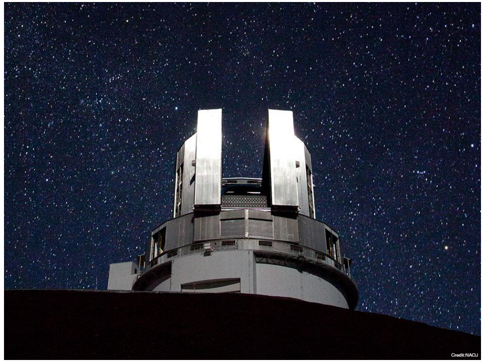


Habitable Words Observatory

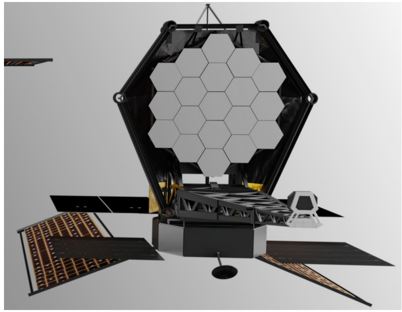
Exploring contributions from Subaru Telescope

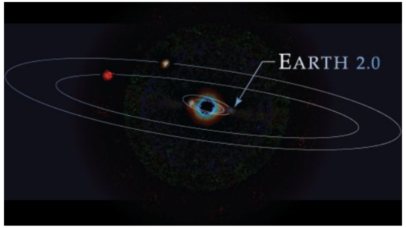
Olivier Guyon *(guyon@naoj.org)*

Subaru Telescope, ABC & University of Arizona

Subaru Users Meeting, Oct 2025

HWO mission





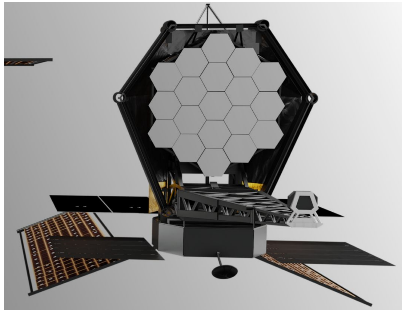
~6m NUV/Opt/NIR observatory NASA-led, launch by ~2045

Core science goal (prioritized in Astro2020): Image **habitable exoplanets** + direct spectroscopy to study their atmospheres -> search for **biomarkers**

Realized by **coronagraph instrument** that includes wavefront control (adaptive optics) + starlight suppression.

Technology development efforts needed over the next ~decade to realize this challenging instrument.

Japan’s role in HWO mission



NASA is welcoming international partners to HWO.

Japan considering contributing to:

- NIR coronagraph
- UV spectrograph

JAXA/ISAS established the HWO-J task force (chair: K. Enya) to explore these.

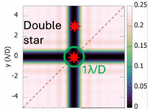
This presentation relates to the <u>NIR coronagraph</u>, and how Subaru Telescope could participate.

Why NIR coronagraph as a Japanese contribution?

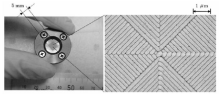
Strong Technical Expertise

Components

Industry expertise
Optics/photonics, photonic circuits, detectors



DL coronagraph (Matsuo, Ito et al.)



Potonic-crystal, broadband masks, WFC (Murakami, Nishikawa, Yoneta et al.)

Systems

Mask for CGI

Testbed at NAOJ/ATC

EXIT testbed at Hokkaido

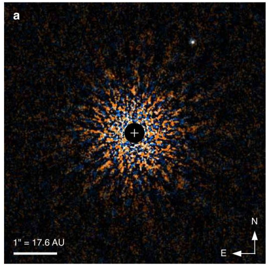
3.8-meter Seimei SEICA

Subaru SCExAO, IRD/REACH

NIR-focused

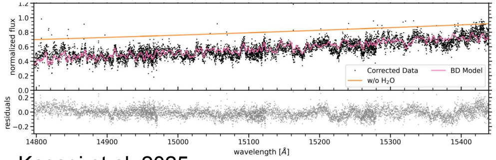
Strong NIR Science Expertise

NIR exoplanet imaging (HiCIAO, SCExAO)



Kuzuhara et al. 2013

NIR exoplanet spectroscopy, atmosphere characterization (CHARIS, IRD/REACH)



