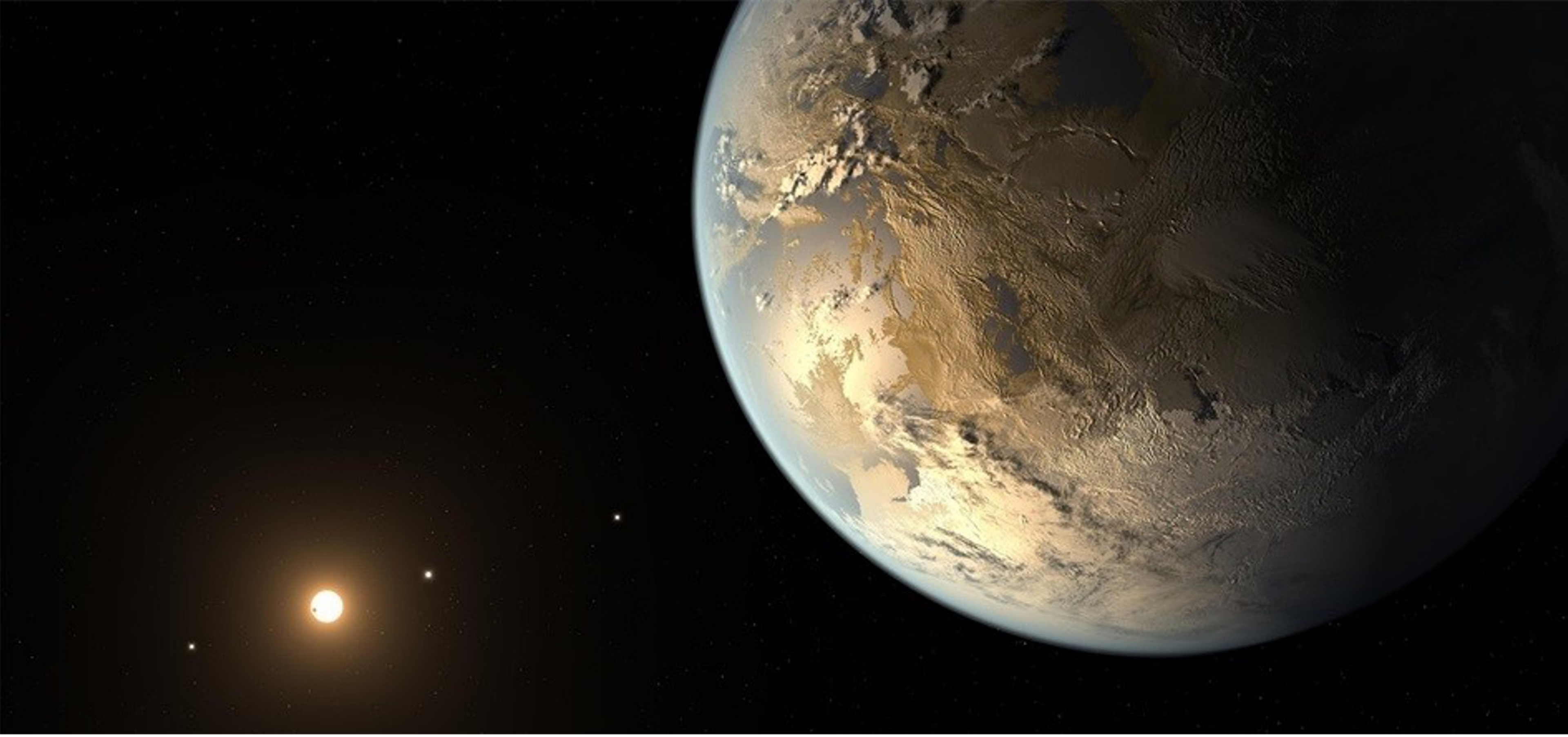


NASA Exoplanet Exploration Program

The Coronagraph Technology Roadmap Working Group

ExEP Colloquium, June 11th 2024

Pin Chen (NASA ExEP, JPL/Caltech), Laurent Pueyo (STScI), Nick Siegler (NASA ExEP, JPL/Caltech)
Please see full list of participants in this report

Coronagraph Technology Roadmap Scope

Pin Chen
(NASA ExEP, JPL)

Primary Objectives:

1. Create a roadmap for coronagraph technologies to reach TRL 5 in this decade for the Habitable Worlds Observatory and describe path to TRL 6.
2. Inform NASA on prioritized investments in architectures, H/W, modeling, manufacturing capabilities, and test facilities to ensure coronagraph technology readiness.

Laurent Pueyo
(STScI)

- Will include coronagraph optics, WFS&C, detectors, and postprocessing
- Will encompass the observatory as part of the environment in which the coronagraph instrument must perform
- Will review HabEx/LUVOIR reports to identify any significant updates and changes for a ~ 6m observatory
- Will incorporate lessons learned from the Roman Space Telescope's Coronagraph Instrument
- Will include experts from industry, academia, NASA Centers, and government labs

Participants: THANK YOU !!!

Name	Affiliation
Ardila	JPL
Arenberg	Northrop Grumman
Bailey	JPL
Belikov	ARC
Bendek	JPL
Bolcar	GSFC
Bottom	U. Hawaii
Carrier	Lockheed Martin
Chen	ExEP
Coyle	Ball Aerospace
Crill	ExEP
Damiano	JPL

Name	Affiliation
Dube	JPL
Feinberg	GSFC
Groff	GSFC
Guyon	NAOJ
Jovanovic	Caltech
Juanola	GSFC
Kasdin	Princeton
Krist	JPL
Levine	JPL
Mawet	Caltech
Mennesson	JPL
Menzel	GSFC
Morgan	ExEP
Nordt	Lockheed Martin

Name	Affiliation
Poberezhskiy	JPL
Pogorelyuk	MIT
Por	STScI
Potier	JPL
Pueyo	STScI
Quijada	GSFC
Redding	JPL
Ruane	JPL
Scheucher	JPL
Scowen	GSFC
Shi	JPL
Siegler	ExEP
Sirbu	ARC

Name	Affiliation
Sitarski	GSFC
Soummer	STScI
Stahl	MSFC
Stapelfeldt	ExEP
Stark	GSFC
Steiger	STScI
Trauger	JPL
Wallace	JPL
Warfield	ExEP
Young	N. Ariz. U. / GSFC
Zhao	JPL
Zhou	JPL
Ziemer	JPL
Zimmerman	JPL

- NUV Design-Point Lead: Roser Juanola-Parramon (GSFC)
- Vis Design-Point Lead: Vanessa Bailey (JPL)
- NIR Design-Point Lead: Olivier Guyon (NAOJ)
- UV Target List: Eric Mamajek (ExEP), Karl Stapelfeldt (ExEP), Dmitry Savransky (Cornell)
- EBS Validation & UI Lead: Sarah Steiger (STScI)
- Detector & Dichroic-Beamsplitter Fact Finding: John Trauger (JPL)
- Hybrid Lyot Coronagraph Design & Segment Edge Roll-off Simulation Software Lead: Dwight Moody (JPL)
- Coating Uniformity Sensitivity Analysis: John Krist (JPL)

CTR Deliverables

1. Submitted CTR task plan for ExoTAC review (May 2023)
2. Delivered DM Spatial-Temporal Stability Requirements to DMTR (Jun 2023)
3. Delivered requirement on inter-segment reflectance uniformity to USORT (Jun 2023)
4. Produced a provisional HWO UV Target List (Jul 2023)
5. Developed open-source Error Budget Software (EBS) (Sep 2023)
6. Co-authored the “UV Technology to Prepare for the Habitable Worlds Observatory” white paper (Sep 2023)
7. Supported development of HWO’s Coronagraph Exploratory Cases (Feb 2024)
13. Participated in HWO Exoplanet Science Yield Working Group’s Exposure-Time Calibration task (Mar 2024 - present)
14. Produced the “UV Coronagraph Point Design” white paper (Jun 2024)
15. Coronagraph Technology Roadmap Final Report (Draft produced in May 2024. Currently under revision per feedback)

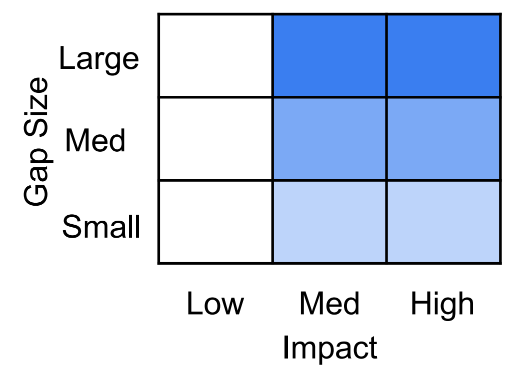
Executive Summary of Findings

Executive Summary

We summarize our findings in terms of coronagraph technology gaps to achieving TRL 5 for the Habitable Worlds Observatory

- The impact of each gap is quantified using the Provisional Key Driving Requirements
- .Their derivation utilized the open-source Error Budget Software (EBS) developed under CTR, with comparisons to relevant literature.
- The gaps sizes are based on current State of the Art

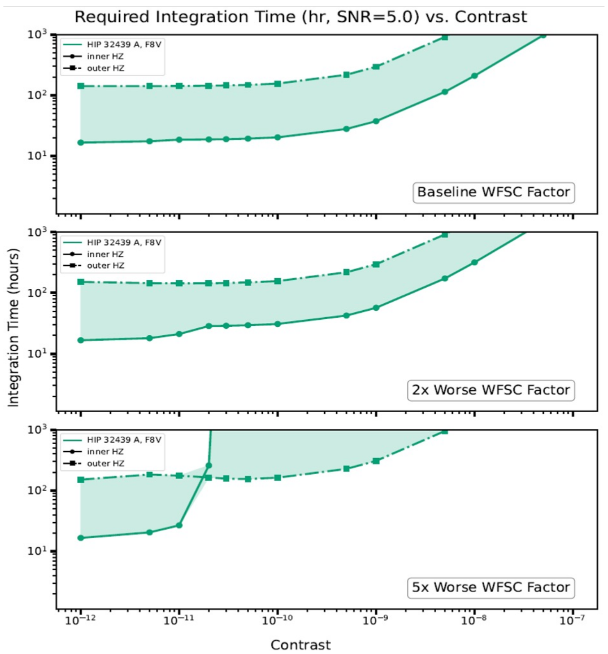
<u>Impact:</u>
Low: insignificant to small benefit to projected mission return
Medium: moderate benefit to projected mission return
High: significant benefit to projected mission return
<u>Gap size:</u>
Small: Requirement ~ 2 x SotA performance
Medium: Requirement ~ 2-10 x SotA performance
Large: Requirement 10 x SotA perfromance
<u>Priority for technology road maps:</u>
Dark Blue: Invest immediately in multiple technology options, including
emergent technologies where appropriate. Balance portfolio in consideration of impact.
Medium Blue: Invest timely in SotA technologies. Balance portfolio in consideration of impact
Cyan: Advance existing technologies with appropriate timeline.



Executive Summary

We developed an Error Budget Software and used it to derive many key provisional requirements.

- Full documentation of the computation settings and outputs will be available on the code repository by the end of August 2024: https://github.com/chen-pin/ebs
  - The software is a wrapper around the EXOSIMS yield calculator
  - Uses the same mathematical formalism and equations as the Roman CGI error budget. [Nemati et al. (2020) JATIS, Nemati et al. (2023) JATIS].
  - Cross-validation with AYO almost done as part of CDS/CTR/ESYWG, C. Stark, S. Steiger, Armen Tokadijan.
  - Contributors and advisors thus far: Pin Chen, **Sarah Steiger (STScI),** Dmitry Savransky (Cornell), Vanessa Bailey (JPL)



Executive Summary

- **WFE-Stability Environment Gap.** The coronagraph instrument is not able to achieve required contrast noise floor for planet detection in relevant environment of observatory and DMs WFE instabilities. **Large gap, High impact.**

- **Starlight-Suppression-Optics Subsystem Gap**. Do not meet static performance (throughput, IWA/FoV, raw contrast, wavelength, and bandwidth) requirements to enable mission exoplanet yield. **Medium gap for Vis, Large gap for UV & IR, Medium impact.**

- **Mission efficiency Gap.** HWO design concepts utilize dichroic beam splitters for multi-channel observations. Such optics have never been tested. **Large gap, High impact.**

- **Detectors Gap :** Detectors do not meet noise, dynamic range, and lifetime requirements. **Small gap for imaging, Large gap for spectroscopy, Medium impact (imaging) High impact (spectroscopy).**

