Exoplanet Instrumentation with an ASM

***Olivier Guyon*[1,2,3,4]*, Thayne Currie*[1]**
(1) Subaru Telescope, National Astronomical Observatory of Japan
(2) National Institutes for Natural Sciences (NINS) Astrobiology Center
(3) University of Arizona
(4) JAXA

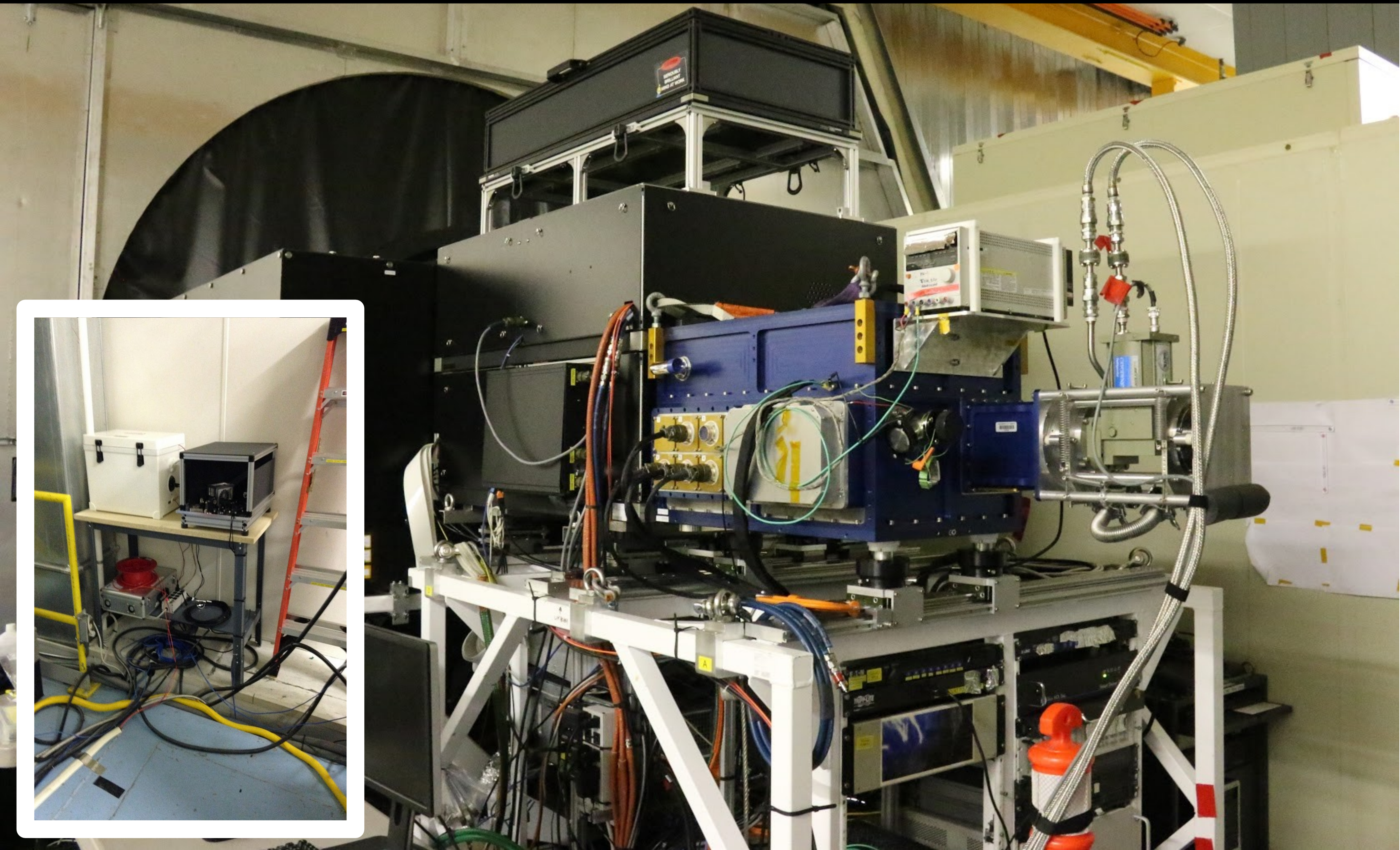
SCExAO team + instrument teams

SCExAO Subaru Coronagraphic Extreme Adaptive Optics

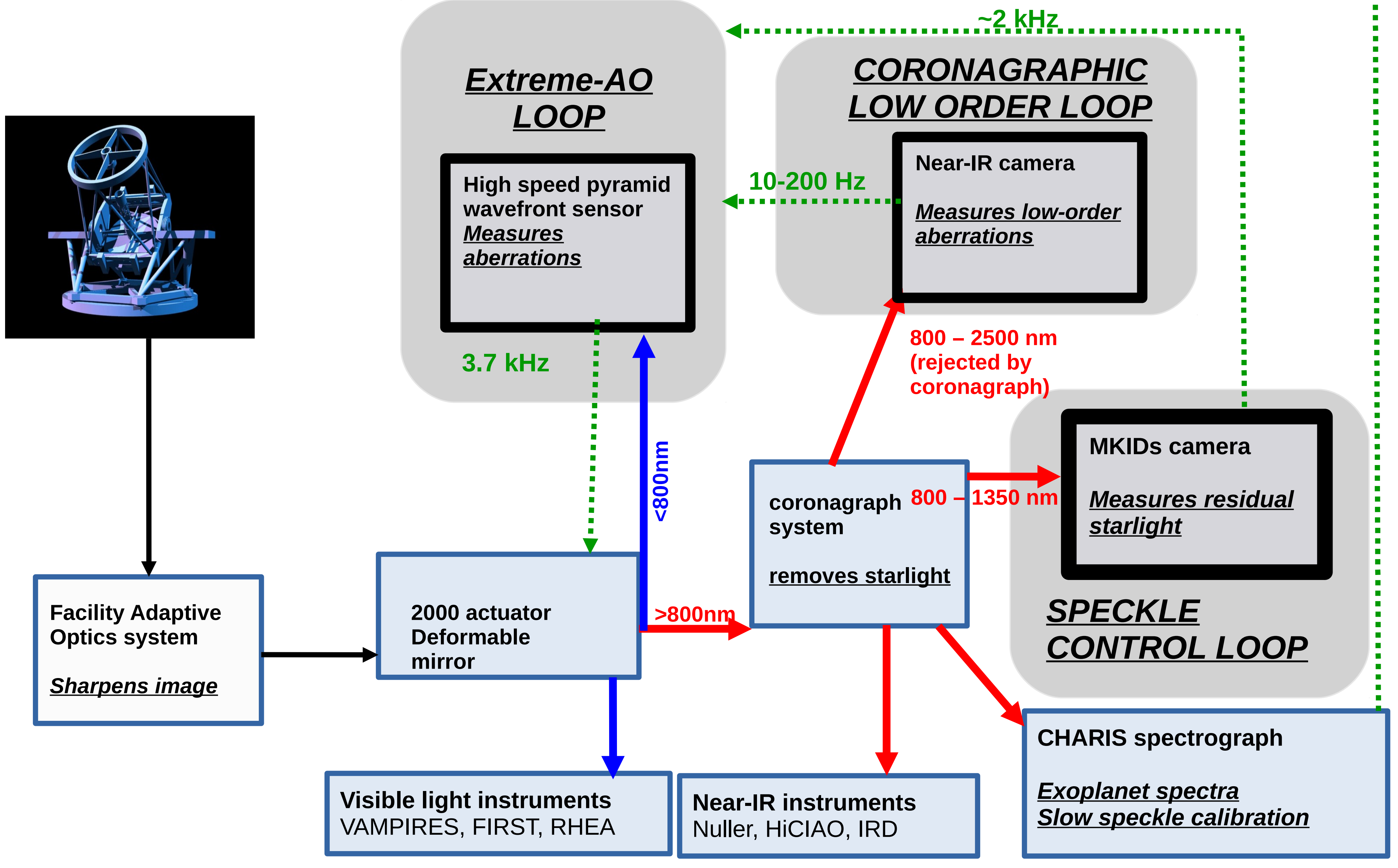
Jun 15, NAOJ

SCExAO

Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics



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 run in July 2016
- **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**

