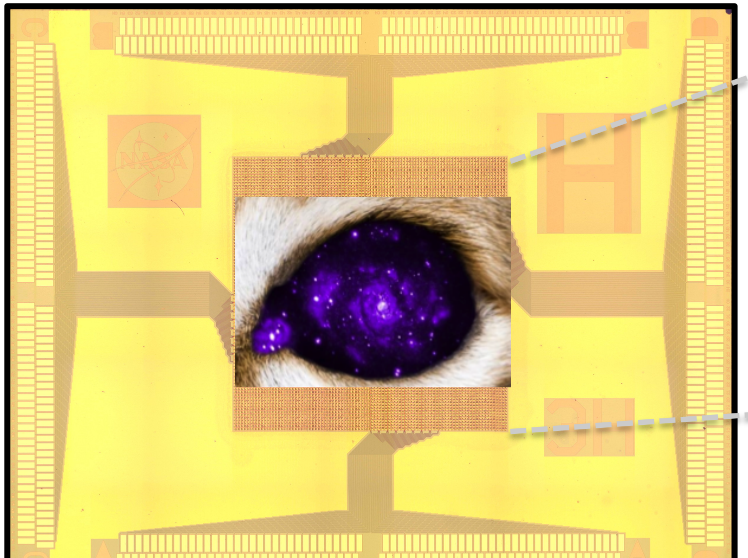
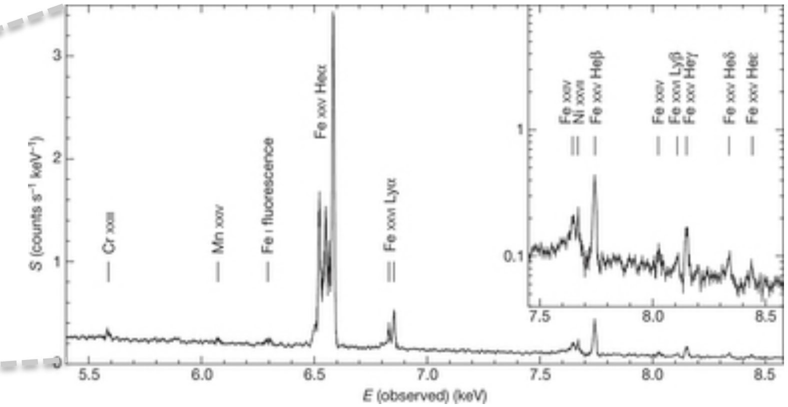
Revealing the Invisible Universe





Options for the Lynx X-ray microcalorimeter "Whiskers"

Lynx 4th face-to-face meeting
Huntsville, April 7th, 2017

Simon Bandler – X-ray microcalorimeter group at NASA/GSFC

- Programmatic updates – Microcalorimeter IWG subgroup
- Technical updates
- Trades
- Example options
- Discussion of Lynx microcalorimeter science drivers

New Lynx Microcalorimeter IWG sub-group has been formed:

1. Simon Bandler - GSFC - Co-chair	- Detectors
2. Enectali Figueroa-Feliciano - Northwestern - Co-chair	- Detectors-science interface
3. Joel Ullom – NIST	- Read-out
4. Dan Swetz – NIST	- Read-out
5. Vincent Kotsubo – NIST	- Cryogenics
6. Jeffrey Olson - Lockheed Martin	- Cryogenics
7. Megan Eckart – GSFC	- Read-out
8. Stephen Smith – GSFC	- Detectors
9. Kent Irwin – Stanford	- Read-out
10. Mike DiPirro – GSFC	- Cryogenics
11. Stephen Kuenster – Stanford	- Read-out
12. Dan McCammon – Wisconsin	- Detectors
13. Doug Bennett – NIST	- Read-out
14. Kazuhiro Sakai – GSFC	- Read-out and data processing
15. Doug Swartz - NASA/MSFC	- Program office oversight
16. Ben Zeiger – Luxel	- IR blocking filters
17. Kevin Ryu - MIT Lincoln Laboratories	- Supporting technologies

Telecon schedule:

1. Introductory telecon - March 13th, 2017
   - Introductions to working group members
   - Overview of Lynx
   - Status of Lynx requirements
   - What are the tallest poles?
   - Review of plans for this IWG sub-group and telecon topics

2. Discussion of options/capabilities of the microcalorimeter focal plane array – April 5th, 2017
   - basic detector design options & parameters needed to set read-out requirements
   - fabrication approaches

   Possible sub-topic that may require separate discussion/telecon:
   - telescope pointing and dithering: requirements
   - what effective angular resolution is possible based upon use of dithering techniques
   - other spacecraft requirements

3. Discussion of the read-out options/capabilities –April 10-14th
   - CDM option
   - microwave SQUID multiplexer option
   - other read-out options
   - cryogenic requirements
   - plan for Lynx read-out baseline
   - identify and rank tallest poles for the read-out

4. Potential mechanical designs of focal plane assembly & other cryogenic components. – April 24-28th
   - magnetic shielding and environment requirements
   - FPA design
   - amplifier design
   - what cabling & packaging options exist/need to be developed
   - what is the basic envelope of the package
   - filters

5. Discussion on cryogenics - May 2017

- basic approach options to cryostat design, to meet read-out, size and mass requirements
- how much redundancy is required?
- review of Athena-X-IFU cryostat design, IXO cryostat design, as well as cryostats for other missions
- basic plan for the number of cryogenic models/systems within program
- process for estimating mass and cost

6. Flight electronics for reading out instrument detectors & data processing. - May 2017

- what are the processing requirements
- how to adapt to ever evolving of read-out electronics developments
- initial estimates/thoughts on how this might be done
- process for estimating the mass and power of the electronics, and output data rates

Other activities:

7. GSFC Instrument Design Laboratory: Wednesday June 21st -> Tuesday June 27th

- June 6th – Pre-work meeting
- **all welcome. Please contact me if you are interested in participating!**
- feeds into current Marshall ACO mission study ending July 2017.
- feeding into Decadal studies interim report at end of 2017.

Later:

8. Establish more detailed baseline and goal instrument requirements.
9. Develop TRL definitions and estimate of timetable for evolving to TRL-6 by PDR.
10. Develop and iterate technology development plan.

Full study ends in 2019 – exact dates under review

Suggested Lynx microcalorimeter requirements for initial study

- Pixel size: 1”
- Field-of-View: At least 5’ x 5’
- Energy resolution [FWHM]: < 5 eV
- Count rate capability: < 1 count per second per pixel
- For a focal length of optic of 10 m, 1” corresponds to 50 μm pixels

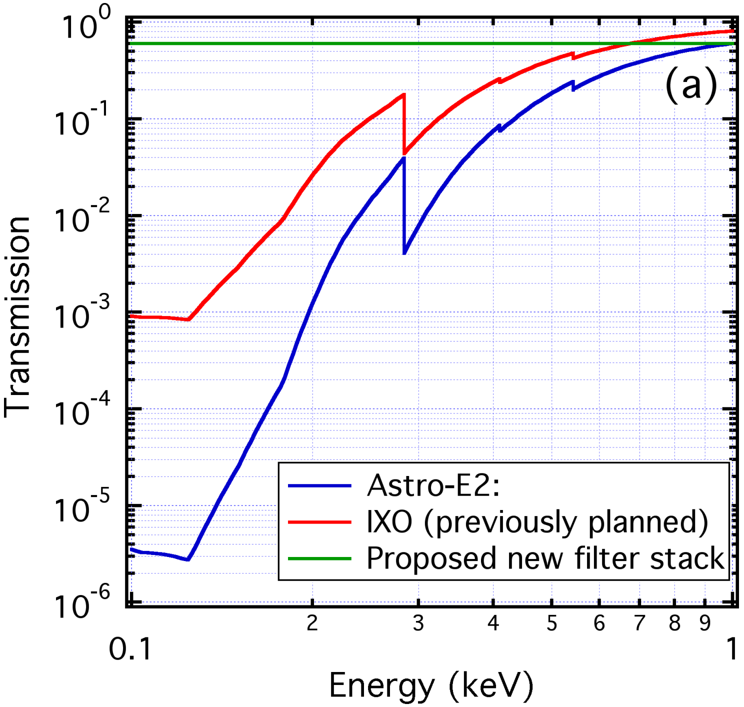
5’ field-of-view with 1” pixels requires a nominal 300 x 300 array => 90,000 pixels

Current rough guess at improvements most desired for better science return for Lynx microcalorimeter:

1. Smaller pixel pitch closer to ~ 0.5”
   – at least in some sub-region of 0.5 – 1’,
   - preferably in whole array but less needed in out regions

2. Better energy resolution
   - Making the smaller pitch Hydras will likely improve the energy resolution.

3. Improvement in filter throughput at low energies (0.1 – 1 keV) – to better see X-rays from the high red-shift Universe.
   - not willing to sacrifice area/response 1-10 keV.
   - F-number of telescope is ~ 3.3

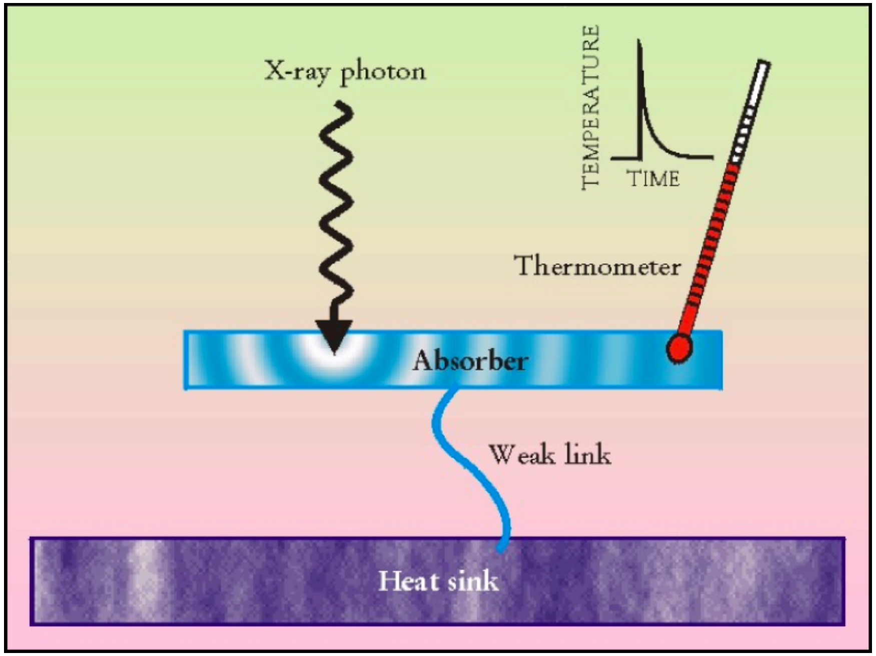


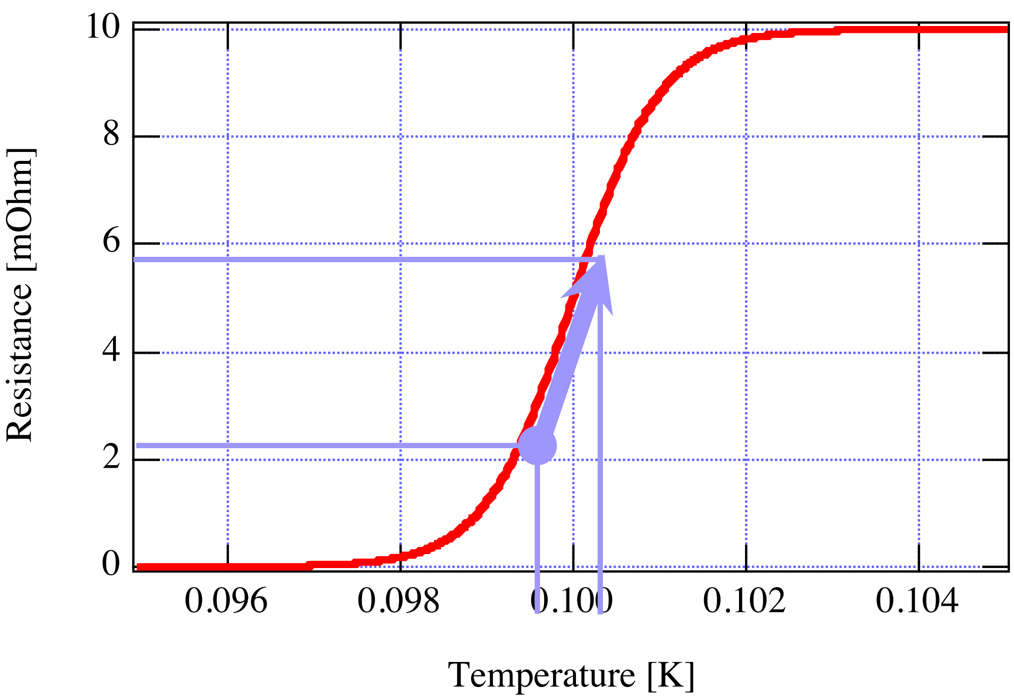
4. Increasing the field of view

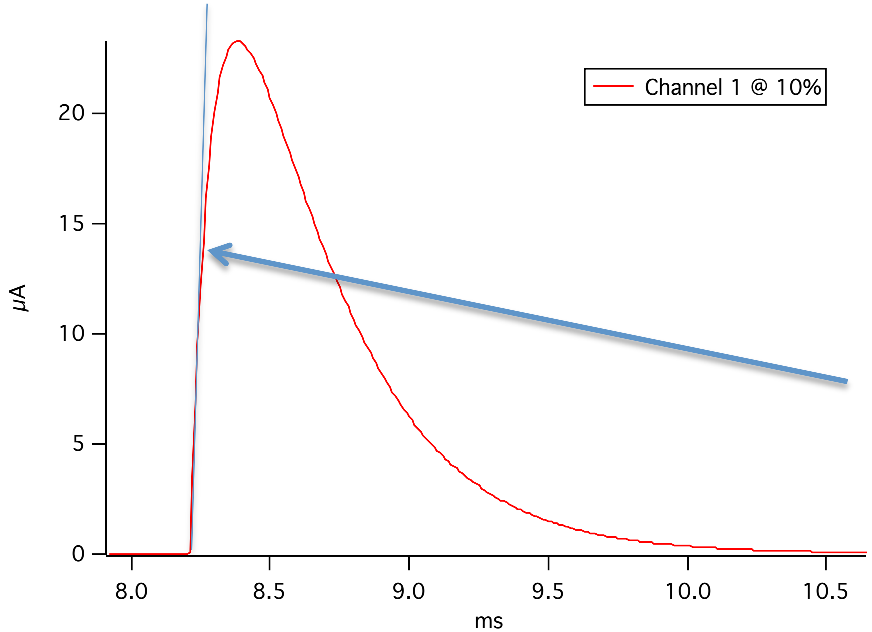
5. Increasing dynamic range from ~ 10 keV to ~ 15 keV or higher.

