A Fast Path to Imaging and Characterizing Habitable Exoplanets around the Nearest Stars with TMT

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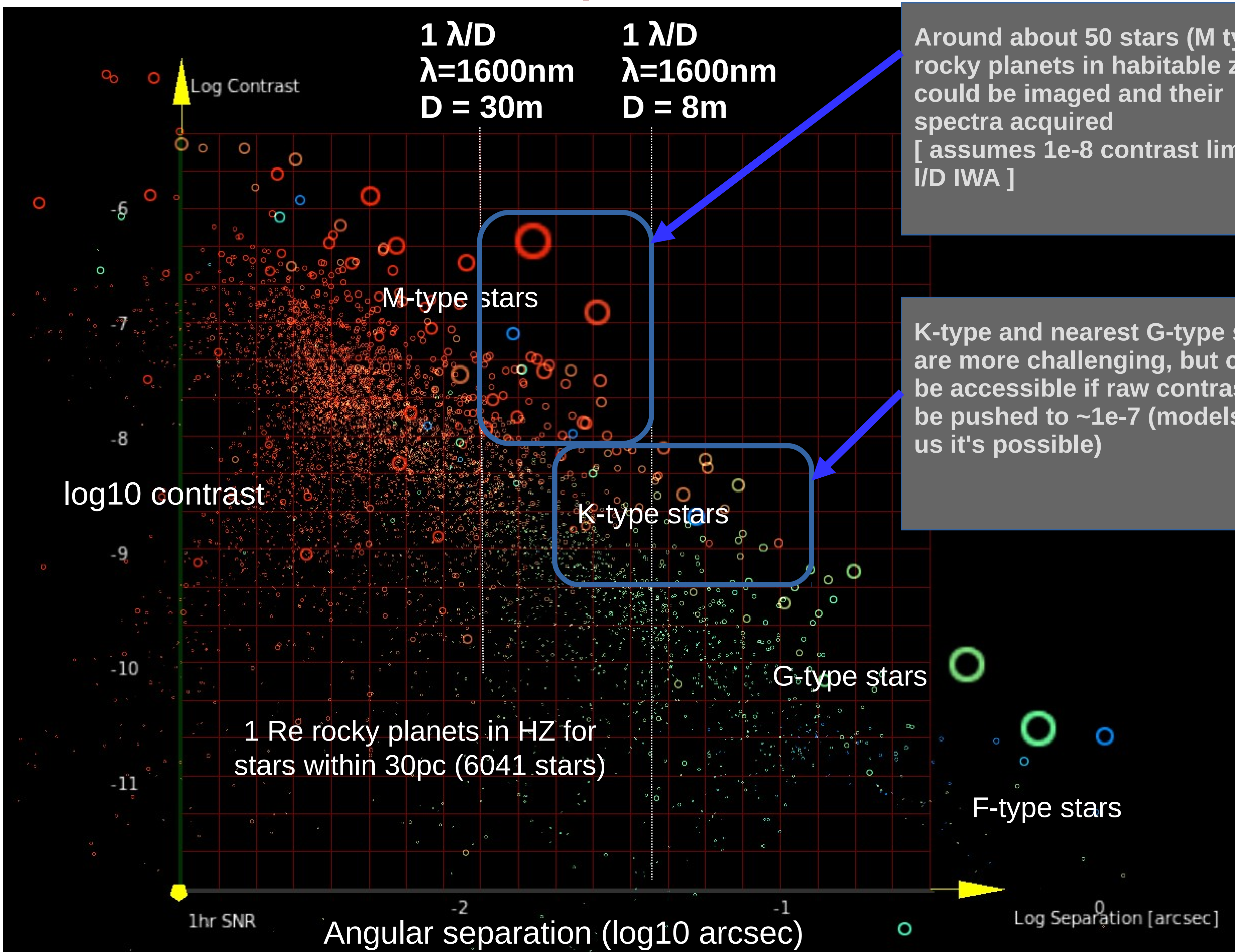
SCExAO team + instrument teams

Subaru Coronagraphic Extreme Adaptive Optics

May 26, Kyoto

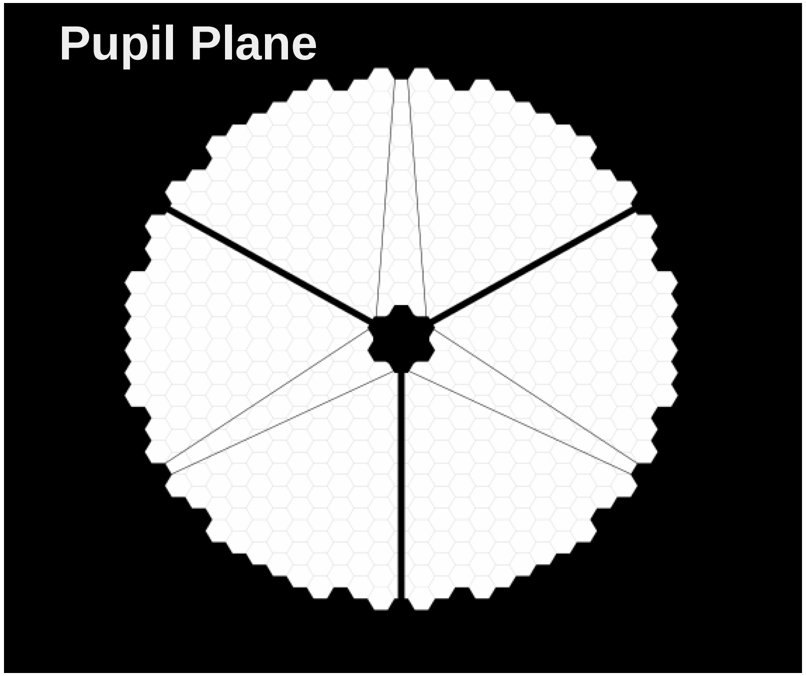
Most exciting science case: spectroscopic characterization of Earth-sized planets with TMT

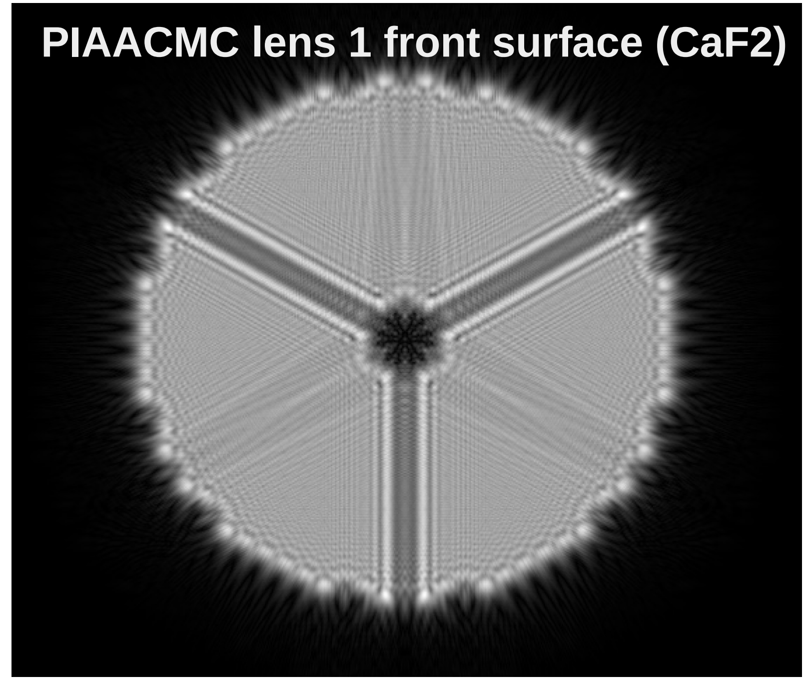


Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

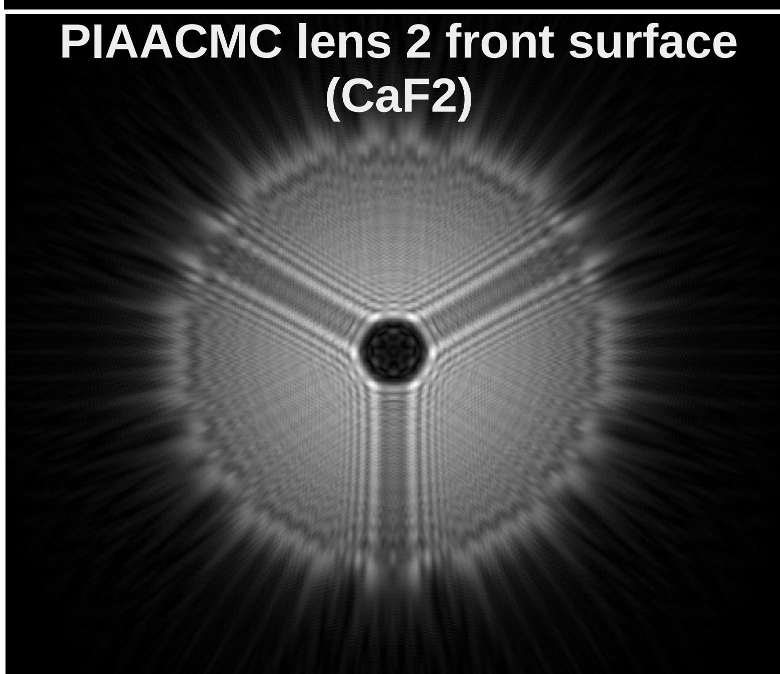
K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

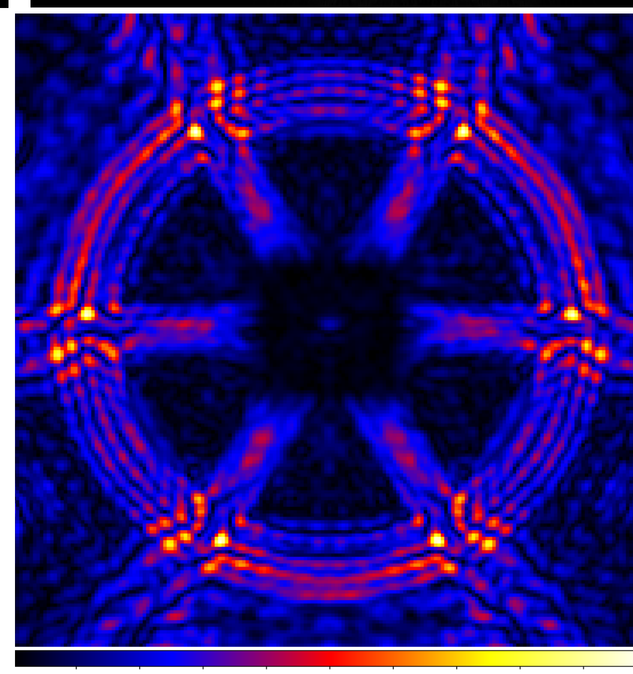
TMT coronagraph design for 1 l/D IWA





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

WFC architecture
5 key requirements

[1] High-efficiency WFS
M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires (D/r0)^2 times more light than diffraction-limited WFS (Pyramid)
This is a **40,000x gain for TMT** (assuming r0=15cm) → 11.5 mag gain

[2] Low latency WFC (High-speed WFS + predictive control)
System lag is extremely problematic → creates "ghost" slow speckles that last crossing time
Need ~200us latency (10 kHz system, or slower system + lag compensation)

[3] Multi-wavelength WFC
Wavefront chromaticity is a serious concern when working at ~1e-8 contrast
Visible light (~0.6 – 0.8 um) photon carry most of the WF information, but science is in near-IR

[4] System architecture must address non-common path errors
It doesn't take much to create a 1e-8 speckle !

[5] Telemetry
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing

Contrast limits

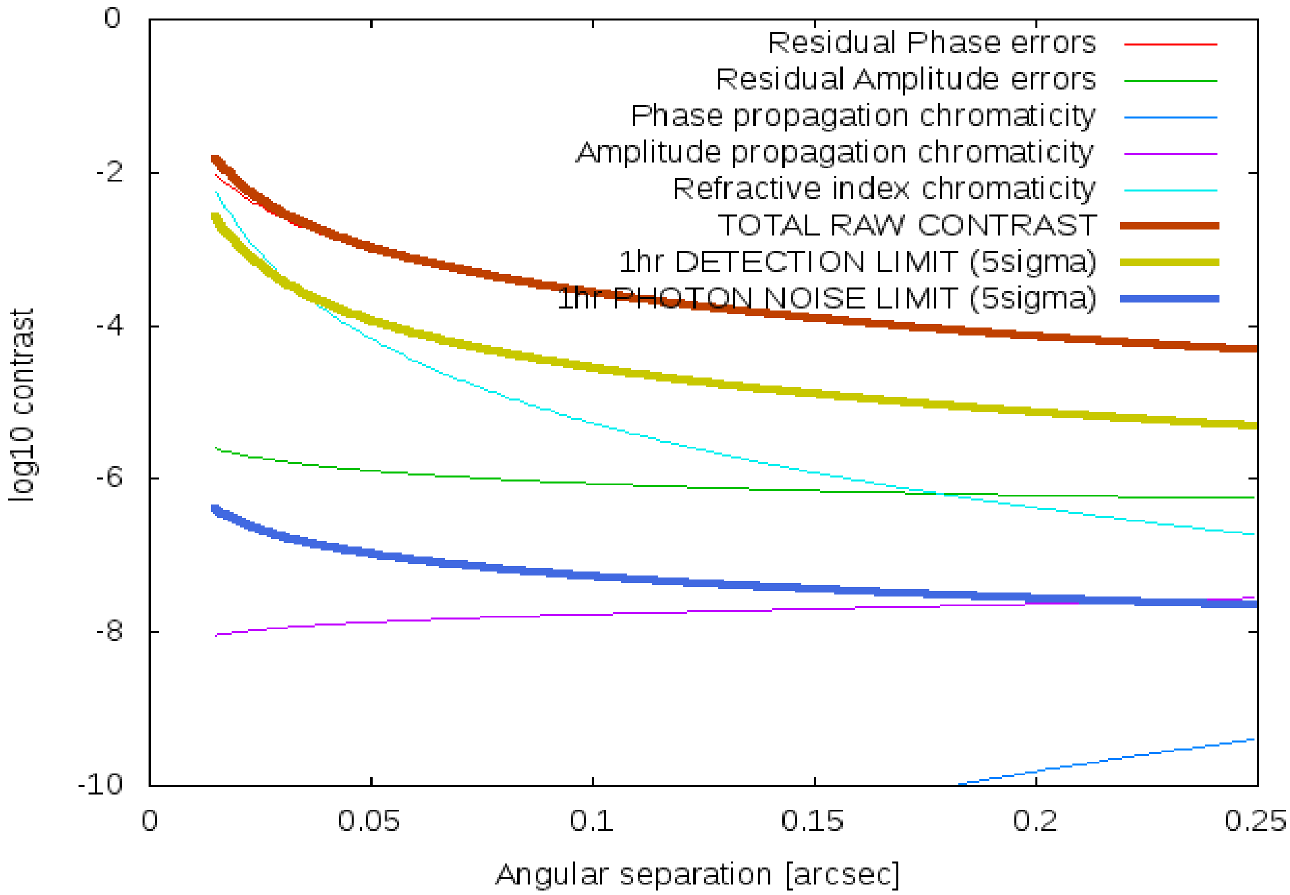
Assumptions:

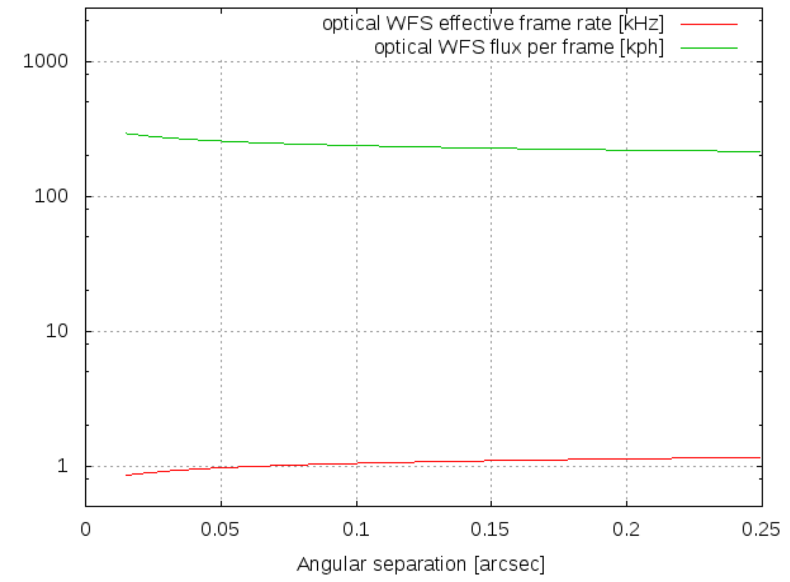
I mag = 8 (WFS – 100 targets)
H mag = 6 (Science)

Noiseless detectors
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: SH-based system, 15cm subapertures

