Segmented Coronagraph Design and Analysis (SCDA)
A study by the Exoplanet Exploration Program

Stuart Shaklan
Jet Propulsion Laboratory, California Institute of Technology
November 3, 2016

Mirror Tech/SBIR/STTR Workshop 2016
Greenbelt, MD

Overview

- Defining the SCDA task
- Funded Teams
- Selection of apertures, comparison of their relative merits
- Progress on Apodized Pupil Lyot Coronagraph (APLC)
- Progress on Vortex and Lyot Coronagraphs (VC, LC)
- Progress on Phase Induced Amplitude Apodization Coronagraphs

Defining the SCDA Task

- Find coronagraph designs that enable direct imaging of exo-earths with large, segmented-aperture, partially obscured telescopes.
- Identify attributes of reference apertures that impact perfromance: central obscuration, spiders, gaps, aperture perimeter
- Optimize for science return

- Consider the fundamental limit set by finite stellar diameter;.
  - Assume pointing errors are small compared to stellar diameter, e.g. sub-mas
- Ignore polarization since that is a function of f/#, on- or off-axis, coating, bandpass, and bandwidth.

- Initial design investigation
- Collaboration/ Cross-fertilization encouraged
- Will inform technology gap and future technology investments.

Selection of Apertures

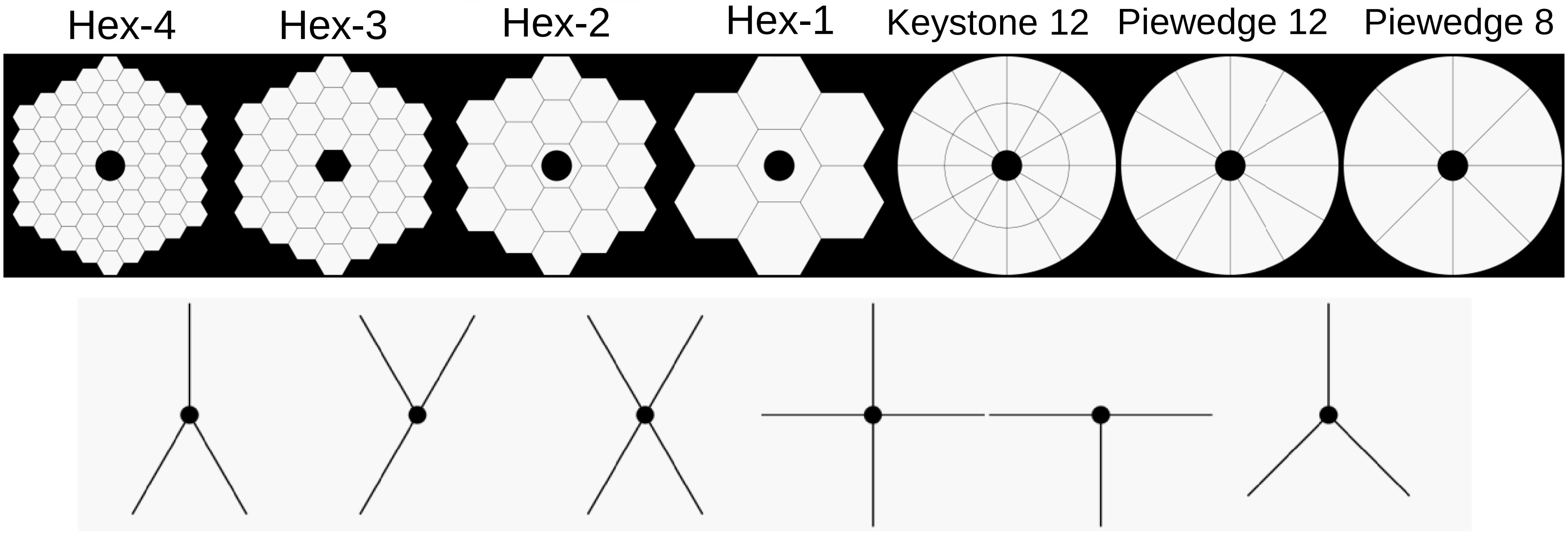


Figure 1 Apertures and secondary support structures selected for the study include four composed of hexagonal segments, one with keystone segments, and 2 with pie wedges. All are 12 m flat-to-flat or 12 m in diameter with 1.68 m diameter secondary obscurations (except the missing hex segment in the 3-ring hex). All segment edge gaps including edge roll-off are 20 mm wide. Secondary support strut widths are 25 mm and 100 mm. Aperture names, from left to right, are: 4-ring Hex, 3-ring Hex, 2-ring Hex, 1-ring Hex, Keystone-24, Pie wedge-12, and Pie wedge-8. Secondary supports are referred to as “Y”, “y,” “X”, and “T,” with two versions of “X” and “Y” for the respective hex and circular apertures.

- This set of apertures and secondary mirror supports represents the likely range of segmented apertures that could be manufactured and launched without on-orbit assembly.
- An SLS is assumed.
- The optical prescription for all telescopes is the same: f/1.25 12-m diameter primary, nearly parabolic, with secondary mirror 13.1 m in front of primary. Secondary obscuration is 14%. Cassegrain field is 10 arcsec diameter.

Comparison of Aperture Relative Merits

Table 1 Relative challenges of designs under consideration. Green to red designates least to most challenging. No absolute scale of difficulty is implied.

	APERTURES						
	4 ring	3 ring	2 ring	1 ring	Keystone 24	Pie wedge 12	Pie wedge 8
Segment Shape	Hex	Hex	Hex	Hex	Keystone	Pie wedge	Pie wedge
Max Segm. Dimension	1.54 m	1.98 m	2.77 m	4.62 m	2.5 m x 3.14 m	5 m x 3.14 m	5 m x 4.71 m
Segments	🟩	🟨	🟧	🟥	🟧	🟥	🟥
Backplane	🟩	🟩	🟧	🟥	🟧	🟧	🟥
Stability	🟩	🟨	🟨	🟥	🟨	🟥	🟥
Launch Configuration	🟨	🟩	🟧	🟥	🟧	🟥	🟥
SM Support	🟩	🟩	🟩	🟨	🟧	🟥	🟥
Overall Ranking	🟩	🟨	🟧	🟥	🟧	🟥	🟥

A document detailing the trades is available at:

*https://**exoplanets**.nasa.gov/system/.../211_**SCDA**ApertureDocument050416.pdf*

Authors: Feinberg, Hull, Knight, Krist, Lightsey, Matthews, Stahl, Shaklan

Funded Teams

- Apodized Pupil Lyot Coronagraph (APLC)
    - Led by R. Soummer, with N. Zimmerman, M. Ndiaye (Post-doc), J. Mazoyer (Post-doc), C. Stark
- Vortex Coronagraph (VC) and Lyot Coronagraph (LC)
    - Led by D. Mawet, with G. Ruane (Post-doc), and J. Jewell (JPL)
- Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
    - Led by O. Guyon, with J. Codona, R. Belikov, students.
- Optimization approaches
    - R. Vanderbei working with the teams

- Teams began work early in CY16.

- Presently the Visible Nuller team is not funded through SCDA as they are focused on TDEM activities.

Progress on Apodized Pupil Lyot Coronagraphs

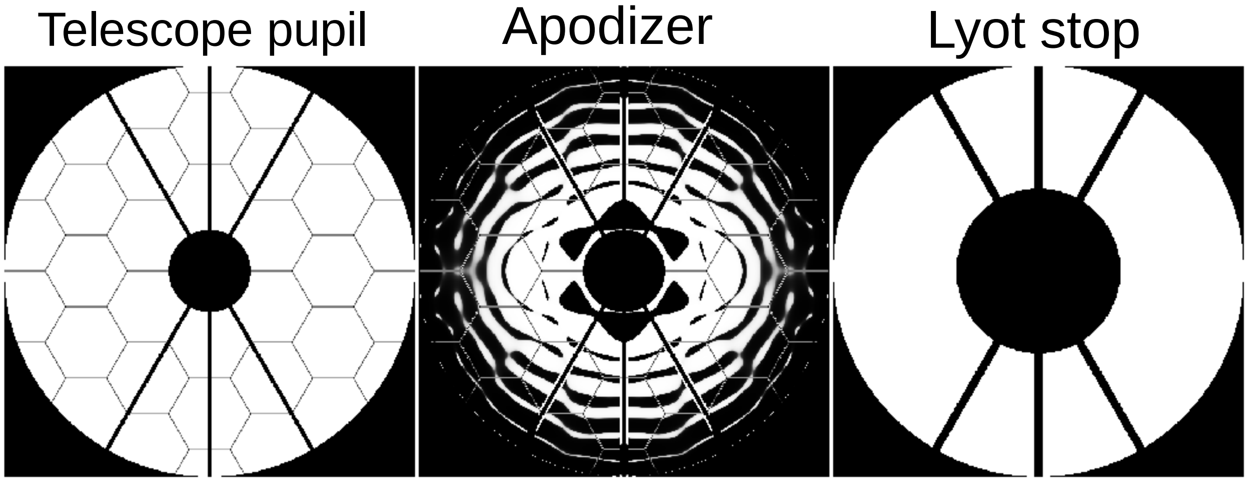
- **The following slides from the APLC group at STScI detail:**

- Advancements in coronagraph throughput and bandwidth since starting the SCDA study.
- Improving robustness against magnification and alignment errors.
- Improving robustness using wave front control.
- Advances in search space and optimization using a supercomputer
- A comparison of throughput for different apertures, showing that presently Keystone segments are preferred over hex segments.
- The Keystone segments in the obscured, on-axis design have nearly the same science return as an off-axis circular monolith.

