

Coronagraph Design Survey for Future Exoplanet Direct Imaging Space Missions

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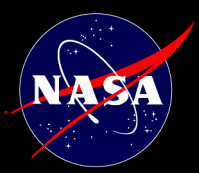
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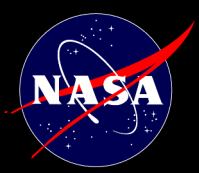
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Starlight Suppression Workshop, Caltech: 8/9/2023



Outline

- Motivation (the why?)
- Survey goals and deliverables (the what?)
- Process (the how?)
- Conclusions

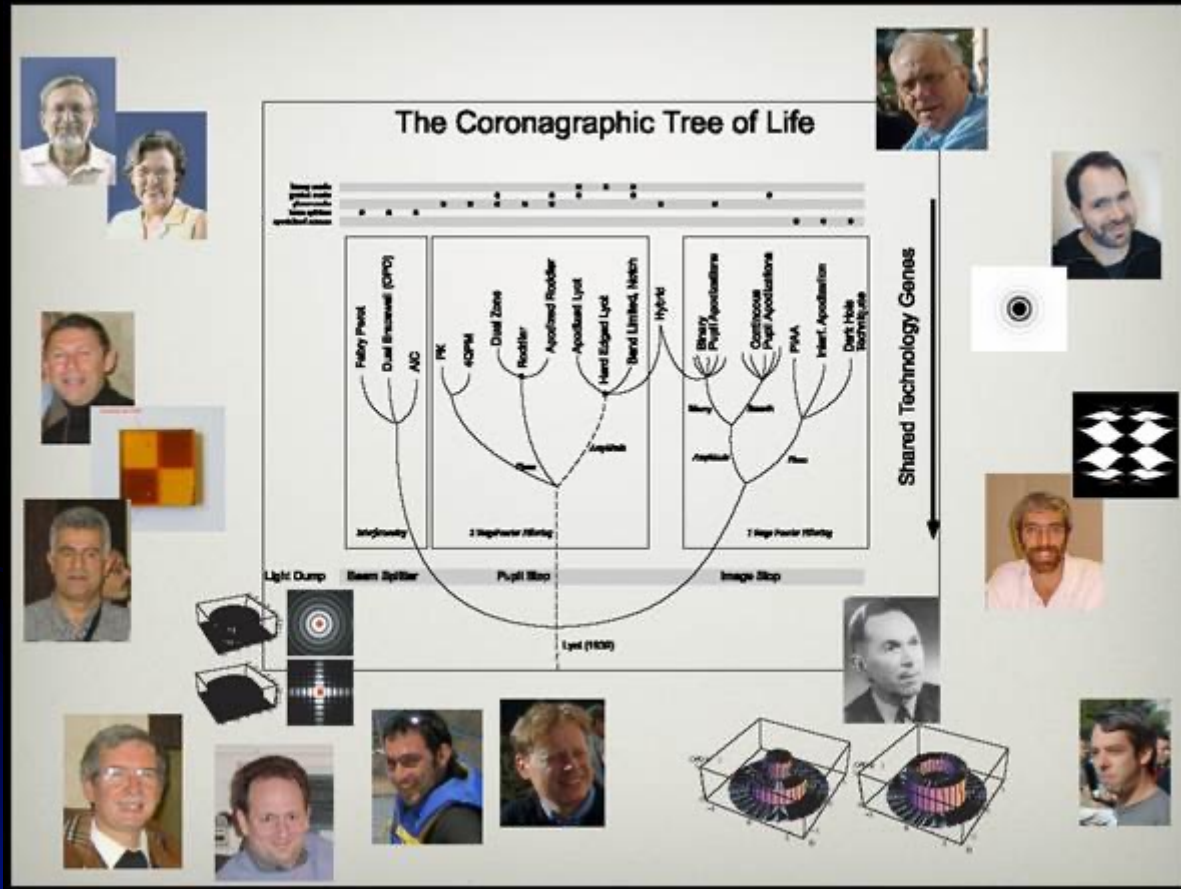


Outline

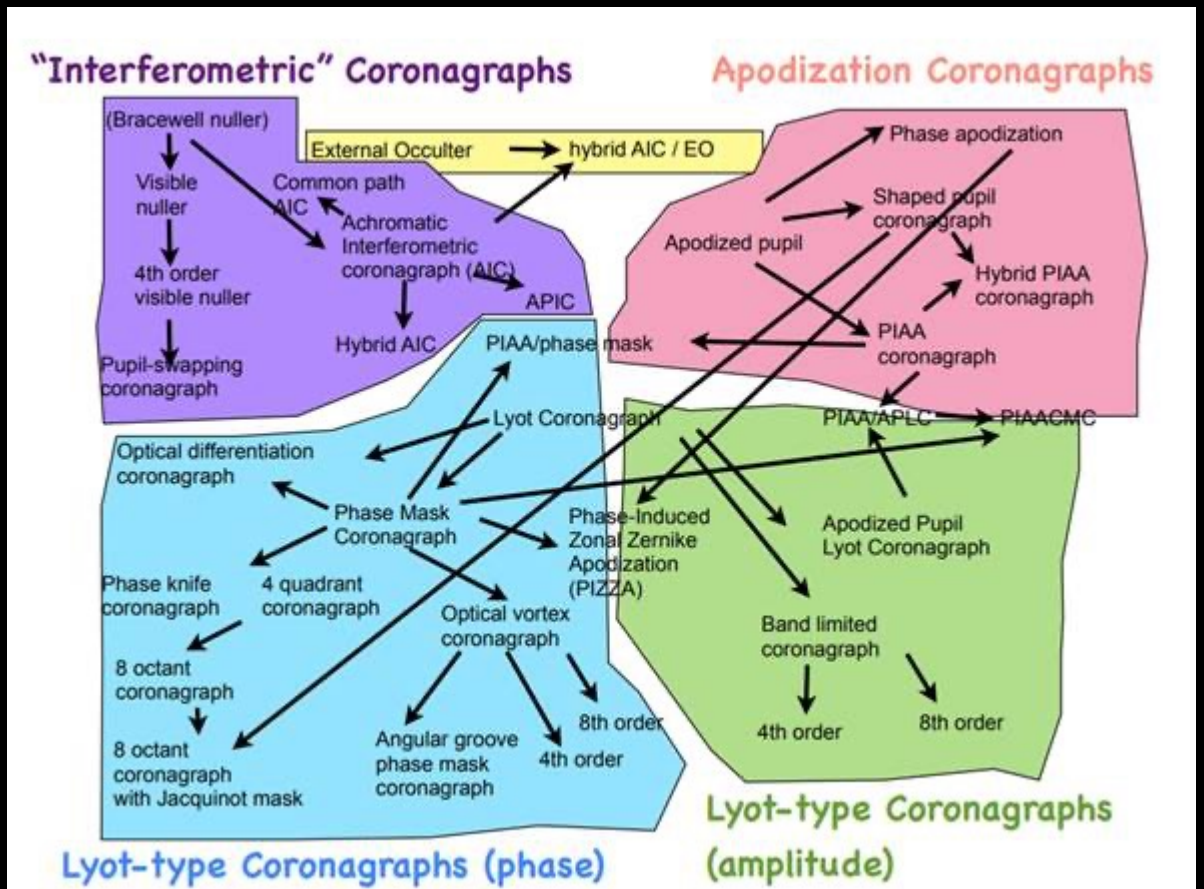
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There is a rich trade space of coronagraph designs to explore

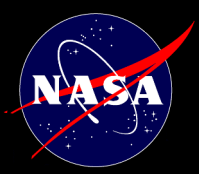


Courtesy of James Lloyd, 2003

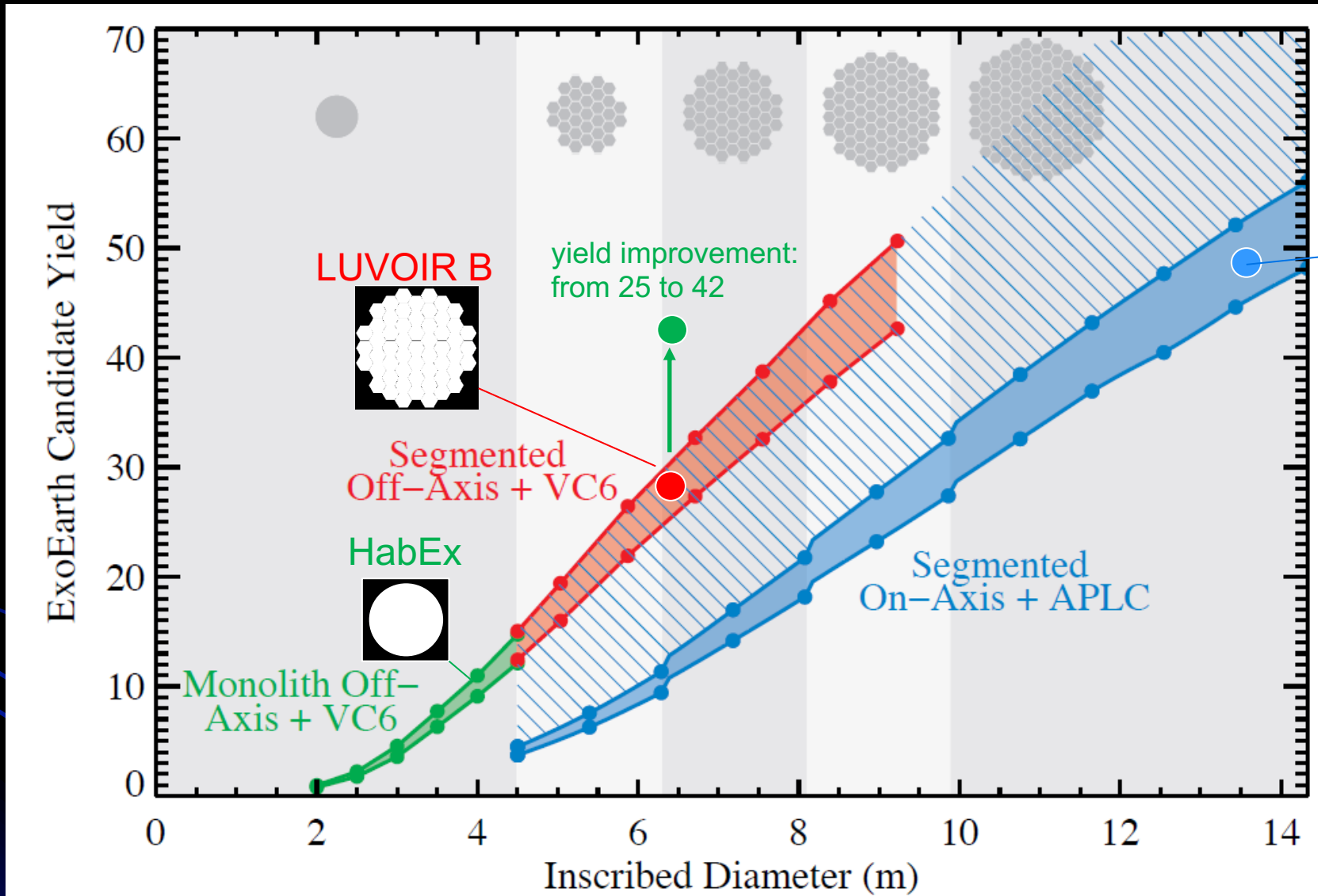


Olivier Guyon, 2009

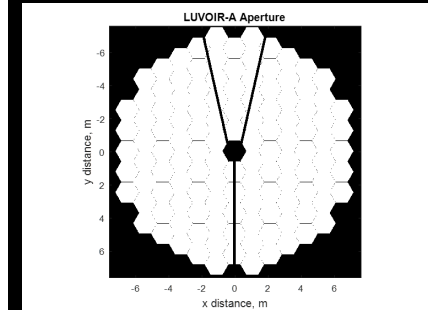
Why do we still need to explore different designs? Didn't LUV0IR / HabEx do this already, and shouldn't we focus on getting to 1e-10?



