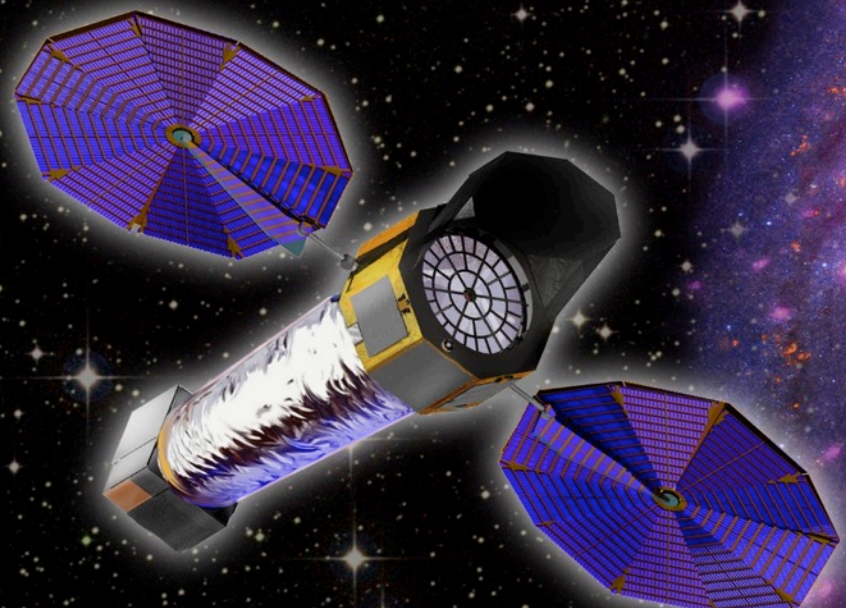
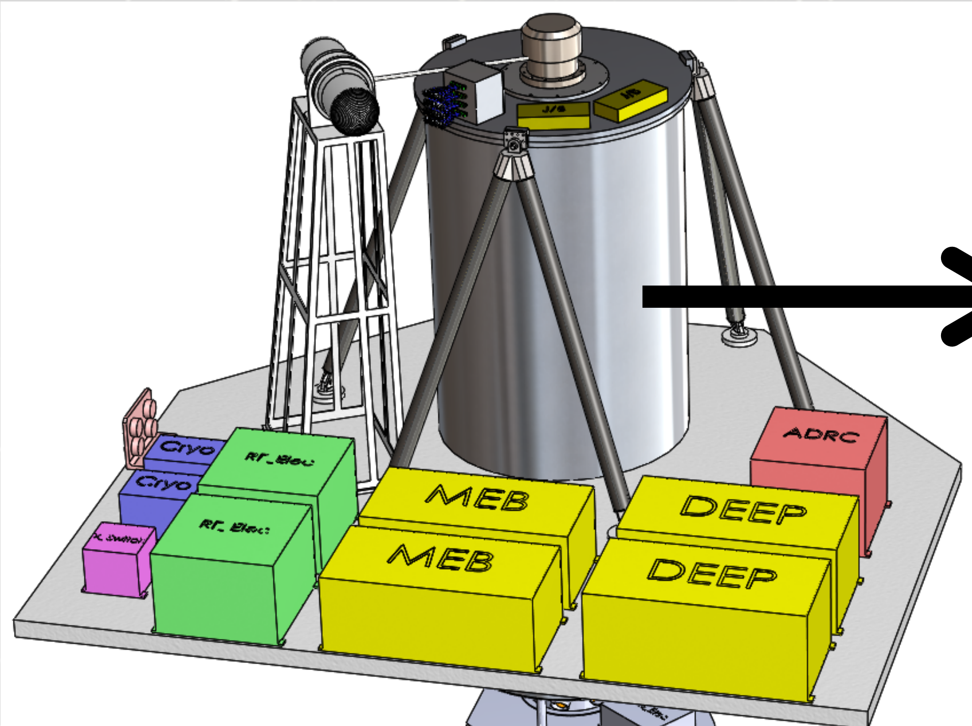
The Design of the Lynx X-ray Microcalorimeter (LXM)

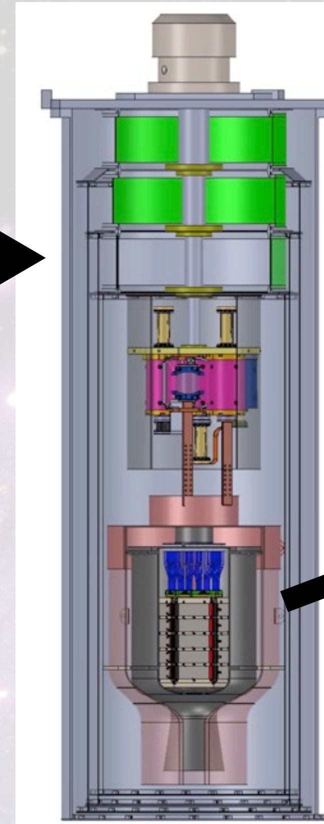
Simon Bandler, NASA/Goddard Space Flight Center

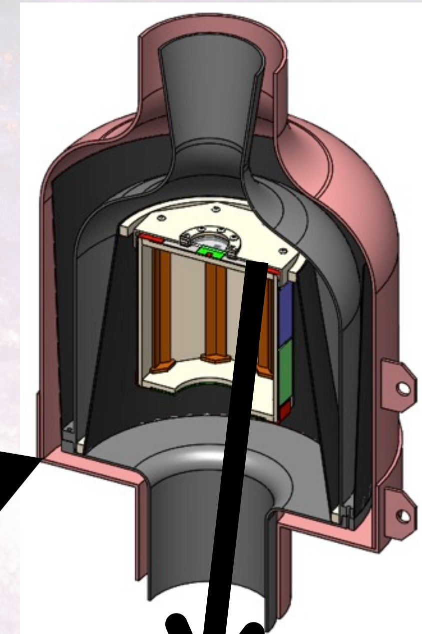
– on behalf of the LXM sub-group of the Lynx instrument working group

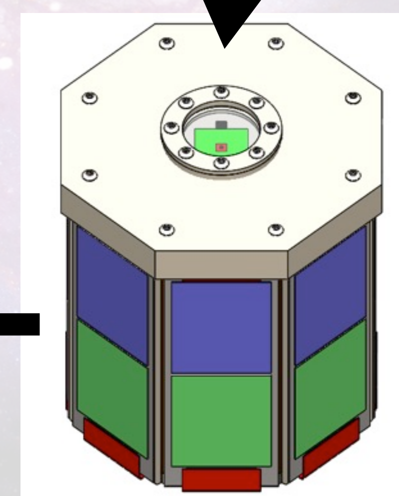


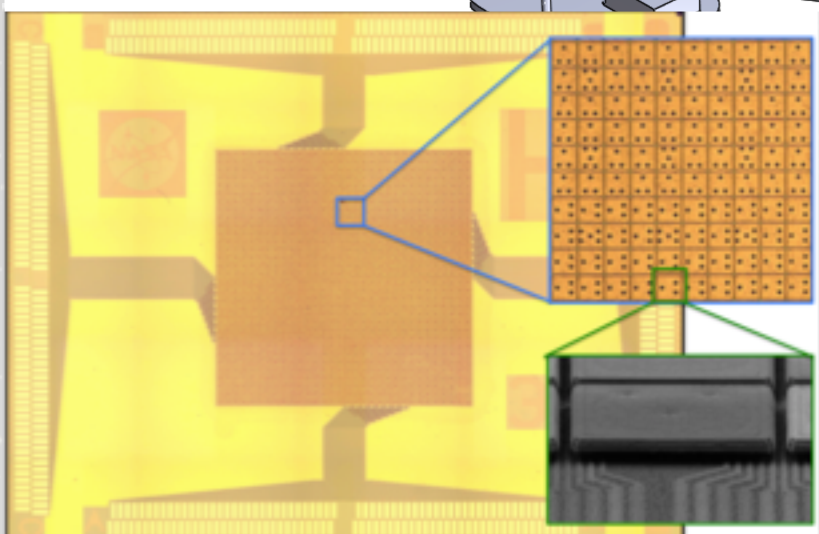
Lynx X-ray Microcalorimeter





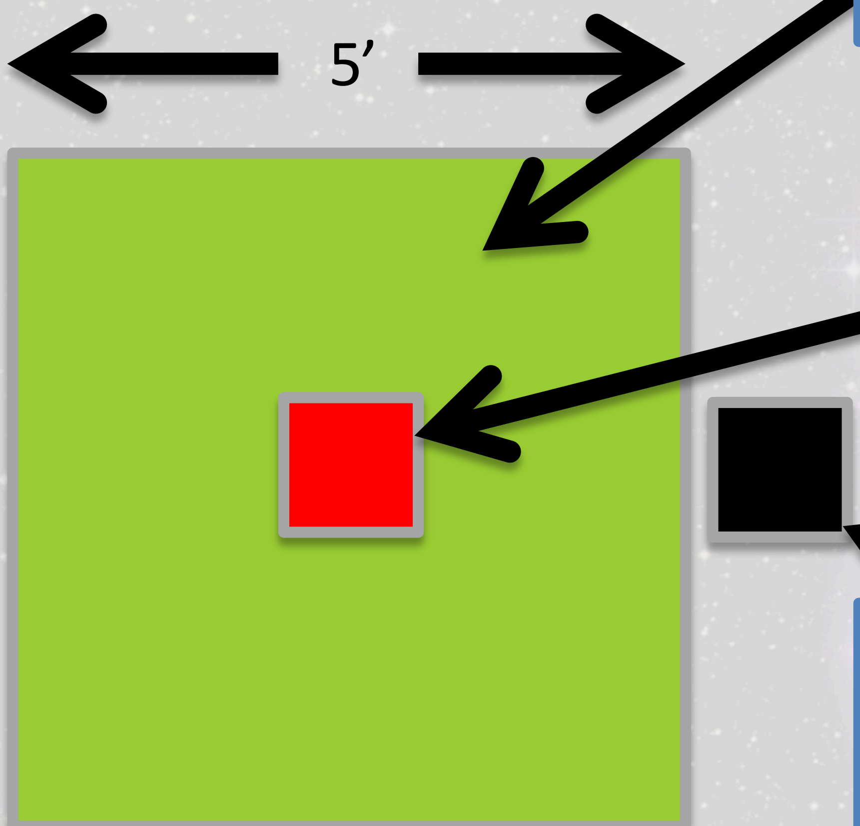






~ 100,000 pixels!

LXM Focal Plane Layout



Main Array
- 1” pixels, 5’ FOV, 50 μm pixels, hydra-25
- ΔE = 3 eV
- Up to 7 keV
- 86,400 pixels

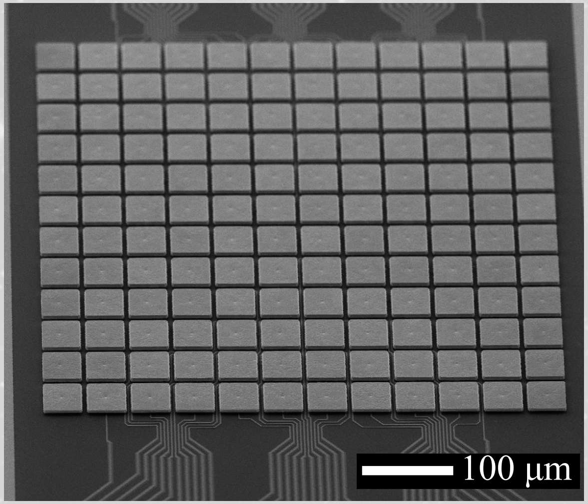
Enhanced Main Array:
- 0.5” pixels, 1’ FOV, 25 μm pixels, hydra-25
- ΔE = 2.0 eV
- Up to 7 keV
- 12,800 pixels

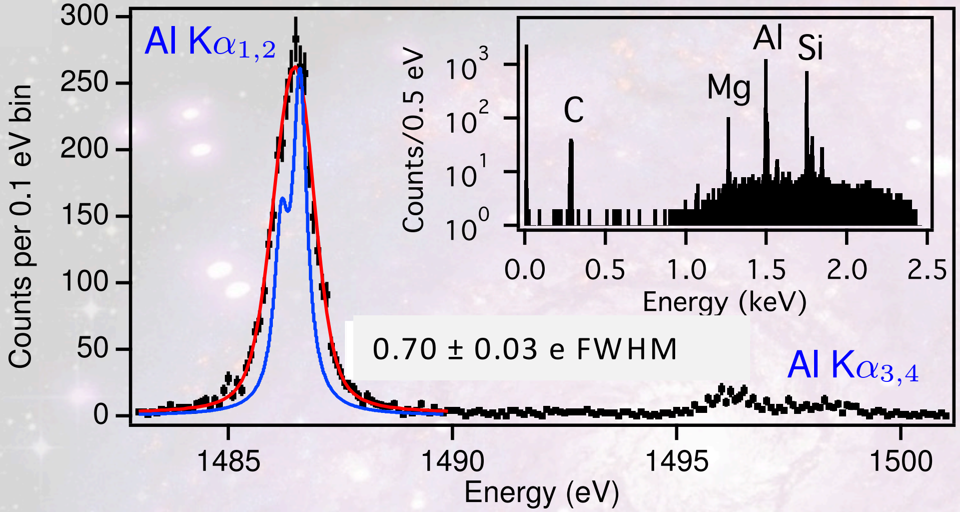
Ultra-Hi-Res Array
- 1” pixels, 1’ FOV, 50 μm single pixels
- ΔE = 0.4 eV
- Up to 0.8 keV
- 3,600 pixels

- *Study of metallicity in galaxy clusters to z=3 as probe of galaxy formation processes near peak of cosmic star formation*
- *Determine effects of AGN energy feedback on ISM & determine physical state of gas near SMBH sphere of influence in nearby galaxies*
- *Study of plasma physics effects related to dissipation of energy from AGN outflows.*
- *Will spatially & spectrally resolve starburst-driven winds in low-redshift galaxies*