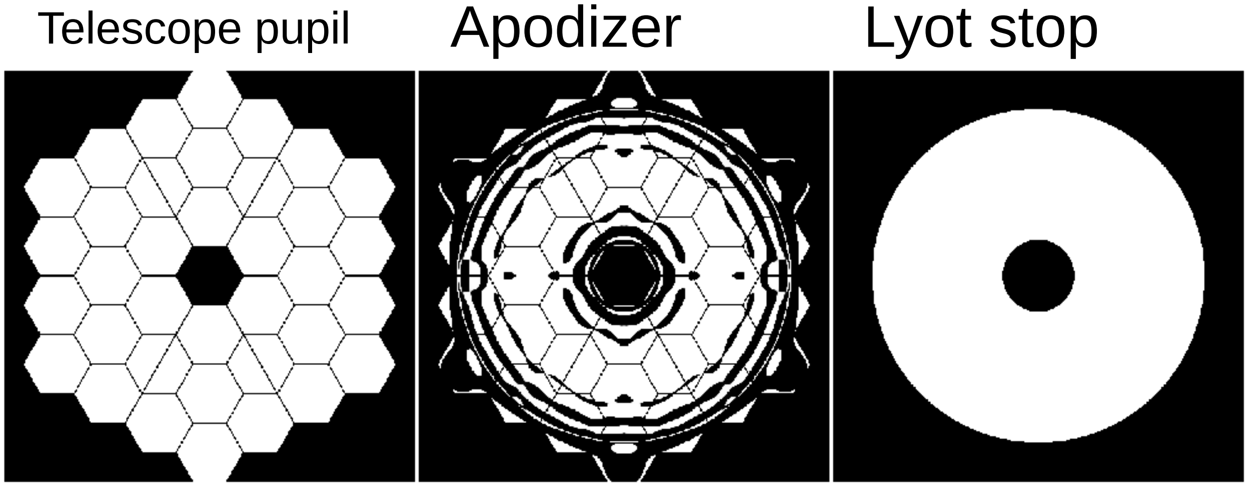
- Note: These are intermediate results requiring further study.

APLC performance progress, before/after SCDA

“ATLAST” APLC
N’Diaye et al. ApJ 818, 2 (2016)
10^{-10} contrast over 10% BW
Working angle 4 – 10 λ/D
$T_{0.7/circ}$ = 7.0%



SCDA 3-ring Hex APLC
10^{-10} contrast over 15% BW
Working angle 4 – 10 λ/D
$T_{0.7/circ}$ = 15.5%

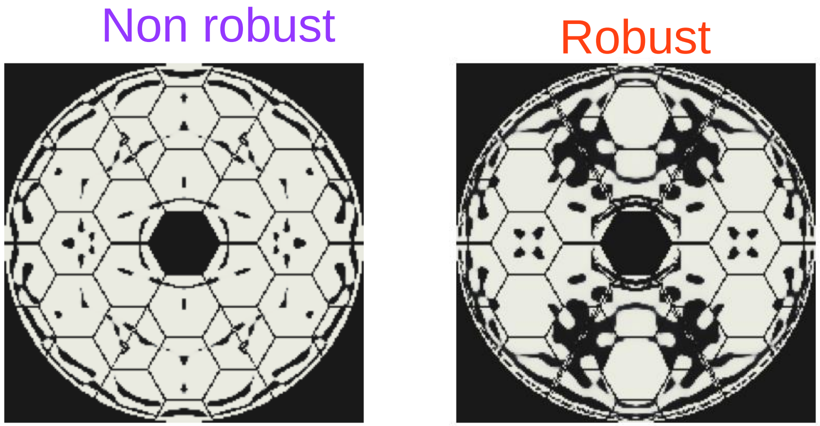


The throughput metric $T_{0.7/circ}$ is the coronagraph PSF energy inside of a photometric aperture of radius 0.7 λ/D, normalized to the energy incident on a circular area matched to the telescope aperture. This gives an aperture-independent metric for how efficiently the combined telescope and coronagraph can direct available energy to the planet PSF core.

Toward robust APLC/SP designs

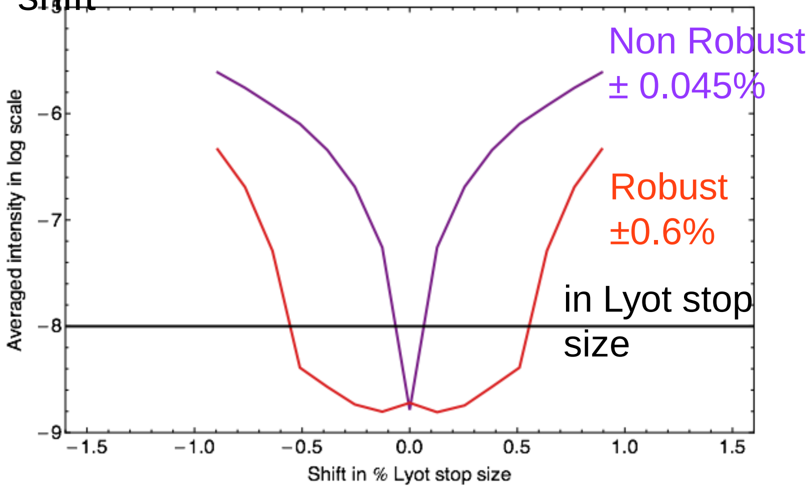
- Development of robust designs to produce dark zone for multiple, translated versions of the Lyot stop simultaneously
- First results: increase in alignment tolerance by ~10 for 10^8 contrast design
- Next step: find robust solutions with 10^{10} contrast

SP for APLC with 4.3λ/D radius FPM to produce a 10^8 contrast dark zone between 6-10λ/D



Relative loss in transmission/throughput

Dark zone averaged intensity vs y-axis Lyot shift



Non Robust ± 0.045%

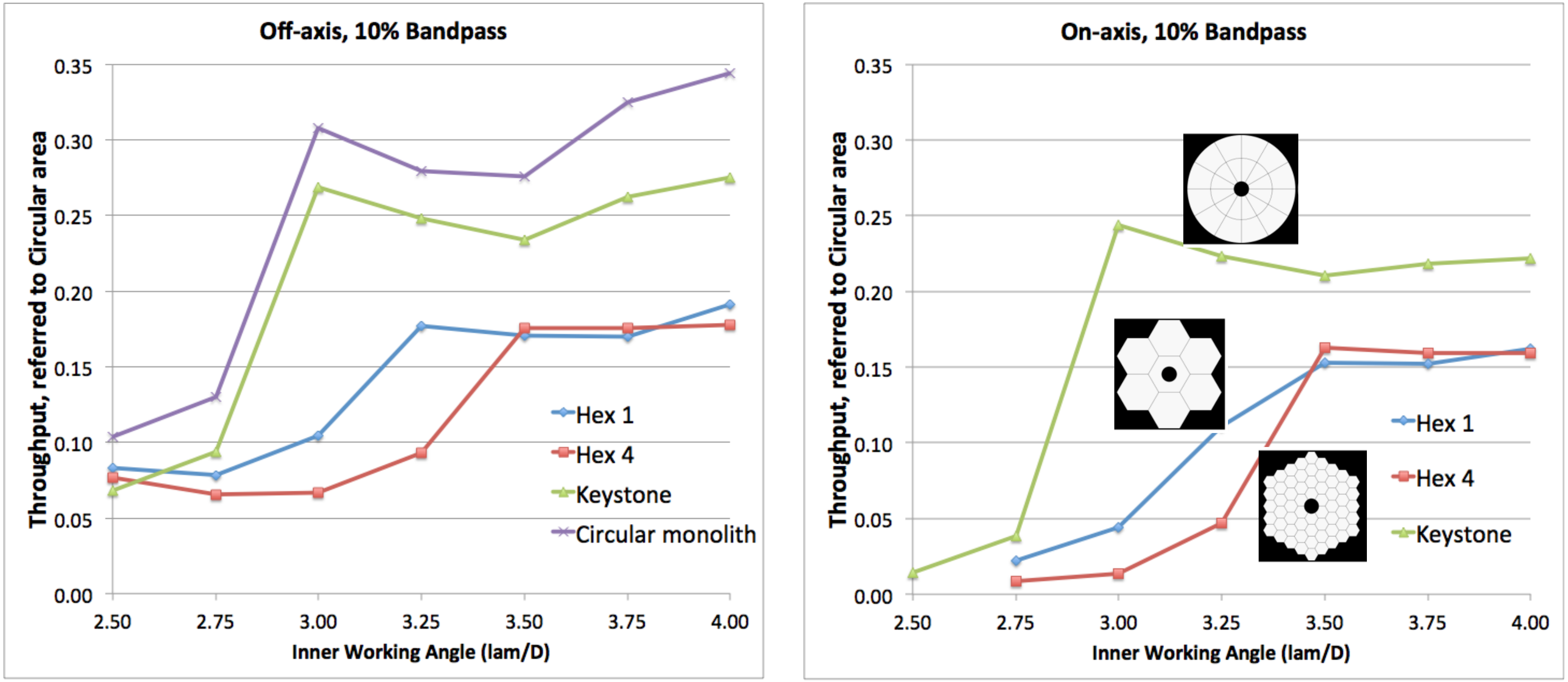
Robust ±0.6%

in Lyot stop size

August-Sep 2016: New APLC design survey with expanded parameter range

- 3100 new designs optimized on NCCS Discover supercomputer
- All SCDA reference apertures (hexagonal, pie, and keystone primaries)
- Inner working angles down to 2.5 λ/D
- With and without central obscuration (on-axis versus off-axis)
- Contrast fixed at 10^{-10} throughout