6. Being able to accommodate higher count rates than currently assumed.

Transition-edge Sensor microcalorimeter basics:



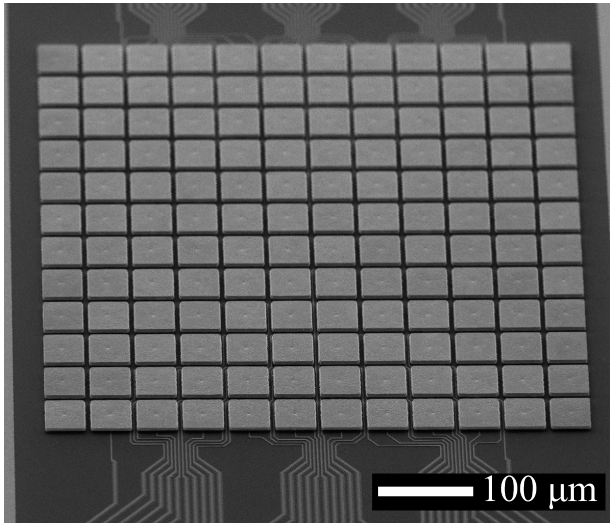




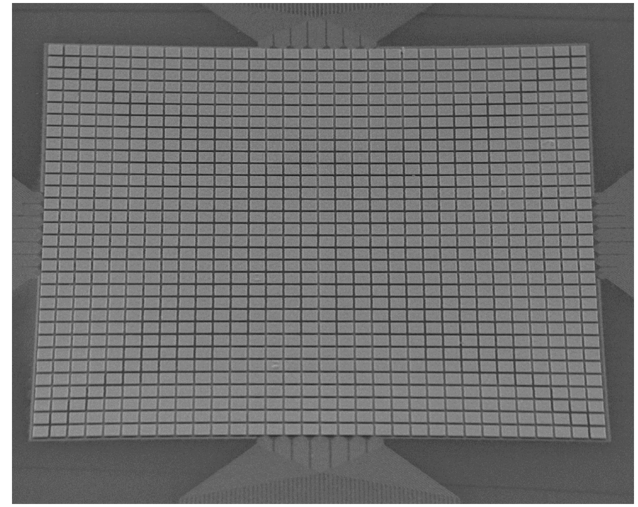
Superconductor voltage-biased in its transition

- Slope of this line is called the *"slew rate"*
- Higher slew rates are harder to read out (require more bandwidth)

12x12 array of pixels on 50 um pitch:

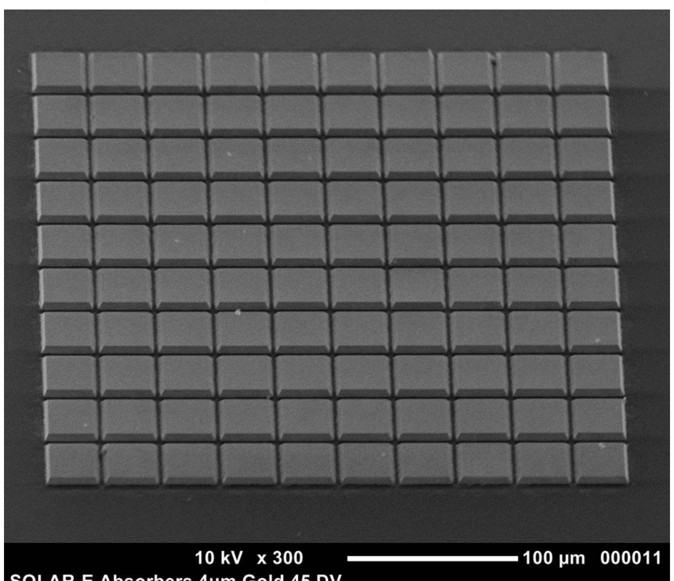


32x32 array of pixels on 75 um pitch:



Single pixel TESs under investigation – 25-35 µm pitch:

10 x 10 Array on 35 micron pitch



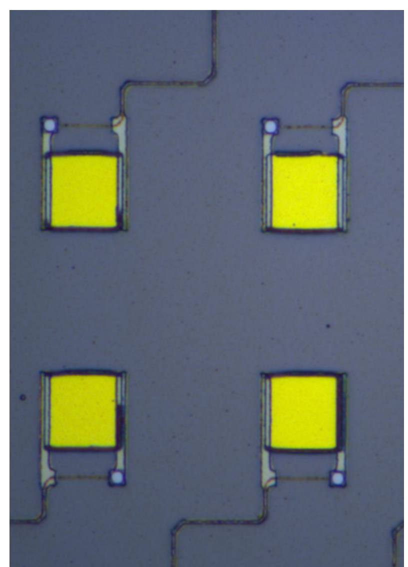
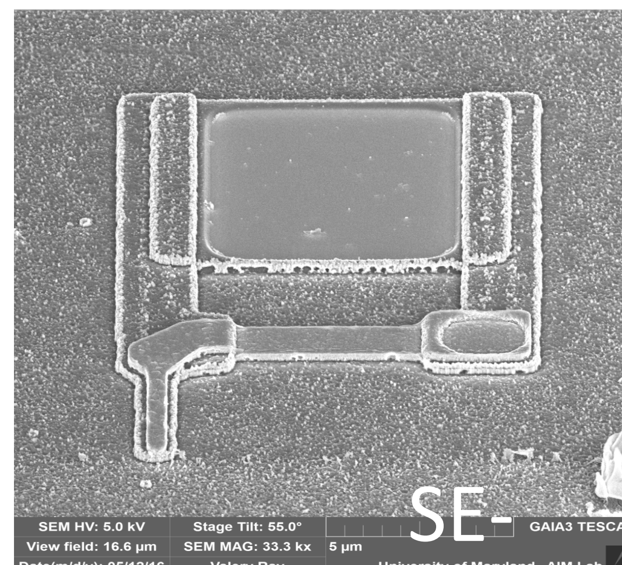
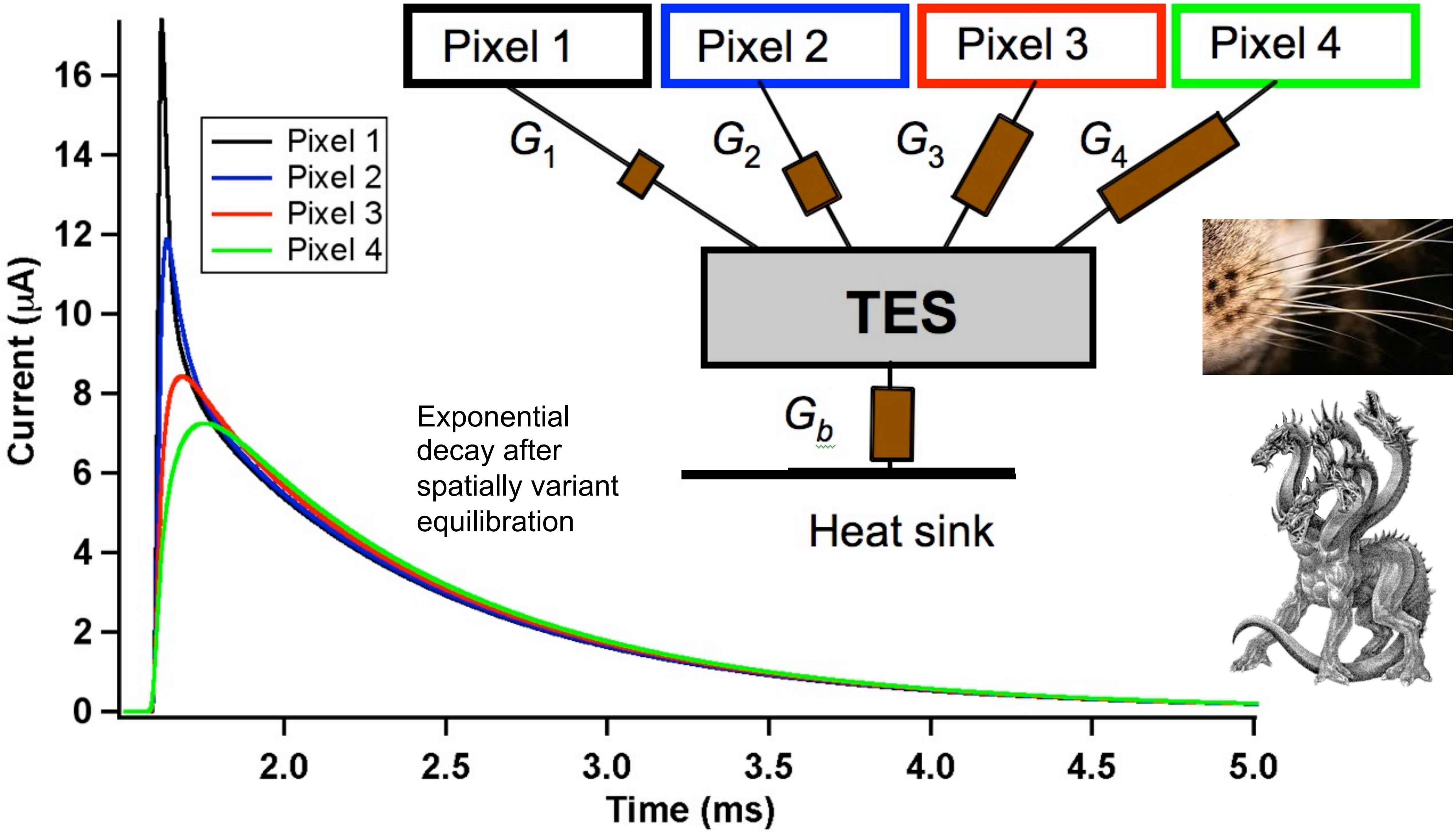


Image (FIB) of 7 um TES:



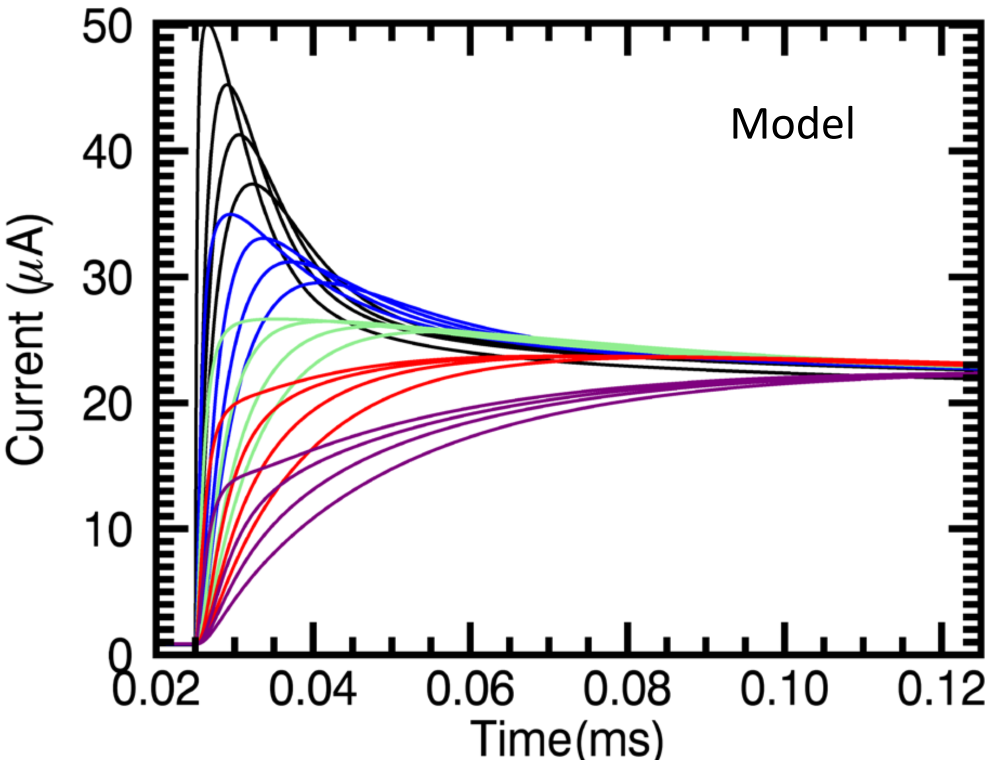
Multi Absorber TES "Hydras" - 1 TES, 4 absorbers

