Subaru Coronagraphic Extreme Adaptive Optics

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SCEXAO team

Feb 26, NAOJ / Mitaka

Subaru Coronagraphic Extreme-AO (SCExAO)

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VAMPIRES
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AMES RESEARCH CENTER
NASA
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AO188
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M. Galvin
M.A. Peters
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COCORO
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M. Tamura
HOKKAIDO UNIVERSITY
NAOJ National Astronomical Observatory of Japan
Kyoto University, Founded 1897

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VECTOR VORTEX
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FIBER INJECTION
T. Kotani
H. Kawahara
N. Cvetojevic
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MKIDS
B. Mazin
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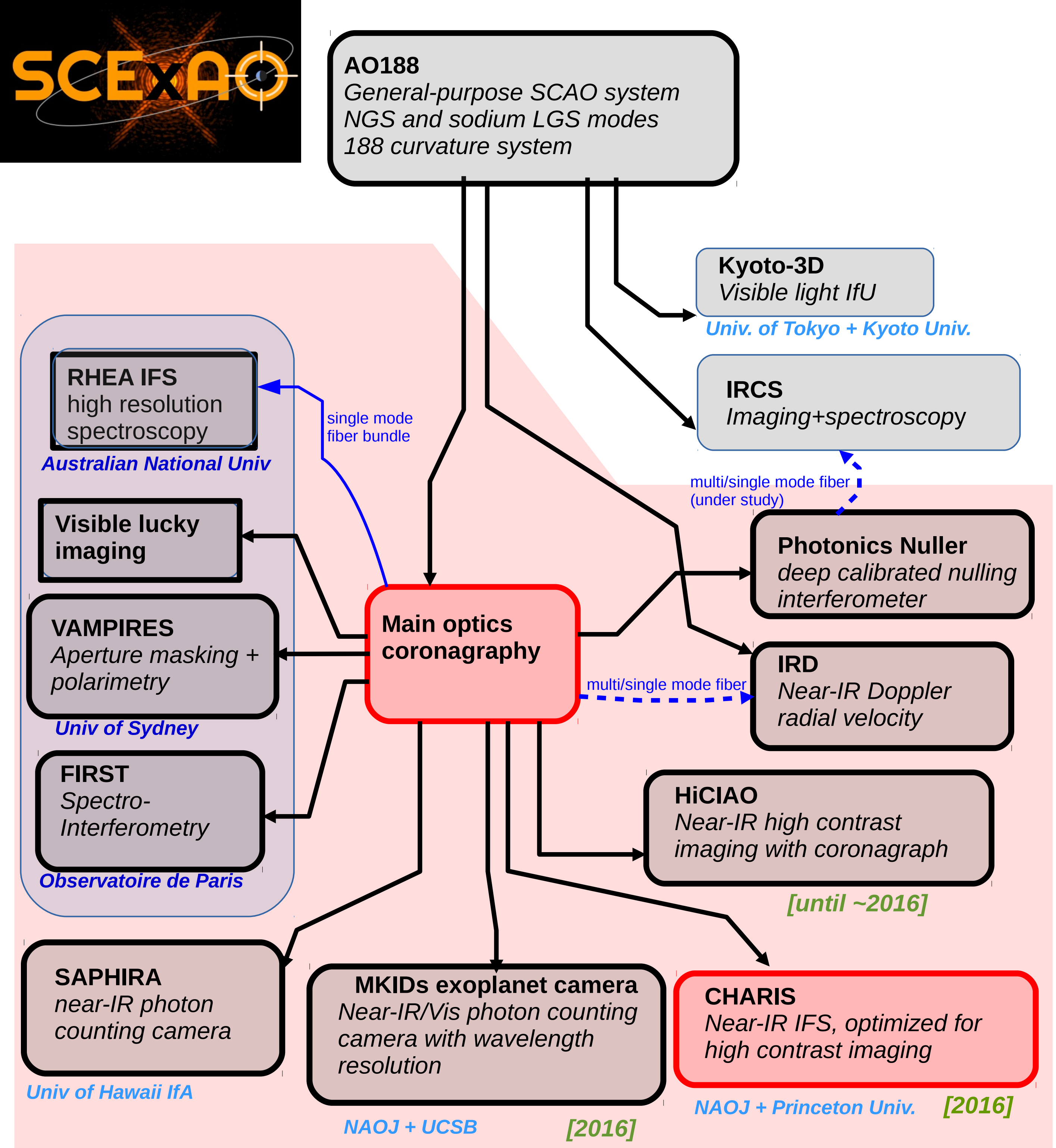
SAPHIRA
S. Goebel
D. Hall
D. Atkinson
M. Chun
Institute for Astronomy University of Hawaii

EI DETECTORS
H. Mohseni
M. Ulmer
Northwestern



SCExAO is a central part of Exoplanet instrumentation at Subaru Telescope

Together with its modules and IRD, it provides Subaru Telescope with unique and broad exoplanet discovery and characterization capabilites

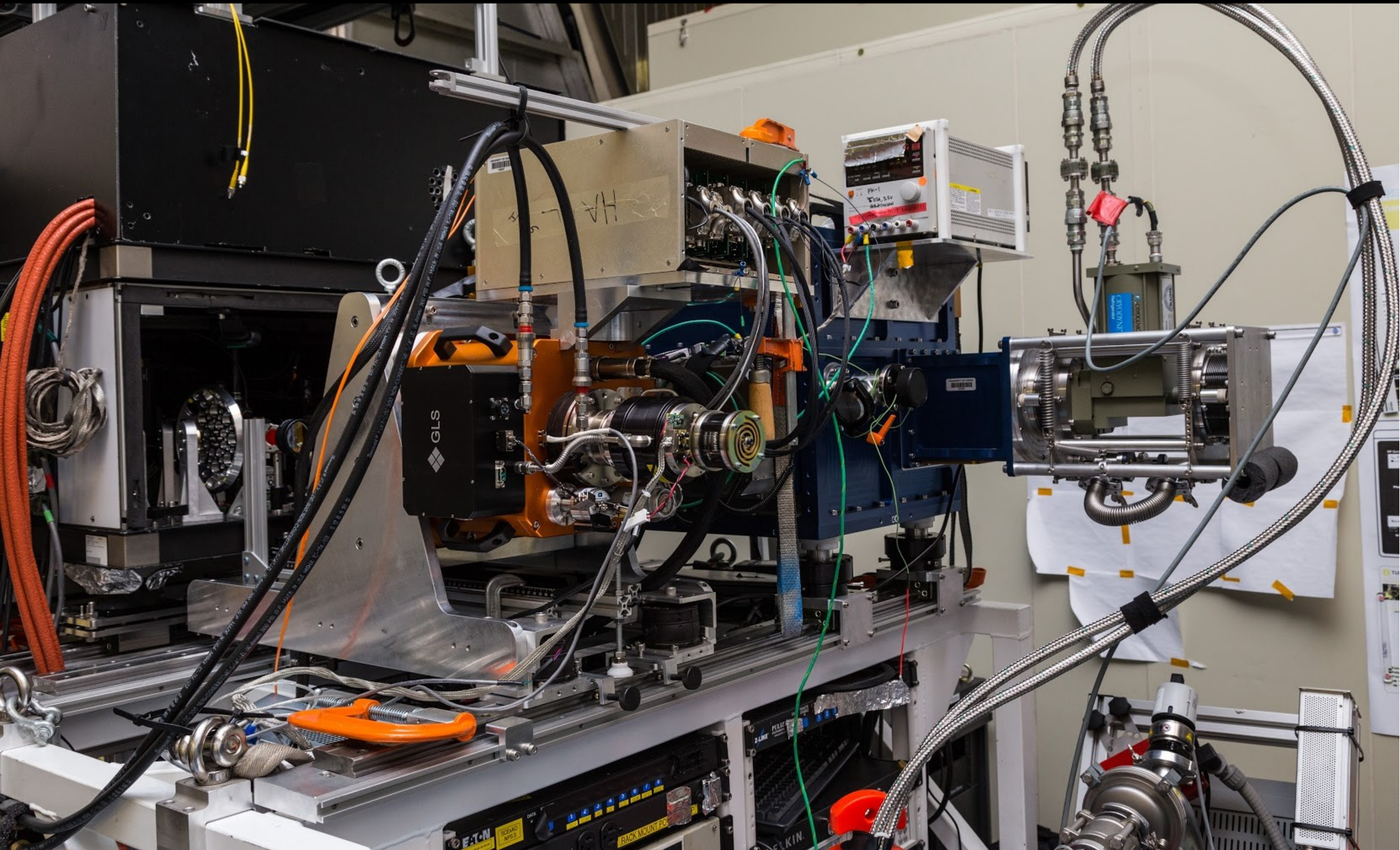
We are preparing SCExAO to be visitor instrument on TMT

OPTIMIZED FOR SMALL IWA (<0.1 arcsec)
→ reflected light giant planets on Subaru
→ Earths around M-type stars on TMT

Subaru Coronagraphic Extreme Adaptive Optics

SCExAO

Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics

Wavefront sensing:

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

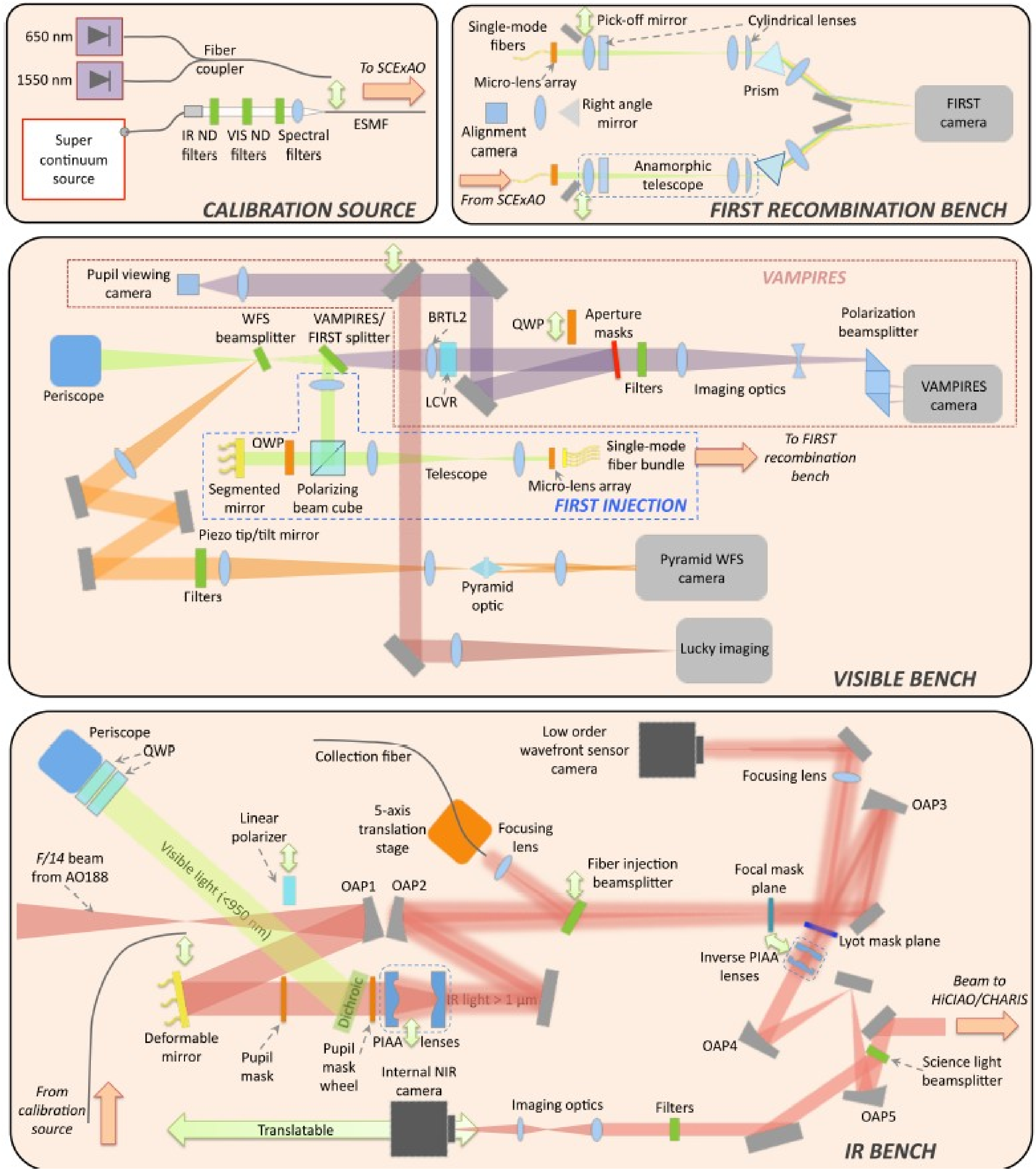
2k MEMS DM

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

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

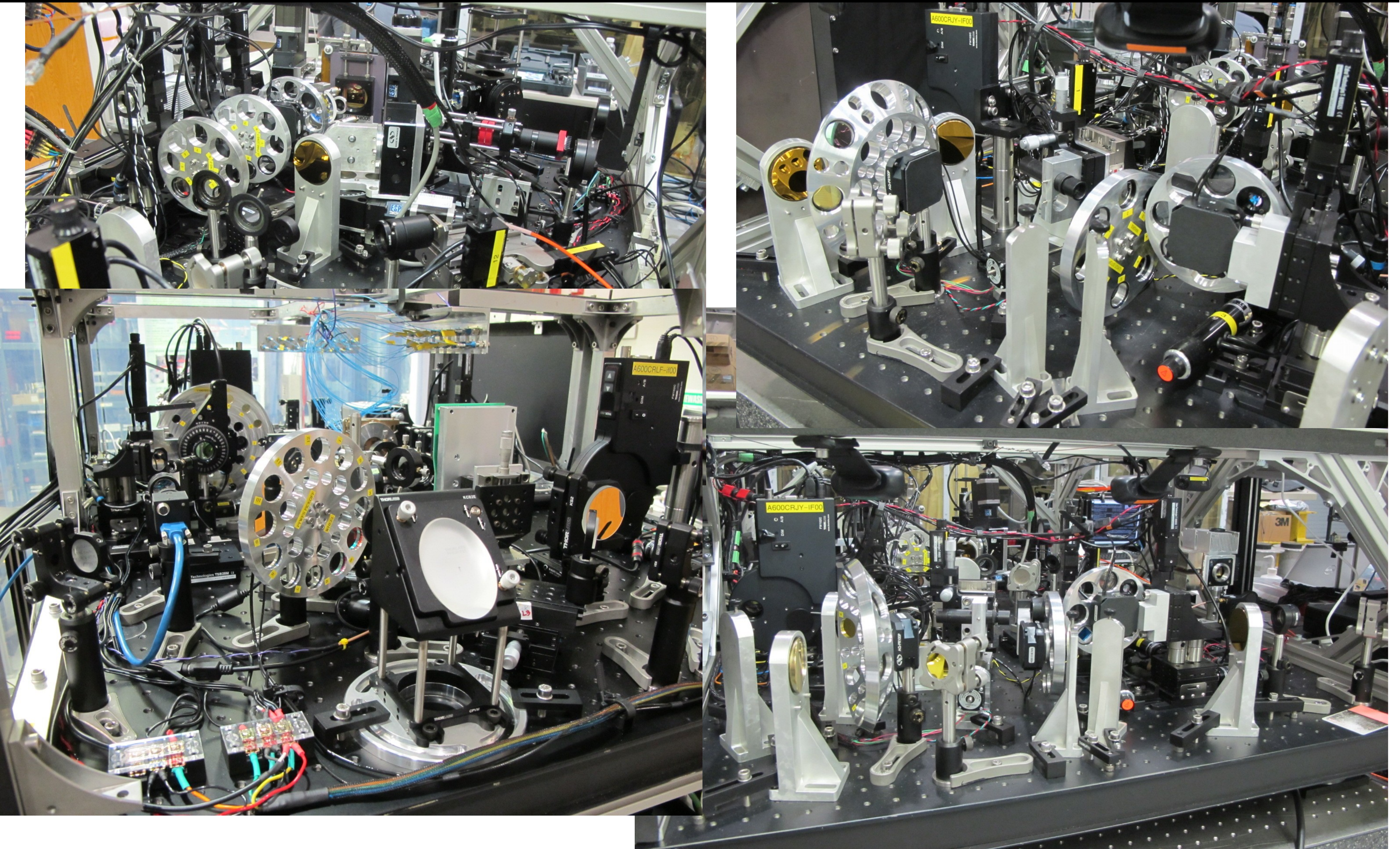
Fibered Imager for a Single Telescope (FIRST) (VIS)
Fourier Lucky imaging (VIS)

