High Contrast Imaging R&D at the Subaru Coronagraphic Extreme Adaptive Optics

Olivier Guyon

Subaru Telescope, National Astronomical Observatory of Japan,
National Institutes for Natural Sciences (NINS)

University of Arizona

Astrobiology Center, National Institutes for Natural Sciences (NINS)

Breakthrough Initiatives team member (Starshot and Watch)

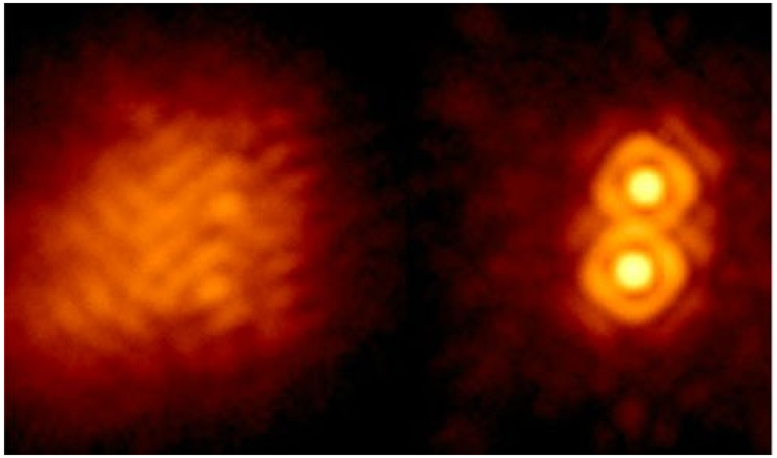
Adaptive Optics (AO)

Atmosphere Turbulence: Earth's atmosphere introduces strong and fast optical aberrations

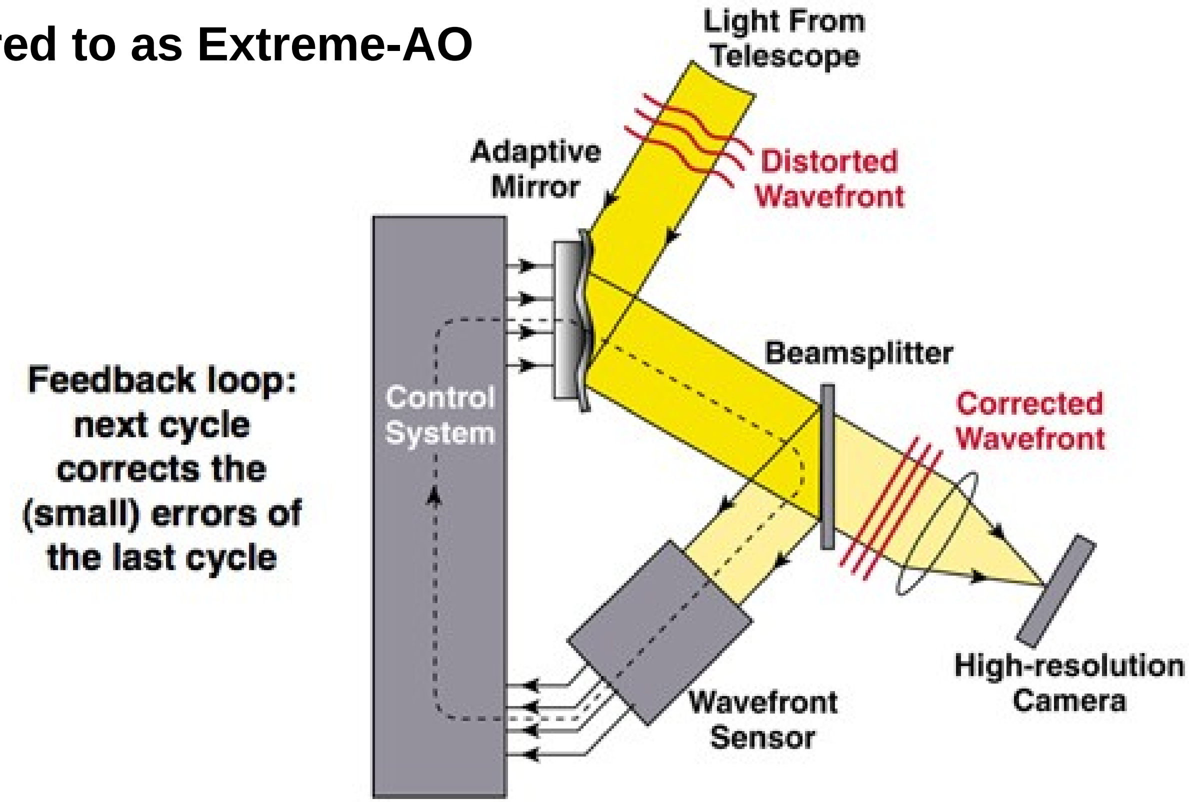
Aberrations must be continuously **measured** and **corrected** to provide sharp images.

Imaging exoplanets is particularly demanding, as the planet is much fainter that the star it orbits: very little room for error !
→ **AO for exoplanet imaging is referred to as Extreme-AO**

AO OFF AO ON



Palomar obs / NASA JPL



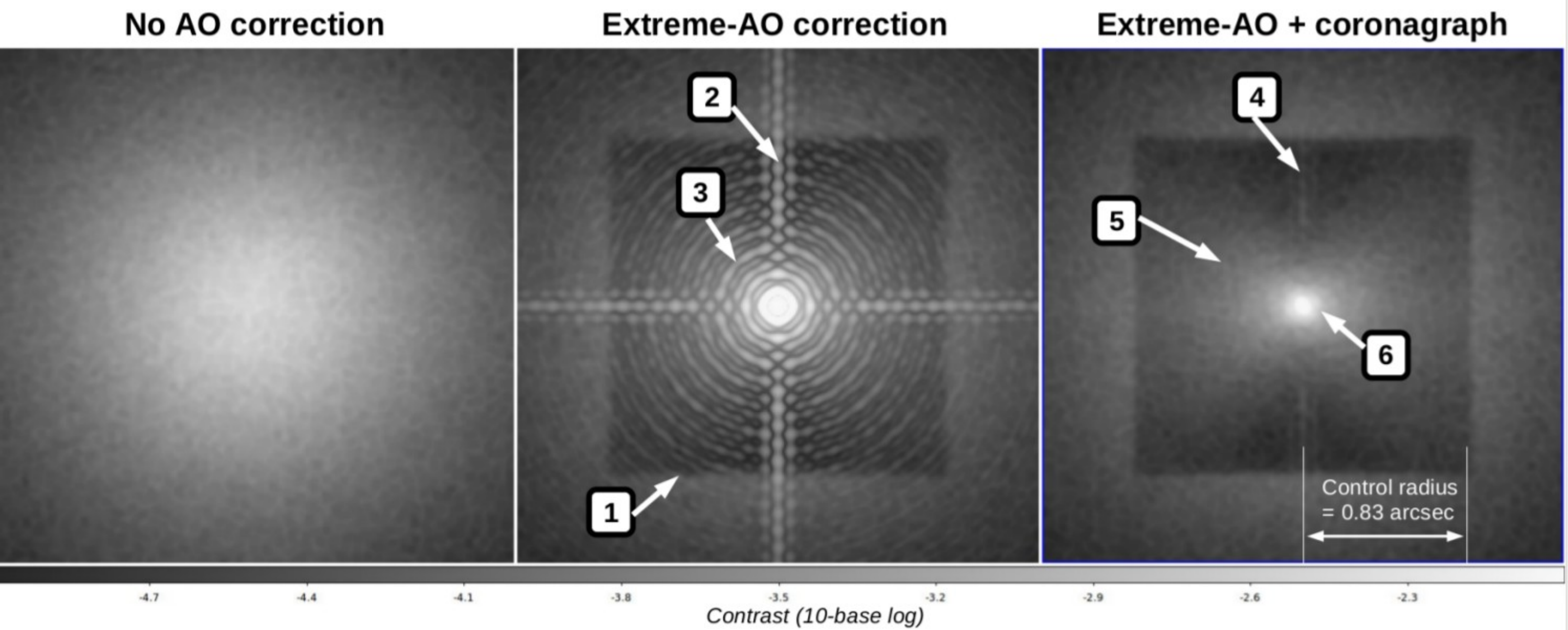
Imaging exoplanets requires two techniques to be combined:

- **Extreme-AO corrects atmospheric turbulence**
- **A coronagraph masks the light of the bright star**

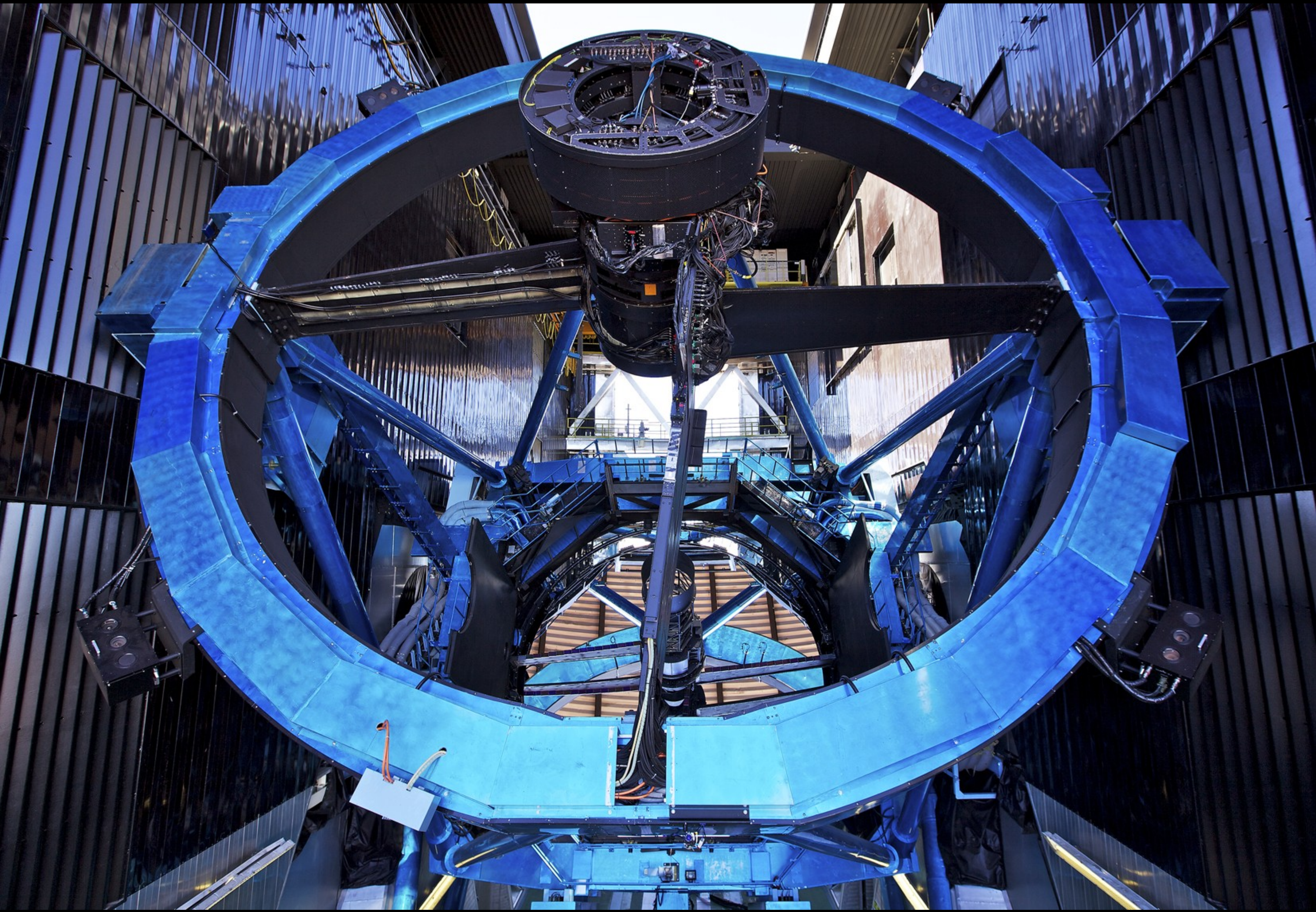
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: "butterfly" wind effect
6: Coronagraphic leak (low order aberrations)

Simulated images below show how Extreme-AO and Coronagraphy deliver high contrast image of a star

Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag



Subaru Telescope (8.2m diameter) has an exoplanet-imaging instrument (SCExAO)
The instrument team is developing advanced Extreme-AO techniques

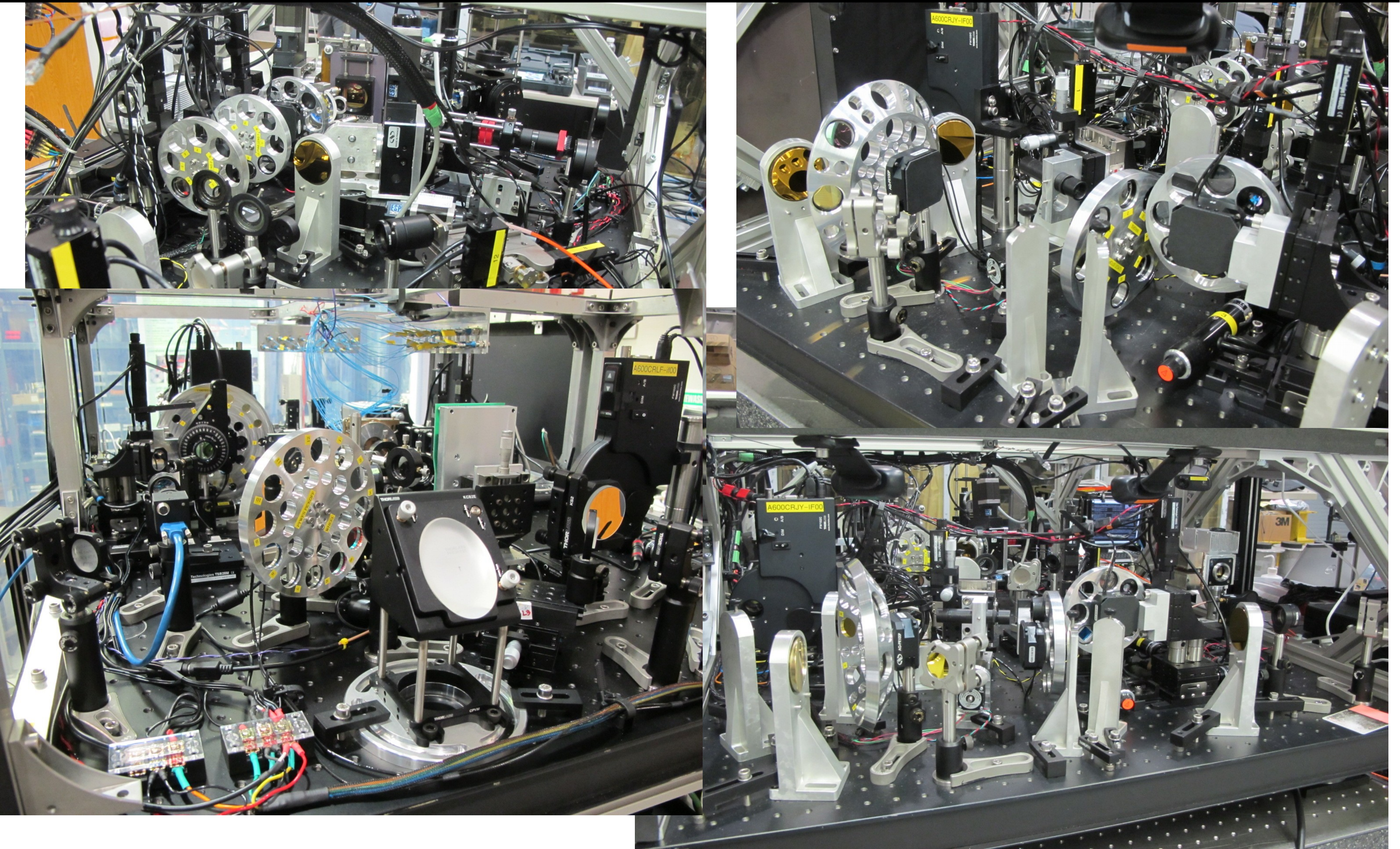


Subaru Telescope (view from inside dome) Photograph by Enrico Sachetti

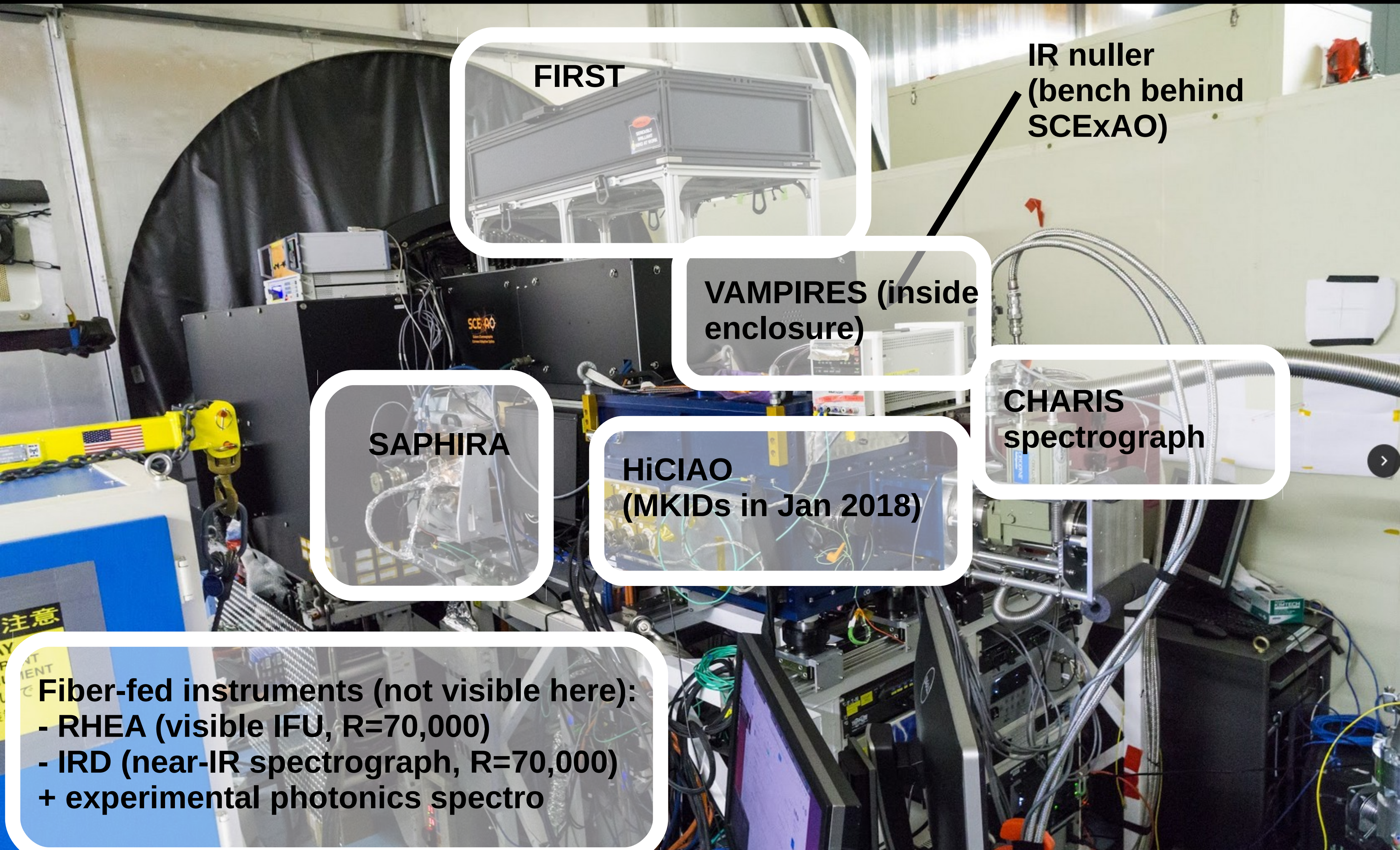
SCExAO Subaru Coronagraphic Extreme Adaptive Optics