Throughput of best designs as a function of IWA

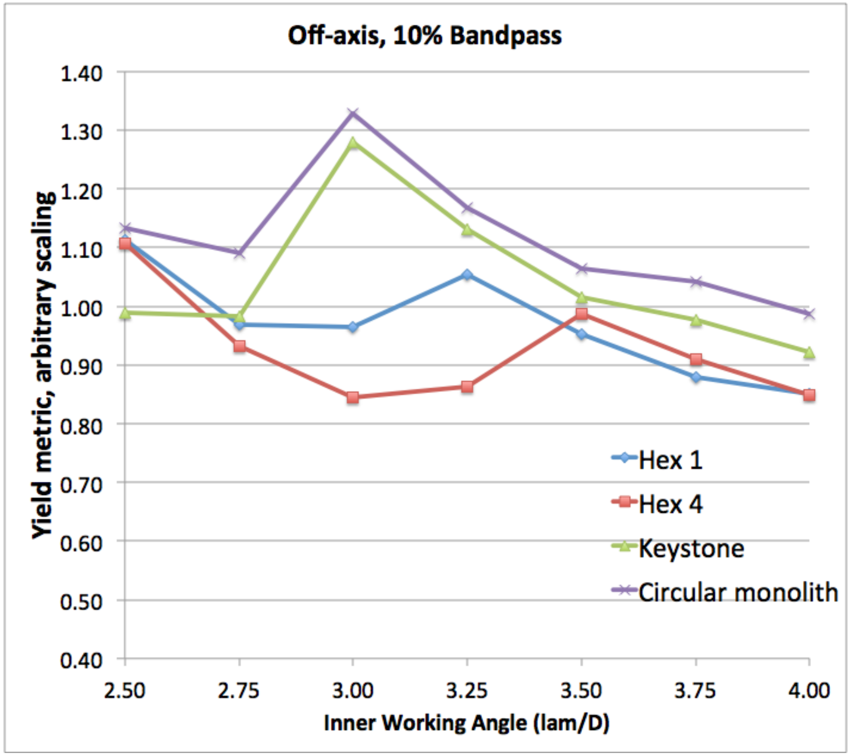


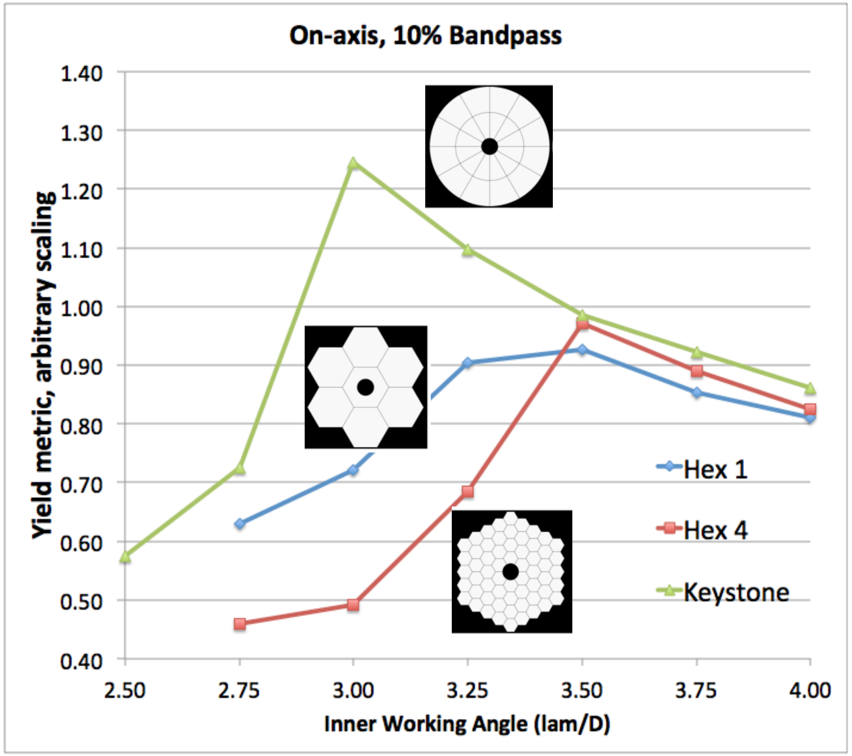
August-Sep 2016: New APLC design survey with expanded parameter range

Applying a provisional scientific yield metric from C. Stark’s 2015 analysis:

$\mathrm{Yield} \propto (\mathrm{throughput})^{0.35} \times (\mathrm{bandwidth})^{0.30} \times (\mathrm{contrast})^{-0.1} \times (\mathrm{IWA})^{-1}$

Proportional *yield metric* of best designs as a function of IWA





August-Sep 2016: New APLC design survey with expanded parameter range

Key results from new survey

- Designs with unobscured (off-axis) pie/keystone primaries approach the performance ceiling defined by the circular monolith APLC.

- At IWA 3.5 λ/D and above, performance on all hexagonal apertures is similar, but at smaller IWA the 1-ring Hex designs maintain significantly higher throughput.

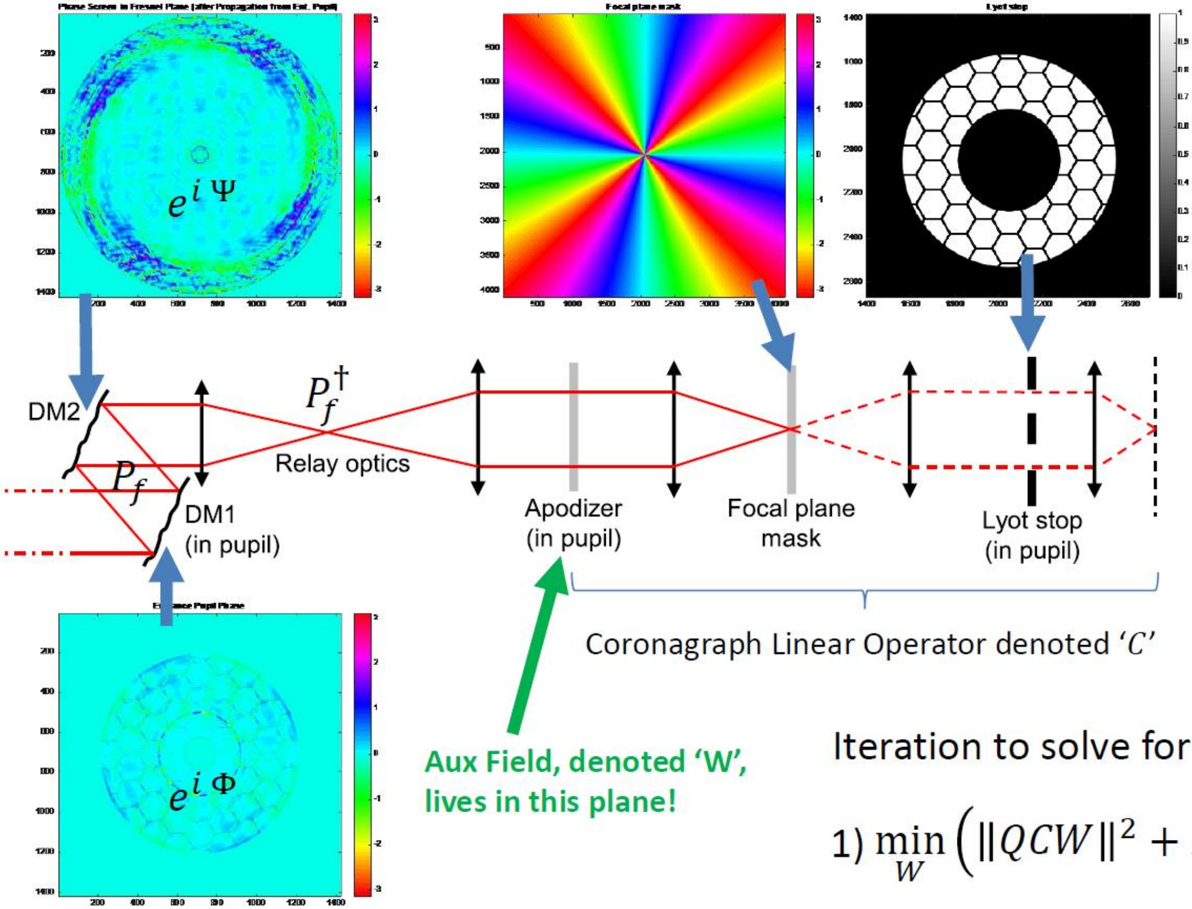
Progress on Vortex and Coronagraphs

- **The following slides from G. Ruane (Caltech) and J. Jewell (JPL) detail:**
- A new optimization approach that solves for an “auxiliary field” that maximizes dark hole characteristics.
- Prior to SCDA, no high-contrast VC solutions for segmented aperture. The new optimization has led to viable designs.
- Designs for charge 4, 6, and 8 vortices.
- Improving robustness using wave front control.
- As with APLC, Keystone/Pie-wedge has higher throughput than Hex segment apertures.