Broadband diffraction limited internal cal. Source + phase turbulence simulator



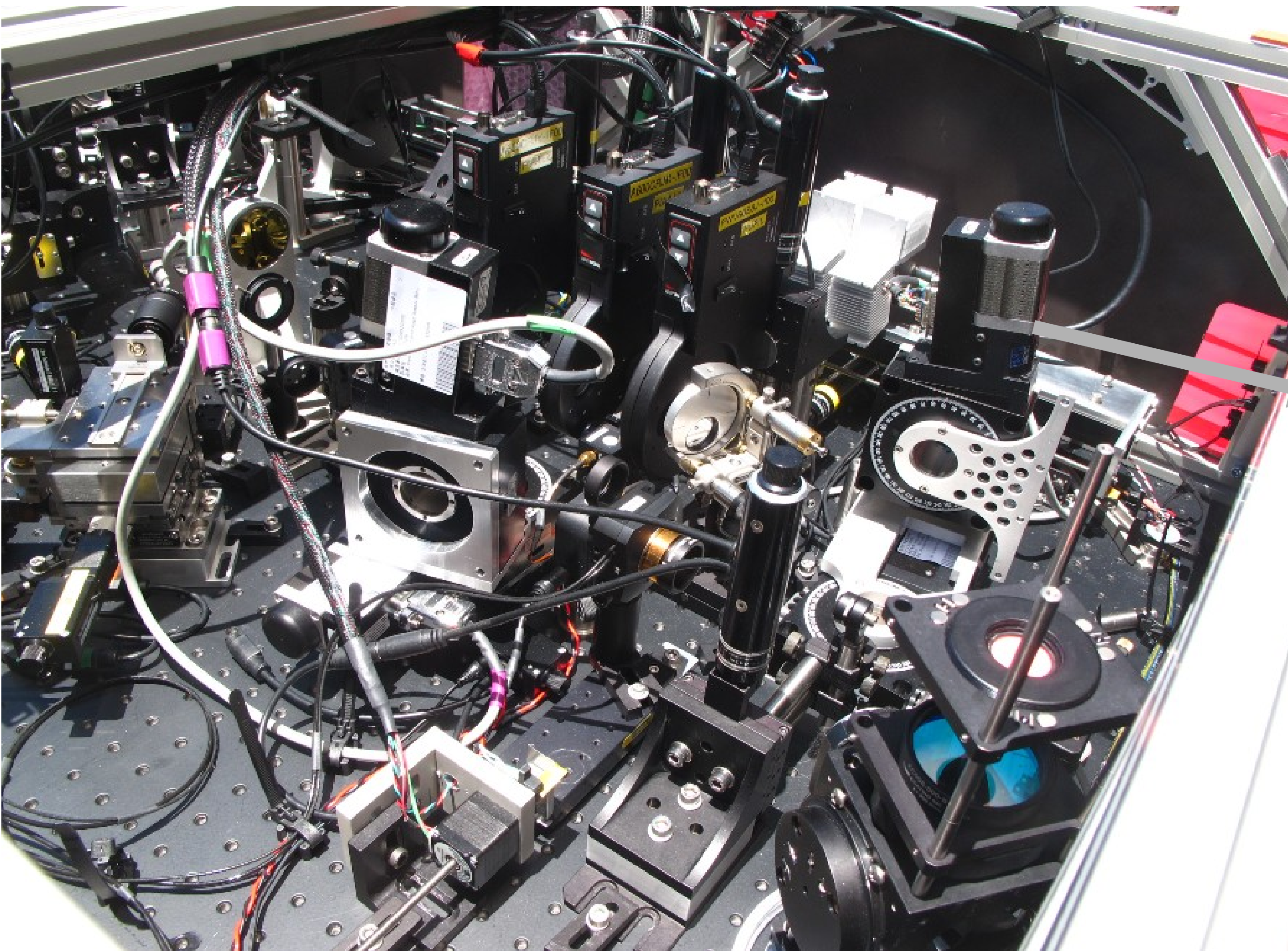
SCExAO

Subaru Coronagraphic Extreme Adaptive Optics

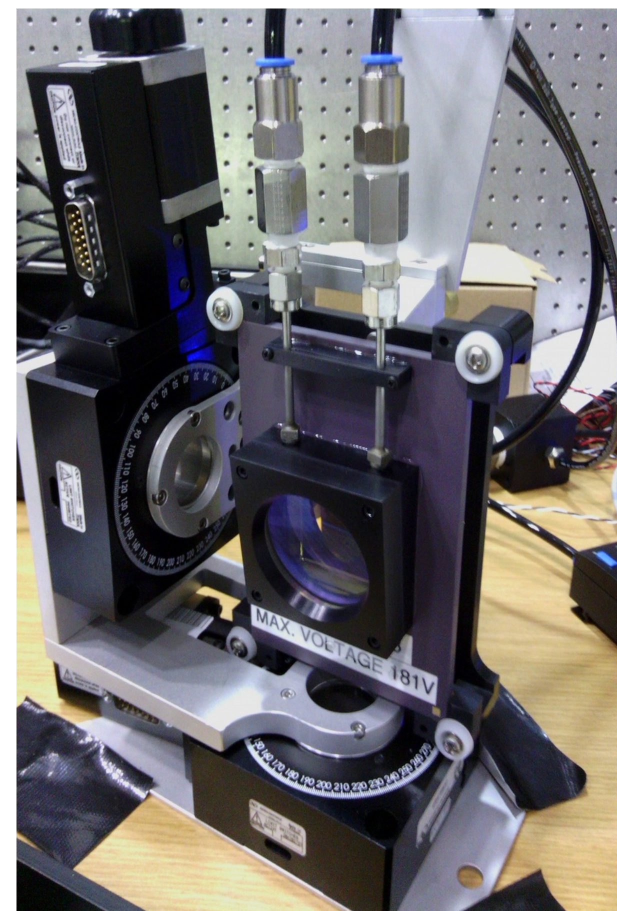


Subaru Coronagraphic Extreme Adaptive Optics

Coronagraphs



Deformable mirror



Extreme-AO loop

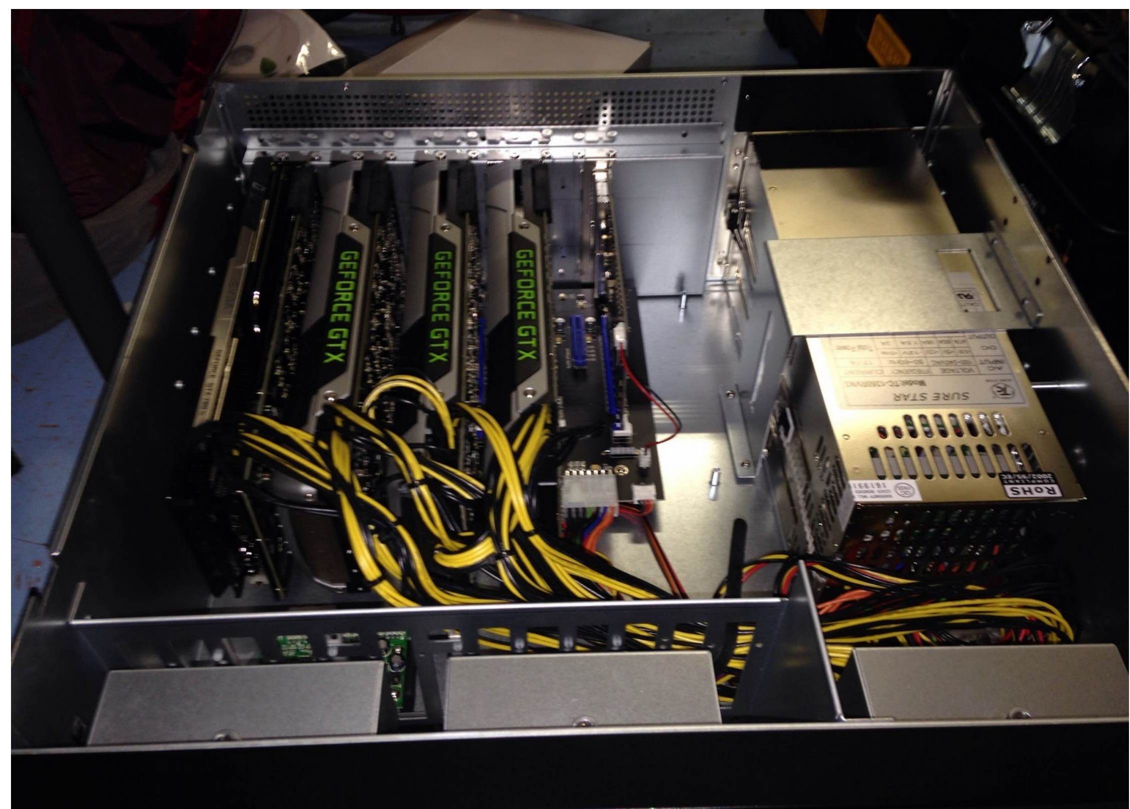
2000 actuators MEMs DM running at 3.6 kHz (fastest ExAO system)
deep depletion EMCCD → very sensitive

Now reaching 80% SR in H under challenging conditions (m=7 star, 50mph wind)

Recent upgrade allows 3.6kHz loop operation with zonal and modal reconstruction
→ low-latency control
→ modal reconstruction for predictive / LQG control (under development)

SCExAO uses 25,000 cores running >1GHz

One of two GPU chassis



How SCExAO achieves high contrast

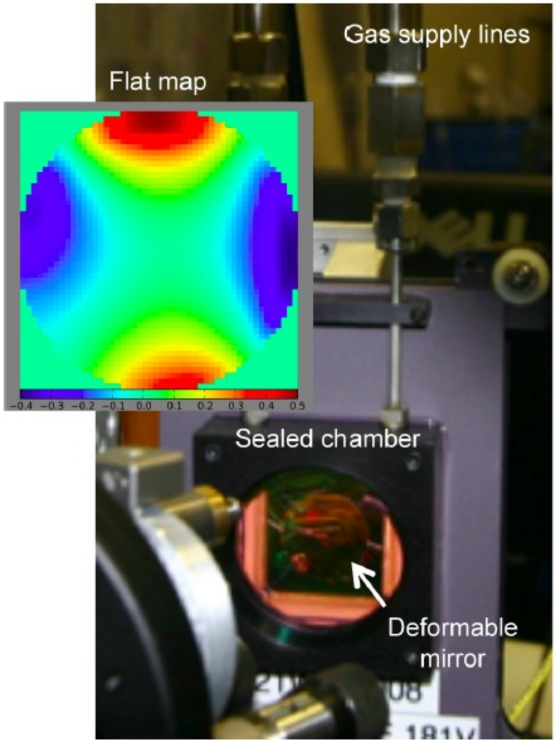
(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits r>1 l/D region

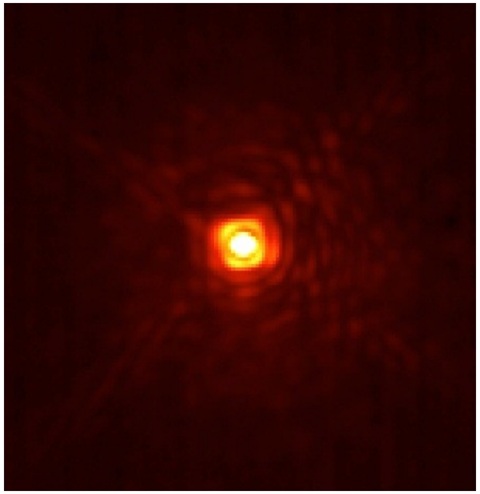
(2) Extreme-AO with fast diffraction-limited WFS
→ removes wavefront errors

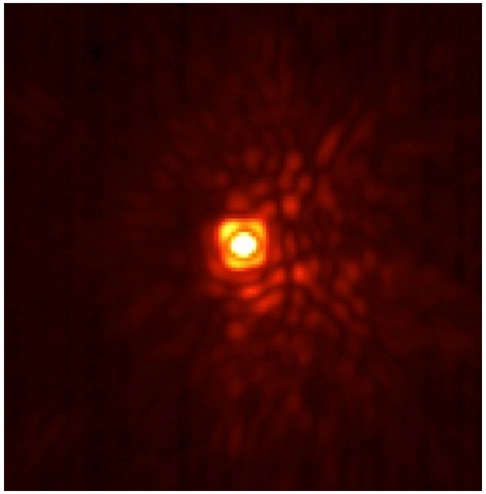
(3) Near-IR LOWFS
→ keeps star centered on coronagraph and controls Focus, Astig, etc..
→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control
→ modulates, removes and calibrates residual speckles

Requires fast low-noise detectors







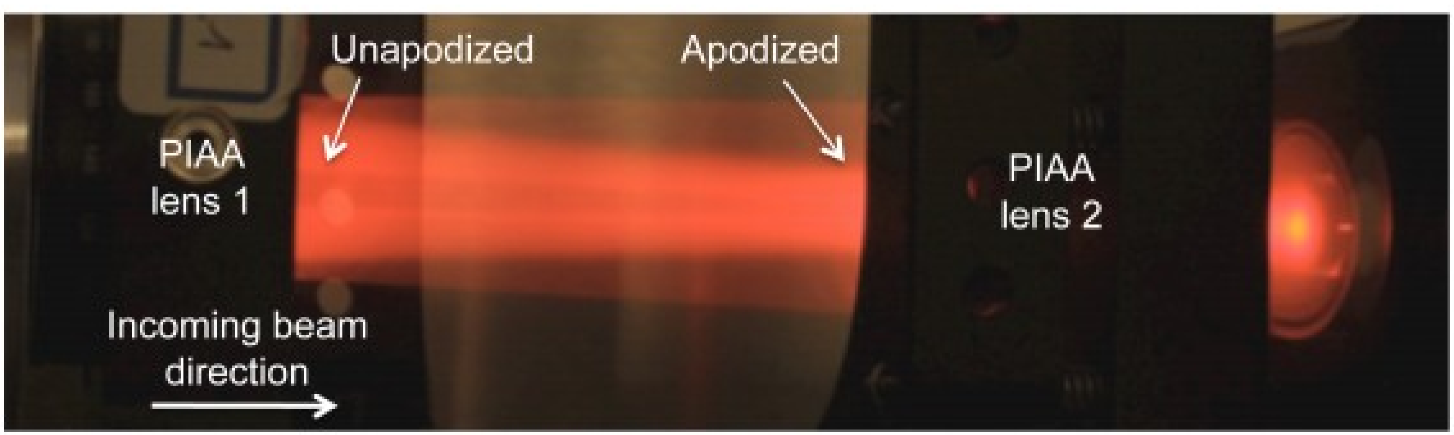
Speckle nulling on-sky

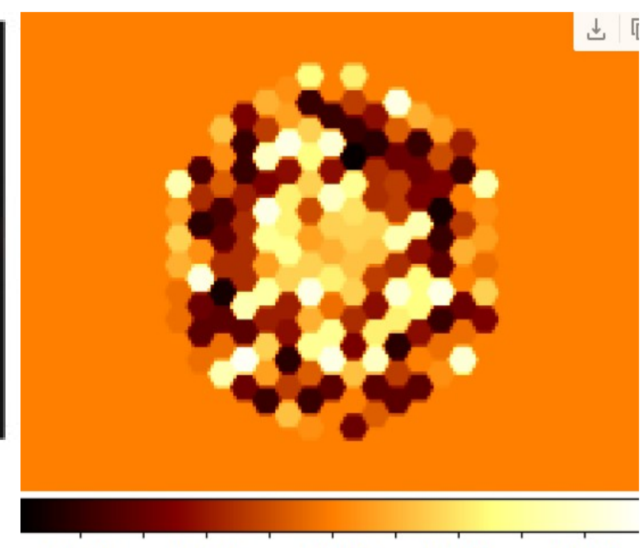
Coronagraphs

"The Subaru Coronagraphic Extreme Adaptive Optics System: Enabling High-Contrast Imaging on Solar-System Scales"
Jovanovic et al.
Publications of the Astronomical Society of the Pacific, Volume 127, issue 955, pp.890-910

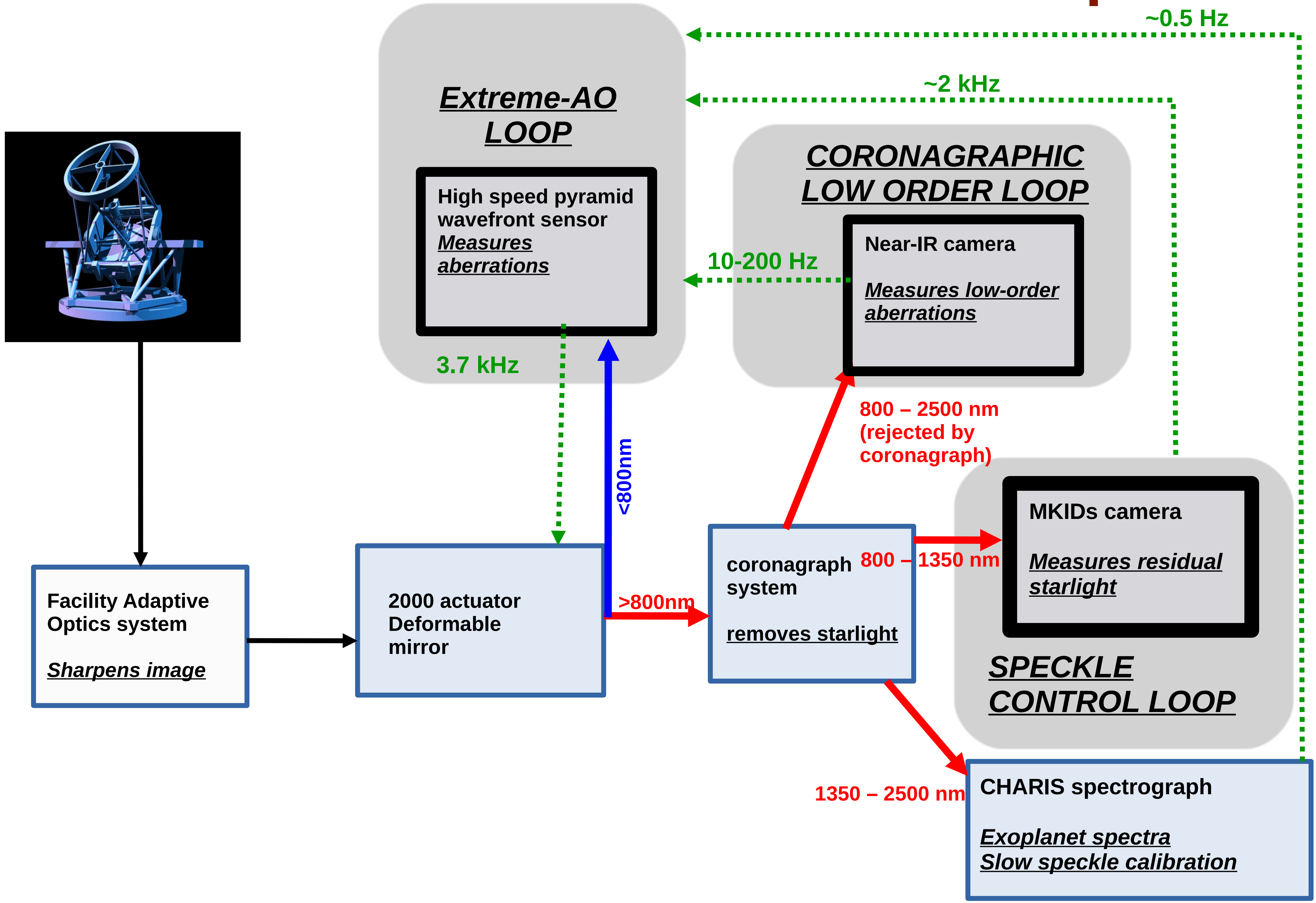
TABLE 8. DETAILS OF SCExAO CORONAGRAPHS.

Coronagraph type	Inner working angle (λ/D)	Waveband(s)
PIAA	1.5	y-K
PIAACMC	0.8	y-K
Vortex	2	H
MPIAA + Vortex	1	H
MPIAA + 8 Octant	2	H
4 quadrant	2	H
Shaped pupil	3	y-K

