SCExAO: Combining high speed, high sensitivity wavefront control and low inner working angle coronagraphy

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VECTOR VORTEX

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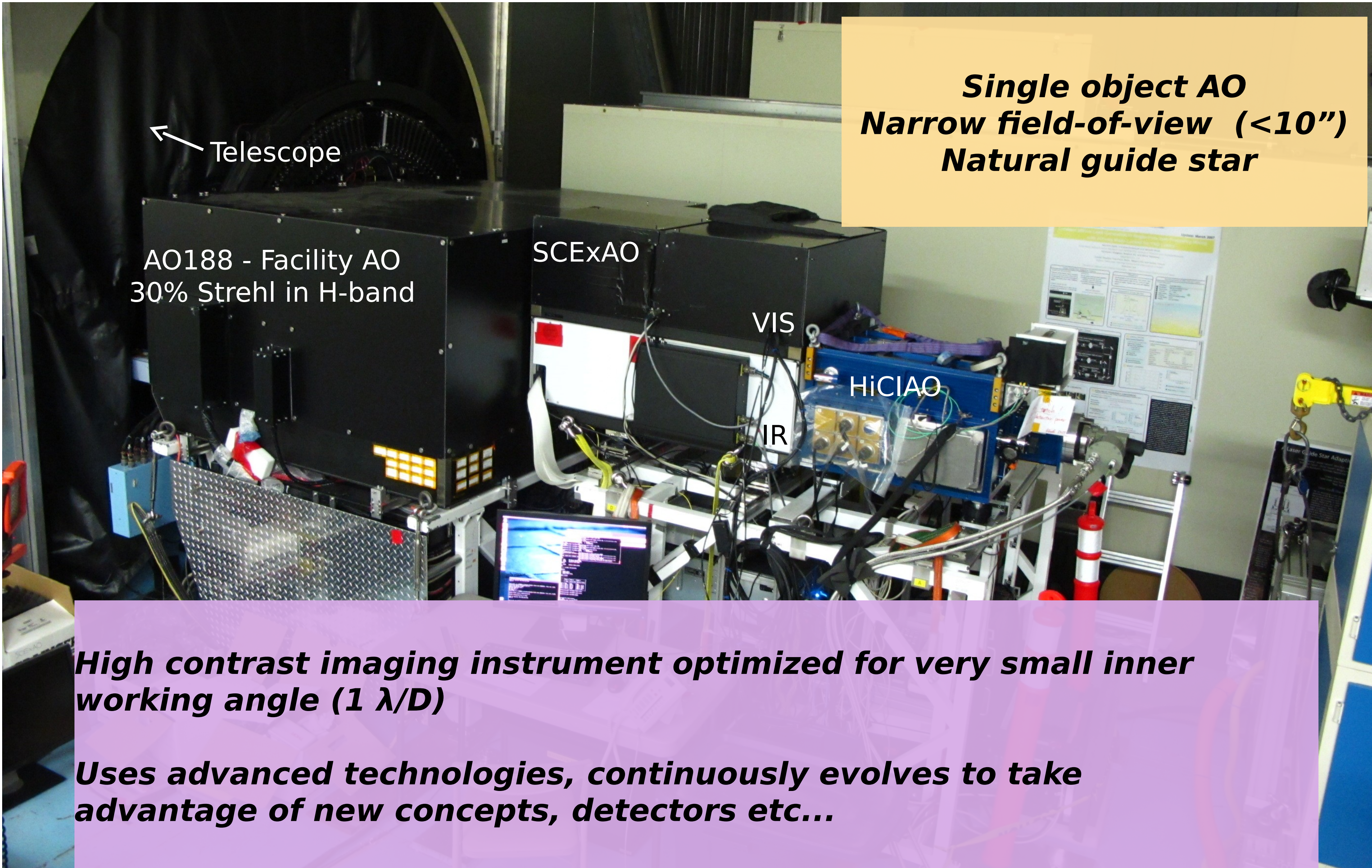
PENNSTATE 1855
AAO

Subaru Coronagraphic Extreme AO (SCExAO)



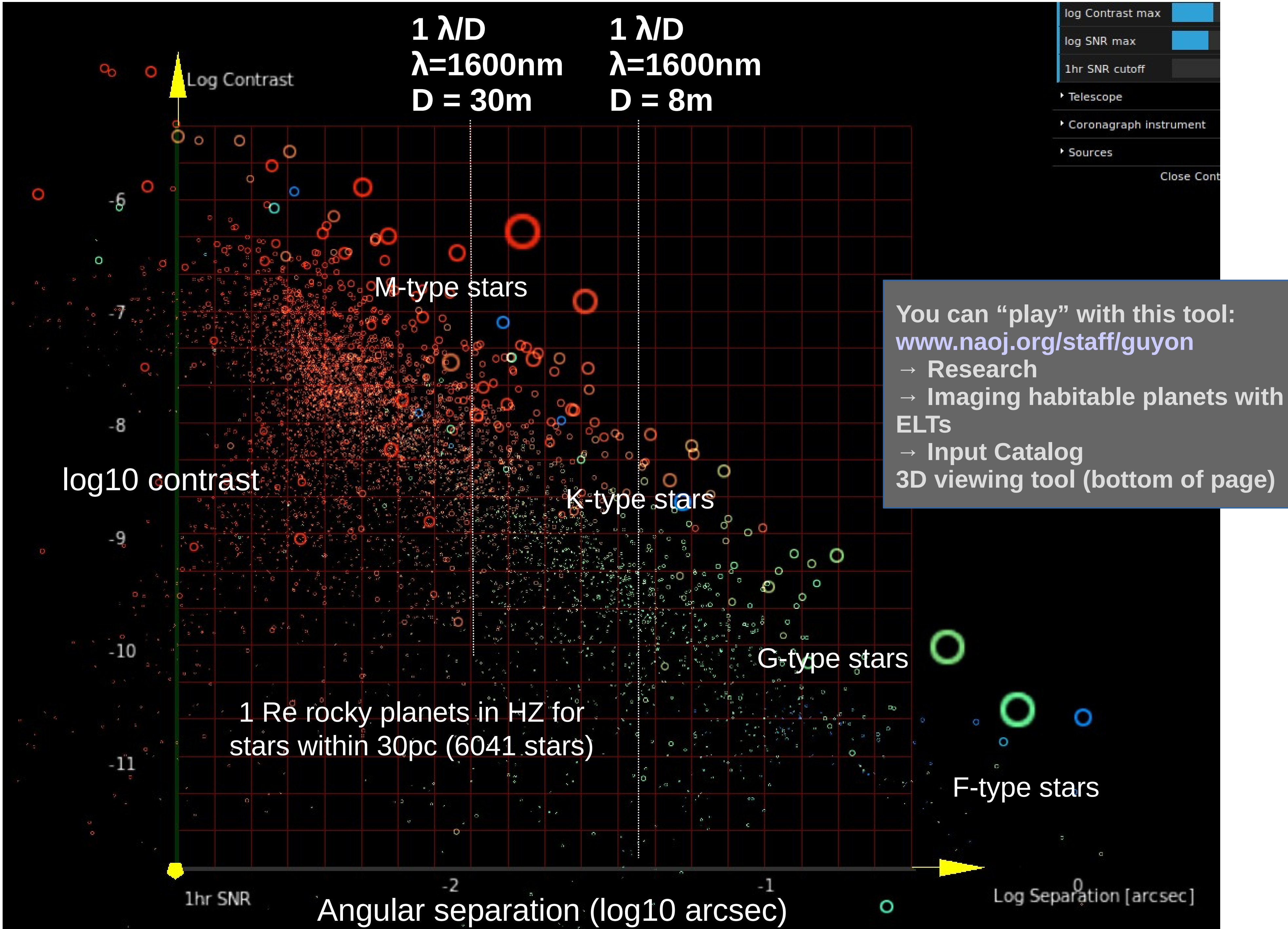
Single object AO
Narrow field-of-view (<10")
Natural guide star

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...

Prototype for ELT habitable planets spectroscopic characterizer
→ visitor instrument on TMT

Reflected light Earth-sized planets with ELTs



Wavefront sensing:

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

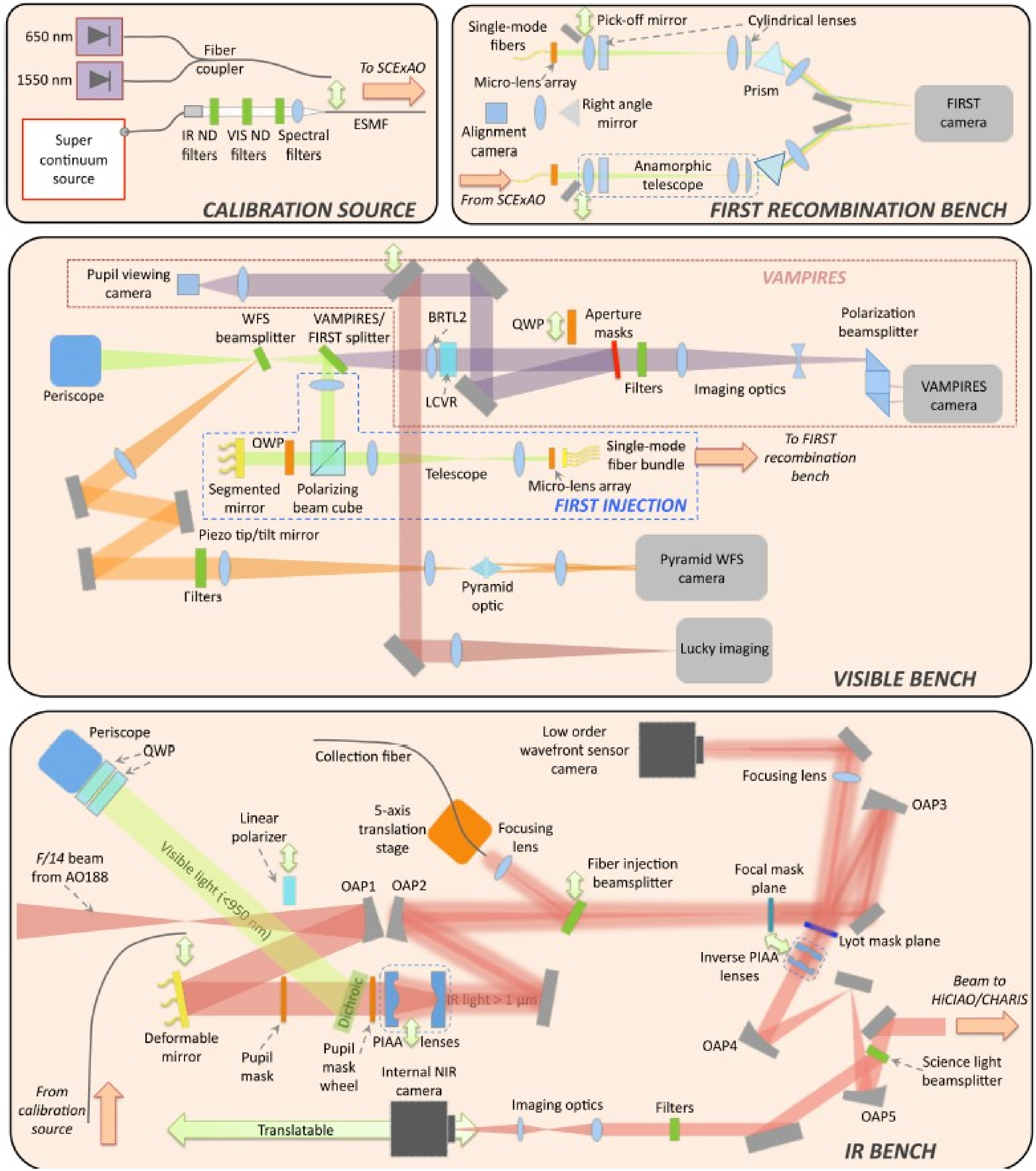
2k MEMS DM

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

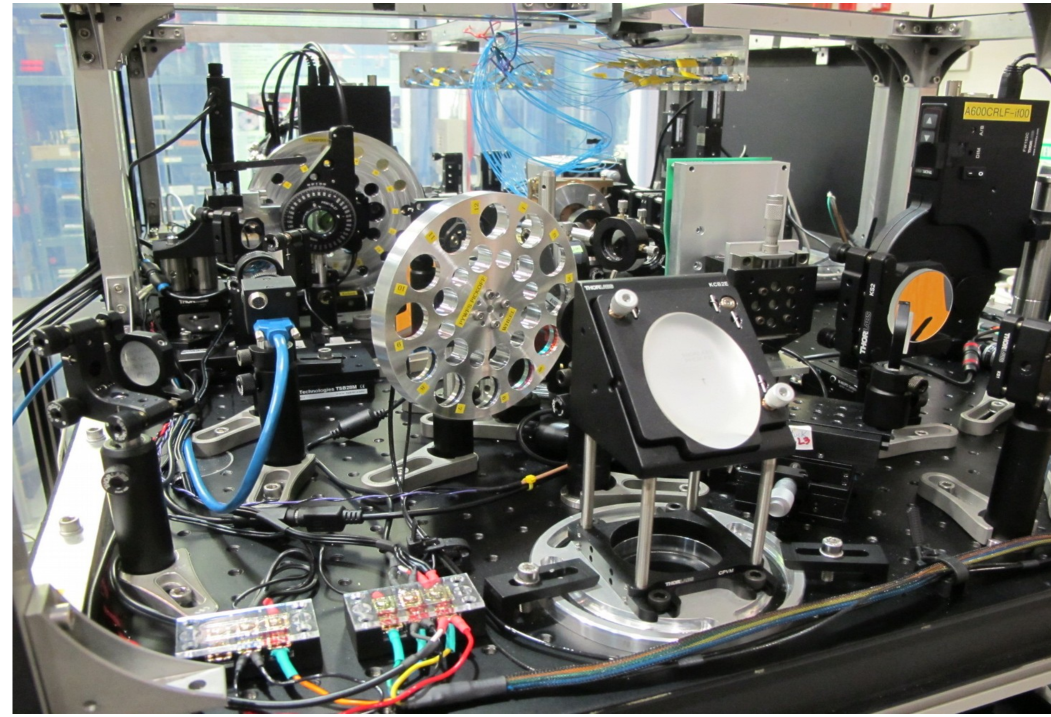
Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetory Signatures (VAMPIRES) (VIS)

