
Recent TDM improvements

- Faster digital electronics.
- Wider-bandwidth analog electronics.
- Low-pass of digital switching signals (reduced column-column crosstalk).



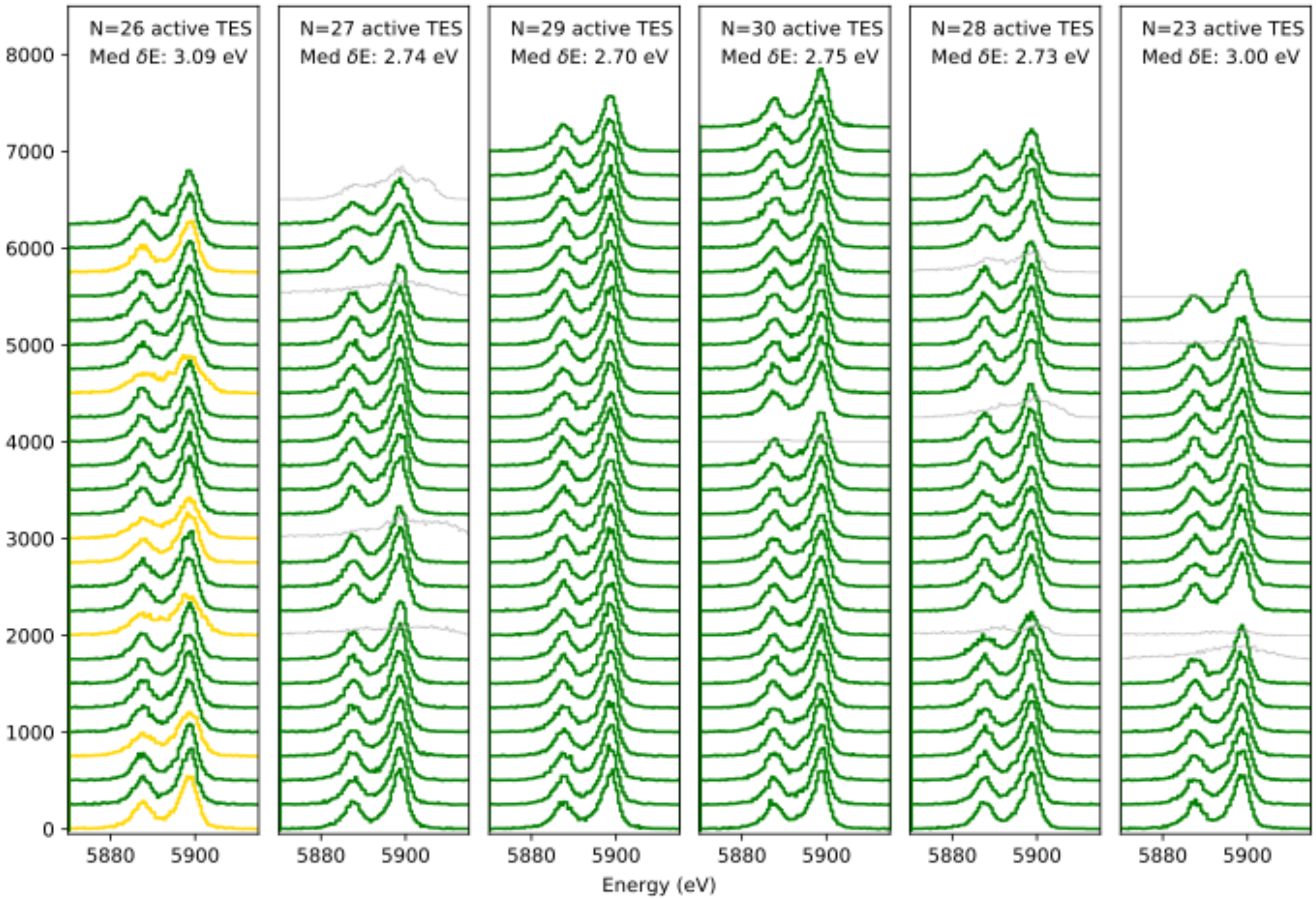
6x32 array of fast detectors (GSFC)



- 256-detector array selected out of a 1024-detector chip.
- Highly uniform performance, apart from 7 lowest TESs.