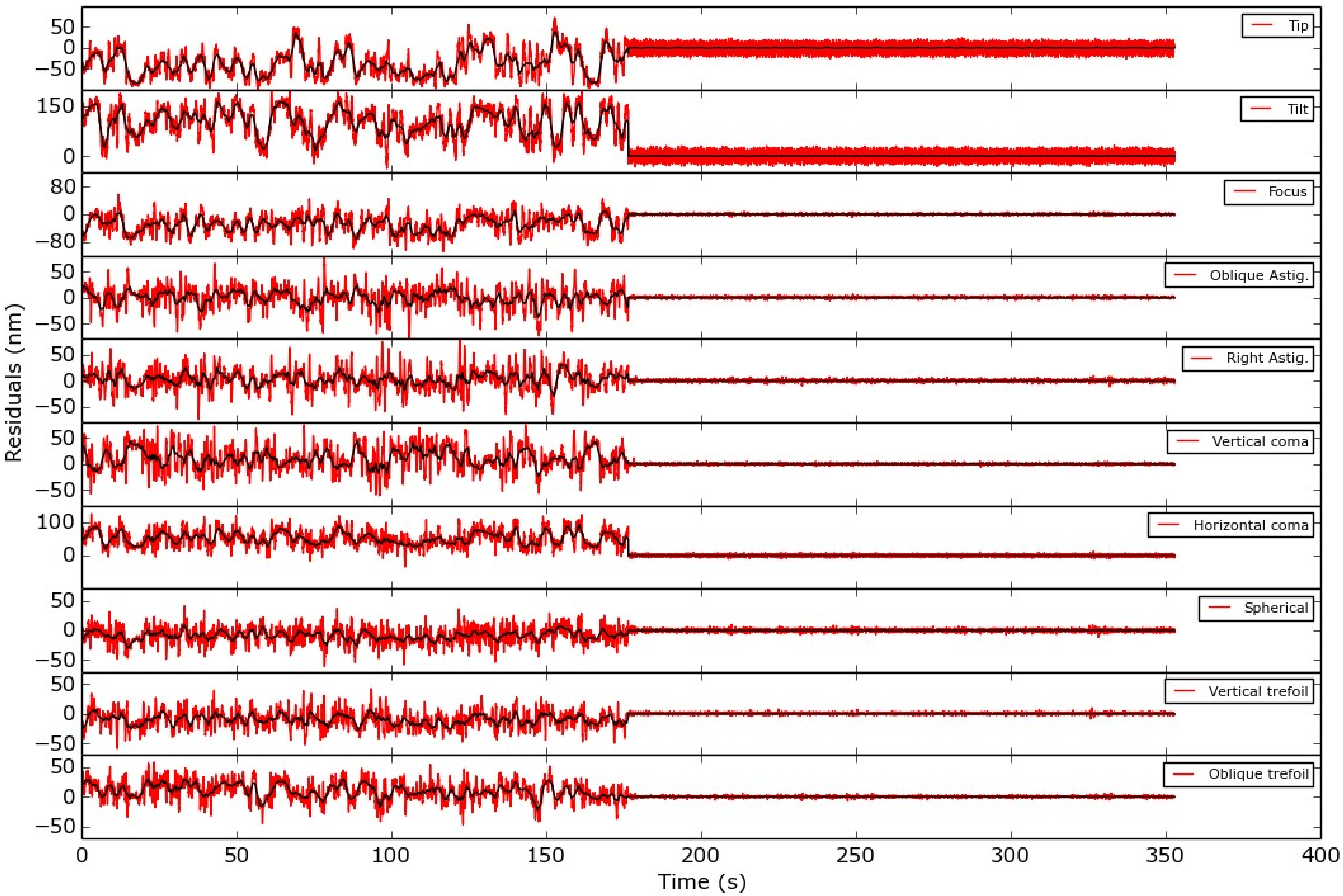




SCExAO: wavefront control loop



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

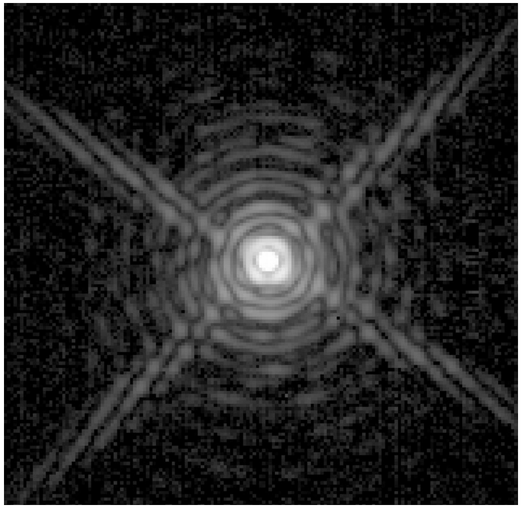


Ref: Singh et al. 2015

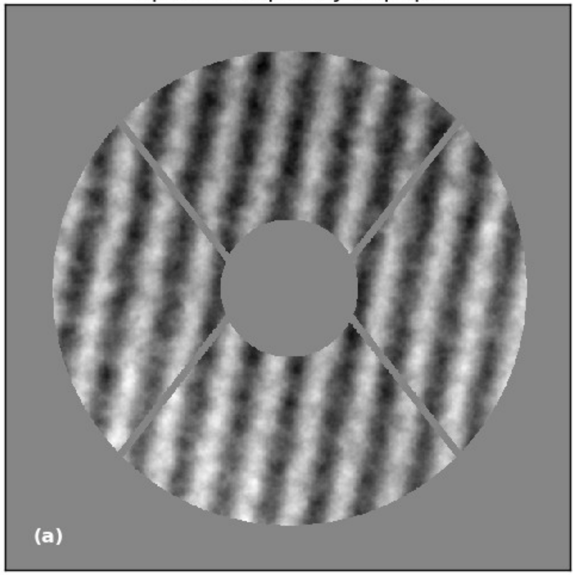
Systematically removing speckles

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

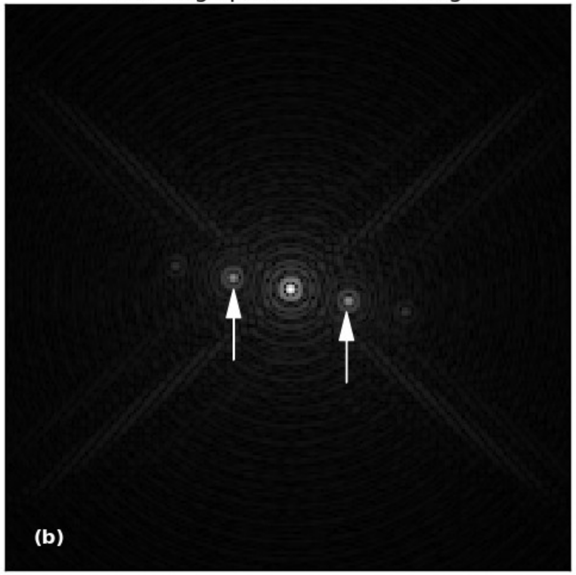
Typical SCExAO PSF



Spatial frequency in pupil

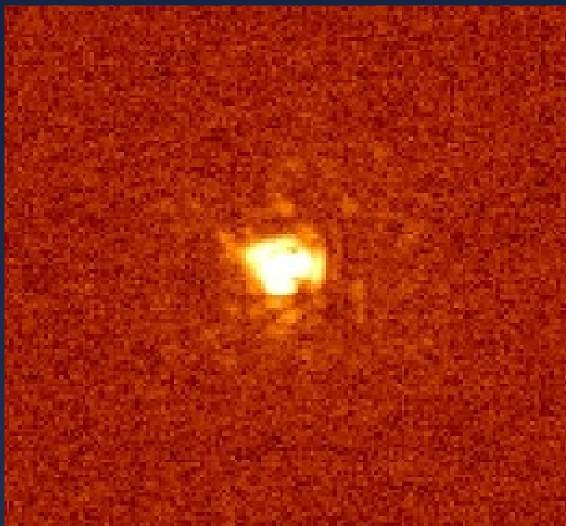


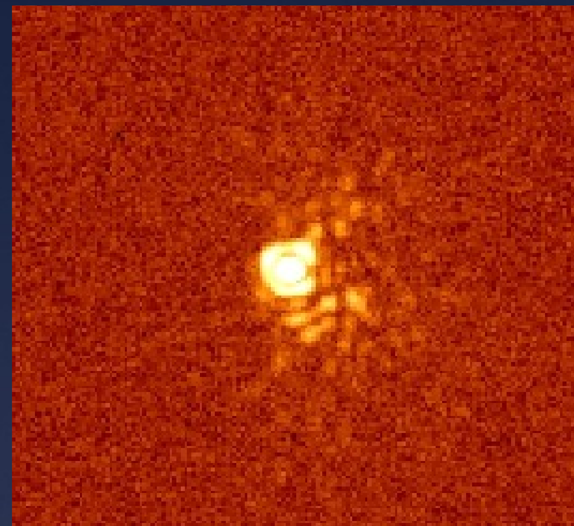
Matching speckles in the image



speckle nulling results on-sky (June 2014)

Single frames: 50 us





Meta data:

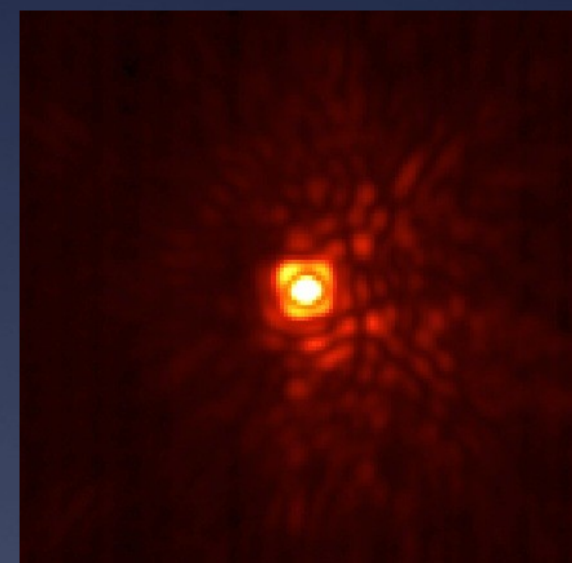
Date: 2nd or June

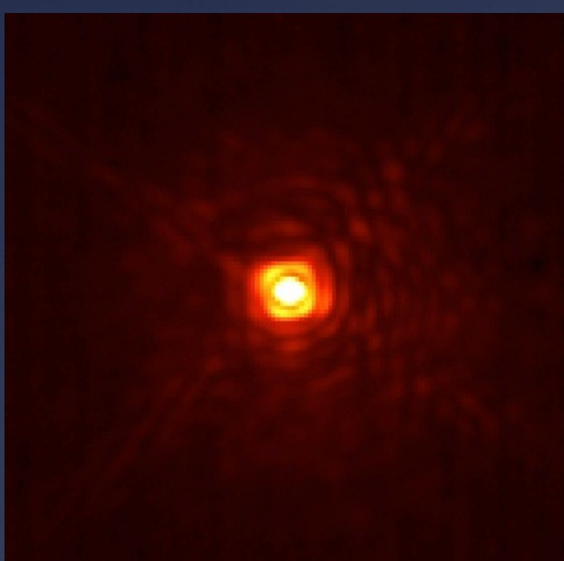
Target: RX Boo (also repeated on Vega)

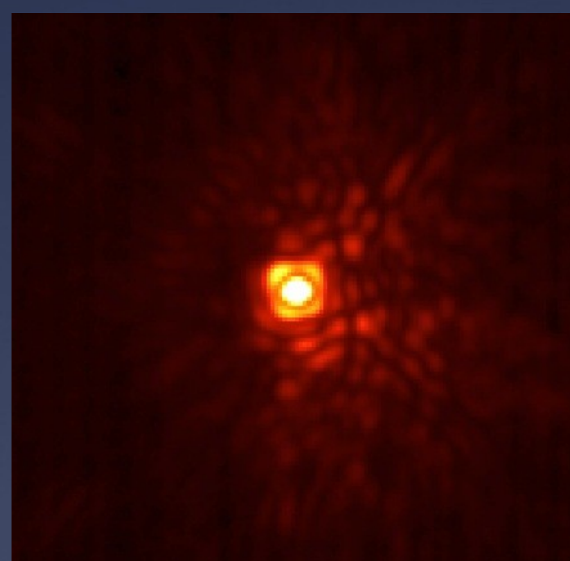
Seeing: <0.6”

AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)

Coronagraph: None (used Vortex on Vega)



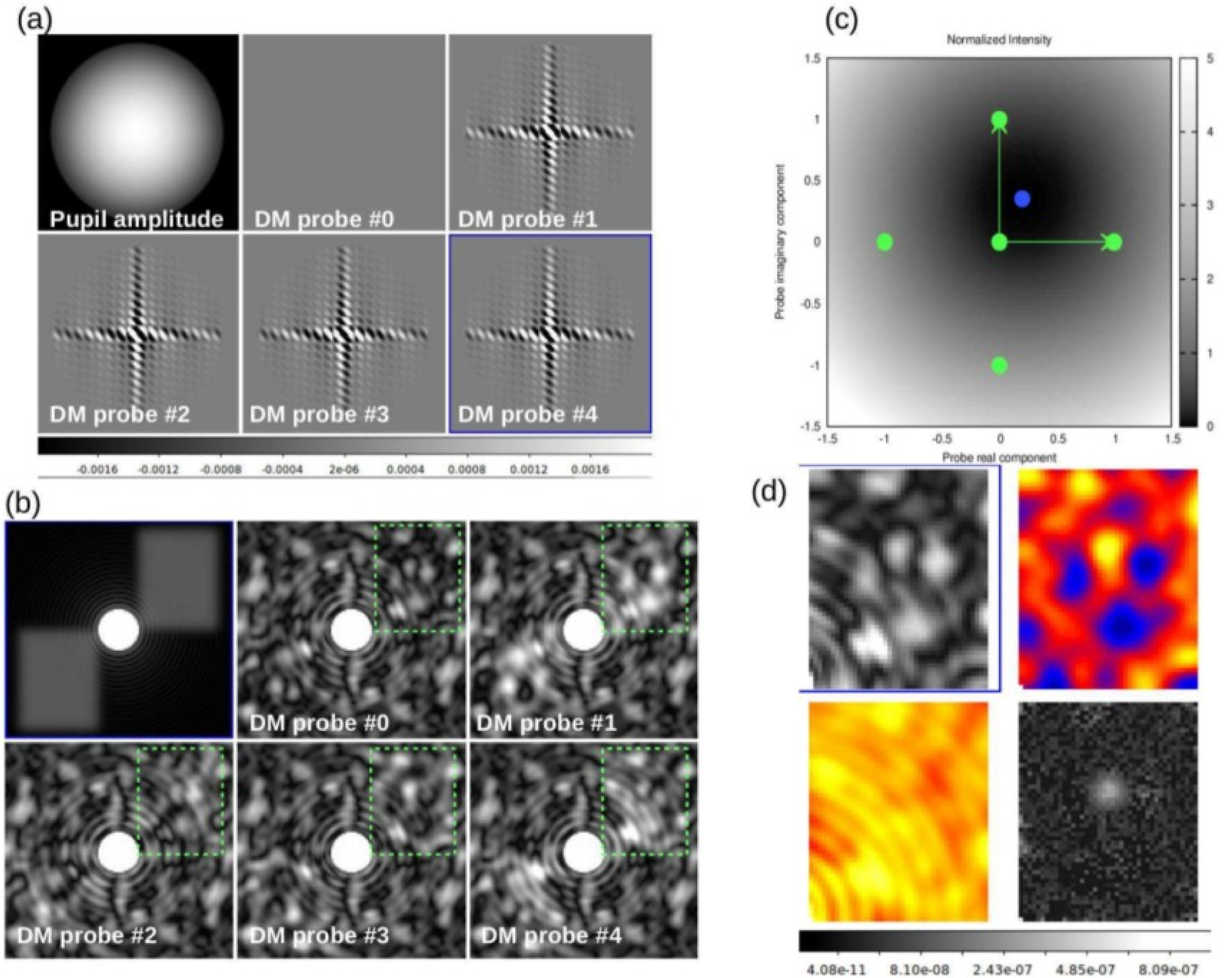




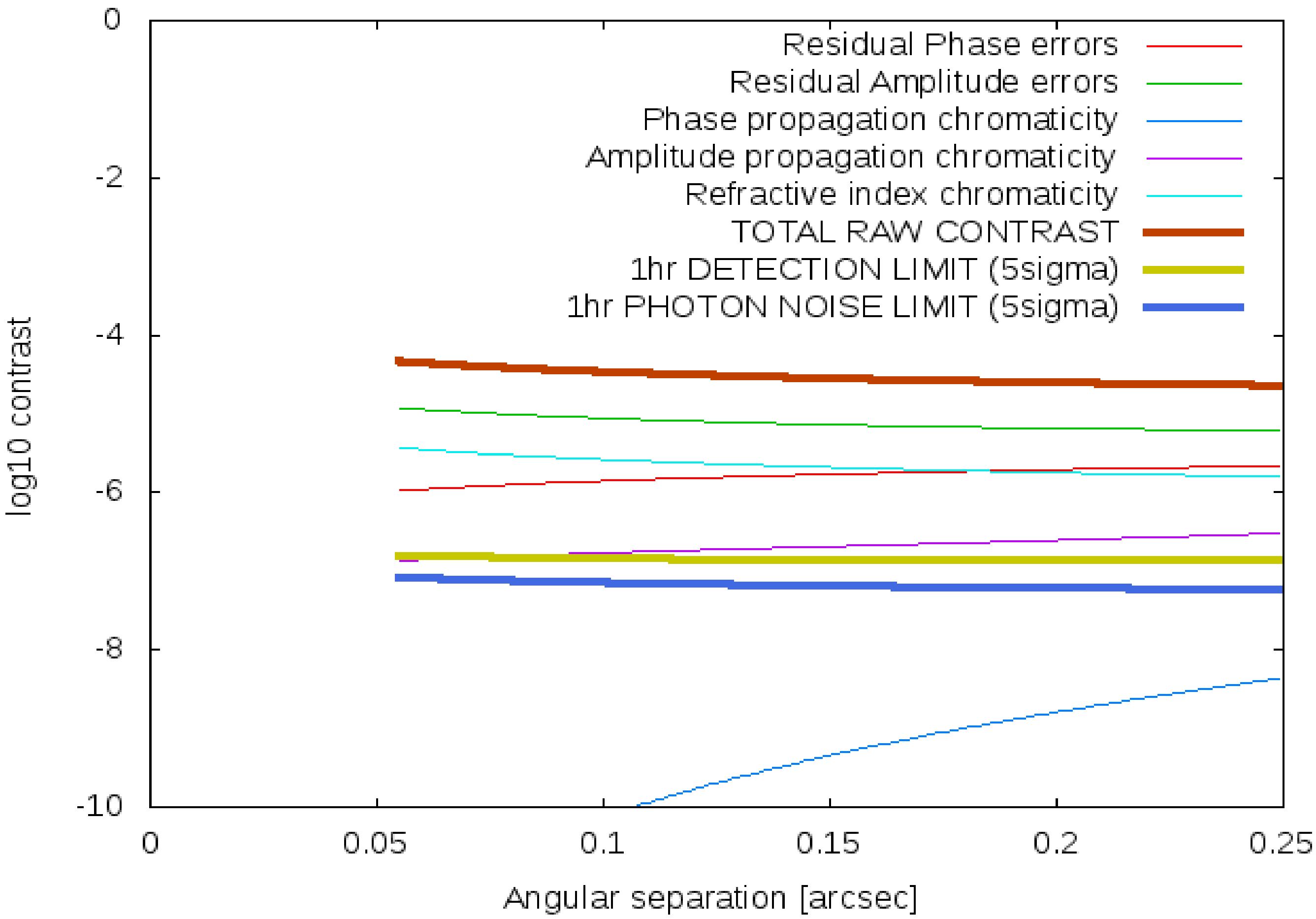
Sum of 5000 frames: shift and add

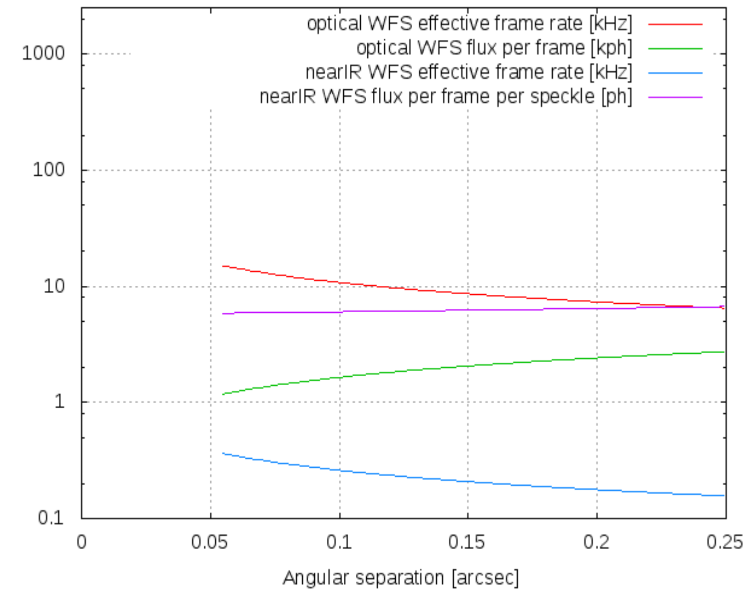
Martinache, F. et. al.

Coherent Speckle Differential Imaging



8m: Pyramid-based system + nearIR Speckle Control → 1e-8 contrast





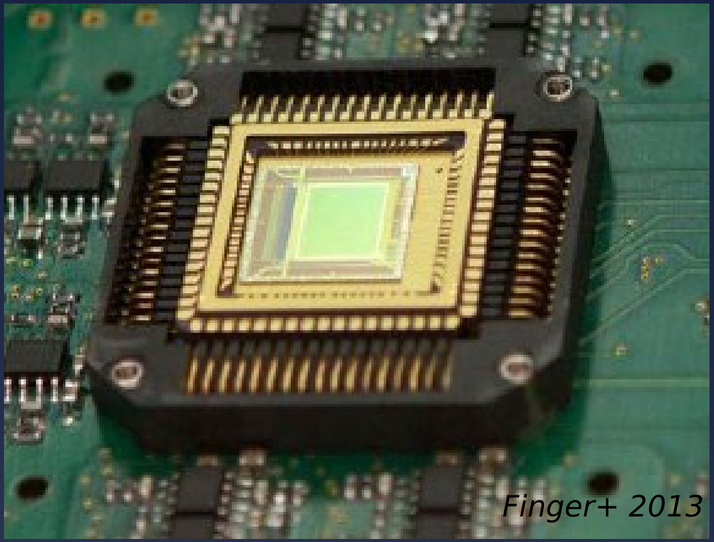
300Hz speckle control loop (~1kHz frame rate) is optimal

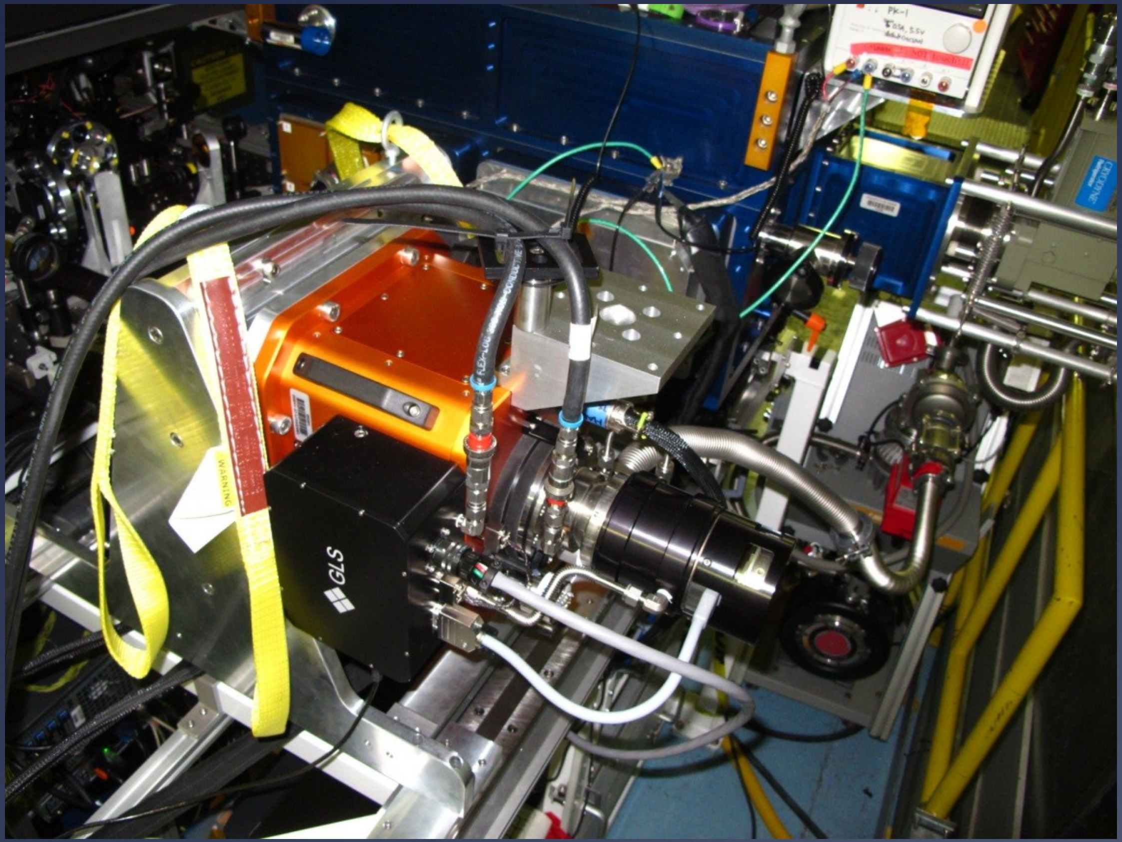
Residual speckle at ~5e-5 contrast and fast → good averaging to detection limit at few 1e-7

