Coronagraph Design Survey for Future Exoplanet Direct Imaging Space Missions

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ExEP colloquium : 05/20/2024


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

3 Synergistic but Distinct Roadmap and Survey Efforts

NASA EXOPLANET EXPLORATION PROGRAM

Coronagraph Technology Roadmap

Pin Chen
(NASA ExEP)

Laurent Pueyo
(STScI)

Primary Objectives:

1. Roadmap for coronagraph technologies to reach TRL 5 for HWO.
2. Inform NASA on prioritized investments to ensure coronagraph technology readiness.

ExEP Colloquium: June 11
(Final written report to follow)

Deformable Mirror Technology Roadmap

Eduardo Bendek

Duncan Liu
(NASA JPL)

Tyler Groff
(NASA GSFC)

Primary Objectives:

1. Roadmap for DM technologies to reach TRL 5 for HWO.
2. Inform NASA on prioritized vendors, manufacturing needs, and test facilities to ensure DM technology readiness.

ExEP Colloquium: June 7
(Final written report to follow)

Coronagraph Design Survey

Rus Belikov
(NASA ARC)

Chris Stark
(NASA GSFC)

Primary Objectives:

1. Survey and document viable coronagraph architectures for HWO.
2. Identify novel coronagraph technologies for which NASA's technology development investments could be efficiently leveraged.

ExEP Colloquium: now!
(Final written report to follow)
Future briefings:

- START-TAG F2F, June 3rd, 11:10 - 11:45
- SPIE poster and proceedings (June)

Outline

- **Motivation, goals, deliverables**
- **Results**
  - Summary of findings
  - Information Matrix
  - Process and CDS pipeline
  - Technical performance and robustness
  - Maturity
  - Science Yields
- **Conclusions**

Outline

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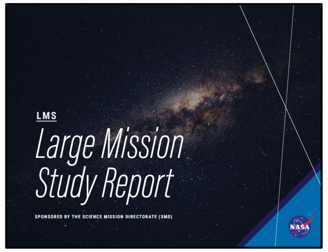
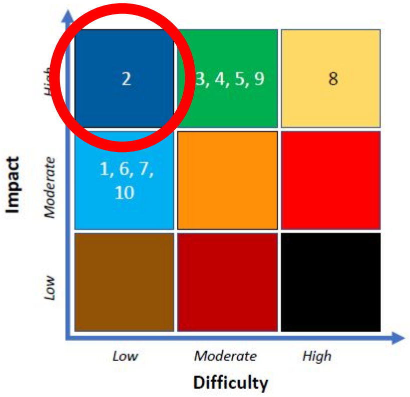
Motivation: let's make HWO as great a mission as possible!
LMS and Decadal Survey recommend thorough, early, well-funded trades

LMS (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 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*

Astro2020

"Inadequate funding for concept studies, concept, and technology development"

- "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.

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**[…]*"

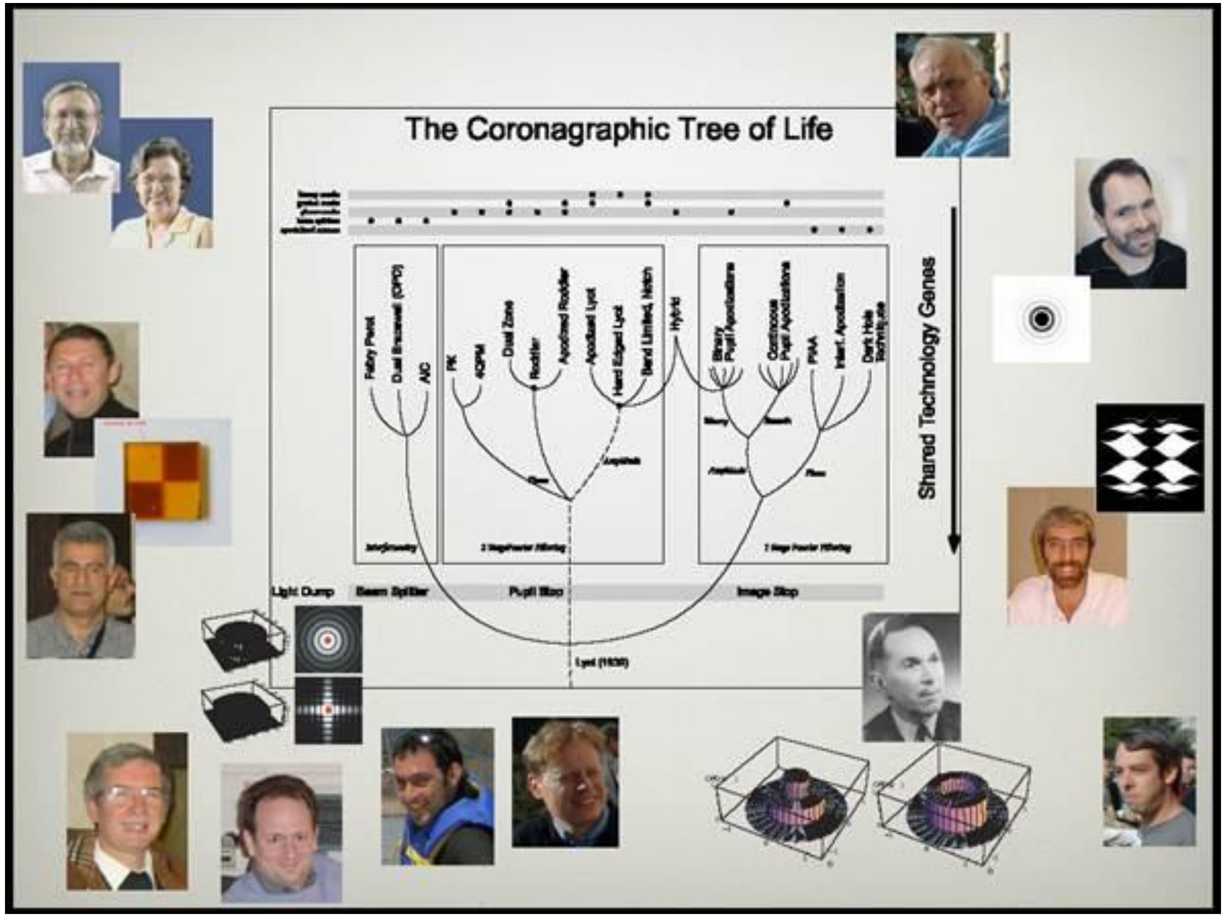
- SMD's large mission study report (https://science.nasa.gov/about-us/large-mission-study)

*"[GOMAP] 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,"*

- Astro2020 Decadal Survey (2021).

Coronagraph design trade space is very rich

Many coronagraph designs have been invented since Lyot's original 1930 concept, with several new advances since 2019



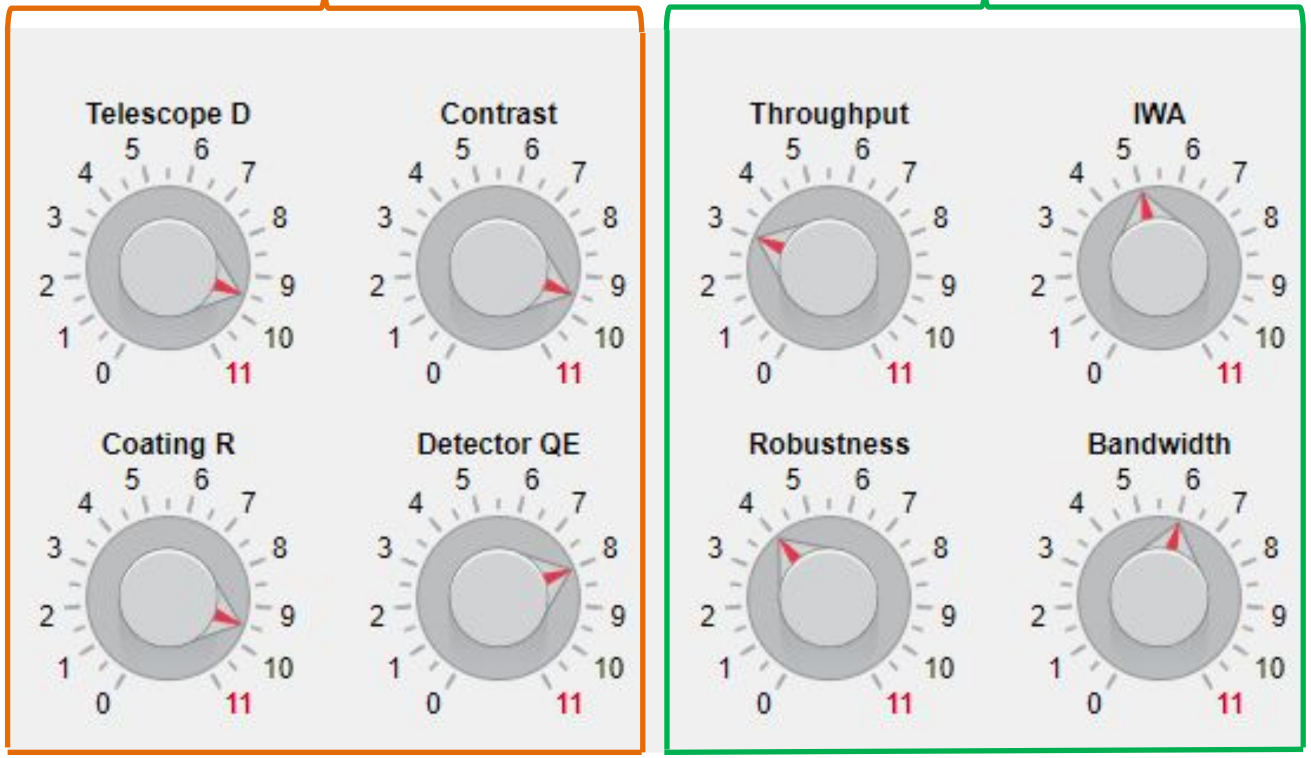
Courtesy of James Lloyd, ~2003

Coronagraph trade space has powerful levers/knobs to reduce risk and cost on mission

Examples of "knobs"

Knobs that may be close to saturation
(a lot of non-coronagraphic knobs are in this category)

Knobs with a lot of room to improve before physics limits
(a lot of coronagraphic knobs are in this category)



Yield estimates have already improved by ~50% or more with new coronagraph designs since 2019
Potential to relax key requirements (such as stability and even contrast, etc.)

Note: the knobs on this slide are meant as a high-level cartoon for illustration purposes only. Values of the knobs are n
meant to represent accurate values. (Later slides will show a more quantitative analysis of some of the knobs.)

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
- Inform and facilitate upcoming HWO trade and parameter studies
- Enable coronagraph designers to rapidly evaluate and iterate their designs according to a uniform set of metrics for HWO

Products and Deliverables

- **Information Matrix summarizing our surveyed coronagraphs**
  - **No downselecting! (Fact-finding only.)**
  - Intended to be a living document, periodically updated as coronagraphs mature, new designs become available, and possible changes to metrics (including yield) become standardized

- **Survey briefings and Final Report**
  - Description of process
  - Surveyed coronagraph options
  - Survey findings

- **Software Pipeline**
  - Intended as a tool for
    - START / TAG, to facilitate rapid coronagraph parameter studies
    - Coronagraph designers, to facilitate evaluation of their designs according to HWO metrics, and guide optimizations
  - Public release coming soon (please contact us if you would like a demo / preview)

Outline

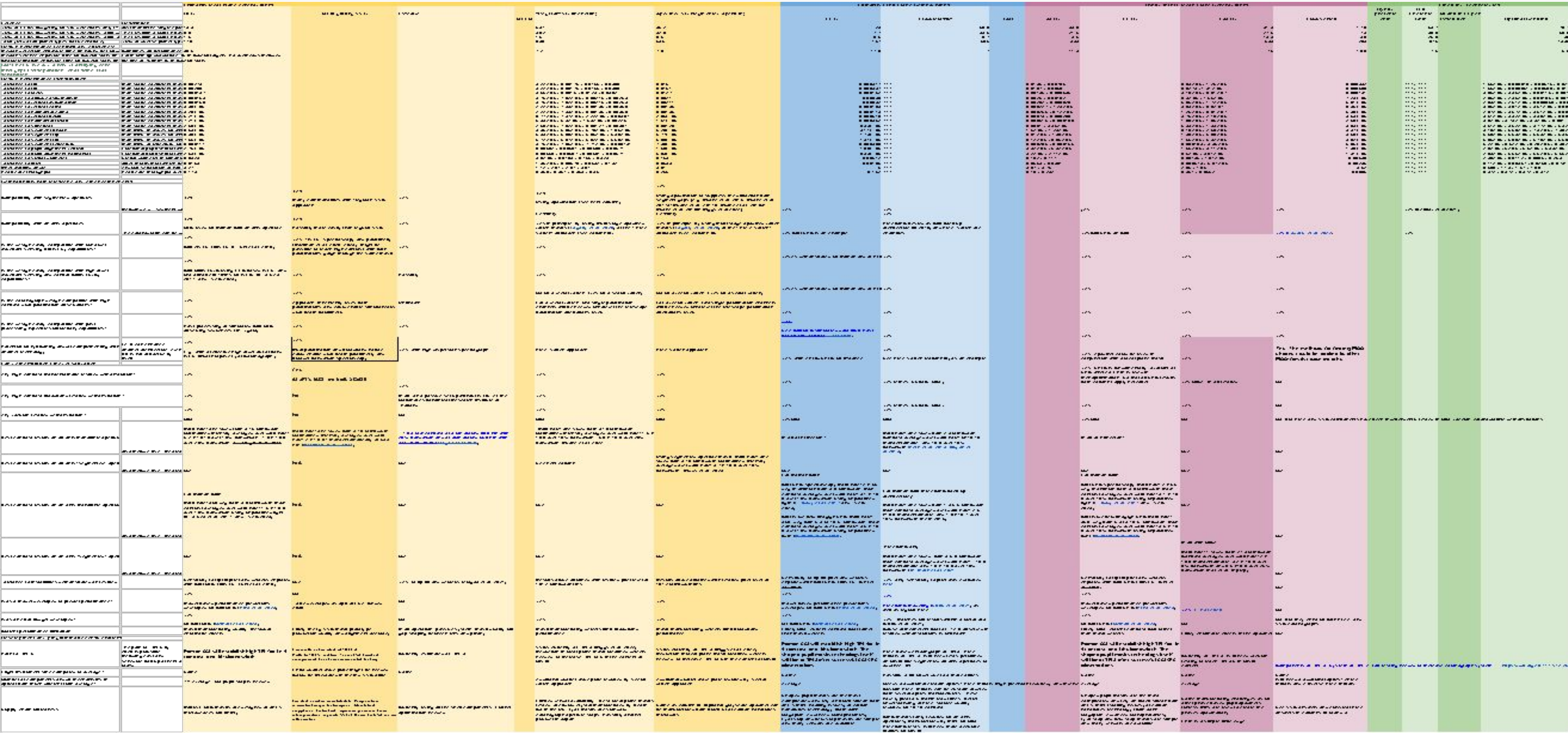
- **Motivation, goals, deliverables**
- **Results**
  - Information Matrix
  - Process and CDS pipeline
  - Technical performance and robustness
  - Maturity
  - Science Yields
- **Findings and conclusions**

Survey Summary Matrix: rows are metrics

Current version located at: https://docs.google.com/spreadsheets/d/1Z_D0H4VA1RWyBxuk5VzW4reOKAijnSUGaVjzP_vVWRQ/edit#gid=2138297368

Permanent location of the living version: TBD

We will zoom in on this matrix in later slides



Survey Summary Matrix: rows are metrics

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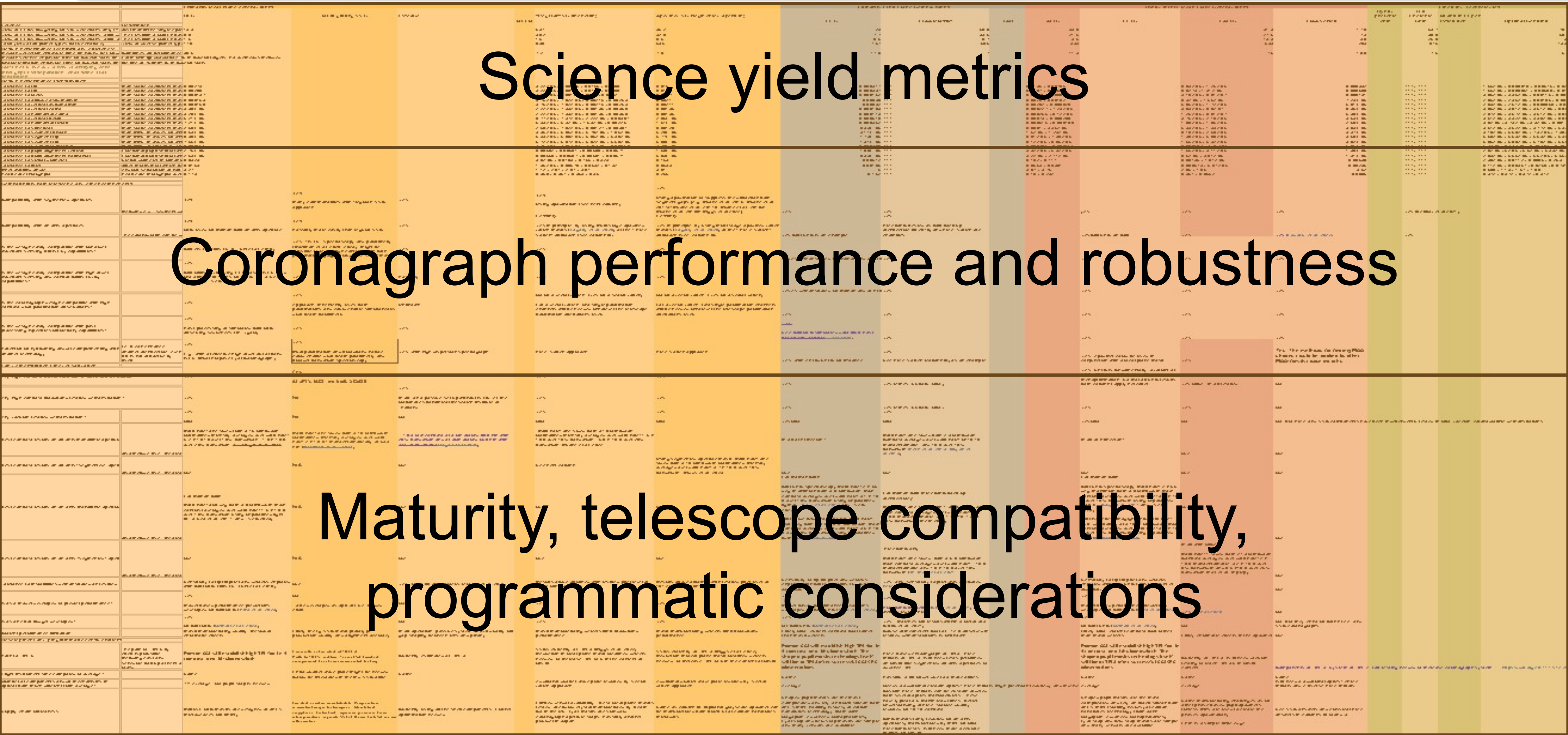

Survey Summary Matrix: columns are coronagraphs

Current version located at: https://docs.google.com/spreadsheets/d/1Z_D0H4VA1RWyBxuk5VzW4reOKAijnSUGaVjzP_vVWRQ/edit#gid=2138297368

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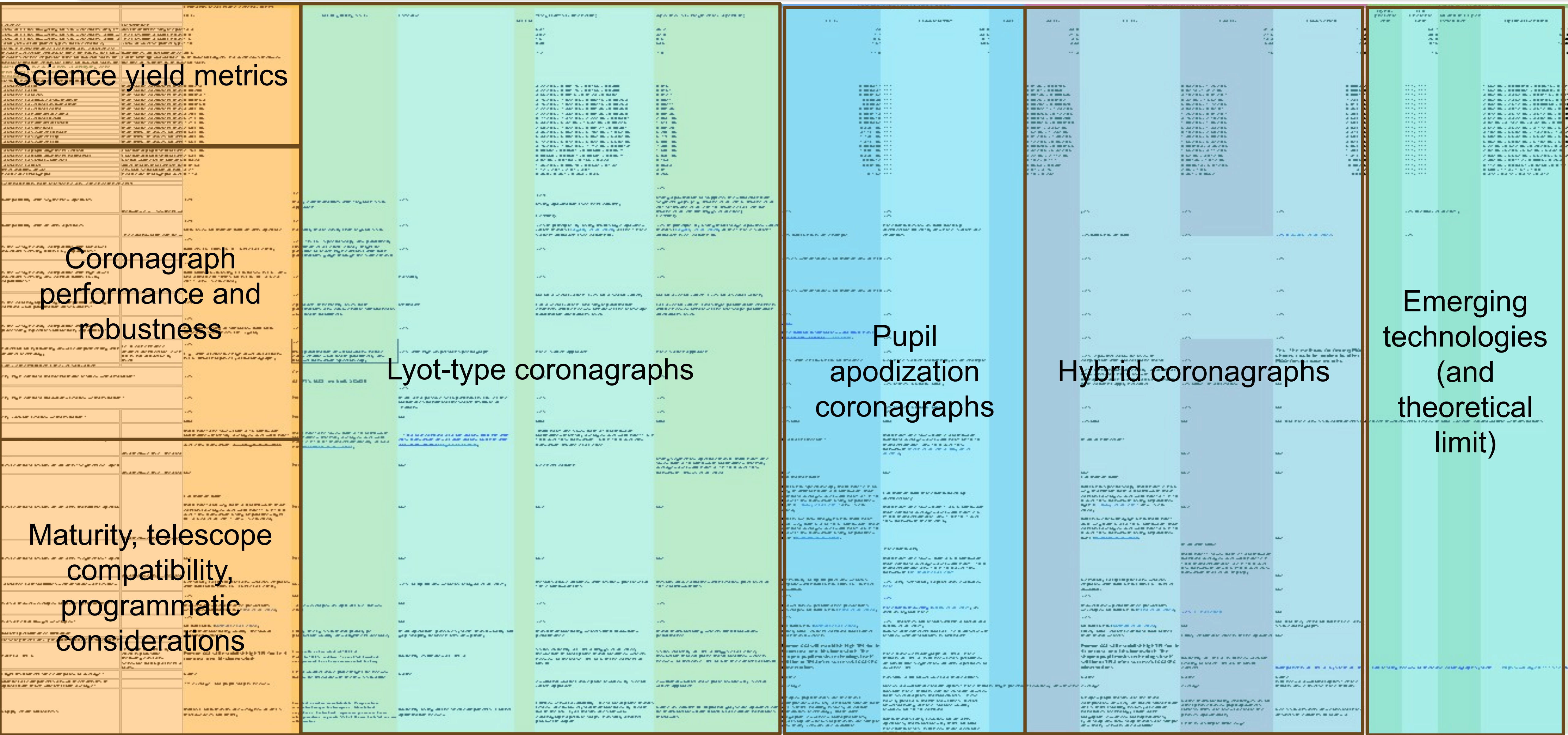
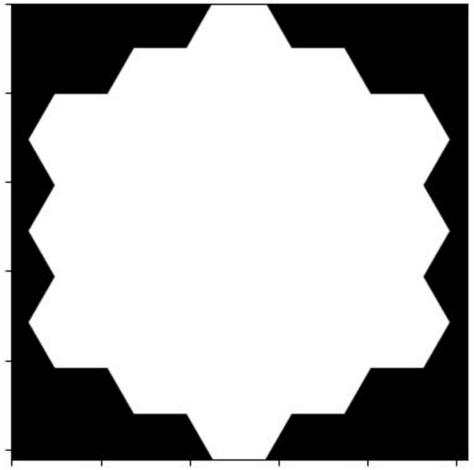


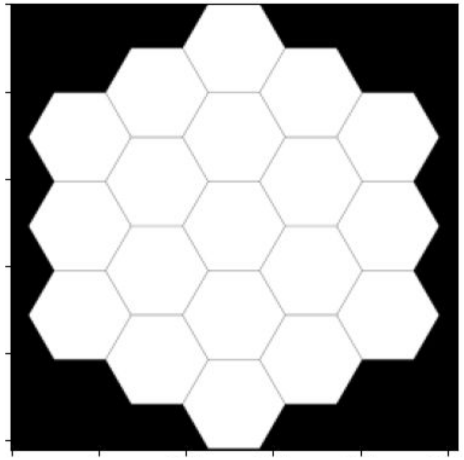
Overview of Apertures and Surveyed Designs

USORT monolithic



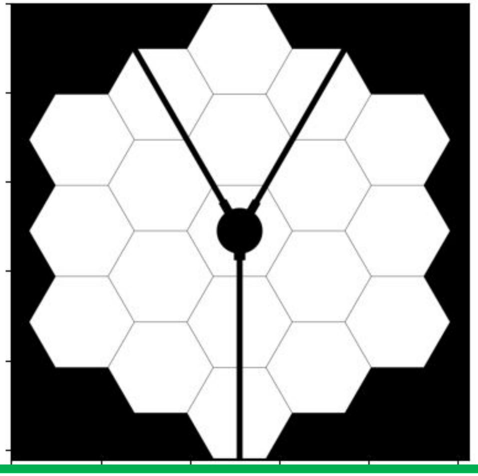
VC (4 designs)
LCPPC (1 design)
PIAA (1 design)
Optimal 2N (4 designs)

USORT off-axis



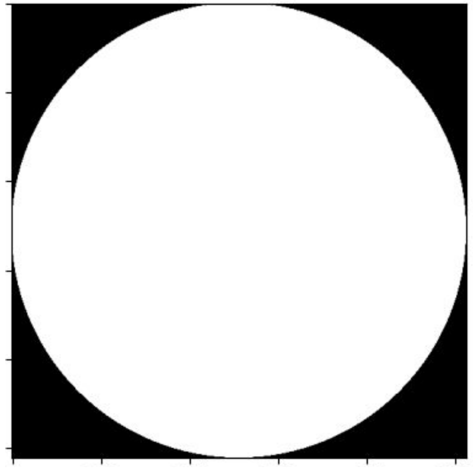
AAVC (1 design)
SPC (1 design)
APLC (2 designs)
PIC (5 designs)
Optimal 2N (4 designs)

