Path to facility instrument for AO3k, SCExAO and CHARIS

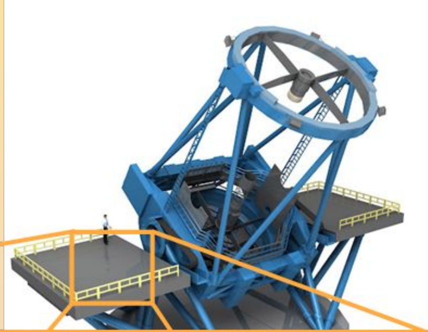
Julien Lozi, Olivier Guyon, Sébastien Vievard, Vincent Deo, Kyohoon Ahn, and the extended AO3k and SCExAO teams

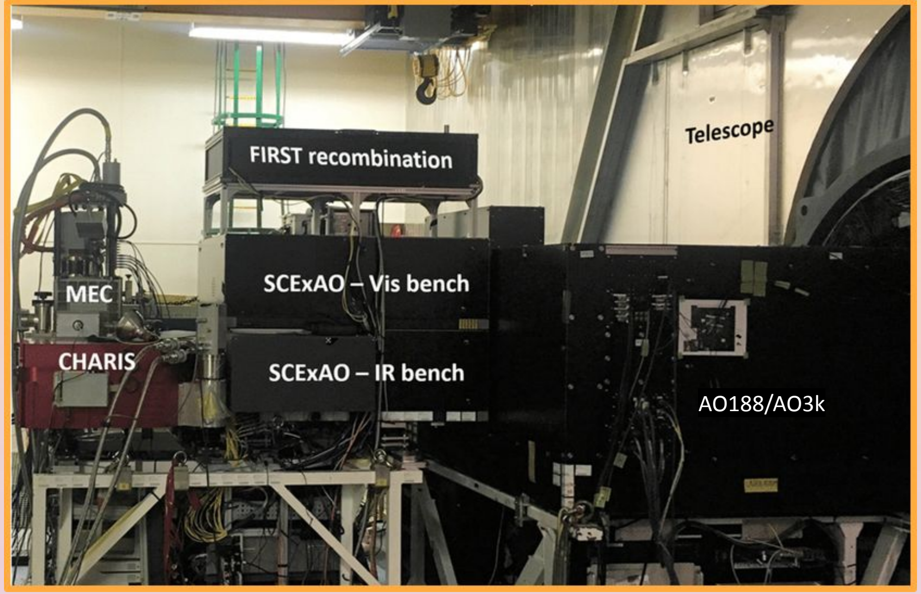
SCExAO Overview

The **Subaru Coronagraphic Extreme Adaptive Optics** platform

Testbed during the day — **Instrument** during the night

- **At the IR Nasmyth platform of the Subaru Telescope, Maunakea, Hawaii, 4139 m altitude.**
- 50 nights/year (40+ of science)
- Began in 2009 as a Coronagraph+WFS/C demonstrator behind AO188.
- First light in S11A, Science operation started in S14B with HiCIAO.
- First Open-Use nights with CHARIS in 217A, and with VAMPIRES in S18A.
- Grew to a full high-contrast platform, testing:
  - Wavefront control
  - Coronagraphy
  - Imaging
  - Interferometry
  - Spectroscopy
  - Polarimetry
  - Photonics





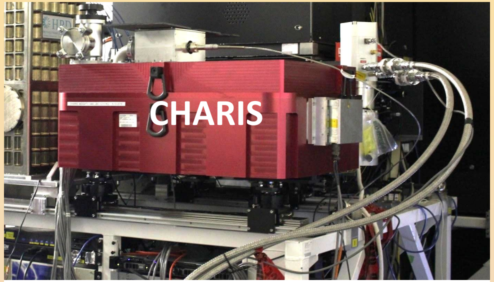
See Poster P11 (REACH) & P26 (FIRST) , Olivier's talk in the HWO sessions and my talk in the TMT session for some experimental work.

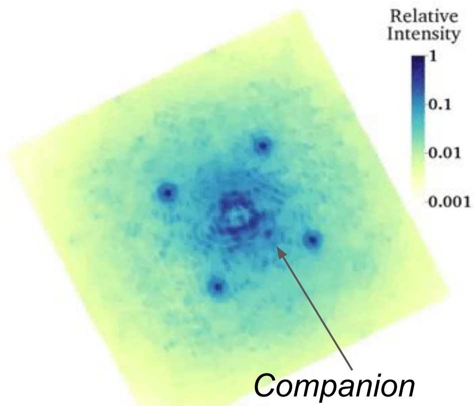
CHARIS Overview

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

Most of the SCExAO science papers use CHARIS data.





Example of CHARIS data cube

Show highlights | Show abstracts | Hide Sidebars

2022NatAs...6..751C 2022/04 cited: 116
Images of embedded Jovian planet formation at a wide separation around AB Aurigae
Currie, Thayne; Lawson, Kellen; Schneider, Glenn *and 30 more*

2019ApJ...877L...3C 2019/05 cited: 82
No Clear, Direct Evidence for Multiple Protoplanets Orbiting LkCa 15: LkCa 15 bcd are Likely Inner Disk Signals
Currie, Thayne; Marois, Christian; Cieza, Lucas *and 30 more*

2018AJ....156..291C 2018/12 cited: 56
SCExAO/CHARIS Near-infrared Direct Imaging, Spectroscopy, and Forward-Modeling of κ And b: A Likely Young, Low-gravity Superjovian Companion
Currie, Thayne; Brandt, Timothy D.; Uyama, Taichi *and 30 more*

2020ApJ...904L..25C 2020/12 cited: 44
SCExAO/CHARIS Direct Imaging Discovery of a 20 au Separation, Low-mass Ratio Brown Dwarf Companion to an Accelerating Sun-like Star
Currie, Thayne; Brandt, Timothy D.; Kuzuhara, Masayuki *and 27 more*

2023Sci...380..198C 2023/04 cited: 38
Direct imaging and astrometric detection of a gas giant planet orbiting an accelerating star
Currie, Thayne; Brandt, G. Mirek; Brandt, Timothy D. *and 31 more*

2022ApJ...934L..18K 2022/08 cited: 38
Direct-imaging Discovery and Dynamical Mass of a Substellar Companion Orbiting an Accelerating Hyades Sun-like Star with SCExAO/CHARIS
Kuzuhara, Masayuki; Currie, Thayne; Takarada, Takuya *and 33 more*