Reason 1: Designs have improved since LUVOIR / HabEx reports...



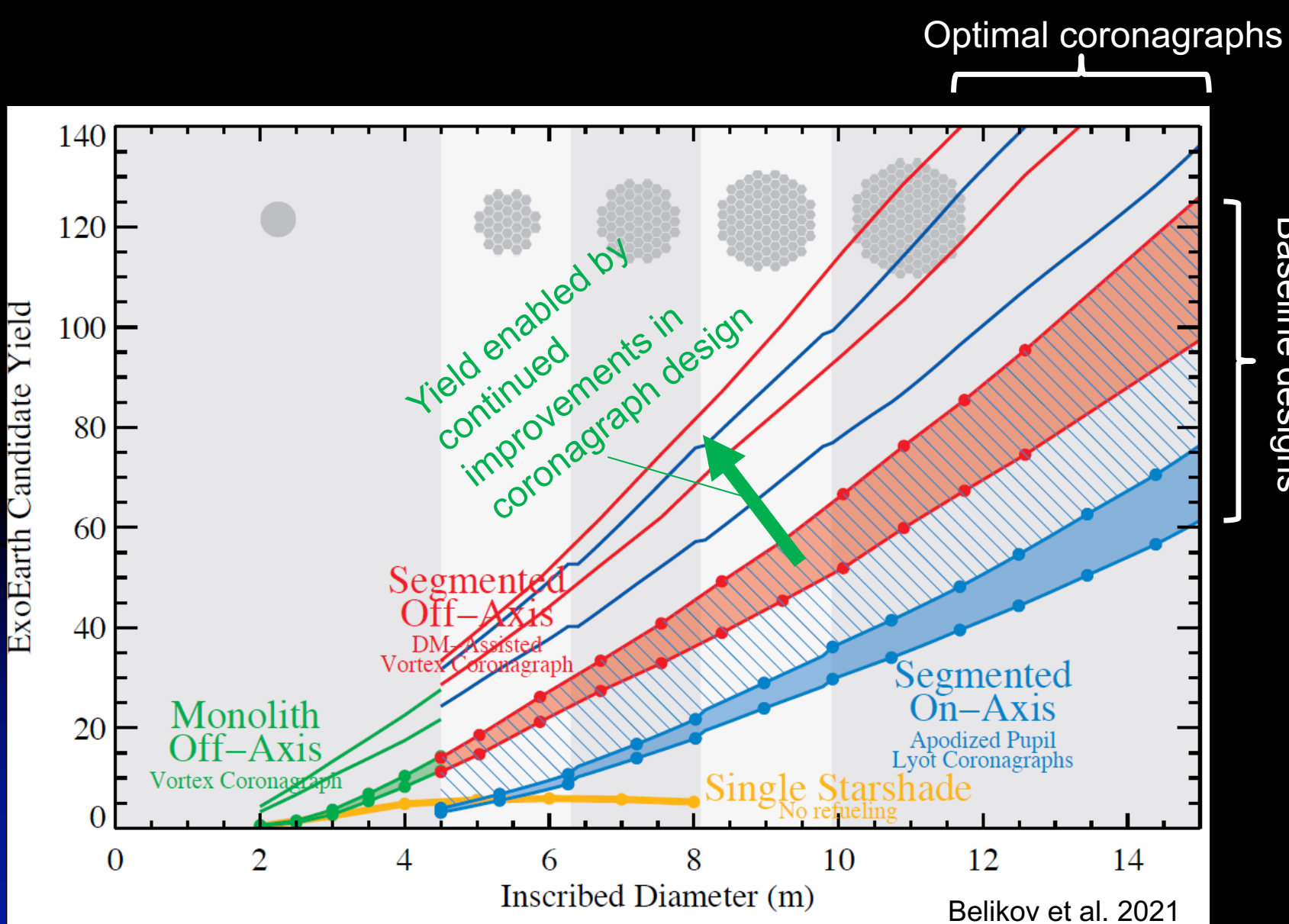
LUVOIR A



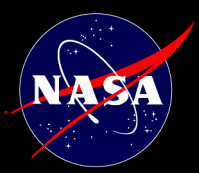
Underlying image: Stark C., et al., 2019



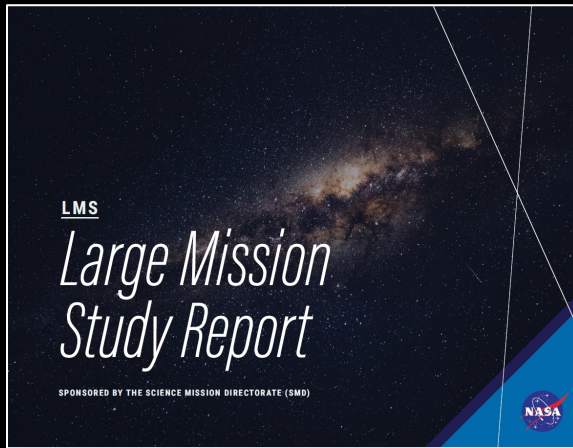
Reason 1: ... and still have a lot of room to improve before they hit fundamental physics limits



- Optimal coronagraphs achieve 2-4 greater yield than currently baselined coronagraphs (for a fixed bandwidth and system QE)
- Gap between obstructed and unobstructed apertures can be closed!
 - Enabling larger aperture for the same cost, and/or risk reduction / cost savings
- Caveats: optimal coronagraph yields
 - Show where theoretical limits are, but not how to get there practically
 - May or may not require exotic architectures
 - Are partially based on IWA improvements, which may have other limitations
 - Useful as a target, guide, and inspiration for coronagraph design



Reason 2: LMS and Decadal Survey recommend thorough, early, well-funded trades



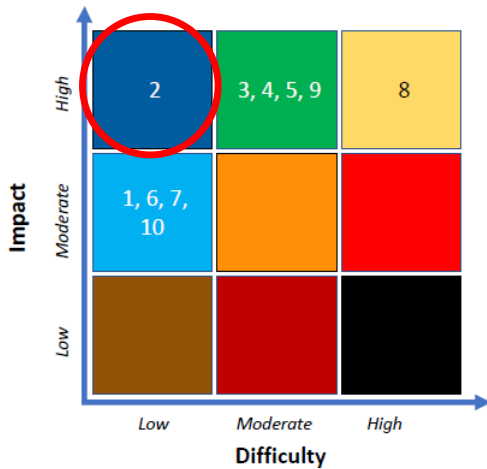
(2020)

- Finding: “During the Pre-Phase-A period, requirements development and **architecture trades are often over-constrained**, driving the mission unnecessarily toward very expensive solutions[...].”
- Recommendation: “[...]Conduct requirements analyses and architecture trades during pre-phase-A that quantify science vs. cost, thereby preventing unnecessary adoption of very expensive solutions[...].”
 - SMD’s large mission study report (<https://science.nasa.gov/about-us/large-mission-study>)

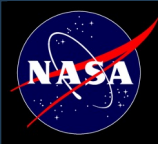
- “**Inadequate funding for concept studies, concept, and technology development**”
 - One of several common issues identified by the “Flagship Assessment Team” in 2013: National Aeronautics and Space Administration, “Cost and Schedule Growth in NASA Missions: Findings and Recommendations from the Explanation of Change Study and Flagship Mission Assessment,” Office of the Center Director, NASA Goddard Space Flight Center, 2013.

- “**annual funding [should be] provided in the early stages of development, to cover feasibility studies, technology developments and prototype development,**”
 - Bitten, R.E., Shinn, S. A., Emmons, D. L., “Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions,” IEEE (2019).

Classification of Recommendations from the Large Missions Study



No.	Recommendation Title
1	Pre-Phase A Team Composition
2	Pre-Phase A Architecture Trades and Desclope Options
3	System Maturity Assessment
4	Technology Integration into Complex Systems
5	Analytical Tools
6	Cost and Schedule Estimation
7	Standing Review Boards (SRBs)
8	Instrument Selection Process
9	SMD Capabilities
10	Center Capabilities



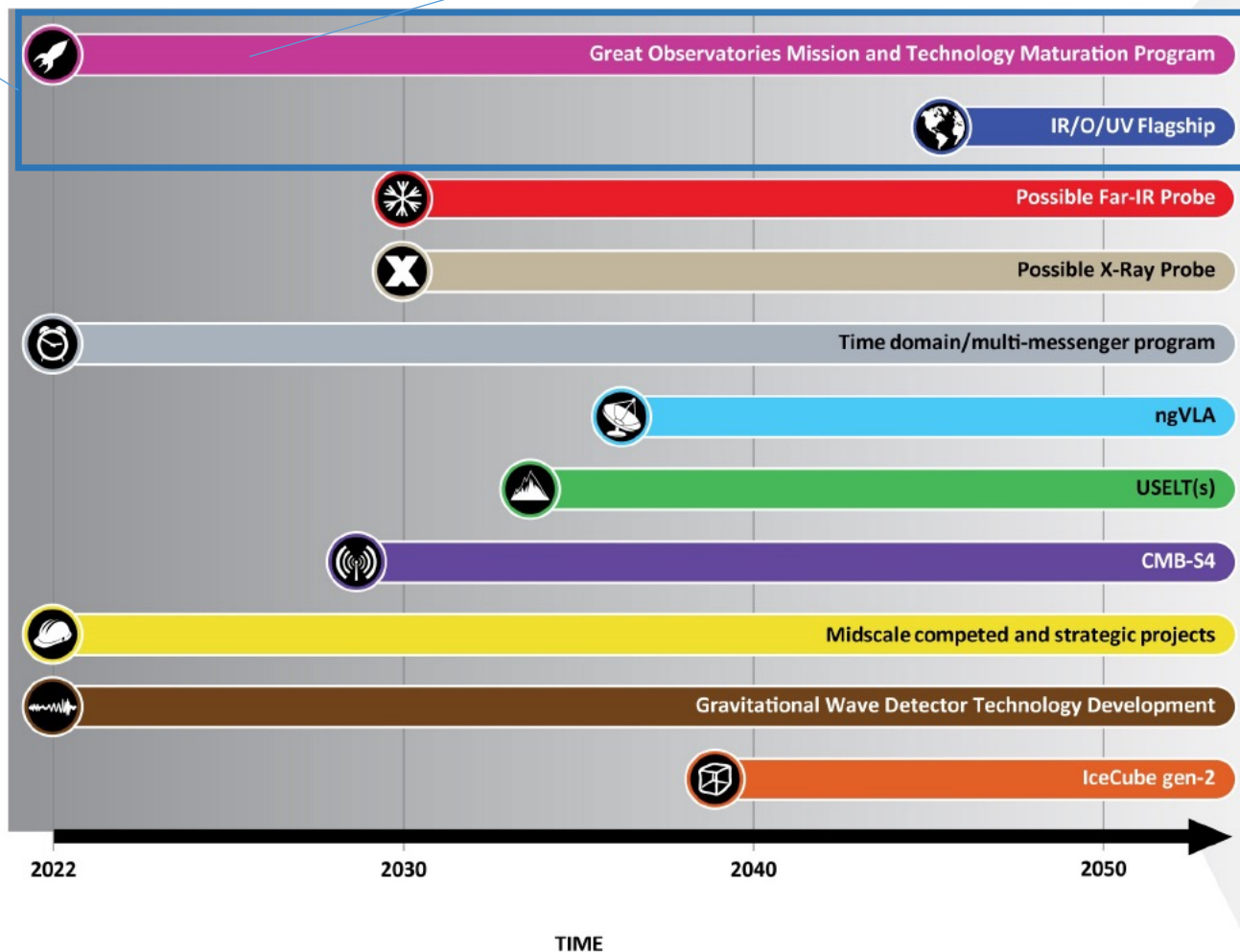
Reason 2b: Reducing risk and cost of HWO is an important goal of GOMAP

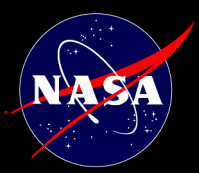
Two of the top recommendations of Astro2020 decadal survey:

The decadal survey recommends a large (~6m diameter) Infrared/Optical/Ultraviolet space telescope with high-contrast imaging and spectroscopy as the first mission to enter the Great Observatories Mission and Technology Maturation Program. This is an ambitious mission with the goal of searching for biosignatures from habitable zone exoplanets and providing a powerful new facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade with a target launch in the first half of the 2040's.