- Note 1: No interesting solutions have been found for Lyot Coronagraphs. Image plane mask optimization is required for broadband performance. So far we have worked on pupil plane, not image plane, optimization.
- Note 2: As with APLC, these are intermediate results requiring further study.

Auxiliary Field Optimization: Powerful New Approach to Optimizing the DM shapes and Pupil Amplitude Profile

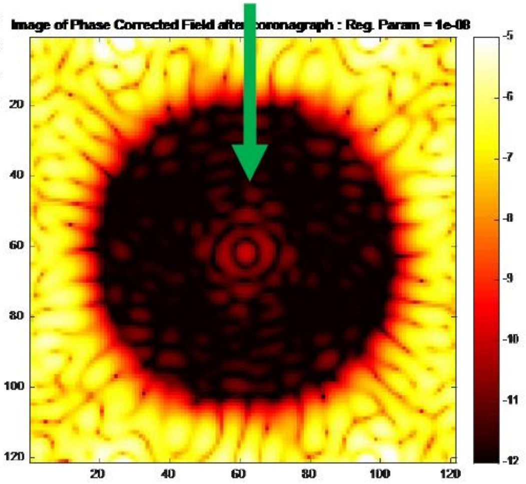
Iterative Solution of Phase Control with an Auxiliary Field (Jeff Jewell, JPL)



Coronagraph Linear Operator denoted ‘C’

Aux Field, denoted ‘W’, lives in this plane!

Goal: Minimize diffracted light in region ‘Q’ in image plane



Iteration to solve for phase control D.o.F:

1) $$\min_{W}\left(\|QCW\|^2+\lambda\left\|W-P_f^\dagger e^{i\Psi}P_f e^{i\Phi}A\right\|^2\right)$$

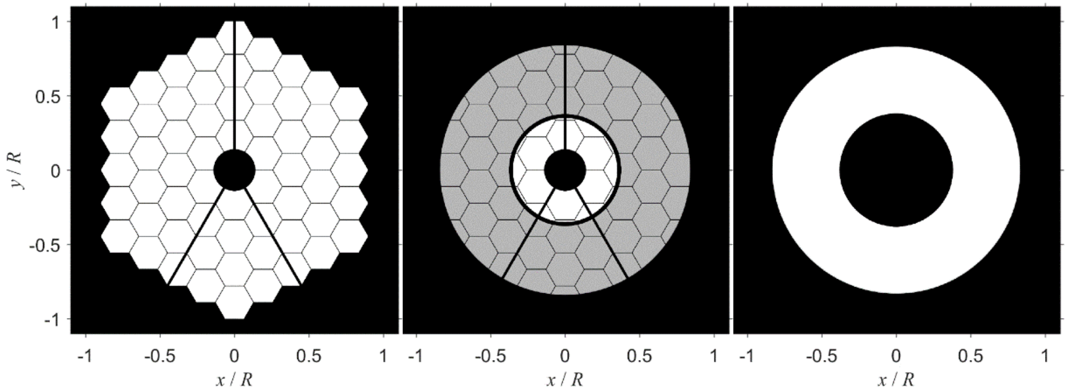
$$W=\left(\lambda I+C^\dagger QC\right)^{-1}\lambda P_f^\dagger e^{i\Psi}P_f e^{i\Phi}A$$

2) $$\min_{\{\Psi,\Phi\}}\left\|W-P_f^\dagger e^{i\Psi}P_f e^{i\Phi}A\right\|^2$$

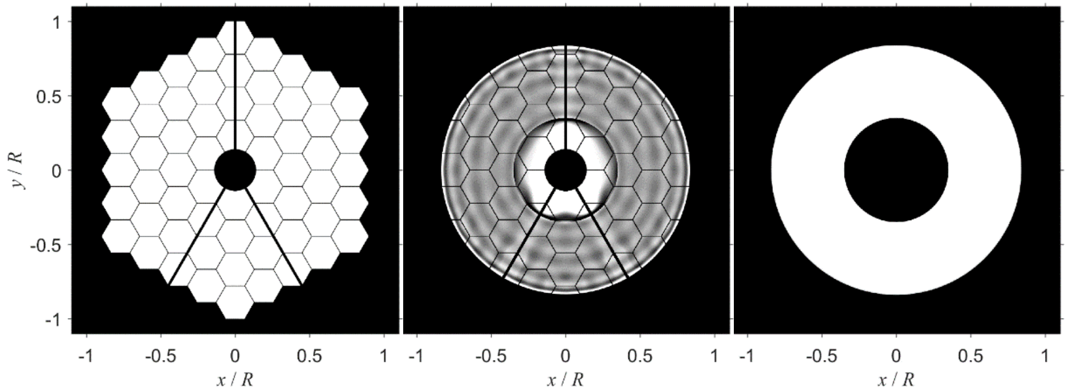
- Fresnel Propagators denoted P_f and (backwards) $P_f^\dagger$
- Goal is to find phase solutions in the entrance pupil $e^{i\Phi}$ and out of plane $e^{i\Psi}$ for any aperture in order to directly minimize on-axis source light in the image plane “dark hole”

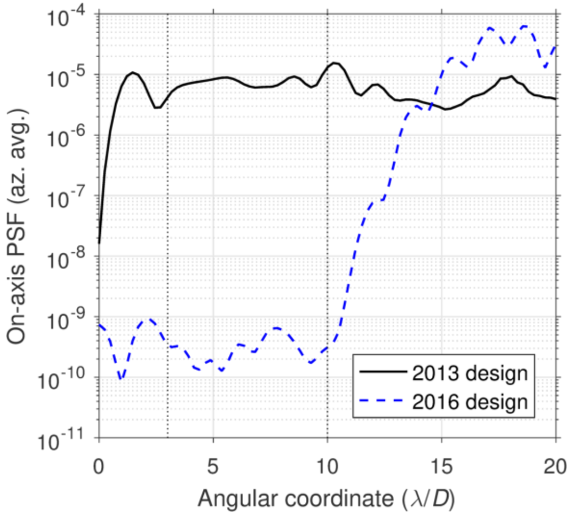
VC Performance Progress, Before/After SCDA

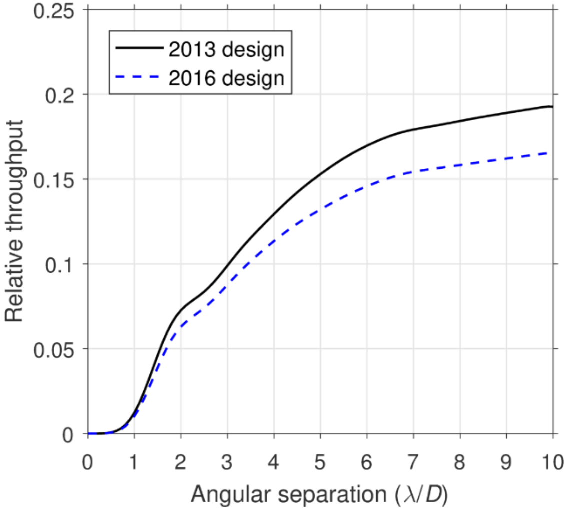
Design based on Mawet et al. (2013)



Design based on Ruane et al. (2016)