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

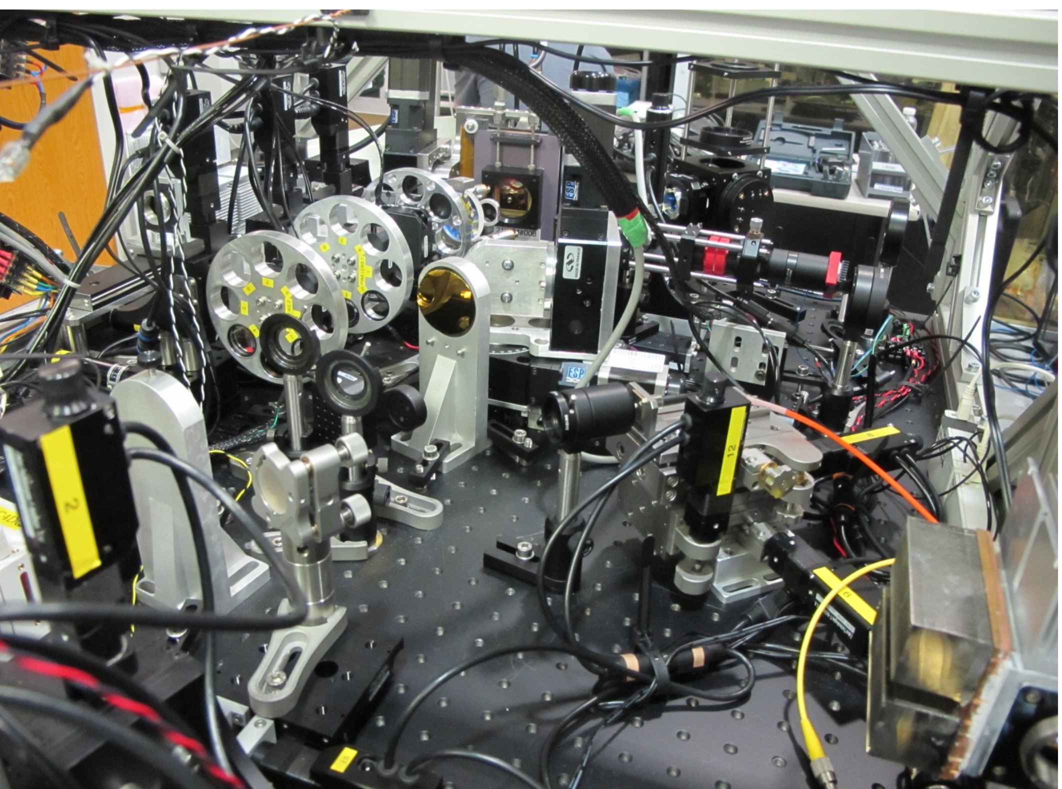
Broadband diffraction limited internal cal. Source + phase turbulence simulator

