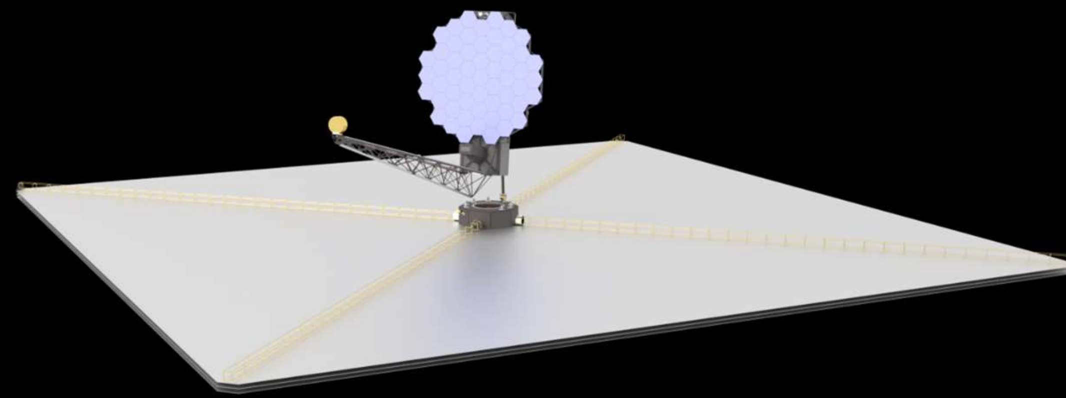
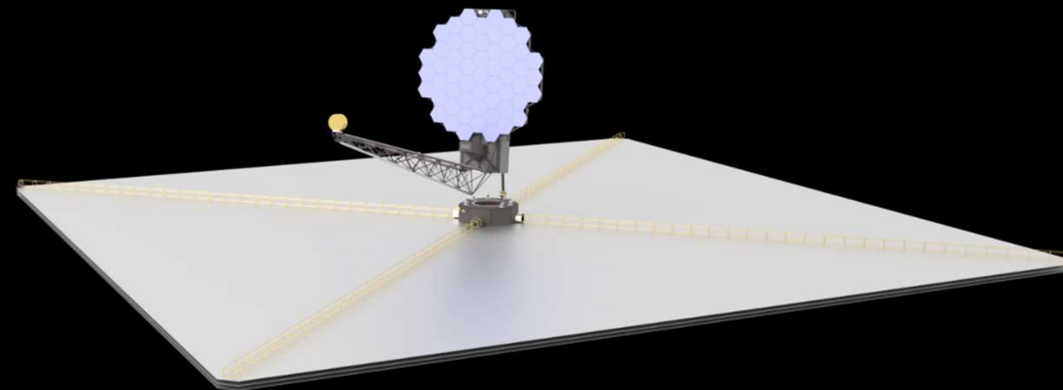


UV Spectroscopy with the Habitable Worlds Observatory: Instrument Capabilities and Technology Needs

Kevin France – University of Colorado

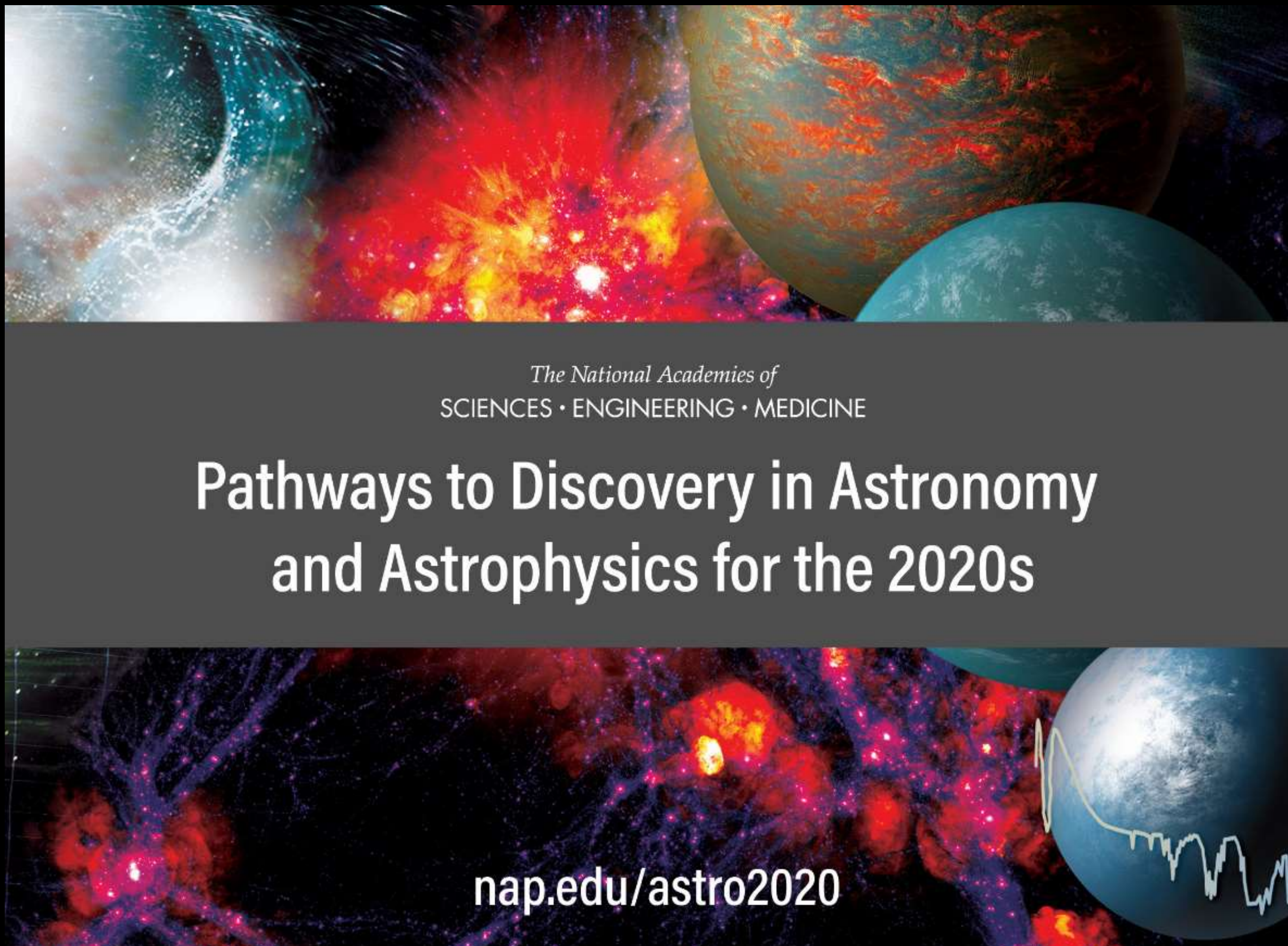
NUVA eMeeting

24 October 2024



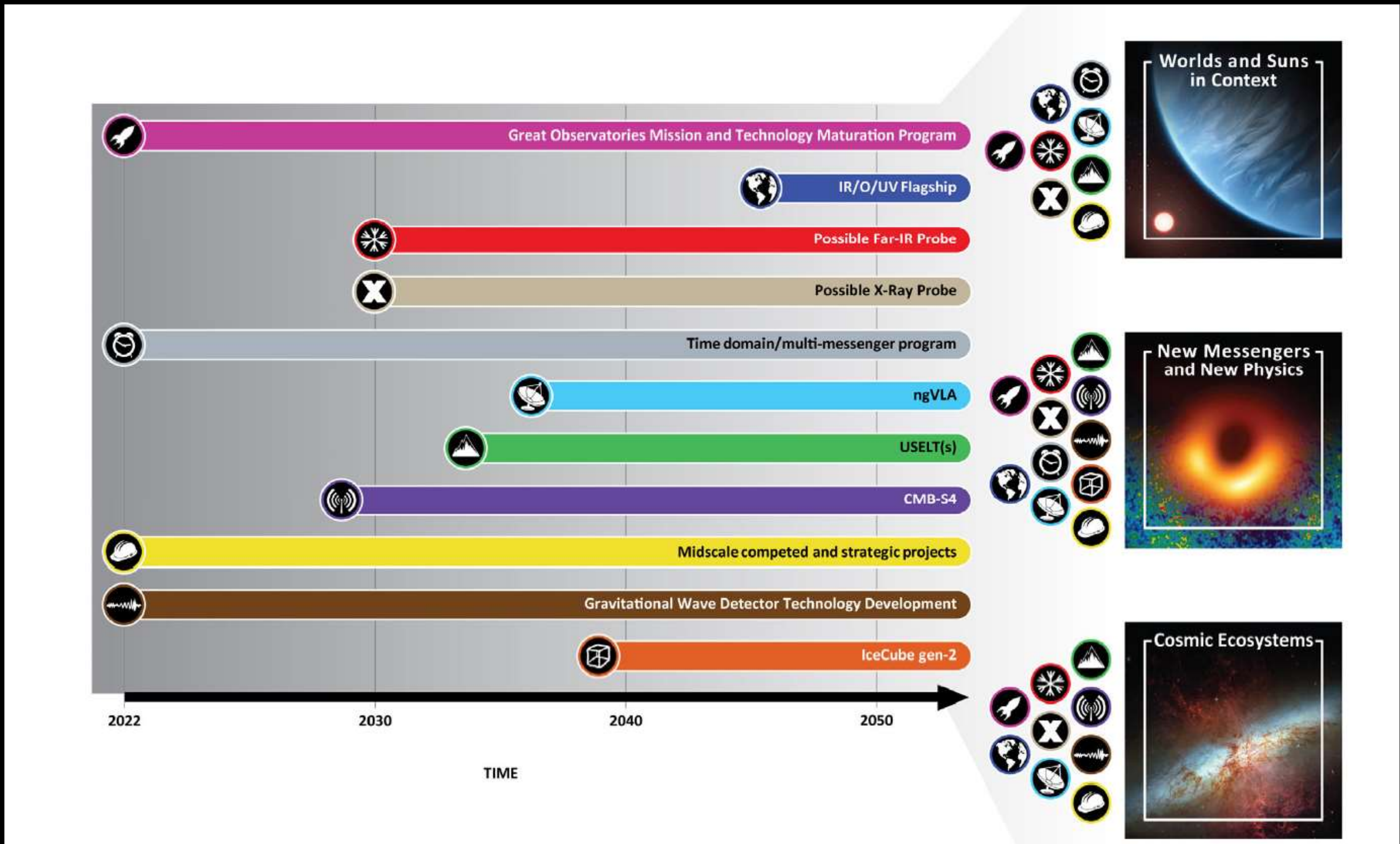
UV Spectroscopy with the Habitable Worlds Observatory: Instrument Capabilities and Technology Needs

Kevin France, Brian Fleming (Colorado), Stephan McCandliss (JHU)
Paul Scowen, Aki Roberge, Manuel Quijada, Javier Del Hoyo (NASA/GSFC),
Luis Rodriguez de Marcos (Catholic University of America and NASA/GSFC
(CRESST II Agreement)), Shouleh Nikzad, John Hennessy, Michael Hoenk
(NASA/JPL), Oswald Siegmund (UC Berkeley), Jason Tumlinson (STScI/JHU)



https://nap.nationalacademies.org/resource/26141/interactive/

"THE SURVEY RECOMMENDS THAT THE FIRST MISSION TO ENTER THIS PROGRAM IS A LARGE (~6 M APERTURE) INFRARED/OPTICAL/ULTRAVIOLET (IR/O/UV) SPACE TELESCOPE."



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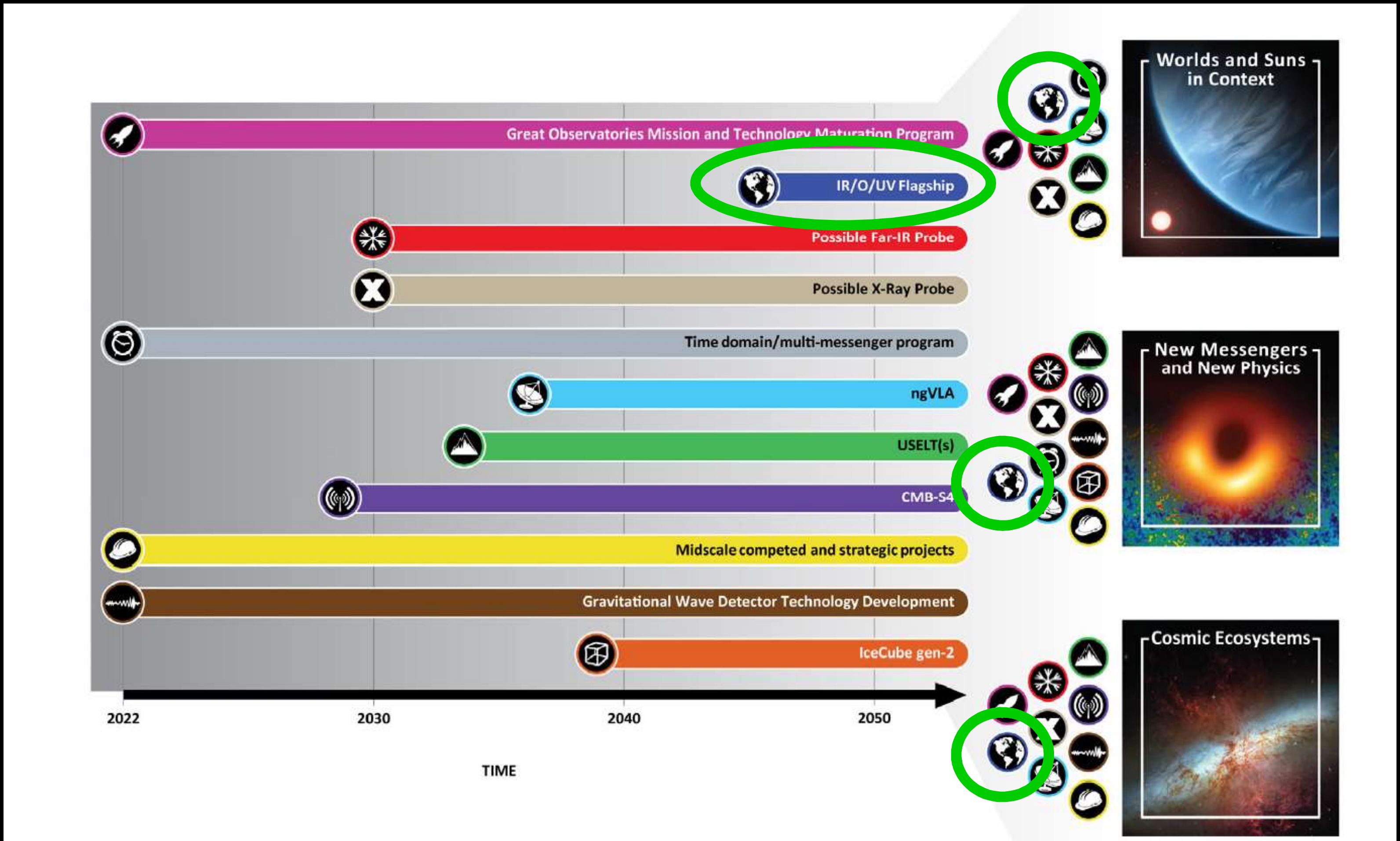
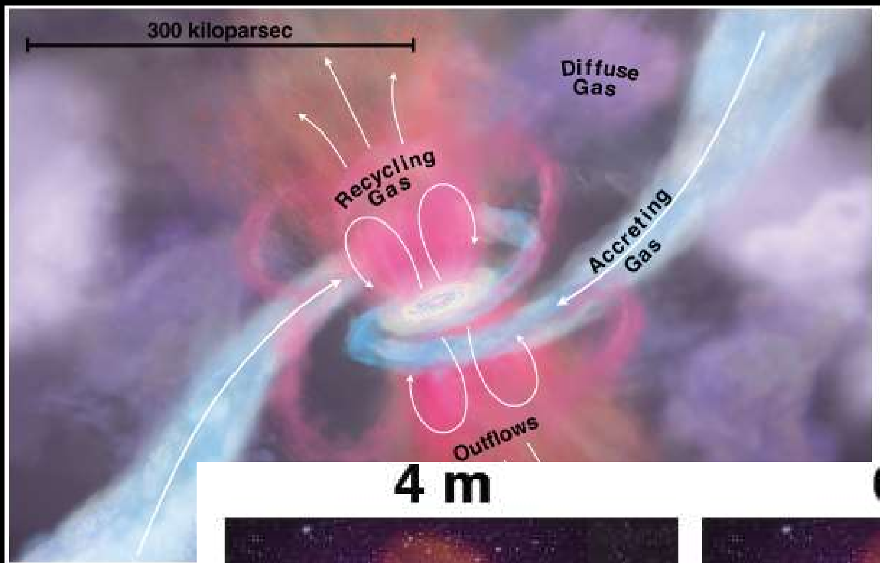
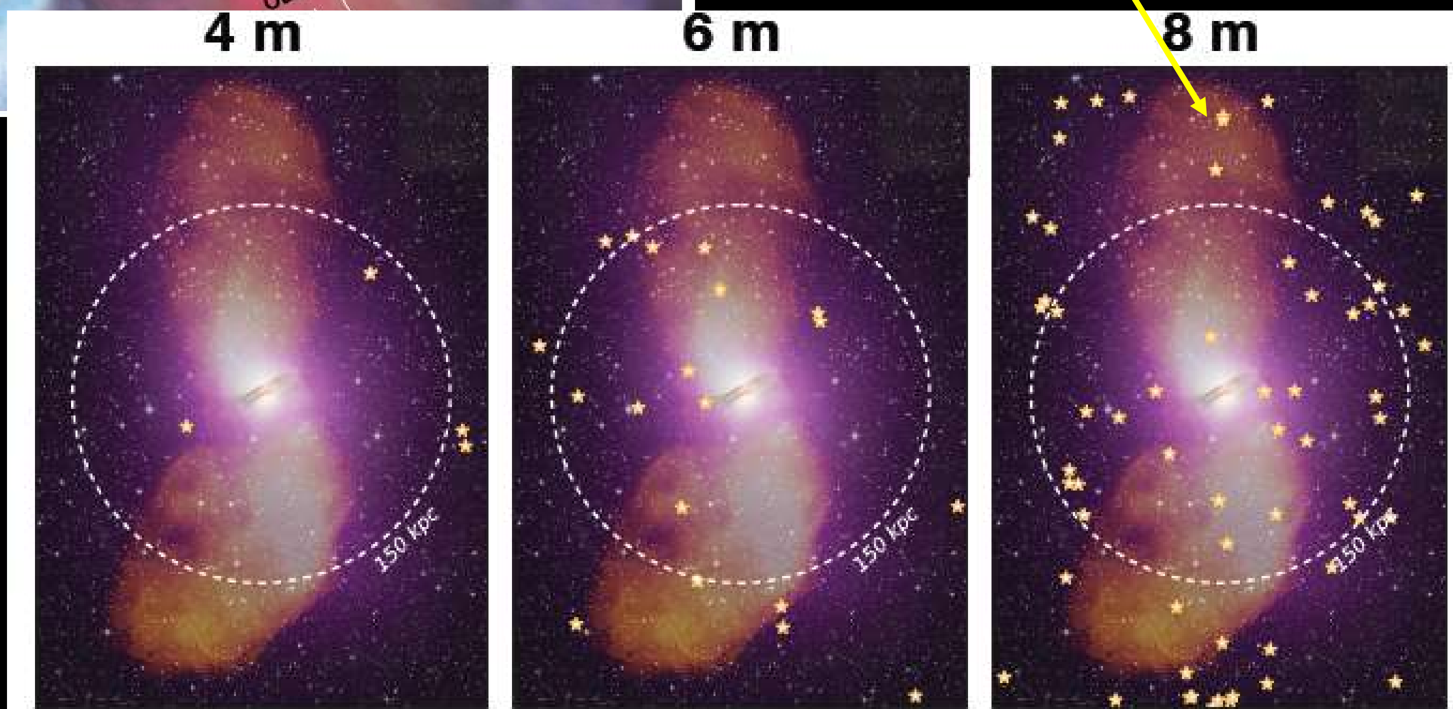


