Coronagraph Design Survey for Future Exoplanet Direct Imaging Space Missions

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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

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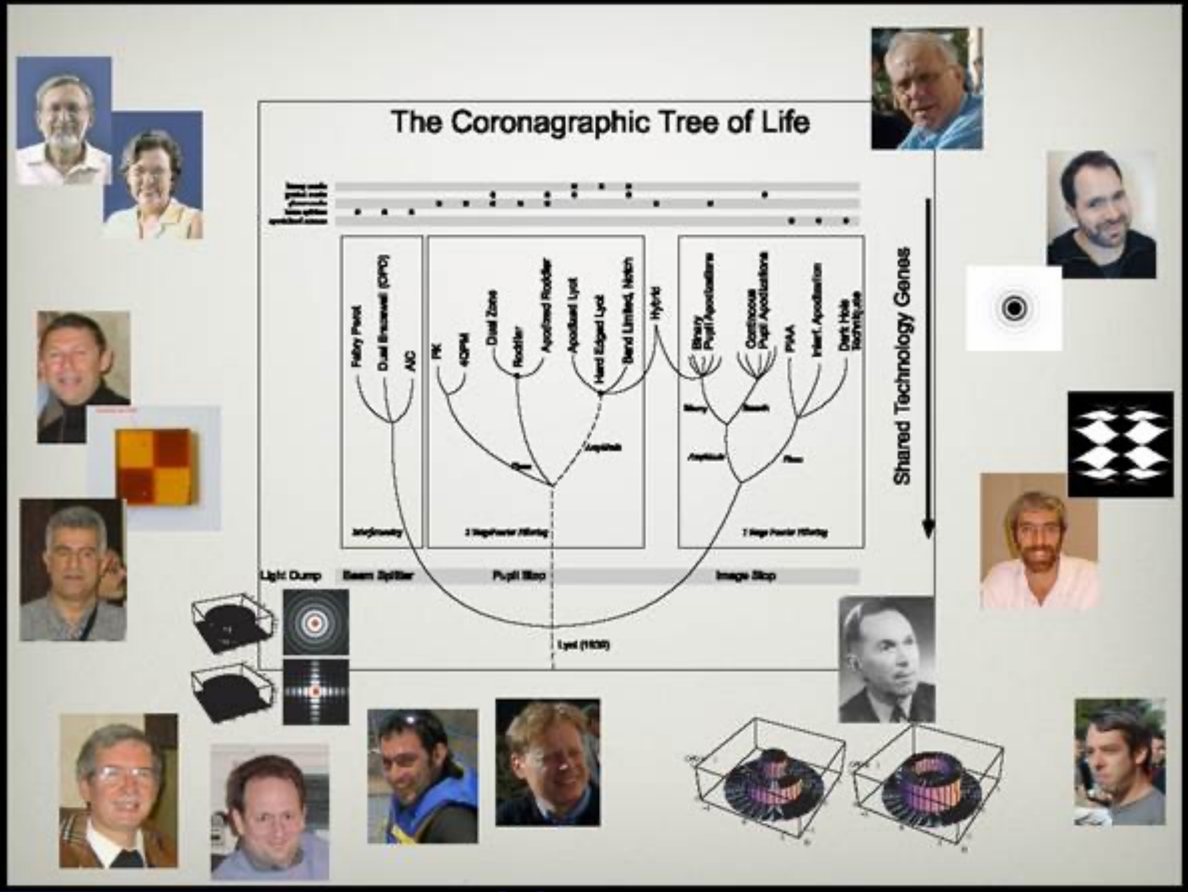
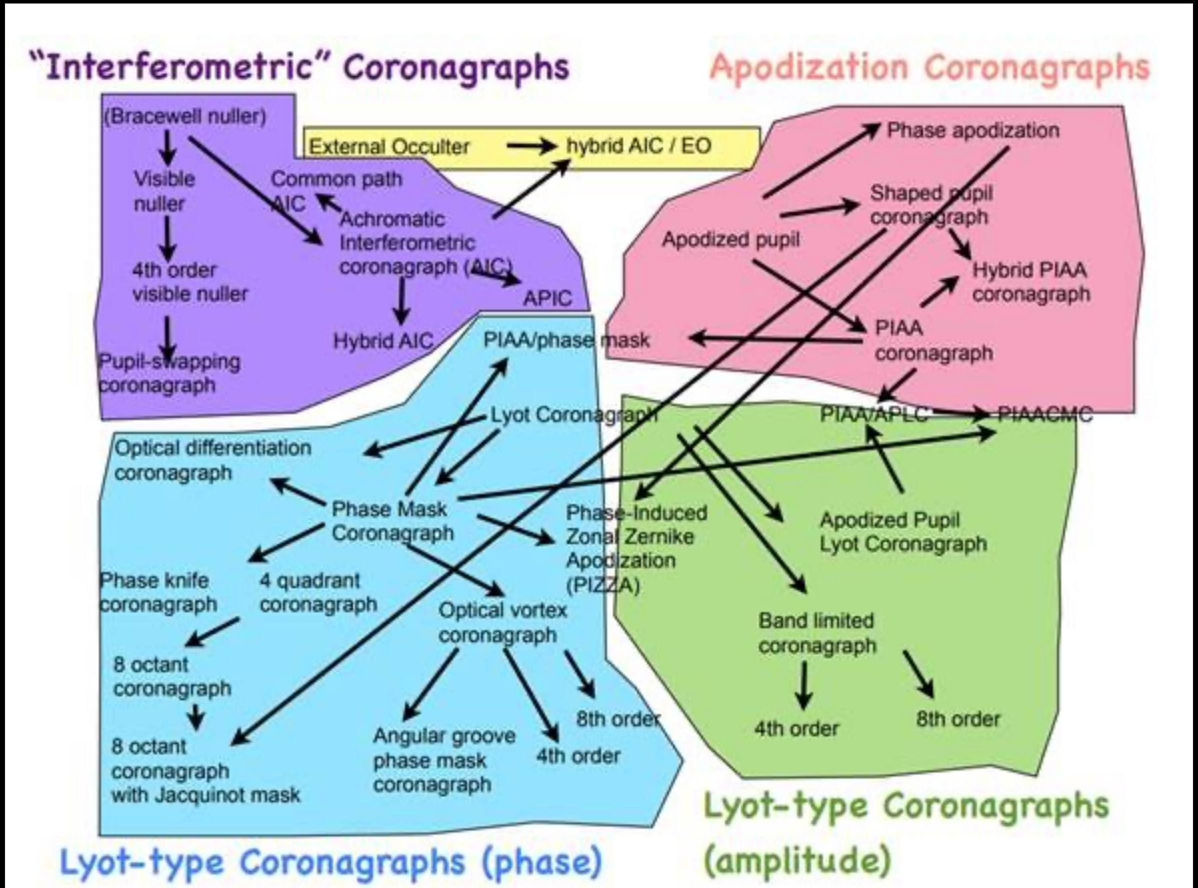
There is a rich trade space of coronagraph designs to explore



