Multi-Star Wavefront Control for Roman CGI

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Roman Dark Hole Algorithms Working Group

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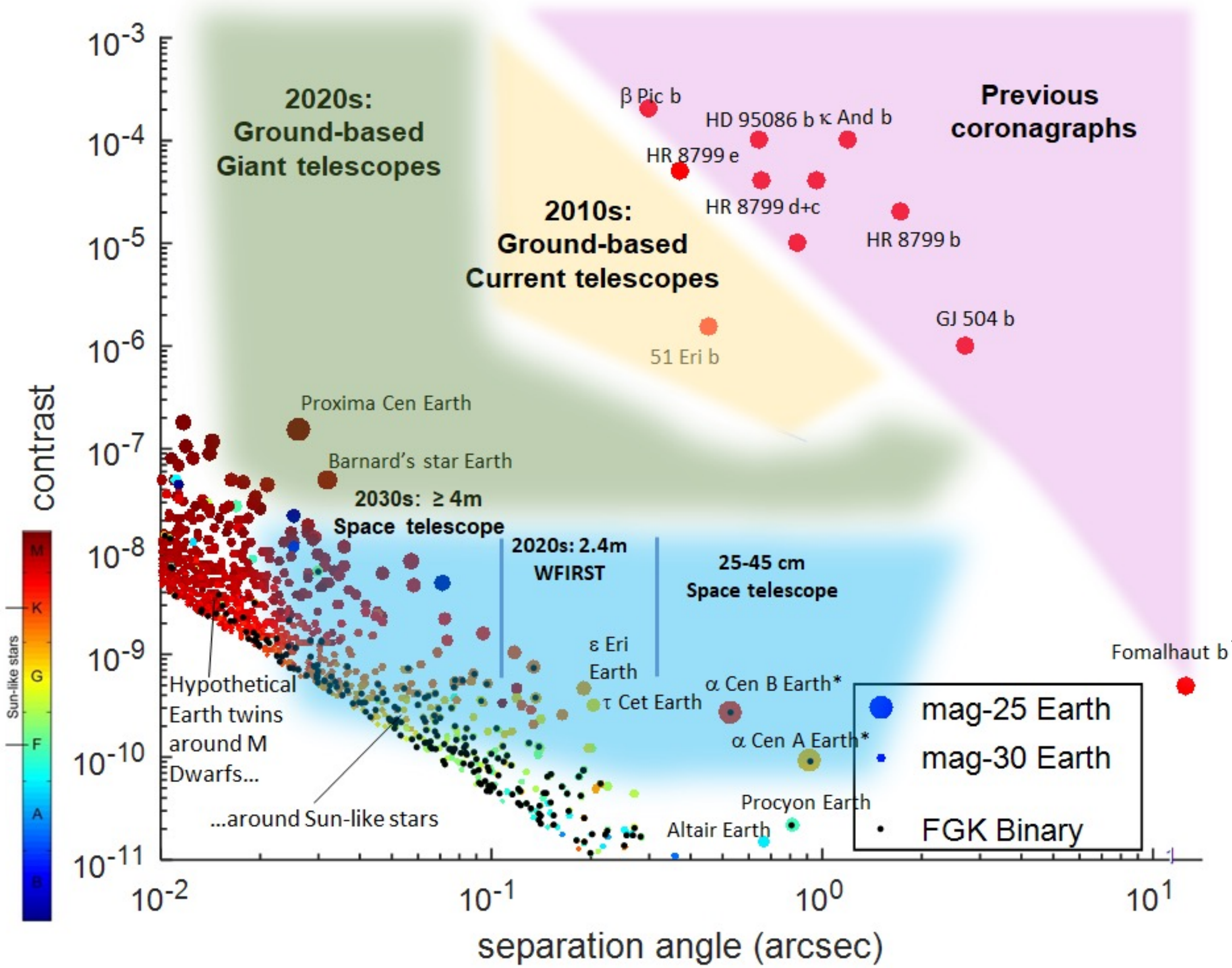
Overview

1. Motivation for Binary Star Imaging
2. Multi-Star Imaging Mode with CGI
3. Multi-Star Wavefront Control Sensitivities

Hubble Image of Alpha Centauri A & B

Multi-Star Systems increase **quantity** Of direct imaging targets



Plotting hypothetical exo-Earth contrast for all stars within 20 pc (based on Guyon 2019)

~1/2 of all FGK stars are in binary systems

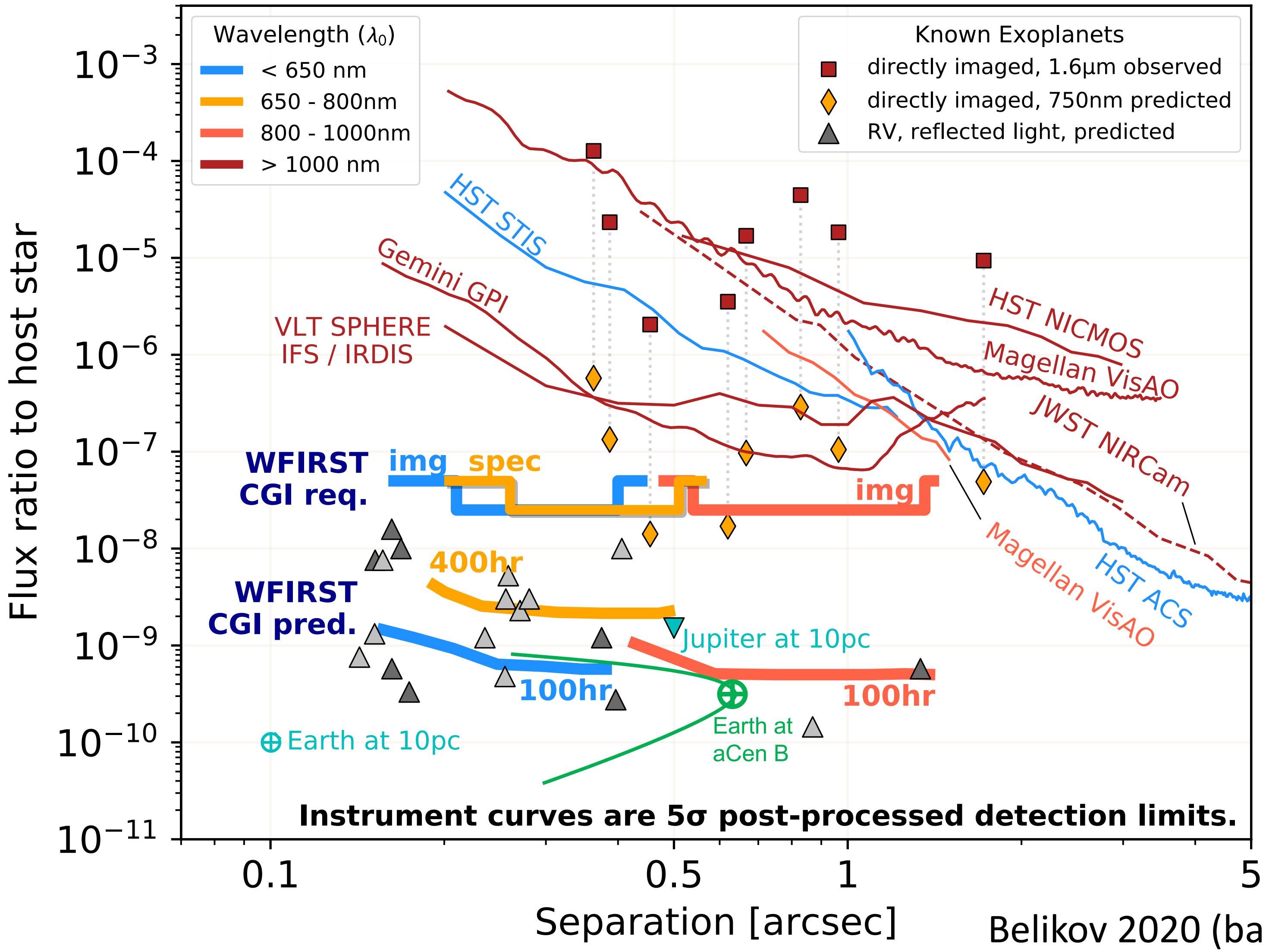
- **41/67 in 10 pc**
- **259/519 in 20 pc**

Alpha Centauri A & B is a special science case:

- **3x closer** than any other star system
- **3x better spatial/spectral** resolution

Multi-Star systems increases **quality & diversity** of direct imaging targets

Roman CGI *may* be able to image Earth twins



Belikov 2020 (based on Bailey 2019)

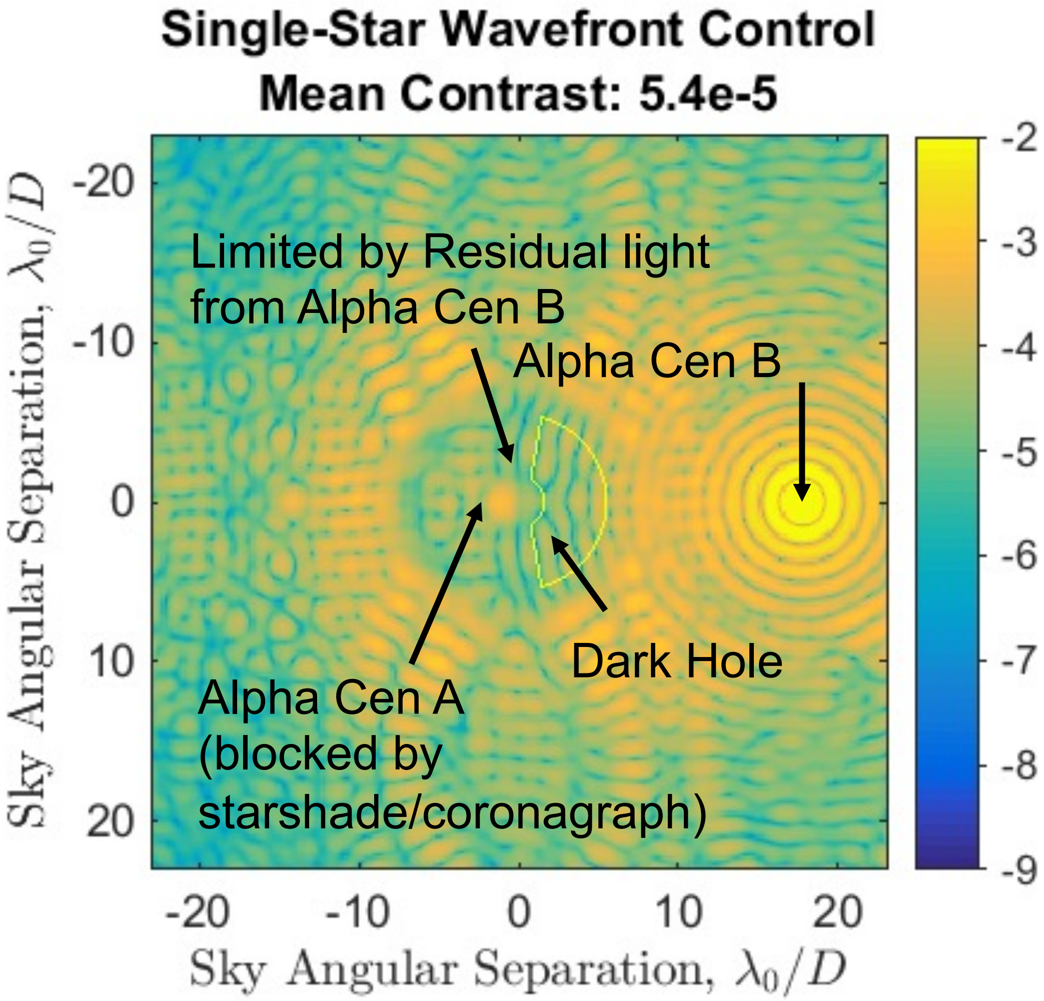
Alpha Cen AB enables ≳ 3x better IWA and resolution than any other FGK star.