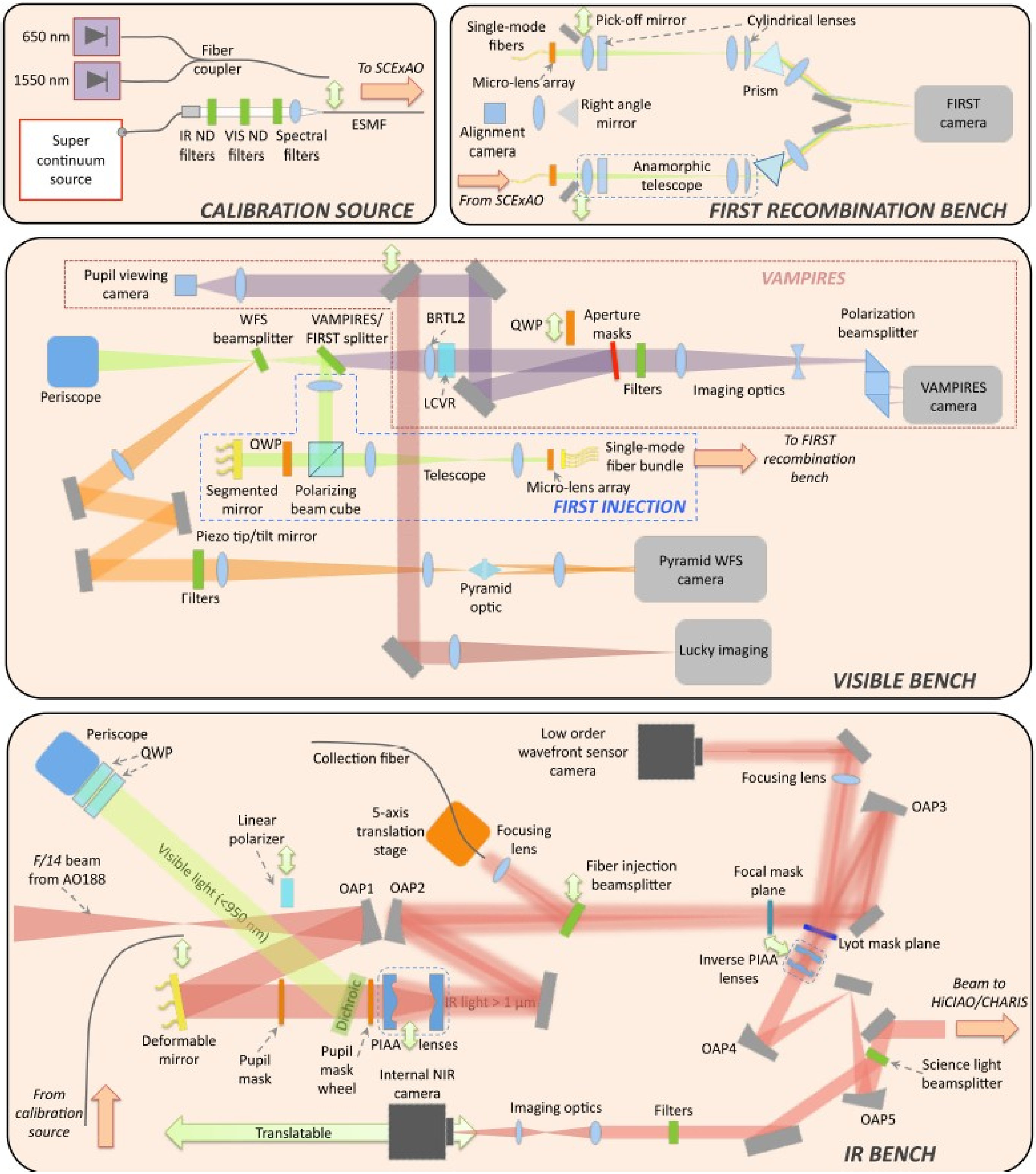
Wavefront sensing:

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

2k MEMS DM

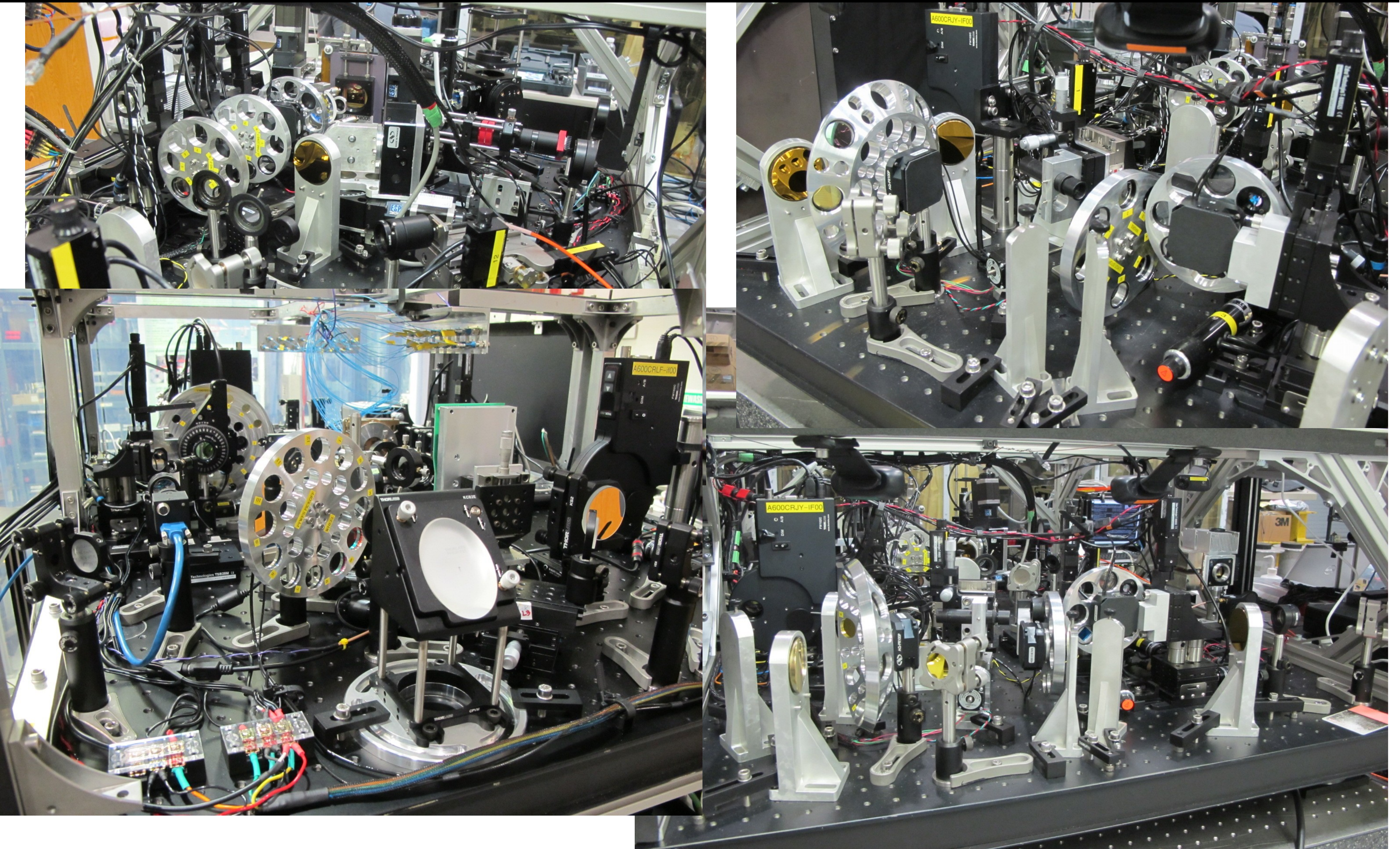
Numerous **coronagraphs** – PIAA, Vector Vortex, 4QPM, 8OPM, shaped pupil (IR)

