High contrast imaging from the ground with combined visible light extremeAO and nearIR speckle control

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(2) Univ. of Arizona
(3) UC Santa Barbara
(4) Observatoire de la Cote D'Azur
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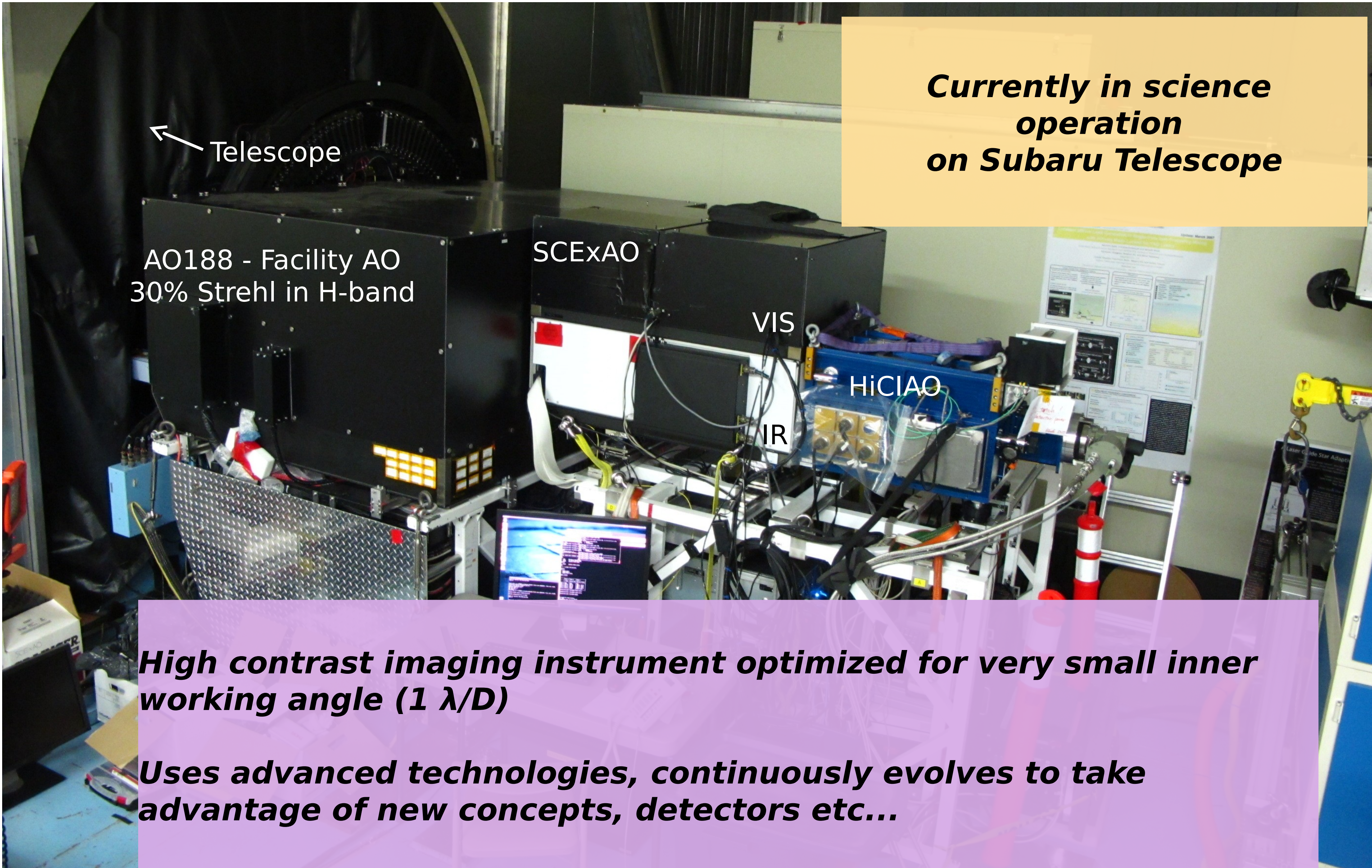
Subaru Coronagraphic Extreme AO (SCExAO)



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

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

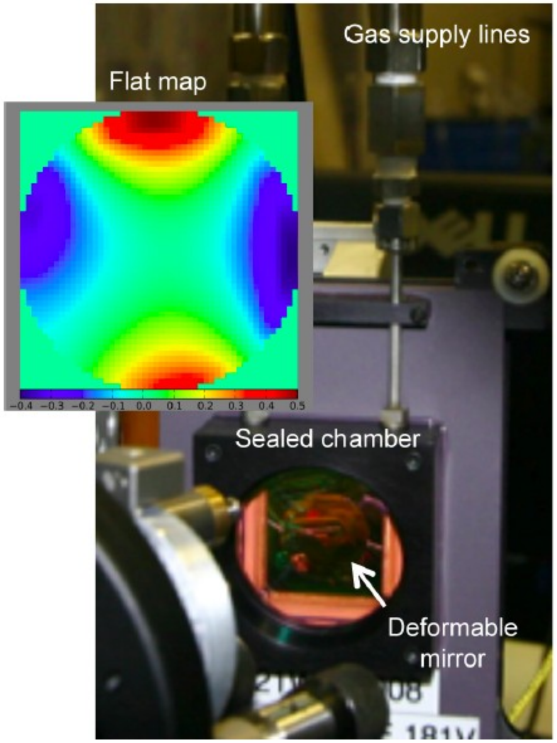
(3) Near-IR LOWFS

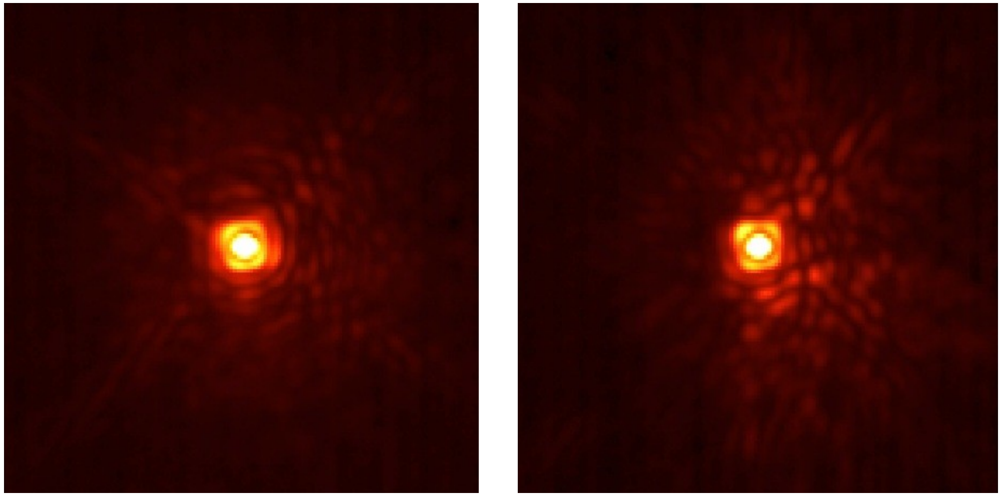
→ keeps star centered on coronagraph and controls Focus, Astig, etc..

→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control

→ modulates, removes and calibrates residual speckles





Speckle nulling on-sky

Wavefront sensing:

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

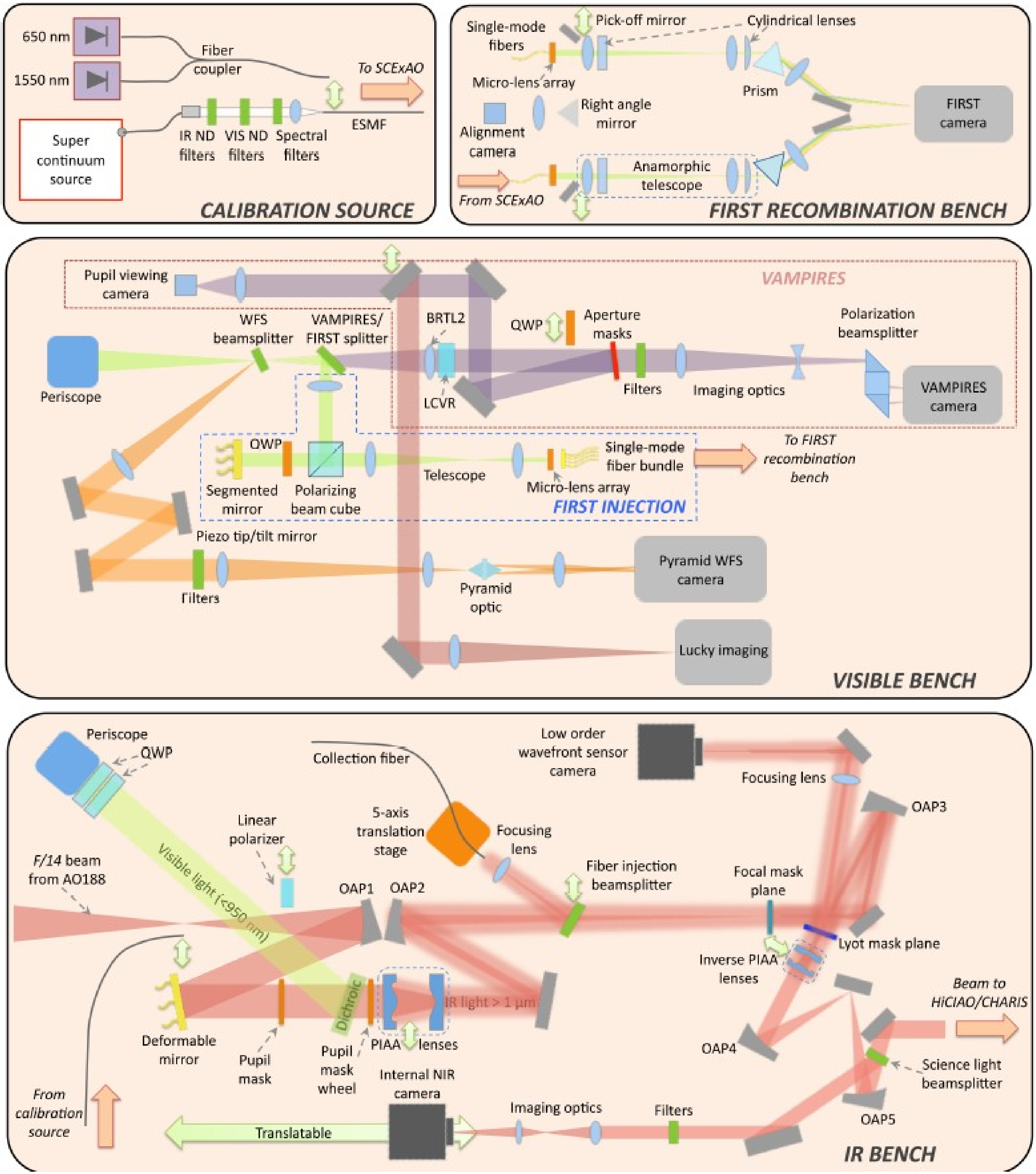
2k MEMS DM

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

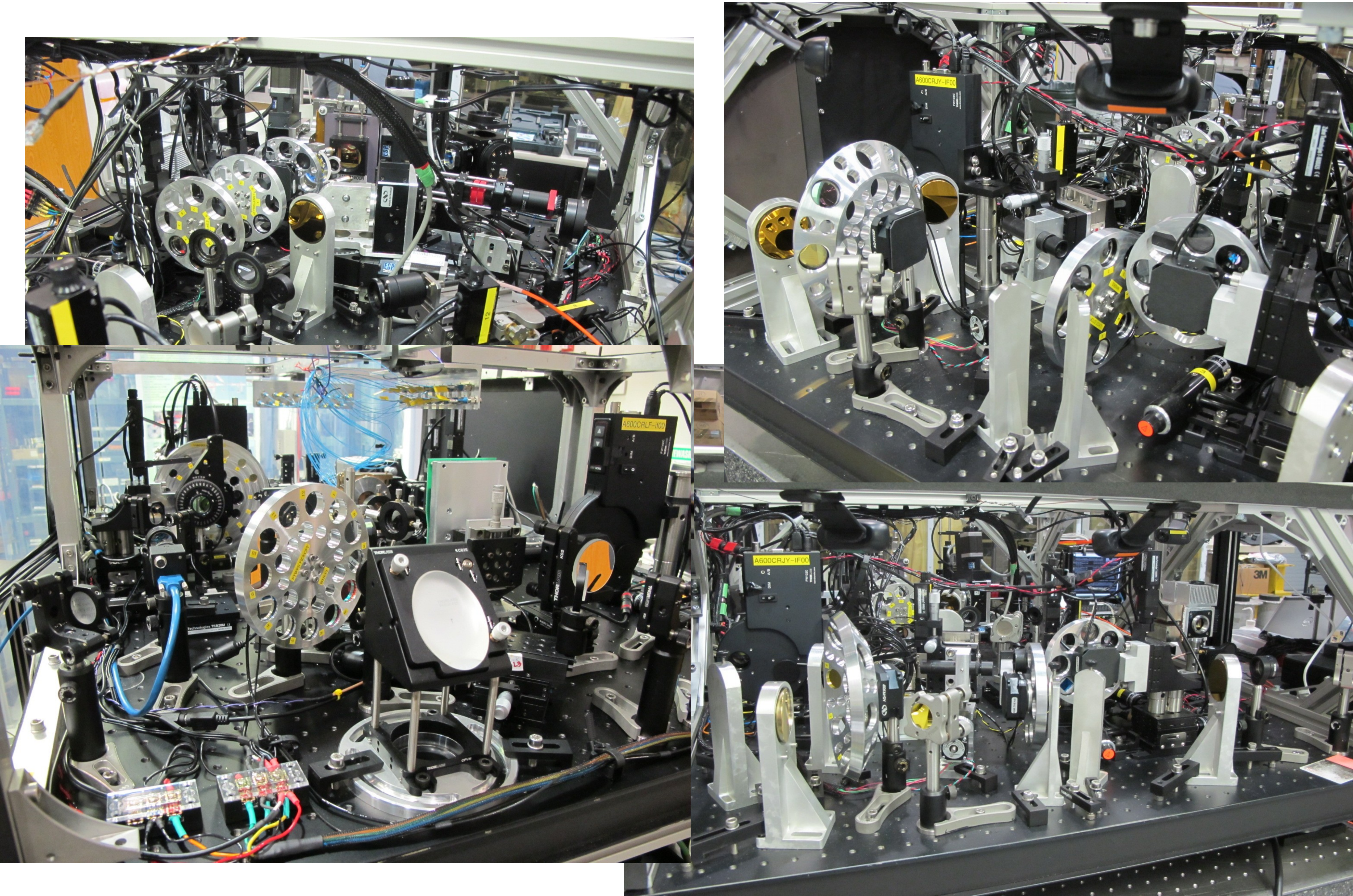
Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetory Signatures (VAMPIRES) (VIS)

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

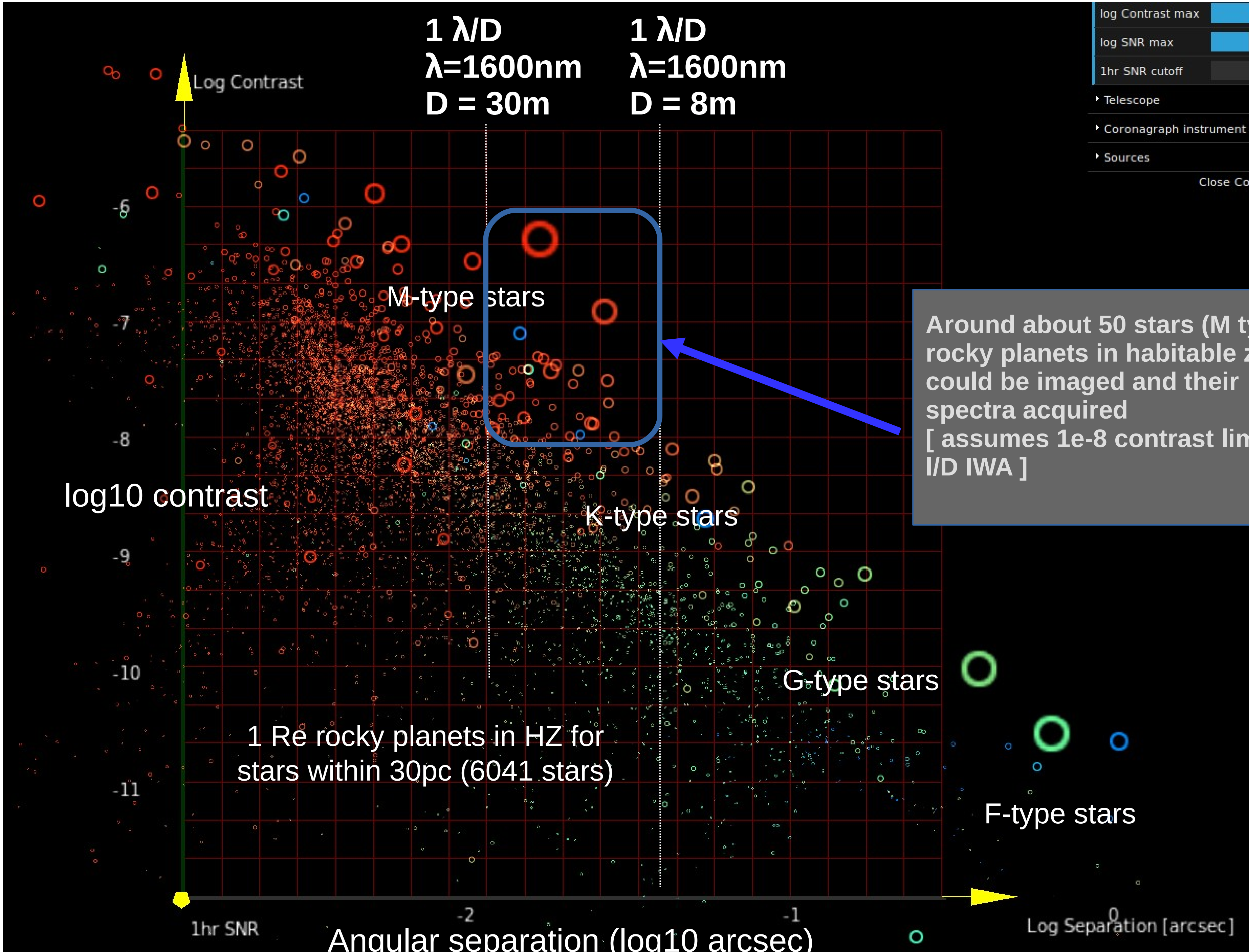
Broadband diffraction limited internal cal. Source + phase turbulence simulator