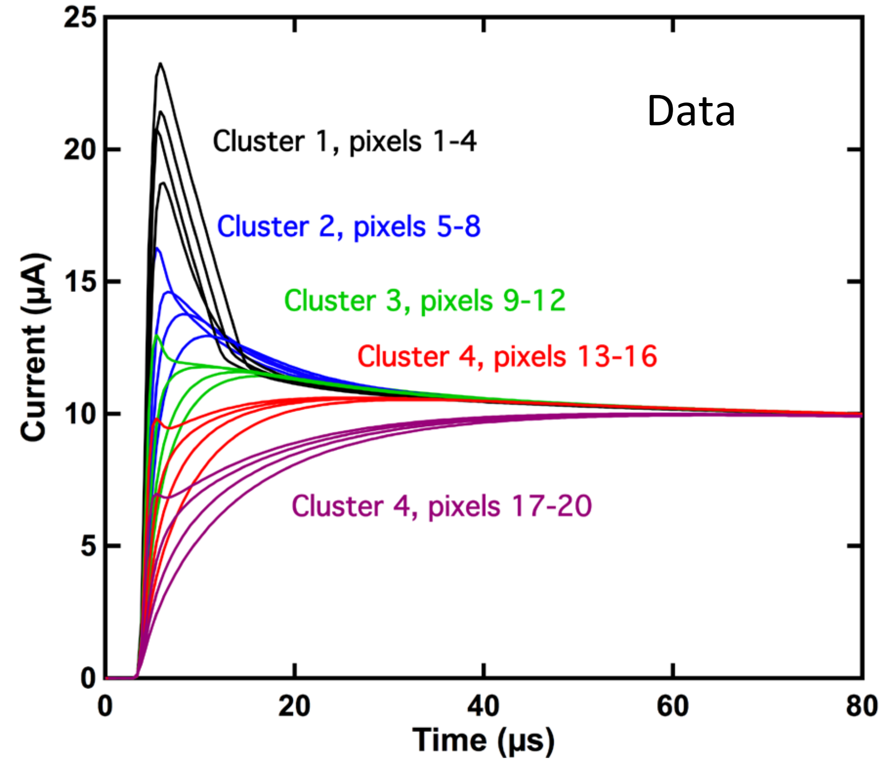
– increase field of view for a fixed number of read-out channels



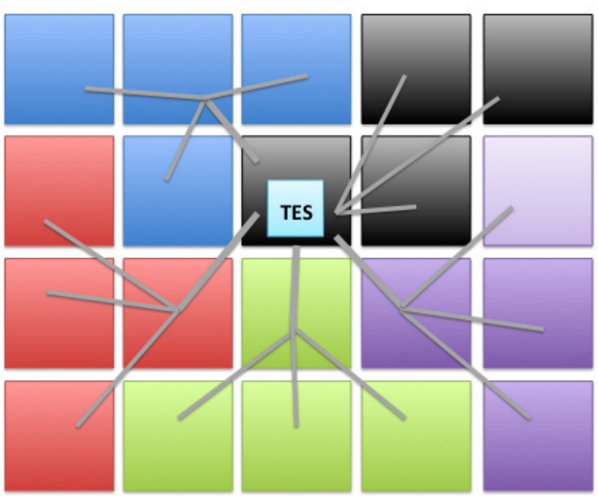
Also works with MCCs

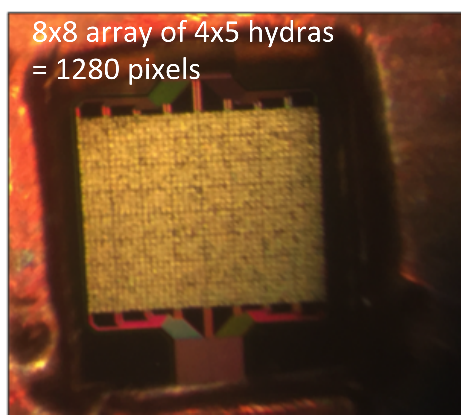
Technical updates: 20-absorber TES hydra

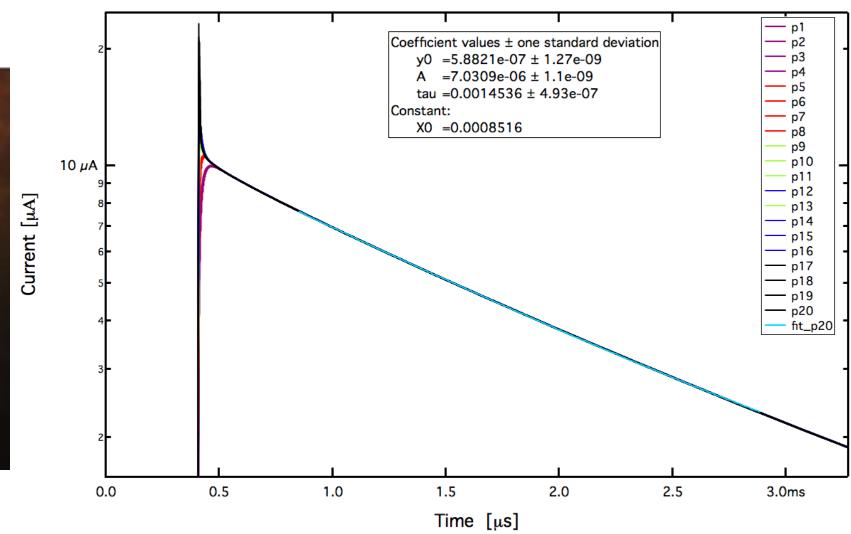




- Qualitatively similar pulse shapes compared to model.

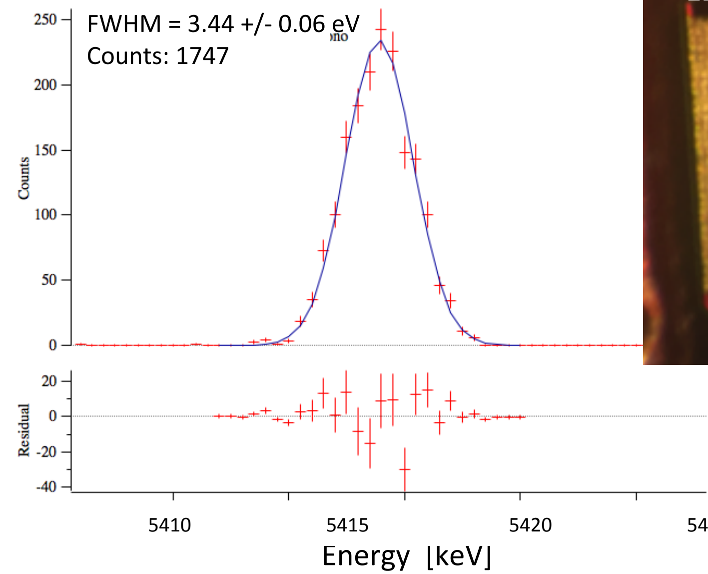


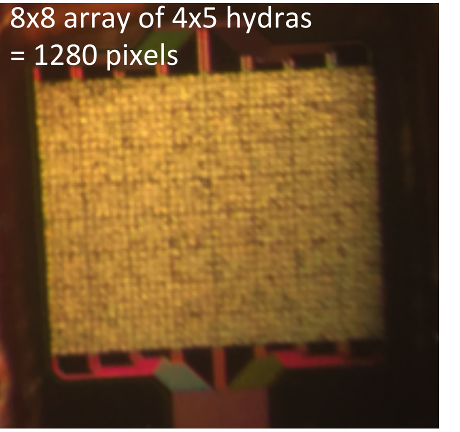


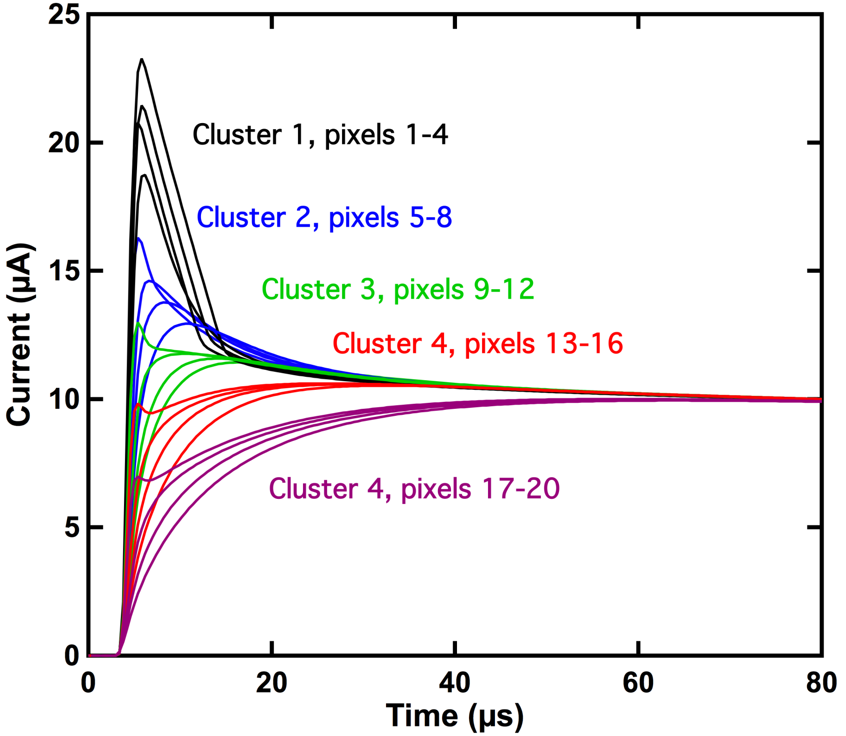


6) First 20-pixel hydra results

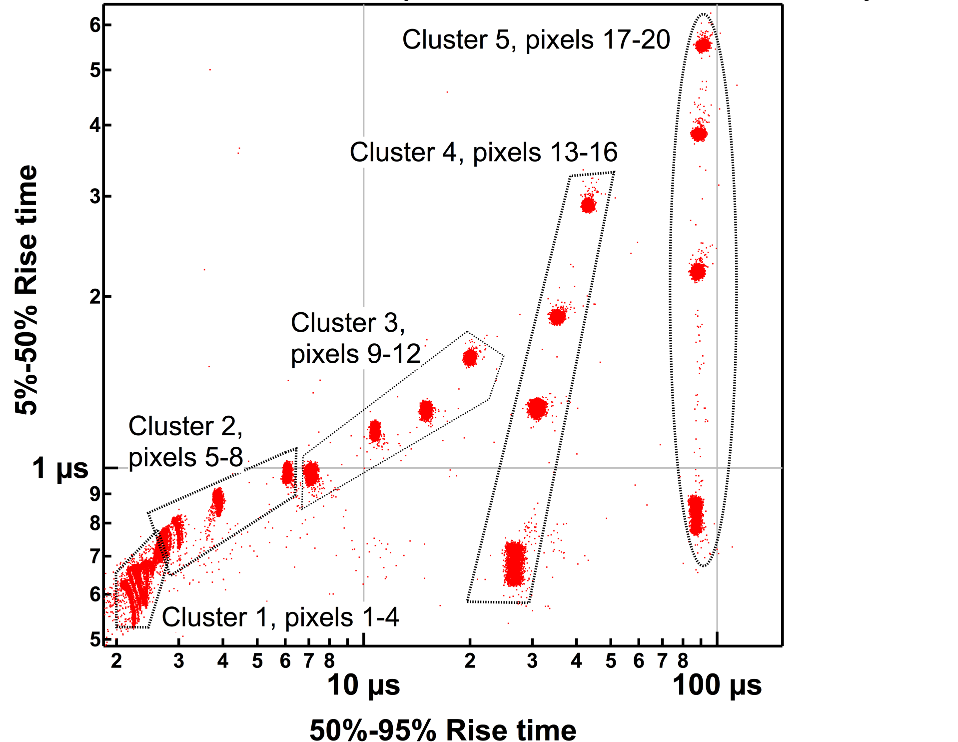
- The absorbers are 50×50×4.2 μm electroplated Au.
- $\langle \Delta E_{FWHM} \rangle = 3.39 \pm 0.18$ eV at Cr (5.4 keV) for all 20 pixels.
- Used 2 rise-time metrics to characterize pre-equilibration signal.
  - τ_{rise1} = 5-50% pulse height
  - τ_{rise2} = 50-95% pulse height