Given the large costs and development timescales for the next generation of space telescopes, the decadal survey recommends that NASA create the **Great Observatories Mission and Technology Maturation Program** as a new approach for planning and implementing large missions. The program would provide **early investment in technology development** for multiple mission concepts to **lower the risks and costs** of projects before they become too complex, large, and costly. The first entrant for the maturation program should be a large Infrared/Optical/Ultraviolet space telescope. The second entrants should be strategic Far-Infrared and X-ray missions.

Astro2020 cost appraisal for GOMaP: \$1.2B this decade (FY2020\$, see p. S-8, table S.5)

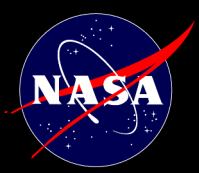




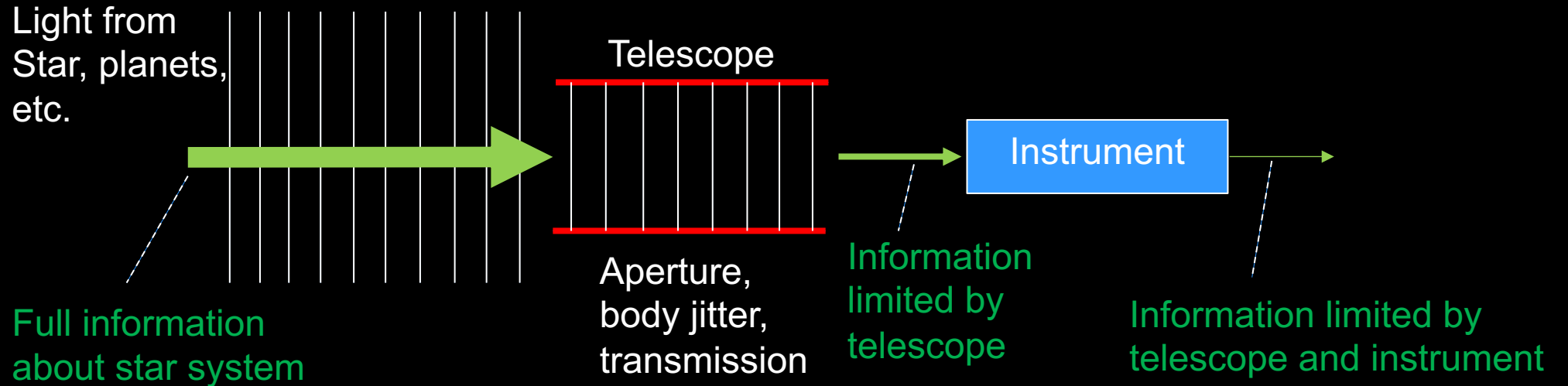
Reason 3: More powerful instruments are necessary to guard against “yield erosion”

Mission	Originally expected/desired yield	Actual or currently expected yield
Kepler	~25 Earth analogs (Borucki et al. 2003)	$o(1)$
Roman CGI	~25 reflected light planets (circa 2013-2015)	$o(1)$
HWO	~25 characterized potentially habitable planets	?

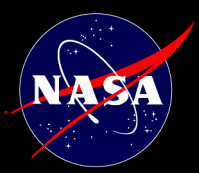
- There are more ways in which expected science yields can decrease than increase
- So, yield estimates tend to go down as a mission concept matures



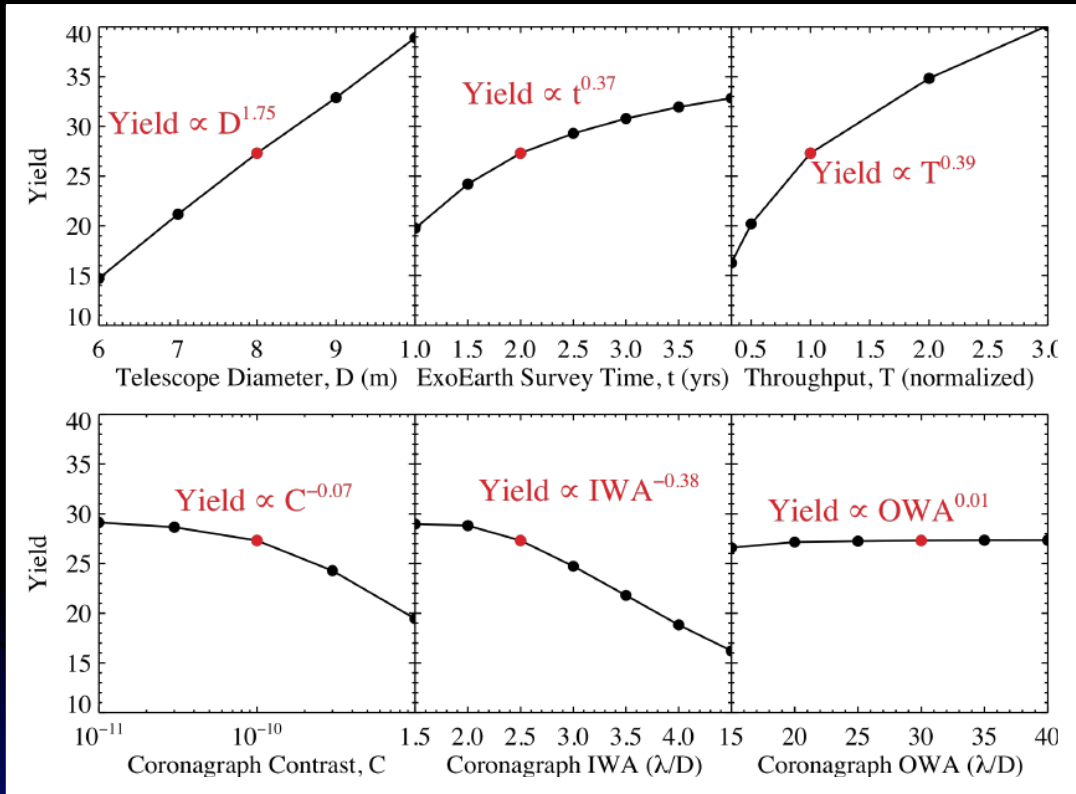
Reason 4: On a flagship, improving the instrument is possibly the strongest lever to improve the mission



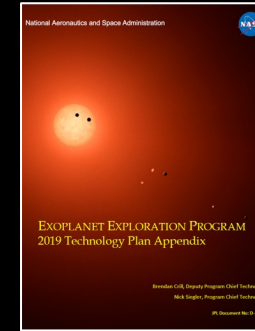
- Instruments are often performance bottlenecks
 - unless they are physics-limited
- Instrument technology research and development:
 - Small fraction of mission cost for a flagship
 - large impact on
 - mission performance
 - requirements relaxation
 - risk reduction
 - large, leveraged ROI ("better" is NOT the enemy of "good enough")
 - until physics limits are reached, or investment becomes a significant fraction of mission cost
- On a flagship, should always aim for physics-limited instrument performance
 - at least while development cost of an instrument is a small fraction of mission cost



Reason #5: 1e-10 contrast is important, but is one of many dimensions of trade space



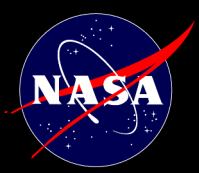
Stark et al. 2019



Technology gap list, ExEP

Technology Gap and Description	Current State-of-the-Art	Performance Goals and Objectives
<p>Coronagraph Contrast and Efficiency</p> <p>The capability to suppress starlight and receive planet light with a coronagraph to the level needed to detect and spectrally characterize Earth-like exoplanets in the habitable zones of Sun-like stars.</p>	<p>unobscured pupil: 4×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (Lyot coronagraph demo in HiCAT); obscured pupil: 1.6×10^{-8} raw contrast at 10% bandwidth across angles of 3-9 λ/D (Roman CGI Lab Demos); segmented/unobscured pupil: 2.5×10^{-8} raw contrast in monochromatic light across 6-10 λ/D (Lyot coronagraph demo in HiCAT)</p>	<p>Maximized science yield in imaging and spectroscopy for a direct imaging telescope/mission. $\leq 10^{-10}$ raw contrast, $>10\%$ throughput, inner working angle $\leq 3 \lambda/D$, outer working angle $\geq 45 \lambda/D$ [TBD], 20% bandwidth; obscured/segmented pupil</p> <p>For the two distinct cases of monolith and segmented primary mirrors, Sub-gaps that could partially or fully close this gap:</p> <ul style="list-style-type: none"> - Coronagraph Architecture - Deformable Mirrors - Computational Throughput on Space-rated processors - High bandwidth optical communication between space and ground - Coronagraph Efficiency - Autonomous on board WFSC architectures

- Coronagraph contrast is of course critical and challenging, but
 - diminishing returns once $o(1e-10)$ contrast is reached (because zodi / exozodi starts to dominate)
 - is NOT fundamentally limited by coronagraph architecture (for point sources): requires primarily time and effort in the lab
- Coronagraph “efficiency” (throughput, IWA, tolerance to stellar size, etc.) is also very critical
 - IS fundamentally coronagraph architecture-limited: decisions made without a thorough trade can be very costly
 - Requires continued innovation (TRL0-4)



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Survey Goals

1. **Survey and document viable coronagraph designs across the world that can inform the Habitable Worlds Observatory about their capabilities and technology readiness.**
2. **Facilitate future evaluation and comparison of the coronagraph designs to advance based on a set of technical and programmatic assessment criteria.**
3. **Identify novel coronagraph technologies that could mature rapidly for which NASA's technology development investments could be efficiently leveraged.**

Intended Application

- Provide to GOMAP, START, TAG, and ExEP management an assessment of coronagraph technologies that can be used to evaluate risk and performance for a Habitable Worlds Observatory.



Survey Contents

Background

- Role of coronagraph in the Habitable Worlds Observatory mission and how it affects mission yields and performance

Suggested Wants / Opportunities / Risks / Assumptions

- Establish what are Desirements, Opportunities, Risks, and assumptions the survey will assess for different coronagraph designs.