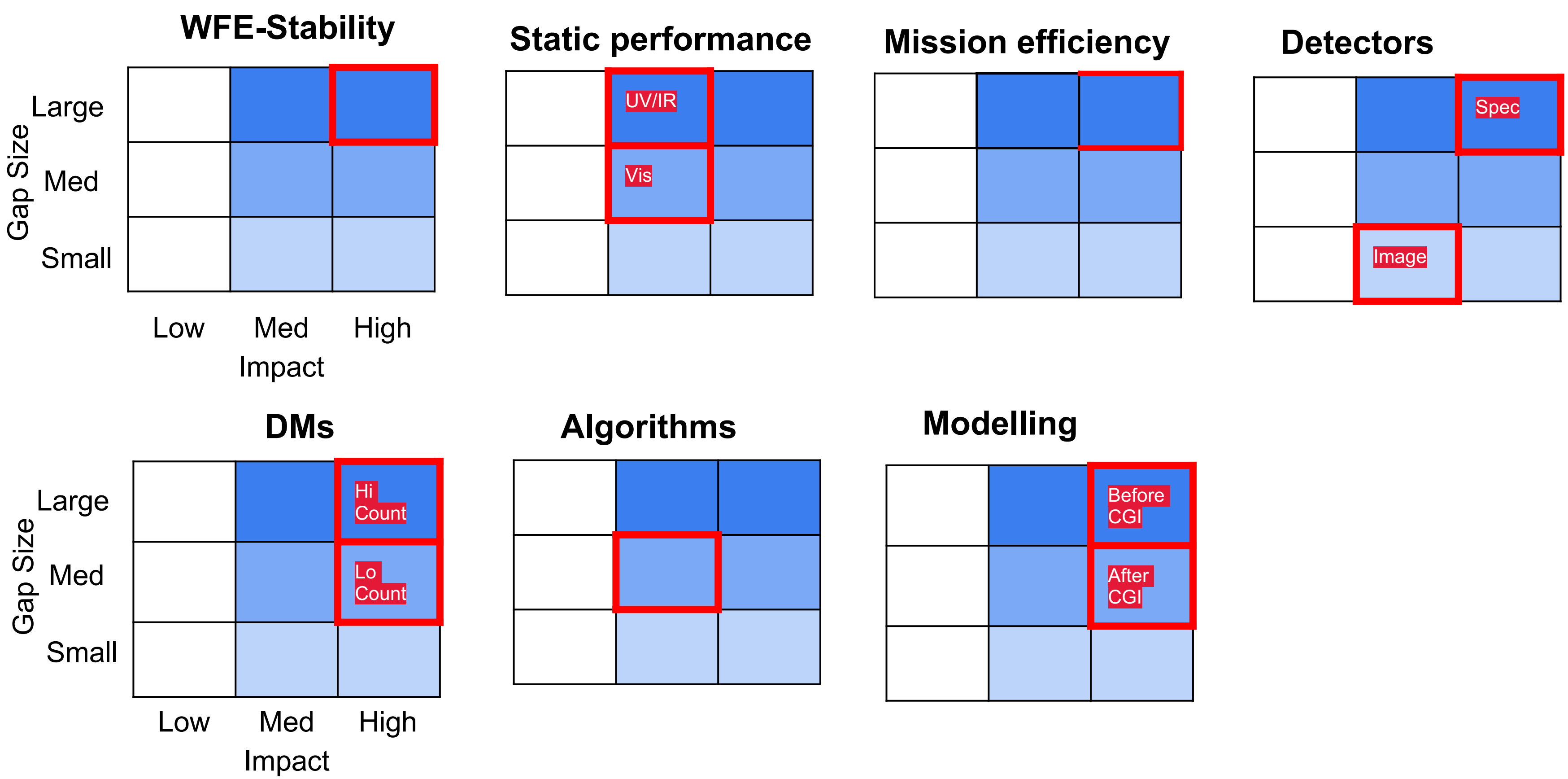
Executive Summary

- **Deformable Mirrors Gap.** DM subsystem not meeting actuator count, stability, surface, mass/volume, and/or schedule requirements. **Large gap for actuator count, Medium gap for everything else, High impact**.

- **Algorithms Gap.** Starlight-Suppression and post processing. Dark-hole-digging algorithms not able to compute solutions. Post processing enhancement insufficient for required planet detection/characterization. **Medium gap, Medium impact.**

- **Modelling Gap**. Model does not capture all contributions to instrument noise floor. Knowledge gap. **Large gap before CGI flight, Medium gap after CGI flight, High impact.**

Executive Summary



The report discusses how to advance technologies to close these technology gaps.

Table of Contents of the report

Key findings

1. Visible. Static contrast in testbeds is not far from what needed, and Roman will fly key hardware.

2. Near IR. Angular resolution is challenging. Emergent technologies might be only path to large # of IR spectra.

3. UV can be simplified to increase throughput/lower resolution to make # of UV photometry. No existing test facilities.

4. Wavefront stability daunting if only using telescope. Coronagraph AO is needed. Existing proofs of concept in lab and with Roman.

5. Investment in DMs needed as soon as possible.

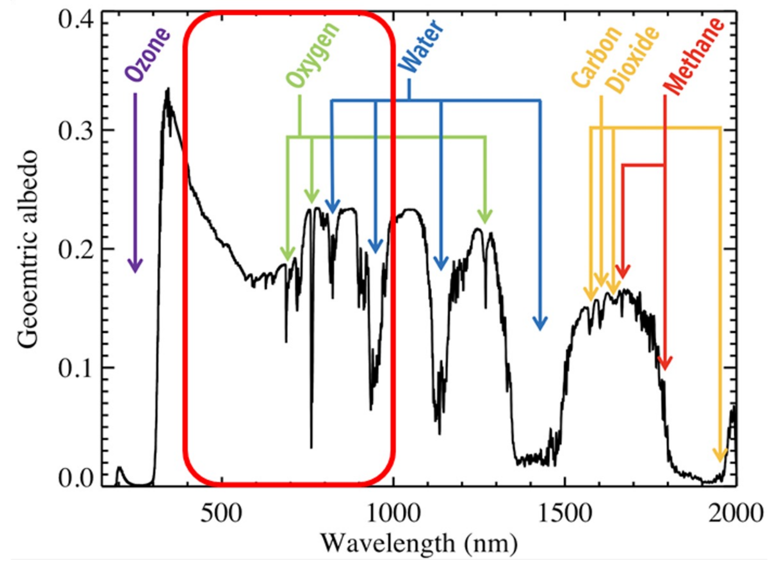
6. Spectroscopic considerations need to be included in static starlight suppression system.

7. Better detectors, algorithms (post processing and wavefront control) and multiplexing capabilities will ease component level requirements.

Coronagraph static performance and mission efficiency

Key performances for HWO Visible channel.

- **Spectral coverage and resolution** [LUVOIR Final Report]
  - H_2O: **0.94 µm**, **20% BW**, **SNR=8.5** photometry
  - O_2: **0.76 µm**, **20% BW**, **SNR=10**, **R = 140** spectroscopy
- **Core throughput 0.3**
- **IWA 60 mas**
- **Raw Contrast 3 x 10^{-10}**



C. Stark

Performance Gap

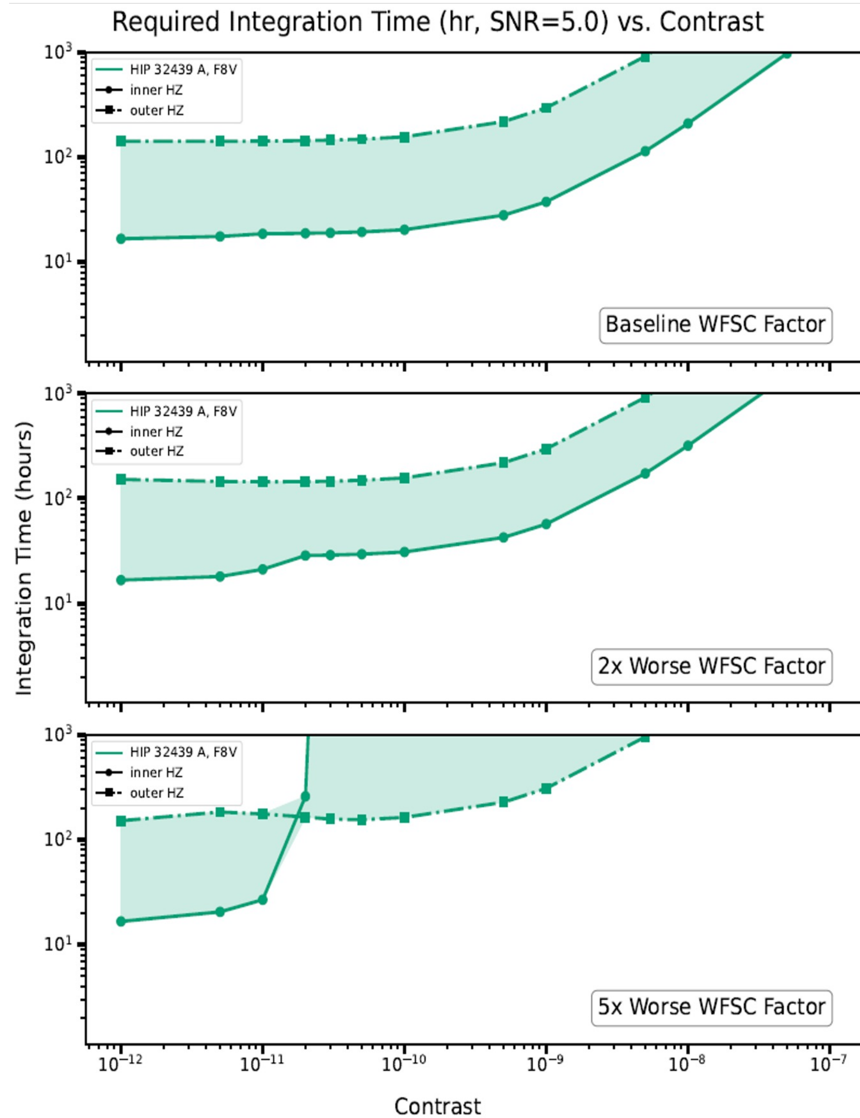
- Simultaneous achievement of 3 x 10^{-10} raw contrast and 0.3 core throughput with 20% bandwidth, while maintaining SoTA contrast sensitivity.
- In general, SotA coronagraphs demonstrate only one of these three KPP at a time

Detail of HWO EBS Visible Channel calculations

- Exozodi brightness (at 3 zodis) is equivalent to 6e-10 ~1e-9 flux-ratio levels for our fiducial stars, buffering the impact of raw contrast.

- However, stellar speckles are coherent. They can amplify the effects of WFE instability via the cross term, whereas zodiacal light is incoherent.

Raw contrast gap does increases time to SNR. Unstable contrast prevents planet detection.



Starlight-Suppression Optics: Vis Lab Demonstrations

- JPL's High Contrast Imaging Testbed (HCIT) facility's Decadal Survey Testbed (DST) currently has a baseline contrast of 4×10^{-10} mean contrast, 3 - 8 λ/D full annular dark zone, 10% bandwidth
- 20-bit electronics + ghost-reflection mitigation -> 2×10^{-10}
- Lab demonstrations have not simultaneously achieved all performance targets needed for an efficient mission

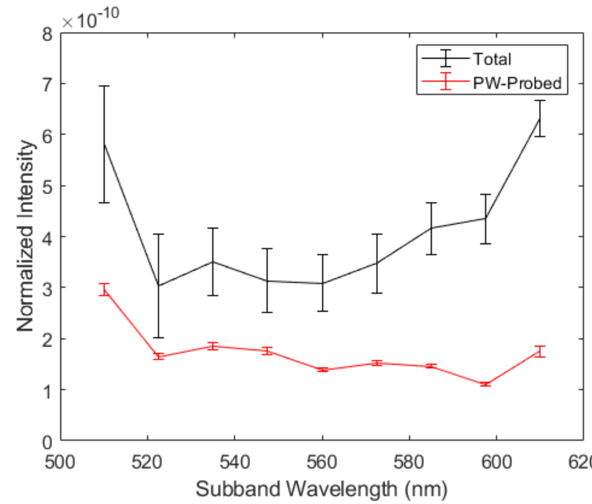
- Roman Coronagraph will bring many Starlight Suppression Optics to TRL 9.
- Roman Coronagraph TVAC surpassed threshold requirements

- Lab demonstrations and Roman coronagraph do not feature key multiplexing optics

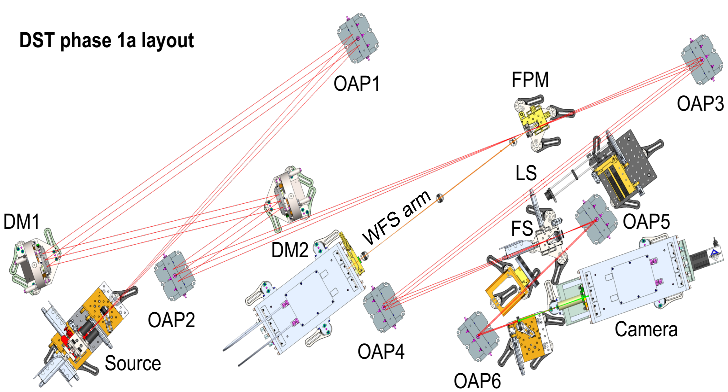
Performance of Vis lab demonstration on par with what is needed for HWO. More complex systems needed to be demonstrated

