High-Contrast Imaging of Binary Stars with Starshades

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Starshade SIP Meeting

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Overview

1. *Motivation for Binary Star Direct Imaging*
2. Direct Imaging of Binaries with Starshades

Hubble Image of Alpha Centauri A & B

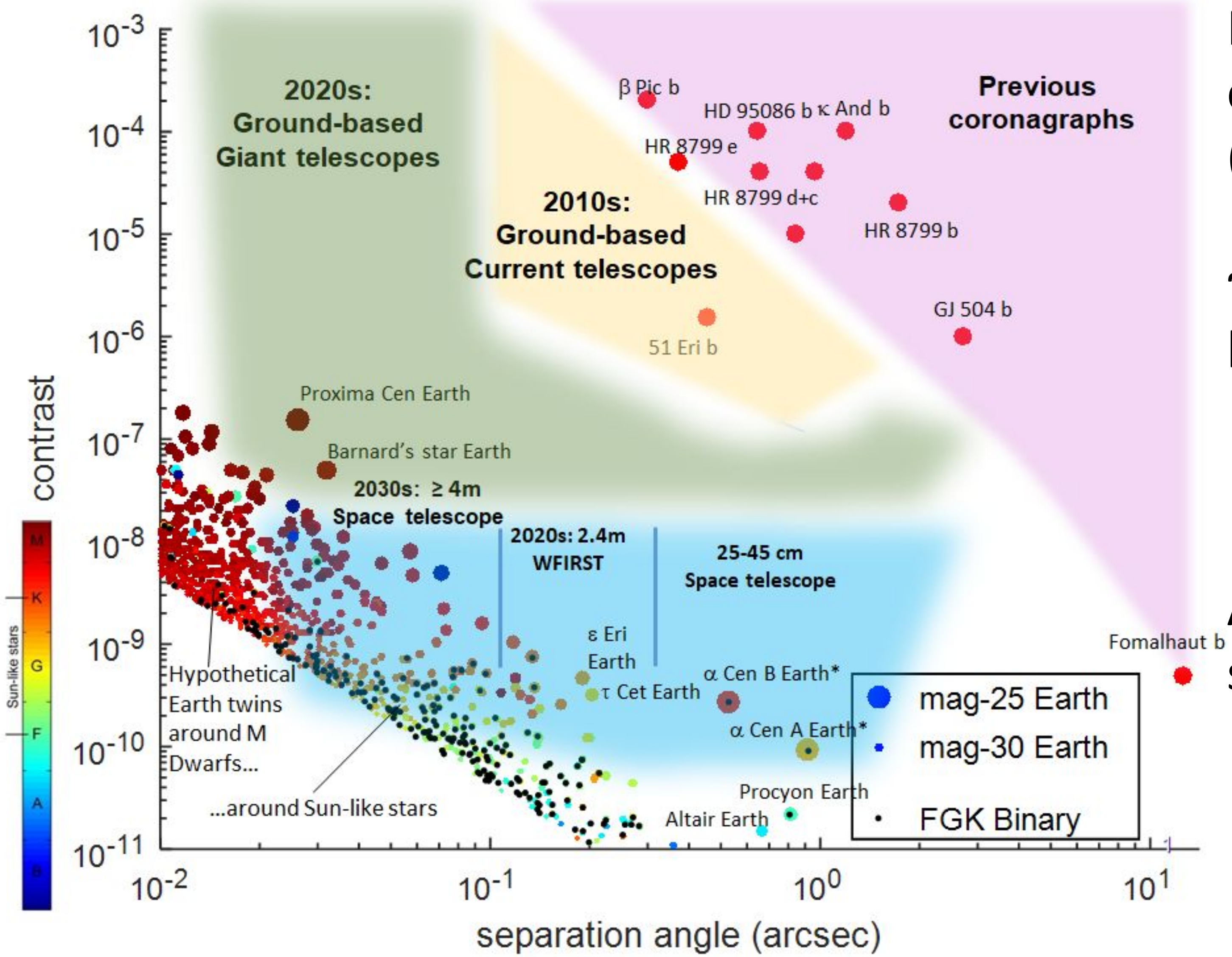
Why Binaries? Nearby FGK Targets for Roman

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 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

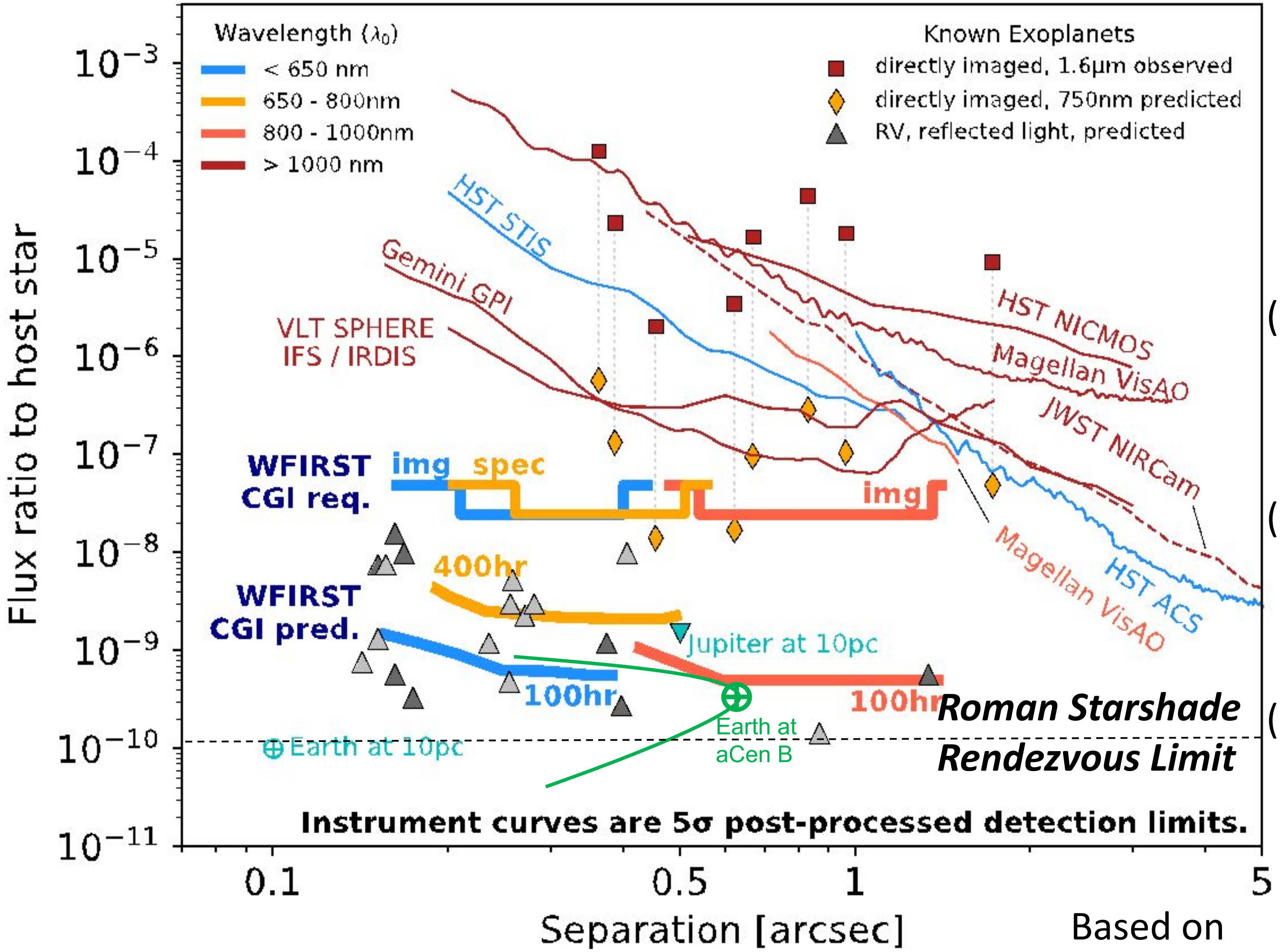
- **41/67 in 10 pc**
- **259/519 in 20 pc**