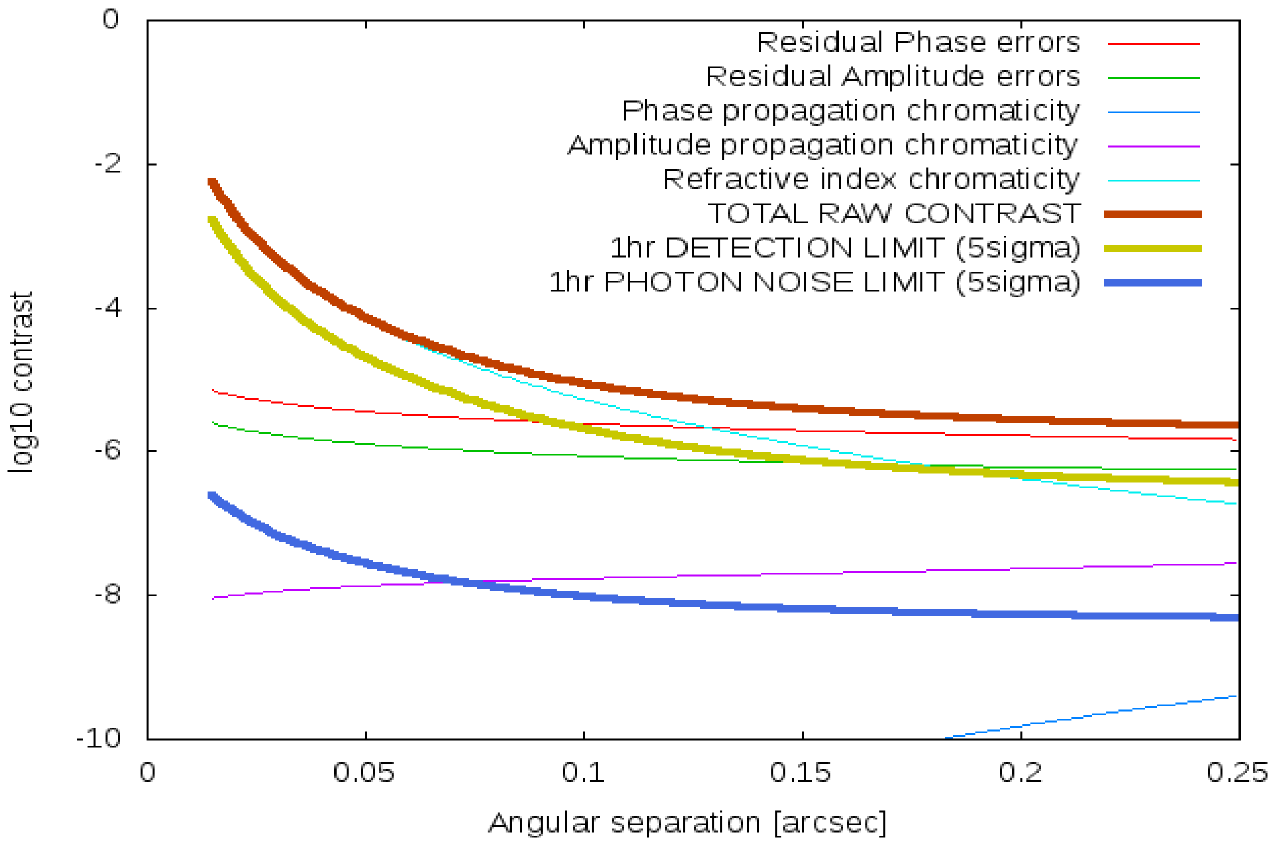


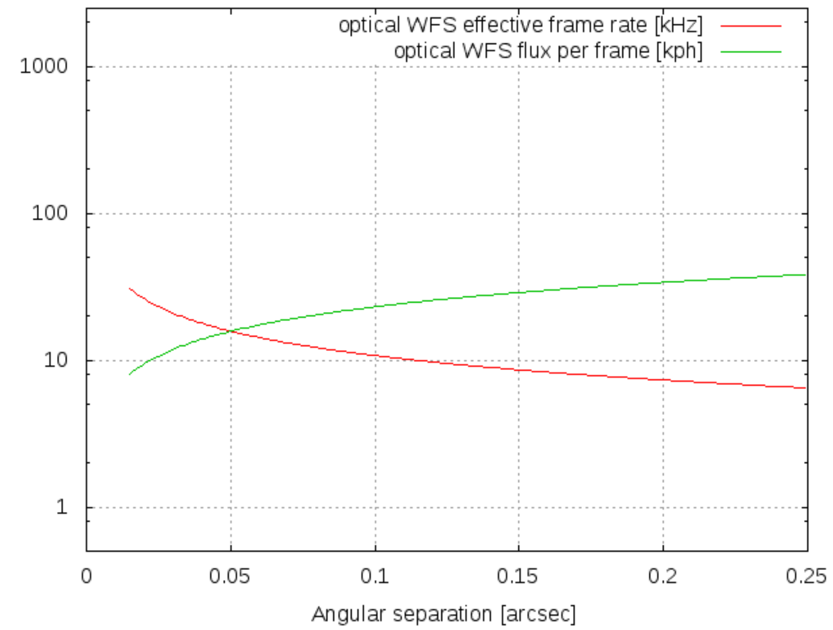


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

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

[1+2] 30m: Pyramid-based system

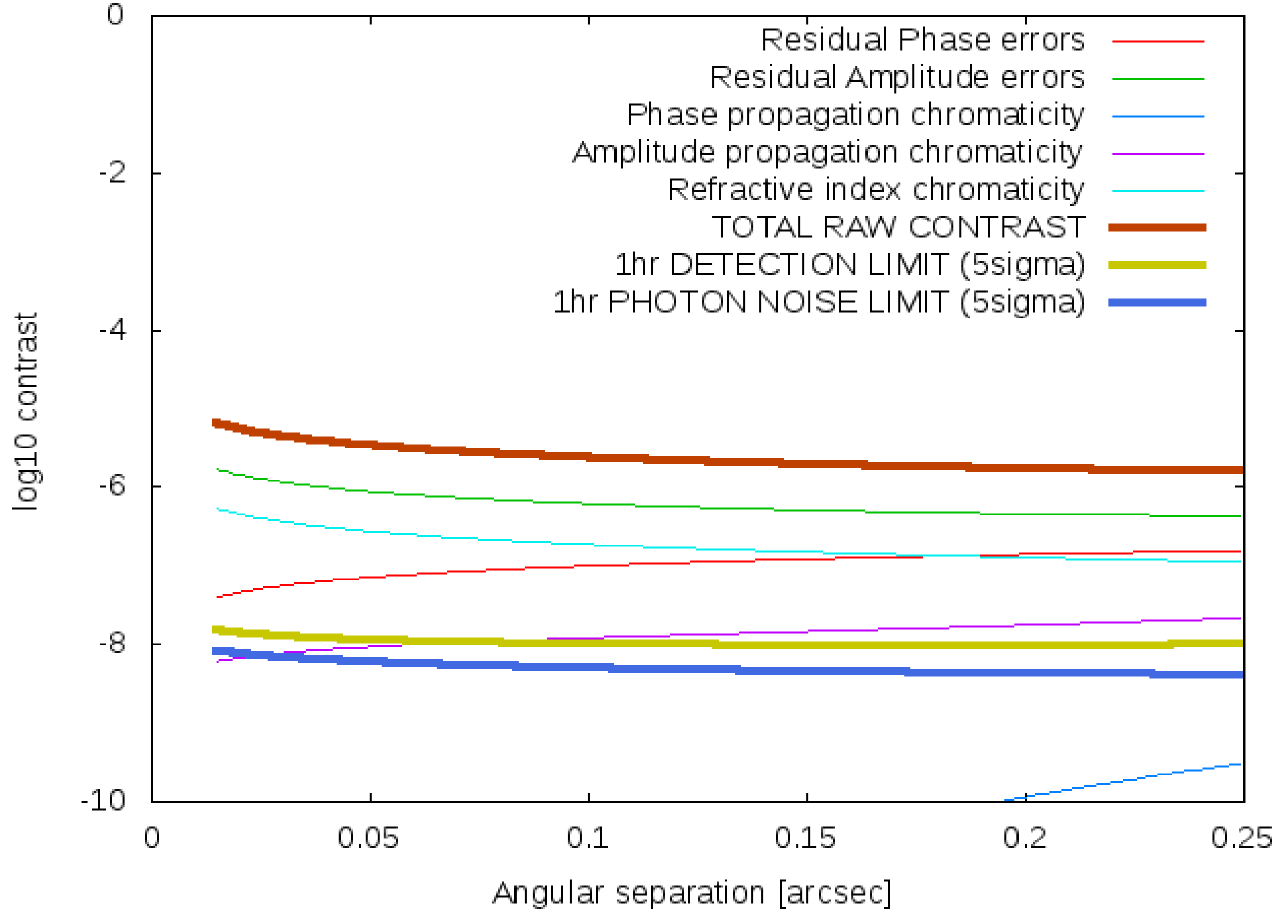


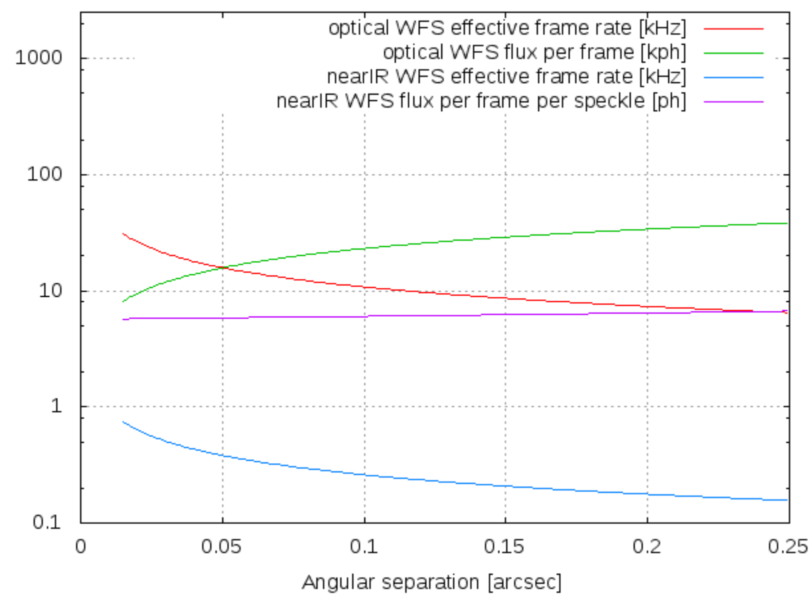


More sensitive WFS, can run faster (10kHz) with ~10 kph per WFS frame
Limited by atmosphere chromaticity

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

[1+2+3+4] 30m: Pyramid-based system + speckle control afterburner

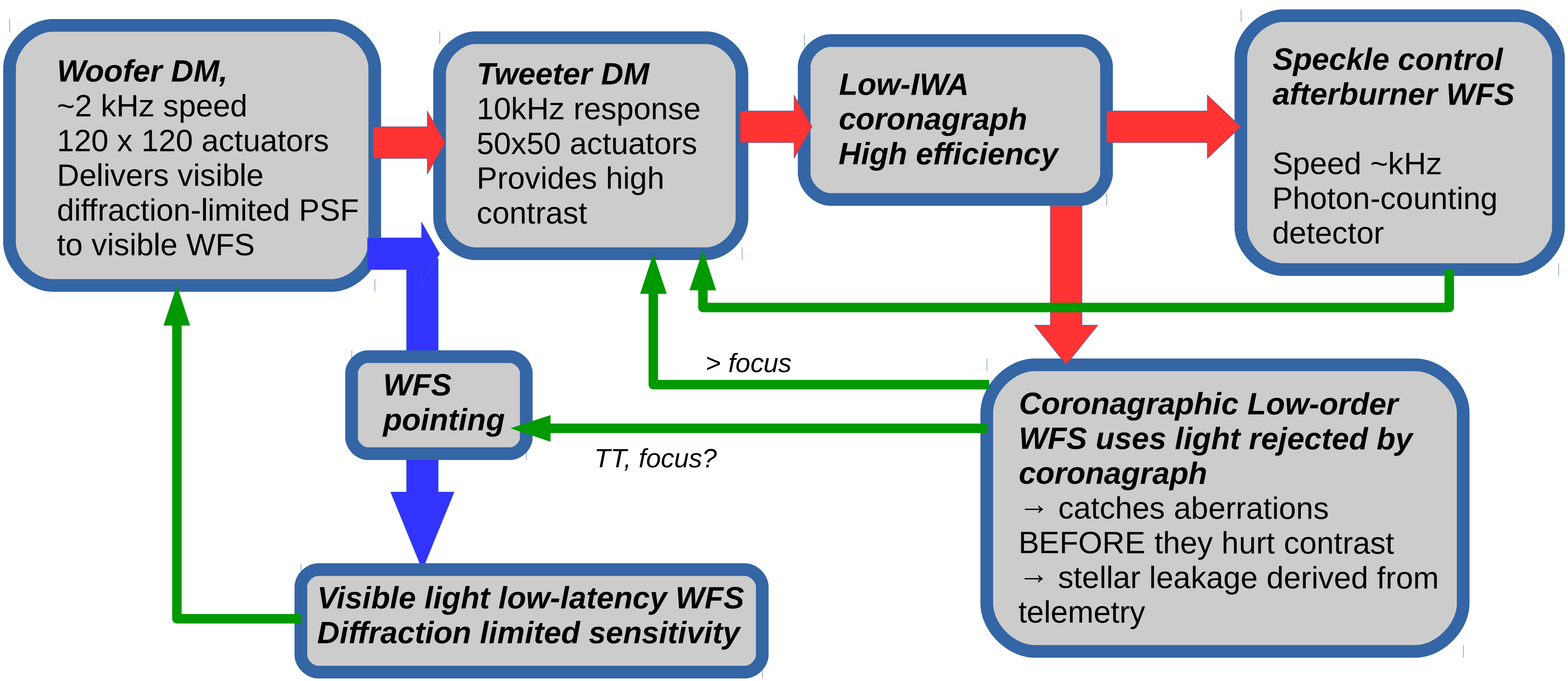




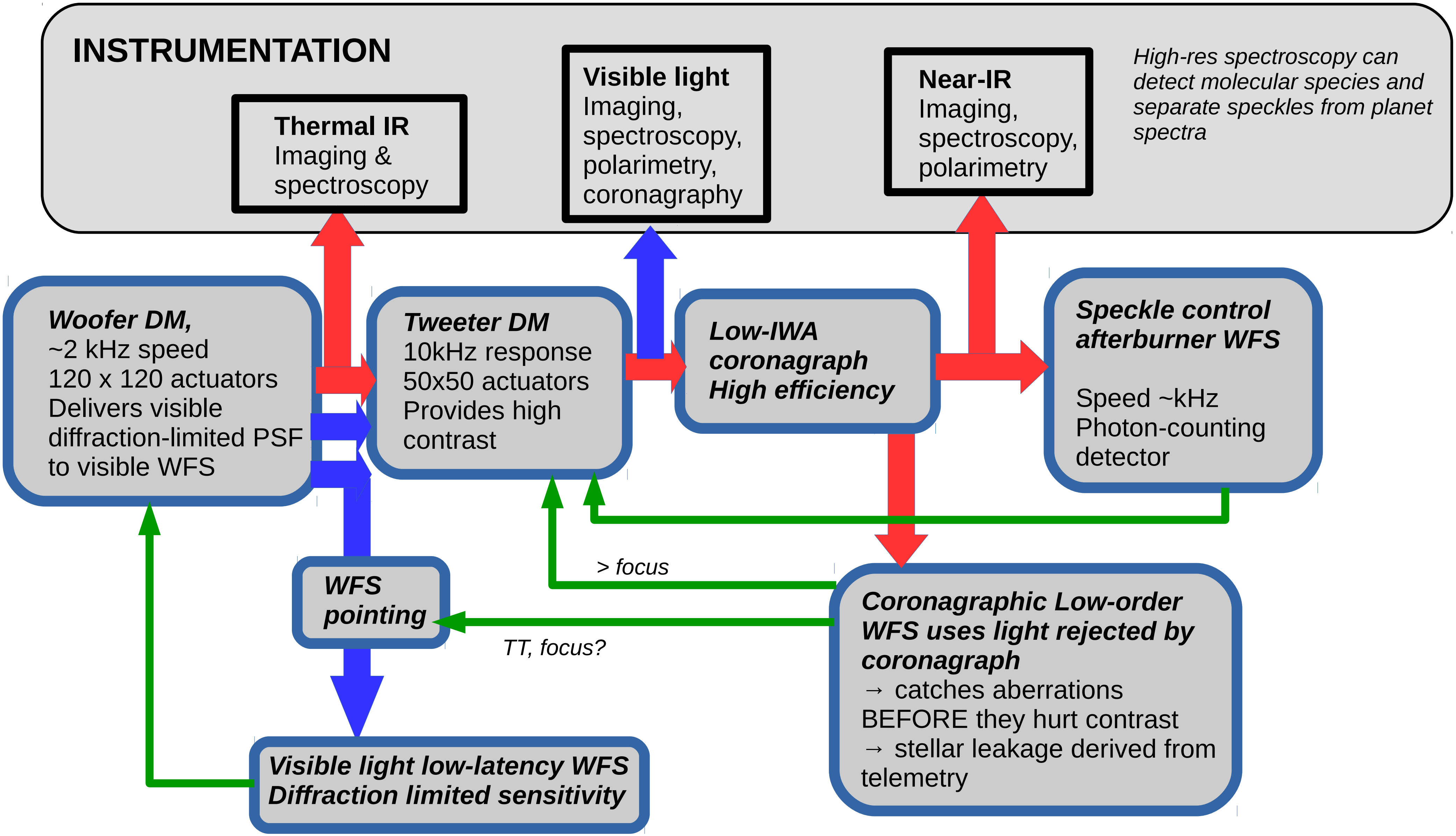
300Hz speckle control loop (~1kHz frame rate) is optimal

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

WFC architecture : proposed approach



System architecture with instrumentation



Can we do it ?

