Prototyping TMT exoplanet imaging instrumentation at Subaru Telescope

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

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National Institutes of Natural Sciences Astrobiology Center

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Teams:
SCExAO, AO188, ULTIMATE(-START)
CHARIS, VAMPIRES, MEC, GLINT, FIRST, RHEA, REACH
TMT-PSI (Japan, US, Canada)

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INTRODUCTION

The Thirty Meter Telescope (TMT) will have the angular resolution and collecting area to directly image and characterize rocky terrestrial size exoplanets in the habiable zone of nearby stars. Spectroscopy of the planet atmospheres may reveal biomarkers indicative of life. The main challenges to achieve these observations is to finely control and calibrate residual starlight in the high contrast imaging system. NAOJ and ABC, in collaboration with partners, are actively prototyping the TMT Planetary Systems Imager instrument at the Subaru Telescope. We describe the development program, which focuses on on-sky deployment and validation of core techniques, and will also provide unique scientific opportunities on the Subaru Telescope for observations of exoplanets, disks and stellar physics.

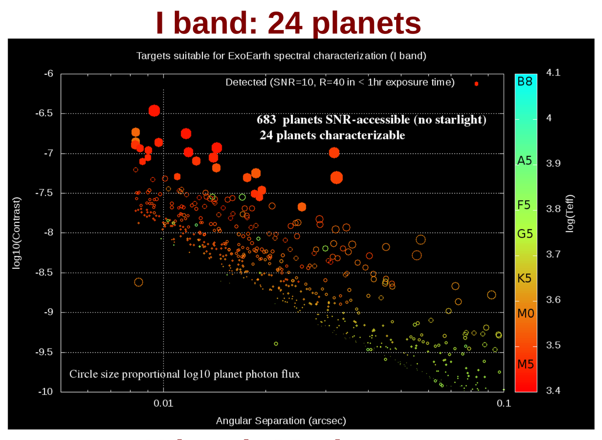
SCIENCE GOAL

Derived from photon-noise SNR analysis

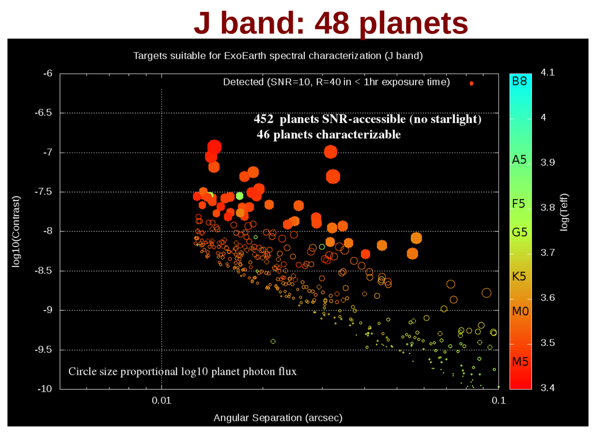
ASSUMPTIONS
- SNR is limited by photon noise from both starlight and planet light
- Raw contrast limited by residual WF errors (not by coronagraph defects)
- ExAO system delivers 1e-6 raw contrast at 1um
- Every star has one Earth analog