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** of direct imaging targets

Roman CGI *may* be able to image Earth twins



Based on Bailey 2019

Alpha Cen enables ~3x better IWA and resolution

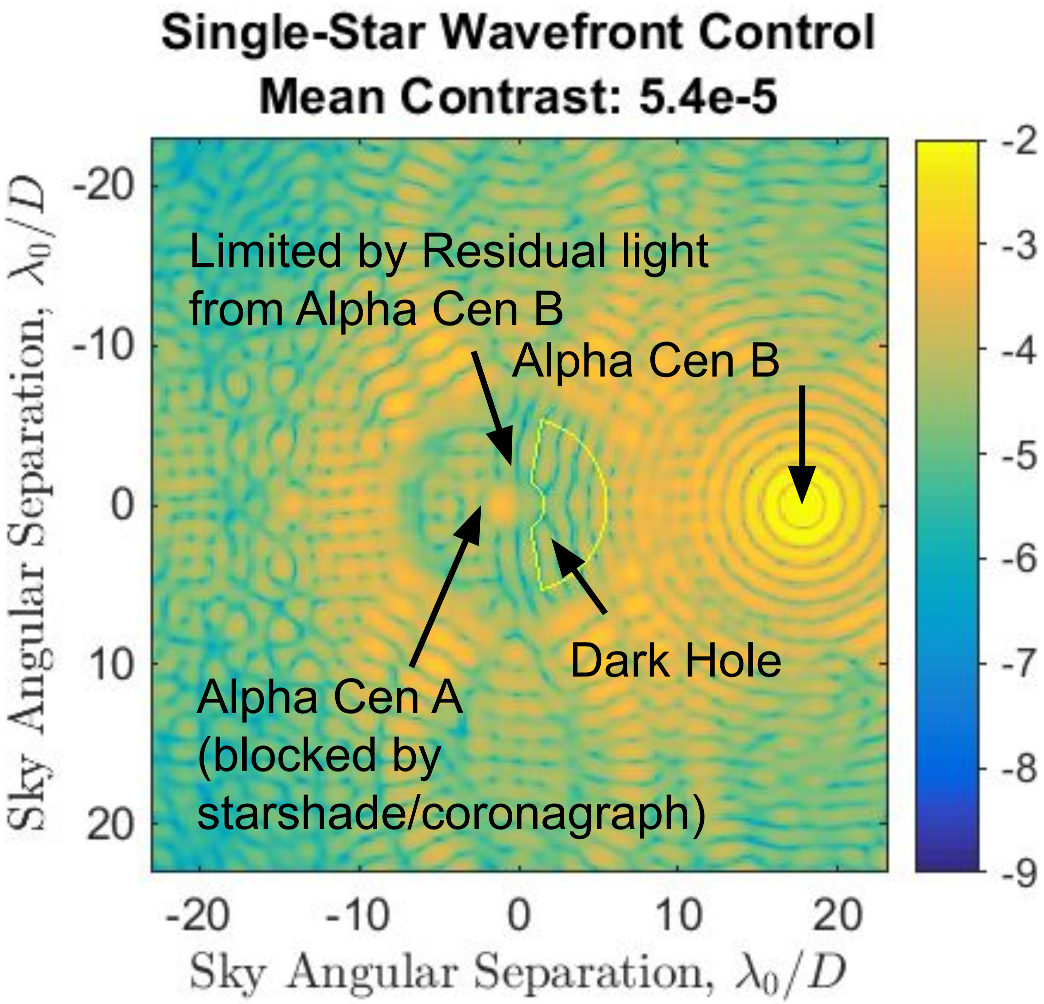
- Due to unusual proximity, breaks common-wisdom assumptions about what Roman can do:

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

(2) For a Roman Starshade Rendezvous, completeness is significantly improved and an Earth-like planet around Alpha Cen A or B would be within sensitivity limits

