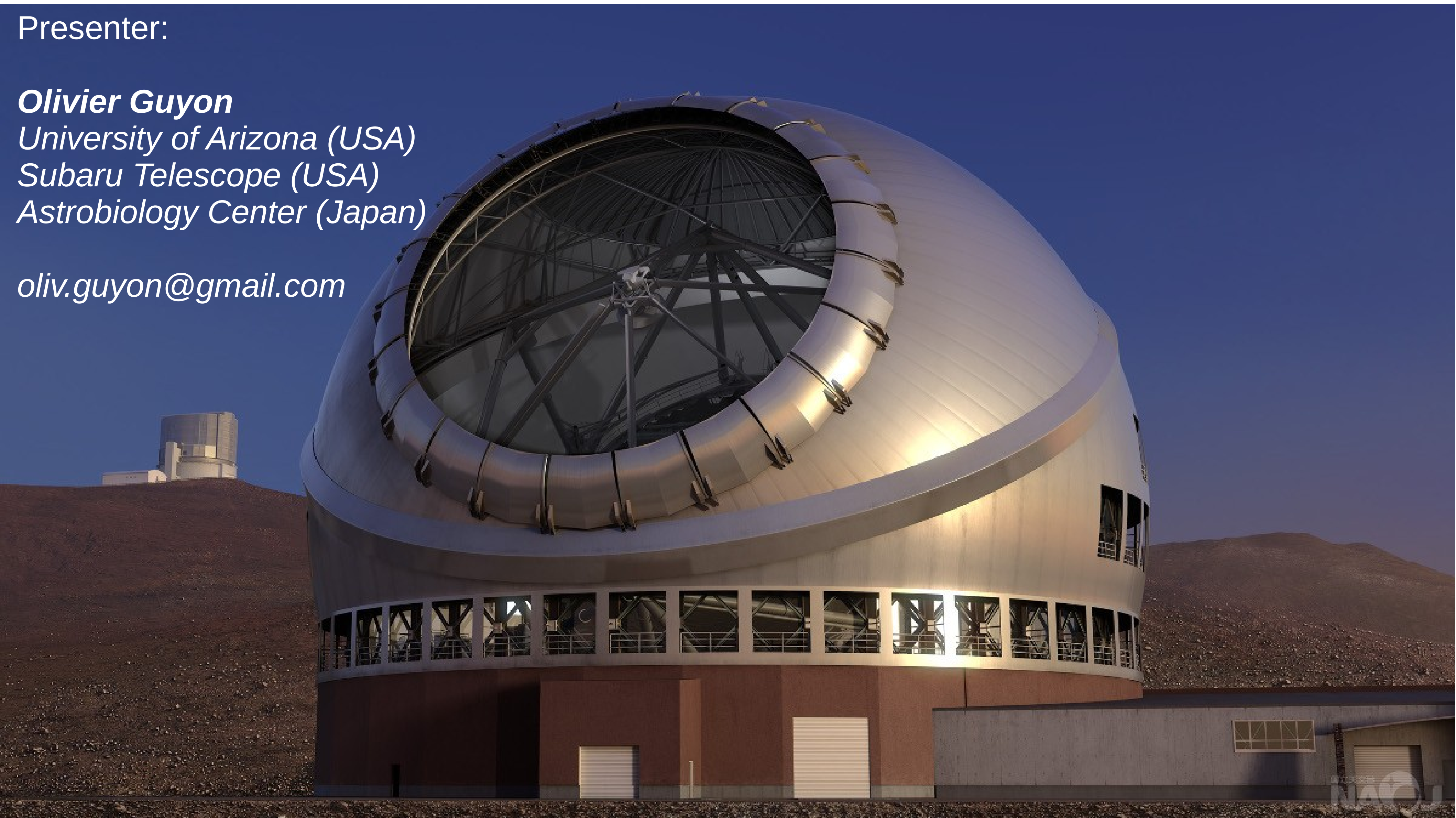
Wavefront control architecture and expected performance for the TMT planetary systems imager

TMT-PSI team

Presenter:

Olivier Guyon
University of Arizona (USA)
Subaru Telescope (USA)
Astrobiology Center (Japan)

oliv.guyon@gmail.com



Science Goals & Instrument Capabilities

Broad science reach, enabled by unprecedented angular resolution and sensitivity

Exoplanets and Disks (Core Science)
- Planetary systems architectures
- Exoplanets characteristics – Bulk properties, Atmosphere compositions
- **Exoplanet Habitabilitiy (search for biomarkers and habitable environments)**
- Disks: Morphology (planet/disk interaction), dust properties

Solar system
- Volcanic eruptions on Io
- Organics in Comets
- Asteroid multiples
- Planetary Atmospheres

Galactic Astronomy
- Stellar multiplicity
- Stellar evolution
- Inner Regions of Circumstellar Disks
- Ice Lines in Disks
- Dust streamers in Interacting Binaries
- Compact Objects

Extragalactic Astronomy
- QSOs / AGNs

Core Science drives instrument design
→ Broad wavelength coverage
→ Spectroscopy
→ Polarimetry
→ High Contrast Imaging

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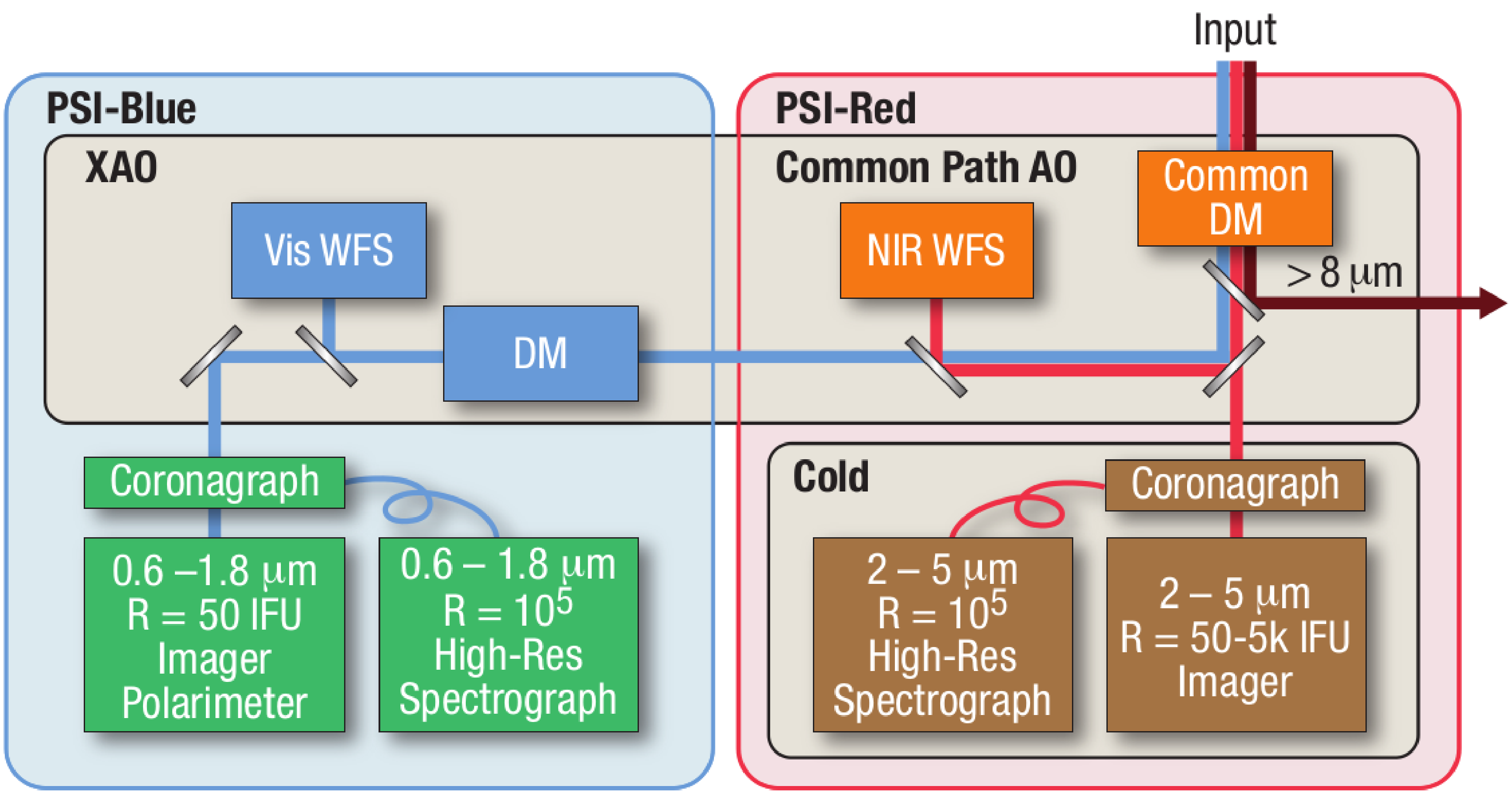
High Contrast Habitable Planets Imaging and Characterization at near-IR/optical

This is the most challenging science goal: drives most WFS/C performance requirements

Focus of THIS presentation (everything else is easier)

Instrument Architecture (notional)



Wide wavelength coverage
3 science outputs for cameras/spectrographs:

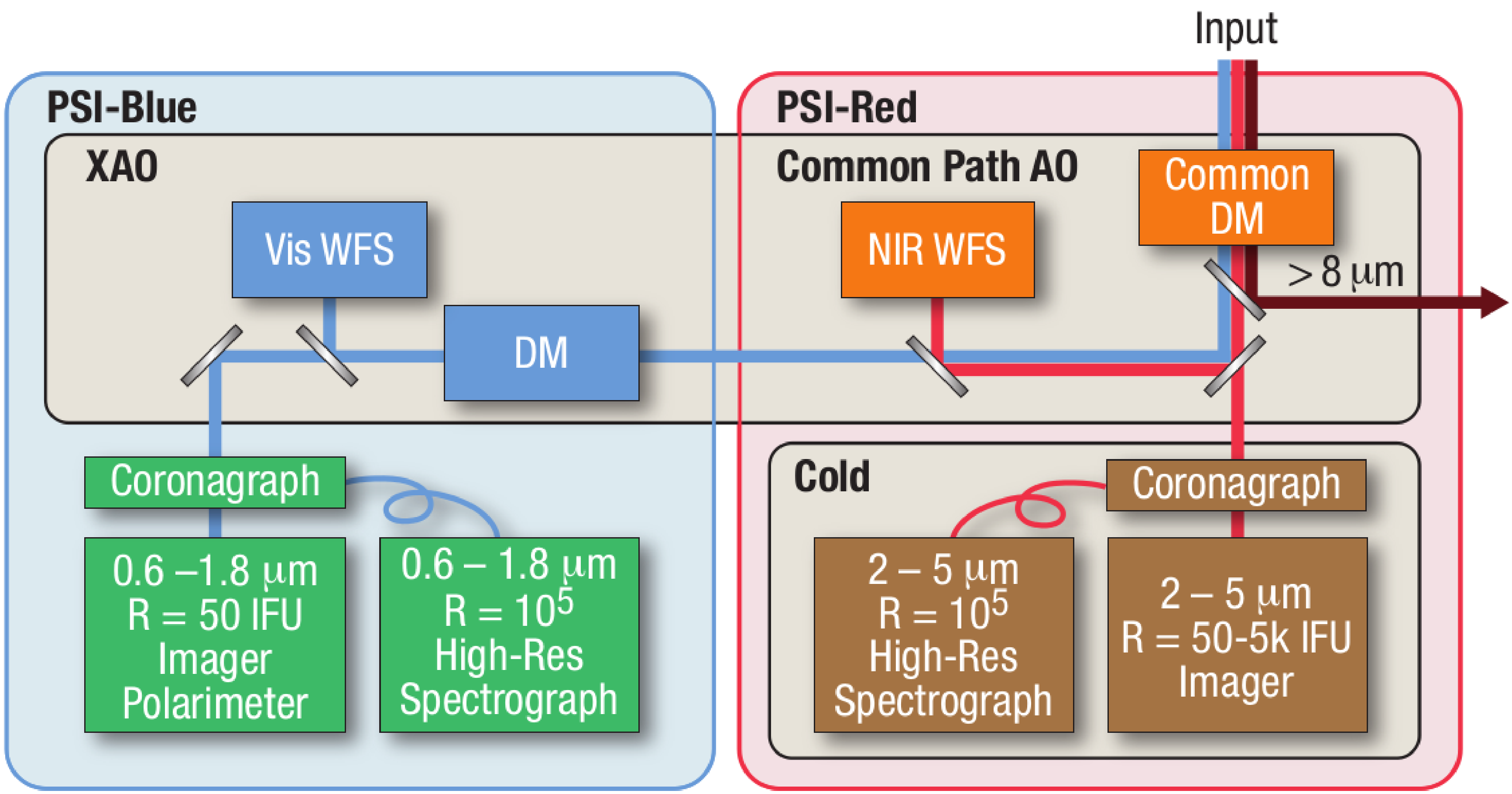
- Thermal IR (> 8 um) could be feeding MICHI
- Near-IR (2-5 um)

Cold

Warm

- Optical (< 1.8 um)

Instrument Architecture (notional)



PSI-Blue provides ExAO & high contrast
Its most challenging science goal is to image and characterize habitable planets

Warm optics, **deployed at first light and upgradeable**: coronagraph masks, control algorithms, back-end instrumentation modules

2+ um science does not critically rely on extreme AO/HCI performance (background-limited)

Common DM feeds all ports
Cryogenic coronagraph and relay optics.
Notionally deployed as facility-class instrument at first light