2020AJ....160..150W 2020/09 cited: 37
On the Chemical Abundance of HR 8799 and the Planet c
Wang, Ji; Wang, Jason J.; Ma, Bo *and 10 more*

2019ApJ...875...38R 2019/04 cited: 31
Multi-epoch Direct Imaging and Time-variable Scattered Light Morphology of the HD 163296 Protoplanetary Disk
Rich, Evan A.; Wisniewski, John P.; Currie, Thayne *and 58 more*

2023AJ....165...39F 2023/02 cited: 27
Astrometric Accelerations as Dynamical Beacons: Discovery and Characterization of HIP 21152 B, the First T-dwarf Companion in the Hyades
Franson, Kyle; Bowler, Brendan P.; Bonavita, Mariangela *and 28 more*

2021AJ....162...44S 2021/08 cited: 25
SCExAO/MEC and CHARIS Discovery of a Low-mass, 6 au Separation Companion to HIP 109427 Using Stochastic Speckle Discrimination and High-contrast Spectroscopy
Steiger, Sarah; Currie, Thayne; Brandt, Timothy D. *and 29 more*

VAMPIRES Overview

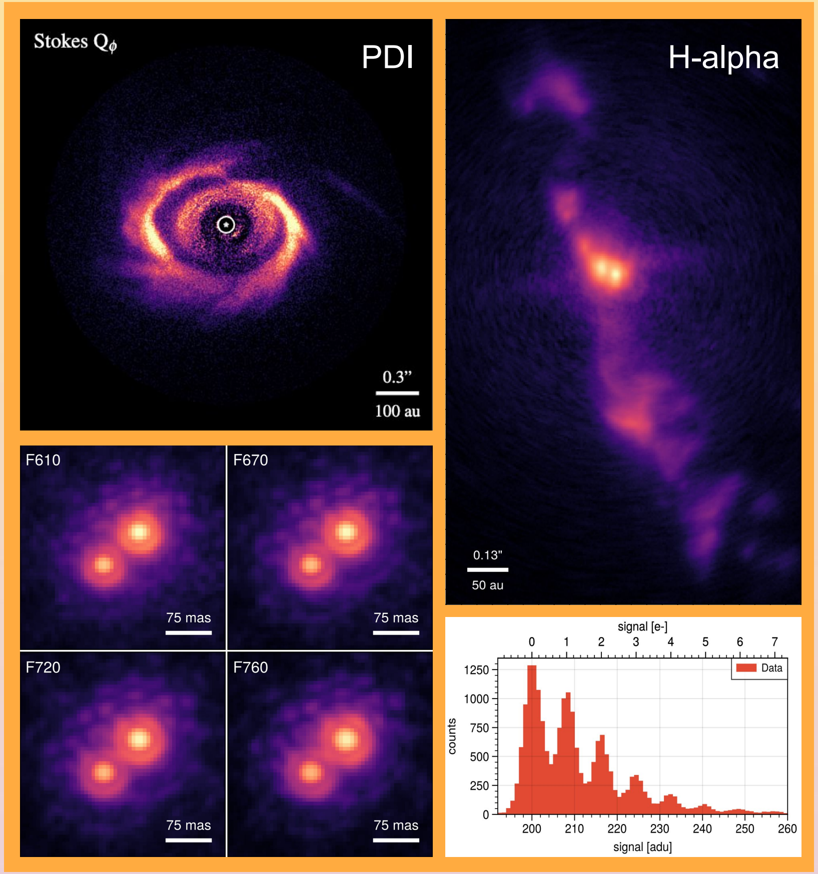
Major Science Objective: Visible High-resolution Imaging/Interferometry of Evolved Stars, Disks

- Wavelength range: 600 - 800 nm
- 3”x3” FOV
- Polarimetry (can sync with CHARIS + FastPDI)
- Slow mode (HWP only)
- Fast mode (HWP + FLC)
- Coronagraphy: four classic Lyot coronagraph
- Multi-band imaging (MBI)
- 3 to 4 fields imaged simultaneously using dichroics
- Sparse Aperture Masking (SAM)
- 7, 9, 18-hole + annulus aperture masks
- Narrowband imaging
- H-alpha / SII
- Differential switching available to reduce NCPA

Data Processing:

- VAMPIRES DPP (github.com/scexao-org/vampires-dpp)
- Frame calibration, registration, selection, collapsing and PDI (no post-processing for SDI or SAM)

See Poster P32 for more details about VAMPIRES and its science.



AO3k: Overview of the upgrade of AO188

AO3k provides XAO level correction to instruments behind it. The main upgrade is the heart of the system: **A 3000-actuator deformable mirror**.

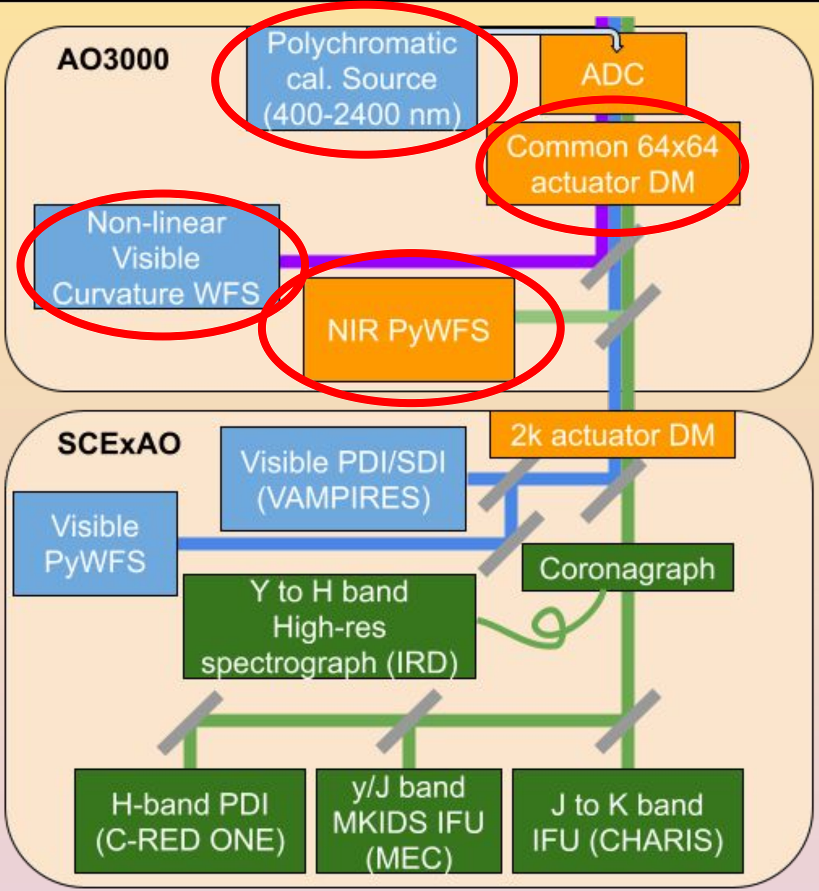
To control this DM, two new wavefront sensors are in the works:

A NIR PyWFS allows us to reach redder targets: K- to M-type stars, and stars with dust extinction. These will be the prime targets for imaging habitable planets with ELTs (See Poster P13).