SCExAO

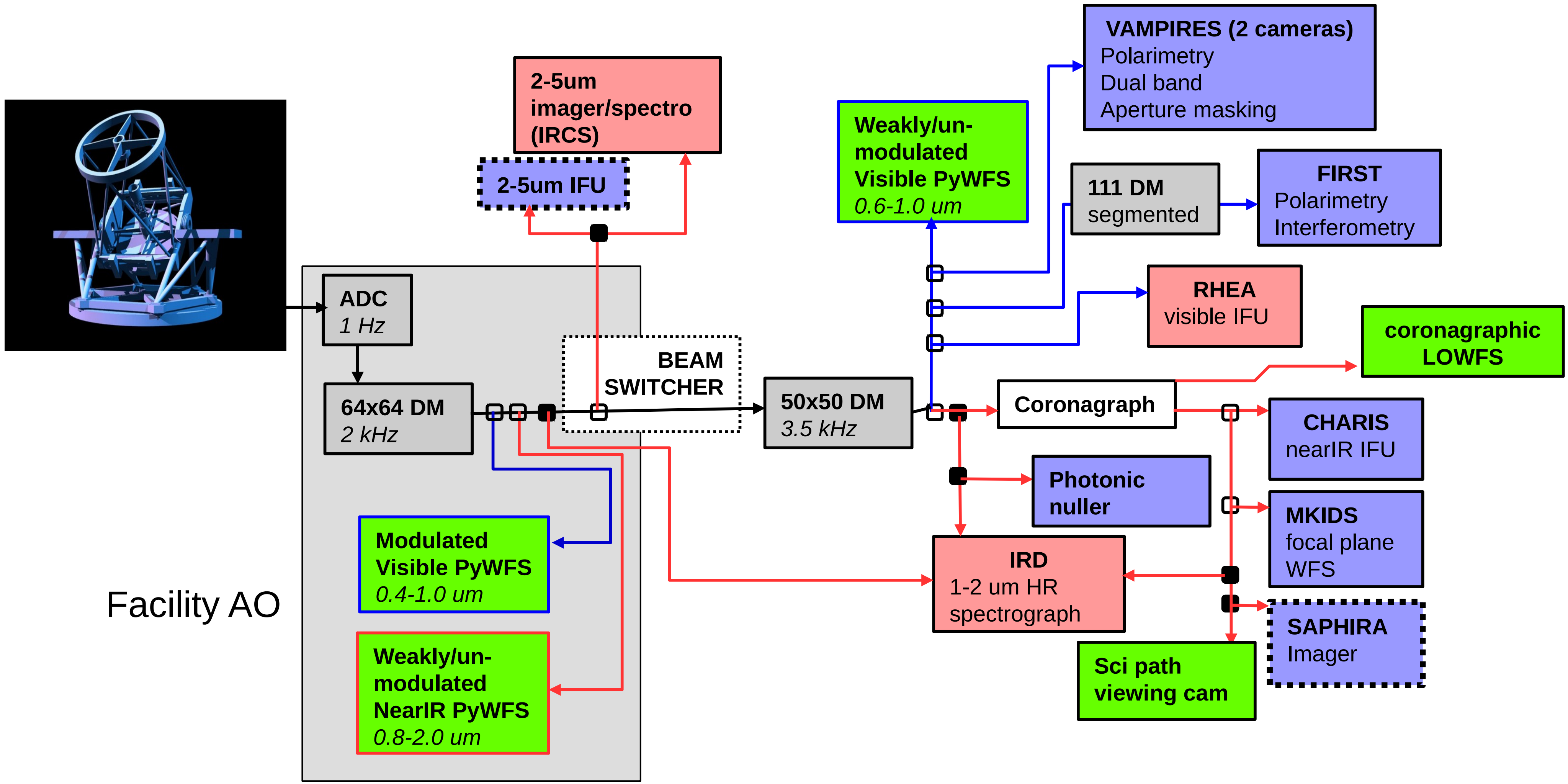
Subaru Coronagraphic Extreme Adaptive Optics

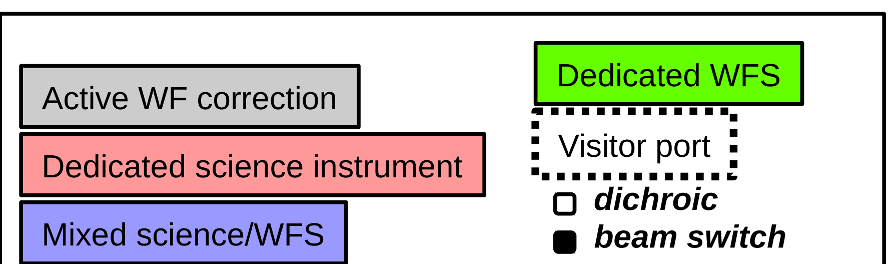


SCExAO Subaru Coronagraphic Extreme Adaptive Optics



SCExAO Light path

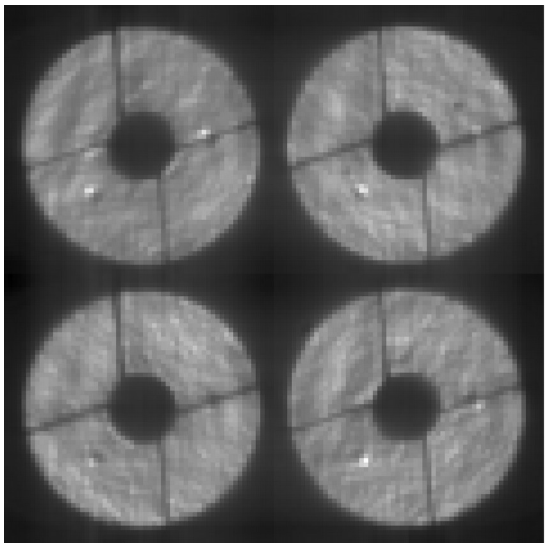


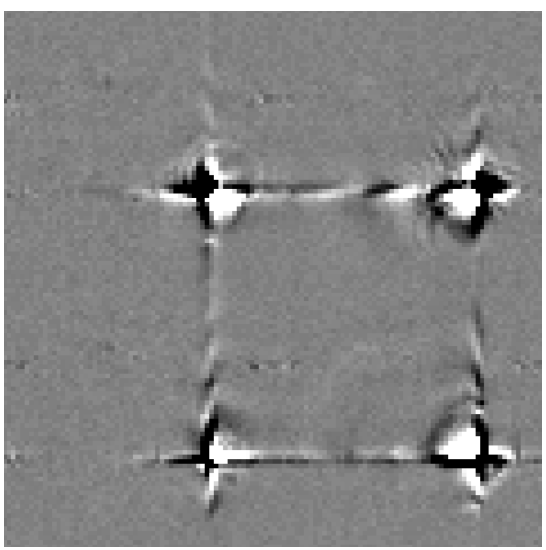


11 wavefront sensors

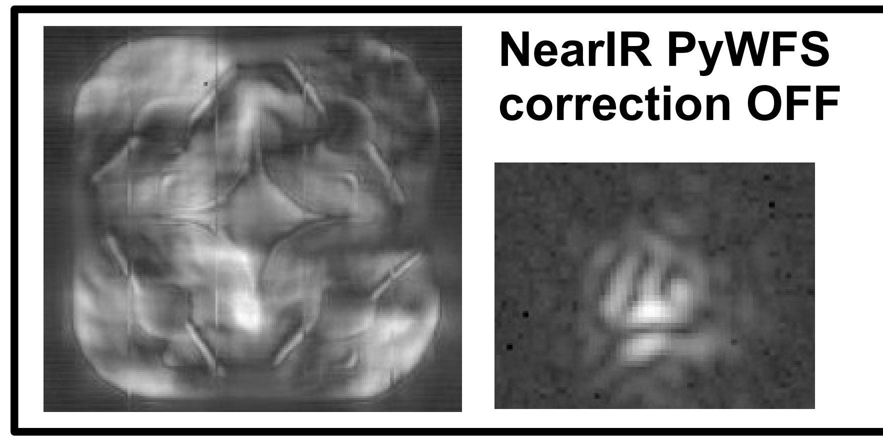
High performance WFS

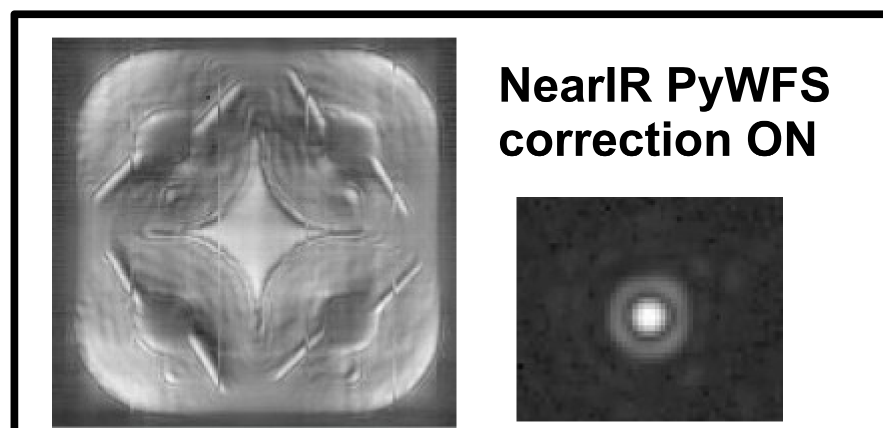
Low-modulation PyWFS (600-900nm)
14400 sensors → 2000 actuators
loop runs at up to 3.5 kHz



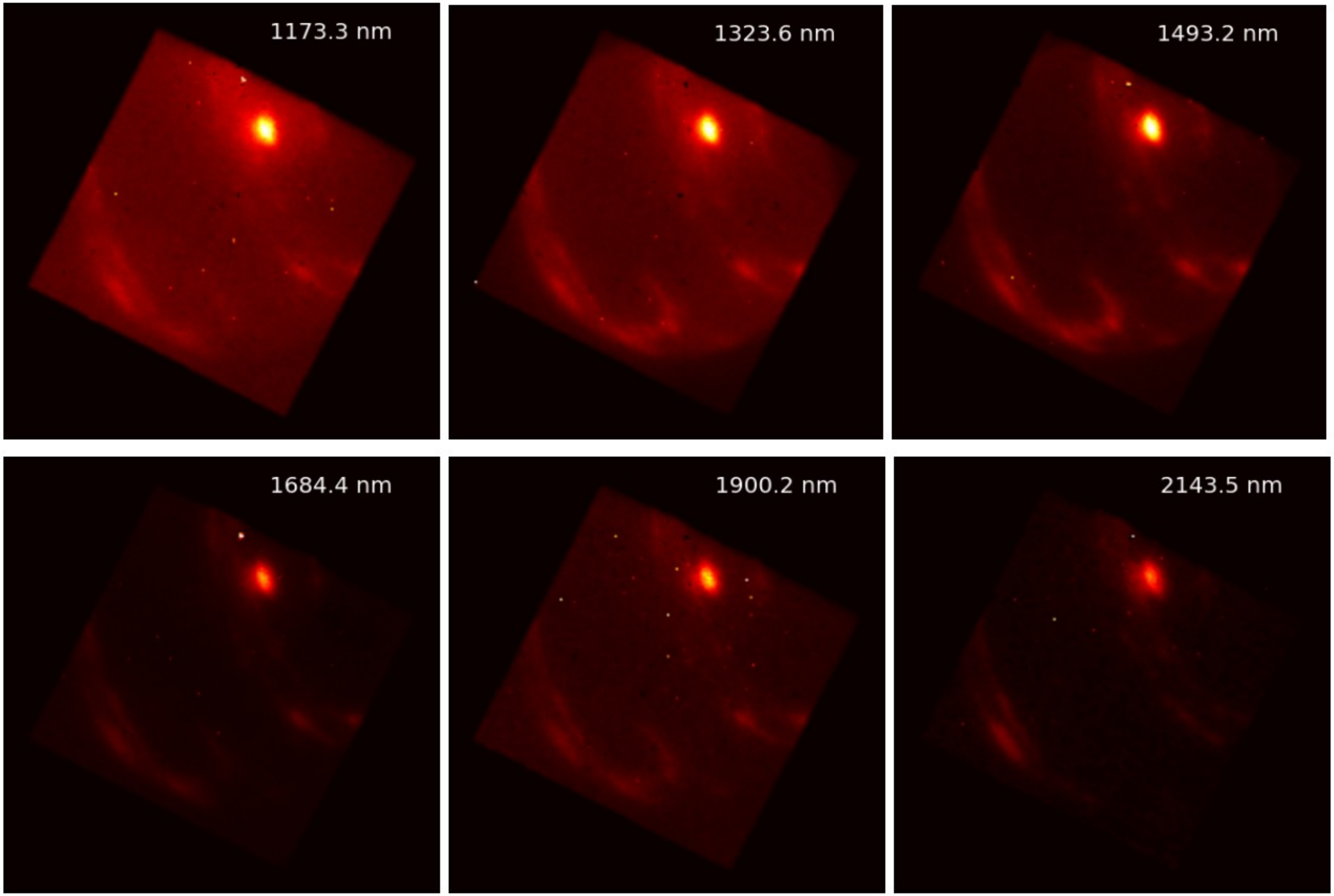


Unmodulated PyWFS demo (H band, SAPHIRA)
14400 sensors → 2000 actuators





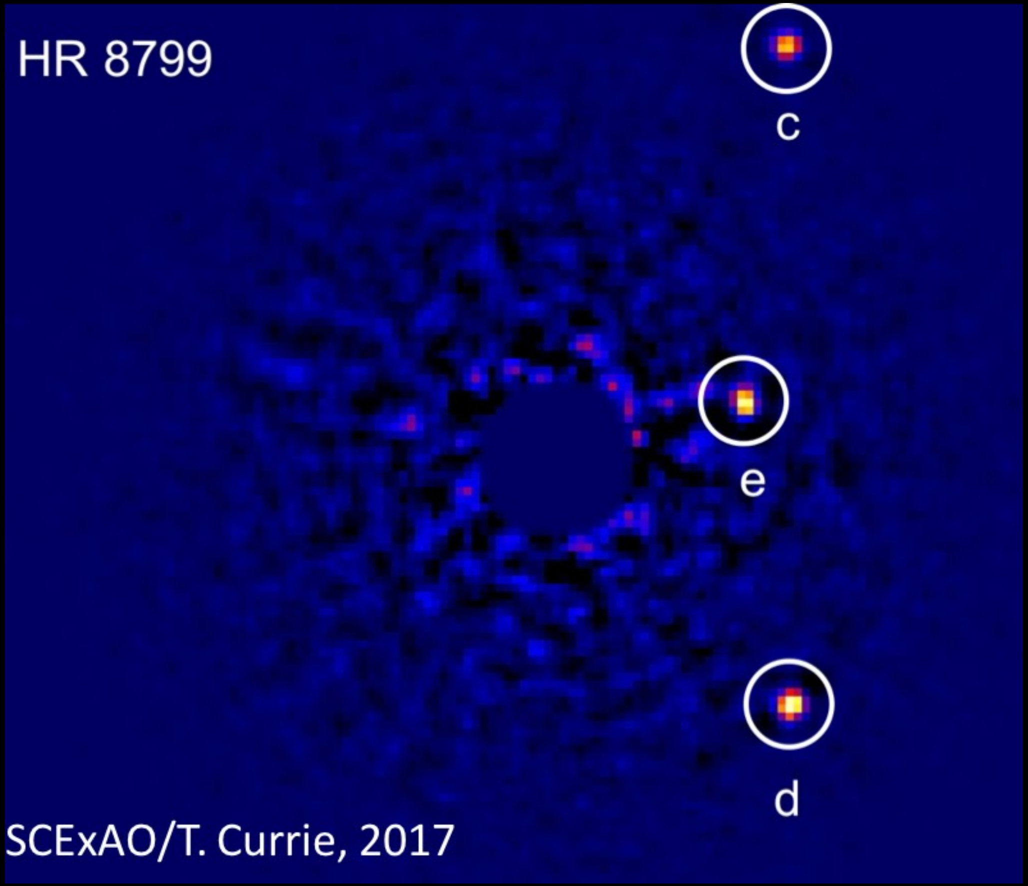
Neptune imaged with SCExAO doesn't fit in field of view ! (using CHARIS camera)



HR8799

Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

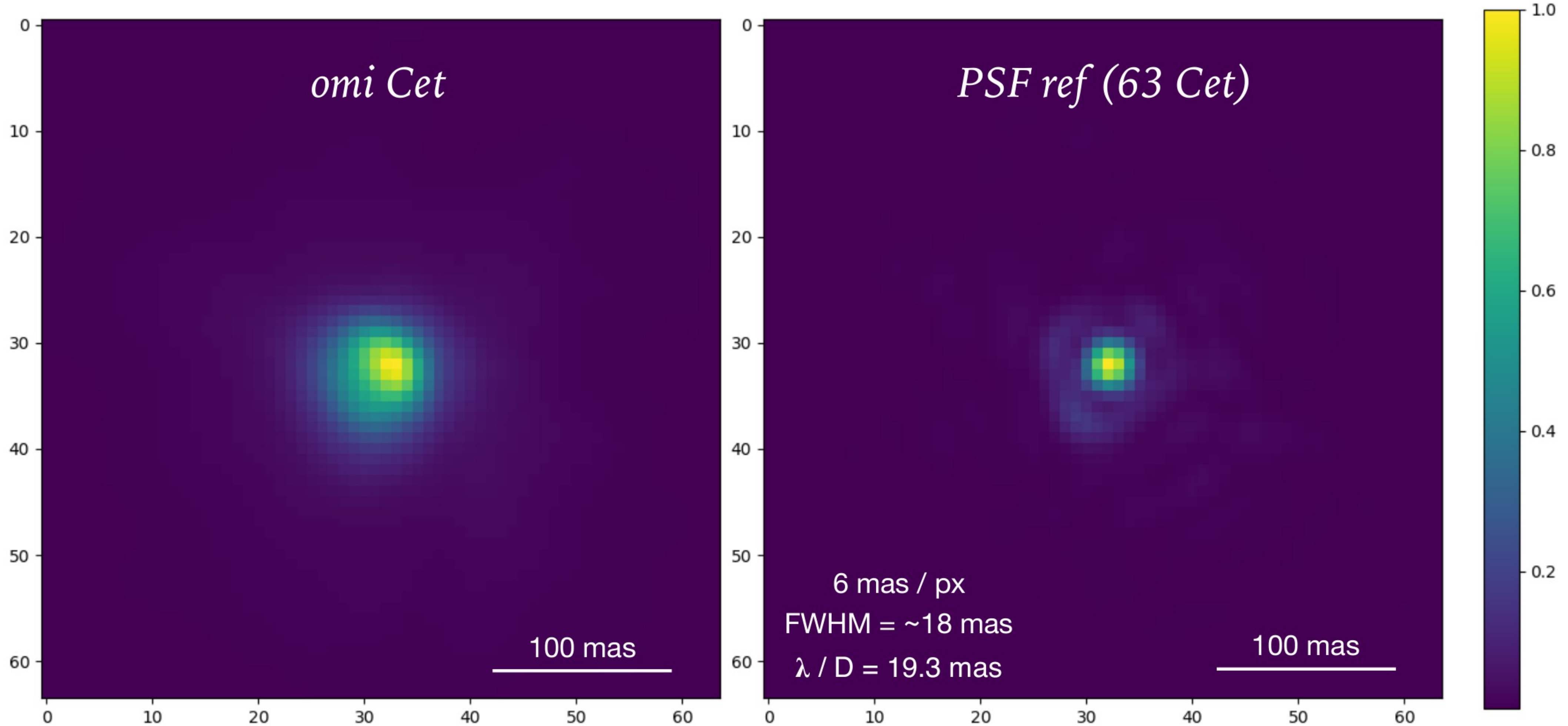
Subaru Telescope/ SCExAO (Currie et. al 2017)



VAMPIRES Update Feb 2018

Key improvement 2017-18: Full Pupil speckle-imaging / PDI mode

- Direct imaging of Mira-variable star omi Cet - clear asymmetry seen.
  - Speckle imaging - diffraction-limited



Observed 12/09/2017

Preliminary VAMPIRES science

Circumstellar dust around Red Supergiant μ Cephei

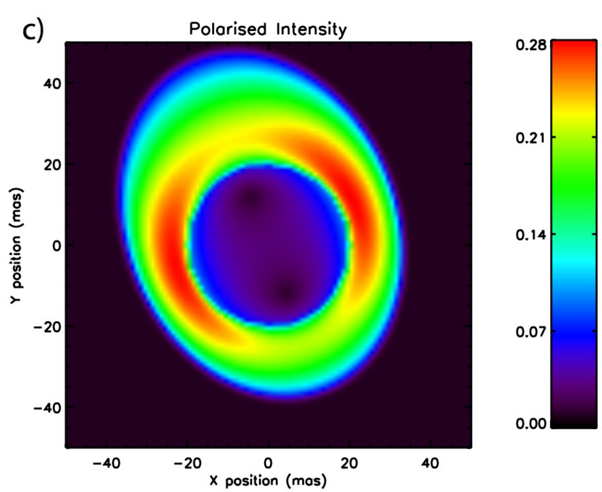
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

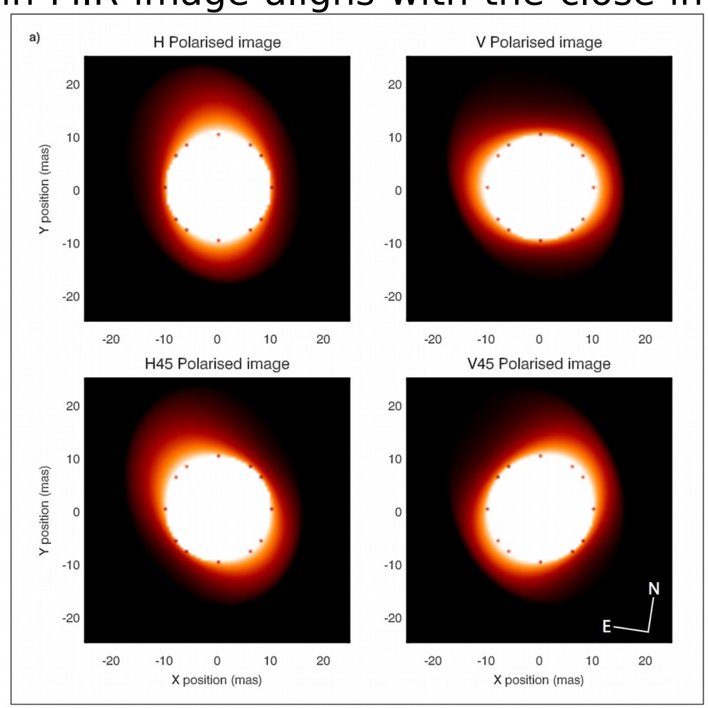
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