Rise time vs rise time plot, for Cr and Mn x-rays



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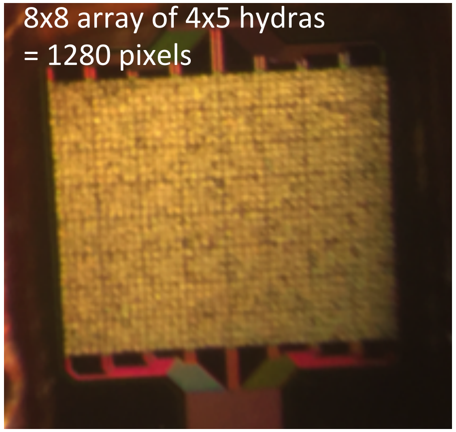
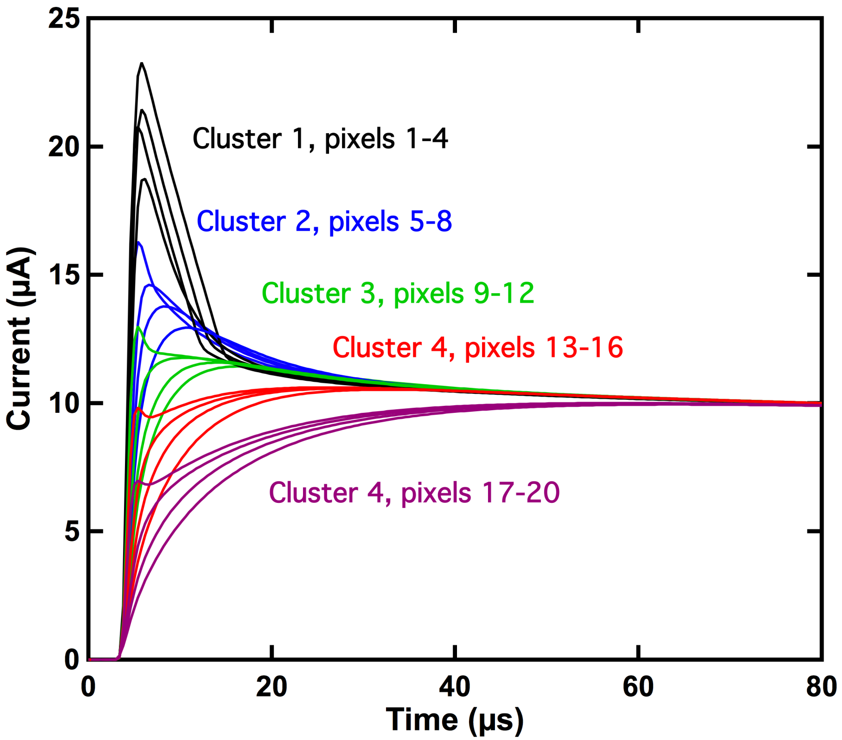
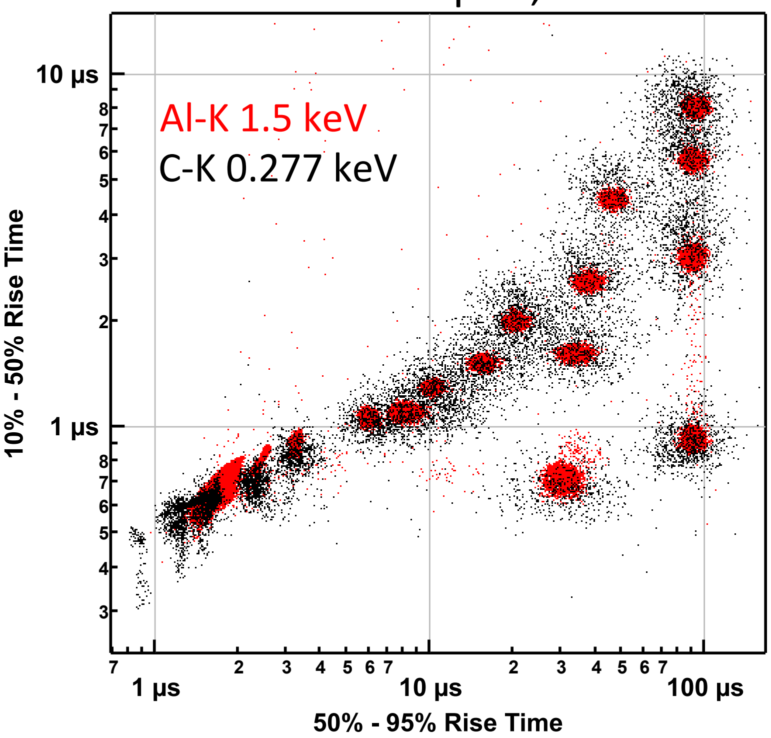
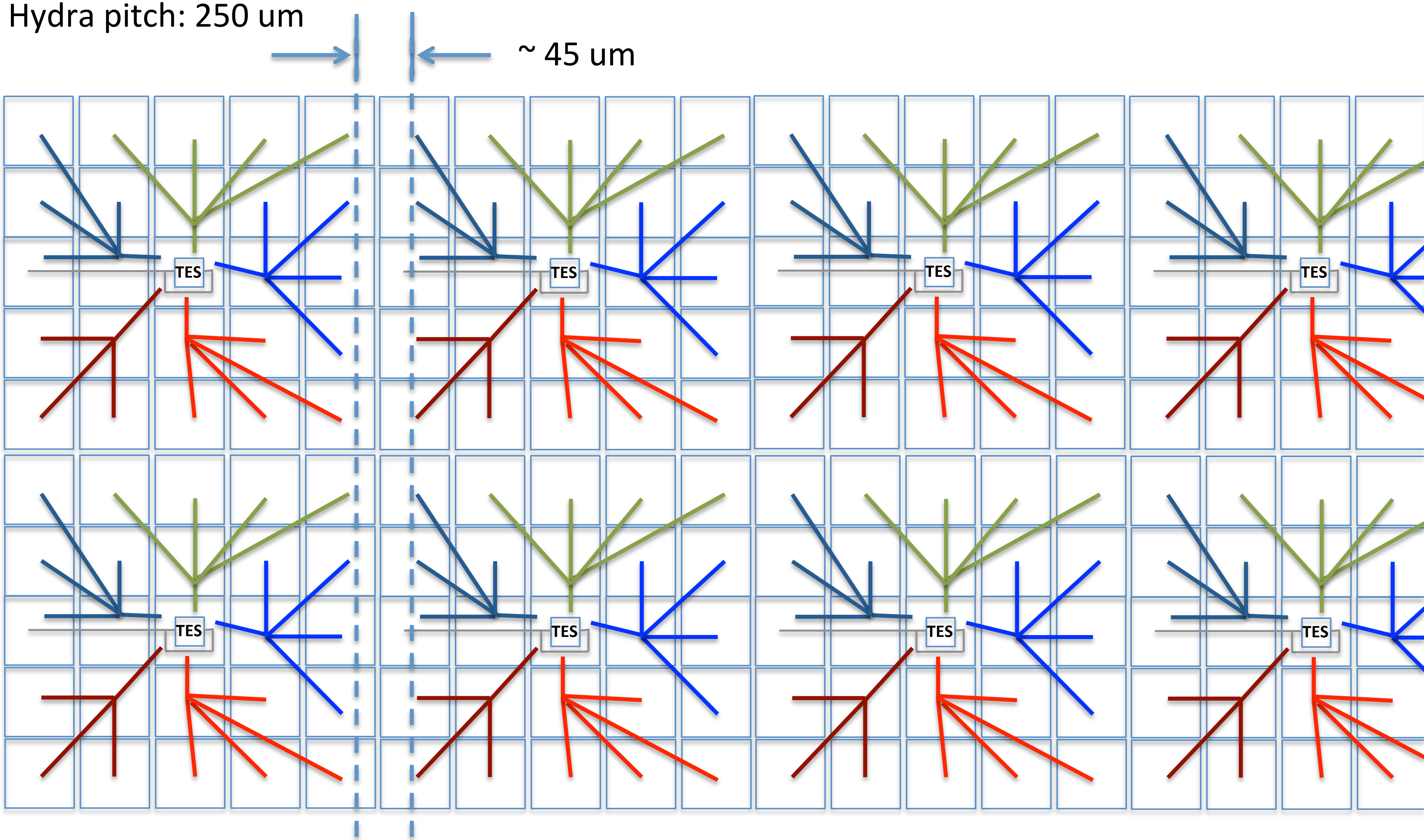




Rise time vs rise time plot, for C and Al x-rays

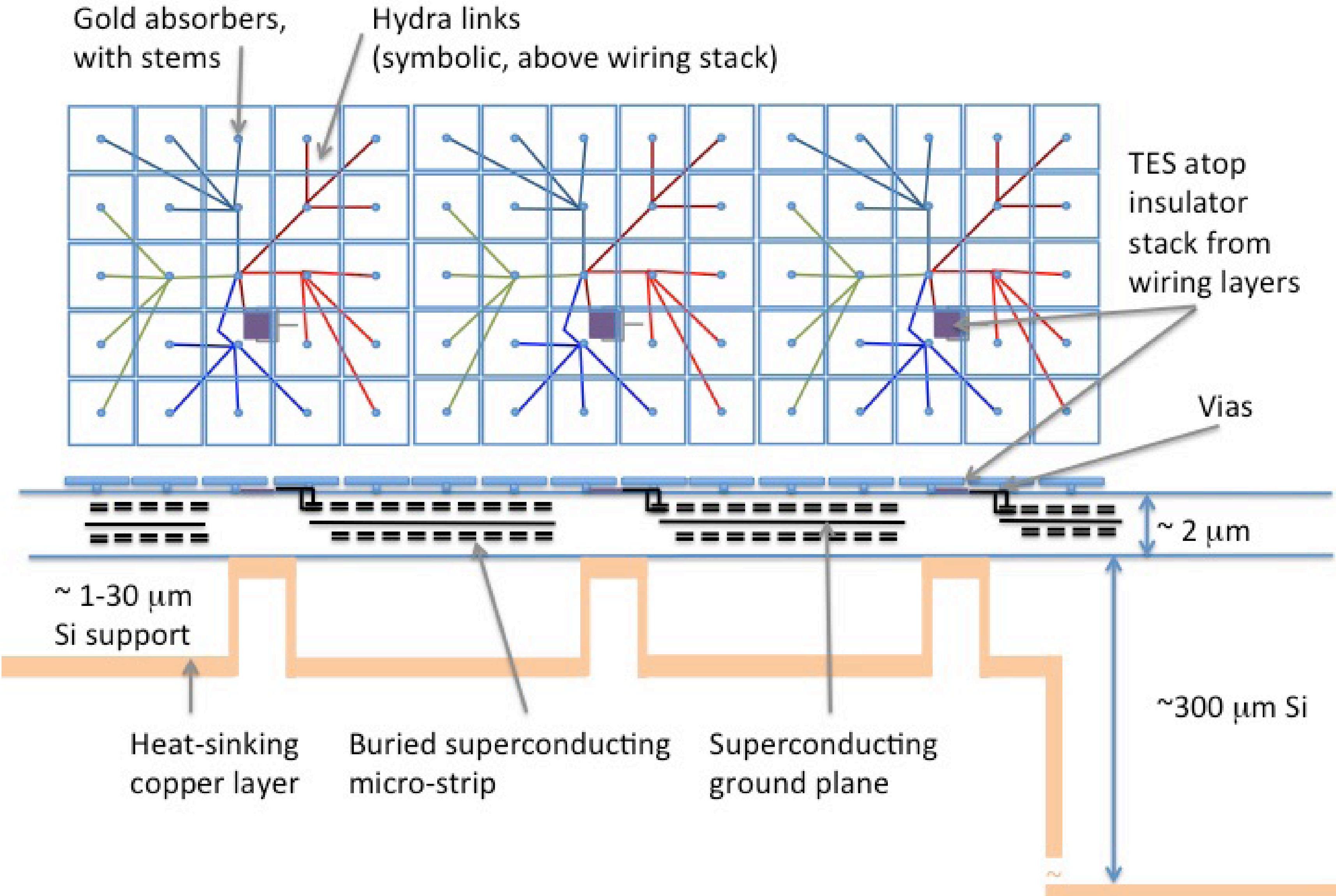


Pixel pitch: 50 um
Hydra pitch: 250 um

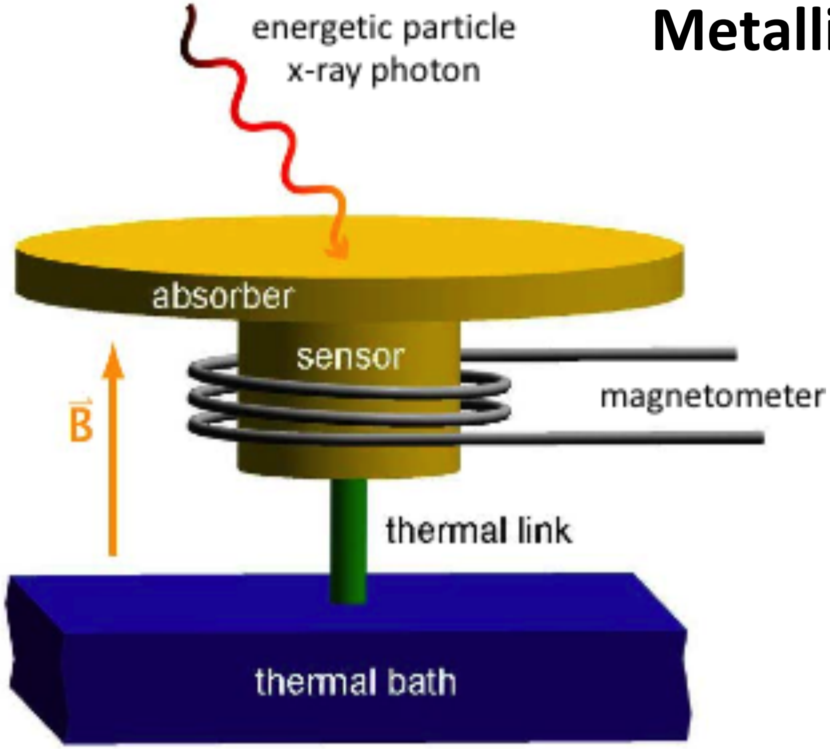


- For 60x60 array of Hydras => 15 micro-strip => pitch of ~ 2-3 μm
- Shrinking pitch a factor of 2 not practical for large region – 30 micro-strip in 22.5 μm region
  => Buried wiring then desirable

Where we would eventually be heading:



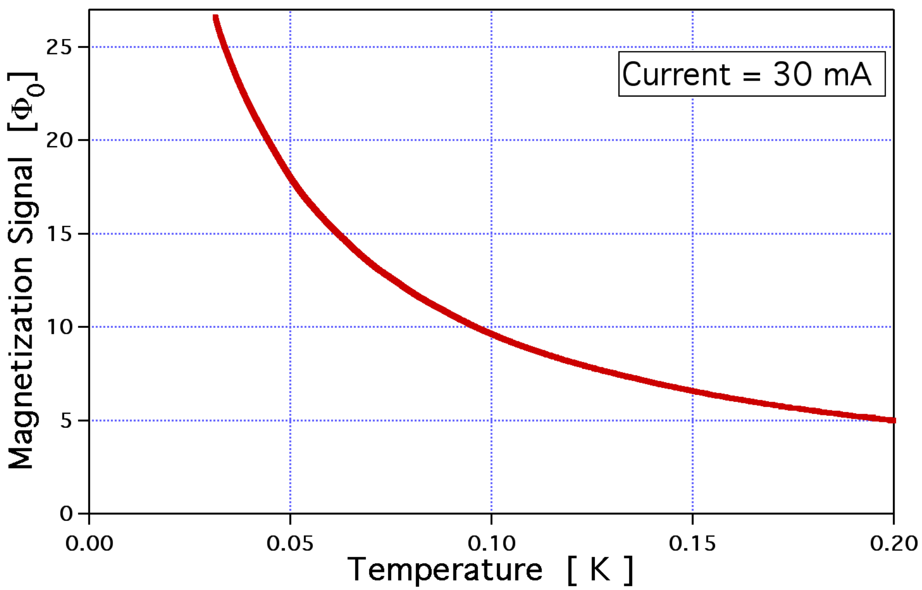
Metallic Magnetic Calorimeters (MMC)



