Jet Propulsion Laboratory
California Institute of Technology

Shaped Pupil Hybrid Lyot Coronagraph (SPHLC) Design for the WFIRST CGI

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and the Coronagraph Design Team

November 2, 2017

The decision to implement the WFIRST mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

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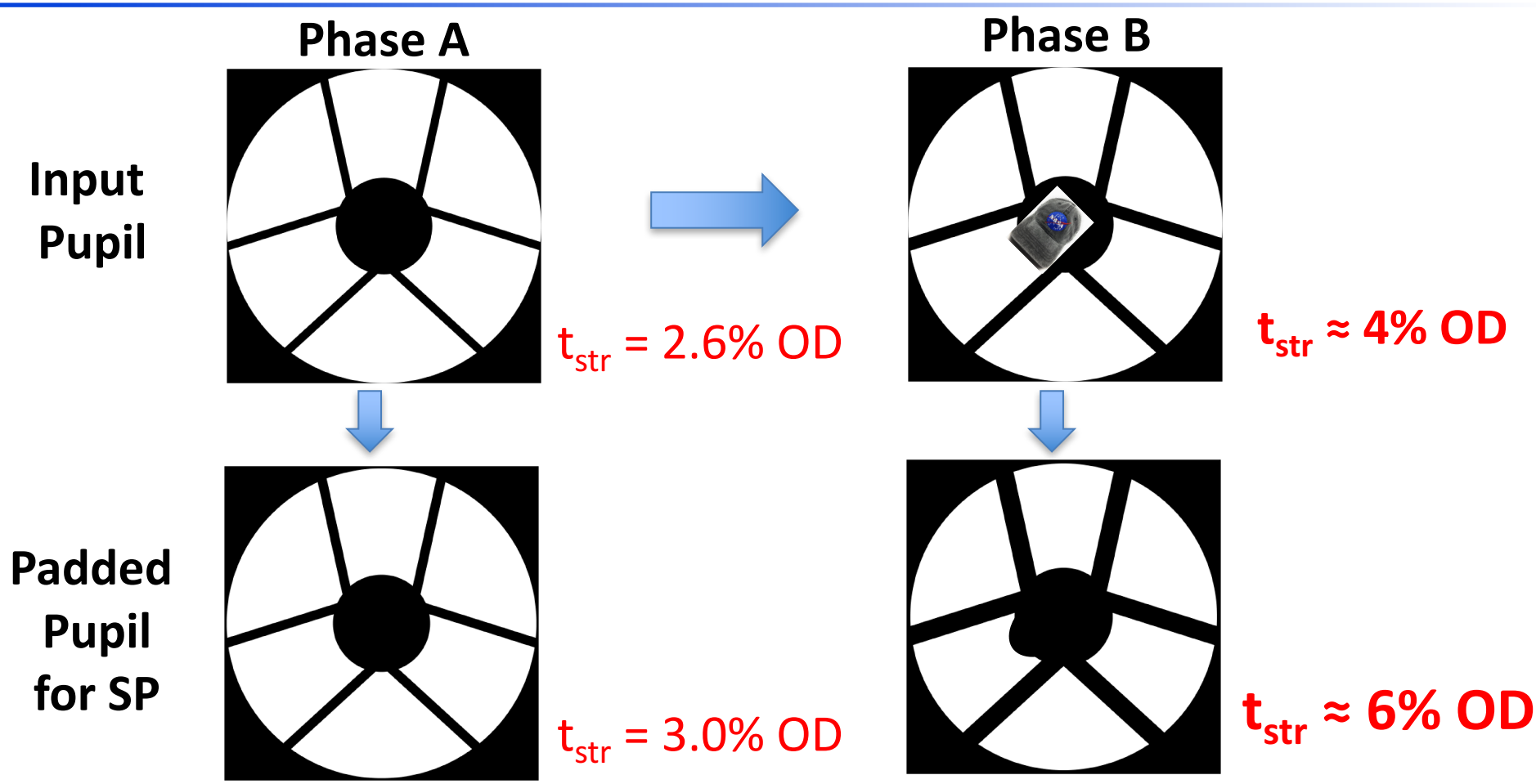
Pupil Growth



Struts for SP would need to be padded ~+/- 1% extra to account for

1) Pupil misalignment (translation and clocking)
2) Final CGI mask delivery before final telescope pupil known
3) On-orbit movement of struts to rotate secondary mirror

➢ ***Terrible for SP throughput***

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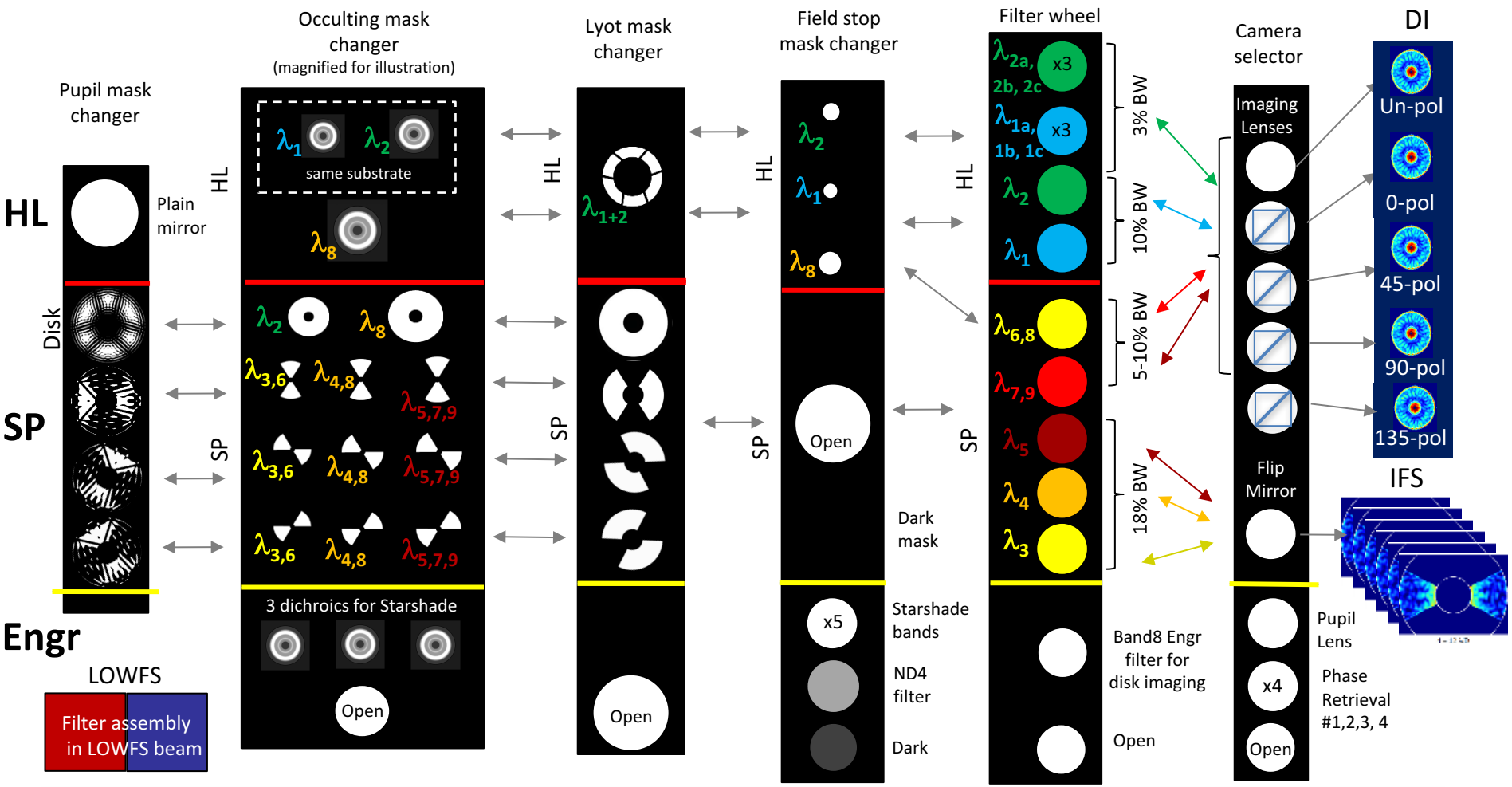
Previous CGI Modes