Technology exists NOW (except for DM) – We are NOT WAITING for new technology

- **High performance coronagraphs** working well beyond contrast requirement in lab (space development), and implementations for segmented pupils are being built and tested
- **Photon-counting detectors** now exist in visible (EMCCD) and near-IR (SAPHIRA, MKIDS)
- **WFS solutions** have been demonstrated in controlled (stable) environment: unmodulated Pyramid WFS, speckle control, LOWFS, and some of it demonstrated on-sky

However, most of what we need has never been tested on sky and integrated into a system → this is what we need to do NOW on current large telescopes

This is what the SCExAO program at Subaru is doing now

It takes yrs of hard work to put all of this together, learn what works, and optimize algorithms / designs (including data reduction)
The SCExAO platform provides a welcoming environment to do this work

Subaru Coronagraphic Extreme Adaptive Optics

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S. Lacour
F. Marchis
S. Vievard
O. Lai
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AO188
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E. Serabyn
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NASA JPL

CHARIS
J. Kasdin
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M. Galvin
M. Carr
PRINCETON UNIVERSITY

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M. Tamura

MKIDS
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FIBER INJECTION
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PyWFS
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THE UNIVERSITY OF ARIZONA

SAPHIRA
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Institute for Astronomy, University of Hawai'i

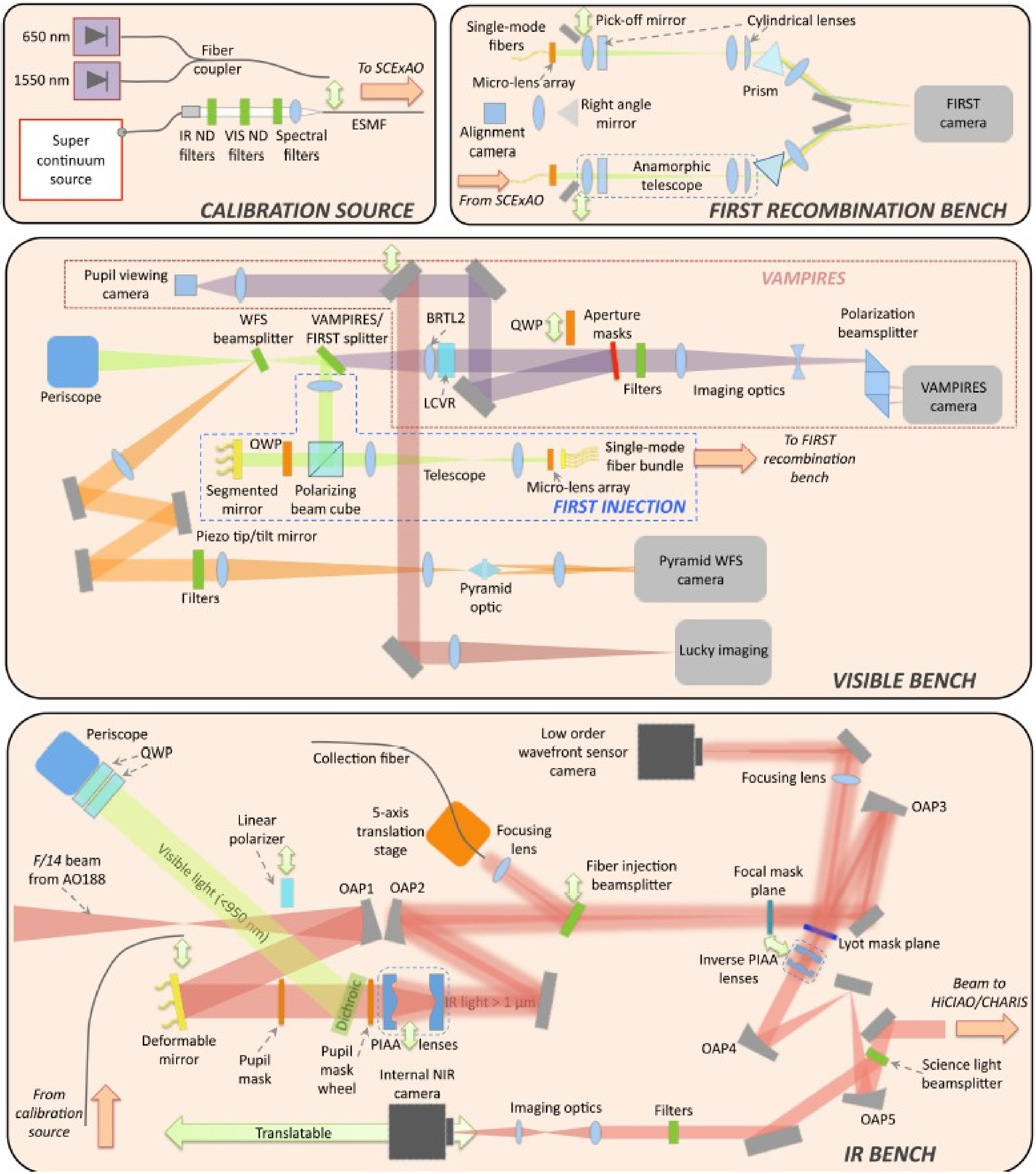
Wavefront sensing:

- 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)

Broadband diffraction limited internal cal. Source + phase turbulence simulator



SCExAO modules

The wavefront control feeds a high Strehl PSF to various modules, from 600 nm to K band.

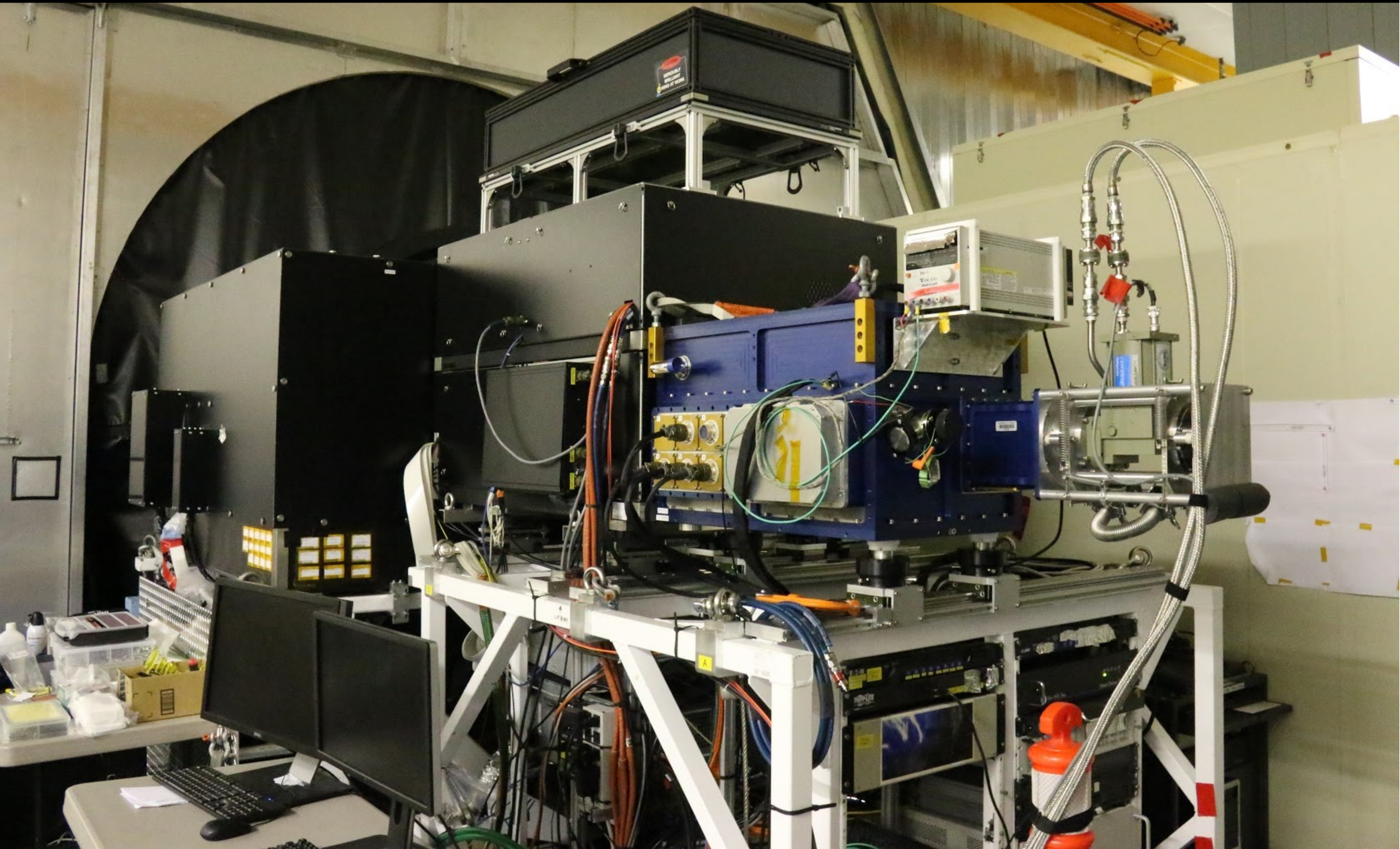
Visible (600 – 950 nm):

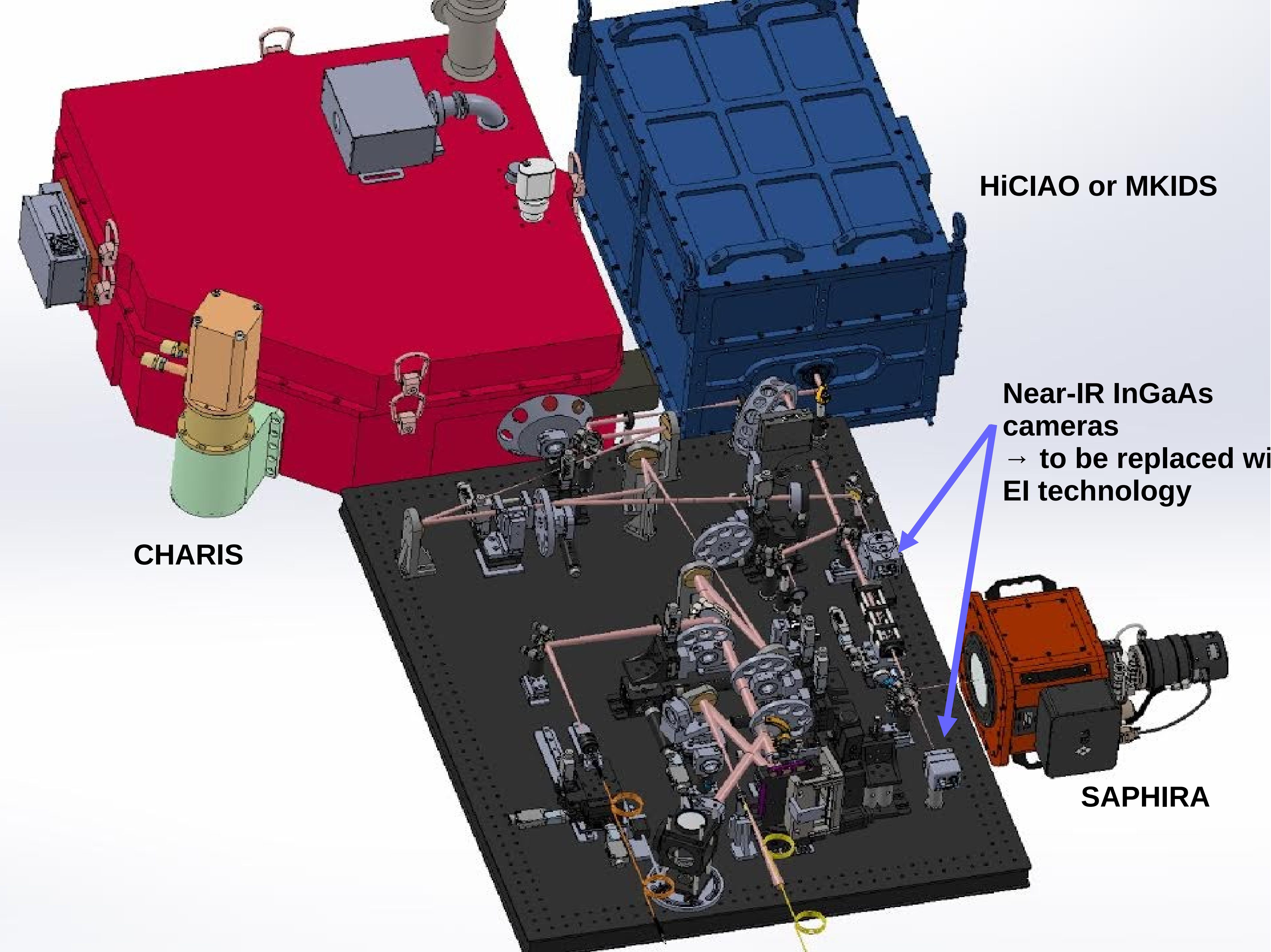
- **VAMPIRES**, non-redundant masking, polarimetry, soon H-alpha imaging capability
- **FIRST**, non-redundant remapping interferometer, spectroscopic analysis
- **RHEA**, single mode iber injection, high-res spectroscopy, high-spatial resolution on resolved stars

IR (950-2400 nm):

- **HiCIAO**, high contrast imager, y to K-band
- **SAPHIRA**, high-speed photon counting imager, H-band (for now)
- **CHARIS**, IFS (J to K-band), just delivered! Commissioning in 2 months
- **MEC, MKID detector**, high-speed energy discriminating photon counting imager (y to J-band), delivery in early 2017
- **NIR single mode injection**, high throughput high resolution spectroscopy. Soon will be connected to the new IRD
- **NULLER → GLINT**

Subaru Coronagraphic Extreme Adaptive Optics





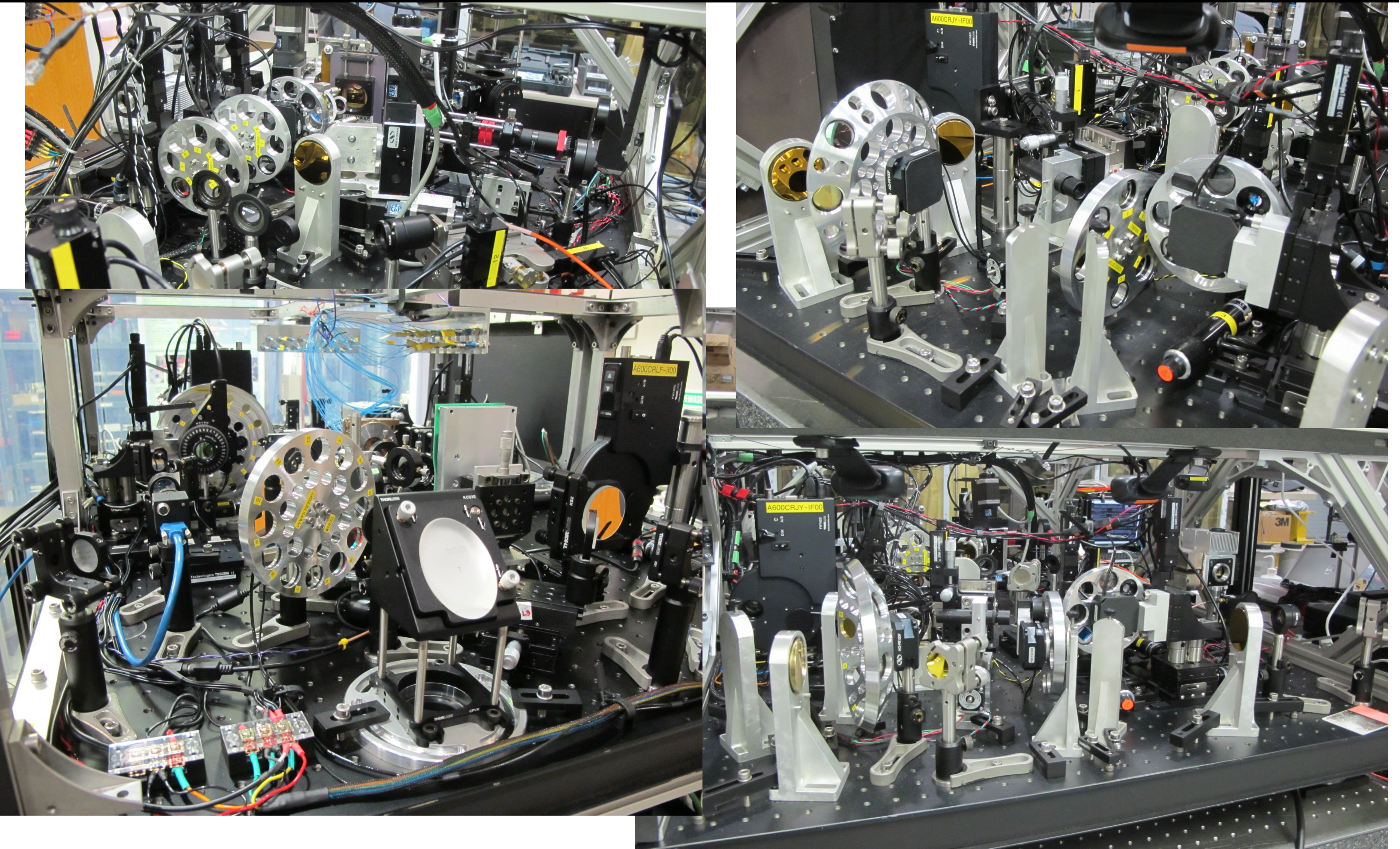
HiCIAO or MKIDS
Near-IR InGaAs cameras
→ to be replaced wi
EI technology
CHARIS
SAPHIRA

SCExAO

Subaru Coronagraphic Extreme Adaptive Optics

SCExAO

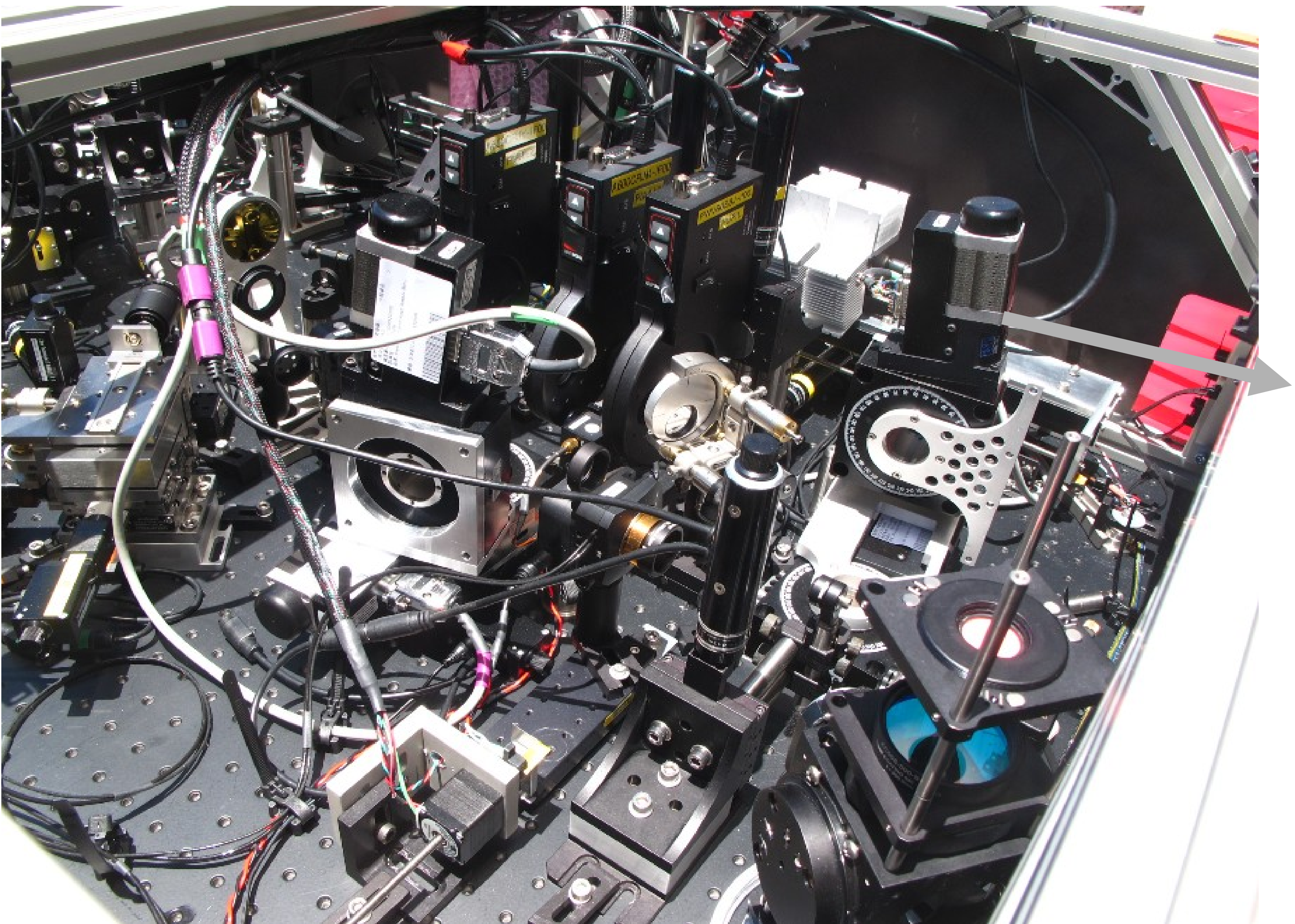
Subaru Coronagraphic Extreme Adaptive Optics