Paramagnetic sensor: Au:Er

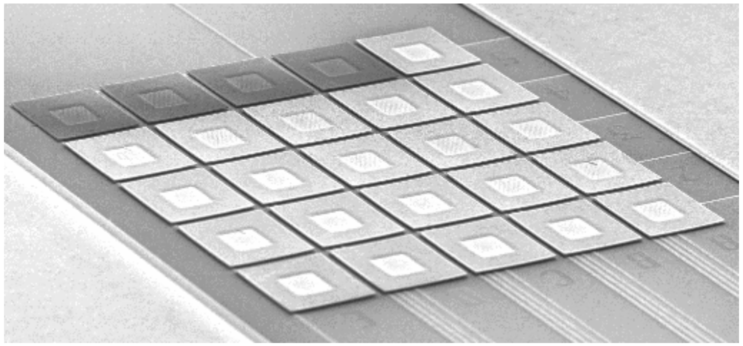
$$M \propto \frac{1}{T}$$

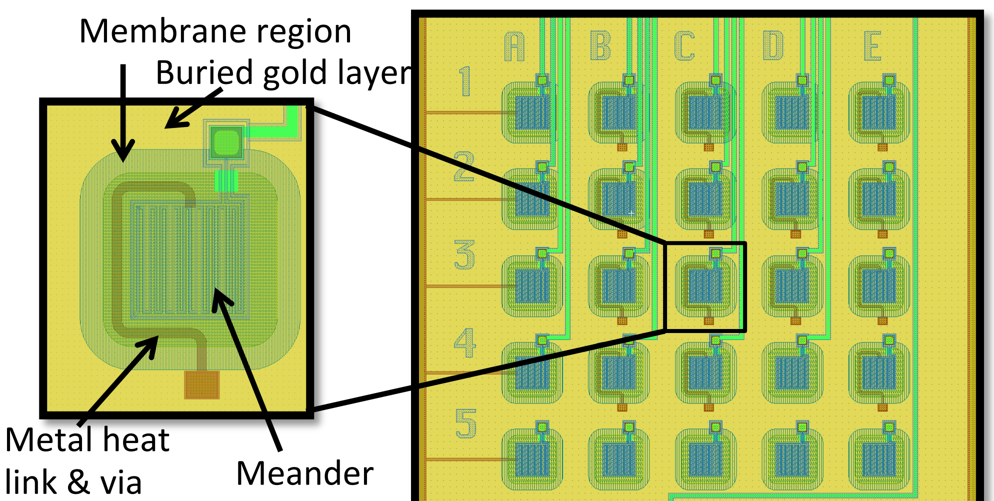
$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{\delta E}{C}$$



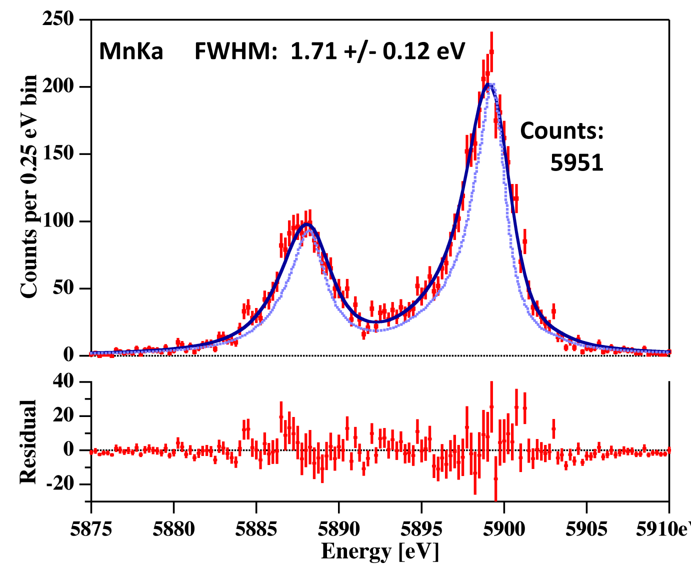
- No heat dissipated in the sensor
- No electrical Johnson noise
- Performance properties based upon equilibrium thermodynamics

Magnetic Calorimeter results:





Best performance observed in 0.25 mm pixels:



MagCal “hydras” also demonstrated and under development for Lynx.

- $T \approx 32$ mK
- $I_f = 35$ mA
- Absorbers 250 x 250 x 3 μm – all gold
- Very linear detector

TESs versus MagCals – each has it's advantages

MMCs:

- Potentially better energy resolution for any given pixel absorber properties
- Very good linearity and well-behaved curvature versus energy, with almost no sensitivity to external magnetic field
  (=> good for calibration accuracy, uniformity etc.)
- No heat dissipated within array, making thermal management within large arrays easier
- No electrical connection between sensor and read-out
  - Can allow design of metallic thermal link to heat bath
    (which is easier to control)
- Read-out is more demanding – likely requires an additional parametric amplifier per read-out channel

TESs

- Easier to read out
- Higher TRL
- TES transition properties are complicated, and somewhat difficult to control
  - Uniformity and calibration could be more difficult

What are the tallest poles for making larger microcalorimeter instruments such as are desired for Lynx?

1. Being able to read out the large number of TESs within the constraints of cryogenics, complexity, compatibility with space-flight. Hydras => very high slew rates.

2. Complexity of fabricating arrays with sufficient number of pixels, good enough energy resolution, small enough pitch, sufficient heat-sinking, and reliable wiring to amplifiers.

3. Heat load from wiring and heat generated by read-out – such as from SQUIDs and HEMTs.

4. Being able to discriminate X-ray events in many-absorber Hydras down to very low energies.

5. Ease of calibration.

6. How to make sufficient contacts between detector chip & low-temperature read-out with sufficiently low cross-talk?
    - Wire-bonding – becomes inconvenient when numbers become large
    - Bump bonding – reworkability is an issue
    - Flex designs, coax designs

7. Flight qualified room temperature electronics for Lynx-scale array.
    - Power load/cost from large number of electronics channels

8. Complexity of FPA design, and integration of GHz technologies.

9. Pulse processing complexity / feasibility

10. Suspended mass at 50 mK – needs to be sufficiently small to keep frequency of first mechanical resonance low.

Read-out: CDM or microwave-SQUIDs for Lynx?

- If we assume "Hydra" approach, with ~ 25 absorbers per TES

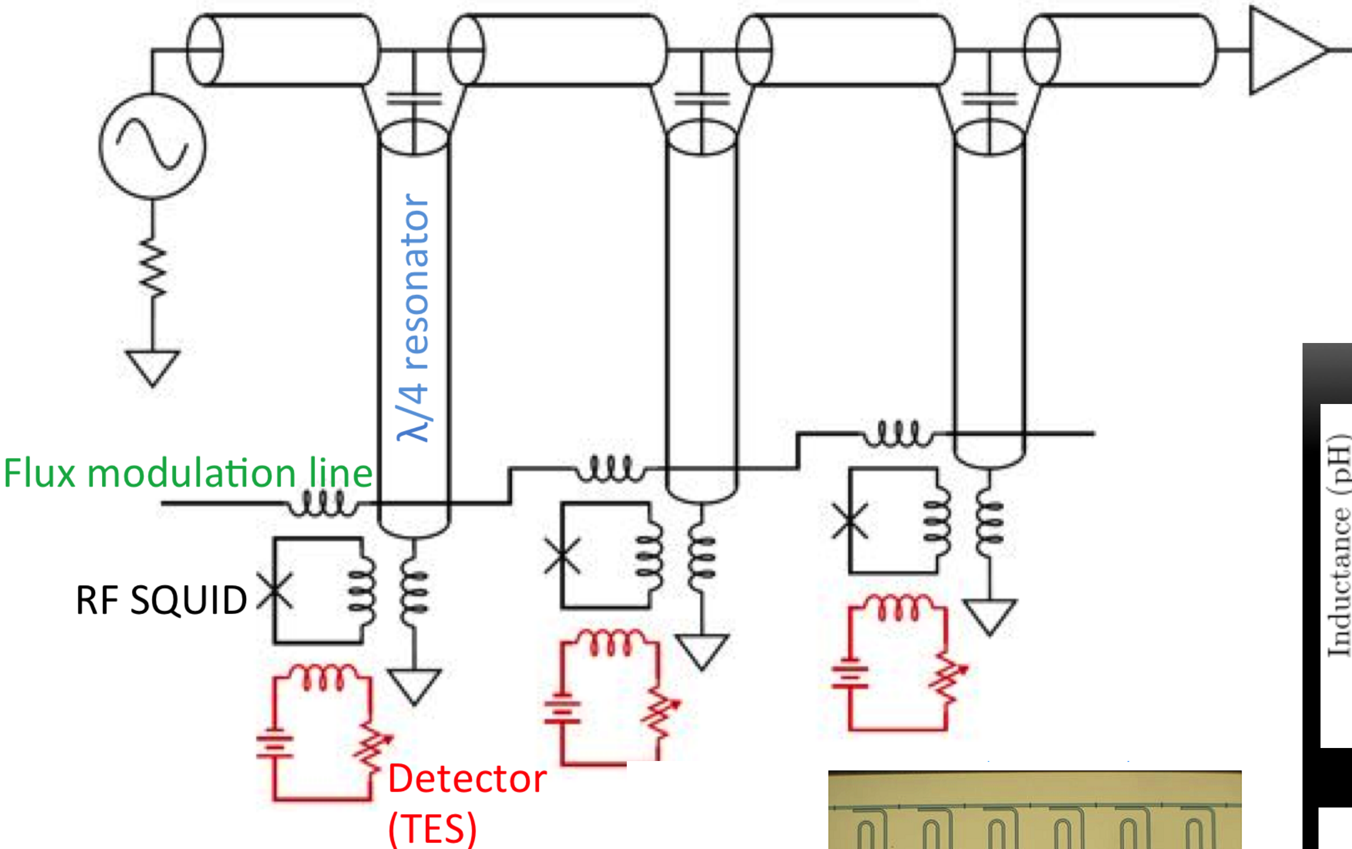
⇒ the number of sensors needed to be read out (~3600) is the same as is currently proposed for the X-ray Integral Field Unit instrument on Athena (~3840)

But, read-out of each TES hydra is *much harder* than each X-IFU single-pixel!

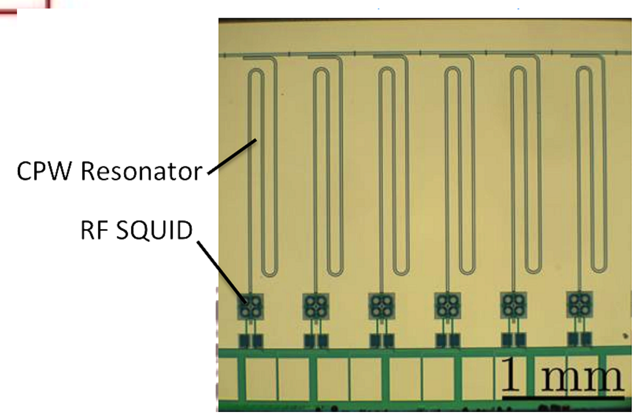
- Read-out properties will most likely drive the array capabilities

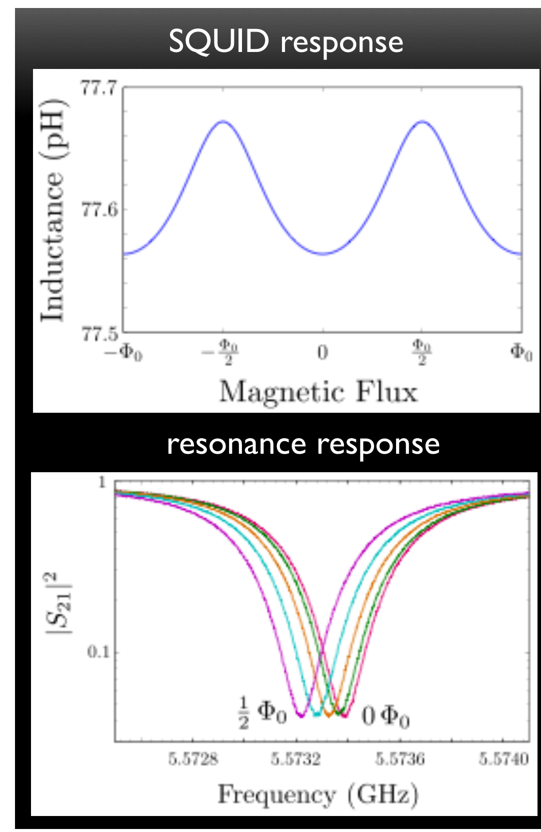
- Read-out ultimately limited by:
  - Cryogenics (larger, more expensive cryostats, with more cryocoolers, will have more cooling power)
  - Success of read-out R&D – still evolving
  - Complexity of focal plane design and packaging of wiring/cables
  - Mass of 50 mK that will need to be launched

Microwave (GHz) SQUID Resonators are advancing rapidly, have the most potential, and are ready to become baseline read-out for Lynx calorimeter



