STScI | SPACE TELESCOPE SCIENCE INSTITUTE

EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

Thoughts on Tech Development for HWO

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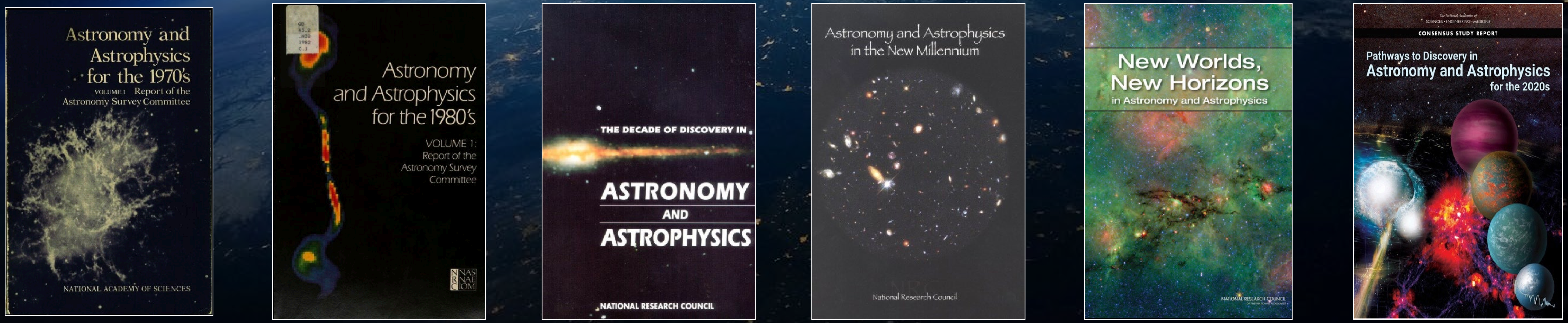
STScI Head of Community Missions

January 2023

How We Got Here - Astrophysics Decadal Surveys

HUBBLE | CHANDRA | SPITZER | WEBB | ROMAN | The NGOs



1972 | 1982 | 1991 | 2001 | 2011 | 2021

courtesy Grant Tremblay

THE NEW GREAT OBSERVATORIES

Transformative