SCExAO hardware

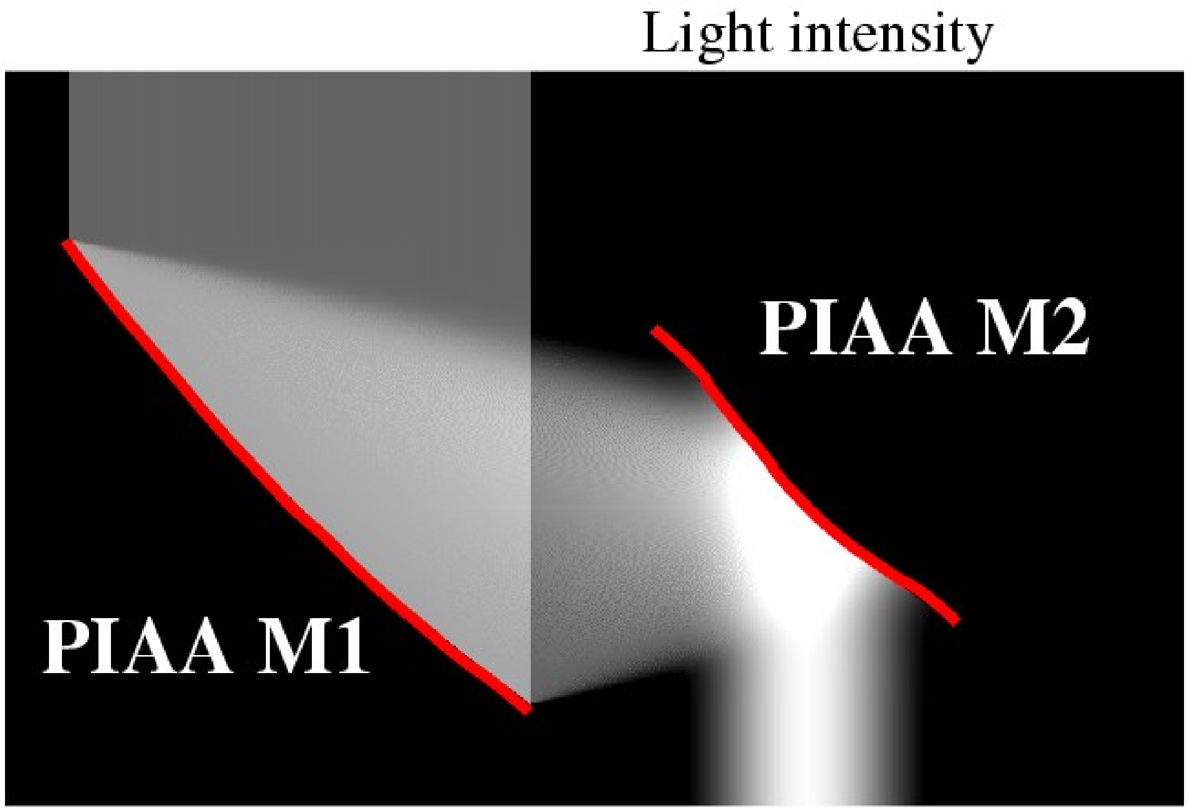


Most exciting science case: spectroscopic characterization of Earth-sized planets with TMT



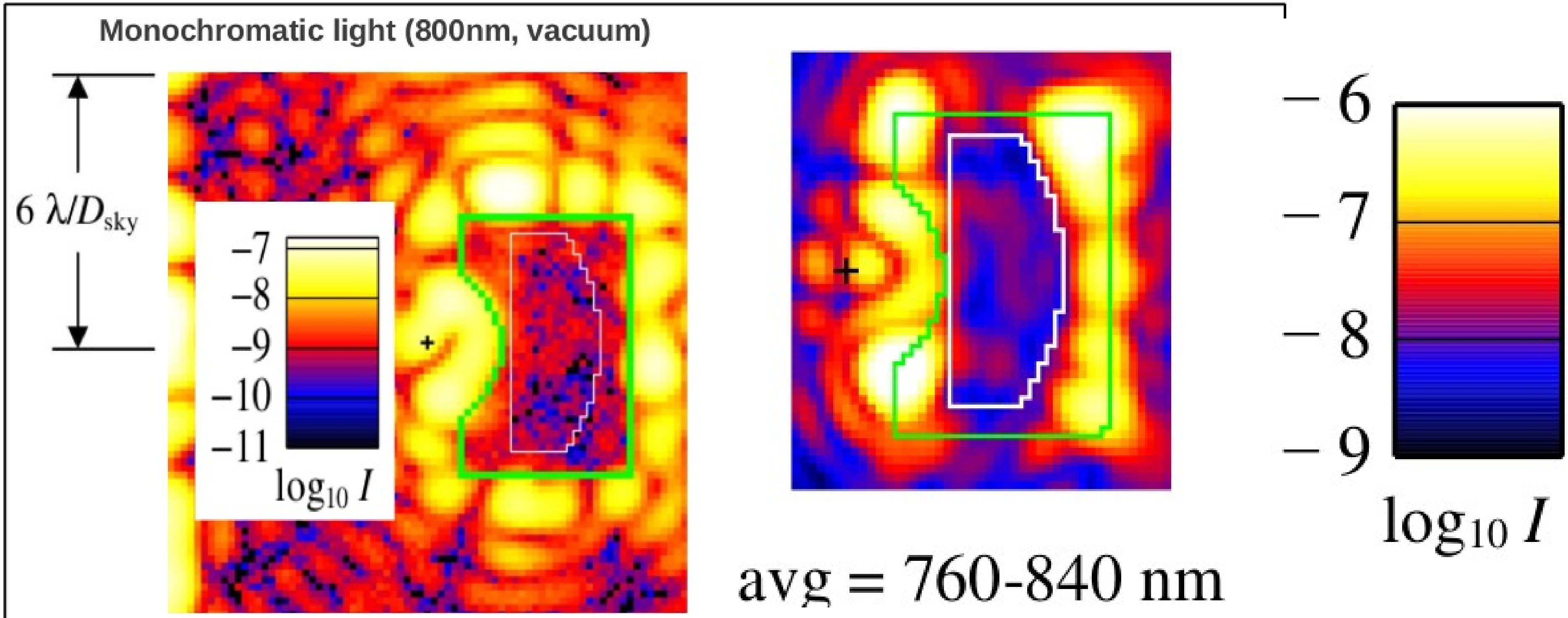
Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

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

(largely) lossless apodization

Creates a PSF with weak Airy rings

Focal plane mask: -1<t<0

Induces destructive interference inside downstream pupil

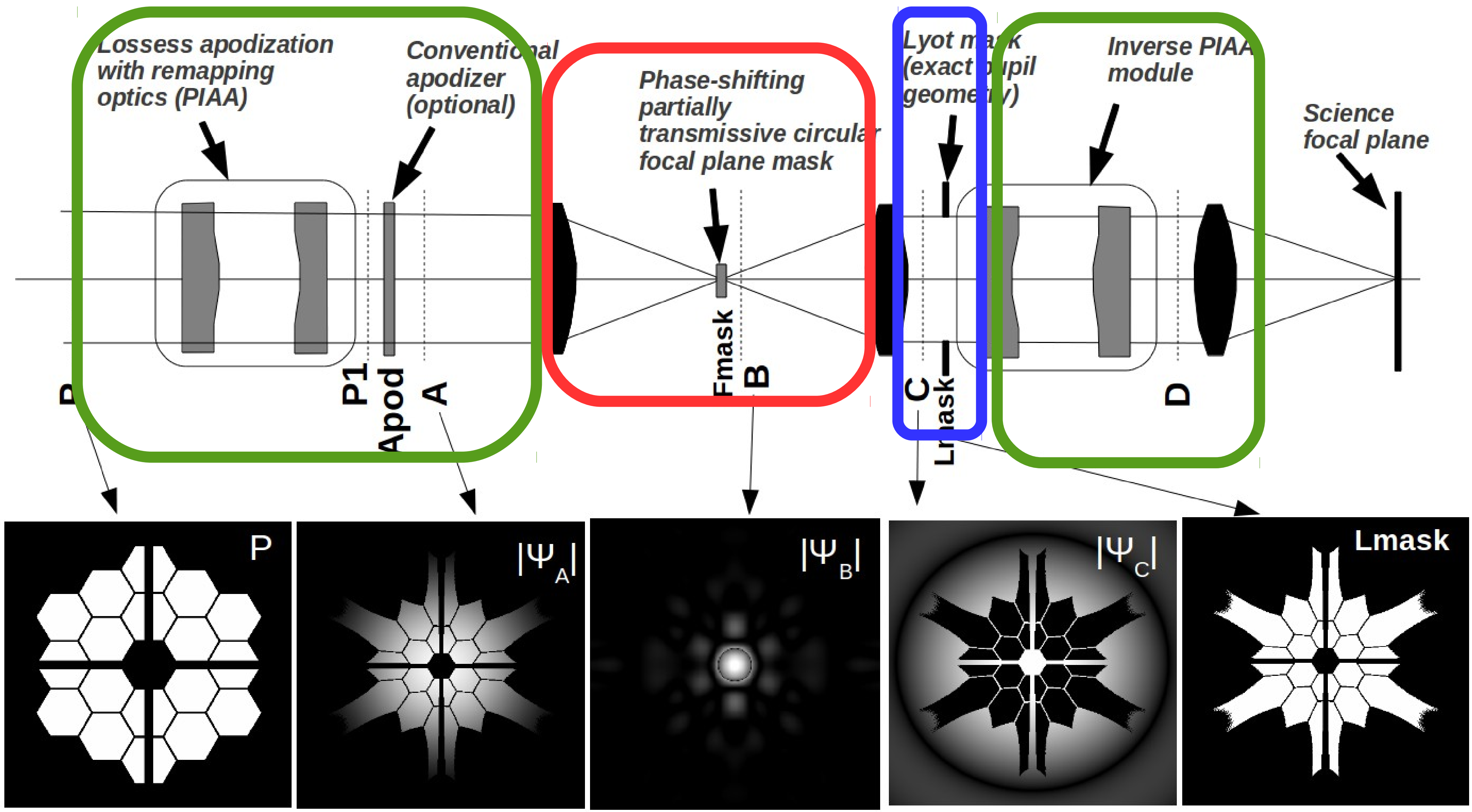
Lyot stop

Blocks starlight

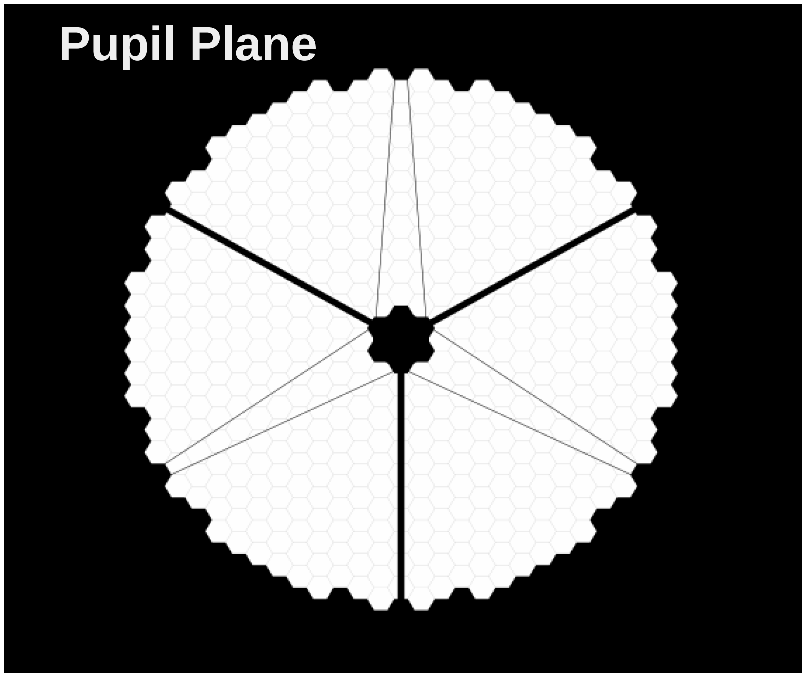
Inverse PIAA (optional)

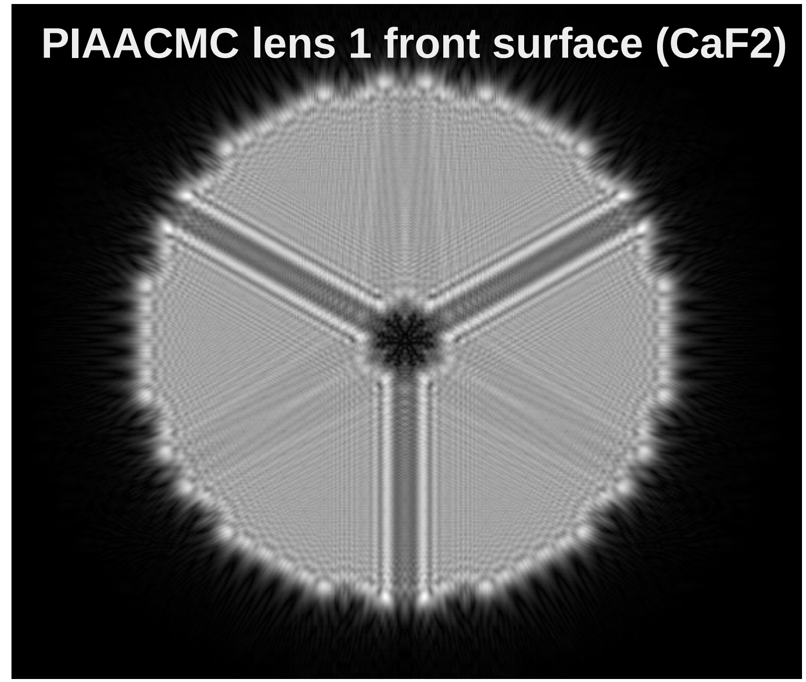
Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

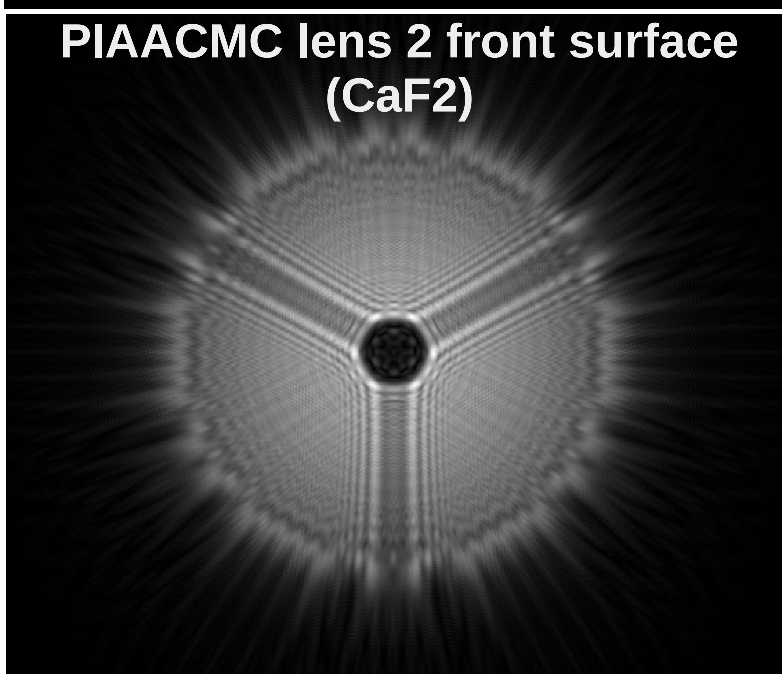


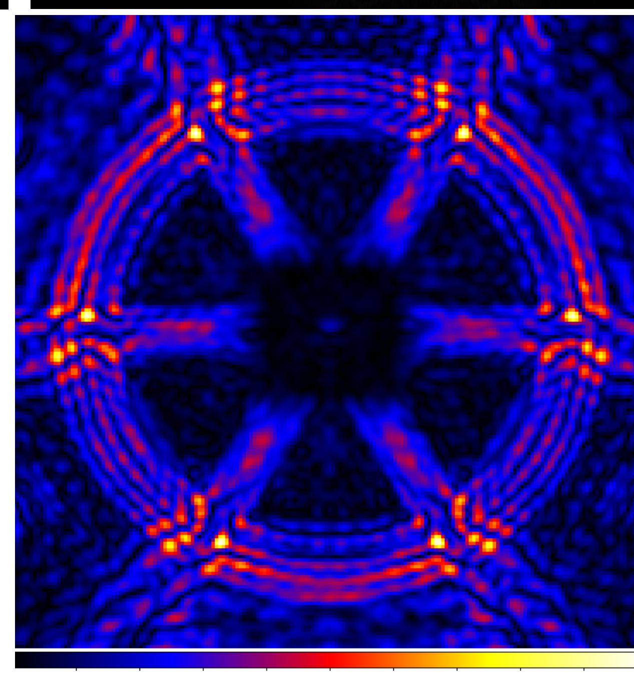
TMT coronagraph design for 1 l/D IWA





To be updated with new pupil shape





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

Focal plane mask designed for broadband operation AND stellar angular size

Mask has ~500 zones, each a different thickness

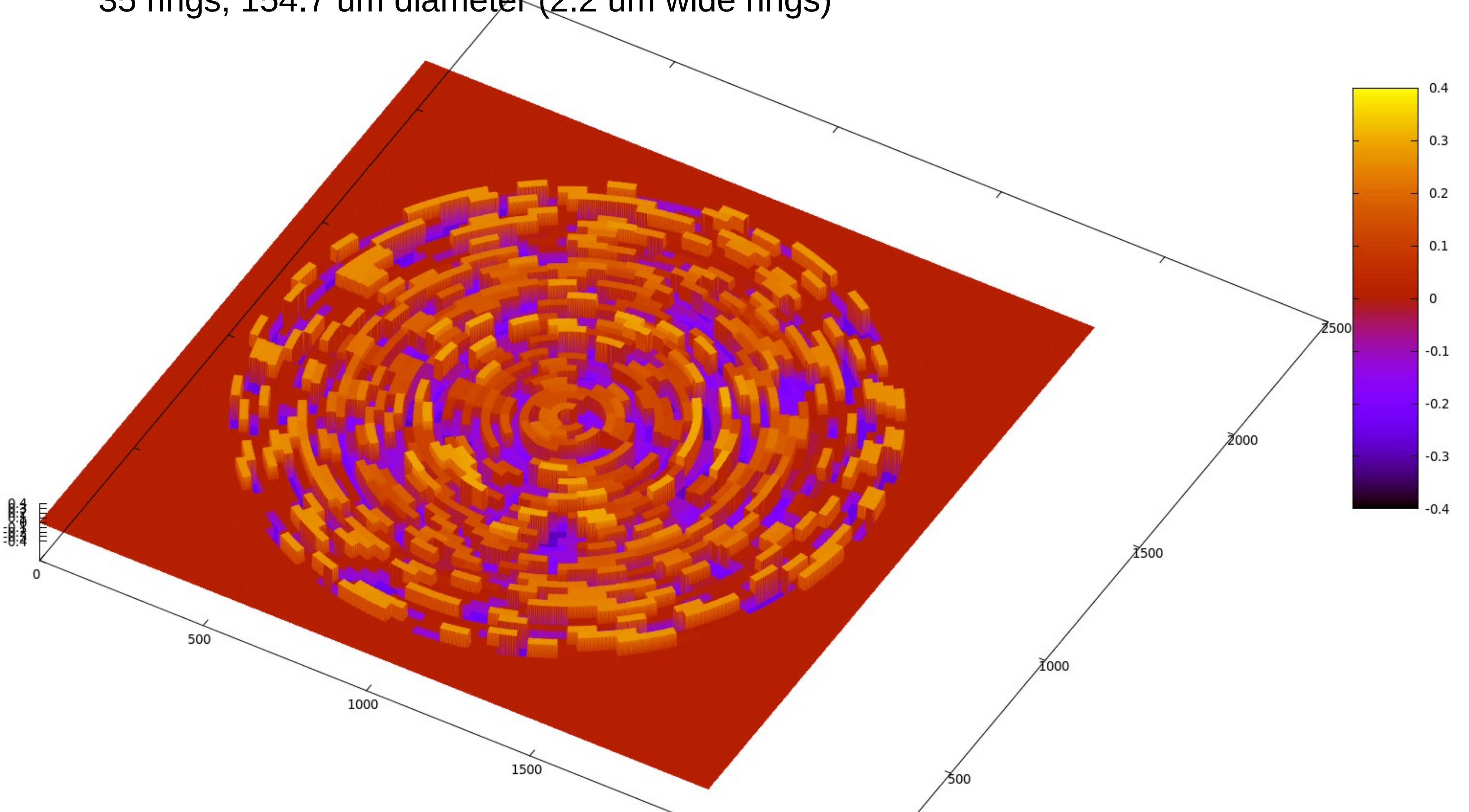
Computer optimization of the zones thicknesses to simultaneously:

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

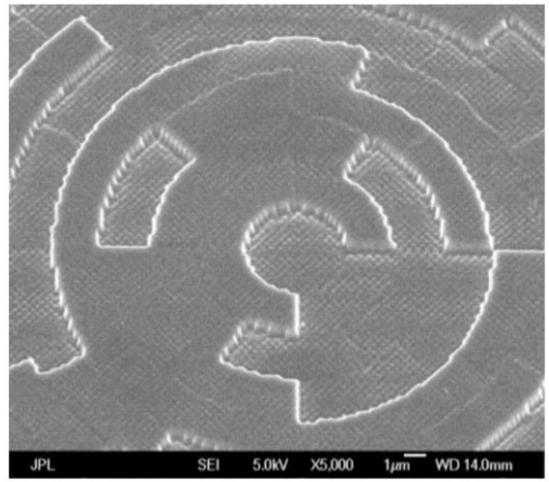
With 500 zones, 1e-7 raw contrast achievable with IWA = 1.2 l/D over 20% band

