High Performance Coronagraphy for Large Segmented Apertures

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Outline

Scientific motivation

Theory: Can coronagraphs work on segmented apertures ?

The WFIRST success story

Coronagraph concepts for segmented apertures

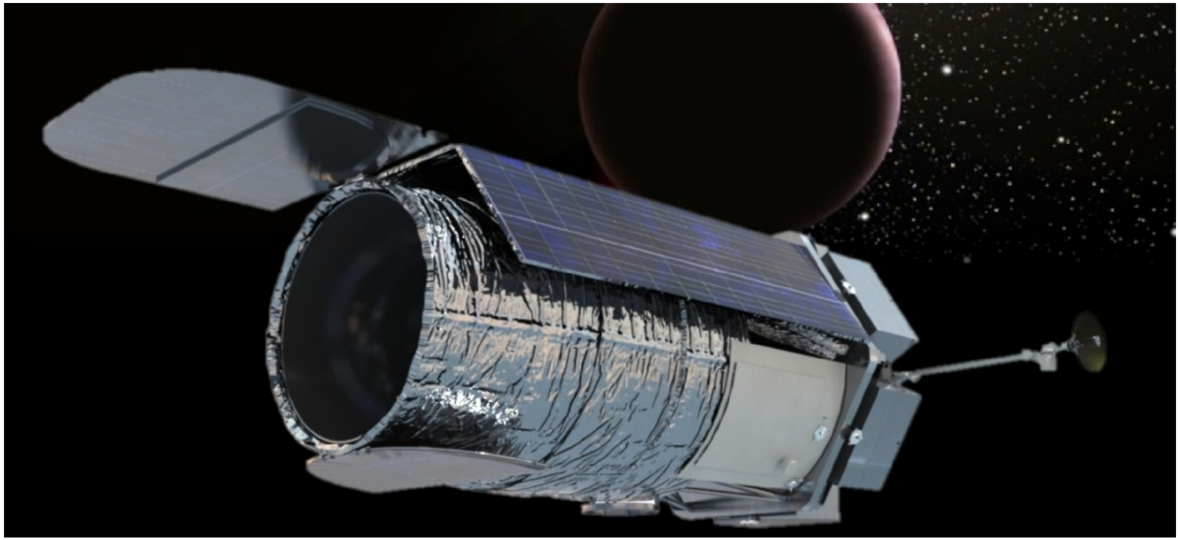
PIAACMC

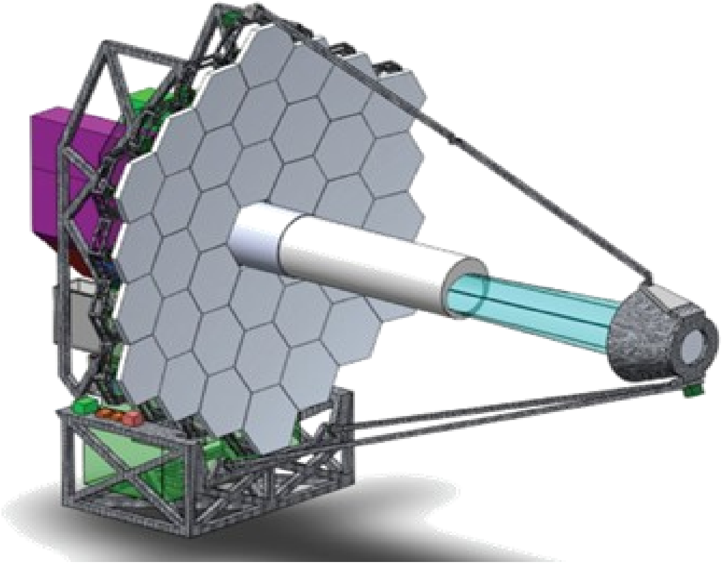
Wavefront control

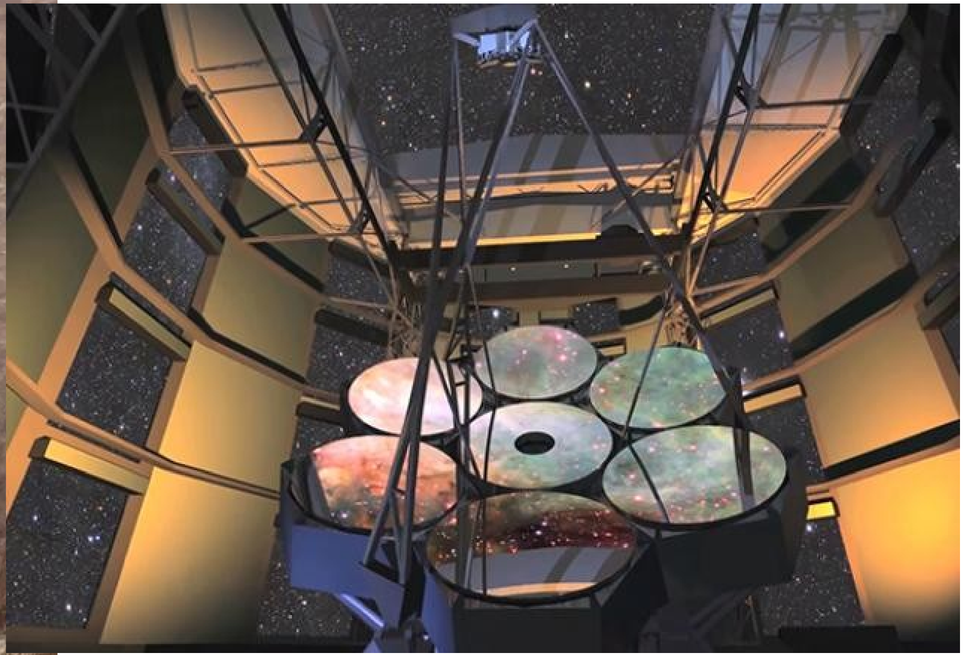
Large ground-based segmented apertures

Space/Ground complementarity

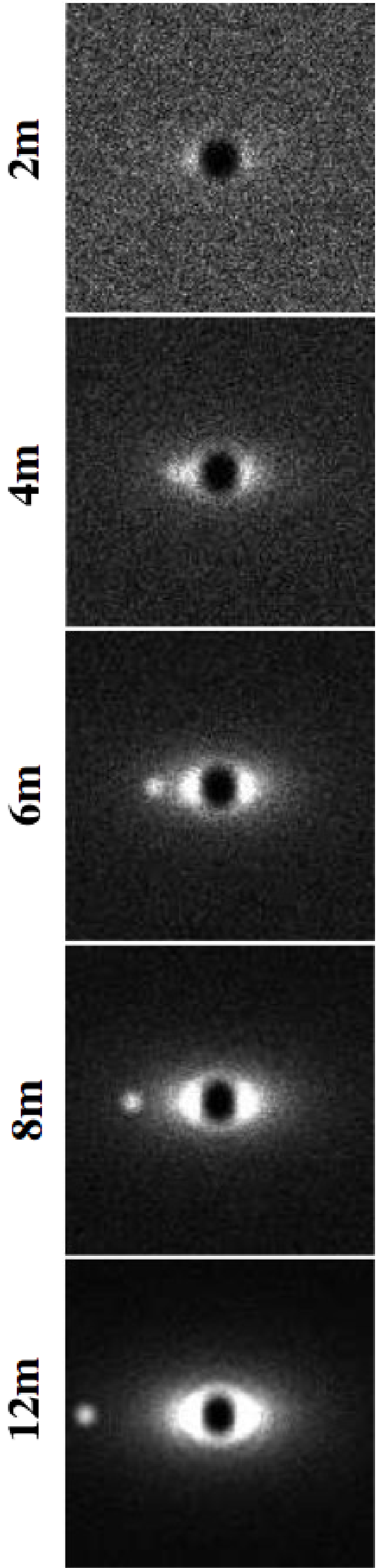
Scientific Motivation: Large apertures will be segmented







Why big apertures ?



Exoplanet imaging mission science return increases very quickly with aperture

Efficiency & Yield

- Number of IWA-accessible planets goes as D^3
- Exposure time required to reach given SNR goes as D^{-4} for most low-mass planets (zodi+exozodi → background-limited detection)

Characterization

- Access to longer wavelength spectroscopy, $\lambda_{max} \sim D$
- Light can be sliced in multiple bins: spectral resolution, time domain, polarization
- Better astrometry → better orbits, dynamical masses
- Resolving (time-variable) structures in exozodi

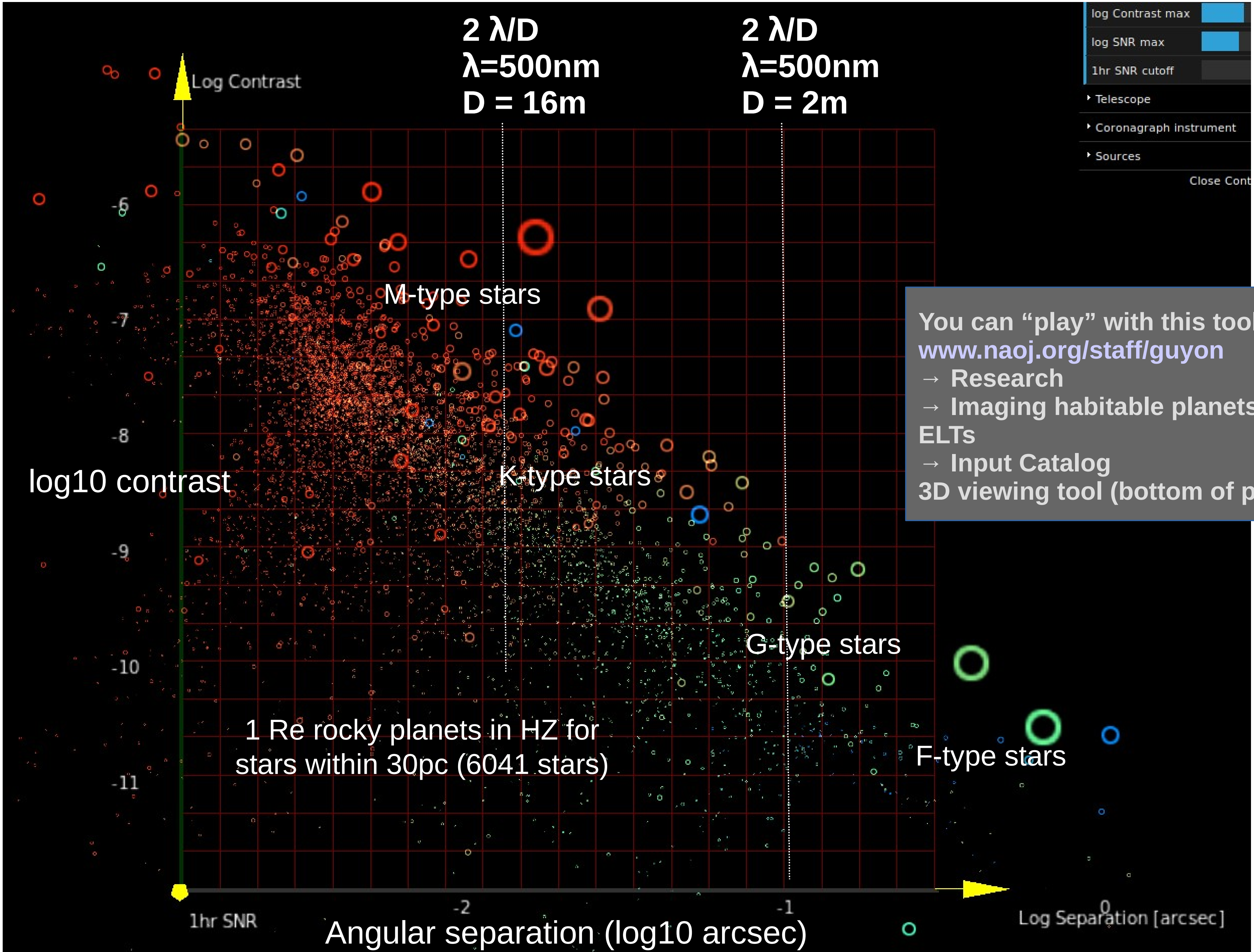
Data quality

- Higher angular resolution → less confusion between multiple planets, exozodi clumps
- More light → better PSF calibration

Diversity

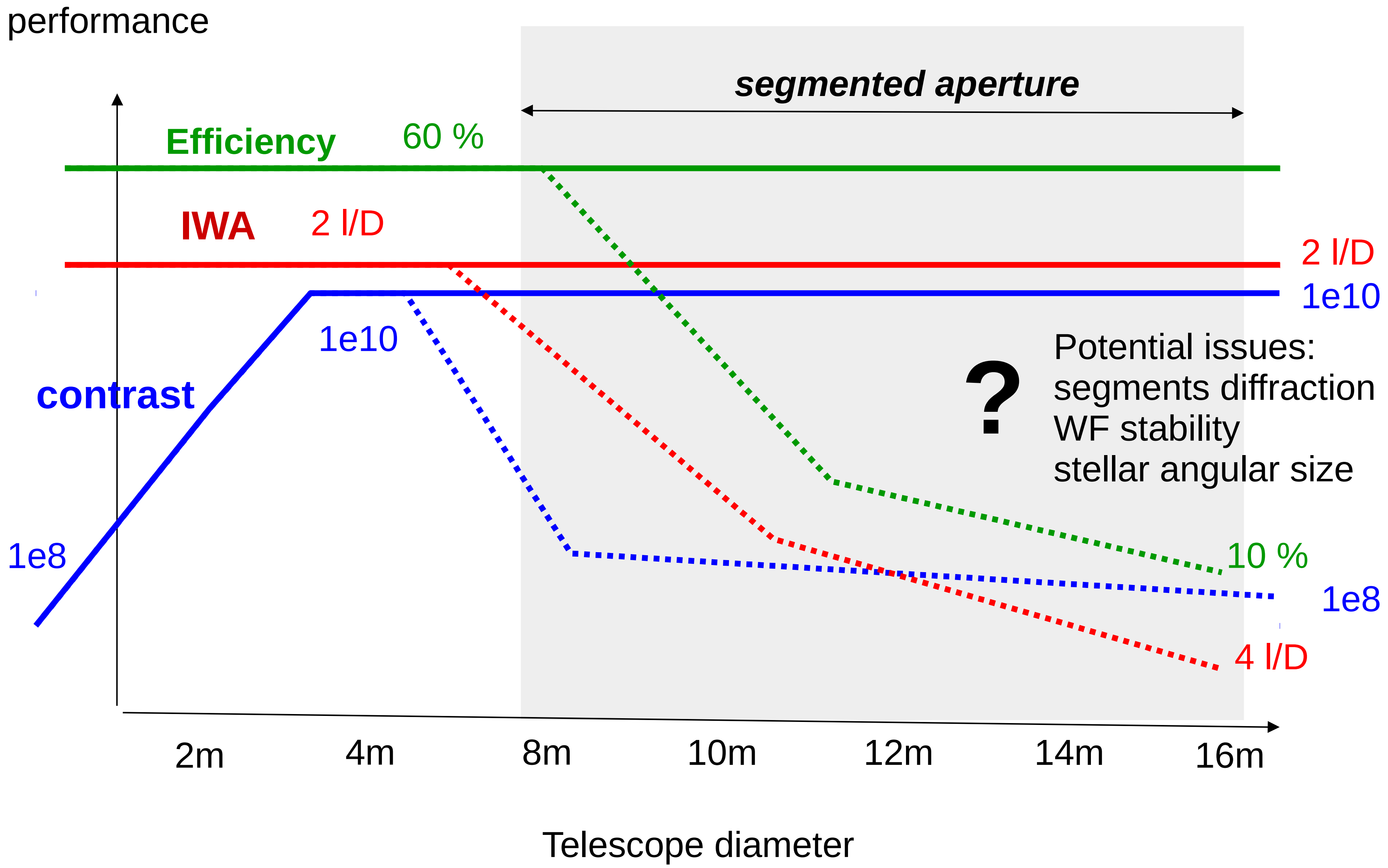
- Larger aperture allows habitable planets to be observed around a wider range of stellar types

Large aperture + high contrast → habitable planets can be imaged around a wide range of spectral types



You can "play" with this tool:
www.naoj.org/staff/guyon
→ Research
→ Imaging habitable planets with ELTs
→ Input Catalog
3D viewing tool (bottom of page)

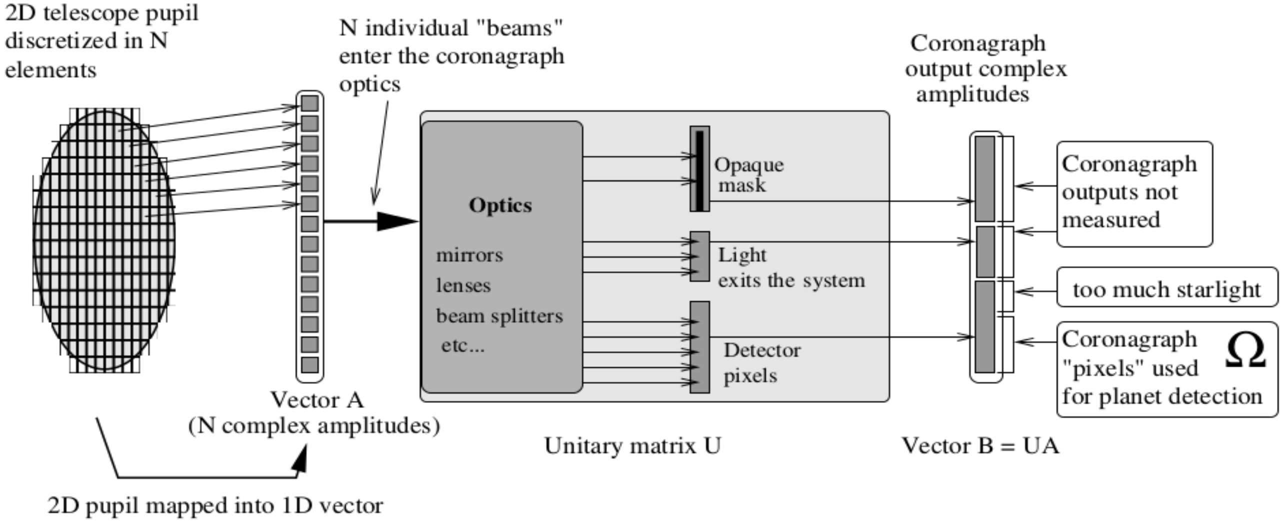
Science vs. aperture: how does performance scale with aperture ?



Potential issues:
segments diffraction
WF stability
stellar angular size

What does coronagraph theory tell us about segmented apertures ?

Coronagraphy limits derived from complex amplitude linearity



“Theoretical Limits of Extrasolar Terrestrial Planet Detection with Coronagraphs” Guyon et al. 2006

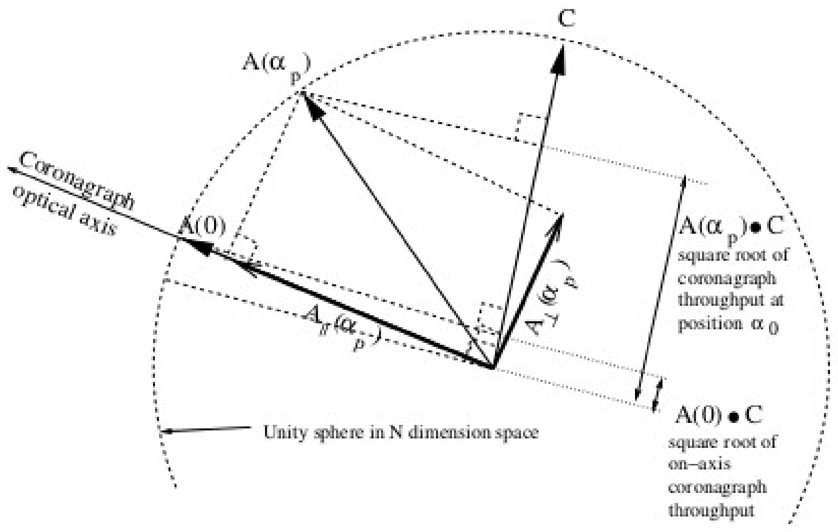
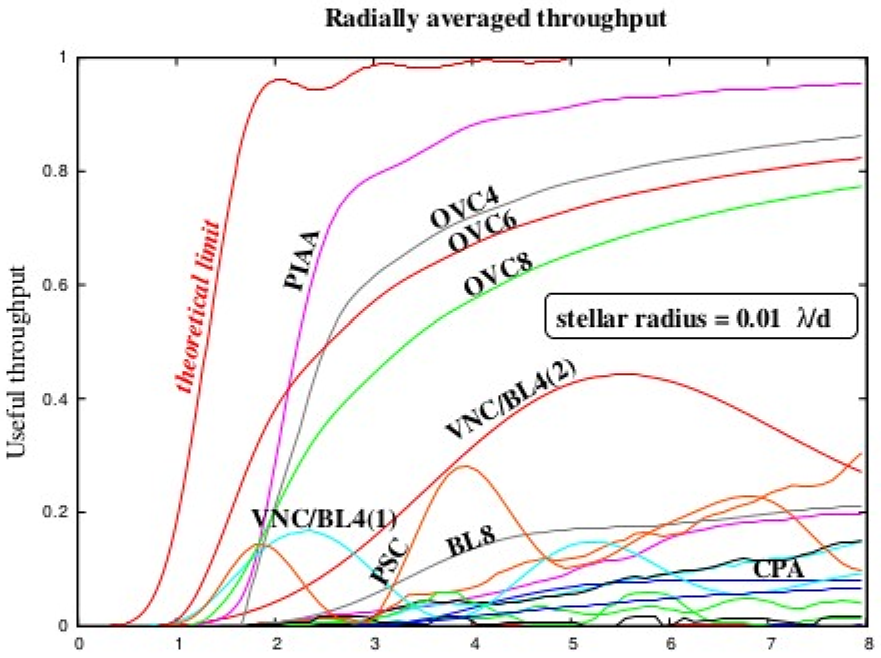


Fig. 5.— Graphical representation of the coronagraph optimization problem.



Important findings:
Contrast/IWA/throughput limit

FULL suppression of coherence point source possible, with 100% throughput coronagraph and IWA ~ 0.5 l/D

Theoretical throughput curve = (1-Airy)^2
→ **Not a strong link between segmented and full aperture**

Strong fundamental limit imposed by stellar angular size

point source: IWA ~ 0.5 l/D
0.1 l/D disk → IWA ~ 2 l/D

Sun-like star at 10pc, as seen in visible light by 10m telescope

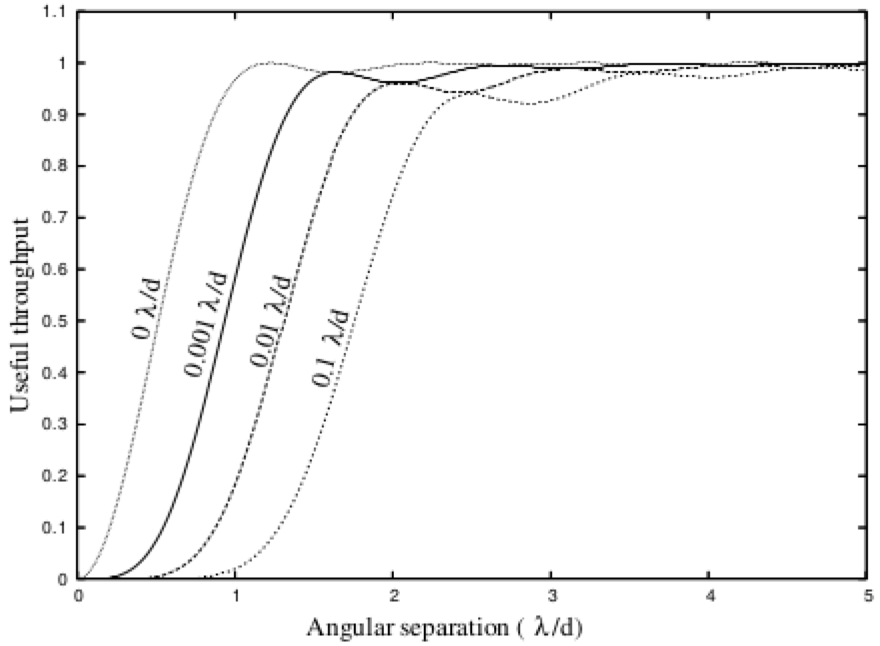


Fig. 9.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

Important findings: The ideal coronagraph could conceptually be built with discrete optics

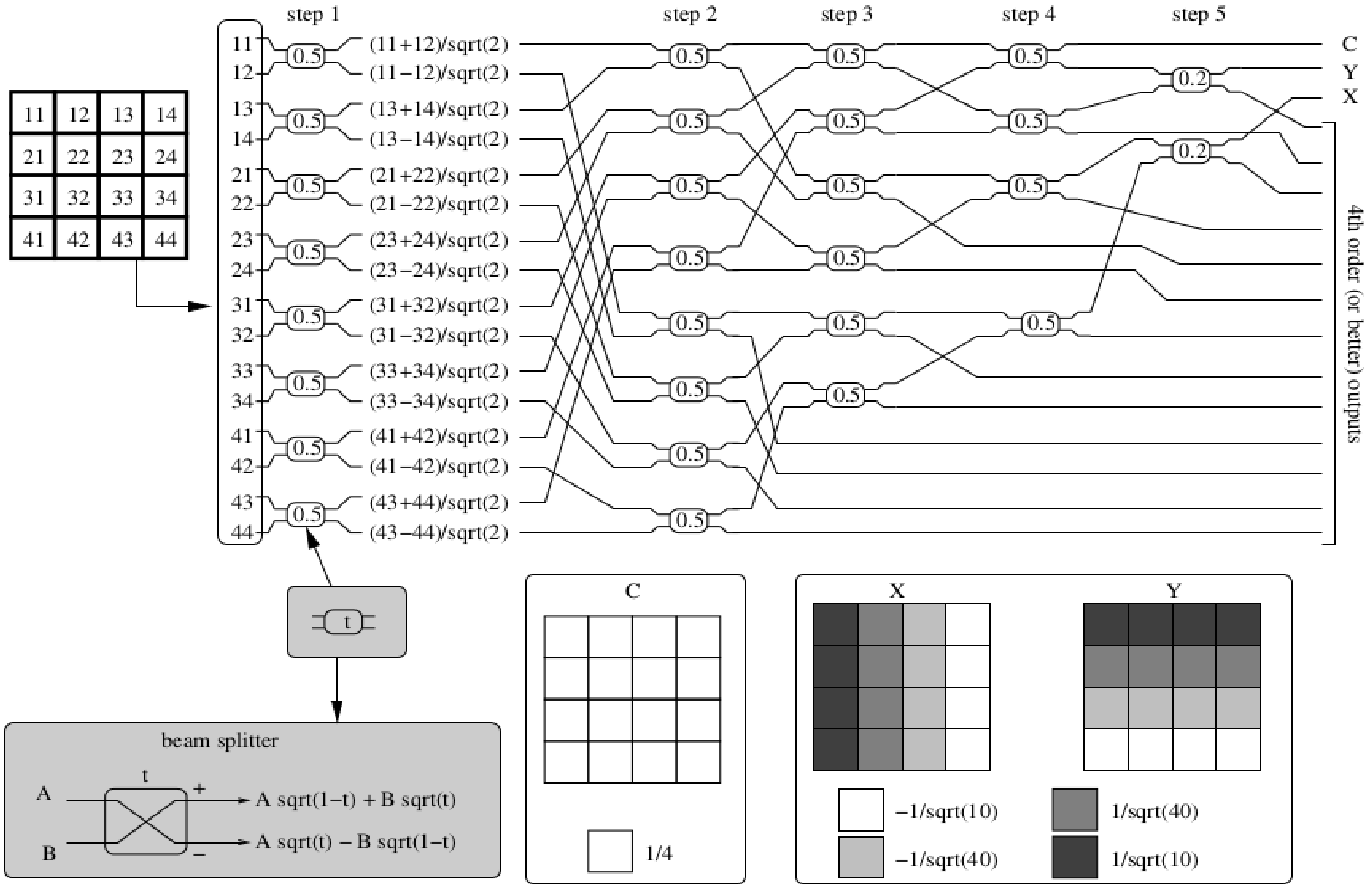


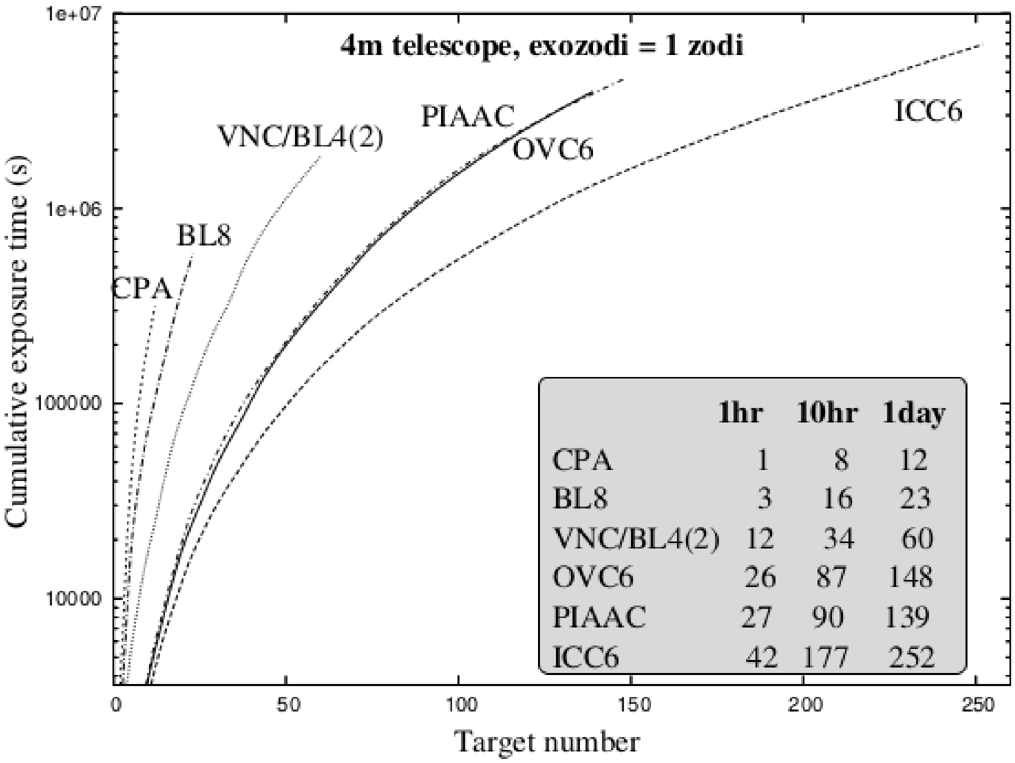
Fig. 10.— Example of a beam splitter-based coronagraphs with $c_0 = c_1 = c_2 = 0$ (perfect rejection of the first 3 vectors M_i) designed for a square aperture. The telescope pupil (top left) is decomposed in a series of individual subpupils (shown in the input vector on the right of the pupil) which undergo interferometric combinations through beam splitters. The coronagraph outputs isolates the first 3 modes found in an extended source, as shown in the bottom right: C ($= M_0$), X ($= M_1$) and Y ($= M_2$). This coronagraph produces a 4^{th} order null and therefore provides some immunity to stellar angular size. The same technique can be generalized to circular pupil and better sensitivity to stellar angular size (more vectors M_i isolated).