Kasagi et al. 2025

IRD & SCExAO supported by ABC

High Science Value

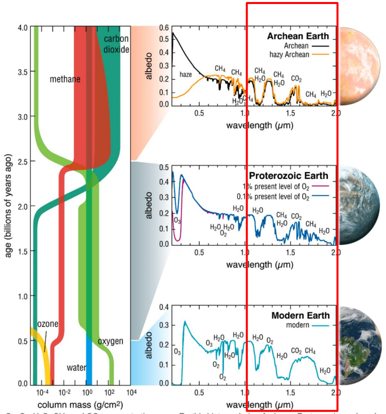


Figure 3.1-6. O_2, O_3, H_2O, CH_4 and CO_2 concentrations over Earth's history, during Archean, Proterozoic, and modern Earth eras. HabEx is required to be able to detect the gaseous byproducts from oxygen-producing synthesizers (all EECs) or methane-producing synthesizers (some EECs), if present at concentration levels similar to Earth over the last 3.5 Gy of its history. This covers part of the Archean Era as well as the full Proterozoic and Modern Eras during which life has been present on Earth. Credit: Britt Griswold, Giada Arney, and Shawn Domagal-Goldman.

NIR is the spectral range richest in information, including biomarkers

Key Subaru Contributions to HWO's NIR Coronagraph

Testbed

- Flexible testbed for imaging and spectroscopy
- In-lab and on-sky modes
- Can test components, systems, and algorithms
- Complementary with deep contrast vacuum testing

Training young researchers

- Grow HWO-J community for long-term effort (launch ~2045)
- Develop joint technical+science expertise

Developing "photonic" spectroscopy

Photonic Nulling Spectrograph (PNS)
- Validate PNS in lab
- On-sky PNS-based exoplanet spectroscopy -> demonstrate spectral extraction, data analysis

(Precursor) observations

HWO targets:
- Ultra-Doppler -> Targets, masses
- SCExAO -> Companions, dust, spin axis

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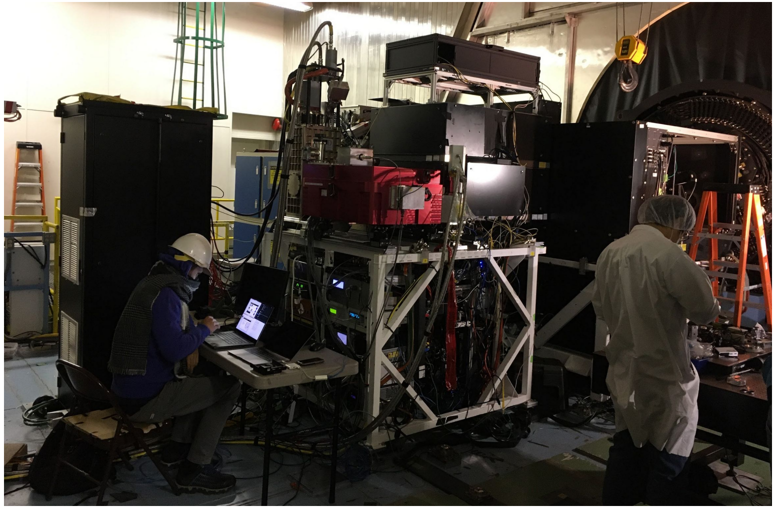
Exoplanet Instrumentation @ Subaru

Subaru hosts world-leading NIR exoplanet instrumentation in **high contrast imaging** (SCExAO) & **high resolution spectroscopy** (IRD)



SCExAO is both a **science instrument and a technology development platform** (unique in the world).

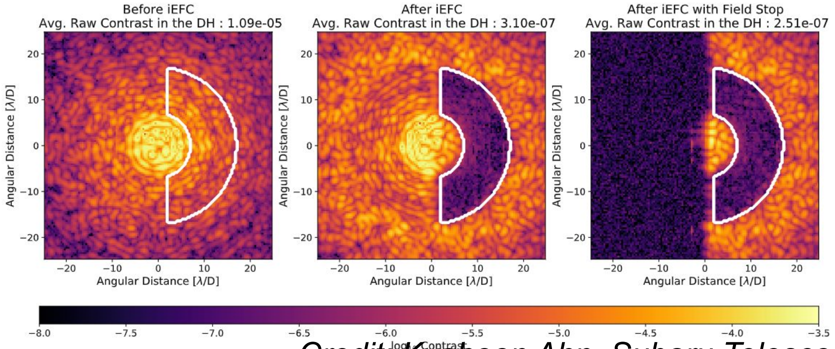
R&D is carried out through international collaborations with research groups outside Subaru Telescope (Japan, US, Europe, Australia, Canada).

Training ~4 PhD students per yr in high contrast imaging technology & science.