Survey

- Coronagraph designs and their current TRL
- Quantifying value-added of each technology: potential to increase yield, relax mission/telescope requirements, and reduce cost plus risk.
- Assessing feasibility and schedule of developing each design to TRL 5
- Fact finding, data gathering, analyses when needed, no down-selecting

Results (deliverable Final Report)

- Documented list of coronagraph designs used to compare and inform future down-select options
- List will include the opportunities enabled by promising but less mature options, along with their risks and challenges.
- Survey findings



Fact-finding and organizing using the Kepner-Tregoe matrix

Options, Descriptions, Assessment Criteria, Opportunities, and Risks to be captured through fact-finding

Assessment Criteria *

* informed by the APD Technology Gap List and coronagraph architecture SMEs

Decision Statement					
Description		Option 1	Option 2	Option 3	
Feature 1					
Feature 2					
Feature 3					
Musts					
M1		✓	✓	✓	
M2		✓	?	?	
M3		✓	✓	X	
Wants					
W1	W1%	Rel score	Rel score	Rel score	
W2	W2%	Rel score	Rel score	Rel score	
W3	W3%	Rel score	Rel score	Rel score	
	100% Wt sum =>	Score 1	Score 2	Score 3	
Risks		C	L	C	L
Risk 1		M	L	M	L
Risk 2		H	H	M	M
Final Decision, Accounting for Risks					
C = Consequence, L = Likelihood					

Survey Matrix

	Primarily focal-plane coronagraphs					Primarily pupil-plane coronagraphs				Hybrid (pupil+focal) plane coronagraphs				photonic chip / theoretical limits				Enhancing technologies					
	HLC	LCPPC	EWaCo	MSPM	VVC	SPC	PIAA		APLC	SPLC	PAPLC	PIAA-Vortex		Hybrid photonic ch	Full Photonic Chip	Optimal Cor limit		DPLC	RAP	ILOWFC	fiber-nulling	AAFS	
Science																							
Yield of EECs budgeting for VIS detections only																							
Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection																							
Yield of EECs budgeting for VIS detections, orbit, and CO2/CH4 detection at 1.65 microns																							
Yield of diverse planet types																							
Yield of EECs at glint phase angles																							
Yield of EECs characterizable at near-UV																							
Number of detectable molecules																							
Design performance (contrast and efficiency)																							
Median exposure time per target during blind search																							
Exposure time for fiducial star (Earth twin @ quadrature)																							
Exposure time for characterization																							
Contrast over xx to yy wavelength range																							
Contrast as a function of working angle, stellar size, bandwidth																							
Core throughput as a function of working angle, stellar size, bandwidth																							
core throughput @ X/D																							
PSF sharpness																							
IWA																							
FOV																							
OWA > XX																							
Single-coronagraph spectral bandwidth																							
Theoretical max performance																							
Design performance (sensitivities)																							
Sensitivity to LO aberrations																							
Sensitivity to static aberrations																							
Sensitivity to dynamic aberrations																							
Sensitivity to segment misalignments																							
Alignment of instrument to telescope pupil																							
Tolerance to instrument component errors (including alignment)																							
Tolerate DM defects (dead actuators)?																							
Sensitivity to DM parameters																							
Tolerate unknown pupil distortion/magnification errors?																							
Tolerate primary and secondary mirror reflectivity variations/errors																							
Tolerate lateral mask alignment errors inside instrument																							
Tolerate rotational mask alignment errors																							
Sensitivity to amplitude aberrations																							
Compatibility with telescope and other components																							
Compatibility with segmented apertures																							
Compatibility with on-axis apertures																							
is the design not easily compatible with critical instrument capabilities																							
Ability to integrate LOWFS?																							
Compatibility with WFS&C																							
Compatibility with spectrograph																							
Compatibility with post-processing																							
Requires polarization splitting/filtering?																							
Requires specialized optical train (e.g., pupil remapping)																							
Potential for hybridizing and/or complementing with another technology																							
Compatible with polarimetry																							
Lab demonstration / model validation																							
Demonstrated raw contrast in testbed																							
Tolerance to instabilities demonstrated on testbed																							
Model accuracy demonstrated on testbed																							
Fidelity of model used to predict performance, including error budget and post-processing																							
Development and programmatic considerations																							
Path to TRL 5																							
Development cost																							
Development time																							
Manufacturability																							
flight instrument much larger or much smaller than average?																							
Number of components and/or mechanisms in optical train much different from average?																							
Supply-chain robustness																							
Single-source fabrication?																							
Does it fill a critical gap?																							
Architecture applicable to other missions? (E.g. after HWO)																							

Science yield metrics

Coronagraph performance and robustness

Maturity, telescope compatibility, programmatic considerations

Survey Matrix

Science

Yield of EECs budgeting for VIS detections only
 Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection
 Yield of EECs budgeting for VIS detections, orbit, and CO2/CH4 detection at 1.65 microns
 Yield of diverse planet types
 Yield of EECs at glint phase angles
 Yield of EECs at various stellar sizes
 Number of detections per hour

Science yield metrics

Design performance (contrast and efficiency)

Median exposure time per target during blind search
 Exposure time for fiducial star (Earth twin @ quadrature)
 Exposure time for characterization

Contrast over xx to yy wavelength range

Contrast as a function of working angle, stellar size, bandwidth
 Core throughput as a function of working angle, stellar size, bandwidth
 Core throughput @ X/D
 PSF sharpness
 IWA
 FOV
 OWA > XX
 Single-coronagraph spectral bandwidth
 Theoretical max performance

Coronagraph performance and robustness

Design performance (sensitivities)

Sensitivity to LO aberrations
 Sensitivity to secondary mirror errors
 Sensitivity to dynamic aberrations
 Sensitivity to segment misalignments
 Alignment of instrument (e.g. tip-tilt)
 Tolerance to instrument component errors (including alignment)
 Tolerate DM defects (dead actuators)?
 Sensitivity to DM parameters
 Tolerate unknown pupil distortion/magnification errors?
 Tolerate primary and secondary mirror reflectivity variations/errors
 Tolerate lateral mask alignment errors inside instrument
 Tolerate rotational mask alignment errors
 Sensitivity to amplitude aberrations

Compatibility with telescope and other components

Compatibility with segmented apertures
 Compatibility with on-axis apertures
 Is the design not easily compatible with critical instrument capabilities?
 Ability to integrate LOWFS?
 Compatibility with WFS&C
 Compatibility with spectrograph
 Compatibility with post-processing
 Requires polarization splitting/filtering?
 Requires specialized optical train (e.g., pupil remapping)
 Potential for stray light from instrument baffles
 Compatible with polarimetry

Maturity, telescope compatibility, programmatic considerations

Lab demonstration completed?
 Demonstrated raw contrast in testbed
 Tolerance to instabilities demonstrated on testbed
 Model accuracy demonstrated?
 Fidelity of model to flight performance including post-processing

Development and programmatic considerations

Path to TRL 5
 Development cost
 Development time
 Manufacturability
 Flight instrument much larger or much smaller than average?
 Number of components and/or mechanisms in optical train much different from average?
 Supply-chain robustness
 Single-source fabrication?
 Does it fill a critical gap?
 Architecture applicable to other missions? (E.g. after HWO)

Primarily focal-plane coronagraphs

HLC LCPPC EvWaCo MSPM VVC

Primarily pupil-plane coronagraphs

SPC PIAA

Hybrid (pupil+focal) plane coronagraphs

APLC SPLC PAPLC PIAA-Vortex

photonic chip / theoretical limits

Hybrid photonic chip Full Photonic Chip Optimal Cor limit

Enhancing technologies

DPLC RAP ILOWFC fiber-nulling AAFS

Lyot-type coronagraphs

Pupil apodization coronagraphs

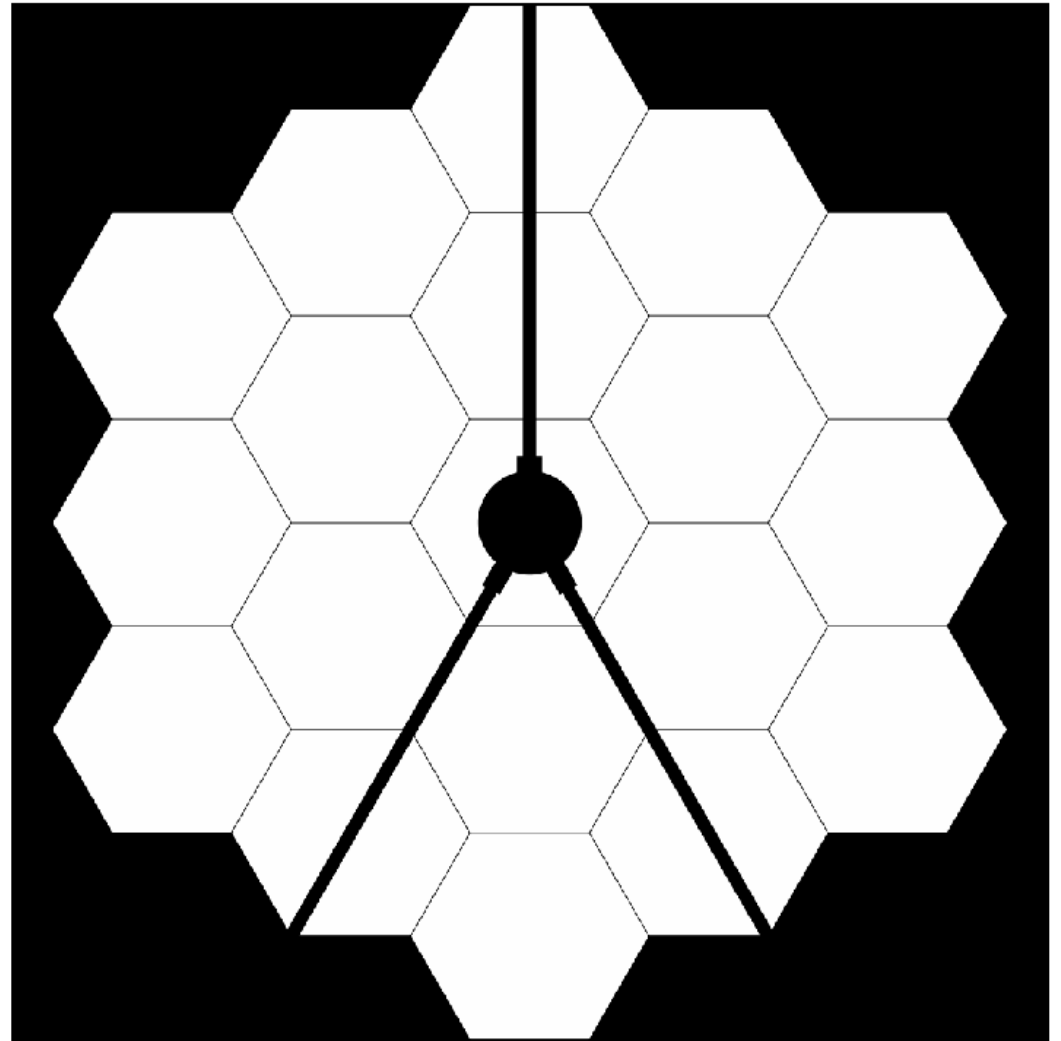
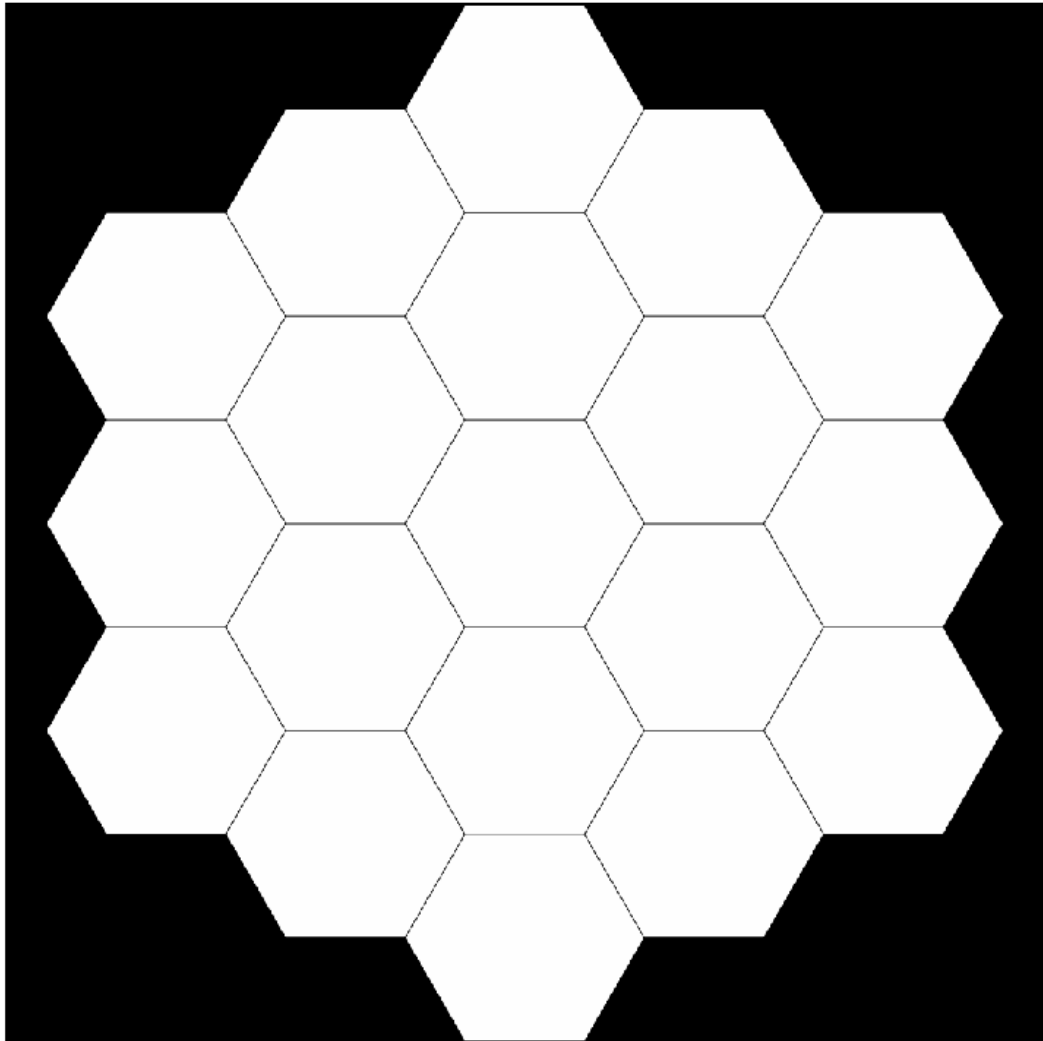
Hybrid coronagraphs

