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

AO3k at Subaru: First on-sky results of the facility extreme-AO

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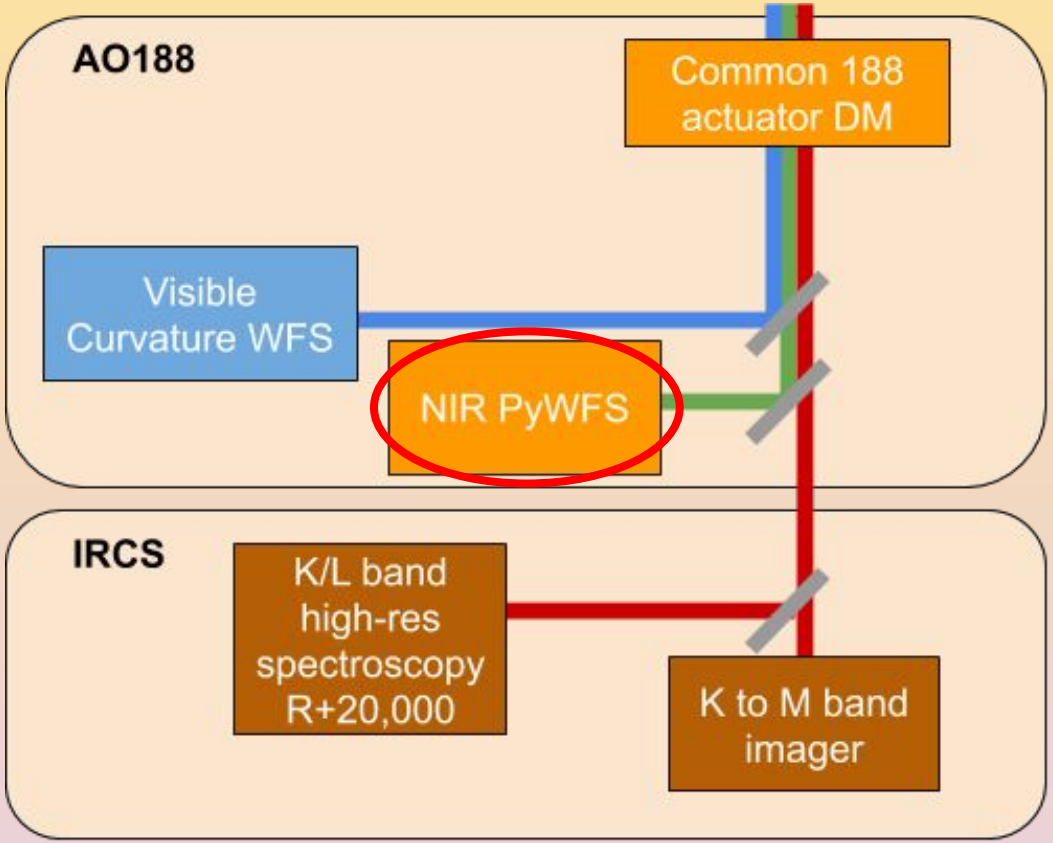
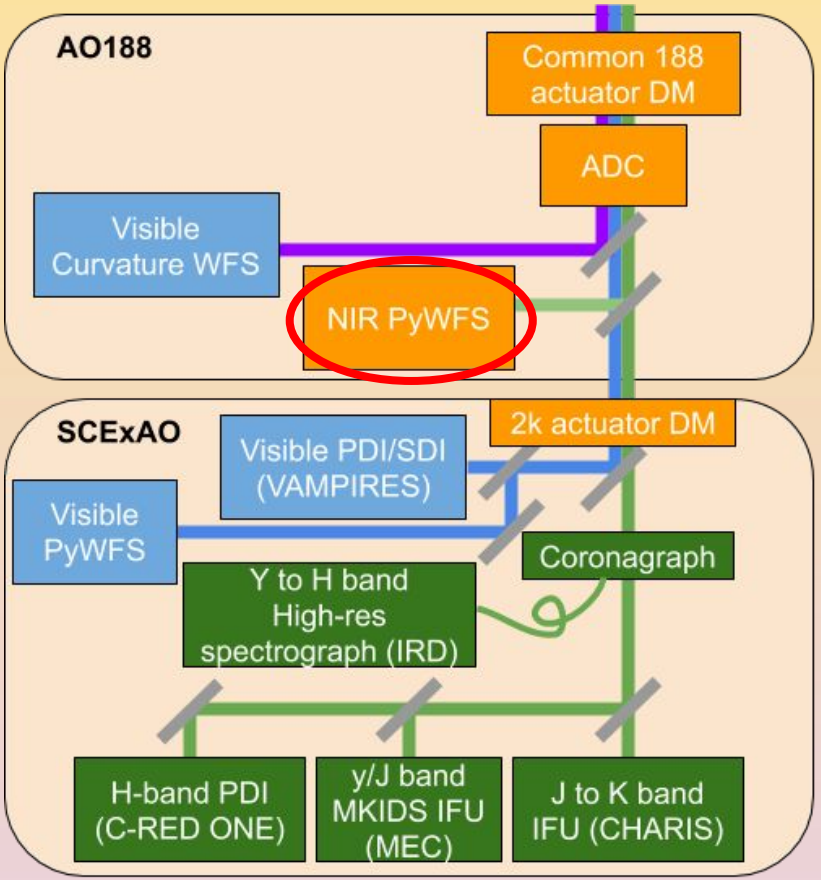
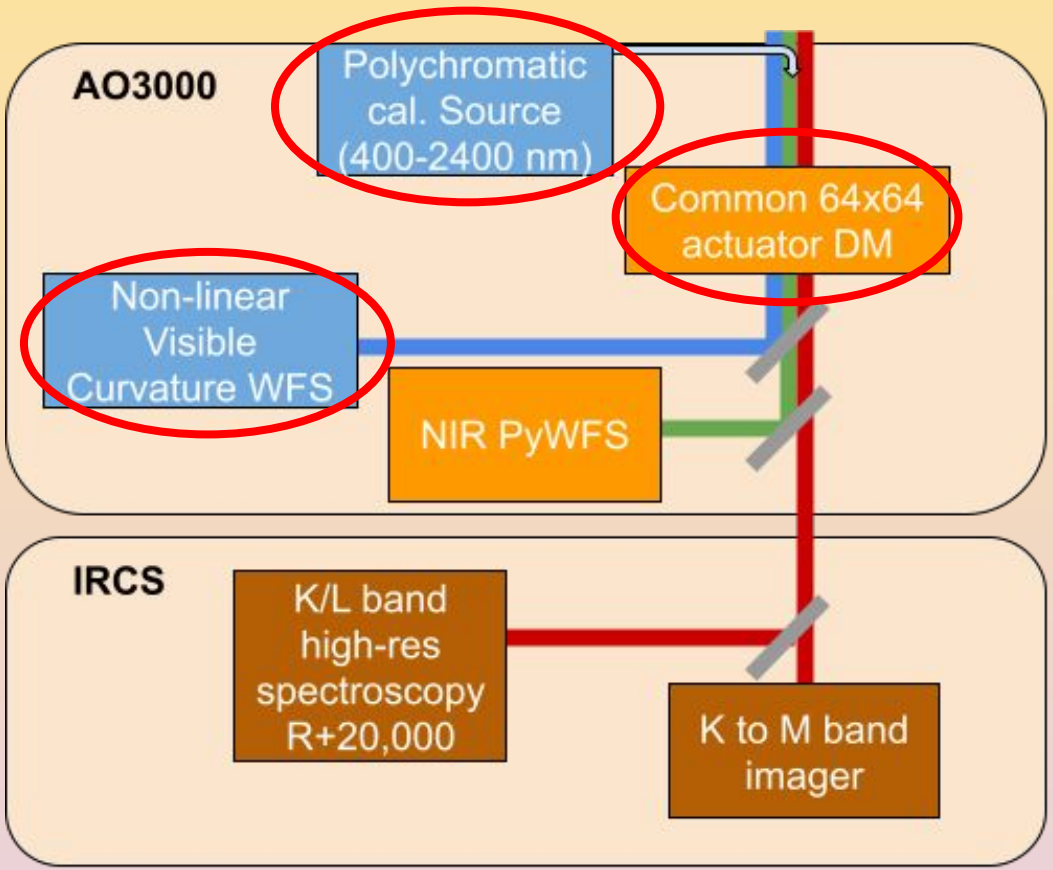
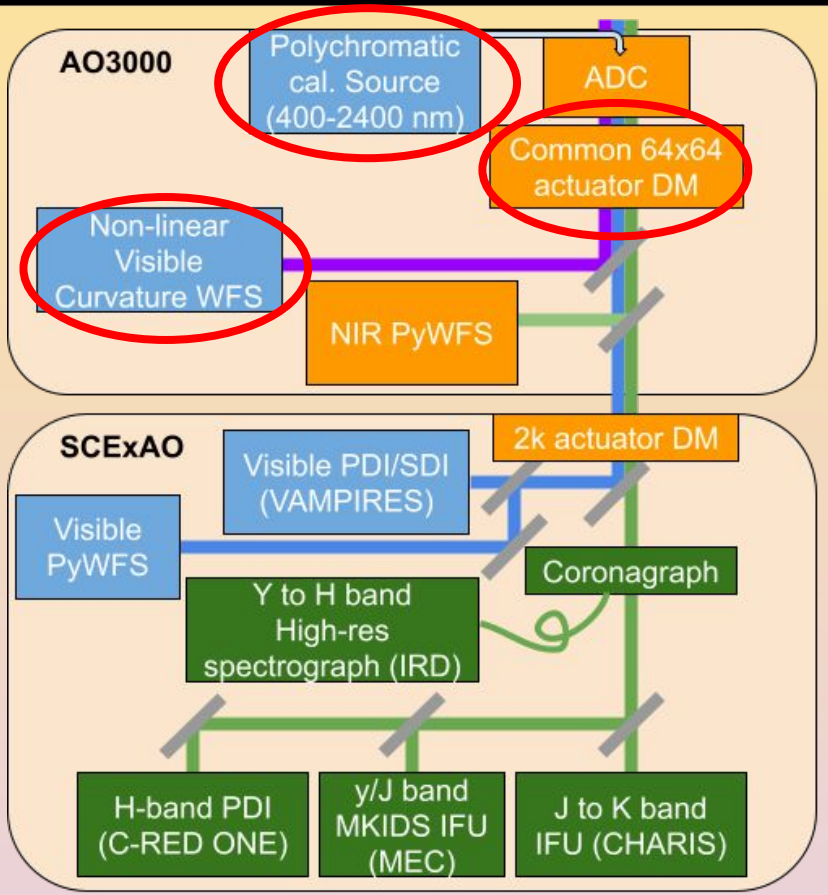
AO3k Phase Ia: NIR WFS (2023)





