Grating development and the Rockets for Extended-source X-ray Spectroscopy

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20 November 2024

PhysCos Early Career Workshop

A brief introduction

Dec. 2021 - PhD in Astrophysics from Penn State University

- Dissertation: “A reflection grating spectrograph for extended-source soft-x-ray astronomy”

2022 – 2024 - Postdoctoral position in Space Astrophysics Laboratory at the California Institute of Technology (Caltech)

Apr. 2024 – present - Research Assistant Professor of Physics at Caltech

<u>Major technology projects</u>

- UV & X-ray diffraction grating development (fabrication, characterization, tech advancement)
  - SAT23 award for gratings for the Habitable Worlds Observatory
- X-ray sounding rocket instruments (e.g. tREXS)
- UV suborbital balloon project (FIREBall)

Why develop grating technologies?

Current Technology Gap Priorities

TECHNOLOGY GAPS: OVERVIEW / TECH GAP PRIORITIES / PRIORITIZATION PROCESS / TECH GAP DESCRIPTIONS

Following a multi-month prioritization process involving managers, technologists, scientists, and subject-matter experts from NASA's Astrophysics Division (APD) and the Program Offices, as well as independent reviewers, the following is the Astrophysics Technology Gap Priority List. This list will inform APD technology development planning as well as decisions on what technologies to solicit and will be considered when making funding decisions. Tiers are in descending priority order. All gaps within any given tier are to be considered equally prioritized (which is why the gaps are arranged alphabetically within each tier). Tier 4 (Non-Strategic) is reserved for gaps deemed not to enable or enhance any strategic Astrophysics mission, and as such will not automatically be included in the next prioritization cycle.

Tier 1 Technology Gaps

Priority Tier 1: Technology gaps determined to be of the highest interest to APD. Advancing technologies to close these key gaps is judged to be most critical to making substantive near-term progress on the highest-priority strategic astrophysics missions. The program office technologists recommend solicitations and award decisions address as many of these technology gaps as possible.

- Coronagraph Contrast and Efficiency in the Near IR
- Coronagraph Contrast and Efficiency in the Near UV
- Coronagraph Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
- High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High-and Low-Blazed-Angle UV Gratings
- High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
- High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
- High-Resolution, Lightweight X-ray Optics
- High-Throughput, Large-Format Object-Selection Technologies for Multi-Object and Integral-Field Spectroscopy
- Integrated Modeling for HWO: Multi-Physics Systems Modeling,Uncertainty Quantification, and Model Validation
- Large-Format, High-Resolution Far-UV (100-200 nm) Detectors
- Large-Format, High-Resolution Near-UV (200-400 nm) Detectors
- Low-Stress, Low-Roughness, High-Stability X-ray Reflective Coatings
- Mirror Technologies for High Angular Resolution (UV/Visible/Near IR)
- Optical Blocking Filters for X-ray Instruments
- Scaling and Metrology for Advanced Broadband Mirror Coatings for HWO

From gap description:

replicated onto thin substrates. Alignment into large arrays needs to be demonstrated.

Source: NASA Astrophysics Projects Division

The Rockets for Extended-source X-ray Spectroscopy (tREXS)

- Specifications:
  - ≈10 sq. deg. FOV
  - Spectral resolving power ≈ 40 – 60
  - Primary sensitivity from ≈0.3 – 0.8 keV (≈15 – 40 Å)
  - Optimized for O-VII, O-VIII, N-VI, and C-VI emission

Image credit: Nahks Tr'Ehnl

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- Instrument components:
  - Mechanical beam-shaper modules
  - X-ray reflection gratings
  - Focal plane camera

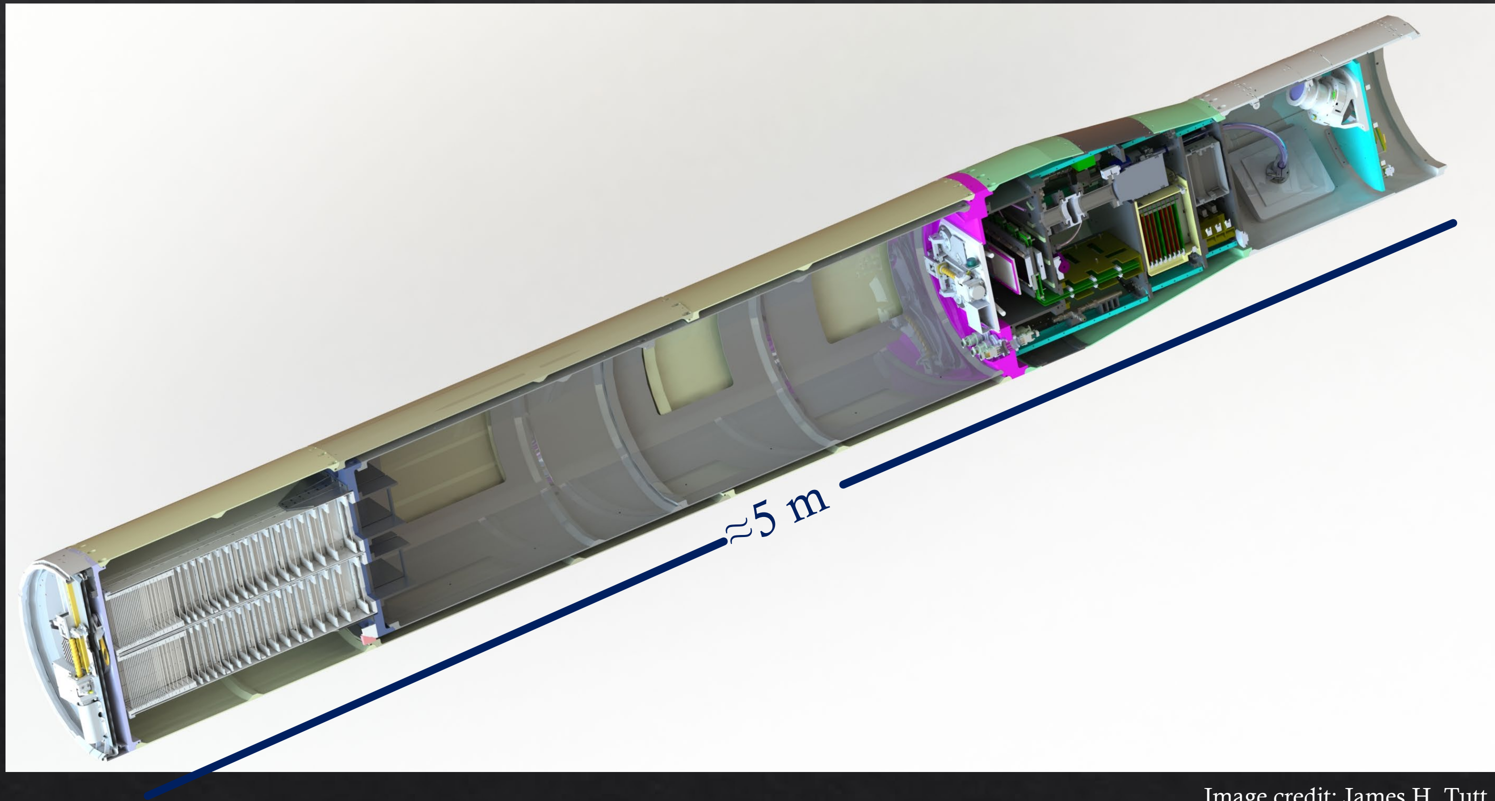
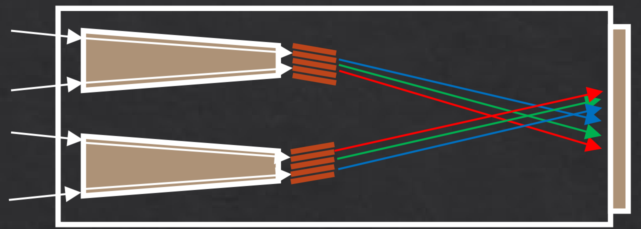
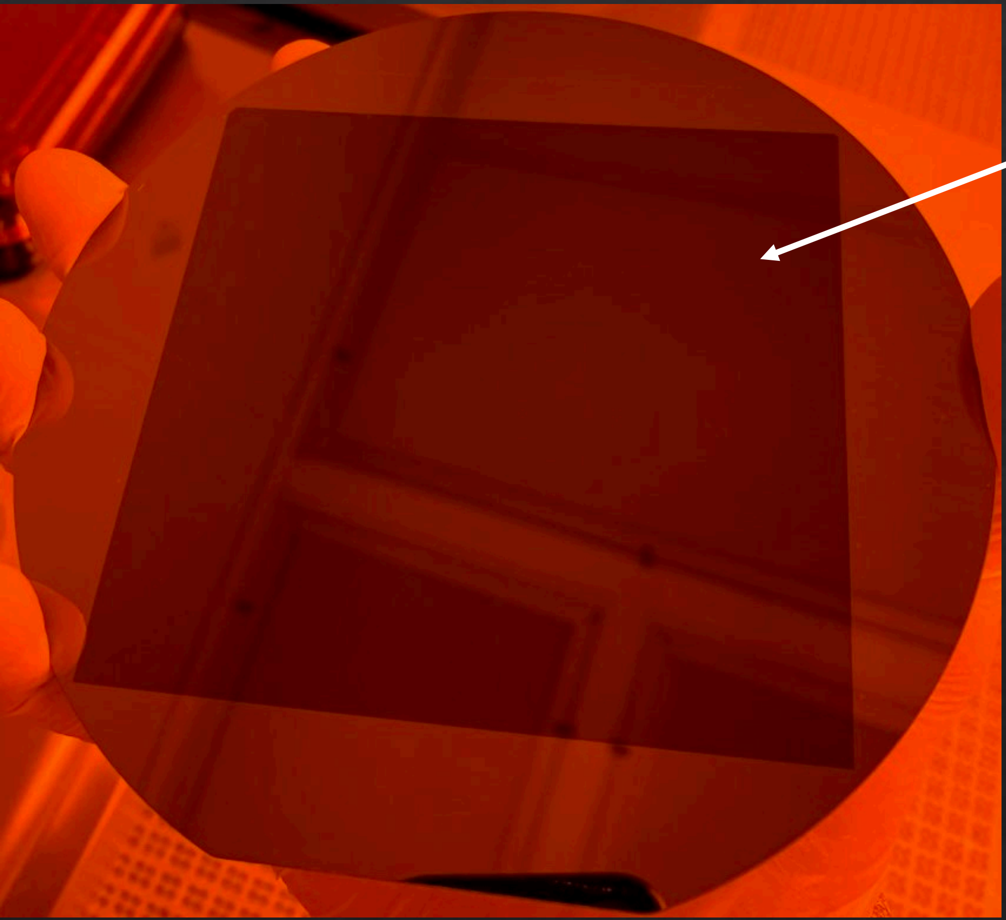