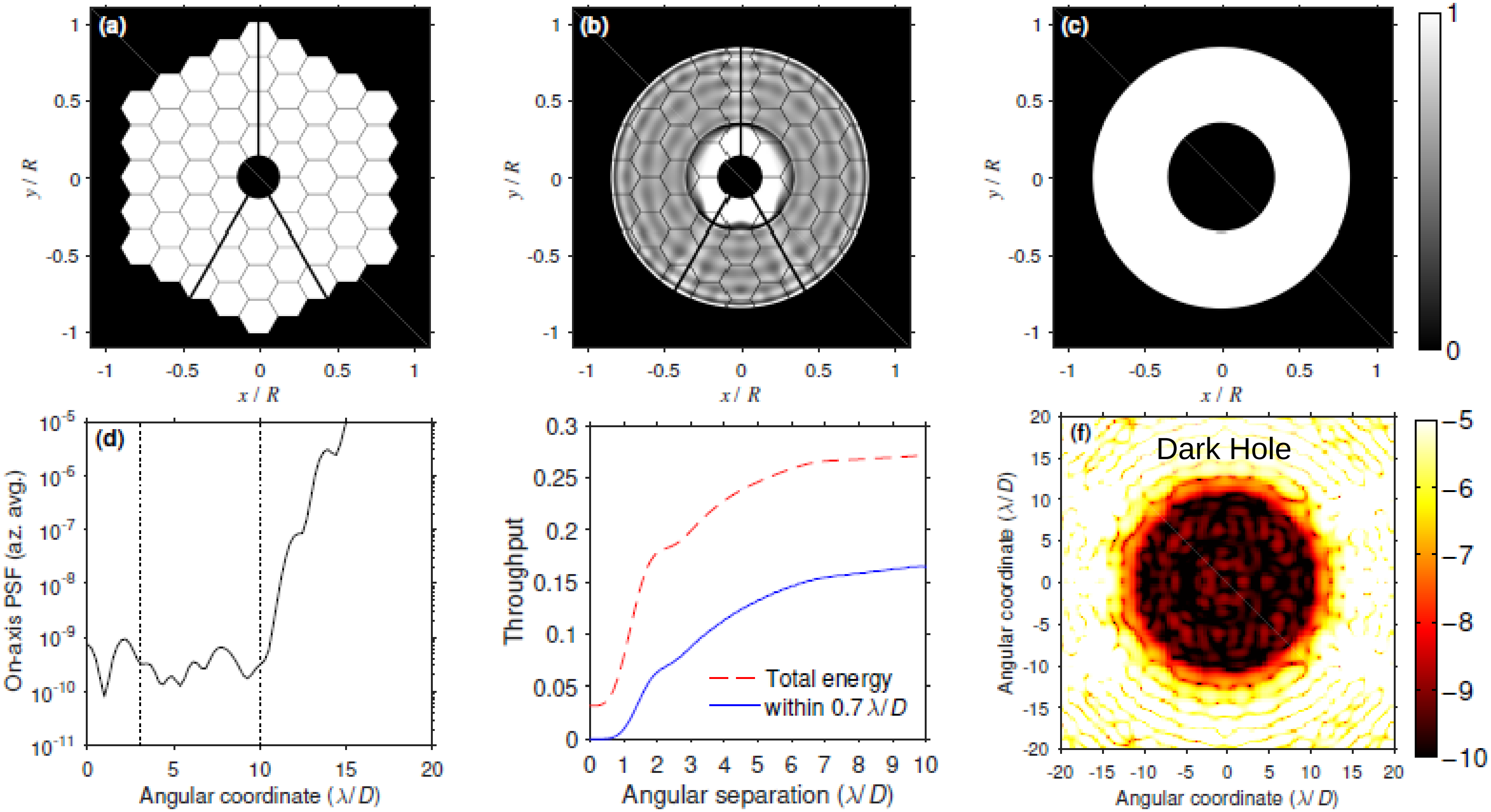




Apodized vortex coronagraphs may now be designed for segmented aperture telescopes. (charge 4 shown)

New Class of VC Solutions: Amplitude Masks

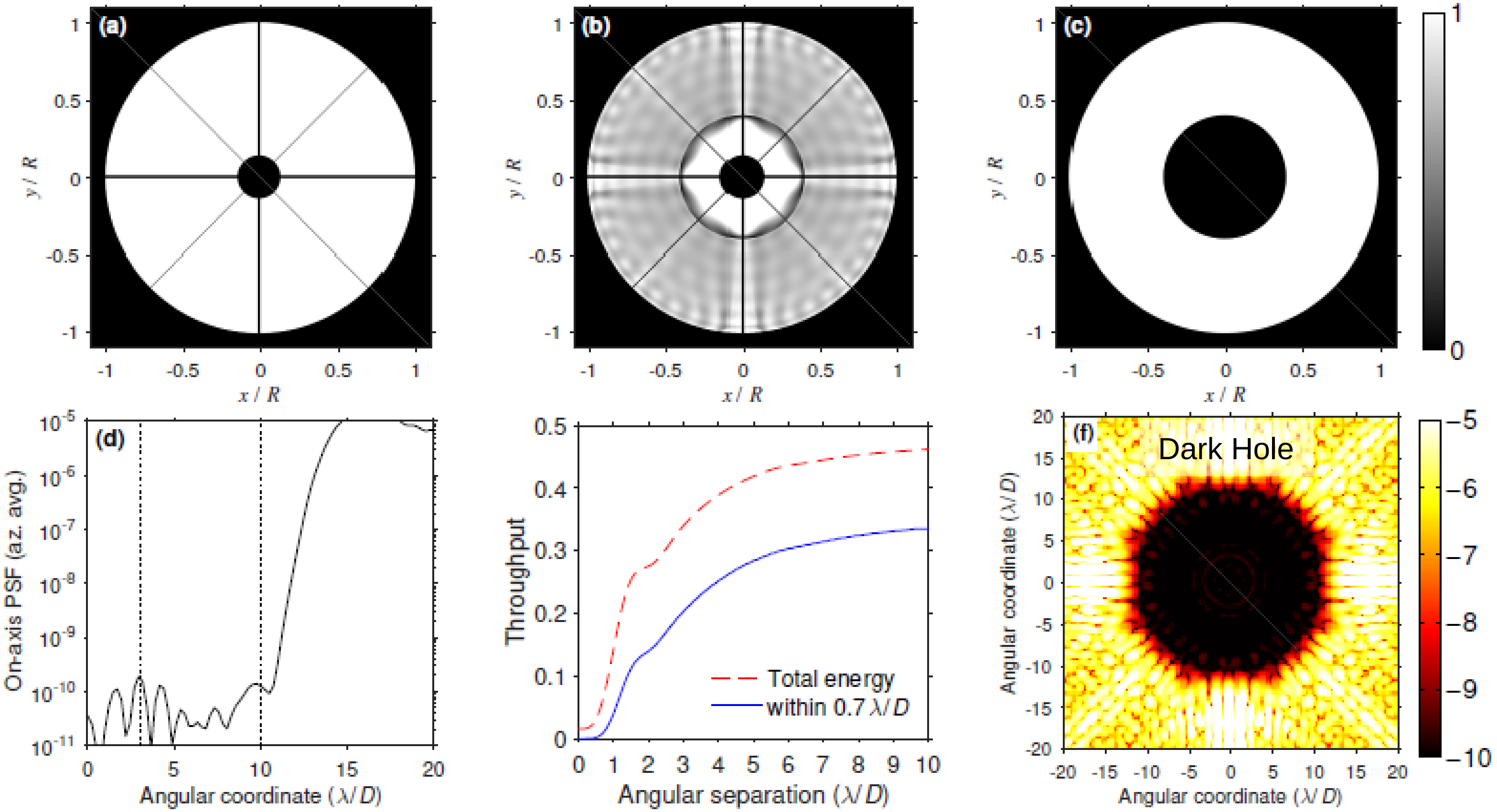
- The Dark hole is formed using a gray scale apodizer at a pupil plane, a charge-4 vortex mask, and an annular Lyot stop. It is not necessary to use DMs for diffraction control; their stroke can be used to compensate for aberrations.



DMs are not used to form the dark hole. The gray-scale mask can be manufactured using a half-tone approach with ~10 um pixel resolution.

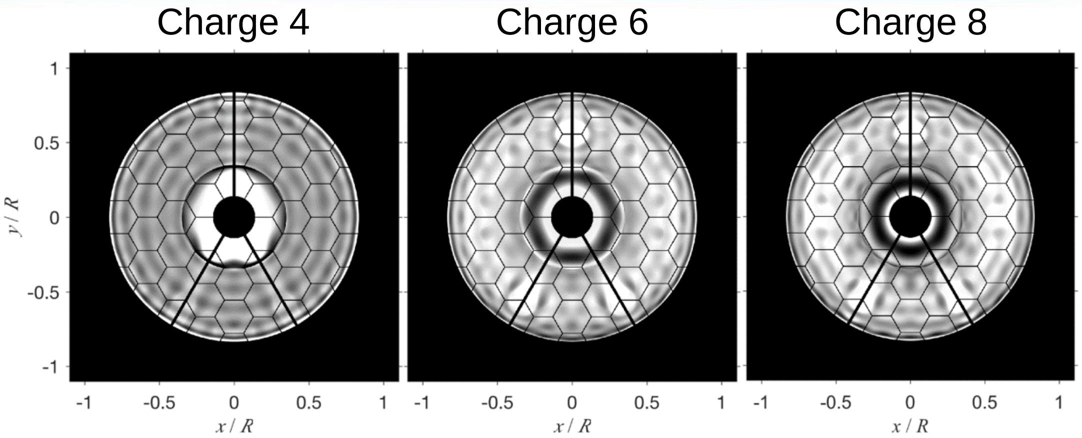
New Class of VC Solutions: Amplitude Masks

- Solutions are shown for the Pie-wedge aperture.