USORT on-axis



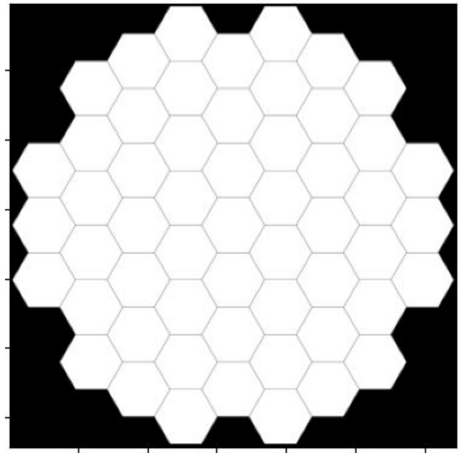
PIAA-VC (1 design)
Optimal 2N (4 designs)

HabEx / monolithic



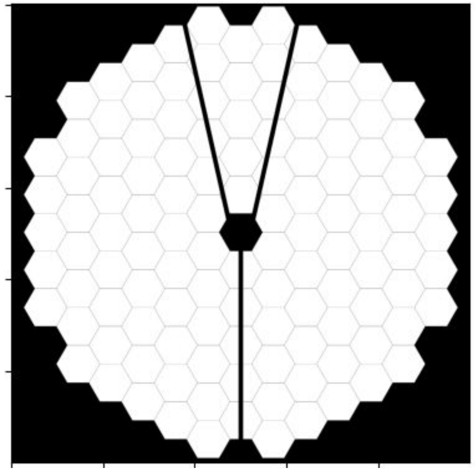
Vector vortex (4 designs)
Optimal 2N (4 designs)

LUVOIR B



AVC (2 designs)
HLC (1 design)

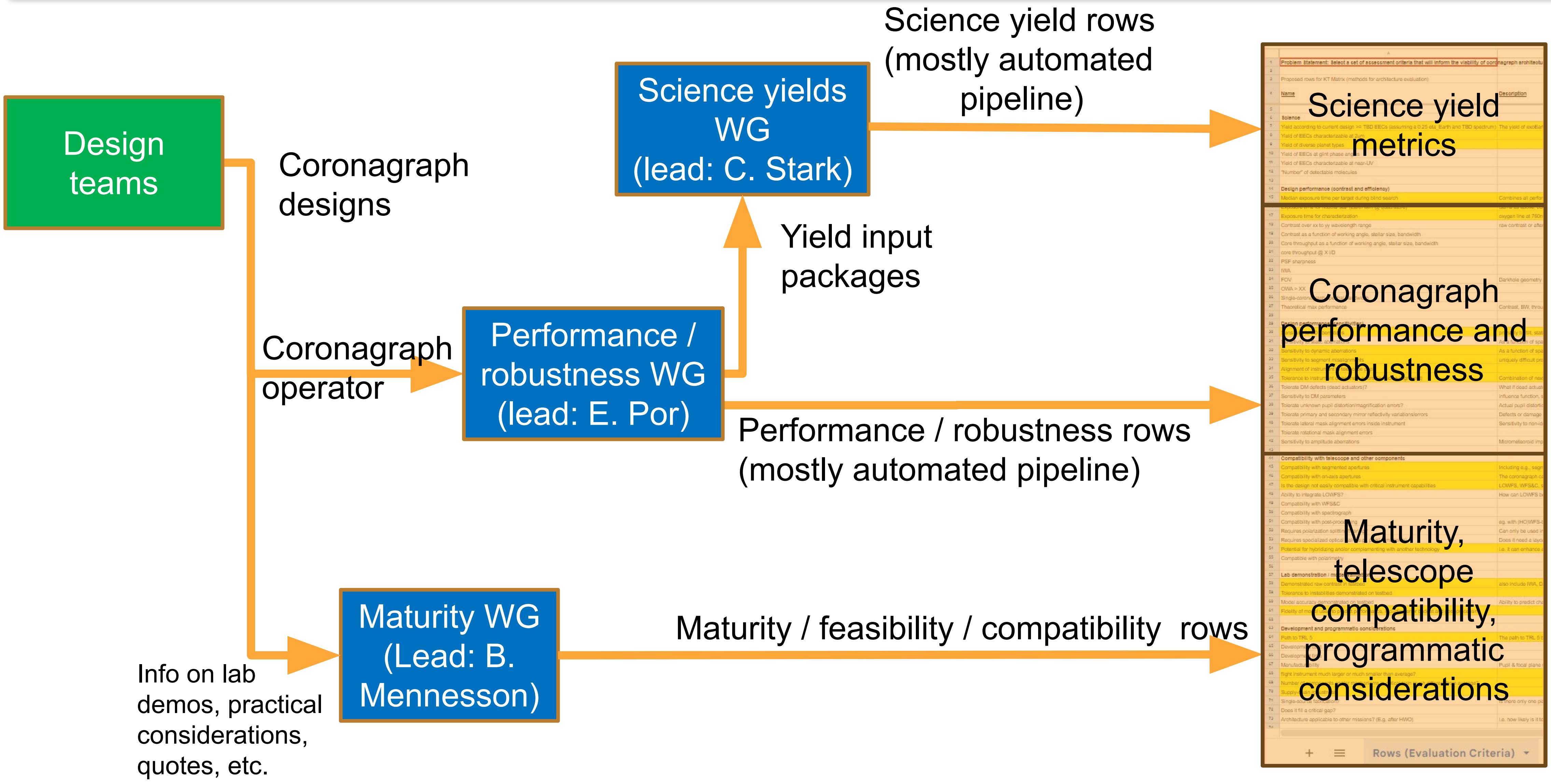
LUVOIR A



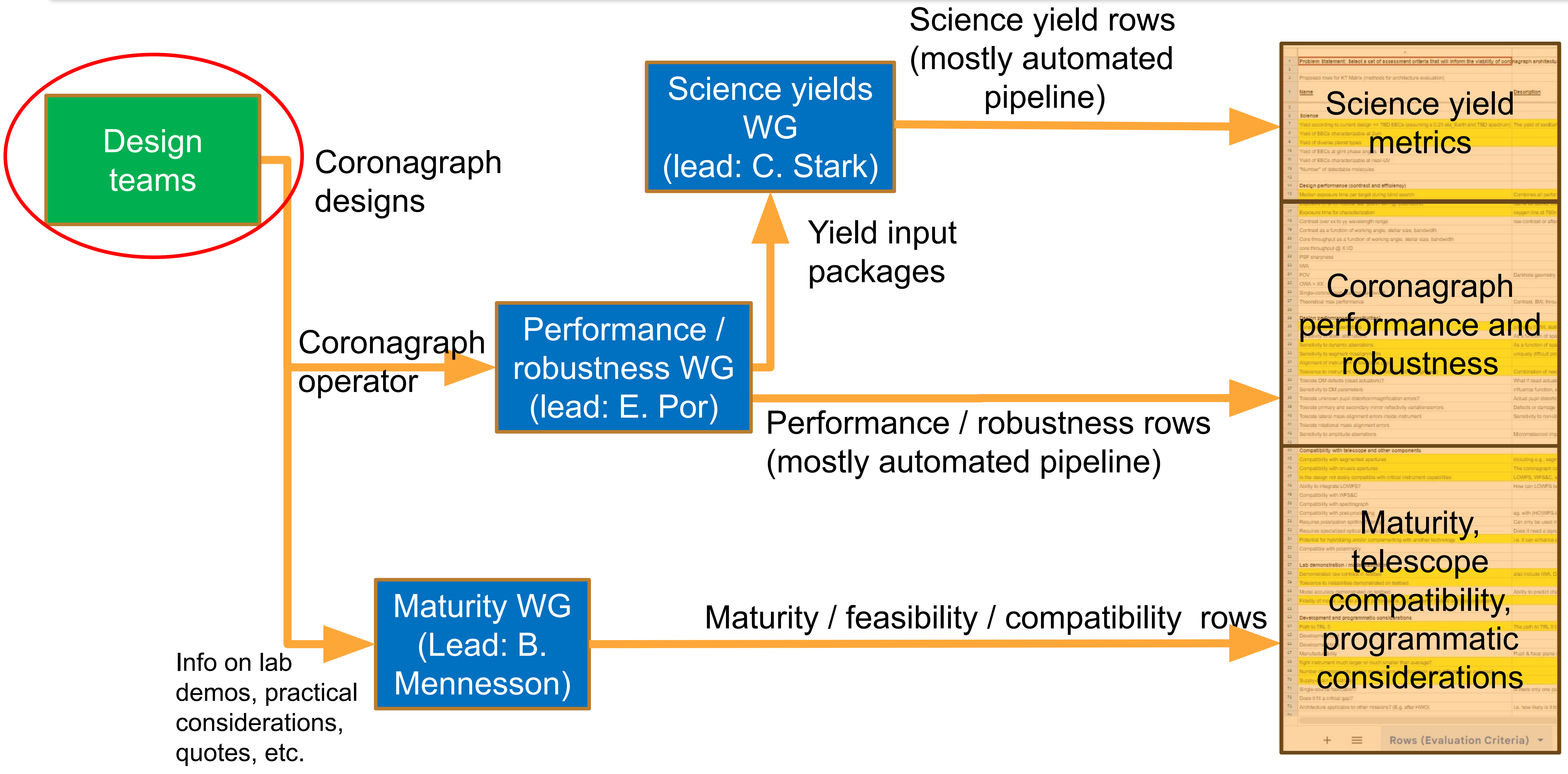
APLC (3 designs)
PAPLC (1 design)

15 architecture concepts surveyed, + 1 optimal coronagraph (theoretical limit) + 5 enhancing techs
28 coronagraph designs surveyed, + 16 optimal coronagraph designs, spanning **6 apertures**

Workflow and Pipeline



Workflow and Pipeline



Coronagraph Designs Submitted to Coronagraph Design Survey

NASA EXOPLANET EXPLORATION PROGRAM

Primarily focal-plane

Vortex Coronagraphs

Hybrid Lyot Coronagraph

Evanescent Wave Coronagraph (EvWaCo)

Metasurface-based scalar phase mask

Broadband Liquid-crystal phase-plate coronagraph system enabling wavefront sensing, spectroscopy, and polarimetry

Primarily pupil-plane

Shaped Pupil Coronagraph (SPC)

PIAA: Phase-Induced Amplitude Apodization

Interferometric Apodization by Homothety (IAH)

Hybrid

PIAA-Vortex Coronagraph

Shaped Pupil Lyot Coronagraphs (SPLCs)

Phase Apodized Pupil Lyot Coronagraphs (PAPLCs)

Emerging

Hybrid Photonic Coronagraphs (HPCs)

Photonic Coronagraph

Optimal n-th order coronagraphs (theoretical limit)

Enhancing

Dual Purpose Lyot Coronagraphs

Redundant Apodized Pupil

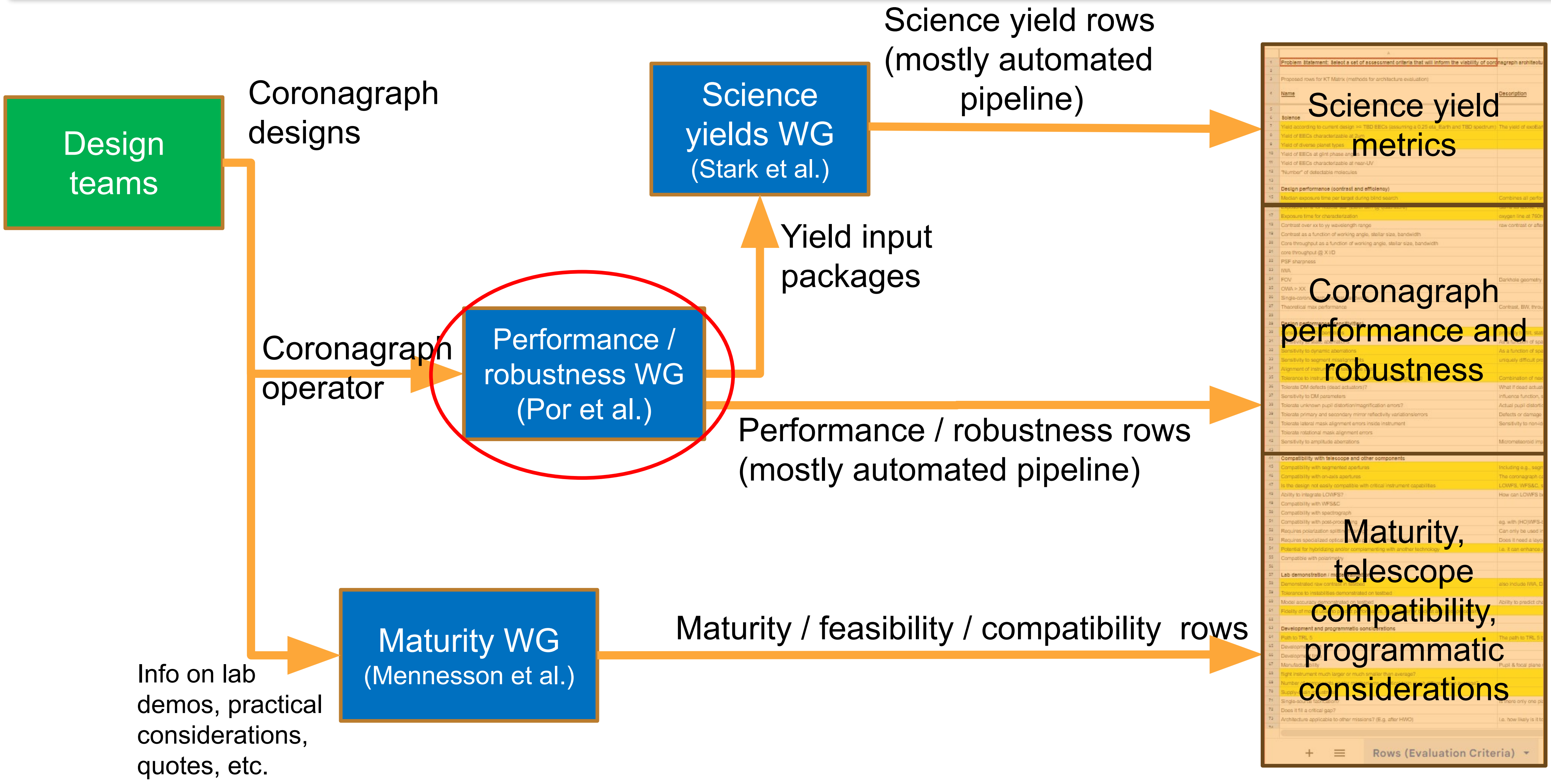
Integrated Dynamic Low-Order Wavefront Control

Single-mode fiber-nuller coronagraph

Adaptive apodization for fiber-fed spectroscopy

Pipeline designed to accept new coronagraph designs in the future, and iterations of existing designs

Workflow and Pipeline



Coronagraph Design Survey Pipeline

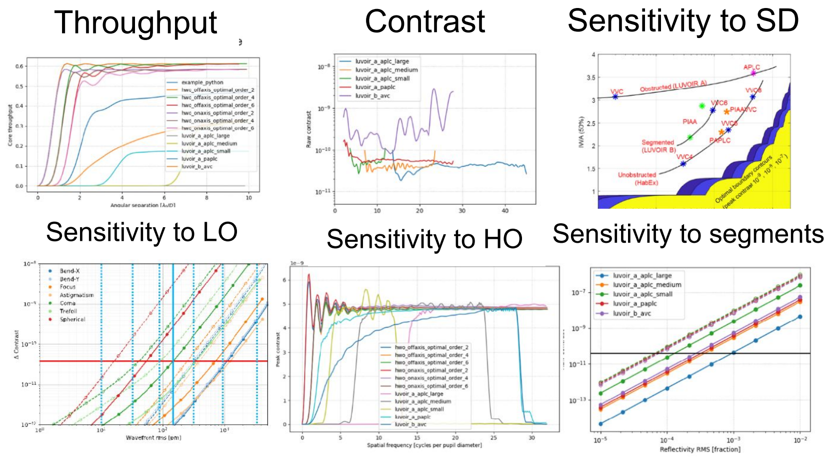
Emiel Por (primary author), Ruslan Belikov, Kevin Fogarty, John Krist, Roser Juanola Parramon, Susan Redmond, Dan Sirbu

Coronagraph design teams (worldwide)

Coronagraph design 1
Coronagraph design 2
…
Coronagraph design N
…

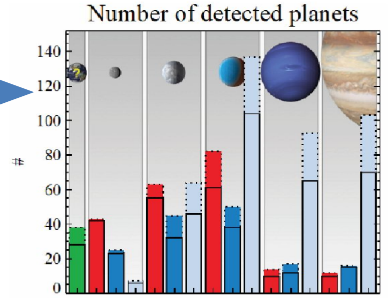
CDS performance and sensitivity calculator

Standard AYO input file package



AYO or EXOSIMS

AYO: Stark et al.
EXOSIMS: Savransky et al.



Process:

1. Design coronagraph
2. Convert to CDS standard form
3. Run pipeline
4. Get coronagraph performance metrics and yields
5. Iterate as needed

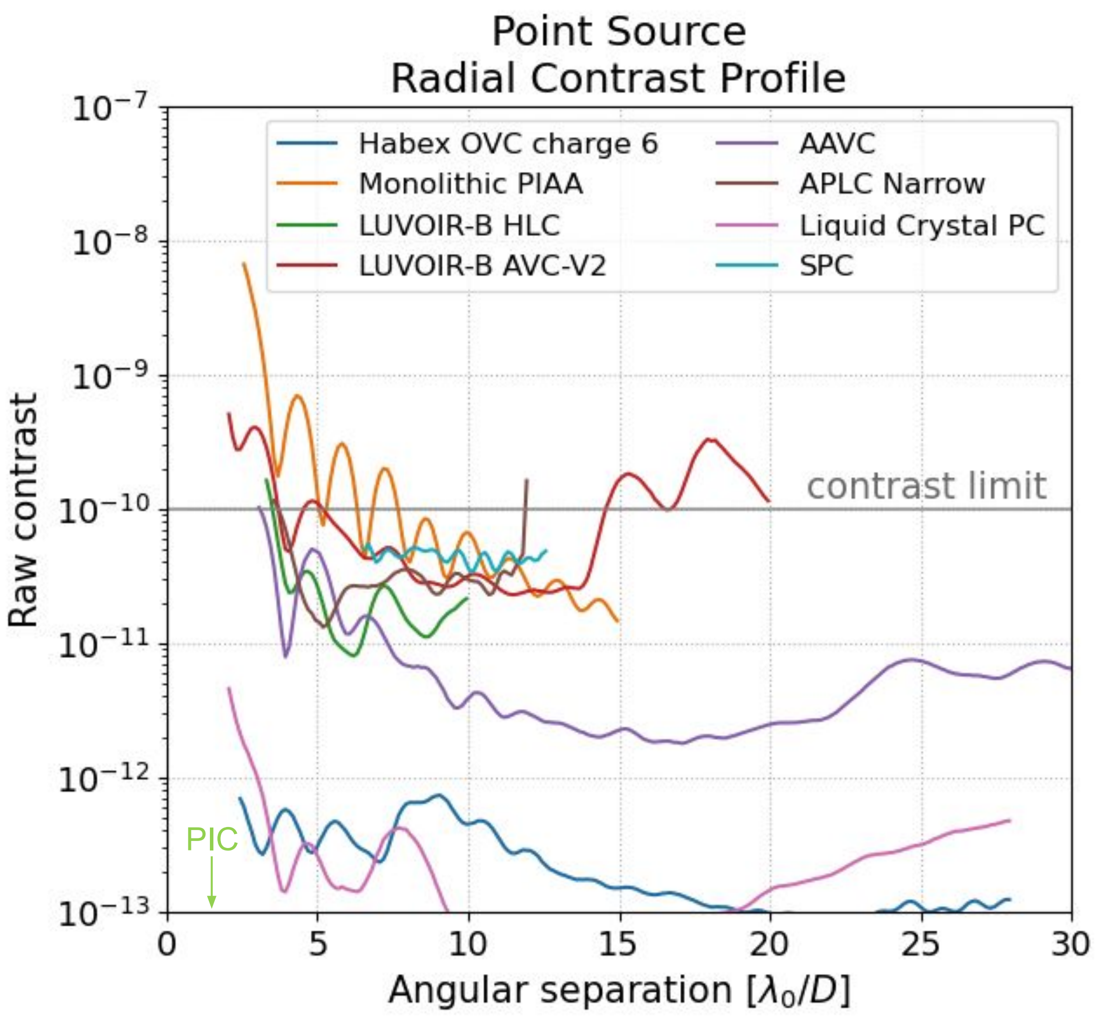
New python toolset

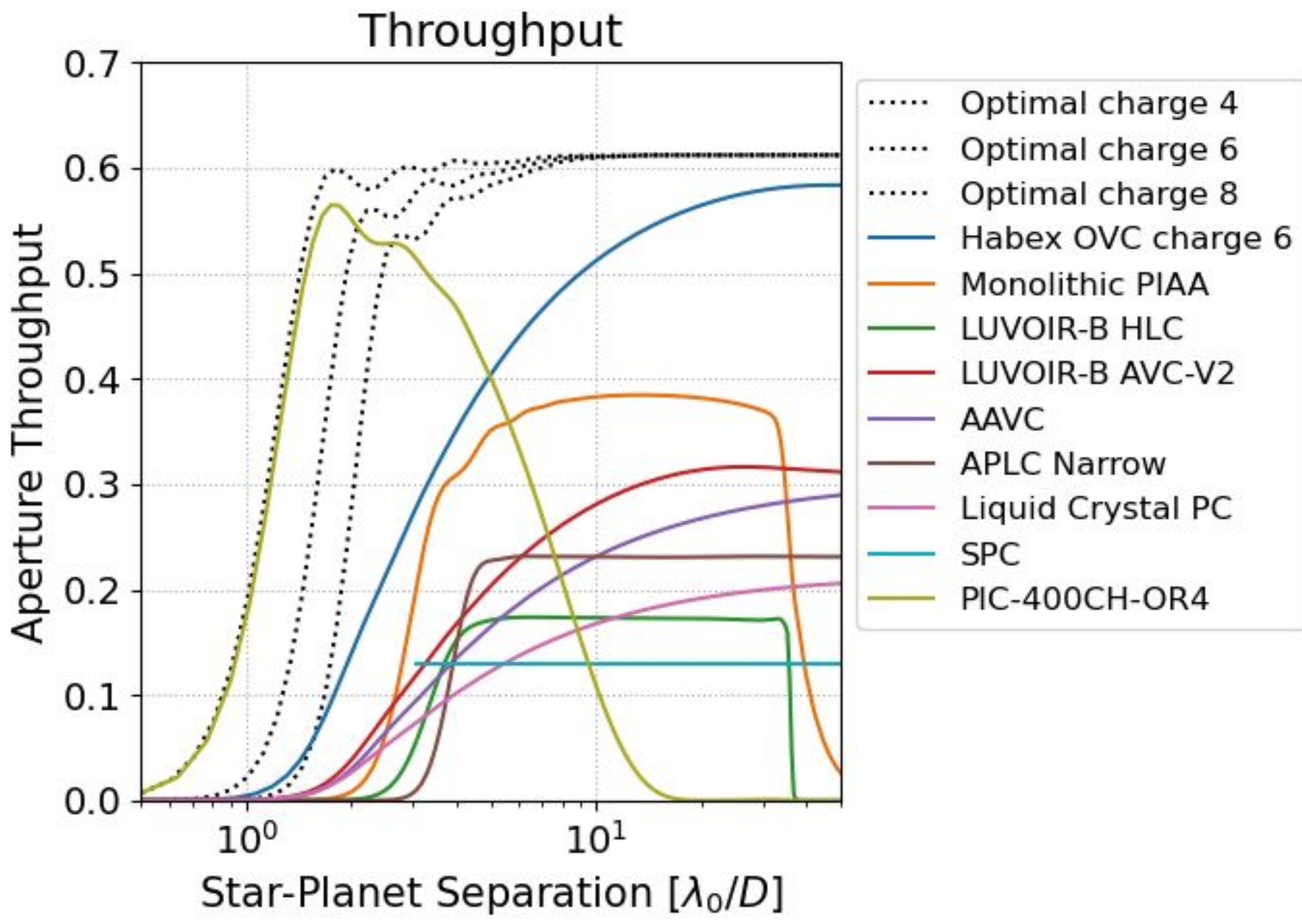
- Automated batch processing of coronagraphs
- Typical processing time minutes to hours per coronagraph (depending on coronagraph operator)
- Planned open-source release soon (please contact us if you would like a demo / preview)

Features / design goals:

- **Automation and rapid-turnaround** (minutes or hours per coronagraph for complete set of metrics+yields)
- **Standardized interface to coronagraph designs and to yield calculators:** batch processing, apples-to-apples comparisons
- **Simplicity** and low barrier of entry to coronagraph designers and START/TAG team members