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

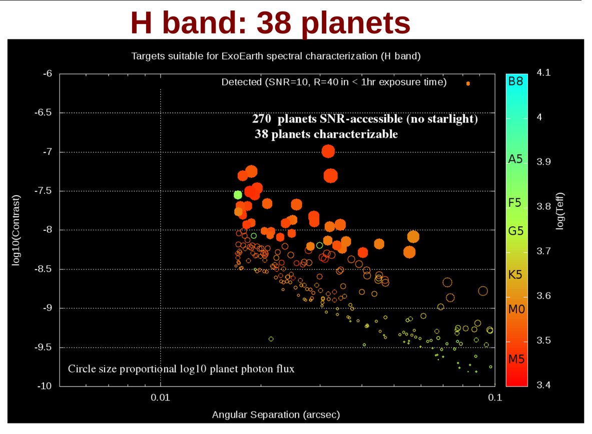
I band: 24 planets



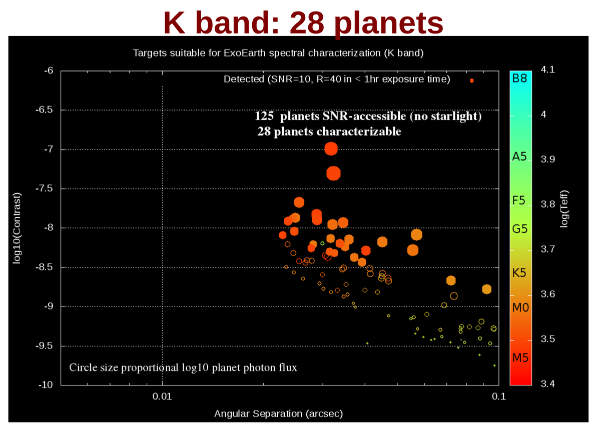
J band: 48 planets



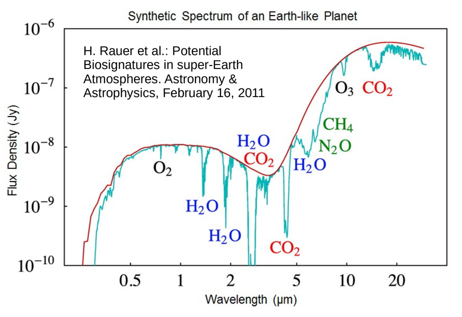
H band: 38 planets



K band: 28 planets

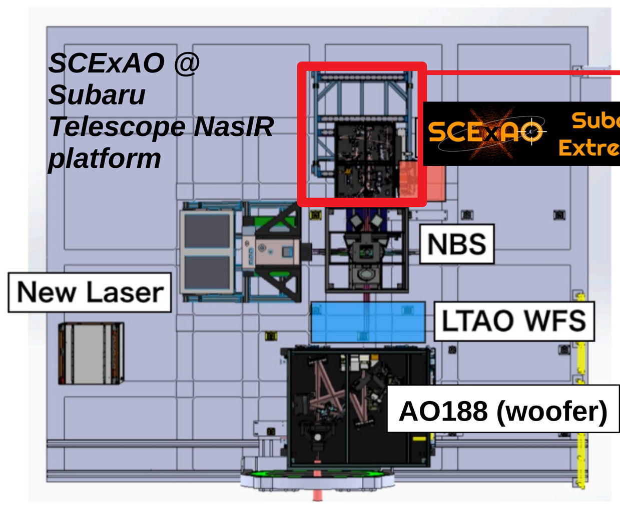


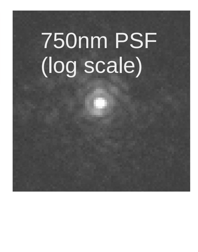
KEY FINDINGS
- Best targets are M-type stars (M0-M6)
- Optimal wavelength is near-IR (especially J & H bands), suitable for detection of O2 (1.27um), H2O, CH4, CO2

