High Definition Imaging & Workhorse Camera

Shouleh Nikzad

Jet Propulsion Laboratory, California Institute of Technology

Ultraviolet Science and Technology Interest Group (UVSTIG) Splinter Session

AAS, Seattle, WA

10 January 2022

Imaging and Spectroscopy Enabling Science

- The Astro2020-recommended 6-m IROUV observatory, recently named Habitable World Observatory (HWO) will utilize imaging and spectroscopy
- HWO in size, falls between two large observatories studied in detail by vast groups of the community in NASA—funded efforts leading up to and submitted for consideration to the decadal, i.e., Large Ultraviolet Optical Infrared (LUVOIR) survey and Habitable Exoplanet Observatory (HabEx)
- These studies are an excellent starting point to take stock of what is available, what can be made today and in near future while recognizing that further studies will be needed for HWO science, mission, and technology development
- I will briefly discuss two of the instrument point designs developed by LUVOIR and HabEx, point out their enabling features and some of the key technologies used. I will also mentioned some enabling technologies that could positively affect future camera and spectrograph designs.

Large UV/Optica/IR Surveyor (LUVOIR)

National Aeronautics and Space Administration

LUVOIR

FINAL REPORT

www.nasa.gov

LUVOIR

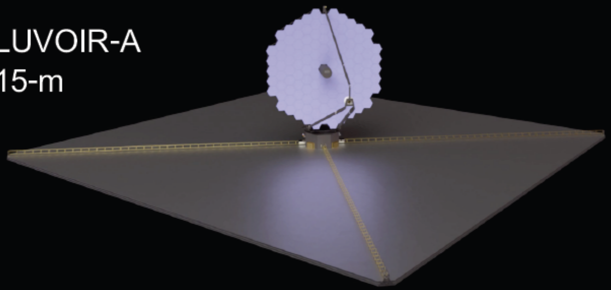
LARGE UV / OPTICAL / INFRARED SURVEYOR

TELLING THE STORY OF LIFE IN THE UNIVERSE

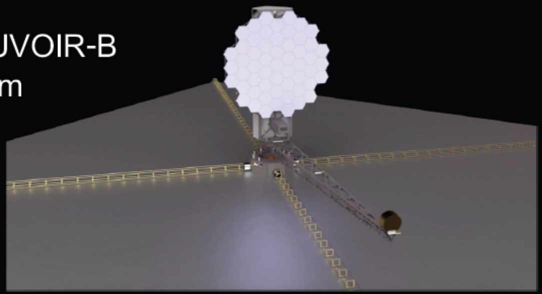
https://asd.gsfc.nasa.gov/luvoir/

TWO POWERFUL AND SCALABLE SPACE OBSERVATORIES, RESPONSIVE TO DIFFERENT FUTURE LANDSCAPES, TO ANSWER THE QUESTIONS OF THE 2030S AND BEYOND

LUVOIR-A
15-m



LUVOIR-B
8-m



OBSERVATORY CHARACTERISTICS

Community-driven observing program

Serviceable and upgradable modular design

Sun-Earth L2 orbit

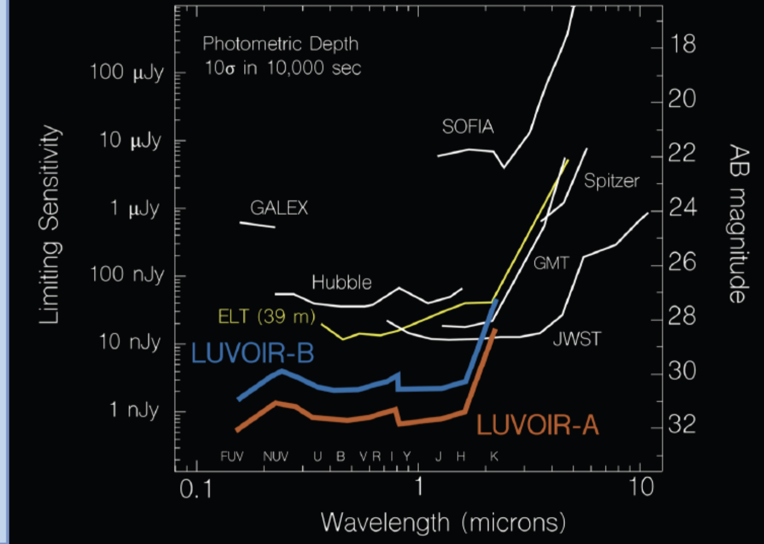
Late 2030s launch date

5-year prime mission; 10 yrs. consumables; 25-year lifetime goal for non-serviceable components

Diffraction limited at 500 nm; 270 K telescope operating temp.

Field-of-regard: Sun-Telescope-Target angles > 45 degrees (3π steradians)

Tracking speed: 60 mas/sec (2x JWST)

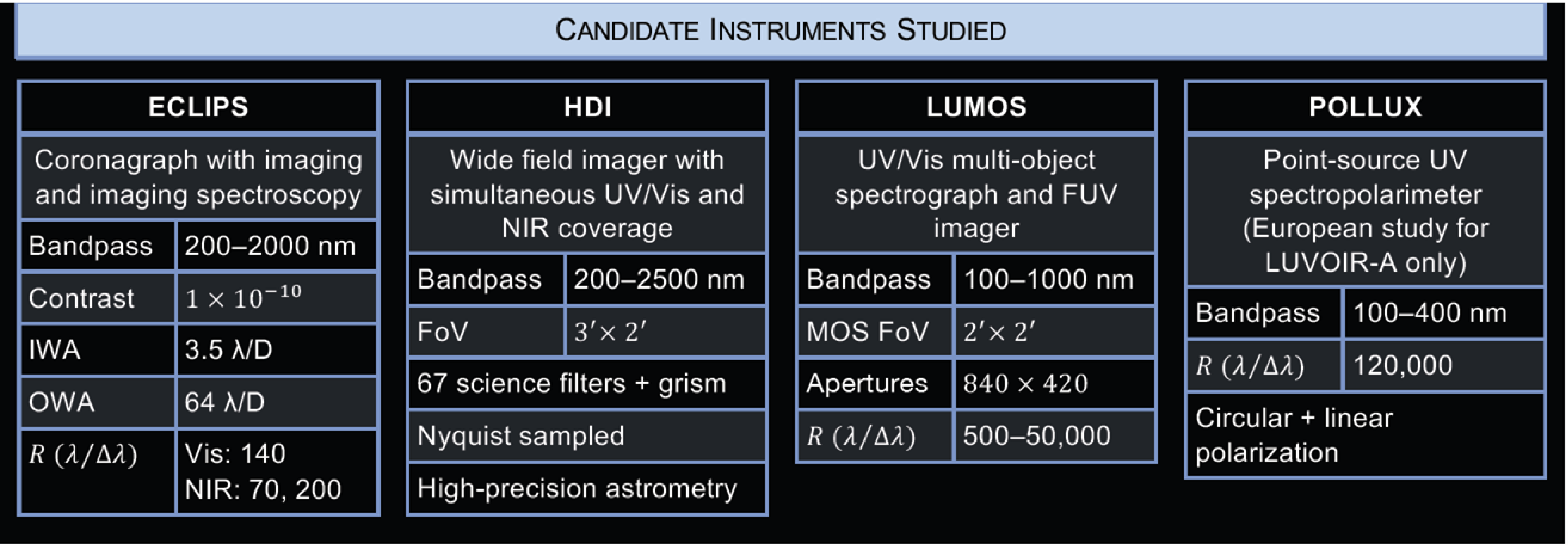


LUVOIR Signature Science Cases (Final Report)

1. Determine the occurrence rates of Earth-like conditions on rocky worlds around Sun-like stars (**Chapter 3**)
2. Search habitable exoplanet candidates for signs of life and confirm habitability (**Chapter 3**)
3. Characterize potentially habitable ocean moons in the solar system (**Chapter 3**)
4. Compare the atmospheres of a diverse set of exoplanets (**Chapter 4**)
5. Study planet formation via observations of planetary systems with a wide range of ages (**Chapter 4**)
6. Reveal clues to the formation of the solar system via study of its smallest bodies (**Chapter 4**)
7. Probe the smallest scales across cosmic time to constrain the properties of dark matter (**Chapter 5**)
8. Constrain the properties of dark matter via high precision astrometry (**Chapter 5**)
9. Trace ionizing light and its impact on structure over cosmic time (**Chapter 5**)
10. Understand the ways in which matter flows into and out of galaxies (**Chapter 6**)
11. Study the assembly of galaxies at multiple spatial scales (**Chapter 6**)
12. Probe the impact of star formation upon galaxy evolution (**Chapter 6**)

https://asd.gsfc.nasa.gov/luvoir/reports/

LUVOIR Instruments—HDI Context



CANDIDATE INSTRUMENTS STUDIED

ECLIPS

Coronagraph with imaging and imaging spectroscopy

Bandpass	200–2000 nm
Contrast	1×10^{-10}
IWA	3.5 λ/D
OWA	64 λ/D
$R\ (\lambda/\Delta\lambda)$	Vis: 140 NIR: 70, 200

HDI

Wide field imager with simultaneous UV/Vis and NIR coverage

Bandpass	200–2500 nm
FoV	$3' \times 2'$
67 science filters + grism	
Nyquist sampled	
High-precision astrometry	

LUMOS

UV/Vis multi-object spectrograph and FUV imager

Bandpass	100–1000 nm
MOS FoV	$2' \times 2'$
Apertures	840×420
$R\ (\lambda/\Delta\lambda)$	500–50,000