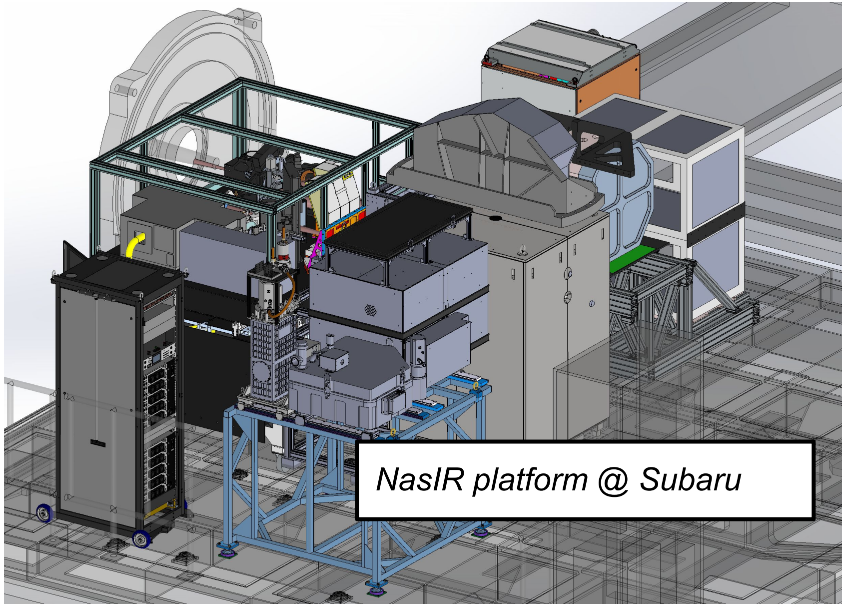
SCExAO's **major areas of ongoing technology development** are also those **needed to realize HWO's ambitious goals, especially in NIR**: starlight suppression, WFS/C algorithms, PSF reconstruction, detectors, DMs, photonics.

SCExAO as a testbed

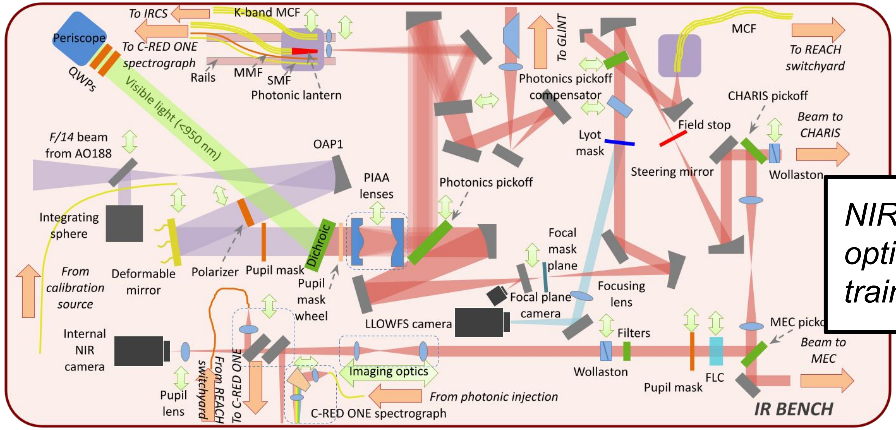
Currently reaches ~1e-7 contrast with ~1e-8 stability