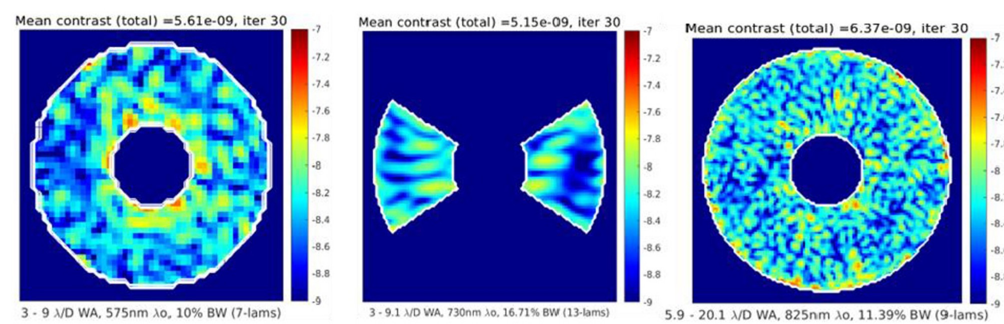
Starlight-Suppression Optics: Vis Lab Demonstrations

Contrast, 3.82E-10 Total		Measured	Model/Indirect Expectation	Morphology
Modulated 1.81E-10	LSB effect of DM actuators	8.78E-11	~1E-10	Specklish
	Chromatic Control Residual	9.32E-11	~4E-11	Specklish
Unmodulated 2.01E-10	Occulter Ghost (+Chromatic Residual)	1.01E-10	~1E-10	Patterned March with wavelength
	Testbed LoS Jitter impact	4.19E-11	< 1E-11	Centered
	Unknown	5.04E-11	N/A	Diffused

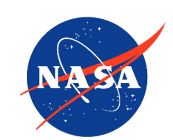


DST phase 1a layout





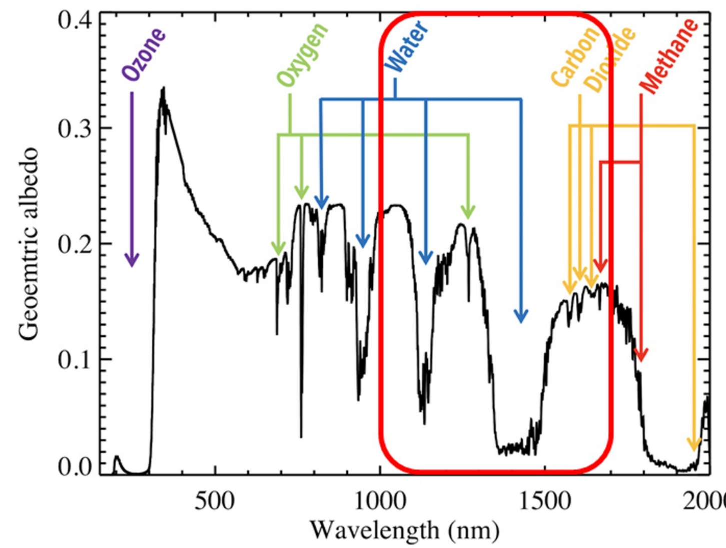
MUF =1	HLC-nFOV	SPC-spec	SPC-wFOV
Static Raw Contrast	5.6e-9	5.15e-9	6.4e-9
Total expT (w/o overheads)	43 hr	114 hr	80 hr



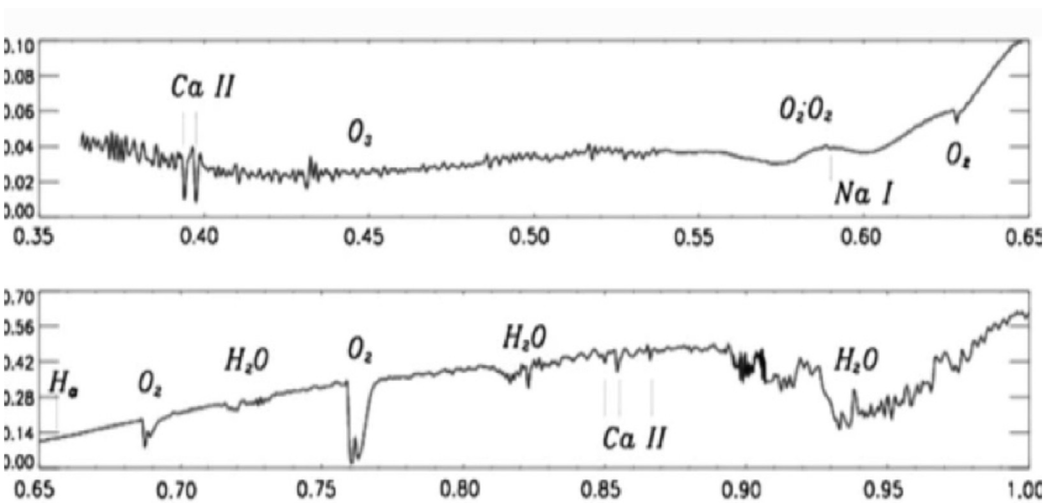
Key performances for HWO IR channel:

- **<u>Spectral coverage and resolutions</u>**

  [Damiano & Hu 2022]
    - H_2O: 1.1 µm, 20% BW, SNR=20, R = 40 spectroscopy
    - CO_2: **1.6 µm**, **20% BW**, **SNR = 20**, **R = 40** spectroscopy
- **<u>Core throughput 0.3</u>**
- **<u>IWA:</u> 60 mas**
- **<u>Raw contrast:</u>** **~ 3×10^{-10}**



- IR features key spectroscopic diagnostics essential to contextualize Vis spectrum.

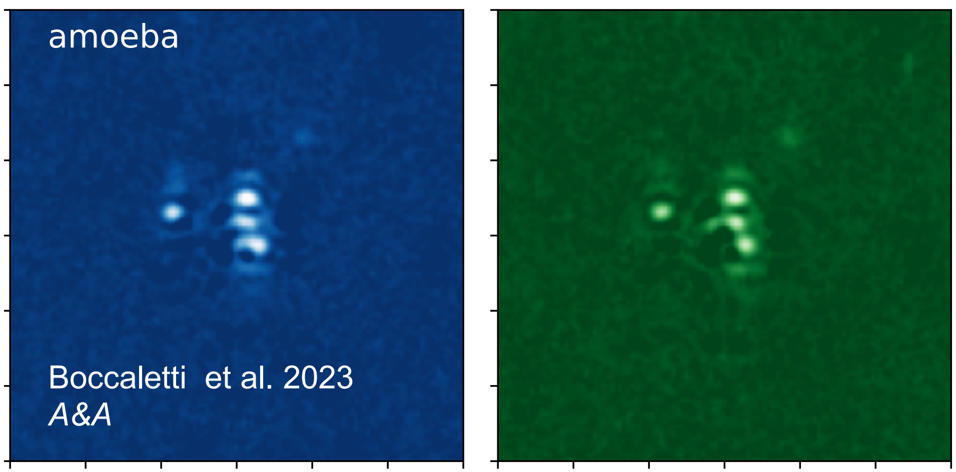


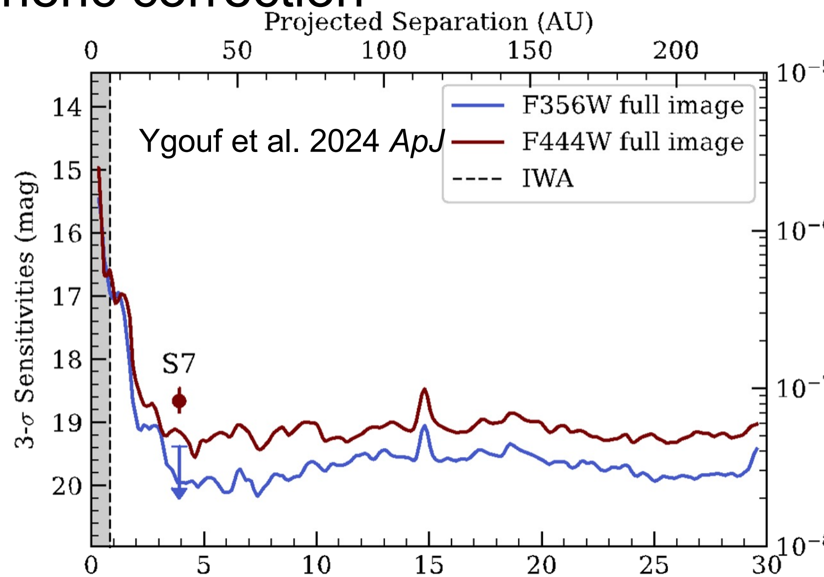
Max resolution in IR is very dependent on available detector technology.

60 mas IWA = 1.1 λ/D for λ=1.6 µm & D=6 m. Major NIR challenge

Starlight Suppression Optics: Near Infrared instrument

- State of the Art: Near-IR coronagraphs observe exoplanets from the ground and in space, but not at HWO performance levels
  - JWST NIRCam operates routinely at $1x10^{-4}$ raw contrast, $1x10^{-5}$ post processed, and $4x10^{-7}$ on a bright star [e.g. Ygouf et al. 2024 *ApJ*].
  - JWST MIRI operates at ~2 lambda/D
  - Ground based coronagraphs operates routinely at $1x10^{-5}$ raw contrast, $1x10^{-6}$ post processed, $5x10^{-7}$ on a bright star. Ground based coronagraphs use DMs for atmospheric correction

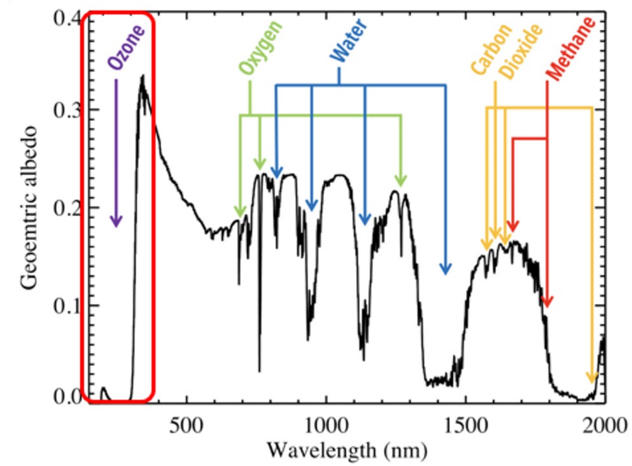


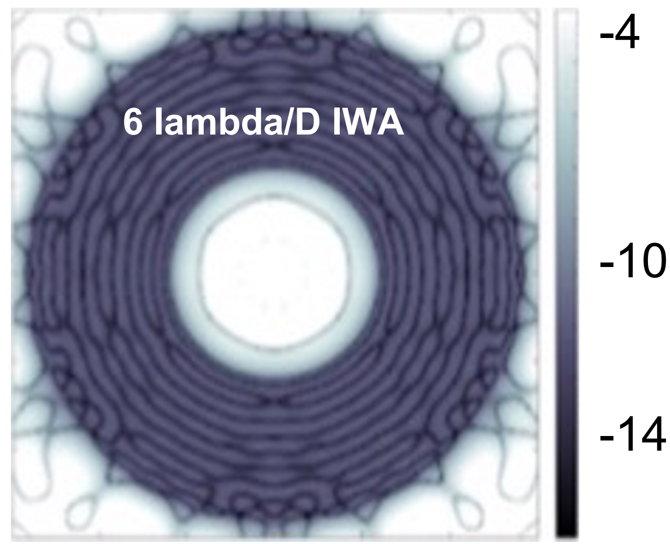


Community heritage in Near IR coronagraph at ~1e-6 contrasts with AO DMs on the ground and no DMs in space.

Key performances for HWO UV channel:

- Spectral coverage and resolutions
  - O_3: 250 - 300 nm, 20% BW, SNR = 20, R = 7 photometry
- Core throughput 0.2
- IWA 60 mas
- Raw contrast ~ 1×10^{-10}





UV coronagraph can tolerate larger IWA (in λ/D) but needs higher throughput than Vis coronagraph.
UV coronagraphs are more sensitive to wavefront errors.

Starlight Suppression Optics: Near-Ultraviolet

- **See the CTR UV Report "A near-ultraviolet coronagraph instrument study for the Habitable Worlds Observatory" led by R. Juanola Parramon.**

- **Major Technology Challenges & Gaps**
  - Low detectable photon flux
    - Low throughput due to lower coating reflectance vis. Lower detector QE compared to vis
    - Stars are dimmer, and therefore lower planetary flux as well, compared to vis
    - CTR estimated the UV system throughput/QE.