AO3k Phase Ib: New ALPAO DM (2024)



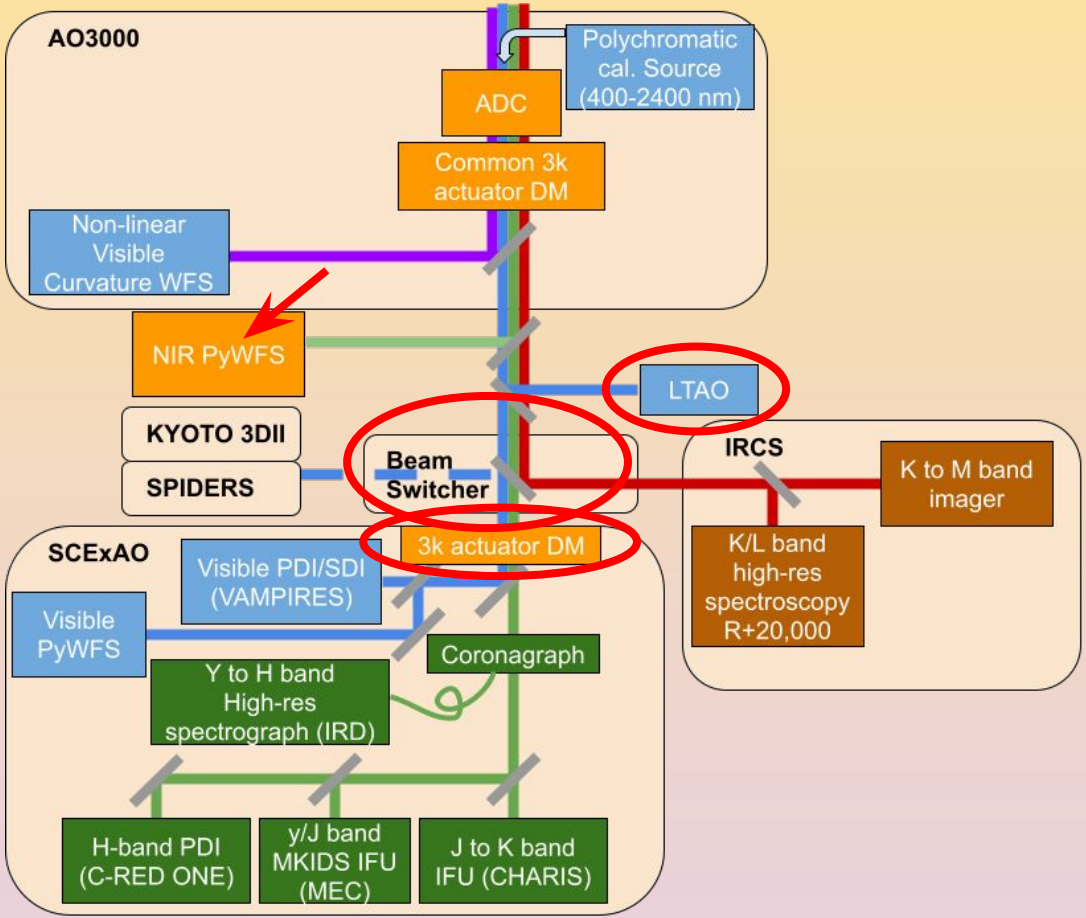


AO3k Phase II: NBS (2024-2025)

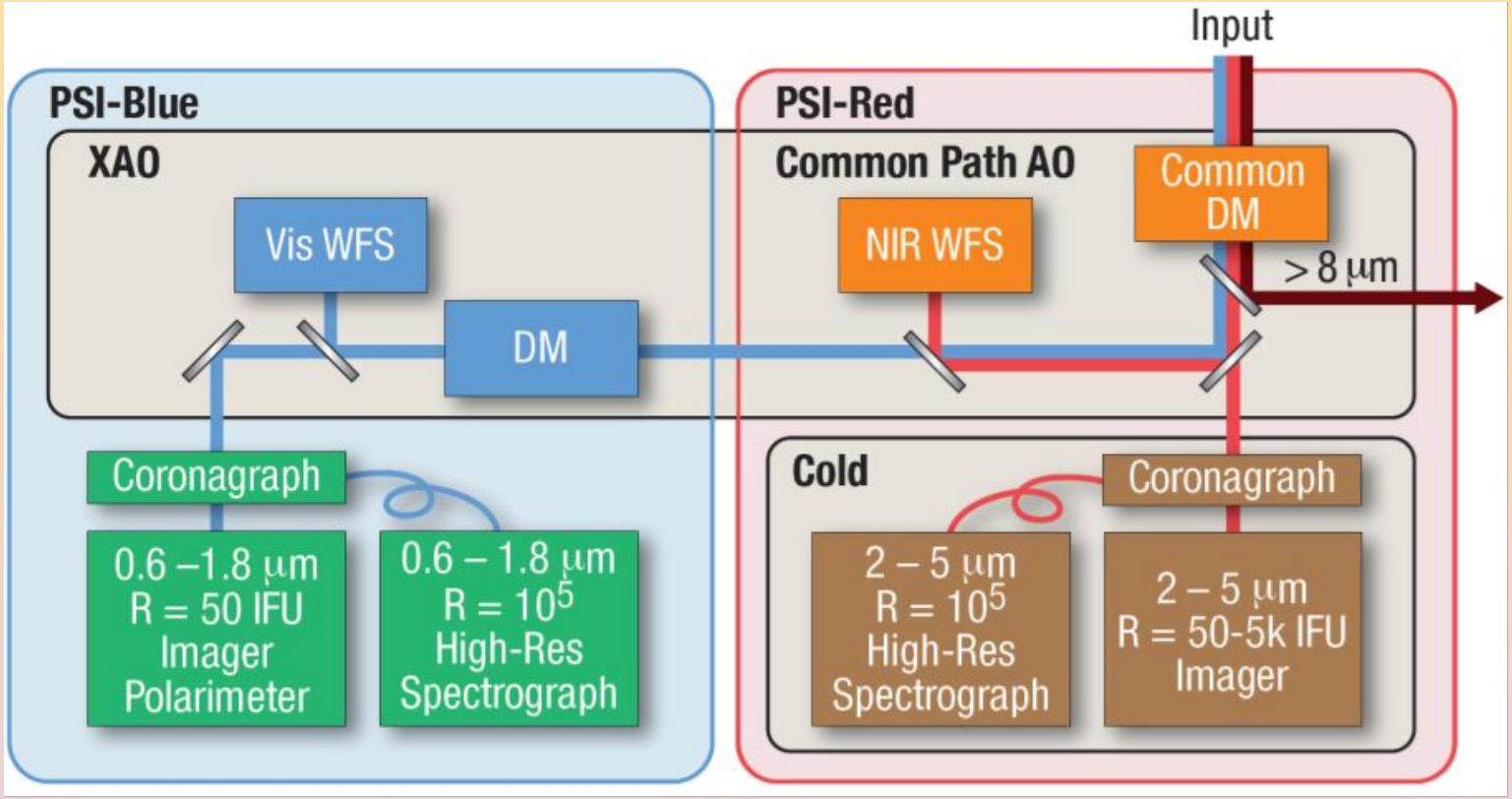
In Phase II, a new Nasmyth beam switcher (NBS) will allow for simultaneous observations with SCExAO and IRCS, and the addition of other instruments with easy and fat switching between them.

The NIR PyWFS will relocate outside of AO3k, next to the new LTAO.

SCExAO will also upgrade its DM with a segmented 3k DM.