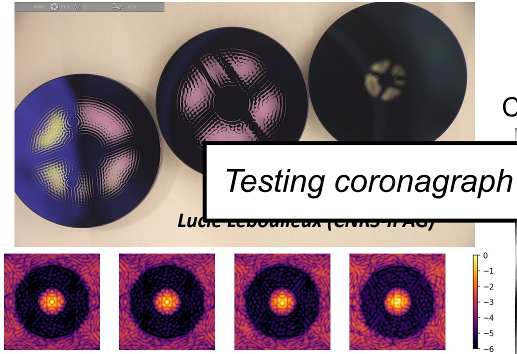
Credit: *Kyohoon Ahn, Subaru Telescope*



NasIR platform @ Subaru

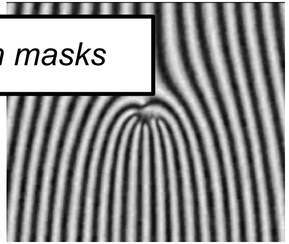


NIR optical train



Testing coronagraph masks

Colorlink Japan Prototype



Key Subaru Contributions to HWO's NIR Coronagraph

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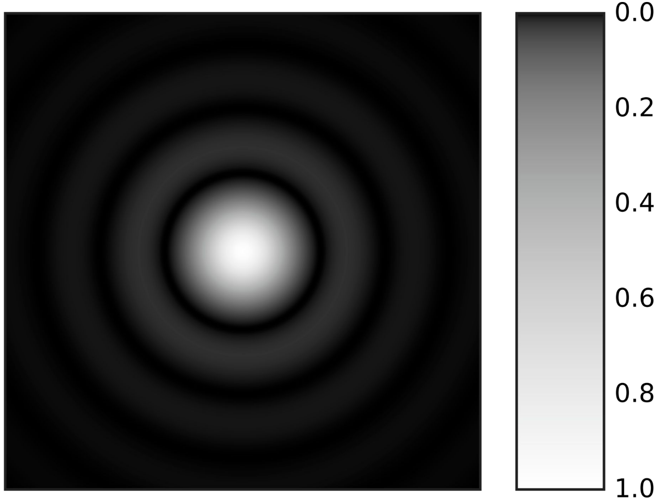
Incoherent Spectroscopy

“Classical” Incoherent spectroscopy

Sum (in intensity) light over an aperture, then disperse it

Examples: IfUs (CHARIS), MMF (PFS), slit spectrographs

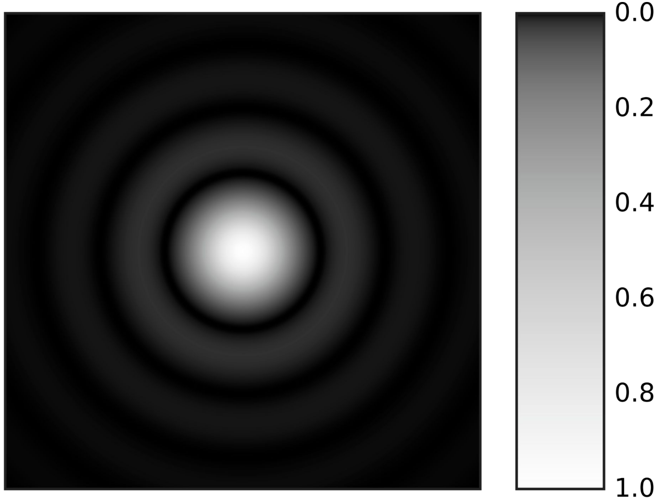


Incoherent vs. Coherent Spectroscopy

"Classical" Incoherent spectroscopy

Sum (in intensity) light over an aperture, then disperse it

Examples: IfUs (CHARIS), MMF (PFS), slit spectrographs



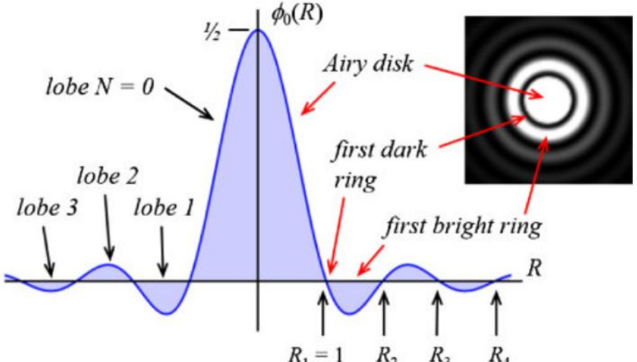
Coherent spectroscopy

Sum (**in complex amplitude**) light **of the source electric field**, then disperse it **(SMF)**

Examples: AO+SMF (REACH)

Very wasteful:

- Collects lots of background
- Requires many pixels (IfU)
- Does not adapt to distorted PSF (from coronagraph)



= Modal decomposition of electric field (EF)

Optical projection of light on planet EF -> minimum background, and ~100% of the planet light

Background-limited sensitivity (ideal case, Airy)

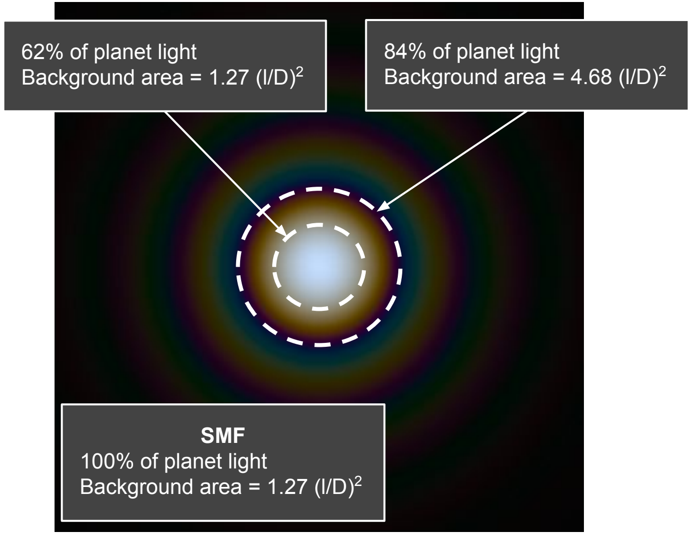
In background-limited regime, we must maximize exoplanet flux Fp while minimizing background flux Fb

