SCExAO

Subaru Coronagraphic Extreme Adaptive Optics

すばるコロナグラフ極限補償光学装置

SCExAO: Status of the Instrument, testbed and system-level demonstrator for PSI

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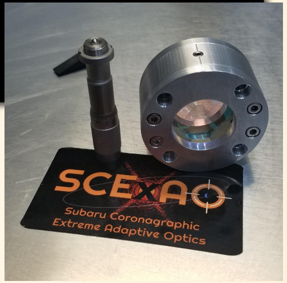
SCExAO An International Collaboration



Subaru Telescope, National Astronomical Observatory of Japan

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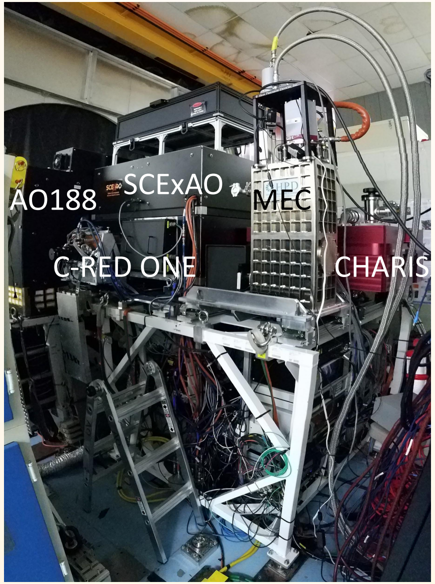
SCExAO overview

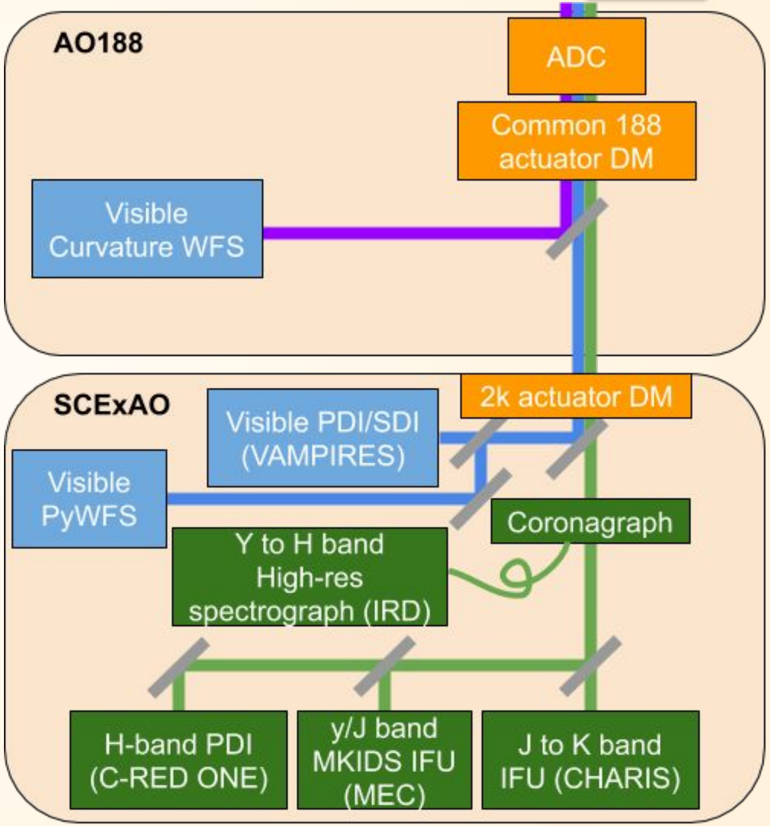
SCExAO: Subaru Coronagraphic Extreme Adaptive Optics

High-contrast PI instrument installed on the IR Nasmyth platform of the Subaru Telescope.

Very modular design that enables testing of new technologies necessary for future high-contrast imagers as a laboratory testbed.

But it is also an instrument used on-sky to perform competitive science.

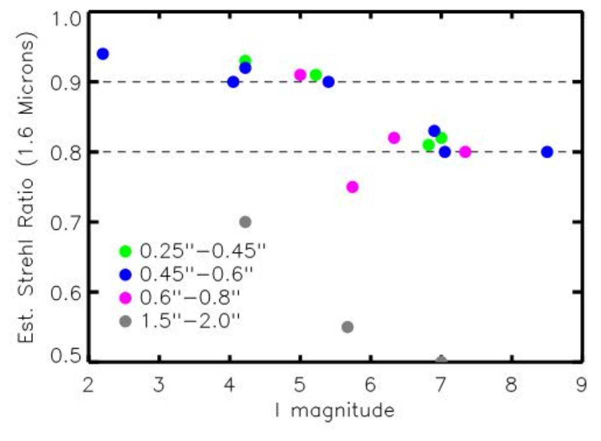


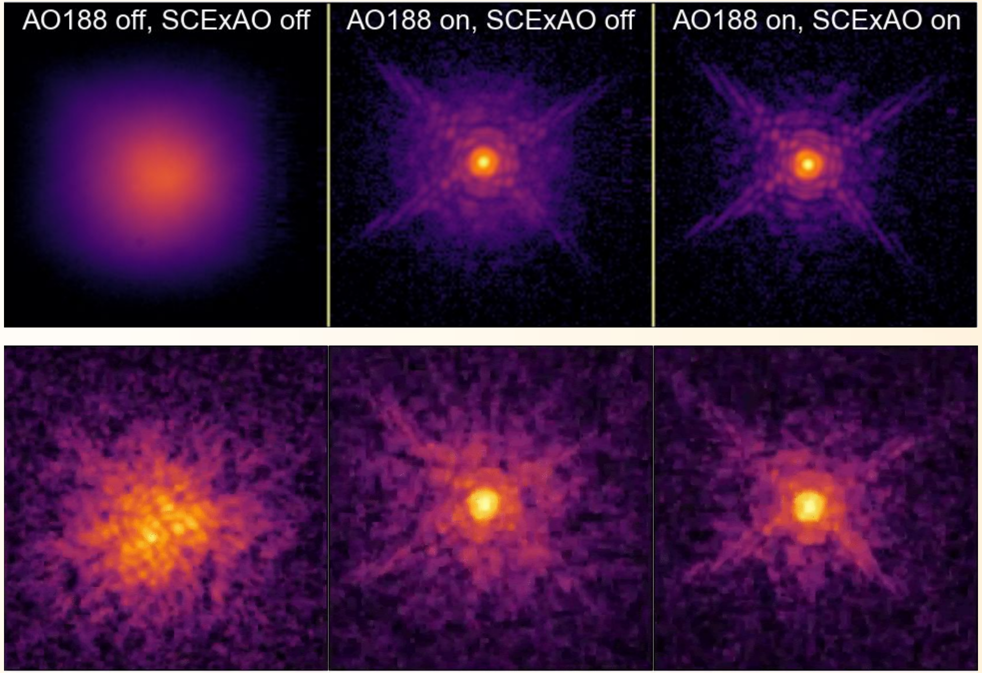


The “classical” high-contrast imaging modes

Extreme-AO Correction

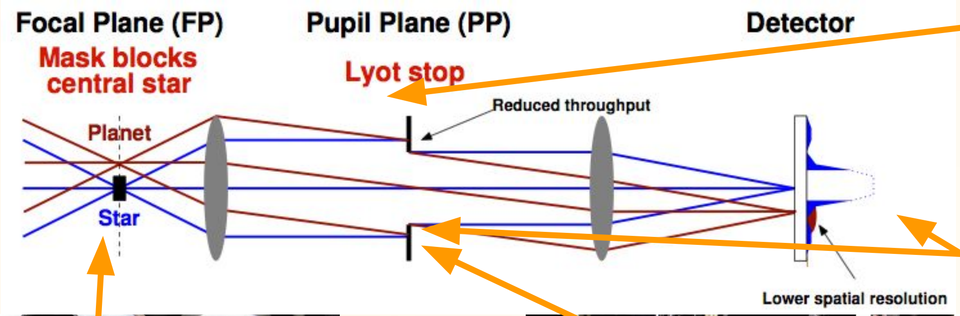
- Visible PyWFS (800-900 nm)
- 1200 controlled modes
- 1-3.5 kHz loop speed
- ExAO R-mag limit: 9-10
- Some correction down to R-mag ~14
- Strehl ratios > 90% with good seeing