Ultra-Hi-Res Array Development

Gold absorber: 45 μm x 45 μm x 4.2 μm, $T_c \approx$ 60 mK under bias

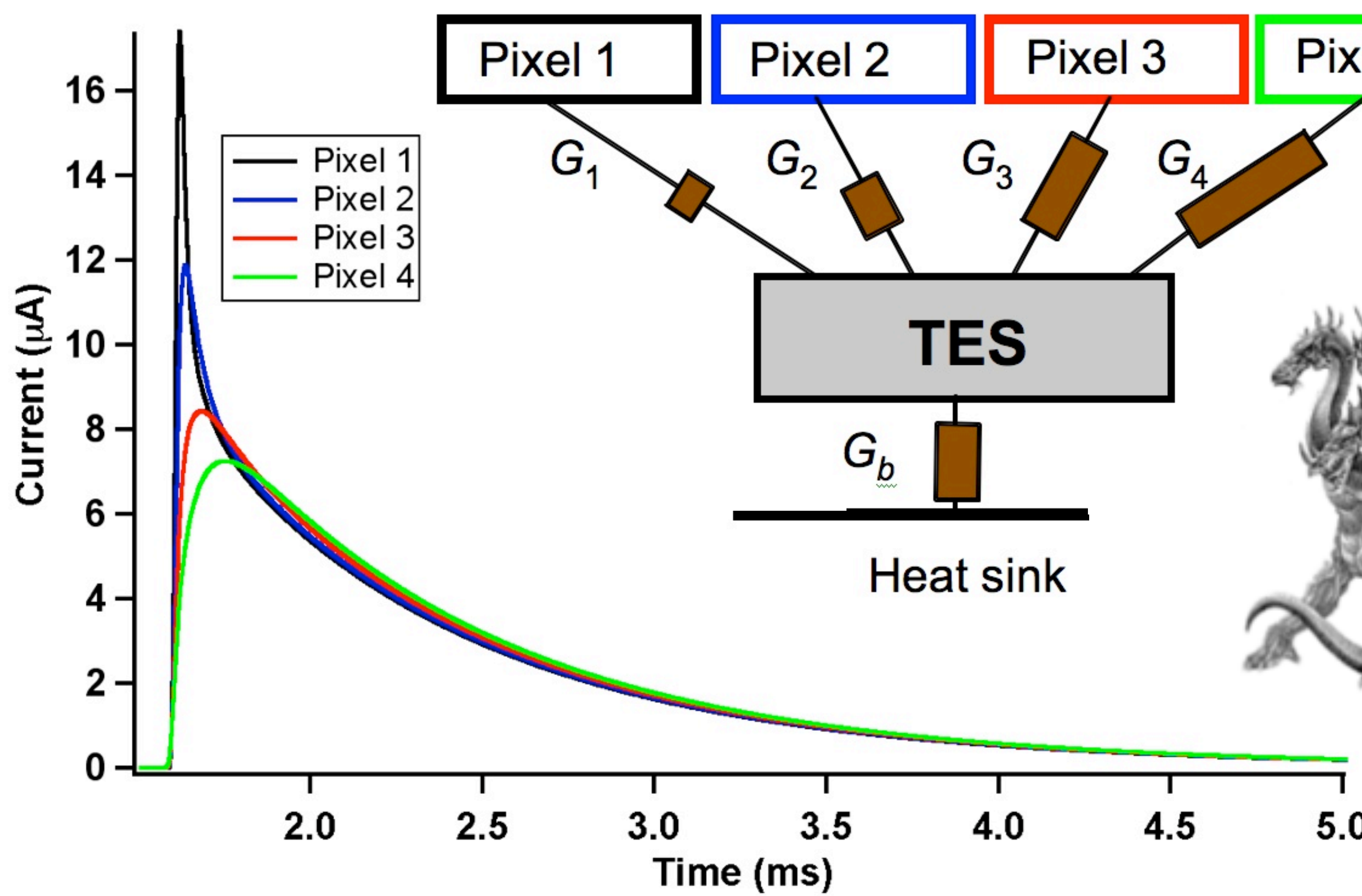




- Energy resolution = 0.70 eV [FWHM] at 1.5 keV
- Best achievable resolution at low energies with this design ~ 0.4 eV
- *S.-J. Lee et al.,* Appl. Phys. Lett. **107**, 223503 (2015)
- For Ultra Hi-Res array, absorber 4 times thinner = > 2 times better energy resolution.

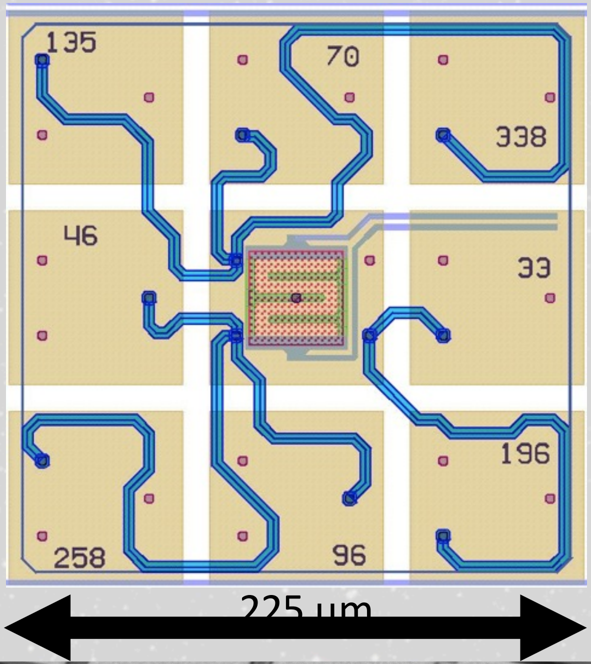
=> < 0.4 eV possible

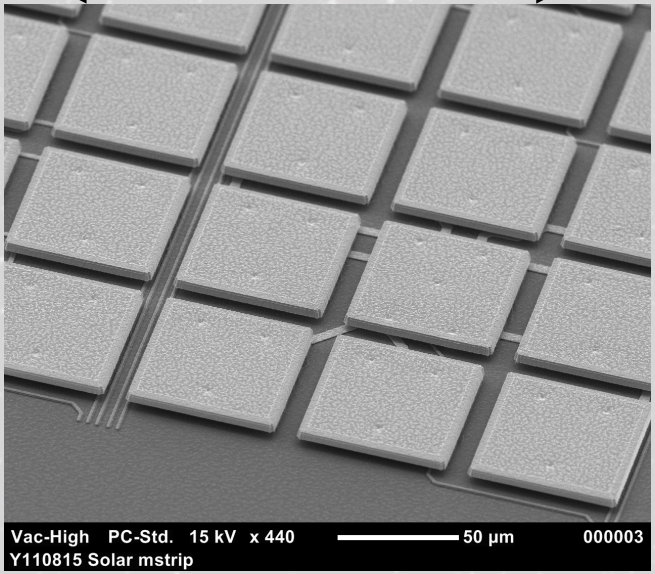
Multi Absorber TES "Hydras" - 1 TES, 4 absorbers

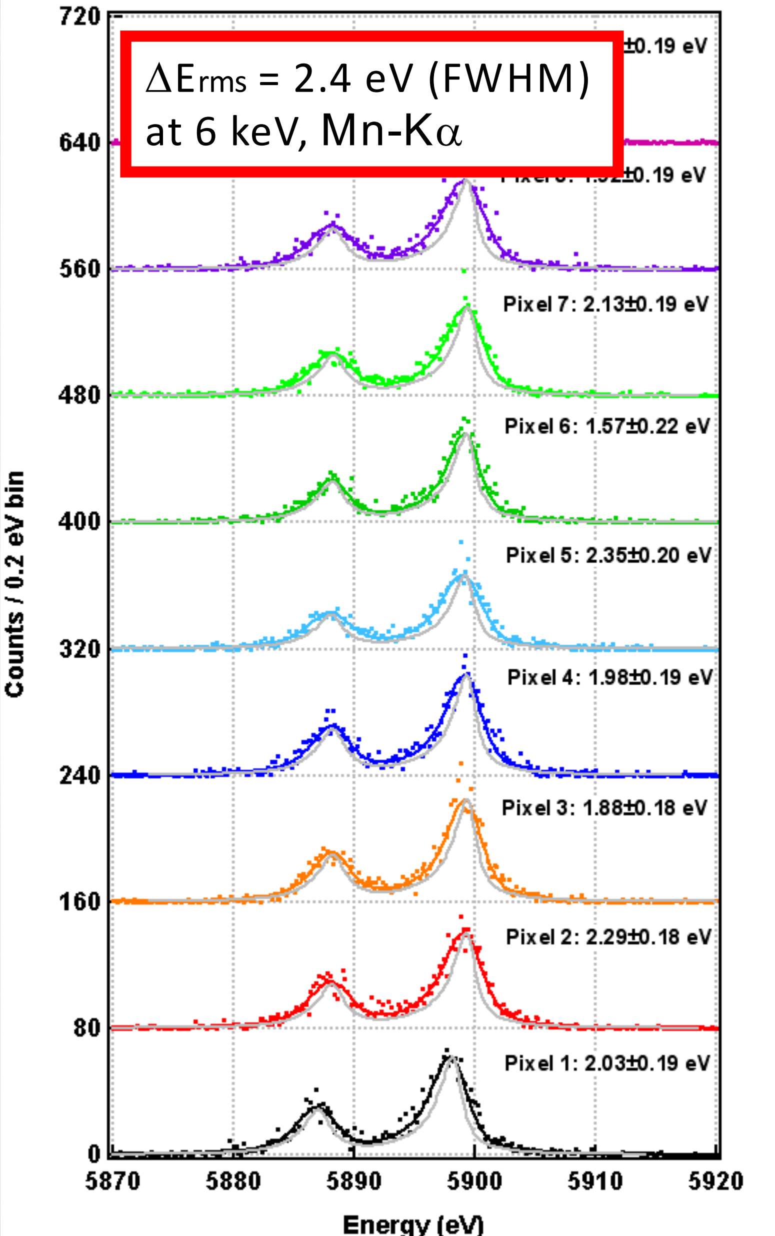


Also works with MCCs

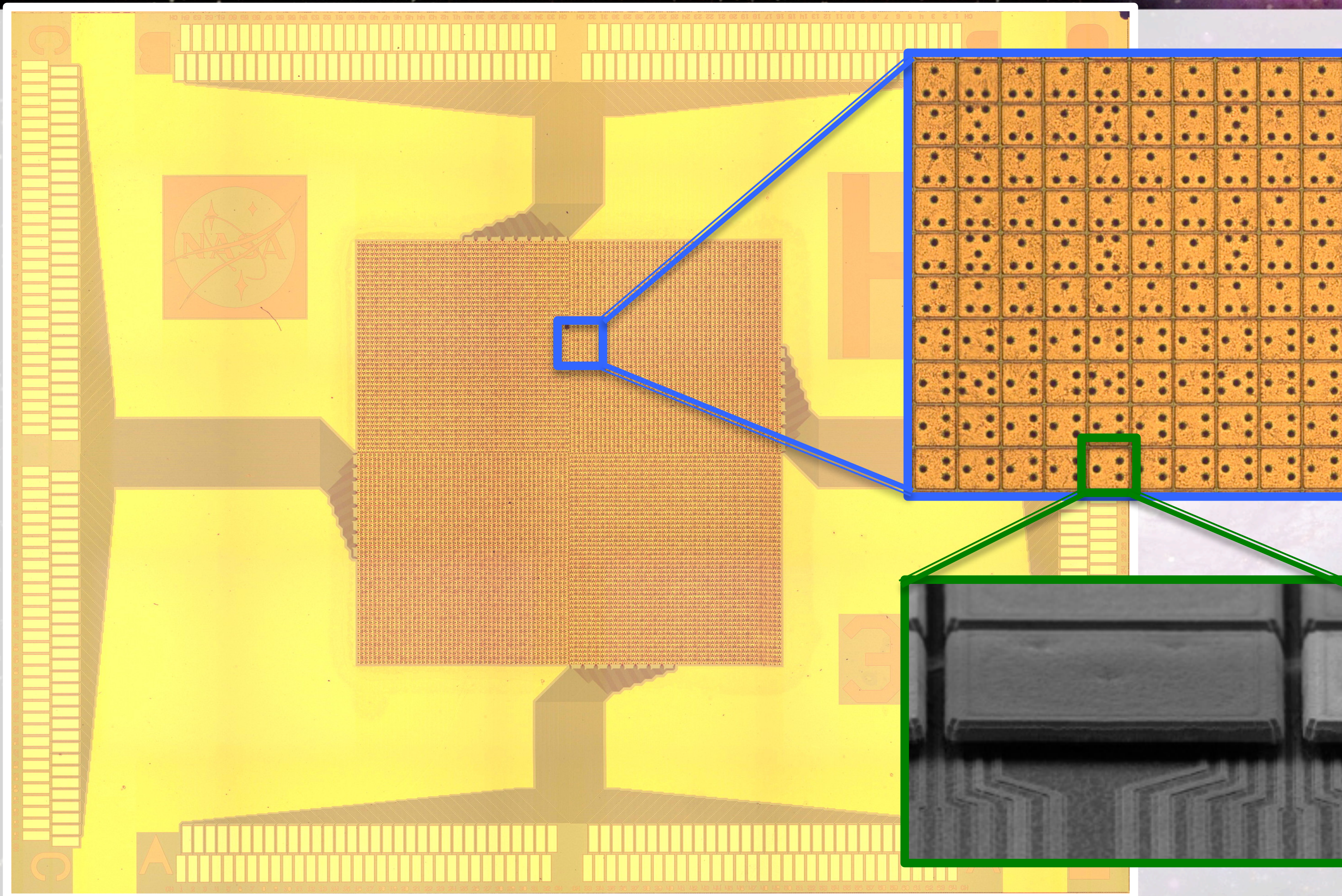
Hydras with 3x3 array of 65 μm absorbers, 5.0 μm thick