Cosmic Ecosystems

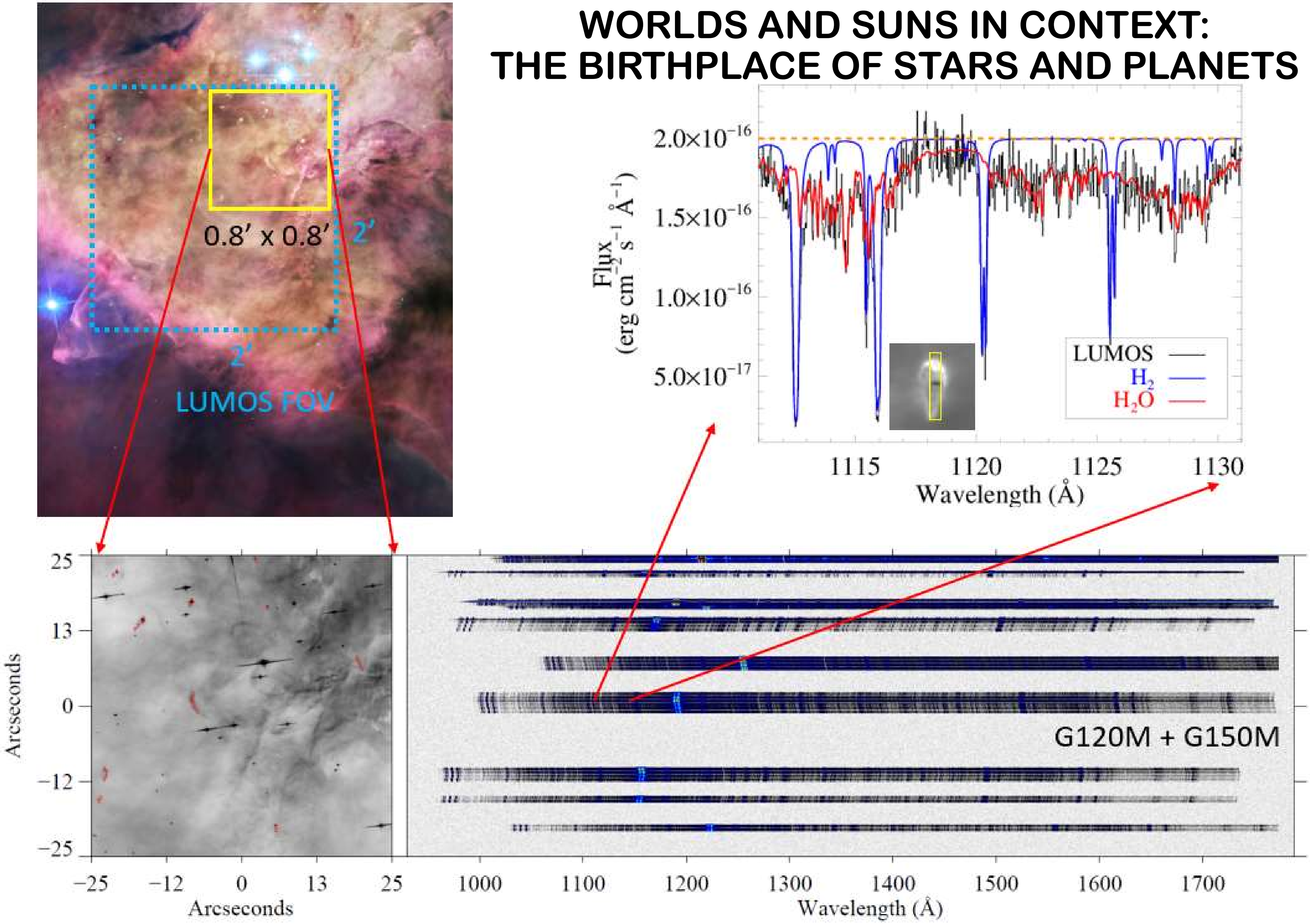




★ Background QSOs observed with S/N > 10 in FUV continuum in < 1 hour

LUVOIR Final Report 2019

WORLDS AND SUNS IN CONTEXT: THE BIRTHPLACE OF STARS AND PLANETS



France et al. 2017; LUVOIR Final Report 2019

The HWO Instrument Recommendation from EOS-1

"The mission will also need focal plane instrumentation to acquire:

- images and spectra over the range of **100 nm** to 2 microns with
  - parameters similar to cameras and spectrometers proposed for the Large Optical UV Infrared Telescope (LUVOIR) and the Habitable Exoplanet Observatory (HabEx)."

"These instruments would include:

- moderately wide-field **imaging at UV**, optical and near-IR wavelengths as well as
- **multi-object spectroscopy** over a similar wavelength range."

The Habitable worlds Ultraviolet Multi-object Spectrograph (HUMS): What do we need and how will we get there?

Outline:

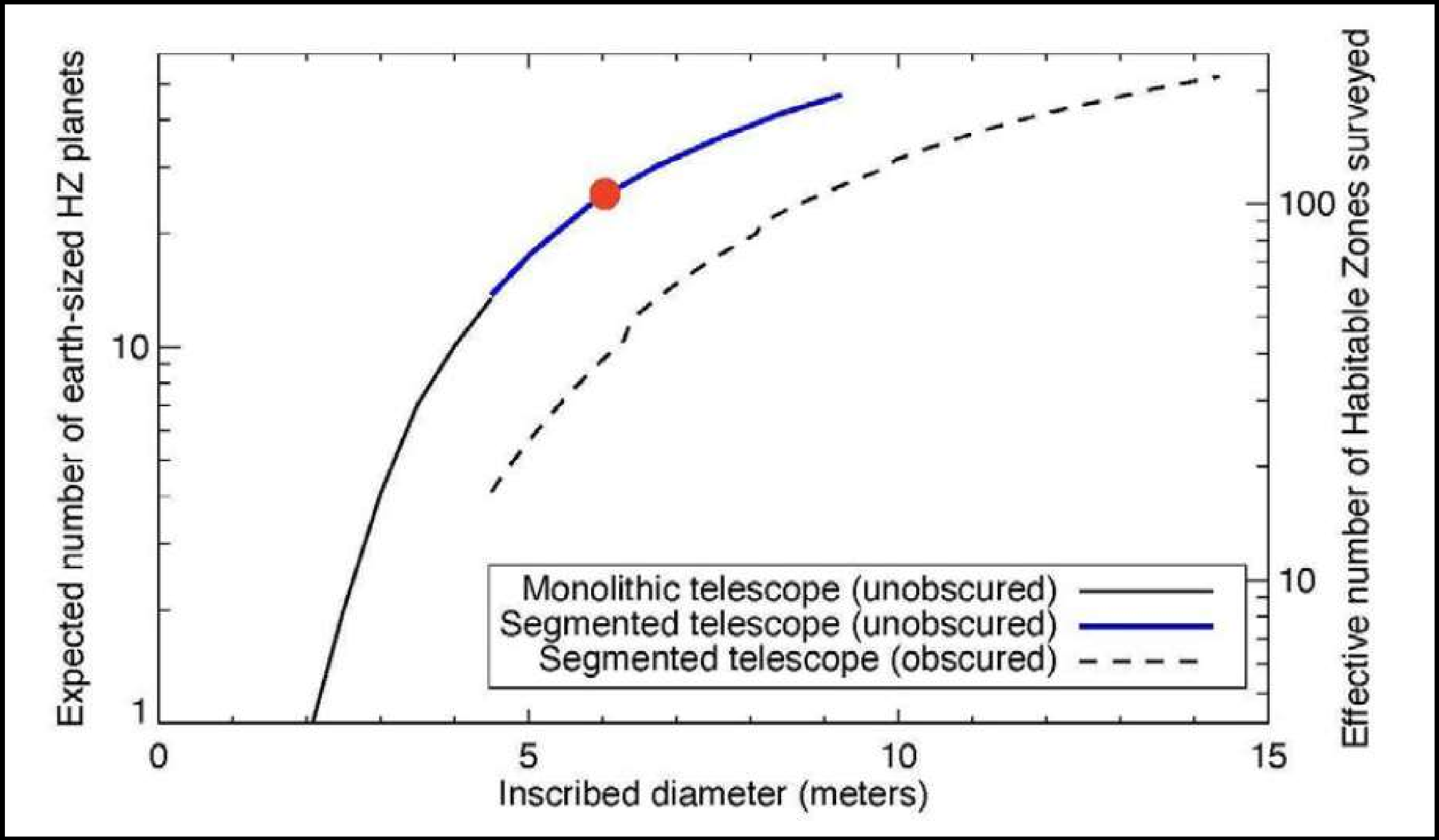
1. Leveraging our previous investments

2. Overview of key technologies needed to enable UV imaging and spectroscopy on HWO

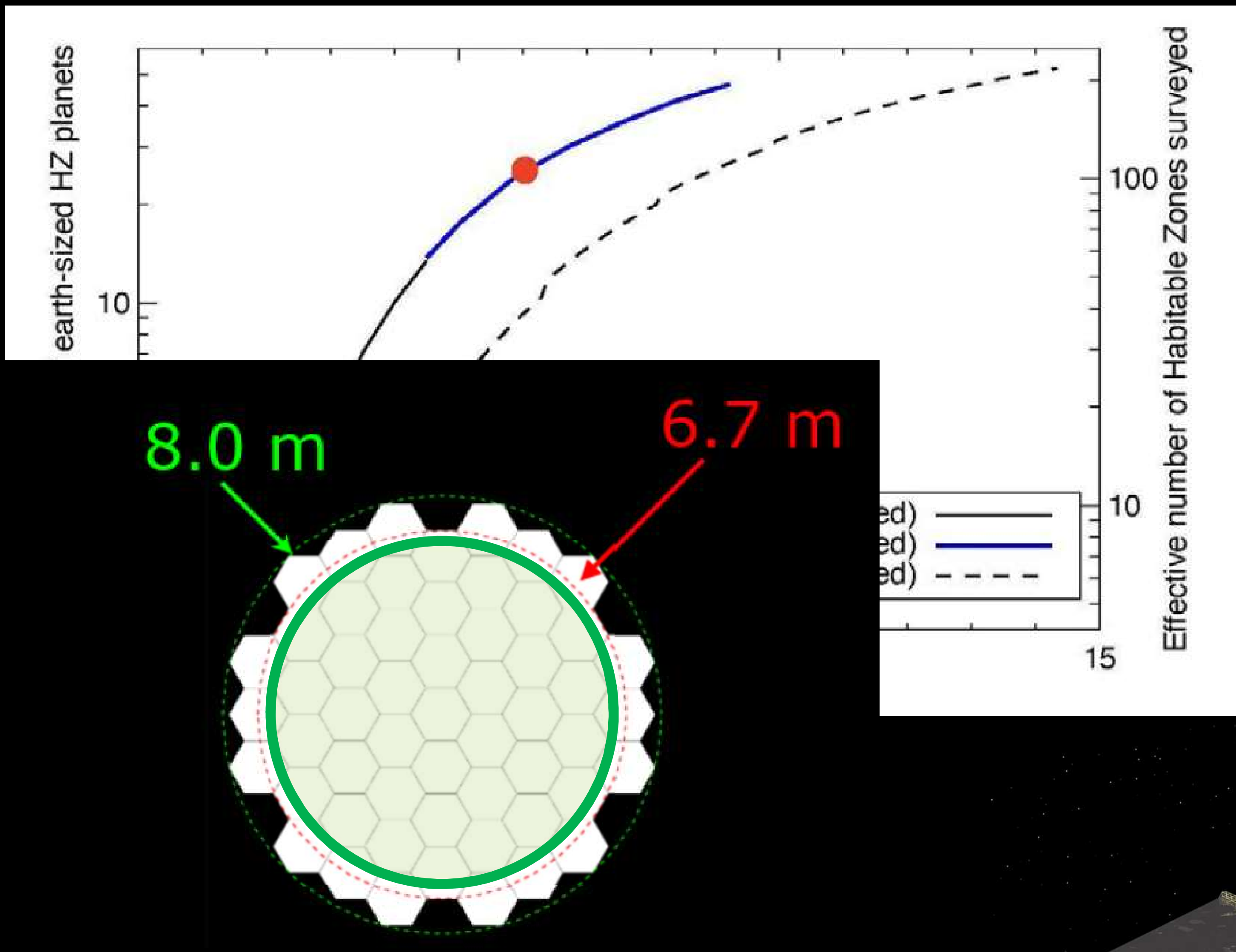
3. Laboratory testbeds and prototype instruments