SAPHIRA Infrared APD array

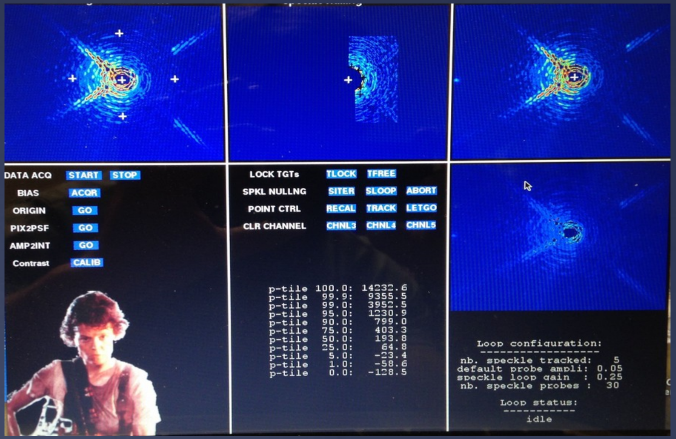
HgCdTe avalanche photodiode
manufactured by Selex

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



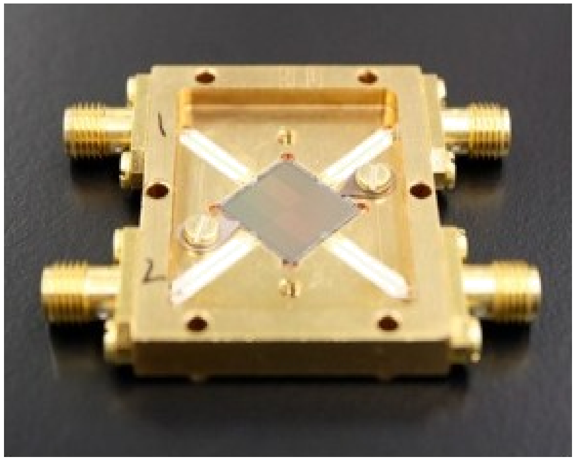


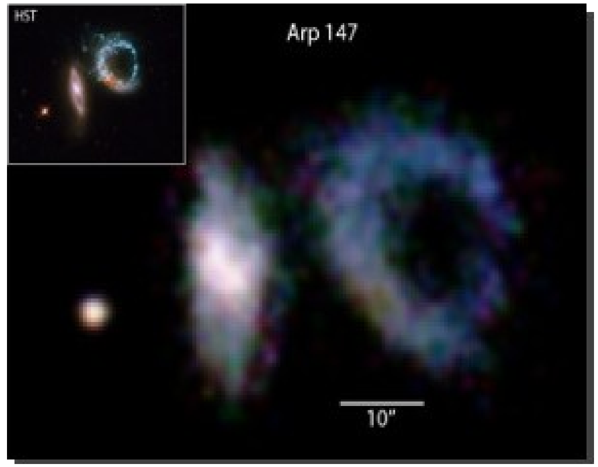
50 frame average

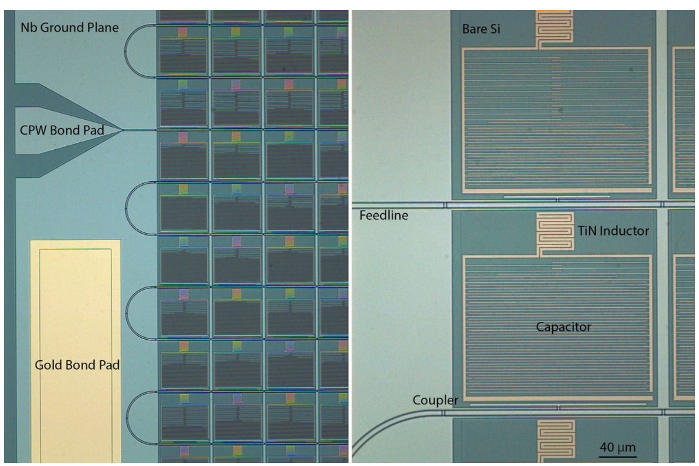


MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera







Pixels are microwave resonators at ~100mK
photon hits → resonator frequency changes

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

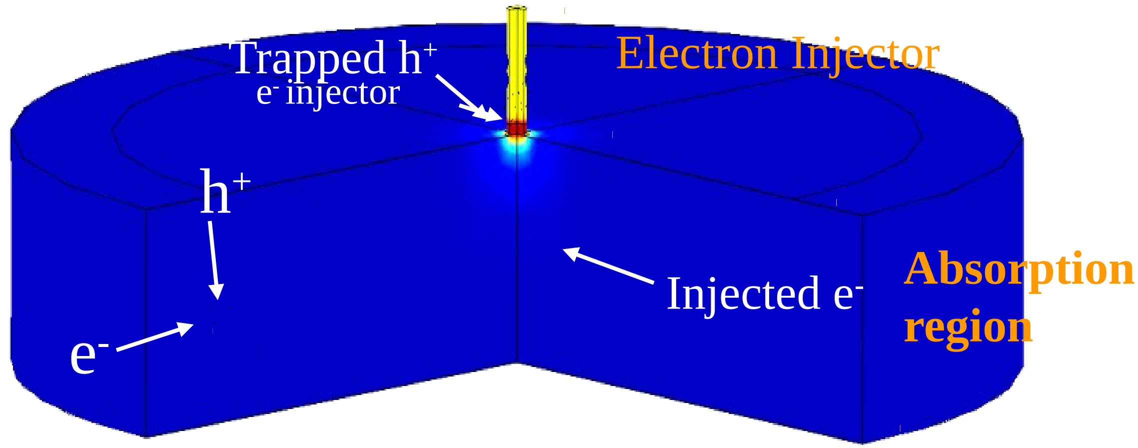
Delivery to SCExAO in CY2016

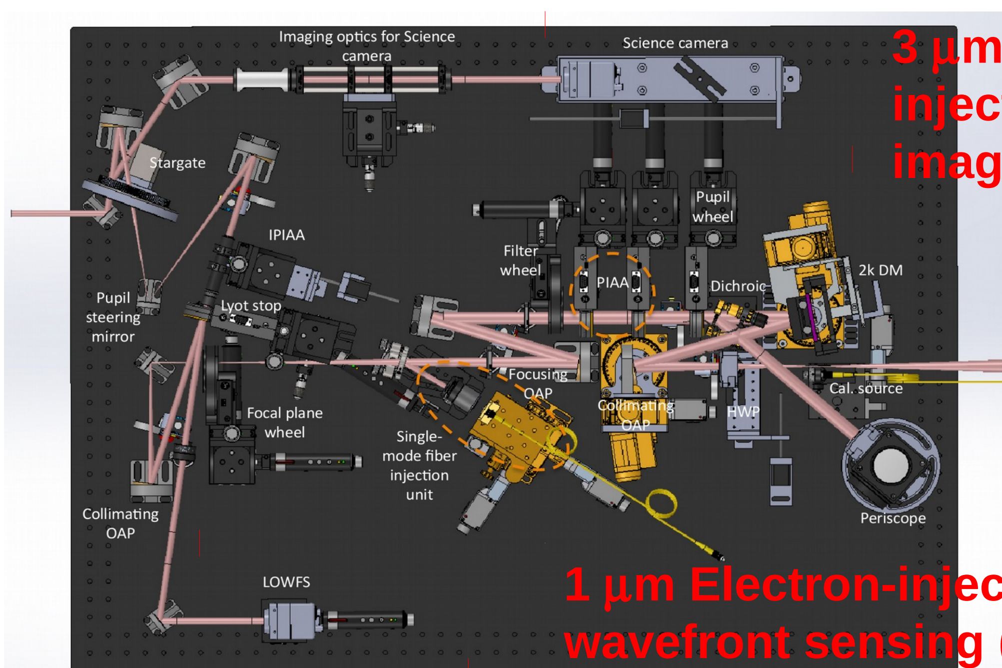
Electron-injector nearIR camera
(Northwestern Univ / Keck foundation)

NORTHWESTERN UNIVERSITY

W.M. KECK FOUNDATION

SUBARU TELESCOPE
National Astronomical Observatory of Japan





3 µm Electron-injection speckle imaging camera

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

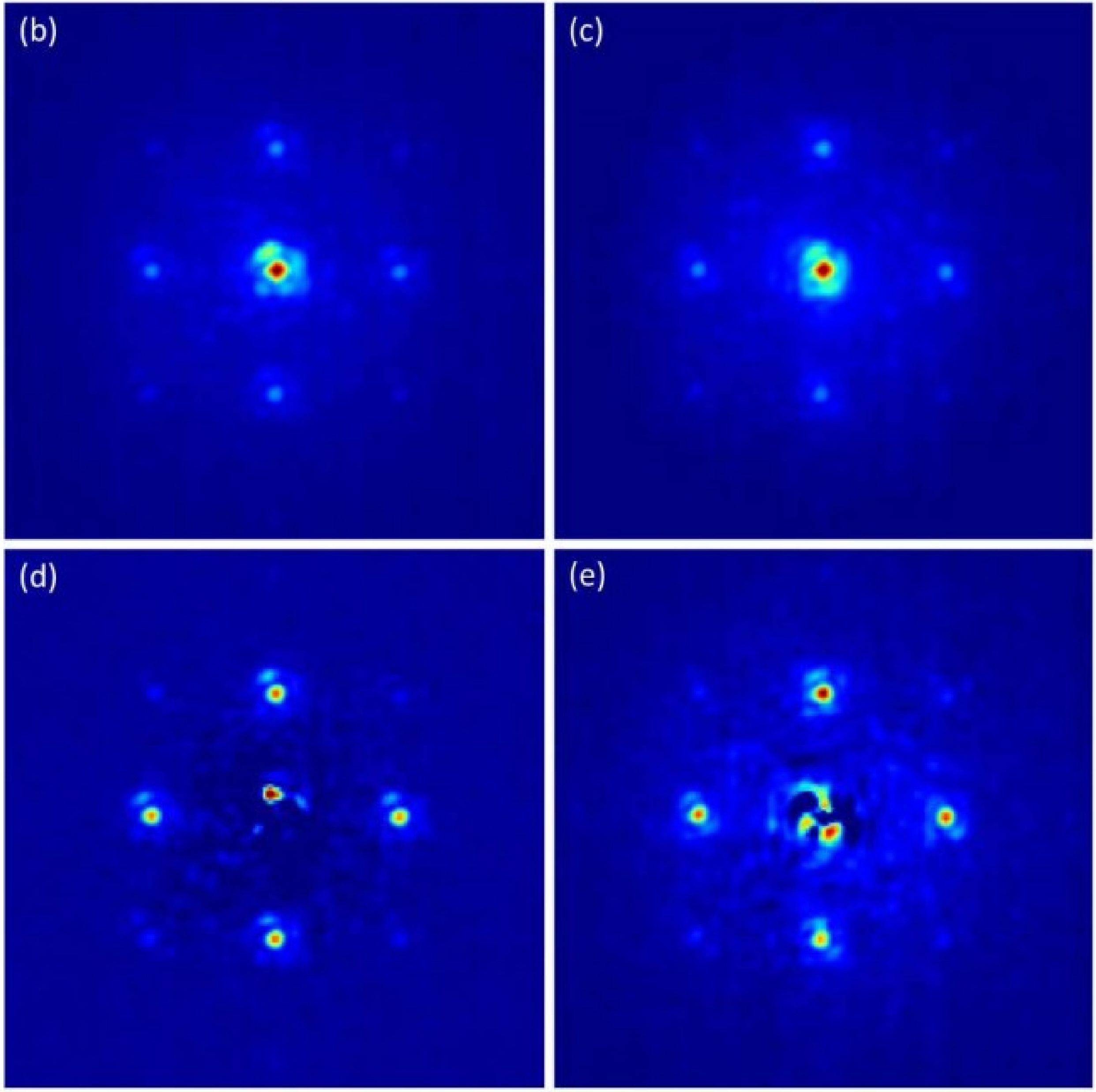


FIG. 3.— (a) Image of PSF. PSF with 2 sets of artificial speckles at 10 λ/D (400 mas) from the PSF, (b) incoherent speckles, (c) coherent speckles. PSF subtracted image (d) with incoherent speckles (e) with coherent speckles. A square-root stretch was applied and the minimum and maximum of each image adjusted for maximum contrast. Data taken on Beta Leo on the 1^{st} of April, 2015.

Astrometric calibration

"Artificial Incoherent Speckles Enable Precision Astrometry and Photometry in High-contrast Imaging"

Jovanovic, N.; Guyon, O.; Martinache, F.; Pathak, P.; Hagelberg, J.; Kudo, T.

The Astrophysical Journal Letters, Volume 813, Issue 2, article id. L24, 5 pp. (2015)

Now modulating at 3.6 kHz !!!
(Feb 2016)

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

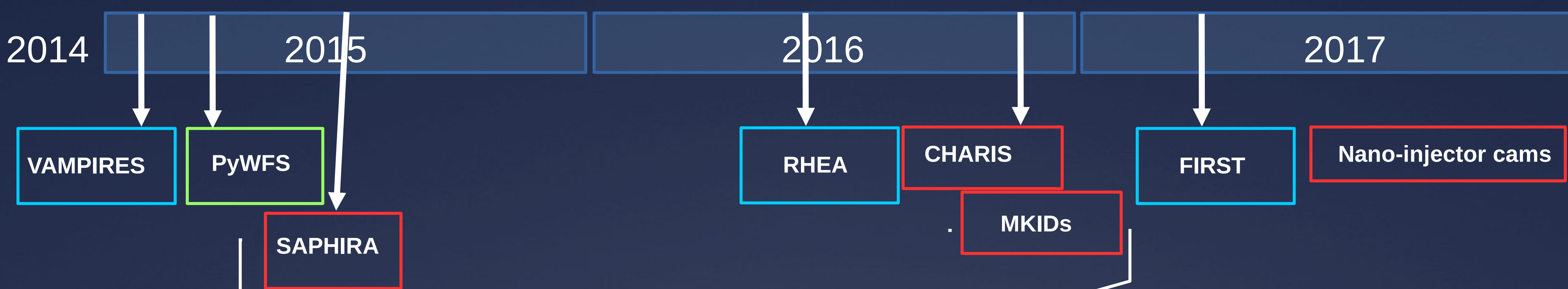
NearIR planet detection at moderate contrast

→

NearIR planet imaging at high contrast
Visible light interferometry, polarimetry (disks, stellar physics)

→

Near-IR spectroscopic characterization
Ultra-High contrast → reflected light
strong visible light capabilities



Phase 1 operation

LOWFS + slow speckle control → Moderate contrast improvement over HiCIAO

Small IWA (~2 l/D) coronagraphy

Phase 2 operation

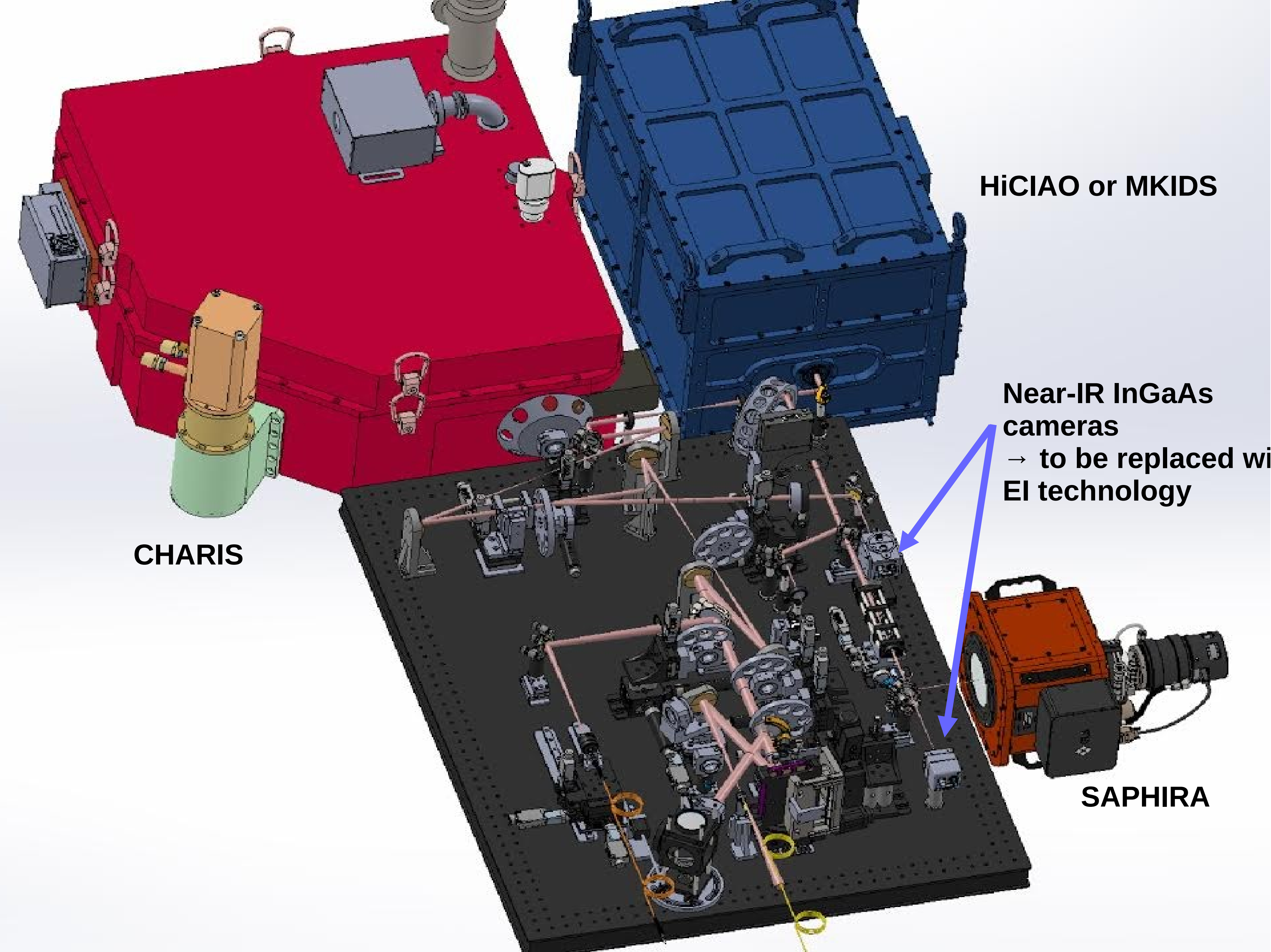
Significant contrast improvement over HiCIAO thanks to ExAO
High SR (~0.9)
→ more robust performance for coronagraph and LOWFS systems