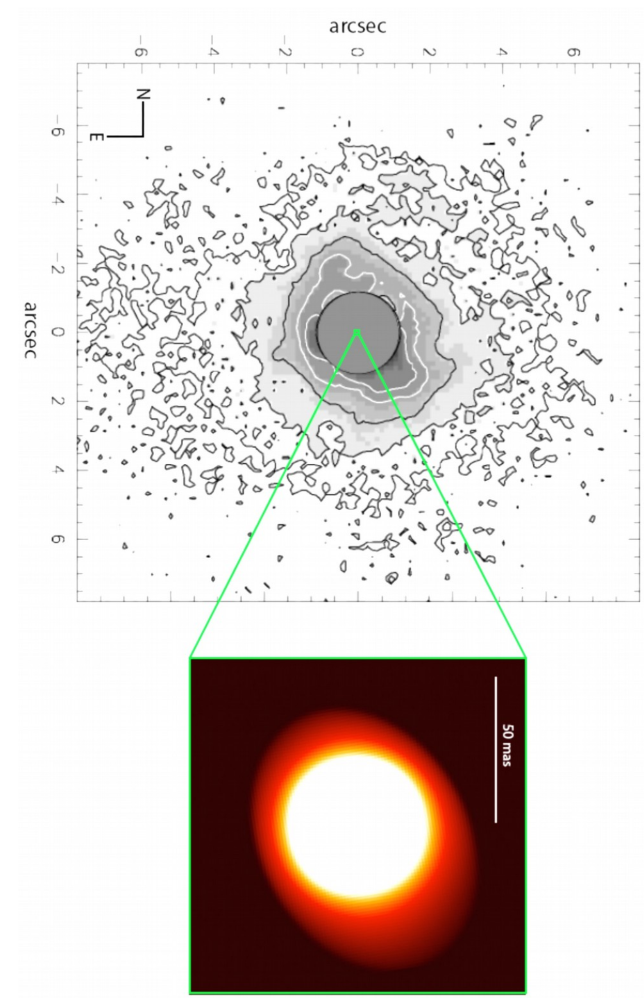
Scattered-light fraction: 0.081 ± 0.002

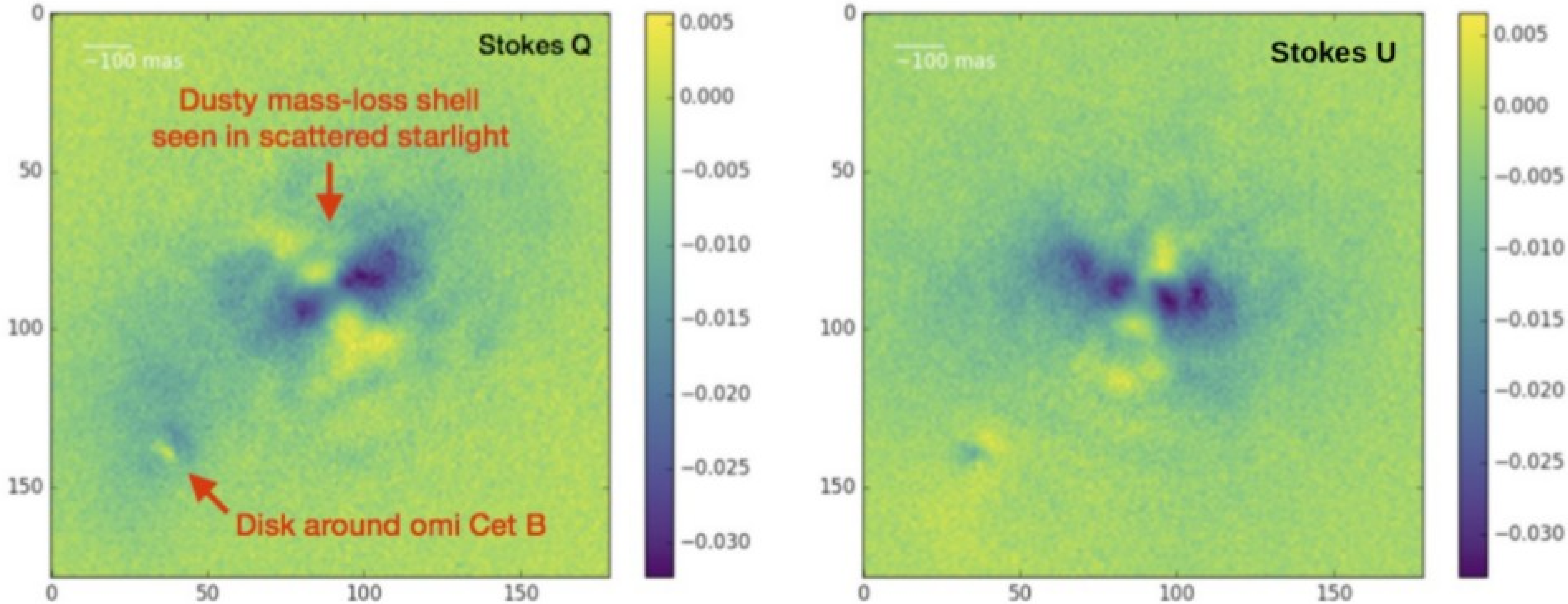
PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

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.









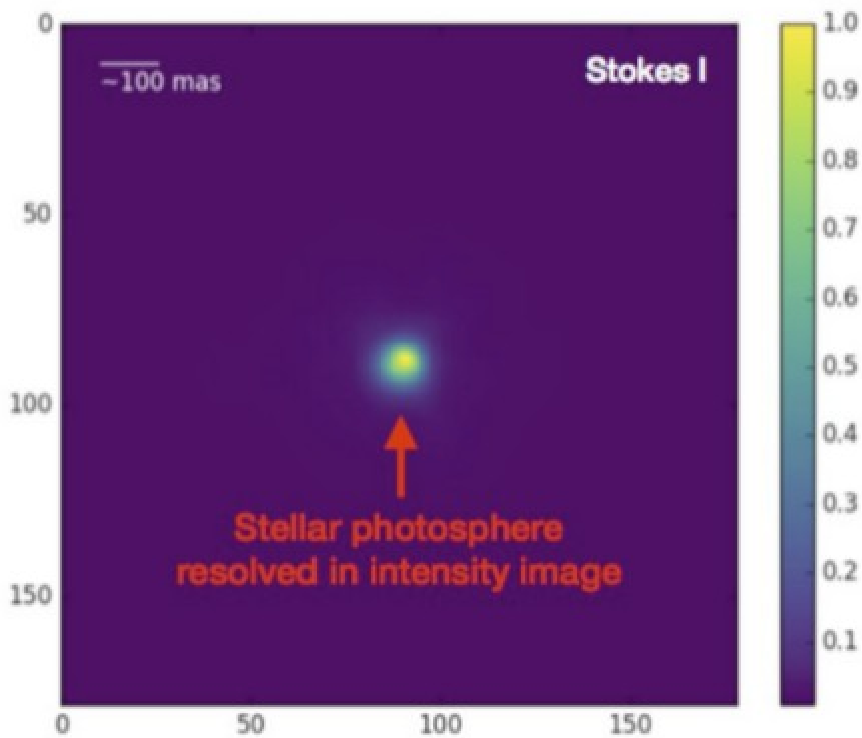


Figure 4: Omi Ceti (Mira) polarimetric imaging
Fractional stokes Q (upper left), U (upper right) and I (lower left) images of *omi Cet* and the surrounding mass-loss shell, taken at 750 nm with VAMPIRES. In the polarisation images the mass-loss shell and associated nebulosity is clearly seen, as well as the circumstellar disk around its companion *omi Cet B*. Understanding the mass-loss process relies on properly constraining dust grain size distributions and species (at separate spatially resolved points). This requires observations across a wide set of wavelengths, including Y, J and H band, in addition to R and I as probed by VAMPIRES.

VAMPIRES Update Feb 2018

Hα SDI mode implemented with 1st on-sky tests complete

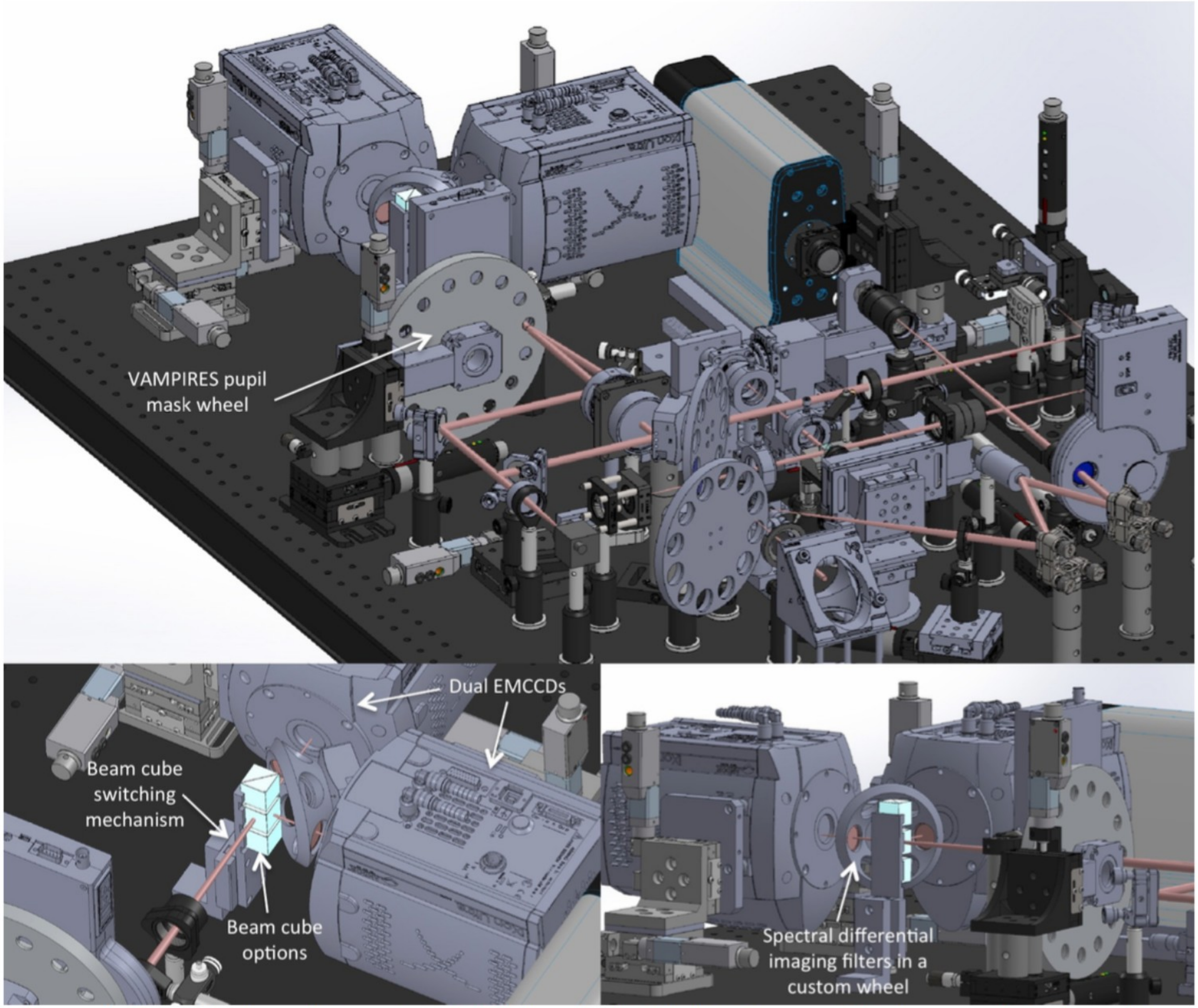


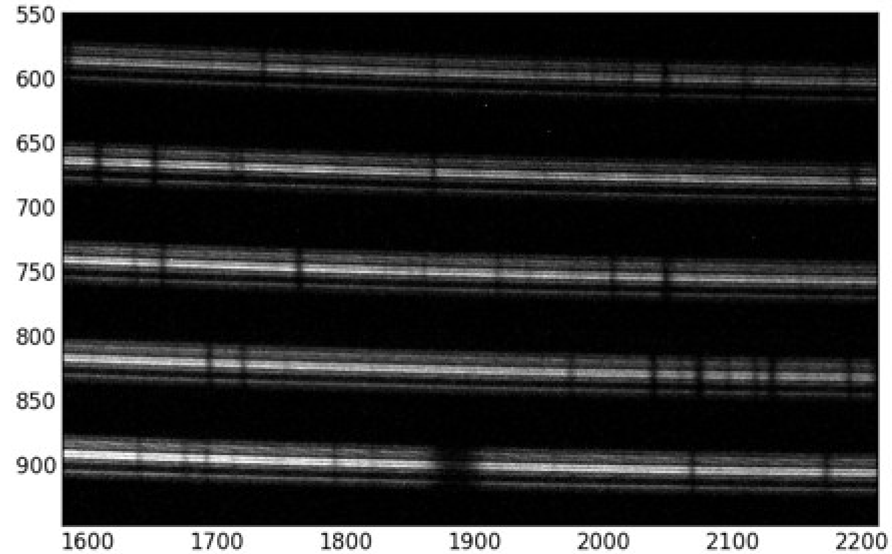
Figure 4: (Top) A view of the entire visible bench of SCExAO. (Bottom left) A zoomed in view of the beam cube switching mechanism. (Bottom right) A zoomed in view of the wheel to switch the filters for differential imaging mode.

Ongoing research / future opportunities

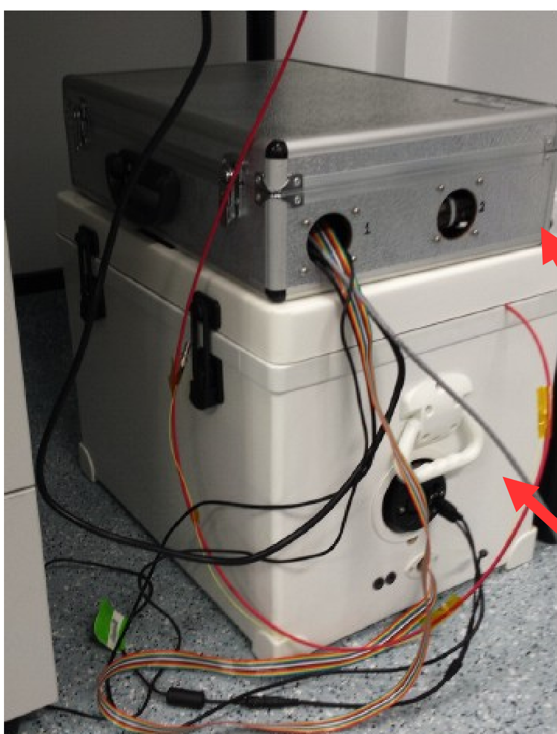
RHEA: Replicable High-resolution Exoplanet & Asteroseismology (PI: Michael Ireland, ANU)

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



RHEA electronics

RHEA spectrograph optics + detector

SCExAO feeding IRD

Jovanovic, Kawahara, Kotani, Guyon

Simultaneous spectroscopy of planet and background speckles

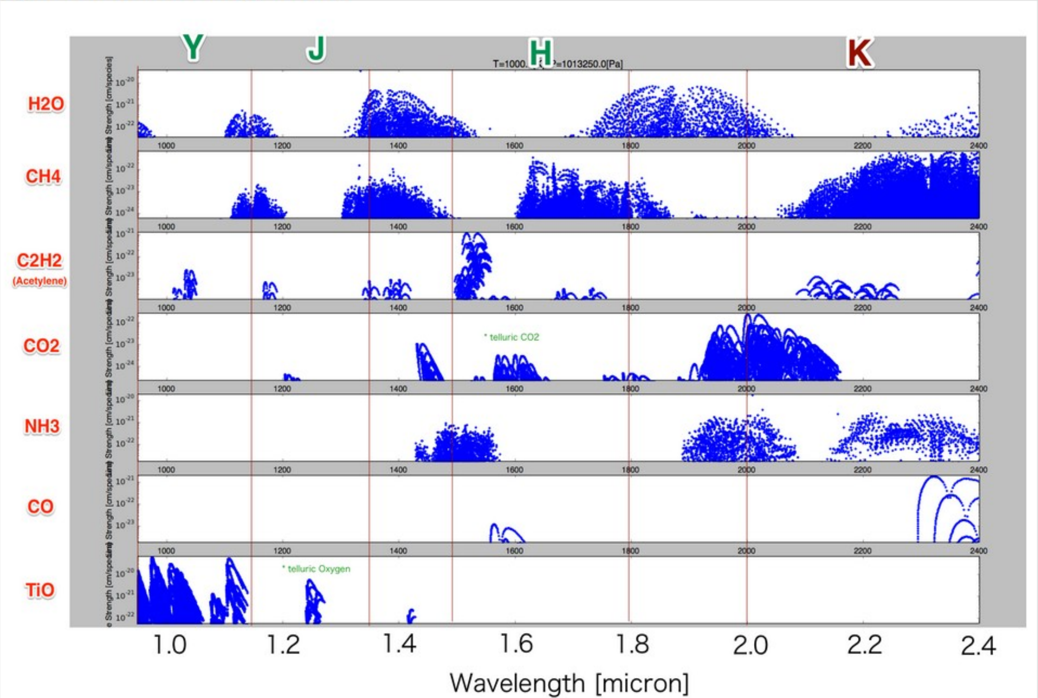
Spectroscopic characterization of exoplanets
Exoplanet search using high spectral resolution signatures as differential signal

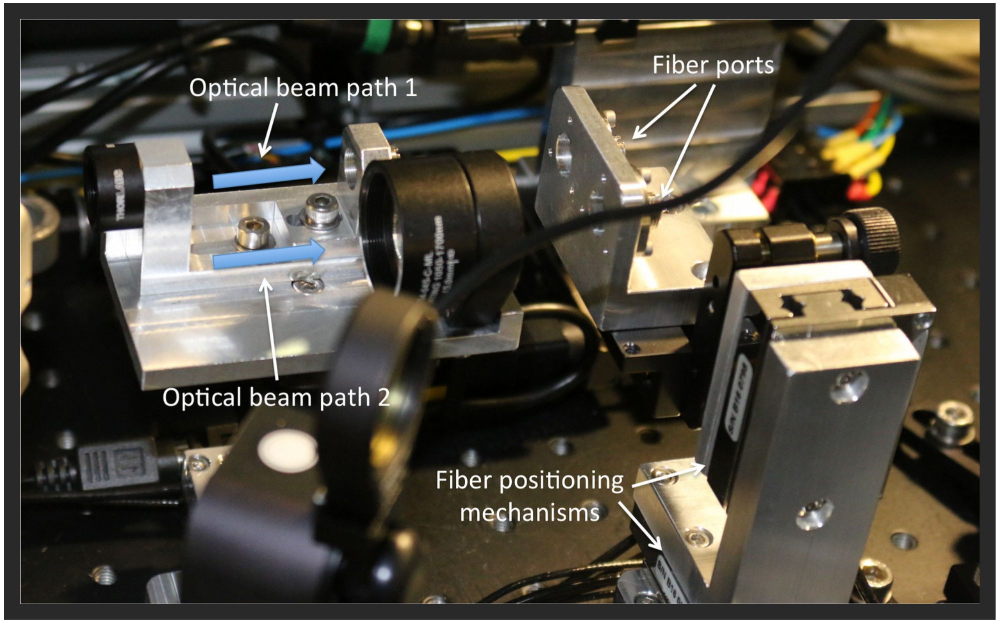
- H-band is most useful for self-luminous planets.
- J-band is less useful for the self-luminous one although it's very important for habitable planets.
- Y-band exhibits worse contrast in general, and it's just important for UV absorbers (TiO & VO) in hot planets (>~2000K).