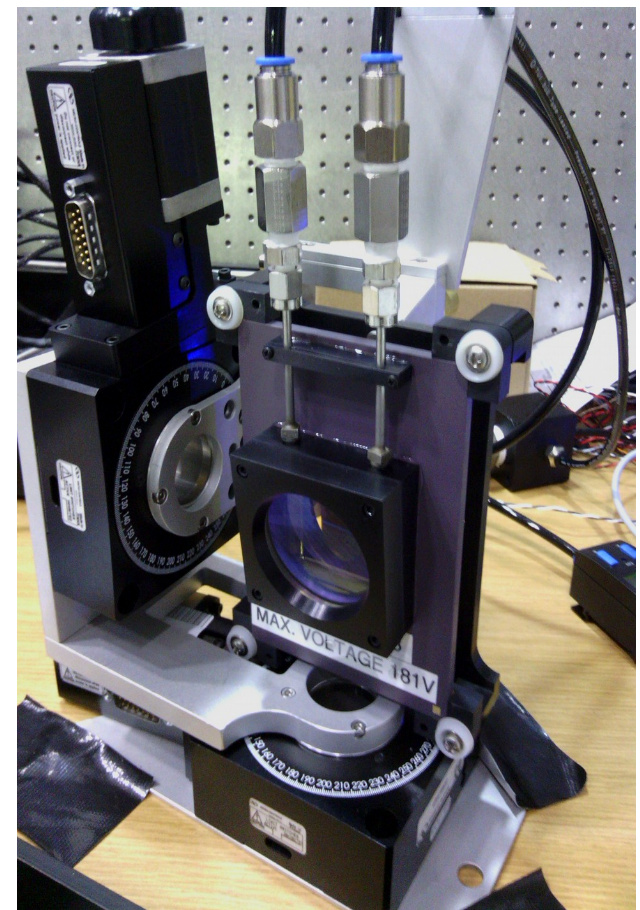
Subaru Coronagraphic Extreme Adaptive Optics

SCExAO

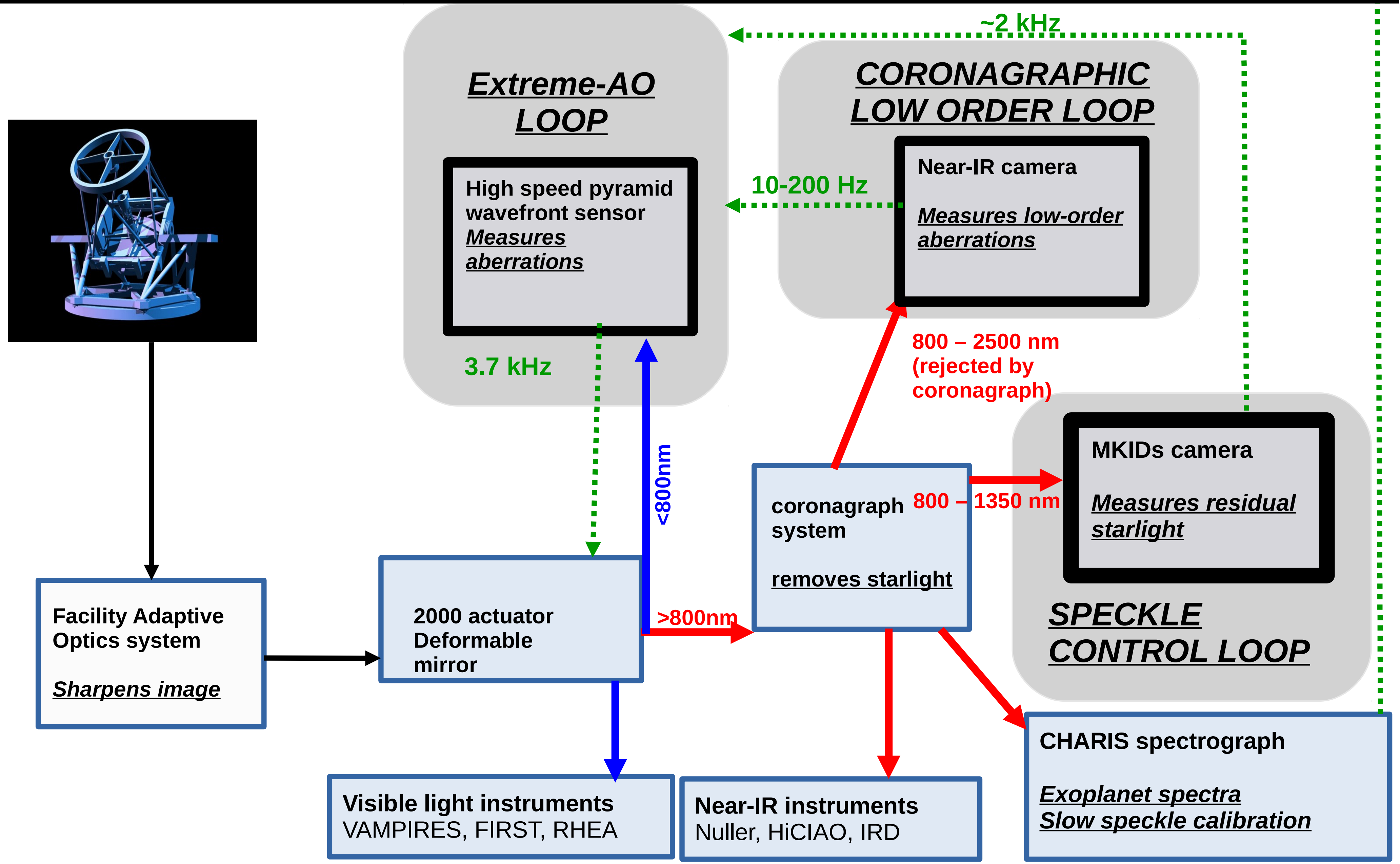
Coronagraphs



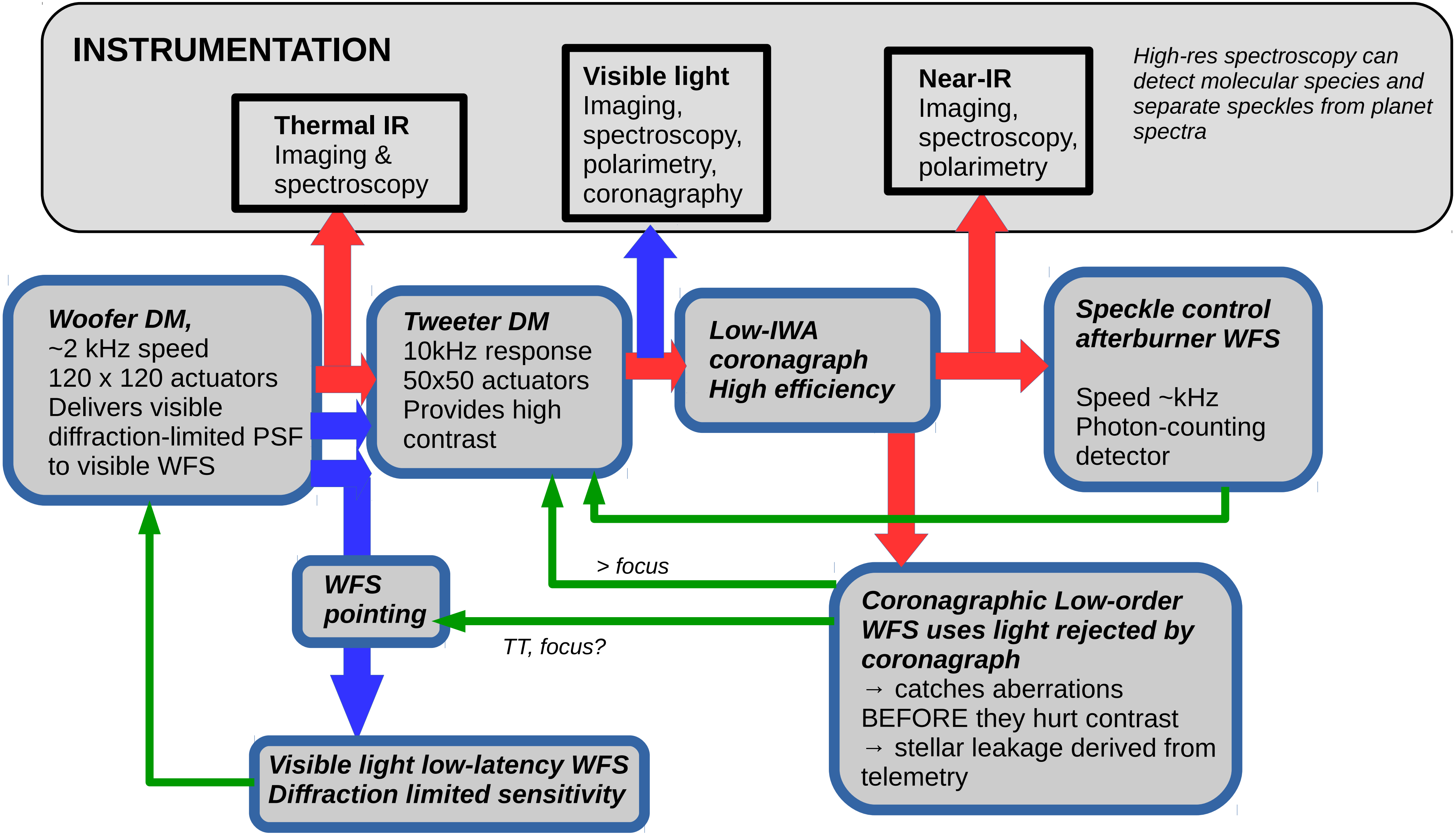
Deformable mirror



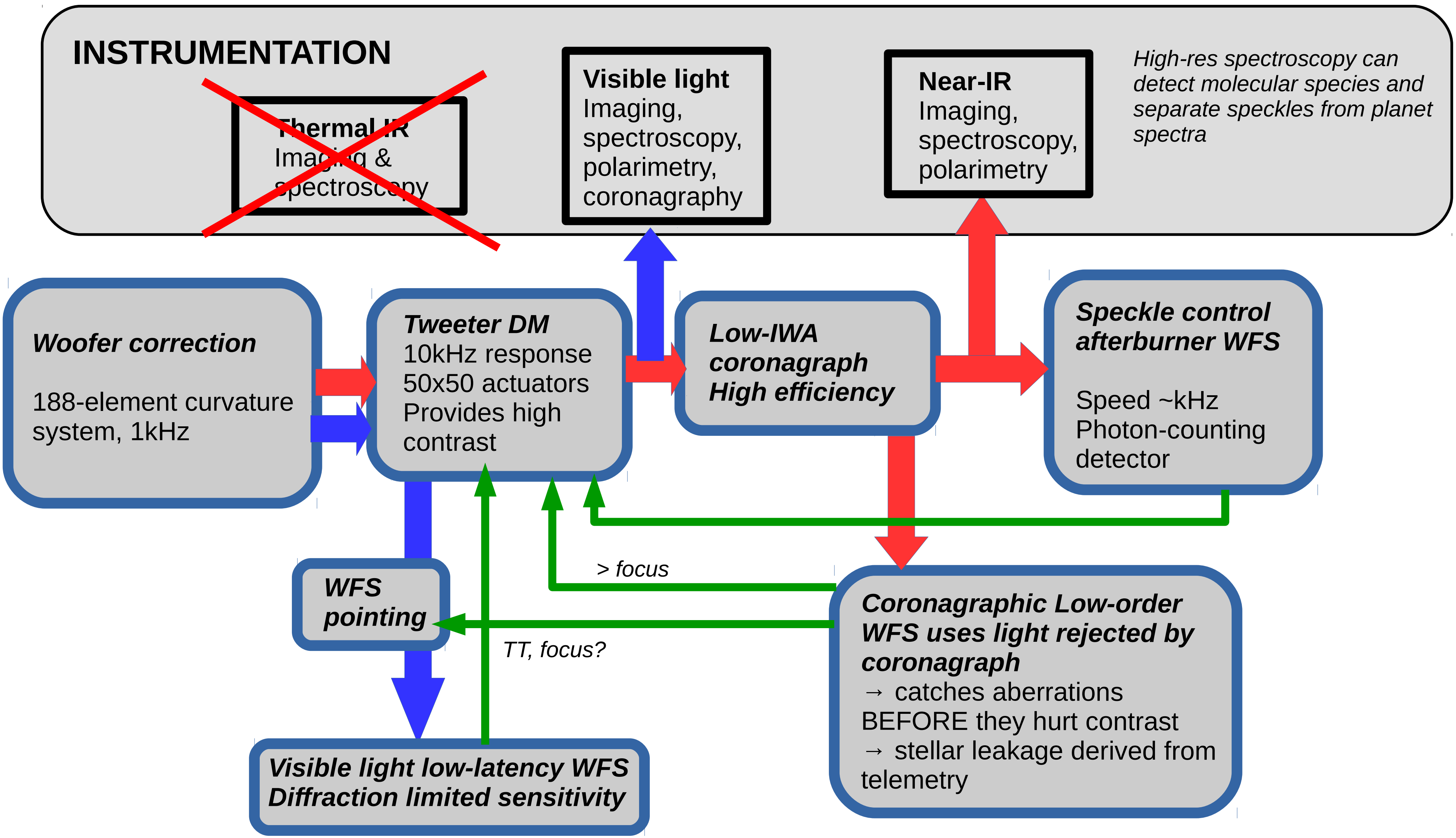
Subaru Coronagraphic Extreme Adaptive Optics



System architecture with instrumentation

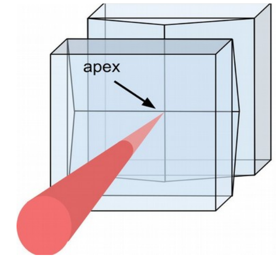


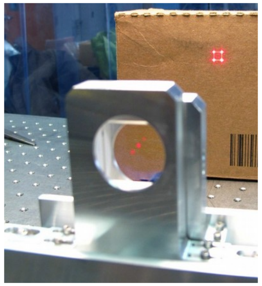
SCExAO @ Subaru (2017)



Low latency WFC in visible light at the diffraction limit sensitivity

SCExAO Subaru Coronagraphic Extreme Adaptive Optics





2000 actuators MEMs DM running at 3.6 kHz
deep depletion EMCCD

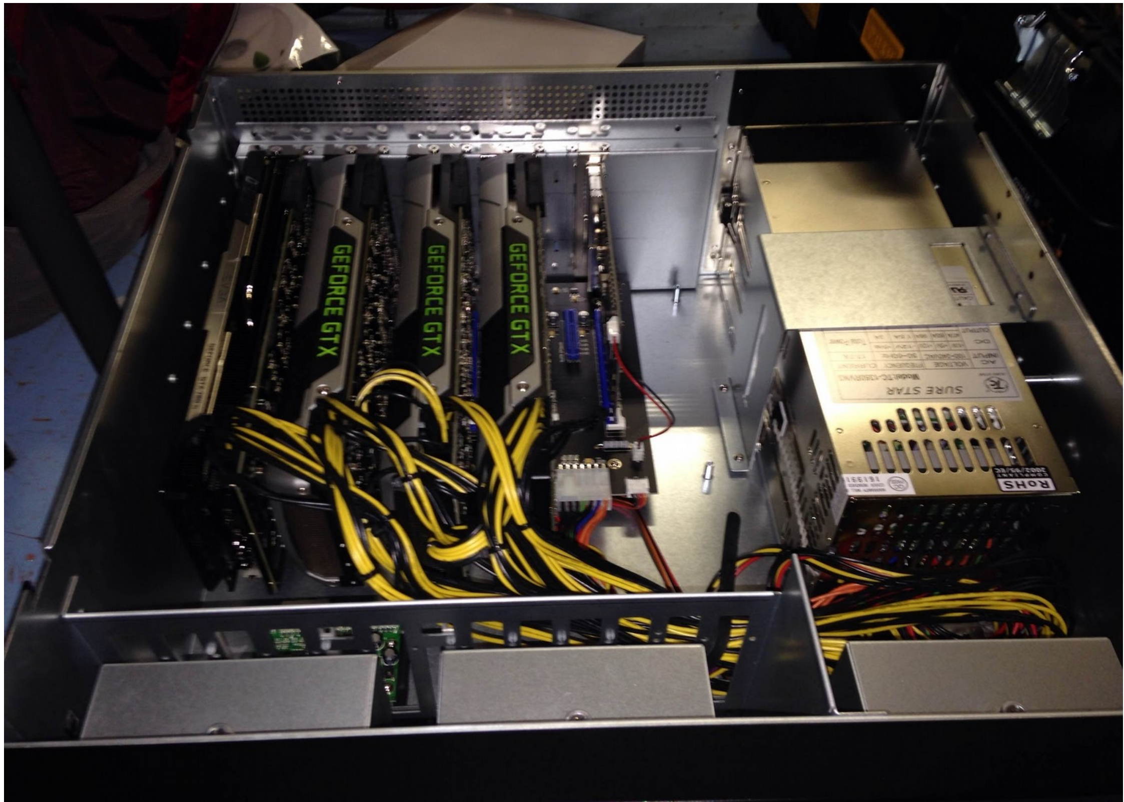
Non-modulated pyramid WFS cannot rely on slope computations
→ full WFS image is multiplied by control matrix