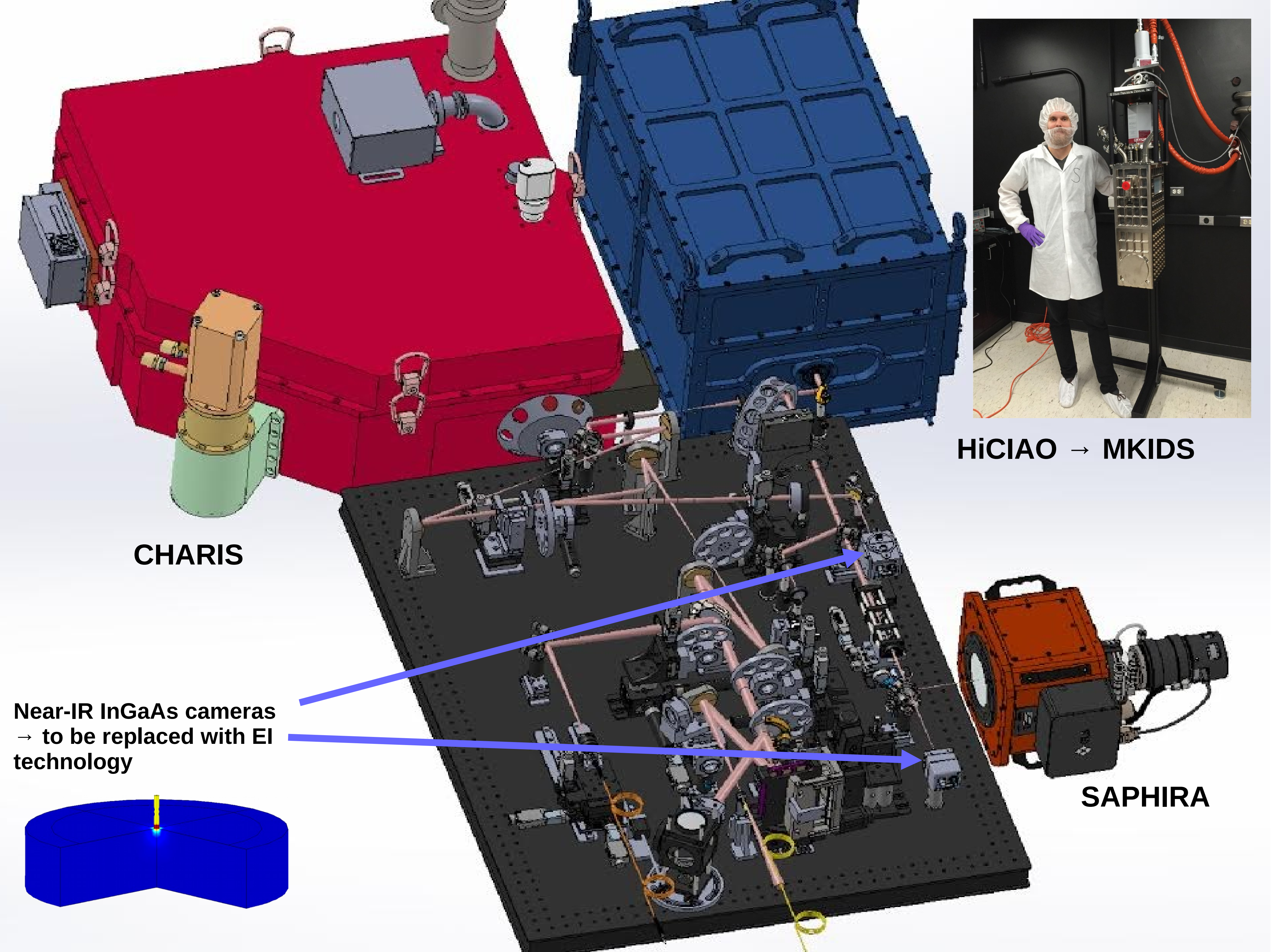
Broadband diffraction limited internal cal. Source + phase turbulence simulator



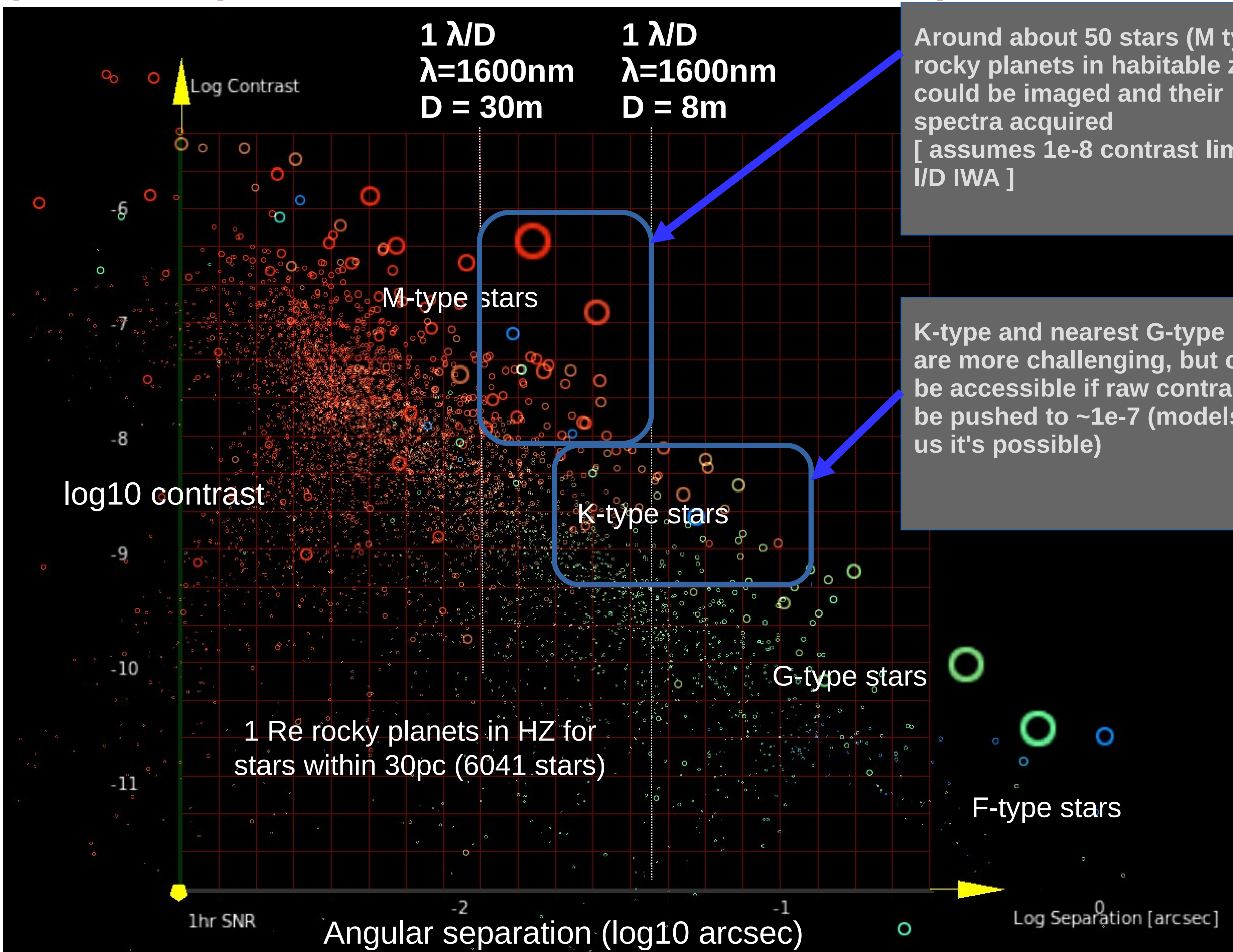
SCExAO

Subaru Coronagraphic Extreme Adaptive Optics




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

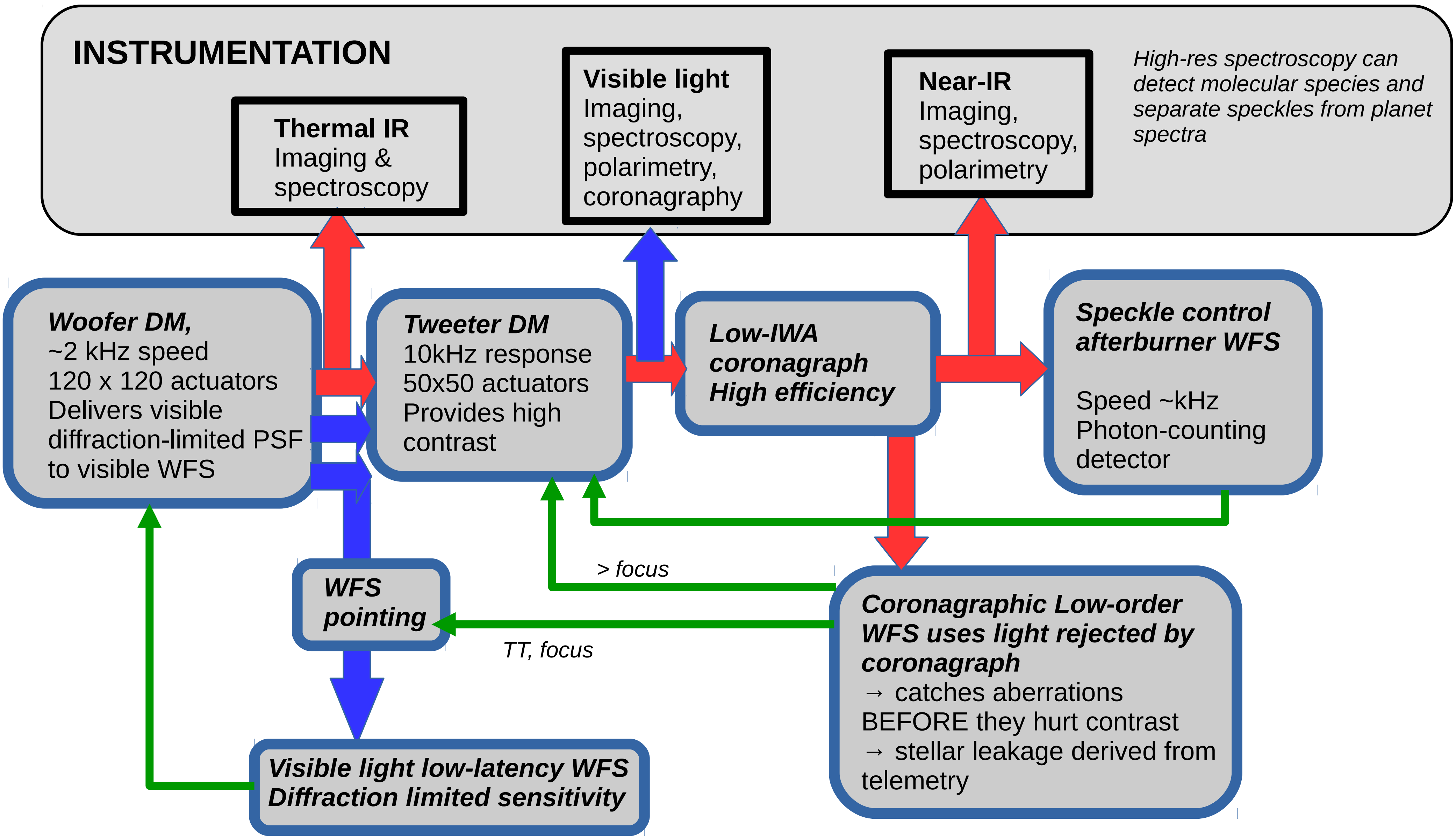
Where is SCExAO heading ?
Spectroscopic characterization of Earth-sized planets with TMT