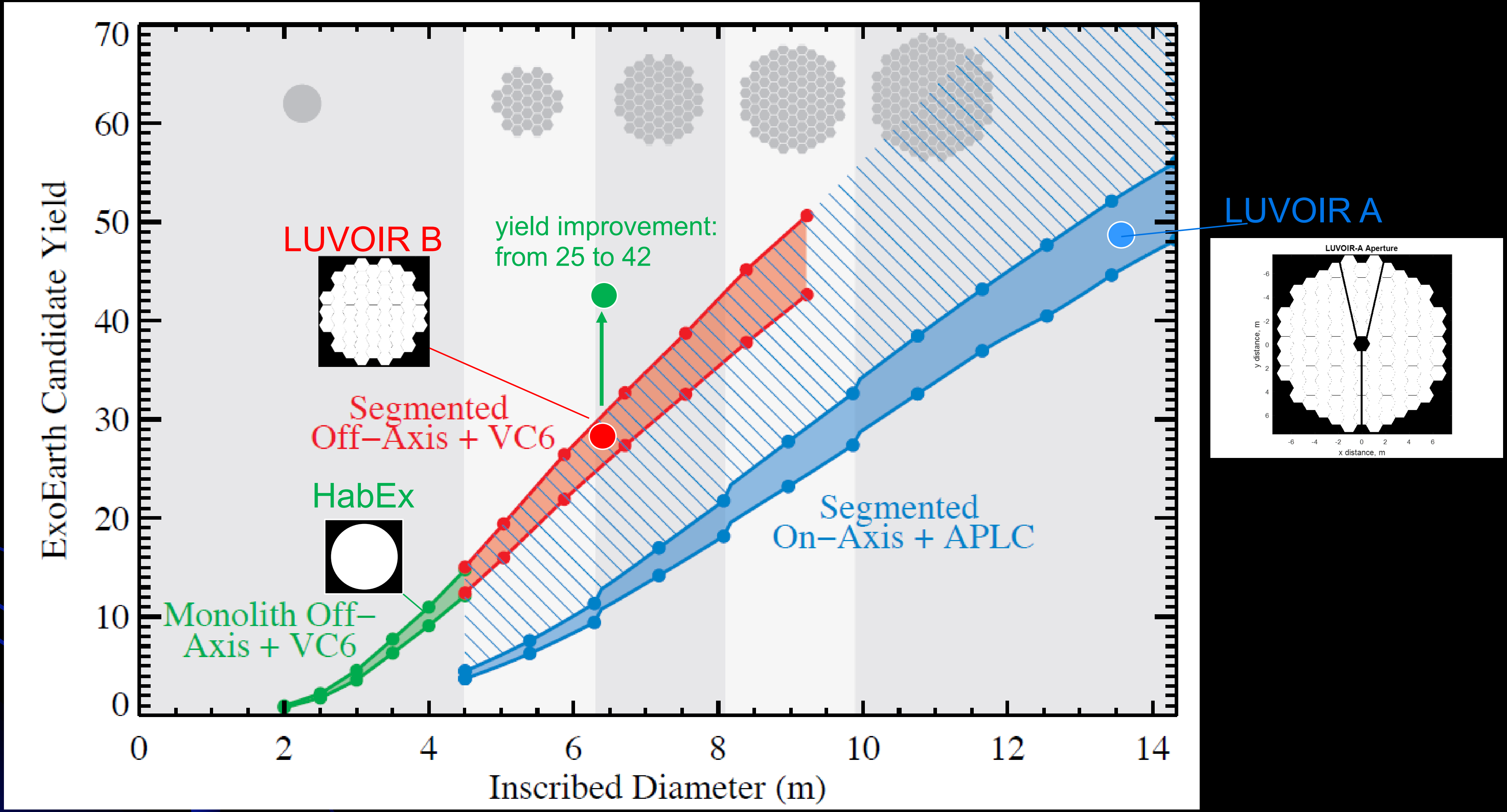
Courtesy of James Lloyd, 2003



Olivier Guyon, 2009

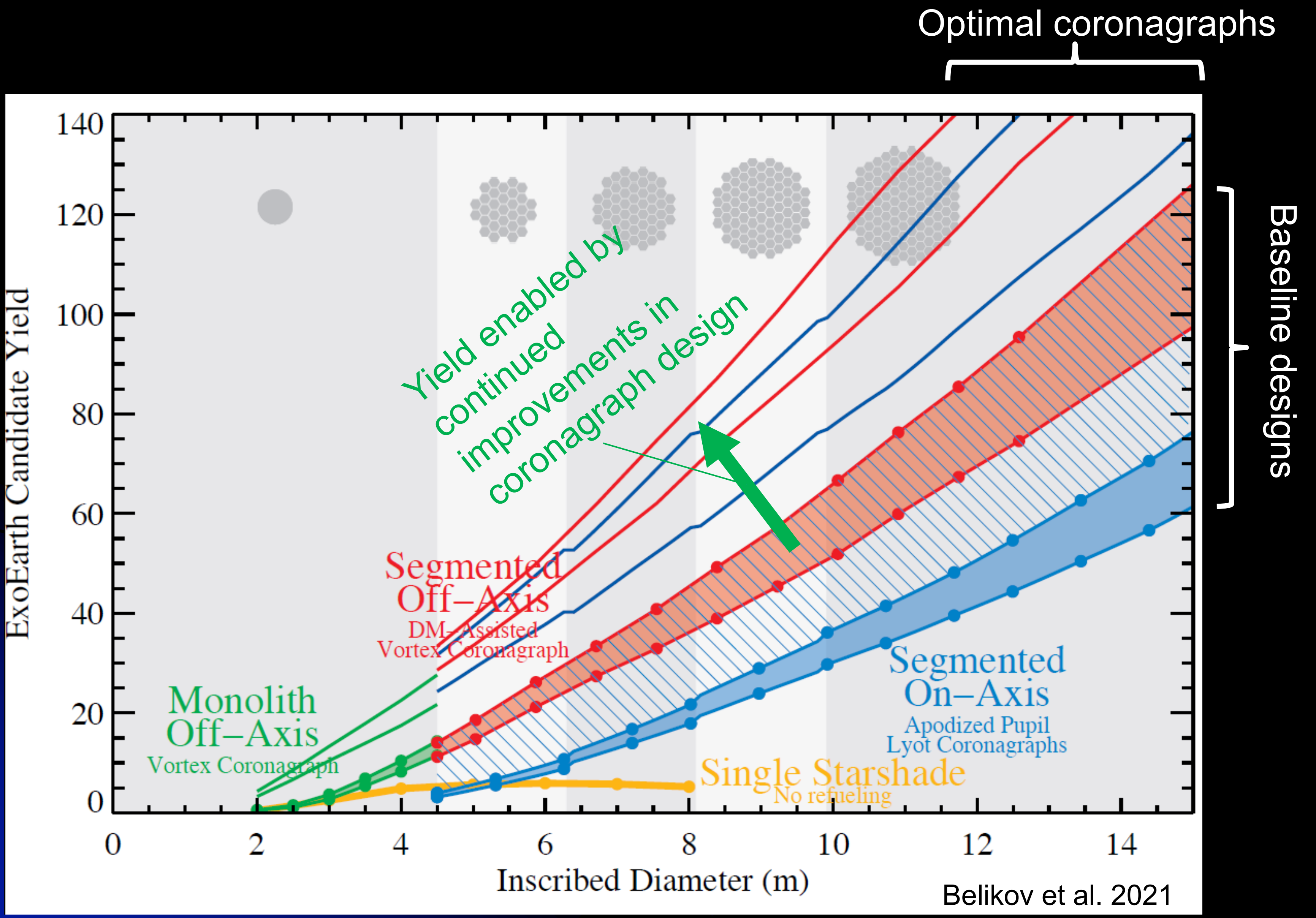
Why do we still need to explore different designs? Didn't LUVOIR / HabEx do this already, and shouldn't we focus on getting to 1e-10?

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



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

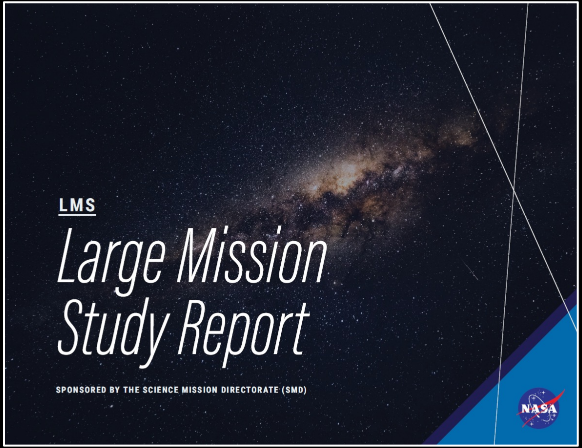
Reason 1: … and still have a lot of room to improve before they hit fundamental physics limits



Belikov et al. 2021

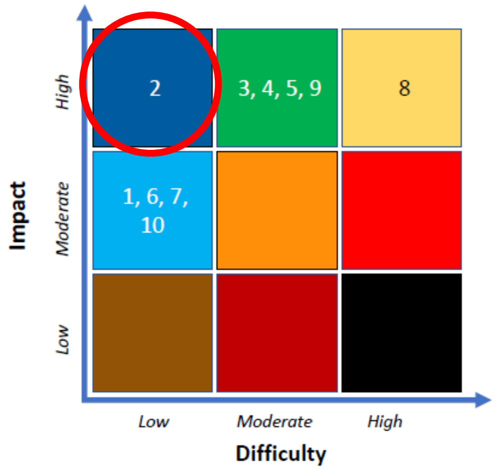
- Optimal coronagraphs achieve 2-4 greater yield than currently baselined coronagraphs (for a fixed bandwidth and system QE)
- Gap between obstructed and unobstructed apertures can be closed!
  - Enabling larger aperture for the same cost, and/or risk reduction / cost savings
- Caveats: optimal coronagraph 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)

Classification of Recommendations from the Large Missions Study



No.	Recommendation Title
1	*Pre-Phase A Team Composition*
2	*Pre-Phase A Architecture Trades and Descope 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*

- 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).