A non-linear Curvature WFS will replace the current visible WFS. It will provide better correction than AO188, even on faint targets (See Poster P2).

Adding a second XAO system (SCExAO) behind AO3k allows to **do more precise speckle control and reach higher contrasts.**

A new polychromatic calibration source will help better calibrate the wavefront sensors and science instruments behind (See Poster P14).



Science Objectives

The key science of SCExAO/CHARIS is the formation & evolution of planetary systems

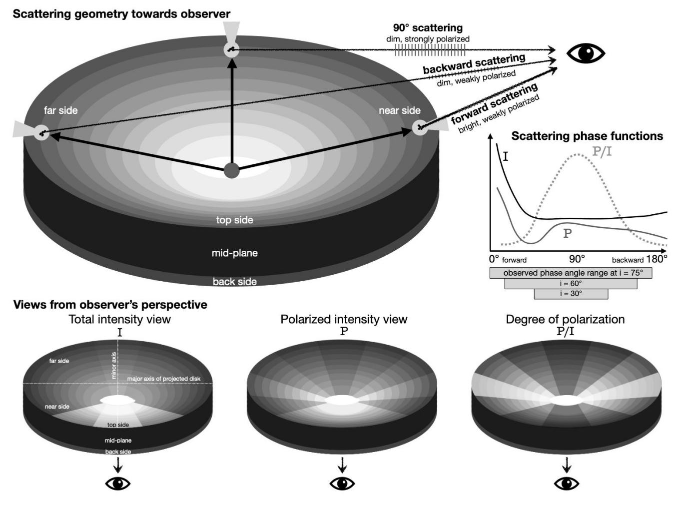
- Detection and spectral characterization of exoplanets & substellar mass companions
- Detection of characterization of circumstellar disks (morphology, dust grain size)

CHARIS is also a general-purpose instrument for narrow-field diffraction-limited spectro-imaging

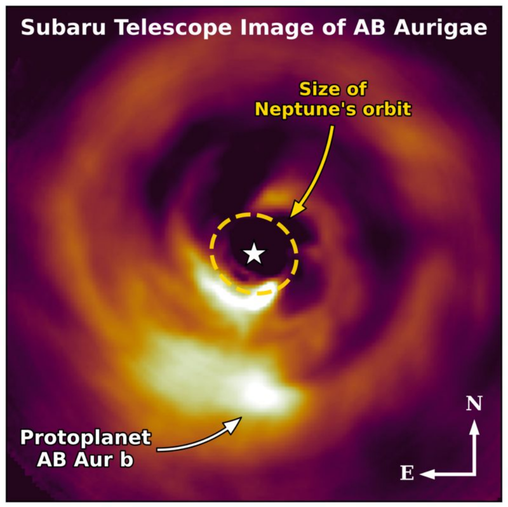
- Stellar evolution (star formation, mass loss in evolved stars)
- Planetary system: small bodies, satellites of giant planets, Neptune

In visible, VAMPIRES' goal is to image and characterize circumstellar disks

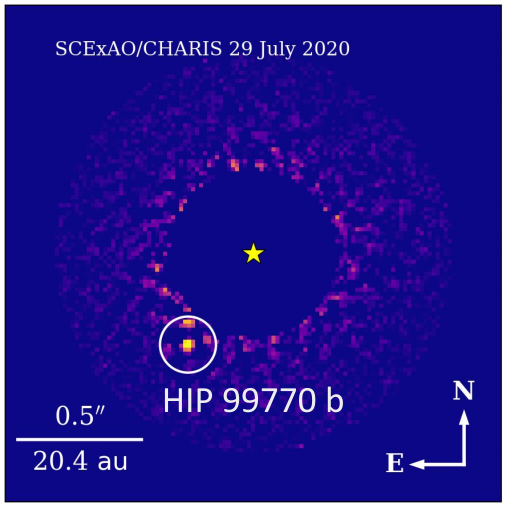
- Doing so in visible light provides an angular resolution advantage over NIR
- Disks are characterized (grain size) by multi-band polarized light imaging



