

Entering a new Era of Adaptive Optics with more powerful Deformable Mirrors

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Acknowledgements

This presentation is about technologies on two telescopes on Maunakea. I recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawai'ian community, and consider myself fortunate to have the opportunity to conduct observations from and work on this mountain.





Acknowledgements

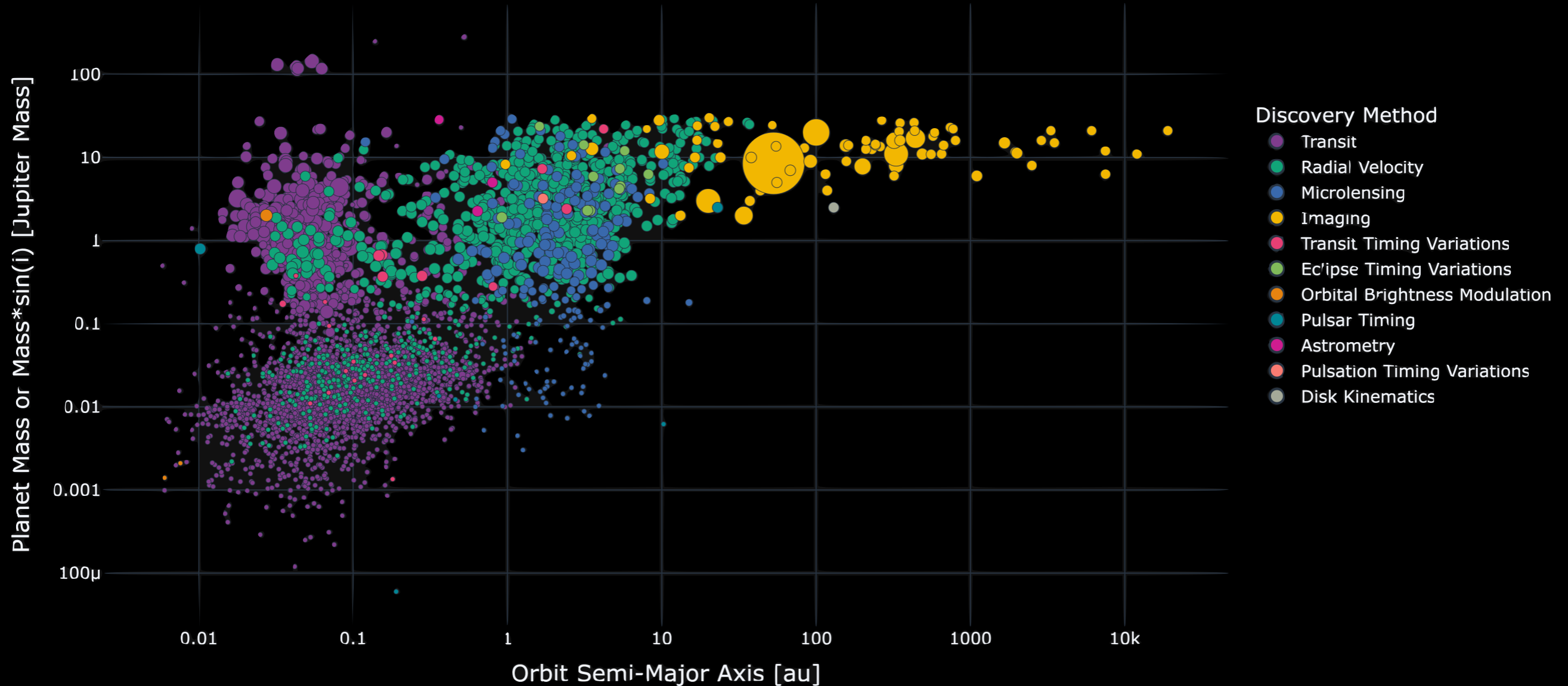
I would like to thank the respective instrument teams at Subaru Telescope and WM Keck Observatory for giving me this opportunity to work with them on these projects that take us to the next generation of Adaptive Optics and prepare us for the upcoming era of ELTs.

I am grateful to my thesis advisors, Michael Bottom and Jonathan Williams for their support and paving the bridge that connected me to these institutions and the projects I am a part of today.

The Basics

Discovering Planets

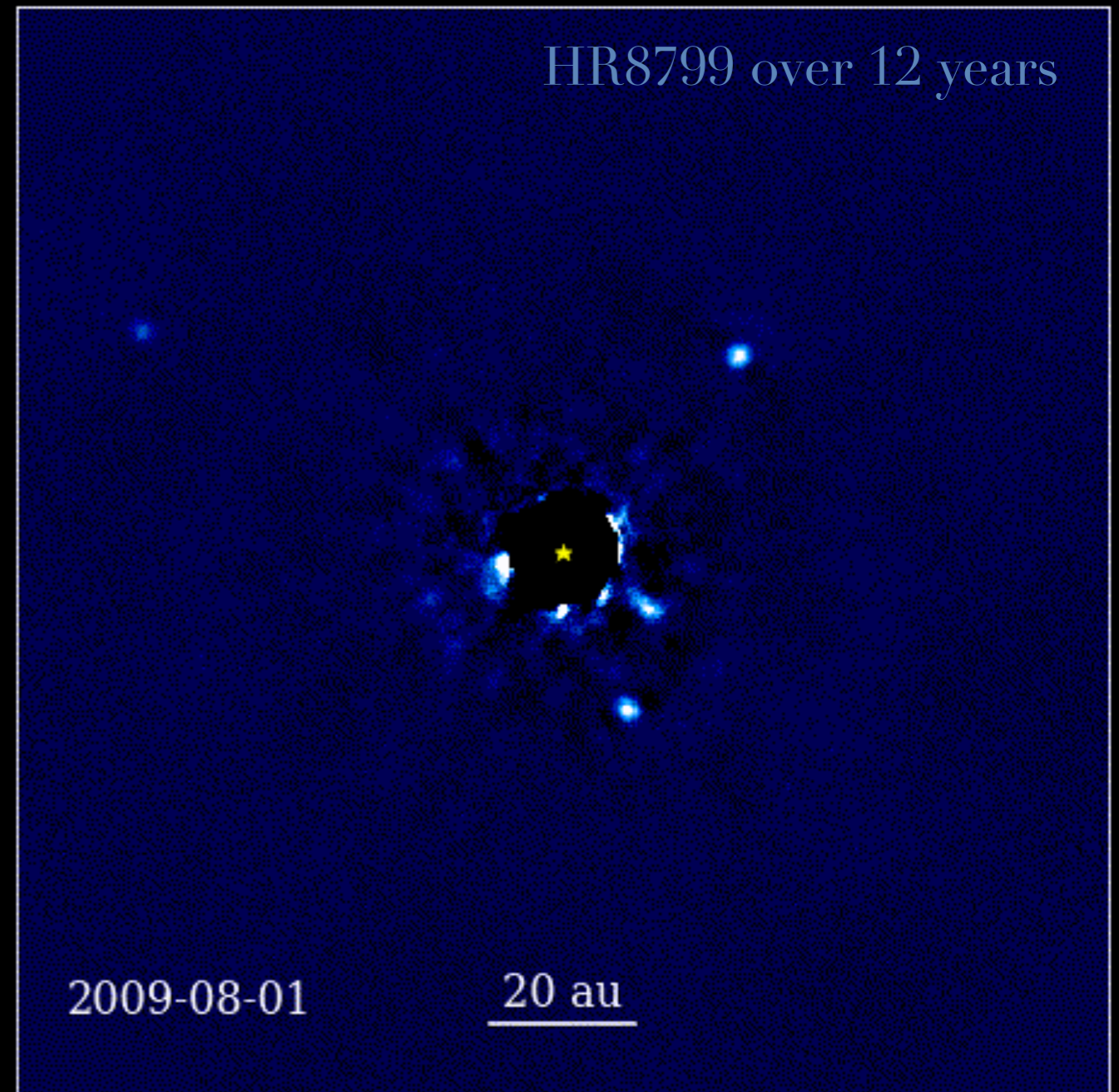
NASA Exoplanet Archive, exoplanetarchive.ipac.caltech.edu, 2024-06-13 12:10:50



High Contrast (Direct) Imaging

Goal

Enable direct detections of faint sources in the vicinity of a much more luminous source

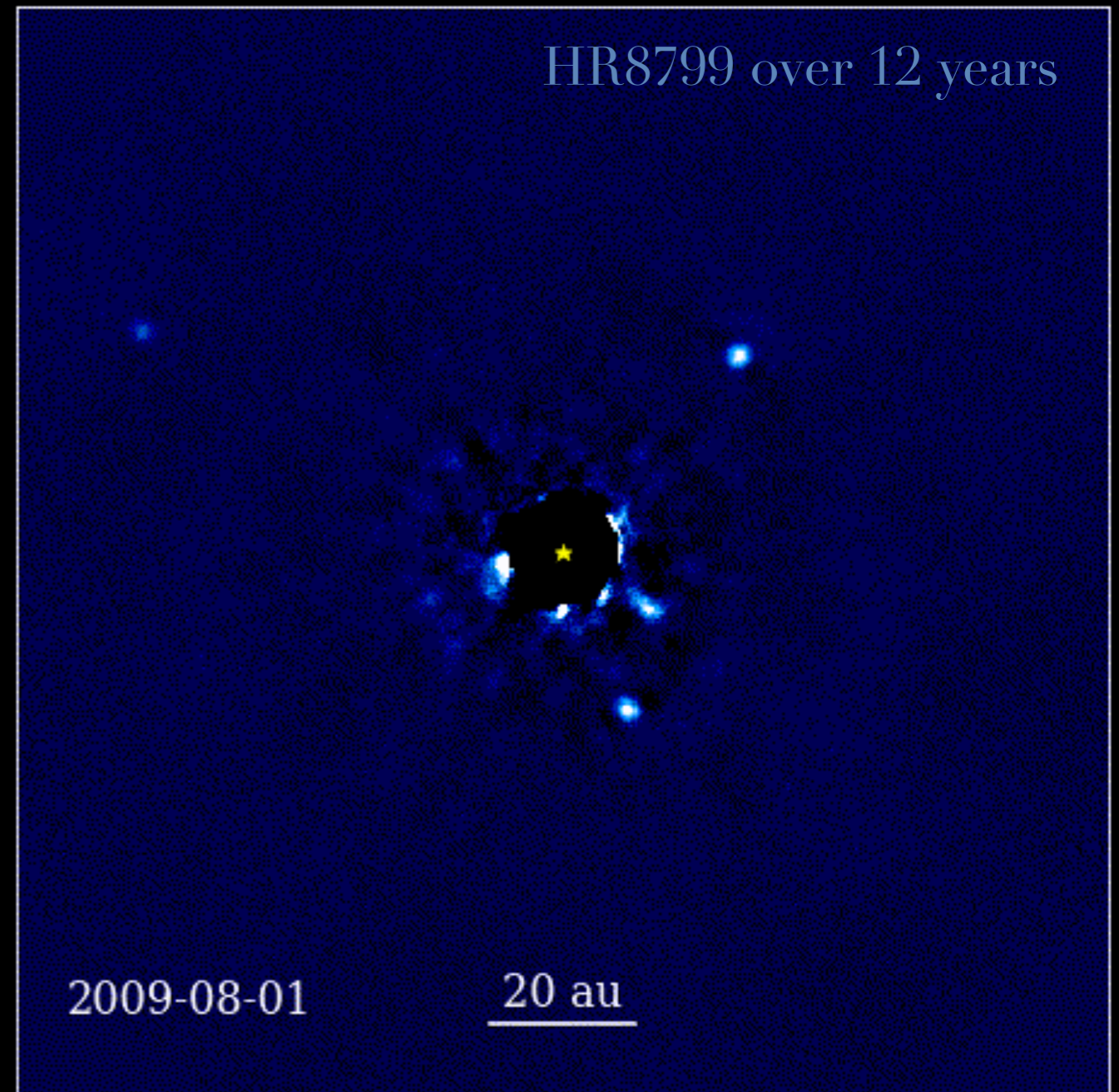


Jason Wang (Northwestern)/William Thompson (UVic)/
Christian Marois (NRC Herzberg)/Quinn Konopacky (UCSD)

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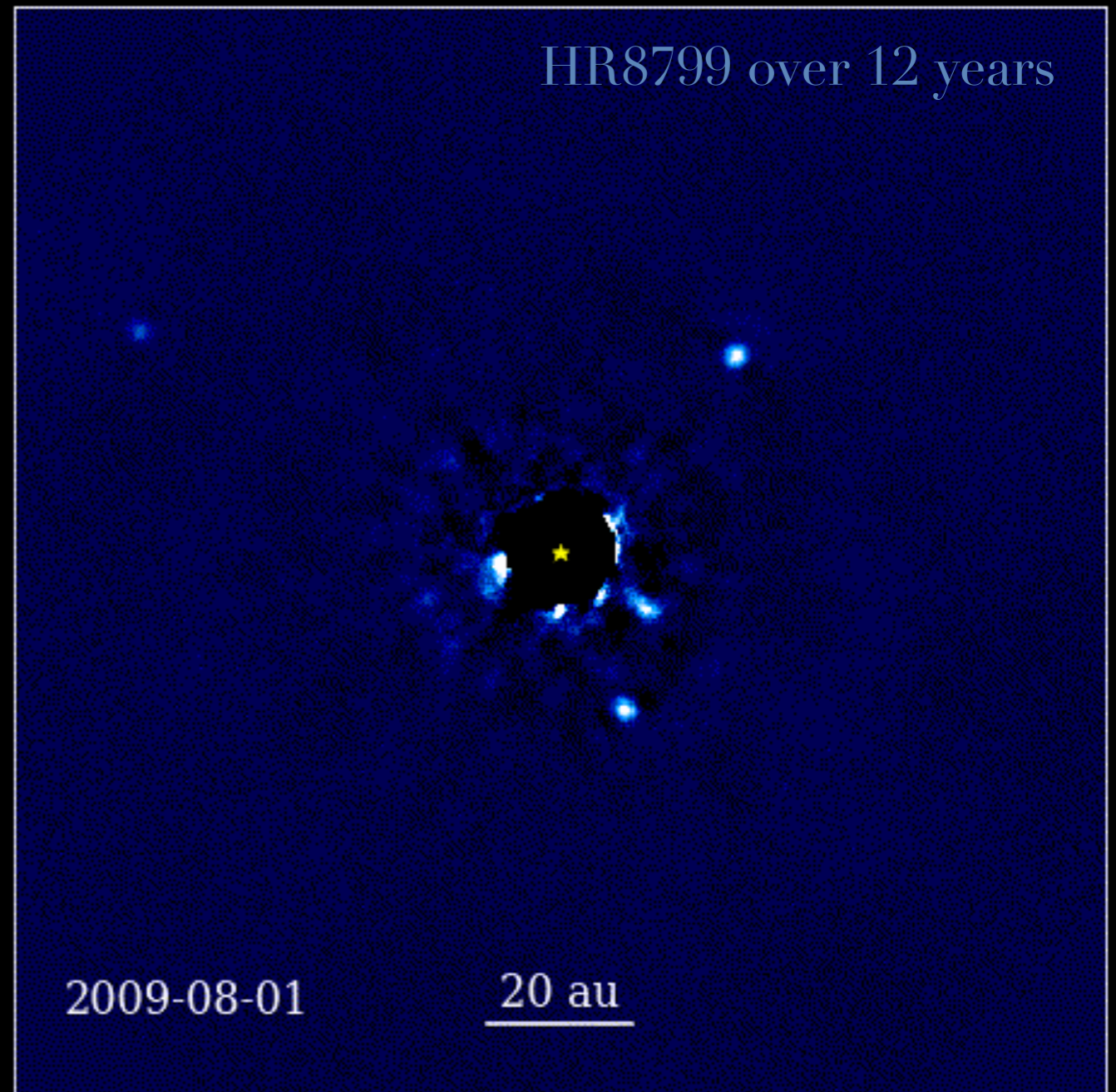
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Components