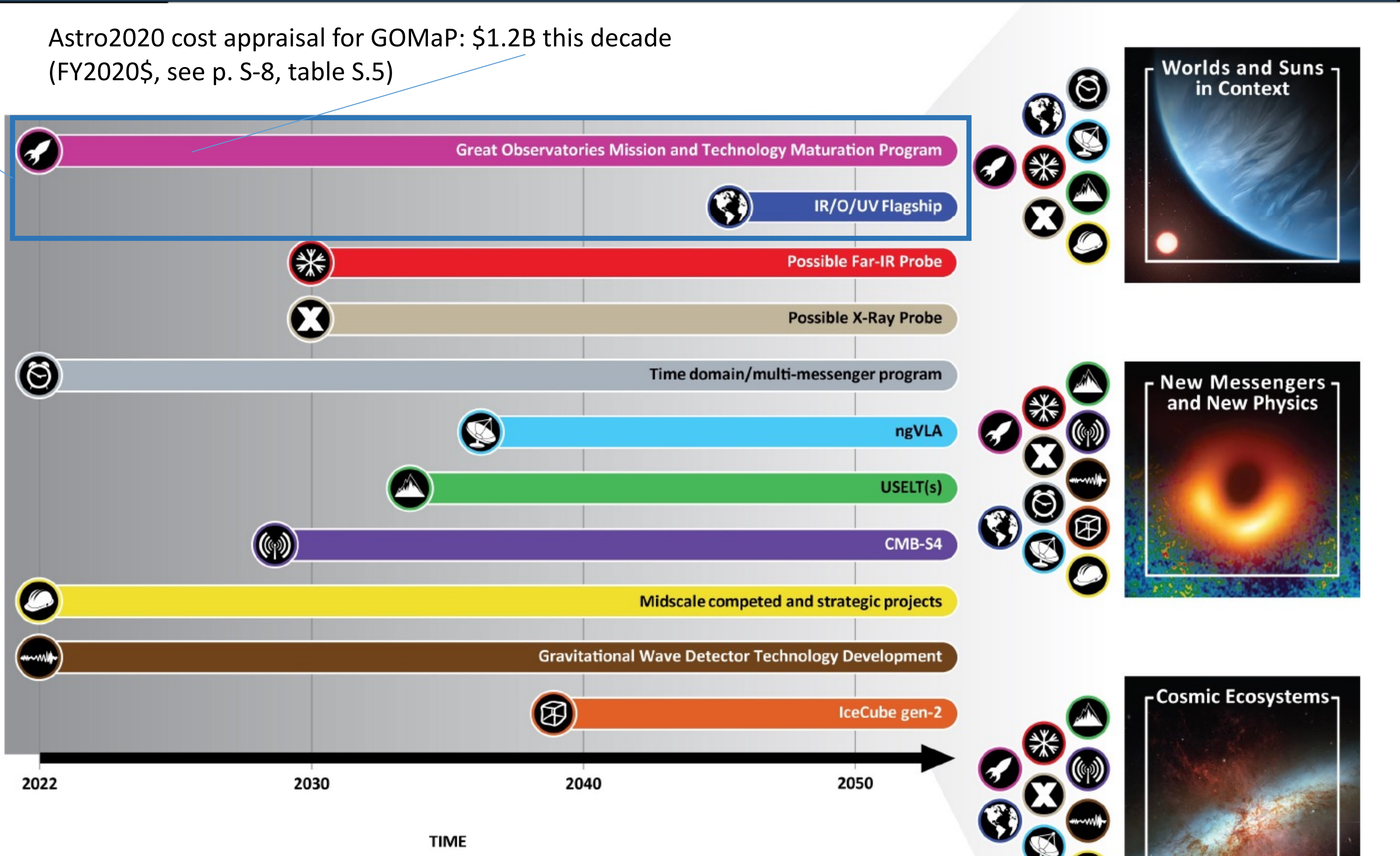
Reason 2b: Reducing risk and cost of HWO is an important goal of GOMAP

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)



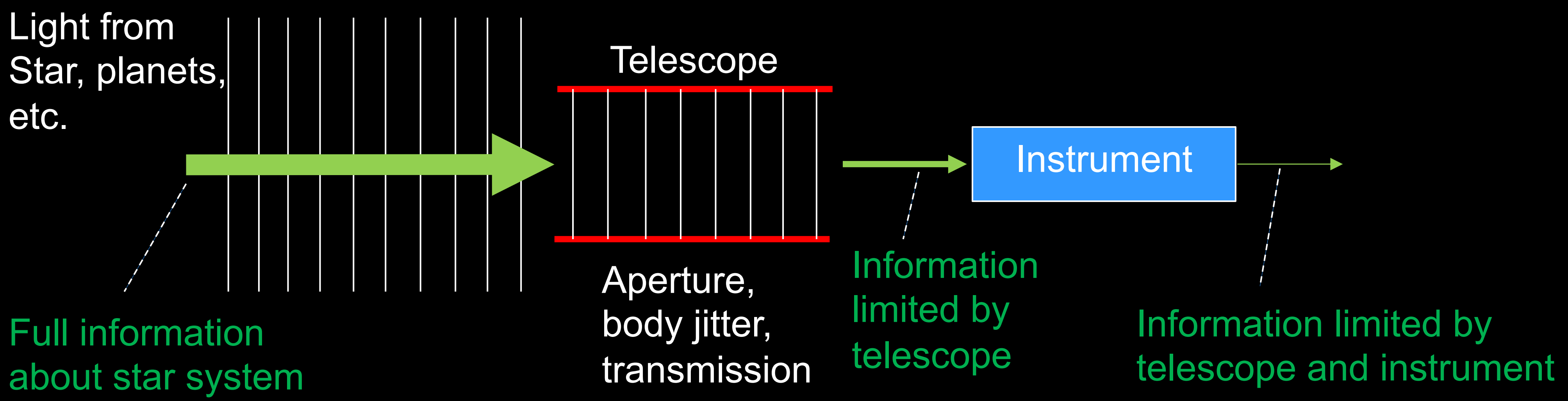
https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

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	?

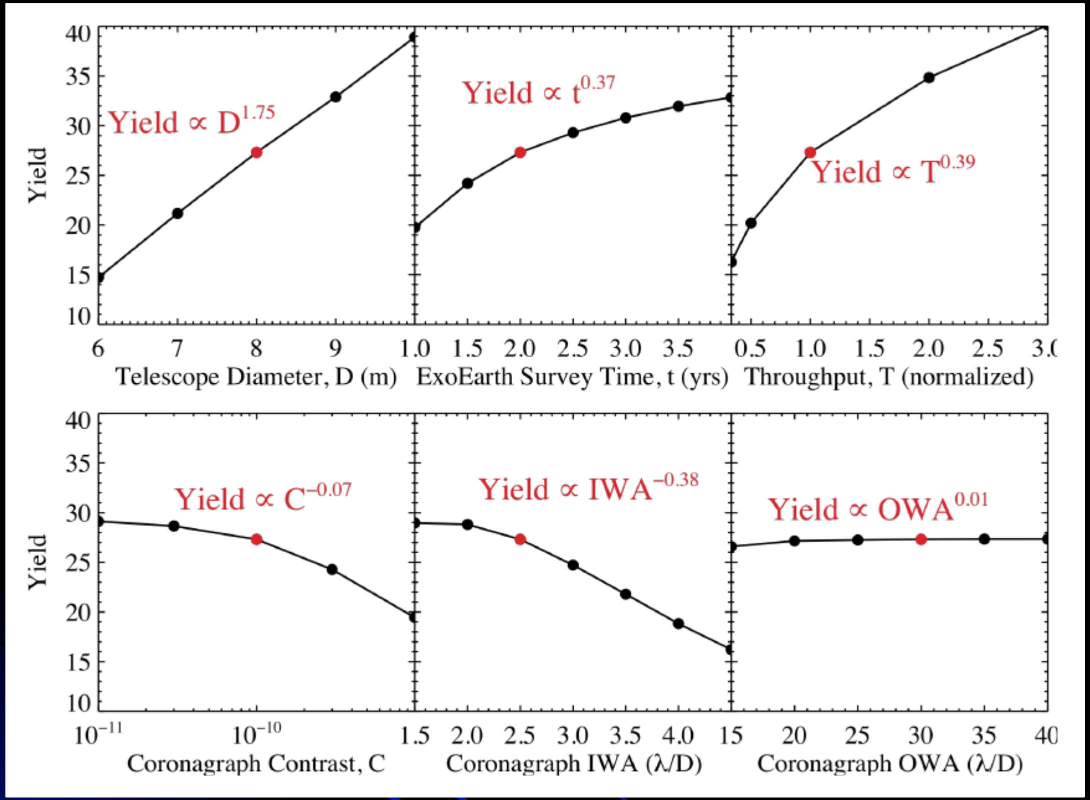
- There are more ways in which expected science yields can decrease than increase
- So, yield estimates tend to go down as a mission concept matures

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

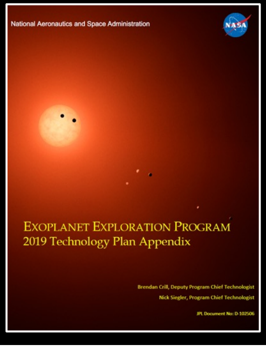


- Instruments are often performance bottlenecks
  - unless they are physics-limited
- Instrument technology research and development:
  - Small fraction of mission cost for a flagship
  - large impact on
    - mission performance
    - requirements relaxation
    - risk reduction
  - large, leveraged 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*
Coronagraph Contrast and Efficiency 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.	unobscured pupil: 4×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (Lyot coronagraph demo in HCIT); obscured pupil: 1.6×10^{-9} 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)	Maximized science yield in imaging and spectroscopy for a direct imaging telescope/mission. ≤ 10^{-10} raw contrast, >10% throughput, inner working angle ≤ 3 λ/D, outer working angle >= 45 λ/D [TBD], 20% bandwidth; obscured/segmented pupil For the two distinct cases of monolith and segmented primary mirrors, Sub-gaps that could partially or fully close this gap: - 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 / exozidi 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								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	*Weights*							
	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	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	EvWaCo	MSPM	VVC		SPC	PIAA		APLC	SPLC	PAPLC	PIAA-Vortex		Hybrid photonic chi	Full Photonic Chip	Optimal Cor limit		DPLC	RAP	ILOWFC	fiber-nulling	AAFFS
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 l/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