NUV throughput	3%	9%	18%
mag limit (NUV,AB)	35.64	36.84	37.64
N(total stars)	121	150	158*
N(F-type)	66 (max)	66 (max)	66 (max)
N(G-type)	45	55 (max)	55 (max)
N(K-type)	10	29	37
N(M-type)	0	0	0

- **Low UV throughput eliminate 26% of viable (vis) targets in the ExEP HWO Target List. The loss was mainly in K stars.**
- **Need to minimized the number of reflections and transmissions in order to maximize throughput**

- **UV coronagraphy has never been tested in the lab.**

Required Facilities: Subscale-Pupil Starlight-Suppression Test Facility (SSTF)

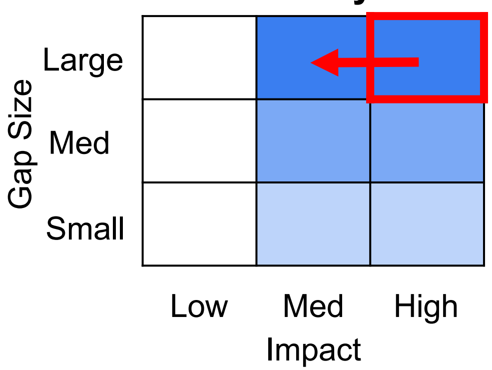
- The SSTF must enable the following functionalities
  - Validate raw contrast as a function of angular separation
  - Validate predicted coronagraphic throughput as a function of angular separation
  - Validate predicted planetary PSF footprint
  - Validate predicted starlight-suppression bandwidth
  - **Validate contrast sensitivities to WFEs**
  - **Characterize manufactured performance of key optical components for incorporation into models**
  - **Validate models of coronagraphic performance to optical imperfections and manufacturing tolerances**
  - Characterize performance dependence on detector characteristics
  - Enable validations at required HWO wavelengths

Required Facilities: Subscale-Pupil Starlight-Suppression Test Facility (cont’d)

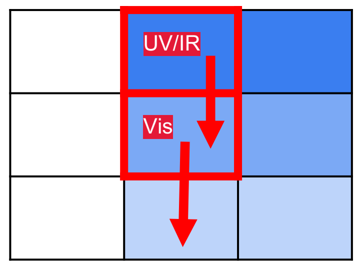
- Comments
    - The SSTF will need different types of testbeds/test-stations
        - coronagraph testbeds
        - optical-component characterization test stations
    - For validation, coronagraph testbed performance must exceed requirements for in-orbit performance to serve as the “ruler.” Raw contrast is a key parameter, and it needs to be $< 1 \times 10^{-10}$ (to surpass 3×10^{-3} for in-orbit raw contrast) .
    - Pupil screens (“phase plates”) and specialized DMs can be utilized to generate stimuli for contrast-sensitivity measurements
    - Combination of source + detectors in the testbeds should have characteristics scalable to the flight noise level.
    - **HWO will need a sufficient number of coronagraph testbeds to enable simultaneous testing of multiple coronagraphs. HWO will likely require a combination of coronagraphs, each optimized for distinct objectives, to achieve all of its requirements.**

Closing gaps with SSTF

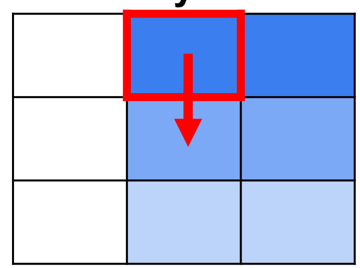
Robust coronagraphs help **WFE-Stability**



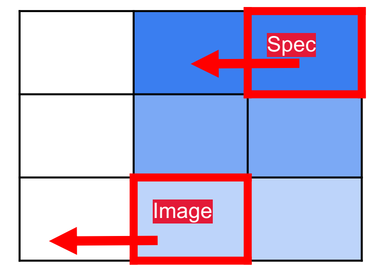
Better contrast, IWA help **Static performance**



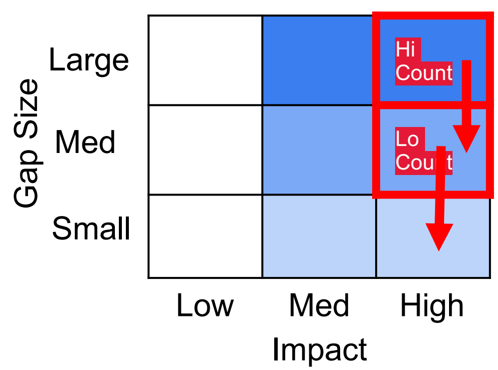
Dichroic validation helps **Mission efficiency**



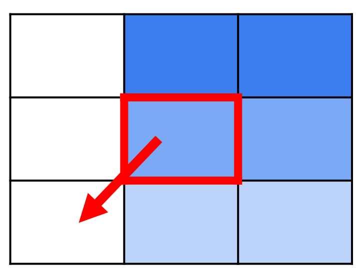
High throughput helps **Detectors**



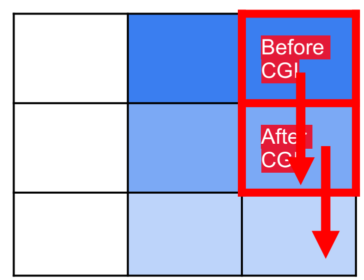
SSTF is **DMs** end to end test facility



SSTF demonstrates faster DH **Algorithms**



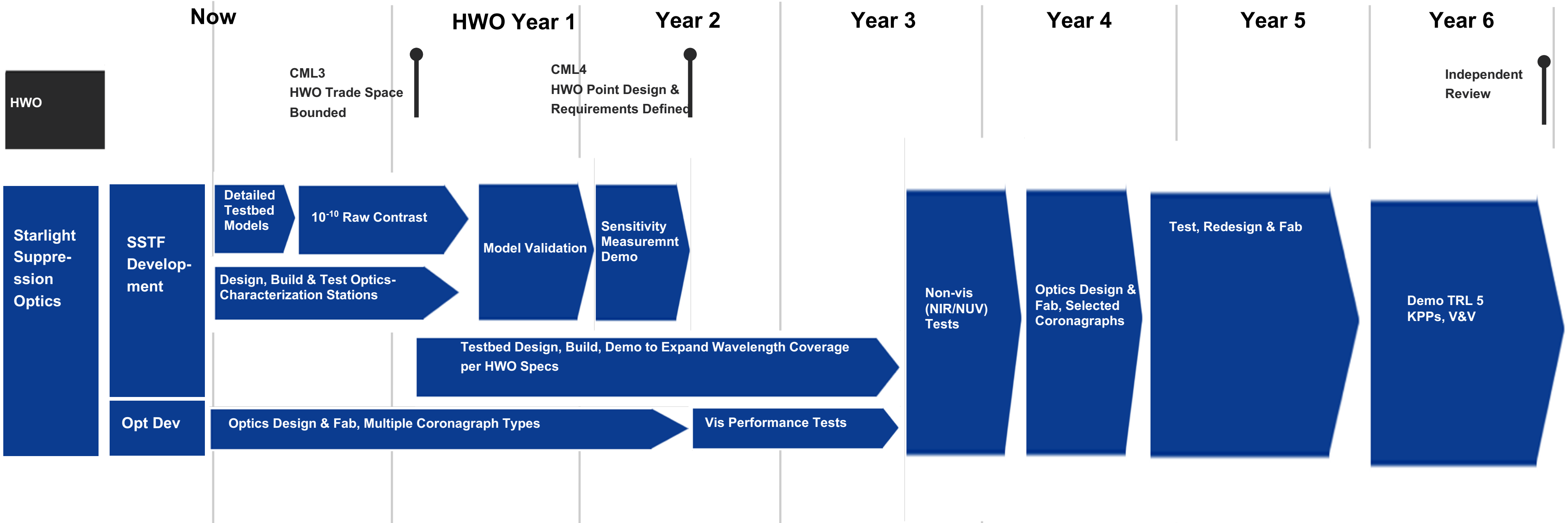
SSTF measures sensitivities used for **Modelling**



SSTF helps close other gaps than Static Performance gap

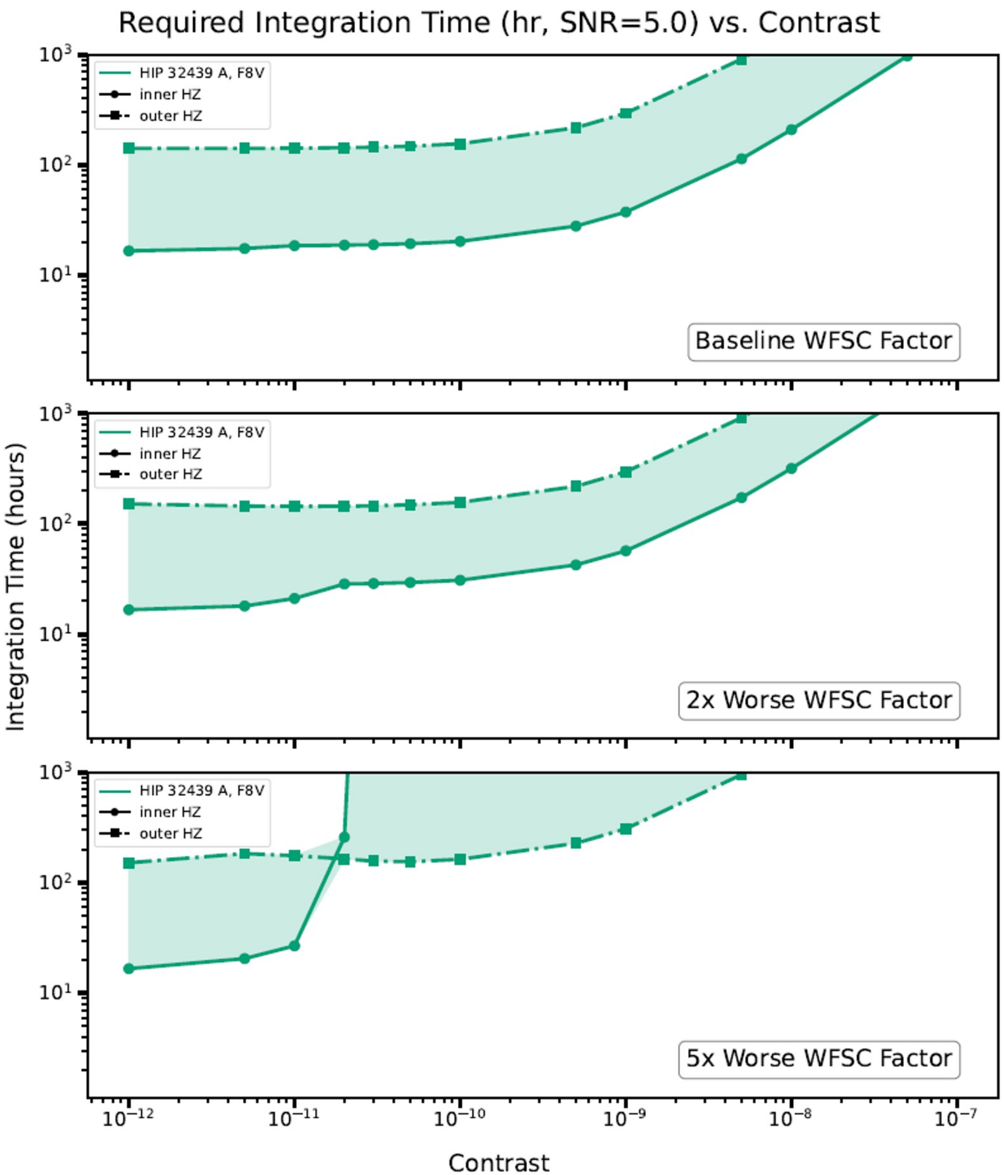
Timeline Assumptions

- Astro2020 recommended that crucial technologies reach TRL 5-6 before the Independent Review. Astro2020 envisioned that HWO technology development to take 6 years, requiring $800M (FY2020) total technology-maturation investment.
- We derived notional timescales using the following boundary conditions
  - **Overall timeline for developing critical HWO technologies is six years, based on Astro2020**
  - **The six year clock starts when NASA begins investing in HWO technology on the ~ 10^8 $/yr scale**
  - The overall timeline show comprises the above-mentioned six years plus a lead-in period (starting now)
  - Within each development tack of critical technology element , we estimated the relative required timescale for each phase and fit the end-to-end timescale into the overall timeline
- **As such, this is *not* a grass-roots-estimated schedule**
- **The end of each arrow-shaped bar represents a milestone (in accomplishing the corresponding task/objective)**
- **Whether or not the envisaged schedule can be accomplished depends on invested resources**


Now
HWO Year 1
Year 2
Year 3
Year 4
Year 5
Year 6
HWO
CML3
HWO Trade Space Bounded
CML4
HWO Point Design & Requirements Defined
Independent Review
Starlight Suppre-ssion Optics
SSTF Develop-ment
Detailed Testbed Models
10^{-10} Raw Contrast
Model Validation
Sensitivity Measuremnt Demo
Design, Build & Test Optics-Characterization Stations
Testbed Design, Build, Demo to Expand Wavelength Coverage per HWO Specs
Non-vis (NIR/NUV) Tests
Optics Design & Fab, Selected Coronagraphs
Test, Redesign & Fab
Demo TRL 5 KPPs, V&V
Opt Dev
Optics Design & Fab, Multiple Coronagraph Types
Vis Performance Tests

Wavefront Error Stability
Coronagraph AO

The impact of noise floor with EBS



- Example of EBS calculation on a fiducial star.
- Note that star is one of the most challenging ones on ExEP target list (see CDS presentation).