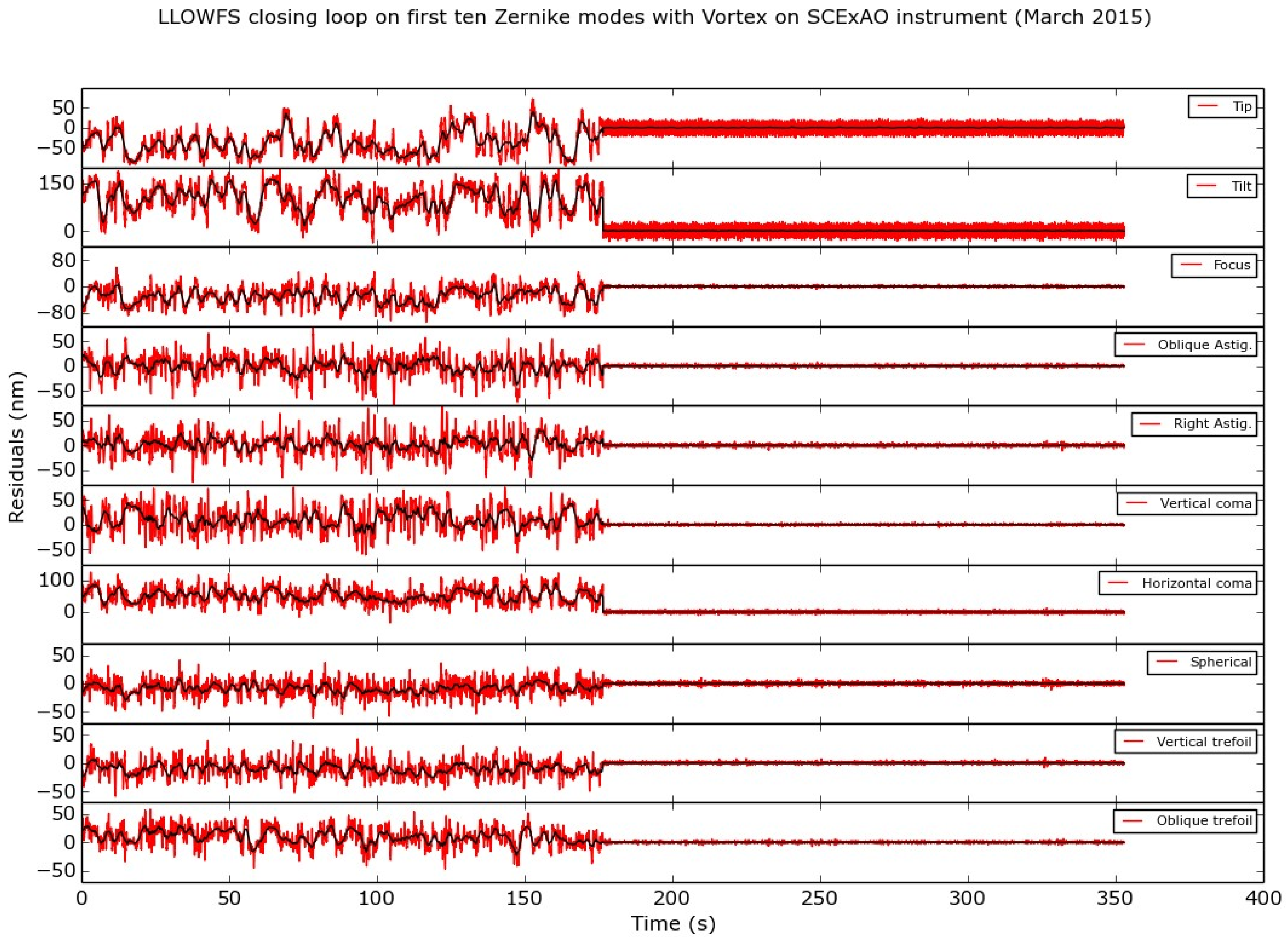
Now delivering 70-80% SR in H

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 30,000 cores running >1GHz

One of two GPU chassis





Ref: Singh et al. 2015

Focal plane WF control (Martinache et al. 2016)

Closed-loop focal plane wavefront control with the SCExAO instrument
Martinache, Jovanovic & Guyon
A&A, 2016

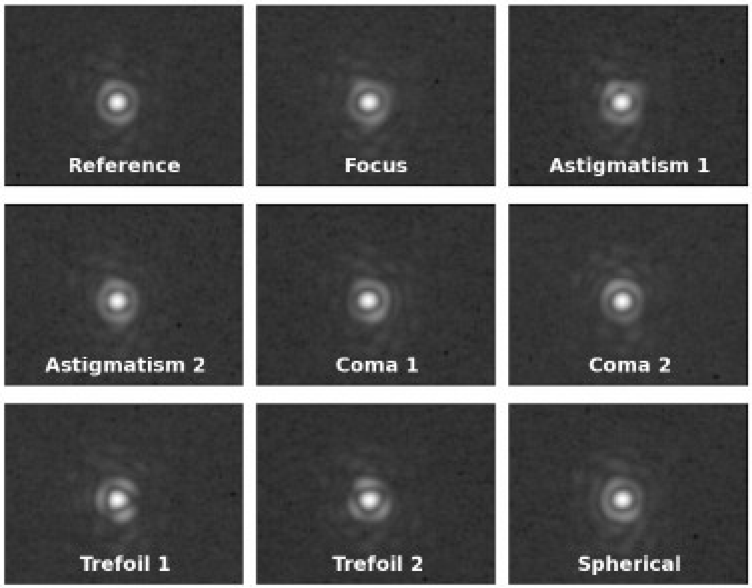


FIG. 5.— Calibration data for the APF-WFS acquired by the SCExAO science camera. Top left: the reference PSF, acquired with the system in its starting state. From left to right and top to bottom: the PSF after the corresponding Zernike mode has been applied. A non-linear scale is used to better show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

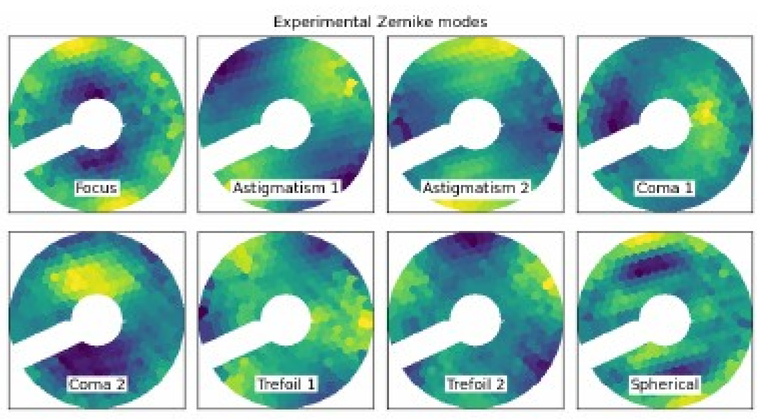


FIG. 6.— Experimentally recovered Zernike modes. Save for the spherical aberration, one will observe that the modes extracted from the analysis of the images of Fig. 5 do reproduce the features expected after looking at the theoretical reconstructed modes presented in Fig. 4.

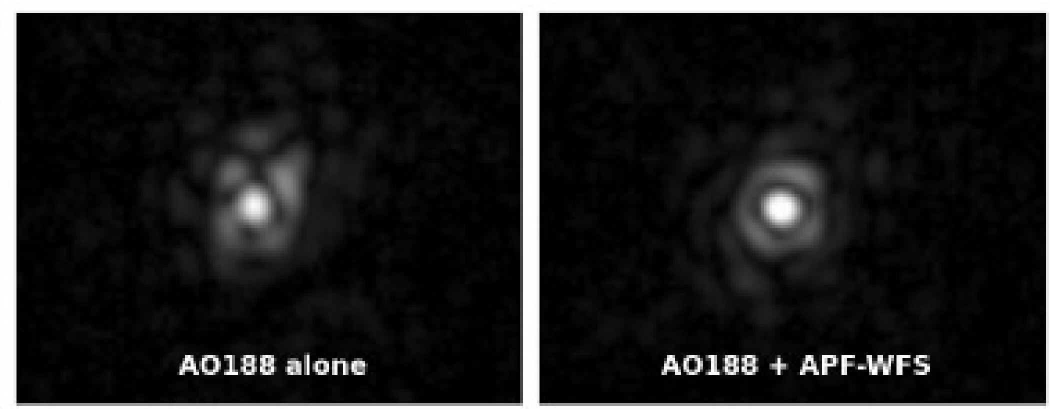
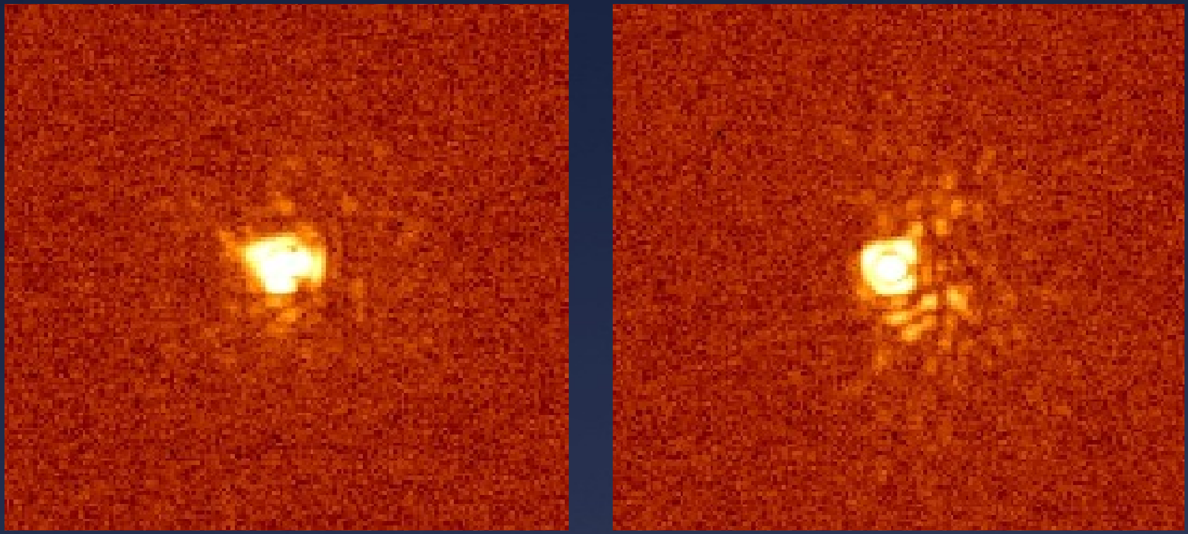
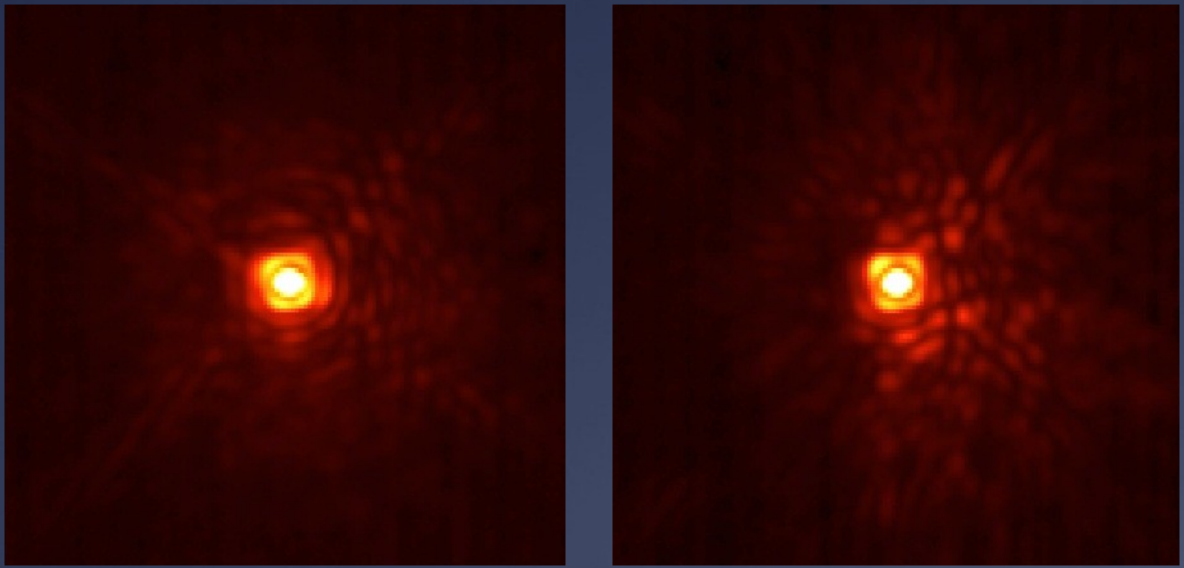


FIG. 8.— Illustration of the impact of the APF-WFS. Left: 0.5 ms PSF acquired by SCExAO's internal science camera after the upstream AO loop has been closed. Right: identical exposure acquired 30 seconds after the APF-WFS loop has been closed. Despite residual imperfections due to dynamic changes, the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

speckle nulling results on-sky (June 2014)

Single frames: 50 us





Sum of 5000 frames: shift and add

Meta data:

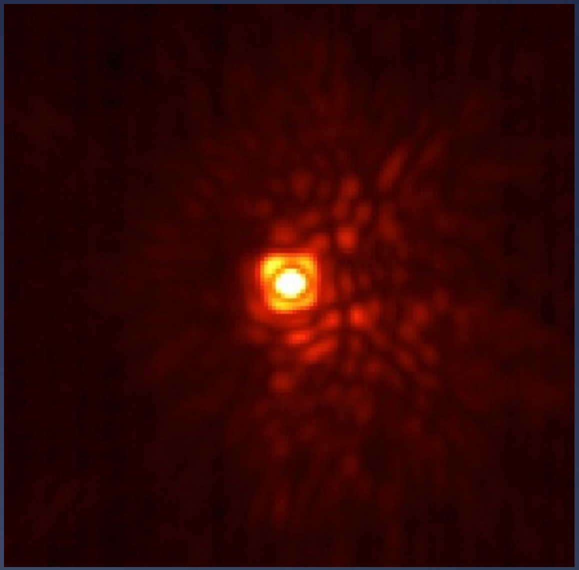
Date: 2nd or June

Target: RX Boo (also repeated on Vega)

Seeing: <0.6”

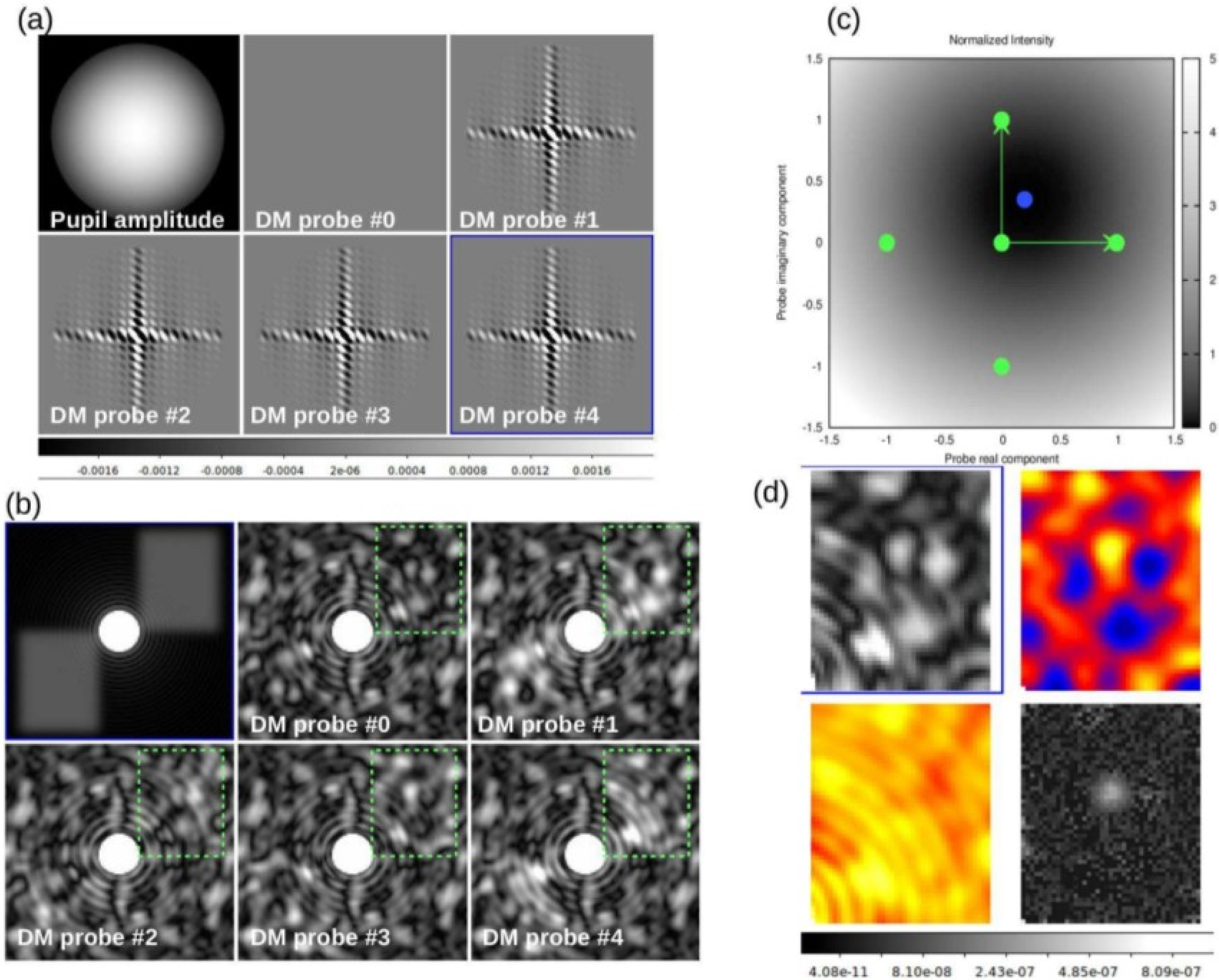
AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)

Coronagraph: None (used Vortex on Vega)



Martinache, F. et. al.