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 system architecture with instrumentation



ASM & Exoplanet Instrumentation

[1] ASM can be step #1 of Multi-step correction for ExAO
Very helpful to have ASM, but not essential (internal DM is nearly as good)

[2] ASM enables long wavelength Exoplanet imaging & spectroscopy
ASM is essential to long wavelength sensitivity
But window of opportunity will close in TMT era: difficult to make up for aperture size

[3] Multi-object RV
FOV is likely too small to be competitive, except for clusters

[4] Astrometry
Dense field + sharp PSF
Multi-wavelength concept

[1] ASM as step #1 of multi-DM ExAO system

Extreme-AO systems use multiple correction steps to achieve high contrast:

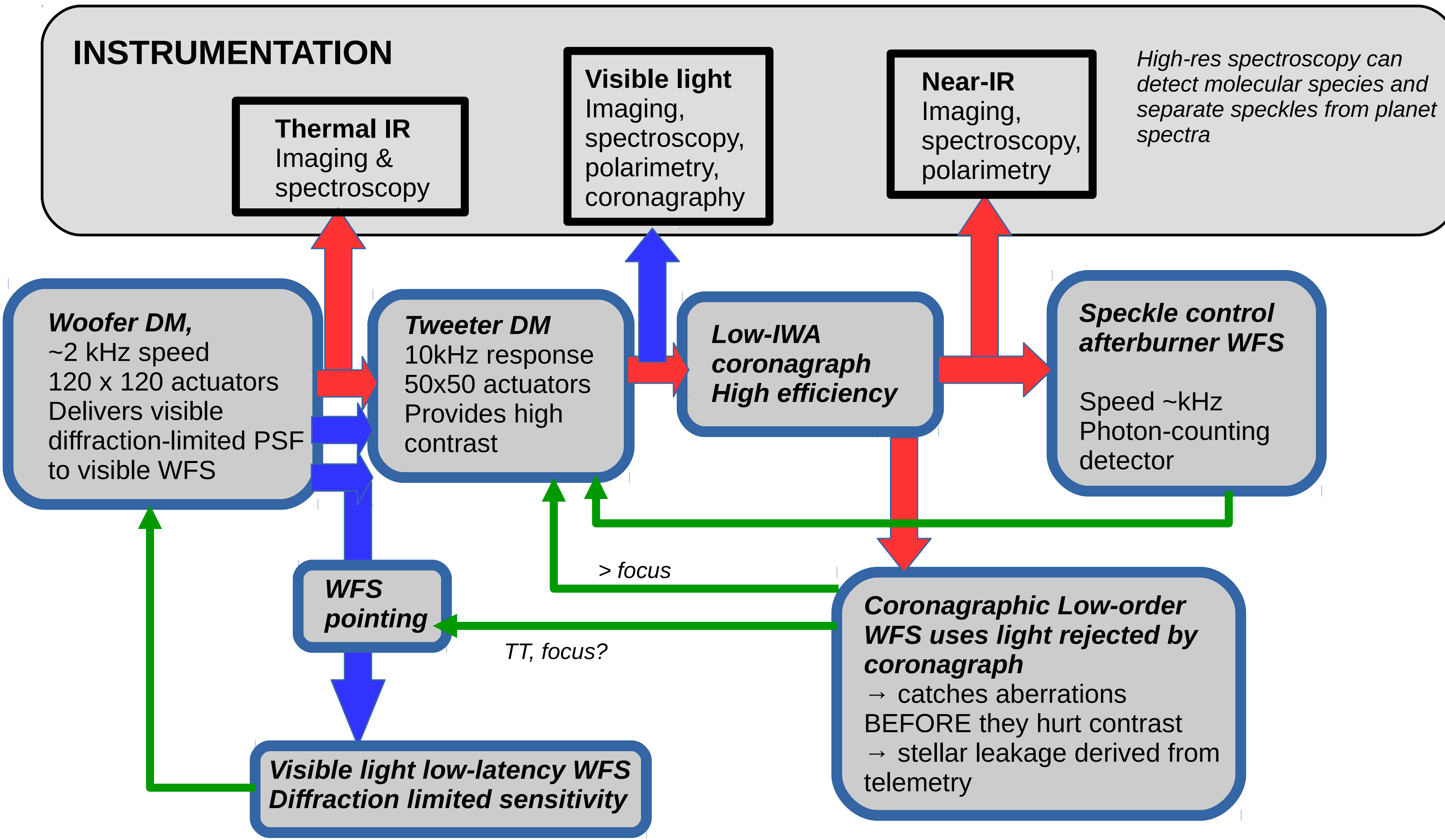
Step #1: **Achieve diffraction limit in wavefront sensor** (usually visible light)
→ WFS runs in diffraction-limit sensitivity regime
→ $(D/r0)^2$ WFS sensitivity gain

Step #2: **High contrast speckle control** running in linear regime

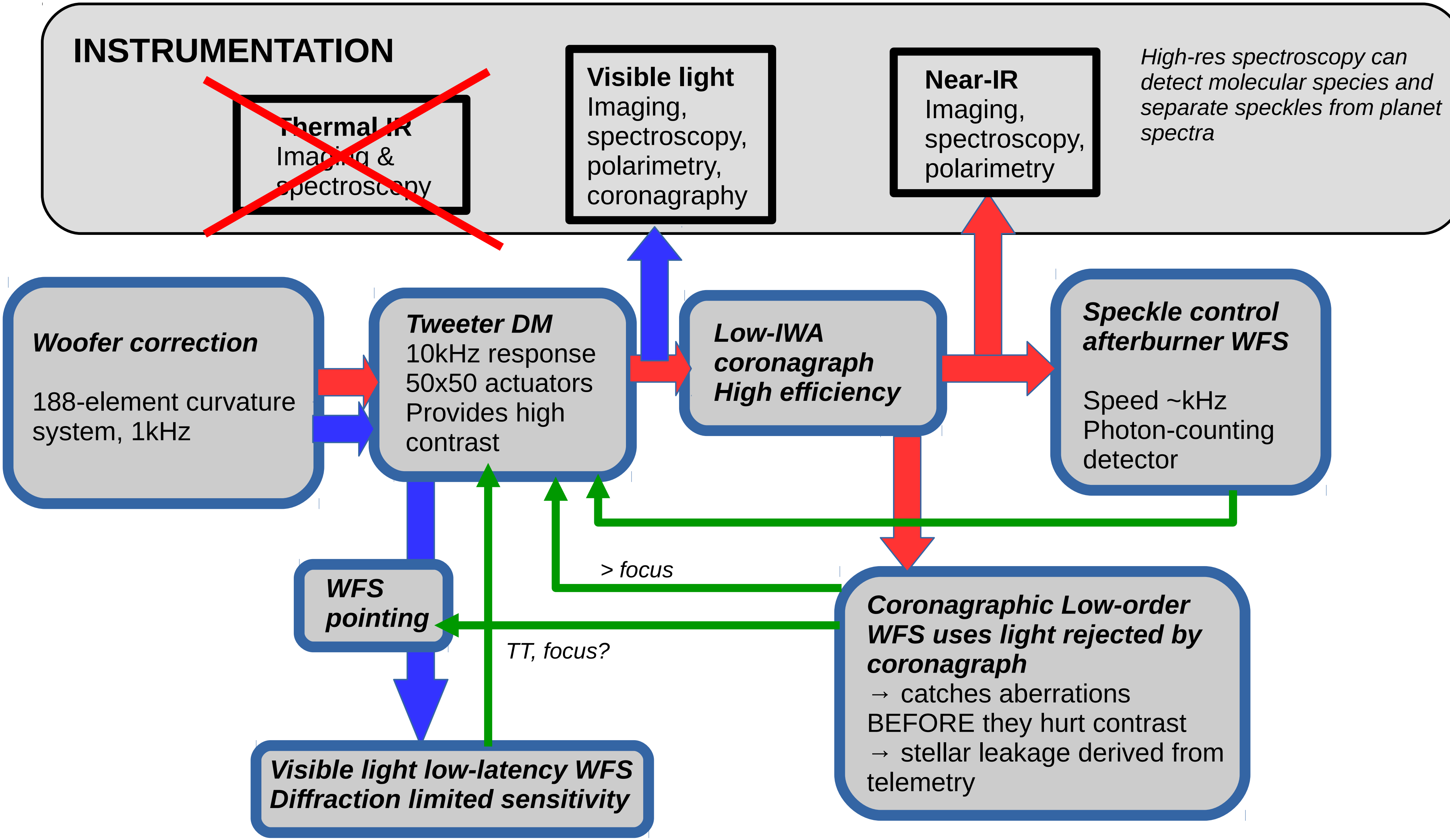
Step #1 may require woofer + tweeter architecture