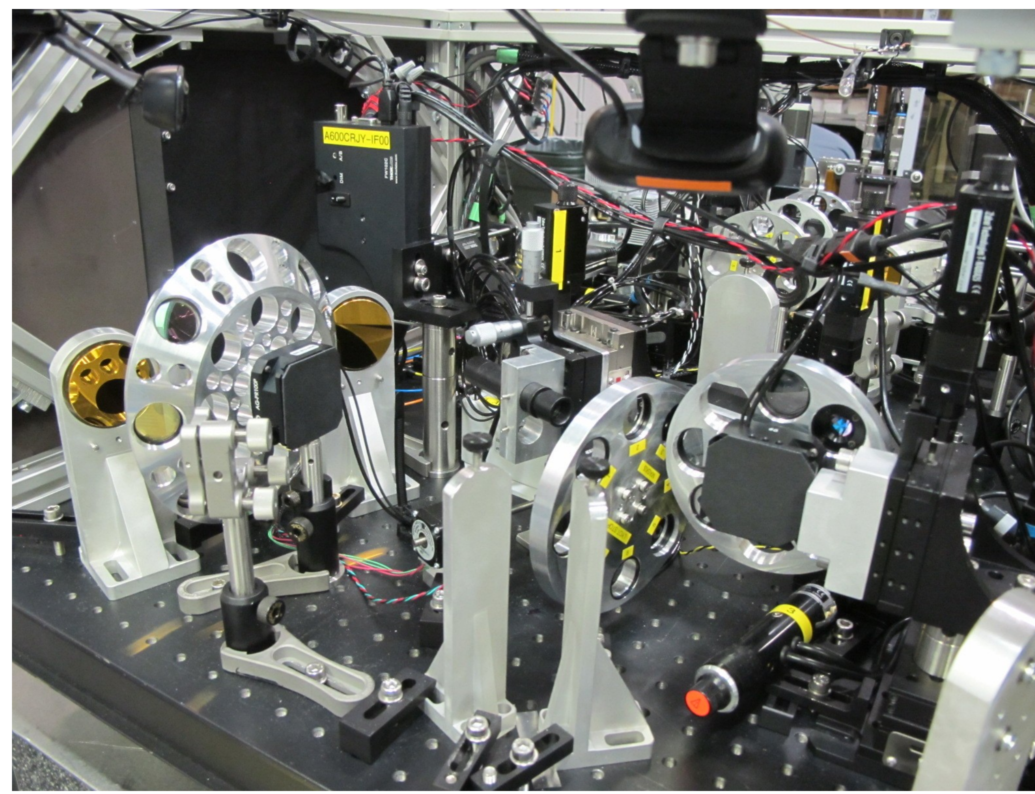


SCExAO visible bench →

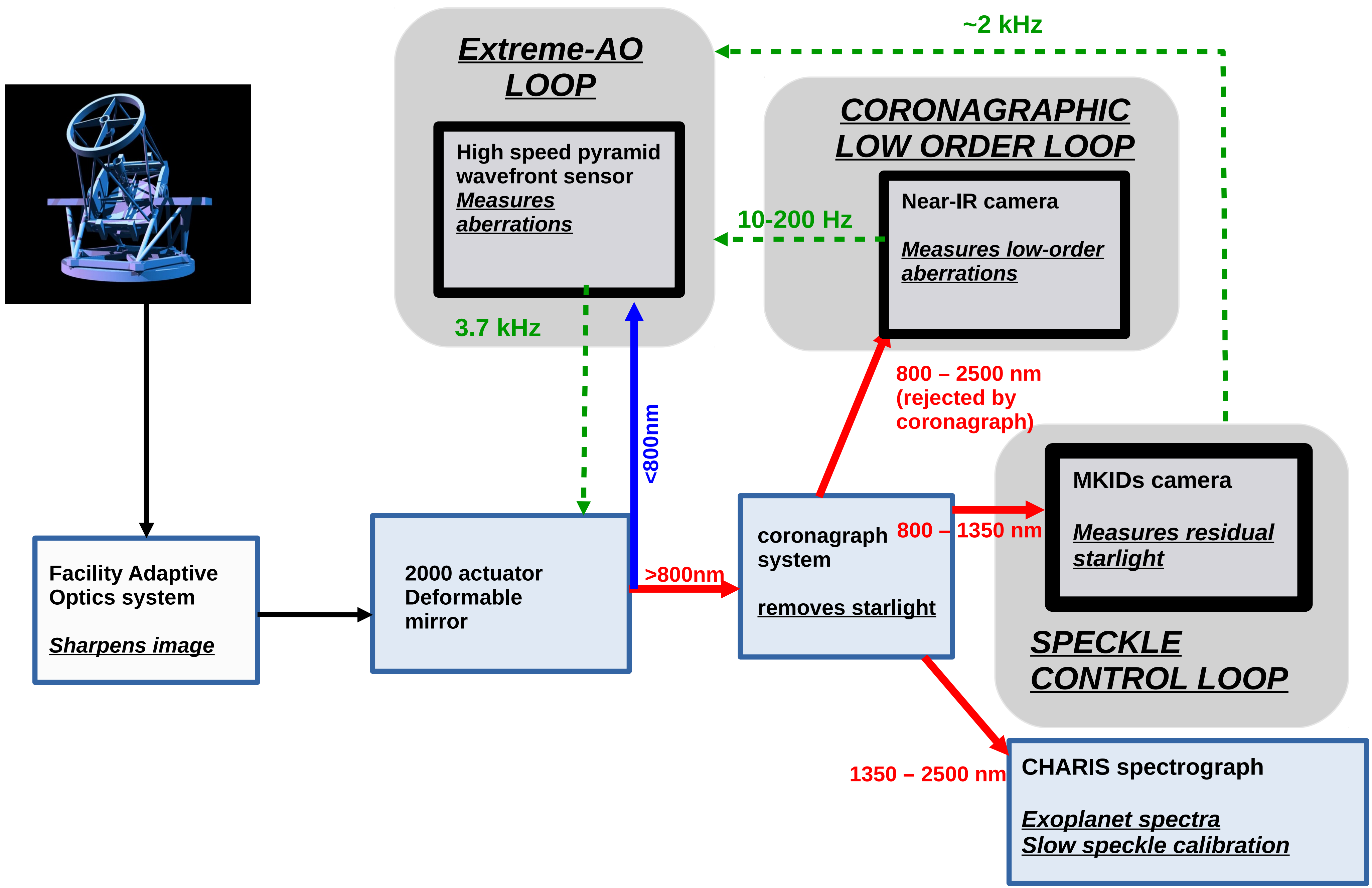


SCExAO near-IR bench

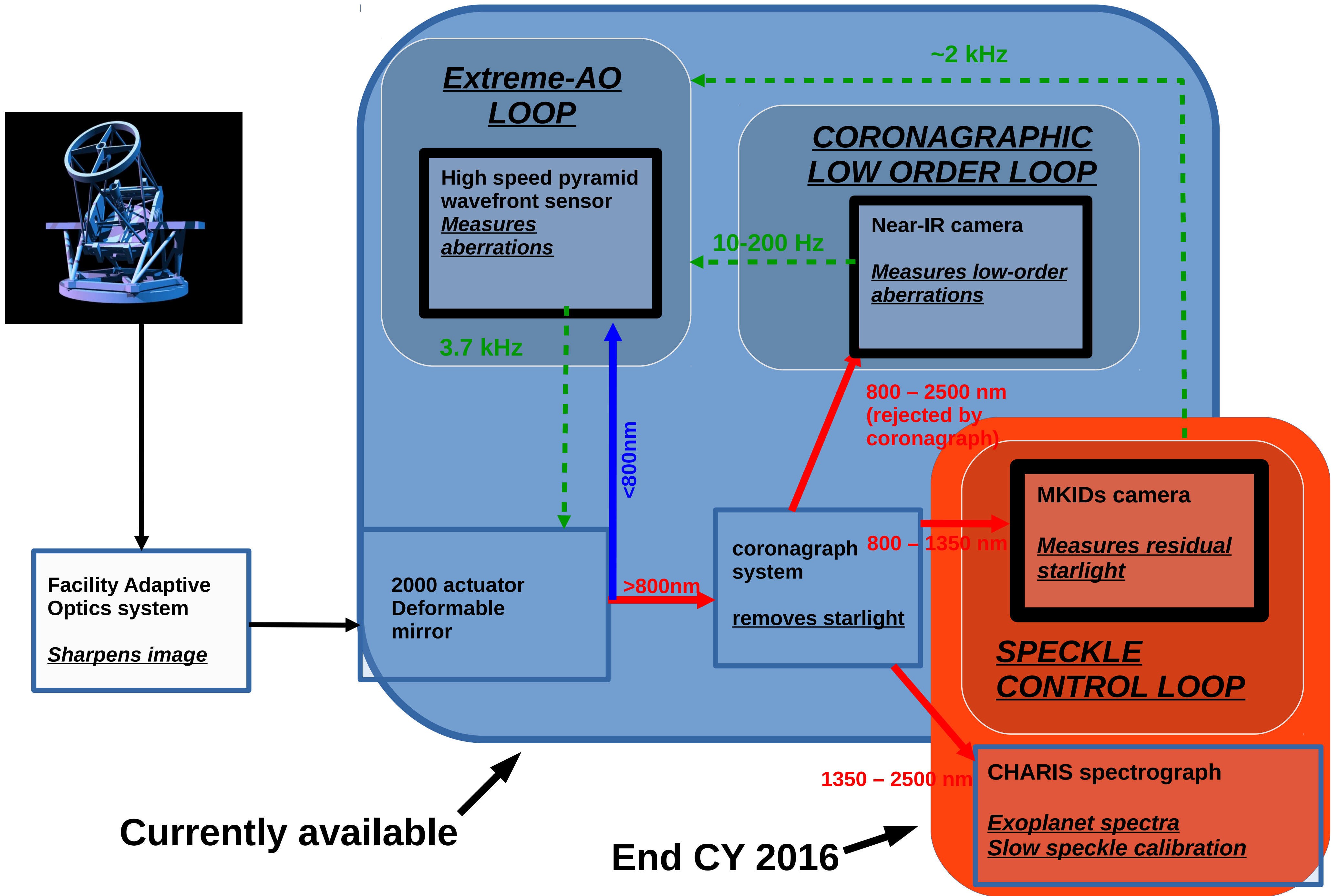




SCExAO: wavefront control loop



SCExAO: wavefront control loop



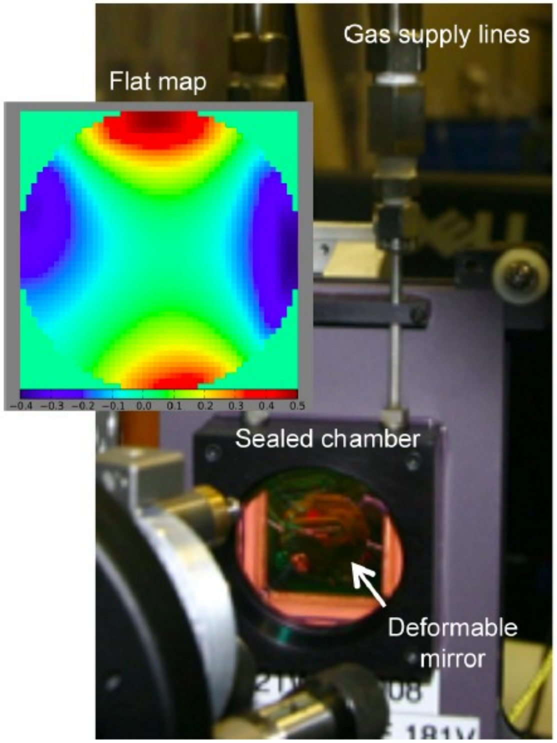
How SCExAO achieves high contrast

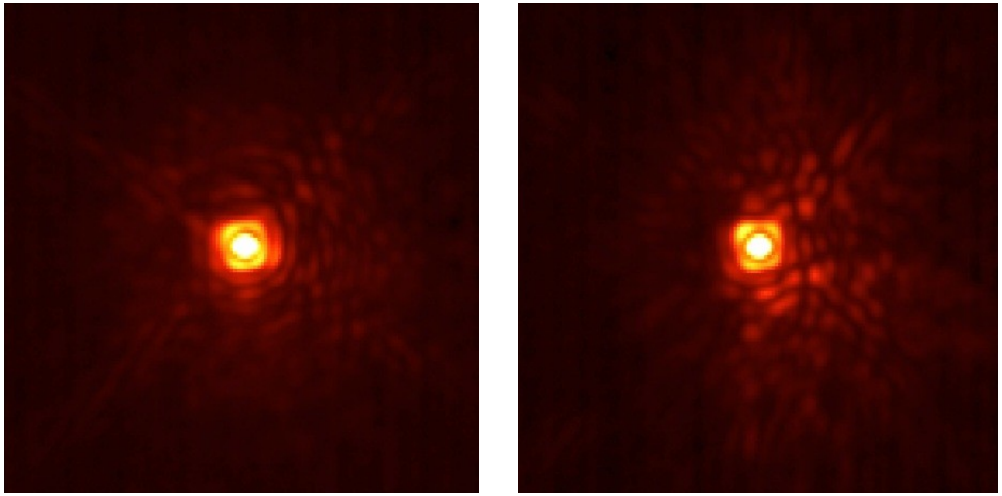
(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits r>1 l/D region

(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



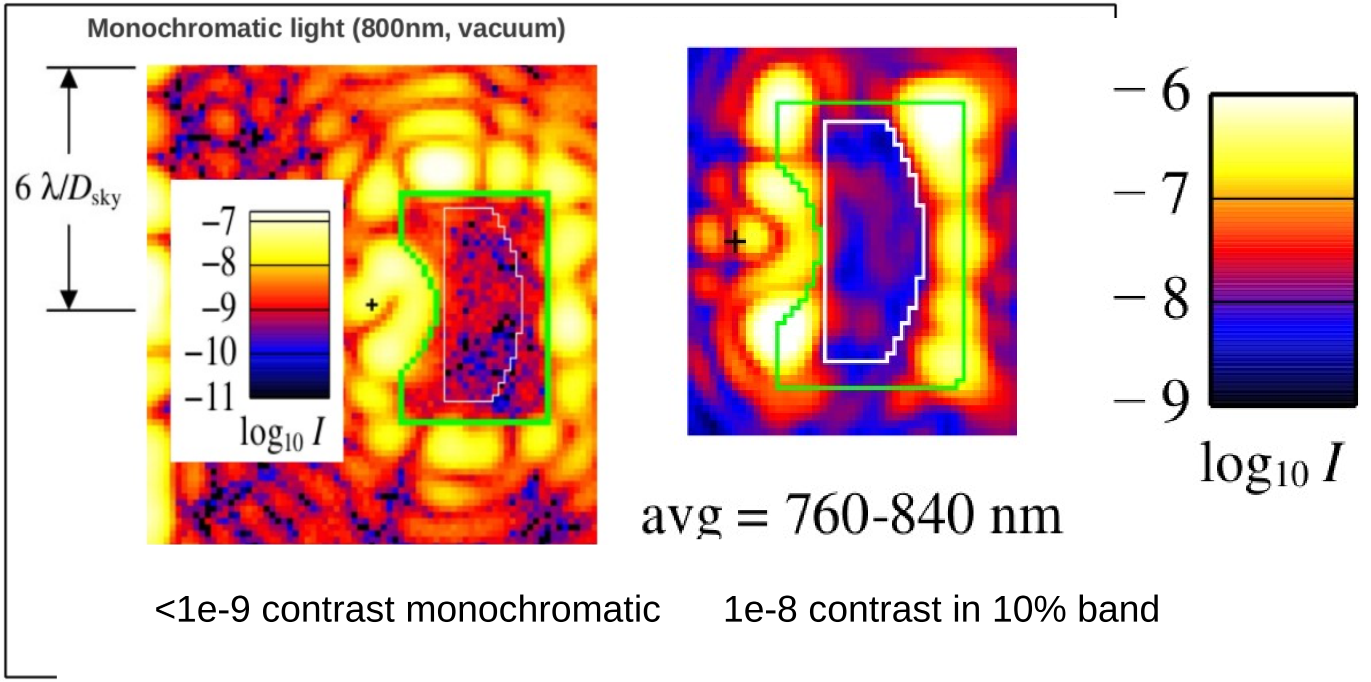


Speckle nulling on-sky

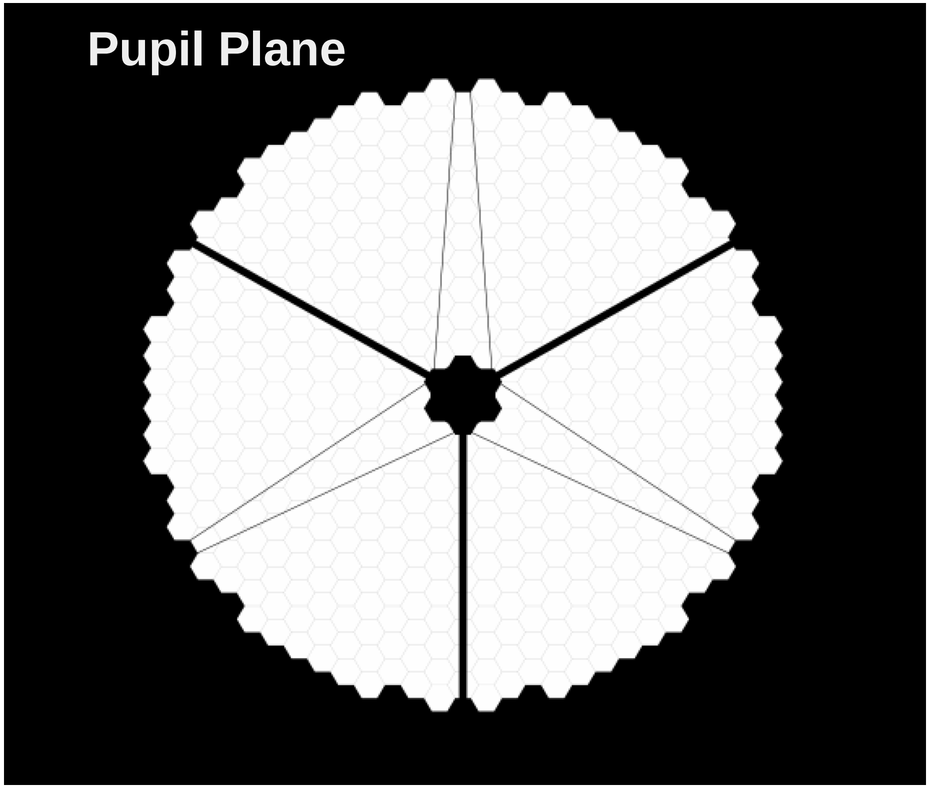
Coronagraphy

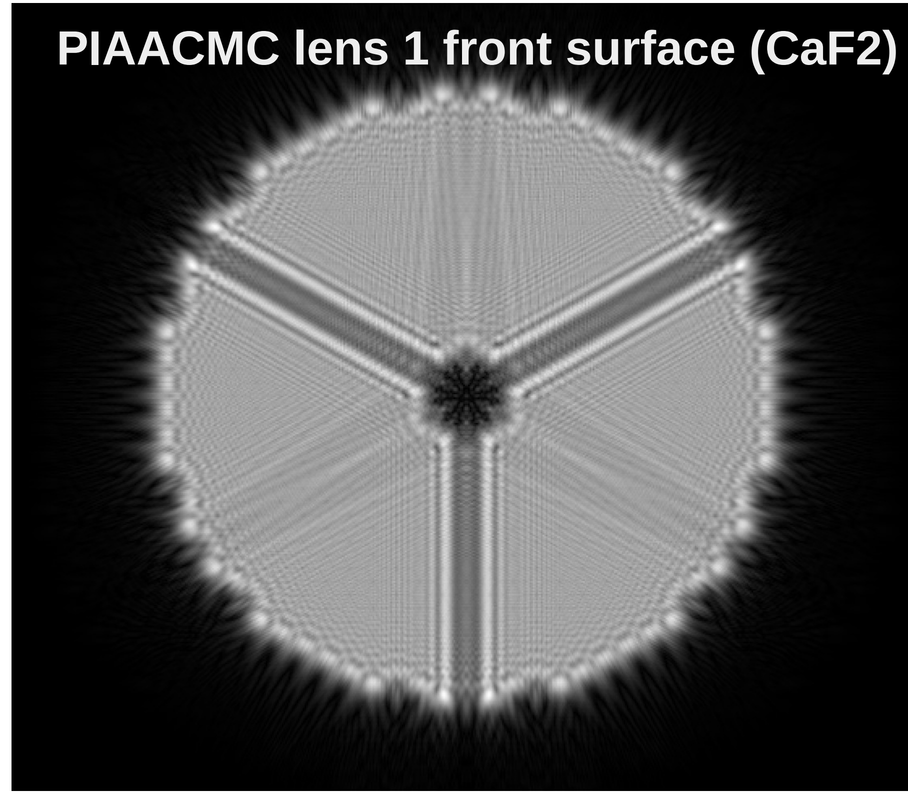
SCExAO's coronagraphs (PIAACMC, Vector Vortex) offer ~1 l/D IWA and high throughput

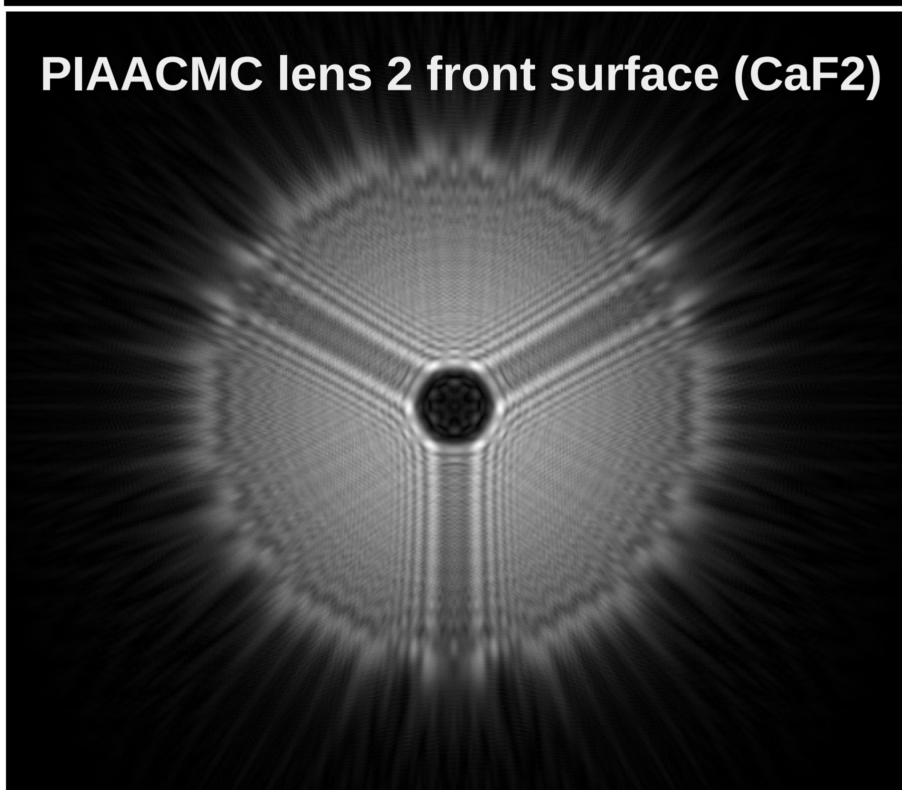
New coronagraphs can reach 1-2 l/D IWA at ~1e-7 raw contrast in nearIR... on almost any pupil (compared to ~1e-3 at best on today's best ExAO systems)