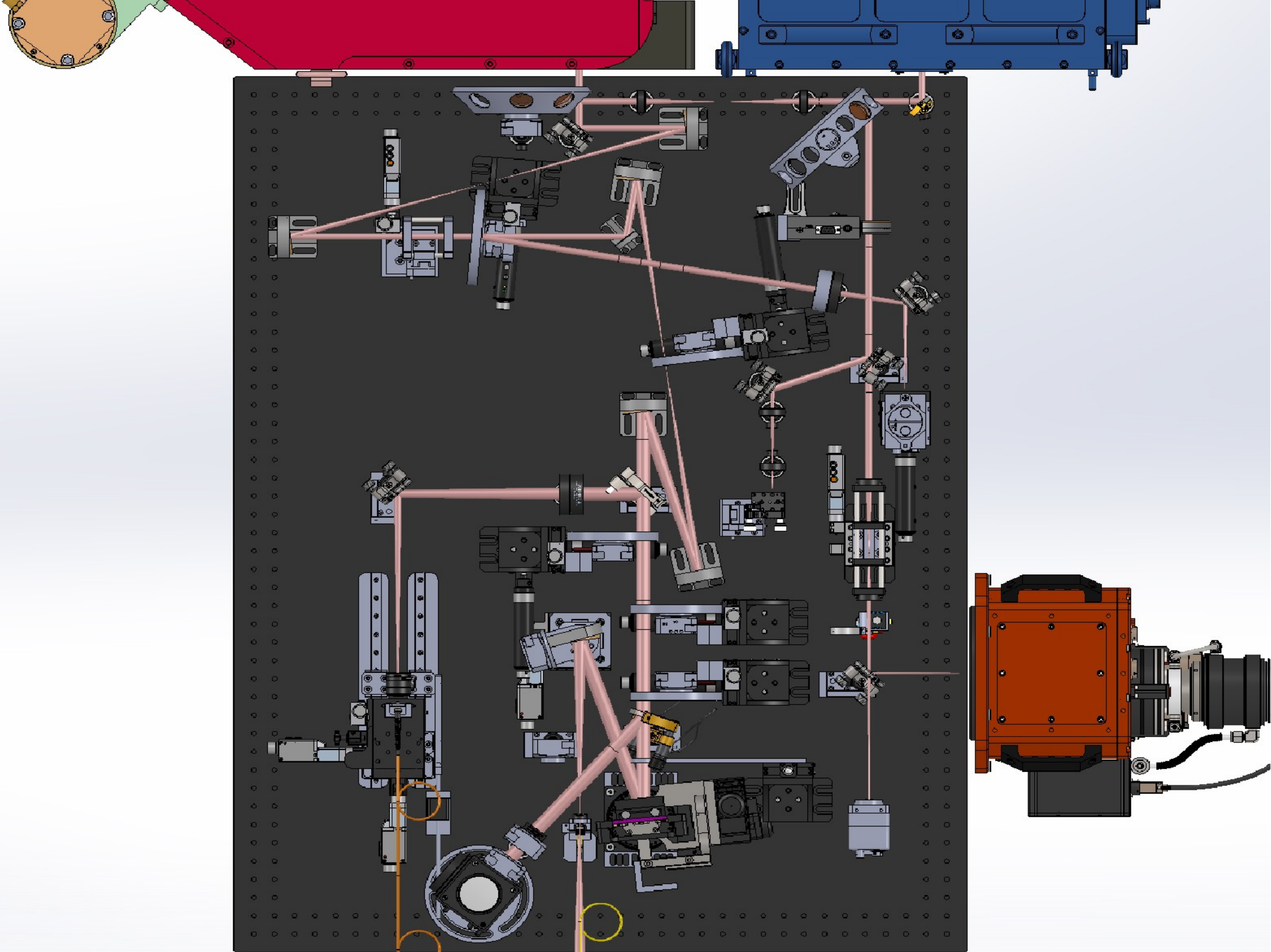
Smaller IWA (~1 l/D)

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


HiCIAO or MKIDS
Near-IR InGaAs
cameras
→ to be replaced wi
EI technology
CHARIS
SAPHIRA



APF-WFS (Martinache et al.)

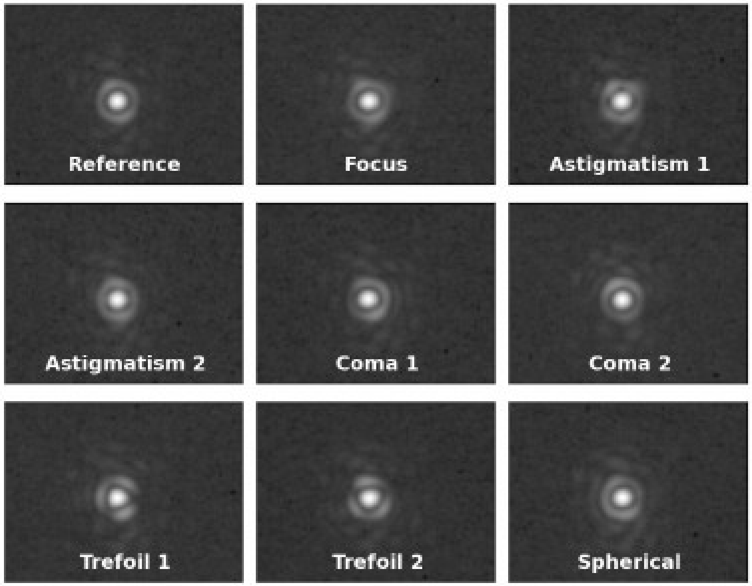


FIG. 5.— Calibration data for the APF-WFS acquired by the SCExAO science camera. Top left: the reference PSF, acquired with the system in its starting state. From left to right and top to bottom: the PSF after the corresponding Zernike mode has been applied. A non-linear scale is used to better show the impact of a 30 nm RMS DM modulation.

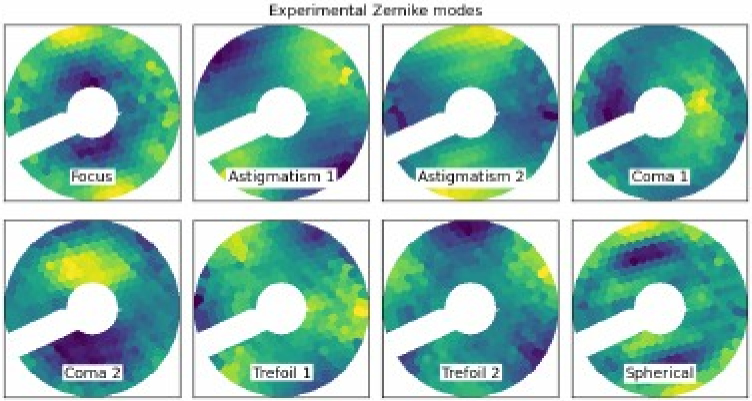


FIG. 6.— Experimentally recovered Zernike modes. Save for the spherical aberration, one will observe that the modes extracted from the analysis of the images of Fig. 5 do reproduce the features expected after looking at the theoretical reconstructed modes presented in Fig. 4.

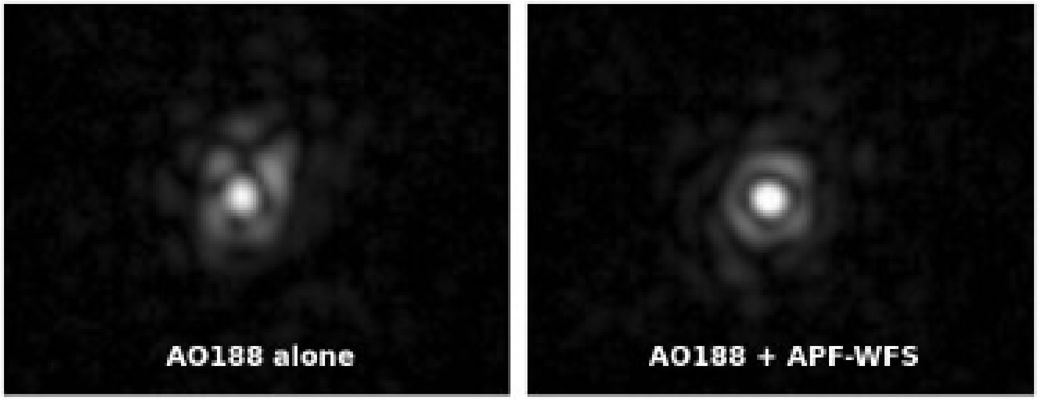
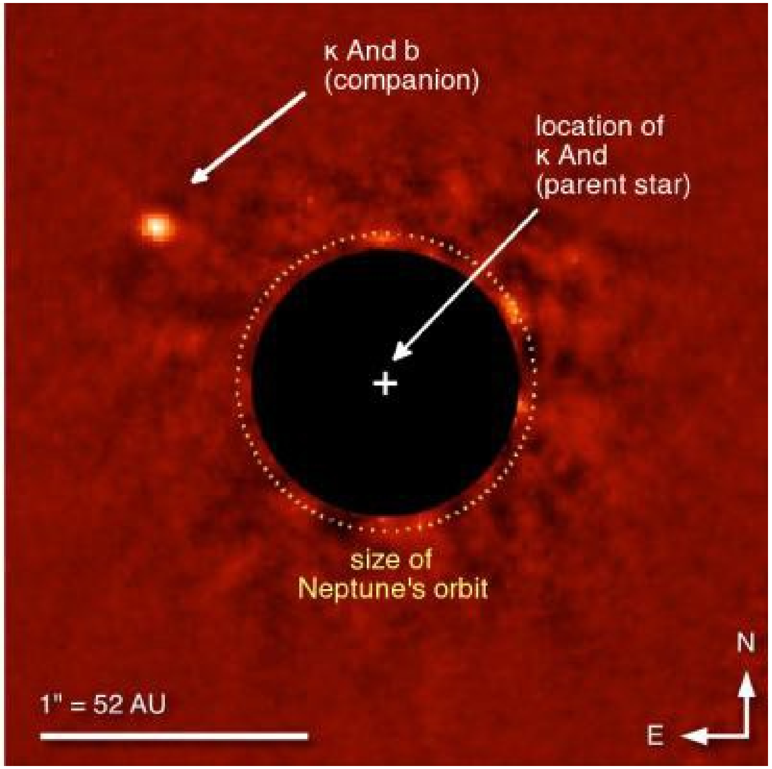


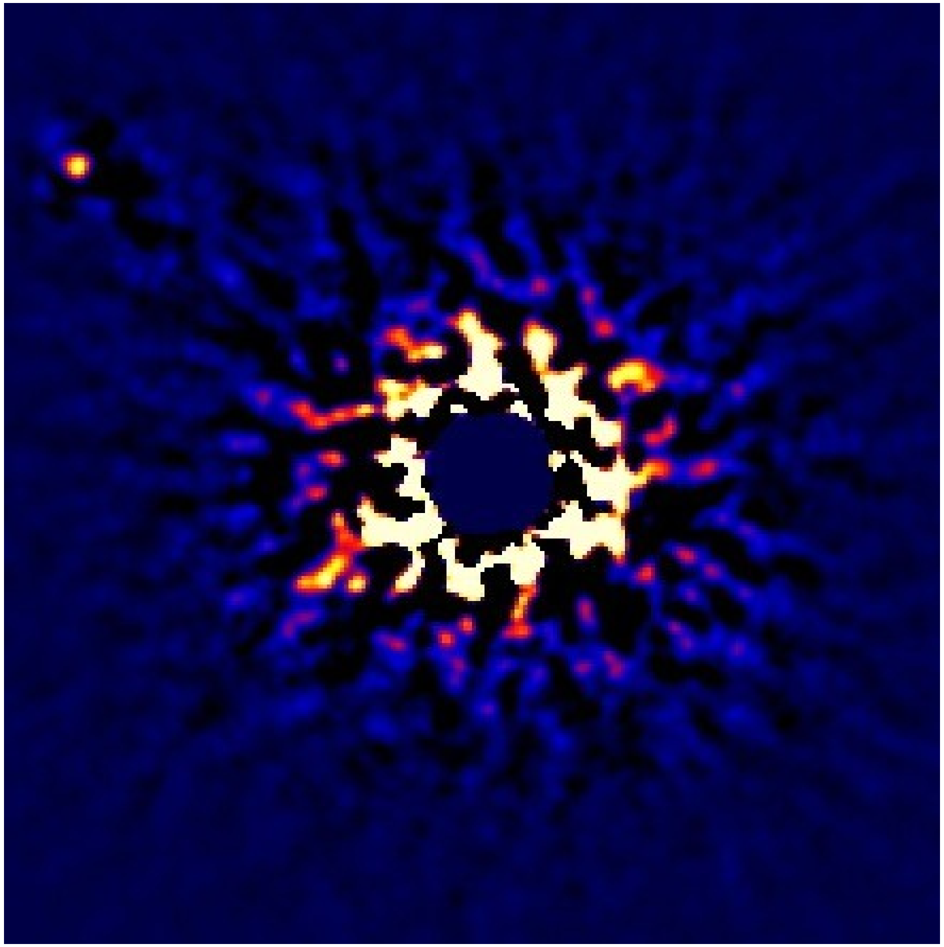
FIG. 8.— Illustration of the impact of the APF-WFS. Left: 0.5 ms PSF acquired by SCExAO's internal science camera after the upstream AO loop has been closed. Right: identical exposure acquired 30 seconds after the APF-WFS loop has been closed. Despite residual imperfections due to dynamic changes, the PSF quality is obviously improved.

HiCIAO + SCExAO: Kappa Andromedae (Currie et. al, in prep)