- Adaptive Optics
- Coronagraphy
- Differential Imaging



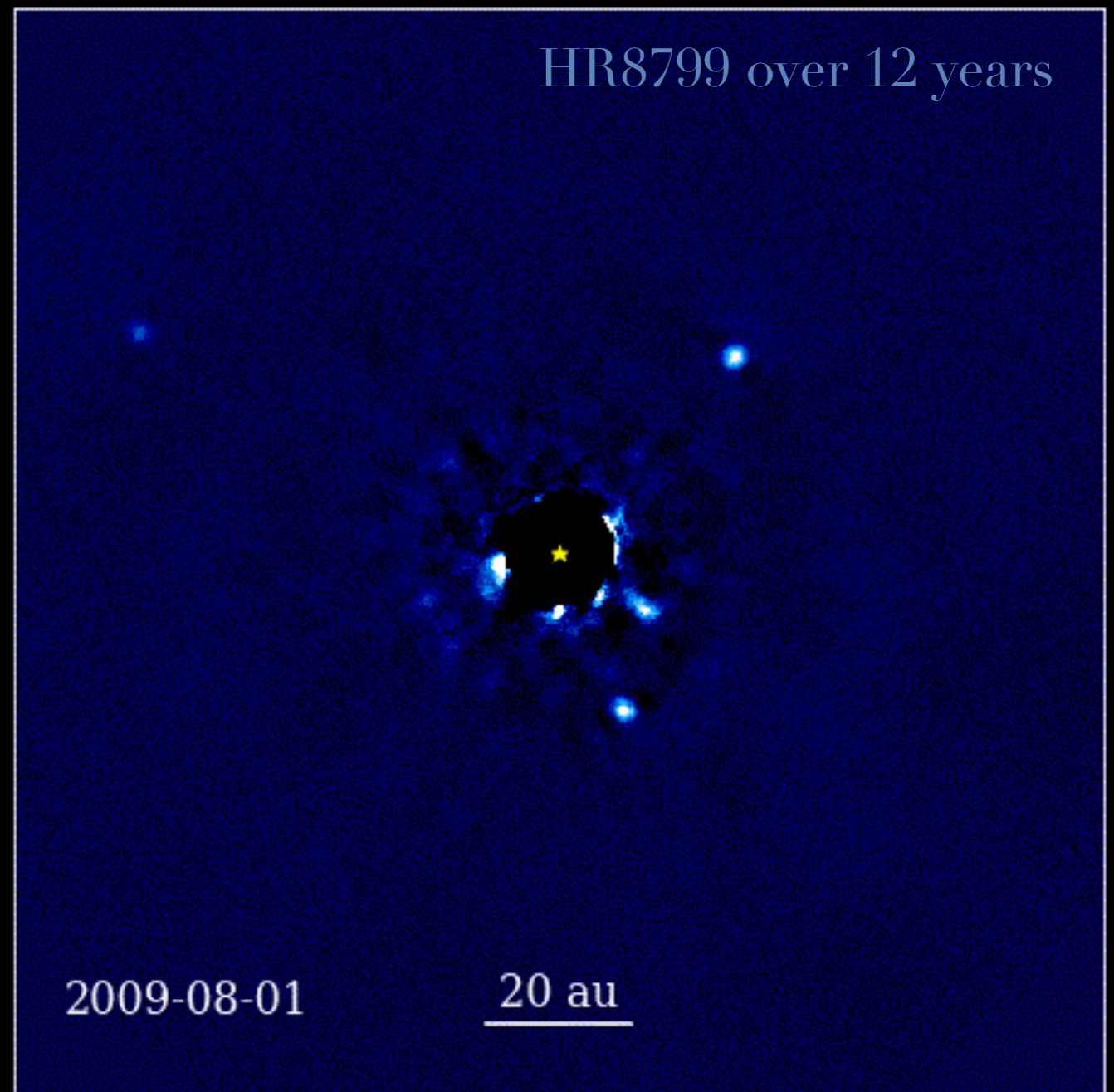
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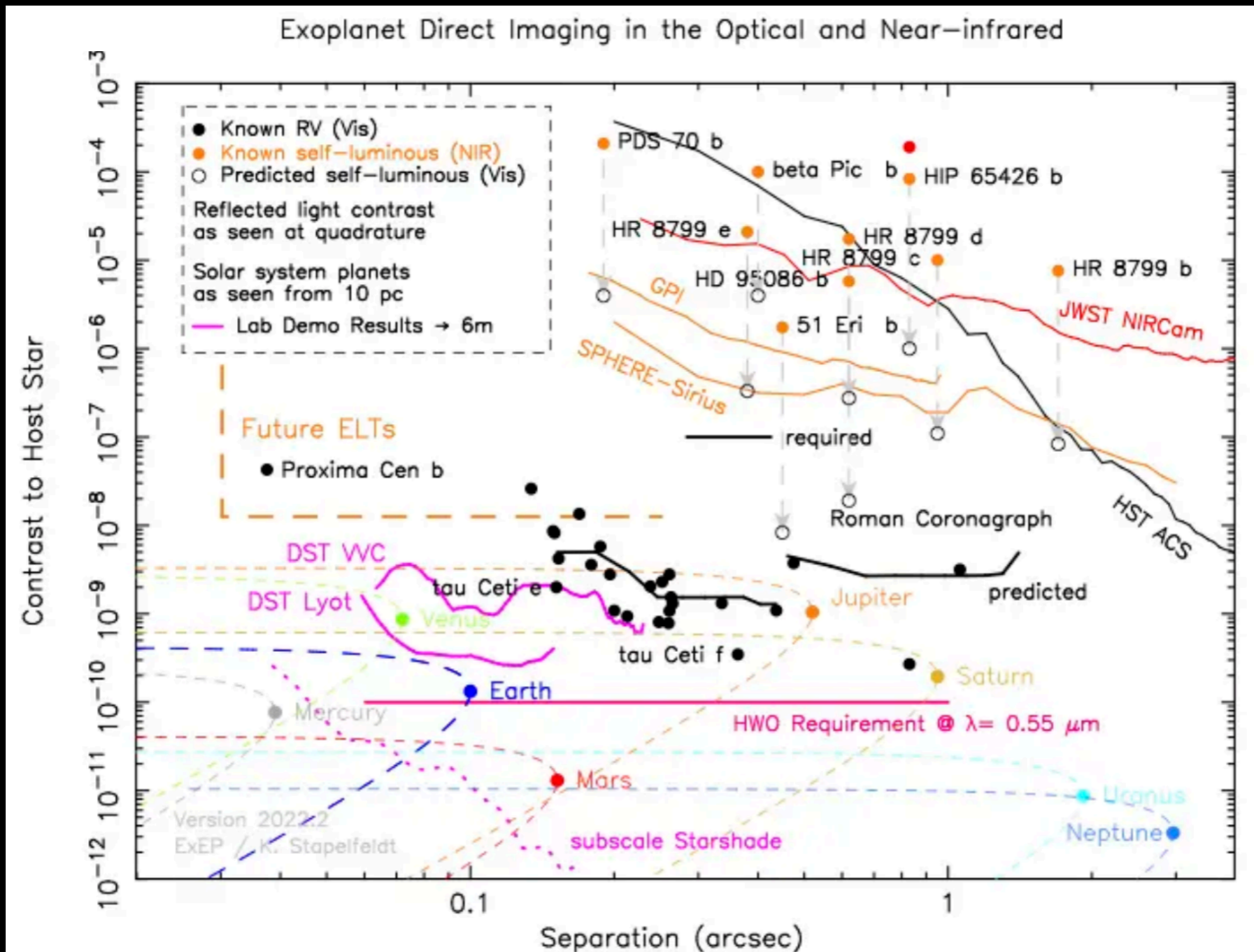
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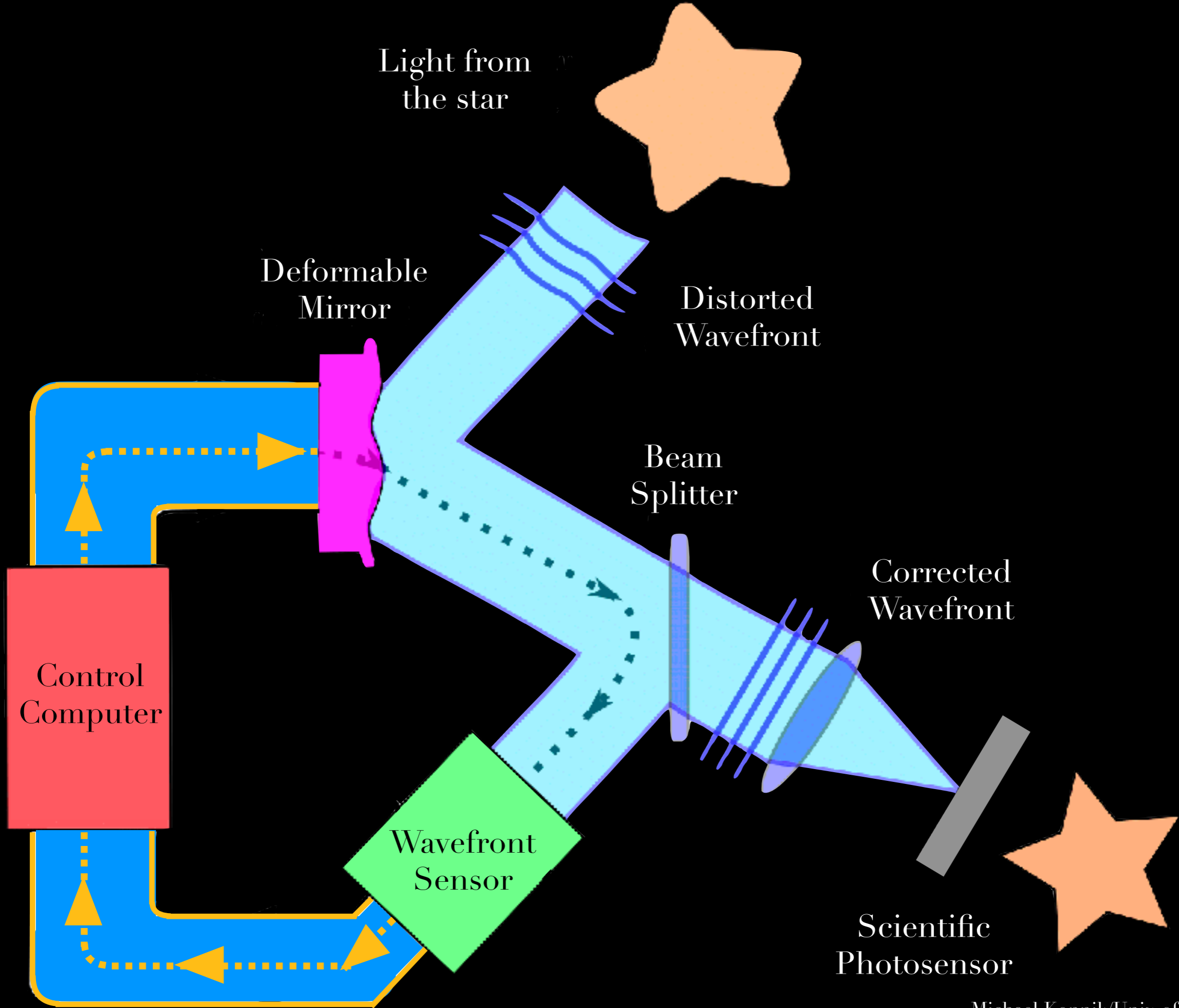
Components

- Adaptive Optics
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- Differential Imaging



Direct Imaging





Light from the star



Deformable Mirror

Distorted Wavefront

Beam Splitter

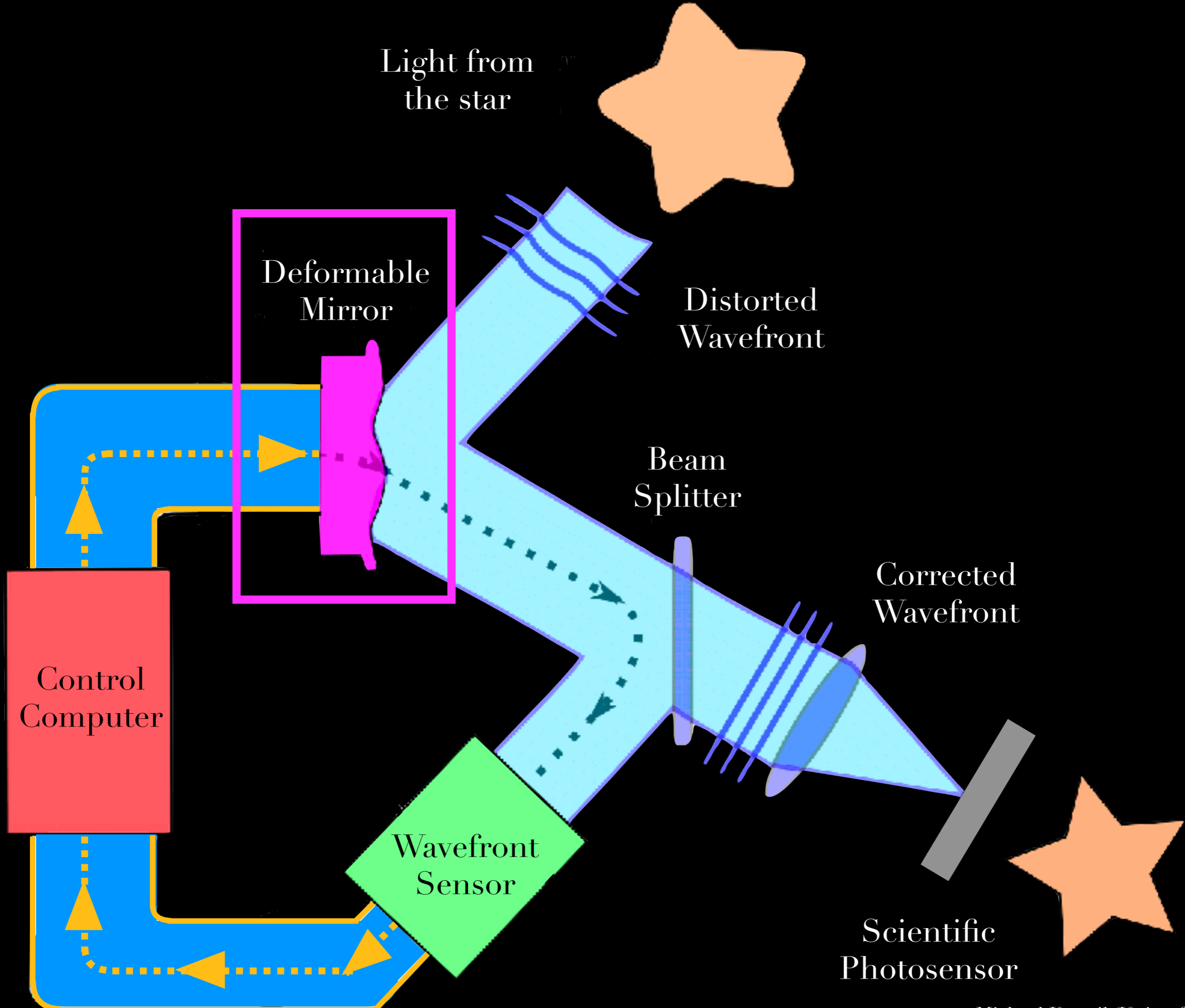
Corrected Wavefront

Control Computer

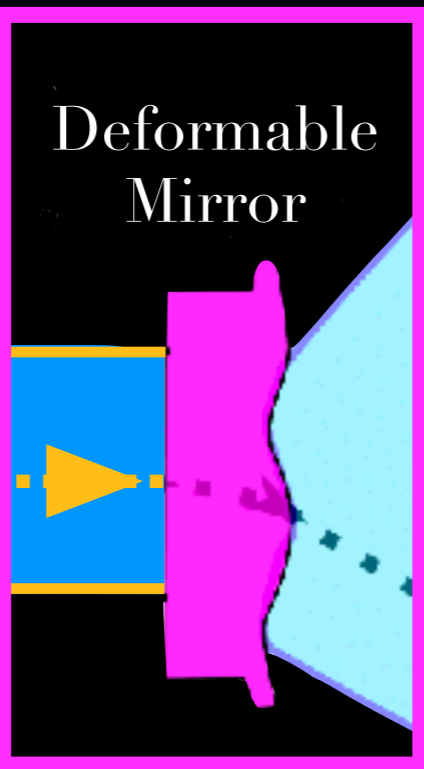
Wavefront Sensor

Scientific Photosensor





Light from the star



Deformable Mirror

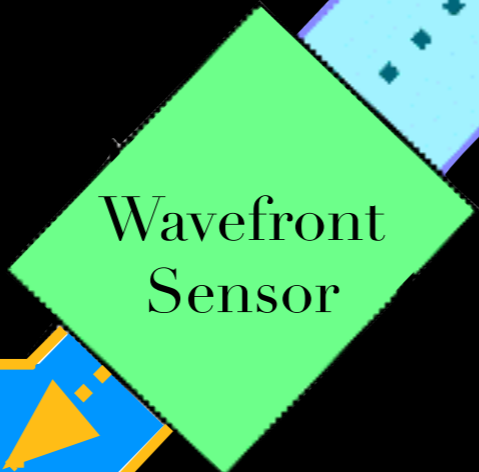
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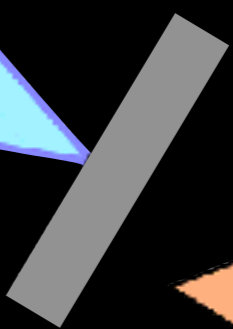
Corrected Wavefront



Control Computer



Wavefront Sensor



Scientific Photosensor



Motivation

Upgrades — HAKA and AO3K

High Order Keck Adaptive Optics (HAKA) Upgrade: Improve corrections of atmospheric fitting error to optimize Keck AO system's performance for high contrast science by upgrading the **Keck II DM**, Shack-Hartmann wavefront sensor, and real-time controller to create a new high-order DM system.

Upgrades — HAKA and AO3K

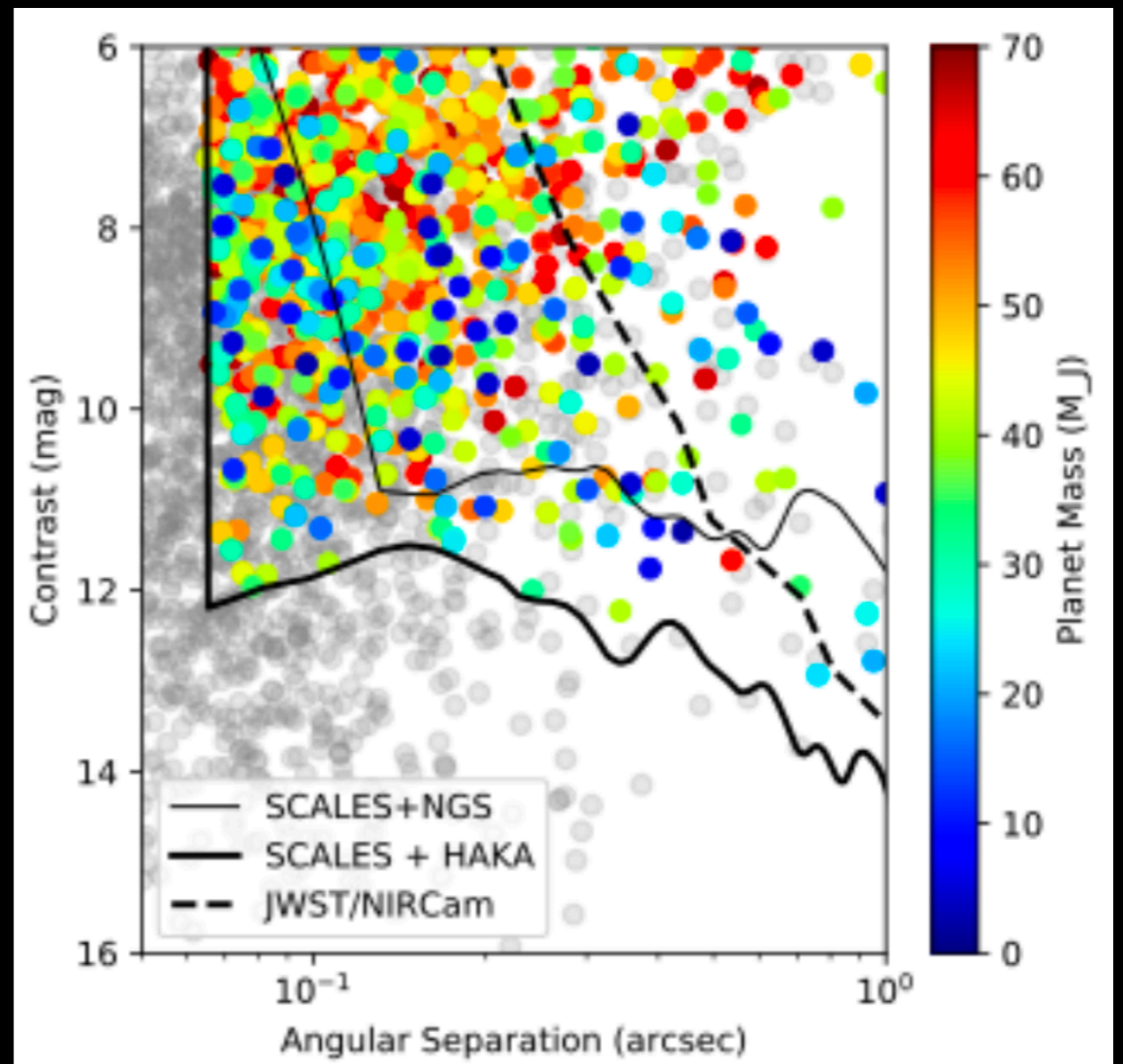
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Adaptive Optics 3K (AO3K) at Subaru: Reach deeper contrasts for high-contrast imagers, fainter targets for imaging and spectroscopy, and redder targets through a phased upgrade of the AO system — installing a new NIR pyramid wavefront sensor, **upgrade to a higher order DM**, non-linear curvature visible wavefront sensor, and upgrade of the real-time control system.