Due to unusual proximity, breaks common-wisdom assumptions about what Roman can do:

(1) At *gibbous phase*, an Earth-like planet *around Alpha Cen B may* be within CGI's sensitivity limits (depending on final performance)

(2) Optical imaging could detect ≳ 3x finer structure in exozodi due to spatial resolution for aCen

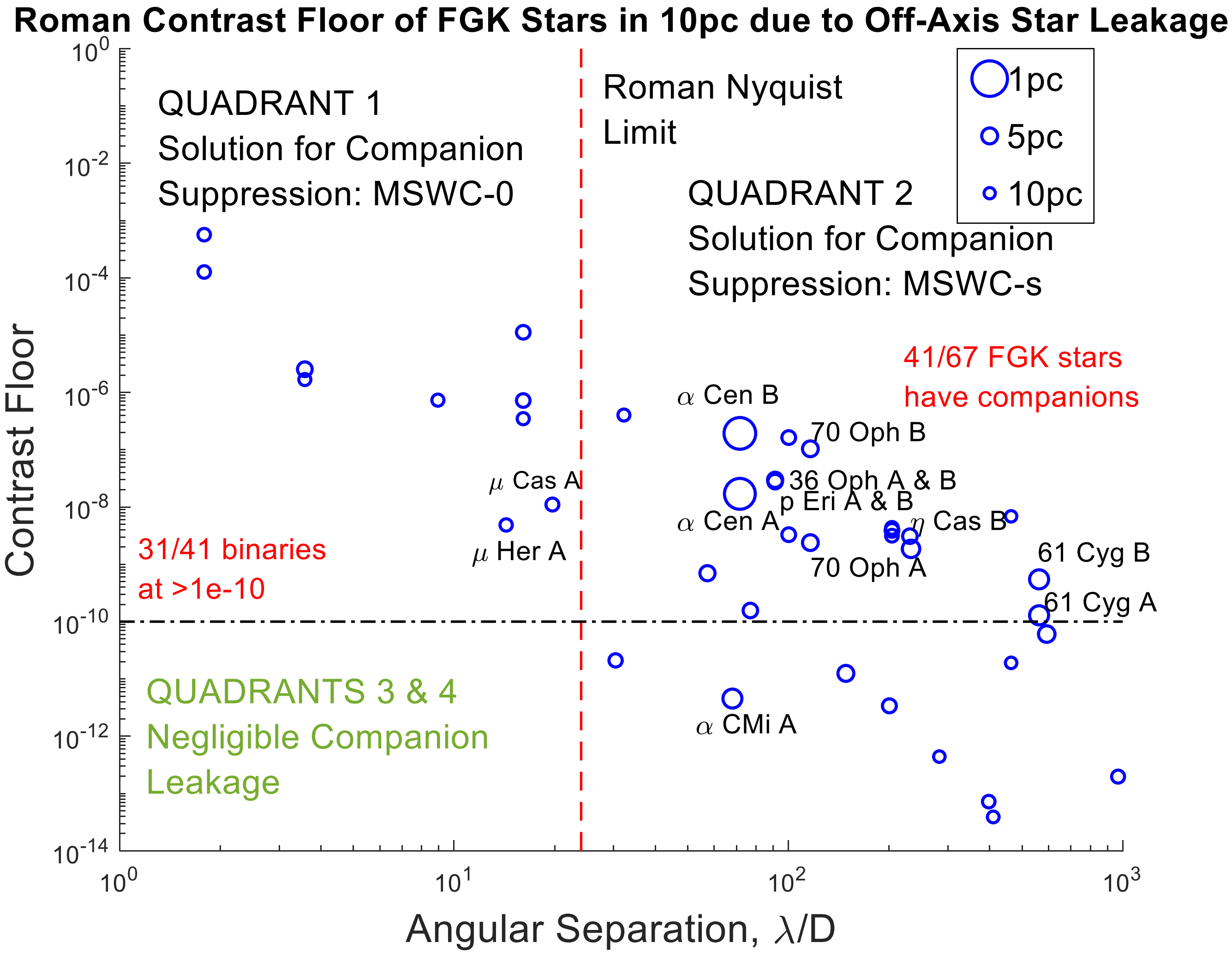
Direct Imaging Challenges with Binary Stars



Challenges due to binary:

- Off-axis leakage from the binary companion creates a *contrast floor*
- Depth of the contrast floor is a function of the *binary separation* and *brightness fraction*
- A coronagraph for the off-axis companion is insufficient as contrast would be limited by its *random speckles*!

Light Leakage from Binary Companions (10 pc)



Roman PSD characteristics (provided by J. Krist)

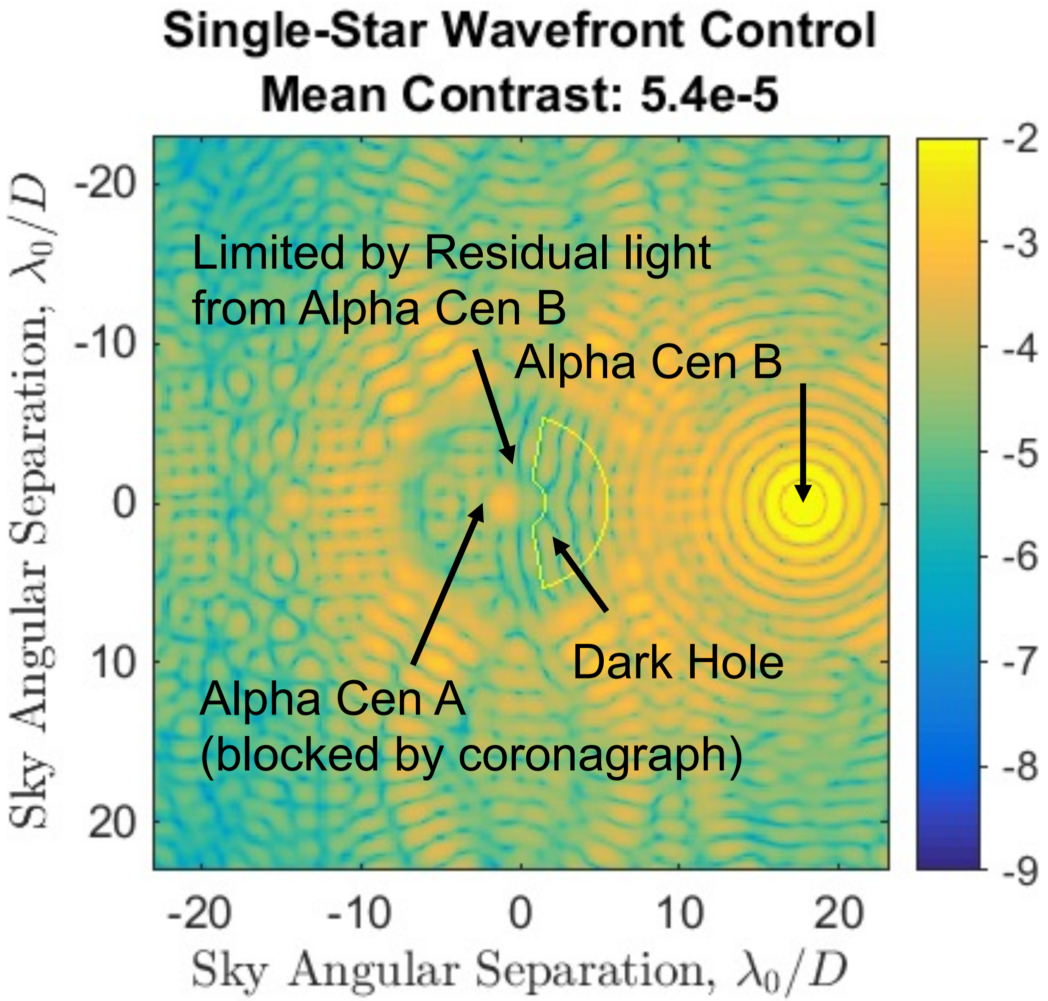
- D = 2.4m
- λ = 650nm
- 20 nm RMS with $f^{-2.5}$ power spectrum
- 48x48 DM

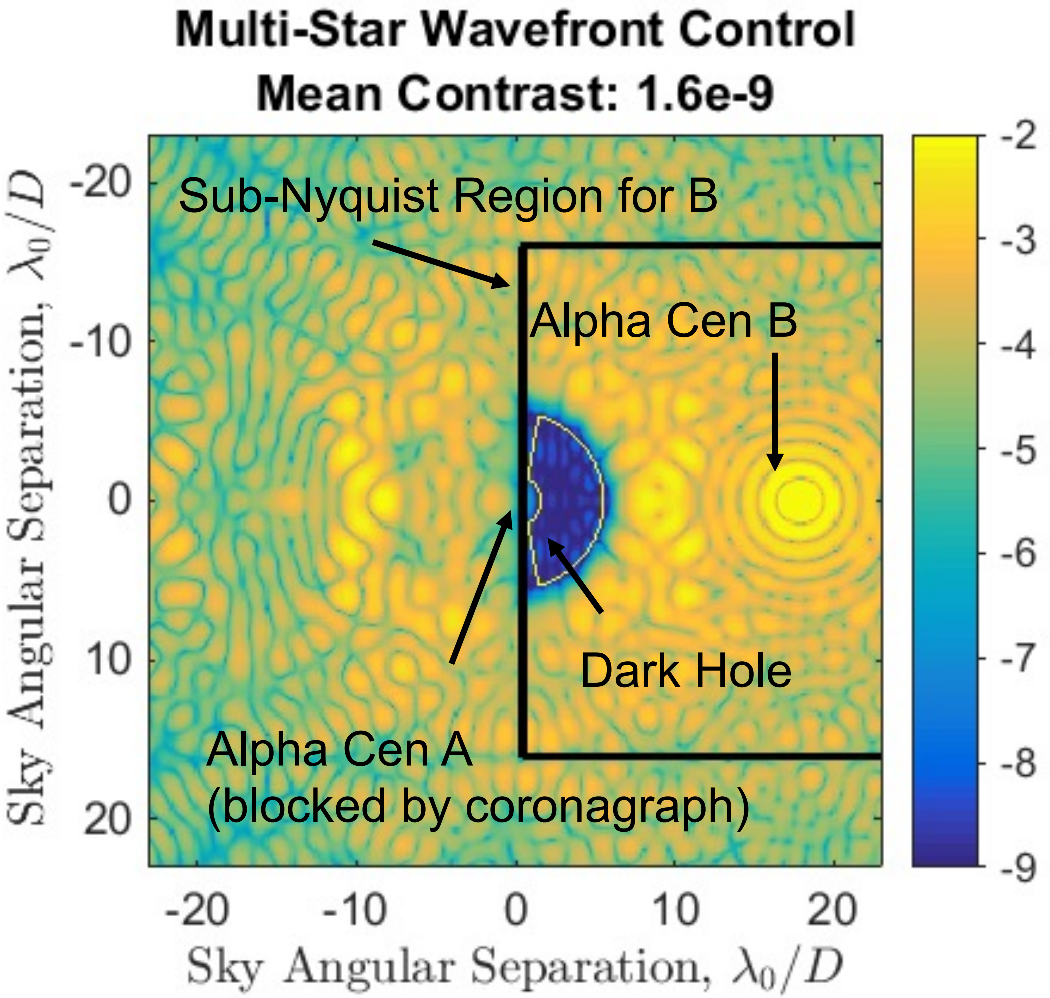
Note: *Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star*

Required companion suppression:

- 31/41 have leakage > 1e-10
- 27/41 have leakage > 1e-9

Multi-Star Wavefront Control

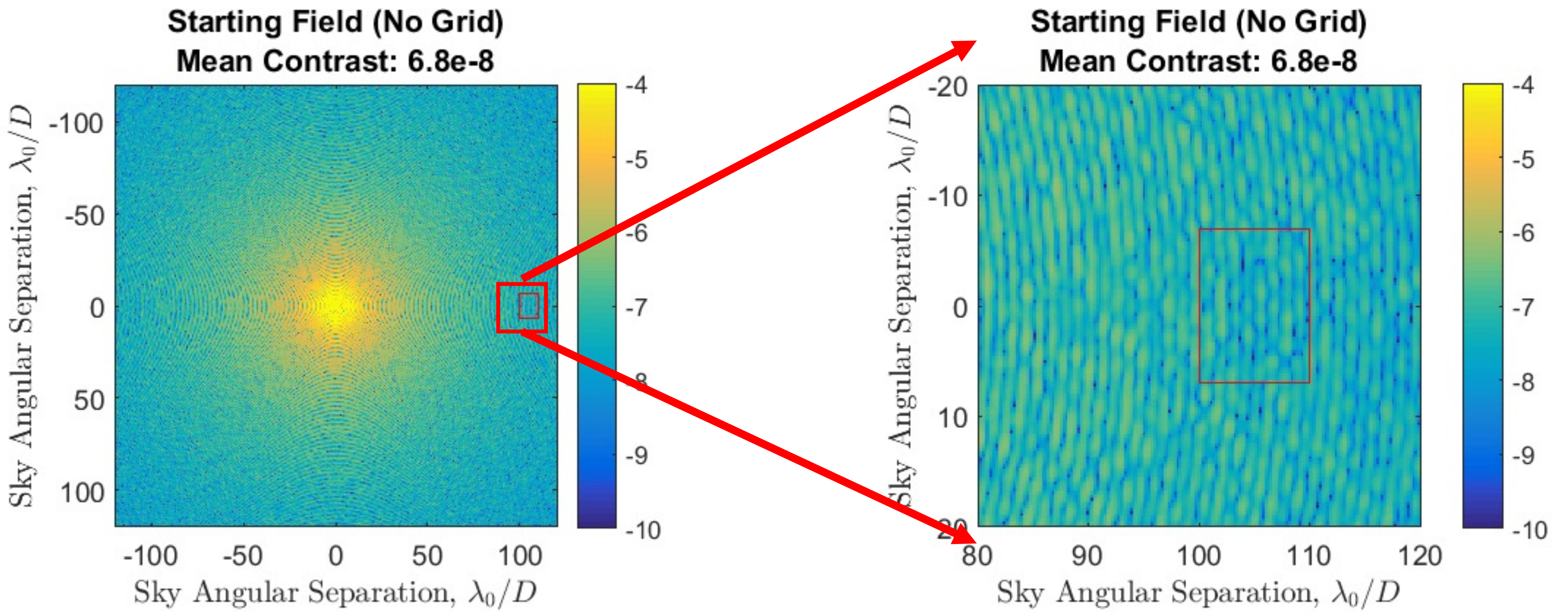




Idea: Use independent modes on the DM to generate spatially overlapping dark holes for each star