Example CHARIS science results

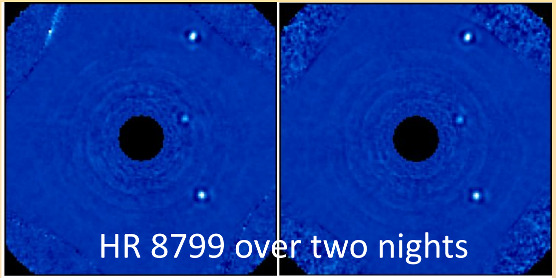


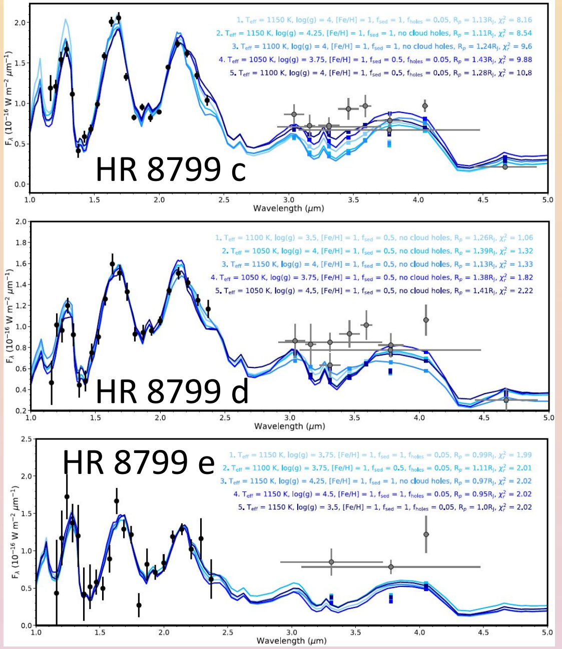
T. Currie et al., Nature 2022

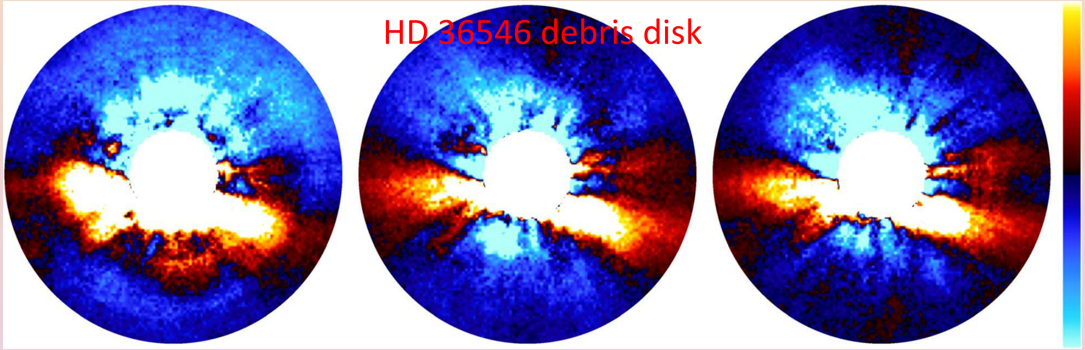


T. Currie et al., Science 2023

J. Wang et al., AJ 2022







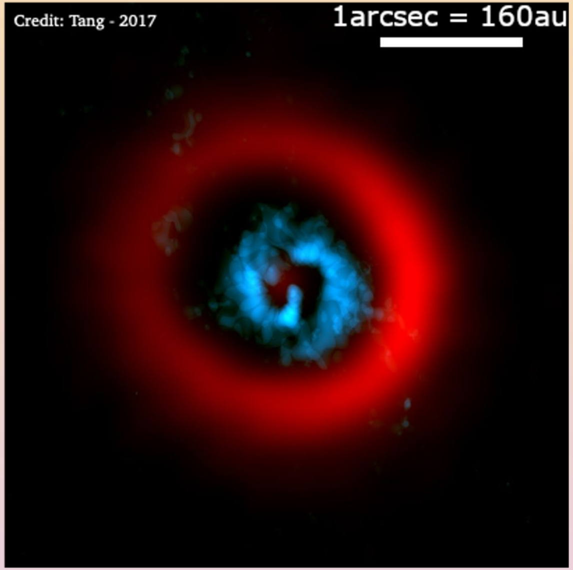
K. Lawson et al., AJ 2021

CHARIS & ALMA

One of CHARIS' advantages is its complementarity with ALMA & sub-mm disk observations.

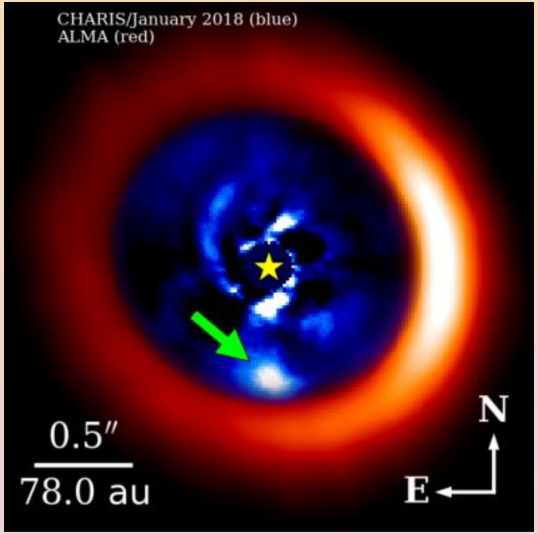
ALMA reveals dust (most sensitive to ~mm size grains) and gas (with kinematics).

CHARIS reveals fine dust grains with polarimetry and thermal emission from planet(s).



Red: ALMA sub-mm (dust)

Blue: ALMA CO emission



Red: ALMA sub-mm (dust)