for the scientific aims of the next decades and for fields and problems yet unknown.

Achievable

by maturing technologies wisely and building on the experience of past flagships

Inclusive

by pursuing open science in which the best ideas rise to the top and all are welcome

Ready

to proceed to development, supported by a strong and united community

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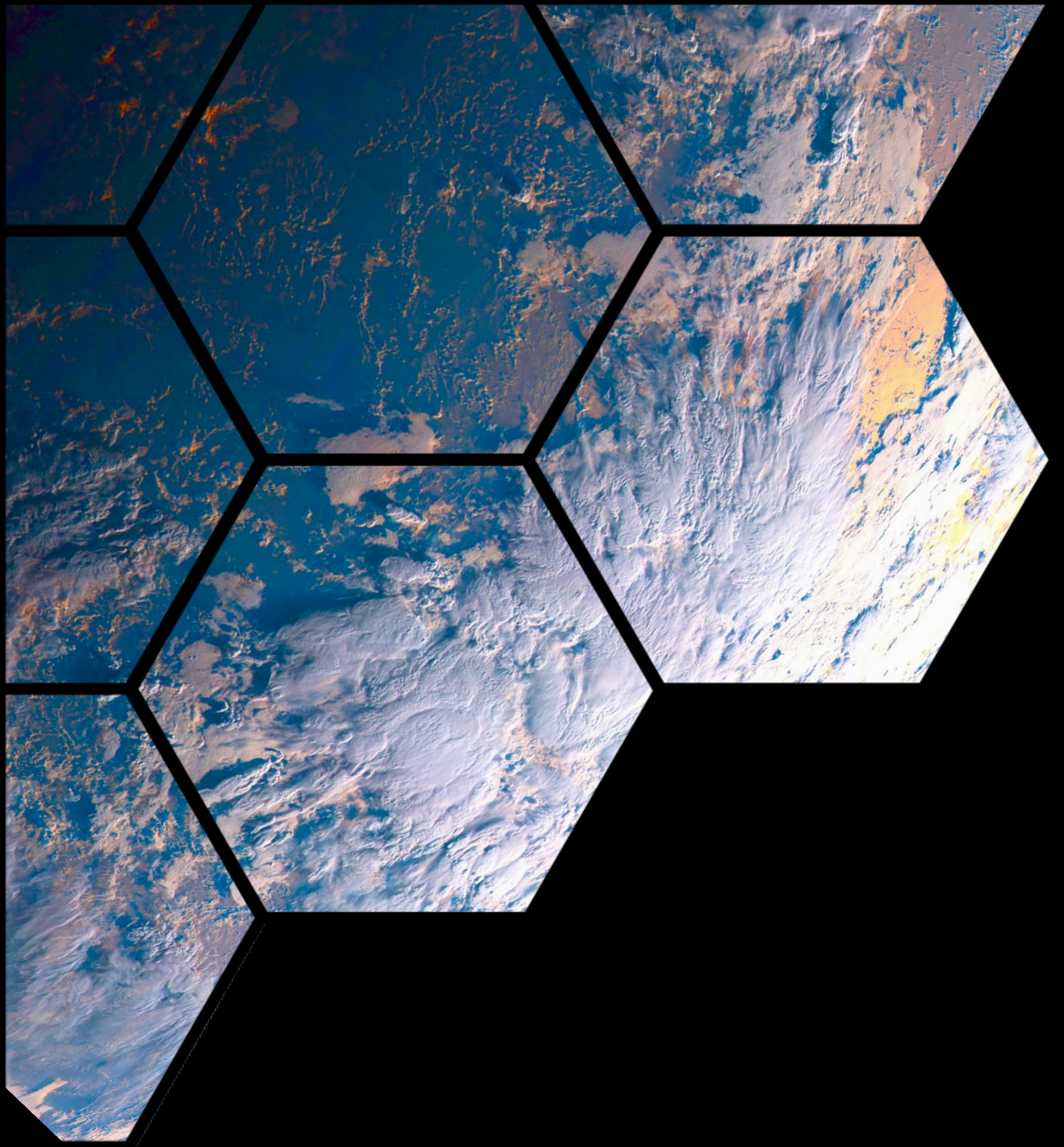
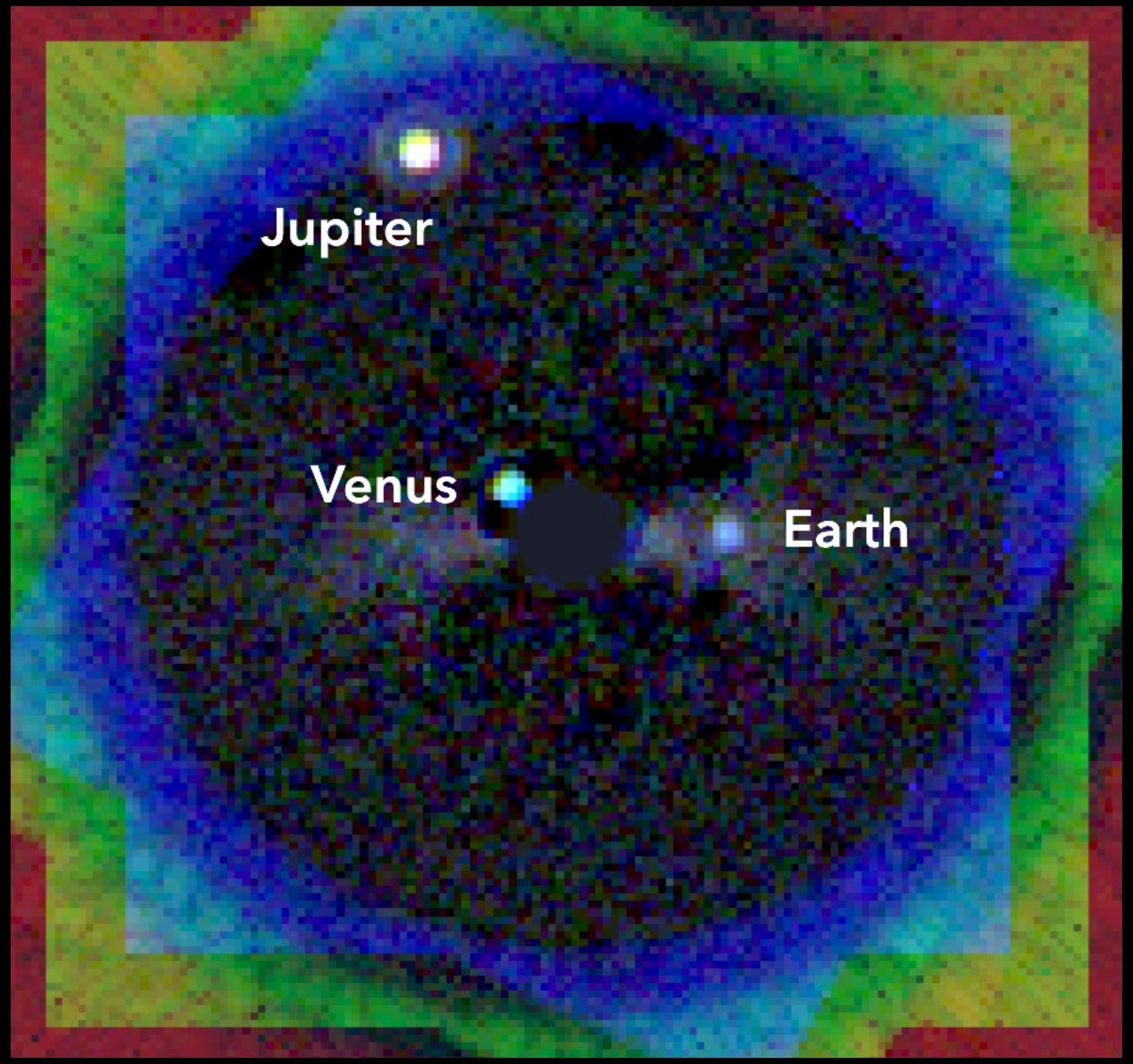
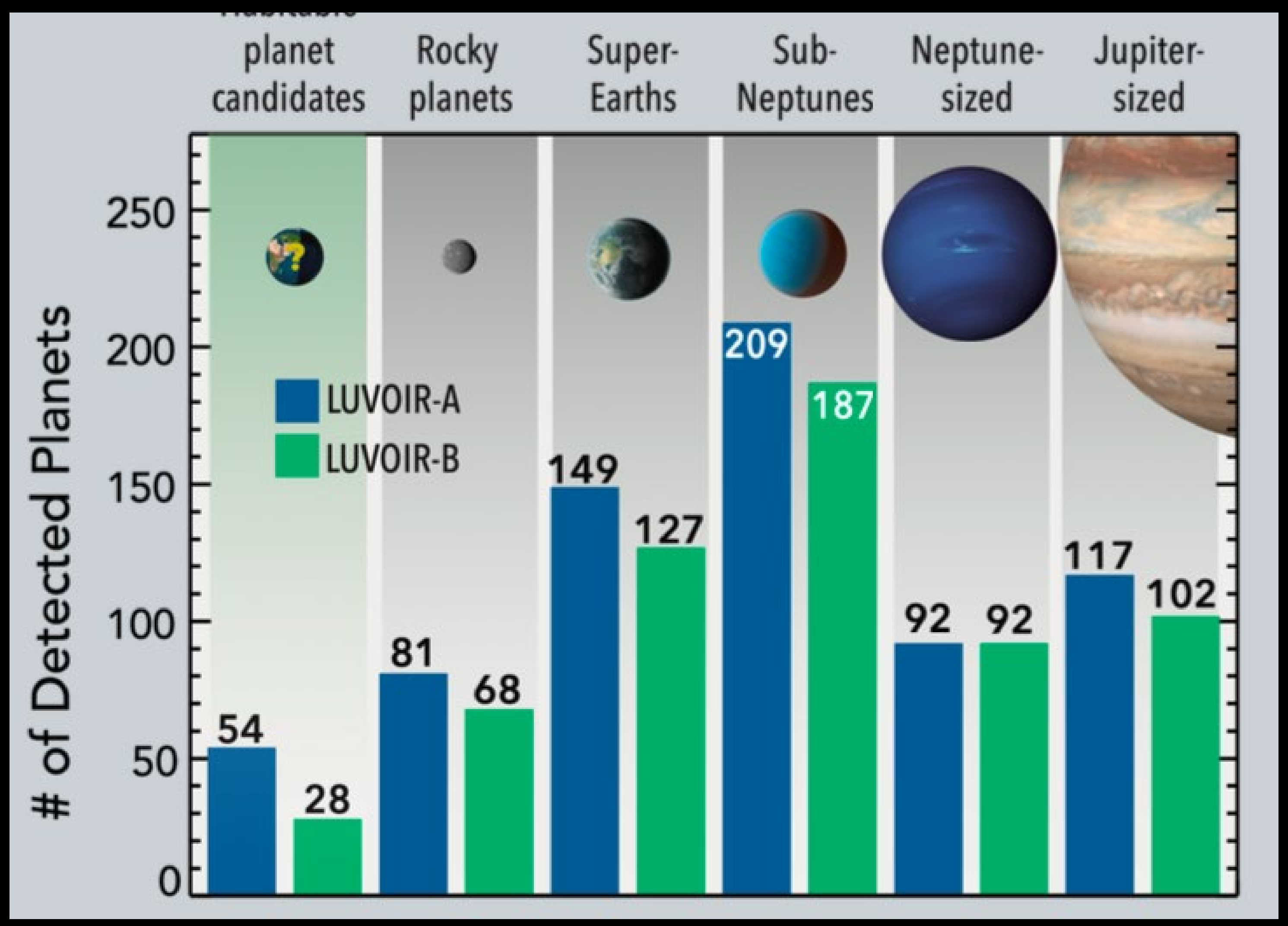
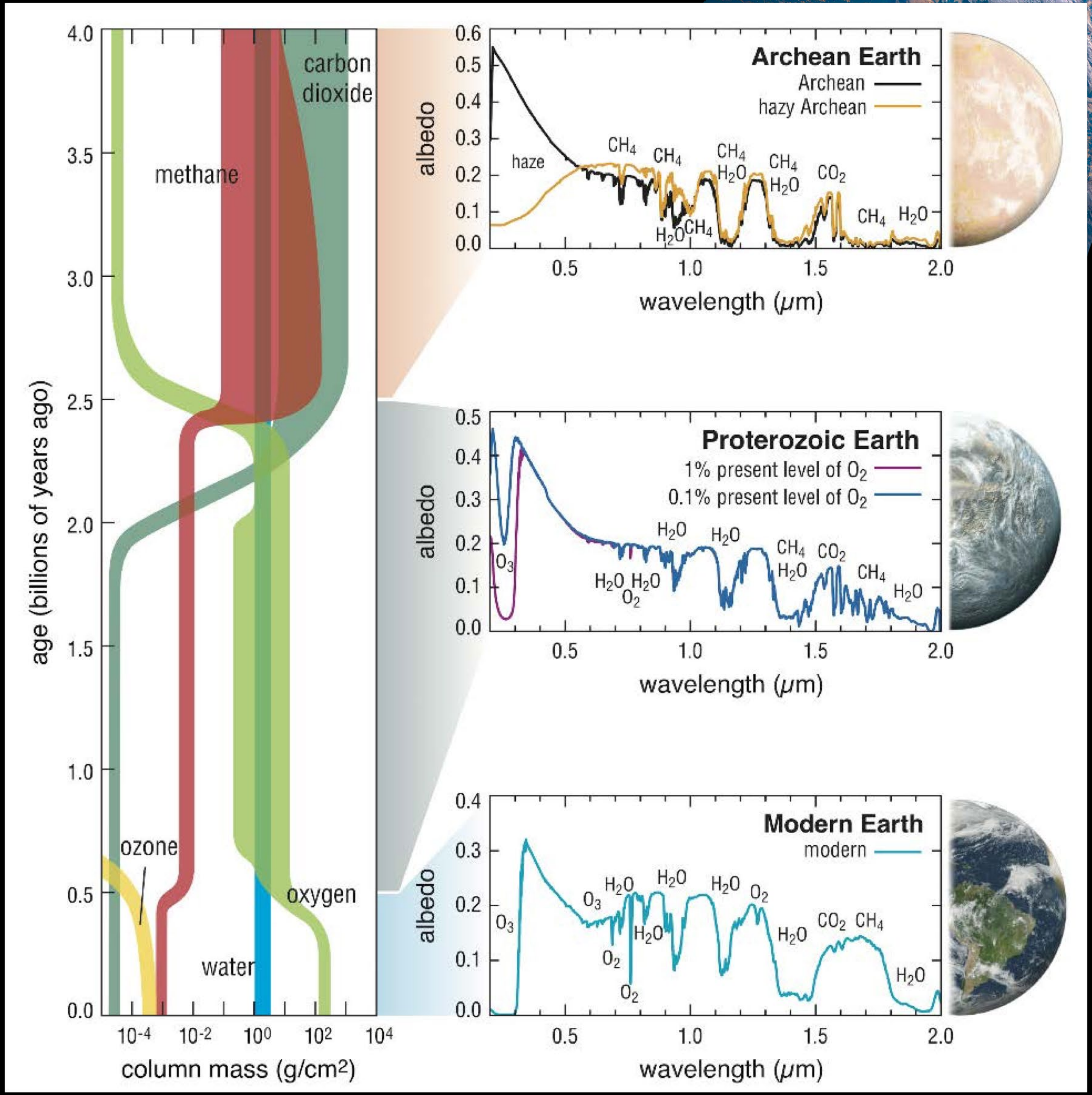