HAKA Science Objectives: Exoplanets

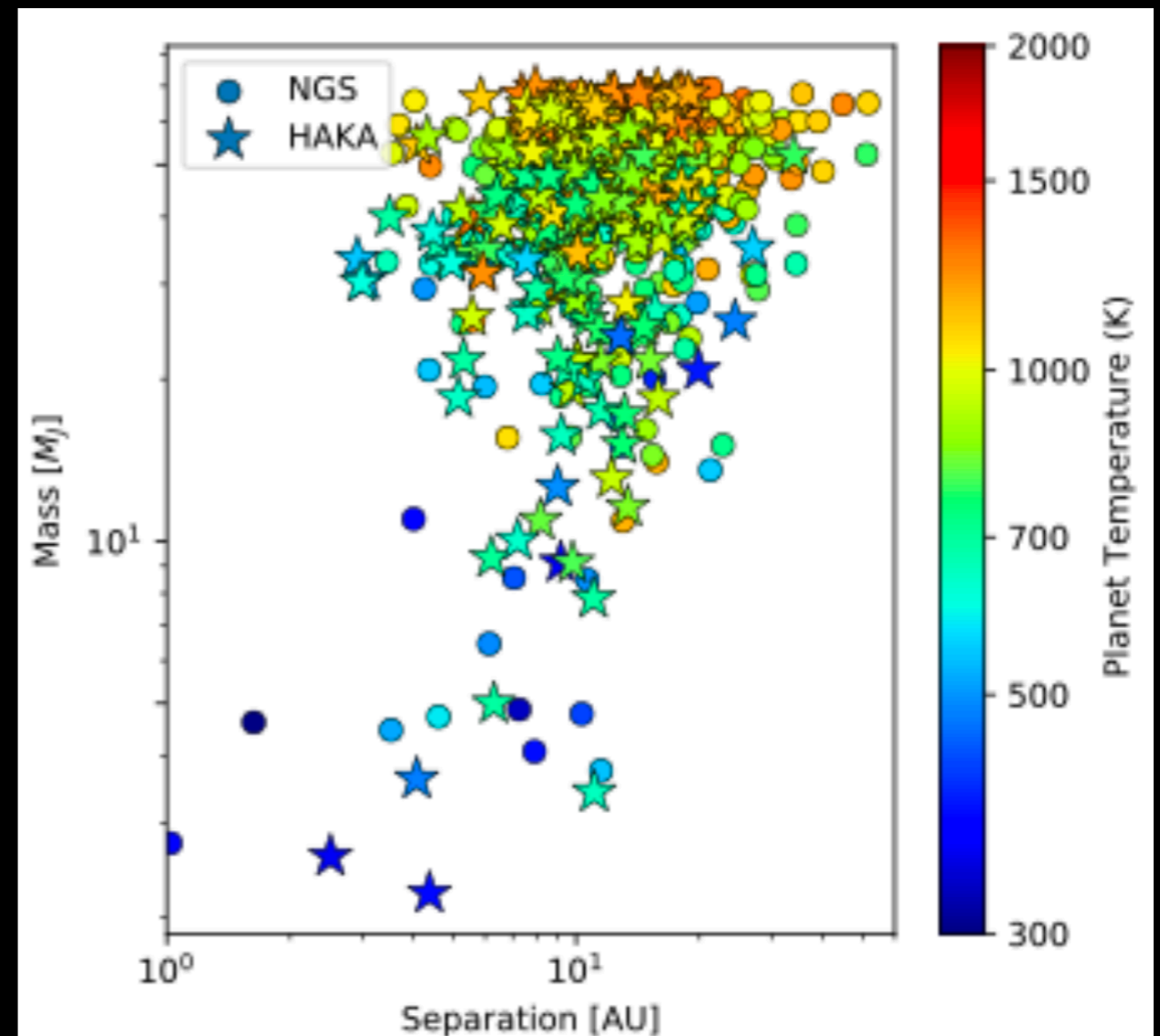
HAKA Science Objectives: Exoplanets

- Direct imaging and spectroscopic characterization of old, cold exoplanets



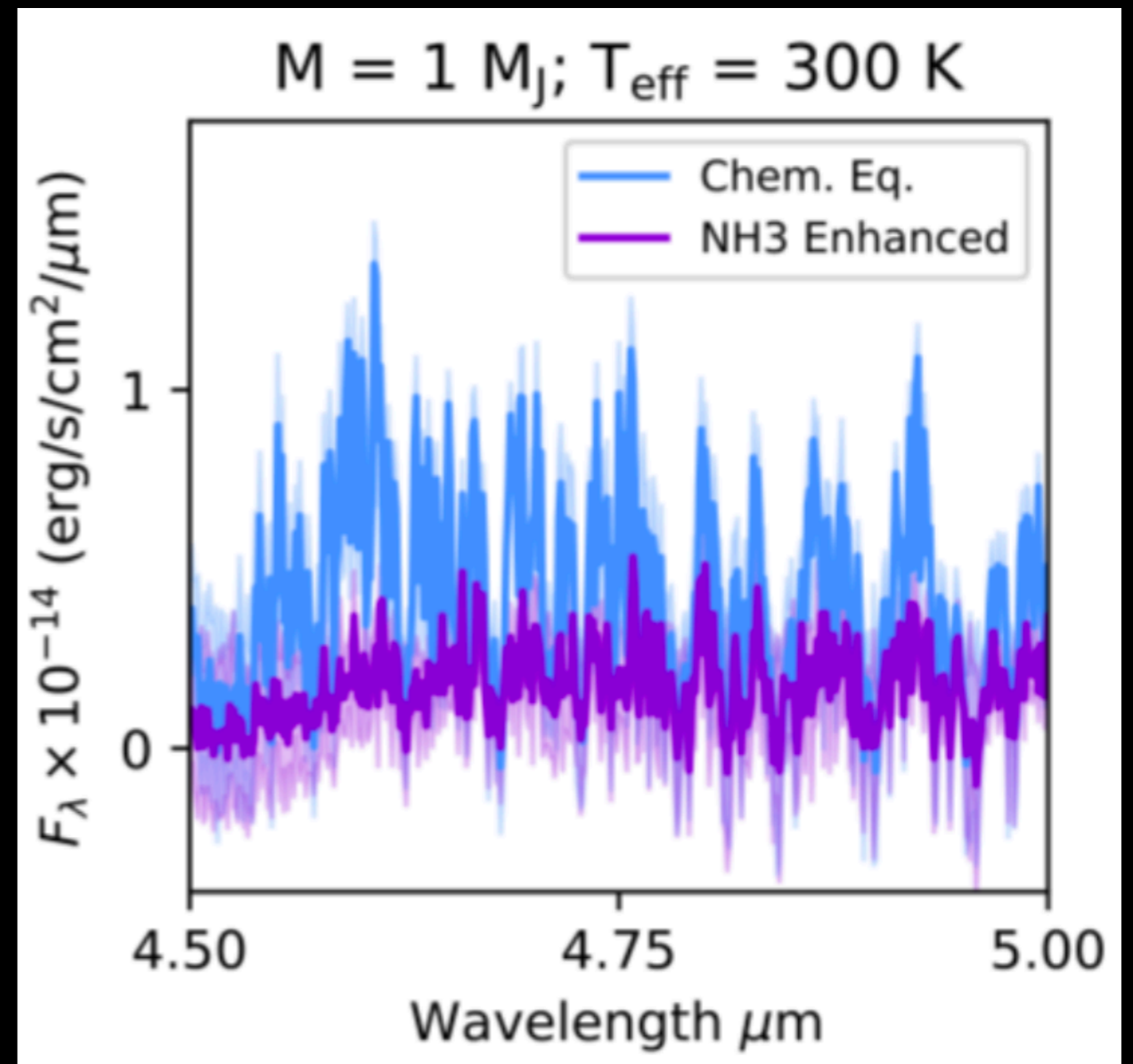
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- ◉ Direct imaging and spectroscopic characterization of old, cold exoplanets
- ◉ Twice the number of planets with the AO upgrade in the extended *Gaia* era.



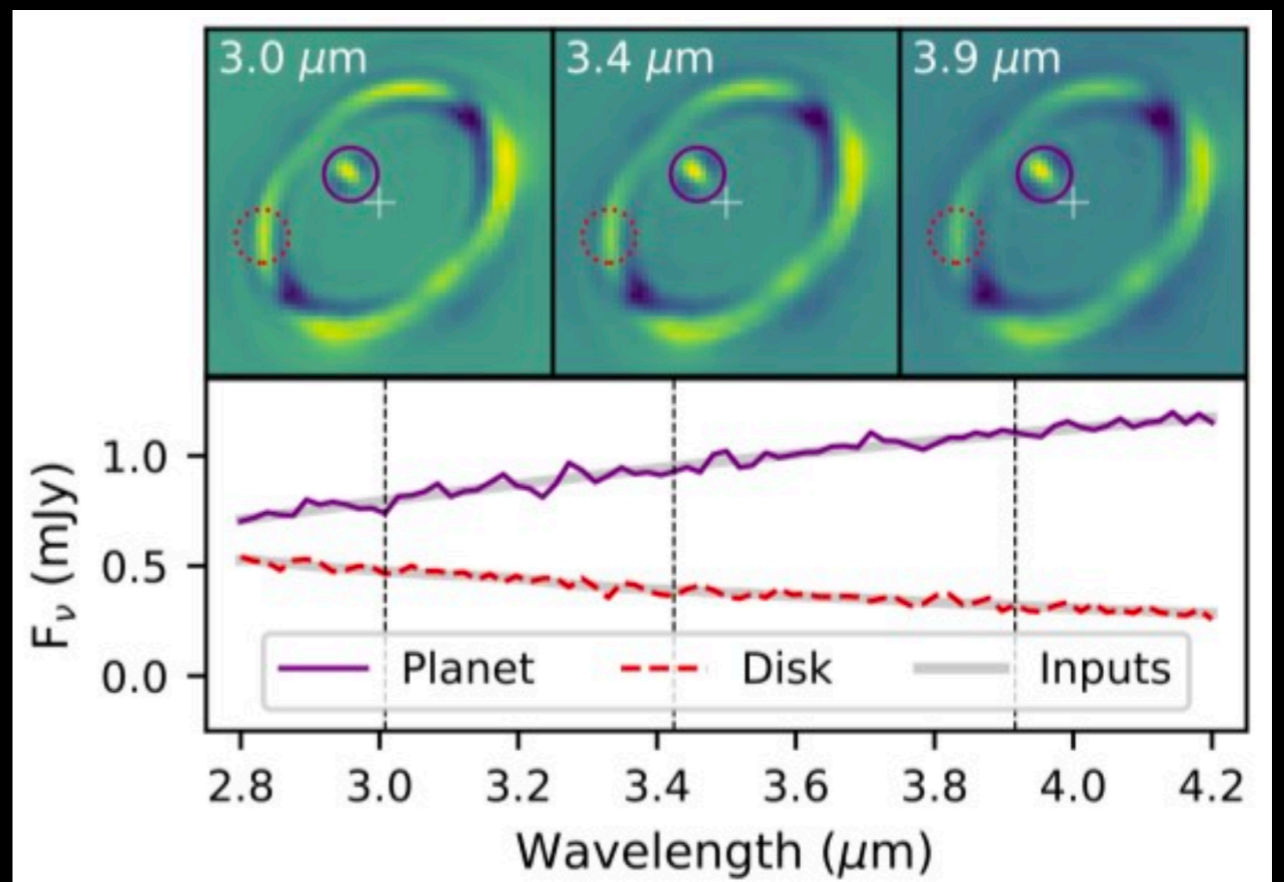
HAKA Science Objectives: Exoplanets

- ◉ Direct imaging and spectroscopic characterization of old, cold exoplanets
- ◉ Twice the number of planets with the AO upgrade in the extended *Gaia* era.
- ◉ High contrast $R \sim 3000$ mid-IR spectroscopy allowing line-by-line identification of molecules, including abundances of major absorbers (CH_4 , CO , H_2O , NH_3 , PH_3) and also more tenuous species (CH_3D , GeH_4 , C_2H_2 , C_2H_4).



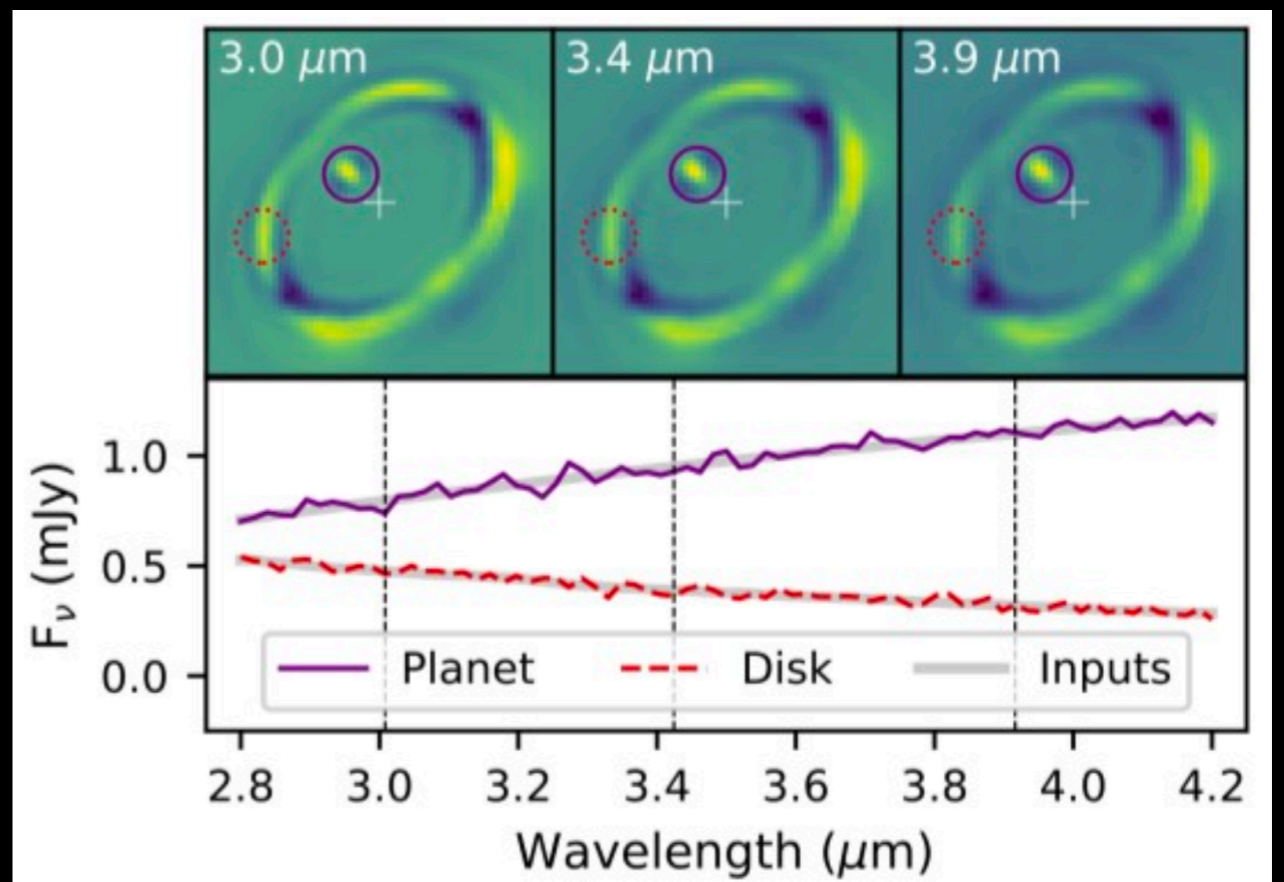
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- Enhance imaging of protoplanets in their nascent disk and observe mass accretion



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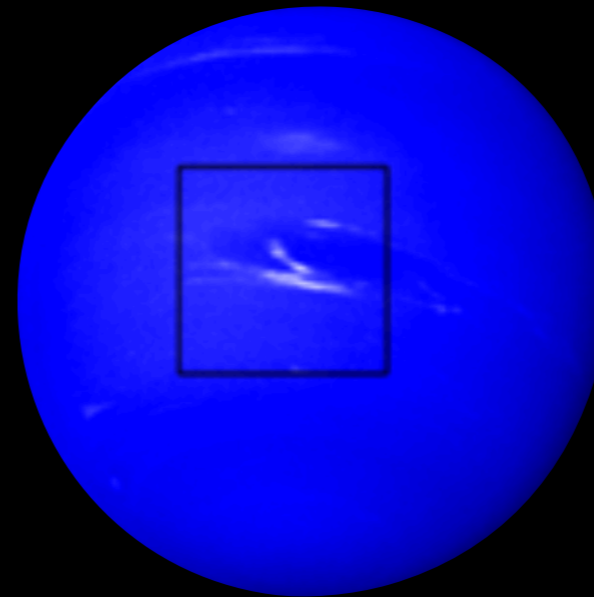
- ◉ Enhance imaging of protoplanets in their nascent disk and observe mass accretion
- ◉ Protoplanetary Disks: High spatial resolution mapping of dust, H₂O ice, and organic features in disks.



HAKA Science Objectives: Solar System

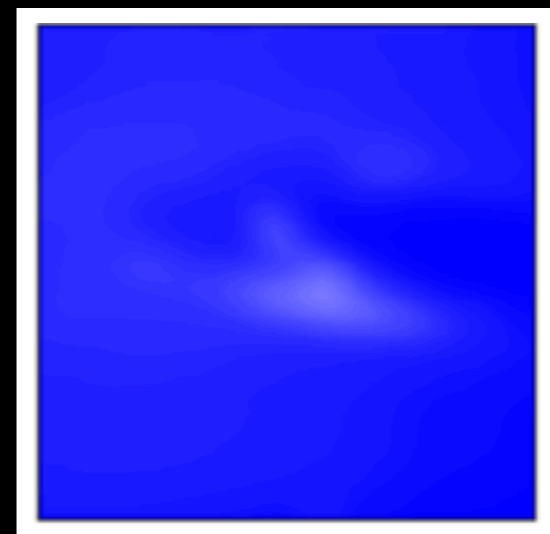
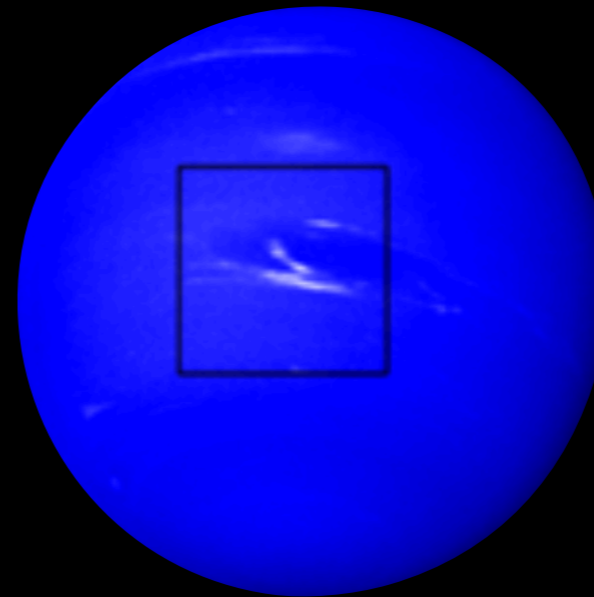
HAKA Science Objectives: Solar System