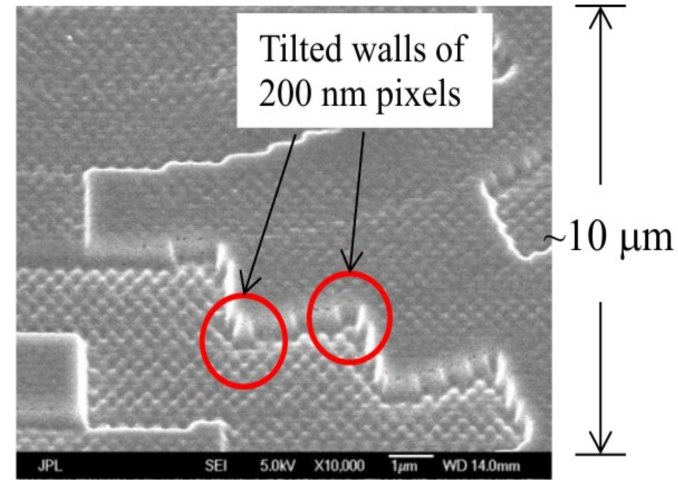
Focal plane mask (vertical scale amplified) for 1e-9 raw contrast, 1.3 l/D IWA (WFIRST visible light mask)

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

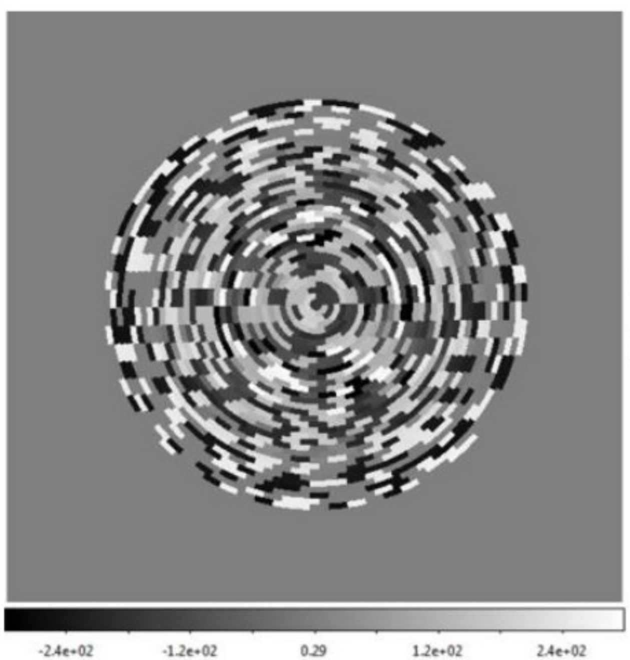


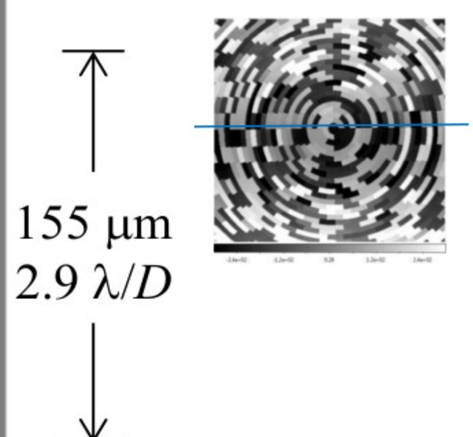
Mask characterization → OK to 1e-7 raw contrast at 550nm at 2 l/D (Kern et al. 2015)

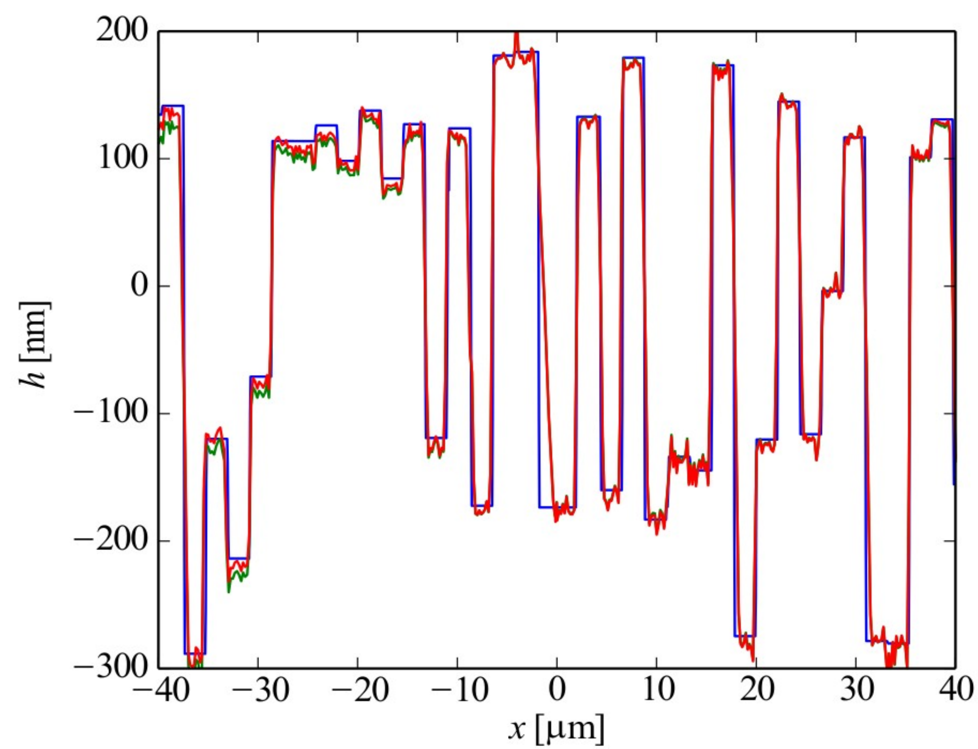




Design



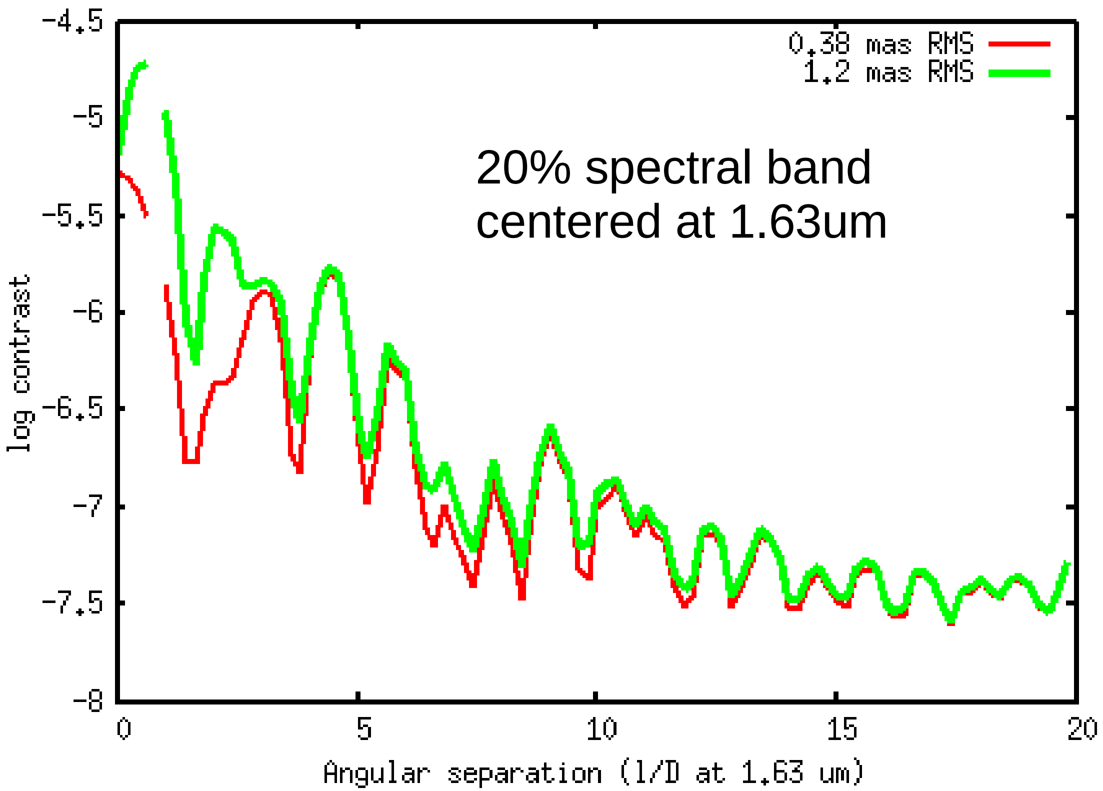




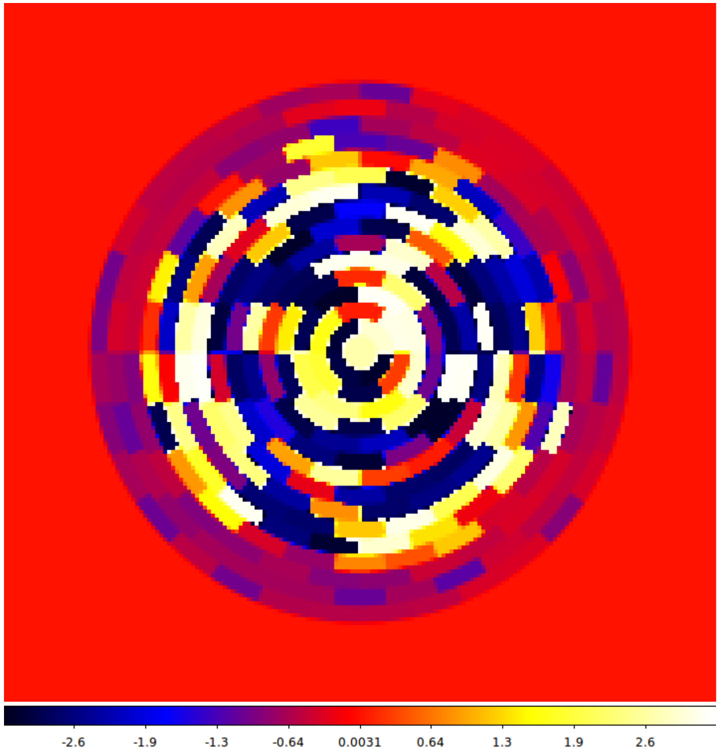
PIAACMC for SCExAO

CaF2 transmissive PIAA lenses
SiO2 transmissive focal plane mask
Design takes into account material dispersion for broadband optimization

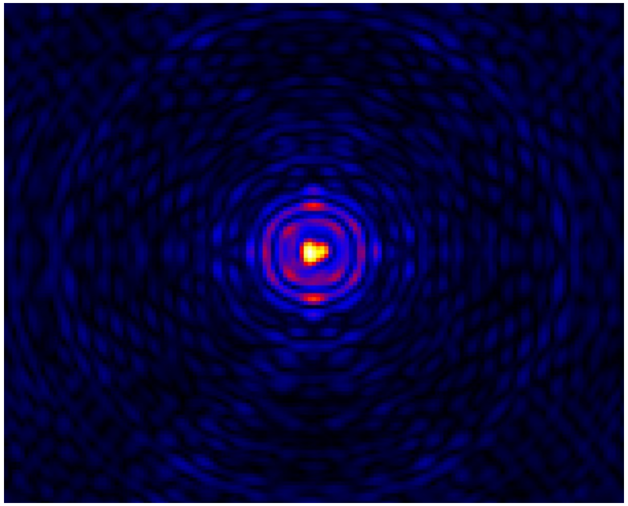
~1.1 l/D IWA
70% throughput
Raw contrast ~1e-6 (see curves below) in 20% wide band with 1mas RMS jitter



focal plane mask
SiO2 zones computer-optimized



PSF for 1.2mas RMS jitter (green curve on left)



WFC contrast limits

Assumptions:

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

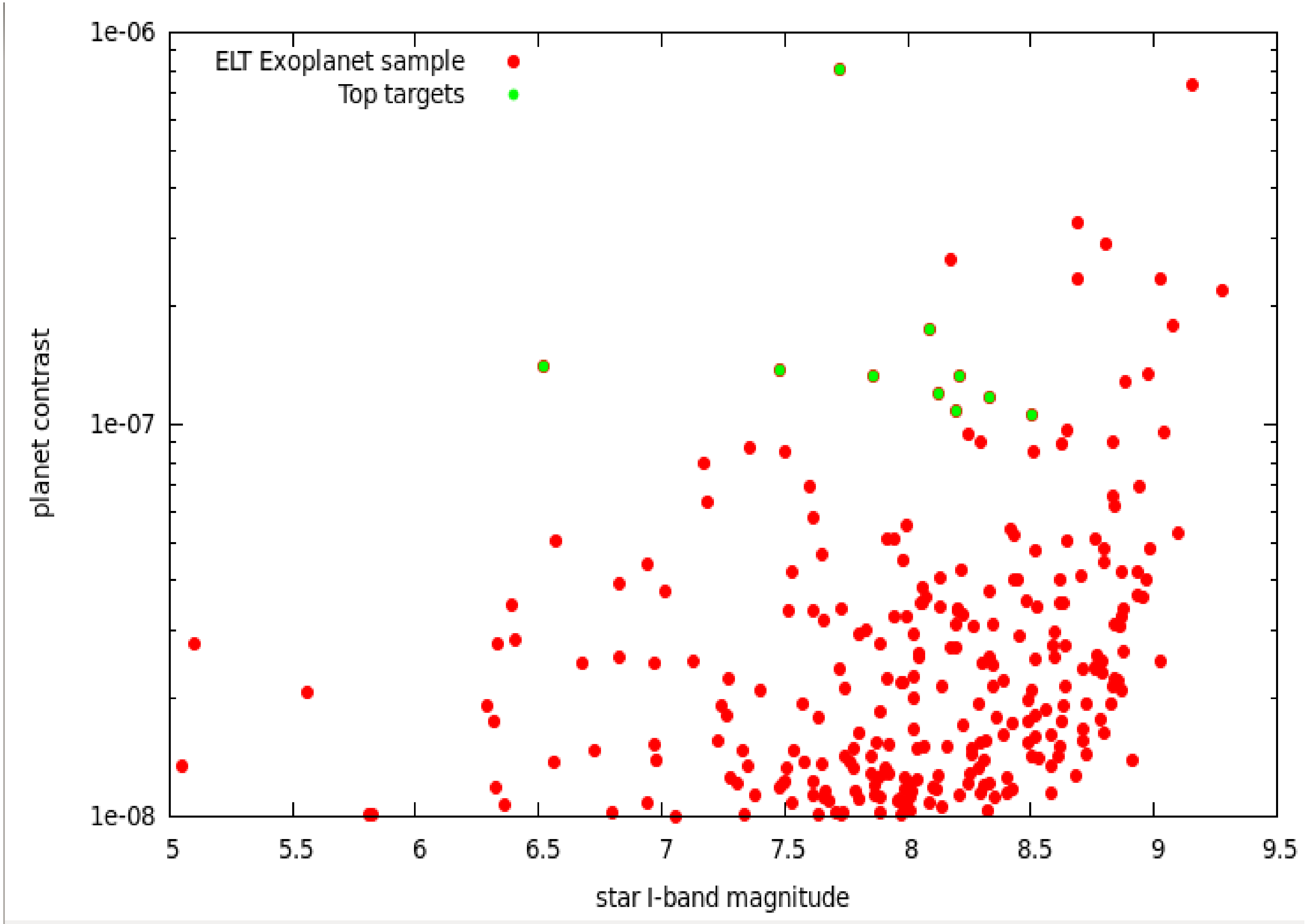
Noiseless detector
1.3 l/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

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

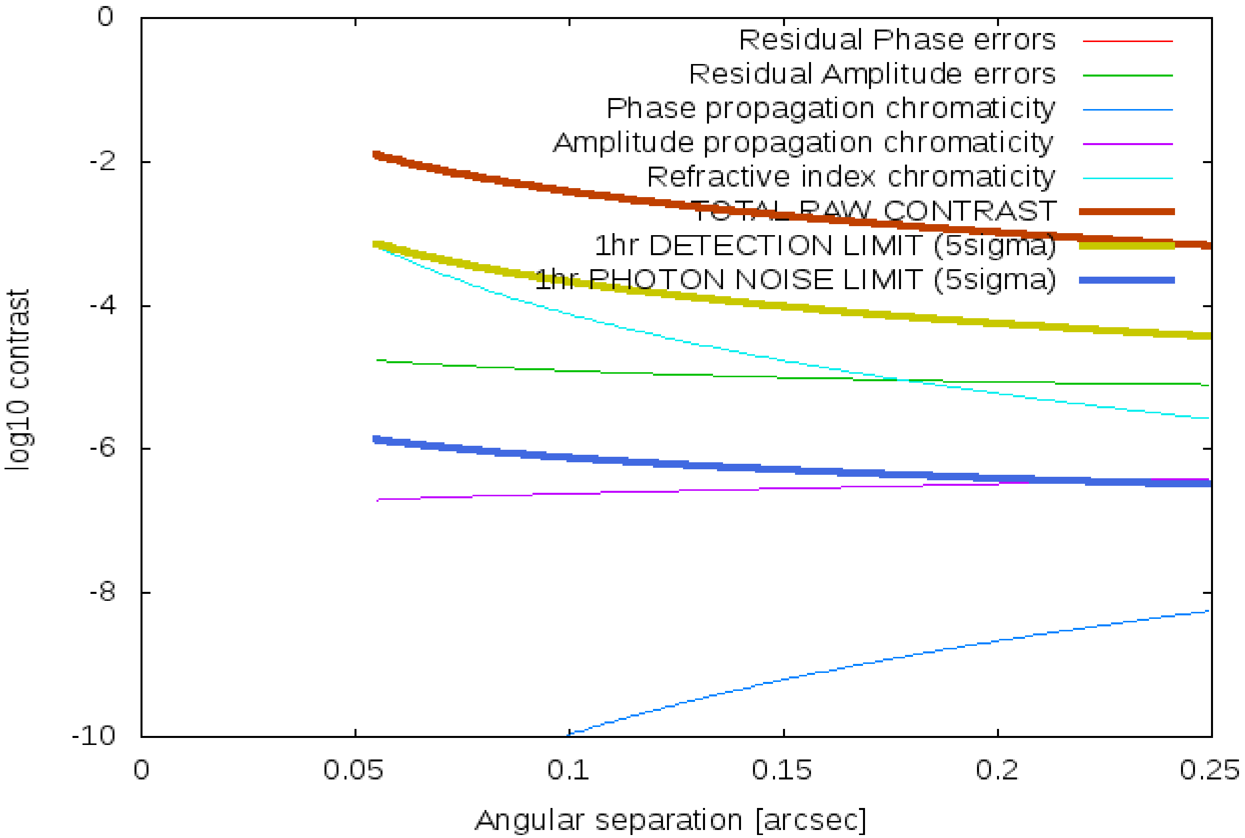
(assumes Earth albedo, contrast and separation for max elongation)