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

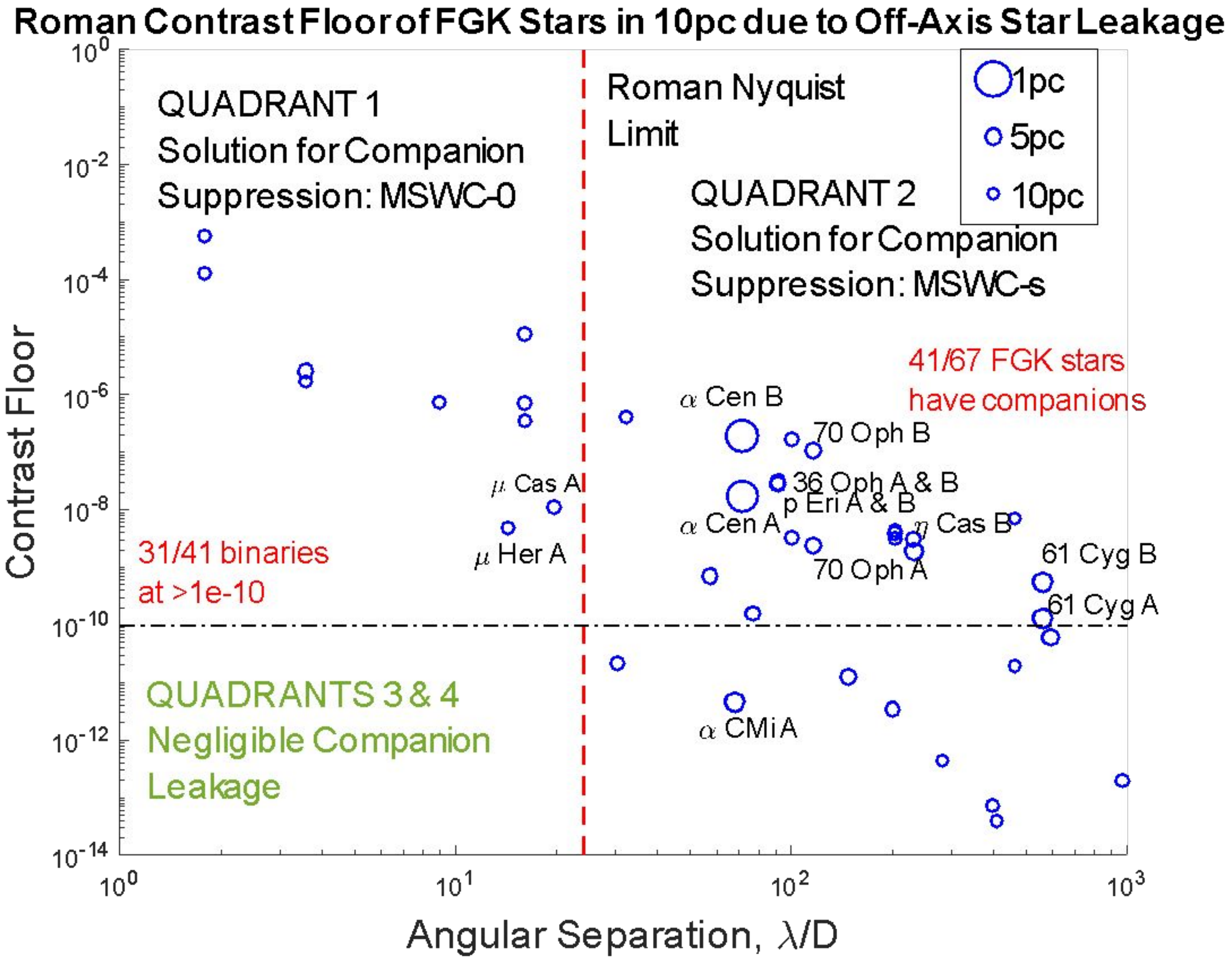
Direct Imaging Challenges with Binary Stars



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 *speckles*!

Light Leakage from Binary Companions (10 pc)



Roman PSD characteristics (provided by J. Krist)

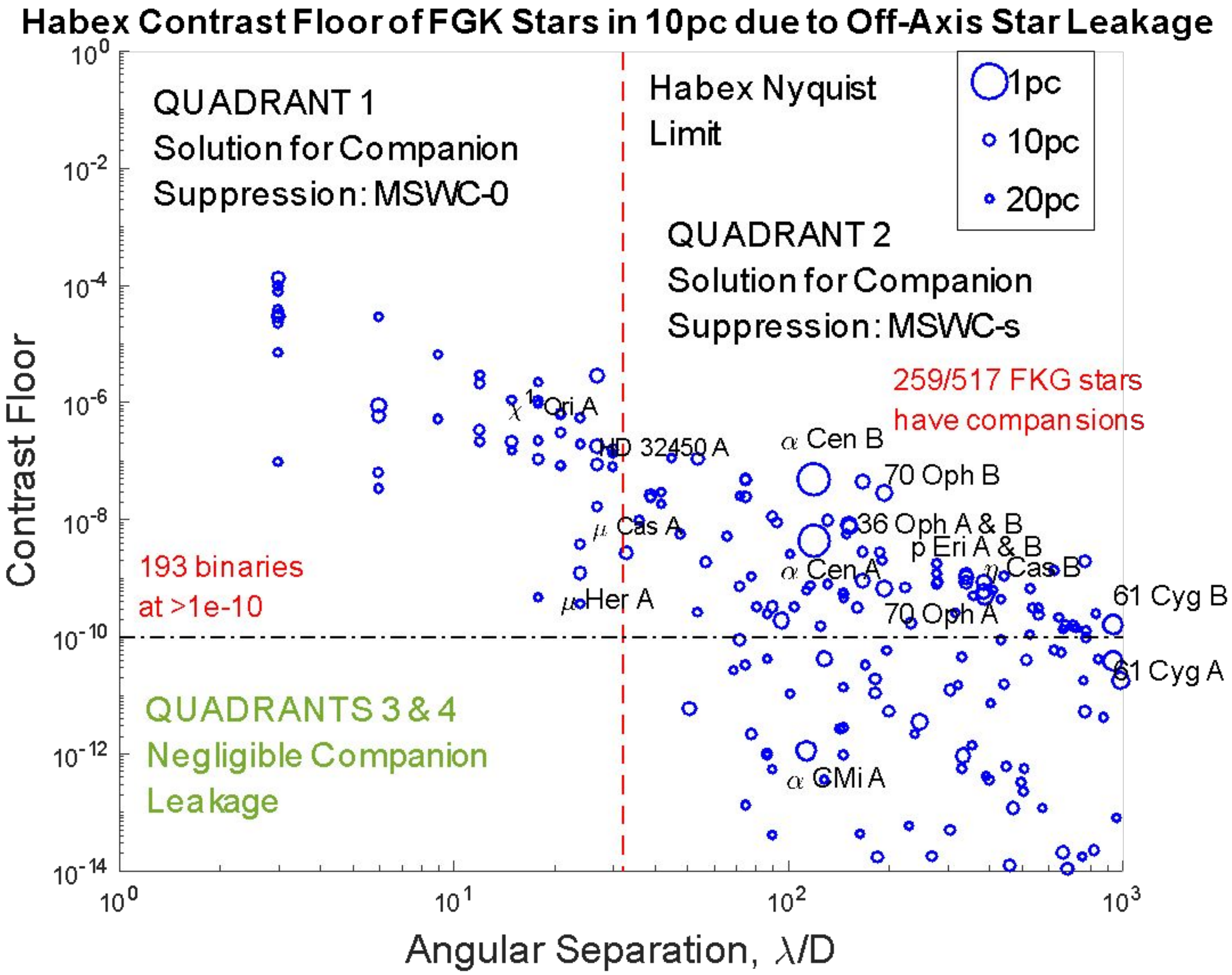
- D = 2.4m
- λ = 650nm
- 20 nm RMS with $f^{-2.5}$ power spectrum
- 48x48 DM