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

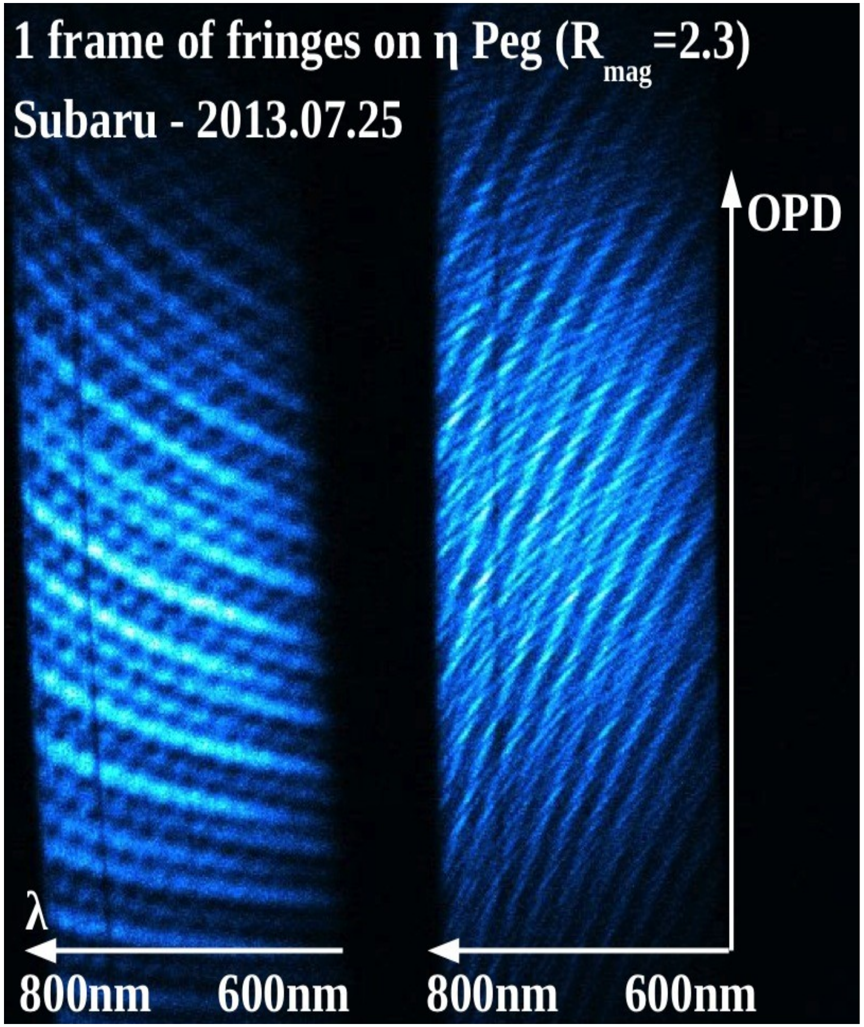
band	modlecules
y	TiO, VO, FeH, H2O
J	CH4(weak), H2O, FeH, Fe(5-6 lines), K(4 lines), Na(2 lines)
H	CH4, C2H2, CO2, NH3, CO(weak), H2O, FeH

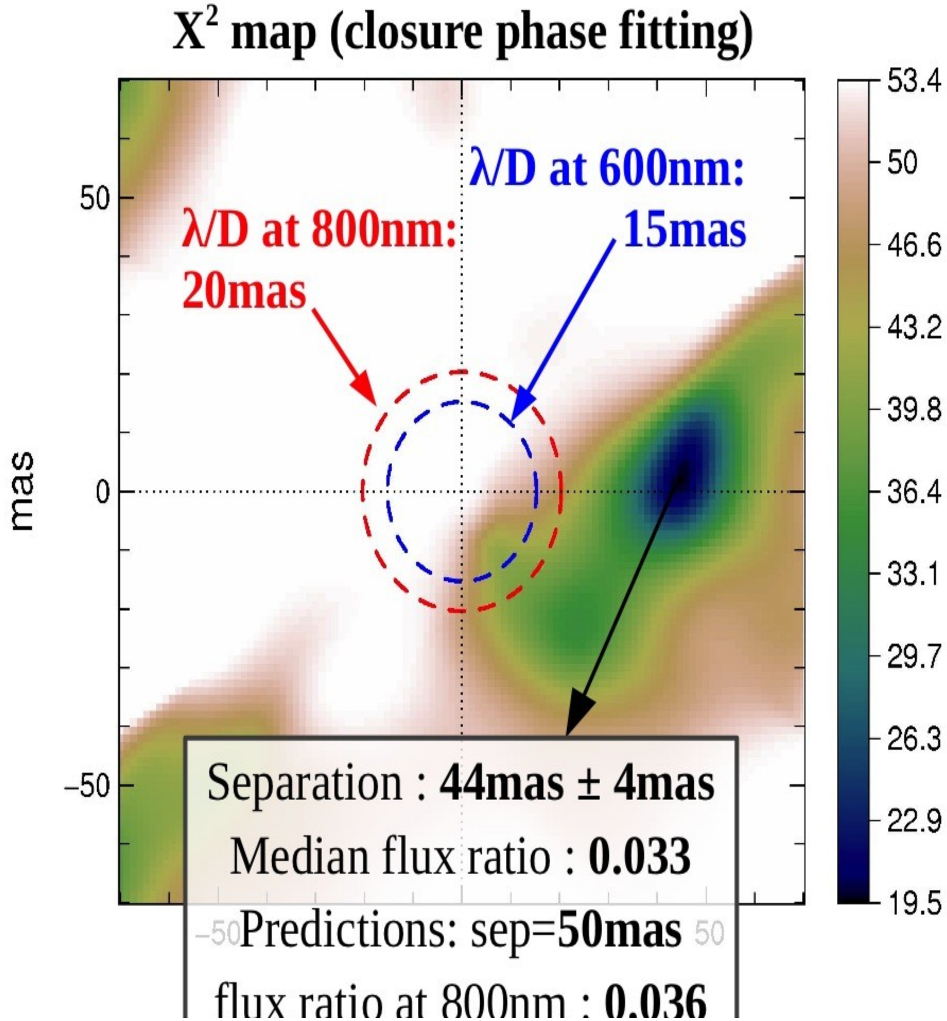
Figure 1. HITRAN Line Intensity (T=1000K)

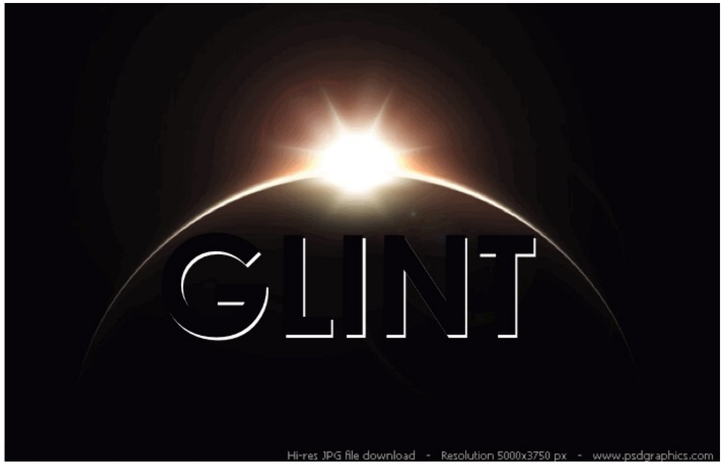




FIRST visible light interferometer (stellar physics mostly)







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

Near-IR photonic nuller chip

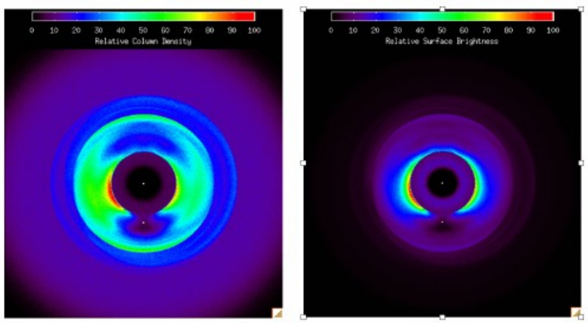


Figure 1: Dust density (Left panel) and simulated 10 μm near-IR image (Right panel) for an exozodiacal disk containing a 5 Earth-mass planet in a 1 AU orbit$^{XX Stark}$. Shepherding of the dust by orbital resonanaces is clearly visible, and presents a significantly more prominent marker to a remote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

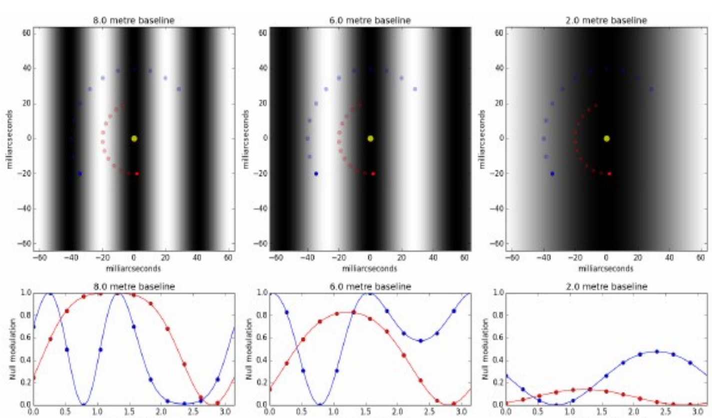
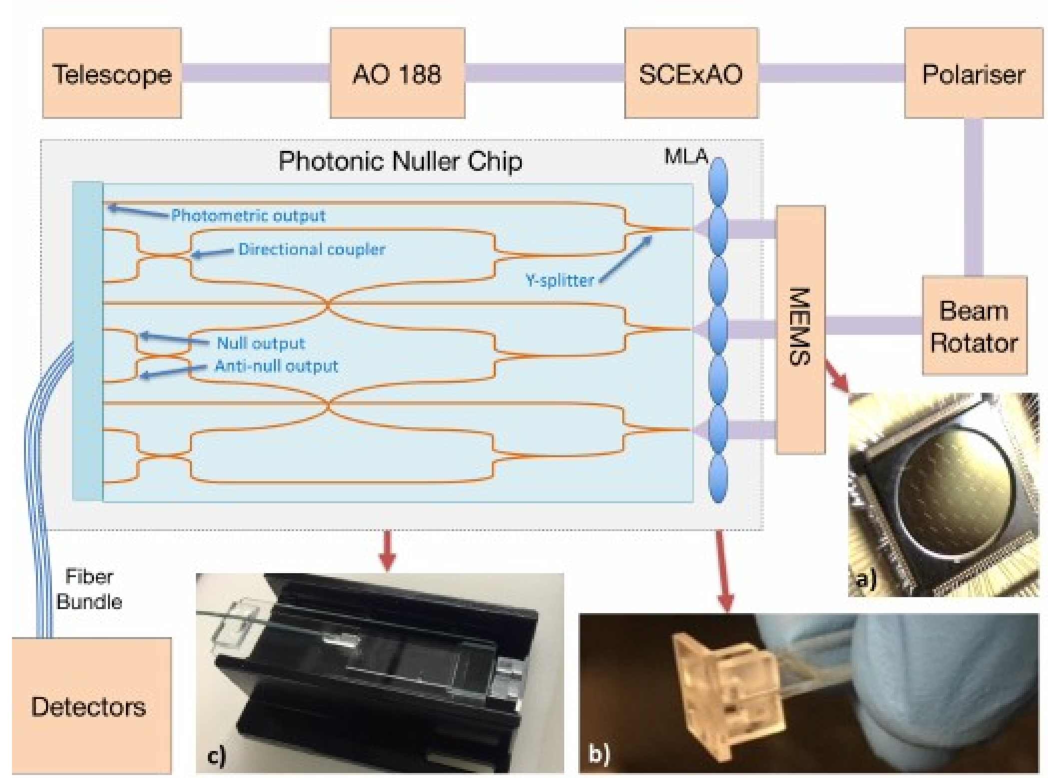
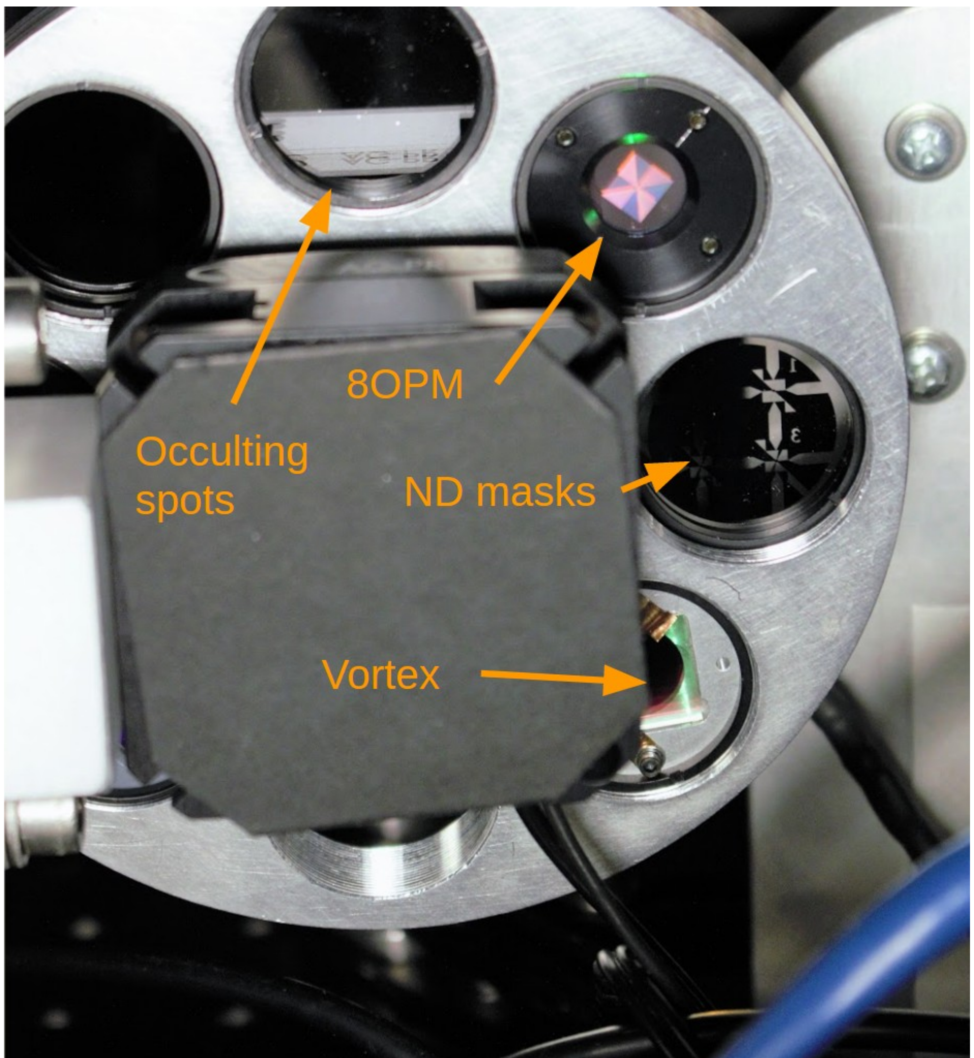


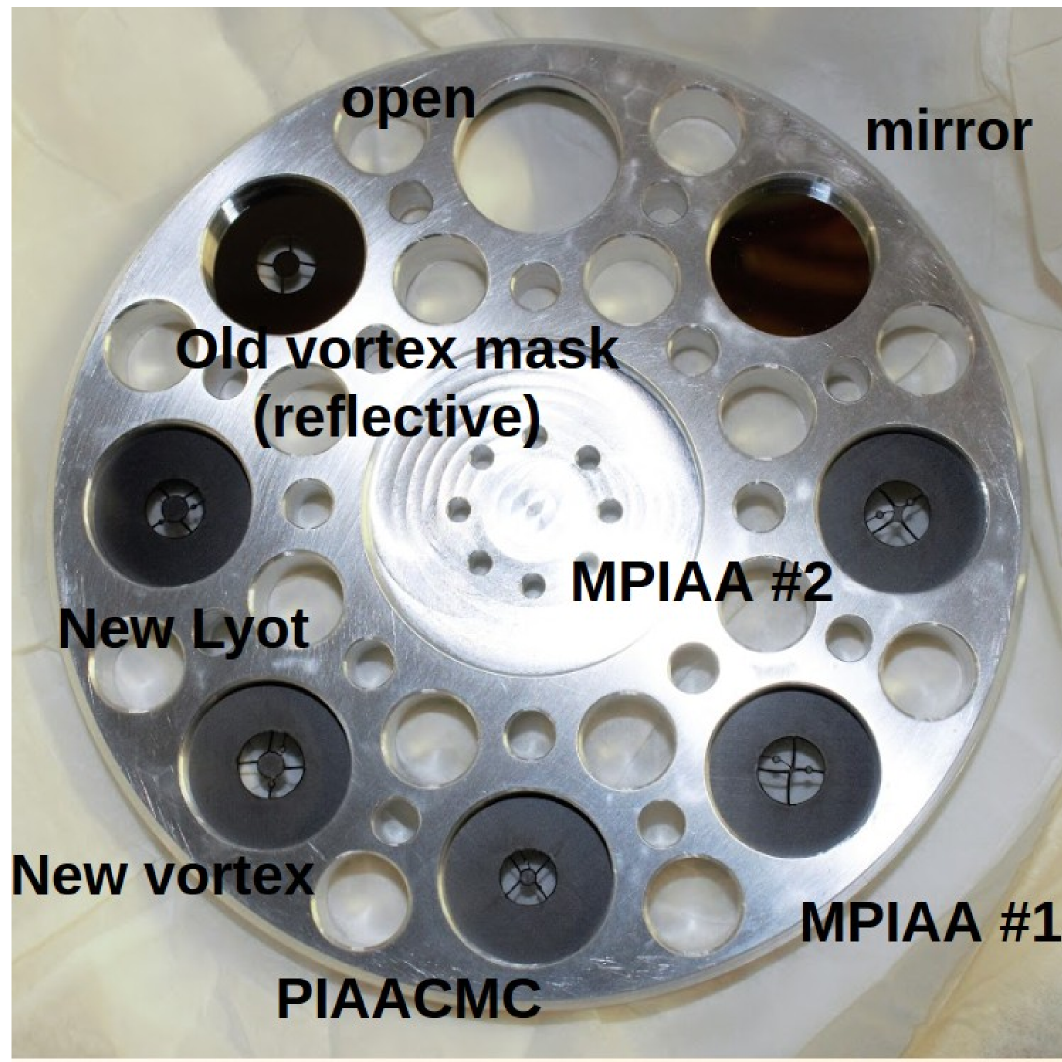
Figure 2: *Upper Panels* illustrate a star (yellow dot) lying centered within the pattern of a 2-beam nuller where its light is suppressed, while hypothetical planets (red, blue) traverse the interferometer fringes as the instrument is rotated. *Lower Panels* show the resultant planetary transmission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

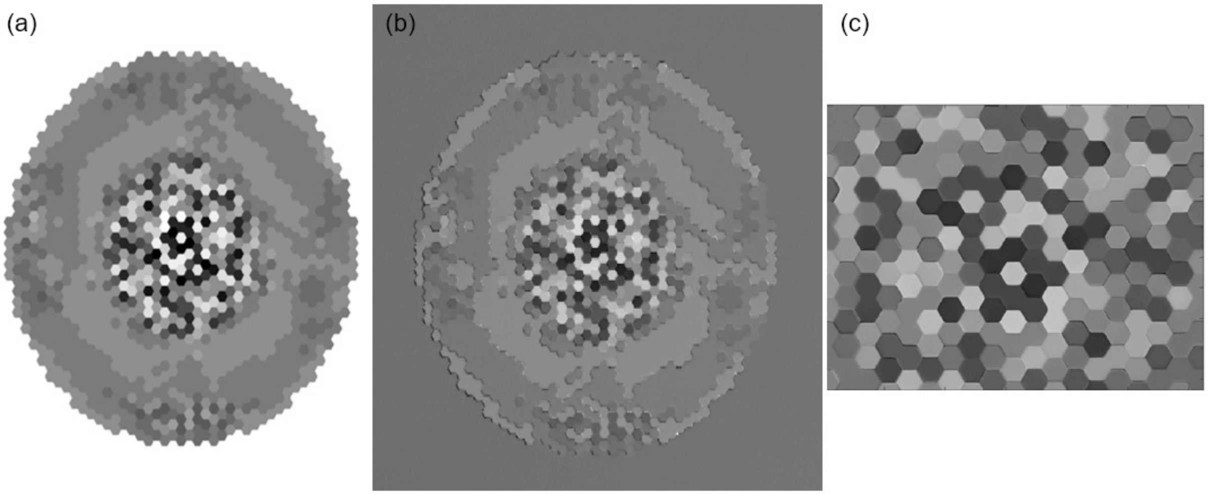


Coronagraphy

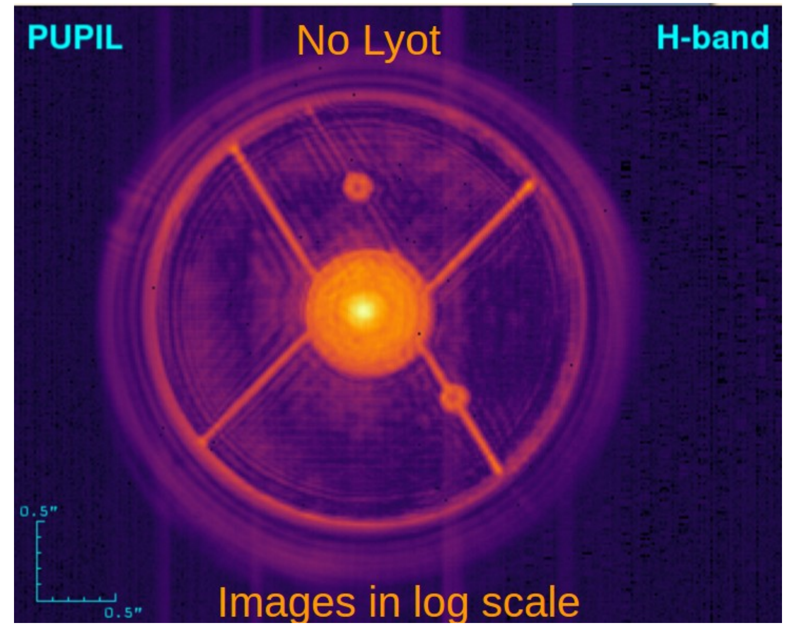
Coronagraphs:
- Vortex
- Lyot
- PIAACMC
- 8QPM
- Shaped Pupil
- vAPP