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Lyot-type coronagraphs

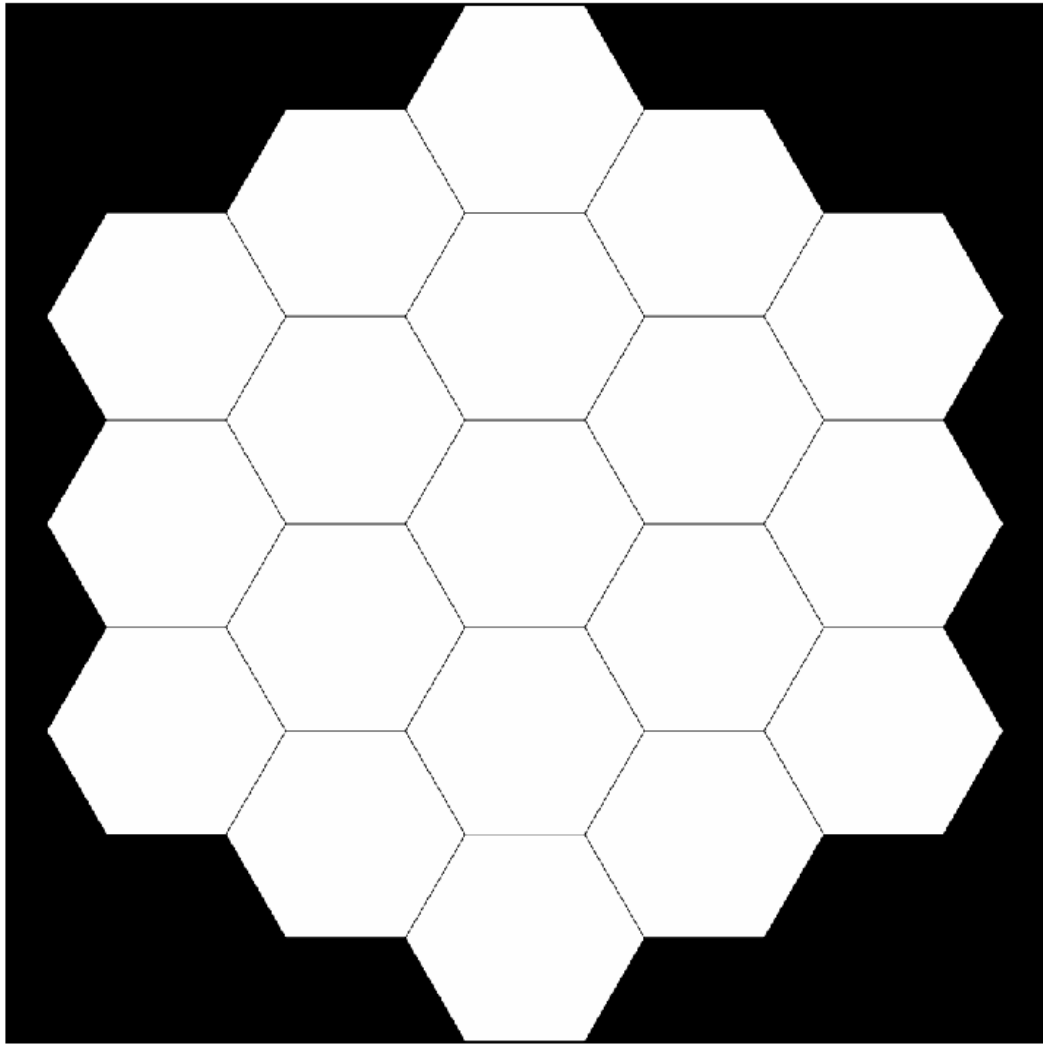
Pupil apodization coronagraphs

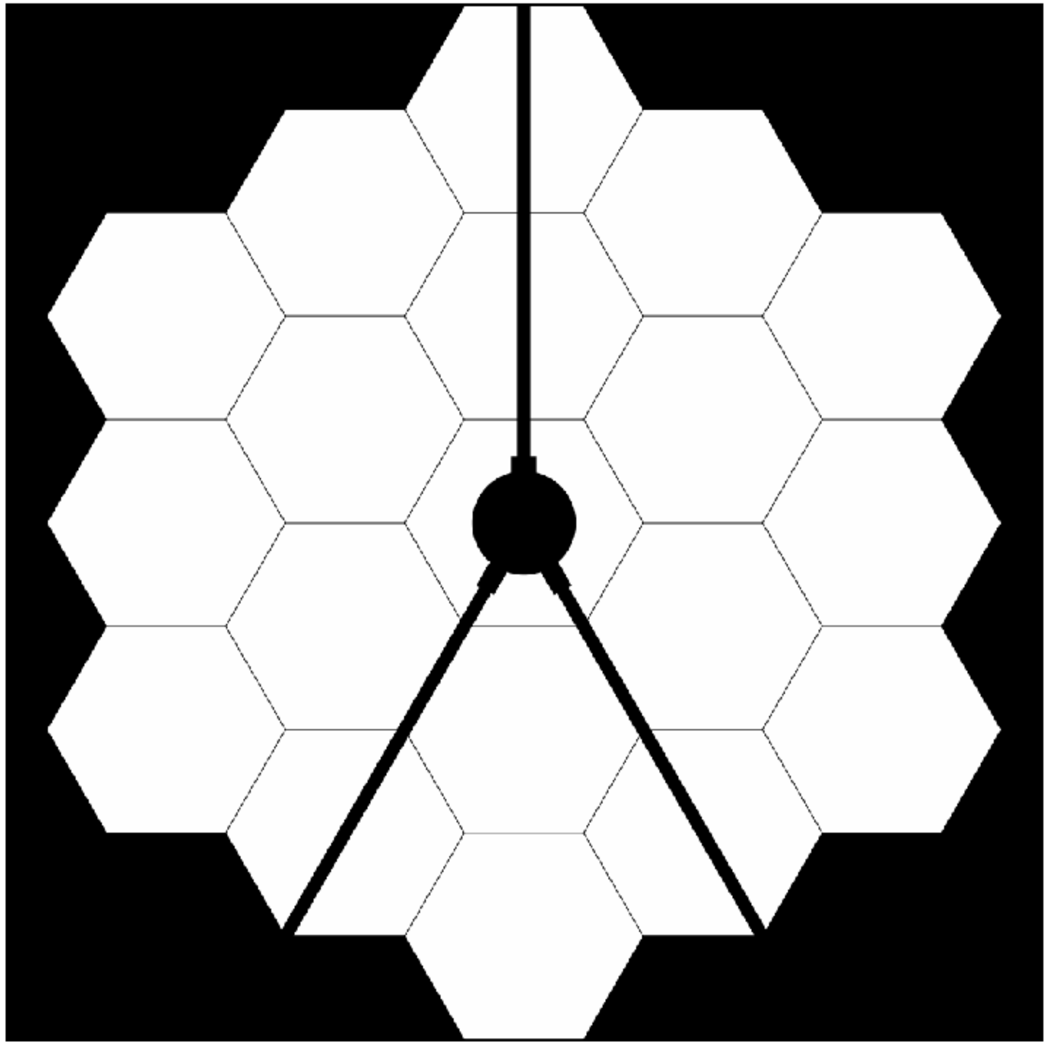
Hybrid coronagraphs

Photonic coronagraphs (and theoretical limit)

