PIAACMC for Segmented Apertures

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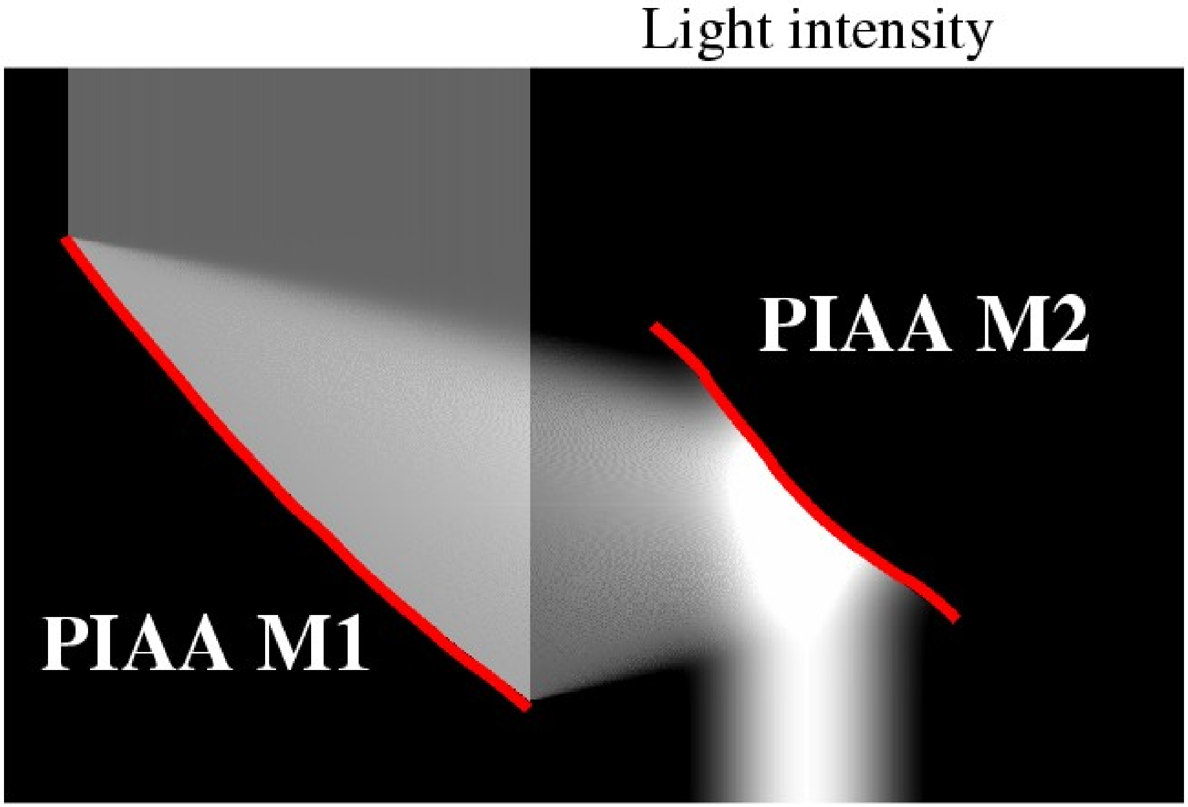
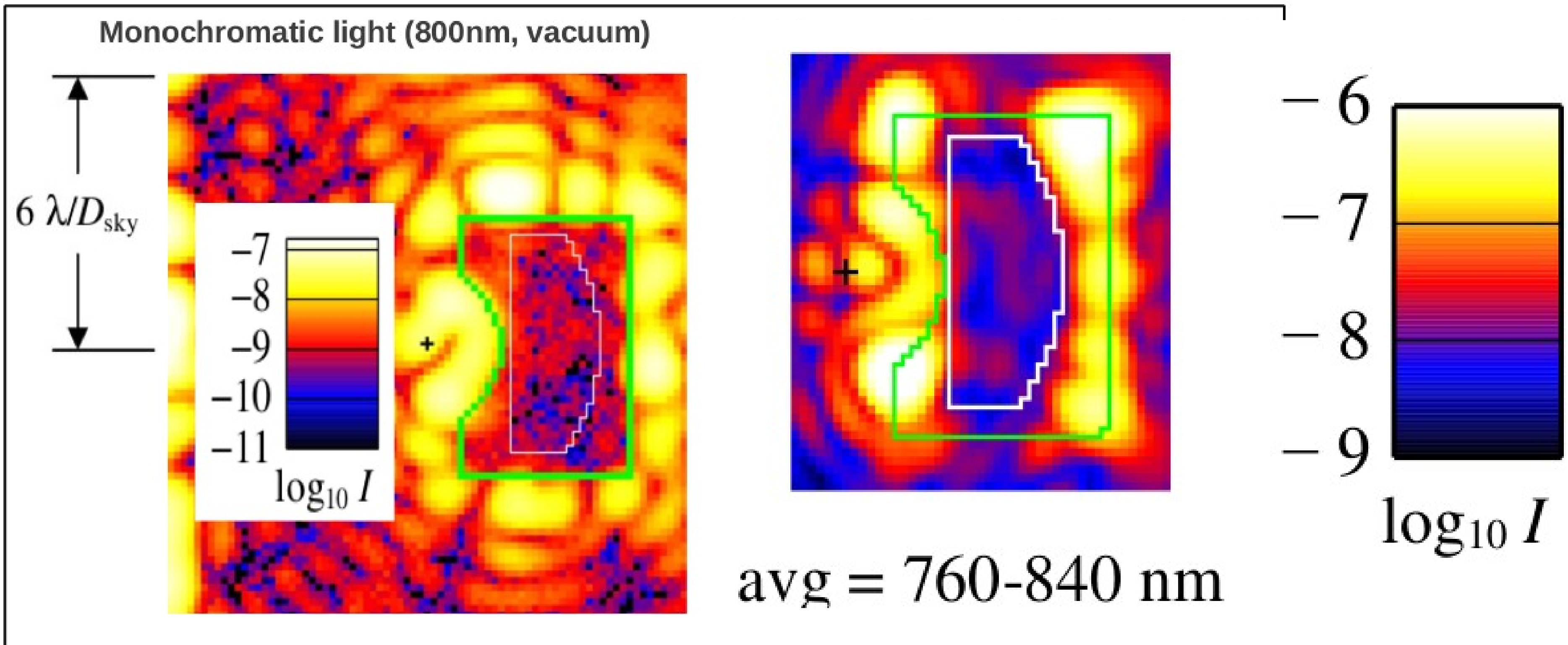
Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)



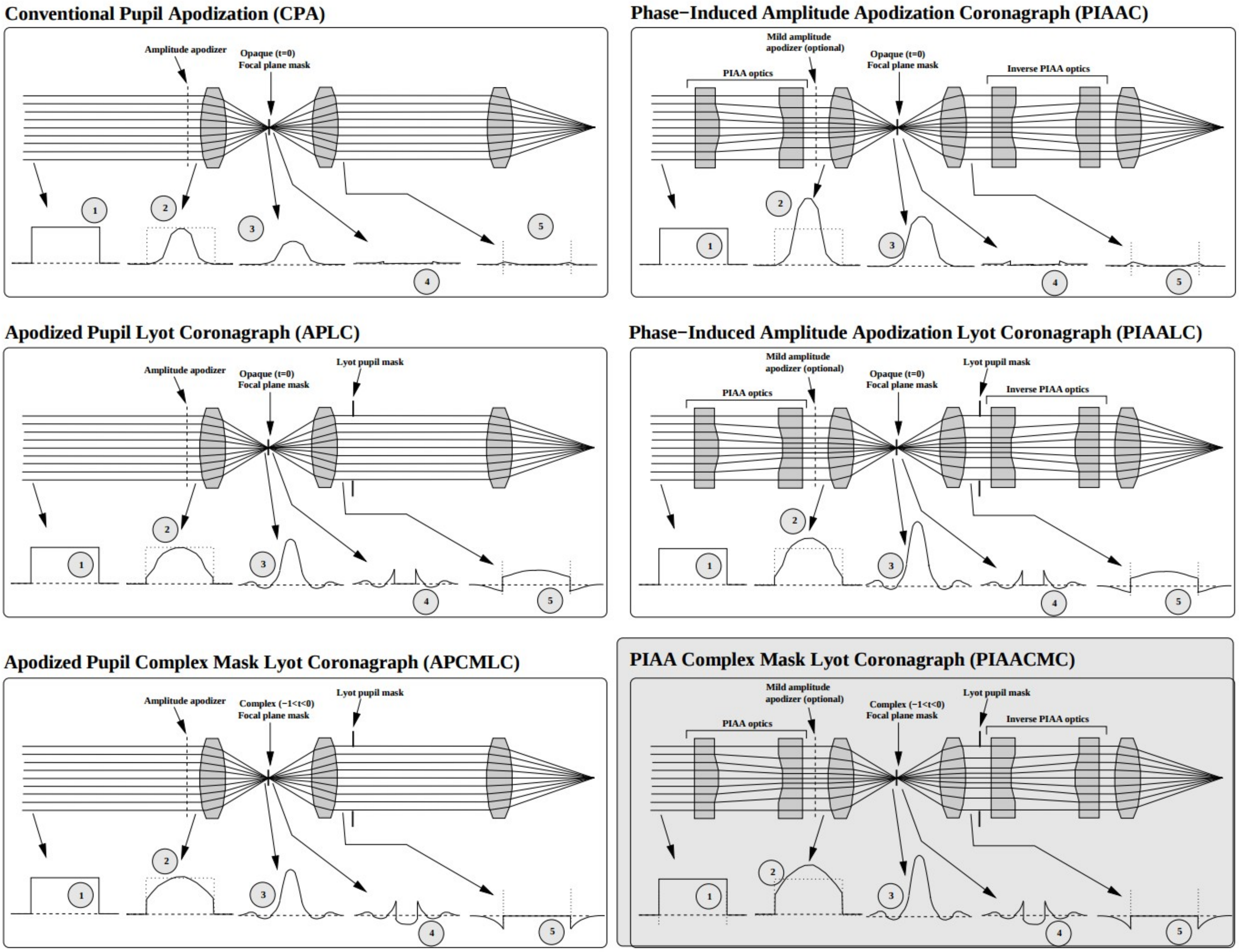
Uses lenses or mirrors for lossless beam apodization

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


Conventional Pupil Apodization (CPA)
Amplitude apodizer
Opaque (t=0)
Focal plane mask
1
2
3
4
5
Phase−Induced Amplitude Apodization Coronagraph (PIAAC)
Mild amplitude
apodizer (optional)
PIAA optics
Opaque (t=0)
Focal plane mask
Inverse PIAA optics
1
2
3
4
5
Apodized Pupil Lyot Coronagraph (APLC)
Amplitude apodizer
Opaque (t=0)
Focal plane mask
Lyot pupil mask
1
2
3
4
5
Phase−Induced Amplitude Apodization Lyot Coronagraph (PIAALC)
Mild amplitude
apodizer (optional)
PIAA optics
Opaque (t=0)
Focal plane mask
Lyot pupil mask
Inverse PIAA optics
1
2
3
4
5
Apodized Pupil Complex Mask Lyot Coronagraph (APCMLC)
Amplitude apodizer
Complex (−1<t<0)
Focal plane mask
Lyot pupil mask
1
2
3
4
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PIAA Complex Mask Lyot Coronagraph (PIAACMC)
Mild amplitude
apodizer (optional)
PIAA optics
Complex (−1<t<0)
Focal plane mask
Lyot pupil mask
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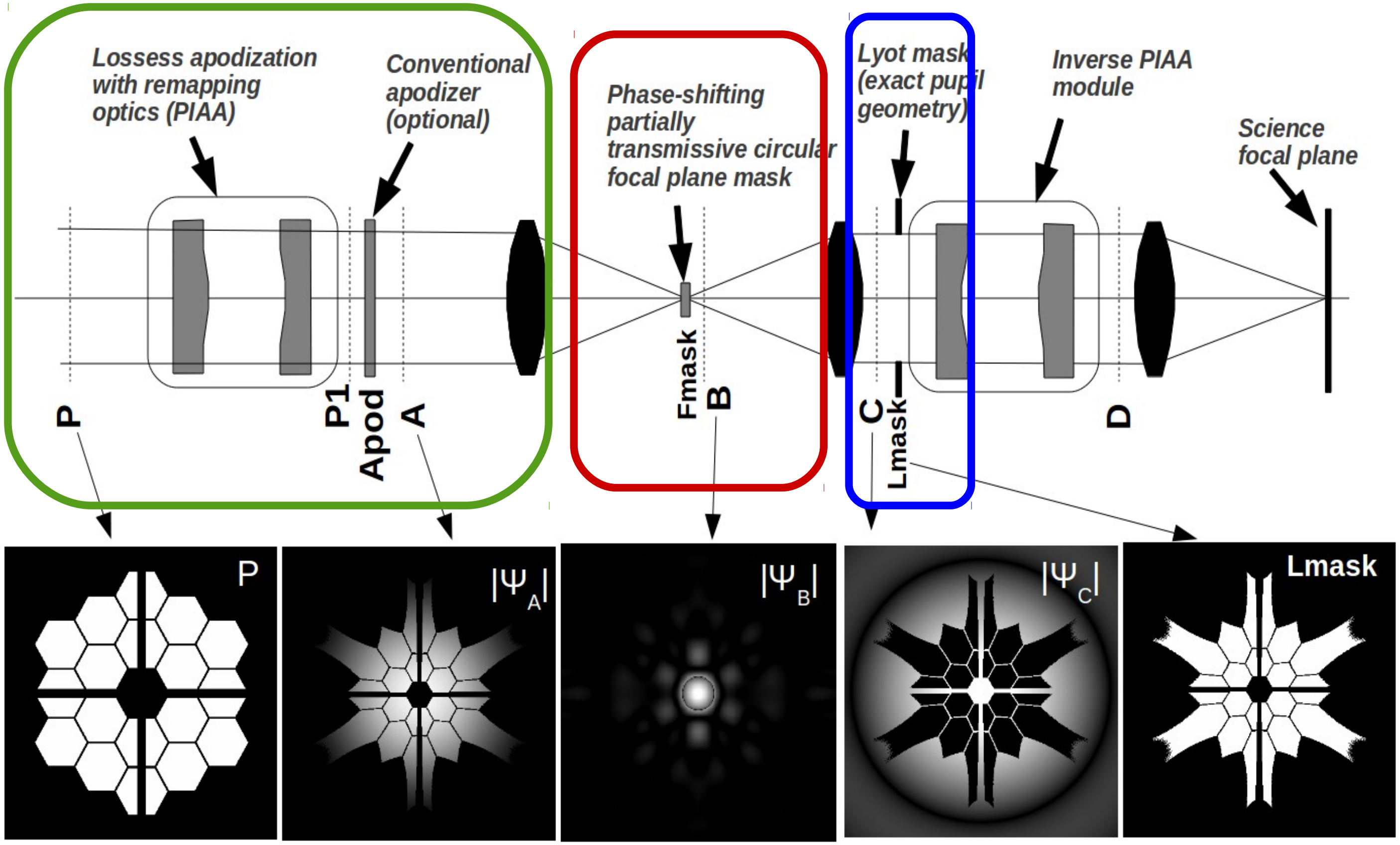
PIAACMC concept

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

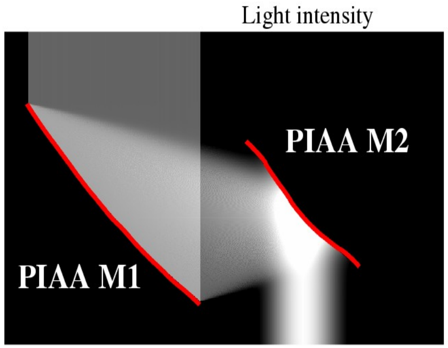


Achieves starlight suppression by combining:

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

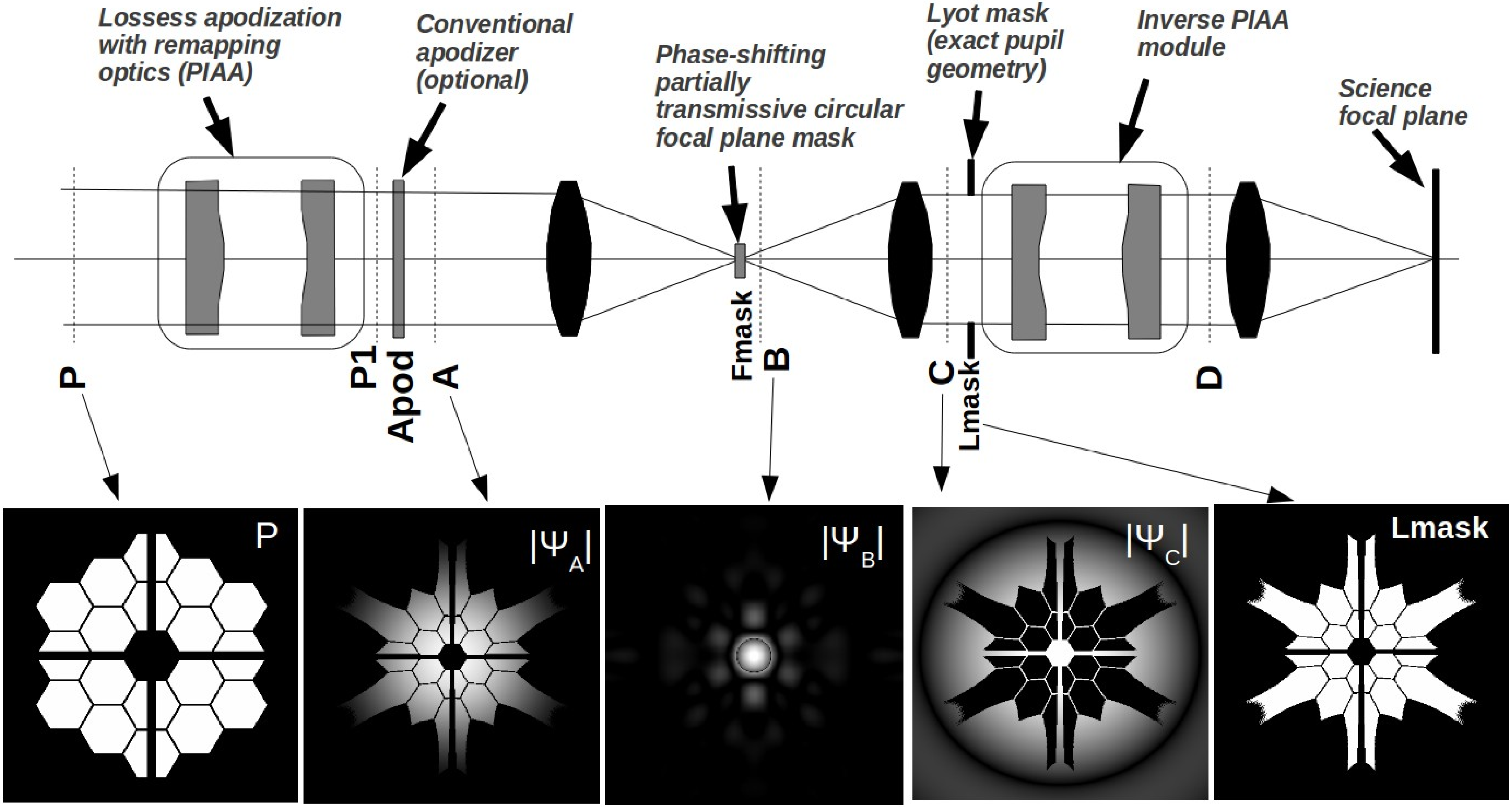
Focal plane mask
complex amplitude $-1<t<0$
Induces destructive interference inside downstream pupil

Lyot Stop
Blocks starlight



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

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)

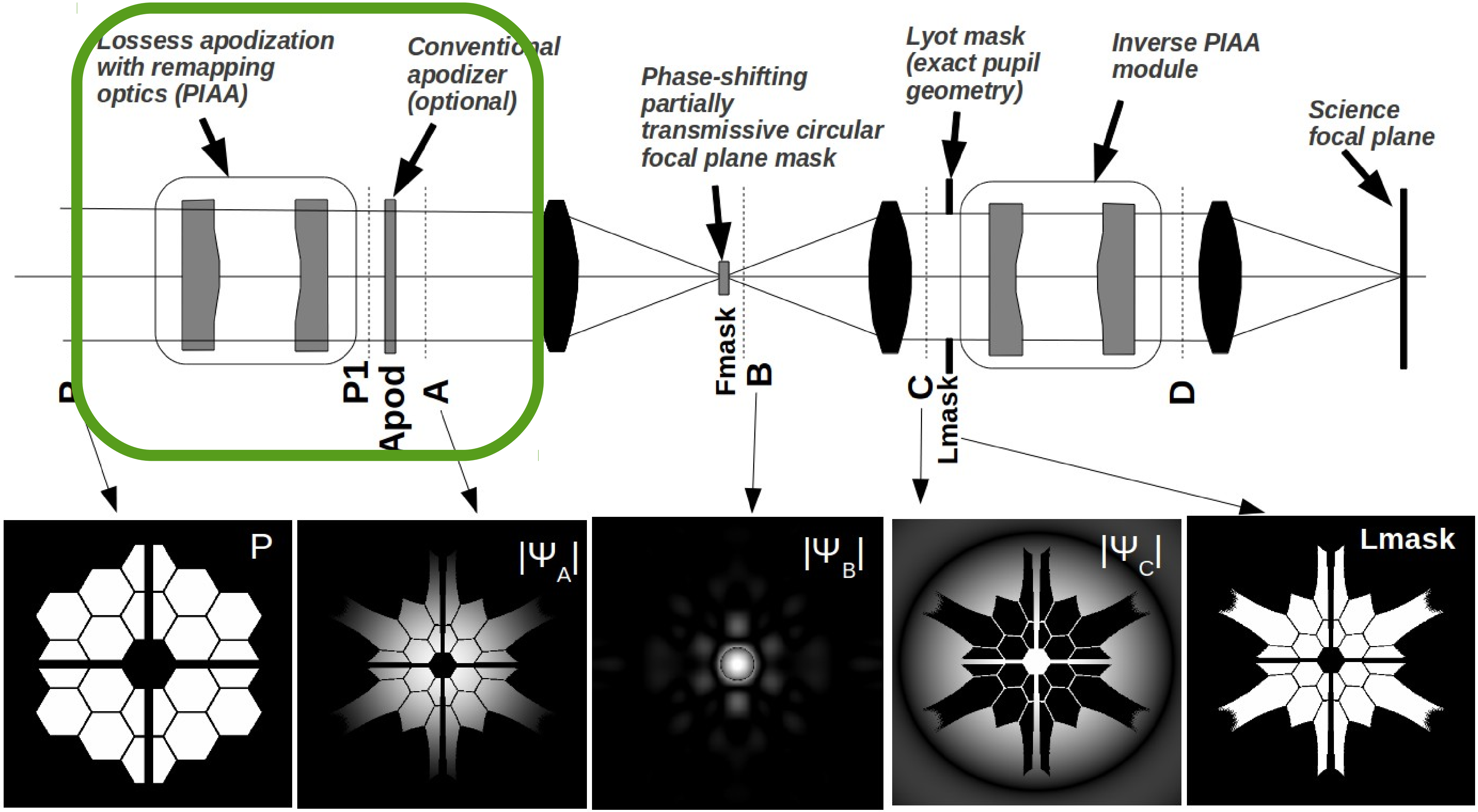
Inverse PIAA module

Science focal plane

(largely) lossless apodization

Creates a PSF with weak Airy rings

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



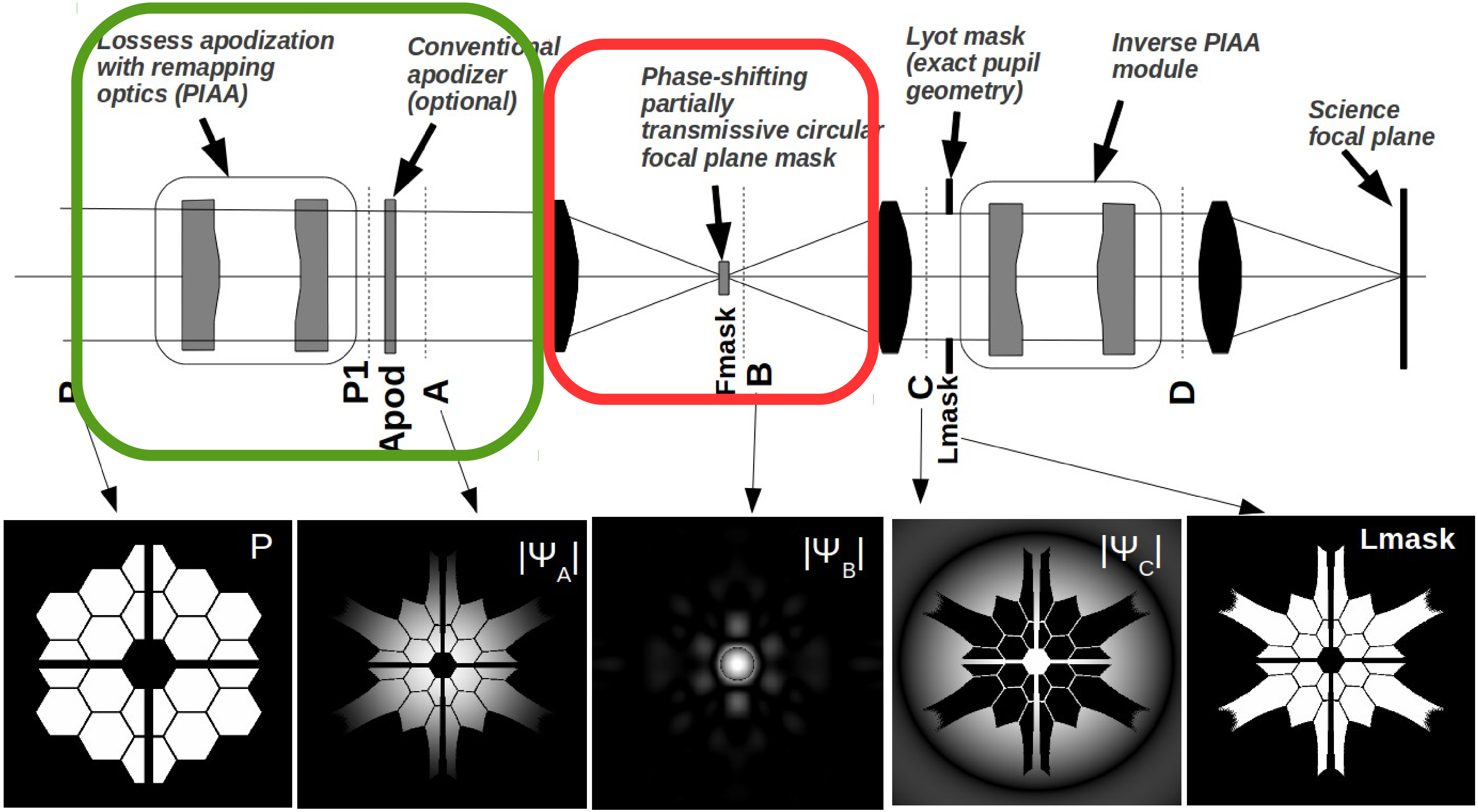
(largely) lossless apodization

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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Blocks starlight