Wavefront control architecture for ExAO

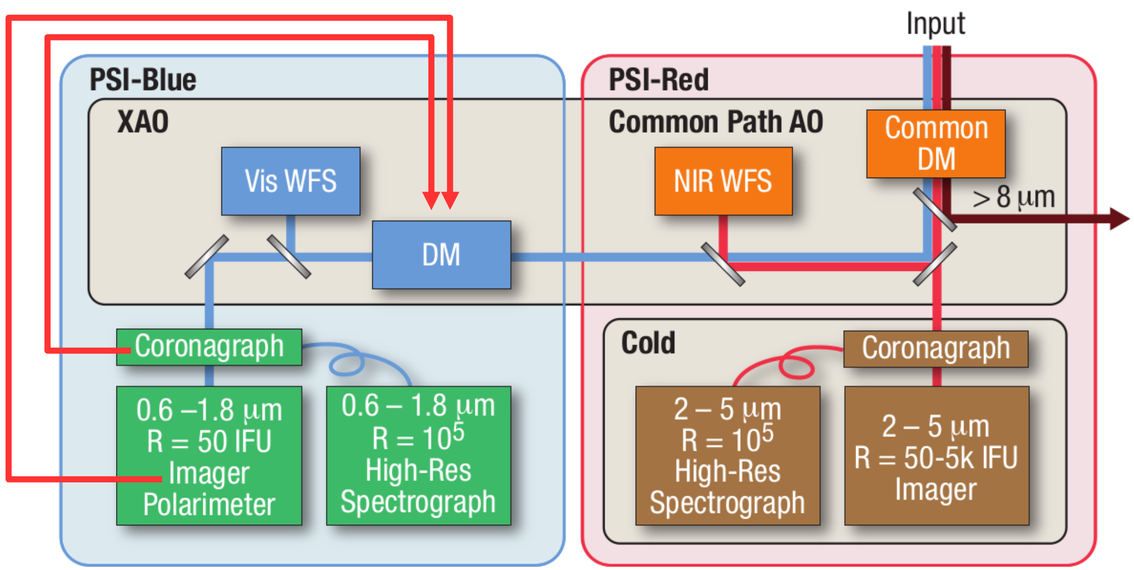
Two-stage correction:
Common DM (~120x120 large stroke) → fast MEMs (~60x60 or larger)

Dual near-IR and visible WFS provides :
(1) Correction on a broad range of targets
(2) High ExAO performance:
- Sensitivity: using both vis and nearIR
- Robustness: nearIR WFS for coarse correction, visible for high precision

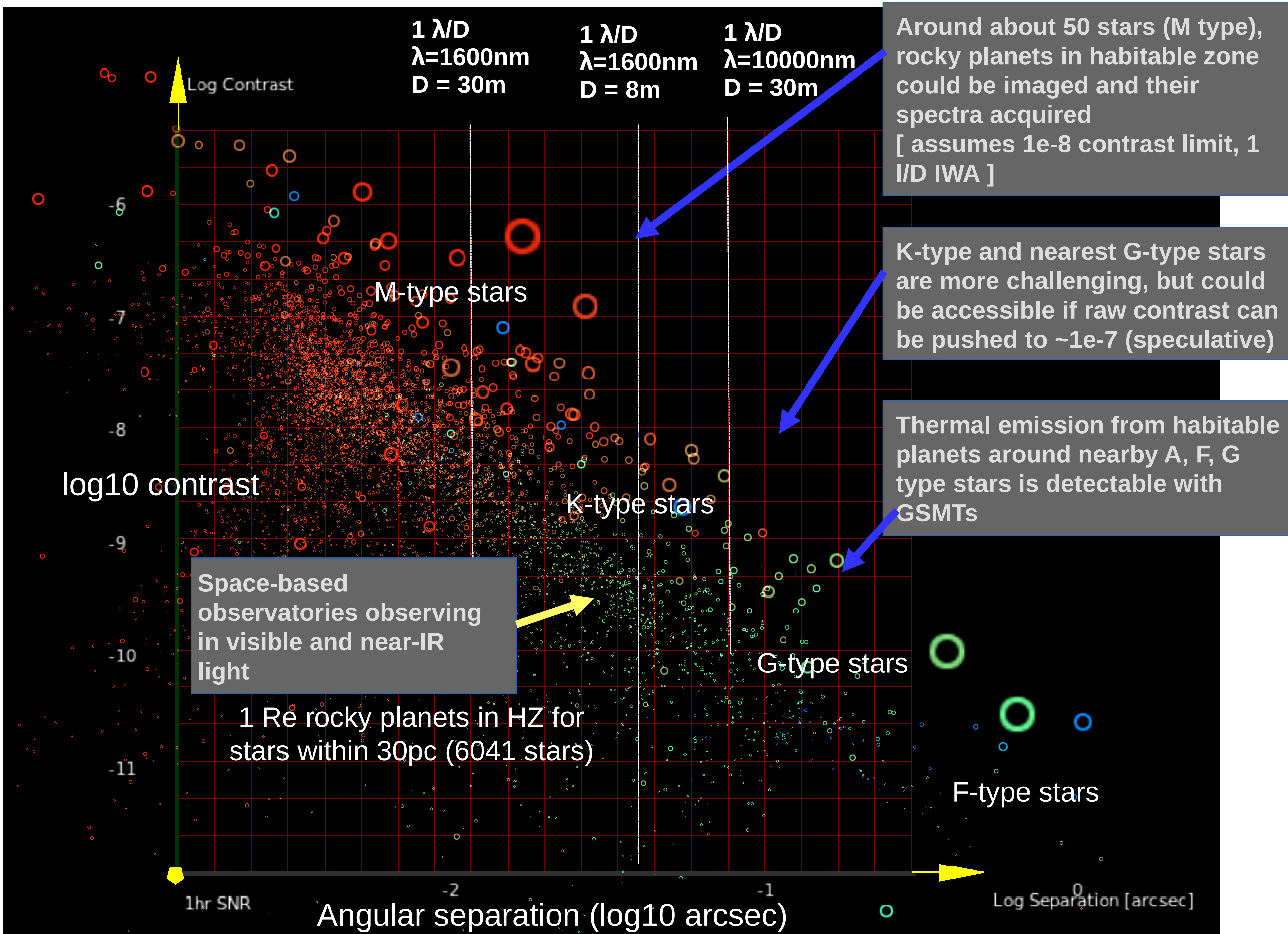
ExAO instrumentation is integral part of HCI WFS/C

Speckle control:
Post-coronagraphic image feeds control loop

Low-Order WFS/C:
Light discarded by coronagraph encodes low-order aberrations



Contrast and Angular separation
Hypothetical Earth-like planets



Contrast / Separation requirements

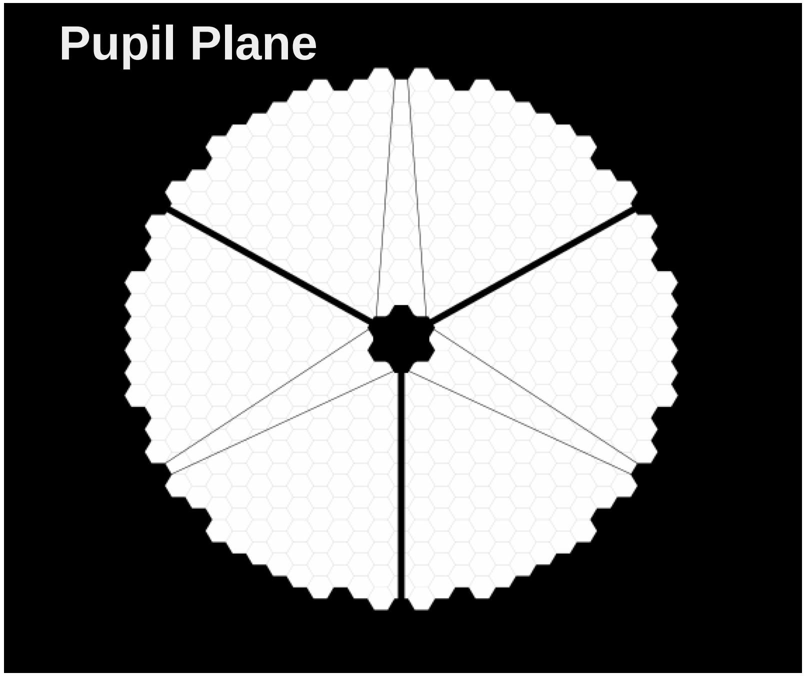
PSI's ultimate goal: habitable planet observations around nearby M-type stars:
Separation ~2 l/D, ~1e-8 contrast, mR~10

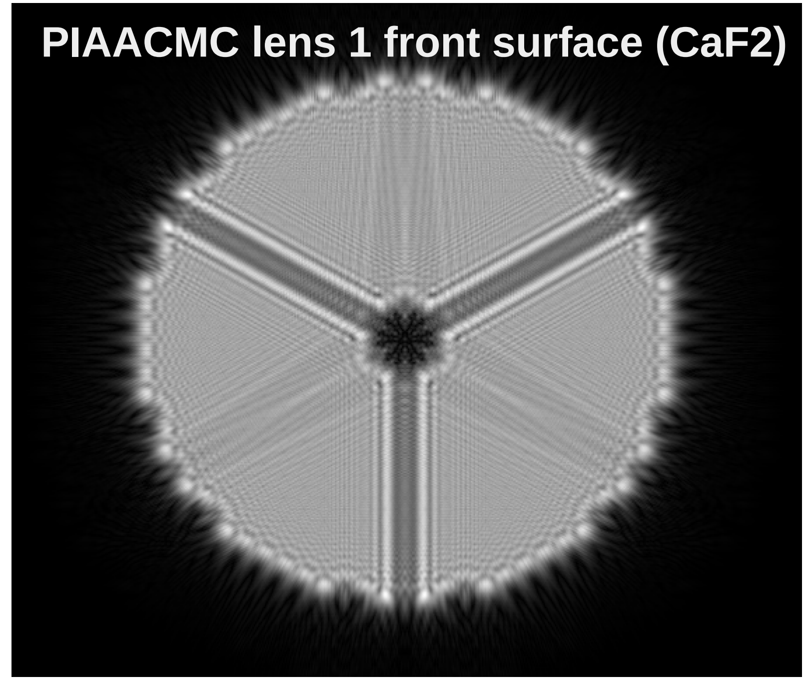
Small IWA coronagraphy

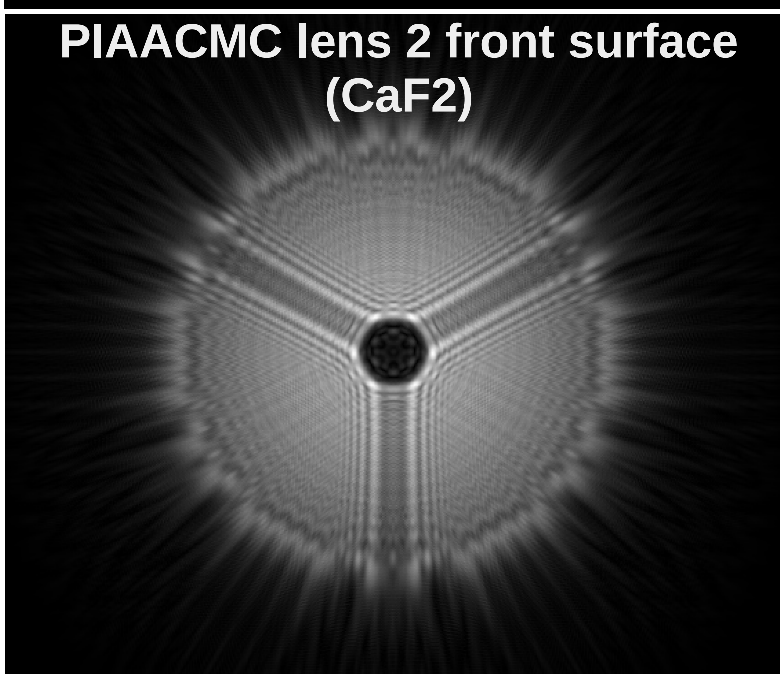
ExAO + Differential imaging

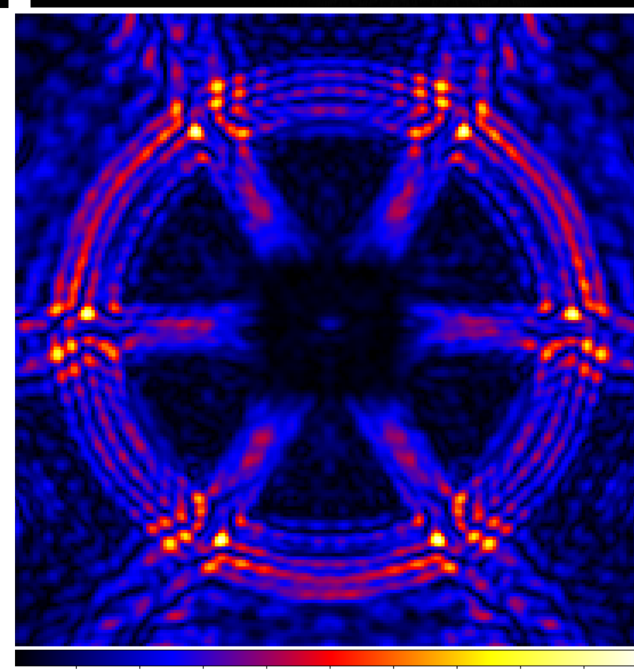
Efficient WFS, multi-band, multi-sensor, predictive control

TMT coronagraph design for 1 l/D IWA









PSF at 1600nm

3e-9 contrast in 1.2 to 8 l/D

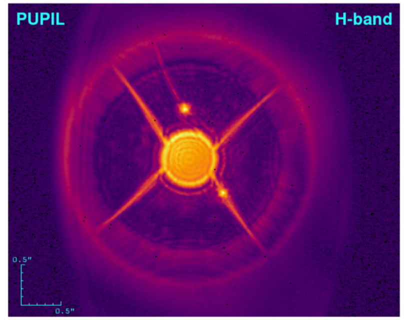
80% off-axis throughput

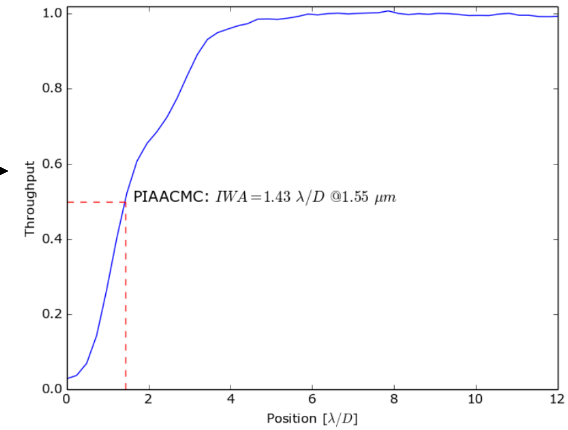
1.2 l/D IWA

CaF2 lenses
SiO2 mask

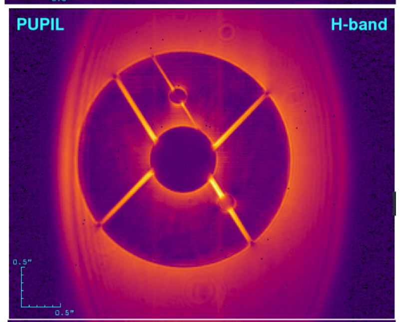
Small-IWA coronagraphs already in operation on-sky