Enhancing technologies

Baseline Pupils





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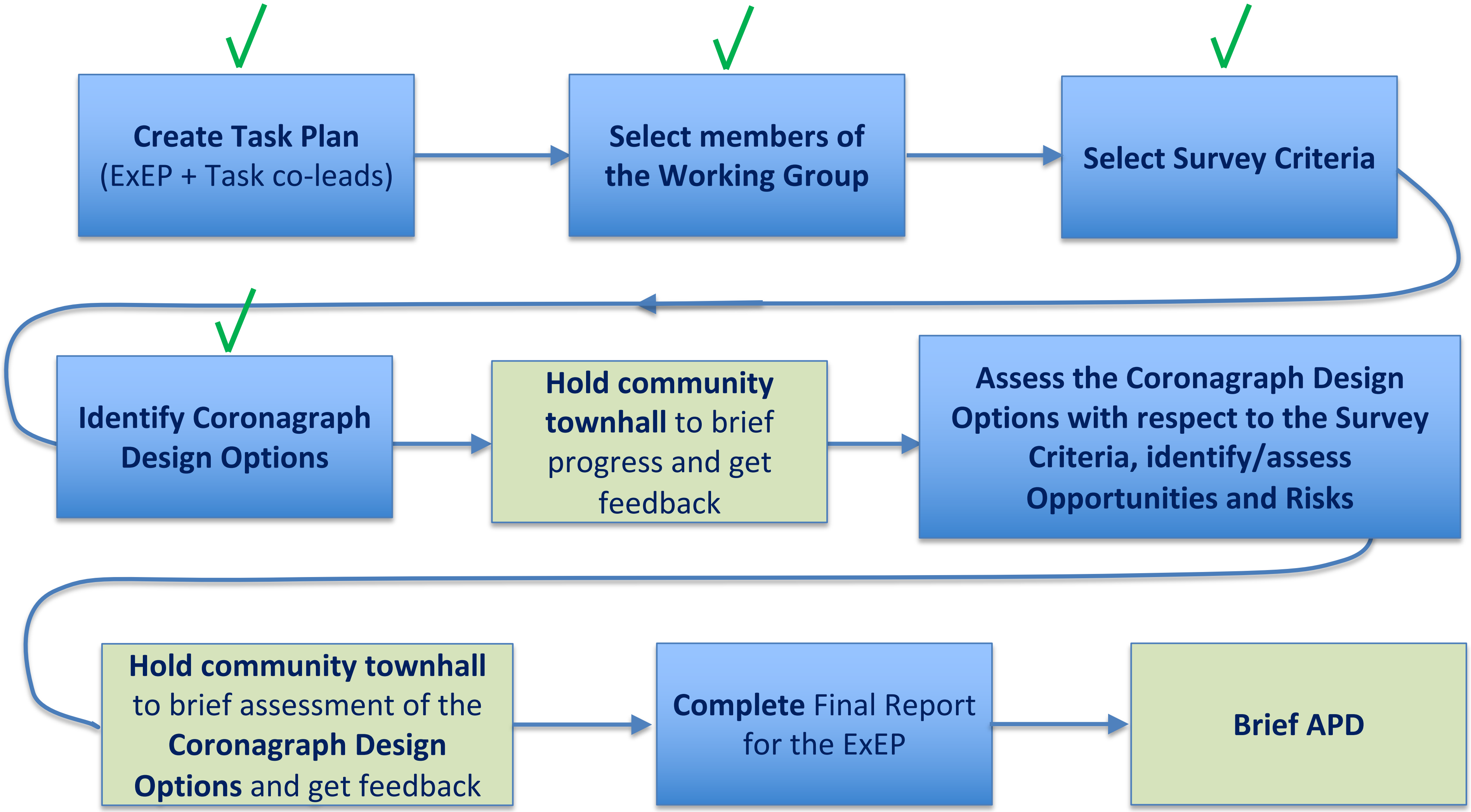
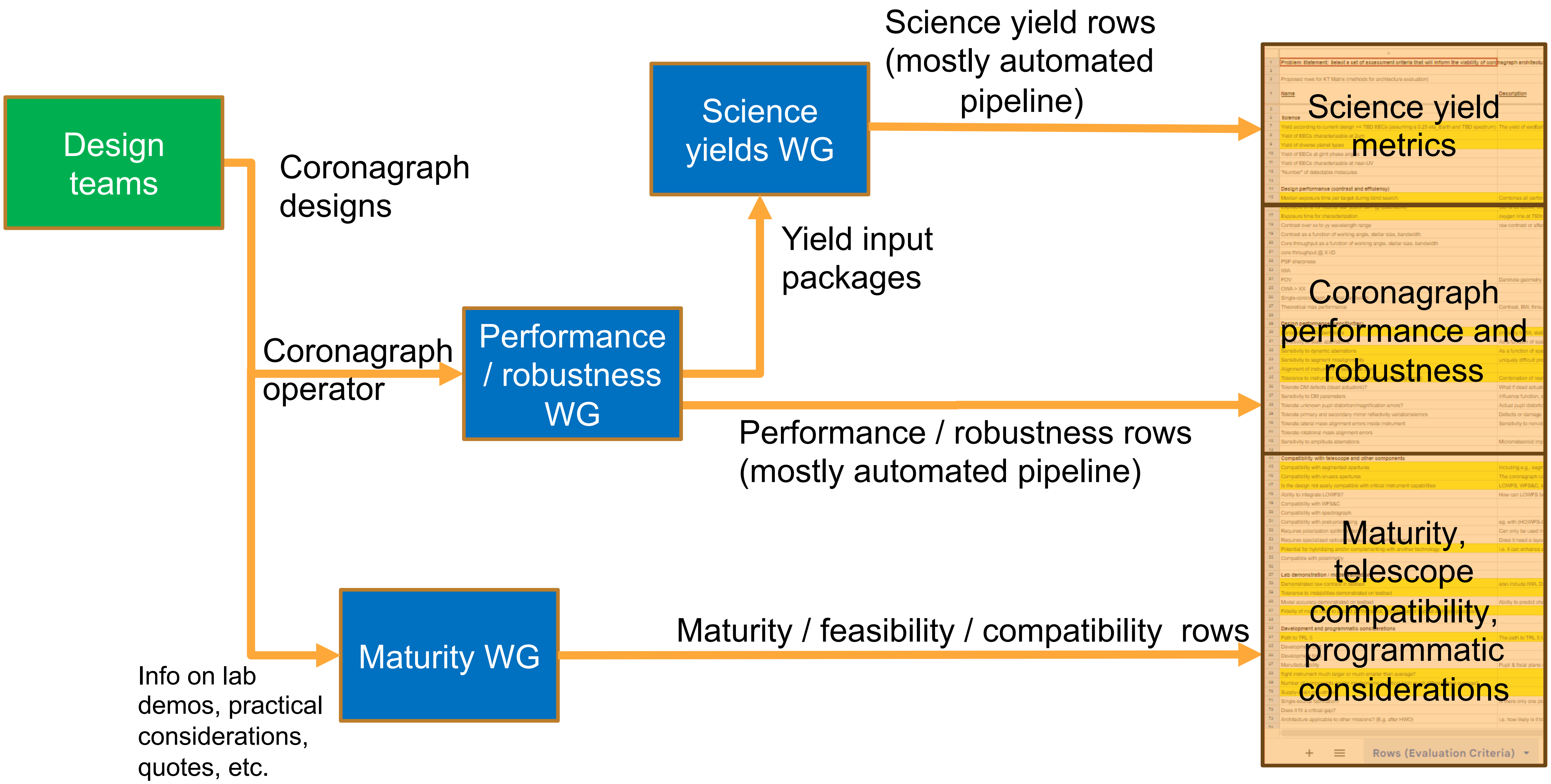
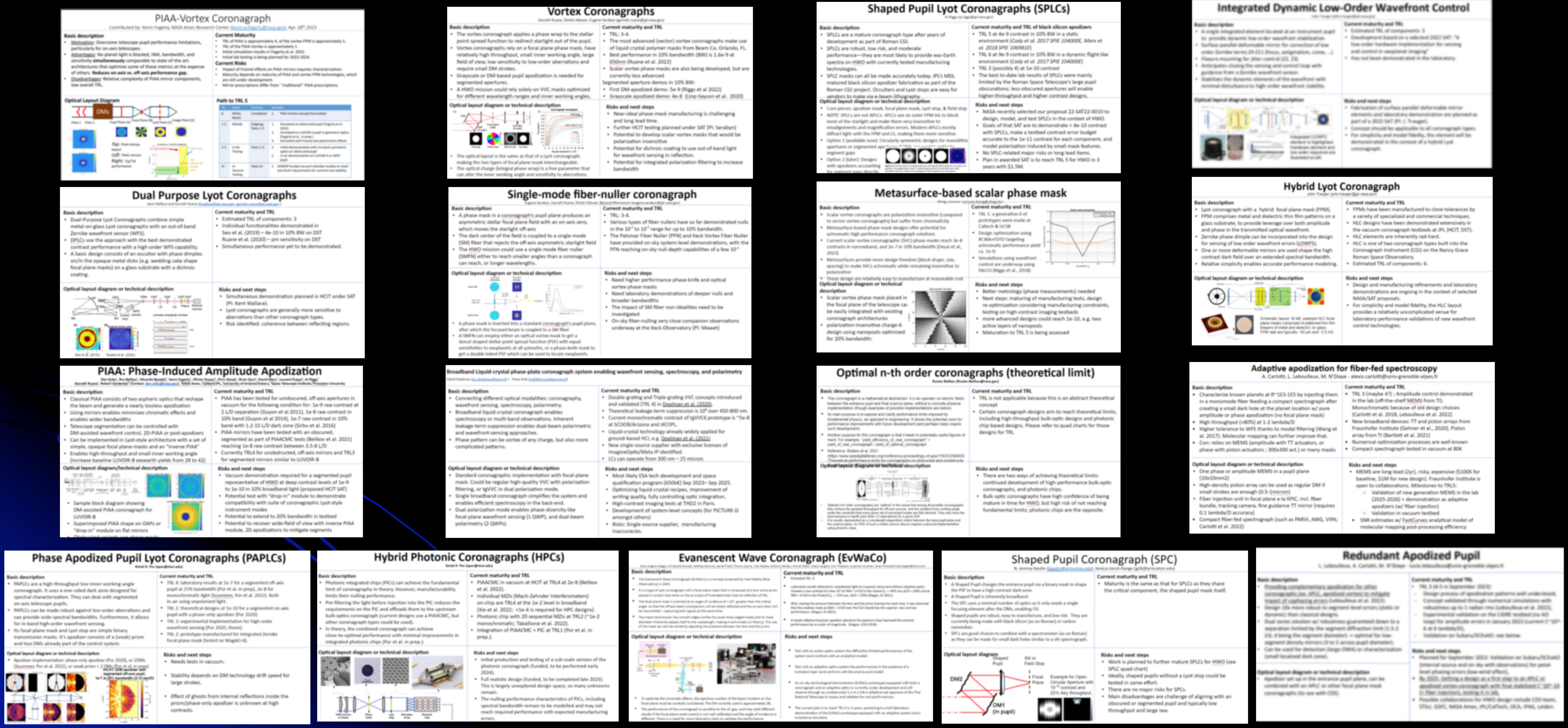

Create Task Plan (ExEP + Task co-leads)
Select members of the Working Group
Select Survey Criteria
Identify Coronagraph Design Options
Hold community townhall to brief progress and get feedback
Assess the Coronagraph Design Options with respect to the Survey Criteria, identify/assess Opportunities and Risks
Hold community townhall to brief assessment of the Coronagraph Design Options and get feedback
Complete Final Report for the ExEP
Brief APD

Workflow


Design teams
Coronagraph designs
Coronagraph operator
Science yields WG
Yield input packages
Performance / robustness WG
Maturity WG
Info on lab demos, practical considerations, quotes, etc.
Science yield rows (mostly automated pipeline)
Performance / robustness rows (mostly automated pipeline)
Maturity / feasibility / compatibility rows
Science yield metrics
Coronagraph performance and robustness
Maturity, telescope compatibility, programmatic considerations
Rows (Evaluation Criteria)