Important findings: Science yield would be AMAZING !

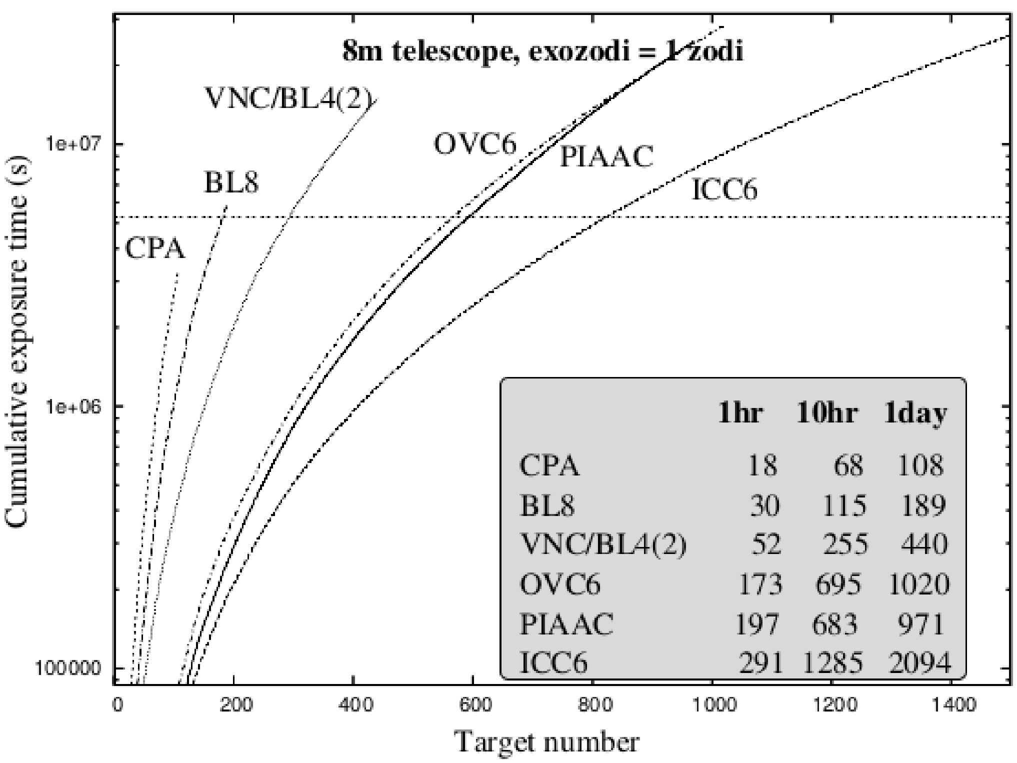
8m telescope

Detection:
~1000 stars could be surveyed for habitable planets in 4 month of open shutter time

Characterization:
High SNR spectroscopy, access to near-IR



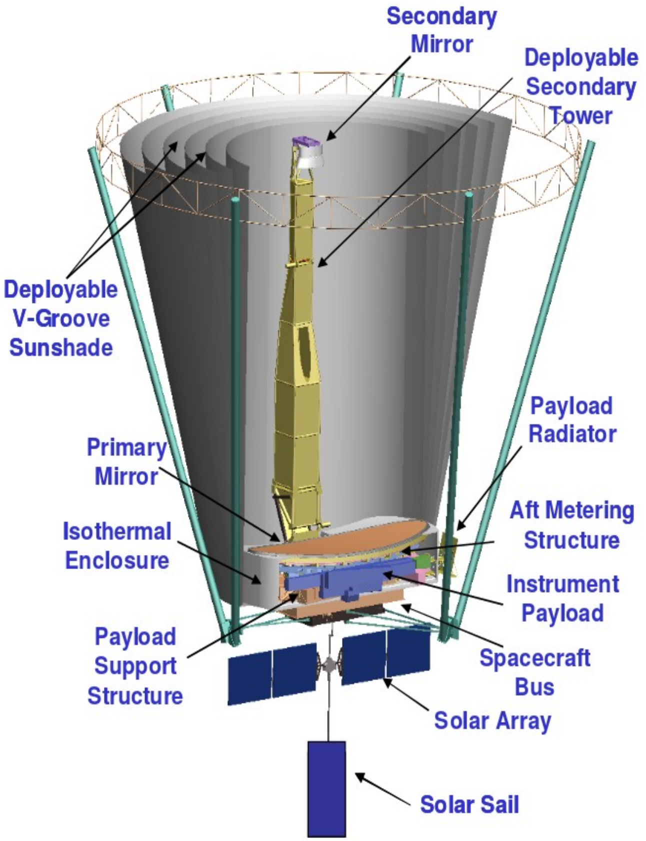
	1hr	10hr	1day
CPA	1	8	12
BL8	3	16	23
VNC/BL4(2)	12	34	60
OVC6	26	87	148
PIAAC	27	90	139
ICC6	42	177	252



	1hr	10hr	1day
CPA	18	68	108
BL8	30	115	189
VNC/BL4(2)	52	255	440
OVC6	173	695	1020
PIAAC	197	683	971
ICC6	291	1285	2094

The WFIRST success story

History of coronagraphs on “unfriendly” apertures

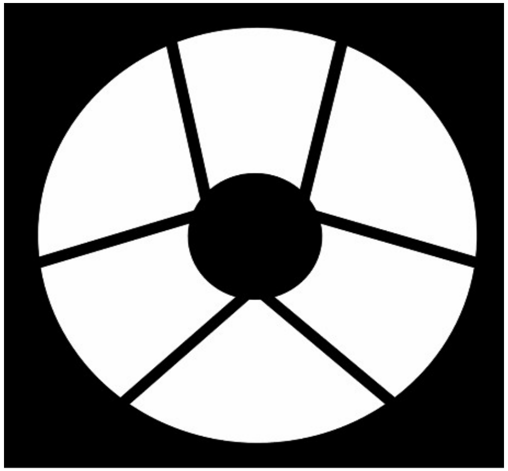


The dark ages (~ 2000 → 2012)
“Directly imaging habitable planets REQUIRES a monolithic unobstructed telescope”
→ TPF-C and smaller mission concept studies use off-axis telescopes
A few ideas for use of centrally obscured apertures emerge, but receive little attention

2012, The AFTA challenge: Designing a coronagraph for a centrally obscured aperture becomes a survival issue
→ within a very short time, 3 credible options emerge (SPC, HLC, PIAACMC)

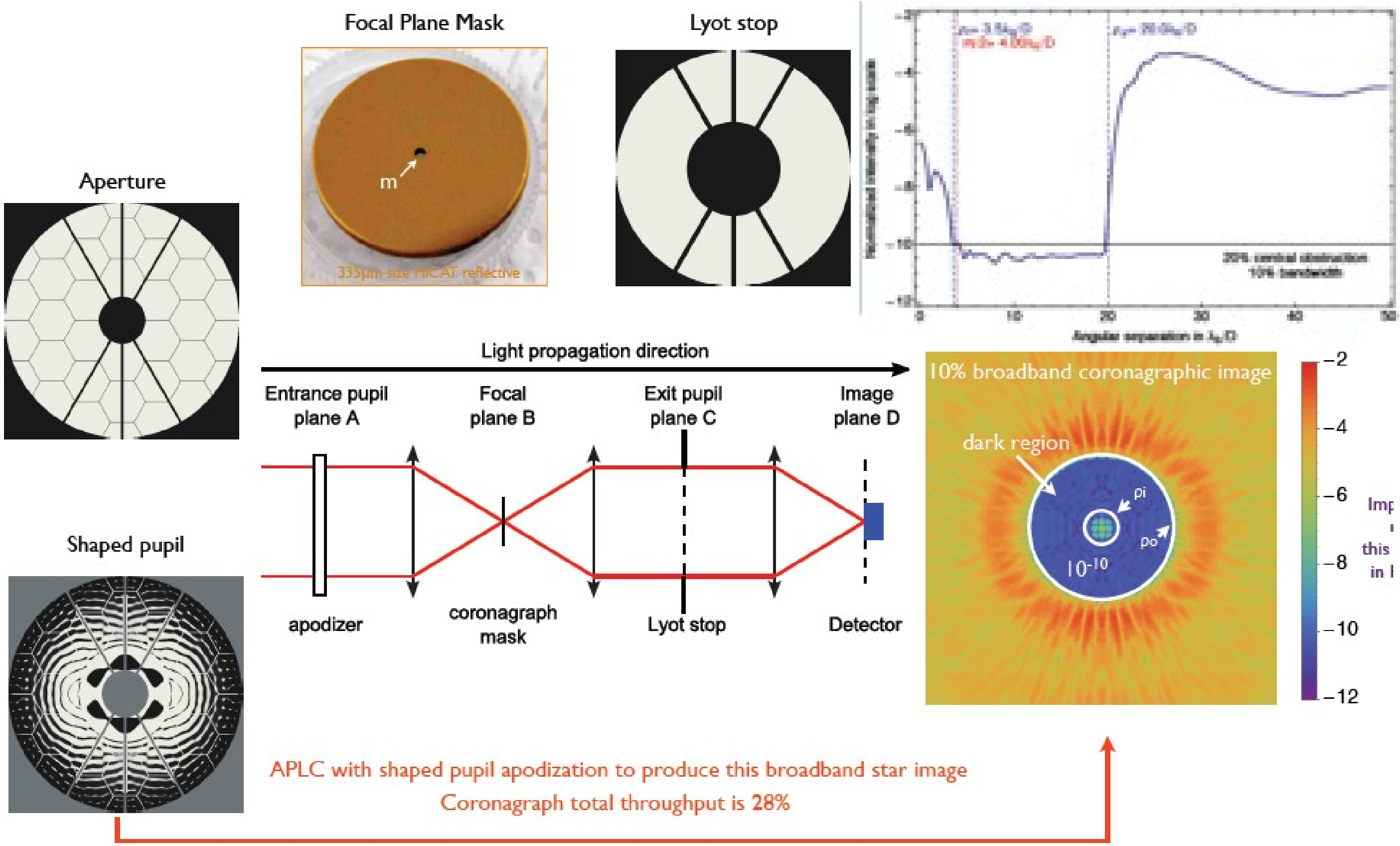
BUT, it appears that adapting coronagraphs to centrally obscured aperture comes at a high performance cost:
- SPC further looses throughput due to spiders and central obscuration
- HLC requires large DM stroke and undersized Lyot stop to cancel light diffracted by spiders → efficiency loss

→ risk of poor performance on segmented apertures ?

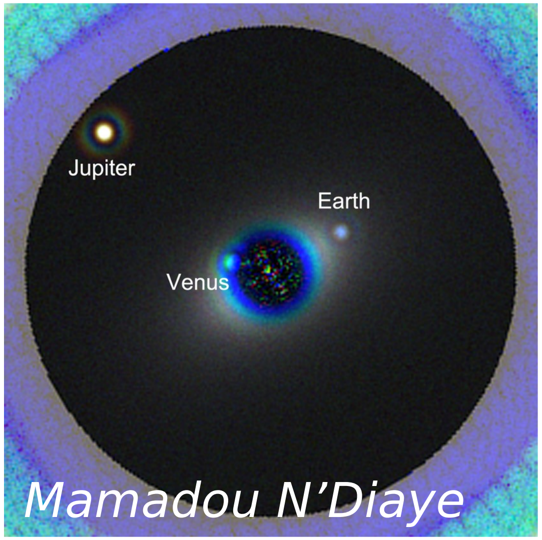


Coronagraph concepts for segmented apertures

Apodized Pupil Lyot Coronagraph (APLC) is compatible with segmented apertures



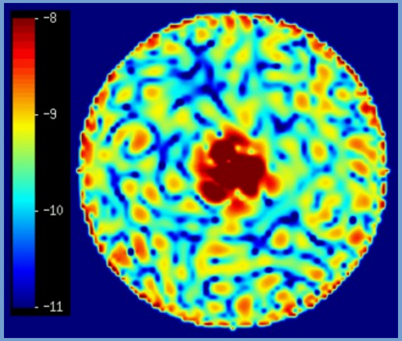
APLC with shaped pupil apodization to produce this broadband star image
Coronagraph total throughput is 28%



Simulated visible light image of a solar system twin at 13 pc

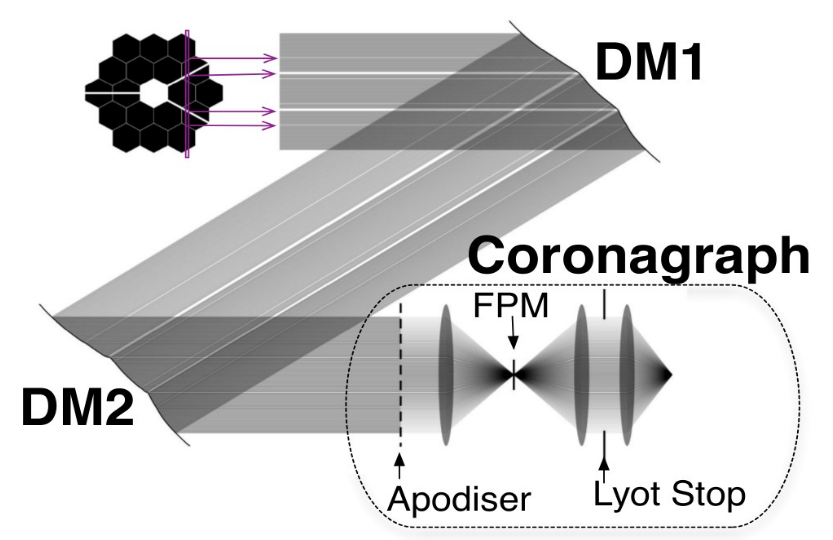
Combines pupil binary apodization and opaque focal plane mask
IWA = 3.6 l/D, contrast ~1e-10 in broadband
28% throughput is similar to WFIRST-AFTA

Wavefront control mitigates diffracted light by segments



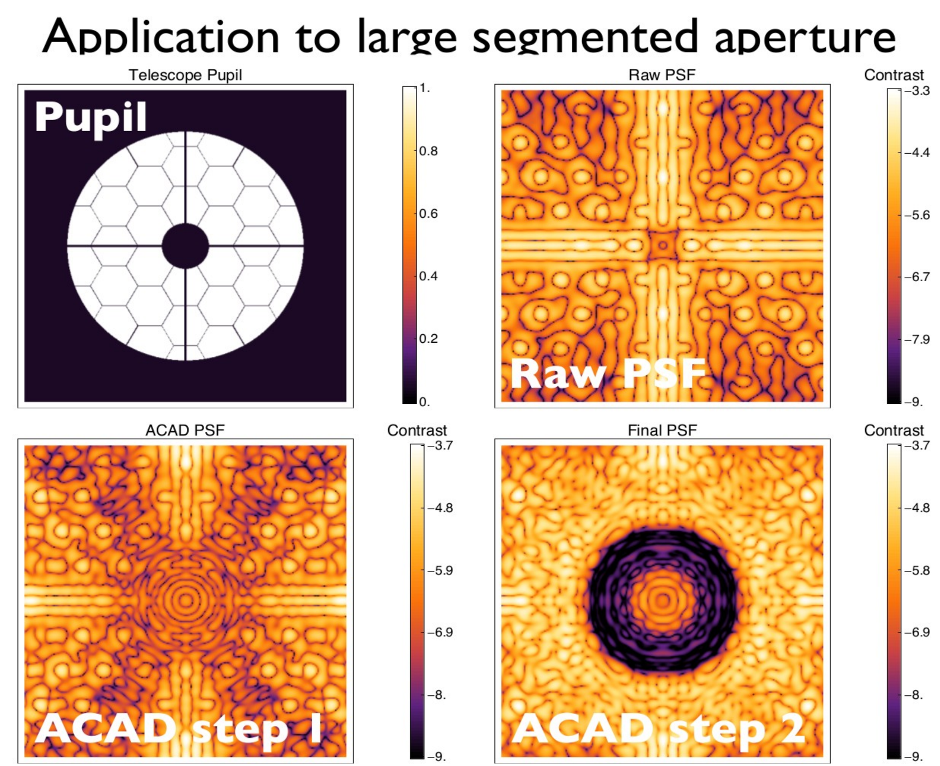
WFIRST-AFTA HLC simulated image (J. Krist, JPL)

HLC uses two deformable mirrors to cancel diffraction by WFIRST telescope spiders by several orders of magnitude



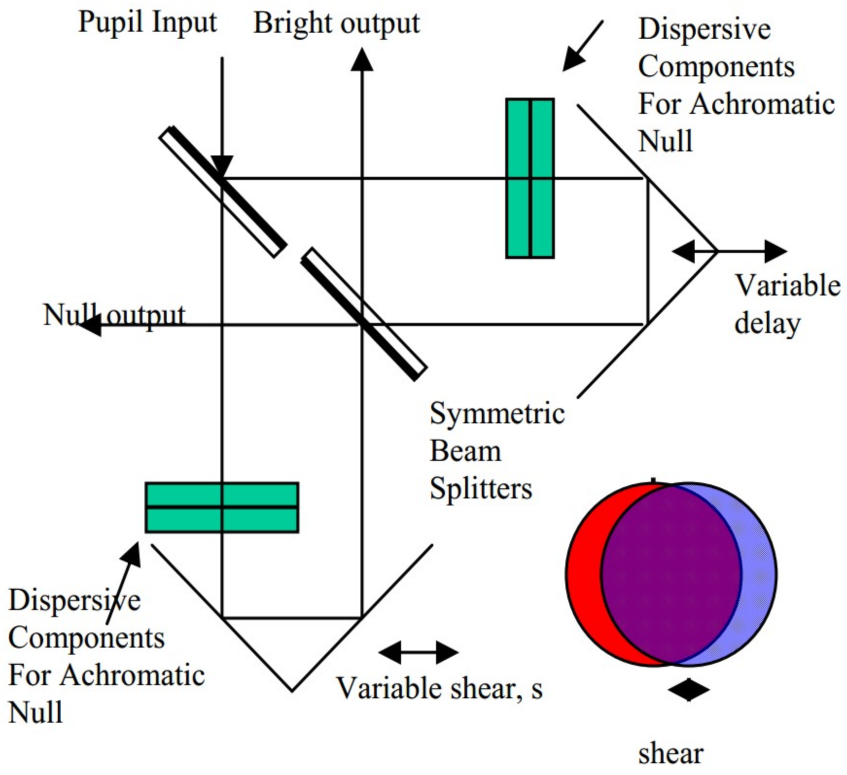
ACAD generalizes this approach to segmented apertures
Several orders of magnitude gain in contrast

Pueyo & Norman 2013


Application to large segmented aperture

Limitations: DM stroke, some efficiency loss, limited wavelength coverage (10-20% ?)

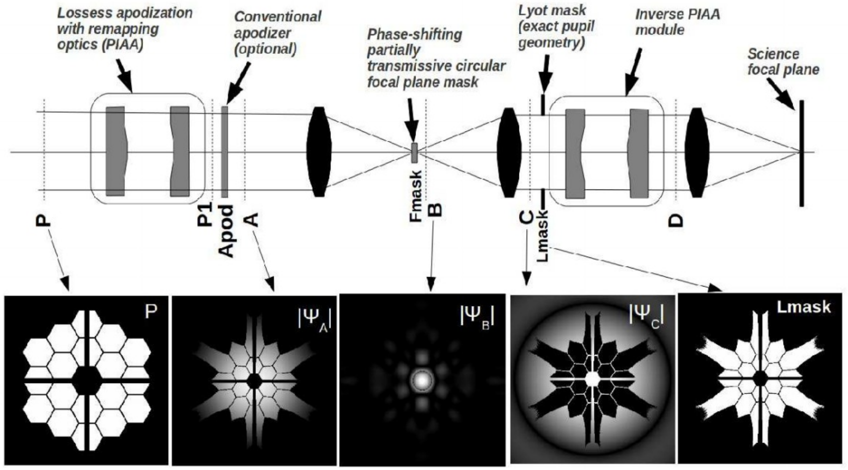
Approaches that are inherently insensitive to aperture geometry exit (no performance loss induced by segmentation)



Visible nulling coronagraph (VNC)

Destructive interference between shifted copies of the pupil

Shift can be integer multiple of segments

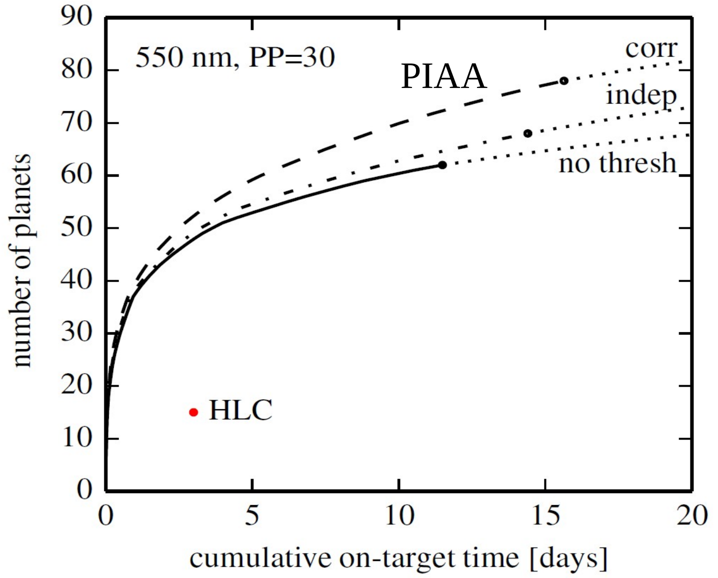


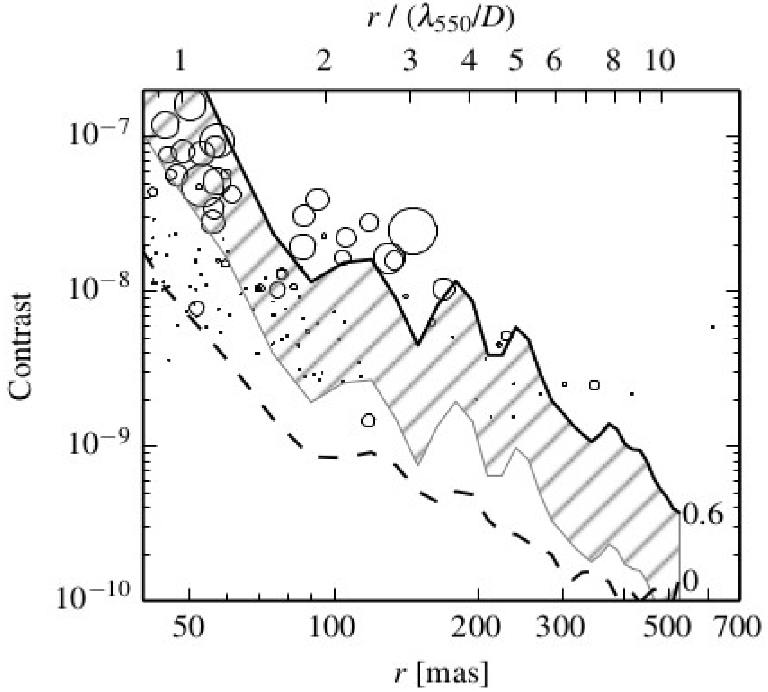
PIAACMC

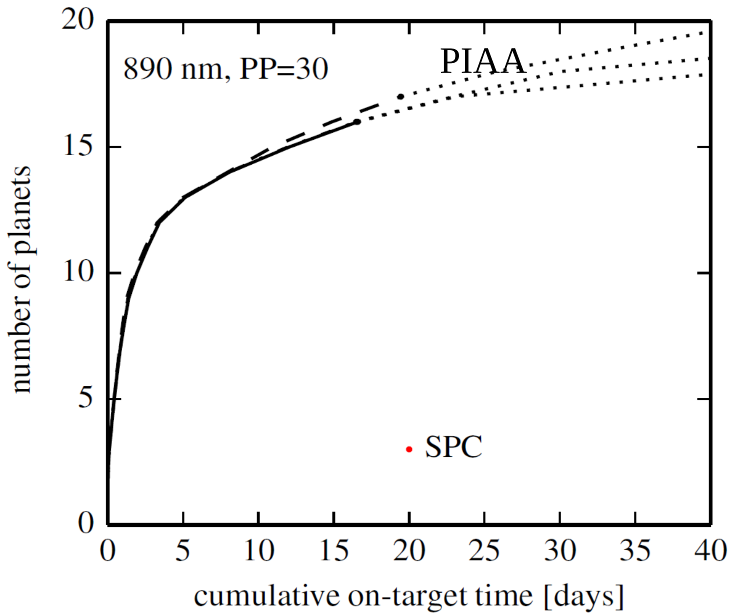
Uses lossless apodization (beam shaping) + diffractive focal plane mask