Habitable Worlds Observatory

100 Hab Zone searches, and hopefully 25 "Earths"

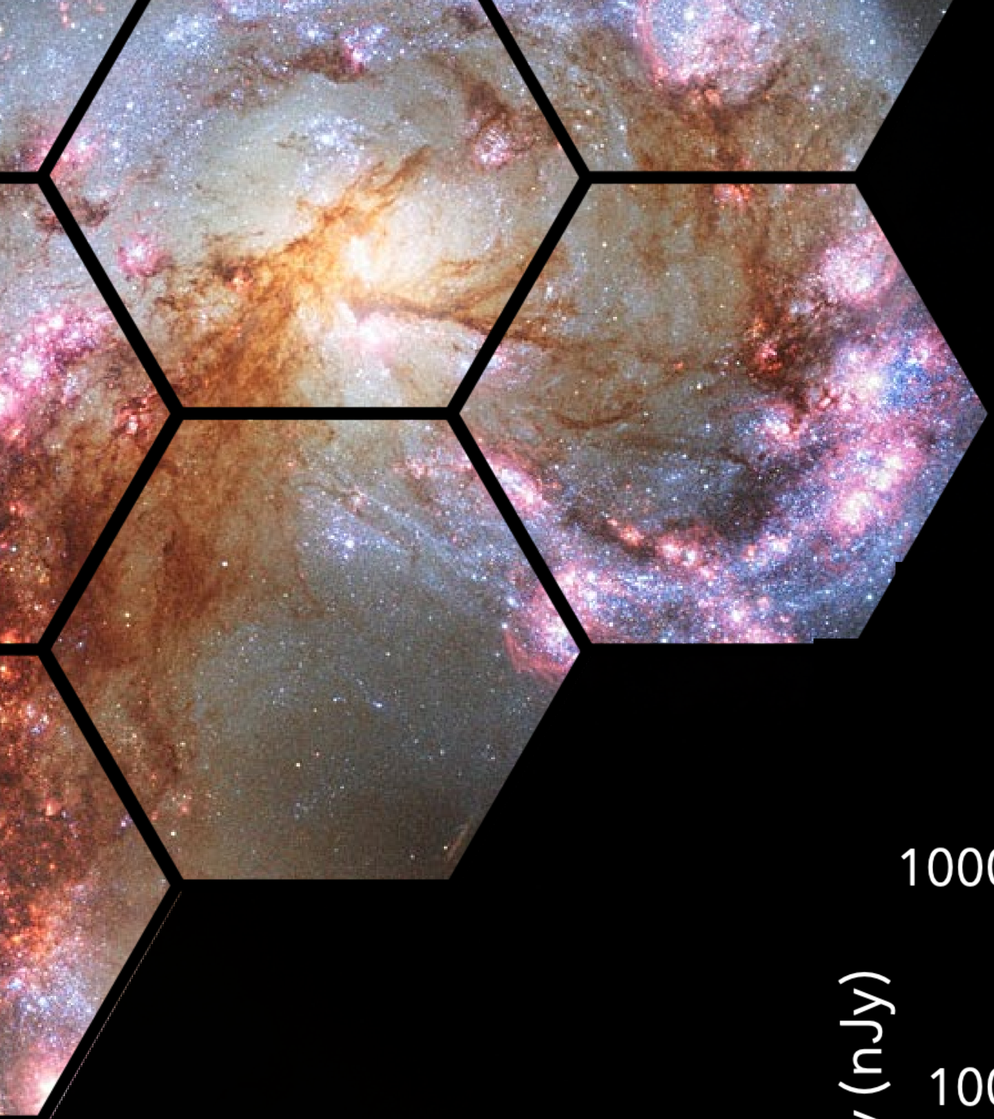




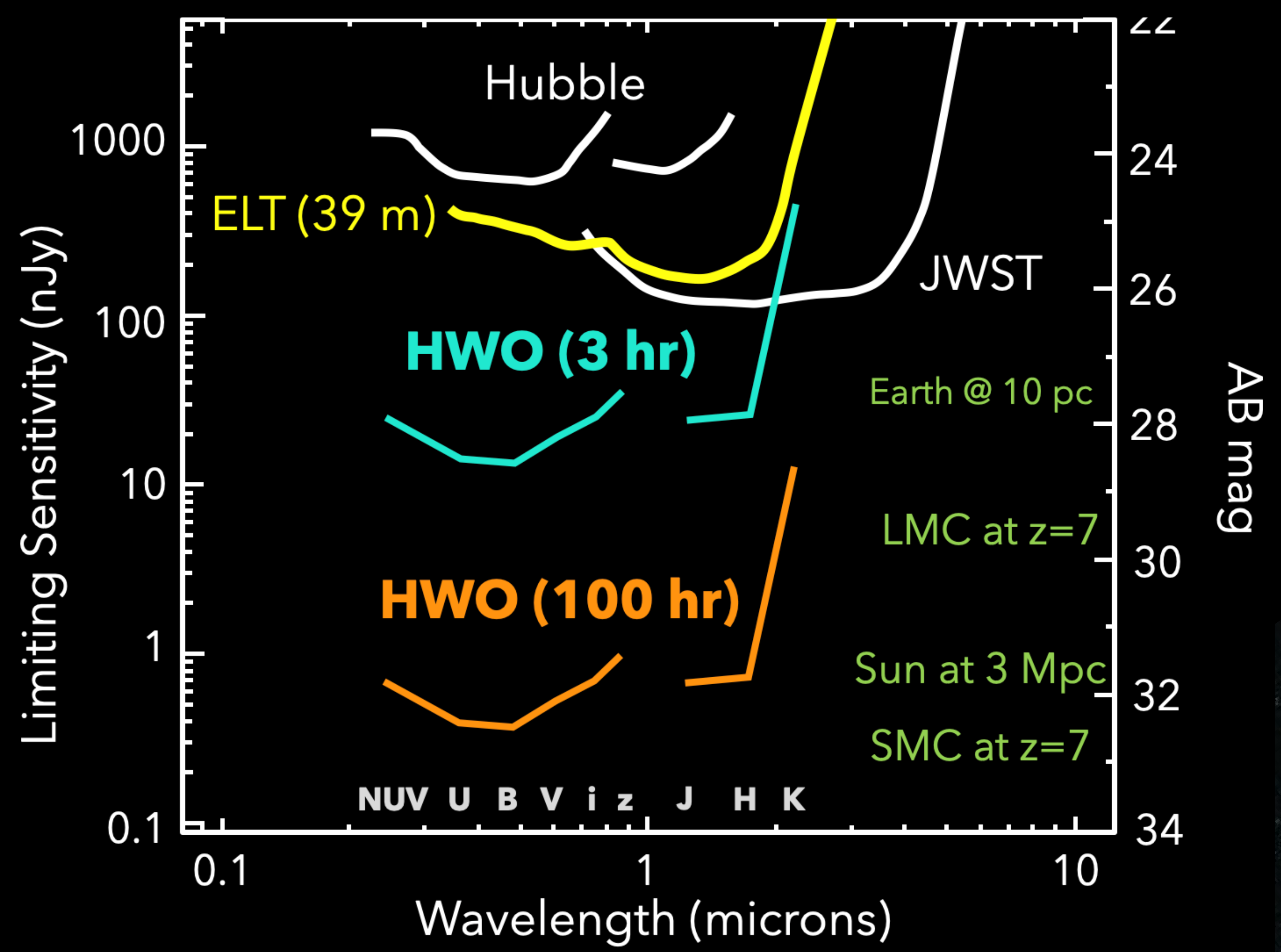


The Copernican and Darwinian revolutions rolled together.

Habitable Worlds Observatory

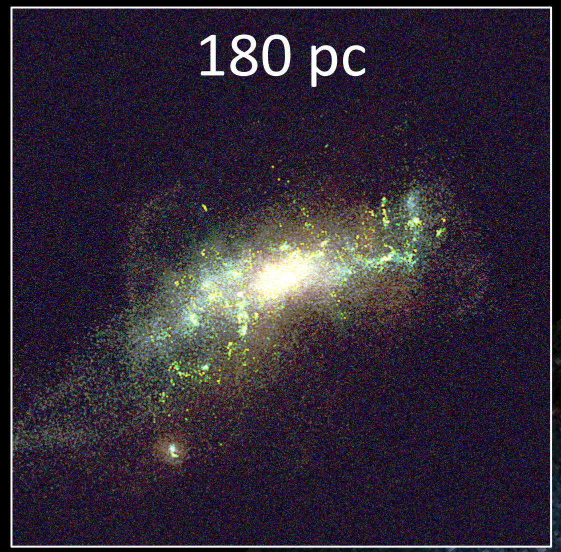


Revolutionary Depth

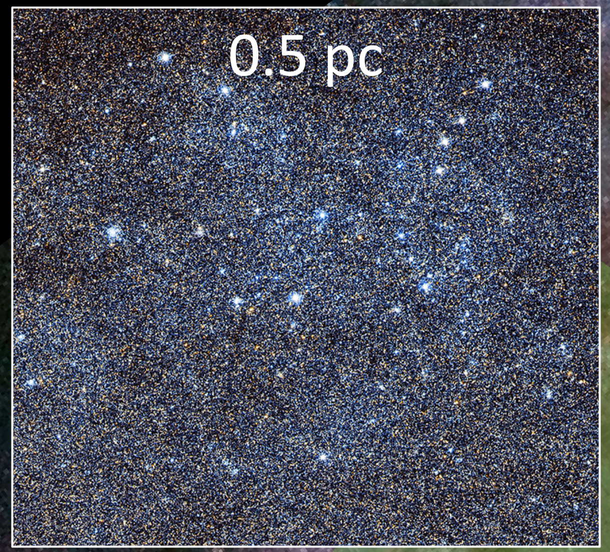


Spatial Resolution

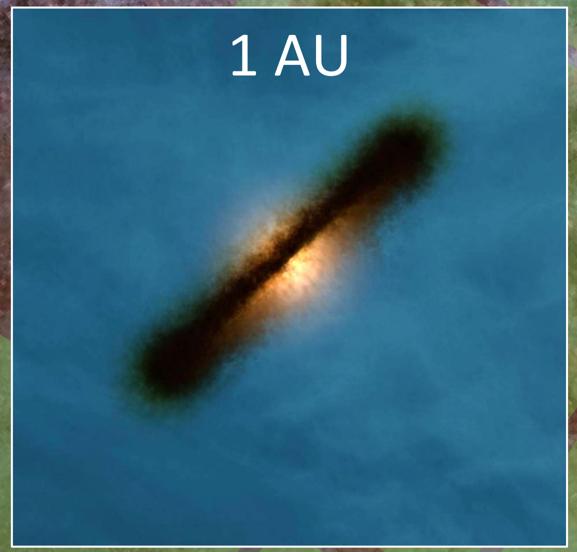
at z = 2



at 5 Mpc



at 50 pc



at 3 AU

Transformative general astrophysics from radically new resolution, depth, and multiplexing

Cold — Gas Temperature Probed by Key Ultraviolet Lines — Hot

Wide-Field, High Spatial Resolution UV Multiobject Spectroscopy

T H E N E W G R E A T O B S E R V A T O R I E S

Transformative

for the scientific aims of the next decades and for fields and problems yet unknown.

Achievable

by maturing technologies wisely and building on the experience of past flagships

Inclusive

by pursuing open science in which the best ideas rise to the top and all are welcome

Ready

to proceed to development, supported by a strong and united community

Achievable with lessons learned from:

JWST

It works! We can deploy complex systems and operate them at the diffraction limit, so let's evolve from this.
Make future missions "evolutions" but not "revolutions" on existing designs and engineering.

Using a big rocket provides ample mass and volume margin to reduce system complexity.

Mature architecture and technology fully before starting development phase, to better align funding.

Other missions

Costs cannot be estimated robustly, and therefore controlled, until a design is matured.
This will increase costs in the early phases but make flagships cheaper in the long run.

Plan for servicing to expand capabilities, control initial costs, and reduce risks.

Build to schedule so as to avoid an open ended development path (like planetary missions).

es Maturation Program (GOMAP), now started by NASA, will incorporate these lessons in

All the New GOs have Tall Poles, and Detailed Plans

Table 11-1. *Technology components in the high-contrast coronagraph instrument technology system.*

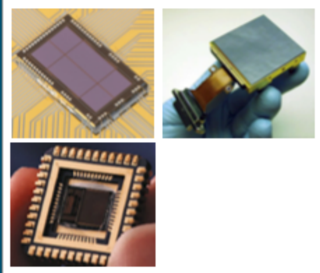
Section	Technology Component	Implementation Options	State of the Art	Capability Needed	FY19 TRL	In LUVOIR Baseline?
12.2.1.3	Coronagraph Architecture	Apodized Pupil Lyot Coronagraph (APLC)	6.3×10^{-6} over 6% bandpass in air. Validated models with WFIRST CGI SPC demonstrations	1×10^{-10} raw contrast >10% bandpass <4 λ/D inner working angle 64 λ/D outer working angle Robust to stellar diameter and jitter	4	✓
		Vortex Coronagraph (VC)	8.5×10^{-9} contrast over 10% band with unobscured pupil. SCDA modeling for unobscured, segmented pupil		3	✓
		Phase-Induced Amplitude Apodization (PIAA)	SCDA modeling results for unobscured, segmented pupil		3	
		Hybrid-Lyot Coronagraph (HLC)	3.6×10^{-10} contrast over 10% band in DST. SCDA modeling for unosbcured segmented pupil		3	
		Nulling Coronagraph (NC)	5×10^{-9} narrowband at 2.5 λ/D		3	
12.2.1.4	Deformable Mirrors	Micro-Electro-Mechanical Systems (MEMS)	Available up to 64 x 64 actuators; 8.5×10^{-9} contrast demonstrated with 32 x 32 actuators	128 x 128 actuators Stable actuators (low creep) Diffraction-limited surface quality (< 3 nm surface roughness)	4	✓
		Lead-Magnesium-Niobate (PMN) Macro-scale	$<1 \times 10^{-8}$ contrast demonstrated with 48 x 48 actuator Xinetics DMs (WFIRST CGI Testbed)		5	
12.2.1.7	Wavefront Sensing	Out-of-band Wavefront Sensing	Model predicting <10 pm residual error with nonlinear ZWFS, Mv = 5 source	Wavefront stabililty ~10 pm RMS ~1 Hz bandwidth with Mv < 9 source Able to capture wavefront spatial frequencies on the order of segment-to-segment drift and DM actuators	3	✓
		Low-order Wavefront Sensing	<0.36 mas RMS line-of-sight residual error; <30 pm RMS focus, Mv = 5 source (WFIRST CGI Testbed)		6	✓
		Artificial Guide Star	Concept study for guide star spacecraft and wavefront sensing control loop completed.		3	
12.2.1.10	UV/VIS Low-noise Detector	Electron-Multiplying CCD	1k x 1k WFIRST Detector: 7x10–5 e-pix/s dark current 0 e- read noise 2.3x10–3 CIC	3×10^{-5} e-/pix/s dark current 0 e- read noise 1.3×10^{-3} e-/pix CIC >80% QE at all	4	✓
			Prototype devices fabricated with			