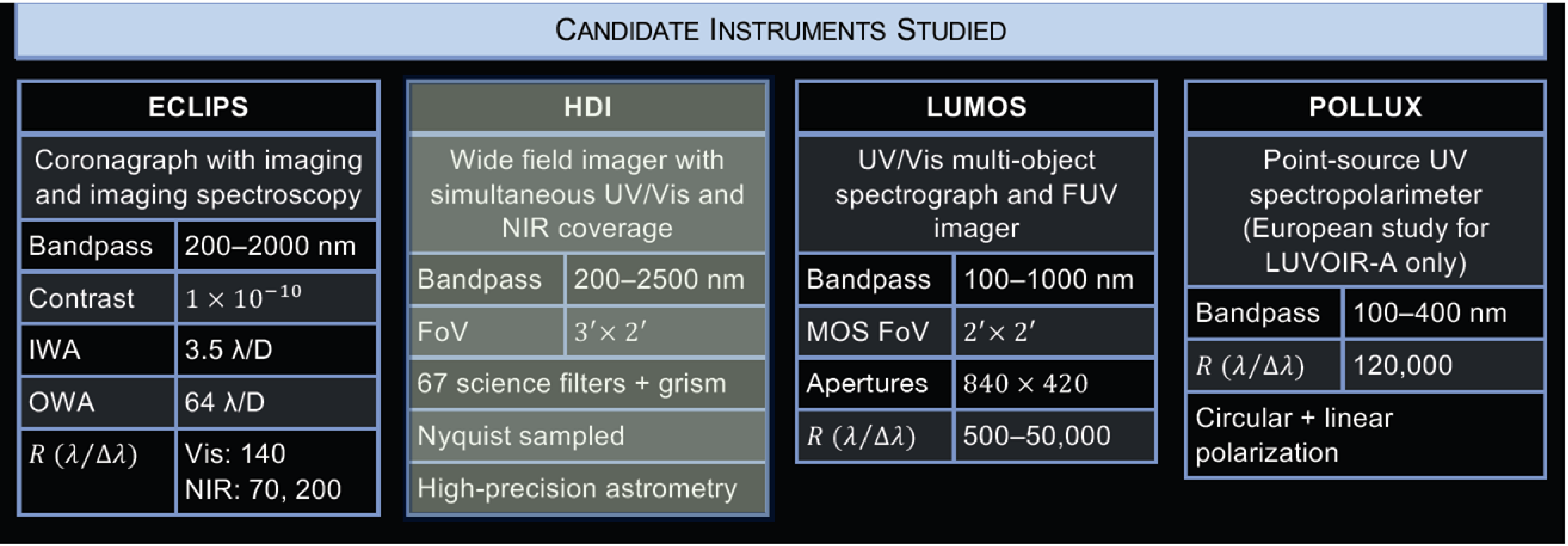
POLLUX

Point-source UV spectropolarimeter (European study for LUVOIR-A only)

Bandpass	100–400 nm
$R\ (\lambda/\Delta\lambda)$	120,000
Circular + linear polarization	

High Definition Imager (HDI): high spatial resolution camera covering–2500 nm, incorporating high precision astrometry capability

LUVOIR Instruments—HDI Context



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LUVOIR HDI Specifications

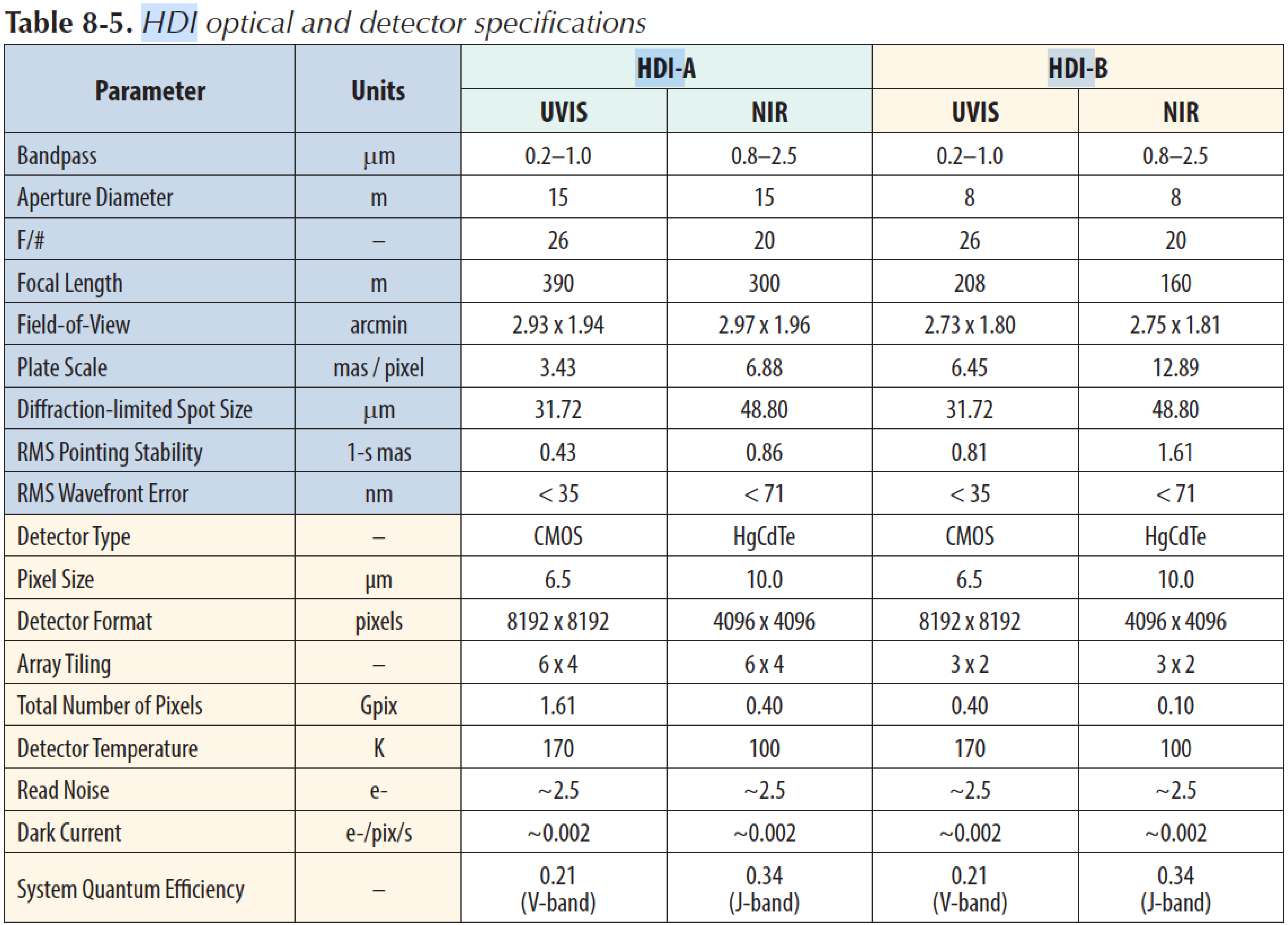
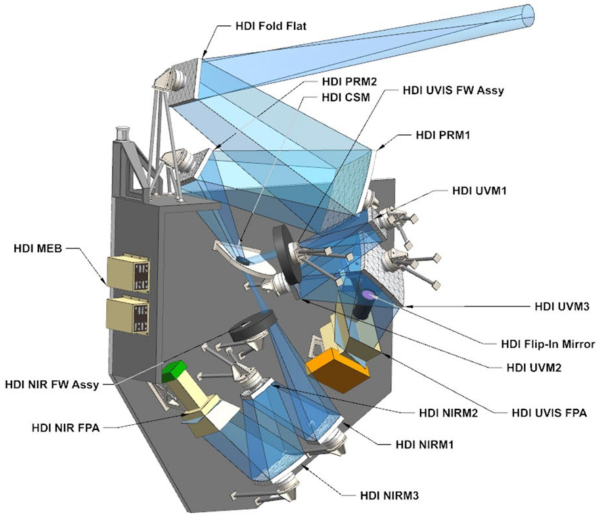
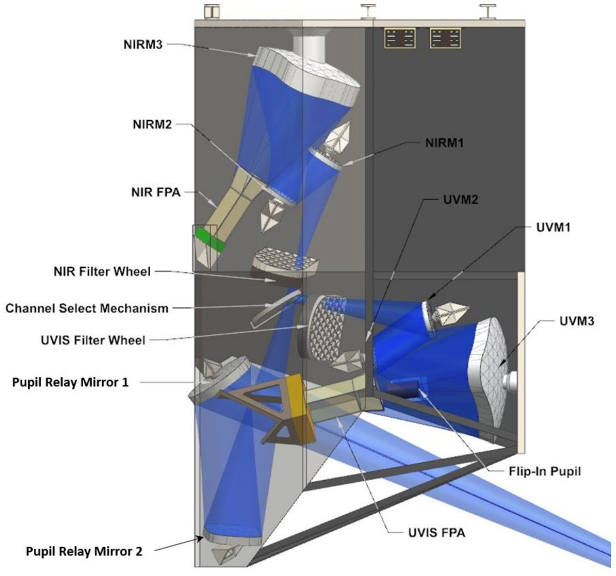


Table 8-5. *HDI optical and detector specifications*

Parameter	Units	HDI-A		HDI-B	
		UVIS	NIR	UVIS	NIR
Bandpass	µm	0.2–1.0	0.8–2.5	0.2–1.0	0.8–2.5
Aperture Diameter	m	15	15	8	8
F/#	–	26	20	26	20
Focal Length	m	390	300	208	160
Field-of-View	arcmin	2.93 x 1.94	2.97 x 1.96	2.73 x 1.80	2.75 x 1.81
Plate Scale	mas / pixel	3.43	6.88	6.45	12.89
Diffraction-limited Spot Size	µm	31.72	48.80	31.72	48.80
RMS Pointing Stability	1-s mas	0.43	0.86	0.81	1.61
RMS Wavefront Error	nm	< 35	< 71	< 35	< 71
Detector Type	–	CMOS	HgCdTe	CMOS	HgCdTe
Pixel Size	µm	6.5	10.0	6.5	10.0
Detector Format	pixels	8192 x 8192	4096 x 4096	8192 x 8192	4096 x 4096
Array Tiling	–	6 x 4	6 x 4	3 x 2	3 x 2
Total Number of Pixels	Gpix	1.61	0.40	0.40	0.10
Detector Temperature	K	170	100	170	100
Read Noise	e-	~2.5	~2.5	~2.5	~2.5
Dark Current	e-/pix/s	~0.002	~0.002	~0.002	~0.002
System Quantum Efficiency	–	0.21 (V-band)	0.34 (J-band)	0.21 (V-band)	0.34 (J-band)