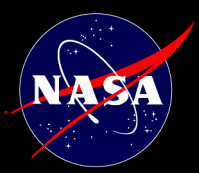
Photonic coronagraphs (and theoretical limit)

Enhancing technologies



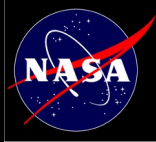
Baseline Pupils



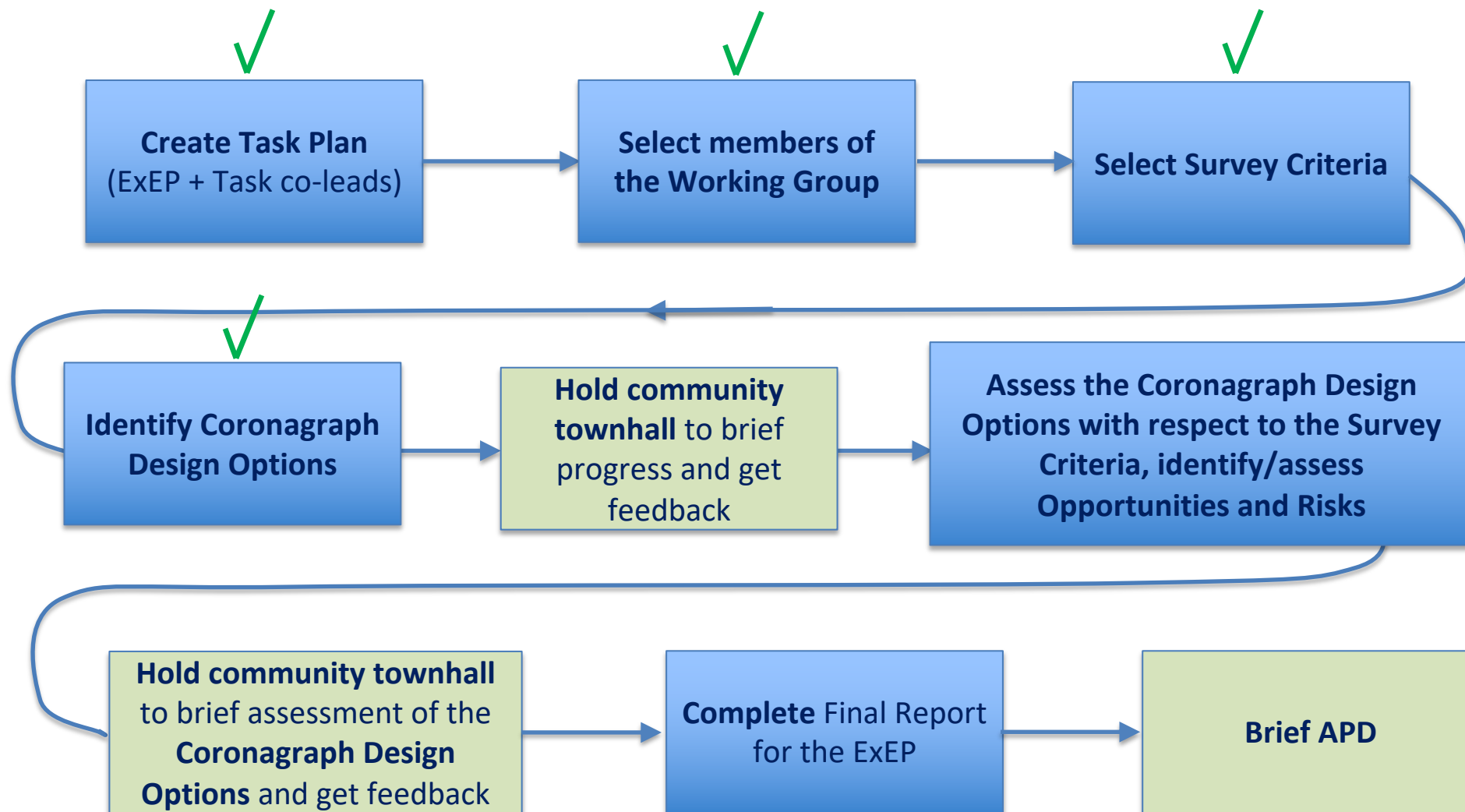


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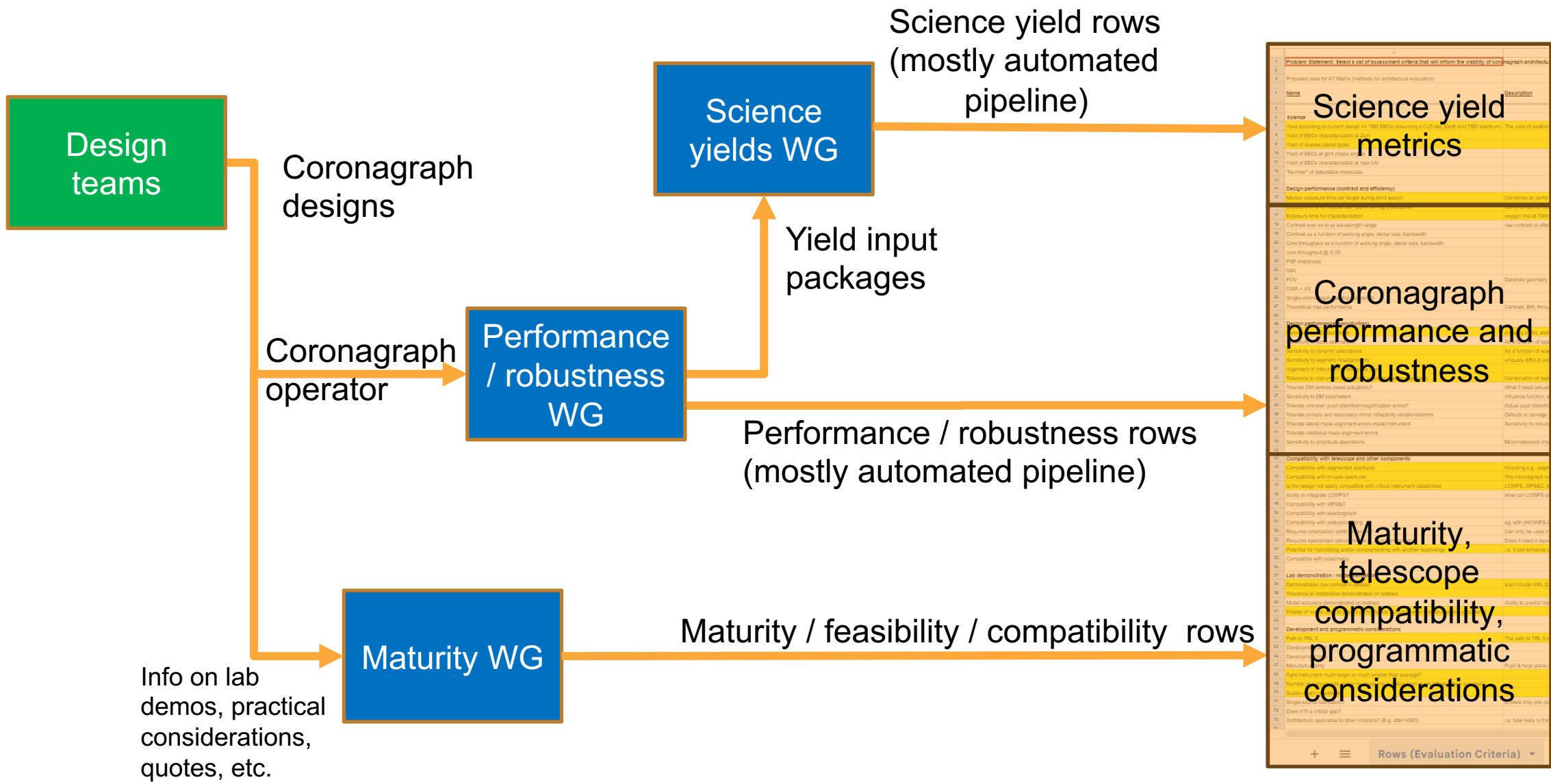