Blue: CHARIS

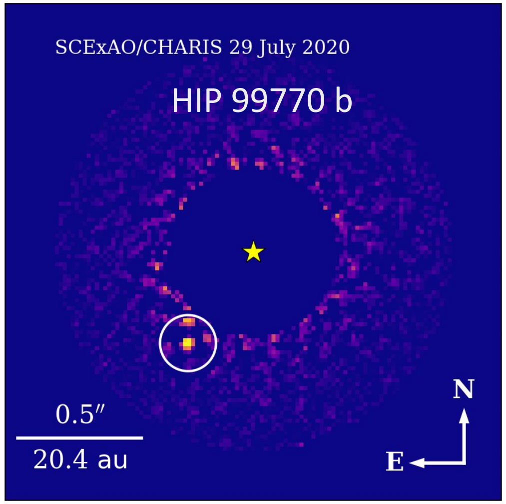
T. Currie et al., Nature 2022

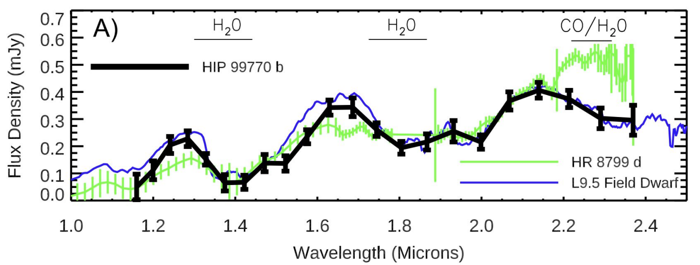
CHARIS, Astrometry & RV

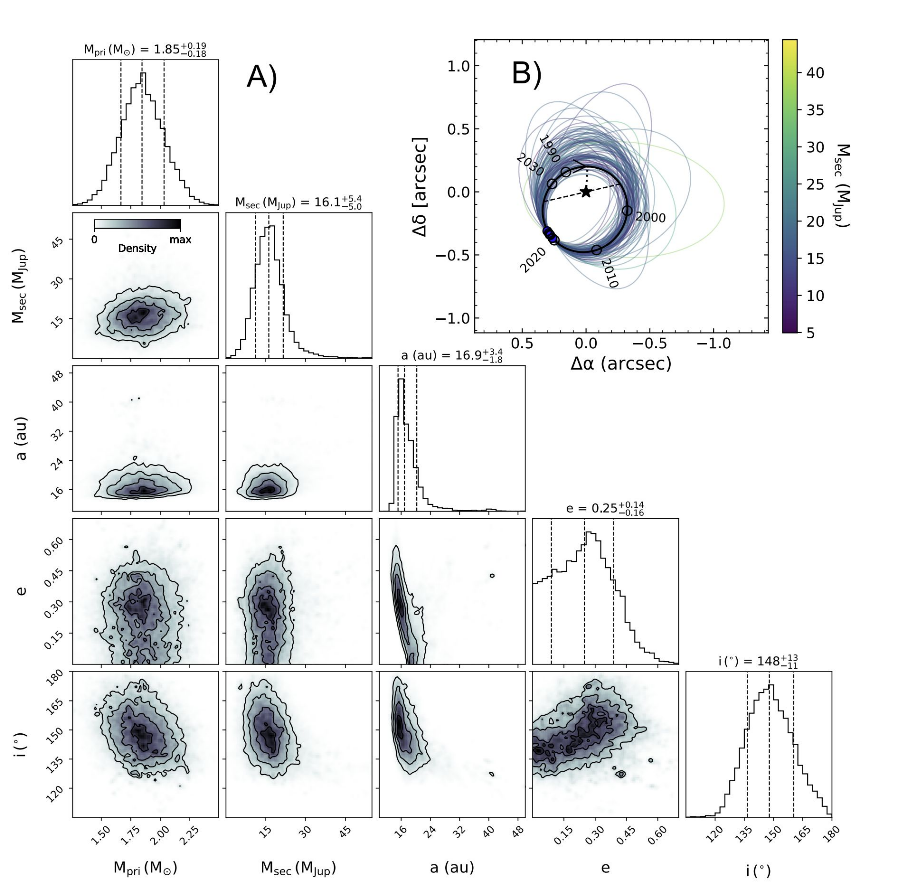
Astrometry missions (Hipparcos & Gaia) and RV measure gravitational pull of planet(s) on central star.

CHARIS spectro-imaging confirms and characterizes planet(s).

See Thayne Currie's talk and Kuzuhara-San's talk tomorrow about science results with CHARIS.





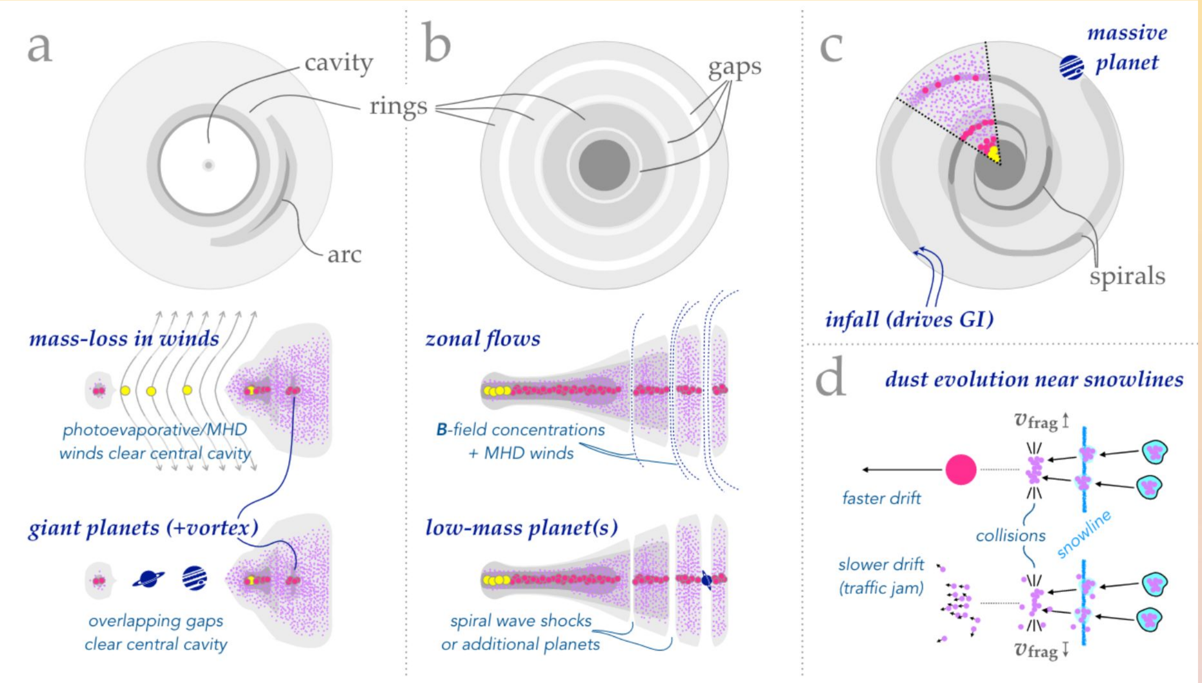


T. Currie et al., Science 2023

VAMPIRES: Planet Signatures

Angular resolution is critical to mapping disk features (rings, spiral arms, gaps, clumps).

- ALMA maps large grains & gas kinematics
- VAMPIRES/PDI maps small grains with improved angular resolution
- VAMPIRES/Halpha finds accreting planets within disks
- CHARIS finds thermal emission sources (planets)