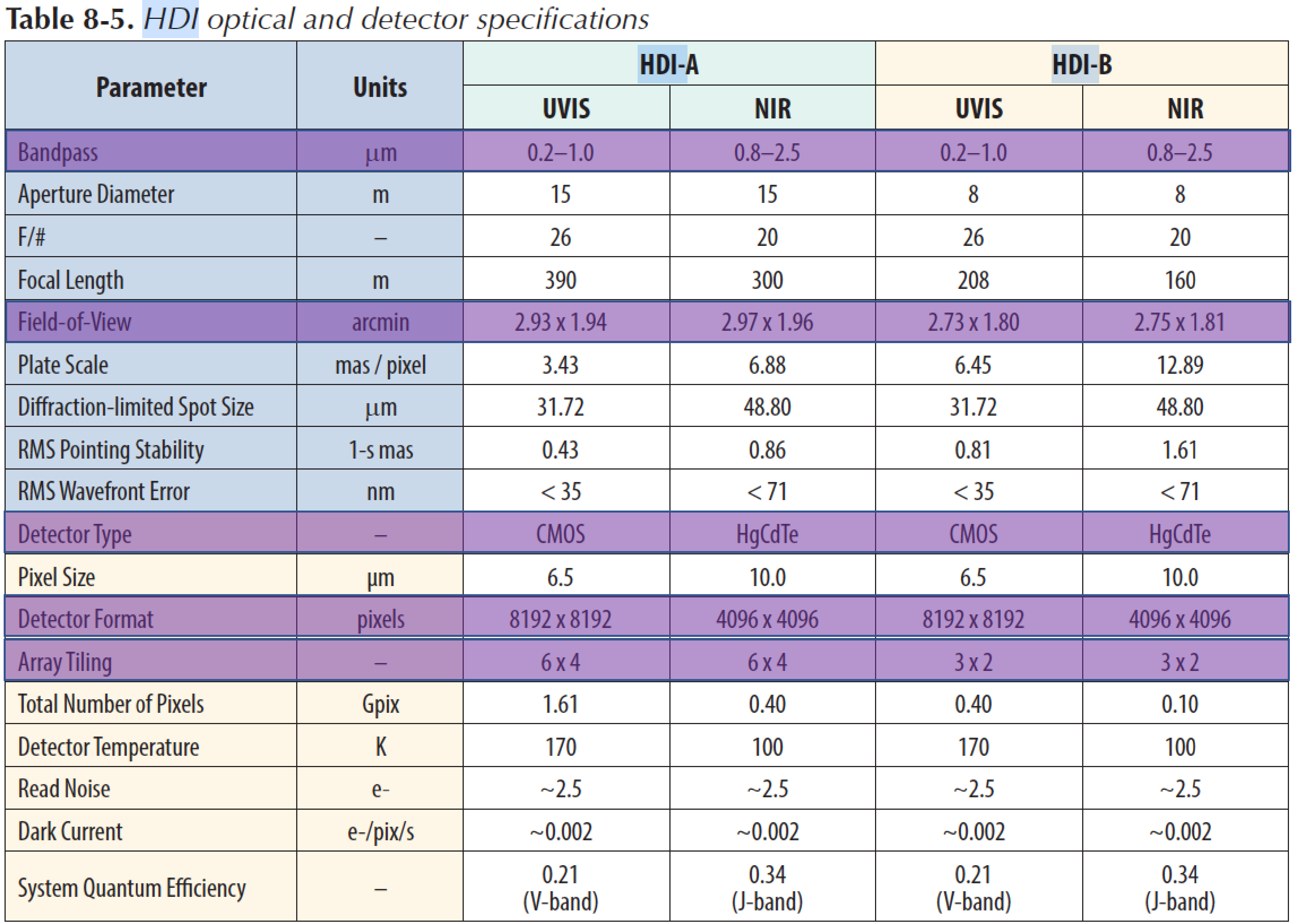


HDI-A



HDI-B

LUVOIR HDI Specifications



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F/#	–	26	20	26	20
Focal Length	m	390	300	208	160
Field-of-View	arcmin	2.93 x 1.94	2.97 x 1.96	2.73 x 1.80	2.75 x 1.81
Plate Scale	mas / pixel	3.43	6.88	6.45	12.89
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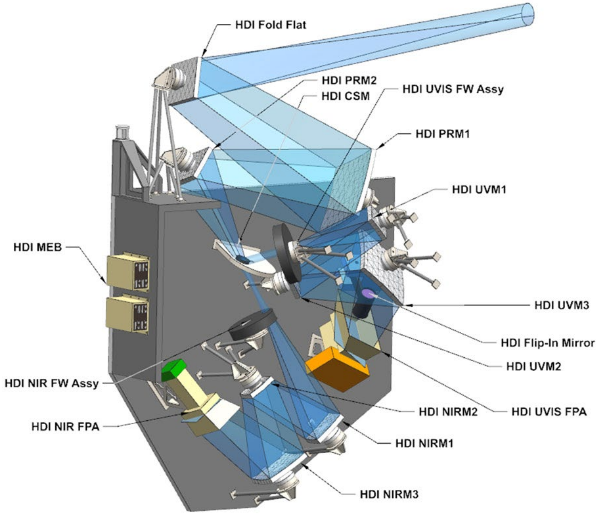
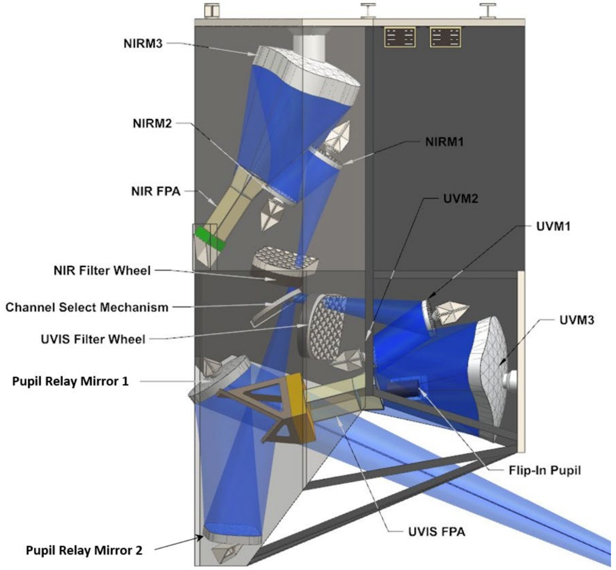
Detector Format	pixels	8192 x 8192	4096 x 4096	8192 x 8192	4096 x 4096
Array Tiling	–	6 x 4	6 x 4	3 x 2	3 x 2
Total Number of Pixels	Gpix	1.61	0.40	0.40	0.10
Detector Temperature	K	170	100	170	100
Read Noise	e-	~2.5	~2.5	~2.5	~2.5
Dark Current	e-/pix/s	~0.002	~0.002	~0.002	~0.002
System Quantum Efficiency	–	0.21 (V-band)	0.34 (J-band)	0.21 (V-band)	0.34 (J-band)