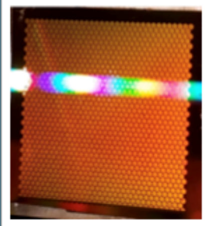
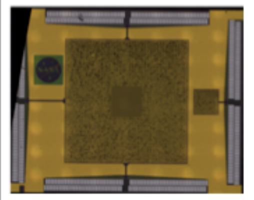
ultrastable optics
high contrast imaging
UV/optical coatings
and detectors

LYNX

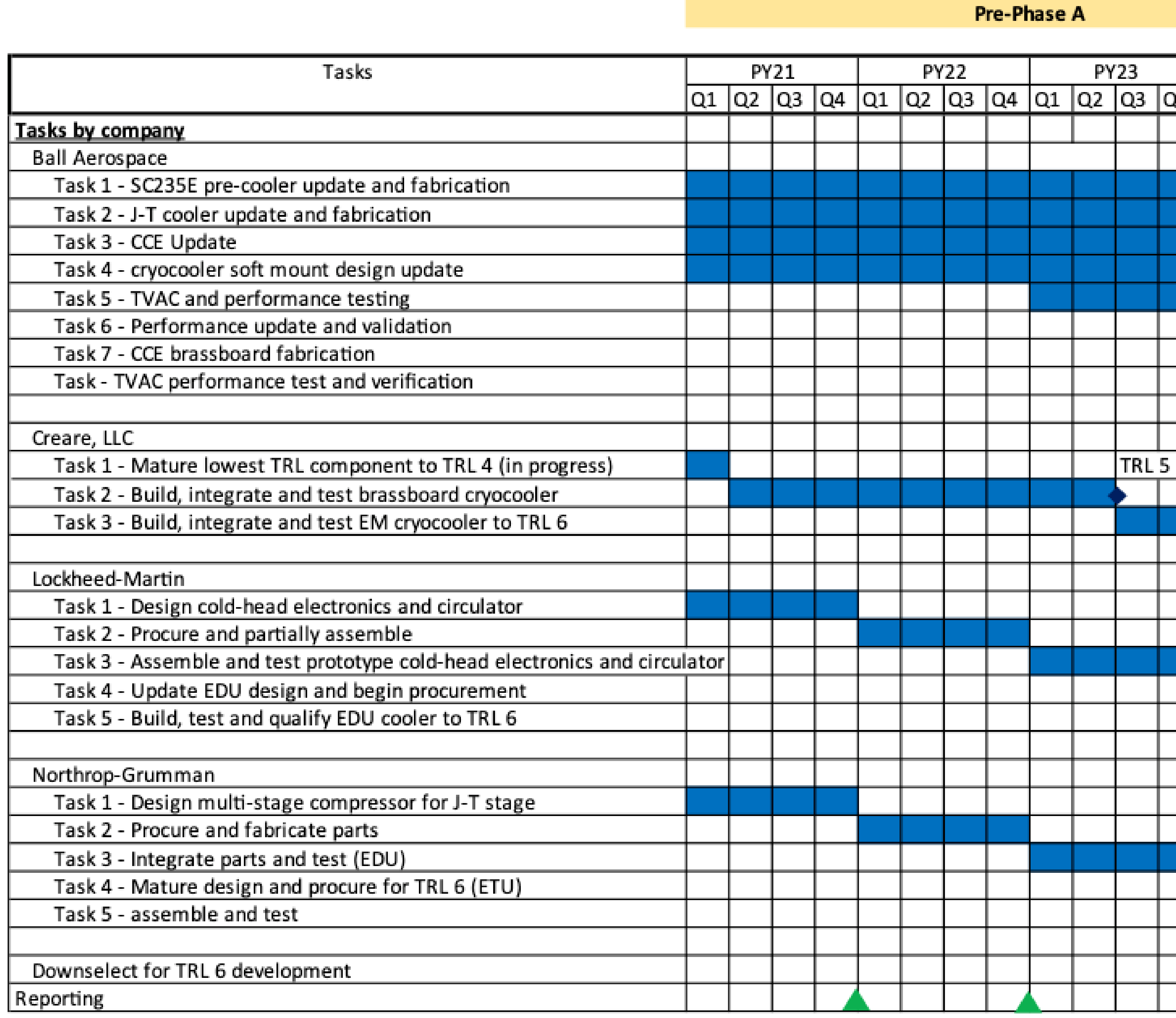
meta-shell optics with 30,000 segments
detectors for imaging spectroscopy
high resolution dispersers
high resolution microcalorimeters

Table 7.1. *Lynx*-enabling technologies requiring technology maturation.

	Technology	Function	Development Challenges	Development Path	AD2 - Rationale
Lynx Mirror Assembly (LMA)	Silicon Meta-shell Optics – Modular design with many thousands of thin, lightweight mirror segments integrated (via modules/meta-shells) into the *Lynx* Mirror Assembly **Current TRL = 3** 	Provide high-resolution imaging over the large field of view and broad energy range needed to meet *Lynx* science goals	• Demonstrate a reliable fabrication process to mass produce quality mirror segments • Verify processes for assembling the required 611 mirror modules • Demonstrate assembly processes for 12 meta-shells • Demonstrate final assembly, alignment, and testing processes	• Develop alternate mirror technologies in parallel with baseline • Fabrication, alignment, coating, bonding, and qualification of single-mirror segment pairs (TRL 4) • Fully populating and qualifying multiple mirror modules and a single meta-shell (TRL 5) • Assembly and qualification testing of subscale (3 meta-shell) engineering model *Lynx* Mirror Assembly (TRL 6)	• TRL 4: $AD^2 = 3$ – All required fabrication processes (substrate, coating, bonding, alignment) demonstrated, process refinement for mass production to be developed • TRL 5: $AD^2 = 3$ – Alignment and bonding processes will carry over from TRL 4 development; iterative fabrication assembly process required to ensure throughput and environmental survivability is straightforward • TRL 6: $AD^2 = 3$ – As with TRLs 4 and 5, this is a relatively straightforward (albeit intricate) assembly, fit, and test phase that will likely require iterations; No fundamental barriers are apparent.
High-Definition X-ray Imager (HDXI)	Imaging spectrometer leveraging pixelated silicon sensor technology heritage from many ground- and space-based applications **Current TRL = 3** 	Provide large-format, high-throughput, sub-arcsec angular resolution at moderate spectral resolution over broad X-ray energy band to meet *Lynx* science goals	• Provide excellent low-energy X-ray response (high quantum efficiency) and fine spatial resolution at high frame rates • Demonstrate low detector noise, high pixel-to-pixel response uniformity, and reliable readout processing	• Demonstrate required sensor (with Application-Specific Integrated Circuit (ASIC)) noise, resolution, and quantum efficiency at high and low energies in representative multichannel sensor • Demonstrate required performance of integrated sensor/ASIC system of representative size before and after environmental testing • Demonstrate required performance of ¼-size focal plane in relevant environment before and after environmental testing	• TRL 4: $AD^2 = 5$ – Optimization of pixelated silicon sensors and ASICs is standard industry practice, but all science requirements must be demonstrated on a single custom sensor; may require long lead-times • TRL 5: $AD^2 = 2$ – Integrating a sensor/ASIC and associated readout electronics for evaluation to TRL 5 is largely an engineering activity • TRL 6: $AD^2 = 2$ – Combining multiple sensors and ASICs into an engineering model focal plane of pixelated silicon sensors has high heritage from many missions

	Technology	Function	Development Challenges	Development Path	AD2 - Rationale
X-ray Grating Spectrometer (XGS	Very high resolving power, dispersive, soft X-ray spectrometer optimized for efficiency at astrophysically critical atomic line energies **Current TRL = 4** 	Provide high-throughput, very high resolving power, dispersive spectroscopy to meet *Lynx* science goals for bright, point-like sources	• Fabricate high- efficiency diffraction gratings (thin grating bars but deep device layers with low support structure obscuration) • Advance metrology for alignment and mounting to preserve energy resolution (Line Spread Function (LSF)). Develop "chirped" gratings to maintain LSF of large grating facets	• Develop alternate grating array technology in parallel with baseline • Increase depth and decrease width of grating bars using Deep Reactive-Ion Etching and KOH polishing solution • Leverage experience from past mission development as foundation for alignment metrology and assembly • Build toward TRL 6 large-scale prototype matched to LMA TRL 6 demonstrator	• TRL 5: $AD^2 = 3$ – Fabricating grating membranes with reduced structural obscuration is an incremental development but must pass environmental tests; conception and implementation of metrology infrastructure for mounting and alignment in brassboard is new development. • TRL 6: $AD^2 = 3$ – Fabricating larger grating membranes with designed grating bar widths and period chirp will leverage semiconductor and Micro-Electrical Mechanical Systems (MEMS) industry practices – most development is incremental
Lynx X-ray Microcalorimeter (LXM)	Large-format fine pixel microcalorimeter with three pixel array types providing a large range of scientific capabilities **Current TRL = 3** High-bandwidth microcalorimeter readout **Current TRL = 3** Focal Plane Assembly (FPA) and Optical Photon Blocking Filters **Current TRL = 4** Cryogenic cooling system **Current TRL = 4** 	Provide high-spatial resolution energy dispersive imaging capabilities to meet multiple *Lynx* science goals	• Reduce slew rates for the thermal multiplexed pixels to adequately match the readout capabilities of the μMUX readout • Reduce thermal crosstalk • Avoid substantial energy degradation from crosstalk in readout circuitry at relevant mux factors • Advance cryocooler and ADR technologies to required TRL within schedule and budget	• Develop alternate sensor technology in parallel with baseline • Fabricate heat-sinking of arrays with buried wires through multiple approaches to achieve best thermal crosstalk reduction • Design readout components and operational parameters (e.g., tone power to amplifiers) to mitigate crosstalk • Leverage *Athena*'s X-ray Integral Field Unit (X-IFU) development for *Lynx* Focal Plane Array • Utilize two independent industry-based cryocooler design and development paths and choose best option	• TRL 4: $AD^2 = 3$ – Existing TES-based arrays lack only standard testing; μMUX readout needs optimization for bandwidth required – testing/modeling efforts indicate no fundamental design limits for LXM • TRL 5: $AD^2 = 3$ – Arrays require advancement in heatsinking – buried wire technology scale-up straightforward; significant carryover from ongoing development efforts for multiple terrestrial applications expected for readout advancement ($AD^2 = 4$); cryocooler advancement requires funding investment • TRL 6: $AD^2 = 2$ – Straightforward engineering advancement of arrays to full size; readout integration into new FPA geometry is AD2 = 4; new FPA is an engineering effort leveraged from *Athena* ($AD^2 = 3$) – blocking filter sizing and environmental testing not a technical challenge; cryocooler straightforward optimization between structural and thermal performance