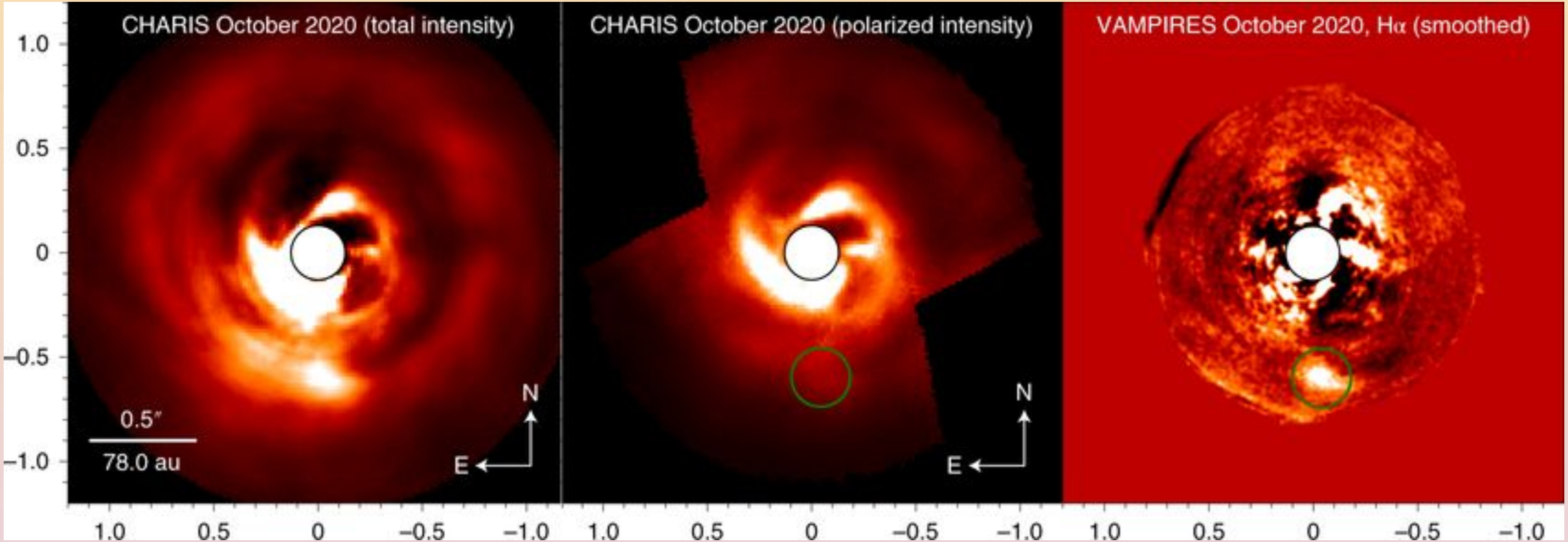


Andrews+ 2020

VAMPIRES + CHARIS

AB Aur b accreting planet detected by combination of :

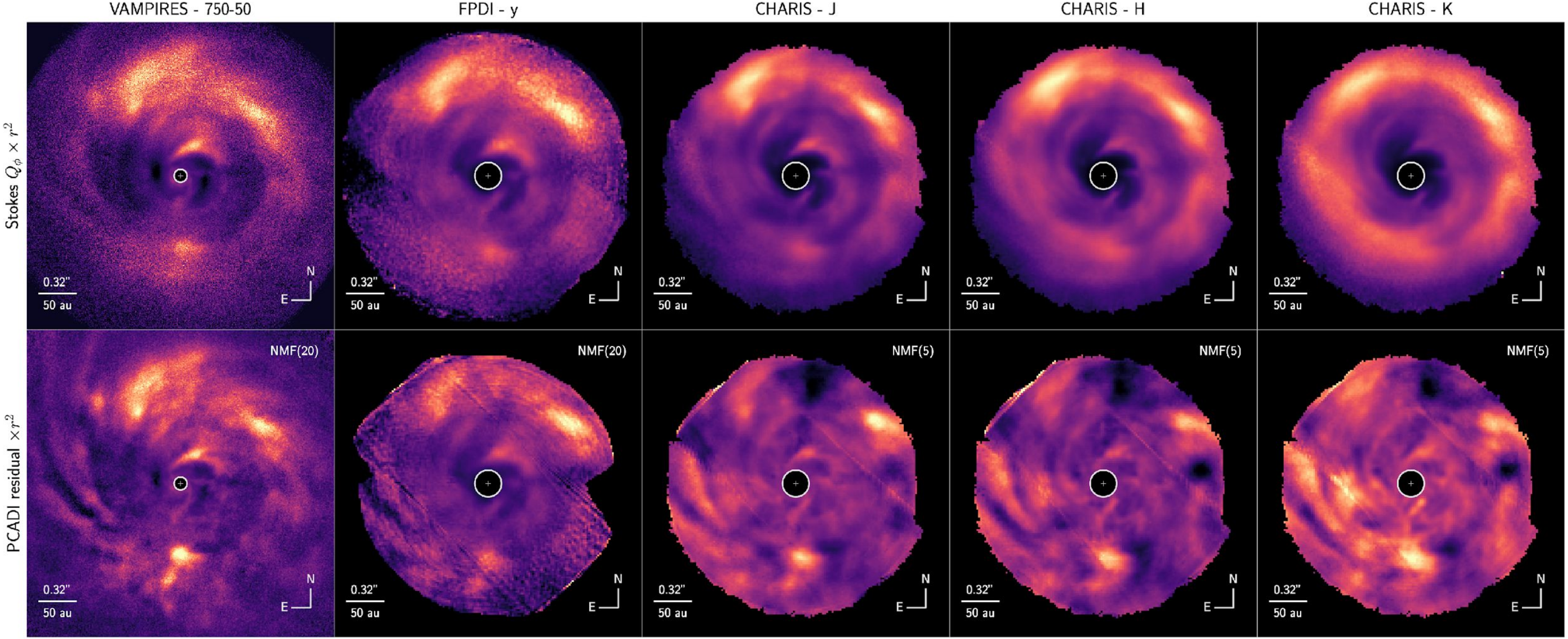
- Thermal emission (CHARIS)
- Lack of polarized emission in NIR (CHARIS), indicating that above thermal emission is unlikely to be from dust
- Strong Ha emission (VAMPIRES), indicative of ongoing accretion on planet