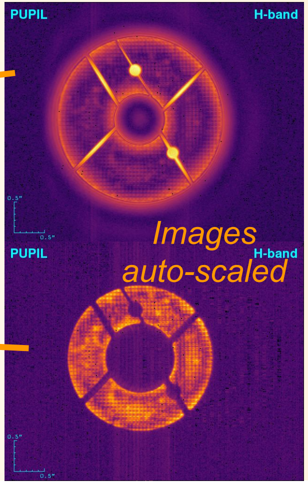


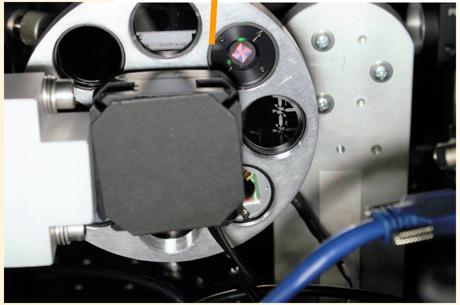


Coronagraphs With Small IWA

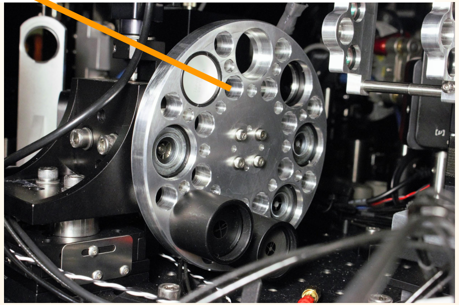
Principle of the Lyot Coronagraph: the simplest way to mask the starlight



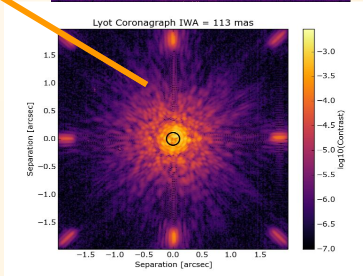




Focal plane mask wheel

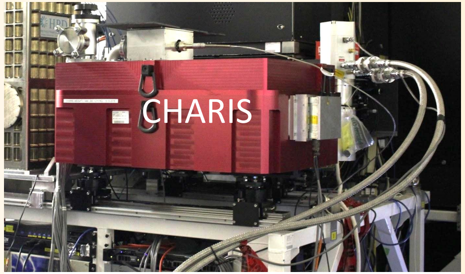


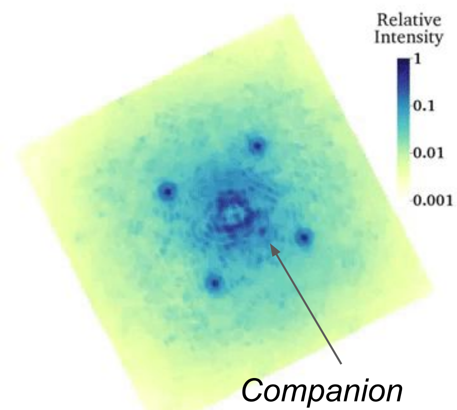
Lyot stop wheel



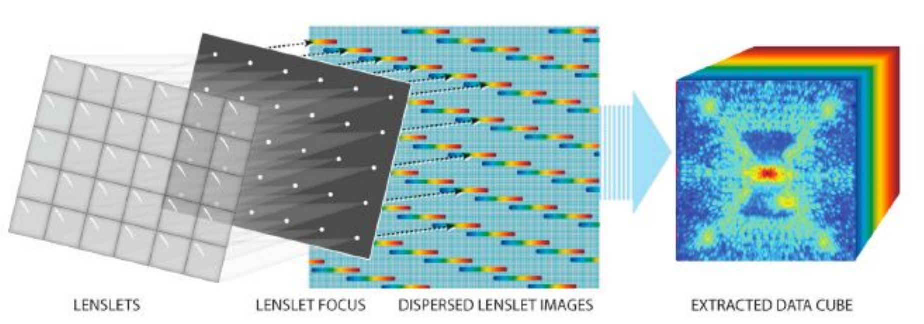
Major Science Objective: Spectral characterization of Exoplanets, Disks, Brown dwarfs

- 2.07”x2.07” FOV
- LOW RESOLUTION MODE:
  - R~19, J+H+K Band
  - 65-70% instrument throughput
  - 10-15% from atmosphere to detector
- HIGH RESOLUTION MODE:
  - R~70-90: J, H, and K Bands
  - 55-60% instrument throughput
  - ~15% from atmosphere to detector

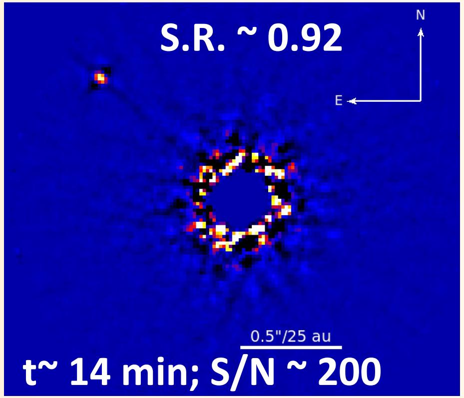


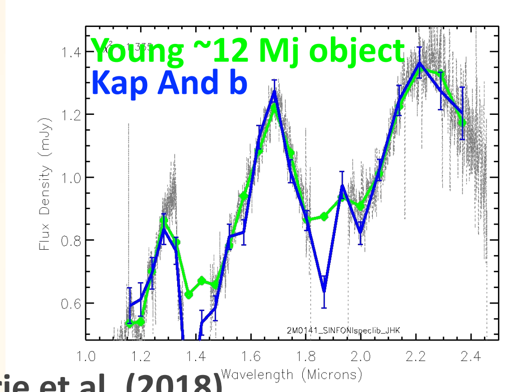


Example of CHARIS data cube

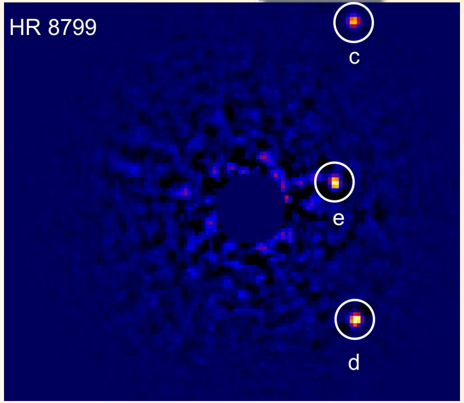


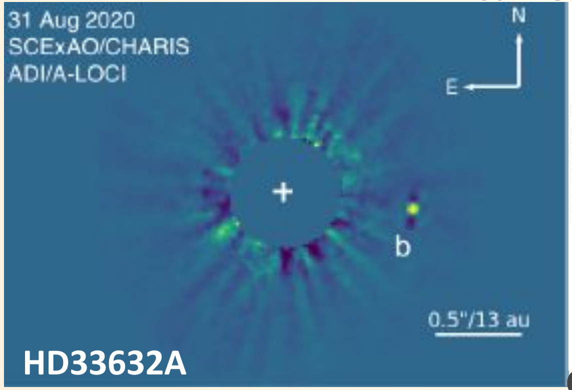
SCExAO Exoplanet / Brown Dwarf Characterization

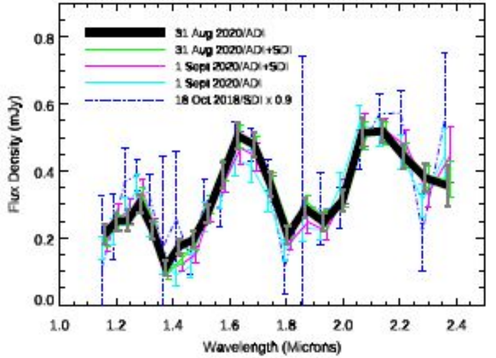




Currie et al. (2018)





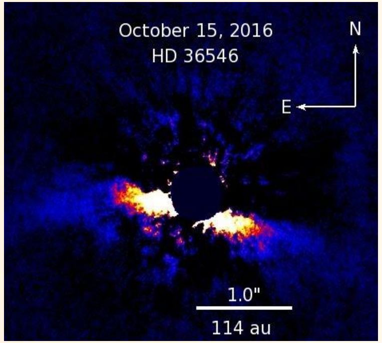


Currie et al. (2020)

One of the main goal is the characterization of exoplanets and brown dwarves, mainly using the low-resolution mode of CHARIS.

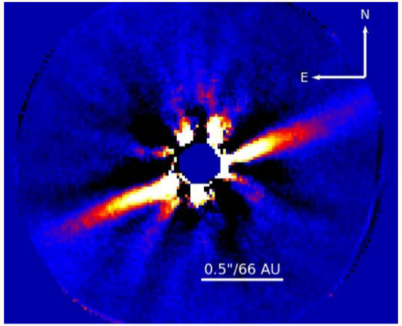
A new target selection strategy was implemented using stars with excess RV signal: out of 35 observed targets, we discovered 1 new exoplanet (to be announced soon), 2 BDs and 8 M-dwarfs.