Process





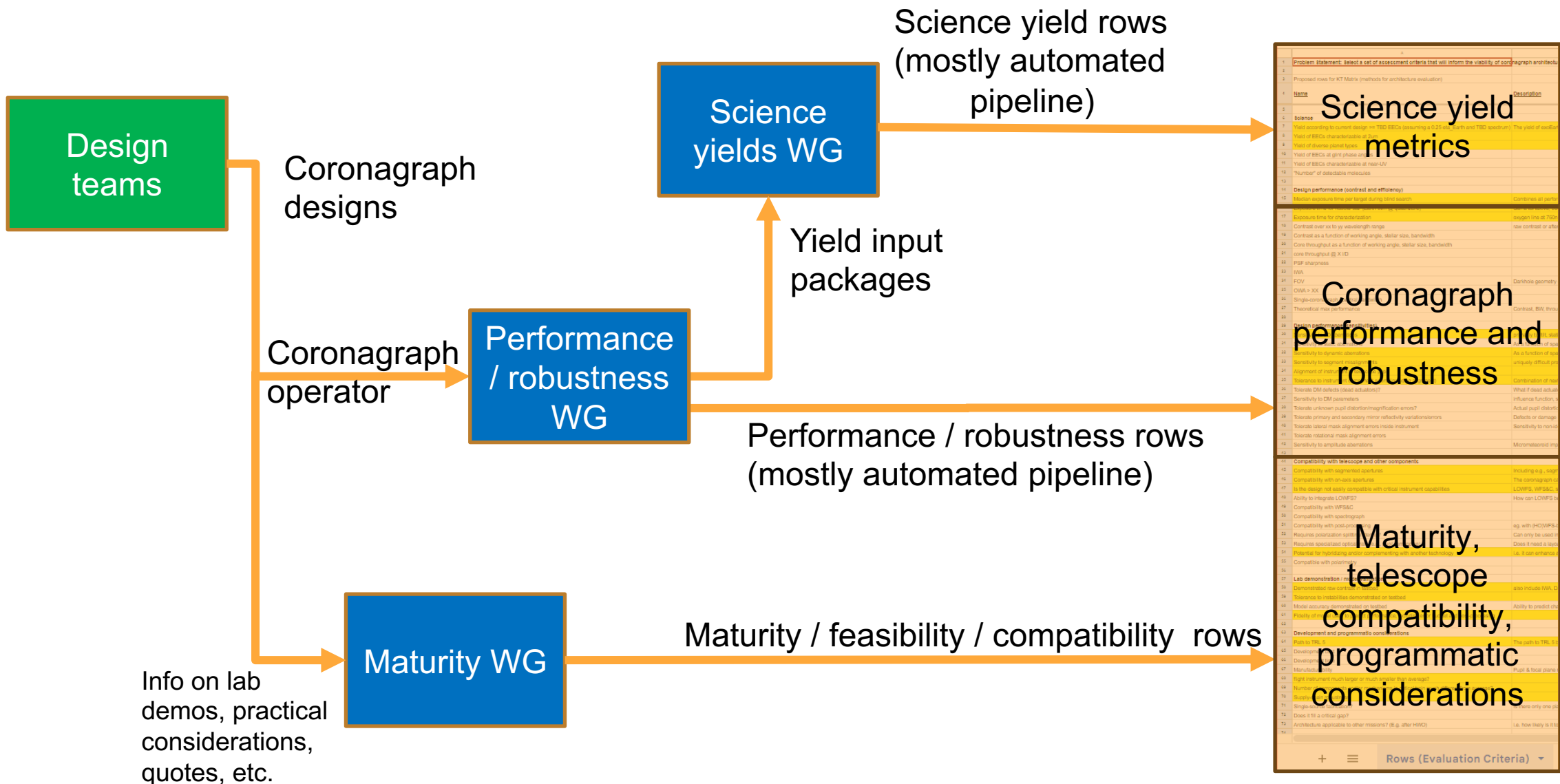
Workflow



Name	Description
Science yield metrics	
1	Problem Statement: Select a set of assessment criteria that will inform the viability of coronagraph architectures
2	Proposed rows for KT Matrix (methods for architecture evaluation)
3	
4	
5	
6	Science
7	Yield according to current design (on TSD ECCs assuming a 2.25 arc min slit TSD aperture). The yield of coronagraphs
8	Yield of ECCs characterized at 0.15 arc min
9	Yield of diverse planet types
10	Yield of ECCs at 0.15 arc min
11	Yield of ECCs at 0.15 arc min
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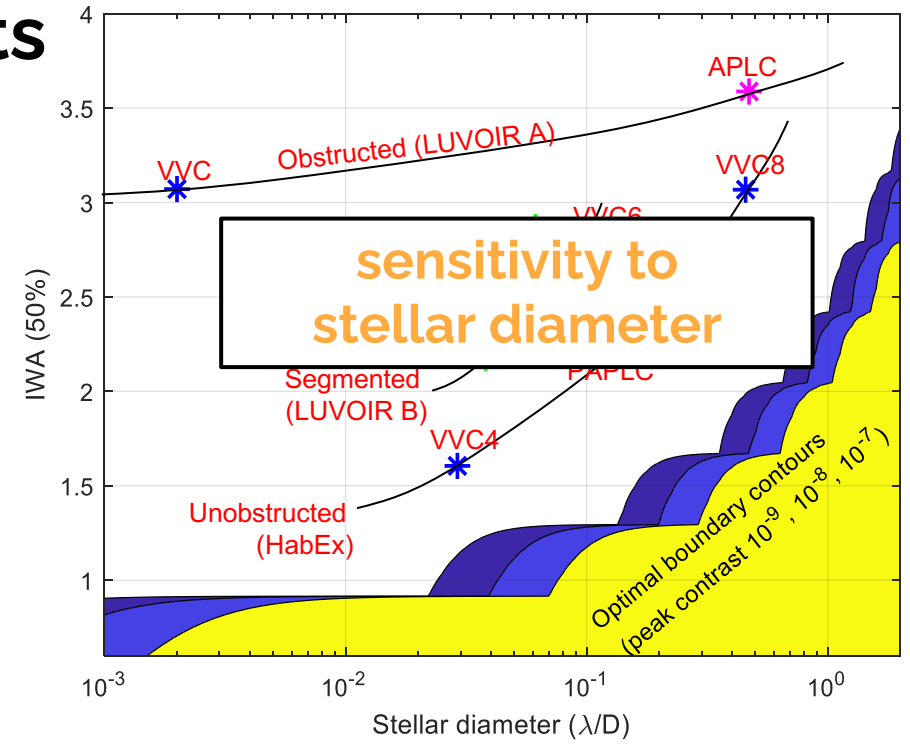
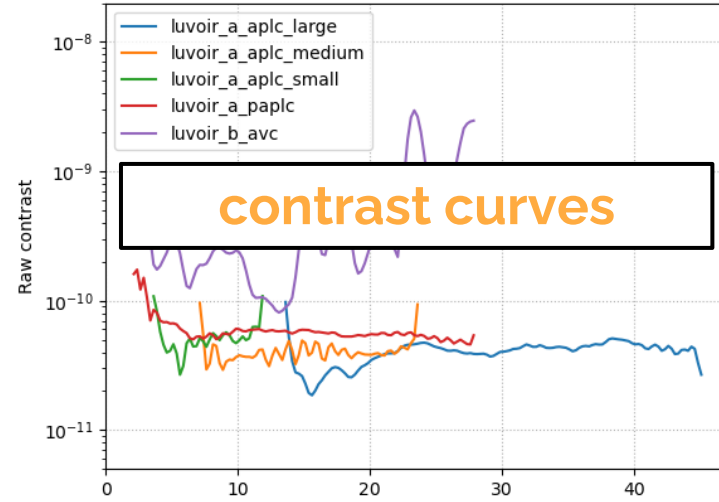
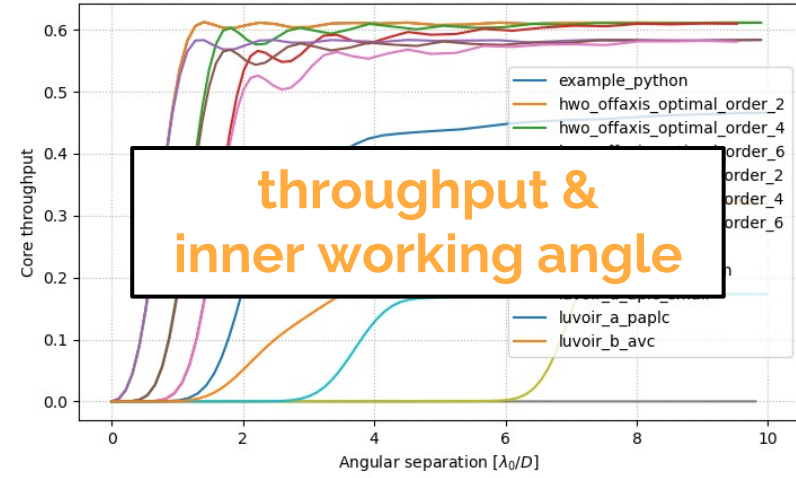
Workflow



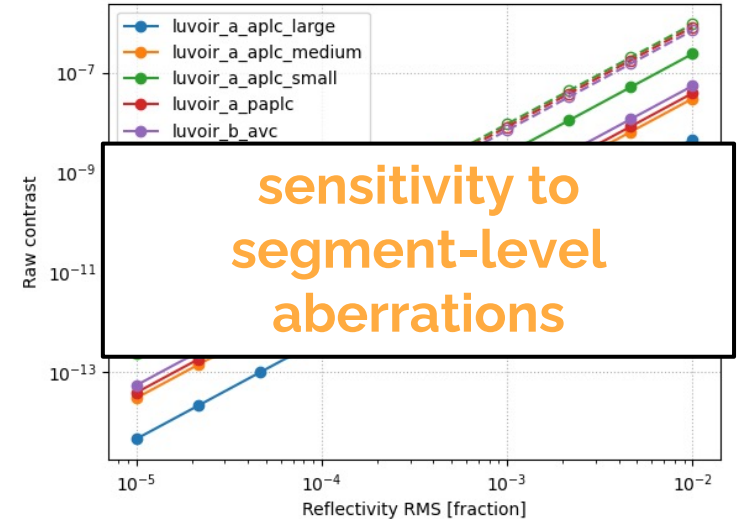
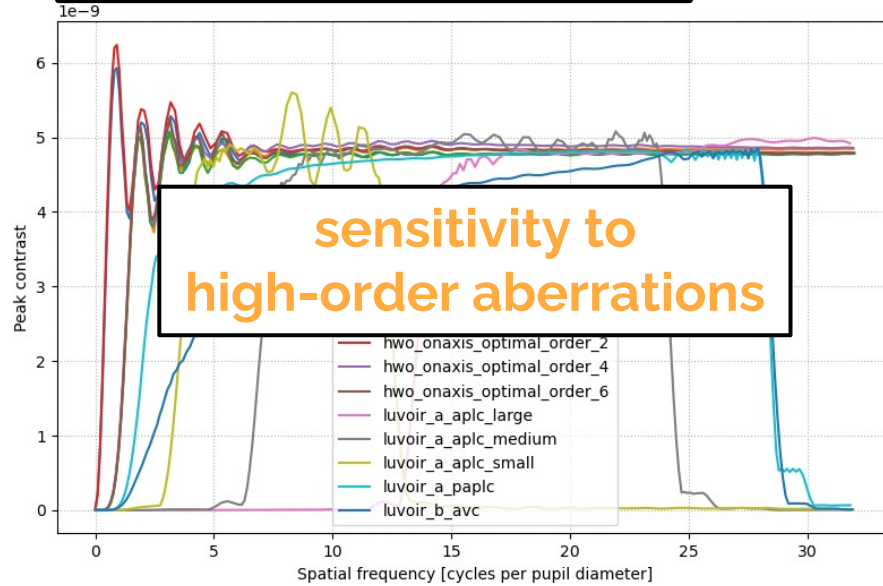
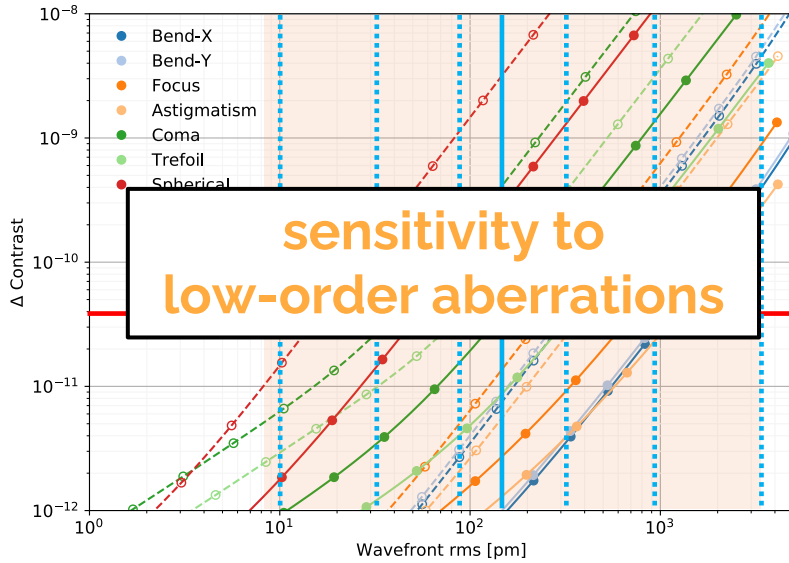
Name	Description
Science yield metrics	
1	Problem Statement: Select a set of assessment criteria that will inform the viability of coronagraph architectures
2	Proposed rows for KT Matrix (methods for architecture evaluation)
3	
4	
5	
6	
7	Yield according to current design on TRD EBCCs (assuming a 2.25 arc min slit TRD aperture). The yield of coronagraphs
8	Yield of EBCCs characterized at 0.15 arc min
9	Yield of diverse planet types
10	Yield of EBCCs at 0.15 arc min
11	Yield of EBCCs characterized at near-UV
12	"Number" of detectable molecules
13	
14	
15	Design performance (contrast and efficiency)
16	Monitor exposure time per target during simo search
17	
18	Baseline time to characterization
19	Contrast over six to six wavelength range
20	Contrast as a function of working angle, stellar size, bandwidth
21	Core throughput as a function of working angle, stellar size, bandwidth
22	Core throughput @ X-ID
23	PSF sharpness
24	IRV
25	POV
26	OWM x XIV
27	Single-comb
28	Theoretical max performance
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Performance / robustness pipeline products