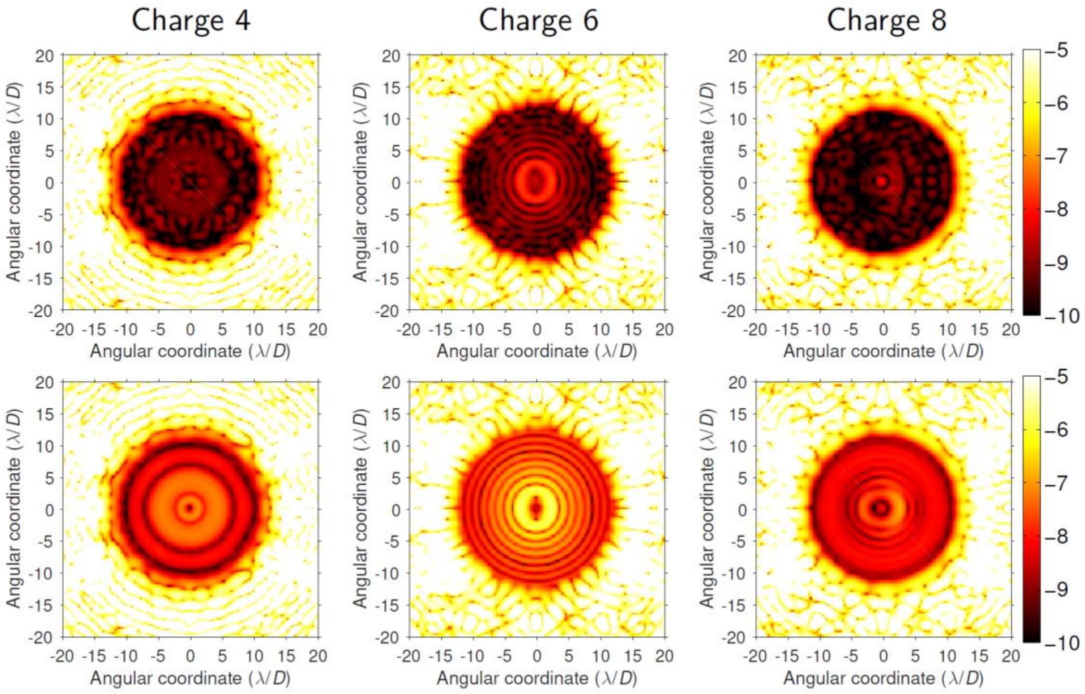


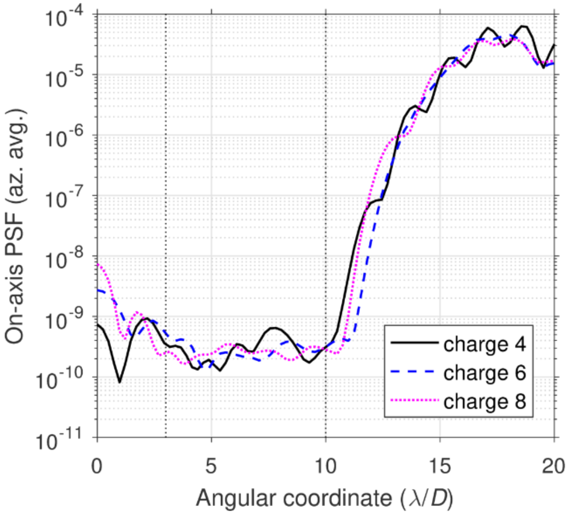
The gray scale mask solutions will be broad band to the extent that the Vortex image plane masks can be made broad band.

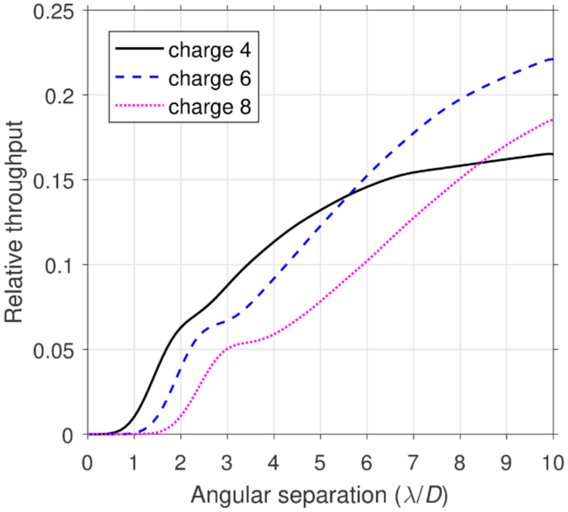
Higher charge VCs to reduce sensitivity to finite stellar size and tip/tilt



Angular size of star: $0.01\lambda/D$ (top row) and $0.1\lambda/D$ (bottom row)







Progress on PIAACMC Coronagraphs

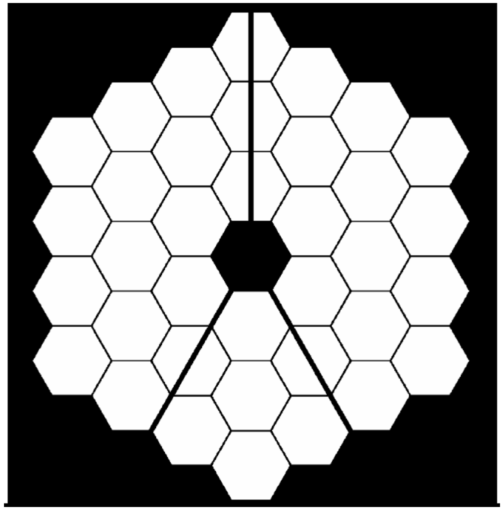
- **The following slides from O. Guyon, J. Codona, and R. Belikov detail:**
- Calculations on theoretical limits of the rejection of starlight due to the finite diameter of the star and pointing jitter.
- Novel linear optimization approach has been developed to aid in robustness against finite size of star and broad band performance.

- Example design shown for 3-ring hex, 10% bandpass, point source target.

PIAACMC Design Result

10% bandpass at 800 nm, point source

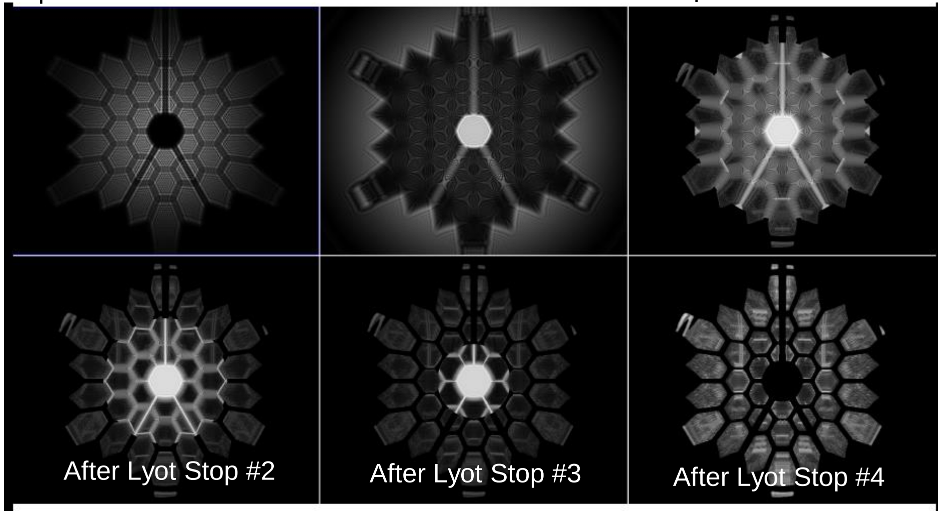
Input Pupil 3-ring Hex



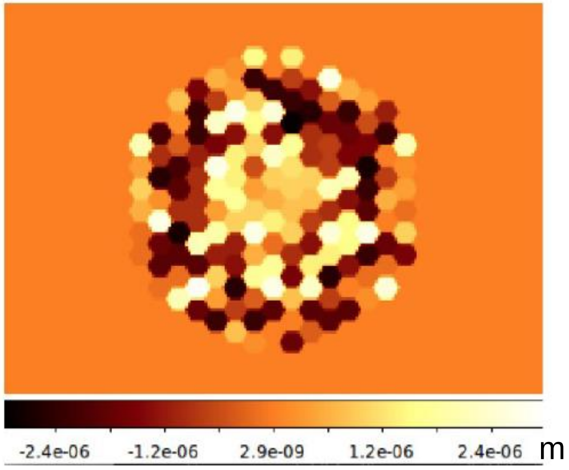
Light amplitude on 2nd PIAA mirror, showing apodization.

Post-focal plane mask light distribution

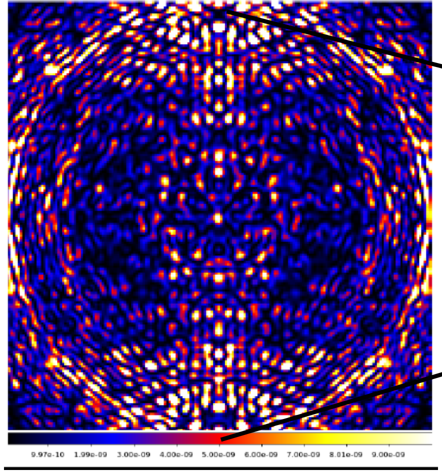
Light distribution immediately after Lyot Stop #1



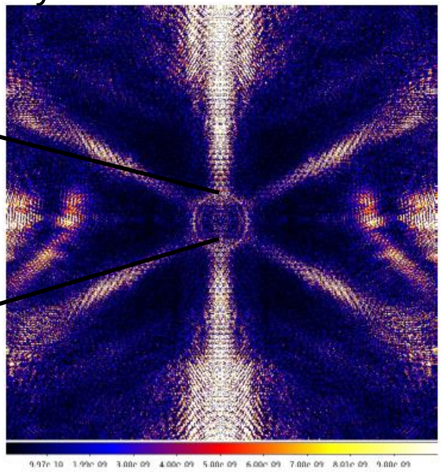
Typical focal plane complex mask (phase only transmission).



Dark Hole 1.5-8 l/D
2.8e-9 average contrast



Wider view showing scatter beyond dark hole.



FY16 Results Summary

- Generated white paper on segmented coronagraph aperture
- *Powerful new optimization approaches* employed for Vortex and PIAA coronagraphs.
- Significant advances have been made in *coronagraph throughput* for on-axis segmented mirrors.
  - Throughput of APLC has doubled, and bandwidth increased by 50% compared to 2015.
- Significant advances in *coronagraph robustness*.
  - APLC designs allow ~0.6% scale errors, and wavefront control allows an additional 0.2% margin.
- Significant progress *in coronagraph contrast*
  - Broadband (10%) contrast of 1e-10 for both APLC and VC.
  - Viable VC designs did not exist for segmented apertures in 2015.
- *Inner working angles* of >3 lambda/D for APLC and VC.
- *Supercomputers* employed to explore thousands of designs (APLC).
- *Powerful new optimization approach* opens design space for VC.
  - Viable solutions with amplitude-only masks (DMs not needed).
- Pie-wedge and Keystone emerging as significantly higher throughput than Hex segment apertures.
  - On-axis APLC designs approach off-axis (unobscured) in coronagraph performance.
  - With VC, off-axis design has double the throughput of on-axis.