Off Axis Coronagraph Designs Point Source



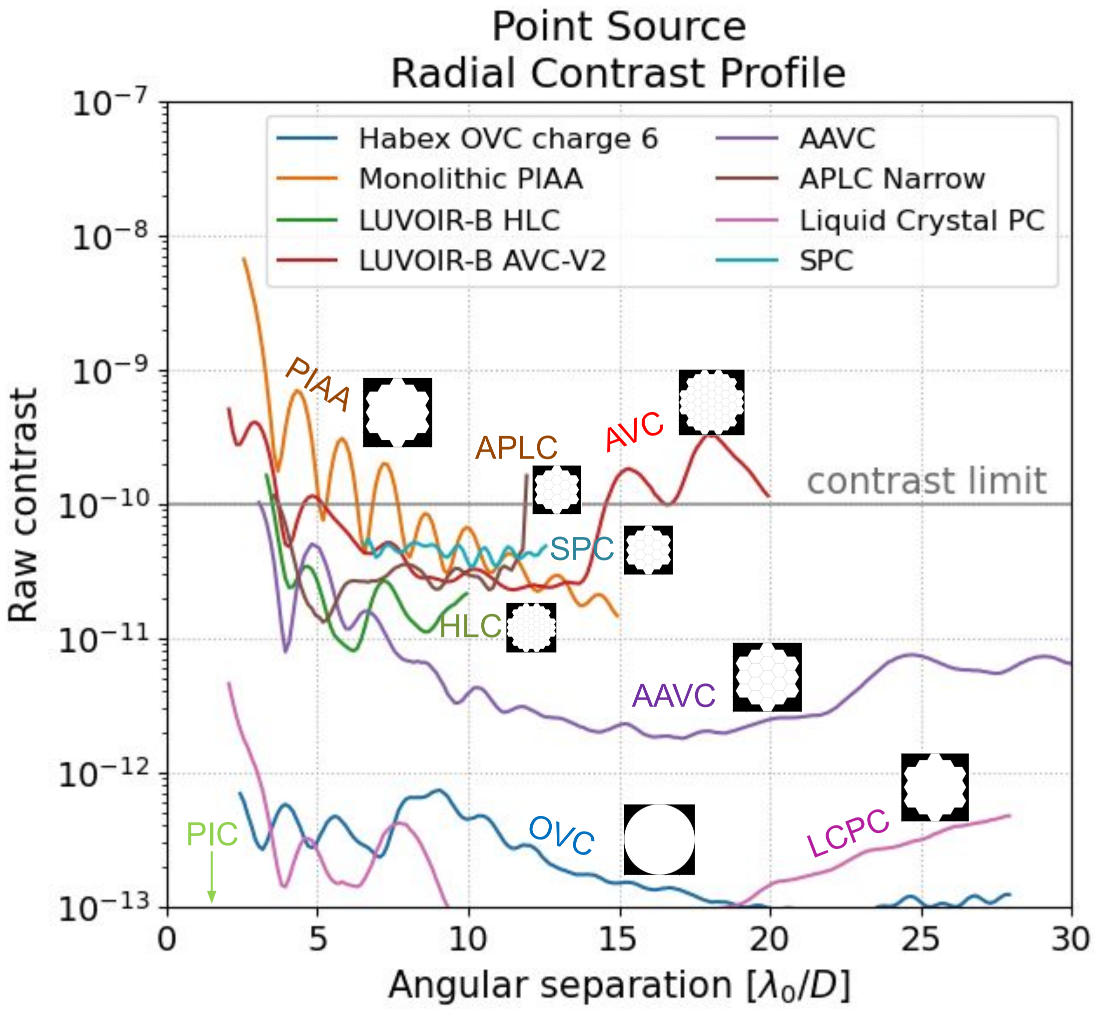


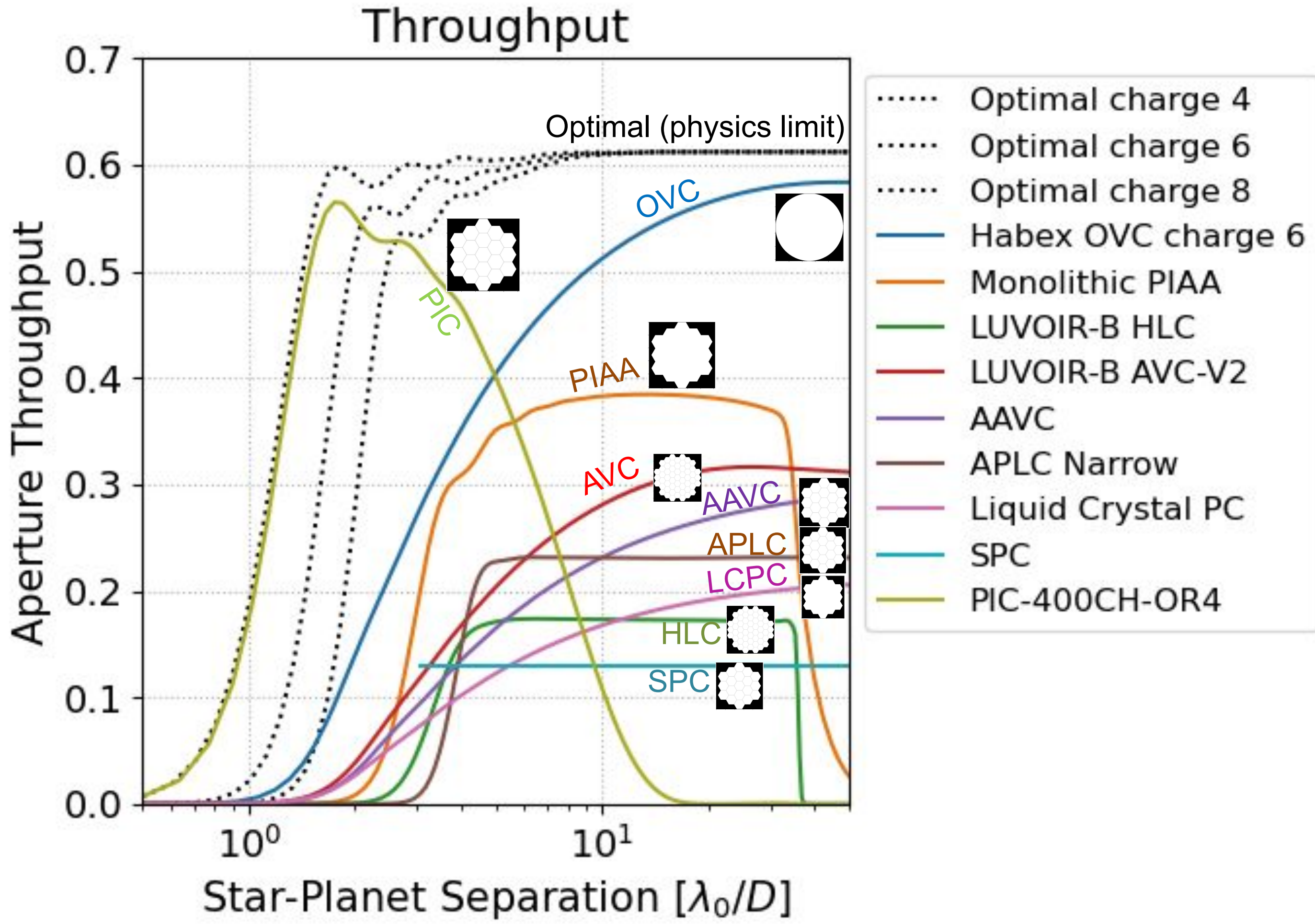
Key trade: coronagraph performance vs. maturity (effectively, science performance vs. technical risk)

Plots created by Emiel Por and Susan Redmond

Note: many coronagraph designs have not yet been optimized

Off Axis Coronagraph Designs Point Source





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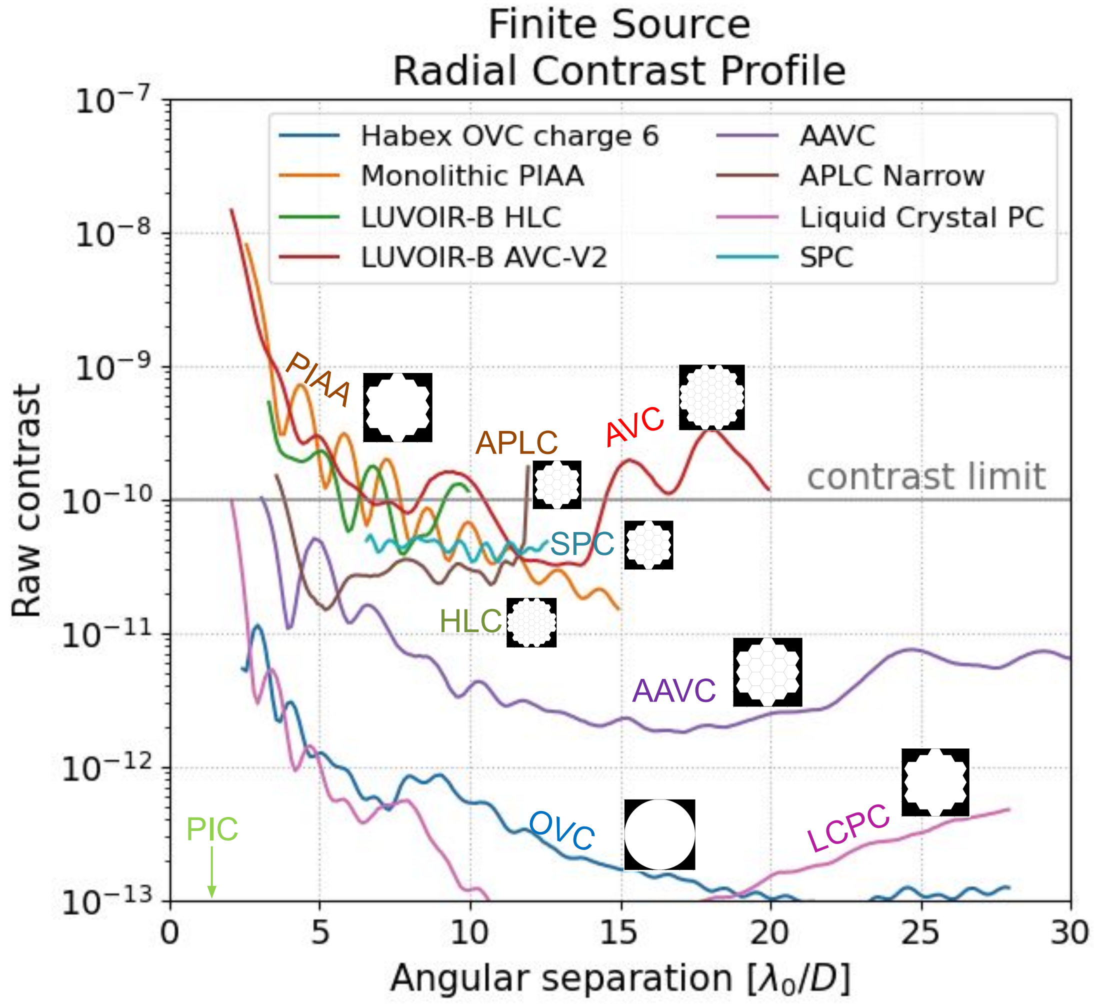
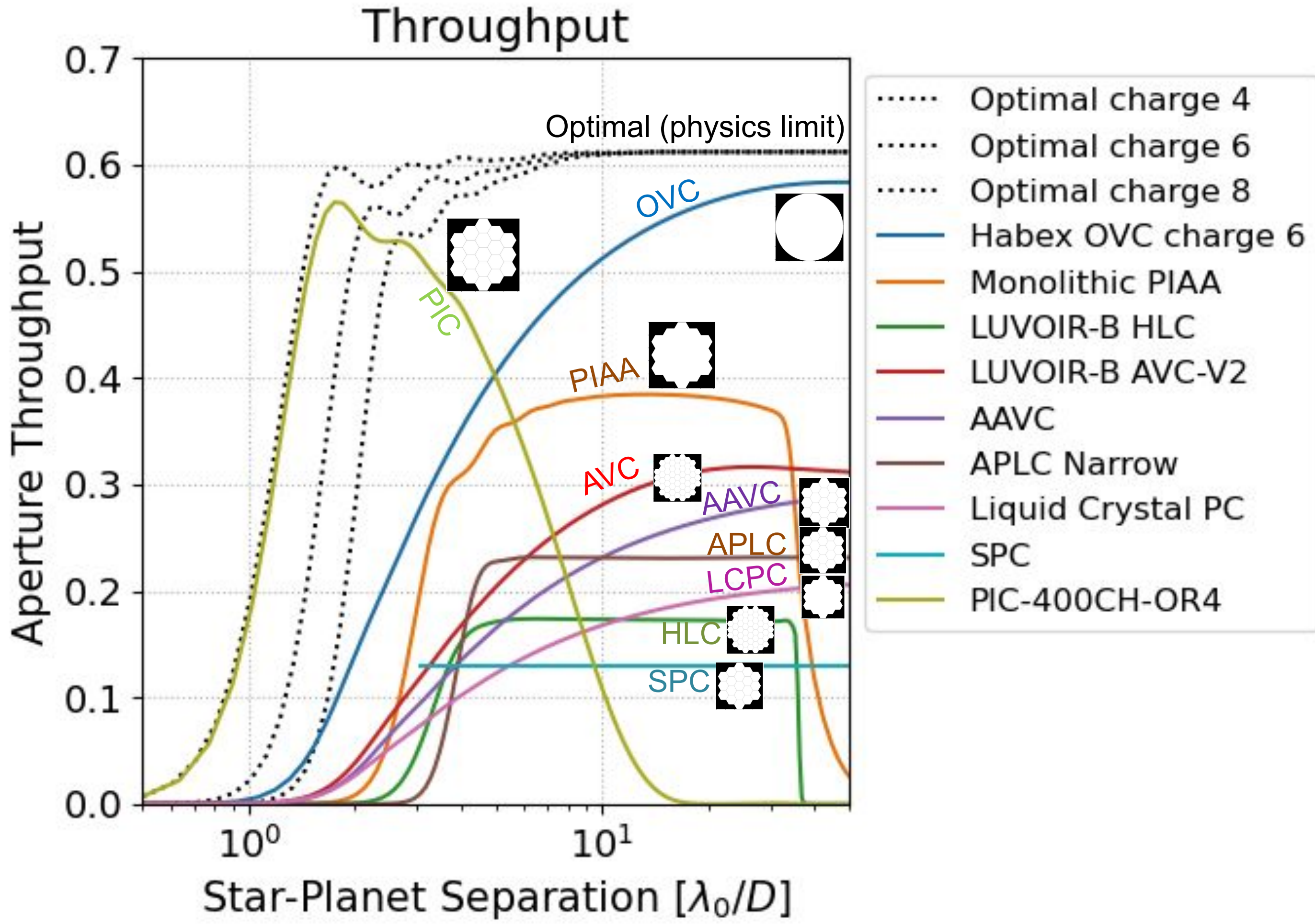
Off Axis Coronagraph Designs Finite Source





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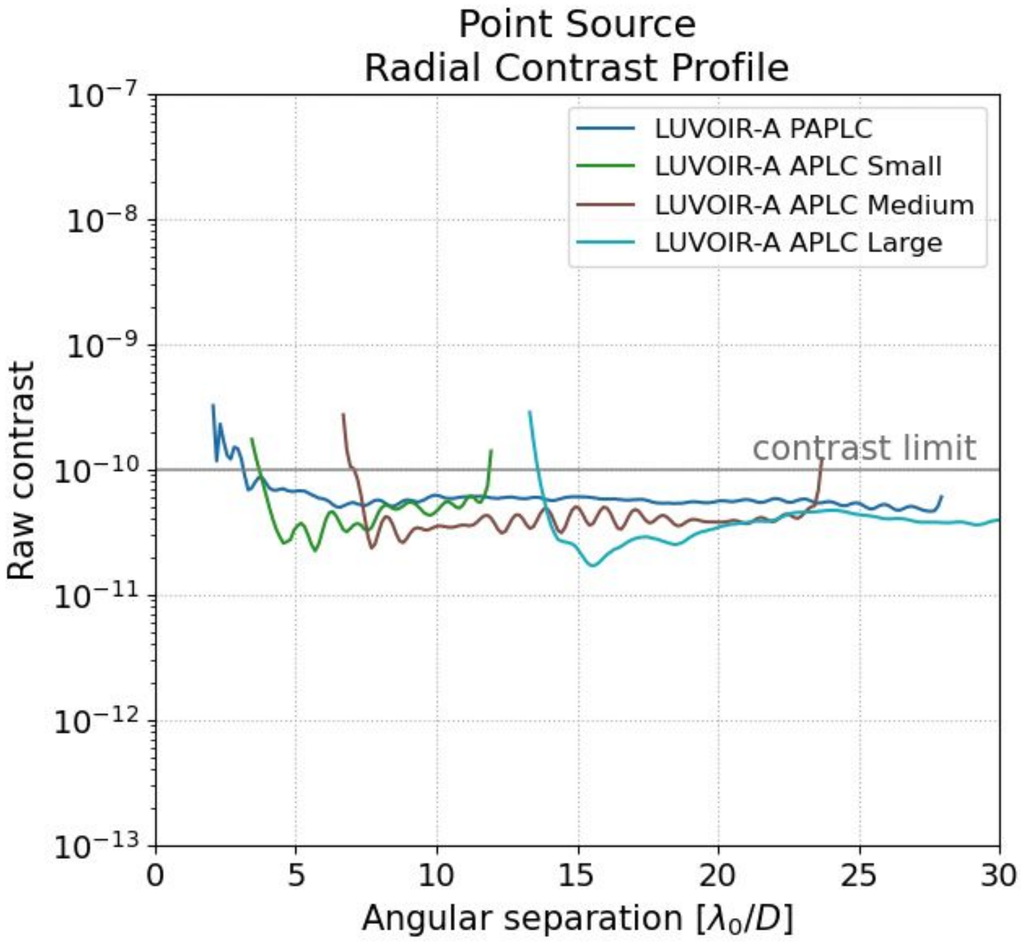
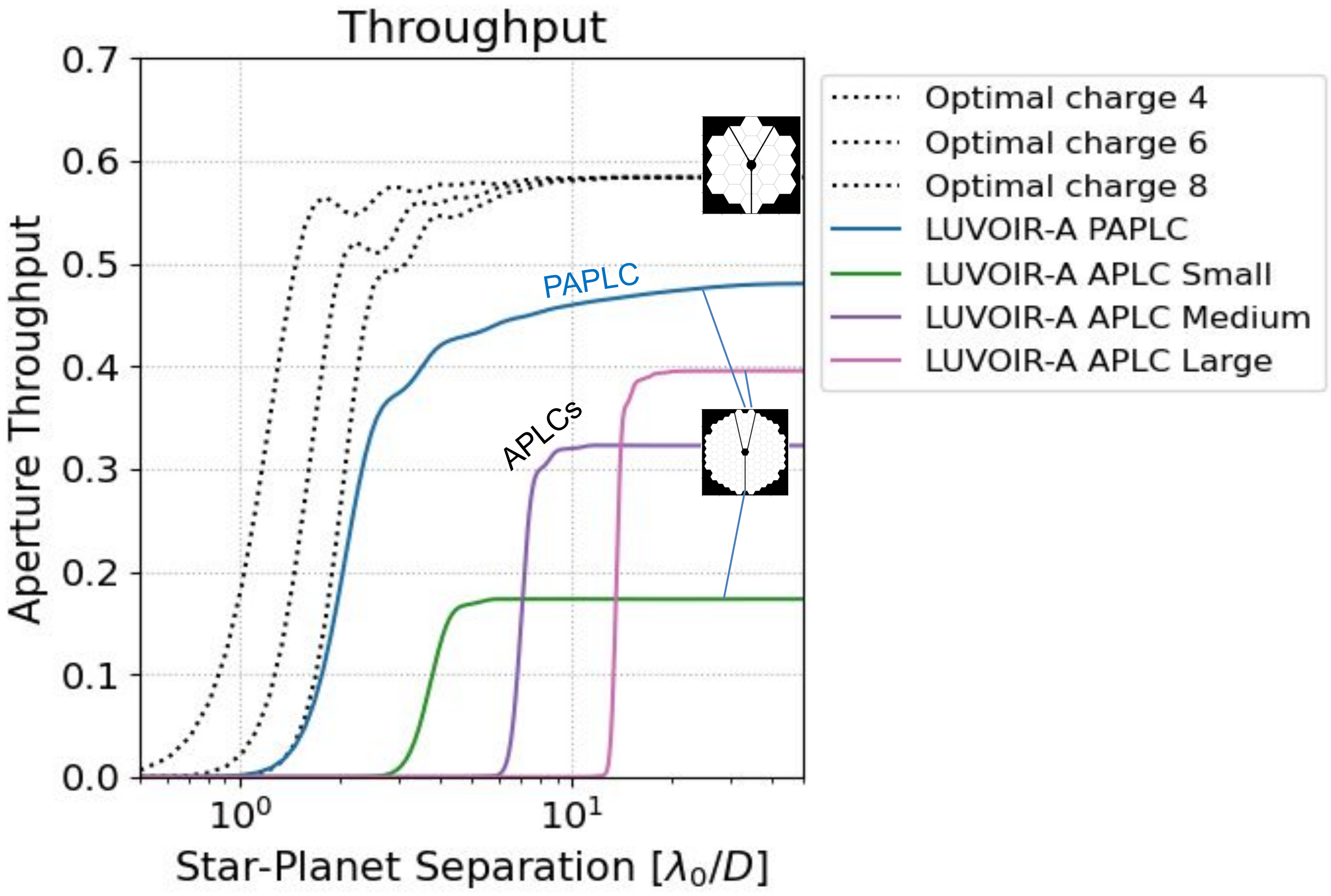
On-Axis Coronagraph Designs Point





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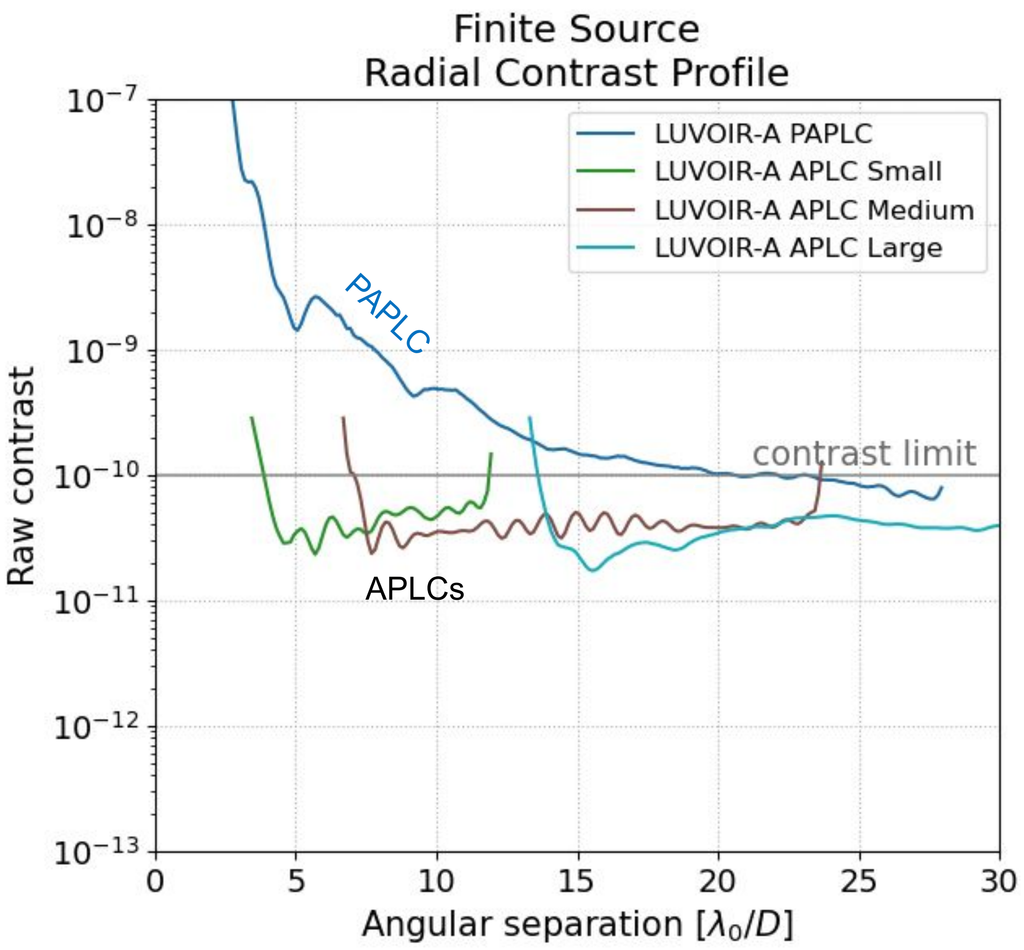