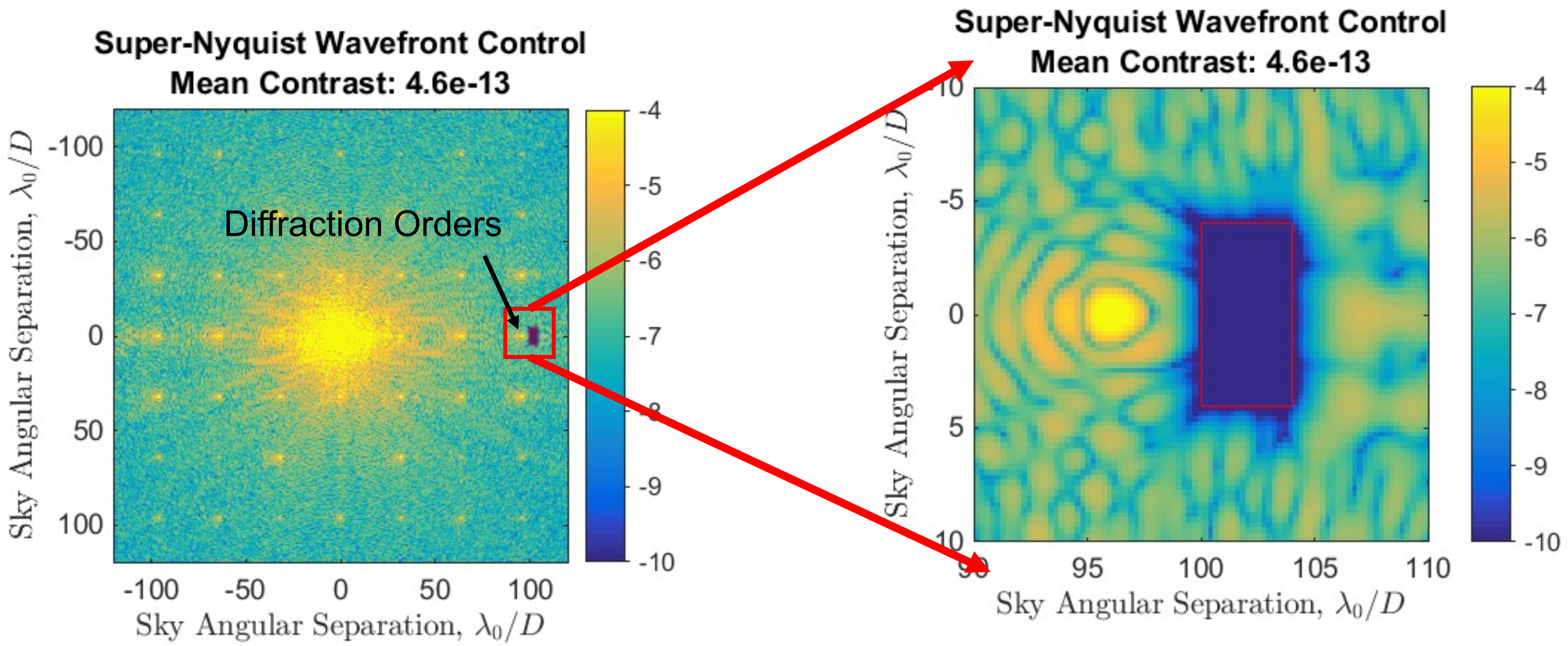
Concept developed by Belikov et al 2015, Thomas et al. 2017, Sirbu et al 2018

Before Super-Nyquist Wavefront Control



Idea: Control leakage at wide angular separations outside of the DM's control region

After Super-Nyquist Wavefront Control



For details on SNWC technique see paper on astro-ph: Thomas et al. (2017)

Roman SPC-WFOV Mask Baseline

<u>Roman SPC WFOV Imaging Mode</u> allows imaging from 6-20 λ/D:

- coverage of habitable zones of Alpha Cen AB
- designed for mean contrast of 9×10^{-10} at 10% bandwidth at 825 nm (Riggs 2020)
- SPC WFOV experimentally verified down to 3.5e-9 contrast level at 10% bandwidth (Marx et al, 2018)

<u>Diffractive pupil</u> superimposed on SPC WFOV Mask design creates diffraction orders to allow Super-Nyquist Wavefront Control (Bendek et al 2018)

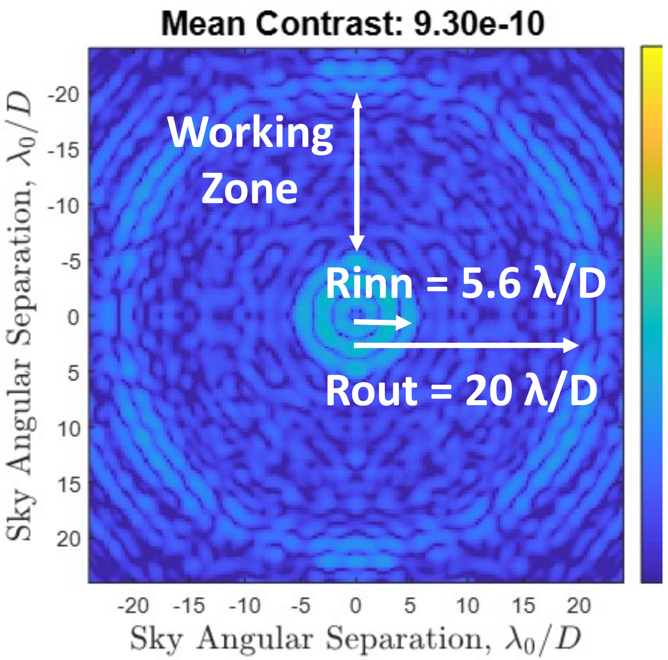
<u>MSWC Mode Configuration</u>:

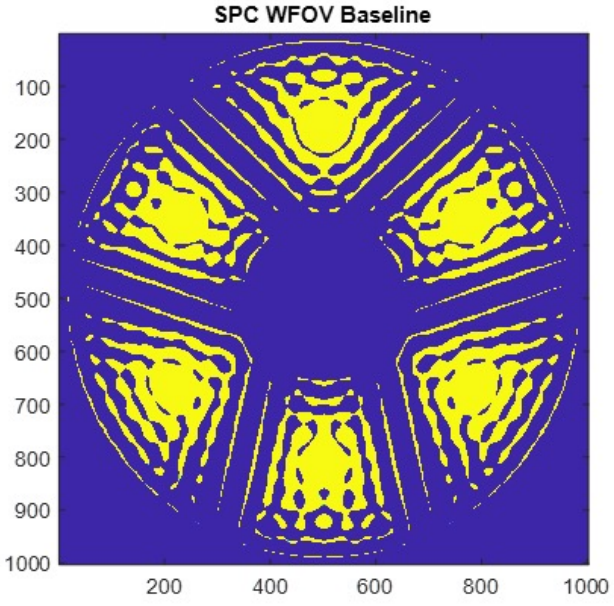
SPAM: MSWC Mask (SPC WFOV + Diffraction Grating)

FPAM: Matching SPC WFOV Mask

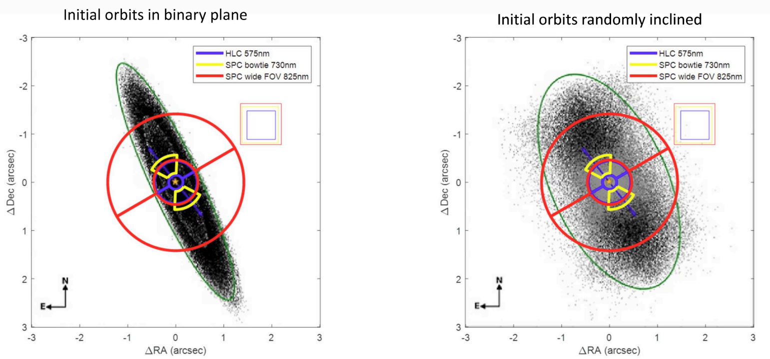
LSAM: Matching SPC WFOV Lyot Stop

FSAM: Custom 9x9 L/D rectangular field stop (Bendek et al 2021)



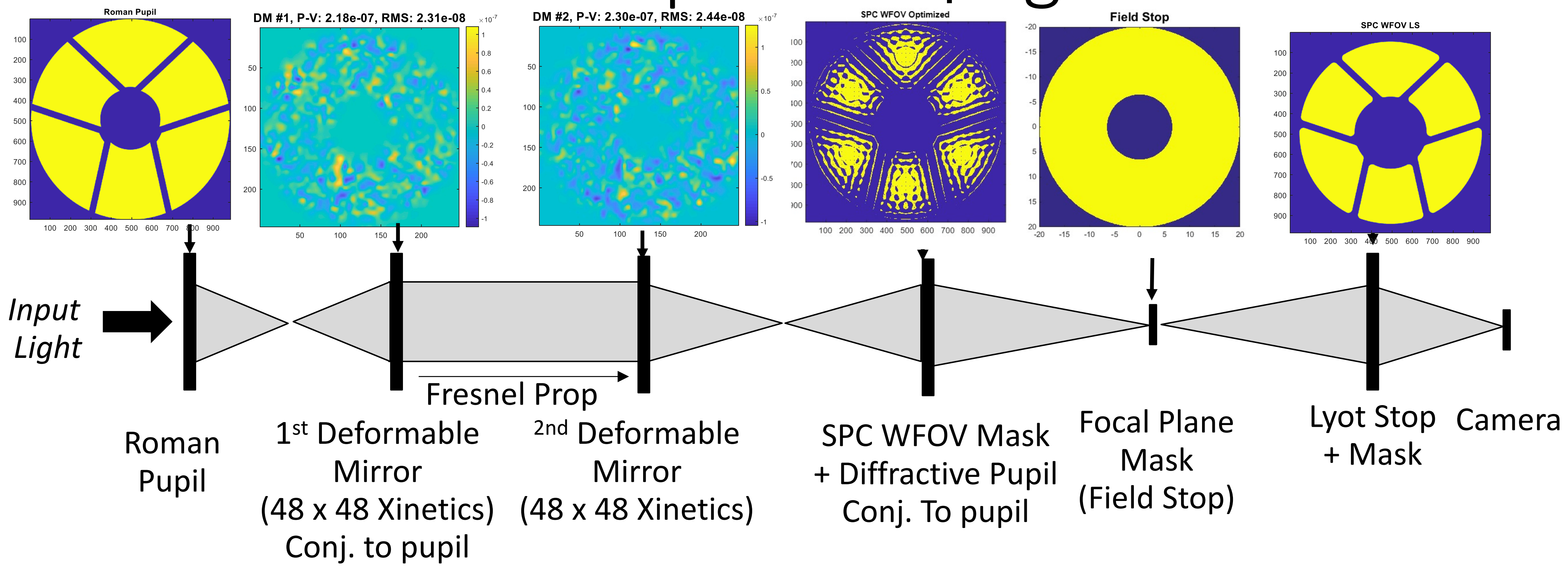


Designed by Riggs 2020



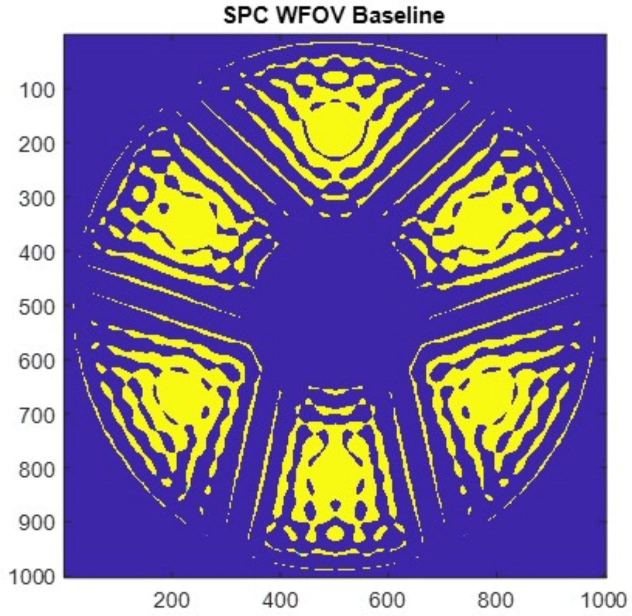
Belikov 2020
(based on Quarles 2016)