<u>**ASM is well-suited for step #1 correction, alone or with a tweeter (MEMS)**</u>

TMT system architecture with instrumentation



SCExAO @ Subaru (2017)



[2] Thermal imaging of exoplanets with ASM

3-10um imaging of exoplanet is largely background-limited
With ASM, only 2 (Cass) or 3 (Nas) reflections

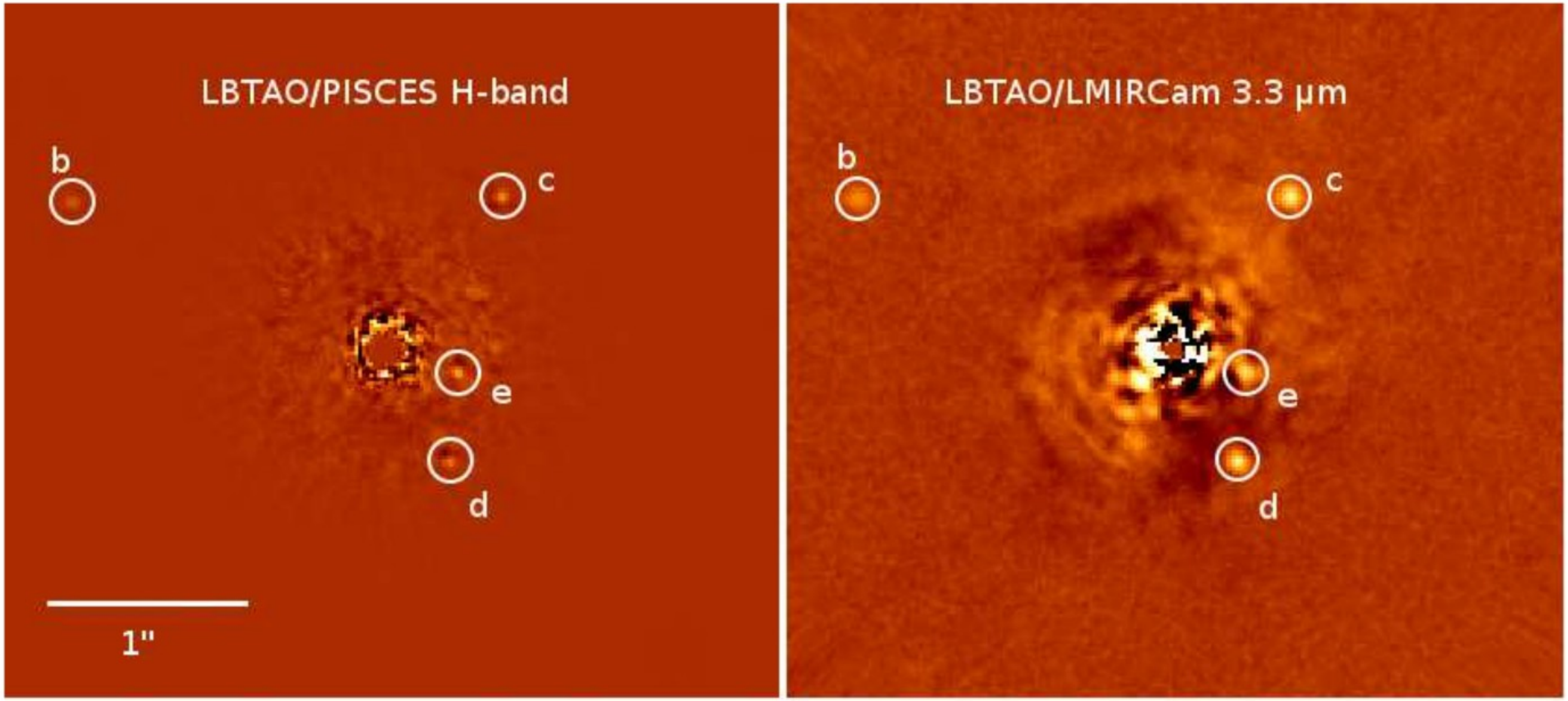
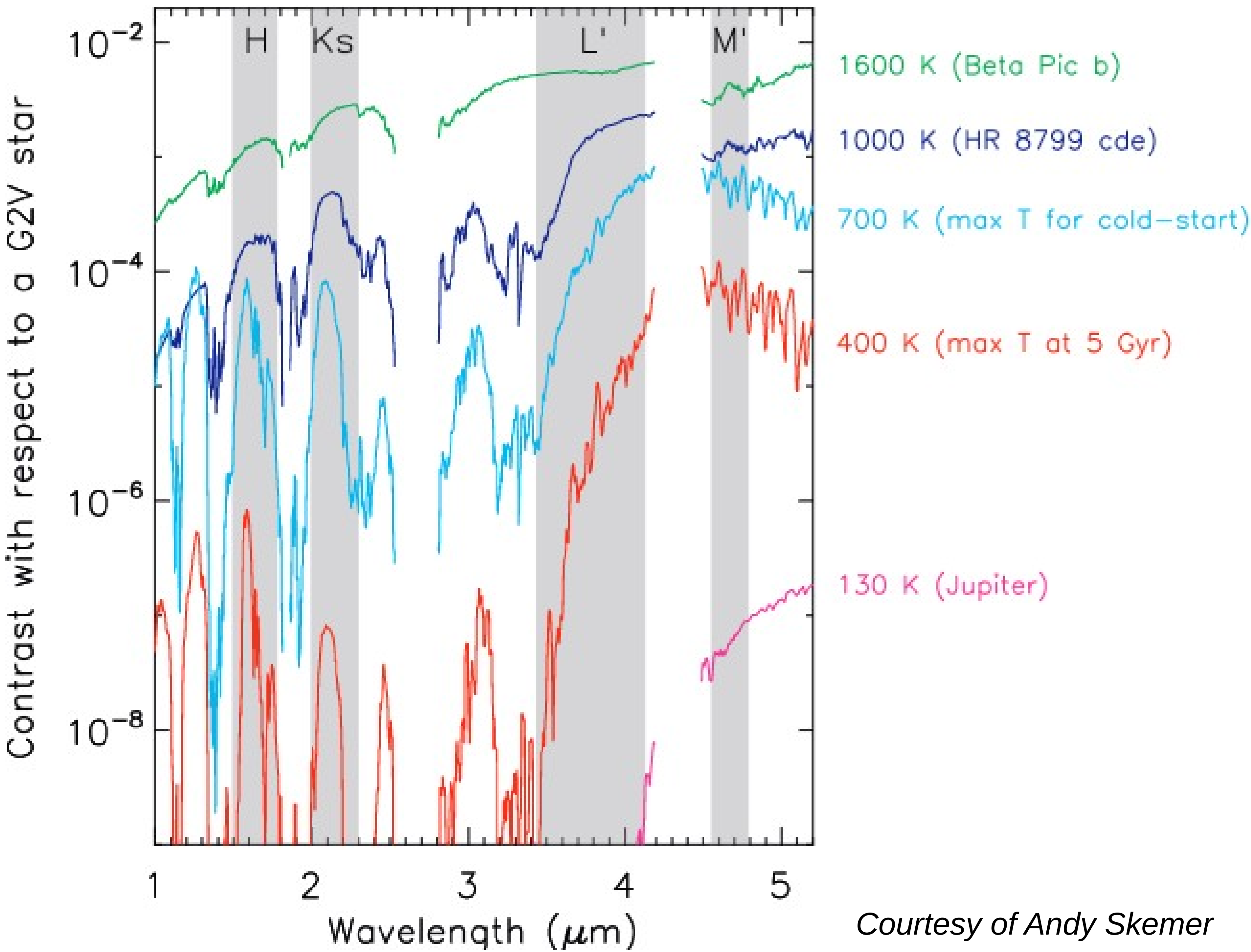


Fig. 1.— LBT First Light AO images of the HR 8799 planetary system at H-band and 3.3μm. These images comprise the first detection of HR 8799 e at either wavelength, and the first unambiguous detections of HR 8799 b and d at 3.3μm.