Image credit: James H. Tutt

Spectrograph channels (x4 in instrument; shared focal plane)

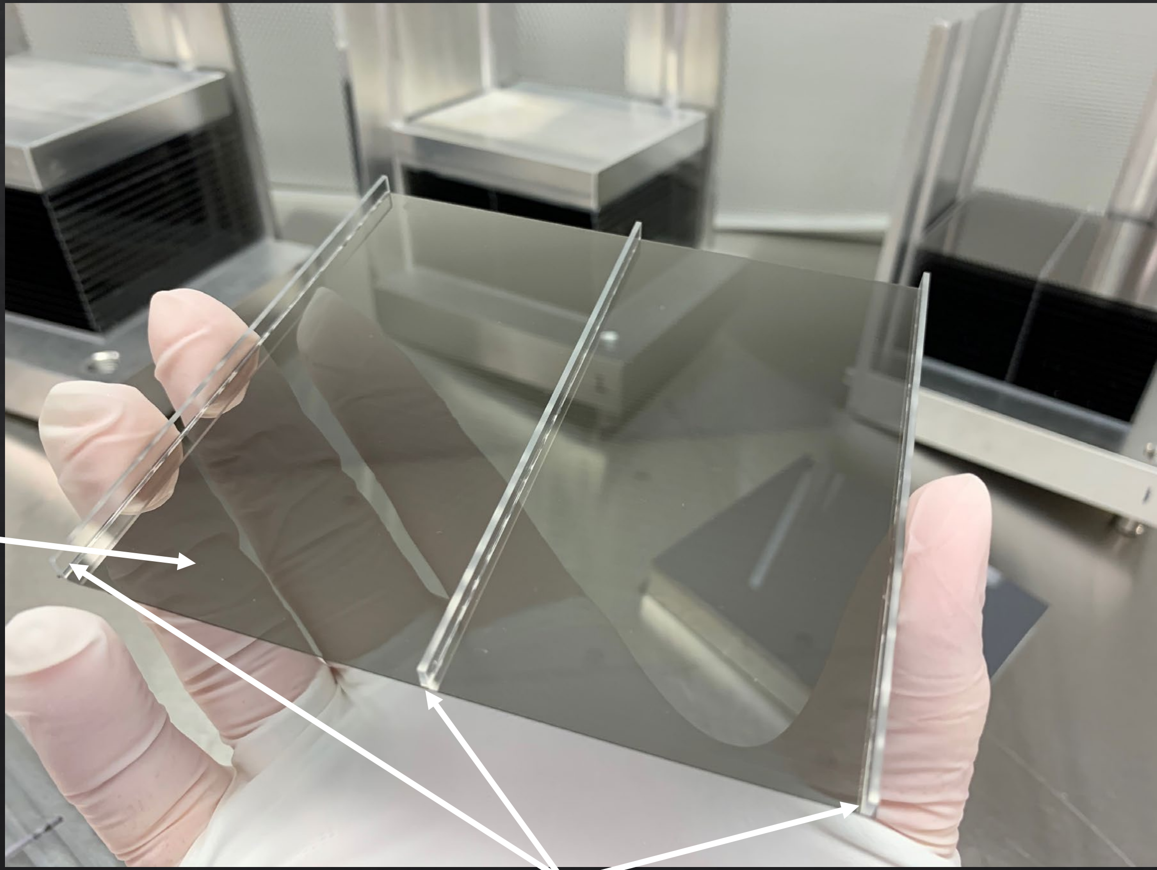
Reflection gratings



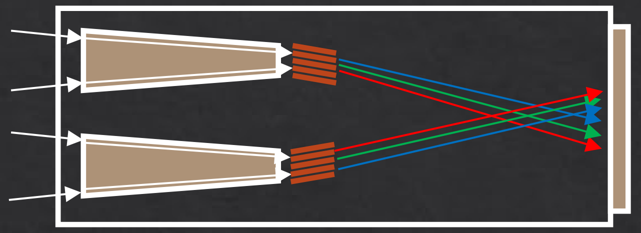