Currie et al., Nature Astronomy 2022

Example: AB Aur

3x Improved angular resolution

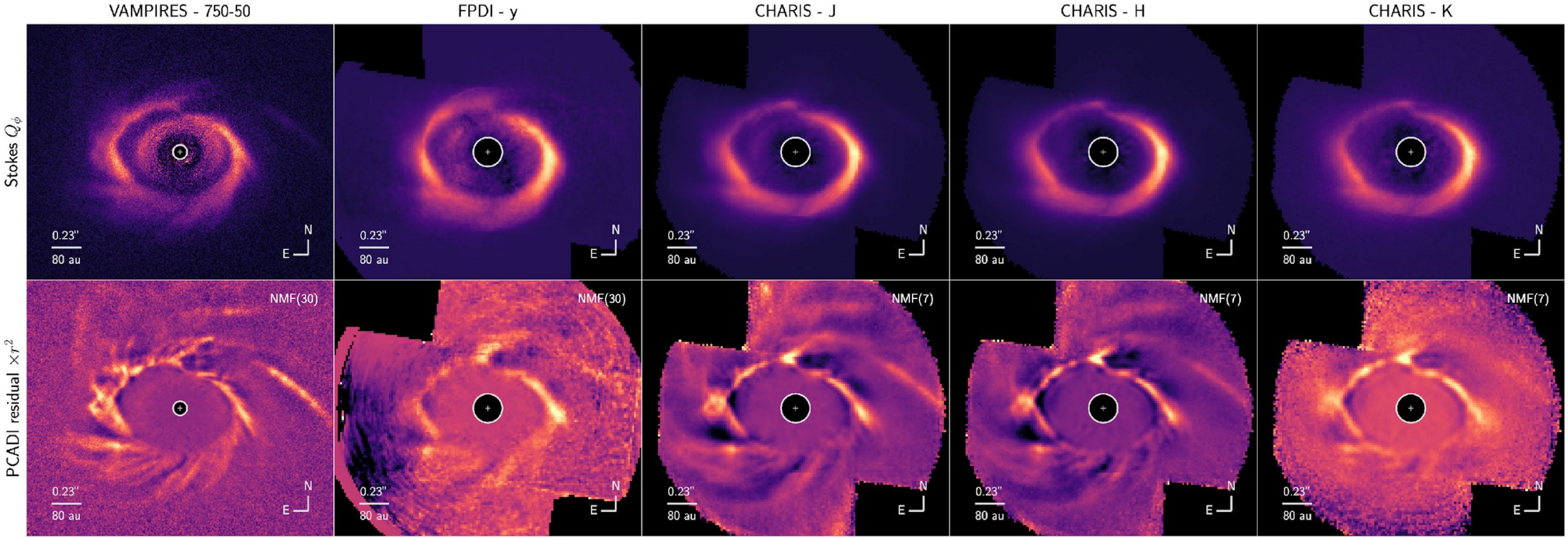


Lucas et al. 2024

All data captured *simultaneously*

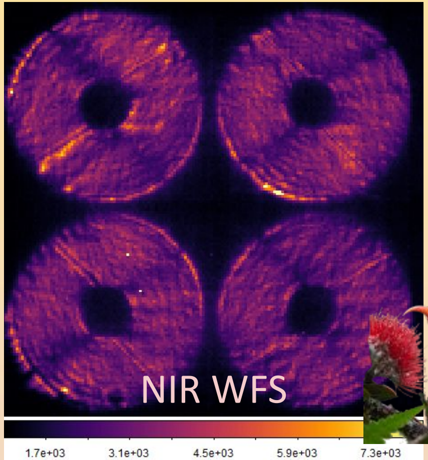
Example: HD 34700

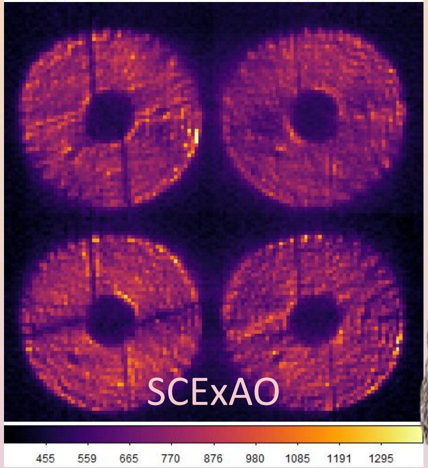
3x Improved angular resolution



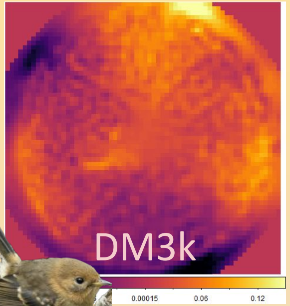
Lucas et al. 2024

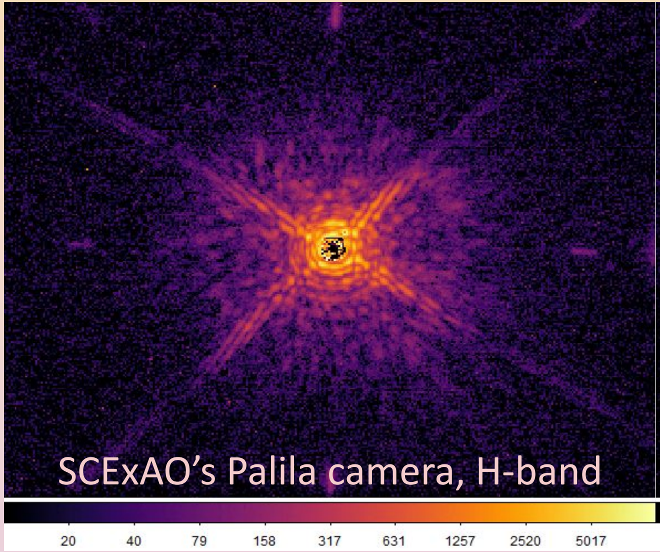
AO3k+SCExAO First XAO^2 on sky



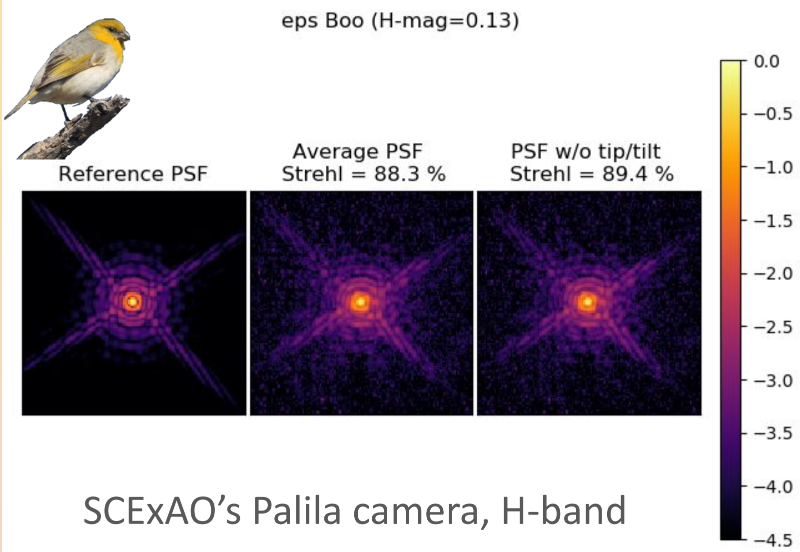


- First light was in May 2024. We closed the loop for the first time with both PyWFS on **Hōkūleʻa (Arcturus, α Boo)** and **Piraʻetea / Hawaiki (Deneb).**
- AO3k's NIR WFS was running at 1 kHz, correcting ~2000 modes
- SCExAO's PyWFS was running at 2 kHz, correcting ~1200 modes
- Some petaling was observed (mostly due to SCExAO),not easily seen by both WFSs, since the NIR WFS wavelength is about 2x the SCExAO PyWFS wavelength.
- **This is the highest number of actuators ever put on a telescope. We are now pushing the limit on what a 8m-class telescope can do.**