λ_1= 508nm λ_2=575nm λ_3=660nm λ_4=770nm λ_5=890nm

λ_{1a}= 491nm λ_{1c}= 524nm λ_{2a}=555nm λ_{2b}=594nm λ_6=661nm λ_8=721nm λ_7=883nm λ_9=950nm

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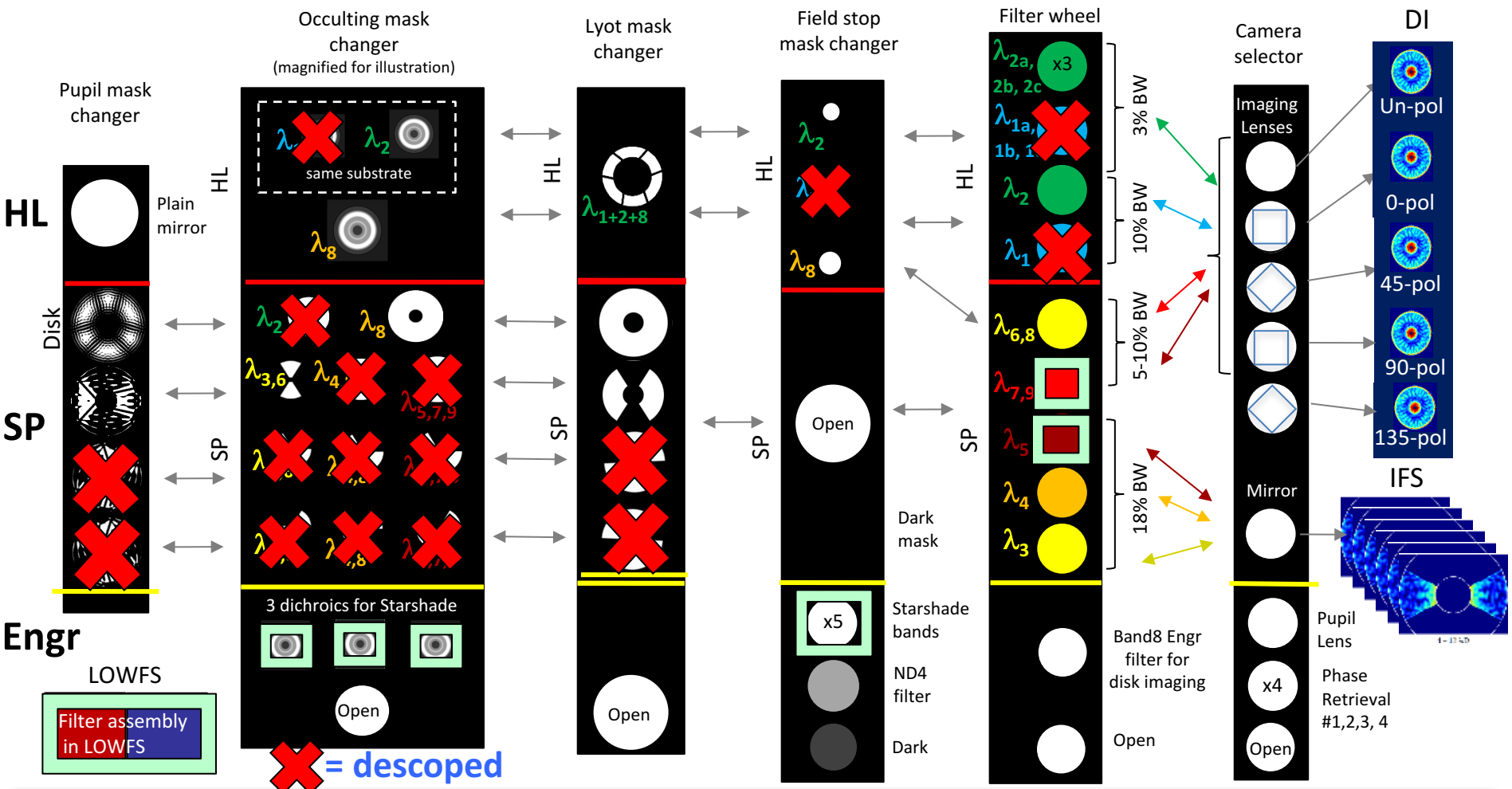
Descoped CGI Modes

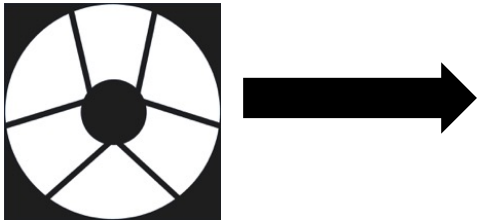


λ_1= 506nm λ_2=530nm λ_3=630nm λ_4=770nm λ_5=890nm

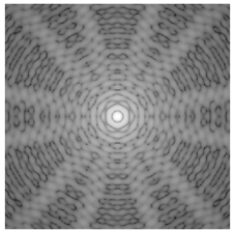
λ_{1a}= 489nm λ_{1c}= 523nm λ_{2a}=556nm λ_{2c}=594nm λ_6=661nm λ_8=721nm λ_7=883nm λ_9=940nm