Coronagraph technologies / designs submitted to Coronagraph Design Survey



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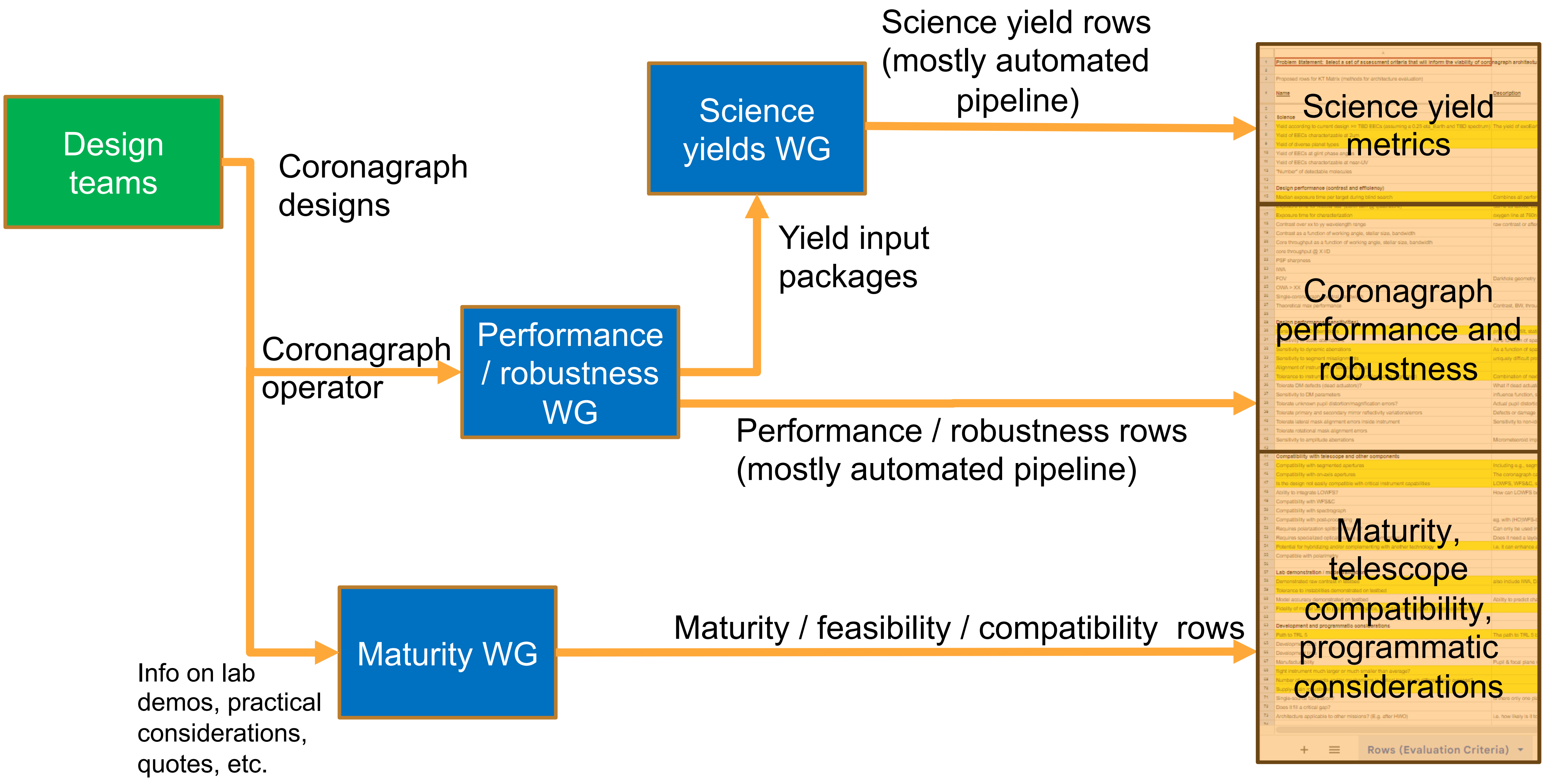
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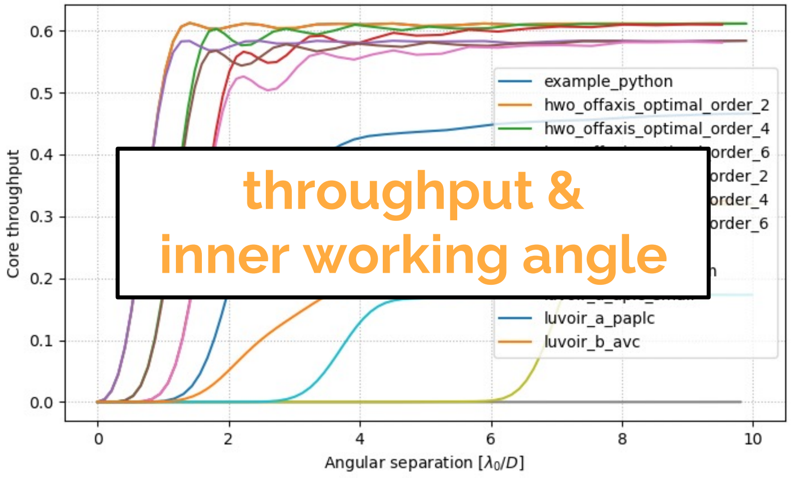
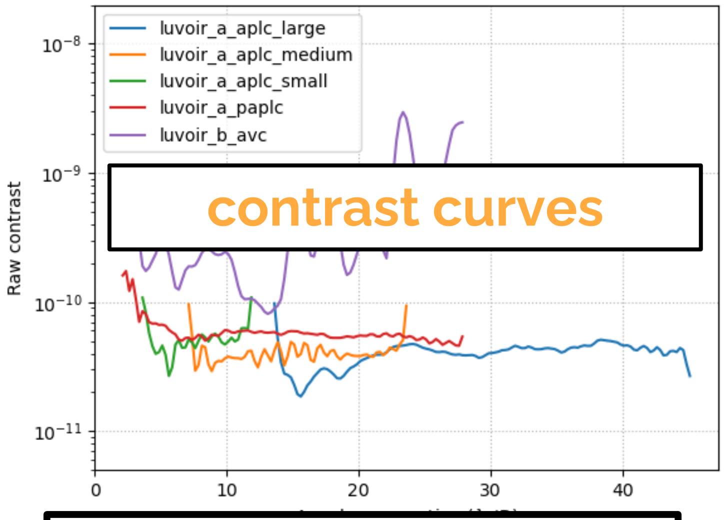
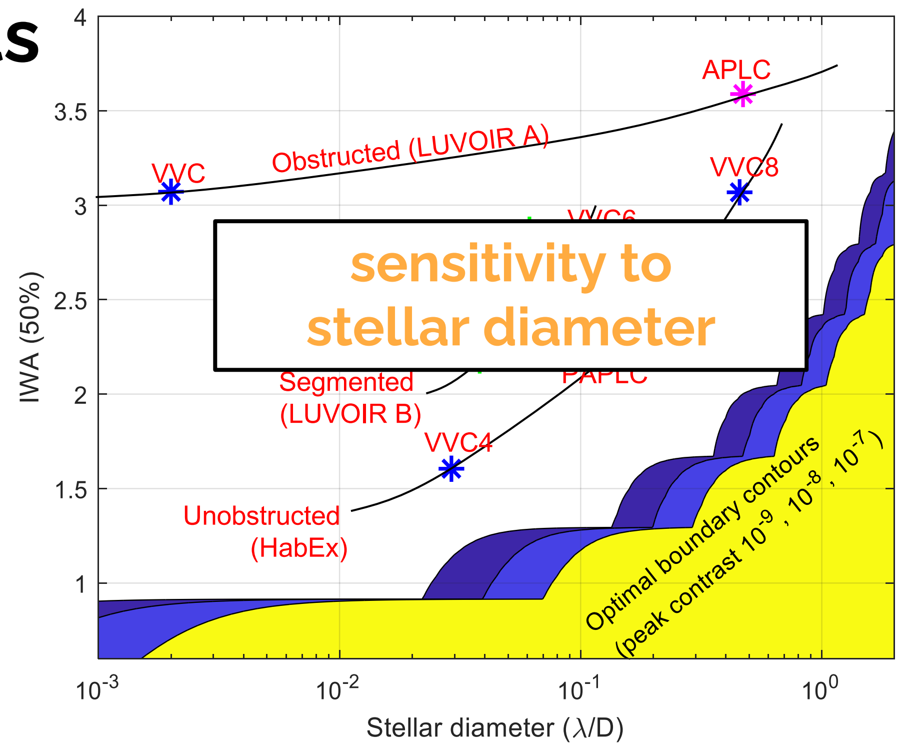
Performance / robustness pipeline products

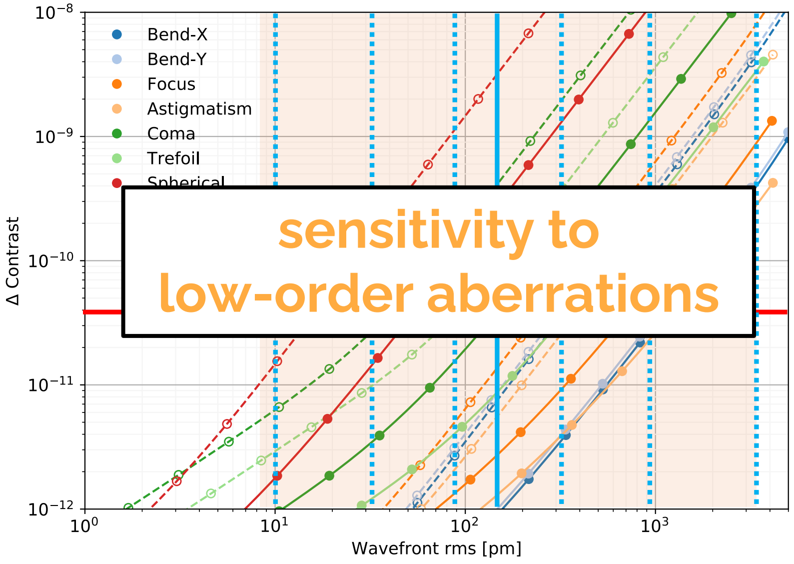
(Working group lead: Emiel Por)