Skemer et al. 2012



Courtesy of Andy Skemer

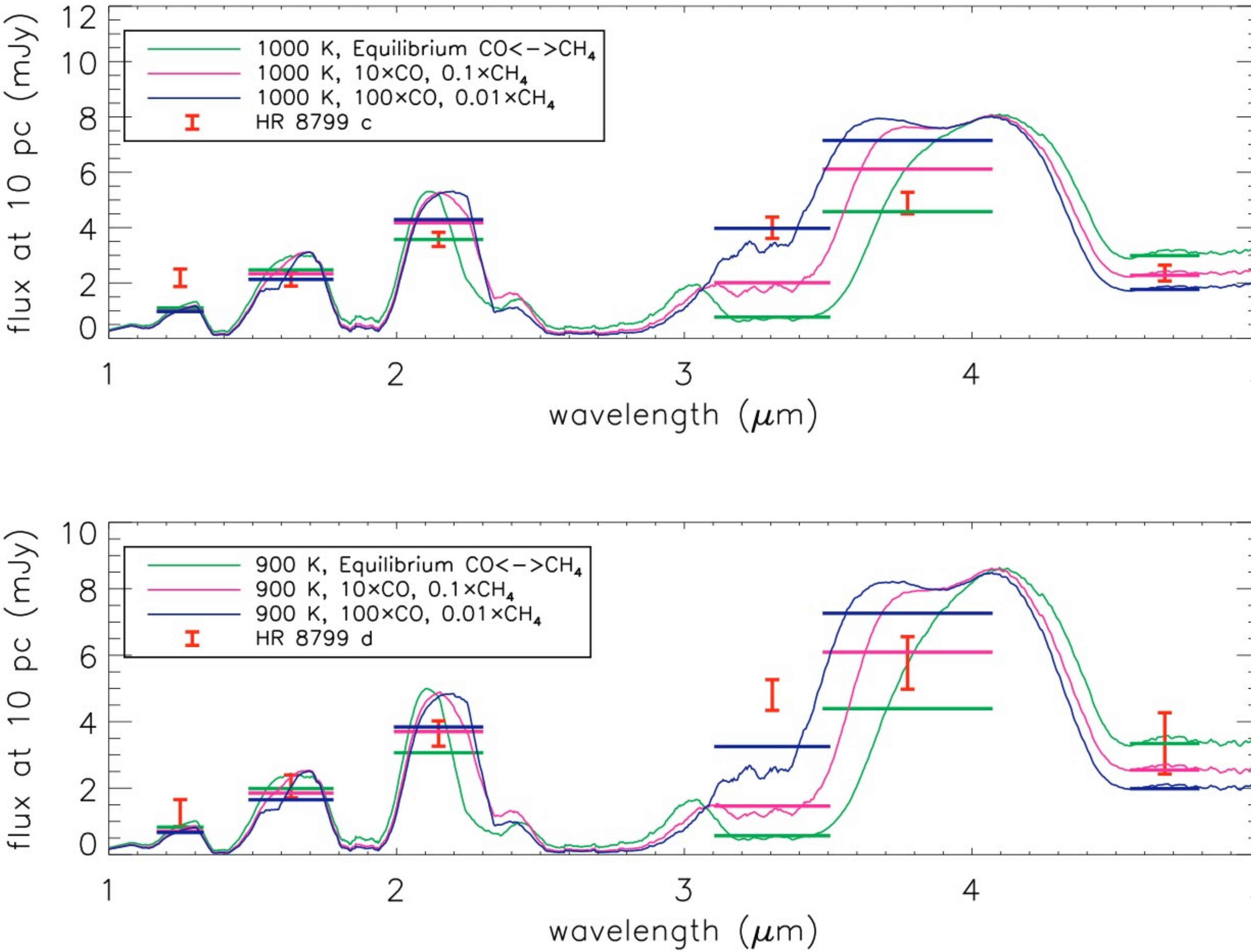


Fig. 8.— Same as Figure 6 (top) but for HR 8799 c and d. As was found for HR 8799 b, our non-equilibrium chemistry models are unable to fit the 3.3μm-L' colors of HR 8799 c and d.

[3] Wide field multi-object Radial Velocity

High precision RV has so far been limited to single objects

Multi-object RV could be done in open clusters with a few arcmin FOV to probe exoplanet population around young stars

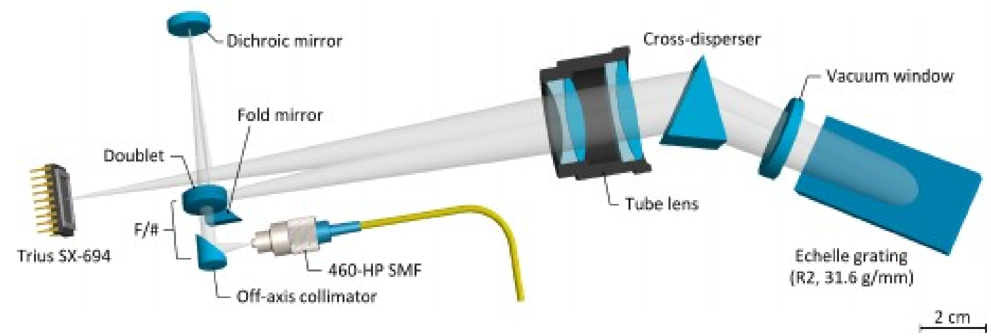
Large aperture is required for sensitivity
Simultaneous multi-object RV is mitigates telluric absorpion “noise” (common to all sources in field)

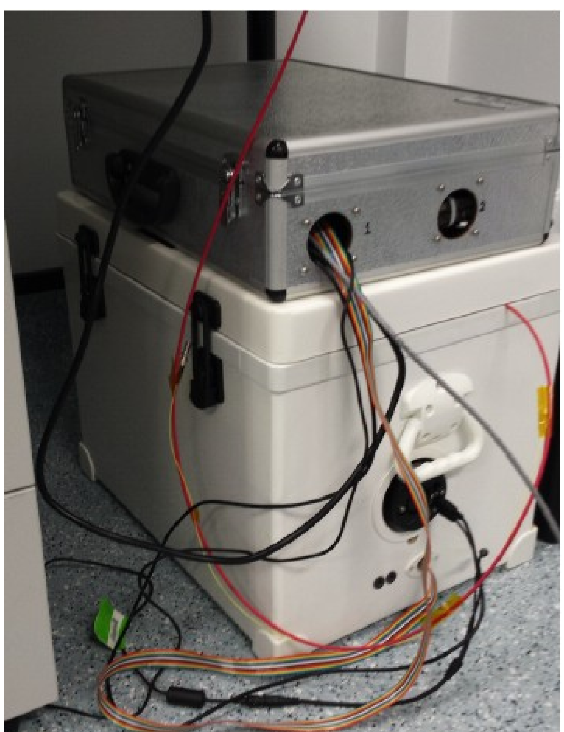
AO correction is key :
AO fiber-fed (single mode) spectrographs can be very compact and stable