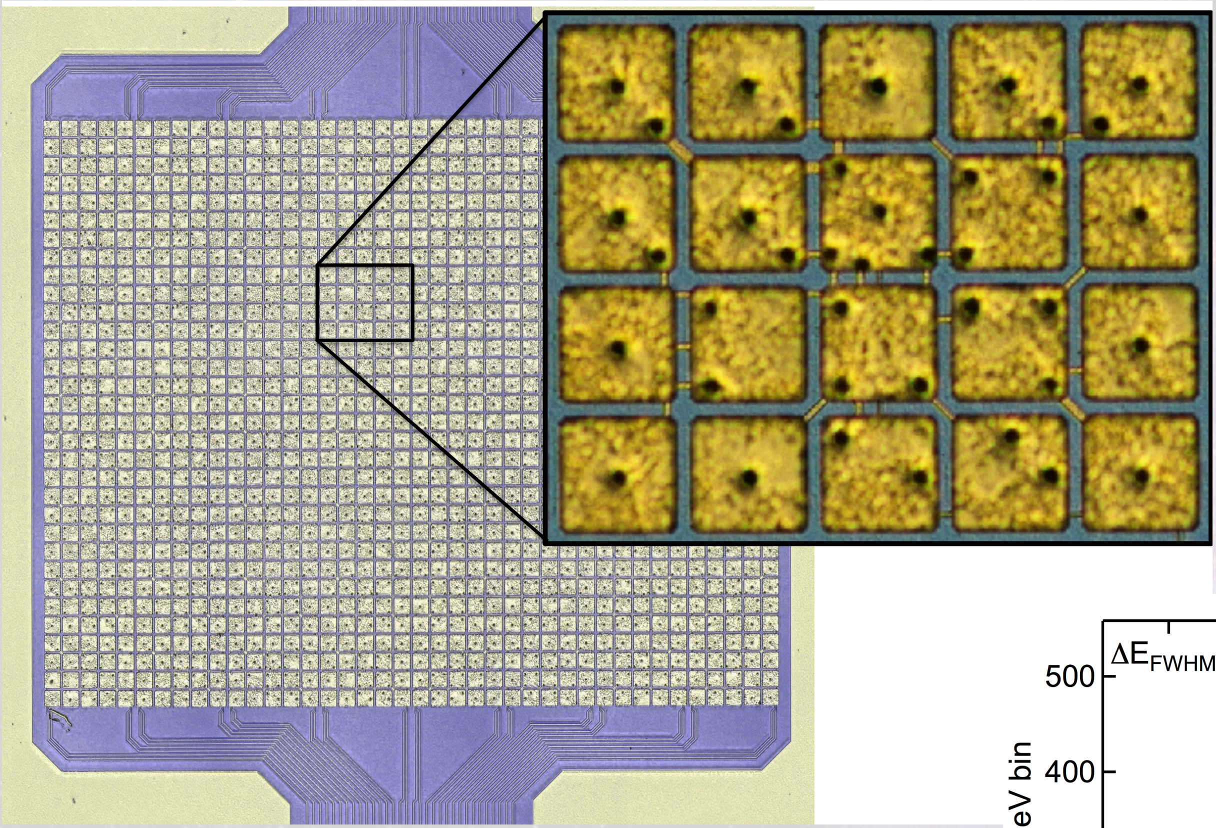
Main Array Development: 10 Kilo-pixel array fabricated with 3x3 hydras

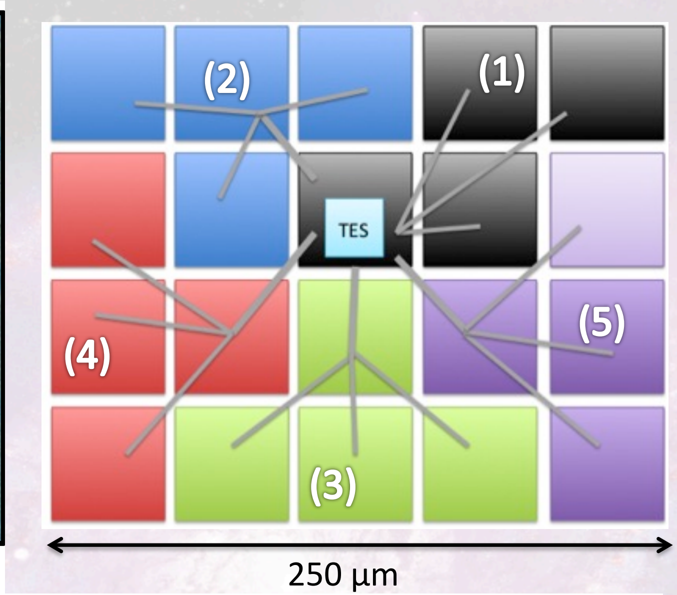


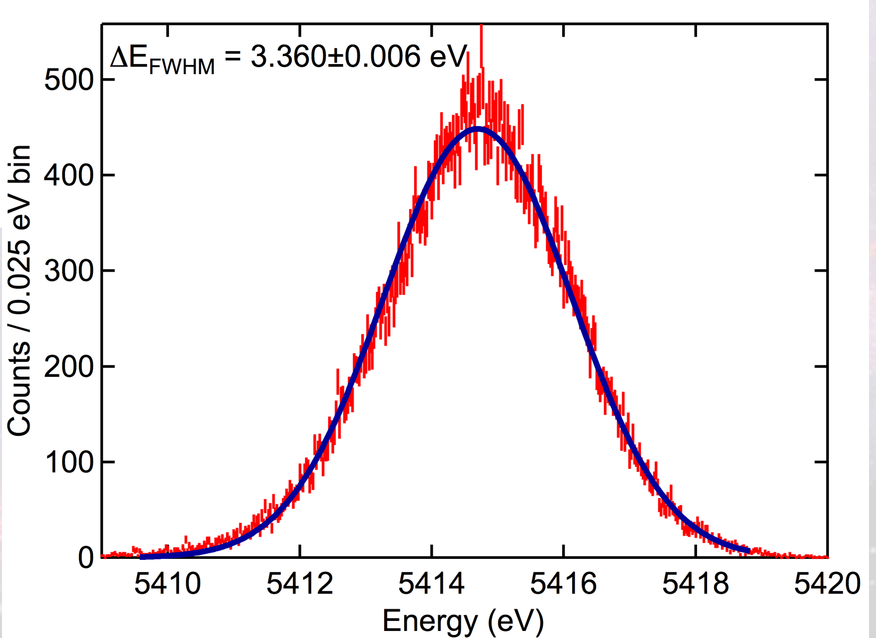
96x96 array (9216 pixels) - fully wired within array – absorbers on 75 μm pitch

- 32x32 array of 3x3 Hydras

Main Array Development: 20 Absorber Hydras



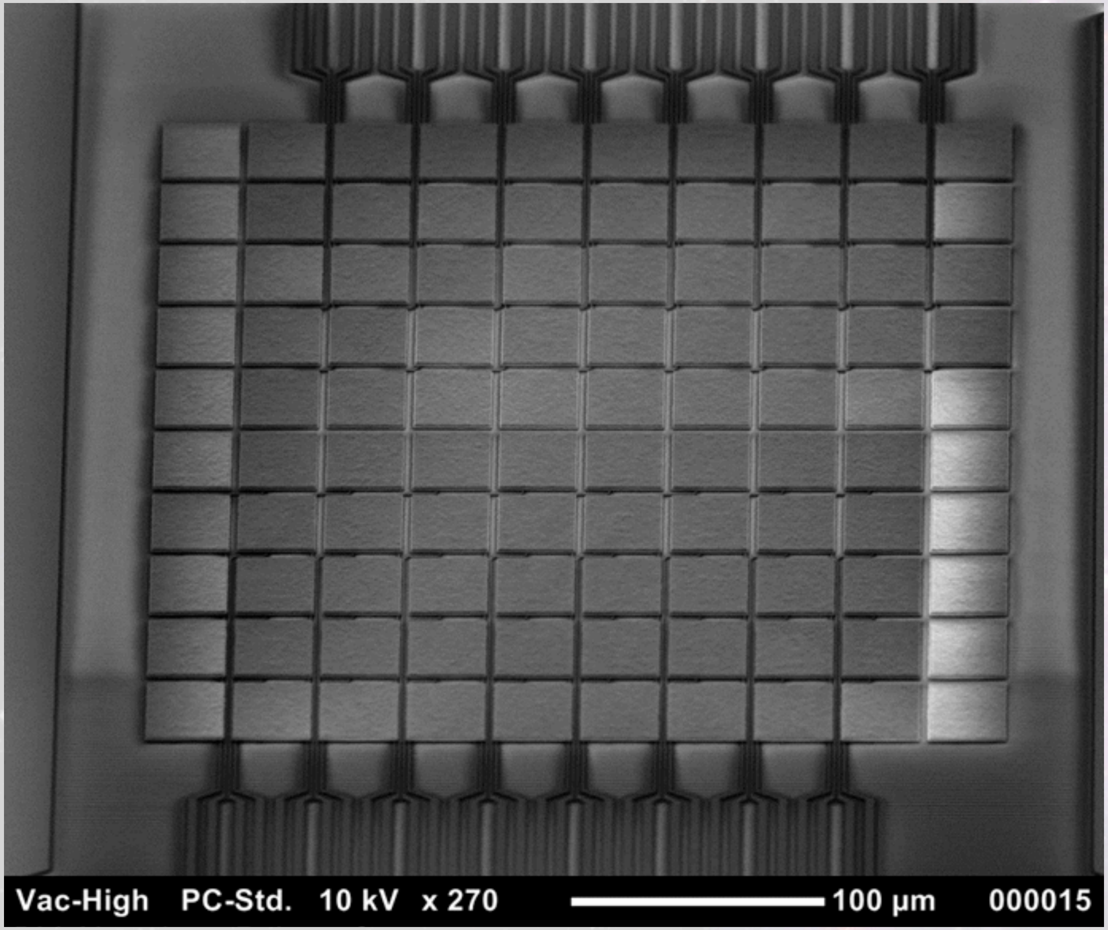


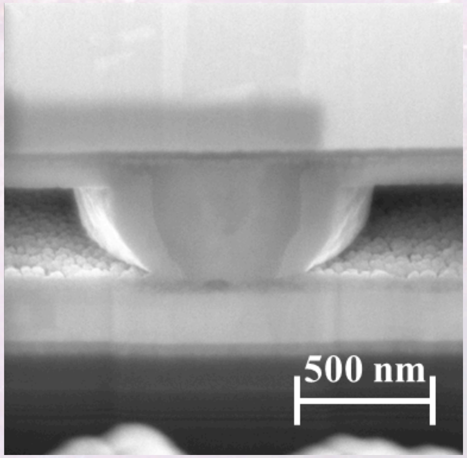


- Combined spectrum from all 20 hydra pixels for Cr Kα1 X-rays give ΔE = 3.36 eV (FWHM).
- Also showed good performance for 1.5 keV and 277 eV X-rays, where most pixel populations could still relatively easily be discriminated from rise-time.

Enhanced Main Array

- Will require pixels on a 25 μm pitch.
- Below is an example of a 10 x 10 array of pixels on a 35 μm pitch.
- Each absorber cantilevered above substrate on a single 1 micron diameter "stem"



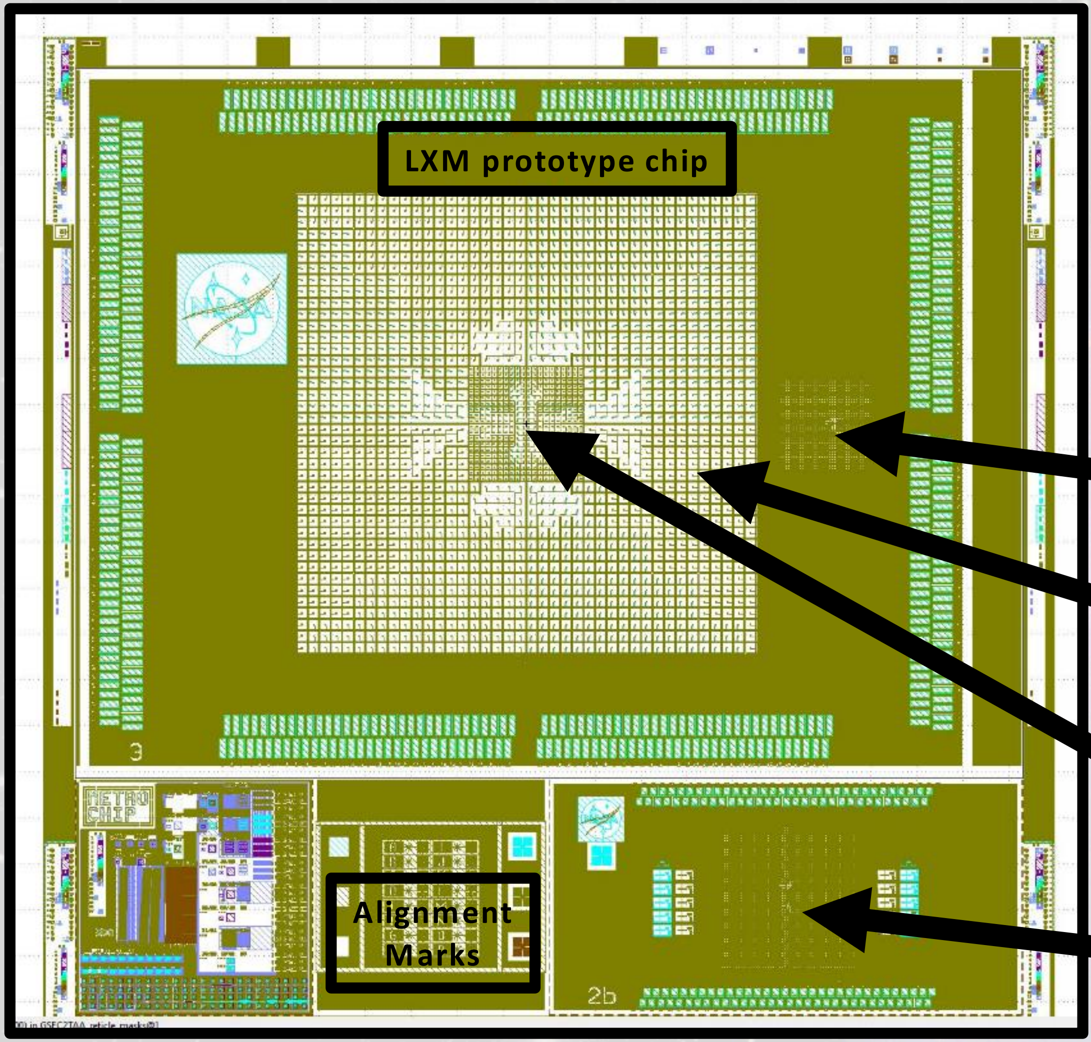


A.M. Datesman et al., *"Reduced-Scale Transition-Edge Sensor Detectors for Solar and X-ray Astrophysics"*, IEEE Transactions on Applied Superconductivity, Volume: 27, Issue: 4, June 2017.