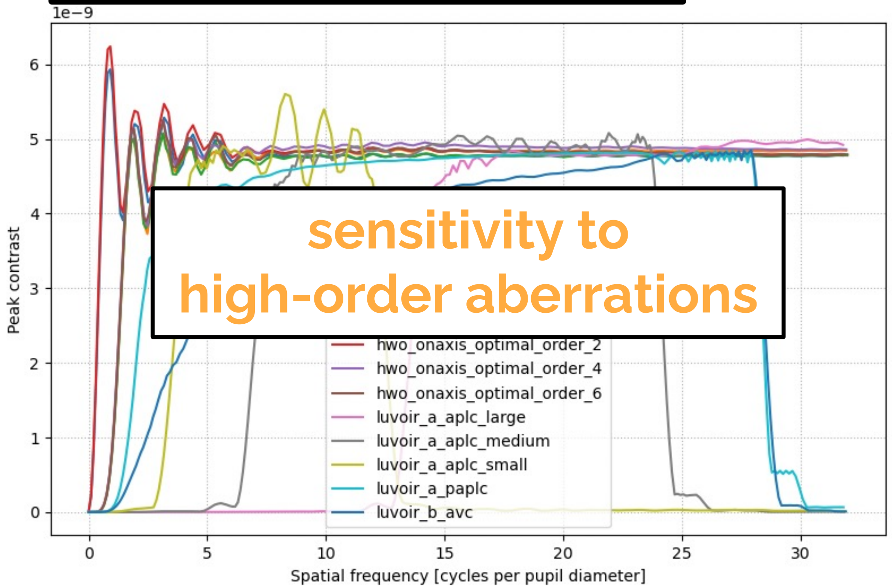


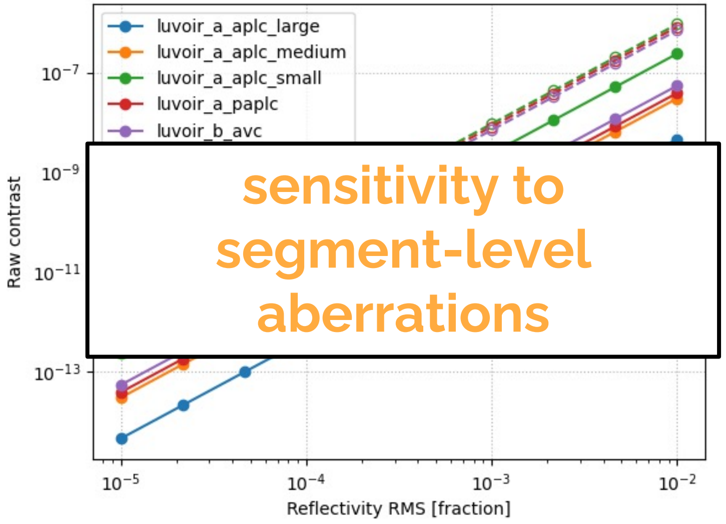




and more!







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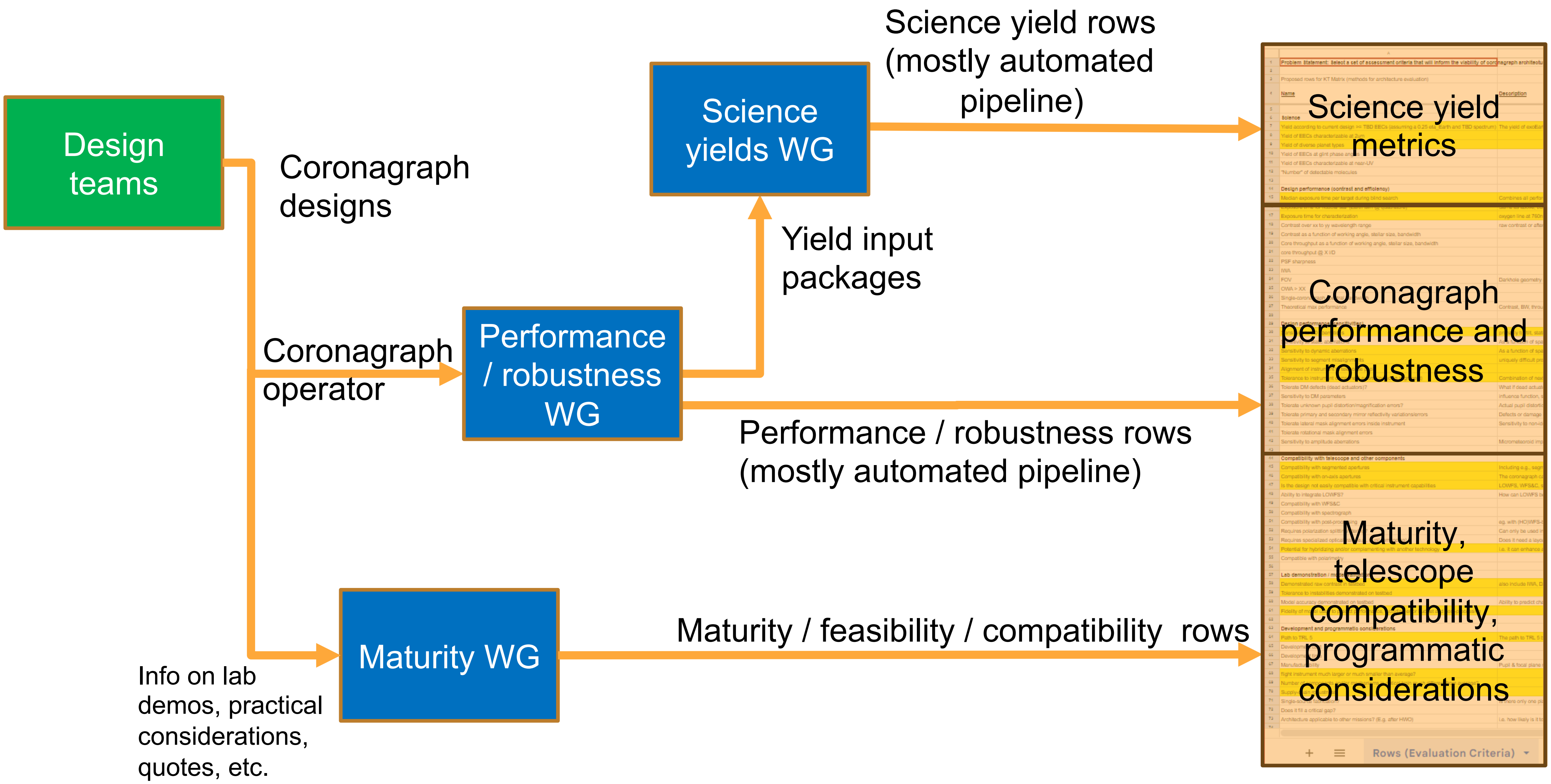
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Science Yield working group

(led by Chris Stark)

Draft evaluation criteria

Science
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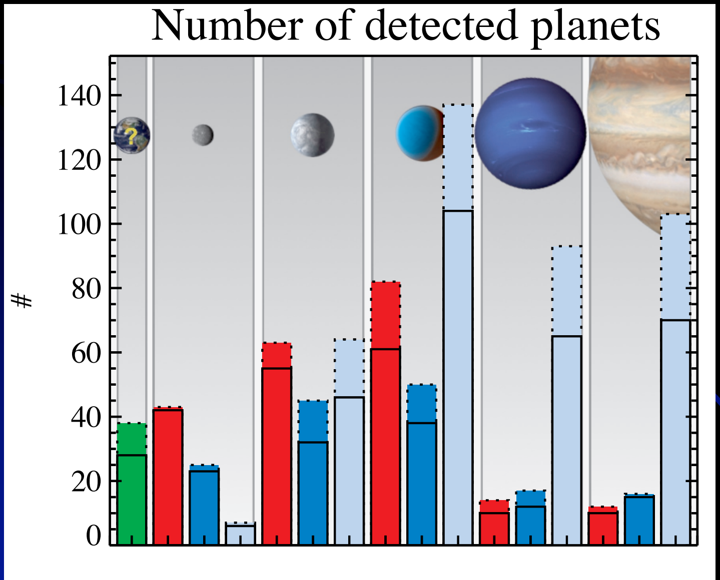
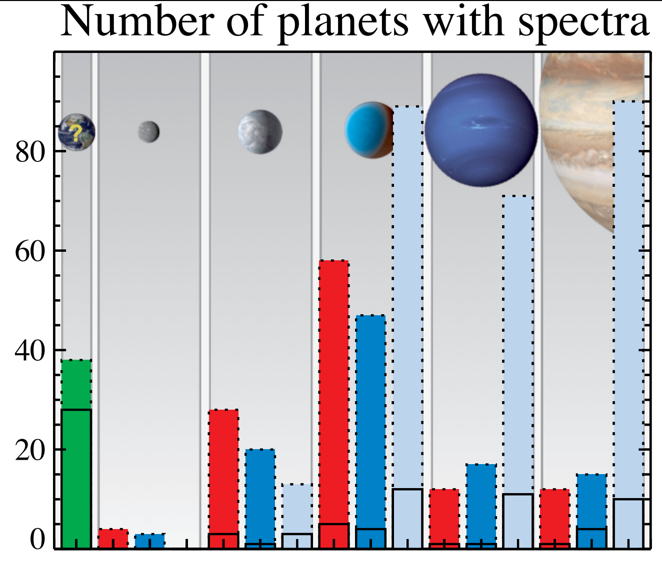
Design performance (contrast and efficiency)
Median exposure time per target during blind search
Exposure time for fiducial star (Earth twin @ quadrature)
Exposure time for characterization