Grating master, 35^{o} blaze angle

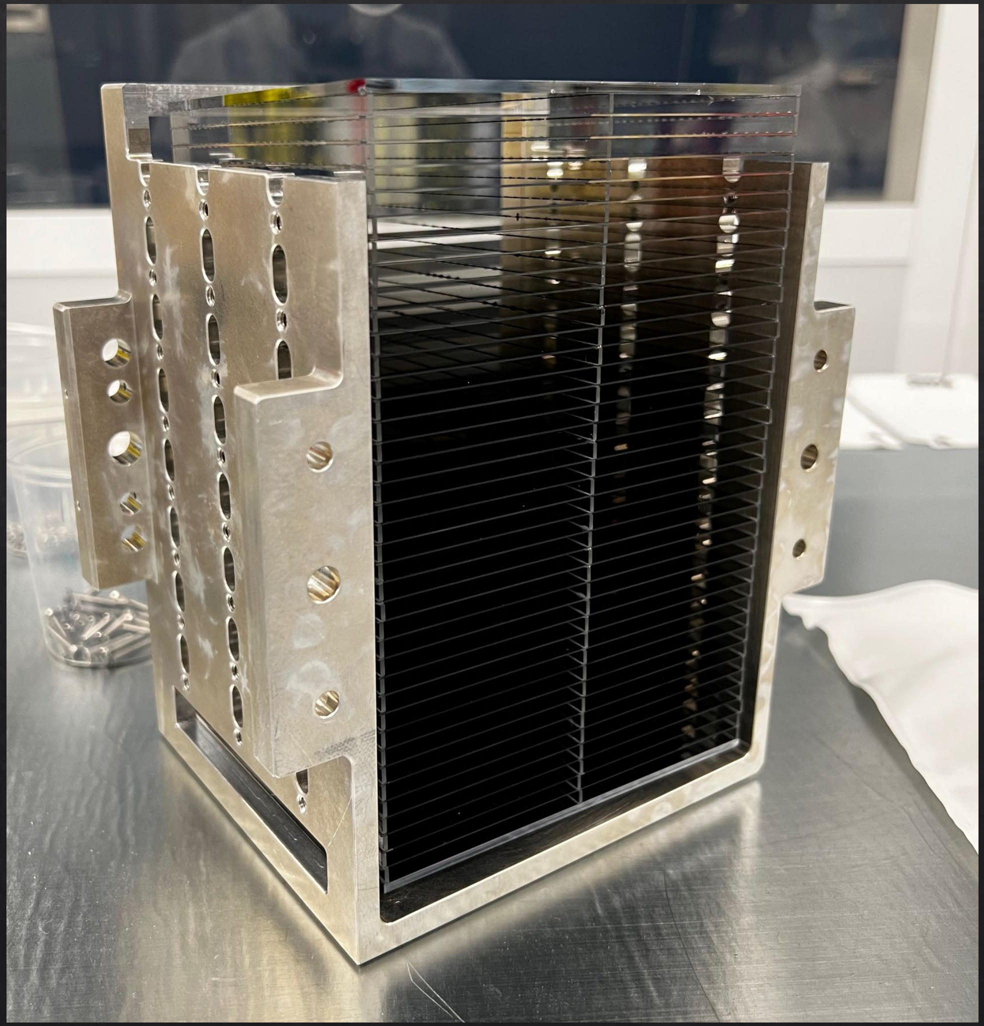
Grating replica on 0.4-mm substrate



Alignment ribs

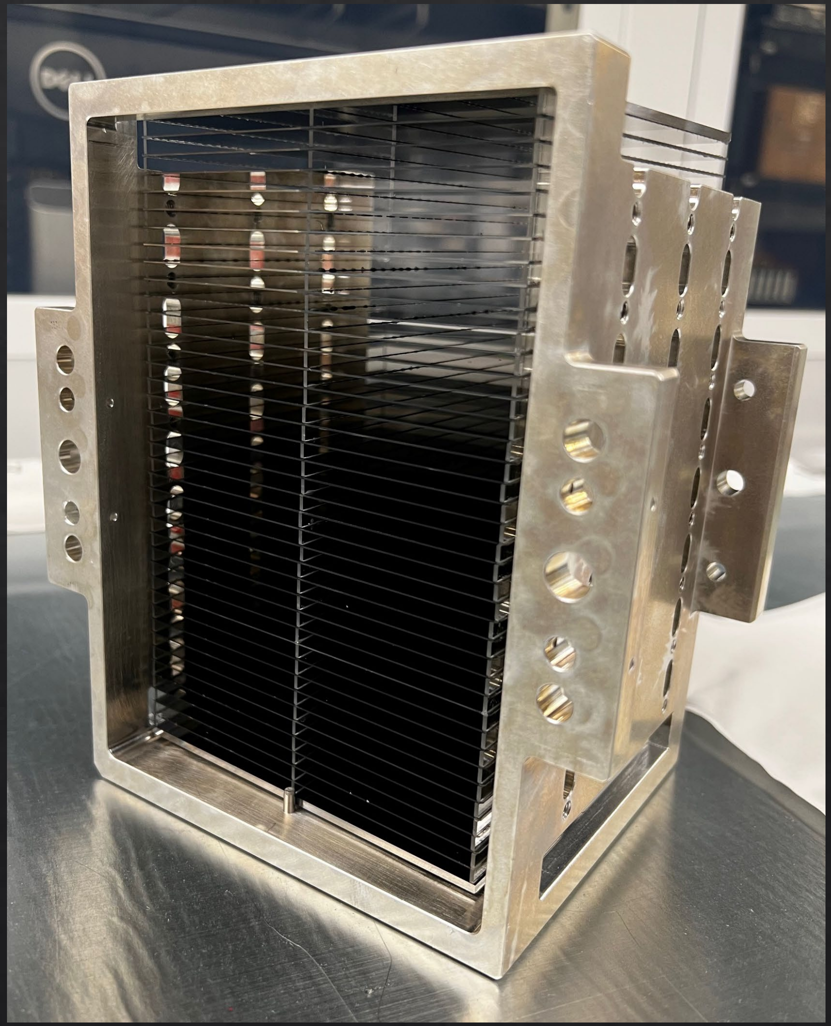


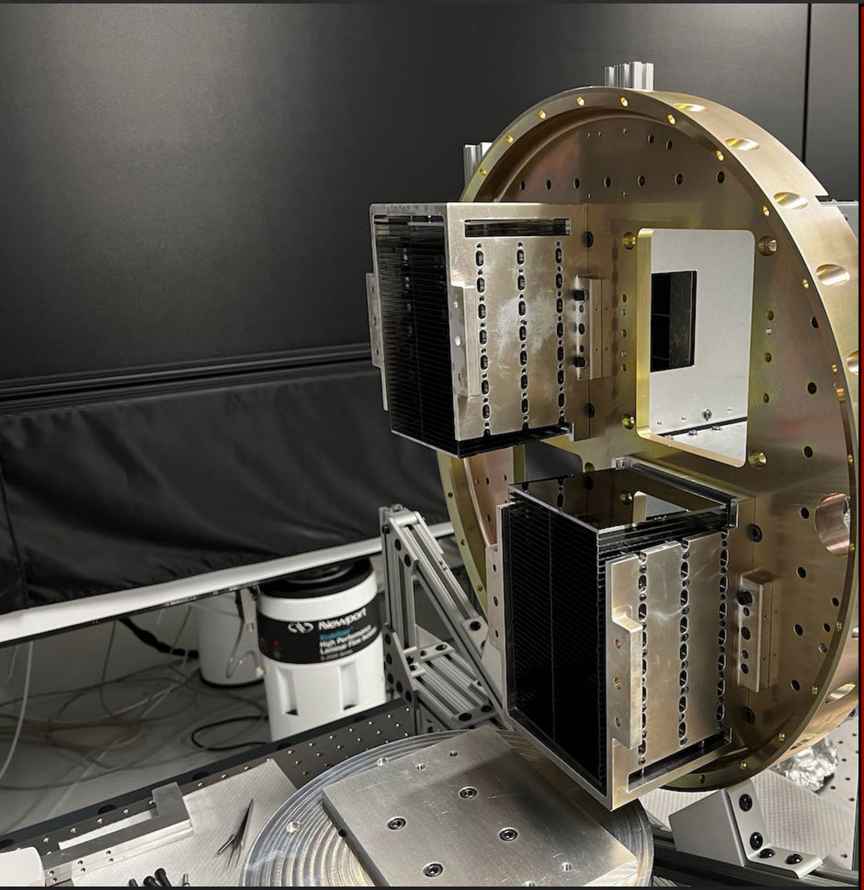