cryocoolers for 4.5 K
sub-Kelvin detector cooling
TES/KIDS detectors
mid-IR detector arrays



Title	Description	Section	State of the Art	Capability Needed
UV Microchannel Plate (MCP) Detectors	Low-noise detectors for general astrophysics as low as 115 nm	*Section 11.4.4.3*	• MCPs: QE 44% 0.115–0.18 μm with alkalai photocathode, 20% with GaN; dark current ≤0.1–1 counts/cm²/s with ALD activation and borosilicate plates	• Dark current <0.001 e-/pix/s (173.6 counts/cm²/s), in a space radiation environment over mission lifetime, • QE>50% for 115–300 nm wavelengths
Microthrusters	Jitter is mitigated by using microthrusters instead of reaction wheels during exoplanet observations	*Section 11.6.1.1*	• Colloidal microthrusters 5–30 μN thrust with a resolution of ≤0.1 μN, 0.05 μN/√Hz, 100 days on-orbit on LISA-Pathfinder • Colloidal microthrusters with 100 μN thrust and 10-year lifetime under development • Cold-gas micronewton thrusters flown on Gaia (TRL 9), 0.1 μN resolution, 1 mN max thrust, 0.1 μN/sqrt (Hz), 4 years of on-orbit operation	• Thrust capability: 350 μN with 16 thruster cluster • Thrust resolution 4.35 μN • Thrust noise: 0.1 μN/√Hz • Operating life: 5 years
Enhancing Technologies				
Far-UV Mirror Coating	Observatory Science imaging as low as 0.1 μm	*Section 11.7.1.1*	• For a ~0.1 μm cutoff, Al + LiF + AlF_3 has been demonstrated at the lab proof-of-concept level with test coupons achieving reflectivities ▪ for >200 nm: 80% ▪ for 103–200 nm: 70% ▪ Lifetime: no loss of reflectivity after 3-year lab storage	• Reflectivity from 0.3–1.8 μm: >90% • Reflectivity from 115–300 nm: >80% • Reflectivity from 103–115 nm: >50% • Operational life: >10 years
Delta-Doped UV Electron Multiplying CCDs	Low-noise detectors for general astrophysics as low as 0.1 μm	*Sect 11.7*		
Microshutter Arrays	An array of apertures for the UV spectrometer	*Sect 11.7*	in FORTIS sounding rocket summer 2019 • 840 × 420 electrostatic, buttable array developmental model with partial actuation	

Let's take this one.
LUVOIR/Habex UV optical
coatings and detectors.

Status of Each Item as of LUVOIR Report (2019)

Based on Table 11-3 of LUVOIR Report

Black font = current status as of 2018, from Table 11-3 of LUVOIR Final Report

7	System prototype demonstration in an operational environment.											
LUVOIR Preliminary Design Review												
6	System / sub-system model or prototype demonstration in an operational environment.						meets requirements for 100-150 nm					
5	Component and/or breadboard validation in relevant environment.			Meets performance requirements, but is environmentally unstable								8K x 8K devices exist with 18 micron pixels, lacks high speed subarray readout for guiding
4	Component and/or breadboard validation in lab environment					>5000:1 contrast achieved on re-windowed XGA format (1024x768) Ninkov SAT ; Quad		meets requirements for 100-150 nm; requires devel for large tile size and integration with cross-strip readout. GaN has better Solar-blind performance		Demonstrated 50% improved QE with CsI photocathode	4K x 4K devices exist, require development for 8K x 8K and readout optimization	
3	Analytical and experimental critical function and/or characteristic proof of concept	Meets performance requirements, but requires demonstration on meter-class optics, validation of uniformity, repeatability, and env. stability **PVD; Quijada SAT; Quad**			840x420 prototype demonstrated, but requires devel. to survive launch Greenhouse SAT ; Quad							
		> 50% over 100-115 nm, > 80% over 115-200 nm > 88% over 200 - 850 nm, > 96% over > 850 nm, < 1% reflectance non-uniformity over primary mirror in coronagraph bandpass (200-2000 nm)			840x420 format, two-side buttable, high contrast		200 mm x 200 mm tile size > 30% QE between 100-200 nm				8K x 9K format, < 7 µm pixels, three-side buttable, ~1 e- read noise, 10^{-4} e-/pix/s dark at 170K	
		Al+eLiF+MgF_2 **Baseline**	Al+eLiF+AlF_3	Al+eLiF	Microshutters **Baseline**	Micromirrors	CsI **Baseline**	GaN **Baseline**	Bi-alkali	Funnel micro	8K x 8K CMOS **Baseline**	4K x 4K CCDs
		Far-UV Broadband Coatings LUVOIR pg. 11-25			Configurable Shutters LUVOIR pg. 11-26		UV Microchannel Plate LUVOIR pg. 11-26				Visible Detectors LUVOIR pg. 11-27	

Strategic Investments in Technology are Ongoing

Development of Digital Micro-mirror Devices for Far-UV Applications

PI: Zoran Ninkov / Rochester Institute of Technology

Objectives and Key Challenges:

- There is a need for a technology to allow for selection of targets in a field of view that can be input to an imaging spectrometer for use in remote sensing and astronomy
- We are looking to modify and develop Digital Micromirror Devices (DMDs) for this application

Significance of Work:

- This work looks to improve the deep-UV performance of COTS DMDs by recoating the DMD mirrors themselves using the coating facility at GSFC and operating them with a custom window or operating in an open mode

Testing DMDs at GSFC (left to right: Lexi Irwin, PhD student; Kate Oram, PhD student; Dmity Vorobiev; and Zoran Ninkov)

Approach:

- Use available 0.7 XGA DMDs that will be recoated with a Al/AlF_3 at GSFC coating facility; test and evaluate such devices both with a window and in an open configuration

Key Collaborators:

- Manuel Quijada and Javier del Hoyo (NASA/GSFC)
- Massimo Robberto (STScI)
- Alan Raisanen (RIT)
- Stephen Smee (JHU)
- Dmitry Vorobiev (U Colorado, Boulder)

Current Funded Period of Performance:

Jan 2018 – Dec 2019

Recent Accomplishments:

- ✓ First XGA devices recoated and found functional
- ✓ Radiation testing completed, analysis proceeding
- ✓ Optical measurement facility assembled and tested
- ✓ Procedure for delivering and coating DMDs at GSFC developed
- ✓ Procedure for using far-UV testing with McPherson monochromator at GSFC developed

Next Milestones:

- TRL Review
- Sufficient recoated DMDs for further testing

Application:

- Proposed for Probe mission ATLAS (Astrophysics Telescope for Large Area Spectroscopy), a small sat project, and a proposed rocket payload

$TRL_{in} = 5$ $TRL_{Current} = 5$ $TRL_{Target} = 5$

Use of Plasma Enhanced ALD to Construct Efficient Interference Filters for the FUV

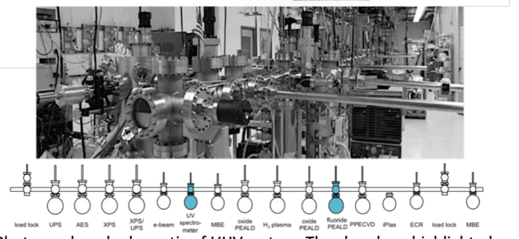
PI: Paul Scowen / ASU

Objectives and Key Challenges:

- Use a range of oxide and fluoride materials to build stable optical layers using Plasma-Enhanced Atomic Layer Deposition (PEALD) to reduce adsorption, scattering, and impurities
- Layers will be suitable for protective overcoats with high UV reflectivity and unprecedented uniformity (compared to thermal ALD)
- Development of single-chamber system to deposit metal oxide and dielectric layers without breaking vacuum

Significance of Work:

- To use the improved ALD capability to leverage innovative ultraviolet/optical filter construction



Photograph and schematic of UHV system. The chambers highlighted in blue were constructed for this project. The fluoride PEALD supports oxygen-free deposition and processing.

Approach:

- Development of existing PEALD system to a single-chamber model
- Atomic layer processing to remove surface oxides from Al
- Development of fluoride deposition on top of Al films
- Demonstration of VUV reflectivity, uniformity, and stability

Key Collaborators:

- Paul Scowen, Robert Nemanich, Brianna Eller, Daniel Messina, Zhiyu Huang, and Hongbin Yu (ASU)
- Tom Mooney (Materion)
- Matt Beasley (Planetary Resources Inc.)

Current Funded Period of Performance:

Dec 2015 through Nov 2019

Recent Accomplishments:

- ✓ PEALD of AlF_3 on sapphire and clean Al
- ✓ Methods to determine optical constants

Next Milestones:

- PEALD of MgF_2
- MgF_2 / AlF_3 filters
- Measure UV reflectivity and transmission of MgF_2 and AlF_3 with accuracy better than 3%
- Determine the optical constants for MgF_2, AlF_3, and Al

Application:

- LUVOIR / HDST / ATLAST / HabEx

$TRL_{in} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 4$

Large format, high dynamic range UV Detector using MCPs and Timepix4 Readouts

PI: John Vallerga/ U.C. Berkeley

Description and Objectives:

Large format (200x200mm) MCP detectors have been baselined as the detector of choice for the Far-UV instruments on the proposed LUVOIR and HabEx missions. To scale to that size while maintaining spatial resolution and dynamic range requires a pixelated anode readout that can be mosaiced over this area. The new photon counting ASIC, called Timepix4 (Tpx4), has all these attributes: large format (28x25mm), buttable on 4 sides, low input noise (75e- rms), sparsified event readout, and events rates exceeding 100 MHz.