Coherent Speckle Differential Imaging



Speckle control: future steps

SAPHIRA camera allows high speed speckle control

→ we will try in July 2016 (new readout electronics ready as of may 2016)

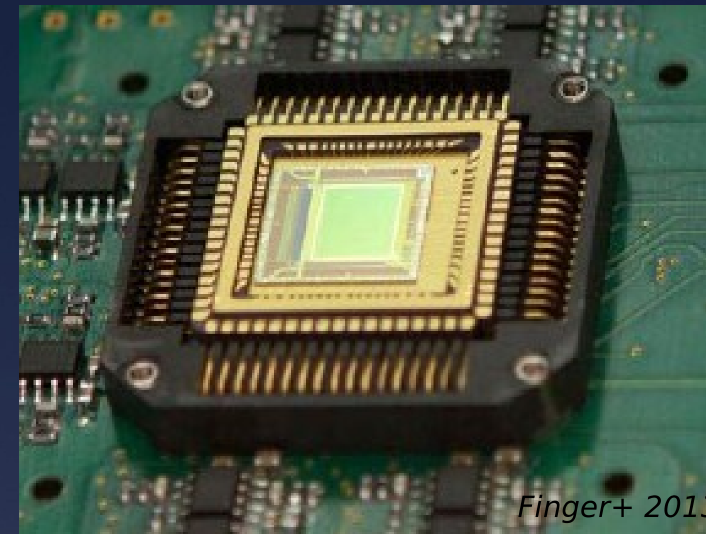
MKIDs camera to be deployed in early 2017

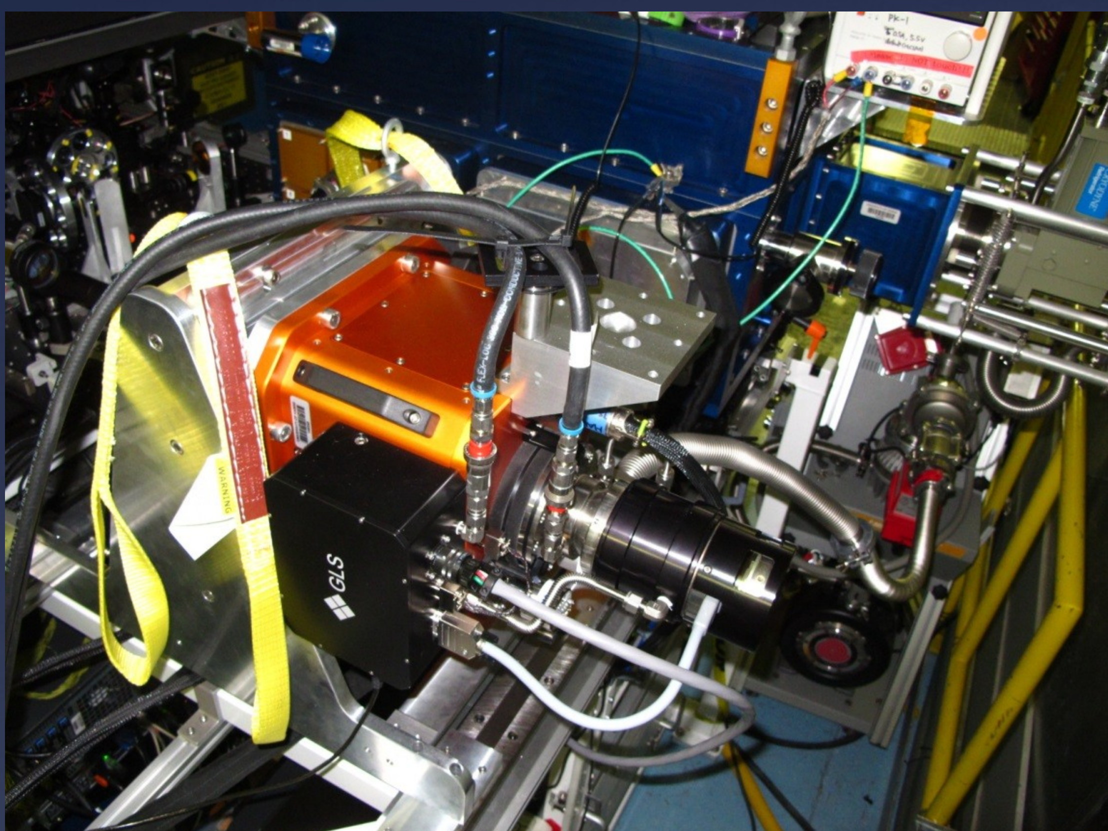
→ higher speed/sensitivity, wavelength information

SAPHIRA Infrared APD array

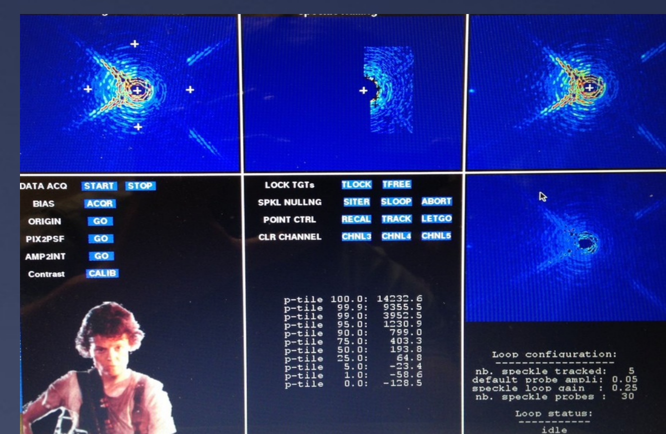
HgCdTe avalanche photodiode
manufactured by Selex

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

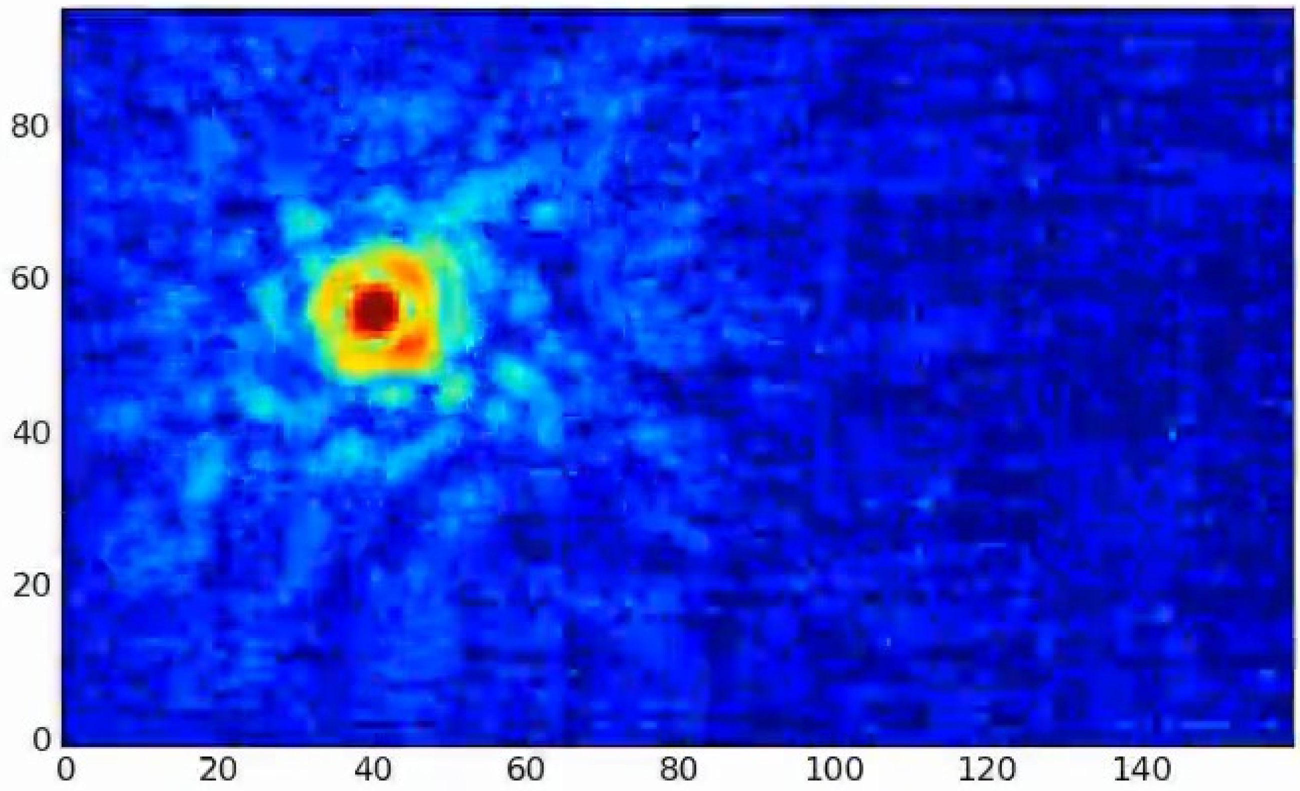




50 frame average

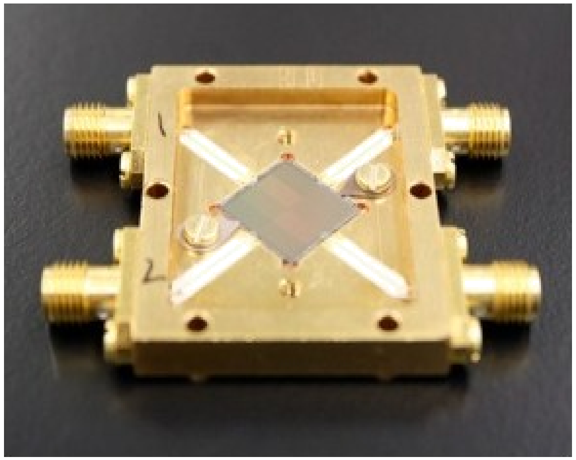


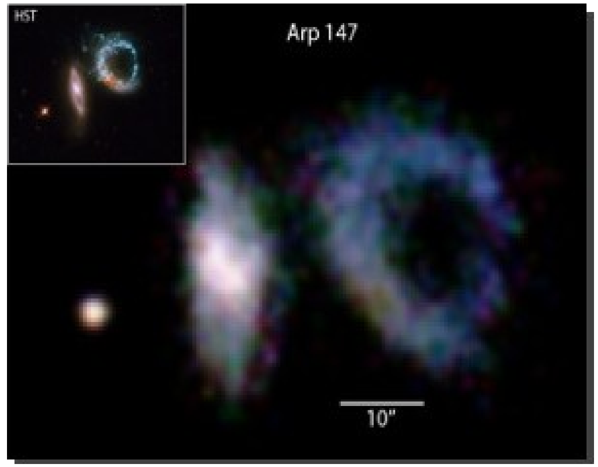
SAPHIRA + SCExAO

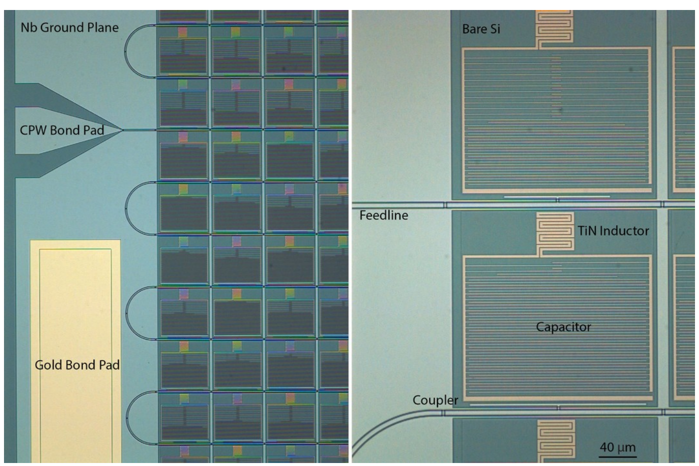


MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera





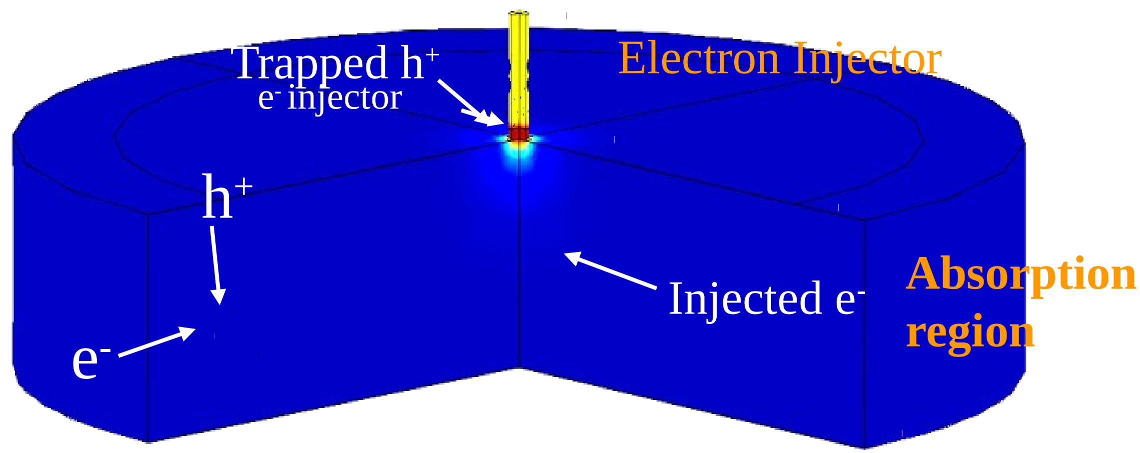


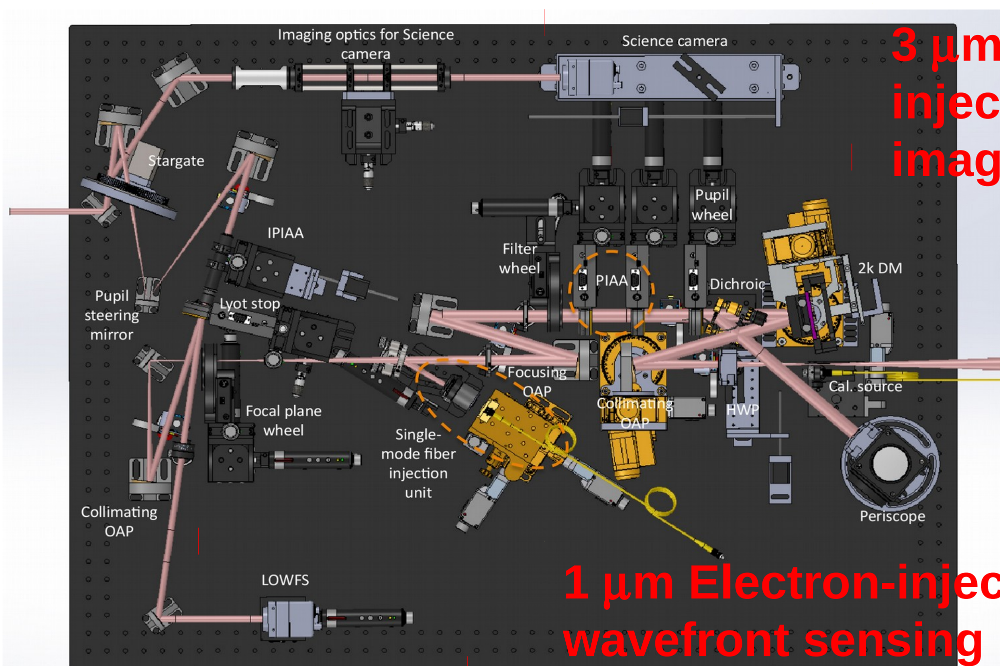
Pixels are microwave resonators at ~100mK
photon hits → resonator frequency changes

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)





3 µm Electron-injection speckle imaging camera

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

High resolution spectroscopy: SCExAO feeding IRD

Jovanovic, Kawahara, Kotani, Guyon

Simultaneous spectroscopy of planet and background speckles

Spectroscopic characterization of exoplanets

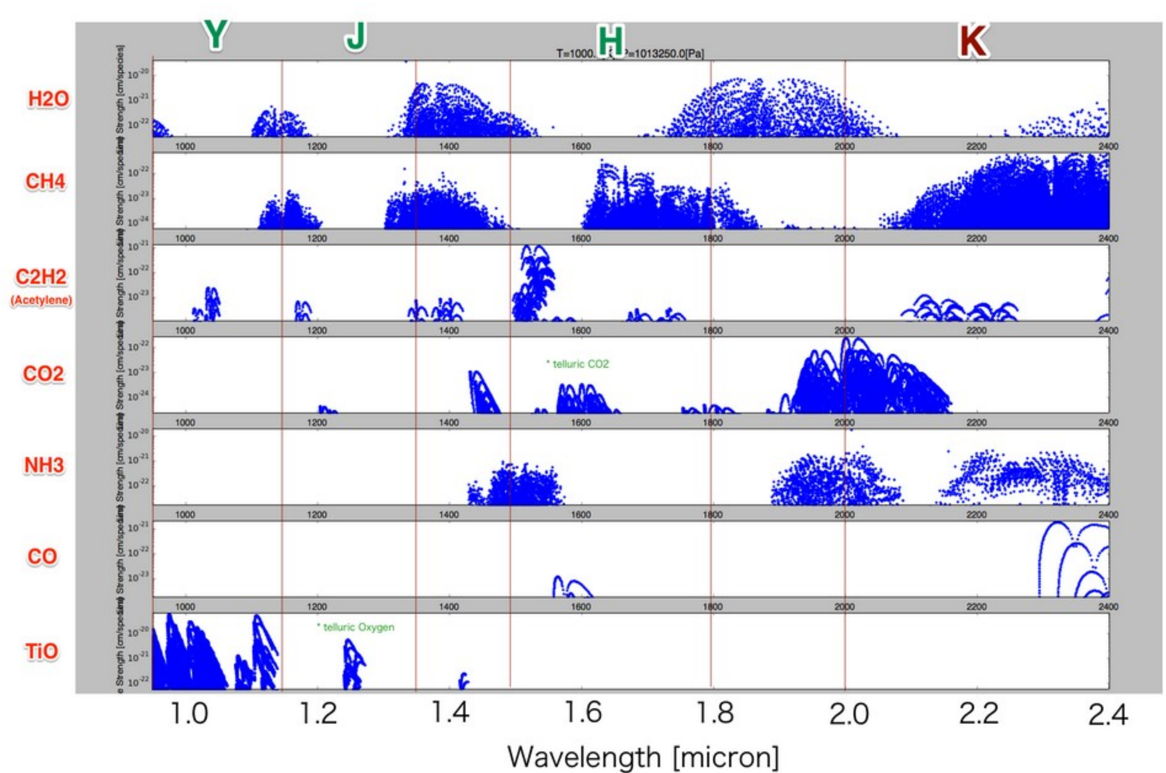
Exoplanet search using high spectral resolution signatures as differential signal