Backup Material

Powerful New Optimization Approaches: Auxiliary Field, and Linear Coronagraph Theory

- Two new approaches, Auxiliary Field Optimization (AFO) and Linear Coronagraph Theory (LCT) have been developed under SCDA funding.
  - These complement the approaches used to date: Electric Field Conjugation (EFC) and its close cousin Stroke Minimization (SM), and Active Correction of Amplitude Discontinuities (ACAD)
- A quick summary of the approaches, with EFC and ACAD discussed as reference points:
- **AFO: for generalized solutions with segmented pupils**
  - New algorithm finds the complex pupil field that best minimizes the dark hole, subject to physical limitations of DMs. Developed in conjunction with the vortex coronagraph design effort.
  - Linear between pupil and image plane.
  - Proven useful for addressing pupil discontinuities in a wide range of conditions: DMs only, amplitude masks only, combinations of both.
  - So far used only to address the pupils and wavefronts, not the design of the coronagraph masks or Lyot Stop.
- **LCT: for design of focal plane masks given an apodization function**
  - New algorithm for optimizing the focal plane mask given a pupil apodization .Developed as part of the PIAA design effort.
  - Linear approach based on expressing arbitrary apodized pupil complex max coronagraph as a series of linear matrix operations.
  - Linear operators provide a means of projecting out undesired modes, e.g. rejecting leakage from tip-tilt or finite star diameter.
- EFC/SM: for ‘fine-tuning’ the broadband dark hole.
  - Use DMs to minimize scatter in the dark hole. EFC sets the contrast goal to C=0. SM minimizes the stroke subject to an iteratively decreasing contrast goal.
  - This algorithm maps DM phase to image plane electric field, which is a non-linear mapping. It requires recalculation of large Jacobian matrices as the DM shapes evolve.
- ACAD: for pre-conditioning the pupil to account for obscuring struts and segment gaps
  - Use ray optics to compute DM shapes that flatten the pupil, effectively filling in segment gaps.
  - Use EFC/SM to account for diffraction and optimize the dark hole.
  - Tends to lead to large DM strokes. Recent developments show that a patient application of SM (thousands of iterations, careful control of convergence) leads to better solutions with smaller DM strokes.

Wavefront control (WFC) to compensate for contrast degradation due to Lyot stop offsets

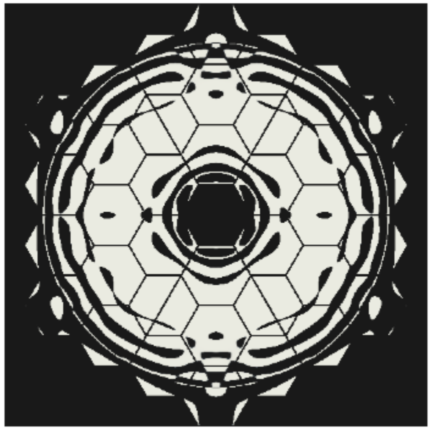
- Combination of non robust APLC/SP design with Stroke Minimization algorithm as WFC (Pueyo et al. 2009, Mazoyer et al. 2016) - code provided by J. Mazoyer

- Assumptions: 2 32x32 Boston DMs with 9.6mm size, z=300mm device separation, 10 nm rms wavefront errors.

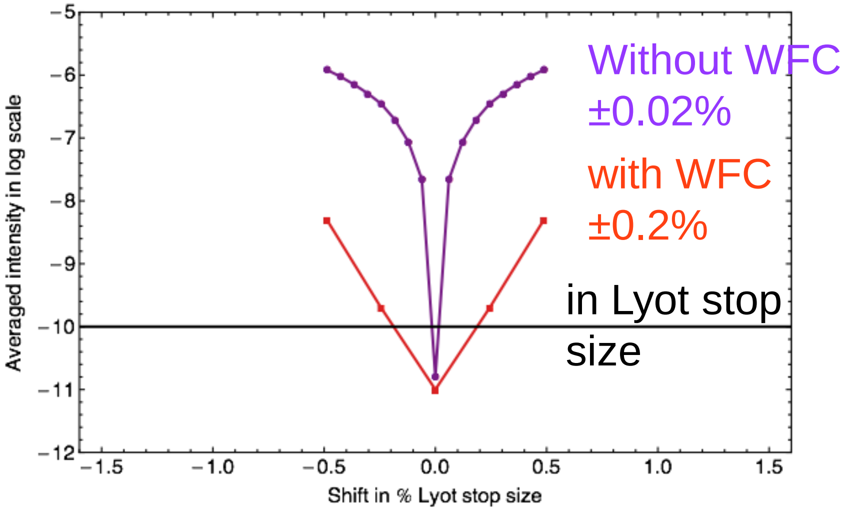
- Results: increase in robustness by ~10 for 10^{10} contrast design over 10% bandpass

- Next steps: combine WFC with alignment-robust design at 10^{10} contrast

SP for APLC with 4λ/D radius FPM to produce a 10^{10} contrast dark zone between 3.5-10λ/D



Dark zone averaged intensity vs y-axis Lyot shift



August-Sep 2016: New APLC design survey with expanded parameter range

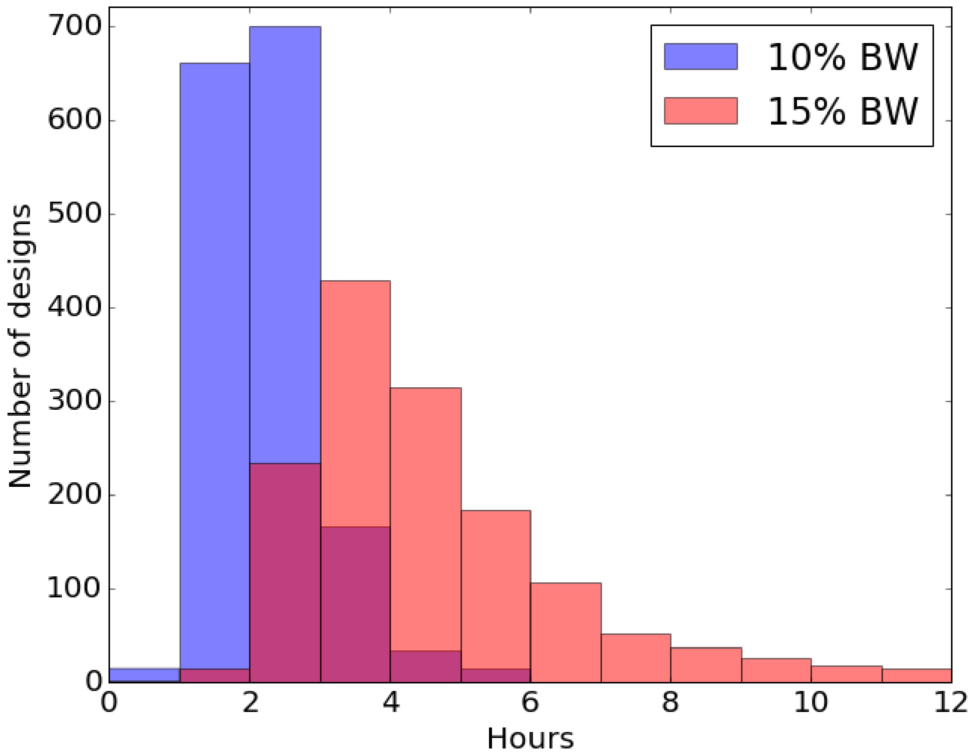
- 3100 new designs optimized on NCCS Discover supercomputer
- All SCDA reference apertures (hexagonal, pie, and keystone primaries)
- Inner working angles down to 2.5 λ/D
- With and without central obscuration (on-axis versus off-axis)
- Contrast fixed at 10^{-10} throughout

NCCS Discover is an efficient tool for running many linear optimization programs to survey the APLC design parameter space.

Up to 50 optimization jobs run concurrently, with typical completion times < 6 hours.

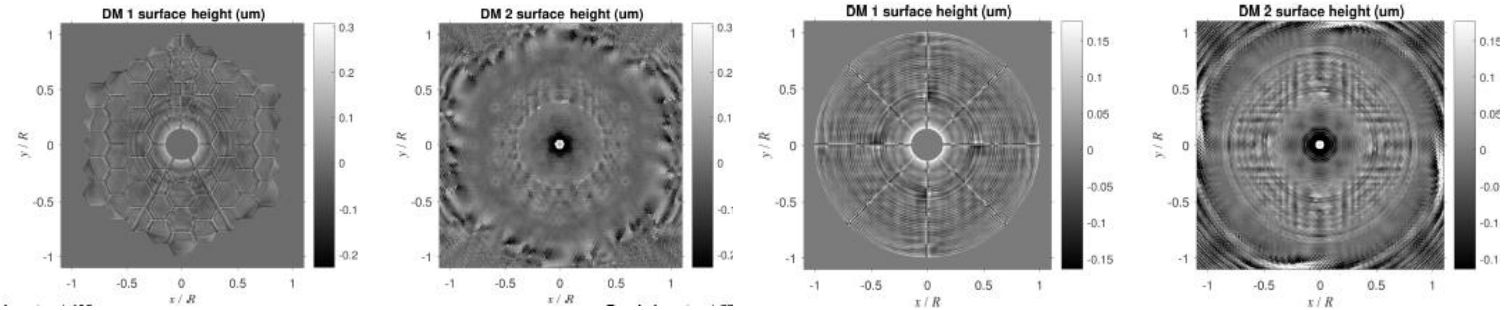
STScI team is preparing to submit a proposal to renew the NCCS allocation in November.