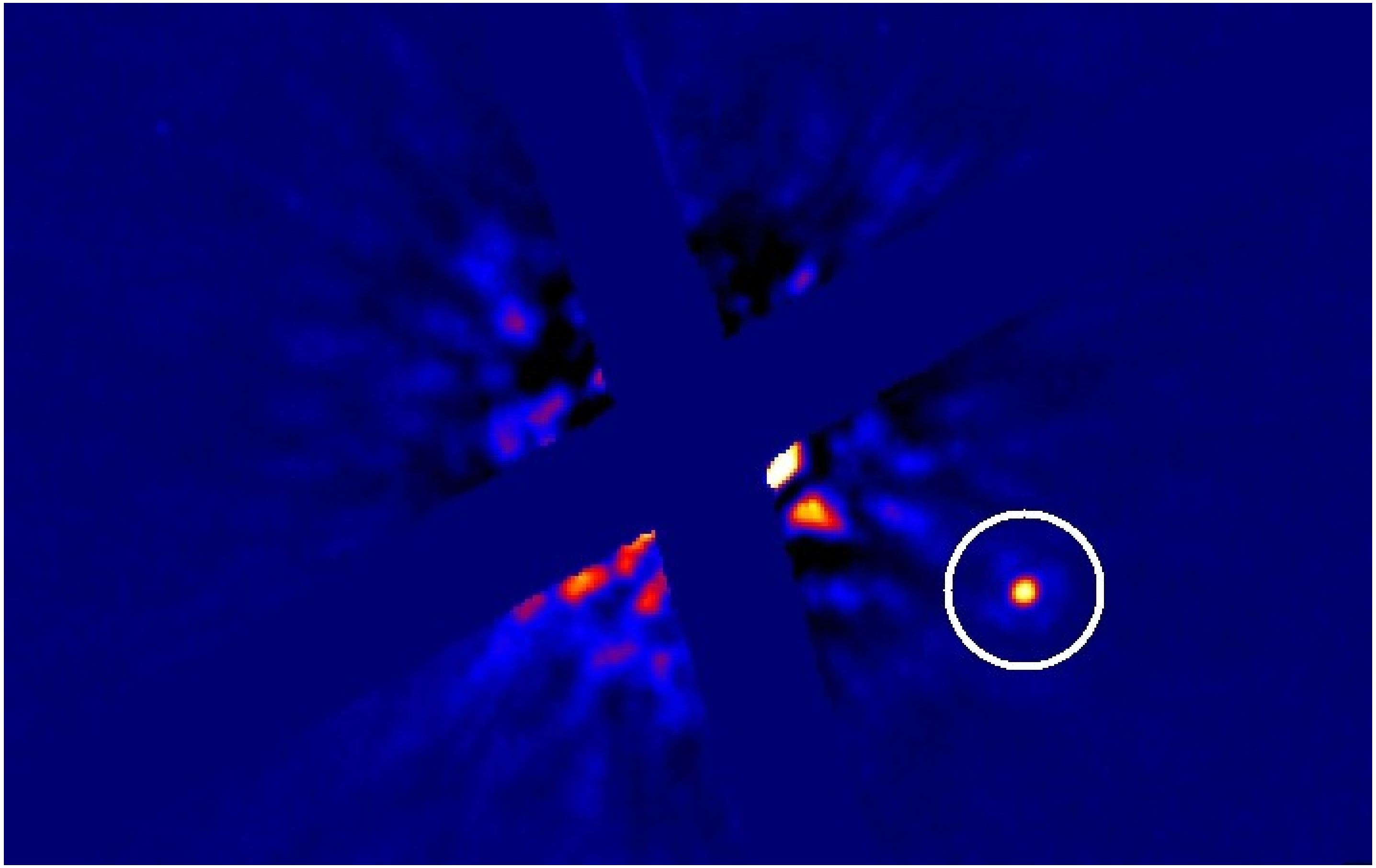
SCExAO + HiCIAO

HiCIAO



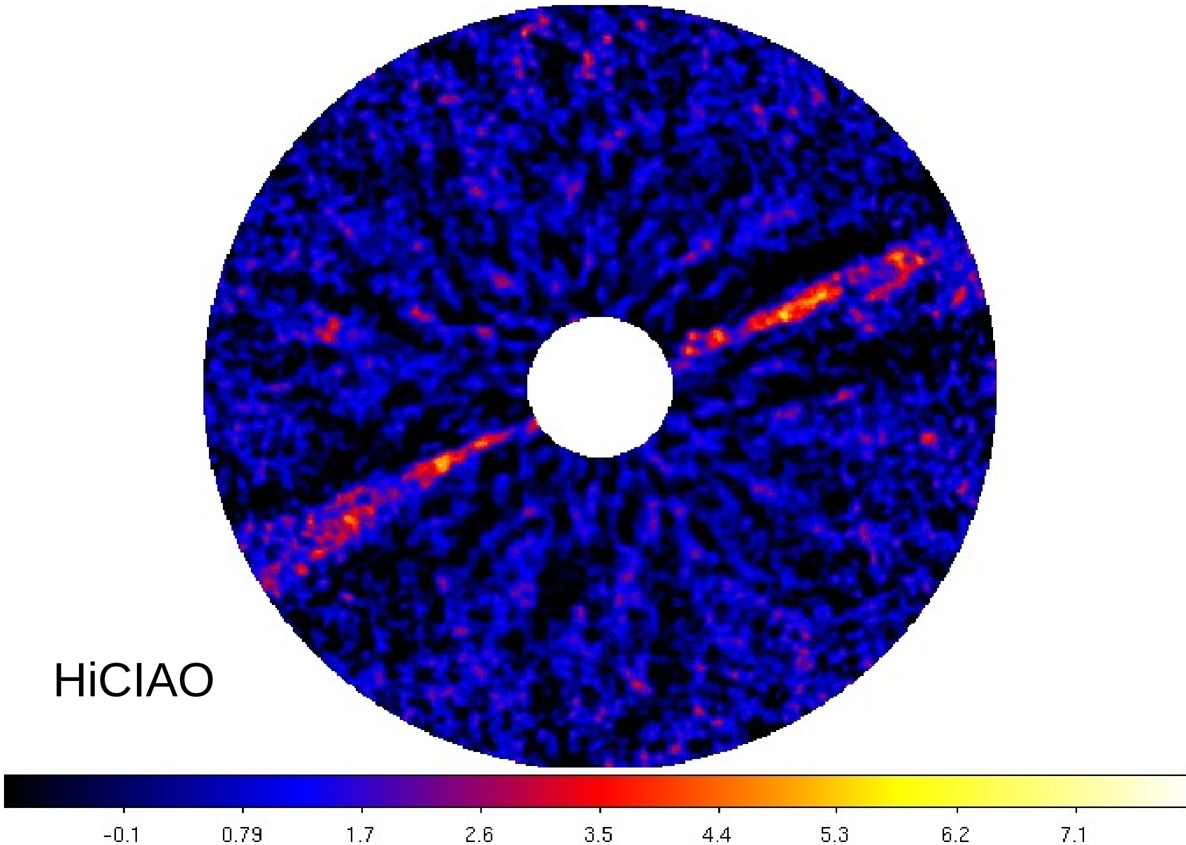


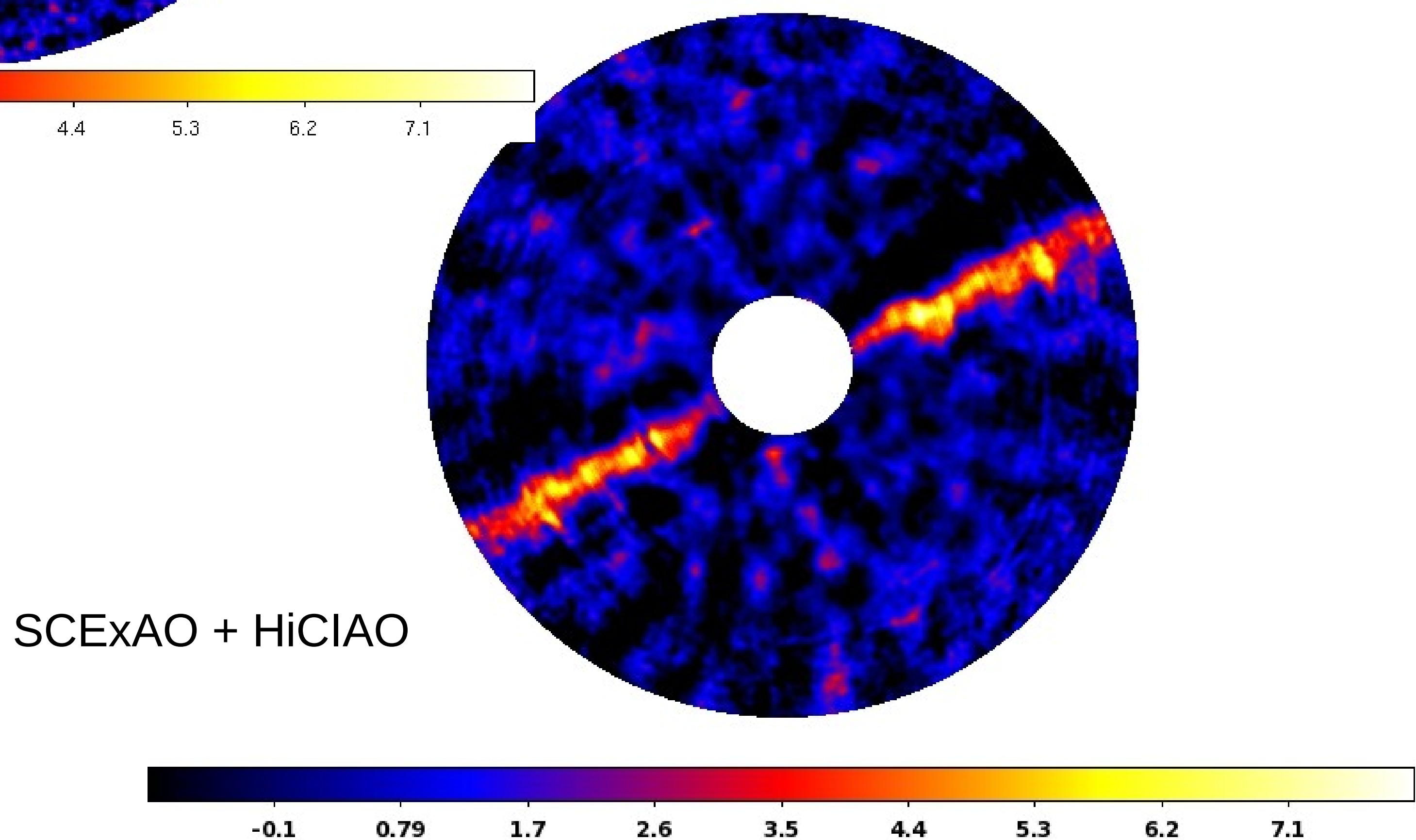
HiCIAO + SCExAO: Substellar companion (sub-arcsec separation)



Garcia, Currie, et al. 2016, in prep.

Also detected with GPI (similar SNR)
SCExAO data used to better constrain the object's temperature, gravity, and mass.

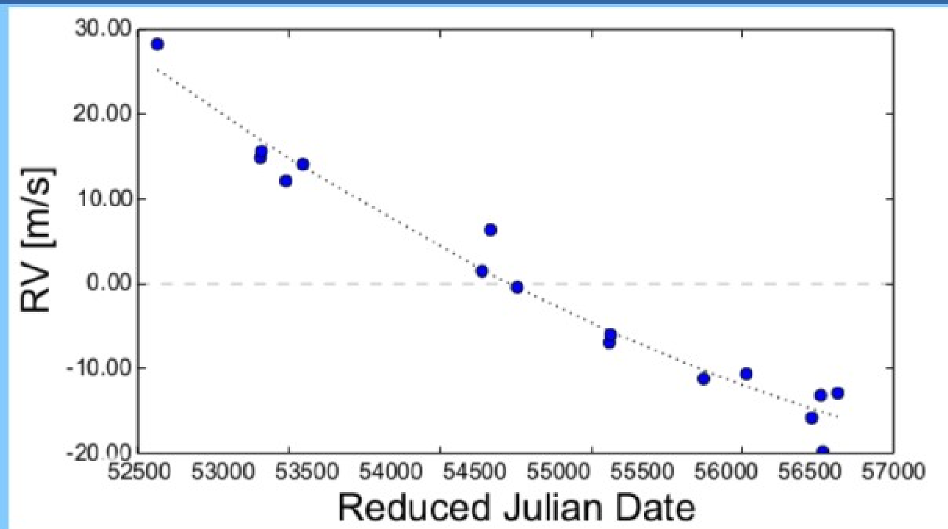




Credit: T. Currie

Direct Imaging Search for Companion Giant Planets and Brown Dwarfs to Sun-like Stars with Radial Velocity Drifts using Subaru/SCExAO

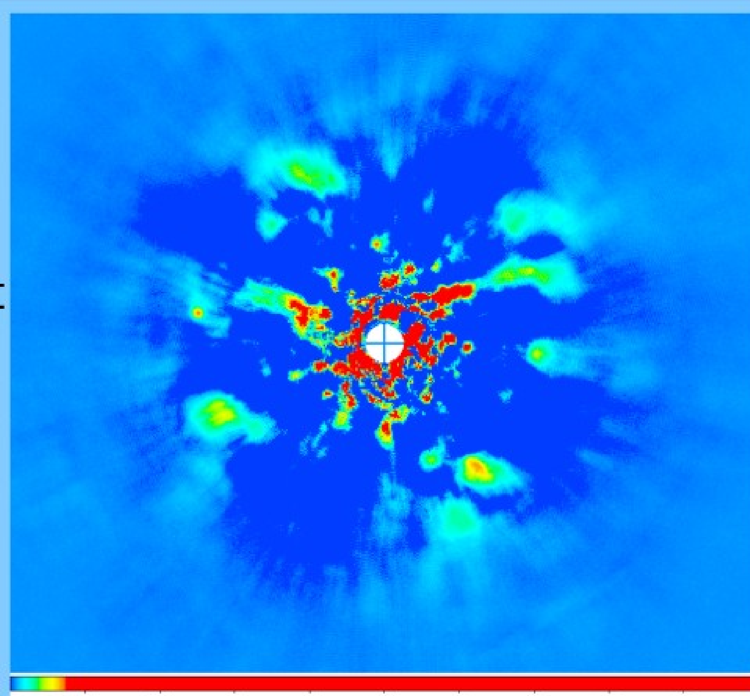
Elodie/Sophie radial velocity drift over 12 years

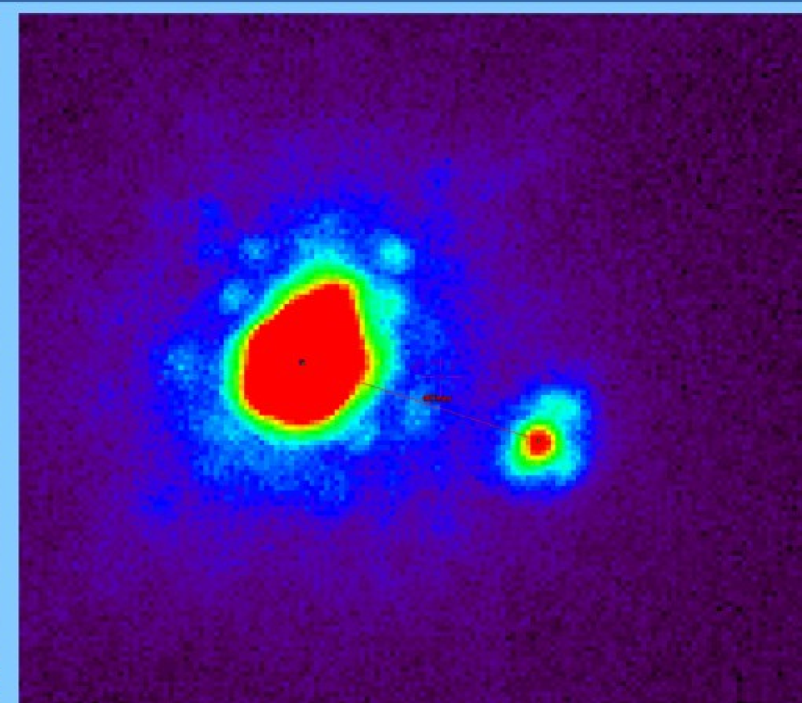


Janis Hagelberg[1]
N. Jovanovic[2,3], J. Lozi[2],
O. Guyon[2,4,5], M. Liu[1],
and the Sophie Consortium

(1) IfA, University of Hawai'i, USA
(2) NAOJ, Subaru Telescope, USA
(3) Department of Physics, Macquarie Univ., Australia
(4) Steward Observatory, Univ. of Arizona, USA
(5) College of Optical Sciences, Univ. of Arizona, USA

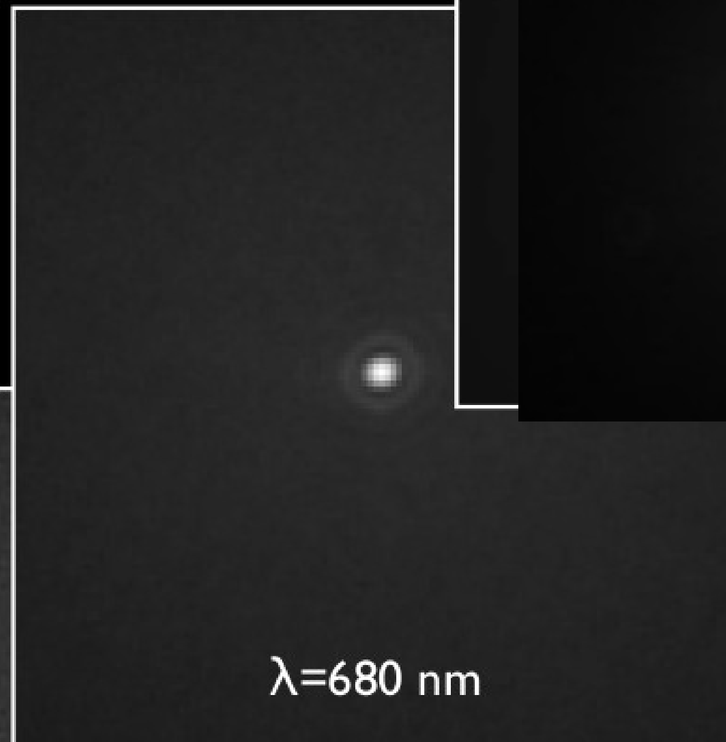
Direct detection of the companions at the origin of the drift

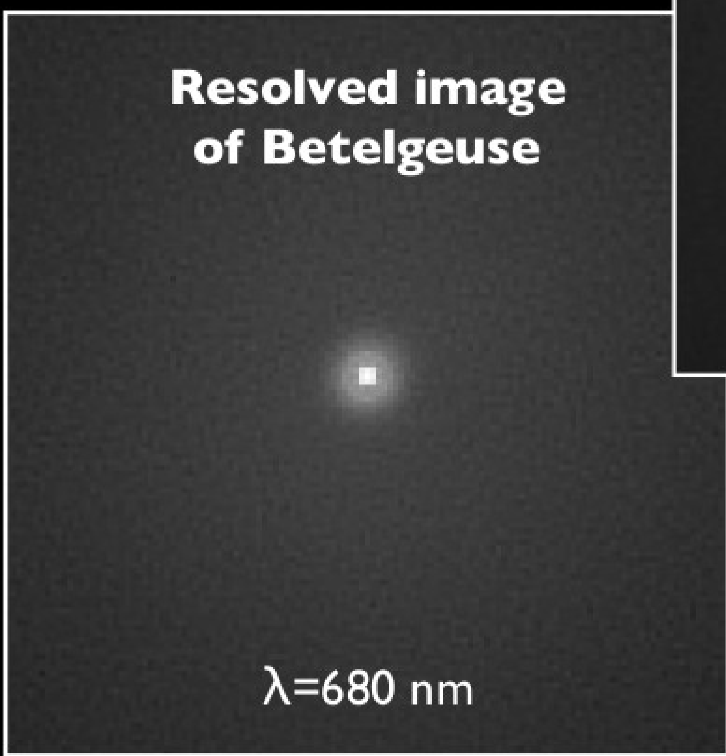




First result in press: Hébrard et al. 2016

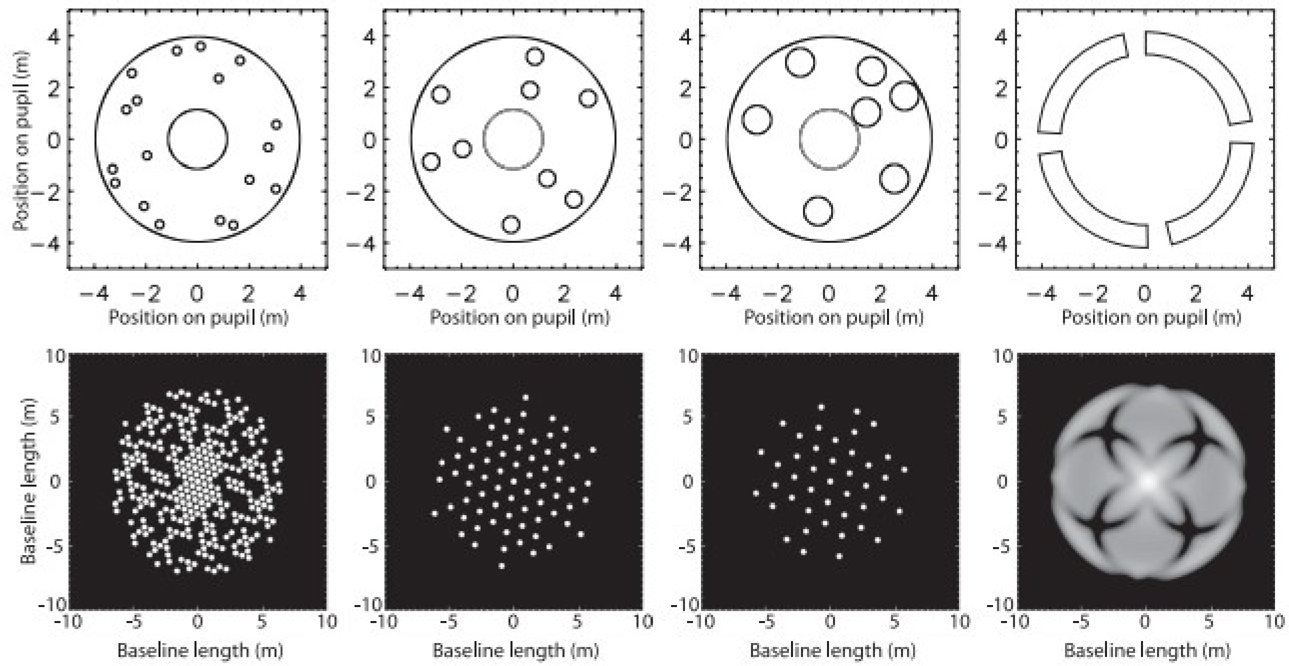
SCExAO visible images
FWHM 17mas
Resolves some stars





PhD dissertation by Vincent Garrel (Oct 2012)

VAMPIRES



2898 *B. Norris et al.*

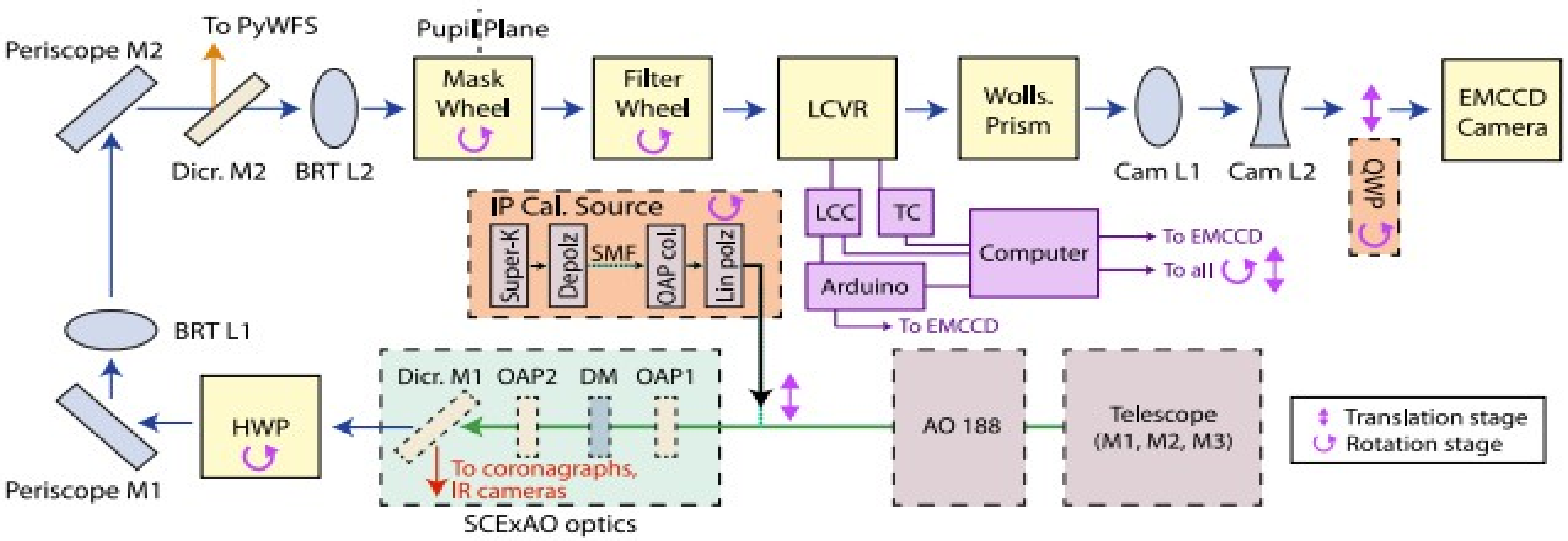
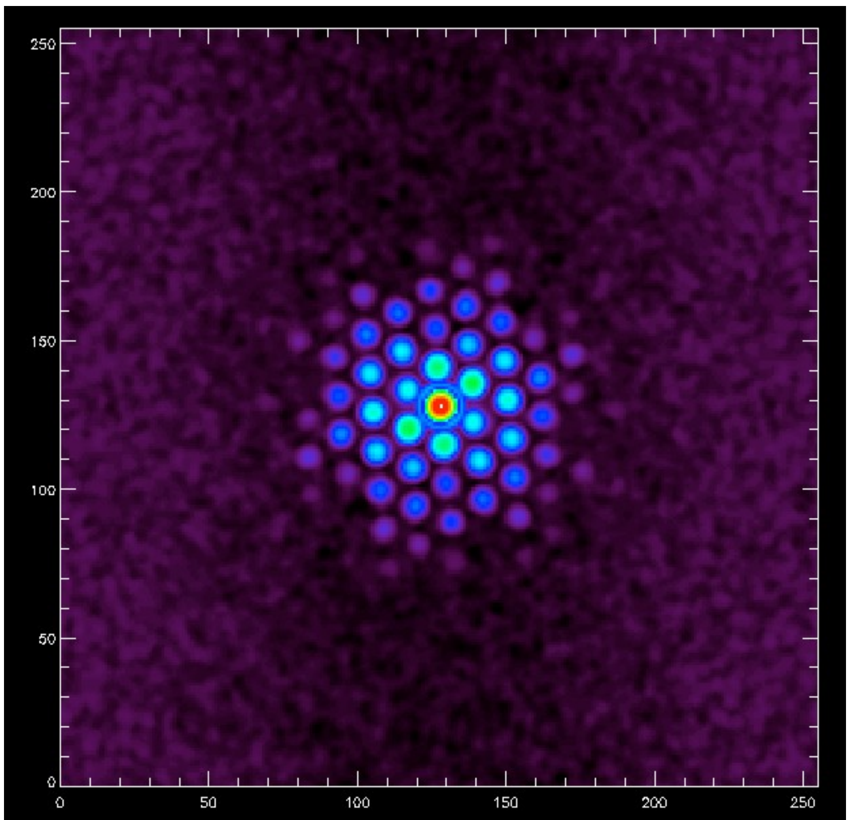


Figure 1. A schematic diagram of VAMPIRES as configured on-sky in 2013 July, with all items relevant to the VAMPIRES beam train shown. Operation of each sub-system is described in the text. Abbreviations: M – Mirror; L – Lens; OAP – Off Axis Parabola; DM – Deformable Mirror; Dicr.M – Dichroic Mirror; HWP – Half-wave plate; BRT – Beam Reducing Telescope; LCVR – Liquid-Crystal Variable Retarder; LCC – LCVR Controller; TC – Temperature Controller; Cam – Camera; QWP – Quarter-Wave Plate; Depolz – Depolarizer; OAP col. – OAP Collimator; Lin polz – Linear polarizer. In an alternative configuration, the HWP can be replaced with a pair of QWP to allow birefringence to be corrected as needed.