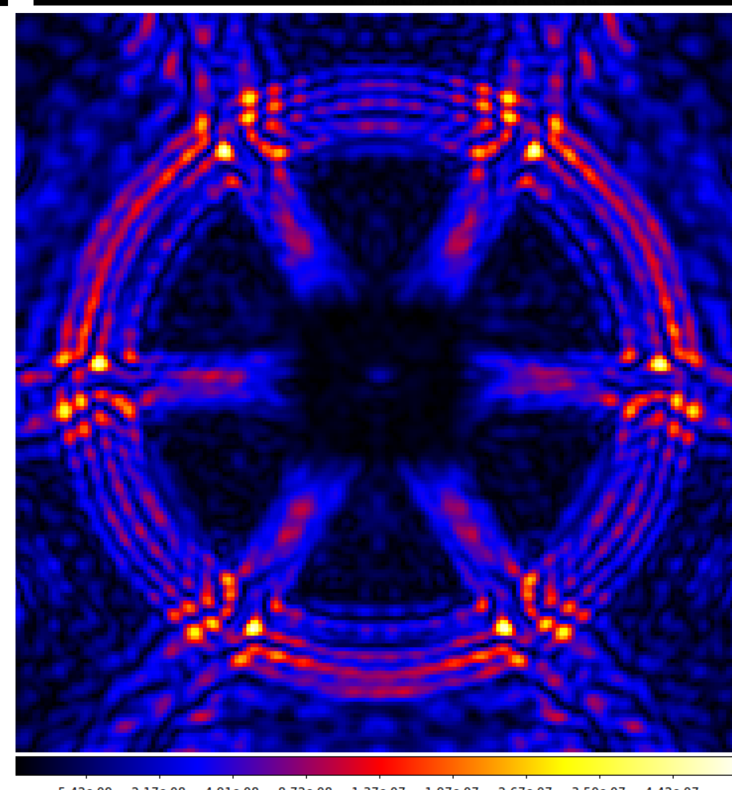


2-4 l/D dark hole, high system throughput
PIAA testbed at NASA JPL
lab results demonstrate PIAA's high efficiency and small IWA (B. Kern, O. Guyon et al.)
→ now moving to PIAACMC









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

Extreme-AO loop

Pyramid WFS
Pyramid optical element with sharp apex (5 um)
Spare from MagAO system (loan, to be replaced by custom dual roof prism assembly)

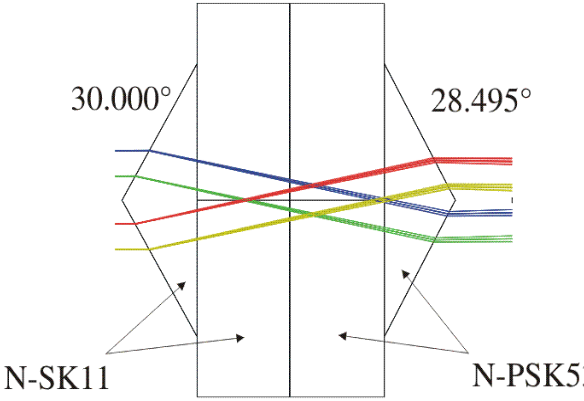
Detector: Ocam2k
Deep depletion EMCCD, 120x120 (binned), 3.7 kHz frame rate, photon-counting

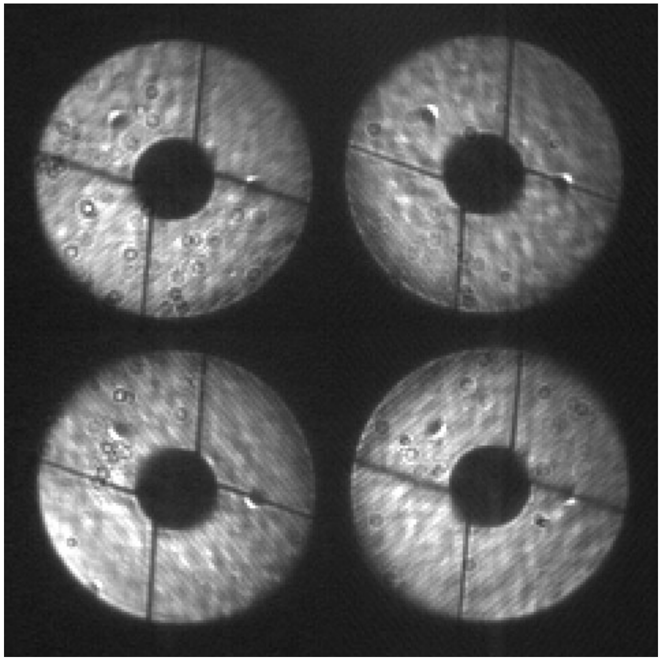
Can run with or without modulation:
- PZT tip-tilt mirror for modulation, amplitude selectable
- on-the-fly control matrix change for bootstrapping from modulation to no modulation
- Full image is multiplied by control matrix to include light diffracted by pyramid apex (14400 x 2000 matrix)

WFS operates in diffraction limited mode

Highly sensitive ((D/r0)^2 gain for TT over seeing-limited WFS)

Excellent closed loop performance



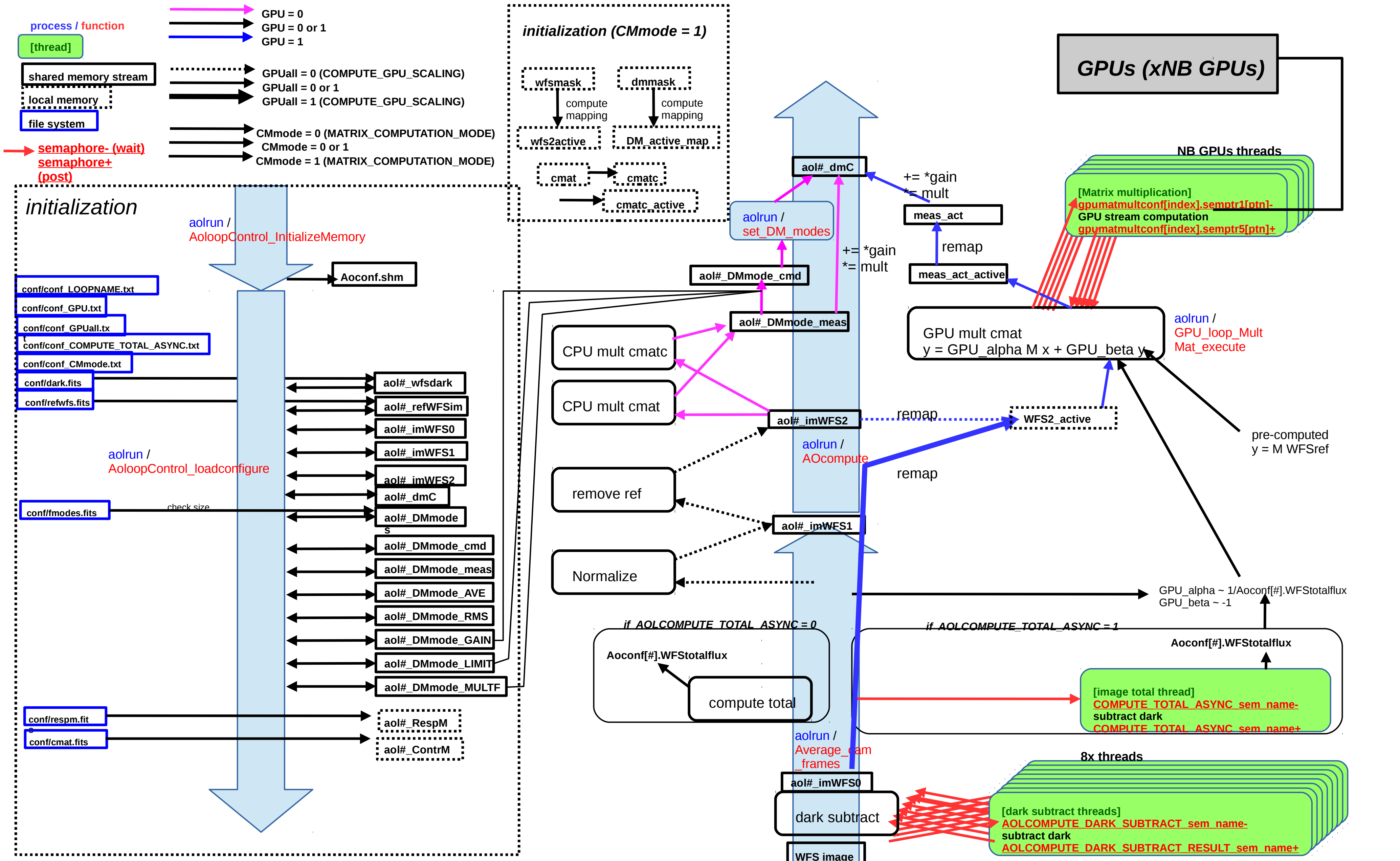


Real time control processes: CPU threads + GPUs (optional)

Heavy use of standardized shared memory image structure. Same code for LOWFS

Easy to add processes (monitoring, viewing, data logging, multiple loops offloads)

[code available at https://github.com/oguyon/AdaptiveOpticsControl]



Extreme-AO results (Apr 9, 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

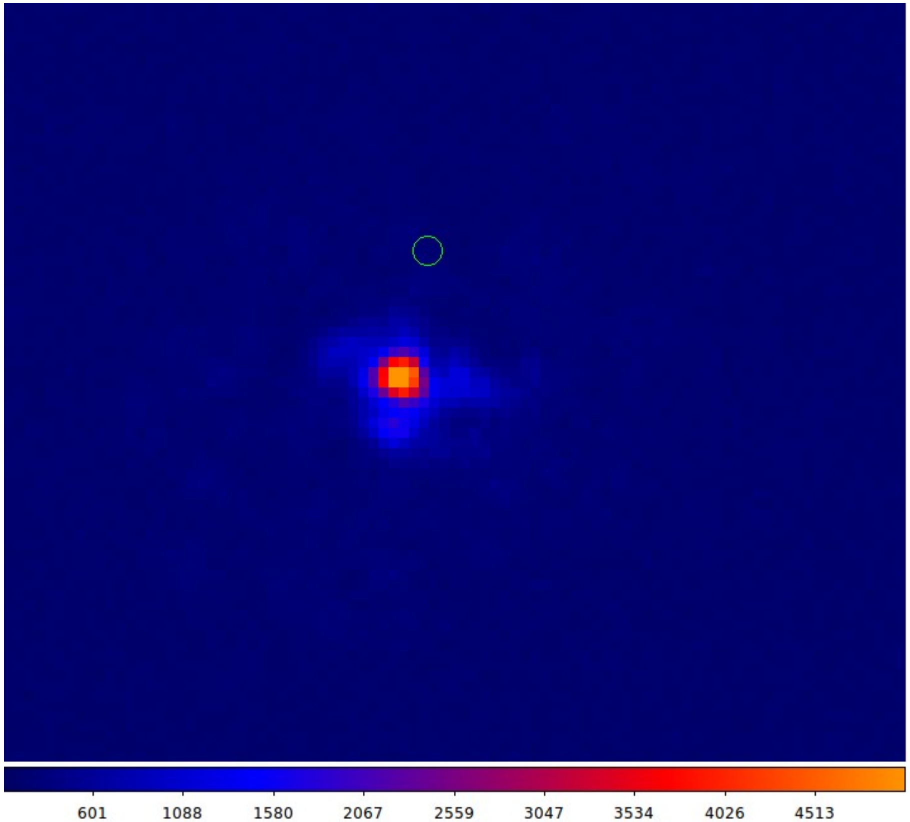


Image (left):

Single image of a diffraction limited PSF at 775 nm

PyWFS works at diffraction-limited sensitivity

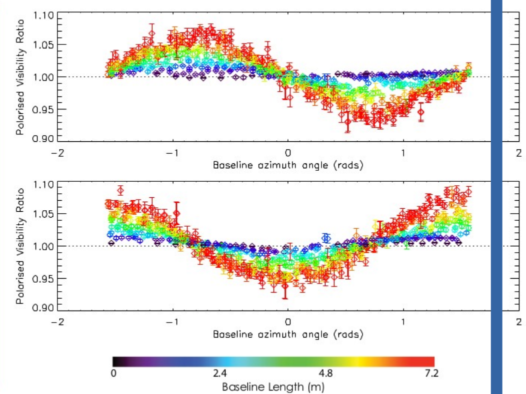
… down to I mag ~ 10 (to be confirmed with further observations)

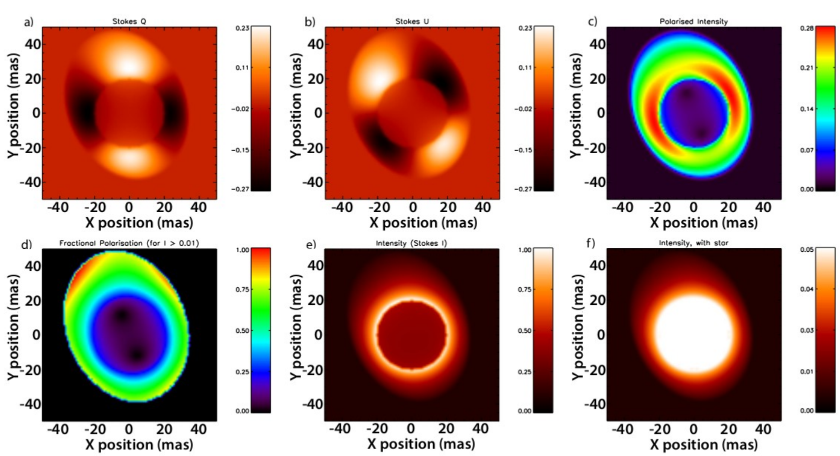
Enhanced visible light science capabilities

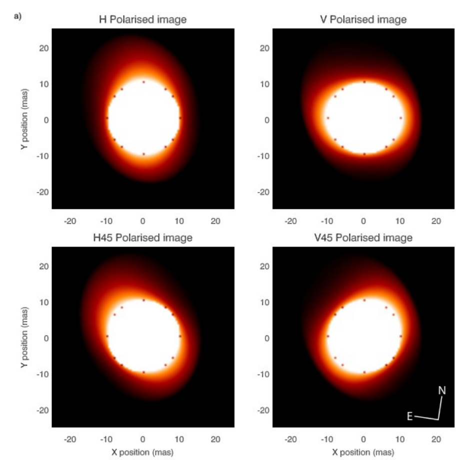
Current VAMPIRES capabilities - Sample commissioning data Sept 2014