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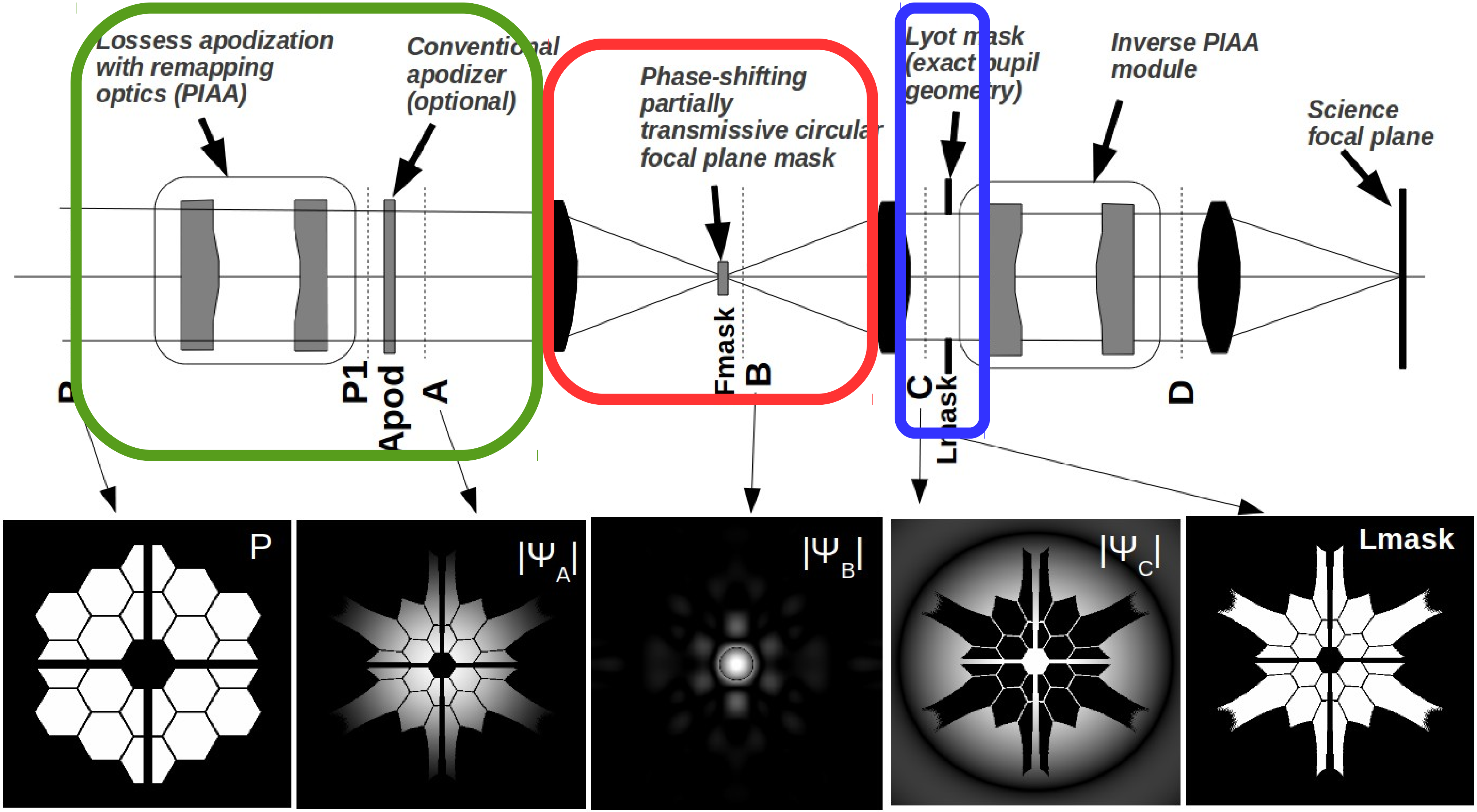
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



(largely) lossless apodization

Creates a PSF with weak Airy rings

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

Induces destructive interference inside downstream pupil

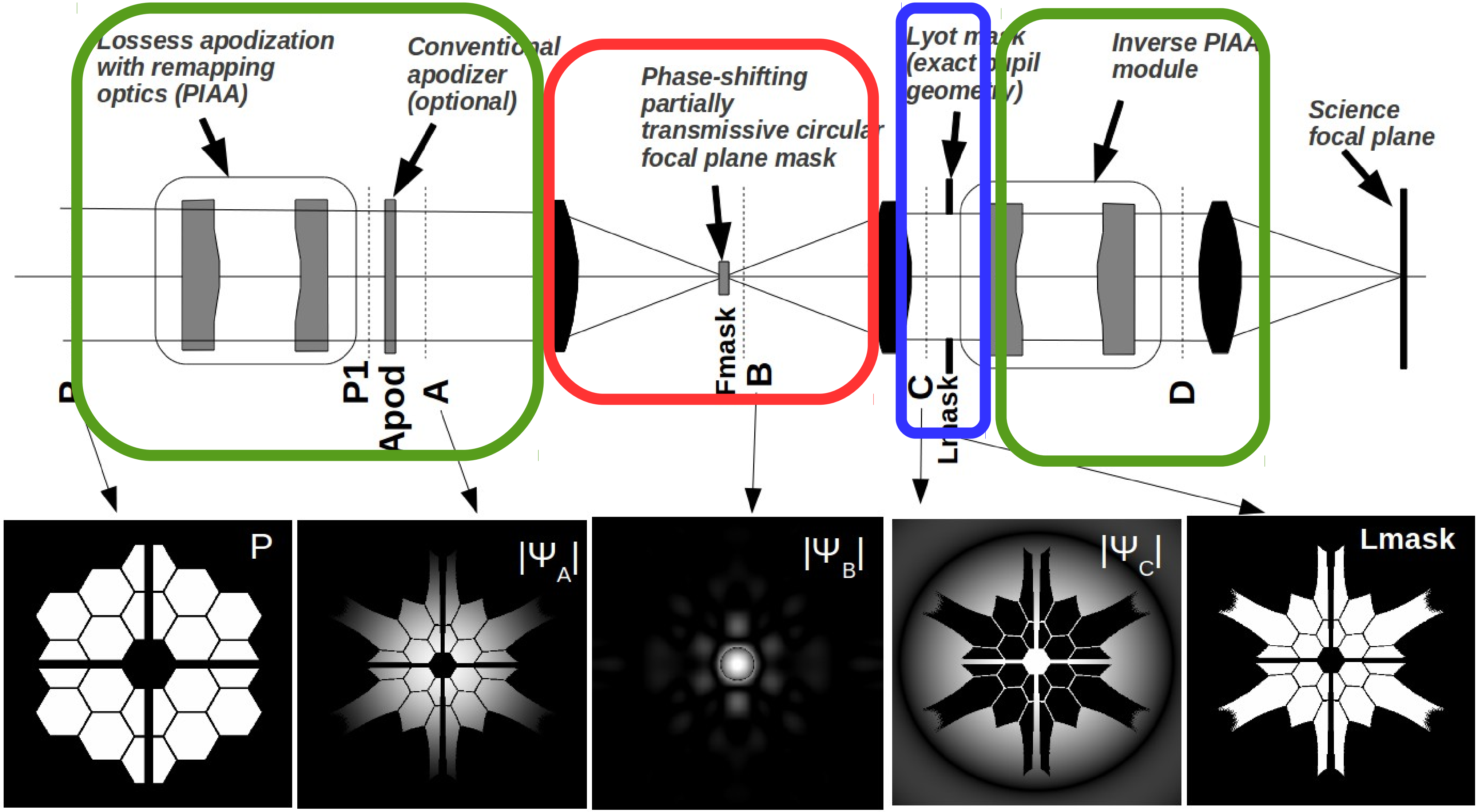
Lyot stop

Blocks starlight

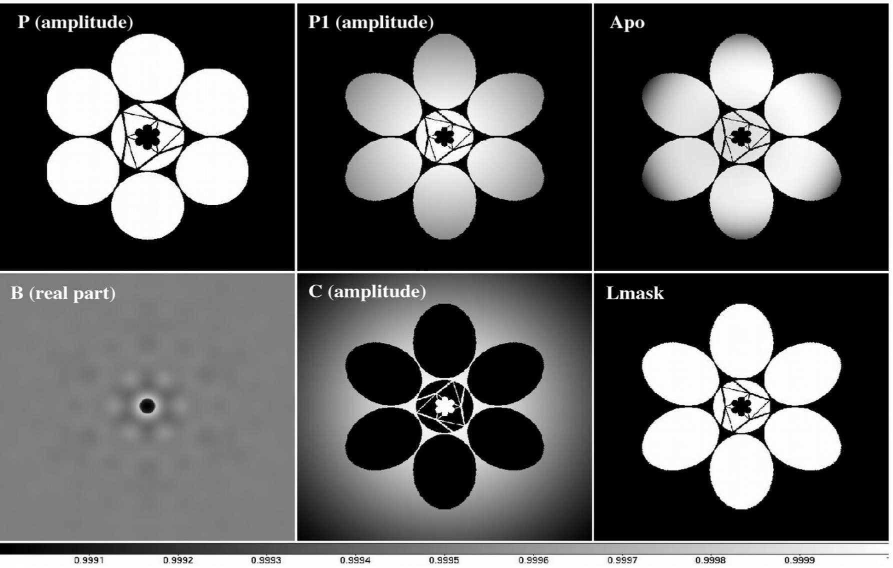
Inverse PIAA (optional)

Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



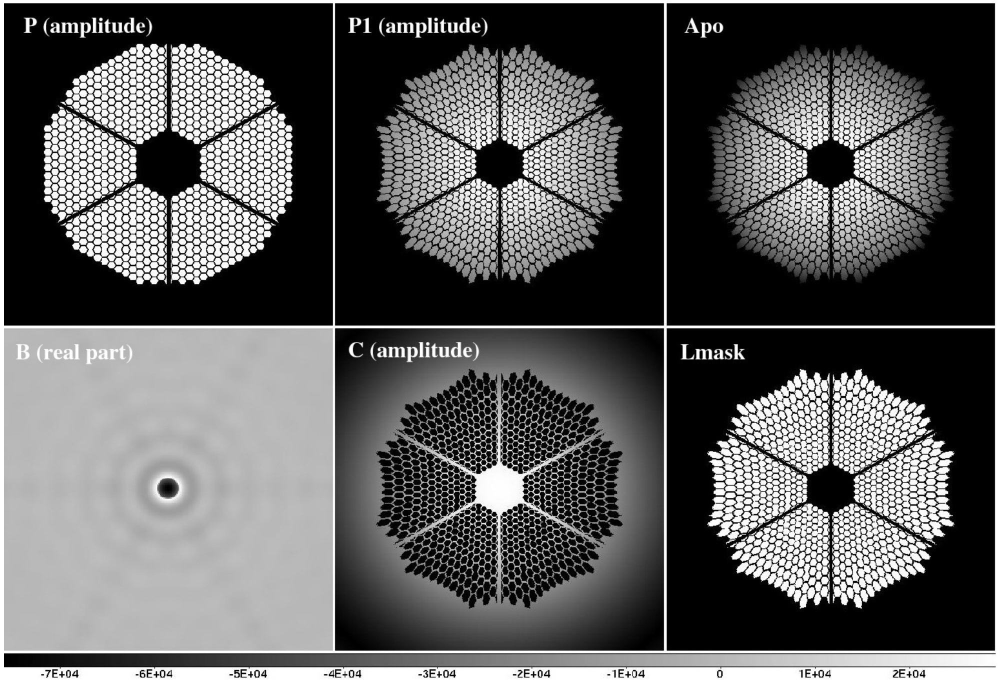
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

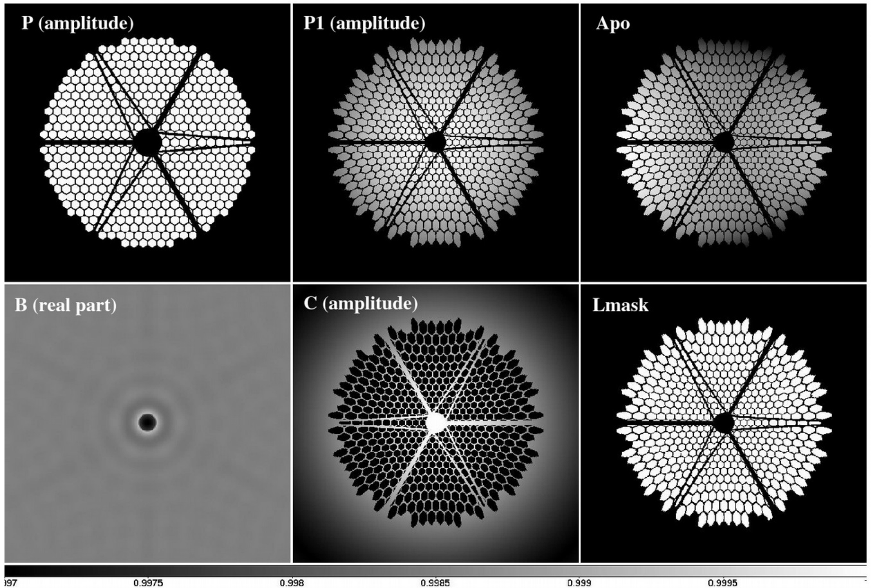


Assuming monochromatic point source:

Sharp high throughput off-axis PSF
360 deg field of view

Pupil shape does not matter !!!





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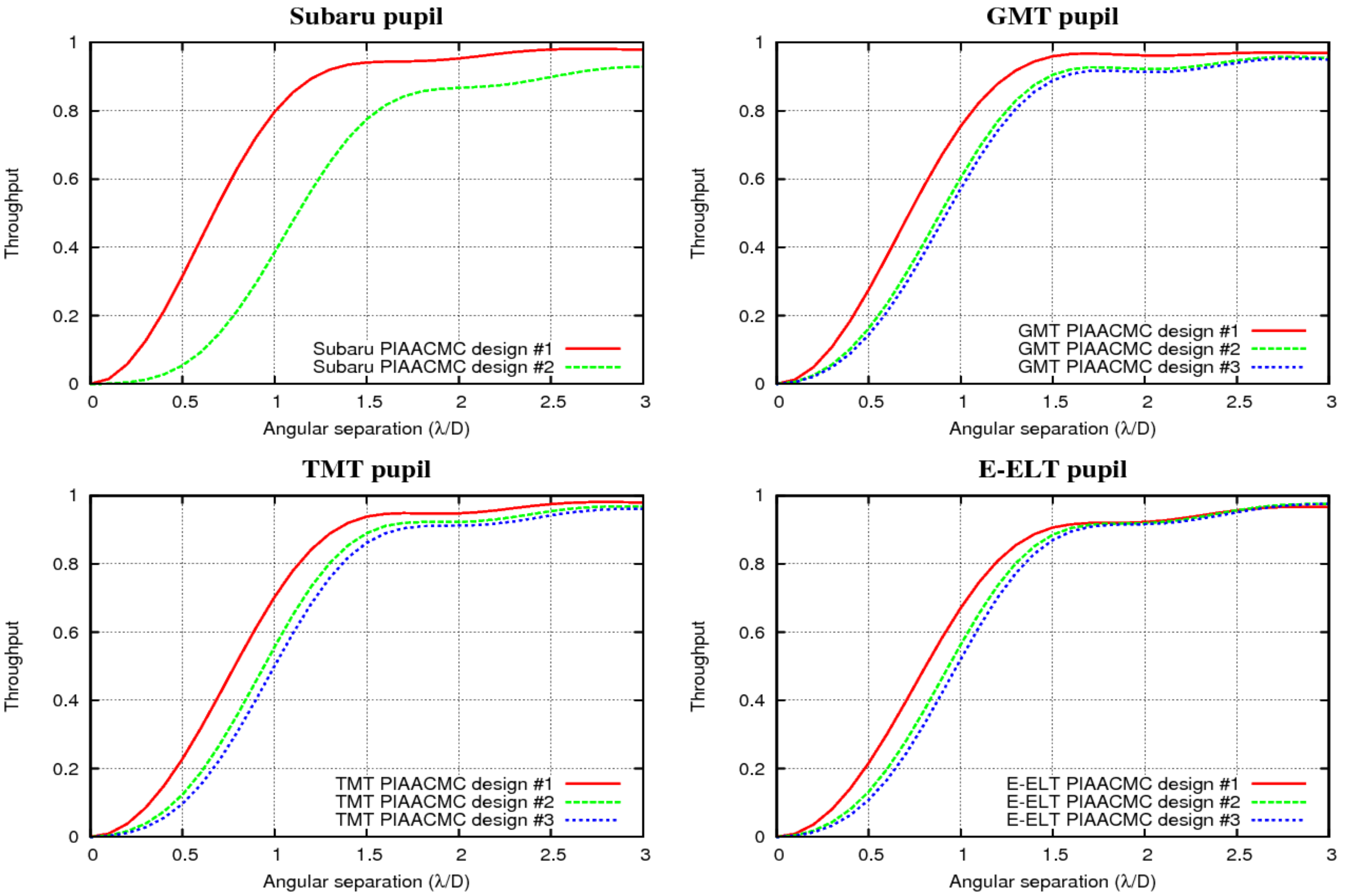
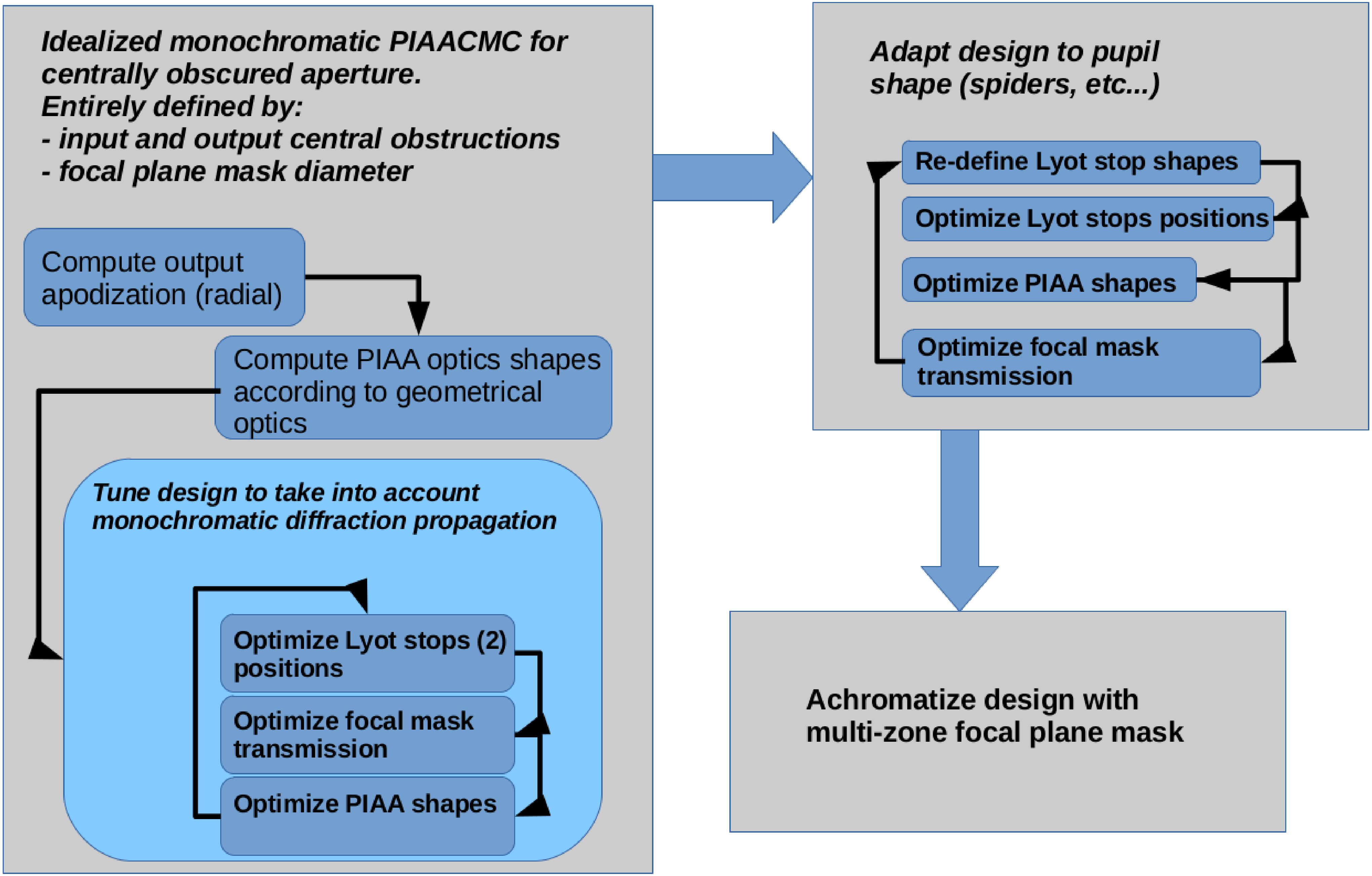


PIAACMC design process

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...)