Old Configuration: 14 Modes

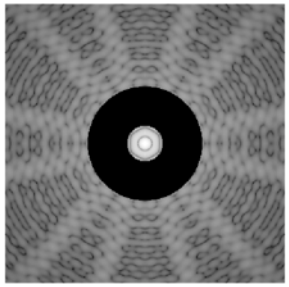
WFIRST pupil



Nominal PSF



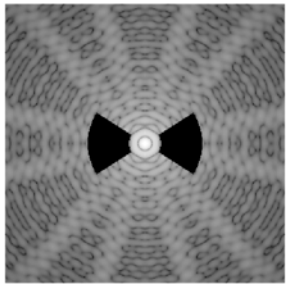
- **Three types of modes to achieve science goals:**



3 Modes

1. **<u>Hybrid Lyot Coronagraph (HLC):</u>** *exoplanet & inner disk imaging*
   - 10% BW, 360° FOV, 3-10 λ_0/D
   - ~4-6% core throughput

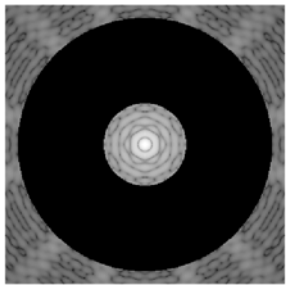
Trauger et al. JATIS 2016



9 Modes

2. **<u>Shaped Pupil Coronagraph (SPC)</u>** for IFS: *exoplanet spectroscopy*
   - 18% BW, 2x65° FOV, 2.8-8.8 λ_0/D, lower sensitivities
   - ~3.5% core throughput

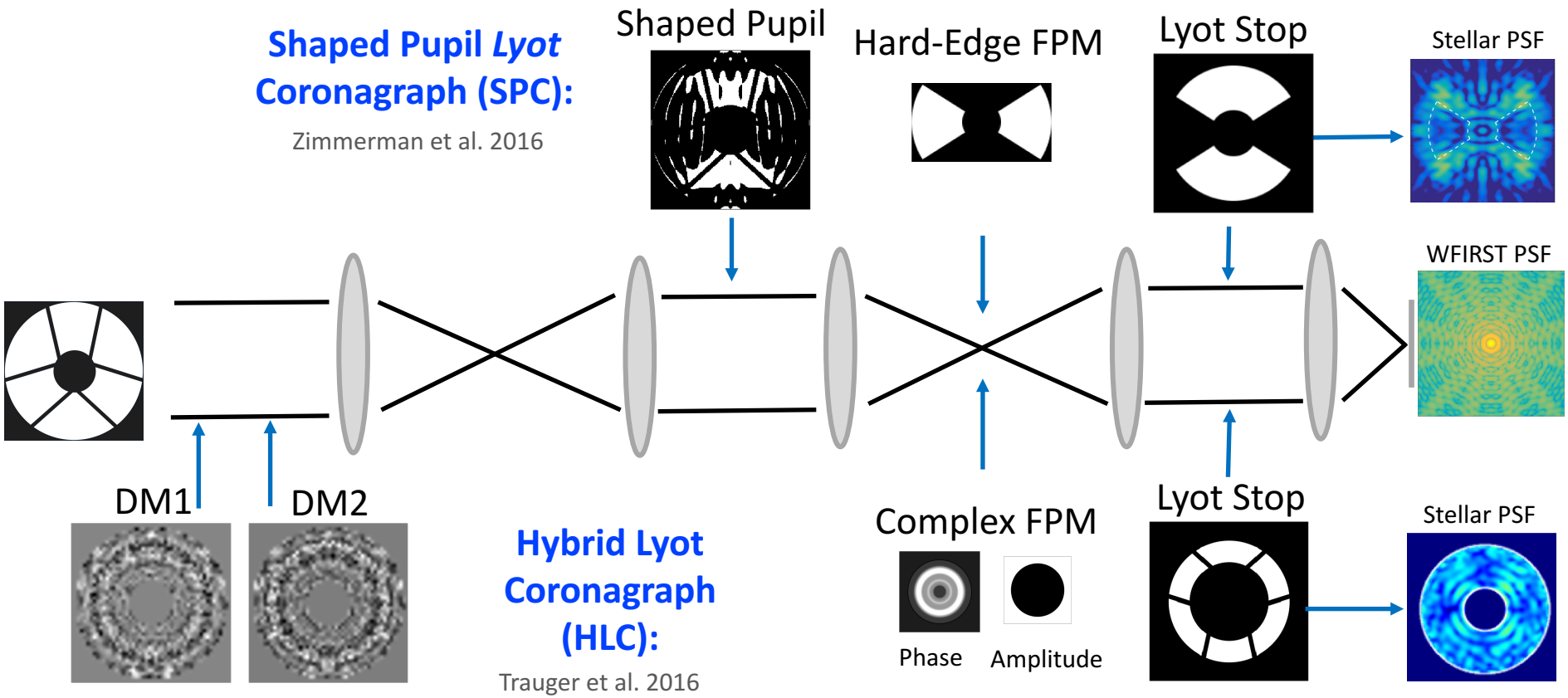
Zimmerman, Riggs, et al. JATIS 2016



2 Modes

3. **<u>Shaped Pupil Coronagraph (SPC)</u>**: *outer disk imaging*
   - 10% BW, 360° FOV, 7-19 λ_0/D
   - 5.5% core throughput