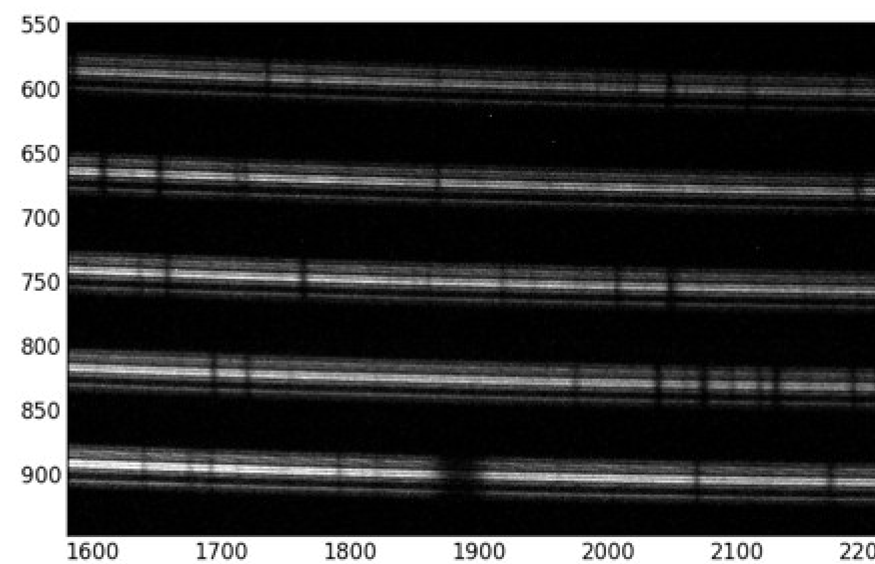
RHEA: Replicable High-resolution Exoplanet & Asteroseismology (M. Ireland & C. Shwab)

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

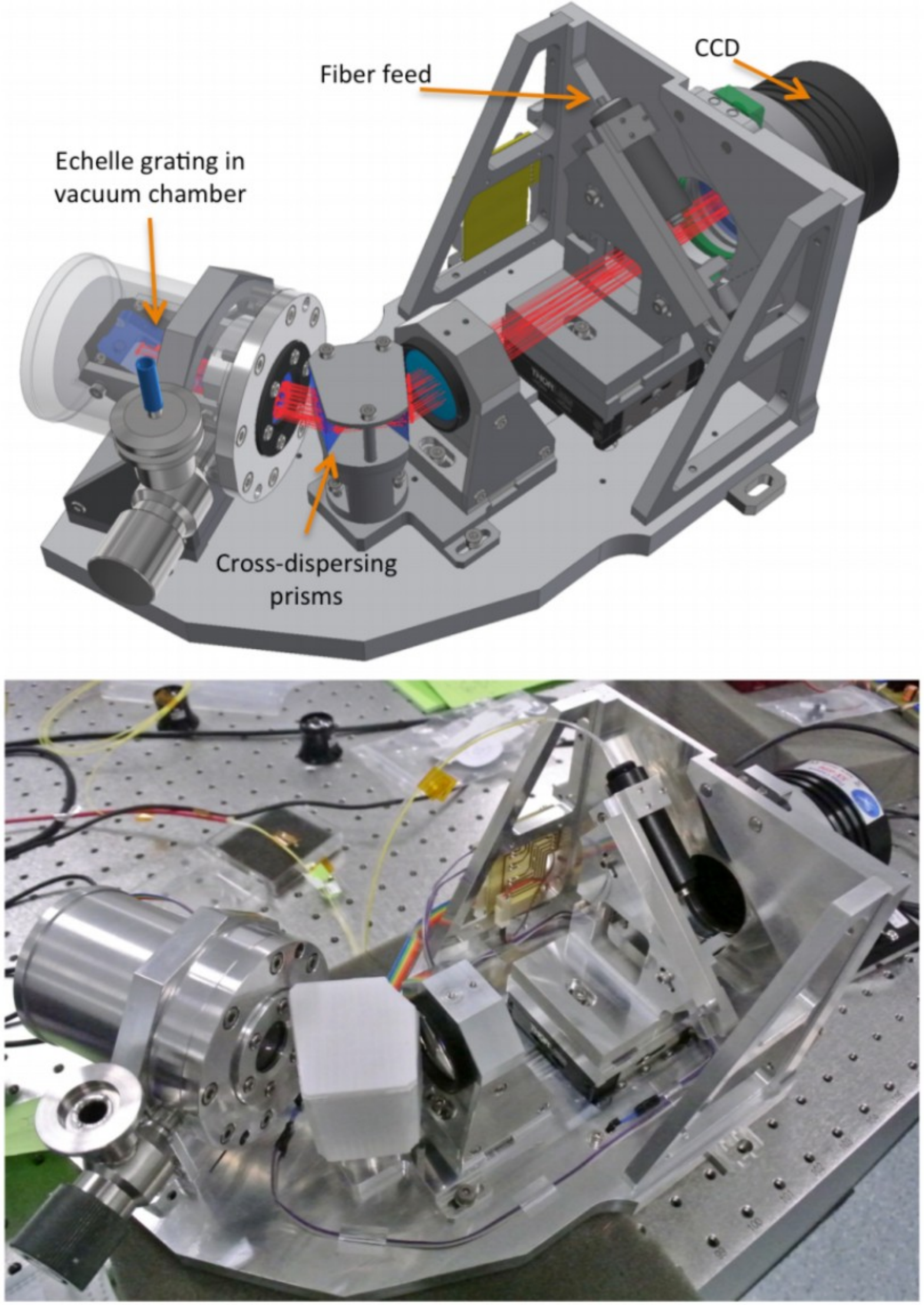
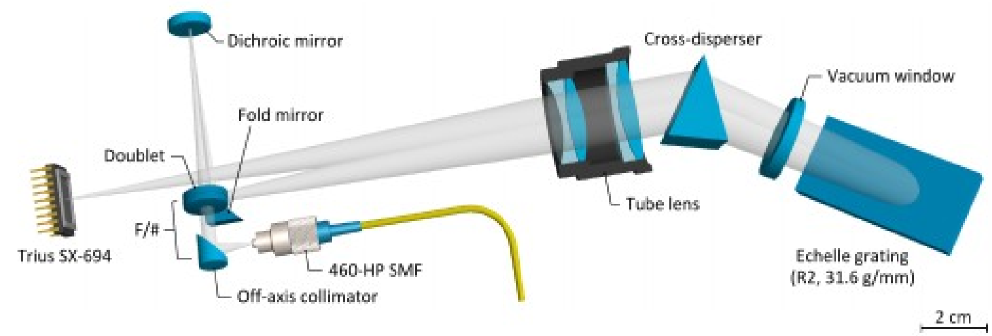


Figure 2. An image of the RHEA spectrograph deployed at Subaru Telescope (Feger *et al.* 2016; Rains *et al.* 2016). (Top) The 3D CAD rendering including the light rays (in red). (Bottom) An as-built image of the instrument. For a sense of scale the instrument is sitting on a standard breadboard with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



Near-IR photonic spectrograph @ SCExAO

(Jovanovic et al.)