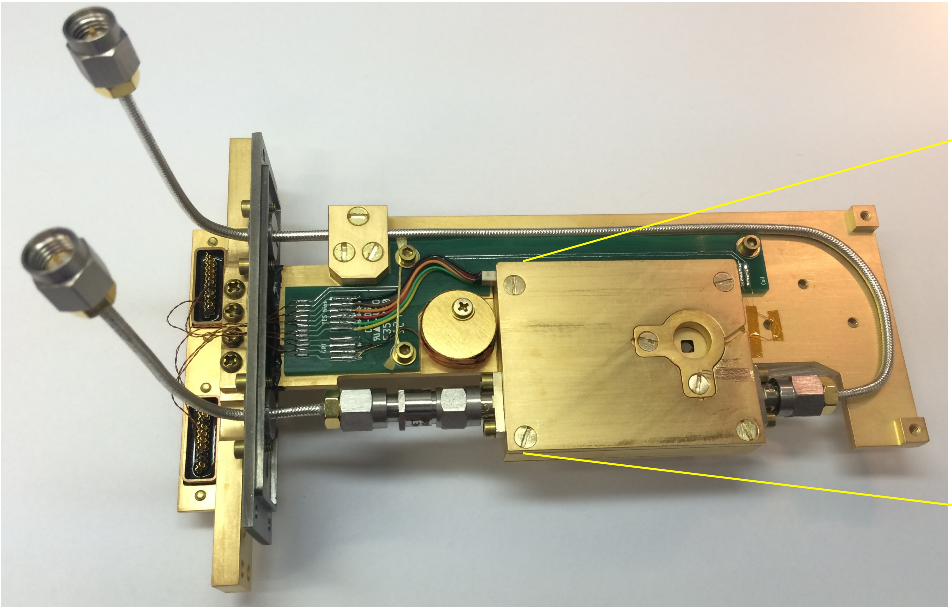
HEMT
amplifier
(High-electron-
mobility transistor)

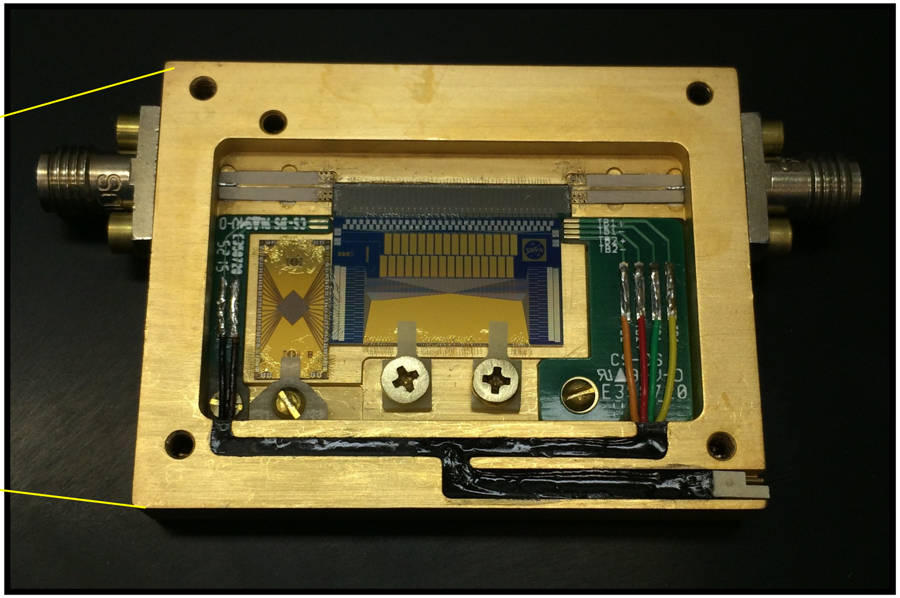




NIST- Boulder developing microwave-SQUID multiplexed read-out for TESs.

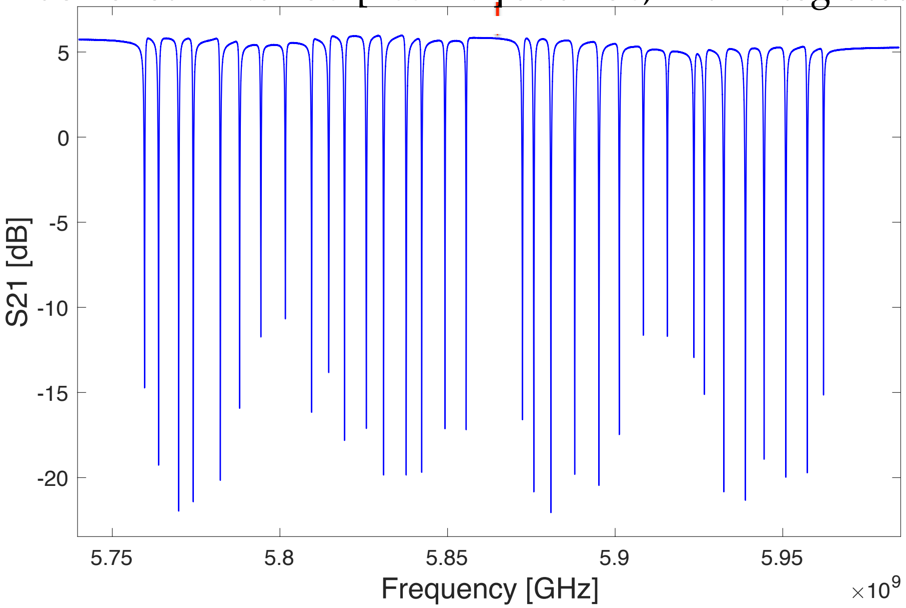
GSFC collaborating to demonstrate X-ray detectors reading TES & MCC microcalorimeter arrays

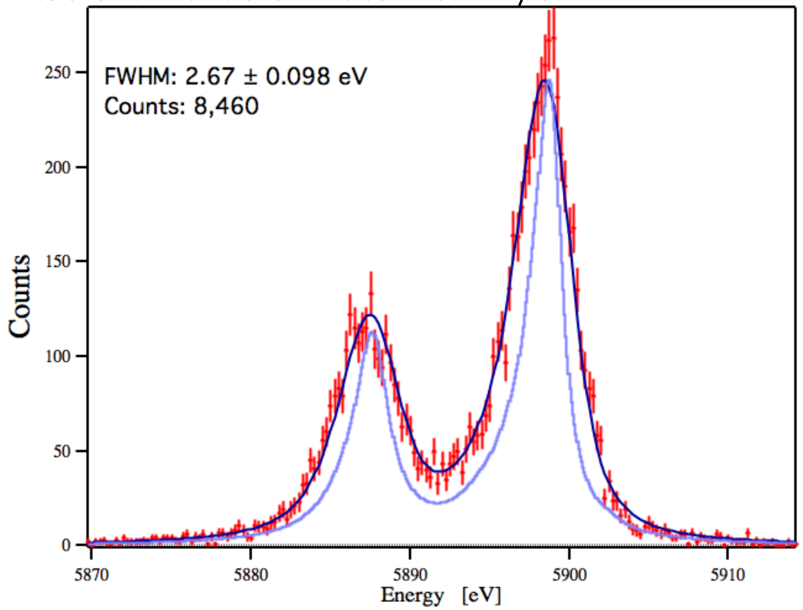




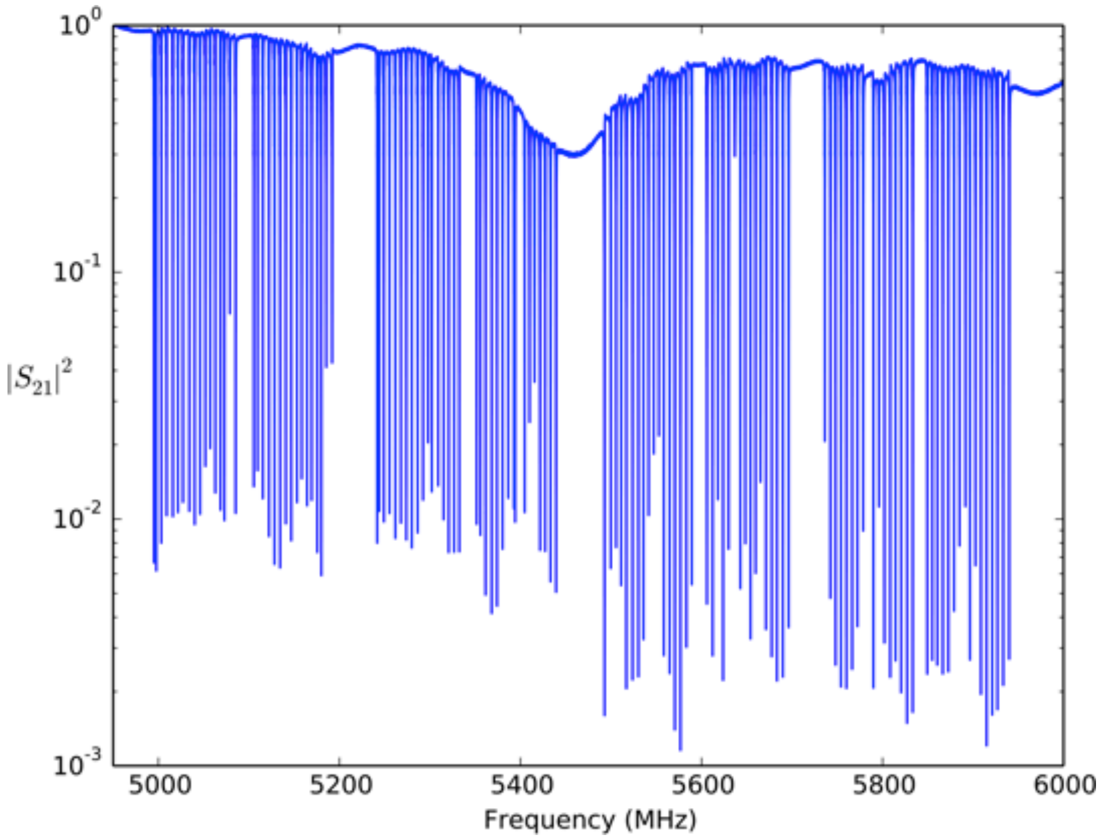
Measuring 32 TES multiplexed at GSFC through resonators spaced by 6 MHz, with frequencies around ~ 5.5 GHz

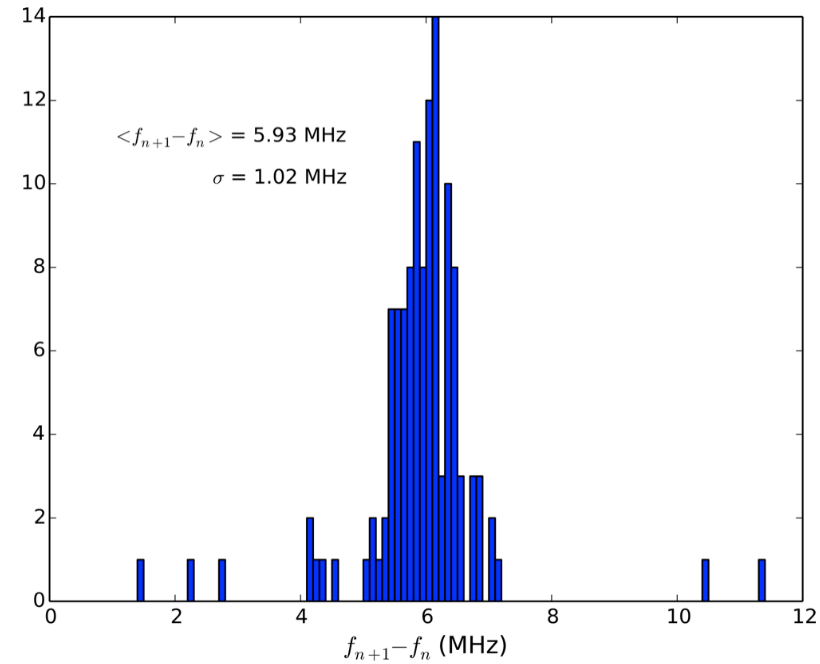
Now achieved ~ 2.67 eV [FWHM] at 6 keV, with integrated NEP= 2.58 eV. Max. slew rate ~ 0.4 A/s.





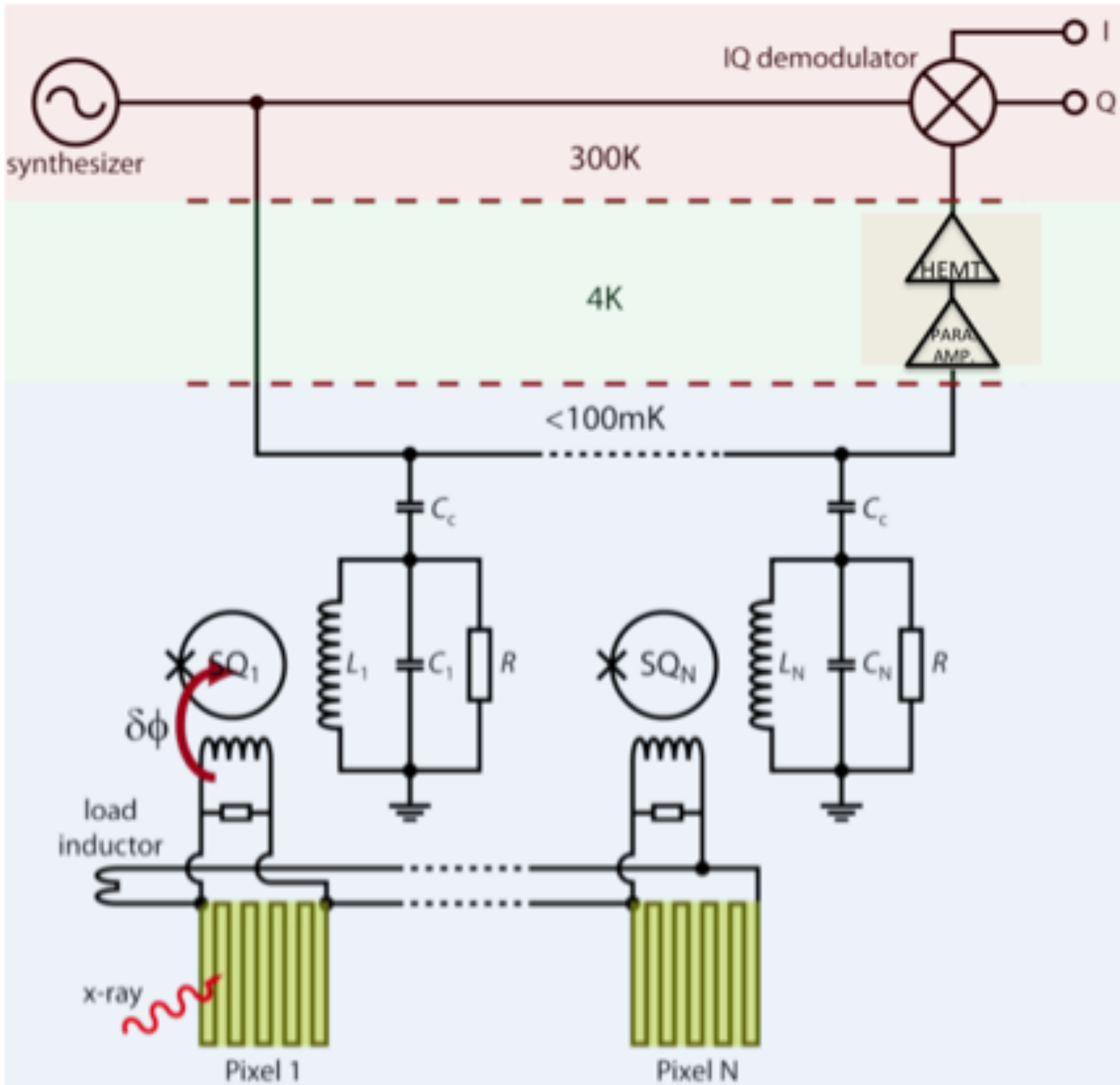
NIST: Use of 4 uwave multiplexer chips: a survey of the 4 bands of nominally 132 total resonances, with bandwidth suitable for microcalorimeters