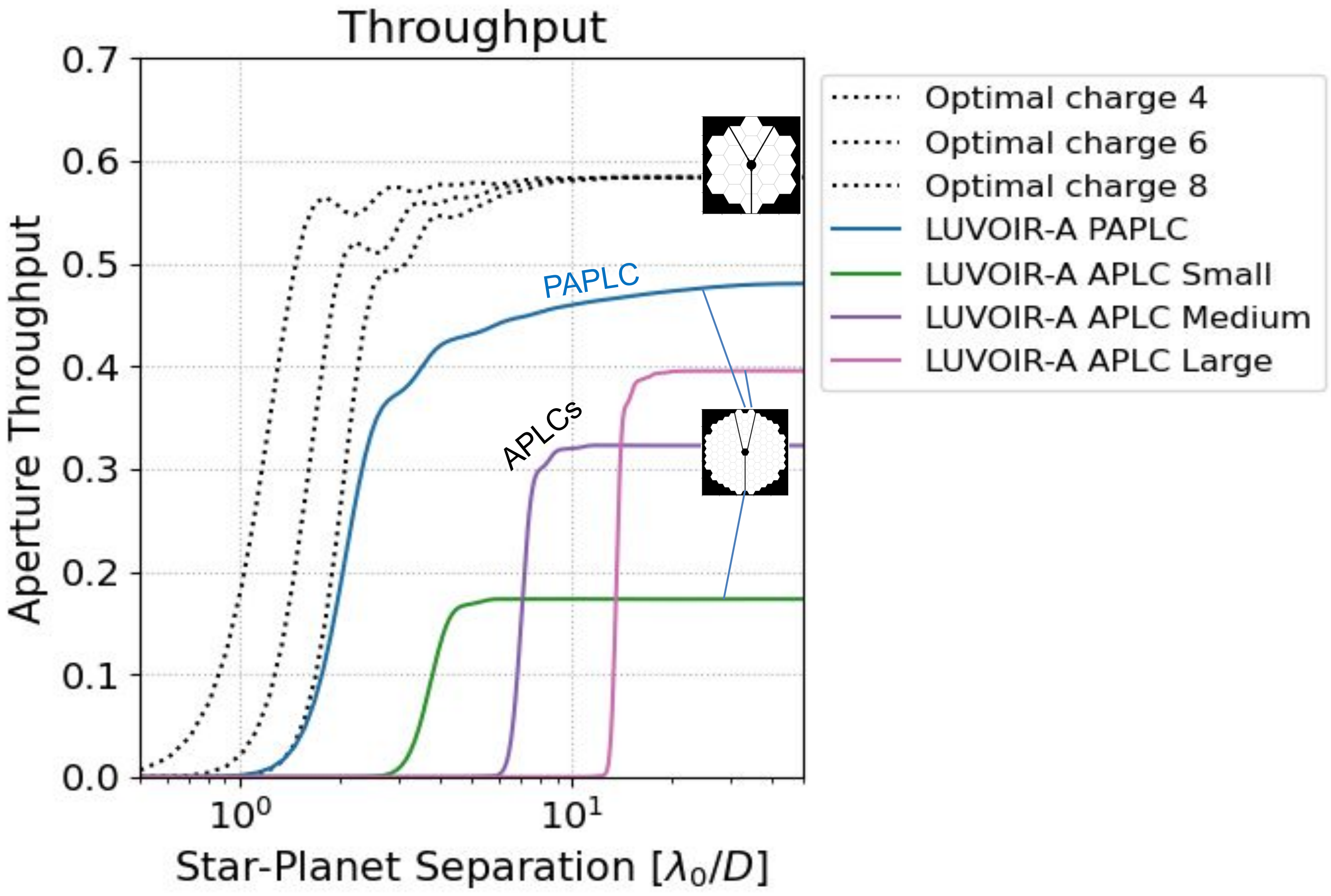

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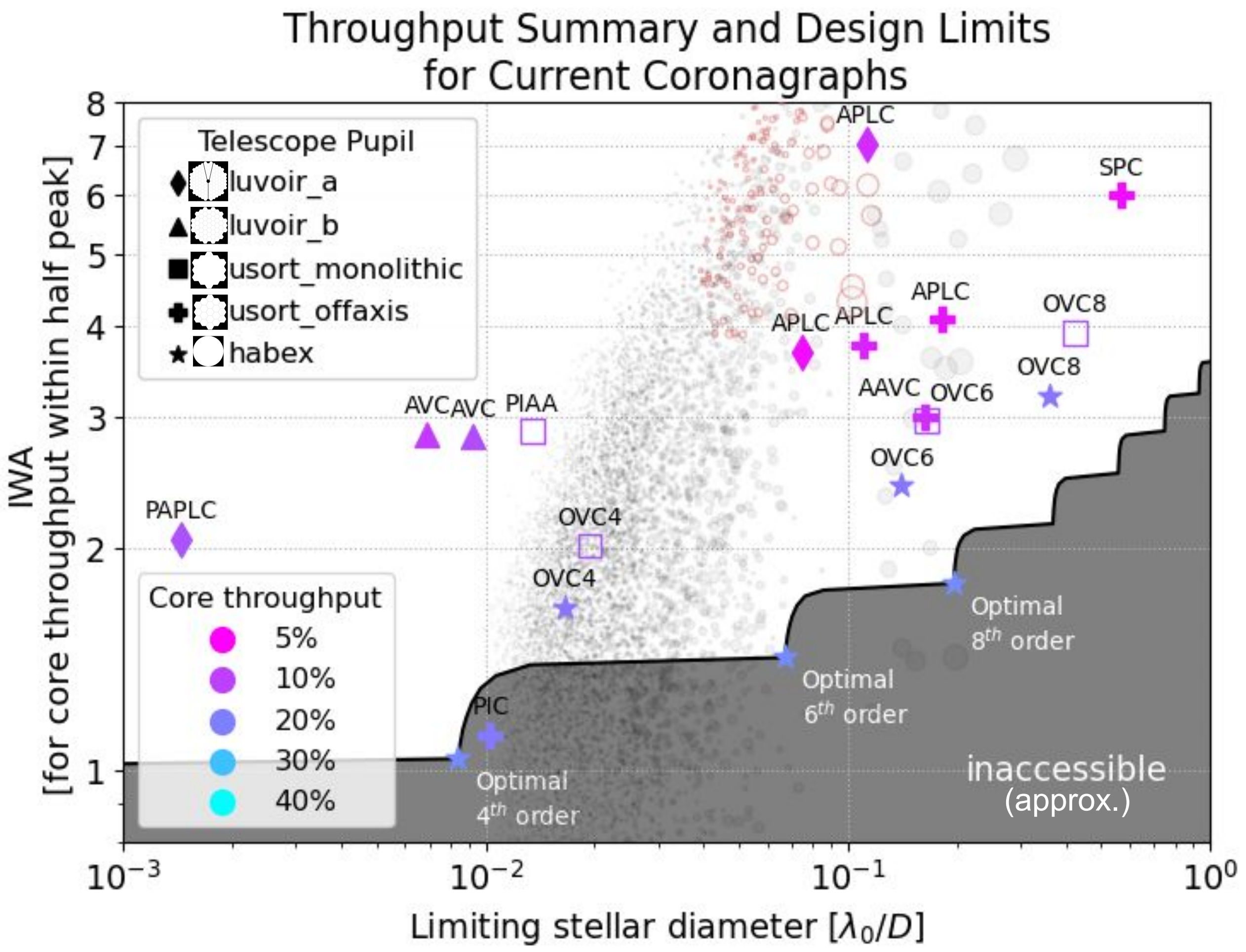
IWA and Robustness to Tip / Tilt / Stellar Size

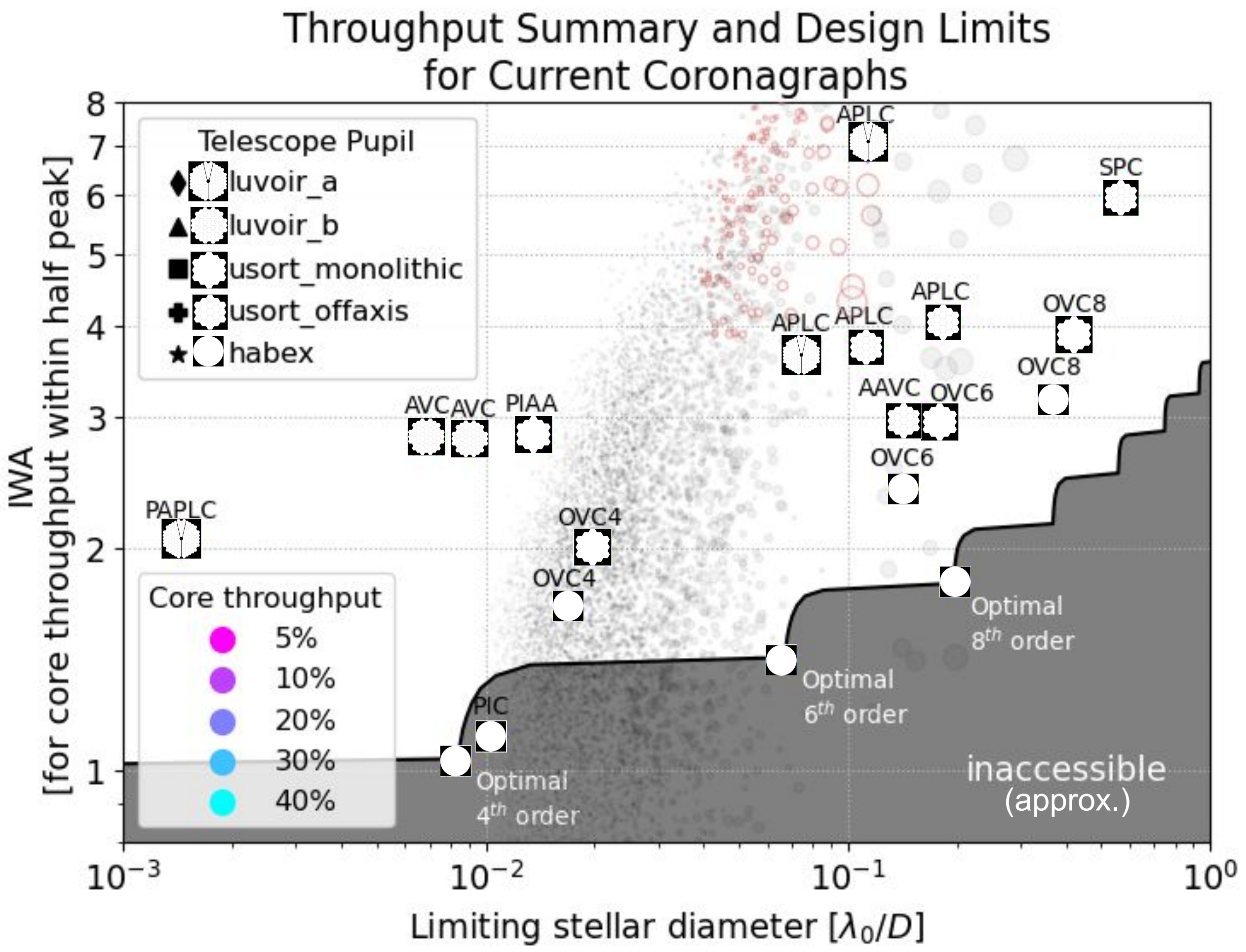


- **Details of plot**
  - Markers represent different coronagraph designs, showing the IWA and stellar diameter for which different coronagraph designs can still maintain < 1e-10 peak contrast
  - "Circles" represent hypothetical planets in the middle of a Habitable Zone
    - Red circles are HWO targets (Mamajek & Stapelfeldt)
    - Black circles are a randomly generated population of systems beyond HWO targets (not real stars)
    - Size of dot represents exo-Earth brightness
    - λ = 500nm
- **Key trade: IWA vs. sensitivity to tip/tilt/stellar size (allows relaxation of telescope jitter requirements)**
- **Substantial gap remains between current coronagraphs and theoretical limits**
  - Especially for segmented and/or on-axis apertures (optimal coronagraph performance is largely insensitive to aperture shape)
  - Opportunity to improve performance, but requires technology development

Plots created by Emiel Por and Susan Redmond

Note: many coronagraph designs have not yet been optimized

IWA and Robustness to Tip / Tilt / Stellar Size



Plots created by Emiel Por and Susan Redmond

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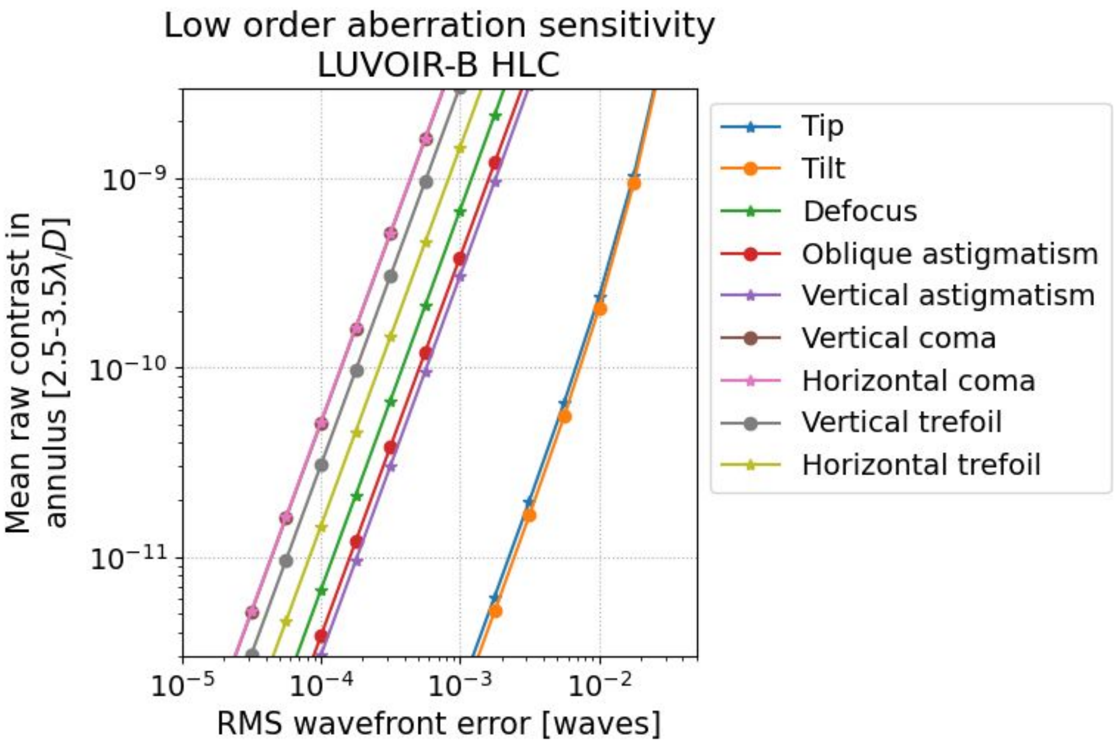
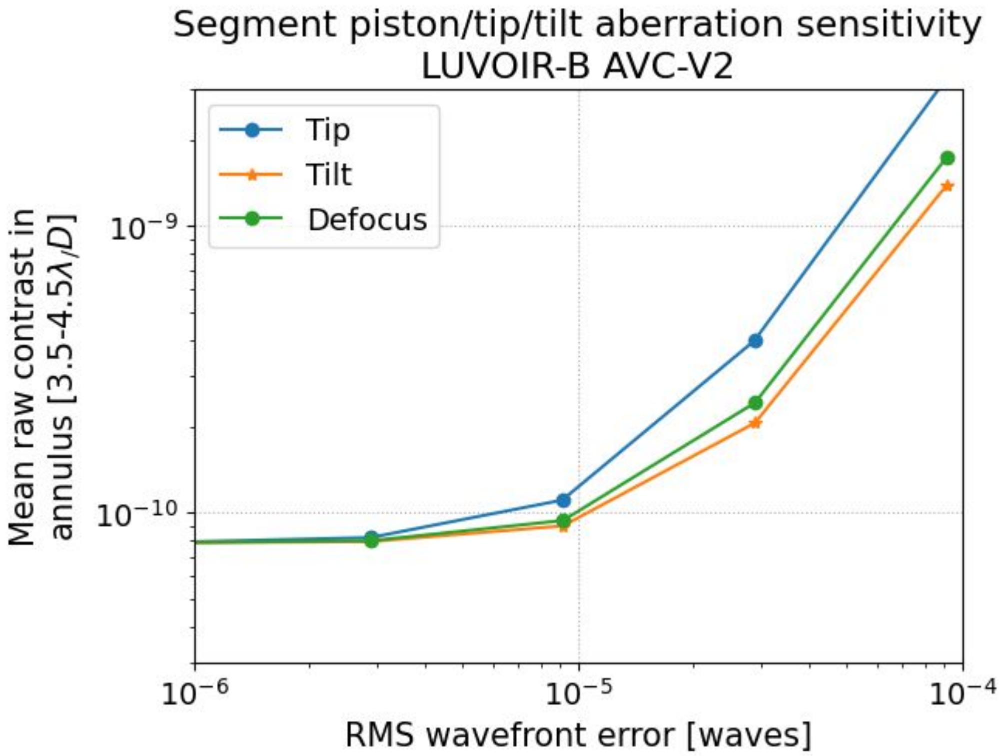
Robustness to Other Aberrations

sensitivity to low-order aberrations

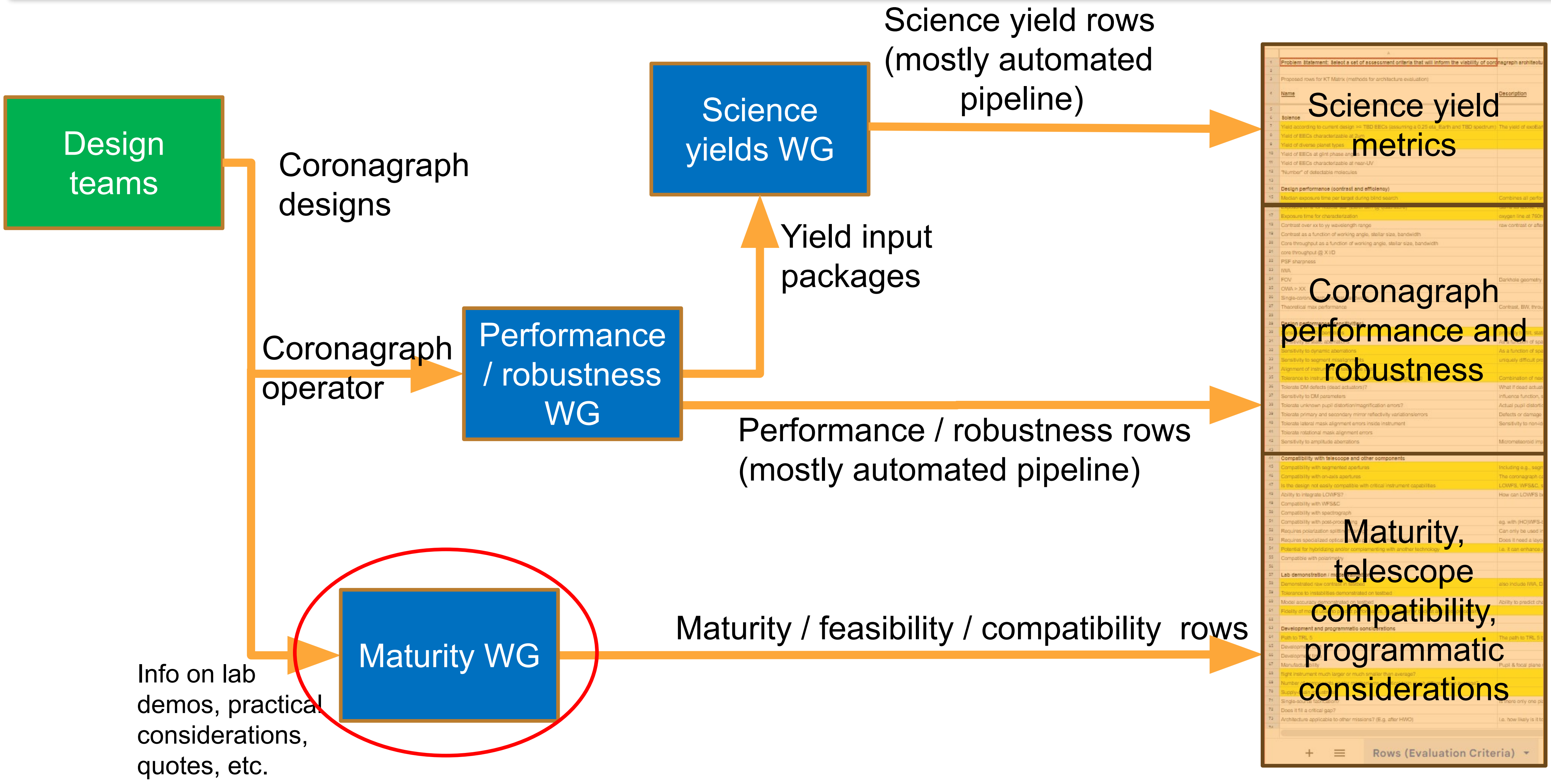


sensitivity to segment-level aberrations



- **Many other instability and aberration modes implemented**
- **Key trade Telescope stability vs. coronagraph robustness (e.g. can we relax the 10pm stability requirements?)**

Workflow and Pipeline



Maturity Working Group

(led by Bertrand Mennesson)

Compatibility with telescope and other components
Compatibility with segmented apertures
Compatibility with on-axis apertures
Is the design easily compatible with low-order wavefront sensing (LOWFS) capabilities?
Is the design easily compatible with high-order wavefront sensing and control (HOWFS/C) capabilities?
Is the coronagraph design compatible with high contrast dual polarization observations?
Is the design easily compatible with post- processing (speckle subtraction) capabilities?
Potential for hybridizing and/or complementing with another technology
Lab demonstration / model validation
Any high contrast monochromatic testbed demonstration?
Any high contrast broadband testbed demonstration?
Any vacuum testbed demonstration?
Best contrast results on off-axis monolithic aperture
Best contrast results on off-axis "segmented" aperture
Best contrast results on on-axis monolithic aperture
Best contrast results on on-axis "segmented" aperture
Tolerance to instabilities demonstrated on testbed
Was a model developed to predict performance?
Was an error budget developed?
Current performance limitation
Development and programmatic considerations
Path to TRL 5
Flight instrument size compared to average?
Number of components and/or mechanisms in optical train much different from average?
Supply-chain robustness

- ***Detailed maturity questionnaire sent to all coronagraph designers***
- ***Answers received and reviewed for 13 designs***
- ***Includes all coronagraph types with broad-band contrast demonstrations***
- ***Consolidated answers under 3 categories (see table)***

Maturity: Extent of Lab Testing

Coronagraph Type	HLC	mg-VVC	EWC	VVC	SP(L)C	PIAA	IAH	APLC	PAPLC	PIAA Vortex	Photonic Chip	Optimal limit	Fiber nulling
Tested in the lab?	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y
Tested broadband?	Y	Y	Y	Y	Y	Y	N	Y	Y	N	N	N	Y
Tested in vacuum?	Y	N	N	Y	Y	Y	N	N	N	N	N	N	N

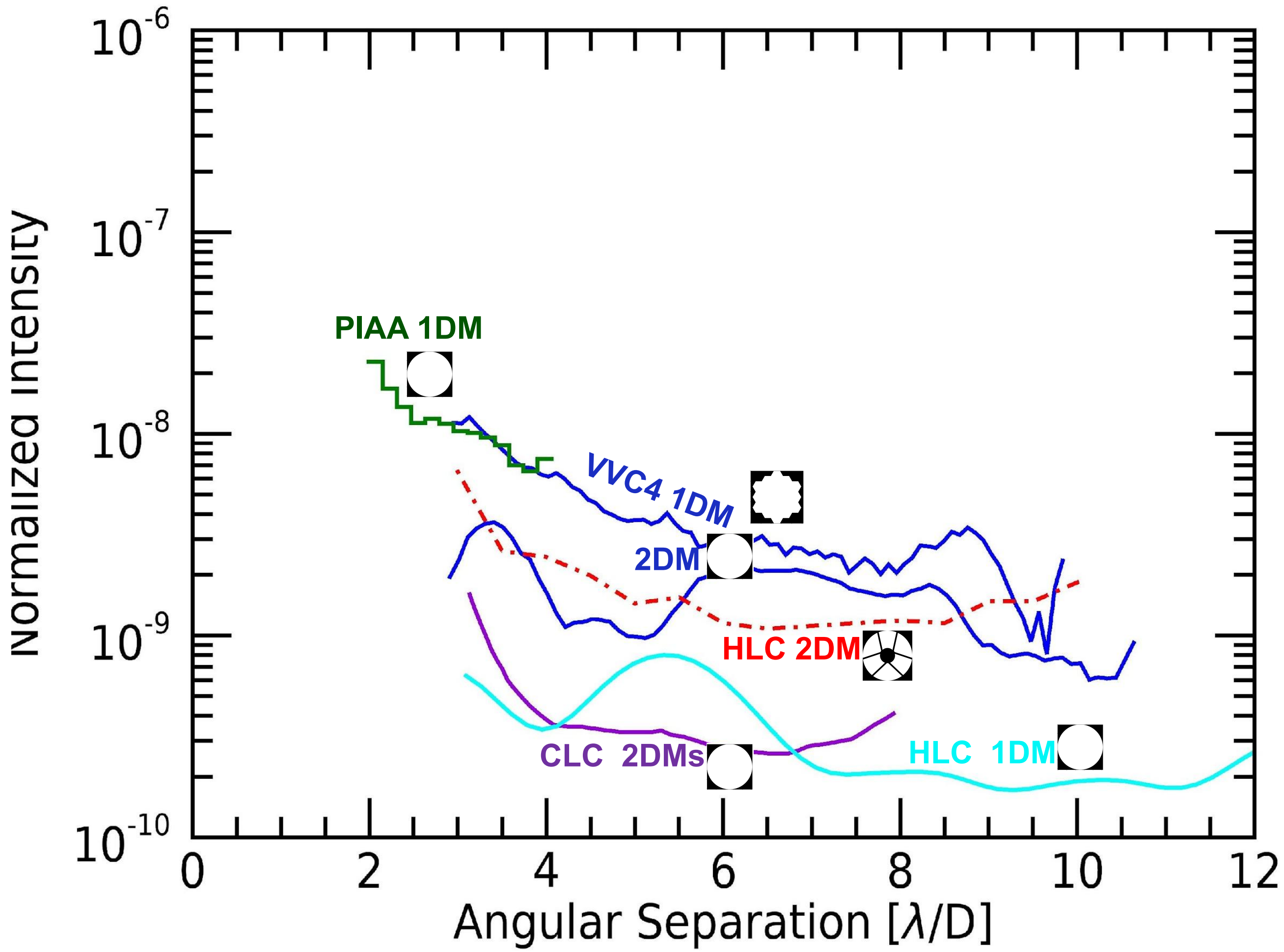
Maturity: Extent of Performance Modeling

Coronagraph Type	HLC	mg-VVC	EWC	VVC	SP(L)C	PIAA	IAH	APLC	PAPLC	PIAA-Vortex	Photonic Chip	Optimal limit	Fiber-nulling
Model developed to predict performance ?	Y	N	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y
Error Budget ?	Y	N	N	Y	Y	Y	N	Y	N	N	N	N	Y
Broadband Performance Limiting Factor	Mask	Mask	Mask	Mask	?	PIAA Optics ?	N/A	In-air	In-air	N/A	N/A	N/A	Non-SM Effects

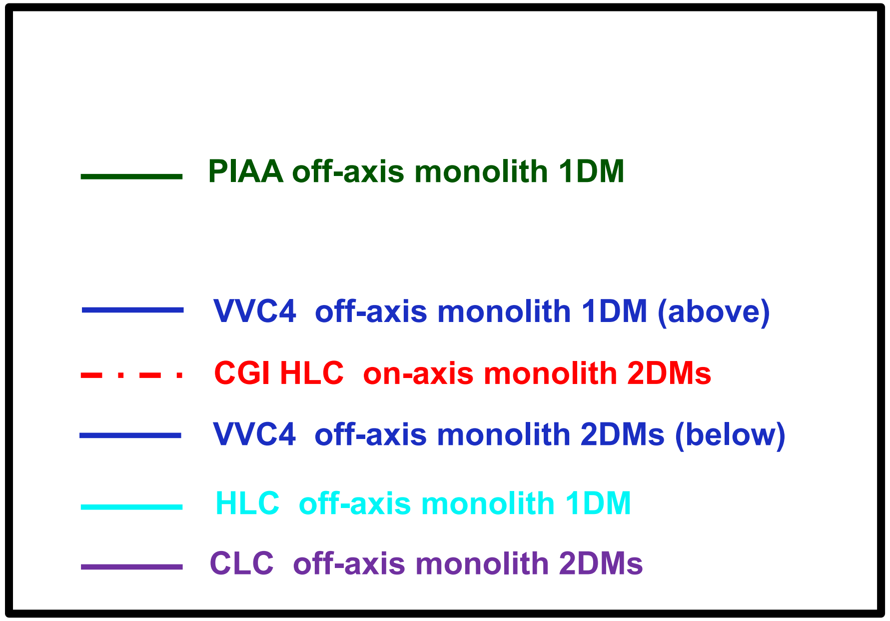
Maturity: Broadband (>~10%) lab contrast results per aperture type