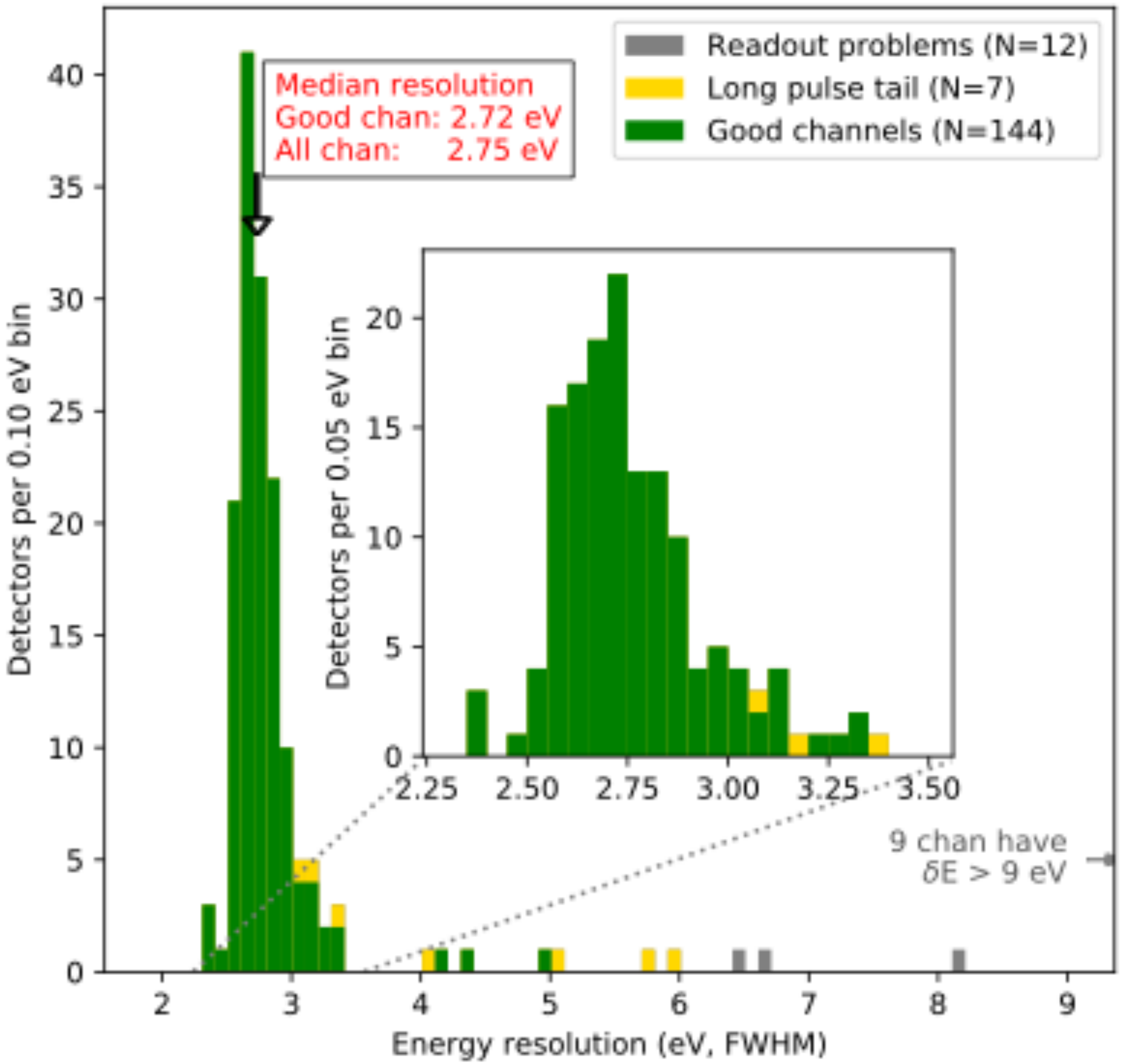
Raw spectra from 163 active TES detectors

- Each plot column = one readout column. (There are between 23 and 30 active TESs per column, but they all have 32 channels of readout.)



- Color code is:
  - Green = good (144)
  - Gray = initially too fast (12)
  - Gold = absorber problem (7 TESs)
- Fully 88% are good detectors with good readout performance at 6.4 μs sampling period.
- The medians indicated in the top of each frame (3.09, 2.74, 2.70, 2.75, 2.73, 3.00 eV) *include all channels, even gold and gray "bad" ones.*

Distribution of the resolutions at 5.9 keV



- Median resolution is 2.75 eV at 5899 eV.
- 32-channel readout, with 6.4 μs frame time.
- 143 best TESs are between 2.3 and 3.4 eV.
- Later recovered the 12 gray (too-fast) TESs with small change in tuning.

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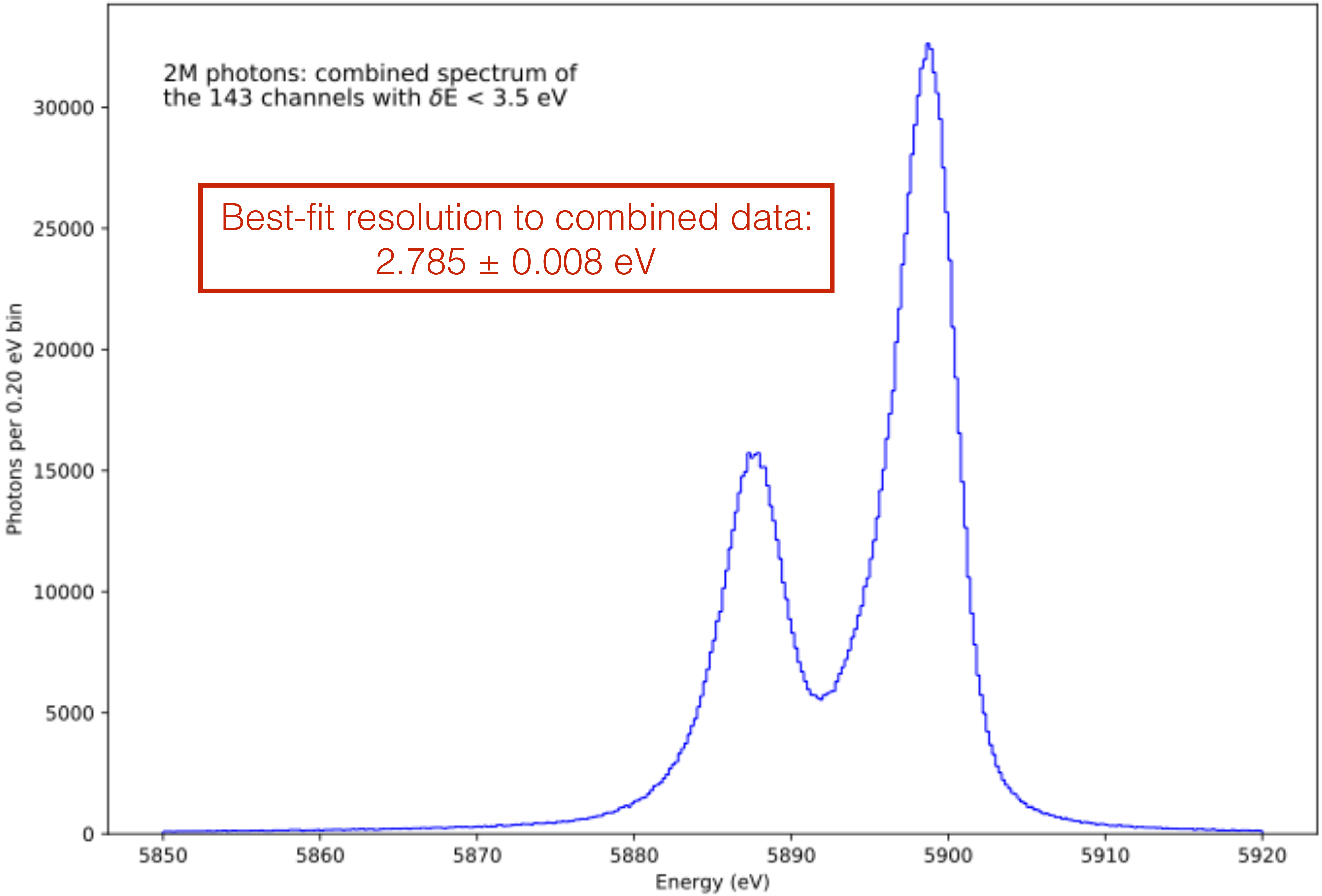
Combined 143-channel spectrum