Protoplanetary / Debris Disk Characterization



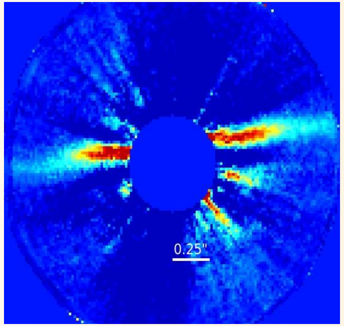
HD 36546 (Currie et al. 2017)

Direct Imaging Discovery of a Luminous Debris Disk



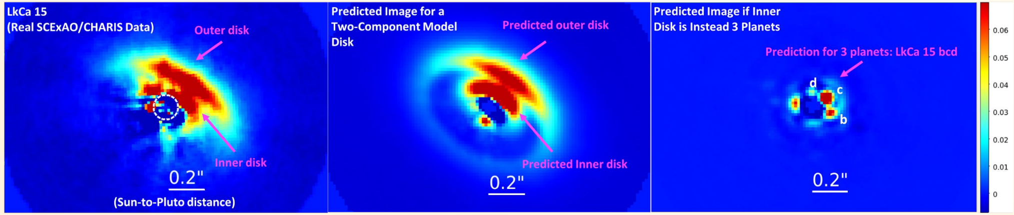
HIP 79977 (Goebel et al. 2018)

Strongly forward—scattering dust from a 60 au belt, neutral to blue disk colors



HD 15115 (Kwon et al. 2018)

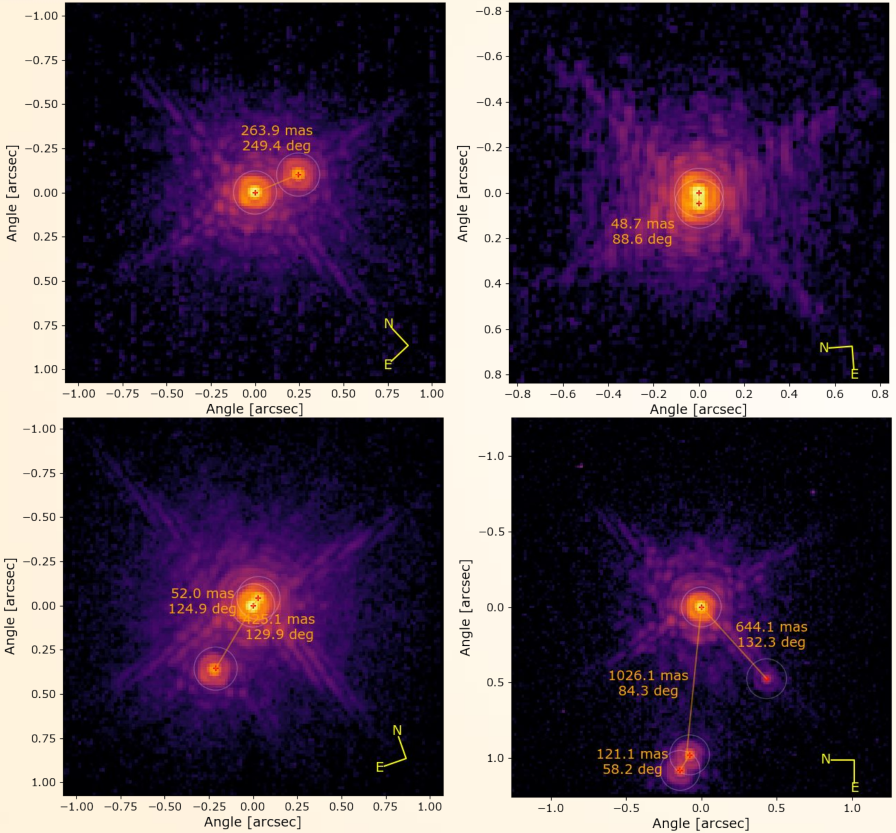
Some evidence for brightness asymmetry at small separations; spatially-resolved spectrum



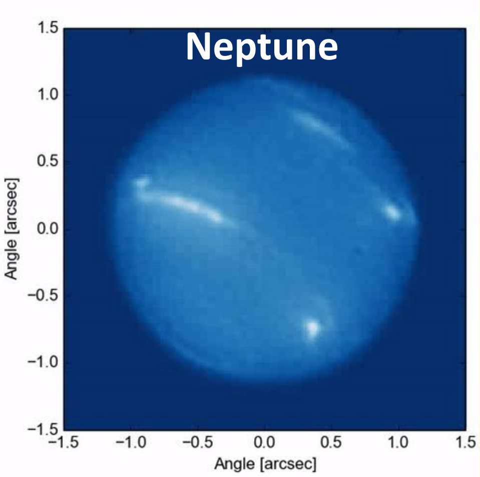
LkCa15 (Currie et al. 2019)

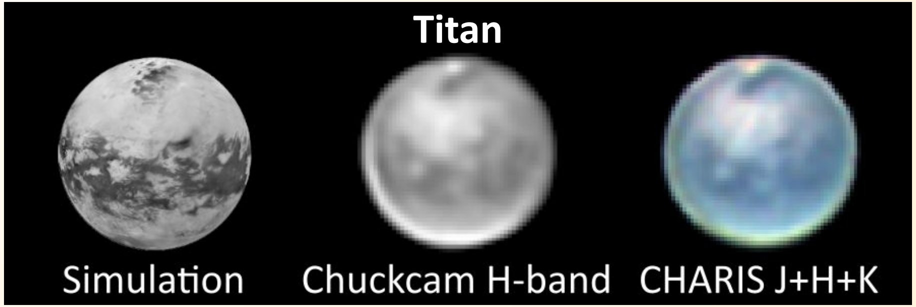
Non-detection of the potential planets

Other high-resolution science



- Binary / multiple-star systems
- A few resolved solar system objects
- Resolved stars



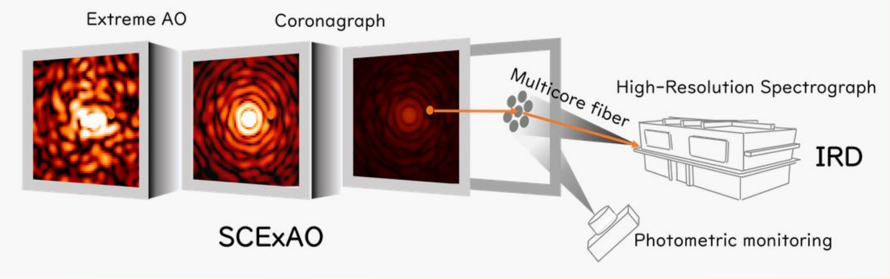


REACH: Hi-Contrast Hi-Res Spectroscopy with IRD

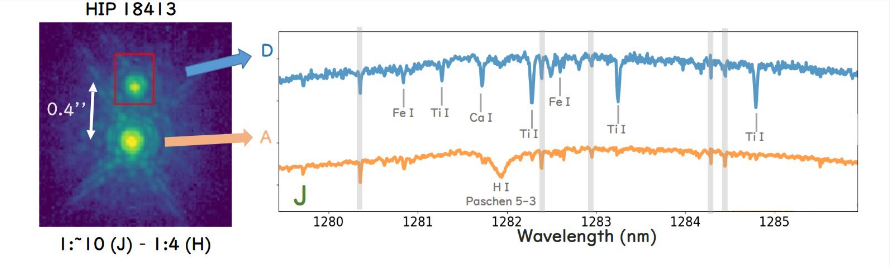
REACH connects the high-contrast imaging capabilities of SCExAO with the high-resolution spectrograph IRD (y- to H-band, R = 100,000).

A multi-core fiber is placed such as one core is aligned on the planet, the other cores sample only residual starlight.

The mode is now available for science observations.



Post-coronagraphic injection of companion light into a single-mode fiber feeding a high-resolution spectrograph

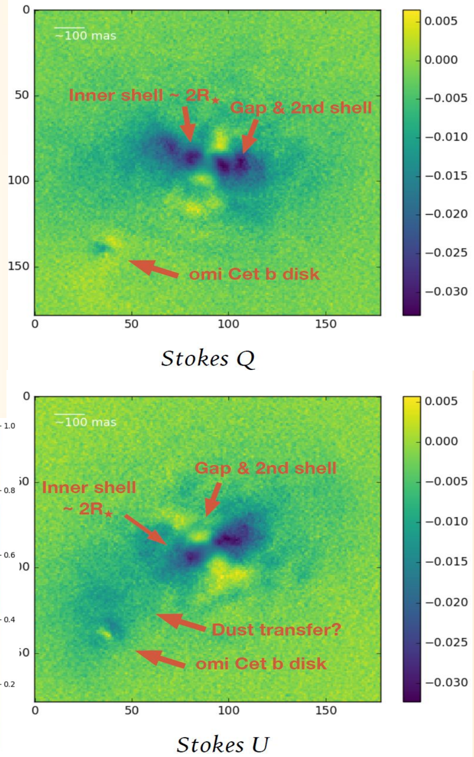


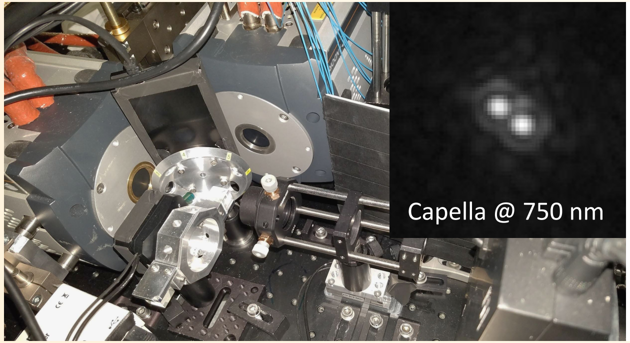
High-dispersion spectra of HIP18413 host star A and companion D obtained during engineering on-sky tests (without coronagraph)

