SCExAO Subaru Coronagraphic Extreme Adaptive Optics
すばるコロナグラフ極限補償光学装置

National Institutes of Natural Sciences Astrobiology Center

Imaging Giant Planets with SCExAO and Habitable Planets on TMT

SCExAO team
AO188, CHARIS, MEC, FIRST
VAMPIRES, RHEA, GLINT, SAPHIRA, Kernel, vAPP/Leiden, MagAO-X teams

PSI team

Olivier Guyon

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

Astrobiology Center, National Institutes for Natural Sciences (NINS)

University of Arizona

OUTLINE

Where are we ?

SCExAO overview

- Instrument overview
- Capabilities
- Science observations

Where are we going ?

Imaging Habitable Planets with TMT

How do we get there ?

Prototyping

Enabling game-changing technologies

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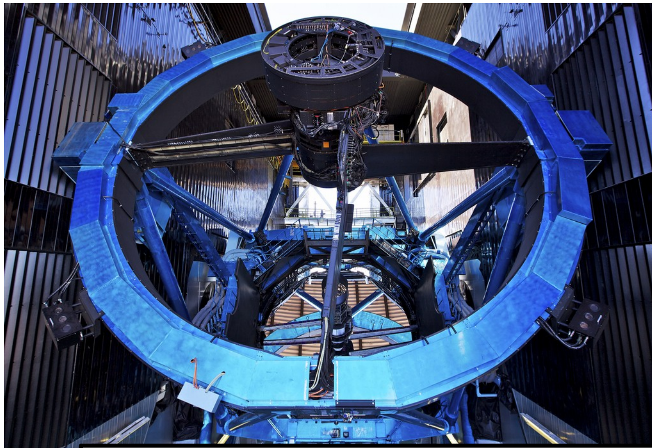
What is SCExAO ?

Leading development platform for High Contrast Imaging



Science instrument in operation for high contrast imaging

Well-supported, matured modules offered for open use

CHARIS (Near-IR)
Princeton, US

VAMPIRES (visible)
Univ. of Sydney, Australia

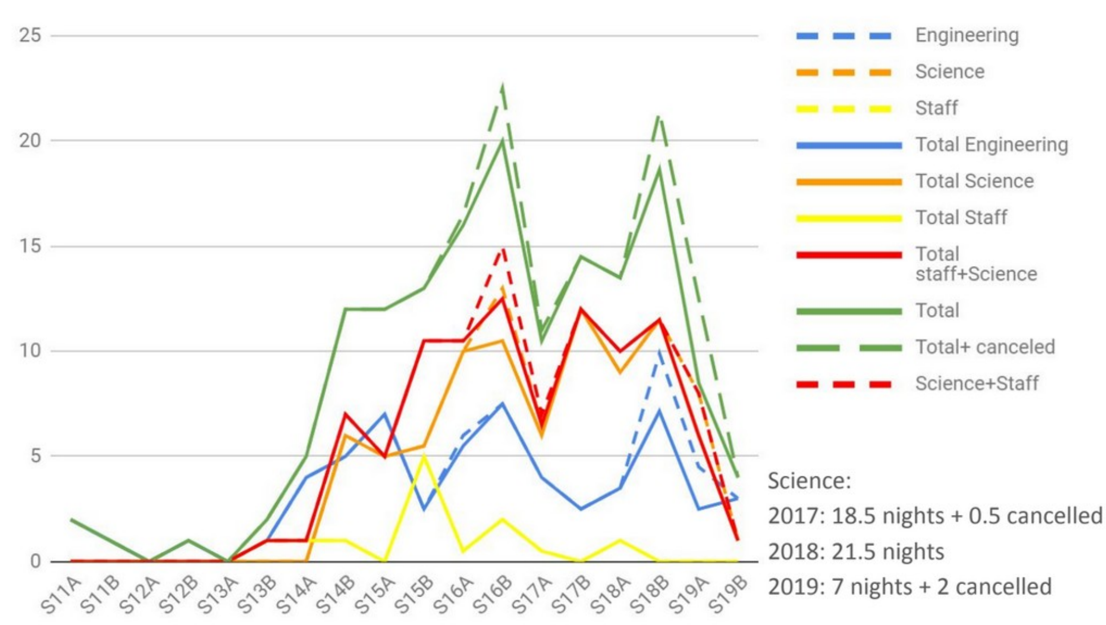
Maturation
Integration
Support

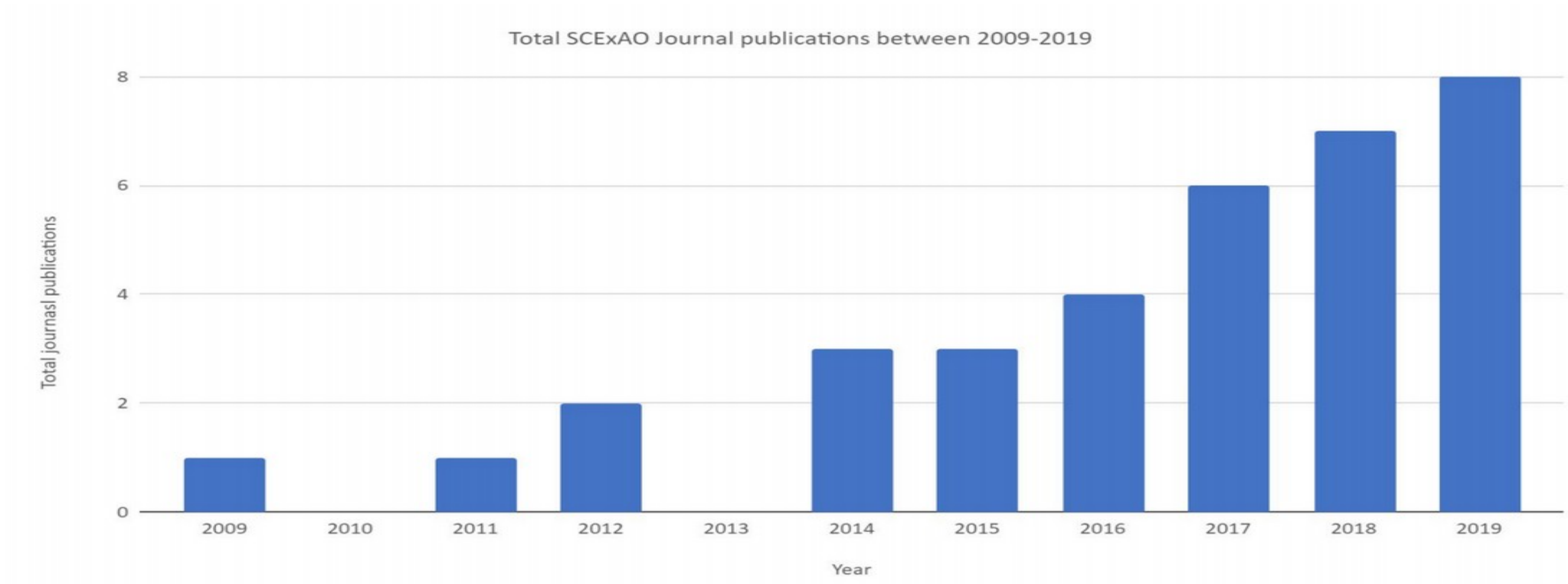
Prototyping for imaging habitable planets with upcoming large telescopes

Modules under development
Prototypes, experiments
Visitor instruments

Observing time & research output

~6 nights per yr for engineering over last few yrs. Currently ~5 refereed technical papers/yr using SCExAO as technology maturation testbed (mosty on-sky).





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Team

Subaru Telescope, National Astronomical Observatory of Japan

Olivier Guyon (PI), Julien Lozi, Sebastien Vievard, Ananya Sahoo, Tomoyuki Kudo, Thayne Currie

Local (Subaru/NAOJ) operation team manages core hardware and software
Operates instrument, fixes things

Full team includes R&D collaborations, modules support, science support

VAMPIRES
P. Tuthill
B. Norris
M.A. Martinod

FPM DESIGN
J. Knight

AO188
Y. Minowa
Y. Hayano
C. Clergeon
Y. Ono
E. Mieda

KERNEL
F. Martinache
M. N'Diaye
R. Laugier
N. Cvetojevic

FIRST
E. Huby
N. Cvetojevic
S. Lacour
T. Kotani
G. Martin
V. Lapeyrere
D. Rouan
G. Perrin
F. Marchis
G. Duchene

PDI
T. Kudo
F. Snik
B. Norris

Science support / SEEDS
T. Currie
M. Tamura
J. Zhang

COCORO
N. Murakami
O. Fumika
N. Baba
T. Matsuo
J. Nishikawa
M. Tamura

RHEA
M. Ireland
C. Schwab
T. Anagnos
A. Rains
T. Feger
D. Coutts

CACAO
J. Males
S. Cetre
A. Sevin
D. Gratadour

VVC
J. Kuhn
E. Serabyn
G. Singh
J. Hagelberg
D. Defrère
D. Mawet

GLINT
B. Norris
M.A. Martinod
T. Lagadec
N. Cvetojevic
S. Gross
A. Arriola
T. Gretzinger
P. Tuthill
M. Withford
J. Lawrence

MKIDS
B. Mazin
A. Walter
N. Fruitwala
A. Butler
S. Meeker
J. Massie
M. Strader
J. Van Eyken
K. Davis

vAPP
F. Snik
D. Doelman
S. Bos
E. Por
C. Keller

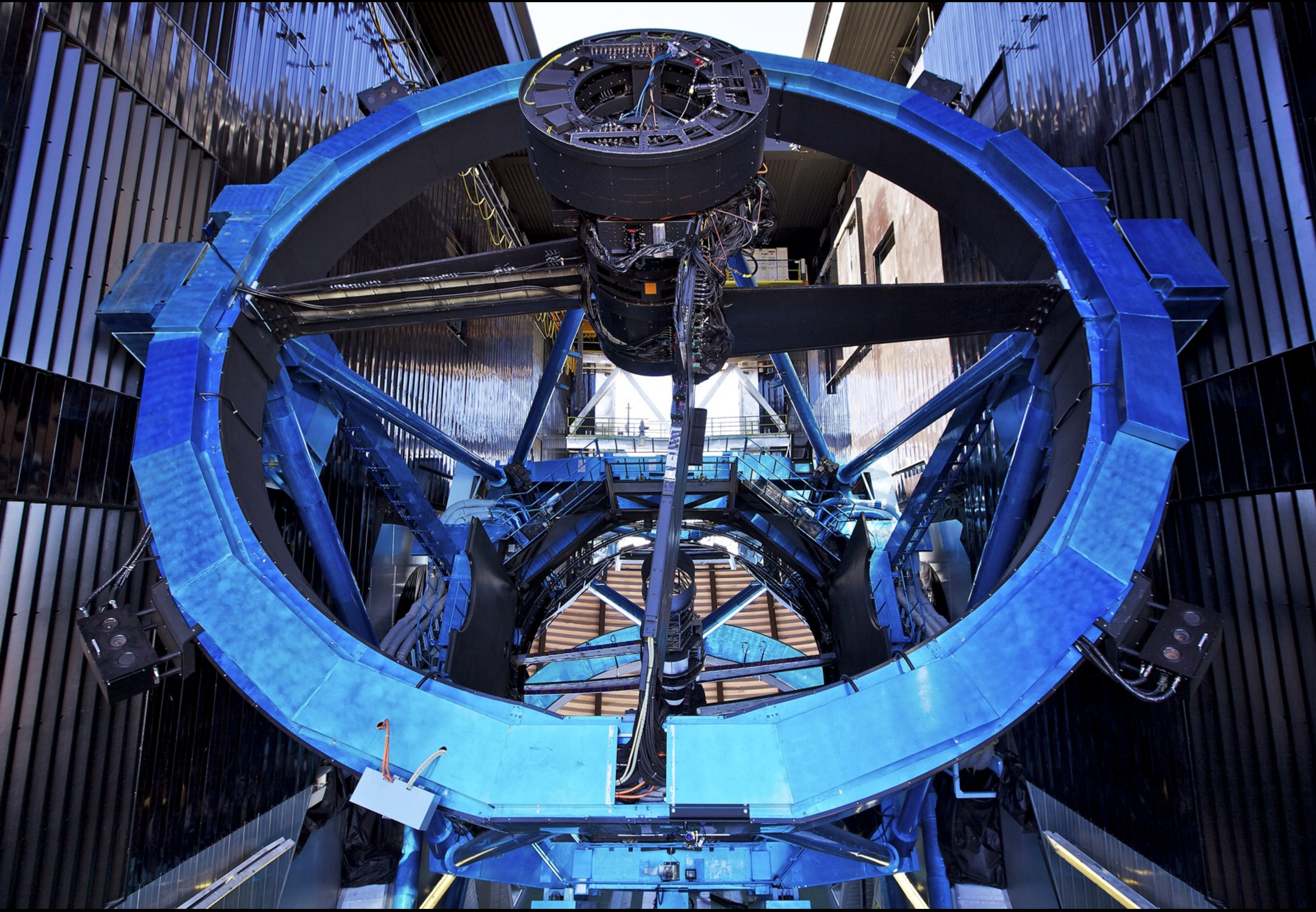
LDFC
T. Currie
S. Bos
K. Miller

IRD/REACH
H. Kawahara
T. Kotani
M. Ishizuka
T. Kudo

SAPHIRA
D. Hall
S. Jacobson
M. Chun
I. Baker

CHARIS
J. Kasdin
T. Groff
J. Chilcote
T. Brandt
M. Galvin
M. A. Peters

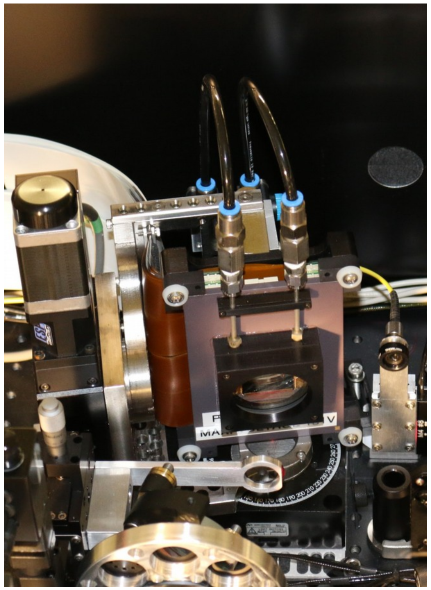
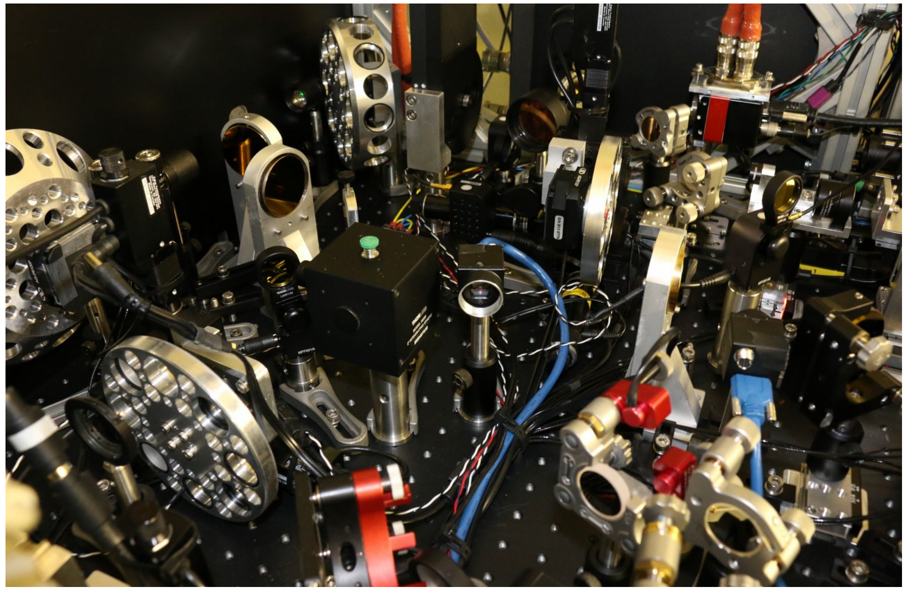
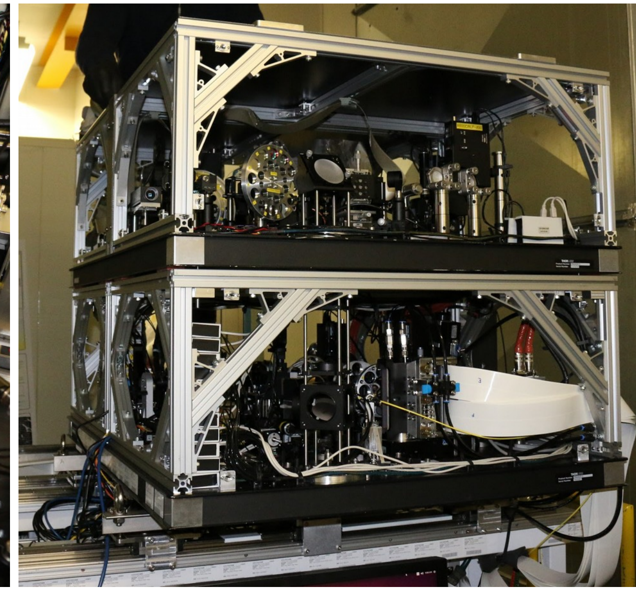
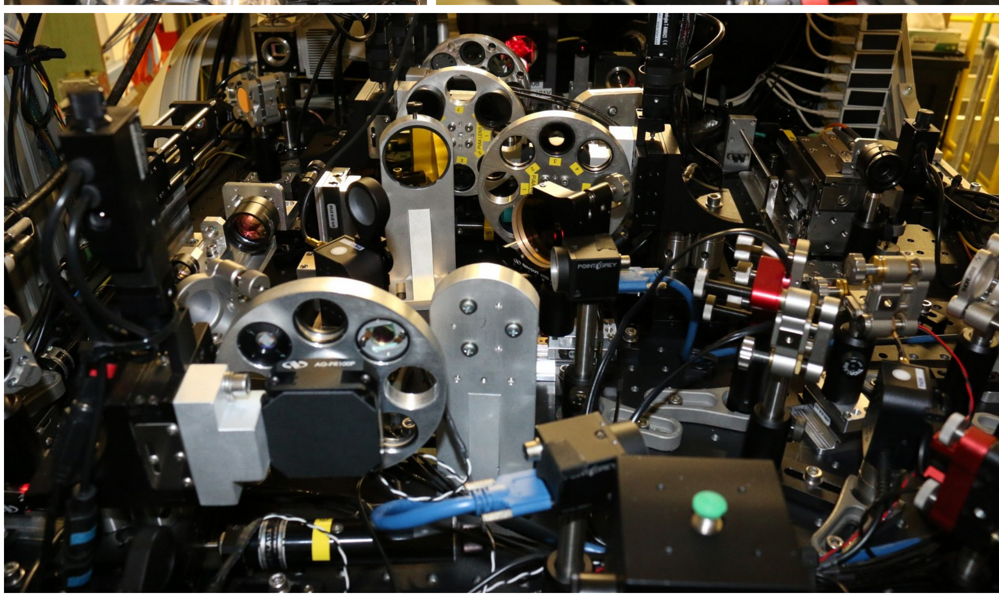
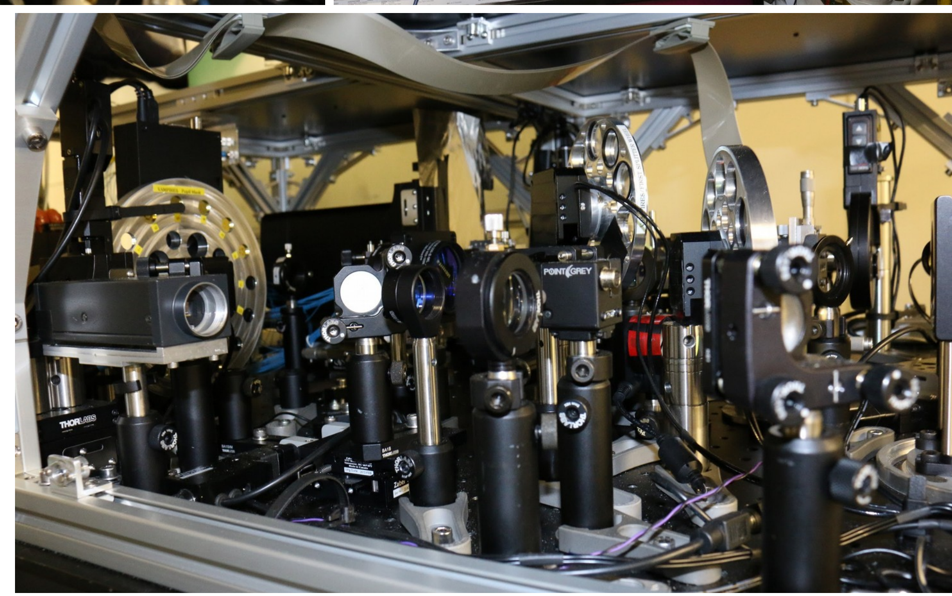
Macquarie University · l'Observatoire de Paris · Australian National University · Princeton University · UCSB · Hokkaido University · Observatoire de la Côte d'Azur · The University of Arizona