Important constraints on bandwidth

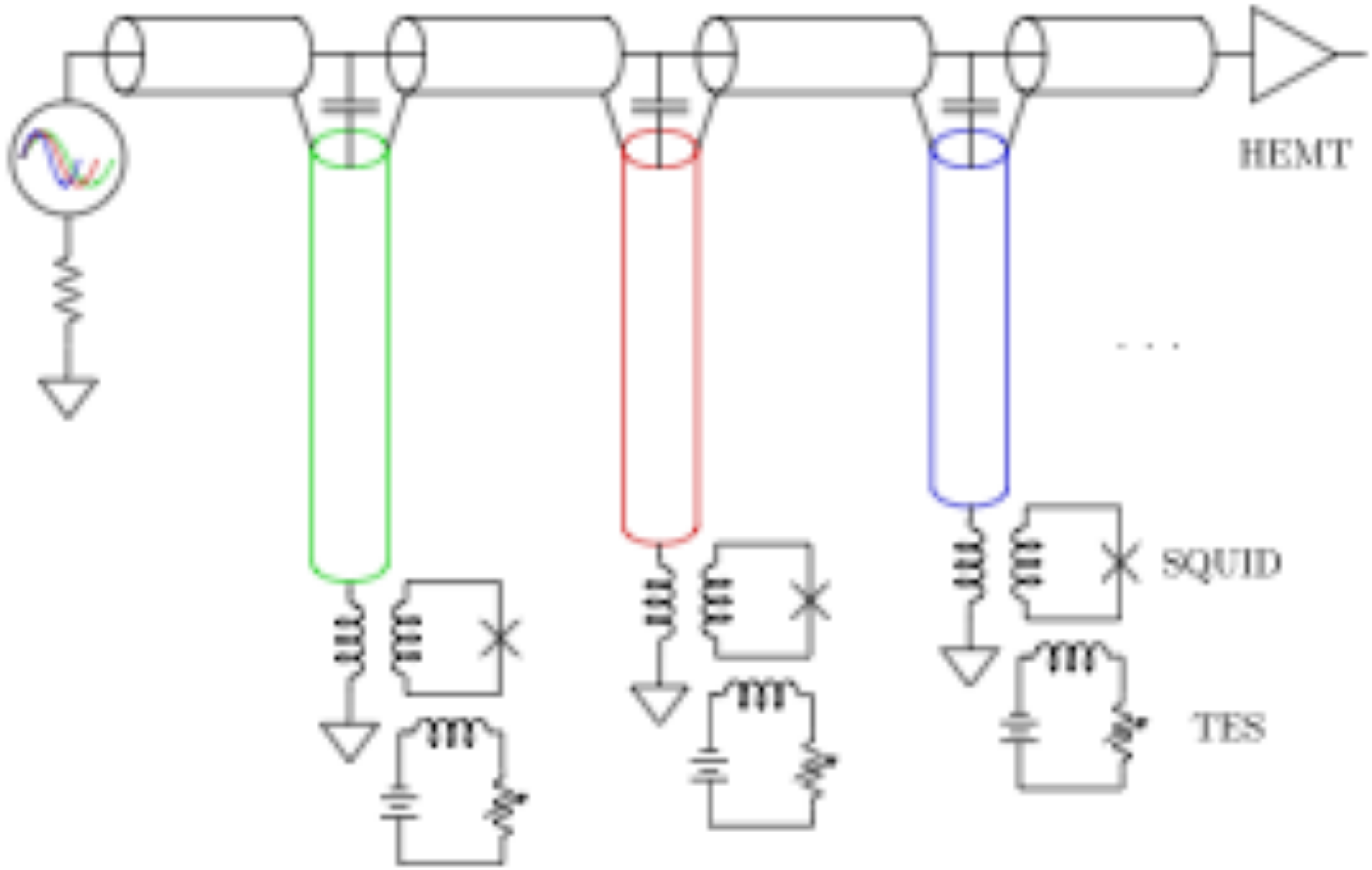
- Your MUX technology needs to offer all of:
  - Low noise
  - High sample rate
  - High slew rate (limitation in 6x32 data)
  - Low crosstalk (if high-rate, high-res)
- Together, these requirements dictate the bandwidth per channel.
- (Total system BW) $\gg$ (Per-sensor signal BW) * (# of channels)
    - Metrology: 6.25 MHz
    - 6x32 EBIT: 20 MHz