- ◉ Probe the atmospheres of our Solar System's ice giants



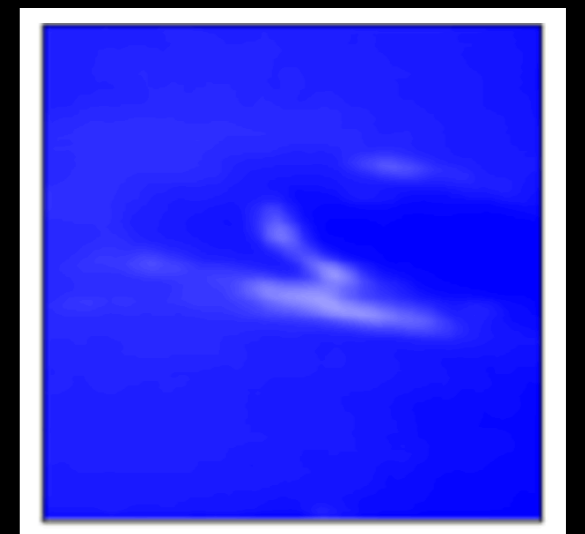
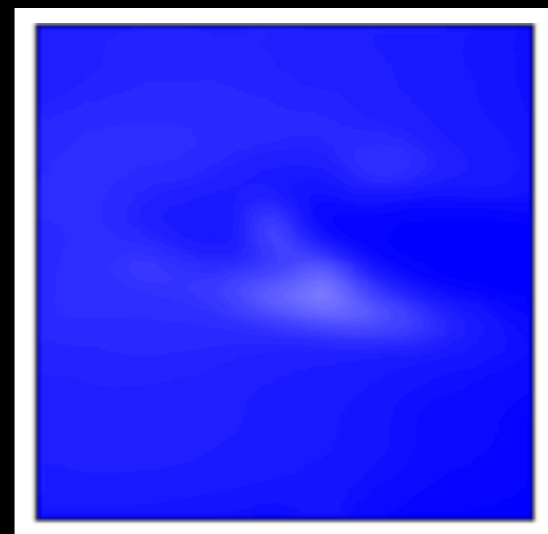
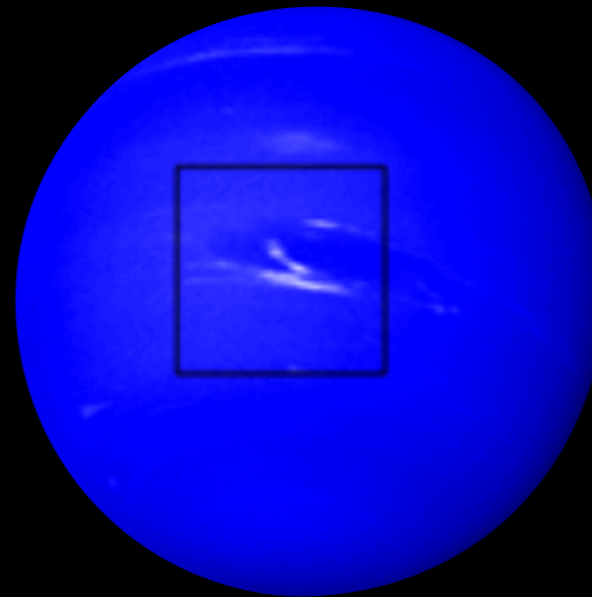
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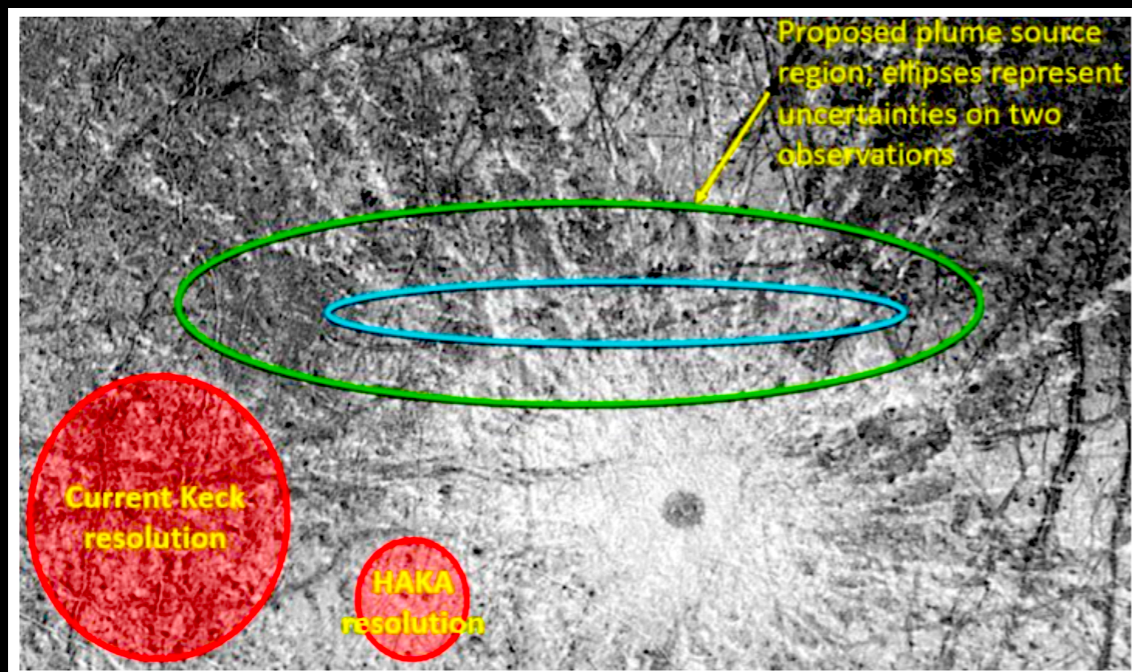
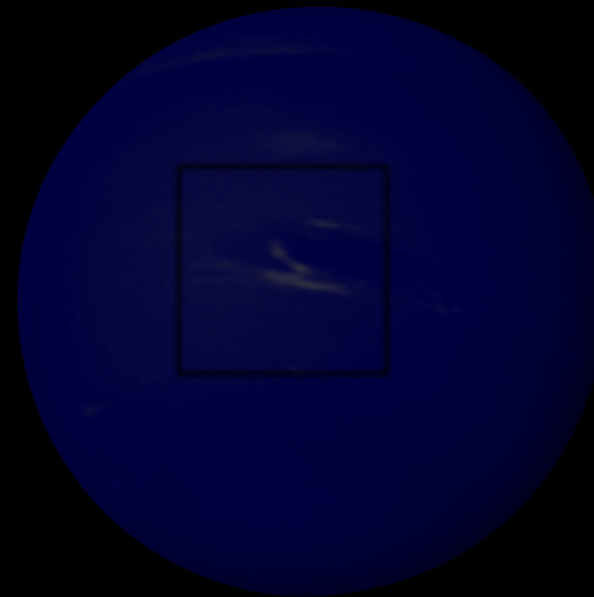
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HAKA Science Objectives: Solar System

- ◉ Probe the atmospheres of our Solar System's ice giants
- ◉ Map the surfaces of the Galilean moons with lesser wavefront errors



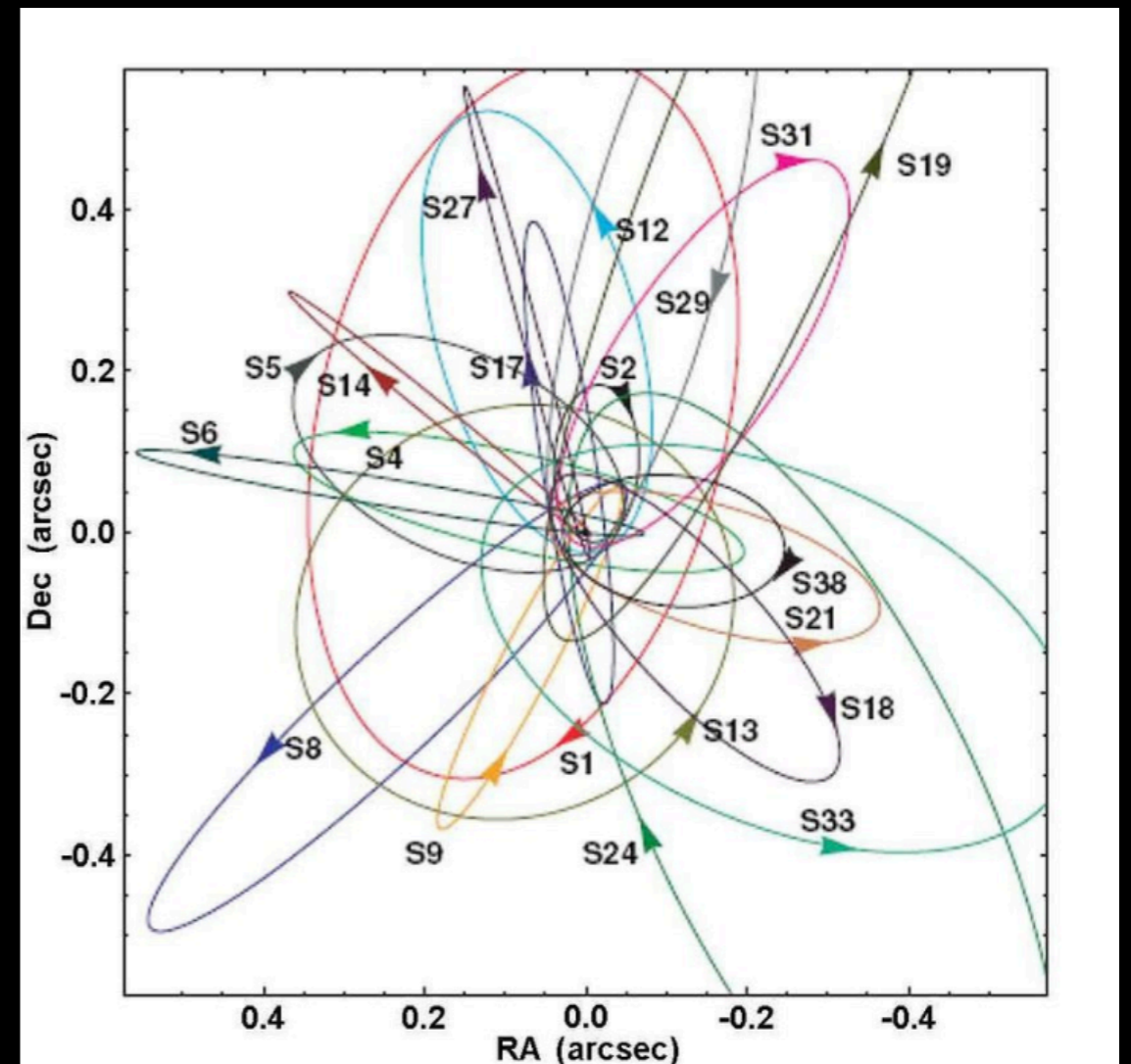
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- ◉ Enhanced imaging and spectroscopy of the stars orbiting the black hole at the Galactic Center

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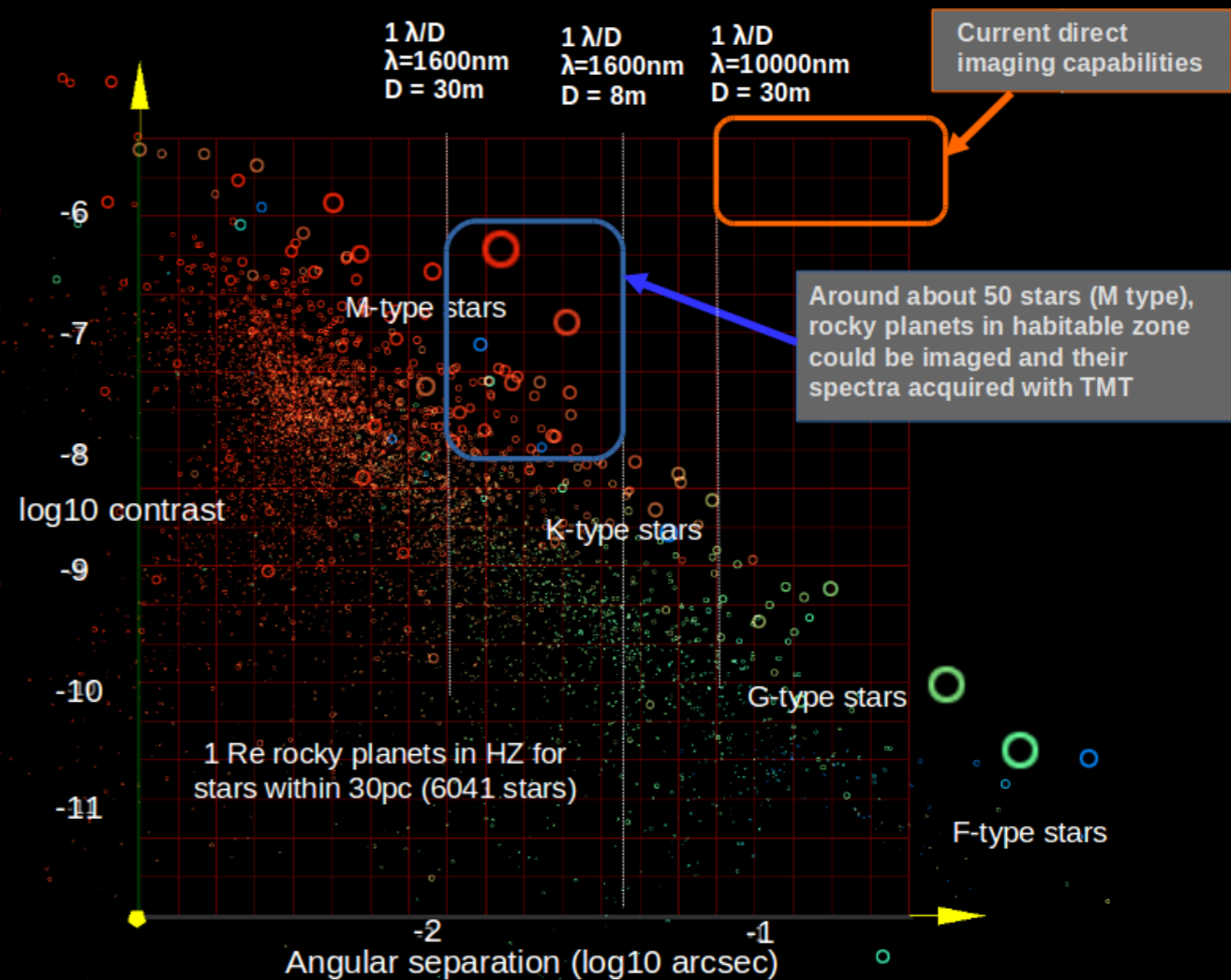
- Enhanced imaging and spectroscopy of the stars orbiting the black hole at the Galactic Center



Subaru/AO3K Team

AO3K Science Objectives

- Enhanced imaging and spectroscopy of the stars orbiting the black hole at the Galactic Center
- Combination of NIR PyWFS and higher order DM will get us to K- to M-type stars, and stars with dust extinction, the prime targets for imaging habitable planets with ELTs



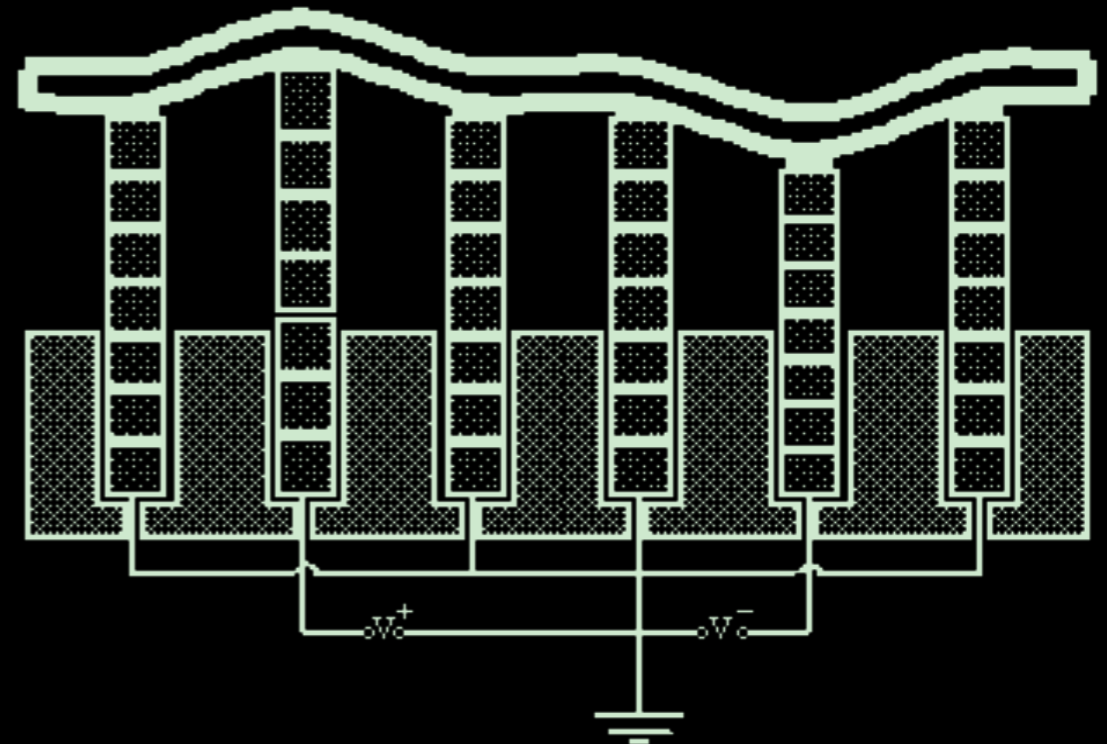
Deformable Mirror

Goal

- Apply an equal and opposite shape of the estimated wavefront to the pupil plane

Design

- A thin mirror supported by an array of actuators
- Actuators move quickly and precisely to shape the mirrored surface to match the estimated wavefront
- Total motion of a single actuator $< 20 \mu\text{m}$



Classic DM with PZT actuators

Why a new Deformable Mirror (DM)?

HAKA Upgrade

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HAKA Upgrade

Current DM

- Over 25 years old (first light— 2/5/99)
- 349 piezoelectric actuators
- Strehl Ratio: ~ 0.6 @ 2 μm
- Fitting Error: 121 nm

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New DM

- 2900 magnetic coil actuators
- Strehl Ratio: ~0.7 @ 2 μm
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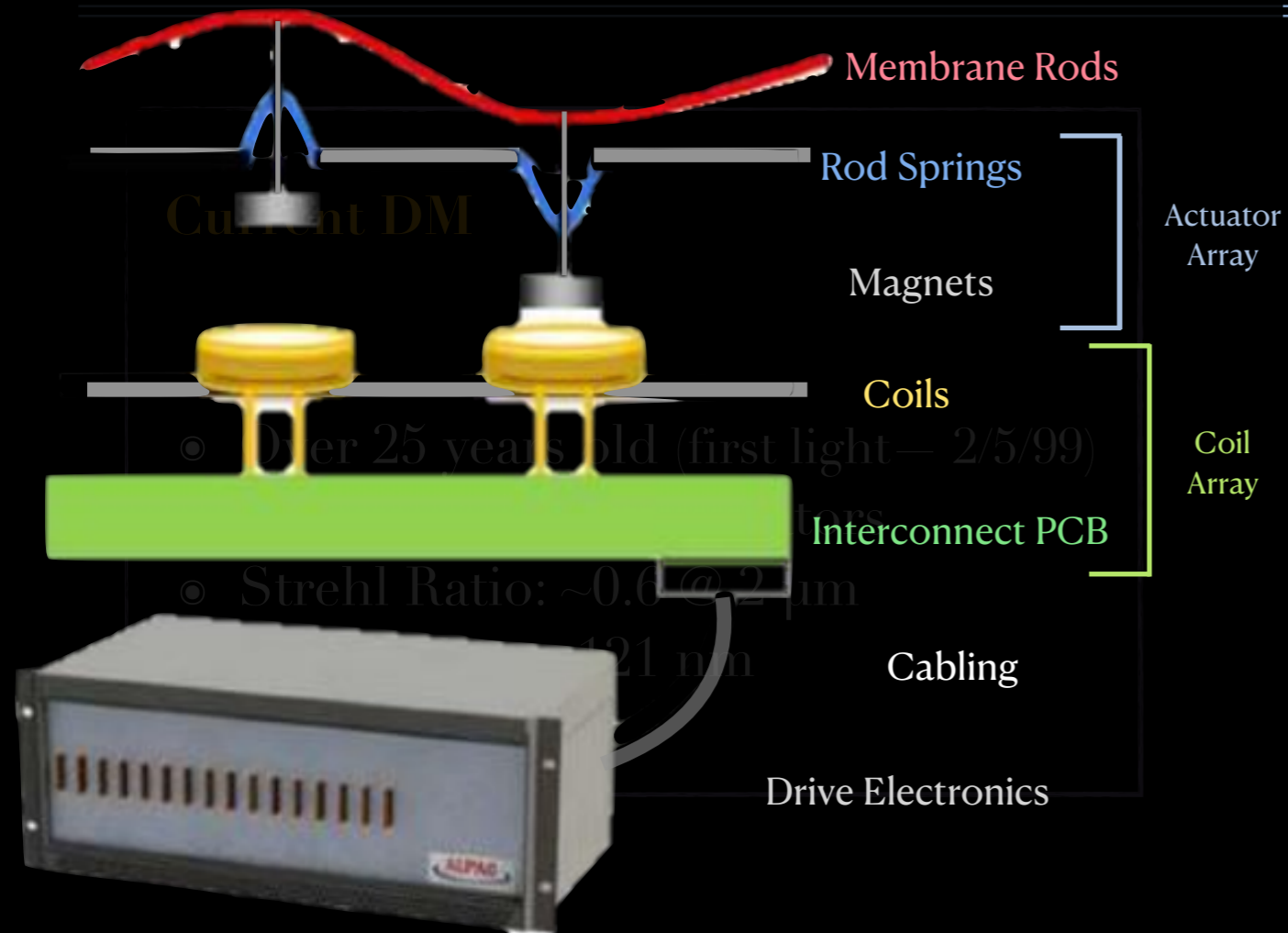
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Fitting Error (σ): Residual error from wavefront correction

$$\text{Strehl Ratio} = \exp[-(2\pi\sigma)^2]$$

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AO3K

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- ◉ About 18 years old (First light with LGS 10/12/'06)
- ◉ 188 bimorph DM actuator
- ◉ Strehl ~20-40% in H band (up to 65% seen with NIR wavefront sensor)