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



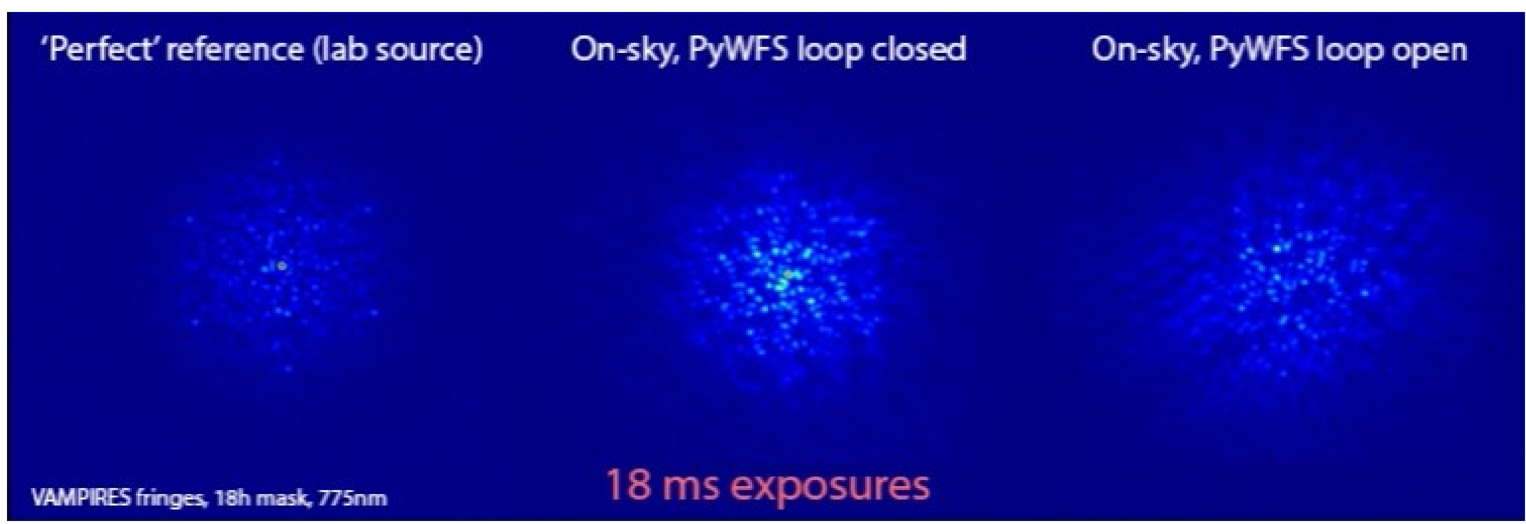




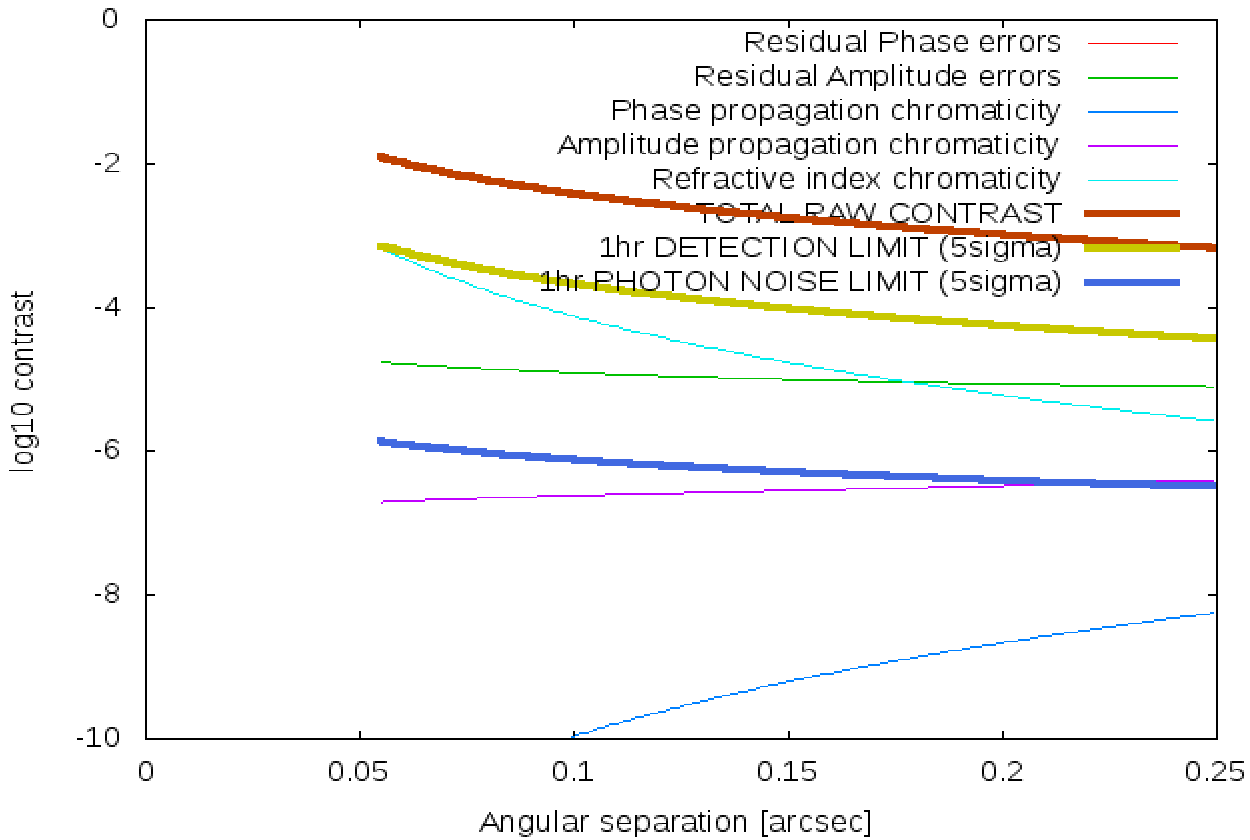
- Imaging
- Differential polarimetric interferometry (VAMPIRES)
- Spectro-interferometry (FIRST)

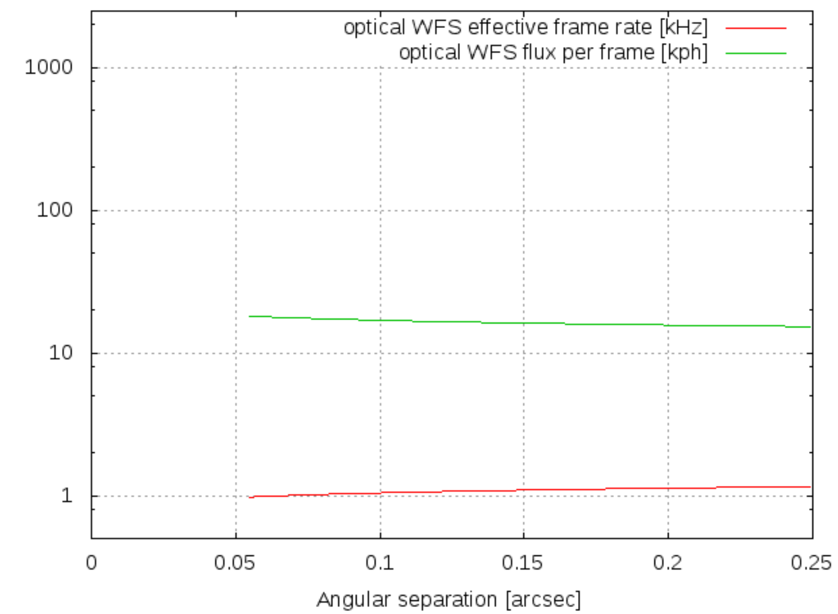
← Example science result VAMPIRES without Extreme-AO

Visible light diffraction limit greatly enhances FIRST and VAMPIRES science capabilities, and ability to achieve high precision on “faint” targets (I mag ~ 10)



8m: Seeing-limited WFS ExAO system





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"

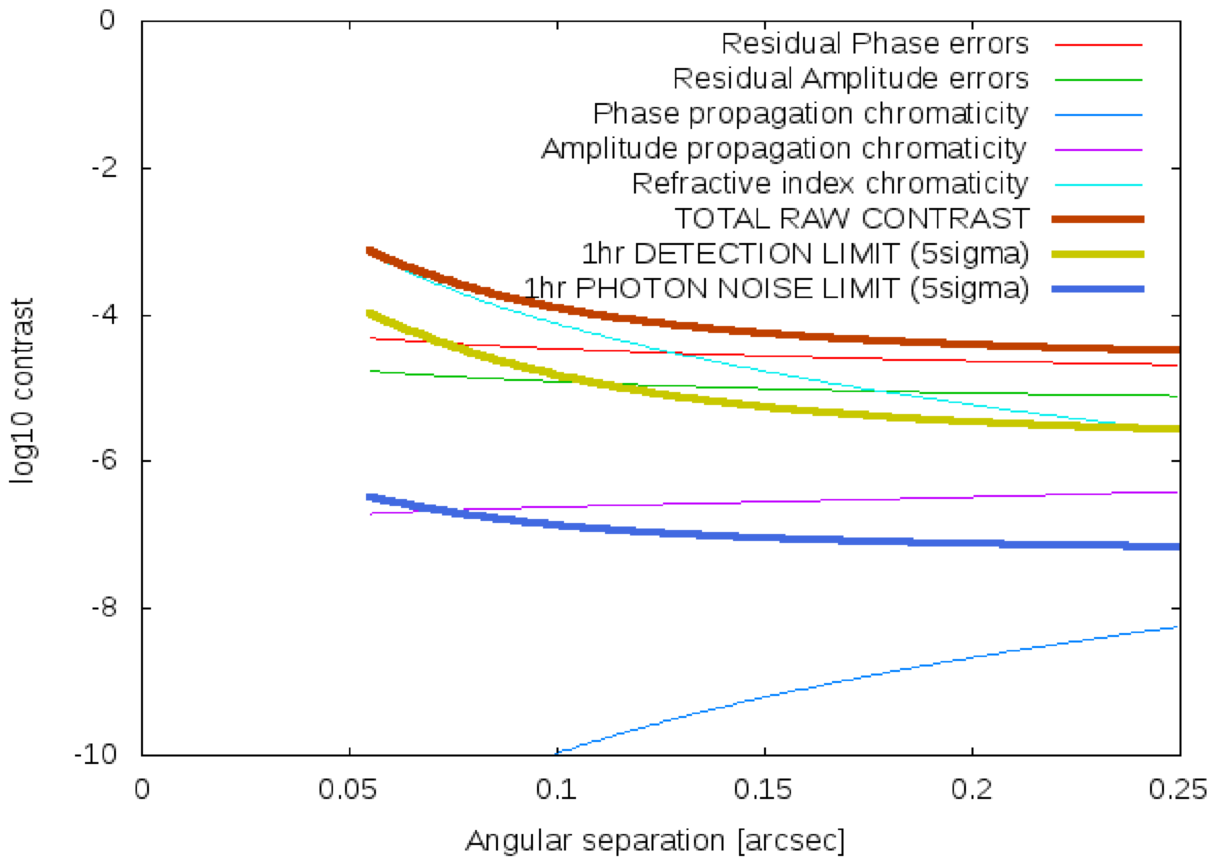
Assumptions:

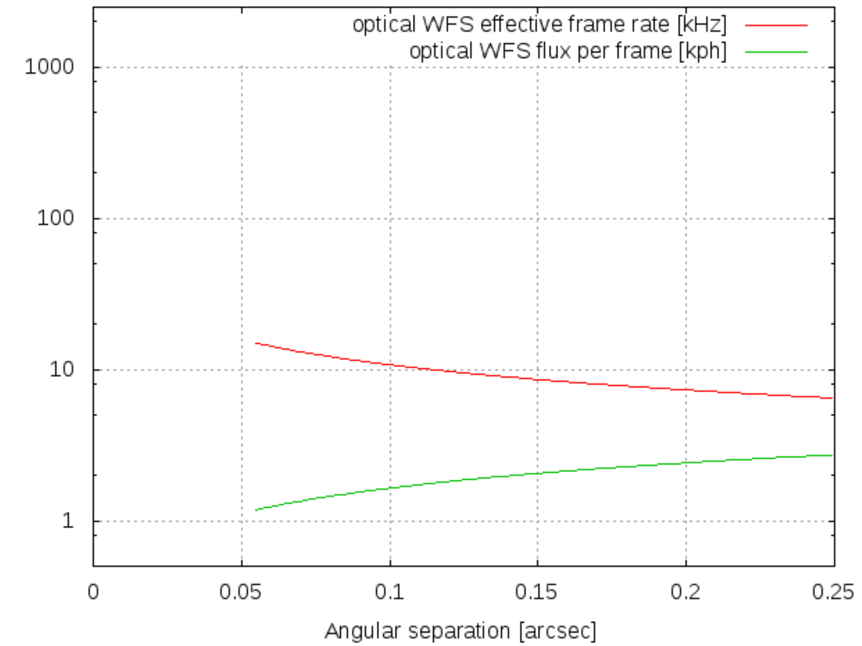
I mag = 8 (WFS > 100 targets)
H mag = 6 (Science)

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

8m: Diffraction limited WFS system





More sensitive WFS, can run faster (10kHz)