Reflection gratings

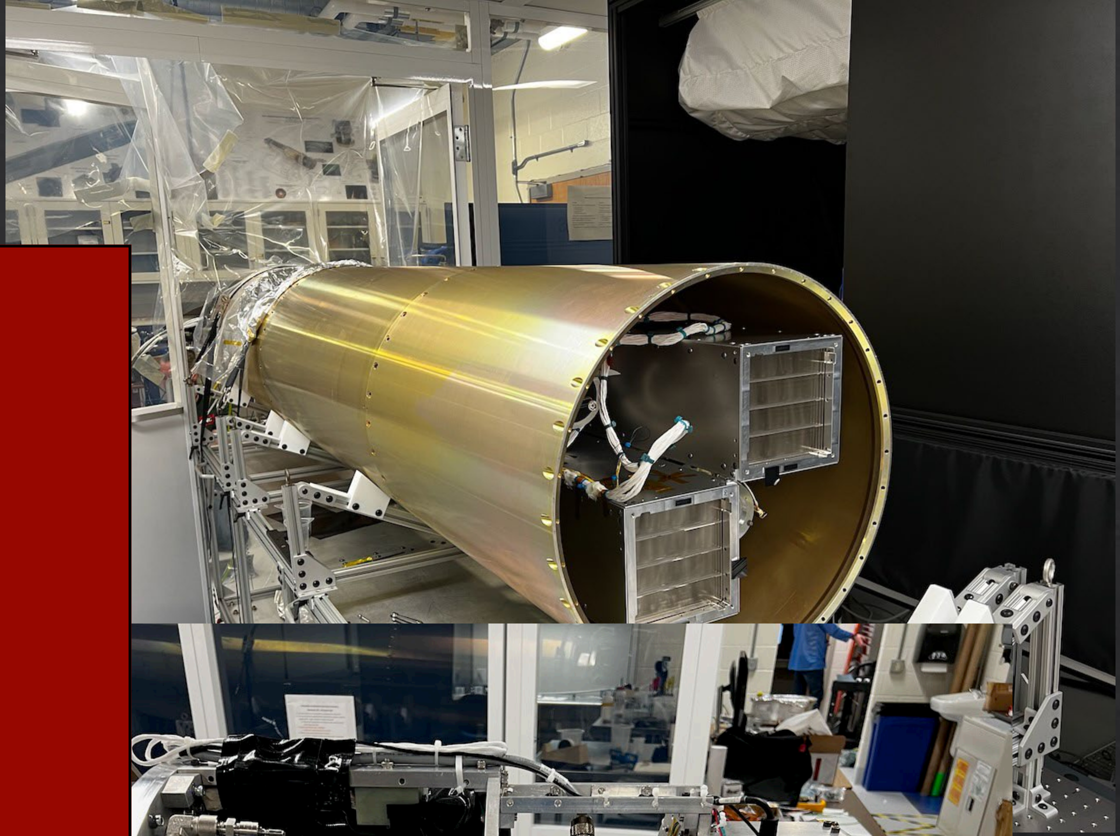


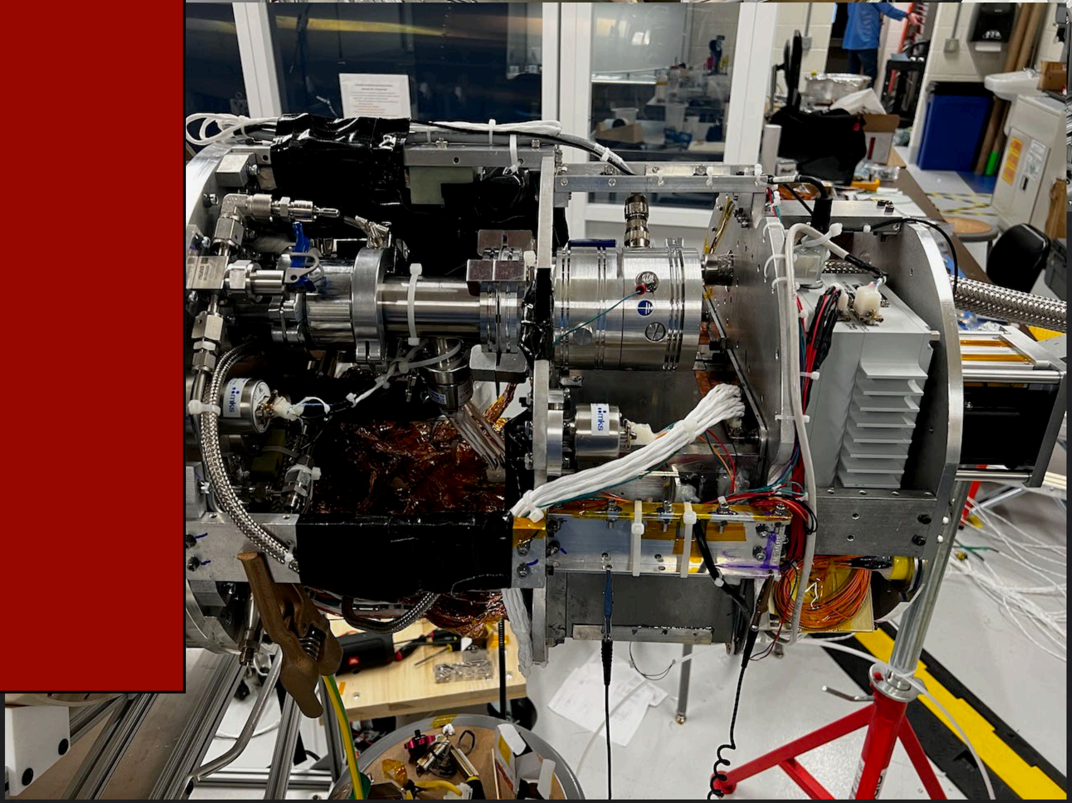
Stacks of 38
gratings per
module

190 total replica
gratings produced!