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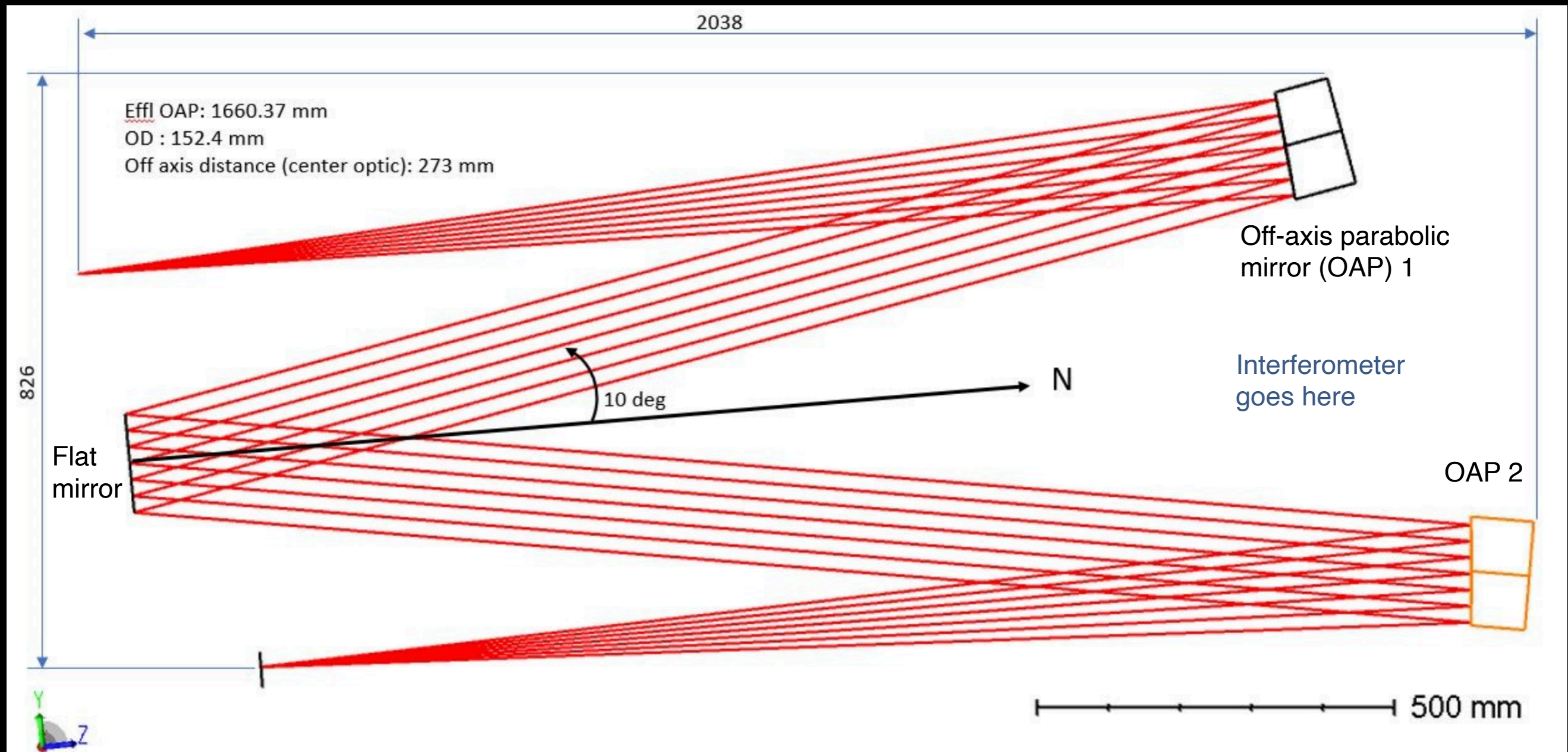
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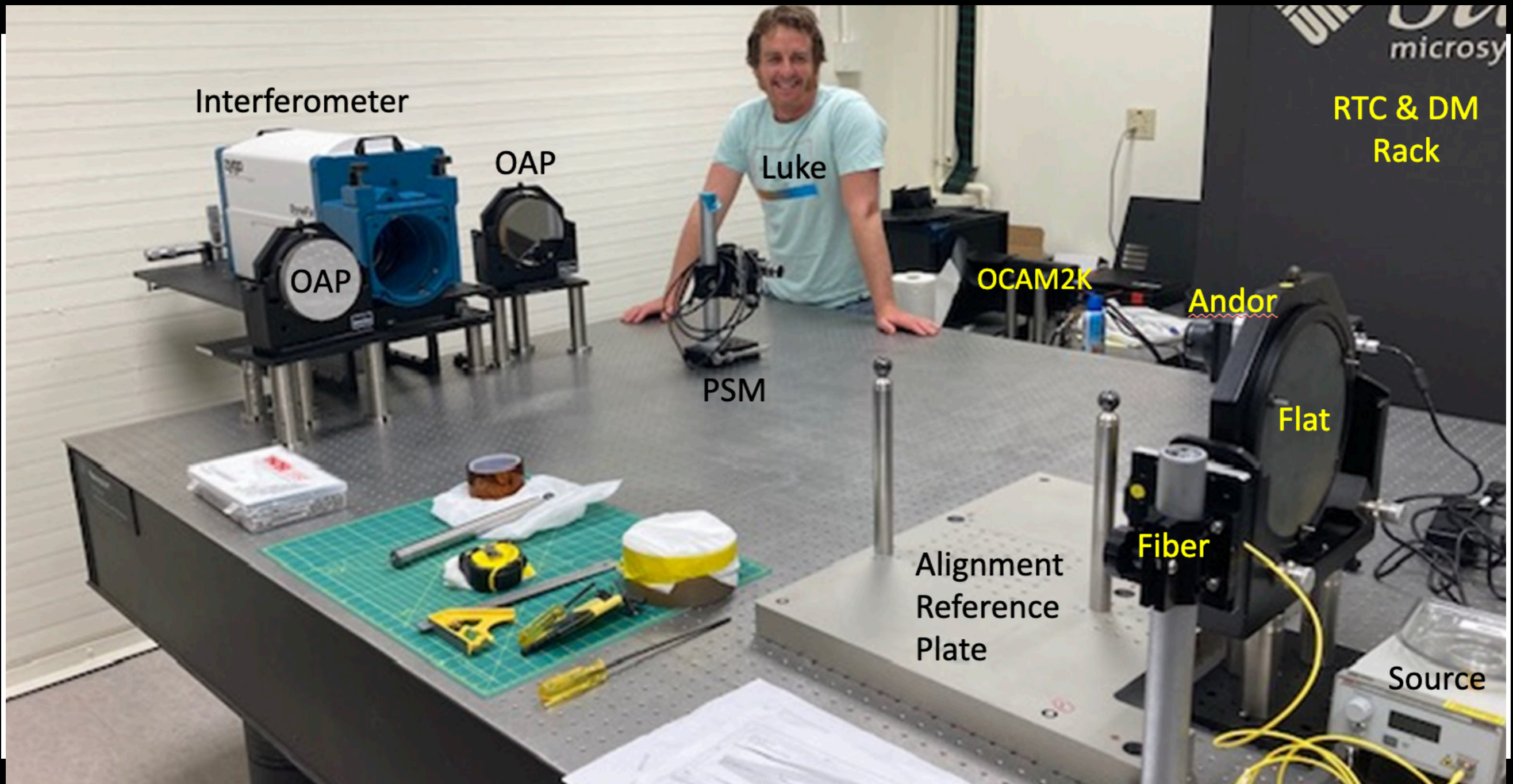
- ◉ 3228 magnetic voice coil actuators
- ◉ Up to 85% of Strehl seen in H-band with NIR wavefront sensor)

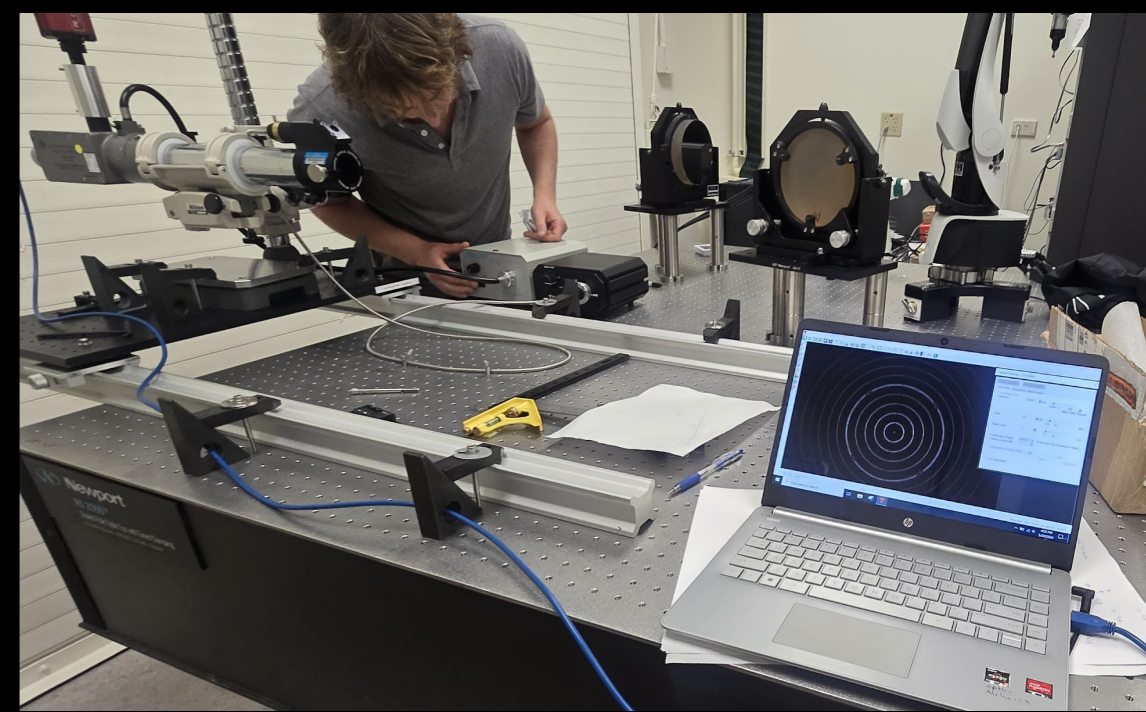
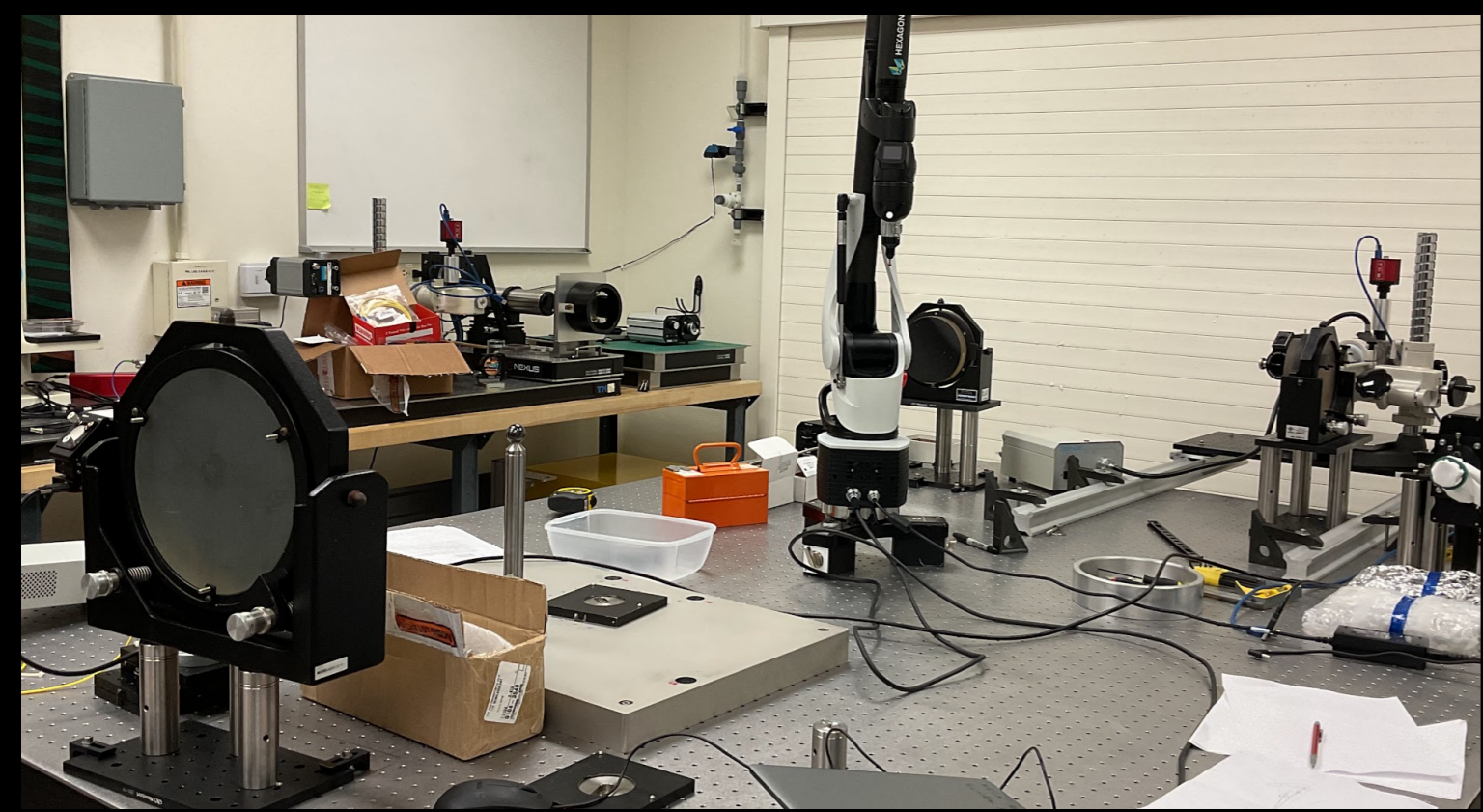
Testing the Deformable Mirror

Step 1: The Test Bench



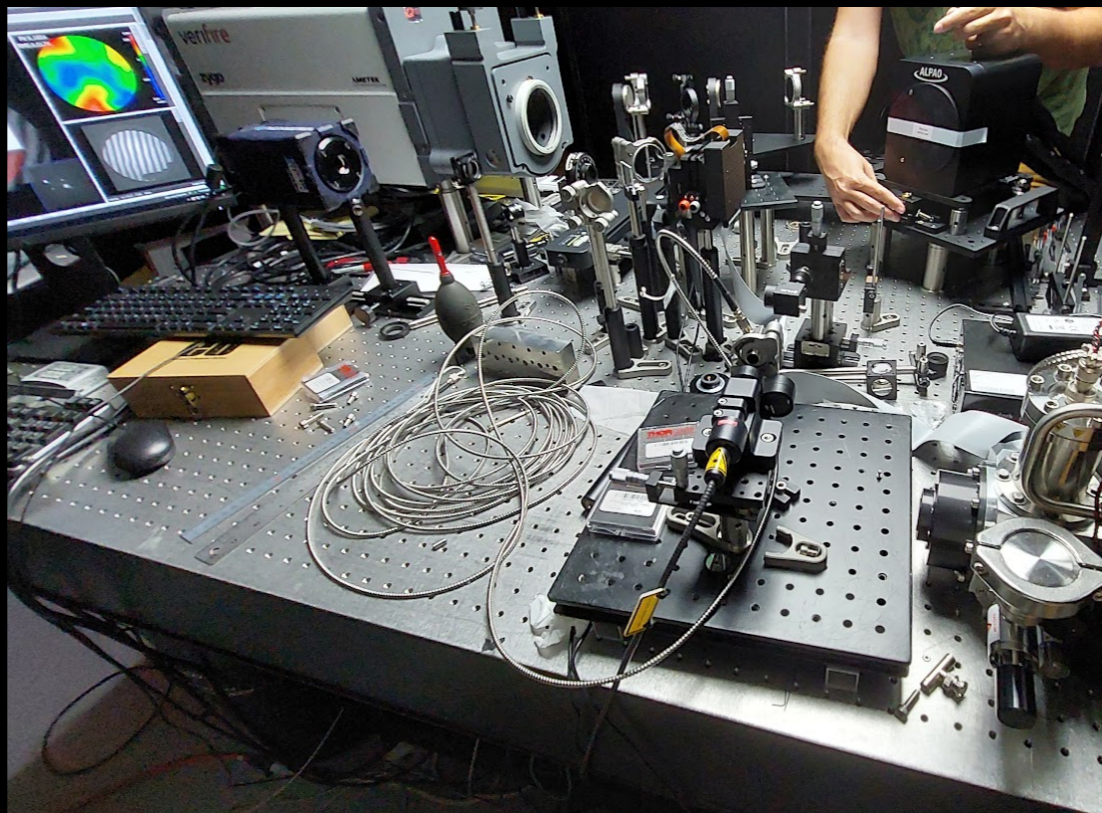
Step 1: The Test Bench



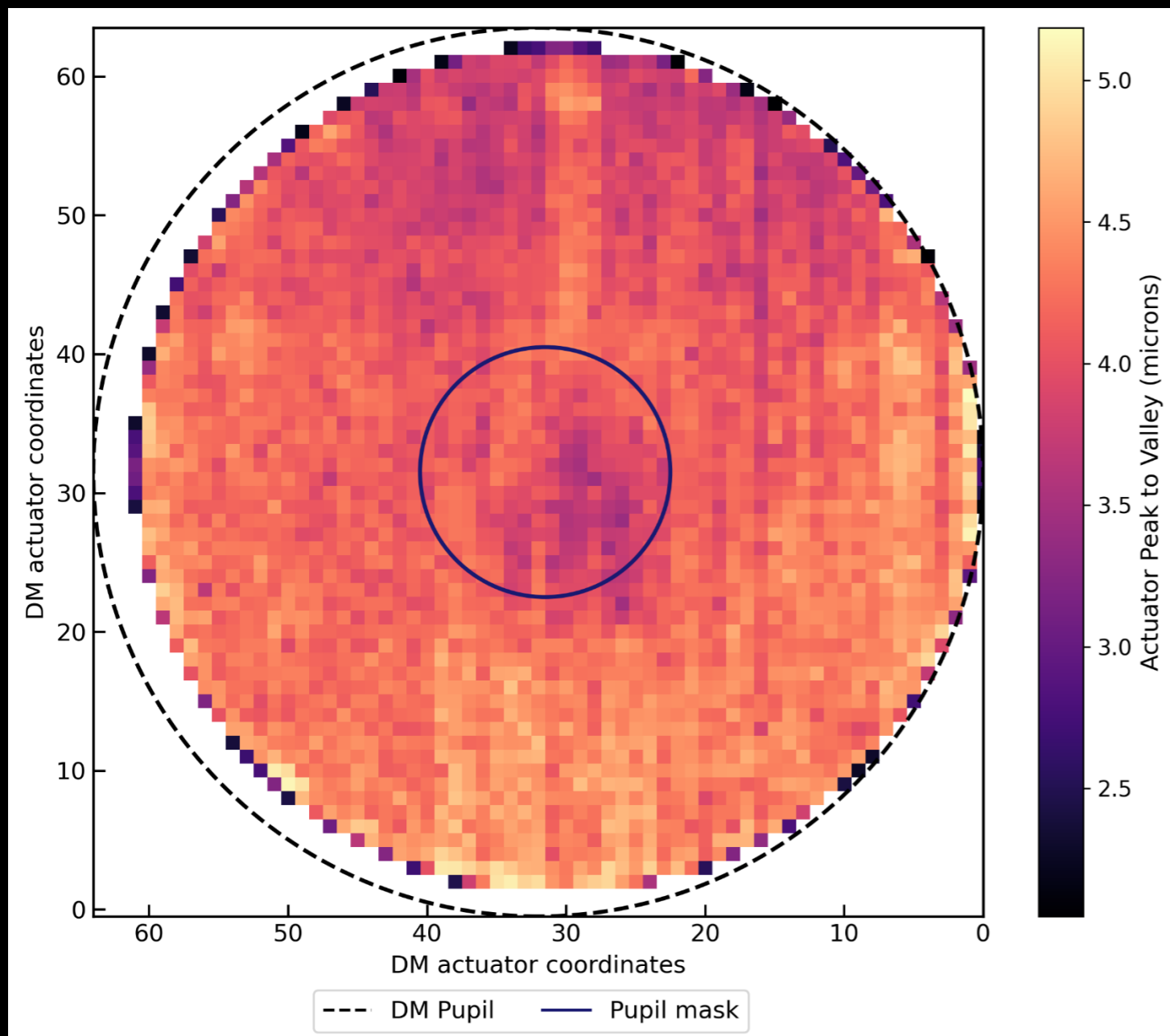


Step 2: DM Characterization

- ◉ **Functional Testing:** Ensure that the DM is working properly and all setup steps work.
- ◉ **Performance Testing:** Test the performance of the DM and compare it to the performance reported by manufacturer.
 - ▶ **Data Acquisition:** Measure different aspects of the DM— temperature, actuator stroke, gain, and power dissipation and consumption.
 - ▶ **Data Analysis:** From the Data Acquisition tests, create an actuator model in the software pipeline for the DM.