GHz bandwidth requires a new approach: μMUX

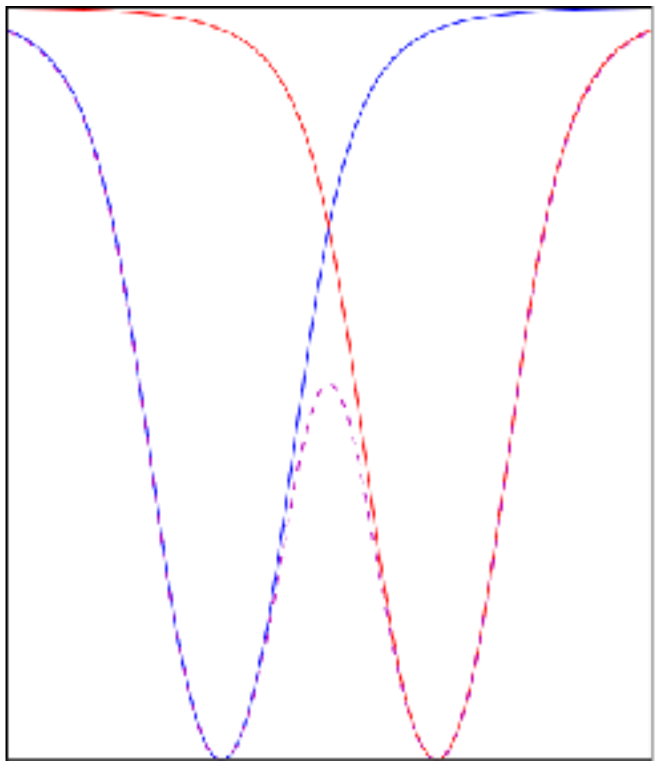
- Each TES is coupled to an rf-SQUID at the bottom of a resonant LC circuit.
- The TES current alters ***L*** and thereby modulates the tone resonating there.