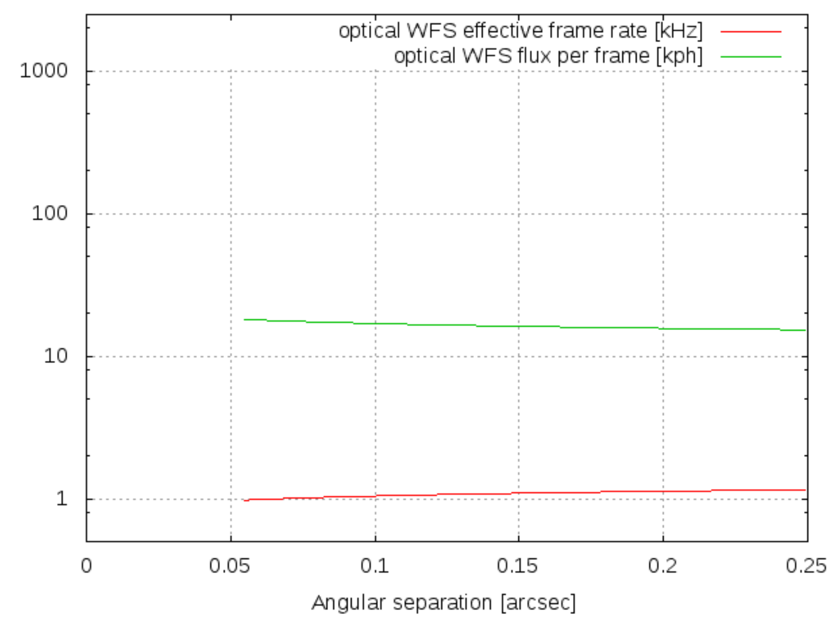
MOST FAVORABLE TARGETS

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

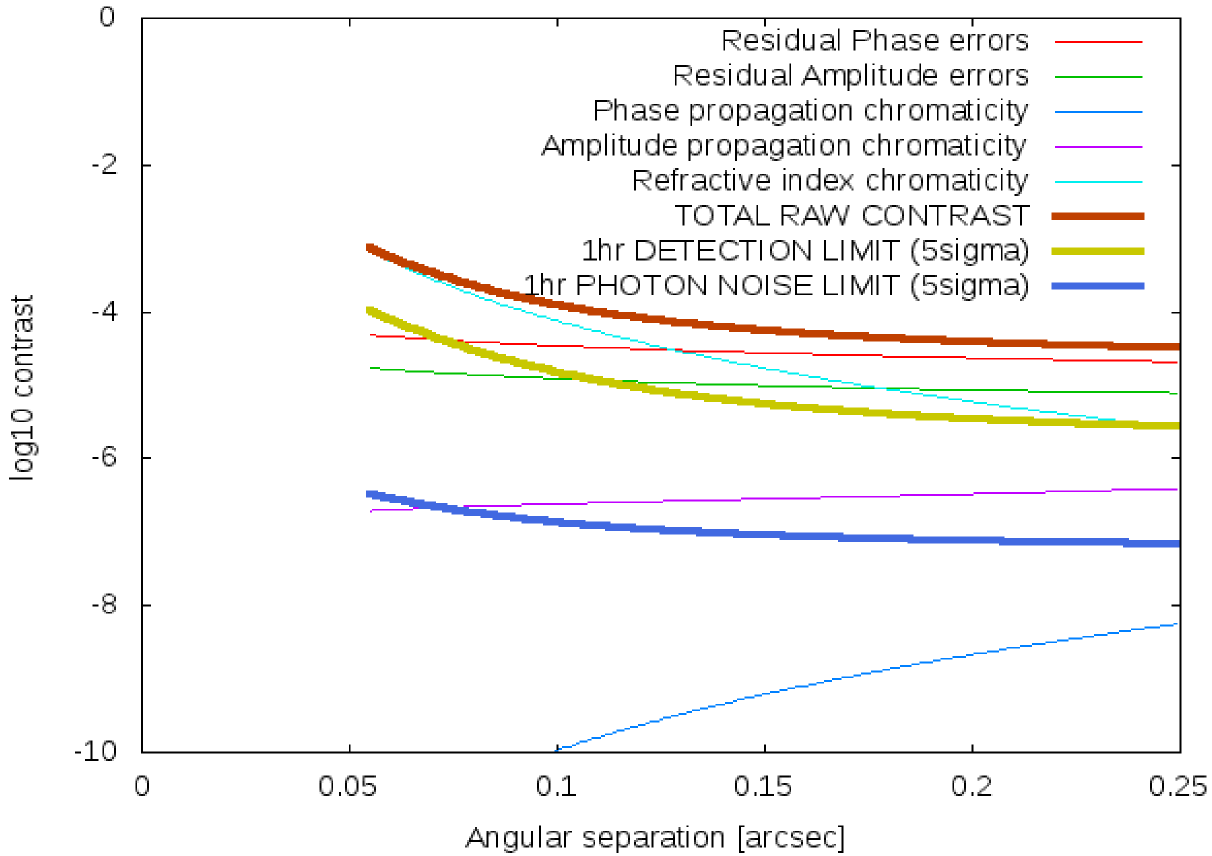


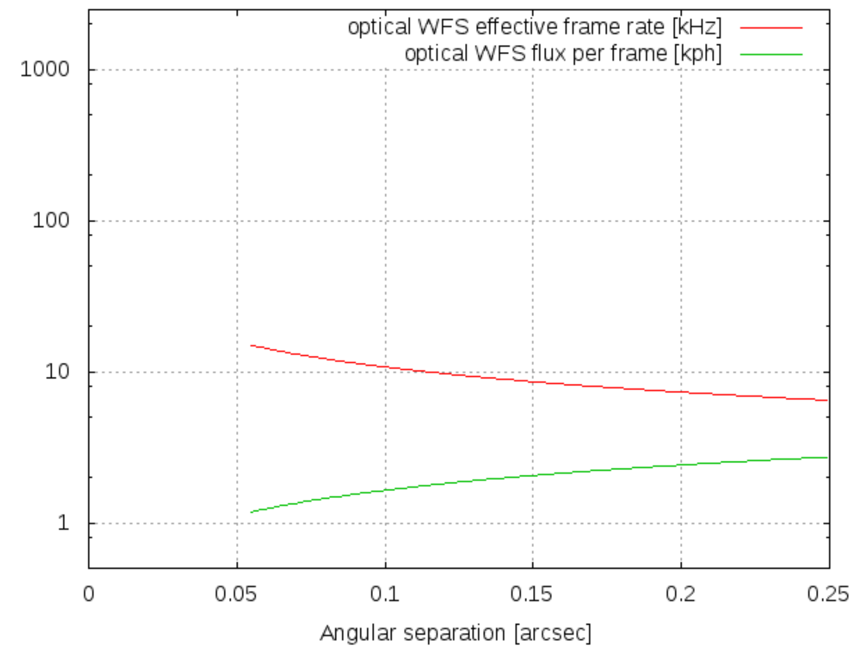


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster)
>10kph per WFS required

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

8m: Pyramid-based system → ~20x gain

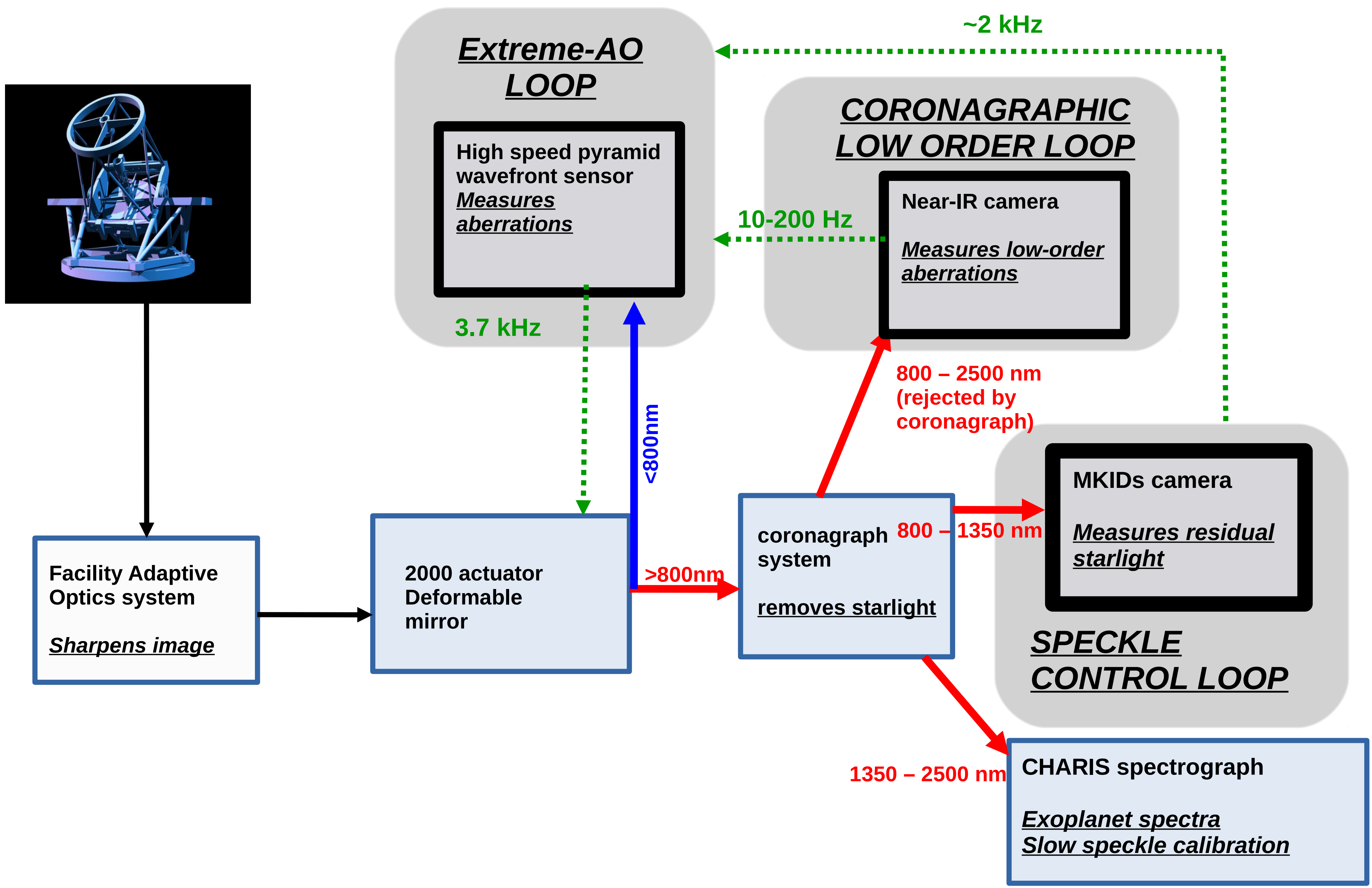




More sensitive WFS, can run faster (10kHz) with few kph per WFS frame
Note: can run slower with predictive control
Limited by atmosphere chromaticity

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

SCExAO: wavefront control loop



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

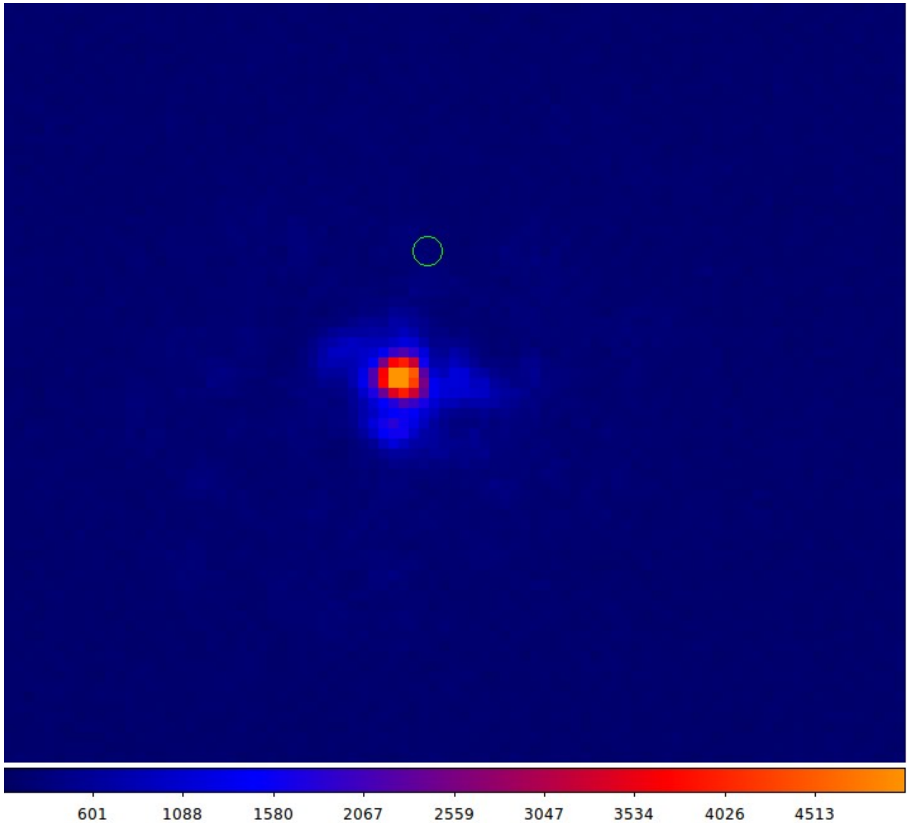


Image (left):
Single image of a diffraction limited PSF at 775 nm

PyWFS works at diffraction-limited sensitivity
... down to I mag ~ 10

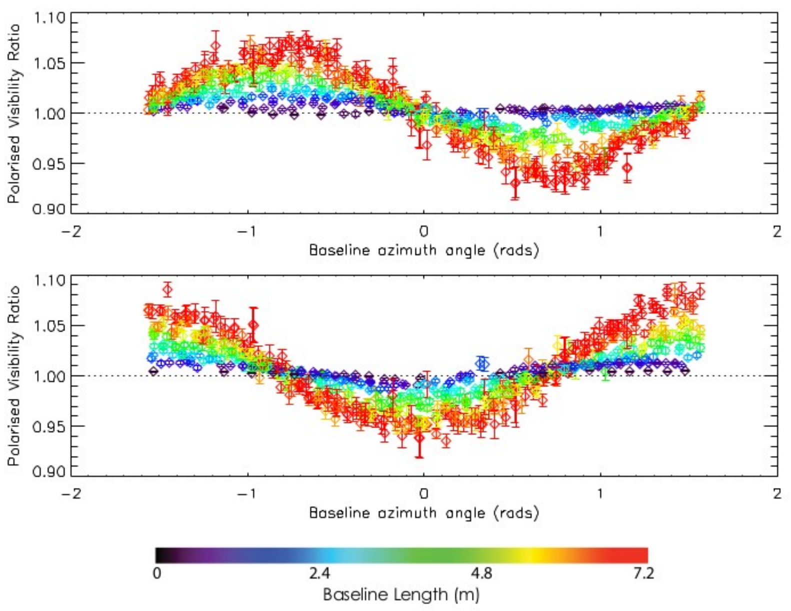
14,400 WFS elements (pixels) → 2000 actuators

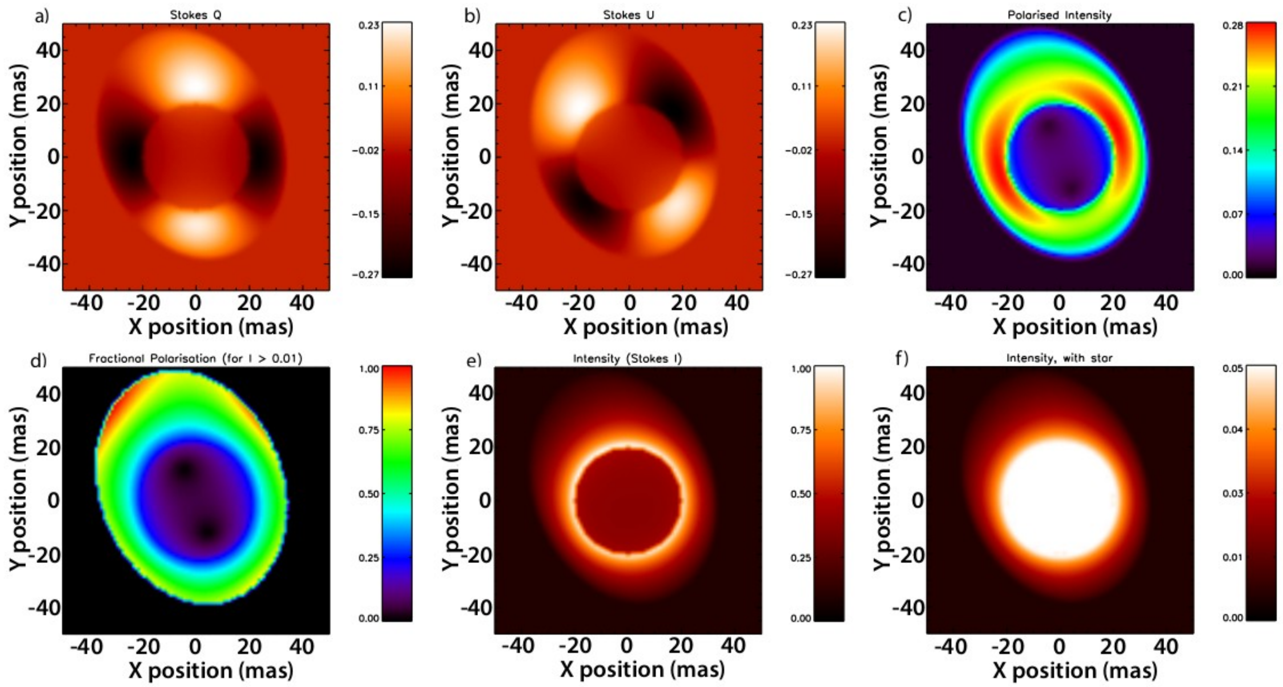
We use 14,400 GPU computing cores to run CM multiplication in 120us
(www.github.com/oguyon/AOloopControl)

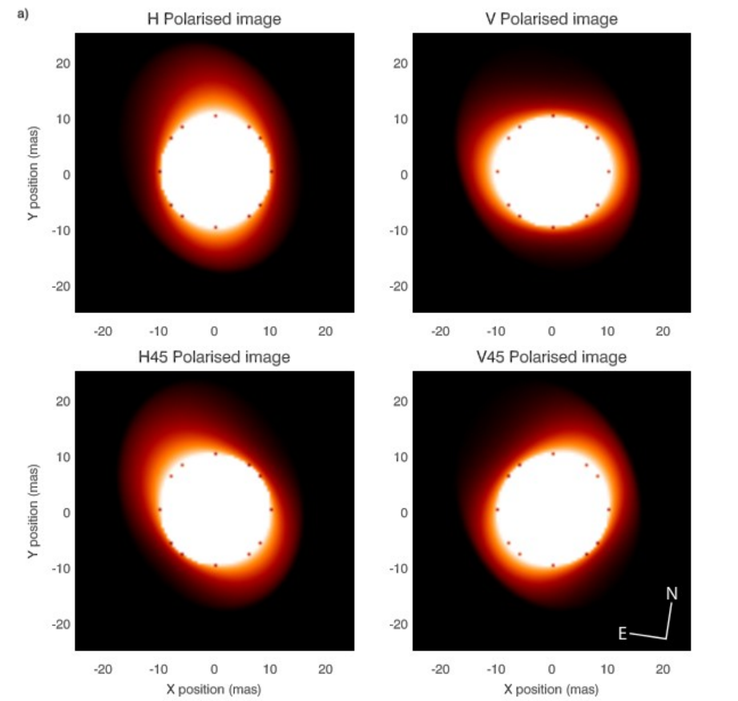
Current VAMPIRES capabilities - Sample commissioning data Sept 2014

Asymmetric dust plume emanating from the red supergiant μ Cephei imaged in scattered light

- Distinctive signature of circumstellar dust clearly visible in polarised differential visibilities **(right)**.
- Model fitting reveals dust plume originating at the photosphere, extended along the north-east axis **(below)**.
- Inner dust shell radius measured to be 9.3 ± 0.2 milliarcseconds
- Multi-wavelength observations will constrain dust grain size distribution and species