SNR ~ sqrt(T) Fp/sqrt(Fb)

-> exposure time T required scales as Fb/Fp^2

Single-mode fiber can couple **all planet light** into fiber (with beam shaping) while collecting the **minimum background contribution** from (4/PI) (lambda/D)^2 sky area.
Conventional spectrograph is defined by entrance aperture radius, within which planet light is collected according to encircled energy and background light is collected according to aperture area.

	Fb area [(l/D)^2]	Fp	Relative efficiency Fp^2/Fb
Single mode fiber	4/PI=**1.27**	1.0	1.0
Aperture r=0.5 l/D	0.79	0.47	0.36
Aperture r=0.635 l/D	1.27	0.625	0.39
Aperture r=1.22 l/D	4.68	0.84	0.19



Single mode fiber (photonic spectrograph) is 2.5x more efficient that an optimally sized aperture feeding a non-photonic spectrograph.

HWO NIR Coronagraphic Spectroscopy

Detections
HWO will detect planets in visible light in ~10hr at R~5, SNR~20

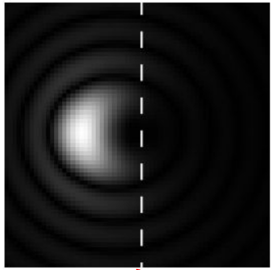
Spectroscopy required week(s) of exposure
VIS spectroscopy requires R~100 -> ~200hr etime (~8 day) .. per band

NIR presents additional challenges
Loss of angular resolution:
-> Must use small-IWA coronagraph with some leakage of starlight (partially resolved)
-> Planet is partially attenuated by coronagraph
-> Planet PSF is distorted, so mixed with background

Coronagraph case: ~10x gain

3 day vs. 1 month

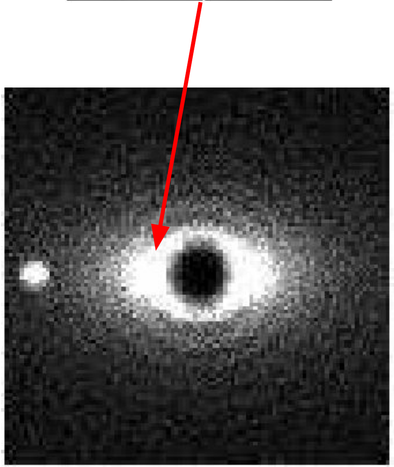
Planet light



Coronagraphic PSF is distorted by coronagraph near its inner working angle
Simulated planet PSF (noiseless, starlight and exozodi removed) for 2 l/D separation, 6th order optical vortex coronagraph

Aperture required to gather most planet light ~ 5 $(l/D)^2$

Total light

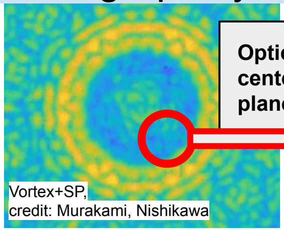


Distorted PSF of inner planet (red arrow) is located in high-background area with strong exozodi and starlight components

Simulated exposure with photon noise

Photonic Nulling Spectrograph (PNS) concept

Coronagraph system +

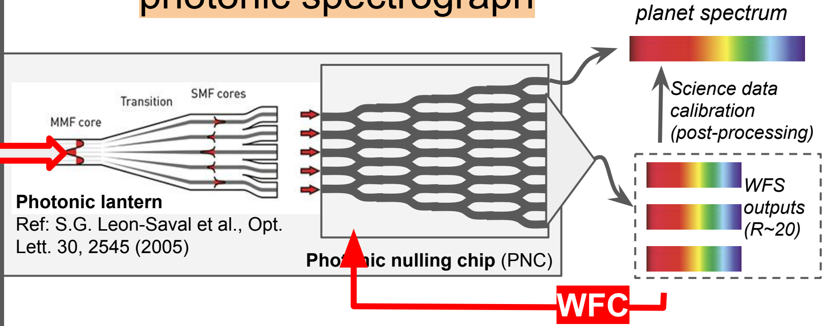


Optical fiber centered on planet location

Creates a **high-contrast image** where most of the starlight is removed.