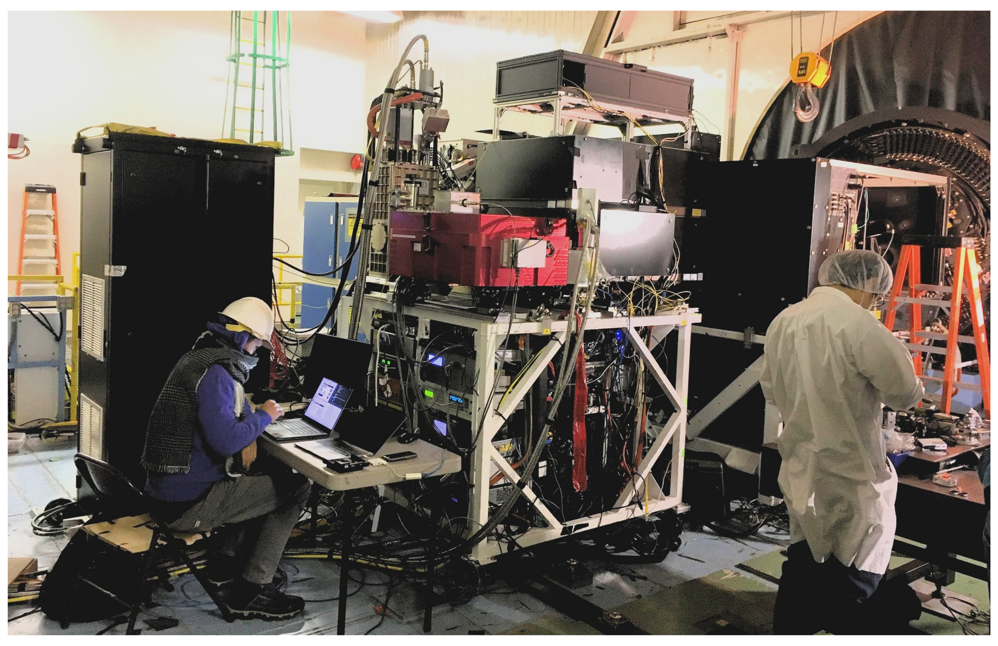


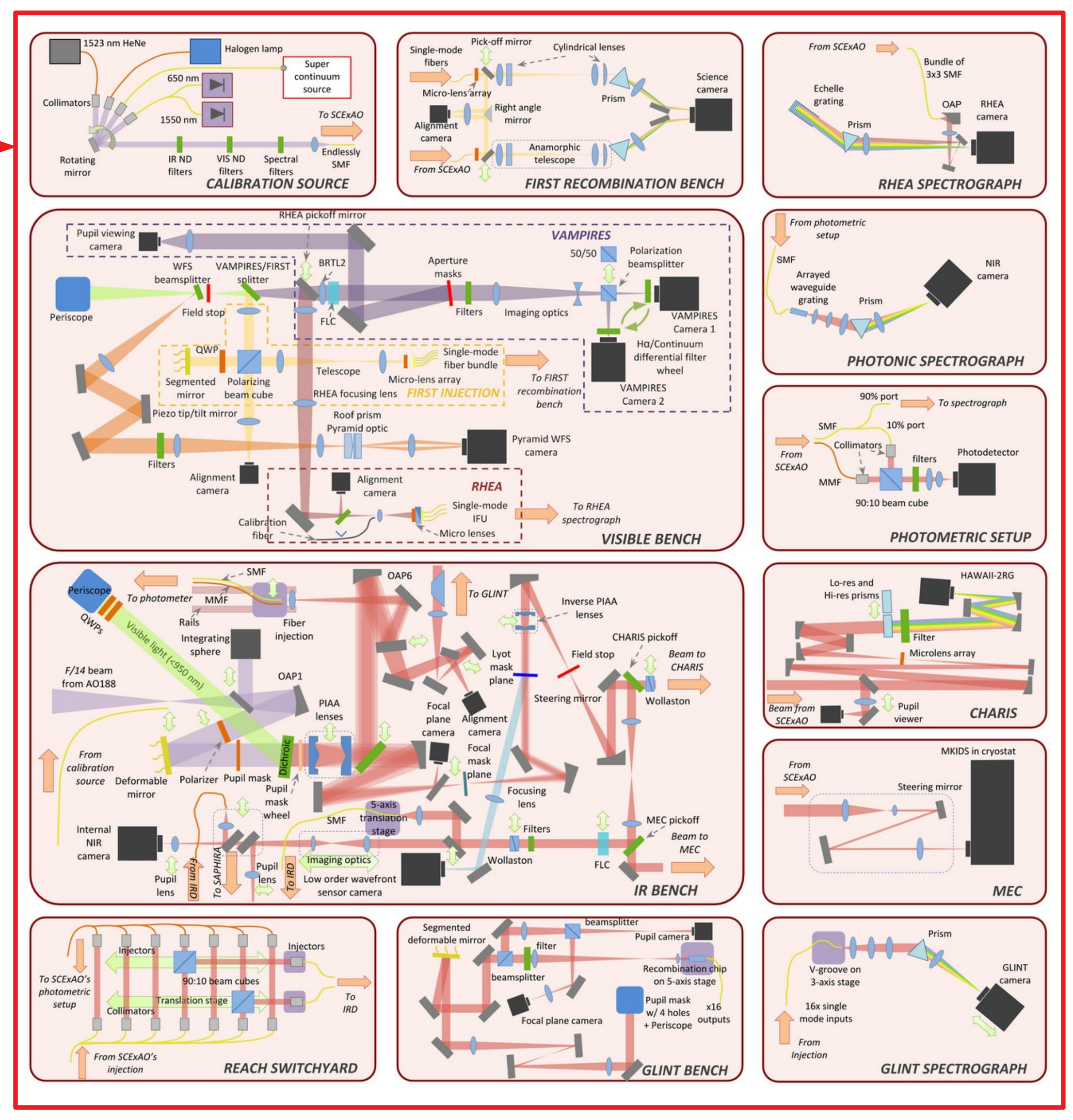
SCEXAO HARDWARE CAPABILITIES

Two-stage WF correction: Curvature → MEMS
(2021 : Woofer replaced by 64x64 ALPAO DM)
Coronagraphs: Vortex, vAPP, PIAACMC, Lyot, Shaped pupil, 8-octans
Instruments: Imaging, spectro-imaging, spectroscopy, PDI, differential spectral imaging









PRIORITY TECH AREAS

Starlight suppression / Coronagraphy
- Exploring coronagraph designs/options, gaining on-sky experience
- Integration between coronagraph and wavefront control system
- Optimizing coronagraph operation and data analysis
- Exploring interferometric nulling (GLINT) as alternative to conventional coronagraphs

Wavefront control and calibration
- High sensitivity wavefront sensing leveraging telescope diffraction limit
- Exploring self-calibrating interferometric WFS options (FIRST, GLINT)
- Sensor fusion: merging multiple WFS signals to gain complete wavefront state knowledge
- Predictive control, speckle control
- Using WFS telemetry to calibrate science data (identify speckles)

Deformable mirror: high actuator count, speed

Advanced detectors - Validating high speed photon counting detector options
Under consideration: MKIDS, EMCCD, sCMOS, SAPHIRA