Limited by atmosphere chromaticity

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

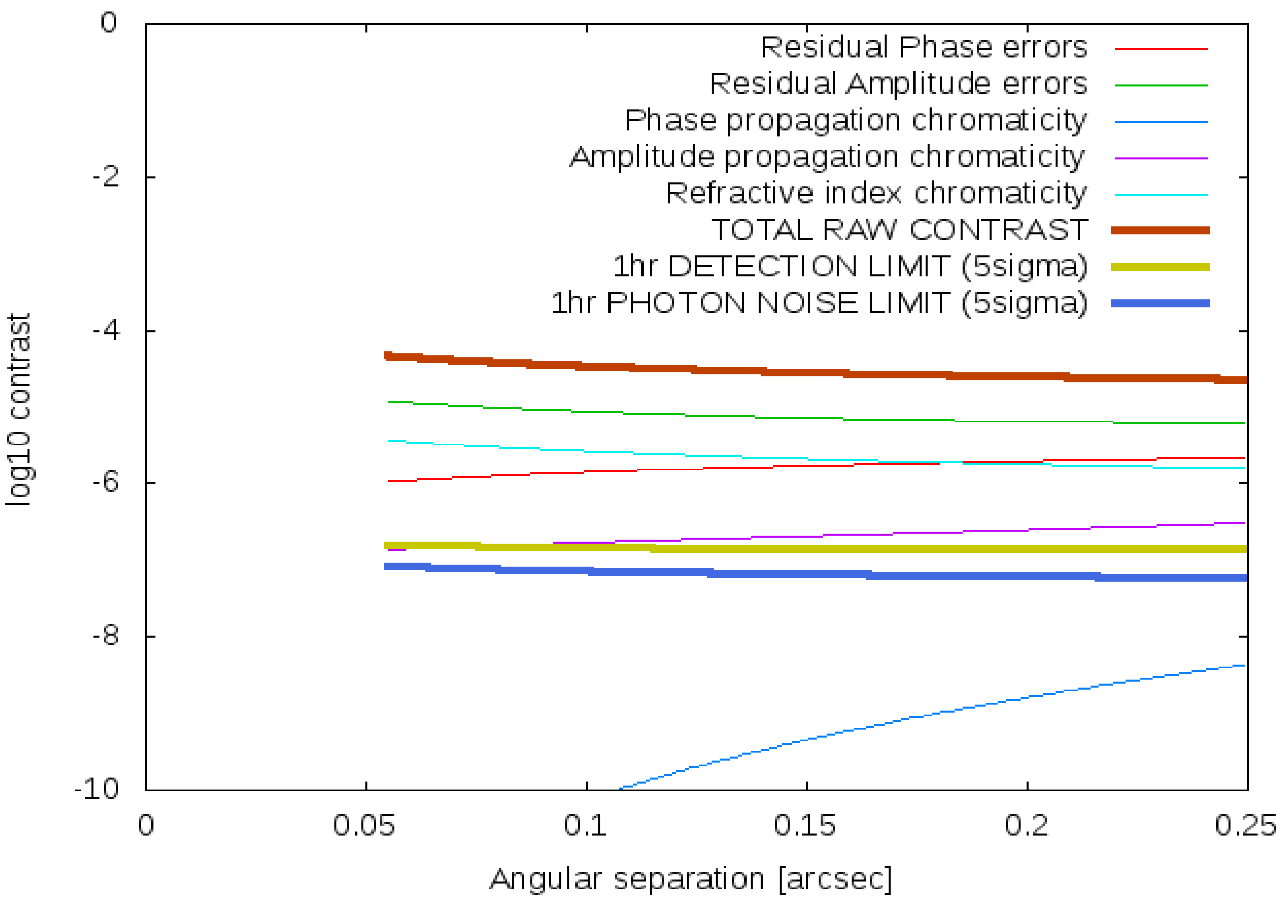
Assumptions:

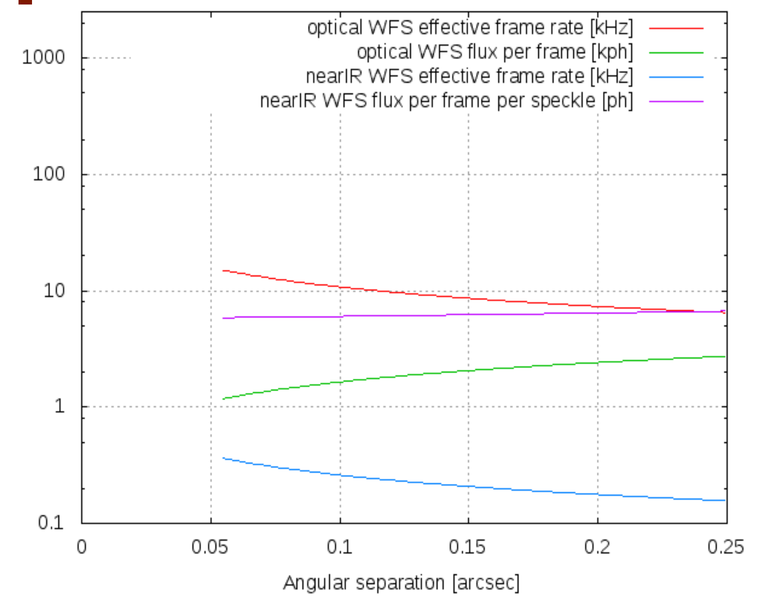
I mag = 8 (WFS > 100 targets)
H mag = 6 (Science)

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

8m: Diffraction limited WFS + near-IR 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 ~1e-7**
… and better for brighter stars

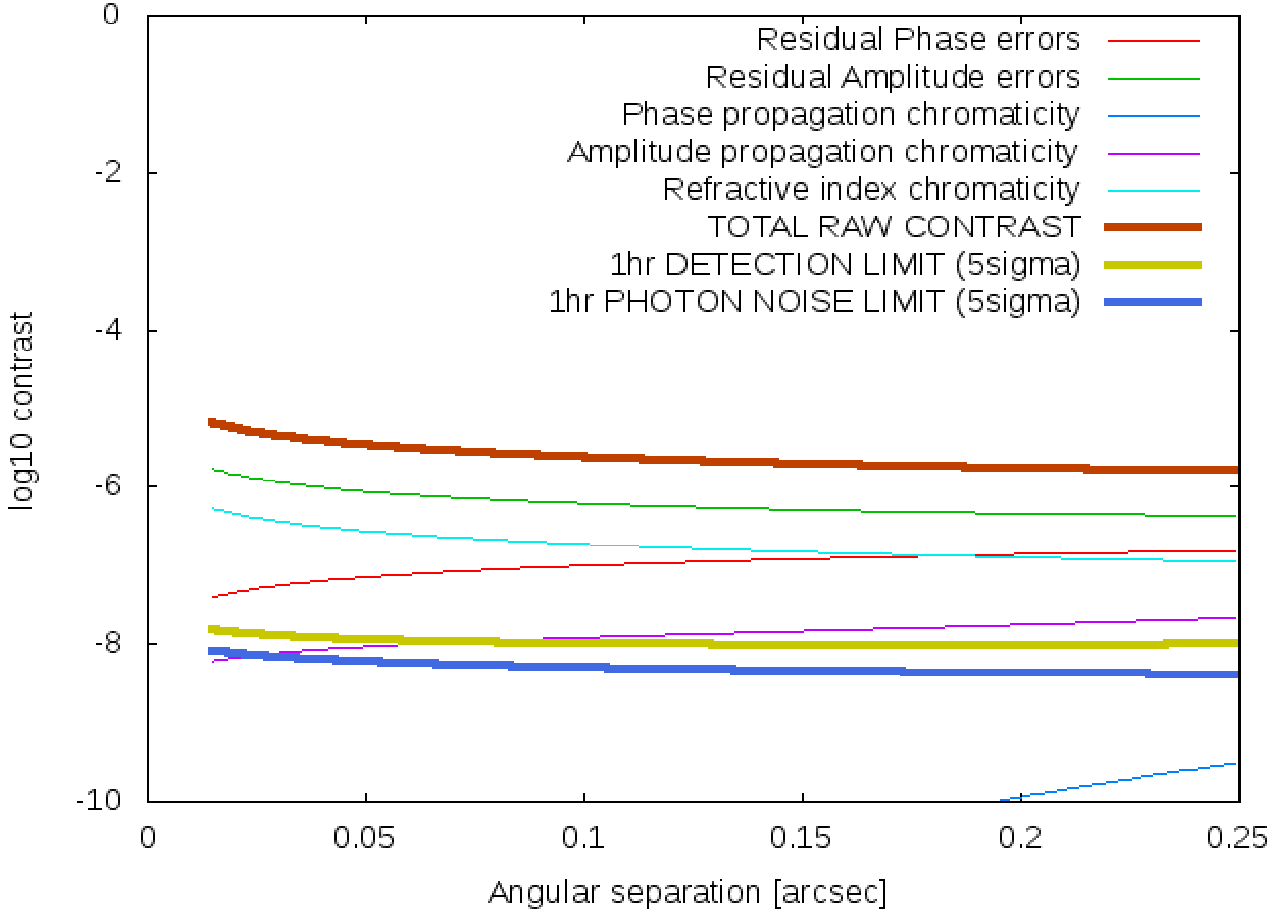
Assumptions:

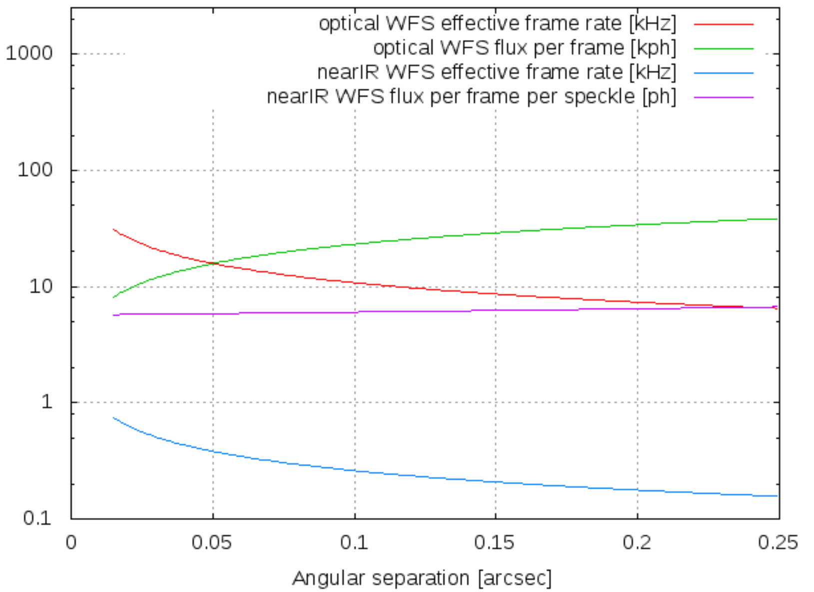
I mag = 8 (WFS > 100 targets)
H mag = 6 (Science)

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

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

MKIDs camera (CY 2016)

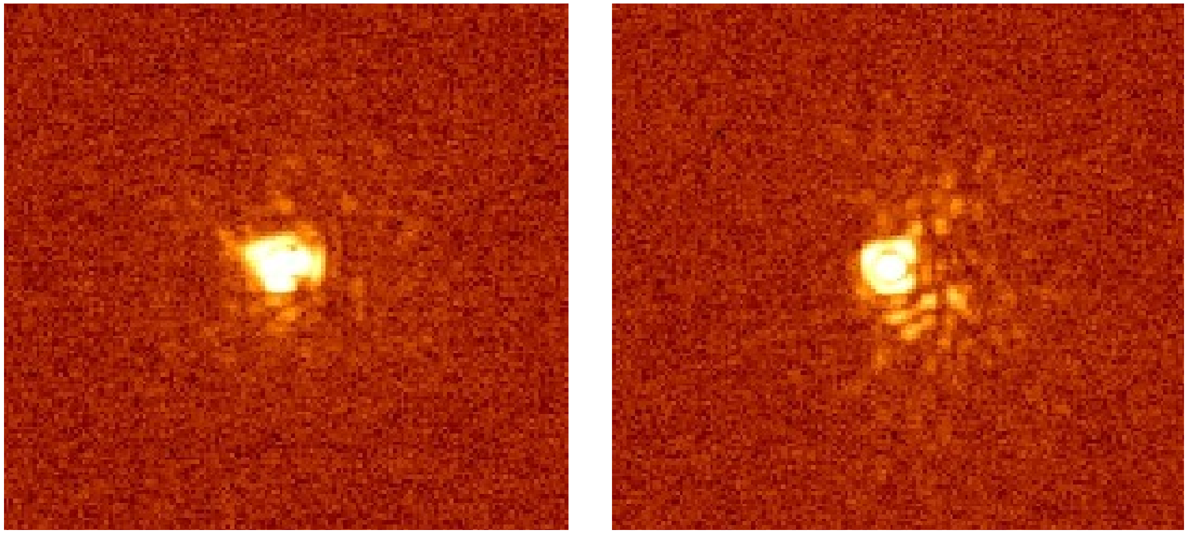
Build by UC Santa Barbara for SCExAO

NearIR photon counting with wavelength resolution
→ broadband light can be used for speckle control

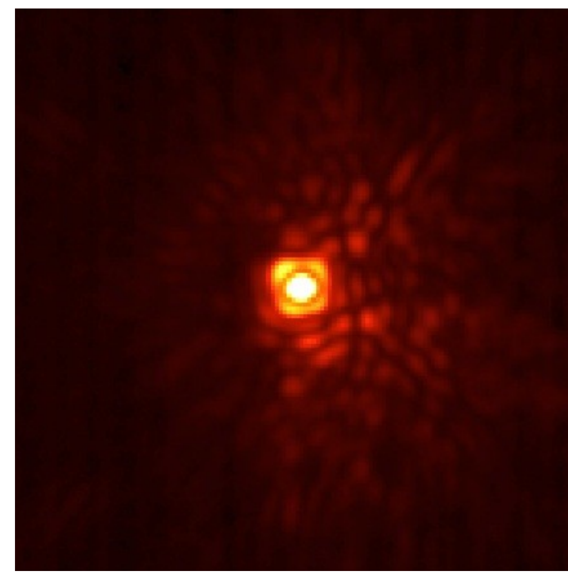
DM state updates issued from few ph/speckle at kHz speed