N synthesized tones in →

N modulated tones out →

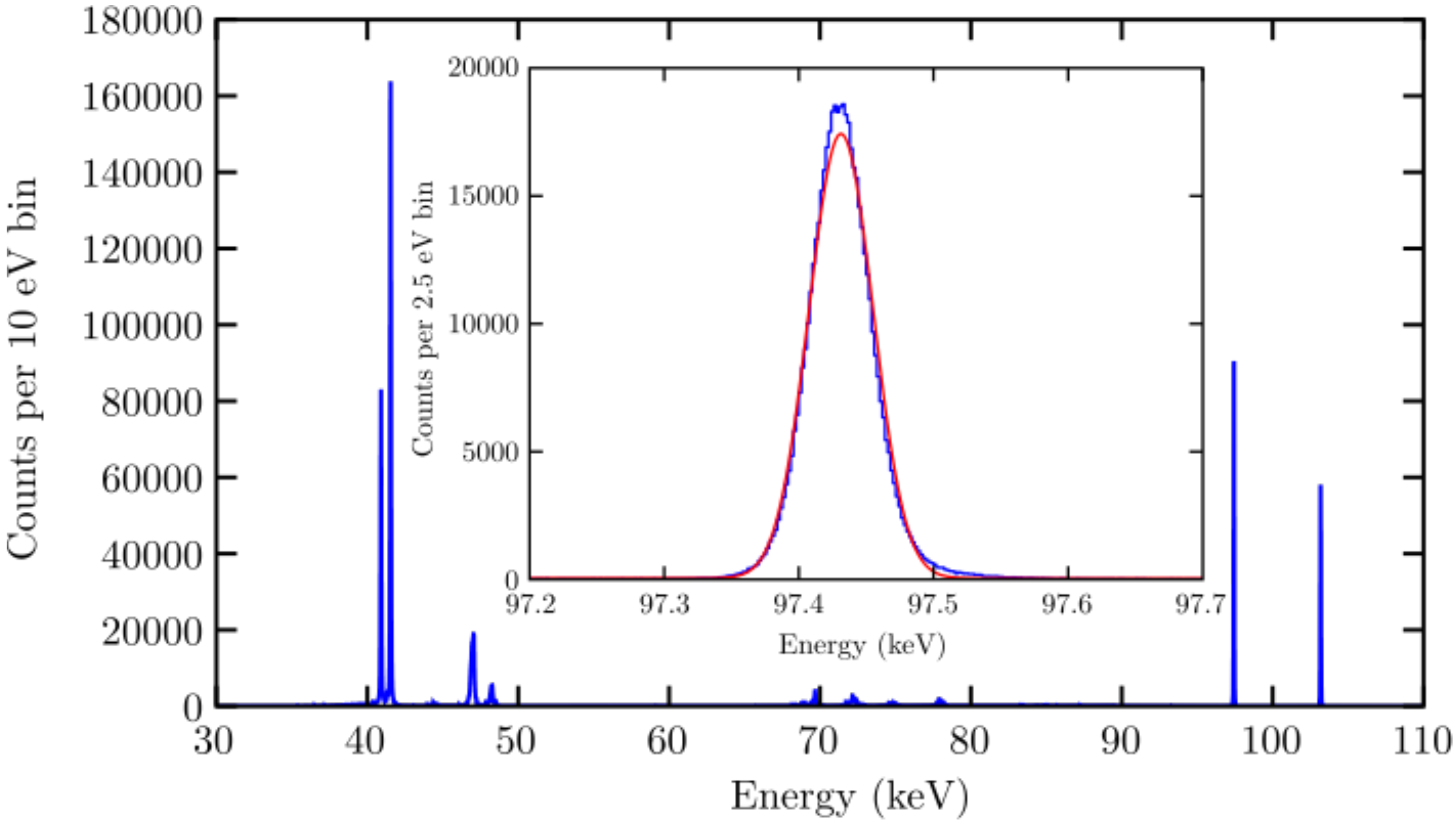


S_{21} contains the signal



One use of GHz bandwidth: 128 TES channels

- 89 TESs, microwave-SQUID multiplexing. ^{153}Gd gamma-ray source.