Key Challenge/Innovation:

- **Demonstrating Tpx4 readout of MCPs with excellent spatial resolution, at very high event rates in a low-power mode**
- **Tpx4 mosaics with minimum gaps between ASICs (<50µm)**
- **New 100x100 MCP detector with Tpx4 readout to be environmentally tested (vibration, thermal, radiation)**

Approach:

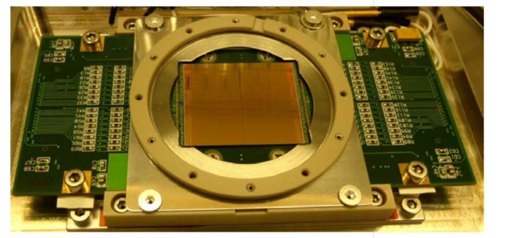
Tpx4 ASICs will first be processed at the wafer level to create Through Silicon Vias (TSVs) and a signal redistribution layer on the backside to enable a ball-grid array pattern. A High Temperature Co-fired Ceramic (HTCC) circuit layout board will be designed to hold a 3x3 array of accurately aligned Tpx4 dies. Signals and Power/Gnd will be distributed on the back side of the HTCC including two 10Gbs transceivers per chip (18 total). This 84x74mm active anode will be placed in a 100x100 mm MCP detector to measure performance in flight like environments.

Key Collaborators:

- **Timepix4/Medipix4 collaboration (14 international institutes) *http://medipix.web.cern.ch/collaboration/medipix4-collaboration***

Development Period:

- **March 1, 2019 - Feb 28, 2022**



Existing MCP/Timepix readout detector, (MCPs removed). We will mosaic a 3x3 array of Tpx4 chips without wirebonds

Accomplishments and Next Milestones:

- **Timepix4 wafer processed with TSVs and BGA redistribution layer - Jan 2021**
- **HTCC ceramic carrier fabricated. - Oct. 2020**
- **Readout of single Tpx4 x-ray sensor using Kintex dev. board. - Oct 2020**
- **Mounting of Tpx4 dies onto HTCC carrier. - Apr. 2021**
- **Tpx4 anode with MCP detector assembly operating in vacuum – Oct 2021**
- **Fully functional MCP – Tpx4 detector with FPGA readout – Jan 2022**
- **Environmental tests of MCP-Tpx4 detector. - July 2022**

Applications:

- **High performance UV (1-300nm) detector for astrophysics (LUVOIR, HabEx, CETUS), planetary, solar, heliospheric, or aeronomy missions**
- **Particle or time of flight detector for space physics missions**
- **Neutron radiography/tomography for material science**

•$TRLin = 4$ $TRLcurrent = 4$ $TRLtarget = 5$

Advanced FUV/UV/Visible Photon-Counting and Ultralow-Noise Detectors

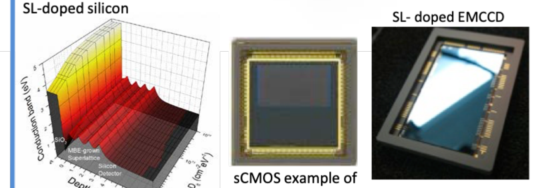
PI: Shouleh Nikzad / JPL, California Institute of Technology

Objectives and Key Challenges:

- Develop and advance TRL of solar-blind (SB), high-efficiency, photon-counting, and ultralow-noise solid-state detectors, especially in FUV (λ < 200 nm)
- Key challenges: SB silicon, large-format arrays, reliable and stable high response in FUV

Significance of Work:

- Key innovations are high and stable UV response through atomic-level control of surface and interfaces, the breakthrough in rendering Si detectors with optimized in-band response and out-of-band rejection, versatility with CMOS and CCD, and uniform large format



Approach:

- Fabricate and process UV detectors by superlattice (SL) doping Electron Multiplying CCDs (EMCCDs) and ultralow-noise CMOS wafers
- Develop multi-stack, integrated, SB filters using atomic-layer deposition (ALD)
- Combine integrated SB filters and SL with CMOS and EMCCDs
- Characterize and validate

Key Collaborators:

- Chris Martin (Caltech)
- David Schiminovich (Columbia University)
- Michael Hoenk (JPL)
- Teledyne-e2v, SRI, AMS-CMOSIS, Alacron

Current Funded Period of Performance:

Jan 2016 – Dec 2019

Recent Accomplishments:

- ✓ EMCCD wafers processed by low-temperature SL-doping
- ✓ Visible-blind filters on SL-doped EMCCDs (optimized: 120-160 nm)
- ✓ FIREBall-2 flown. Detector performed well. Data analysis ongoing.
- ✓ Partnership with CMOS vendors (SRI). Wafer processing underway.
- ✓ Radiation testing moving forward as planned (WFIRST protocol)
- ✓ Room-temperature proton radiation testing on one device
- ✓ Completed testing of low-T-processed SL-doped EMCCD wafers

Next Milestones:

- Pocket pumping characterize devices pre radiation (Aug 2019)
- Complete pad opening, packaging, testing low-T-processed SL-doped EMCCDs (Sep 2019)
- Complete processing first batch of low-noise CMOS wafers (Sep 2019)
- Radiation testing (Nov 2019)

Applications:

- LUVOIR, HabEx, Lynx
- Probes, Explorers, CubeSats

sCMOS $TRL_{in} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 4\text{-}5$

EMCCD $TRL_{in} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 5\text{-}6$

Note: TRLs assessed for 2-D, w/integrated filters

Enhanced MgF_2 and LiF Over-coated Al Mirrors for FUV Space Astronomy

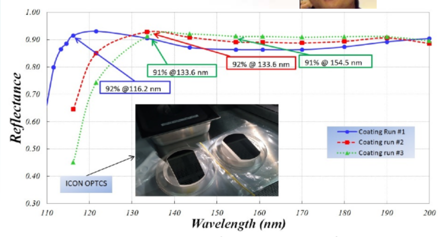
PI: Manuel A. Quijada/Code 551

Description and Objectives:

- Development of high reflectivity coatings to increase system throughput, particularly in the far-UV (FUV) spectral range
- Study other dielectric fluoride coatings and other deposition technologies such as Ion Beam Sputtering (IBS) that is expected to produce the nearest to ideal morphology optical thin film coatings and thus low scatter.

Key challenge/Innovation:

- Achieving high reflectivity (> 90-95%) in the 90 to 250 nm range
- Scaling up coatings to large diameter (1+meter) mirror substrates



Various test runs to produce coatings with over 90% reflectance for ICON optics in FUV

Approach:

- Retrofit a 2 meter coating chamber with heaters/thermal shroud to perform Physical Vapor Depositions at high temperatures (200-300 C) to further improve performance of Al mirrors protected with either MgF_2 or LiF overcoats.
- Optimize deposition process of lanthanide trifluorides as high-index materials that when paired with either MgF2 or LiF will enhance reflectance of Al mirrors at Lyman-alpha.
- Establish the IBS coating process to optimize deposition of MgF2 and LiF with extremely low absorptions at FUV wavelengths.

Collaborators:

- Javier del Hoyo, Steve Rice and Felix Threat (551)
- Jeff Kruk and Charles Bowers (665)

Development Period:

Oct. 1, 2011 – Sept. 30, 2014

Accomplishments:

- Performed end-to-end testing of the 3-step Physical Vapor Deposition (PVD) coating process in 2 meter chamber to enable 1+meter class mirrors with either Al+MgF_2 or Al+LiF coatings for FUV applications
- Completed characterization of lanthanide trifluorides (GdF_3 and LuF_3) to pair them with low-index MgF_2 layers to produce narrow-bands dielectric reflectors at FUV wavelengths
- Production of mirrors with reflectance over 90% in FUV for ICON and GOLD projects.

Applications:

- Application of these enhanced mirror coating technology will enable FUV missions to investigate the formation and history of planets, stars, galaxies and cosmic structure, and how the elements of life in the Universe arose.

$TRLin = 3$ $TRLout = 4$

10-SAT10-0050_2015_APR

Next Generation FORTIS*

*Far-UV Off Rowland-circle Telescope for Imaging and Spectroscopy

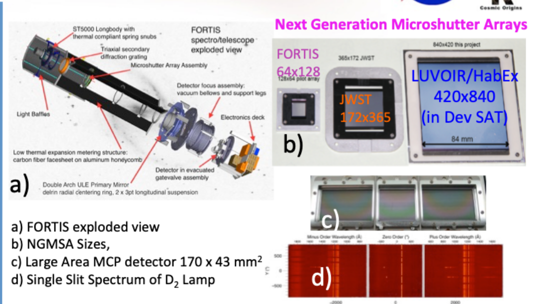
PI: Stephan McCandliss/JHU

Description and Objectives:

- Demonstrate the scientific utility and feasibility of multi-object spectroscopy over wide angular fields in the far-UV. First Science Investigation:
  - Spectroscopy of Hot Star Clusters in galaxy M33
    - How does matter circulate from Disk to CGM?

Key Challenge/Innovation:

- Pulsed Actuated Next Gen Microshutter Arrays(NGMSA)
- New low scatter baffles to trap geo-Lyman alpha light
- Longlife, High QE, Large Area Borosilicate MCP's
- Autonomous Target Acquisitions



a) FORTIS exploded view
b) NGMSA Sizes,
c) Large Area MCP detector 170 x 43 mm²
d) Single Slit Spectrum of D_2 Lamp

Approach:

- Collaborate with GSFC on NGMSA requirements and fabrication
- Sensor Sciences retrofit detector with new borosilicate MCPs with CsI photocathode
- Develop Wide-Field Lyα Geocoronal Simulator (WFLaGS)
- Design light traps suppress Lyα
- Involve graduate and undergraduates all phases of mission

Key Collaborators:

- Brian Welch, Anna Carter, Paul Feldman, William Blair, Luciana Bianchi – JHU
- Matt Greenhouse, S. Harvey Moseley, Alexander Kutyrev, Mary Li – GSFC
- Gerhardt Meurer – U. Western Australia

Development Period:

1 January 2017 to 31 December 2021

Accomplishments and Next Milestone:

- Three flights of FORTIS have proven basic design
- Science results on Comet ISON have been published
- Baseline in-flight instrument performance established:
  - Scattered geo-Lyman alpha tall pole identified
  - Reproduced in-flight scatter signature
- •Upcoming milestones include:
  - Launch of 36.352 UG from WSMR 27 October 2019 (Success!!!)
  - Post flight calibration Fall/Winter 2019/2020
  - Prep for Australia???