Near-full transmission and small IWA

PIAACMC → enhanced science return thanks to small IWA (Kern et al. 2015)



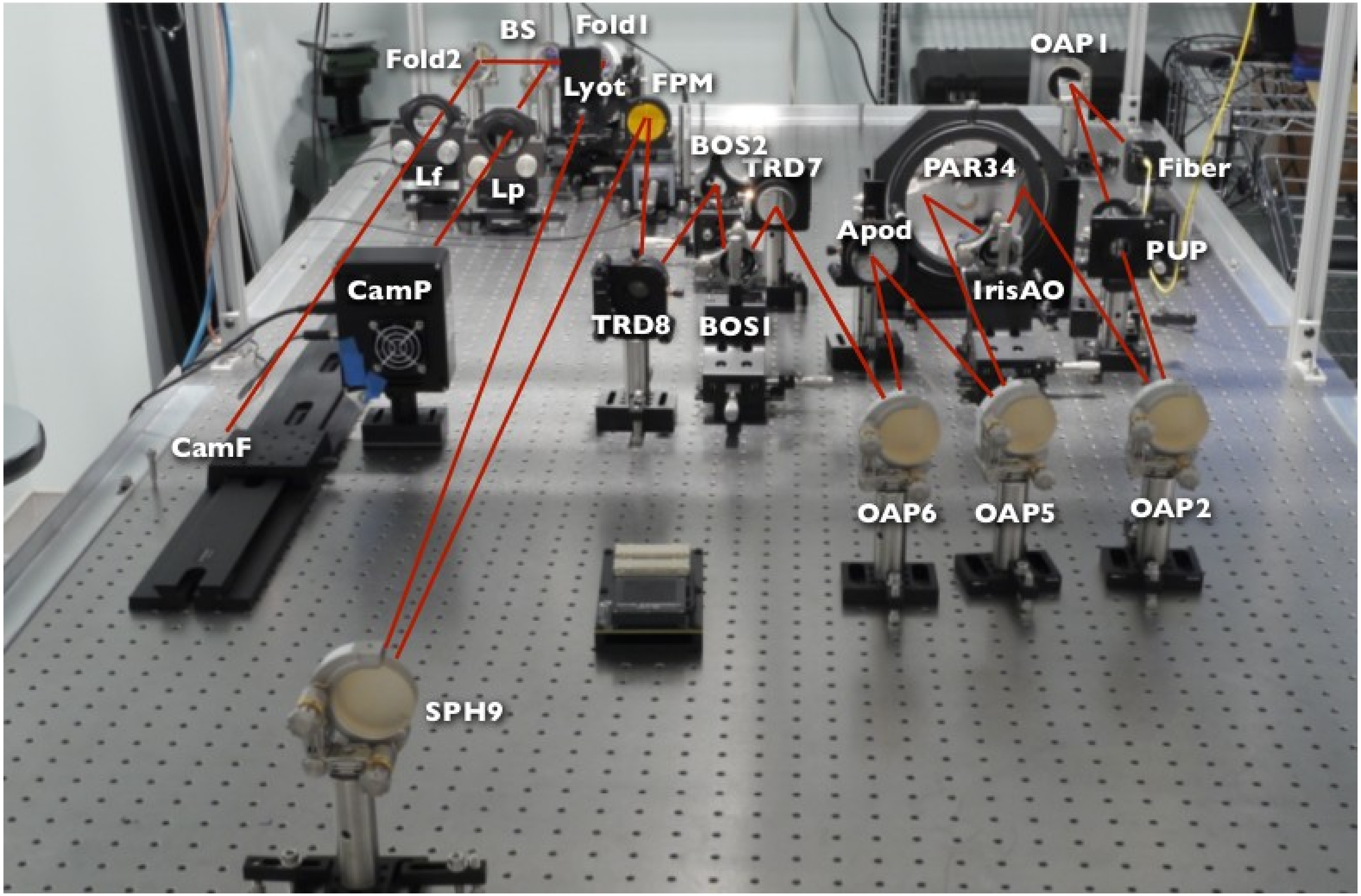




Case	Output channel	wavelength (nm)	band (%)	# pixels	# RV characterizations in less than 1 day each (min, max)		
					HLC	SPC	PIAA
1	imager	465	10	4.9	**15**	**11**	**76**
2	imager	565	10	4.9	**15**	**11**	**87**
3	imager	835	10	4.9	**7**	**5**	**42**
4	imager	670	18	4.9	16	13	85
5	imager	770	18	4.9	10	7	61
6	imager	890	18	4.9	5	5	36
7	IFS	670	1.4	4.9	**4**	**2**	**39**
8	IFS	770	1.4	4.9	**2**	**1**	**30**
9	IFS	890	1.4	4.9	**0**	**0**	**14**

Single polarization for each case, 0.4 mas jitter, post-processing gain = 1/30
Assumes planet location is known

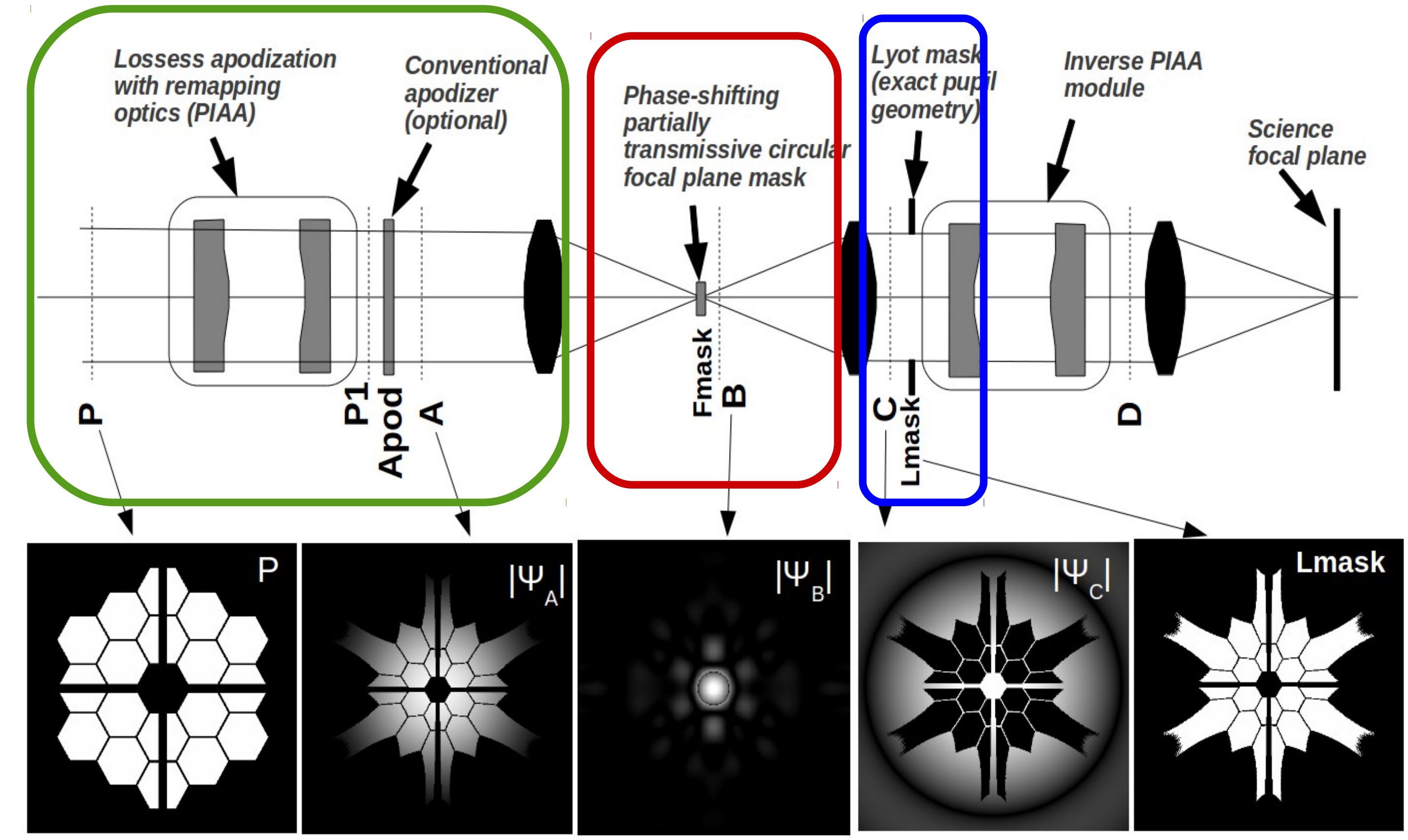
Lab efforts for WFC/coronagraphy on segmented apertures at Univ. of Arizona and Space Telescope



Space Telescope Science Institute lab

Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)

PIAACMC concept

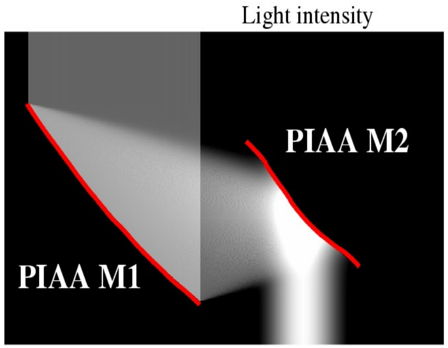

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

Achieves starlight suppression by combining:

Lossless apodization with aspheric optics (lenses or mirrors)
Creates PSF with weak Airy rings

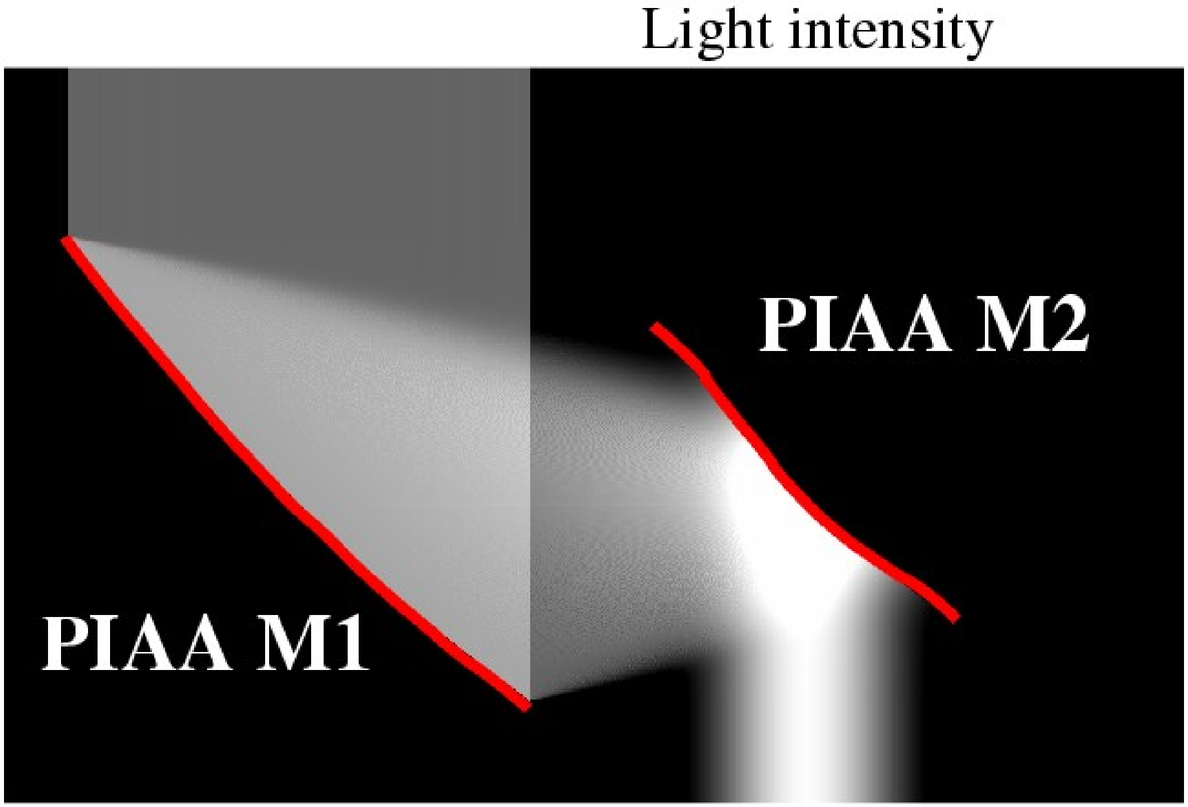
Focal plane mask
complex amplitude $-1<t<0$
Induces destructive interference inside downstream pupil

Lyot Stop
Blocks starlight



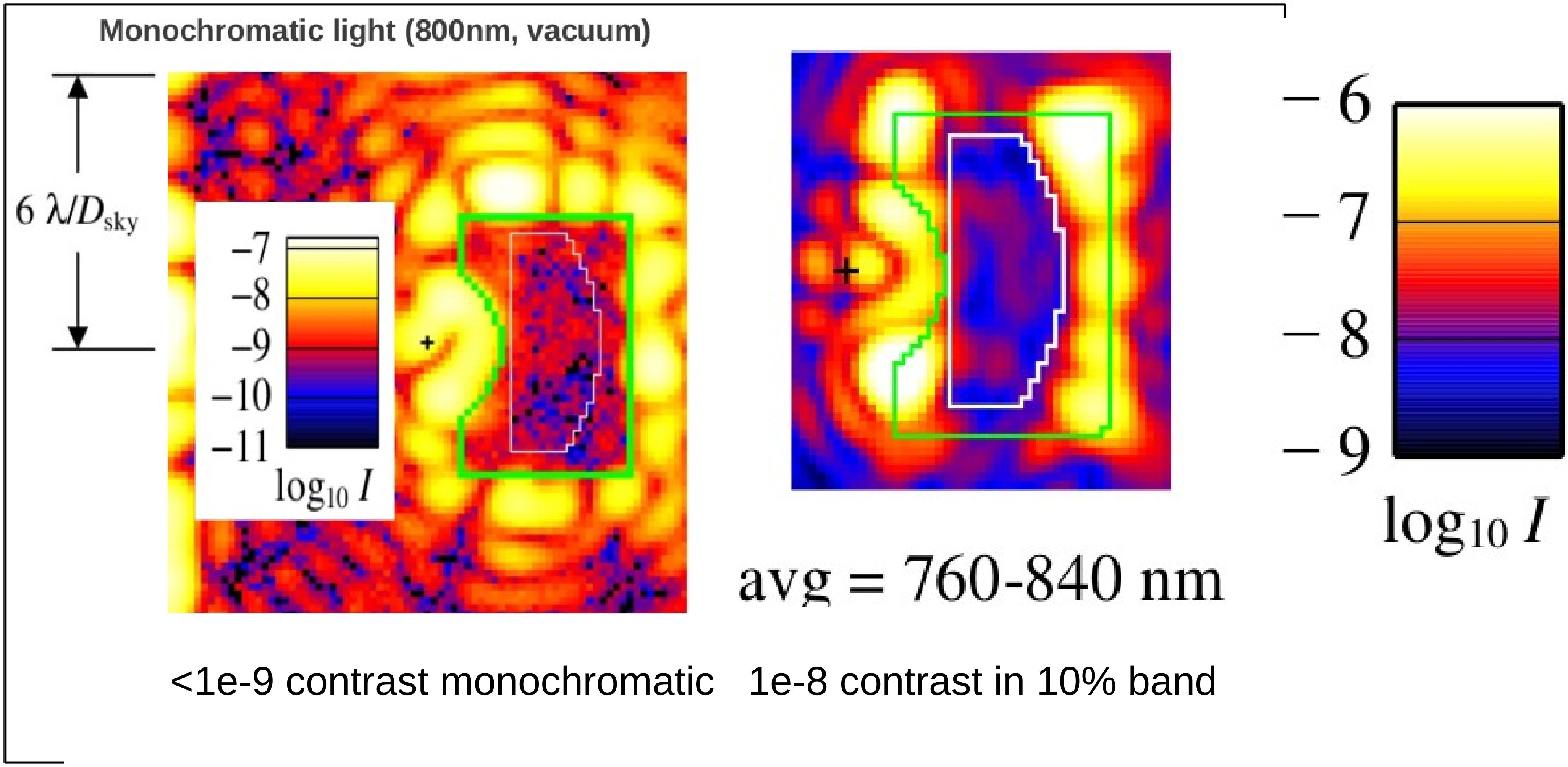
PIAACMC does not care about pupil geometry: segements, spiders, central obstruction OK

Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIACMC)



Uses lenses or mirrors for lossless beam apodization

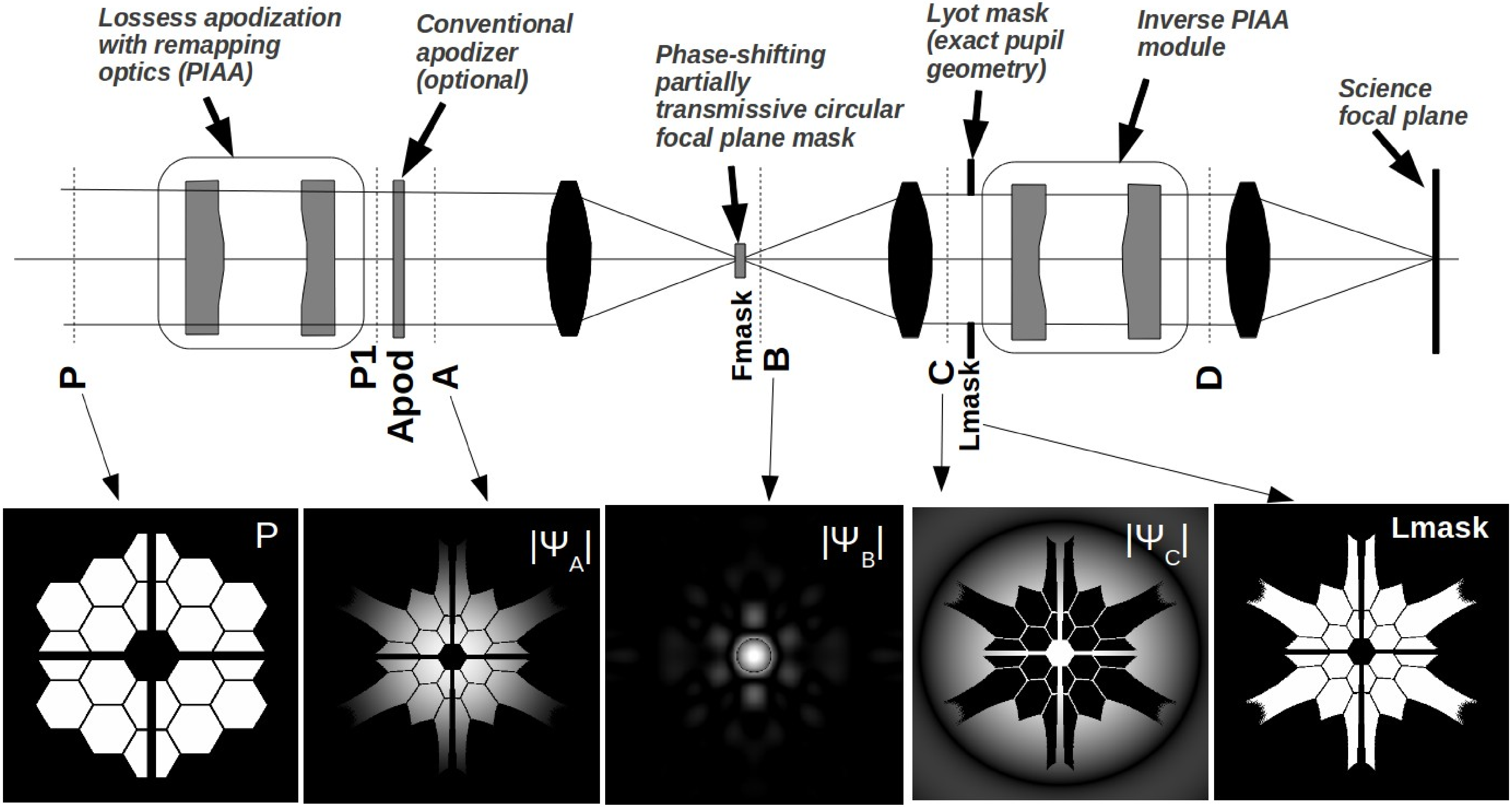
PIAA testbed at NASA JPL : lab results demonstrate PIAA's high efficiency and small IWA (B. Kern, O. Guyon et al.) - now moving to PIAACMC



<1e-9 contrast monochromatic   1e-8 contrast in 10% band

2-4 l/D dark hole, high system throughput

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Lossess apodization with remapping optics (PIAA)

Conventional apodizer (optional)

Phase-shifting partially transmissive circular focal plane mask

Lyot mask (exact pupil geometry)

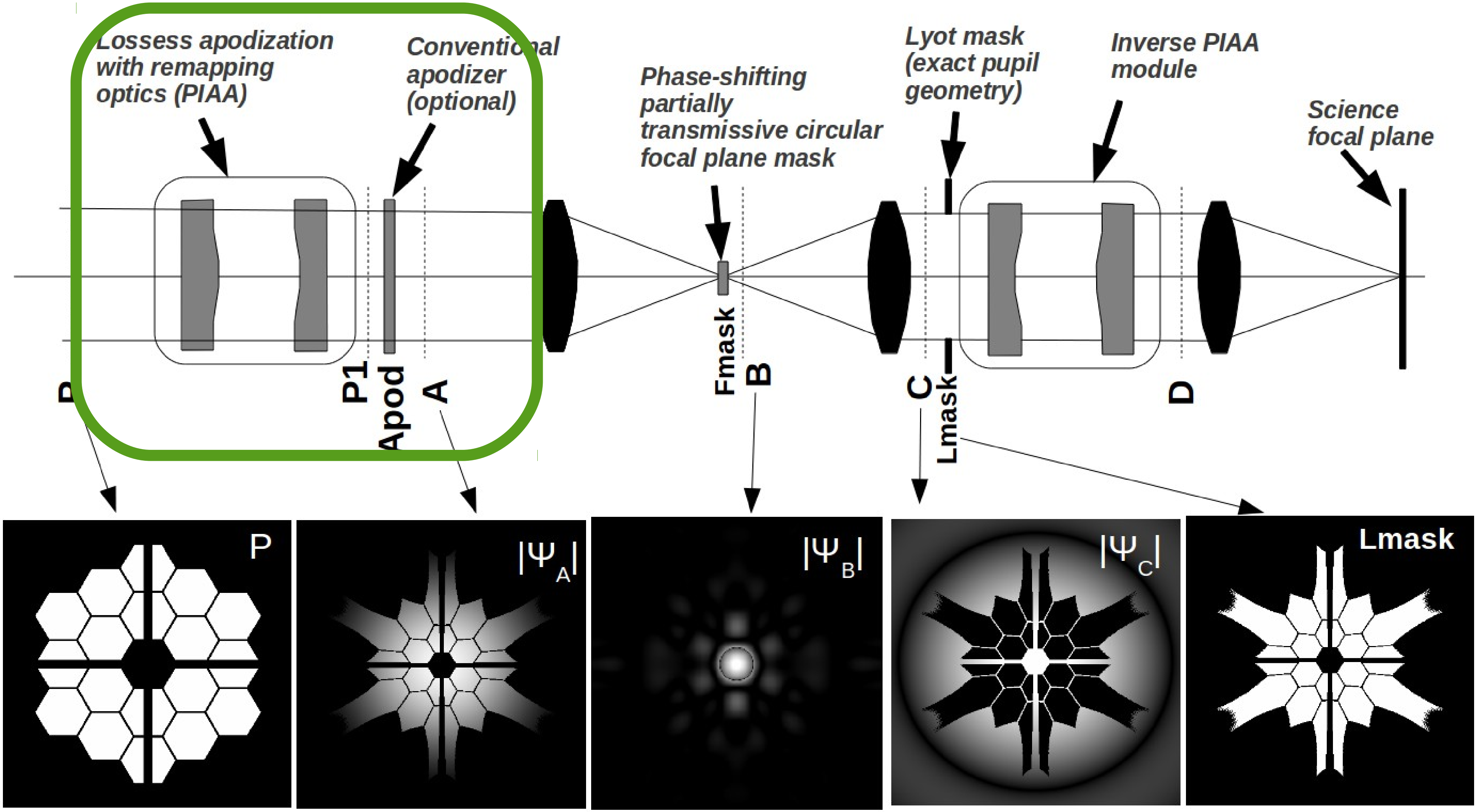
Inverse PIAA module

Science focal plane

(largely) lossless apodization

Creates a PSF with weak Airy rings

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



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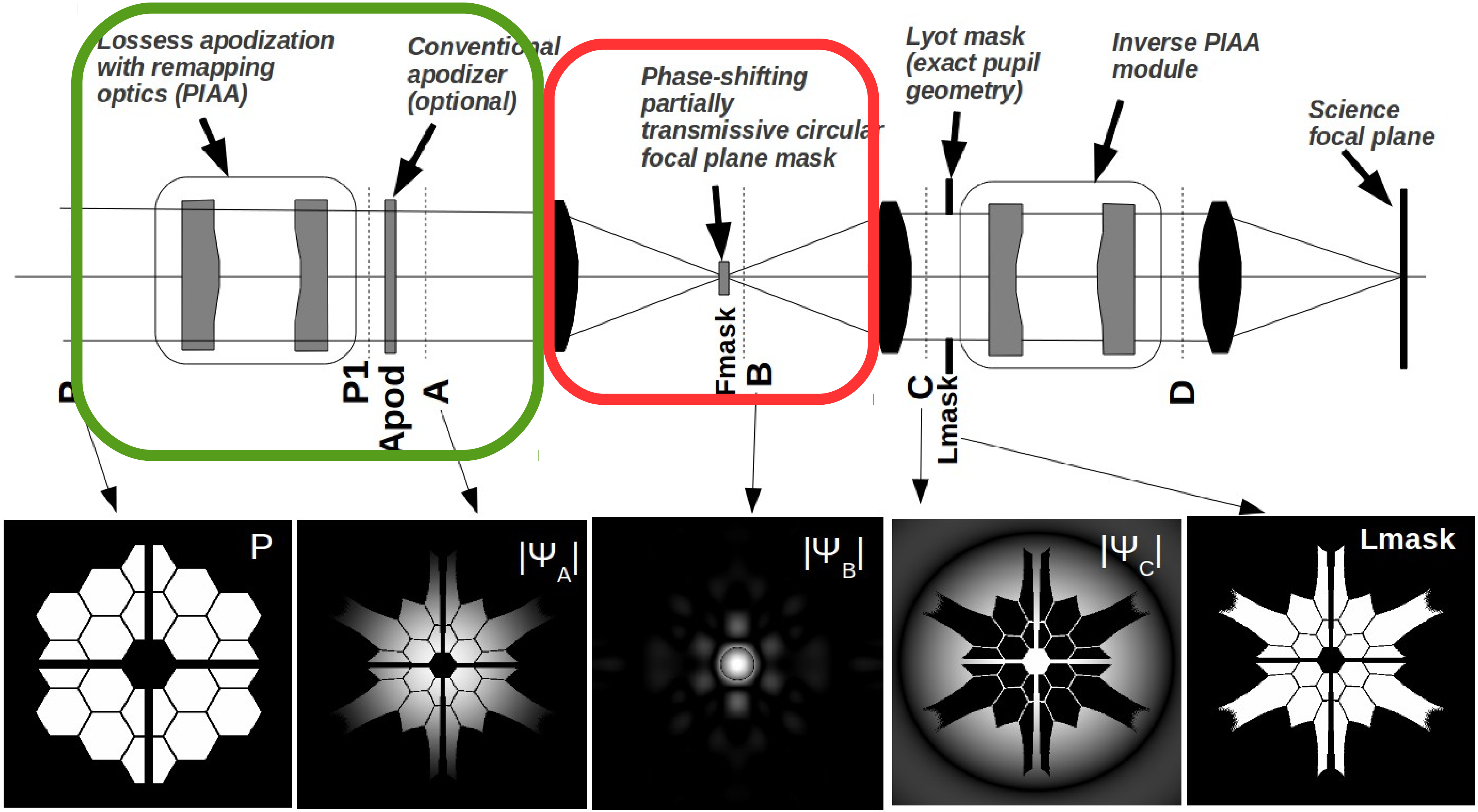
Creates a PSF with weak Airy rings