- Resolution: 50 eV FWHM at 97 keV.



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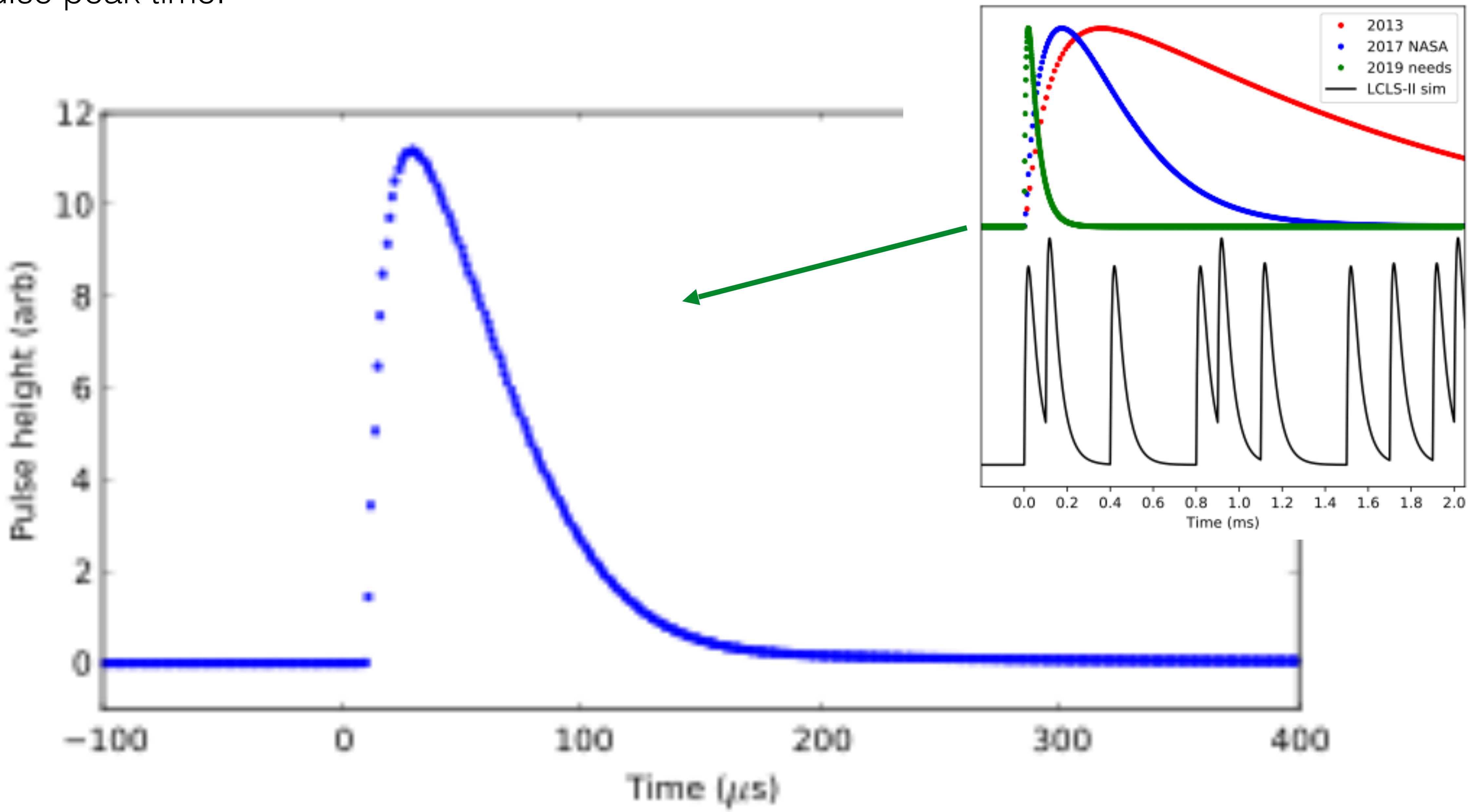
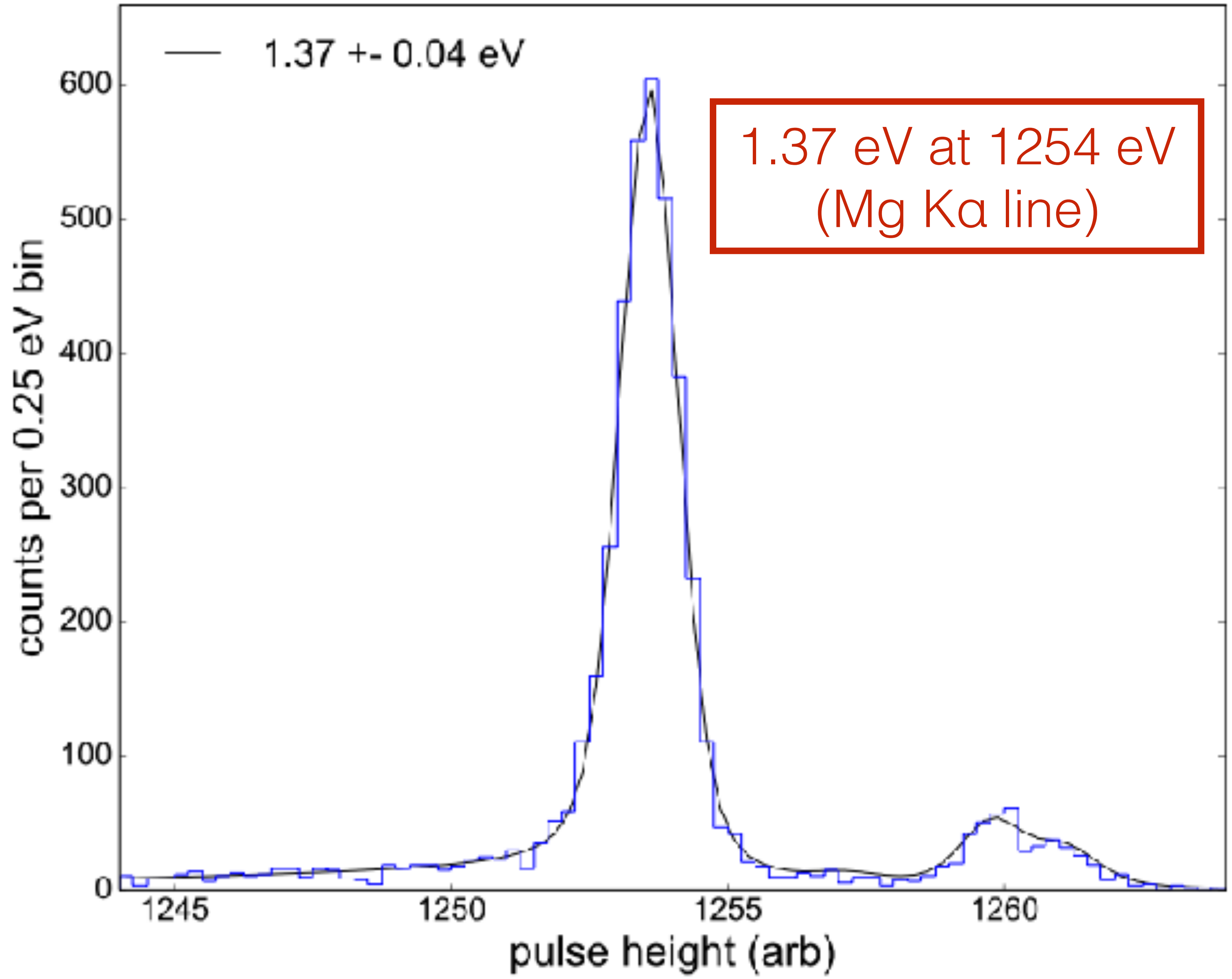
Or use GHz bandwidth for speed