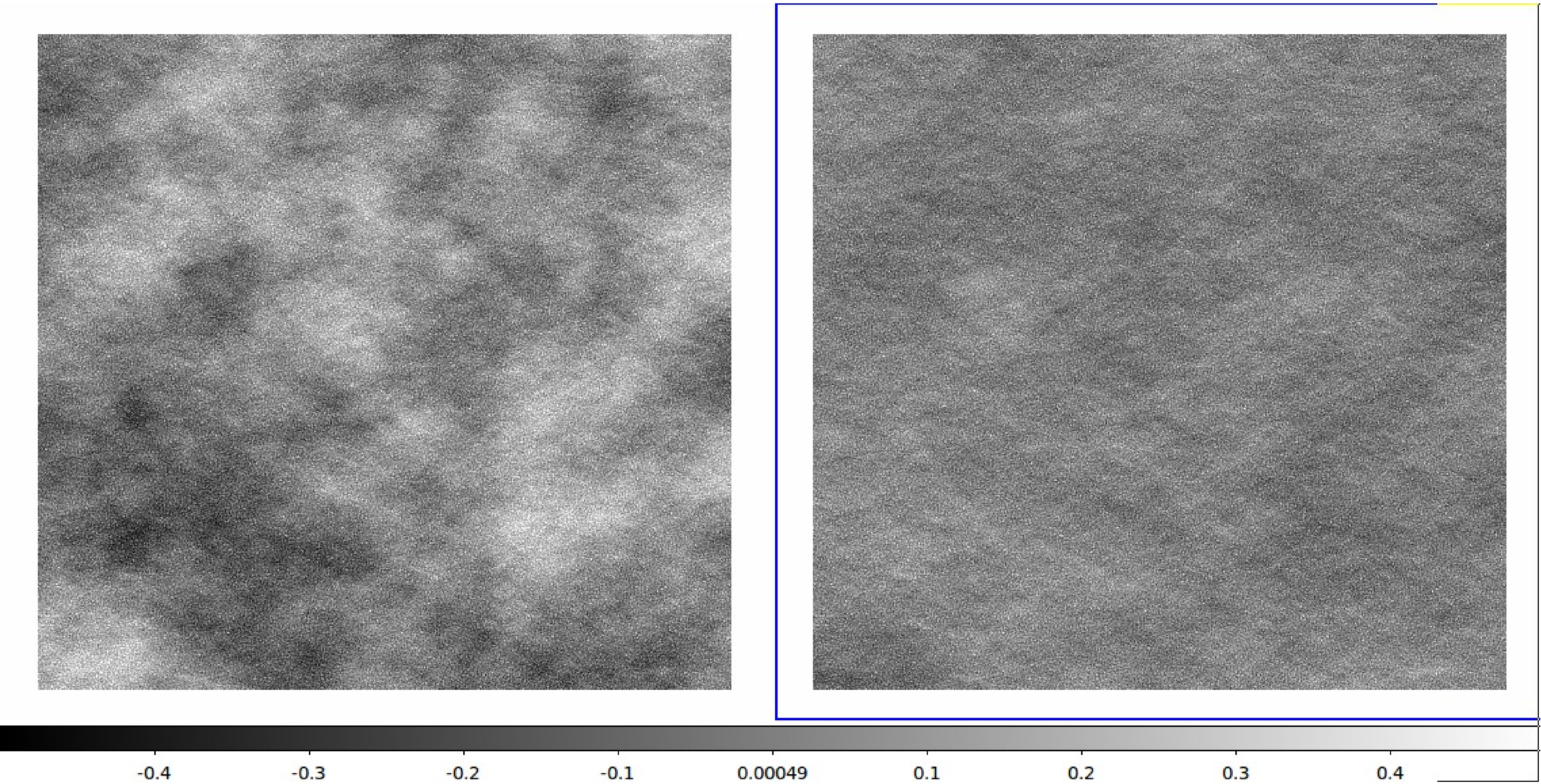
Wavefront chromaticity

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



LOWFS in near-IR → mas TT control

Singh, Lozi, Guyon et al. 2015

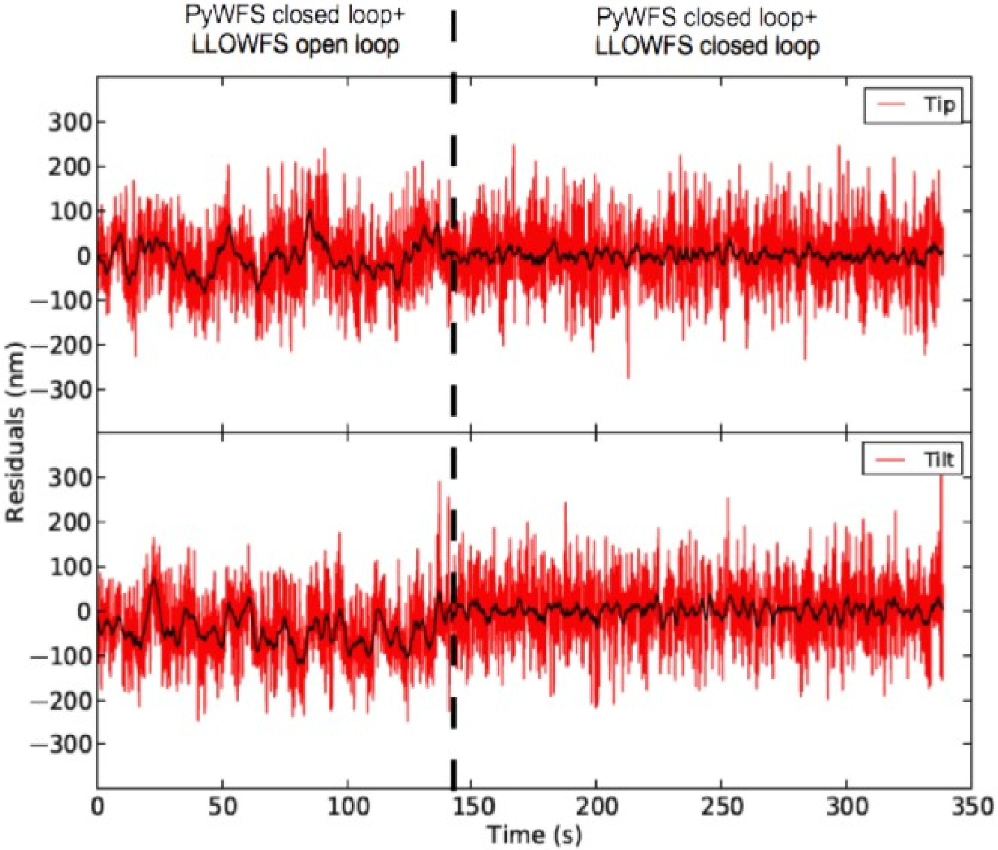


FIG. 14.— On-sky open- and closed-loop residuals of low-order control integrated in the high-order corrections of post-AO188 wavefront residuals. The black data is the moving average of residuals with 2 second window while the red data are the raw residuals. When the low-order loop is open then the high-order loop is correcting the pointing errors only in visible leaving chromatic errors uncorrected. These chromatic errors are significantly reduced when the loop is also closed using LLOWFS. Table 3 summarizes low-order residuals for the differential tip-tilt. (Science target: χ Cyg.)

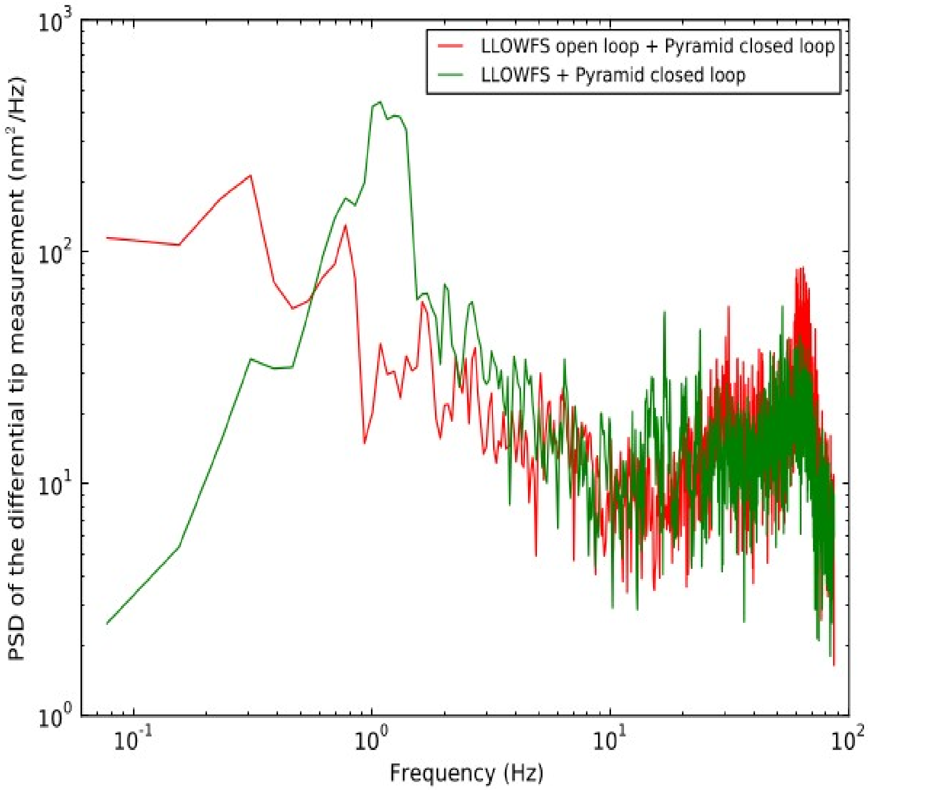
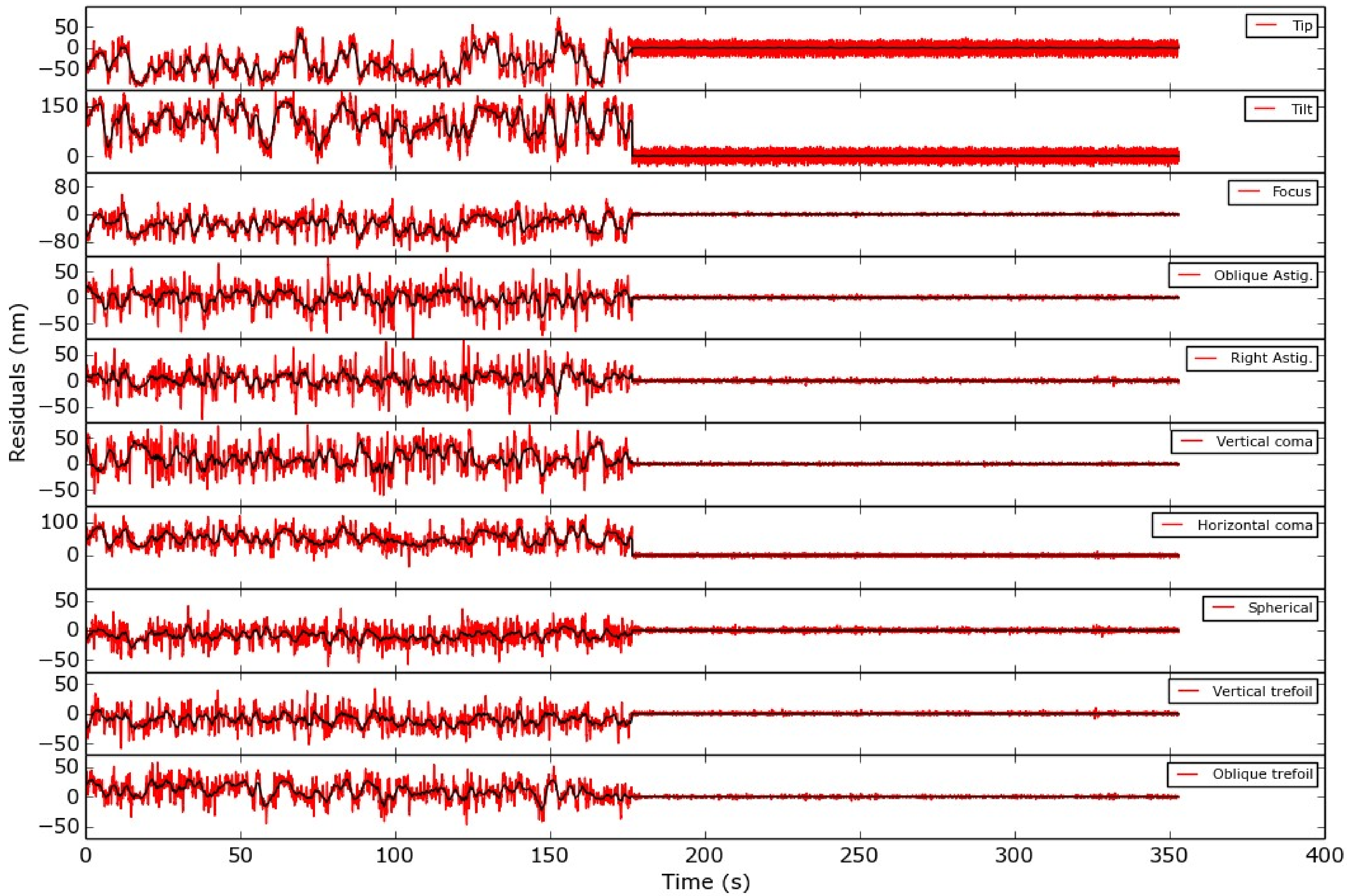


FIG. 15.— On-sky open- and closed-loop PSD of the differential tip aberration in case of PyWFS integration with LLOWFS. Closing the loop with PyWFS appears to reduce the telescope vibrations at 5 and 6 Hz noticed in Fig. 11. The low-order correction provides significant improvement at frequencies <0.5 Hz and an overshoot around 1 Hz because of the difference in the sensing (170 Hz) and the correction (5 Hz) frequency.

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



Ref: Singh et al. 2015 (in prep)

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

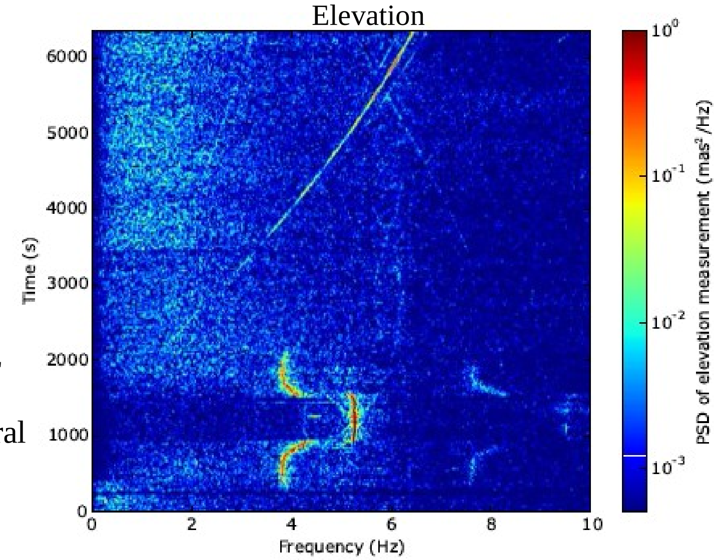
Vibrations evolves from: 0 to 6.4 Hz and 0 – 3.4 HZ

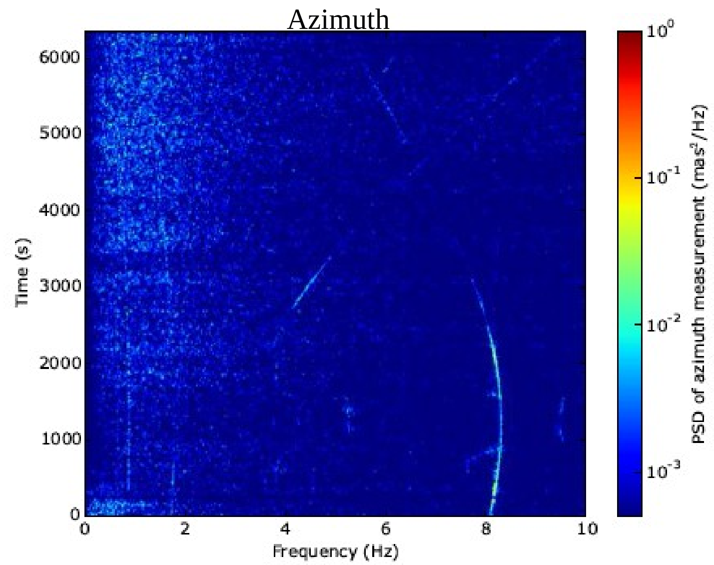
[Vibrations in Azimuth]

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)

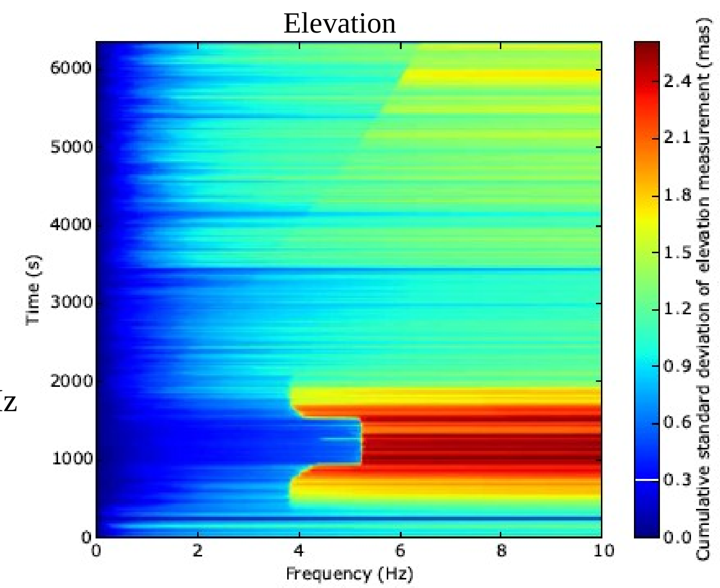
Evolution of the PSD with time

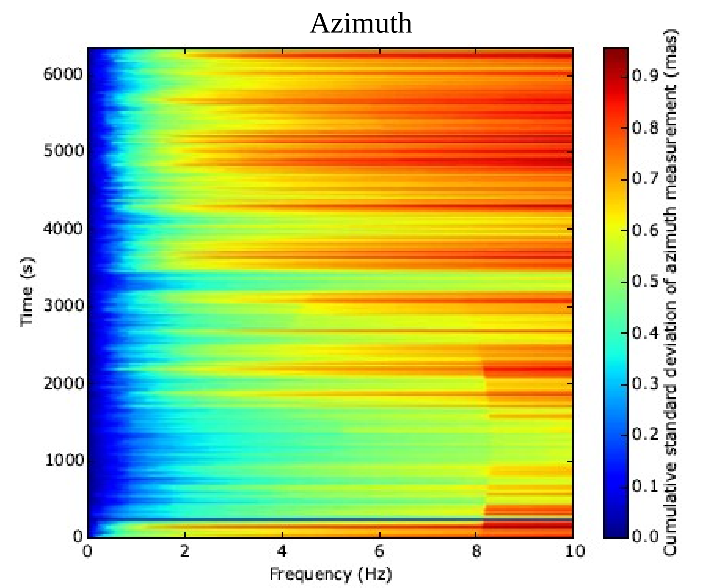




Square root of the Cumulative sum of the PSD

(Cumulative standard deviation of the residuals)