Focal plane mask: -1<t<0

Induces destructive interference inside downstream pupil

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



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Creates a PSF with weak Airy rings

Lyot stop

Blocks starlight

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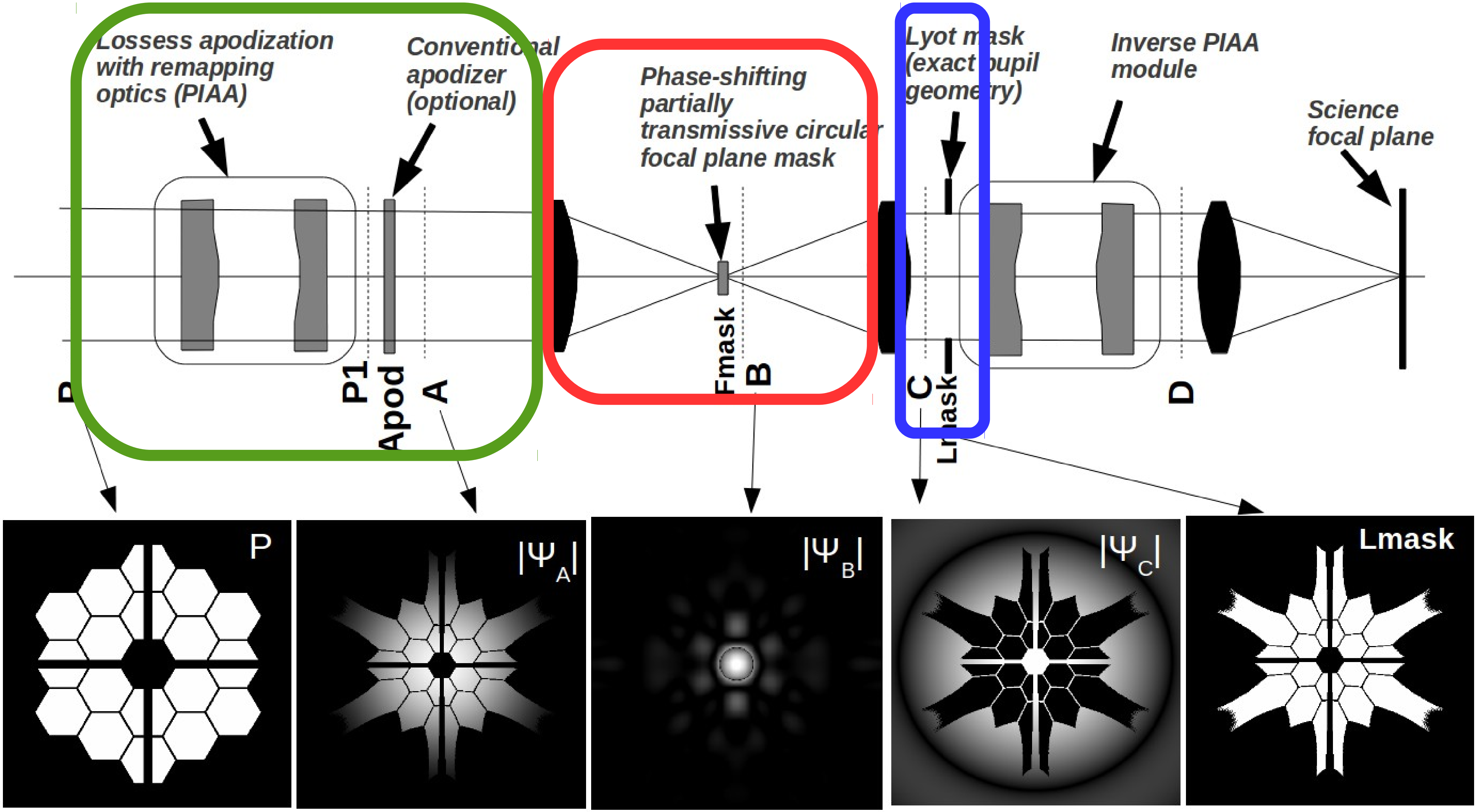
Induces destructive interference inside downstream pupil

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



(largely) lossless apodization

Creates a PSF with weak Airy rings

Focal plane mask: $-1<t<0$

Induces destructive interference inside downstream pupil

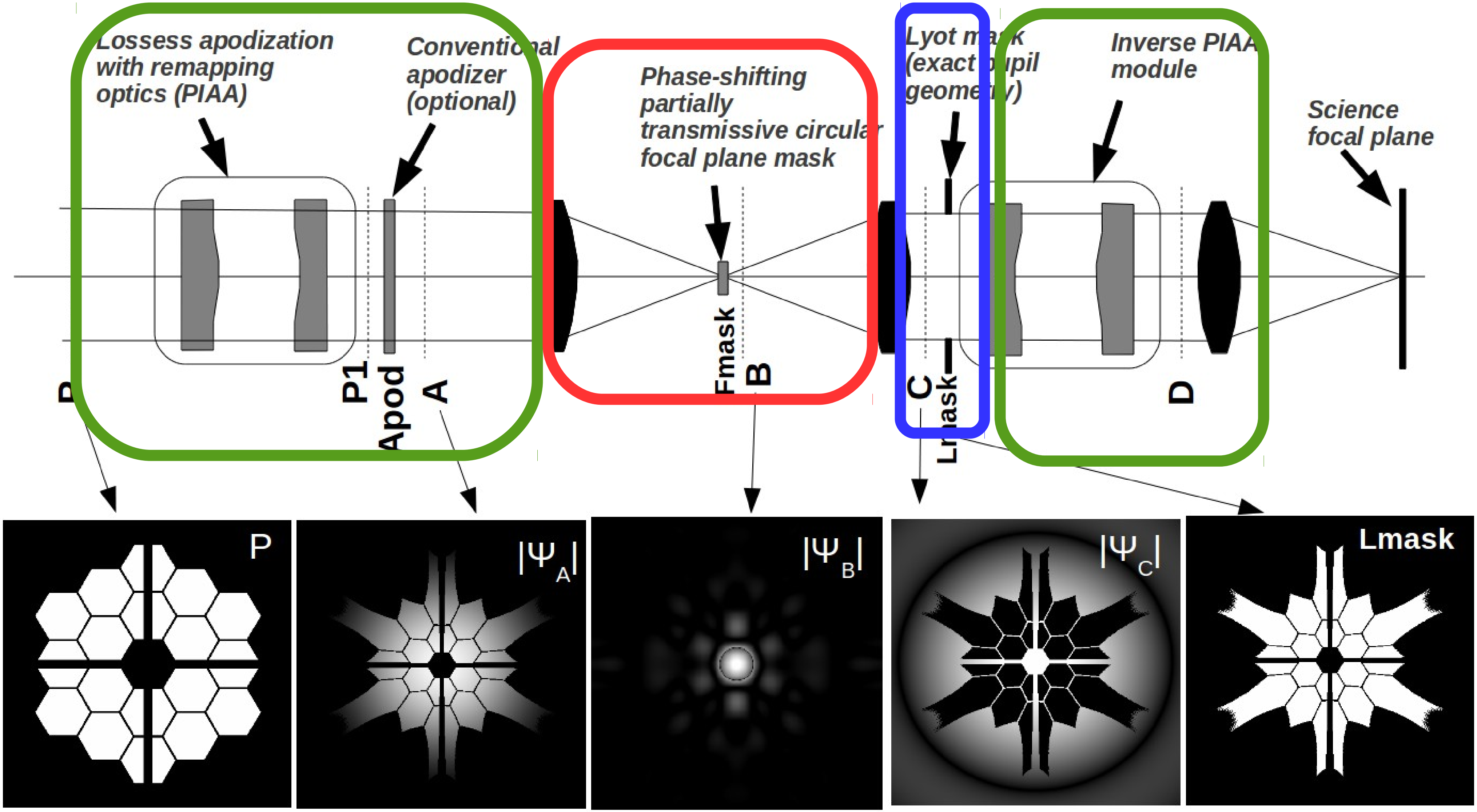
Lyot stop

Blocks starlight

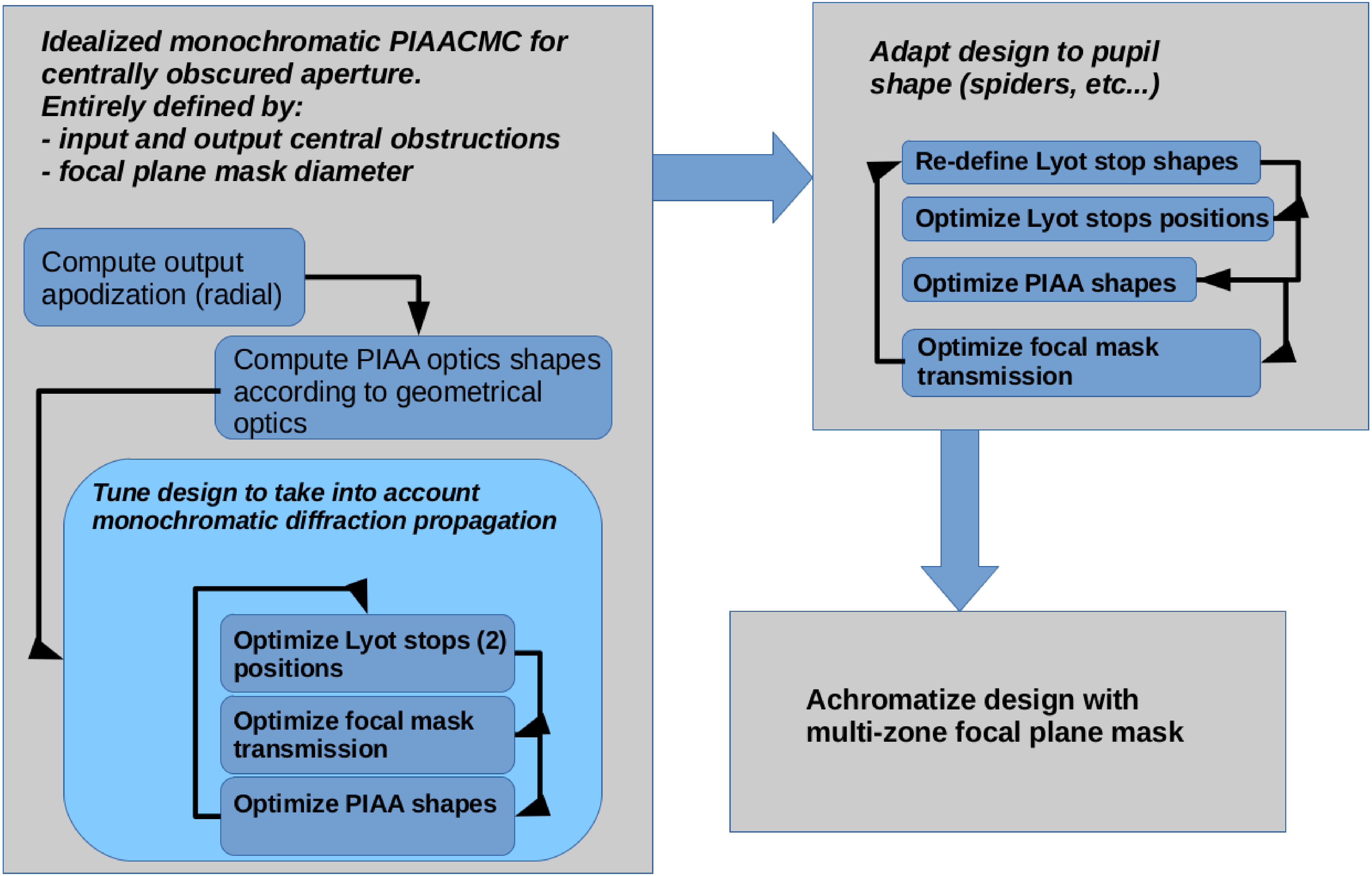
Inverse PIAA (optional)

Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



PIACMC design process



Idealized monochromatic PIAACMC for centrally obscured aperture.
Entirely defined by:
- input and output central obstructions
- focal plane mask diameter

Compute output apodization (radial)

Compute PIAA optics shapes according to geometrical optics

Tune design to take into account monochromatic diffraction propagation

Optimize Lyot stops (2) positions

Optimize focal mask transmission

Optimize PIAA shapes

Adapt design to pupil shape (spiders, etc...)

Re-define Lyot stop shapes

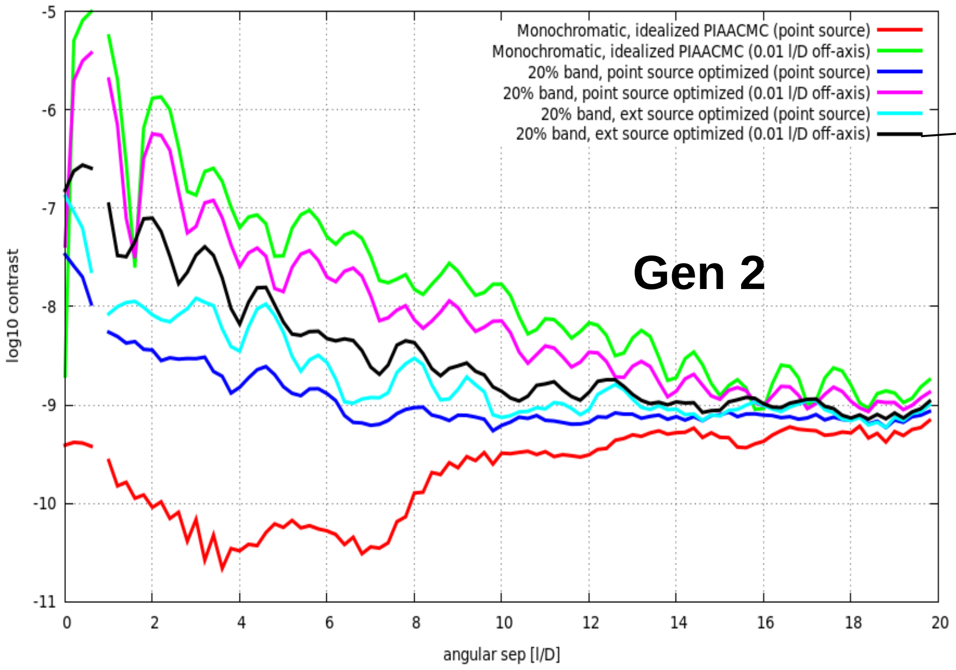
Optimize Lyot stops positions

Optimize PIAA shapes

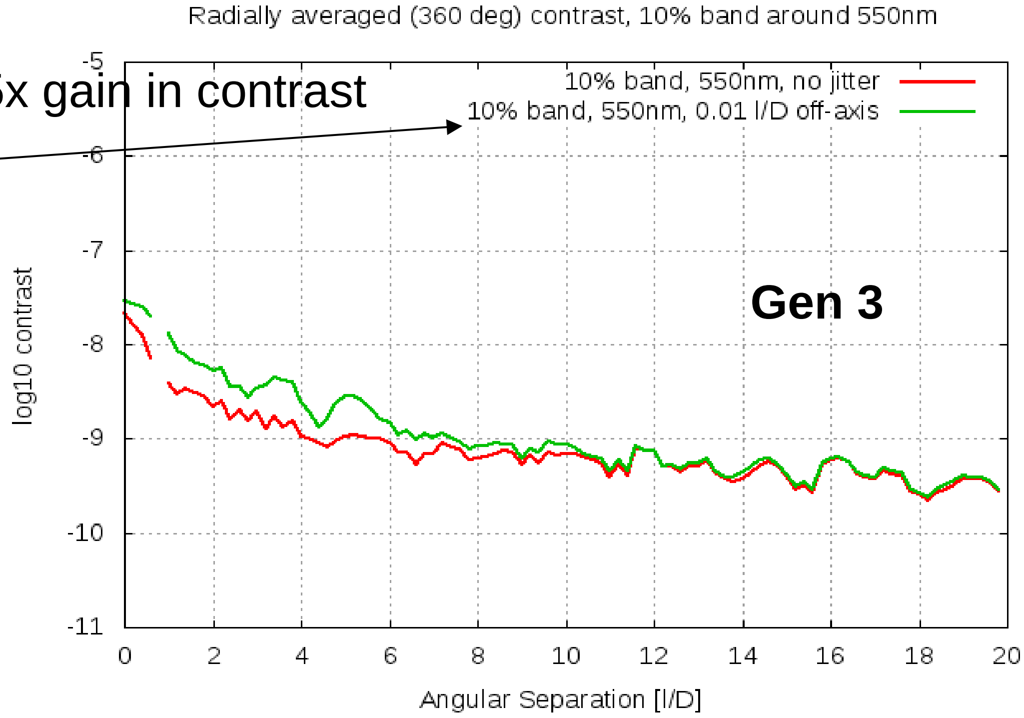
Optimize focal mask transmission

Achromatize design with multi-zone focal plane mask

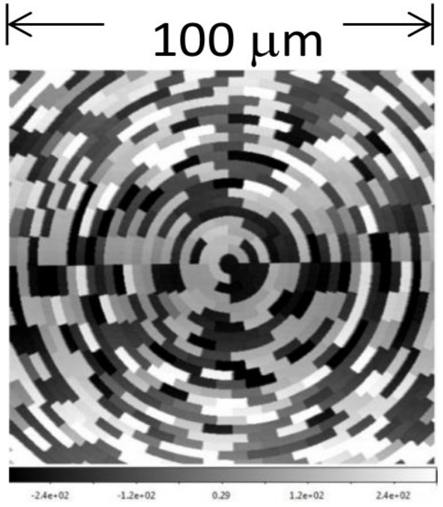
Stellar leak and focal plane mask design on AFTA



15x gain in contrast

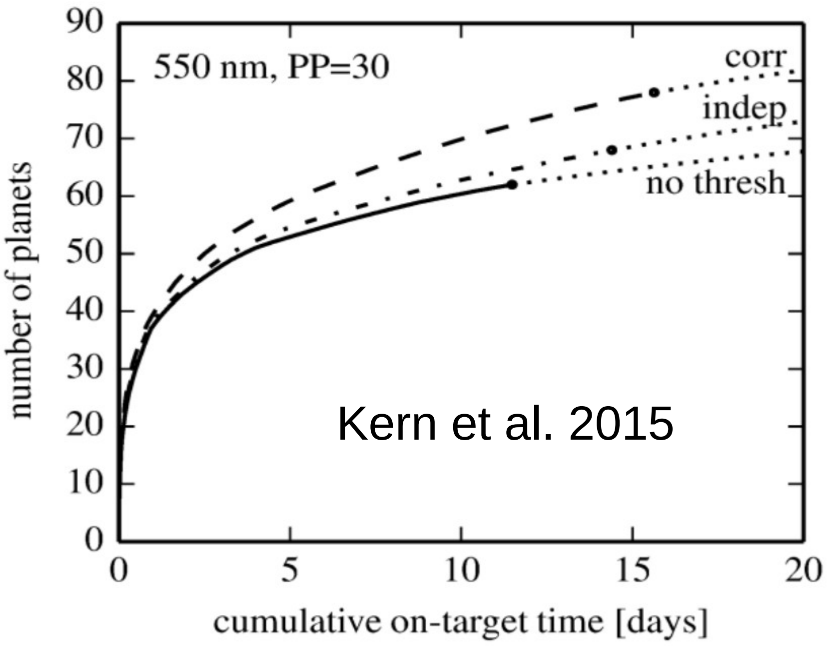


raw



±300 nm scale

Focal plane mask consists of ~1000 zones
Zone height computer-optimized simultaneously for broadband operation and stellar angular size

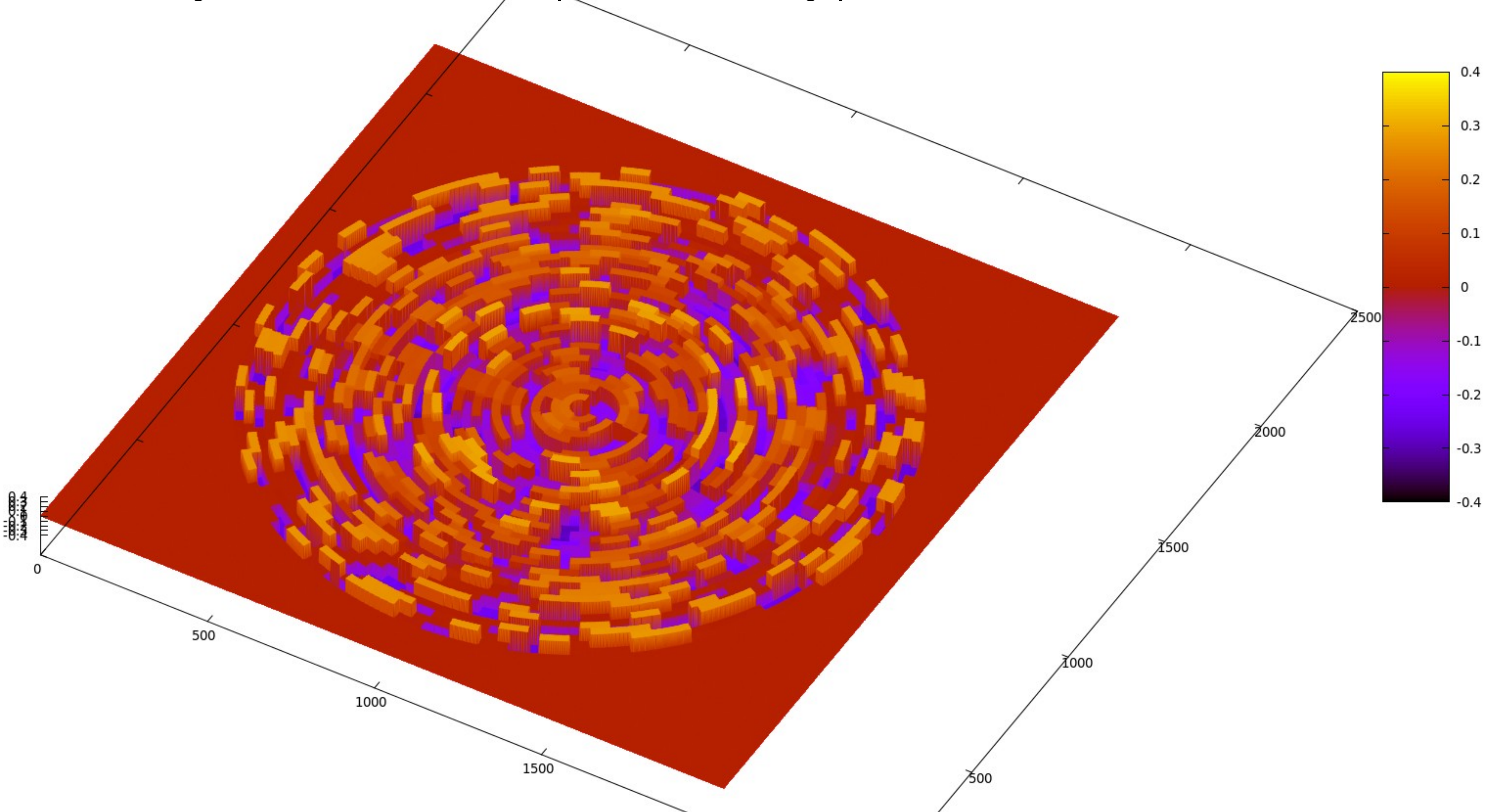


Kern et al. 2015

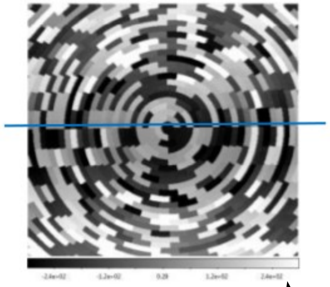
Focal plane mask (vertical scale amplified) for 1e-9 raw contrast, 1.3 l/D IWA (WFIRST visible light mask)

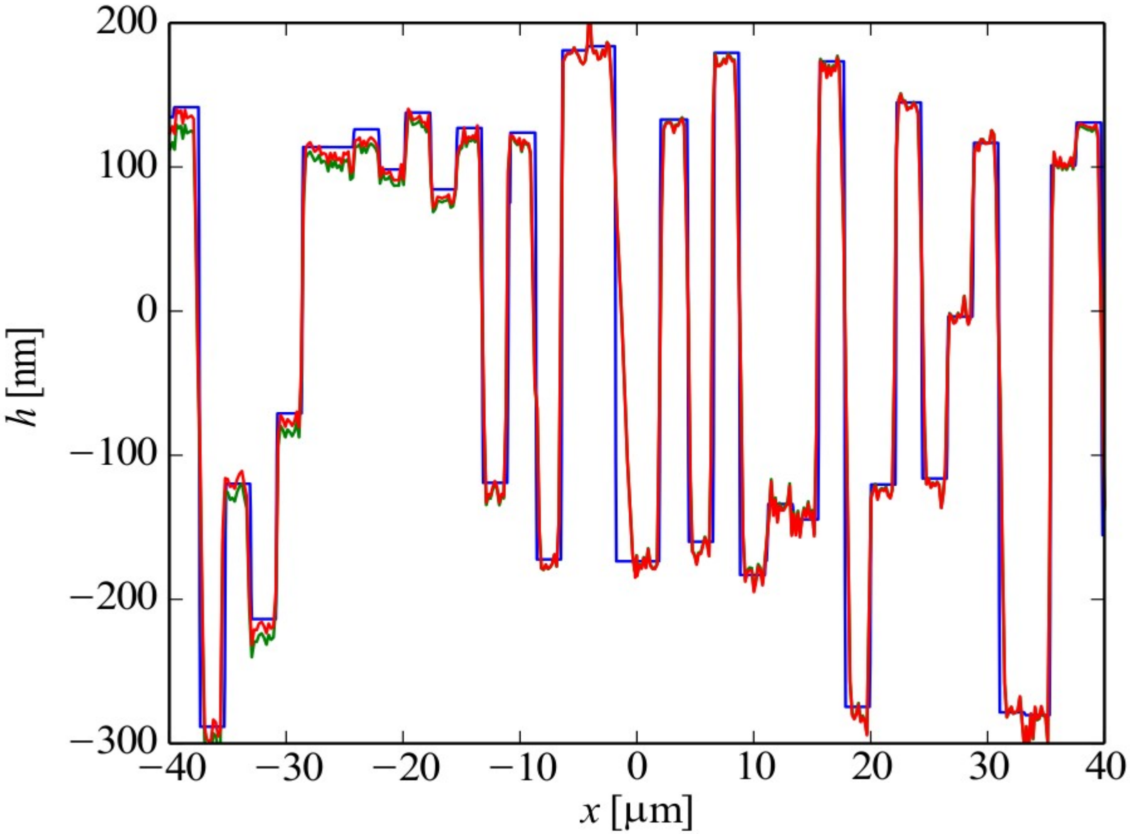
Sag within -/+ 0.3 um

35 rings, 154.7 um diameter (2.2 um wide rings)