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

Required companion suppression:

- 31/41 have leakage > 1e-10

Light Leakage from Binary Companions (20 pc)



Habex PSD characteristics (provided by J. Krist)

- D = 4.0m
- λ = 650nm
- 20 nm RMS with $f^{-2.5}$ power spectrum
- 64x64 DM

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

Required companion suppression:

- 193/259 have leakage > 1e-10

Overview

1. Motivation for Binary Star Direct Imaging
2. *Direct Imaging of Binaries with Starshades*

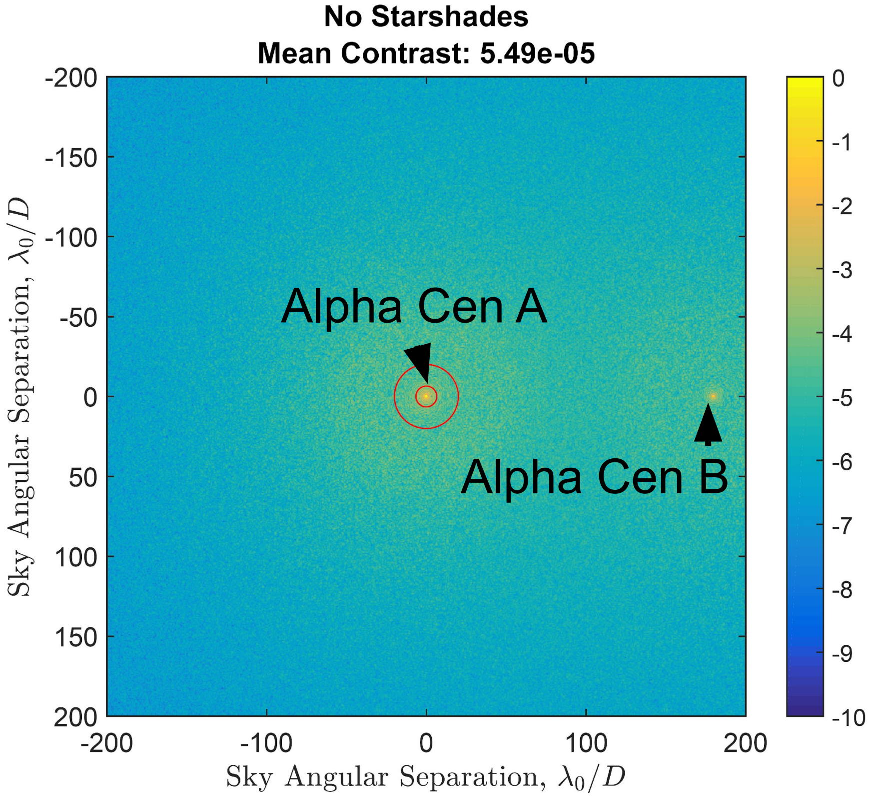
Hubble Image of Alpha Centauri A & B

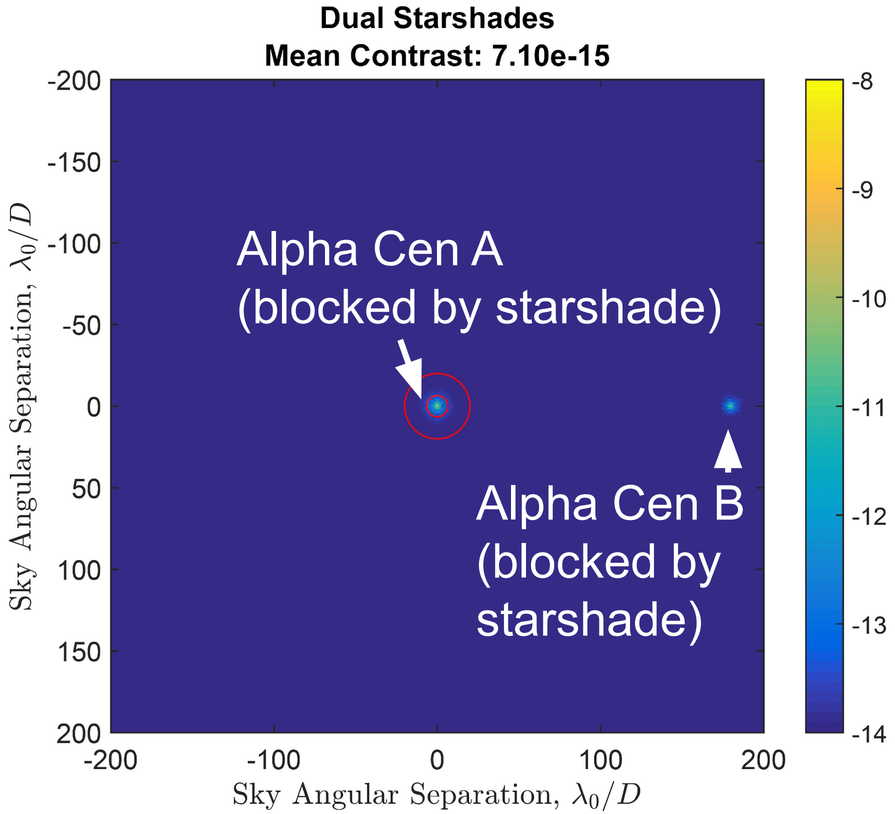
*Assuming DM = NxN actuators

	SCENARIO		WC SOLUTIONS		
	On-axis blocker	**Off-axis blocker**	**Star Separation at < N/2 λ/D***	**Star Separation at > N/2 λ/D***	**Notes**
	Coronagraph	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane
	Coronagraph	2nd Coronagraph	**MSWC-0**	**MSWC-s**	**An off-axis coronagraph would require an additional mask.** The off-axis coronagraph can be compatible with MSWC.
(1)	Starshade	2nd Starshade	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**
(2)	Coronagraph	Starshade	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
(3)	Starshade	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
	Starshade	Coronagraph	SSWC (i.e. standard WC)	**SNWC**	**An off-axis coronagraph would require an additional mask.** The off-axis coronagraph can be compatible with SNWC.

SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0^{th} order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

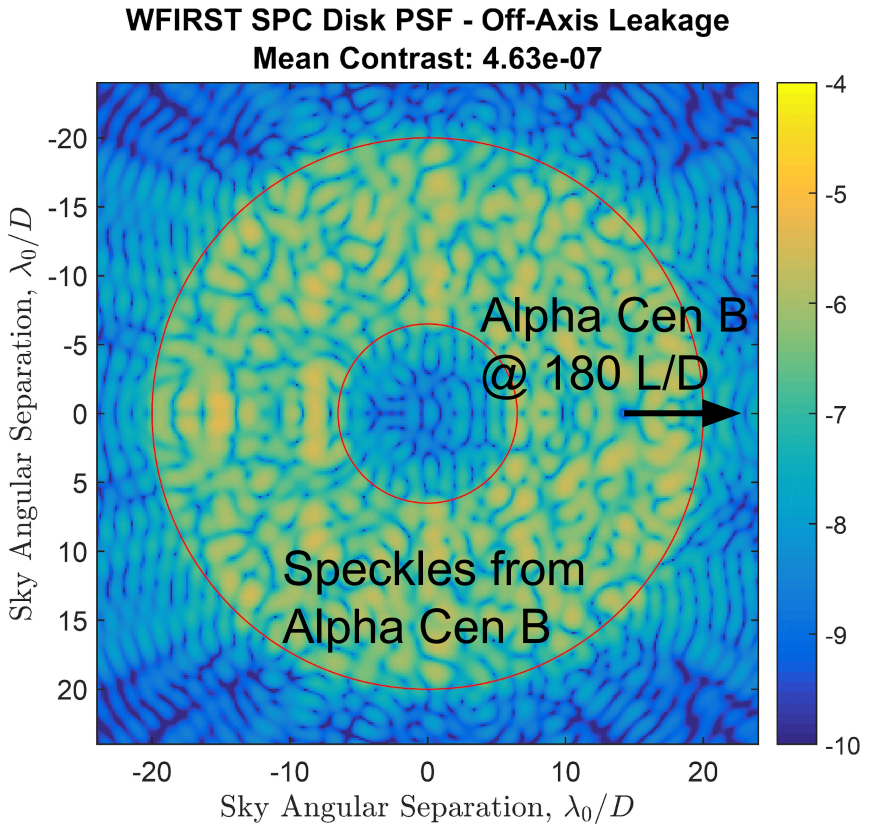
(1) Dual Roman Starshades

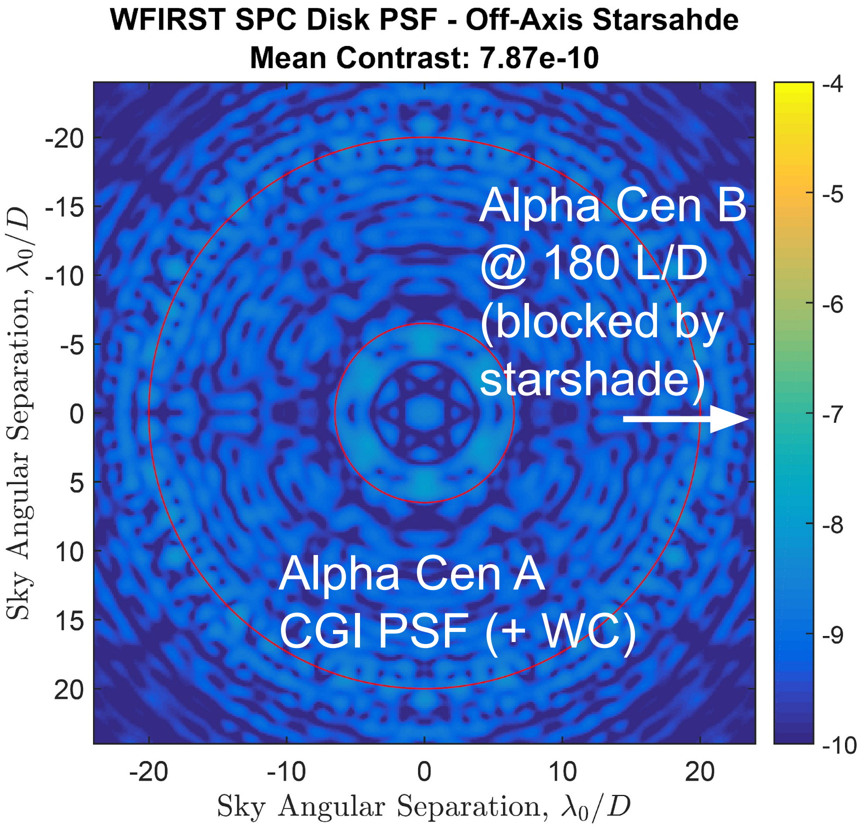




An on-axis and off-axis starshade can effectively suppress both stars operating in wide bandwidths. Requires operation of two starshades simultaneously.