Optimized to preserve planet light: small IWA and broadband performance
Does not need to achieve very deep contrast (~1e-7 OK)

photonic spectrograph



Optimized for high-contrast **<u>spectroscopy of planets with known position</u>**; not optimal for search of new planets.

Uses 2nd stage (after coronagraph) optical fiber and photonic technologies to optimize sensitivity.

Four fundamental advantages :

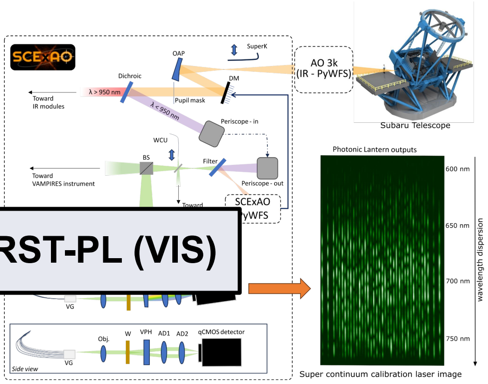
1. **Efficiency** gain: optimal separation of exoplanet light from background
2. **Optimal pixel use**: 1 per spectral element
3. **Starlight suppression** (2nd stage) with photonic <u>nulling</u> chip
4. **Self-calibrating** thanks to pure modal decomposition (can separate WF error from true signal)

Key challenges: Throughput, Chromaticity

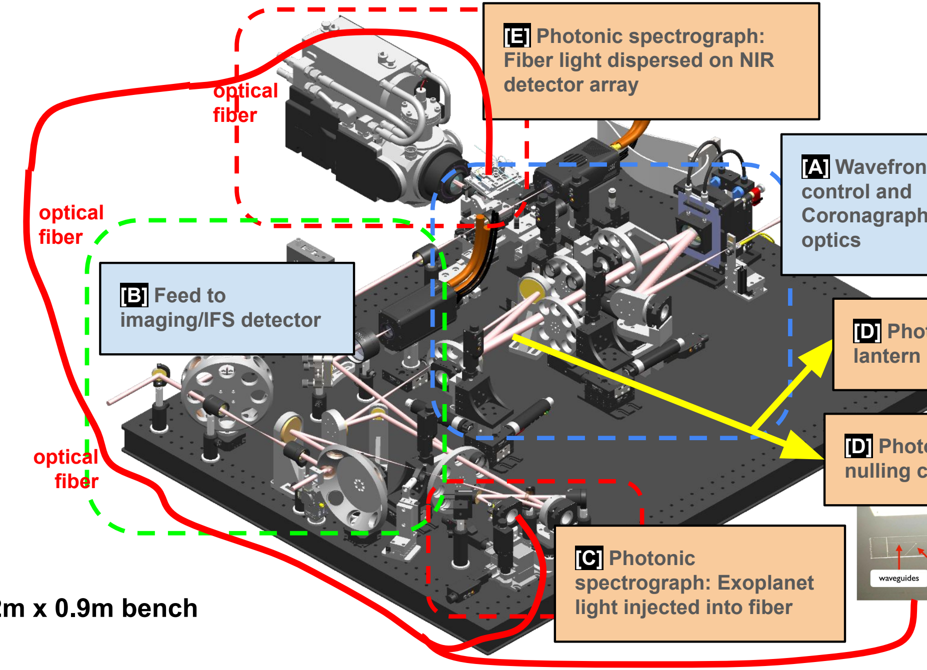
Implementation on Subaru/SCExAO instrument

J. Lozi
REACH team
GLINT team
NIR-PL team
FIRST-PL team
Exo-NINJA team

Funded by JSPS (GLINT) & external grants



FIRST-PL (VIS)