Coronagraph Type	HLC	EWC	VVC	SP(L)C	PIAA(CMC)	APLC	PAPLC	Fiber-nulling
In air or Vaccum?	Vacuum	In air	Vacuum	Vacuum	Vacuum	In air	In air	In air
Off-axis Monolith	5.2×10^{-10} 3-15 λ/D One-sided	~10^{-4} at ~3λ/D	1.6×10^{-9} 3-10 λ/D One-sided	2.4×10^{-9} 4-10 λ/D 90 deg	1×10^{-8} 2-4 λ/D One-sided	tbd		2.5×10^{-5} ~0.5-2 λ/D 360 deg
Off-axis Segmented			4.7×10^{-9} 3-10 λ/D One-sided			tbd	4.2×10^{-8} 2-13 λ/D One-sided*	Would be same
On-axis Monolith (CGI)	1.6×10^{-9} 3-9 λ/D 360 deg			4.1×10^{-9} 3-9 λ/D 2x 65 deg 3.5×10^{-9} 6.3-19.5 λ/D 360 deg	1.8×10^{-7} 1.3-6.5 λ/D One-sided	tbd		Would be same
On-axis Segmented					1.9×10^{-8} 3.5-8 λ/D One-sided	tbd		Would be same

Broad-band Contrast Lab Results (I)



Monolithic apertures only:



Broad-band Contrast Lab Results (II)

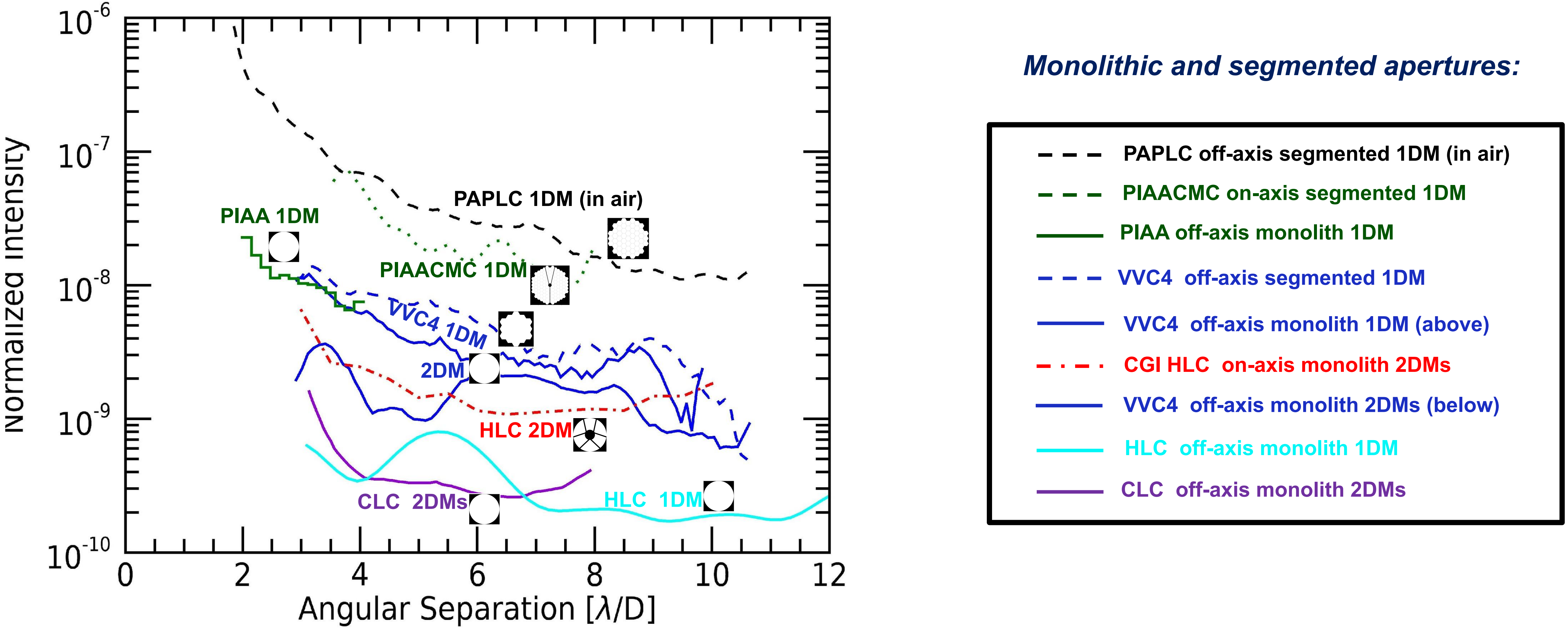
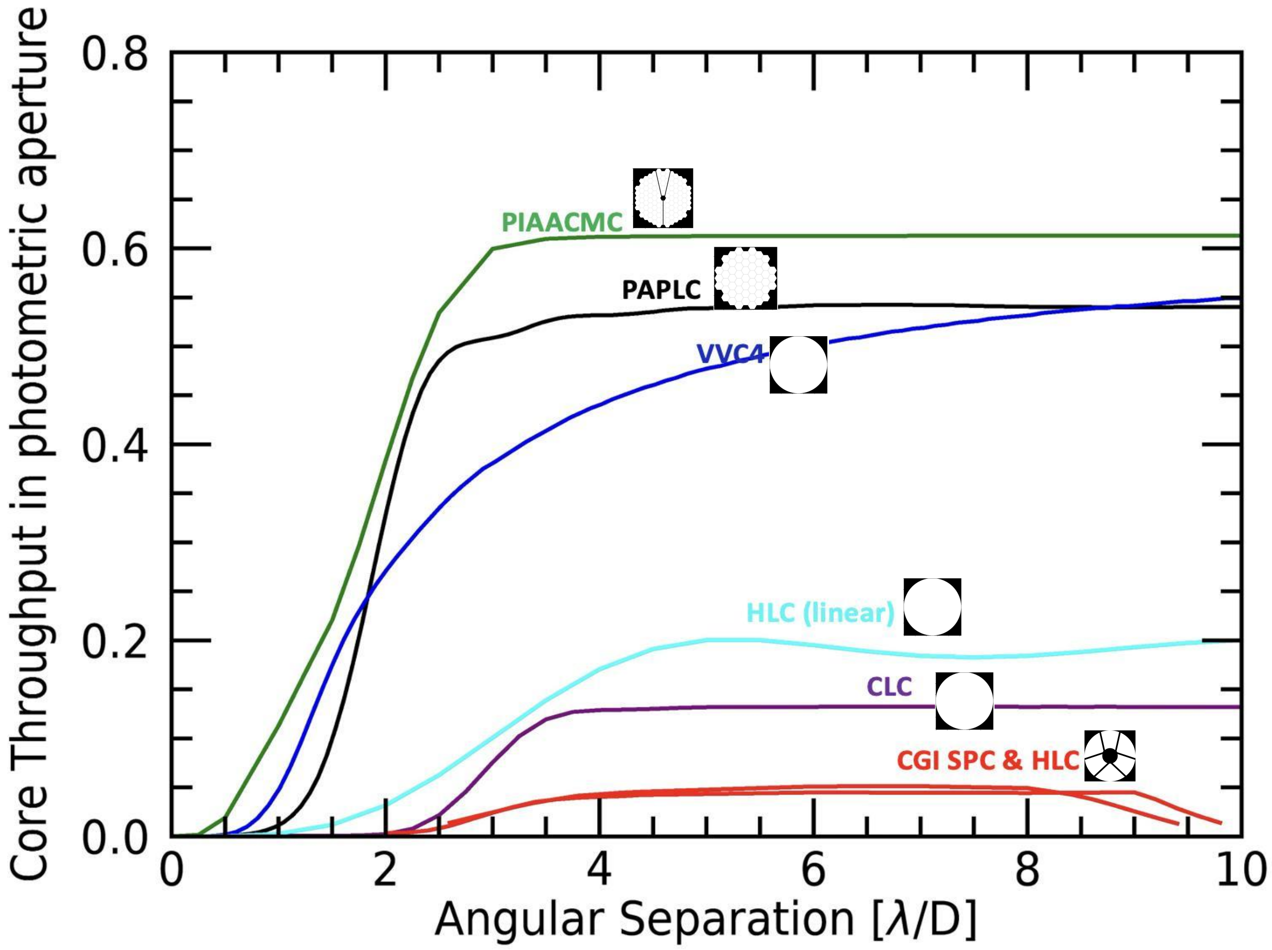


Figure adapted from Mennesson et al. 2024 (https://arxiv.org/pdf/2404.18036). **Best azimuthal mean contrast (normalized intensity) demonstrated to date by different starlight suppression approaches and laboratory experiments over a ~10% spectral bandwidth. The x-axis shows the angular separation in units of λ/D, where D is the entrance pupil *inscribed* diameter and λ is the central wavelength of the bandpass. Coronagraphic results were obtained with either one or two DMs, and for different aperture types: off-axis monolith (plain curves); off-axis segmented (dashed curves); on-axis monolith (dashed dotted curve); and on-axis segmented (dotted curve).**

Off-axis (Exoplanet) Core Throughput of Lab Set-ups



Coronagraph with the deepest contrast demonstrated in the lab tend to have lower exoplanet throughput at small separation

Figure adapted from Mennesson et al. 2024 (https://arxiv.org/pdf/2404.18036).

Core throughput of the broad-band coronagraph lab setups tested so far. Core throughput is given as a function of angular separation in units of λ/D, where λ is the central wavelength and D is the inscribed diameter of the entrance aperture. At a given separation, the core throughput is computed within a circular aperture of radius 0.7λ/D for all systems, except for the Roman HLC and SPC-spec coronagraphs, which have highly-spatially-extended PSFs and for which the PSF FWHM region is used instead. The PIAACMC curve assumes that inverse PIAA optics are used to correct for off-axis PSF distortion (although they were not part of the original lab set-up).

Key Findings of Maturity WG

- Among entries: ~12 coronagraph approaches tested via high contrast lab demos
  - 9 broad-band (>10%)
  - Only 4 tested in vacuum (HLC, SPC, VVC, PIAA)
  - Only 3 on segmented mask (VVC4, PIAACMC) or aperture (PAPLC)
  - Current best results found on monolithic apertures, but only 2 vacuum demo, both on segmented masks: VVC4 (off-axis) and PIAACMC (on-axis)

  ⟶ More vacuum coronagraphic tests urgently needed with segmented apertures

- Most lab tests have concentrated on starlight suppression, which is however not the end of the story. To increase design maturity:

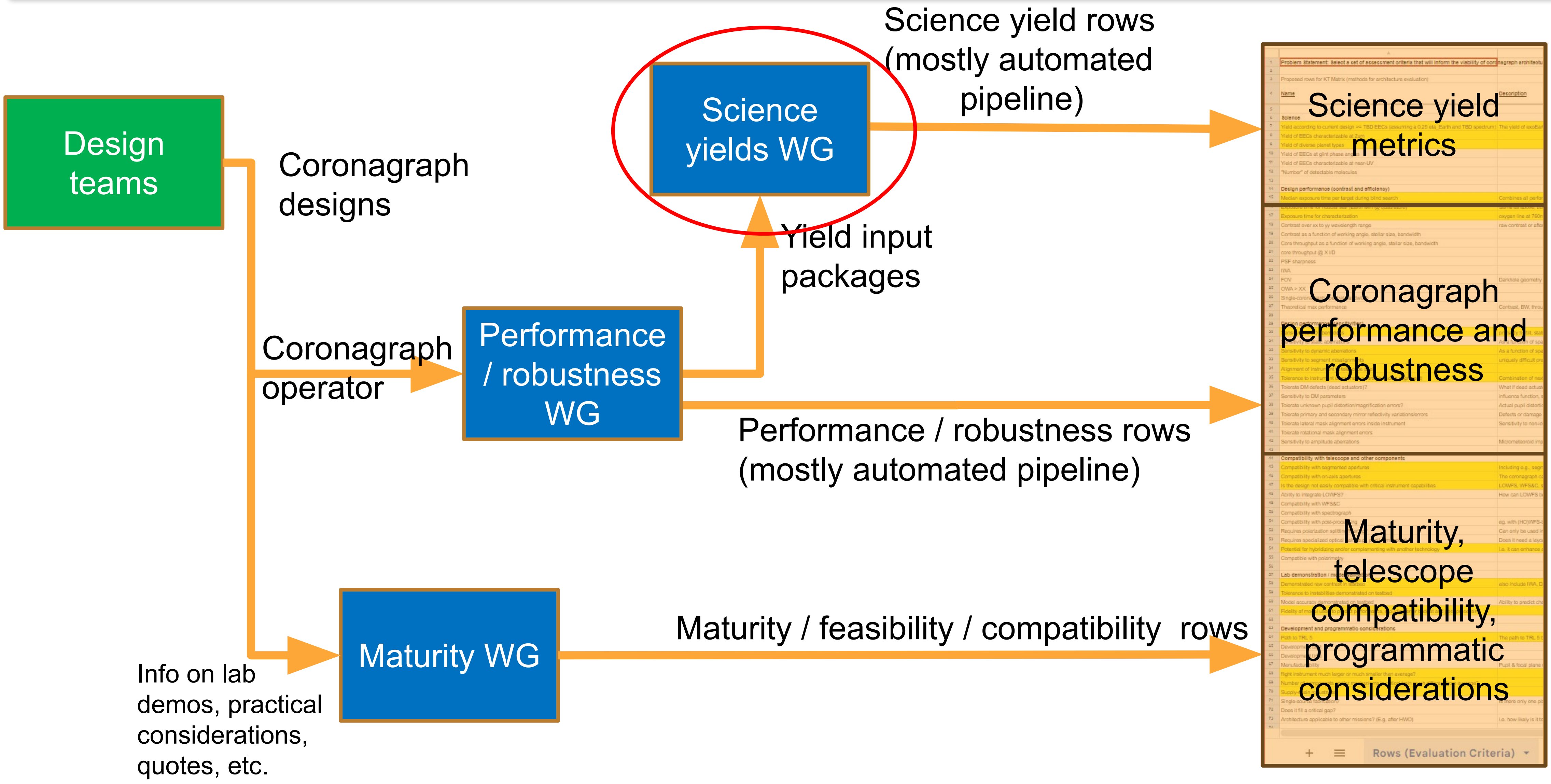
  ⟶ Core throughput should be given more weight

  ⟶ Post-calibration capabilities need to be better quantified to optimize design trade between raw contrast and core throughput (Mennesson et al. 2024, Stark et al. 2024)

- In most cases, broadband performance is inferred to be limited by mask defects

  ⟶ Better mask manufacturing process and inspection *before* coronagraphic testing will improve performance and hence increase TRL for HWO

Workflow and Pipeline



Science Performance Working Group

Members:

- Chris Stark (lead)
- Pin Chen
- Jeremy Kasdin
- Rhonda Morgan
- Laurent Pueyo
- Susan Redmond
- Karl Stapelfeldt
- Armen Tokadjian

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Evaluation Criteria Considered

Name	Description
Science	
Yield of EECs budgeting for VIS detections only	Just maximize single-epoch vis detections, a straightforward yield metric
Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection	The LUVOIR & HabEx baseline requirements for every EEC
Yield of EECs budgeting for VIS detections, orbit, and CO2/CH4 detection at 1.65 microns	The LUVOIR & HabEx basline but with a more demanding CO2/CH4 detection
Yield of diverse planet types	Incidental V band detections of Kopparapu et al. (2018) planet types during EEC s
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	Combines all performance metrics below into one parameter, sampled over all sta
Exposure time for fiducial star (Earth twin @ quadrature)	Same as above, but for a single star: Solar twin at 12 pc
Exposure time for characterization	oxygen line at 760nm; fiducial target
Contrast over xx to yy wavelength range	raw contrast or after post-processing?
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	Darkhole geometry can significantly modify the possible FOV
OWA > XX	
Single-coronagraph spectral bandwidth	
Theoretical max performance	Contrast, BW, throughput, IWA

Science Performance Working Group

Yield Calculation Assumptions

- All assumptions documented
- Description of philosophy, observation strategy, etc.
- Made several assumptions that are more optimistic than LUVOIR study: only two aluminum surfaces, dual VIS channels, no detector noise, no raw contrast floor
- Observations optimized for the performance parameters of the mission

Coronagraph Design Survey Science Performance Working Group: Description of Yield Calculation Assumptions

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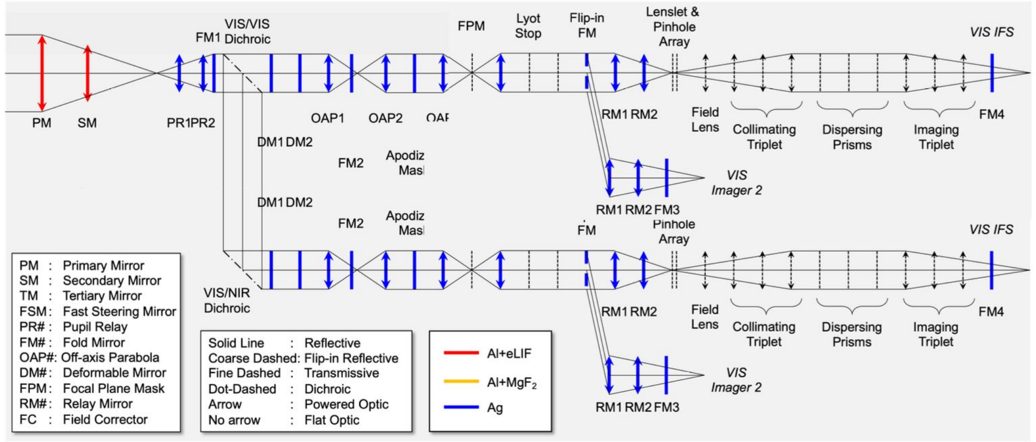
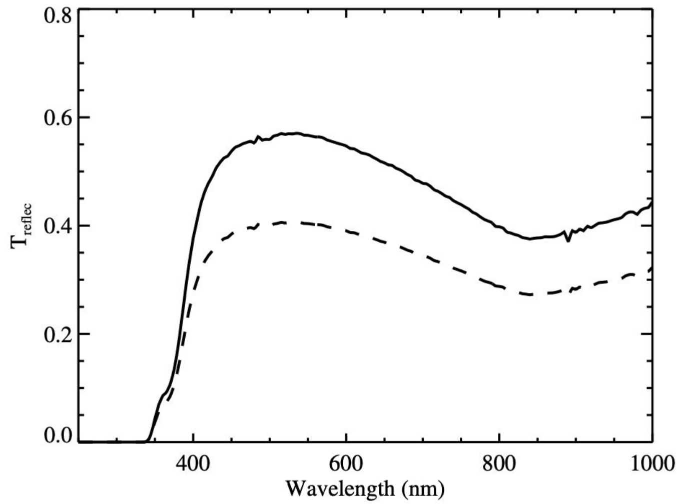
1 Introduction

The Coronagraph Design Survey (CDS) is a 1-year effort initiated by N ration Program (ExEP) to study the range of coronagraph designs possible Observatory. As part of this fact-finding survey, the CDS team's Scienc Group (SPWG) will estimate exoplanet yields for many of these coronagr has identified four primary exoplanet yield metrics, intended to sample c

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
$\tau_{\rm WFC}$	1.3 hrs[a]	Static overhead to dig dark hole
$\tau'_{\rm WFC}$	1.1	Multiplicative overhead to touch up dark hole
D	7.87 m	Telescope circumscribed diameter (USORT aperture)
$D_{\rm ins}$	6.5 m	Telescope inscribed diameter (USORT aperture)
A	Per USORT aperture	Collecting area of telescope (USORT aperture)
X	0.7	Photometric aperture radius in $\lambda/D_{\rm ins}$[b]
Ω	$\pi(X\lambda/D_{\rm LS})^2$ radians	Solid angle subtended by photometric aperture[b]
$\zeta_{\rm floor}$	None	Raw contrast floor enforced regardless of coronagraph design
$\Delta{\rm mag}_{\rm floor}$	26.5	Noise floor (faintest detectable point source at S/N= 10)
$T_{\rm contam}$	0.95	Effective throughput due to contamination applied to all observations
${\rm IWA}_{\rm min}$	1.25 λ/D	Minimum working angle enforced as hard limit
		Detection Parameters
$\lambda_{\rm d}$	0.5 μm[c]	Central wavelength for detection
$\Delta\lambda_{\rm d}$	$2\times\Delta\lambda$	Bandwidth assumed for detection (2 VIS coronagraphs simultaneously)
$\Delta\lambda$	Lesser of 20% and design	Coronagraph design bandwidth
${\rm S/N_d}$	7	S/N required for detection
$T_{\rm optical,d}$	0.56[c]	End-to-end reflectivity/transmissivity at $\lambda_{\rm d}$
$\tau_{\rm d,limit}$	2 mos	Detection time limit including overheads
$n_{\rm pix,d}$	8[c]	# of pixels in photometric aperture of each imager at $\lambda_{\rm d}$
		H_2O Characterization Parameters
$\lambda_{\rm H2O}$	1.0 μm[c]	Wavelength for characterization
${\rm S/N_{H2O}}$	5[c]	Signal to noise per spectral bin evaluated in continuum
${\rm R_{H2O}}$	140	Spectral resolving power
$T_{\rm optical,H2O}$	0.32[c]	End-to-end reflectivity/transmissivity at $\lambda_{\rm H2O}$ including IFS optics
$n_{\rm pix,c}$	96[c]	# of pixels per spectral bin in coronagraph IFS at $\lambda_{\rm H2O}$
$\tau_{\rm H2O,limit}$	2 mos	Characterization time limit including overheads
		CO_2 Characterization Parameters
$\lambda_{\rm CO2}$	1.65 μm	Wavelength for characterization in coronagraph IFS
${\rm S/N_{CO2}}$	12	Signal to noise per spectral bin evaluated in continuum
${\rm R_{CO2}}$	70	Spectral resolving power
$T_{\rm optical,CO2}$	0.5	End-to-end reflectivity/transmissivity at $\lambda_{\rm CO2}$ including IFS optics
$n_{\rm pix,CO2}$	62	# of pixels per spectral bin in coronagraph IFS at $\lambda_{\rm CO2}$
$\tau_{\rm CO2,limit}$	2 mos	Characterization time limit including overheads
		Detector Parameters
ξ	0 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	0 e^- pix^{-1} frame^{-1}	Clock induced charge
$T_{\rm QE}$	0.9	Raw QE of the detector at all wavelengths
$T_{\rm dQE}$	0.75	Effective throughput due to bad pixel/cosmic ray mitigation





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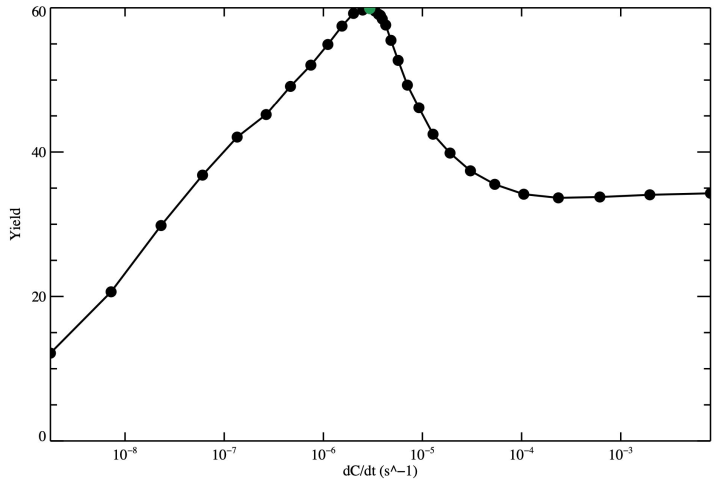
Results

- Pipeline fully connected from coronagraph operator to yield outputs
- Outputs include:
  - List of target stars
  - List of observations
  - Yield convergence checks
  - Coronagraph input checks
  - Multi-planet yields
  - Output visualizations

Target list .csv file

starID	HIP	RA	Dec	Umag	Bmag	Vmag	Rmag	Imag	Jmag	Hmag	Kmag	M_V	dist (pc)	Type	Lstar (Lsun)	Angdiam (mas)	Mass (Msun)	WDS_sep
5	71681.0	219.904	-60.8372	2.89000	2.21000	1.33000	NaN	NaN	-0.0100000	-0.490000	-0.600000	5.68237	1.34749	K1V	0.551684	6.21117	0.895919	5.30000
6	37279.0	114.825	5.22494	0.820000	0.790000	0.370000	-0.0500000	-0.280000	-0.498000	-0.666000	-0.658000	2.65130	3.49736	F5IV-V+DQZ	7.20780	5.48733	1.53000	3.80000
7	71683.0	219.910	-60.8340	0.960000	0.720000	0.0100000	NaN	NaN	-1.45400	-1.88600	-2.00800	4.36237	1.34749	G2V	1.65904	8.87825	1.03521	5.30000
11	97649.0	297.696	8.86839	1.07000	0.980000	0.760000	0.620000	0.490000	0.313000	0.102000	0.102000	2.20962	5.12952	A7Vn	10.4165	3.24843	1.82819	195.800
23	113368.	344.413	-29.6221	1.31000	1.25000	1.16000	1.11000	1.09000	1.03700	0.937000	0.945000	1.72654	7.70357	A4V	17.1943	2.30017	2.11936	12.7000
29	2021.00	6.43511	-77.2542	3.52000	3.41000	2.79000	2.28000	1.94000	1.67600	1.43400	1.37200	3.42099	7.47830	G0V	3.57119	2.32289	1.20000	NaN
31	67927.0	208.671	18.3977	3.44000	3.25000	2.68000	2.24000	1.95000	1.79300	1.53400	1.48500	2.40660	11.3417	G0IV	8.78916	2.20998	1.65000	114.900
32	57632.0	177.265	14.5721	2.30000	2.22000	2.13000	2.08000	2.06000	1.85400	1.92500	1.88300	1.90515	11.0910	A3Va	13.7599	1.43392	2.11464	39.1000
44	95501.0	291.375	3.11479	3.72000	3.68000	3.36000	3.11000	2.95000	2.63600	2.47500	2.44300	2.42624	15.3728	F1IV-V(n)	8.26061	1.15334	1.57126	0.100000
49	16852.0	54.2183	0.401603	5.23000	5.15000	4.30000	4.09000	3.77000	3.19400	2.91600	2.83500	3.58174	13.9204	F9IV-V	3.16109	1.10084	1.12995	NaN
57	5336.00	17.0677	54.9203	5.93000	5.86000	5.17000	4.55000	4.13000	4.03100	3.59700	3.50500	5.74452	7.67530	G5Vb	0.479167	0.979309	0.780000	0.600000
72	54035.0	165.834	35.9697	10.0300	8.96000	7.52000	5.99000	4.79000	4.20300	3.64000	3.25400	10.4906	2.54610	M2+V	0.0238846	1.56289	0.404274	NaN
113	54211.0	166.369	43.5268	11.4400	10.2700	8.82000	7.90000	NaN	5.53800	5.00200	4.76900	10.3670	4.90460	M1.0V	0.0233333	0.803817	0.389767	32.0000
120	16134.0	51.9684	-19.8045	10.9950	9.71200	8.36700	7.54800	6.81800	5.88800	5.25100	5.06800	7.88419	12.4900	K5V	0.237848	0.675897	0.661656	NaN
193	28442.0	90.0816	-31.0287	9.99300	9.01300	7.87300	7.16300	6.52600	5.65900	5.07000	4.90200	6.80011	16.3900	K5V+K5V	0.286686	0.517250	0.692458	NaN
444	105199.	319.646	62.5858	2.77000	2.68000	2.46000	2.22000	2.11000	2.15400	2.13400	2.06600	1.57411	15.0376	A8Vn	17.6740	1.48751	1.78104	196.600
452	77952.0	238.786	-63.4307	3.19000	3.14000	2.85000	2.53000	2.38000	2.23000	2.20900	2.15200	2.37870	12.4240	F1V	8.71255	1.45733	1.57863	152.100
456	46853.0	143.214	51.6773	3.67000	3.64000	3.18000	2.74000	2.47000	2.28000	2.07900	1.97000	2.52328	13.5314	F7V	7.89990	1.61348	1.52000	2.60000
459	71908.0	220.627	-64.9751	3.55000	3.43000	3.19000	2.96000	2.86000	2.54400	2.47100	2.42500	2.11582	16.3997	A7VpSrCrEu	10.9011	1.07131	1.78088	15.7000
496	102422.	311.322	61.8388	4.96000	4.32000	3.41000	2.76000	2.27000	1.91400	1.50400	1.39300	2.62387	14.3624	K0IV	9.17000	2.64393	1.21000	42.4000