PIAACMC
measured IWA = 1.43 l/D

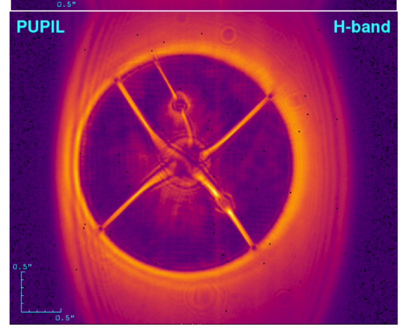


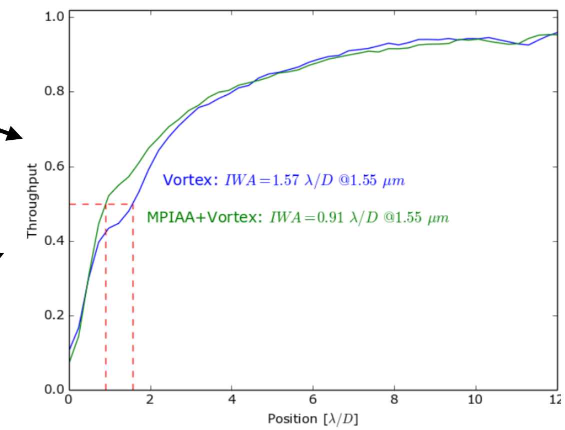


Vortex
measured IWA = 1.57 l/D

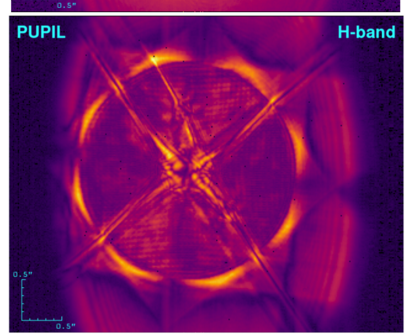


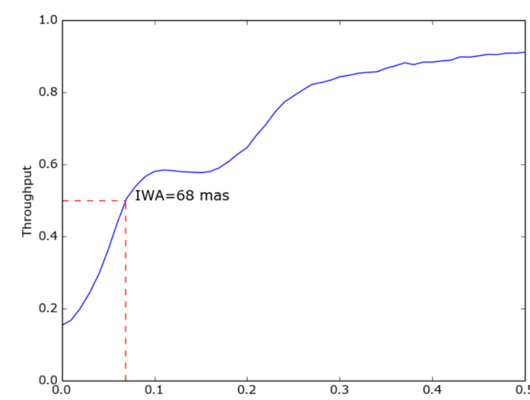
MPIAA + Vortex
measured IWA = 0.91 l/D





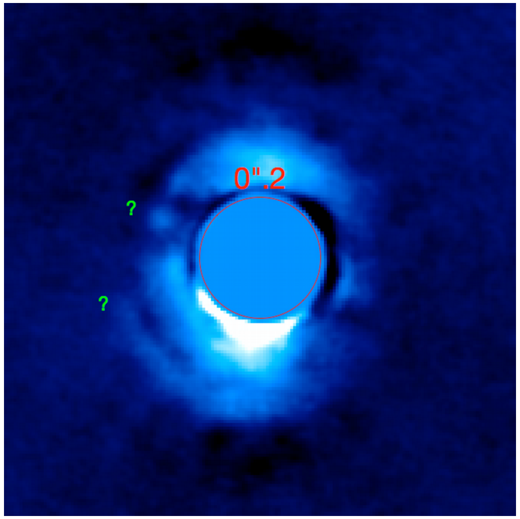
MPIAA + 8QPM
measured IWA = 1.70 l/D



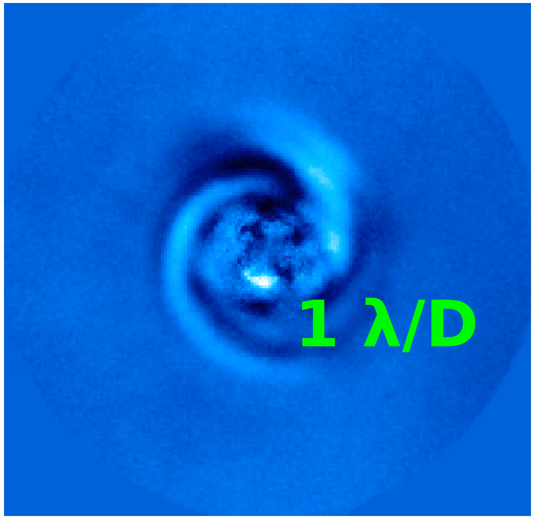


SCExAO: new high-performance coronagraphs ready for science
Paper 10706-207, Time: 6:00 PM - 8:00 PM, Julien Lozi,

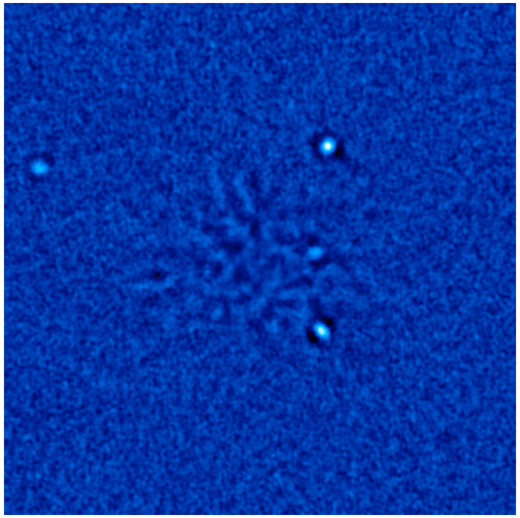
Keck/NIRC2 vortex gallery

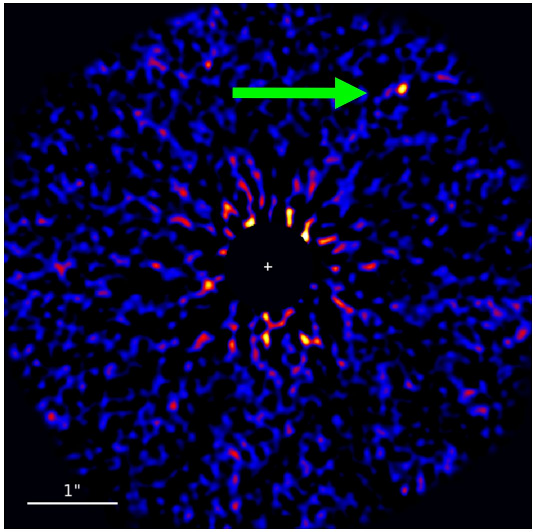


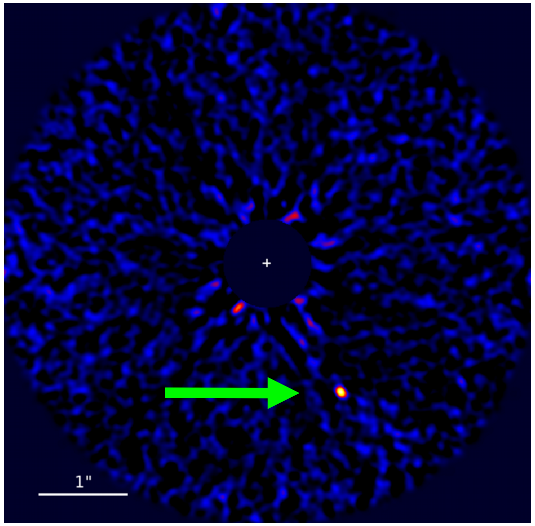
Mawet et al. 2017

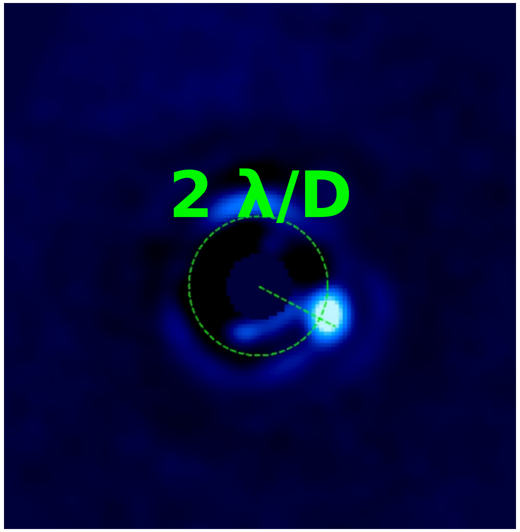


Reggiani et al. 2018


Wertz et al. 2016







Serabyn et al. 2017

Slide courtesy of Dimitri Mawet

Differential Detection Techniques

Angular Differential Imaging (ADI)
Does not address noise limit from slow speckles

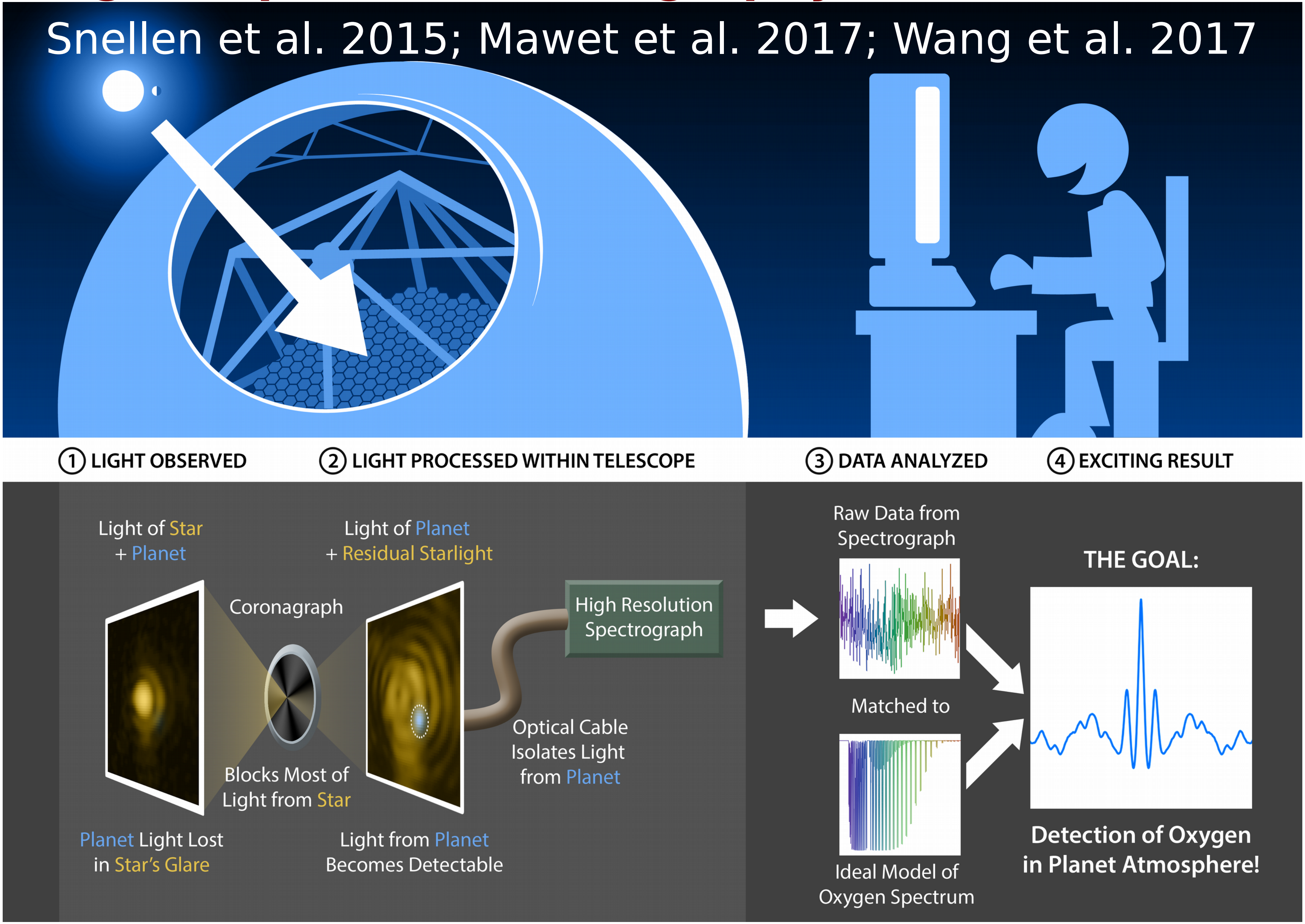
Spectral Differential Imaging (SDI) (low spectral resolution)
Limited by chromaticity in speckles

High Resolution Spectroscopy (Snellen et al., Mawet et al.)
Very clean signal (narrow lines) not present in starlight
But few % of planet light used → photon noise (from starlight) limits use
Great for giant planets. Challenging for Habitable planets.
(See Wang et al. 2017)

Polarization Differential Imaging
Polarized light fraction is small (<10% ?)
→ photon noise (from starlight) limits use

Coherent Differential Imaging
Can use 100% of light
Challenging to implement, calibration issues