3200-actuator DM to be deployed summer 2021 will validate TMT-PSI DM technology

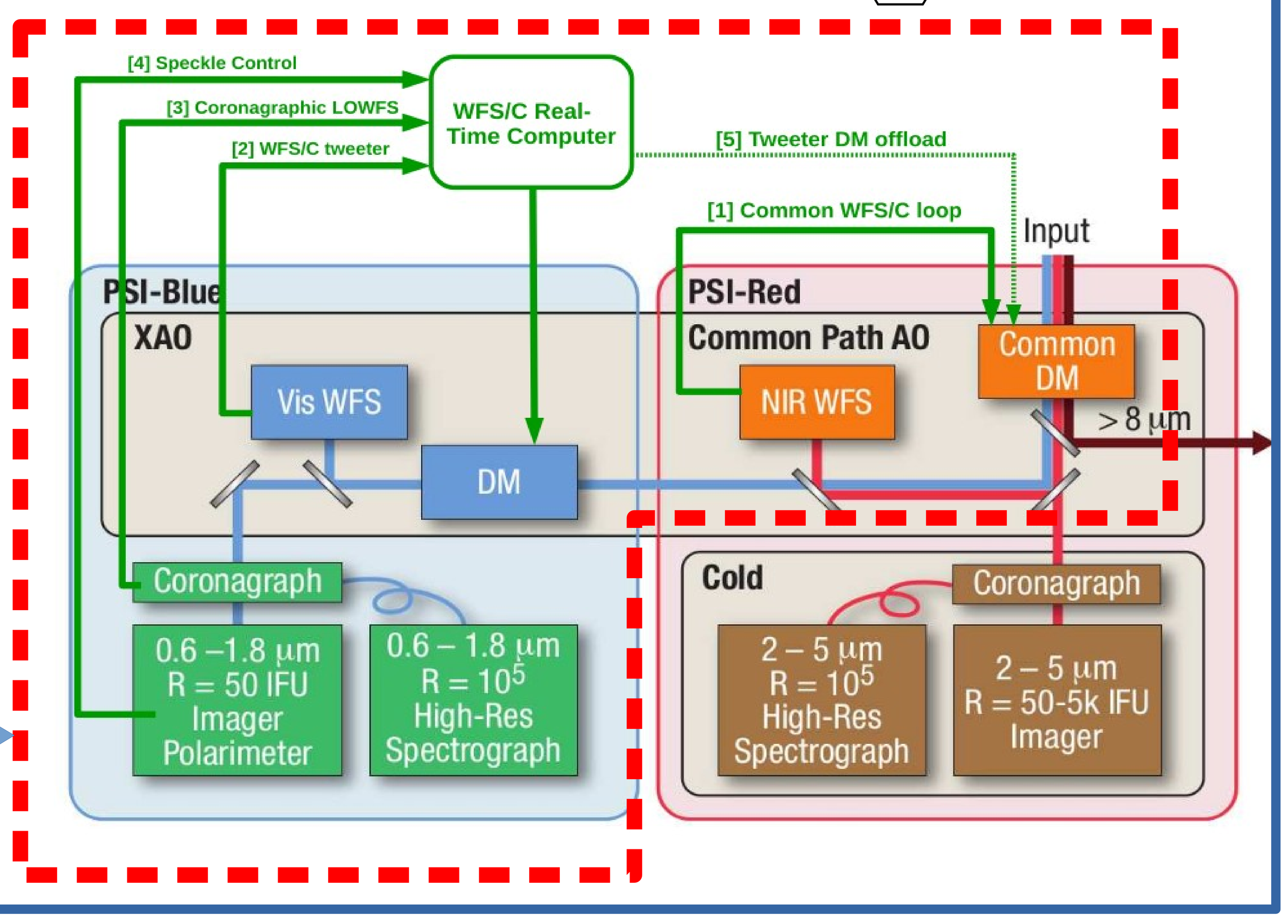
TMT-PSI DESIGN

Current TMT-PSI design and SCExAO implementations are matched, allowing for relevant prototyping of TMT-PSI architecture on Subaru Telescope, including hardware implementation and software algorithms

PROTOTYPING TMT-PSI

SCExAO + modules is prototyping Common-path AO + PSI-BLUE

Includes:
- Common DM (64x64 ½ scale of TMT-PSI common DM)
- NIR WFS (Pyramid)
- MEMS DM
- Vis WFS (Pyramid)
- Coronagraphs
- IFU + PDI in visible and NIR
- High-resolution fiber-fed spectroscopy (REACH)



PROTOTYPING ON SCExAO – USER'S GUIDE

DEPLOYING HARDWARE

Coronagraph masks can be inserted in existing focal plane and pupil plane wheels
Example collaborations: vAPP (Univ. Leiden), 8-octans (Univ. Hokkaido), PIAACMC (Univ. Arizona)

Cameras & instruments can be deployed on visitor port @ nearIR
Examples: UH Saphira, Kernel CRED-1

Fiber-fed instrumentation can take advantage of existing pre-coronagraph and post-coronagraph fiber injection stages.
Examples: REACH coupling to IRD (high spectral resolution), RHEA visible IFU, IRANTI nearIR IFU