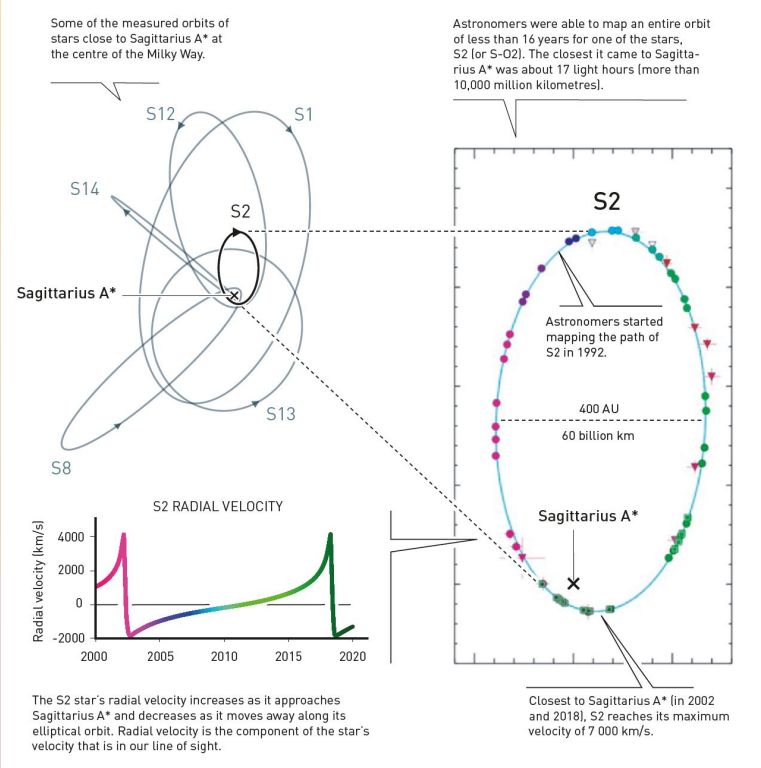


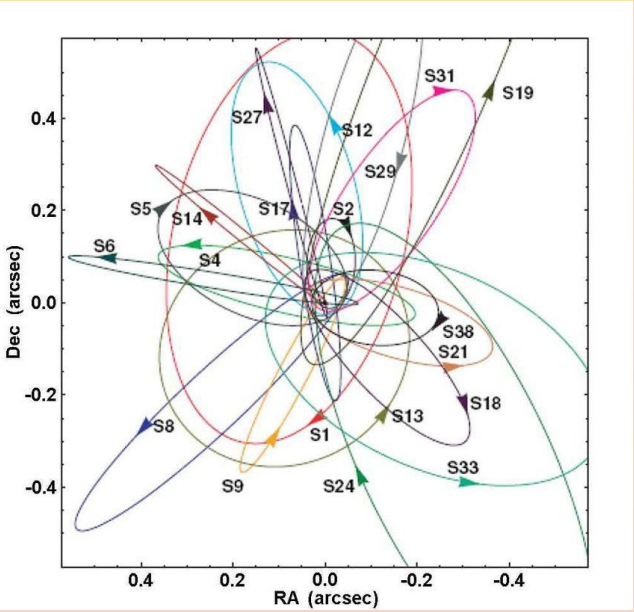
Closer to a TMT-PSI configuration



Science objective: Galactic center

The galactic center is the best target to study and understand the nature of supermassive black holes. Imaging and spectroscopy of the stars orbiting the black hole allow us to constrain its mass and composition. But due to dust extinction, there is no bright star in visible for NGS, but one is bright enough (mH~=10) and close enough for a NIR WFS.



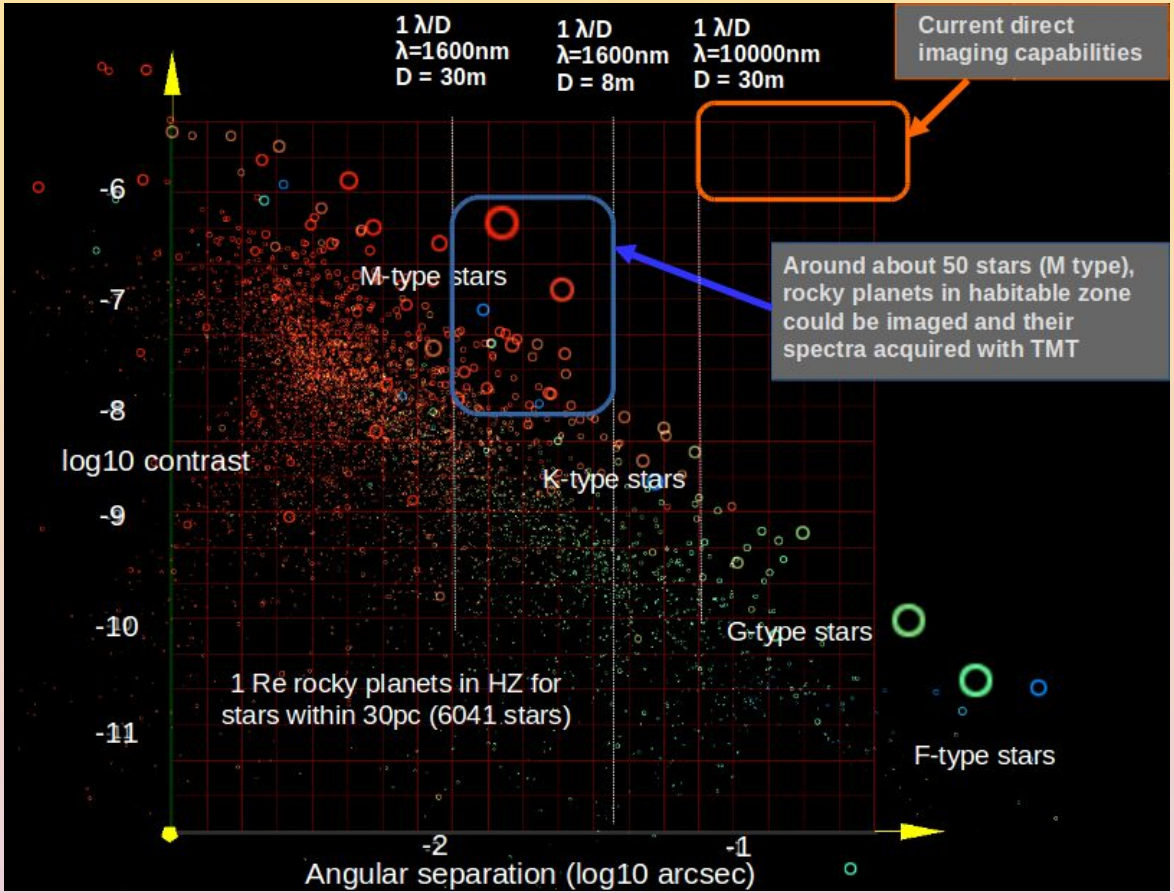


Science objective: towards M-dwarf exoplanets

Sensing at a wavelength closer or even the same wavelength of the science detector removes most of chromatic non-common path aberrations, providing a higher stability of correction.

SCExAO is limited by both AO188's visible WFS (400-600 nm) and SCExAO's visible PyWFS (800-900 nm).

A NIR PyWFS will allow us to reach redder targets: K- to M-type stars, stars with dust extinction.

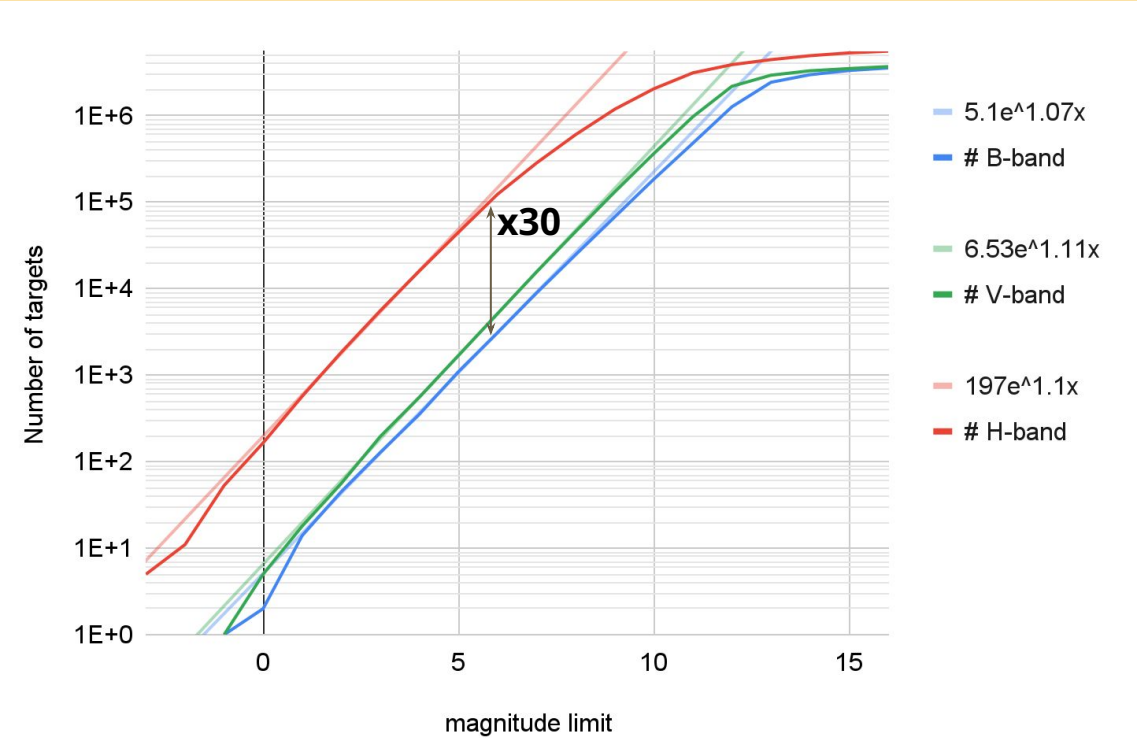


Increase in sky coverage

NasIR instruments have small field-of-view (1 to 20” typically), and without LGS, requires a bright star closeby.