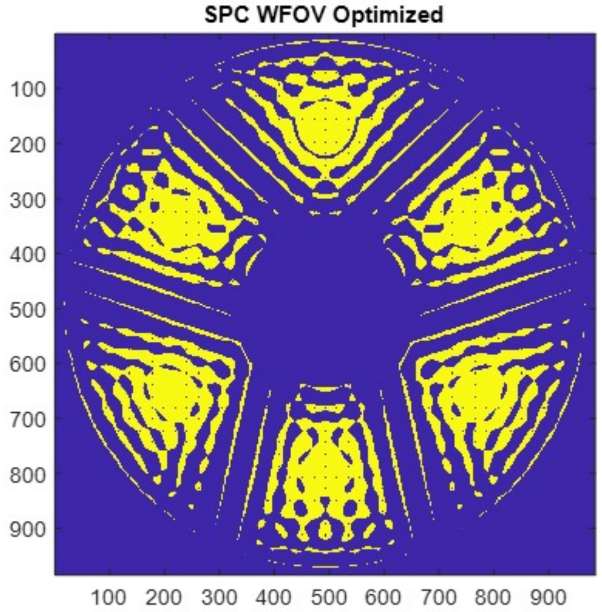
Roman SPC Compact Propagation Model



- Using Fresnel propagation between DMs
- Using optical elements and phase maps publicly available from CGI IPAC

Diffractive Pupil with SPC WFOV Mode



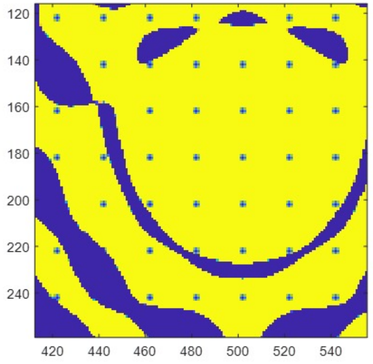


ZOOM-IN

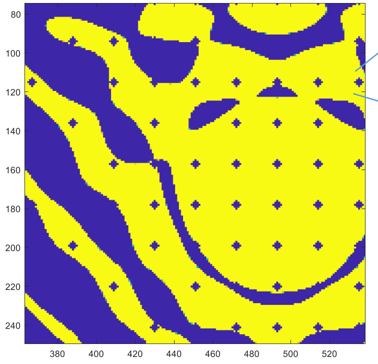
- *Started with SPC WFOV Baseline, and considered two options:*
  OPTION (1) Add DP dots directly onto the mask
  OPTION (2) Add binary DP crosses into optimization
  Optimized by A.J. Riggs

- *Diffractive Pupil Specifications:*
  48x48 repeating diffractive pattern across pupil
  Diffractive orders matching DM Nyquist limit
  3.1% area coverage -> ~1e-4 diffraction order strength
  Flight SPC diameter: **17.0 mm**
  Smallest feature size is **5.6 um**

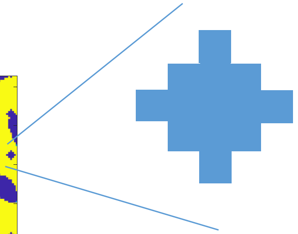
OPTION (1)



OPTION (2)

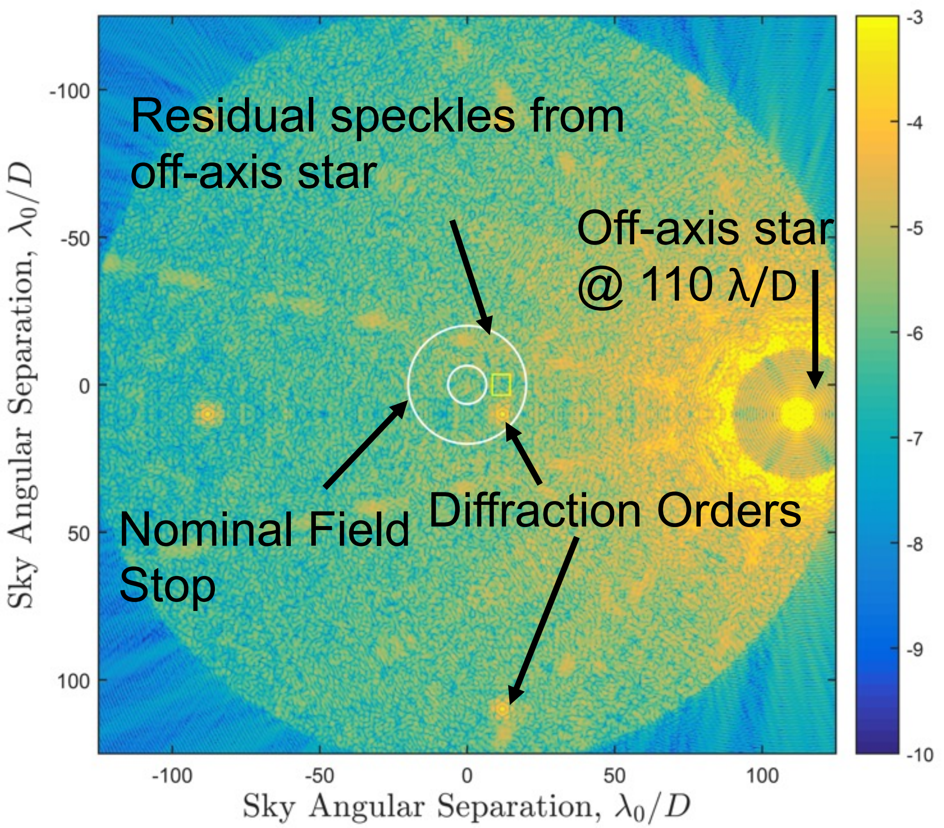


13-dot cross feature

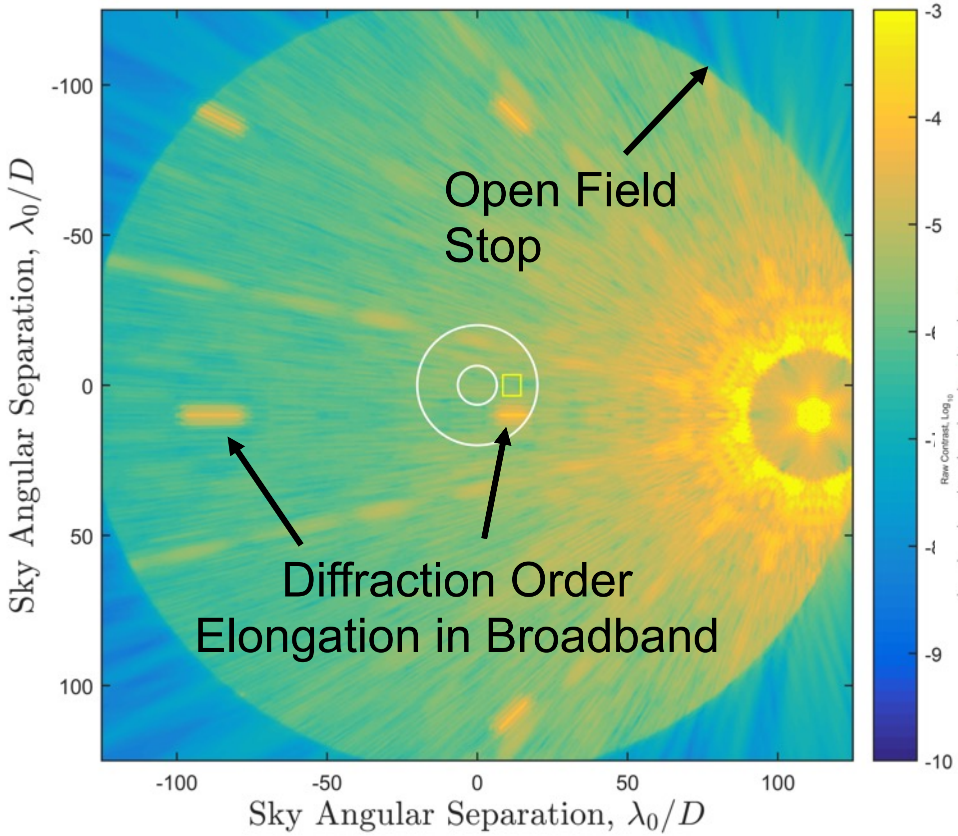


Roman Off-axis Leakage

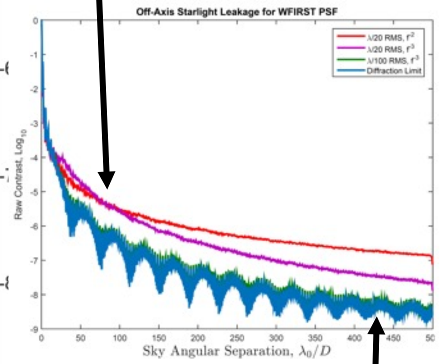
825 nm



825 nm ± 5%



Leakage due to Conservative PSD



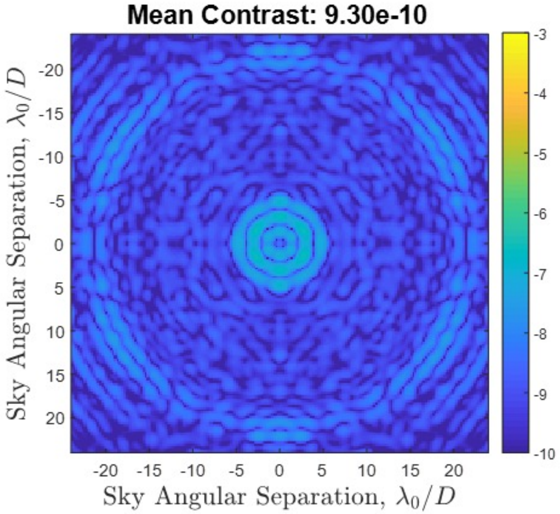
Leakage due to Optimistic PSD

Opening Roman CGI Field Stop to see Off-axis star & its leakage

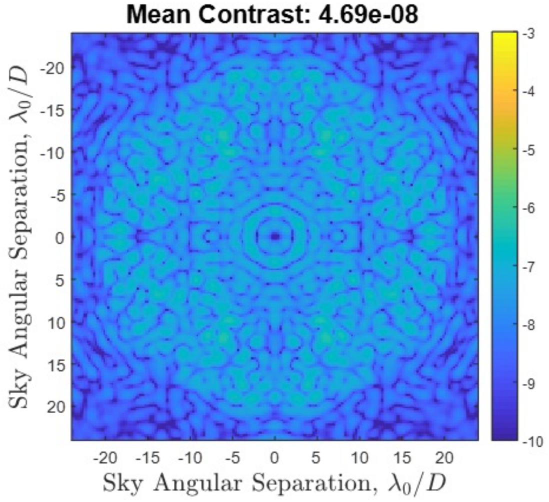
Baseline & Optimized SPC PSFs

OPTION (1)

Baseline PSF

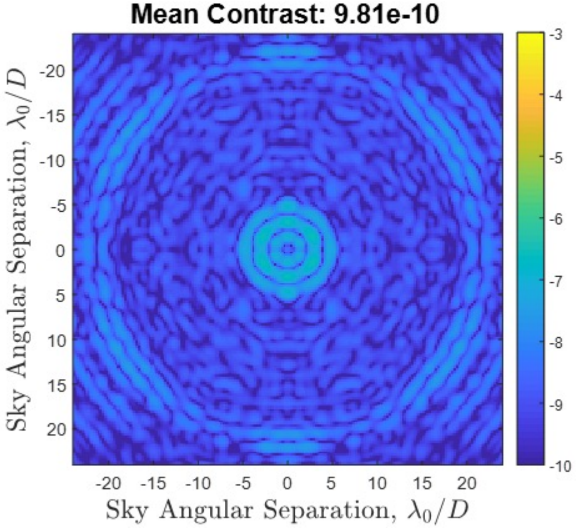


Baseline + Dots PSF



OPTION (2)