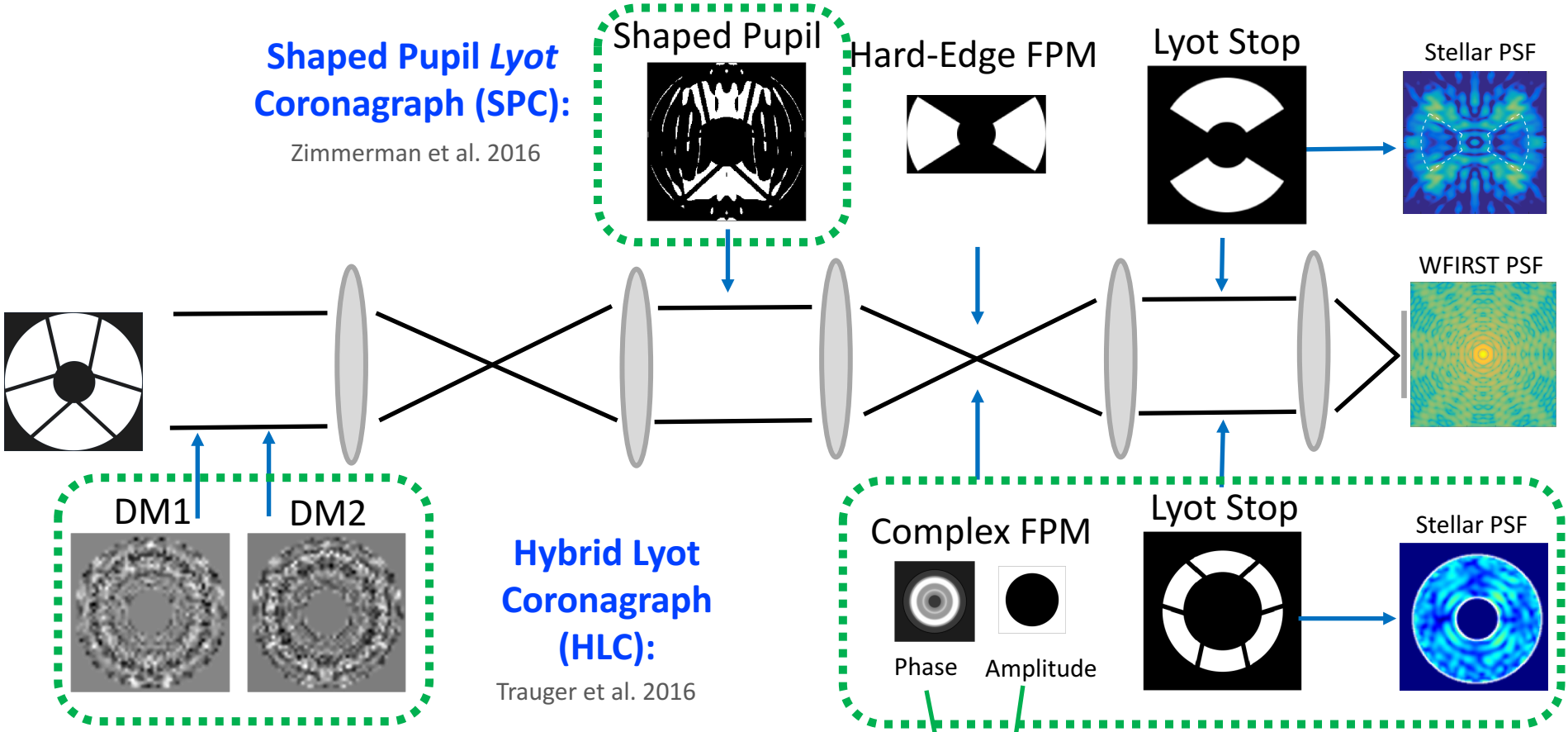
Old Configuration



SPHLC: Combined Coronagraph

Shaped Pupil *Lyot* Coronagraph (SPC):

Zimmerman et al. 2016

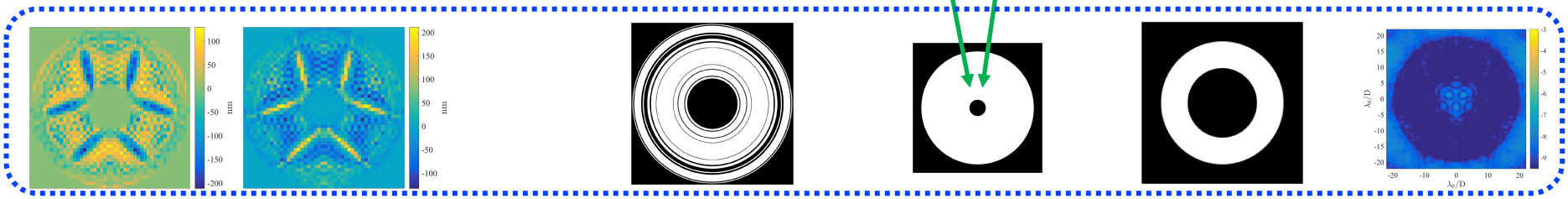


Hybrid Lyot Coronagraph (HLC):

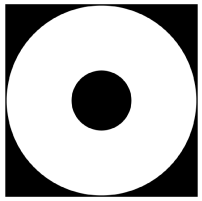
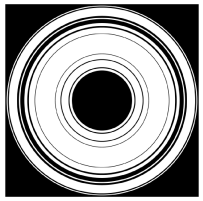
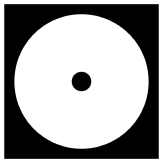
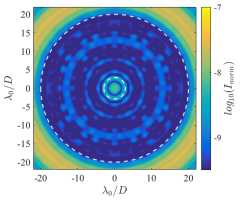
Trauger et al. 2016

SPHLC:

- **Higher throughput** (~7-10%)
- **Full FOV** (~3-21 λ/D, 360°)