LXM Prototype arrays using TESs

- High-yield, high-density, buried multi-layered wiring underneath pixels (MIT/LL).
- Superconducting microstrip wiring & ground planes integrated

⇒ Hydras pixels easily fabricated on nice flat surface



40x40 Ultra-Hi-Res Array
50 μm pitch TES

40x40 Main Array
250 μm pitch TES
25-hydra

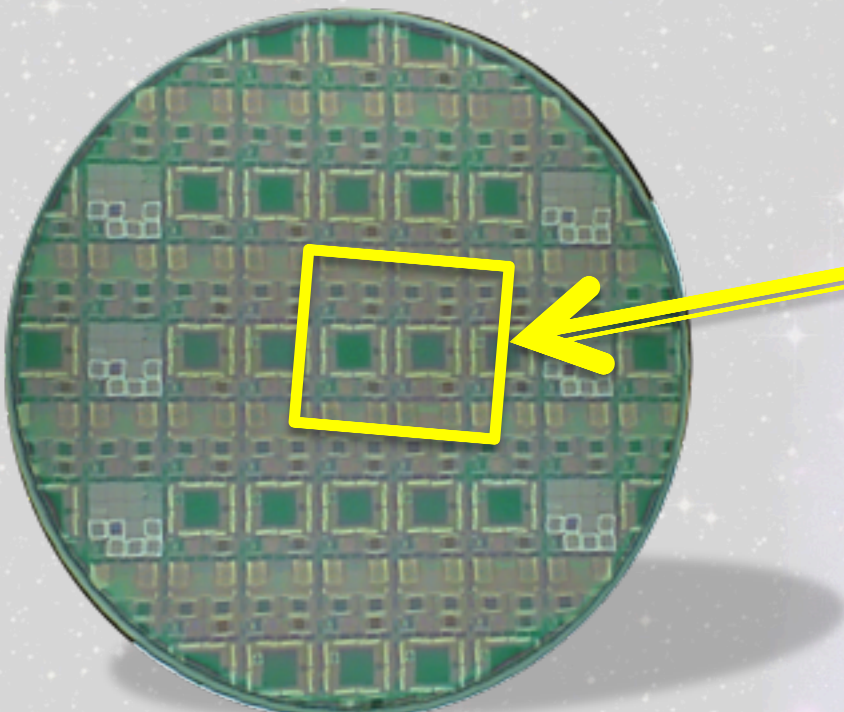
20x20 Enhanced Main array
125 μm pitch TES
25-hydra

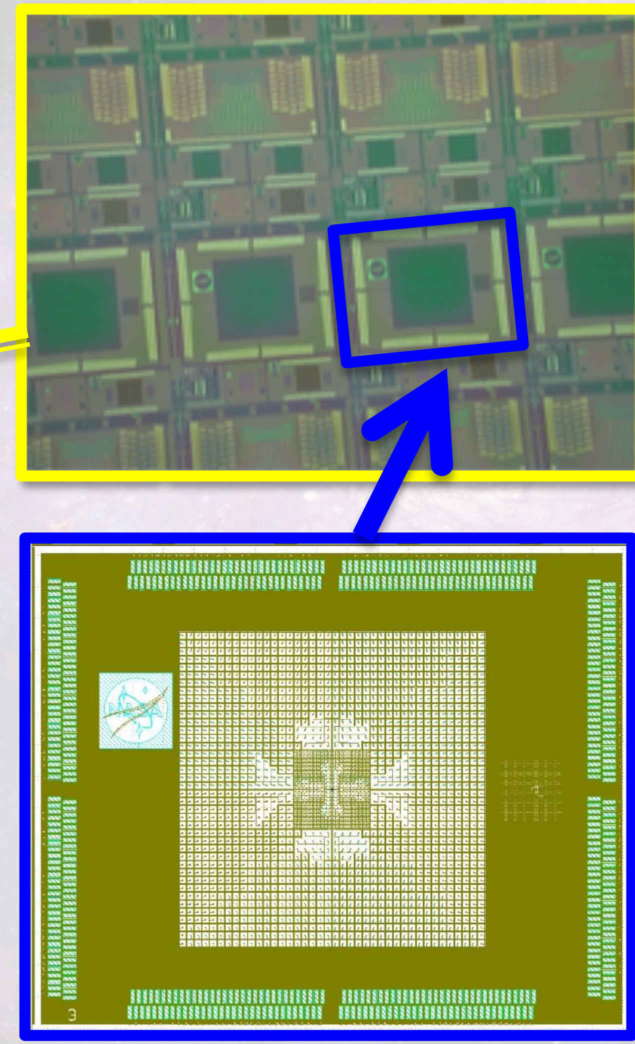
60x60 50 μm single absorber pixels

- About two thirds of the full sized LXM array
- This is a TES microcalorimeter version, MMC one also being developed and currently being fabricated.

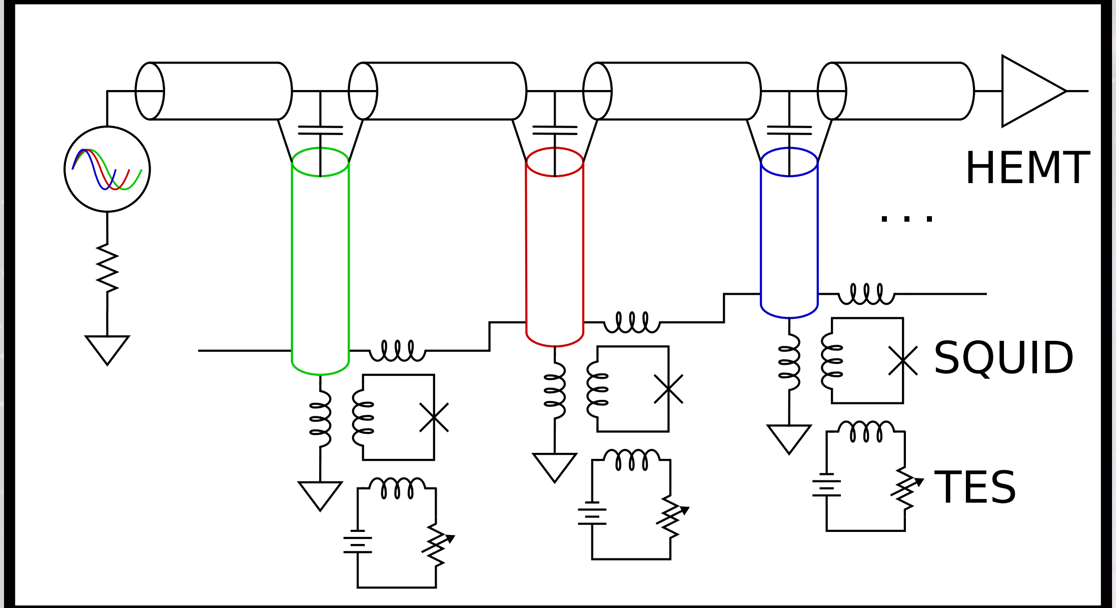
LXM Prototype arrays using TESs

8” wafers, currently being cored down into 4” wafers



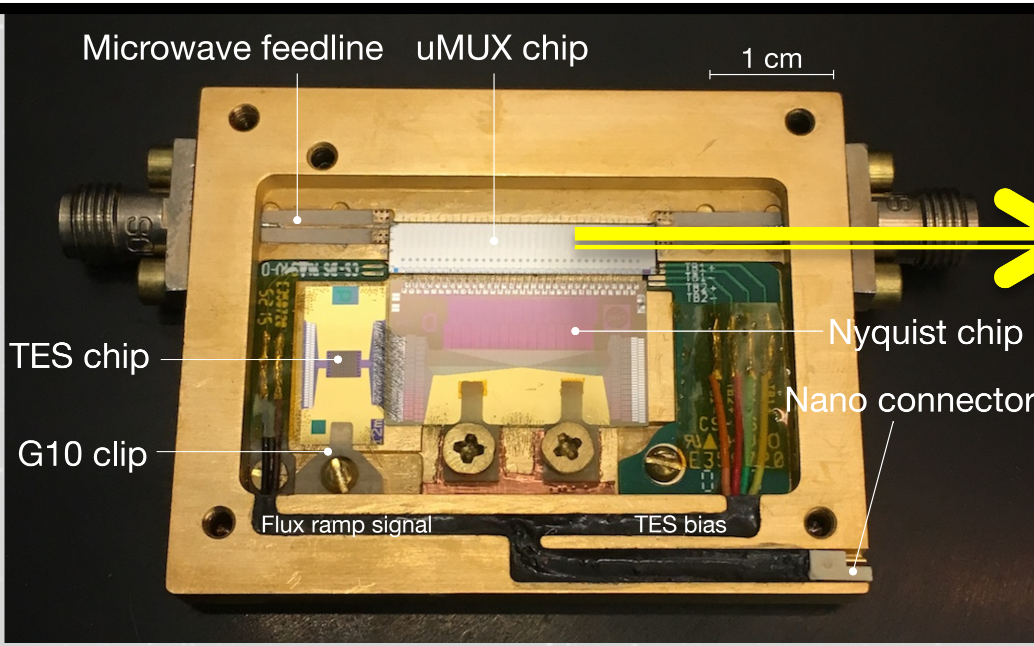


Microwave SQUID Multiplexing

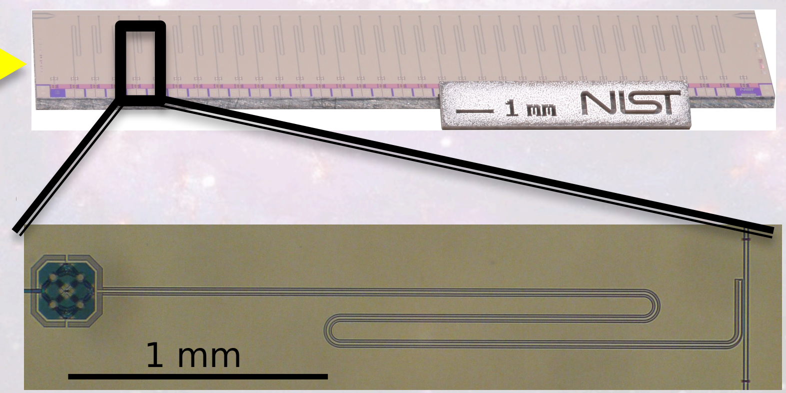


- Circuit diagram for high-resolution X-ray microcalorimeter readout using microwave SQUID multiplexing

- TESs couple to unique microwave resonator
- SQUIDs built into microwave resonator
- Current in input coil modulates resonance frequency



Microwave SQUID resonator chips developed at NIST:



Microwave SQUID Multiplexing

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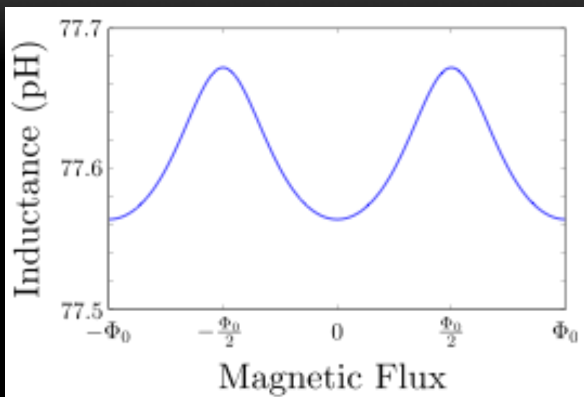
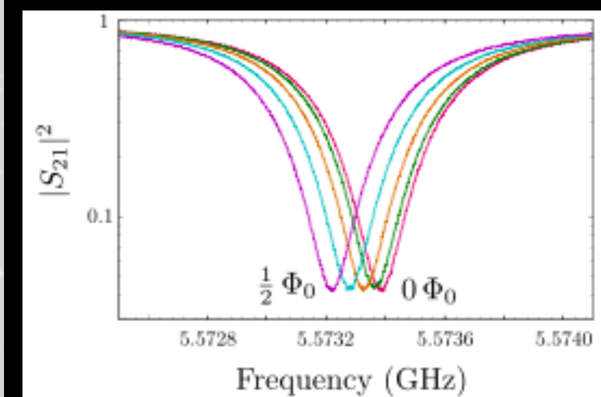
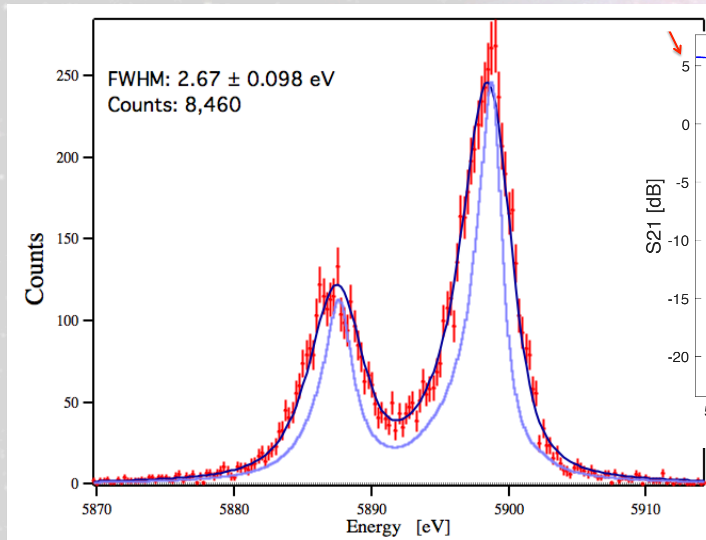
SQUID response