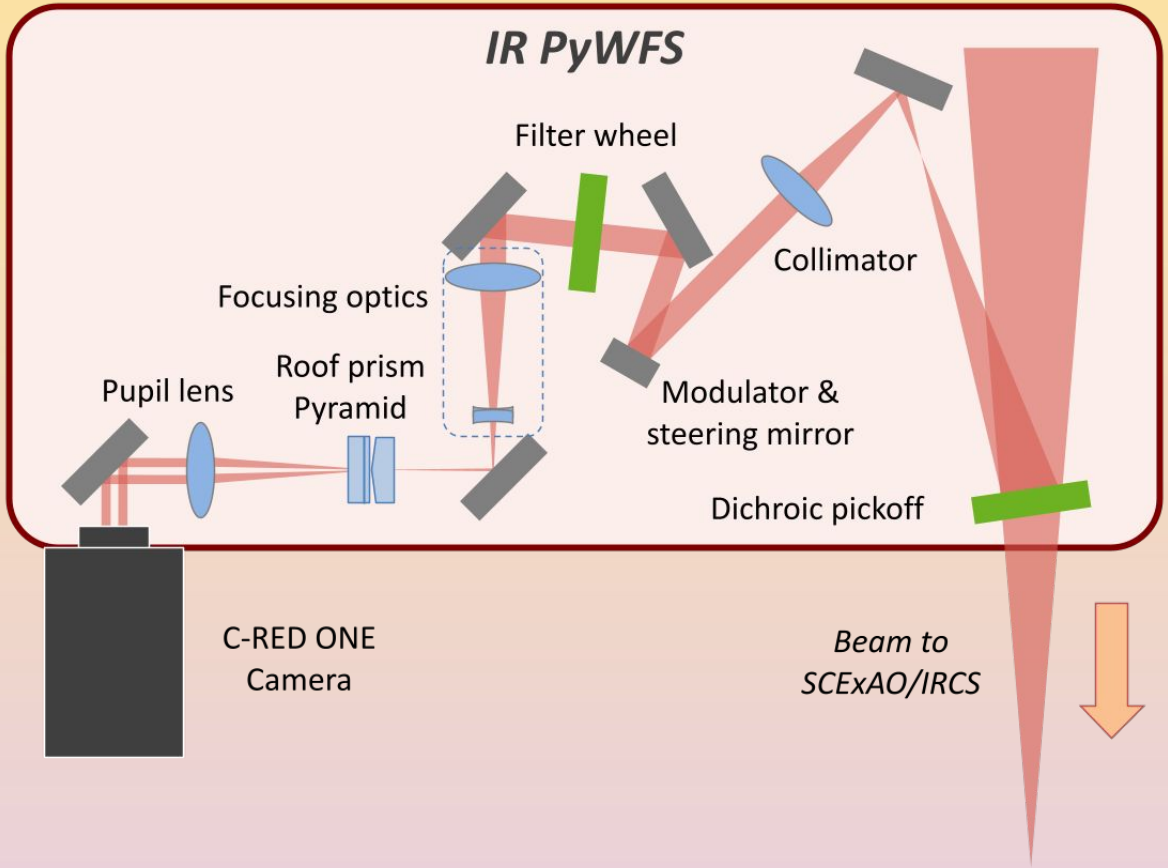
Using the Simbad database of stellar magnitudes, we can see that at same magnitude limit, there are 30x more IR targets (H-band) than visible targets (B-band).

The real gain in available targets depends on the magnitude limits of the visible and NIR wavefront sensors, and the modes used.



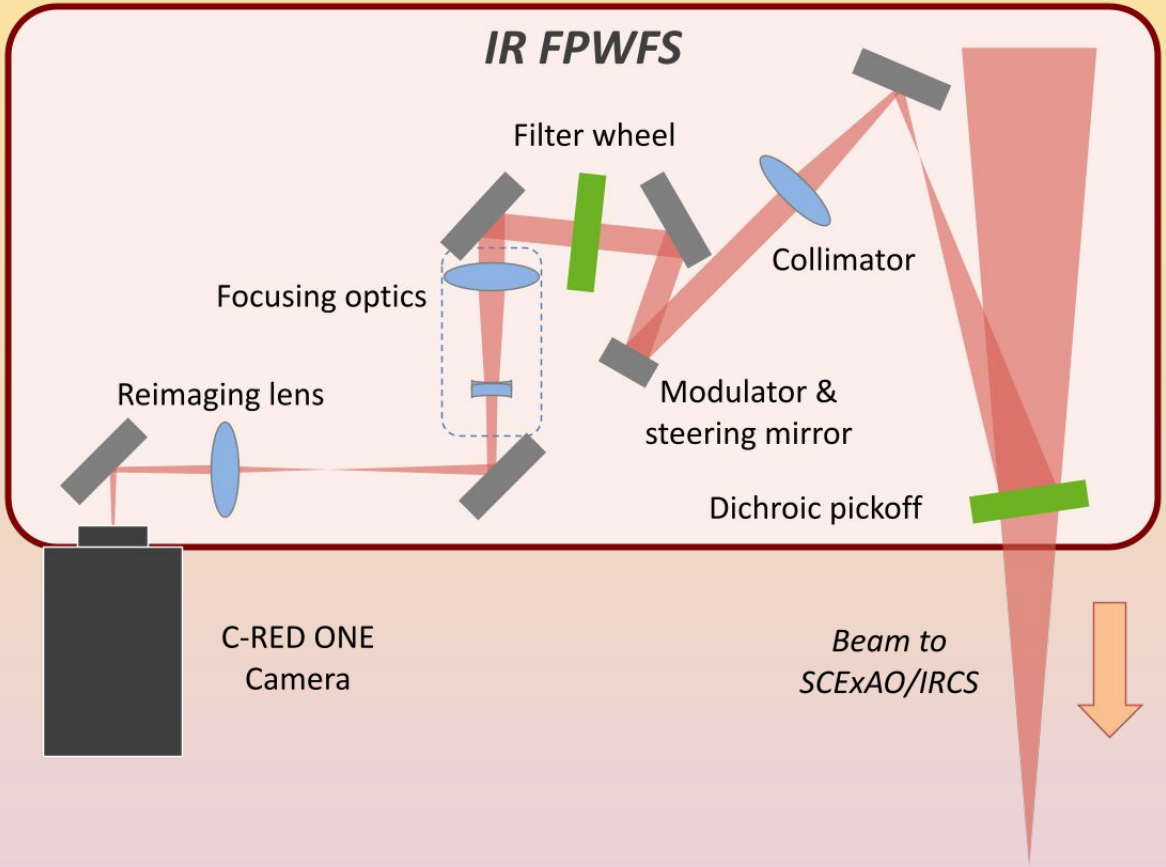
NIR WFS: PyWFS Optical Path

The optical path is simple: The light is picked-off by a dichroic mirror, then collimated by a custom lens. The pupil is reimaged on the modulating & steering mirror. The light is focused again, thanks to a pair of custom converging-diverging lenses, on the tip of a double roof prism pyramid. Finally a pupil lens reimage the pupils on the C-RED ONE camera.



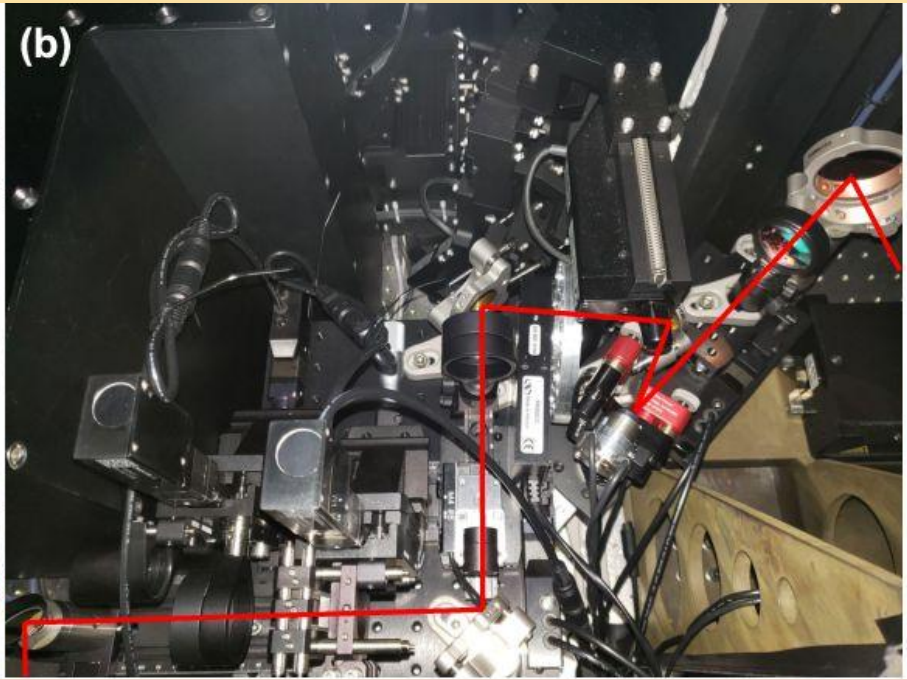
NIR WFS: FPWFS Optical Path

A focal plane imaging mode was added during the optical design, to perform low-order wavefront sensing with a defocused image. This is mostly to complement the LTAO wavefront sensors, but could be used for other applications. For this mode, the pyramid optics are simply removed (offering a pupil viewing mode as well), the last lens is swapped, and the separation between the focusing lenses changed.