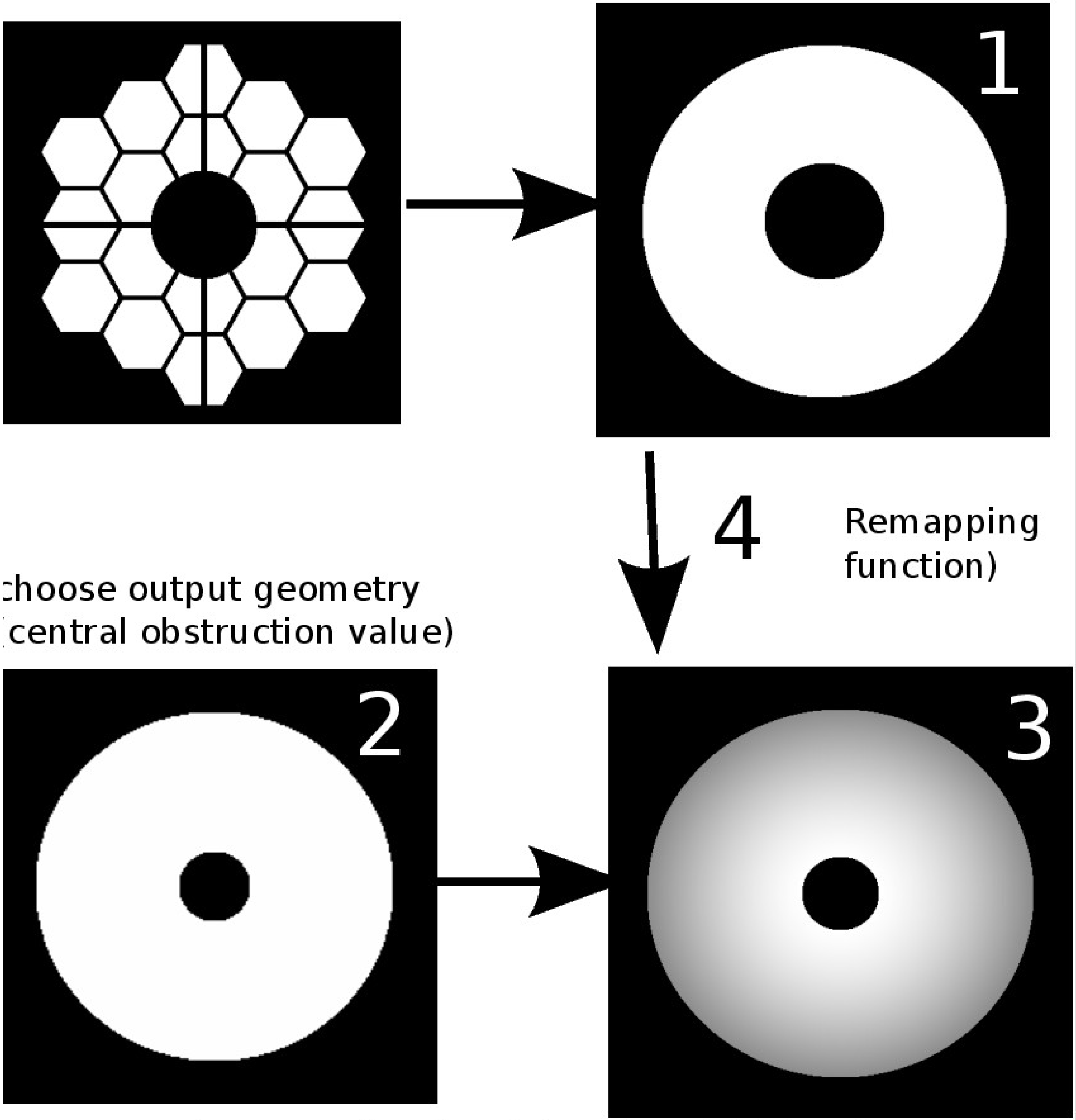
Re-define Lyot stop shapes

Optimize Lyot stops positions

Optimize PIAA shapes

Optimize focal mask transmission

Achromatize design with multi-zone focal plane mask



approximate input pupil as centrally obscured pupil

INPUT

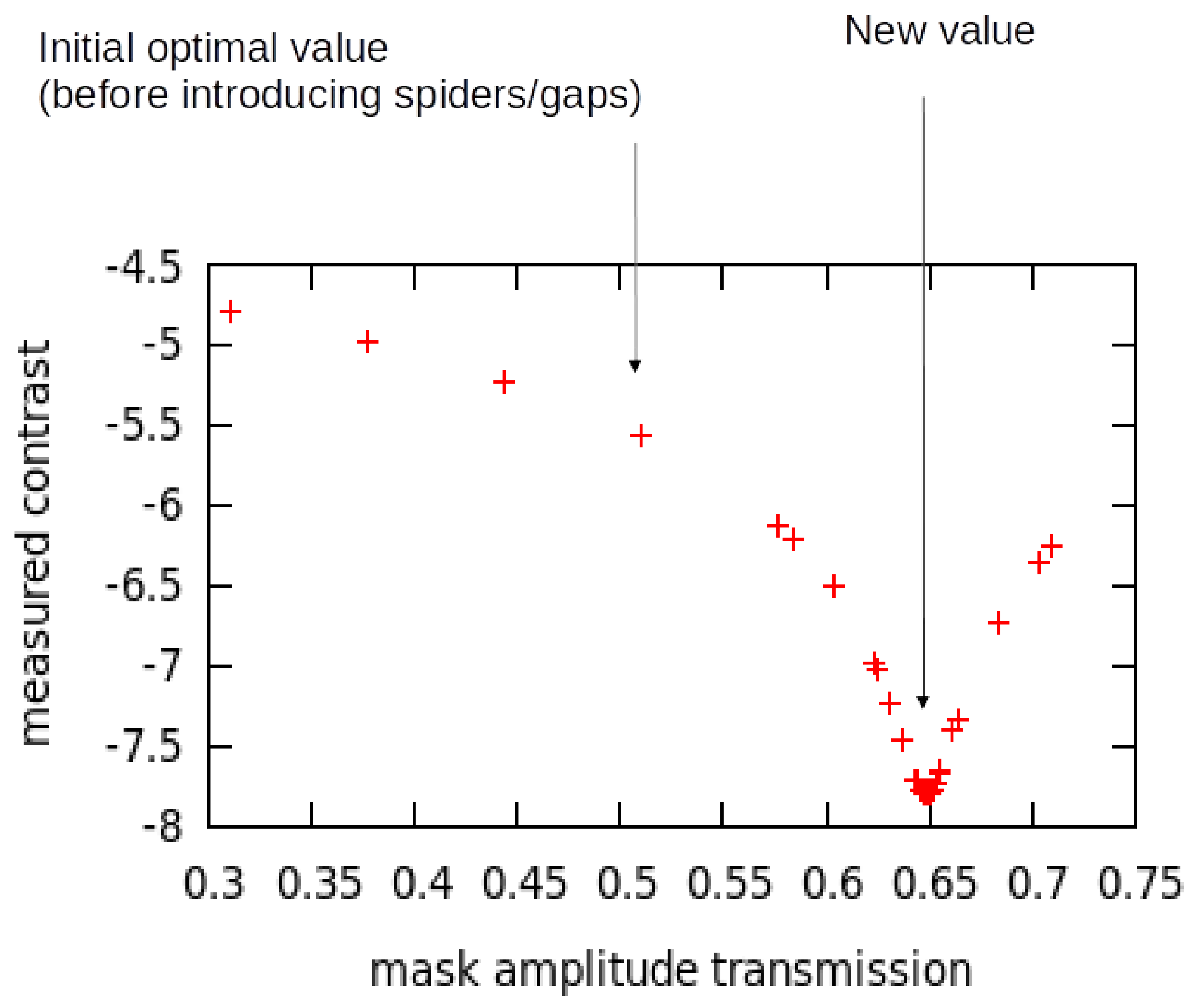
Remapping function)

choose output geometry
(central obstruction value)

OUTPUT

compute generalized prolate spheroidal function

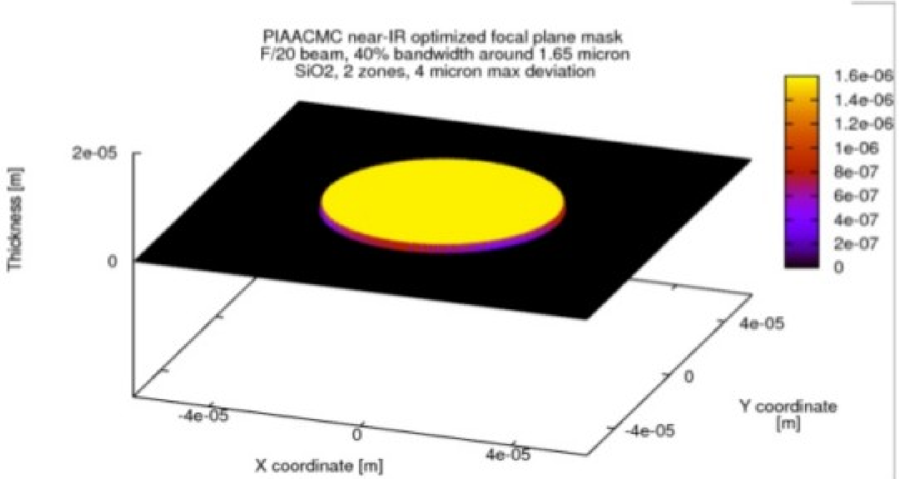
Adding spiders/segments → new focal plane mask transmission

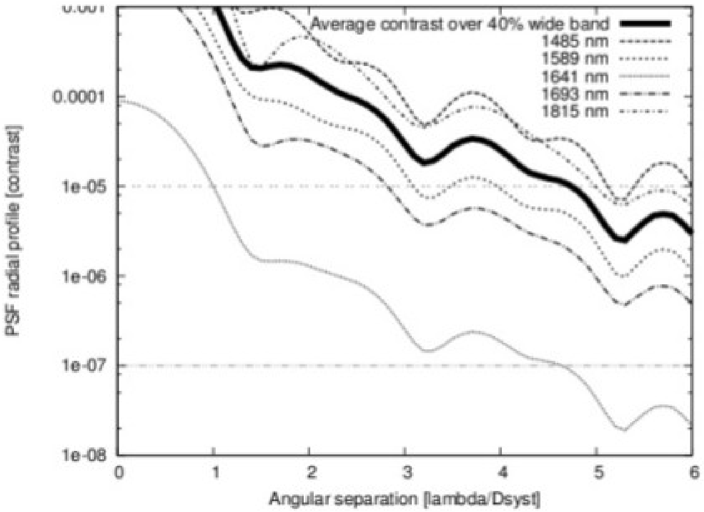


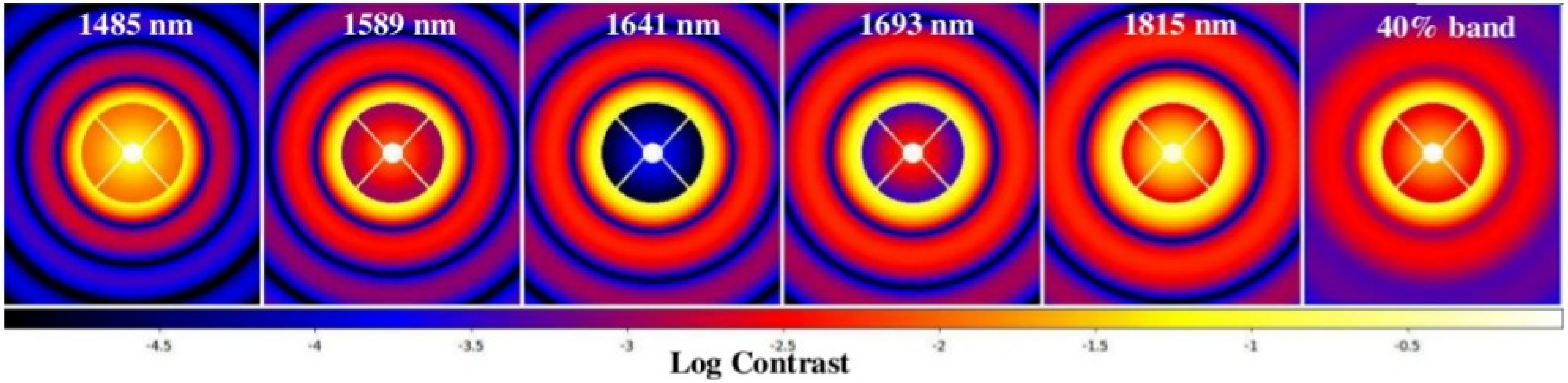
Initial optimal value
(before introducing spiders/gaps)

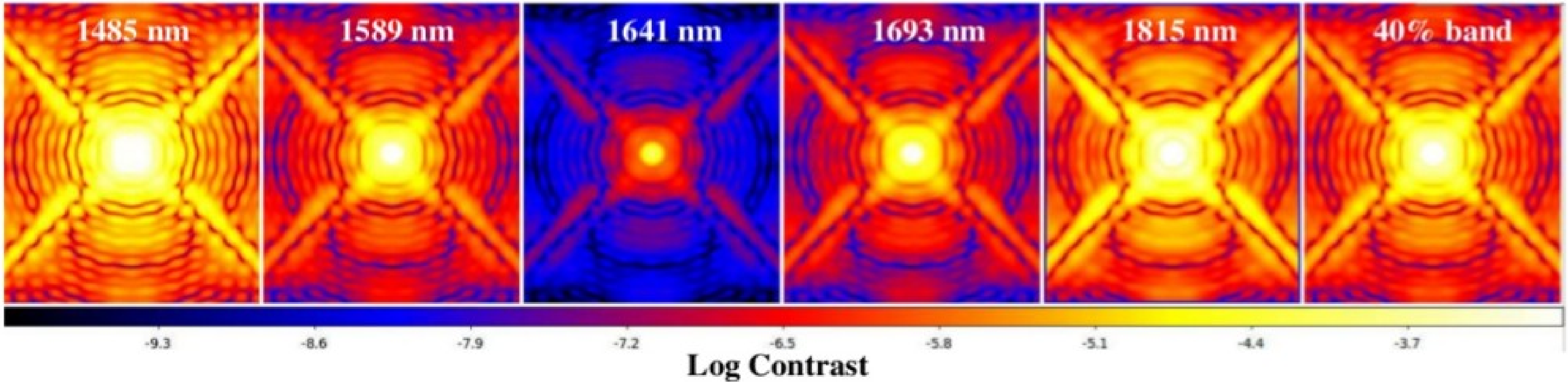
New value

PIAACMC contrast without achromatization: 1e-4 raw contrast across 40% band

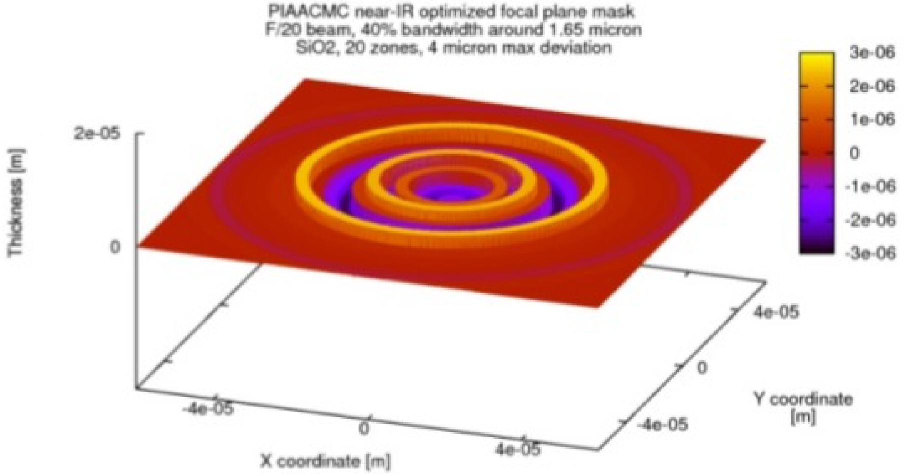


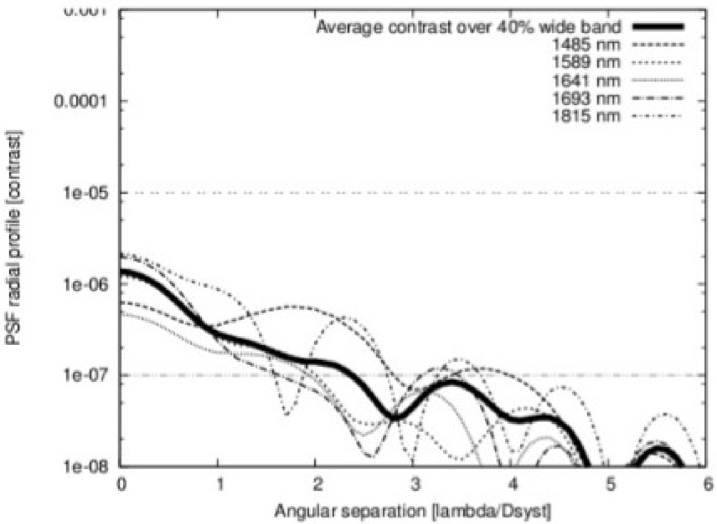


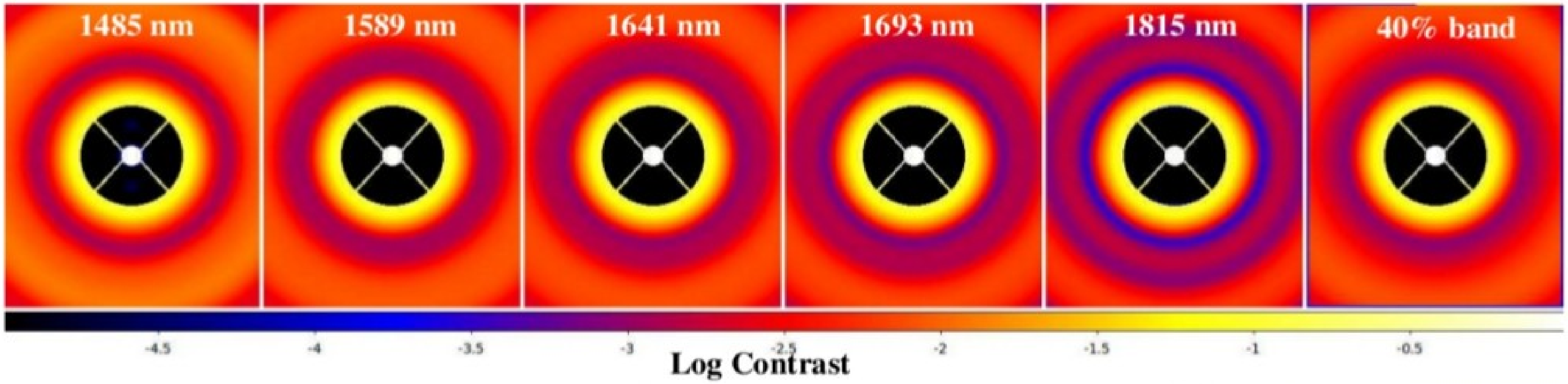


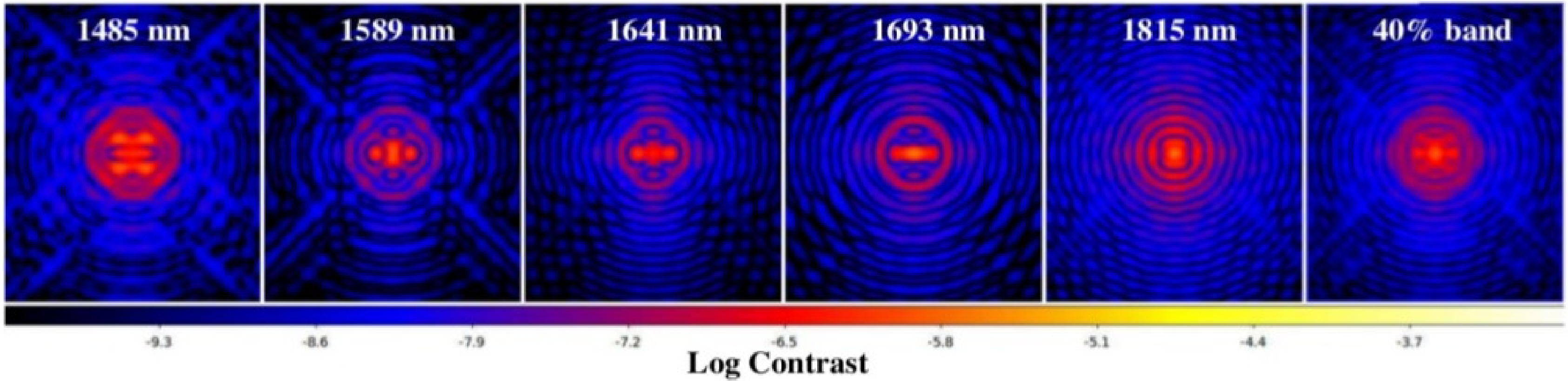


Example: PIAACMC designed for 1e-7 raw contrast across 40% band → 20 zones required









Focal plane mask design

Approach: Break focal plane mask in zones, and find optimal material thickness for each zone

[1] Pre-compute output complex amplitude response to each zone

[2] Define random starting point (each zone allocated a random thickness)

[3] Compute local derivatives of output complex amplitudes for each zone thickness change

[4] Find steepest gradient, and move along this direction until best contrast is reached

[5] go back to step [3], repeat until local minima is reached

Repeat steps [2]-[5] many times

Local derivatives and evaluations are performed simultaneously for multiple wavelengths, and multiple on-sky directions (stellar angular size)

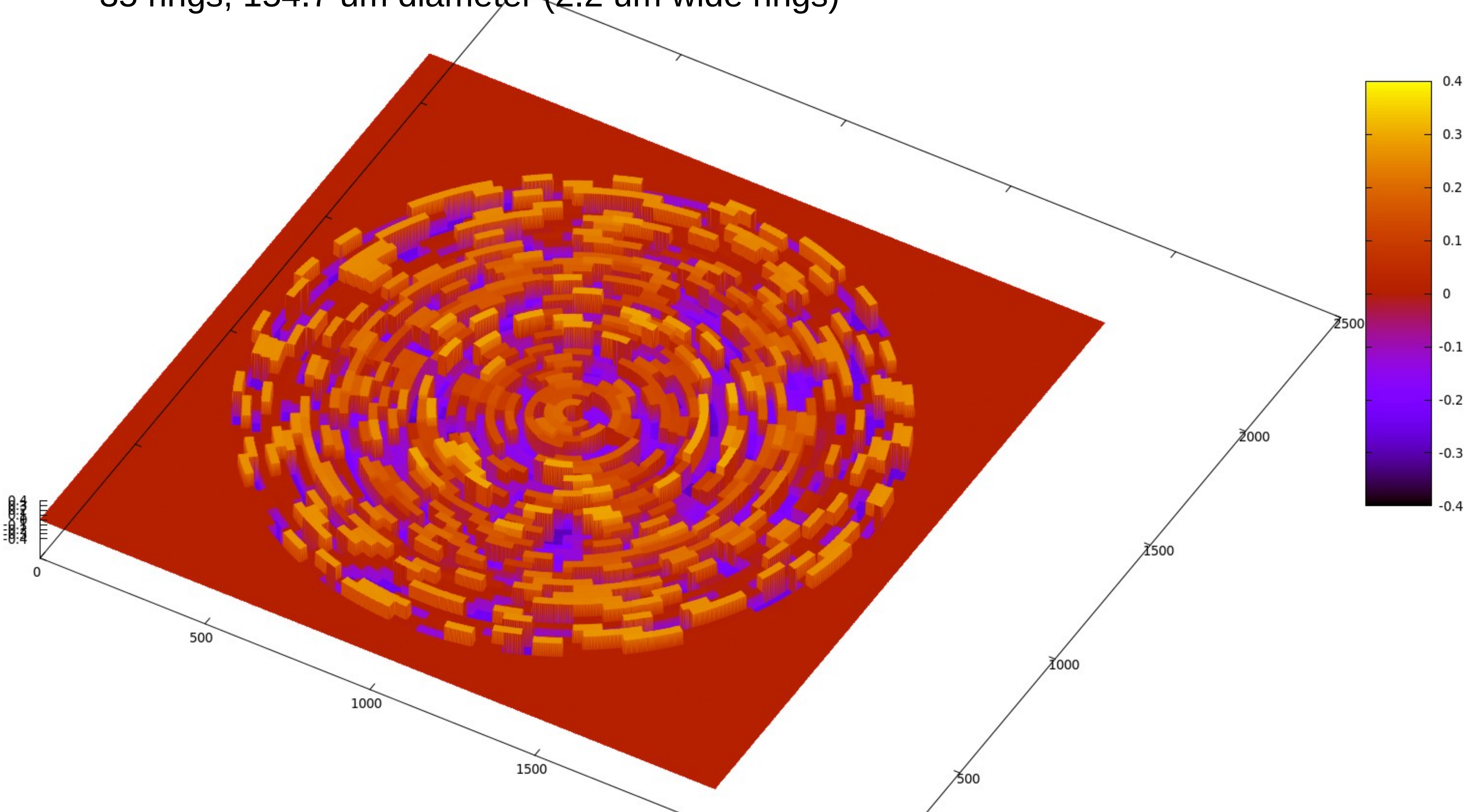
CHALLENGE #1
Focal plane mask manufacturing

mitigation / solutions :
- sectors → hex tiling (→ squares)
- multiple materials ? Stack ?
- Dual DM control