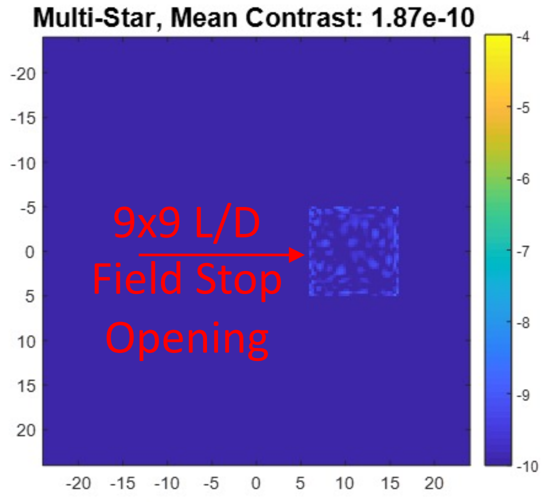
Optimized with Crosses



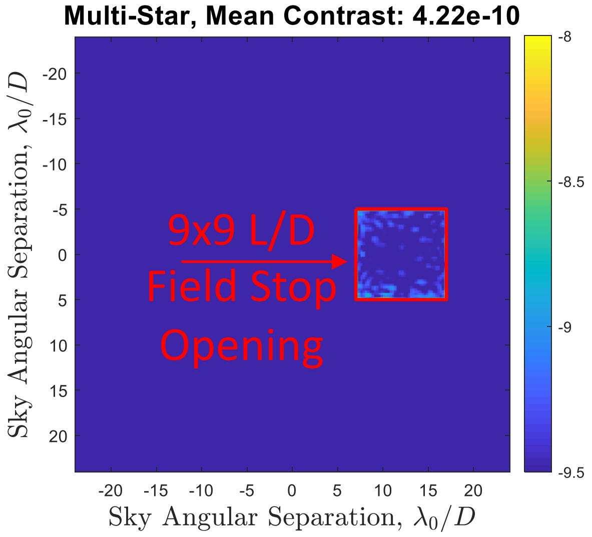
- *Baseline + Dots PSF contrast decreases by 1.5 orders of magnitude from ~1e-9 to ~5e-8*
- *→OPTION (2)* ***recovers the on-axis design performance*** *in the presence of the diffraction grating (at a negligible con throughput)*

Verification with 13-dot MSWC Mask

Monochromatic @ 825 nm



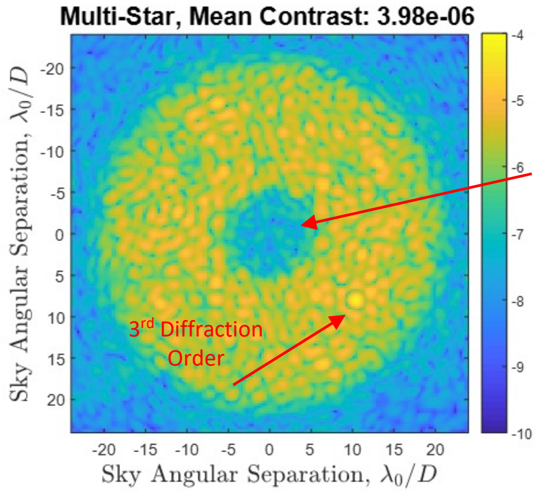
10% Band around 825 nm



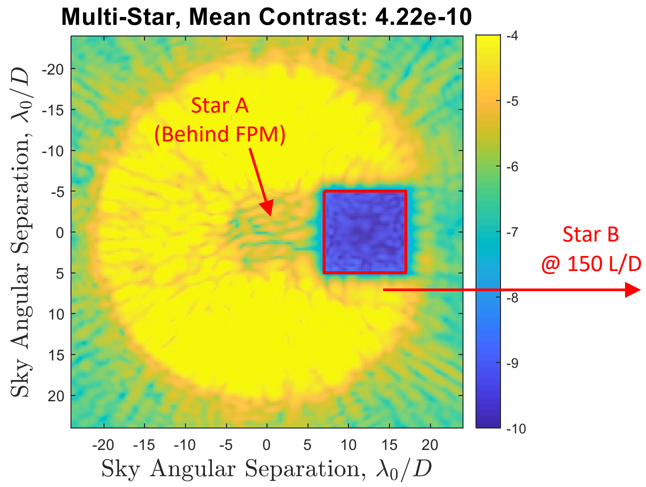
Equal brightness components

DM stroke: ~25 nm RMS

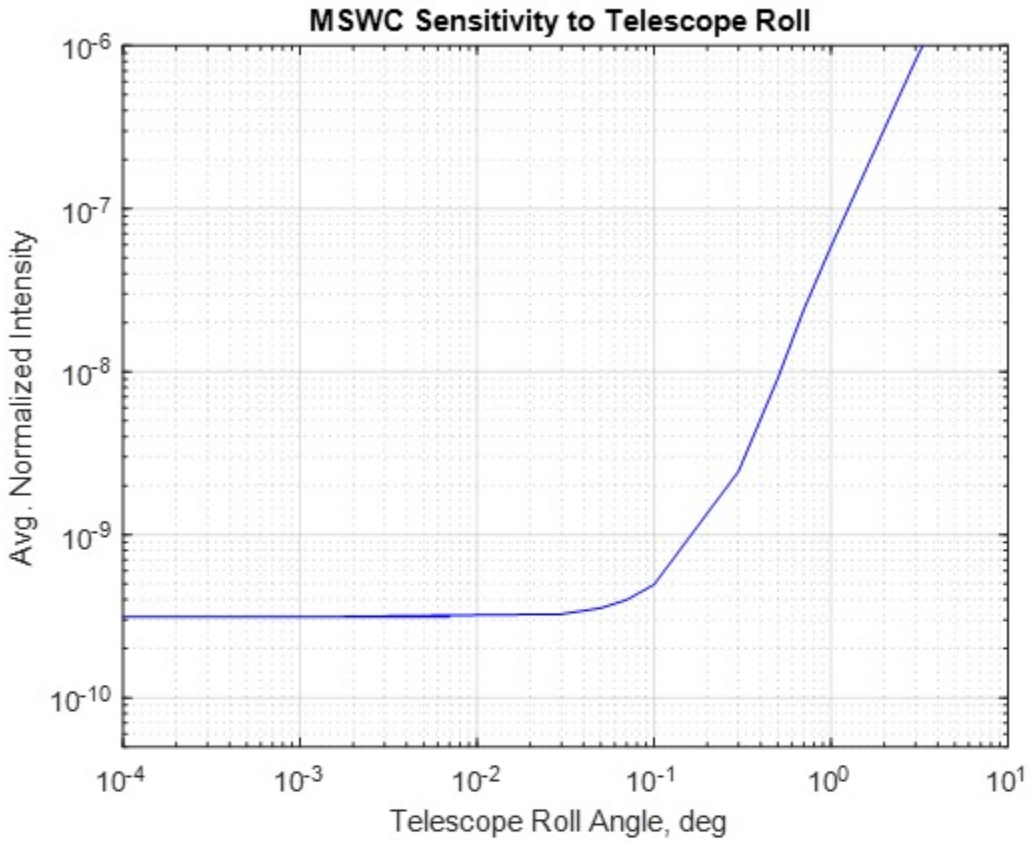
Strehl Ratio: 0.88;