4. Investing in our Early Career colleagues

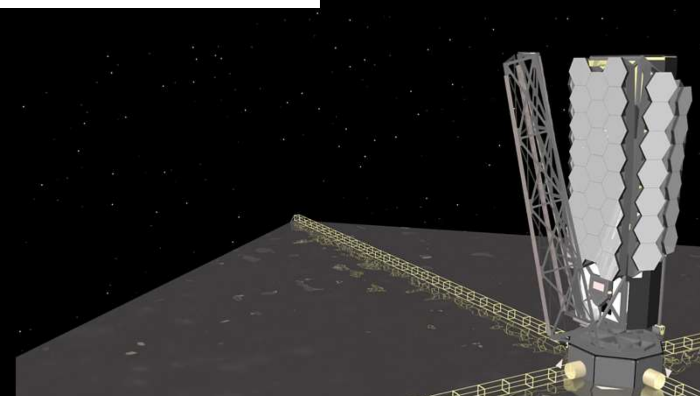
LARGE, ≥ 6 M INSCRIBED



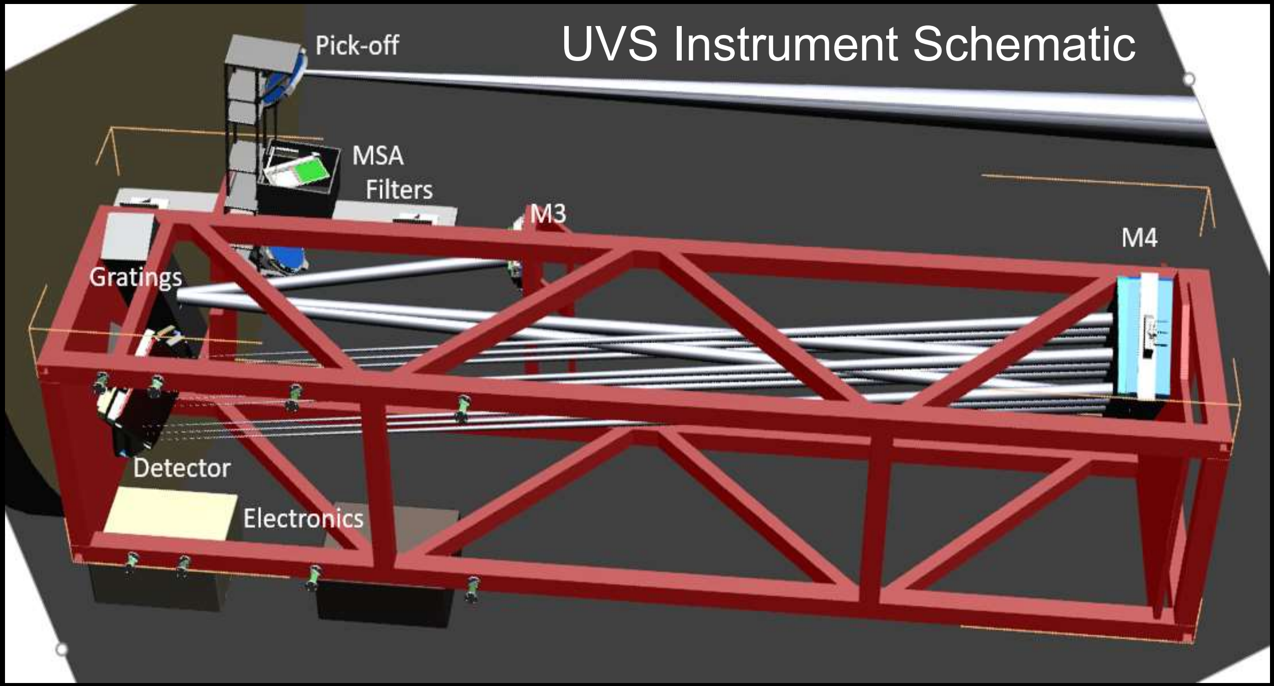
LARGE, ≥ 6 M INSCRIBED



LUVOIR-B



LUVOIR/LUMOS and Habex/UVS: Roadmap UV instrument concepts for HWO

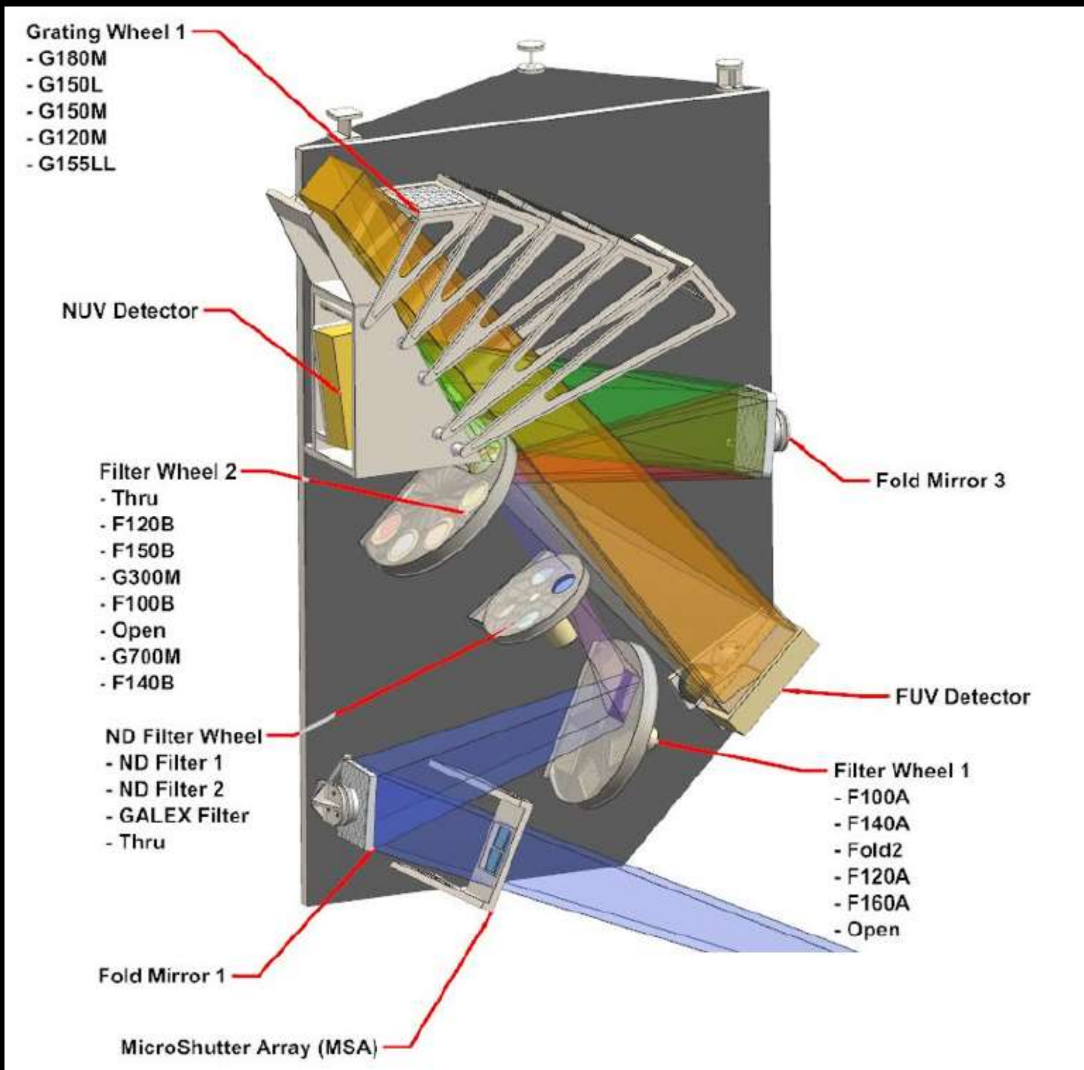


Instrument overview papers:

France et al. SPIE 2017
Scowen et al. SPIE 2019

LUVOIR and Habex final reports, 2019

LUMOS: three channels (FUV, NUV, optical imaging and spectroscopy)



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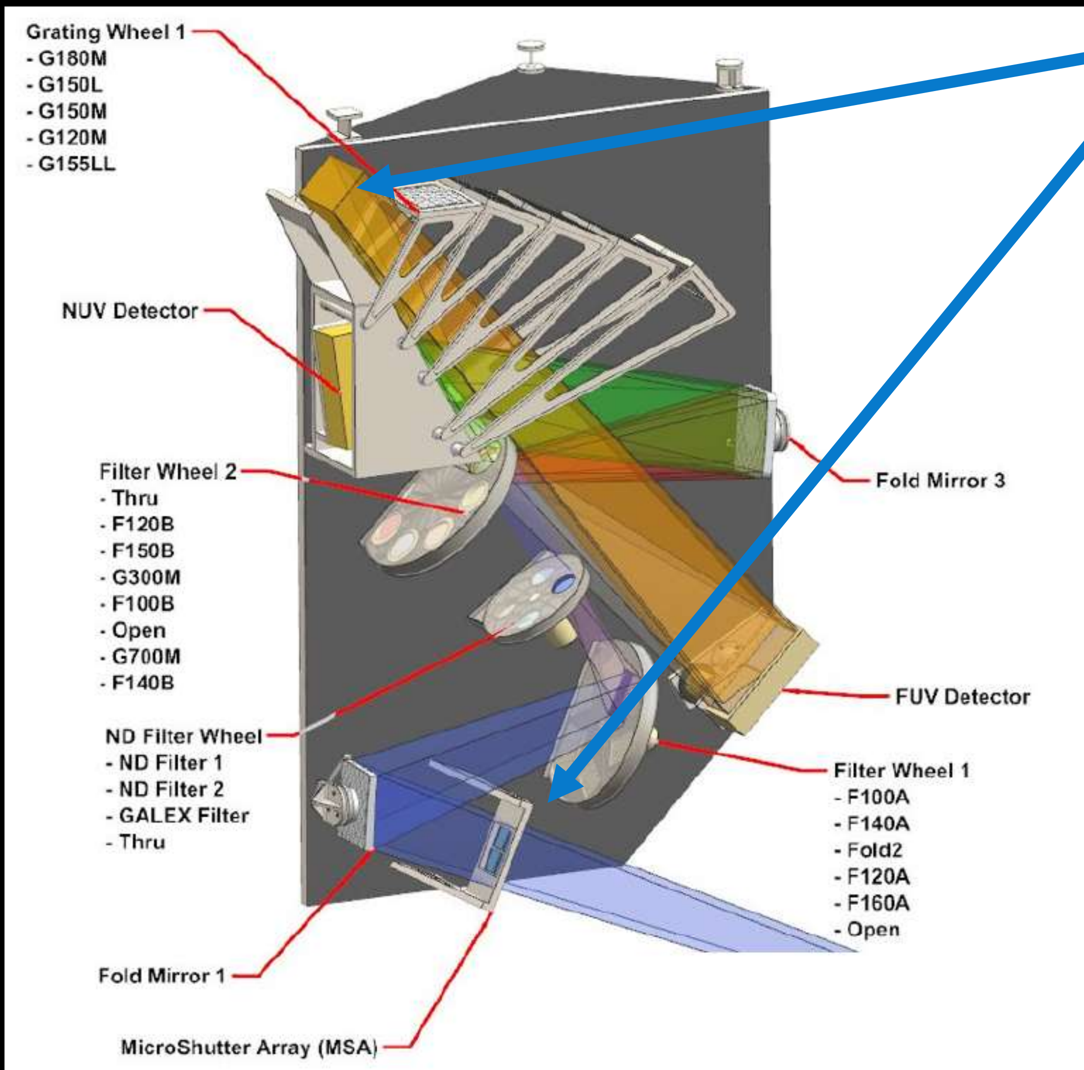

- Low/Med-res (R =500 -> 60K), FUV, NUV, optical **MOS**. FOV = 2’ x 2’

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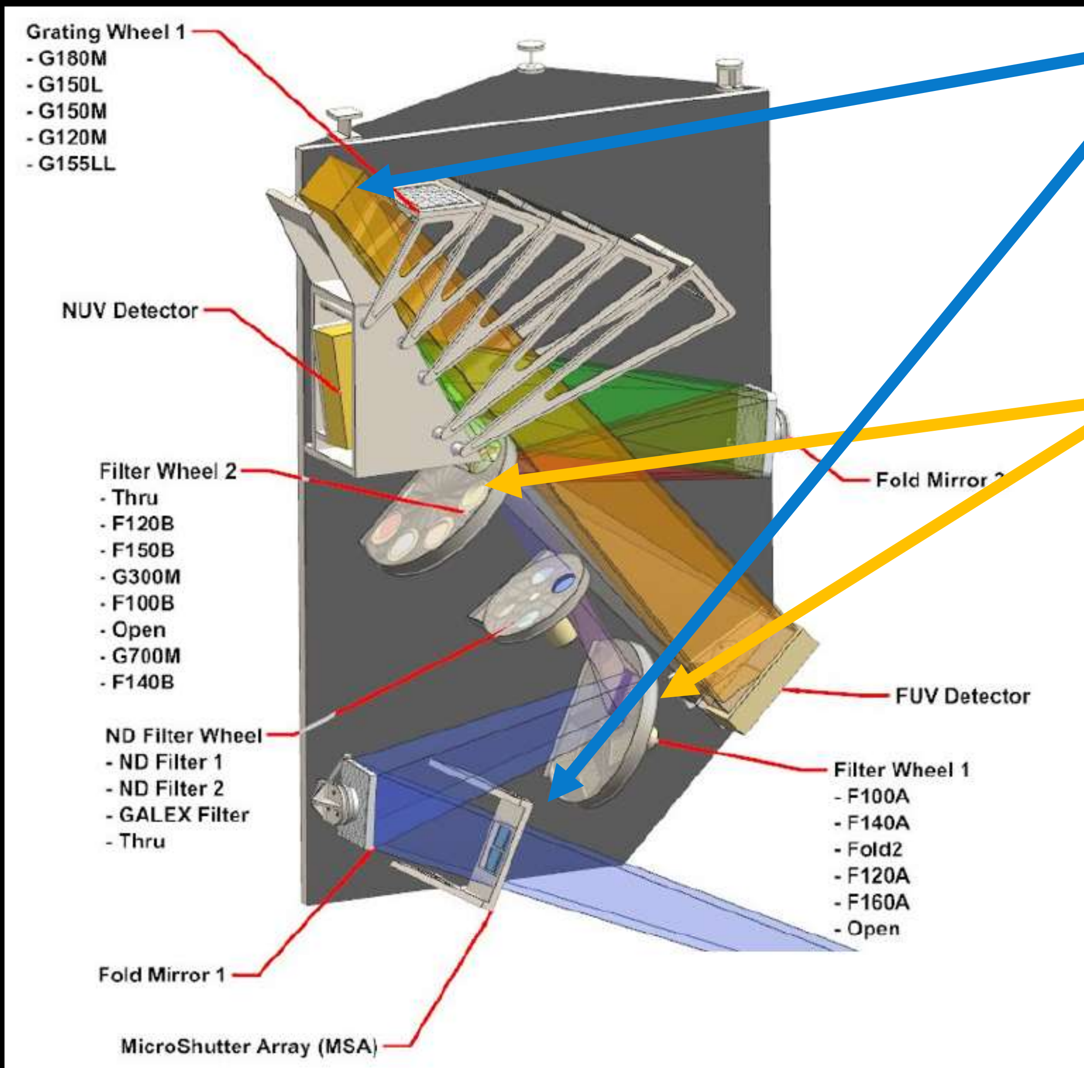

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- FUV **imager**. FOV = 2' x 2' + FUV broad and medium band filters.