- 800,000 samp/sec readout demonstrated with microwave SQUID multiplexing.
- 20 μs pulse peak time.



Fast readout used for high resolution

- Source: Mg Kα fluorescence.
- TES detector: a leading LCLS-II candidate design.
- Should be able to reach 1.0–1.1 eV (better at target energies 200-800 eV).



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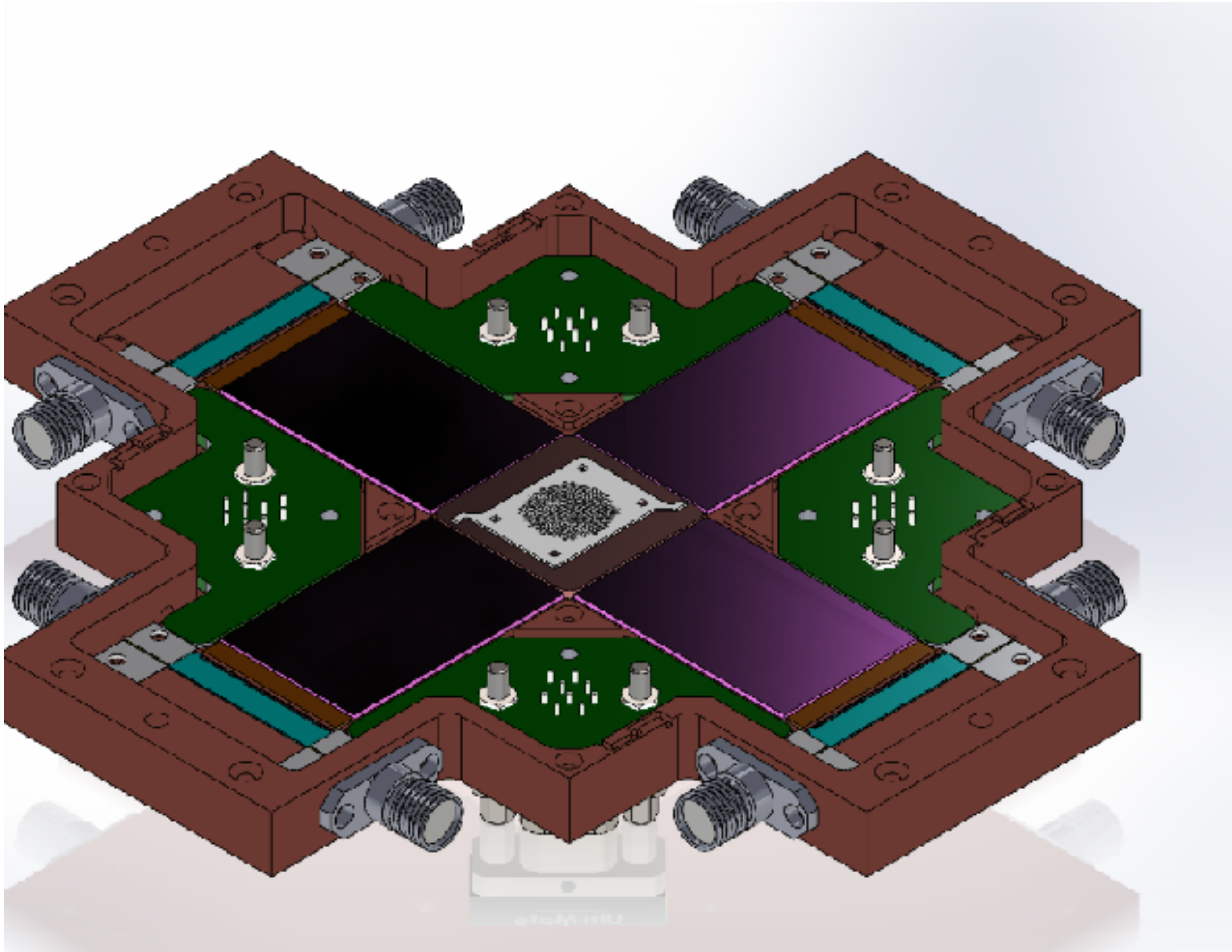
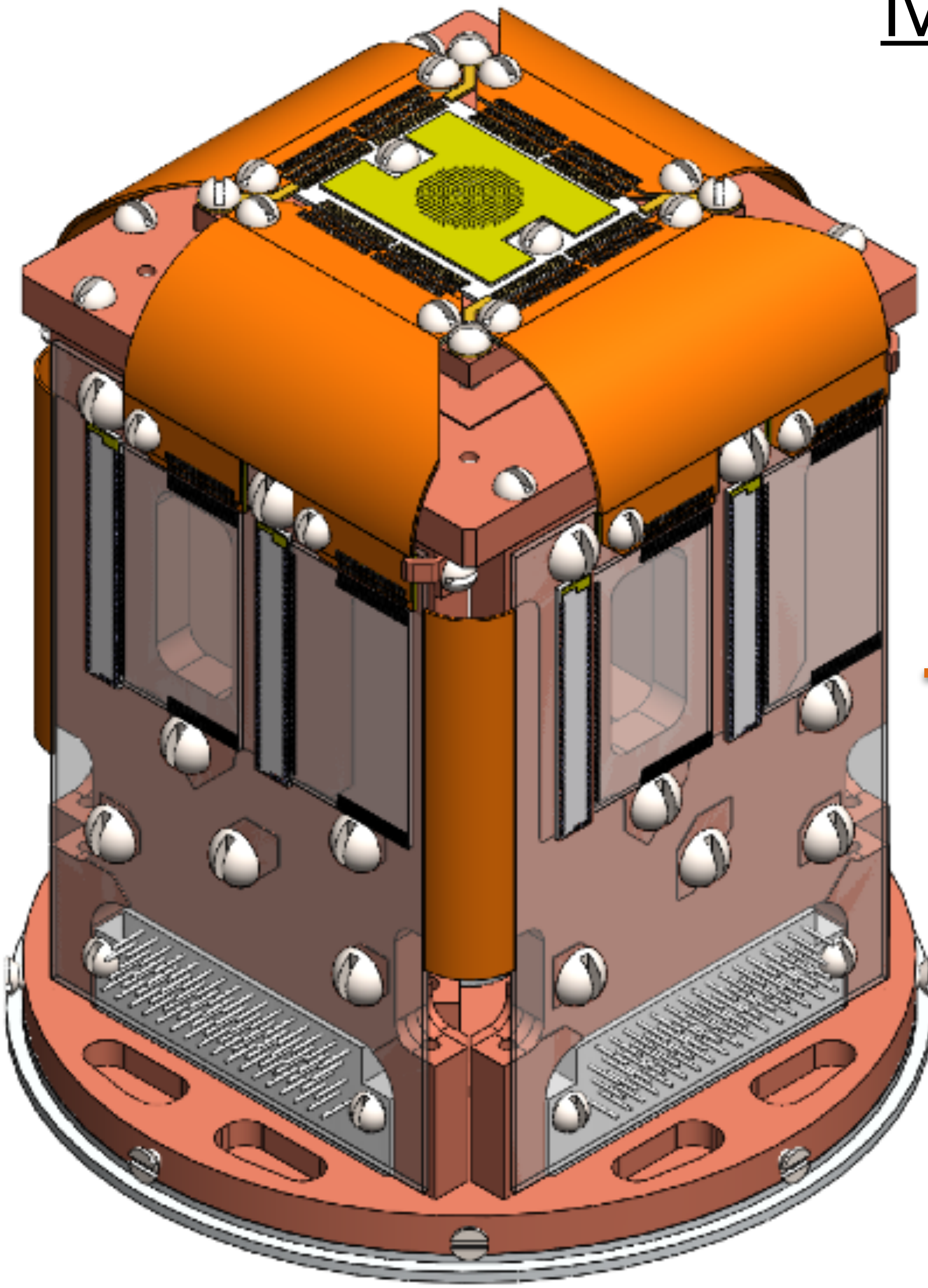
What’s next: 2 GHz bandwidth