USING SCExAO REMOTELY AS TESTBED

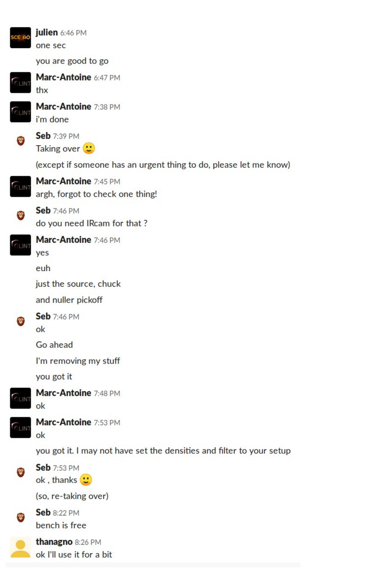
Artificial light source deployed in beam for off-sky testing
Super-K broadband laser source (0.4-2 um), multiple VIS and nearIR filters/attenuators to tune flux

Users can remotely access and control instrument
Moving stages, filters wheels, changing coronagraph, splitters.
Writing on DM(s) and reading camera streams through common cacao-based shared memory interface (Python & C supported).

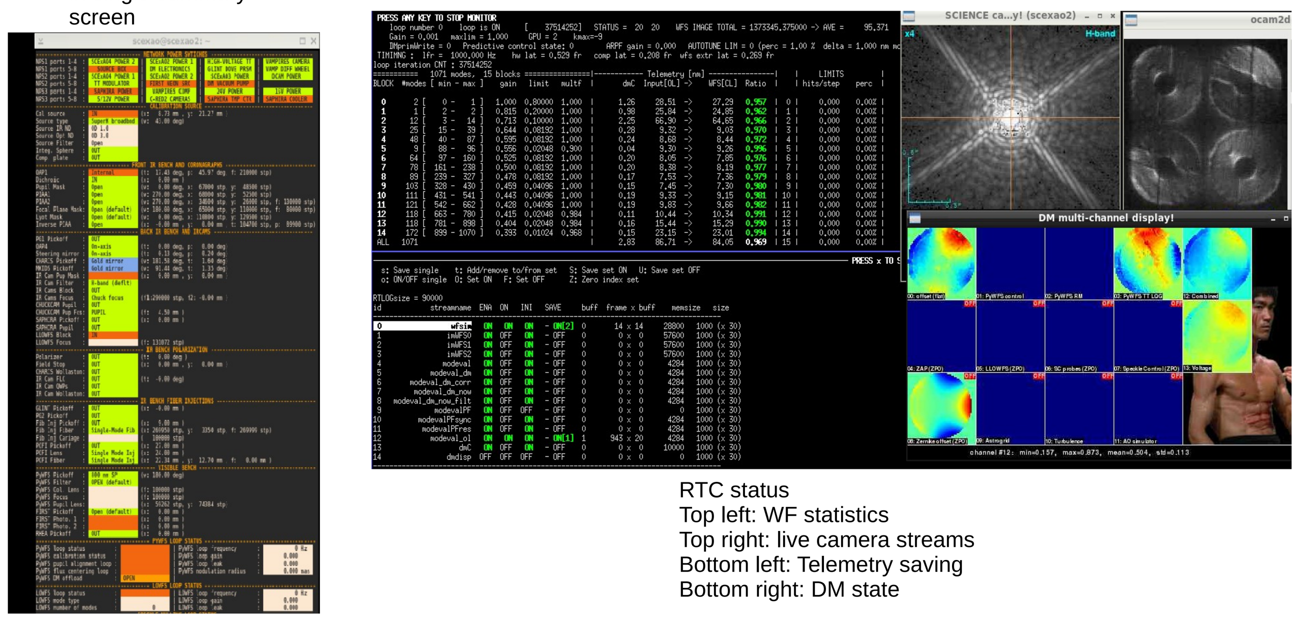
Telemetry saved on disk (~4 TB/hr when saving all streams)