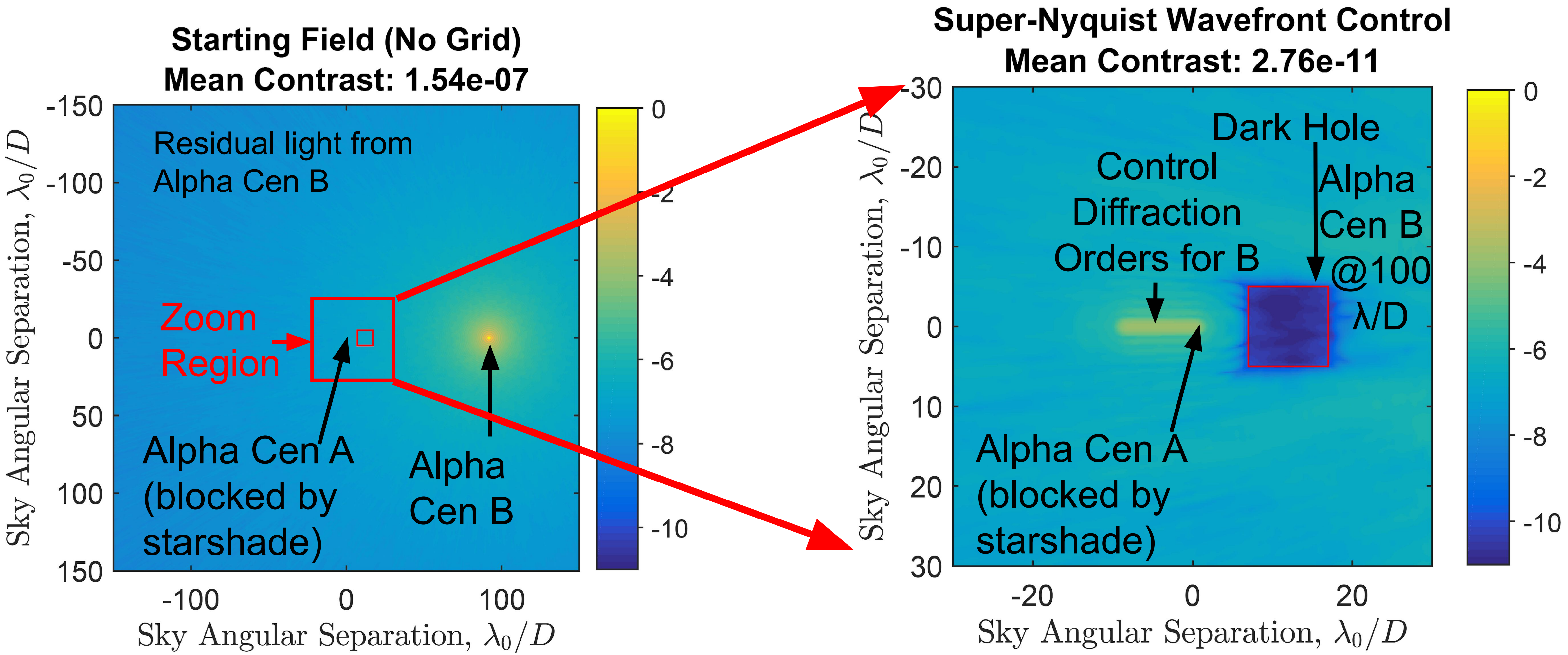
(2) Off-Axis WFIRST Starshade with On-Axis CGI





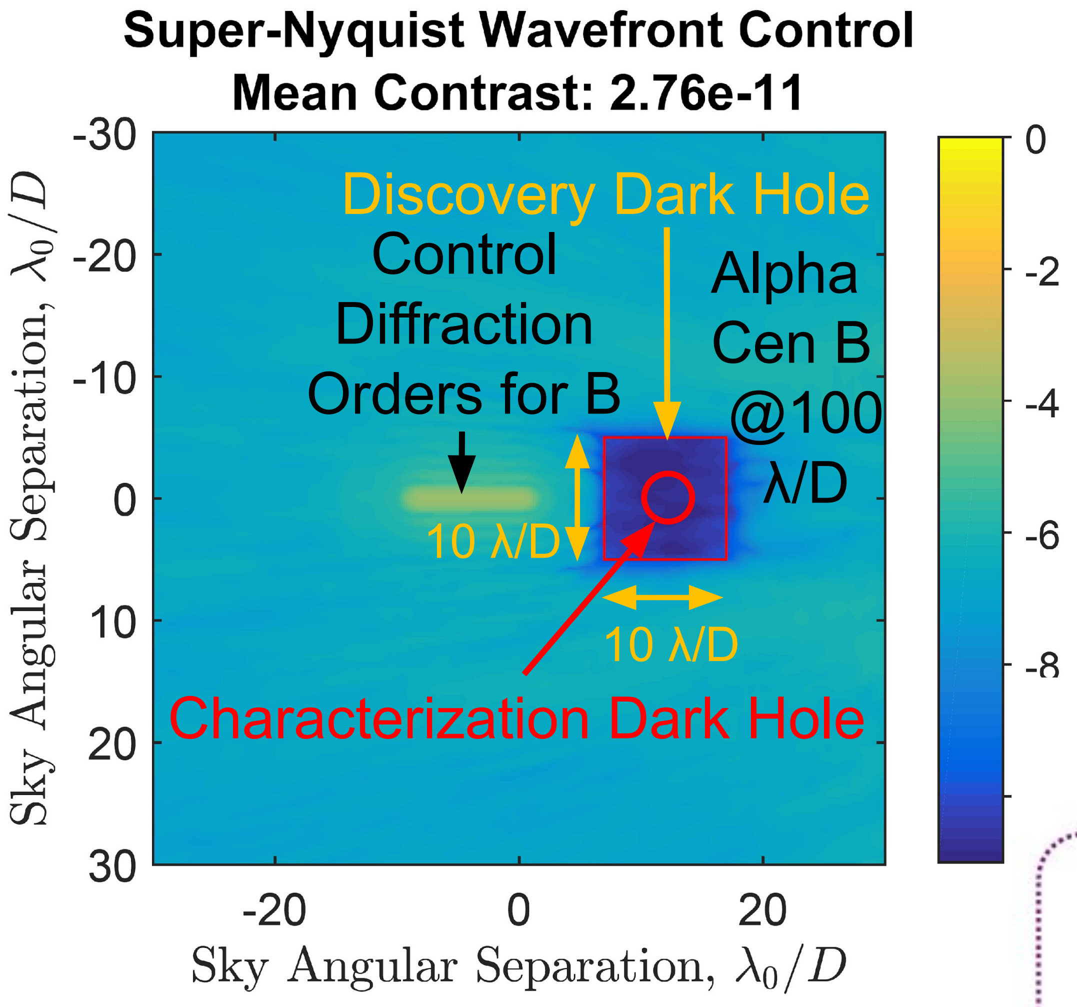
An off-axis starshade removes leakage from Alpha Cen B turning the binary star problem into a single-star problem that can be controlled using the CGI. Performance set by CGI PSF + WC.