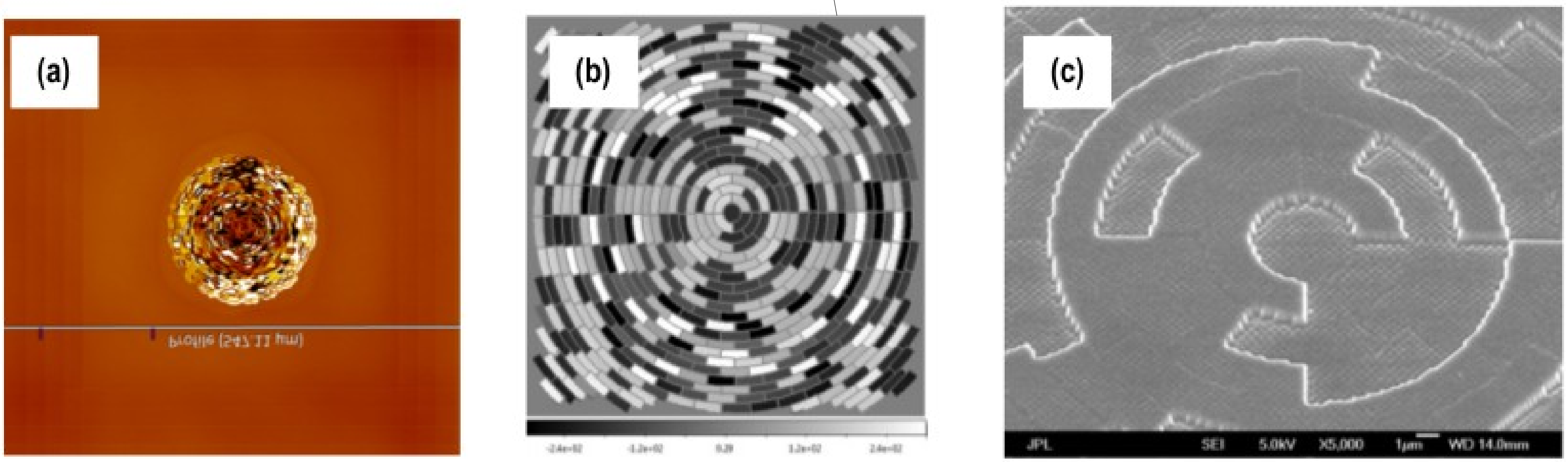


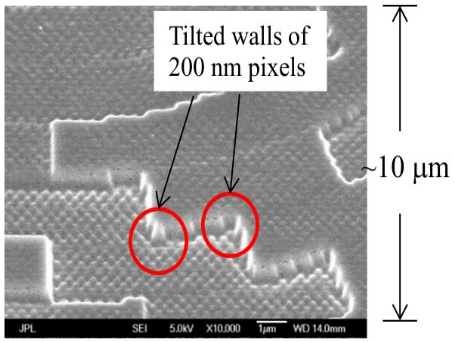
PIAACMC focal plane mask manufacturing





Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)

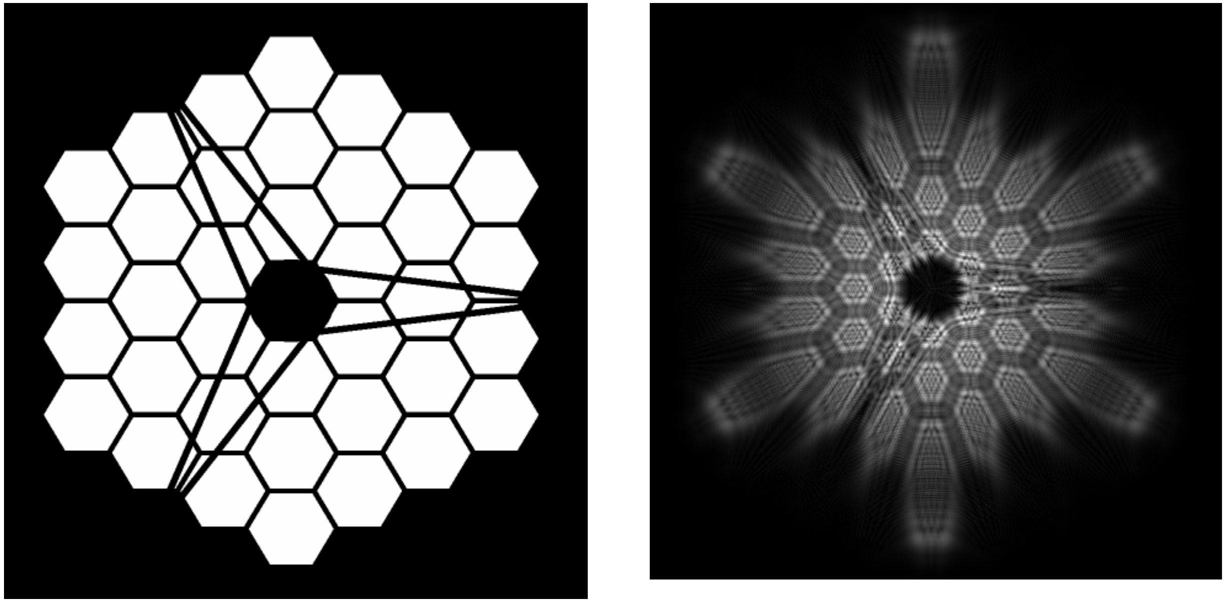




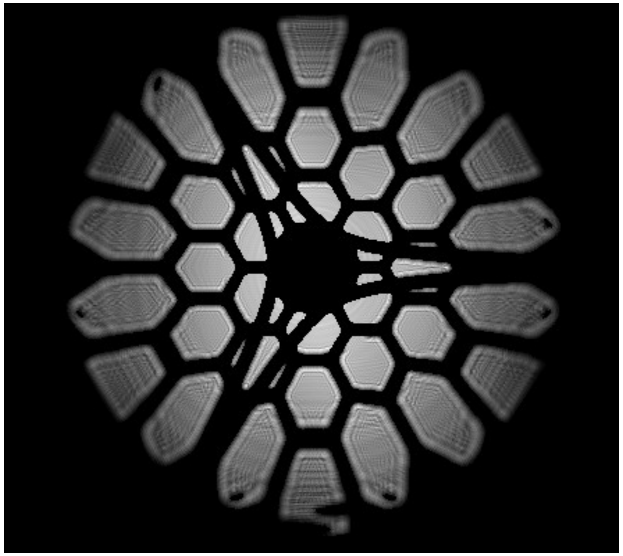
PIAACMC design for 12m segmented telescope
IWA = 1.2 l/D, throughput = 70% (similar to WFIRST-PIAACMC)

Polychromatic diffraction propagation in AFTA-C PIAACMC optical configuration
Reflective focal plane mask

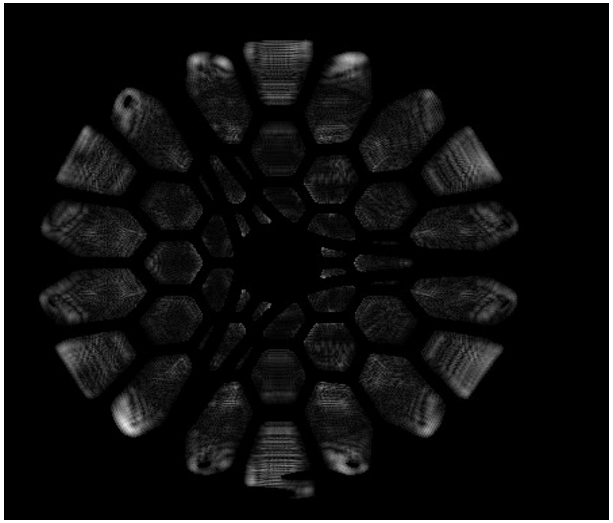
FLAT DEFORMABLE MIRRORS (no ACAD)



Focal plane mask redirects starlight to
LOWFS (reflected by Lyot stop)
70% of planet light goes through Lyot stops
to science image



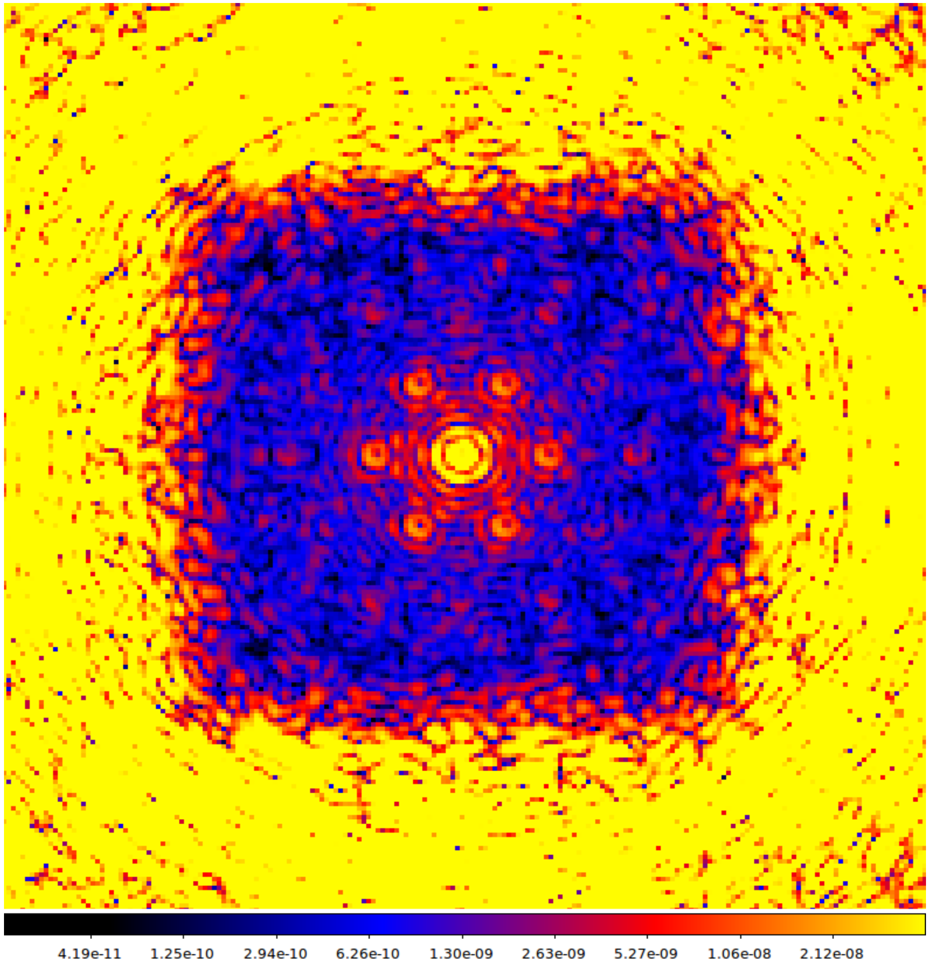
planet light



starlight (very faint)

Stellar PSF dominated by stellar angular size

Further optimization of focal plane mask and WFC (ACAD ?) will reduce leaks due to stellar angular size. This process improved contrast by 15x between PIACMC gen2 and PIAACMC gen3 on AFTA.



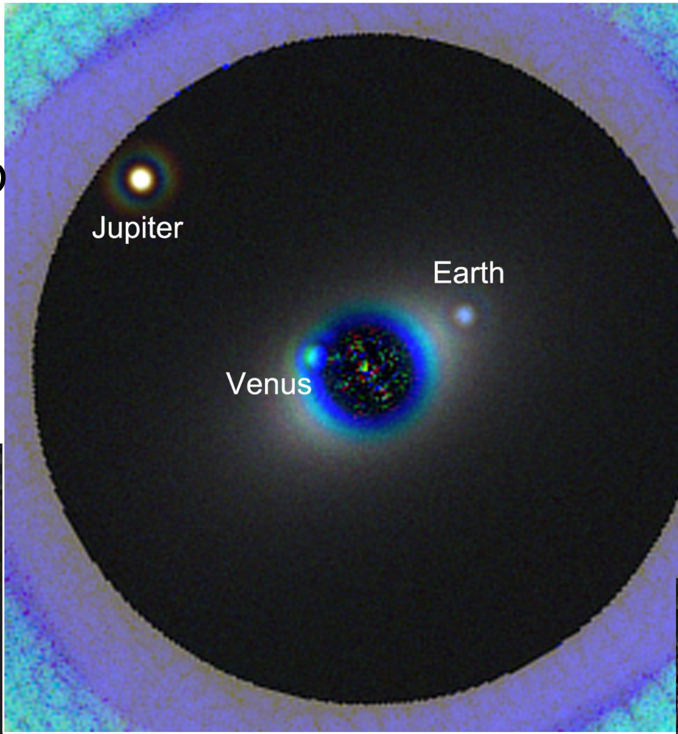
Inner spot+rings due to stellar angular size, at few 1e-9 contrast in 2-4 l/D range

6 small circular spots at 7 l/D due to aperture geometry (side lobes)

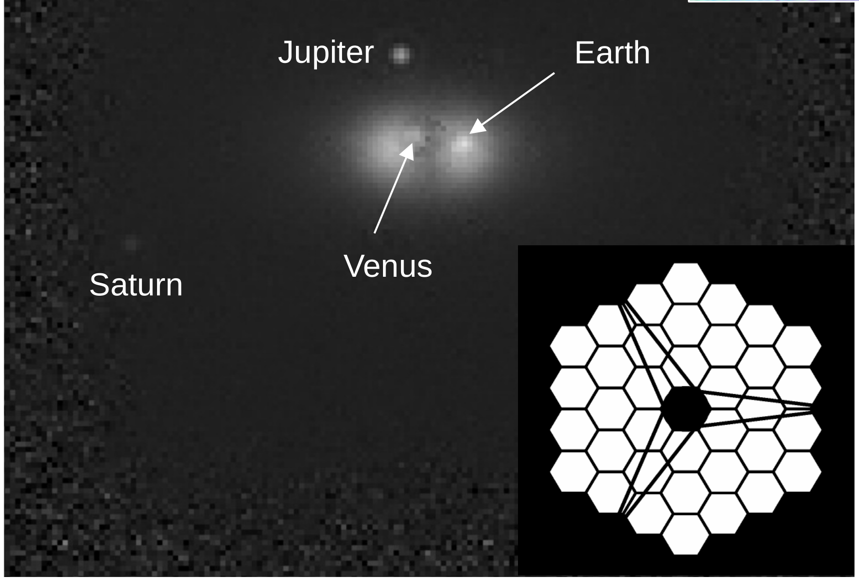
This component is subtracted from image in next slide, assuming photon-noise limit

Simulated images of solar system twin – 12m telescope, 2 day exposure

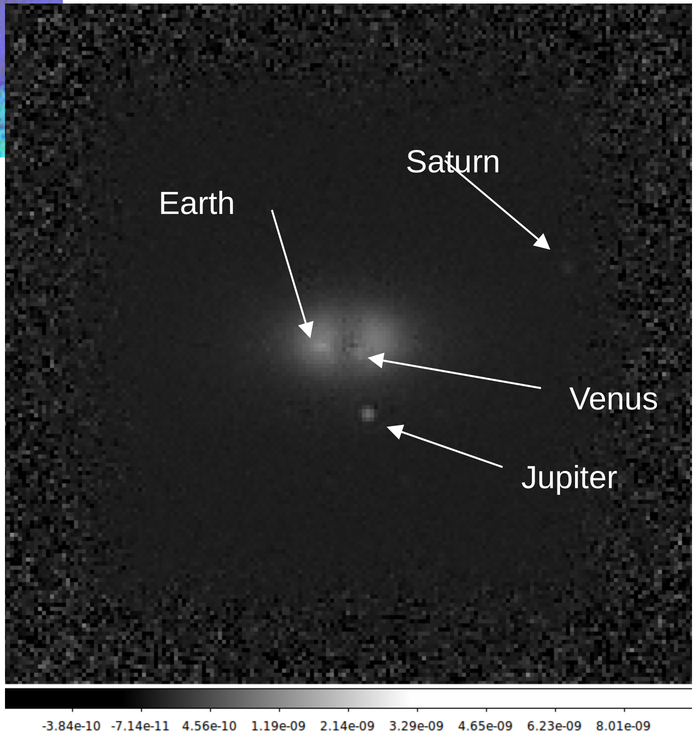
SS twin at 13pc
Visible light
APLC, IWA=3.6 l/D



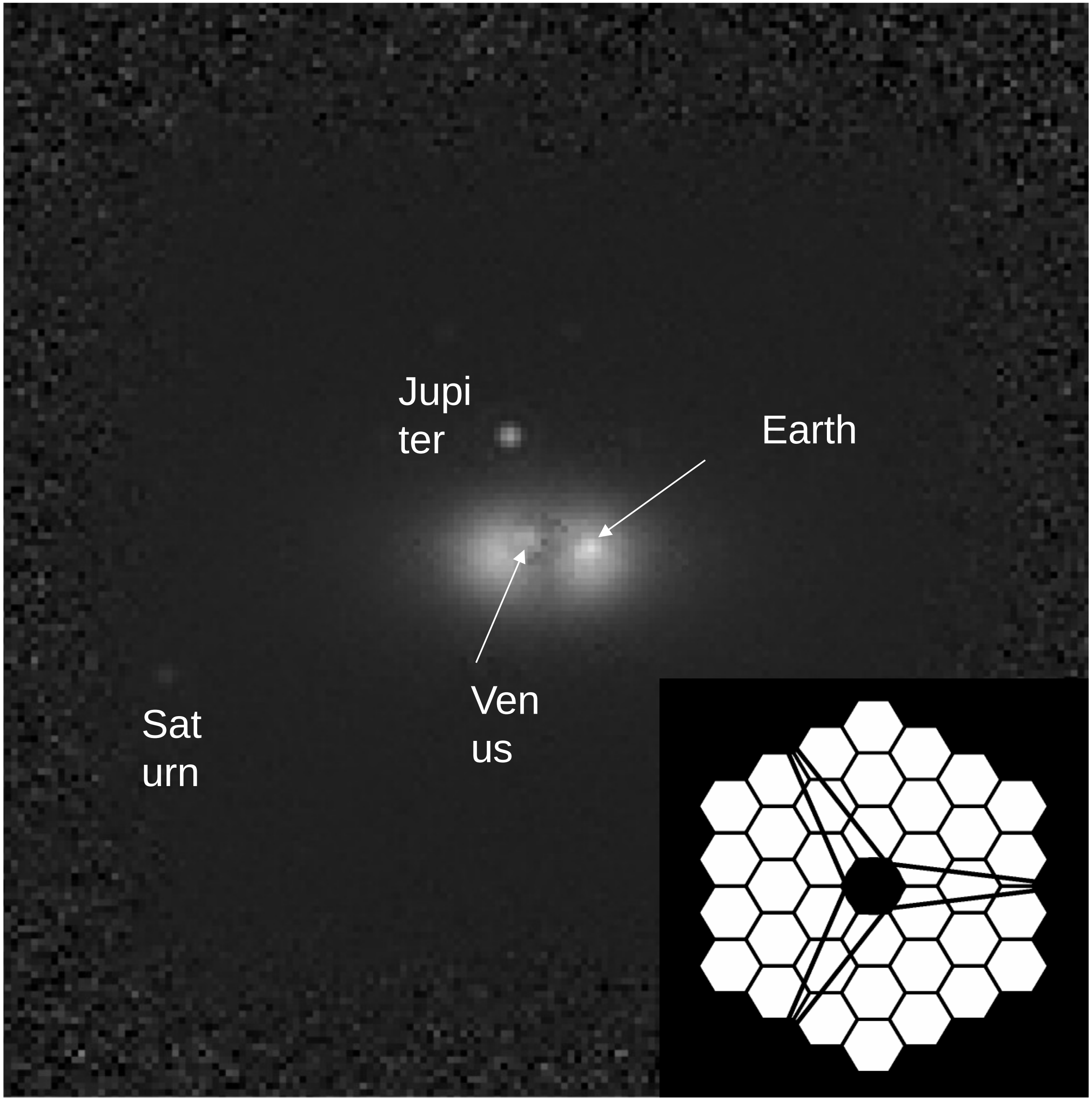
SS twin at 13pc
near-IR (1600nm)
PIAACMC, IWA=1.2 l/D



SS twin at 40pc
Visible (550nm)
PIAACMC, IWA=1.2 l/D



PIAACMC's small IWA enable near-IR spectroscopy of exoEarths with HDST's 12m aperture



Simulated near-IR (1600nm, 20% band) image of a solar system twin at a distance of 13.5pc as seen by a 12m HDST with a 2 day exposure. The pupil geometry adopted for this simulation is shown in the lower right. A Phase-Induced Amplitude Apodization Complex Amplitude Coronagraph (PIAACMC), offering small IWA (1.25 l/D), is used here to overcome the larger angular resolution at longer wavelength. Earth, at 2.65 l/D separation, is largely unattenuated, while Venus, at 1.22 l/D, is partially attenuated by the coronagraph mask. At this wavelength, the wavefront control system (assumed here to use 64x64 actuator deformable mirrors) offers a larger high contrast field of view, allowing Saturn to be imaged in reflected light. This simulation assumes PSF subtraction to photon noise sensitivity. In the stellar image prior to PSF subtraction, the largest light contribution near the coronagraph IWA is due to finite stellar angular size (0.77 mas diameter stellar disk).

Wavefront control

Ultra-stability: limiting segment vibrations

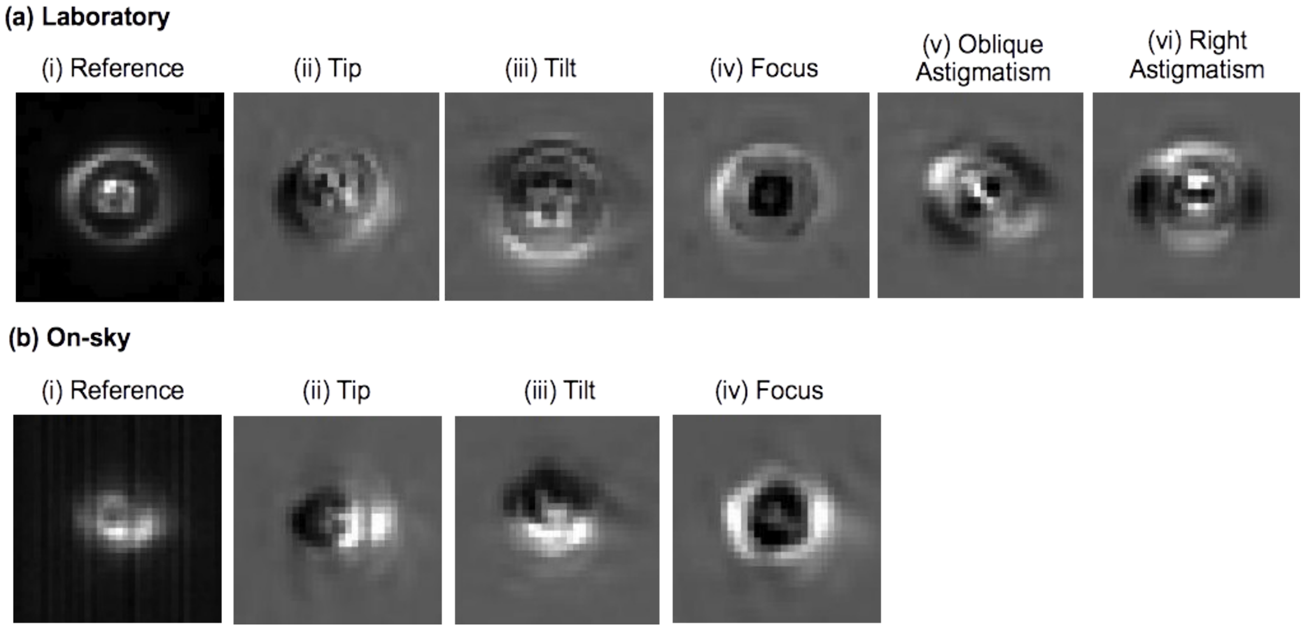
Raw contrast in the 1e-9 to 1e-10 range requires ~10pm stability of combined telescope and WFC.

Continuous speckle control can compensate and calibrate slow thermal drifts, but vibration must be addressed separately (too fast for speckle control)

Vibration and fast WF changes can be addressed with multi-tiered approach, some combination of :

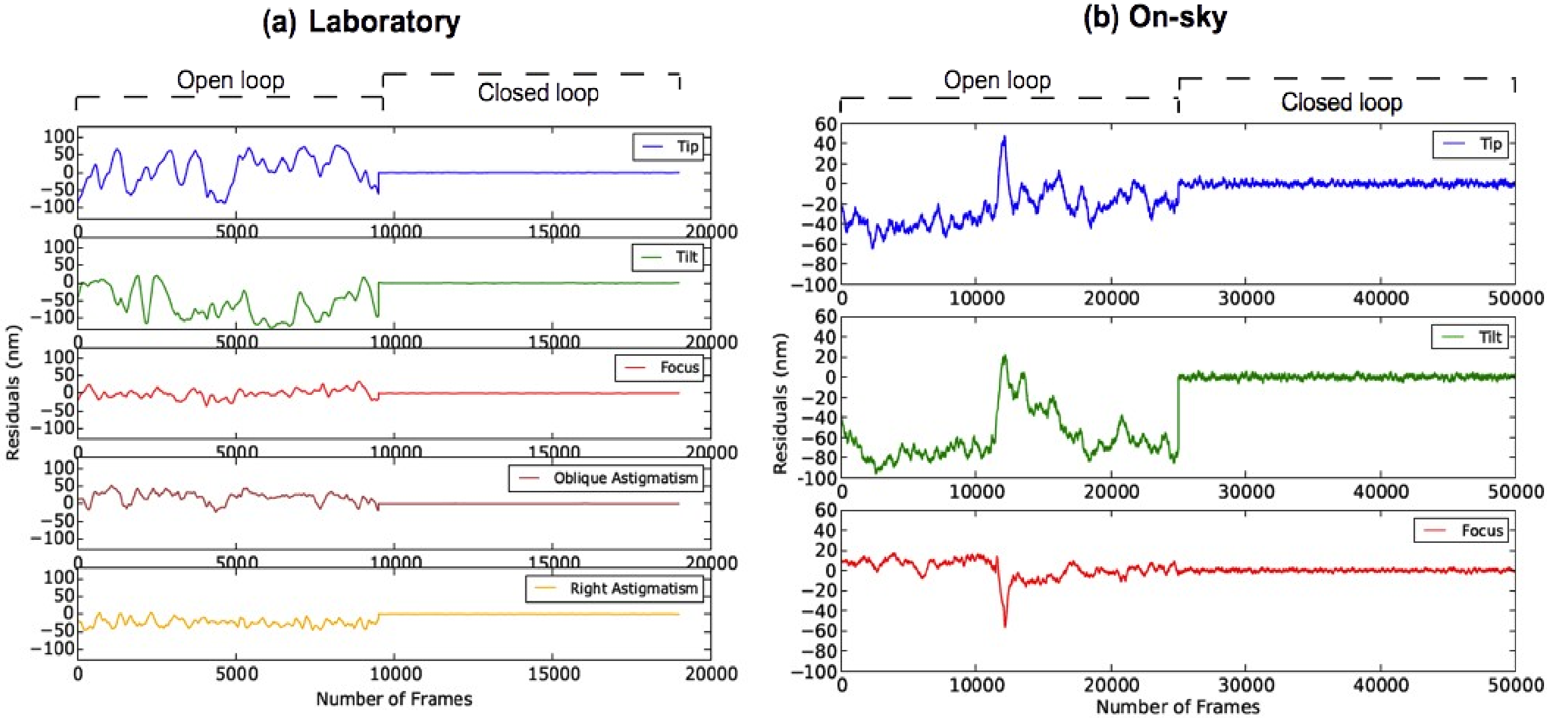
- Using bright starlight for fast sensing of a few modes ***[example: LOWFS concept on WFIRST and SCExAO]***
- Picometer laser metrology ***[SIM and non-NASA heritage]***
- Vibration suppression / isolation ***[industry-developed non-contact isolation]***