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

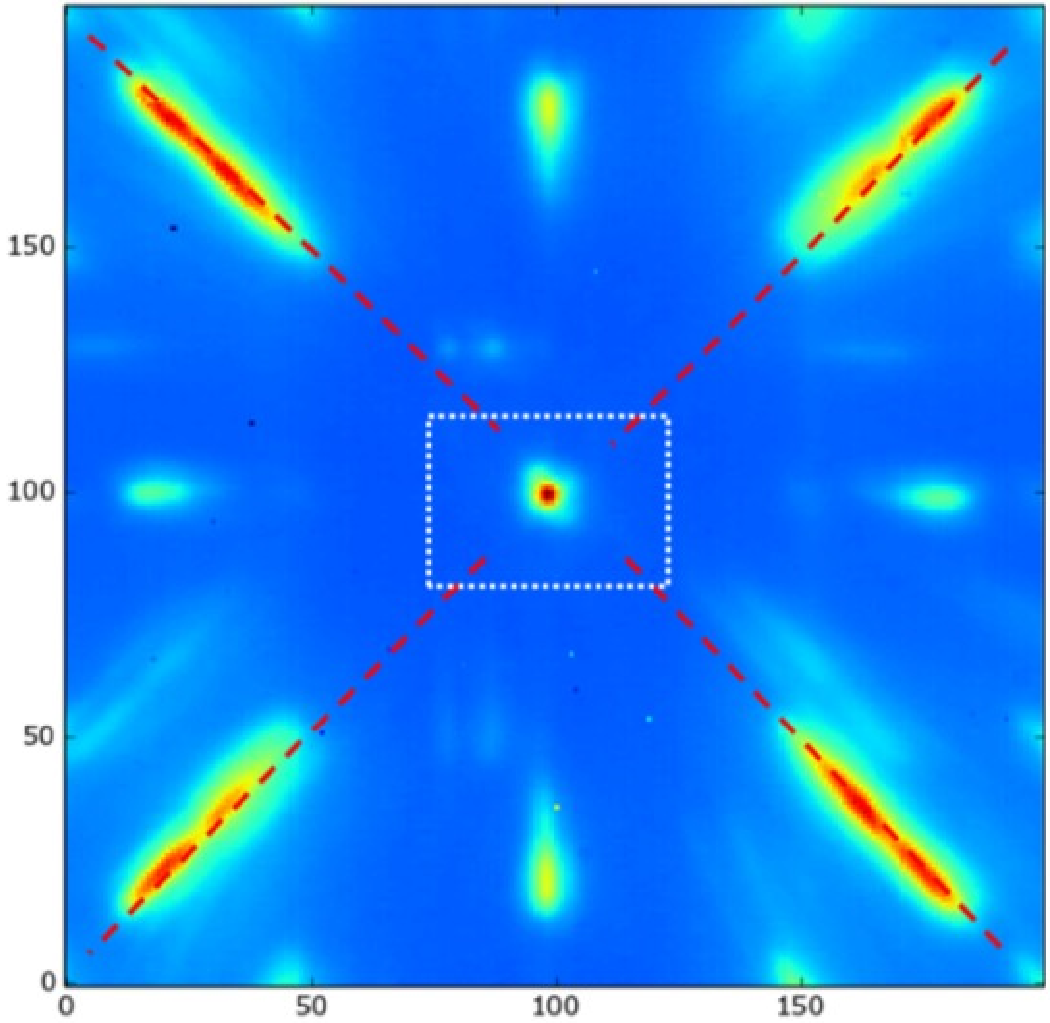


Figure 2: Speckles at 59^0 Elevation

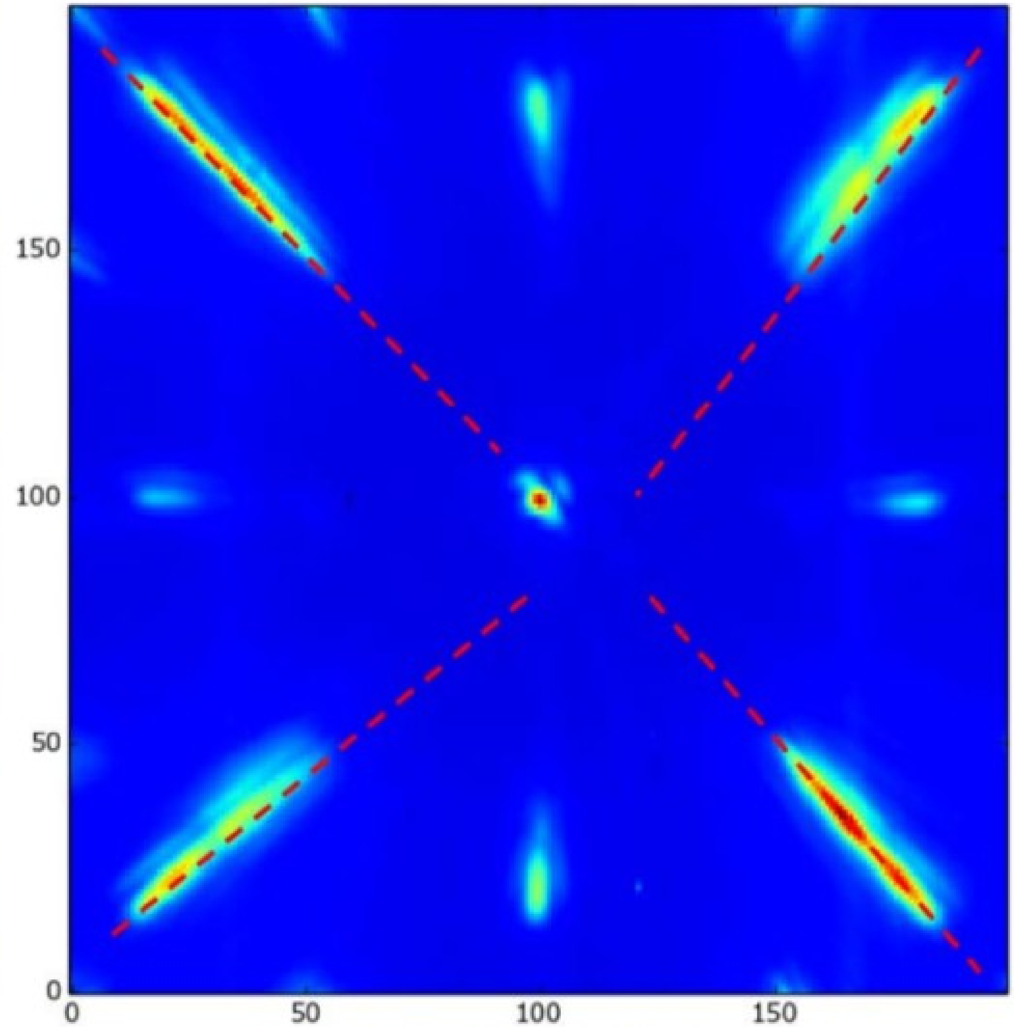


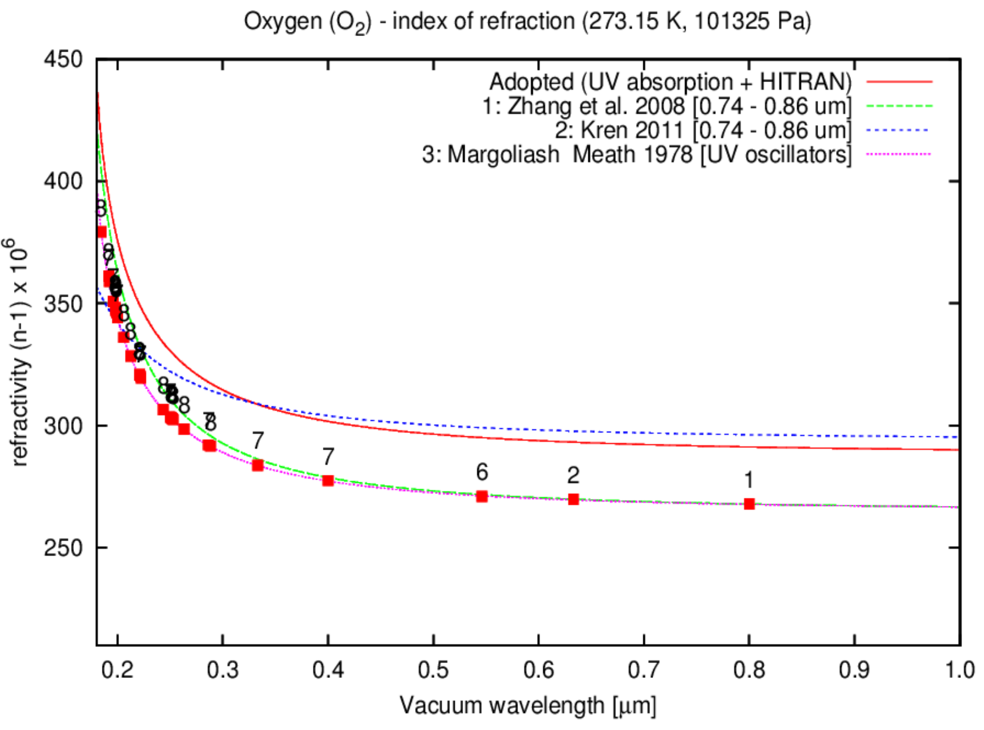
Figure 3: Speckles at 40^0 Elevation

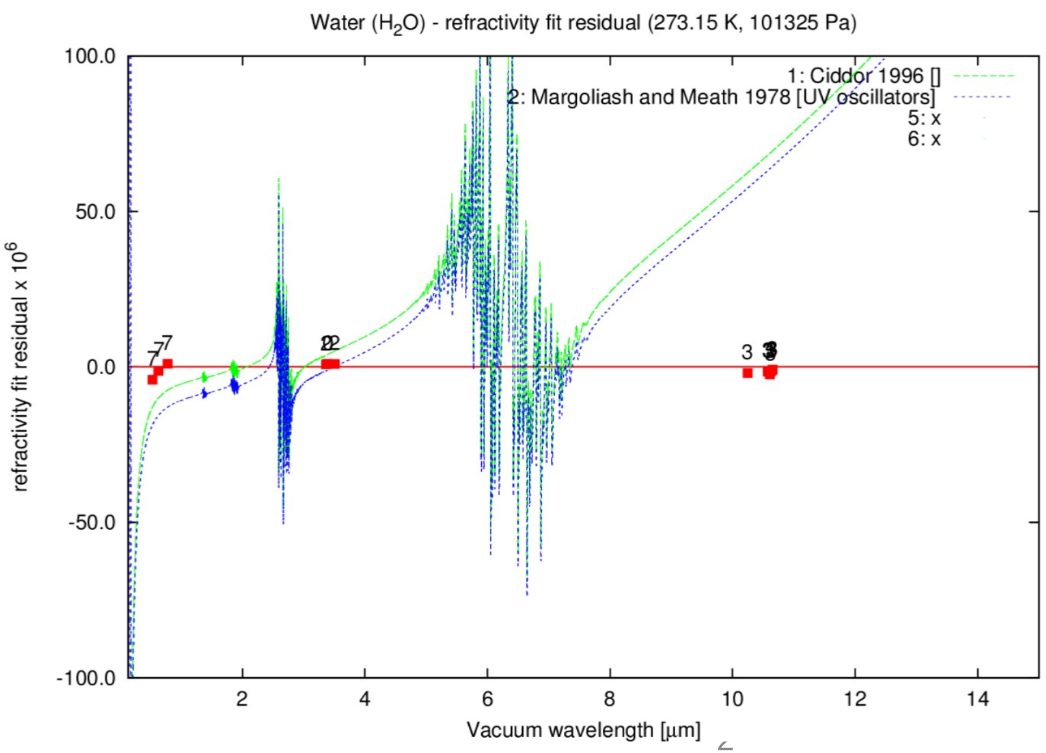
Spectroscopy … the water issue

Simultaneous measurement of star spectra + planet spectra

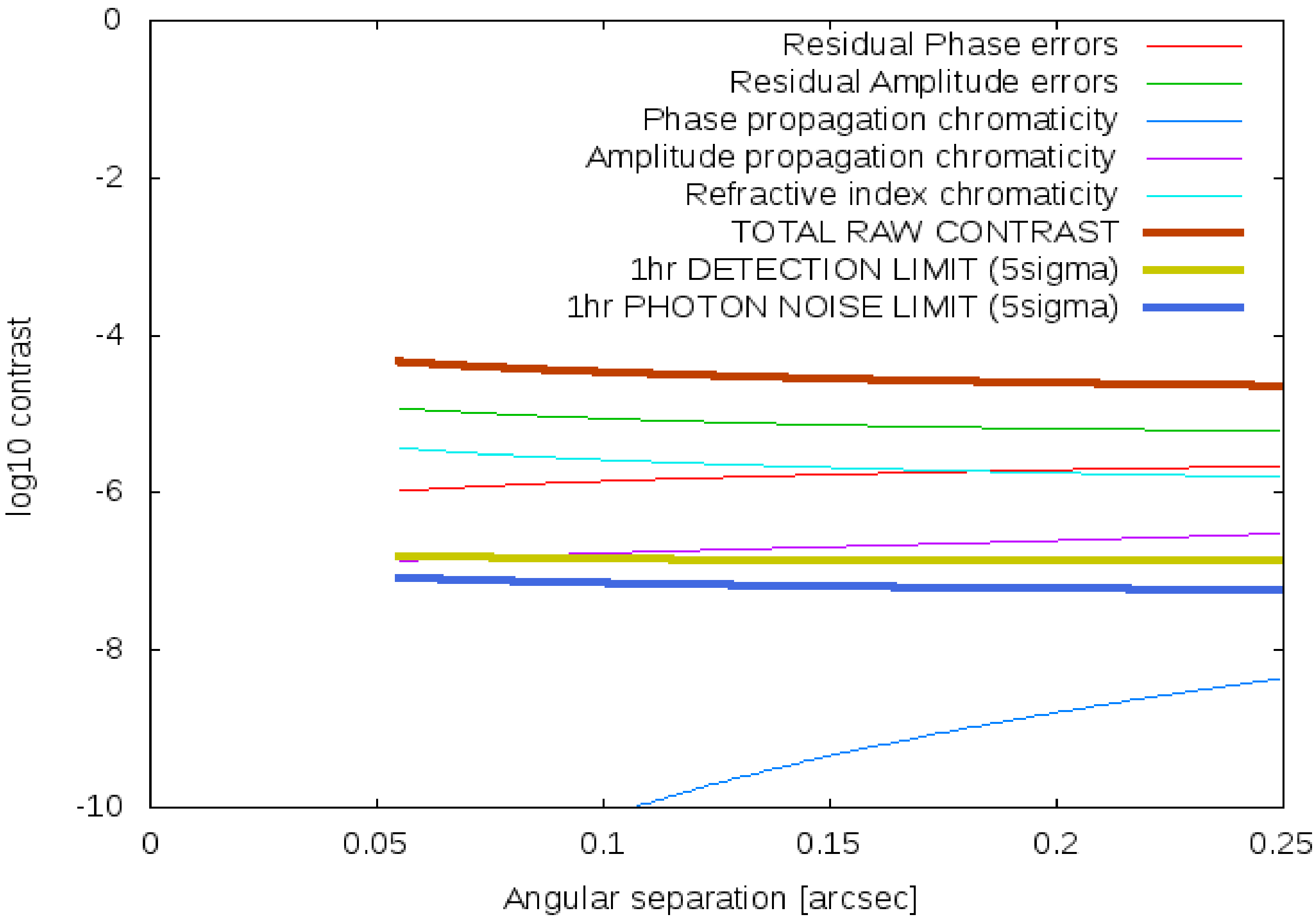
PROBLEM: refractive index near water absorption bands is complicated
→ we are developing high-fidelity atmosphere model

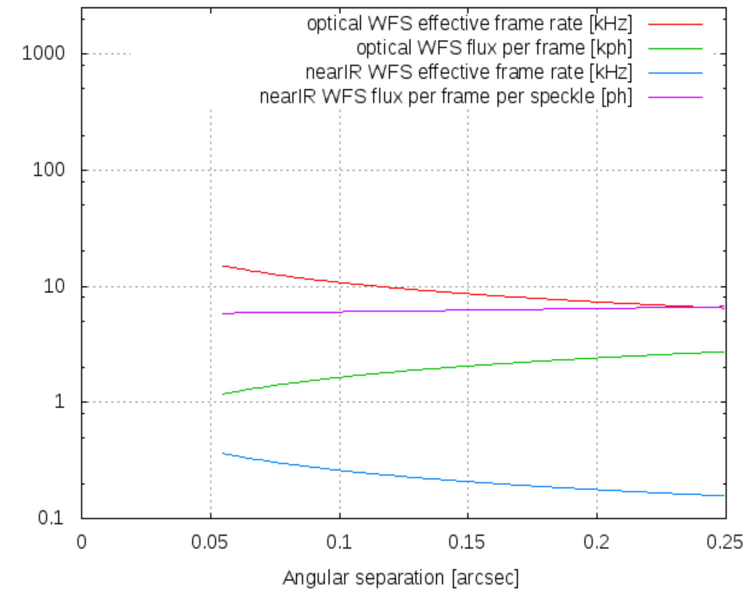
Computing refractive index as a function of wavelength and altitude + diffractive propagation





8m: Pyramid-based system + Speckle Control → 100x contrast gain





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

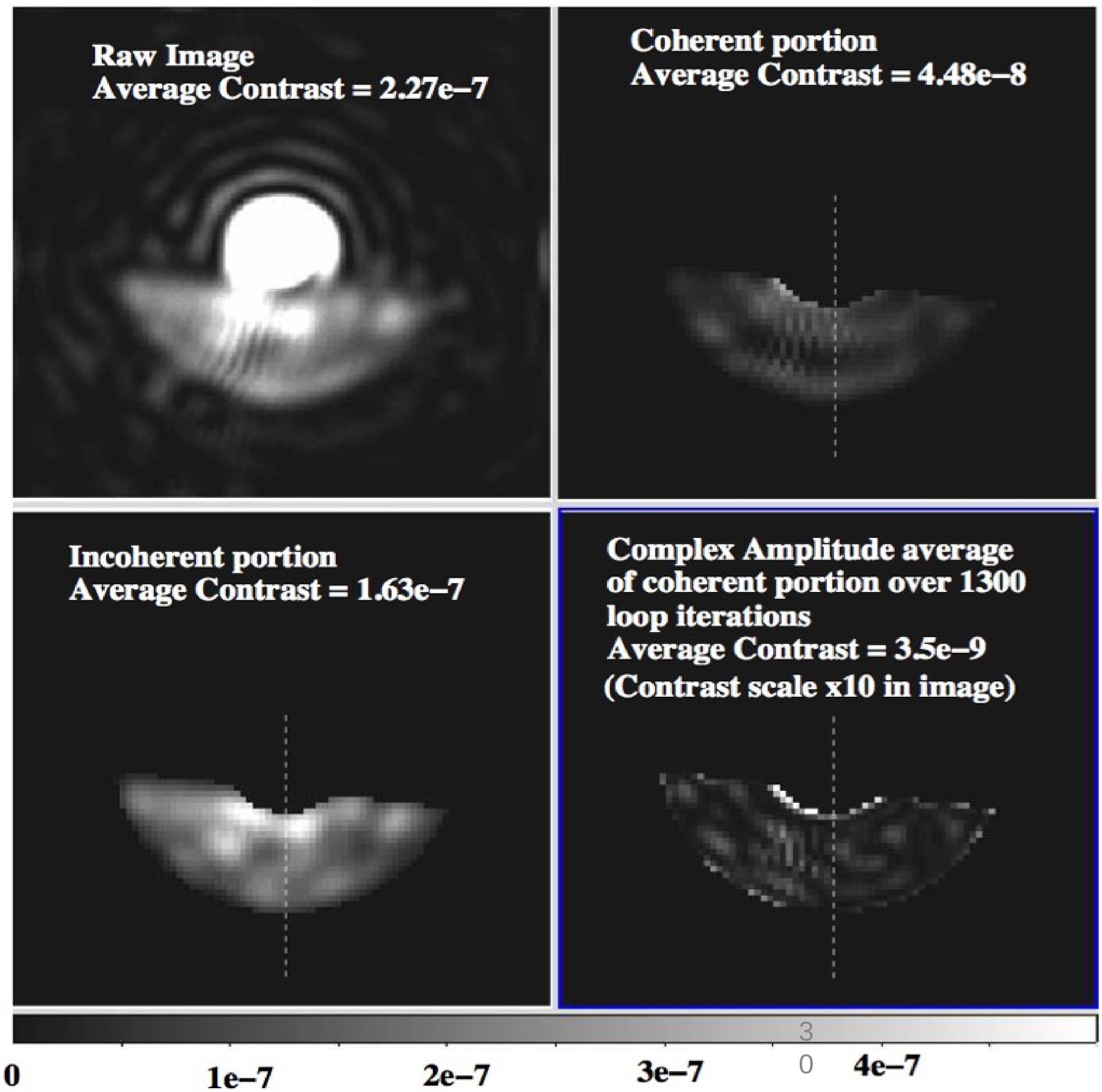
Focal plane WFS based correction and speckle calibration