(Working group lead: Emiel Por)

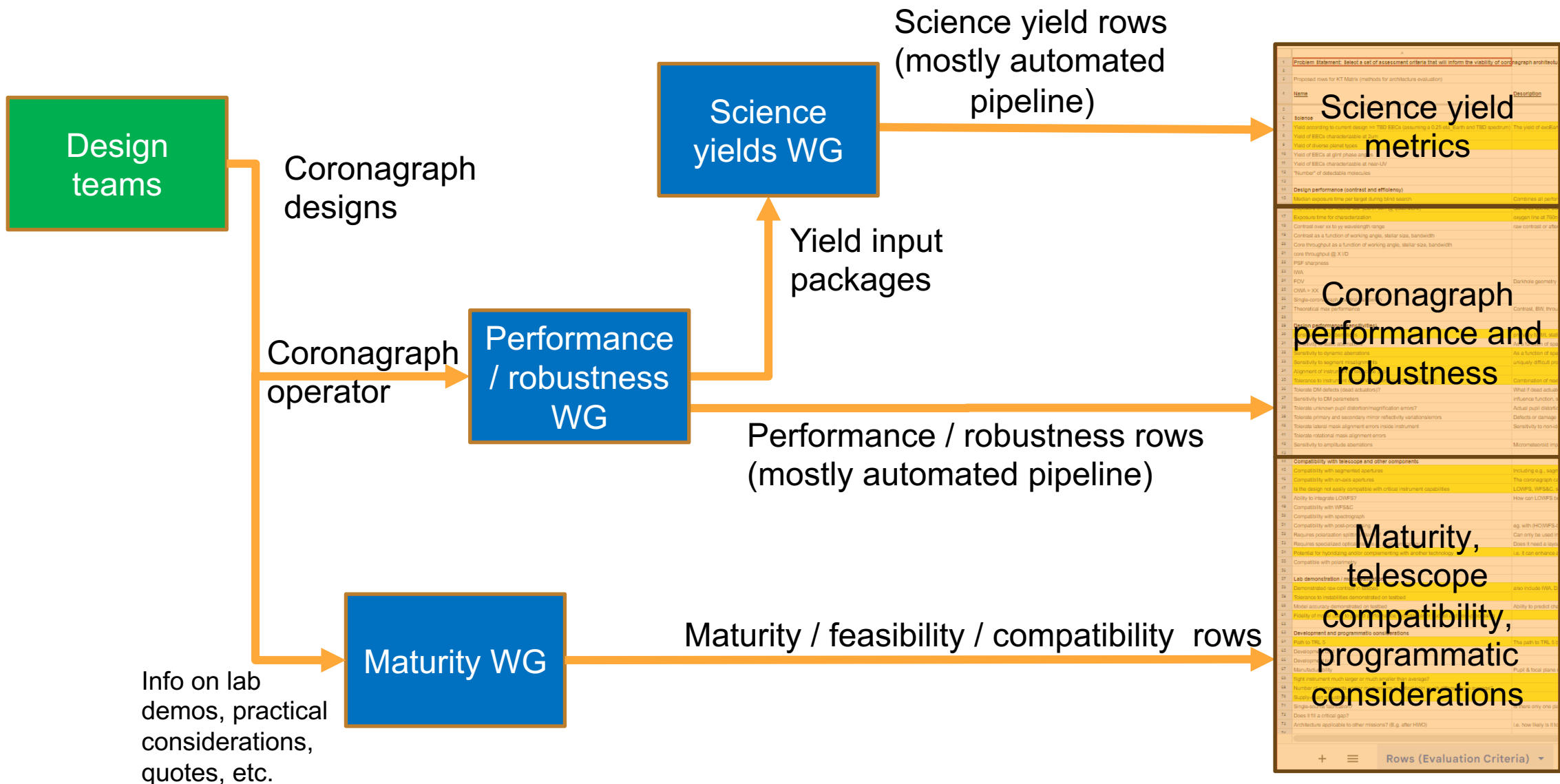


and more!





Workflow





Science Yield working group

(led by Chris Stark)

Draft evaluation criteria

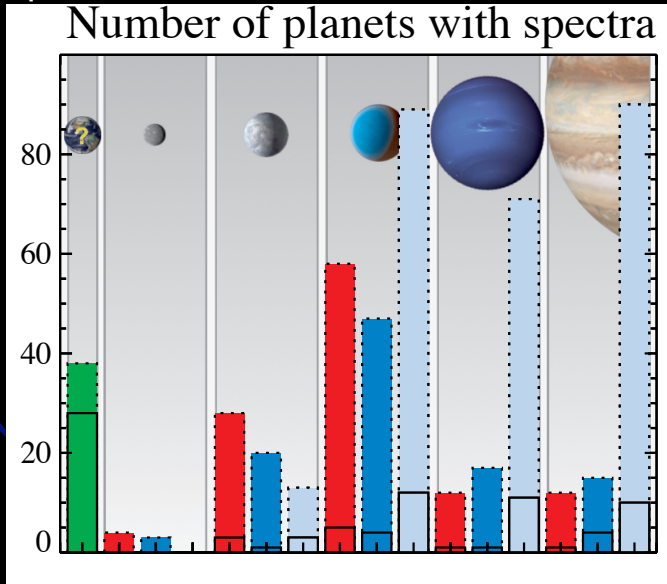
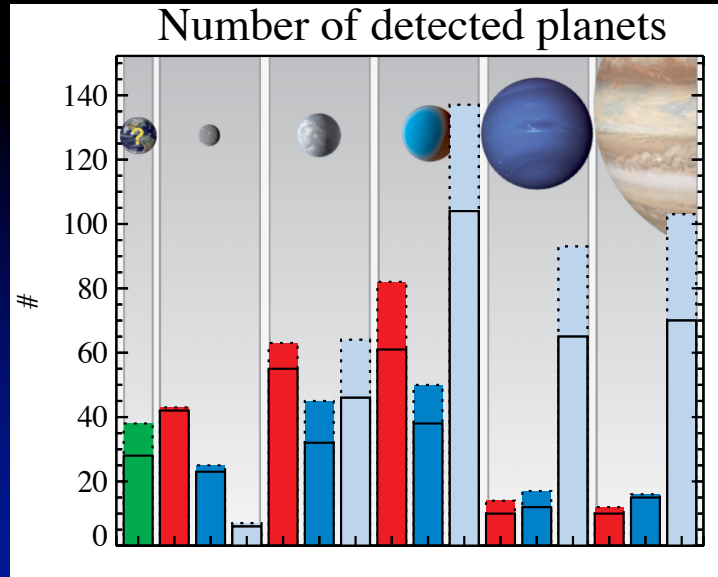
Science
Yield of EECs budgeting for VIS detections only
Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection
Yield of EECs budgeting for VIS detections, orbit, H2O, and CO2/CH4 detection at 1.65 microns
Yield of diverse planet types
Design performance (contrast and efficiency)
Median exposure time per target during blind search
Exposure time for fiducial star (Earth twin @ quadrature)
Exposure time for characterization

Draft fiducial mission parameters

Table 2. Coronagraph-based Mission Parameters

Parameter	Value	Description
General Parameters		
$\Sigma\tau$	2 yrs	Total exoplanet science time of the mission
τ_{slew}	1 hr	Static overhead for slew and settling time
τ_{WFC}	2.7 hrs ^a	Static overhead to dig dark hole
τ'_{WFC}	1.1	Multiplicative overhead to touch up dark hole
X	0.7	Photometric aperture radius in λ/D_{LS} ^b
Ω	$\pi(X\lambda/D_{\text{LS}})^2$ radians	Solid angle subtended by photometric aperture ^b
ζ_{floor}	10^{-10}	Raw contrast floor
$\Delta\text{mag}_{\text{floor}}$	26.5	Noise floor (faintest detectable point source at S/N_d)
T_{contam}	0.95	Effective throughput due to contamination
Detection Parameters		
$\lambda_{d,1}$	$0.45 \mu\text{m}^c$	Central wavelength for detection in SW coronagraph
$\lambda_{d,2}$	$0.55 \mu\text{m}^c$	Central wavelength for detection in LW coronagraph
S/N_d	7	S/N required for detection (summed over both coronagraphs)
$T_{\text{optical},1}$	0.16^c	End-to-end reflectivity/transmissivity at $\lambda_{d,1}$
$T_{\text{optical},2}$	0.33^c	End-to-end reflectivity/transmissivity at $\lambda_{d,2}$
$\tau_{d,\text{limit}}$	2 mos	Detection time limit including overheads
Characterization Parameters		
λ_c	$1.0 \mu\text{m}^c$	Wavelength for characterization in LW coronagraph IFS
S/N_c	5^c	Signal to noise per spectral bin evaluated in continuum
R	140	Spectral resolving power
$T_{\text{optical,IFS}}$	0.23^c	End-to-end reflectivity/transmissivity at λ_c
$\tau_{c,\text{limit}}$	2 mos	Characterization time limit including overheads
Detector Parameters		
$n_{\text{pix},d}$	4^c	# of pixels in photometric aperture of each imager at $\lambda_{d,\#}$
$n_{\text{pix},c}$	96^c	# of pixels per spectral bin in LW coronagraph IFS at λ_c
ξ	$3 \times 10^{-5} e^- \text{pix}^{-1} \text{s}^{-1}$	Dark current
RN	$0 e^- \text{pix}^{-1} \text{read}^{-1}$	Read noise
τ_{read}	N/A	Time between reads
CIC	$1.3 \times 10^{-3} e^- \text{pix}^{-1} \text{frame}^{-1}$	Clock induced charge
T_{QE}	0.9	Raw QE of the detector at all wavelengths
T_{read}	0.75	Effective throughput due to bad pixel/cosmic ray mitigation