LDFC ↔ LOWFS

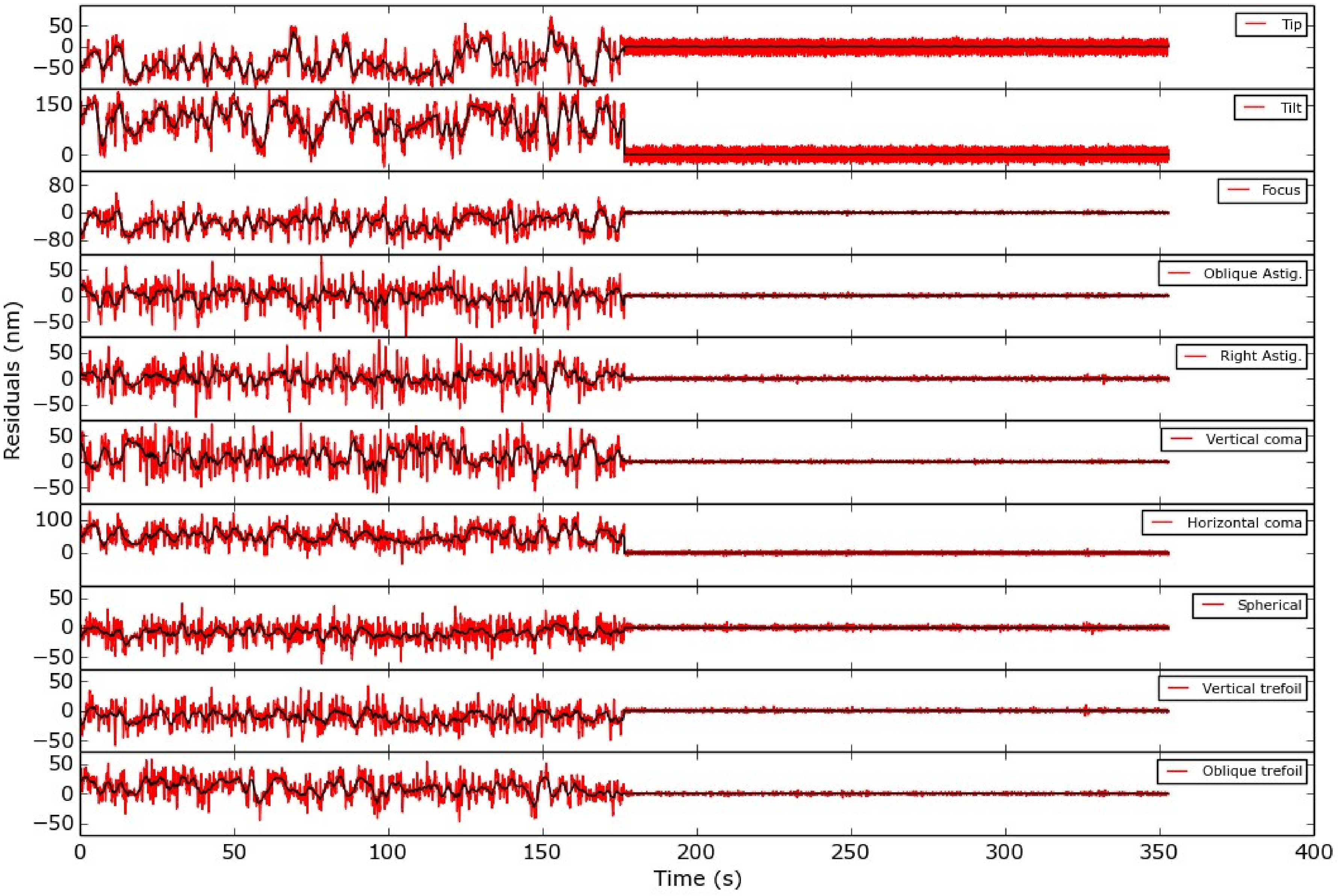


Response Matrix

Residuals



LLOWFS closing loop on first ten Zernike modes with Vortex on SCExAO instrument (March 2015)

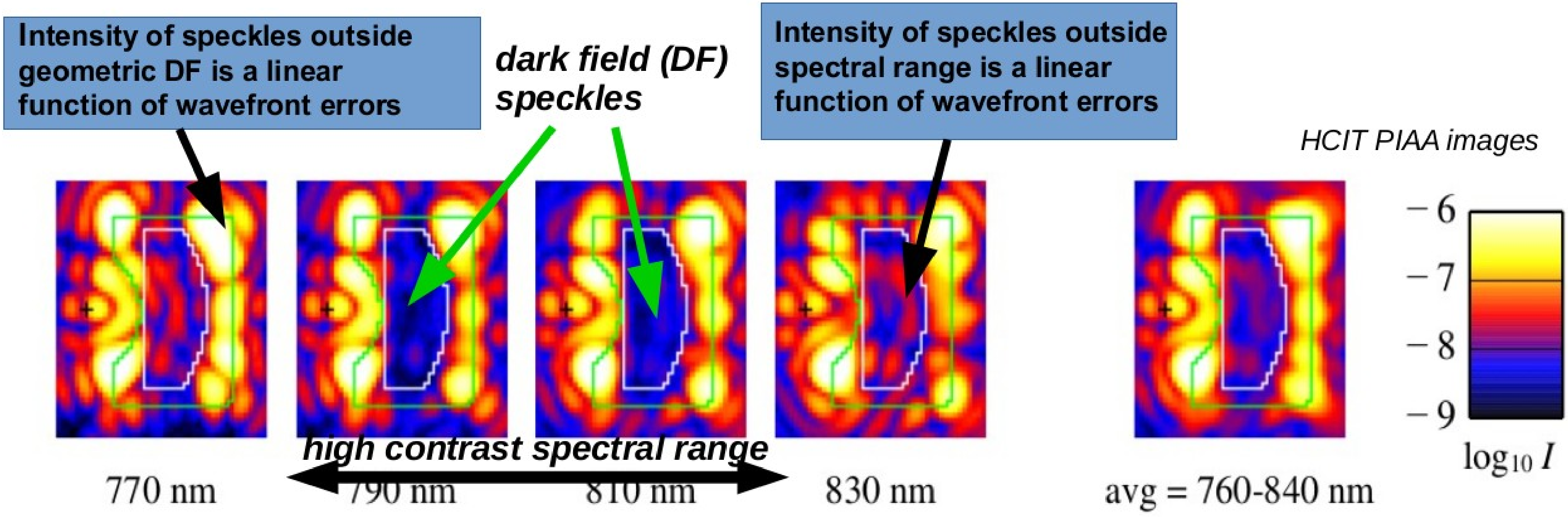


Ref: Singh et al. 2015 (in prep)

Linear Dark Field Control (LDFC)

The series of images below shows intensity as a function of spatial coordinate (x,y) and wavelength (lambda) obtained with the PIAA coronagraph at the JPL high contrast imaging testbed.

The **DARK FIELD (DF)** is the area in (x,y,lambda) space over which starlight is removed.
The **BRIGHT FIELD (BF)** is the area outside the dark field.



Intensity of speckles outside geometric DF is a linear function of wavefront errors

dark field (DF) speckles

Intensity of speckles outside spectral range is a linear function of wavefront errors

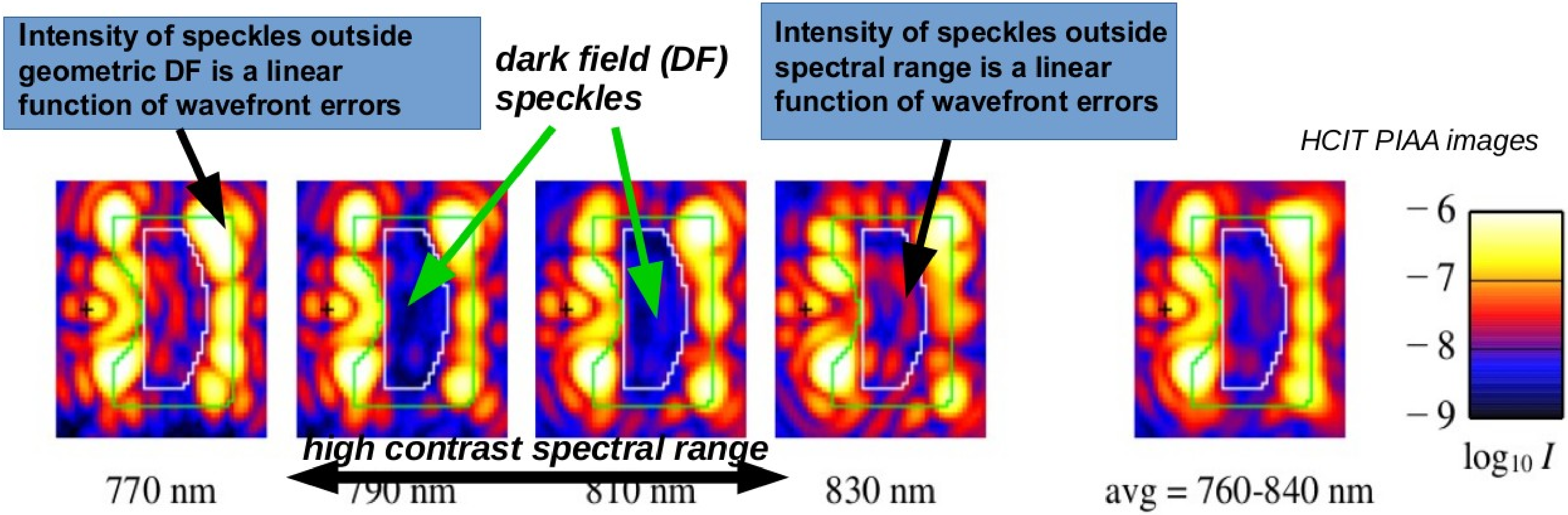
HCIT PIAA images

high contrast spectral range

Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



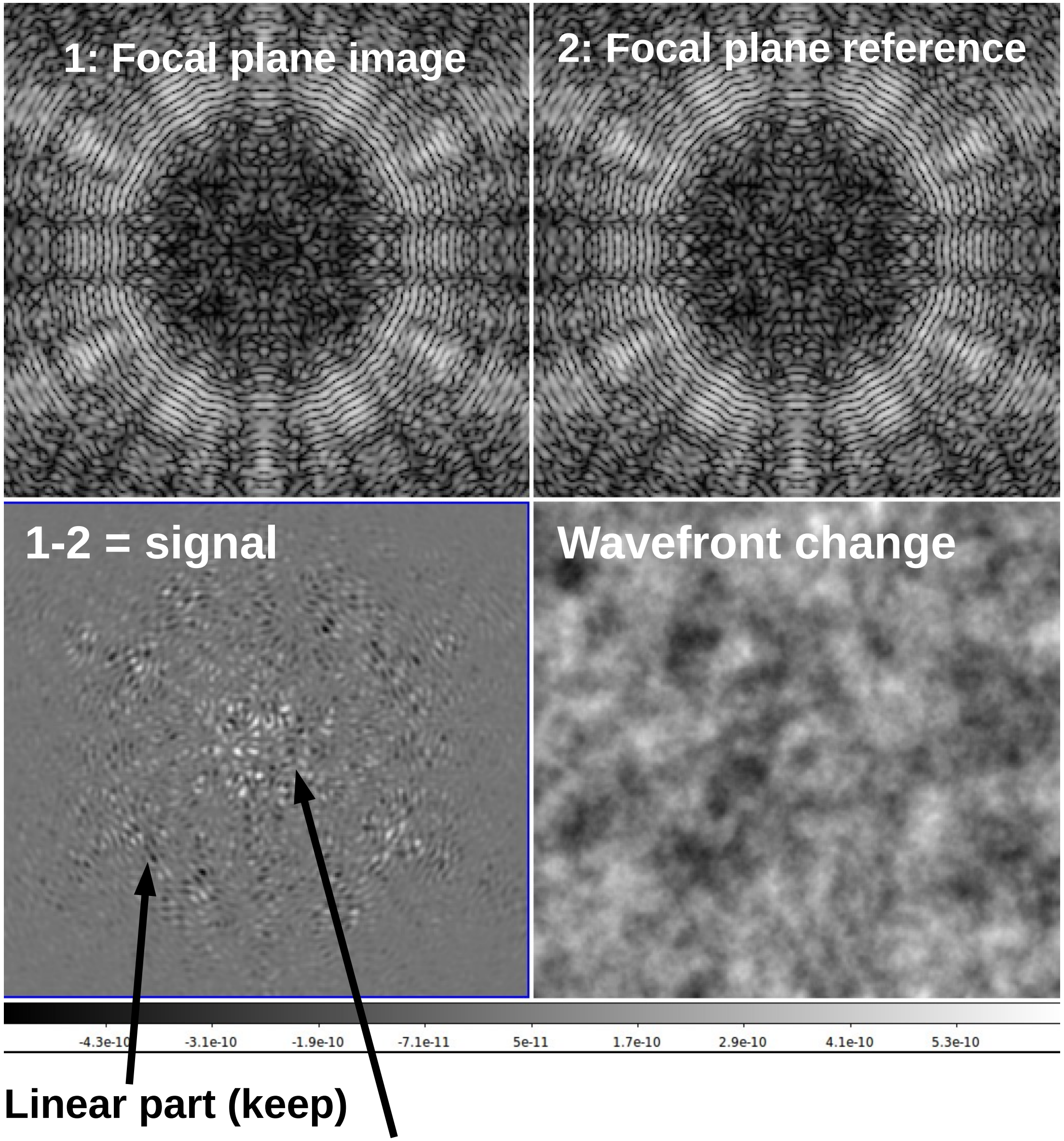
Intensity of speckles outside geometric DF is a linear function of wavefront errors

dark field (DF) speckles

Intensity of speckles outside spectral range is a linear function of wavefront errors

HCIT PIAA images

LDFC steps



Linear part (keep)

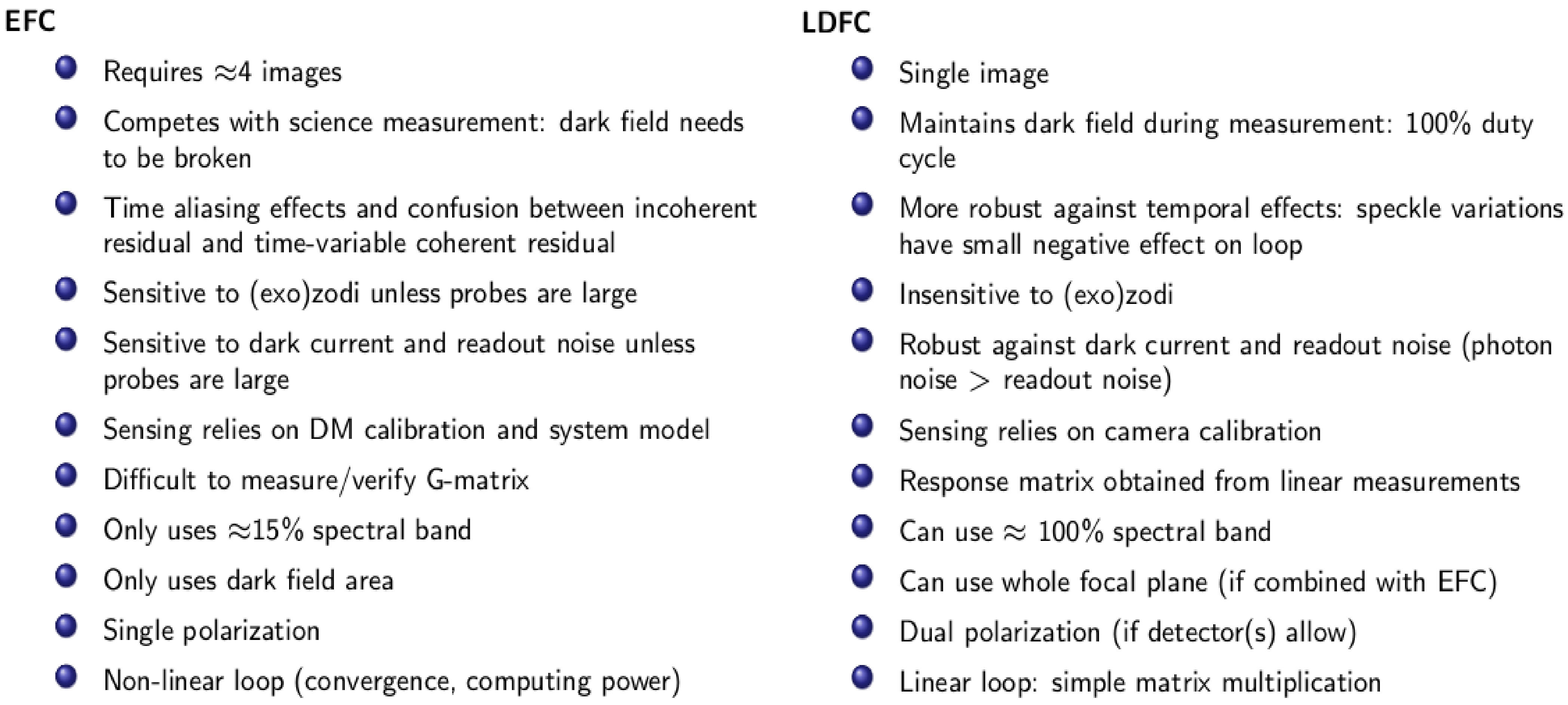
Non-linear part (ignore)

STEPS:

- Take an image
- Subtract reference: this is our signal
- Multiply signal by reconstruction (control) matrix
- Apply DM correction

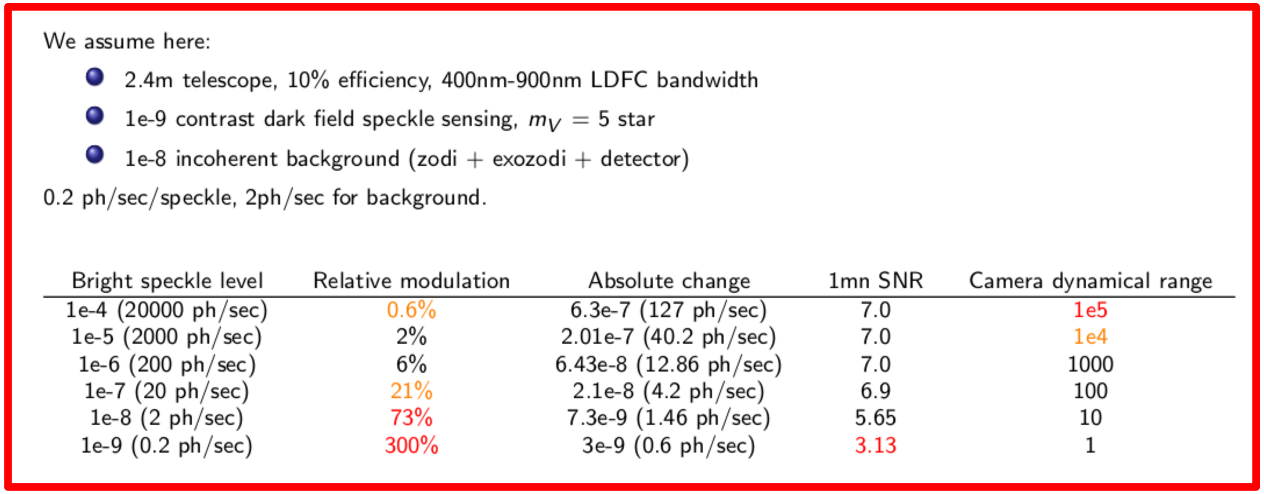
LDFC vs. EFC

LDFC improves wavefront control loop speed by ~20x (more starlight is used for the measurement) and does not require DM modulation.
Linear loop is simpler, more robust that state of the art.



EFC	LDFC
Requires ≈4 images	Single image
Competes with science measurement: dark field needs to be broken	Maintains dark field during measurement: 100% duty cycle
Time aliasing effects and confusion between incoherent residual and time-variable coherent residual	More robust against temporal effects: speckle variations have small negative effect on loop
Sensitive to (exo)zodi unless probes are large	Insensitive to (exo)zodi
Sensitive to dark current and readout noise unless probes are large	Robust against dark current and readout noise (photon noise > readout noise)
Sensing relies on DM calibration and system model	Sensing relies on camera calibration
Difficult to measure/verify G-matrix	Response matrix obtained from linear measurements
Only uses ≈15% spectral band	Can use ≈ 100% spectral band
Only uses dark field area	Can use whole focal plane (if combined with EFC)
Single polarization	Dual polarization (if detector(s) allow)
Non-linear loop (convergence, computing power)	Linear loop: simple matrix multiplication

Application to NASA missions



We assume here:

- 2.4m telescope, 10% efficiency, 400nm-900nm LDFC bandwidth
- 1e-9 contrast dark field speckle sensing, $m_V = 5$ star
- 1e-8 incoherent background (zodi + exozodi + detector)

0.2 ph/sec/speckle, 2ph/sec for background.

Bright speckle level	Relative modulation	Absolute change	1mn SNR	Camera dynamical range
1e-4 (20000 ph/sec)	0.6%	6.3e-7 (127 ph/sec)	7.0	1e5
1e-5 (2000 ph/sec)	2%	2.01e-7 (40.2 ph/sec)	7.0	1e4
1e-6 (200 ph/sec)	6%	6.43e-8 (12.86 ph/sec)	7.0	1000
1e-7 (20 ph/sec)	21%	2.1e-8 (4.2 ph/sec)	6.9	100
1e-8 (2 ph/sec)	73%	7.3e-9 (1.46 ph/sec)	5.65	10
1e-9 (0.2 ph/sec)	300%	3e-9 (0.6 ph/sec)	3.13	1

Case study for WFIRST:

LDFC control bandwidth is 10mn, compared to several hr for state of the art EFC

Key benefits:

- LDFC enables close loop aberration control on science targets, as opposed to the current “set and forget” scheme → deeper contrast can be maintained, and system can be more resilient to small wavefront changes
- LDFC is also a powerful aid to PSF calibration. During science exposures, LDFC images provide live telemetry of wavefront changes.

LDFC is particularly well suited to track cophasing errors on a segmented aperture, using diffraction features created by segments

Observation mode

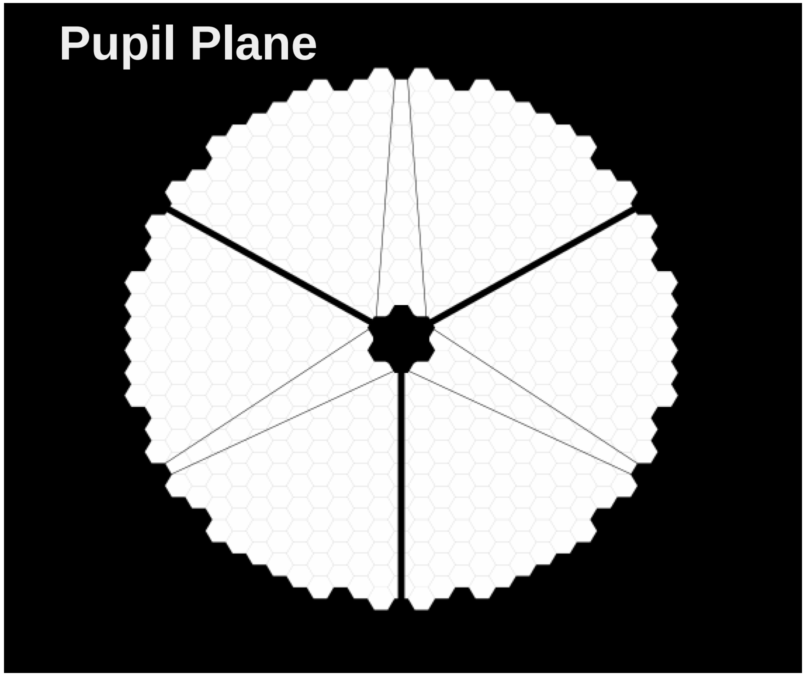
EFC + LDFC calibration on bright source, LDFC on science target:

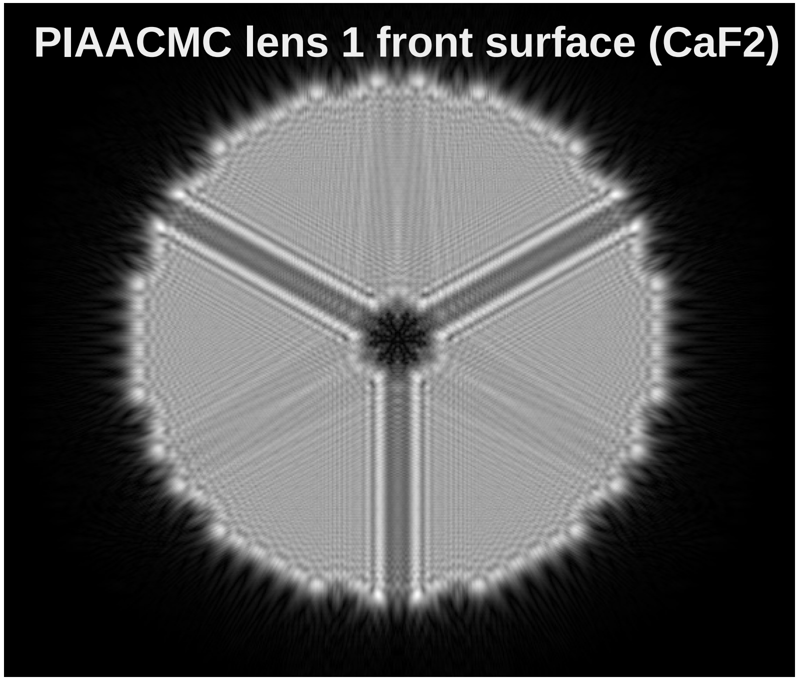
(1) Perform EFC on bright target
(2) Record bright speckles after EFC converges: this is the reference
(3) Modulate DM actuators, record response matrix
(4) Point to “faint” science target
(5) Close LDFC loop to match reference
(6) Optional: Run slow EFC in background, while LDFC is running

LDFC stability condition
Holding bright speckles static (LDFC) will maintain dark hole as long as relationship between bright and dark speckles is constant (analogous to G-matrix stability requirement): this is likely to hold for long periods of time

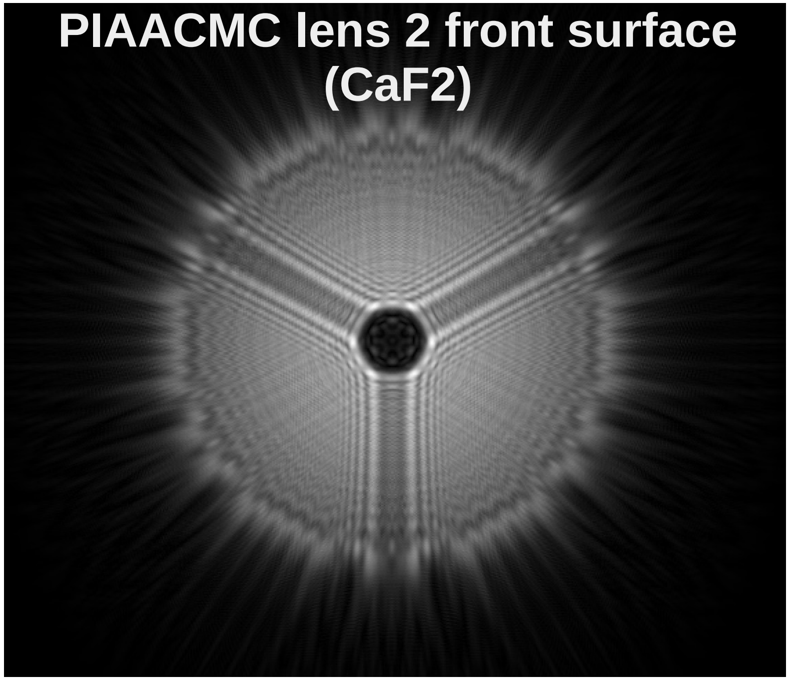
Large Ground-based segmented apertures

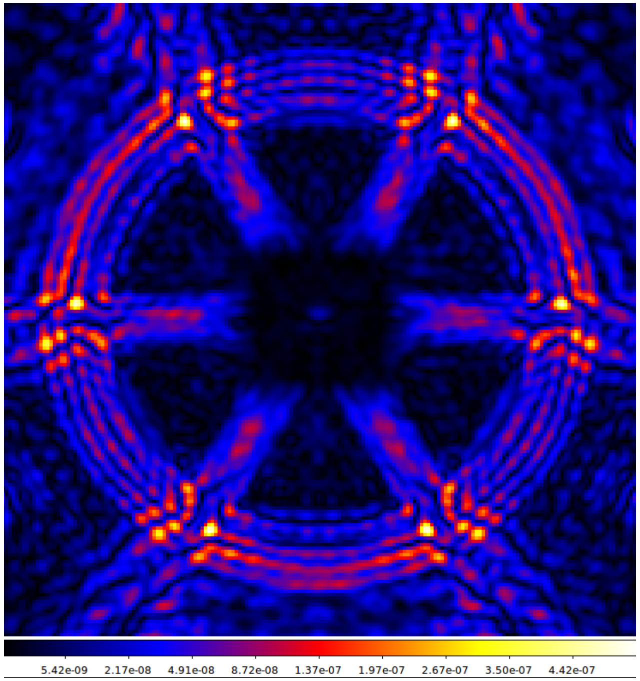
TMT coronagraph design for 1 l/D IWA


Pupil Plane


PIAACMC lens 1 front surface (CaF2)