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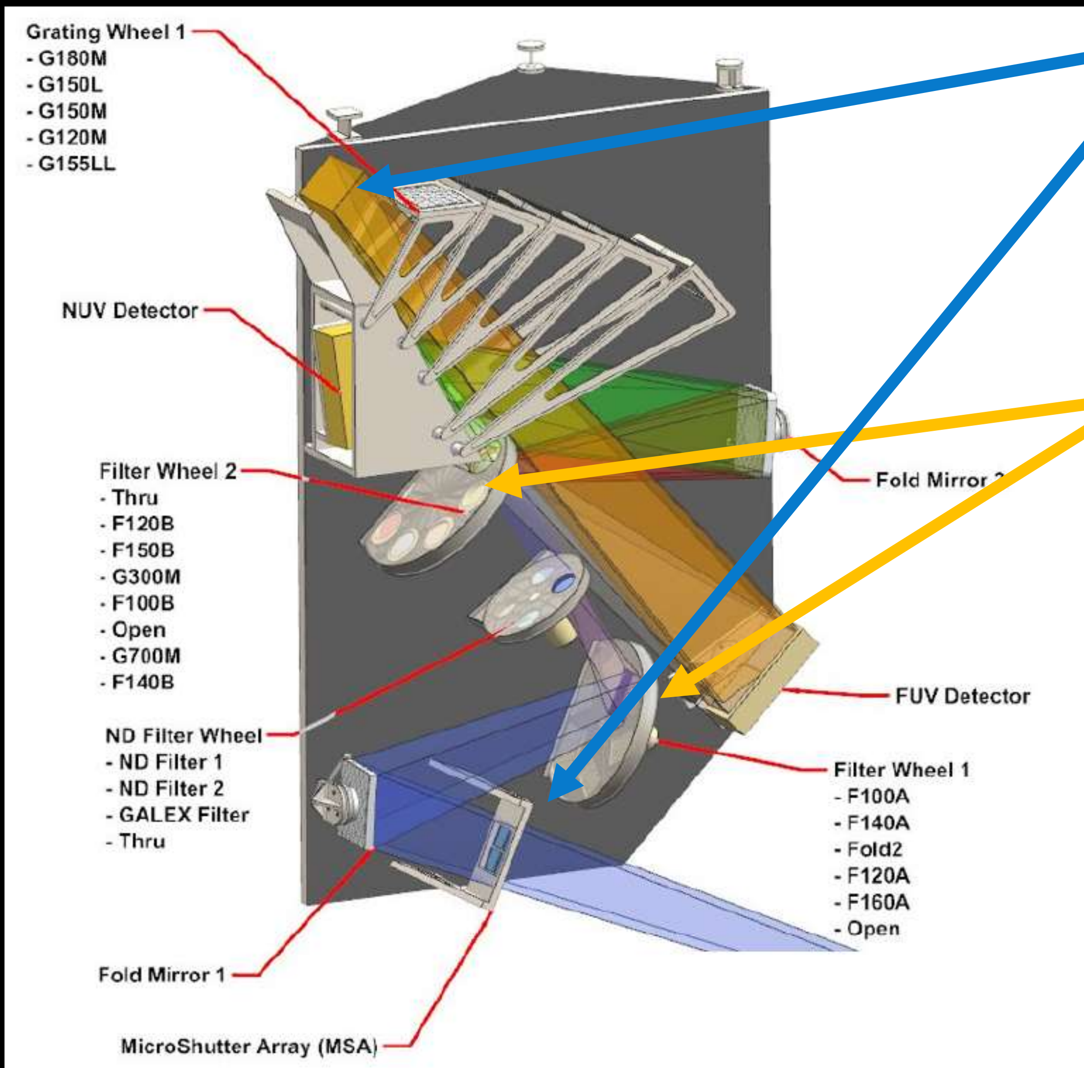
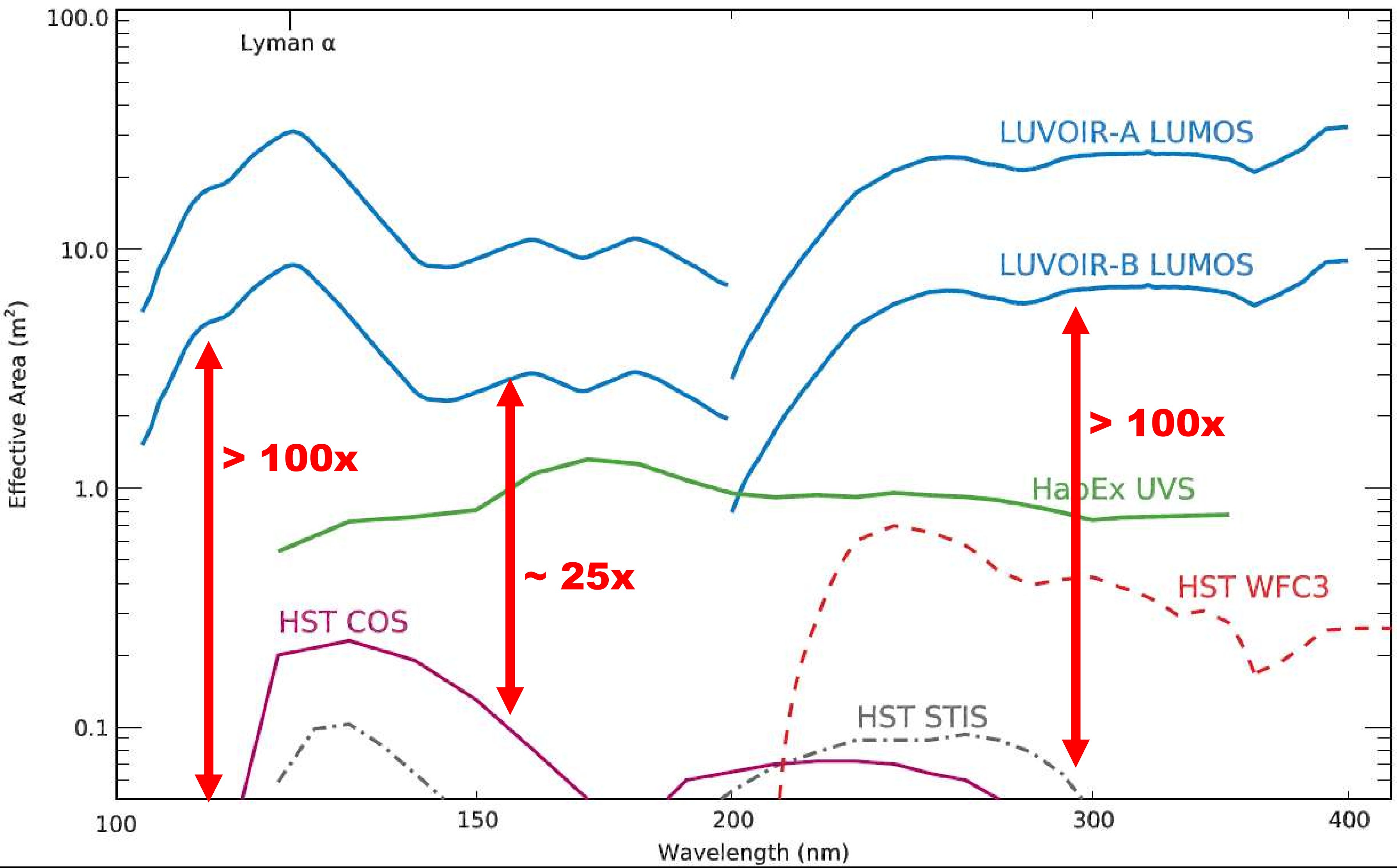


- Low/Med-res (R =500 -> 60K), FUV, NUV, optical **MOS**. FOV = 2' x 2'
- FUV **imager**. FOV = 2' x 2' + FUV broad and medium band filters.
- Not shown: High-res (R ≥ 100K) **point source FUV spectrograph** (complements CNES POLLUX instrument)

Target Sensitivity Performance

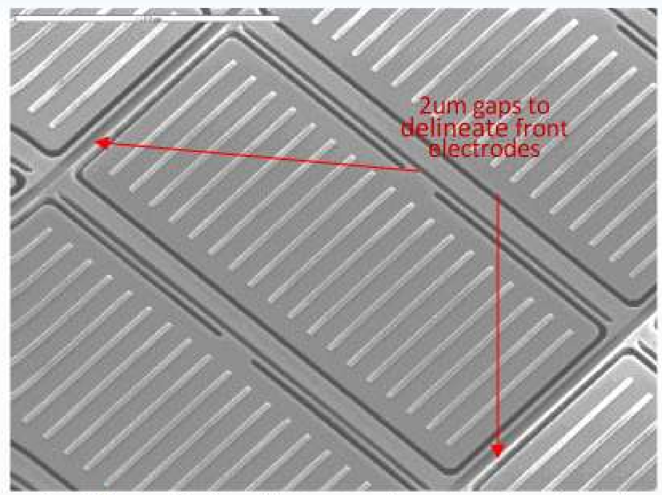


Courtesy of Eric Lopez, NASA/GSFC

Spectral Resolution(s) and Multi-Object Capability

Mode	Peak Sensitivity Band (nm)	Res Pow (best 1'x1' of FOV)	Ang Res (best 1'x1' of FOV, mas)
G120M	100-140	40K	31
G150M	130-170	52K	32
G180M	160-200	59K	33
G155L	100-200	17K	39
G145LL	100-200	530	23
G300M	200-400	33K	23
G700M	400-1000	28K	41
FUV Img	100 - 200	N/A	40

Multi-object selection with micro-shutter arrays (MSAs), development work led at NASA/GSFC



Front side of shutter: column electrodes

~ 800 shutters available per exposure in M & L MOS modes

Each microshutter is ~110 mas (clear) in height, so each is a "long slit" aperture (~2-5 XD resols/shutter).

UV technology needs for HWO* -

UV technology needs for HWO* -

*and other missions

UV technology needs for HWO:

Requirements:

1) High-efficiency spectrograph designs that deliver high angular & spectral performance over ‘wide’ fields

2) Large-format (100 - 200 mm), photon-counting detectors with high global/local rate capability (~5 MHz) and high spatial resolution (20 - 25 μm)

3) Optical Coatings with > 50% reflectance at 103nm, high reflectance into the visible/NIR

4) Multi-object selection mechanisms (e.g., microshutter or micromirror), 420x840 elements, 2 side buttable, 1E-5 scatter at Lyα

5) Band-selecting UV filter technology with ≤ 1% transmission at Lyα

6) Low-scatter, high-efficiency (> 60% peak order) diffraction gratings

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NASA/COPAG UV technology white paper coming soon: lead – Sarah Tuttle, Univ Washington

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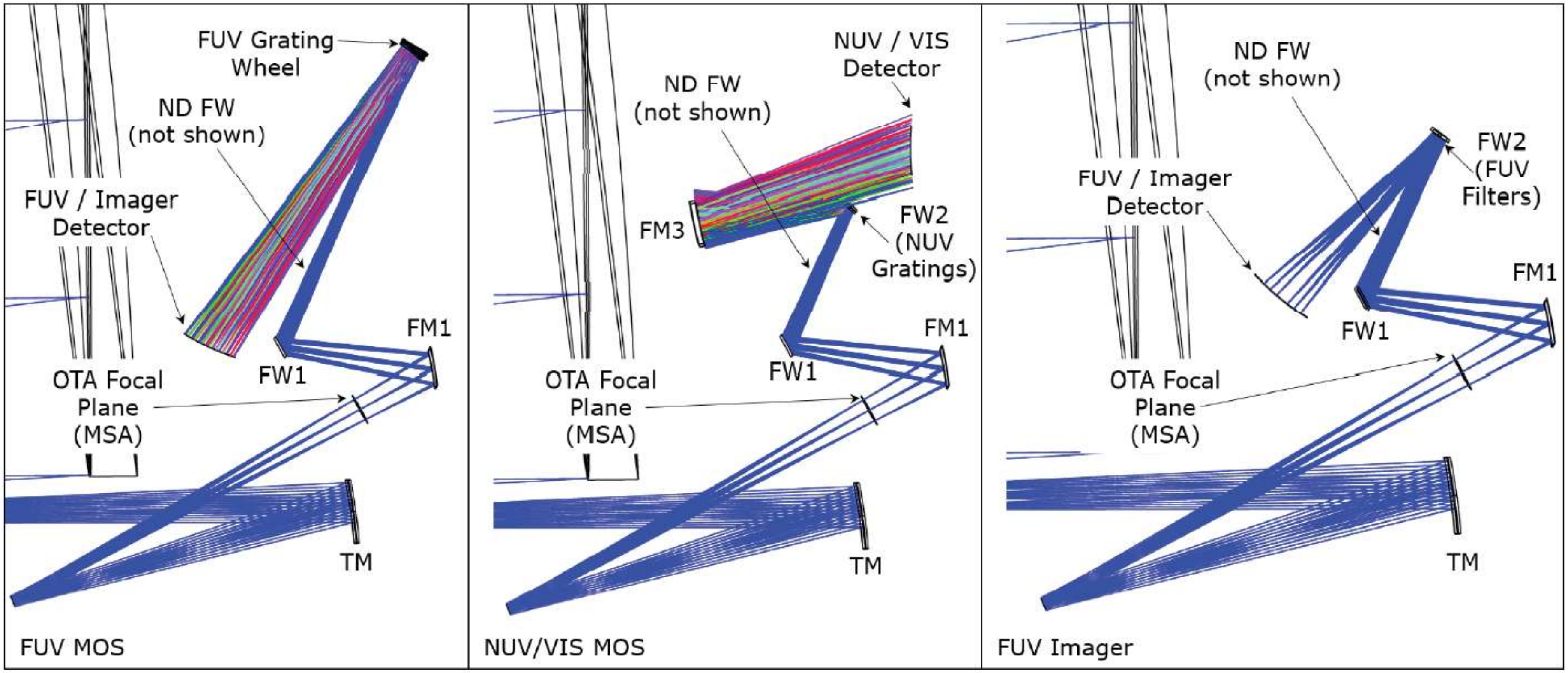

Figure 8-34. *Ray trace of each mode of the LUMOS-B instrument. All three modes share the same field-of-view defined by the microshutter array, and can be selected by inserting the appropriate combination of filters, mirror, and gratings at the FW1, NUV GW/FW2, and FUV GW planes.*

LUMOS-B Performance

G150M: λ ~ 111-189 nm

<R> = 52K, <θ> = 32mas

Mode	Peak Sensitivity Band (nm)	Res Pow (best 1’x1’ of FOV)	Ang Res (best 1’x1’ of FOV, mas)
G120M	100-140	40K	31
G150M	130-170	52K	32
G180M	160-200	59K	33
G155L	100-200	17K	39
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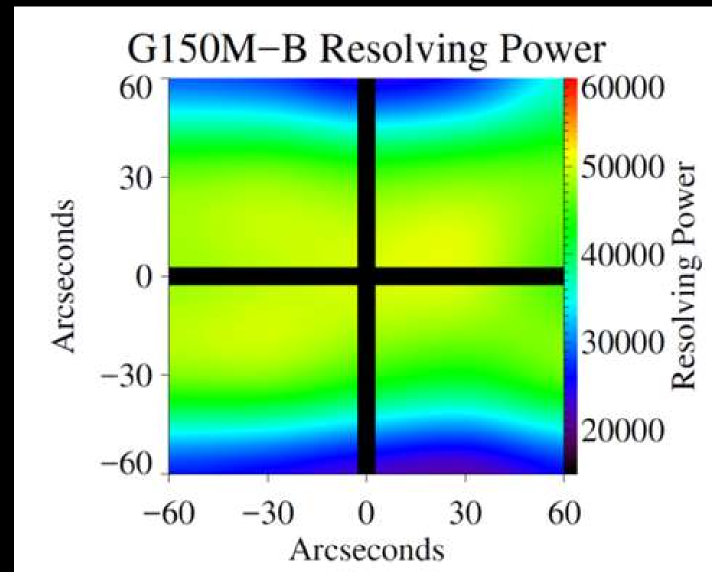
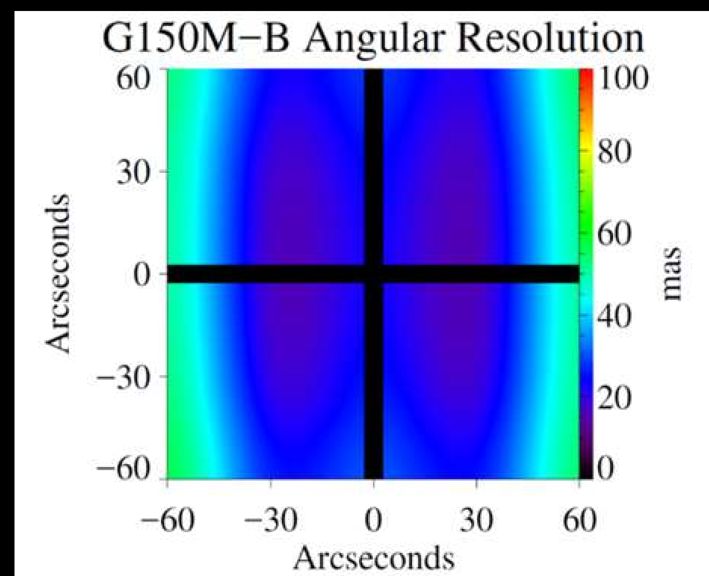
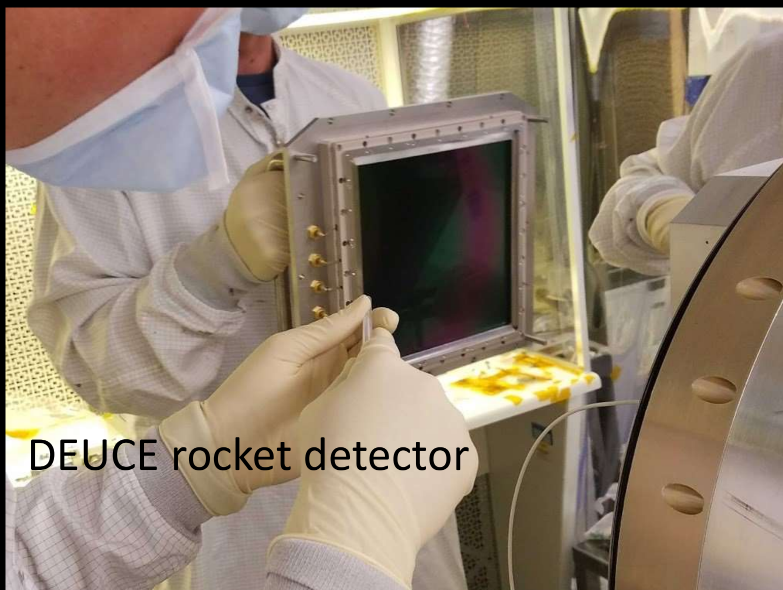