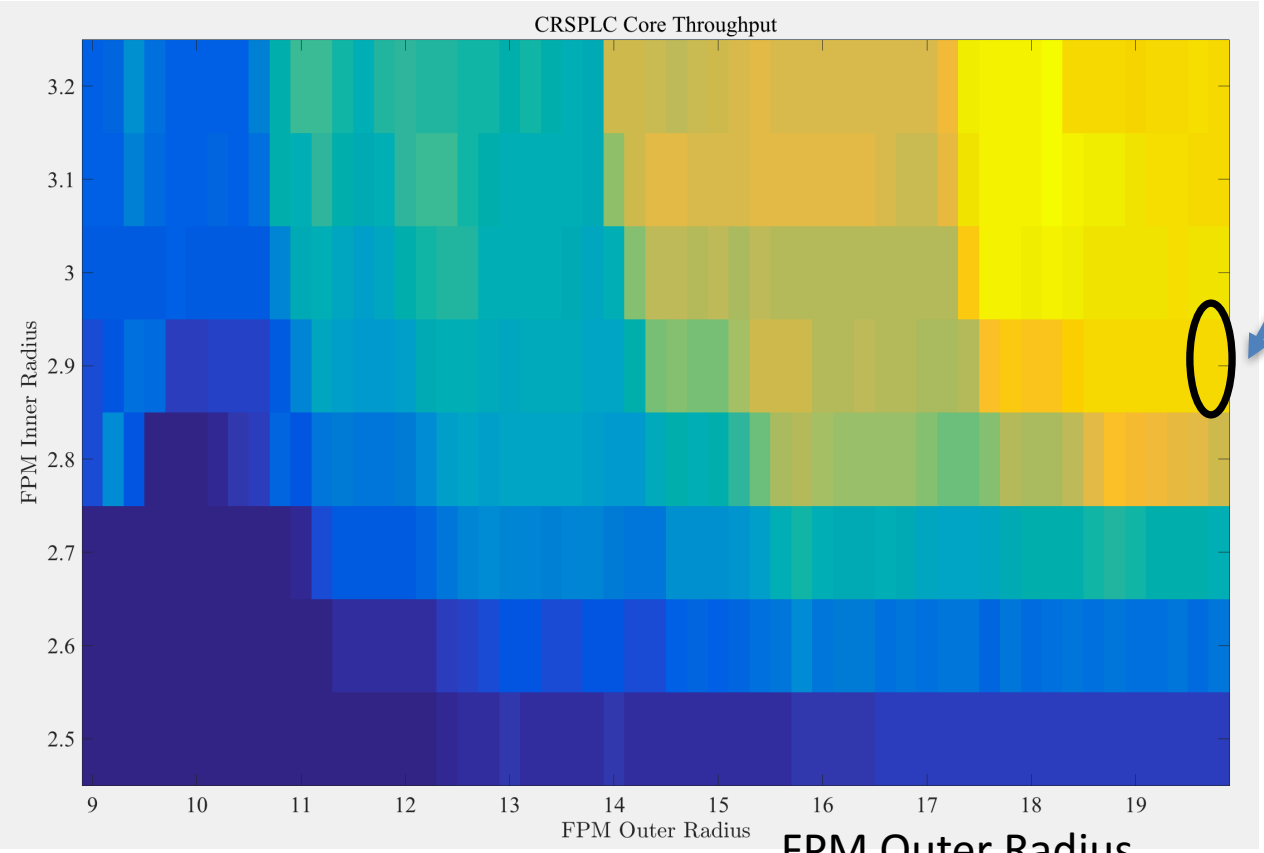


1-D SPLC: Grid Search (10% BW)

Pupil	DM1	DM2	Shaped Pupil	FPM	Lyot Stop	PSF
	flat	flat				

4 x 10^{-10} contrast
9.6% throughput
IWA=3.1
OWA=19.7

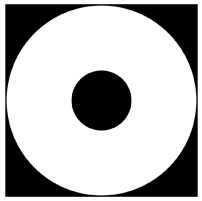
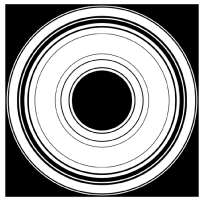
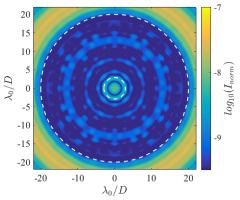
First step: Perform extensive grid search of 1-D optimizations (~1e6 designs)



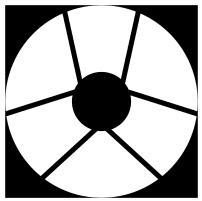
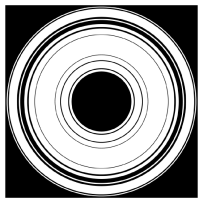
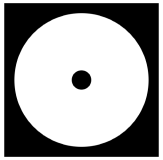
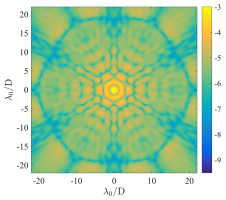
FPM Inner Radius

FPM Outer Radius

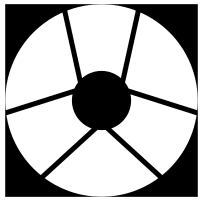
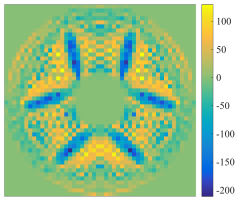
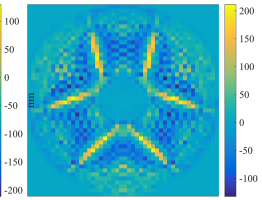
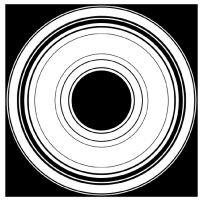
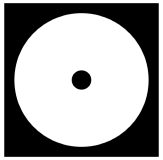
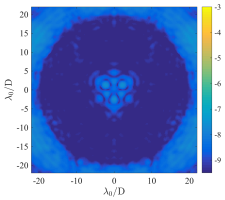
SPHLC (10% BW)

Pupil	DM1	DM2	Shaped Pupil	FPM	Lyot Stop	PSF	
	flat	flat					4 x 10^{-10} contrast **9.6% throughput** IWA=3.1 OWA=19.7

First step: Perform extensive grid search of 1-D optimizations.

	flat	flat					5 x 10^{-6} contrast **7.5% throughput**

Second step: Include struts in pupil and add to Lyot stop.

	 						4 x 10^{-10} contrast **3-7% throughput** IWA=3.1 OWA=19.7

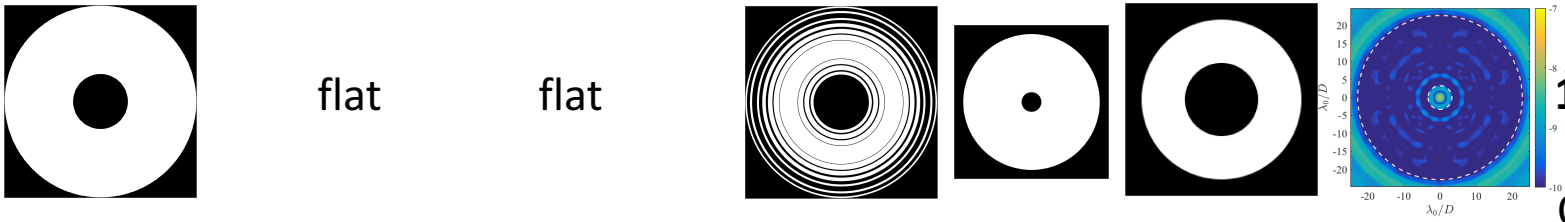
Third step: Use DMs to suppress diffraction from struts.