HDI-A



HDI-B

HabEx

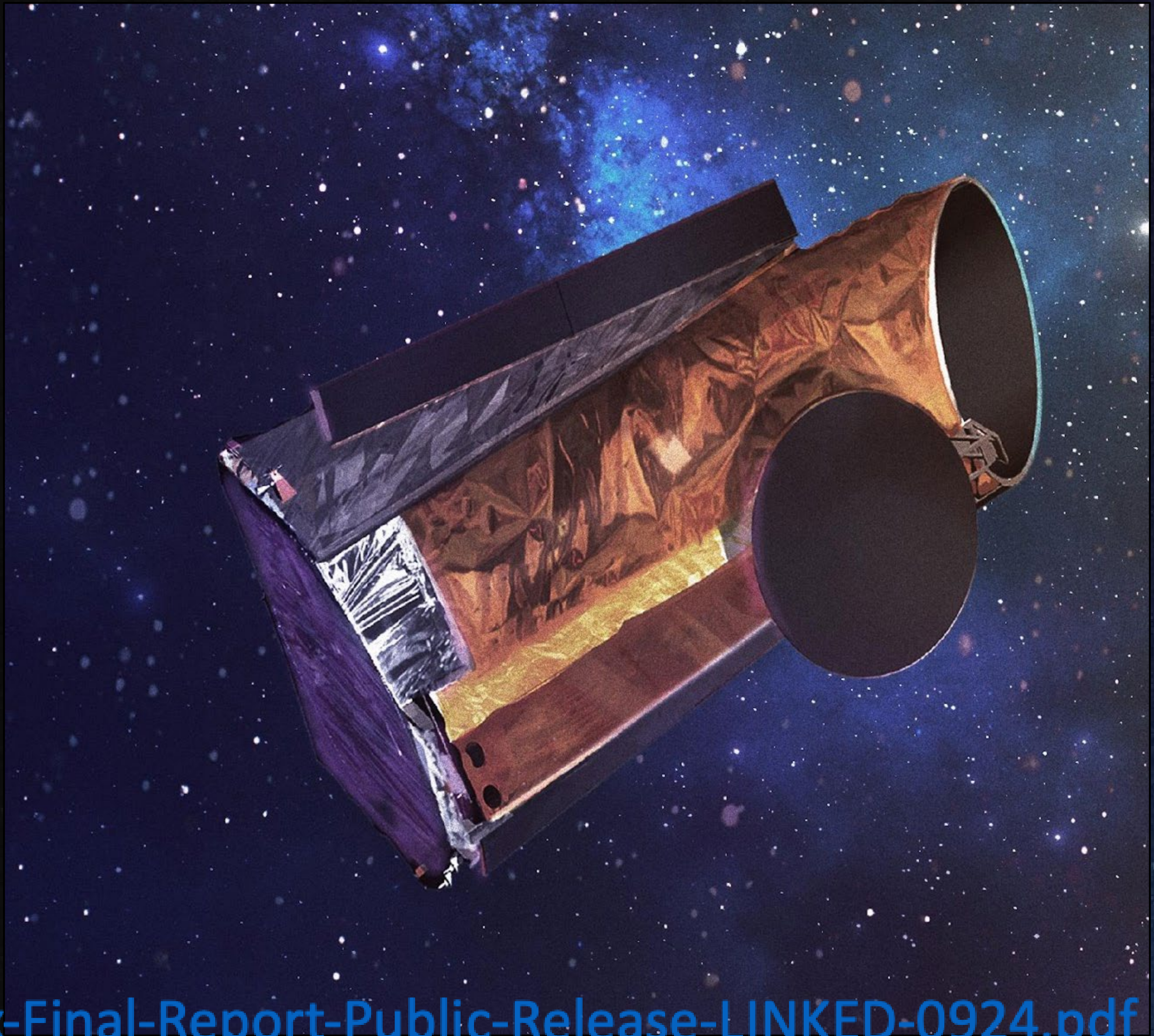
Habitable Exoplanet Observatory

Exploring New Worlds,
Understanding Our Universe

Architecture

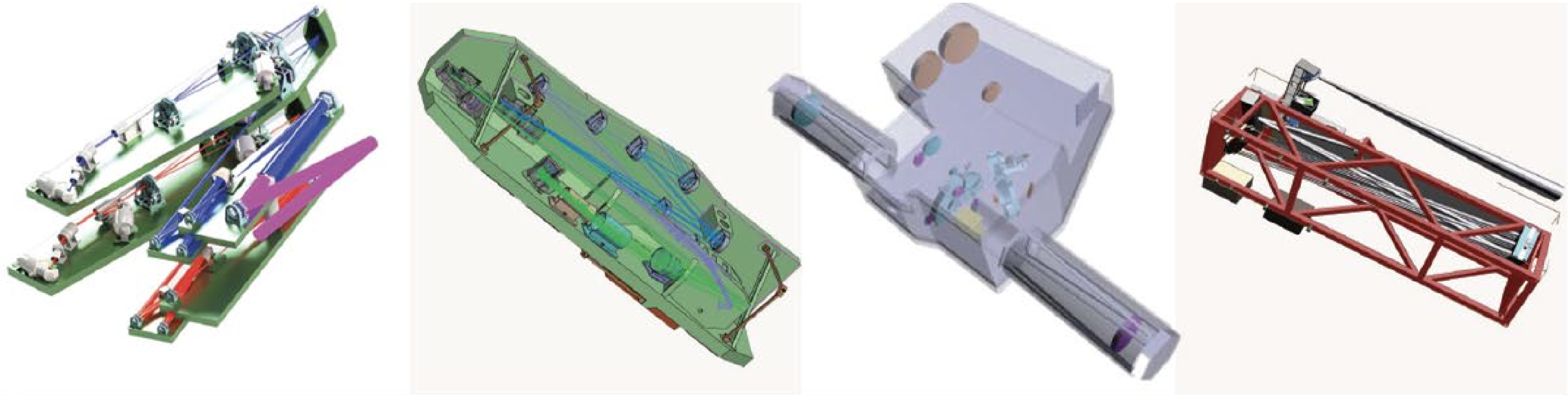
Architecture:

- 4m off-axis f/2.5 aluminum monolith
  - preliminary design completed.
- Four Instruments:
  - Coronagraph Instrument
  - Starshade Instrument
  - UV Spectrograph (UVS)
  - HabEx Workhorse Camera (HWC)
- Launch vehicle
  - SLS Block 1B
- 72m (tip-to-tip) starshade
  - Co-launched with telescope
- Orbit
  - L2
- Launch date and mission length
  - ~ mid-2030s
  - 5 year prime mission



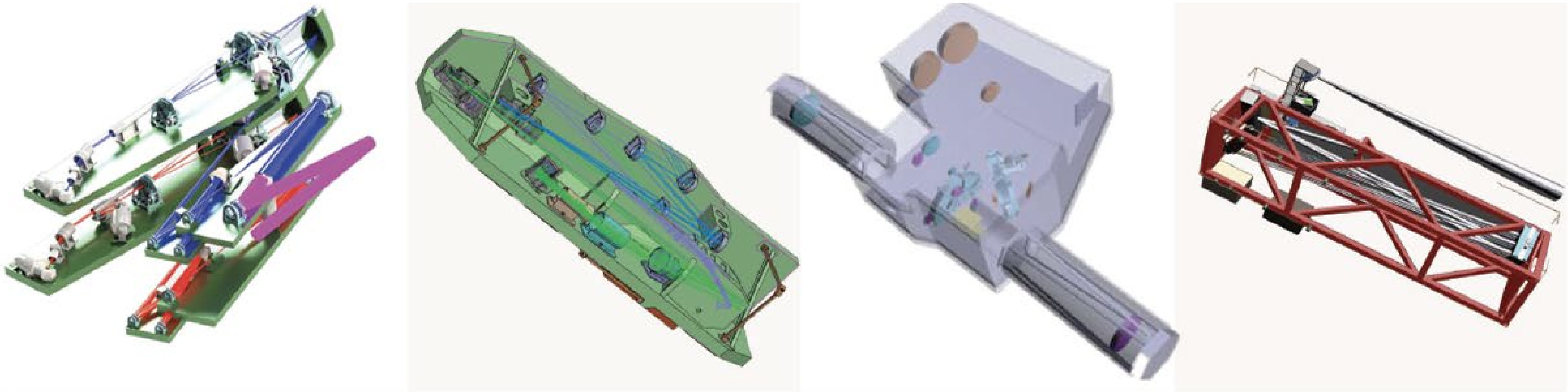
https://www.jpl.nasa.gov/habex/pdf/HabEx-Final-Report-Public-Release-LINKED-0924.pdf

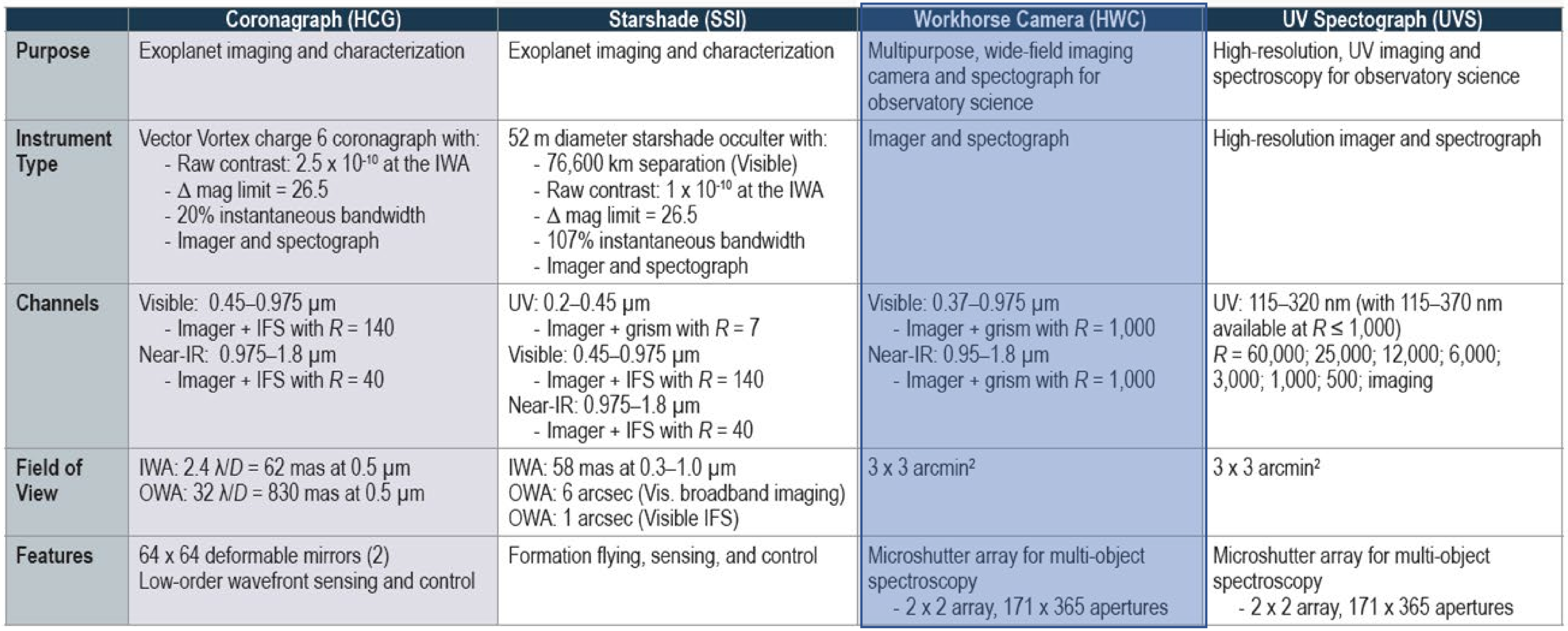
HabEx Instrument suite—HWC Context



	Coronagraph (HCG)	Starshade (SSI)	Workhorse Camera (HWC)	UV Spectograph (UVS)
Purpose	Exoplanet imaging and characterization	Exoplanet imaging and characterization	Multipurpose, wide-field imaging camera and spectograph for observatory science	High-resolution, UV imaging and spectroscopy for observatory science
Instrument Type	Vector Vortex charge 6 coronagraph with: - Raw contrast: 2.5 x 10^{-10} at the IWA - Δ mag limit = 26.5 - 20% instantaneous bandwidth - Imager and spectograph	52 m diameter starshade occulter with: - 76,600 km separation (Visible) - Raw contrast: 1 x 10^{-10} at the IWA - Δ mag limit = 26.5 - 107% instantaneous bandwidth - Imager and spectograph	Imager and spectograph	High-resolution imager and spectrograph
Channels	Visible: 0.45–0.975 μm - Imager + IFS with $R = 140$ Near-IR: 0.975–1.8 μm - Imager + IFS with $R = 40$	UV: 0.2–0.45 μm - Imager + grism with $R = 7$ Visible: 0.45–0.975 μm - Imager + IFS with $R = 140$ Near-IR: 0.975–1.8 μm - Imager + IFS with $R = 40$	Visible: 0.37–0.975 μm - Imager + grism with $R = 1{,}000$ Near-IR: 0.95–1.8 μm - Imager + grism with $R = 1{,}000$	UV: 115–320 nm (with 115–370 nm available at $R \leq 1{,}000$) R = 60,000; 25,000; 12,000; 6,000; 3,000; 1,000; 500; imaging
Field of View	IWA: 2.4 λ/D = 62 mas at 0.5 μm OWA: 32 λ/D = 830 mas at 0.5 μm	IWA: 58 mas at 0.3–1.0 μm OWA: 6 arcsec (Vis. broadband imaging) OWA: 1 arcsec (Visible IFS)	3 x 3 arcmin²	3 x 3 arcmin²
Features	64 x 64 deformable mirrors (2) Low-order wavefront sensing and control	Formation flying, sensing, and control	Microshutter array for multi-object spectroscopy - 2 x 2 array, 171 x 365 apertures	Microshutter array for multi-object spectroscopy - 2 x 2 array, 171 x 365 apertures