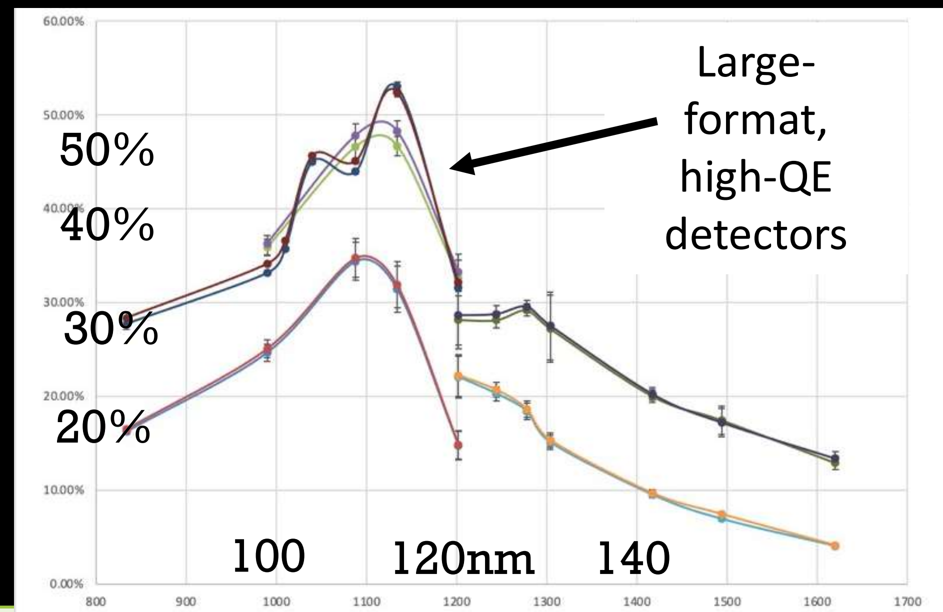


2) Large-format (200 mm), photon-counting detectors with high global/local rate capability (~5 MHz) and high spatial resolution (25 μm)

Instrumental needs:	Prior/Ongoing investments
FUV/NUV: a) QE enhancements across full 100 – 200nm, GaN and bialkali photocathodes b) cross-strip anodes to 200mm sizes	SAT and APRA – laboratory development (PIs – Siegmund, Vallerga, Nikzad) APRA - rocket and cubesat instrument applications (PIs – France, Fleming, Green)
NUV/vis: a) scale to buttable 8k x 8k, b) ~1 e- read noise, 1E-4 e-/pix/s dark at 170K	SAT – JPL programs (PIs – Nikzad, Hoenk) Roman Technology Fellowship - (PI – Hamden) APRA – cubesat and balloon instrument applications (PIs – Martin, Shkolnik)

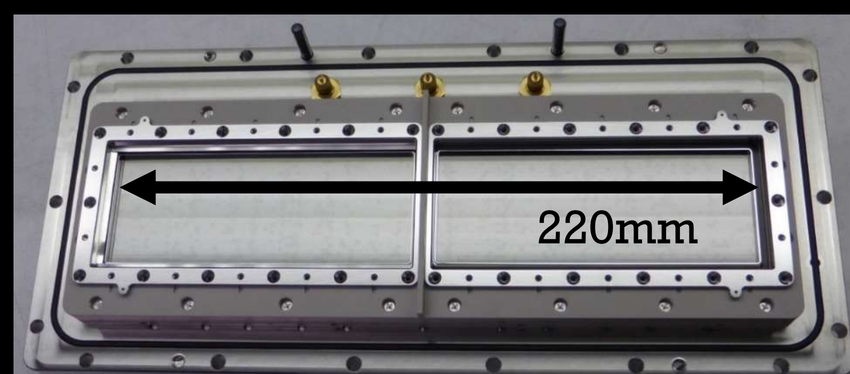
2) Large-format (200 mm), photon-counting detectors with high global/local rate capability (~5 MHz) and high spatial resolution (25 μm)



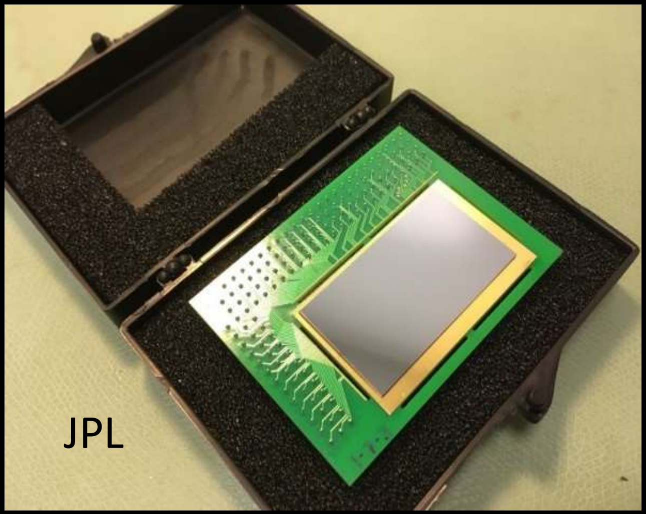


SISTINE -- large (220mm x 40mm) photon counting detector, 1 MHz global rate limit (~50x HST-COS)

DEUCE -- large (200mm x 200mm) photon counting detector



2) Large-format (200 mm), photon-counting detectors with high global/local rate capability (~5 MHz) and high spatial resolution (25 μm)



NUV/vis: A delta doped 8-Megapixel CMOS imager similar to that used on the Europa Imaging System (EIS) for Europa Clipper. SAT effort in progress (PI – Hoenk)

3) Optical Coatings with reflectance > 50% at 103nm

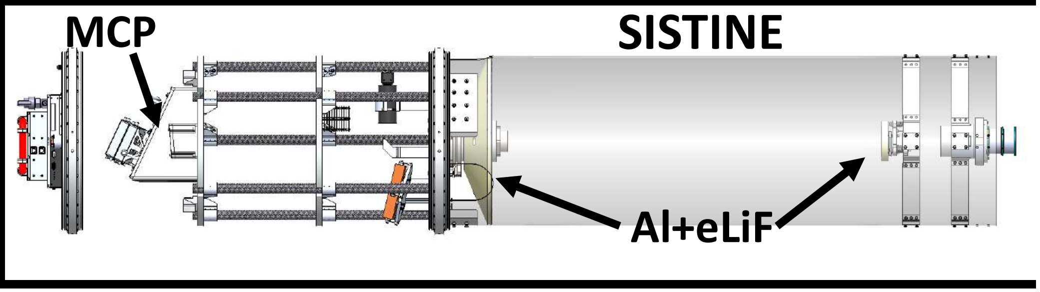
Instrumental needs:	Prior/Ongoing investments
broadband 100 – 2000nm coatings (protected enhanced Al+LiF), > 50% at 103nm, > 80% over 115-200 nm, > 88% over 200 - 850 nm	SAT and APRA – laboratory and process development (PIs – Nikzad, Hennessy, Quijada, France), Roman Technology Fellowship - (PI – Fleming), APRA - rocket and cubesat instrument applications (PIs – France, Fleming)
scaled to ~1m optics	APRA – 0.5m rocket mirror (PI – France)

3) Optical Coatings with reflectance > 50% at 103nm

SISTINE Pathfinder Spectrograph:

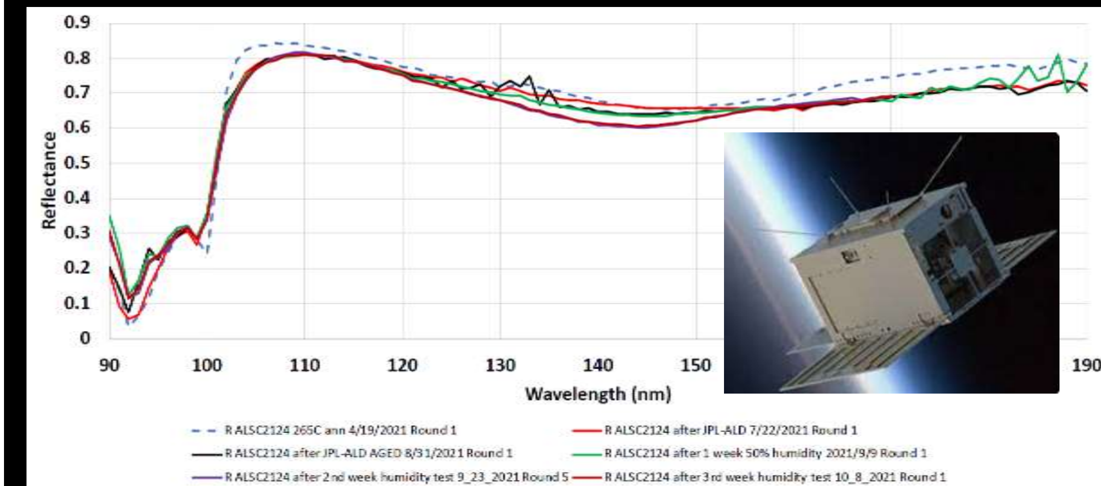
--first time **Al+eLiF coatings** have been deposited on shaped optics (> 2"), and flown. Secondary mirror includes AlF_3 capping layer.

(MgF_2 capping completed on SPRITE)



SISTINE secondary mirror receiving protective ALD overcoat (AlF_3) at JPL MicroDevices Lab (J. Hennessy et al.)

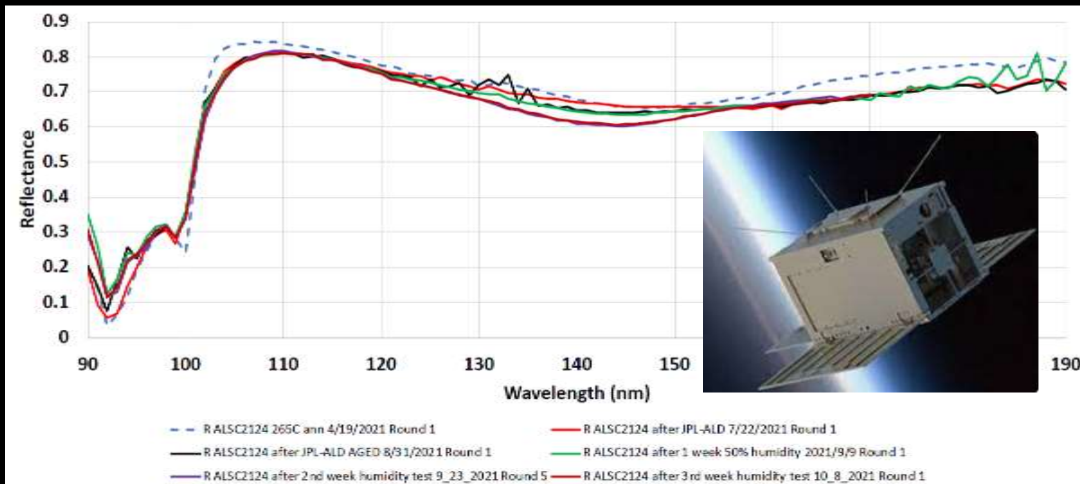
3) Optical Coatings with reflectance > 50% at 103nm



SPRITE Cubesat:

--Plot of the SPRITE humidity test sample after coating with just eLiF (blue dashed line), and then after the MgF2 overcoat (solid lines). The colored curves show no degradation from 103 - 115 nm after four weeks of aging at 50% and 60% relative humidity. (credit – Brian Fleming, CU)

3) Optical Coatings with reflectance > 50% at 103nm



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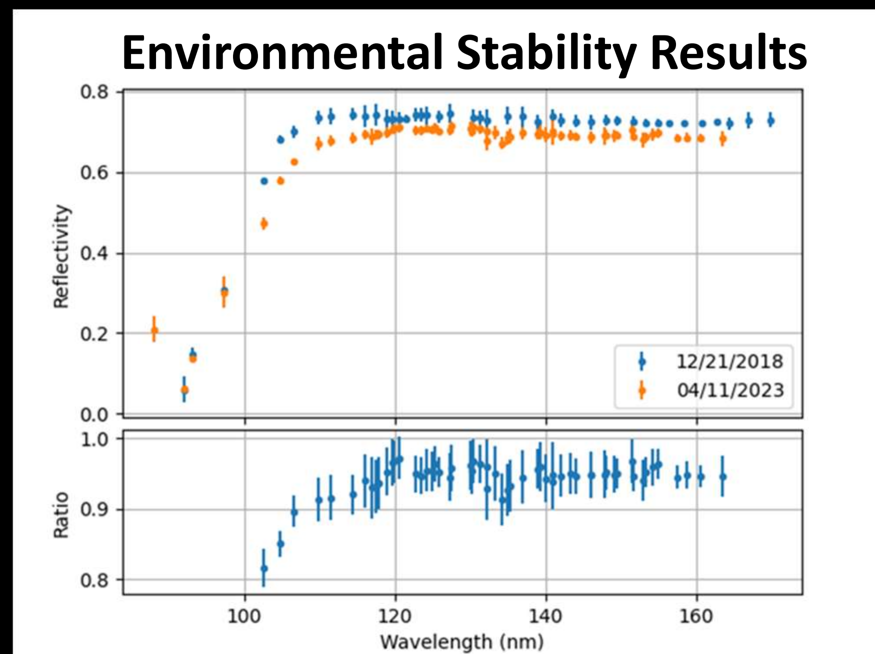


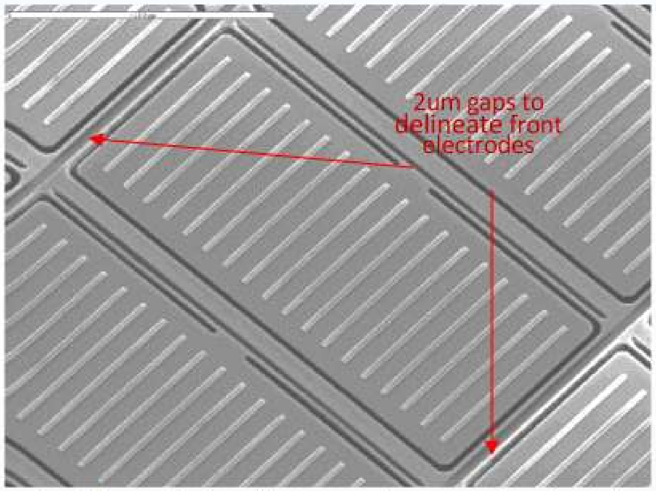
SISTINE Pathfinder Spectrograph:

--Al+eLiF coatings on shaped mirrors, flight tests of Al+eLiF+AlF_3

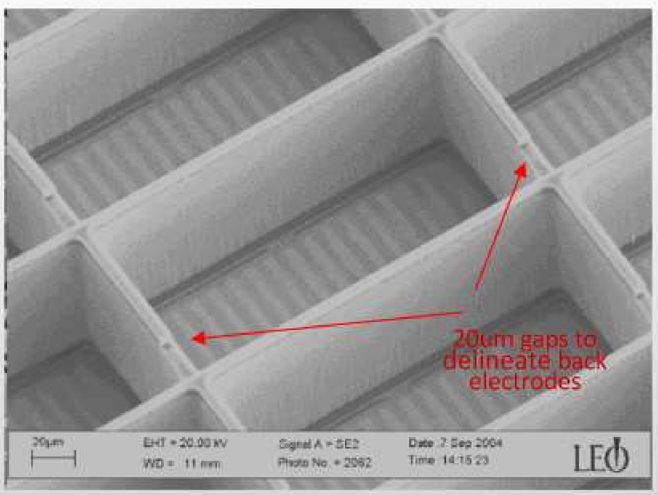
4.5 years, 3 rocket integrations & flights, 4 months in Australia, 6 months in transport: <10% degradation at λ > 105 nm

Nell et al. 2023 – under review

4) Multi-object selection mechanisms (e.g., microshutter or micromirror), 420x840 elements, 2 side buttable, 1E-5 scatter at Lyα



Front side of shutter: column electrodes

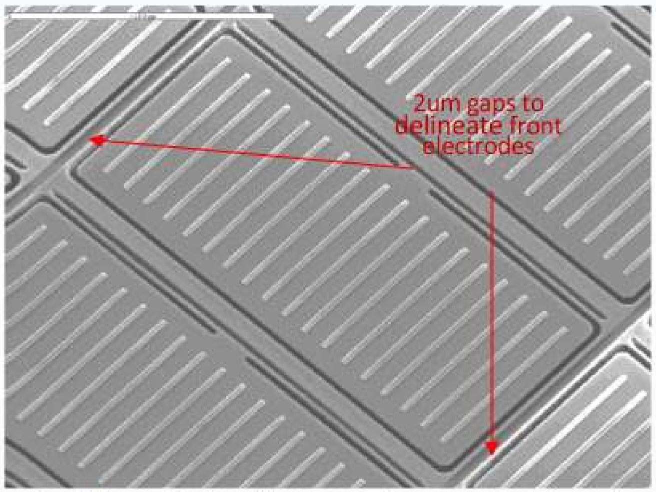


Backside of shutter: row electrodes

NextGen MSA SAT (GSFC)

Figure 1 from NGMSA development report showing fabrication stages of the NexGen array prototype containing 736 X 384 programmable micro-shutters.