Newport





tREXS Status

- Initial tREXS-I project ended in 2023
  - Design, fabrication, testing, assembly, calibration, and first flight
  - Thermal-vacuum system failure on launch rail negated X-ray data collection ☹
  - Two-channel spectrograph (planned for four spectrograph channels) for first flight; hardware for extra channels on hand
- To be proposed in NASA APRA24 solicitation for addition of two more channels, performance improvements, and two more launches!
- Developing ESPA-class SmallSat for highest-resolution maps of X-ray background
  - MBS + grating concept adapted for different form factor – same technology!

tREXS-I team

First space project

* = primary project

Now in grad school

Now in industry/NASA

Faculty/Staff

Randall McEntaffer (PI)
*Drew Miles (PS/PM)
*James Tutt (Research professor)
Tyler Anderson / Michael Betts (EE)
*Daniel Washington (R&D Eng)
Bridget O'Meara (ME)
Fabien Grise (Research professor)
Jake McCoy (Postdoc)

Grad/Post-bacc

*Ross McCurdy (Lead grad student)
Ben Donovan (Grad student)
Taylor Wood (Grad student)
*Christopher Hillman (post-bacc)
*Keir Hunter (post-bacc)
***Jessica Mondoskin (post-bacc)**

Undergraduate Researchers

*Logan Baker (Aero Eng)
*Katherine Brooks (Comp Sci)
*Gianna Gagliardi (Mech Eng)
Juan Gonzalez (Mat Sci)
Sarah Hawks (Eng Sci)
*Gabrielle Hernandez (Phys)
Joseph Kang (EE)
Bailey Myers (Astro)
Eli Papadopoulos (Mat Sci)
*Nestor Pelaez (Aero Eng)
***Vincent Smedile (Astro)**
Adam Stone (Astro)
*Joseph Weston (Aero Eng)
*Natalie Zinski (Astro)

Collaborators

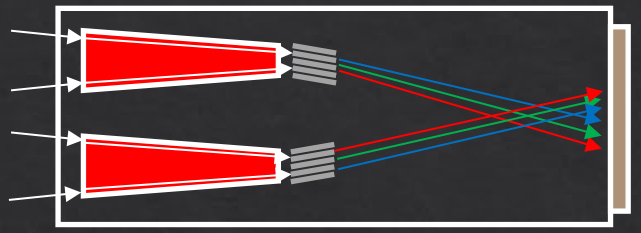
- Penn State Nanofabrication Facility staff
- Philips SCIL Solutions

Suborbital projects enable large NASA missions!

Table 3 List of NASA astrophysics Explorer missions since 2001, including whether the mission PI and instrument had heritage via NASA suborbital programs. Note: the empty entries for instrument heritage reflect the lack of available information, rather than a confirmation of the absence of suborbital heritage.

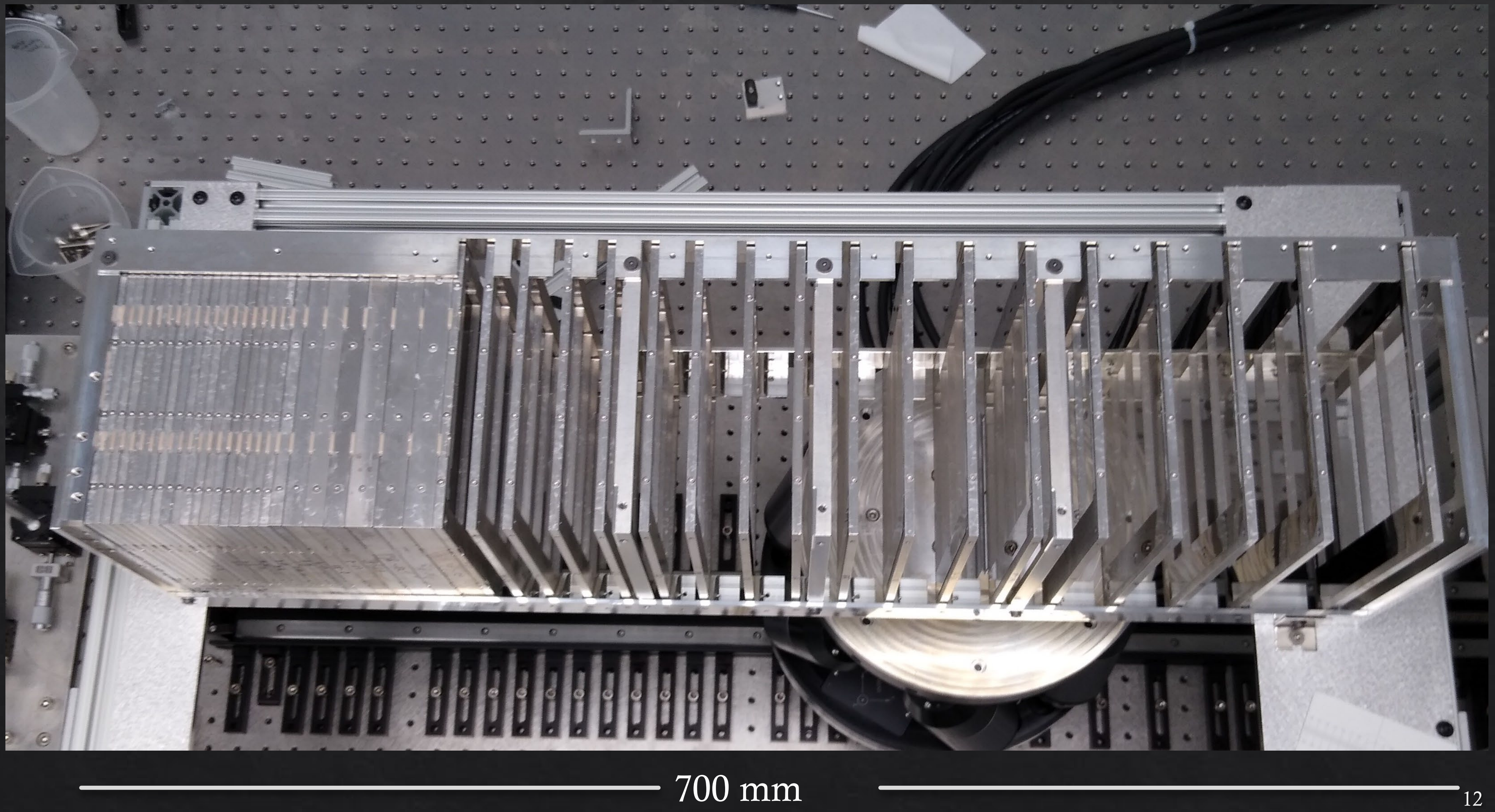
Launch Year	Mission	PI	Instrument Heritage	PI Heritage
2030 (exp.)	UVEX[18]	Harrison	Rockets & Balloons	Balloons[19]
2027 (exp.)	COSI[20]	Tomsick	Balloons[17]	Balloons[17]
2025 (exp.)	SPHEREx[21]	Bock	Rockets[22]	Rockets[23] & Balloons[24]
2021	IXPE[25]	Weisskopf	Rockets	Rockets[26] & Balloons[27]
2018	TESS[28]	Ricker	None[2]	Balloons[29]
2012	NuSTAR[30]	Harrison	Balloons[31]	Balloons[19]
2009	WISE[32]	Wright	-	Rockets & Balloons[33]
2004	Swift[34]	Gehrels	Rockets	Balloons[35]
2003	GALEX[36]	Martin	Balloons	Rockets[37] & Balloons[38]

From in-progress review paper (Miles 2025)