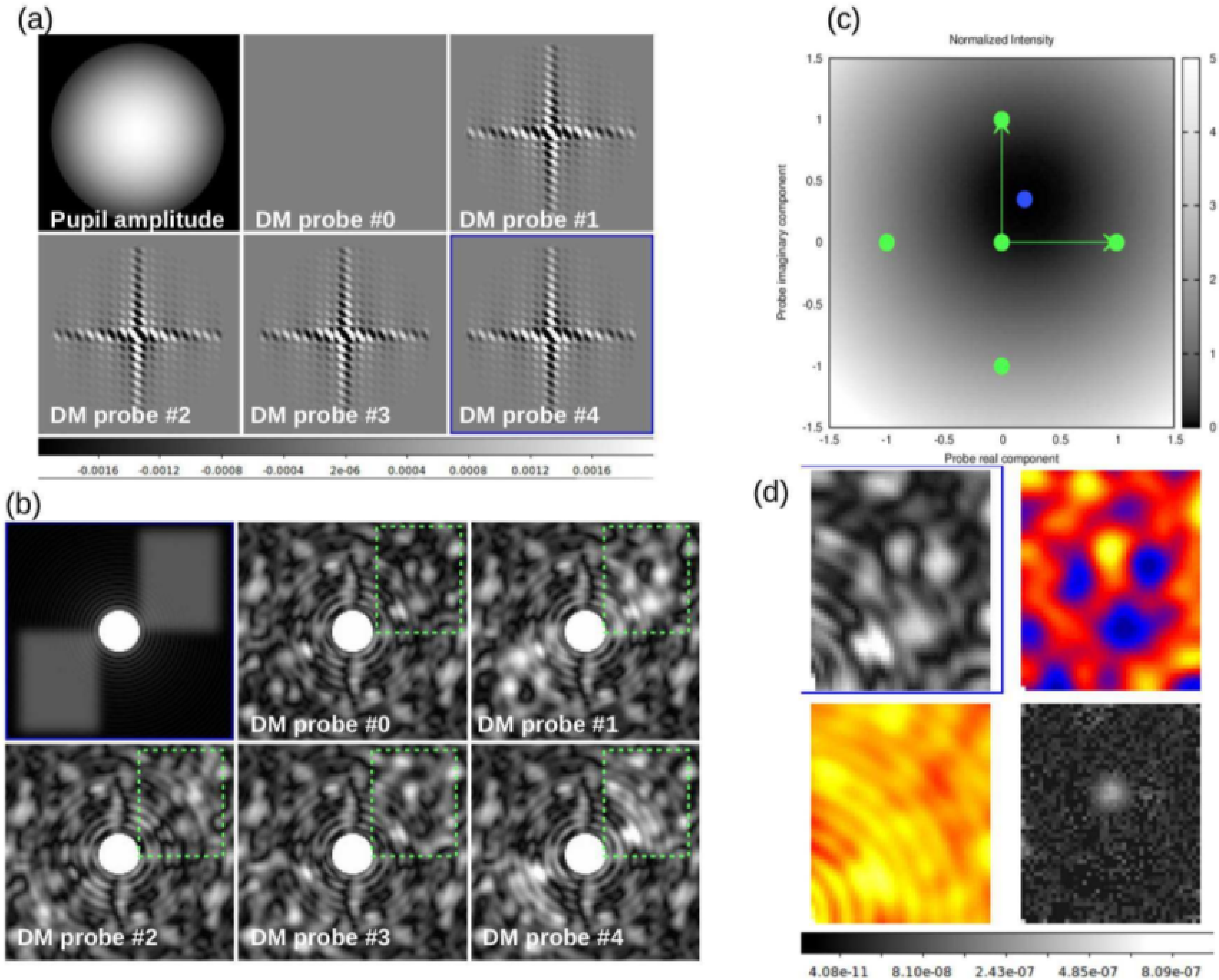
High Dispersion Coronagraphy



See Ji Wang's talk 10703-64 on Thursday pm

… another slide stolen from Dimitri

Coherent Speckle Differential Imaging



Key WFS/C questions

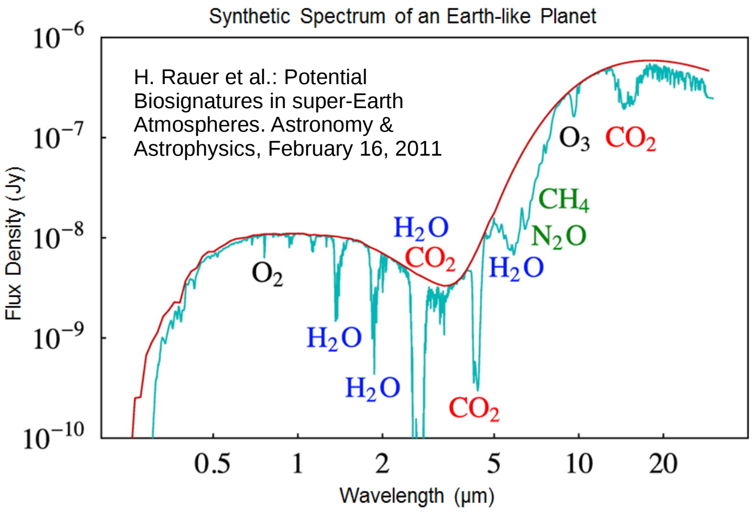
Q1: What is the optimal detection band for reflected light imaging of habitable planets ?

Q2: What raw contrast is required ?

Q3: What is the optimal wavefront sensing wavelength ?

Q4: How to achieve the raw contrast: Challenges and solutions ?

Q1: What is the optimal detection band for reflected light imaging of habitable planets ?



Scientific Value

Blue/visible: Rayleigh scattering
760 nm Oxygen A band

NearIR rich in absorption bands:
Oxygen (1.27um), Water, Methane, Carbon Dioxyde

Thermal emission starts at ~3 um, rich in molecules

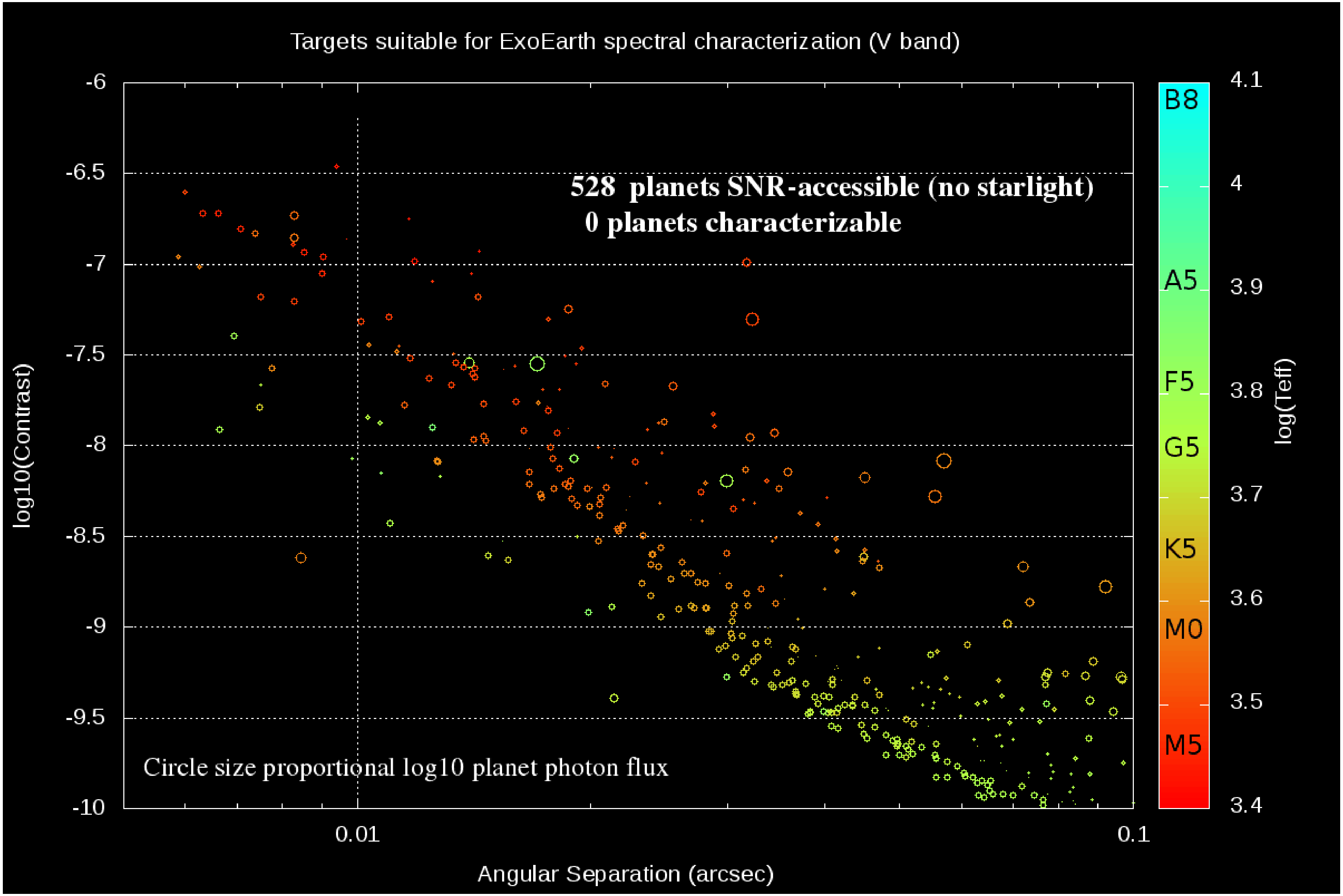
Expected Instrument Capabilities

Let us assume that :
(1) ExAO system can deliver 1e-6 raw contrast at 1um ← Initial guess for Q2
(2) Every star has one Earth analog
(3) Photon noise limit from both starlight and planet light

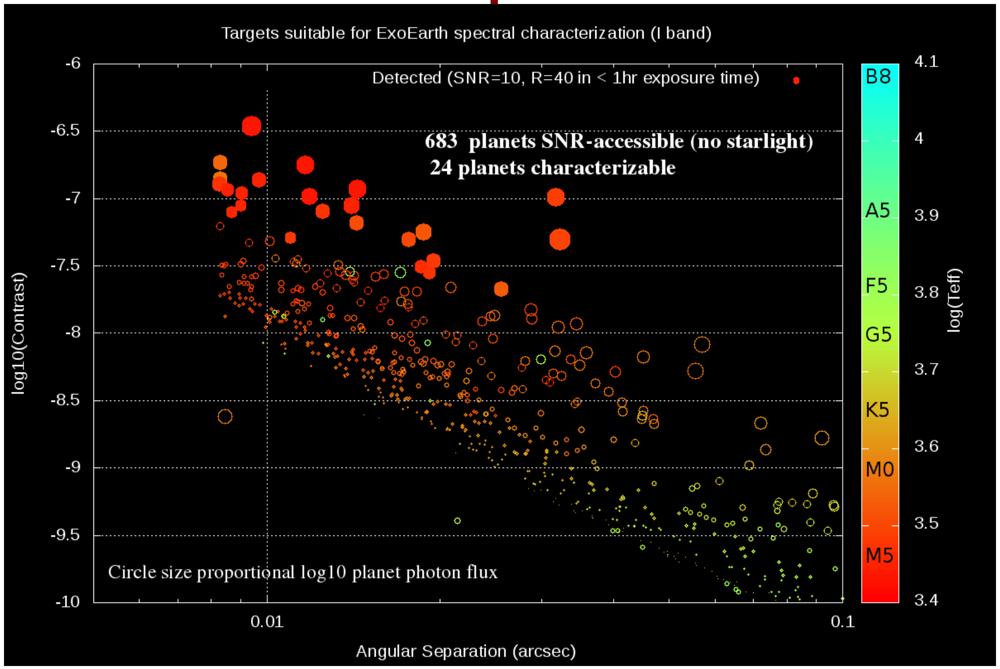
We can scale contrast according to wavelength (C ~ lambda^-2)
.. and scale coronagraph according to wavelength (IWA ~ lambda)

We count, for each spectral band (V, I, J, H, K), how many planets are characterizable:
R=40 spectra at SNR=10 can be acquired in < 1hr
(approximate requirement for spectroscopic detection of key molecular species)

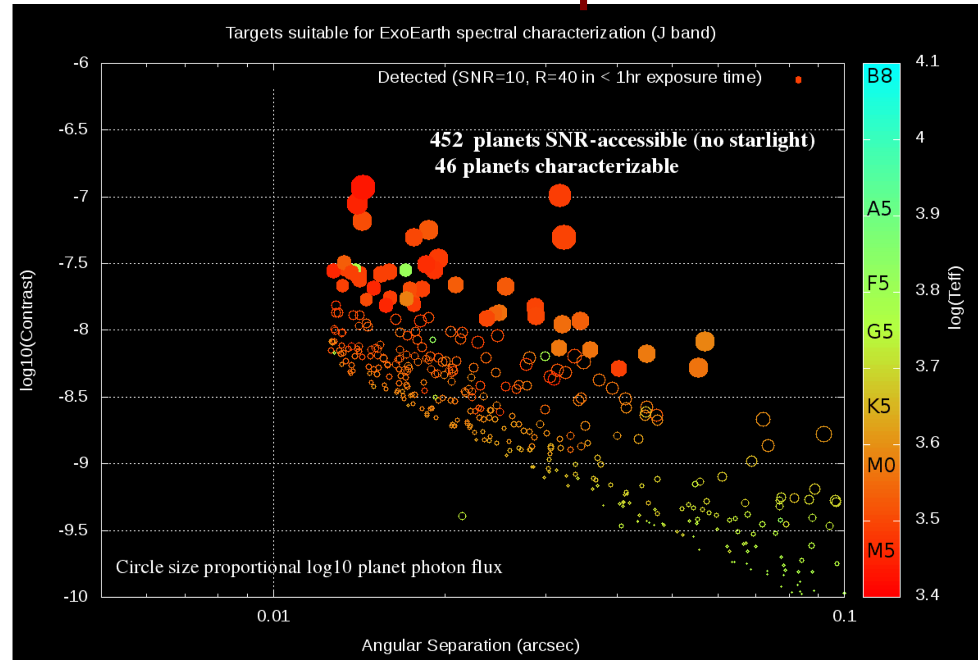
V band
Too much starlight left → 0 planet characterizable