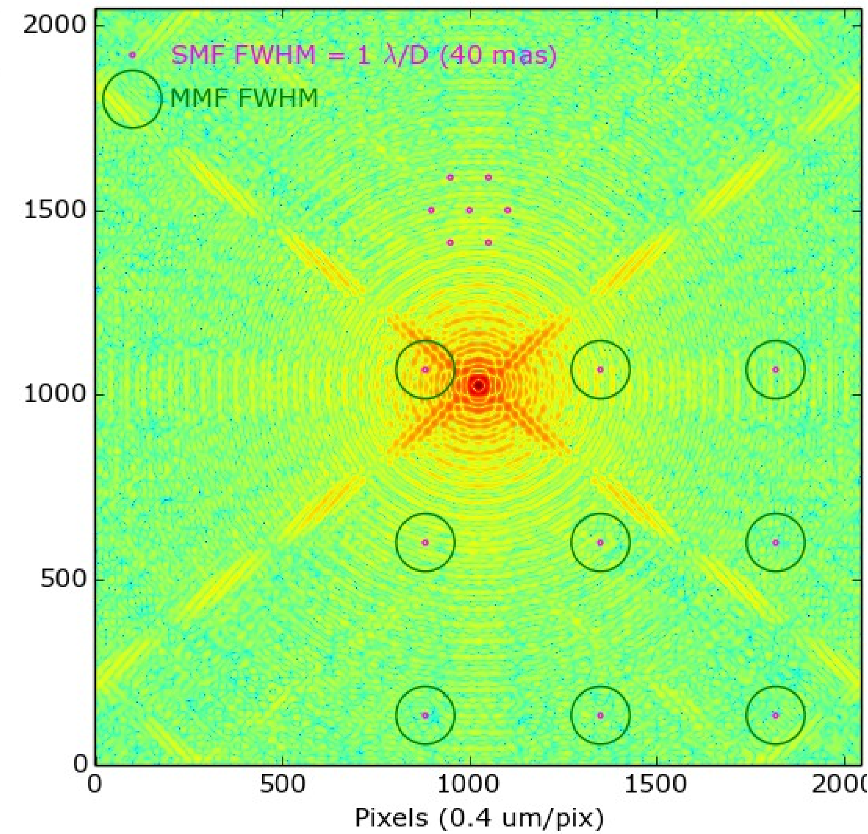
- H-band is most useful for self-luminous planets.
- J-band is less useful for the self-luminous one although it's very important for habitable planets.
- Y-band exhibits worse contrast in general, and it's just important for UV absorbers (TiO & VO) in hot planets (>~2000K).

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)

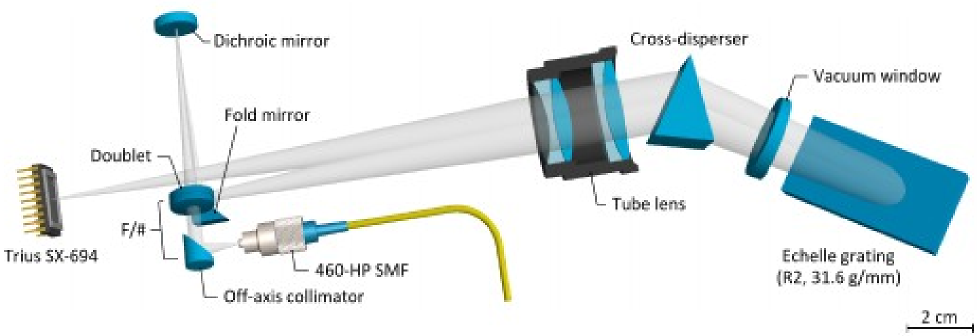


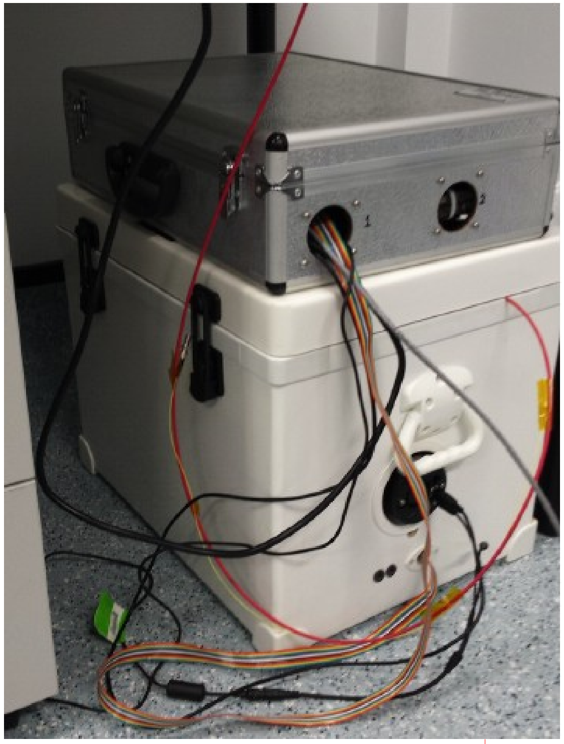


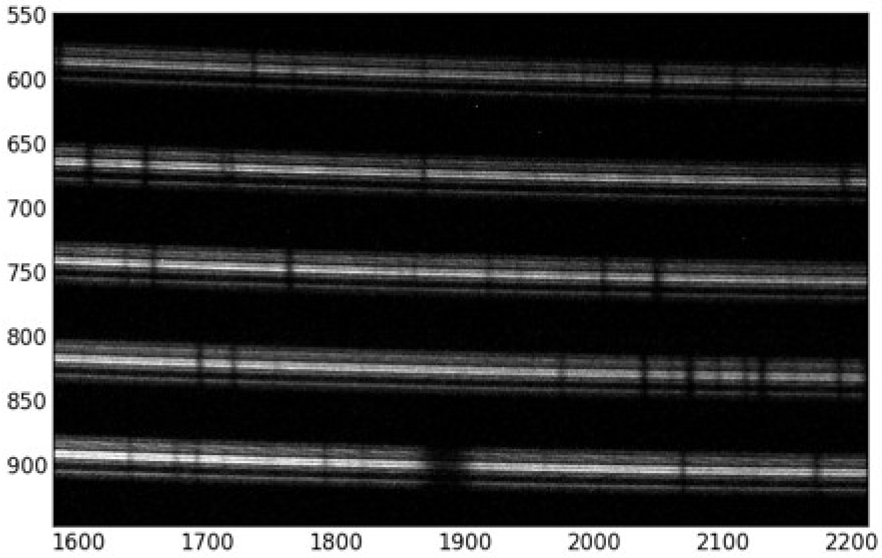
RHEA: Replicable High-resolution Exoplanet & Asteroseismology (M. Ireland & C. Shwab)

The main specifications of RHEA@Subaru are:

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







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

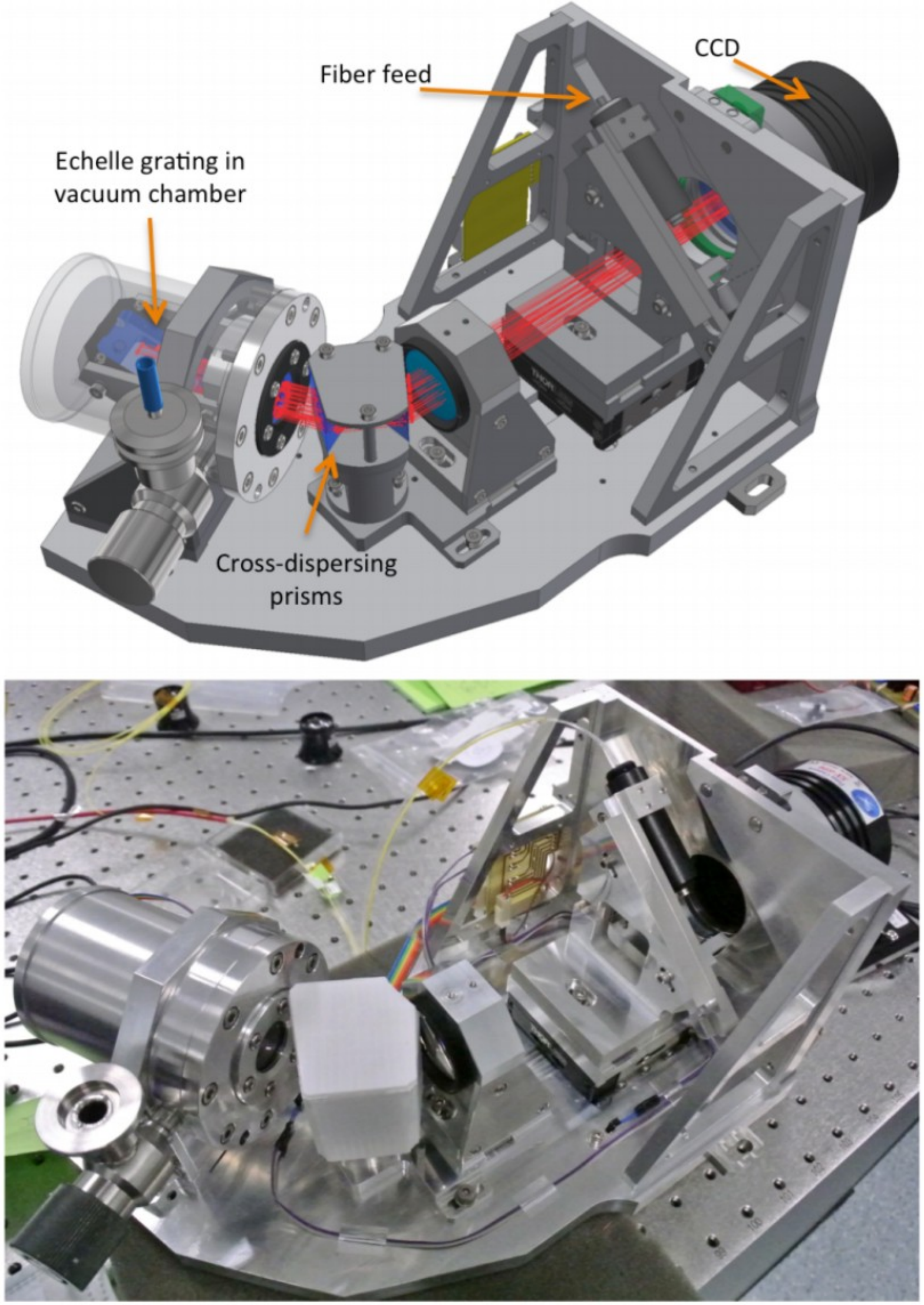
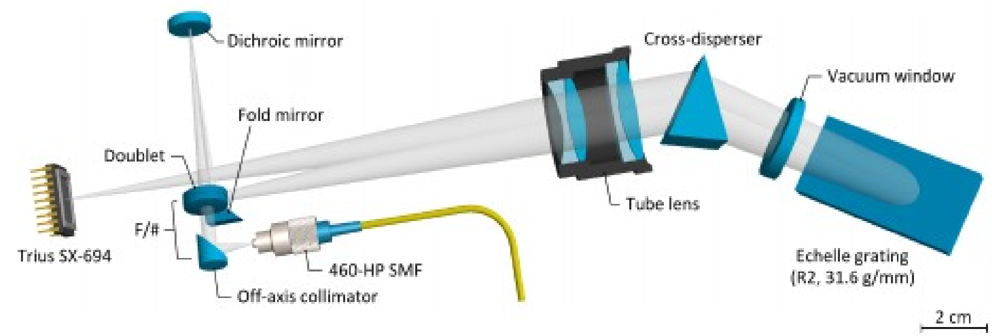


Figure 2. An image of the RHEA spectrograph deployed at Subaru Telescope (Feger *et al.* 2016; Rains *et al.* 2016). (Top) The 3D CAD rendering including the light rays (in red). (Bottom) An as-built image of the instrument. For a sense of scale the instrument is sitting on a standard breadboard with 25 mm hole spacing. Credit: T. Feger, Macquarie University.



Near-IR photonic spectrograph @ SCExAO

(Jovanovic et al.)

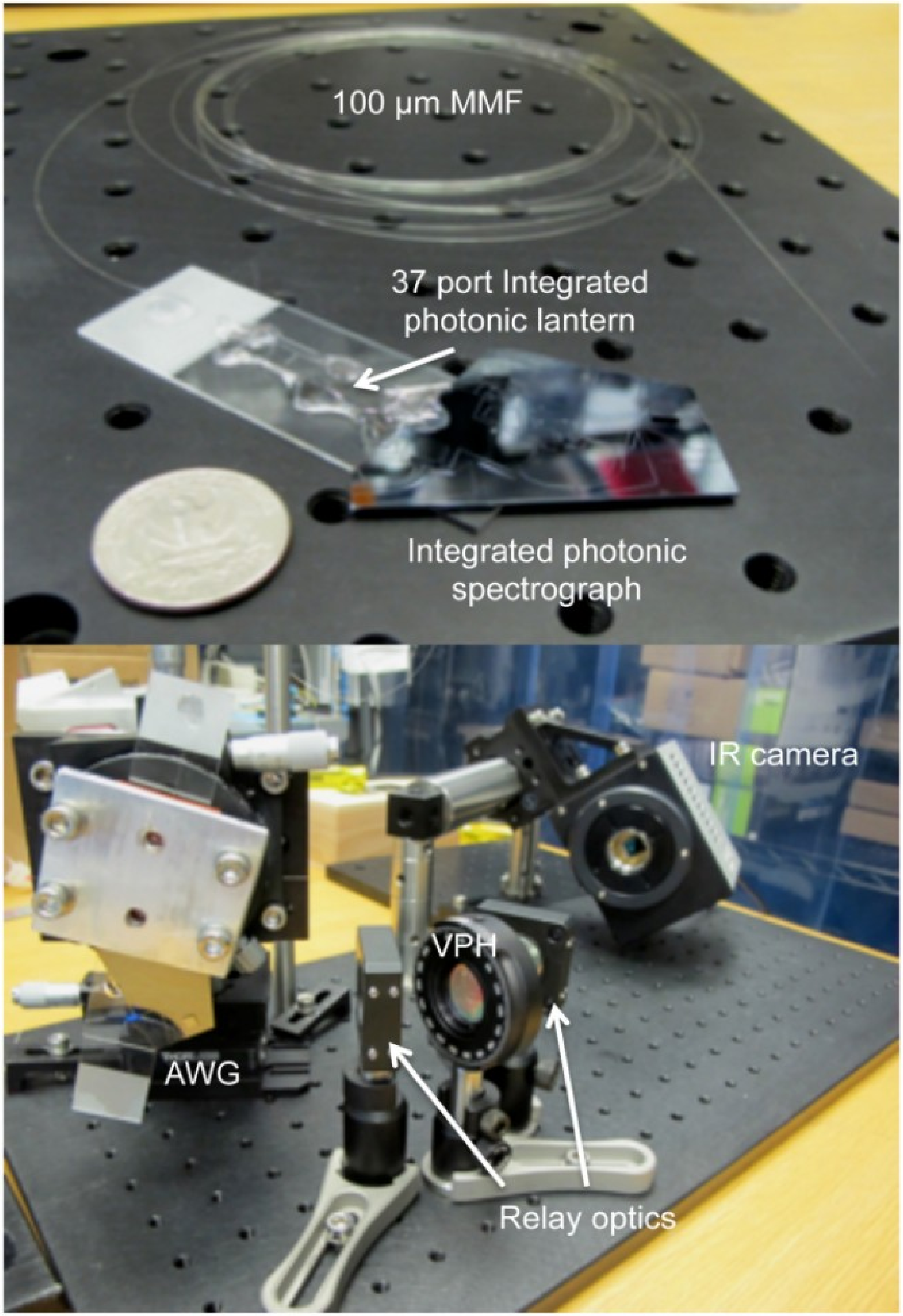


Figure 4. (Top) An AWG directly bonded to an integrated PL. (Bottom) AWG in a low resolution cross-dispersed setup. VPH -

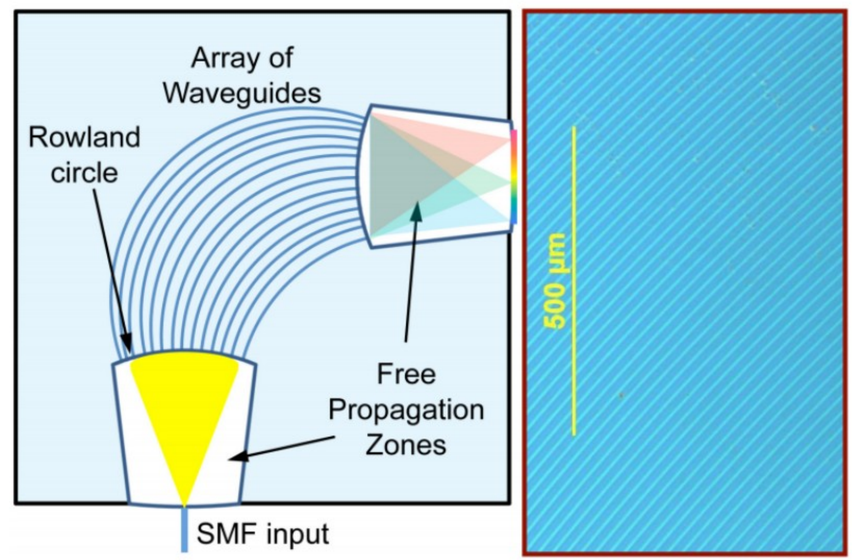


Figure 3. (Left) Schematic of the key components of an AWG. (Right) Microscope image of the a section of the array of waveguides for a typical AWG device.