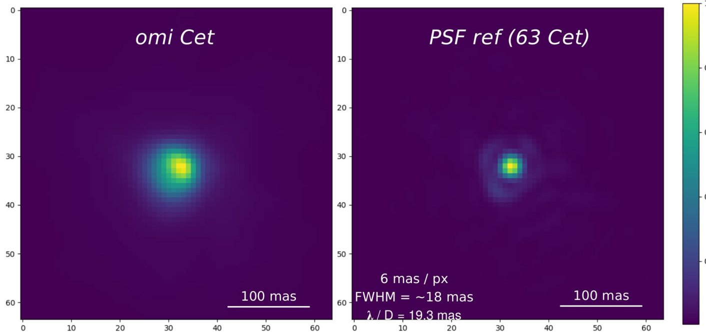
Polarimetry in Visible: VAMPIRES

- VAMPIRES is a visible PDI module, that can be combined with aperture masking interferometry.
- It operates from 600-800 nm and allow for sub-diffraction limited imaging of post AGB stars and disks with full polarimetric information.
- The instrument showed that the 3 levels of polarisation calibration can achieve exquisite normalised visibilities with σ~0.17°!
- A new H-alpha SDI mode is now available.

omi Cet in polarized light

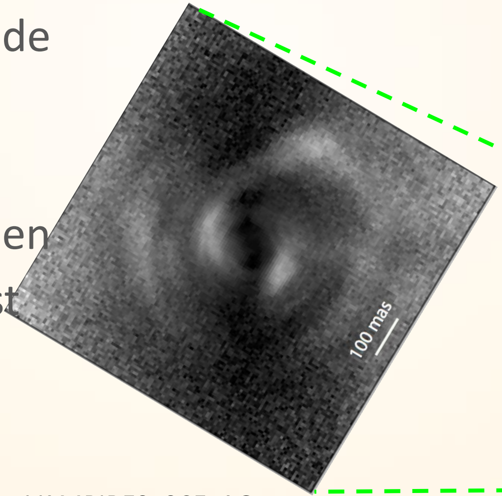




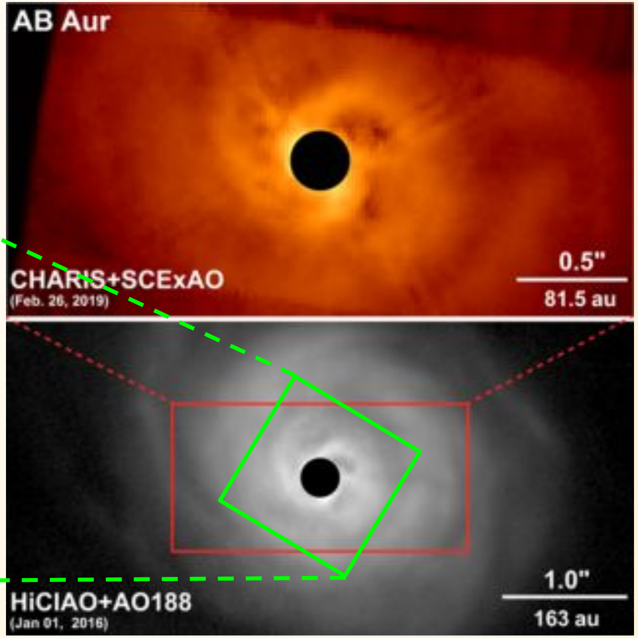


Spectro-Polarimetry in IR with CHARIS

- A new spectro-polarimetric mode with CHARIS is now available, by adding a Wollaston prism before CHARIS (FoV reduced to 1x2 arcsec).
- The spectro-polarimetric mode can measure the fractional polarization signal at the different wavelengths between J and K, and characterize dust grain populations in disks.



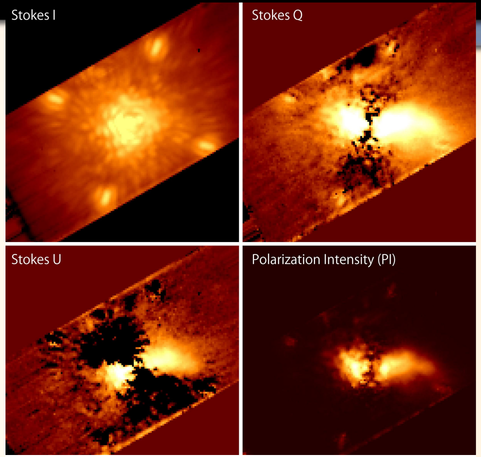
VAMPIRES+SCExAO
(Feb. 2018, work in progress)

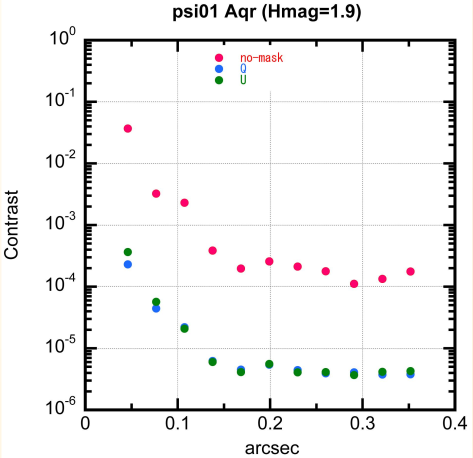


NEW! Fast-IR Polarimetry Open for Science

- A fast PDI mode, similar to VAMPIRES in visible, was added using a Wollaston prism (identical to the CHARIS Wollaston) and a Ferroelectric Liquid Crystal (FLC) for a fast modulation of the polarization.A C-RED ONE camera was purchased for that purpose, and was installed in 2020. Testing was first done with the internal C-RED 2 camera, then the C-RED ONE.

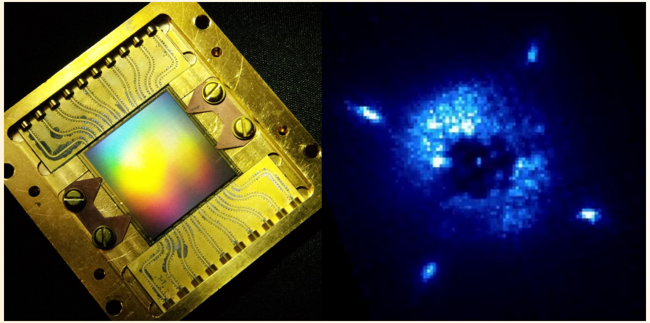
- A raw contrast curve was calculated using only one minute of data on the unpolarized standard star psi01 Aqr, showing that we achieve ~1e-4 raw contrast at ~0.15 arcsec separations, before double-differential processing. The contrast for stokes Q and U were also calculated, showing that we achieve a contrast of a few 1e-6 at 0.15 arcsec with double-differential processing. The addition of a third differential processing using the FLC should improve this further.



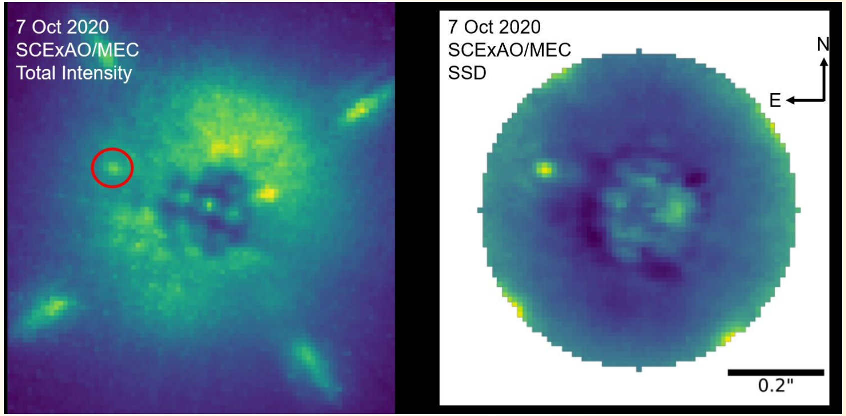


NEW! MEC Open for Science

- MKID Exoplanet Camera (MEC) is a innovative type of noiseless photon-counting detector that can measure each photon's arrival and energy. We can do spectroscopy without a dispersive element!
- A pipeline was developed for data processing, looking at the arrival statistics of photons: the Stochastic Speckle Discrimination (SSD) method.