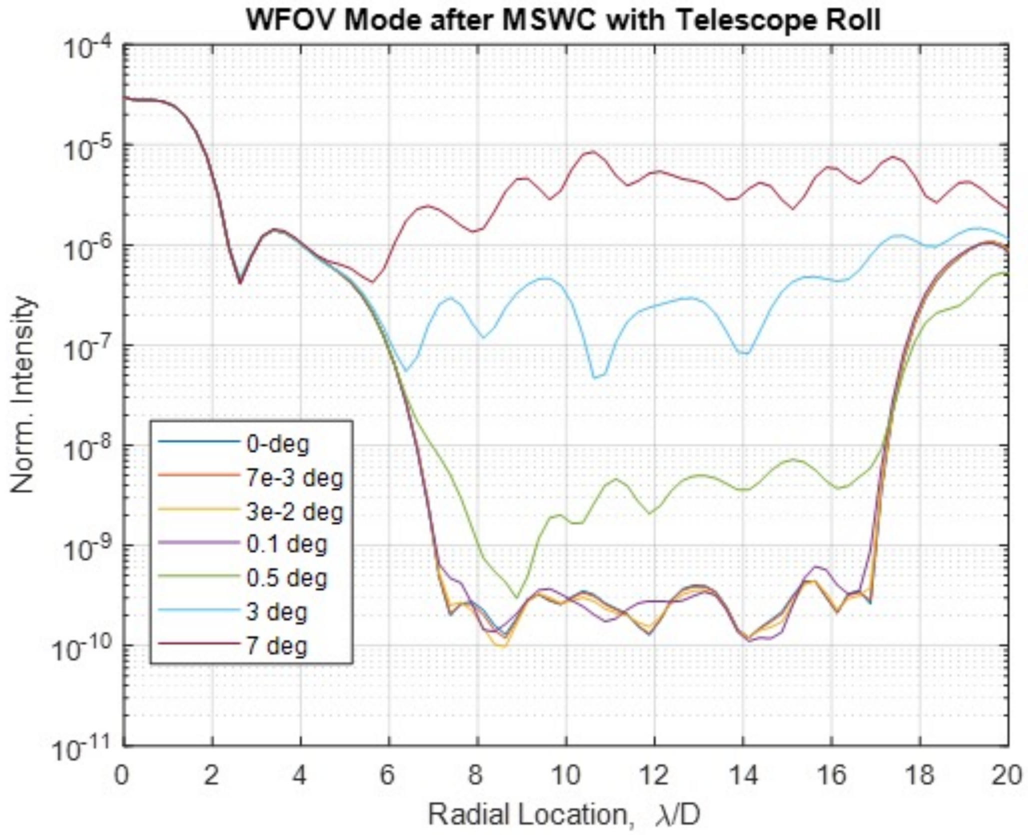


Before WFC
No Field Stop



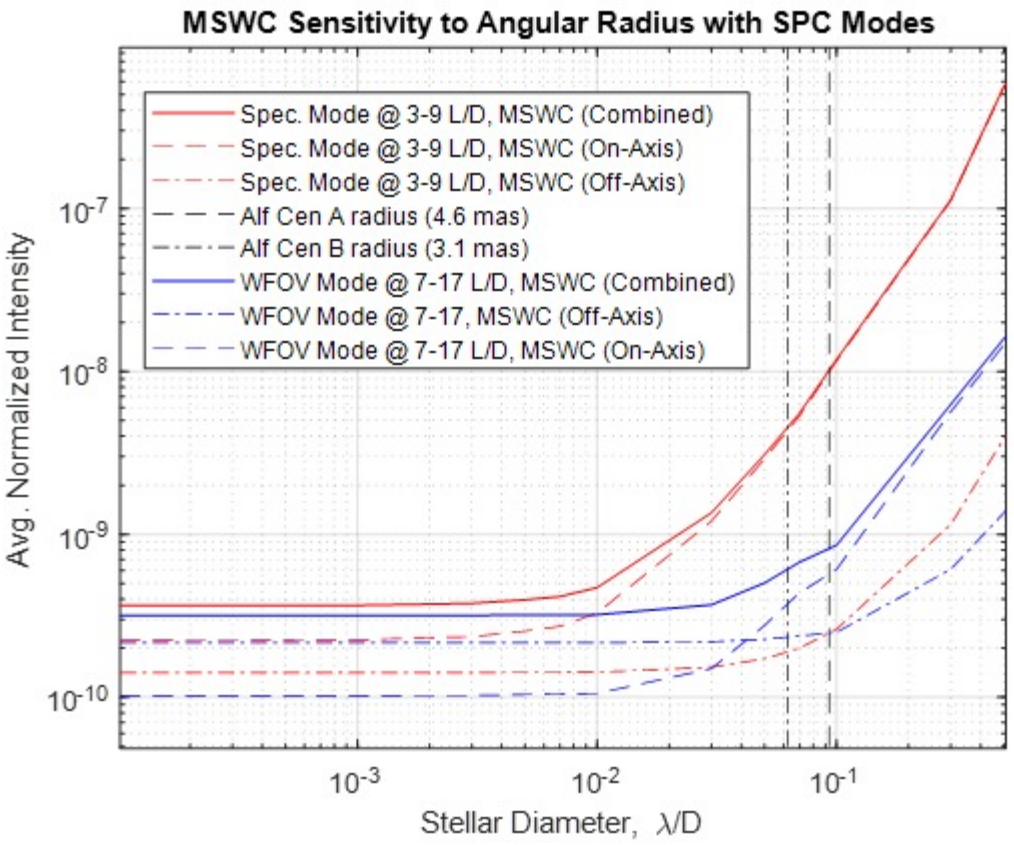
MSWC Sensitivity to Telescope Roll

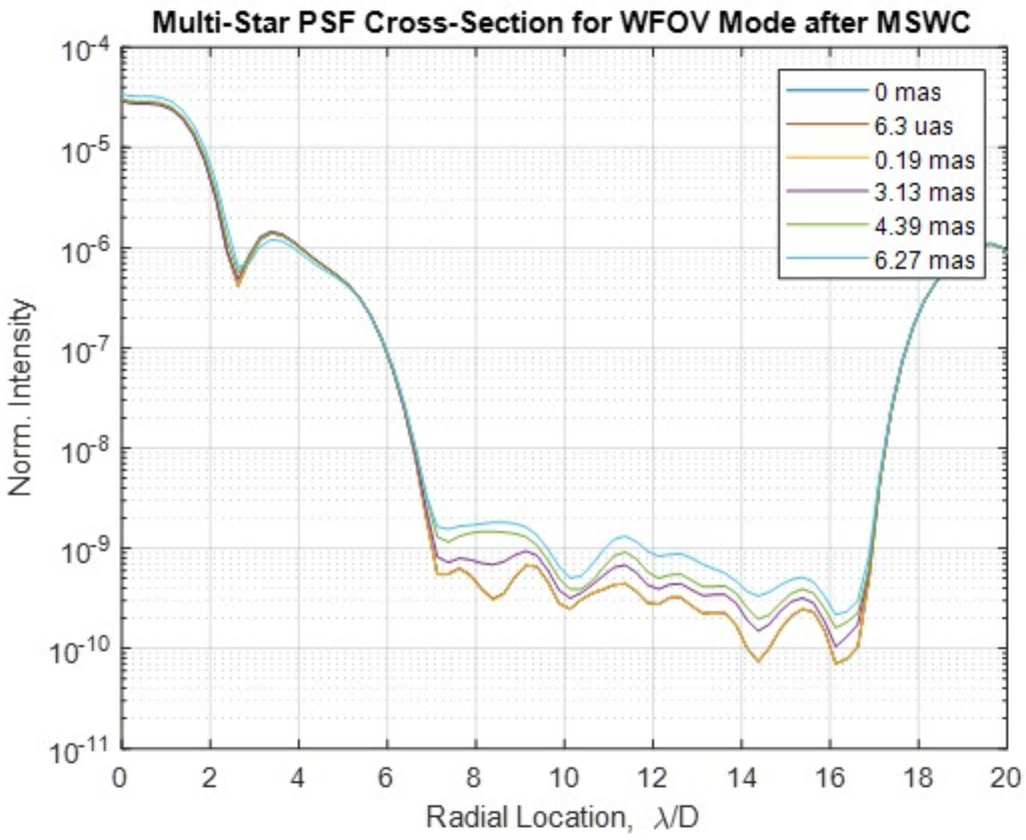




➔ *Expected spacecraft roll is ~0.1" and MSWC is fairly insensitive to roll angles < 0.1 deg*

MSWC Sensitivity to Stellar Diameter & Jitter

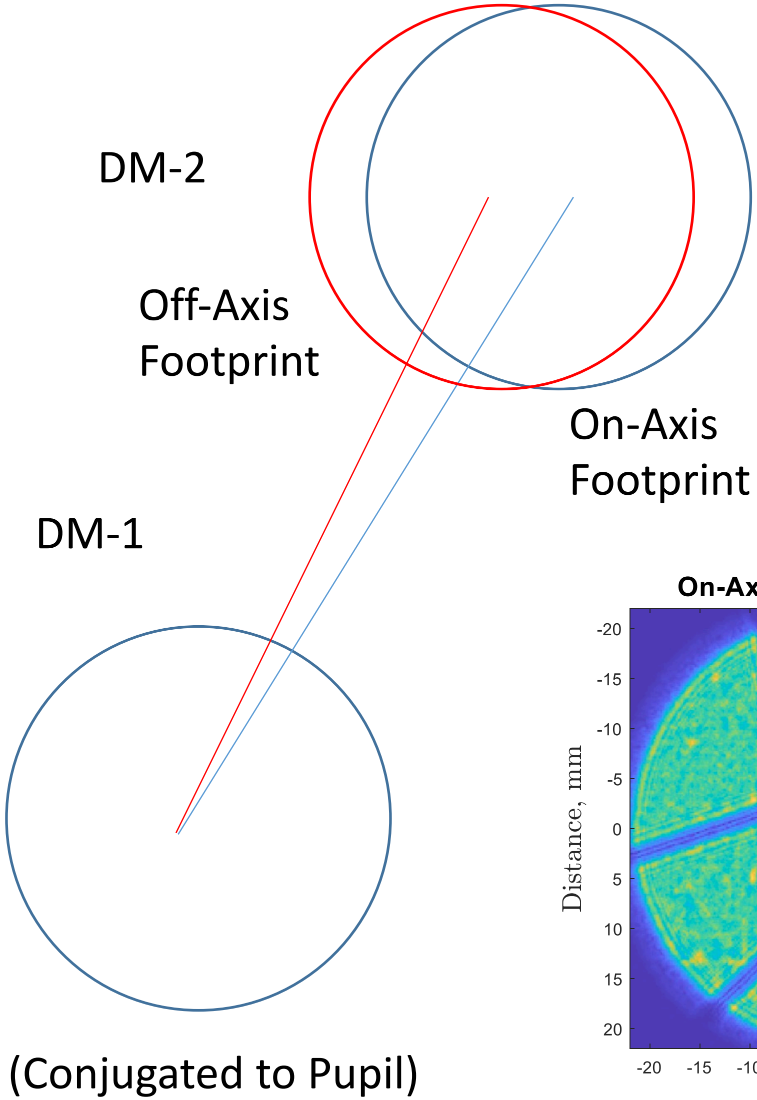




➔ *Expected spacecraft jitter is ~2mas per axis (OS-9) dataset which is less than Alf Cen A/B stellar diameter*

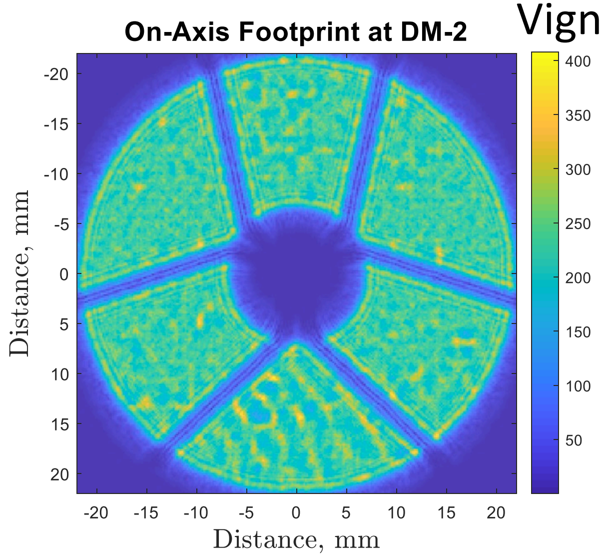
➔ *SPC WFOV mask is fairly insensitive to expected jitter levels due to large IWA*

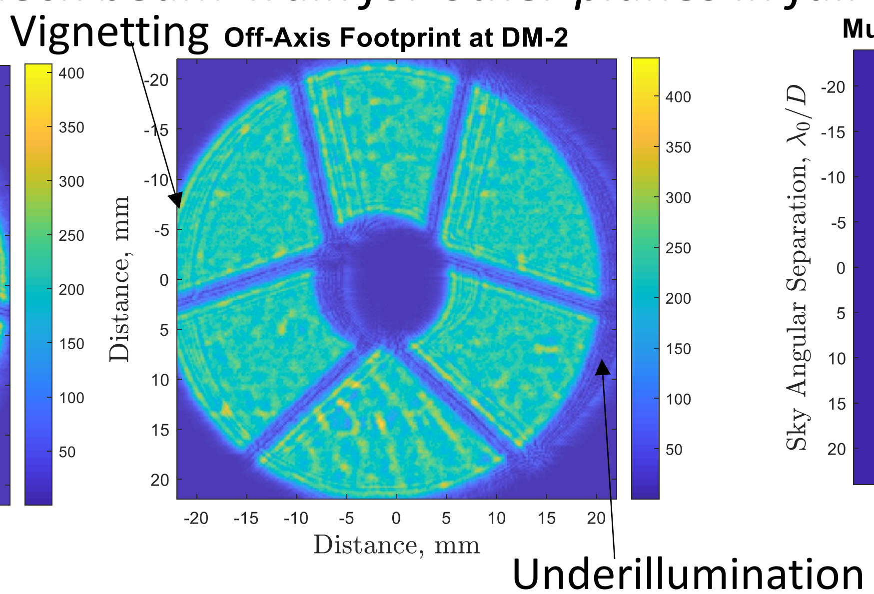
Off-axis Vignetting at DM2

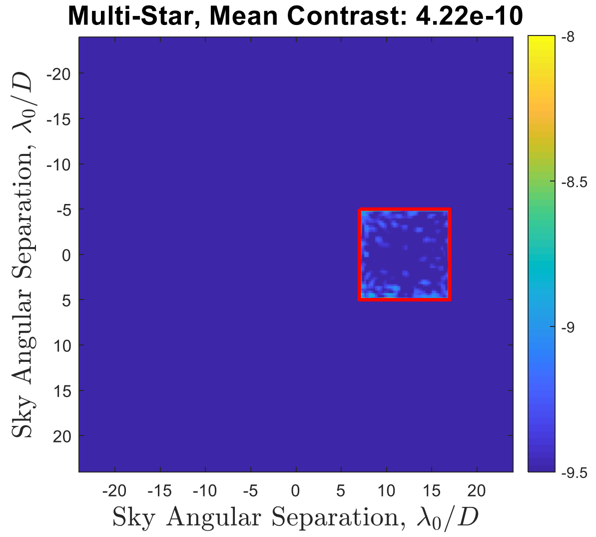


- Beamwalk between DMs causes vignetting due to the off-axis footprint baffled at DM-2
- Example: for 9” off-axis star, a ~2mrad angle at DM-2 corresponds to a lateral footprint translation of 2 mm
  - Illuminates un-controlled actuators on the DM-2 edge
  - Shifted footprint does not illuminate 2 actuator-rings
  - Vignetting off-axis star from DM-2 baffle (4% energy lost)
- MSWC can correct stars at 9” (beam-walk between DMs & circular DM stop is included in compact model)