Non-polarised mode and results

- VAMPIRES can also operate as a conventional (non-polarimetric) non-redundant masking instrument.



Chi Cyg Power spectrum (log scale)
Note fall-off in power at longer BLs, since object is resolved.

Observed S-type star chi Cyg

V ~ 8 at time of observation

VAMPIRES UD Diameter

32.2 ± 0.1 mas (750 nm)

c.f. CHARM Catalogue, Richichi et al. 2005:

UD = 32.8 ± 4.1 mas (V band)

Observed close binary eta Peg

Detection confidence (MC) > 99.9%

Separation 48.9 ± 0.6 mas

c.f. orb. params. Hummel+ 1998 →49.9 mas

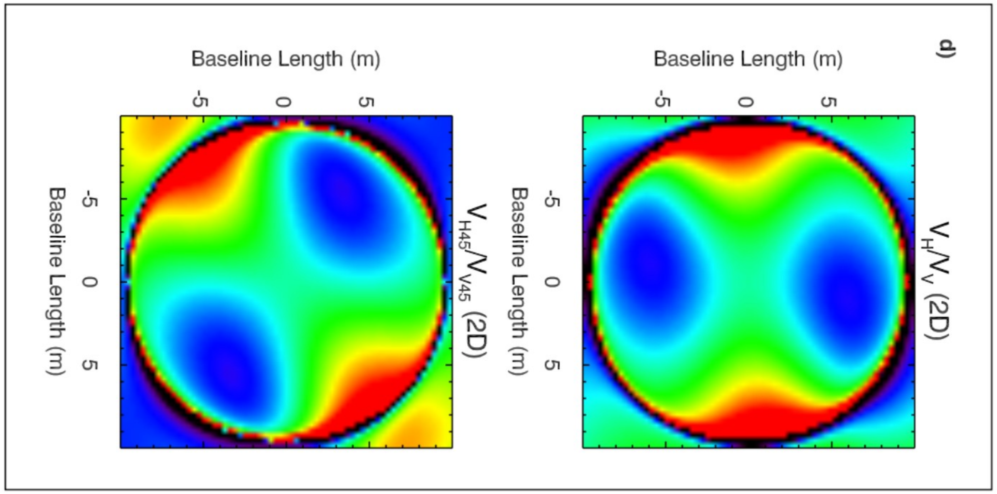
Contrast 3.55 ± 0.06 mag

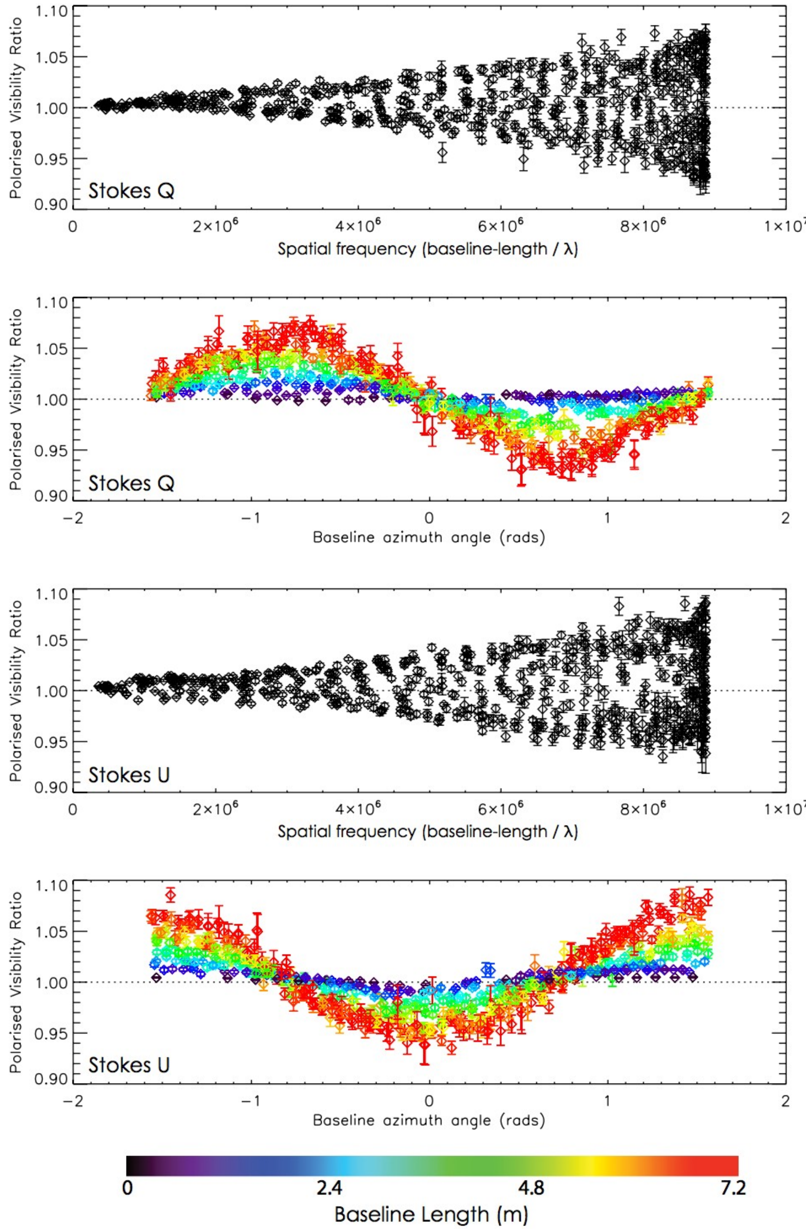
c.f. Hummel+ 1998: 3.61 ± 0.05 mag

Preliminary VAMPIRES science – in preparation

Circumstellar dust around Red Supergiant μ Cephei

- Observed with annulus mask at 775 nm
- Raw differential polarized visibilities show distinctive sinusoidal signature of circumstellar dust shell, with clear asymmetry **(right)**
- Dust scattering model fitted via synthetic differential visibilities **(below)**





Preliminary VAMPIRES science – in preparation

Circumstellar dust around Red Supergiant μ Cephei

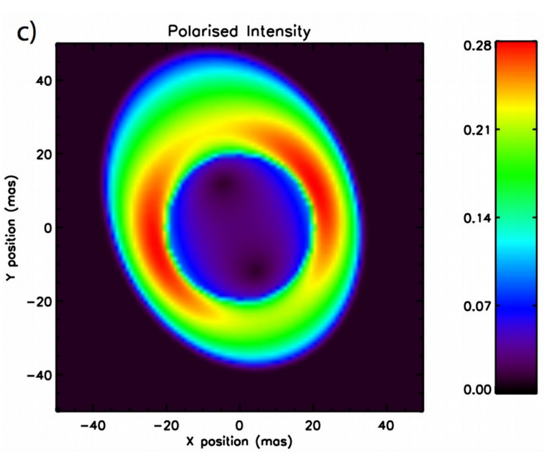
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

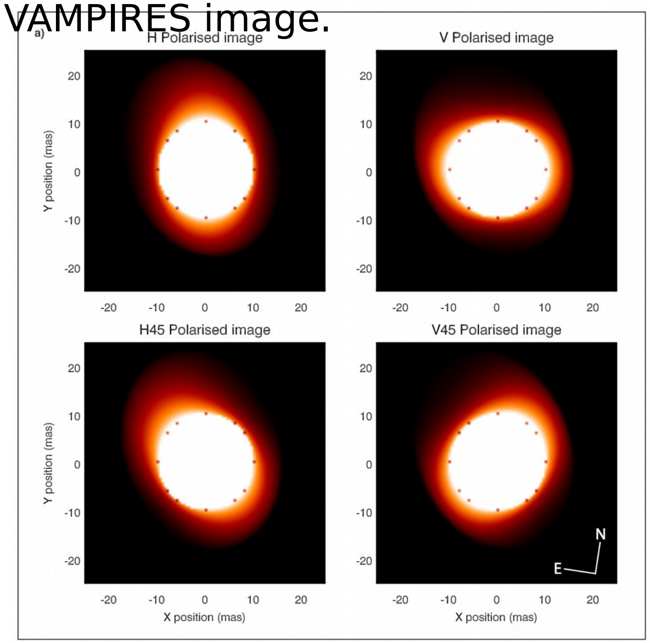
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

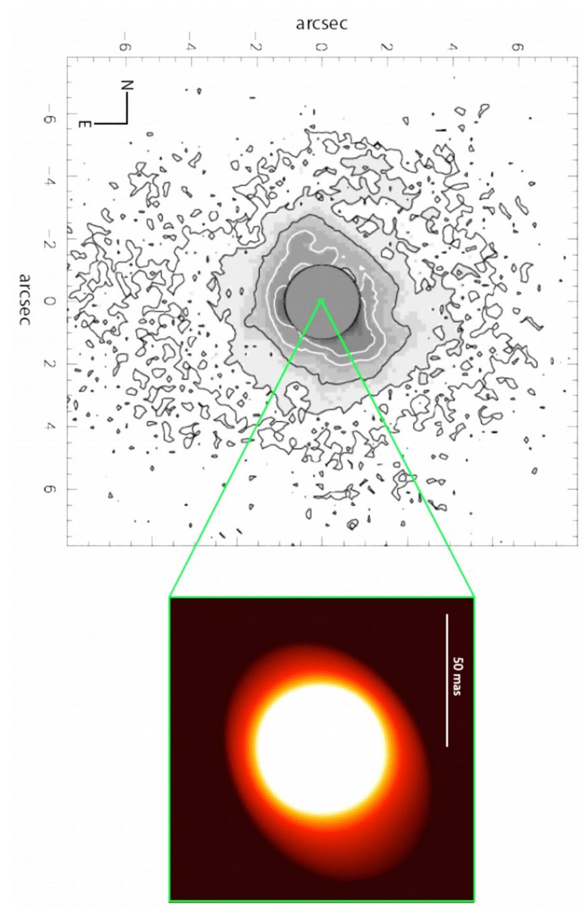
Scattered-light fraction: 0.081 ± 0.002

PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.



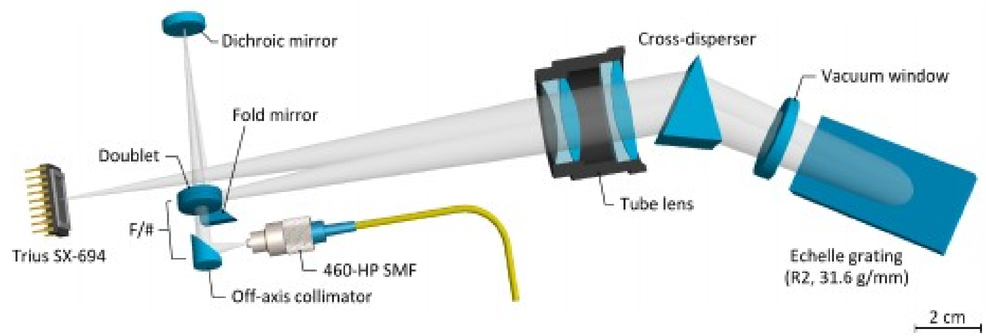


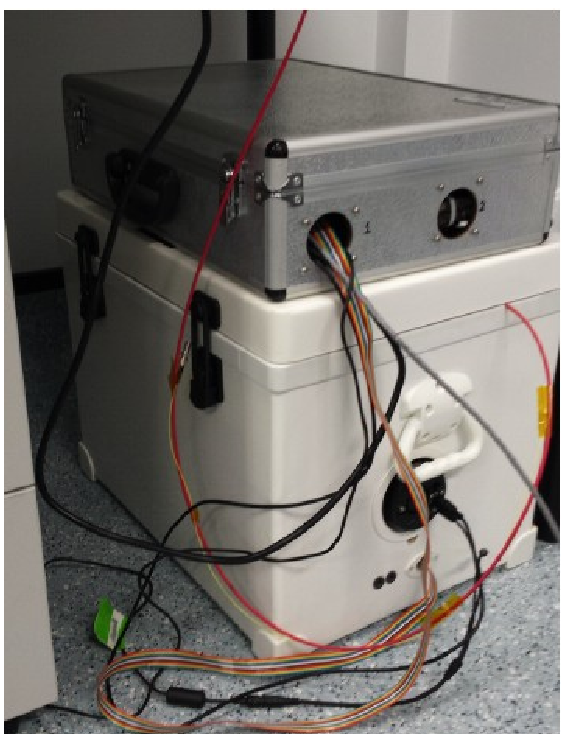


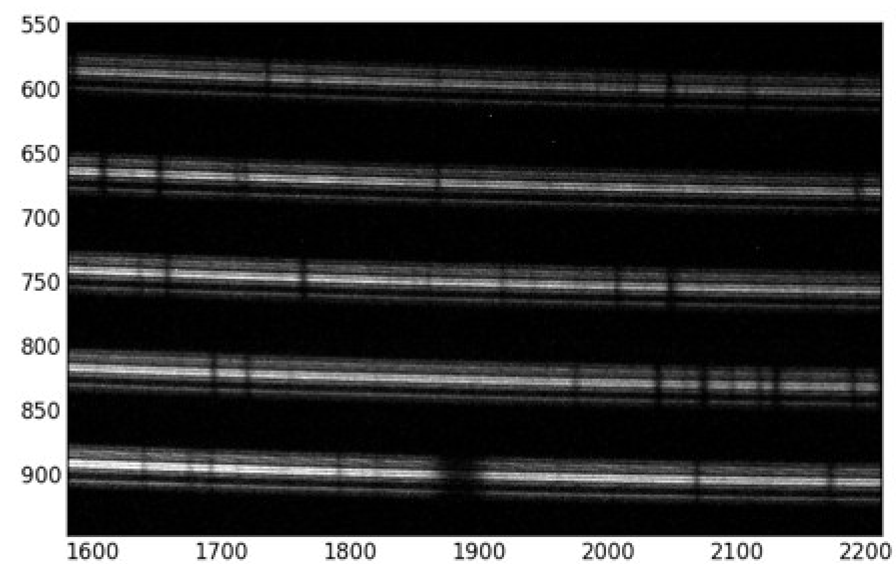
RHEA: Replicable High-resolution Exoplanet & Asteroseismology (PI: Michael Ireland, ANU)

The main specifications of RHEA@Subaru are:

Spatial Resolution	8 milli-arcsec
Spectral Resolution	R∼60,000
Total Field of View	∼4 arcsec
Instantaneous Field of View	40 milli-arcsec
IFU Elements	9 (with dithering capability)
Spectrograph Total Efficiency	40%
Injection Unit Efficiency	Strehl × 0.6

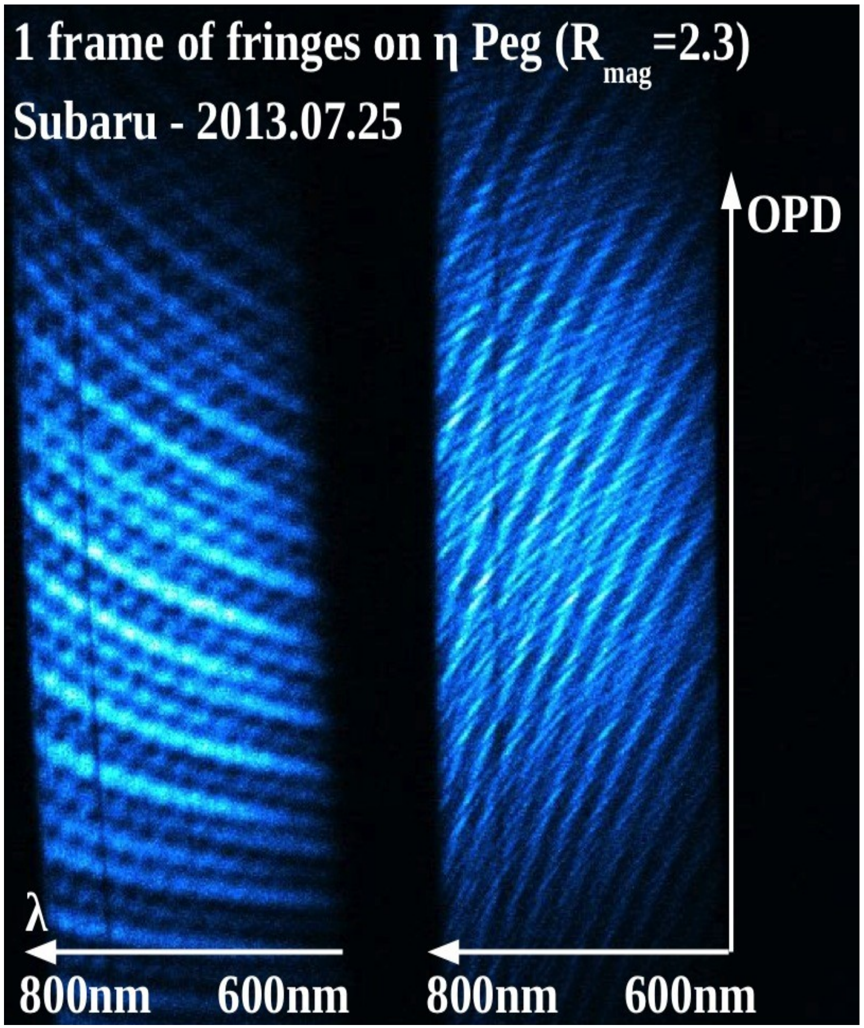


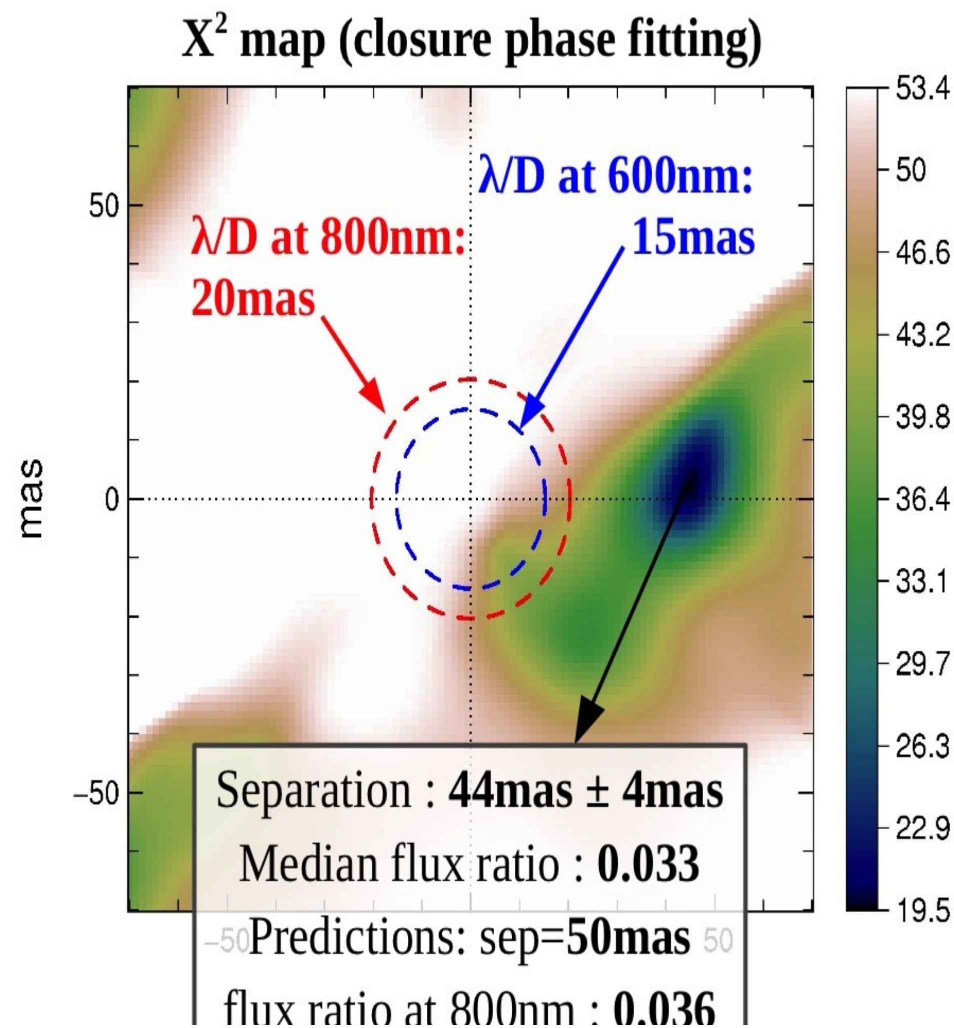




RHEA first light @ Subaru: Eps Vir (detail)
Feb 2016

FIRST visible light interferometer





Near future developments

GLINT: Guided Light Interferometric Nulling Technology (proposed - PI: Tuthill)

Near-IR photonic nuller chip

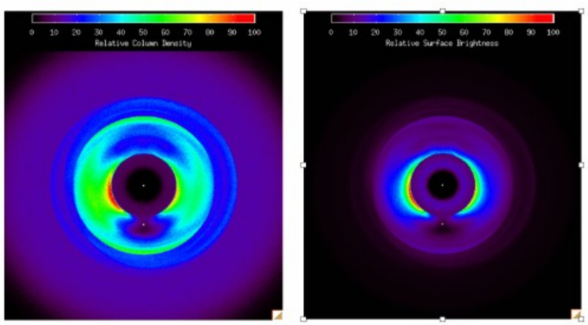


Figure 1: Dust density (Left panel) and simulated 10 μm near-IR image (Right panel) for an exozodiacal disk containing a 5 Earth-mass planet in a 1 AU orbit^{XXStark}. Shepherding of the dust by orbital resonanaces is clearly visible, and presents a significantly more prominent marker to a remote observer than the planet itself.