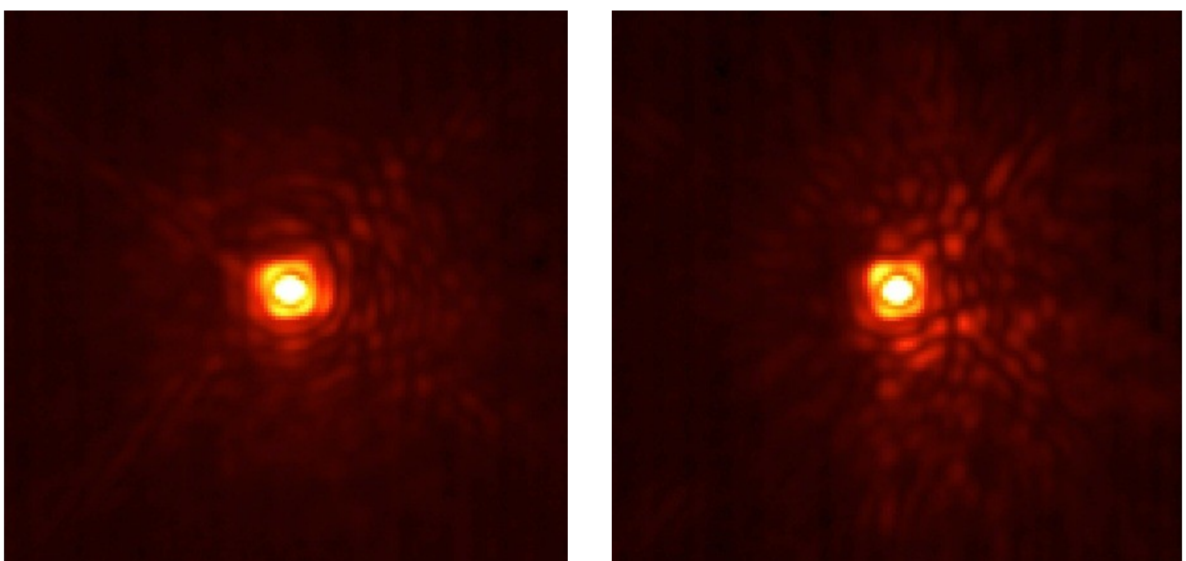
Speckle control results on-sky (June 2014)

Single frames: 50 us



Date: June 2nd
Target: RX Boo (also repeated on Vega)
Seeing: <0.6”
No Coronagraph



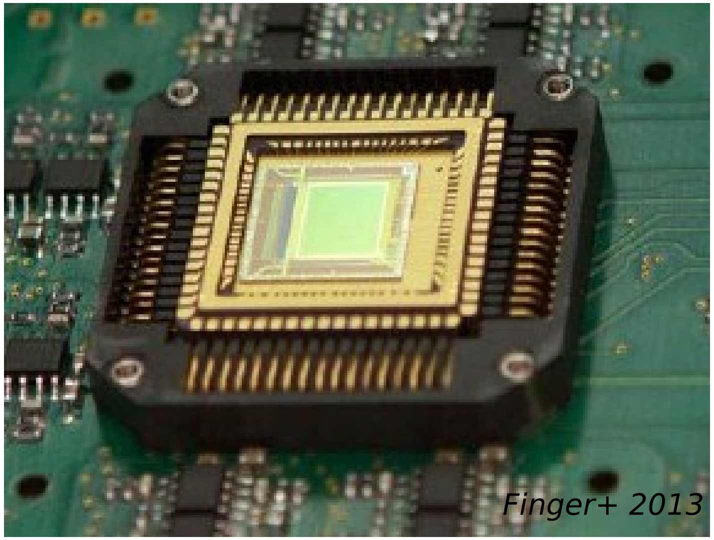


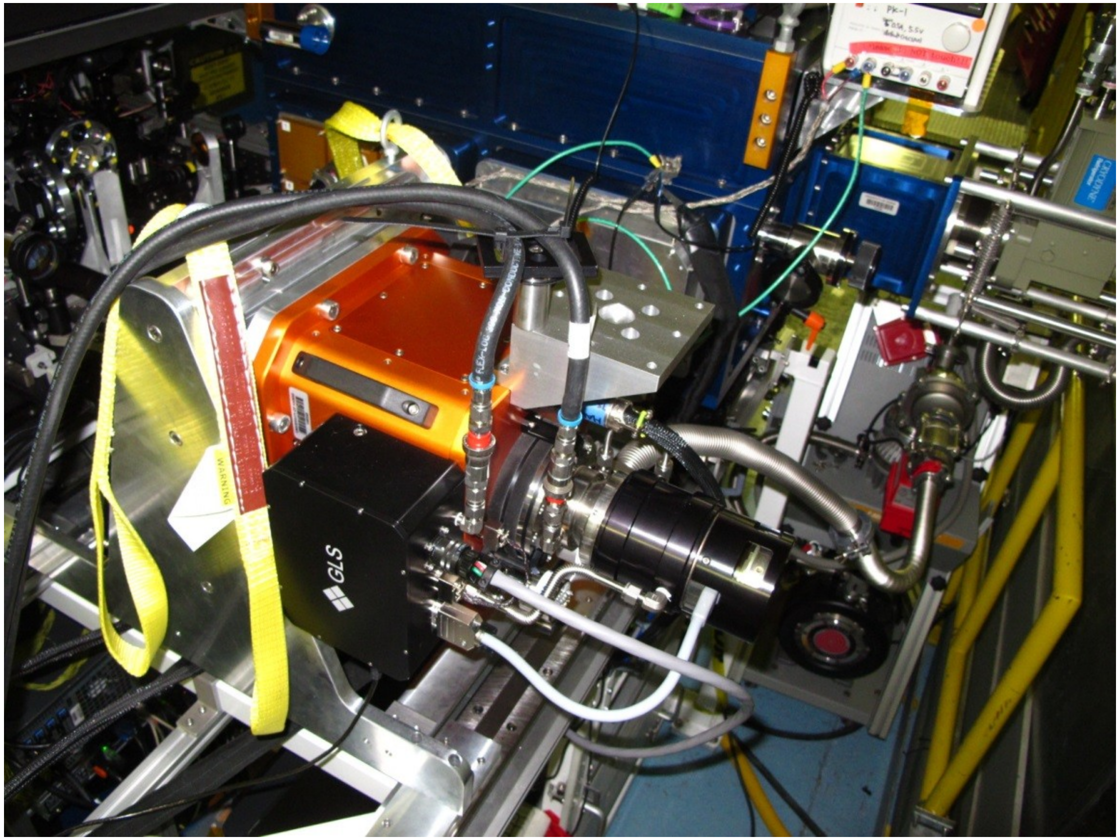
Sum of 5000 frames: shift and add

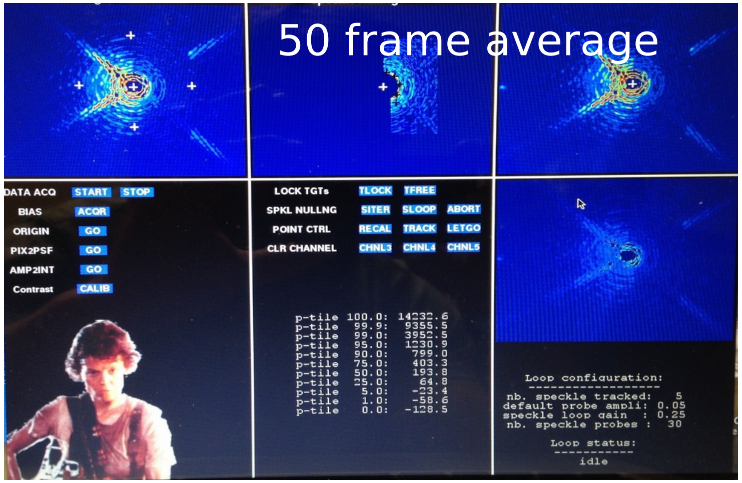
SAPHIRA Infrared APD array (S. Goebel PhD) [University of Hawaii IfA]

HgCdTe avalanche photodiode
manufactured by SELEX

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







Astrometric + photometric calibration (Jovanovic et al. 2015) Atmospheric Dispersion: real-time measurement & correction + water absorption/RI measurement (P. Pathak PhD)