➔ *Need to check beam-walk for other planes in full-model*

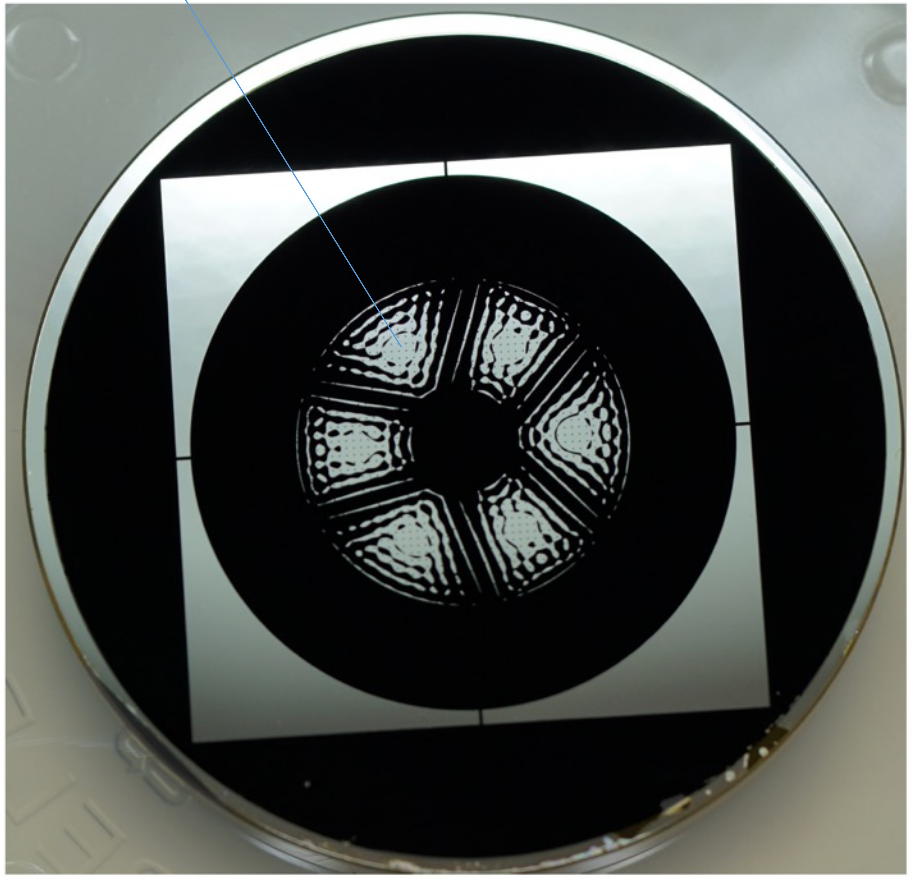




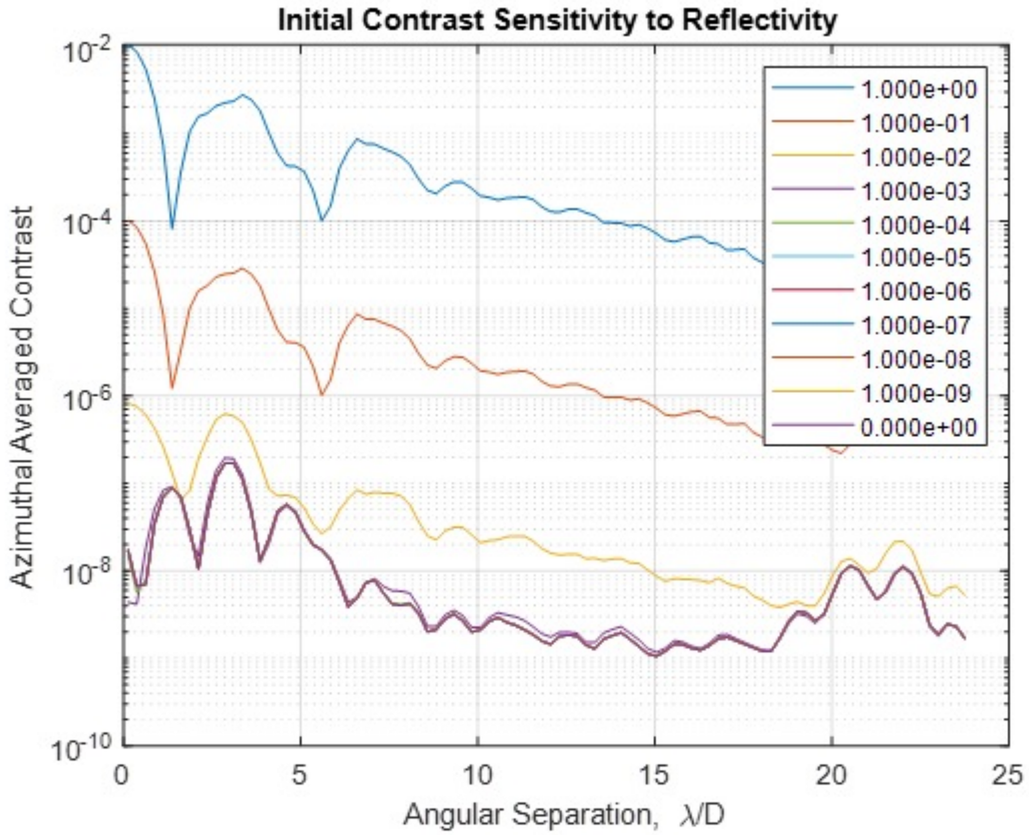


MSWC Sensitivity to Mask Reflectivity

Cross features

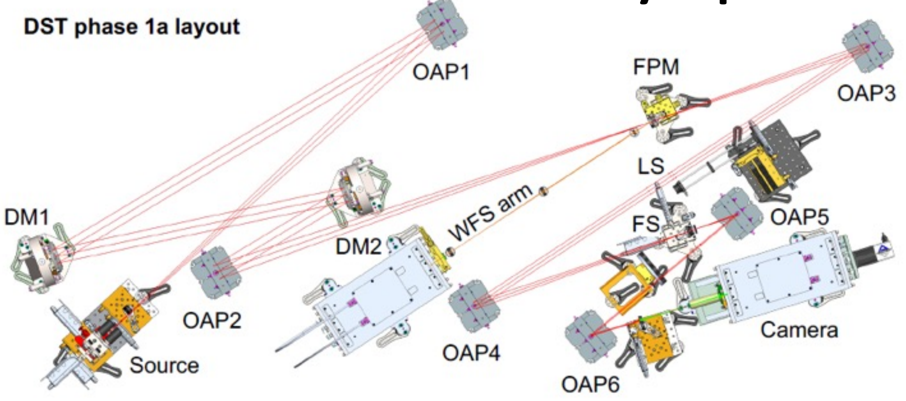


Prototype manufactured by Hagopian 2021
Final mask to be manufactured by MDL



➔ *Amplitude reflectivity less than 1e-3 results in no degradation of performance*

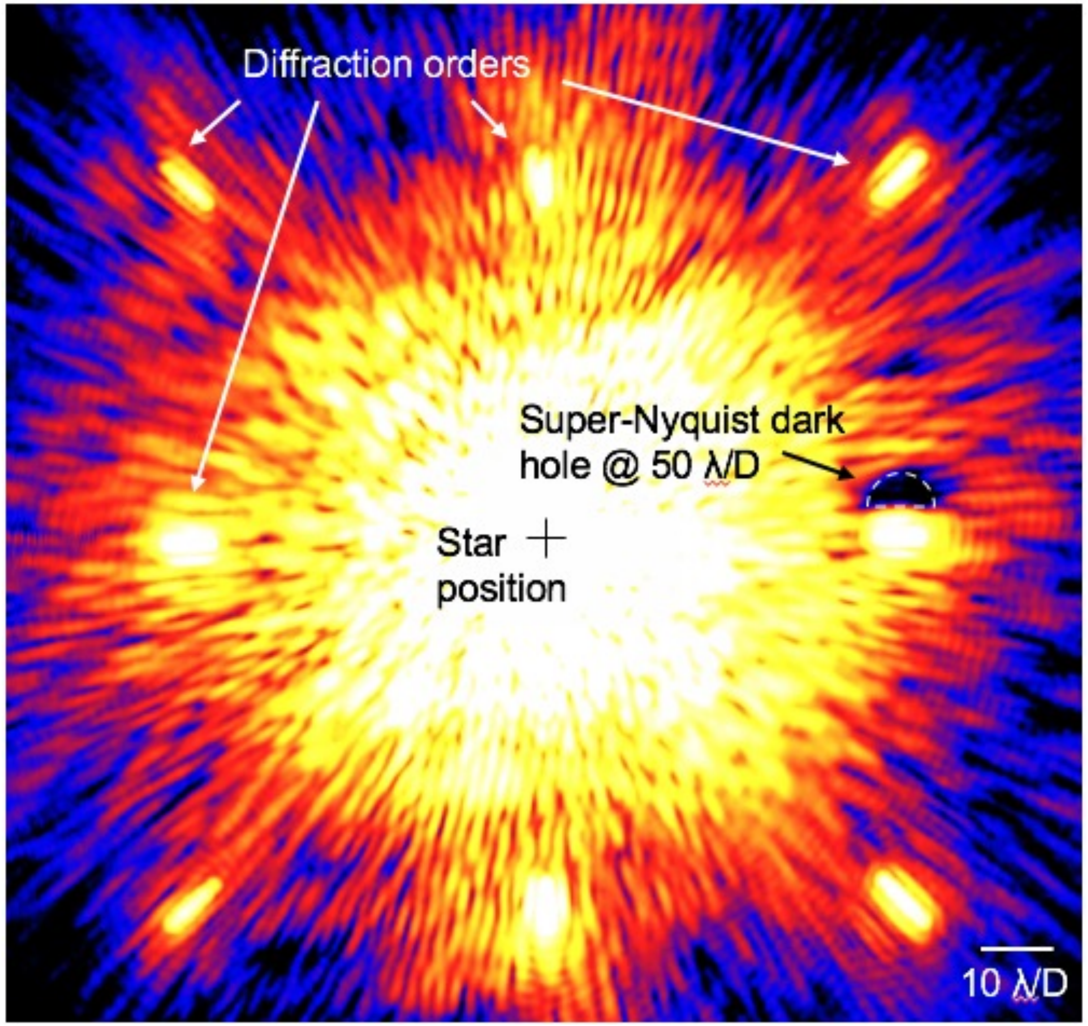
First vacuum demonstrations of super-Nyquist wavefront control



- **Source: single star (demonstrating super-Nyquist capability)**
- **Coronagraph: Lyot Coronagraph**
- **Decadal Survey Testbed (DST) operated by Garreth Ruane (July 2020)**

Summary of Results
monochromatic light, contrast 4e-8
10% broadband light, 4e-7
6e-8 demonstrated in a smaller dark zone

10% broadband light



Future Work

Demonstrated to date:

Compatibility of CGI imaging with MSWC using compact CGI model

(1) line-of-sight jitter / stellar diameter

(2) telescope roll

(3) vignetting between DMs

(4) mask reflectivity

Participation in RHDA:

Increase fidelity of simulations:

(1) demonstration of MSWC with full Roman CGI model

(2) use latest observing Scenario (OS-11) STOP models

(3) generate realistic observation DRMs for science targets

Determine best options to implement MSWC algorithm on Ground-in-the-Loop WFC system.

Create MSWC simulation tools that includes off-axis stars for Roman CGI

(1) MSWC mode recently included in FALCO

(2) MSWC + Ames Coronagraph Efficient Diffraction (ACED) optical propagator libraries on Github:
https://github.com/ARCExoplanetTechnologies

Conclusions

1. **MSWC can improve the science yield and science diversity for Roman CGI, including at least a small chance to detect a potentially habitable planet.**
2. **Simulations show that MSWC is compatible with Roman CGI, and allows it to image planets around binaries with performance comparable to single stars (assuming post-processing would work similarly well for binary stars as it does for single stars).**
3. **Lab demonstrations with coronagraphs have been started, are now at TRL ~3, and are being advanced to 4. These include demonstrations with a real instrument (SCExAO) and in vacuum (DST).**

References

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Backup Slides

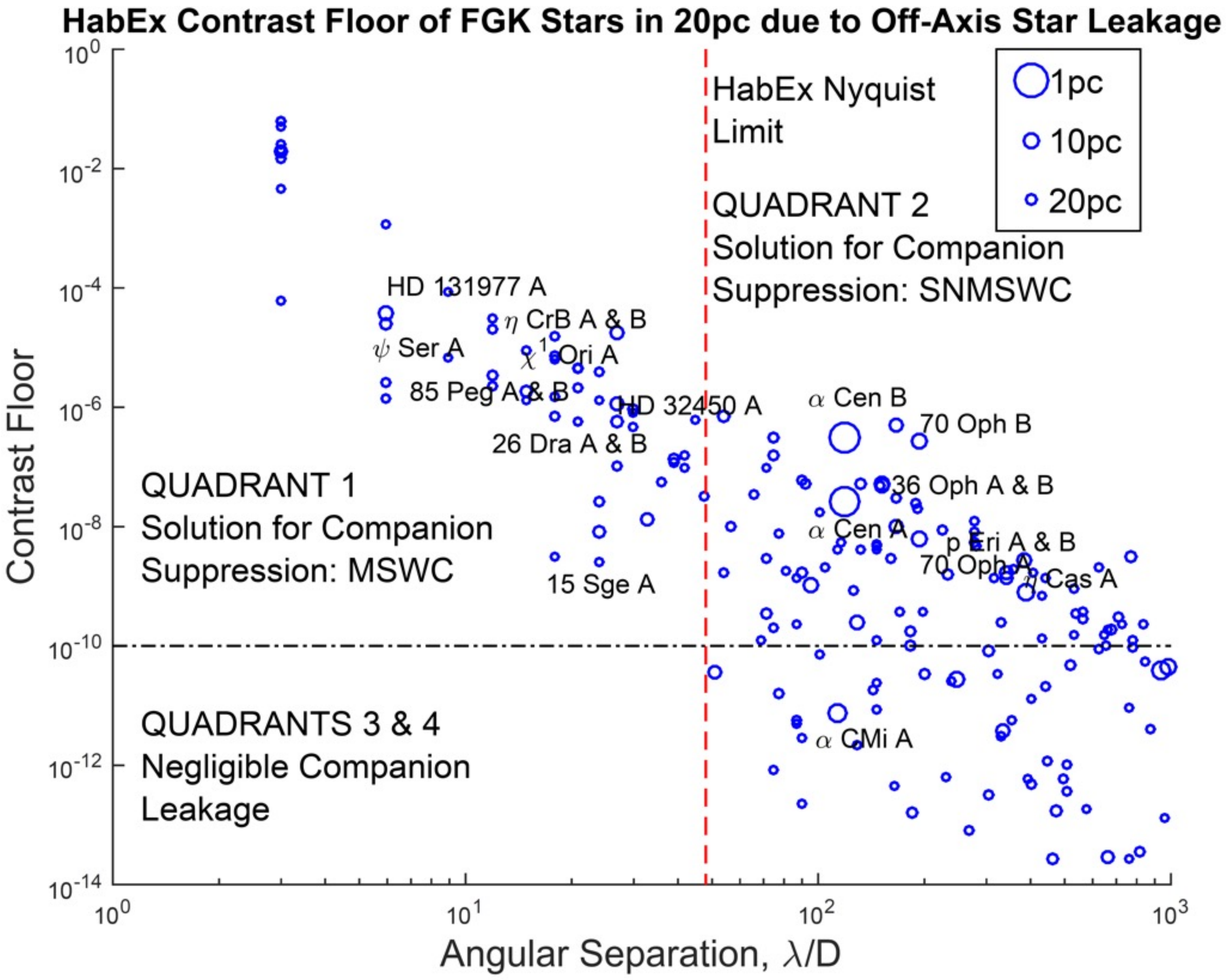
Why Binaries? Nearby FGK Targets for Roman