DMs apodize the struts more efficiently than the shaped pupil mask
- ➢ Better achievable throughput, IWA, and/or contrast

Relevance to LUVOIR

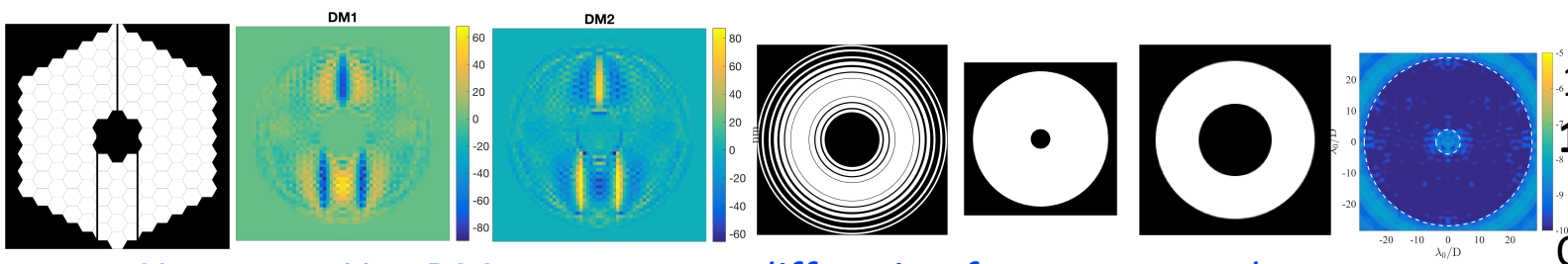
LUVOIR SPHLC (10% Bandwidth)

Pupil | DM1 | DM2 | Shaped Pupil | FPM | Lyot Stop | PSF



8 x 10^{-11} contrast
13.6% abs HM thput
IWA=3.5 λ/D_{ann}
OWA=22.5 λ/D_{ann}

First step: Perform extensive grid search of 1-D optimizations.



1 x 10^{-10} contrast
18.3% rel E.E. thput
IWA=4.1 λ/D_{hex}
OWA=26.7 λ/D_{hex}

Next step: Use DMs to suppress diffraction from struts and segment gaps.

Relevance to LUVOIR technology:

➢**SPHLC is currently the most promising design for LUVOIR.**

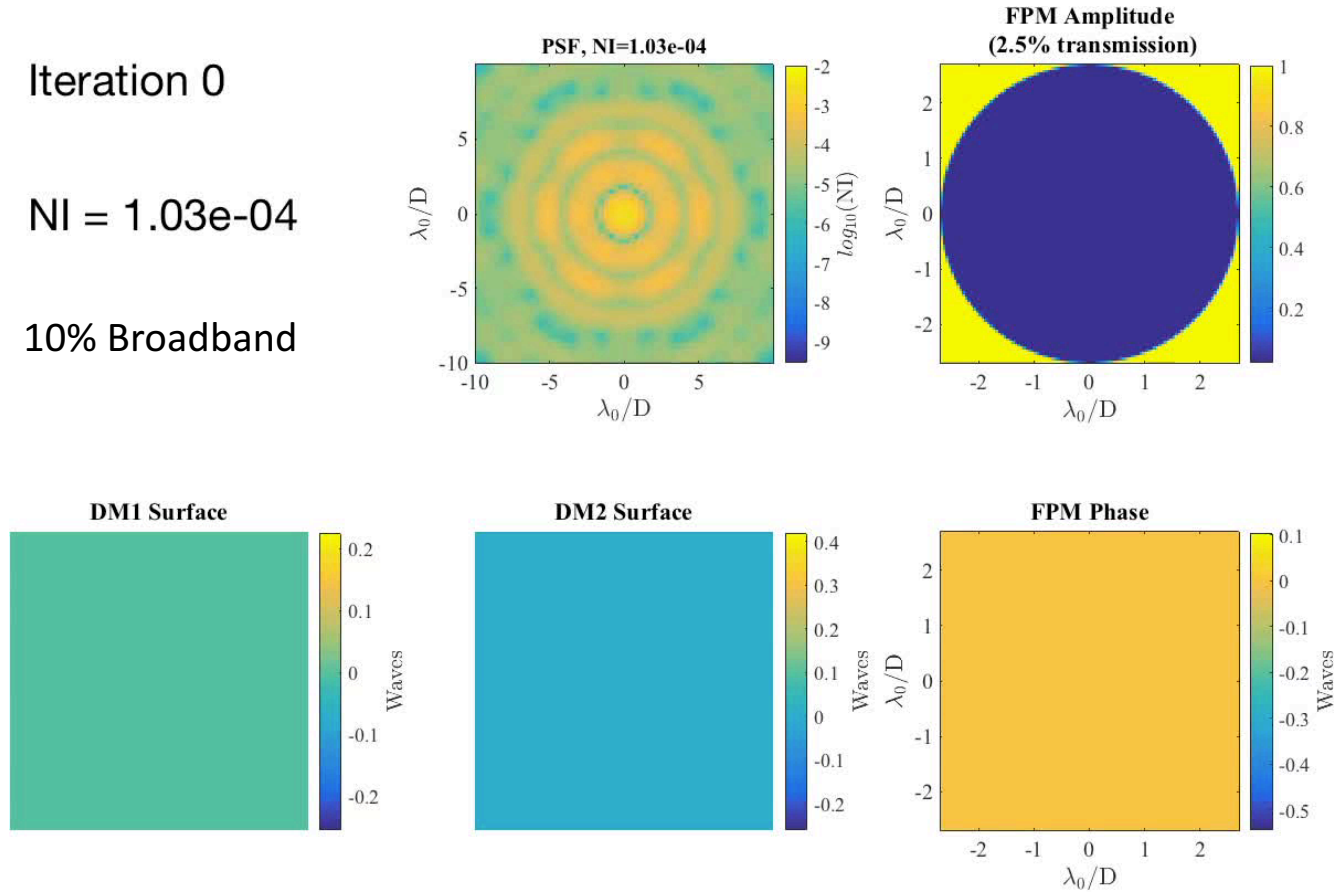
HLCs Design with FALCO

FALCO:
FAst
Linearized
Coronagraph
Optimizer

Iteration 0

NI = 1.03e-04

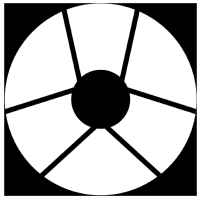
10% Broadband



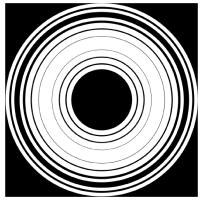
- **My Design Team and I are writing FALCO for many coronagraph architectures:**
  - HLC
  - SP(H)LC
  - AP(H)LC
  - (A)VC
- **Can plug in any telescope pupil** (WFIRST, LUVOIR, HabEx, etc.)