Ben Mates, Doug Bennett, Joel Ullom, Dan Becker et al. (2017)

Magnetic calorimeters with microwave SQUID read-out



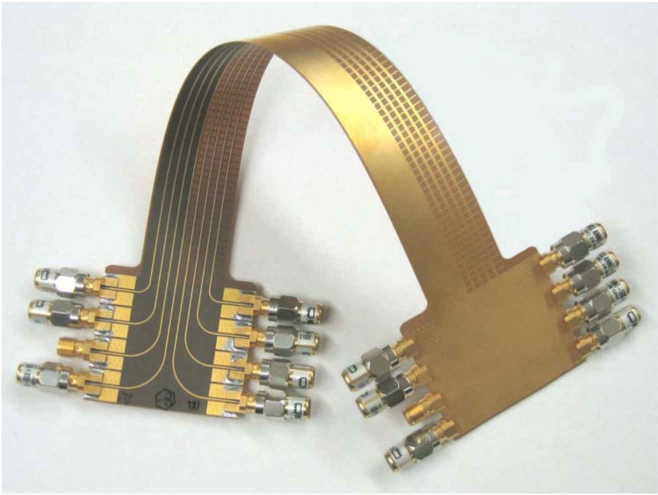
Read-out, in rough numbers:

- Baseline: 3600 TESs needed to be read out

- CDM option: ~ 100 channels reading out ~ 40 TESs each
  - similar to Athena except slew rates are much higher for hydras
  - Hydras require ~1-2 A/s slew rate and ~ 20 pA/rt Hz noise – challenging at 40 rows!

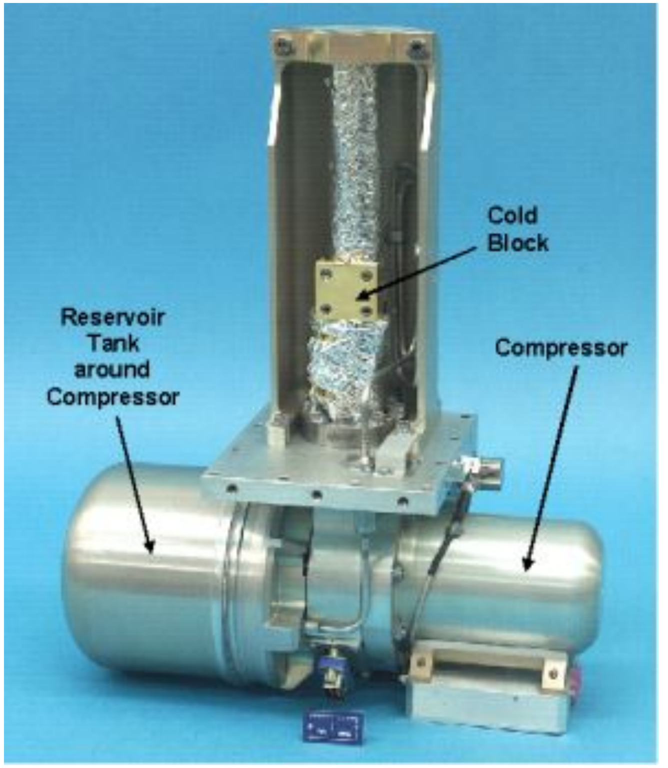
- Microwave SQUID option: ~ 10 channels reading out ~ 400 TESs each
  - Bandpass ~ 4-8 GHz => 4 GHz BW over 400 TES
    => 10 MHz resonator spacing
  - Hydras might require ~1-2 A/s slew rate and ~ 20 pA/rt Hz noise – challenging!
  – GSFC: 0.4 A/s at 6 MHz spacing, NIST: 3A/s at 18 MHz spacing

- For 5’ field-of-view with 0.5” pixels => 40 channels of microwave SQUIDs.
  - 80 coax lines – a lot – new flex technologies needed at low temperatures.



What about power from ~ 10channels of HEMTs at ~ 4K?

- State of the art 4.5 K coolers (JWST) provide ~ 50 mW of cooling power with single cooler
  - => 25 mW of cooling power available
  - => ~20 mW of cooling power available for
- If 4 mW/HEMT, then 40 mW for 10 traditional HEMT channels
  - – cooling at ~4 K is very demanding!
  - - multi-stage HEMTs (1st stage at 4K, next stages at 10-20 Kelvin) could dissipate lower power



Adiabatic Demagnetization Refrigerators - ADR's

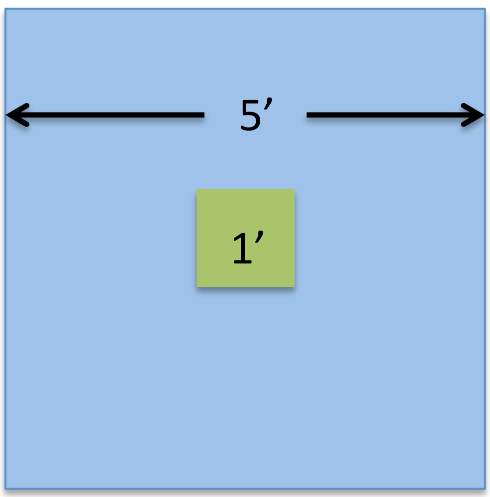
- Continuous ADRs will be capable of ~ 5 uW of cooling at 50 mK, with next heat-sink at 300 mK-2K.

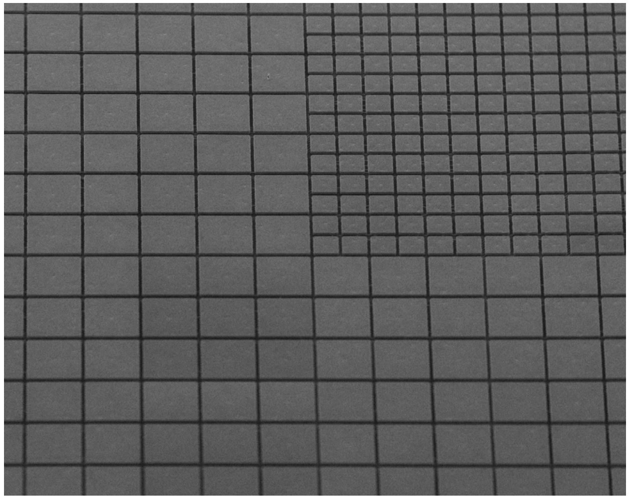
=> 2.5 uW available of cooling power at 50 mK
- needs further study, but should be sufficient

Trades: Pixel size

Angular resolution: 1" pixels or 0.5" pixels?

- 0.5" pixel sizes should be achievable – but not yet demonstrated.
- **Will there be sufficient number counts in 0.5" pixels to do spectroscopy, or will pixel counts simply be grouped anyway?**
- Is the only benefit due to removal of point sources? Is this sufficient to justify 0.5" pixels? Or would generally twice the field-of-view be more beneficial?
- Area fill factor drops as for smaller pixels. For 2 μm gaps, 1" pixels = 92%, 0.5"= 85%.
- Would a sub-region of smaller pixels be valuable?

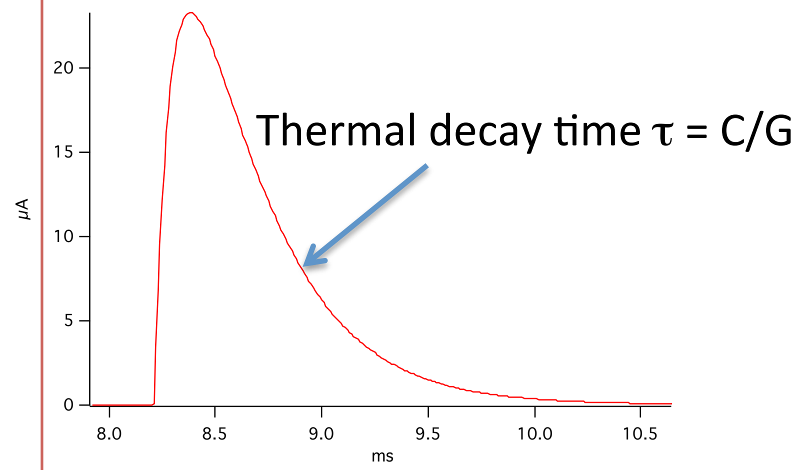




Note: Dithering can help angular resolution, up to angular resolution of X-ray optic, depending on the number of counts (observation time) and the back-ground.
- Requires simulation of various sources

Trades: Count rate

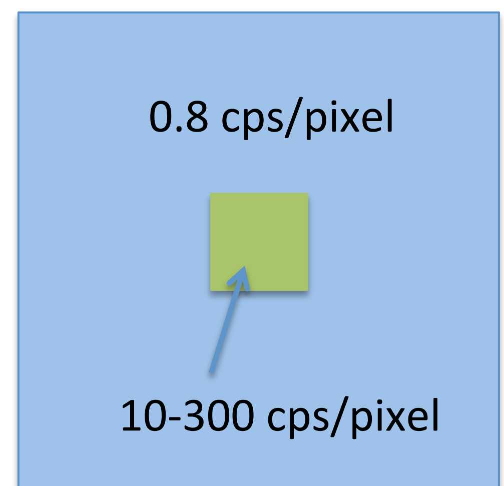
- G is the thermal conductance of pixels (hydras) to the heat bath
- G determines the decay times.
- C.R. approximately proportional to G.
- Rise-time required for hydra discrimination scales with decay time (complicated).
- Slew rate is proportional to $G^{1.5}$ for TESs.
  => halving the count rate requirement reduces the slew rate (b.w.) required by a factor of 2.8 for TESs



- 20 counts/second/hydra currently assumed
  - with 80% throughput for high resolution events (other 20% medium/low res.)

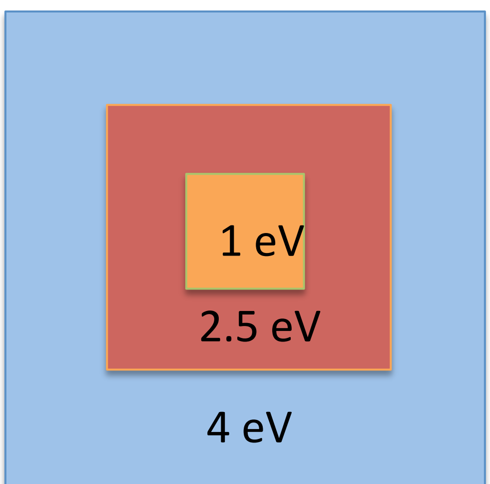
  => ~ 0.1 - 0.2 mCrab for the uniform array (depends on final area of optic) sufficient to image most of the brightest known extended X-ray sources.

- Do we need this count rate capability? Higher? Lower?
- What fraction of observations does this represent?
- Would a neutral density filter and longer observation time for few higher count rate sources be a better trade?
- Is a sub-region for point/small sources with higher count capability desirable (right)?



Trades: Energy resolution

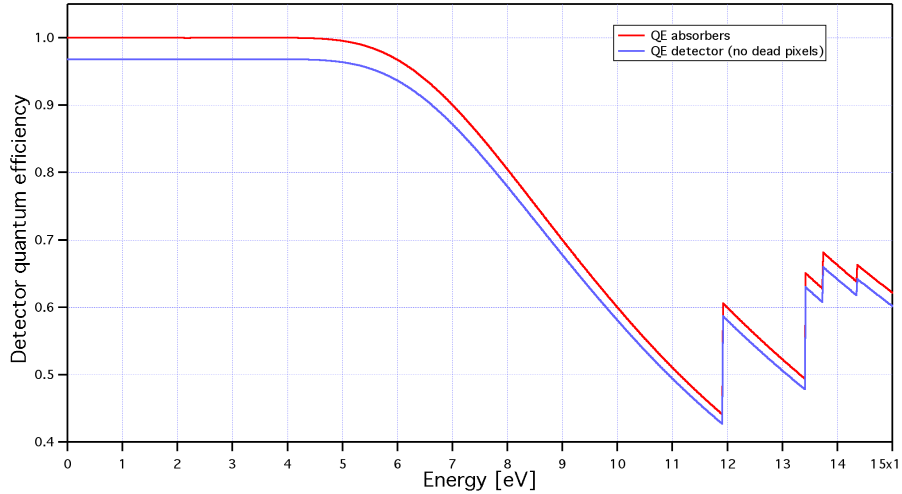
- For an NxN hydra of pixels of size LxL, energy resolution scales approximately as L x N
- ~ 3 eV should be possible with N=5 hydra, and L=50 μm
- ~ 1 eV is possible when N x L < 100 μm – i.e. smaller pixels, fewer absorbers in hydra
- ~0.5 eV should be possible when N x L < 50 μm.
- X-ray QE depends on absorber thickness t. Energy resolution varies as $t^{0.5}$.
- Caution 1: Energy range for best energy resolution [linear response] typically decreases as pixel size decreases (scaling complicated).