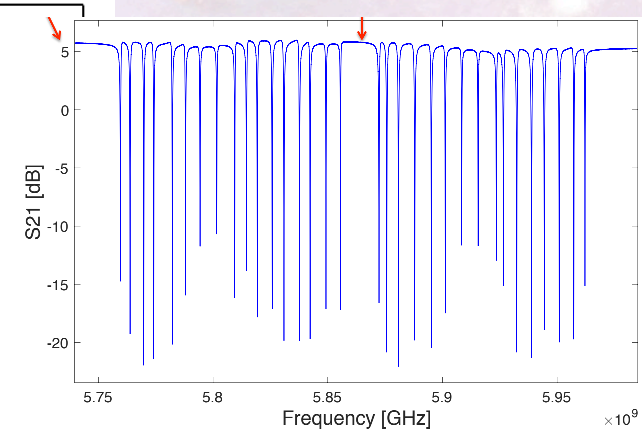


resonance response



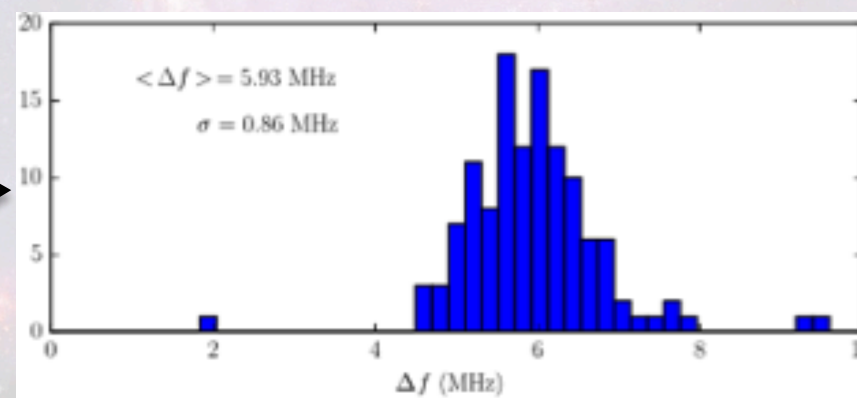
- Measuring 32 TES multiplexed at GSFC through resonators spaced by 6 MHz, with frequencies around ~ 5.5 GHz
- Now achieved ~ 2.67 eV [FWHM] at 6 keV, with integrated NEP = 2.58 eV. Max. slew rate ~ 0.4 A/s.





SOA: Spacing of resonators can be ~ 2 MHz.

- 128 resonators with a 6 MHz spacing.
- Now demonstrated with 128 microcalorimeters attached with no degradation of performance.



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LXM Focal Plane Layout

Baselined, January 2018

NIST 3A/s with spacing with 0.5 Ms/s, 2 MHz BW=> 10 MHz best resonator spacing

Tc=65 mK

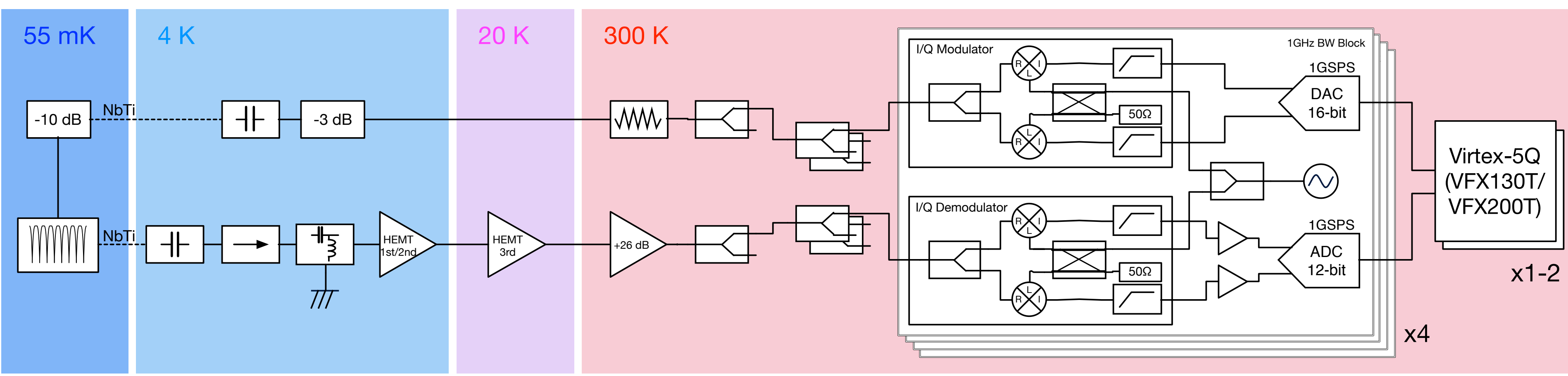
Arrays	FoV arc-min		Pixel size	Thickness um	DE FWHM	# of sensors	Hydra factor	# of pixels	Max slew rate for max E A/s	Energy range (keV)	Samp. rate MHz	Res. spacing (MHz)	# of res.	Margin at max energy	# of HEMTs	Round up
Main array	5'	5x5 hydras	1"	4.0	3 eV	3,456	25	86,400	1.2	6	0.5	10	400	2.5	8.6	10
Enhanced Main Array	1'	5x5 hydras	0.5"	4.0	1.5 eV	576	25	14,400	5	6	2	40	100	2.4	5.8	6
Ultra-Hi-Res Array	1'	Single pixels	1"	1.0	0.3 eV	3,600	1	3,600	0.85	1	0.3	6	667	2.1	5.4	6
														Max # HEMTs "on"		16
														Total # of HEMTs		22
Total						**7,632**		**104,400**						**Total coaxes**		**44**

Enhancement option to be considered later

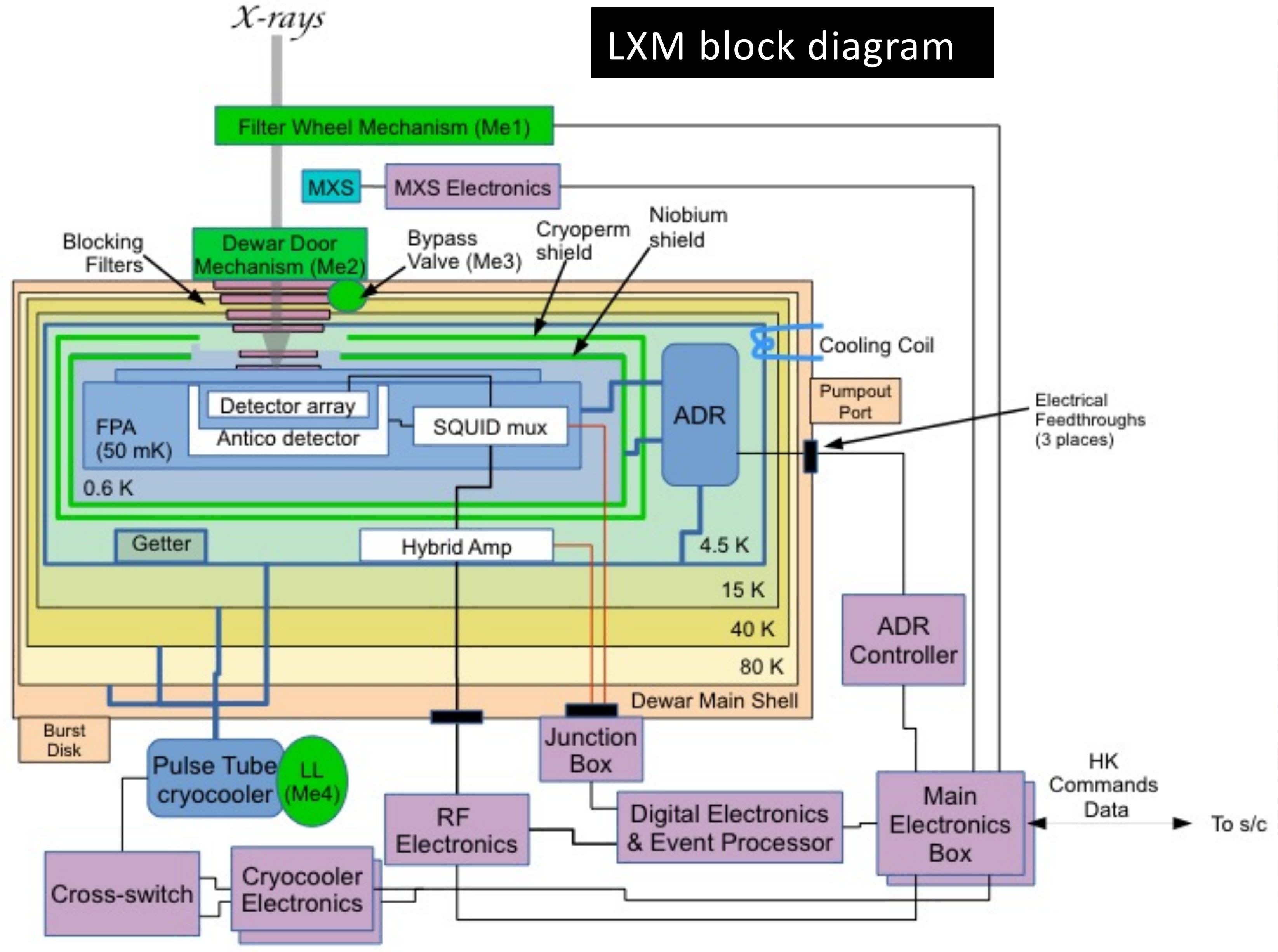
Extended array	20'	Single pixel	5"	0.5	1 eV	54,000	1	54,000	7.168	2	2.8	56	71	2.3	5.9	6
V2: 2 eV Extended Array	20'	Single or 2x2 hydra	5" or 10"	0.5	2 eV	13,500	1 or 4		0.056	2	0.9	1.78	2,250	9.5	6.0	6

Read-out Chain

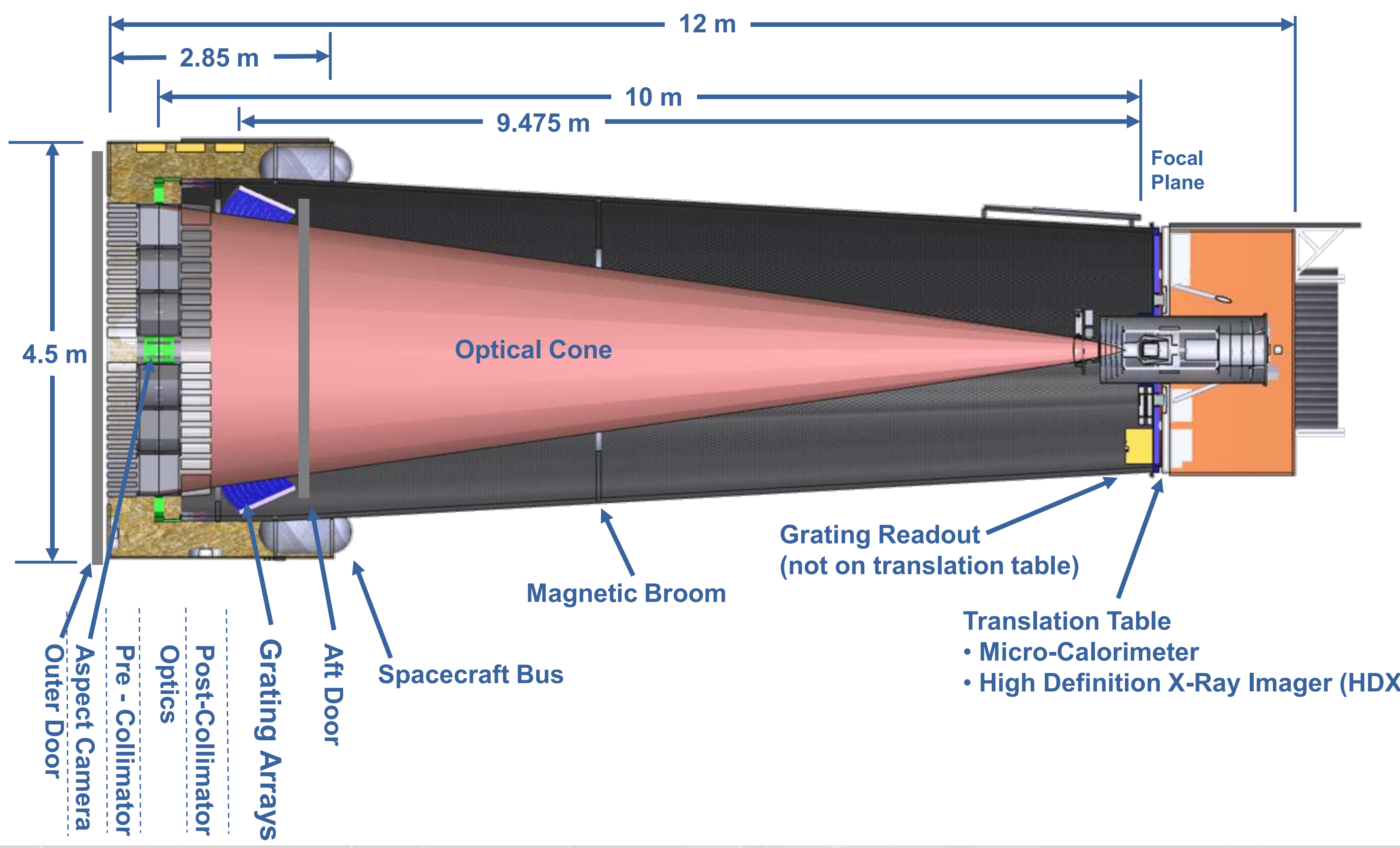
- 4 temperature stages (55 mK / 4 K / 20 K / 300 K)
- 2-stage HEMT at 4.5 K, ~ 1 mW/HEMT with low enough noise temp. and sufficient gain
- Split 4GHz bandwidth to four 1GHz bandwidth blocks
  - 1GHz BW block consists of LO, I/Q modulator, I/Q demodulator, baseband amplifiers, dual-channel 1Gsps DAC and dual-channel 1Gsps ADC
- Use 2 FPGA to handle four 1GHz BW blocks