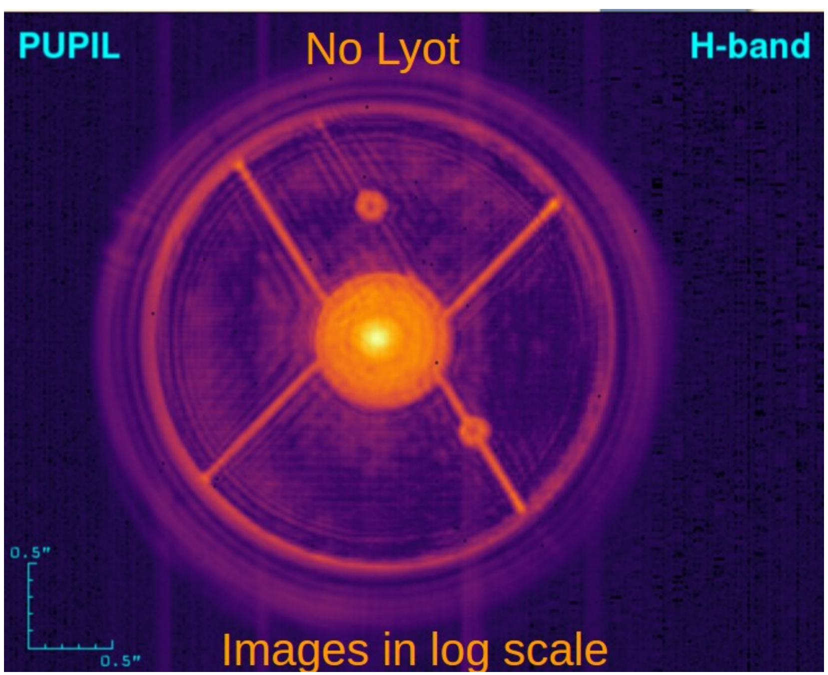




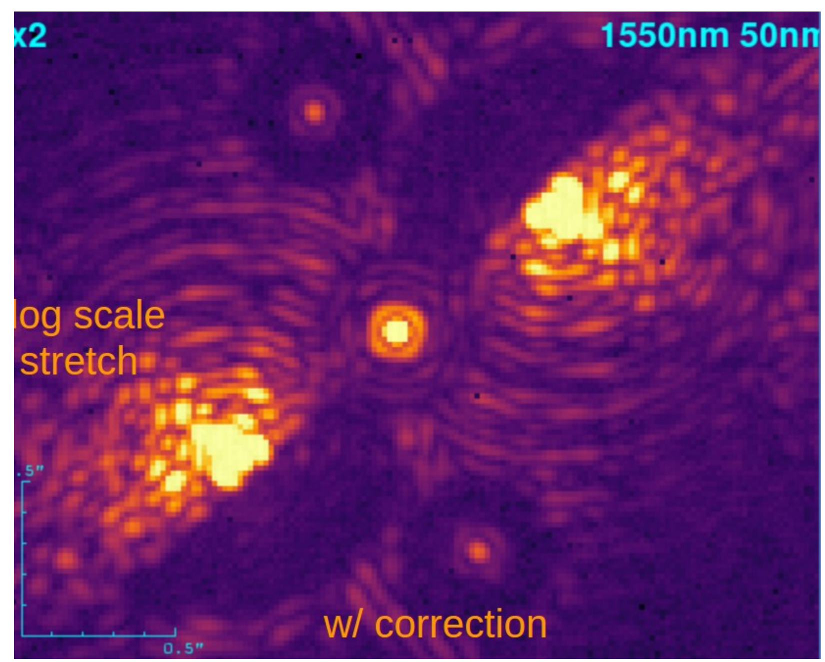


PIAACMC, Knight & Lozi, 2017



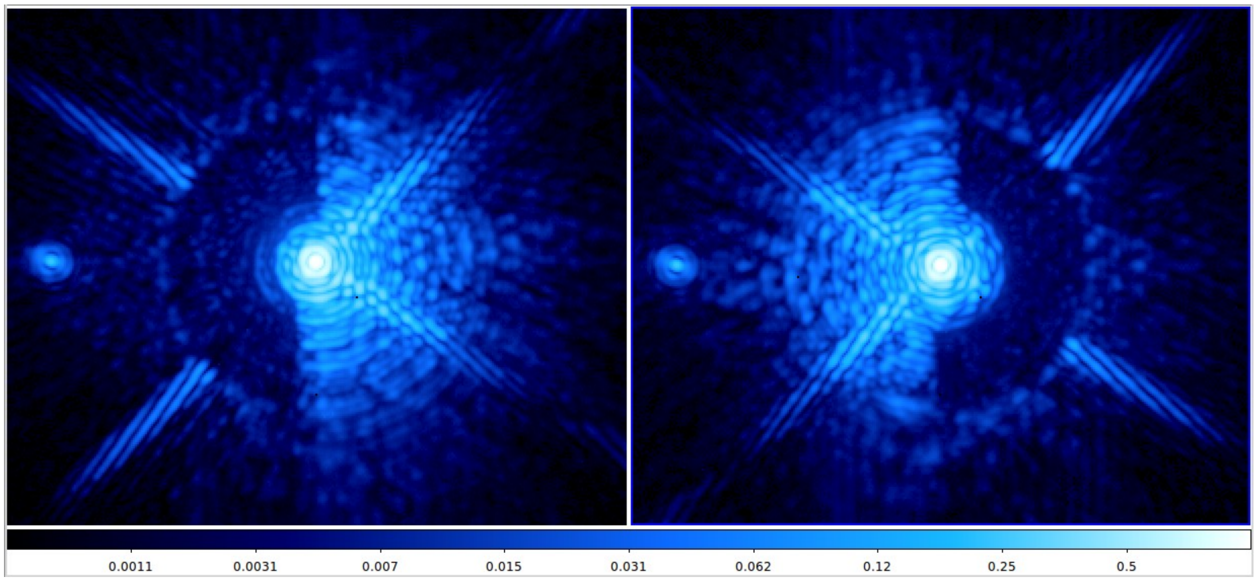


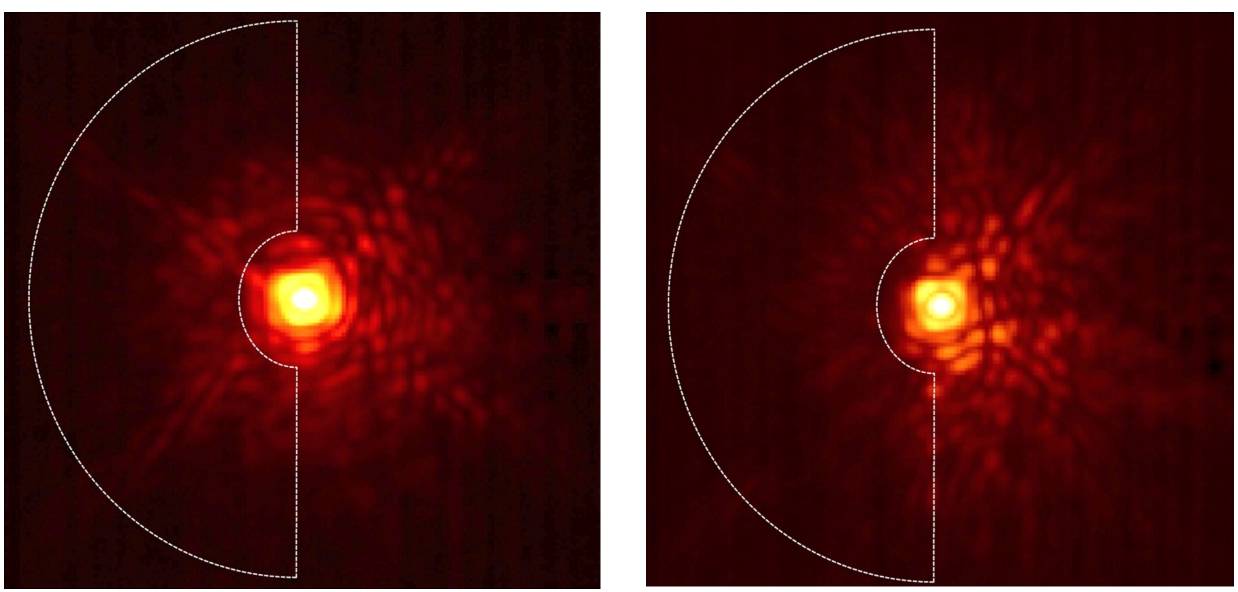
VVC, Lozi & JPL Vortex, 2017



VAPP, Lozi & Leiden University, 2017

Speckle Control





Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

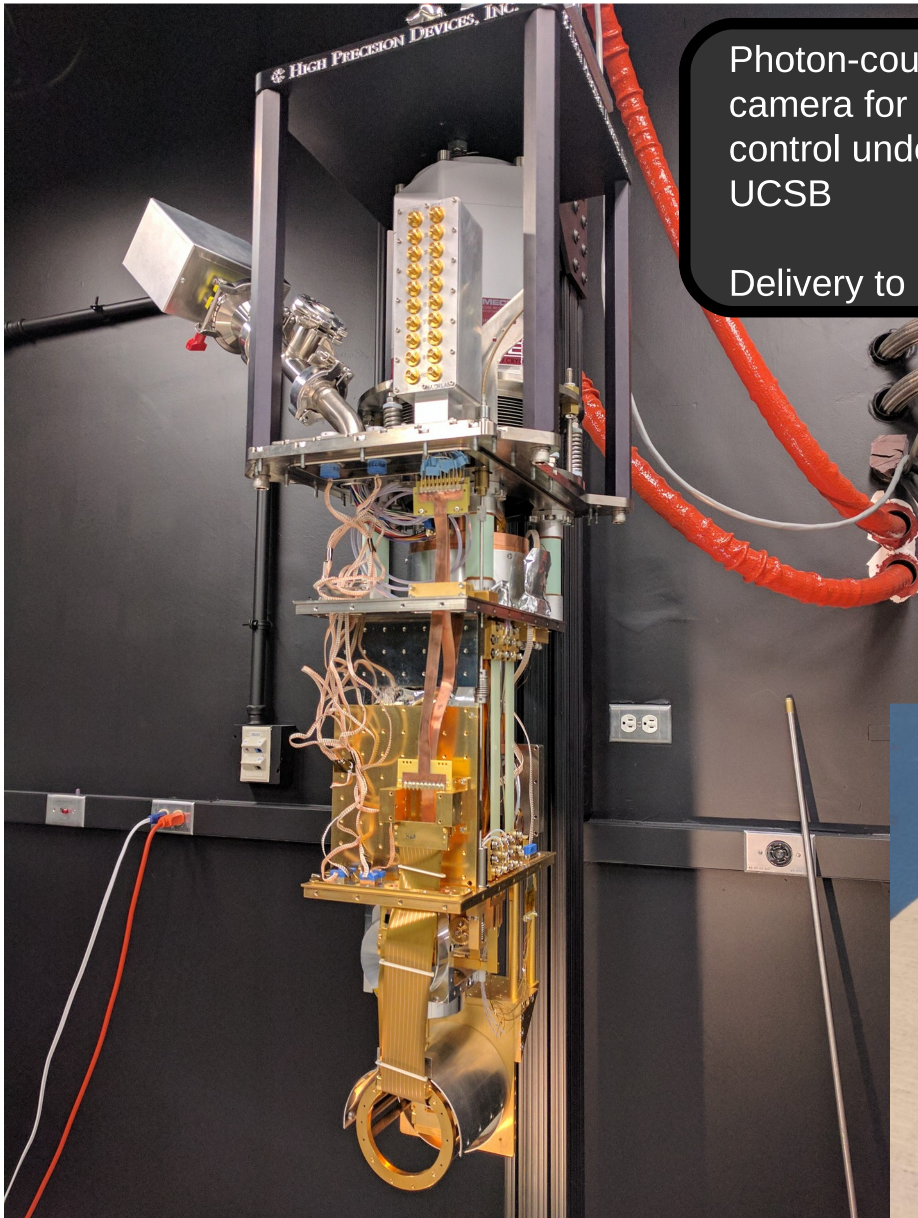
To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates

Observatoire de la CÔTE d'AZUR

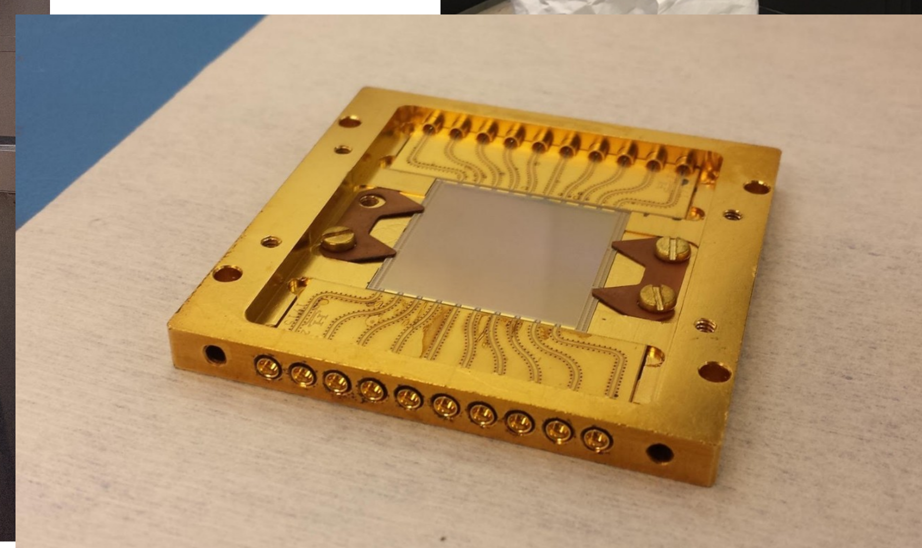
MKIDS camera (built by UCSB for SCExAO)

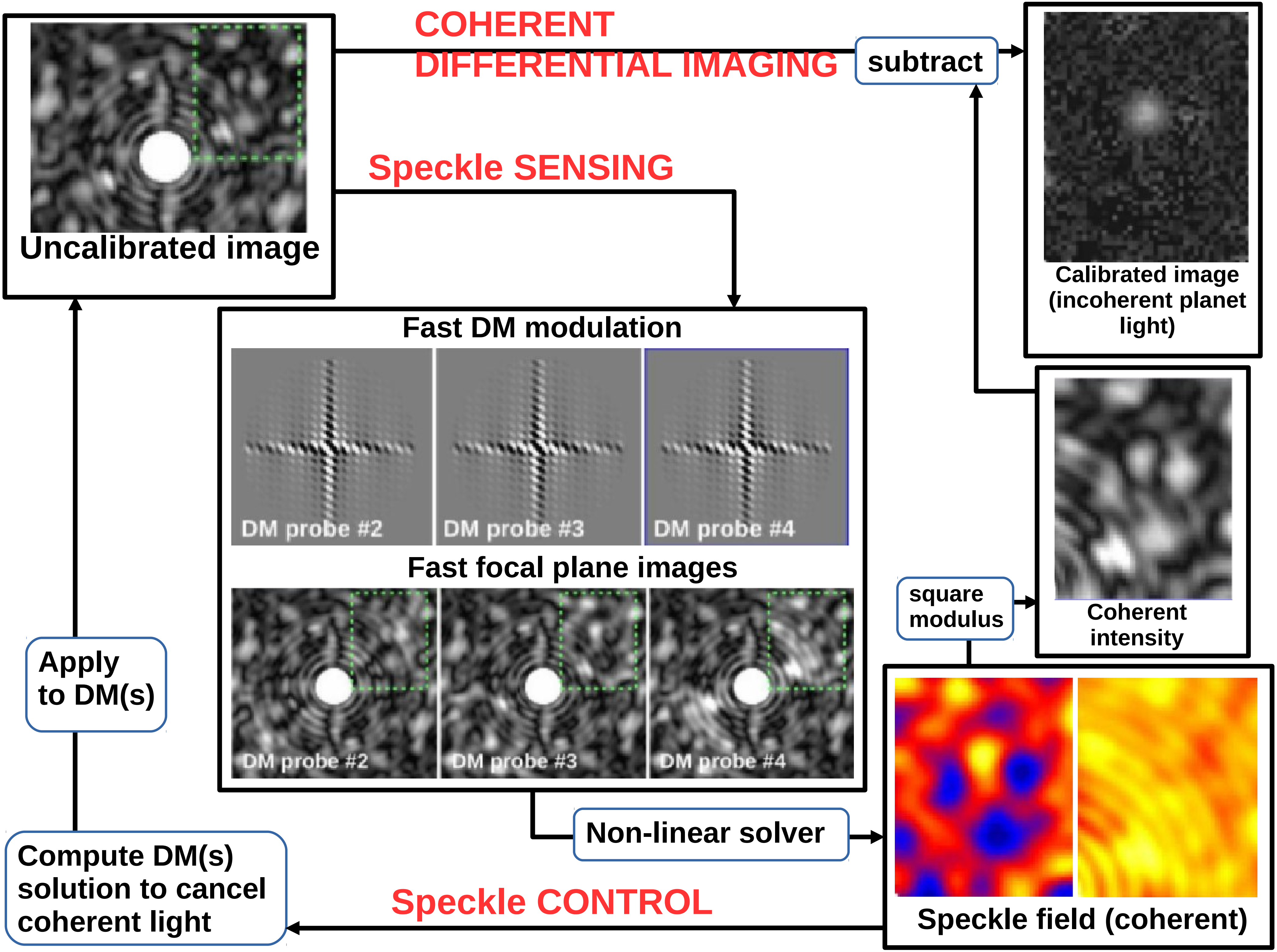
Photon-counting, wavelength resolving 140x140 pixel camera



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

Delivery to SCExAO in jan 2018



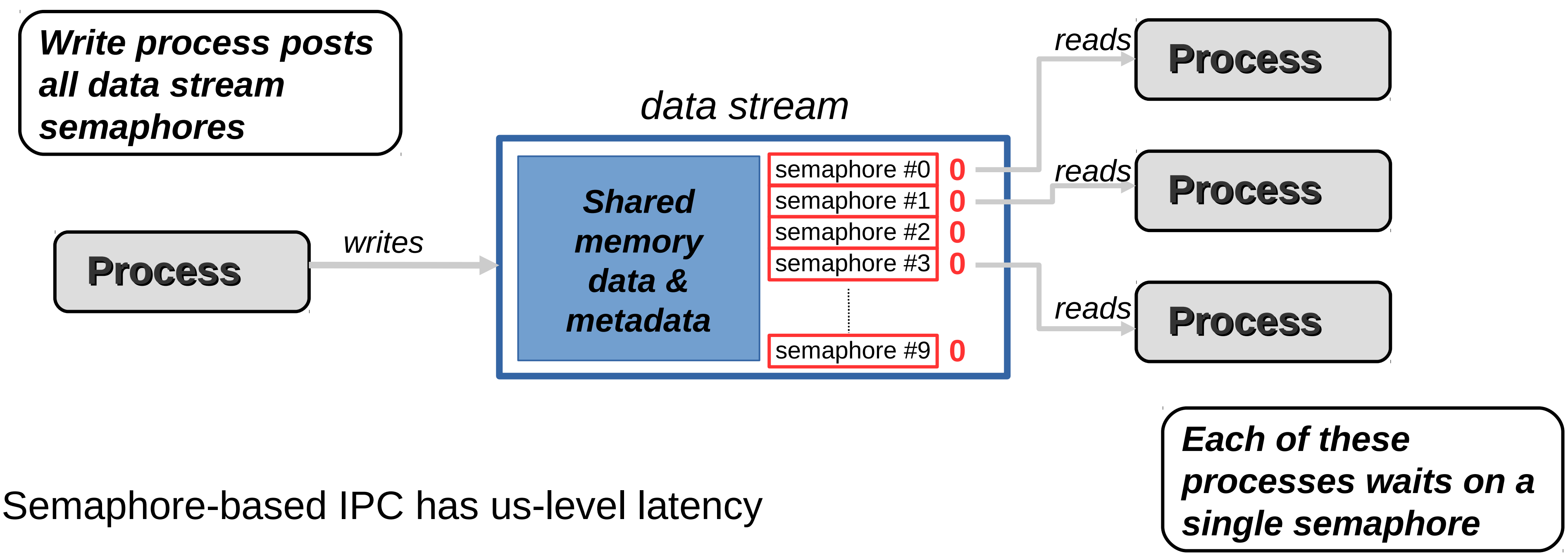


COHERENT DIFFERENTIAL IMAGING
subtract
Uncalibrated image
Calibrated image (incoherent planet light)
Speckle SENSING
Fast DM modulation
DM probe #2
DM probe #3
DM probe #4
Fast focal plane images
DM probe #2
DM probe #3
DM probe #4
square modulus
Coherent intensity
Apply to DM(s)
Non-linear solver
Compute DM(s) solution to cancel coherent light
Speckle CONTROL
Speckle field (coherent)

AO control software (cacao)

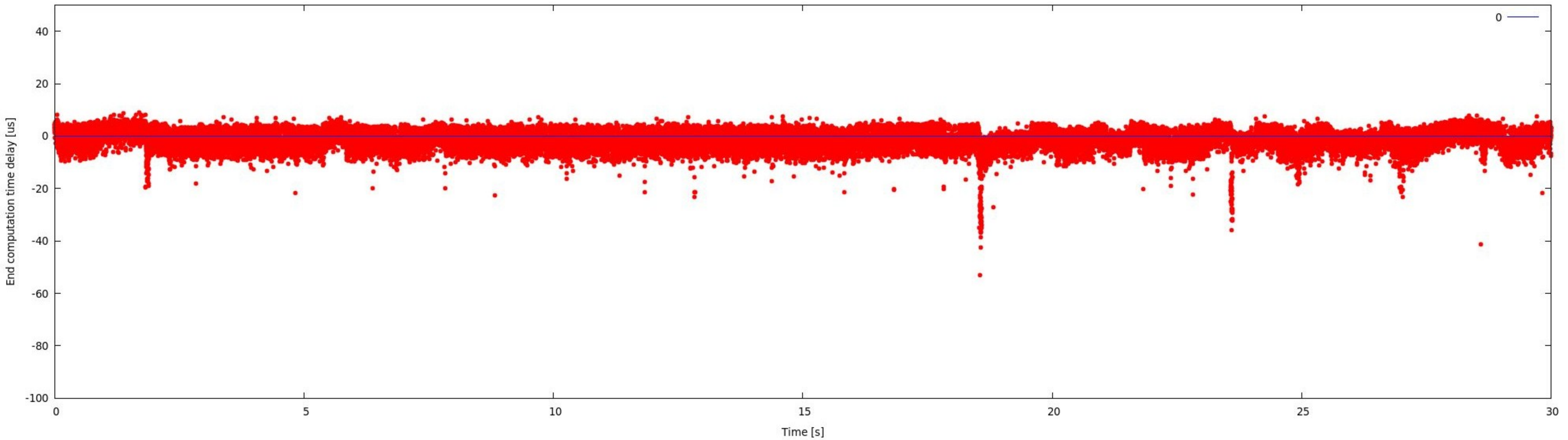
Subaru team is co-leading the development of cacao, a high-performance toolkit for AO control, which is gaining wider adoption (Subaru, Magellan, Keck + ESO?)
We will provide software integration to this new standard.