Application: Enabling Multi-object Spectroscopy for UVOIR future missions (Explorers, Probes, Flagships)

New Tech Readiness	*TRLin*	*TRLcurrent*	*TRLtarget*
Borosilicate MCPs	4	7	7
NGMSA	4	7	7
Low Scatter Baffles	4	7	7

High-Performance Sealed-Tube Cross-Strip Photon-Counting Sensors for UV-Vis Astrophysics Instruments

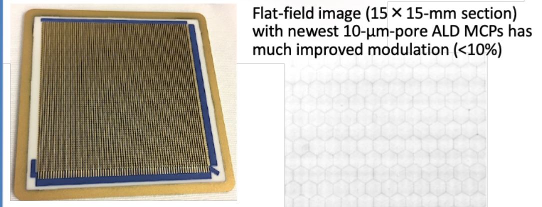
PI: Oswald Siegmund / UC Berkeley

Objectives and Key Challenges:

- Exploit developments in atomic-layer-deposited (ALD) microchannel plates (MCPs), photocathodes, and cross strip (XS) readout techniques to implement a new generation of enhanced-performance sealed-tube photon-counting sensors that span the 115-nm-to-400-nm range; subcomponent areas have achieved considerable technical development, but putting them into a robust, integrated package, advancing the TRL from 4 to 6 for the next UV/Vis astrophysics instruments has not yet been attempted

Significance of Work:

- Format, performance, and capabilities of the scheme is directly relevant to the requirements specified for CETUS, LUVOIR and HABEX, as well as upcoming SMEX, CubeSat and sub-orbital projects



Flat-field image (15 × 15-mm section) with newest 10-µm-pore ALD MCPs has much improved modulation (<10%)

47-mm XS anode with seal ring ready for bonding to Planacon

Approach:

- Adopt current Photonis Planacon 50-mm sealed tube and implement the new technologies within this envelope
  - Implement low UV MgF_2 entrance window and UV-optimized bialkali semitransparent photocathode with narrow (~200-µm) proximity gap
  - Replace standard MCPs with two ALD MCPs, depositing an opaque UV photocathode onto MCP input surface
  - Replace pad-array anode with XS anode readout

Key Collaborators:

- Dr. T. Cremer (Incom Inc.)
- Dr. J. DeFazio (Photonis USA)

Current Funded Period of Performance:

Jan 2018 – Dec 2020

Recent Achievements:

- ✓ ALD MCPs: new 54-mm ALD 10-µm MCPs received, perform much better than original material, flat fields and linearity much improved; tested and ready to install in first Planacon device
- ✓ Planacon: body-anode trial seals completed successfully.
- ✓ XS anodes: 47-mm anodes cut to size, plated, ready for 1st device.
- ✓ New bialkali cathode on MgF_2 , 2 x better QE, stable, and 360-nm cutoff
- ✓ Opaque CsI deposited on initial 10-µm ALD MCPs and QE measured

Next Milestones:

- Initial 10-µm and 20-µm ALD MCPs life-test in progress
- Fabricate and test optimized bialkali cathode on MgF_2 (Aug 2019)
- QE tests and preconditioning of new 10-µm ALD MCPs (Dec 2019)
- Complete 1st planacon tube build (Oct 2019)
- Complete 2nd planacon tube build (Mar 2020)
- Papers, talks for SPIE (Aug 2019) and AMOS (Sep 2019) accepted

Applications:

- Explorer, Probe class (CETUS), Flagship (LUVOIR, HABEX), Suborbital
- Planetary and Earth-observing missions
- Homeland security, biological imaging, high energy physics

$TRL_{in} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 6$

Scalable Microshutter Systems for UV, Visible, and Infrared Spectroscopy

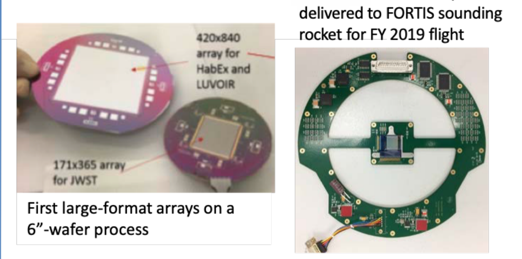
PI: Matt Greenhouse, NASA GSFC

Objectives and Key Challenges:

- Eliminate macro-mechanisms required by the prior JWST magnetic actuation technology
- Develop large-array format and modular packaging for large-field-of-view applications
- Enable electrostatic actuation with high pixel operability
- Enable large-array format compatible with vibration/acoustic flight environment
- Enable 3-side-buttable packaging for large-field-of-view applications

Significance of Work:

- This technology uniquely enables the multi-object spectroscopy objectives of three Decadal Survey mission concept studies (HabEx, LUVOIR, and CETUS)



Microshutter assembly delivered to FORTIS sounding rocket for FY 2019 flight

First large-format arrays on a 6"-wafer process

Approach:

- Evolve shutter mechanical and electrical design to above objectives
- Incorporate improved oxide (ALD) to enable electrostatic actuation
- Incorporate 3D printing to increase manufacturability of large-format design
- Develop drive electronics for electrostatic actuation
- Develop 6"-wafer process and tooling necessitated by new array format requirement
- Incorporate anti-stiction techniques to improve pixel operability

Key Collaborators:

- Stephan McCandliss (JHU)

Development Period:

Oct 2018 – Sep 2021

Accomplishments:

- ALD process developed and going through modification
- Number of pilot arrays are fabricated and assembled
- Suborbital flight assemblies are delivered for FORTIS
- High voltage actuation drivers are selected
- Ceramic substrates were designed
- Large array mask layout was completed

Next Milestones:

- Actuation scheme is being developed and in the process of refinement
- Preparation of large-array testing system

Application:

- Sparse field multi-object spectroscopy
- New missions LUVOIR, HabEx, CETUS, AERIE

$TRL_{in} = 3$ $TRL_{current} = 3$ $TRL_{Target} = 5$

Development of DMD Arrays for Use in Future Space Missions

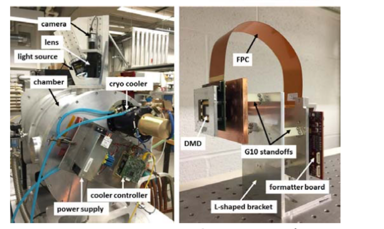
PI: Zoran Ninkov / Rochester Institute of Technology

Objectives and Key Challenges:

- A technology is needed that allows target selection in a field of view that can be input to an imaging spectrometer for remote sensing and astronomy
- We are looking to modify and develop Digital Micro-mirror Devices (DMDs) for this application

Significance of Work:

- Existing DMDs need to have the commercial windows replaced with appropriate windows for the scientific application desired
- The devices need to be evaluated for survivability in a space environment



Low-temperature testing of DMDs at APL/JHU

Approach:

- Use available 0.7 XGA DMDs to develop window removal procedures, and then replace delivered window with a hermetically sealed UV-transmissive window of Magnesium Fluoride, HEM sapphire, and fused silica
- Test and evaluate such devices and as well as Cinema DMDs

Key Collaborators:

- Sally Heap, Manuel Quijada, Jonny Pellish, and Tim Schwartz (NASA/GSFC)
- Massimo Robberto (STScI)
- Alan Raisanen (RIT)

Current Funded Period of Performance:

May 2014 – May 2018

Recent Accomplishments:

- ✓ 0.7 XGA DMD and 1.2 DC2K DMDs delivered
- ✓ XGA devices re-windowed with MgF_2, Sapphire, and fused silica
- ✓ Proton and heavy-ion testing show good results (only SEUs)
- ✓ Contrast measurements indicate high contrast (>5000:1)

Next Milestones:

- Analysis and publication of gamma-ray testing (Dec 2017)
- Measurement, analysis, and publication of UV scattering measurements (Feb 2018)
- Low-temperature long-hold-time testing (Apr 2018)

Applications:

- Can be used in any hyper-spectral imaging mission
- Galaxy Evolution Spectroscopic Probe

$TRL_{in} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 5$

E-Beam-Generated Plasma to Enhance Performance of Protected Aluminum Mirrors for Large-Space-Telescope Astronomy

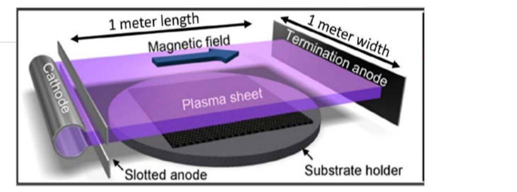
PI: Manuel Quijada/Code 551

Objectives and Key Challenges:

- Development of aluminum-based mirror coatings with high reflectance over a broad spectral range and particularly in the far-ultraviolet (FUV) spectral range
- Development of a plasma-based cleaning process to restore reflectance of mirror coatings in the FUV spectral region

Significance of Work:

- Successful oxide removal and passivation of Al-based coating will open the possibility of developing a large-scale process to enable the intrinsic high reflectance of Al-based reflectors on 1-m class mirrors



The LAPPS is a facility used in NRL, based on e-beams, allowing the generation of very large area (>1m²), highly uniform, low temperature plasmas. Both length and width can be > 1 m if desired.

Approach:

- Produce samples of bare aluminum and overcoat with a metal-fluoride in the 2-m GSFC coating chamber
- Process various Al and metal-fluoride coatings by using the Large Area Plasma Processing System (LAPPS) at the Naval Research Laboratory (NRL)
- Demonstrate oxide removal and fluorination processing on the LAPPS meter-scale facility

Key Collaborators:

- Javier del Hoyo, Ed Wollack, and Vivek Dwivedi (NASA/GSFC)
- David Boris and Scott Walton (NRL)

Current Funded Period of Performance:

Oct 2018 – Sep 2019

Accomplishment:

- ✓ Optimized plasma parameters of the LAPPS reactor to varying process parameters to optimize etching capabilities for Al-based coatings

Next Milestone:

- Oxide removal and passivation of bare Al mirrors with a thin AlF_3 layer

Applications:

- Flagship FUV missions
- Explorer type FUV missions

$TRL_{in} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 4$

High Performance, Stable, and Scalable UV Aluminum Mirror Coatings using ALD

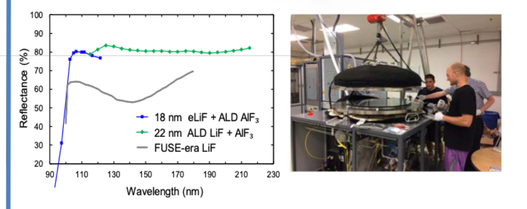
PI: John Hennessy / JPL

Objectives and Key Challenges:

- Atomic layer deposition (ALD) for wide bandpass (100–2500 nm) mirror coatings with emphasis on high performance in the FUV through the use of lithium fluoride based coatings.
- Studying and enhancing long term performance stability.
- Demonstrating ALD scalability trends towards large (>1 m) size mirrors.
- Study fundamentals of aluminum deposition with respect to form birefringence, microstructure, and ALD compatibility.
- Measurement and modeling of reflectance uniformity, wavefront error, and polarization retardance over the full aperture of shaped optics in the wavelength bands of interest to exoplanet coronagraphs.