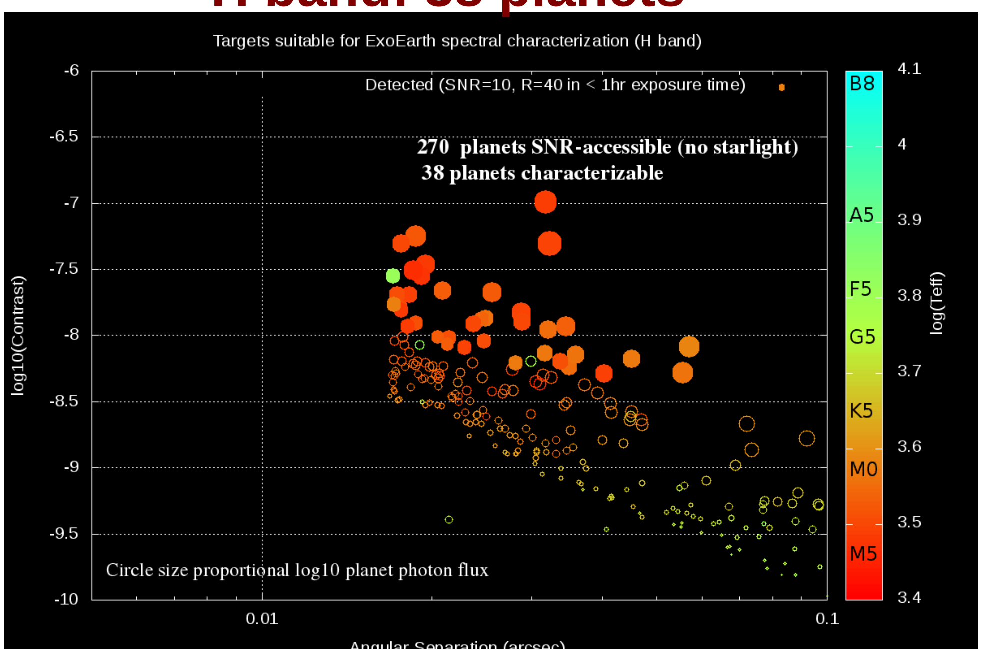
I band: 24 planets



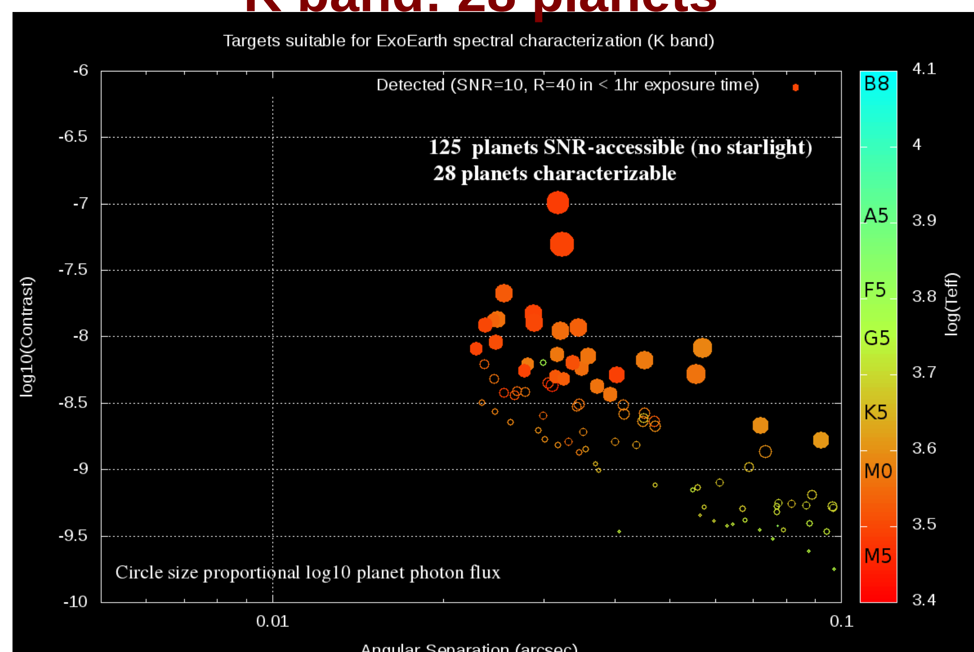
J band: 48 planets



H band: 38 planets



K band: 28 planets



Optimal wavelength range: J & H / Required raw contrast ~1e-5 / Best targets are M0-M6

Q3: What is the optimal wavefront sensing wavelength ?

Blue light: Better information content per photon, but fewer photons
Red light: More photons, but less signal per photon

Table 6 Optimal Wavefront Sensing Wavelength - Linear Regime

Spectral Type	Teff [K]	Optimal Band[a]	Photon flux[b] $[m^{-1}.ms^{-1}]$	Flux gain relative to ... B	R	H
B0V	31500	U	1.08e10	2.14	12.06	1337.0
A0V	9700	B	5.01e7	1.00	4.25	204.7
F0V	7200	B	1.05e7	1.00	2.78	82.1
G0V	5920	B	1.34e6	1.00	1.80	33.7
K0V	5280	B	3.26e5	1.00	1.33	17.6
M0V	3850	R	3.53e4	2.03	1.00	3.93
M4V	3200	I	4.65e3	12.5	1.80	2.83
M8V	2500	J	6.00e2	150.0	11.6	1.98

[a]Optimal bandwidth selected among standard astronomical spectral bands (U, B, R, I, J, H). Assumes fixed relative spectral bandwidth $d\lambda/\lambda$. Central wavelength listed; [b]Assuming 10% effective spectral band at optimal sensing wavelength, main sequence star at 10pc.

Prime wavelength range: 600nm to 900nm

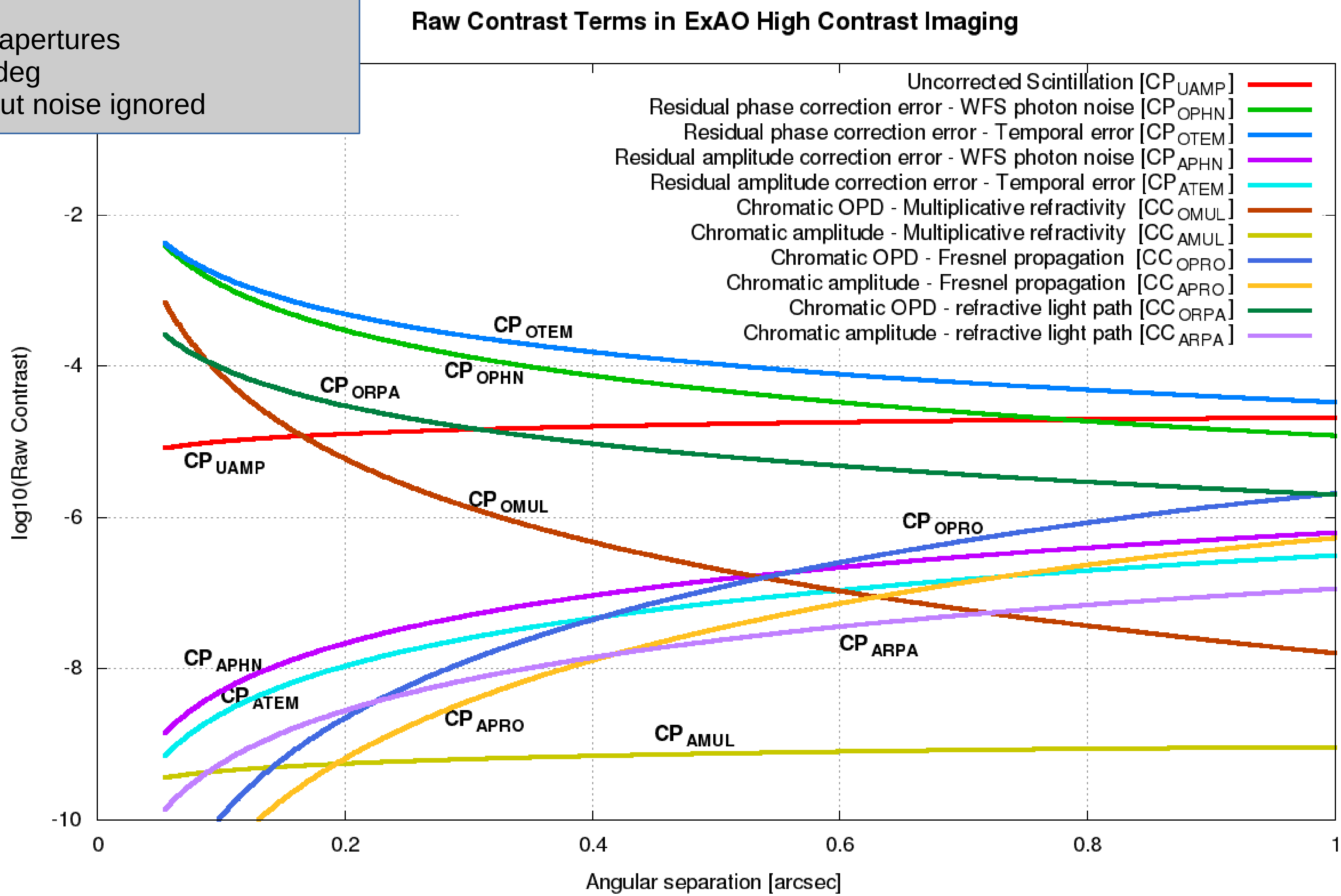
Q4: How to get ~1e-5 to 1e-6 raw contrast in nearIR ?

Approach:
We first establish contrast error budget for ExAO system on a 30m telescope
We assume a “conventional” ExAO system, visible SHWFS / nearIR science camera

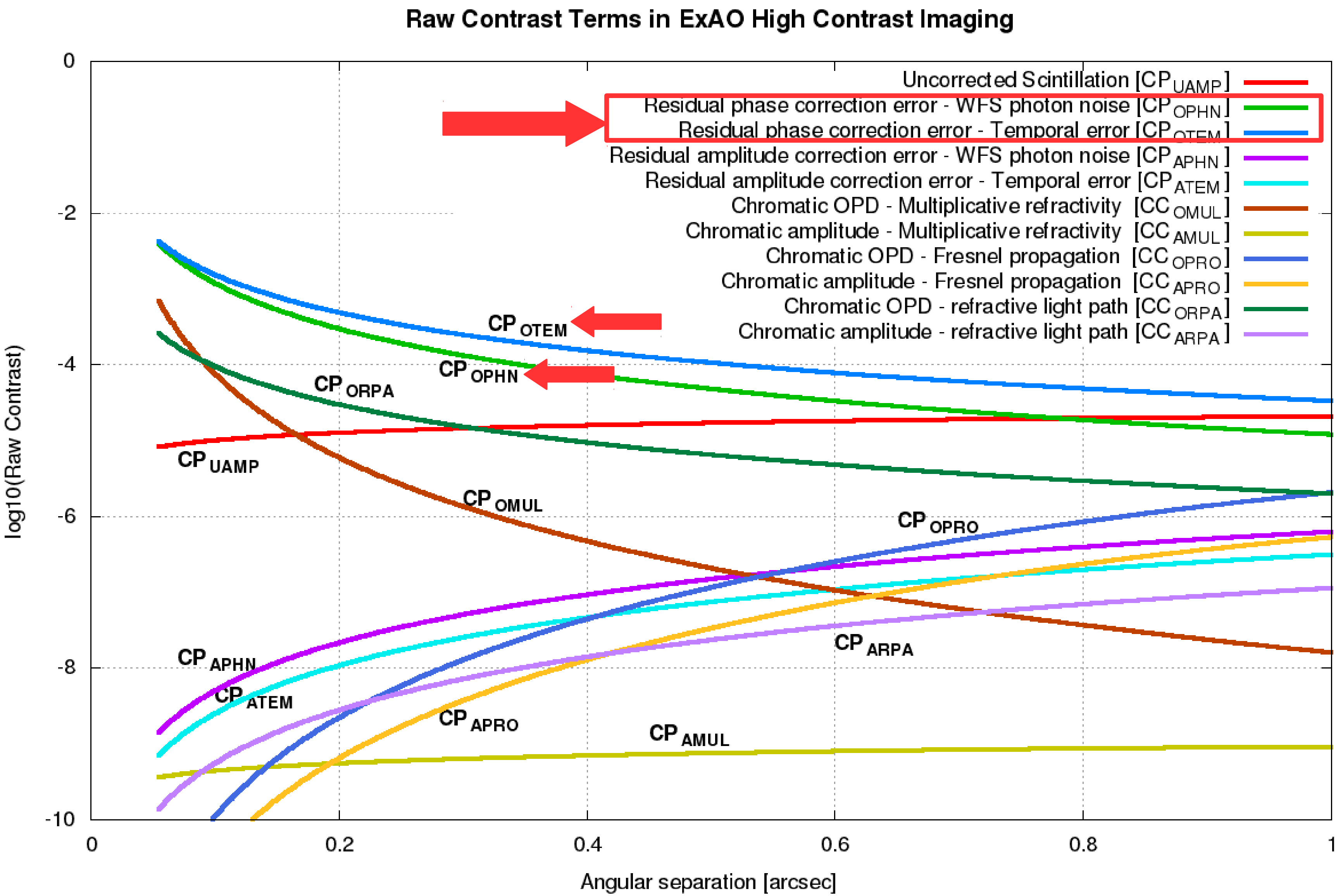
→ Identify dominant error terms and explore solutions

Contrast Error Budget (Primary WFC only)

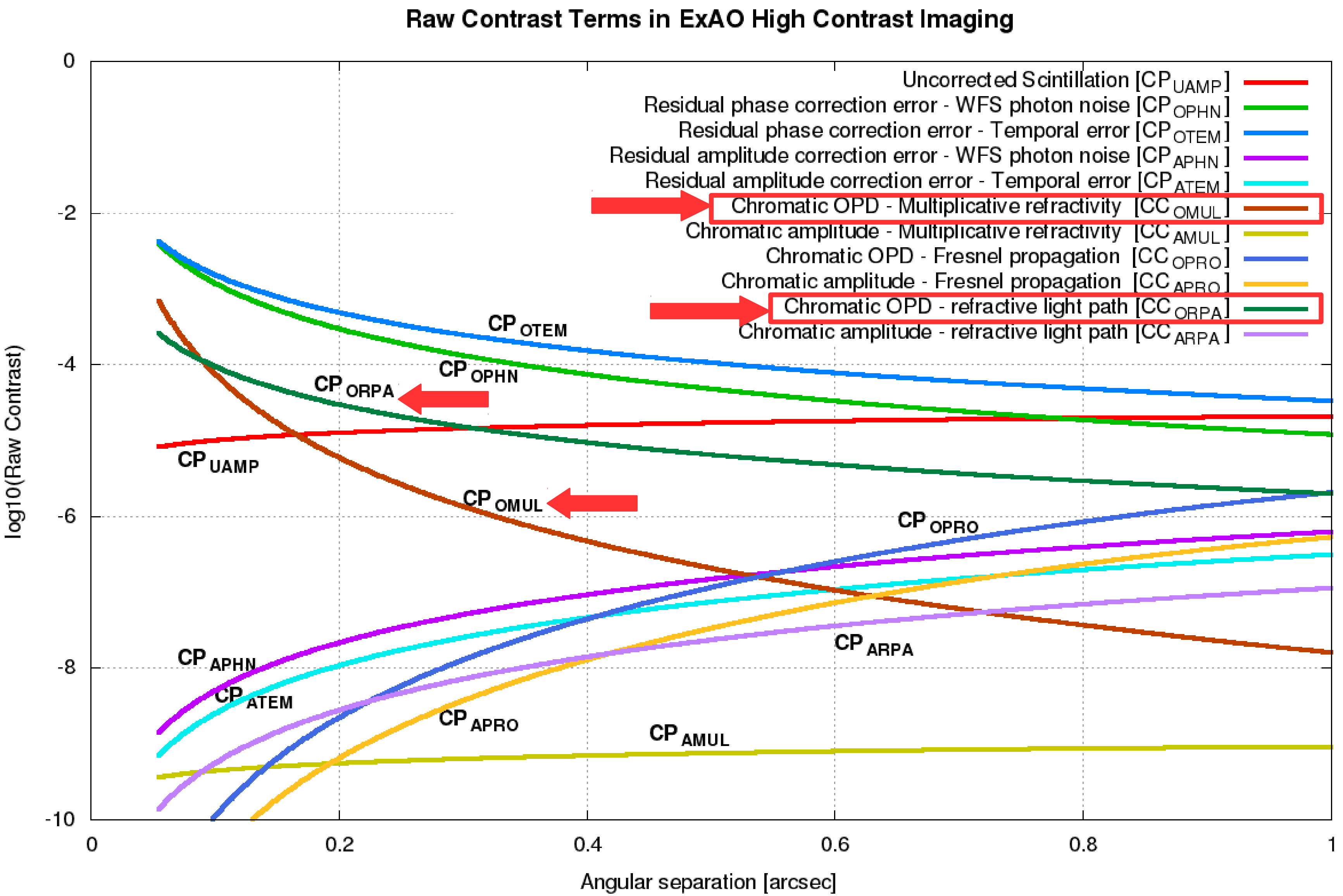
D=8m telescope
High contrast imaging at 1.6 um
Wavefront sensing at 0.8 um
30% efficiency WFS
40% wide WFS spectral band
1 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 8 m/s
Fried parameter r_0 = 0.15 m at 0.5 um
m_I = 8 target
SHWFS 15cm subapertures
Zenith angle = 40 deg
Aliasing and readout noise ignored