Improving SPHLC Designs

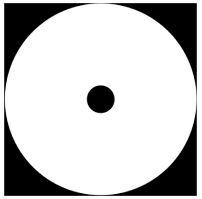
Pupil



SP



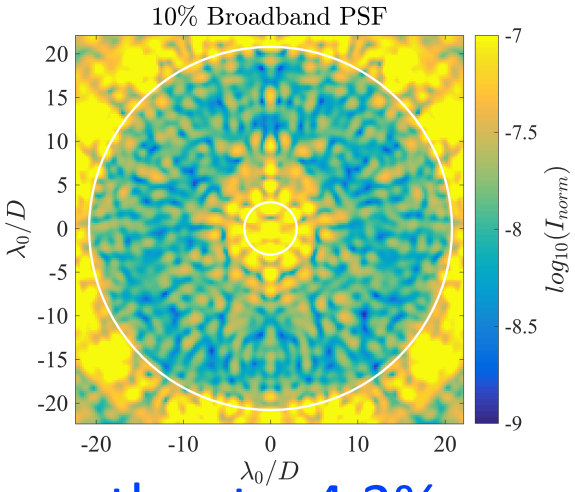
FPM



LS

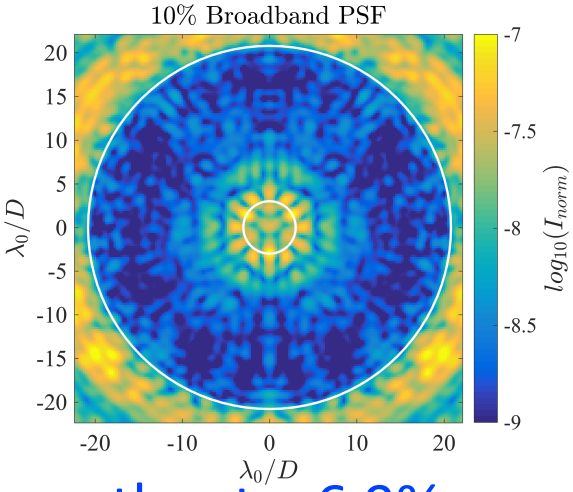
3.0-20.8 λ/D

Δz_{DM} = 1m,
RMS tip/tilt = 1.0 mas
Dstar = 0.5 mas



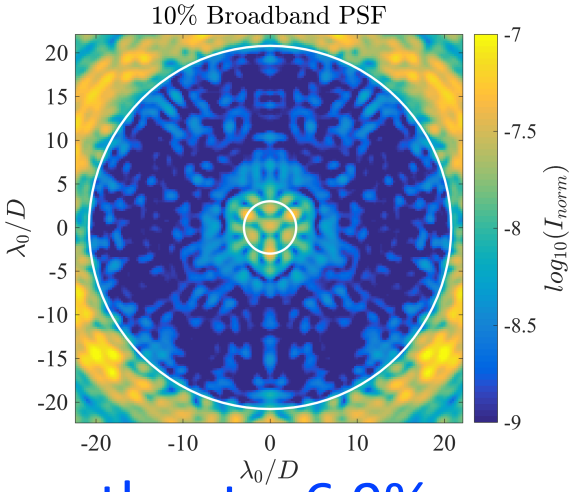
thput = 4.3%

Δz_{DM} = 3m,
RMS tip/tilt = 1.0 mas
Dstar = 0.5 mas



thput = 6.9%

Δz_{DM} = 3m,
RMS tip/tilt = 0.5 mas
Dstar = 0.5 mas

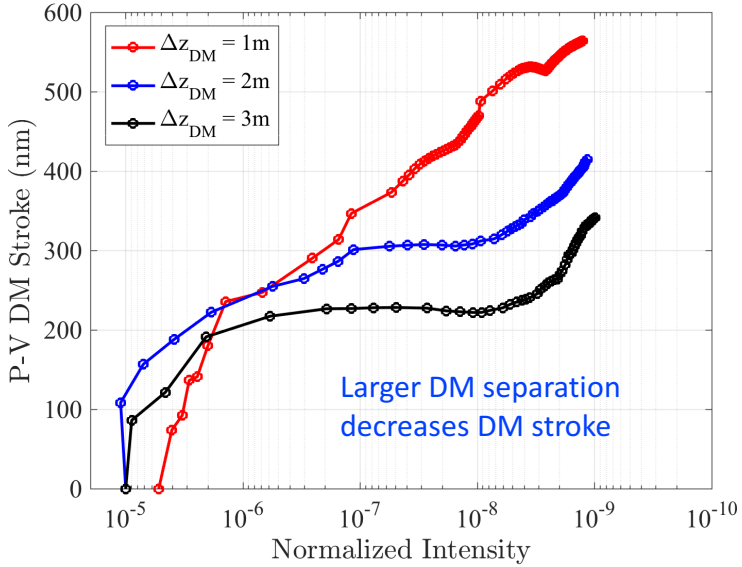


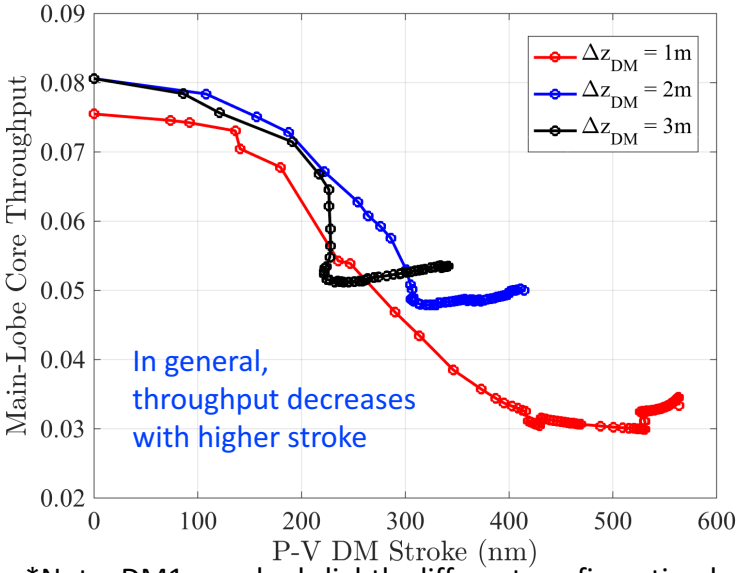
thput = 6.9%

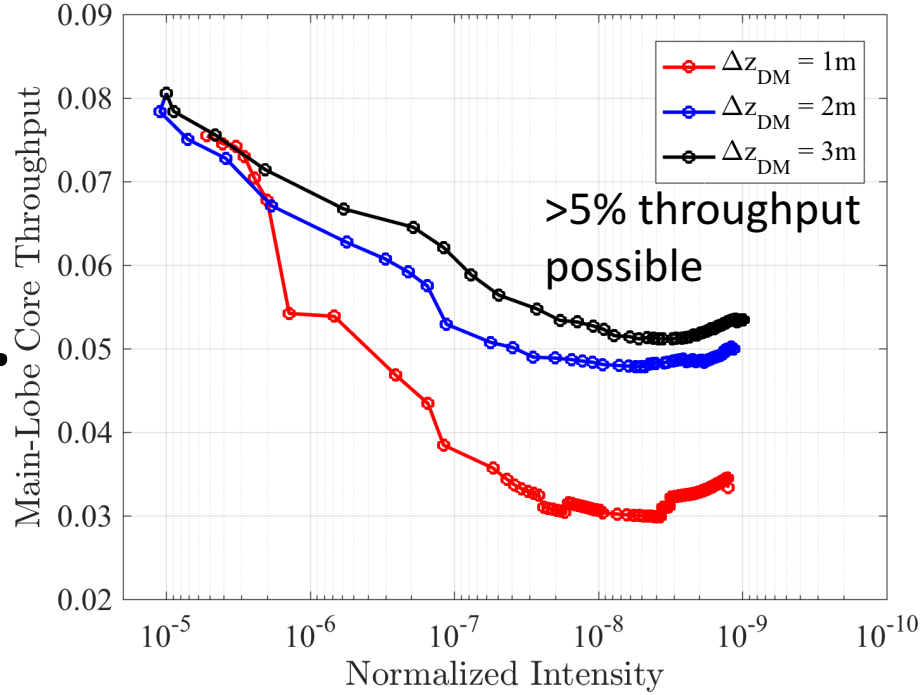
The SPHLC will get better

- These results are only 0 days old and don't yet utilize the robustness methods of the HLC team.

Performance vs DM Separation







Conclusion: Larger DM separation gives
- Lower P-V DM stroke
- Higher core throughput

*Note: DM1 case had slightly different configuration because case with T/T crashed last night.

*core throughput is calculated here as:
(total energy under half-max of main-lobe of off-axis PSF at 6 lambda/D)/(total energy at primary mirror)

Conclusions & Next Steps

Conclusions