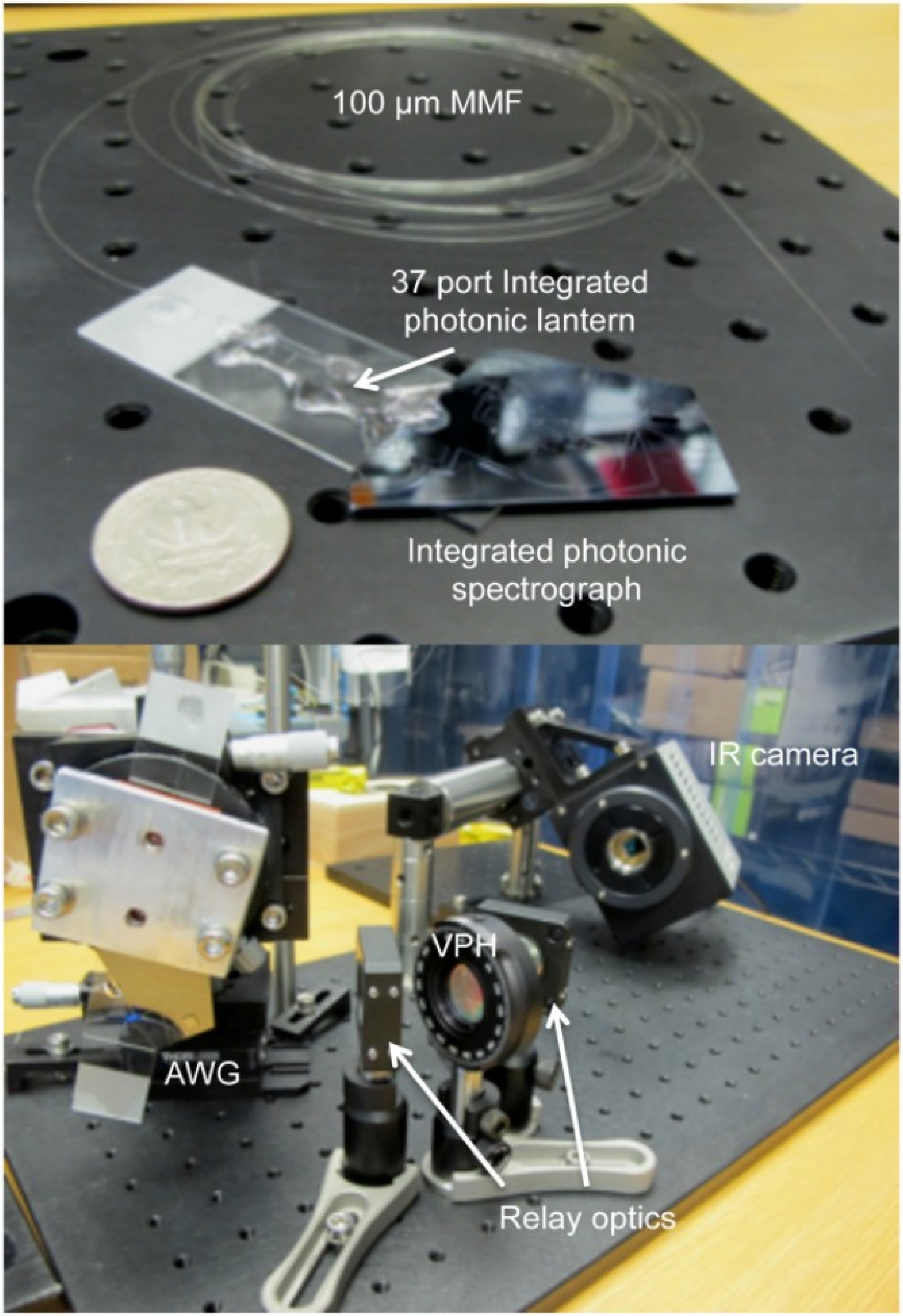


Figure 4. (Top) An AWG directly bonded to an integrated PL. (Bottom) AWG in a low resolution cross-dispersed setup. VPH -

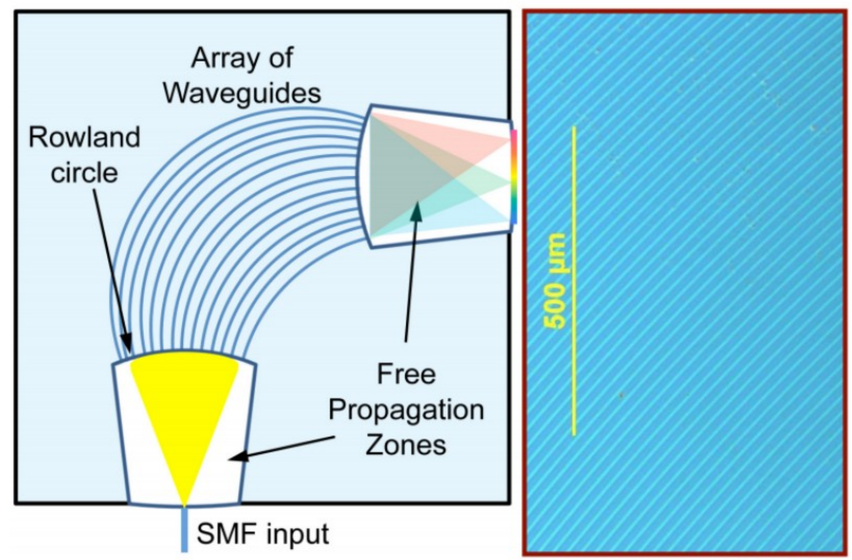


Figure 3. (Left) Schematic of the key components of an AWG. (Right) Microscope image of the a section of the array of waveguides for a typical AWG device.

[4] Astrometry

Astrometry detects the gravitational pull of exoplanets on their host stars
CHALLENGE: Earth analog is ~1 uas signal around nearby star

→ Need sharp PSF, collecting area (photons) and **exquisite calibration**

Noise sources:

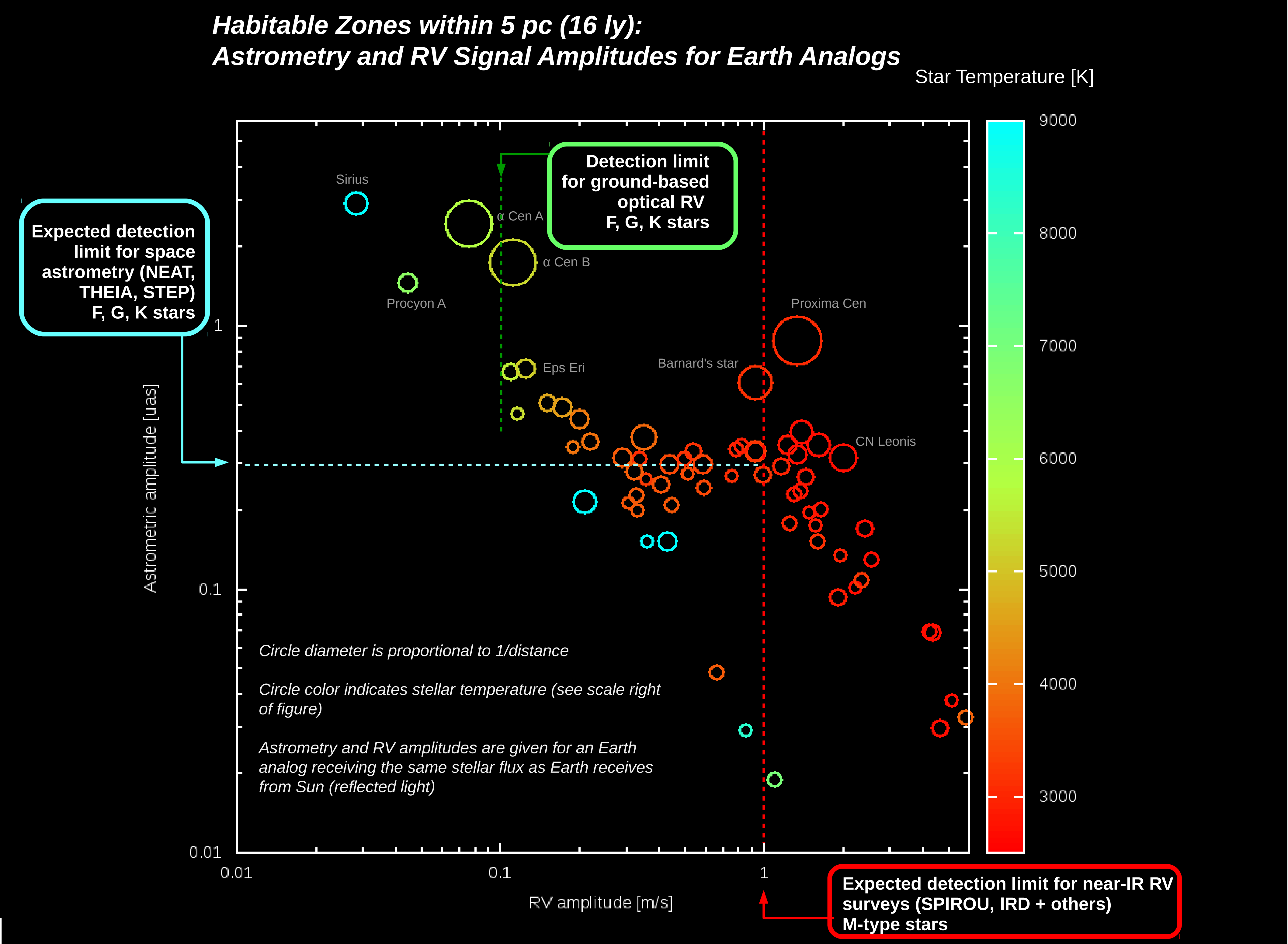
Telescope optics induce distortions

ASM allows 2-mirror system, one of which (primary) is irrelevant
ASM position knowledge predicts telescope distortion

Atmospheric turbulence creates distortions

Very large effect, but has very specific and known chromaticity
→ multi-wavelength observation (simultaneous) + time averaging

Both noise sources create a smooth distortion map, which can be measured accurately with a dense starfield image



Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
Sirius
α Cen A
α Cen B
Procyon A
Eps Eri
Proxima Cen
Barnard's star
CN Leonis
Detection limit for ground-based optical RV F, G, K stars
Expected detection limit for space astrometry (NEAT, THEIA, STEP) F, G, K stars
Expected detection limit for near-IR RV surveys (SPIROU, IRD + others) M-type stars
Astrometric amplitude [uas]
1
0.1
0.01
0.01
0.1
1
RV amplitude [m/s]
Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)
Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

Conclusions

ASM :

[1] Will be Helpful but not essential to near-IR and visible ExAO

[2] Is Essential for thermal IR exoplanet imaging

Not competitive with ELTs

[3] Enables multi-object fiber-fed RV instrument

[4] Enables unique astrometric capability

Unique capabilities in ELTs era

Strong potential for non-exoplanet science