4) Multi-object selection mechanisms (e.g., microshutter or micromirror), IFU image slicer



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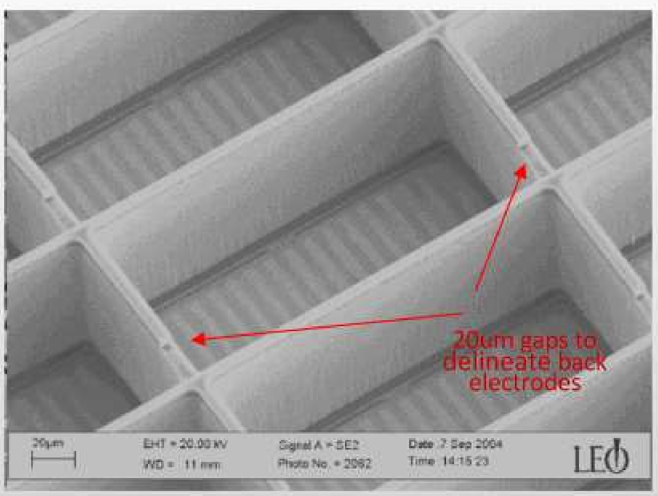

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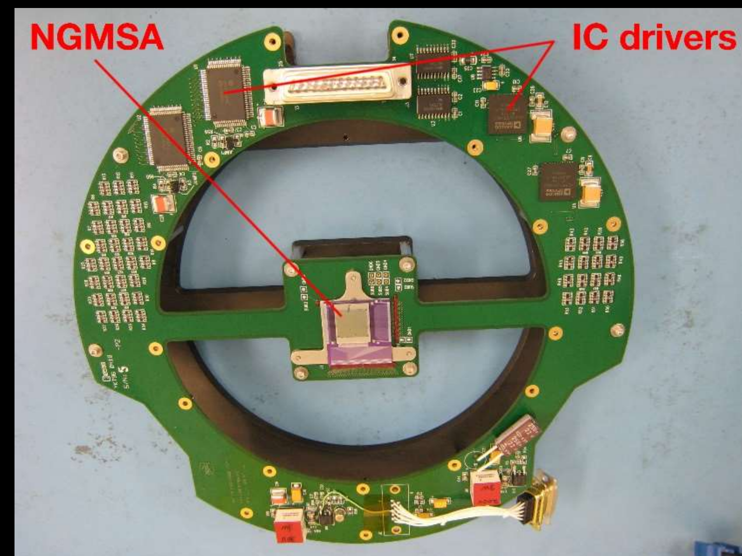


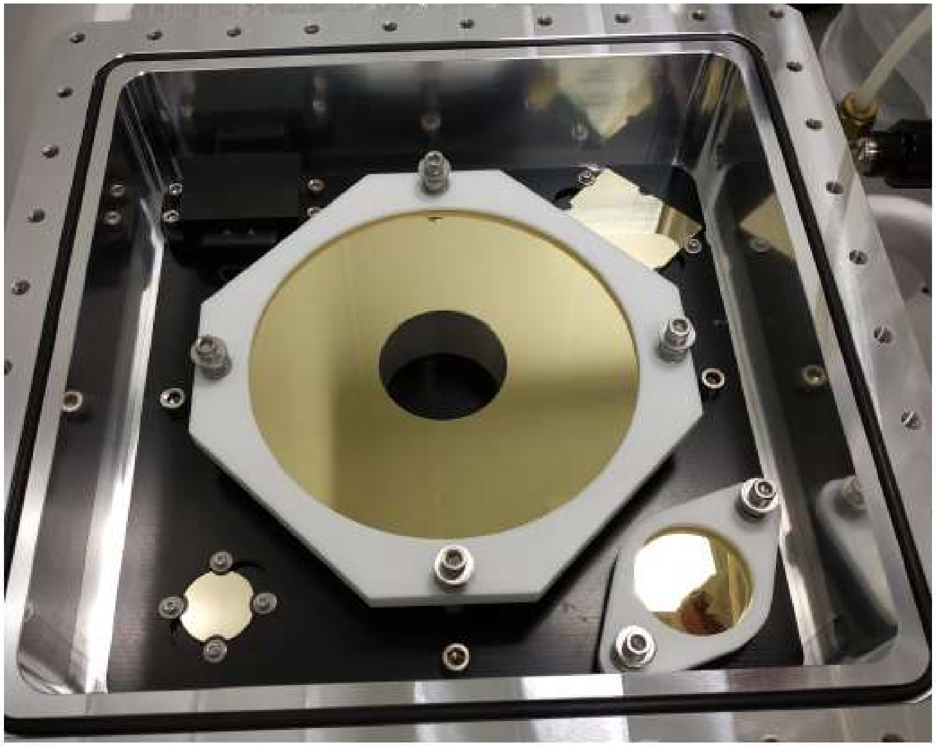
NextGen MSA SAT (GSFC)

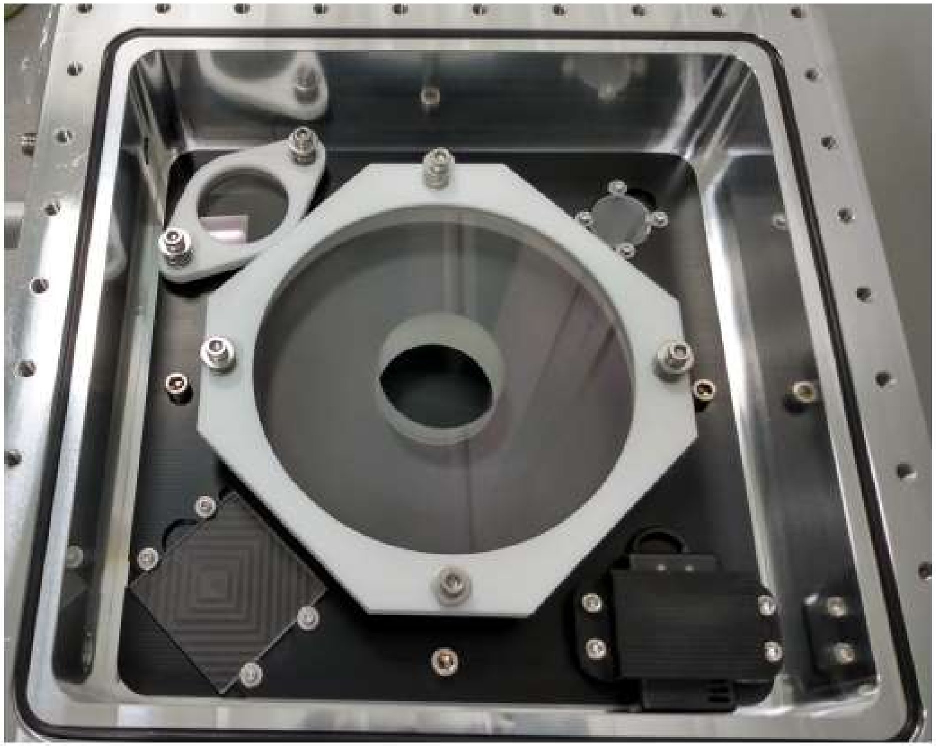
Developing flight-test model for FORTIS sounding rocket mission (PI – S. McCandliss, JHU). Launch – 2024.

5) Band-selecting UV filter technology with ≤ 1% transmission at Lyα

Instrumental needs:	Prior/Ongoing investments
Bandpass selection/Filter definition for 100 – 200nm, particular emphasis on 100 – 120nm > 50% peak transmission 100 – 120nm, > 80% peak transmission > 140 – 200nm ≤ 1% transmission at Lyα (121nm)	APRA – laboratory development (PI – France) CSIC/GOLD (Spain) – Lyβ optimized filters for heliophysics and planetary science

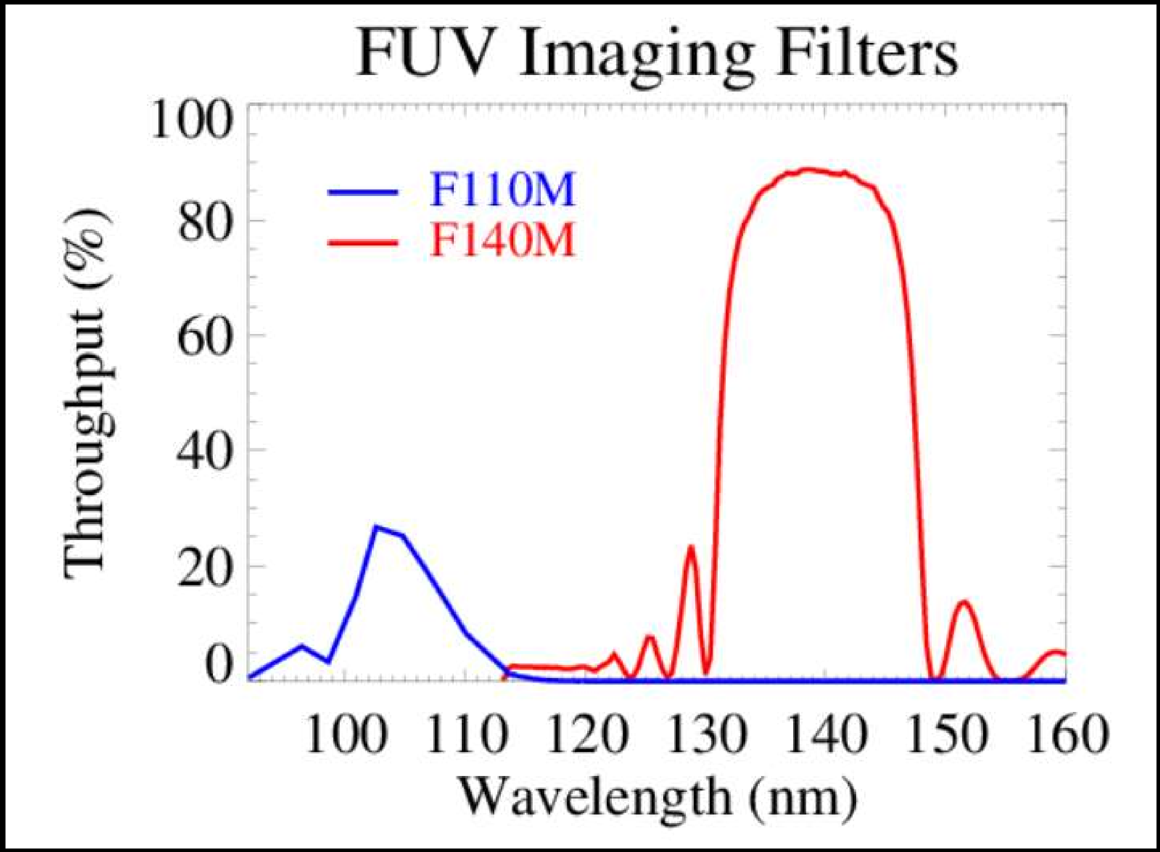
5) Band-selecting UV filter technology with ≤ 1% transmission at Lyα





150mm mirror deposition of test F110M filter
Juan Larruquert & Paloma Reyes, CSIC / Emily Farr, Nick Kruczek & KF, Colorado

5) Band-selecting UV filter technology with ≤ 1% transmission at Lyα



150mm mirror deposition of test F110M filter
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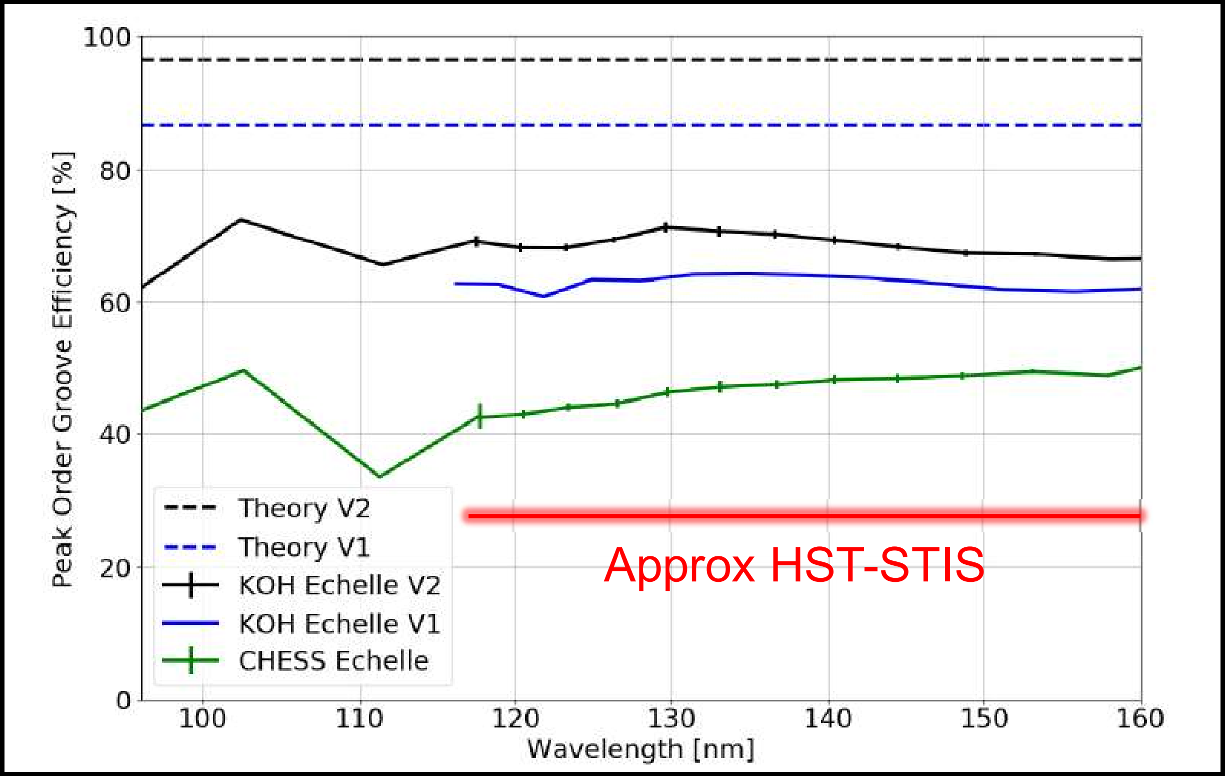
6) Low-scatter, high-efficiency (> 60% peak order) diffraction gratings

Instrumental needs:	Prior/Ongoing investments
High-efficiency, low-scatter echelle gratings (e-beam or lithographic techniques)	SAT – PSU and CU programs (PIs – McEntaffer, Fleming), APRA – design and fab (PI – Green, Hoadley), APRA - rocket applications (PI – France)
High-efficiency, low-resolution, low-blaze angle gratings ($\theta_B \leq 1°$)	APRA - rocket applications (PI – McCandliss, Fleming)

6) Low-scatter, high-efficiency (> 60% peak order) diffraction gratings



PSU X-ray gratings (R. McEntaffer);
CHESS rocket program (K. France);
SAT (B. Fleming, R. McEntaffer);
Kruczek et al. 2022, Grise et al. 2021
APRA (K. Hoadley)

NASA's Great Observatory Maturation Program (GOMAP)

Investment in individual technologies

A combination of:

- process level ("materials physics") development,
- scaling existing technologies to the sizes needed for HWO,
- shifting from a model of 'every component is an individual research project' to the production line that will be needed for HWO (optics, detectors, etc).