Degrading WF stability (by 5x here) **poses a clear breakpoint, where required integration time blows up. On the other hand, degrading raw contrast affects exposure time gradually** (knee @ $3x10^{-10}$)

Provisional Requirements: AO

Open loop (no coronagraph AO) disturbance

Spatial frequency (columns); Temporal frequency (rows)

WFE	[pm]			
	LOW	MID	HIGH	HIGH+
STATIC	20000	15000.00	5000.00	5000.00
LF1	87.30	26.20	40.00	0.00
LF2	87.30	26.20	40.00	0.00
LF3	87.30	5.20	3.50	0.00
MF	17.50	5.20	3.50	0.00
HF	17.50	5.20	3.50	0.00

Open-loop RMS wavefront changes between target and reference star observations

Noise rejection factor

Spatial frequency (columns); Temporal frequency (rows)

	LOW	MID	HIGH	HIGH+
STATIC	0.0E+00	0.0E+00	0.0E+00	0.0E+00
LF1	**1.0E-02**	**1.8E-02**	1.0E+00	1.0E+00
LF2	**1.0E-02**	**1.9E-02**	1.0E+00	1.0E+00
LF3	**9.9E-03**	**8.4E-02**	1.0E+00	1.0E+00
MF	**4.7E-02**	**8.7E-02**	1.0E+00	1.0E+00
HF	**4.8E-02**	**9.0E-02**	1.0E+00	1.0E+00

Drift-mitigation factors. AO subsystem using DMs + post-processing.

These values are representative results of an **EBS Monte Carlo run** that yield reasonable exposure times (~ 1 days for planet detection)

Provisional Requirements: AO

Final, post-AO wavefront “at the FPM” ~ 2 pm

Spatial frequency

Temporal frequency

POST-AO WFE				
	LOW	MID	HIGH	HIGH+
STATIC	0.0E+00	0.0E+00	0.0E+00	0.0E+00
LF1	8.8E-01	4.7E-01	4.0E+01	0.0E+00
LF2	8.9E-01	5.0E-01	4.0E+01	0.0E+00
LF3	8.7E-01	4.3E-01	1.0E+00	0.0E+00
MF	8.2E-01	4.5E-01	1.0E+00	0.0E+00
HF	8.4E-01	4.7E-01	1.0E+00	0.0E+00
SUMSQ	3.7E+00	1.1E+00	3.2E+03	0.0E+00

Final Contrast floor (ppm)

Spatial frequency

Separation

Delta C			
[ARCSEC]	LOW	MID	
4.4E-02	1.2E+01	1.0E+01	**1.6E+01**
6.1E-02	1.2E+01	5.2E+00	**1.3E+01**
7.9E-02	0.0E+00	3.1E+00	**3.1E+00**
9.6E-02	0.0E+00	3.1E+00	**3.1E+00**
1.1E-01	0.0E+00	1.6E+00	**1.6E+00**
1.3E-01	0.0E+00	1.6E+00	**1.6E+00**

Wavefront-stability requirement of 2 pm RMS at the FPM is daunting. Wavefront-to-contrast conversion depends on coronagraph sensitivities. Investments on robust coronagraphs is one way to relax top level stability requirements.

These values are representative results of an **EBS Monte Carlo run** that yield reasonable exposure times (~ 1 days for planet detection)

Coronagraph AO: state of the art

- Picometer sensing and actuation have been demonstrated in laboratory environment.

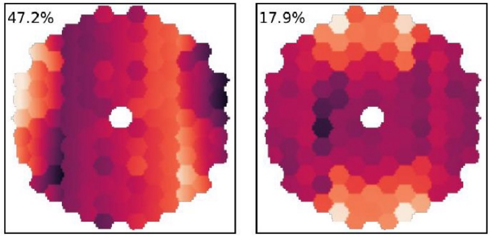
- Sensor SNR fundamentally limits control performance. Therefore stellar brightness fundamentally limits control gain and bandwidth.

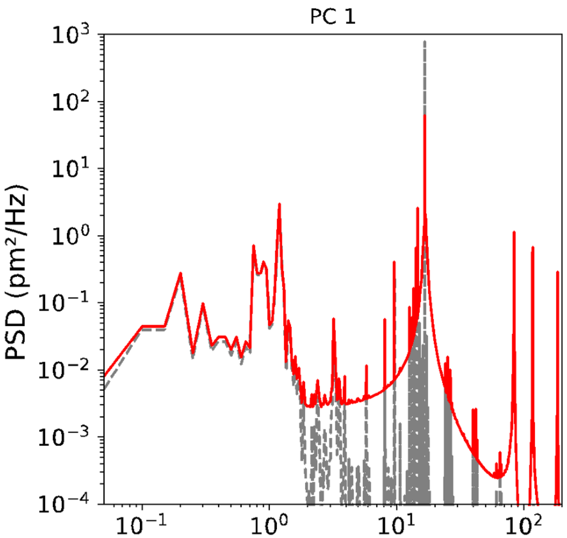
- Multiple sensing and control architectures being demonstrated in laboratory with factors of 10-100 gain and ultimate contrast ~1e-8.

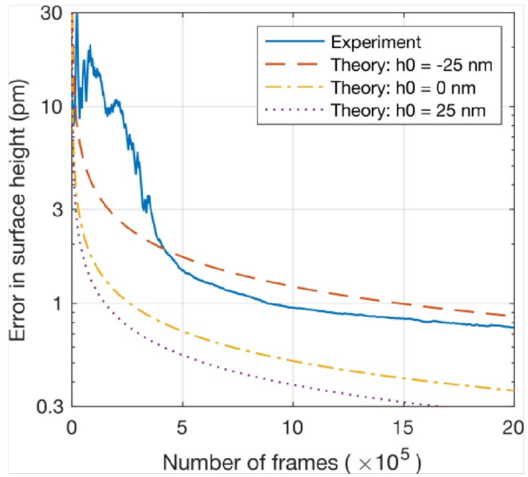
- Roman Coronagraph will bring AO in space to TRL 9 and ultimate contrast <1e-7. Key limitation for Roamn: WFS detector stability

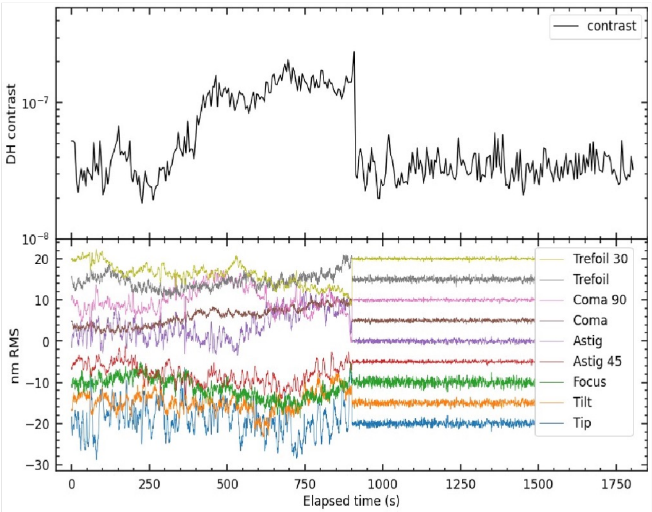
Factors of 10-100 already demonstrated at more moderate raw contrasts. Key sensing components exist.

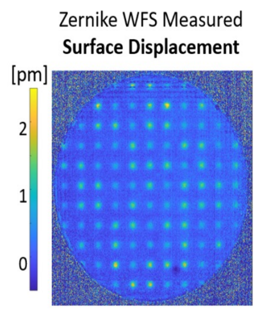
Coronagraph AO: state of the art

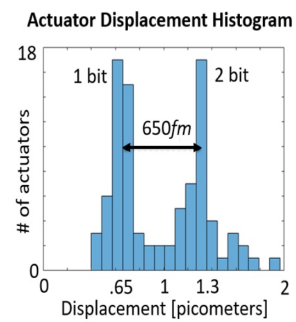












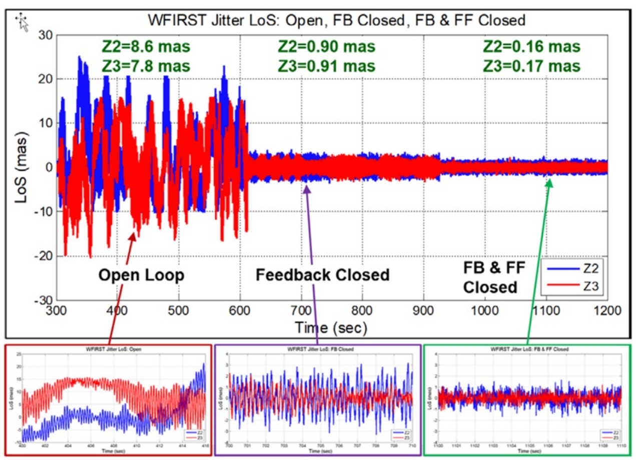
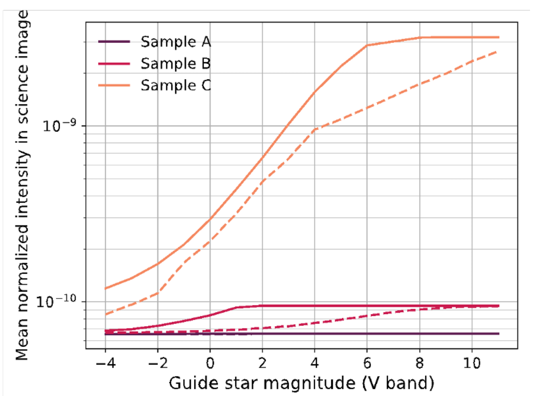
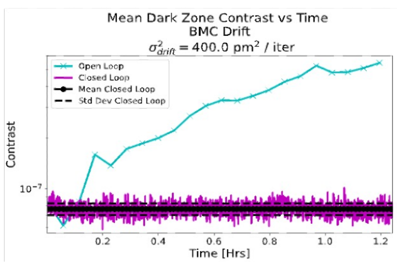
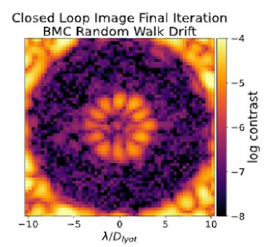


Figure 5. LoS performance with multiple RWA disturbances injected by the JM. The figure shows the time traces of LOWFS sensed LoS tip-tilt errors labeled as Z2 (blue) and Z3 (red). The LOWFS sensor measurements (nm RMS) have been converted to the on-sky LoS angle in unit of milli-arcsecond (mas). The main panel on top shows the time traces of th measured LoS with FSM loops open (left segment), closed loop with feedback (FB) control only (middle segment), and closed loop with both feedback (FB) and feed forward (FF) controls (right segment). The RMS LoS error of Z2 and Z3 of each segments are listed on top of corresponding segments. At the bottom, three panels show the zoom-in view of the traces under different control conditions. Please noted the open loop plot (lower left panel) has a much larger Y-axis scale.

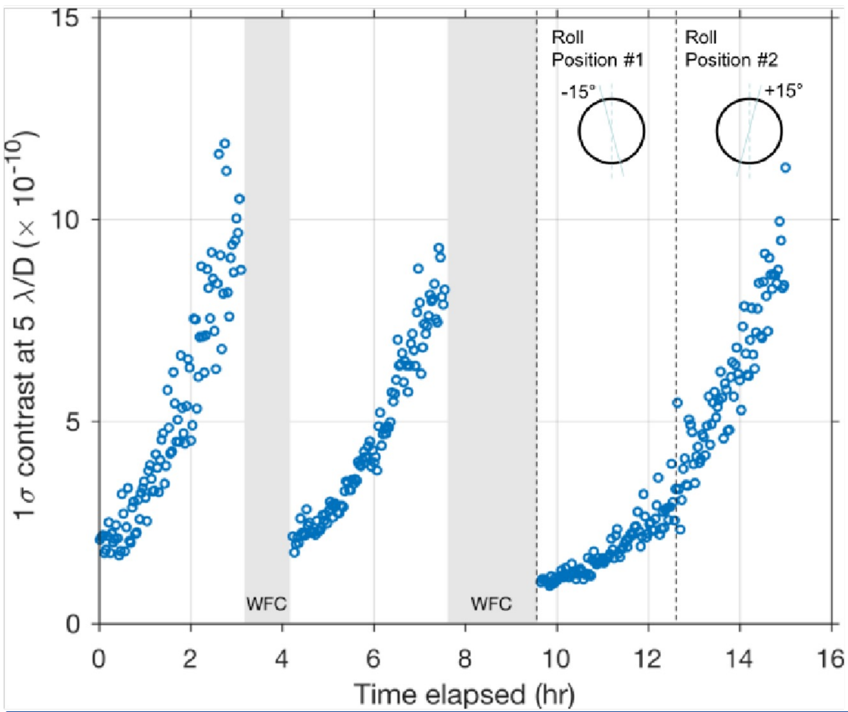






Coronagraph AO: need for a stable test facility

- **State of the art:**Stability of existing vacuum testbeds ~1e-10 per hour drift (Seo et al. 2019). Hypothesized root cause, DM drift.



