Introduction to Early Stage Innovations effort

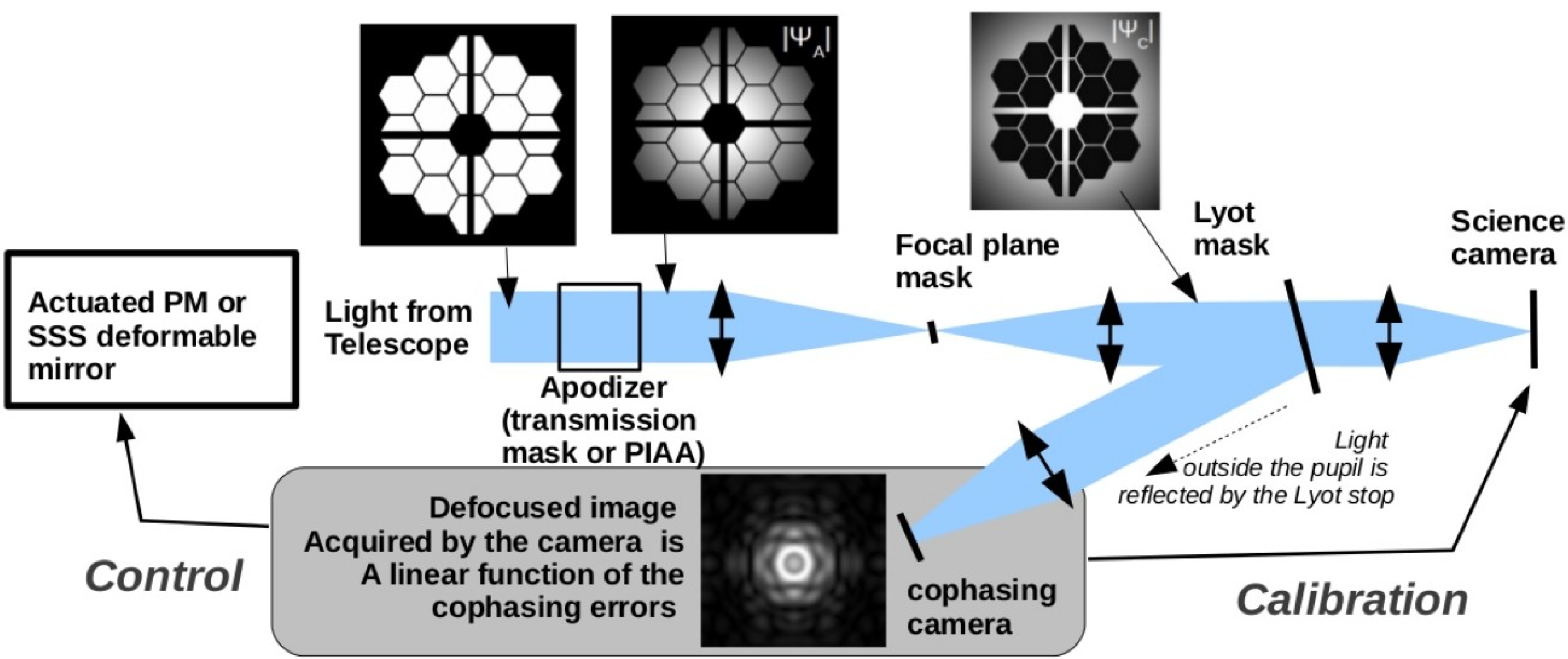
"Wavefront Control for High Performance Coronagraphy on Segmented and Centrally Obscured Telescopes"

Project goals and approach

Develop a highly accurate and efficient technique to measure fine cophasing errors in a starlight suppression system on segmented/centrally obscured apertures. Principle (shown below): use starlight otherwise rejected by the coronagraph Lyot mask to measure cophasing errors.

- **no wavefront modulation required** → does not negatively impact science instrument our other wavefront control loop(s)
- **linear sensor using a single image** → fast control loop
- starlight photons are abundant → **sensitive measurement** of fine cophasing errors
- **compatible with most high performance Lyot coronagraphs** (PIAACMC, Vortex, Band-limited Lyot), and can be generalized to other internal starlight suppression system architectures

Concept/simulation/software (this talk) + lab demo (Kelsey Miller's talk)



Introduction: Core team

Olivier Guyon, University of Arizona
- Project lead
- Software & numerical simulations
- Testbed design

Johanan Codona, University of Arizona
- Testbed control software: camera, deformable mirror
- Algorithms
- Lead for dOTF concept and its application to high contrast imaging

Kelsey Miller, University of Arizona (graduate student, funded by this project)
- Testbed design and assembly

Alexander Rodack, University of Arizona (undergraduate student, funded by project (50%) and Arizona Space Grant Consortium (50%))
- Testbed design and assembly

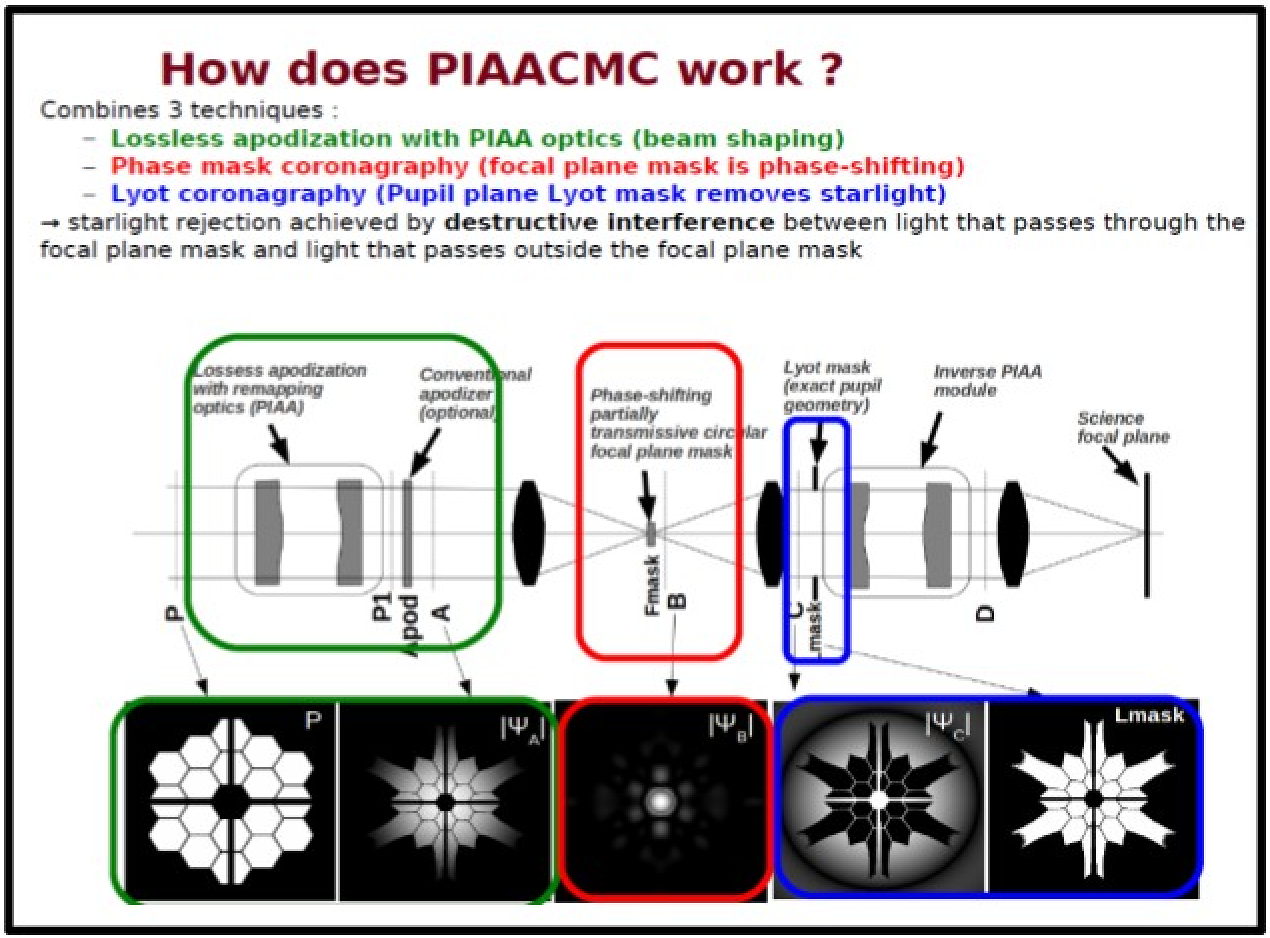
Justin Knight, University of Arizona (graduate student, funded by this project)
- Testbed design and assembly

Scientific rationale

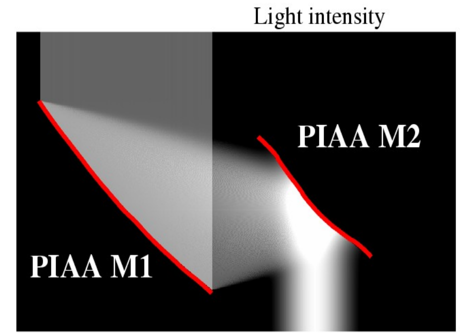
Scientific motivations:

Future large telescopes for direct imaging of exoplanets will likely be centrally obscured and/or segmented

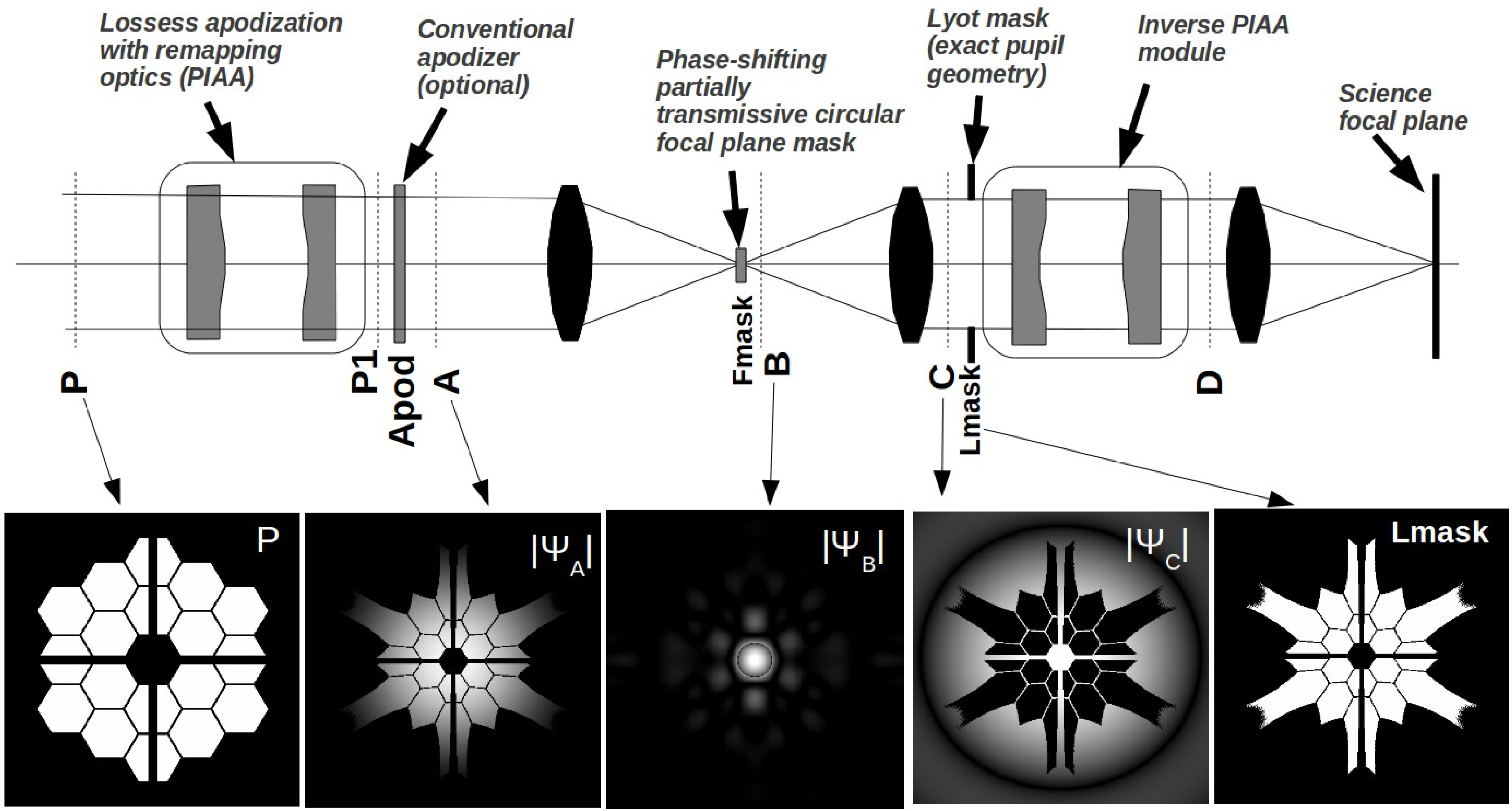
High performance coronagraphs can be designed for segmented and centrally obscured apertures (see example below)
Wavefront stability is the major challenge, especially for segmented apertures for which we expect inter-segment motion & vibration



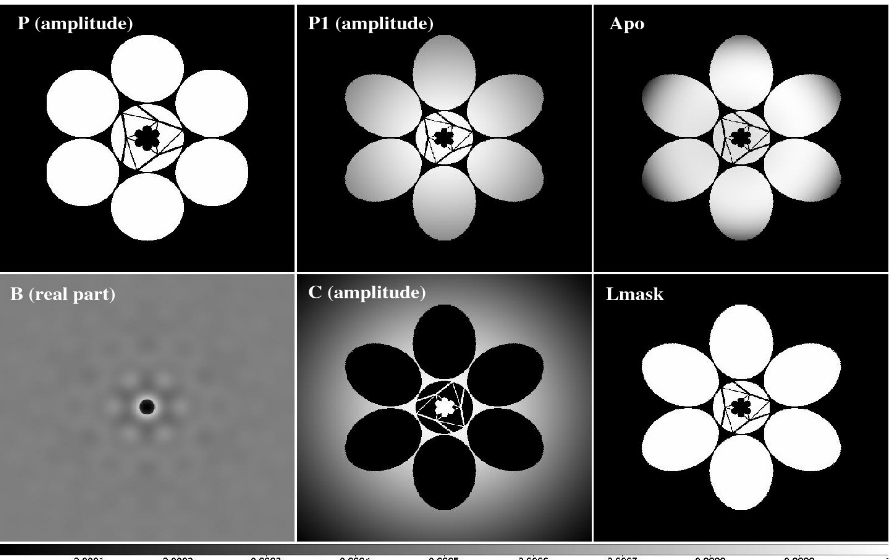
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



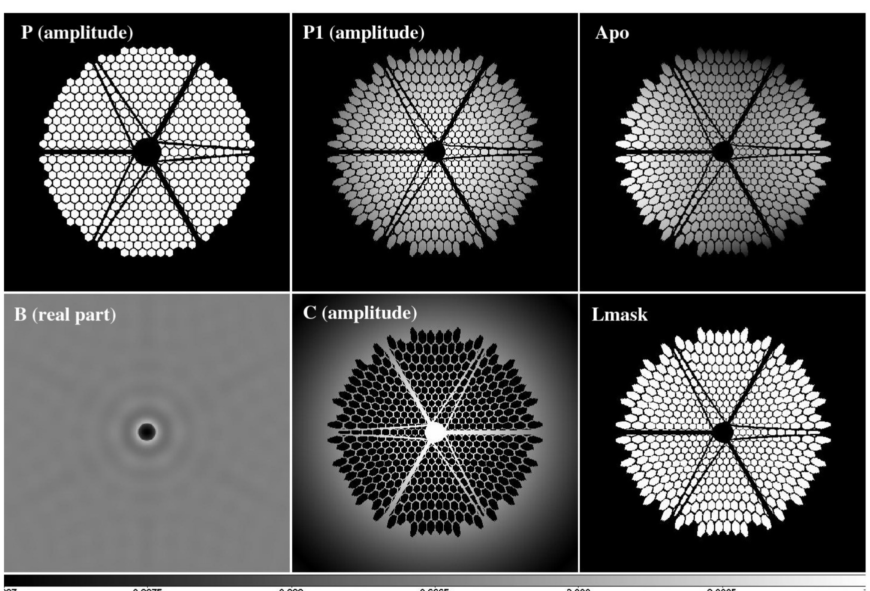
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

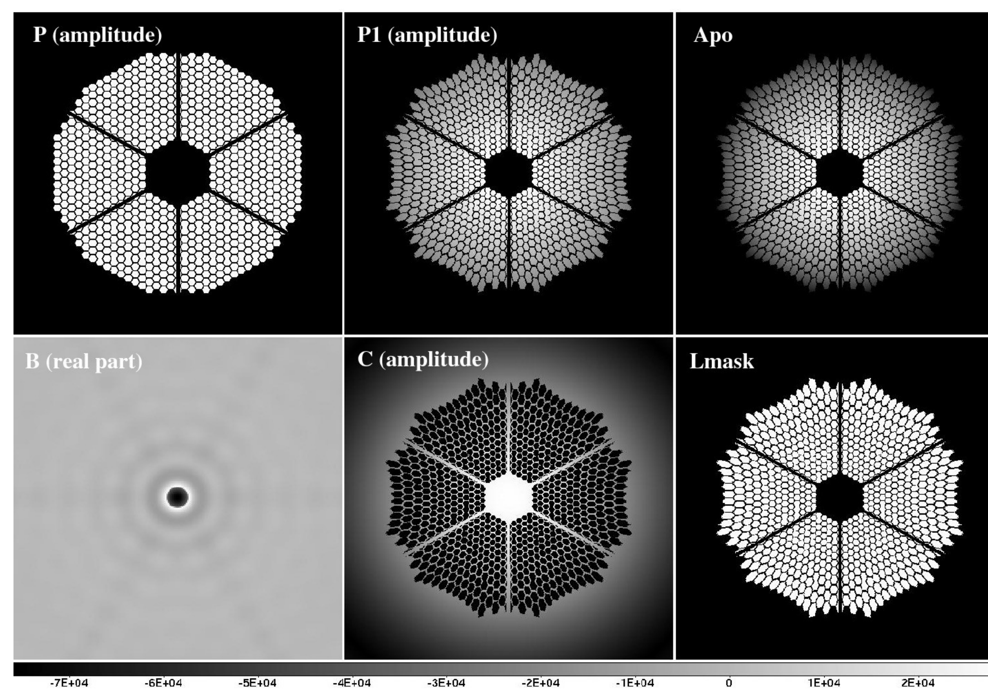


•PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



<u>Pupil shape does not matter !!!</u>





Understanding requirements: segmented apertures

Important scaling laws for segmented apertures:

[1] The **Open-loop cophasing requirement** at small angles is given by:
$d\varphi$ = sqrt(N x Raw Contrast)

- Cophasing error required to meet a given raw contrast level is independent of telescope diameter or coronagraph design
- With a larger number of segments, the cophasing error can be larger, as the corresponding speckle halo is spread over a larger area in the focal plane

[2] The associated **sensing timescale**, including a factor 10 between sensing frequency and closed-loop bandwidth, is, assuming that wavefront sensing is performed at λ=550nm:
$t = 1.31\text{e-}6 \times 2.512^{mV-10} / (\text{Contrast} \times D^2 \times \delta\lambda)$

While a larger number of segments (smaller segment size) corresponds to fewer photon per segment to perform the phase measurement, it also corresponds to a larger allowable cophasing error. The two effect perfectly cancel, yielding, a **timescale which is, for a fixed telescope diameter D, independent of the number of segments**

Understanding requirements: segmented apertures

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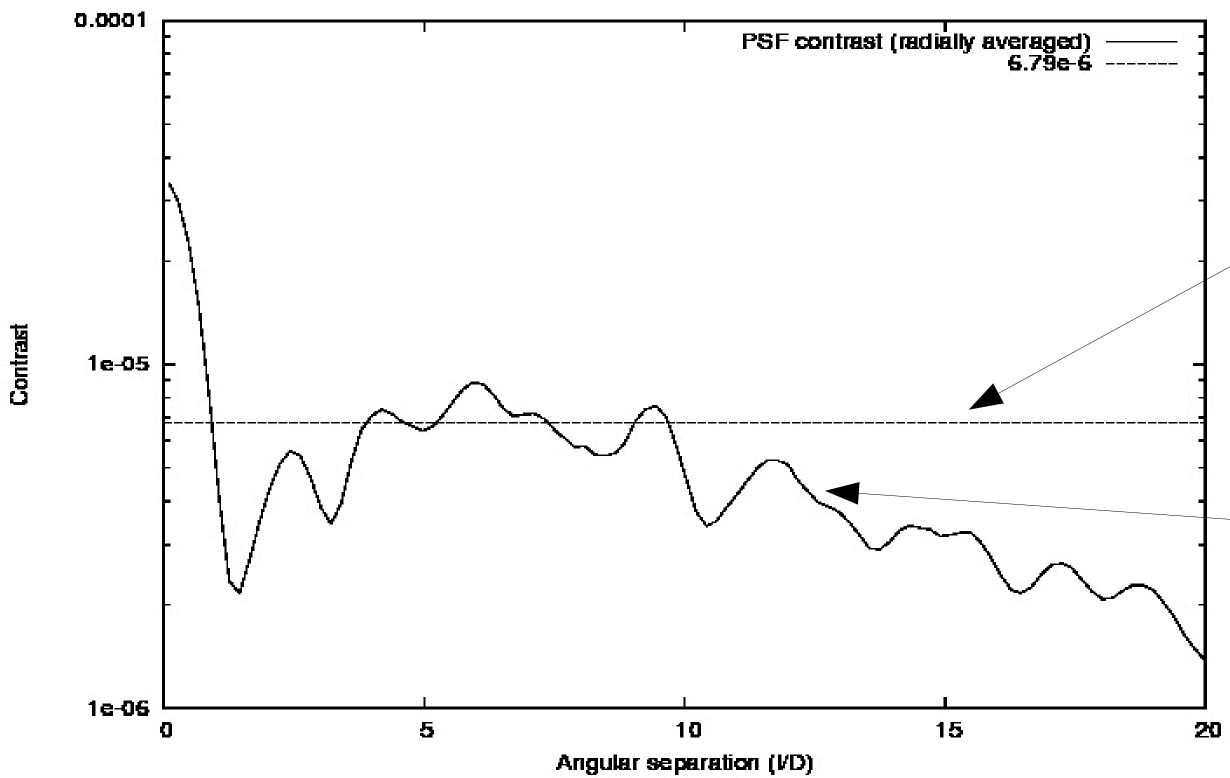


Predicted from equ. [1]

Measured from numerical simulation

Understanding requirements: segmented apertures

wavefront sensing @ λ=550nm with an effective spectral bandwidth δλ=0.1μm.

Telescope diameter & wavelength	Number of segments	Contrast goal (raw)	Target brightness	Cophasing requirement	Stability timescale
4m, 0.55 μm	10	1e-10	V=8	2.8 pm	22 mn
8m, 0.55 μm	10	1e-10	V=8	2.8 pm	5.4 mn
8m, 0.55 μm	100	1e-10	V=8	8.7 pm	5.4 mn

Vibration control is a significant challenge

Table above shows most challenging requirement
For mV = 3, stability timescale is 100 times shorter (few seconds)

Table above ignores potential PSF calibration (segment cophasing errors can produce recognizable PSF features different from exoplanet)

Stellar angular size limit

Sun at 10pc = 1 mas diameter = 0.1 l/D diameter in visible on 10m telescope
2m telescope : 1mas diameter = 0.01 l/D radius in visible

→ imposes strong limit on RAW contrast achievable at small IWA
Star leakage is however known, incoherent and static (assuming good pointing)

“known”
Leakage is determined by coronagraph design (morphology) and stellar angular size (amplitude)
It is usually proportional to star diameter [l/D] squared. Can sometimes be proportional to 4^{th} power of star diameter

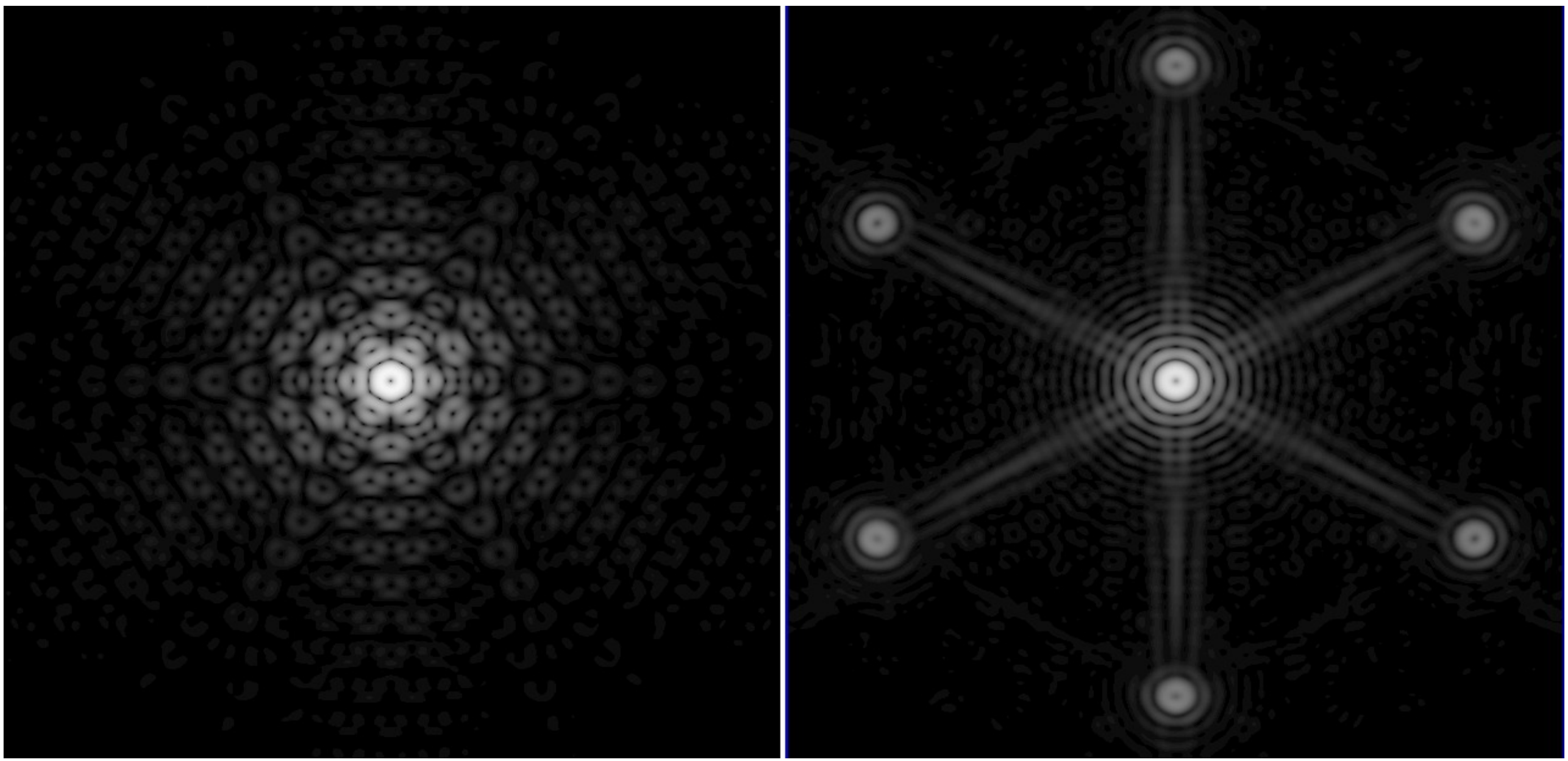
“incoherent”
Does not interfere with speckles due to wavefront aberrations

“static”
Does not change with time

Stellar angular size leak (examples)

Light distribution due to stellar angular size is strongly affected by pupil geometry
→ may be a factor in deciding which pupil geometry works

7 large segments | many small segments

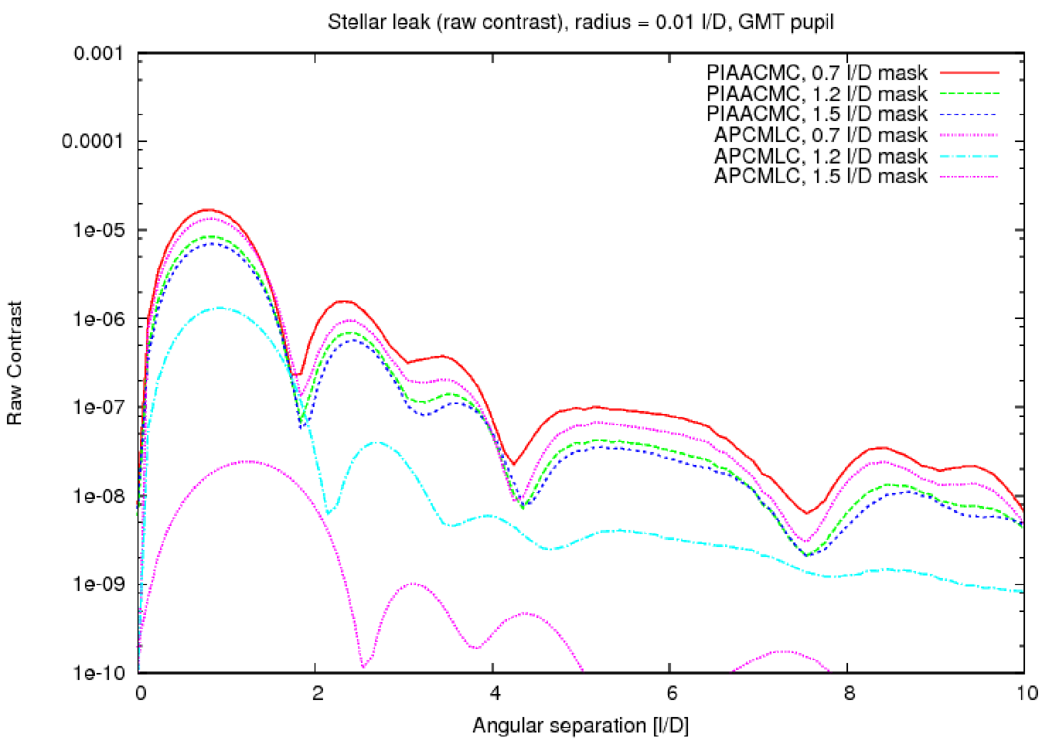


Coronagraphic leak due to stellar angular size for the GMT (left) and TMT (right) pupil, for a 0.01 l/D radius stellar disk and a PIAACMC coronagraph with a a/2 = 1.5 l/Dsyst mask.

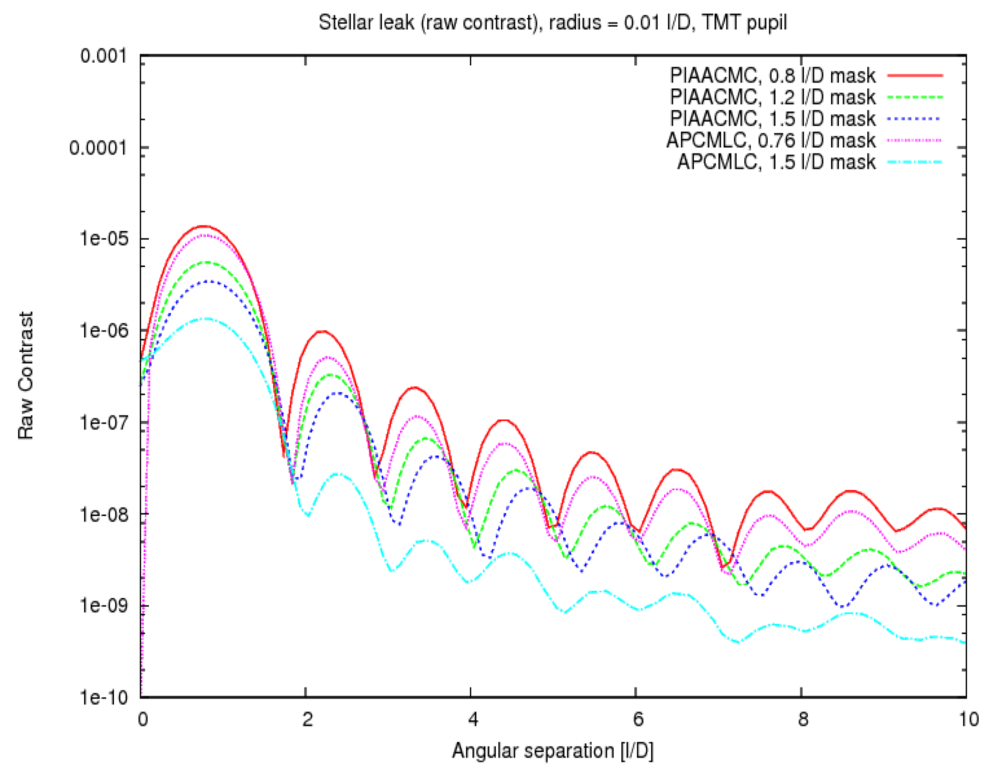
Stellar angular size leak (examples)

Light distribution due to stellar angular size is strongly affected by pupil geometry AND coronagraph design
→ may be a factor in deciding which pupil geometry works

7 large segments



many small segments



No known solution offers ~1e-9 contrast at 2-3 l/D on a large telescope observing nearby stars

→ some PSF subtraction will be required, and stellar size cannot be ignored in SNR computations

Stellar angular size limit: coronagraph design can play a key role

Common wisdom:
Small IWA = high sensitivity to stellar angular size

Evidence:
- Fundamental limits (Guyon et al. 2005)
- Several specific examples of coronagraph designs

If too much stellar leak → increase coronagraph's IWA

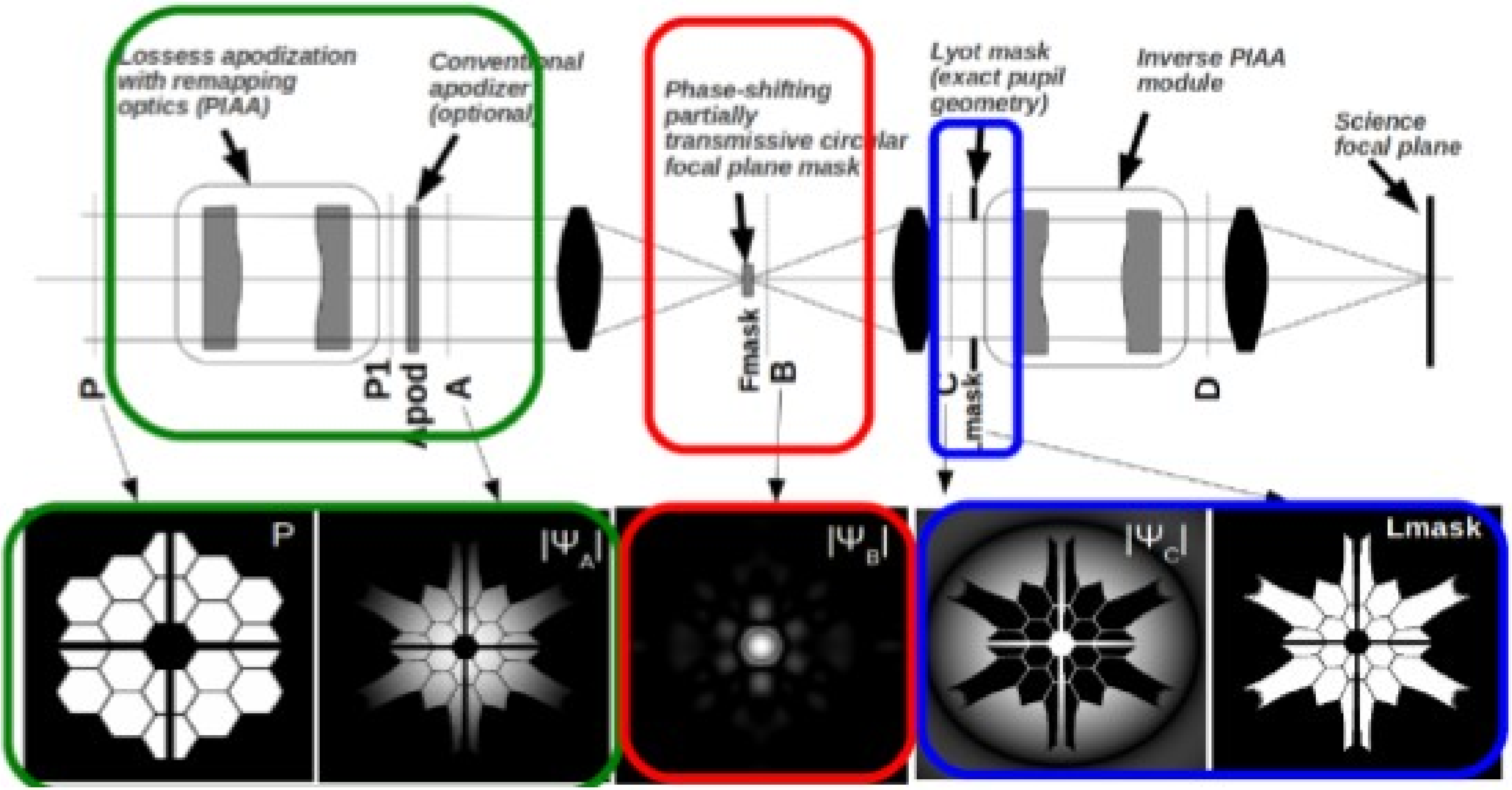
Next slides show this is not always true (example: PIAACMC design for centrally obscured aperture)
→ there is a strong benefit in re-visiting / optimizing coronagraph design for stellar angular size
Note: "untuned" PIAACMC is far from Guyon et al. 2005 fundamental limit

How does PIAACMC work ?

Combines 3 techniques :

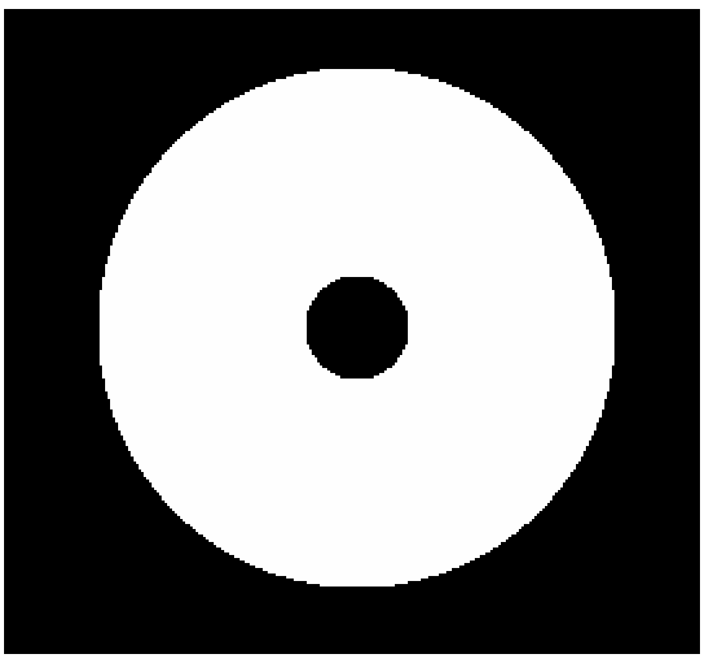
- **Lossless apodization with PIAA optics (beam shaping)**
- **Phase mask coronagraphy (focal plane mask is phase-shifting)**
- **Lyot coronagraphy (Pupil plane Lyot mask removes starlight)**

→ starlight rejection achieved by **destructive interference** between light that passes through the focal plane mask and light that passes outside the focal plane mask

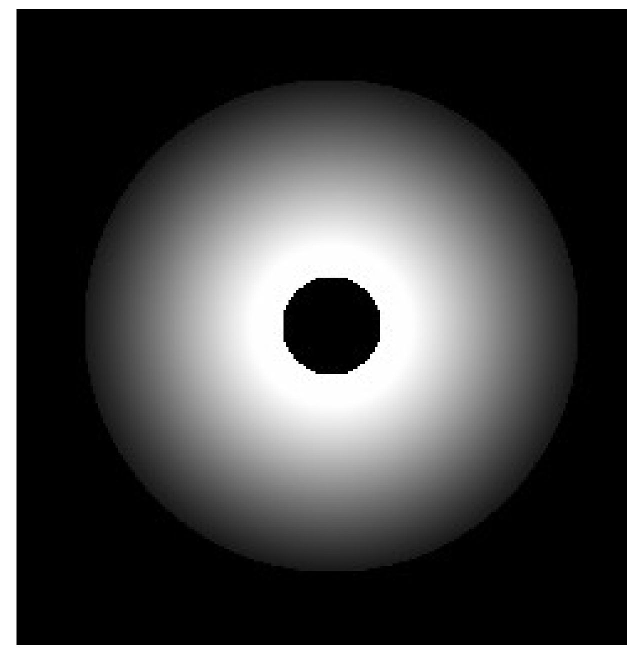


Centrally obscured pupil design optimization

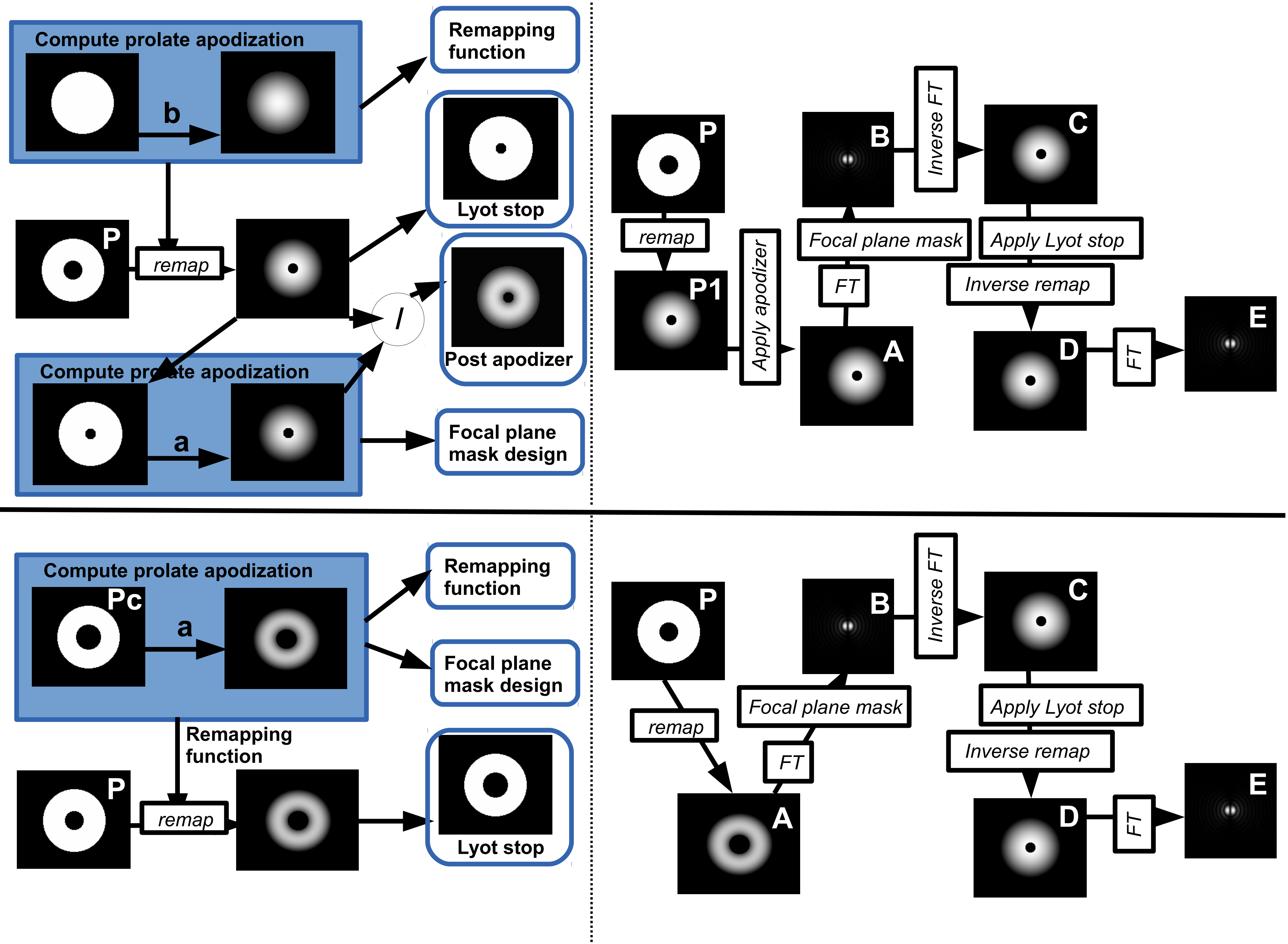
Two key design parameters:
Focal plane mask radius
Output central obstruction size



Input central obstruction



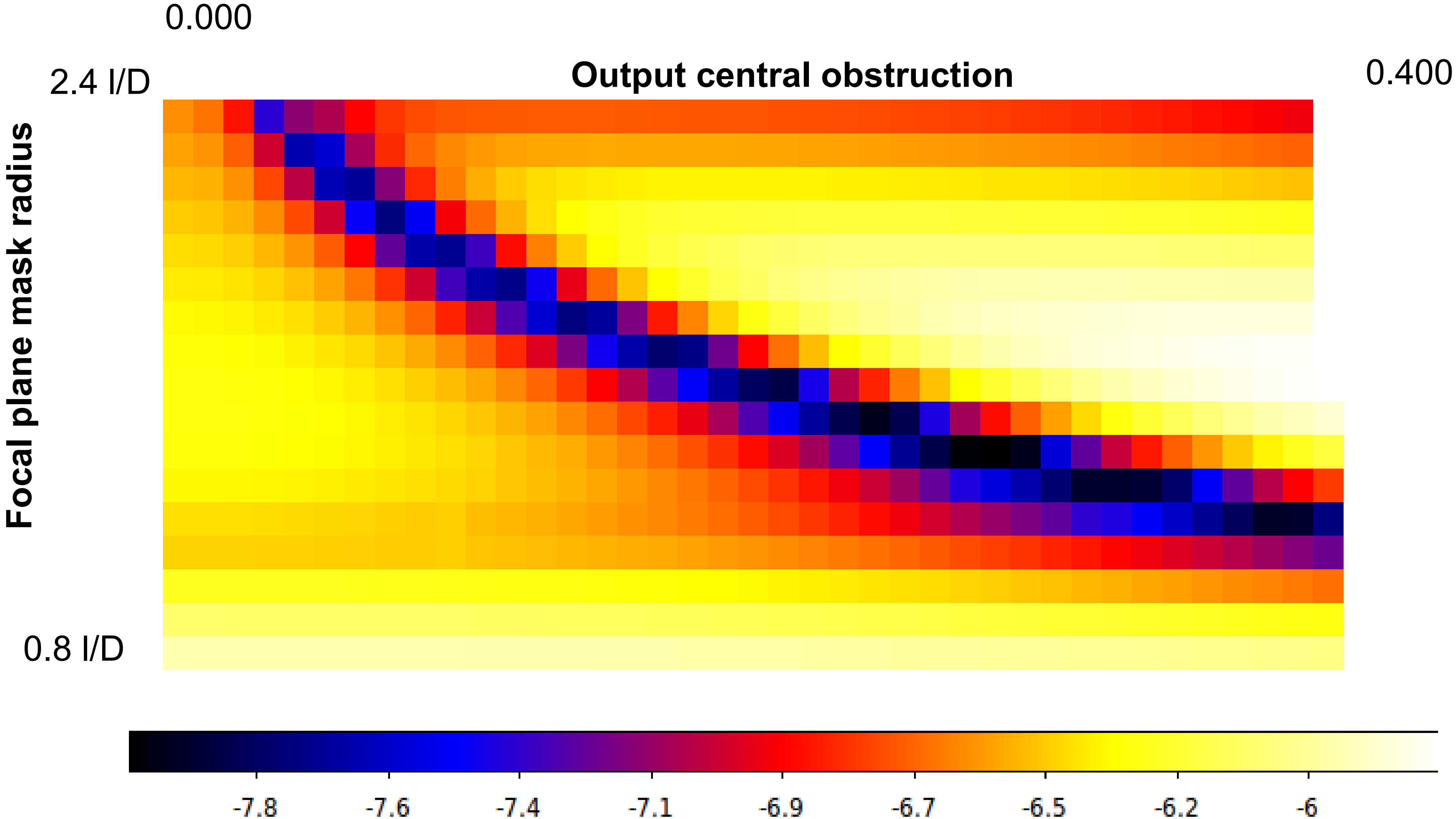
Output central obstruction



Compute prolate apodization
b
Remapping function
Lyot stop
P
remap
/
Post apodizer
Compute prolate apodization
a
Focal plane mask design
P
remap
P1
Apply apodizer
B
Inverse FT
C
Focal plane mask
FT
A
Apply Lyot stop
Inverse remap
D
FT
E
Compute prolate apodization
Pc
a
Remapping function
Focal plane mask design
Remapping function
P
remap
Lyot stop
P
remap
B
Inverse FT
C
Focal plane mask
FT
A
Apply Lyot stop
Inverse remap
D
FT
E

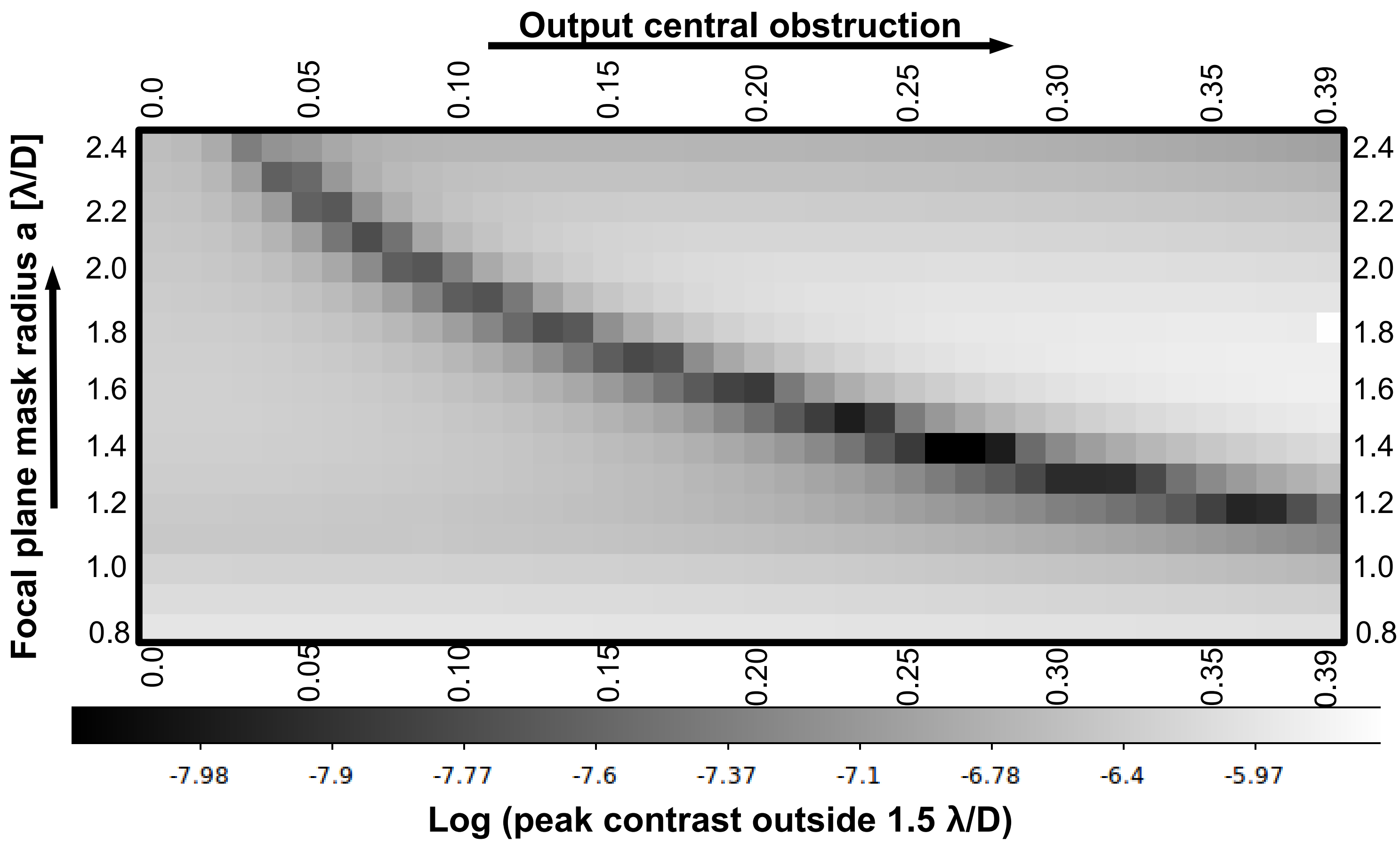
AFTA design optimization

PEAK contrast between 1.5 and 5 l/D when observing a 2% l/D disk

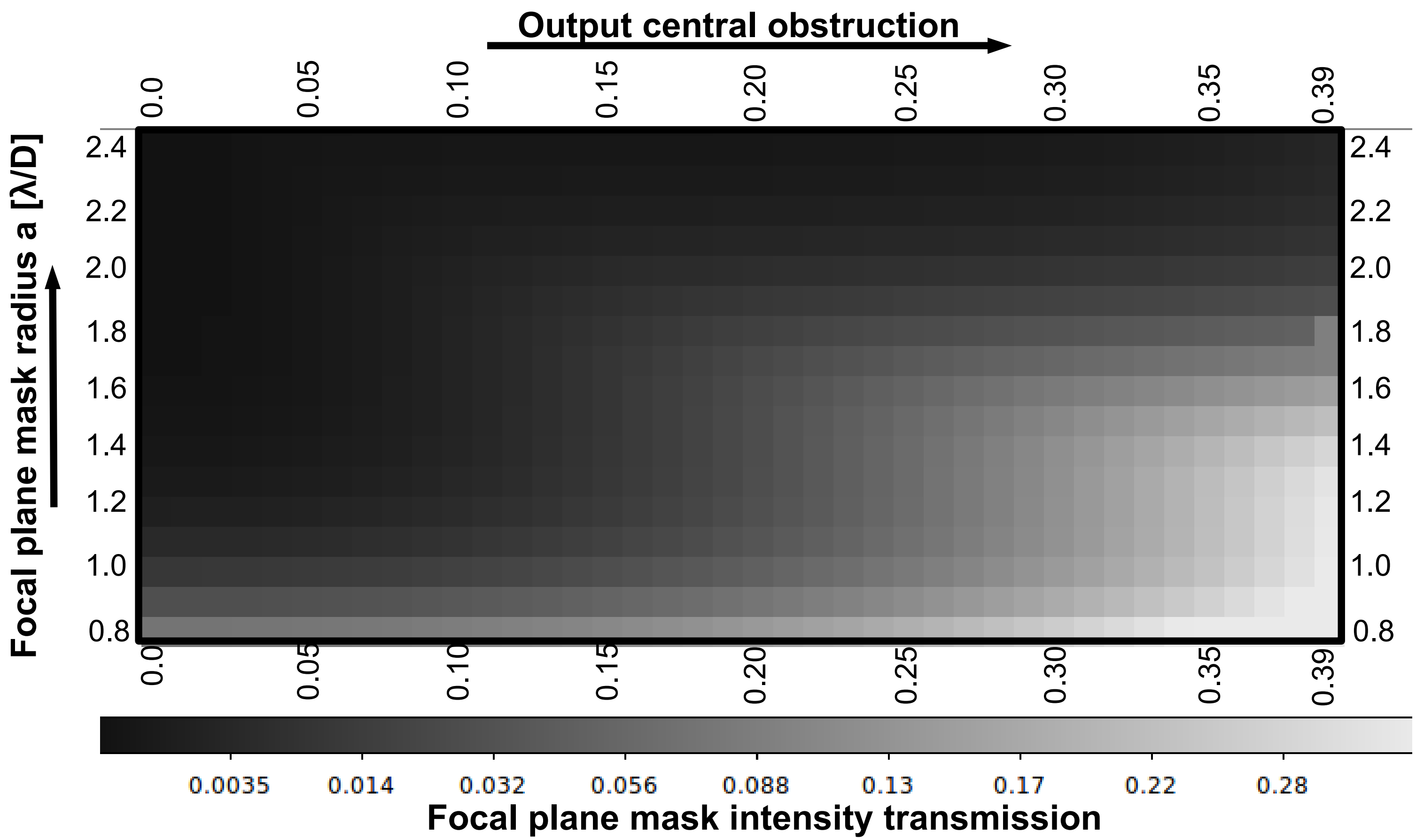


Centrally obscured pupil design optimization

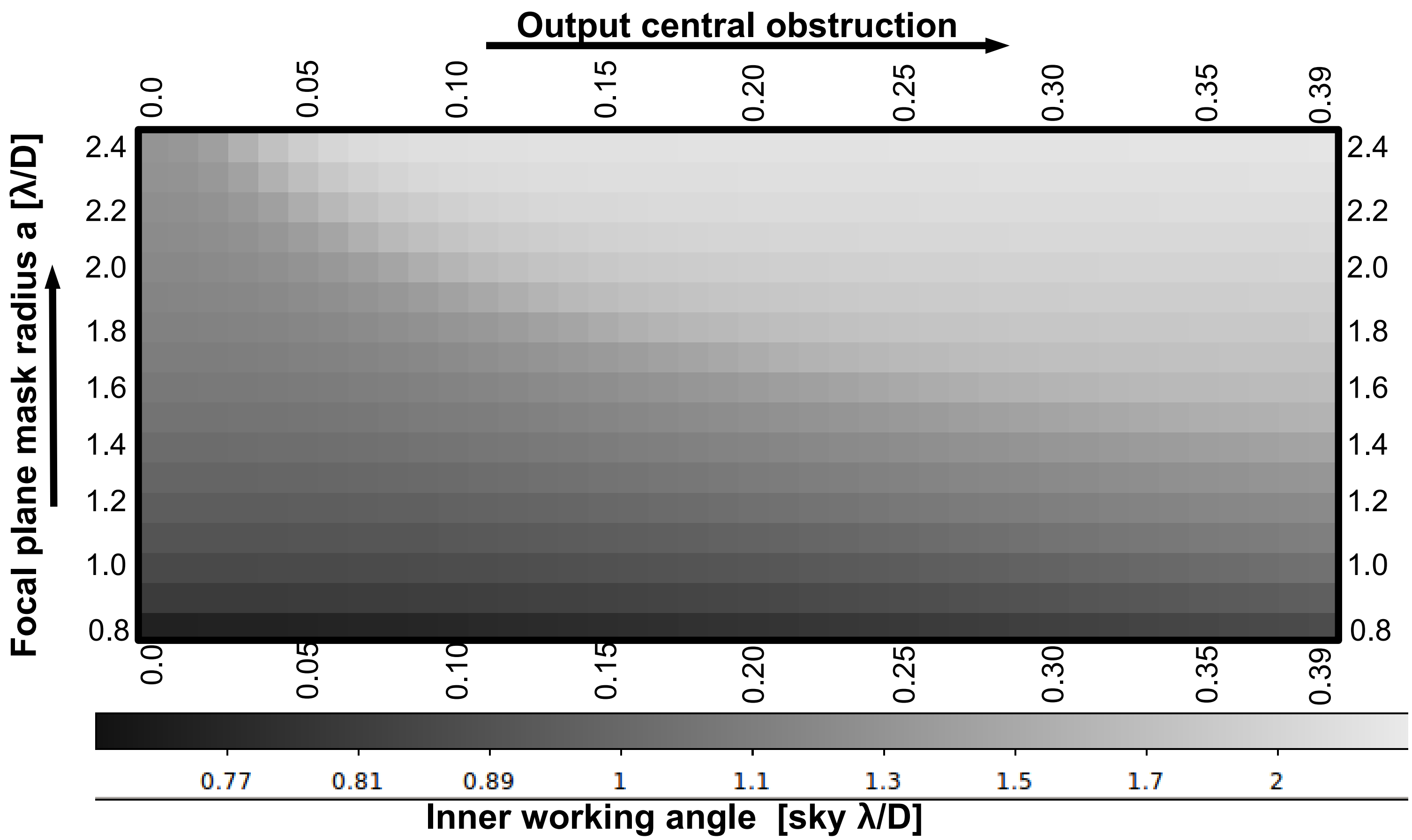
~ two orders of magnitude contrast difference between badly tuned PIAACMC and tuned PIAACMC
For 0.3 output central obstruction, IWA = 1.4 design is much better than IWA = 1.8 l/D design, even when working at ~3 l/D



Centrally obscured pupil design optimization

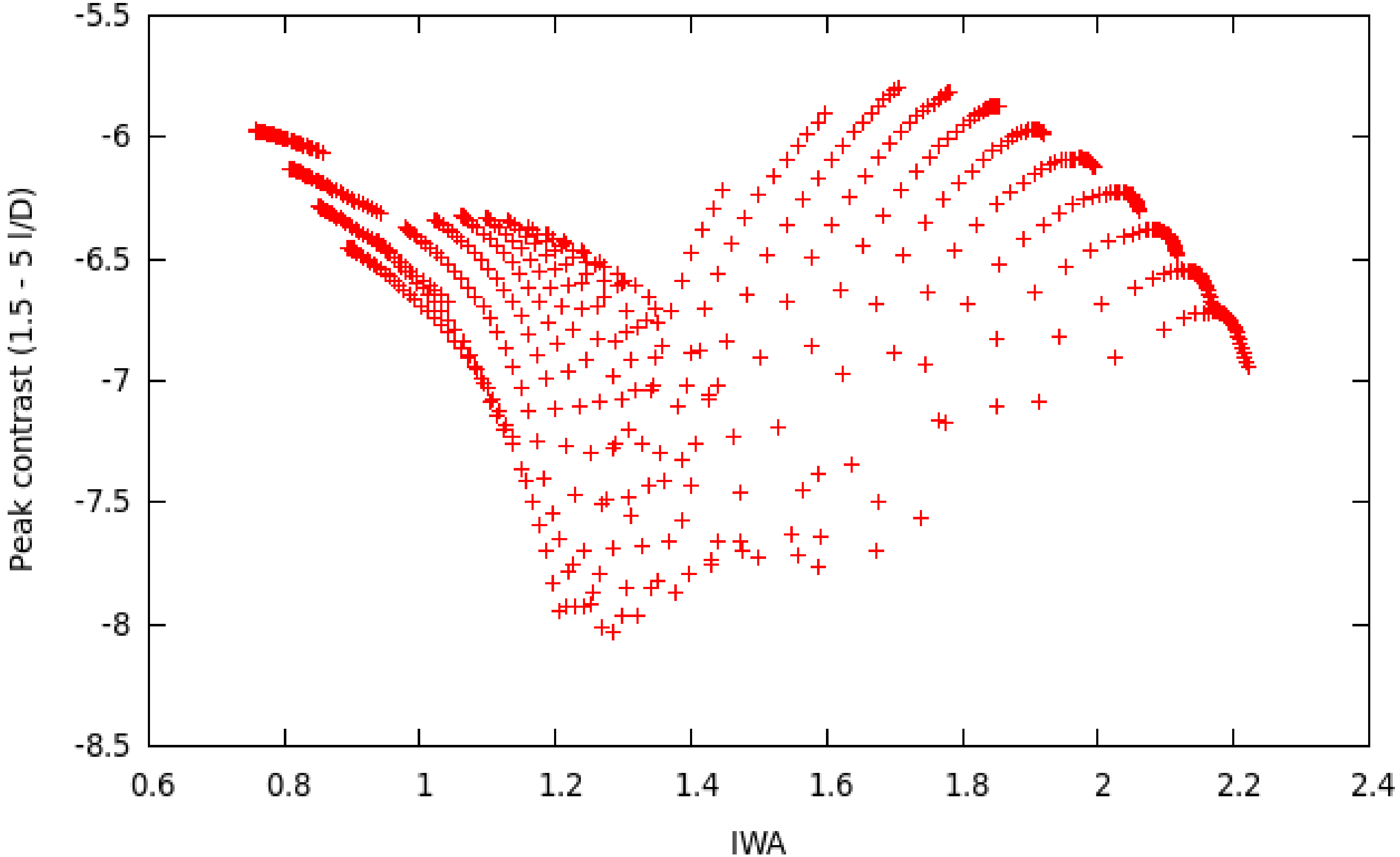


Centrally obscured pupil design optimization



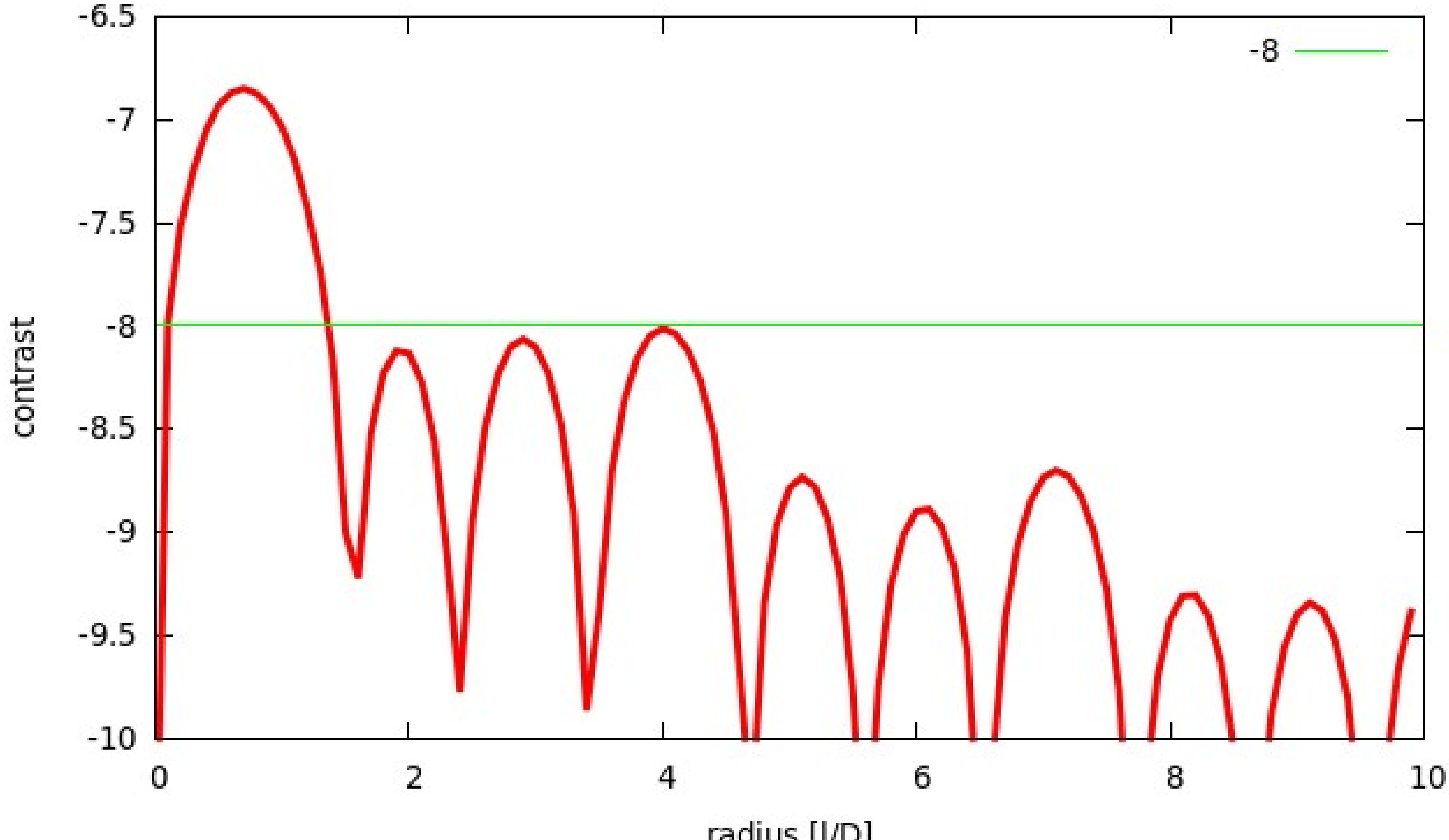
Centrally obscured pupil design optimization

Optimal design has IWA = 1.26 l/D, 7% transmission mask
It is 4th order coronagraph with near-theoretically optimal performance

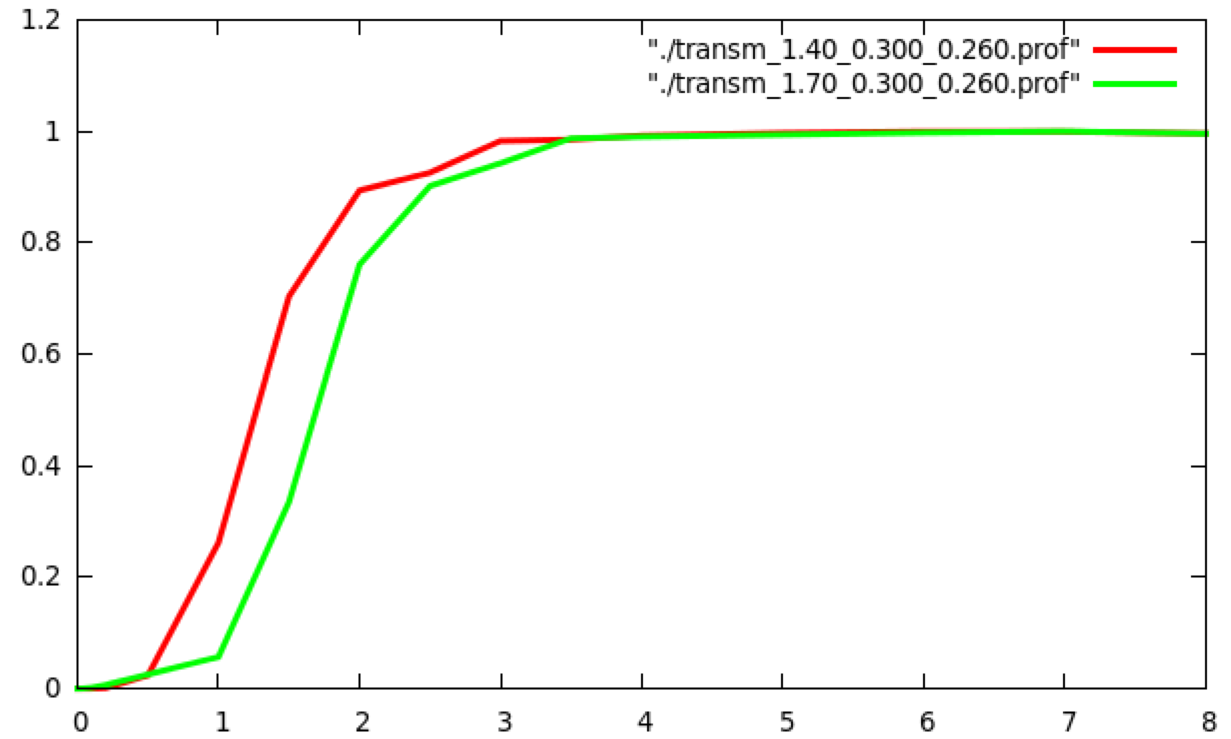


Centrally obscured pupil design optimization

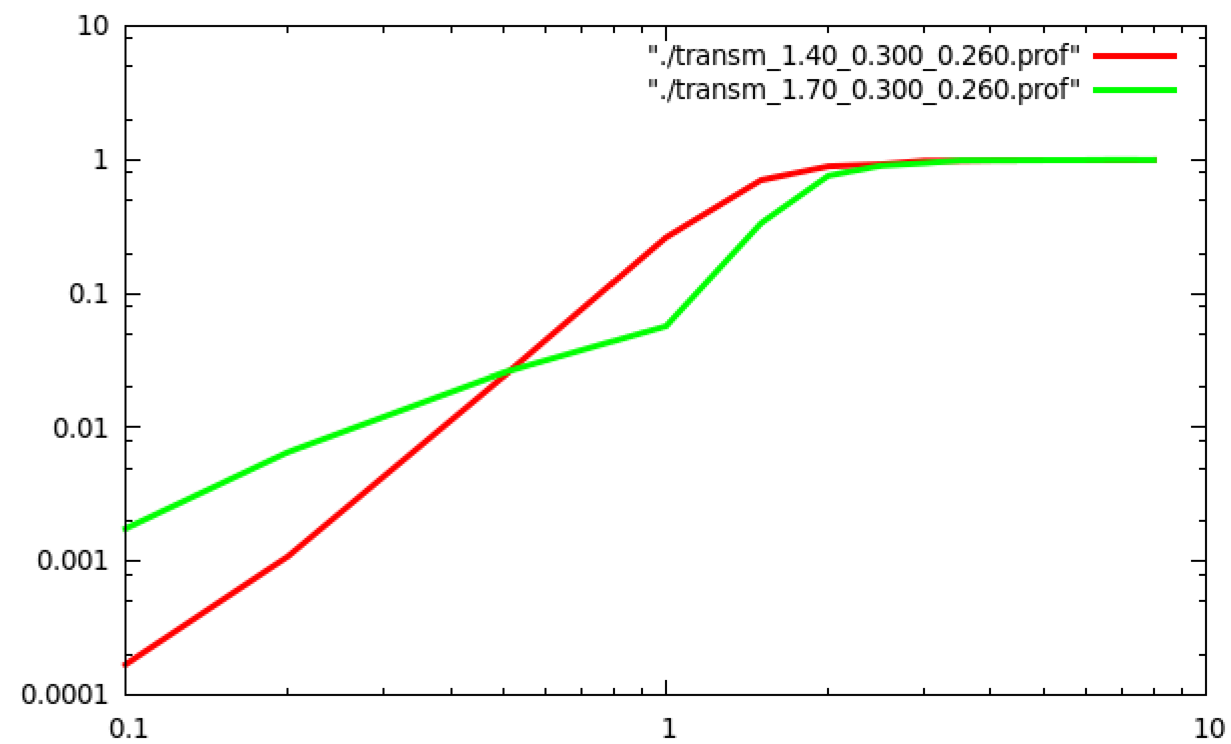
Response to 2% l/D star



Centrally obscured pupil design optimization



Increasing IWA → more sensitive to stellar angular size



Solution is 4th order coronagraph with small IWA

Science return: 2.4 m telescope

Assuming photon-noise limited sensitivity

19 targets for Earths !!
(SNR>5, R=5, 10hr)

Background (1 zodi):
~ 5x planet light

Star diameter:
~ 30x planet light

Typical star diam:
1 to 5 mas

Table 1. Most favorable targets for the direct imaging of an Earth analog, ranked by decreasing SNR. The planet is assumed to be observed at maximum angular separation (given both in arcsec and λ/D) at 0.8 μm. The light contribution are given in contrast unit for the source, the background flux (zodi+exozodi) and stellar leak due to the star finite angular size. The SNR for a 10hr observation is given assuming only photon noise, with a 20% system efficiency and a 20% wide spectral band.

Target	Teff [K]	Dist [pc]	L_{bol} [L_{sun}]	max sep. ["] | [λ/D]	m_V	star Diam [mas] | [λ/D]	Contrast source| background | star	10hr SNR (R=5)
α Cen A	5809	1.34	1.52	0.92 | 13.39	0.01	8.47 | 0.1232	1.15e-10 | 3.05e-11 | 2.95e-09	43.4
α Cen B	5259	1.34	0.50	0.53 | 7.68	1.34	5.93 | 0.0862	3.48e-10 | 8.92e-11 | 1.13e-08	39.7
ϵ Eri	5104	3.21	0.34	0.18 | 2.64	3.73	2.16 | 0.0314	5.12e-10 | 7.44e-10 | 7e-09	24.0
ϵ Ind	4621	3.62	0.22	0.13 | 1.88	4.68	1.88 | 0.0274	7.91e-10 | 1.47e-09 | 1.16e-08	20.4
τ Cet	5527	3.65	0.55	0.20 | 2.95	3.49	2.06 | 0.0300	3.18e-10 | 6.67e-10 | 5.2e-09	18.2
40 Eri	5311	4.98	0.46	0.14 | 1.98	4.43	1.50 | 0.0218	3.78e-10 | 1.49e-09 | 4.21e-09	14.7
61 Cyg A	4530	3.50	0.15	0.11 | 1.63	5.20	1.69 | 0.0246	1.14e-09 | 2.13e-09 | 4.7e-08	12.8
Procyon	6546	3.51	6.93	0.75 | 10.91	0.37	5.44 | 0.0791	2.51e-11 | 5.1e-11 | 1.21e-09	11.4
82 Eri	5418	6.04	0.74	0.14 | 2.07	4.26	1.51 | 0.0219	2.35e-10 | 1.39e-09 | 3.1e-09	10.7
70 Oph	4857	5.10	0.69	0.16 | 2.36	4.21	2.14 | 0.0311	2.53e-10 | 1.14e-09 | 6.96e-09	9.6
η Cas A	6105	5.94	1.29	0.19 | 2.78	3.46	1.59 | 0.0231	1.35e-10 | 7.88e-10 | 3.32e-09	8.6
δ Pav	5582	6.11	1.22	0.18 | 2.63	3.55	1.80 | 0.0262	1.43e-10 | 7.44e-10 | 4.86e-09	8.0
σ Dra	5418	5.75	0.47	0.12 | 1.74	4.67	1.26 | 0.0184	3.69e-10 | 1.92e-09 | 1.61e-08	7.2
Altair	7524	5.12	10.60	0.64 | 9.25	0.77	3.49 | 0.0507	1.64e-11 | 9.03e-11 | 8.96e-10	6.3
ξ Boo A	4761	6.78	0.83	0.13 | 1.96	4.67	1.85 | 0.0268	2.08e-10 | 1.98e-09 | 6.4e-09	5.9
36 Oph B	5104	5.95	0.40	0.11 | 1.55	5.08	1.27 | 0.0184	4.35e-10 | 2.66e-09 | 2.63e-08	5.7
β CVn	5638	8.44	1.15	0.13 | 1.85	4.24	1.24 | 0.0180	1.51e-10 | 1.53e-09 | 5.05e-09	5.5
ζ Tuc	5926	8.59	1.44	0.14 | 2.03	4.23	1.24 | 0.0180	1.21e-10 | 1.54e-09 | 2.87e-09	5.3
β Com	5926	9.13	1.36	0.13 | 1.85	4.23	1.13 | 0.0164	1.28e-10 | 1.51e-09 | 4.17e-09	5.0
χ^1 Ori	5926	8.66	1.08	0.12 | 1.74	4.39	1.06 | 0.0154	1.61e-10 | 1.77e-09 | 6.63e-09	4.8
χ Dra	6105	8.06	2.34	0.19 | 2.76	3.55	1.58 | 0.0230	7.45e-11 | 8.47e-10 | 3.27e-09	4.6
γ Pav	6105	9.26	1.52	0.13 | 1.93	4.21	1.11 | 0.0161	1.14e-10 | 1.57e-09 | 4.02e-09	4.5
γ Lep A	6417	8.93	2.69	0.18 | 2.67	3.59	1.39 | 0.0201	6.46e-11 | 9.2e-10 | 2.7e-09	4.1
ι Per	5985	10.54	2.55	0.15 | 2.20	4.05	1.31 | 0.0191	6.83e-11 | 1.31e-09 | 2.26e-09	3.6
61 Vir	5582	8.56	0.85	0.11 | 1.57	4.74	1.07 | 0.0156	2.05e-10 | 2.25e-09 | 1.89e-08	3.4
θ Per	6045	11.13	2.70	0.15 | 2.15	4.10	1.25 | 0.0182	6.45e-11 | 1.44e-09 | 2.06e-09	3.3