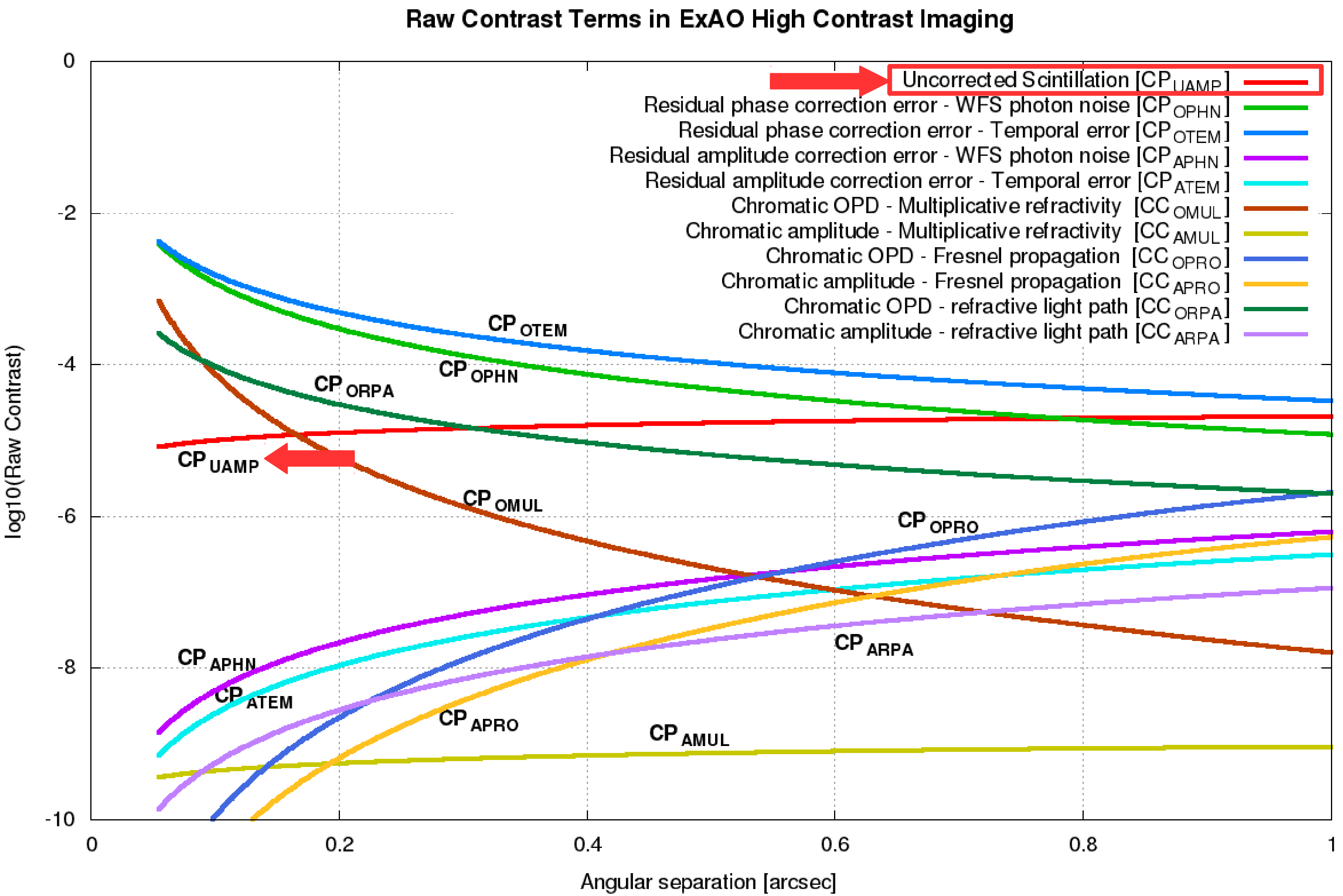
CHALLENGE #1:
WFS sensitivity and time lag



CHALLENGE #2: Chromaticity effects



CHALLENGE #3: Scintillation



Solutions

#1: WFS sensitivity and time lag

→ PSI uses **diffraction-limited WFS approaches**, >1000x more sensitive than SHWFS
Instrument architecture ensures that Pyramid WFS operates in diffraction-limited regime

→ PSI uses **both visible and nearIR light** for WFS for optimal sensitivity

→ PSI uses **predictive control** to replace time lag with (much smaller) prediction error

#2: WFS chromaticity

→ PSI uses near-IR WFS (pupil plane) and speckle control at/near science wavelength

#3: Scintillation

→ PSI uses focal plane speckle control to sense and correct scintillation speckles

Wavefront control architecture for ExAO

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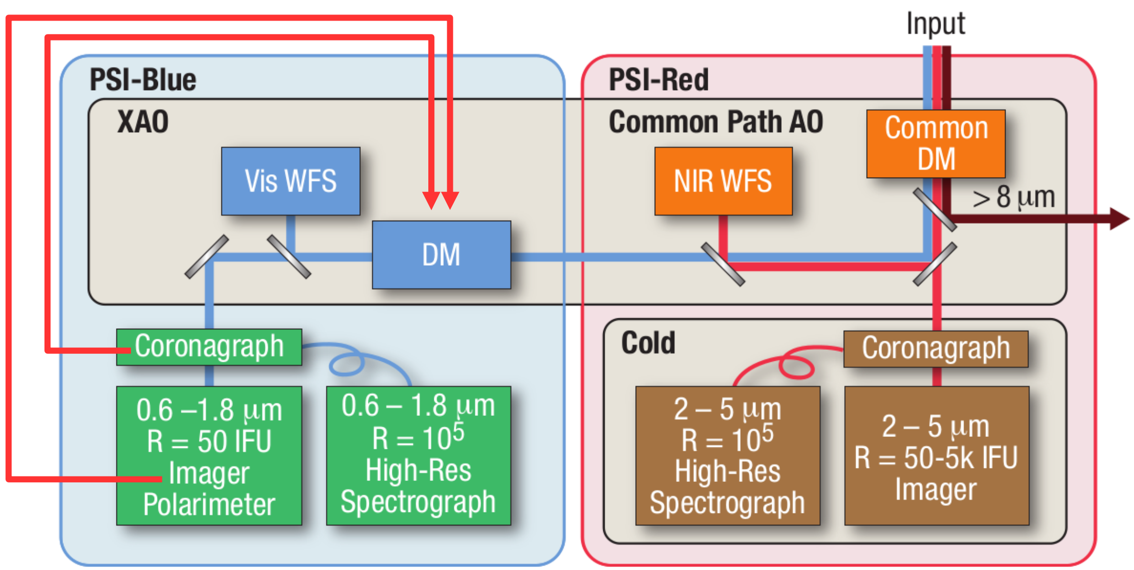


Advanced ExAO requires Advanced Control Algorithms: Predictive Control and Sensor Fusion

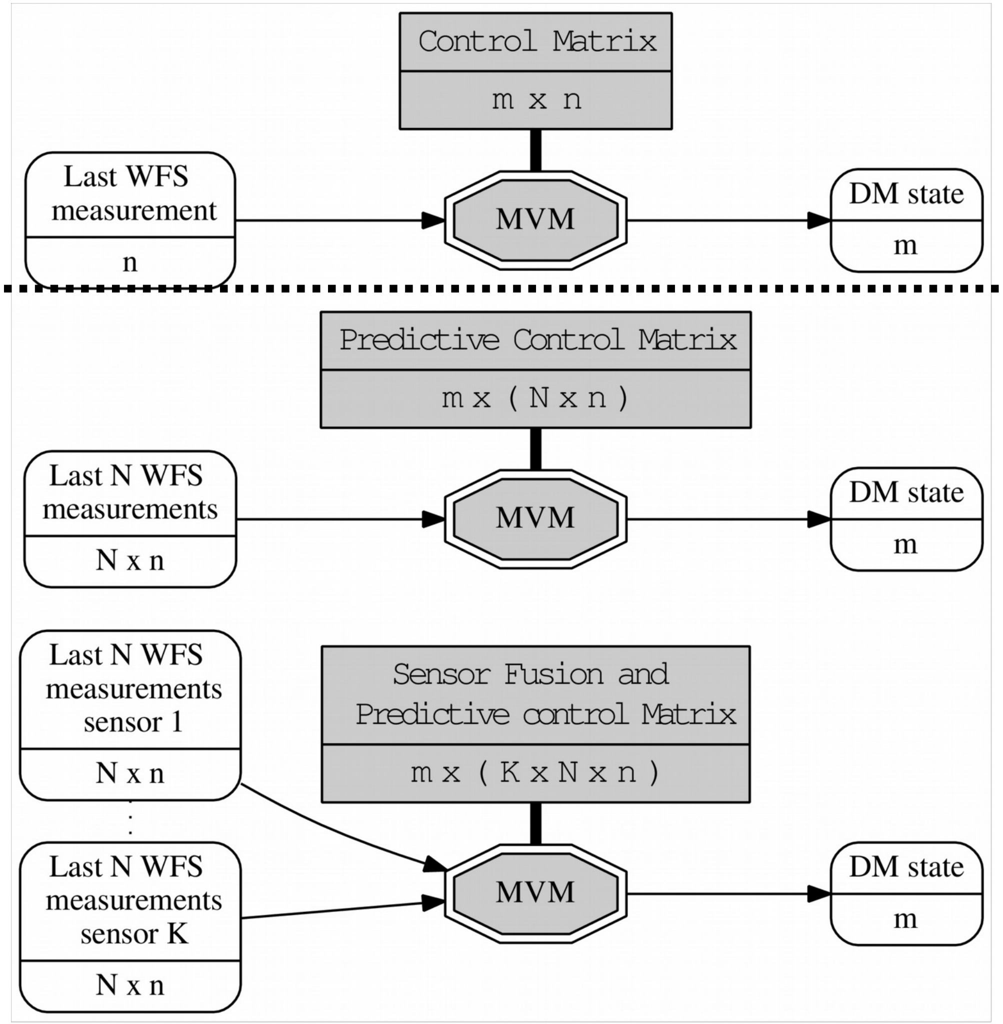
Conventional AO:

<u>Measure</u> RM/CM

Advanced AO control:

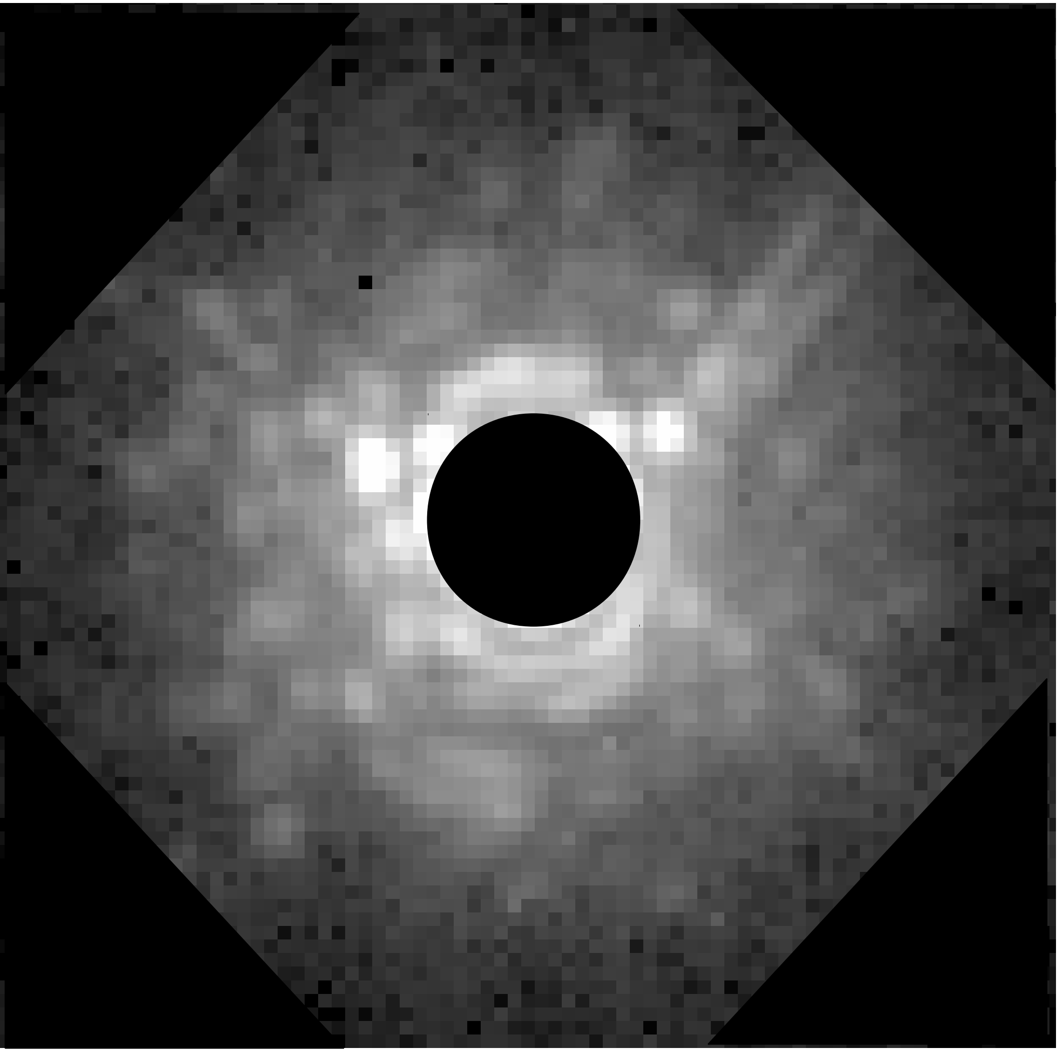
Use past measurements (predictive control) and other measurements (sensor fusion) → control matrix is very big, and usually impossible to measure