Hardware


DANGER
SERIOUSLY BRILLIANT MIND AT WORK
HIGH PRECISION DEVICES, INC.
SCExAO
HPD
DENALI Model 102 Cryostat

Hardware

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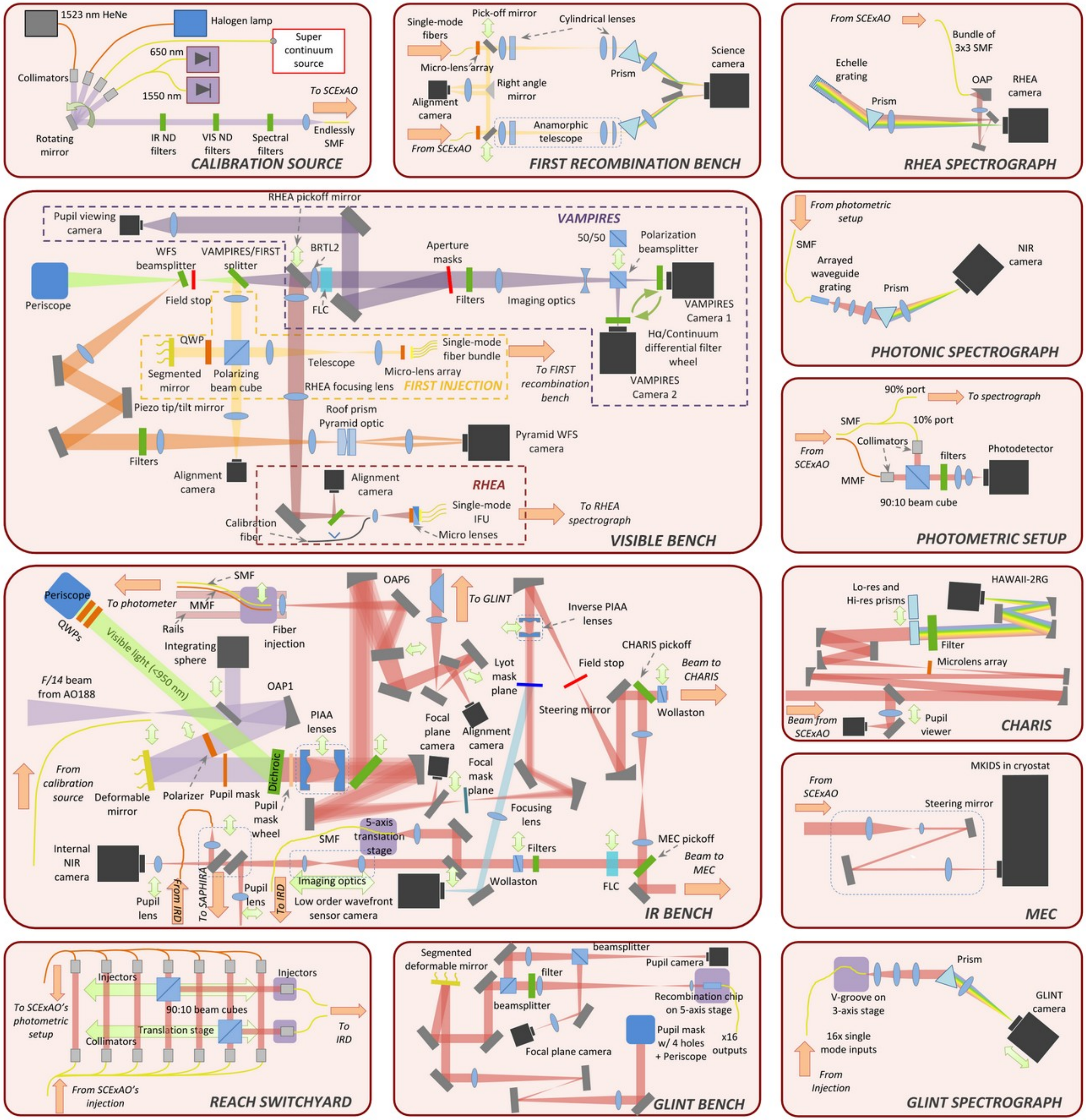
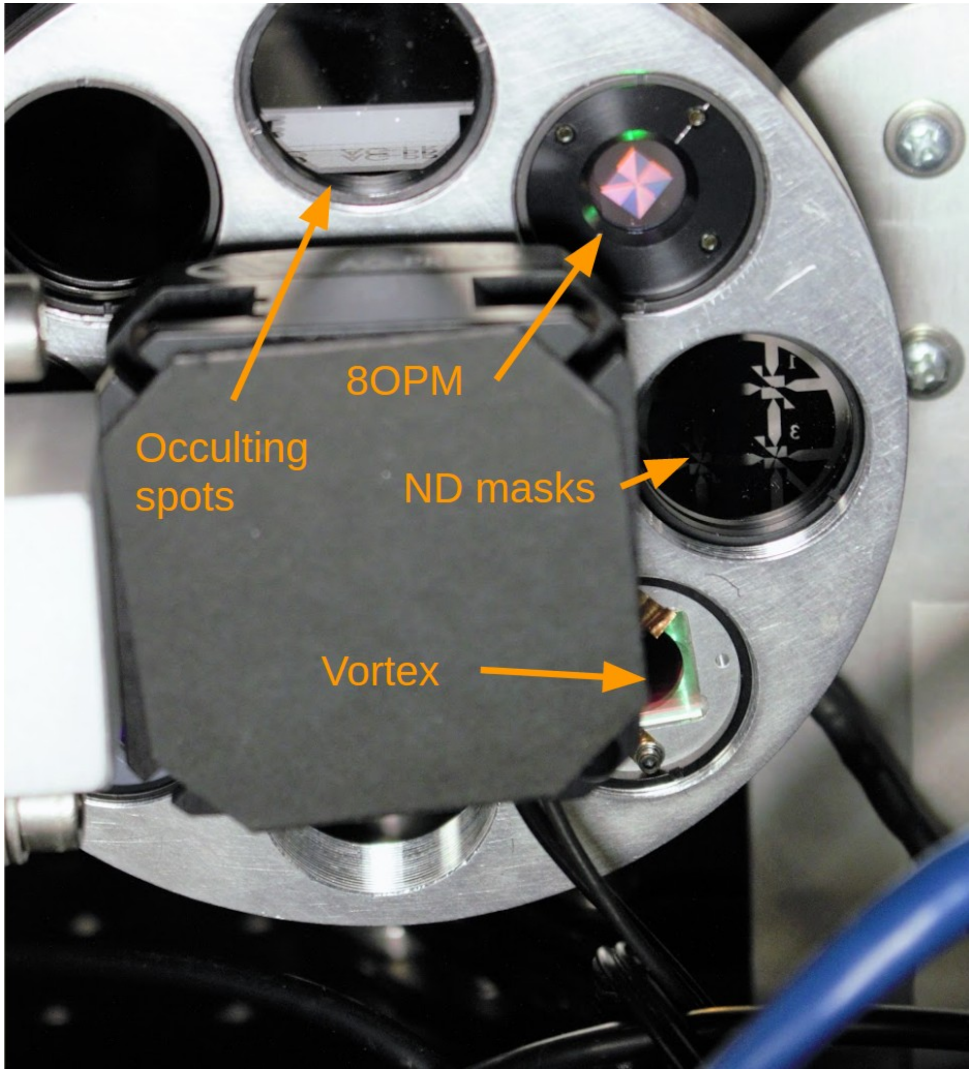
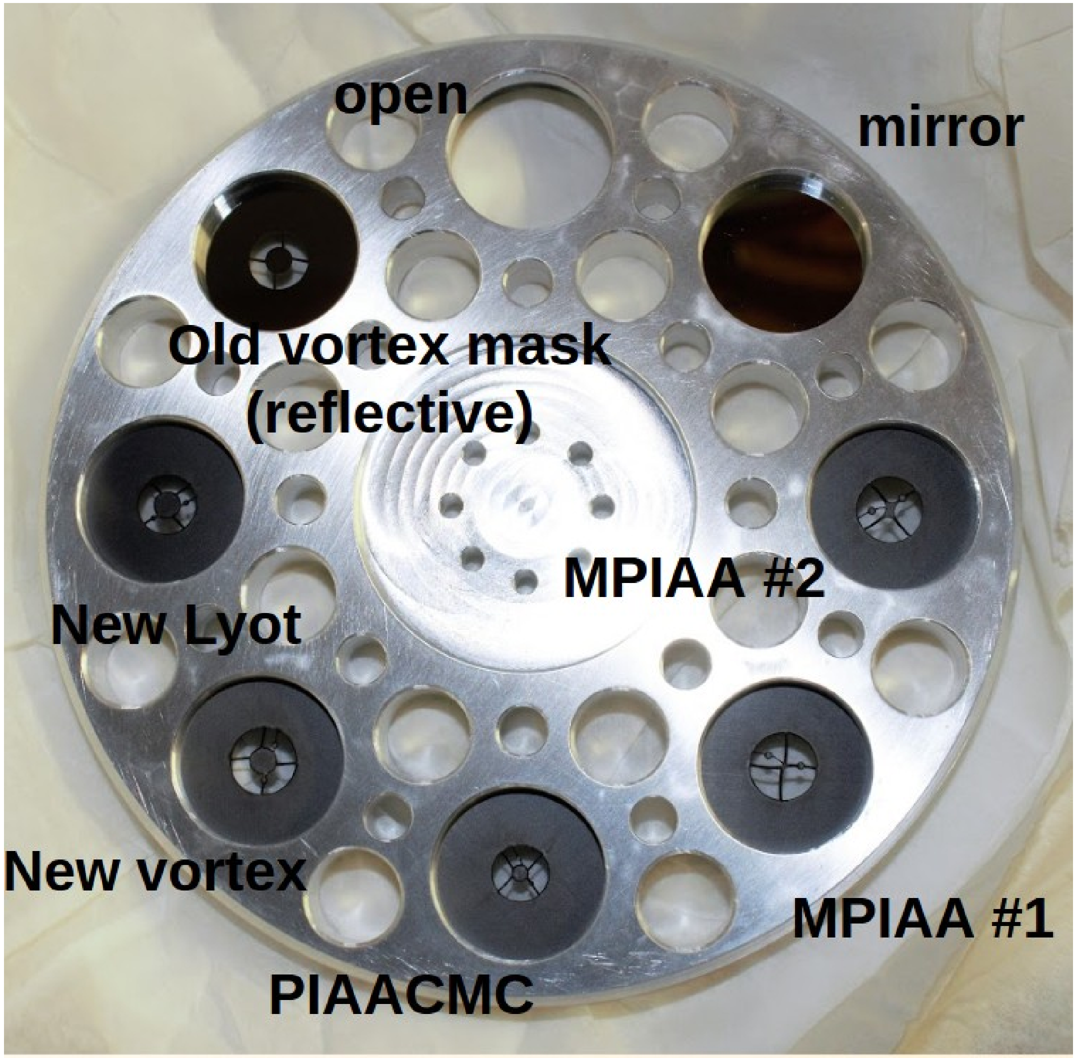
Hardware



Coronagraphy





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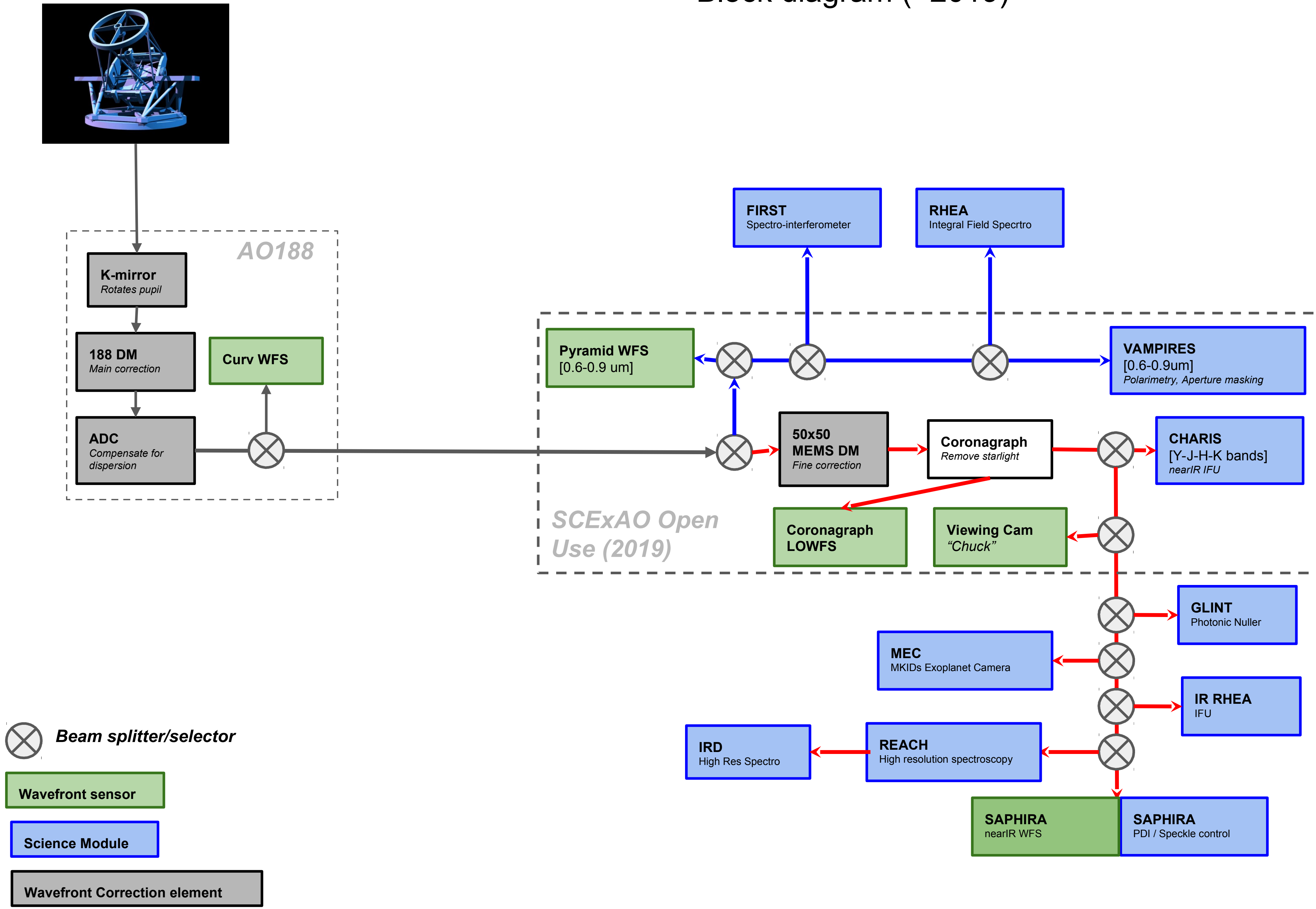
System Overview

Block diagram (~2019)