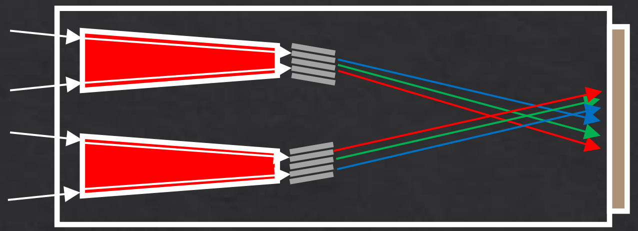


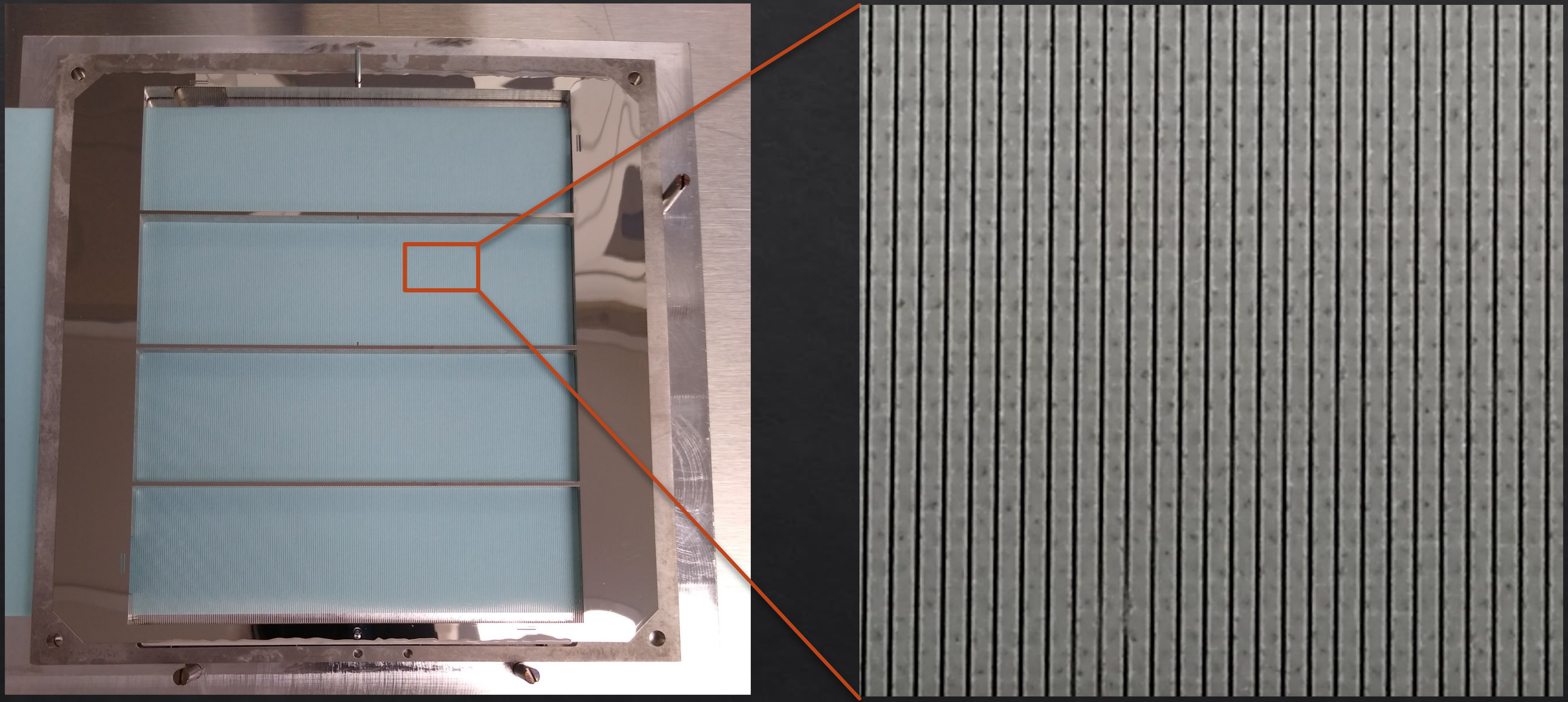
Mechanical beam shapers (MBS)

- Passively sculpt incident light to produce 1D converging beam
- Allows for large FOV (>10 deg^2) and ≈2-3' LSF
- tREXS:
  - 700-mm long module
  - 45 plates/module
  - 2010-mm focal length