To be updated with new pupil shape


PIAACMC lens 2 front surface (CaF2)



PSF at 1600nm

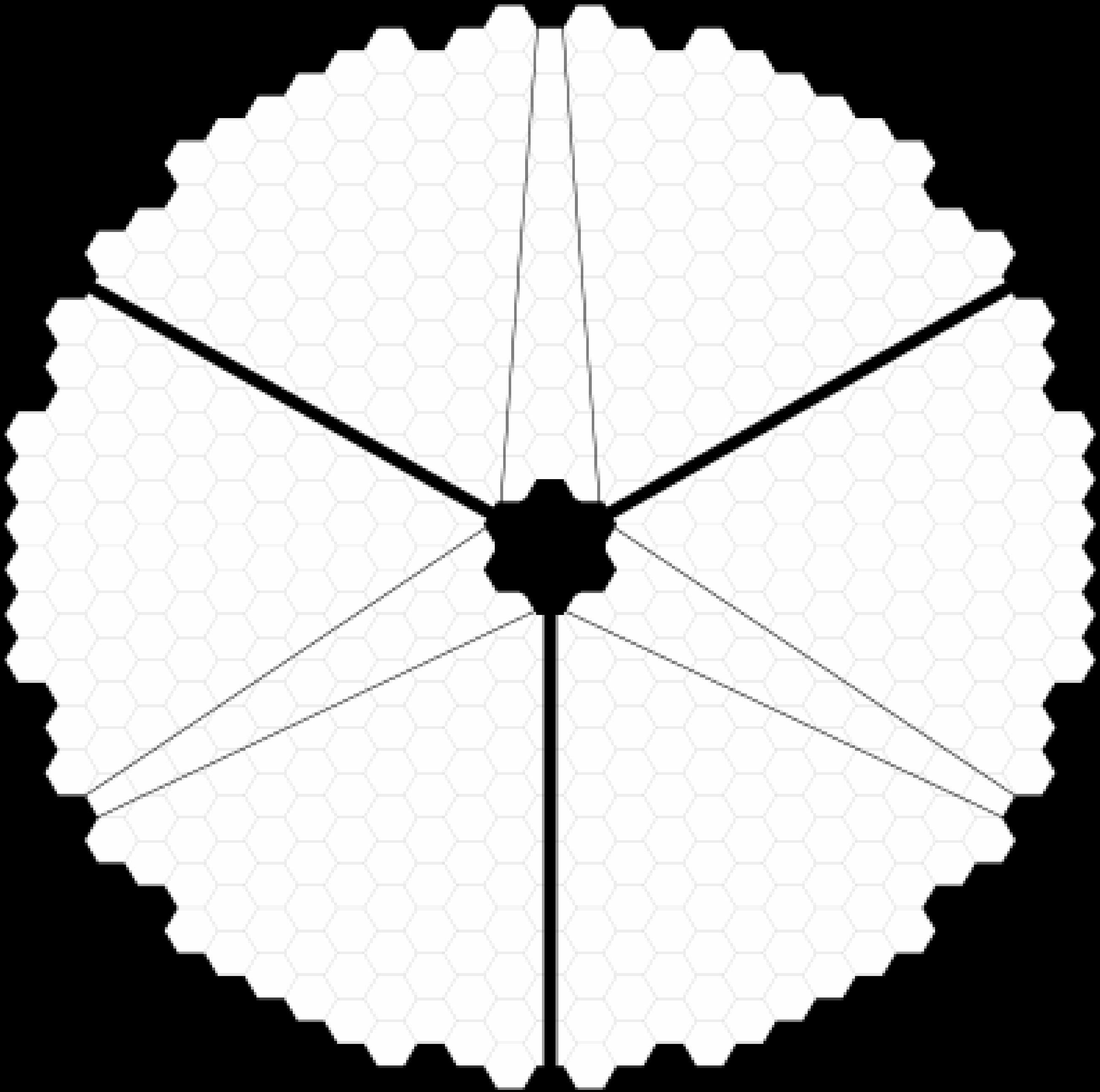
3e-9 contrast in 1.2 to 8 l/D

80% off-axis throughput

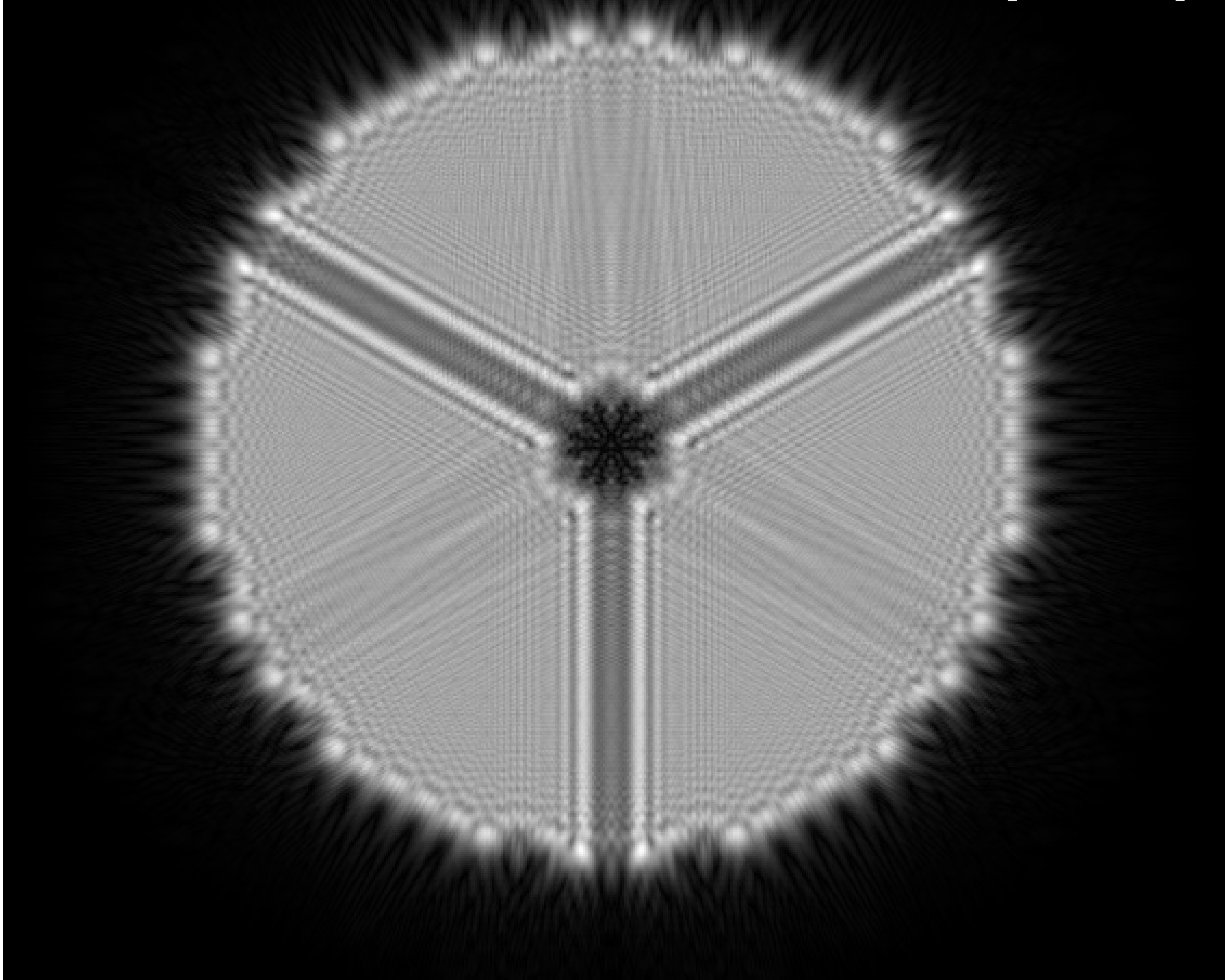
1.2 l/D IWA

CaF2 lenses
SiO2 mask

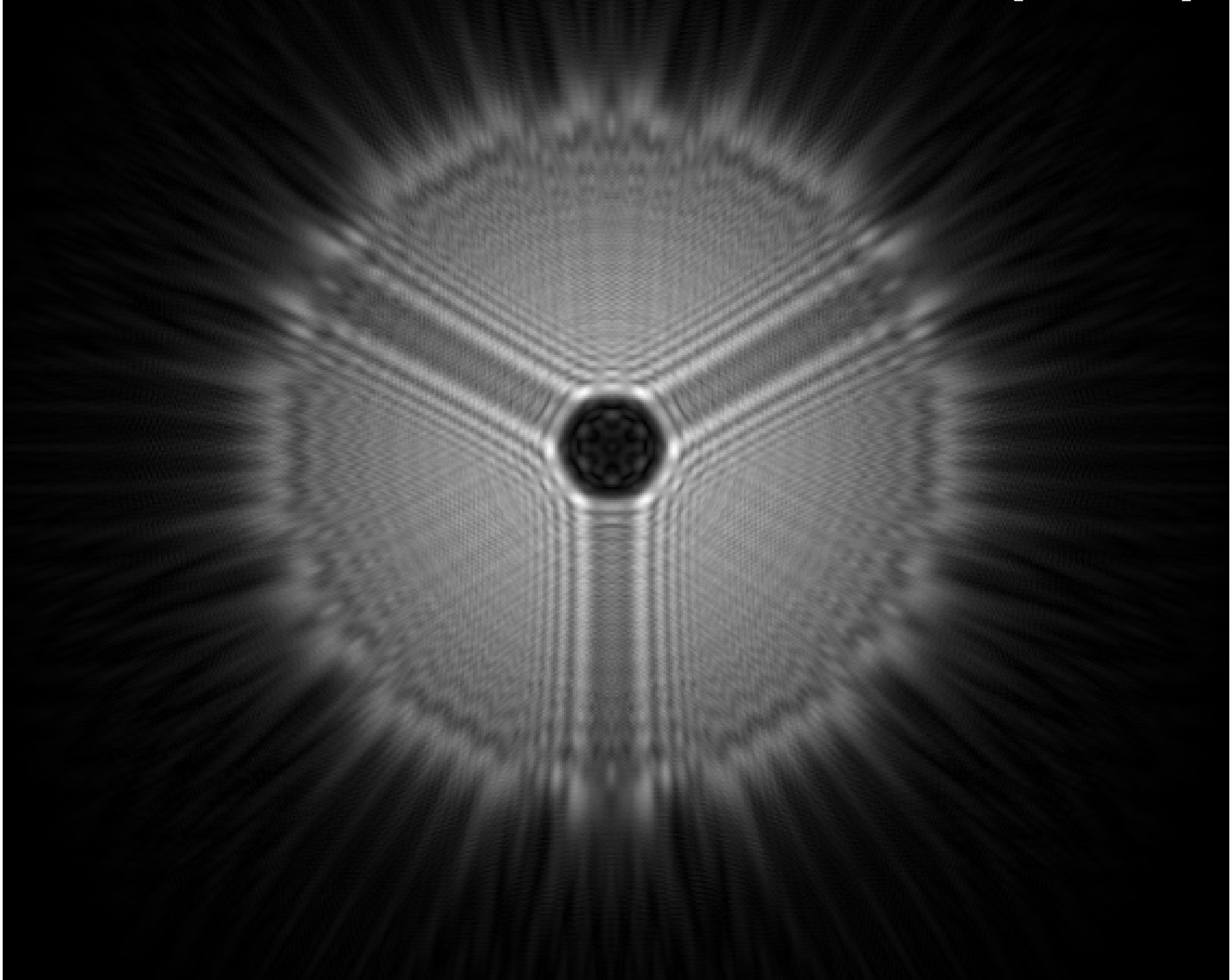
Pupil Plane



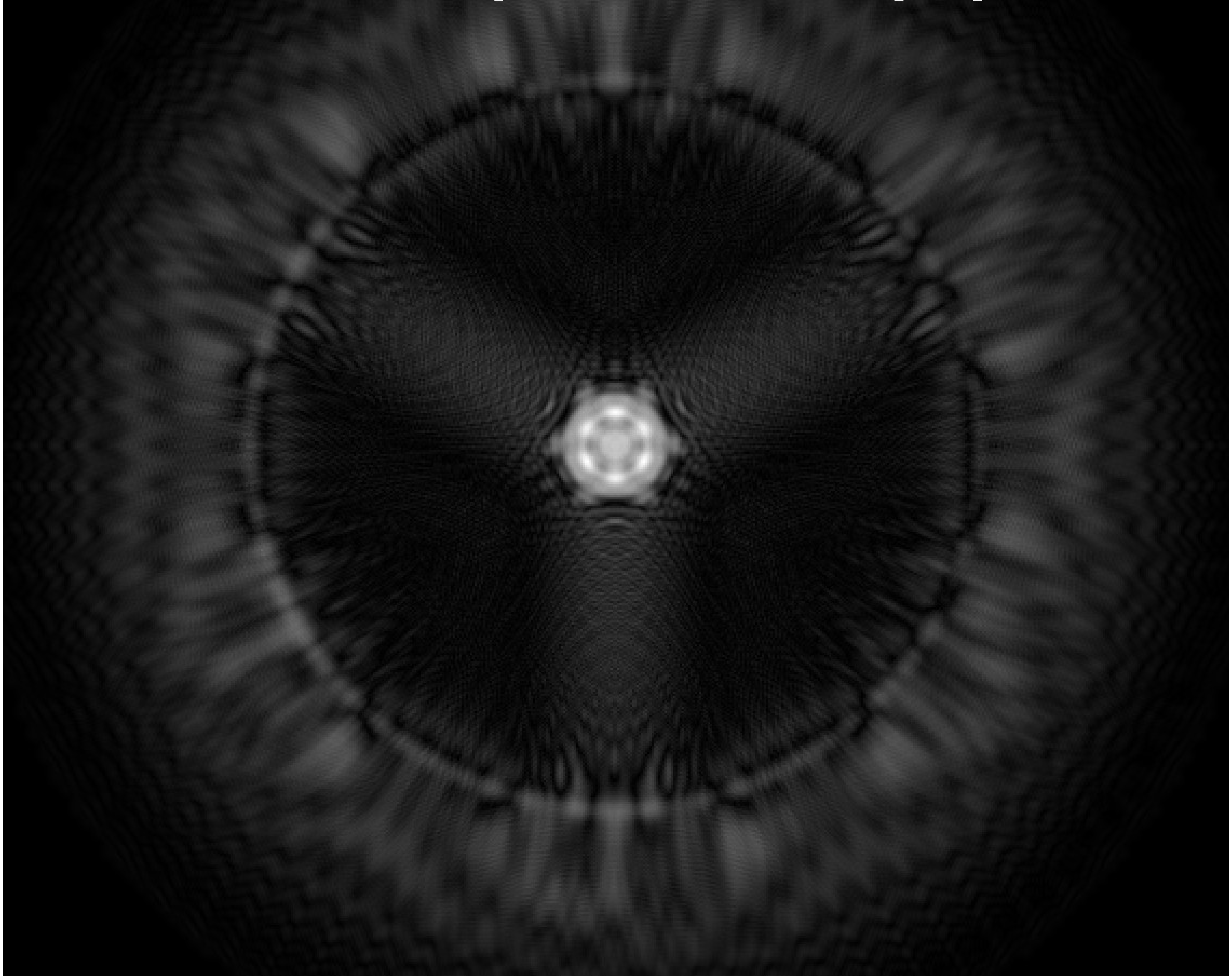
PIAACMC lens 1 front surface (CaF2)



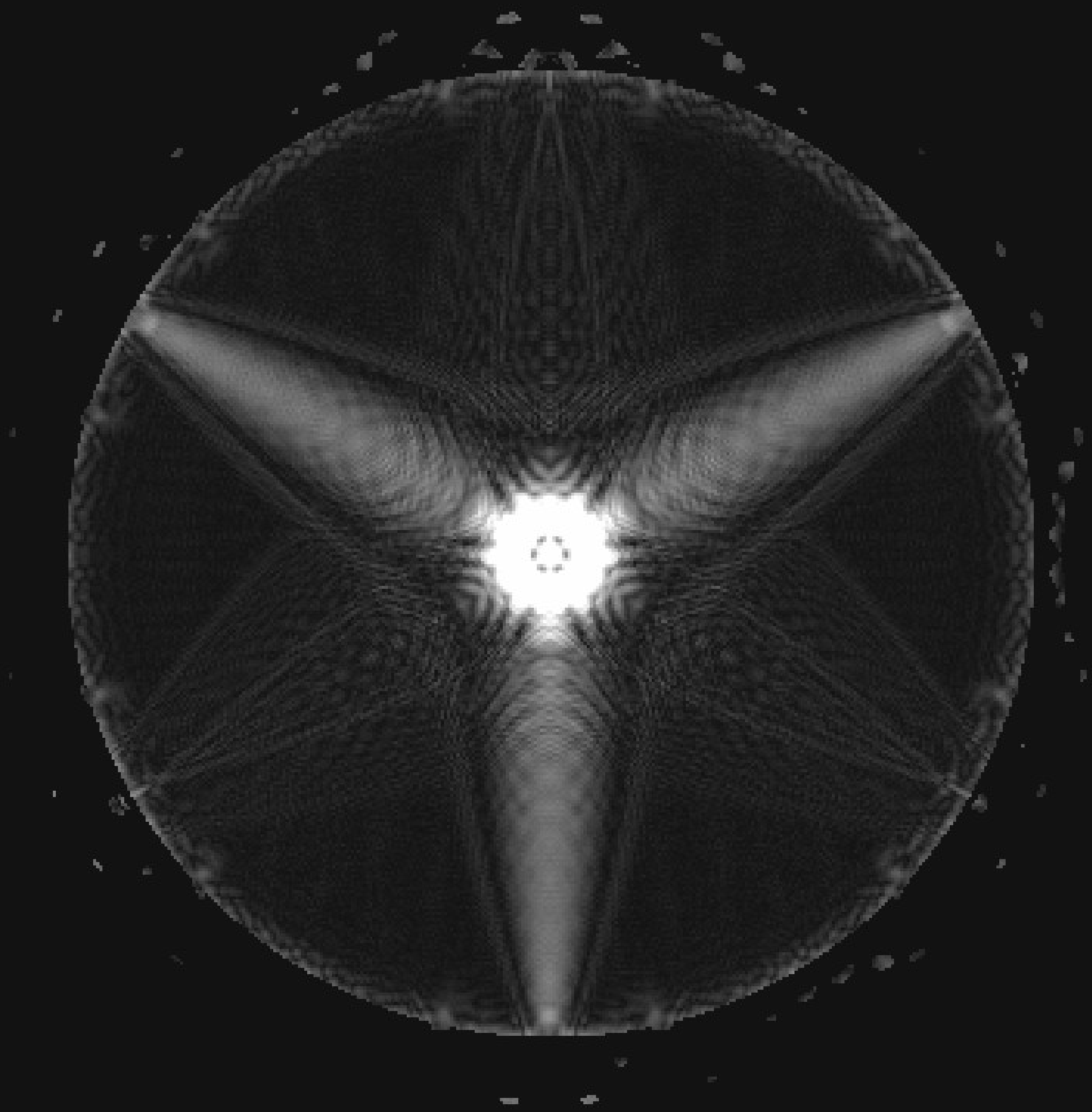
PIAACMC lens 2 front surface (CaF2)



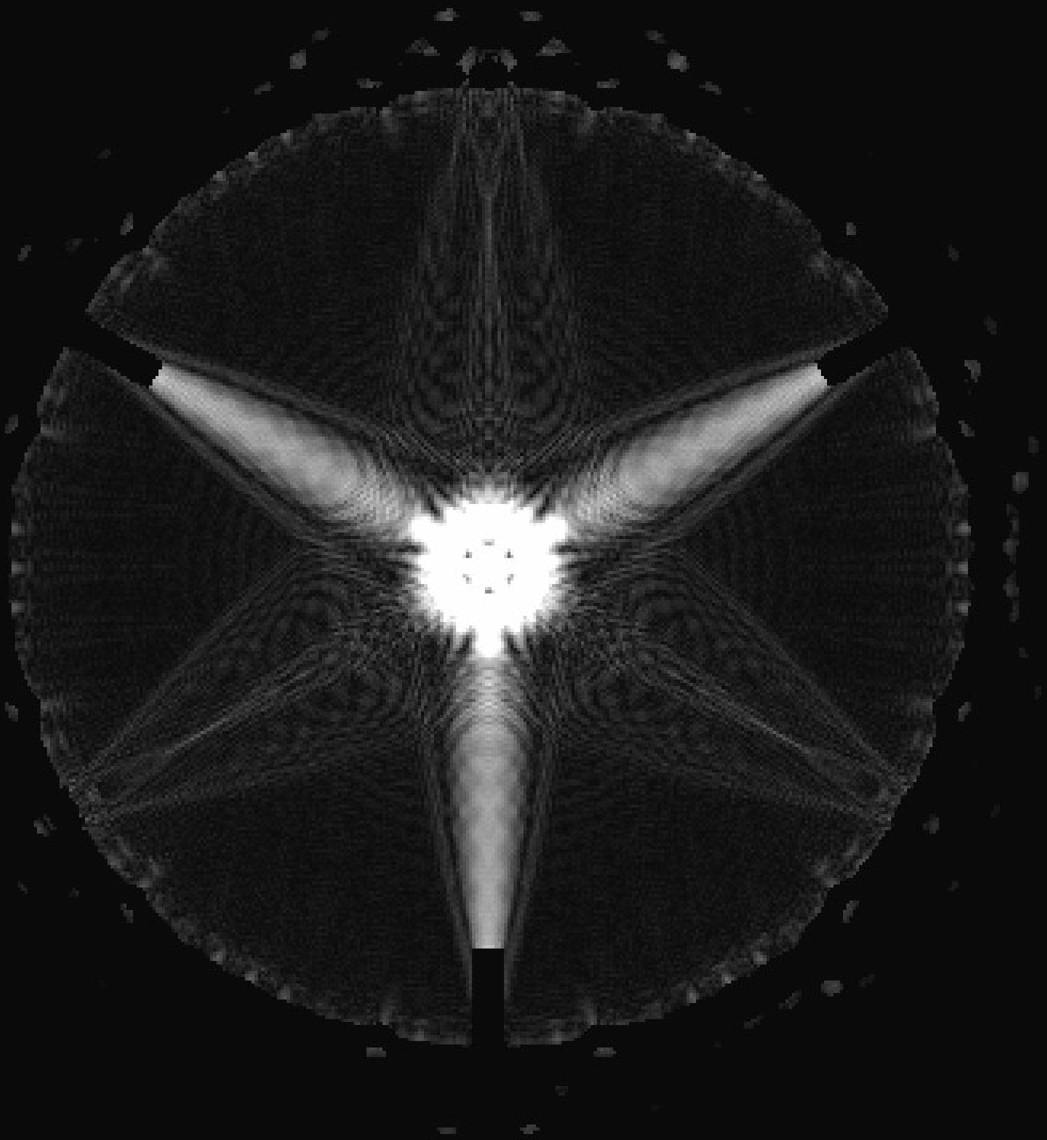
Post focal plane mask “pupil”