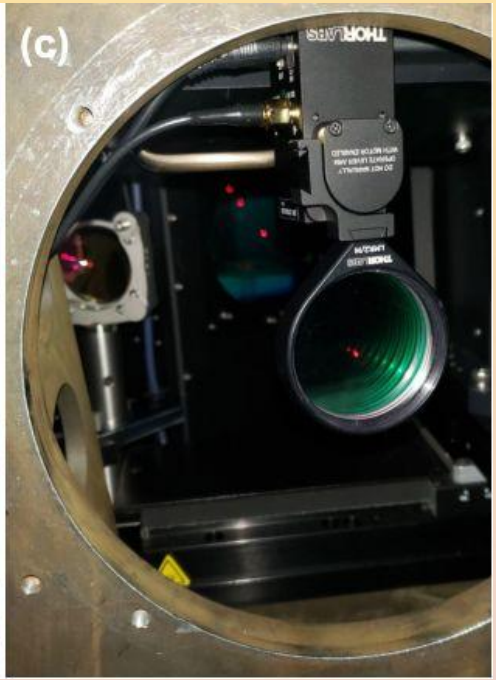


NIR WFS: Installation inside AO188

C-RED ONE

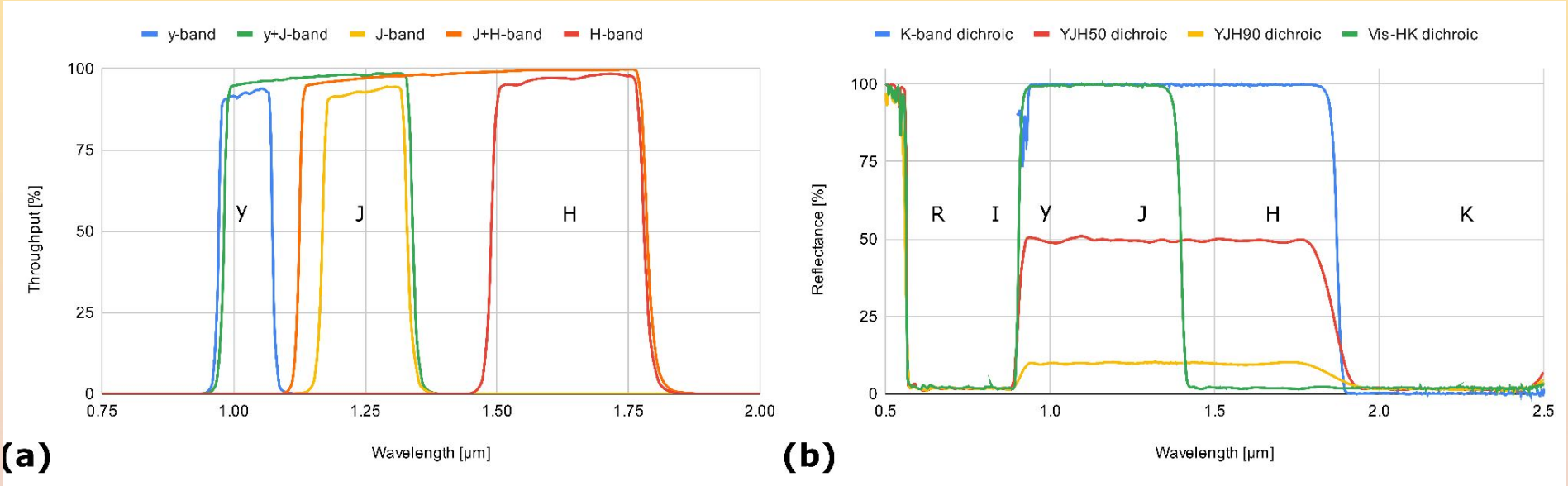


Core optics inside AO188



Dichroic beamsplitter

NIR WFS: Wavelength range

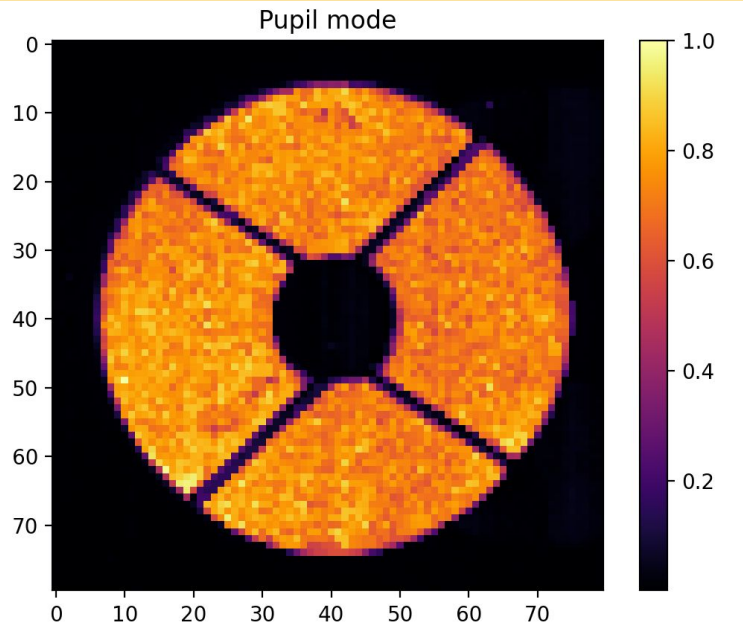


Filters: y, J or H-band filters, dual-band filters (y+J or J+H), or broadband (y+J+H)

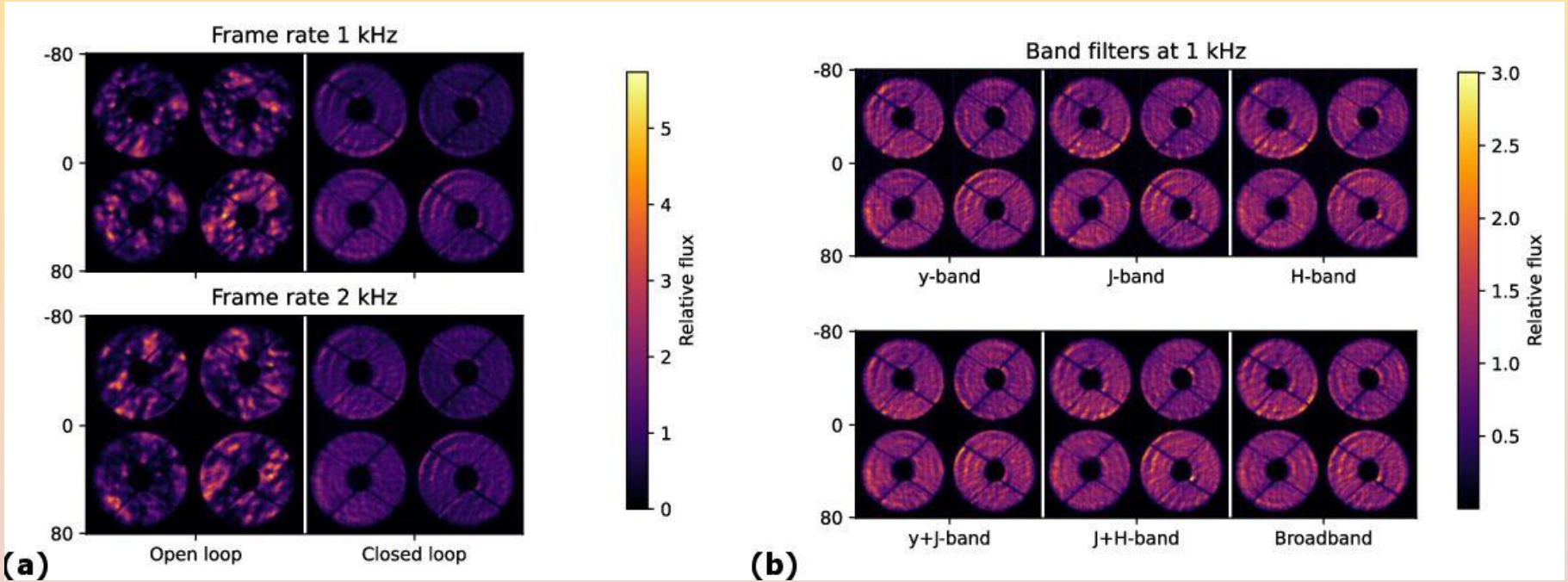
Pickoffs: the light not reflected is transmitted to the science instrument.

NIR WFS: First on-sky observations

- Engineering time was allocated in May 2022 for the first test.
- Data was taken for about 2 hours on-sky (high humidity), switching between modes every few minutes. We took data at different frame rates, different modulations, different filters, in PyWFS mode, FPWFS mode, pupil mode, etc.
- The NIR WFS was running in open-loop, but with the AO188 visible loop closed on the 188-actuator DM.
- The pupil has 68 pixels across, oversampling slightly the 64x64 DM (60 to 62 actuators across the pupil).
- The first on-sky test was highly successful, despite the weather. We had no surprises, only one small mechanical change to make to reduce some off-axis vignetting in FPWFS mode.

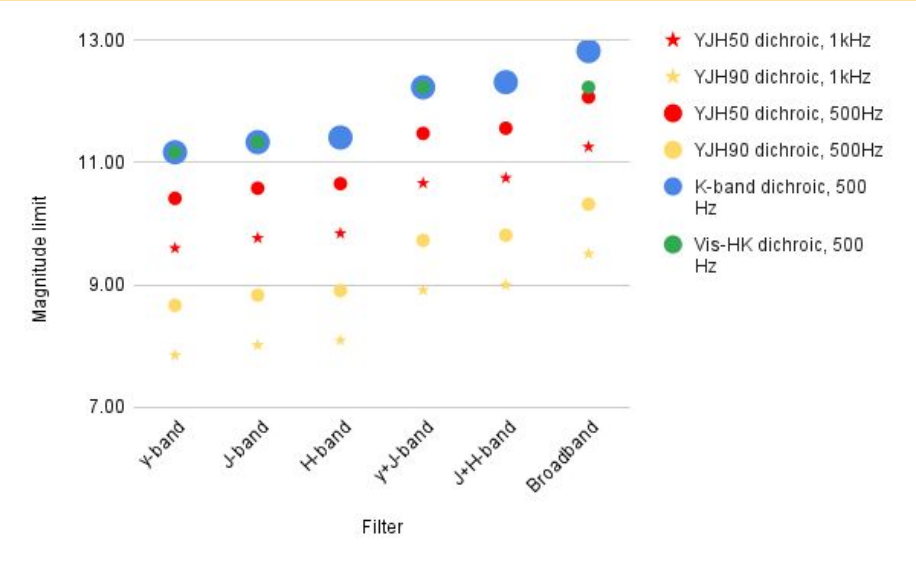


NIR WFS: PyWFS First on-sky tests



30s average for each image (dynamical analysis ongoing). No obvious chromatic effect, as expected. The wavefront sensor is behaving as expected.