<u>Derive</u> CM from WFS(s) telemetry

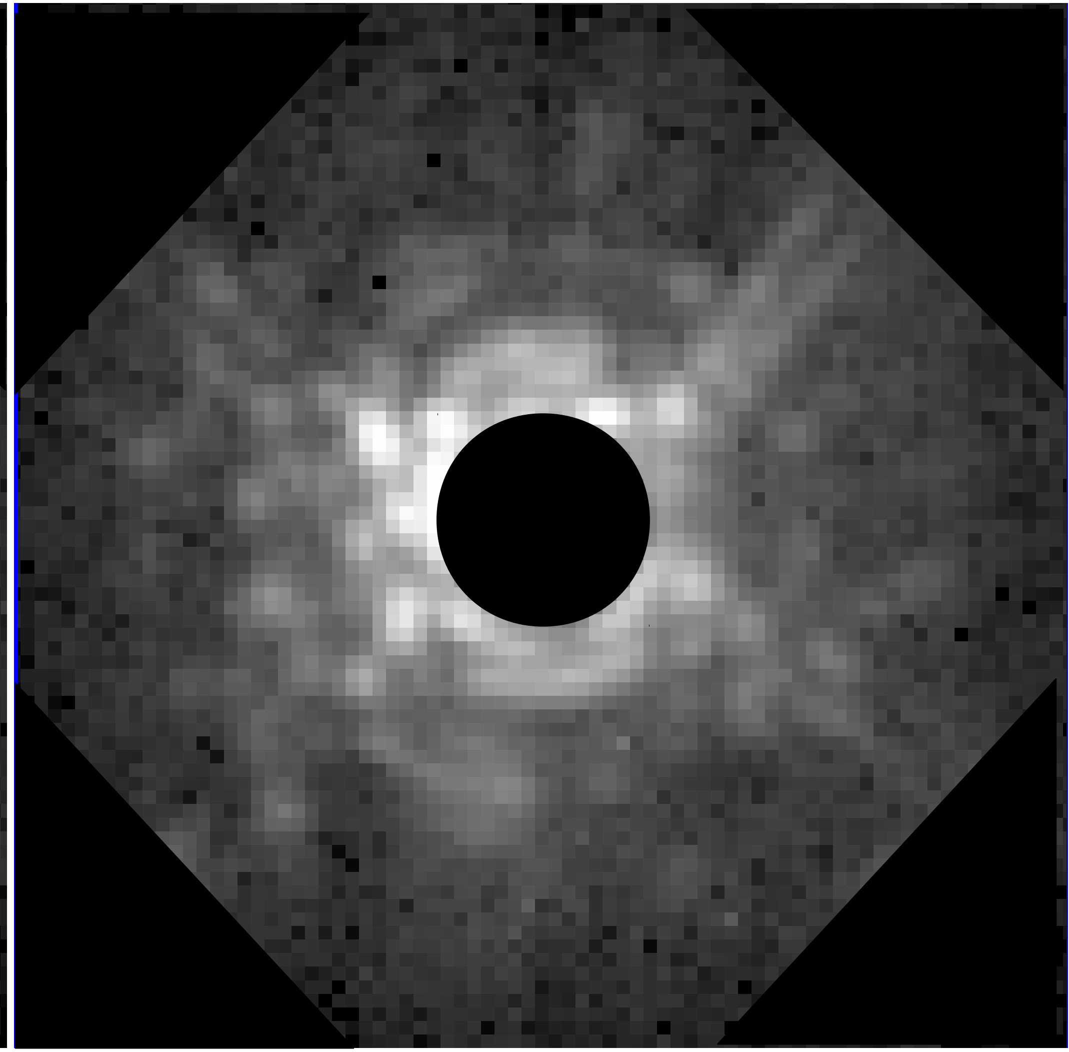


The compute and control for adaptive optics (CACAO) real-time control software package
Olivier Guyon et al.
13 June 2018 • 11:40 AM - 12:00 PM

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

TMT PSI development, prototyping

In addition to lab activities, new on-sky instruments will be validating TMT-PSI subsystems:

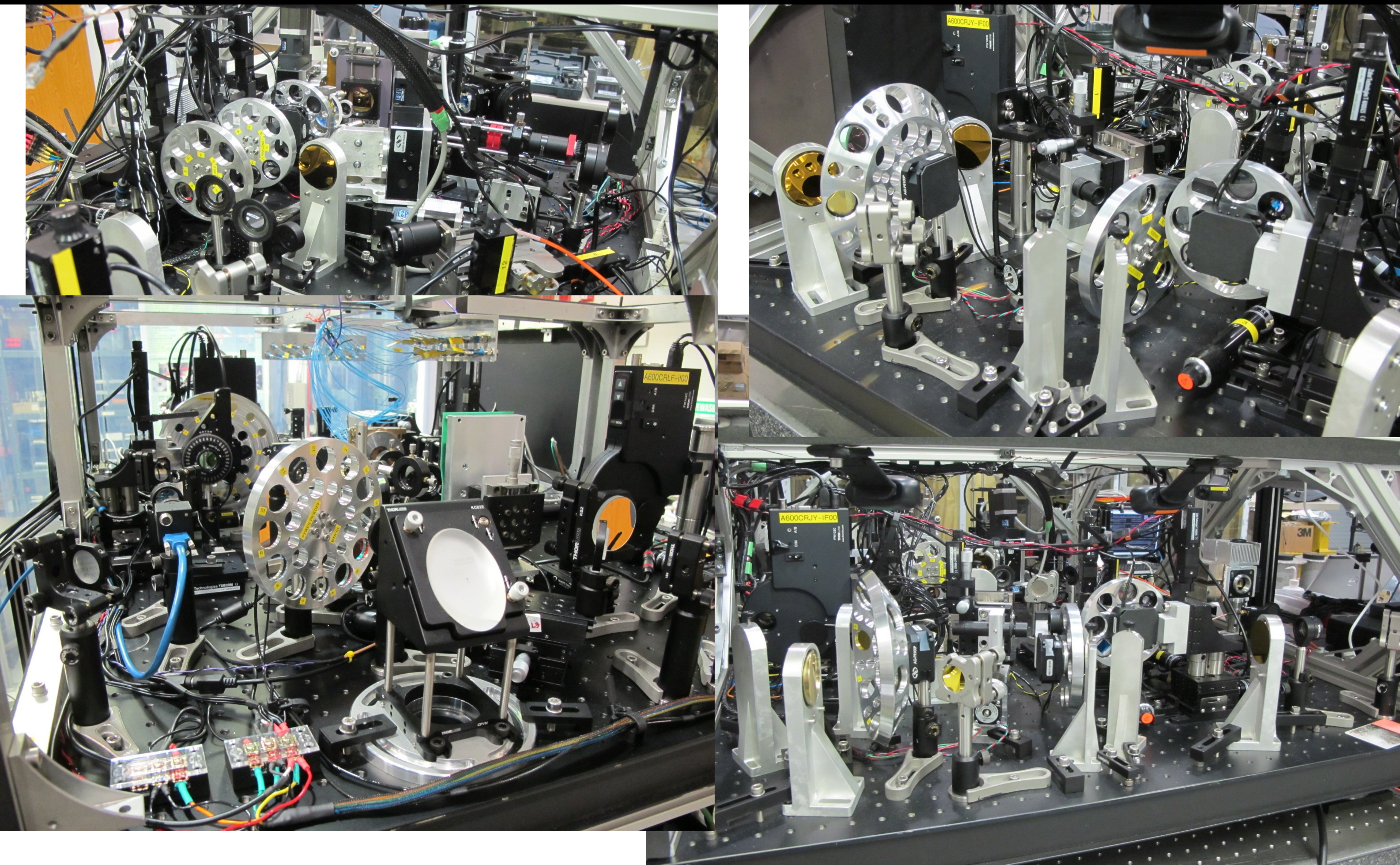
SCExAO @ Subaru
- System-level prototype for PSI-blue, with similar overall architecture
- Multiple Coronagraphs
- Many WFSs, Camera, Modules → system-level testing of WFS/C algorithms
- Focal Plane Speckle Control with MKIDs + other cameras

KPIC @ Keck
- Integrates small-IWA coronagraphy, HDC and near-IR PyWFS
- Prototype for PSI-red (2-5 um)

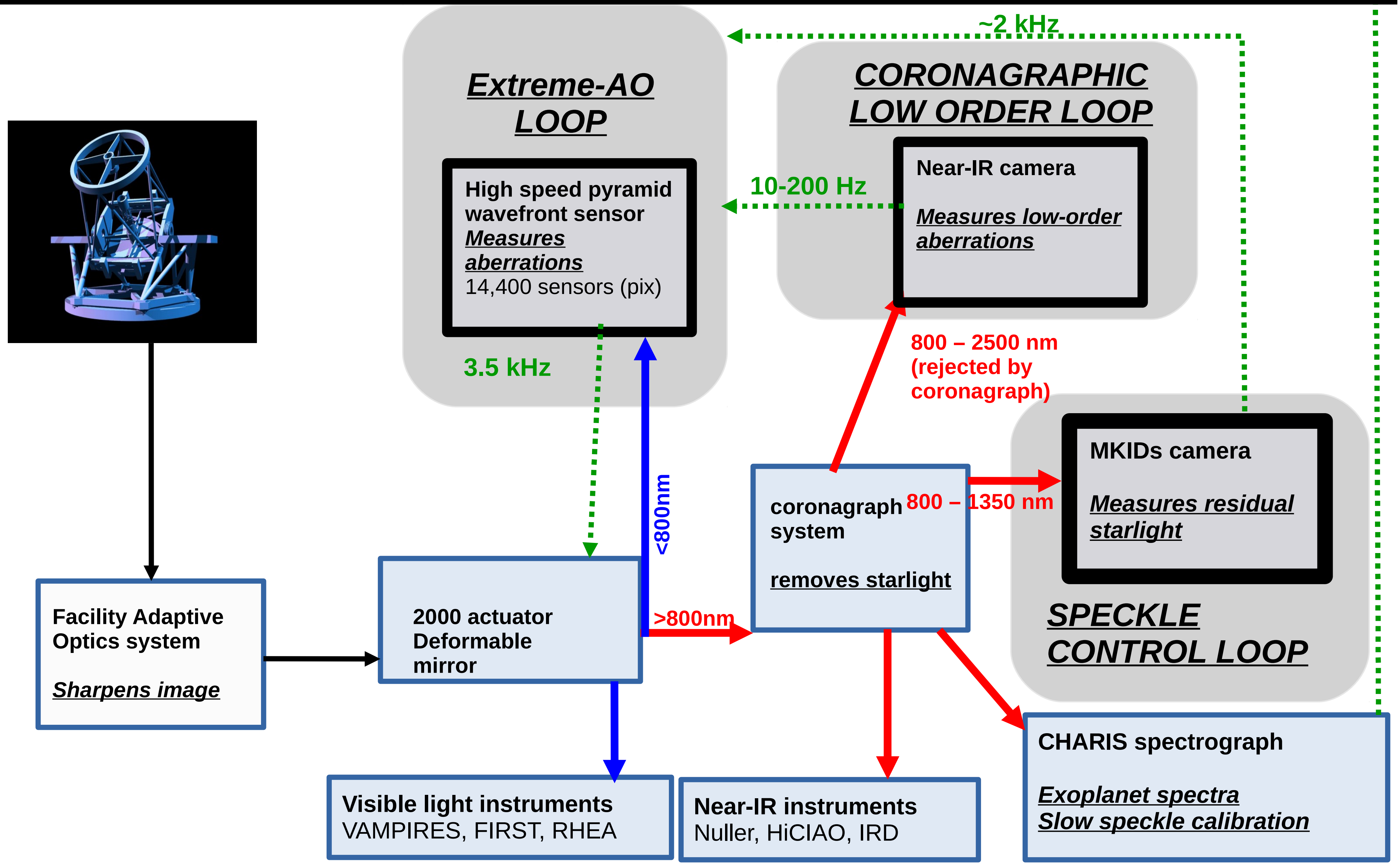
MagAO-X @ Magellan
- Follows similar architecture as SCExAO
- Focus on short wavelength → validation/evaluation of PSI-blue solutions

Possible SPHERE and GPI upgrades
- Pyramid WFS, focal plane WFS, advance AO control

SCExAO Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics



Modules

SCExAO Subaru Coronagraphic Extreme Adaptive Optics

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, with spectral differential imaging capability (h-alpha, SII)

FIRST, non-redundant remapping interferometer, with spectroscopic analysis

RHEA, single mode fiber injection, high-res spectroscopy, high-spatial resolution on resolved stars

IR (950-2400 nm):

HiCIAO - high contrast image (y to K-band)

SAPHIRA - high-speed photon counting imager, (H-band for now)