(3) SNWC with Roman Starshade



An on-axis starshade blocks Alpha Cen A achieving deep contrast and wide bandwidths, while off-axis speckles from Alpha Cen B are blocked using SNWC.

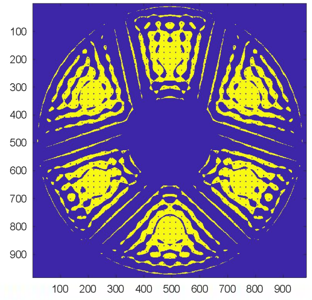
(3) SNWC with Roman Starshade



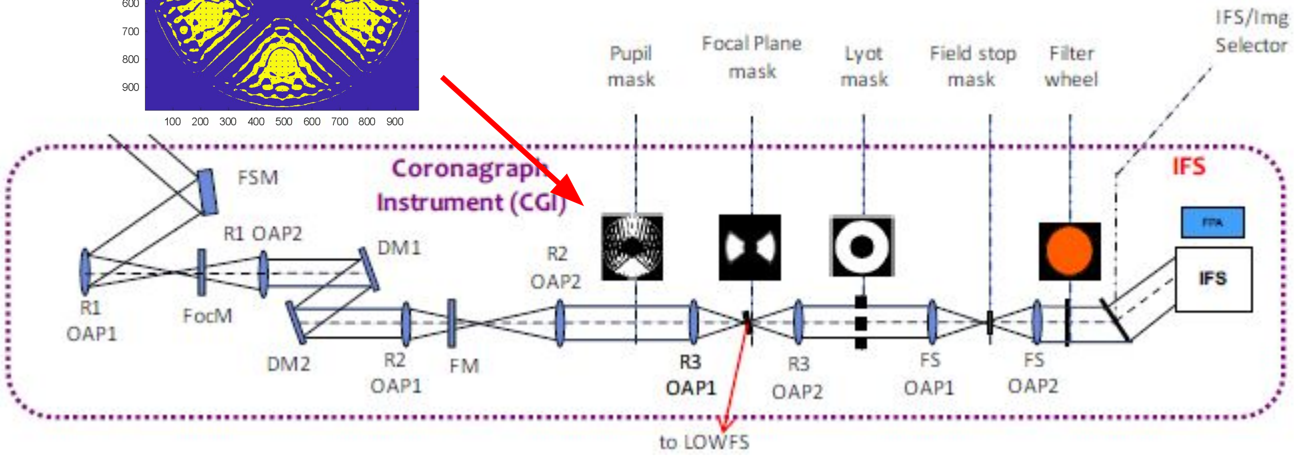
Observation Strategy:

(a) Create a larger 10 λ/D x 10 λ/D discovery region with 10% bandwidth

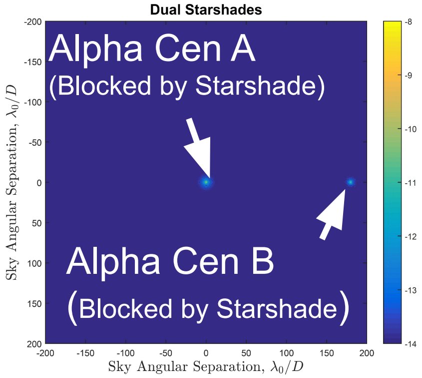
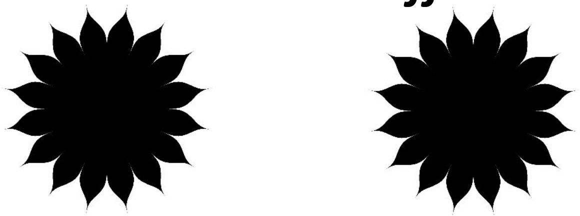
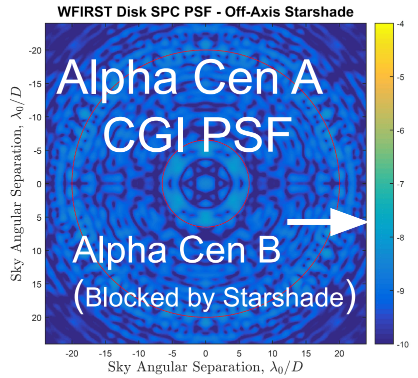
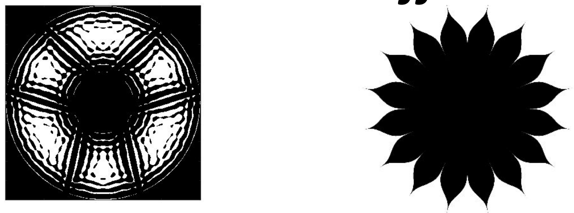
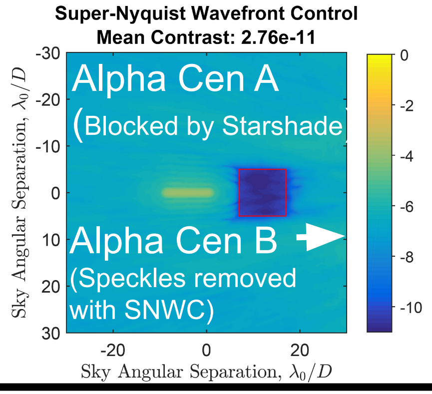
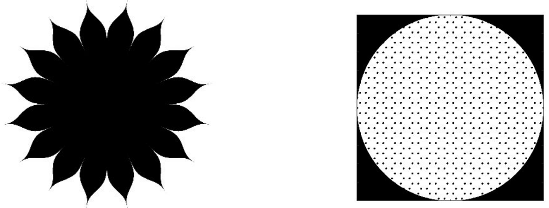
(b) Create a smaller 2 λ/D x 2 λ/D characterization region with 20% bandwidth