MEC 20k-pixel detector and datacube taken on-sky

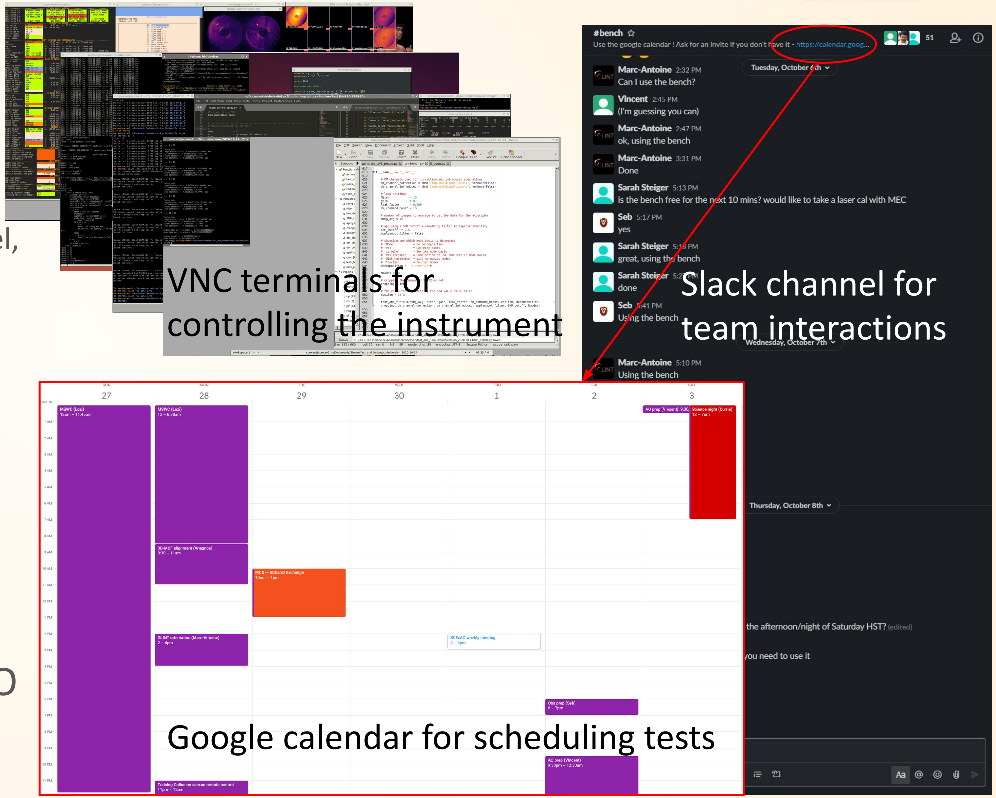


Steiger et al. 2021

SCExAO : a host testbed for remote collaborators

Using SCExAO for R&D

- To use SCExAO, day or night:
  - Contact us for remote access (VPN)
  - Get trained to operate what you need
  - Coordinate use with other users (slack channel, Google calendar)
- The instrument is nearly always online (24/7), routinely used by collaborators (few hrs/day on average).
- SCExAO support team ready to assist. Based in Hilo, ~1.5hr drive from instrument @ Summit
- When you are ready, test on-sky. SCExAO has ~7 nights of engineering per yr.



VNC terminals for controlling the instrument

Slack channel for team interactions

Google calendar for scheduling tests

Software: MILK & CACAO

Unified architecture for SCExAO and AO188 RTCs

Long running development and collaboration - **flexible** and **modular** and **open-source**

- **Hardware side:** now CPUs, GPUs, expand to FPGAs, etc… - abstracting the architecture
- **Software side:** manage async flows, multirate, many-sensors, telemetry, ... with ease and agility

***MILK:** Modular Image processing Library toolkit*

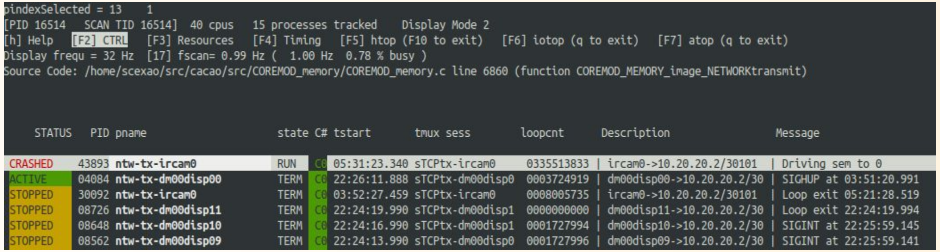
Data structures, basic IO, arithmetic, data processing, etc

***CACAO:** Compute and Control for Adaptive Optics*

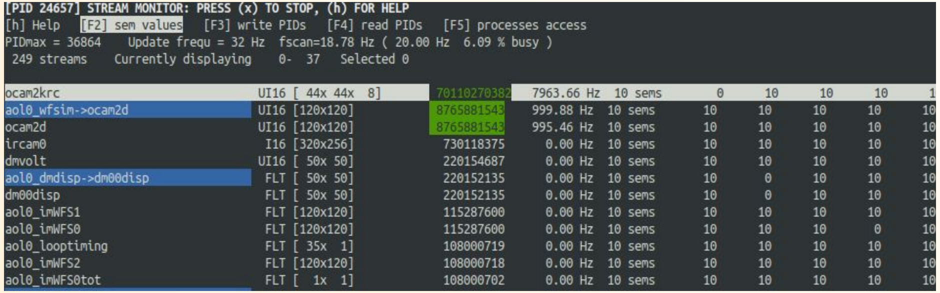
The smart RTC : AO loops, control, predictive, adaptive, fancy stuff, … neural nets soon ?

Streams & Processes

Processes perform data processing on CACAO RTCs



Streams are shared memory data structures

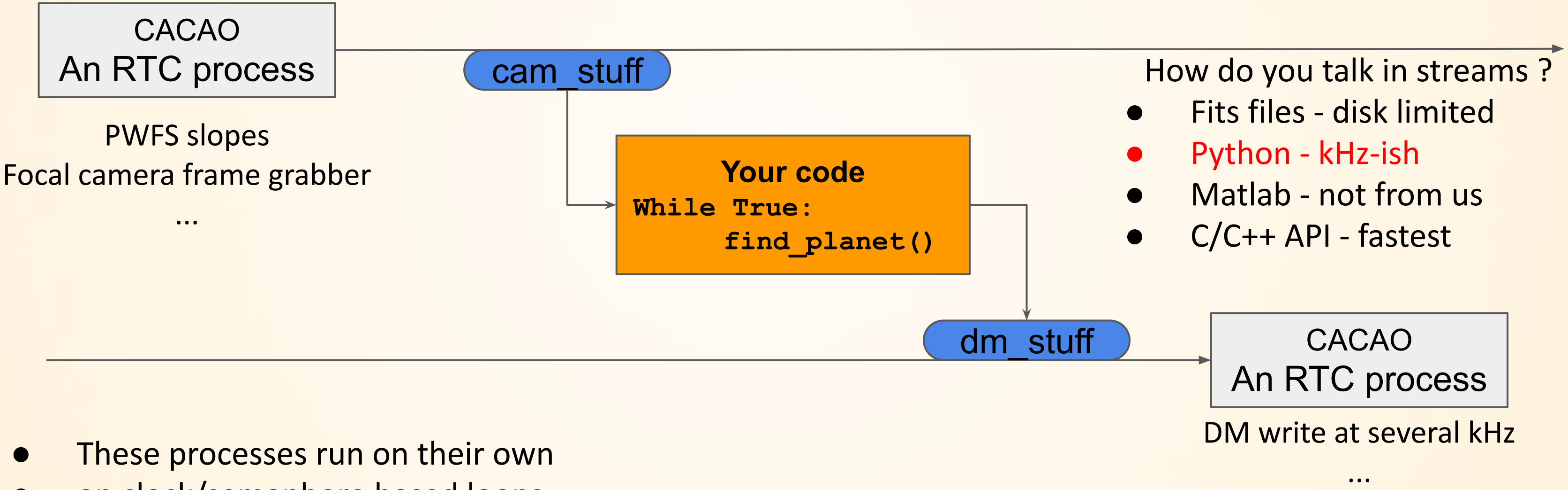


- Directly visible on a RAM disk with a file system representation
- Can be read/written by as many processes as you'd like (reasonably)

Stream/process data flow is achieved through POSIX semaphores

Bring Your Own Code, Plug and Play

An easy way to bring your code to SCExAO is to be compatible with **streams**



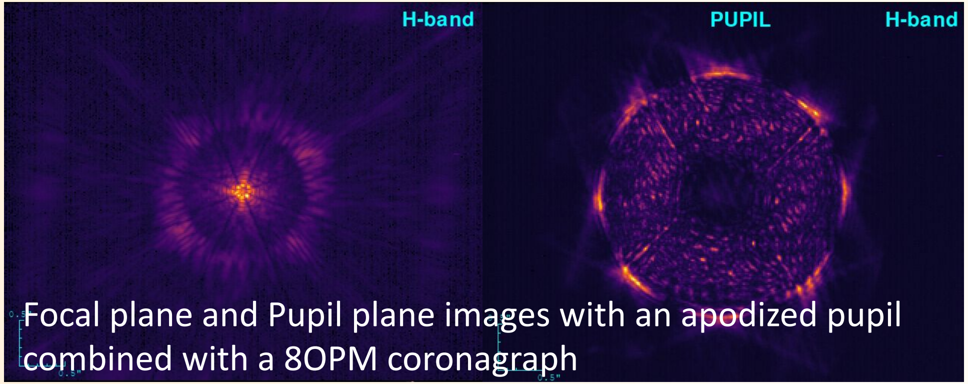
How do you talk in streams ?