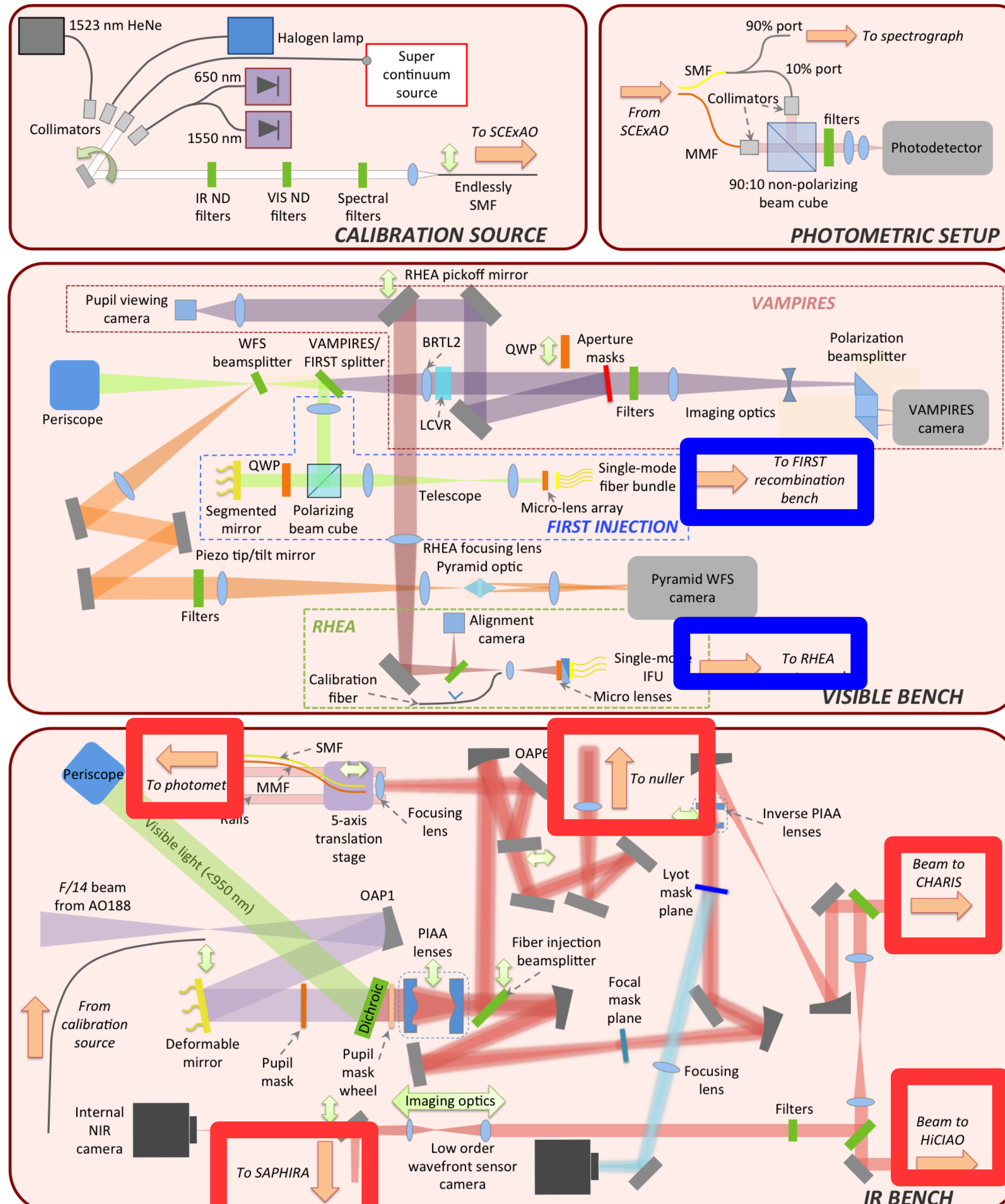
CHARIS - IFS (J to K-band)

MEC - MKIDs detector, high-speed, energy discriminating photon counting imager (y to J-band)

NIR single mode injection, high throughput high resolution spectroscopy. Soon will be connected to the new IRD

Various small IWA (1-3 l/D) coronagraphs for high contrast imaging – PIAA, vector vortex, 8OPM

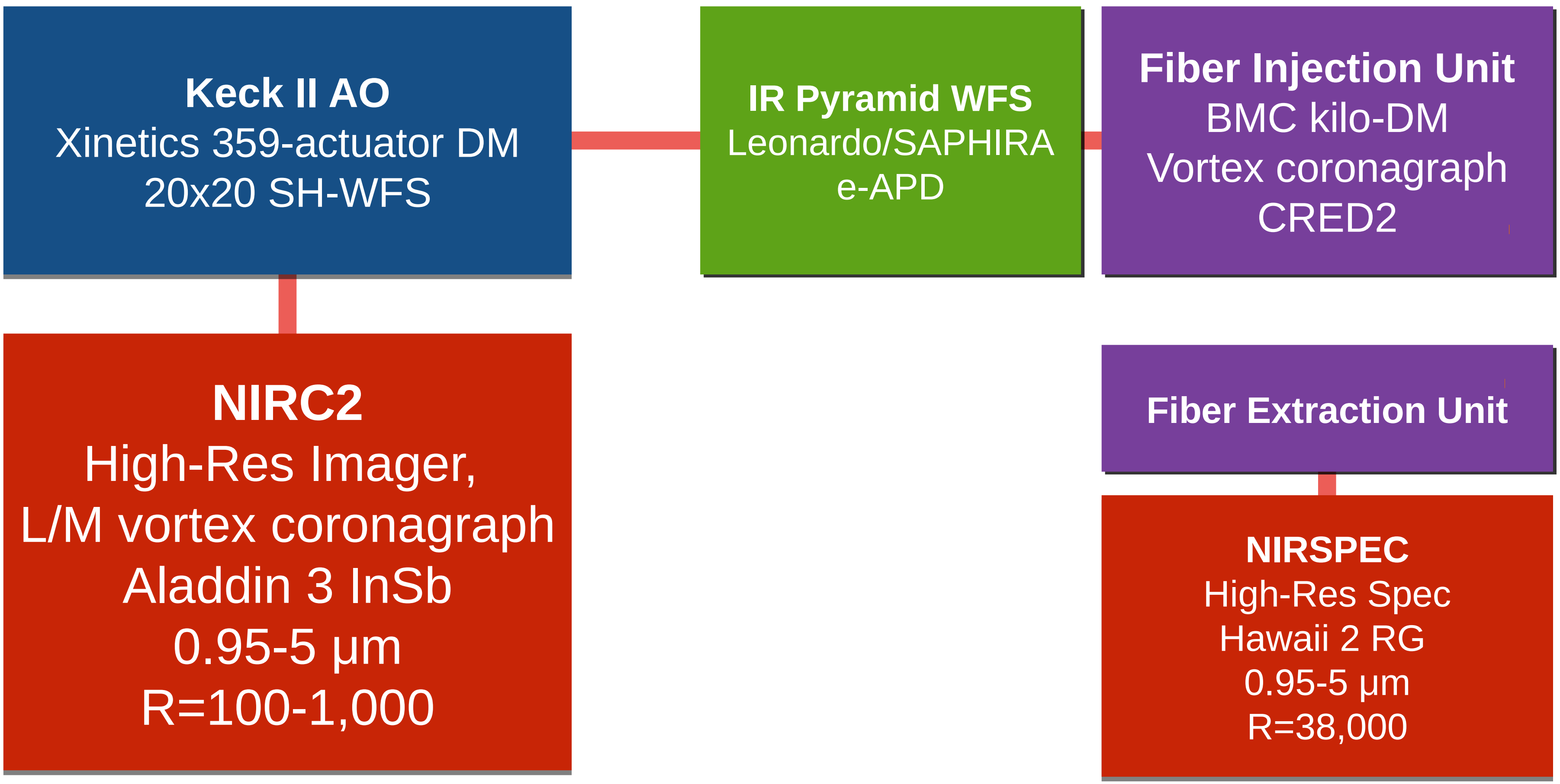
GLINT - NIR nulling interferometer based on photonics



Jovanovic et al, PASP, 127, 890 (2015)

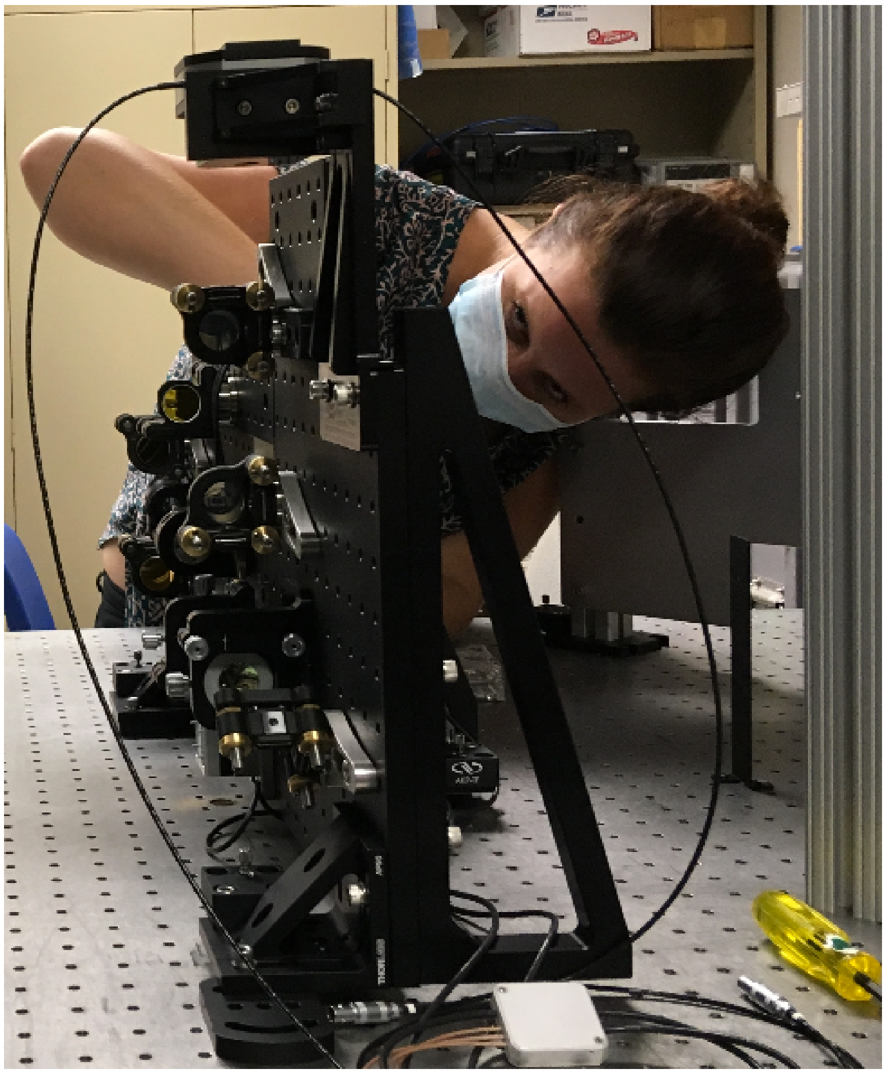
Keck Planet Imager and Characterizer

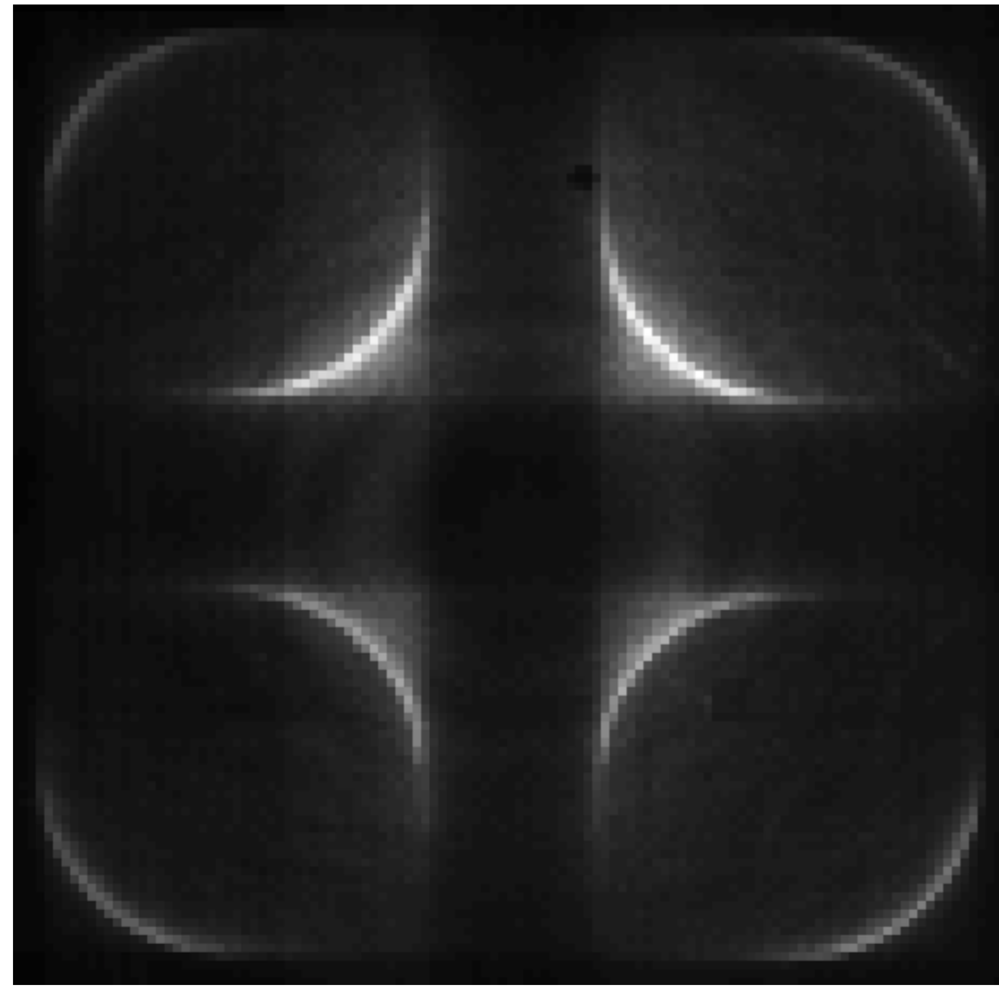
Caltech JPL W. M. KECK OBSERVATORY Maunakea, Island of Hawai'i HEISING-SIMONS FOUNDATION NSF



Giant Planet Imaging

NearIR Pyramid WFS @ KPIC





See Charlotte Bond's invited talk 10703-72, Thursday pm

Next steps, outstanding WFS/C questions

Source faint-ness remains a significant challenge
→ Operating PyWFS at its full efficiency needs to be demonstrated
→ Full benefits of predictive control needs to be quantified

Multi-DM multi-sensor AO operation is challenging
→ How to optimally combine signals
→ Need to develop real-time algorithm, machine learning

Differential detection techniques need to be developed and validated
→ HDC validation
→ CDI validation

High speed focal plane WFS/C is relatively immature
→ Algorithm development
→ On-sky validation
→ Hardware: MKIDs, SAPHIRA, EMCCD

See:
The planetary systems imager: a high-contrast instrumentation platform for the Thirty Meter telescope
Paper 10702-74
Time: 5:00 PM - 5:20 PM
Michael P. Fitzgerald + PSI team