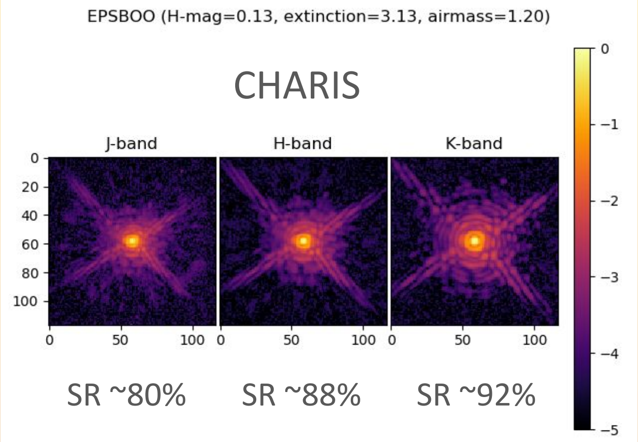


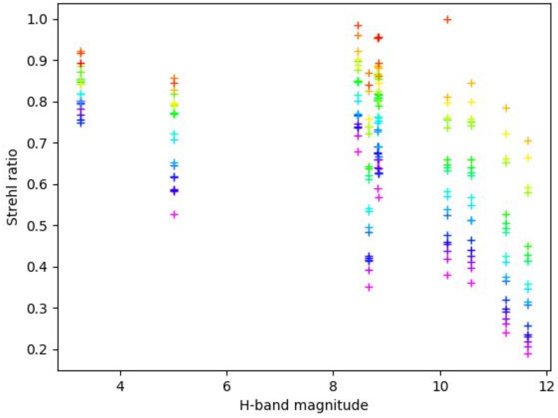


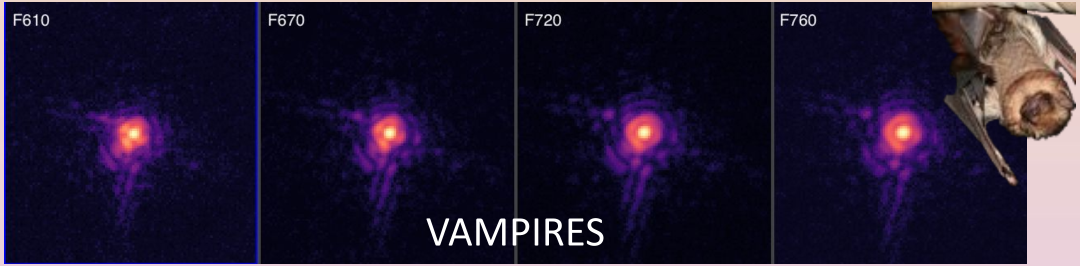
AO3k+SCExAO Powerful correction at all wavelengths



- At first light, we obtained high Strehl, highly stable images.
- The seeing was good/excellent (down to 0.25" at some point!)
- tip/tilt jitter measured @ 1.5 kHz: 2-4 mas!
- Strehl limited by quasi-static low-order modes.
- Diffraction rings are visible even in VAMPIRES.
- CHARIS shows high Strehl down to the magnitude limit of the NIRWFS.







SCExAO: a popular PI instrument at Subaru

	N. of proposed nights (submitted)					N. proposals submitted				
	Total nights	Open Use	TE (Gemini)	TE (Keck)	UH	**Total number**	Open Use	TE (Gemini)	TE (Keck)	UH
S19B	**17.0**	16.0		1.0		**7**	6		1	
S20A	**14.5**	12.0		2.5		**11**	9		2	
S20B	**15.5**	12.0	3.5			**10**	8	2		
S21A	**21.0**	20.0		1.0		**12**	10		2	
S21B	**35.0**	28.0	3.5	3.5		**26**	17	6	3	
S22A	**30.0**	20.0	3.0	1.0	6.0	**24**	17	3	1	3
S22B	**25.0**	11.0	4.5	2.5	7.0	**21**	10	5	3	3
S23A	**20.0**	8.5	1.0	2.0	8.5	**18**	9	1	3	5
S23B	**26.5**	10.5	5.0	1.5	9.5	**18**	8	3	2	5
S24A	**58.0**	45.5		1.0	11.5	**12**	6		1	5
S24B	**20.5**	10.5	3.0	0.5	6.5	**14**	8	2	1	3

Last 3 years (S22A-S24B)

Open use:
57 nights allocated, 106 proposed. **The open use oversubscription is 1.86x.**

Allocated time is **47% open use, 41% UH, 6% TE/Gemini and 6% TE/Keck.**

- # submitted open use proposals peaked in S21B & S22A, but demand is still strong.
- Intensive proposal accepted in S24A.
- Strong demand from UH.
- Allocated VAMPIRES time: 11.5 night over last yr (S24A and S24B), vs. 36 nights for CHARIS

Transition to facility instrument

Transitioning a PI instrument to a facility instrument has never been done before at the Subaru Telescope. **There is no blueprint for such a process**.

SCExAO and its modules (CHARIS, VAMPIRES mainly) have been observing for several years now, more than typical PI instruments, and the demand is still strong thanks to powerful upgrades and the growing field of exoplanets.

To become a facility instrument, some obvious requirements would be:

- A good integration with the telescope software architecture (Gen2, SMOKA, STS, etc.)
- A stable optical path and a reliable instrument
- A user-friendly data processing pipeline, to avoid relying on only a few observers

In the case of AO3k, the SCExAO team worked with the AO188 team to upgrade the facility instrument by adding PI modules like the NIRWFS. The AO3k software architecture is also designed to be integrated in the SCExAO loop control, so we have two XAO systems working together instead of independently.

Challenges & steps

This transition can happen, but it faces a few challenges:

- The SCExAO team lost a few key members recently, and is now stretched thin.

  -> Transition will require additional staffing to first bring SCExAO to facility instrument standards, and then to support instrument operation and assist observers

- SCExAO remains a powerful experimental platform, especially for testing new technologies for TMT and HWO. This was possible thanks to our PI status.

  -> Need clear definition of SCExAO modes/subsystems that become facility, vs. more experimental PI-type modes/subsystems. Phased transition could be considered (CHARIS first ?).

There is now a process underway to explore what a transition to facility would be. A review of the SCExAO project was performed in November to inform Subaru management about the status of each module.

Mahalo nui loa!

ʻAʻohe puʻu kiʻekiʻe ke hoʻāʻo e piʻi.

No cliff is so tall that it cannot be scaled.

- No problem is too great when one tries hard to solve it.

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