LXM block diagram

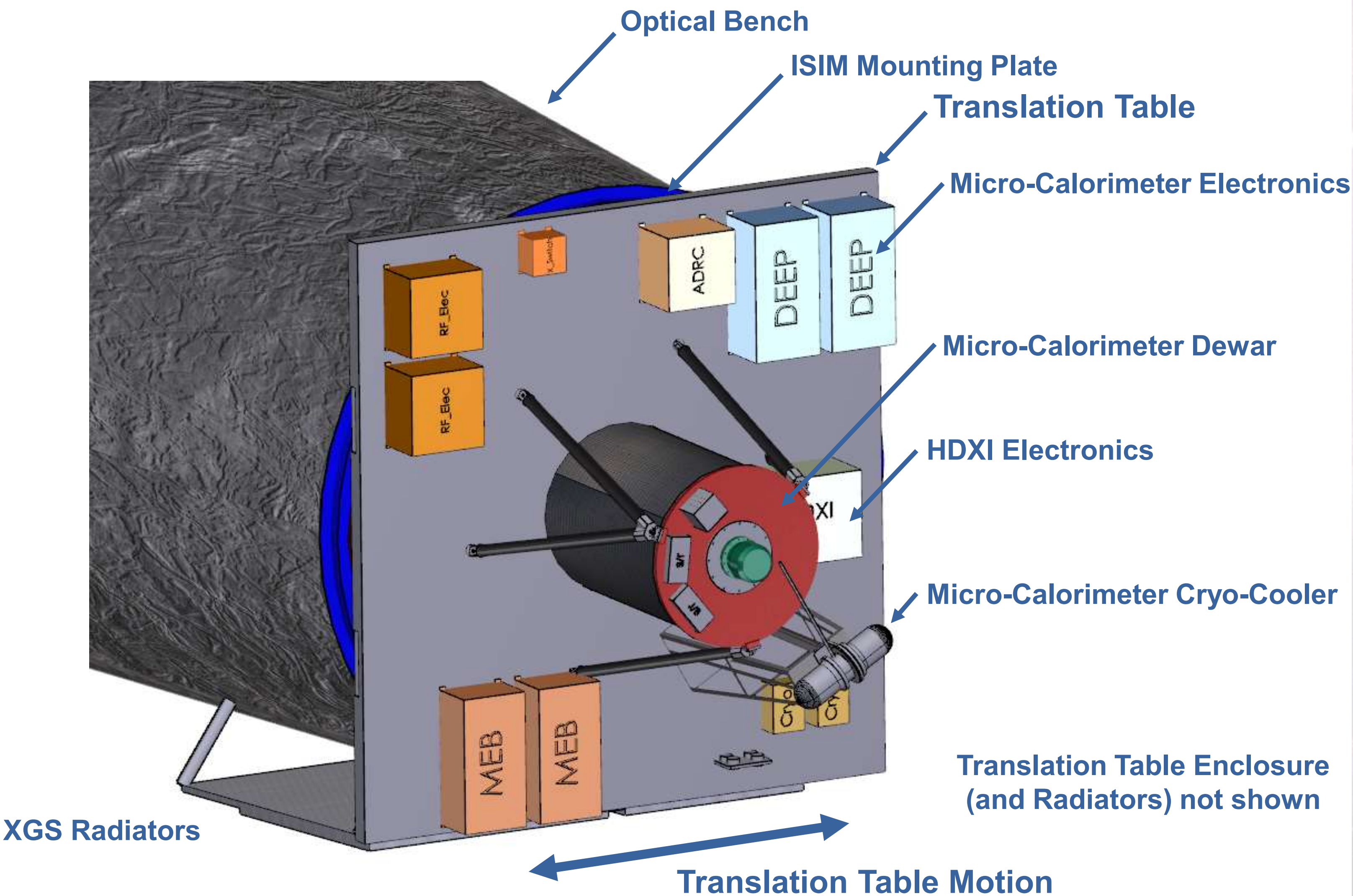


Lynx telescope basic design

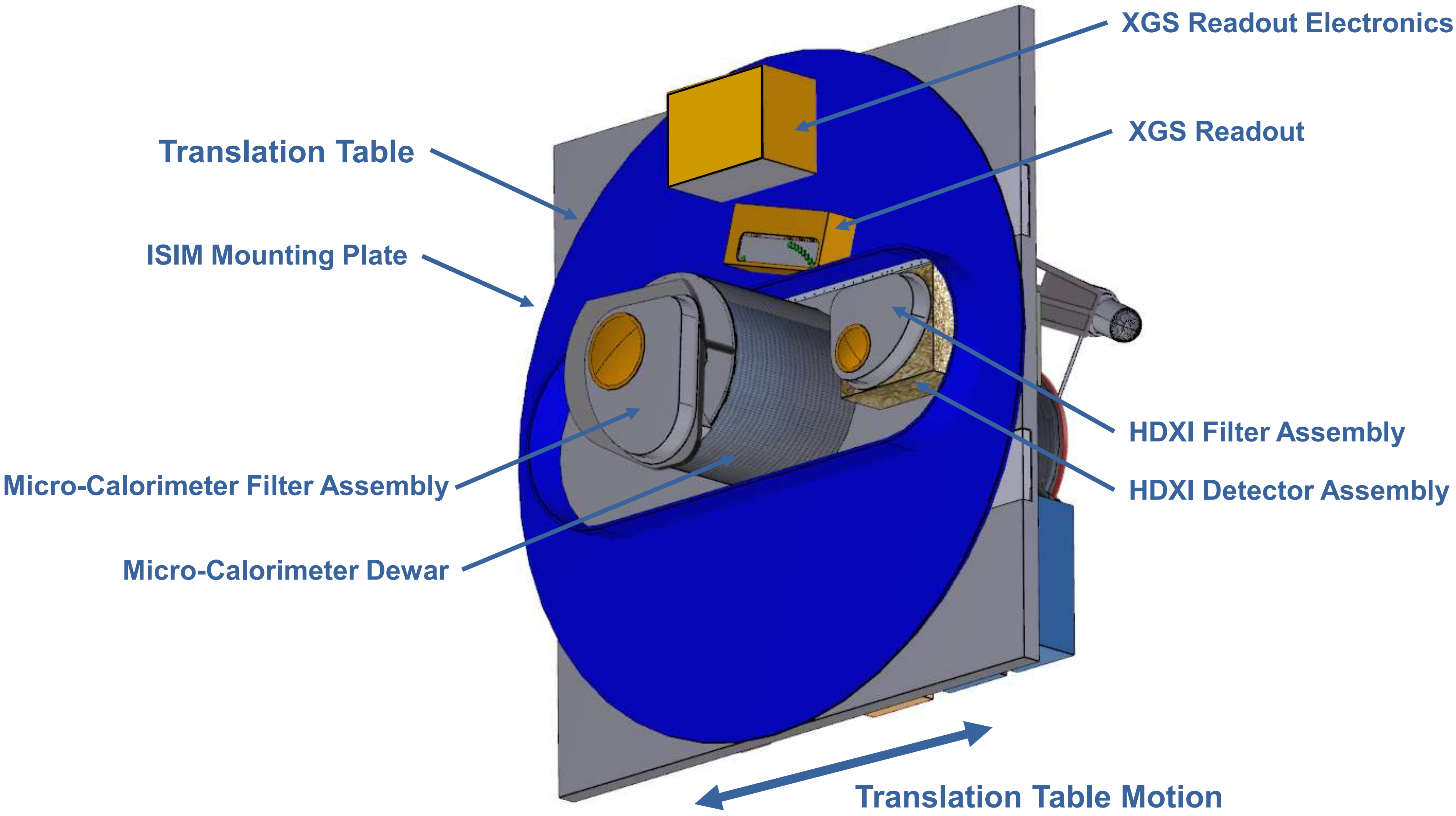


LXM on Translation Table

Aft View



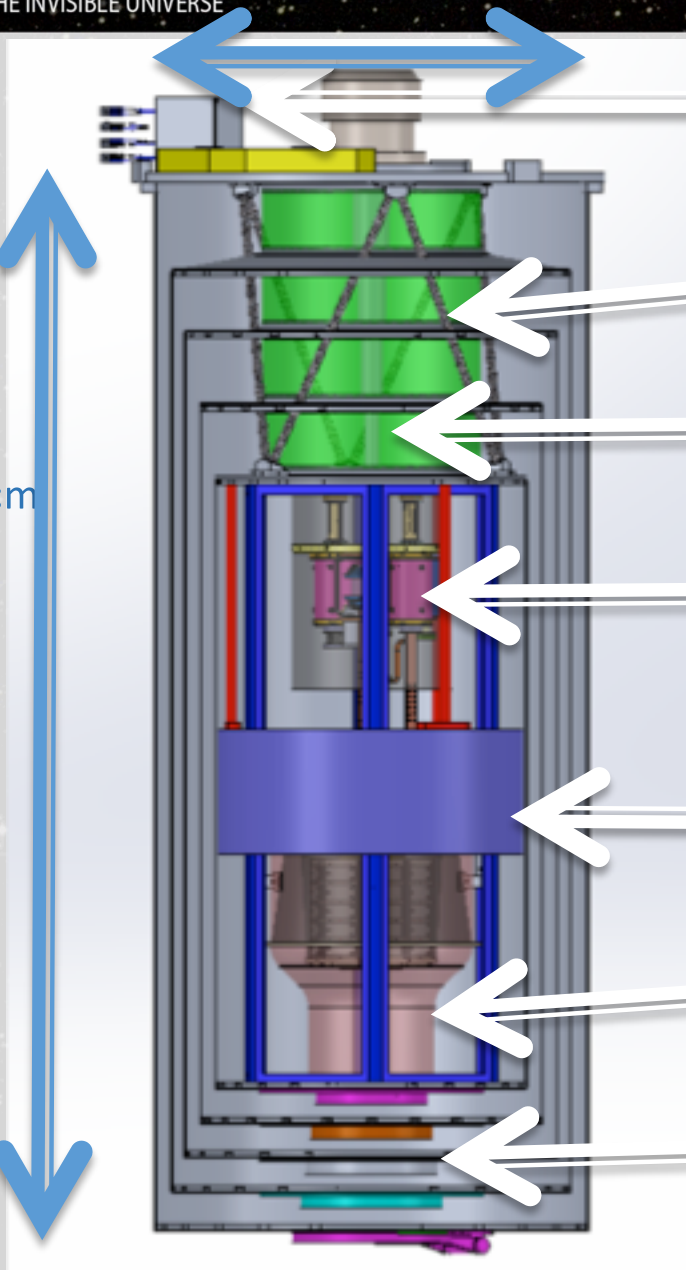
LXM on Translation Table



Inside the cryostat

Diameter
= 70 cm

Length
= 143.2 cm



GHz signals in/out

Support struts

Cryocooler – 4-stage pulse tube cooler

Multi-stage continuous adiabatic demagnetization refrigerator

4.5K Support ring

Focal plane assembly

Aperture assembly
(series of infrared blocking filters)