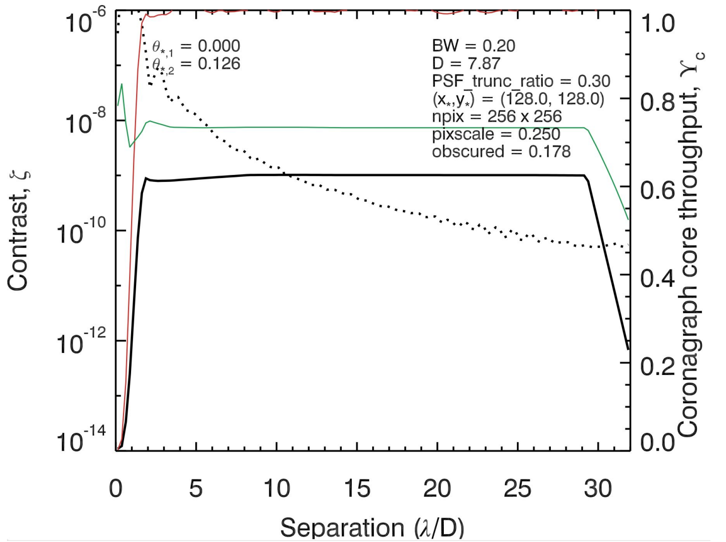
Yield convergence check



Observations list .csv file

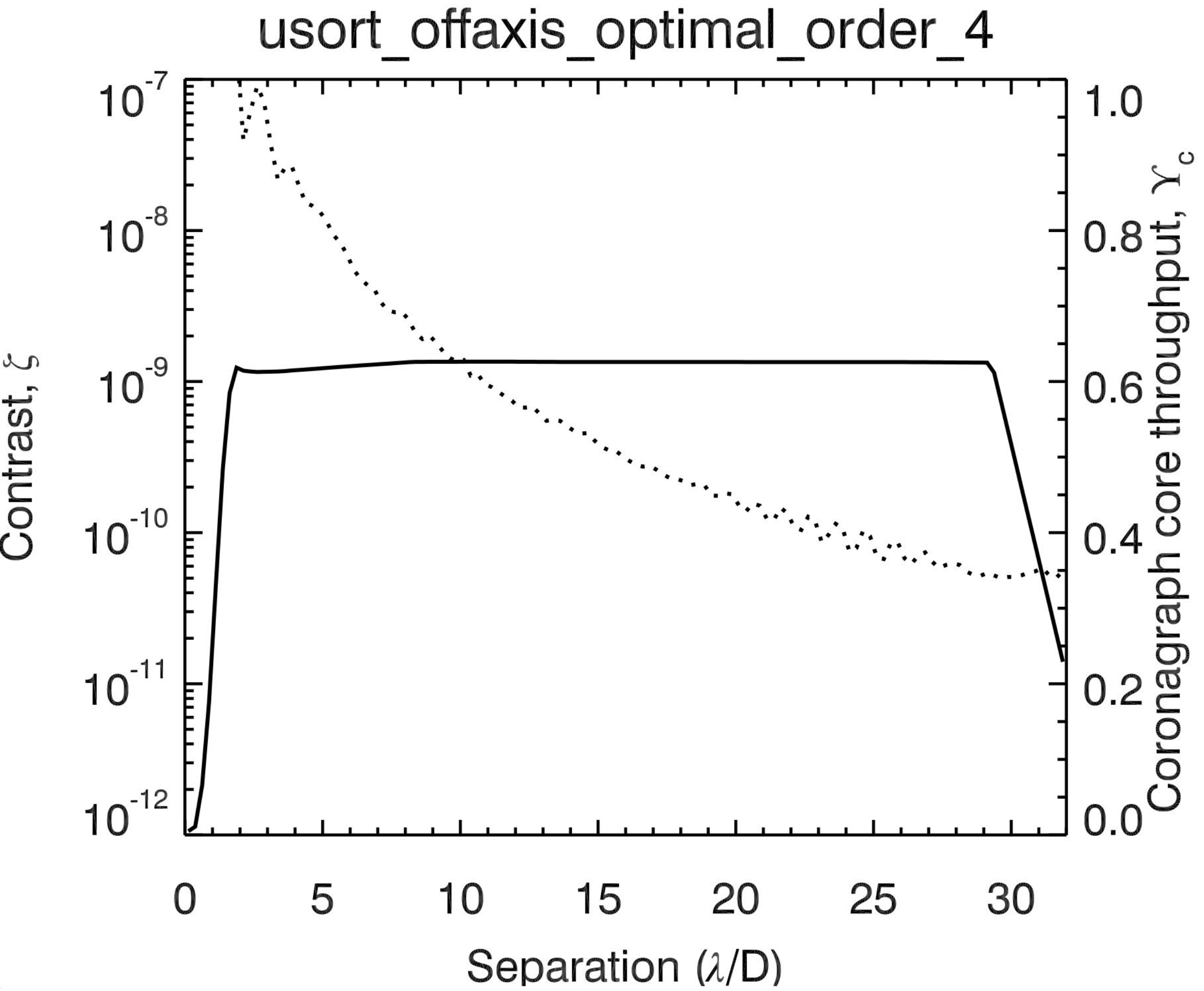
starID	HIP	dist (pc)	Type	nexozodis (zodis)	Visit #	Visit dt (years)	Exp Time (days)	Spec char time (days)	exoEarth candidate yield	Hot Rocky yield	Warm Rocky yield	Cold Rocky yield	Hot SuperEarth yield
72	54035.0	2.54610	M2+V	3.00000	1	0.00000	0.125587	0.0211508	0.208149	0.210312	0.251432	0.611723	0.148311
72	54035.0	2.54610	M2+V	3.00000	2	0.0356277	0.104378	0.00325155	0.0320741	0.0433309	0.0465357	0.0156160	0.0279262
72	54035.0	2.54610	M2+V	3.00000	3	0.0712554	0.0977247	0.000436353	0.00412148	0.0187151	0.0114323	0.00443157	0.0124209
72	54035.0	2.54610	M2+V	3.00000	4	0.106883	0.0962104	1.08148e-05	0.000102524	0.00889002	0.000583212	0.000744329	0.00660048
72	54035.0	2.54610	M2+V	3.00000	5	0.149636	0.0961985	3.01725e-07	2.43476e-06	0.00743769	0.000300021	0.00301117	0.00618358
72	54035.0	2.54610	M2+V	3.00000	6	0.192390	0.0961985	0.00000	0.00000	0.00679488	0.000214532	0.00151507	0.00395706
536	16537.0	3.21978	K2V	3.00000	1	0.00000	0.129220	0.0229232	0.207148	0.470237	0.241562	0.242216	0.341143
536	16537.0	3.21978	K2V	3.00000	2	0.370240	0.0994575	0.00405364	0.0357483	0.0546975	0.0590717	0.0246651	0.0316307
536	16537.0	3.21978	K2V	3.00000	3	0.555360	0.0978112	0.000159971	0.00129849	0.0302847	0.00593950	0.00785867	0.0124064
536	16537.0	3.21978	K2V	3.00000	4	0.814527	0.0976492	2.65354e-05	0.000212333	0.0119276	0.00138700	0.0114038	0.00425977
536	16537.0	3.21978	K2V	3.00000	5	0.888575	0.0966587	4.84043e-06	3.90735e-05	0.00347239	0.000218522	0.000189073	0.00187414
536	16537.0	3.21978	K2V	3.00000	6	0.962623	0.0966587	0.00000	0.00000	0.00263752	0.000190735	0.000194688	0.00114941
867	104217.	3.49607	K7V	3.00000	1	0.00000	0.132553	0.0228610	0.206802	0.304338	0.245597	0.481460	0.220494
867	104217.	3.49607	K7V	3.00000	2	0.175244	0.100058	0.00376063	0.0334595	0.0469353	0.0542615	0.0227262	0.0283948
867	104217.	3.49607	K7V	3.00000	3	0.262867	0.100087	0.000371430	0.00331251	0.0326701	0.0106085	0.0247976	0.0147507
867	104217.	3.49607	K7V	3.00000	4	0.350489	0.100446	9.08505e-05	0.000776254	0.0100630	0.00187566	0.0248743	0.00547432
867	104217.	3.49607	K7V	3.00000	5	0.420587	0.0966437	1.06890e-05	8.54929e-05	0.00804253	0.000375232	0.000389277	0.00420113

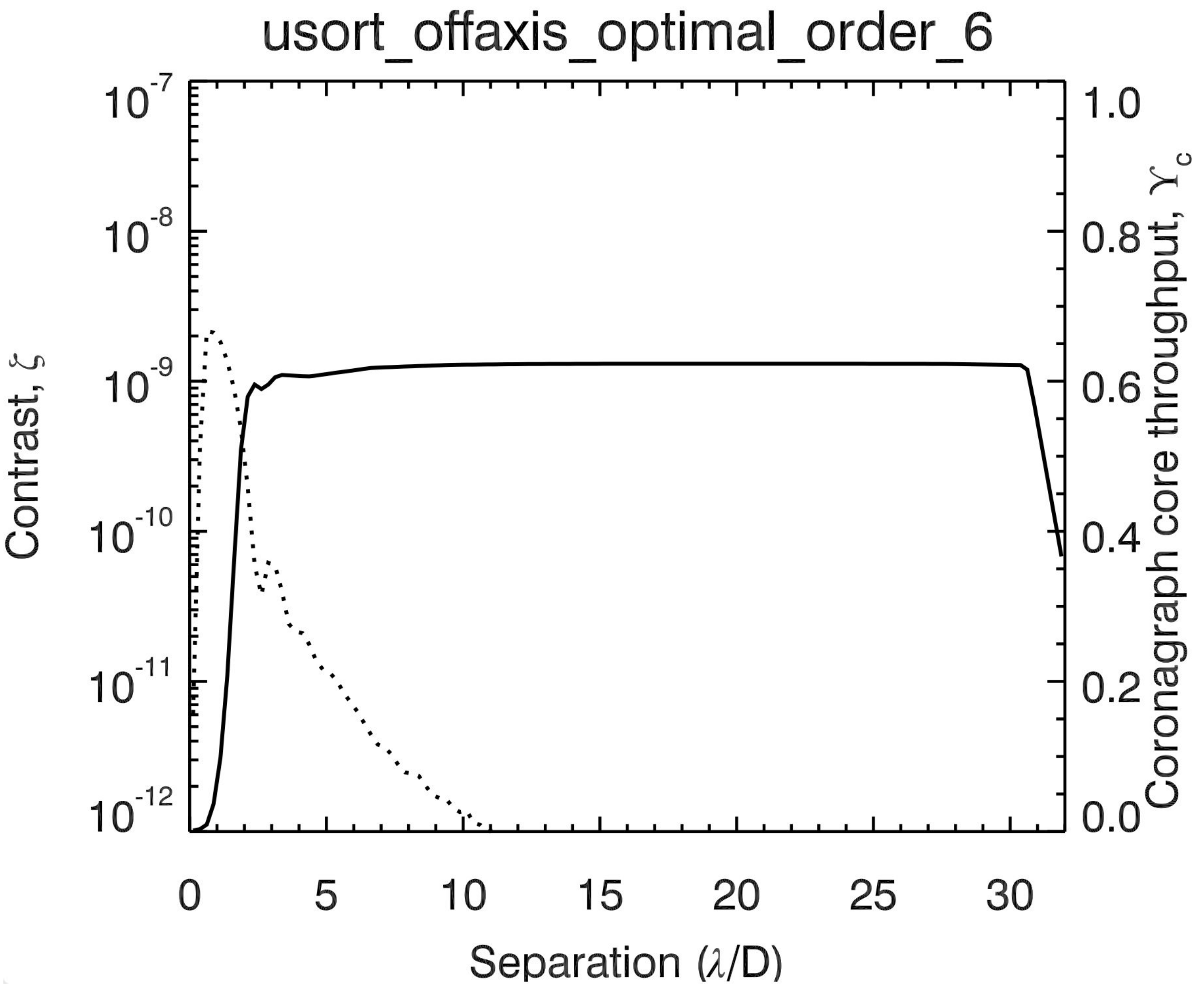
Coronagraph performance check



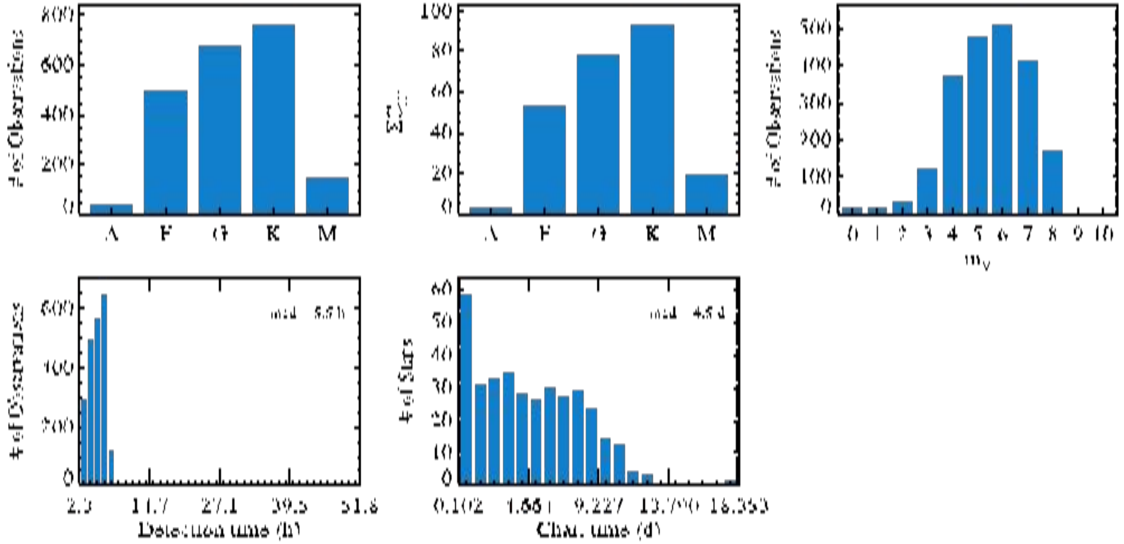
Science Performance Working Group

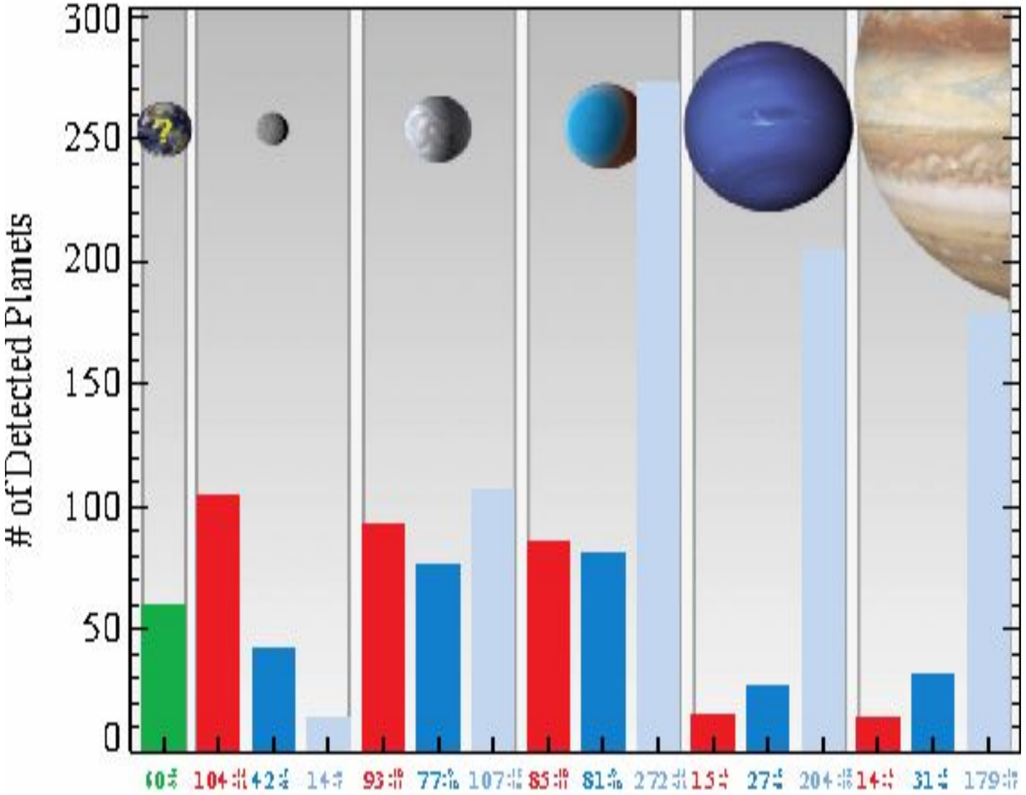
Example Results: USORT off-axis, 6.5m ID, Optimal Coronagraph Limits