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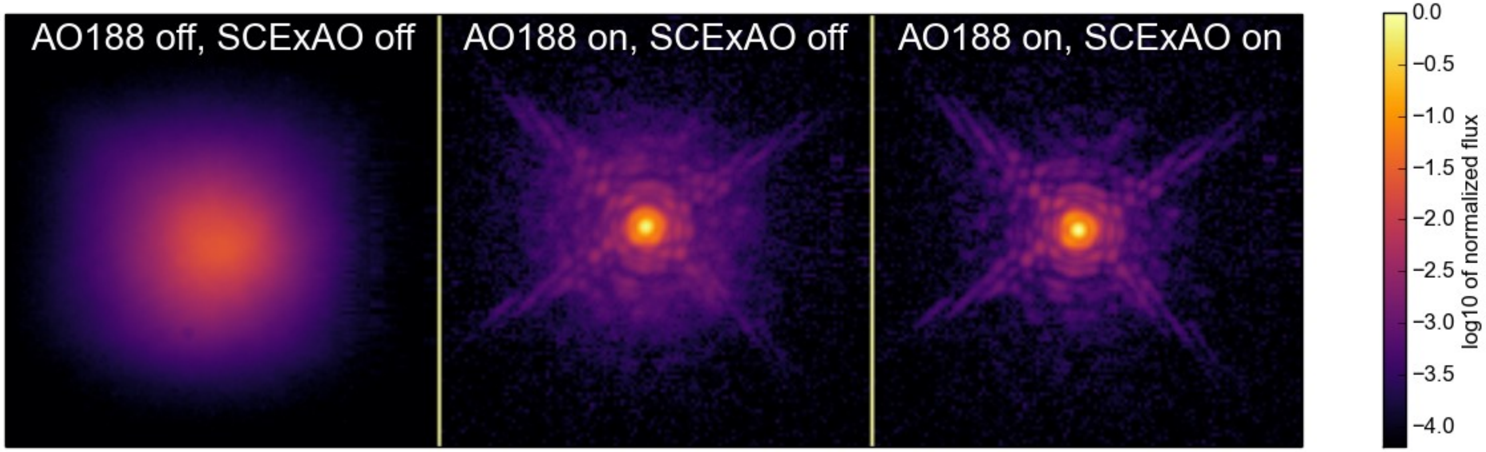
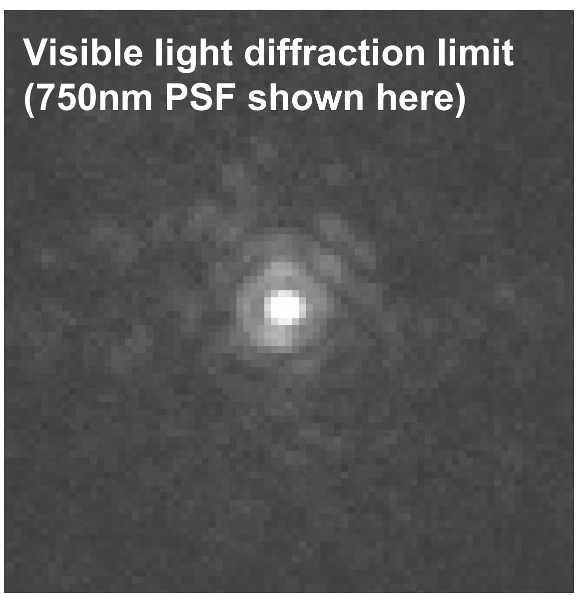
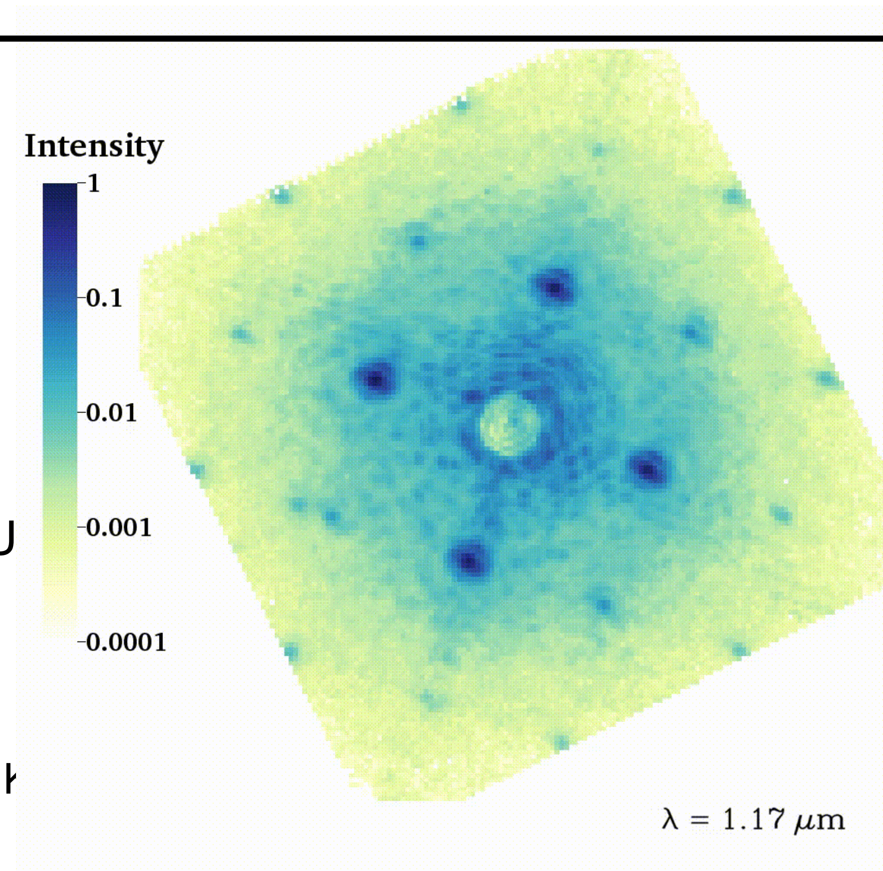
ExAO Image Quality



VAMPIRES instrument
PDI, SDI
Aperture masking



CHARIS Near-IR IFU
2" FOV
16.2mas / lenslet
J/H/K bands
R=19 (low res, J+H+K)
R=70 (high res, J, H or K



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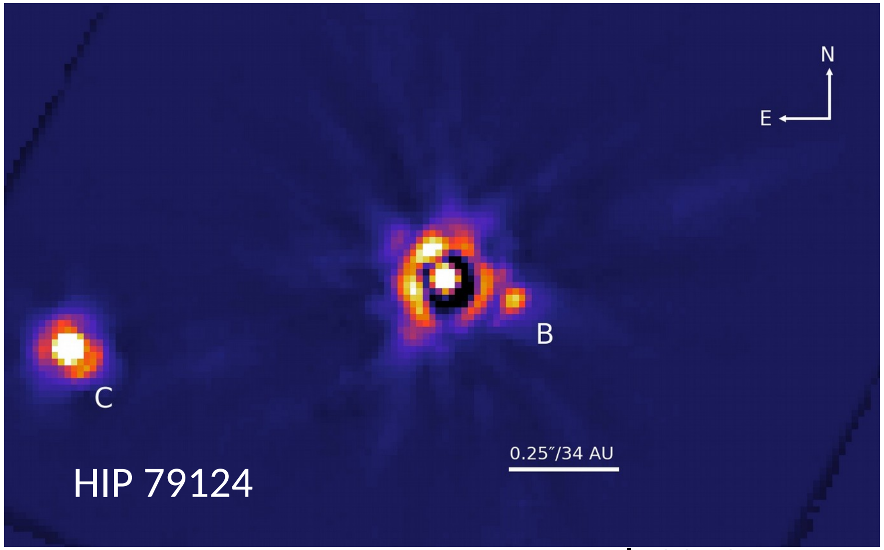
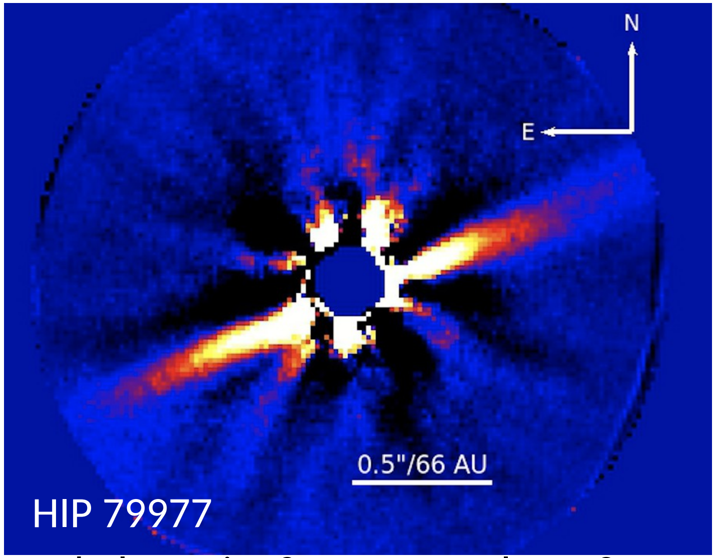
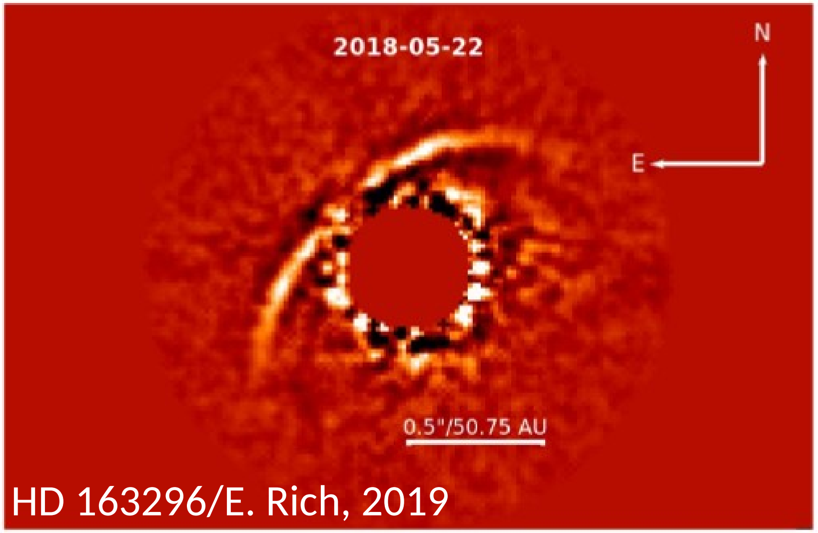
NearIR Images



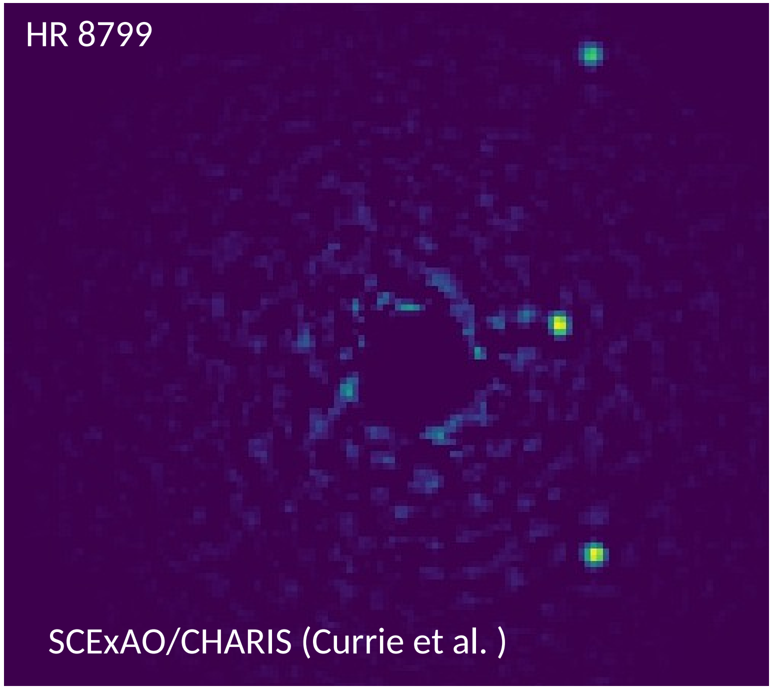
Asensio-Torres, Currie, & Janson et al. 2019



Goebel, Currie, & Guyon et al. 2018



HD 163296/E. Rich, 2019



SCExAO/CHARIS (Currie et al.)

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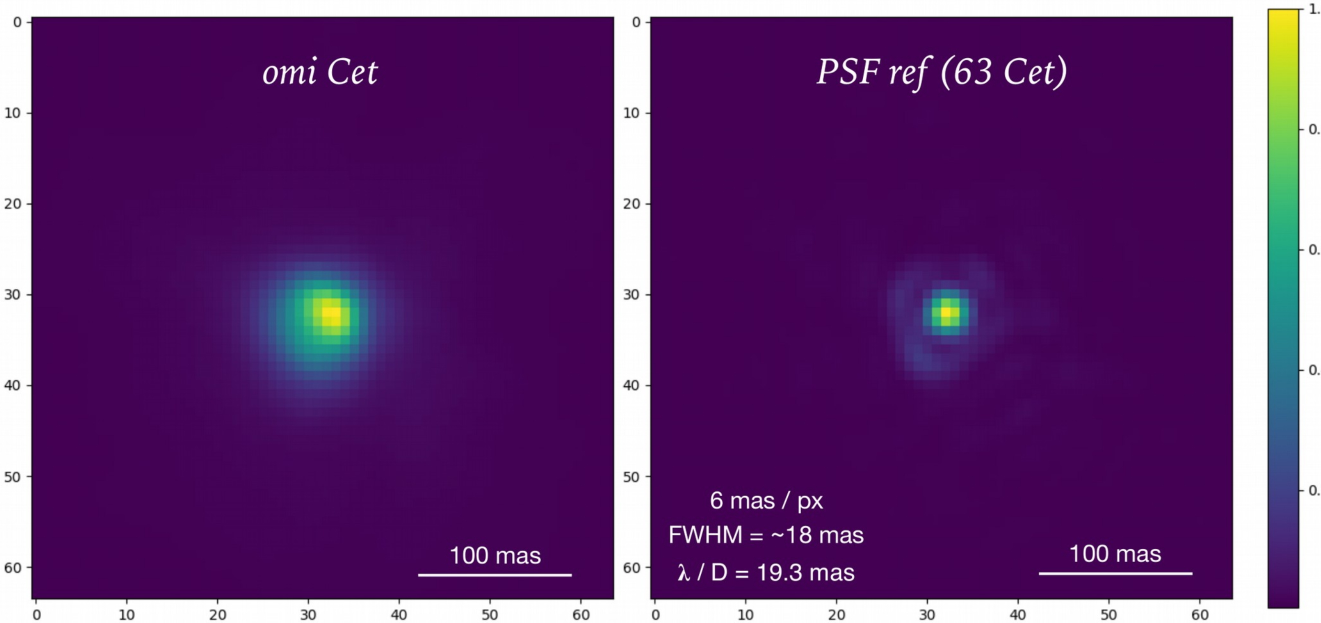
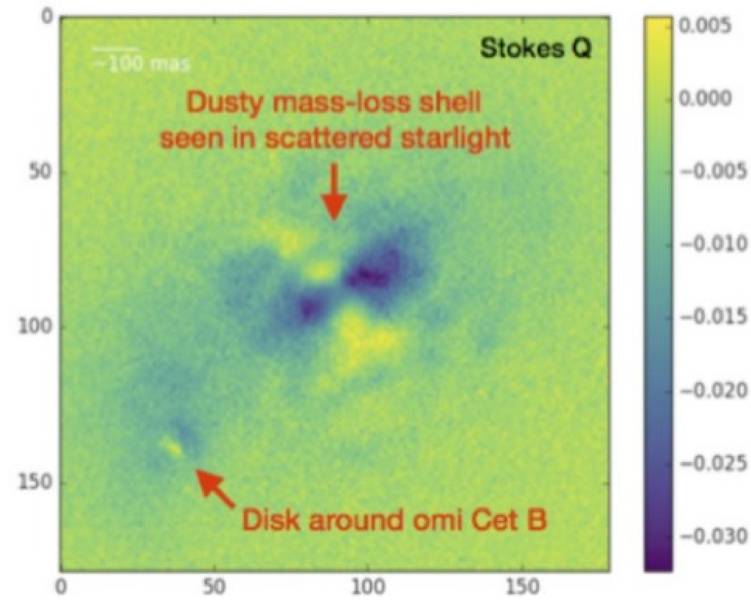
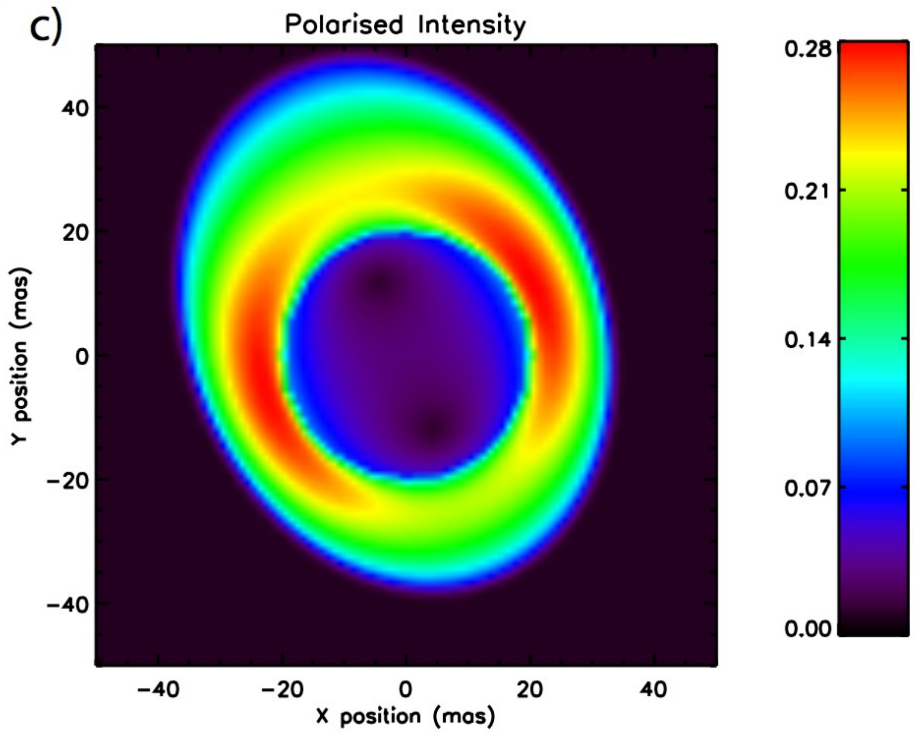
Visible (VAMPIRES)



Observed 12/09/2017



μ Cephei



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

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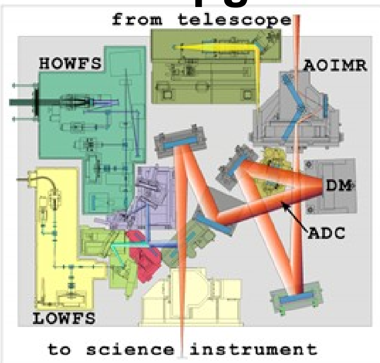
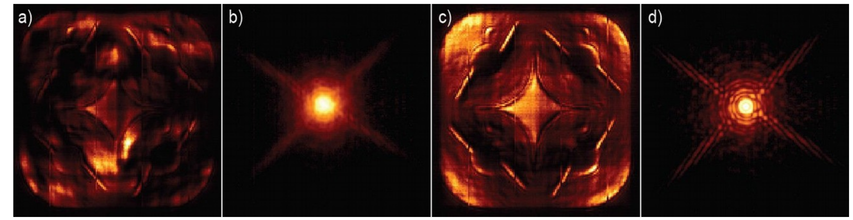
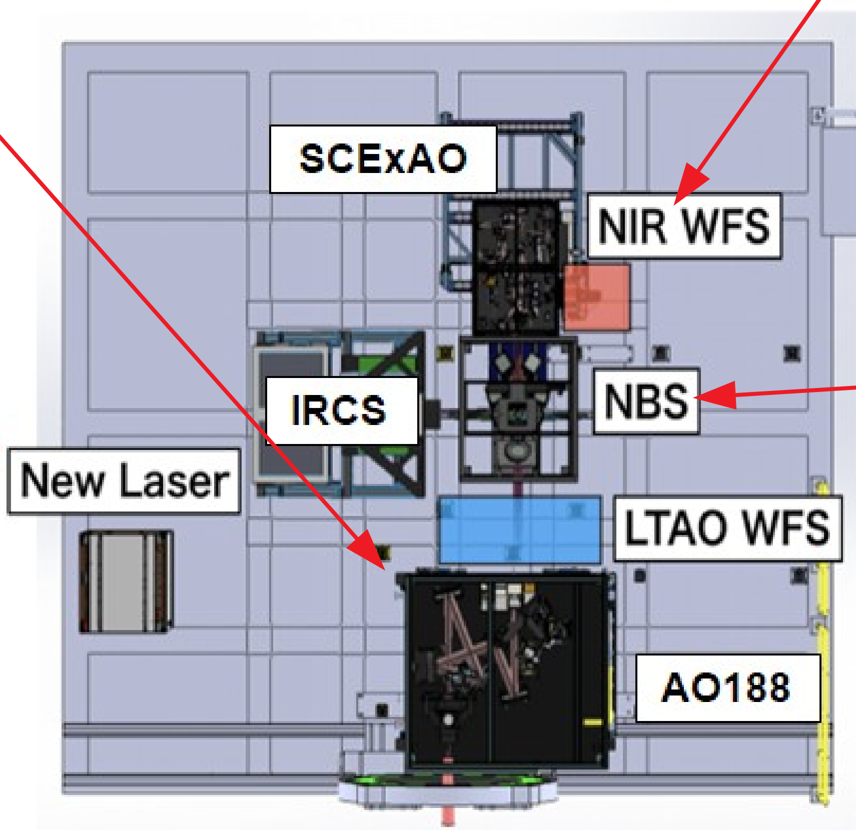
Upgrades (next ~2yr)