[E] Photonic spectrograph: Fiber light dispersed on NIR detector array

[A] Wavefront control and Coronagraph optics

[B] Feed to imaging/IFS detector

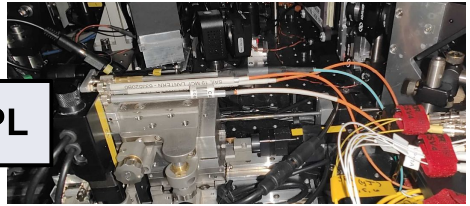
[D] Photonic lantern

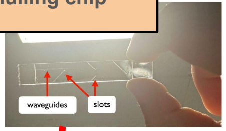
[D] Photonic nulling chip

[C] Photonic spectrograph: Exoplanet light injected into fiber

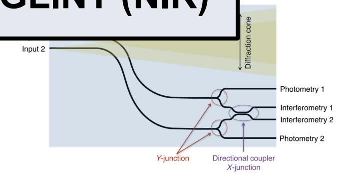
1.2m x 0.9m bench

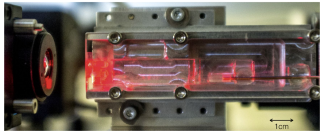
NIR-PL





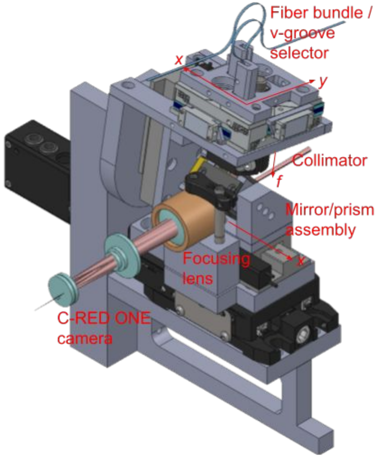
GLINT (NIR)





NIR Photonic Spectrograph

Funding by NAOJ/TMT dev. fund, JSPS/GLINT
Design+realization: J. Lozi

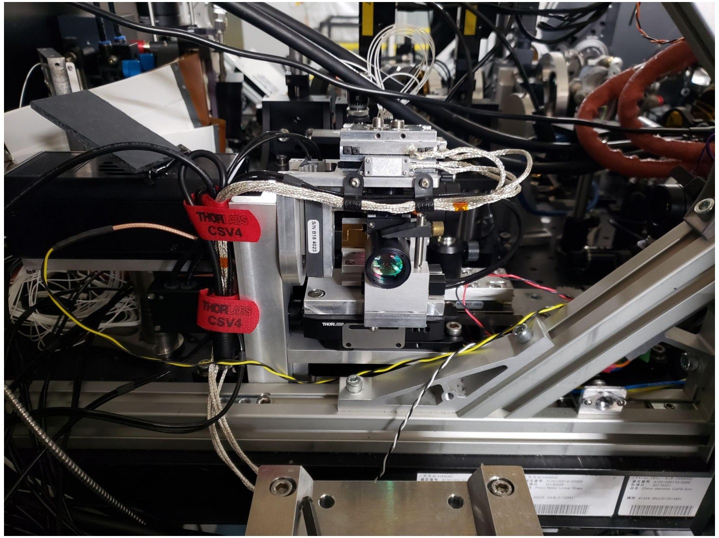


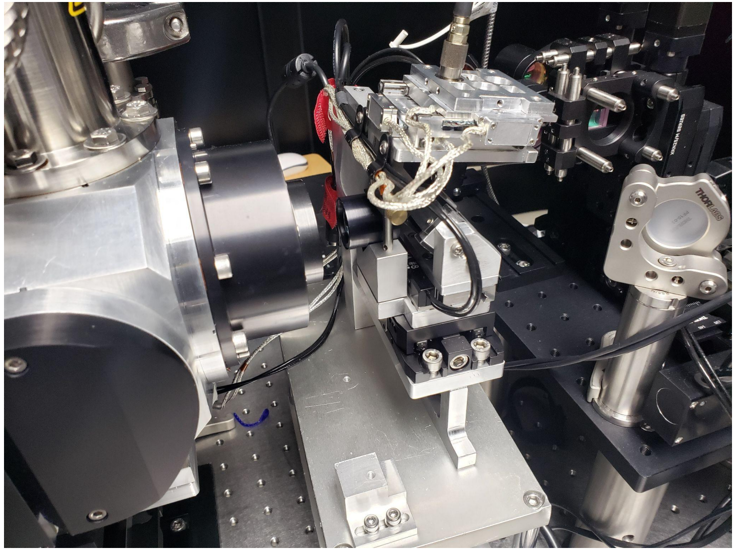
Fiber input to the spectrograph at the top of the unit. Multiple inputs selectable thanks to x/y translation platform

Mirror/prism to select between imaging (no dispersion) and spectroscopy

Side view, Camera on the left

Looking into spectrograph optics from the camera location (camera removed)