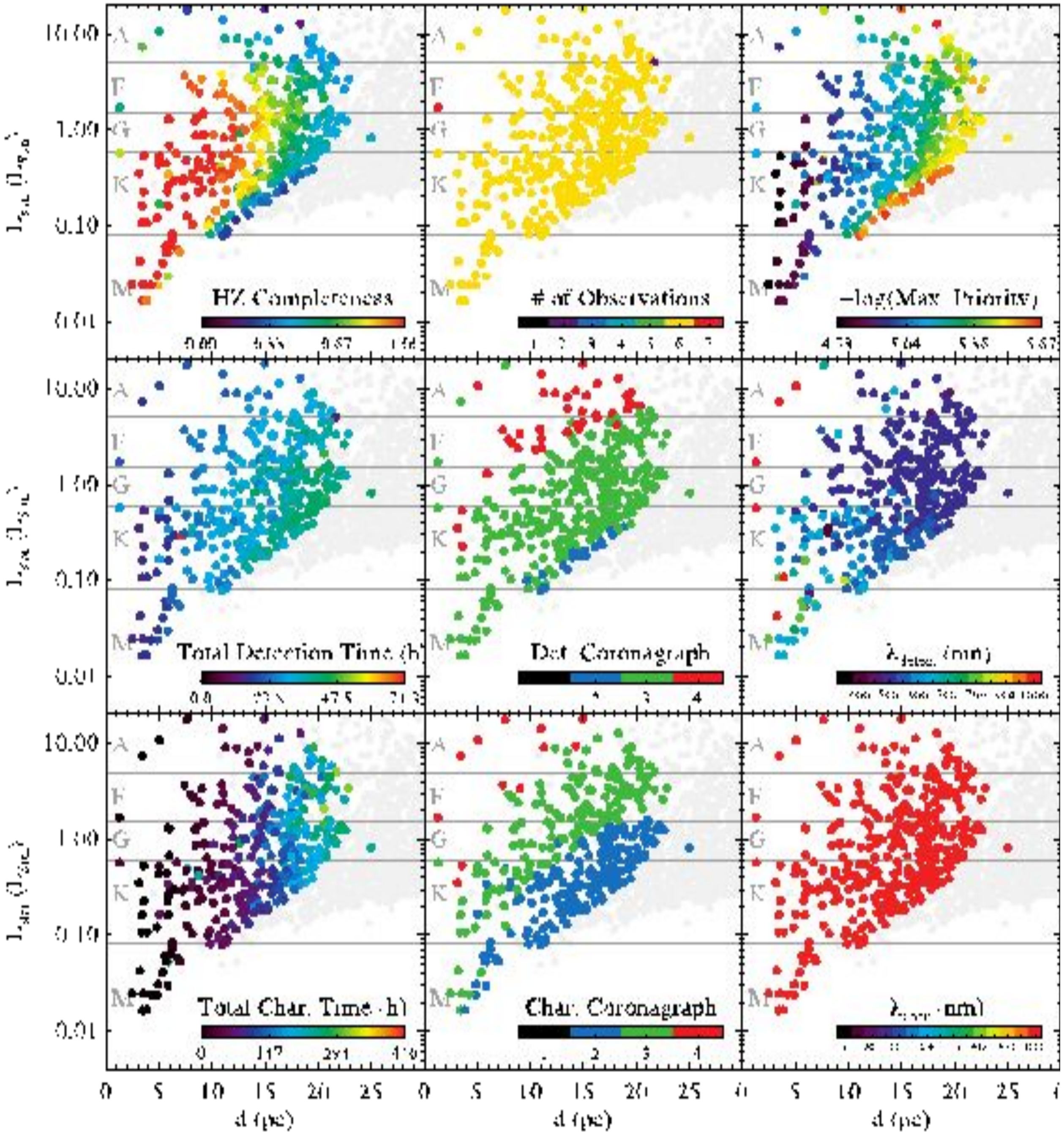




Example Results: USORT off-axis, 6.5m ID, Optimal Coronagraph Limits







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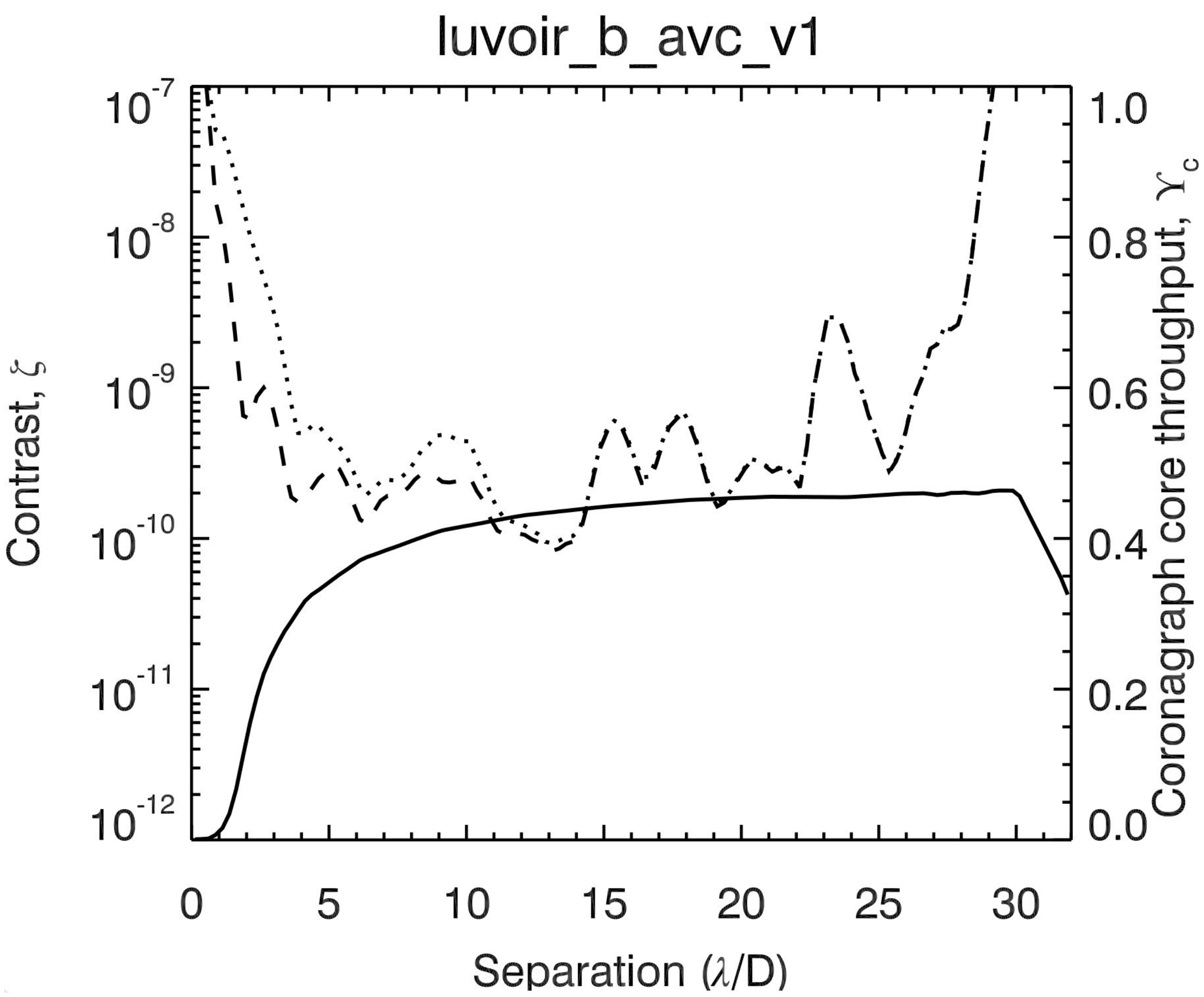
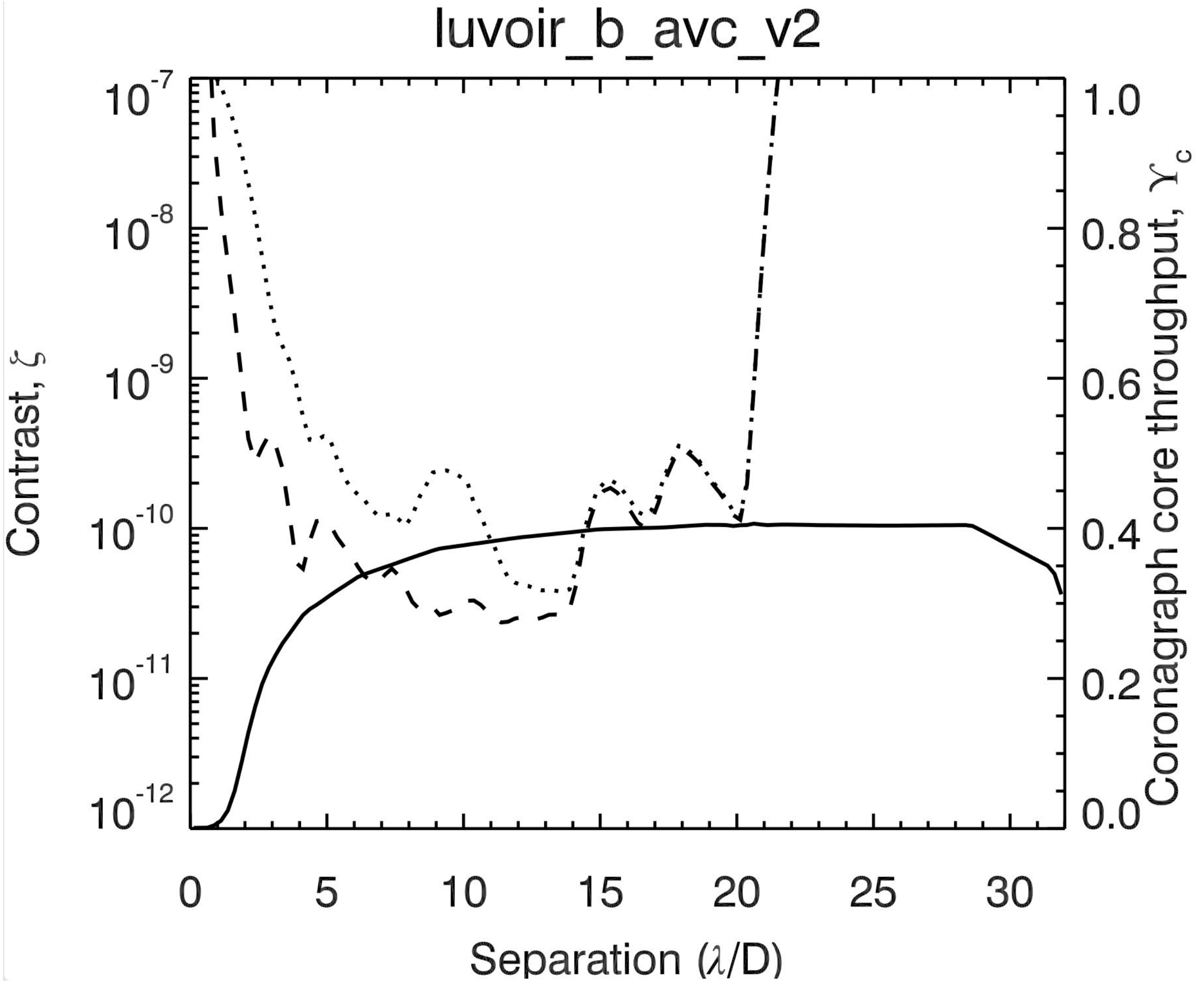
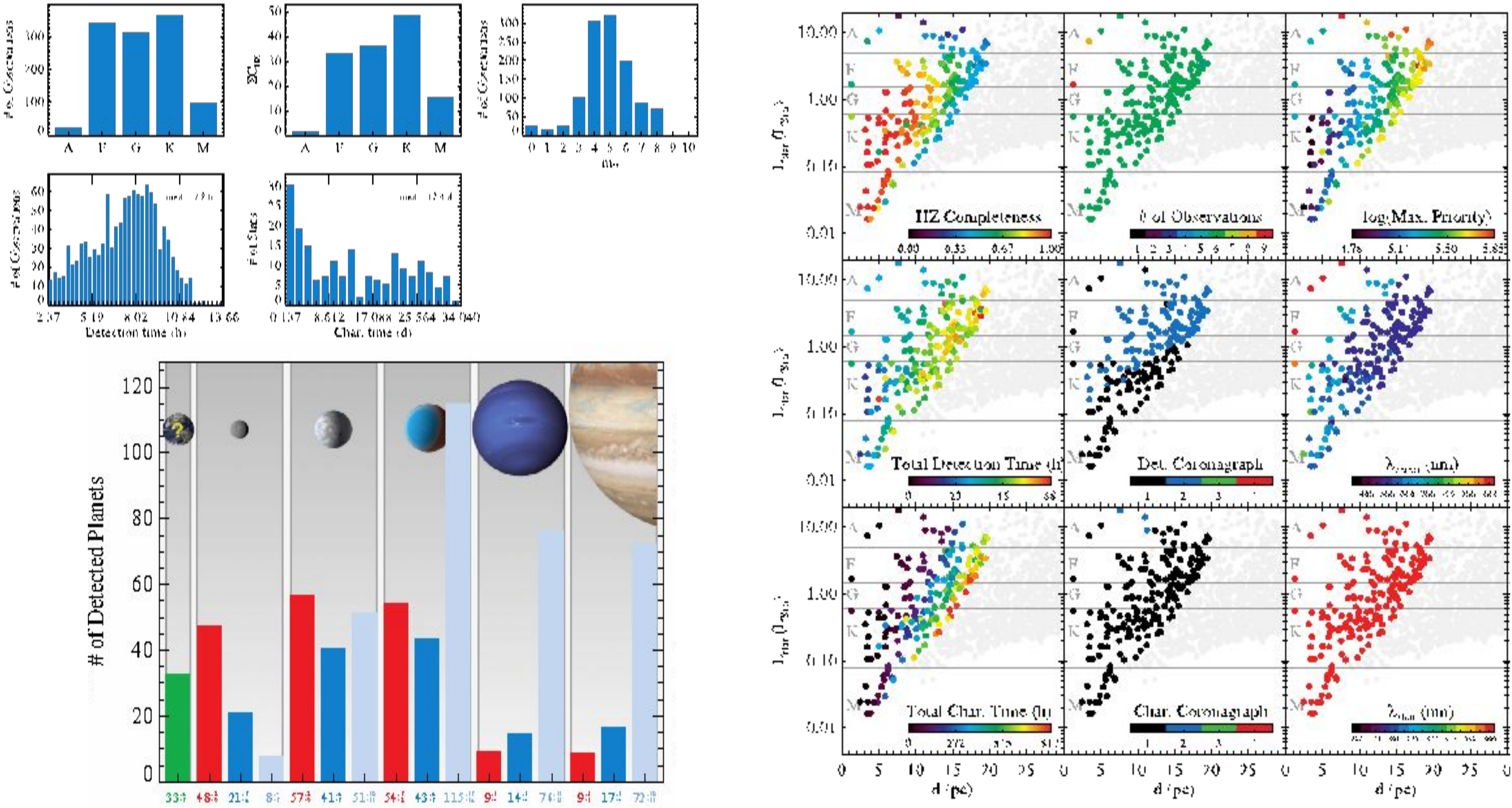
Example Results: LUVOIR-B Off-axis, 6.5 m ID, DM-Apodized Vortex Coronagraph





Example Results: LUVOIR-B Off-axis, 6.5 m ID, DM-Apodized Vortex Coronagraph



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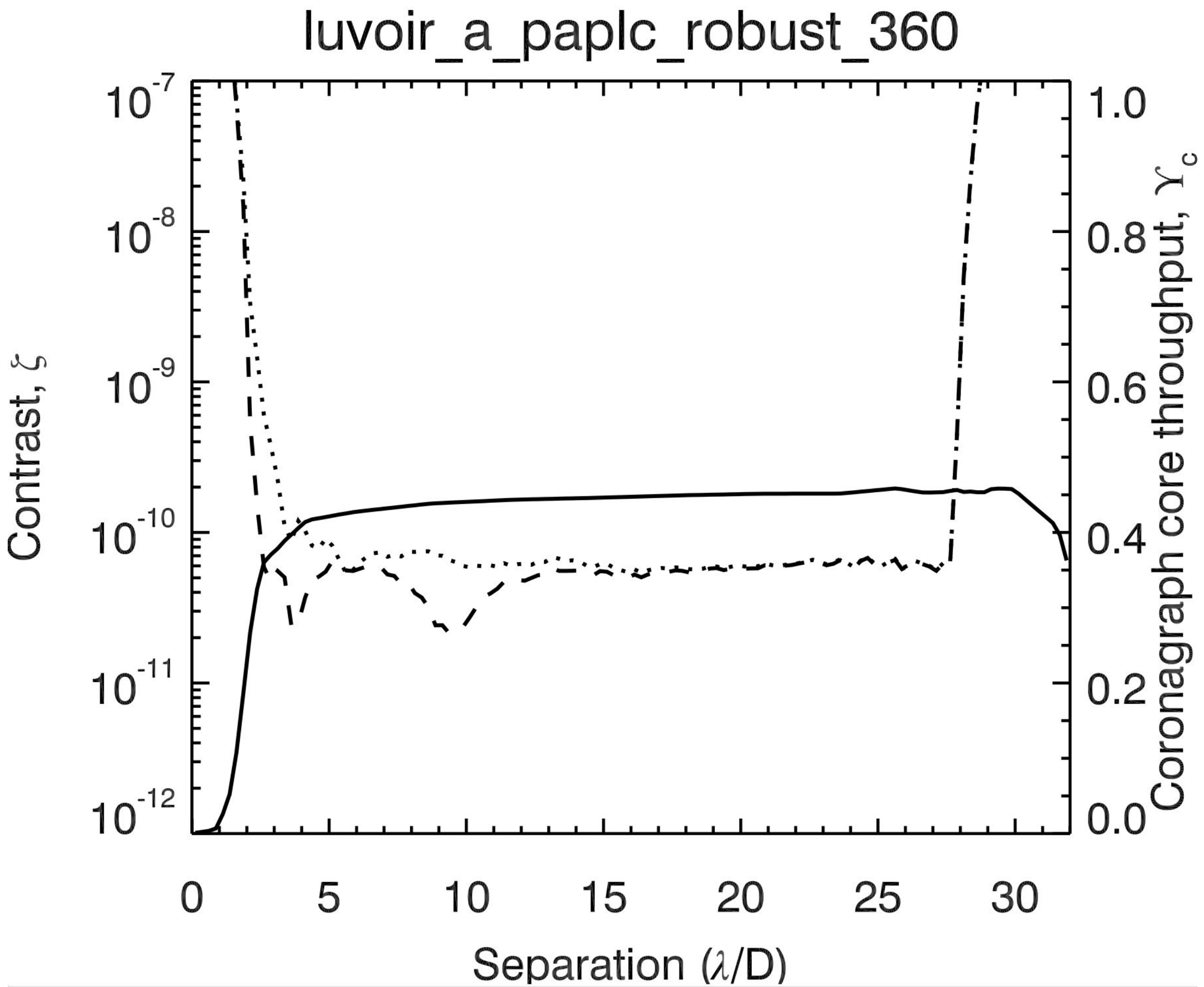
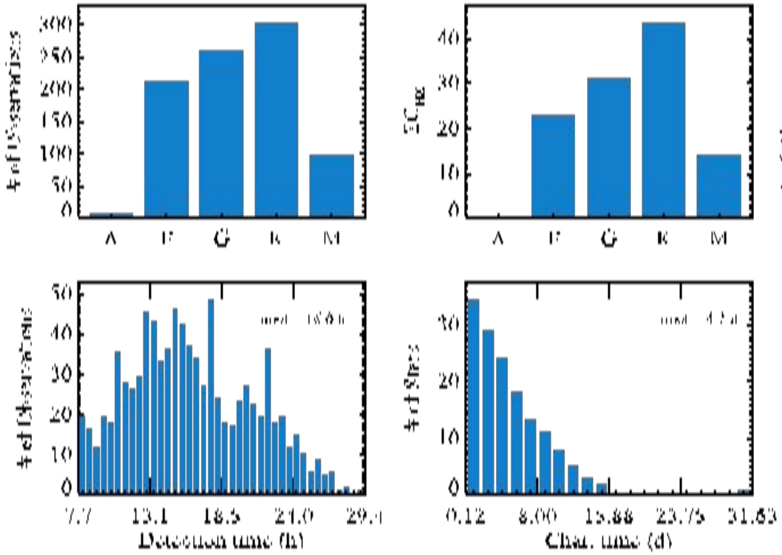
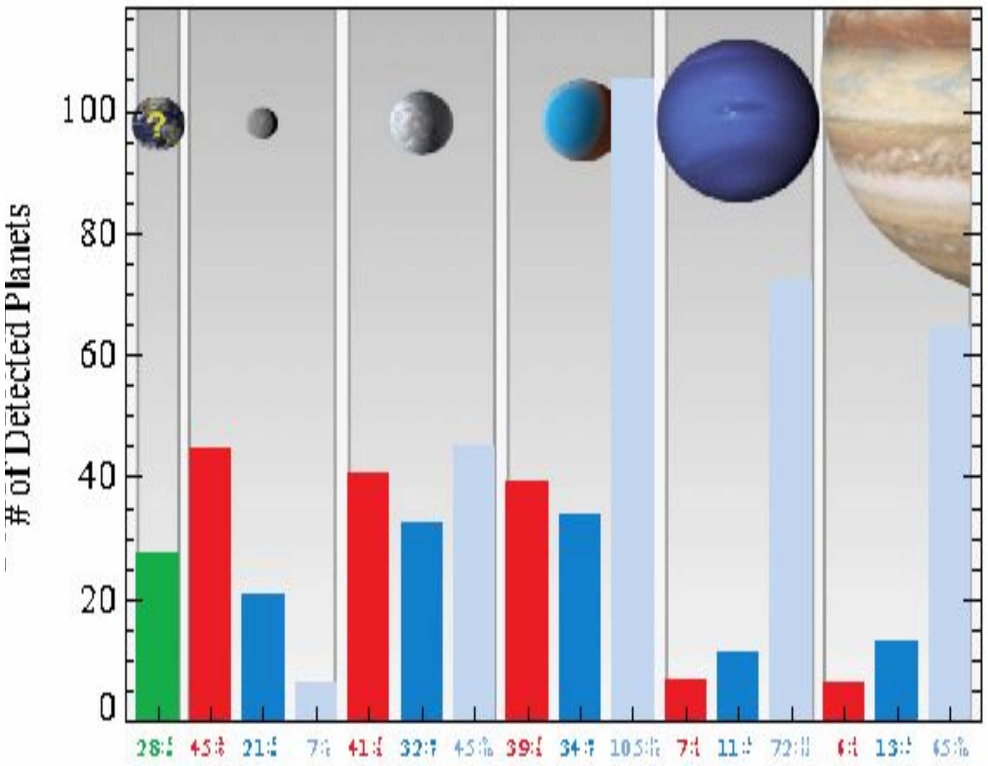
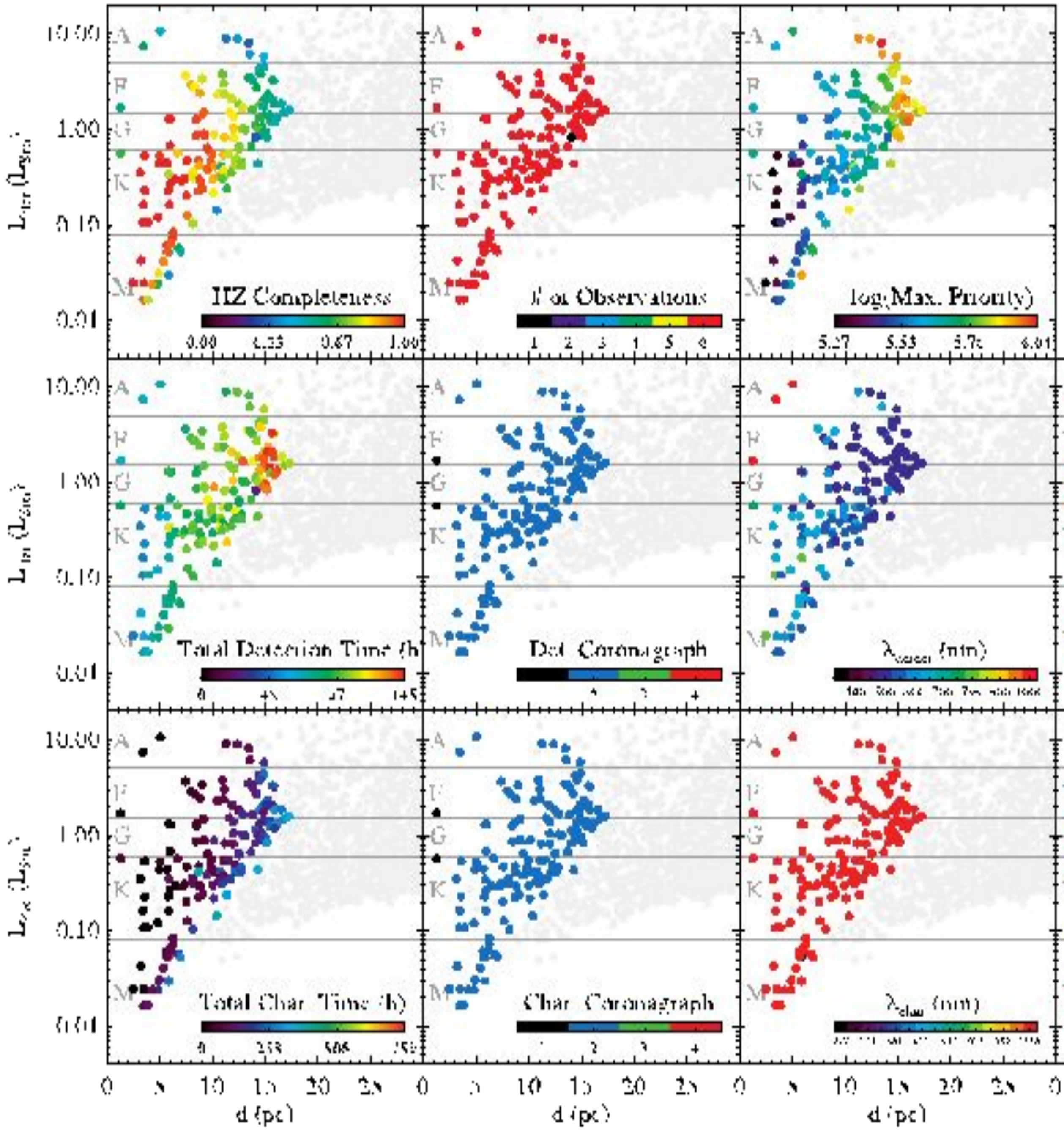
Example Results: LUVOIR-A On-axis, 6.5 m ID, PAPLC



Example Results: LUVOIR-A On-axis, 6.5 m ID, PAPLC







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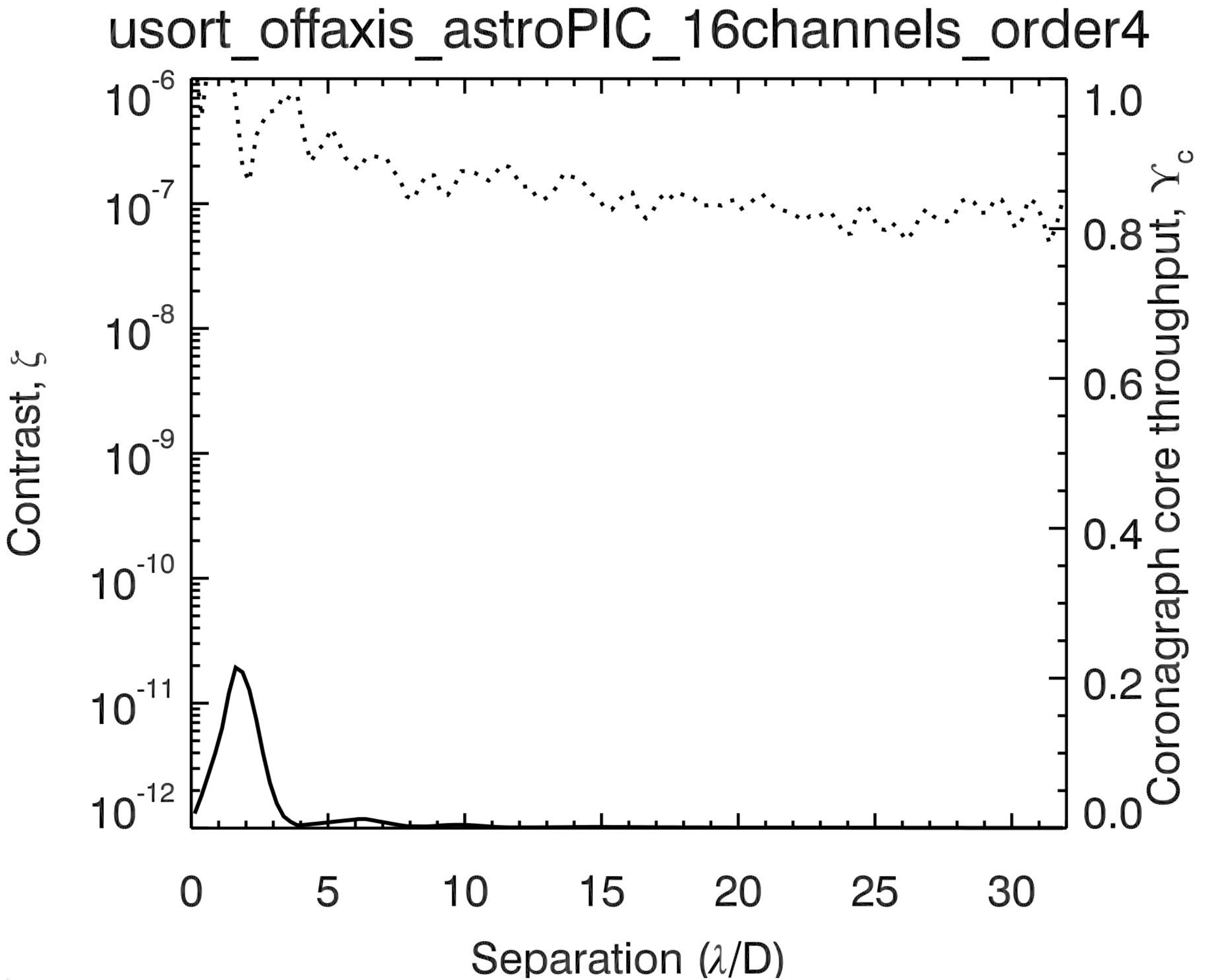
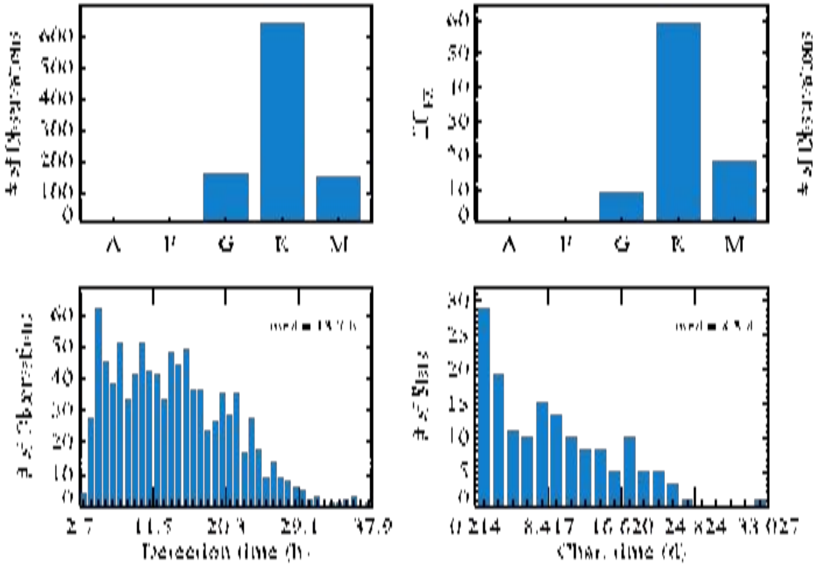
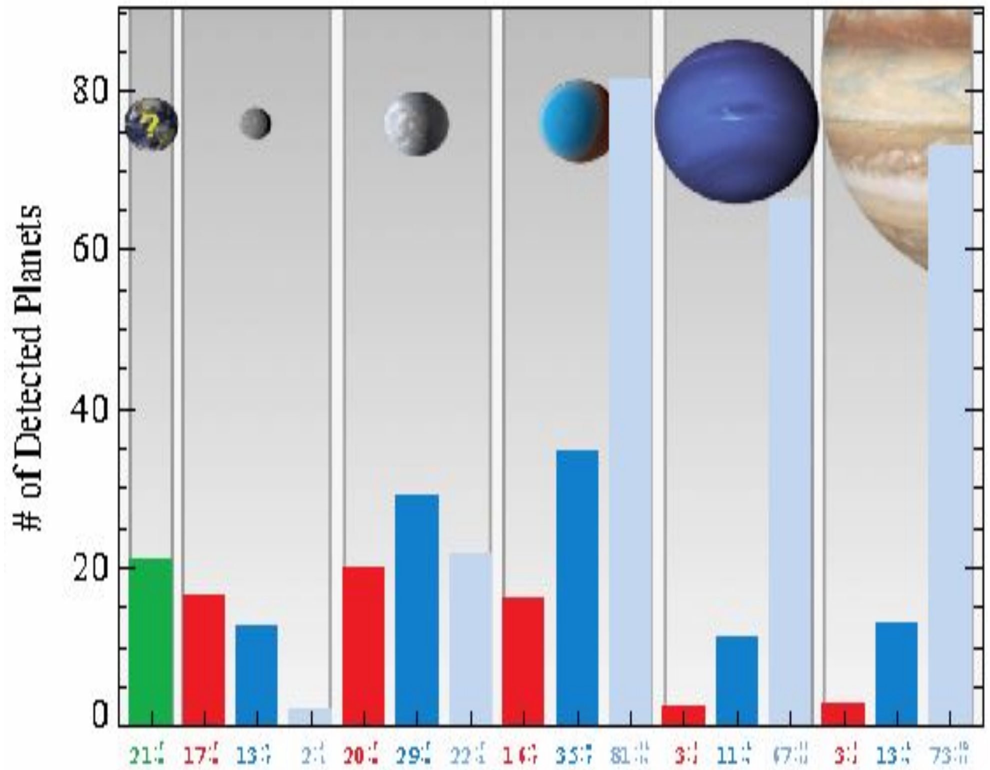
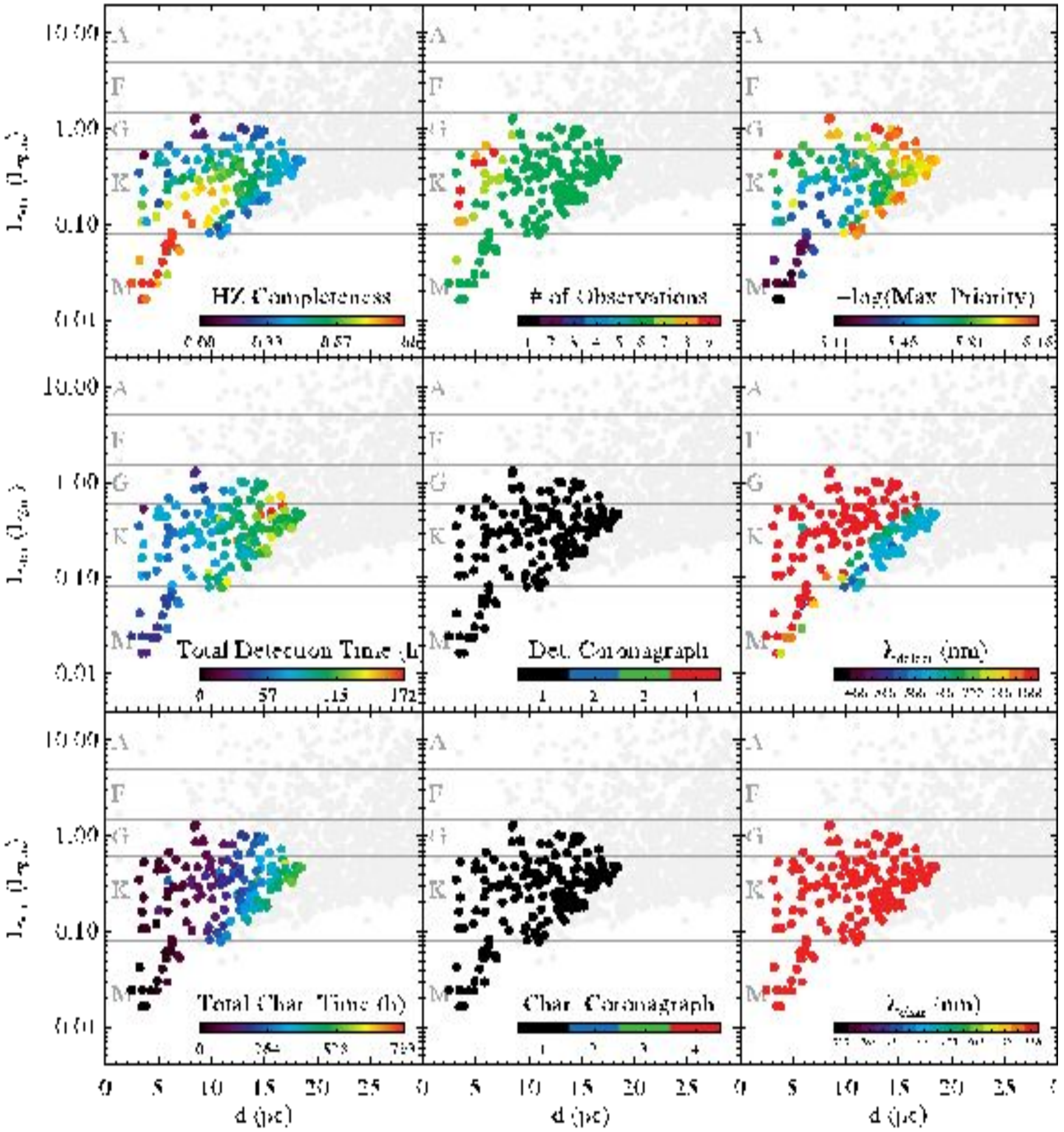
Example Results: USORT Off-axis, 6.5 m ID, 16-channel PIC