HabEx Instruments





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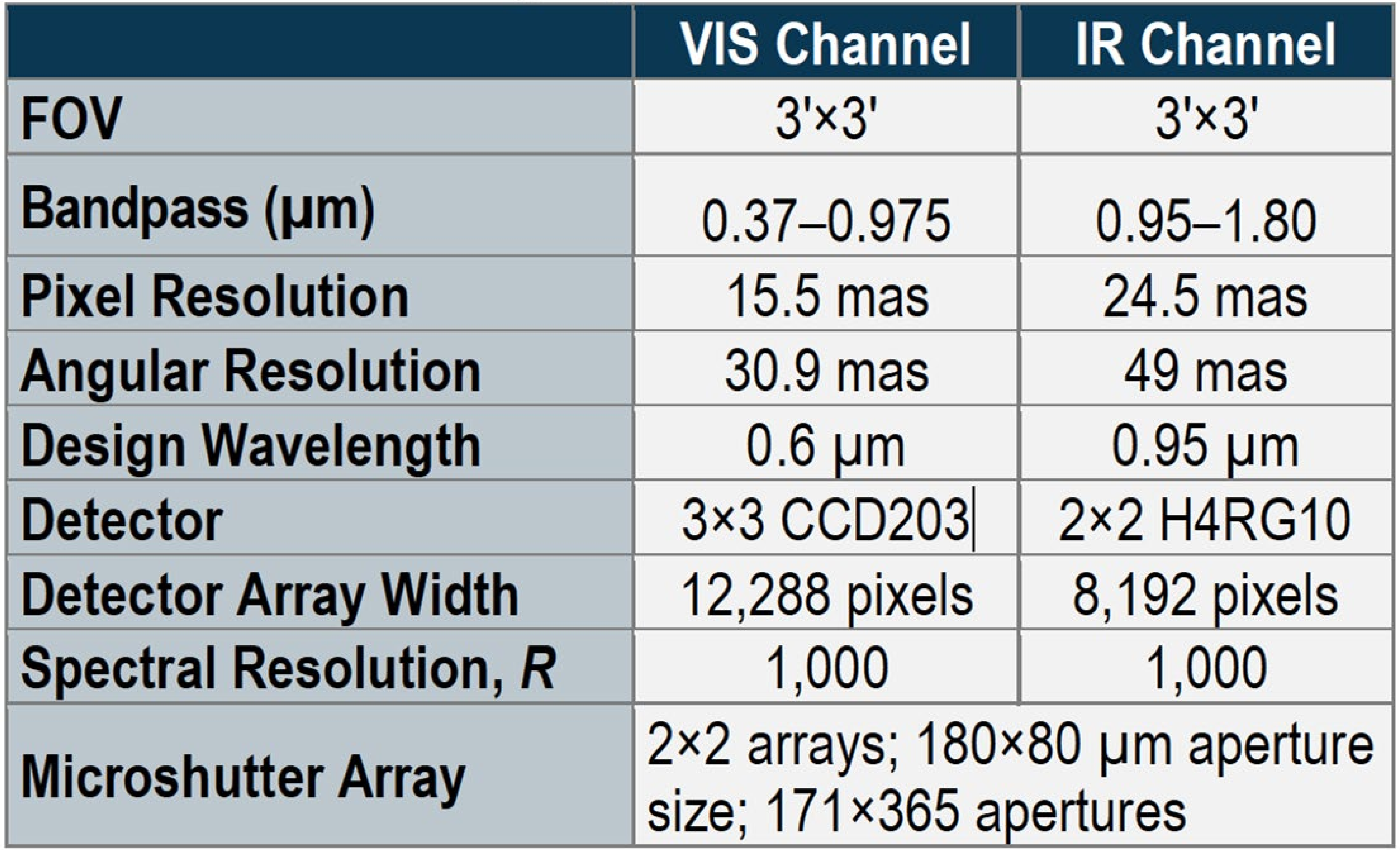
Channels	Visible: 0.45–0.975 µm - Imager + IFS with *R* = 140 Near-IR: 0.975–1.8 µm - Imager + IFS with *R* = 40	UV: 0.2–0.45 µm - Imager + grism with *R* = 7 Visible: 0.45–0.975 µm - Imager + IFS with *R* = 140 Near-IR: 0.975–1.8 µm - Imager + IFS with *R* = 40	Visible: 0.37–0.975 µm - Imager + grism with *R* = 1,000 Near-IR: 0.95–1.8 µm - Imager + grism with *R* = 1,000	UV: 115–320 nm (with 115–370 nm available at *R* ≤ 1,000) *R* = 60,000; 25,000; 12,000; 6,000; 3,000; 1,000; 500; imaging
Field of View	IWA: 2.4 λ/D = 62 mas at 0.5 µm OWA: 32 λ/D = 830 mas at 0.5 µm	IWA: 58 mas at 0.3–1.0 µm OWA: 6 arcsec (Vis. broadband imaging) OWA: 1 arcsec (Visible IFS)	3 x 3 arcmin^2	3 x 3 arcmin^2
Features	64 x 64 deformable mirrors (2) Low-order wavefront sensing and control	Formation flying, sensing, and control	Microshutter array for multi-object spectroscopy - 2 x 2 array, 171 x 365 apertures	Microshutter array for multi-object spectroscopy - 2 x 2 array, 171 x 365 apertures

HabEx Workhorse Camera Specifications

Table 6.6-2. HWC design specifications.



	VIS Channel	IR Channel
FOV	3'×3'	3'×3'
Bandpass (µm)	0.37–0.975	0.95–1.80
Pixel Resolution	15.5 mas	24.5 mas
Angular Resolution	30.9 mas	49 mas
Design Wavelength	0.6 µm	0.95 µm
Detector	3×3 CCD203	2×2 H4RG10
Detector Array Width	12,288 pixels	8,192 pixels
Spectral Resolution, *R*	1,000	1,000
Microshutter Array	2×2 arrays; 180×80 µm aperture size; 171×365 apertures	

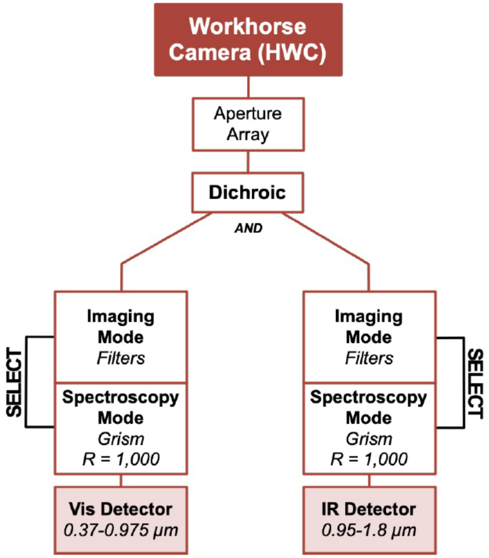
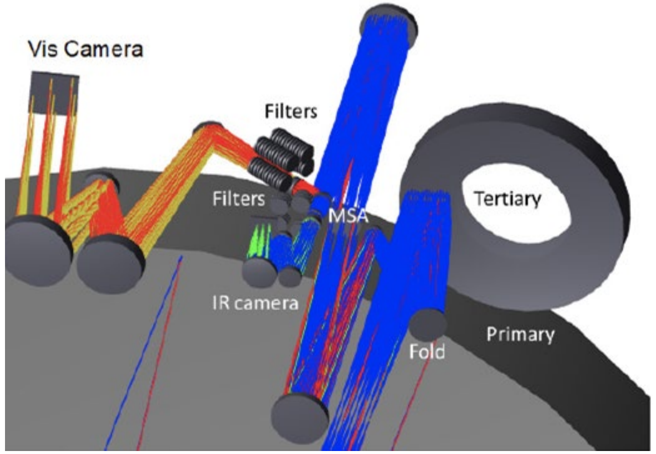


Figure 6.6-2. HWC uses a dichroic to split incoming light into Vis and IR channels. Each channel is capable of imaging and spectroscopy modes through filter or grating selection.



General Astrophysics and Solar System Science Themes

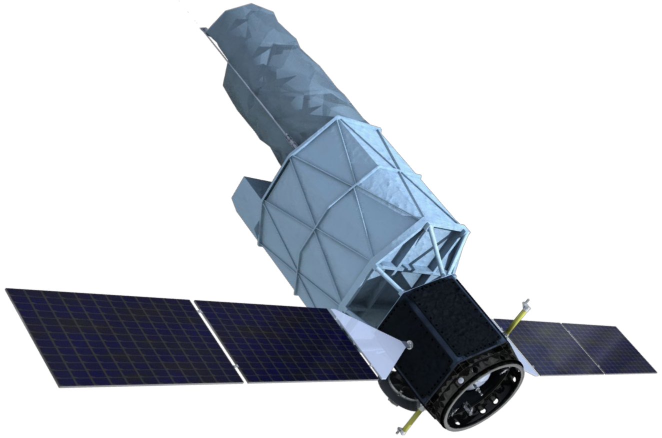
Star Formation Histories of Nearby (Dwarf) Galaxies, Dark Matter in Dwarf Galaxies, Exoplanet Transit Spectroscopy…

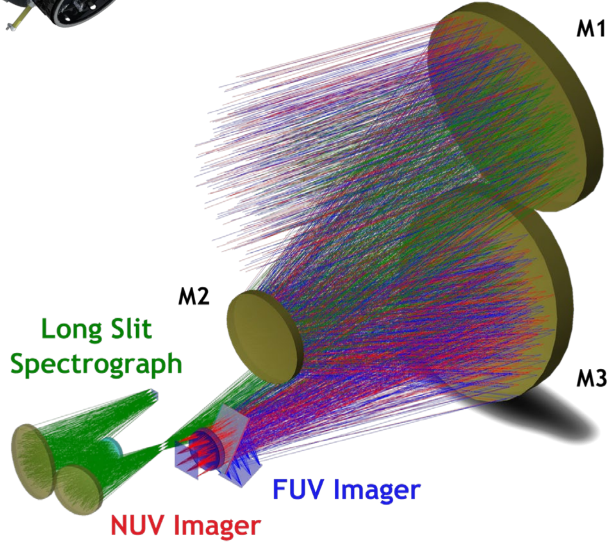
HWC provides lots, lots more….