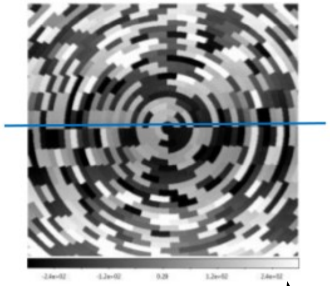
Focal plane mask (vertical scale amplified) for 1e-9 raw contrast, 1.3 l/D IWA (WFIRST visible light mask)

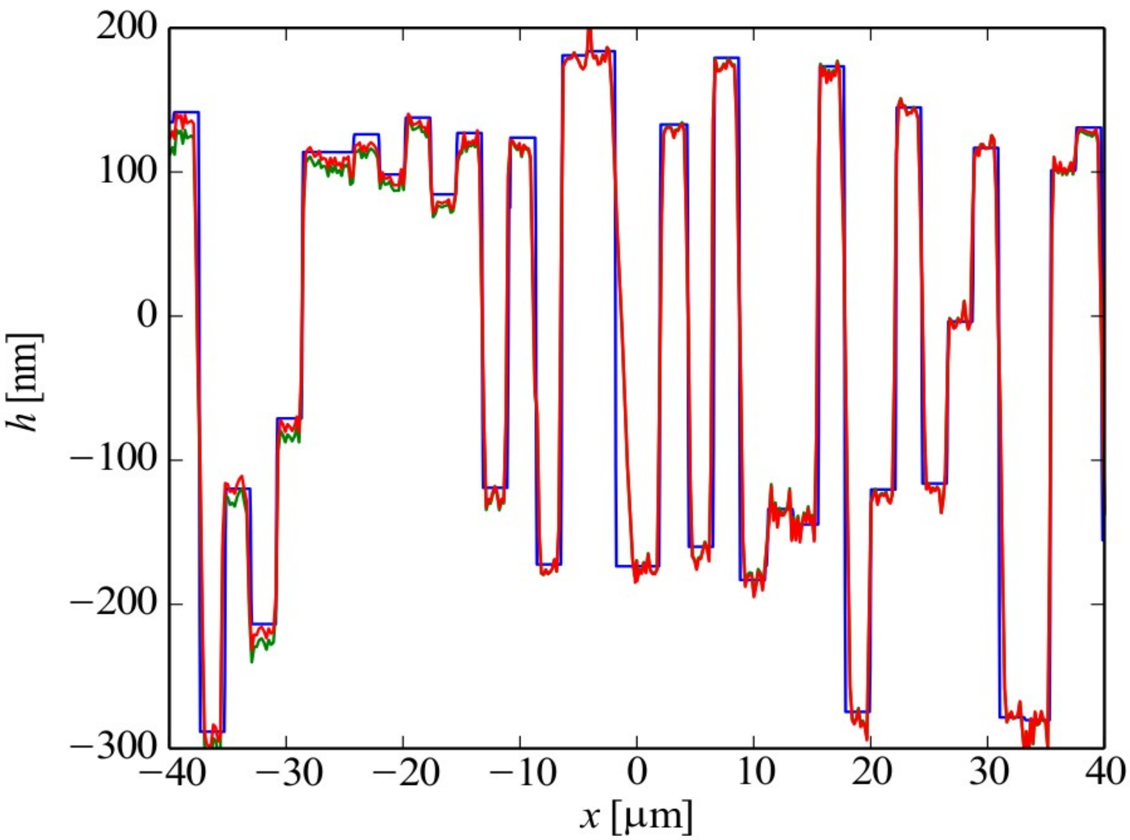
Sag within -/+ 0.3 um

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

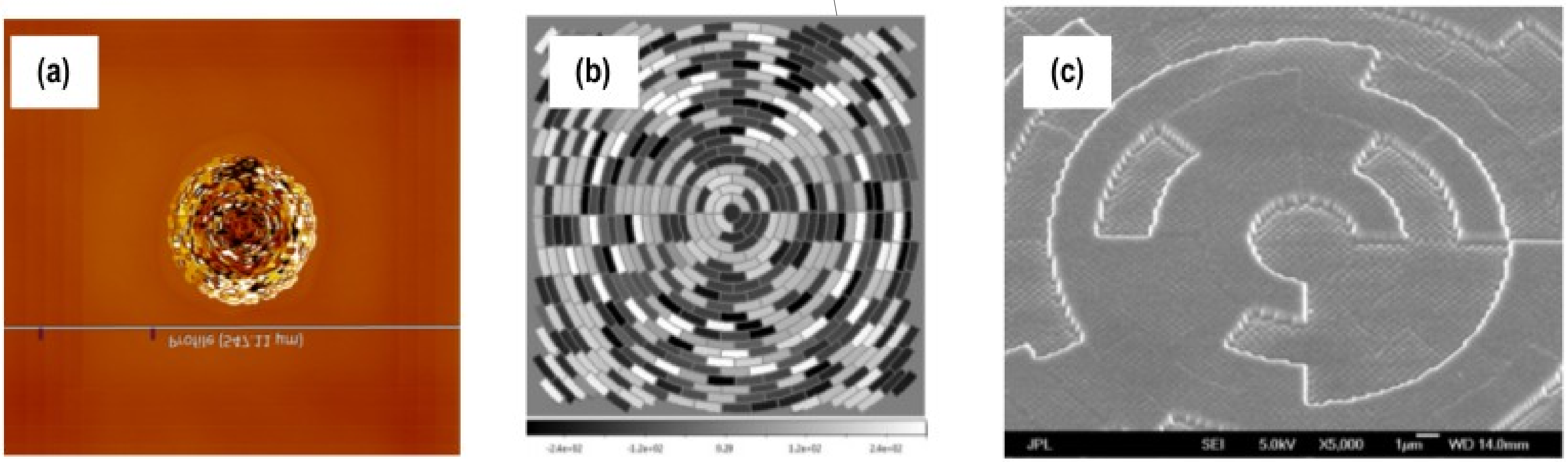


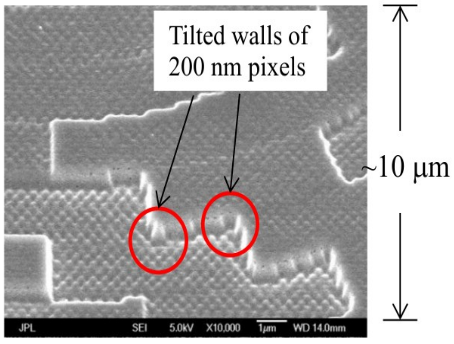
PIAACMC focal plane mask manufacturing



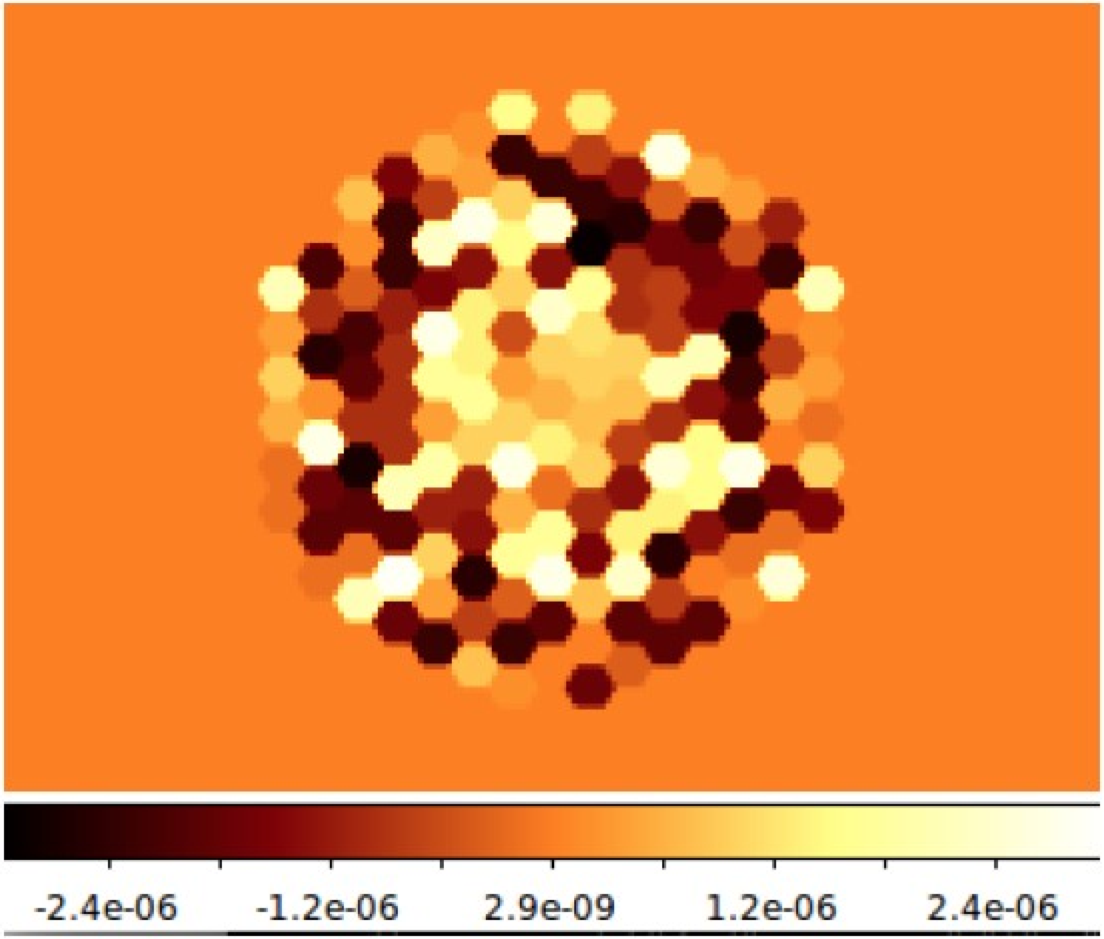


Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)




Tilted walls of 200 nm pixels

Hexagonal tiling



Mask sag [m]

CHALLENGE #2:
Stellar angular size

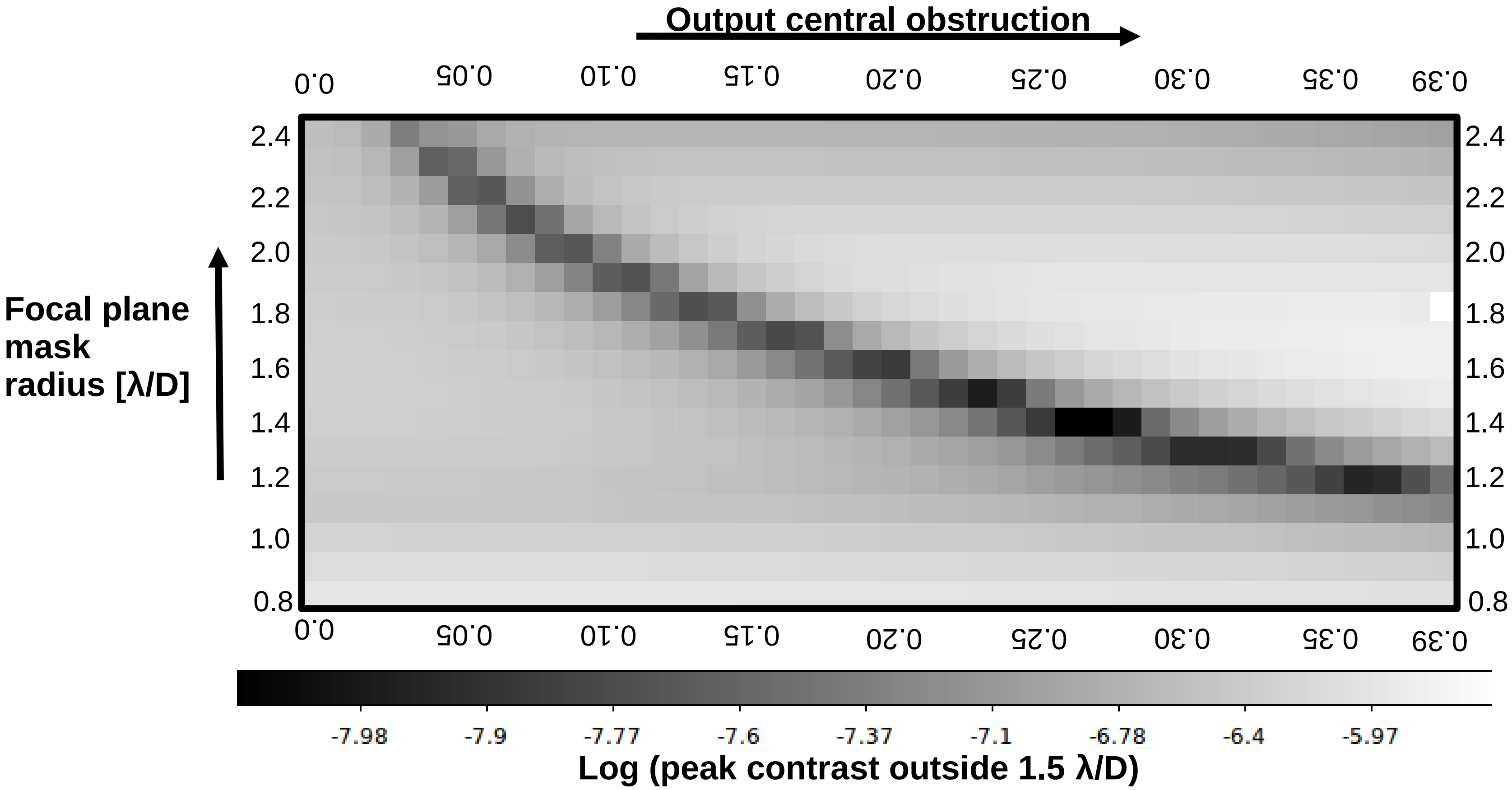
Mitigation approaches:
- Nominal design choice
- Explore APCMLC
- Focal plane mask design
- Dual DM wavefront control

Nominal PIAACMC design has strong effect on stellar leak

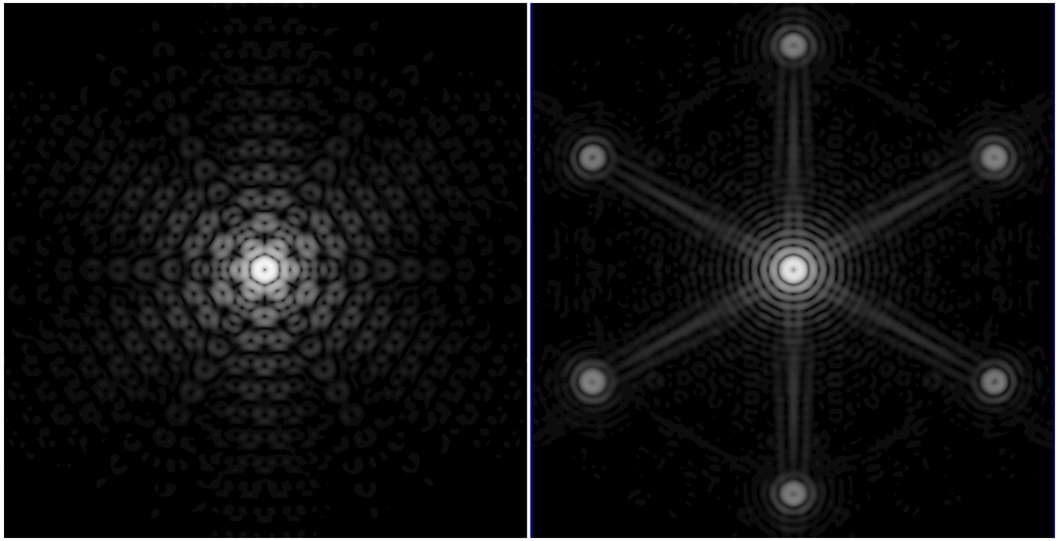
Example: Centrally obscured pupil PIAACMC design optimization, 2% l/D disk

~ two orders of magnitude contrast difference between badly tuned PIAACMC and tuned PIAACMC

For 0.3 output central obstruction, IWA = 1.4 design is much better than IWA = 1.8 l/D design, even when working at ~3 l/D

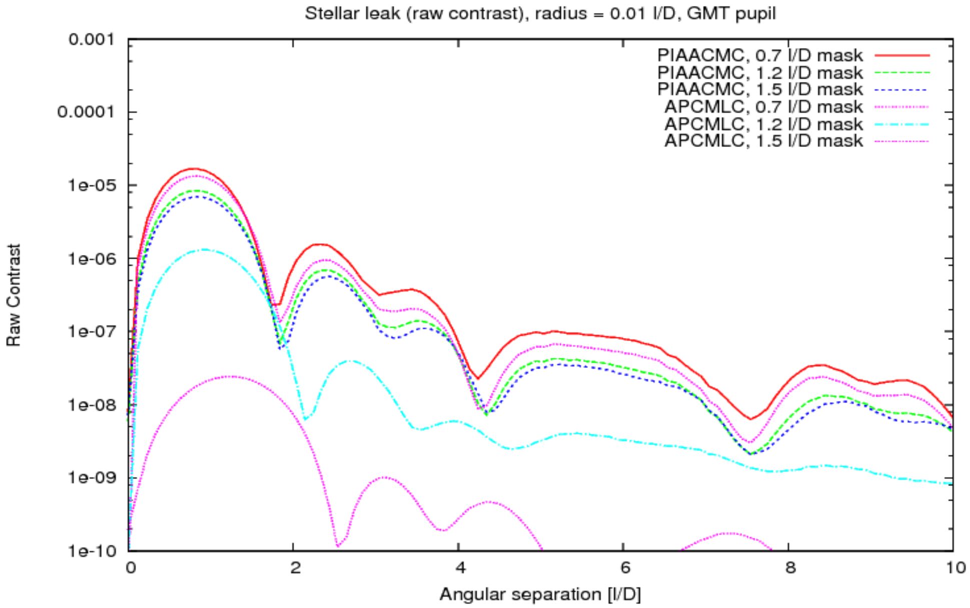


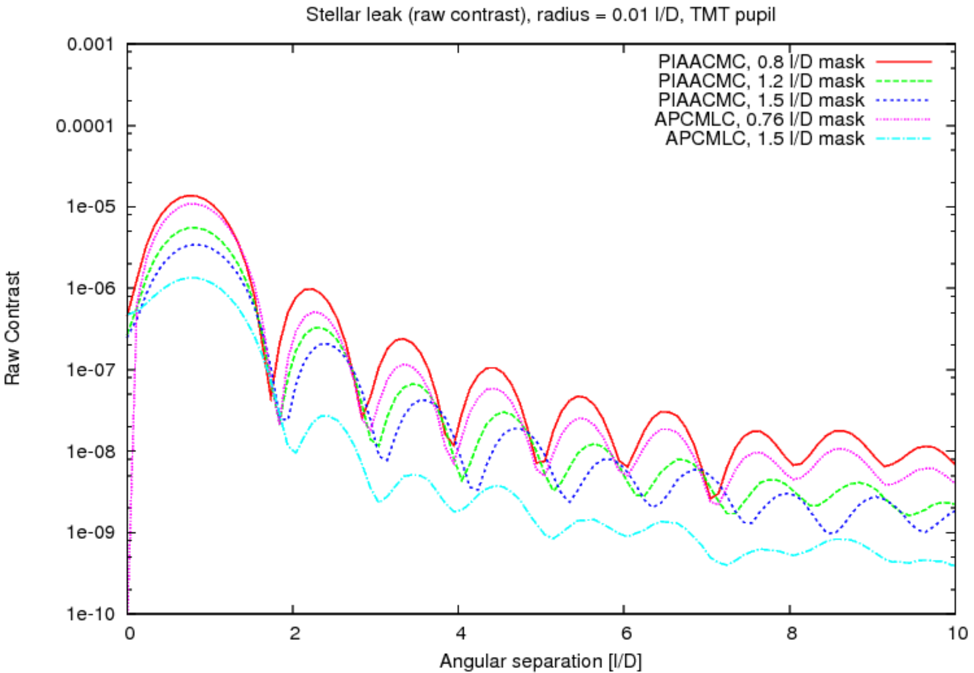
APCMLC is more resilient than PIAACMC



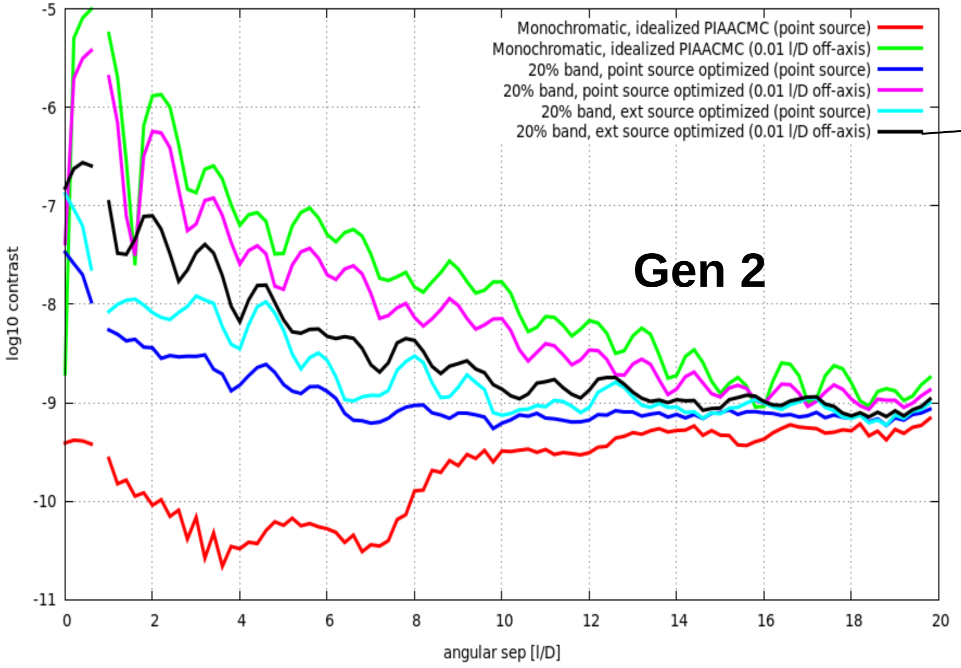
On ELT in near-IR, nearby M dwarf is about 0.1 to 0.5 mas radius
= 0.01 to 0.05 l/D