- Fits files - disk limited
- Python - kHz-ish
- Matlab - not from us
- C/C++ API - fastest

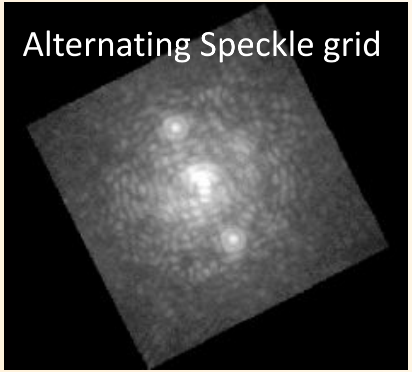
- These processes run on their own
- on clock/semaphore based loops
- You **don't care** about their C I/O interfaces

Current collaborative projects on SCExAO

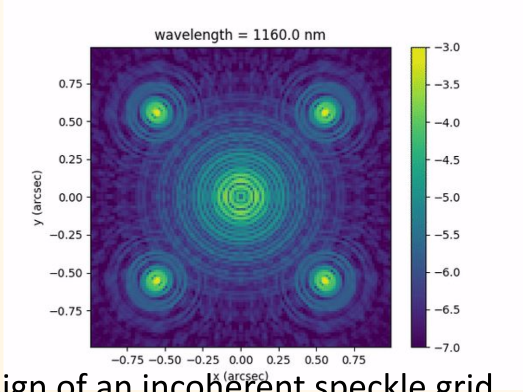
Coronagraphy / Speckle Grid



Focal plane and Pupil plane images with an apodized pupil combined with a 8OPM coronagraph



Alternating Speckle grid



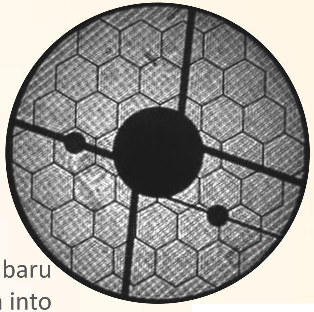
Design of an incoherent speckle grid

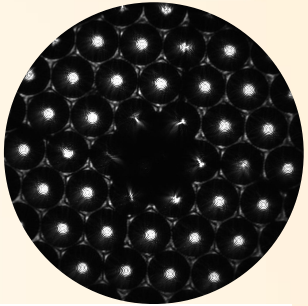
- We continue the development of performant coronagraphs at small inner working angles (VVC, PIACCMC, 8OPM), especially for broadband observations compatible with CHARIS.
- We also work at improving the stability and accuracy of the calibration speckles used for astrometry and photometry.

Interferometric & Fiber Injection Modules

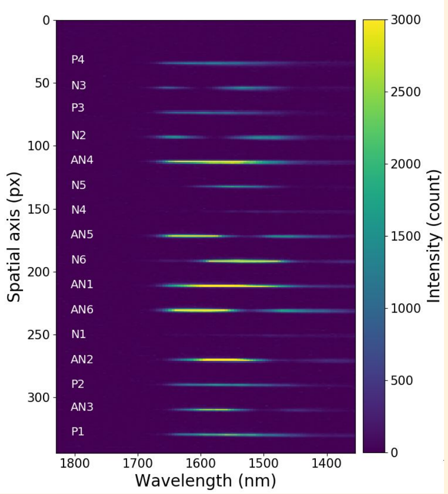
We developed several innovative interferometric and fiber injection modules, for science and WFS:

- FIRST: a visible interferometric module with spectroscopic capabilities.
- GLINT: a NIR photonic nulling interferometer.
- RHEA: a visible 3x3 element IFU with high-res spectroscopy, and now also a NIR version using 3D-printed microlenses on a multi-core fiber.
- Other explorations of WFS using photonic lanterns.





Sampling of the Subaru pupil Injection into single-mode fibers using a micro-lens array for FIRST

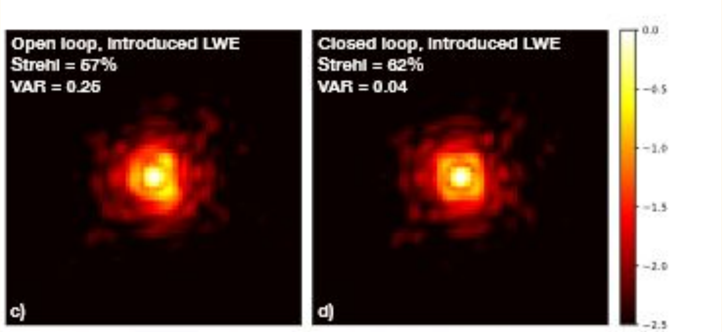


Interferometric output of GLINT, dispersed on the horizontal axis. Some wavelengths are nulled by playing with the optical path difference between channels.

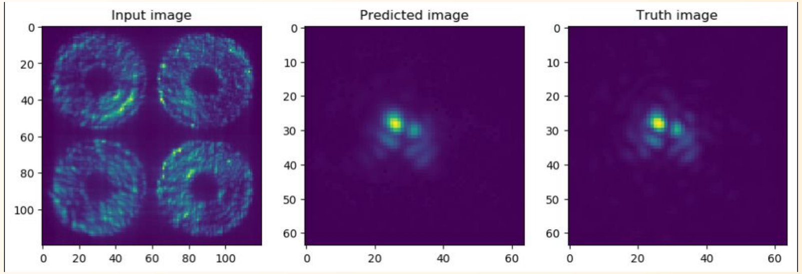
Focal Plane Wavefront Sensing Developments

Focal plane wavefront sensing for low-order aberrations, low-wind/island effect

- Phase retrieval with asymmetric pupil mask: Zernike Asymmetric Pupil (ZAP) WFS
- Phase diversity
  - Linearized Analytic Phase Diversity (LAPD)
  - Mono-plan phase diversity
  - Fast and Furious (sequential Phase Diversity)
- PSF reconstruction from PyWFS using Neural Network
- Reinforcement learning: Direct Reinforcement Wavefront Heuristic Optimisation (DR WHO)



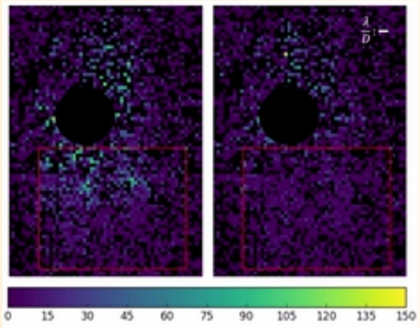
On-sky validation - S. Bos et al. (2020)



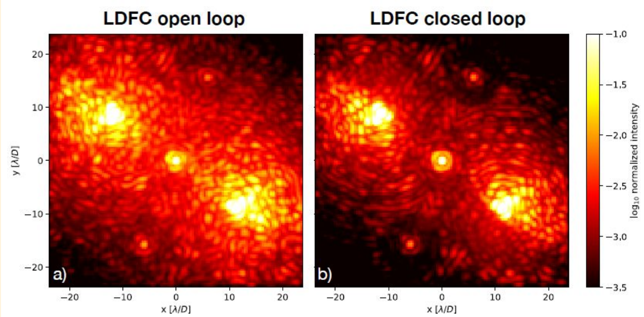
PyWFS telemetry - predicted image from Neural Network - True image

On-sky validation – B. Norris

Focal Plane Wavefront Sensing Developments



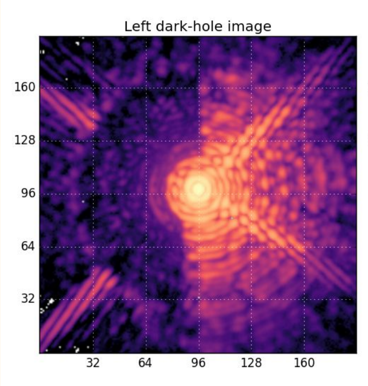
Speckle nulling with a MKID detector

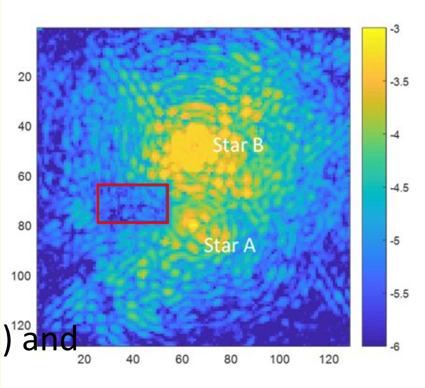


Demonstration of LDFC with the vAPP
Miller et al. 2021

We are developing several speckle suppression & control algorithms for various applications:

- Speckle nulling using the MKIDS IFS MEC
- Speckle nulling for single stars and binary systems using fast IR cameras (C-RED ONE, C-RED 2)
- Speckle control to stabilize dark holes with Linear Dark Field Control (LDFC)
- Various other CDI techniques.