- Astrometry Exoplanet Detection
- Optical Counterparts to X-ray Sources
- Planetary Atmospheres and Exospheres in the Solar System
- Cryovolcanism and Potentially Habitable Icy Worlds
- Distant Galaxy Clusters
- Coronagraphic images of active galactic nuclei (AGN)
- UV Imaging/Spectroscopy of Gravitational Wave Events

The Ultraviolet Explorer (UVEX) –
“Precursor CMOS Detector “

PI: Fiona Harrison, Caltech
Instrument Scientists: Shouleh Nikzad, Roger Smith





Synoptic Two-Band All-Sky Survey

- 50-100x deeper than GALEX
- Complementary to Rubin, Euclid, Roman

Time Domain Capabilities

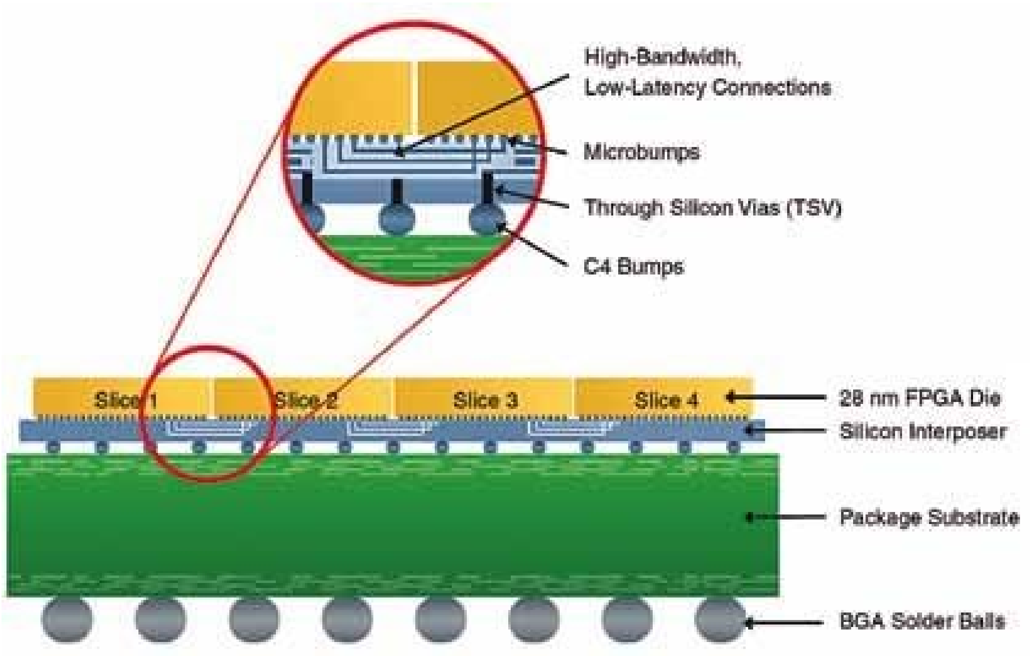
- 3 hr target-of-opportunity response time
- Multiple cadences from hours to months

Slit Spectroscopy

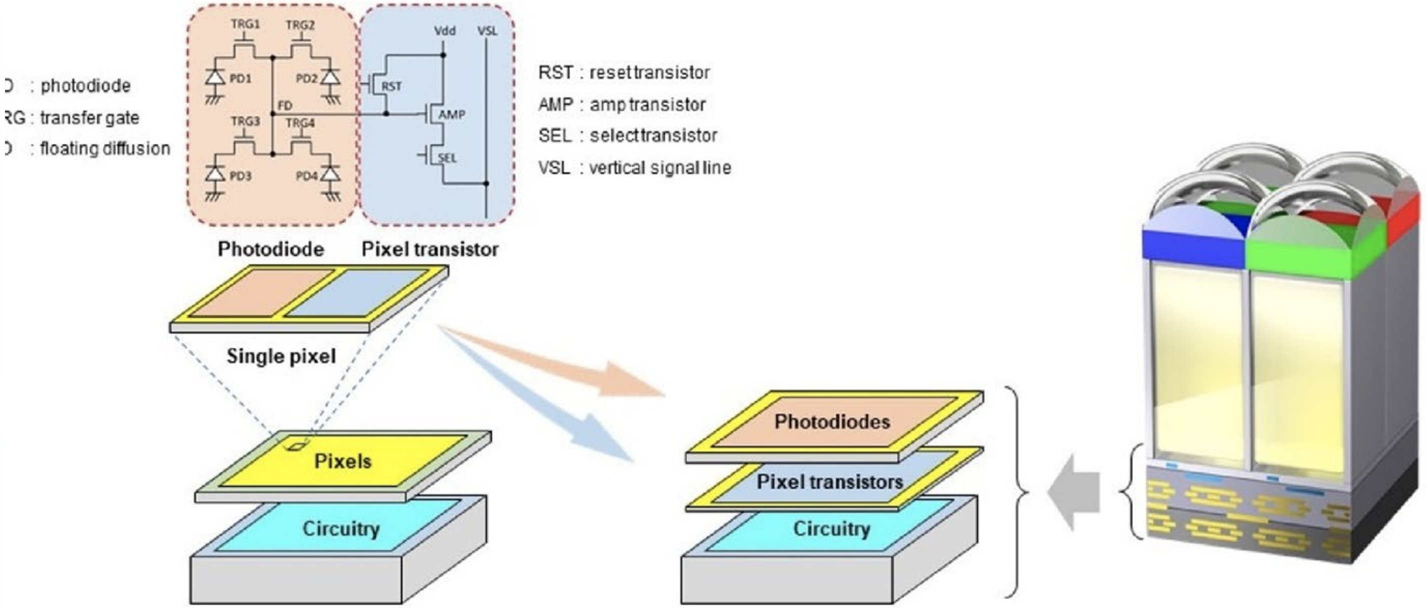
- Sensitive, R>1000 over broad bandpass
- 1-degree long slit with multiple widths

- UVEX has two imaging focal planes made of a three-by-three mosaic of 4k x 4k CMOS detectors (87% fill factor), with coatings optimized for the NUV and FUV bands
- The spectrometer uses one additional 4k x 4k SRI (mkxnk) CMOS detector with a graded coating to match the target wavelength across the detector

3D-Stacked Fabrication for Vertical Integration Silicon CMOS Detectors



Sony's 3D Stacked CMOS Image Sensor Architecture



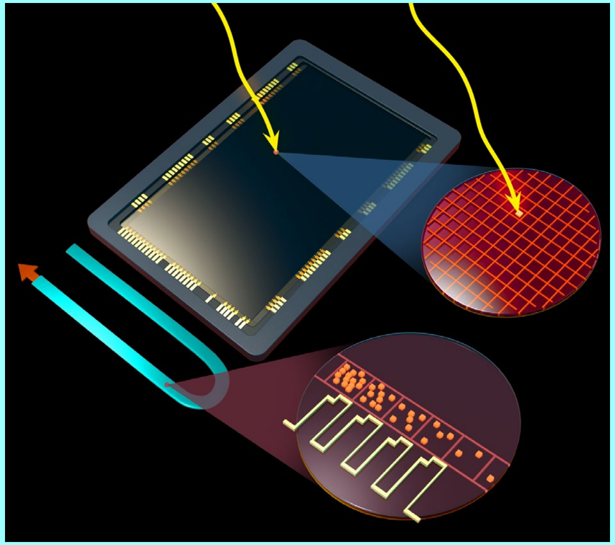
Conventional stacked CMOS image sensor

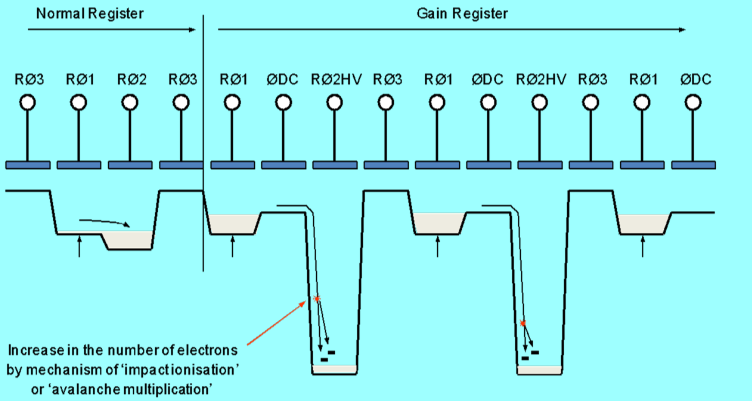
Stacked CMOS image sensor with newly developed 2-Layer Transistor Pixel technology

- Allows for close buttability in mosaics—especially in 4-side buttable situation
- Allows for small pixels
- Allows for better thermal management
- Allows for smaller cameras and instruments

Single Photon Counting, High Efficiency Silicon Detectors

Electron Multiplying CCDs

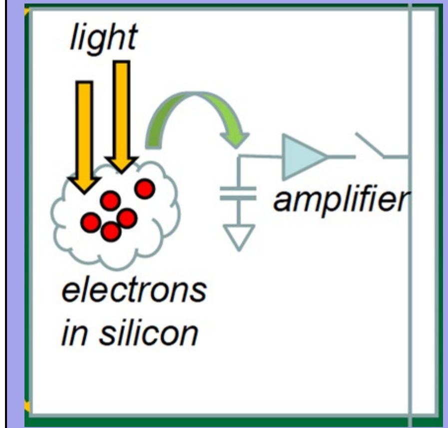


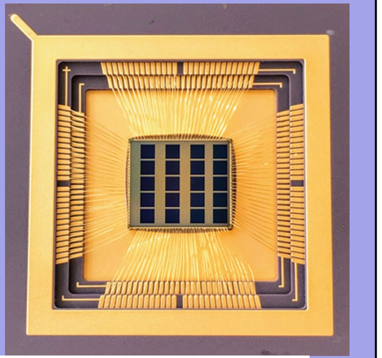


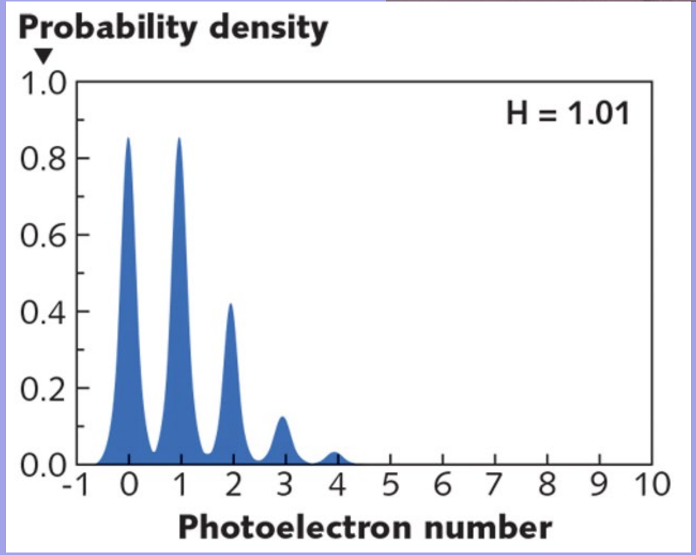
Increase per stage $G_0 \sim 1\%$. Mean gain for n stages: $G = (1 + G_0)^n$