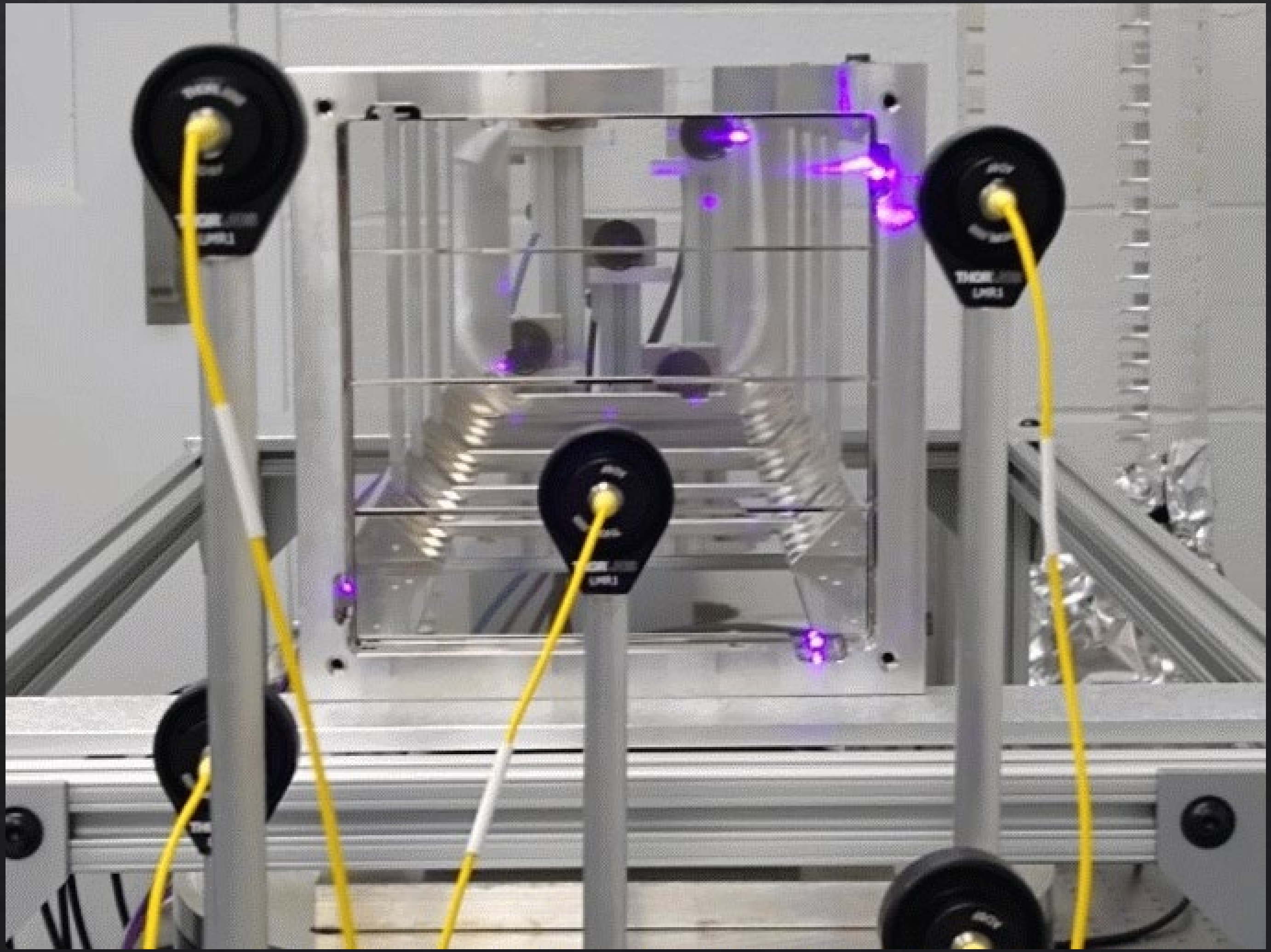
MBS Plates

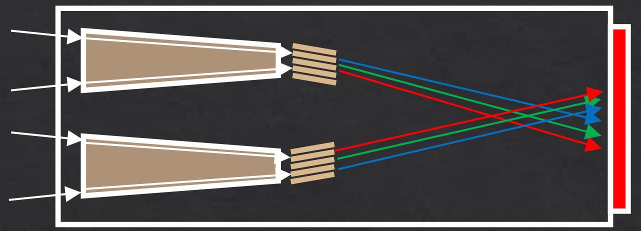




Slit width from 375 – 500 μm; 241 slits/plate; 45 plates

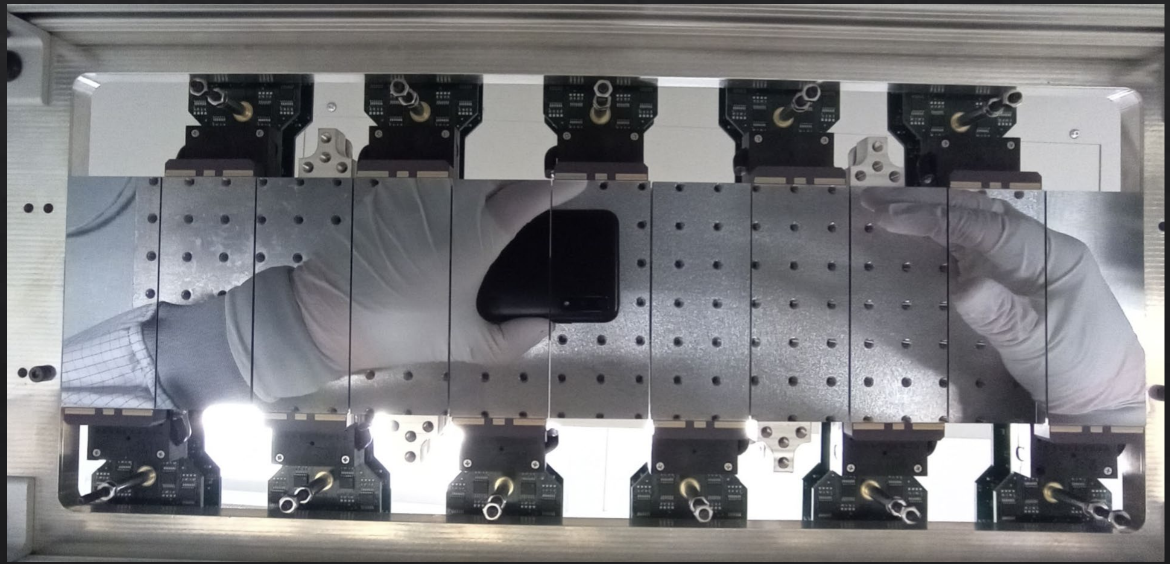
MBS alignment

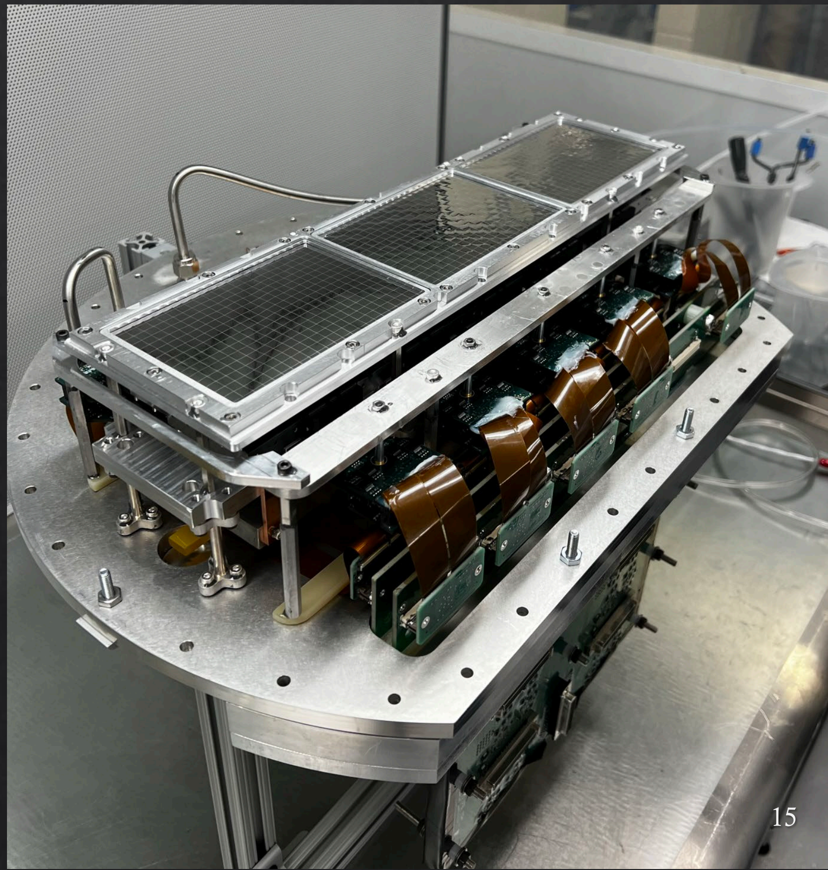




Focal-plane camera

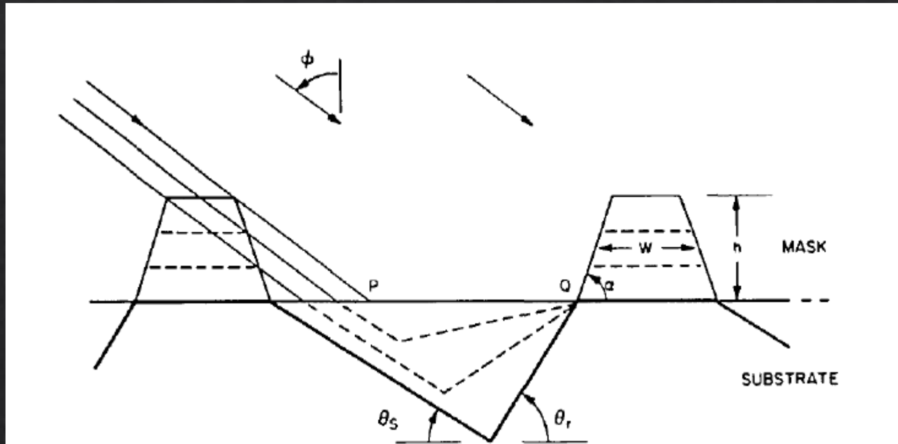
- 11 X-ray CMOS devices
  - Teledyne/e2v CIS 113
  - Custom-built readout and on-board signal processing
  - 1920 x 4608 (97 Mpix total); >250 cm^2 coverage
  - Free-standing, 150-nm Al three-piece optical-blocking filter
  - Cooled to 190K with liquid nitrogen