→ for 1 l/D IWA coronagraph
RAW contrast limited to ~1e5 to 1e-6

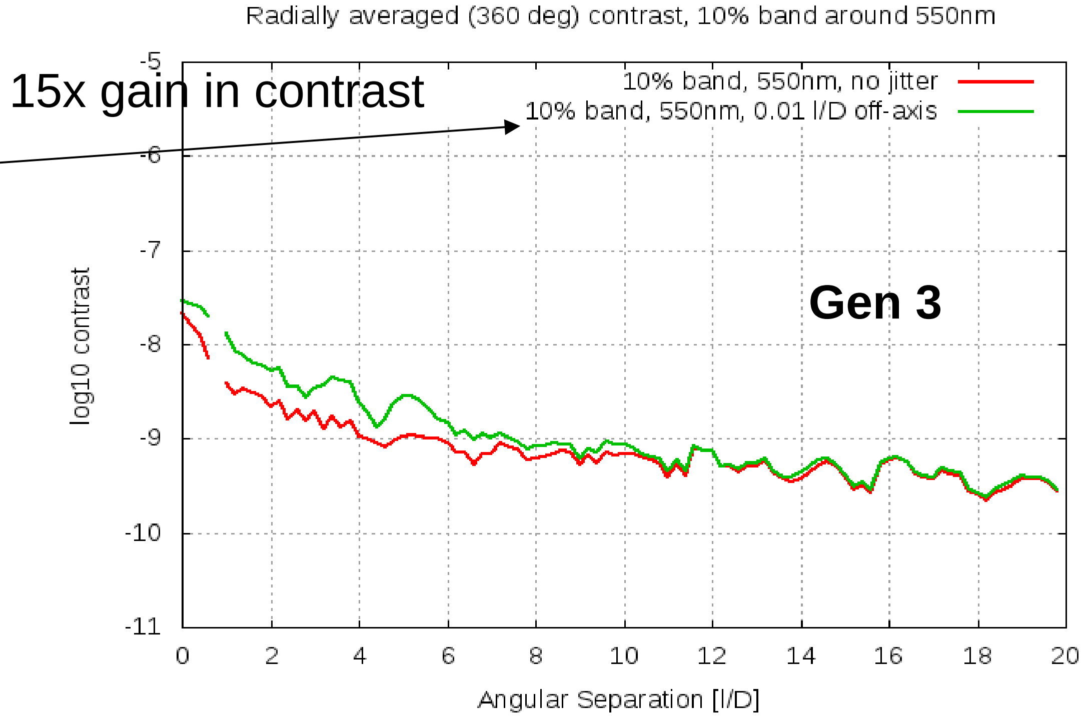


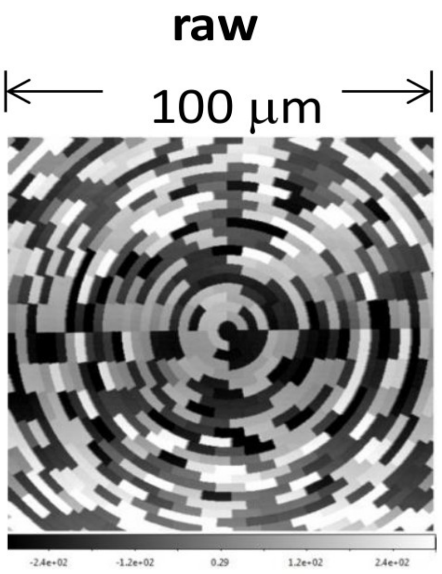


Stellar leak and focal plane mask design on AFTA



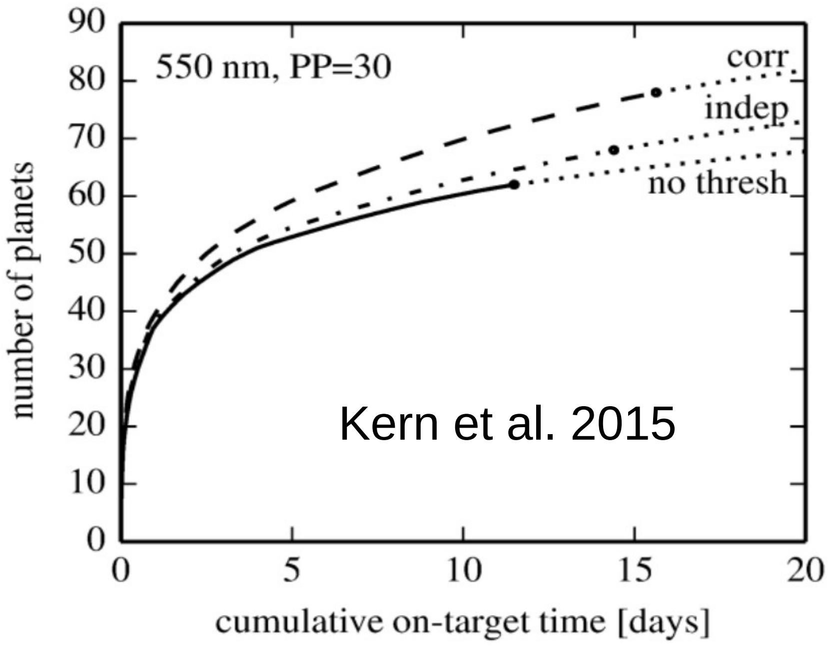
15x gain in contrast





±300 nm scale

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

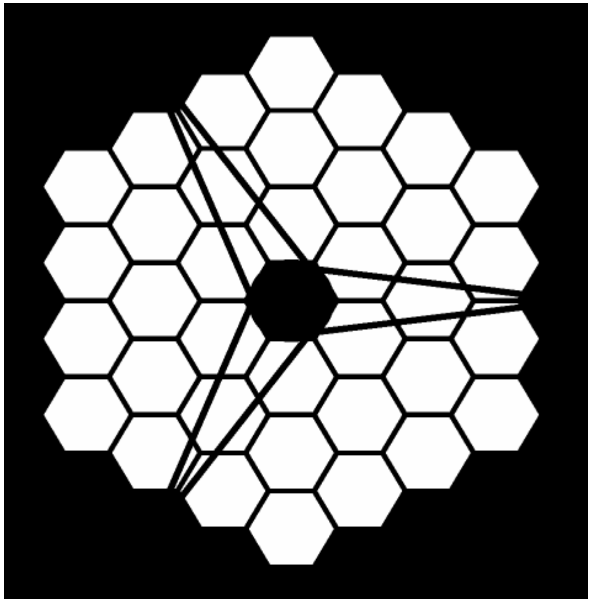


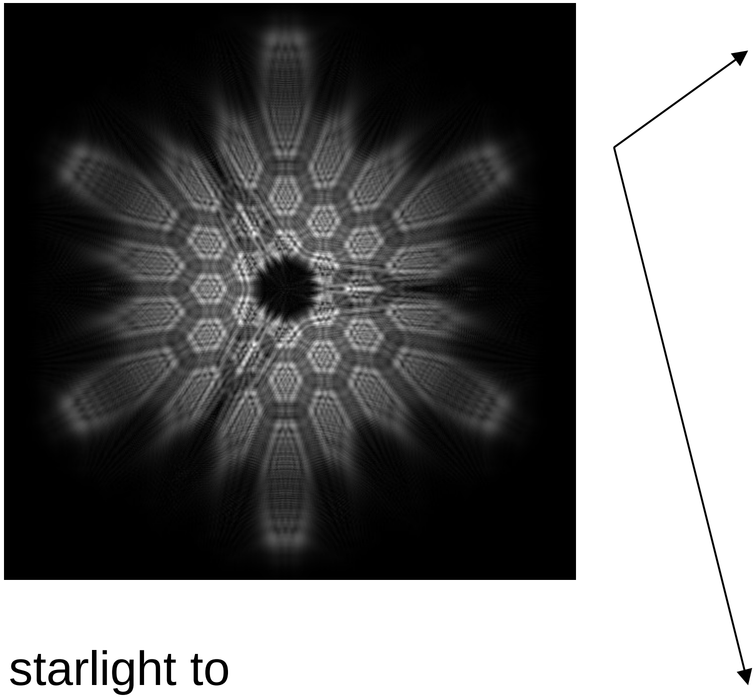
Kern et al. 2015

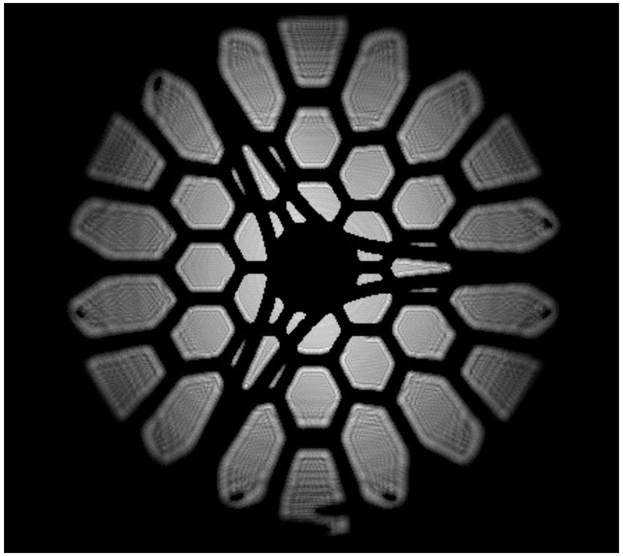
PIAACMC design for 12m segmented telescope
IWA = 1.2 l/D, throughput = 70% (similar to WFIRST-PIAACMC)

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

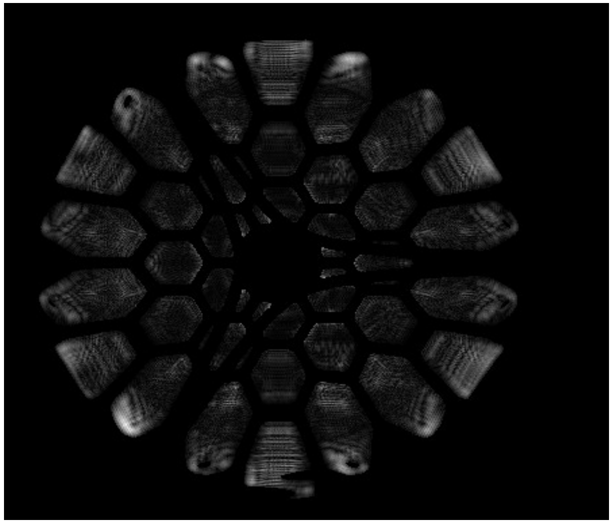
FLAT DEFORMABLE MIRRORS







planet light

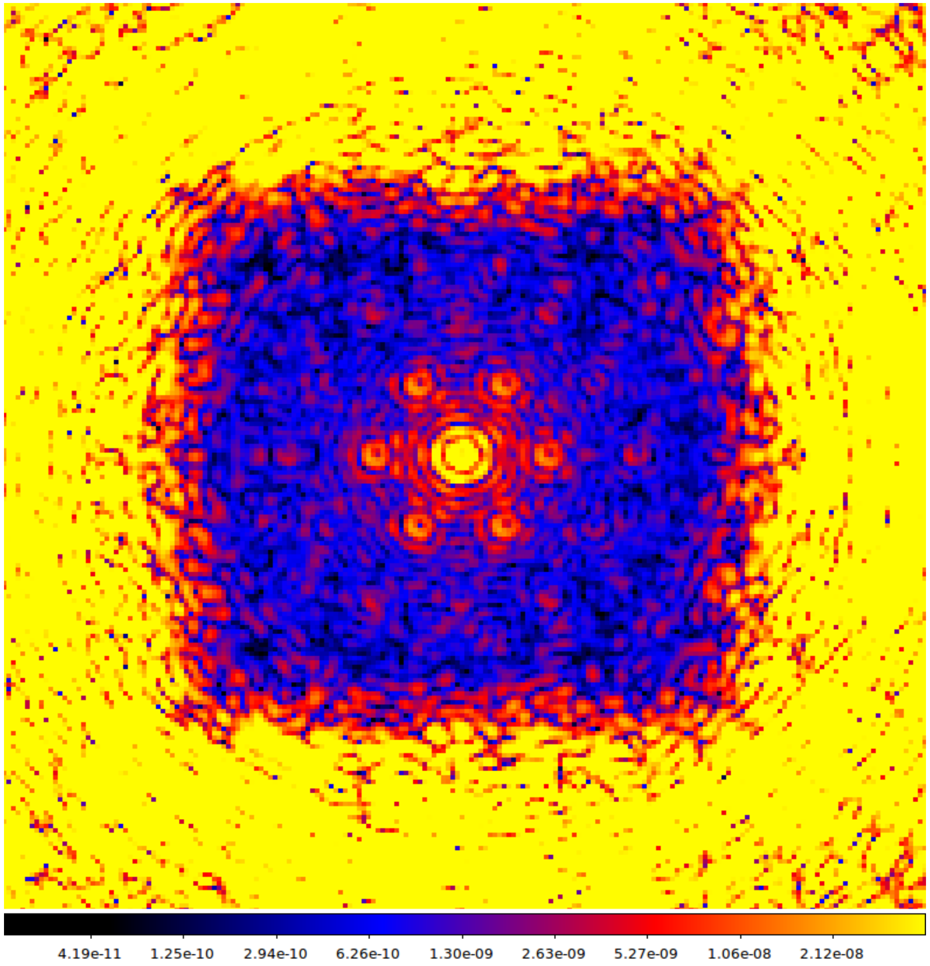


starlight (very faint)

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

Raw contrast currently dominated by stellar angular size

Further optimization of focal plane mask and WFC will be needed to reduce leaks due to stellar angular size.



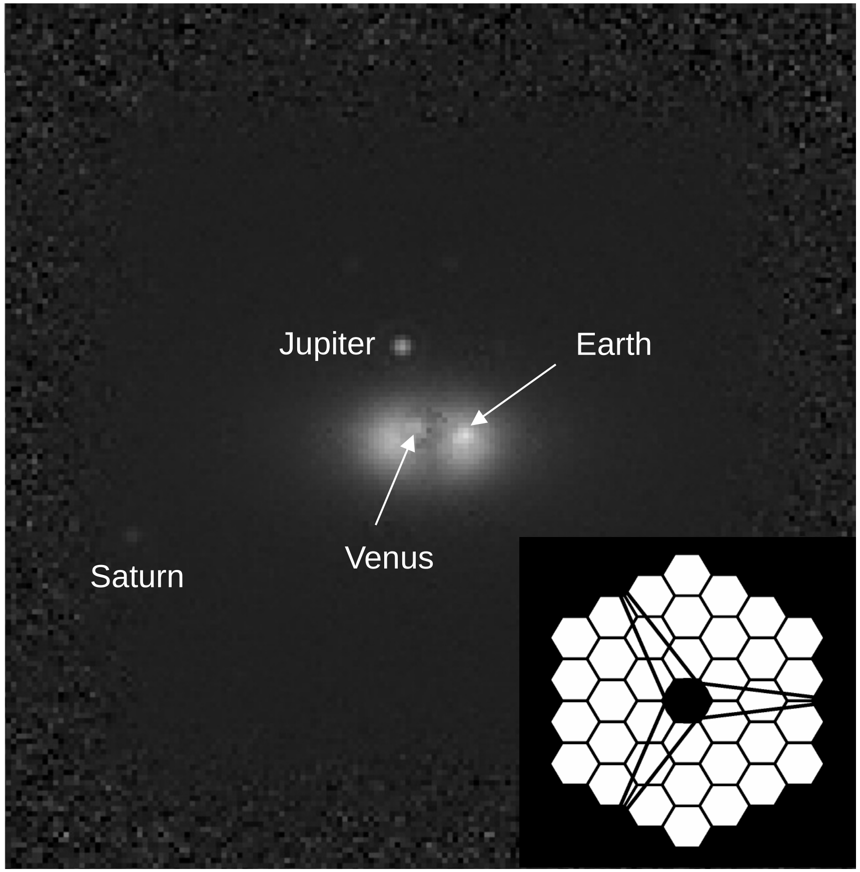
Inner spot+rings due to stellar angular size, at few 1e-9 contrast in 2-4 l/D range

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

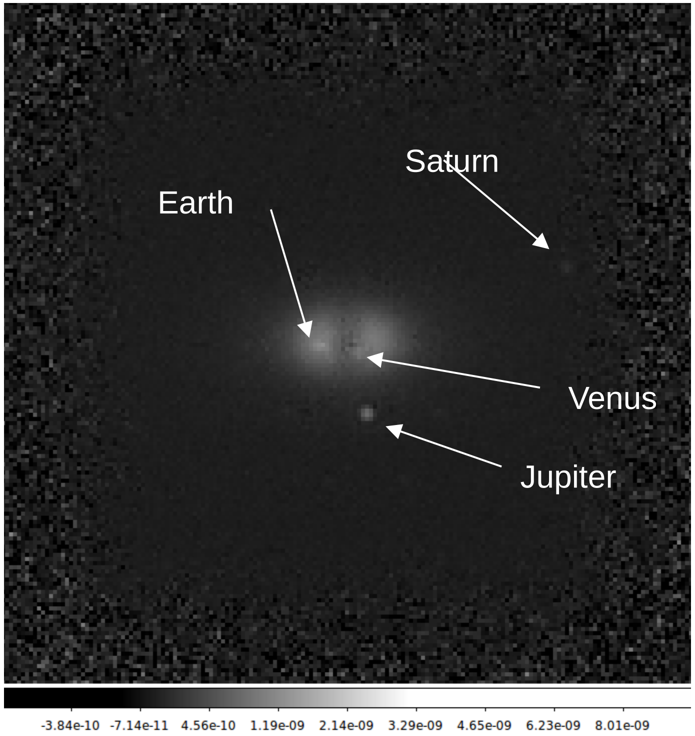
This component is subtracted from image in next slide, assuming photon-noise limit

Simulated images of solar system twin – 12m telescope, 2 day exposure – after photon-noise PSF subtraction

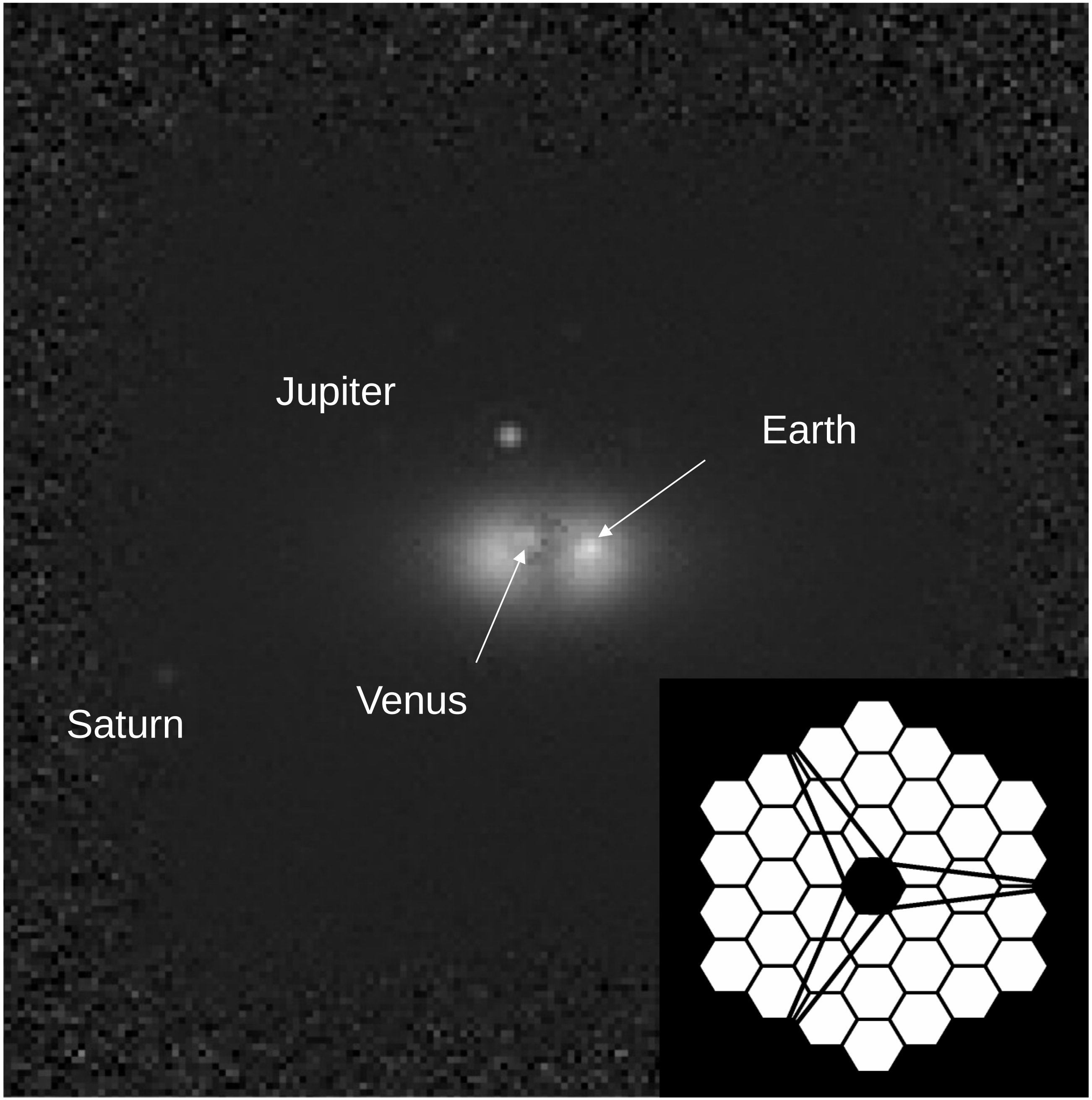
SS twin at 13pc
near-IR (1600nm)
PIAACMC, IWA=1.2 l/D



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

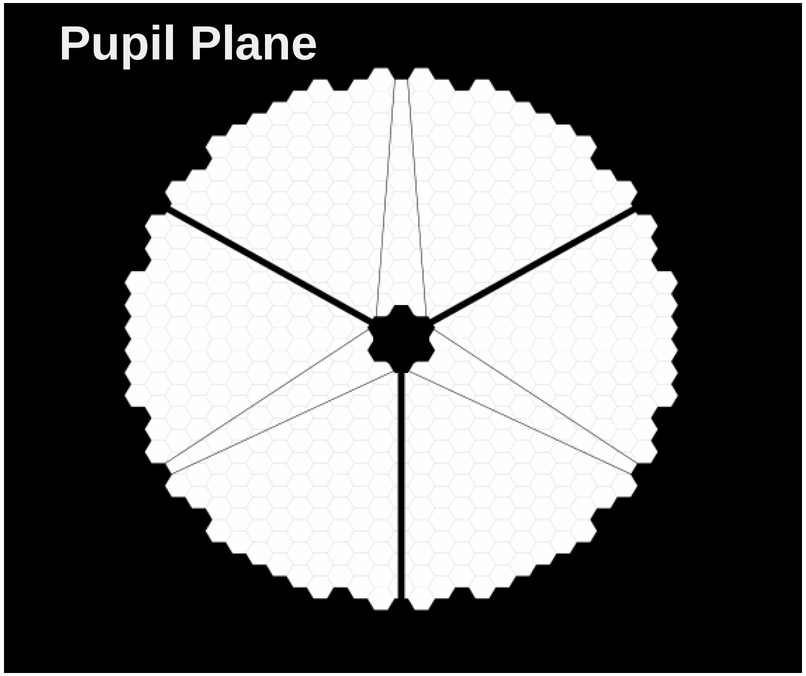


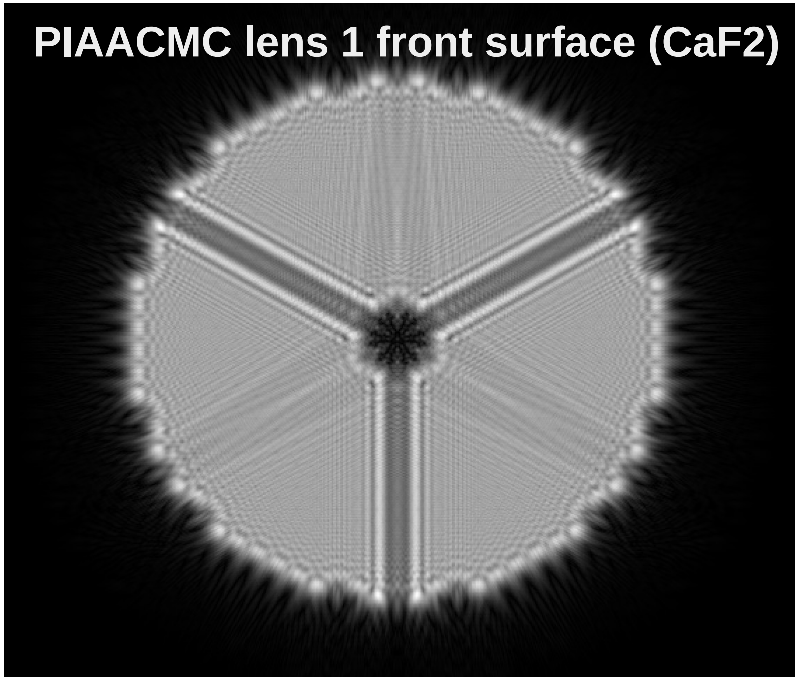
Simulated near-IR (1600nm, 20% band) image of a solar system twin at a distance of 13.5pc as seen by a 12m HDST with a 2 day exposure. The pupil geometry adopted for this simulation is shown in the lower right. A Phase-Induced Amplitude Apodization Complex Amplitude Coronagraph (PIAACMC), offering small 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).