Teledyne-e2v schematic

Quanta Image Sensor

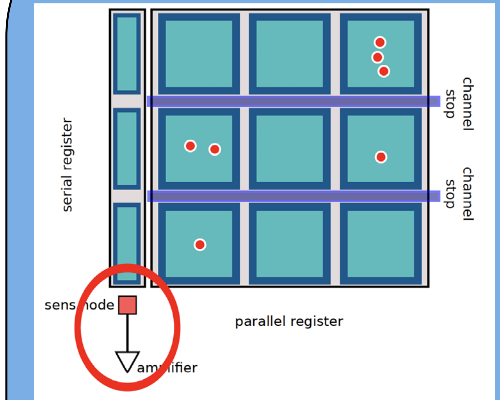




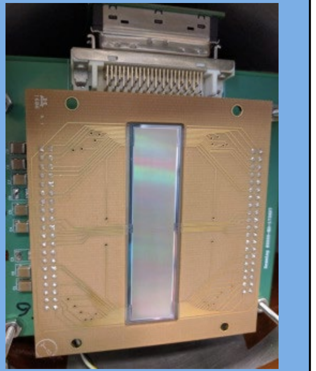


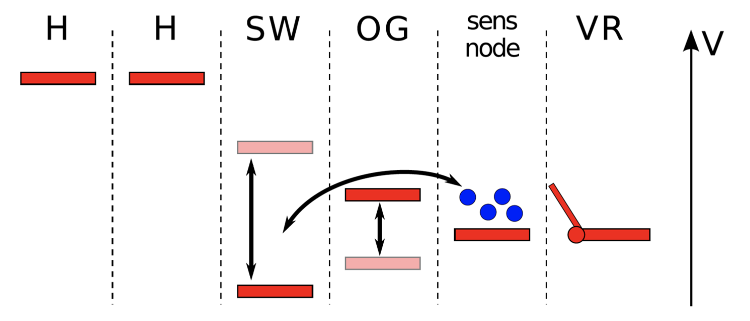
Fossum, Dartmouth

Skipper CCD



Only the readout stage is modified



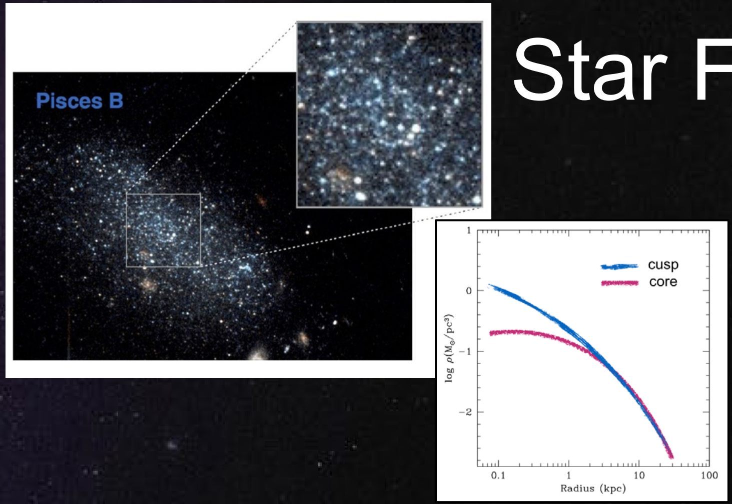


Tiffenberg, APS, 2021

Conclusions

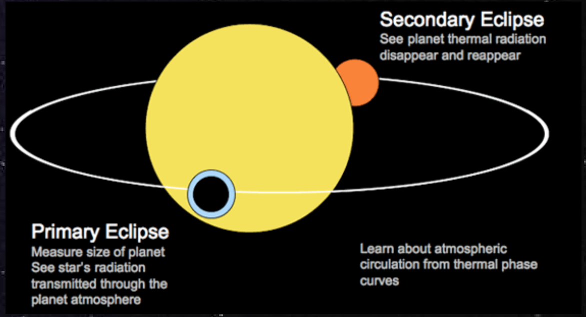
- LUVOIR and HabEx studies have done an incredible job in fitting compelling missions into the allocated cost and getting to point designs of instrument that can be done (with some work) with today’s technology.
- The two studies have shown different perspectives and impressive solutions for future GO. While HWO will need a fresh look, LUVOIR and HabEx studies are excellent starting points.
- Several of the precursor technologies such as CMOS image sensors are being used in Explorers which are a great pathway to the GO.
- Other technologies under development could offer alternative and potentially lower cost options and should be explored—trade space should not be closed too soon
- We need to get started and keep pace on
  - Technology work that is needed/enabling for HWO
  - Keeping industry engaged, focused, and funded
  - Keeping next generation scientists and instrumentalists engaged and funded

Backup Slides

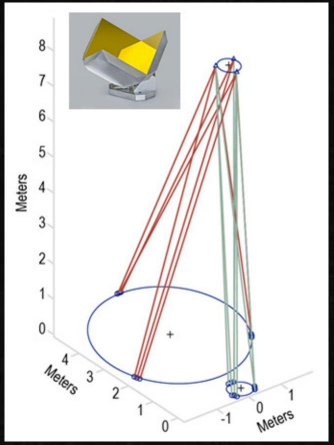


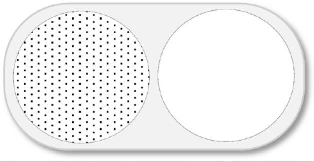
Star Formation Histories of Nearby (Dwarf) Galaxies

Dark Matter in Dwarf Galaxies



Exoplanet Transit Spectroscopy



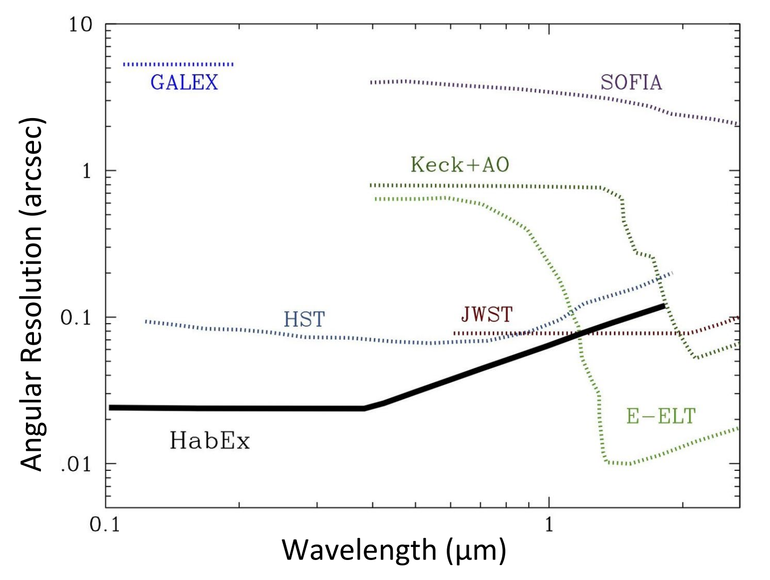


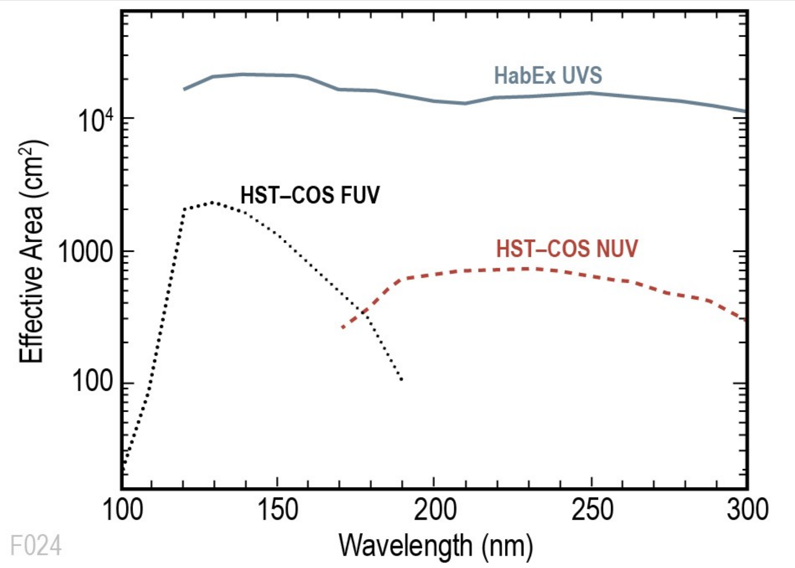
Astrometry Exoplanet Detection

Capabilities: Resolution and Effective Area

Capabilities: Imaging and Spectroscopy

- Diffraction limited at 0.4 µm
  - Better than all current or planned facilities for λ < 1 µm
- Access to wavelengths inaccessible from the ground
- Ultra-stable platform
  - Precision photometry, morphology, astrometry, …
- HabEx Workhorse Camera (HWC)
  - Area 3’ x 3’, 150 nm to 1.8 µm, R=2000
  - Microshutter array
- Ultraviolet Spectrograph (UVS)
  - Area 3’ x 3’, 115-300 nm, resolution up to R=60,000
  - >10x effective area of HST for 115 nm-300 nm
  - Microshutter array





What is the difference between LUVOIR and HabEx ?

Both LUVOIR and HabEx have two primary science goals

- Habitable exoplanets & biosignatures
- Broad range of general astrophysics

The two architectures will be driven by difference in focus

- For LUVOIR, both goals are on equal footing. LUVOIR will be a general purpose “great observatory”, a successor to HST and JWST in the ~ 8 – 16 m class
- HabEx will be optimized for exoplanet imaging, but also enable a range of general astrophysics. It is a more focused mission in the ~ 4 – 8 m class

Similar exoplanet goals, differing in quantitative levels of ambition

- HabEx will *explore* the nearest stars to “search for” signs of habitability & biosignatures via direct detection of reflected light
- LUVOIR will *survey* more stars to “constrain the frequency” of habitability & biosignatures and produce a statistically meaningful sample of exoEarths