SCExAO Path to TMT

Decouple SCExAO evolution from "woofer" stage

2 major upgraded of woofer stage:

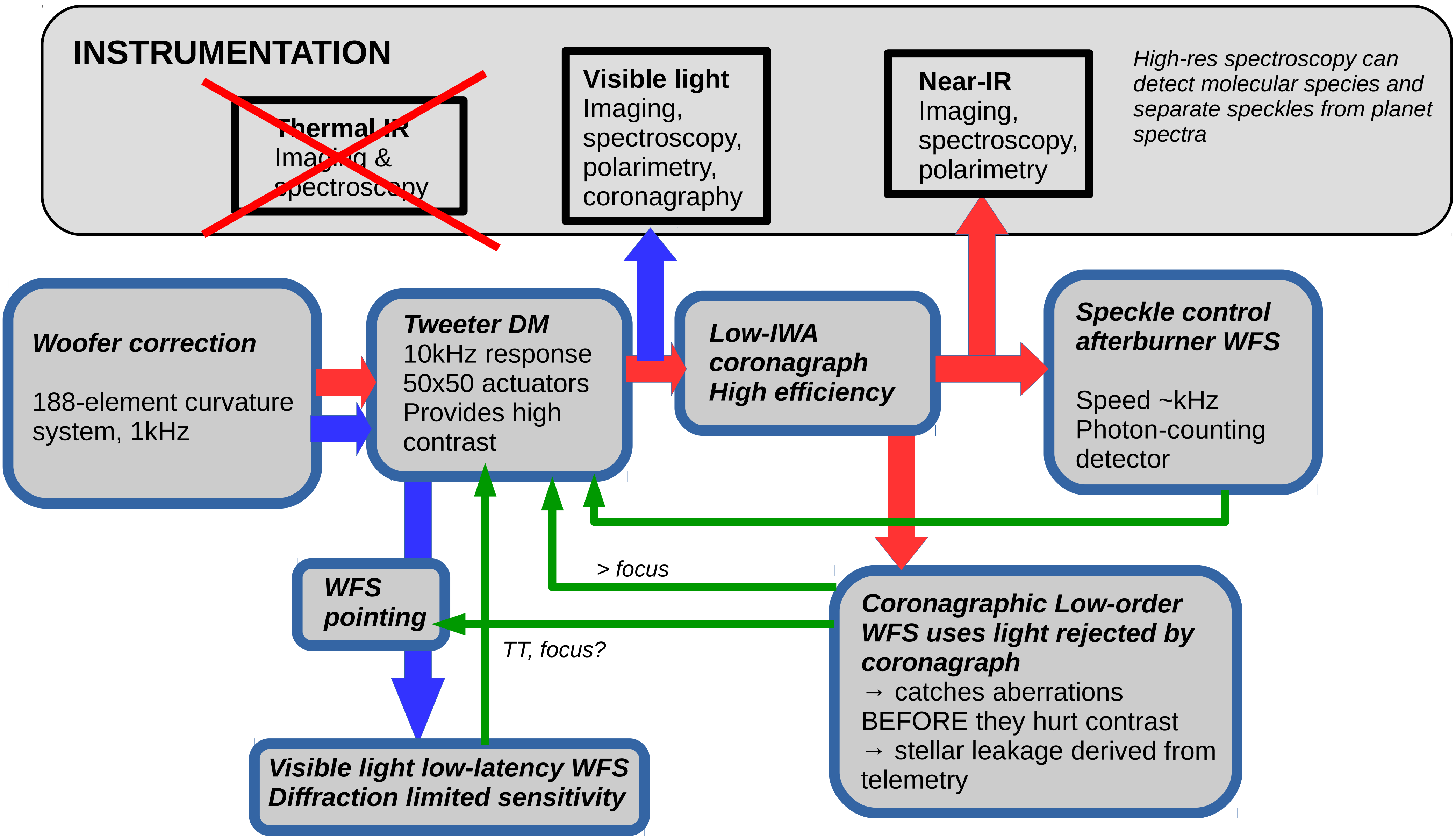
<u>2019: Replace AO188 by subscale woofer stage</u>

- Same actuator pitch and technology on Subaru as final 120x120 DM on TMT
- Near-IR capable pyramid WFS feeds woofer
- ADC, image rotator development
- Implement new thermal IR output port

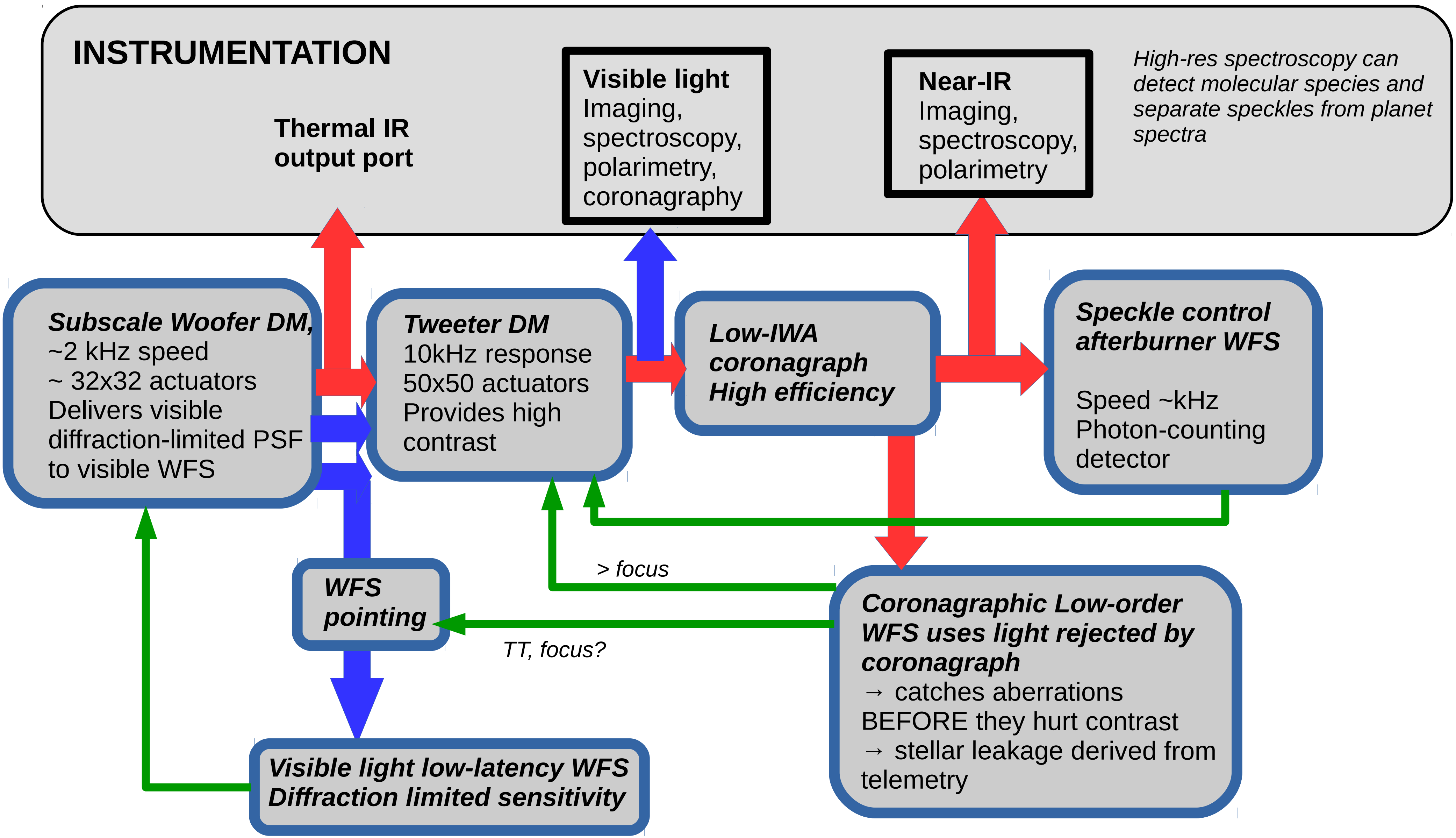
<u>2023: Upgrade woofer stage to TMT hardware</u>
Uses 120x120 DM

Provides ~2 yr of FULL system testing on Subaru prior to TMT deployment

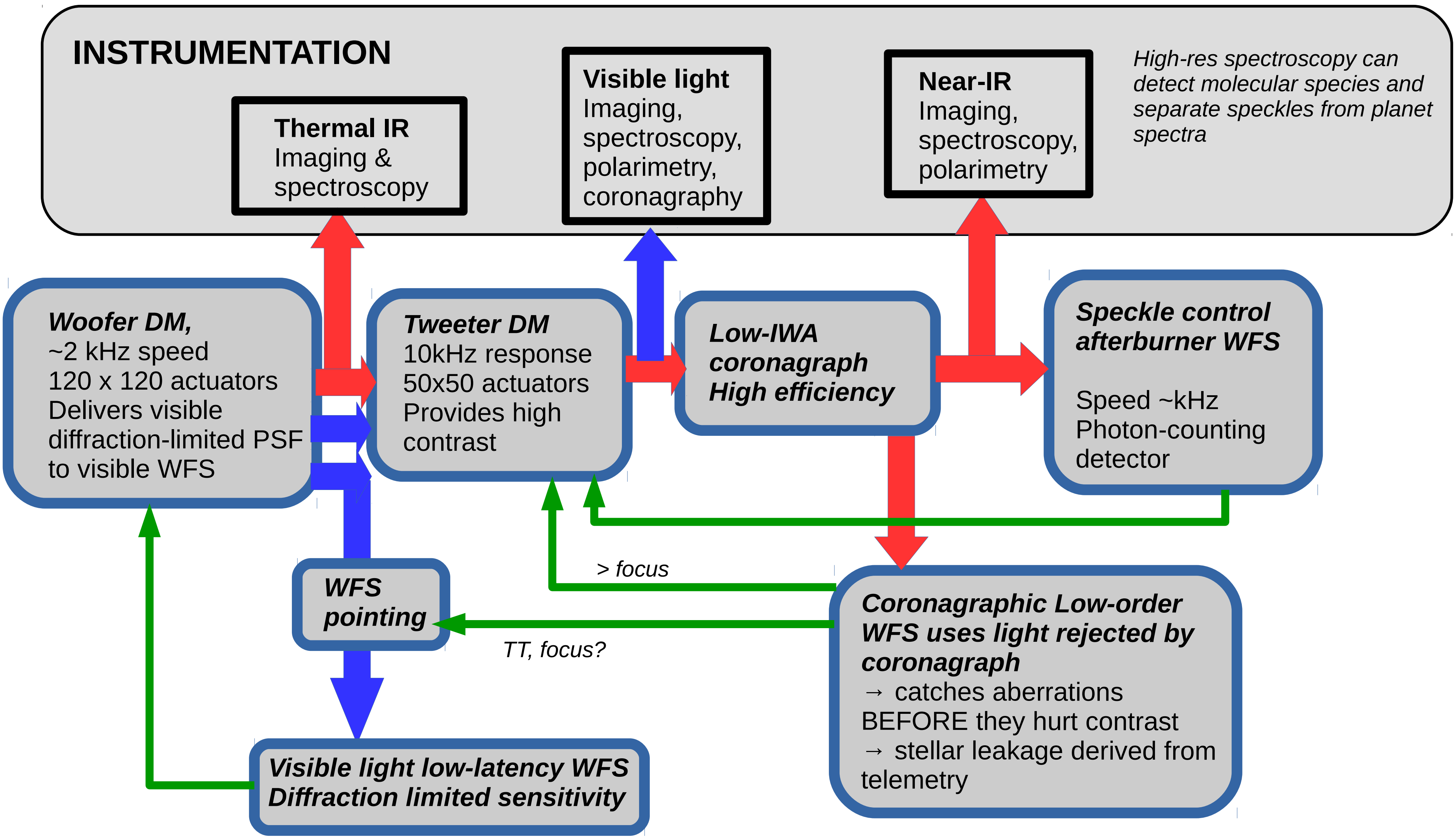
SCExAO @ Subaru (2017)



SCExAO @ Subaru (2019)



SCExAO @ Subaru 2023



Instrument modules

Existing modules (MKIDs, CHARIS, IRD) could be used as-is on TMT system

… but can be greatly improved

Visible light modules (not core science) – come along if ready, but <u>do not drive design</u>
May not receive light during prime science (science-based)
Note: there is value in characterizing star and exozodi dust in vis light

Relationship to 2nd gen instrument

Why consider deploying a precursor ?

High impact science at first light: habitable planets reflected light spectroscopy around the nearest stars

Focusing on a single goal, small number of targets to meet schedule & schedule

Workforce development – attract junior researchers to participate in instrument development AND science on 8m telescope to then drive TMT instrument building/operation/science

Risk mitigation for 2nd generation instrument

Learn what works… what needs fixing (instrument/algorithms AND telescope)

Opens up opportunities for a more incremental approach:

Test subsystems / components on precursor

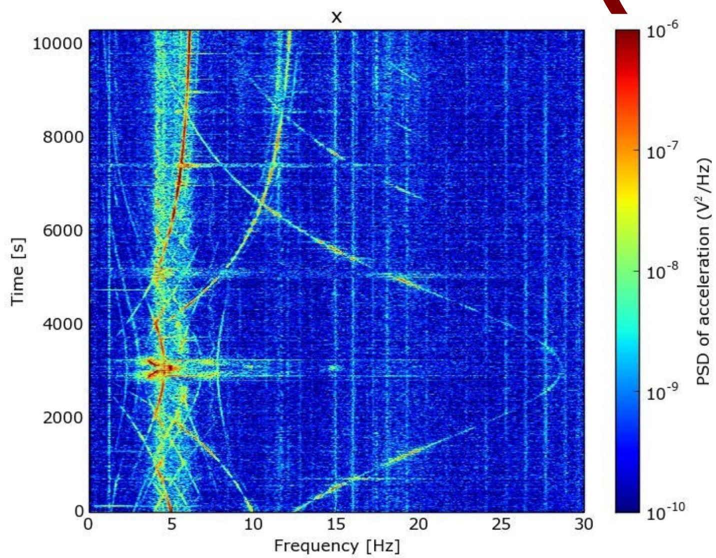
Develop and validate ON SKY : hardware, algorithms

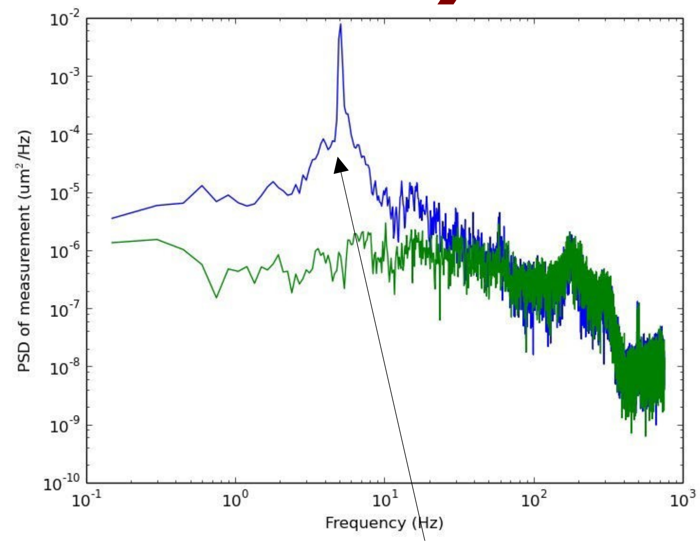
TMT precursor starts NOW on 8m telescope(s) (SCExAO)

Extensive testing on 8m telescope(s) + modeling for jump to larger aperture will mitigate risks and avoid lengthy engineering/learning on TMT.

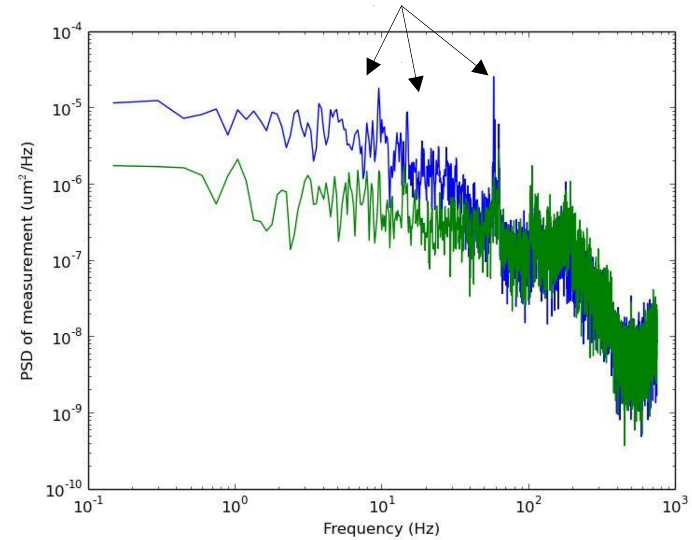
Fully characterized instruments + algorithms (& yrs of experience) would be deployed on TMT

Lessons learned: Telescope does matter (LWE, vibrations)





Corrected vibrations



- The PSF stability is disturbed by telescope vibrations
  - Induced by the telescope motions and the pointing loops
  - Particularly strong during the transit of the target
- A Linear Quadratic Gaussian (LQG) contoller, based on a Kalman filter, is used to correct the vibrations
- An identification loop finds the vibration frequencies in real-time (similar to SPHERE)