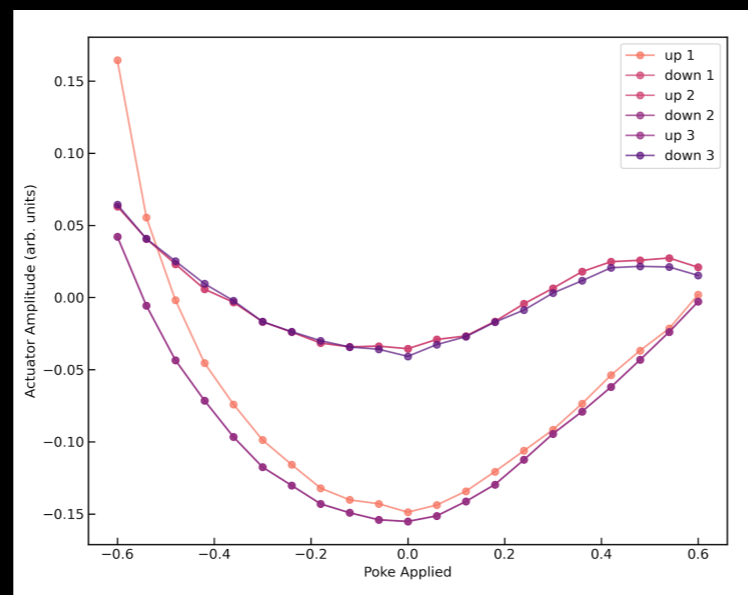
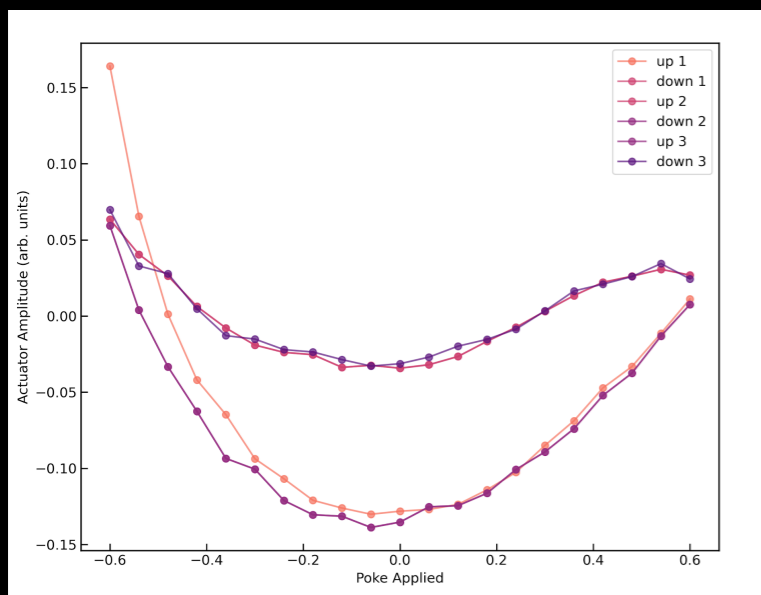
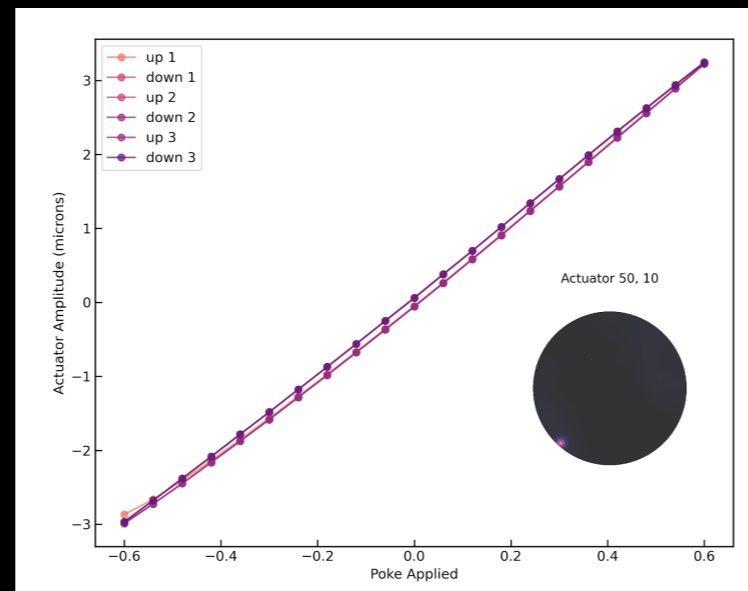
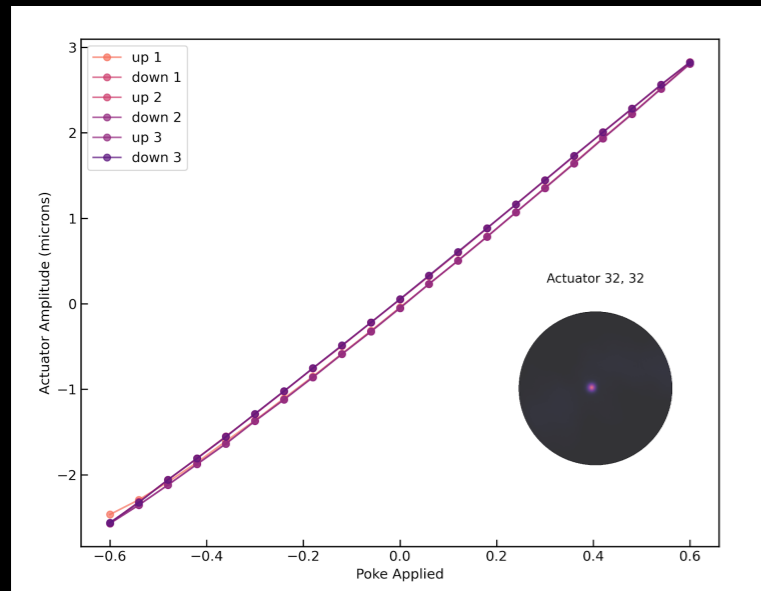
Gain Map



- Mapping the amplitudes of each of the actuators
- Gain map demonstrates the stroke of individual actuators
- “Lazy zone” in the center mostly goes behind a central obscuration

Linearity and Hysteresis

Measurement

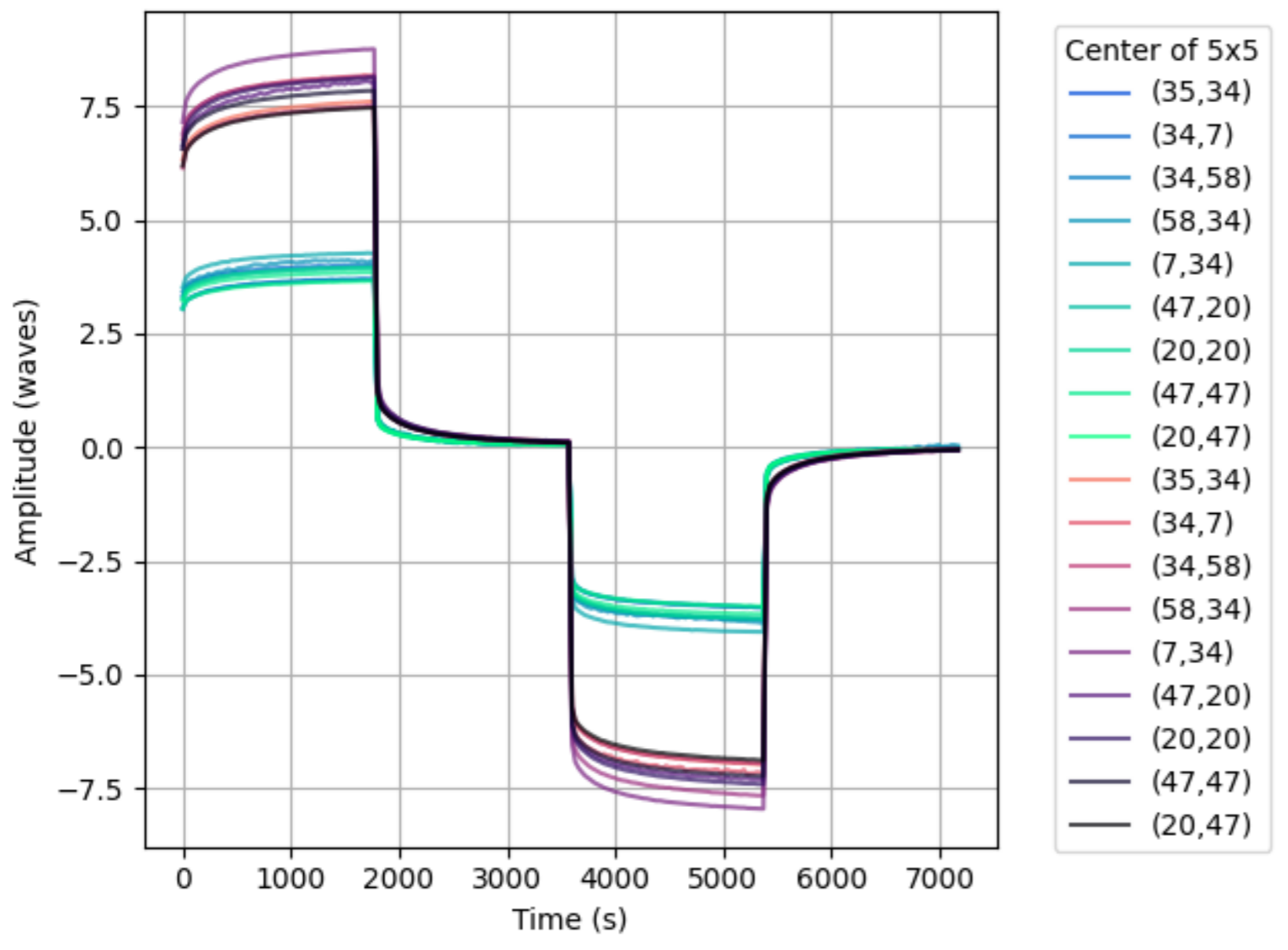
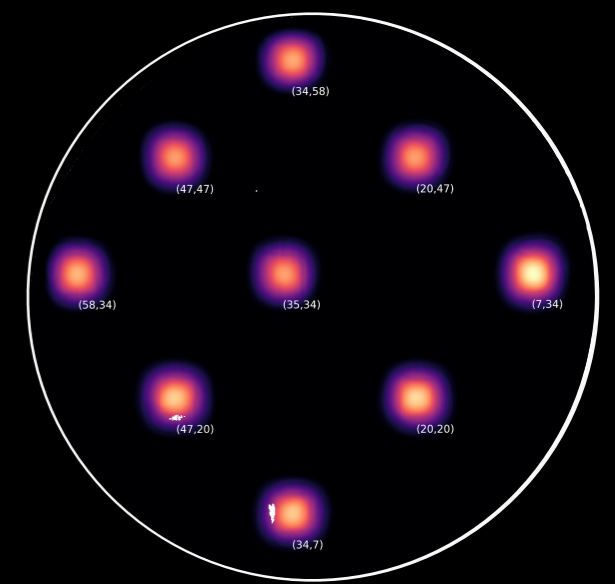


○ A test to check residual positional error from previous actuator position commands, and the repeatability of the stroke

○ Here we pushed select actuators from a negative to a positive stroke and back multiple times and checked if we began and ended at similar amplitudes.

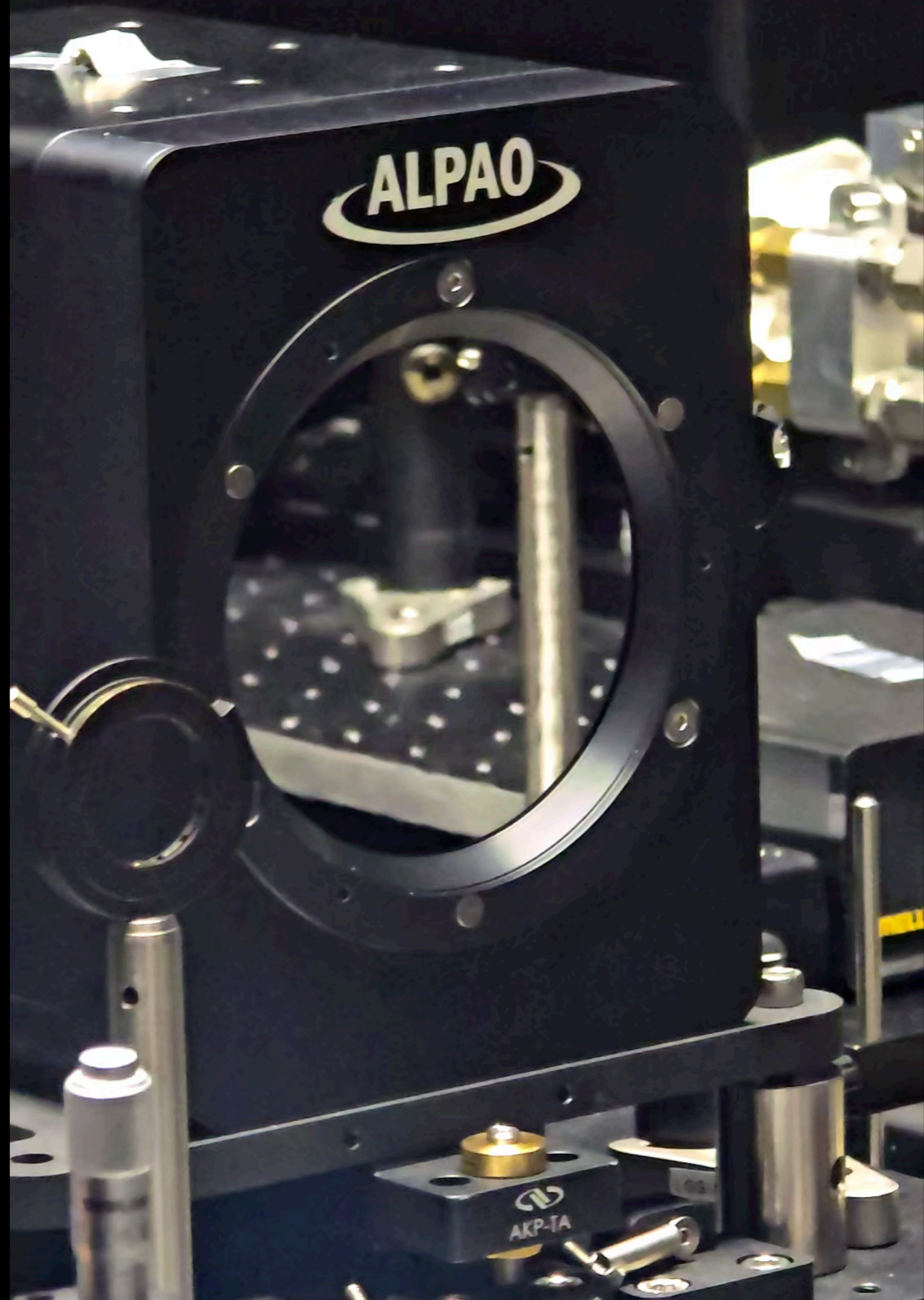
Detrended Measurement

Creep



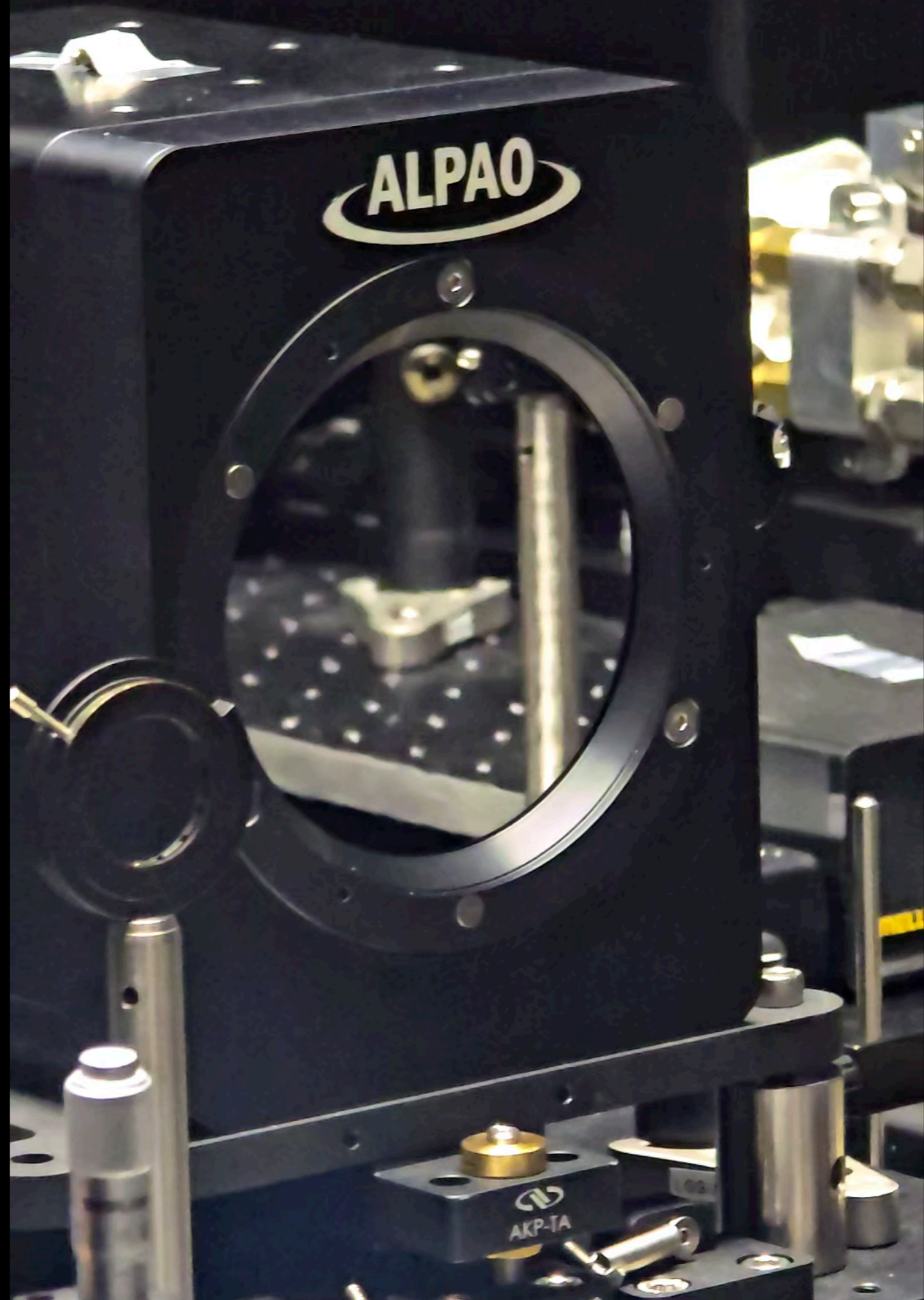
- When the actuator continues to expand or contract even after the voltage change is complete.
- Here we test how stable a set of actuators are under prolonged stress