Examples of products





Howe et al. (submitted)

Draft fiducial mission parameters

Table 2. Coronagraph-based Mission Parameters

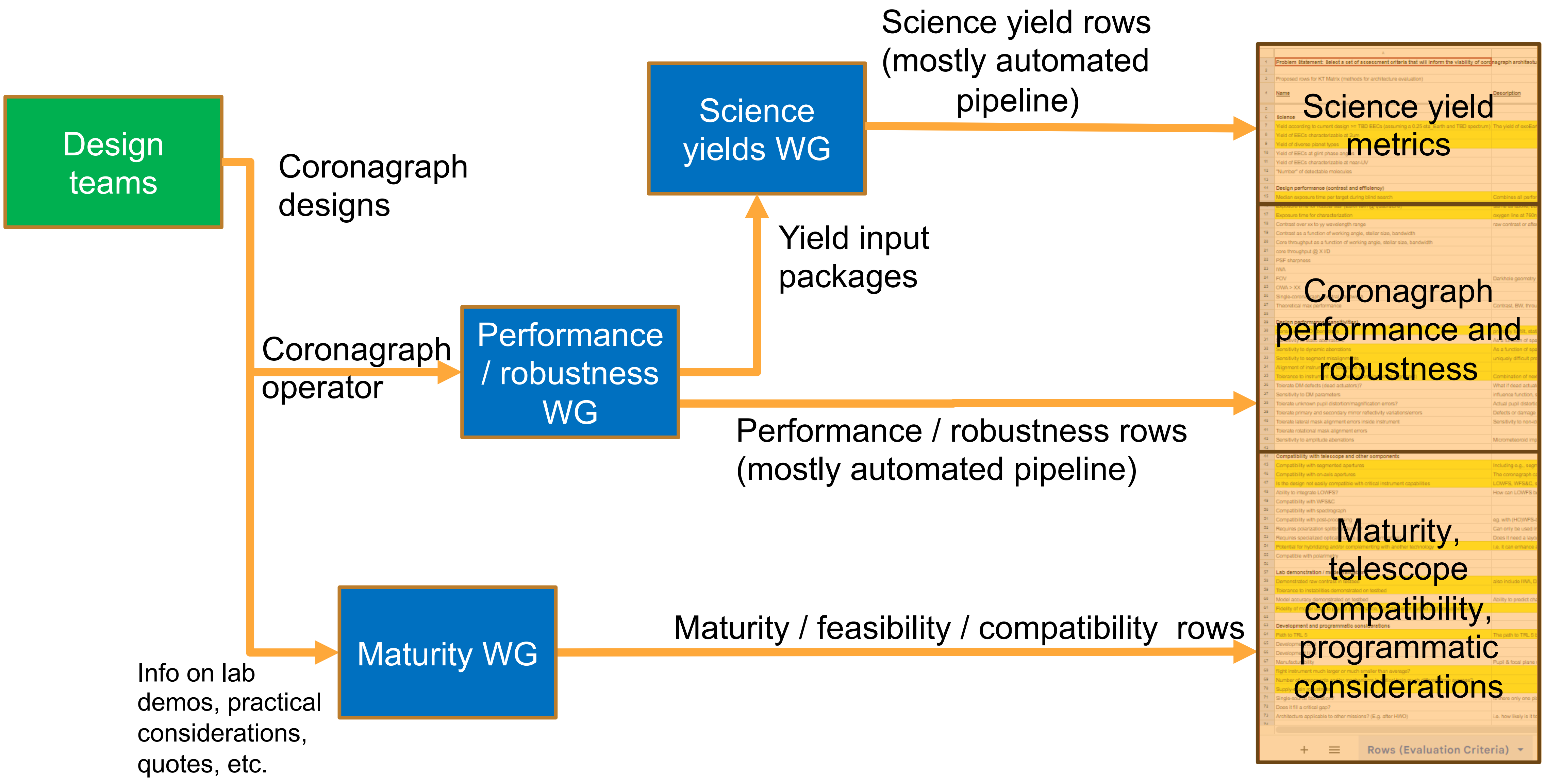
Parameter	Value	Description
		General Parameters
$\Sigma\tau$	2 yrs	Total exoplanet science time of the mission
$\tau_{\rm slew}$	1 hr	Static overhead for slew and settling time
$\tau_{\rm WFC}$	2.7 hrs[a]	Static overhead to dig dark hole
$\tau'_{\rm WFC}$	1.1	Multiplicative overhead to touch up dark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

[a]See Eq. 17 from Ref. ?

[b]$D_{\rm LS}$ is the diameter of Lyot stop projected onto the primary mirror

[c]Example provided at most likely bandpass; AYO optimizes bandpass and adjusts values accordingly.

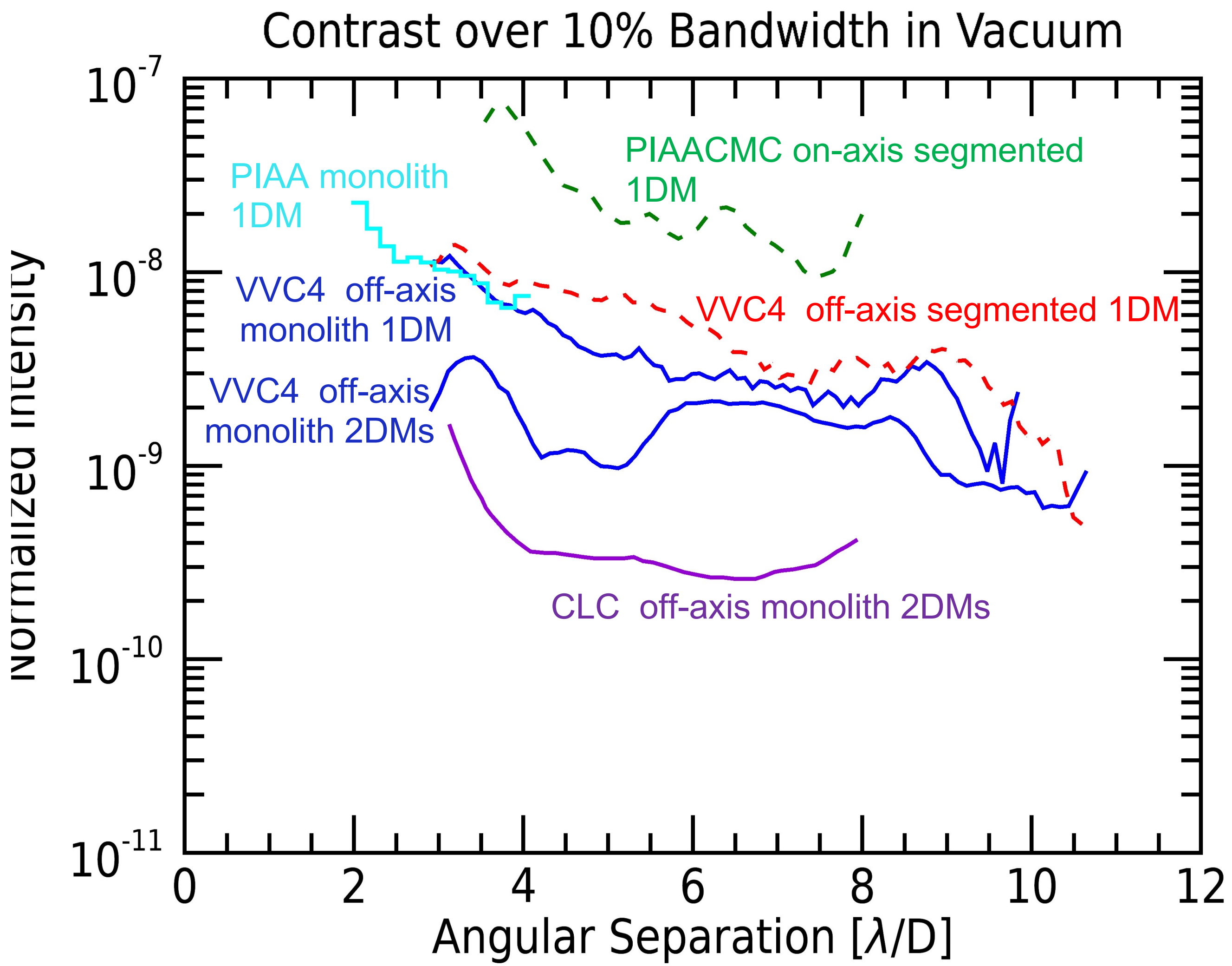
Workflow


Design teams
Coronagraph designs
Coronagraph operator
Performance / robustness WG
Science yields WG
Yield input packages
Science yield rows (mostly automated pipeline)
Performance / robustness rows (mostly automated pipeline)
Maturity WG
Maturity / feasibility / compatibility rows
Info on lab demos, practical considerations, quotes, etc.
Science yield metrics
Coronagraph performance and robustness
Maturity, telescope compatibility, programmatic considerations
Rows (Evaluation Criteria)

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)	



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 LUVOIR/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 ~5e-10.
  - This trade space is coupled with telescope and DMs


~1e-11, 6K λ/D
~2e-10, 4K λ/D
~4e-10, 4K λ/D