AO 188 upgrades (RTC, 64x64 DM)

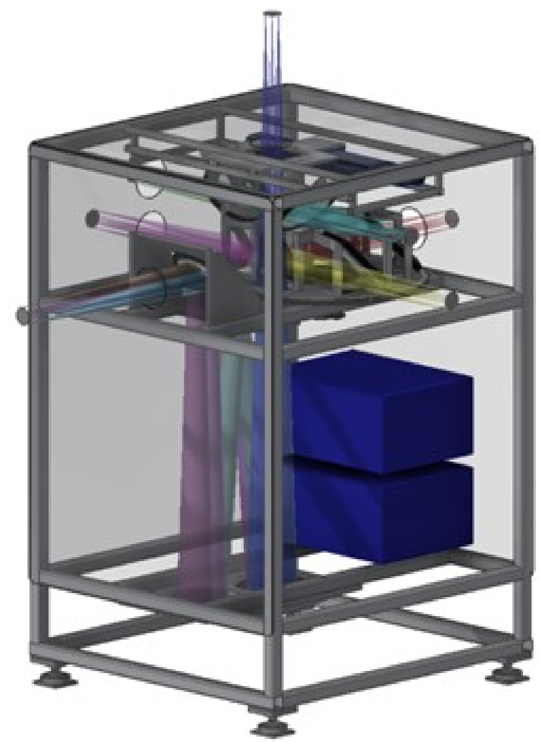


Near-IR Wavefront Sensor





Beam Switcher



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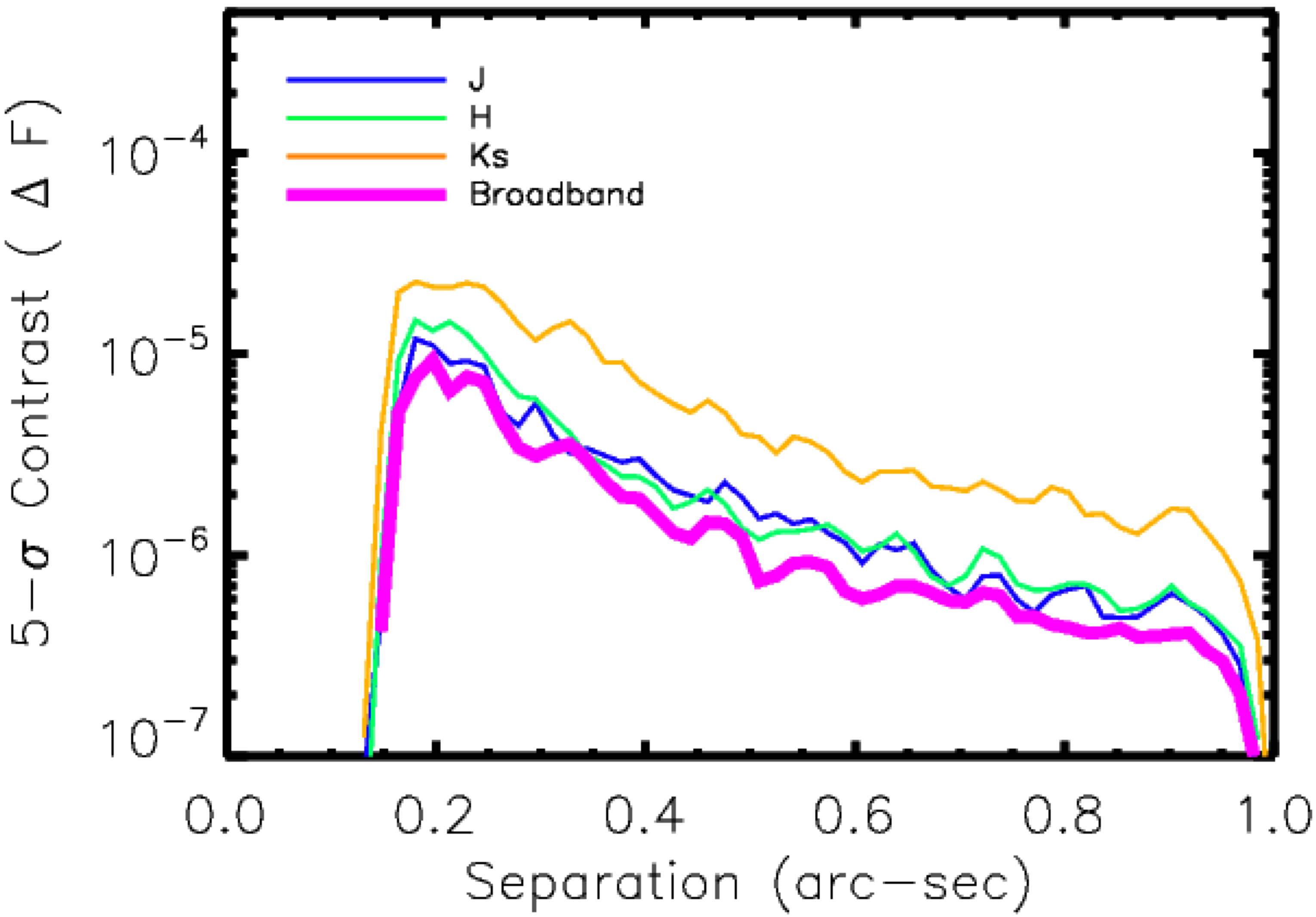
Current Contrast Limit

45mn CHARIS sequence. Data reduction by Thayne Currie.



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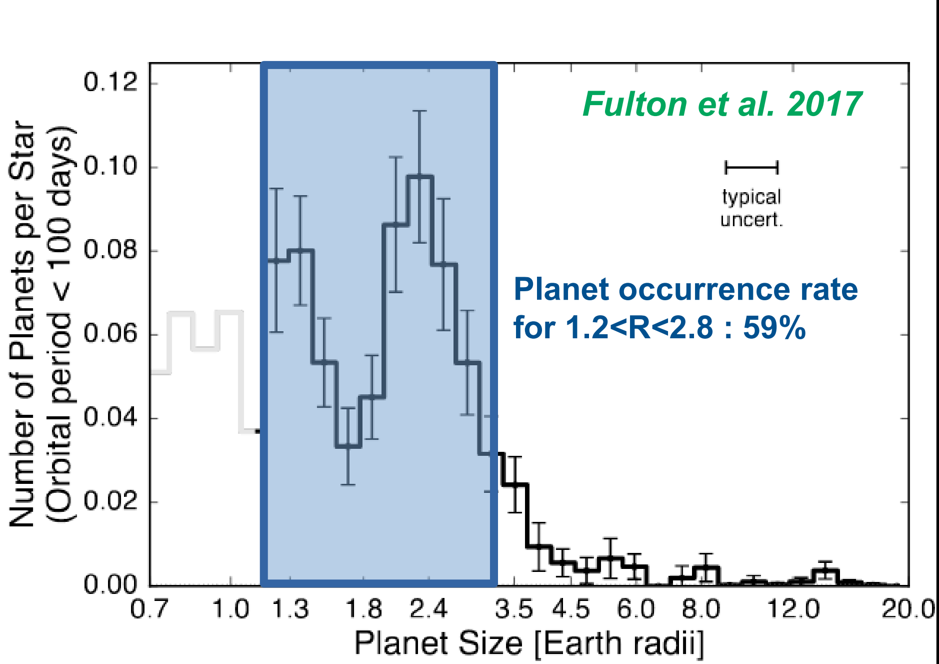
Exoplanet Imaging

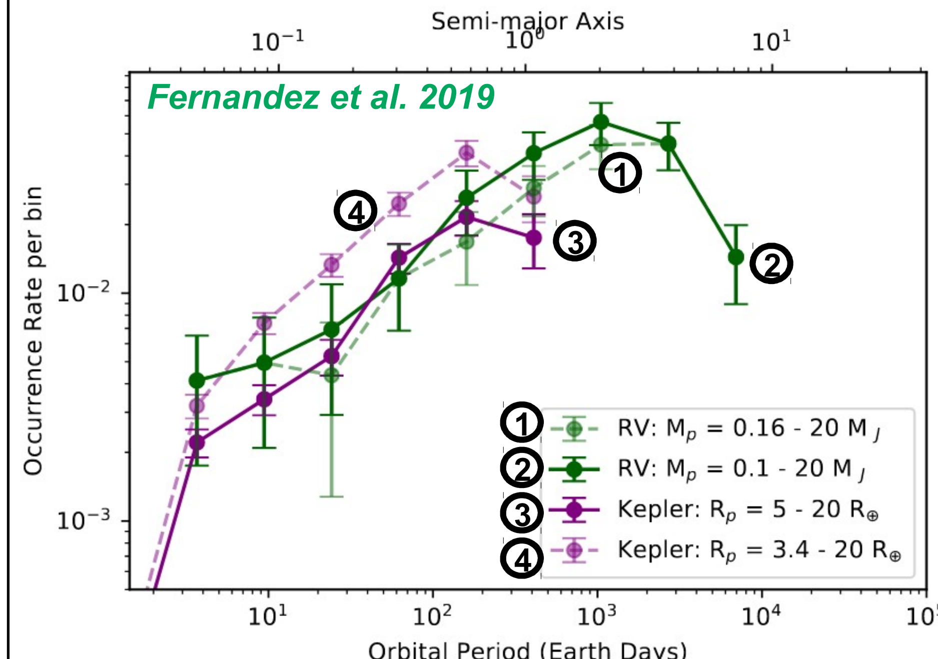
Improved contrast, smaller angular separations →
Lower mass / older planets on smaller orbits

Reflected light imaging of a few nearby giant planets

Small-size planets are abundant



Massive planets are mostly near 1-4 AU



OUTLINE

Where are we ?

SCExAO overview

Instrument overview

Capabilities

Science observations

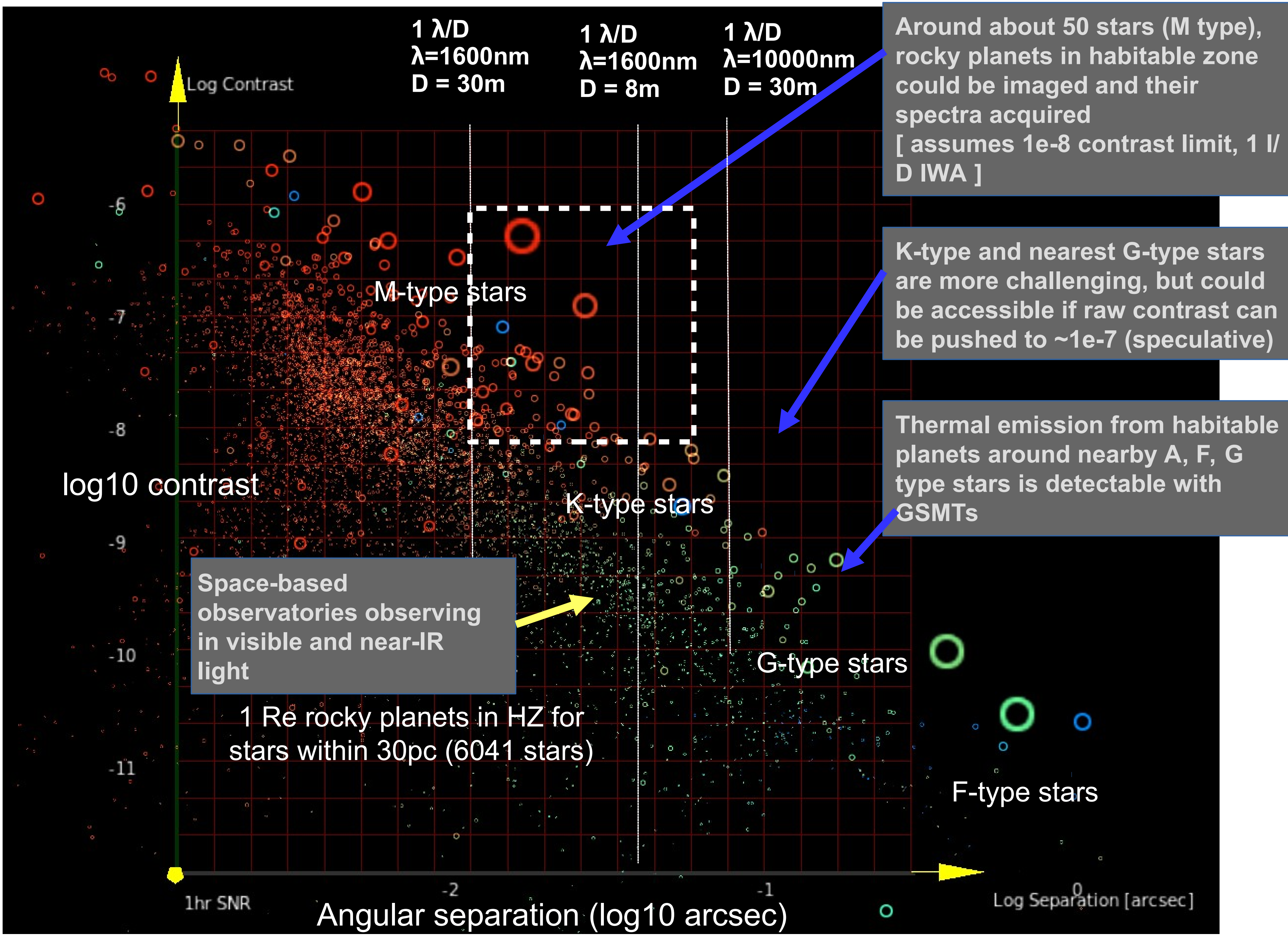
Where are we going ?

Imaging Habitable Planets with TMT

How do we get there ?

Prototyping

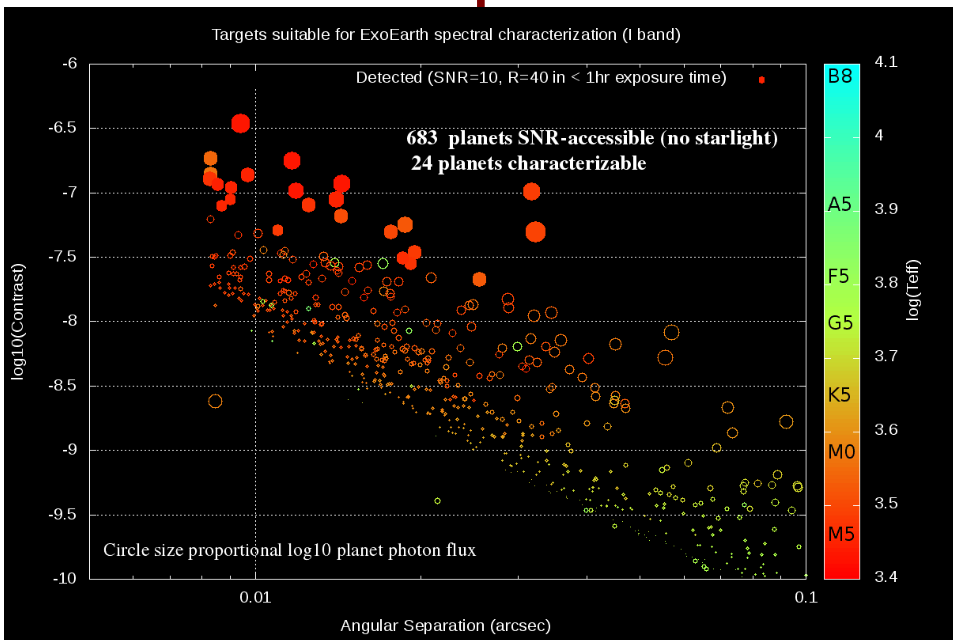
Enabling game-changing technologies



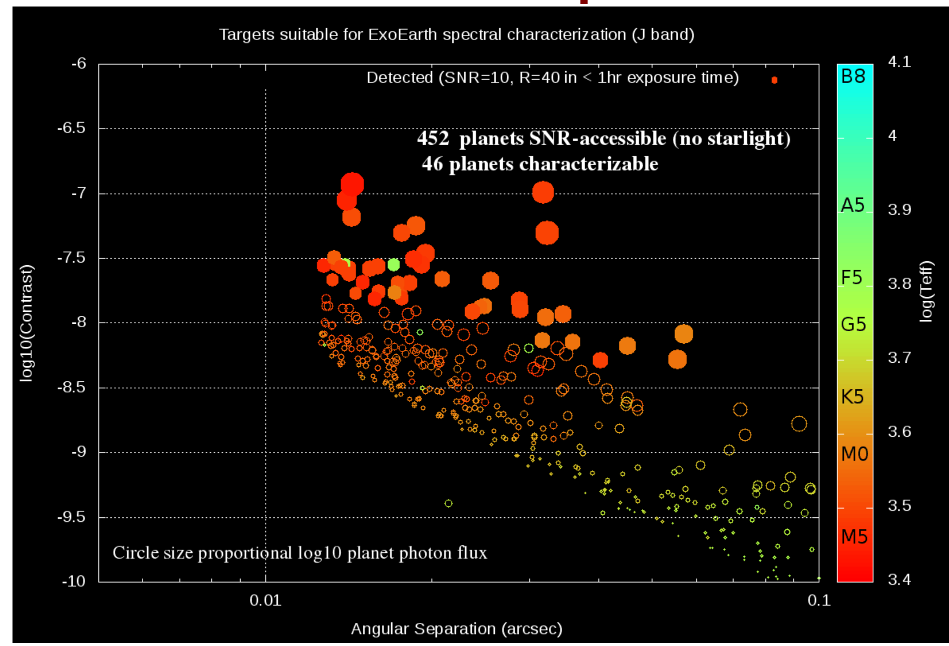
1 λ/D
λ=1600nm
D = 30m
1 λ/D
λ=1600nm
D = 8m
1 λ/D
λ=10000nm
D = 30m
Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]
K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (speculative)
Thermal emission from habitable planets around nearby A, F, G type stars is detectable with GSMTs
Log Contrast
log10 contrast
M-type stars
K-type stars
G-type stars
F-type stars
Space-based observatories observing in visible and near-IR light
1 Re rocky planets in HZ for stars within 30pc (6041 stars)
-6
-7
-8
-9
-10
-11
-2
-1
0
1hr SNR
Angular separation (log10 arcsec)
Log Separation [arcsec]