Significance of Work:

- An alternative to conventional physical vapor deposition (PVD) methods.
- Improvements in performance, repeatability, and scalability are an enabling technology for LUVOIR.



(left) Mirror coatings with ALD LiF significantly exceed the performance of previous PVD LiF demonstrations that were flown on NASA missions like FUSE. (right) The meter-class 'astronomical' ALD tool at UCSC.

Approach:

- JPL's hydrogen fluoride based approach for ALD metal fluorides, as well as thermal atomic layer etching (ALE) to maximize performance of UV protected-aluminum mirror coatings.
- Exploiting the unique capabilities of ALD including nanolaminate structures and mixed composition fluoride overcoats.
- Hardware at UCSC originally developed for ALD-protected silver mirror coatings to demonstrate scale at ~1 meter diameter.
- Facilities developed for flight projects at CU Boulder will allow detailed characterization of 'flight-like' optics.

Key Collaborators:

- April Jewell, K. Balasubramanian, Shouleh Nikzad (JPL)
- Kevin France, Brian Fleming (CU Boulder)
- Nobuhiko Kobayashi (UCSC)

Current Funded Period of Performance:

Jan. 2020 – Dec. 2022

Recent Accomplishments:

- ✓ New project starting FY20

Next Milestones:

- ALD LiF-based coating meeting LUVOIR performance requirements with <1% variation over five independent coating runs.
- First direct comparison of ALD vs. PVD coating dependencies on humidity storage.
- Coating of 200 mm shaped optic with demonstration of <5% reflectance loss in the challenging 100–200 nm spectrum in accelerated aging tests.

Applications:

- LUVOIR, enhancing technology for HabEx.
- Will produce shaped optics relevant for a variety of probe-class, explorer-class, and smallsat instrumentation.

$TRL_{in} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 5$

Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics

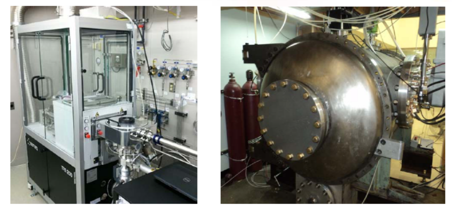
PI: K. 'Bala' Balasubramanian / JPL

Objectives and Key Challenges:

- Development of UV coatings with high reflectivity (>90-95%), high uniformity (<1-0.1%), and wide bandpasses (~100 nm to 300-1000 nm) is a major technical challenge; this project aims to address this challenge and develop durable coatings
- Materials and process development are the main challenges; improvements in existing technology base and significant innovations in coating technology such as Atomic Layer Deposition (ALD) are to be developed

Significance of Work:

- This is a key requirement for future Cosmic Origins and ExoPlanet missions, such as LUVOIR and HabEx.



ALD chamber at JPL 1.2-m coating chamber at Zecoat Corp.

Approach:

- Develop a set of experimental data with MgF_2-, AlF_3-, and LiF-protected Al mirrors in the wavelength range 100-1000 nm for a comprehensive base of measurements, enabling full-scale developments with chosen materials and processes
- Investigate and develop enhanced coating processes including ALD
- Improve characterization and measurement techniques

Key Collaborators:

- John Hennessy, Shouleh Nikzad, Nasrat Raouf, Stuart Shaklan (JPL)
- Paul Scowen (ASU)
- Manuel Quijada (GSFC)

Current Funded Period of Performance:

Jan 2013 – Dec 2015

Recent Accomplishments:

- ✓ Upgraded coating chamber with sources, temperature controllers, and other monitors to produce various coatings
- ✓ Upgraded measurement tools at JPL and GSFC
- ✓ Produced and tested several coatings with MgF_2, AlF_3, and LiF
- ✓ Fabricated several iterations of protective coatings on Al mirrors
- ✓ Developed ALD coating processes for MgF_2, AlF_3, and LiF at JPL
- ✓ Developed and studied Atomic Layer Etching (ALE) techniques
- ✓ Produced and characterized first set of test coupons representing 1m-class mirror to assess uniformity

Further Research Needed:

- Enhancements to conventional coating techniques and ALD and ALE processes to advance the TRL status depending on further funding

Applications:

- Future astrophysics and exoplanet missions such as LUVOIR and HabEx intended to capture key spectral features from far-UV to near-IR

$TRL_{in} = 2\text{-}3$ $TRL_{PI\text{-}Asserted} = 3\text{-}4$ $TRL_{Target} = 5$

Status of Each Item as of ~2021

Based on Table 11-3 of LUVOIR Report

Black font = current status as of 2018, from Table 11-3 of LUVOIR Final Report

Orange font = SAT Quad Charts

7	System prototype demonstration in an operational environment.	SPRITE Prime Mission			FORTIS Rocket for 128x64 format							
LUVOIR Preliminary Design Review												
6	System / sub-system model or prototype demonstration in an operational environment.	SPRITE I&T					meets requirements for 100-150 nm					
5	Component and/or breadboard validation in relevant environment.	ALD on >20 cm optics; aging tests **Hennessy SAT; Quad**		Meets performance requirements, but is environmentally unstable	2021 Greenhouse SAT Goal	UV performance measurements on re-windowed XGAs **Ninkov SAT ; Quad**		Vallerga SAT			Figer SAT	8K x 8K devices exist with 18 micron pixels, lacks high speed subarray readout for guiding
4	Component and/or breadboard validation in lab environment					>5000:1 contrast achieved on re-windowed XGA format (1024x768) **Ninkov SAT ; Quad**		meets requirements for 100-150 nm; requires devel for large tile size and integration with cross-strip readout. GaN has better Solar-blind performance		Demonstrated 50% improved QE with CsI photocathode	4K x 4K devices exist, require development for 8K x 8K and readout optimization	
3	Analytical and experimental critical function and/or characteristic proof of concept	Meets performance requirements, but requires demonstration on meter-class optics, validation of uniformity, repeatability, and env. stability **PVD; Quijada SAT; Quad**			840x420 prototype demonstrated, but requires devel. to survive launch **Greenhouse SAT ; Quad**							
		> 50% over 100-115 nm, > 80% over 115-200 nm > 88% over 200 - 850 nm, > 96% over > 850 nm, < 1% reflectance non-uniformity over primary mirror in coronagraph bandpass (200-2000 nm)			840x420 format, two-side buttable, high contrast		200 mm x 200 mm tile size > 30% QE between 100-200 nm				8K x 9K format, < 7 µm pixels, three-side buttable, ~1 e- read noise, 10^{-4} e-/pix/s dark at 170K	
		$Al+eLiF+MgF_2$ **Baseline**	$Al+eLiF+AlF_3$	Al+eLiF	Microshutters **Baseline**	Micromirrors	CsI **Baseline**	GaN **Baseline**	Bi-alkali	Funnel micro	8K x 8K CMOS **Baseline**	4K x 4K CCDs
		Far-UV Broadband Coatings LUVOIR pg. 11-25			Configurable Shutters LUVOIR pg. 11-26		UV Microchannel Plate LUVOIR pg. 11-26				Visible Detectors LUVOIR pg. 11-27	

This is why it is so important to focus on the key items. . .

Based on Table 11-3 of LUVOIR Report

Black font = current status as of 2018, from Table 11-3 of LUVOIR Final Report

Orange font = SAT Quad Charts

7	System prototype demonstration in an operational environment.	SPRITE Prime Mission			FORTIS Rocket for 128x64 format							
LUVOIR Preliminary Design Review												
6	System / sub-system model or prototype demonstration in an operational environment.	SPRITE I&T		**WHAT**			meets requirements for 100-150 nm		**HAPPENS HERE?**			
5	Component and/or breadboard validation in relevant environment.	ALD on >20 cm optics; aging tests **Hennessy SAT; Quad**		Meets performance requirements, but is environmentally unstable	2021 Greenhouse SAT Goal	UV performance measurements on re-windowed XGAs **Ninkov SAT ; Quad**		Vallerga SAT			Figer SAT	8K x 8K devices exist with 18 micron pixels, lacks high speed subarray readout for guiding
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		> 50% over 100-115 nm, > 80% over 115-200 nm > 88% over 200 - 850 nm, > 96% over > 850 nm, < 1% reflectance non-uniformity over primary mirror in coronagraph bandpass (200-2000 nm)			840x420 format, two-side buttable, high contrast		200 mm x 200 mm tile size > 30% QE between 100-200 nm				8K x 9K format, < 7 μm pixels, three-side buttable, ~1 e- read noise, 10^{-4} e-/pix/s dark at 170K	
		Al+eLiF+MgF_2 **Baseline**	Al+eLiF+AlF_3	Al+eLiF	Microshutters **Baseline**	Micromirrors	CsI **Baseline**	GaN **Baseline**	Bi-alkali	Funnel micro	8K x 8K CMOS **Baseline**	4K x 4K CCDs
		Far-UV Broadband Coatings LUVOIR pg. 11-25			Configurable Shutters LUVOIR pg. 11-26		UV Microchannel Plate LUVOIR pg. 11-26				Visible Detectors LUVOIR pg. 11-27	

Propositions

— **NASA intends to 'build HWO to schedule',** starting with GOMAP.
There is not an indefinite period available to carry low TRL items much longer.

— **The set of technologies that must be matured to meet the performance specs of the LUVOIR and HabEX studies is not large:**

(1) for UV coatings: performance below Lyα, scalability to large optics, and compatibility with a high-performance coronagraph.
(2) For MOS capabilities: microshutter (and/or micromirror) arrays must be scaled up to mission needs and proven in operational environments,
(3) For MCP and CMOS detectors: formats, focal plane packing . . .

— **Let's take advantage of this to focus on the key items that matter most, and <u>build the UV tech dev plan that gets all this to TRL 5-6 during GOMAP</u>.**