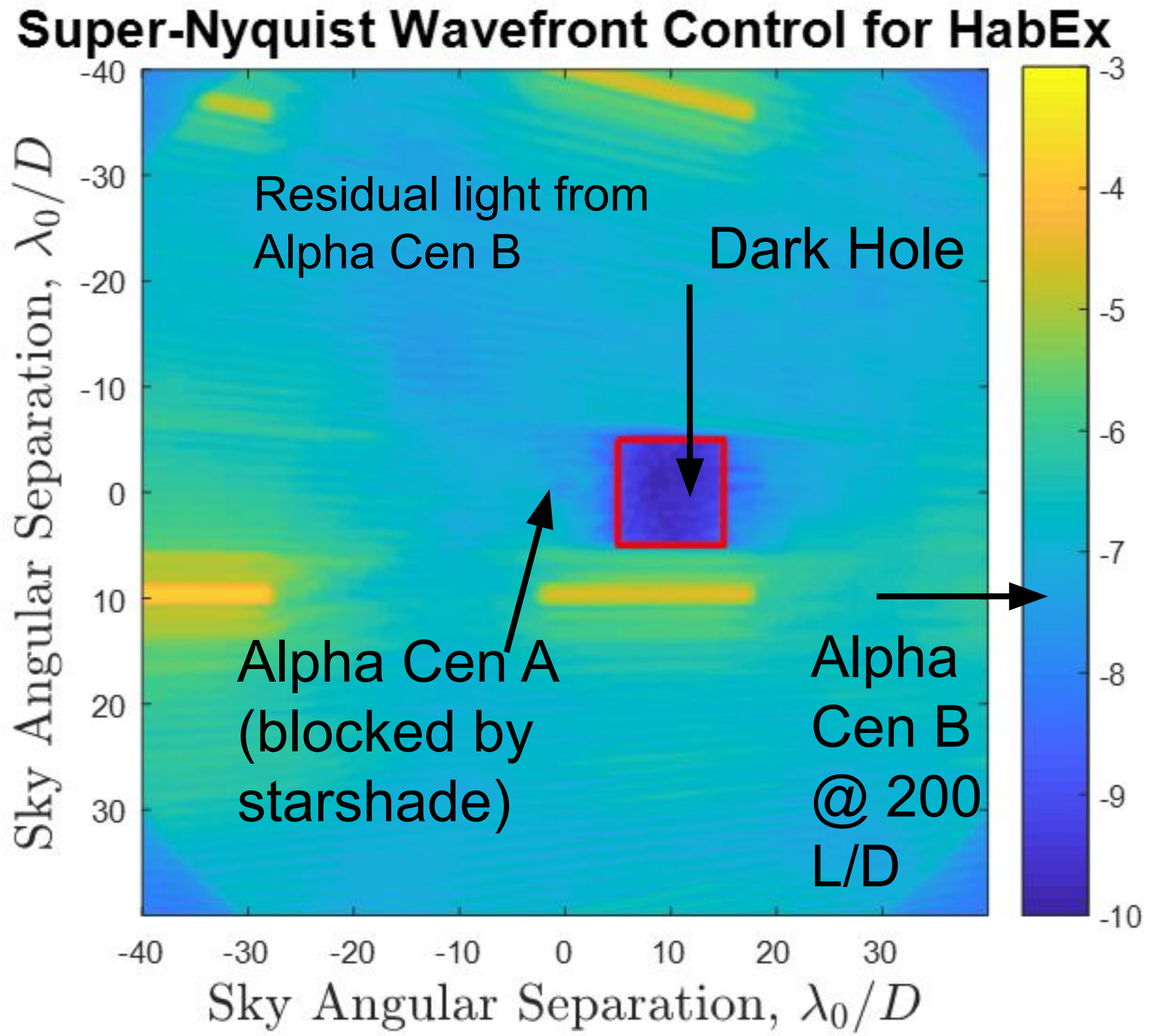
Diffraction Pupil (Bendek 2016, Riggs 2020)



Roman Starshade Multi-Star Imaging Scenarios

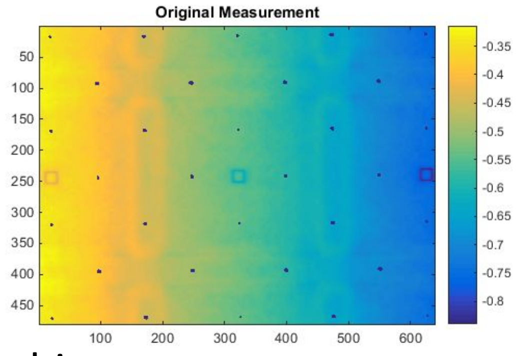
	***(1) Dual Starshade Option*** ***On-Axis*** ***Off-Axis*** 	**Pros:** - Wide characterization bandwidth - Relaxed tolerance for off-axis starshade	**Cons:** - **Two starshades required** - Cannot slew while observing binaries
	***(2) CGI + Starshade Option*** ***On-Axis*** ***Off-Axis*** 	**Pros:** - Uses existing CGI and WFC system - Relaxed tolerance for off-axis starshade	**Cons:** - On-axis **CGI contrast floor at 10^{-9}**
	***(3) Starshade + SNWC Option*** ***On-Axis*** ***Off-Axis*** 	**Pros:** - **Achieves 10^{-10} contrast** - Uses existing WFC system	**Cons:** - May require open slot in SPC wheel for diffraction grating to enable wide binaries

SNWC with Habex Starshade



Simulation parameter summary:

- 10% bandwidth about 650 nm
- 2-DMs [64x64]
- Boston MEMS Quilting
- On-axis star behind focal plane mask
- Off-axis star located 200 λ/D
- Initial contrast: 3e-8
- Final contrast: 1.2e-10



Data Source:
Boston Micromachines

Conclusions

Methods:

- Starshades can be used as the on-axis or off-axis blocker for multi-star imaging:
  (1) Dual starshade option for both on-axis and off-axis stars
  (2) Off-axis starshade with CGI on-axis
  (3) On-axis starshade with SNWC for off-axis leakage control is possibly the most promising option (can reach 10^{-10} contrast and uses existing WFC)
- Demonstrated 1e-10 in simulation for both Roman and Habex starshade scenarios
- **Discussion question: can we maintain compatibility of hybrid operation between starshade imaging mode with coronagraph's WFC to enable binary star imaging?**

Science:

- Starshade + SNWC would enable imaging & characterization of Earth-like planets with Roman
- Multi-star imaging improves quality & quantity of target stars:
  - Alpha Centauri A & B have ~3x better SNR or spatial/spectral resolution
  - Other notable nearby target stars: 61 Cyg A&B, Eta Cass A&B, Mu Her A, Mu Cass A