Optimal Imaging Wavelength

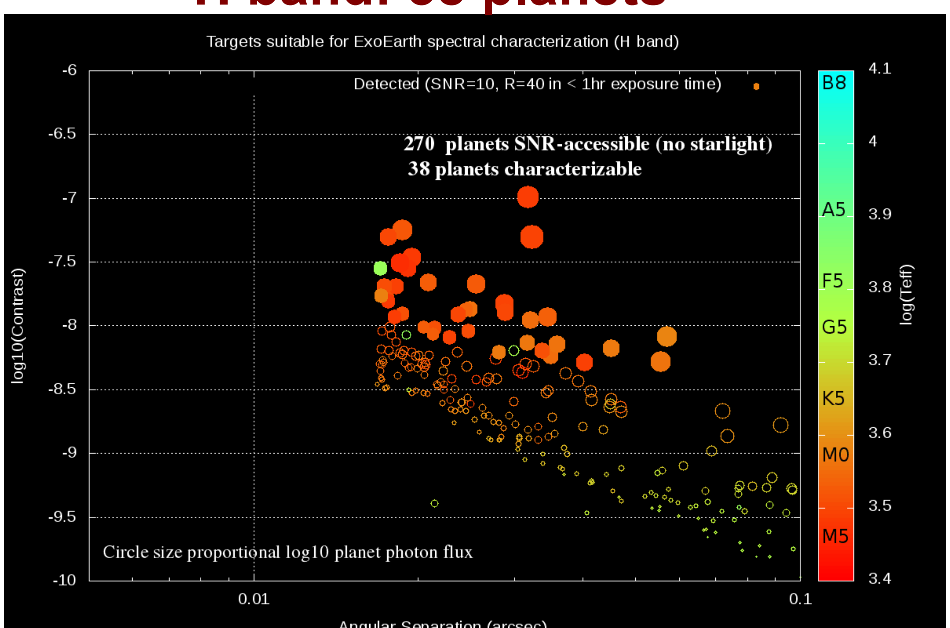
I band: 24 planets



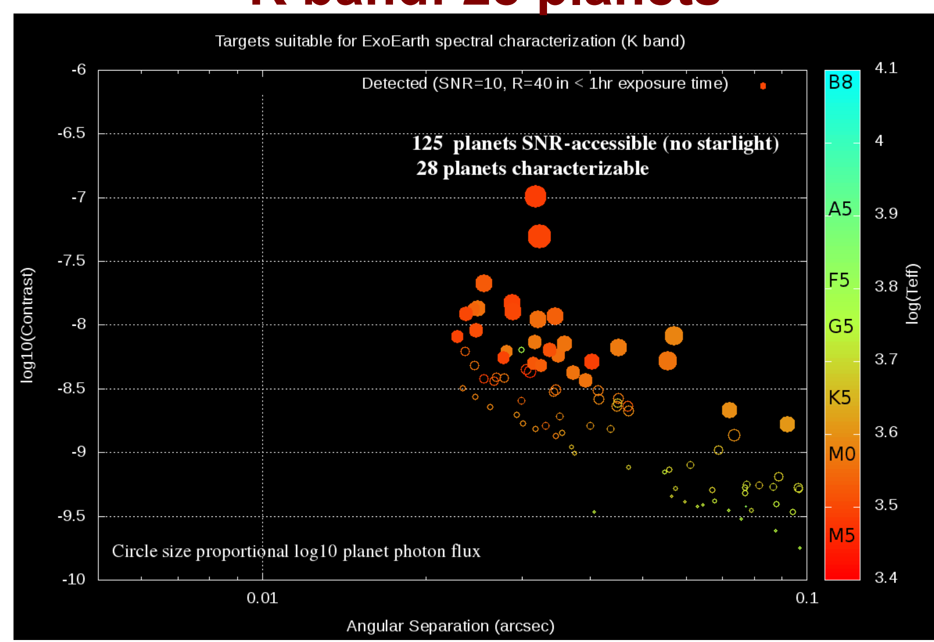
J band: 48 planets



H band: 38 planets



K band: 28 planets

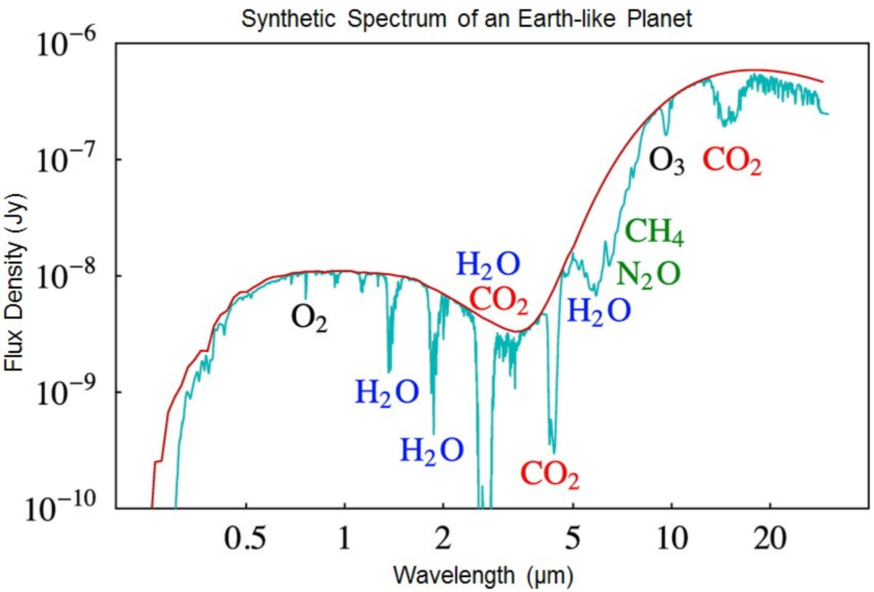


Targets

ASSUMPTIONS for 30m Telescope

- SNR is limited by photon noise from both starlight and planet light
- Raw contrast limited by residual WF errors (not by coronagraph defects)
- ExAO system delivers 1e-6 raw contrast at 1um
- Every star has one Earth analog

Raw contrast scales as lambda^-2, IWA scales as lambda
SNR limit: SNR=10 at R=40 in 1hr



KEY FINDINGS

- Best targets are M-type stars (M0-M6)
- Optimal wavelength is near-IR (especially J & H bands), suitable for detection of O2 (1.27um), H2O, CH4, CO2

PSI

ExAO WFS: 1e-5 raw contrast required

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

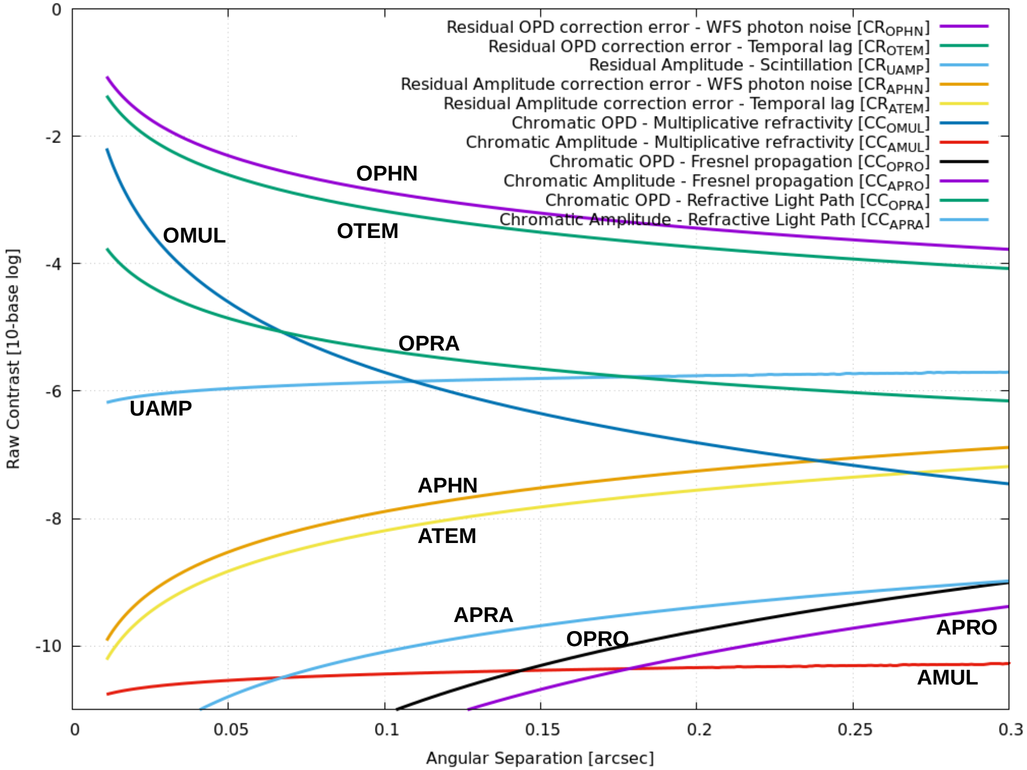
[a]Optimal bandwidth selected among standard astronomical spectral bands (U, B, R, I, J, H). Assumes fixed relative spectral bandwidth $d\lambda/\lambda$. Central wavelength listed; [b]Assuming 10% effective spectral band at optimal sensing wavelength, main sequence star at 10pc.

KEY FINDINGS

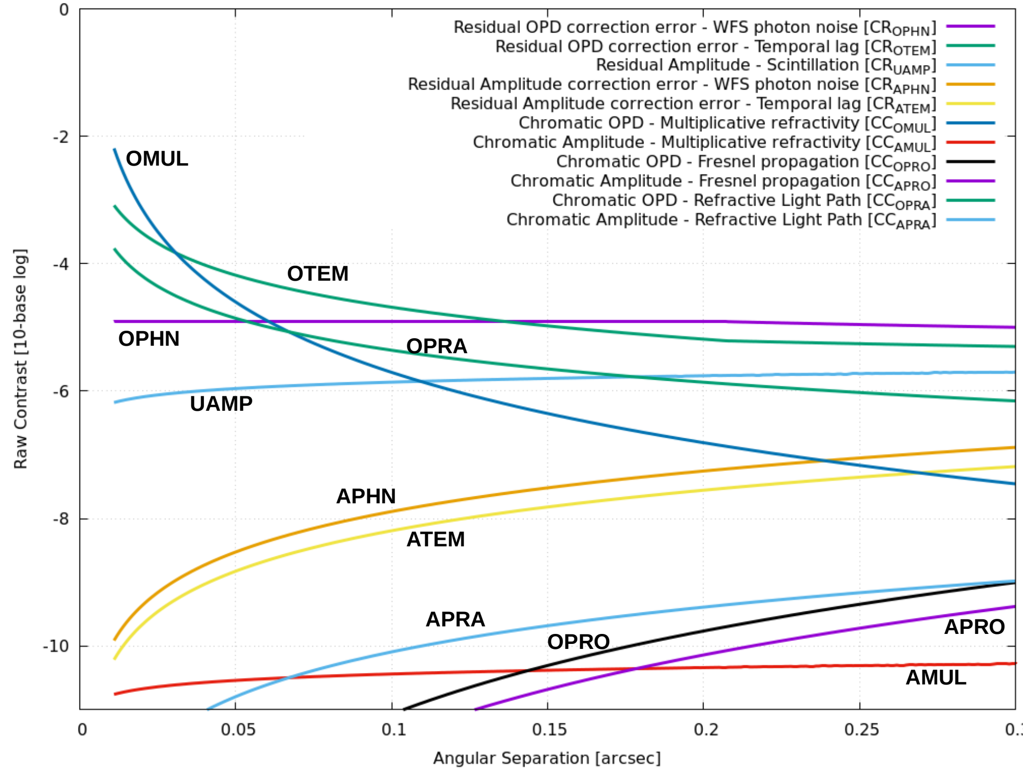
- WFS at red/NearIR (0.6-1um), optimal for M-type stars
- IWA should be ~1.5 l/D
- Raw contrast <1e-5 (ideally 1e-6), detection limit ~1e-8
- ExAO loop running on I~8 target

ExAO raw contrast error terms

Seeing-limited WFS, 1 kHz

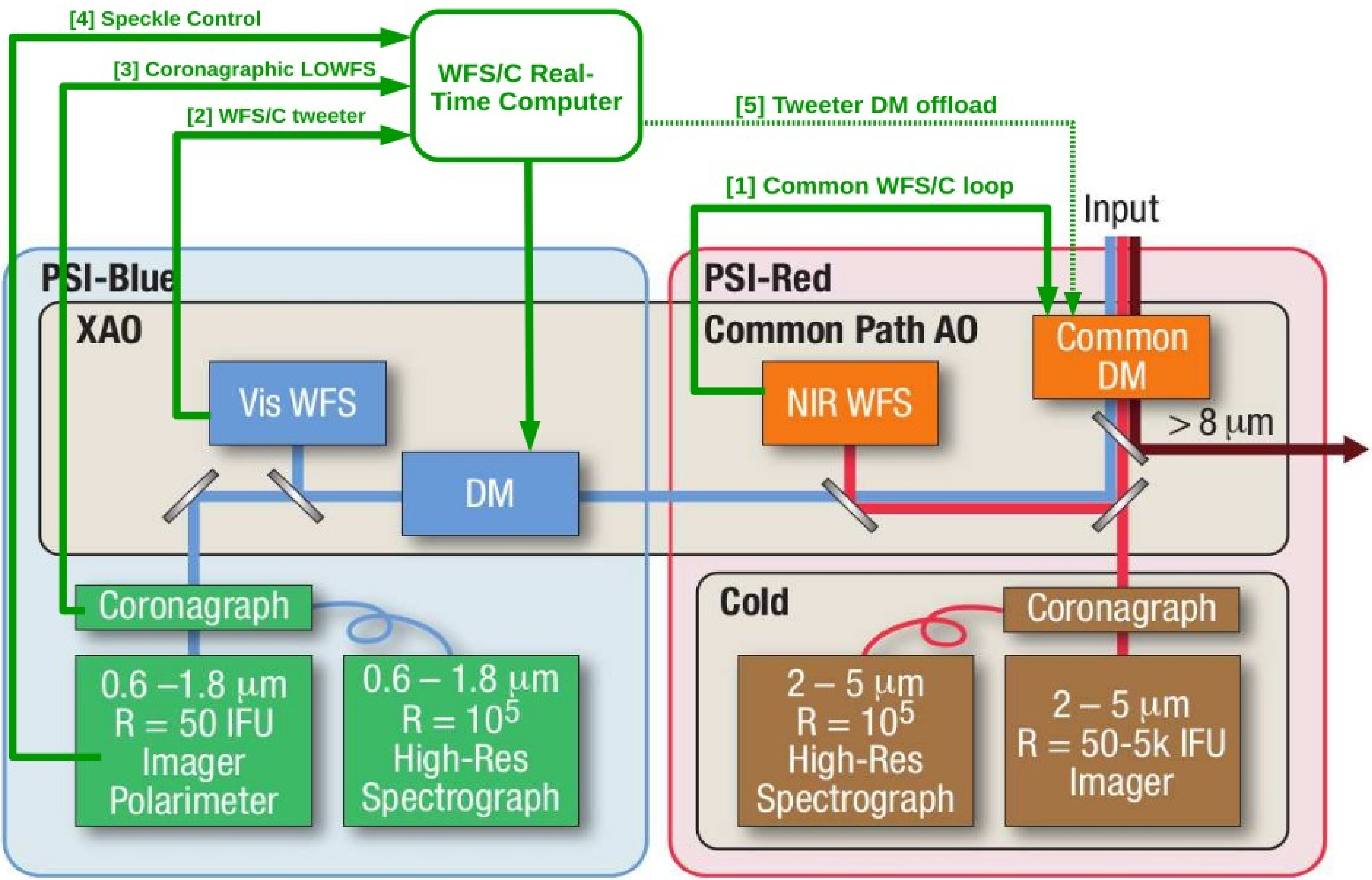


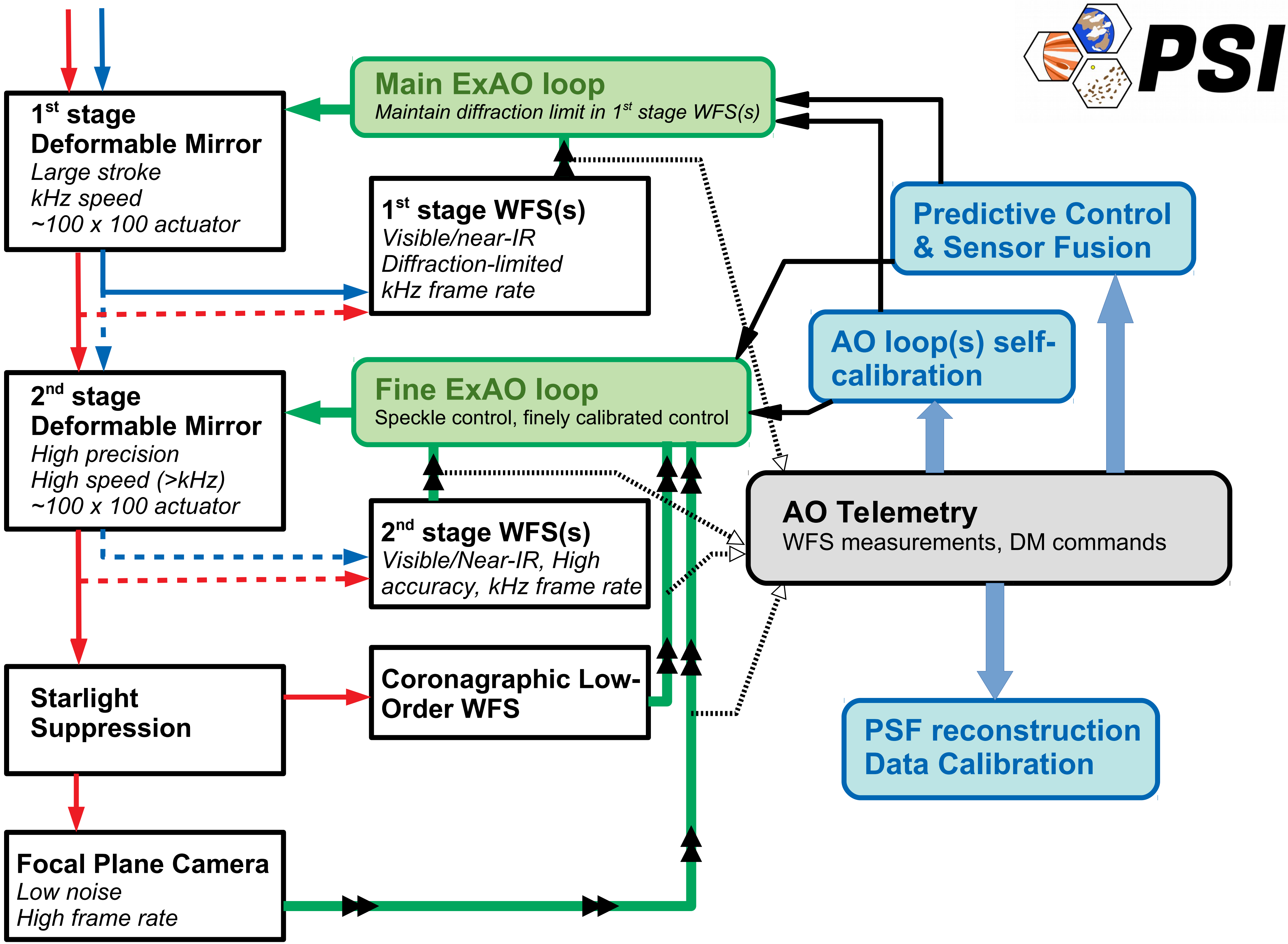
Diffraction-limited WFS, 3 kHz



ExAO system must use **efficient WFS**, handle **chromaticity**, **scintillation**, and be **highly accurate** to meet 1e-5 requirement

PSI instrument concept design





PSI
1st stage Deformable Mirror
Large stroke
kHz speed
~100 x 100 actuator
Main ExAO loop
Maintain diffraction limit in 1st stage WFS(s)
1st stage WFS(s)
Visible/near-IR
Diffraction-limited
kHz frame rate
Predictive Control & Sensor Fusion
AO loop(s) self-calibration
2nd stage Deformable Mirror
High precision
High speed (>kHz)
~100 x 100 actuator
Fine ExAO loop
Speckle control, finely calibrated control
2nd stage WFS(s)
Visible/Near-IR, High accuracy, kHz frame rate
AO Telemetry
WFS measurements, DM commands
Starlight Suppression
Coronagraphic Low-Order WFS
PSF reconstruction
Data Calibration
Focal Plane Camera
Low noise
High frame rate