Lab demonstration of speckle nulling (top) and multi-star wavefront control (bottom)

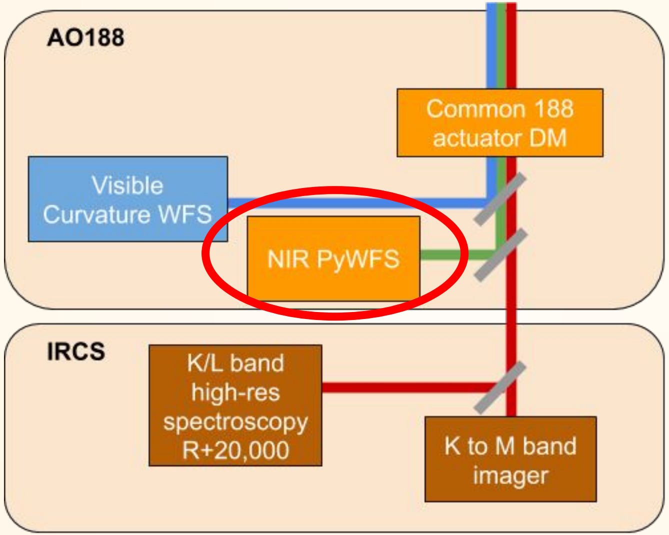
SCExAO

Major upgrades (2020-2022)

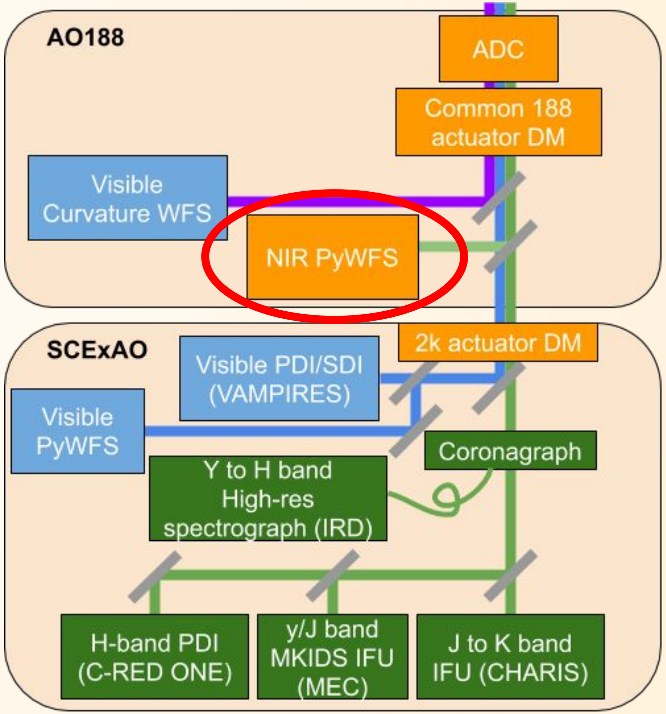
Steps to get closer to the TMT-PSI configuration

Towards PSI Phase Ia: NIR PyWFS for AO188

The first upgrade will be the addition of a NIR PyWFS inside AO188, benefiting both SCExAO and IRCS behind AO188.



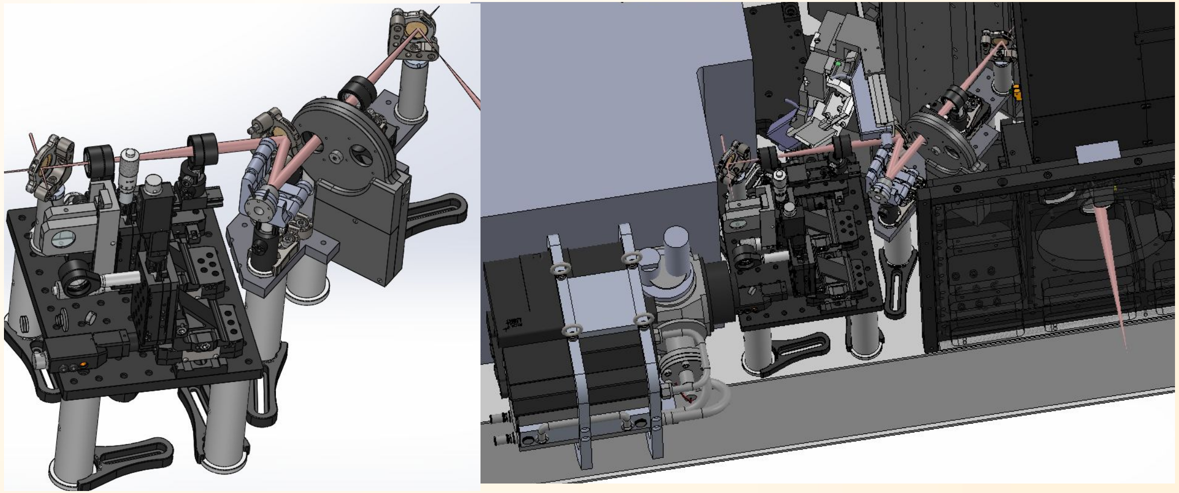
Configuration AO188+IRCS



Configuration AO188+SCExAO

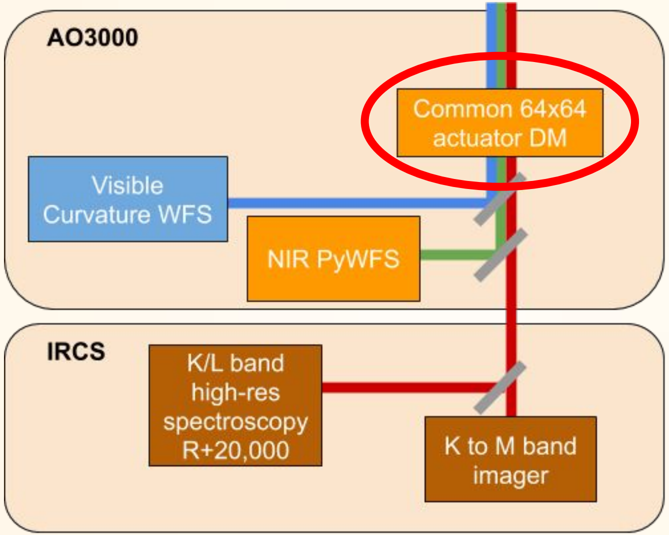
Towards PSI Phase Ia: NIR PyWFS for AO188

- The NIR PyWFS, designed for y to H-band, uses a C-RED ONE camera (shared with the fast IR PDI mode for now), originally for a spectroscopic study of the galactic center with IRCS.
- The NIR PyWFS will be available for the other modules of SCExAO.
- The design uses mostly off-the-shelf mechanical parts, custom-made achromatic lenses, and a custom pair of roof prisms similar to SCExAO's Vis PyWFS.

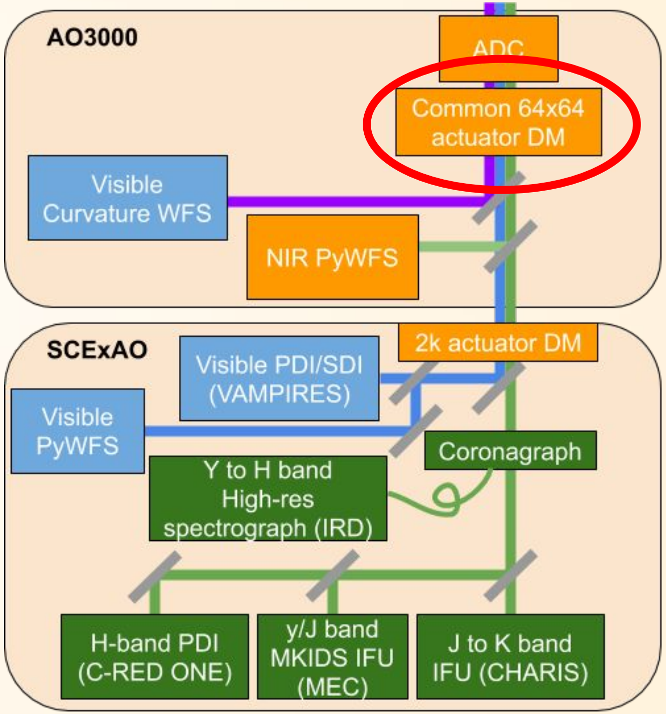


Towards PSI Phase Ib: ALPAO 64x64 DM

The second upgrade will replace the current 188-actuator DM with an ALPAO 64x64-actuator DM, with more than 3000 actuators inside the pupil. AO188 will then become AO3000.