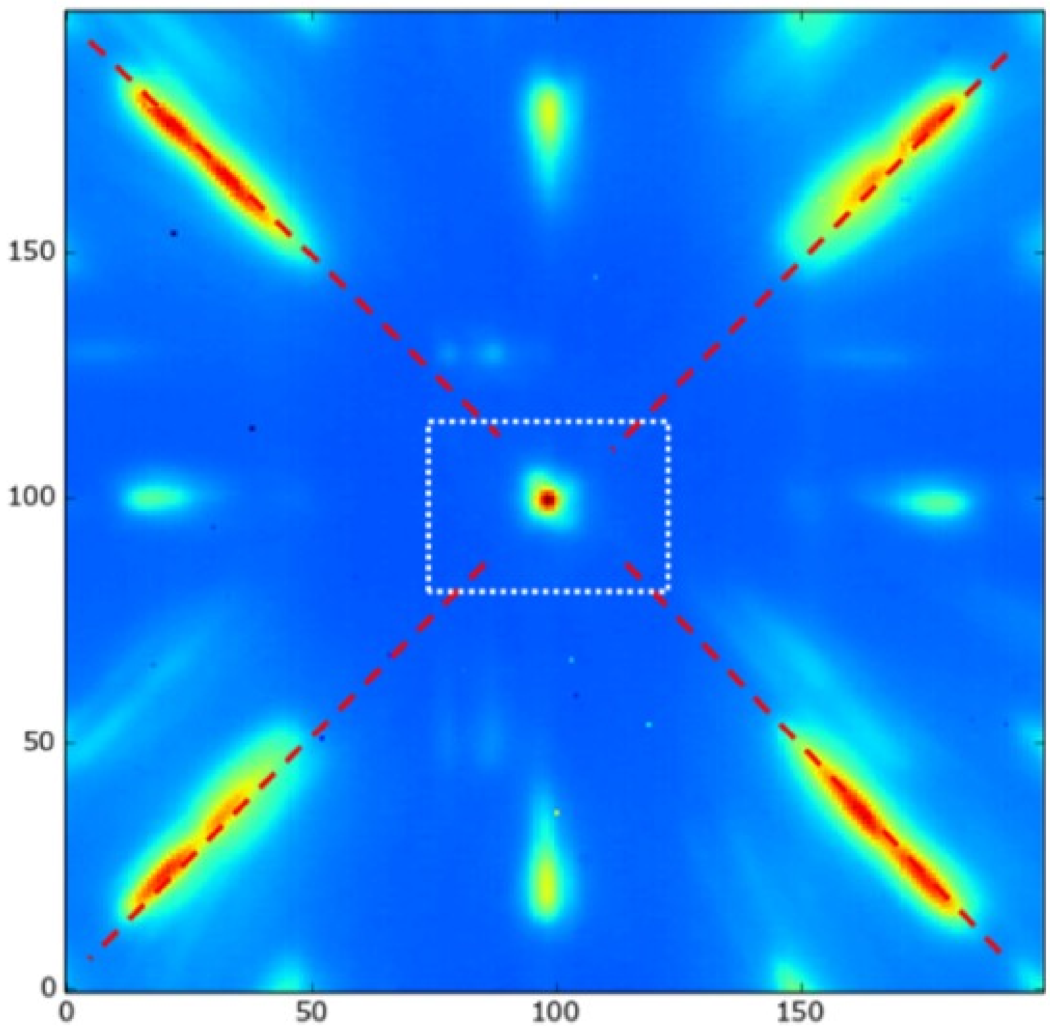


Figure 2: Speckles at 59⁰ Elevation

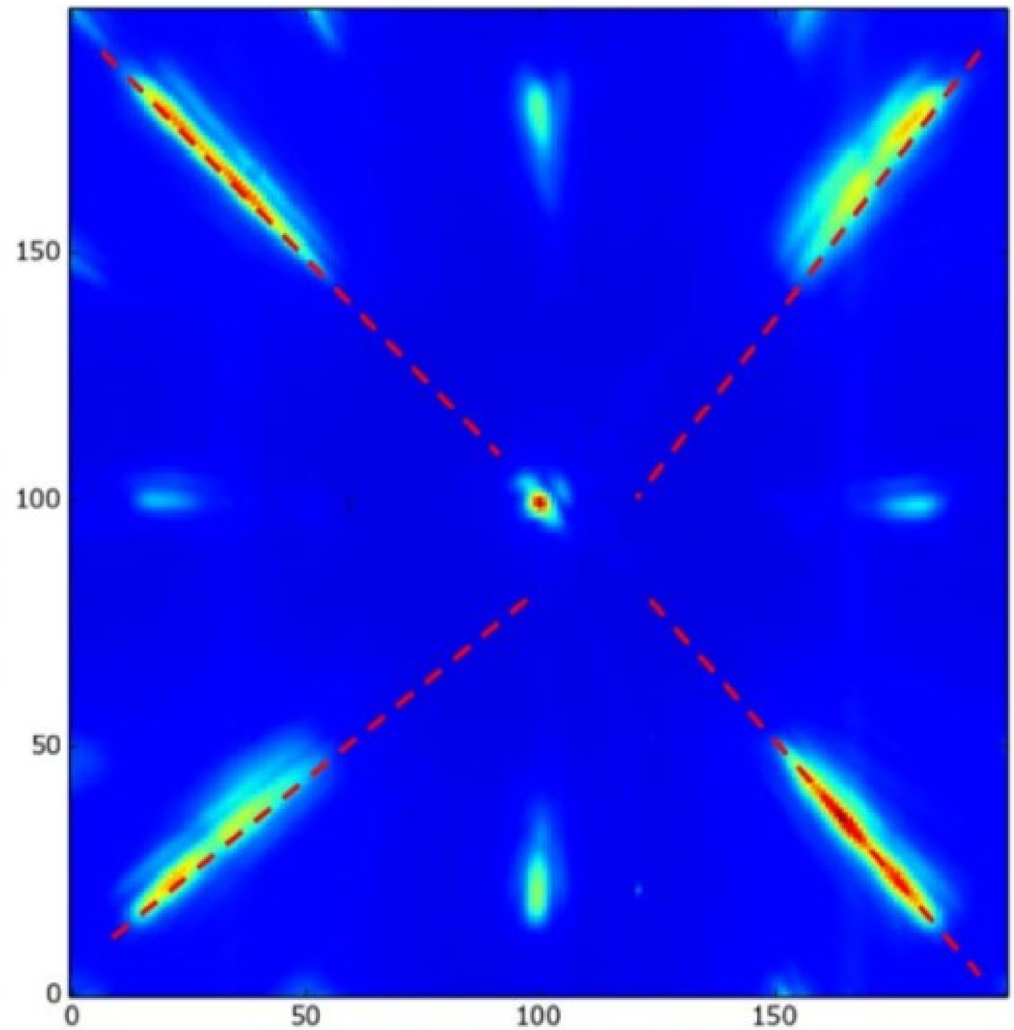
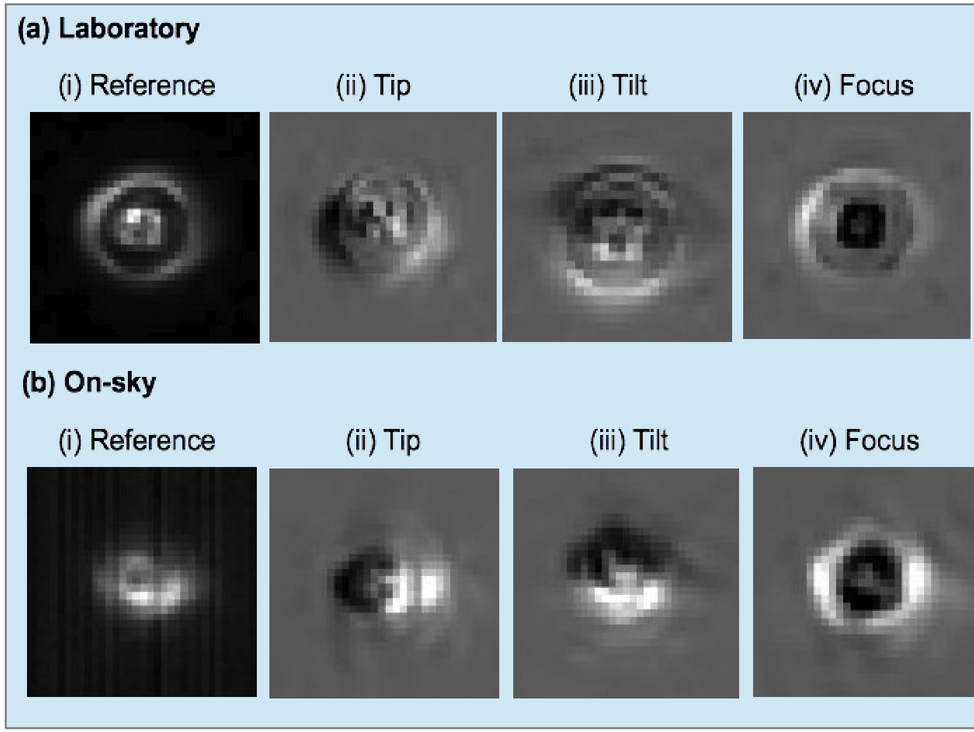


Figure 3: Speckles at 40⁰ Elevation

LLOWFS: Laboratory & On-sky

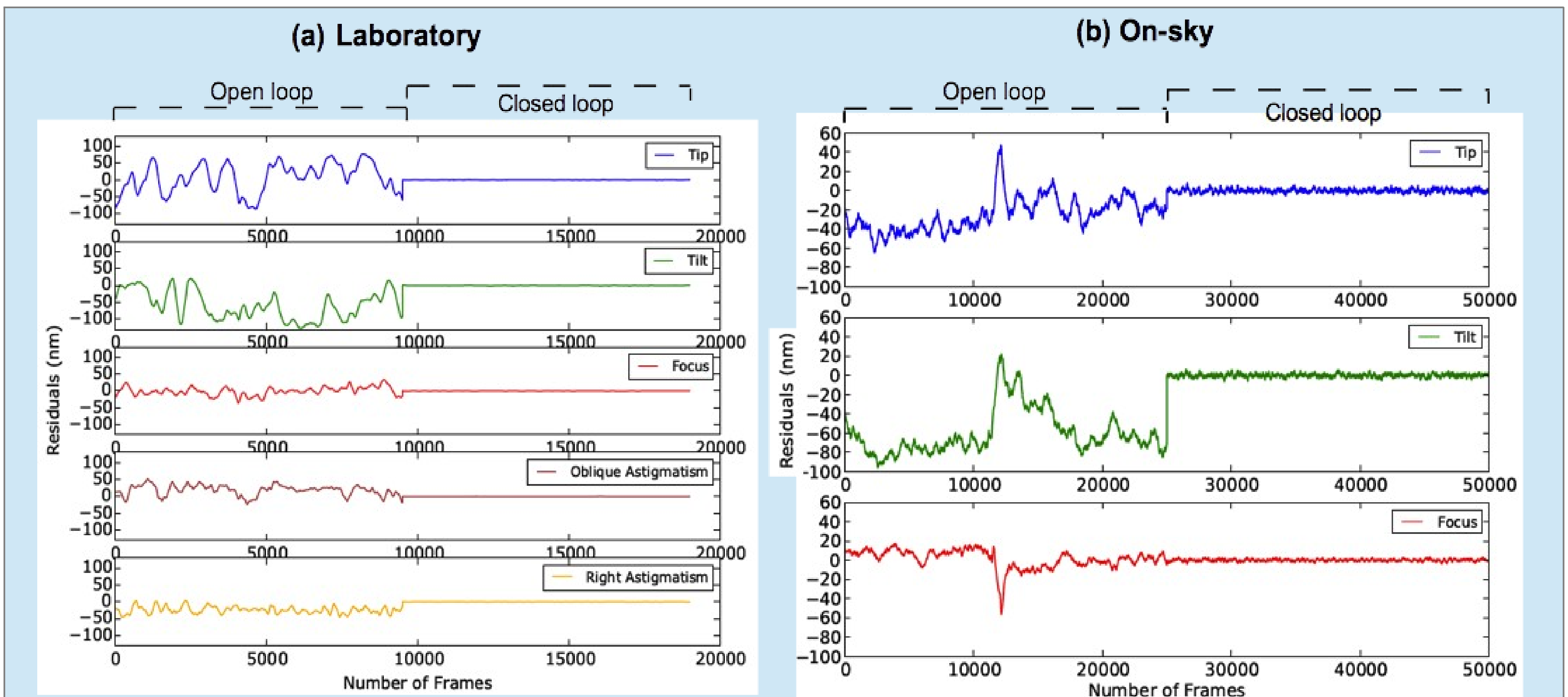
Note: Simulated dynamic turbulence with amplitude: 100 nm rms and wind speed: 10 m/s is applied upstream of the coronagraph with the Laboratory experiments



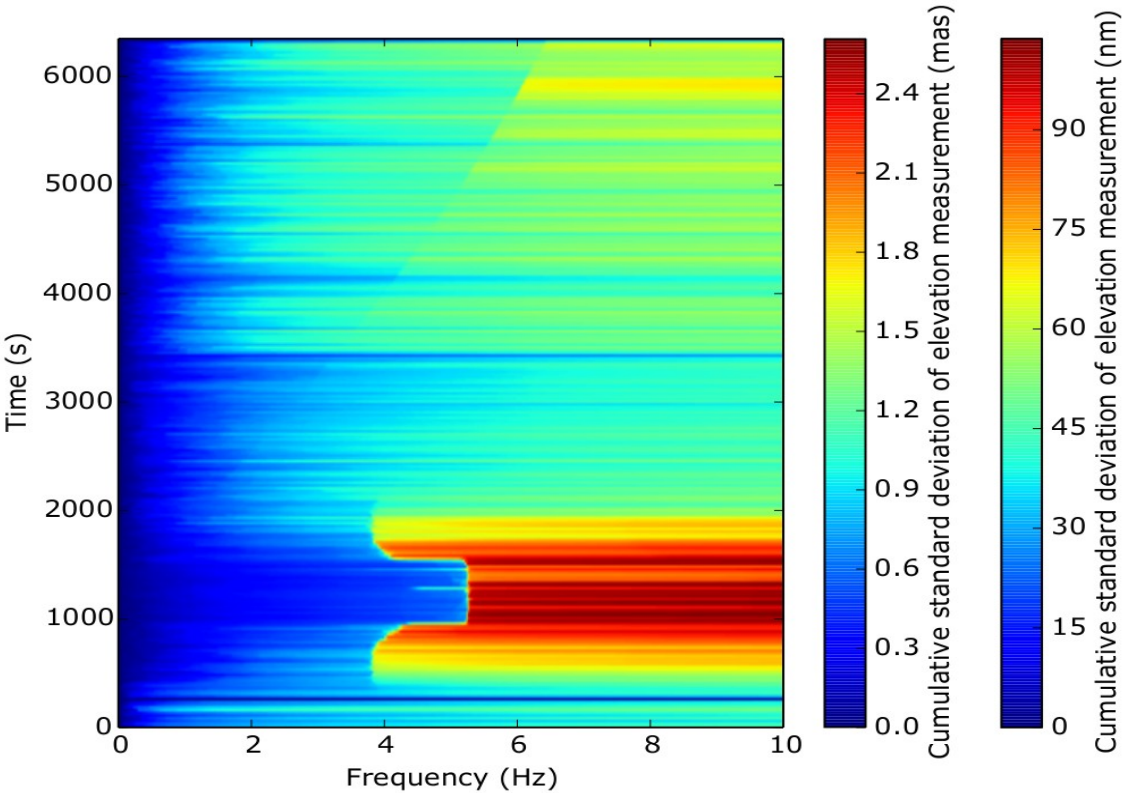
Response Matrix

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

Residuals



Vibrations: currently ~mas level

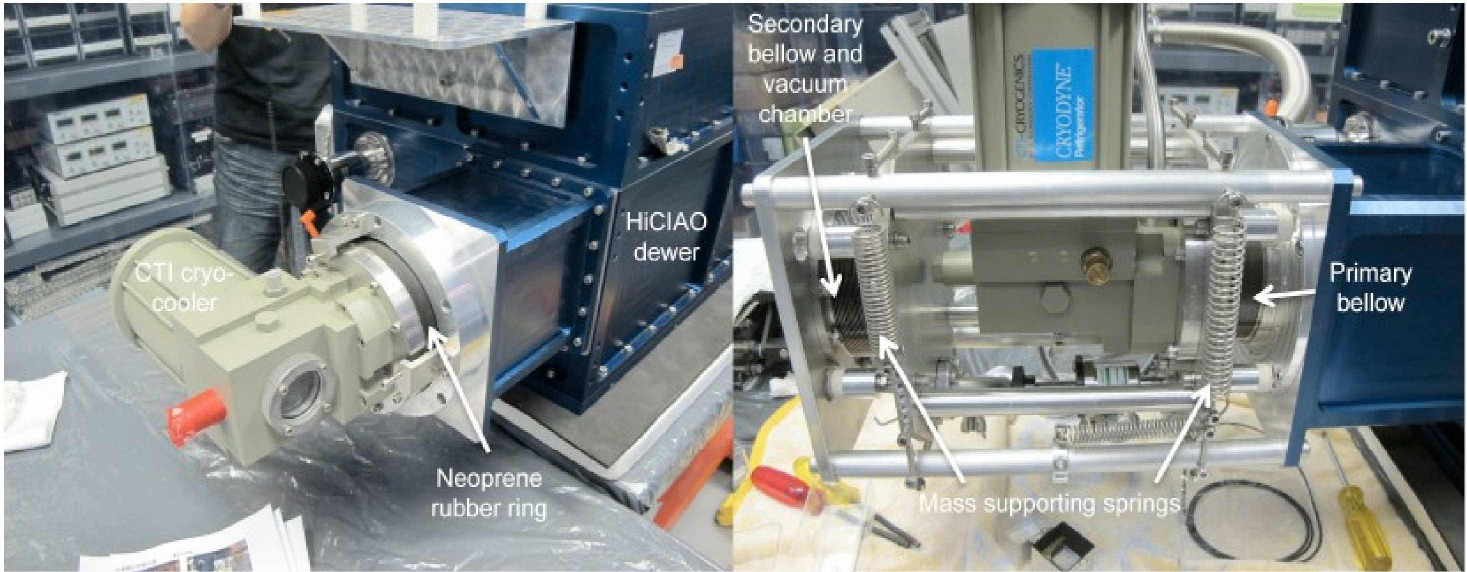


Measured residual vibration in nearIR

2 mas residual near transit
(due to telescope mount encoders)

[See Lozi et al. poster]

HiCIAO upgrade (2014) →



Conclusions

SCExAO available for use on Subaru → you can apply for time

check website (www.naoj.org → Instruments → SCExAO) for current status and capabilities / available modes

Current and future major activities in next 2 yr:

Hardware:

MKIDs (2016)

CHARIS IFS (2016)

Control & Software:

Integrating speckle control loop with Pyramid and LOWFS loops

Including predictive control in control loops

Including WFS telemetry in data processing (real-time estimation of coronagraph leaks and coherent light PSF features)

SCExAO as a visitor instrument on TMT: Preparing scientific and technical plan

Top priority: demonstrating on Subaru on-sky performance corresponding to habitable planet imaging on TMT

Other presentations:

N. Jovanovic (current status)
J. Kuhn (Vector Vortex)
T. Groff (CHARIS IFS)
J. Hagelberg (early science)
J. Lozi (LOWFS, jitter control)
E. Huby (FIRST module)
T. Currie (early science)