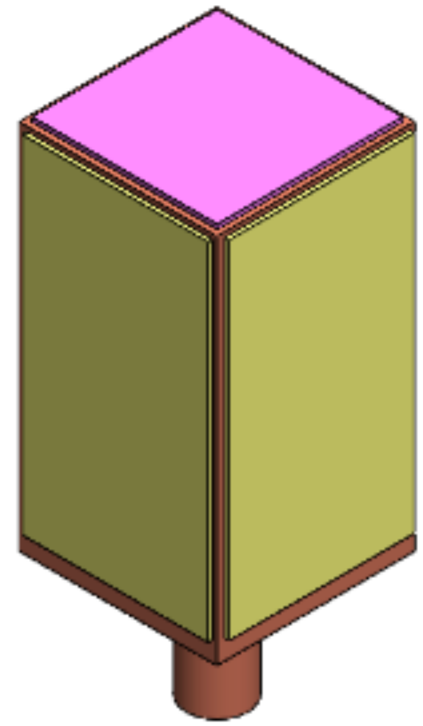


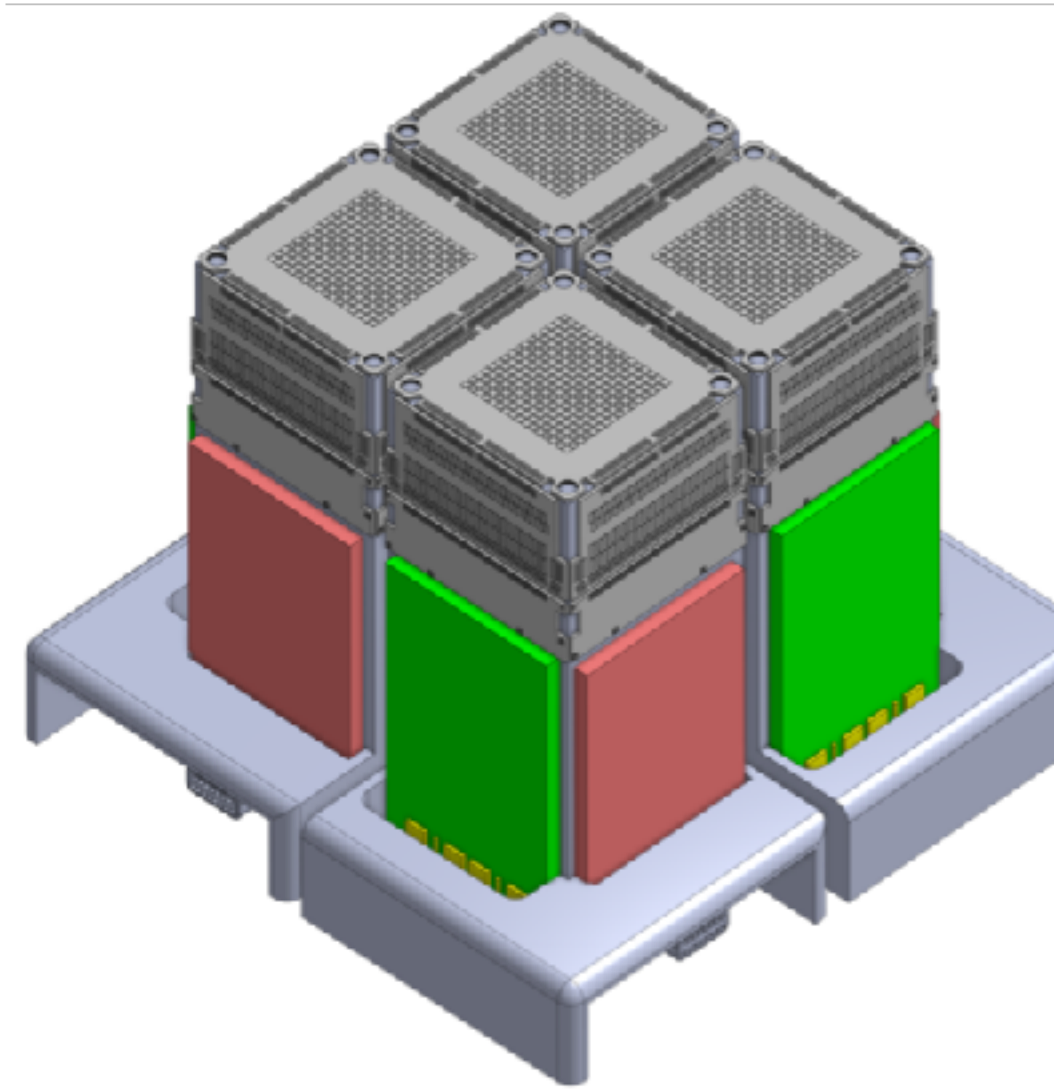
A μMUX test system for 2 GHz bandwidth.

Microsnouts



- How do we reach (and exceed) the scale of 1000 fast pixels?





Conclusions

- TDM technology is reaching its full potential.
- For much faster and/or more numerous sensors, we need much wider system bandwidth.
- Demonstrations have been made of 100+ readout channels AND 20 μs (fast) detectors.
- Work is underway to move from these demonstrations to real spectrometers.

Arrival-time effects

- Great result, but we can see that we're already approaching this system's speed limits:
- Some TES rising edges too fast. Fixed with re-tuning of the SQUIDs, but it's a problem that's not going away as long as detectors are this fast.
- Here are 3 examples from the 163 active TESs: