OUTLINE

SCExAO overview & lessons learned

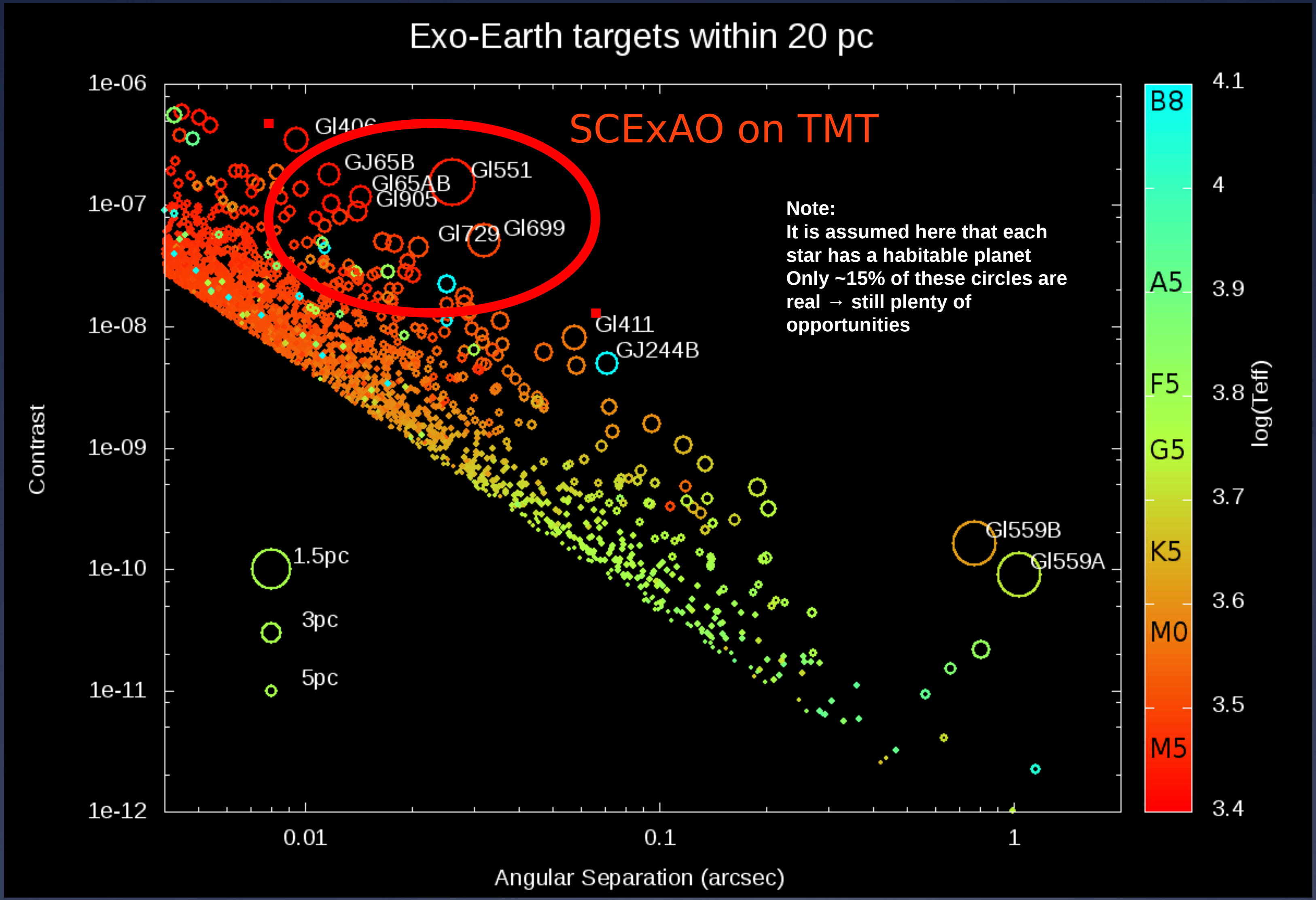
Visible light instrumentation for TMT

High contrast imaging in near-IR:

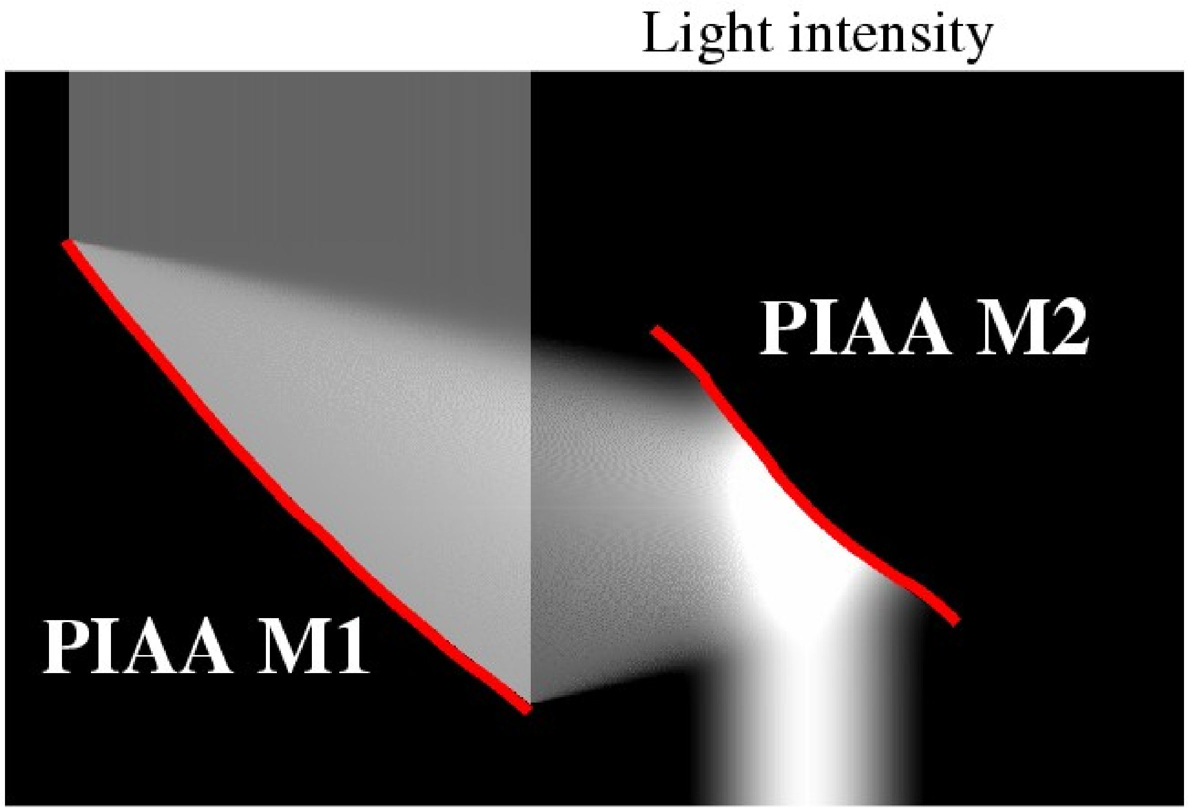
- Coronagraphy
- Wavefront control

SCExAO and TMT

We intend to ready SCExAO for TMT, as a visitor instrument soon after first light
Prime science case (focused survey):
spectroscopy of habitable planets around nearby M-type stars
SCExAO is ideally suited for this (high contrast + small IWA)

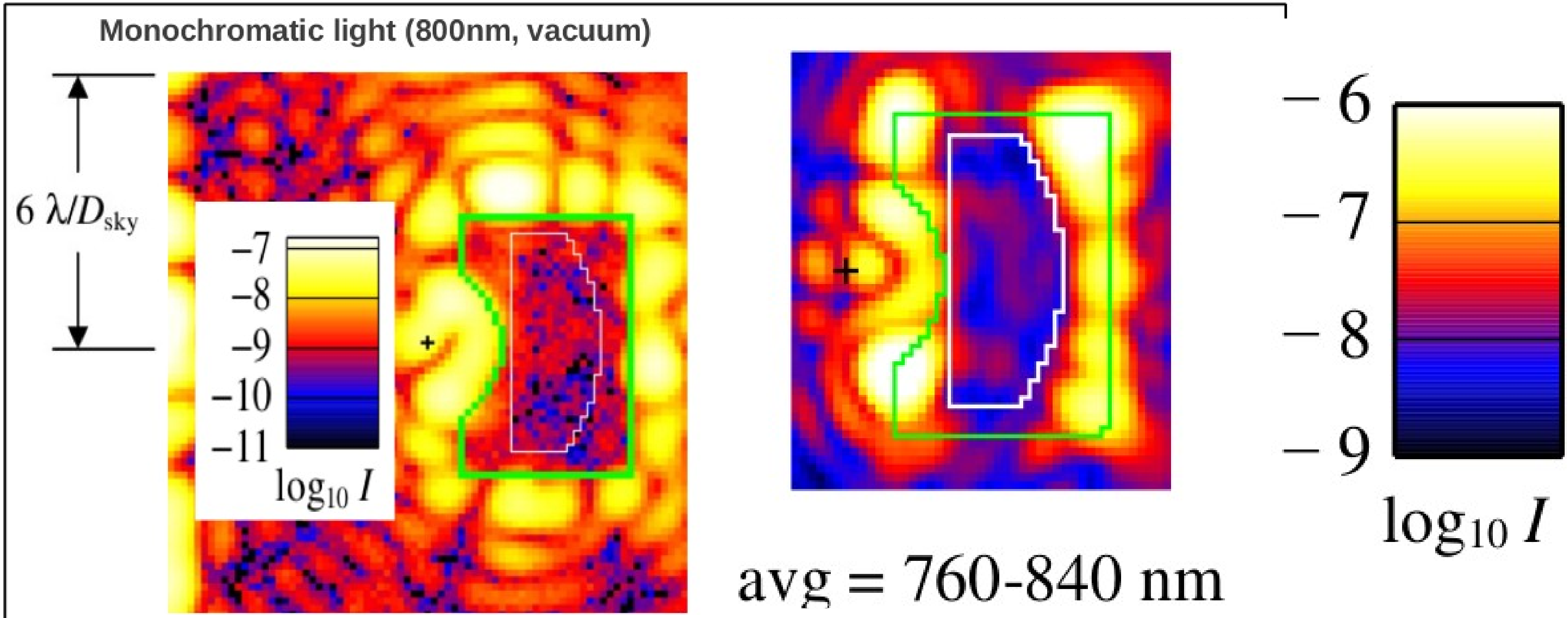


Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)



Uses lenses or mirrors for lossless beam apodization

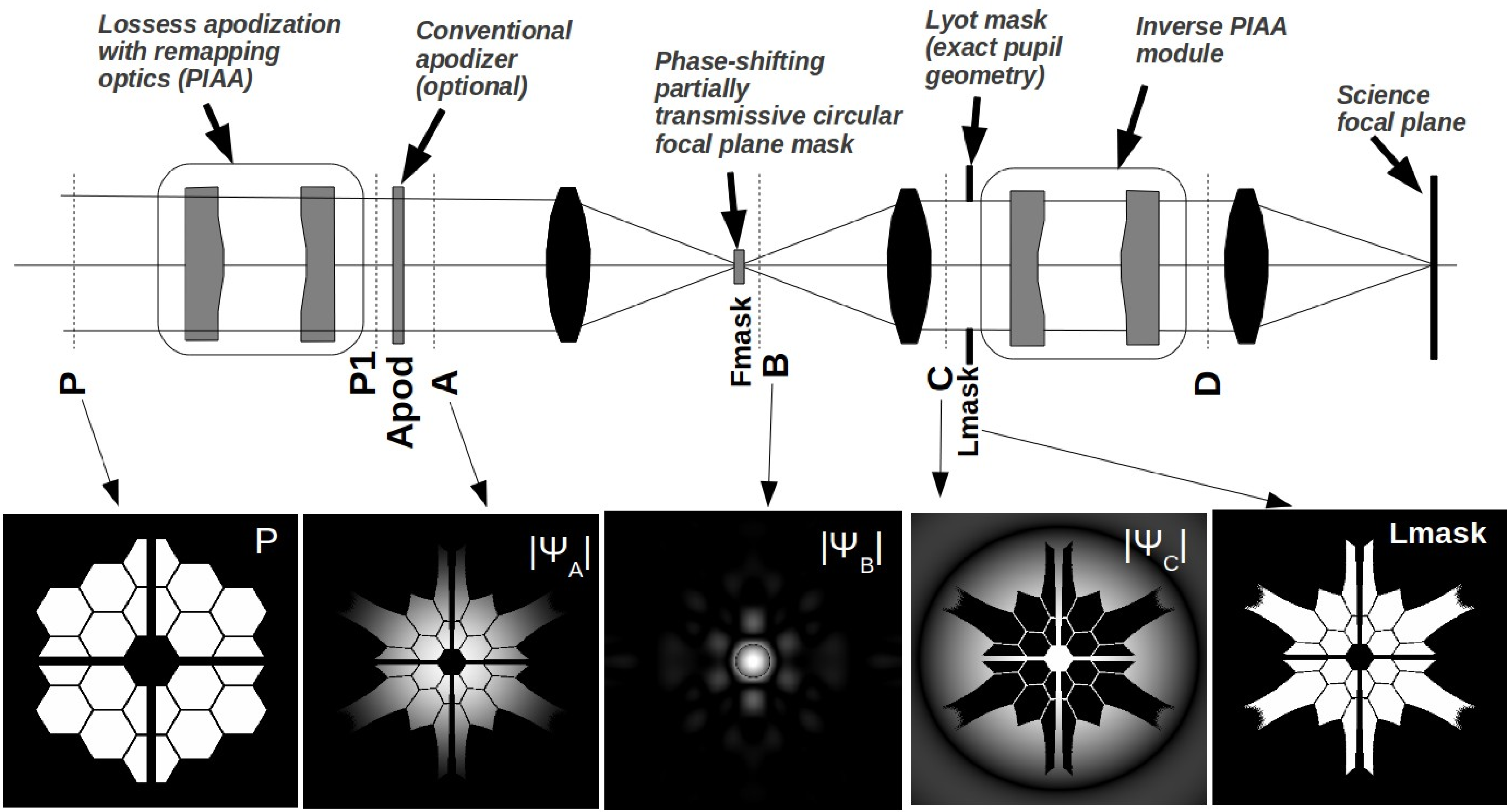
PIAA testbed at NASA JPL : lab results demonstrate PIAA's high efficiency and small IWA (B. Kern, O. Guyon et al.) - now moving to PIAACMC



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

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

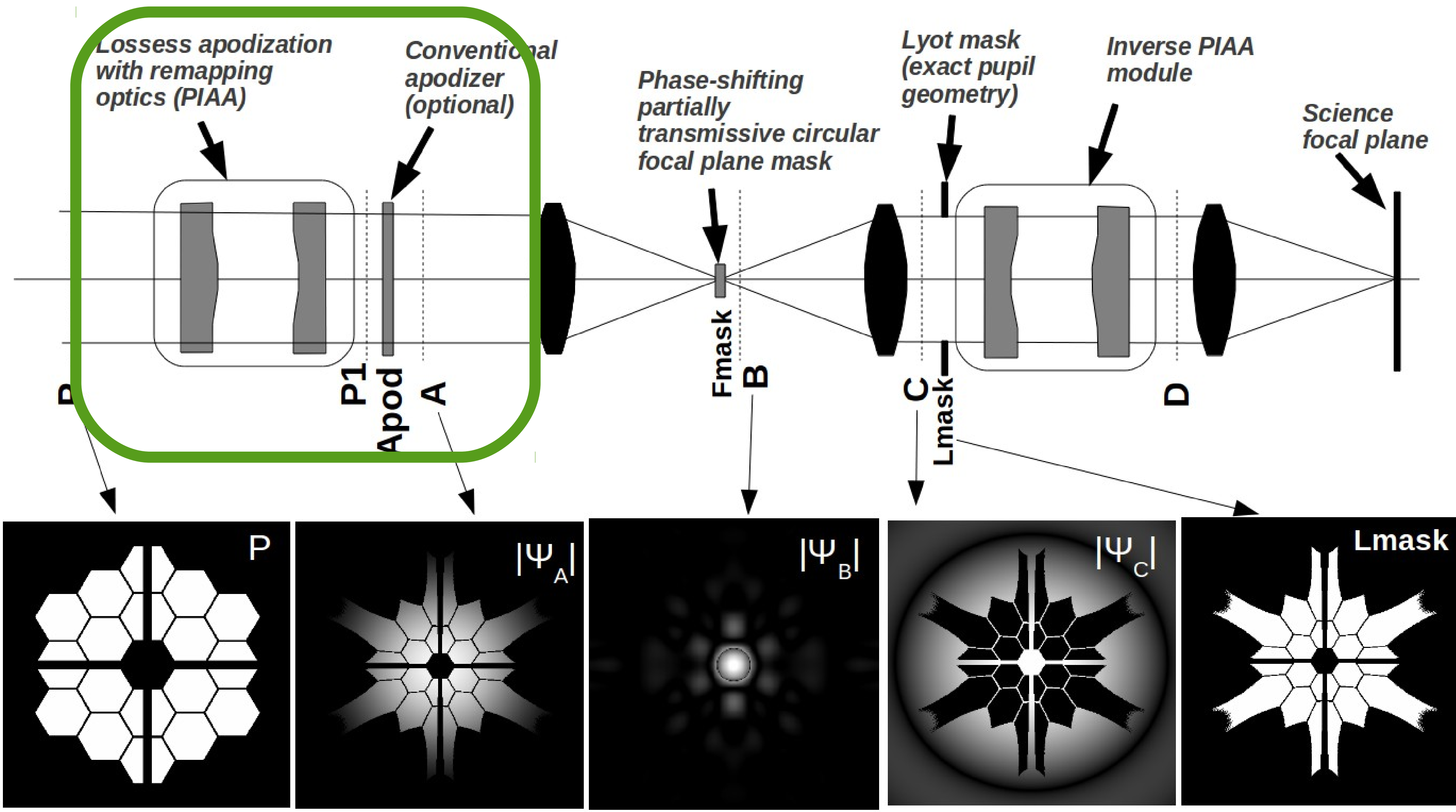
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



(largely) lossless apodization

Creates a PSF with weak Airy rings

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



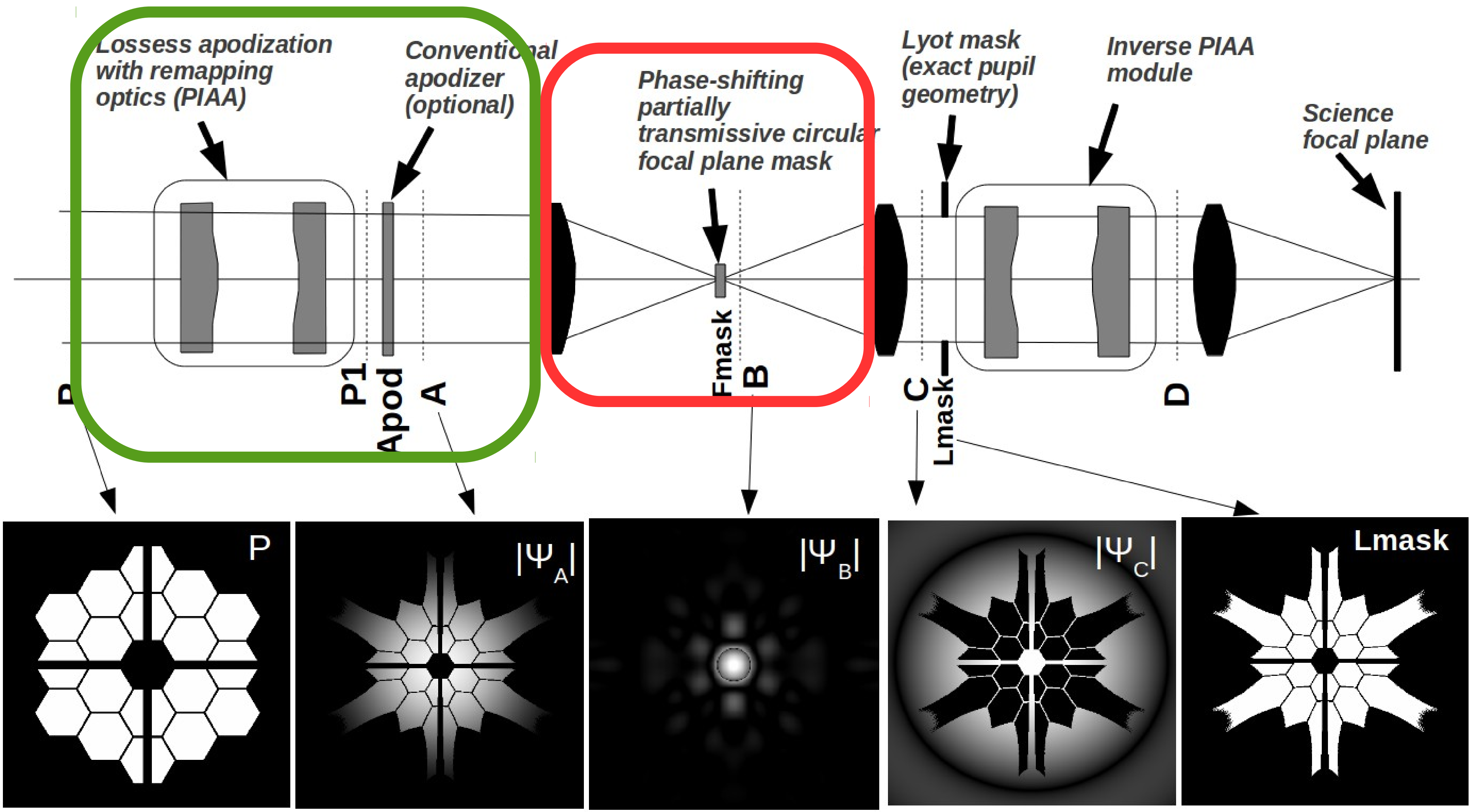
(largely) lossless apodization

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)

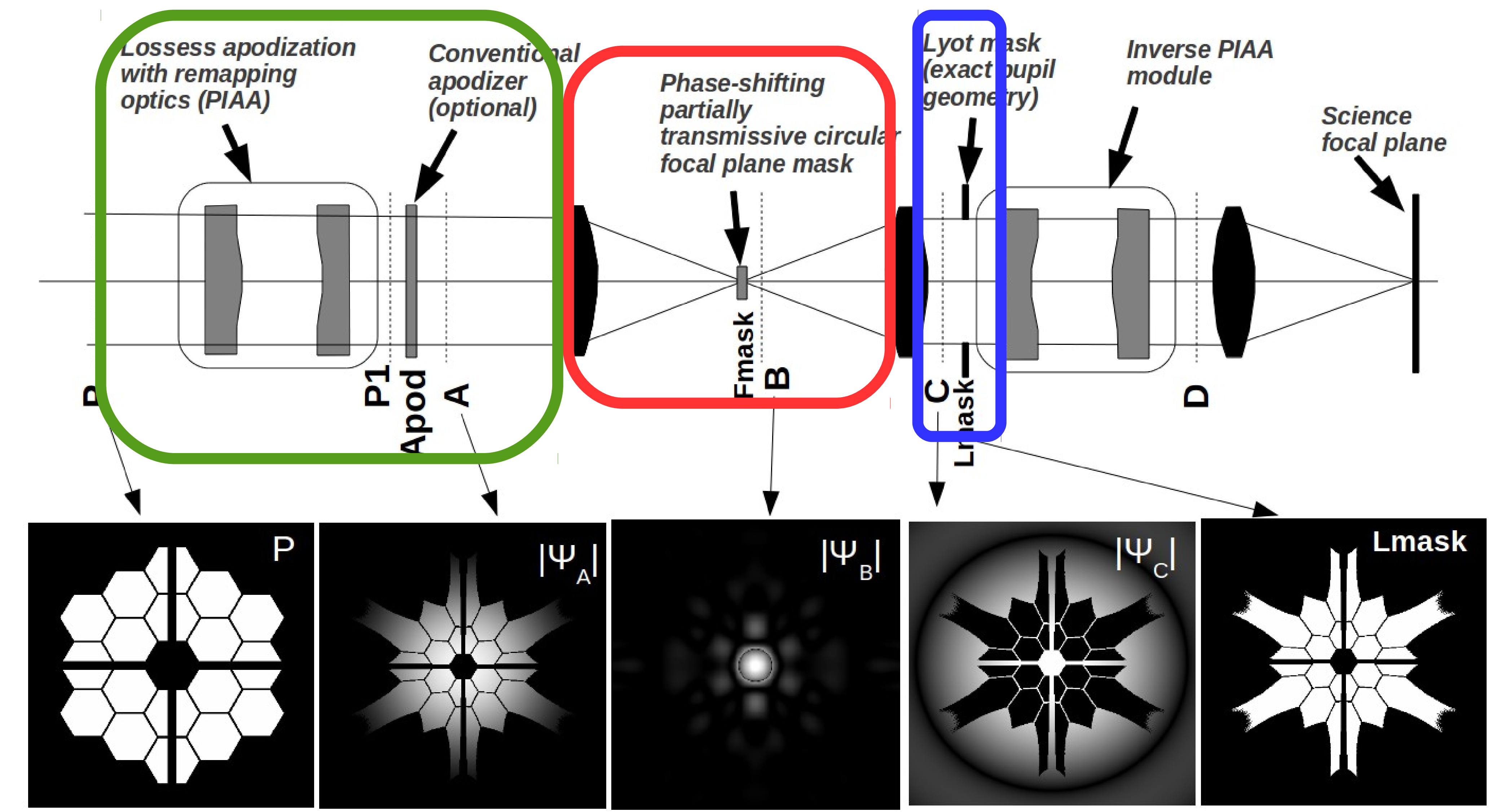


(largely) lossless apodization
Creates a PSF with weak Airy rings

Lyot stop
Blocks starlight

Focal plane mask: -1<t<0
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

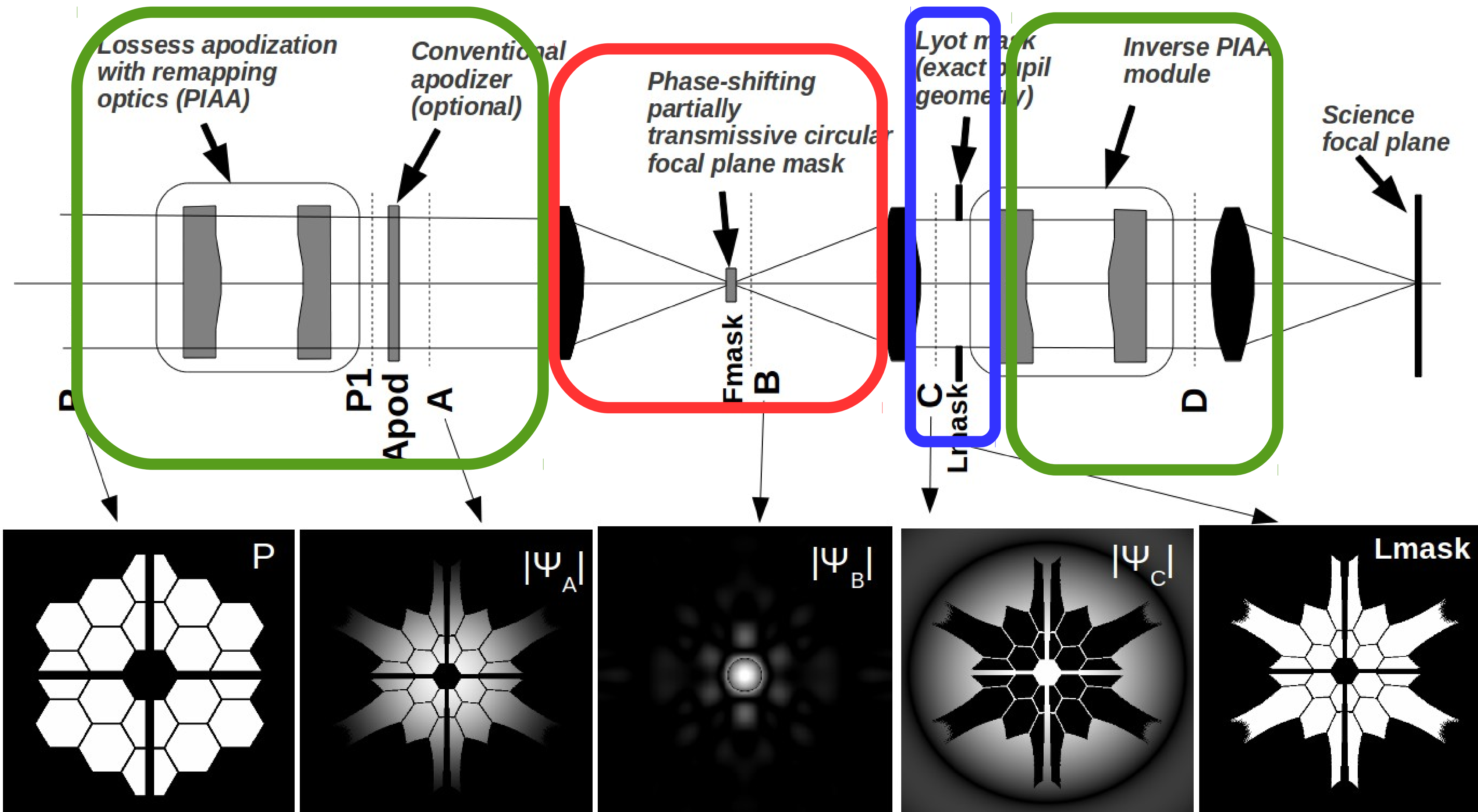
Lyot stop

Blocks starlight

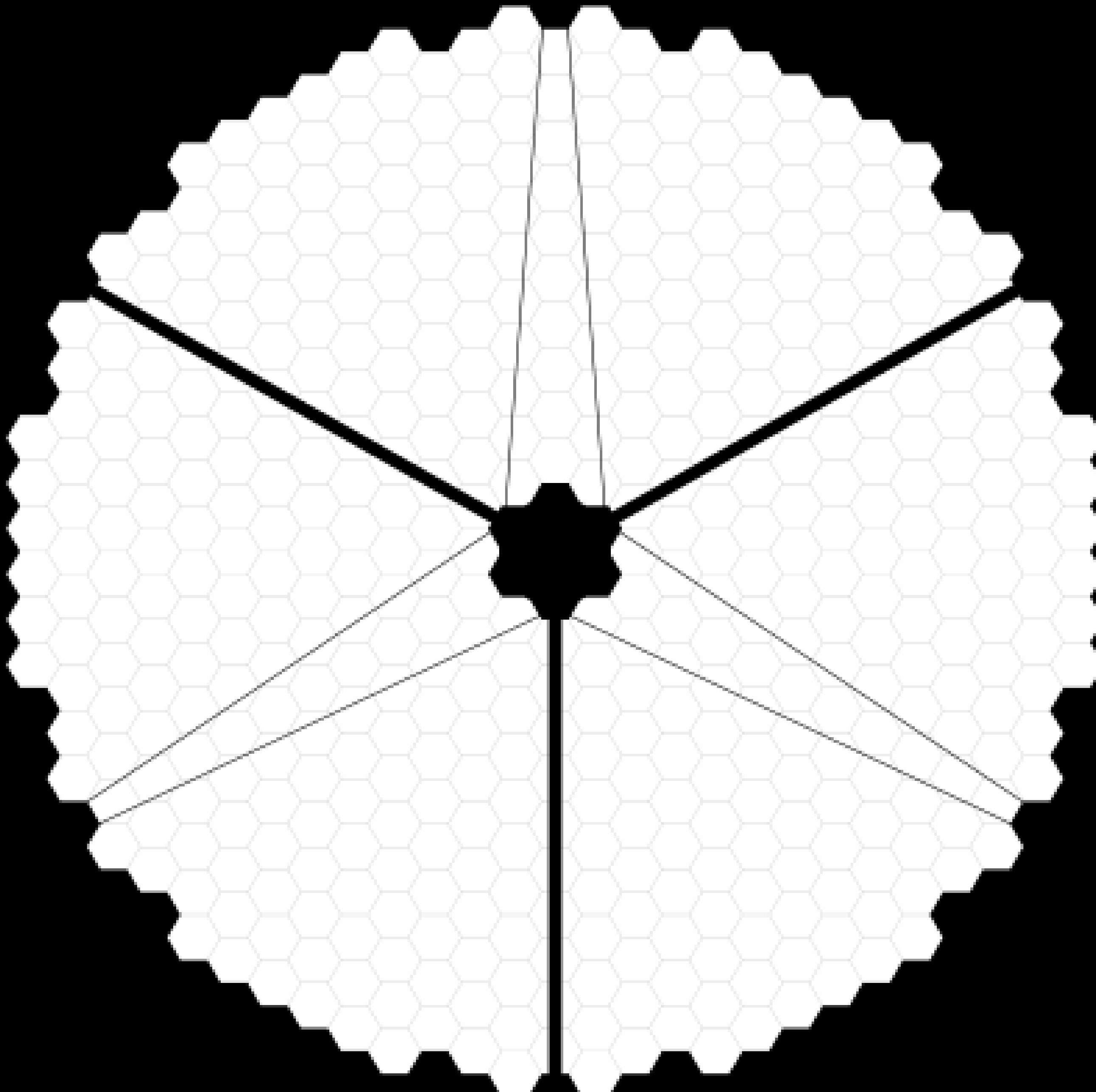
Inverse PIAA (optional)

Recovers Airy PSF over wide field

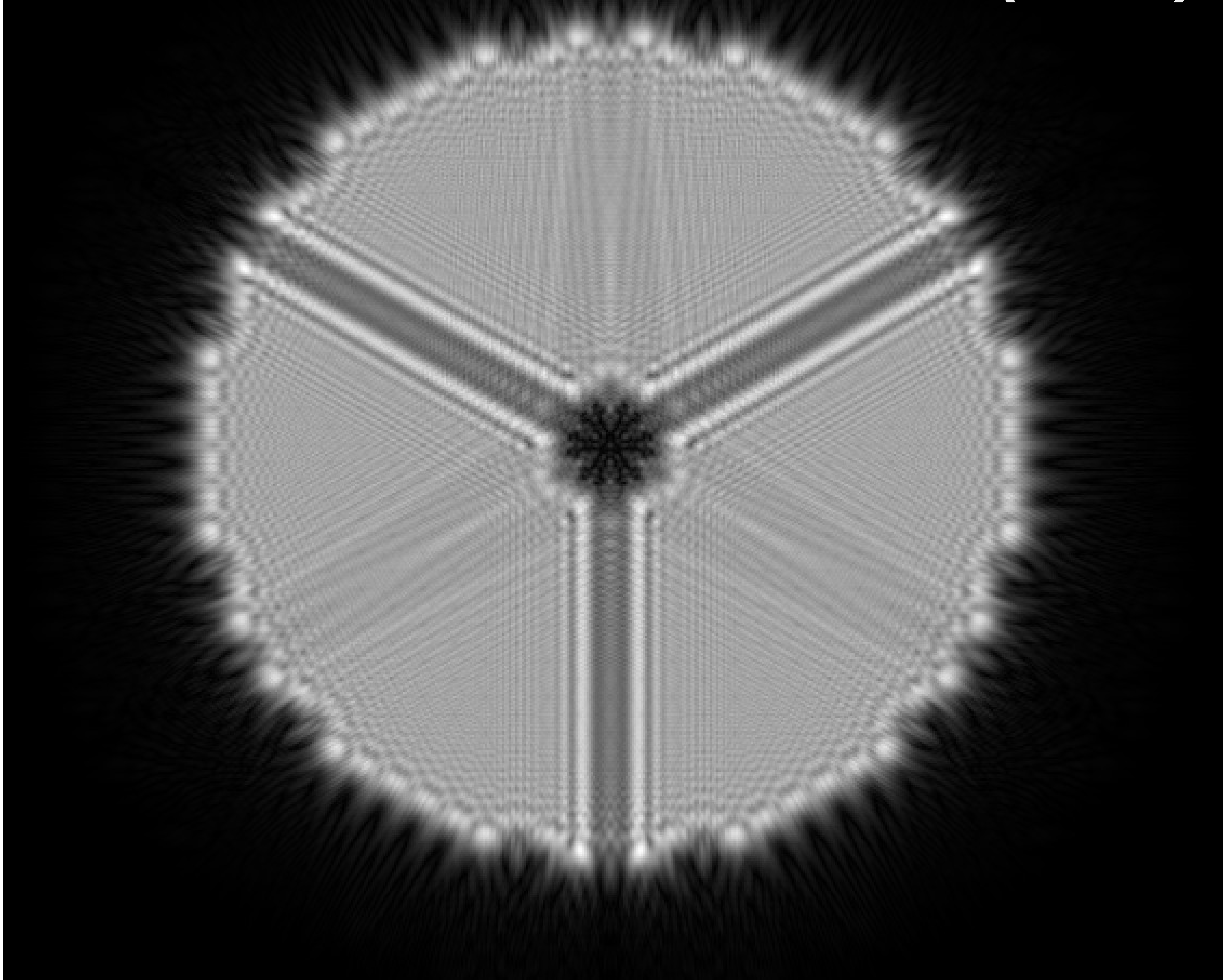
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



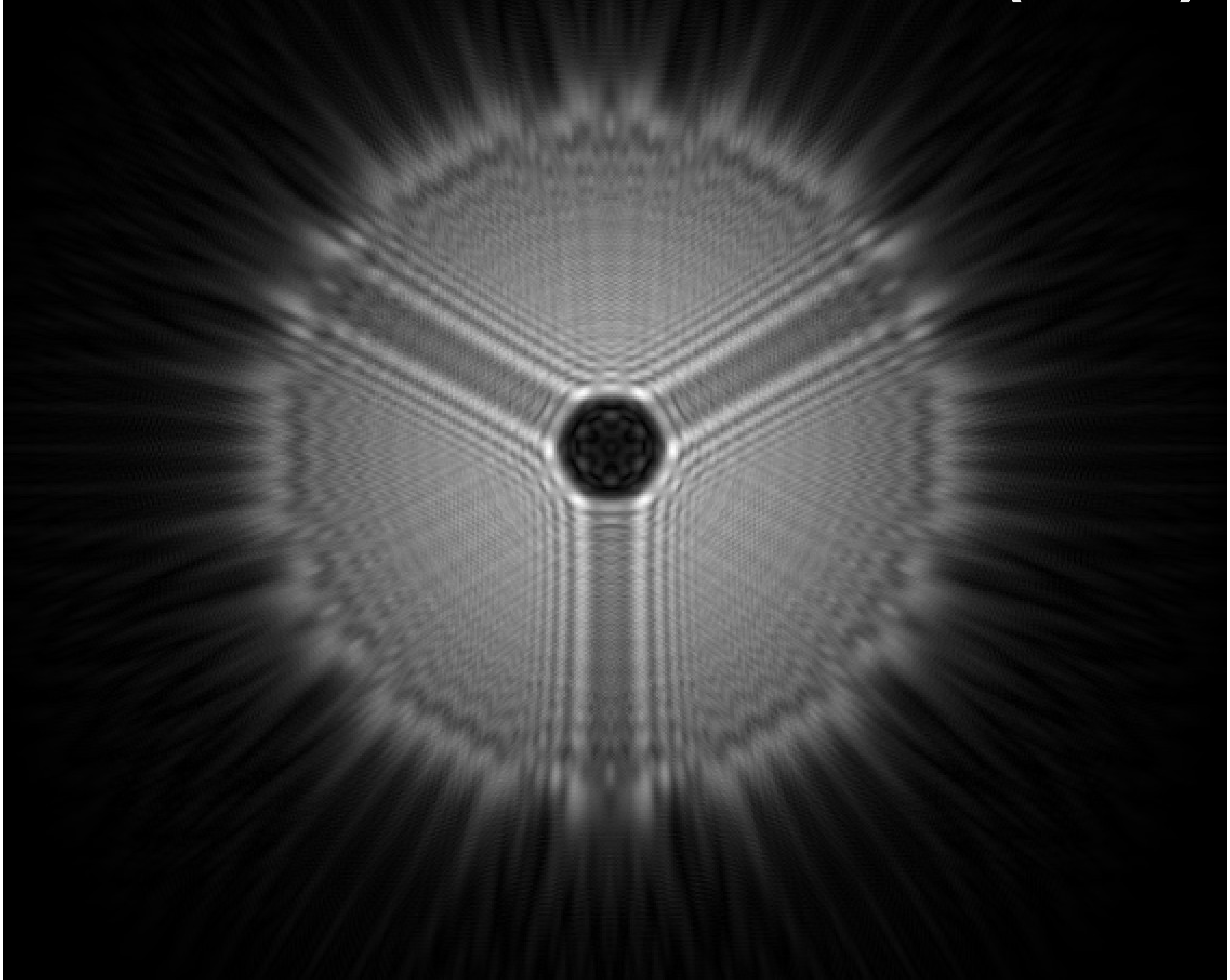
Pupil Plane



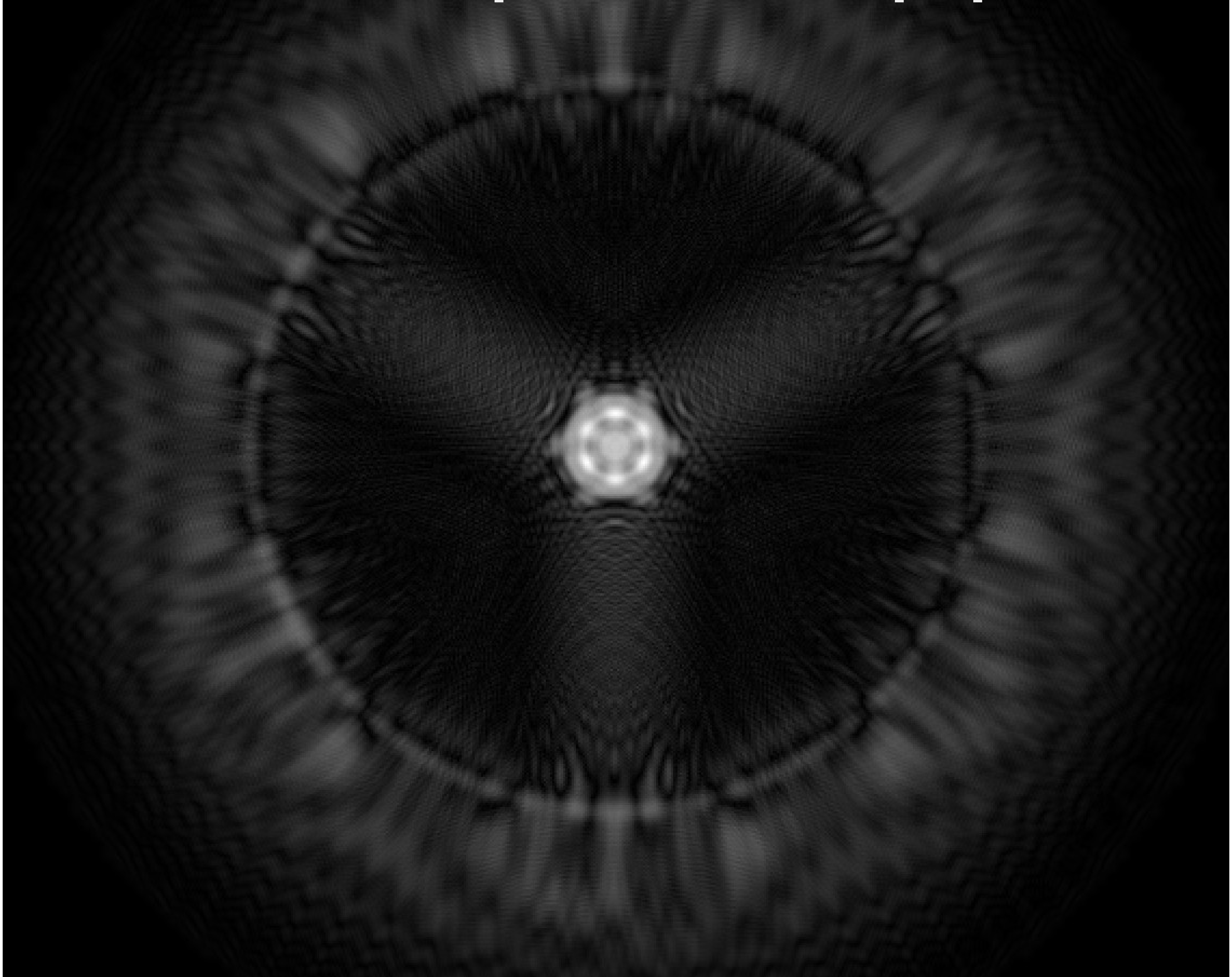
PIAACMC lens 1 front surface (CaF2)



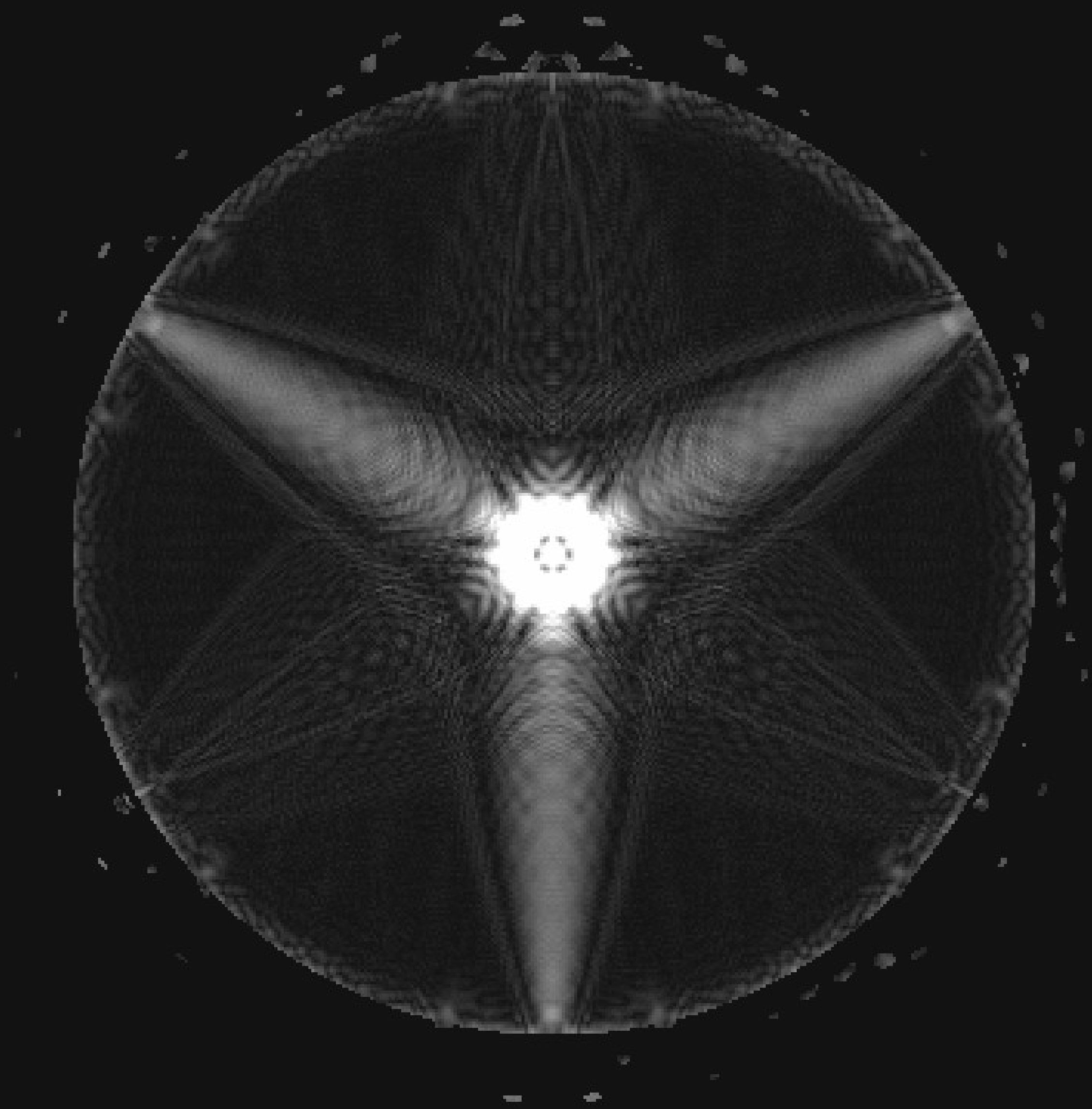
PIAACMC lens 2 front surface (CaF2)



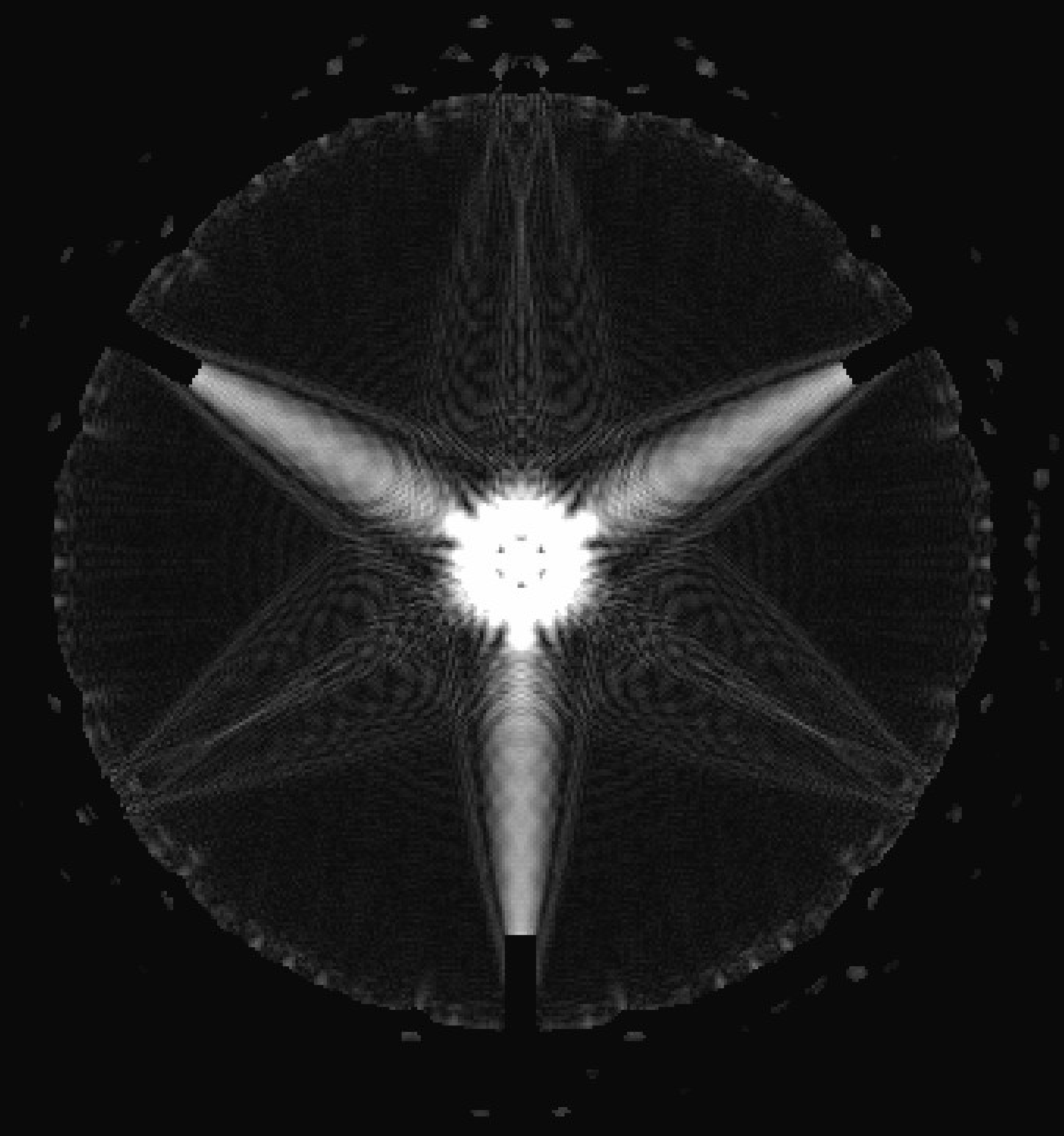
Post focal plane mask “pupil”



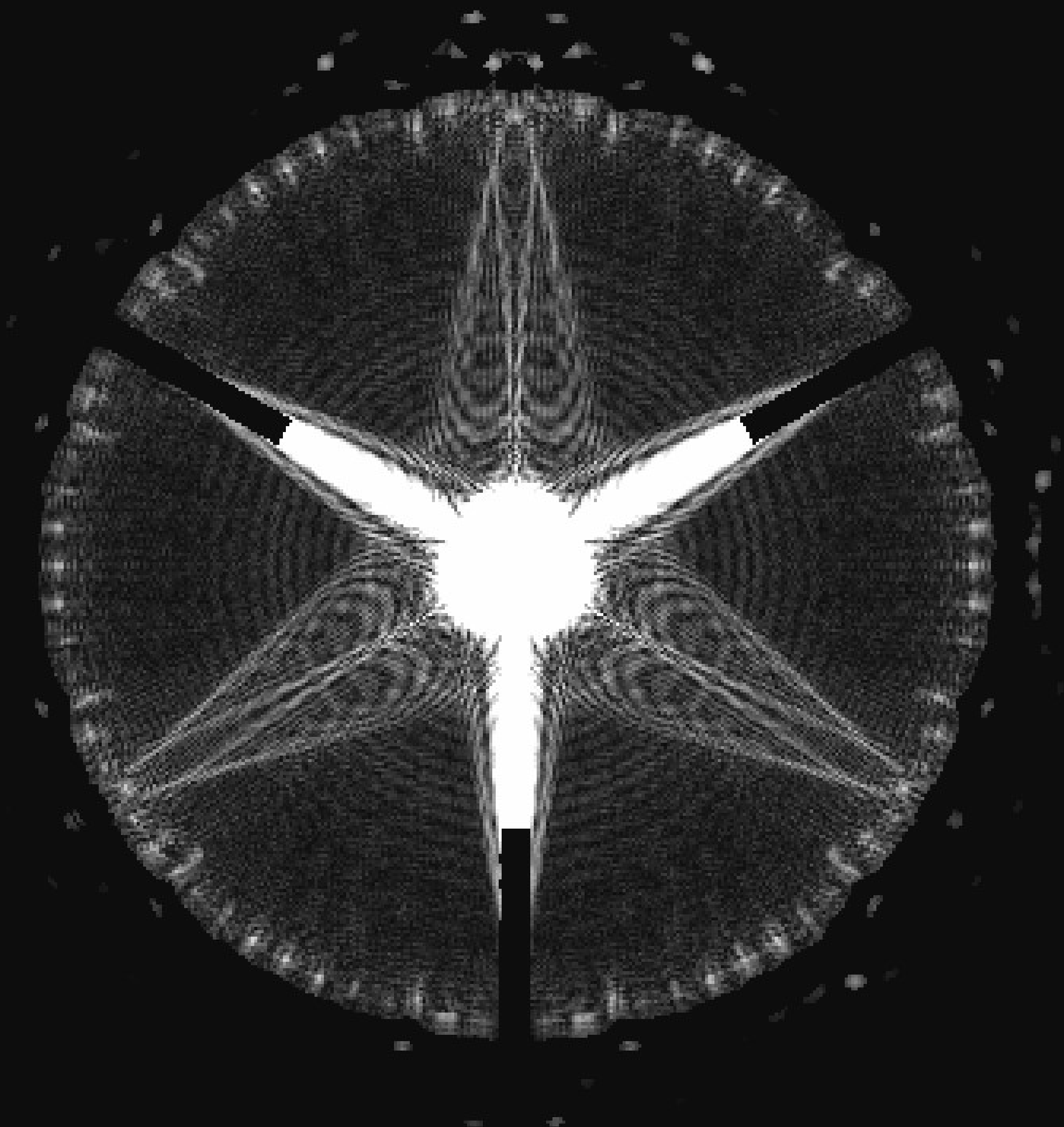
Stop #1



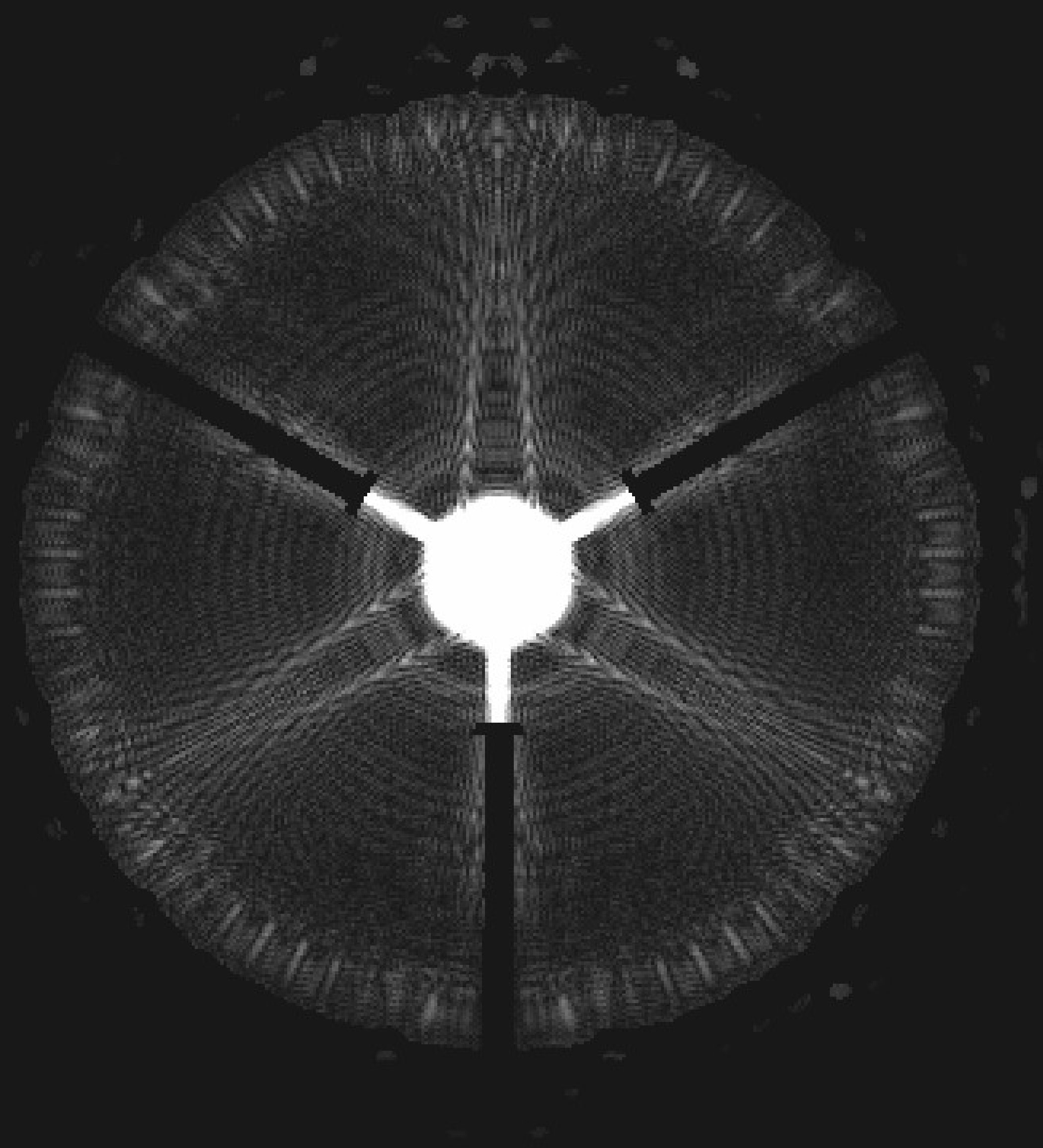
Stop #2



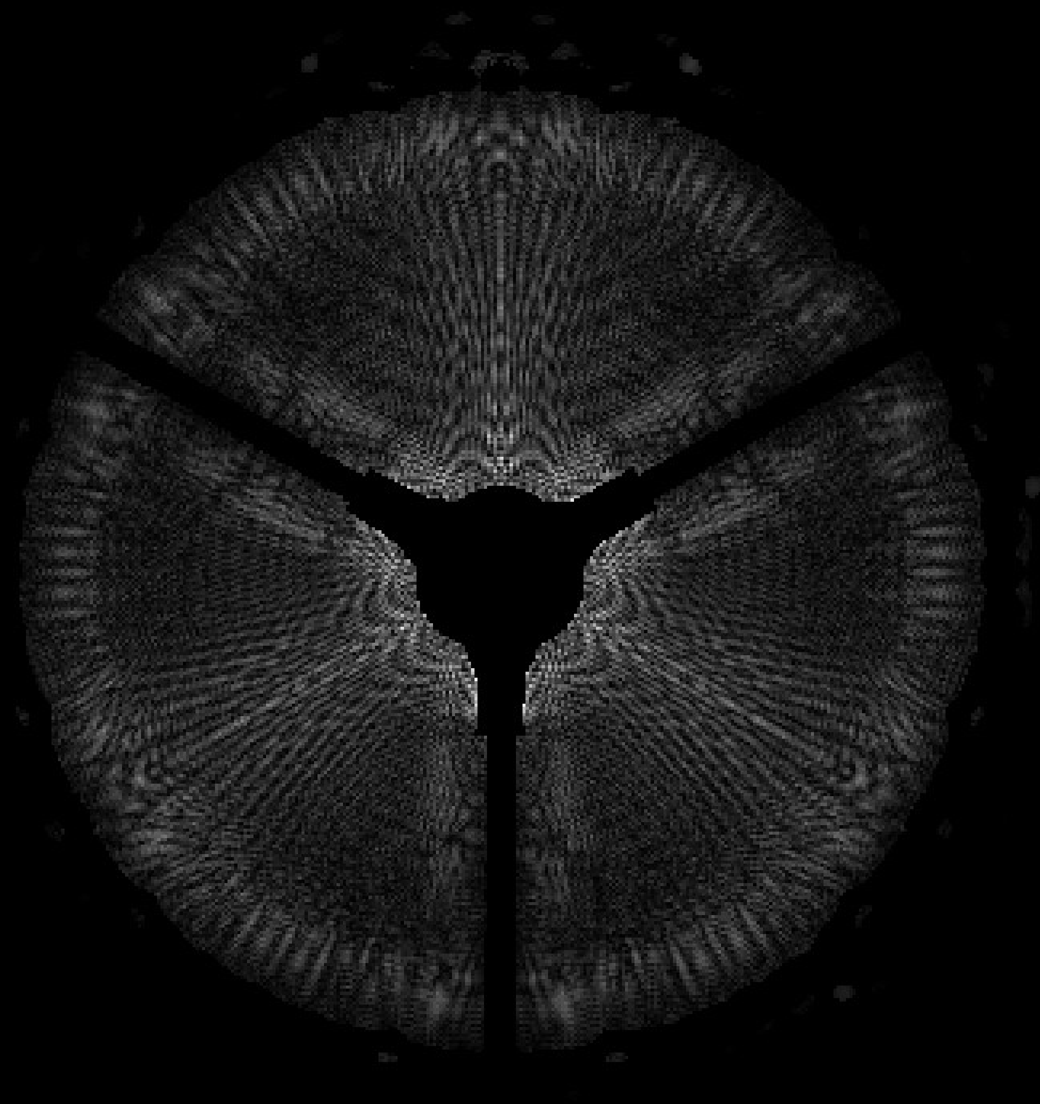
Stop #3

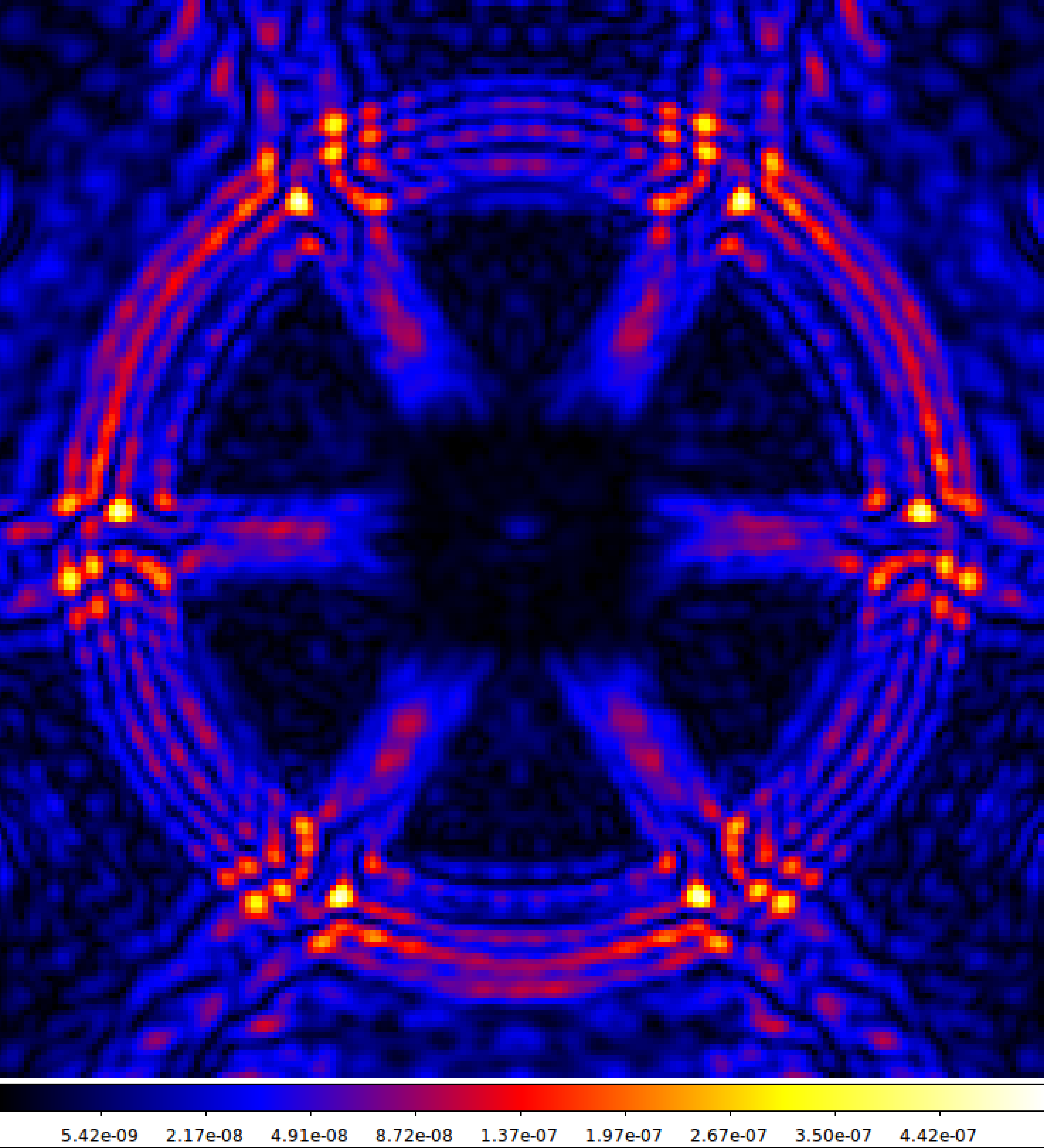


Stop #4



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

Focal plane mask designed for broadband operation AND stellar angular size

Mask has ~500 zones, each a different thickness

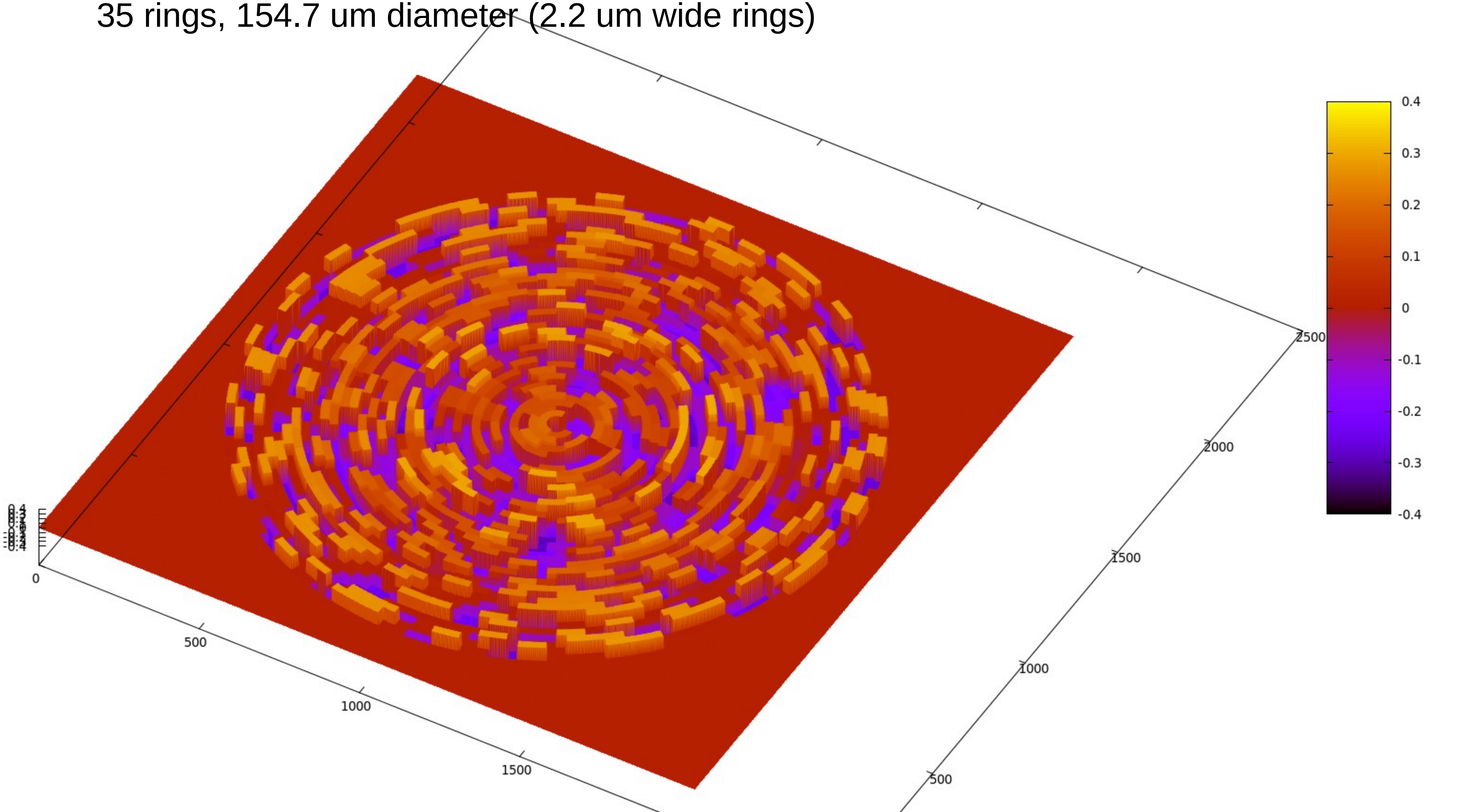
Computer optimization of the zones thicknesses to simultaneously:

- Achieve broadband contrast (including compensation of known chromaticity)
- Null a ~1mas diameter area → **100x gain in contrast**

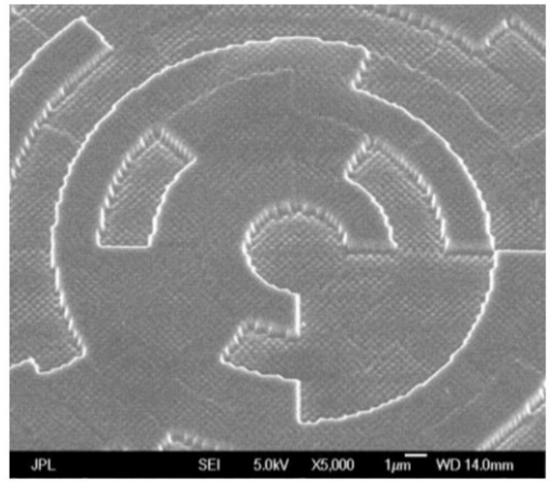
With 500 zones, 1e-7 raw contrast achievable with IWA = 1.2 l/D over 20% band

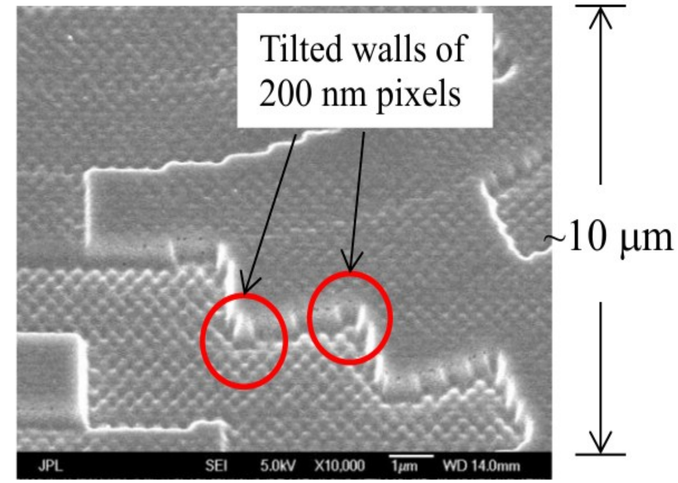
Focal plane mask (vertical scale amplified) for 1e-9 raw contrast, 1.3 l/D IWA (WFIRST visible light mask)

Sag within -/+ 0.3 um
35 rings, 154.7 um diameter (2.2 um wide rings)

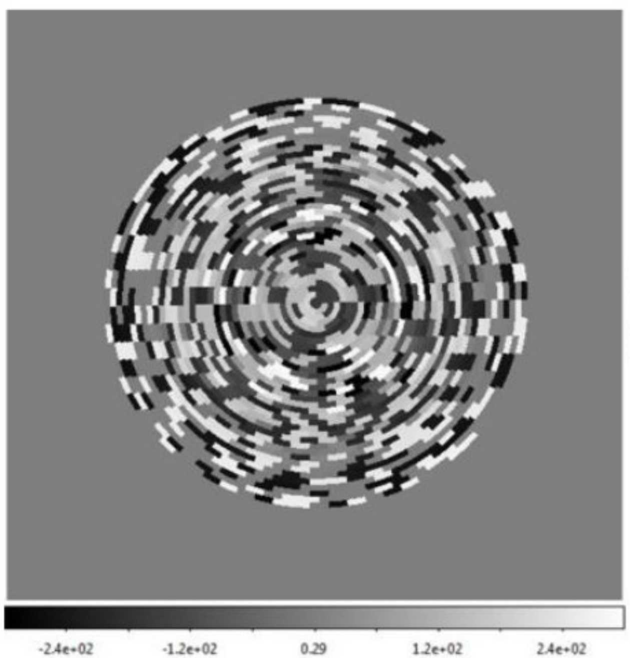


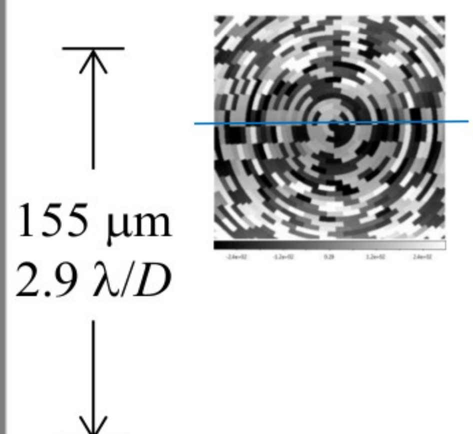
Mask characterization → OK to 1e-7 raw contrast at 550nm at 2 l/D (Kern et al. 2015)

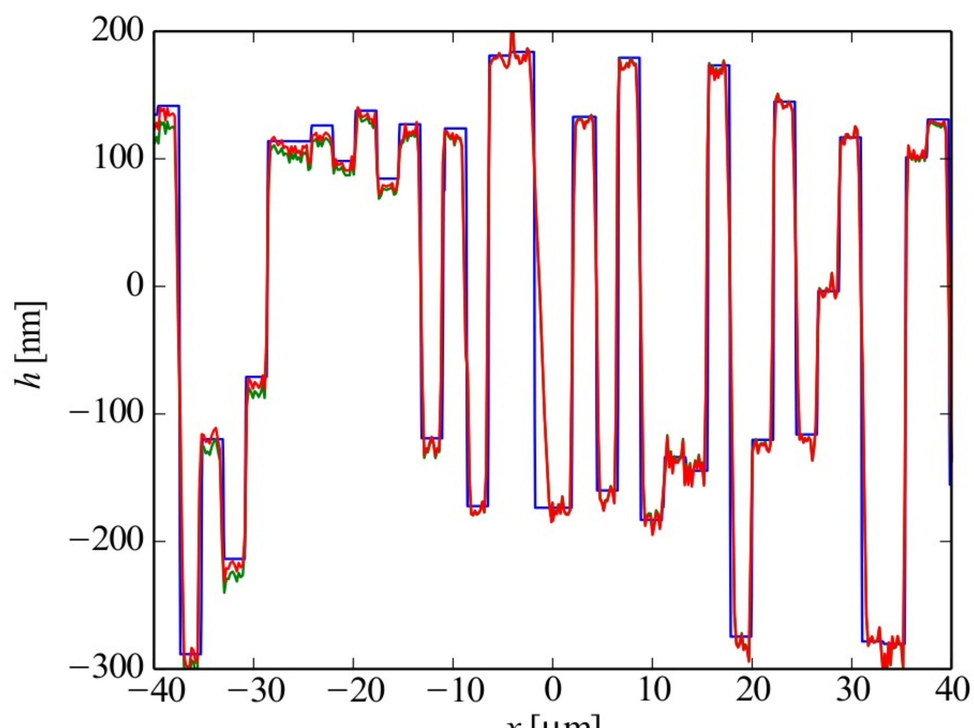




Design







Contrast limits

Assumptions:

I mag = 8 (WFS – 100 targets)
H mag = 6 (Science)

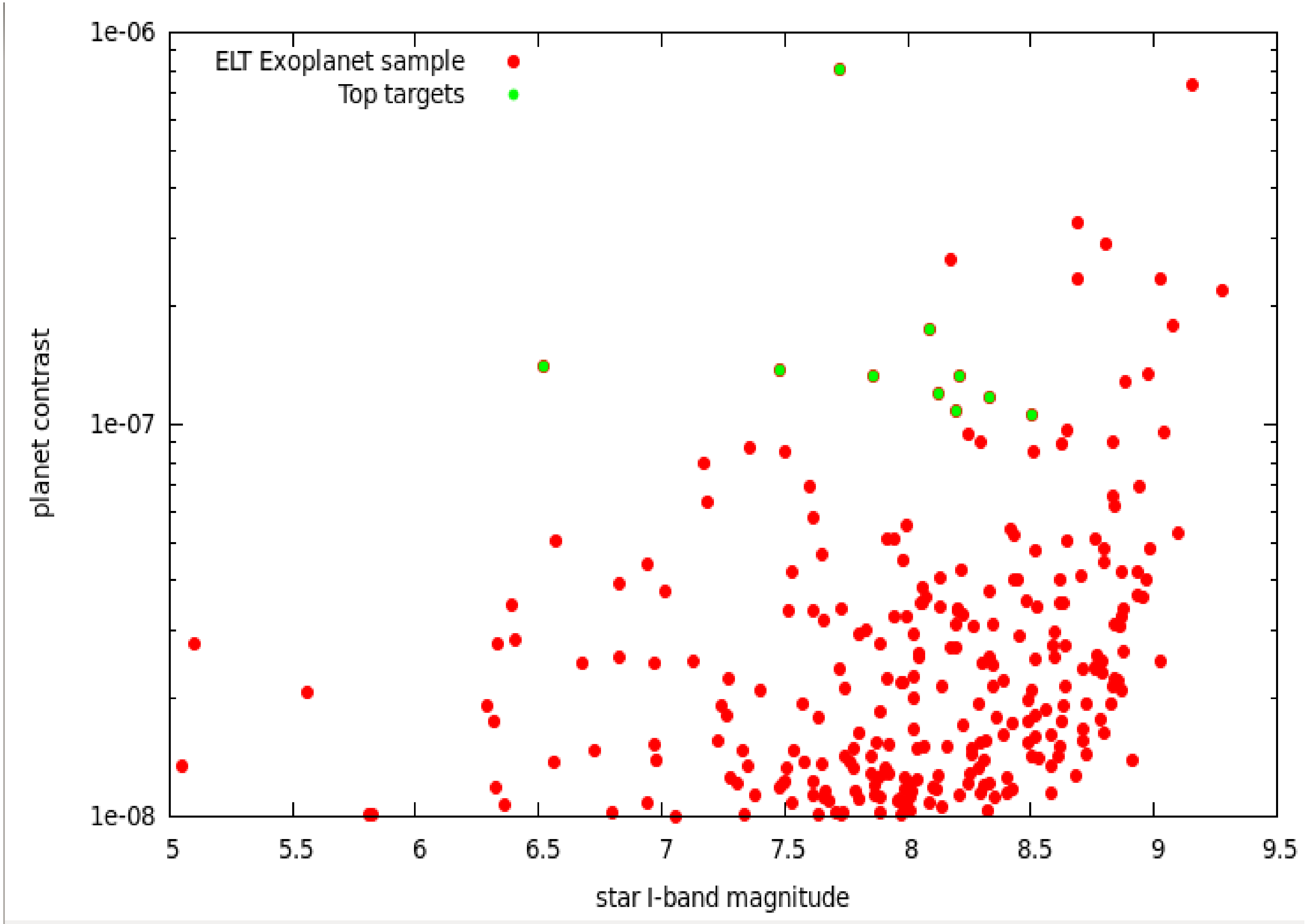
Noiseless detector
1.3 l/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea “median” atmosphere

Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)



Reflected light from HZ Super-Earths: Top 10 targets for a 30m telescope

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

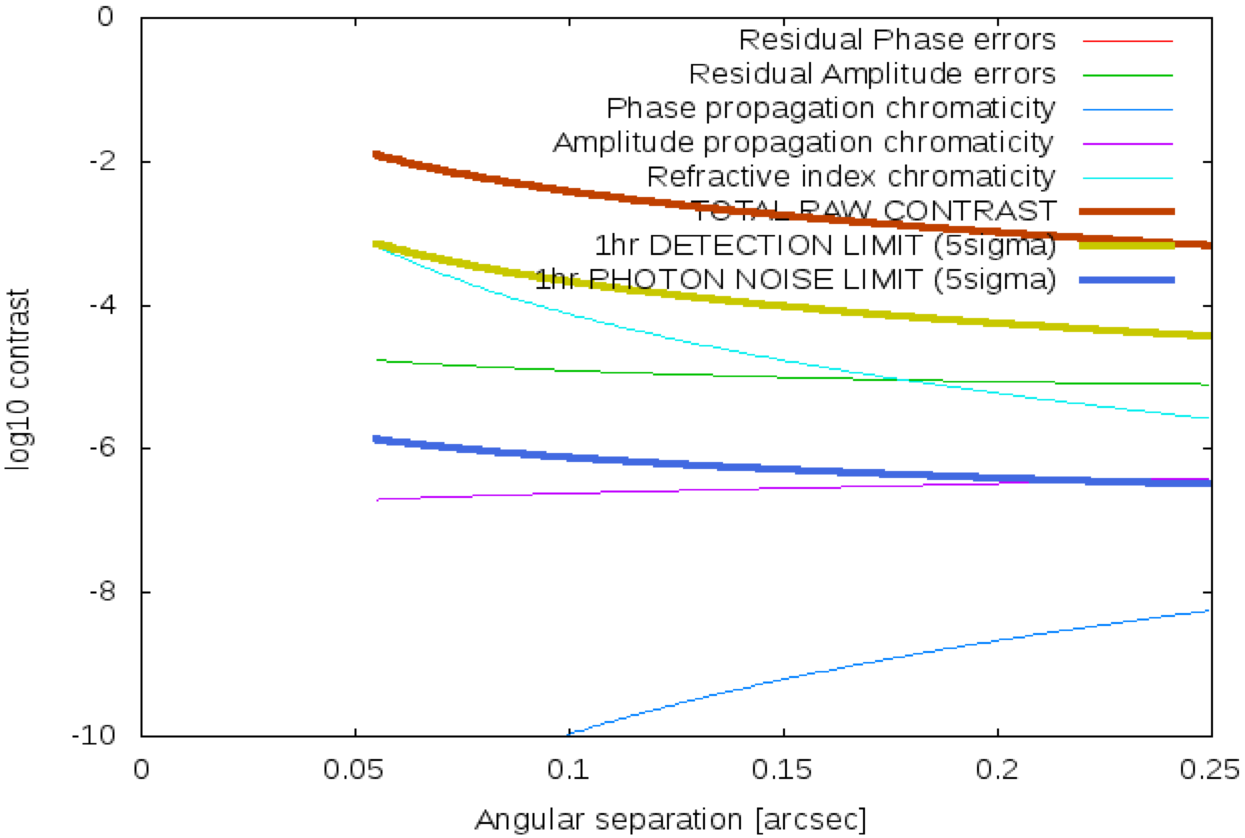
(assumes Earth albedo, contrast and separation for max elongation)

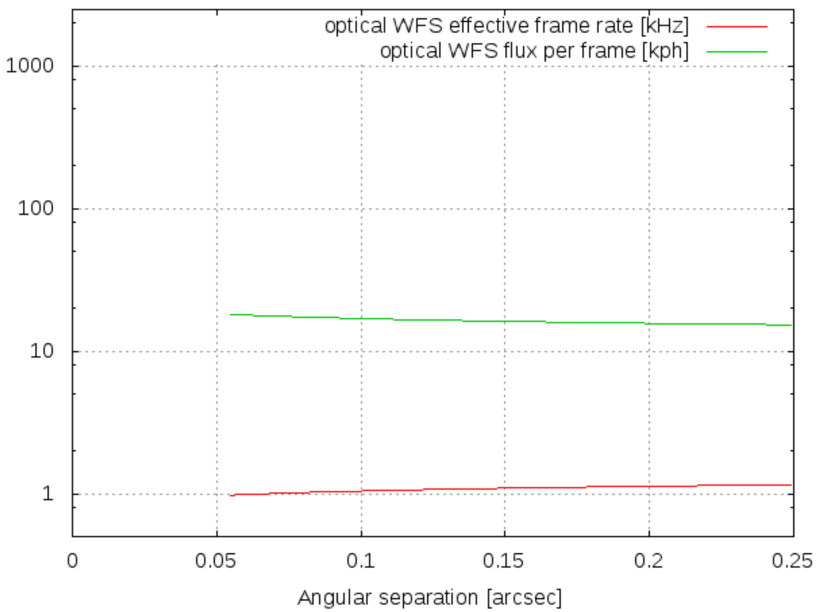
MOST FAVORABLE TARGETS

STAR							PLANET				
Name	Type	Distance	Diameter	L_{bol}	m_V	m_R	m_H	Separation	Contrast	m_H	Notes, Multiplicity
Proxima Centauri (Gl551)	M5.5	1.30 pc	0.138 R_{Sun} 0.990 +- 0.050 mas [1]	8.64e-04	11.00	9.56	4.83	22.69 mas	8.05e-07	20.07	RV measurement exclude planet above 3 Earth mass in HZ [Endl & Kurster 2008]
Barnard's Star (Gl699)	M4	1.83 pc	0.193 R_{Sun} 0.987 += 0.04 mas [2]	4.96e-03	9.50	8.18	4.83	38.41 mas	1.40e-07	21.97	-
Kruger 60 B (Gl860B)	M4	3.97 pc	0.2 R_{Sun}[3]	5.81e-03	11.30	9.90	5.04	19.20 mas	1.20e-07	22.35	-
Ross 154 (Gl729)	M4.5	2.93 pc	0.2 R_{Sun}[3]	5.09e-03	10.40	9.11	5.66	24.34 mas	1.37e-07	22.82	-
Ross 128 (Gl447)	M4.5	3.32 pc	0.2 R_{Sun}[3]	3.98e-03	11.10	9.77	5.95	18.99 mas	1.75e-07	22.84	-
Ross 614 A (Gl234A)	M4.5	4.13 pc	0.2 R_{Sun}[3]	5.23e-03	11.10	9.82	5.75	17.51 mas	1.33e-07	22.95	Double star (sep=3.8 AU)
Gl682	M3.5	4.73 pc	0.26 R_{Sun}[3]	6.41e-03	10.90	9.70	5.92	16.93 mas	1.09e-07	23.33	-
Groombridge 34 B (Gl15B)	M6	3.45 pc	0.18 R_{Sun}[3]	5.25e-03	11.00	9.61	6.19	20.98 mas	1.33e-07	23.39	150 AU from M2 primary
40 Eri C (Gl166C)	M4.5	4.83 pc	0.23 R_{Sun}[3]	5.92e-03	11.10	9.88	6.28	15.93 mas	1.18e-07	23.61	35AU from 40 Eri B (white dwarf), 420 AU from 40 Eri A (K1)
GJ 3379	M4	5.37 pc	0.24 R_{Sun}[3]	6.56e-03	11.30	10.06	6.31	15.09 mas	1.06e-07	23.75	-

[1] Angular diameter (uniform disk, non limb-darkened value) measured by optical interferometry with VLTI Demory et al. 2009
[2] Uniform disk angular diameter from Lane et al. 2001
[3] No direct measurement. Approximate radius is given. If possible, radius is extrapolated from photometry using K magnitude and radius vs. absolute K magnitude relationship in Demory et al. 2009

8m: SH-based system, 15cm subapertures

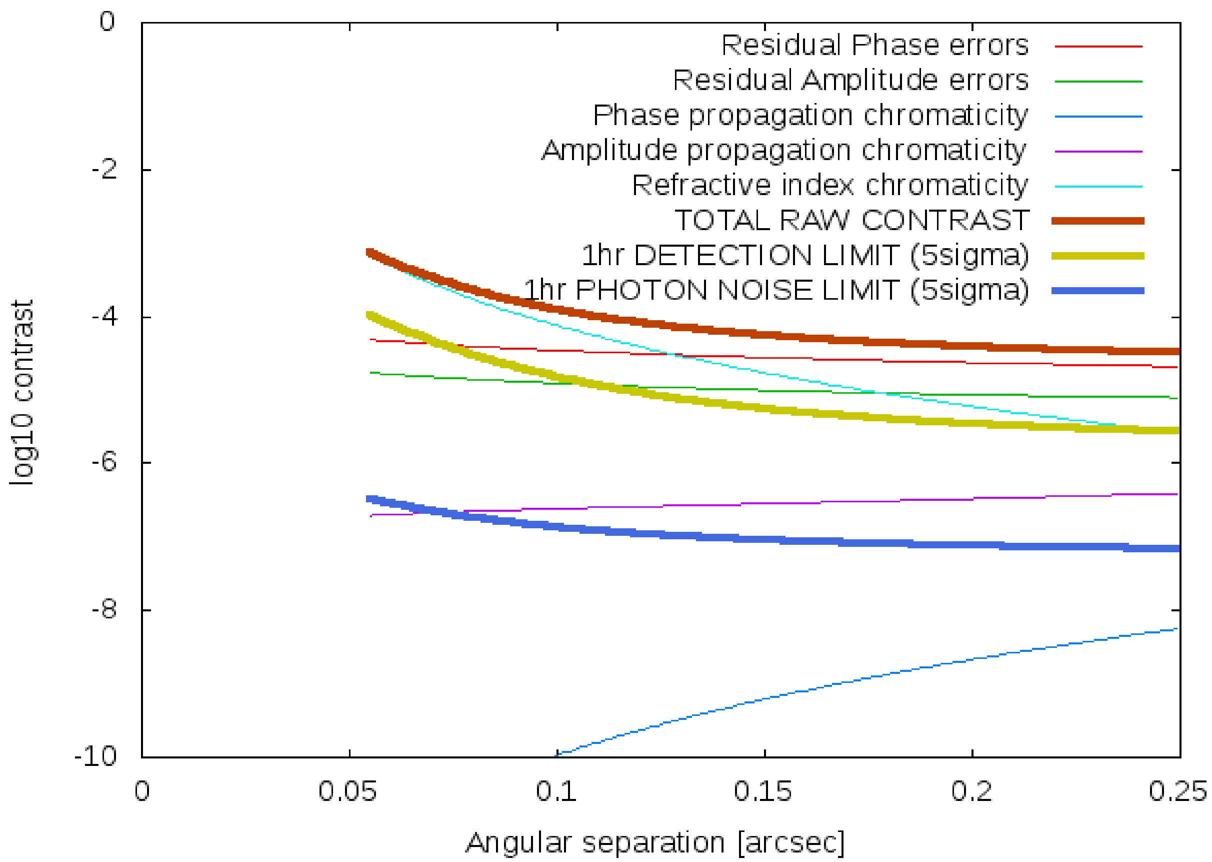


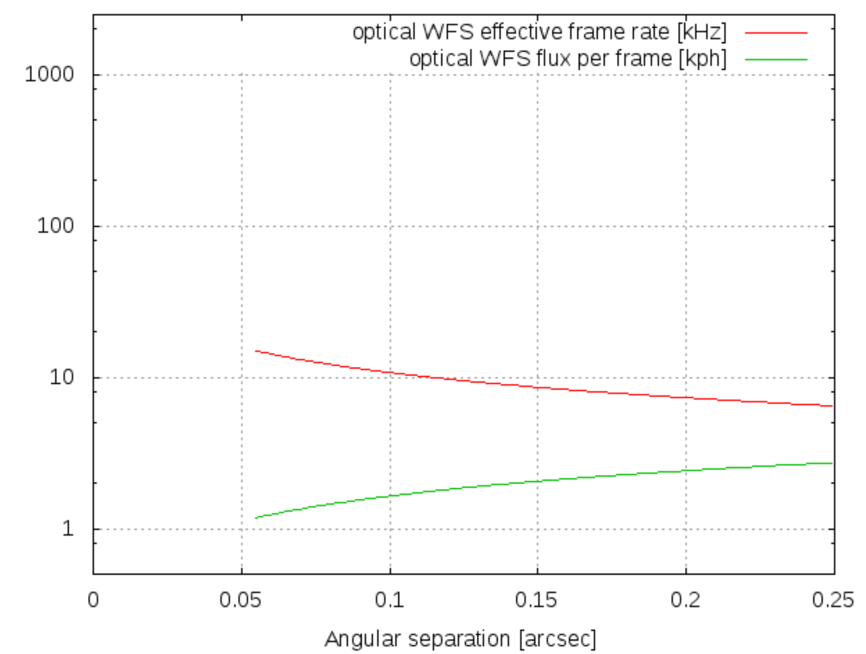


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster)
>10kph per WFS required

Detection limit ~1e-3 at IWA, ~1e-4 at 0.2”

8m: Pyramid-based system

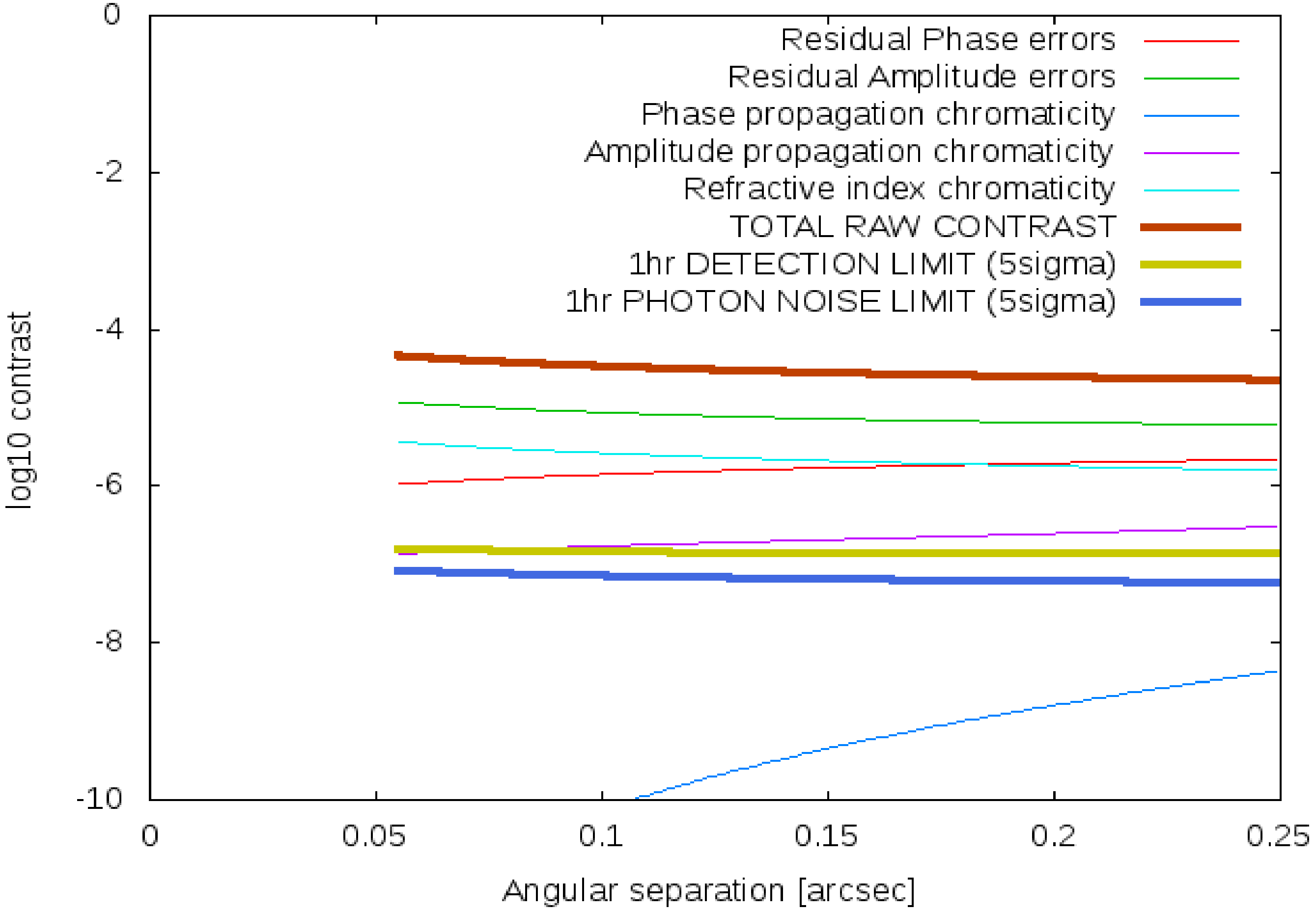


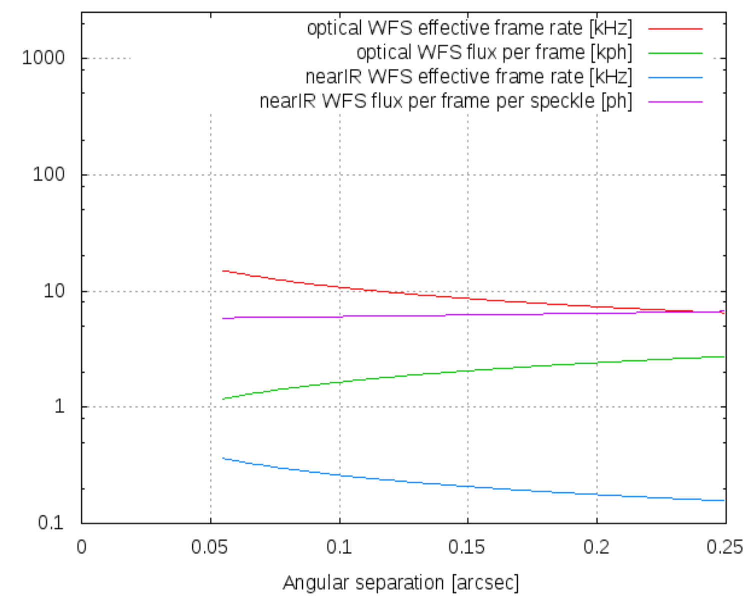


More sensitive WFS, can run faster (10kHz) with few kph per WFS frame
Limited by atmosphere chromaticity

Detection limit ~1e-4 at 2 l/D

8m: Pyramid-based system + Speckle Control

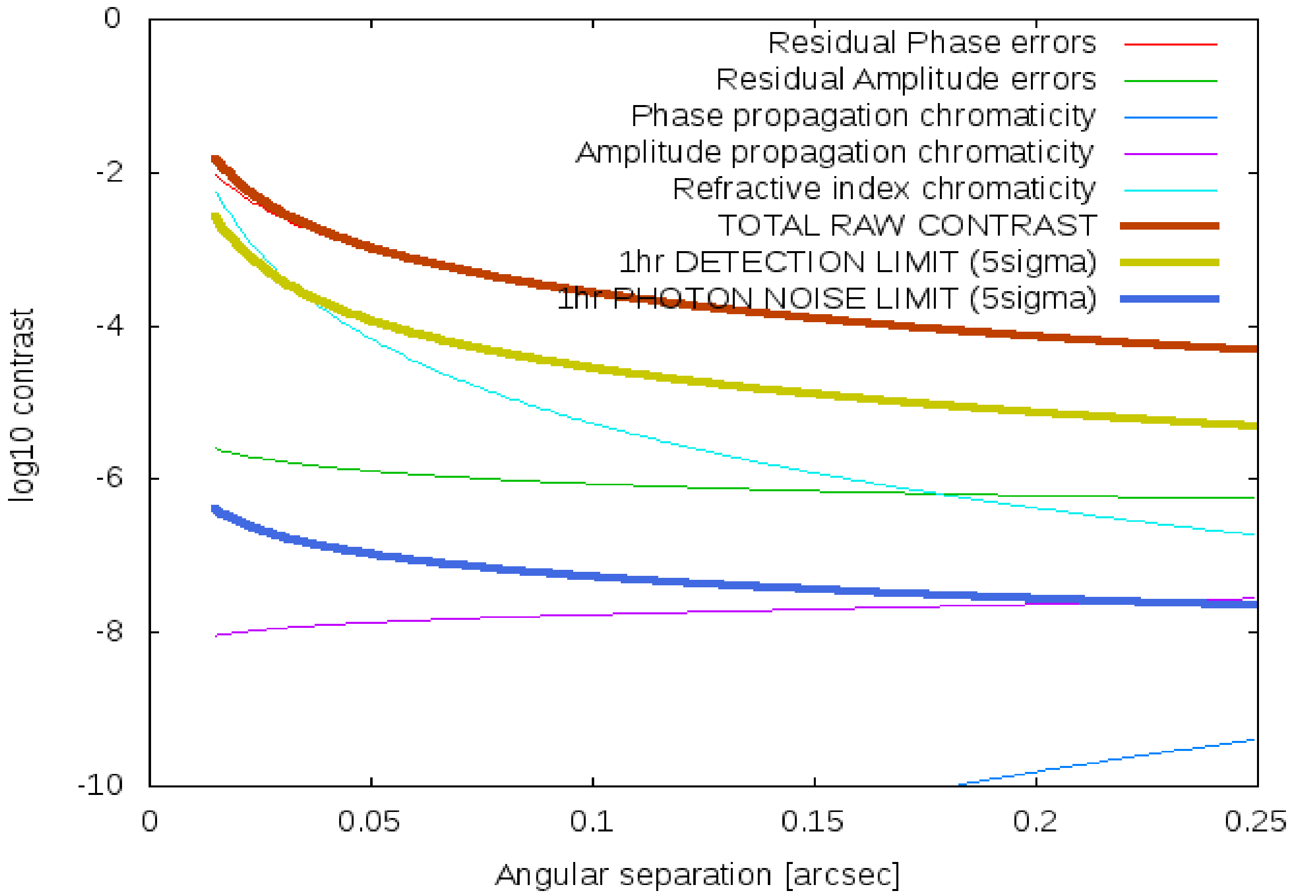


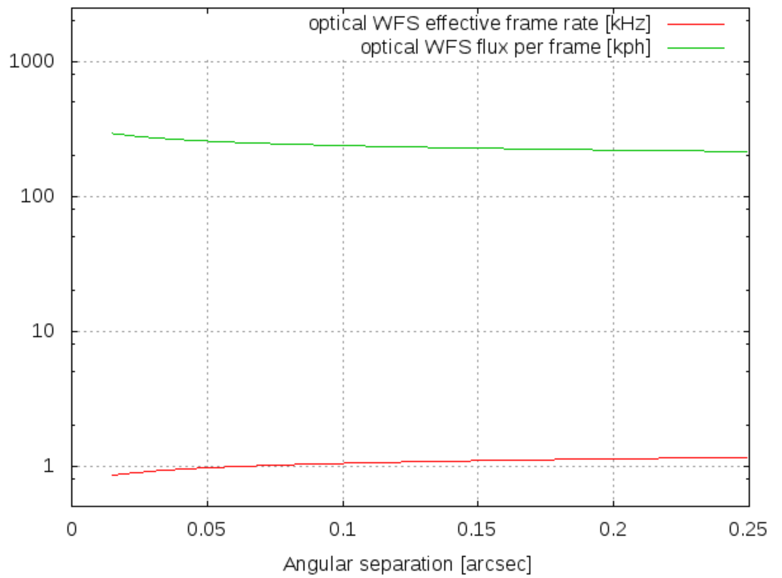


300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~5e-5 contrast and fast → good averaging to detection limit at few `1e-7

30m: SH-based system, 15cm subapertures

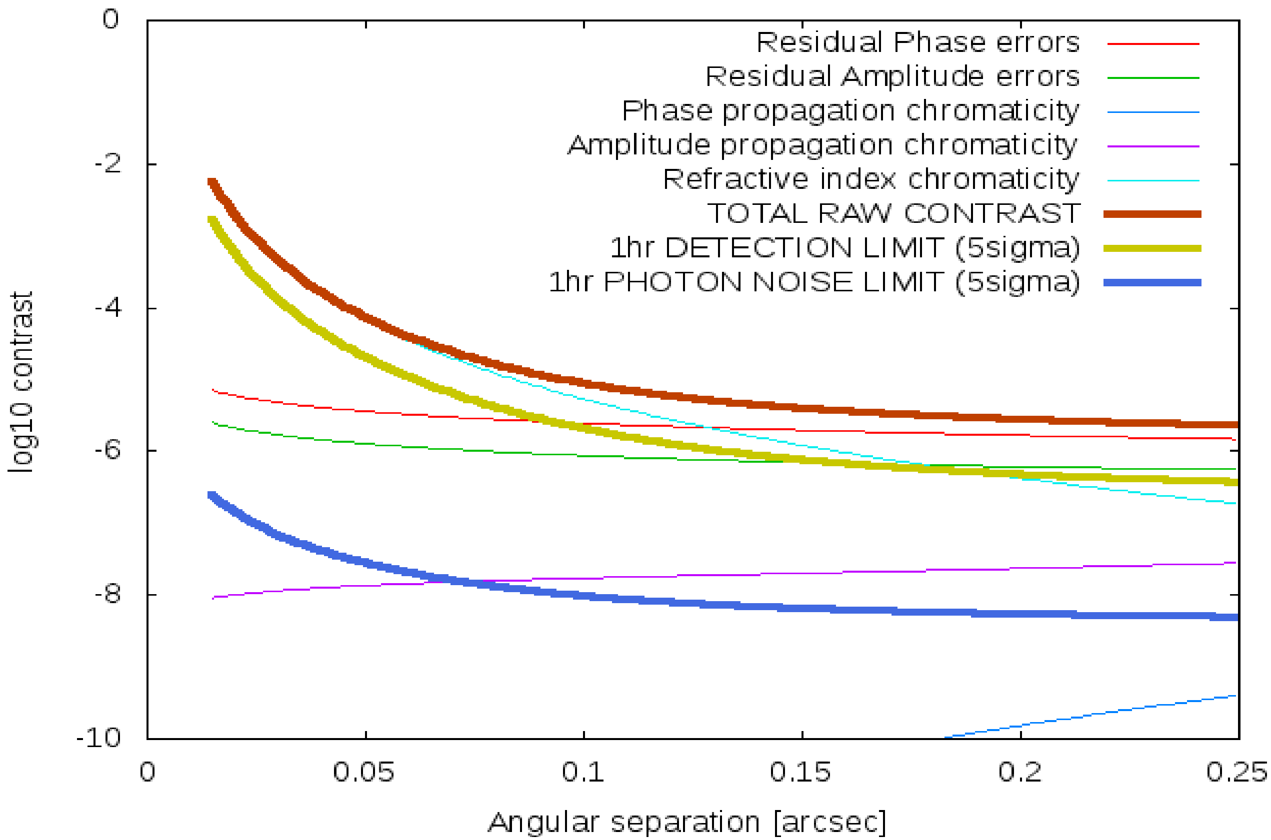


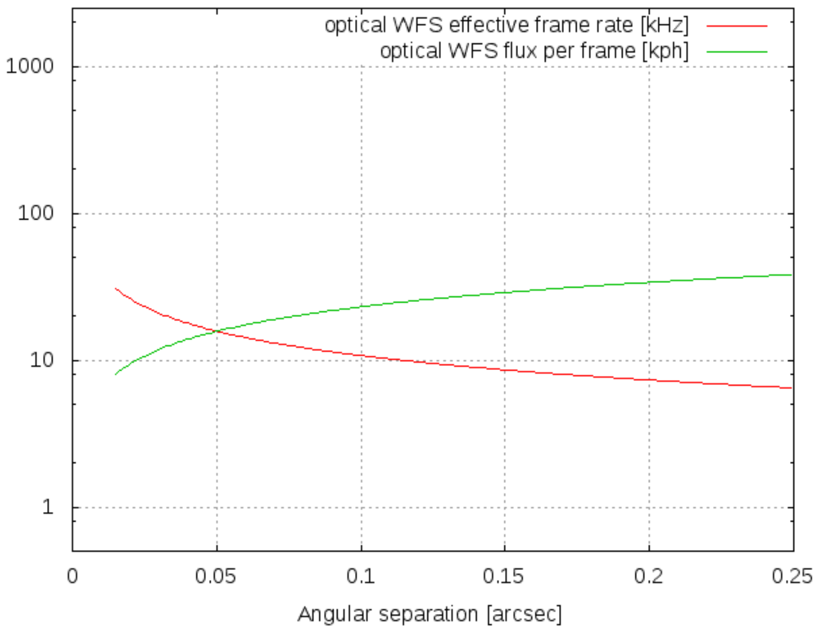


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, **POOR AVERAGING due to crossing time**

30m: Pyramid-based system

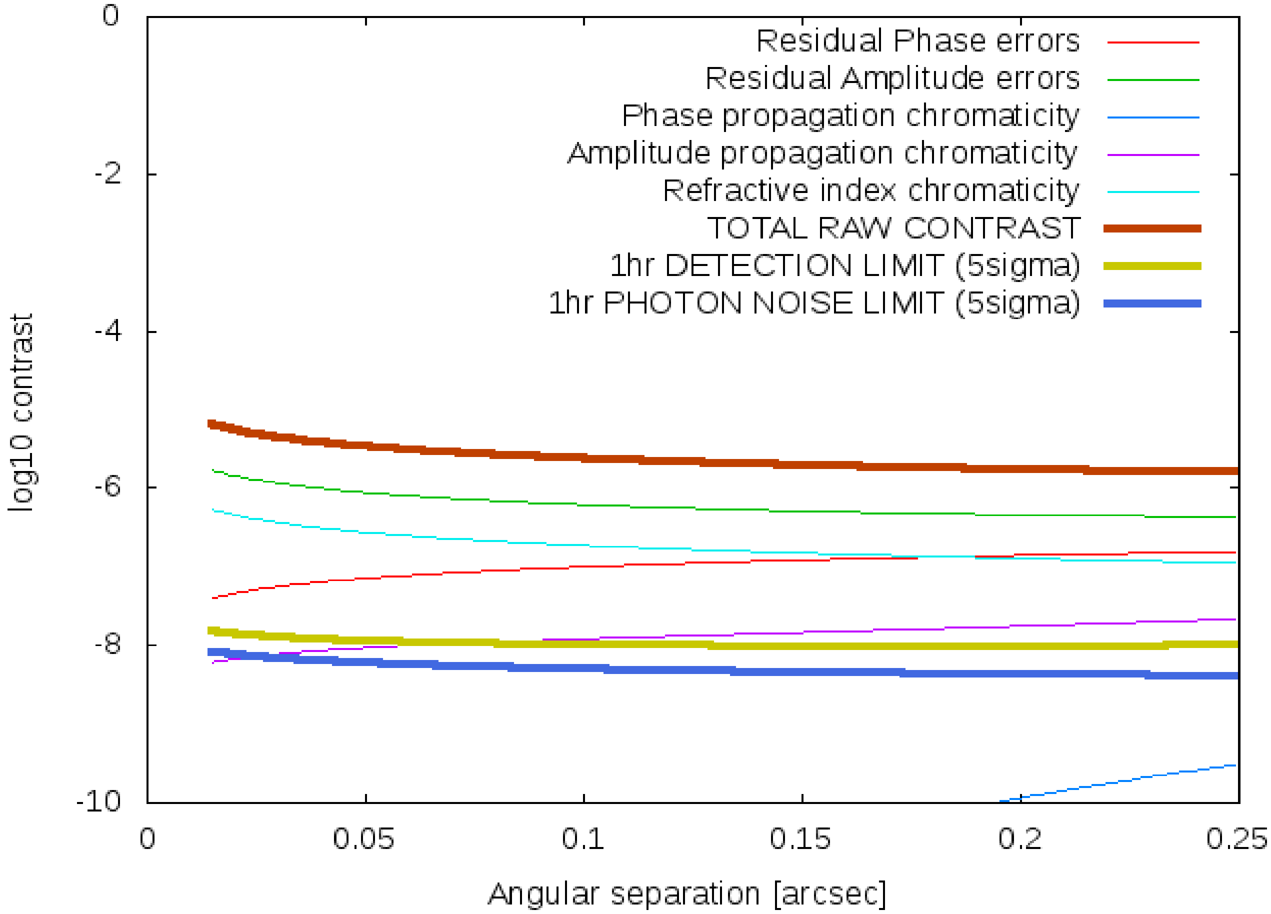


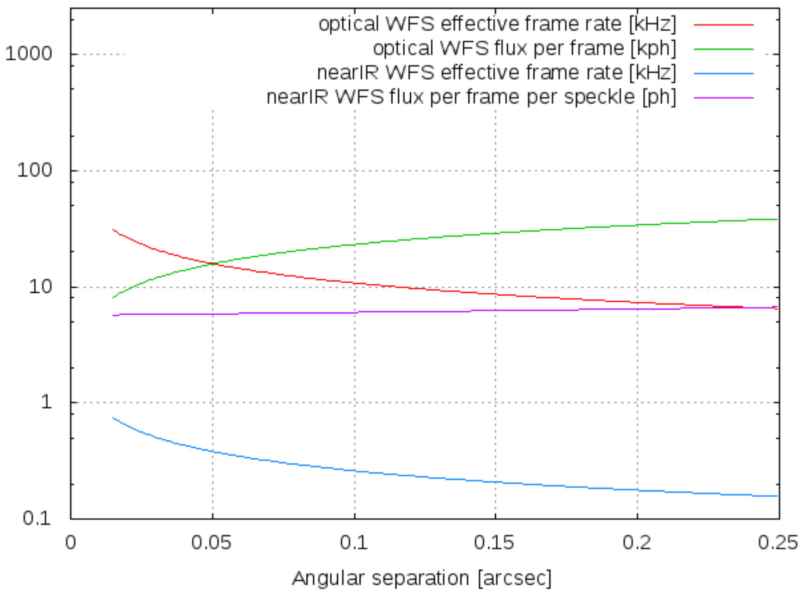


More sensitive WFS, can run faster (10kHz) with ~10 kph per WFS frame
Limited by atmosphere chromaticity

~((D/CPA)/r0)^2 flux gain: ~10,000x in flux = 10 mag near IWA
Sensitivity now equivalent to I mag = -2 with SHWFS

30m: Pyramid-based system + speckle control





300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

Speed ...

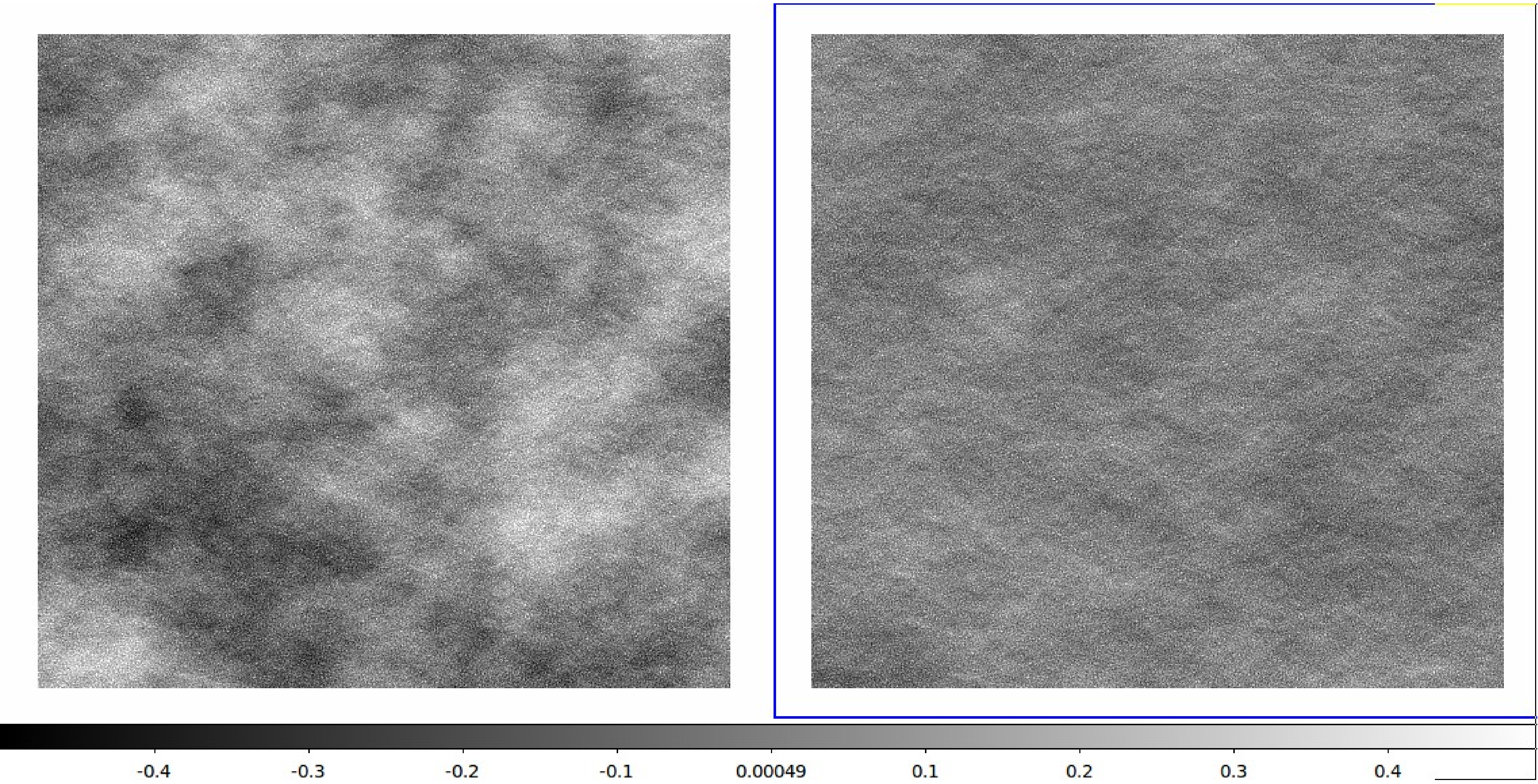
Optimal OPD scaling

0.6 um vs 1.6 um: 1.4% difference in (n-1)

0.8 um vs 1.6 um: 0.7% difference in (n-1)

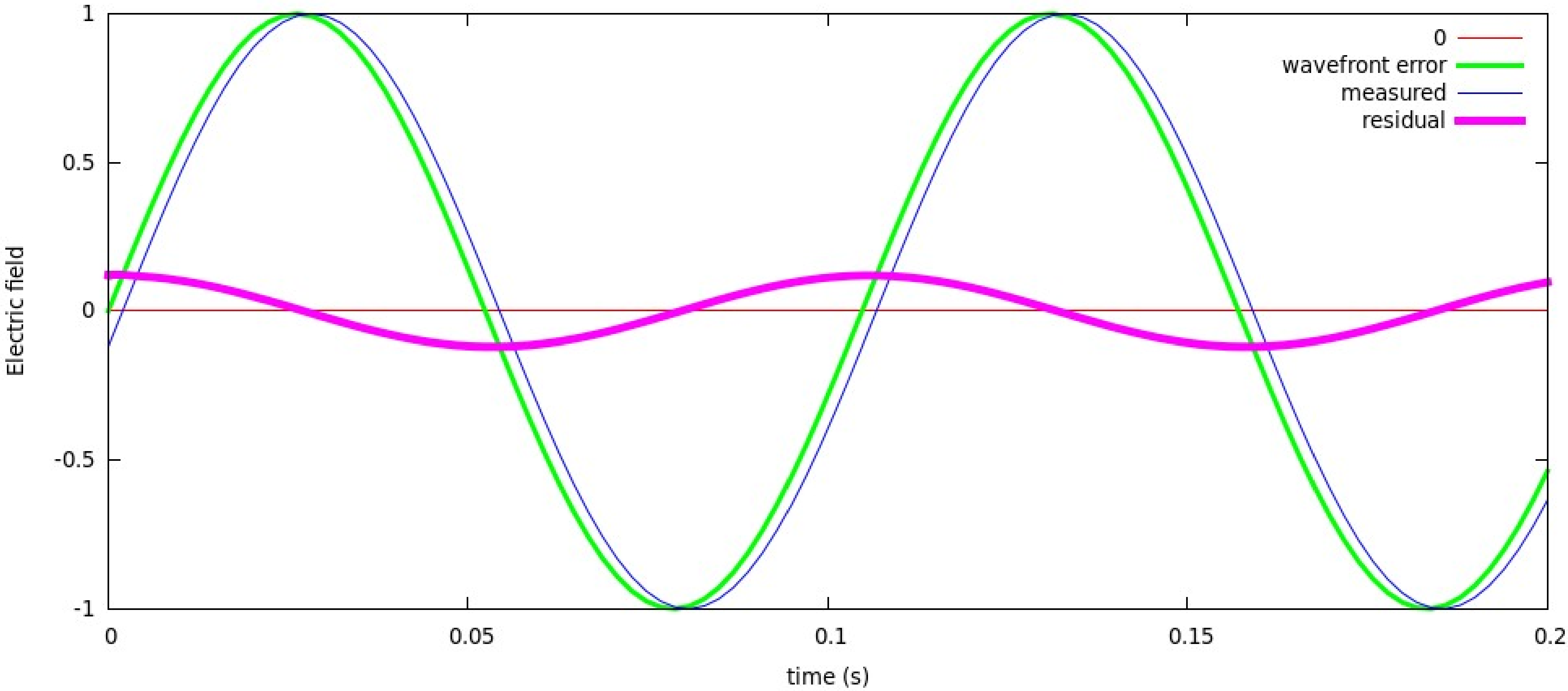
Scaling removes most of the low order OPD chromaticity

Multiplicative coefficient (here 1.017) can be computed, but difficult to separate telescope errors from atmosphere

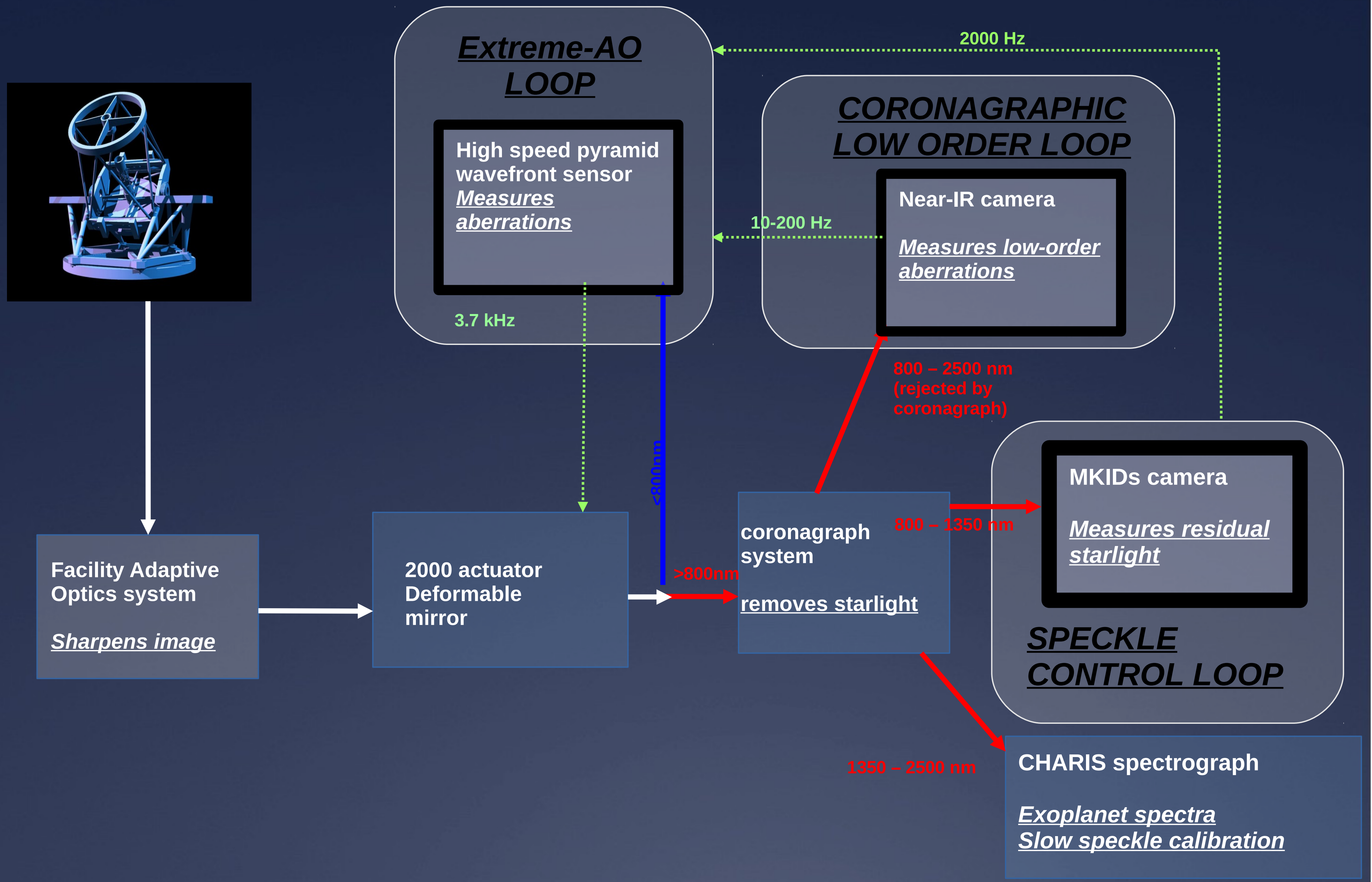


Predictive control

Time lag speckles are the main source of planet-looking speckles in DM control area
→ predictive control is essential



Wavefront control for ultra-high contrast (2016)



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

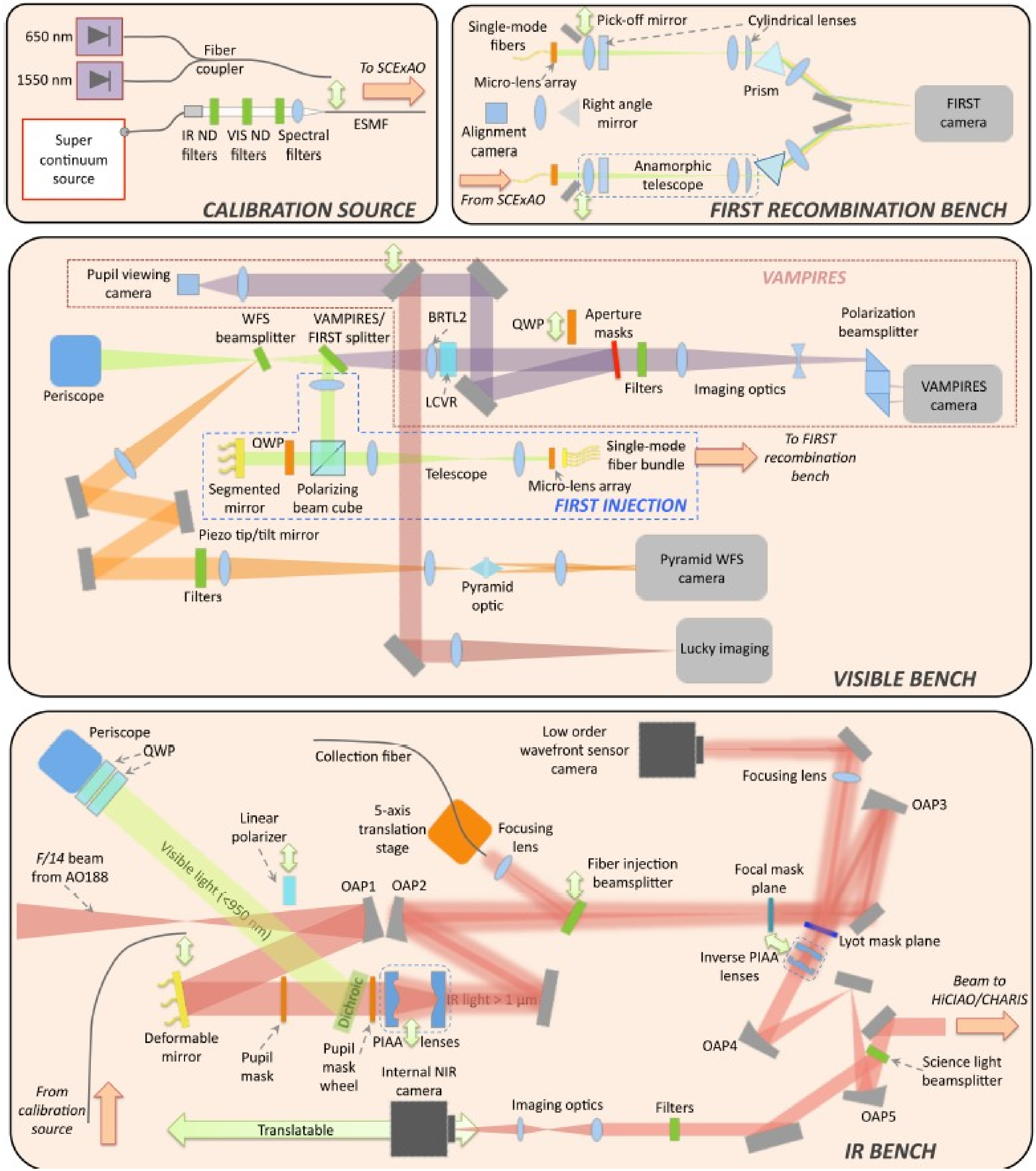
2k MEMS DM

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



How SCExAO achieves high contrast

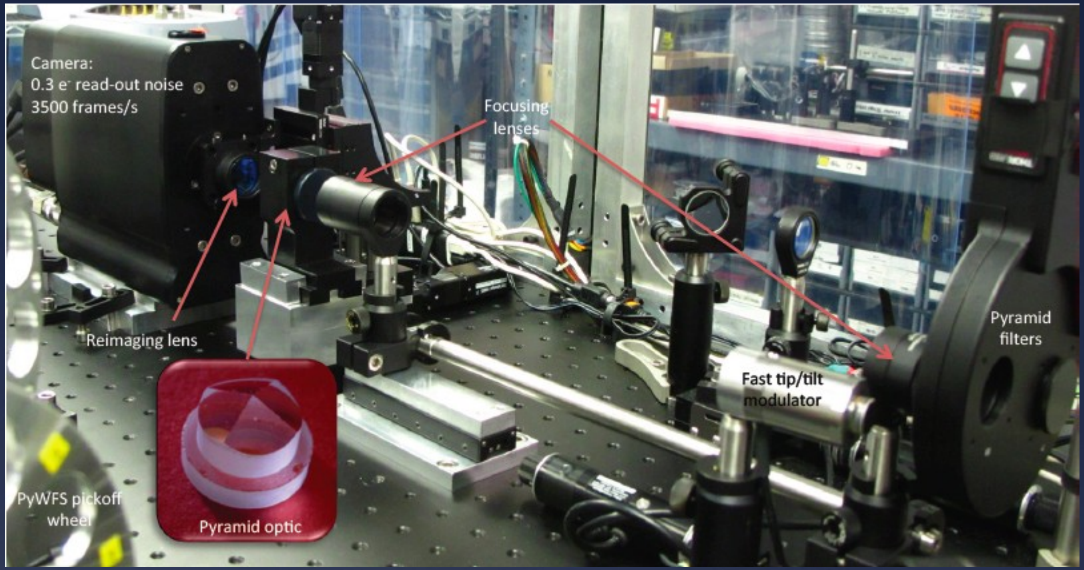
Uniquely combines 4 techniques:

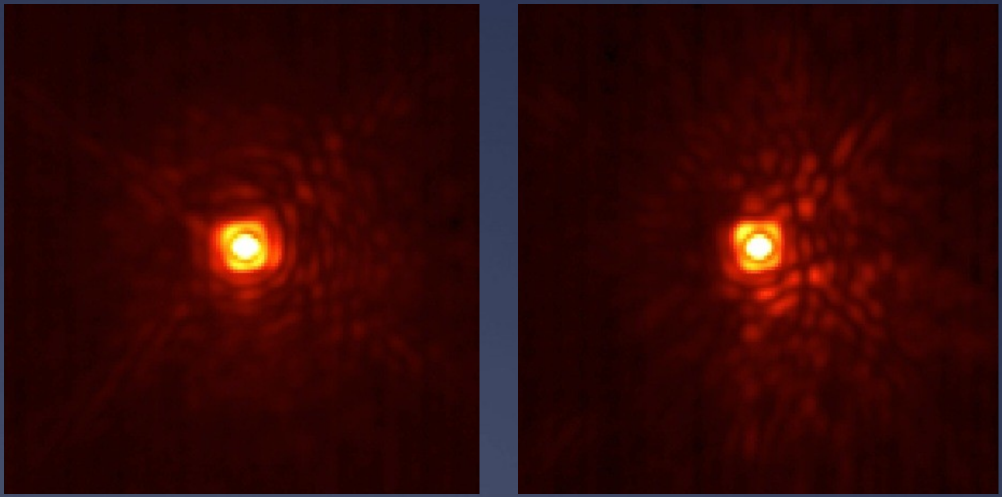
Extreme-AO
→ removes wavefront errors

Coronagraphy
→ removes diffraction (Airy rings)

LOWFS
→ keeps star centered on coronagraph
→ records residual WF errors to help process data

Speckle control
→ modulates, removes and calibrates residual speckles





Speckle nulling on-sky

Extreme AO on-sky results (Results from April 9th, 2015)

1205 modes corrected at 3.5kHz using 2000 act DM (1600 illuminated)

deep depletion EMCCD, 240x240 pix (binned to 120x120 to run faster)

EM gain = 600 on faint stars → true photon-counting

System can switch control matrix on-the-fly → bootstrapping between modulation and no modulation

Full image multiplied by control matrix → uses diffraction features

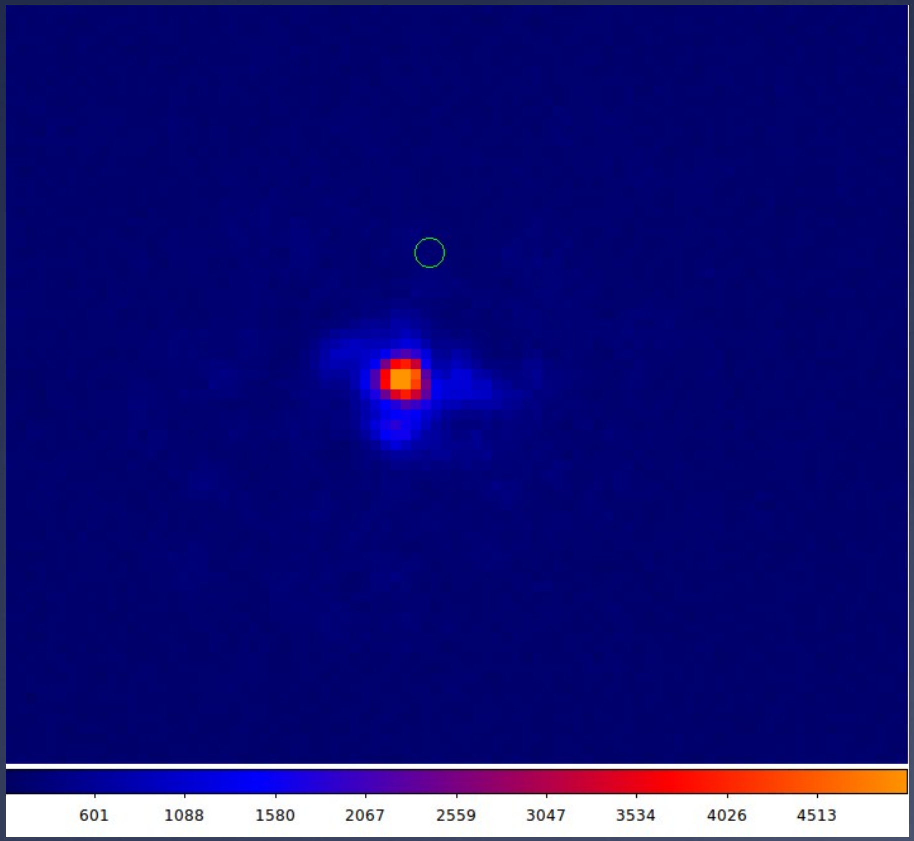


Image (left):

Single image of a diffraction limited PSF at 775 nm

PyWFS works at diffraction-limited sensitivity

... down to I mag ~ 10 (to be confirmed)

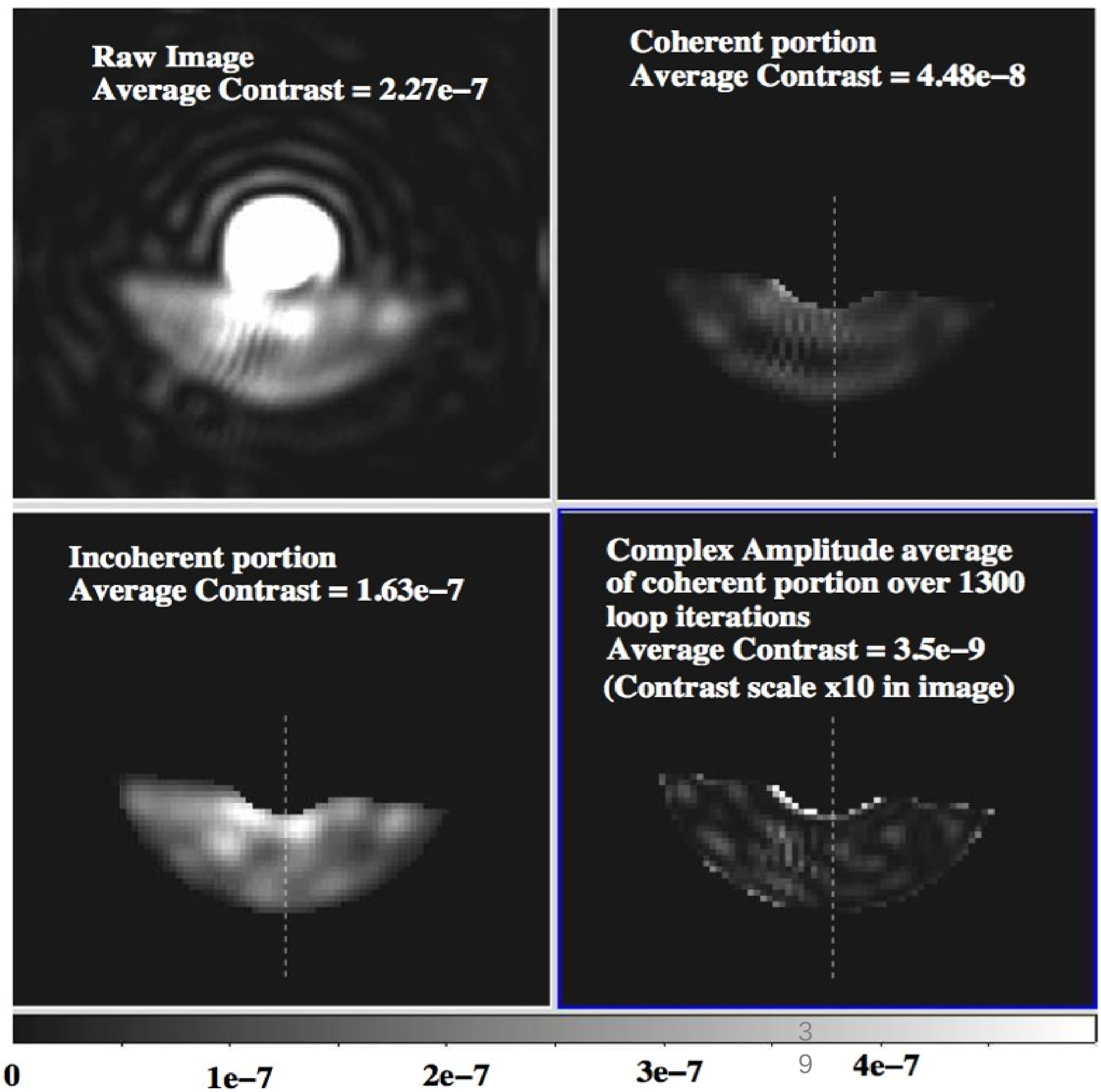
Focal plane WFS based correction and speckle calibration

2e-7 raw contrast obtained at 2 λ/D

Incoherent light at 1e-7
Coherent fast light at 5e-8
Coherent bias <3.5e-9

Test demonstrates:
- ability to separate light into coherent/incoherent fast/slow components
- ability to slow and static remove speckles well below the dynamic speckle halo

Guyon et al. 2010



Atmospheric Dispersion
Real-time measurement & correction
+ water absorption/RI measurement

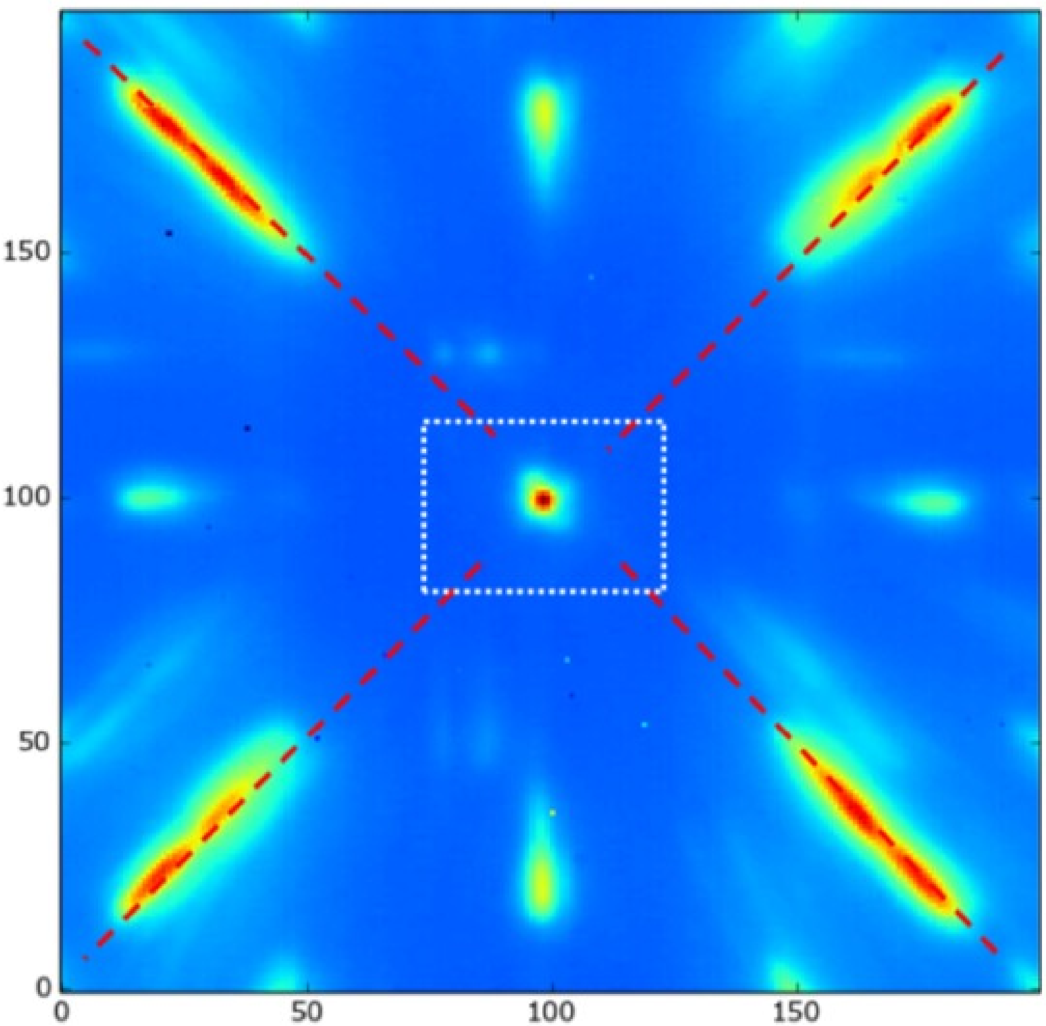


Figure 2: Speckles at 59⁰ Elevation

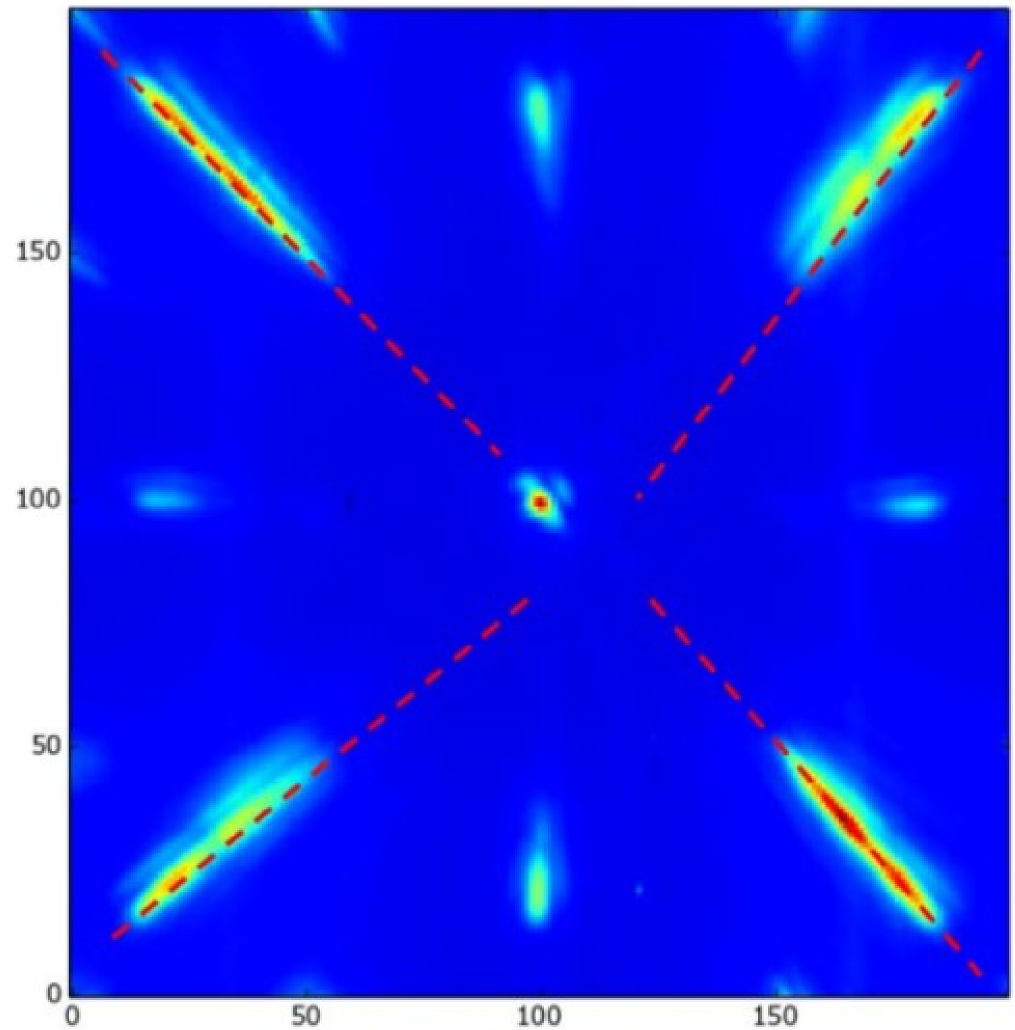


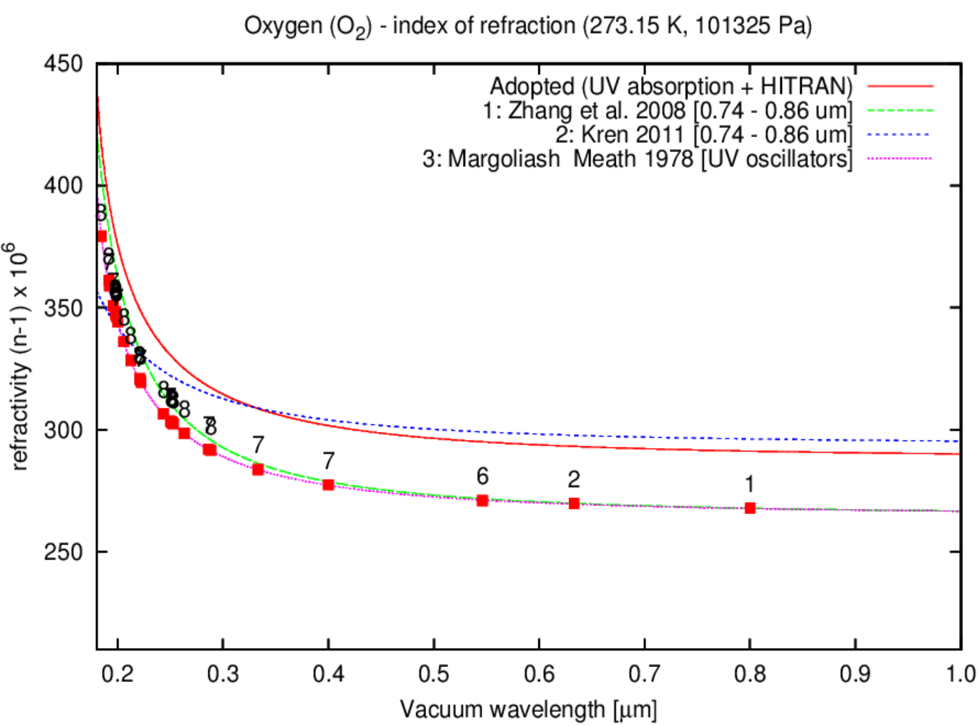
Figure 3: Speckles at 40⁰ Elevation

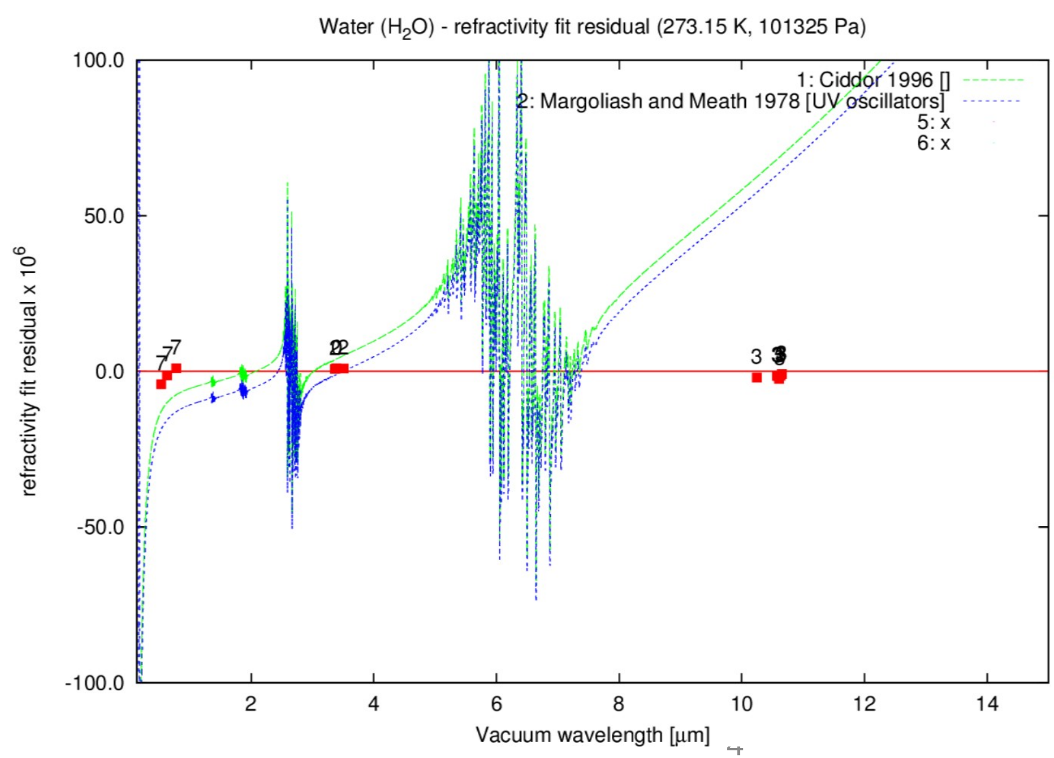
Spectroscopy … the water issue

Simultaneous measurement of star spectra + planet spectra

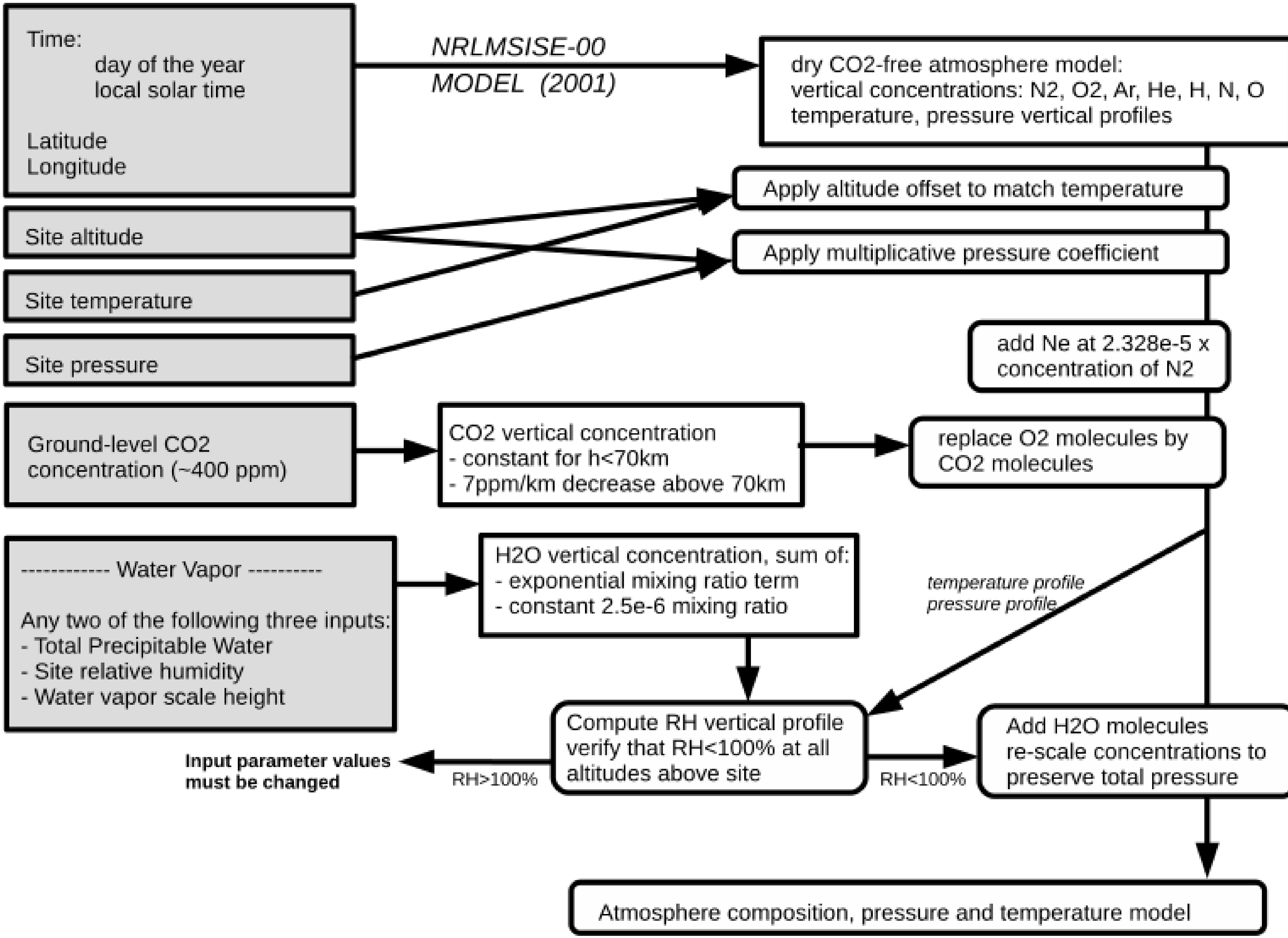
PROBLEM: refractive index near water absorption bands is complicated
→ we are developing high-fidelity atmosphere model

Computing refractive index as a function of wavelength and altitude + diffractive propagation





Atmosphere model (composition, temperature, pressure)



Vibrations

Elevation: 62°

Transit time: 9.5 mins

Vibrations in Elevation

Pre-, During, Post-transit

Vibration peaks: 3.8, 4.4, 5.2 Hz

Corresponding harmonics: 7.6, 8.0, 9.6 Hz

10.4 Hz is probably folded by the temporal resolution of the sensor

These vibrations are due to the encoder of the elevation axis.

Around the transit, the motion of the telescope is very small, probably hitting the resolution limit of this encoder.

Throughout the observation

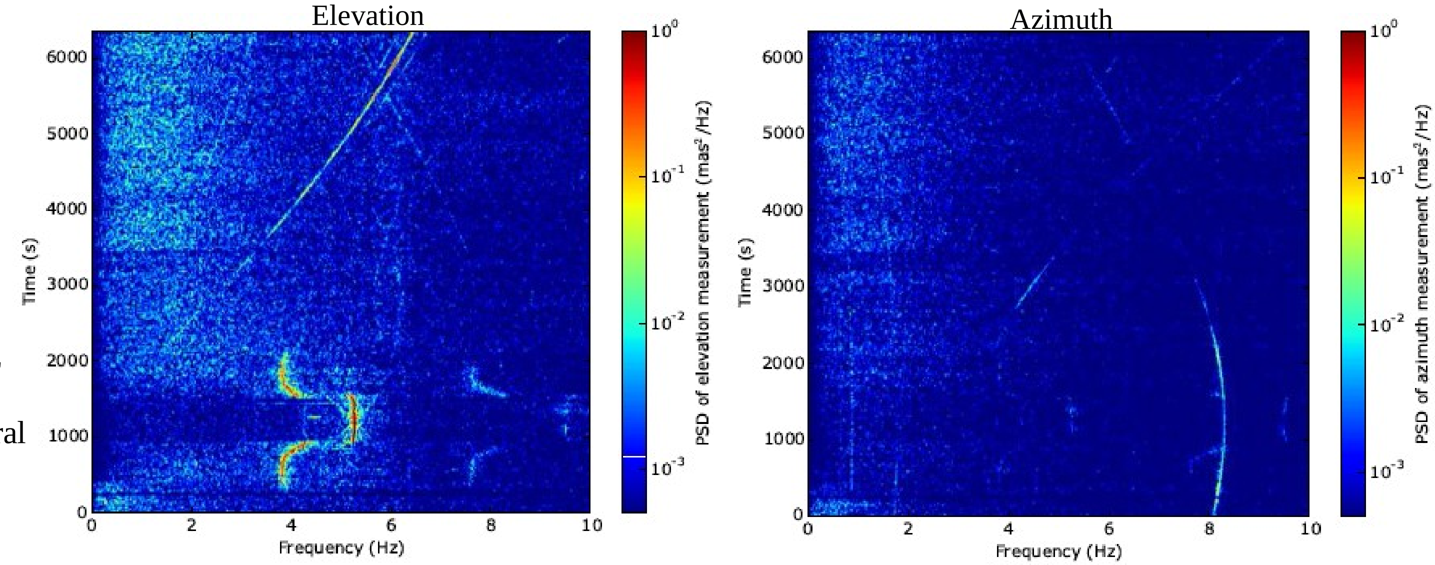
Vibrations evolves from: 0 to 6.4 Hz and 0 – 3.4 HZ

Vibrations in Azimuth

Strongest vibration: 8.3 – 5.2 Hz

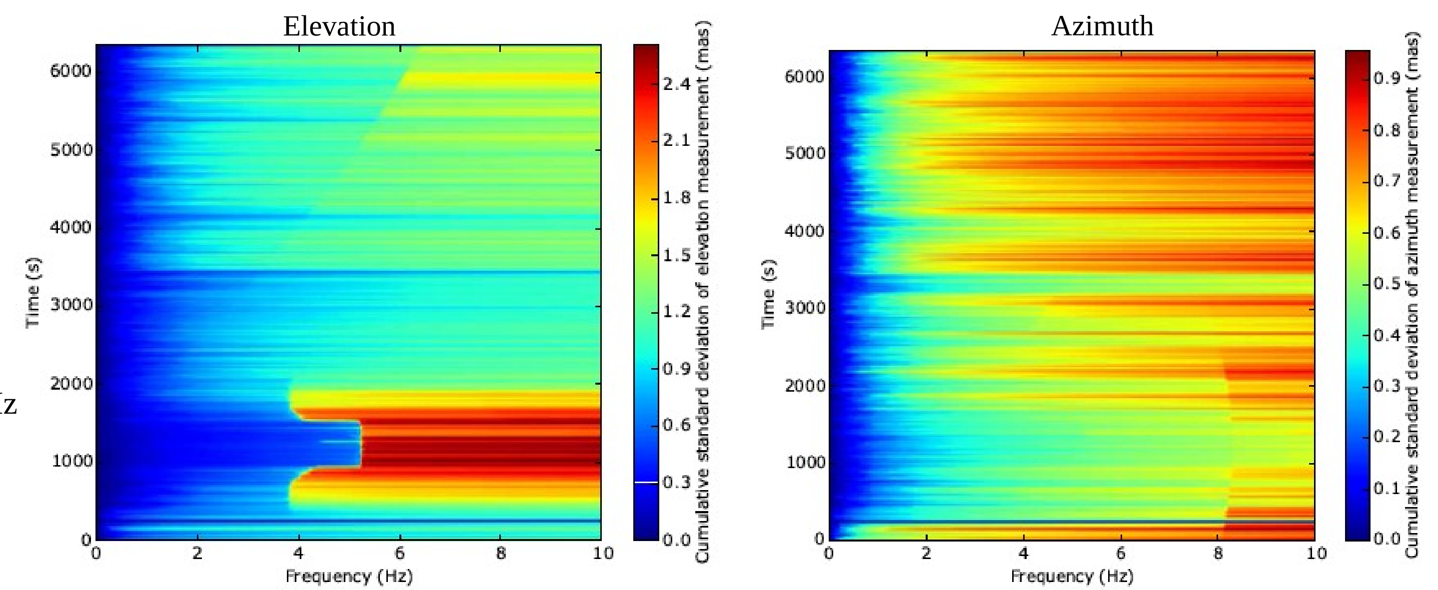
Another fainter vibrations: 3.4 – 9.6 Hz (may be the folded harmonics of the vibration going from 10.4 – 16.6 Hz)

Evolution of the PSD with time



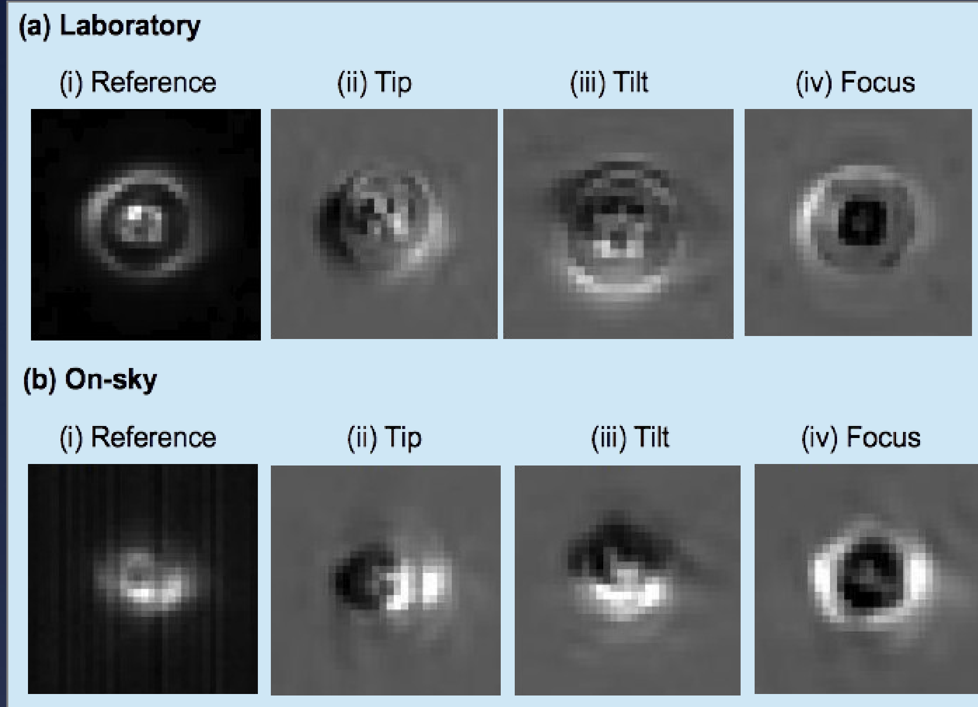
Square root of the Cumulative sum of the PSD

(Cumulative standard deviation of the residuals)



LLOWFS: Laboratory vs On-sky

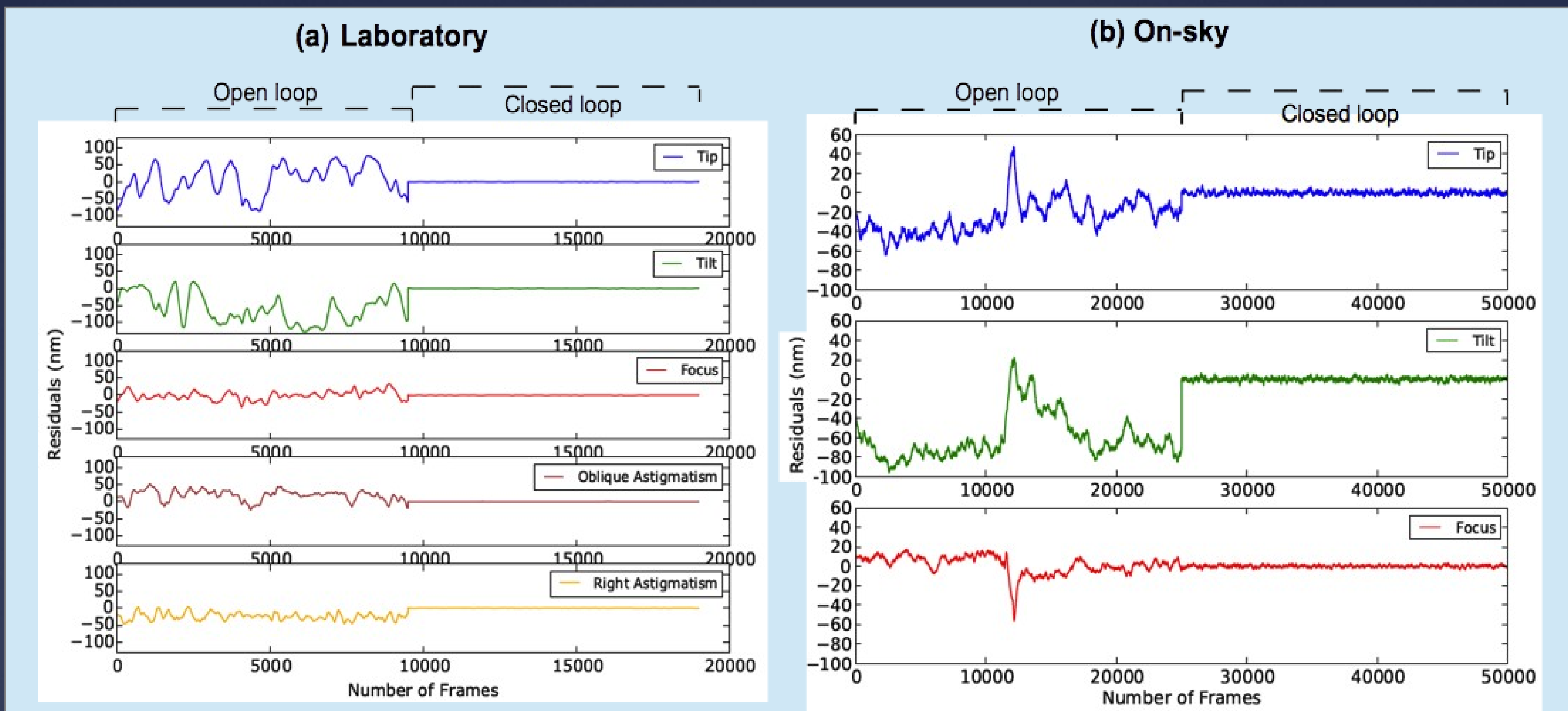
Note: Simulated dynamic turbulence with amplitude: 100 nm rms and wind speed: 10 m/s is applied upstream of the coronagraph with the Laboratory experiments



Response Matrix

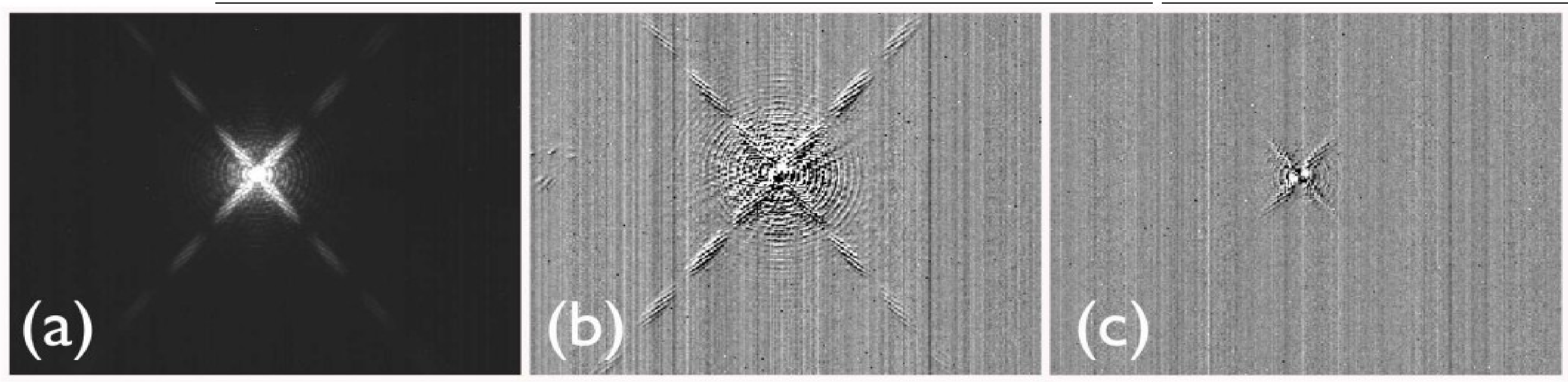
obtained by applying phasemaps of respective modes with amplitude of 60 nm rms onto the DM

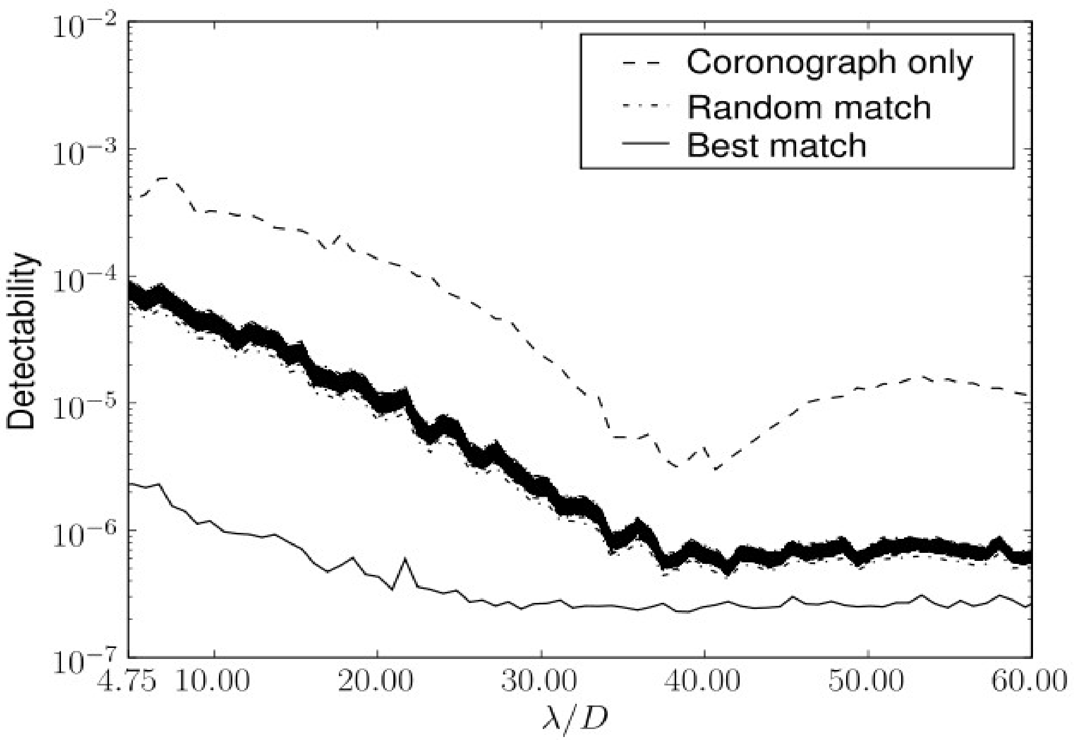
Residuals



Coronagraph leaks calibrated to 1% in SCExAO (Vogt et al. 2011)

Co-added science image | Standard PSF subtraction | MMA

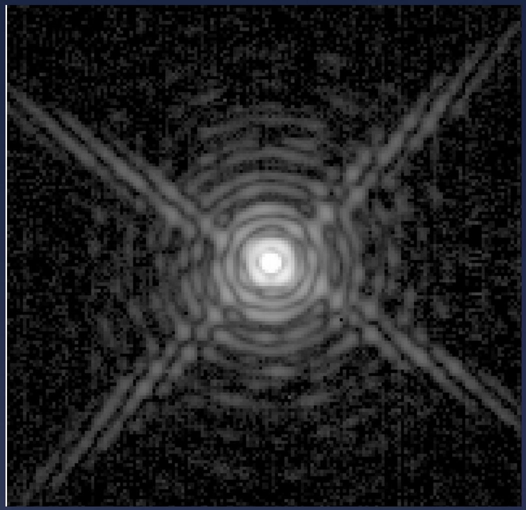


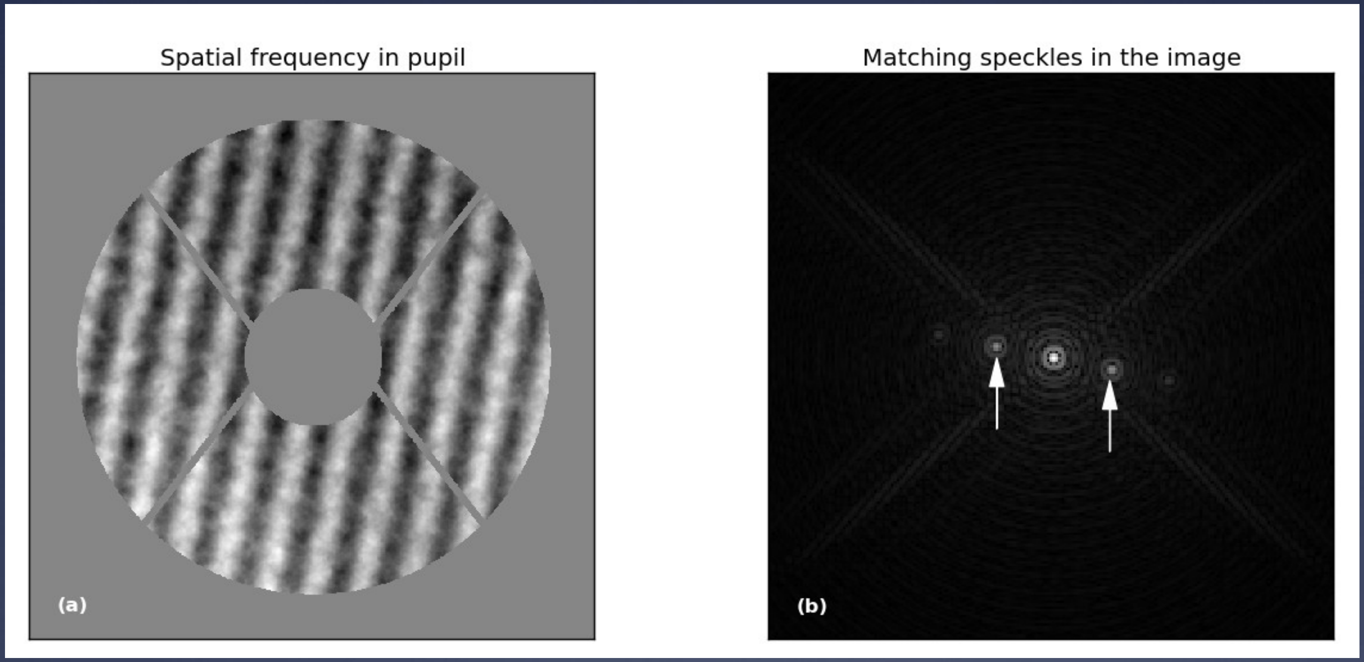


Systematically removing speckles

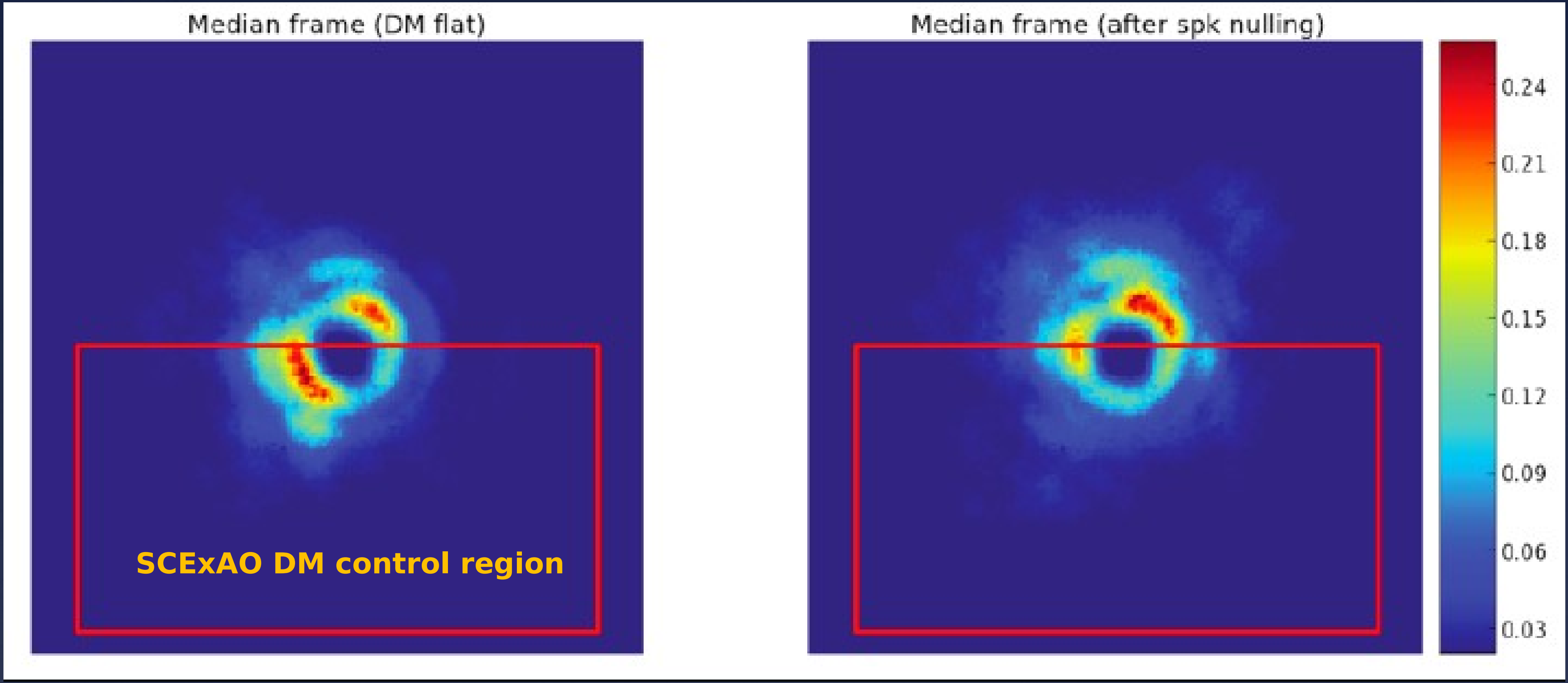
Presence of static & slow-varying aberrations in the path of science camera sets contrast limit at present

Typical SCExAO PSF





First on-sky speckle nulling on-sky (Nov. 2012)



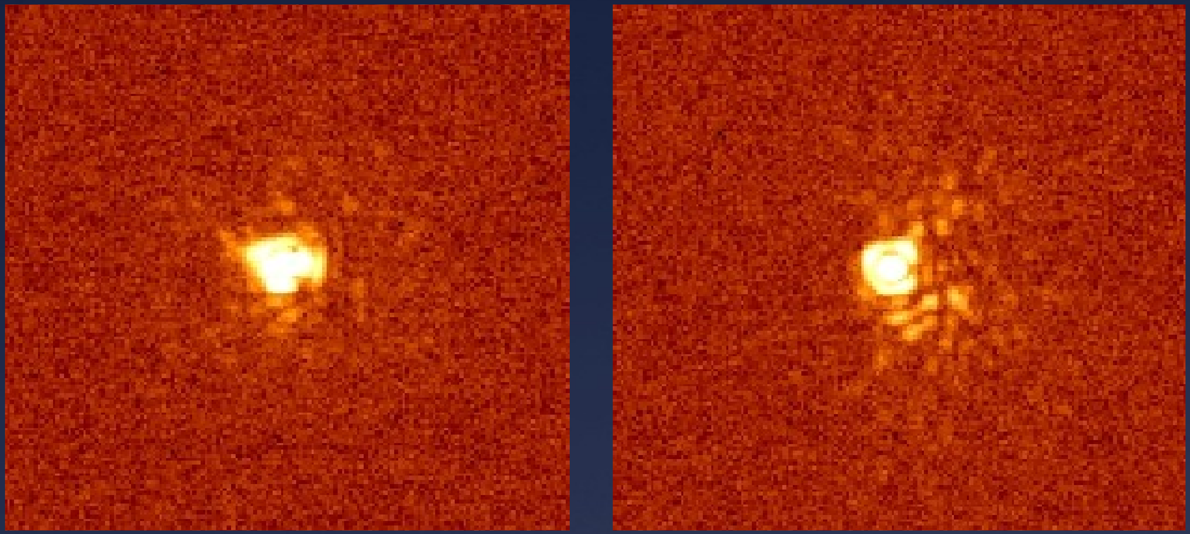
DM flat

Speckle Nulled

Single pair of long exposures (1.5 sec) on Pollux by HiCIAO
Reduction of the diffraction features in raw images – mean increase in contrast of ~2 for brightest ring.

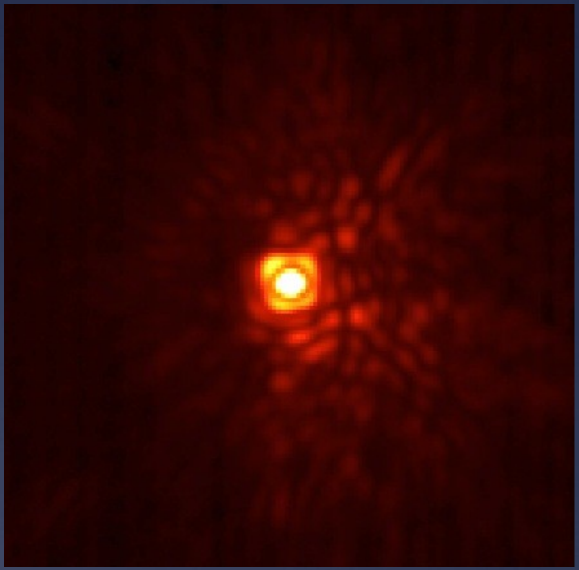
speckle nulling results on-sky (June 2014)

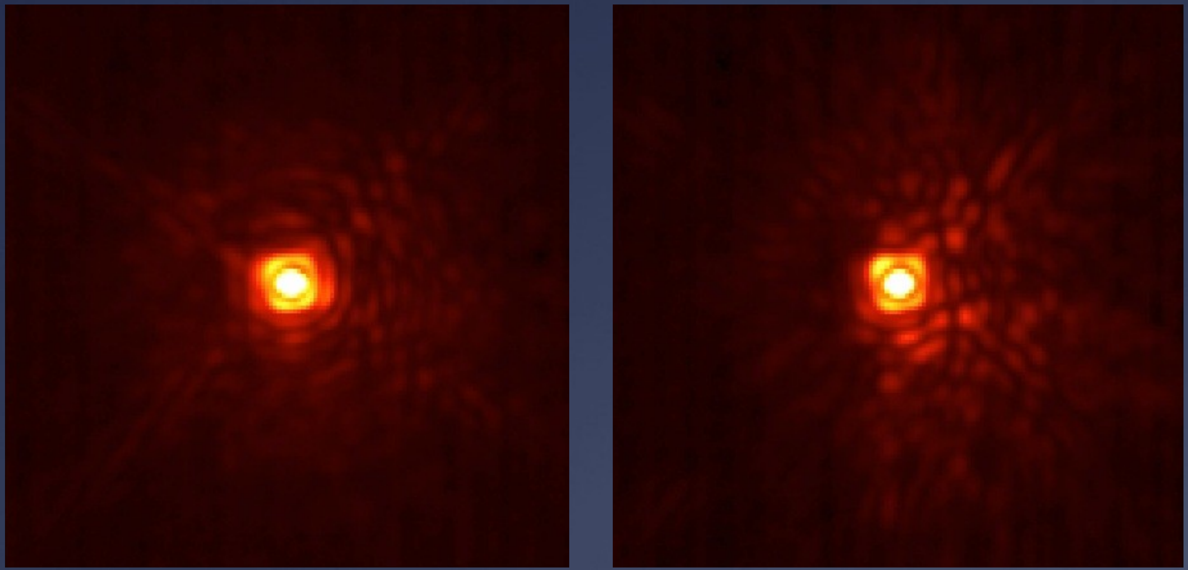
Single frames: 50 us



Meta data:

Date: 2nd or June
Target: RX Boo (also repeated on Vega)
Seeing: <0.6”
AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)
Coronagraph: None (used Vortex on Vega)





Sum of 5000 frames: shift and add

Martinache, F. et. al. On-sky speckle nulling with the Subaru coronagraphic extreme AO (SCExAO) instrument, paper no: 9148-70, Thursday, 4 pm, AO session

SAPHIRA Infrared APD array

HgCdTe avalanche photodiode
manufactured by Selex

Specifications
320 x 256 x 24µm
32 outputs
5 MHz/Pix