Blazed gratings – IBE

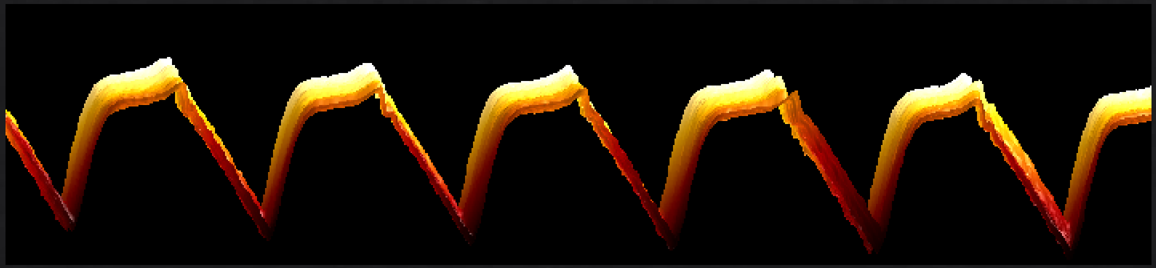
- Expose pattern to directional ion beam to form blazed facets based on etch geometry:
  - V_s and V_m are etch rates of substrate and mask, respectively
  - θ_p is the angle of maximum etch rate for given material



Johnson & Ingersoll (1981)

$$\frac{V_s(\varphi + \theta_s)}{\sin\theta_s} = \frac{V_m(\theta_p)\cos(\alpha+\varphi)}{\cos\varphi\,\sin(\alpha+\varphi-\theta_p)}$$

6) Blaze grating with IBE



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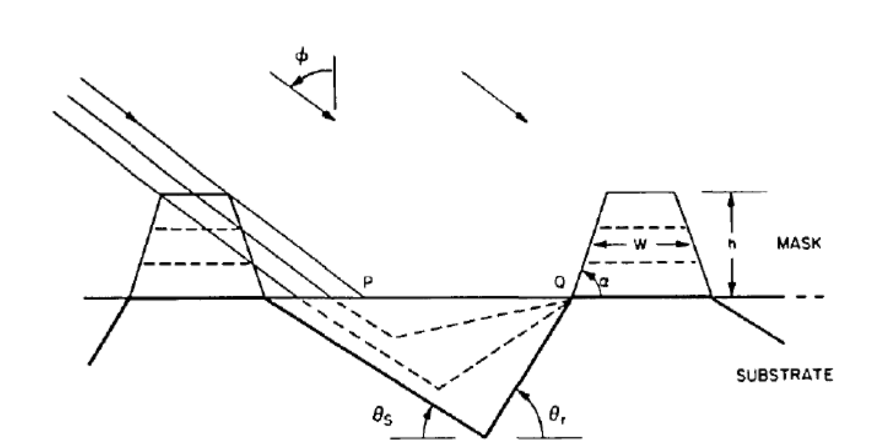

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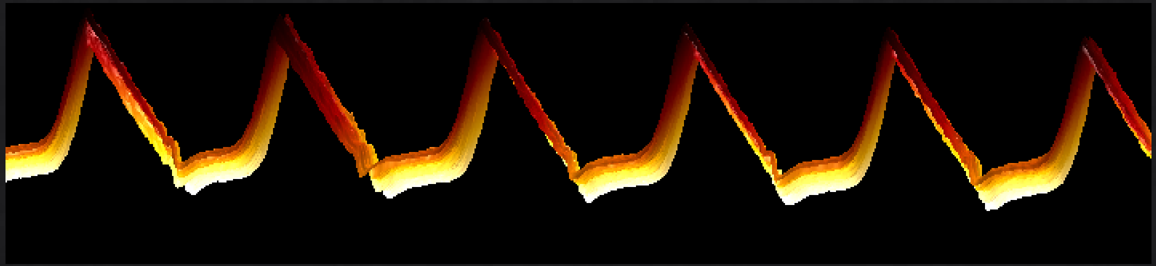

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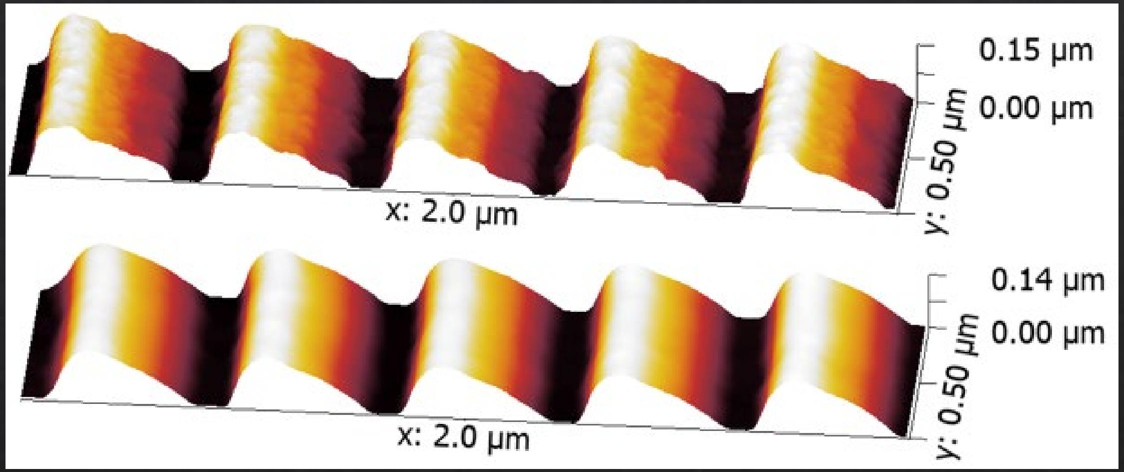
Blazed gratings – thermally-activated selective topography equilibration (TASTE)



Grating	Avg. Absolute Eff.	Avg. Peak Order Eff.	Avg. Relative Eff.
IBE	≈36%	≈18%	≈60%
TASTE (small period)	≈38%	≈23%	≈65%
KOH (Arcus)	≈60%	≈42%	≈85%

- Uses greyscale EBL to produce 3D structures in resist, then thermal reflow to produce shaped facet

Challenges with TASTE:

- Beam step size and spot size become a significant fraction of the feature
- Exposure time increases with complexity of pattern
- Electron scattering is more of a concern
- Features are more sensitive to resist contrast
- Resist process blur has a bigger effect

Why develop grating technologies?

Gap Name	Tier	Performance Goals and Objectives
High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings (from HWO START/TAG)	1	The technical goal should include the development and in-vacuum demonstration of several classes of diffraction gratings: **High Resolution: E**chelle gratings capable of achieving R ≥ 50,000 with ≥ 80% peak-order groove efficiency and I/I0 < 1e-3 at Δλ = 1 nm post-coating, with supporting simulations predicting the observed performance. This performance should extend through the far ultraviolet (FUV; 100 – 180 nm) bandpass. **Medium/Low Resolution:** Aberration correcting (curved grooves) solutions on curved substrates demonstrating groove efficiencies ≥ 60% post-coating and I/I0 < 1e-5 at Δλ = 1 nm **Ultra-low blaze angles:** (≤ 2°) gratings demonstrating ≥ 60% groove efficiency and I/I0 < 1e-5 at Δλ = 5 nm post-coating **UV Coatings on gratings:** Demonstrated compatibility with state-of-the-art FUV coating techniques with < 1% loss in relative diffraction efficiency. **Grating Characterization:** Specialized vacuum characterization facilities for scatter, resolution, ghosting and efficiency measurements.
High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy	1	Demonstrate CAT gratings and OPGs with high efficiency (>45%) and resolving power (> 7500) with size > 50 x 50 mm^2. CAT grating open area (illuminated by x rays and not blocked by support structures) > 70%. This requires a scalable (many hundreds of gratings), large-area fabrication process for ~ 6 μm deep, ~ 40 nm wide grating bars and narrow support structures. OPGs require fabrication processes for modestly blazed grooves (~30-50°) in radial groove patterns that can be replicated onto thin substrates. Alignment into large arrays needs to be demonstrated.

Source: NASA Astrophysics Projects Division