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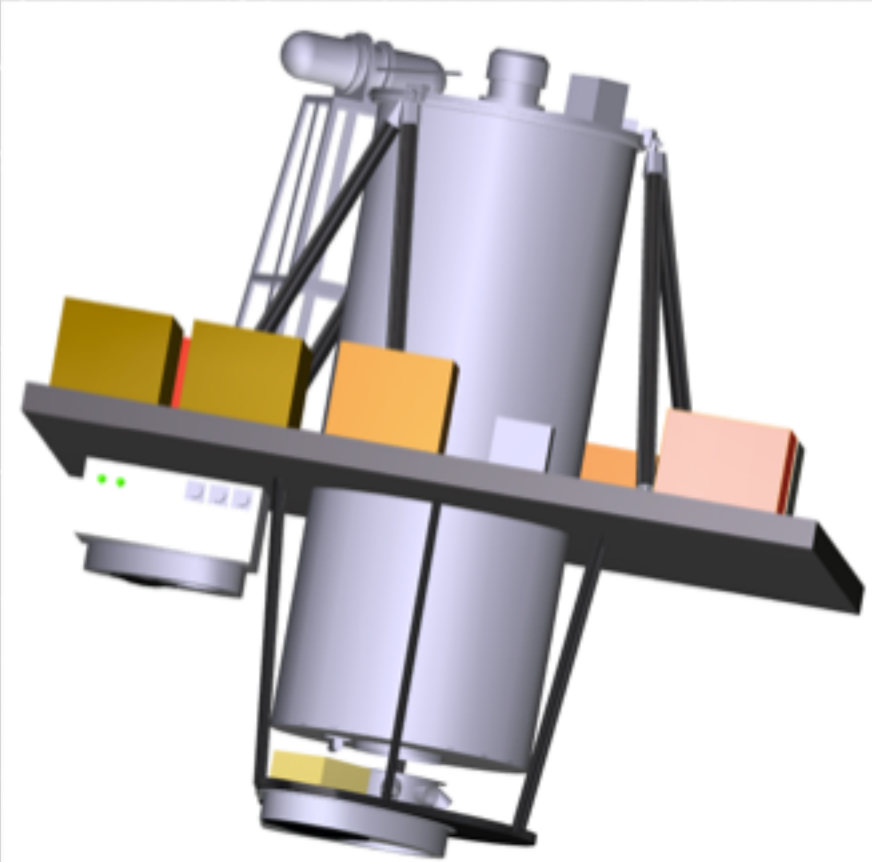
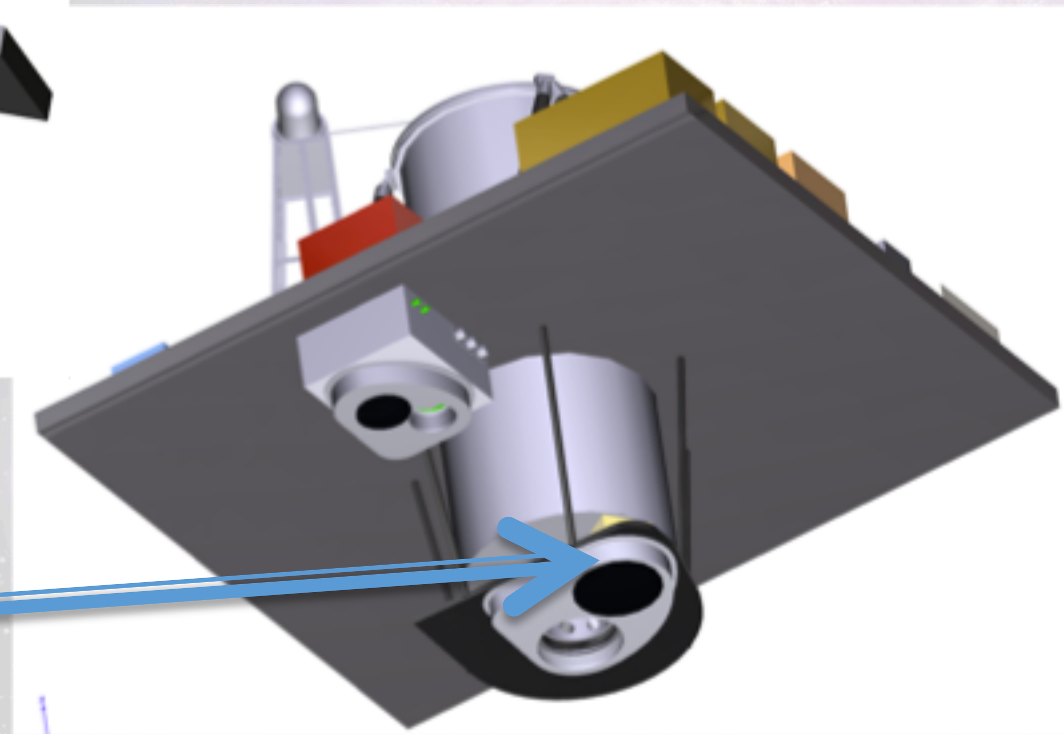
Filter wheel and calibration sources





Rotatable filter “paddles”

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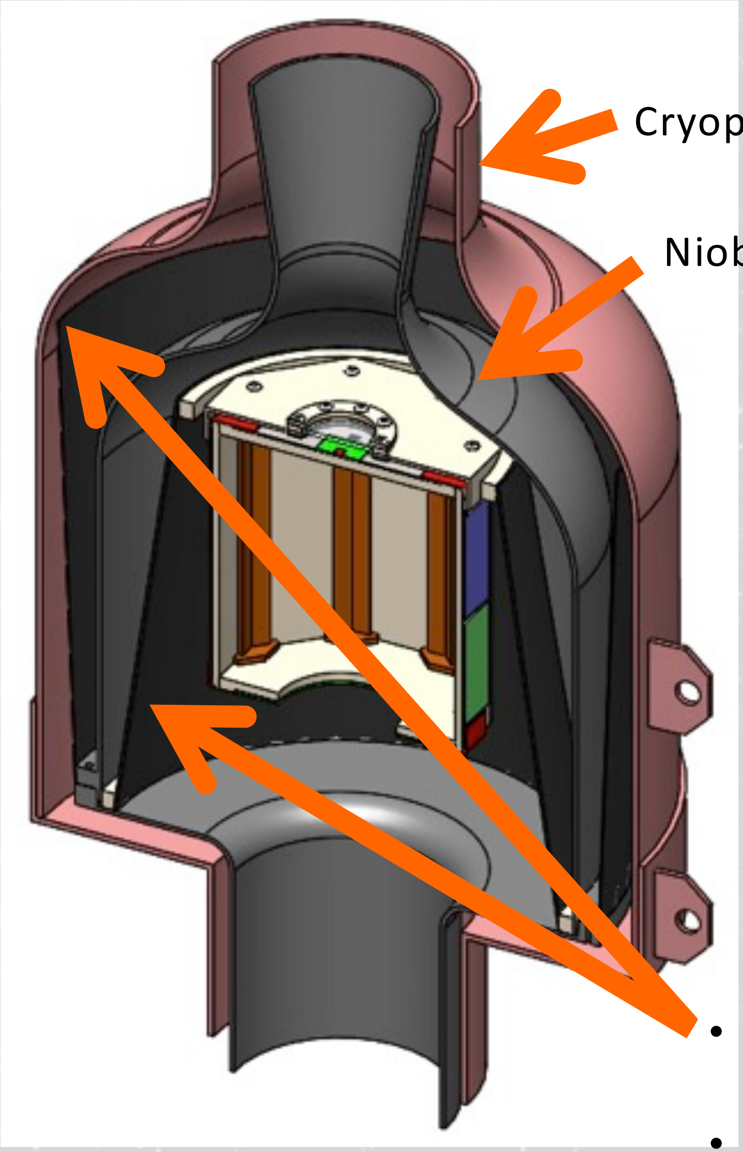
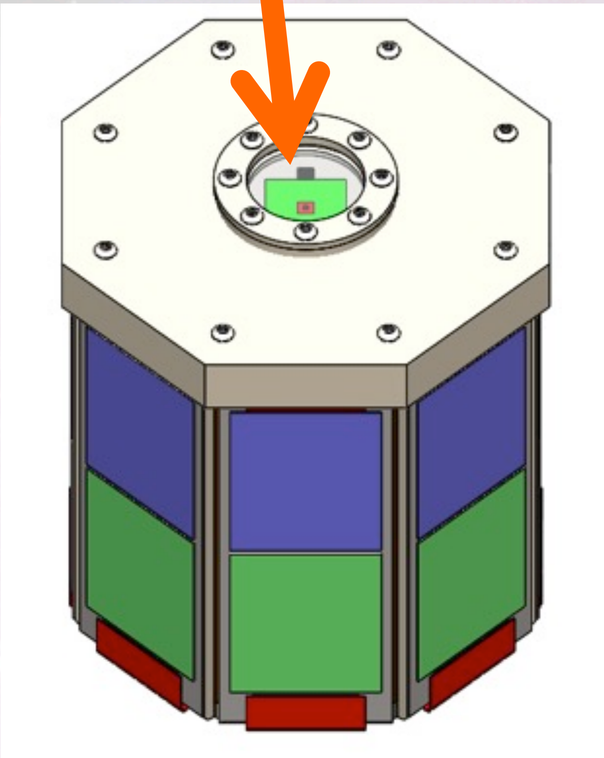
Notional Focal Plane Assembly Design



Cryoperm shield

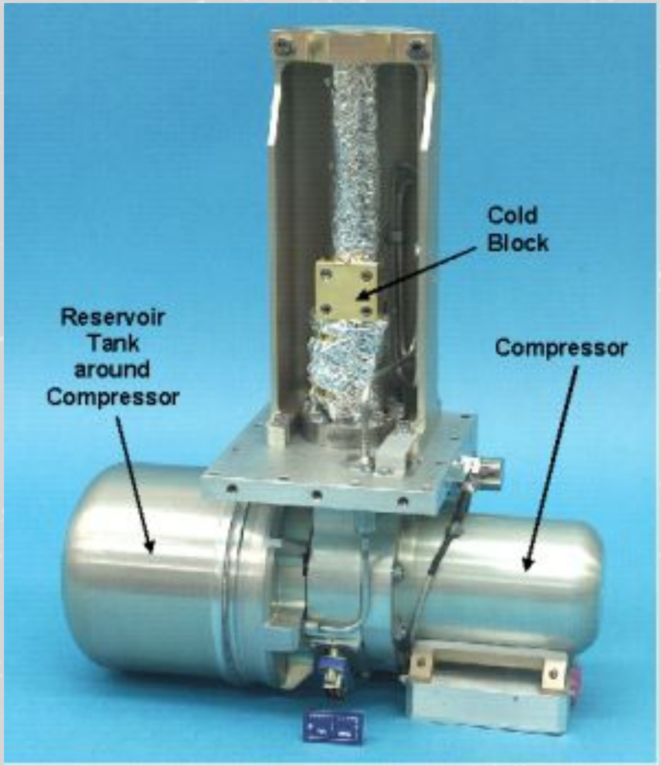
Niobium shield

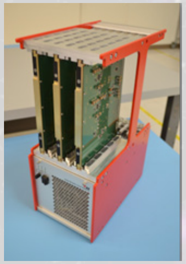
Focal plane array – 10 m to optics



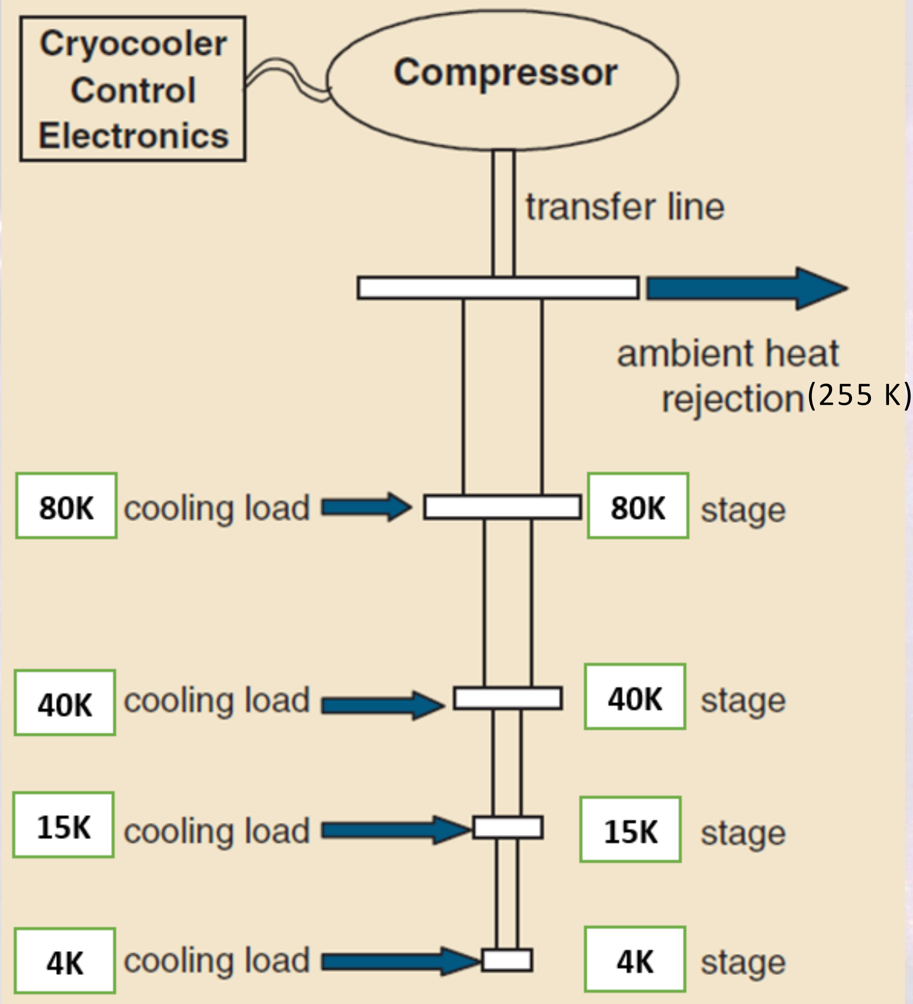
- Thrust cones (T300, 3 layers, 0.68 mm thick) to support lowest temp. stages
- Mech. analysis – will survive launch loads, no buckling

4-Stage Stirling-Type Pulse Tube Cryocooler currently baselined for design purposes





Cryocooler: TRL-4
Electronics: TRL-5



- 4-Stage Cryocooler:
  - 4.5K (50 mW)
  - 15K (65 mW)
  - 40K (180 mW)
  - 80K (3.6 W)
- Mass: ~23 kg (Compressor ~ 16 kg)
- Heat pipes to remove compressor & cold head heat dissipation

- Vibration (<100Hz): ~ 10mN with soft mounting
- Electronics:

  Power available: 800+ W, Power needed: 507 W

  Reliability > 98.5%

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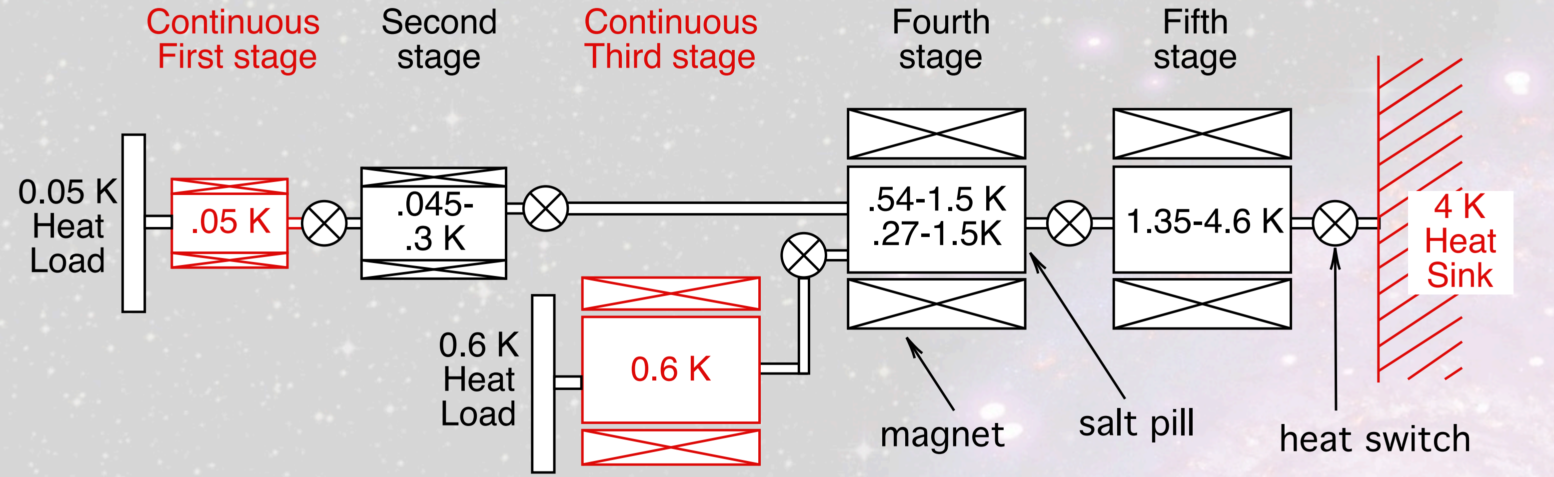
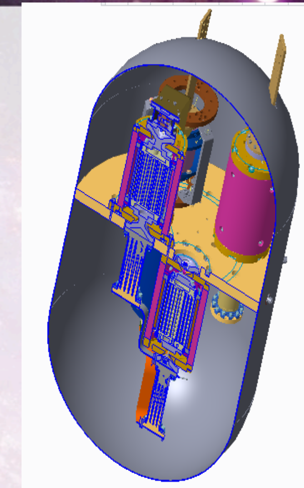
5-stage Adiabatic Demagnetization Refrigerator





Stage	Details	T range	Max Avg cooling power*	Nom Avg cooling power	Avg heat rejection	Peak heat rejection
5	150 g GLF, 3 T	1.35-4.6 K	1.41 mW	1.00 mW	4.0 mW	~20 mW
4	200 g CPA, 2 T	0.54-1.5 K 0.27-1.5 K	0.66 mW 0.30 mW	0.25 mW 0.05 mW	0.68 mW 0.31 mW	
3	60 g GLF, 1 T	0.6 K	0.31 mW	0.25 mW	0.25 mW	
2	100 g CPA, 0.5 T	0.045-0.3 K	0.012 mW	0.006 mW	0.050 mW	
1	100 g CPA, 0.1 T	0.05 K	0.012 mW	0.006 mW	0.006 mW	

Meets cooling requirements (3 µW @ 0.05 K, 124 µW @ 0.6 K) with required 100% margin

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LXM Development Milestones

Life-Cycle Phases	Pre-Phase A: Concept Studies		Phase A: Concept & Tech Development	Phase B: Prelim. Design & Tech Completion
Life-Cycle Gates		KDP-A 10/1/24	KDP-B 11/1/26	KDP-C 10/1/28
Project Life-Cycle Reviews	SOTA TRL: 3-4 03/18	MCR 8/1/24	SRR 7/1/26	PDR 7/1/28

TRL3

- Analytical studies and lab demonstrations that indicate proof of concept include characterizing and validating multi-pixel TES-detectors relevant to Lynx requirements and pixel arrays.
- Demonstrate feasibility of readout architecture.

TRL 4

- Demonstrate the required performance (pitch, energy resolution, energy range) with appropriate wiring density for all pixel types
- Demonstrate required microwave SQUID circuitry with appropriate noise, and resonator widths and spacings.
- Demonstrate basic functionality of the HEMT amplifier architecture
- Demonstrate large-size thin-film filters with high transmission above 0.2 keV

TRL 5

- X-ray testing of focal plane assembly that includes a hybrid array of all required pixel types with required wiring scale, heat sinking, and performance; readout of required pixel types with required density of resonators; and appropriate HEMT architecture with cabling.
- Assembly includes cryogenic system and realistic support structure.
- X-ray test demonstrates feasibility of achieving Lynx performance requirements in simulated operational environment.

TRL 6

- Critical environmental and X-ray test of a scalable flight-like assembly that demonstrates that Lynx requirements are met.

Technology Drivers		
	• Sensor Arrays & Readout	• Focal plane assembly

Total Mass Estimate: 468 kg

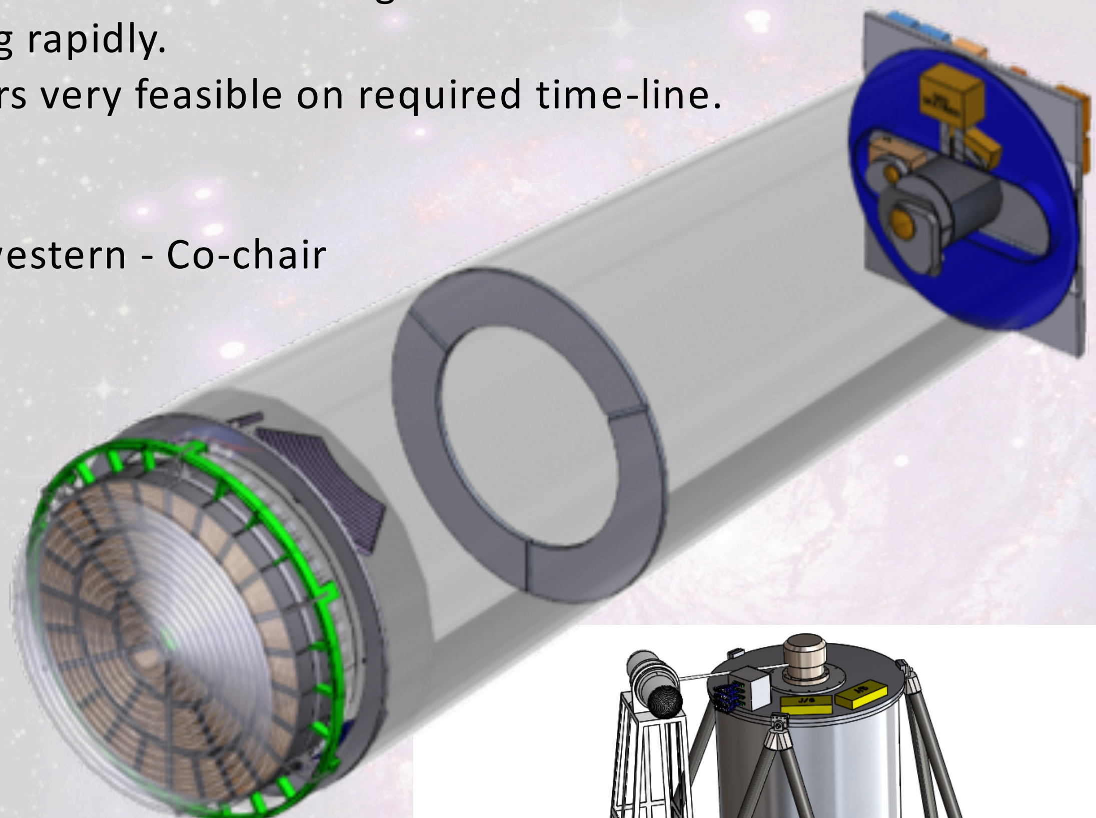
- Cryostat: 164 kg
- Electronics boxes: 146 kg
- Harnesses: 34 kg
- Thermal: 72 kg
- Other: 52 kg

Total Power Estimate: 1,832 W

Cost: CBE~ $380M (FY20), just completing second round of costing.

Conclusions / Co-authors from the Lynx IWG LXM sub-group

- The LXM instrument has a well-established baseline design.
- Technology development is advancing rapidly.
- Meeting of LXM requirements appears very feasible on required time-line.



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4. Megan Eckart – GSFC
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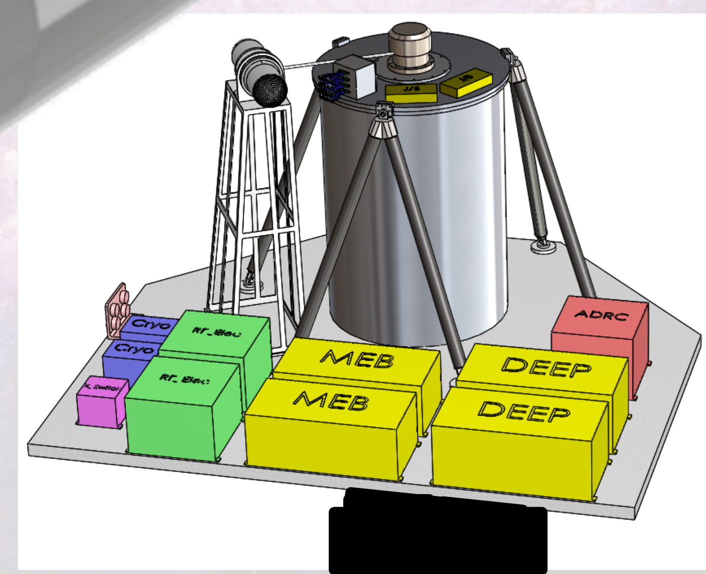
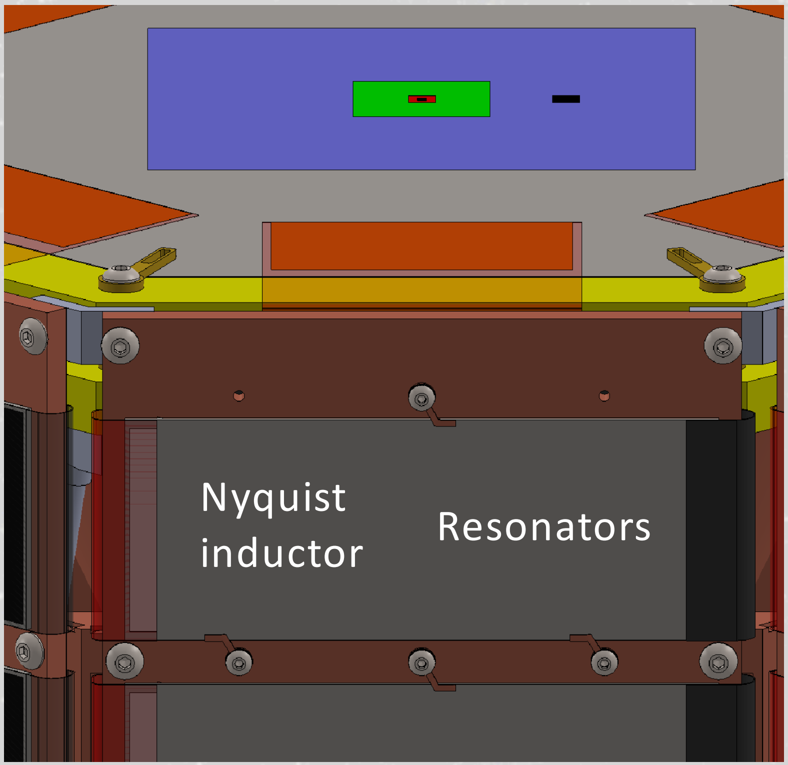
6. Wonsik Yoon – GSFC
7. Mike DiPirro – GSFC
8. Joel Ullom – NIST
9. Doug Bennett – NIST
10. Dan Swetz – NIST
11. Ben Mates – NIST
12. Kent Irwin – Stanford
13. Jeffrey Olson - Lockheed Martin
14. Dan McCammon – Wisconsin
15. Doug Swartz - NASA/MSFC
16. Ben Zeiger – Luxel
17. Kevin Ryu - MIT Lincoln Labs.



Back-up



Detailed parts of FPA design:

Side panels with:

(1) Microwave SQUID resonator multiplexing chips for reading out the TESs

(2) Shunt/nyquist inductors chips for TES bias circuit

Lynx 3 main science pillars

2. THE INVISIBLE DRIVERS OF GALAXY FORMATION AND EVOLUTION

- Lynx will map hot gas around galaxies and in Cosmic Web.
- The assembly, growth, and state of visible matter in cosmic structures is largely driven by violent processes that produce and disperse large amounts of energy & metals into surrounding medium as hot ionized baryons.
- Will characterize all significant modes of energy feedback including:

BH feedback:

- *spectro-imaging of SMBH spheres of influence*
- *density diagnostics in AGN winds*
- *extended narrow emission line regions*
- *AGN-inflated bubbles in elliptical galaxies*
- *plasma physics*

Galactic winds feedback:

- *Spatially and spectrally resolve hot phase of galactic winds*