Optimization completion time per design



Apodize with DMs or Gray-Scale Masks?

- DM solutions: higher throughput but likely lower bandwidth and less robust than amplitude mask solution..



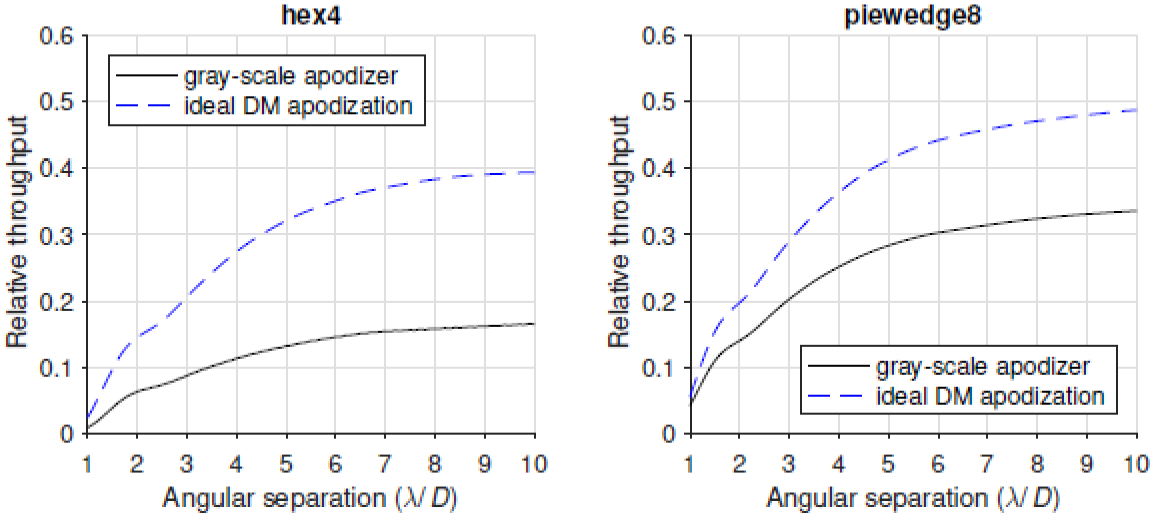
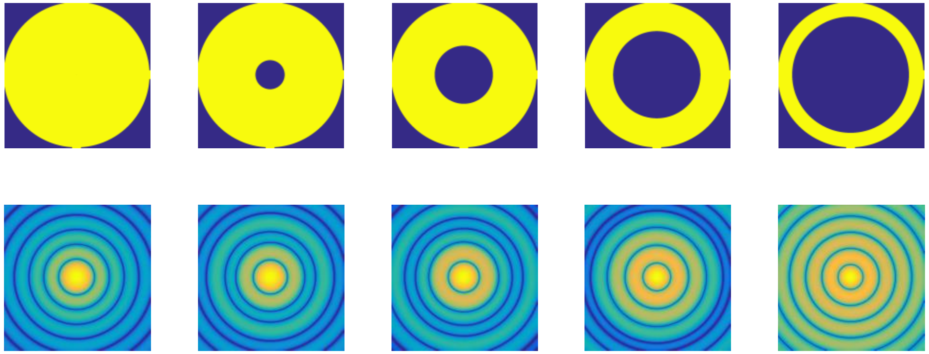
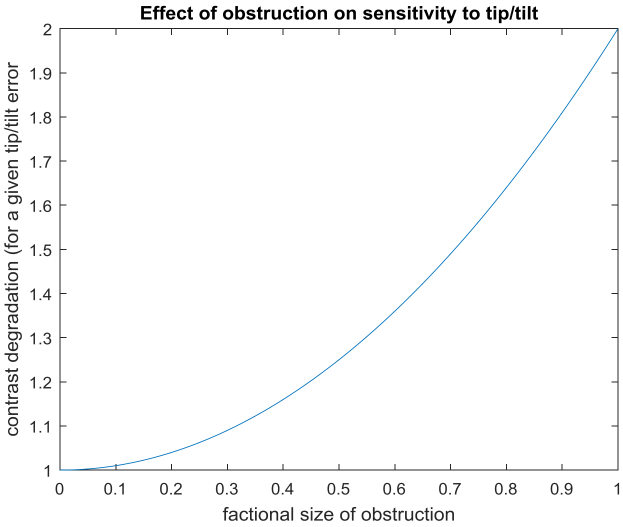


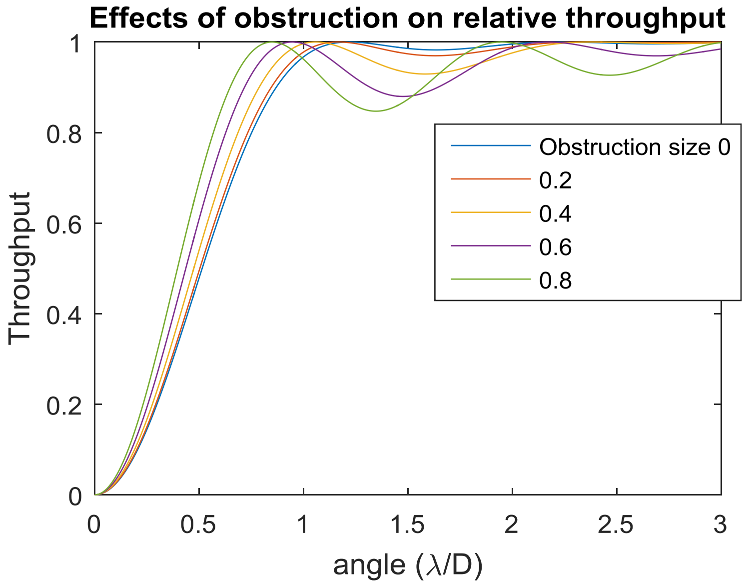
Figure 6: *Throughput comparison between the gray-scale mask and DM-based apodization methods for the (left) hex4 and (right) piewedge8 apertures. The relative throughput is defined here as the energy in the PSF core (energy within a $0.7\lambda/D$ of the source position), normalized to the PSF core throughput of the telescope.*

Here, DMs are used instead of gray scale masks, leading to significantly improved throughput. Bandwidth will be limited (trying for 10% minimum bandpass)

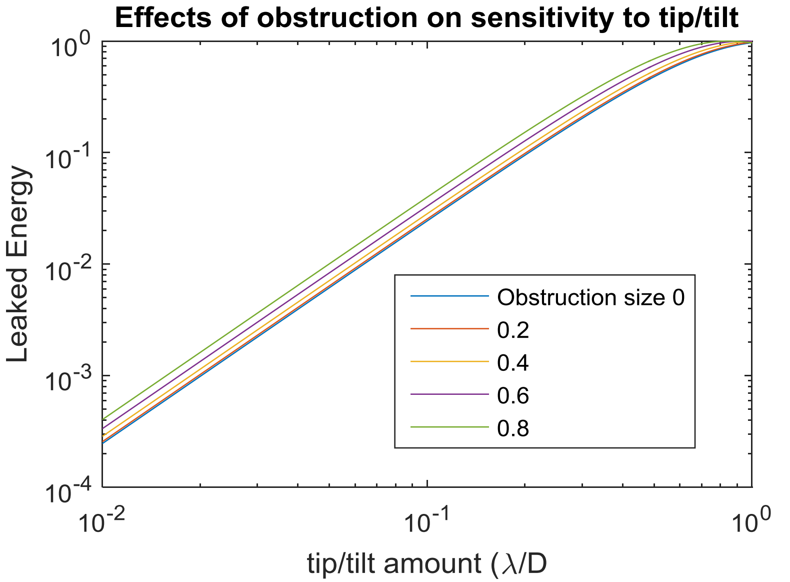
Does obstruction affect ideal coronagraph performance?







IWA gets more aggressive



Sensitivity to tip/tilt gets slightly worse

IWA, Contrast, and aberration sensitivity trades for ideal coronagraph

- For an ideal coronagraph of n-th order,
  - $IWA \sim \sqrt{\frac{n^2+2n}{8\pi}}$
    - Meaning: “blind spot” area in units of (λ/D)^2 is equal to the number of blocked modes
    - n-th order ideal coronagraph blocks an additional n/2 modes compared to n-1st order
  - Tip/tilt sensitivity: $Contrast = C\, r^n$, where
    - $C = o(1)$ is a constant
    - *r* is the amount of tip/tilt error in units of λ/D
- Eliminating order *n* leads to fundamental limit:
    - $Contrast \sim r^{\sqrt{8\pi\, IWA^2+1}\,-\,1}$

Example: D=2.4 m, unobstructed

IWA (λ/D)	r: tip/tilt error	Contrast	n (order)
1	0.4 mas	3e-9	4
2.2	7mas	1e-10	10

- At 0.4 mas, can in principle achieve 1 l/D IWA (increasing science yield by a factor of 3-10?)
- At 2.2 l/D IWA, can tolerate uncorrected jitter of 7mas
- These limits are roughly similar for segmented and monolithic telescopes, and do not strongly depend on obstruction.