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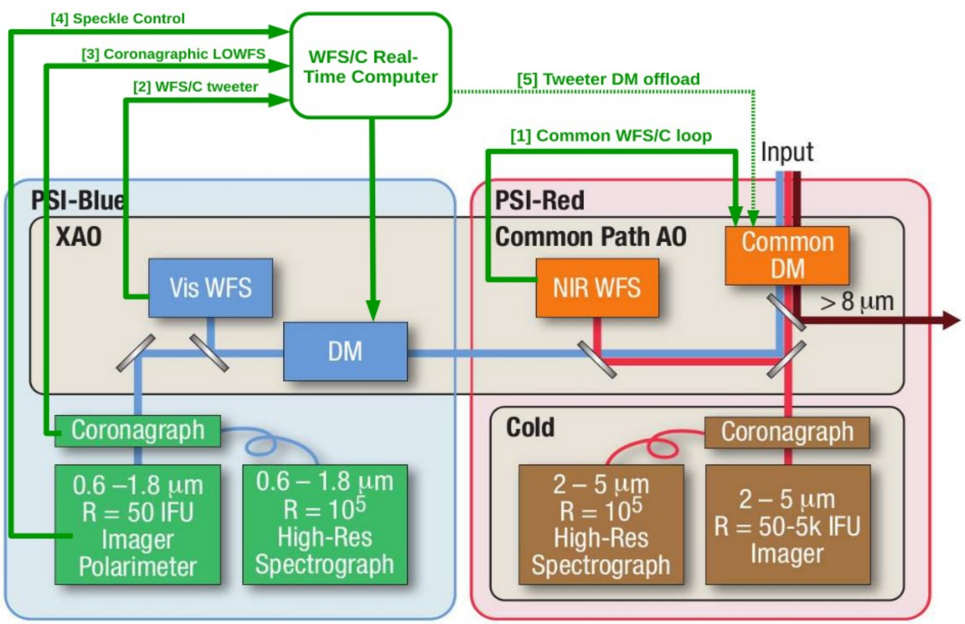
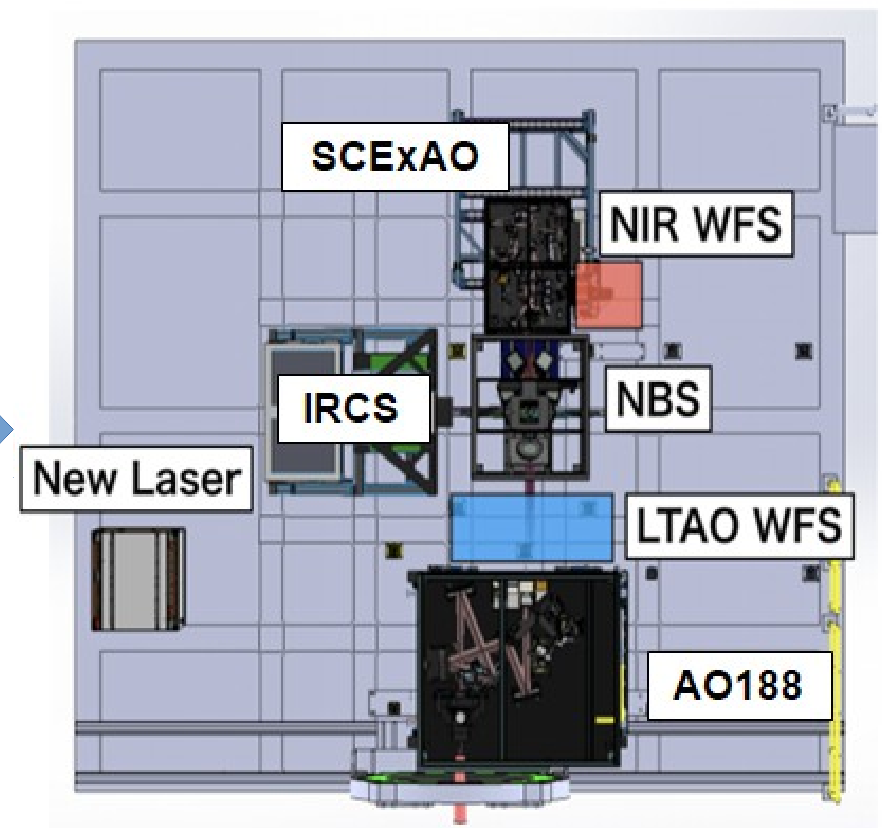
SCExAO is becoming system-level hardware precursor to PSI





Key PSI subsystems/components/technologies validated on SCExAO include:

- Magnetic deformable mirror, MEMS, SAPHIRA detectors, MKIDS
- Fiber injection, Coronagraphy
- Advanced wavefront control

Subaru Coronagraphic Extreme Adaptive Optics

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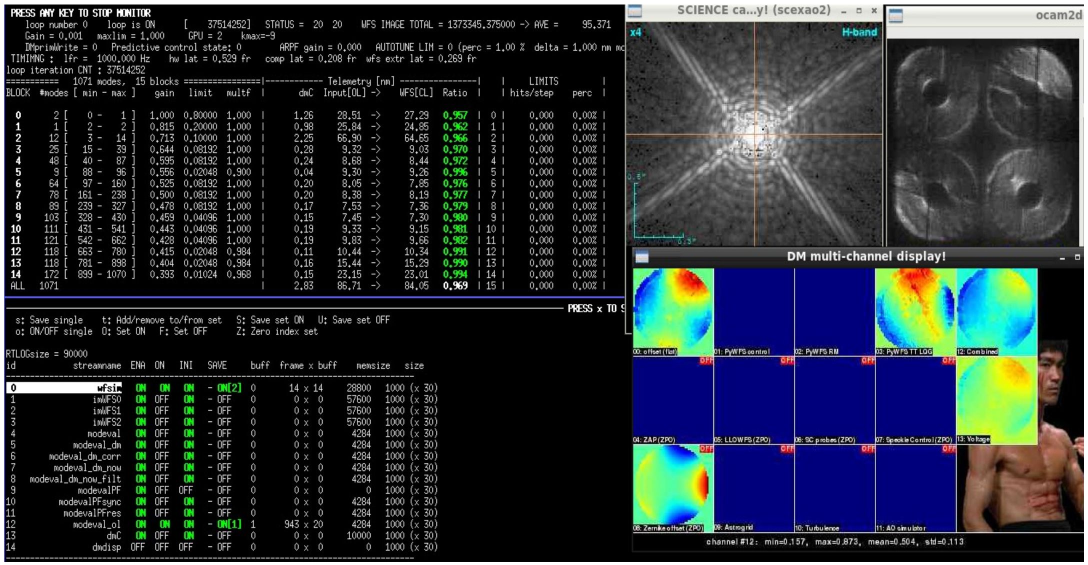
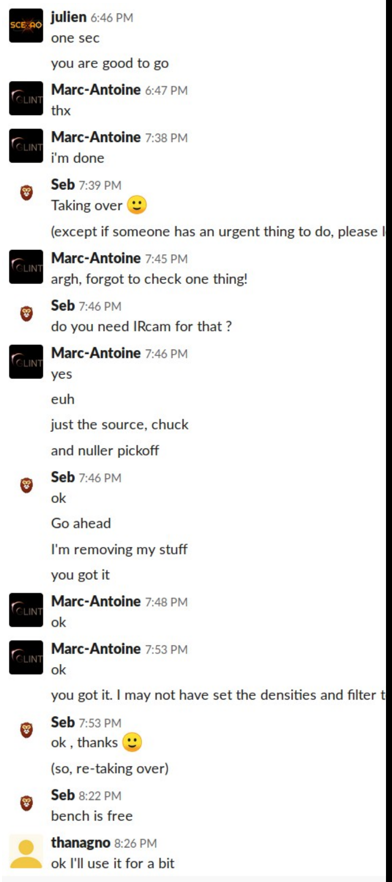
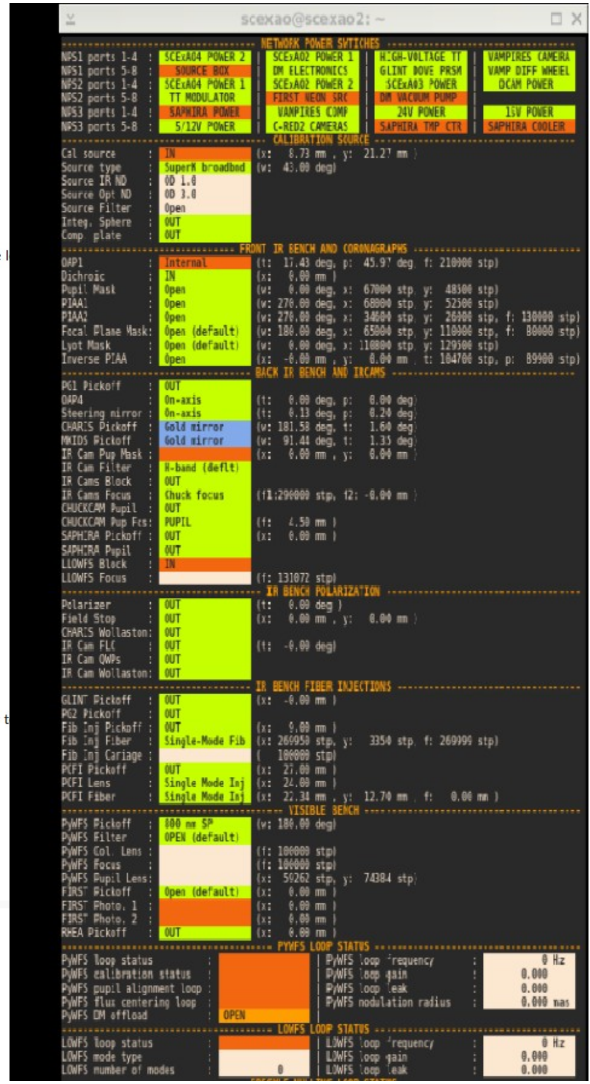
Enabling R&D







SCExAO WFS/C relies on collaboratively developed open-source cacao package
→ common framework to develop, deploy and test new algorithms

SCExAO used as a daytime testbed for external colllaborators to operate and run tests

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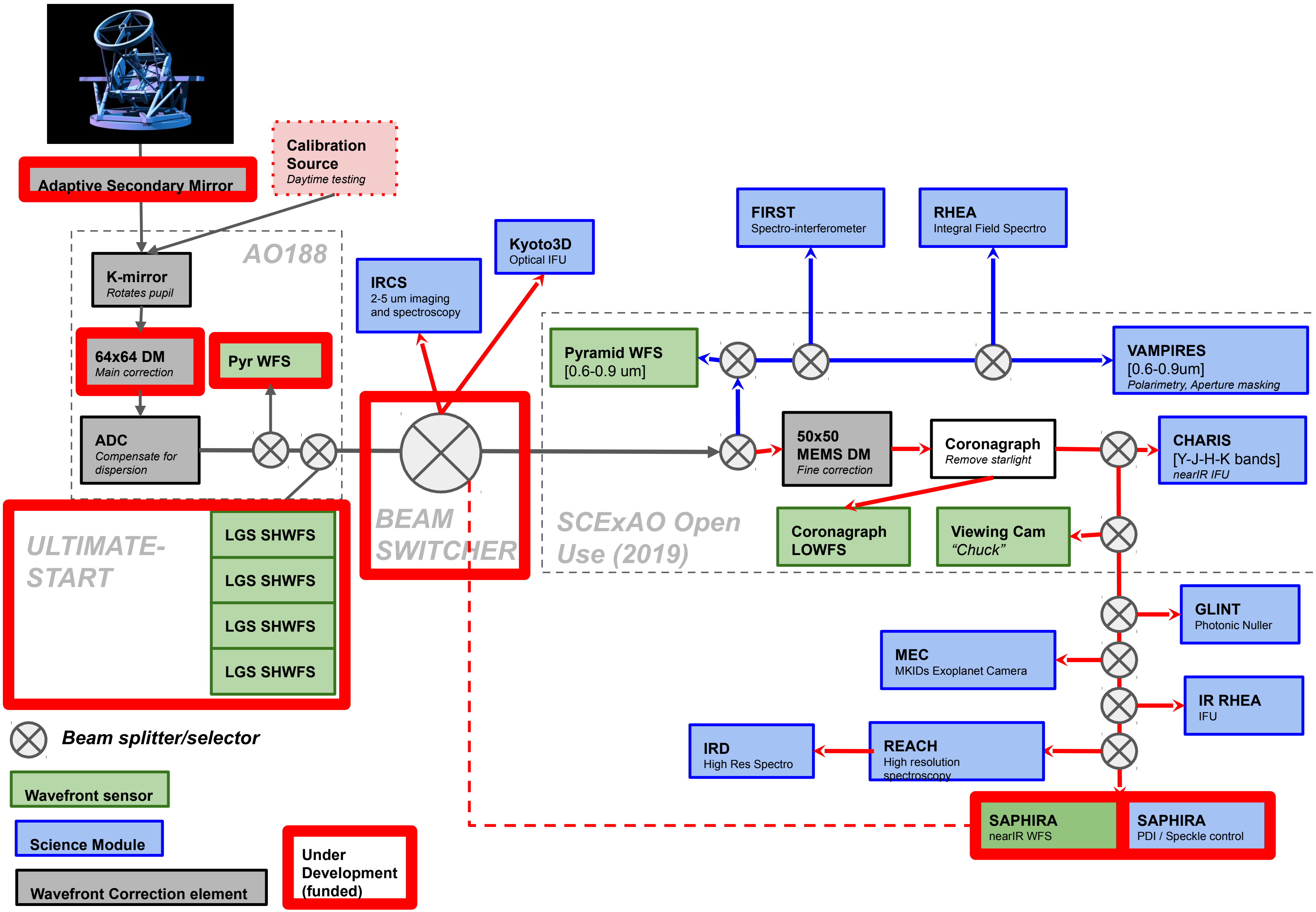
Block Diagram



Top 6 Game-changing technologies

Hardware

Detectors
- High speed photon counting for WFS
- Low noise for spectroscopy
- Wavelength-resolving (MKIDS)

Deformable Mirrors
- Large stroke & actuator count (Magnetic)
- High speed, high precision (MEMS)

Astrophotonics
Using coherent waveguides to transport, filter and combine light
- Fiber-fed spectroscopy / IFU
- Interferometric imaging
- Interferometric Nulling
- Combining all of the above

Software

Advanced WFS/C algorithms
- Predictive control
- Sensor Fusion
- Non-linear WFS/C

Machine learning / AI
High performance computing

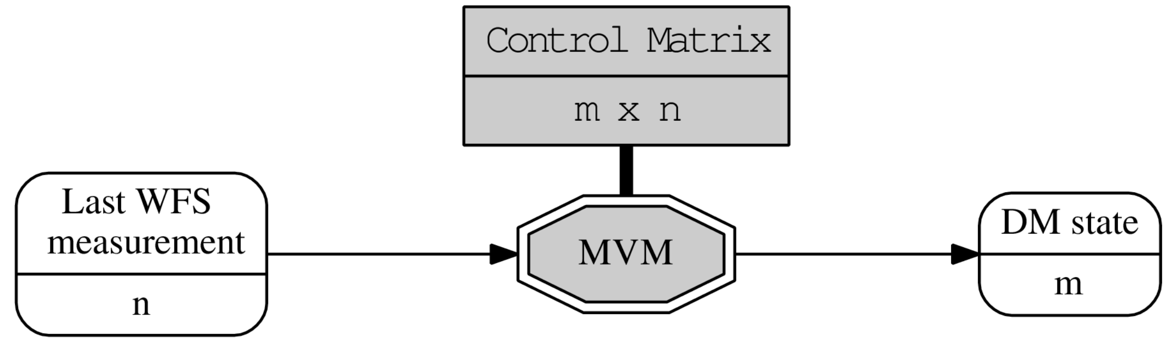
Real-time PSF calibration
- Specke noise removal

Focal Plane WFS/C
- Speckle nulling
- Coherent Differential Imaging
- LDFC

A new approach to Adaptive Optics control

Conventional AO:

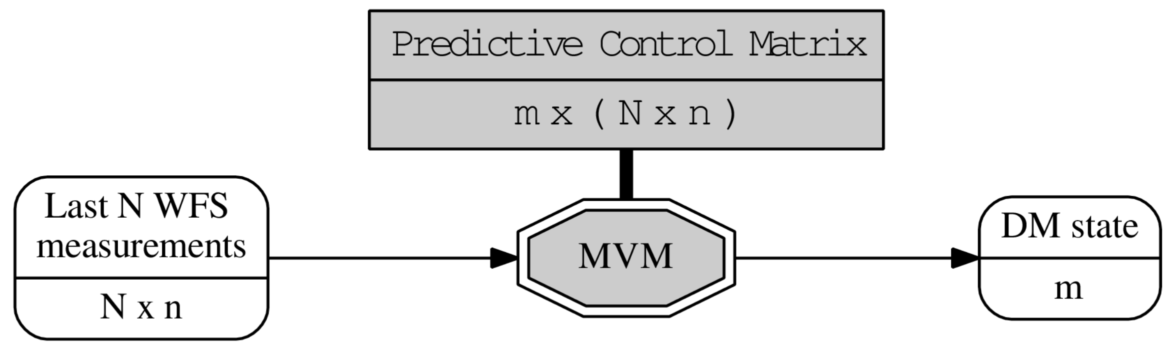
We calibrate the system in the lab, and then apply a linear input-output control law

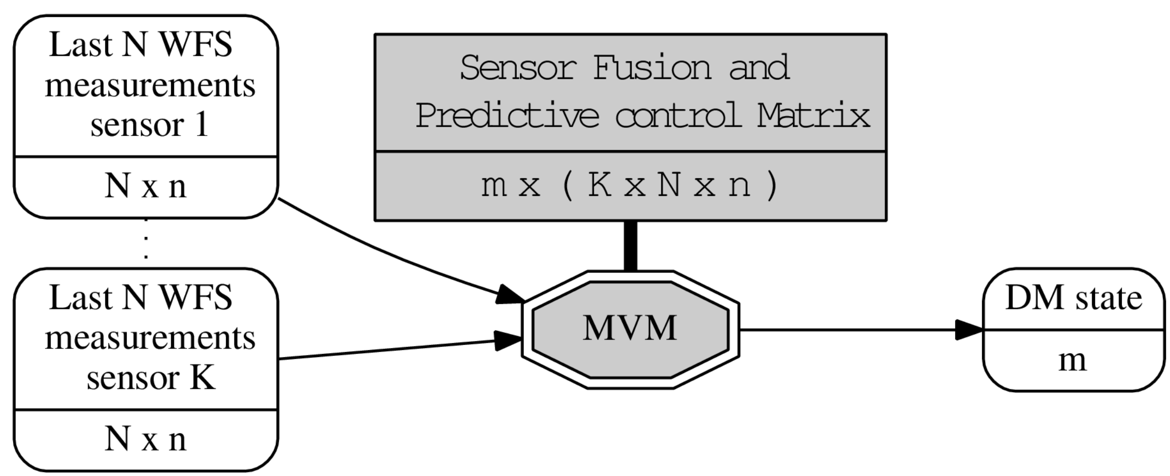


Advanced AO control:

We continuously, optimally **<u>derive</u>** the input-output controller from the real-time data streams.