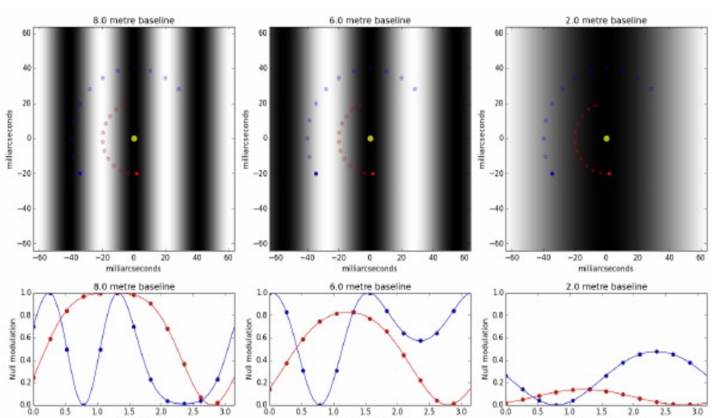
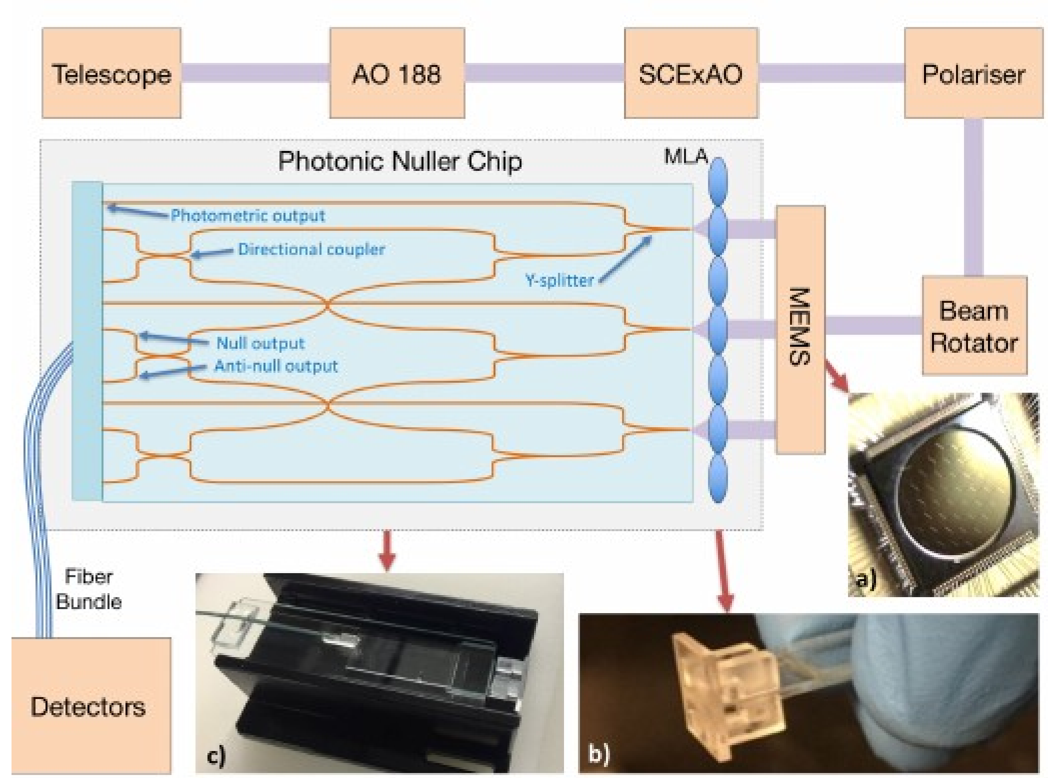


Figure 2: *Upper Panels* illustrate a star (yellow dot) lying centered within the pattern of a 2-beam nuller where its light is suppressed, while hypothetical planets (red, blue) traverse the interferometer fringes as the instrument is rotated. *Lower Panels* show the resultant planetary transmission signals produced at the output.



SCExAO feeding IRD

Jovanovic, Kawahara, Kotani, Guyon

Simultaneous spectroscopy of planet and background speckles

Spectroscopic characterization of exoplanets

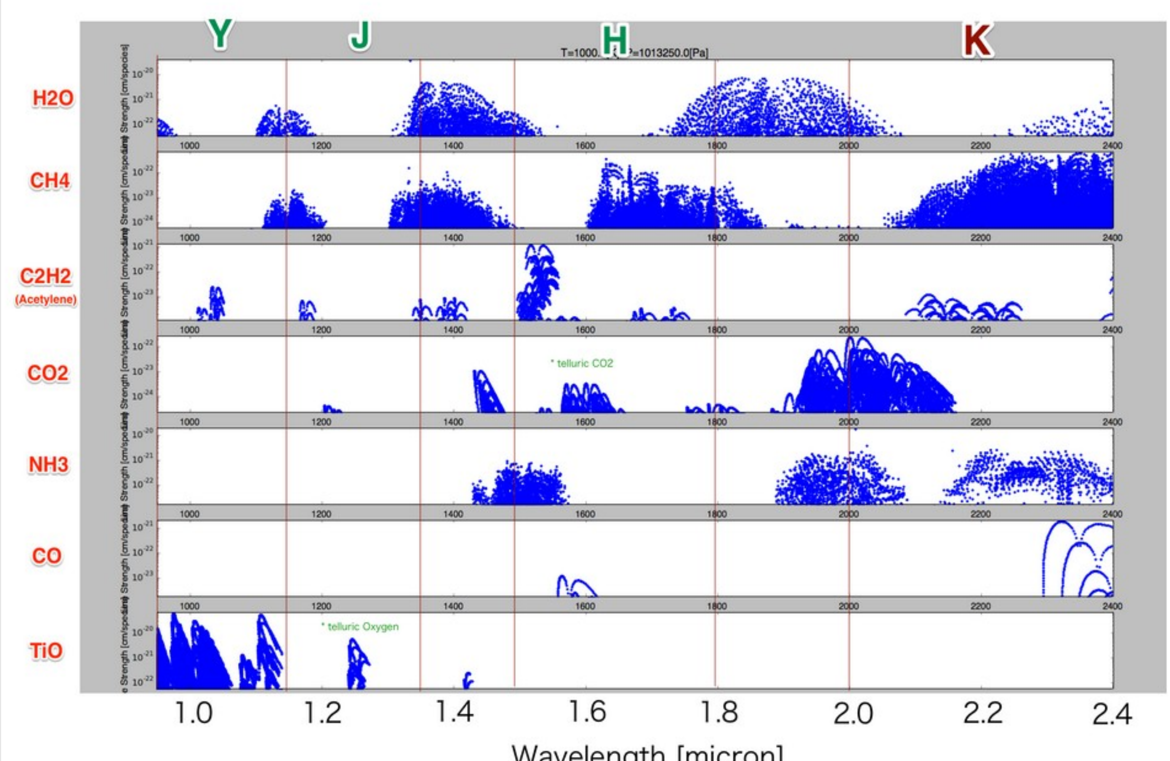
Exoplanet search using high spectral resolution signatures as differential signal

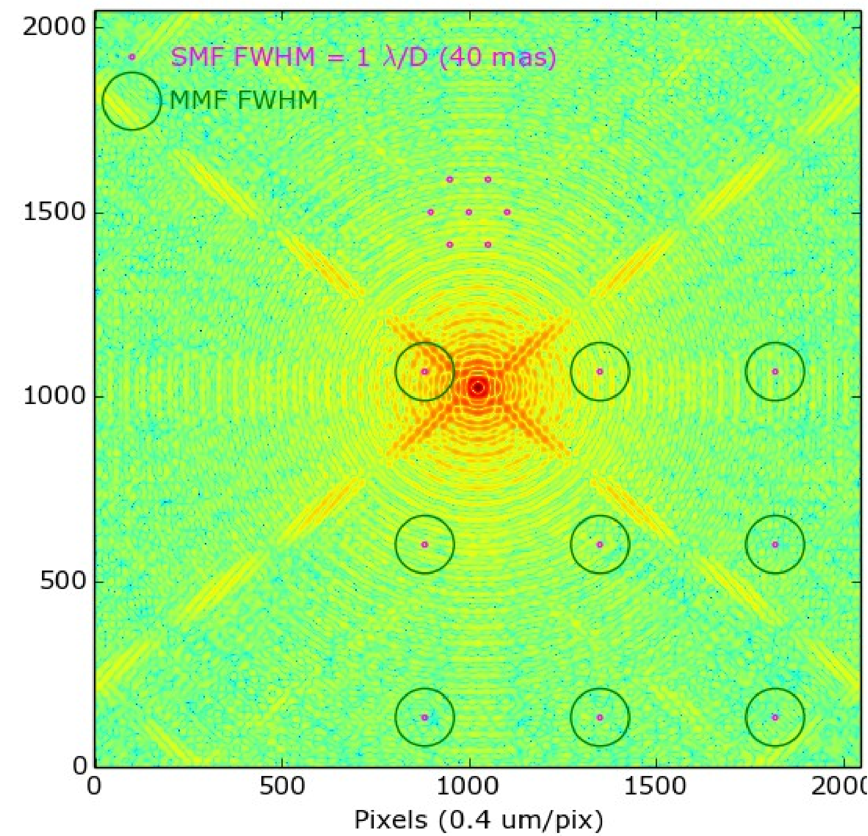
- H-band is most useful for self-luminous planets.
- J-band is less useful for the self-luminous one although it's very important for habitable planets.
- Y-band exhibits worse contrast in general, and it's just important for UV absorbers (TiO & VO) in hot planets (>~2000K).

Table 1. Important molecules in Y, J, and H bands

band	modlecules
y	TiO, VO, FeH, H2O
J	CH4(weak), H2O, FeH, Fe(5-6 lines), K(4 lines), Na(2 lines)
H	CH4, C2H2, CO2, NH3, CO(weak), H2O, FeH

Figure 1. HITRAN Line Intensity (T=1000K)





"Woofer" AO upgrade

Replace AO188 with optimized AO correction

Would include near-IR Pyramid WFS

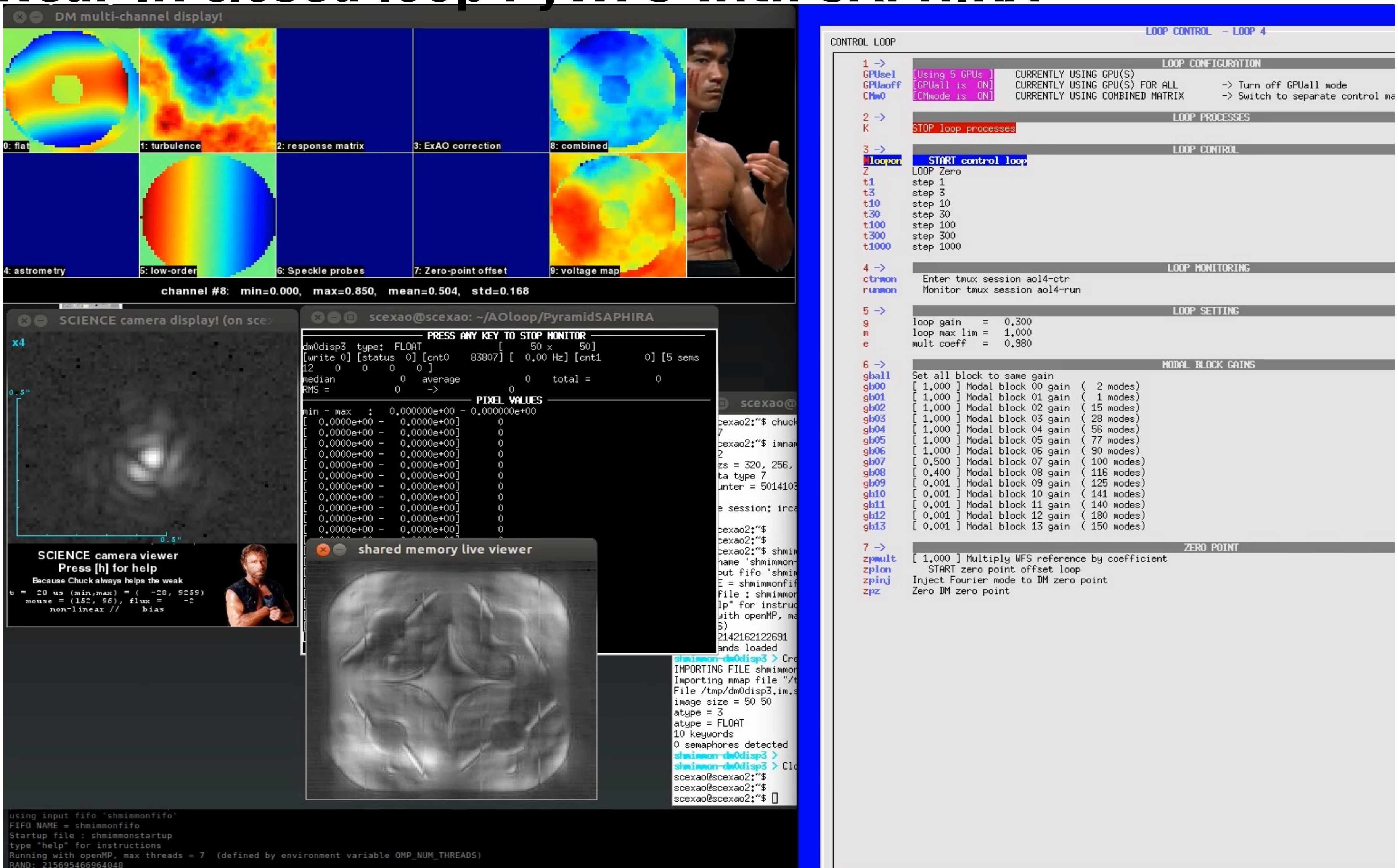
→ high throughput feeding to IRD

→ more flexibility / Wavelength coverage for visible light modules

→ higher high contrast imaging performance

→ path to TMT instrument

Near-IR closed loop PyWFS with SAPHIRA

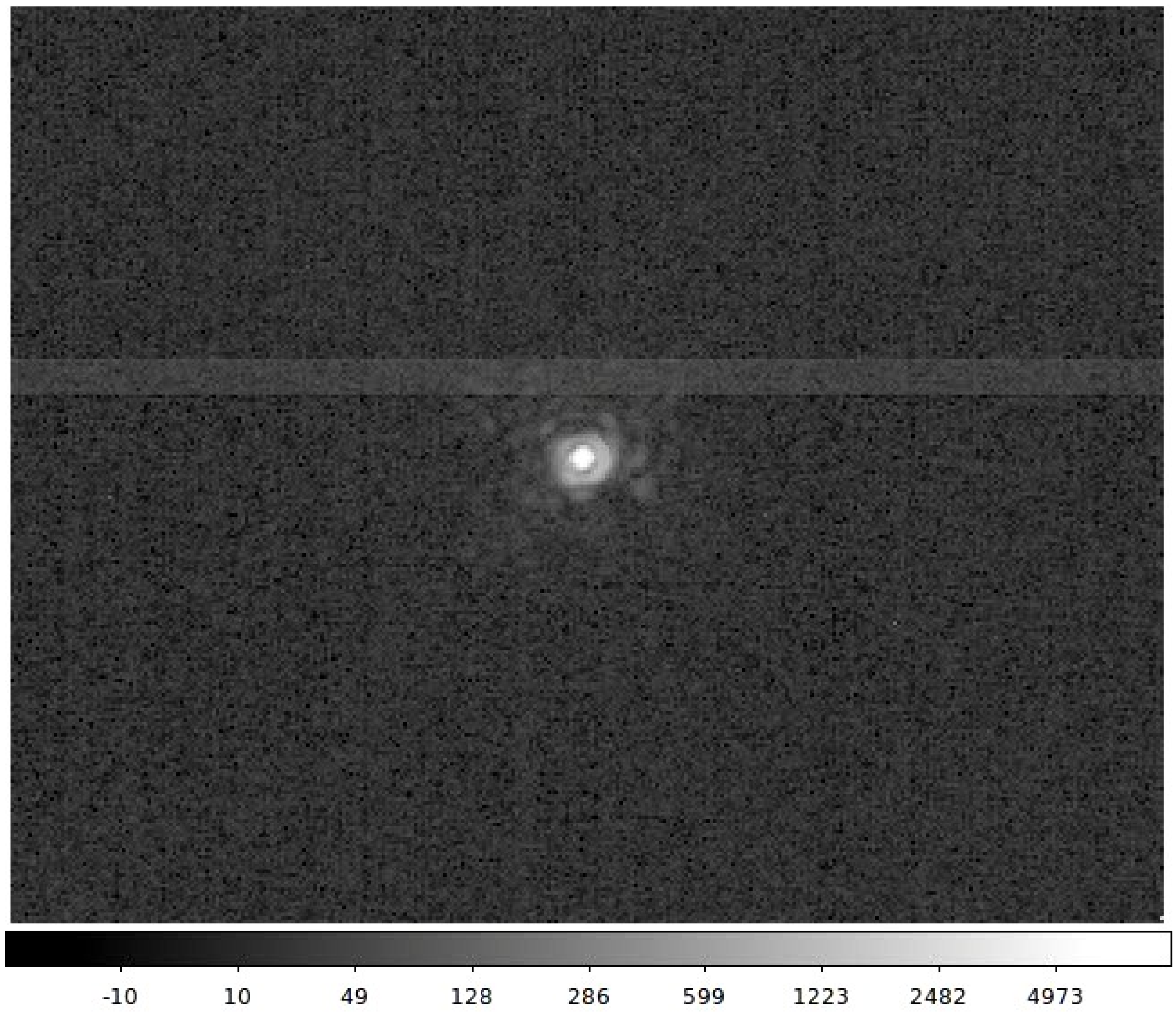


The ongoing fight against vibrations

5-30 Hz telescope vibrations
Due mostly to telescope Alt encoders

Short-term solutions:
- Install accelerometers on telescope
- Feed-forward loop to AO188 TT
- LQG control

Long-term:
Change encoders



SCExAO uniquely expands exoplanetary system characterization capabilities at Subaru

Where would habitable planets be in contrast/separation ?