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

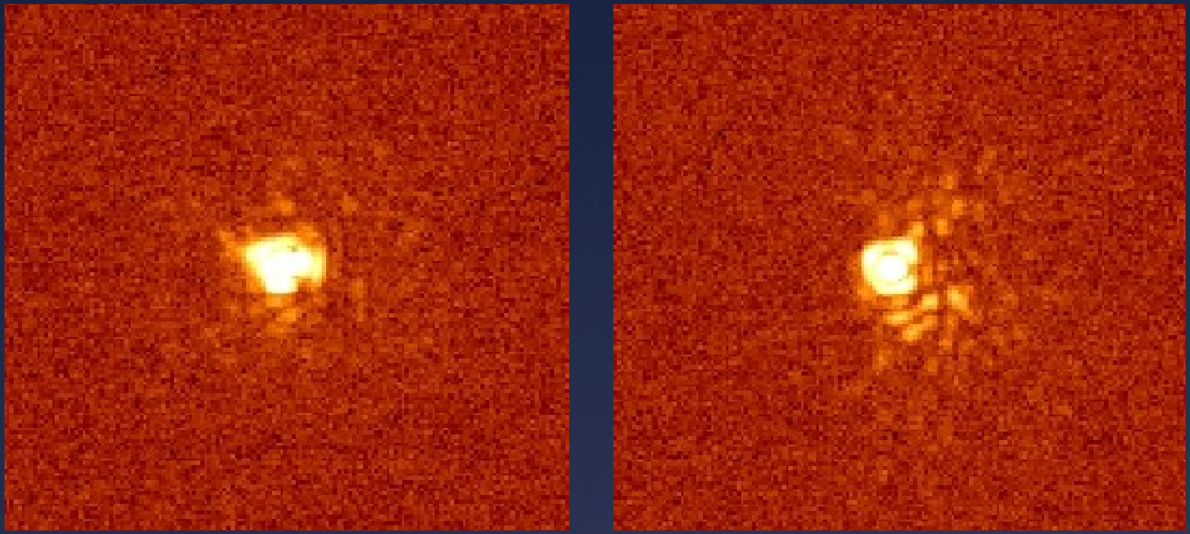


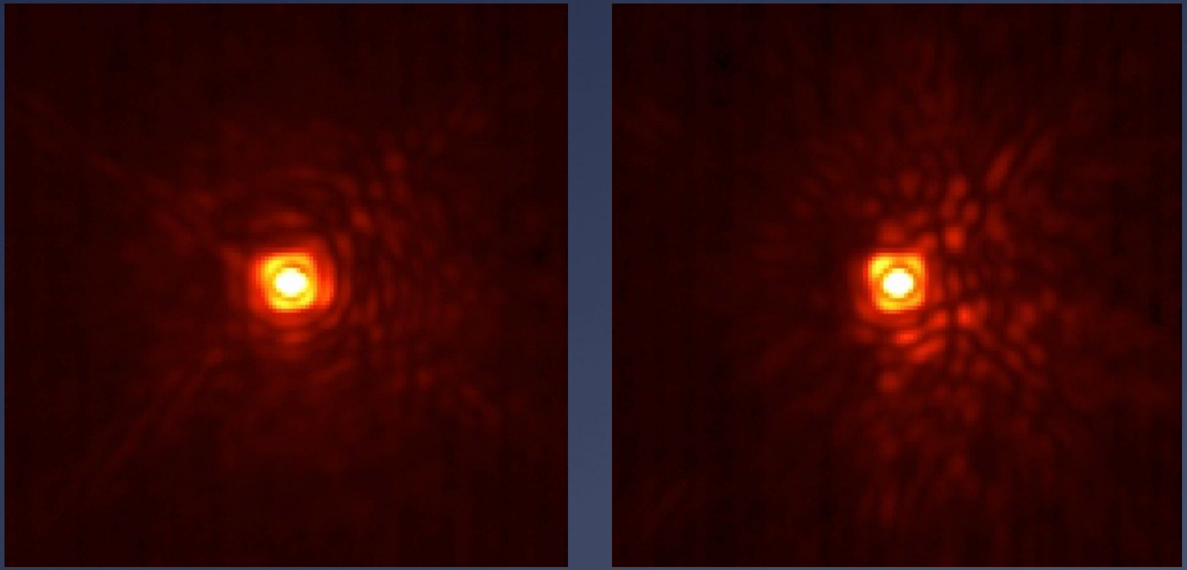
speckle nulling results on-sky (June 2014)

Meta data:

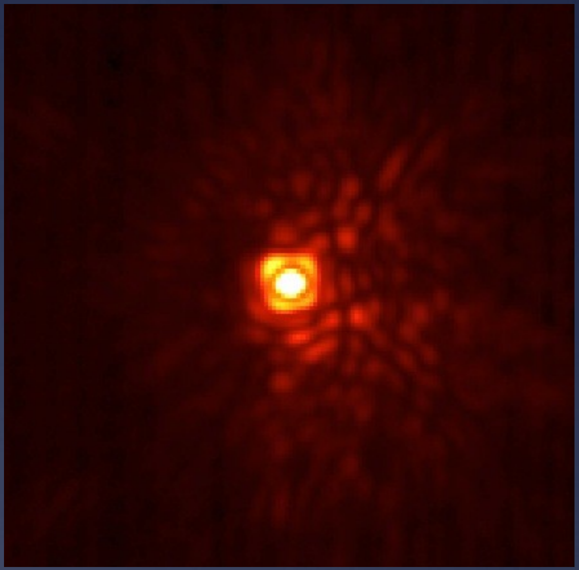
Date: 2nd or June
Target: RX Boo (also repeated on Vega)
Seeing: <0.6”
AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)
Coronagraph: None (used Vortex on Vega)

Single frames: 50 us





Sum of 5000 frames: shift and add

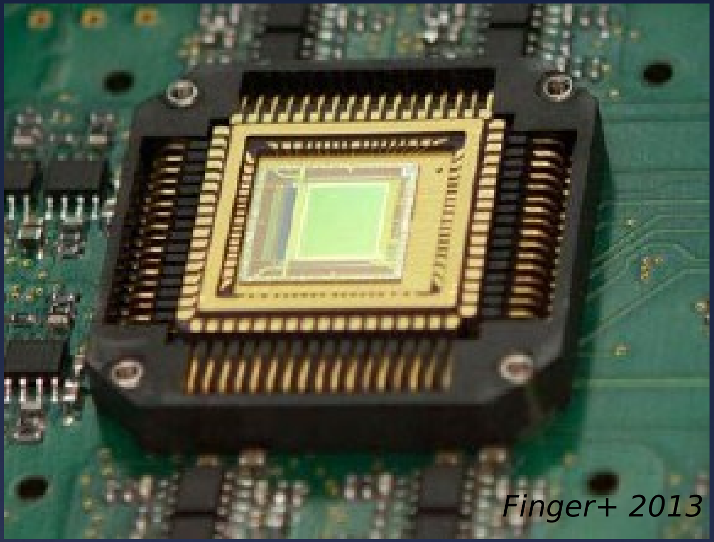


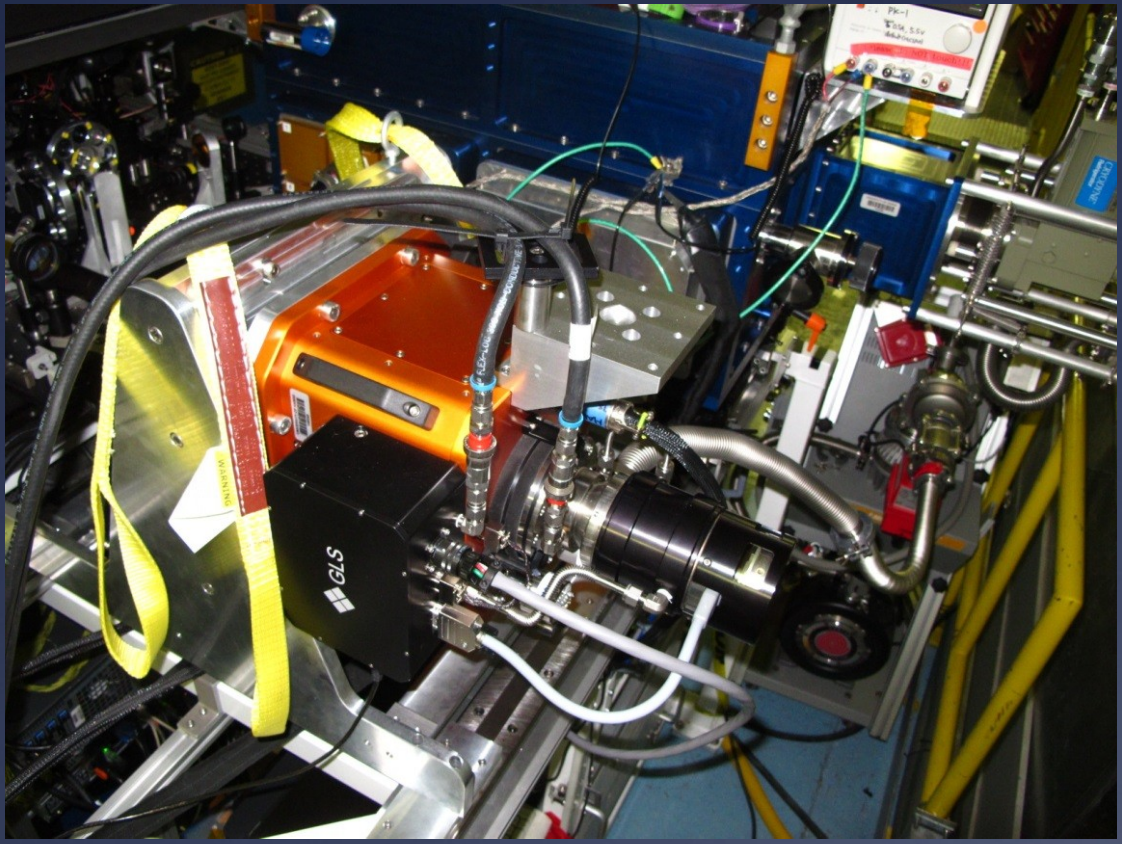
Martinache, F. et. al.

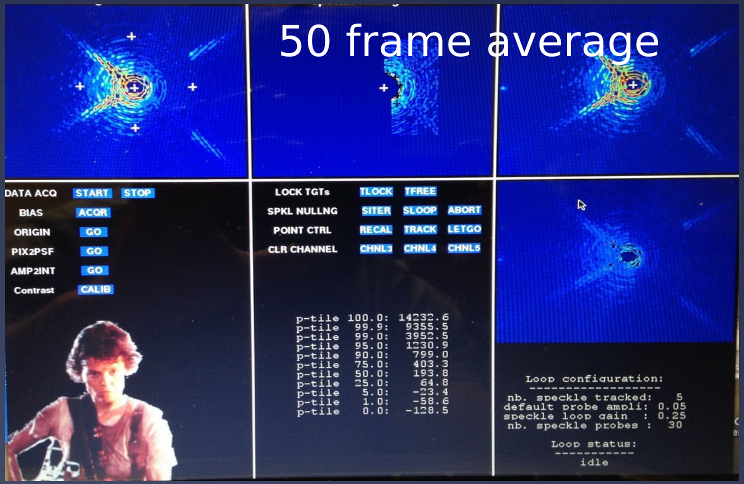
SAPHIRA Infrared APD array

HgCdTe avalanche photodiode
manufactured by Selex

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

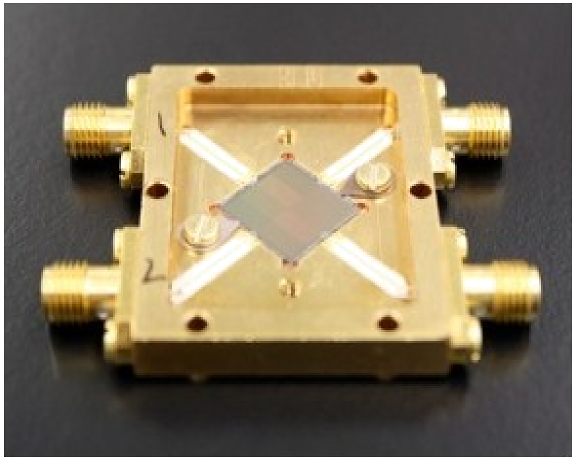


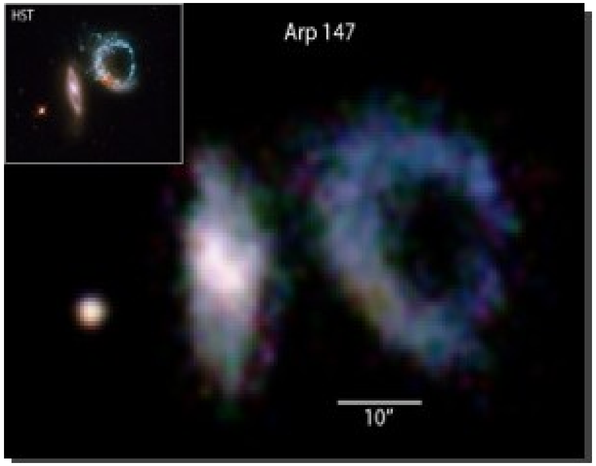




MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera

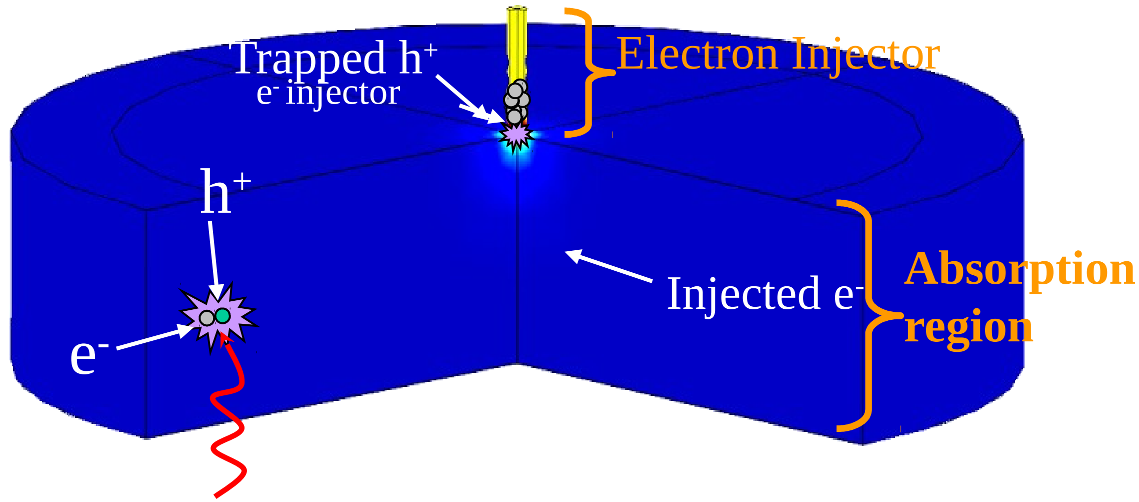


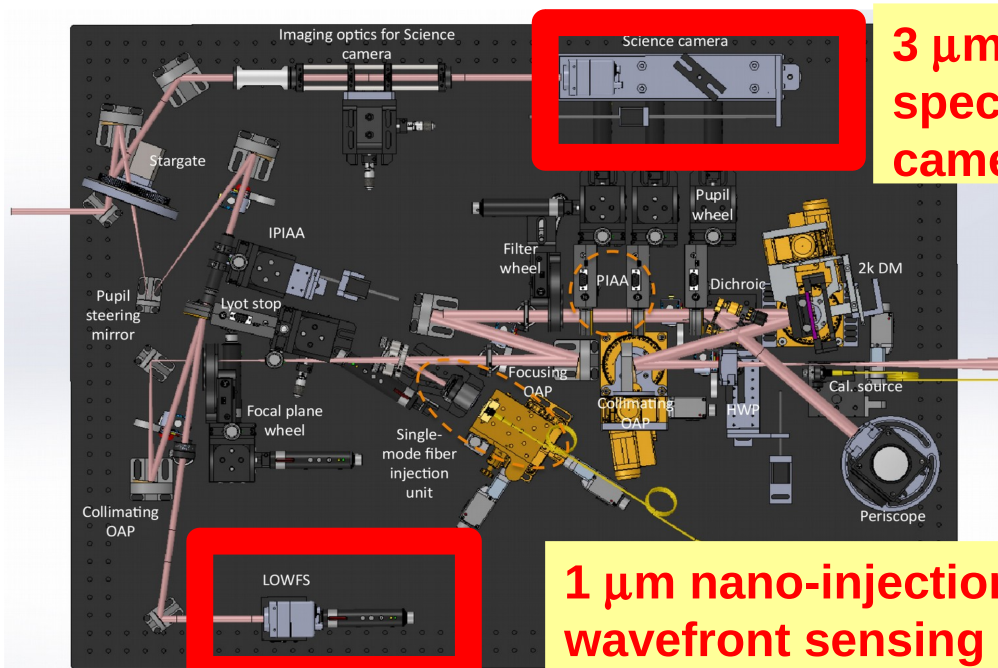


Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in CY2016

Nano-injection nearIR camera (Northwestern Univ / Keck foundation)

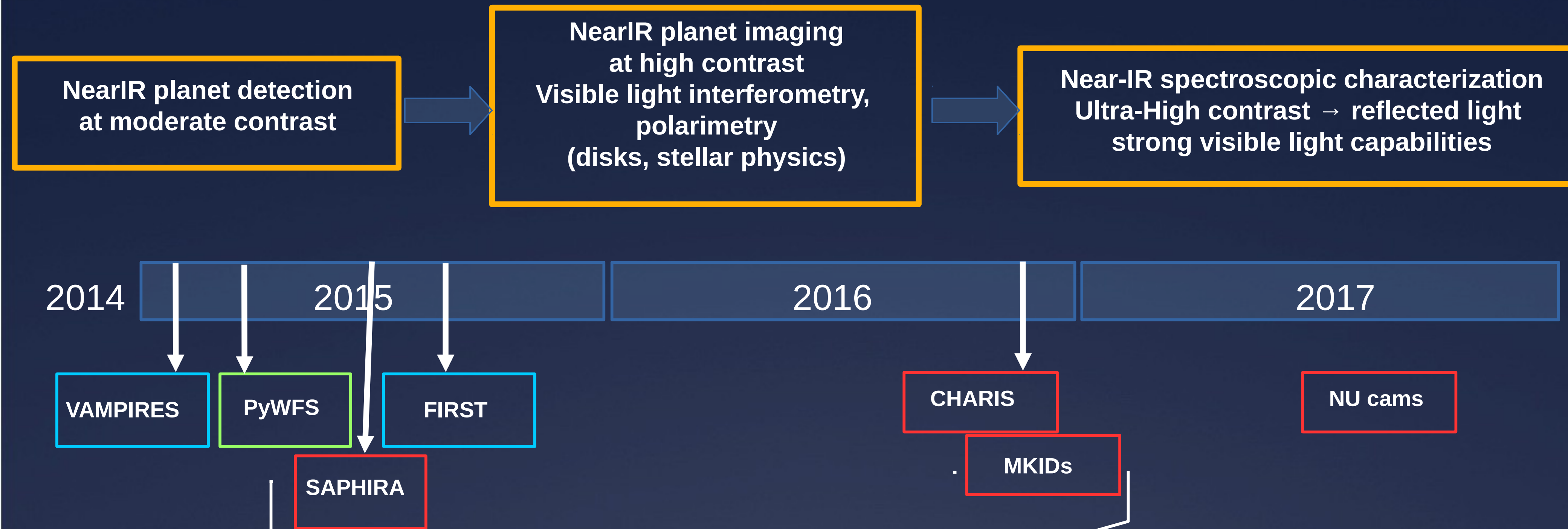




3 µm nano-injection speckle imaging camera

1 µm nano-injection low-order wavefront sensing (pointing) camera

SCExAO high contrast imaging capabilities: expected schedule for capabilities offered to observers