This is a formidable computing challenge:
input has ~10,000 degrees of freedom, output has ~2,000 degrees of freedom, and controller must compute solutions at 3 kHz framerate





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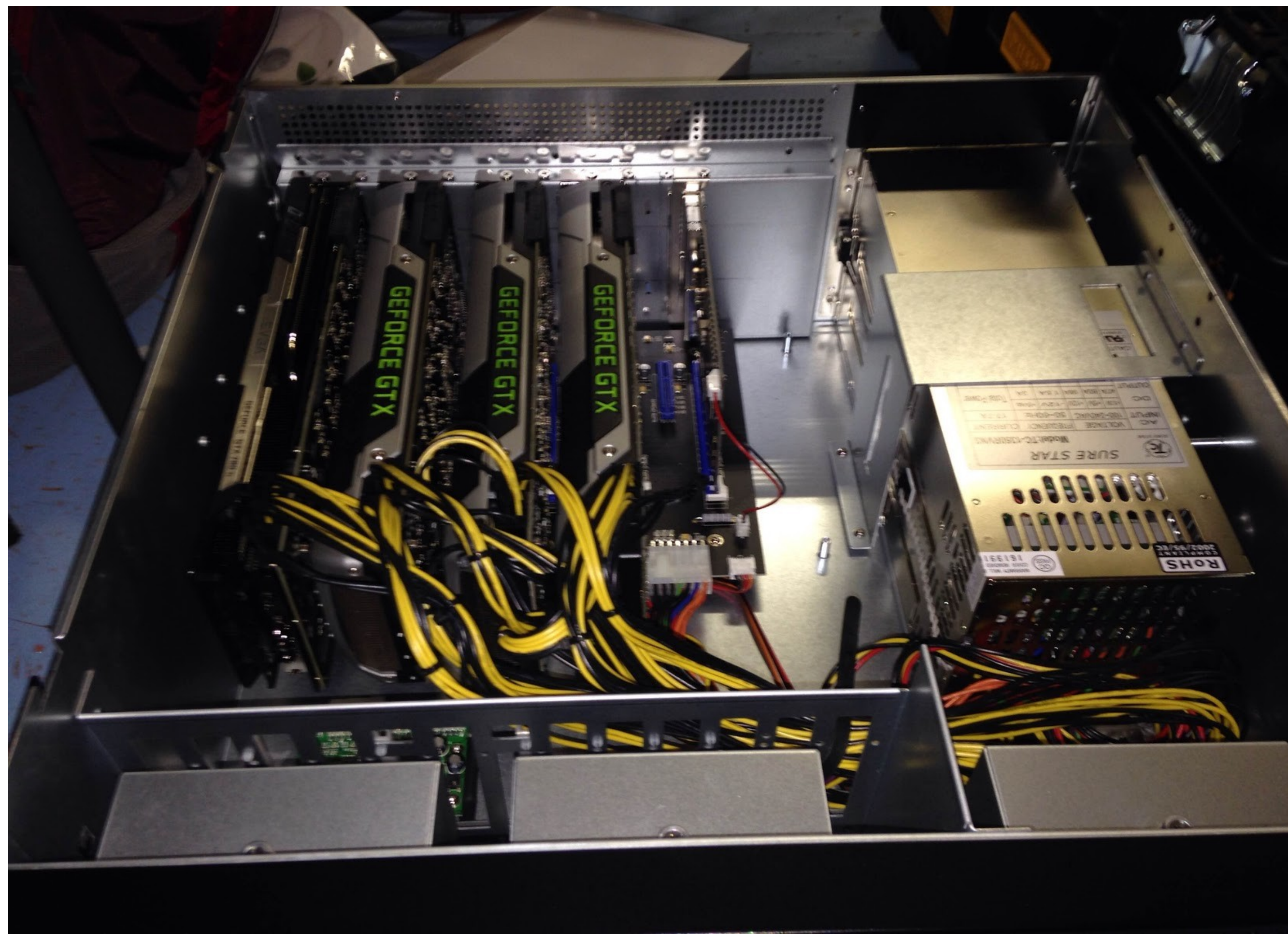
High Performance Computing

One of two GPU chassis

SCExAO uses 35,000 cores running @~1.6GHz



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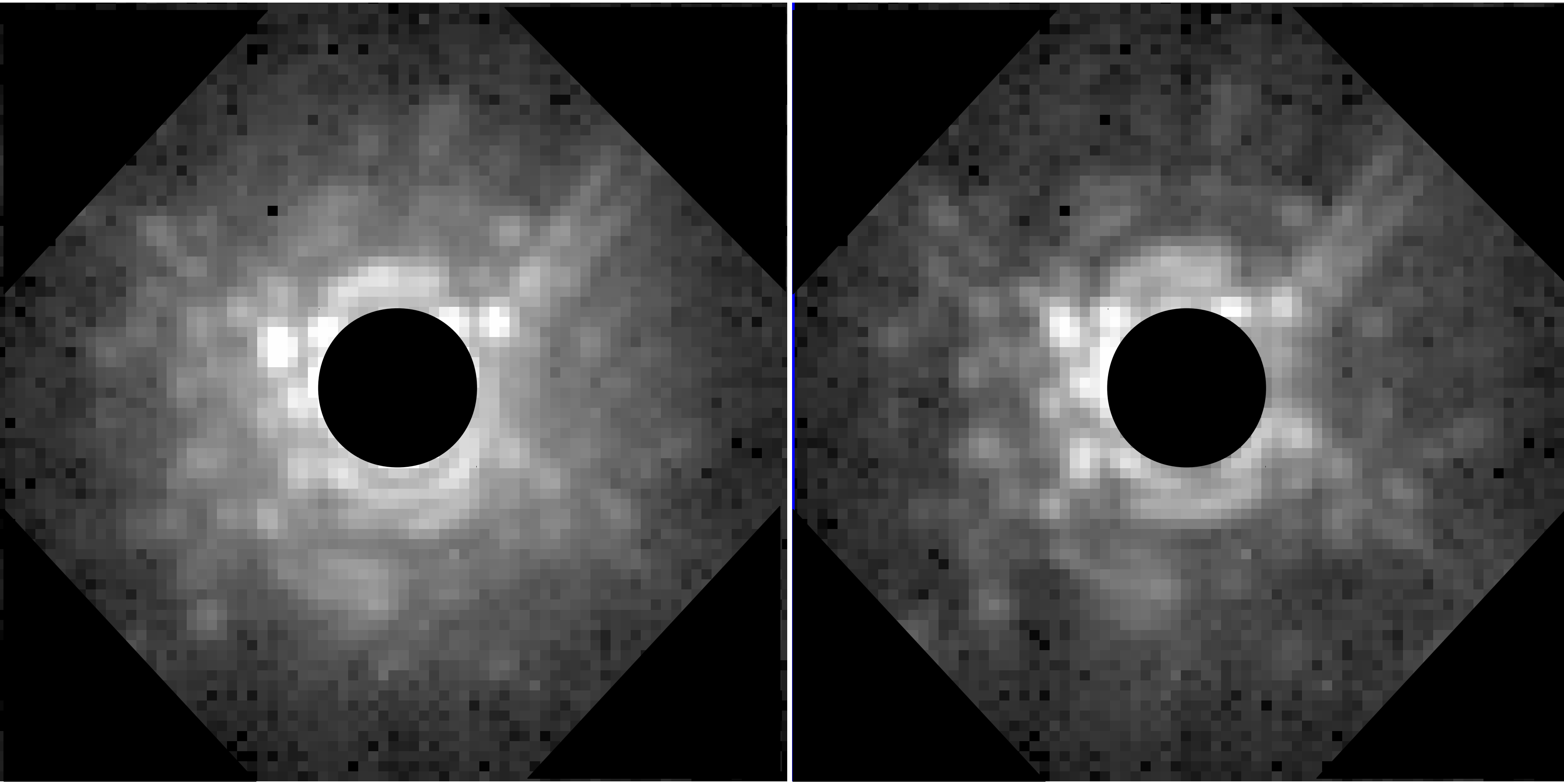
Predictive Control
3x contrast improvement



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

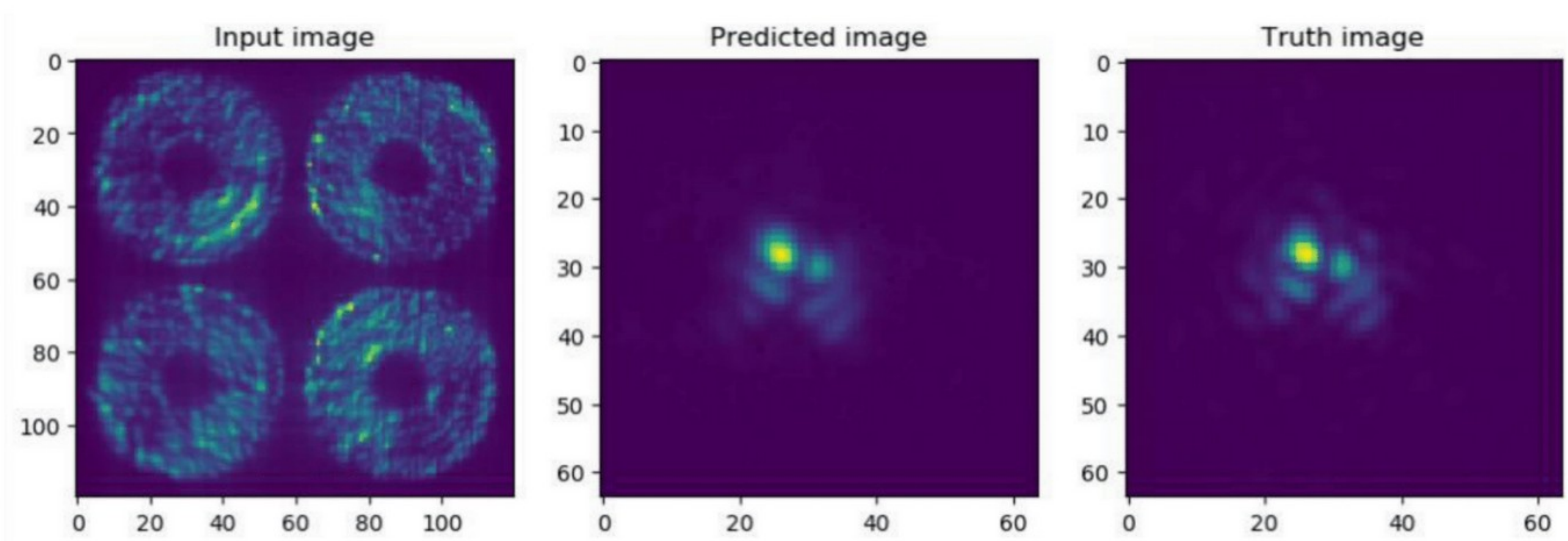
PSF calibration from real-time telemetry

→ it should be nearly impossible for speckles to "hide"

Two goals:
#1 improve **Wavefront control** sensitivity and accuracy
#2 provide real-time stellar PSF estimate for **PSF subtraction**

Promising… but realtime reconstruction of PSF from multiple WFSs is very challenging

Early work: PSF reconstruction using NN successfully estimates visible PSF (B. Norris, Univ. of Sydney)



Reinforcement Learning

AO loop can learn in real time by monitoring focal plane PSF

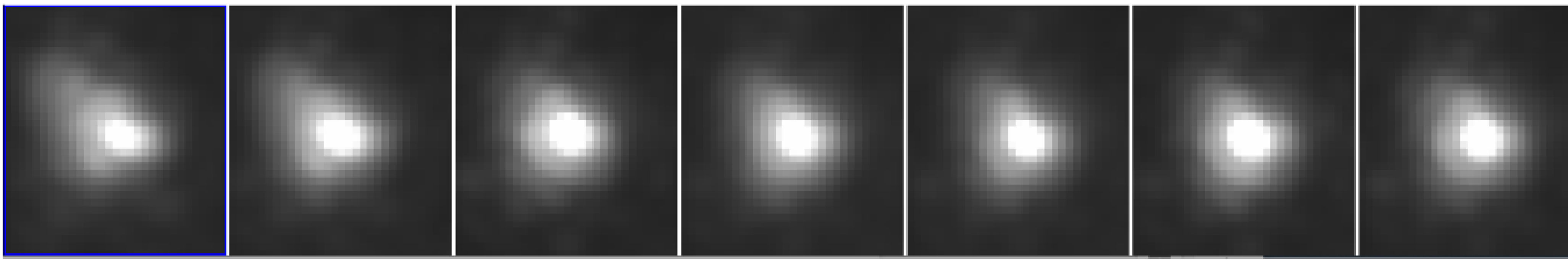
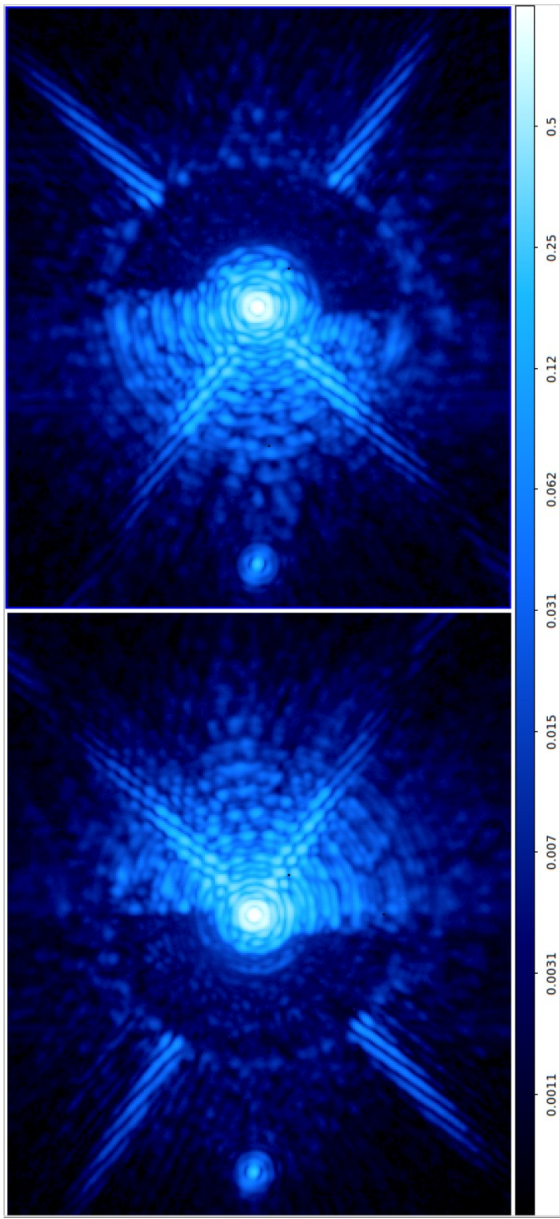
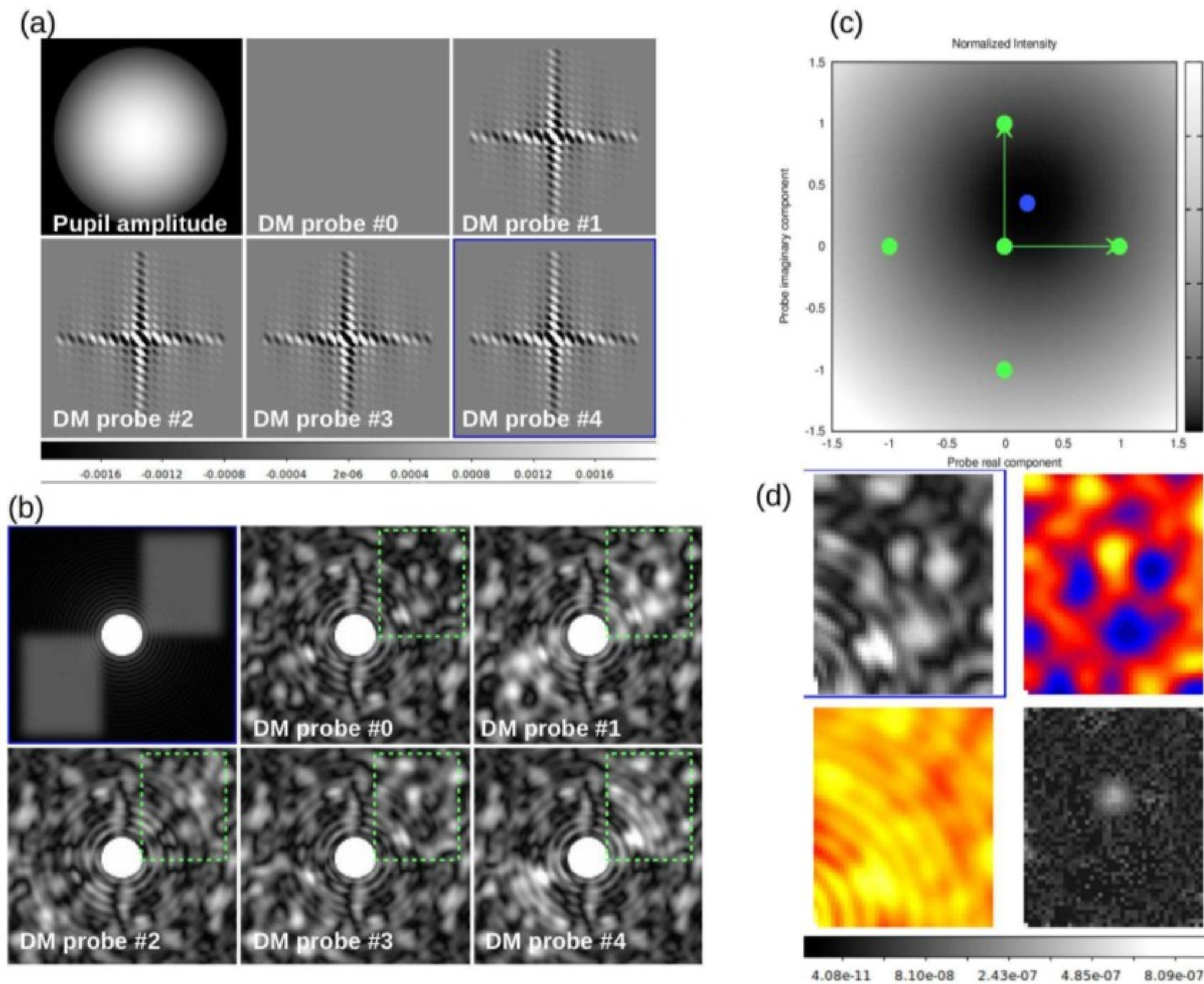


Figure 5: On-sky demonstration of re-inforcement learning for PSF sharpening, using reference updating sensor fusion. The SCExAO pyramid WFS reference on the internal source does not match the on-sky reference due to differences in pupil illumination and variations of chromatic non-common path errors, so it must be learned on-sky from monitoring of the real-time PSF quality. Once the XAO loop is closed, an algorithm identifies the 1% best PSFs and selects the corresponding WFS frames from the real-time WFS telemetry stream. These selected WFS frames are averaged together every 30sec for noise reduction, and the resulting new WFS frame replaces the WFS reference. As the algorithm proceeds, the pyramid WFS is continuously rewarded for high quality PSFs, and the visible light PSF quality improves. The evolution of the on-sky visible (670nm) selected PSFs is shown here over a 21mn period (3.5mn between consecutive PSFs) on the SCExAO system. The strong coma aberration present in at the beginning of the sequence is automatically removed.