NIR WFS: PyWFS magnitude limits



Filter	Dichroic			
	K-band	YJH50	YJH90	Vis-HK
Y-band	mY=11.2	mY=10.4	mY=8.7	mY=11.2
J-band	mJ=11.3	mJ=10.6	mJ=8.8	mJ=11.3
H-band	mH=11.4	mH=10.7	mH=8.9	N/A
Y+J-band	mJ=12.2	mJ=11.5	mJ=9.7	mJ=12.2
J+H-band	mH=12.3	mH=11.6	mH=9.8	N/A
Broadband	mH=12.8	mH=12.1	mH=10.3	mJ=12.2

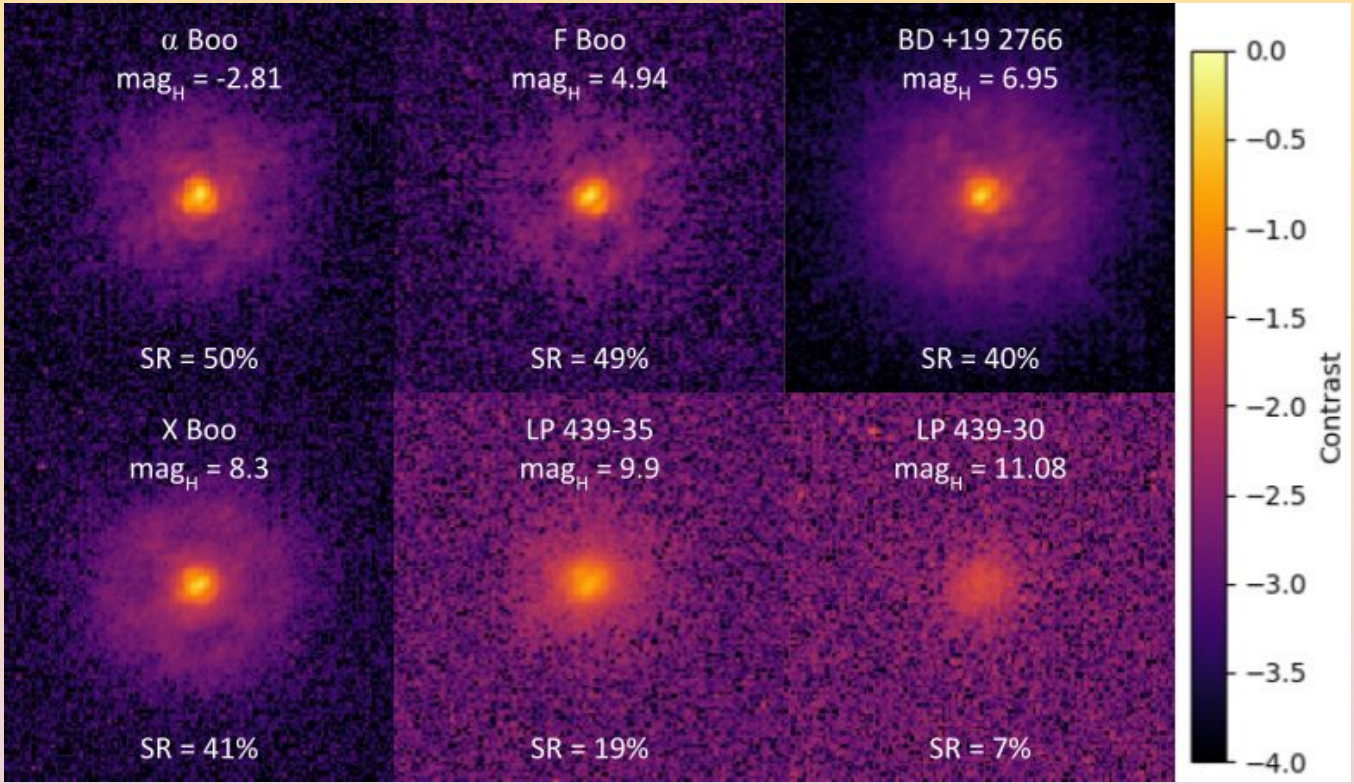
- Meaningful magnitude limits were calculated by using the visible PyWFS experience (we can close the loop at 500 Hz on a mag. 11 star, with a SNR per pix. of 0.12).
- The real magnitude limits will depend heavily on the spectral type and dust attenuation.
- The values are applicable to AO3k (independent of DM)
- A tradeoff between performance and magnitude limit will be applicable for AO3k, especially with observations without ADC.

NIR WFS: On-sky closed loop tests

- Due to the delay in the manufacturing of the new ALPAO 64x64 DM, it was decided to prepare the NIR WFS for Open-Use observations using the original 188-actuator DM.
- The on-sky results presented here where taken during the engineering night of May 3, 2023.
- We ran the AO loop at 500 Hz with the YJH50 dichroic beamsplitter. The seeing was above average: 0.7 to 1.1". We observed several targets with similar magnitudes in J and H.
- Images were recorded with SCExAO's internal SWIR camera Palila (First Light Imaging C-RED 2, y- to H-band), and the CHARIS integral field spectrograph in broadband mode (J- to K-band).
- Close-loop operation was very successful and showed better results than with the visible curvature wavefront sensor.

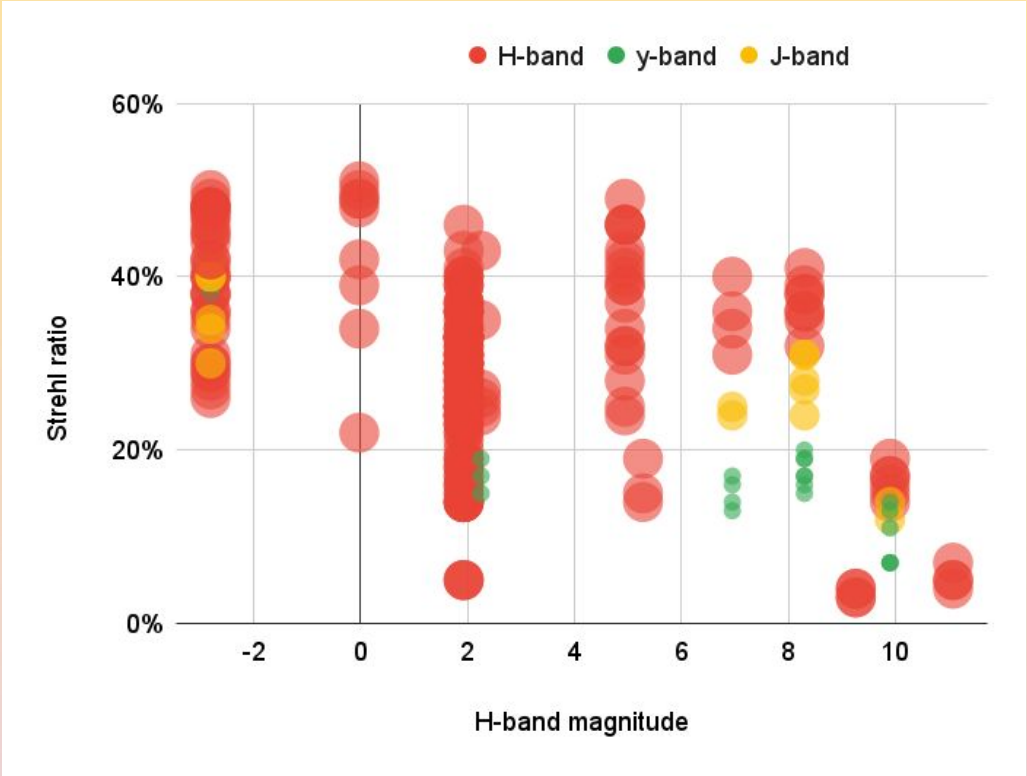
NIR WFS: closed-loop results

- H-band Strehl measurements obtained with SCExAO's Palila camera, over a few seconds, for targets with various magnitudes. Each image is 2x2".
- Strehl ratios higher than 50% were measured in H-band, despite average seeing!



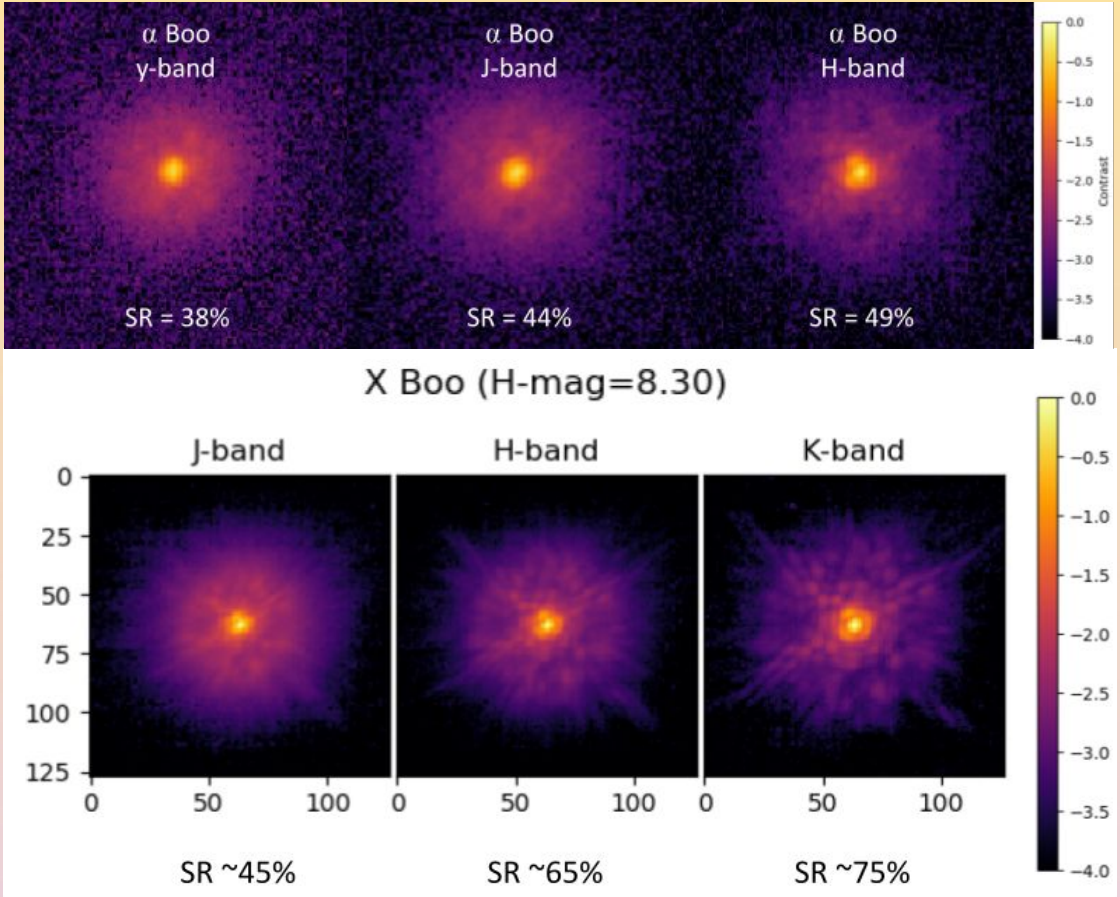
NIR WFS: Strehl vs. magnitude

- Compilation of all the Strehl measurements taken with SCExAO's Palila camera in y-, J- and H-band. This includes times where we were tuning various parameters, so some Strehl values can be much lower than optimal.
- The higher values for each magnitude would represent the performance of the loop in normal conditions.
- The Strehl ratio is over 40% until magnitude ~9, then decreases.
- This was done with the YJH50 dichroic, so the result would be shifted by ~+0.75 magnitude with the K-band dichroic, and ~-1.75 with the YJH90 dichroic.