ALPAO



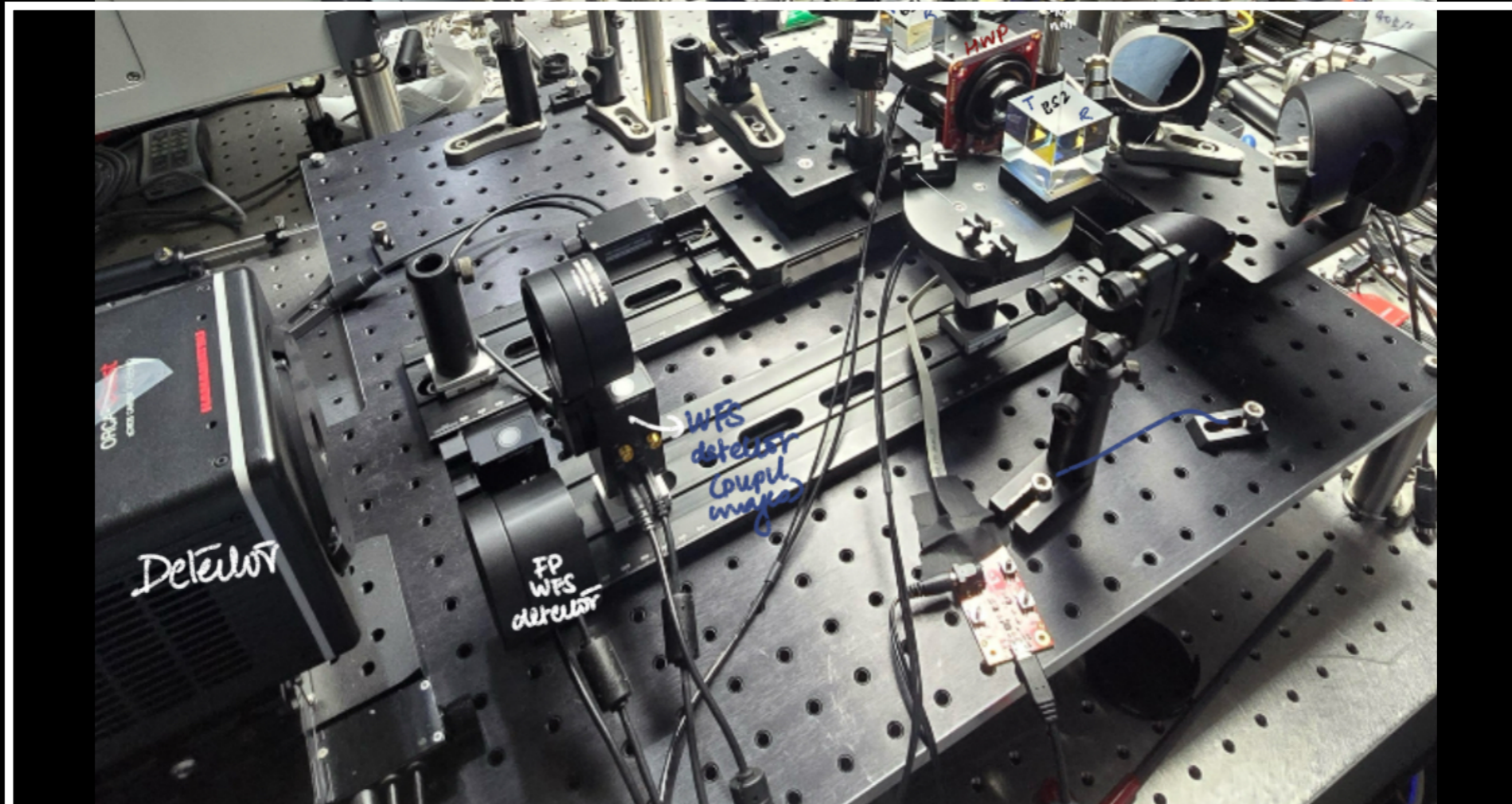
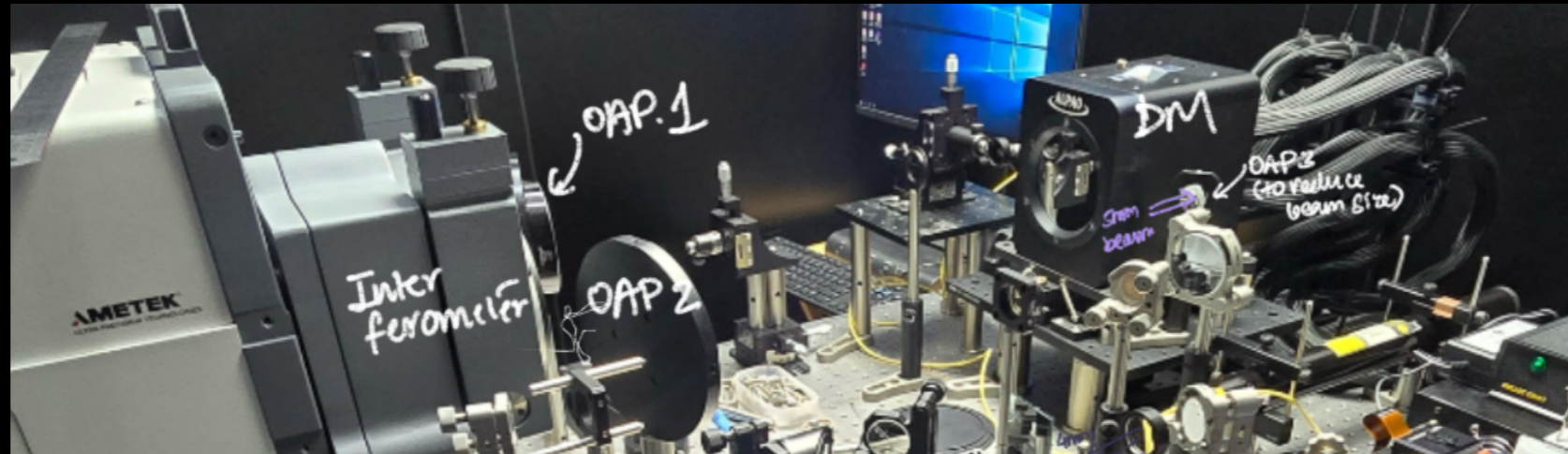
AKP-TA

ALPAO



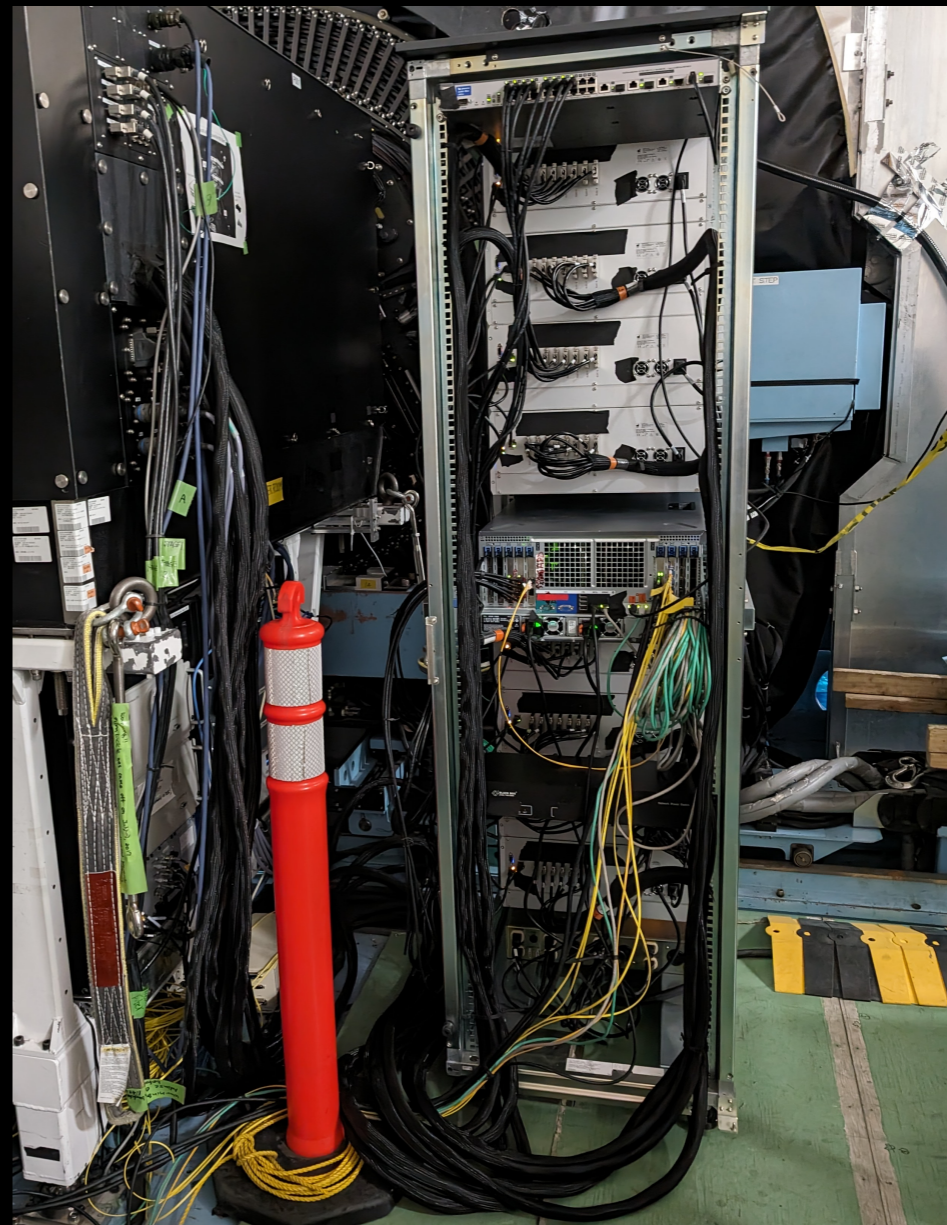
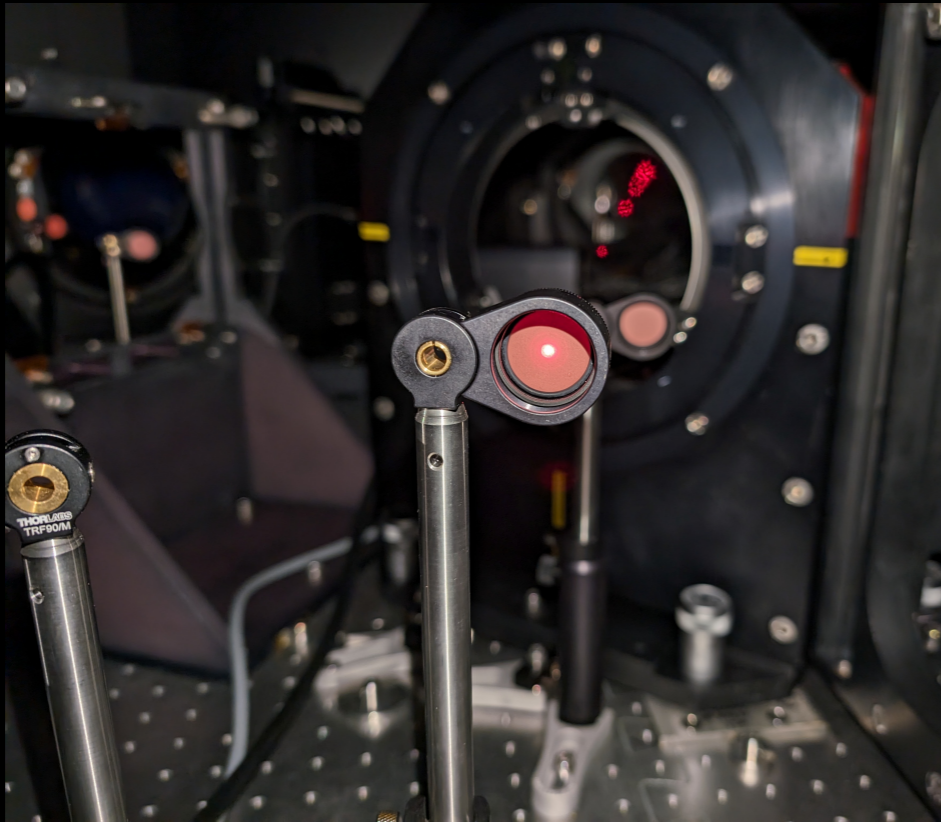
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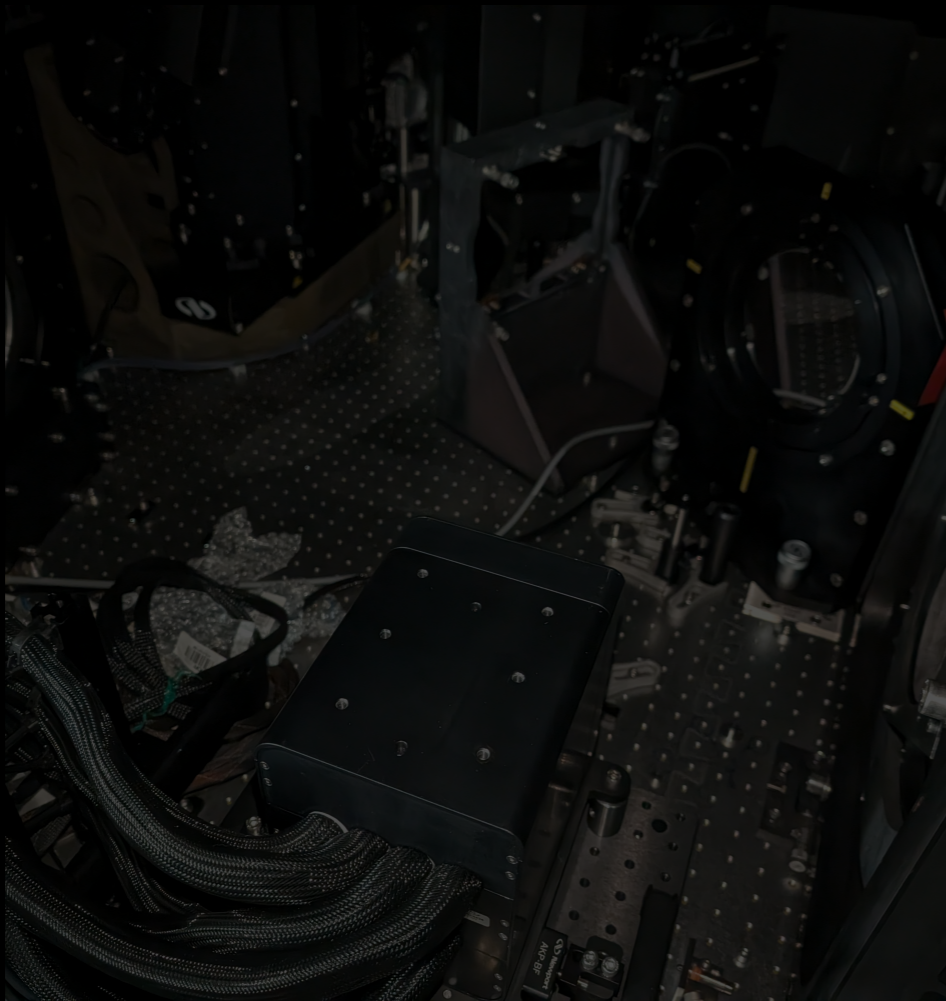
Step 3: Closing the AO Loop I



Summit Installation

Ft. The Subaru DM







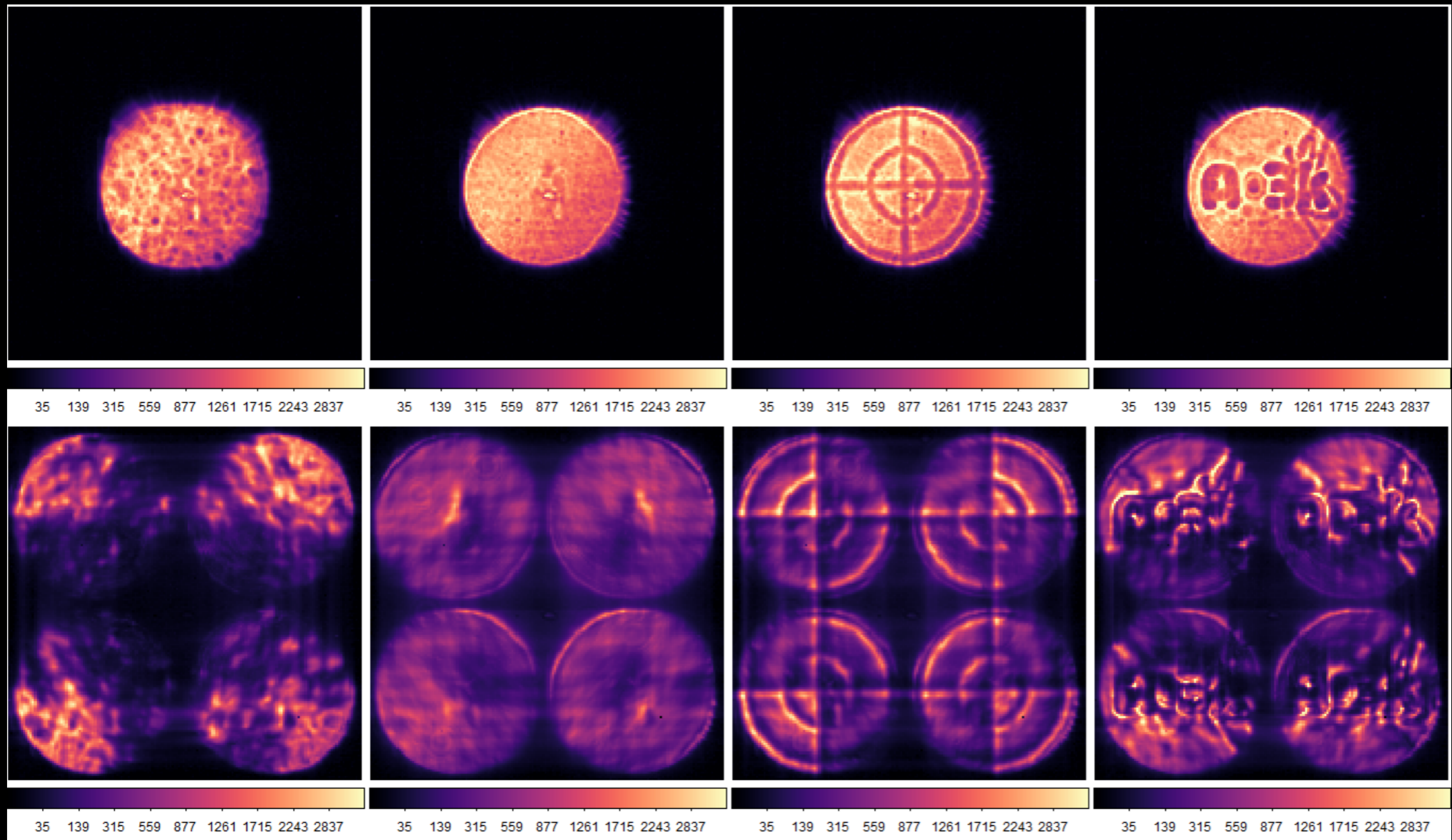
ALPAO

AKP-TA
Newport
AKP-BC

THORLABS MB2530/M

THORLABS
RS05PM

Step 4: Summit Installation



From Left to Right: Quasi-pupil plane (Top) and NIR WFS (Bottom) images of: Subaru/AO3K
Rest shape, Best flat from lab, Flat+Bullseye, Flat+logo.