Focal Plane WFS/C





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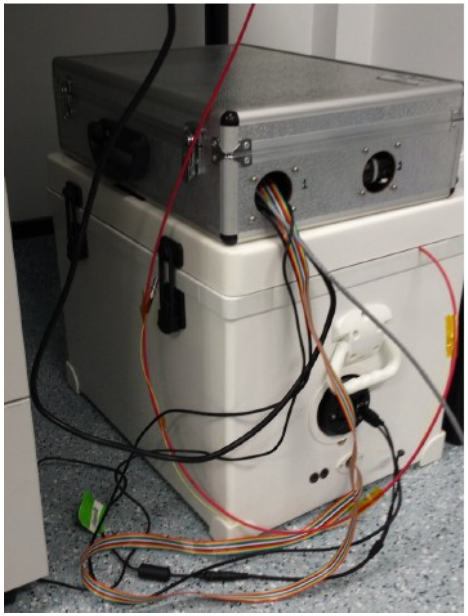
Fiber-fed HR spectroscopy (R~70,000 to 100,000)

Visible

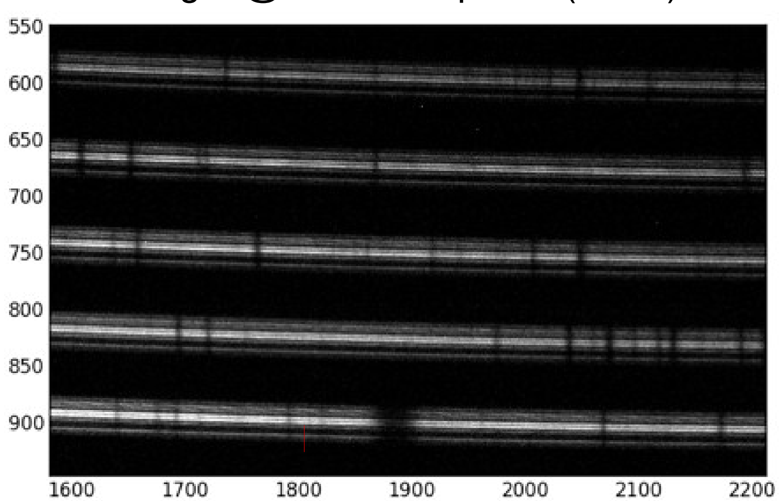


RHEA

Replicable High-resolution Exoplanet & Asteroseismology

(Michael Ireland, ANU
Christian Schwab, Macquarie Univ)

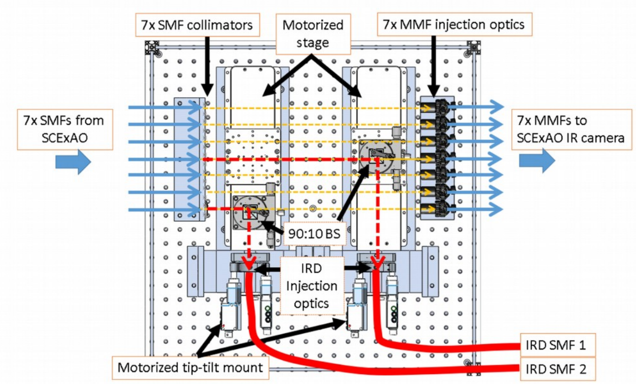
RHEA first light @ Subaru: Eps Vir (detail) Feb 2016

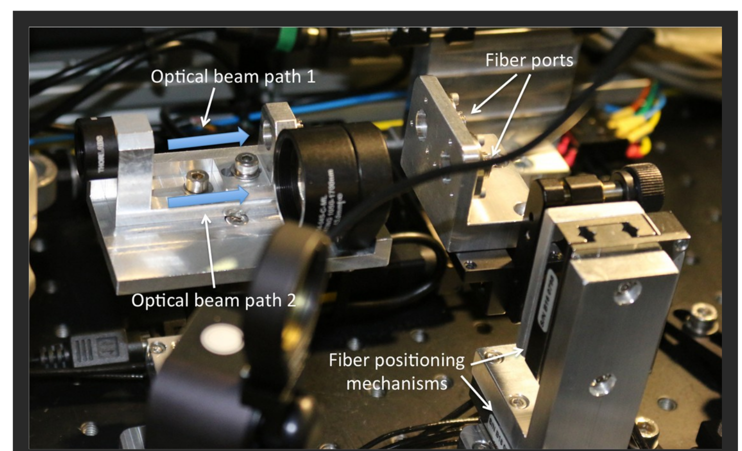


Near-IR

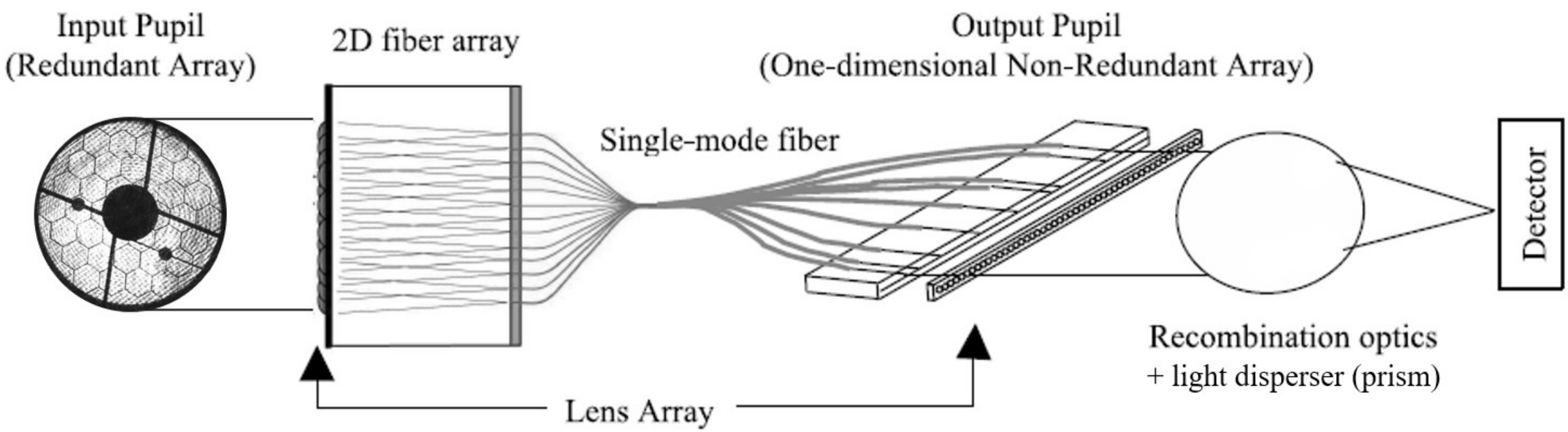
REACH

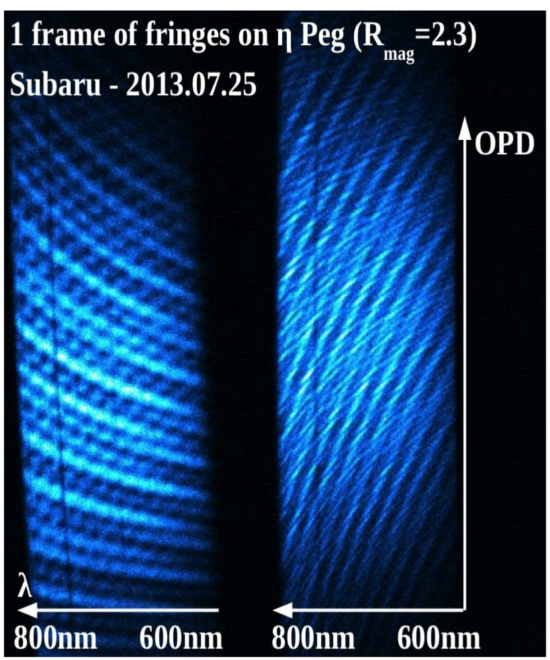
SCExAO→ IRD feed
T. Kotani, H. Kawahara

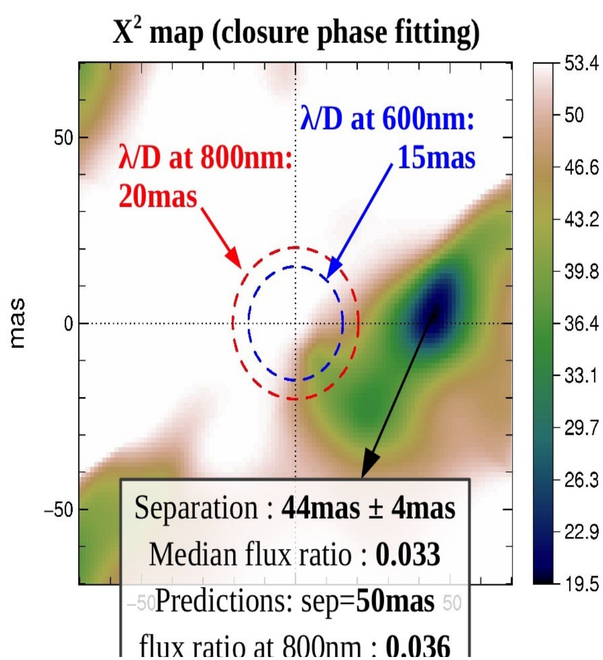


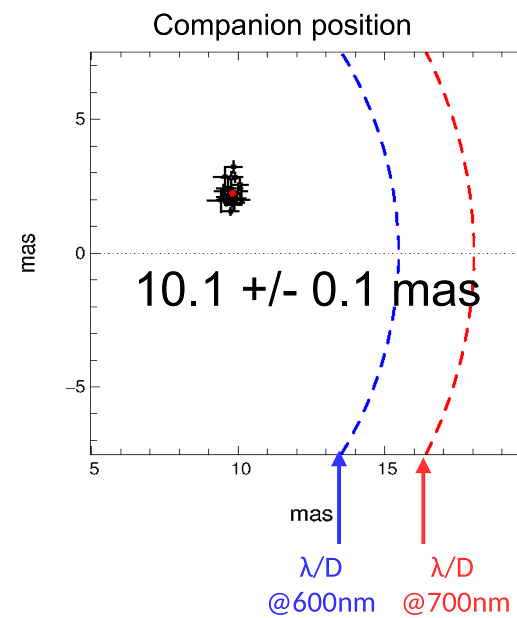


Fiber Interferometry: FIRST spectro-imaging (vis)









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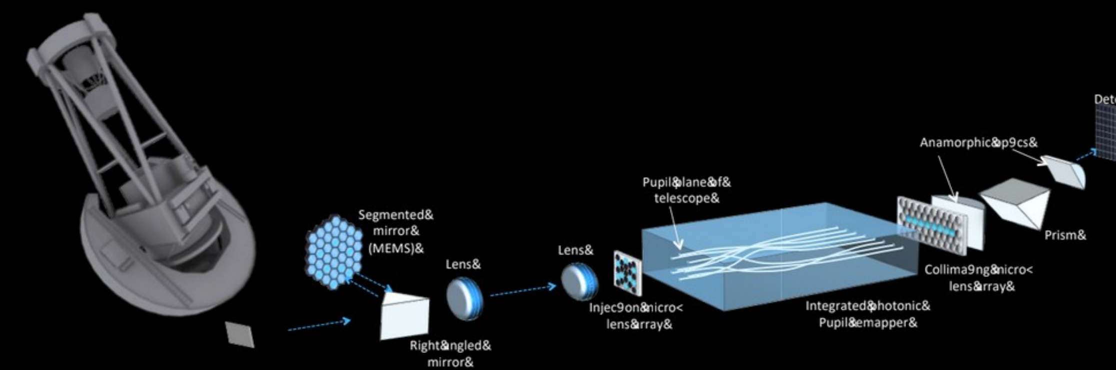
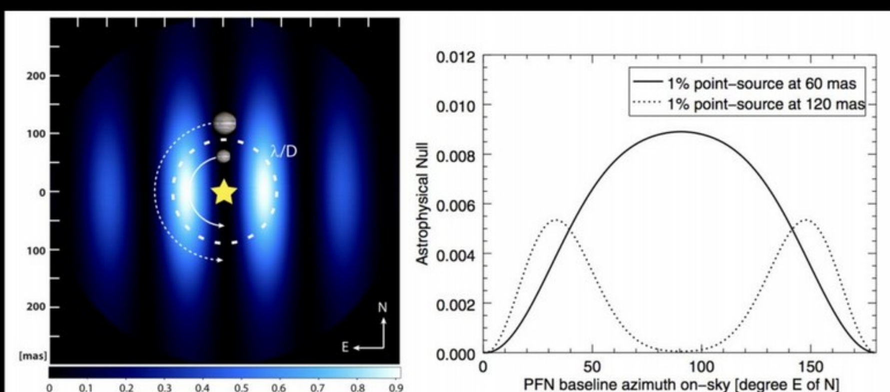
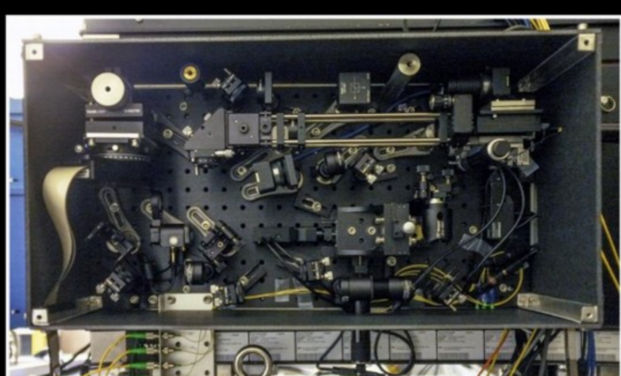
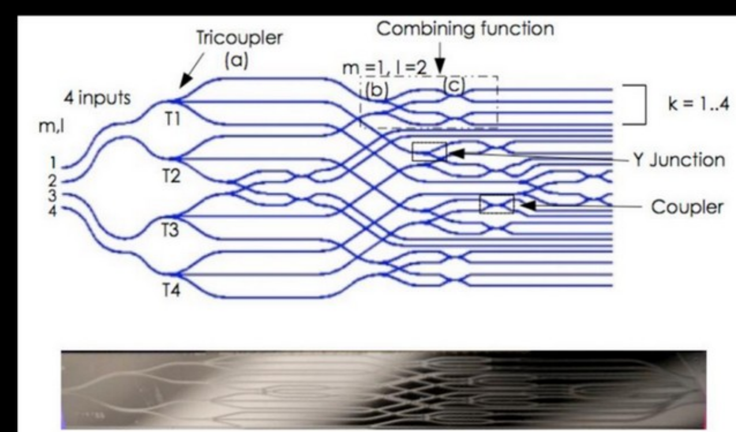
GLINT spectro-nulling (NIR)









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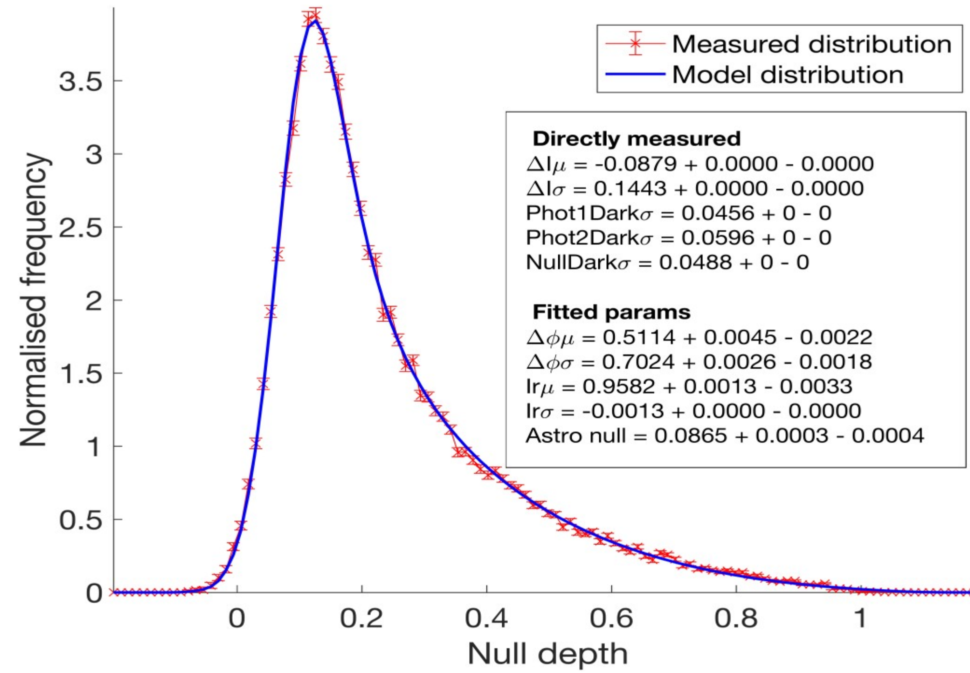
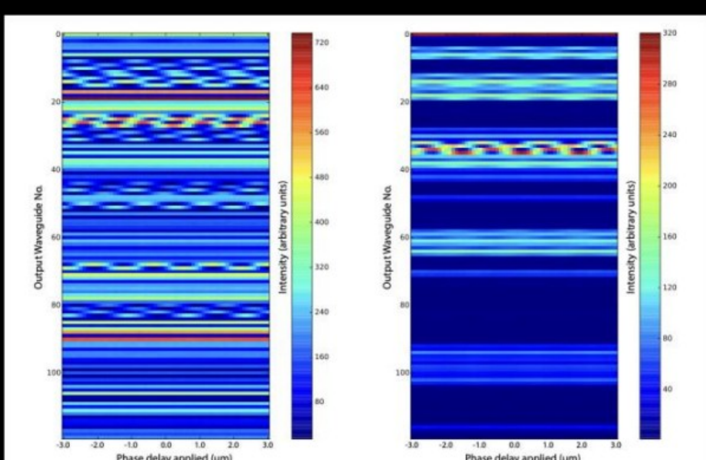
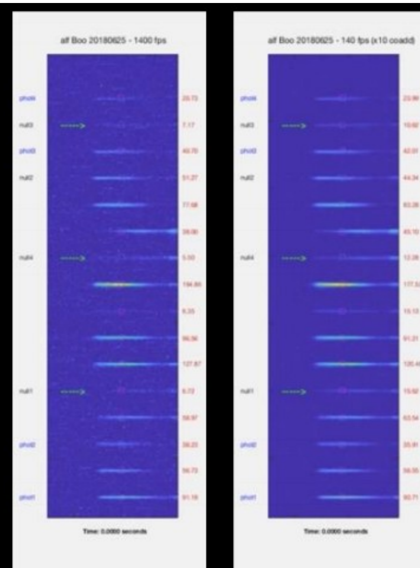
GLINT







Chi Cyg observed June 2017
Null depth= 0.0865 +- 0.0004
→ **diameter = 21.6 mas**
(literature values: 20-25 mas)

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CONCLUSIONS

PSI

Large ground-based telescopes (ELTs) will provide **the first opportunity to image and characterize (spectroscopy) habitable planets** around the nearest stars

High contrast imaging **technologies are fast evolving**, and hold the key to meet the challenging contrast requirements.

On-sky prototyping and validation is essential to include advanced technologies in the TMT-PSI design. SCExAO @ Subaru is playing this role.

SCExAO is designed to be a prototype for PSI, leveraging community resources and making it easy for collaborators to participate.