Performance Gap: Contrast stabilization commensurate w/ requirement of 2 pm at the FPM in the presence of the disturbances commensurate with HWO thermal and dynamical environment (note that both control gain and capture range are important).

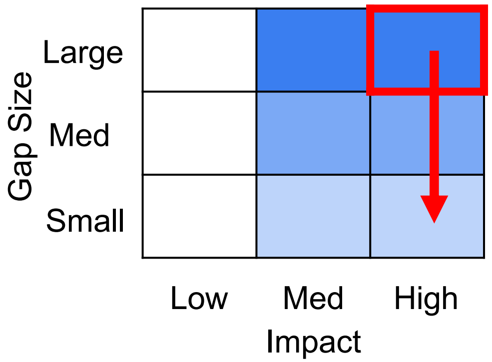
Simulations Gap: **Predicted/simulated wavefront noise rejection levels need to be validated with experimental data.**

Required Facilities: Representative-Pupil AO Test Facility (AOTF)

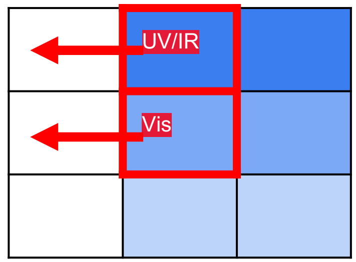
- Functional requirements:
  - Utilize a segmented OTA simulator of an adequate dimensional scale (e.g., scaled telescope stimulus optics with angles of incidence representative of a full-scale optical system)
  - **Utilize light sources and detectors that yields WFS noise commensurate with HWO projections**
  - **The AOTF does not necessarily require a starlight-suppression subsystem**
  - **If AOTF performance does not meet flight stability requirements (environment drift too large), extrapolation, with uncertainty quantification, to contrast stability science requirements using high fidelity modeling.**
  - Validate coronagraph AO performance
    - Demonstrate dynamic contrast stability in the presence of time varying disturbances representative of the observatory thermal and dynamical environment.

Closing gaps with AOTF

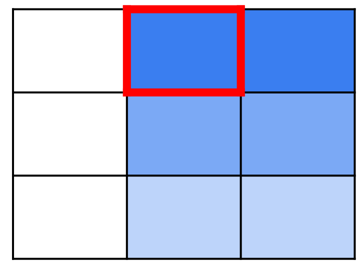
AOTF is will closes
WFE-Stability gap



Stable wavefront
enables degraded
Static performance

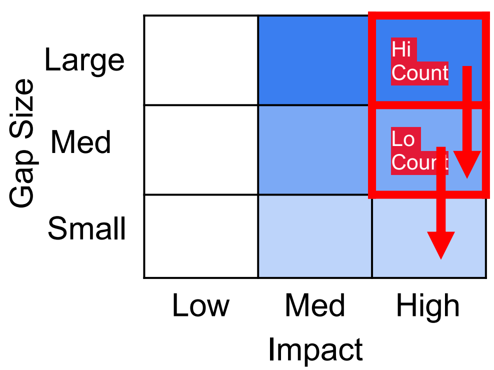


Mission efficiency

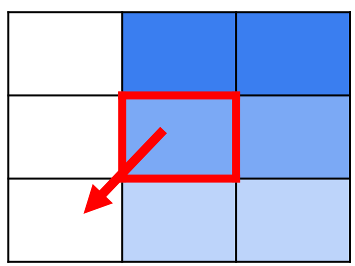


Detectors

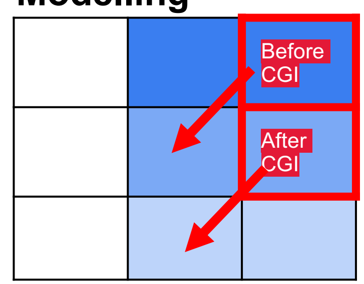
AOTF is **DMs** end to
end test facility



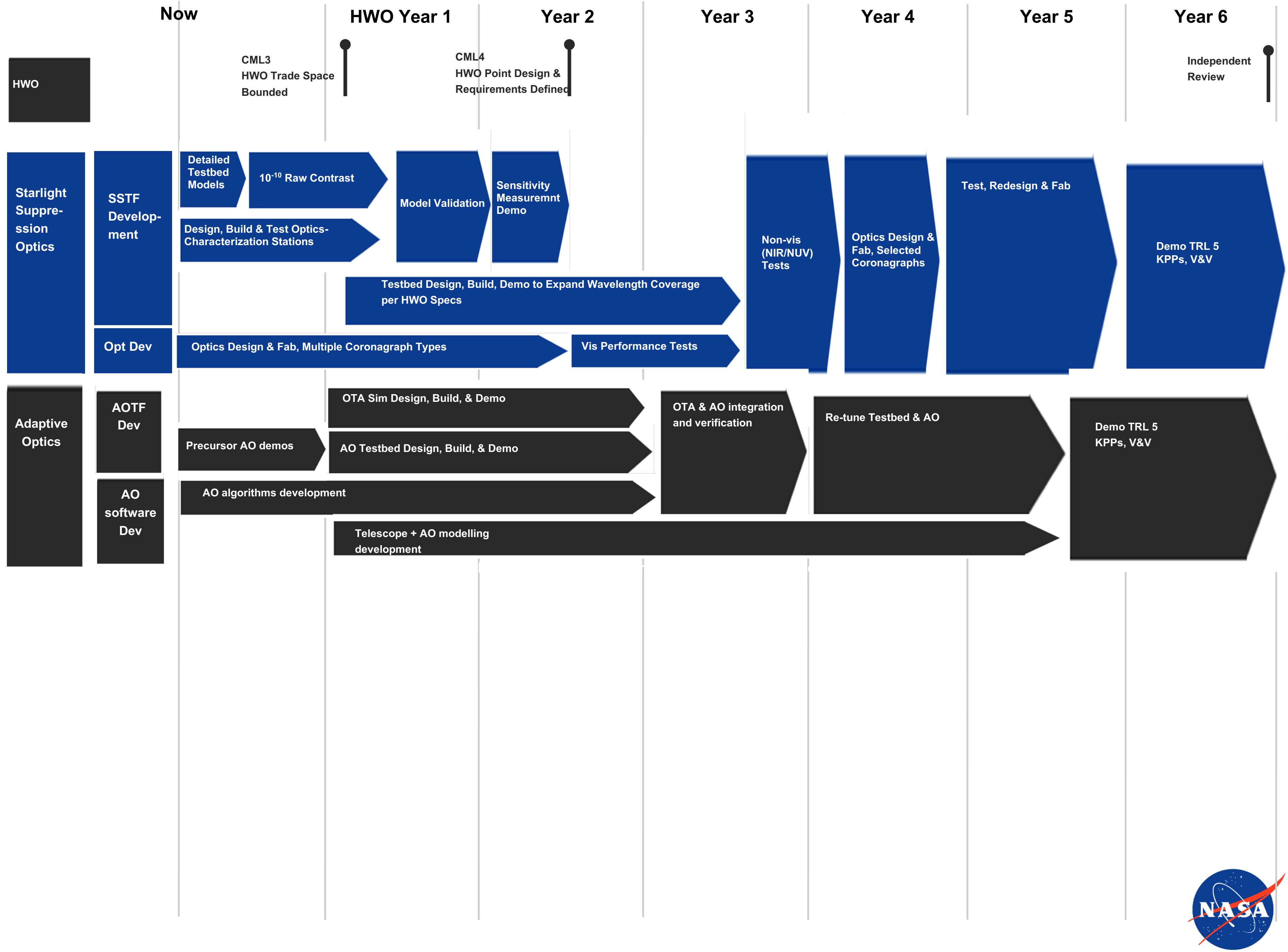
AOTF demonstrates
WFS&C + PP
Algorithms



AOTF measures
noise rejection
predicted by
Modelling



AOTF helps close other gaps than WFE- Stability gap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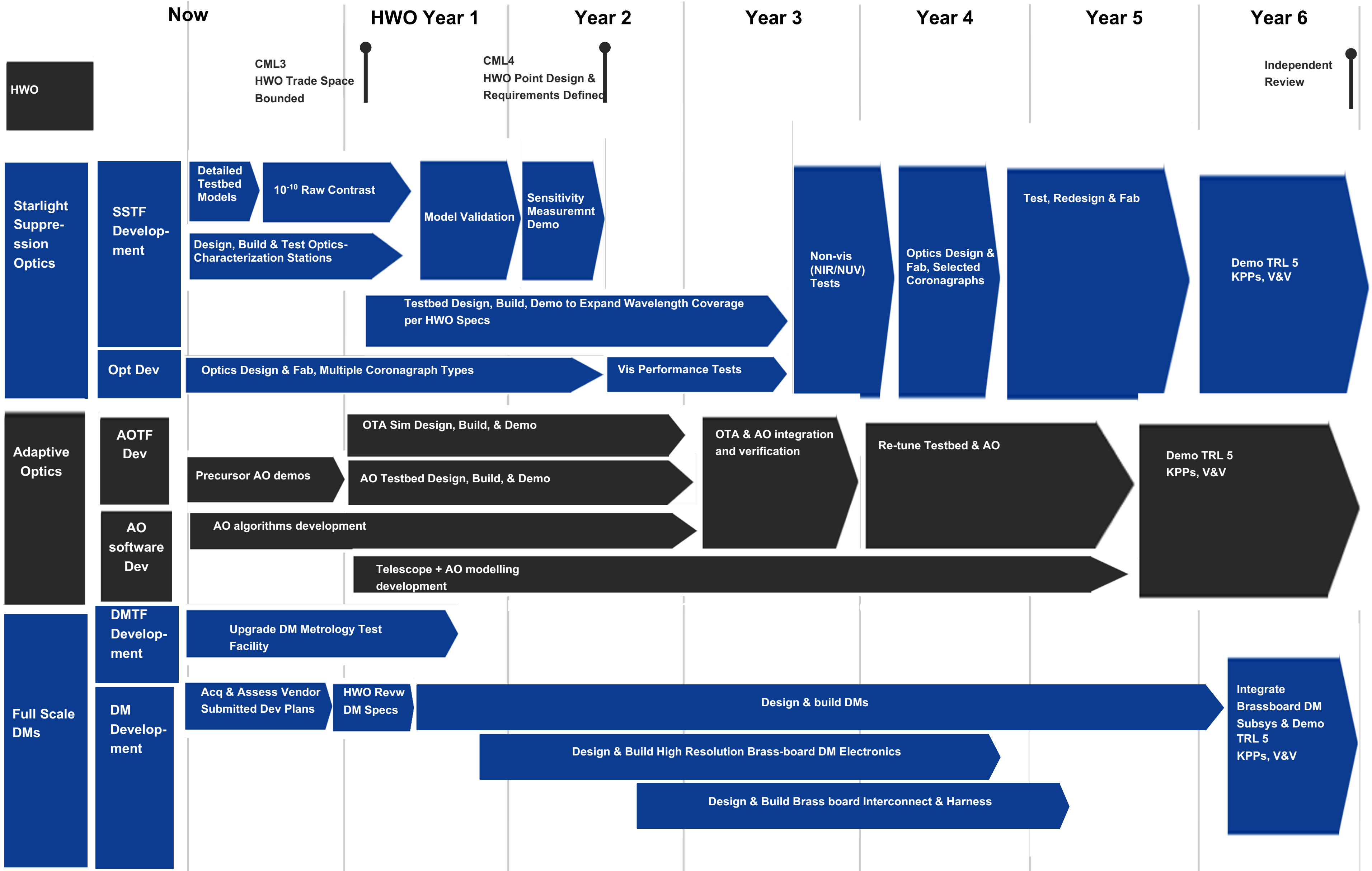
Demo TRL 5 KPPs, V&V
Telescope + AO modelling development
NASA

Deformable Mirrors

See DM TR colloquium

Deformable Mirrors: General Conclusions

- **See the <u>Deformable Mirror Technology Roadmap</u> (DMTR) for a comprehensive report**
- <u>Overall Status</u>:
  - No technology meets all requirements
  - Two technologies are clearly the most mature: PMN/electrostrictive and MEMS/electrostatic
  - <u>Array Size Limit</u>: Using current fabrication technologies for either approach, exceeding ~ 96 x 96 array size will be difficult
- **<u>Major Technology Gaps</u>**:
  - **Both technologies: production yield of DMs with all actuators meeting requirements**
  - **Current test facilities are not adequate to verify milestone demonstrations (e.g. pm stability at short timescales) of DMs, esp. as we develop them to full 96x96 format**
  - **Compact drive electronics with path to flight**