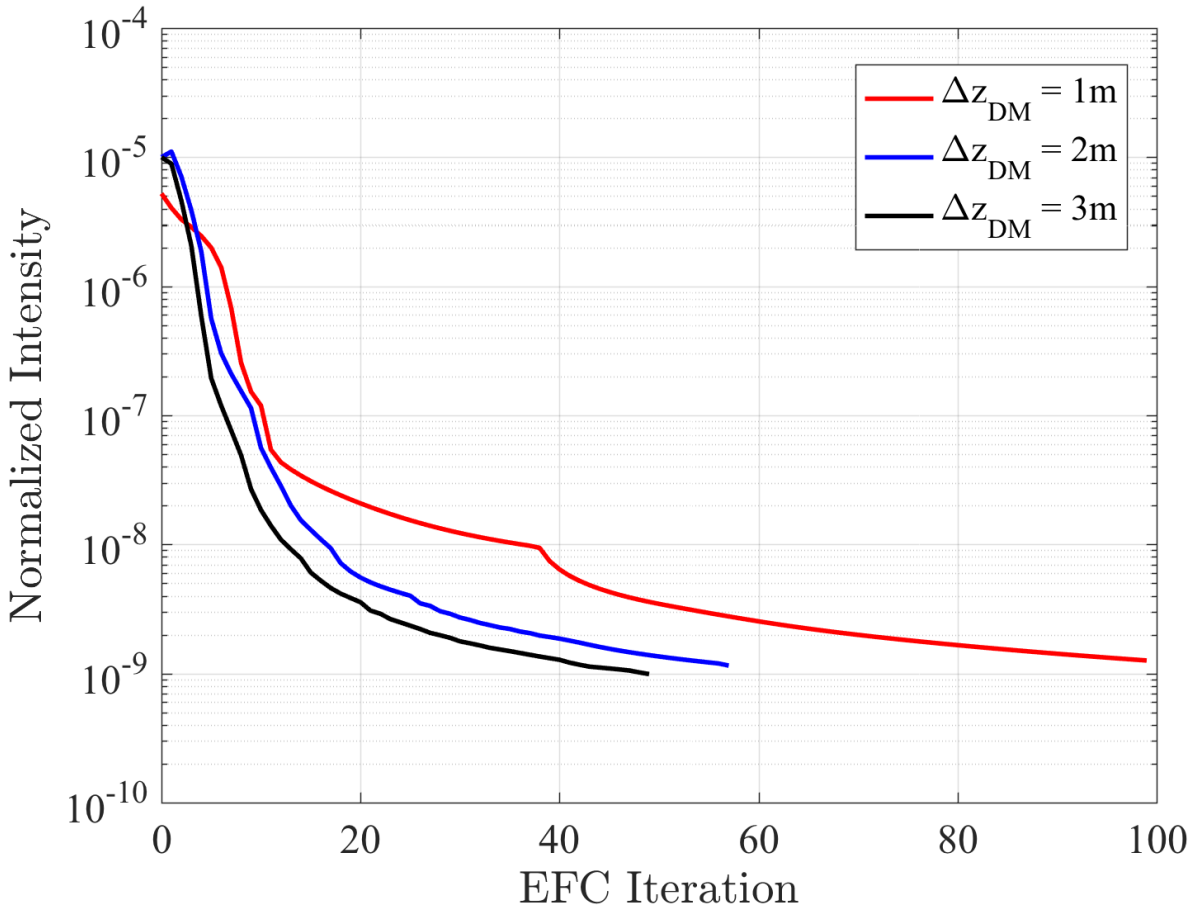
- **SPHLC is a promising new combination of HCIT-proven components**
  - Full FOV → **Fewer modes**. 2-4 in total
  - **~2-3x higher throughput** → Helps offset worse contrast
  - Robust to pupil misalignment and strut uncertainty
  - SPHLC is currently best design for LUVOIR.

- **DMs should be farther apart for SPHLC to have:**
  - Higher throughput
  - Less DM stroke
  - Faster convergence to dark hole DM settings
  - *(Refer to 2017 SPIE paper and 2 papers by Johan Mazoyer on cases for APLC or apodized vortex coronagraph.)*
  - **Boston Micromachines**: 2.5x smaller pitch → 6.25x larger effective DM separation

Next Steps

- Include the true **thin film equations** in the complex FPM model.
- Constrain the **DM actuator stroke**
- Analyze and optimize for **polarization** (astigmatism) aberrations
- Design **trade studies**:
  - Spectral **bandwidth** vs IWA,throughput
  - **DM separation** vs throughput,DM stroke

Contrast vs EFC Iteration



- Larger inter-DM separation:
  - Reduces DM stroke for same contrast
  - **Faster convergence**