Caution 2:
Generally instruments need margins on energy resolution requirements
- 1.5 eV requirement might need a 1 eV detector design
- Athena X-IFU: a 2 eV detector needed for a 2.5 eV requirement

Trades: Energy range

Energy resolution versus energy range ……….



- Mirror effective area and microcalorimeter quantum efficiency drops above 7 keV

- Energy range of TESs and MMCs will most likely be limited by maximum slew rate

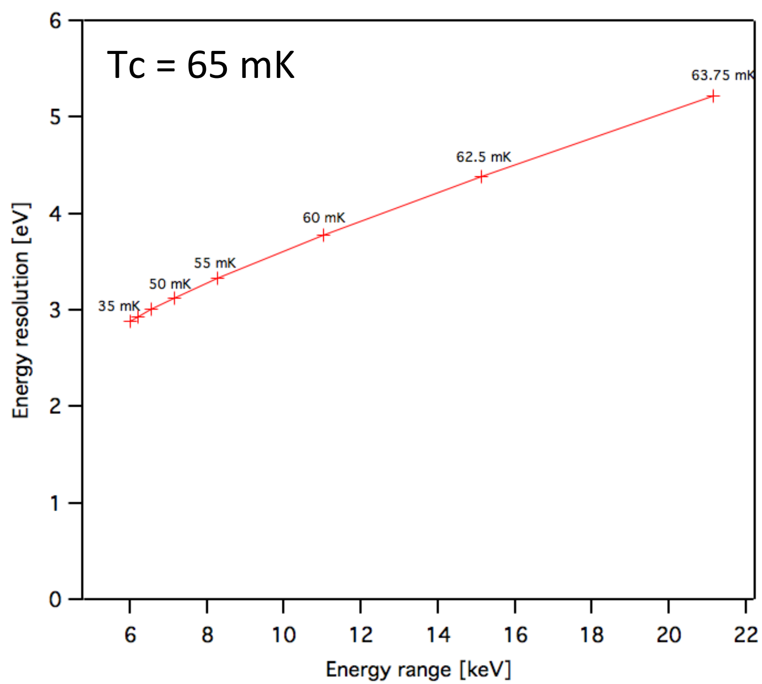
  [Without read-out considerations, energy range of MMCs much larger than TESs]

- Energy range of TESs can always be extended by lowering slew rate, by operating heat-sink temperature closer to Tc and operating with a lower bias current.

- Energy range of MMCs can always be extended by operating with lower fields or by operating at higher temperatures.

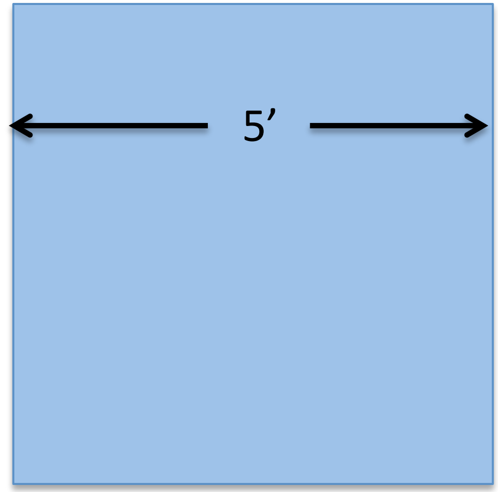
- In either case, this will causes degradation in energy resolution and make calibration of different modes more complicated.

- Right is an illustrative example of how the energy resolution might vary as a function of energy range, by increasing the bath temperature.



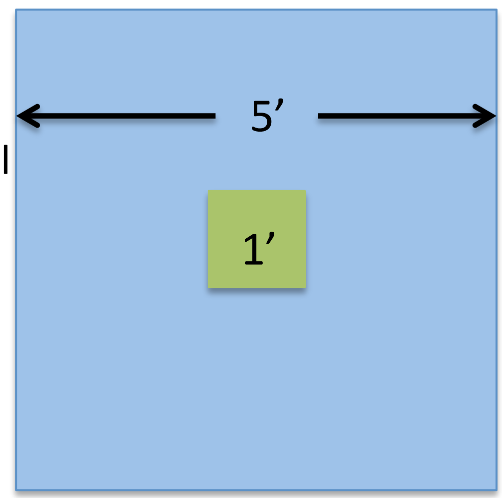
Examples of options for Focal plane designs

Option 1. Baseline
Easiest option



- 5′ FOV
- 1″ pixels
- FWHM: 5 eV [3 eV]
- 0.8 cps/pixel

Option 2. 12% more pixels
Up to (x4) S.R. increase per pixel
=> 48% harder to read out



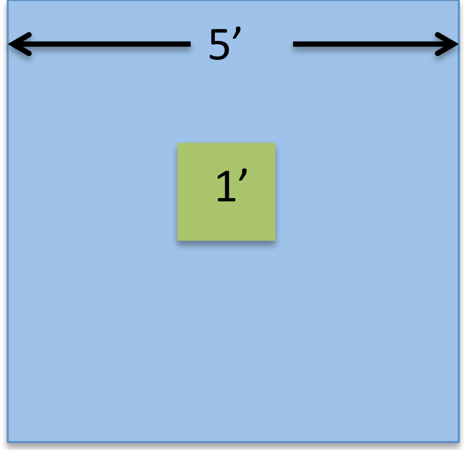
- 5′ FOV
- 1″ pixels in outer region
- 0.5″ pixels inner 1′ region
- FWHM: 3 eV in outer region
- FWHM: 1.5 eV in inner region
- 0.8 cps/pixel

Option 3. All 0.5″ pixels: 4 times as many pixels
⇒ Up to 16 times harder to read out
- could make easier (to ~4 times harder to read out) by degrading FWHM (1.5 eV - > ~2.5 eV)
– more complicated trade keeping S.R. constant

Examples -continued

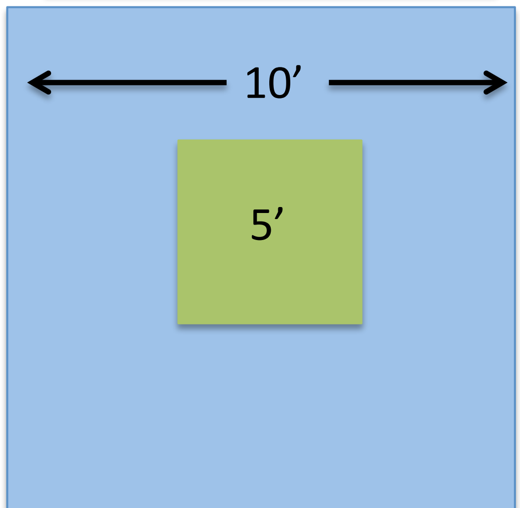
Option 4. 80% harder
to read-out

High energy response (>2 keV)
with degraded energy resolution



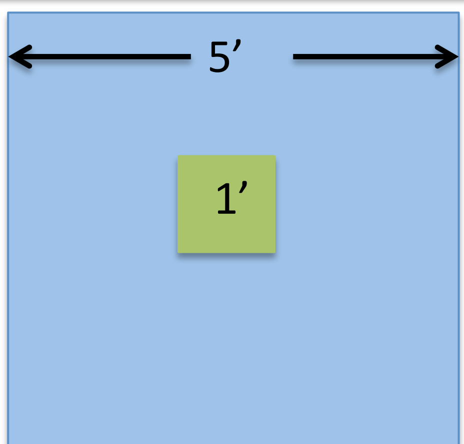
- Same as option 2 except 3x3 hydras of 0.5” pixels in inner 1′
- FWHM: ~1 eV in inner 1′

Option 5. 27% harder
to read-out



- 10′ FOV
- 2” pixels in outer 10′ region (1 μm gold)
- 1” pixels inner 5′ region (4 μm gold)
- FWHM: 3 eV in outer region up to 2 keV
- FWHM: 3 eV in inner region up to 6 keV
- 0.8 cps/pixel in inner region
- 0.4 cps/pixel in outer region

Option 6.
High count rate core
44 times harder
to read-out!

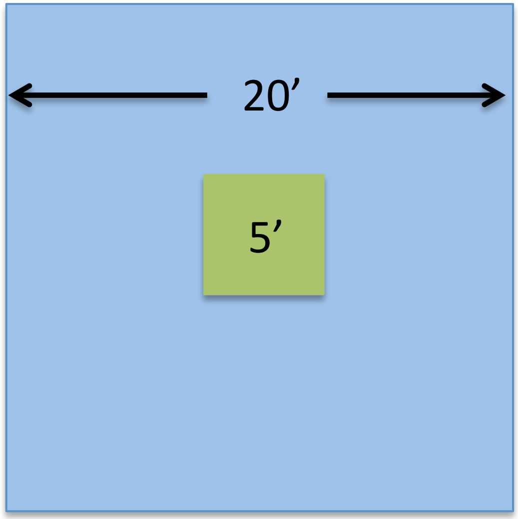


- 5′ FOV
- 1” pixels in outer region
- 1” pixels inner 1′ region – no hydra
- FWHM: 3 eV in outer region
- FWHM: ~2 eV in inner region
- 0.8 cps/pixel – outer region
- 10 cps/pixel – inner region

Examples -continued

Option 7(a).
The “Joel dream version”
63% harder to read-out

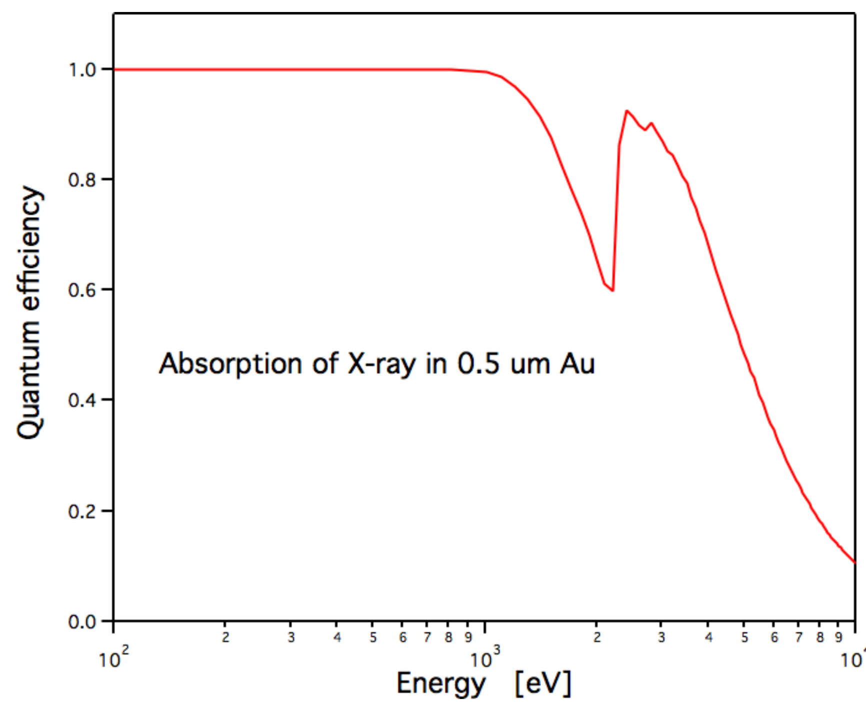
Compromise 7(b):
12.5% harder for 10’ outer region



- 20’ FOV
- 5” pixels in outer 10’ region (0.5 μm gold)
- 1” pixels inner 5’ region (4 μm gold)
- FWHM: ~1 eV in outer region up to 2 keV
  - Pixel size is 250 um x 250 um x 0.5 μm
- FWHM: 3 eV in inner region up to 6 keV
- 20 cps/hydra in inner region
- 5 cps/5” pixel in outer region

Additional read-out:
x15 (area) /8 (C.R.) /3 (Energy range)
= 0.63

But:
- need to develop new (very slow) pixel design (requires membranes)
  – very different research effort!
- compatibility within hybrid array, high density wiring within frames/muntins
- larger FOV will require larger filters (harder)
- larger number of resonators more closely packed (better frequency spacing control), lower bandwidth (being developed for IR)
- more connections (bump bonds) from detector array to read-out
- Thermal management within array much more complicated
- Large size of array could drive required fabrication effort to 6” wafers, and larger (heavier) focal plane assembly



Concluding slide: What are the most important science drivers for Lynx X-ray microcalorimeter?

- Which observations are the most important to model to determine requirements?

=> Which detector properties do we need to focus on over the next 2 years to sufficiently improve TRL for 2020 Decadal survey?

Is the following order the correct order of priority?

1. Smaller pixel pitch closer to ~ 0.5”
   – at least in some sub-region of 0.5 – 1’,
   - preferably in whole array but less needed in out regions

2. Better energy resolution
   - Making the smaller pitch Hydras will likely improve the energy resolution.

3. Improvement in filter throughput at low energies (0.1 – 1 keV) – to better see X-rays from the high red-shift Universe.
   - not willing to sacrifice area/response 1-10 keV.
   - F-number of telescope is ~ 3.3

4. Increasing the field of view

5. Increasing dynamic range from ~ 10 keV to ~ 15 keV or higher.

6. Being able to accommodate higher count rates than currently assumed.

Backup

10) Modeled 20 pixel hydra for lynx

- L = 200nH
- 6 keV, dI/dt = 5.4, 1.2, 0.80, 0.59 A/s (1st 4 pixels)
    - But assume first pixel is removed, and its heat capacity added to TES sensor
- Trade-off needs to be studied when noise model fully implemented.