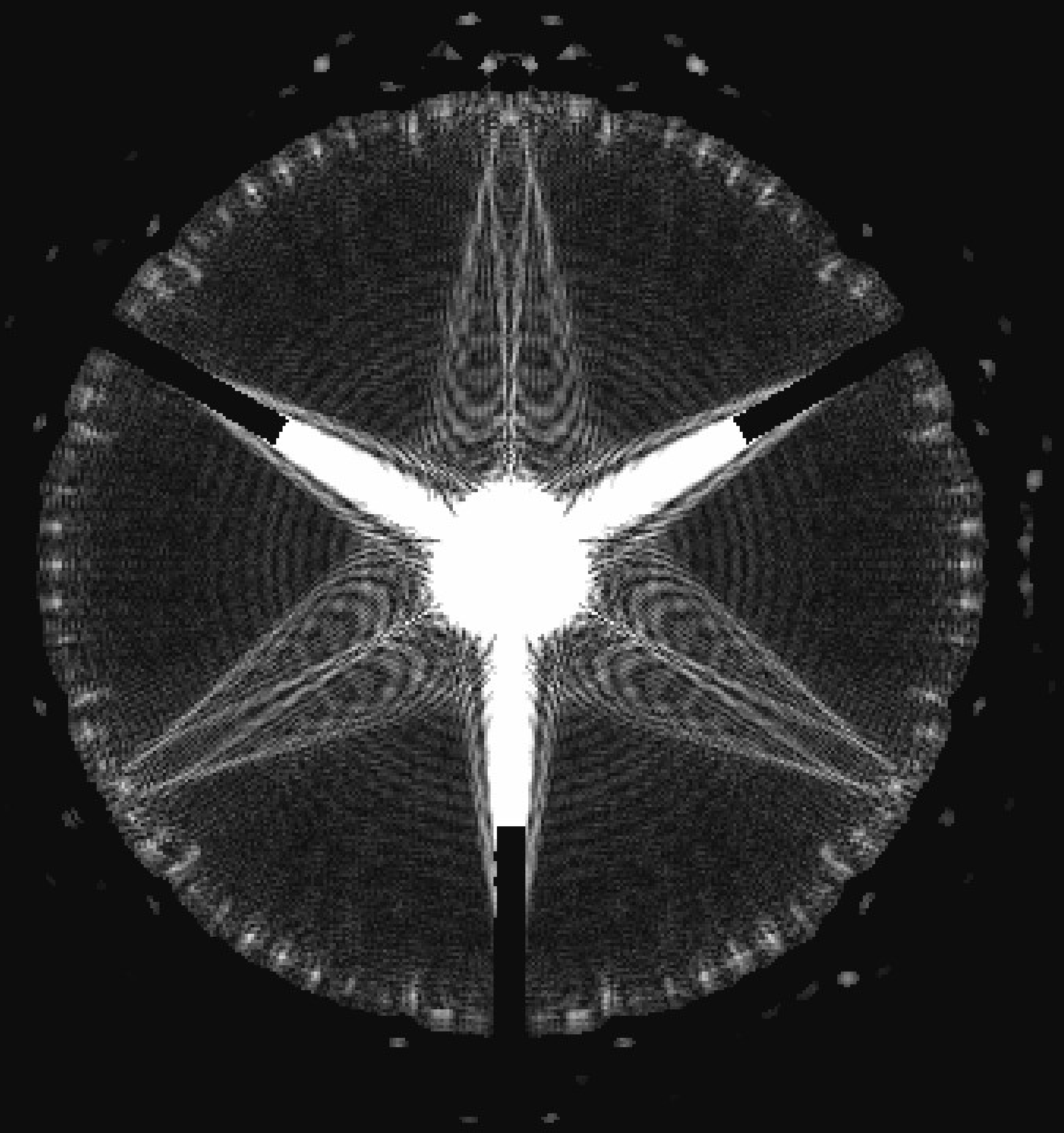
Stop #1



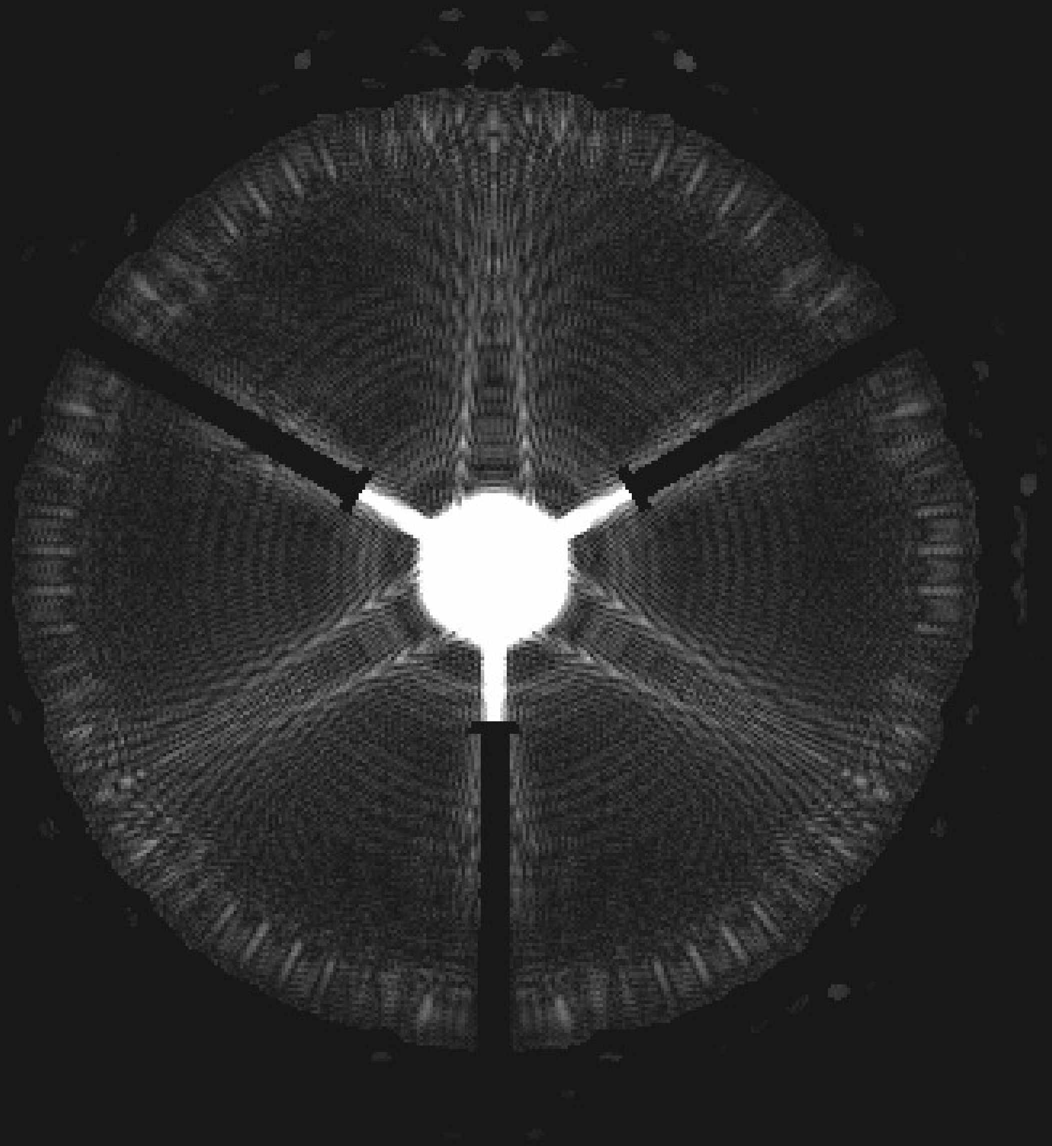
Stop #2



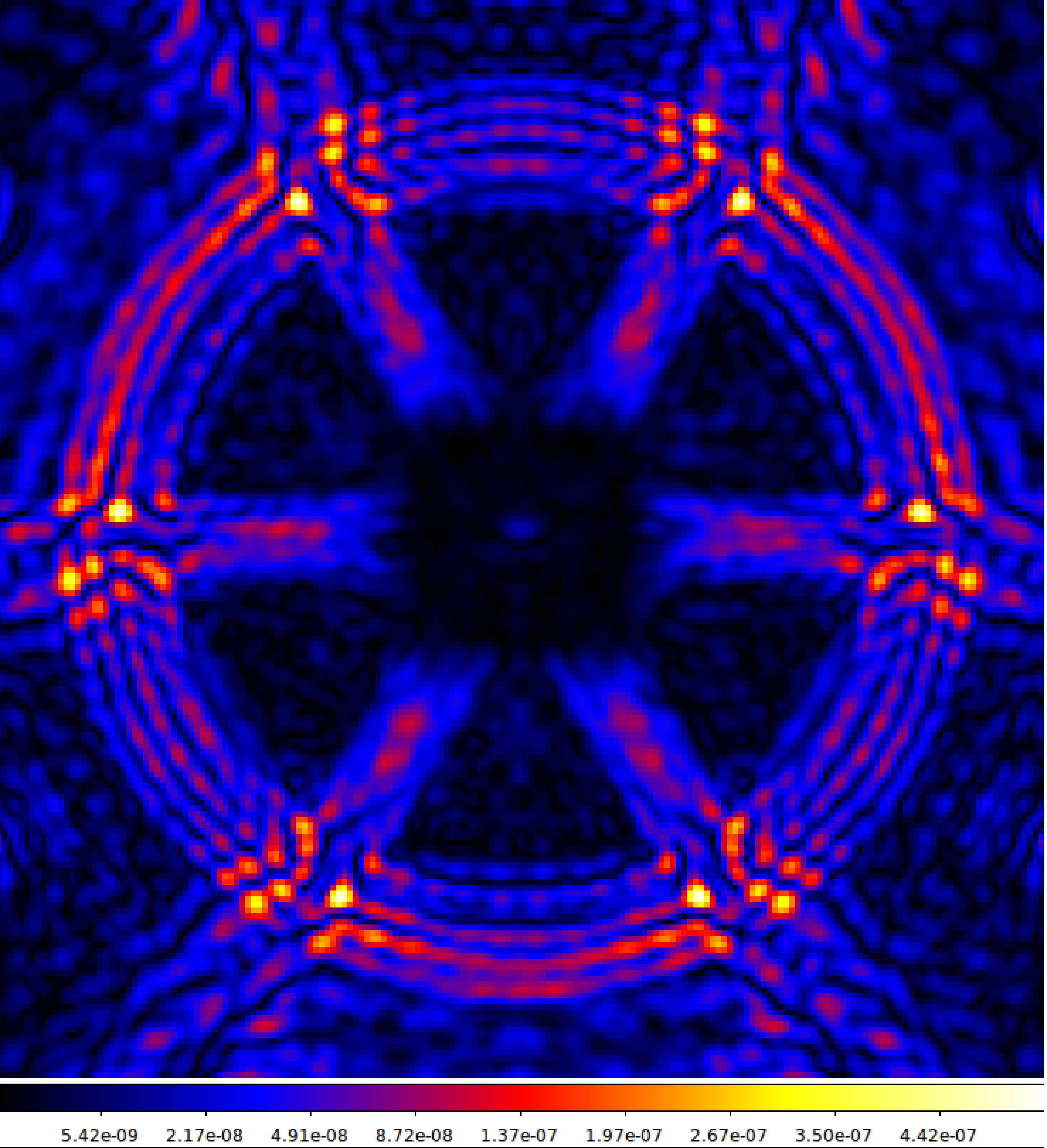
Stop #3



Stop #4



Stop #5



PSF at 1600nm

3e-9 contrast in 1.2-8 l/D

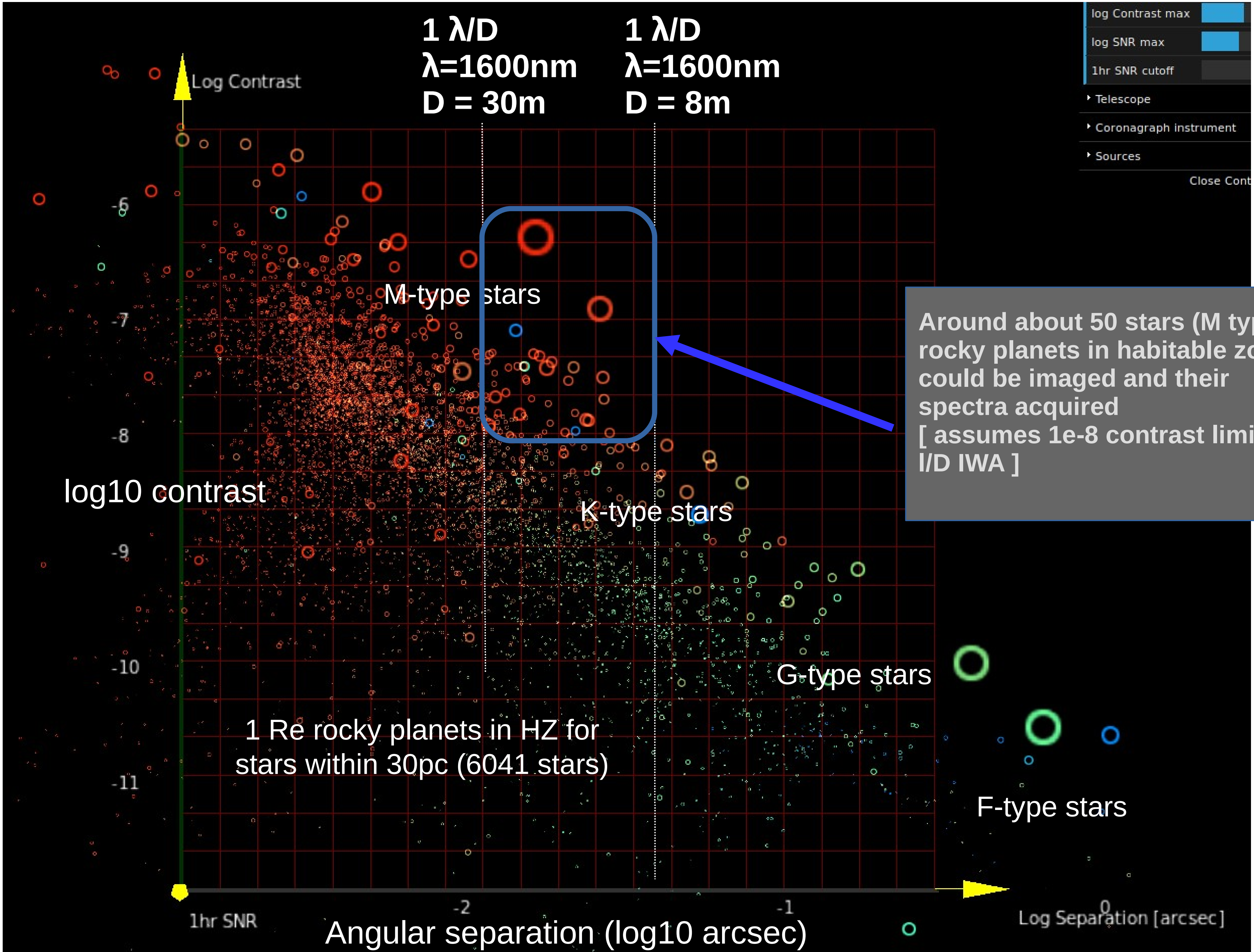
80% off-axis throughput

1.2 l/D IWA

CaF2 lenses
SiO2 mask

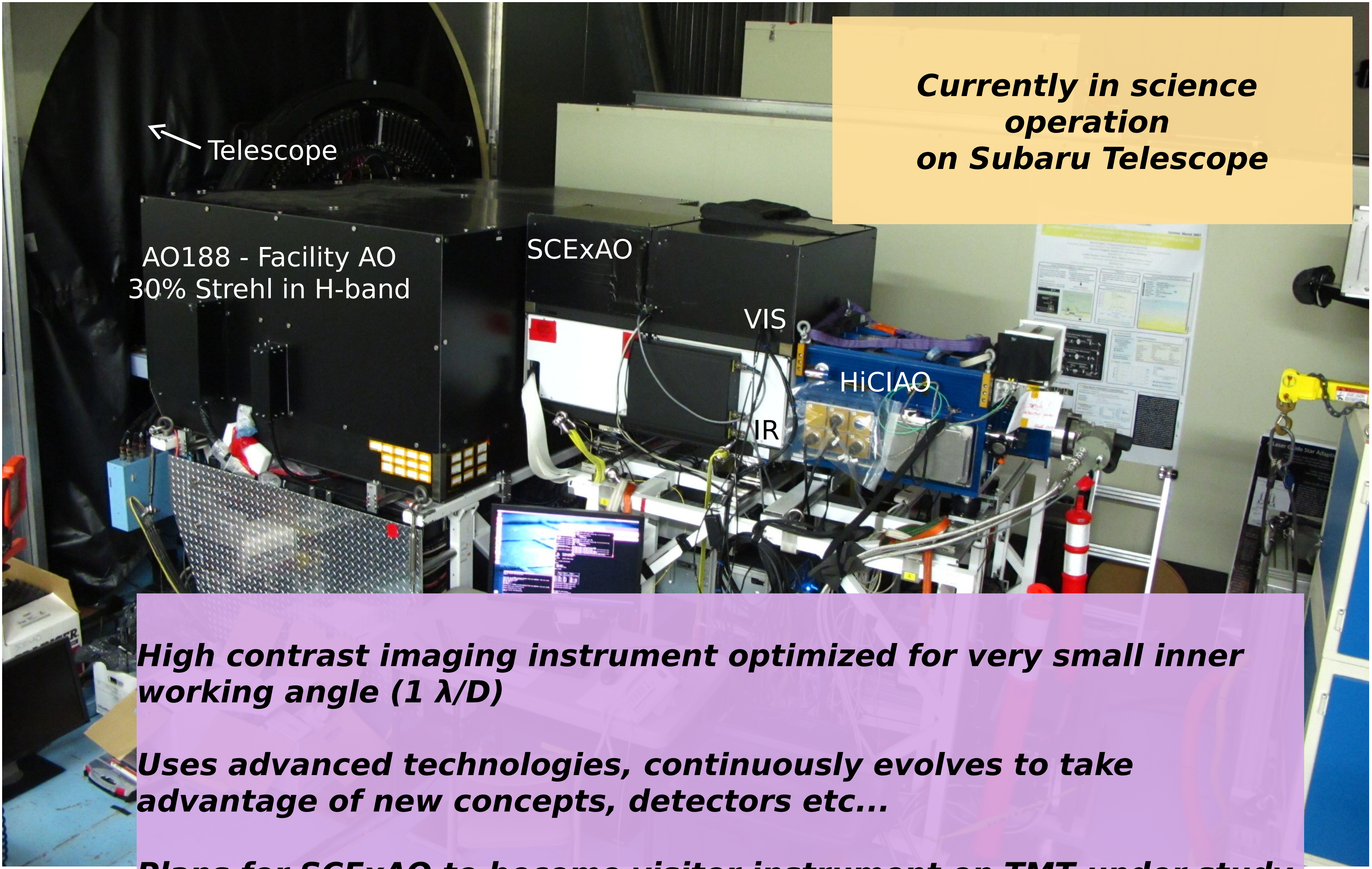
Space / Ground complementarity

Most exciting science case: spectroscopic characterization of Earth-sized planets with TMT



Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [assumes 1e-8 contrast limit, 1 l/D IWA]

Subaru Coronagraphic Extreme AO (SCExAO)



Currently in science operation on Subaru Telescope

High contrast imaging instrument optimized for very small inner working angle (1 λ/D)

Uses advanced technologies, continuously evolves to take advantage of new concepts, detectors etc...

Plans for SCExAO to become visitor instrument on TMT under study
→ will submit to TMT technical and scientific proposal

Wavefront sensing:

- Non-modulated pyramid WFS (VIS)
- Coronagraphic low order wavefront sensor (IR) for non-common tip/tilt errors
- Near-IR speckle control

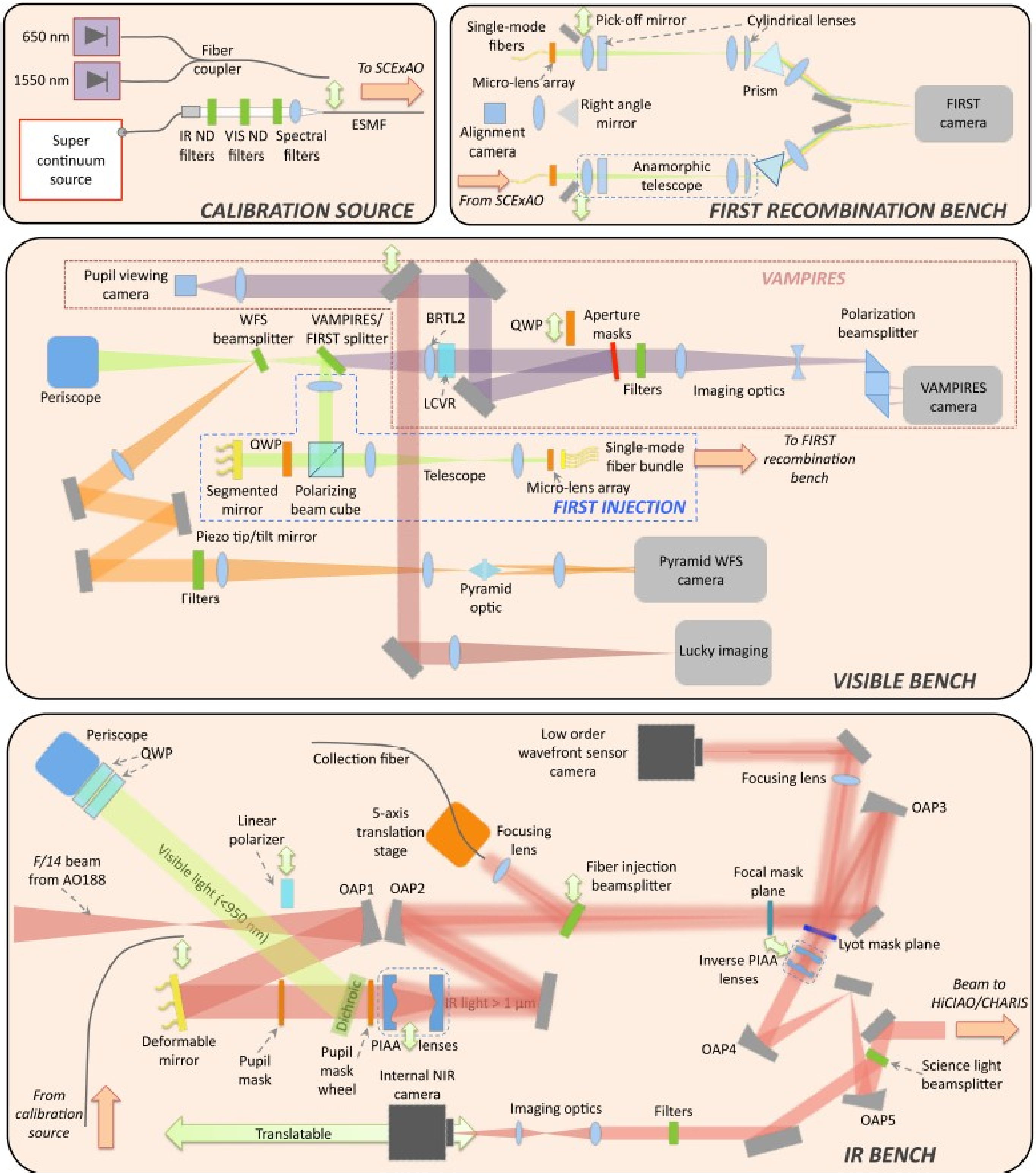
2k MEMS DM

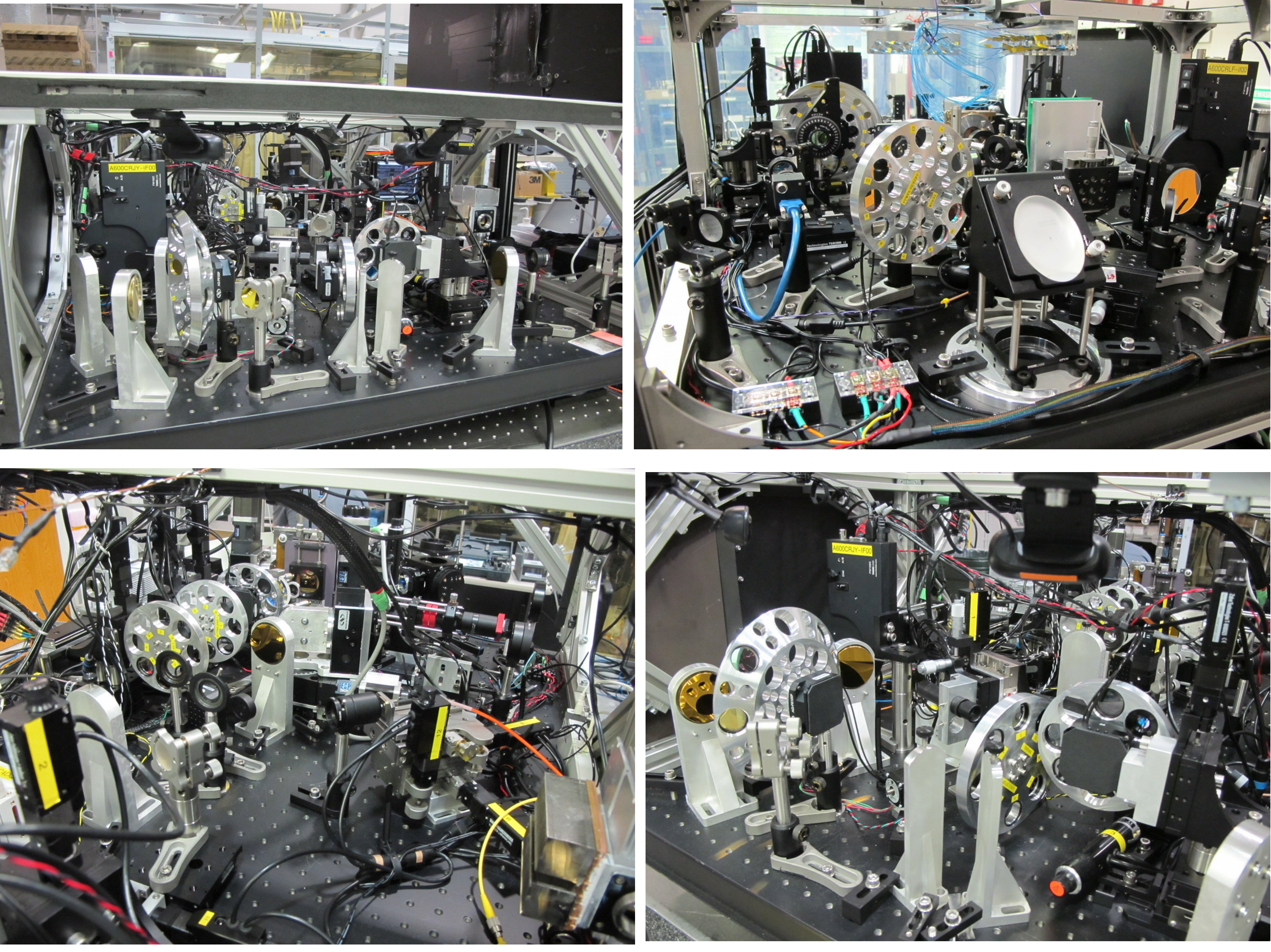
Numerous **coronagraphs** – PIAA, Vector Vortex, 4QPM, 8OPM, shaped pupil (IR)

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetory Signatures (VAMPIRES) (VIS)

Fibered Imager for a Single Telescope (FIRST) (VIS)
Fourier Lucky imaging (VIS)

Broadband diffraction limited internal cal. Source + phase turbulence simulator




A600CRJY-IF00
A600CRLF-II00
A600CRJY-IF00

How SCExAO achieves high contrast

(1) Small IWA, high throughput Coronagraphy

→ removes diffraction (Airy rings), transmits r>1 l/D region

(2) Extreme-AO with fast diffraction-limited WFS

→ removes wavefront errors

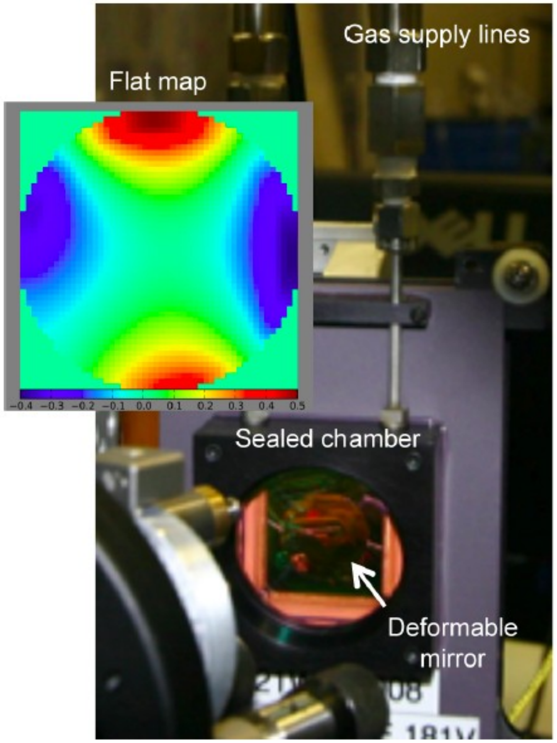
(3) Near-IR LOWFS

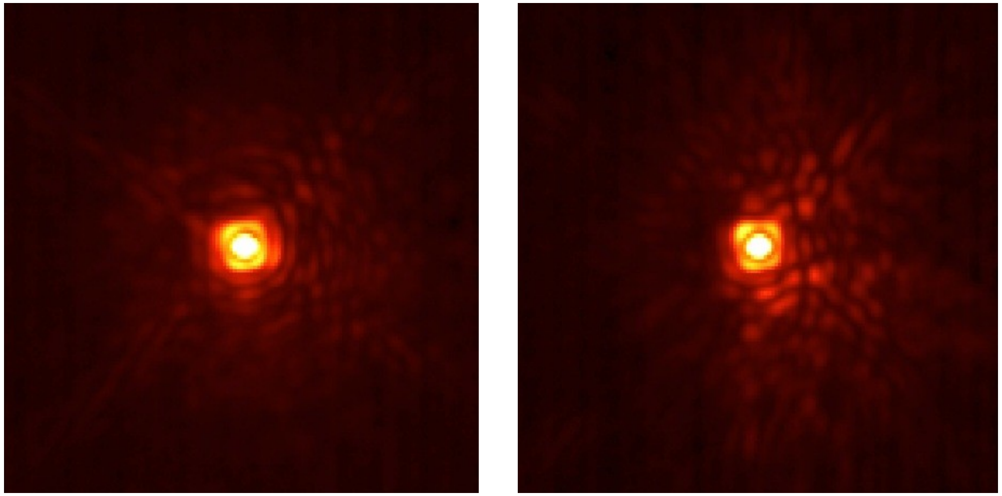
→ keeps star centered on coronagraph and controls Focus, Astig, etc..

→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control

→ modulates, removes and calibrates residual speckles





Speckle nulling on-sky

Conclusions, path forward

Exoplanet imaging science (yield <u>and</u> quality) increases steeply with aperture size. Large space telescope + coronagraph required for search of biomarkers on a sample of rocky planets in HZ of nearby stars

Two highest priority technologies:

Internal coronagraphs are compatible with segmented apertures. At least 2 concepts can be deployed on segmented aperture with little to no performance loss.
→ Need to continue / ramp up technology development effort for coronagraph and WFC on large space-based segmented apertures
→ Emulate/follow AFTA coronagraph process: simulation/science team evaluate designs, designers improve designs, lab demos with well-chosen milestones

A large segmented aperture for high contrast imaging requires a **stable ultra low-vibration primary mirror.**
→ Need engineering study + scaled lab demos