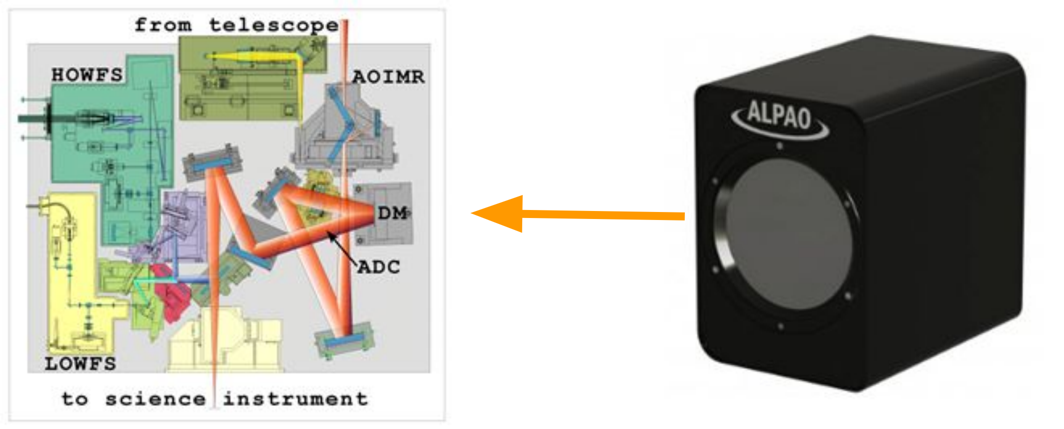
Configuration AO3000+IRCS



Configuration AO3000+SCExAO

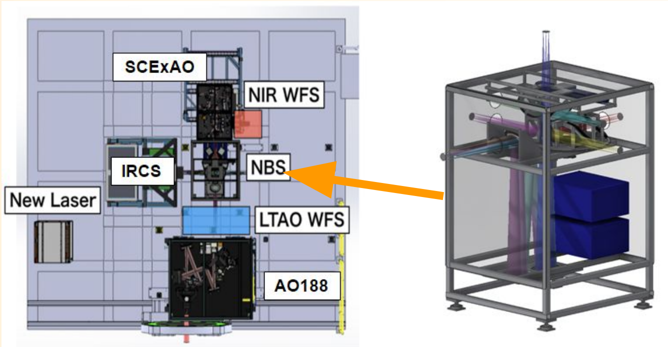
Towards PSI Phase Ib: ALPAO 64x64 DM

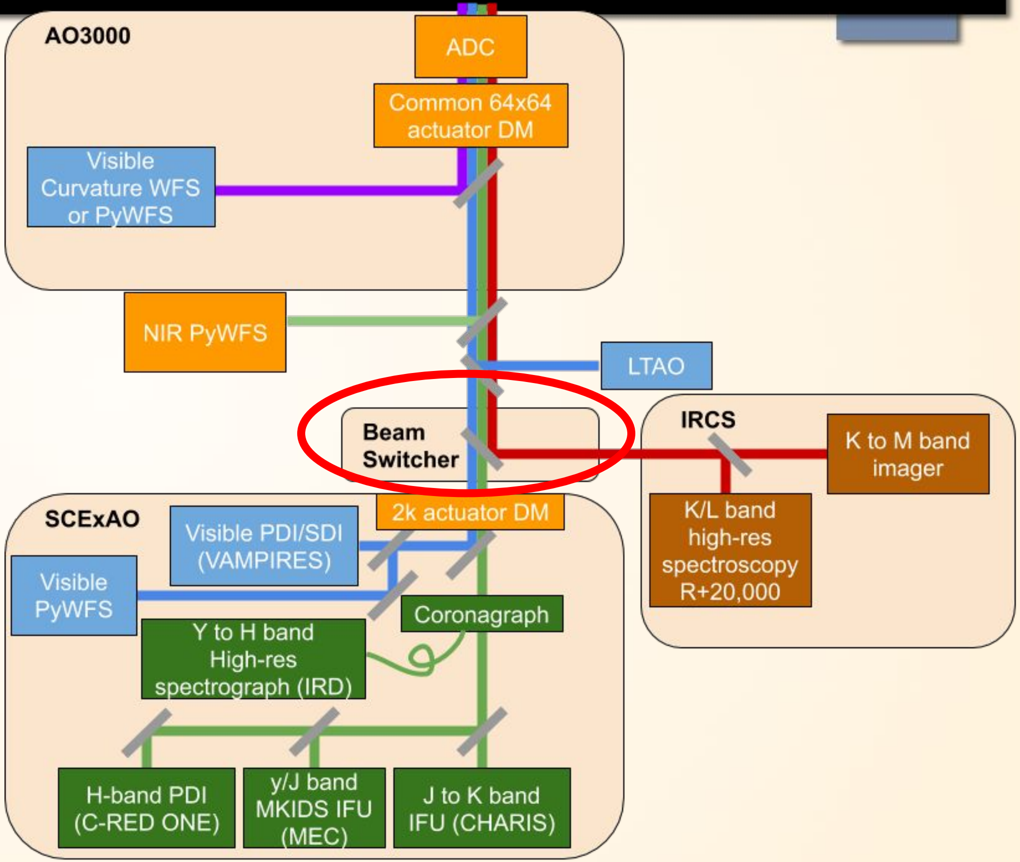
- The new NIR PyWFS is designed to work with the new DM. They will provide ExAO performance right after the first stage of AO correction.
- It is almost a drop-in replacement: The new DM has about the same physical size as the old one. The tip-tilt mount of the old DM will be moved to another flat mirror in the path.
- AO188's WFS will also be upgraded at a later date, possibly with a visible PyWFS with an OCAM2K.



SCExAO Towards PSI Phase II: Beam Switcher

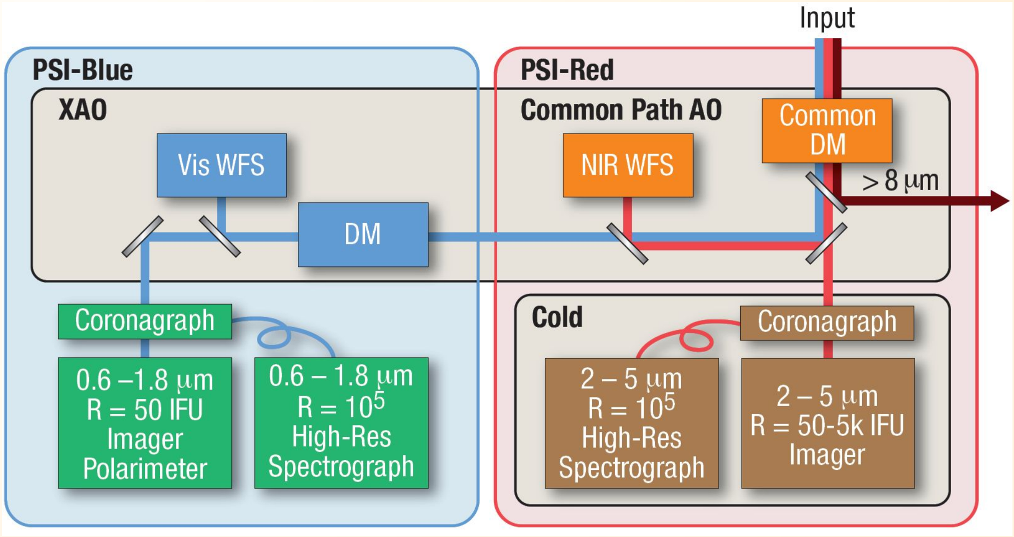
In Phase II, a new beam switcher will allow for fast switching or simultaneous observations with SCExAO, IRCS, a new LTAO WFS, and potential visitor instruments.





Towards PSI Phase II: Beam Switcher

- SCExAO is already testing critical hardware and algorithms for TMT-PSI: photon counting cameras, (predictive/focal plane) wavefront control, advanced coronagraphy, single mode fiber injection, etc.
- The new beam switcher will allow to split the light between SCExAO (~PSI-blue) and a NIR instrument (~PSI-red) like IRCS, or other visitor instruments (NIR IFS? Hi-Res spectrograph?)



Conclusions

- SCExAO is a unique instrument, able to simultaneously perform competitive science, while testing new technologies routinely for future high-contrast imagers like TMT-PSI.
- The framework allows for a large number of international collaborations, with groups testing remotely or in-situ new hardware, software and algorithms.
- We are demonstrating key techniques that are necessary if we want to reach the imaging of Earth-size planets with TMT.
- The global architecture of the IR Nasmyth platform at Subaru will also evolve rapidly in the next 2 years, to become an ideal on-sky system validation of TMT-PSI.
- New collaborations are always possible, if you have some new ideas!