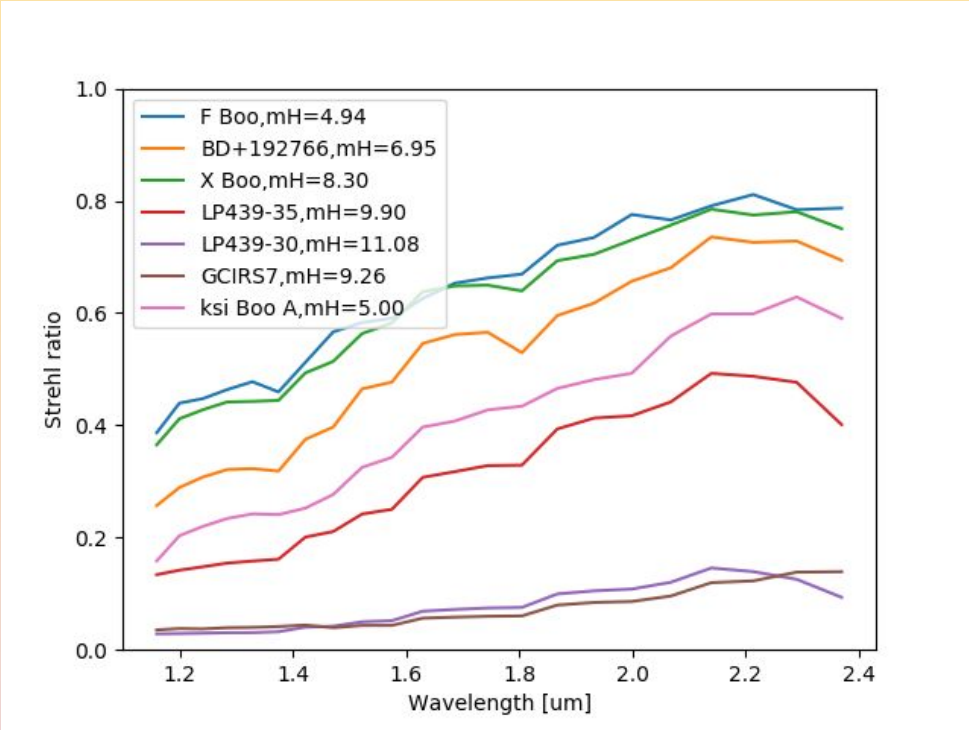
NIR WFS: Strehl vs. magnitude

- Top: Strehl ratio measurements in y-, J- and H-band with Palila, on the target α Boo.
- Bottom: Strehl ratio measurements in J-, H- and K-band with CHARIS, on the target X Boo.
- The dark hole (control region of the deformable mirror) is visible, even at short wavelengths. This is a sign that the correction is excellent, even better than with the curvature wavefront sensor for which this dark hole was never observed.



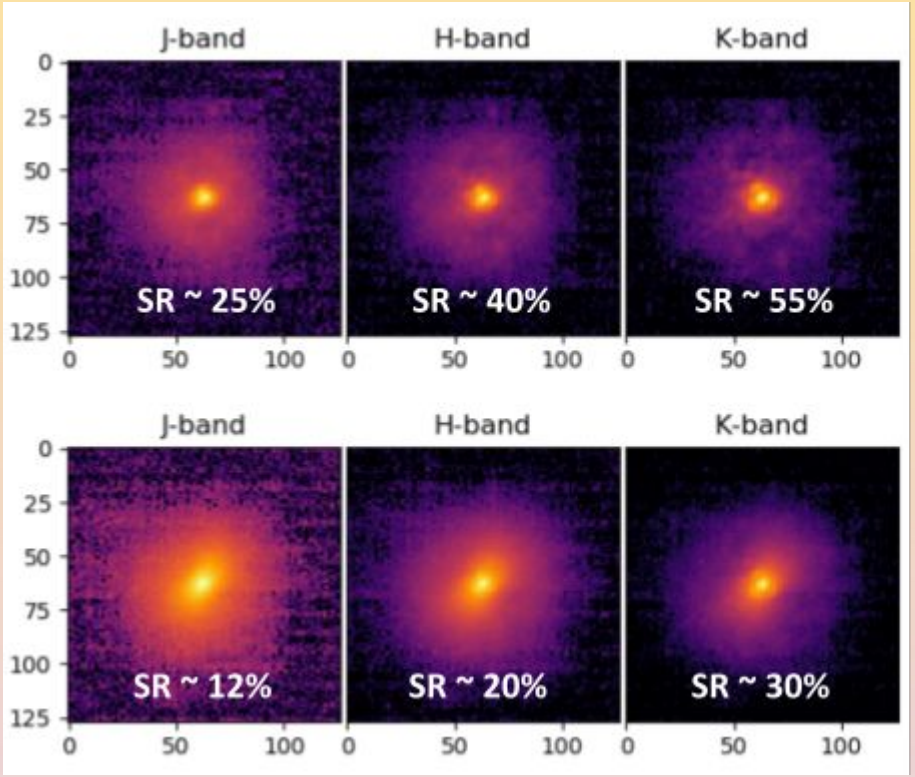
NIR WFS: Strehl vs. magnitude

- Strehl ratio measurements for the best frame of each target, for each wavelength slice of CHARIS in broadband mode.
- Most curves tend to plateau and even decrease after 2 µm, which is probably an effect of the increased thermal background that was not subtracted properly.
- Otherwise, the Strehl ratio evolves pretty linearly with wavelength.
- Strehl went up to 80% in K-band!



NIR WFS: Anisoplanatism

- Strehl ratio measurements on the binary ξ Boo AB (H-mag ~5 for both stars).
- The loop was closed on ξ Boo A, then the NIR WFS was steered on the companion ξ Boo B.
- The seeing was about 0.8” with high altitude turbulence and relatively high wind.
- The Strehl ratio of ξ Boo B is reduced by ~50% compared to ξ Boo A, with a strong wind-driver halo visible. The effect of anisoplanatism depends strongly on the atmospheric conditions.
- The patrol field of view can be extended up to >±10”