NASA GOMAP

Laboratory and flight testbeds for future missions –

NASA GOMAP

Laboratory and flight testbeds for future missions –

We also need to invest in system-level prototype/test instruments for both the laboratory and space.

These instruments provide powerful inputs to Phase A-level trades and decisions (~2029), so we need to do this soon.

1) Investment beyond APRA-levels in suborbital missions (balloons and rockets).
2) Laboratory prototype testbed instruments (used with great impact for starlight suppression research)
3) Small missions that combine process development / scaling with systems-level testing, science, and early-career training

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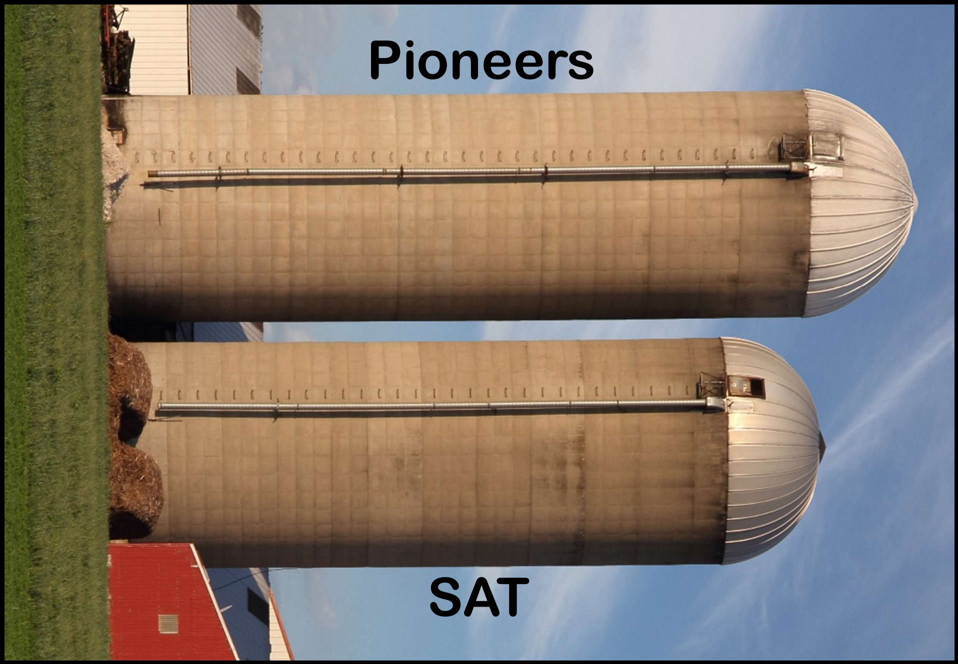
GOMAPPING!

Laboratory and flight testbeds for future missions –



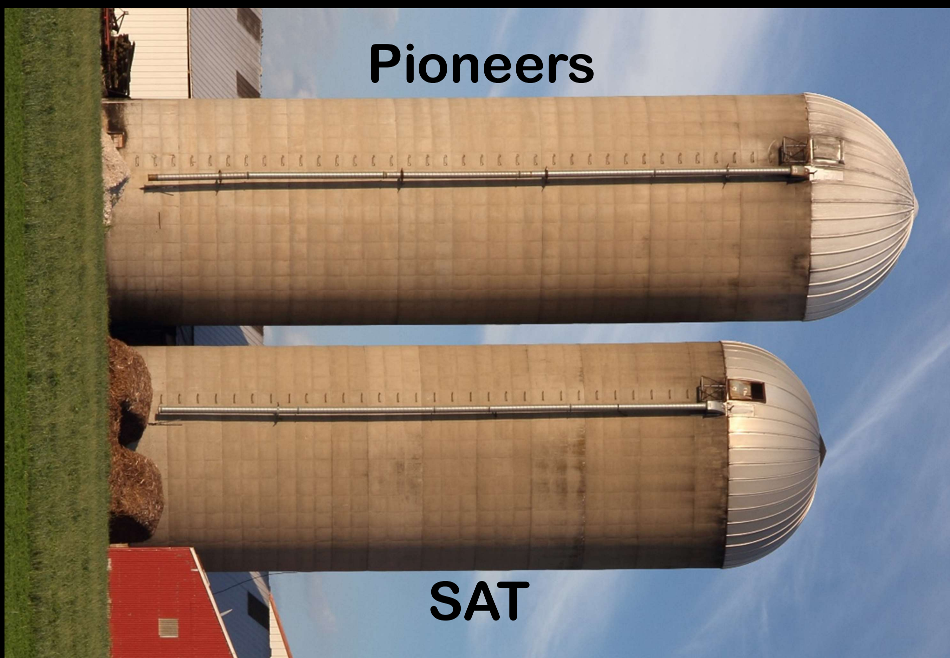
Pioneers: NASA small satellite missions, ~$20M

SAT (Strategic Astrophyiscs Technology): focused laboratory technology efforts

NASA GOMAP

Laboratory and flight testbeds for future missions –

Pioneers provide a model for small mission development that COULD advance technology and conduct preparatory science



SAT provides a model for focused technology development that could be rapidly used in a flight program

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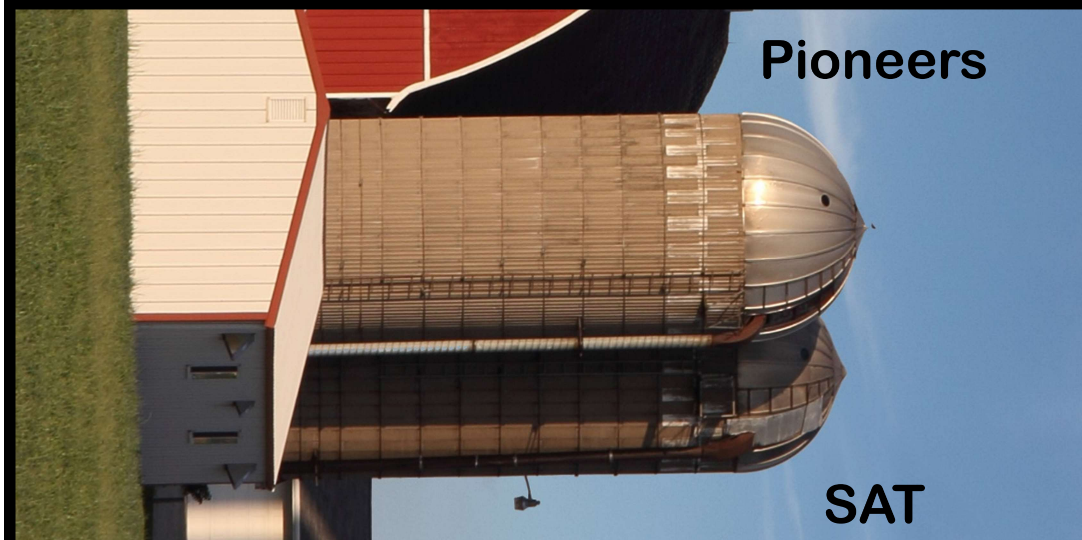
Laboratory and flight testbeds for future missions –



NASA GOMAP

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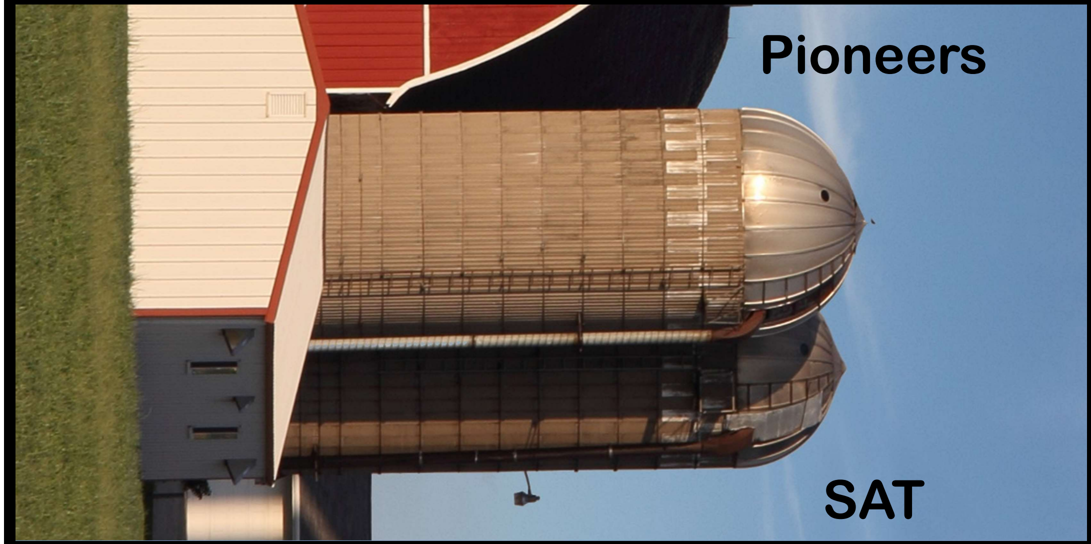

Smallsat
Technology
Accelerated
Maturation
Platform

Pioneer + SAT → STAMP

NASA GOMAP

Laboratory and flight testbeds for future missions –

STAMP-1 (S-1):
Prototype multi-object spectrograph

- Scaling up coating technology
- Flight test NGMSA (EM)
- Long-duration tests of candidate UV detectors

- Local galaxy survey (low-z analogs to HWO's high-z targets)

- Develop leaders for implementation of HWO

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Smallsat Technology Accelerated Maturation Platform (STAMP)

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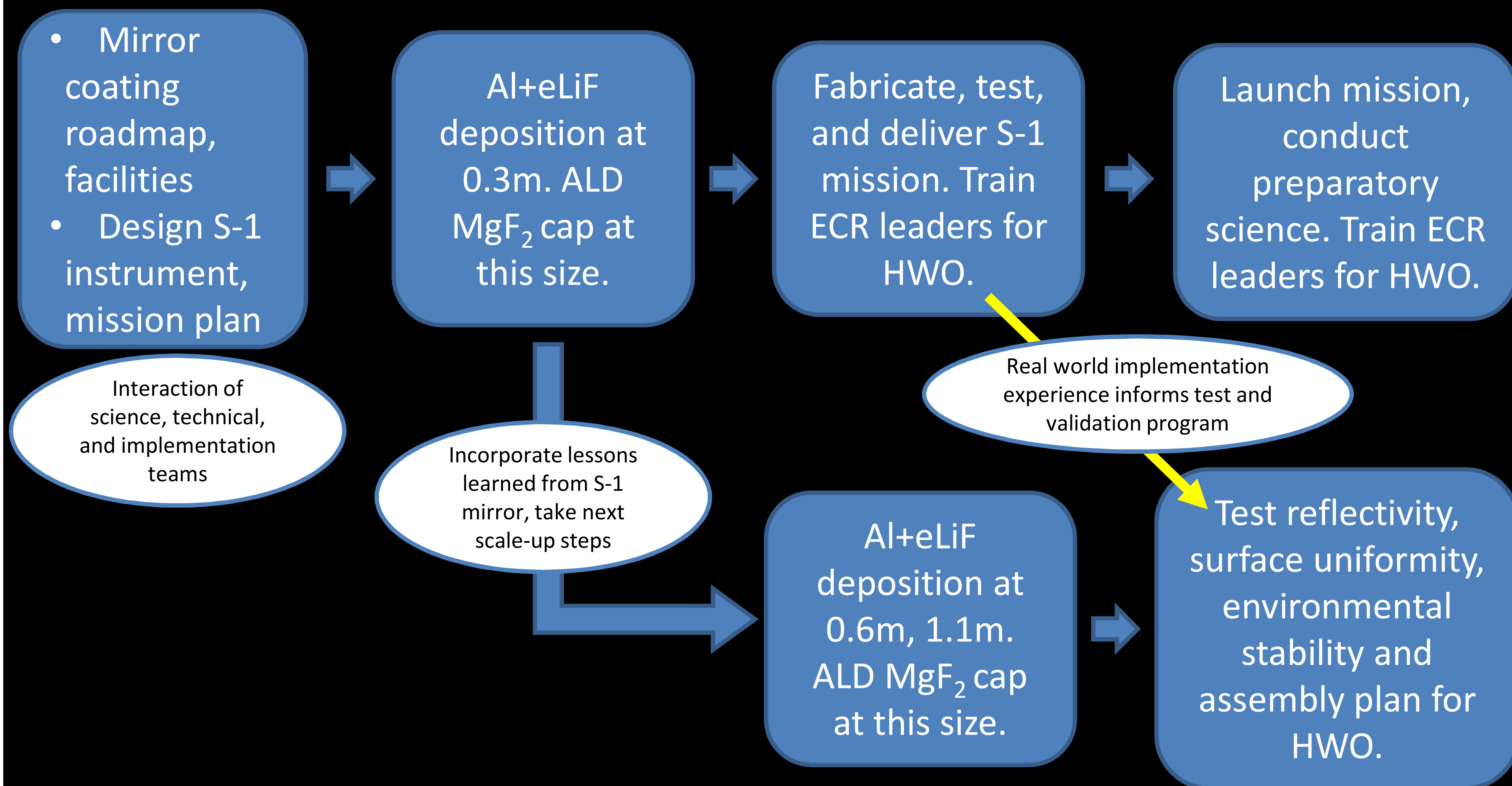

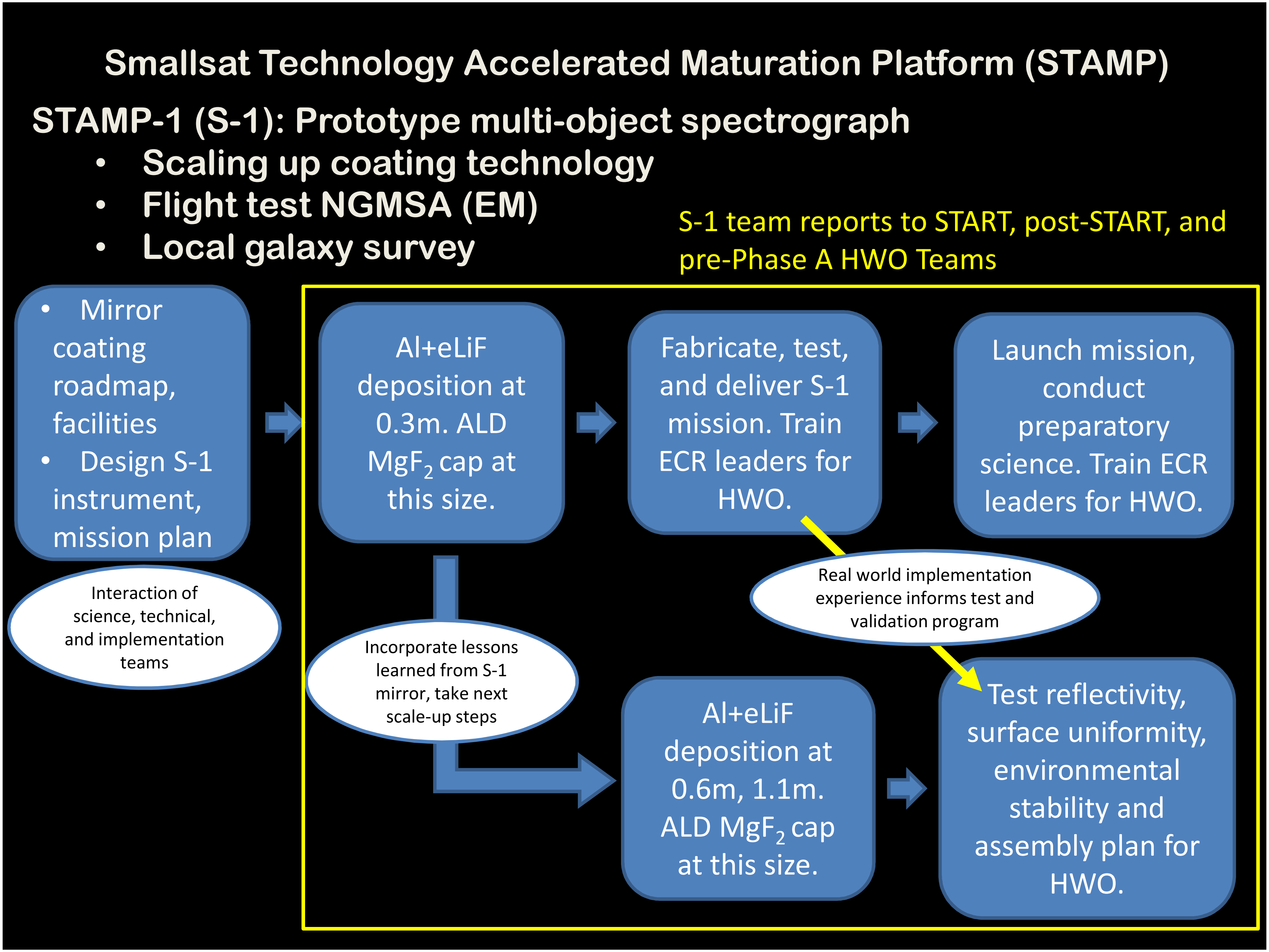
Smallsat Technology Accelerated Maturation Platform (STAMP)
STAMP-1 (S-1): Prototype multi-object spectrograph
• Scaling up coating technology
• Flight test NGMSA (EM)
• Local galaxy survey
S-1 team reports to START, post-START, and pre-Phase A HWO Teams
• Mirror coating roadmap, facilities
• Design S-1 instrument, mission plan
Interaction of science, technical, and implementation teams
Al+eLiF deposition at 0.3m. ALD MgF_2 cap at this size.
Fabricate, test, and deliver S-1 mission. Train ECR leaders for HWO.
Launch mission, conduct preparatory science. Train ECR leaders for HWO.
Real world implementation experience informs test and validation program
Incorporate lessons learned from S-1 mirror, take next scale-up steps
Al+eLiF deposition at 0.6m, 1.1m. ALD MgF_2 cap at this size.
Test reflectivity, surface uniformity, environmental stability and assembly plan for HWO.