Phase 1 operation

LOWFS + slow speckle control → Moderate contrast improvement over HiCIAO

Small IWA (~2 l/D) coronagraphy

Phase 2 operation

Significant contrast improvement over HiCIAO thanks to ExAO
High SR (~0.9)
→ more robust performance for coronagraph and LOWFS systems

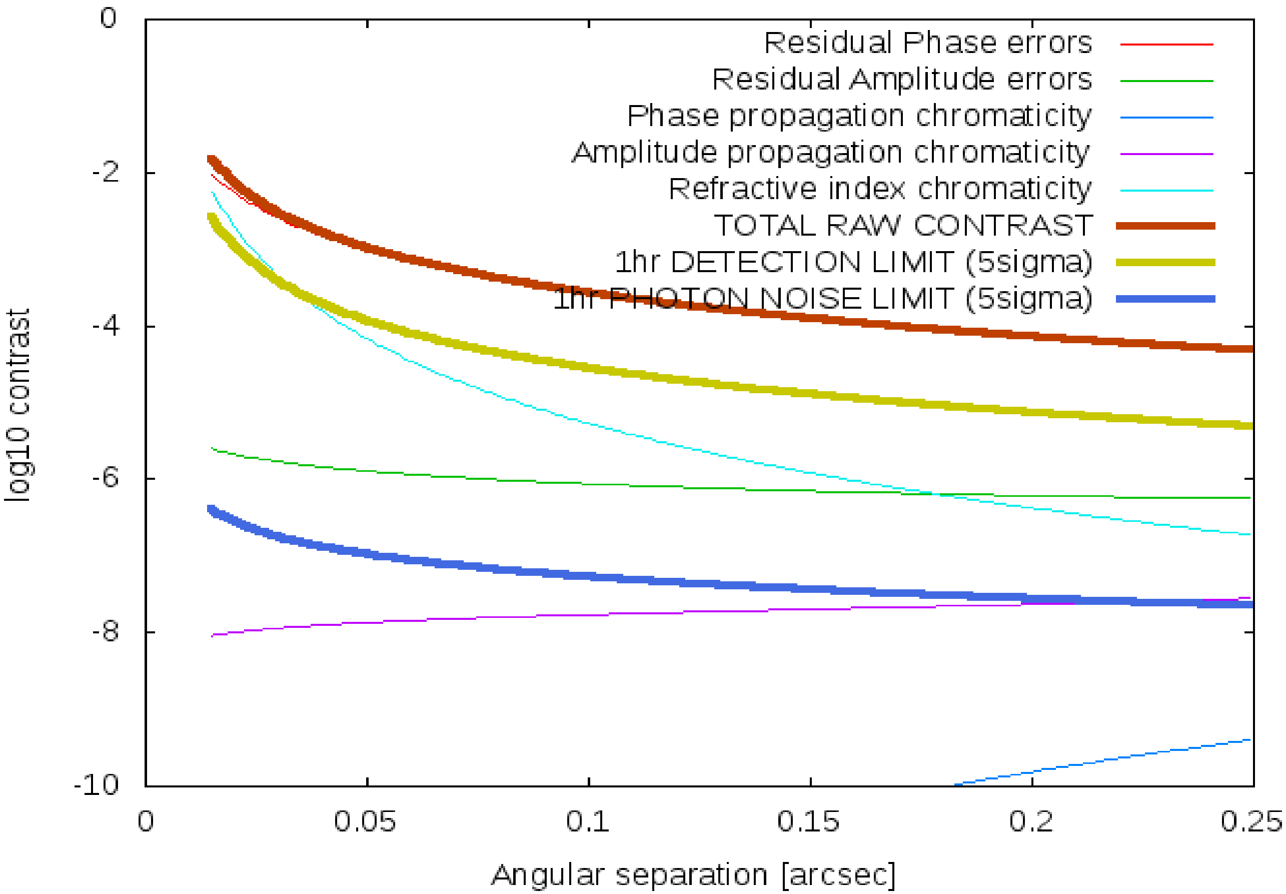
Smaller IWA (~1 l/D)

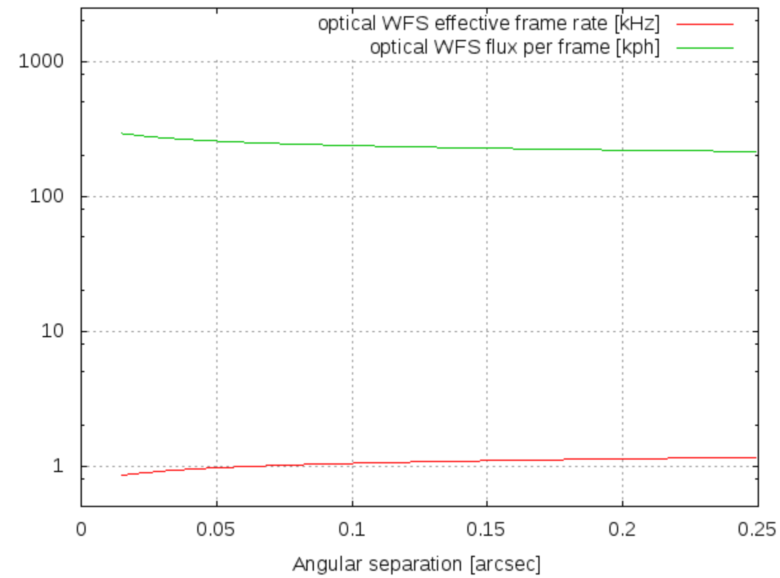
Full system (CHARIS+MKIDS)

MKIDs camera → faster speckle control and better calibration → significantly higher contrast at small separation (~1e-8)

Spectroscopy:
CHARIS + MKIDS provide spectroscopy from ~0.8 um to 2.7um

30m: SH-based system, 15cm subapertures

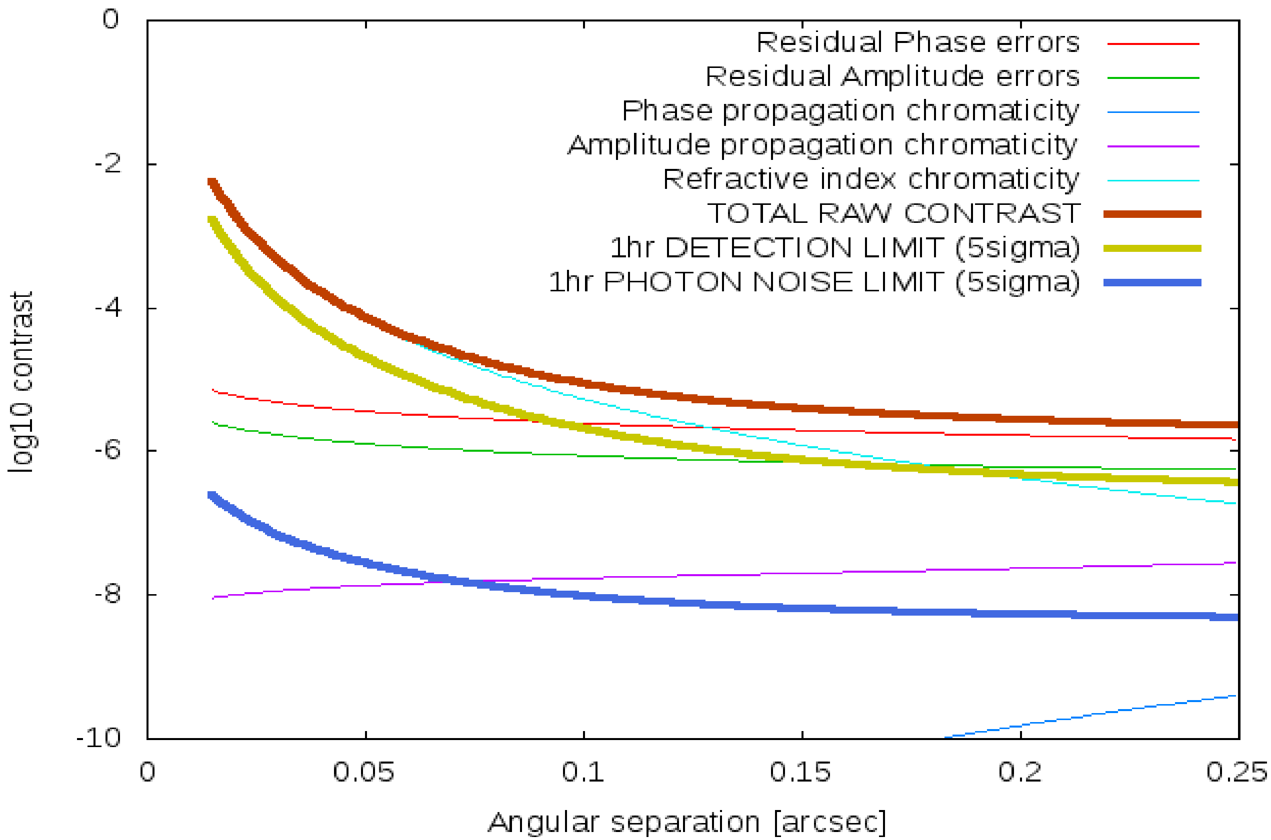


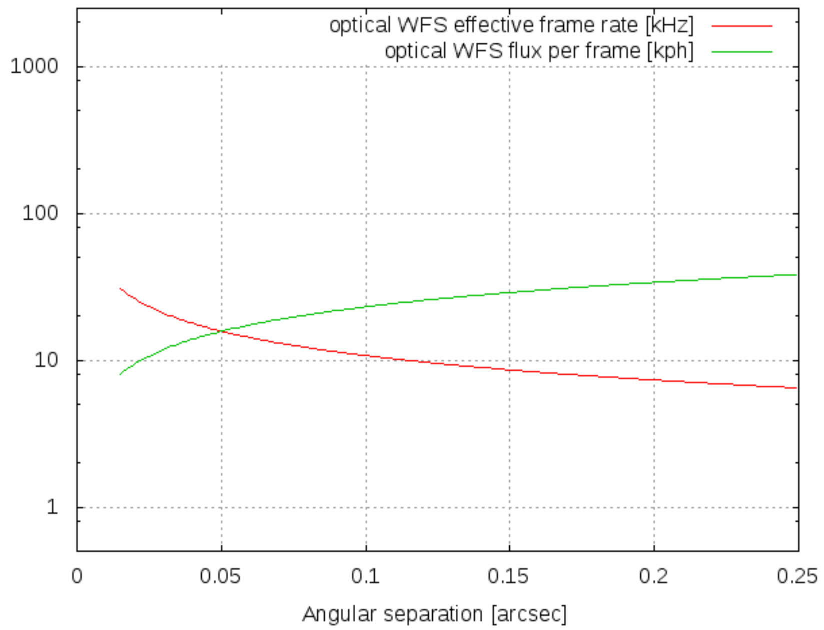


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

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

30m: Pyramid-based system

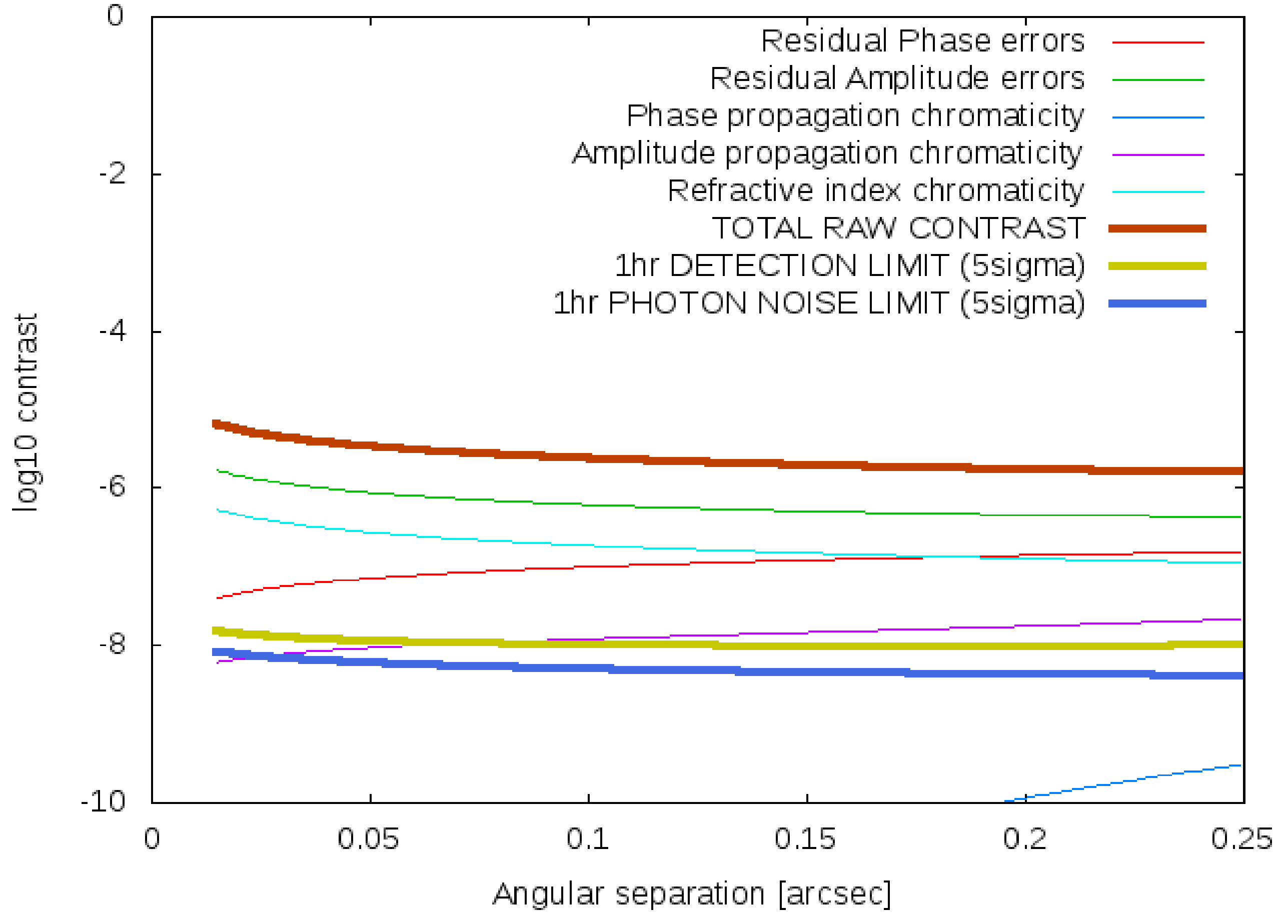


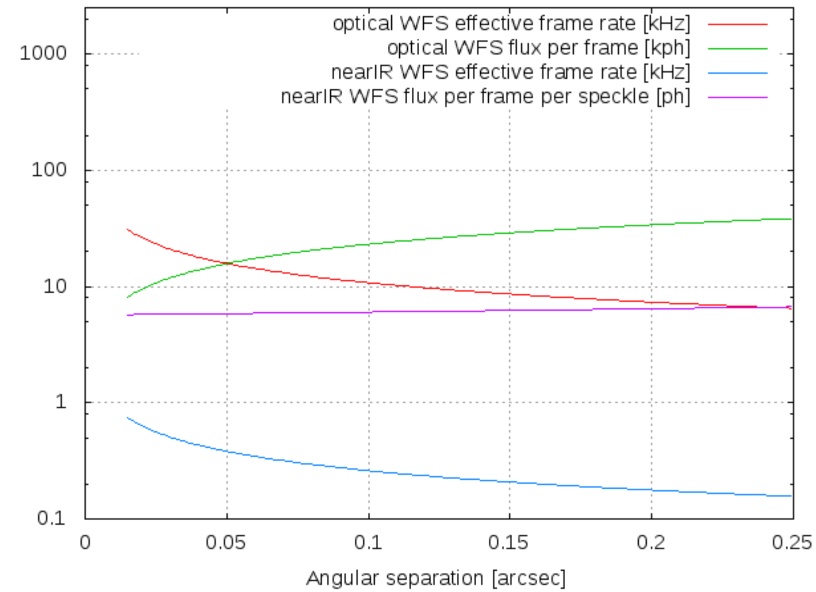


More sensitive WFS, can run faster (10kHz) with ~10 kph per WFS frame
Limited by atmosphere chromaticity

~((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

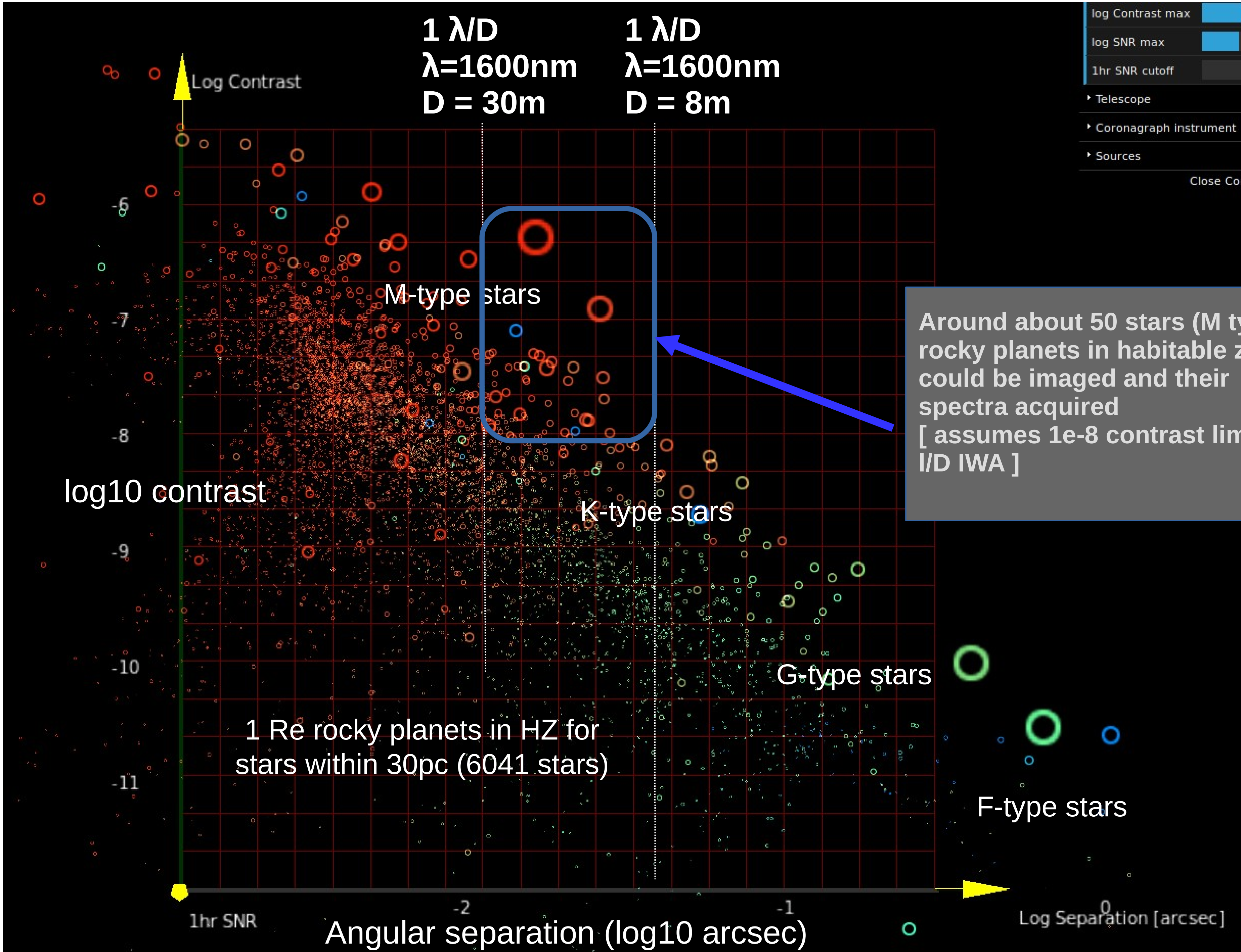




300Hz speckle control loop (~1kHz frame rate) is optimal

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

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]