Examples of products



Howe et al. (submitted)

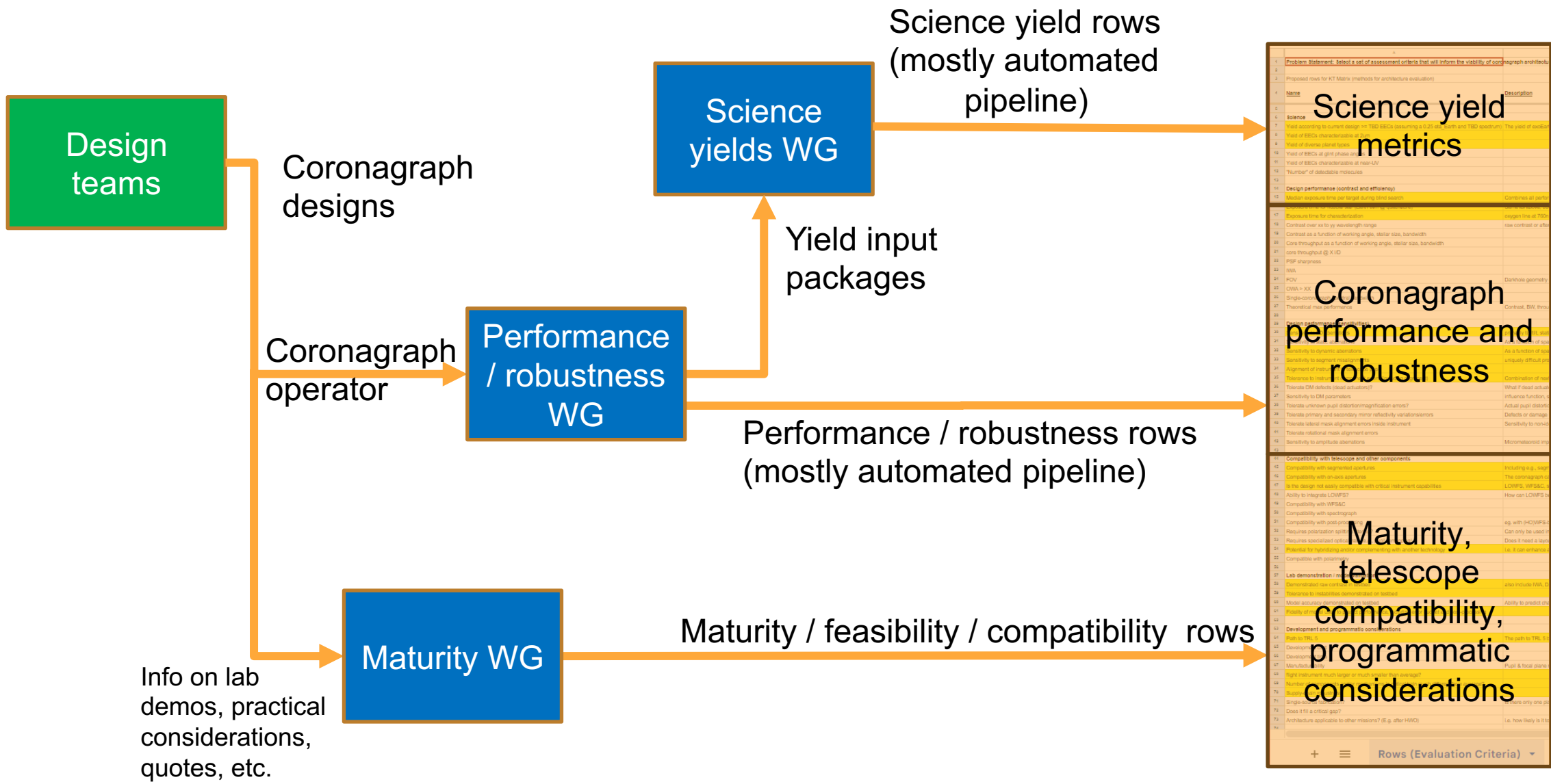
^aSee Eq. 17 from Ref. ?

^b D_{LS} is the diameter of Lyot stop projected onto the primary mirror

^cExample provided at most likely bandpass; AYO optimizes bandpass and adjusts values accordingly.



Workflow



Name	Description
Science yield metrics	
1	Problem Statement: Select a set of assessment criteria that will inform the viability of coronagraph architectures
2	Proposed rows for KT Matrix (methods for architecture evaluation)
3	
4	
5	
6	Science
7	Yield according to current design (on TSD ECCs assuming a 2.25 micron star TSD spectrum). The yield of coronagraphs
8	Yield of ECCs characterized at 1000 nm
9	Yield of diverse planet types
10	Yield of ECCs at 1000 nm
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200	Yield of ECCs at 1000 nm



Maturity / Compatibility / Programmatic

(led by Bertrand Mennesson)

Compatibility with telescope and other components

Compatibility with segmented apertures

Compatibility with on-axis apertures

Is the design not easily compatible with critical instrument capabilities

Ability to integrate LOWFS?

Compatibility with WFS&C

Compatibility with spectrograph

Compatibility with post-processing

Requires polarization splitting/filtering?

Requires specialized optical train (e.g., pupil remapping)

Potential for hybridizing and/or complementing with another technology

Compatible with polarimetry

Lab demonstration / model validation

Demonstrated raw contrast in testbed

Tolerance to instabilities demonstrated on testbed

Model accuracy demonstrated on testbed

Fidelity of model used to predict performance, including error budget and post-processing

Development and programmatic considerations

Path to TRL 5

Development cost

Development time

Manufacturability

flight instrument much larger or much smaller than average?

Number of components and/or mechanisms in optical train much different from average?

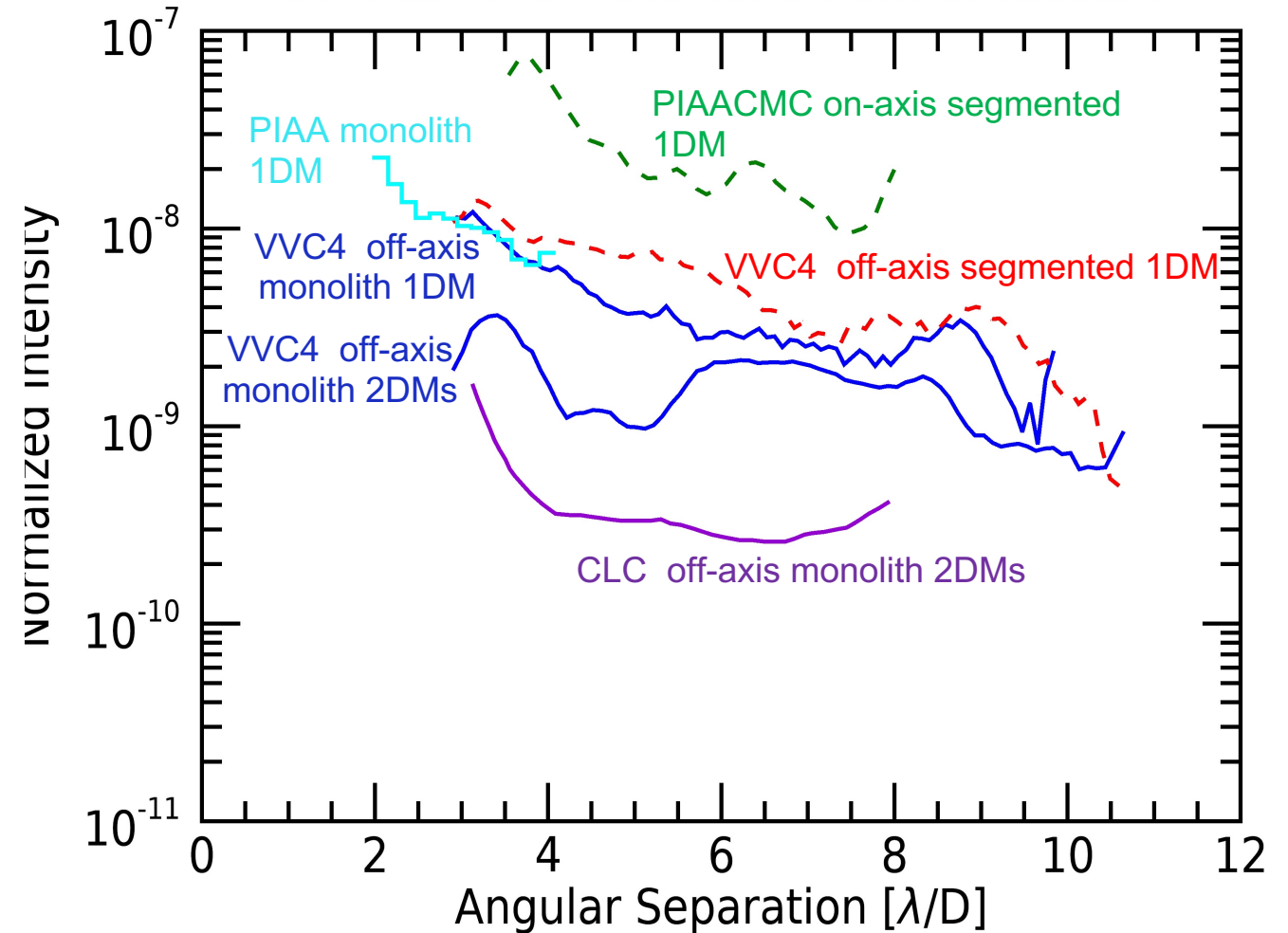
Supply-chain robustness

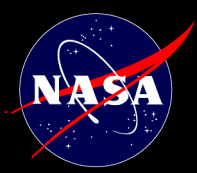
Single-source fabrication?

Does it fill a critical gap?

Architecture applicable to other missions? (E.g. after HWO)

Contrast over 10% Bandwidth in Vacuum

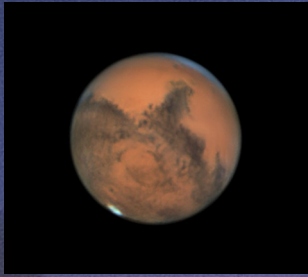




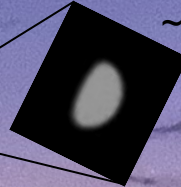
Conclusions / Preliminary Findings

- CDS is surveying viable coronagraph designs to facilitate future trade studies for HWO
 - Results will be summarized by a KT-like matrix, and detailed in a written report
 - Automated pipeline will also be made available
 - CDS is NOT doing any down-selects
- Coronagraph designs have improved since LUVVOIR/HabEx reports, and can provide a strong lever to improve HWO performance, reduce risk and cost:
 - Improve yield by 2-4x
 - Relax telescope requirements, such as stability
 - Enable a potentially lower-cost on-axis aperture without sacrificing performance
 - Can leverage future advances in technology driven by large industrial markets (such as photonic chips)
- There is a rich trade space of coronagraphs to explore
 - Demonstrating $1e-10$ is important, but other metrics (such as robustness, bandwidth, IWA, throughput) are better levers for improving yield, once we are below $\sim 5e-10$.
 - This trade space is coupled with telescope and DMs





$\sim 1e-11, 6K \lambda/D$



$\sim 2e-10, 4K \lambda/D$



$\sim 4e-10, 4K \lambda/D$