Step 5: Closing the AO loop II

The screenshot displays the control interface for the AO3K system, divided into three main sections:

- One-Eight-Eight DM multi-channel display!**: A grid of 13 sub-windows showing various wavefront sensor channels. Channels 00-11 are currently turned OFF, as indicated by red text below each window. Channel 12, labeled "Combined", shows a clear wavefront. Channel 13, labeled "Clipping diff", shows a speckle pattern. A status bar at the bottom of this window reads: "CCh-Channel #03: min=0.000, max=0.000, mean=0.000, std=0.000 - TT [-0.55, -0.51] [1]".
- liwi PyWFS**: A window showing four sub-images of the wavefront sensor. The top-left image is labeled "800 nm SP (dffit)" and the bottom-right image is labeled "BLOCK". Below the images, the text reads: "liwi PyWFS Help press [h], quit [x] EMGain = 97 - Mfps = 999.93 160x160 - m,M = -1689,11663 mouse (29, 145) = -1 1/3 | -bias".
- nir3k**: A terminal window titled "aorts@aorts:~/AOloop/nir3k-rootdir 164x25" showing a "FUNCTION PARAMETER MONITOR". The terminal displays configuration parameters for the AO loop, including: "AOloopindex 7 AO loop index", "loopON OFF loop on/off (off=freeze)", "loopNBstep -1 loop nb steps (-1 = inf)", "loopZERO OFF loop zero", "loopgain 0.100000 loop gain", "loopmult 0.900000 loop mult", and "looplimit 0.200000 loop limit".

Step 5: Closing the AO loop II

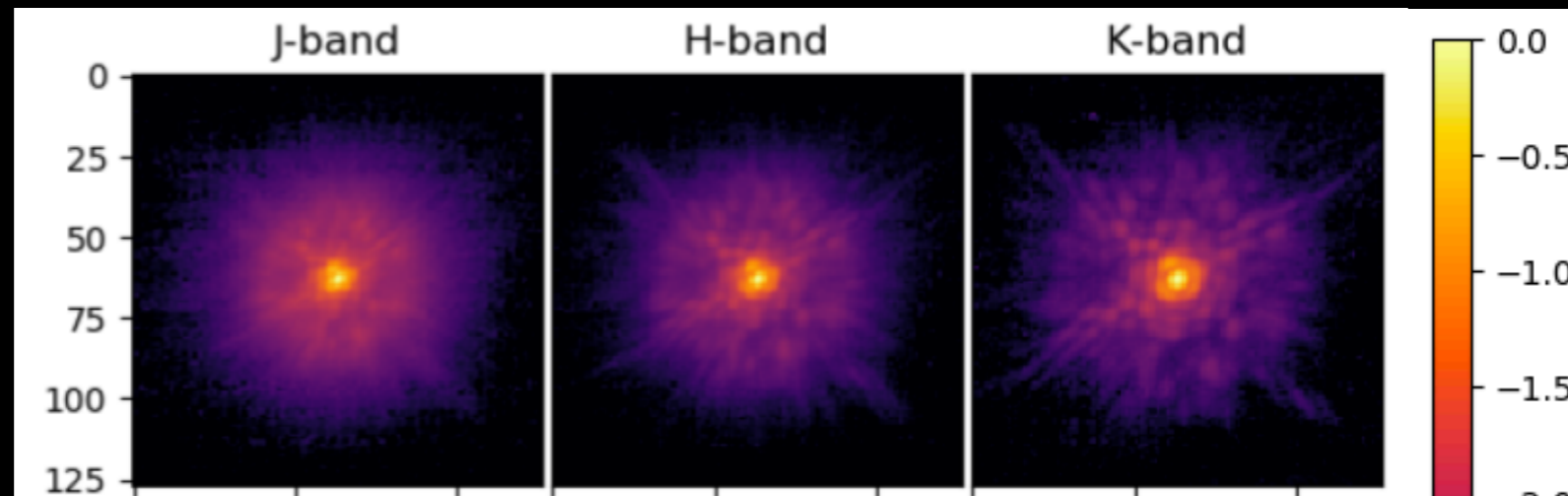
The screenshot displays the AO control software interface, divided into several windows:

- One-Eight-Eight DM multi-channel display!**: A grid of 13 sub-plots showing wavefront sensor data and control parameters. The plots are labeled: 00: offset (flat), 01: PyWFS oontrol, 02: PyWFS RM, 03: PyWFS TT LOG, 12: Combined, 04: ZAP (ZPO), 05: LLOW FS (ZPO), 06: SC probes (ZPO), 07: Speckle Control (ZPO), 13: Clipping diff, 08: Zernike offset (ZPO), 09: Ast rogrid, 10: Turbulence, 11: AO simulator. A status bar at the bottom indicates: "CCh-Channel #03: min=0.000, max=0.000, mean=0.000, std=0.000 - TT [-0.55, -0.51] [1]".
- liwi PyWFS**: A window showing four sub-plots of wavefront sensor data. The bottom right corner contains a small image of a bird and the text: "liwi PyWFS Help press [h], quit [x] EMGain = 97 - Mfps = 999.93 160x160 - m,M = -1689,11663 mouse (29, 145) = -1 1/3 | -bias".
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Parameter	Value	Description
AOloopindex	7	AO loop index
inmval	[LOC 1] sol7_modevalWFS [1942x1]	input mode values from WFS
outmval	[LOC 1] sol7_modevalDM [1942x1]	output mode values to DM
loopON	OFF	loop on/off (off=freeze)
loopNBstep	-1	loop nb steps (-1 = inf)
loopZERO	OFF	loop zero
loopgain	0.100000	loop gain
loopmult	0.900000	loop mult
looplimit	0.200000	loop limit

Step 5: Closing the AO loop II

X Boo
H-mag: 8.30

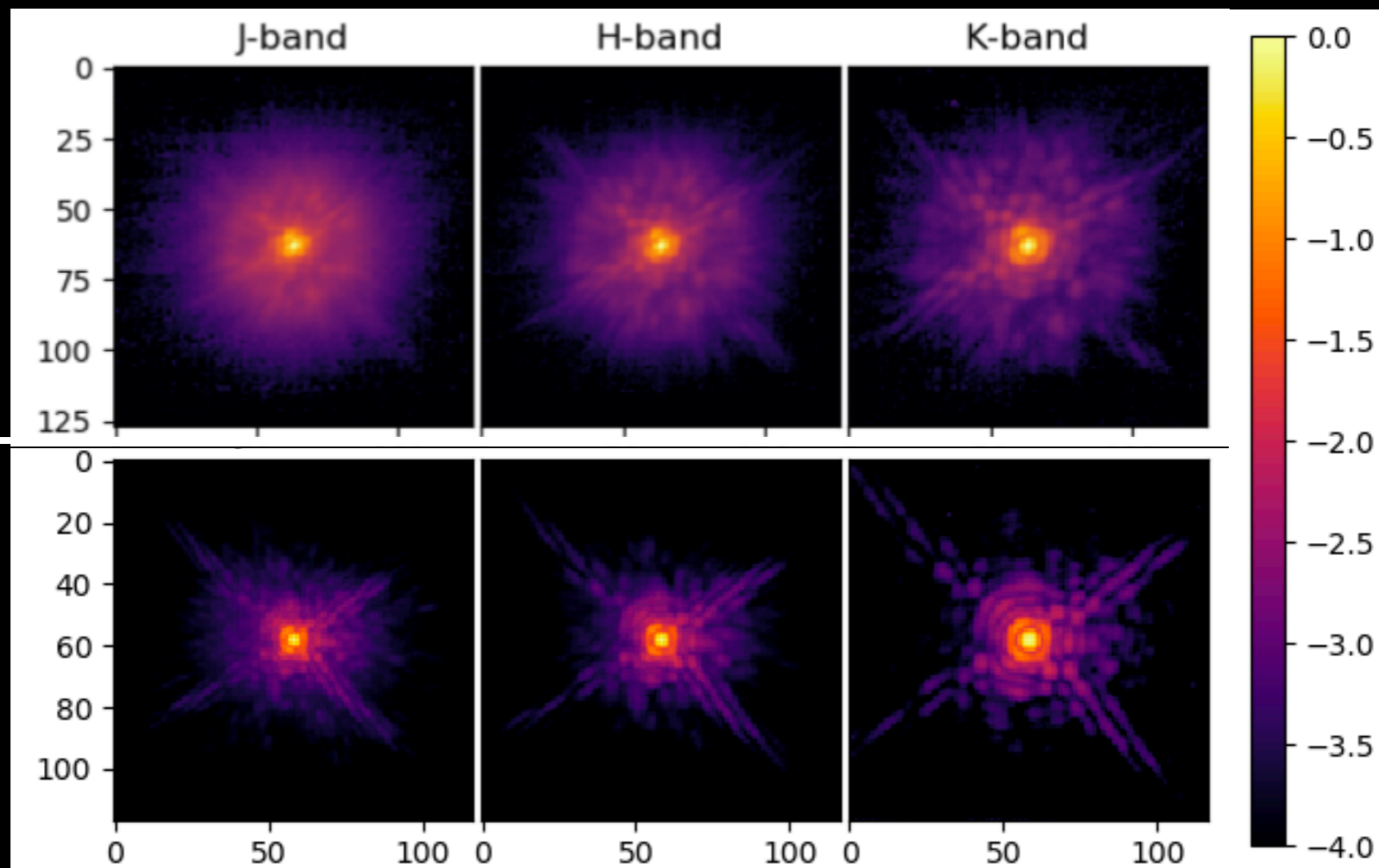


J: ~45%
H: ~65%
K: ~75%

Strehl

Step 5: Closing the AO loop II

X Boo
H-mag: 8.30



HD 172449
H-mag: 8.18

J: ~45%
H: ~65%
K: ~75%

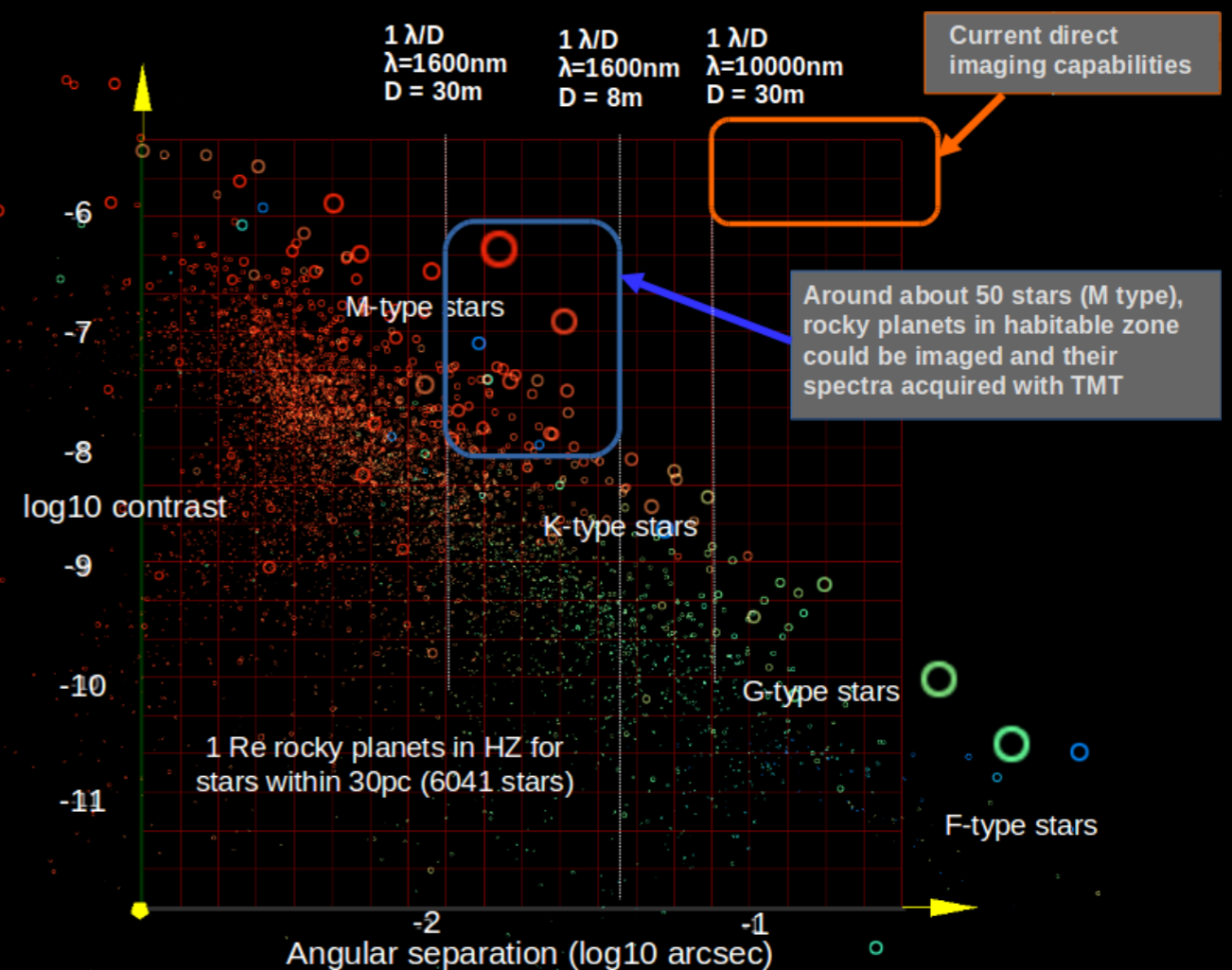
Strehl

J: ~75%
H: ~85%
K: ~90%

Concluding Notes

(Major) Goal of the Upgrades — Better Exoplanet Science

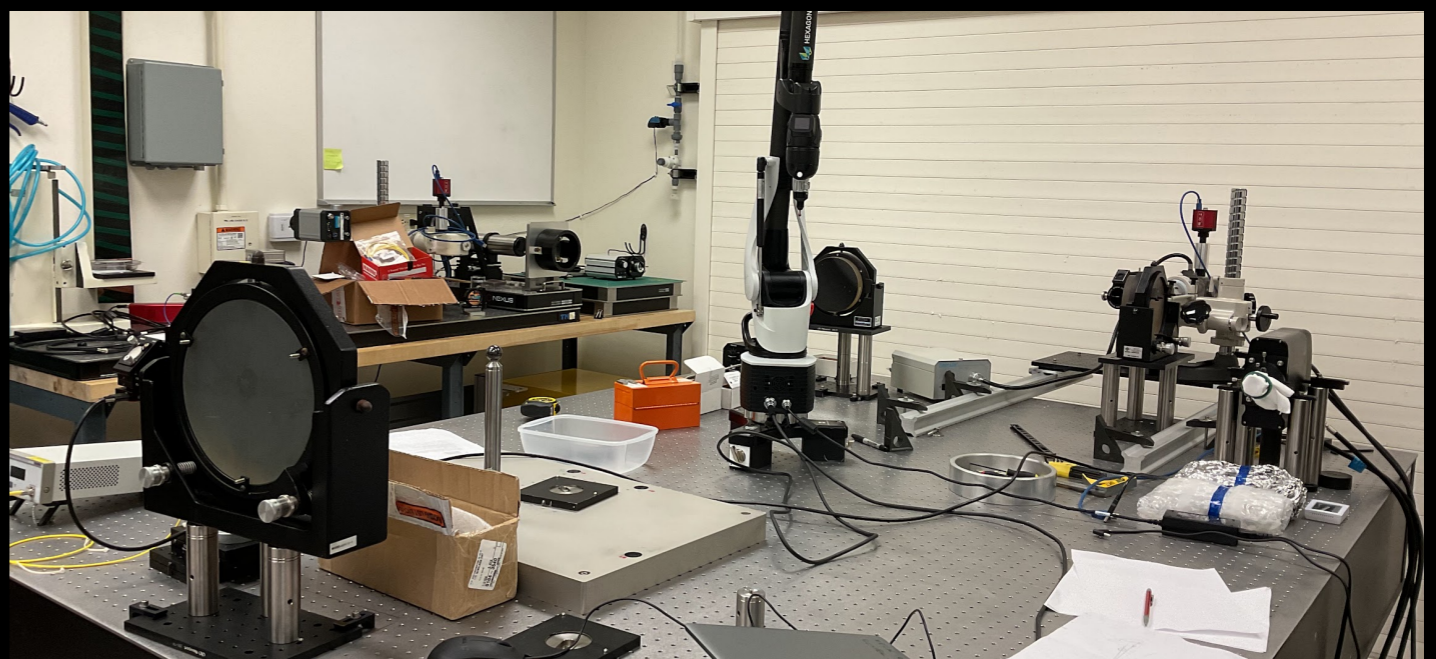
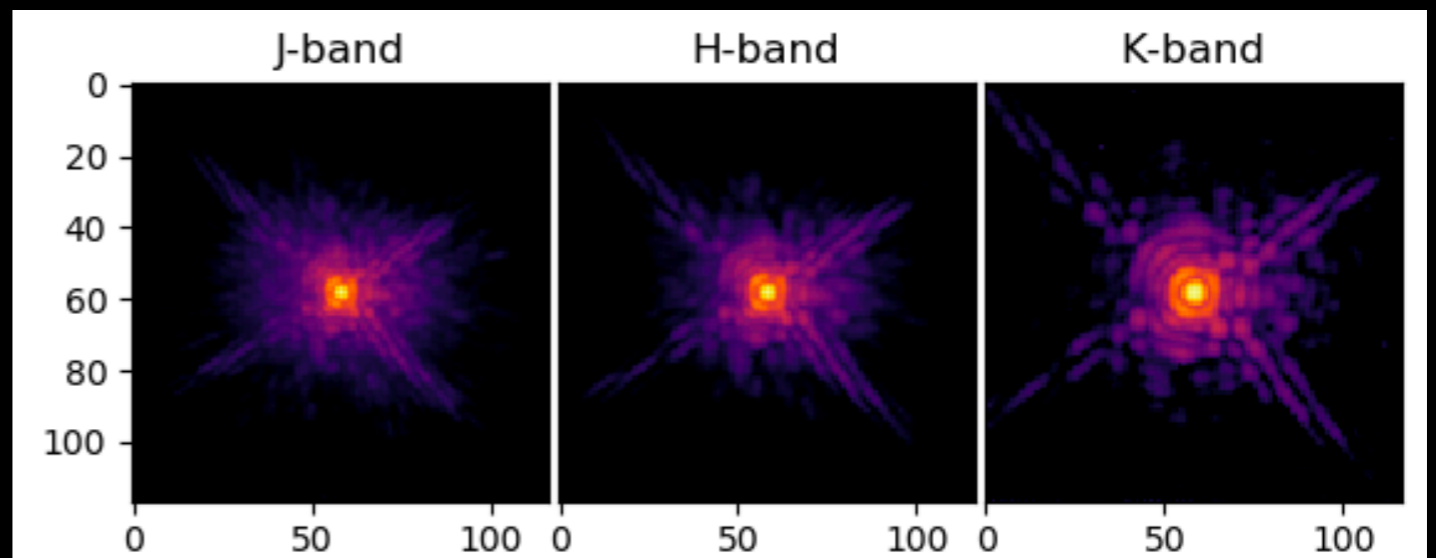
We will be able to access a less explored regime of planets in direct imaging— exoplanets that have lower contrasts than those detectable by JWST, and improve atmosphere characterization of exoplanets with more resolved spectral lines and identifying more tenuous molecular species



Where are we with the upgrades now?

Subaru— the new DM is on sky,
and the engineering nights have
reported much high Strehl

Keck— lab set up in progress



The Future...

These upgrades provide a technology demonstration for improvements in wavefront control and short wavelength AO for future extremely large telescopes.

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