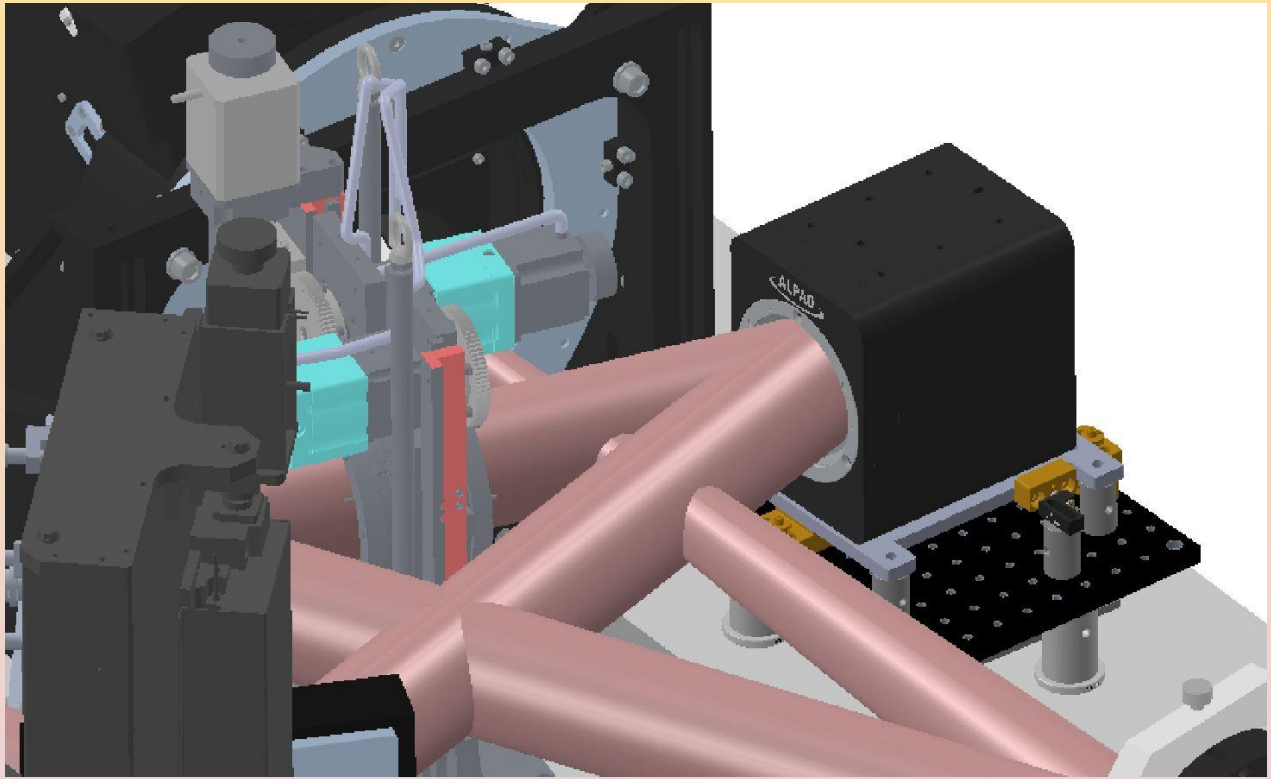
ξ Boo A

Separation: 7.2 “

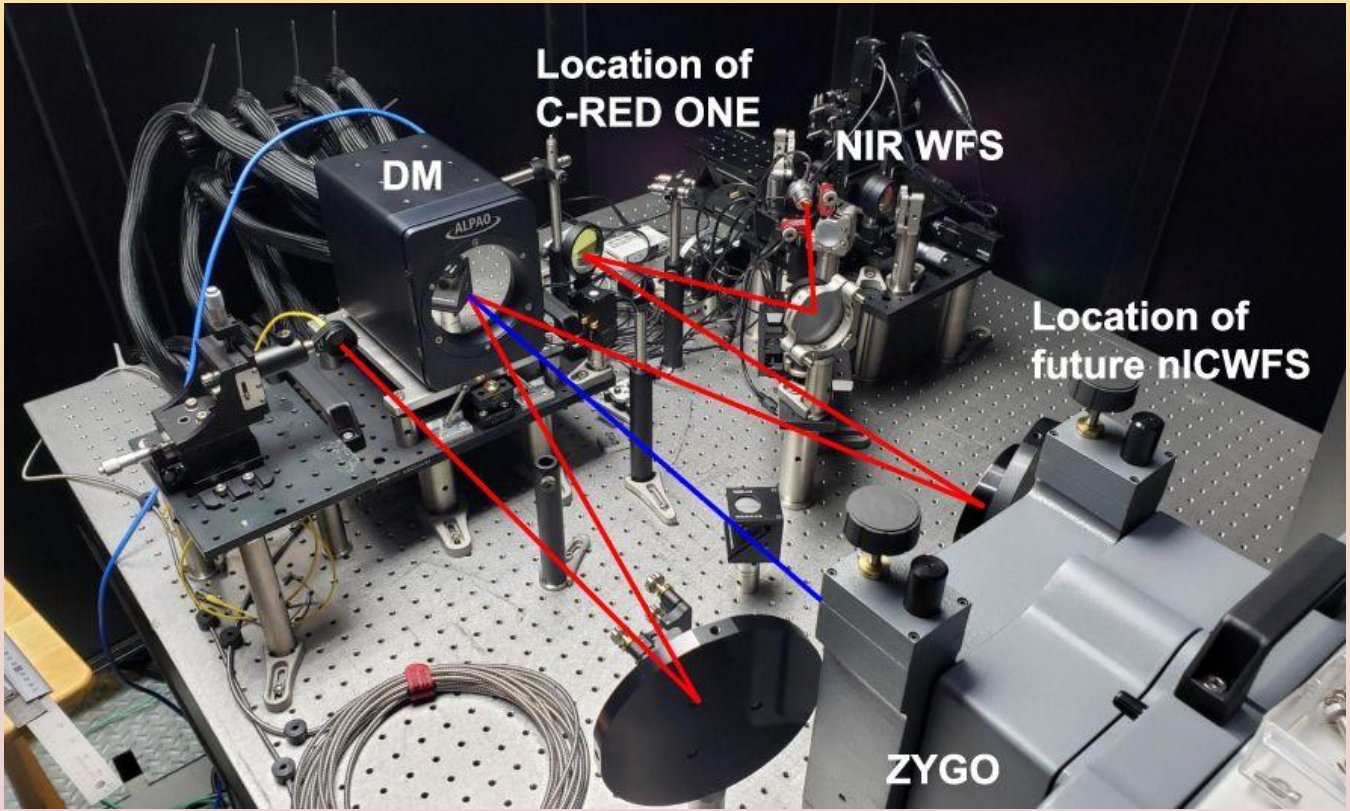
ξ Boo B

AO3k next steps: New ALPAO 64x64 DM

- The new DM will be a drop-in replacement of the old 188-element DM.
- It has ~3000 actuators in the pupil.
- This DM will not have high-speed tip/tilt like the previous one due to the weight.
- The original fast tip/tilt mount will migrate to AO3k's M2 mirror (right before the DM)
- Combined with the NIR WFS or the nICWFS, it will provide ExAO performance to all NasIR instruments.
- It will be the most performant AO system on a 8m class telescope in the world!



AO3k next steps: DM Testing setup

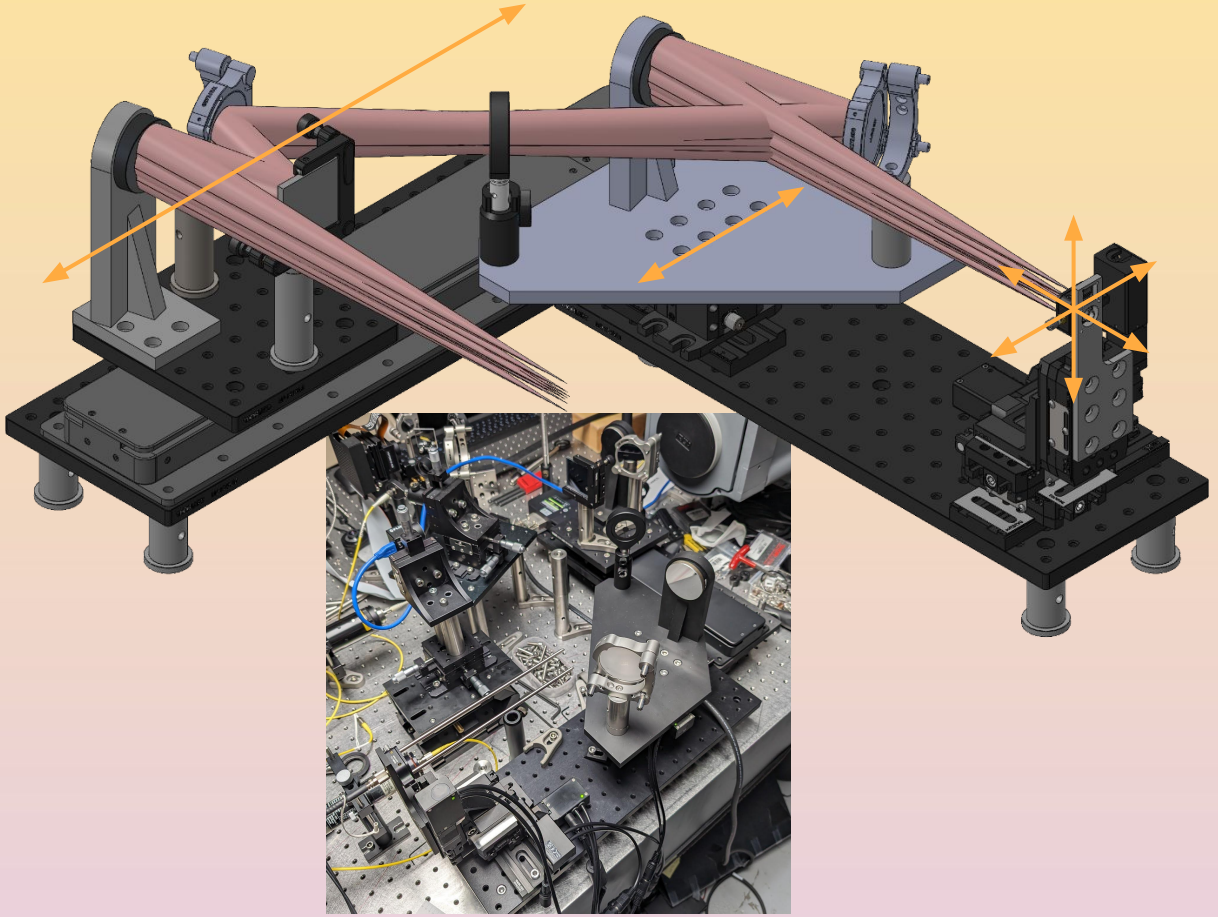


We are building a testbed in Hilo to test the DM with the new nICWFS. A Zygo looks at the shape of the DM at the same time.

The DM passed the custom today! It will arrive in Hilo in the next few days!

AO3k next step: New calibration source

- The original source of AO188 only contains 3 laser diodes: 532nm , 633nm and 1055 nm.
- A polychromatic source is necessary to calibrate the NIR WFS and the nlCWFS
- With this new source, we can close the loop internally to perform tests and calibrations during the day.
- The source was assemble and tested in Hilo, and is ready to be installed at the summit.



Conclusion

- AO188 will become the first stage XAO system AO3k, by the addition of a new NIR WFS and new visible nlCWFS, combined with a new 64x64 deformable mirror. It will provide extreme-AO performance right out of the first stage AO, for all the NasIR instruments of Subaru.
- The integration of the NIR WFS was successful and the first on-sky tests, open loop and closed loop, provided very promising results.
- **The NIR WFS is now ready for Open-Use observations, starting in S24A!**
- The DM will arrive in Hilo this week!
- We will characterize it in Hilo in the next few months
- If validated, it will be installed inside AO188 in May 2024 for its first on-sky testing.
- We will have the most performant AO system in the world!
- Once the beam switcher is in place with SCExAO and IRCS behind, we will have the perfect experimental demonstration of PSI-Blue and Red for TMT.

Mahalo nui loa!

Ma ka hana ka ʻike.

In working one learns.

-Knowledge can be acquired by doing

"ʻŌlelo Noʻeau – Hawaiian Proverbs and Poetical Sayings," by Mary Kawena Pukui.