Approach:
Build AO control loop as a finite set of CPU-mananged processes.
Processes can manage computations on GPGPU(s)
Interprocess communication (IPC) is contained in data: cacao streams are held in shared memory and contain semaphores
→ Complexities of IPC are handled by compiler and Kernel (semaphores, shared memory)



Semaphore-based IPC has us-level latency

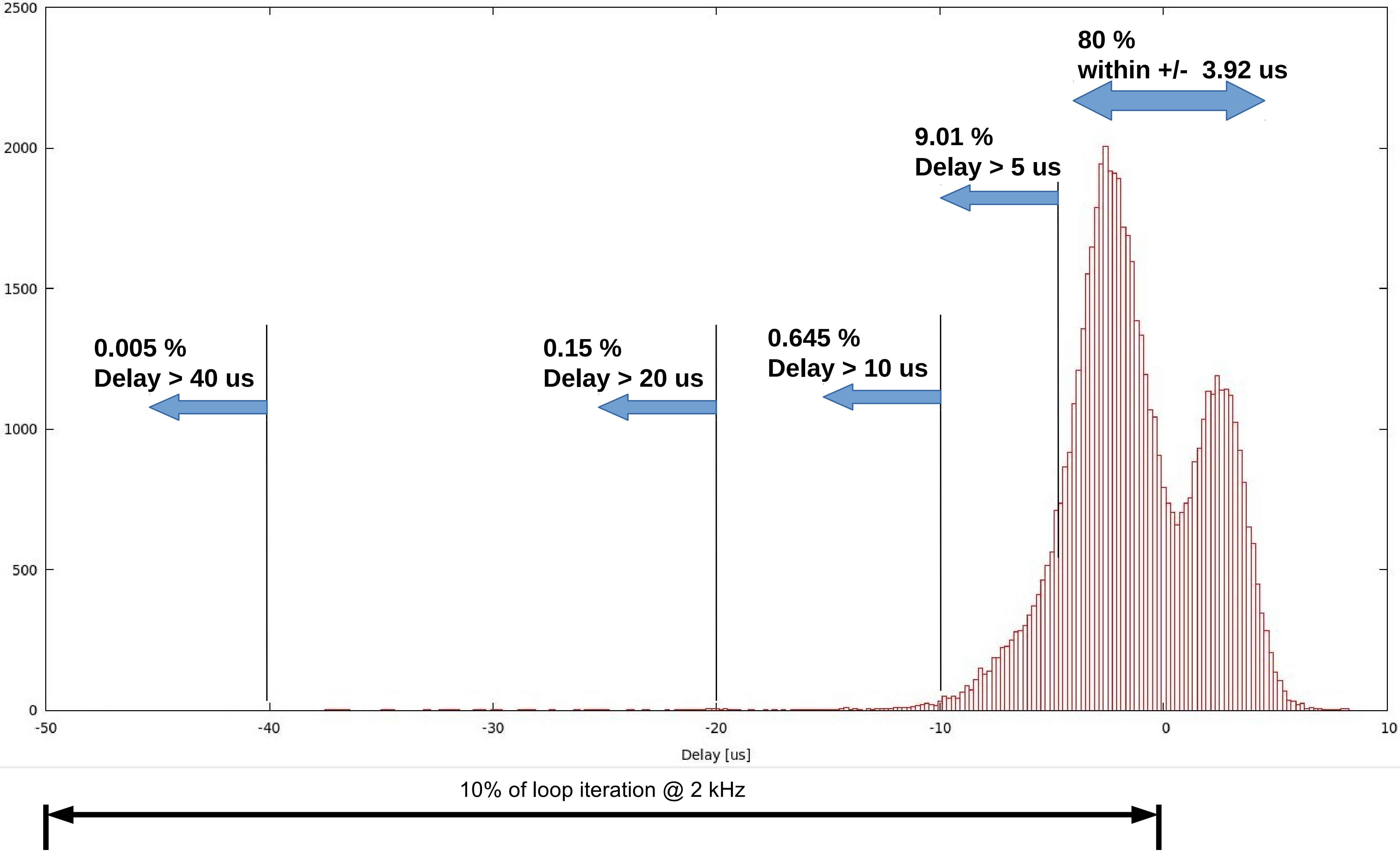
End-to-end Timing Jitter
RMS < 5 us, max delay ~50us



End-to-end timing jitter measured by monitoring completion time of last real-time stream: modal pseudo-open loop coefficients.

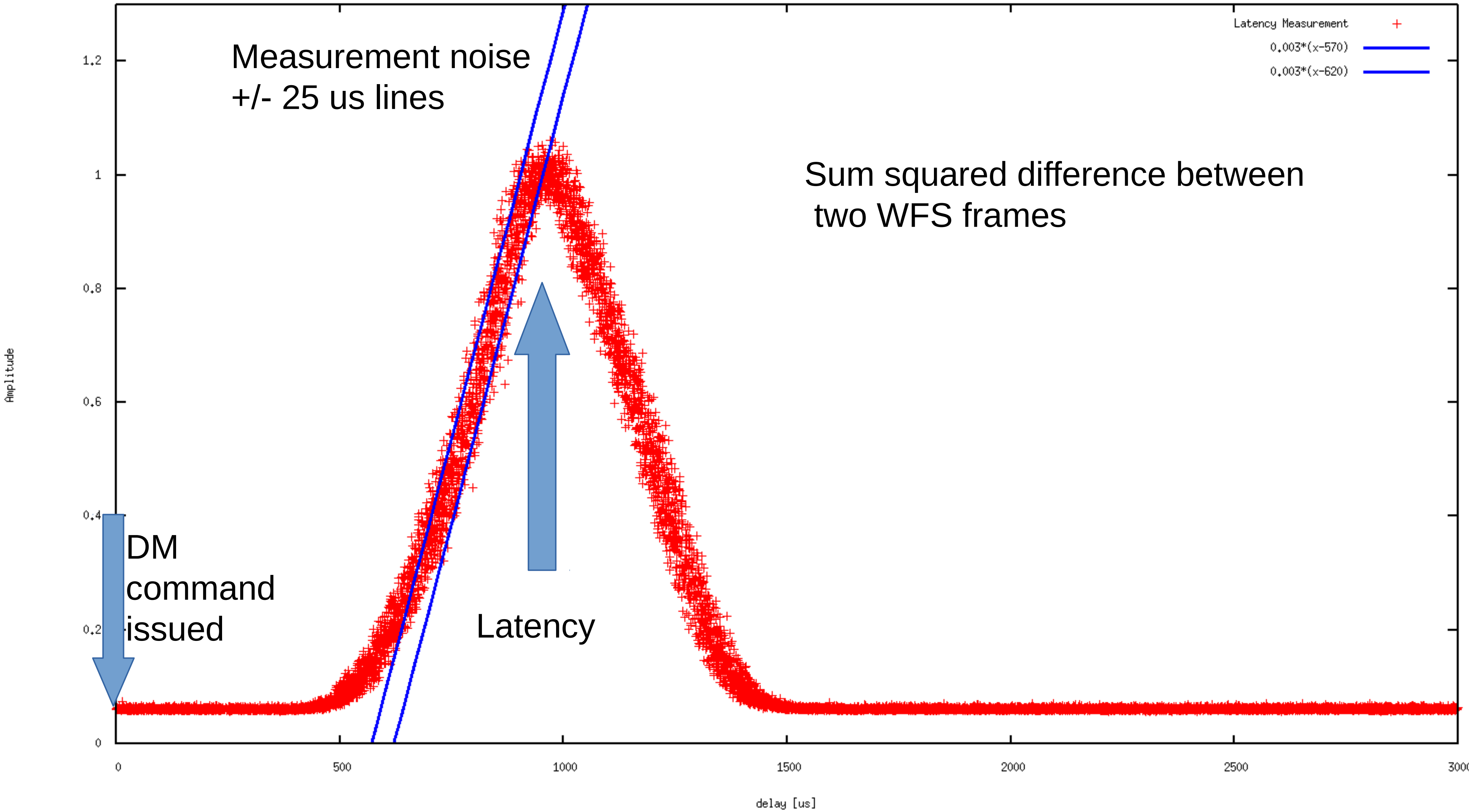
Jitter includes following components:
- Hardware synchronization (PyWFS tip-tilt mirror)
- Camera readout
- Data transfer over TCP link
- All real-time computations, CPU and GPU
- Time measurement errors

End-to-end Timing Jitter Histogram, measured @ 2kHz



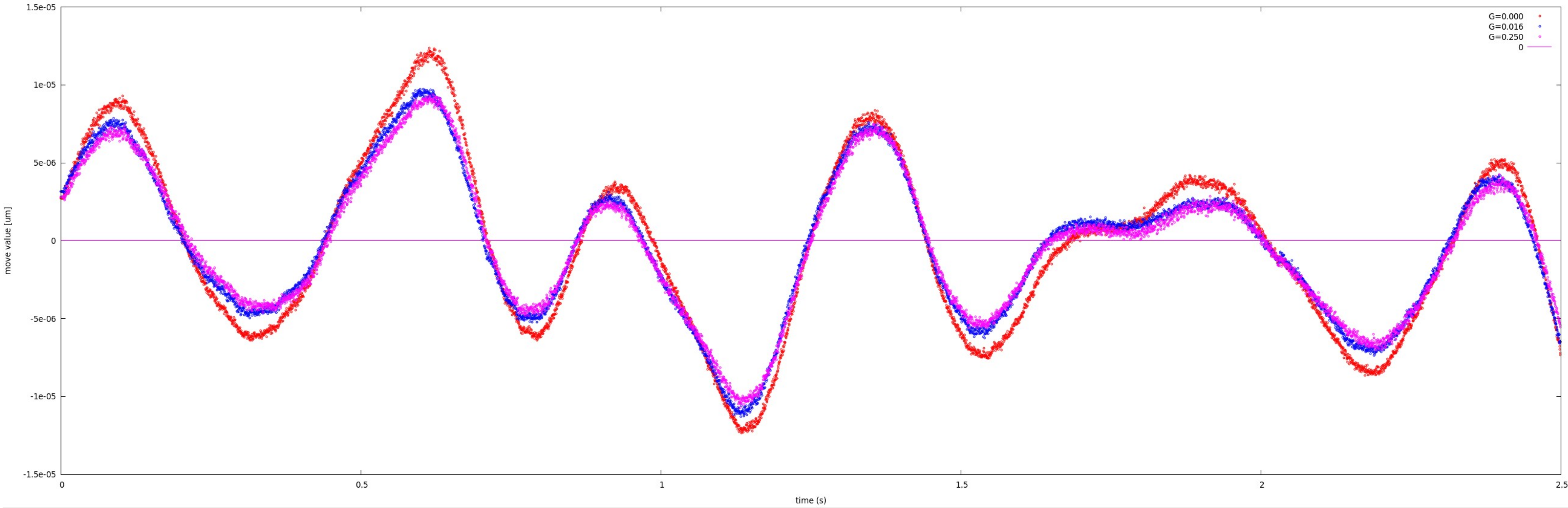
Hardware Latency measured on SCExAO

Time between DM command issued and corresponding WFS signal observed
(Camera readout + TCP transfer + processing + DM electronics)



Open loop reconstruction
Comparison between gain values

G=0.000 → over-estimates OL values
All G>0.0 reconstructions match at %-level

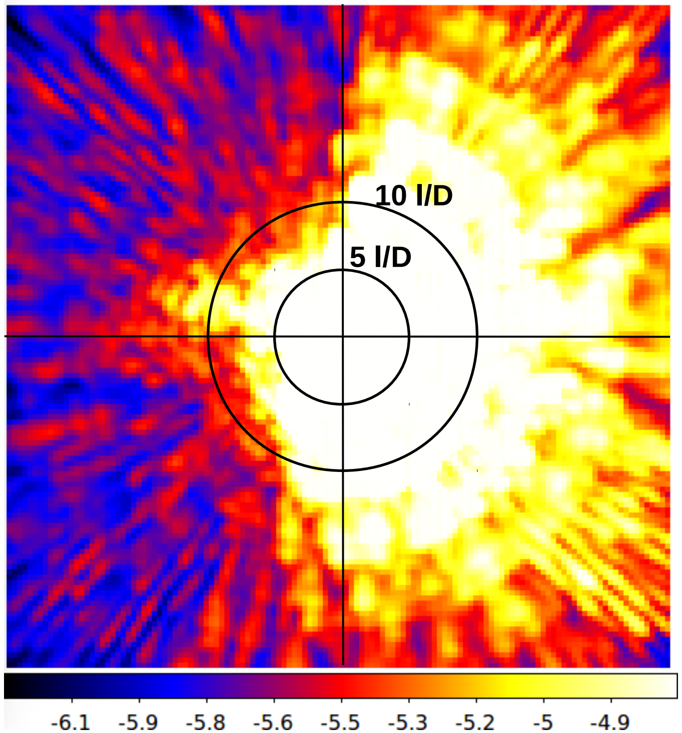


G=0.000 test relies entirely on WF residuals for OL estimation
G>0.000 tests rely mostly on DM values for OL estimation

Test shown here uses full speed RM acquisition which underestimates RM by ~15% due to DM time-of-motion → reconstructed WFs from WFS are over-estimated by ~15%

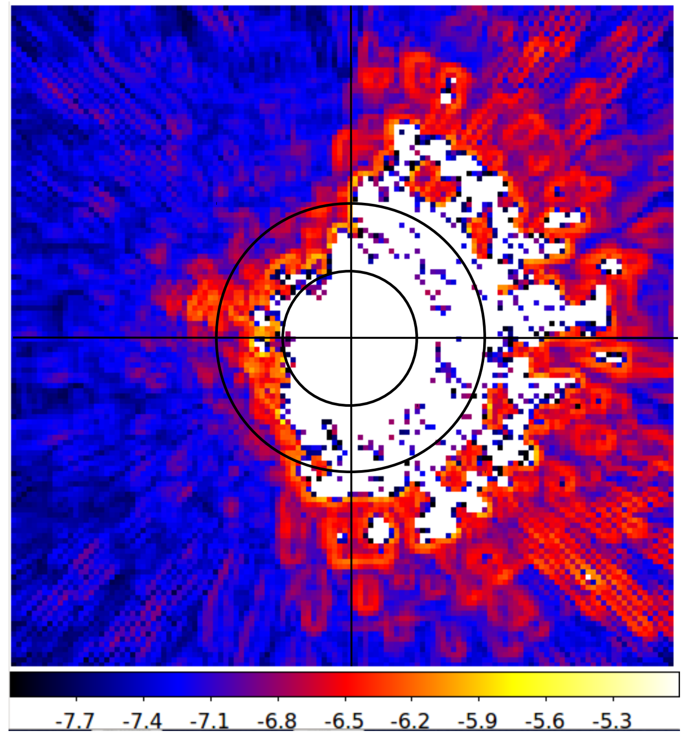
Conventional Lyot Coronagraph, Broadband light: 0.9-1.7 um (62% wide band)

Raw Contrast



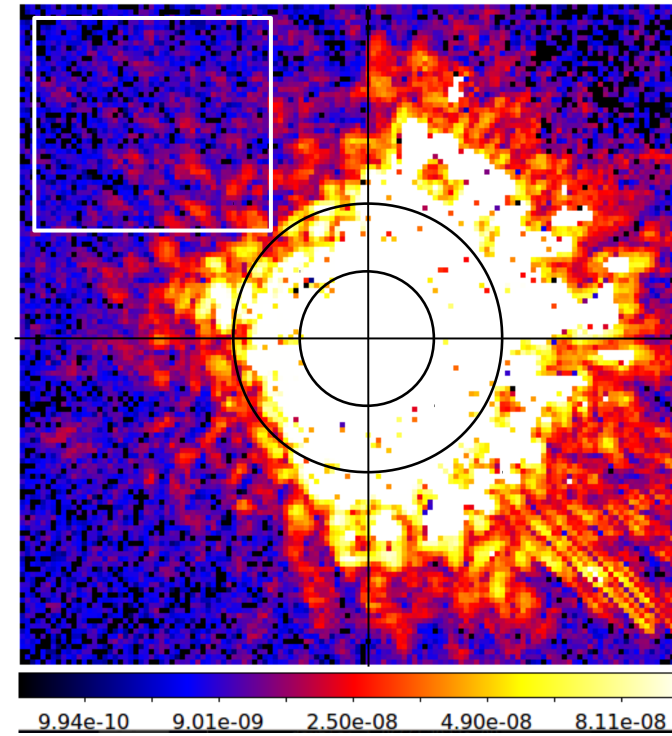
Average raw contrast [15-20 l/D] = 2.3e-6

Open-loop contrast stability

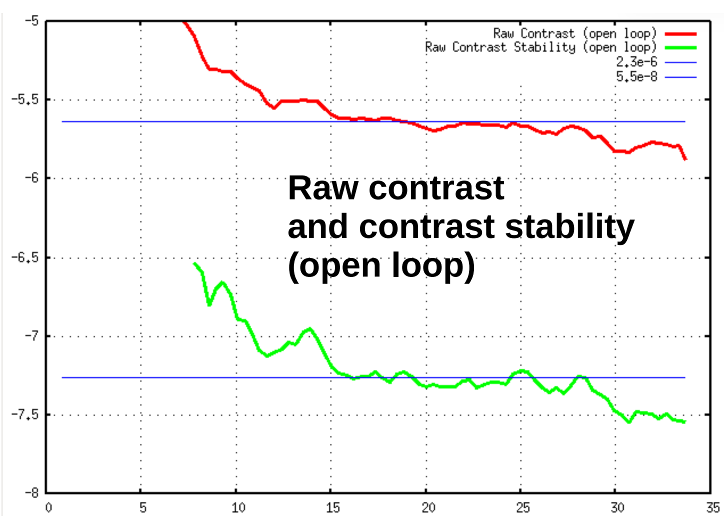


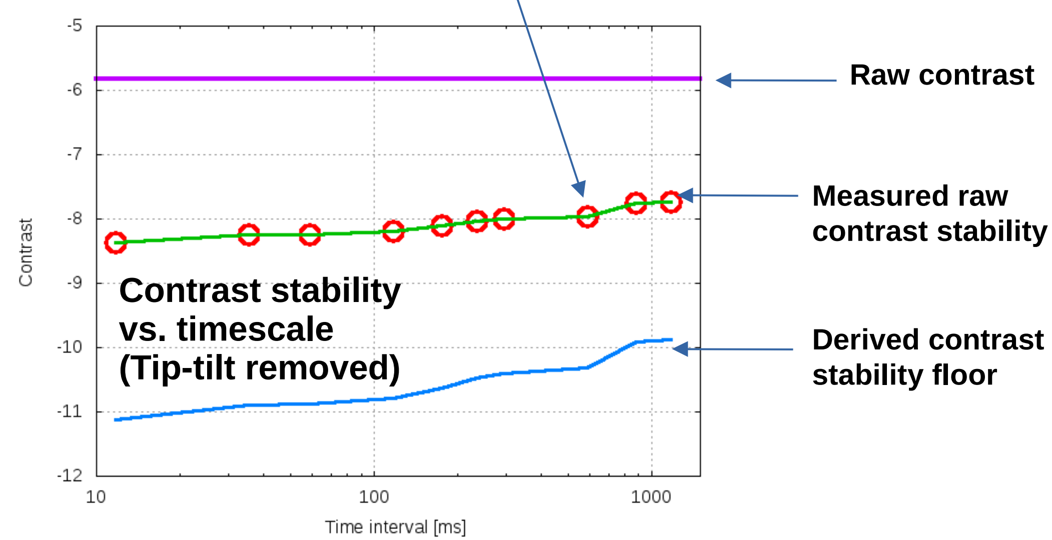
Average raw contrast stability [15-20 l/D] = 5.5e-8

Contrast stability over 0.6 sec



Average raw contrast stability [11-34 l/D] = 1.1e-8 (averaged value within white box)