GOMAPPING!

People for future missions –


People for future missions – NASA's Suborbital Program
PIs:
KF
Dr. Briana Indahl
Prof. Brian Fleming
(CUTE, SPRITE, MANTIS cubesats, HST/COS, ESCAPE, STAR-X/UVT, and numerous rocket missions)
Research Scientists:
Dr. Dolon Bhattacharyya
Dr. Dmitry Vorobiev
Dr. Ambily Suresh
Junior Engineers: Dana Chafetz, Stefan Ulrich, Nick DeCicco
Emily Witt
Dr. Nick Kruczek
Dr. Allison Youngblood
Ph.D. and M.S. Students:
Dr. Arika Egan
Prof. Keri Hoadley
Dr. Fernando Cruz-Aguirre
Nico Nell (AE)
Dr. Chris Moore
Robert Kane (ME)
Emily Farr
Mattie Bowen

Summary: UV Instruments for HWO

Many of the driving science cases in Cosmic Ecosystems and Worlds and Suns in Context require UV imaging and spectroscopic capabilities that far exceed what is possible with existing observatories, including

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Many of the driving science cases in Cosmic Ecosystems and Worlds and Suns in Context require UV imaging and spectroscopic capabilities that far exceed what is possible with existing observatories, including

- 100 – 1,000 nm spectral range
- R ~ 500 – 60,000 MOS over full spectral range (≥ 2’ x 2’)
- R > 100,000 point source spectroscopy, 100 – 170nm
- < 50 mas FUV and NUV imaging (≥ 2’ x 2’; multiple filters)
- > 25-100x effective area of HST-COS, imaging spectroscopy, hundreds of objects at a time.

The path to the Habitable worlds Ultraviolet Multi-object Spectrograph

kevin.france@colorado.edu

The path to the Habitable worlds Ultraviolet Multi-object Spectrograph

The next 5 years: advance the required technologies through a combination of laboratory and flight experiments that simultaneously bring early-career scientists and engineers into this field, invest in these technologies to scale them to the size/level required for HWO.

kevin.france@colorado.edu

Additional Slides: A talk unto themselves

The path to the Habitable worlds Ultraviolet Multi-object Spectrograph

Our charge for the next 5 years: advance the required technologies through a combination of laboratory and flight experiments that simultaneously bring early-career scientists and engineers into this field, invest in these technologies to scale them to the size/level required for HWO.

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UV technology needs for future flagship missions:

1) High-efficiency spectrograph designs that deliver high angular & spectral performance over ‘wide’ fields

2) Large-format (100 - 200 mm), photon-counting detectors with high global/local rate capability (~5 MHz) and high spatial resolution (20 - 25 µm)

3) Optical Coatings with > 50% reflectance at 103nm, high reflectance into the visible/NIR

4) Multi-object selection mechanisms (e.g., microshutter or micromirror), 420x840 elements, 2 side buttable, 1E-5 scatter at Lyα

5) Band-selecting UV filter technology with ≤ 1% transmission at Lyα

6) Low-scatter, high-efficiency (> 60% peak order) diffraction gratings

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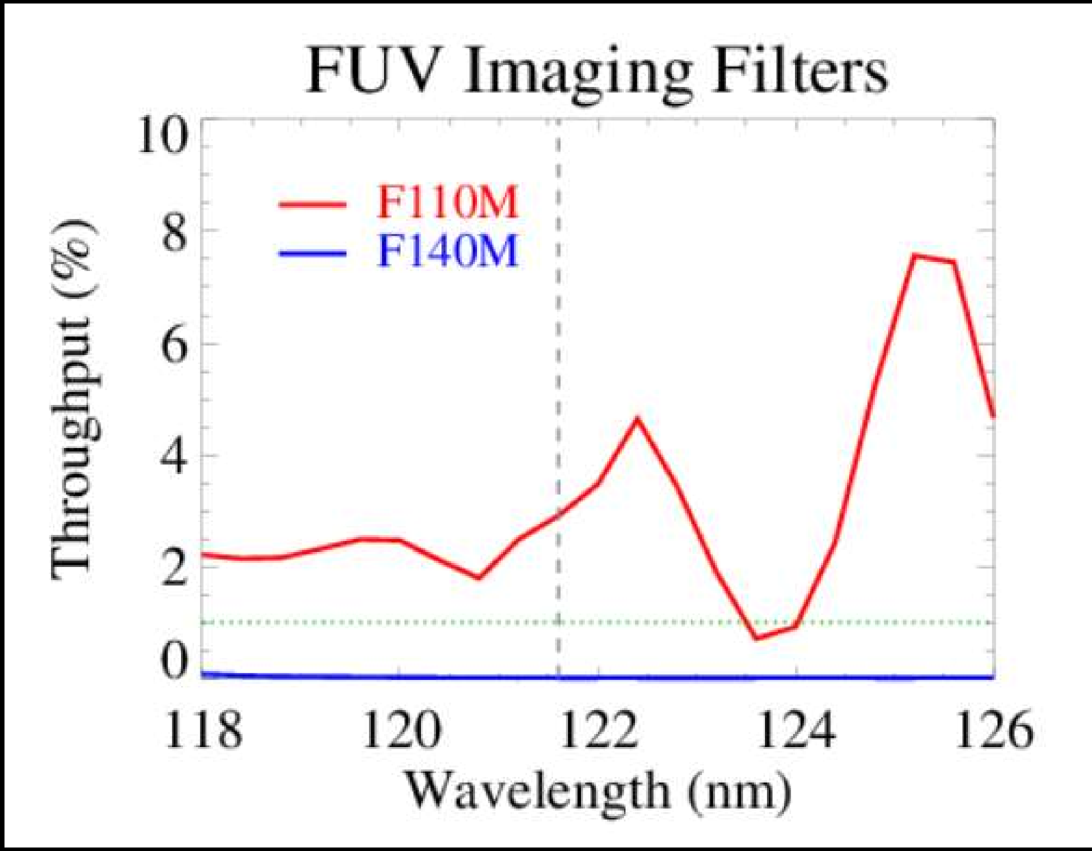

Juan Larruquert & Paloma Reyes, CSIC / N. Kruczek & K. France, Colorado rocket program

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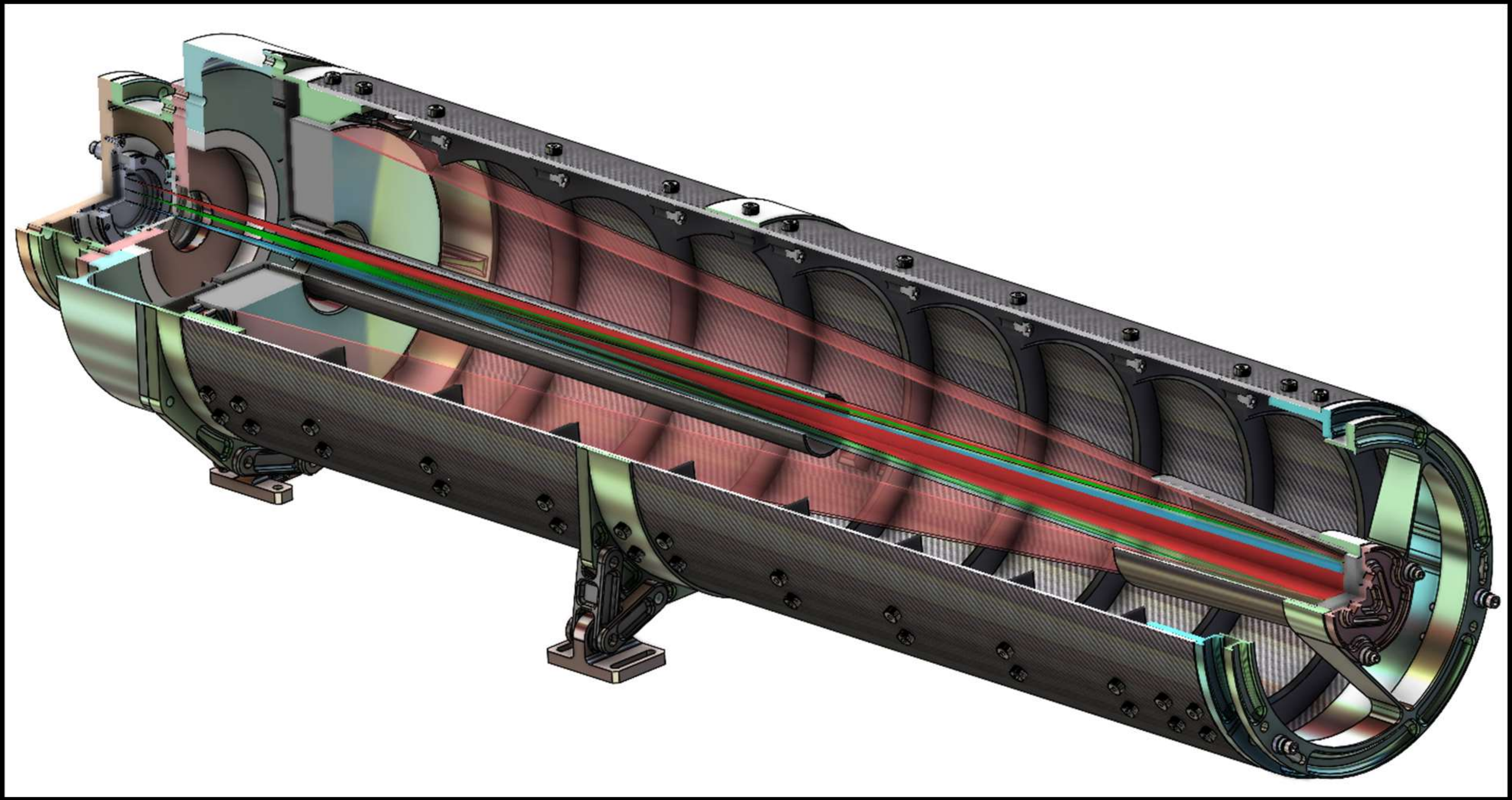

150mm diameter telescope array in four of the medium-band filters (N. Kruczek & K. France, Colorado rocket program)

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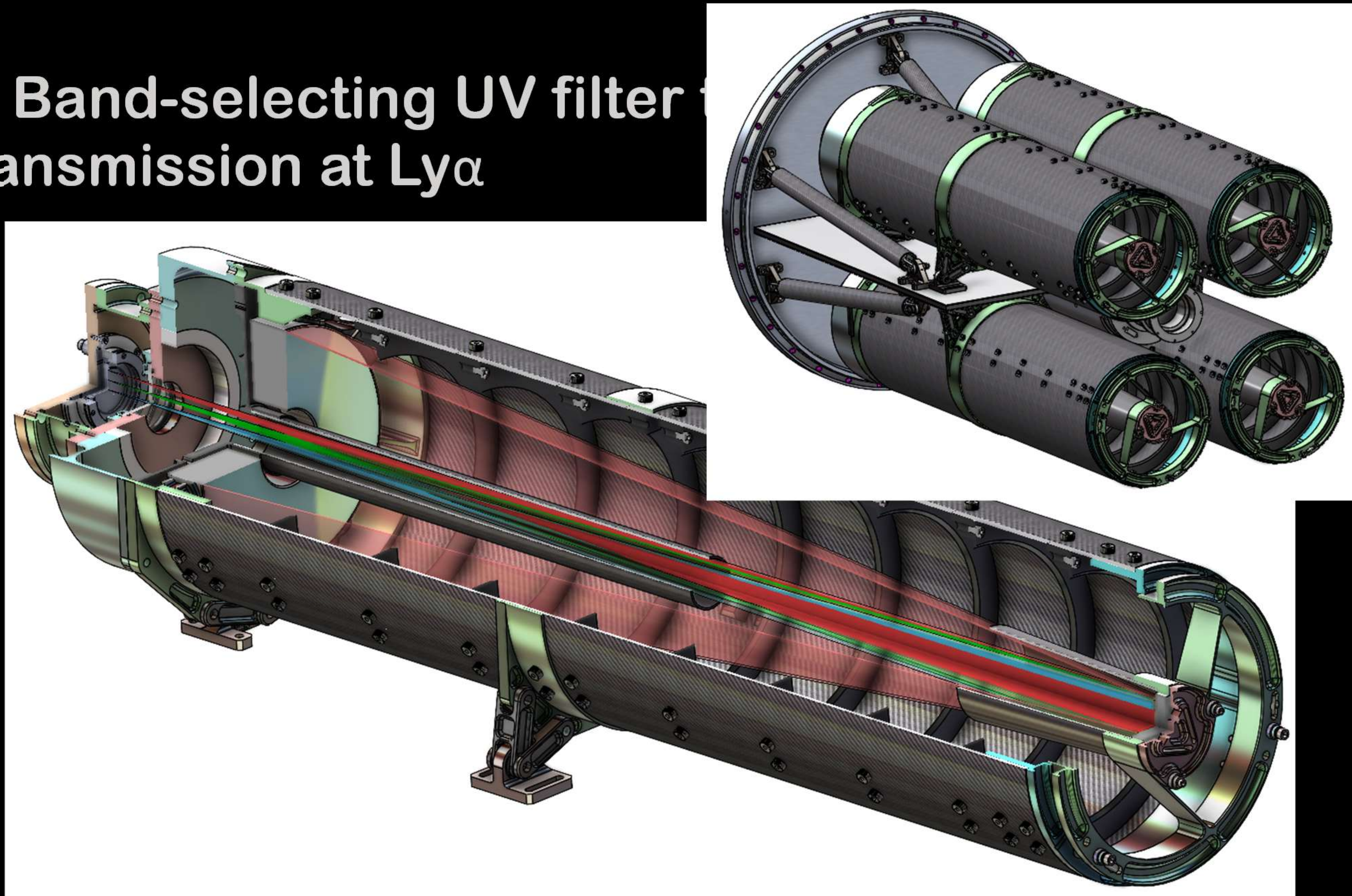

150mm diameter telescope array in four of the medium-band filters
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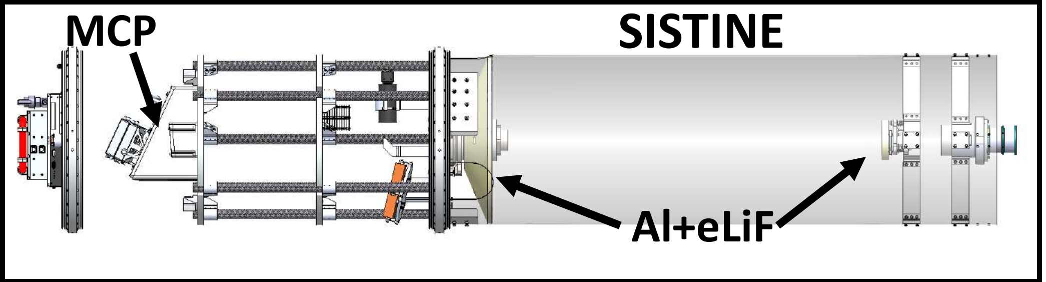
3) Optical Coatings with reflectance > 50% at 103nm

SISTINE Pathfinder Spectrograph:

--**Al+eLiF coatings on shaped mirrors, up to 0.5m**

--first time these coatings have been deposited on large (> 2") and shaped optics



Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**