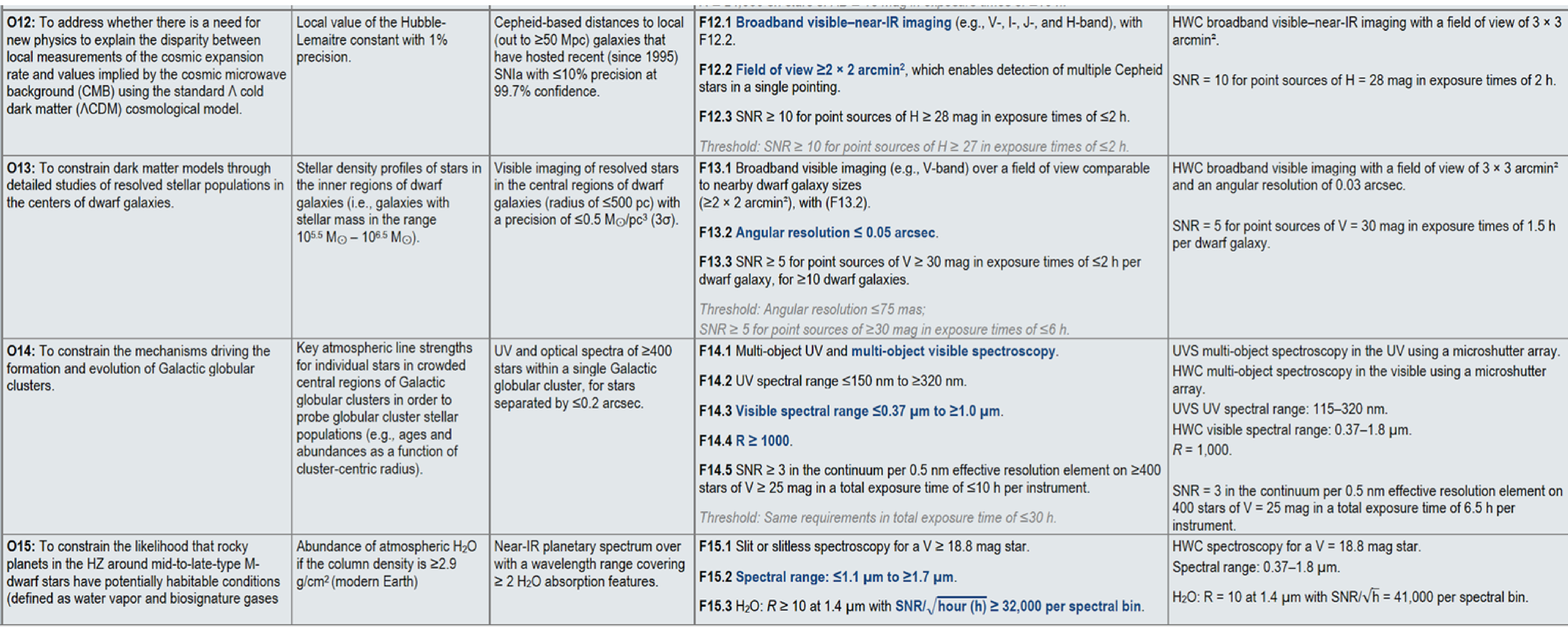
The two studies will provide a continuum of options for a range of futures

HabEx Workhorse Camera Requirements

The HabEx Workhorse Camera and spectrograph (HWC) requirements stem from Objectives 12 through 15 in the STM. The HWC requires a minimum 2.0 Å~ 2.0 arcmin2 field of view and a microshutter array to conduct MOS. The most demanding spectral resolution is set by the globular cluster science in Objective 14 (Section 4.6). The Hubble constant science in Objective 12 (Section 4.4) drives the photometric precision of the instrument. Table 5.4-8 identifies the key HWC requirements.

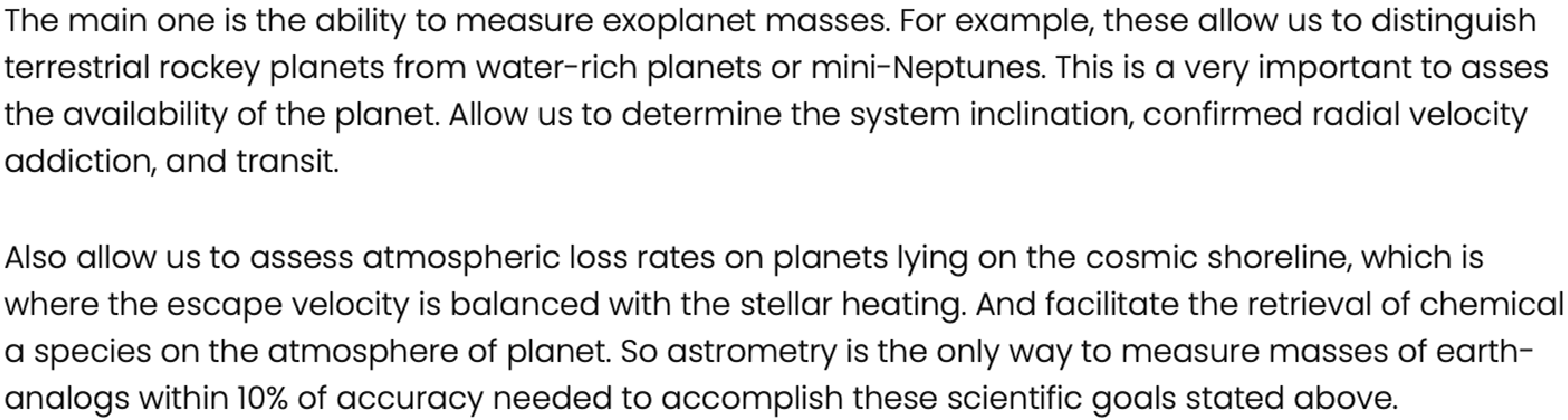
Parameter	Requirement	K	D	Source
Spectral Range	≤0.37 µm to ≥1.7 µm	✓		STM
Spectral Resolution, *R*	Up to ≥1,000 depending on the measurement	✓		STM
Angular Resolution	≤25 mas	✓		STM
FOV	≥2 × 2 arcmin2	✓		STM
Multi-Object Spectroscopy	Yes	✓		STM
Noise Floor	≤10 ppm	✓		STM

HabEx Workhorse Camera Requirements from STM O12-15



O12: To address whether there is a need for new physics to explain the disparity between local measurements of the cosmic expansion rate and values implied by the cosmic microwave background (CMB) using the standard Λ cold dark matter (ΛCDM) cosmological model.	Local value of the Hubble-Lemaitre constant with 1% precision.	Cepheid-based distances to local (out to ≥50 Mpc) galaxies that have hosted recent (since 1995) SNIa with ≤10% precision at 99.7% confidence.	**F12.1** **Broadband visible–near-IR imaging** (e.g., V-, I-, J-, and H-band), with F12.2. **F12.2** **Field of view ≥2 × 2 arcmin²**, which enables detection of multiple Cepheid stars in a single pointing. **F12.3** SNR ≥ 10 for point sources of H ≥ 28 mag in exposure times of ≤2 h. *Threshold: SNR ≥ 10 for point sources of H ≥ 27 in exposure times of ≤2 h.*	HWC broadband visible–near-IR imaging with a field of view of 3 × 3 arcmin². SNR = 10 for point sources of H = 28 mag in exposure times of 2 h.
O13: To constrain dark matter models through detailed studies of resolved stellar populations in the centers of dwarf galaxies.	Stellar density profiles of stars in the inner regions of dwarf galaxies (i.e., galaxies with stellar mass in the range $10^{5.5}$ $M_\odot$ – $10^{6.5}$ $M_\odot$).	Visible imaging of resolved stars in the central regions of dwarf galaxies (radius of ≤500 pc) with a precision of ≤0.5 $M_\odot/pc^3$ (3σ).	**F13.1** Broadband visible imaging (e.g., V-band) over a field of view comparable to nearby dwarf galaxy sizes (≥2 × 2 arcmin²), with (F13.2). **F13.2** **Angular resolution ≤ 0.05 arcsec**. **F13.3** SNR ≥ 5 for point sources of V ≥ 30 mag in exposure times of ≤2 h per dwarf galaxy, for ≥10 dwarf galaxies. *Threshold: Angular resolution ≤75 mas;* *SNR ≥ 5 for point sources of ≥30 mag in exposure times of ≤6 h.*	HWC broadband visible imaging with a field of view of 3 × 3 arcmin² and an angular resolution of 0.03 arcsec. SNR = 5 for point sources of V = 30 mag in exposure times of 1.5 h per dwarf galaxy.
O14: To constrain the mechanisms driving the formation and evolution of Galactic globular clusters.	Key atmospheric line strengths for individual stars in crowded central regions of Galactic globular clusters in order to probe globular cluster stellar populations (e.g., ages and abundances as a function of cluster-centric radius).	UV and optical spectra of ≥400 stars within a single Galactic globular cluster, for stars separated by ≤0.2 arcsec.	**F14.1** Multi-object UV and **multi-object visible spectroscopy**. **F14.2** UV spectral range ≤150 nm to ≥320 nm. **F14.3** **Visible spectral range ≤0.37 µm to ≥1.0 µm**. **F14.4** **R ≥ 1000**. **F14.5** SNR ≥ 3 in the continuum per 0.5 nm effective resolution element on ≥400 stars of V ≥ 25 mag in a total exposure time of ≤10 h per instrument. *Threshold: Same requirements in total exposure time of ≤30 h.*	UVS multi-object spectroscopy in the UV using a microshutter array. HWC multi-object spectroscopy in the visible using a microshutter array. UVS UV spectral range: 115–320 nm. HWC visible spectral range: 0.37–1.8 µm. R = 1,000. SNR = 3 in the continuum per 0.5 nm effective resolution element on 400 stars of V = 25 mag in a total exposure time of 6.5 h per instrument.
O15: To constrain the likelihood that rocky planets in the HZ around mid-to-late-type M-dwarf stars have potentially habitable conditions (defined as water vapor and biosignature gases	Abundance of atmospheric H_2O if the column density is ≥2.9 g/cm² (modern Earth)	Near-IR planetary spectrum over with a wavelength range covering ≥ 2 H_2O absorption features.	**F15.1** Slit or slitless spectroscopy for a V ≥ 18.8 mag star. **F15.2** **Spectral range: ≤1.1 µm to ≥1.7 µm**. **F15.3** H_2O: R ≥ 10 at 1.4 µm with **$SNR/\sqrt{hour\ (h)}$ ≥ 32,000 per spectral bin**.	HWC spectroscopy for a V = 18.8 mag star. Spectral range: 0.37–1.8 µm. H_2O: R = 10 at 1.4 µm with $SNR/\sqrt{h}$ = 41,000 per spectral bin.

From Eduardo Benkek



The main one is the ability to measure exoplanet masses. For example, these allow us to distinguish terrestrial rockey planets from water-rich planets or mini-Neptunes. This is a very important to asses the availability of the planet. Allow us to determine the system inclination, confirmed radial velocity addiction, and transit.

Also allow us to assess atmospheric loss rates on planets lying on the cosmic shoreline, which is where the escape velocity is balanced with the stellar heating. And facilitate the retrieval of chemical a species on the atmosphere of planet. So astrometry is the only way to measure masses of earth-analogs within 10% of accuracy needed to accomplish these scientific goals stated above.