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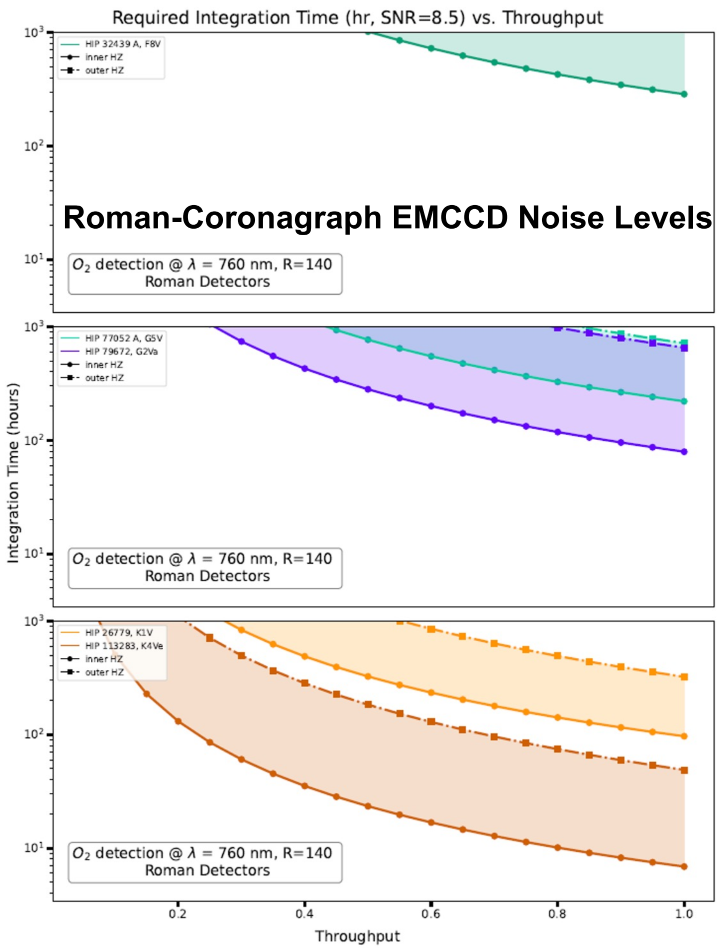
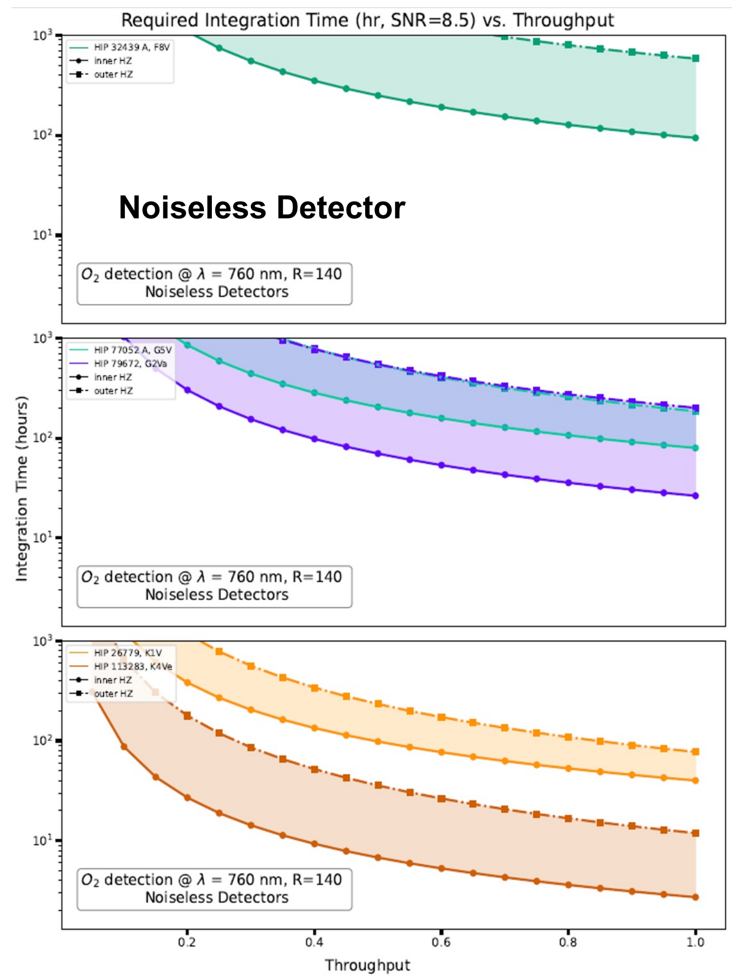
Design & Build Brass board Interconnect & Harness

Exoplanet spectroscopy, at all wavelengths

Spectroscopy, detectors and starlight suppression

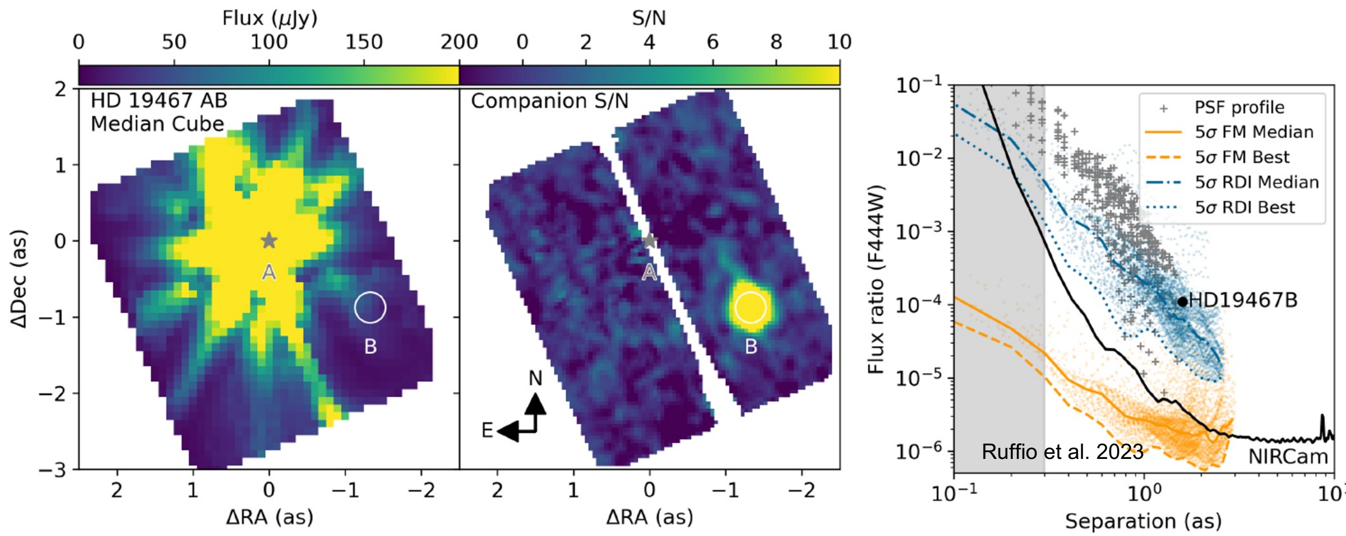




Coronagraph throughput drives spectroscopic exposure time, even with a noiseless detector

Spectroscopy: State of the Art

- R~20-70, IFS based, routinely used for self-luminous exoplanet detection using ground based instruments at ~1×10^{-5} contrasts.
- R~2000 will be routinely used for self-luminous exoplanet characterization with JWST at ~1×10^{-5} contrasts. (Ruffio et al., 2023).
- R~30000 routinely for self-luminous exoplanet characterization using ground based instruments at ~1×10^{-5} contrasts. (Xuan et al. 2022).

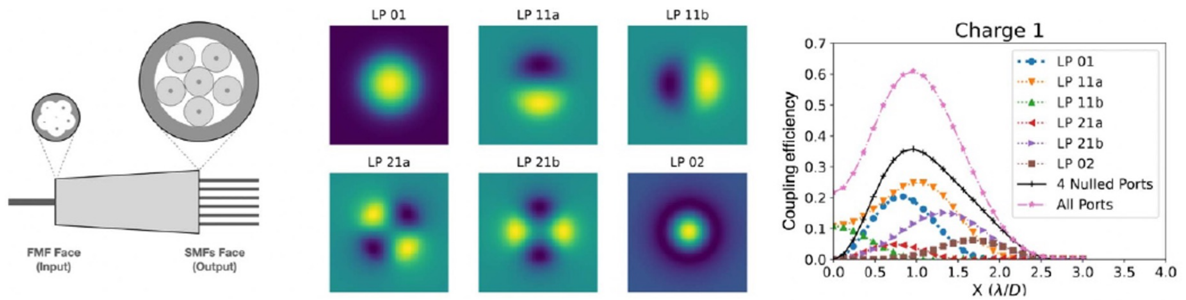


Community has a lot of experience with direct spectroscopy of self-luminous exoplanets up to ~1e-6 contrast

Starlight suppression techniques for Spectroscopy

- State of the Art: Lab Demos & Emergent Tecnologies
  - **Currently, there is a paucity of coronagraph designs or laboratory demonstrations that provide adequate IWA to reach habitable zones above 1 μm**
  - **Photonic Lantern Nuller (PLN)** works at small IWA: mode-selective photonic lantern separates incident light into individual fiber-propagation modes. Modal cross-talk currently limit achievable contrast to $10^{-2.}$
  - **Vortex Fiber Nulling (VFN):** Broadband lab-demo [Echeverri et al. 2023, Proc. SPIE]. Null depth: Contrast (null depth/planet coupling efficiency): 1×10^{-3},Throughhput: 7.7%, Bandwidth: 15% @ 0.65 μm, IWA: 0.8 λ/D OWA: 1.9 λ/D

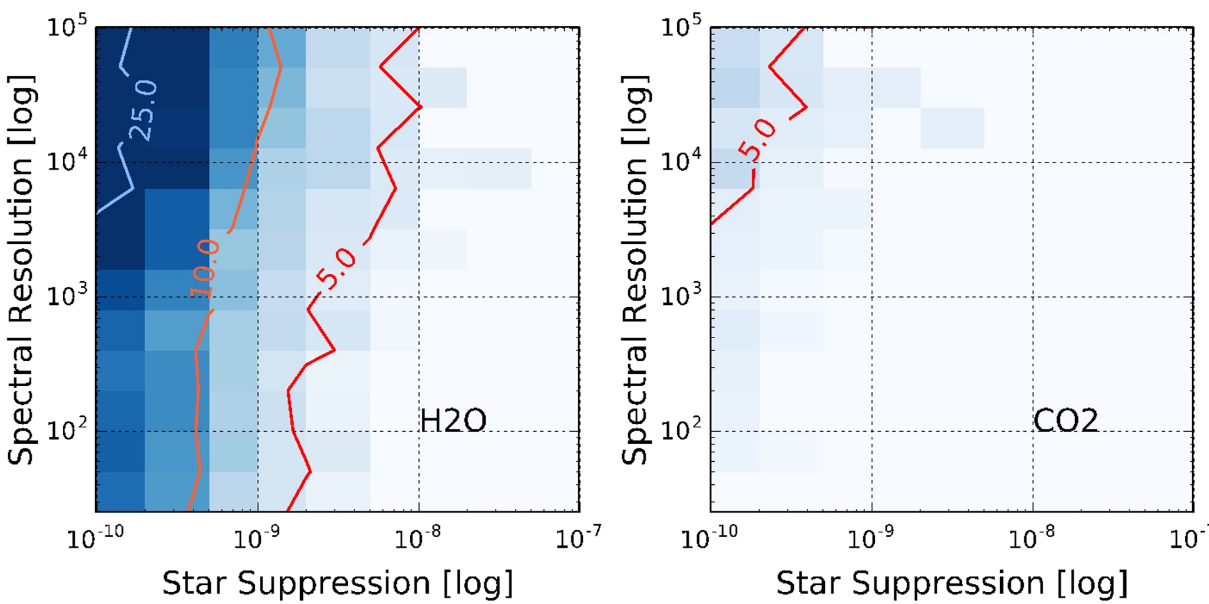
Fig. 39 from Jovanovic et al. (2023) showing how a PLN maps LP modes of input light into single-mode fibers, resulting in selective ports that suppress on-axis light



Emerging technologies may offer a path to Near IR spectroscopy.

Spectroscopy: Gaps

- **<u>Major Knowledge gaps:</u>**
  - How does contrast gain scale with spectral resolution in the reflected light regime?
  - How does chromaticity of speckle (at ~3×10^{-10} level) impact the measurement of the planet's continuum.
- **<u>Major experimental gap:</u>**
  - Lack of vacuum tests coupling coronagraphs and spectrograph at ~3×10^{-10} levels



Knowledge gap can be closed with simulations.

Experimental gap needs as facility.