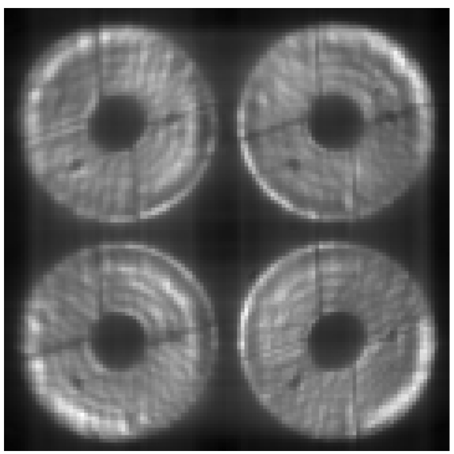


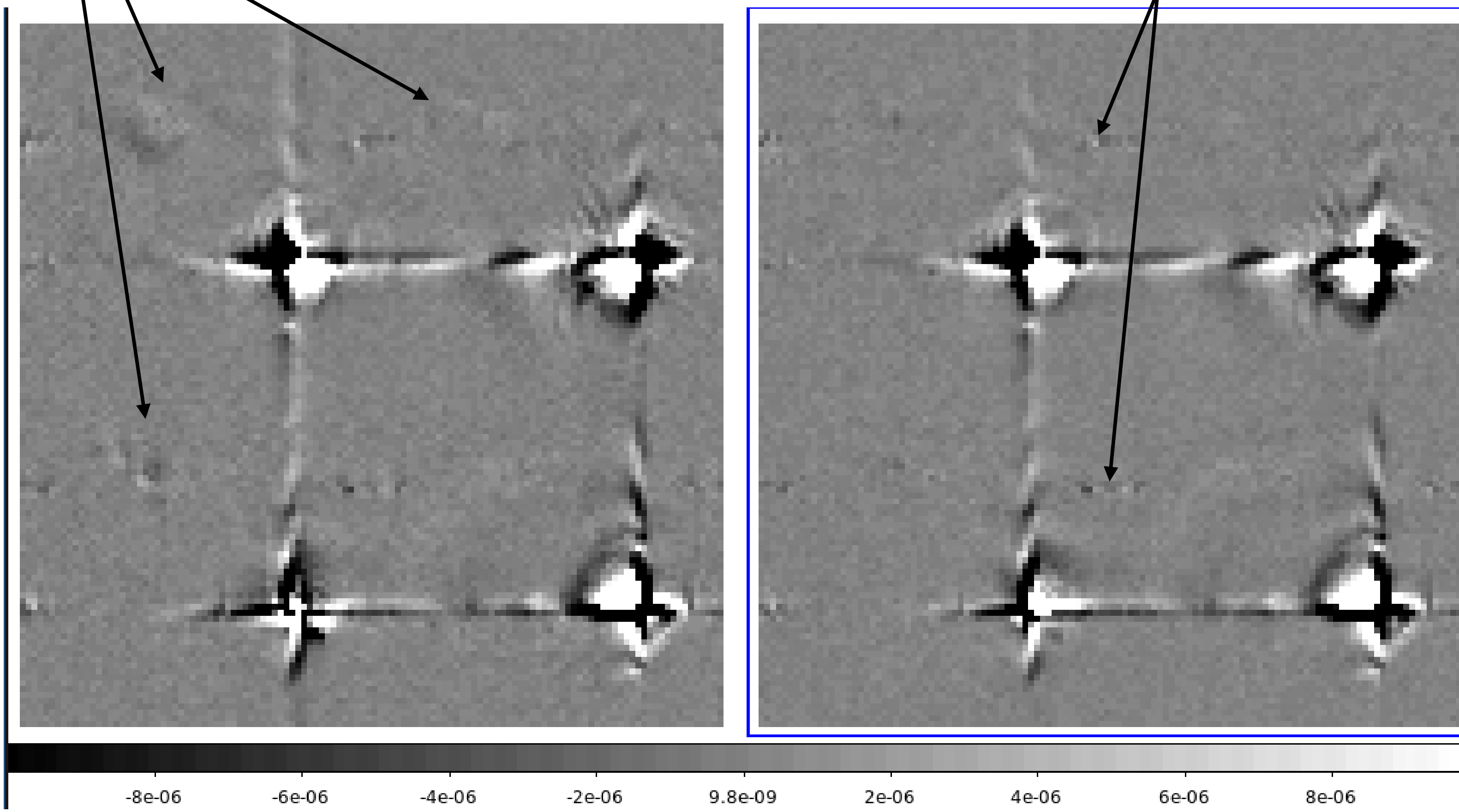


Fast RM acquisition (4000 Hadamard pokes in 2s @ 2 kHz) + Removing temporal DM response from response matrix by using two poke sequences

Temporal bleeding from previous poke pattern (should be removed from RM)

Camera readout RF coupling between pixels
~1% electronic ghosts at 2kHz frame rate
Needs to be kept in RM



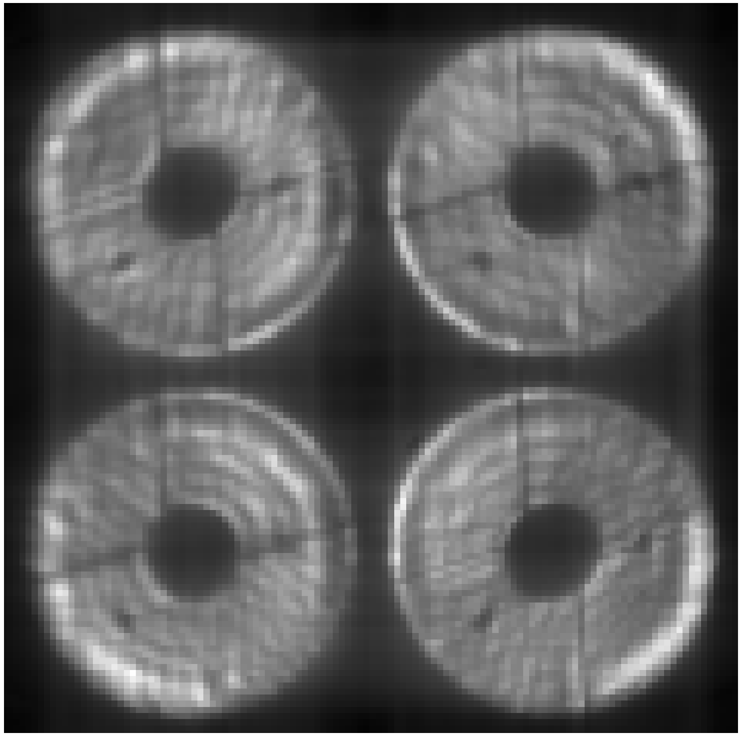


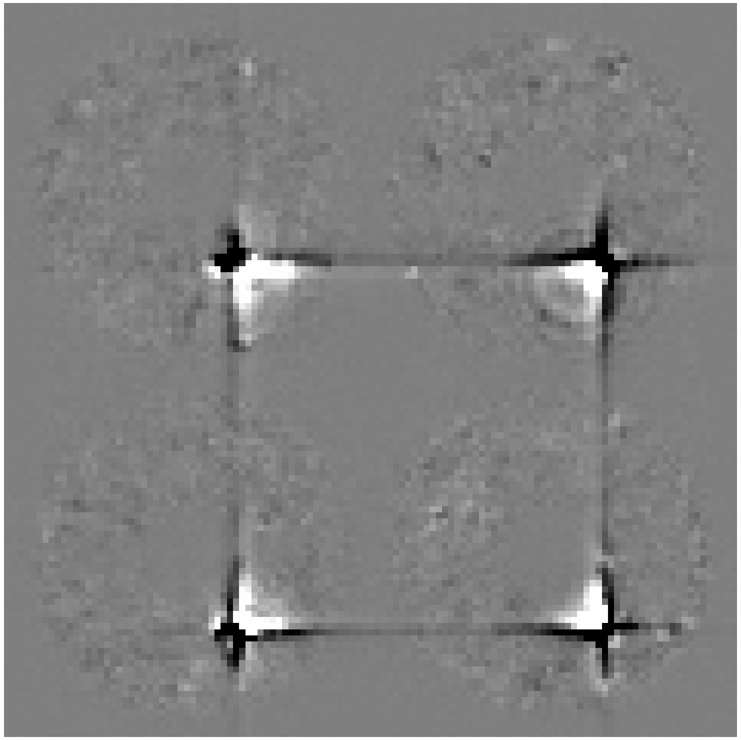
RM assembled from single poke sequence:
+- +- +- +-

RM assembled from average of two poke sequences:
+- +- +- +-
+- -+ +- -+

RMs reconstructed from Hadamard pokes, 2kHz modulation (DM moves during EMCCD frame transfer)

Multi-channel DM virtualization & timing knowledge/stability
→ <u>on-sky</u> response matrix acquision, while ExAO loop running

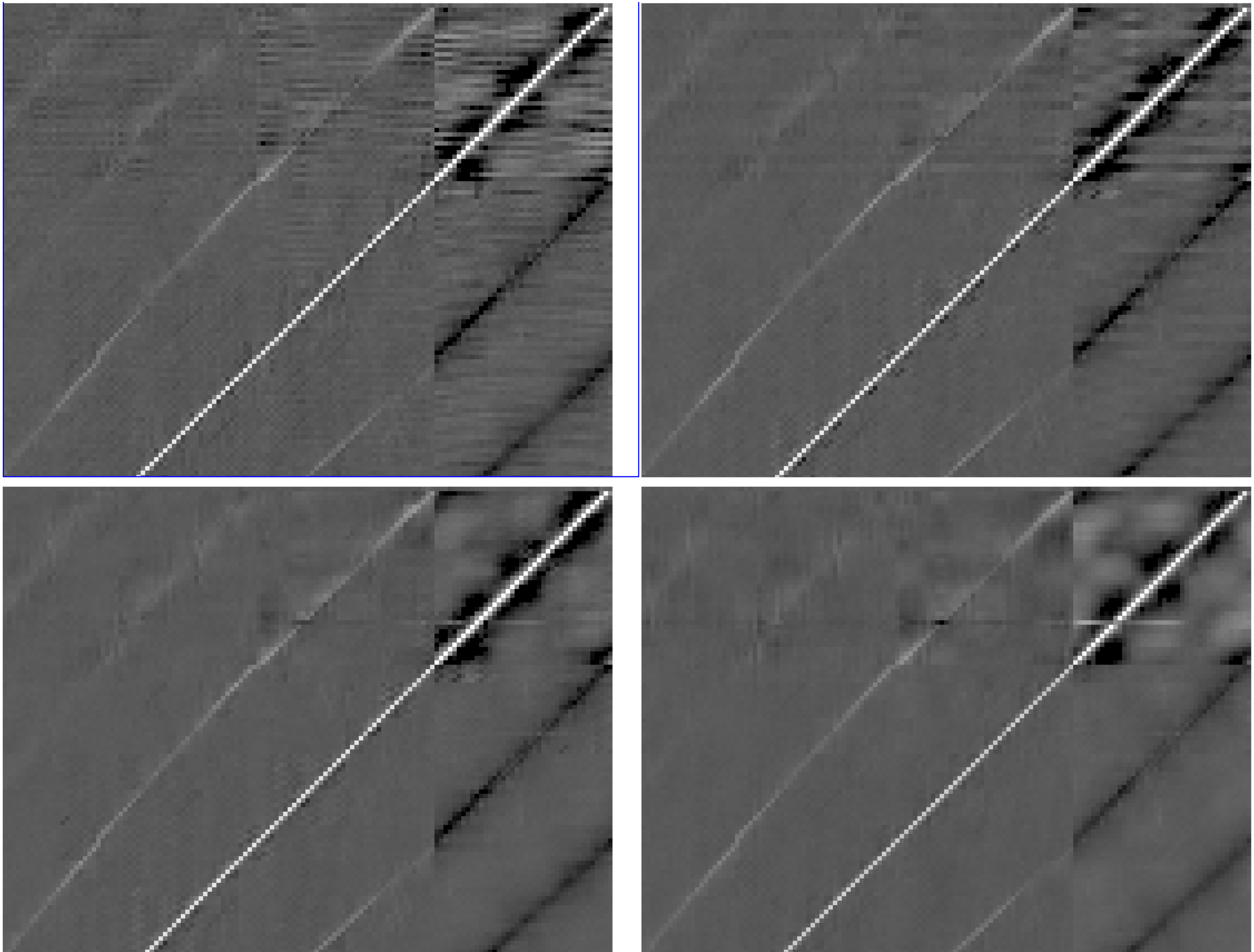




Left: WFS reference
Right: Response to single actuator poke (one of 2000)

RM measurement @ 2kHz takes 4000 pokes = 2 sec
Multiple RMs averaged to increase SNR

Removing Hysteresis and DM-induced vibrations from response matrix calibration (piezo curvature DM)



Predictive Control

The main fundamental limit to Extreme-AO correction are that :
(1) FLUX
The star used for measuring aberrations has limited flux
→ measurements are noisy
(2) SPEED
Turbulence is moving fast, and it's very difficult to catch up.
Note: There are also unavoidable latencies in the hardware

In conventional AO systems, we can average the last few measurements to reduce noise → **this adds latency**, so this is not a viable solution for Extreme-AO

SOLUTION: **Predictive control** optimally uses the last few measurements to predict the aberrations at the time of correction
CHALLENGE: The temporal relationships between past and future aberrations are not known in advance and change continuously (depends on wind speeds and many other things) → we must learn them in real-time: **machine learning**

The Machine Learning challenge

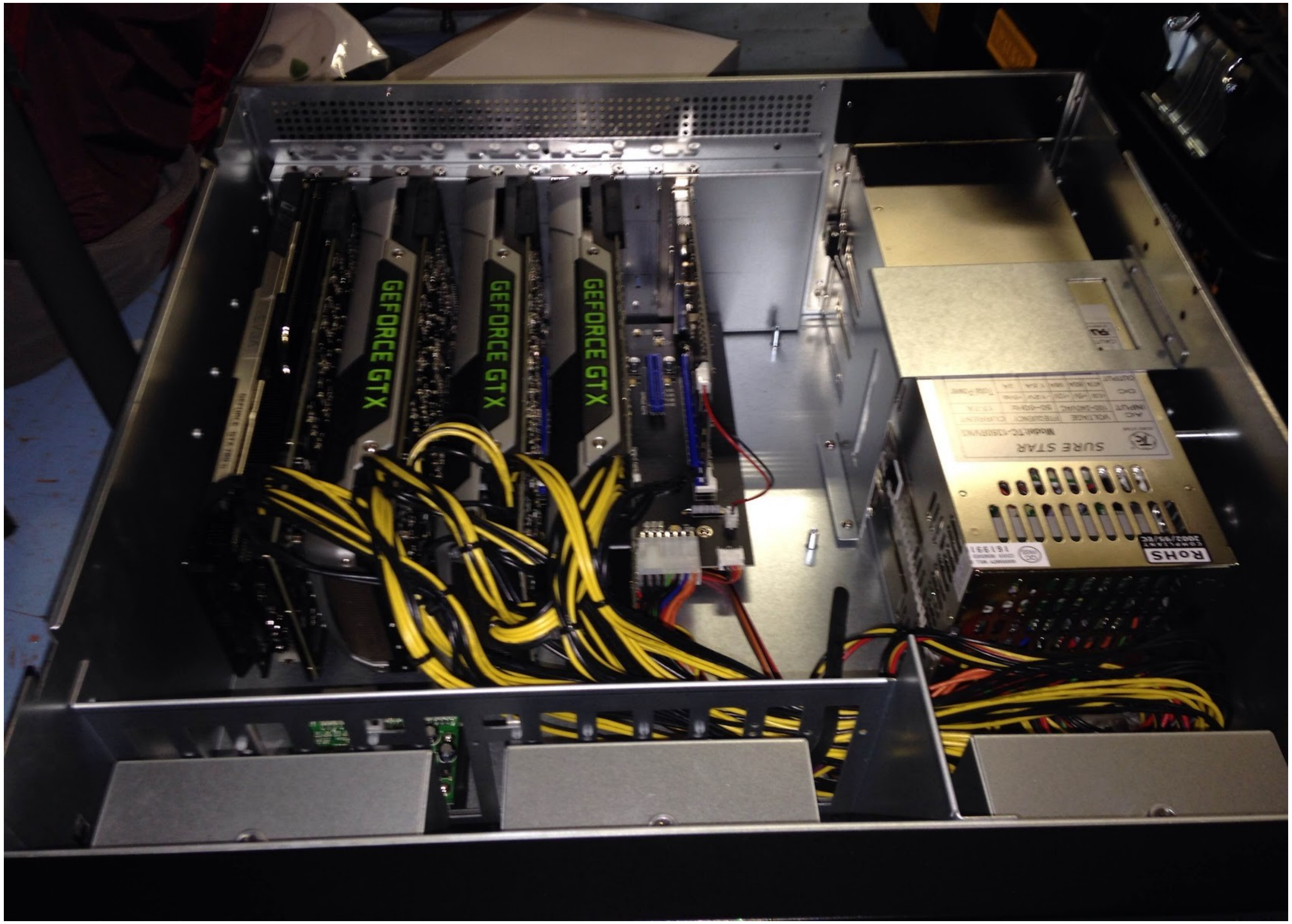
Need to derive 100s of millions of control matrix (CM) values within minutes, using billions of samples...

Example:
SCExAO, 3 kHz, 10-step predictive control, 100 sec training
Input: 14,400 x 3,000 x 100 = 4.32e9 measurements
Output: 14,400 x 2000 x 10 = 288e6 CM coefficients

Solution:
We deploy linear ***Machine Learning*** technique on a modal control space (smaller # of dimensions).
We use GPU cores (35,000 cores @ 1.6 GHz in SCExAO main RTC).

The Machine Learning challenge

One of two GPU chassis



SCExAO uses 30,000 cores running @1.3GHz

Re-thinking adaptive optics

The machine learning approach to predictive control is part of a wider machine learning approach to adaptive optics

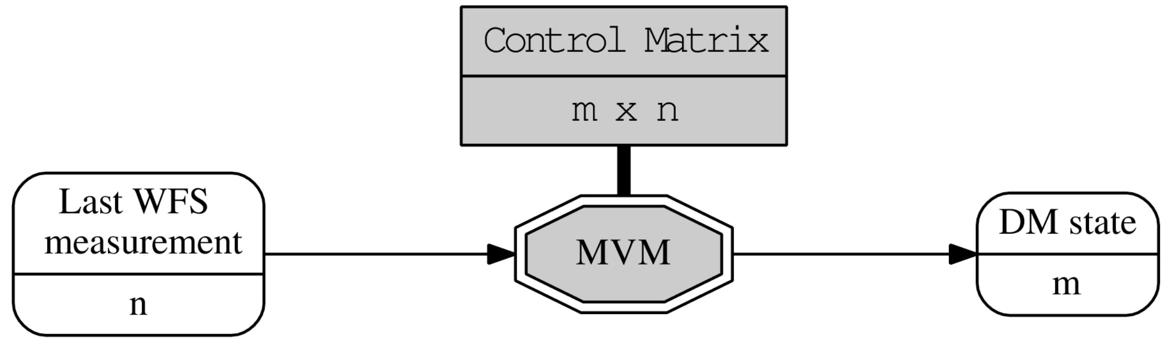
Conventional adaptive optics (pre-2018):
Off-sky calibration are performed to write a static control law.
The control law is captured in a control matrix (CM) linking the last measurement to a correction

Machine learning based AO:
The control law is continuously optimized based on analysis of real-time measurements. The control law includes predictive control and can also include sensor fusion if multiple sensors are deployed

Predictive Control and Sensor Fusion

Conventional AO:

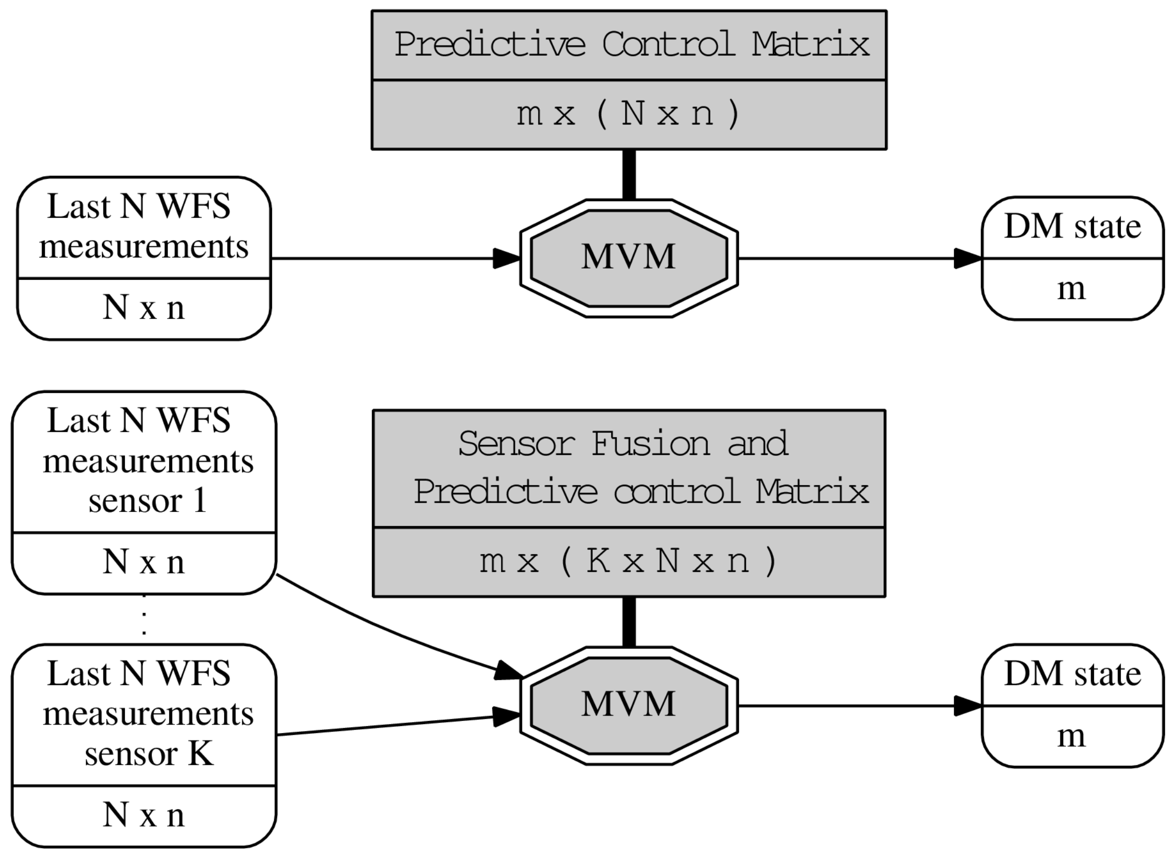
We **measure** RM/CM



Advanced AO control:

We want to use past measurements (predictive control) and other measurements (sensor fusion) → control matrix is very big, and usually impossible to measure

We **derive** CM from WFS(s) telemetry

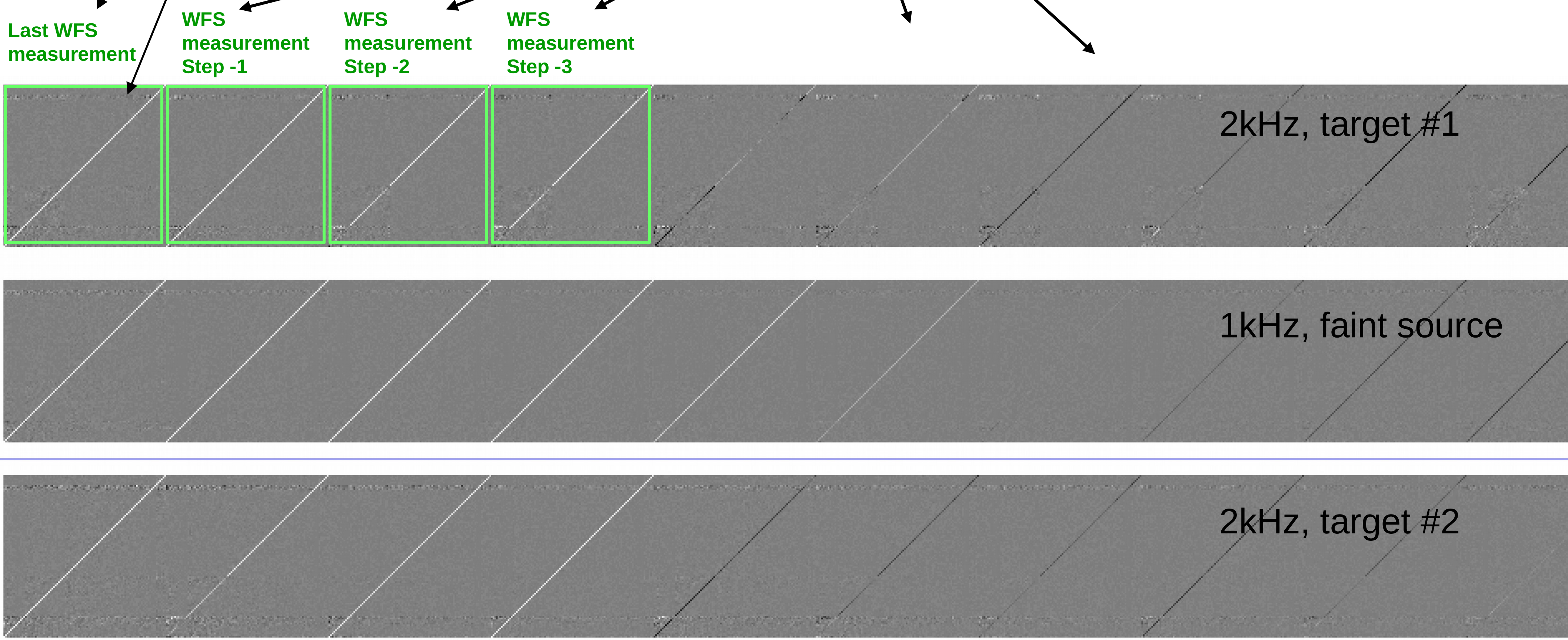


On-sky predictive control matrix (modal representation, 100 modes shown)

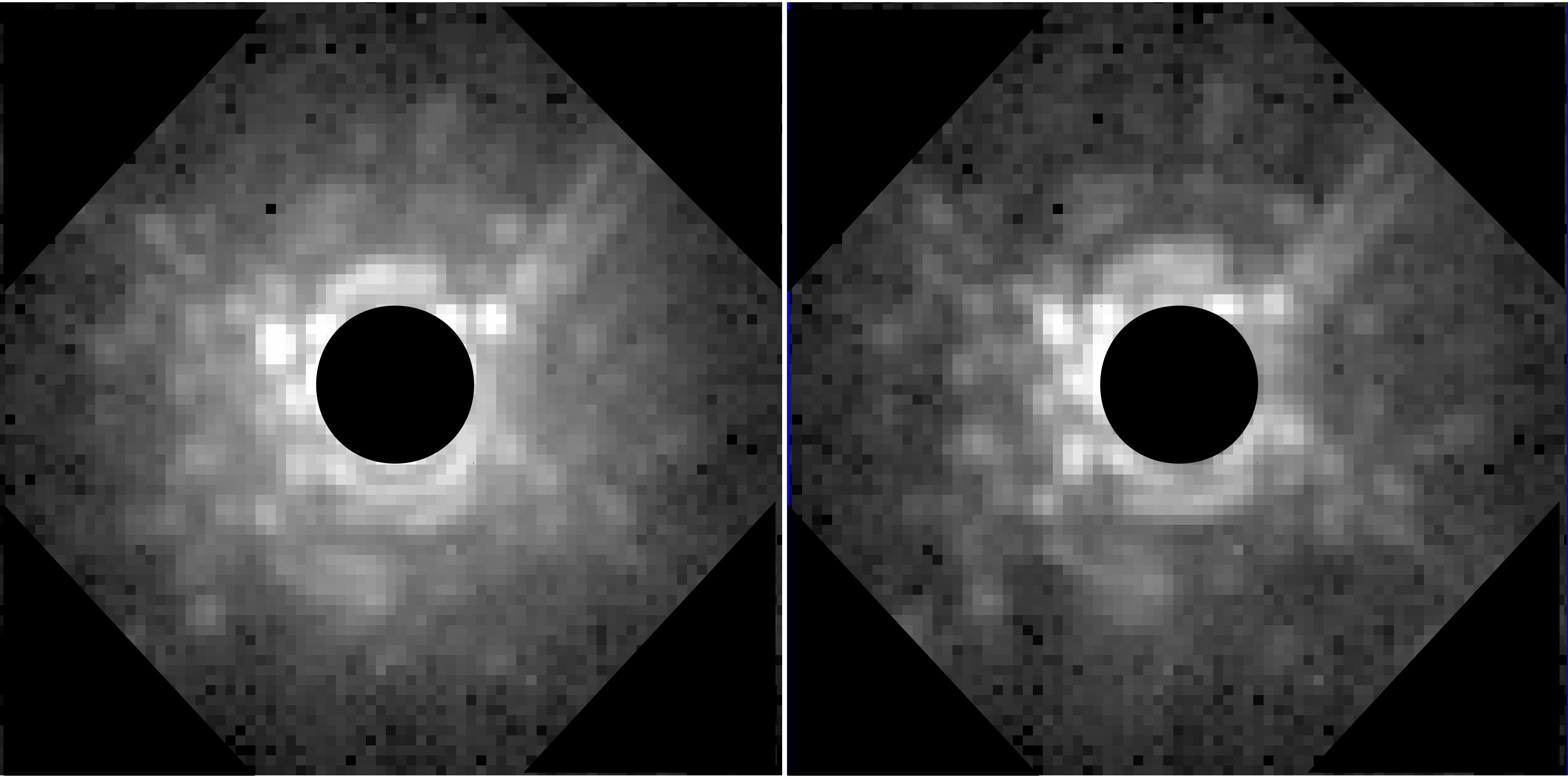
Conventional AO would have control matrix 100 x 100 elements Identity matrix

Optimal control adds elements outside of diagonal

Predictive control adds these blocks to control matrix



First on-sky results (2 kHz, 50 sec update) → 2.5x raw contrast improvement

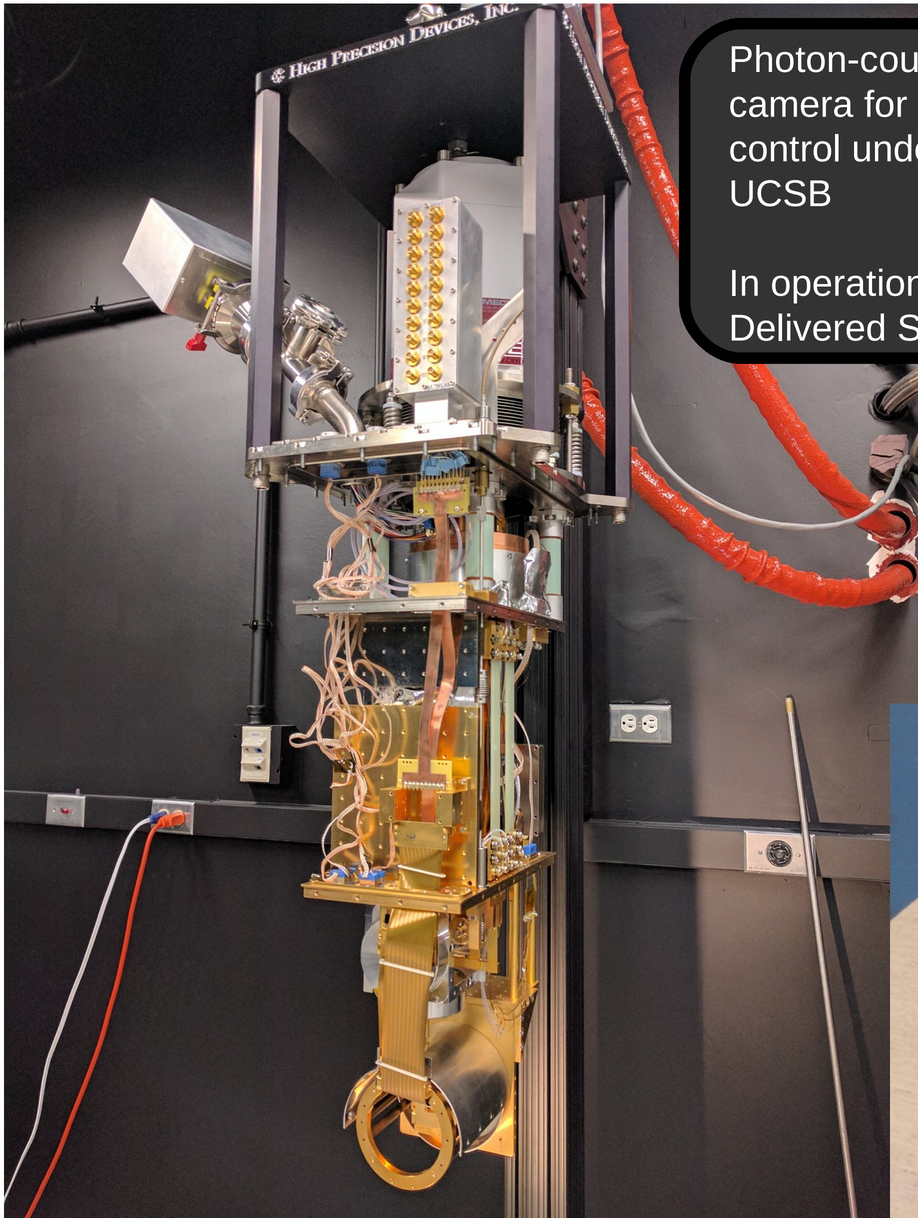


OFF (integrator, gain=0.2) ***ON***

Average of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale

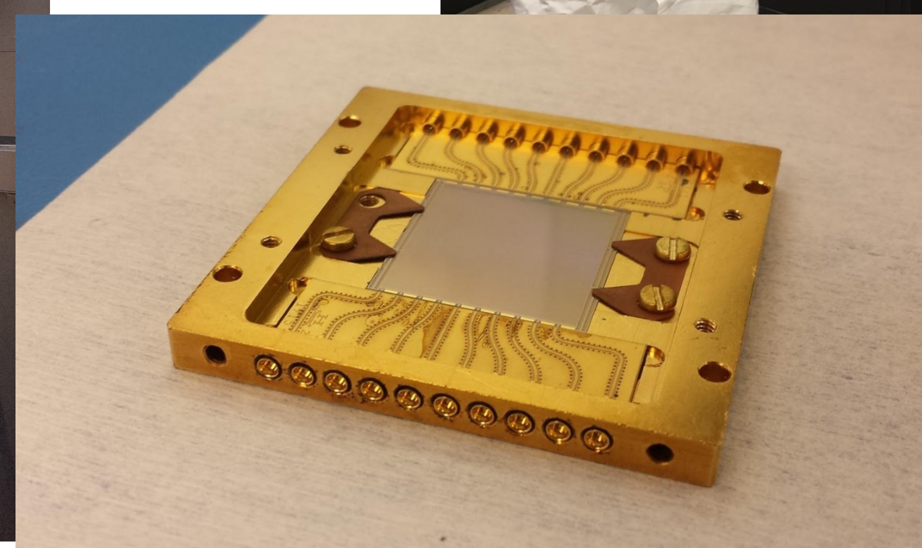
New detectors

Photon-counting, wavelength resolving 140x140 pixel camera



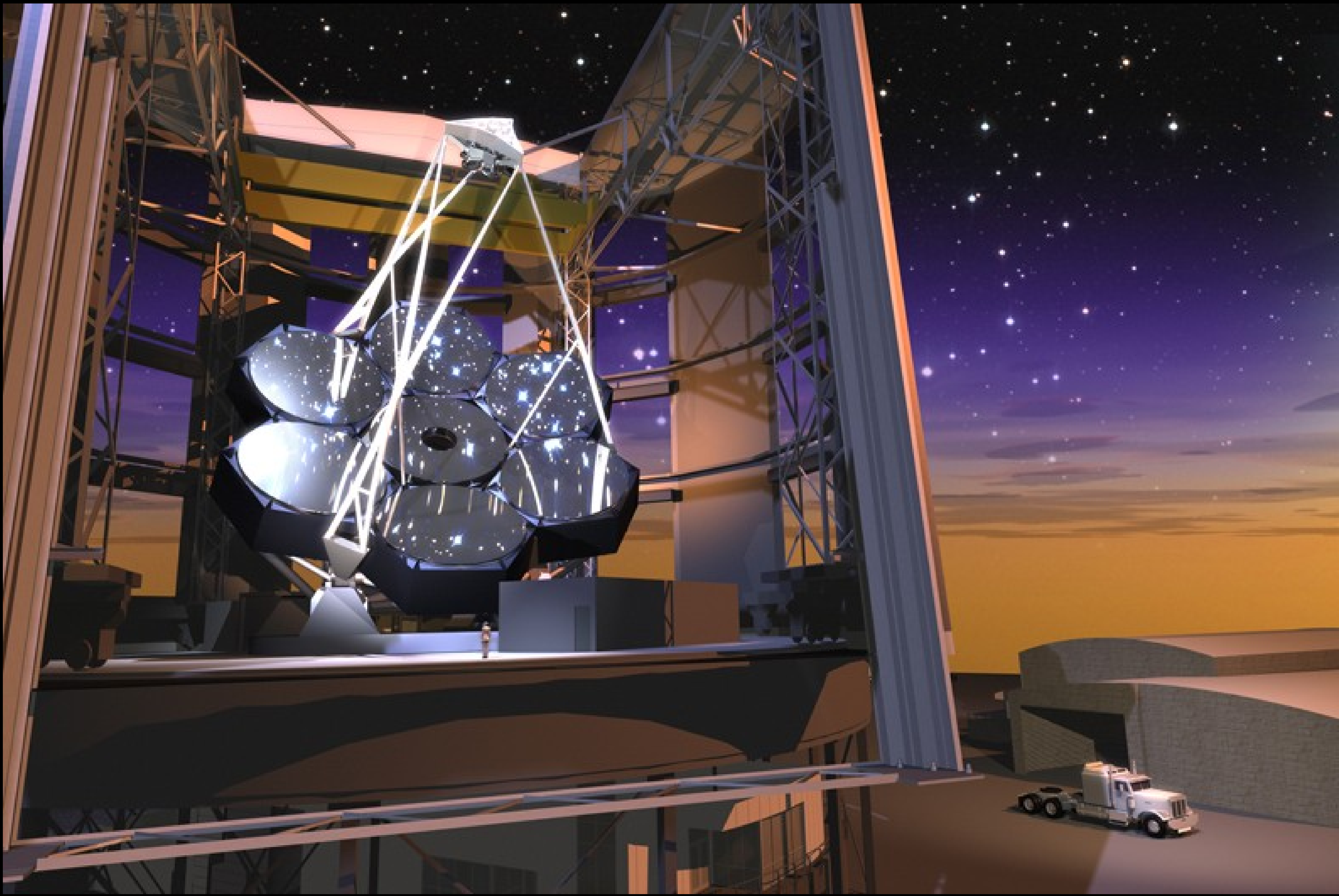
Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

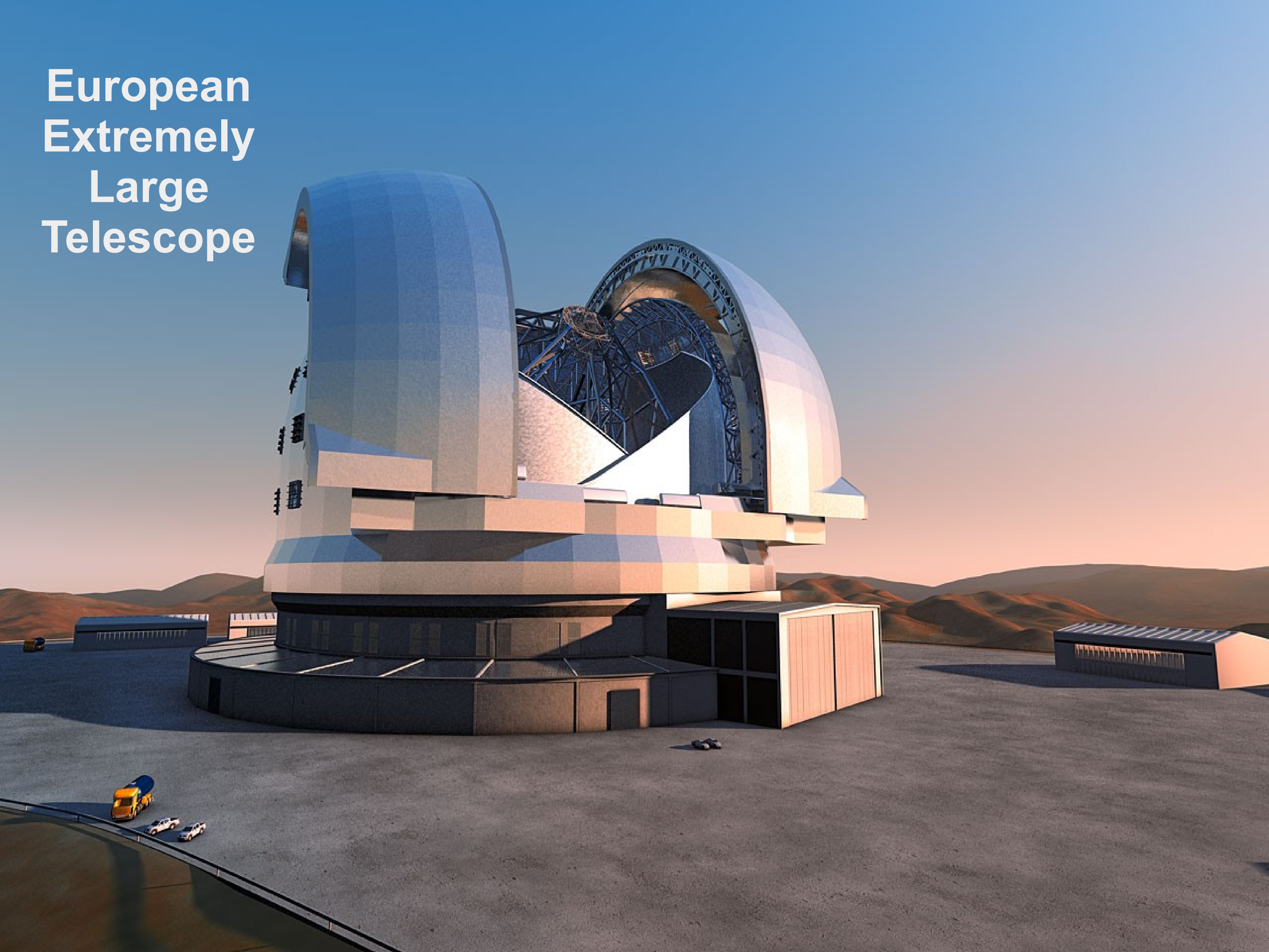
In operation @ Palomar
Delivered SCExAO March 2018



Thirty Meter Telescope

Giant Magellan Telescope




European
Extremely
Large
Telescope

Towards Habitable Planets Imaging

Tools tested on current large telescopes will enable habitable planet imaging on 30-m class telescopes currently in development

Significant challenges in real-time data processing algorithms to extract signal from noise… at multiple kHz with multiple sensors

Habitable planets are stars cooler than Sun will be the easiest to image with large ground-based telescopes
(cooler star → more moderate contrast)