1	common_name	sptype	Vmag	d (pc)	M	Sol. Lum.	BB Temp	IHZ (AU)	IHZ (as)	IHZ (ld)	OHZ (AU)	OHZ (as)	OHZ (ld)
2	*** alf Cen A**	**G2V**	**0.01**	**1.32**	**4.40**	**1.45**	**5568**	**1.13**	**0.86**	**15.31**	**2.08**	**1.57**	**28.13**
3	*** alf Cen B**	**K1V**	**1.33**	**1.25**	**5.84**	**0.39**	**5051**	**0.60**	**0.48**	**8.58**	**1.12**	**0.90**	**16.04**
4	* eps Eri	K2Vk:	3.73	3.22	**6.19**	**0.28**	5051	0.51	0.16	2.84	0.95	0.30	5.31
5	*** 61 Cyg A**	**K5Ve**	**5.21**	**3.49**	**7.50**	**0.08**	**4348**	**0.29**	**0.08**	**1.48**	**0.56**	**0.16**	**2.85**
6	*** 61 Cyg B**	**K7Ve**	**6.05**	**3.49**	**8.34**	**0.04**	**4348**	**0.29**	**0.08**	**1.48**	**0.56**	**0.16**	**2.85**
7	*** alf Cmi A**	**F5IV-V+**	**0.37**	**3.51**	**2.64**	**7.29**	**6776**	**2.37**	**0.67**	**12.06**	**4.25**	**1.21**	**21.64**
8	* eps Ind	K5V	4.69	3.62	6.90	0.15	4603	0.38	0.10	1.86	0.72	0.20	3.55
9	* tau Cet	G8.5V	3.5	3.65	5.69	0.44	5534	0.63	0.17	3.08	1.15	0.32	5.66
10	HD 88230	K8V	6.61	4.87	8.17	0.04	4069	0.21	0.04	0.78	0.42	0.09	1.53
11	*** omi02 Eri**	**K0.5V**	**4.43**	**4.98**	**5.94**	**0.35**	**5221**	**0.57**	**0.11**	**2.04**	**1.06**	**0.21**	**3.79**
12	*** 70 Oph A**	**K0-V**	**4.123**	**5.09**	**5.59**	**0.48**	**5143**	**0.67**	**0.13**	**2.36**	**1.25**	**0.25**	**4.40**
13	*** 70 Oph B**	**K4V**	***6.17***	**5.09**	**7.64**	**0.07**	**4350**	**0.23**	**0.05**	**0.82**	**0.44**	**0.09**	**1.55**
14	*** 36 Oph A**	**K2V**	**5.12**	**5.46**	**6.43**	**0.22**	**5134**	**0.46**	**0.08**	**1.52**	**0.86**	**0.16**	**2.83**
15	*** 36 Oph B**	**K1V**	**5.08**	**5.98**	**6.19**	**0.28**	**5134**	**0.51**	**0.08**	**1.52**	**0.95**	**0.16**	**2.83**
16	* sig Dra	G9V	4.68	5.75	**5.88**	**0.37**	5342	0.58	0.10	1.81	1.07	0.19	3.34
17	**HD 131977**	**K4V**	**5.72**	**5.84**	**6.89**	**0.15**	**4493**	**0.38**	**0.06**	**1.16**	**0.73**	**0.12**	**2.23**
18	*** eta Cas A**	**G0V**	**3.52**	**5.95**	**4.65**	**1.15**	**6047**	**0.98**	**0.28**	**5.03**	**1.78**	**0.51**	**9.12**
19	*** eta Cas B**	**K7Ve**	**7.51**	**5.95**	**8.64**	**0.03**	**3967**	**0.17**	**0.03**	**0.52**	**0.34**	**0.06**	**1.02**
20	V* V2215 Oph	K5V	6.34	5.97	7.46	0.09	4389	0.29	0.05	0.88	0.56	0.09	1.69
21	**HD 191408 A**	**K2.5V**	**5.32**	**6.02**	**6.42**	**0.22**	**5076**	**0.41**	**0.07**	**1.23**	**0.74**	**0.12**	**2.20**

Nearest 20 Stars:
13 Multi-Stars
4/7 Multi-Star Hab. Zones w/in Roman FOV

Legend:
BOLD – Binaries
Color – Hab.Zone w/in Roman FOV
Green – Companion can be ignored
Red – Companion must be suppressed

Multi-Star Direct Imaging Science with HabEx



Multi-Star Science Statistics:

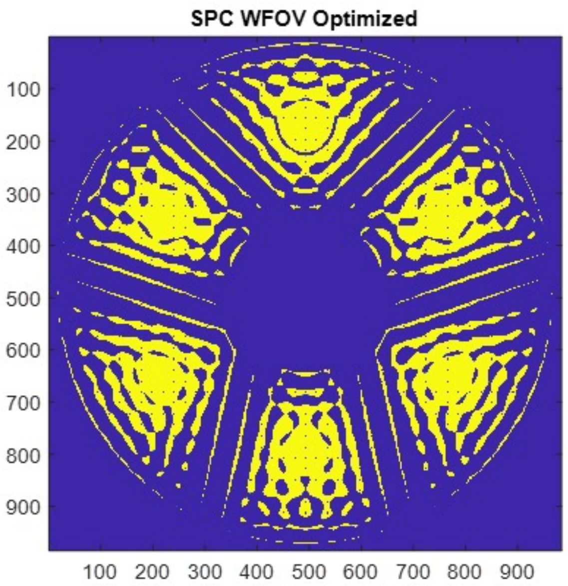
- 517 FGK stars within 20pc
- 259 multi-stars (optical or dynamical)
- 193 stars limited at > 1e-10
  - 40 stars with sep. < N/2 λ/D

HabEx assumptions:

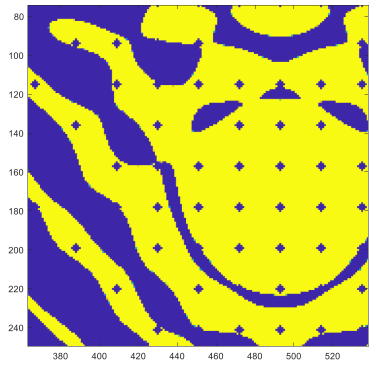
- D = 4m
- λ = 650nm
- λ/20 RMS with f^{-3} power spectrum
- 96x96 DM

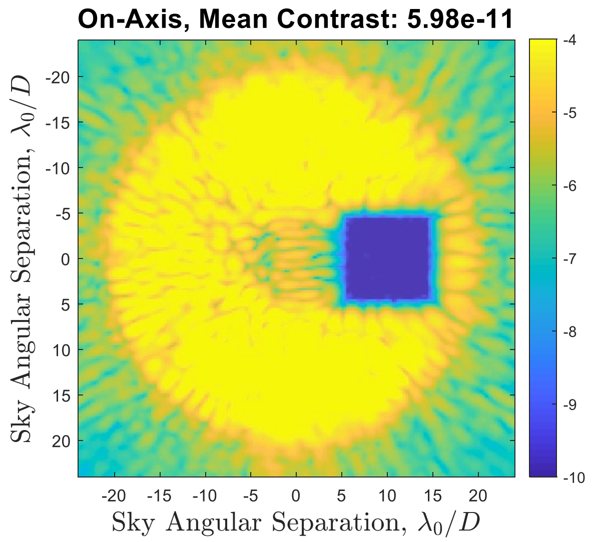
Note: *Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star*

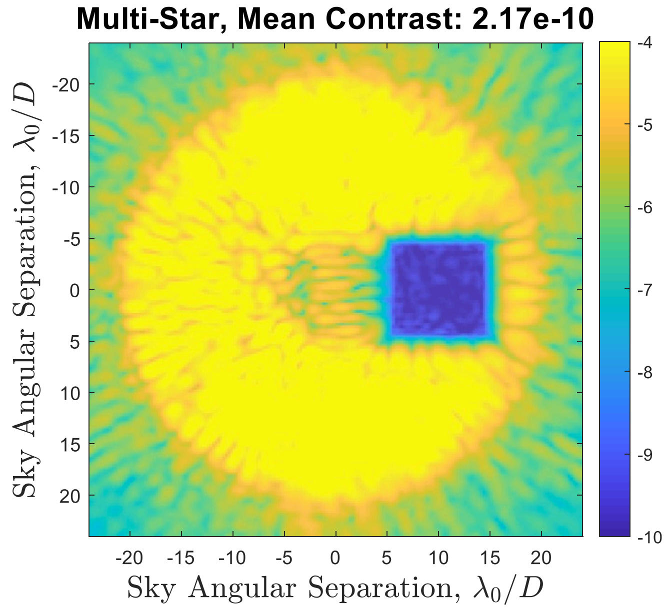
MSWC Baseline Scenario (5-band control)

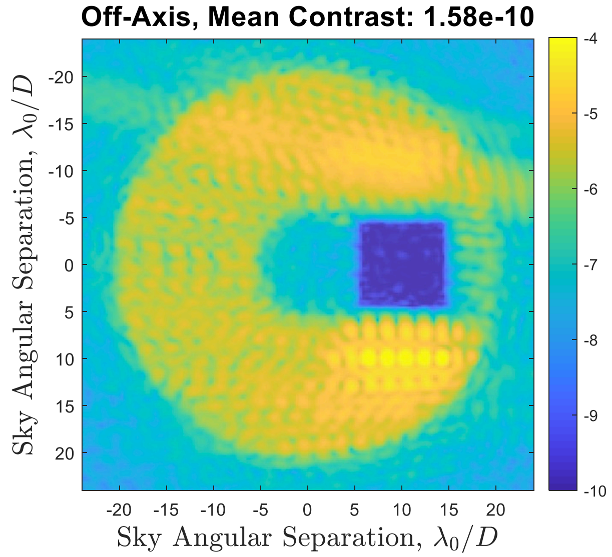


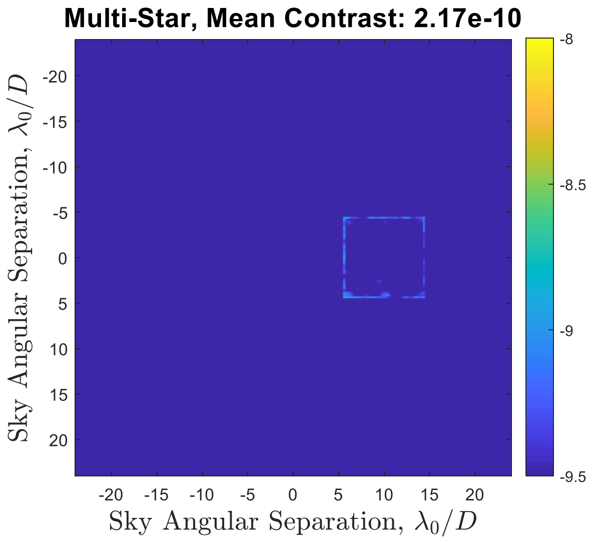
Zoom-in for 13-dot MSWC Mask











DST Vacuum Demonstration (monochromatic)