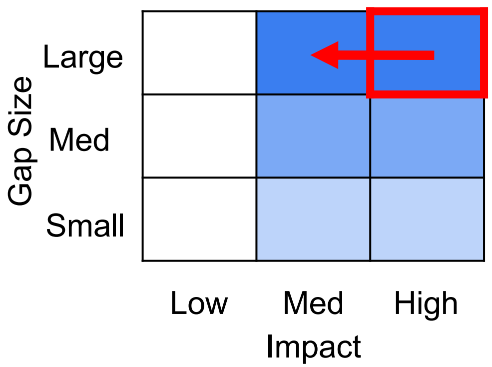
Required Facilities: Spectrometer & Post-processing Test Facility (SPTF)

- Functional requirements
  - **Demonstrate integrated throughput of spectrograph architectures**
  - **Demonstrate spectroscopic detector technologies “in-situ”**
  - **Demonstrate post-processing techniques that might relax stability requirements during long spectroscopic exposures.**

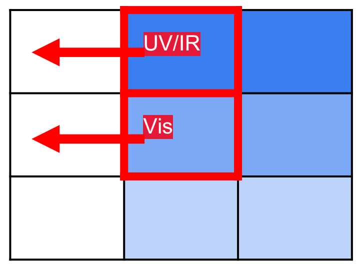
- Key performance requirements
  - Throughput driven by science requirements (EBS, yield calculations).
  - Requirements on post-processing gains TBD.

Closing gaps with SPTF

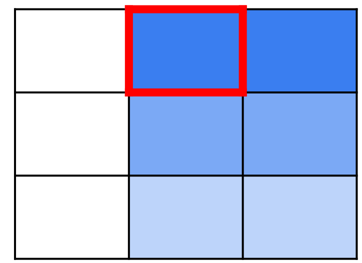
Post processing with SPTF will reduce impact of **WFE-Stability**



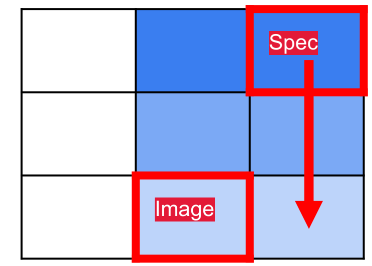
SPTF demonstrate operations with degraded **Static performance**



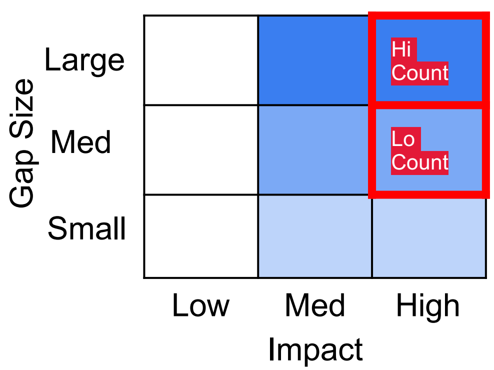
Mission efficiency



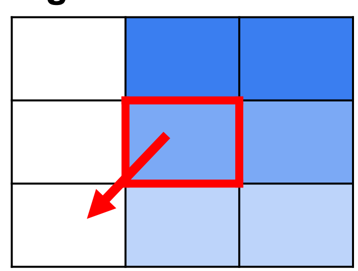
SPTF demonstrates **Detectors** in relevant environment



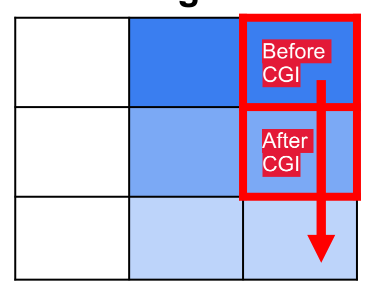
DMs



SPTF will demonstrate PP **Algorithms**

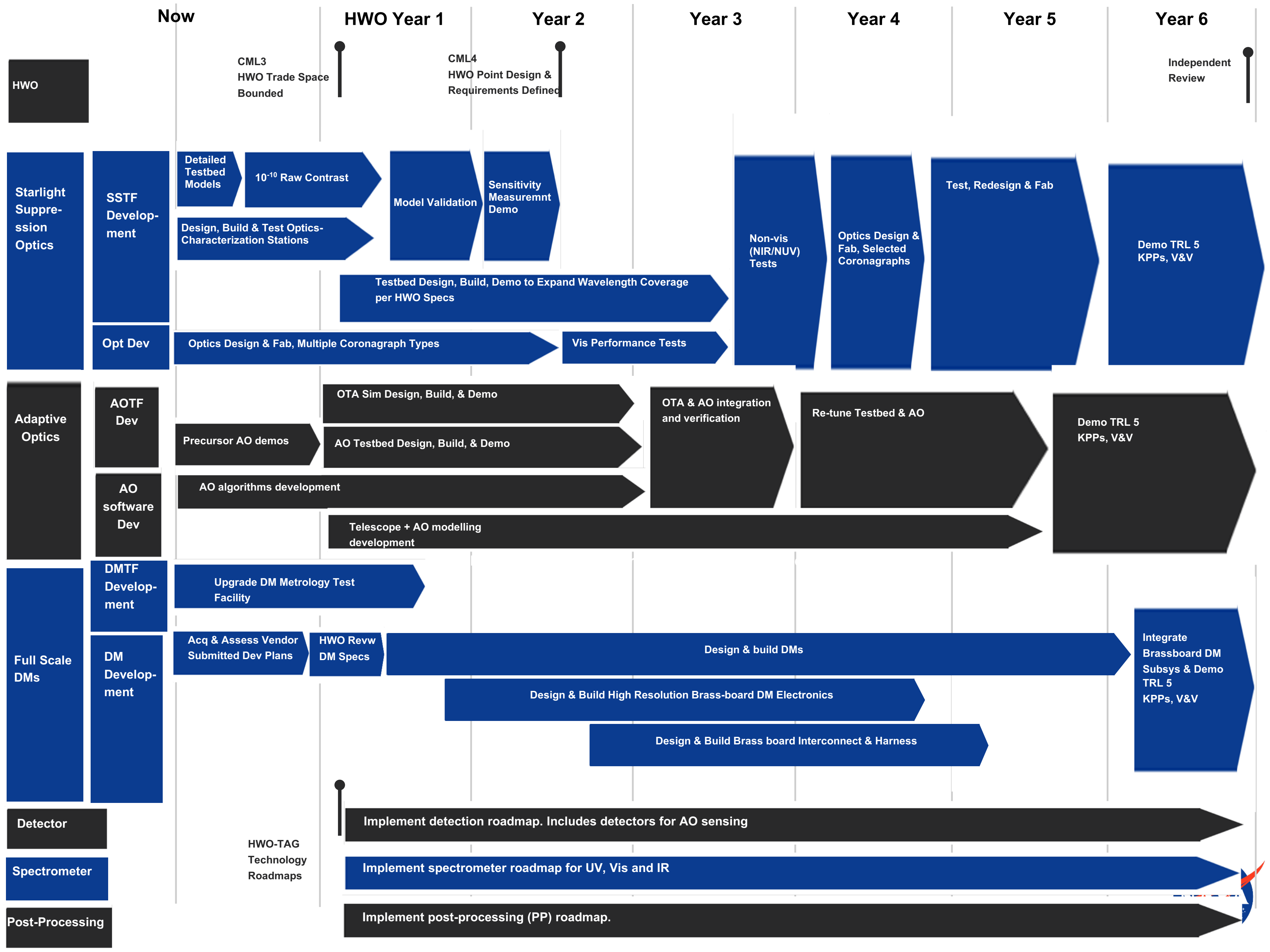


SPTF anchors spectrograph **Modelling**



SPTF helps close other gaps than detectors

Final roadmap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Design & Build High Resolution Brass-board DM Electronics
Design & Build Brass board Interconnect & Harness
Integrate Brassboard DM Subsys & Demo TRL 5 KPPs, V&V
Detector
Implement detection roadmap. Includes detectors for AO sensing
HWO-TAG Technology Roadmaps
Spectrometer
Implement spectrometer roadmap for UV, Vis and IR
Post-Processing
Implement post-processing (PP) roadmap.

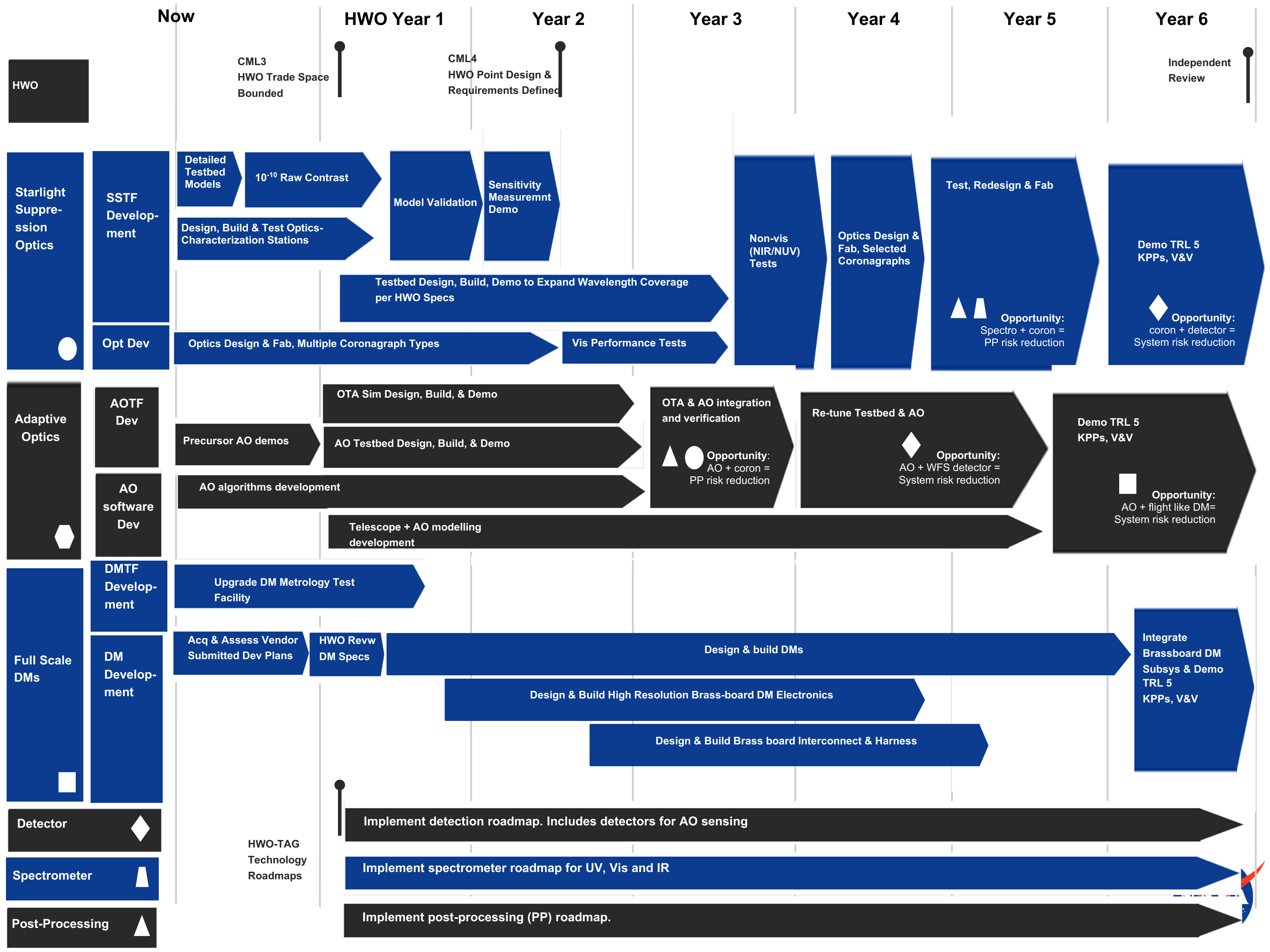
Maturation Plan: Opportunities

- **This maturation plan assumes a cross cutting modelling effort that gather experimental results from all technology element and yields the final products for TRL 5 demonstration.**

- The next slide shows opportunities in risk reduction by integrating different critical technology elements before TRL 5.

- Each critical technology element is represented by a different symbol.

- Appearance of a symbol in the track of another critical technology element represents an integration opportunity.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Demo TRL 5 KPPs, V&V
Opportunity: coron + detector = System risk reduction
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Telescope + AO modelling development
OTA & AO integration and verification
Opportunity: AO + coron = PP risk reduction
Re-tune Testbed & AO
Opportunity: AO + WFS detector = System risk reduction
Demo TRL 5 KPPs, V&V
Opportunity: AO + flight like DM= System risk reduction
Full Scale DMs
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DM Develop-ment
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Design & build DMs
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Detector
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HWO-TAG Technology Roadmaps
Implement detection roadmap. Includes detectors for AO sensing
Implement spectrometer roadmap for UV, Vis and IR
Implement post-processing (PP) roadmap.

Summary of major investment (hardware)

- **DM development needs to start as early as possible**

- **Multiple vacuum testbeds are necessary. At least one per bandpass (UV/VIS/IR) and one dedicated to wavefront stability (AO).**

- **Feasibility of UV testbed needs to be studied in detail before implementation.**

- **System level risk will be carried by model. Significant testbed resources need to be invested for model validation.**

- **Multiple opportunities for system-level risk reduction exist after year 2 by integration critical technology elements on same testbed.**

Back up