Example Results: USORT Off-axis, 6.5 m ID, 16-channel PIC







Science Performance Working Group

Science Performance Working Group Information Matrix

	Focal-Plane Coronagraphs			Pupil-Plane Coronagraphs		Hybrid Coronagraphs			Emerging Technologies	
	HLC	VC (monolith)	DMAVC (segmented)	SPC	PIAA (classic)	AAVC	APLC	PAPLC	Full Photonic Chip	Optimal Coro. Limit
Science Yields										
EEC Yield (VIS detections only)	16% (13)	68% (54)	57% (45)	30% (24)	64% (51)	44% (35)	43% (34)	39% (31)	81% (65)	100% (78)
EEC Yield (Detect + orbits + H2O search)	15% (9)	67% (40)	55% (33)	13% (8)	56% (34)	47% (28)	36% (22)	46% (28)	81% (49)	100% (60)
EEC Yield (Detect + orbit + CO2 search)	5% (2)	50% (15)	32% (10)	2% (1)	29% (9)	28% (8)	15% (5)	44% (13)	86% (26)	100% (30)
Total yield of all planet types	13% (170)	62% (838)	47% (635)	12% (157)	45% (605)	43% (582)	25% (333)	40% (543)	65% (875)	100% (1345)
Exposure Times										
Median detection time for blind survey	5.6x (31 hrs)	1.3x (7 hrs)	1.4x (8 hrs)	3.2x (18 hrs)	1.3x (7 hrs)	2.1x (11 hrs)	2.1x (11 hrs)	2.9x (16 hrs)	1.4x (8 hrs)	1x (6 hrs)
Median detection time for fiducial stars	102x (107 hrs)	2.5x (2.6 hrs)	4.0x (4.2 hrs)	310x (325 hrs)	2.5x (2.6 hrs)	8.6x (9.0 hrs)	6.6x (6.9 hrs)	8.5x (8.9 hrs)	3.0x (3.1 hrs)	1x (1.1 hrs)
Median char. time for fiducial stars										

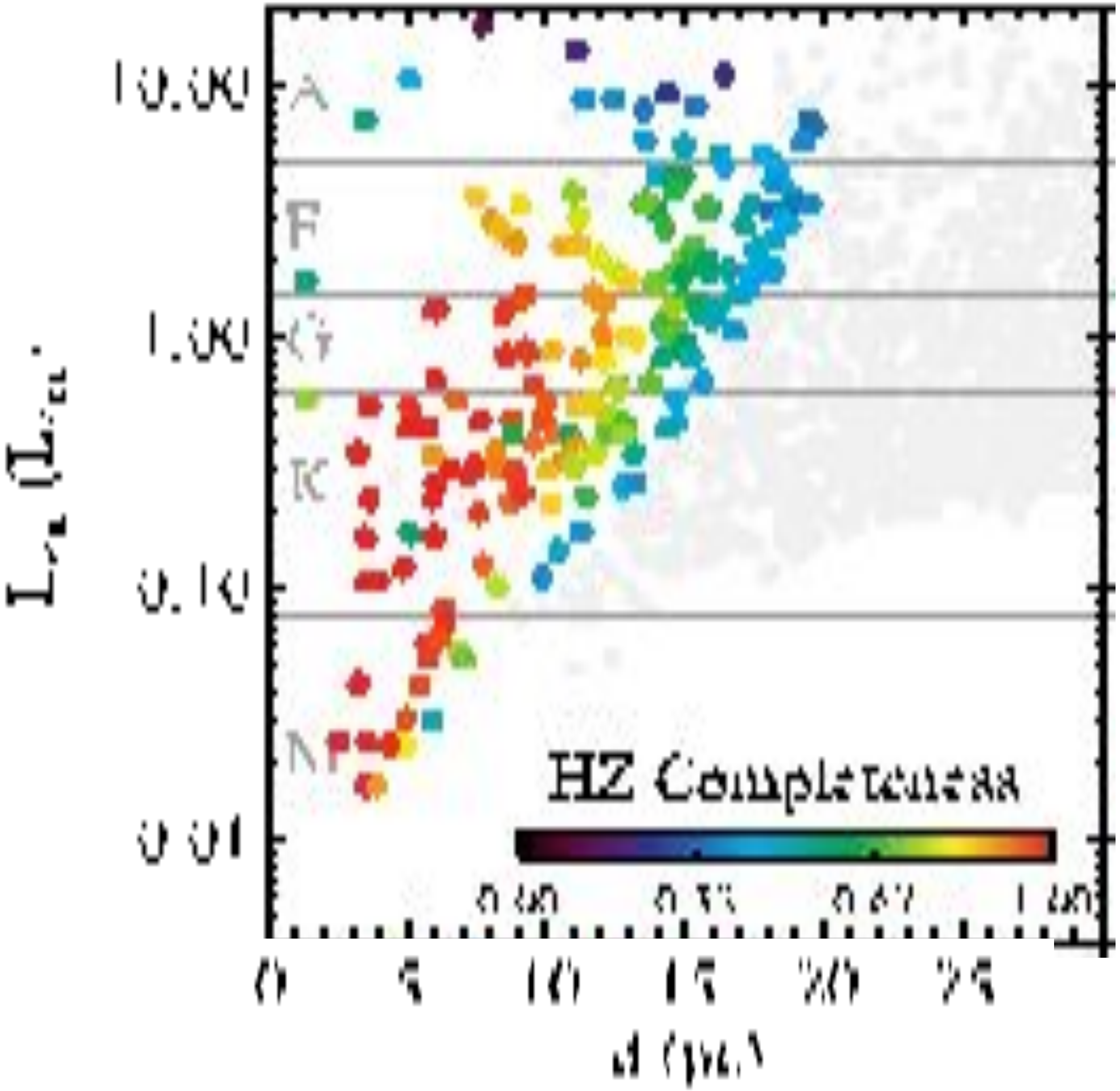
Notes:

- **Absolute yields should not be compared to LUVOIR/HabEx studies, as different assumptions were made.**
- **CDS recommends emphasis be placed on *relative*, not absolute, performance at this point in time.**
- **Some coronagraphs could be improved with further design work.**

Example Results: LUVOIR-B Off-axis, 6.5 m ID, DM-Apodized Vortex Coronagraph

5 Fiducial CTR Stars:

- HIP 32439
- HIP 77052
- HIP 79672
- HIP 26779
- HIP 113283



Example Results: LUVOIR-B Off-axis, 6.5 m ID, DM-Apodized Vortex Coronagraph

5 Fiducial CTR Stars:

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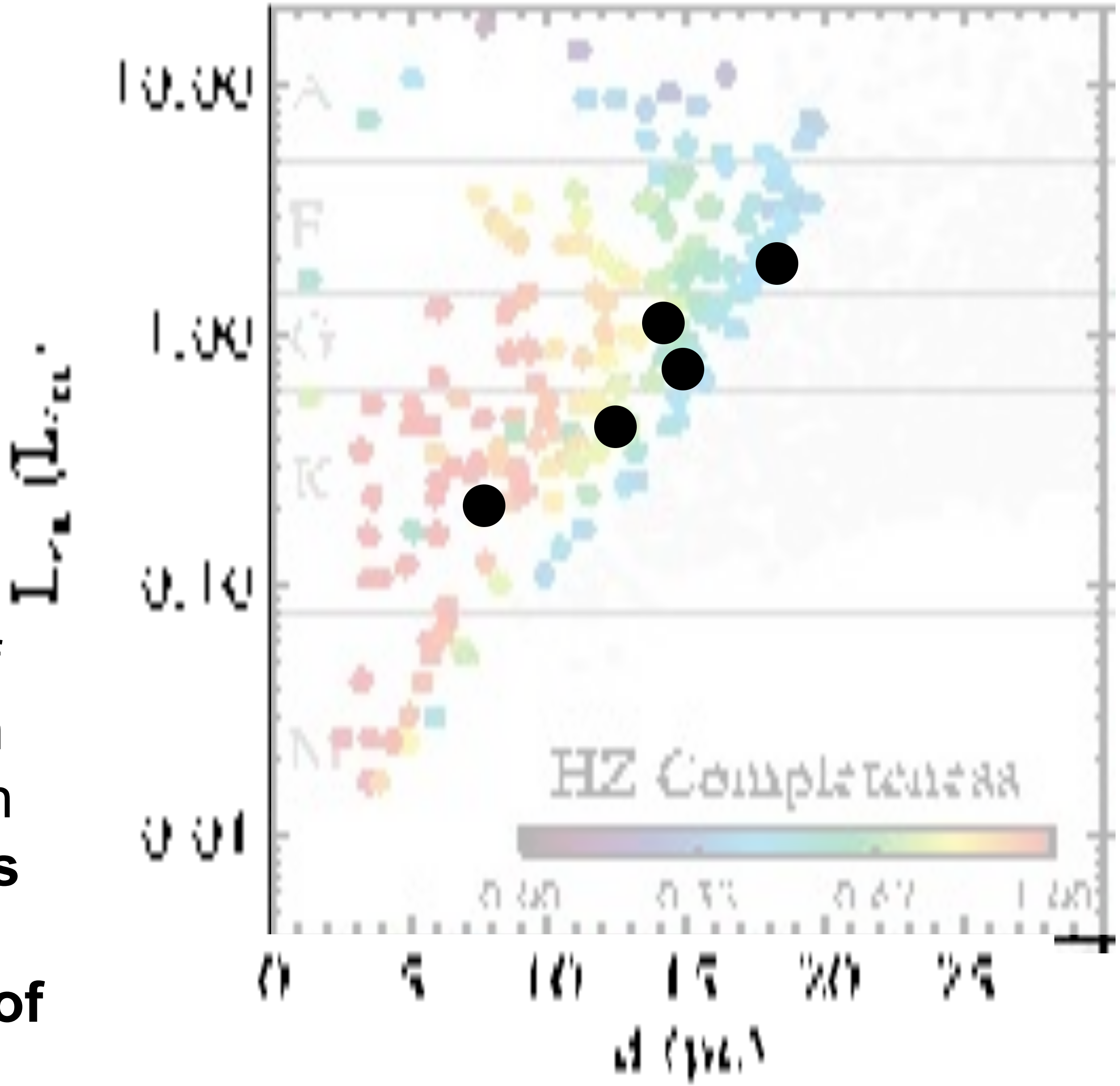


The CTR fiducial stars push the limits of many coronagraphs--not good detection candidates for HLC, not good O2 search candidates for many coronagraphs. **This highlights the dangers of prescribing targets. Targets should be the result of yield calculations.**

Science Performance Working Group

ETC Cross-Model Validation Effort

- Validating exposure time calculators among yield codes
- Coordinated with Coronagraph Technology Roadmap study and START/TAG Exoplanet Science Yield sub-Working Group (ESYWG)

A	B	C	D	E	F	G	H
Broadband detection. Use USORT OVC with default diameter							
Find full list of assumptions here: https://drive.google.com/file/d/1pQ0AIIRWHi350b							
Fiducial Star: HIP 113283							
			lambda = 500 nm				
			Person / Code	Person / Code	Person / Code	Person / Code	Person / Code
Parameter	**Description**	**Units**	**C. Stark / AYO**	**S. Steiger / EBS**	**A. Tokadjian / EXO**	**P. Plavchan / https**	**V. Kofman / PSG**
Basic parameters	*Expected to be inputs to the co*						
F_0	Flux zero point at λ	photons cm^-2 nm^-1 s^-1	13476	1.18E+04	1.19E+04		
m_lambda	apparent magnitude at lambda		7.01E+00	6.45E+00	6.916		
L_star	bolometric luminosity of star	L_Sun	0.2	1.96E-01	0.2		
dist	distance to star	pc	7.6	7.60E+00	7.61		
D	circumscribed diameter of teles	m	7.87	7.87E+00	6.5		
A	collecting area of telescope	cm^2	4.28E+05	4.28E+05	3.32E+05		
λ	Central wavelength of bandpas	nm	5.00E+02	5.00E+02	500		
Δλ	Bandwidth	nm	100	1.00E+02	100		
nzodis	# of zodis		3	3.00E+00	3		
SNR	Required signal to noise ratio		7	7.00E+00	7		
t_overhead,static	Fixed overhead (additive)	s	8.25E+03	8.28E+03	8.28E+03		
t_overhead,dynamic	Dynamic overhead (factor that		1.1	1.10E+00	1		
det_DC	Dark current	counts pix^-1 s^-1	3.00E-05	3.00E-05	3.00E-05		
det_RN	Read noise	counts pix^-1 read^-1	0.00E+00	0.00E+00	0		
det_CIC	Clock induced charge	counts pix^-1 photon_count^-1	1.30E-03	1.30E-03	1.30E-03		
det_tread	Time between reads	s	1.00E+03	-			
det_pixscale	Detector pixel scale	mas	6.55E+00	6.55E+00	6.61E+00		
dQE	Effective QE due to degradatio		7.50E-01	7.50E-01	0.75		

Calibration spreadsheet: https://drive.google.com/drive/u/1/folders/1iURjzKsqGG6_EXyJRNEAadZU0Rc93ZJa

Members of ETC Calibration Group (ESYWG, CDS, & CTR):

- **Sarah Steiger**
- **Armen Tokadjian**
- Dmitry Savransky
- Rhonda Morgan
- Karl Stapelfeldt
- Corey Spohn
- Peter Plavchan
- Pin Chen
- Rus Belikov
- Laurent Pueyo

Science Performance Working Group

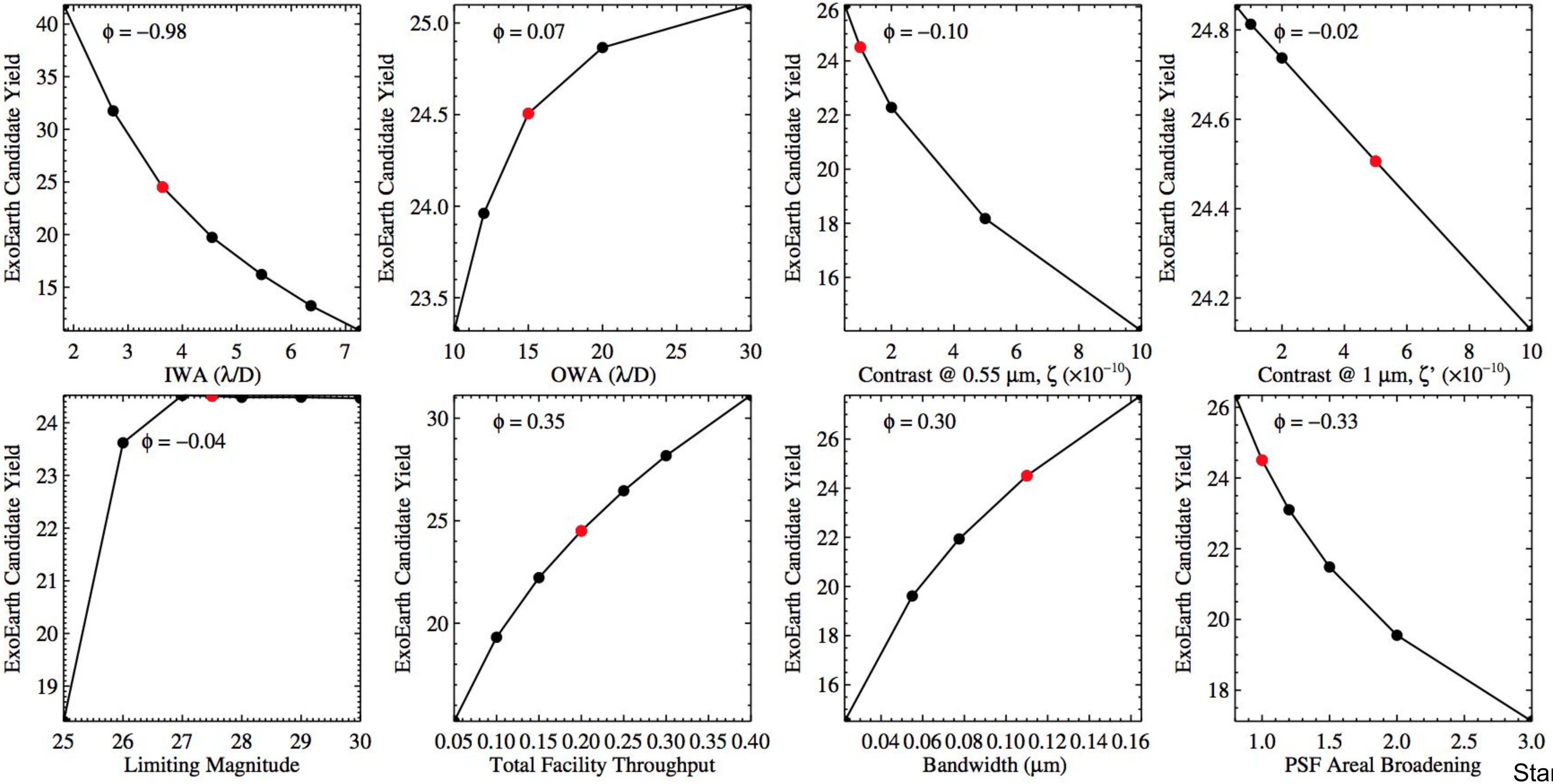
ETC Cross-Model Validation Effort

- Comparing exposure times, count rates, and intermediate parameters
  - detection at 500 nm and 1000 nm
  - characterization to detect O2 and 800 nm and H2O at 1000 nm
- 5 fiducial stars spanning late F to late K
- Should wrap up by mid-May
- Will keep all documentation for others to calibrate to later
- Has resulted in multiple updates to exposure time/yield calculators
- ESYWG will produce draft report by end of May prior to June F2F
  - Lessons learned
  - Calibration document
  - Instructions & methods
- May host a future “hack” day for community members

Science Performance Working Group

CDS Results are a “Snapshot in Time”

- **No CDS results are the final word, as no iteration with coronagraph designers occurred**
- **Future iterations could improve performance; lots of design lever arms available**



Stark et al. (2014)

Findings

- **Substantial progress has been made since the LUVOIR and HabEx final reports.**

- **Coronagraph design trade space is multi-variate and complex.**
  - Prescribed observations can bias comparisons; target list and science observations must be jointly optimized given coronagraph's capabilities

- **Many (but not all!) of the coronagraph designs submitted to the CDS study adopt a similar optical layout.**
  - By accommodating more coronagraphs HWO may be able to reduce risk

- **Improvements in coronagraph efficiency and robustness to aberrations, if achieved, could significantly improve HWO science yield and reduce overall mission risk**

Findings

- **There are coronagraph designs that, in theory, can provide adequate robustness to expected HWO-like WF aberrations.**

- **Of primary importance is the demonstration of *high-efficiency designs* in the laboratory.**

- **HWO could benefit from further pipeline development with a focus on establishing standardized interfaces between key codes and automated execution.**

- **More data gathering, iteration, and analysis is required before a down-select can occur. *Early down-selection could negatively affect coronagraph development.***

Unaddressed and Potential Issues

- CDS did not fund all designers and may not be a comprehensive or unbiased study (but is intended to be a good starting point).
- Not all designs adopted a USORT aperture. We included scaled Habex, LUVOIR-A, and LUVOIR-B designs.
- None of the coronagraph designs were iterated during the CDS efforts. Some designs may benefit more than others from iterative design.
- CDS did not iterate the PM design or look at things like sensitivity to gaps. See SCDA reports.
- CDS abstracted the issue of WFSC and assumed negligible WFE for baseline performance and yield estimates. The impacts of WFE are described via contrast sensitivity calculations. (But, CDS pipeline architecture is compatible with adding WFSC.)
- CDS did not consider combinations of differing coronagraph “flavors.” HWO may end up using different types of coronagraphs for different stars.

How START & TAG Can Use the CDS Deliverables

Deliverable 1: Report and Documentation

Coronagraph Development	System Development	Science Strategies
Understand the options for coronagraph design for HWO	Identify which spatial modes predominantly affect contrast, to iterate telescope design	Identify the ideal targets for each coronagraph
Identify commonalities in the path toward TRL5	Inform instrument alignment tolerances and methods	Identify the range of useful working angles (in λ/D) (*it's often < IWA*)
Identify key manufacturing/industry investments	Inform error budgets	Estimate yields for various science metrics

Deliverable 2: The CDS Software Pipeline

This will enable HWO studies to…

- Standardize analyses for more reliable comparisons
- Continue to evaluate additional coronagraph designs
- Easily evaluate yields for customized mission parameters/coronagraphs
- Evaluate PSF subtraction methods and incorporate into yield calculations

Summary and Final Remarks

- **CDS surveyed coronagraph designs to facilitate future trade studies for HWO**
  - 16 designs + 6 enhancing tech.; wide range of maturity and performance; new designs since HabEx/LUVOIR
- **Modeling tools have been developed and will be delivered to TAG and community**
  - Rapid turnaround, modular, apples-to-apples evaluation of coronagraph designs, including yields
  - Can serve the future PO in the down-select process
- **Several key trades identified, such as**
  - Parallel coronagraph channels
  - Telescope stability vs. coronagraph robustness (and/or better WFC, post-processing)
  - Raw contrast vs. coronagraph efficiency (robustness, bandwidth, IWA, throughput, etc.)
  - On-axis vs. off-axis aperture
- **Future useful analyses noted, including**
  - A survey of possible design changes to the system and potential benefits
  - Incorporation of WFSC and polarization aberrations into CDS pipeline
  - Study of how multiple coronagraph designs could work together

3 Synergistic but Distinct Roadmap and Survey Efforts

Coronagraph Technology Roadmap

Pin Chen
(NASA ExEP)

Laurent Pueyo
(STScI)

Primary Objectives:

1. Roadmap for coronagraph technologies to reach TRL 5 for HWO.
2. Inform NASA on prioritized investments to ensure coronagraph technology readiness.

ExEP Colloquium: June 11

Deformable Mirror Technology Roadmap

Eduardo Bendek

Duncan Liu
(NASA JPL)

Tyler Groff
(NASA GSFC)

Primary Objectives:

1. Roadmap for DM technologies to reach TRL 5 for HWO.
2. Inform NASA on prioritized vendors, manufacturing needs, and test facilities to ensure DM technology readiness.

ExEP Colloquium: June 7

Coronagraph Design Survey

Rus Belikov
(NASA ARC)

Chris Stark
(NASA GSFC)

Primary Objectives:

1. Survey and document viable coronagraph architectures for HWO.
2. Identify novel coronagraph technologies for which NASA's technology development investments could be efficiently leveraged.

ExEP Colloquium: just concluded
Future briefings:

- START-TAG F2F, June 3rd, 11:10 - 11:45
- SPIE poster and proceedings (June)