CHALLENGE #3:
Segment gaps issue

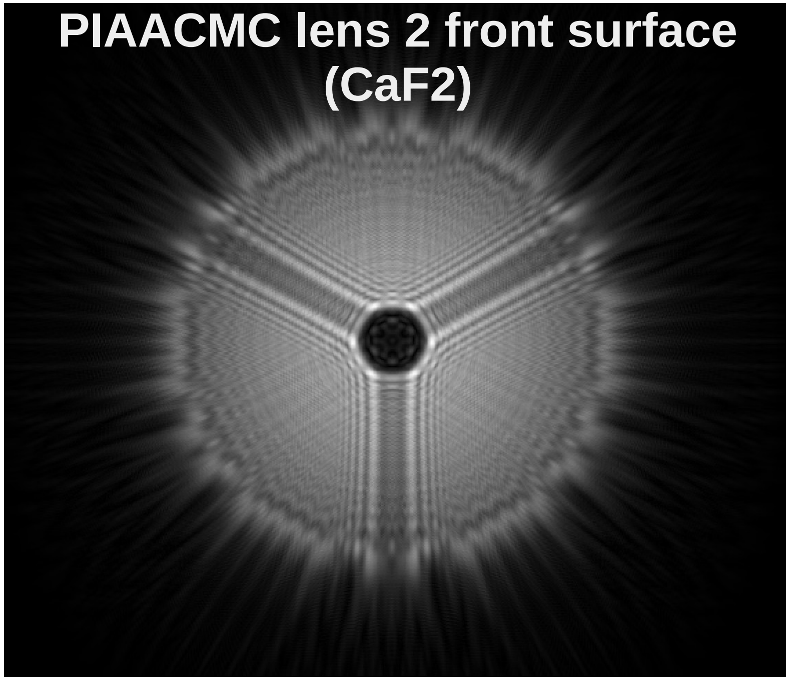
Example :
Large Ground-based segmented aperture (TMT)
(monochromatic, mask + freeform PIAA shapes optimization)

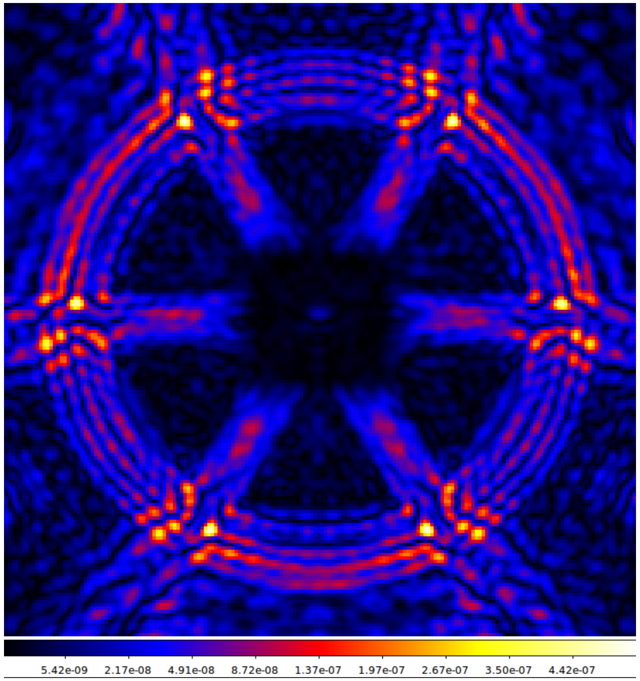
TMT coronagraph design for 1 l/D IWA


Pupil Plane


PIAACMC lens 1 front surface (CaF2)

To be updated with new pupil shape


PIAACMC lens 2 front surface (CaF2)



PSF at 1600nm

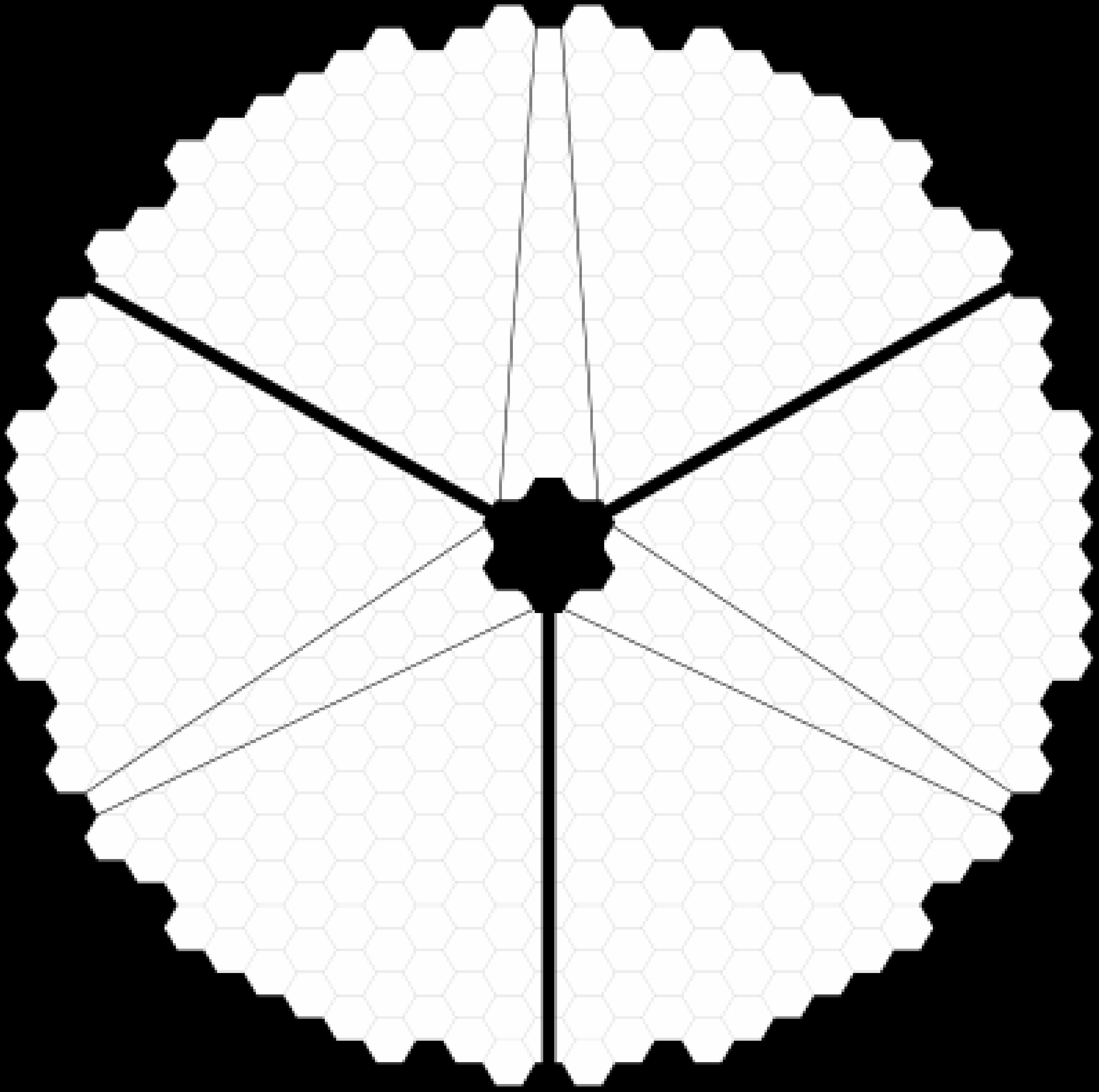
3e-9 contrast in 1.2 to 8 l/D

80% off-axis throughput

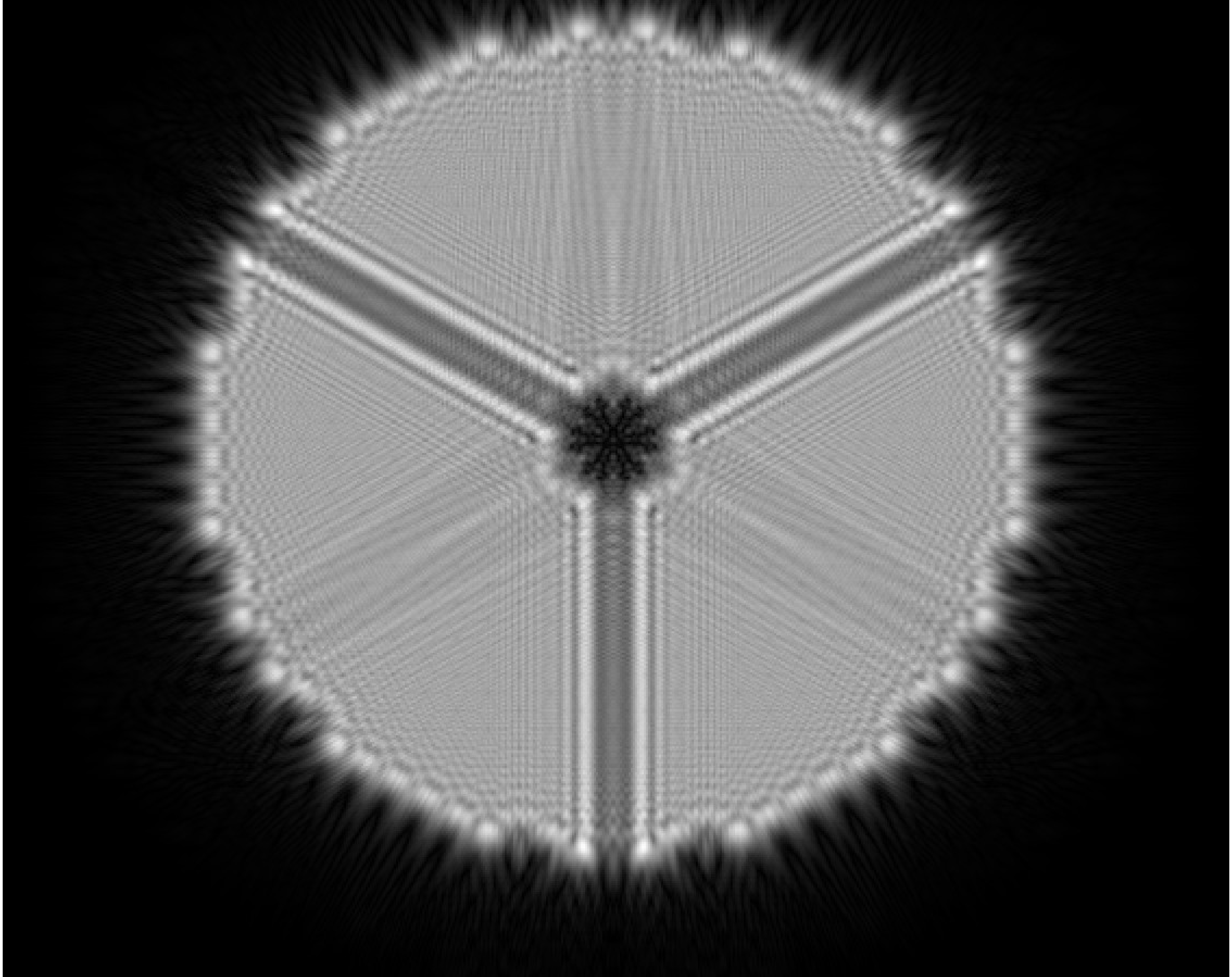
1.2 l/D IWA

CaF2 lenses
SiO2 mask

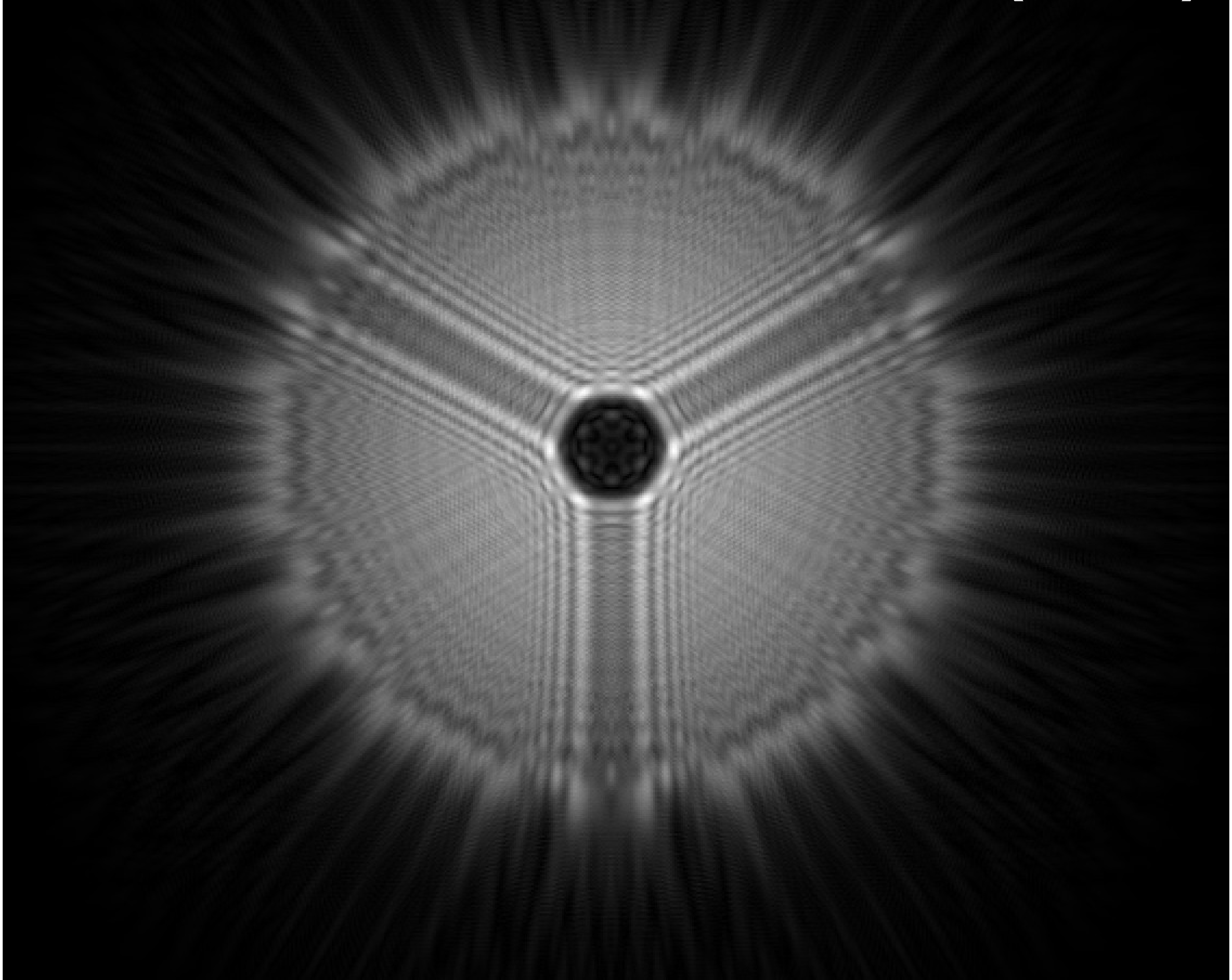
Pupil Plane



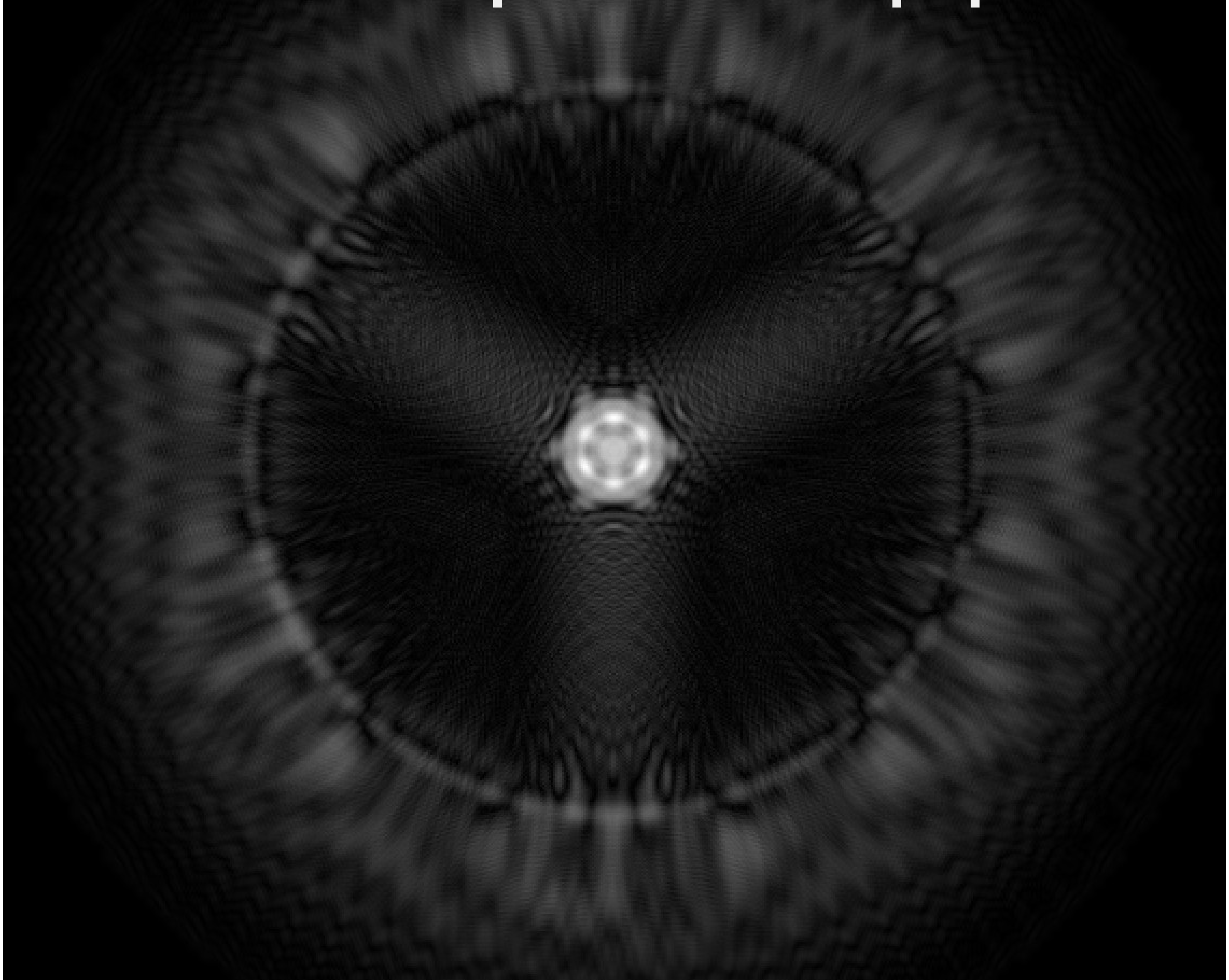
PIAACMC lens 1 front surface (CaF2)



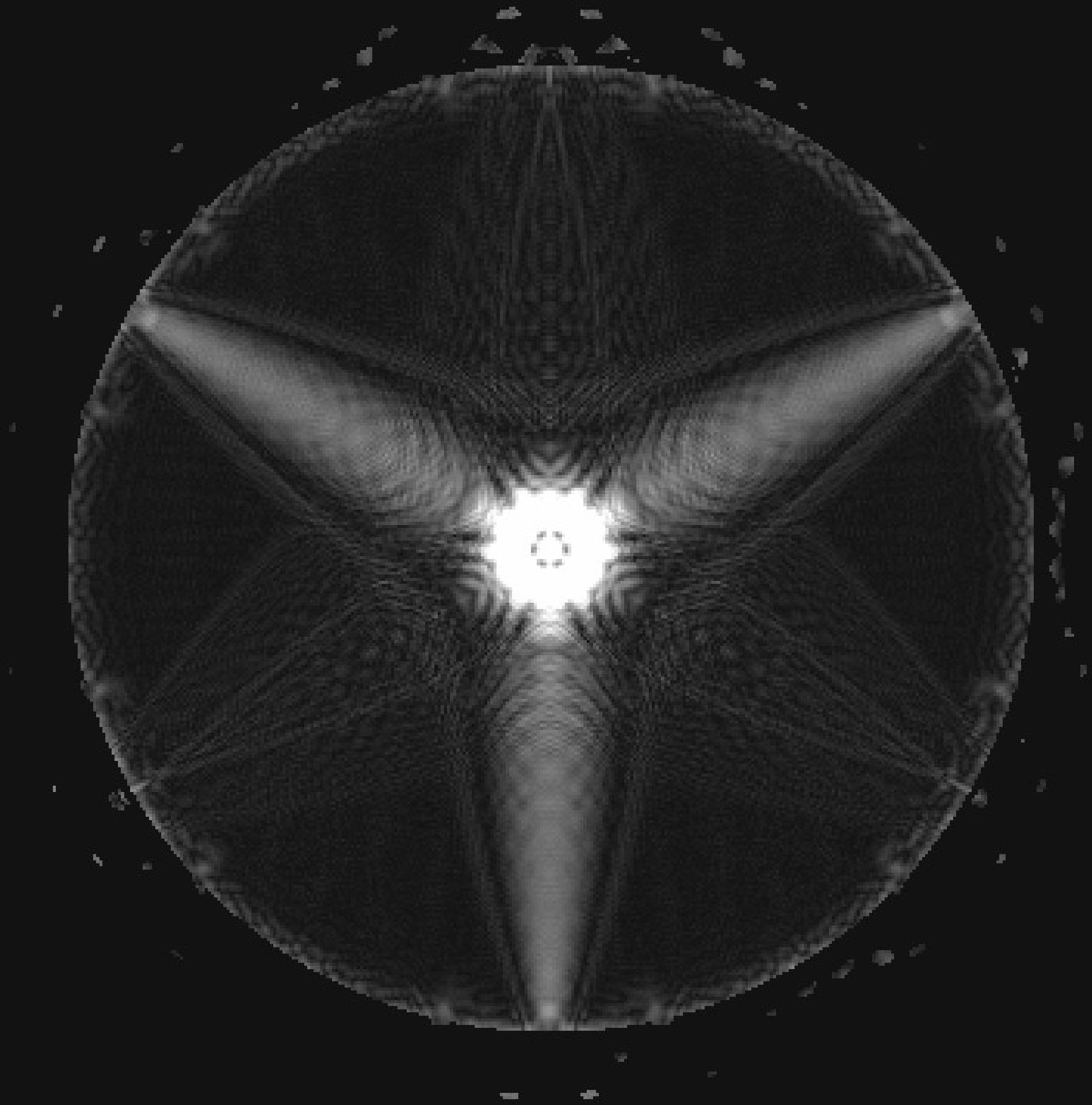
PIAACMC lens 2 front surface (CaF2)



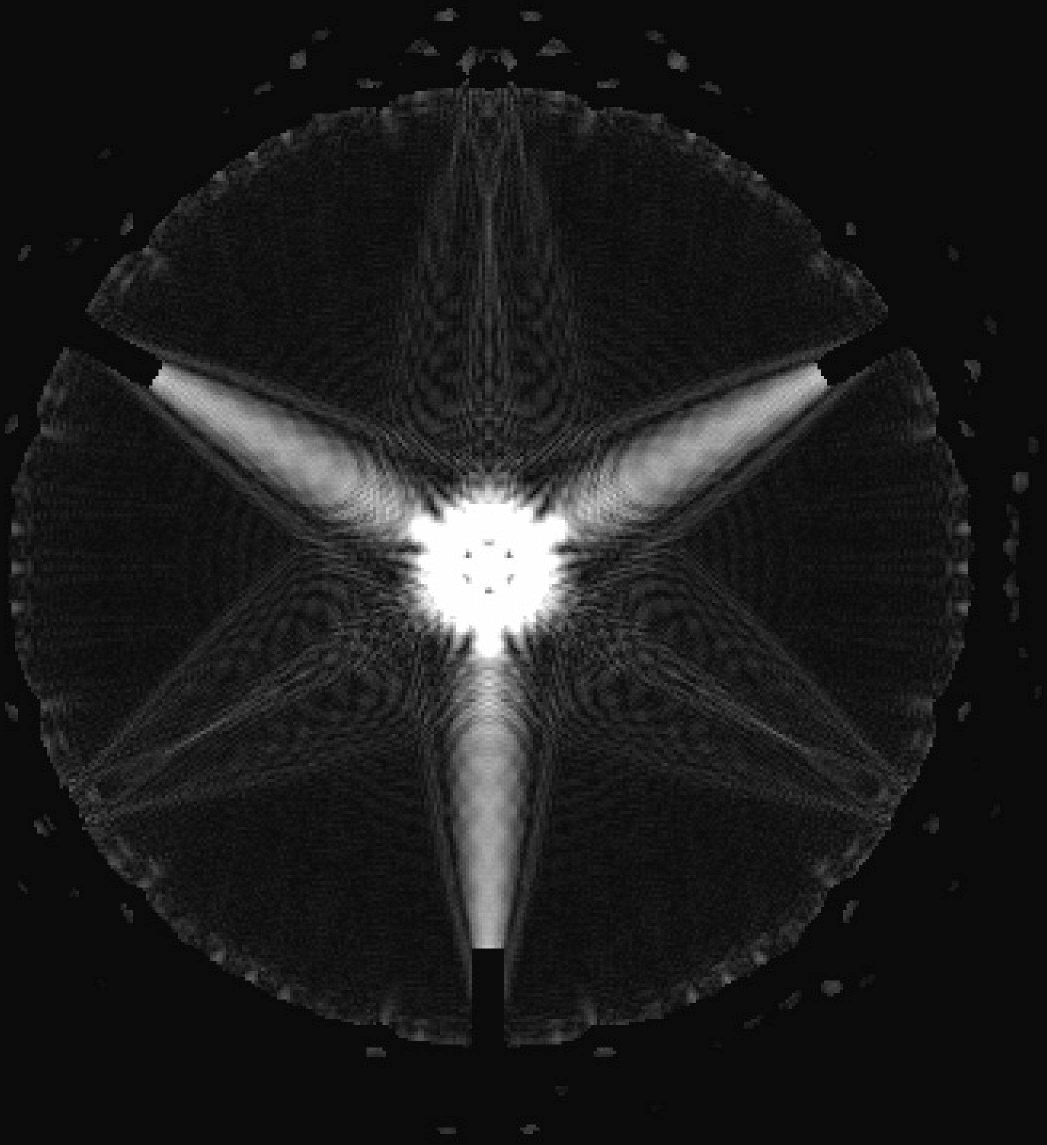
Post focal plane mask “pupil”



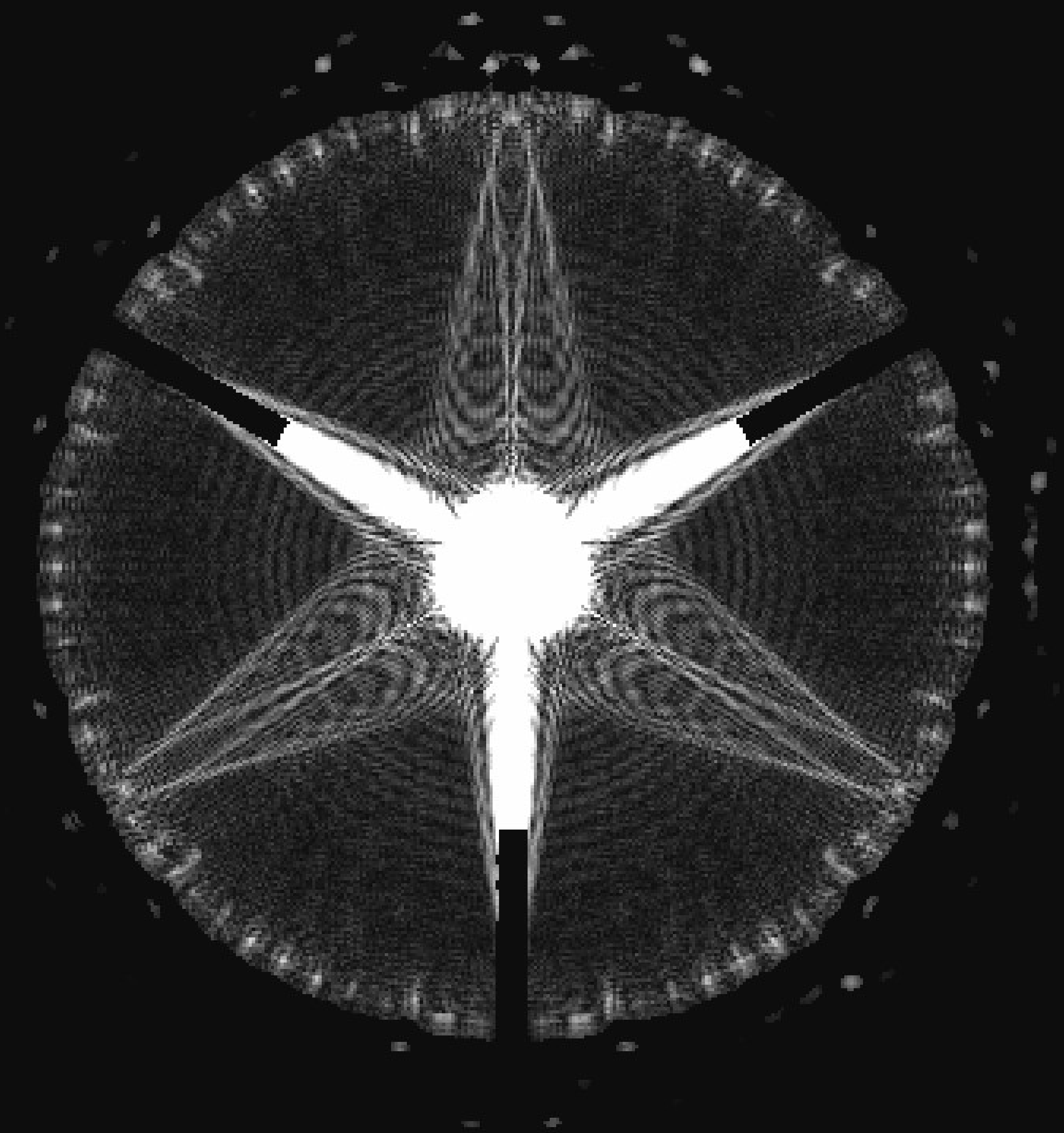
Stop #1



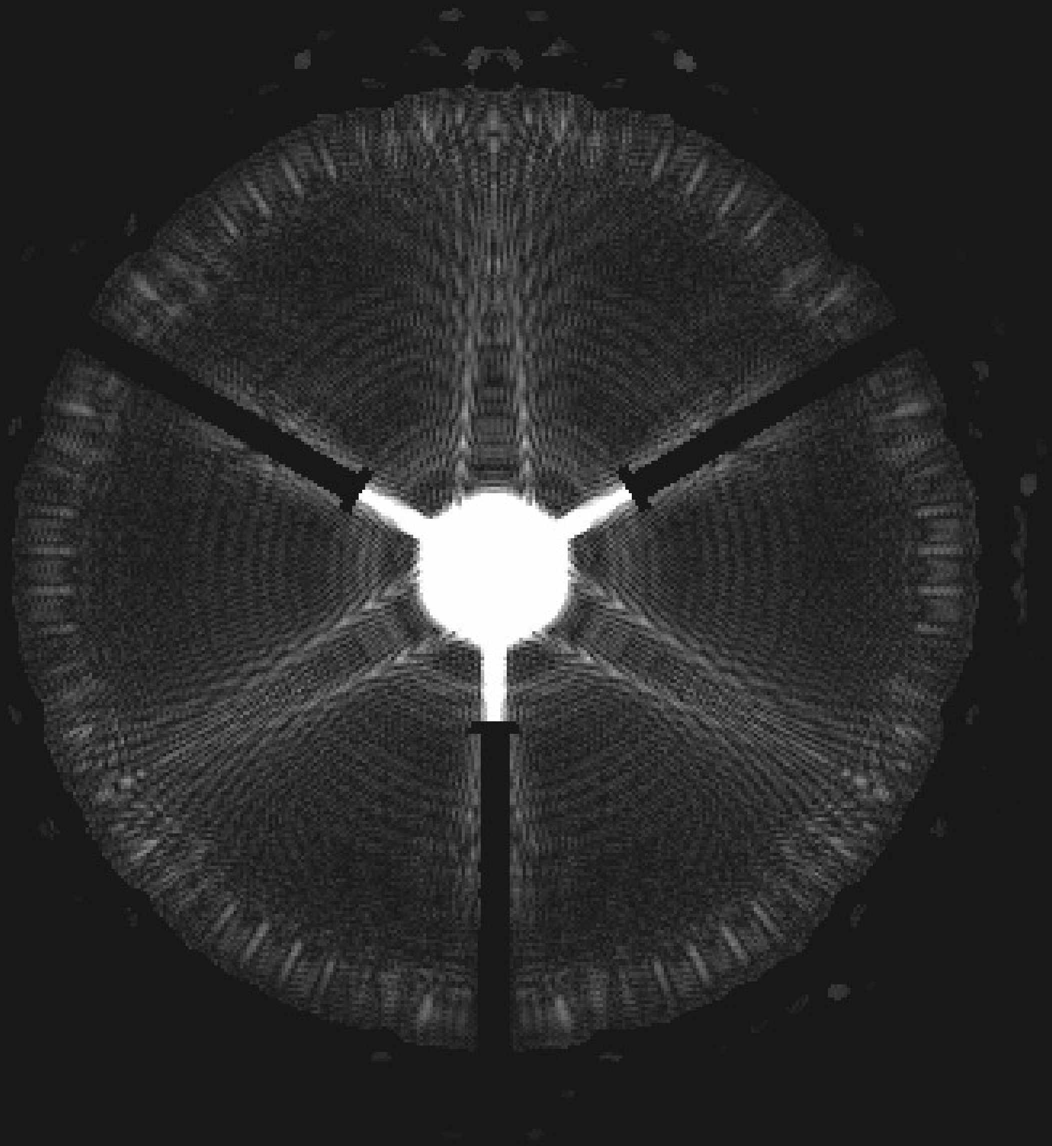
Stop #2



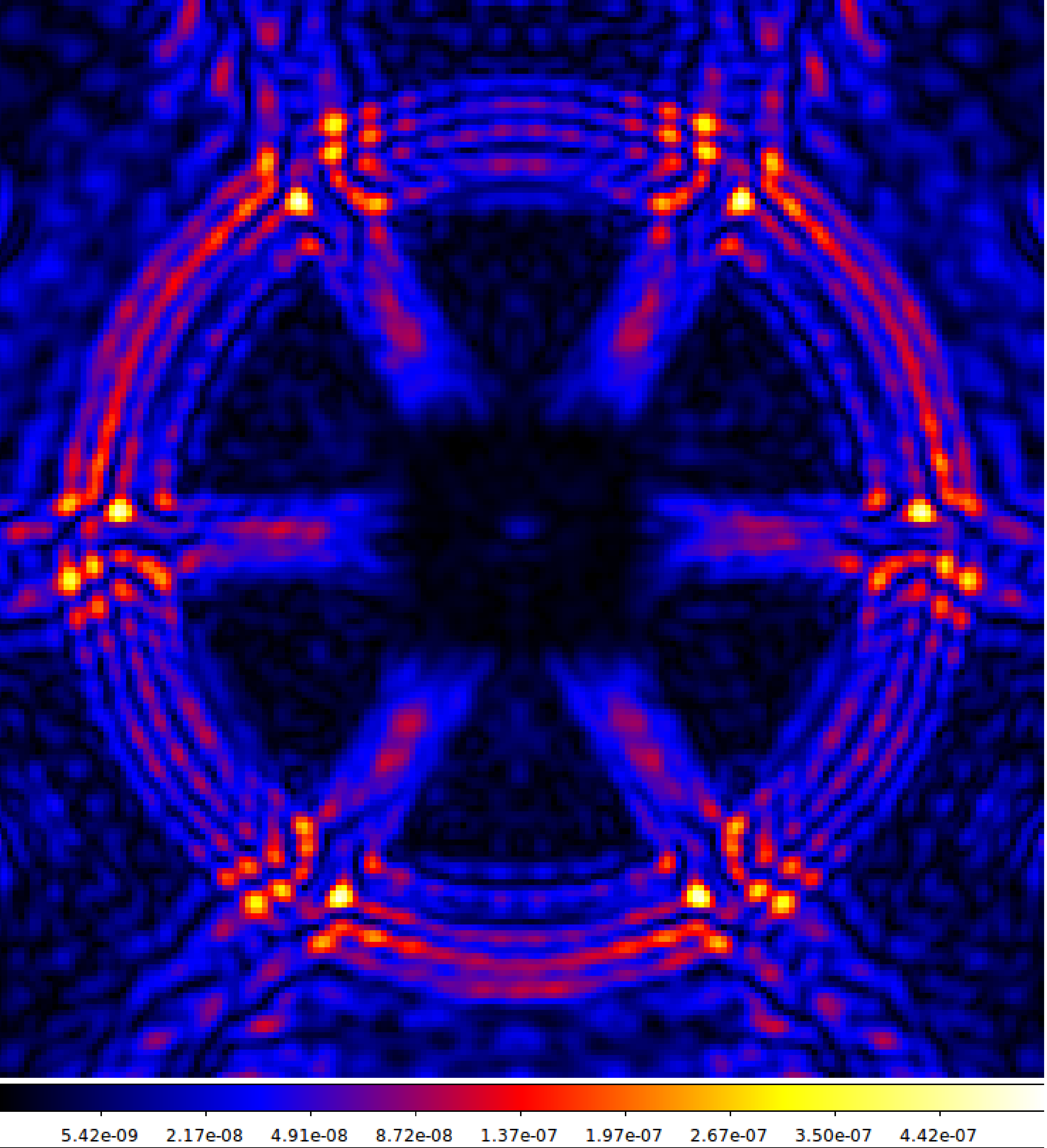
Stop #3



Stop #4



Stop #5



PSF at 1600nm

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

80% off-axis throughput

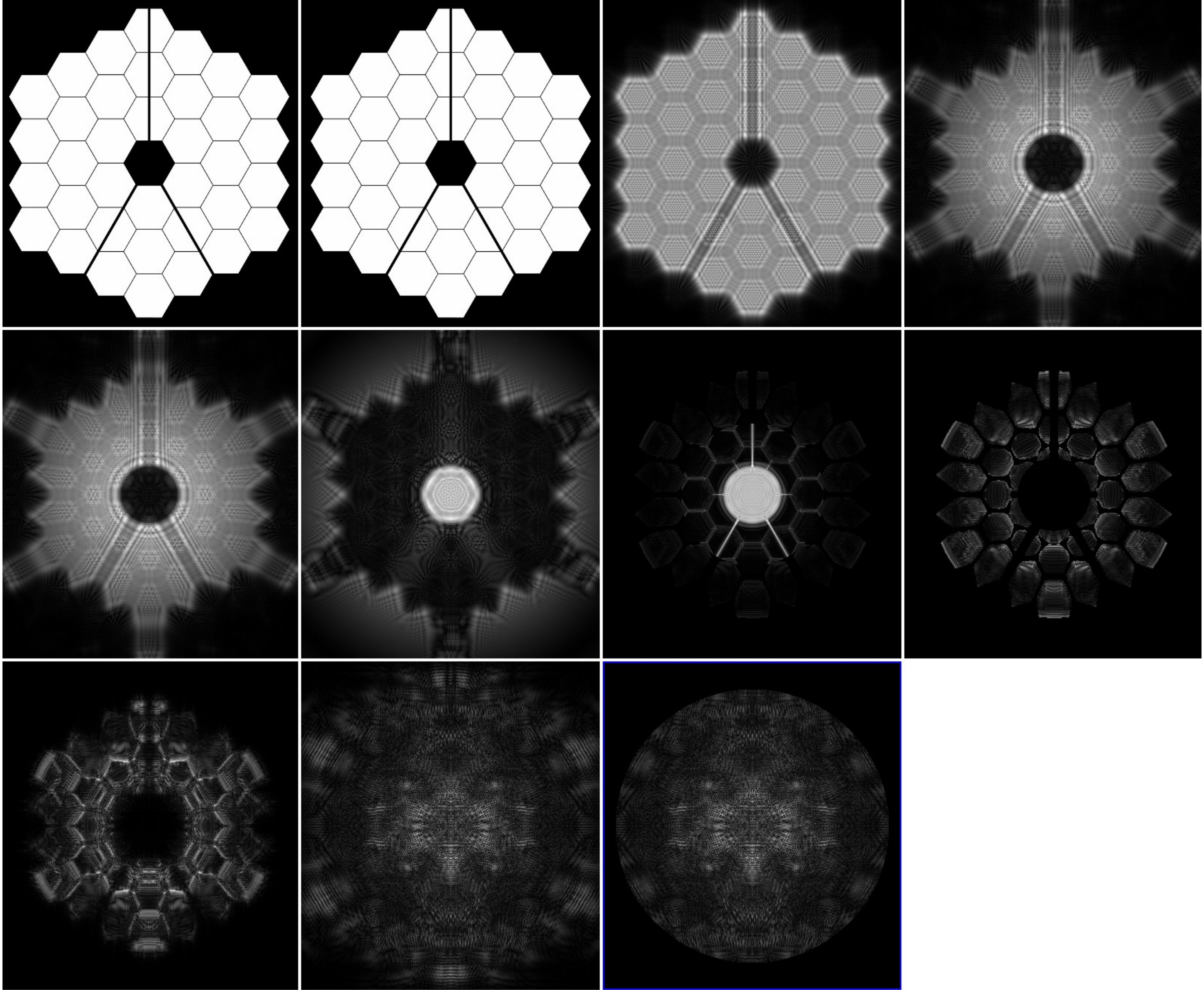
1.2 l/D IWA

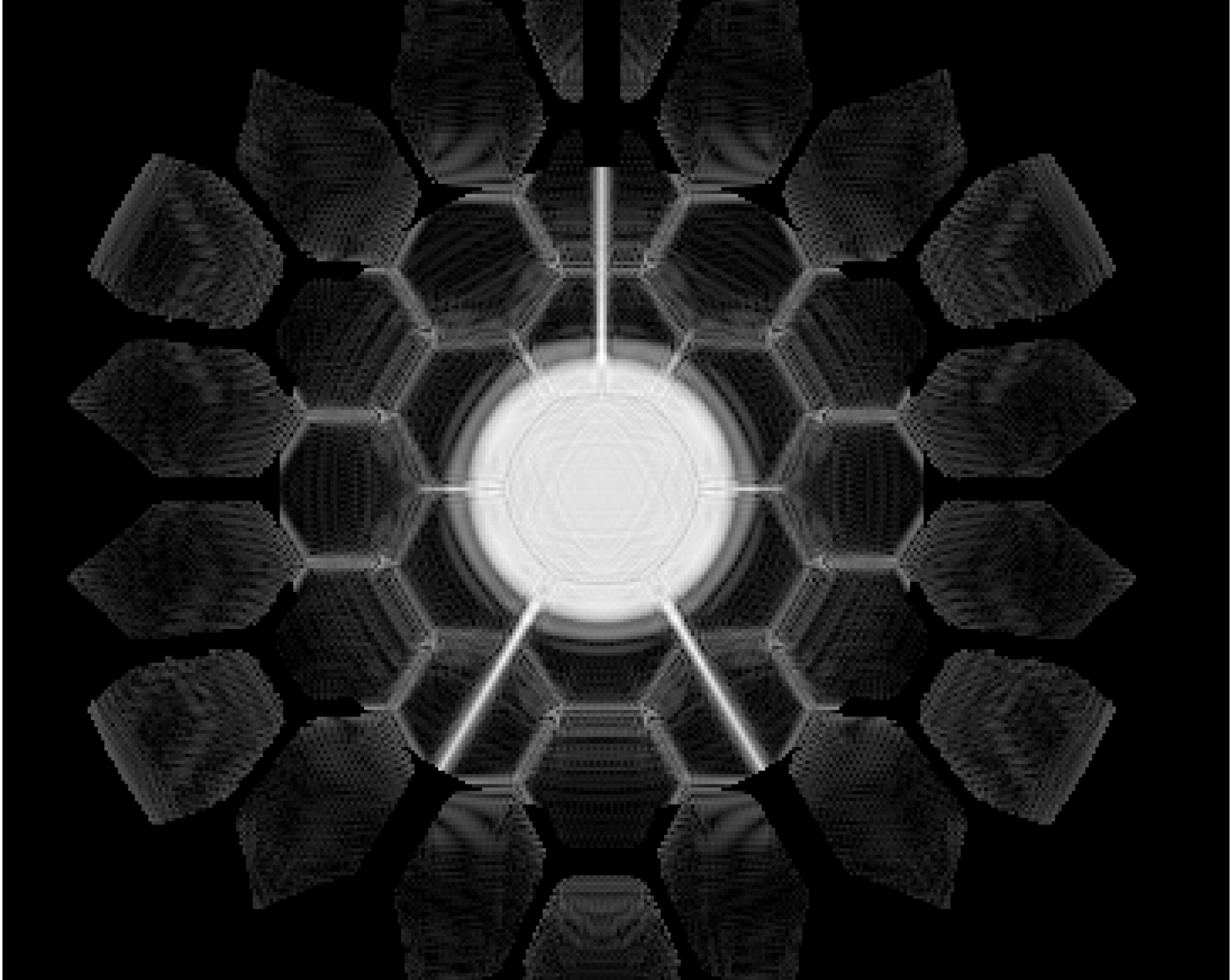
CaF2 lenses
SiO2 mask

Second example

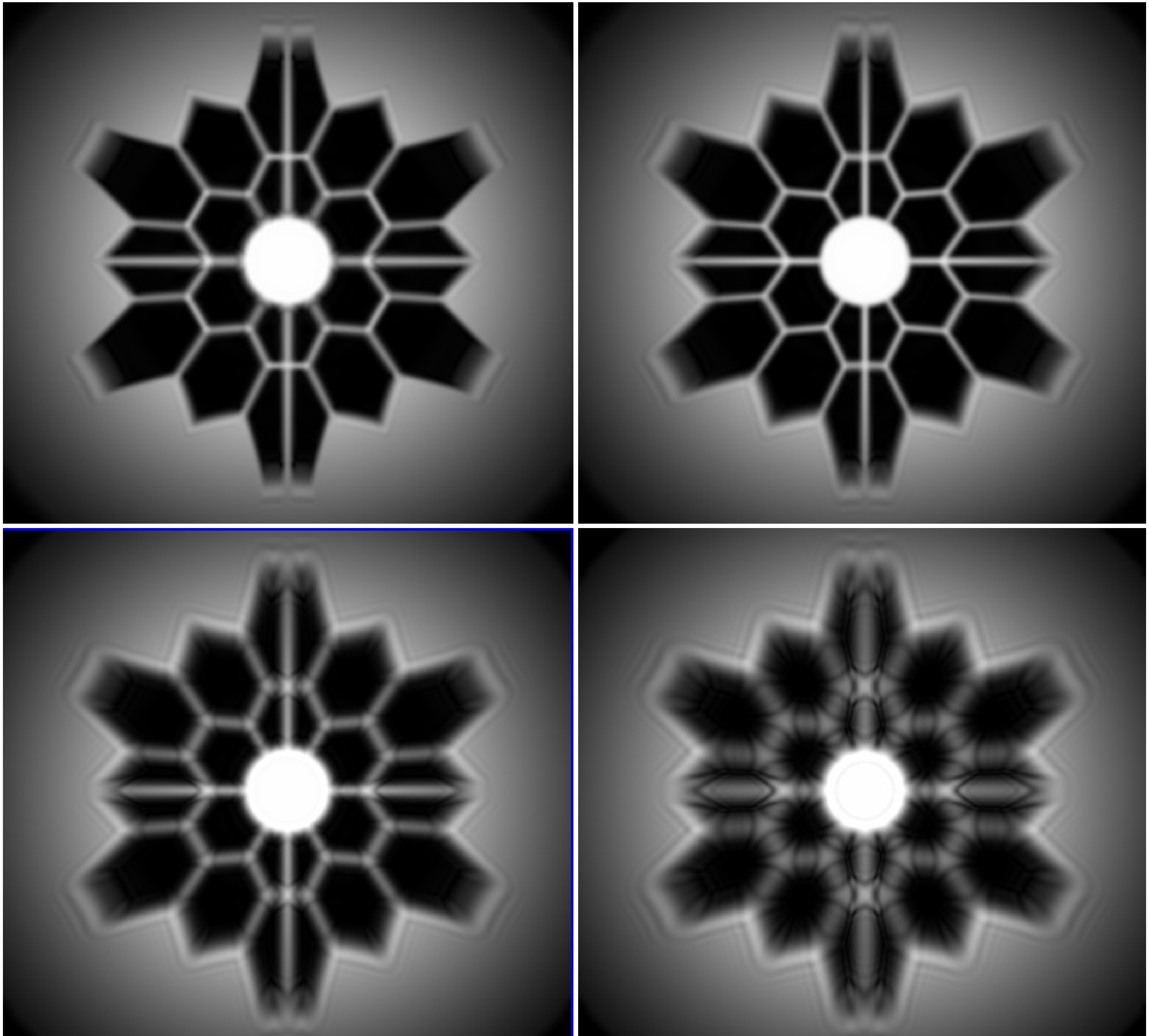
2-ring and 3-ring segmented pupils
Optical design identical to WFIRST PIAA
(beam compressing telescope, pupil well outside PIAA system)

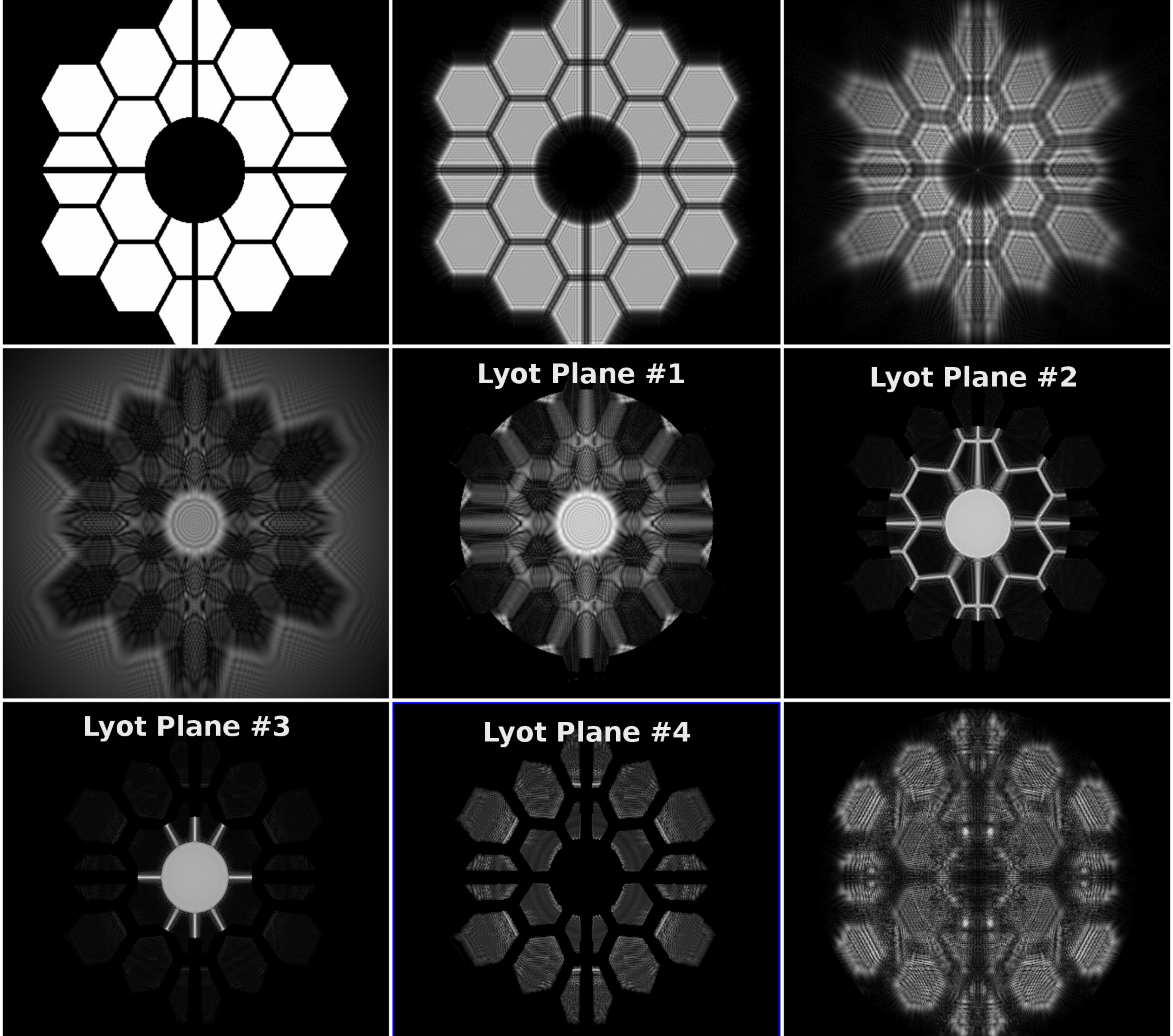
Mirror sizes: 1.2x to 1.5x beam diameter
array size: 1024x1024, pupil radius = 200 pix

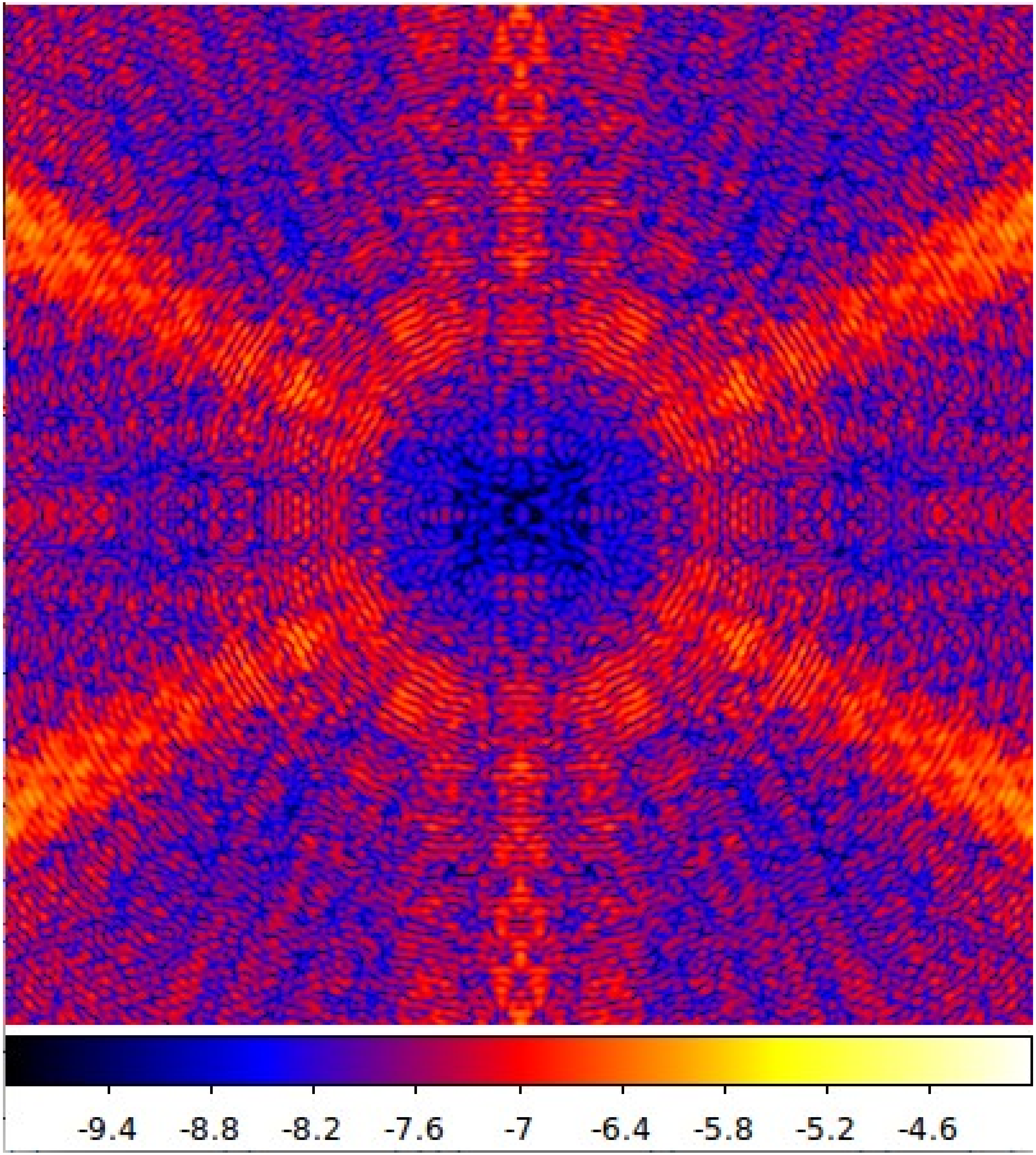




Re-imaged segment gaps (10% band)

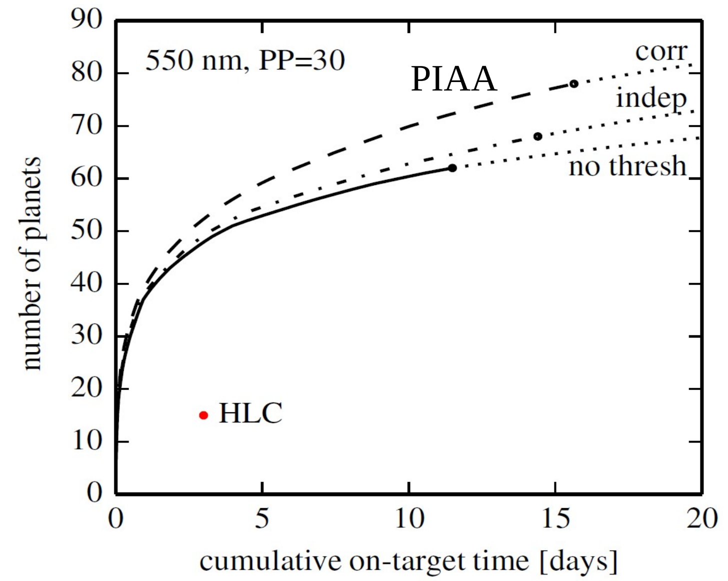


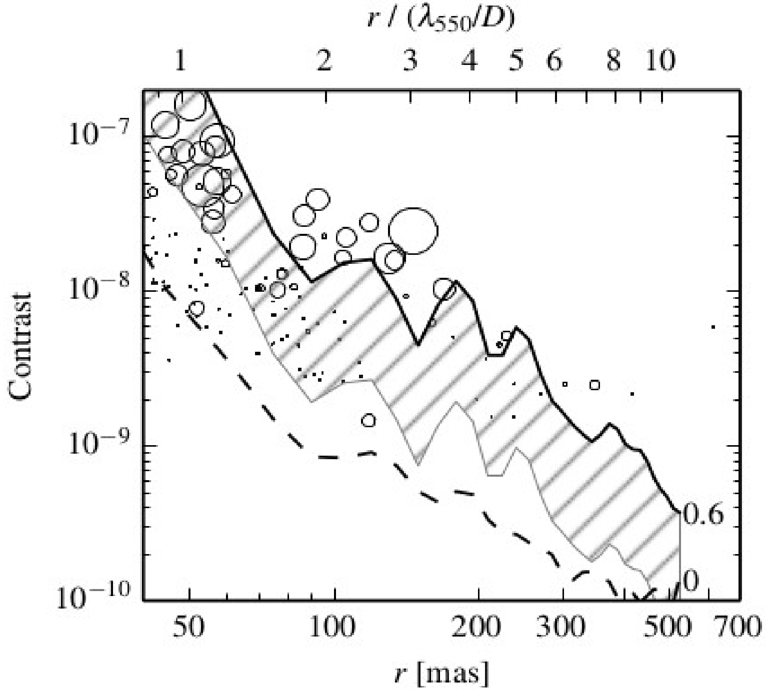

Lyot Plane #1
Lyot Plane #2
Lyot Plane #3
Lyot Plane #4

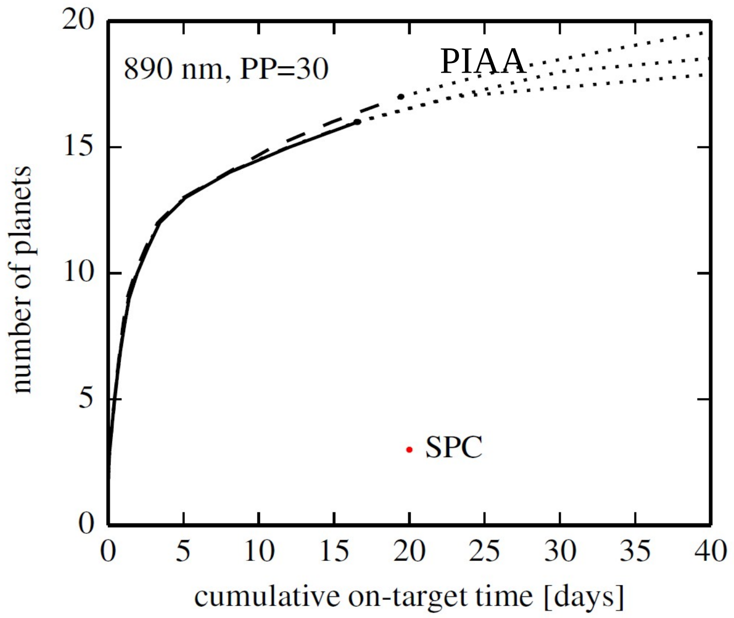

-9.4
-8.8
-8.2
-7.6
-7
-6.4
-5.8
-5.2
-4.6

Science yield

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



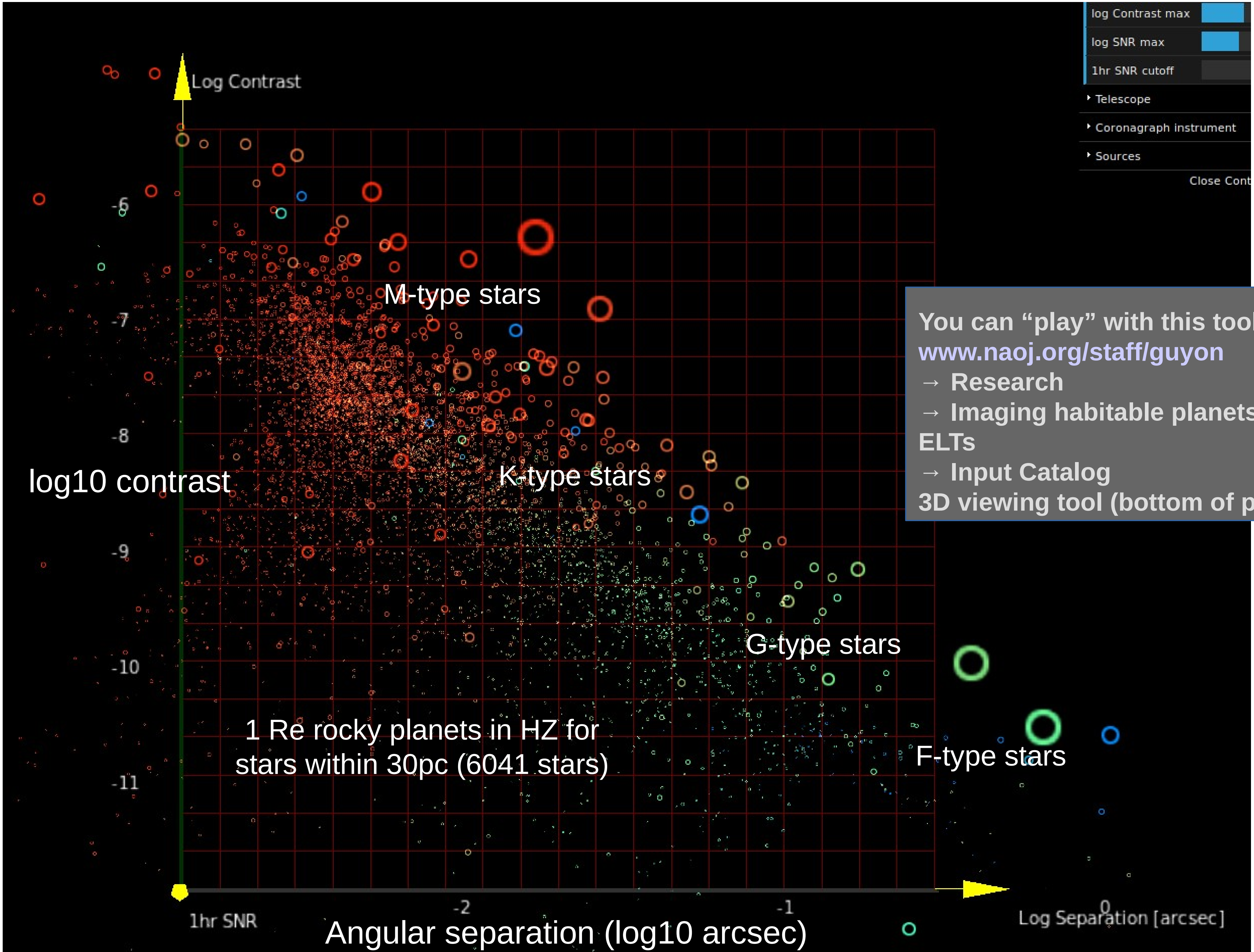




Case	Output channel	wavelength (nm)	band (%)	# pixels	# RV characterizations in less than 1 day each (min, max)		
					HLC	SPC	PIAA
1	imager	465	10	4.9	15	11	76
2	imager	565	10	4.9	15	11	87
3	imager	835	10	4.9	7	5	42
4	imager	670	18	4.9	16	13	85
5	imager	770	18	4.9	10	7	61
6	imager	890	18	4.9	5	5	36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

Where would habitable planets be in contrast/separation ?



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)

30-m telescope, H band

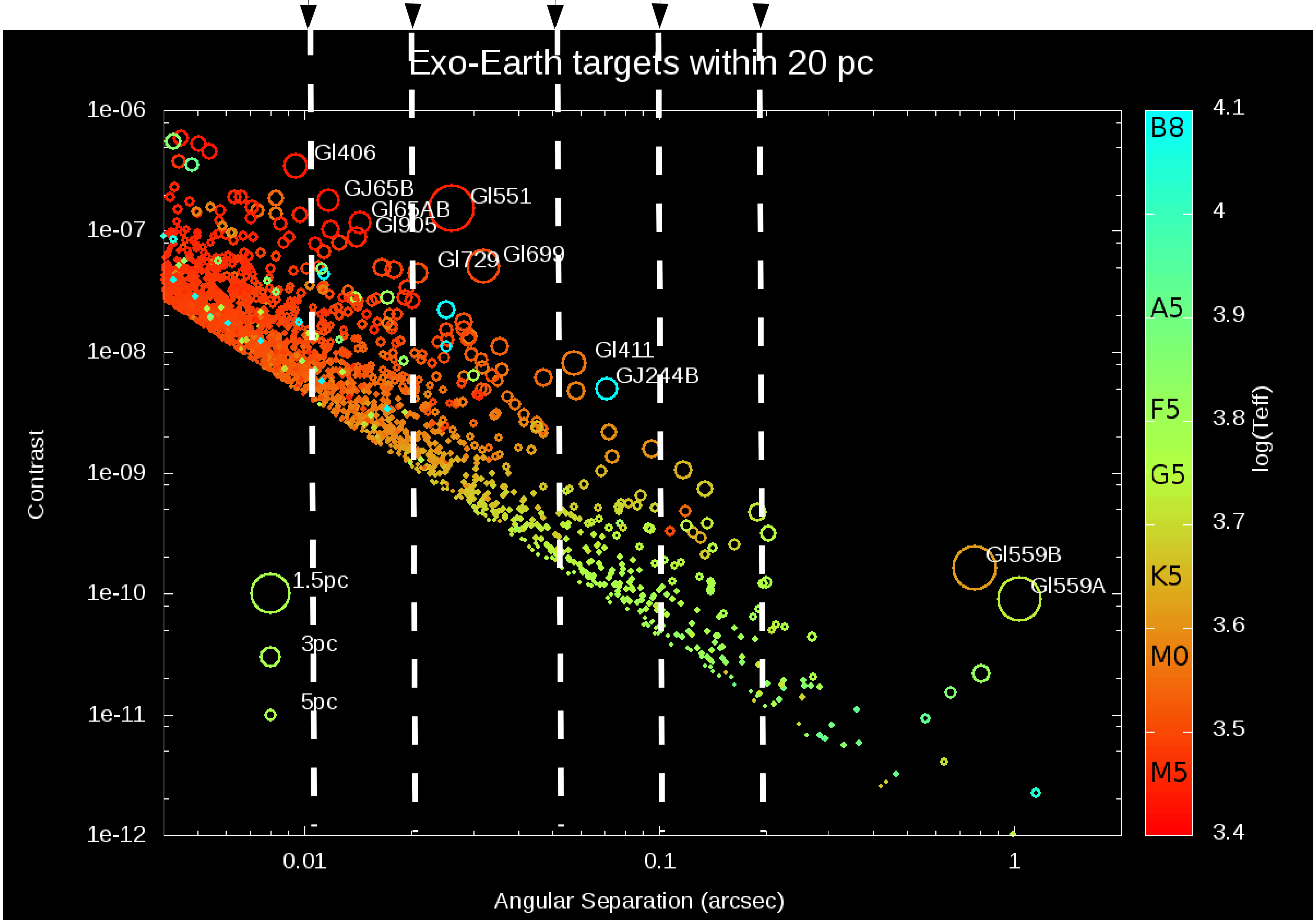
1 l/D 2 l/D

2.4-m telescope, 0.5 um

1 l/D 2 l/D 4 l/D

Ground-based

Space



Conclusions / future work

3 main outstanding issues for PIAACMC:

- Understanding limits imposed by stellar angular size
- Managing light diffracted by gaps in realistic optical system (not Fraunhofer propagation)
- Understanding focal plane mask manufacturing limits… and propagation effects with small feature sizes

Mapping PIAACMC performance to science:

Small IWA, but sensitive to stellar angular size

→ best suited for near-IR work, distant targets or cooler stars

(using PIAACMC to work at ~5 l/D is probably not an optimal solution)