USER INTERFACE

Remote users coordinate access using dedicated slack "bench" channel



Status of stages and filter wheels provided in single summary screen

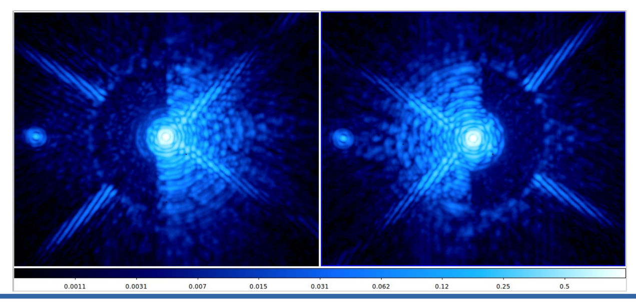


RTC status
Top left: WFS statistics
Top right: live camera streams
Bottom left: Telemetry saving
Bottom right: DM state

EXAMPLE RESULTS

FOCAL PLANE WFS/C (speckle control)

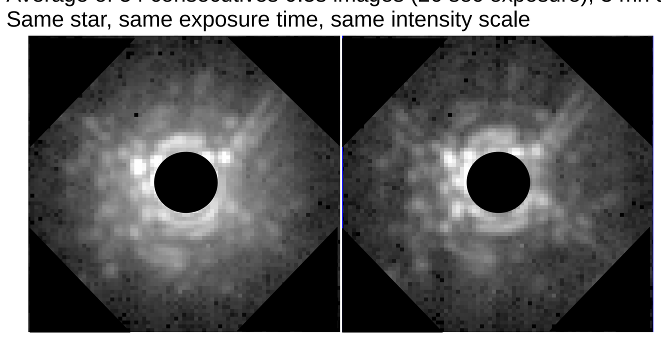
Off-sky and on-sky
Can use EMCCD, fast InGaAs, MKIDs or SAPHIRA detectors



Speckle nulling (Martinache et al.)

PREDICTIVE CONTROL

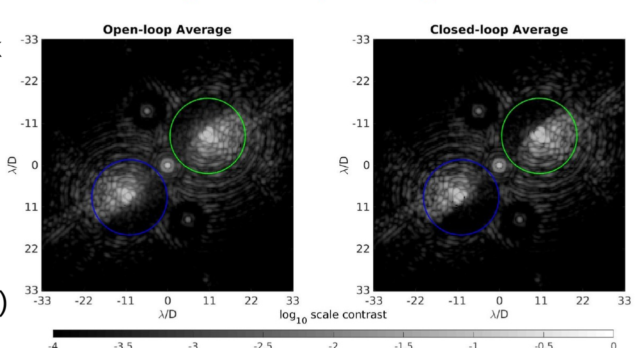
Average of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale



OFF (integrator, gain=0.2) ON

LINEAR DARK FIELD CONTROL (LDFC)

Uses bright speckles t ocontrol dark fied in inear control loop



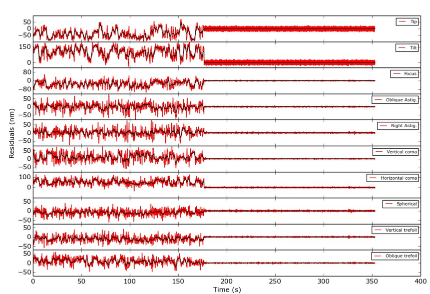
LDFC demo with VAPP coronagraph (Bos & Miller)

SENSOR FUSION

Multiple sensors combined for increase WFS sensitivity and reliability

Coronagraphic Low-Order WFS operates in nearIR simultaneously with visible WFS to address low-order aberrations

(Singh et al. 2015+)



PSF RECONSTRUCTION

Deep neural net used to reconstruct PSF from WFS telemetry

NN-based PSF reconstruction from PyWFS telemetry (Norris & Wong 2019)

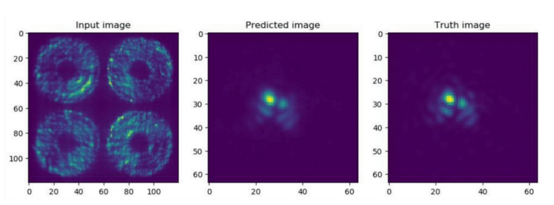
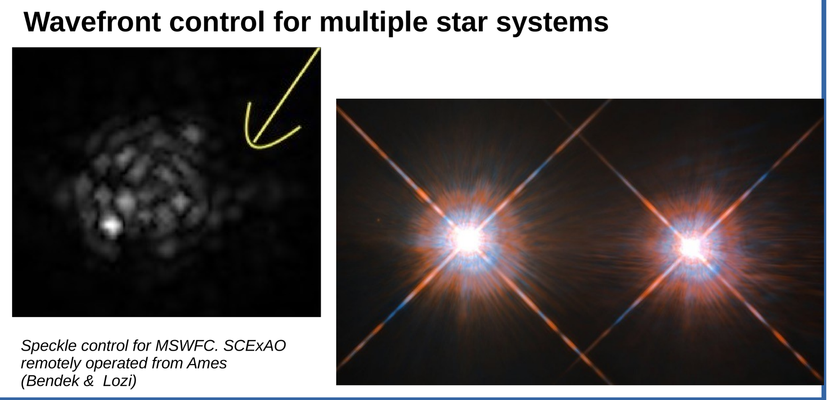


Figure 4: On-sky demonstration of PSF estimation from SCExAO WFS telemetry using a neural network. The training set for this supervised learning problem is constructed by aligning pyramid WFS and visible light PSF frames on the same time reference (hardware lag compensation). While training is slow, inference can be performed in real-time on modern GPUs equipped with tensor cores. We note that visible PSF reconstruction is highly non-linear and particularly sensitive to small wavefront errors. For this simple problem (single input, single output supervised learning), a well-interpolated look-up table built from a clustering algorithm may achieve similar PSF reconstruction quality, but would be considerably more demanding in computing power and memory usage: the main advantage of a neural network approach may here be fast inference speed. Courtesy of Barnaby Norris, Univ. of Sydney.

MULTI-STAR WFS/C

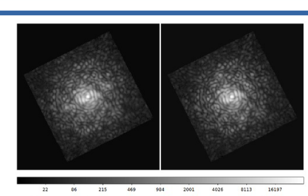
Wavefront control for multiple star systems



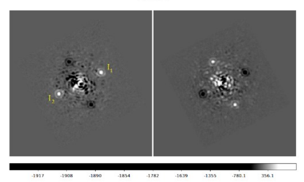
Speckle control for MSWFC. SCExAO remotely operated from Ames (Bendek & Lozi)

PHOTOMETRIC & ASTROMETRIC CALIBRATION

Fast-modulated incoherent speckles are added to focal plane by DM commands for precise photometric and astrometric calibration



(a) Images of two consecutive reduced data slices of β Leo before subtraction obtained from CHARIS at 1744 nm with two alternate fainter speckle patterns where they are barely visible.



(b) Images of two consecutive reduced data slices of β Leo after subtraction obtained from CHARIS at 1744 nm. After subtracting two consecutive frames, the calibration speckles can be clearly seen.

On-sky validation of alternating speckle grid calibration technique (Sahoo et al. 2020)

REINFORCEMENT LEARNING

AO systems continuously learns from focal plane PSF feedback

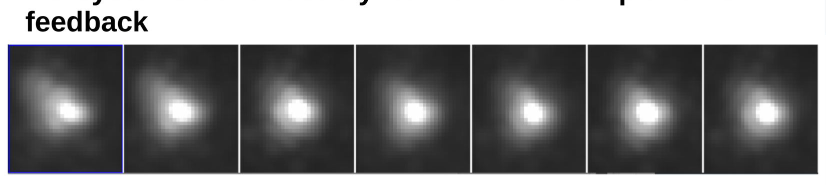


Figure 5: On-sky demonstration of re-inforcement learning for PSF sharpening, using reference updating sensor fusion. The SCExAO pyramid WFS reference on the internal source does not match the on-sky reference due to differences in pupil illumination and variations of chromatic non-common path errors, 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.

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