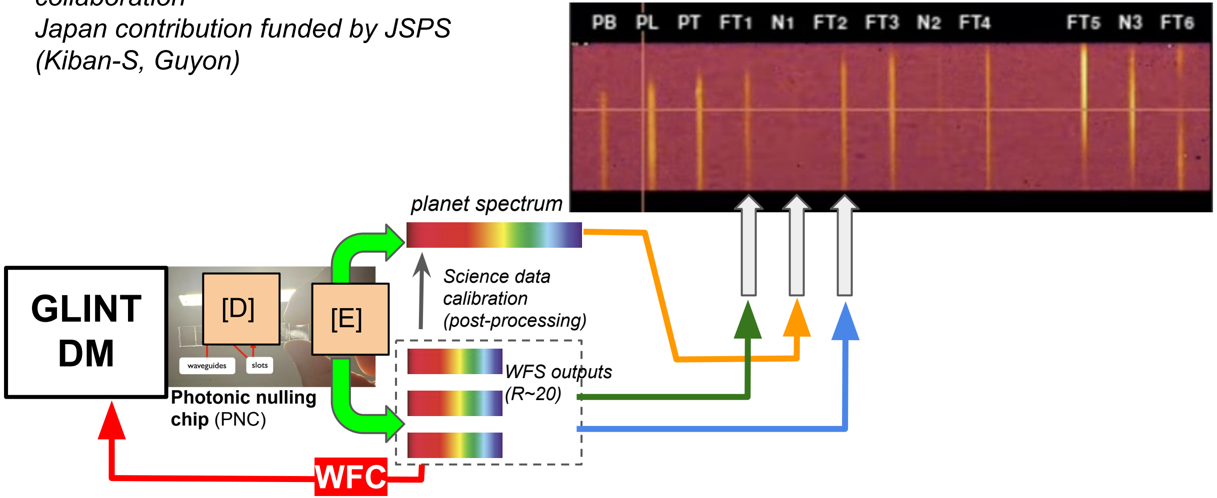




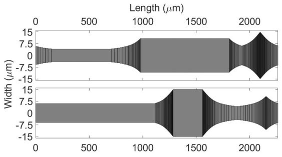
On-sky demo [may 2025, GLINT]

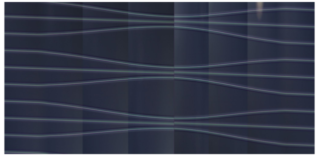
GLINT is a Japan/Australia collaboration
Japan contribution funded by JSPS (Kiban-S, Guyon)

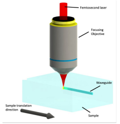
Efficiency
Optimal pixel use
Starlight suppression
Self-calibrating

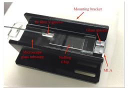


High throughput (80% through chip)
Broadband null thanks to tricouplers + phase shifters





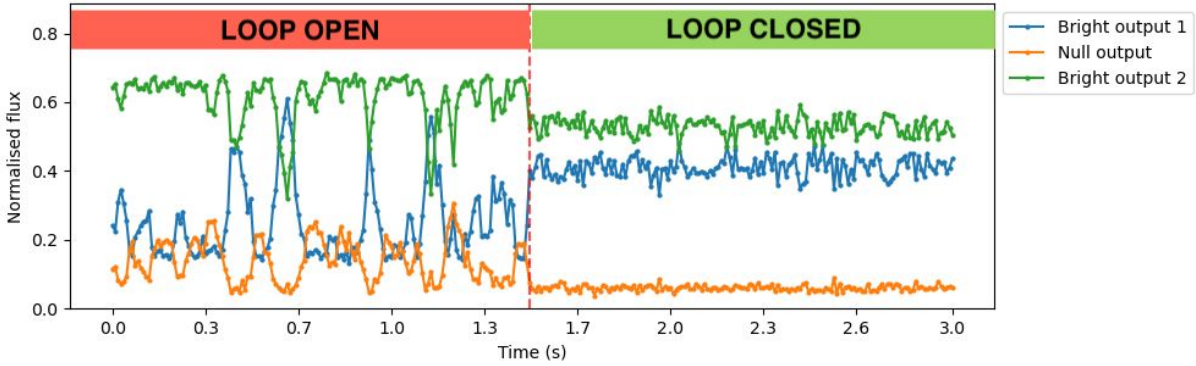




Arcadi, E.

E. Arcadi, Norris+ 2020 MNRAS

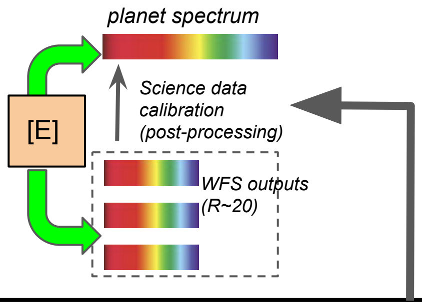
Manufactured @ Univ. Macquarie, Australia



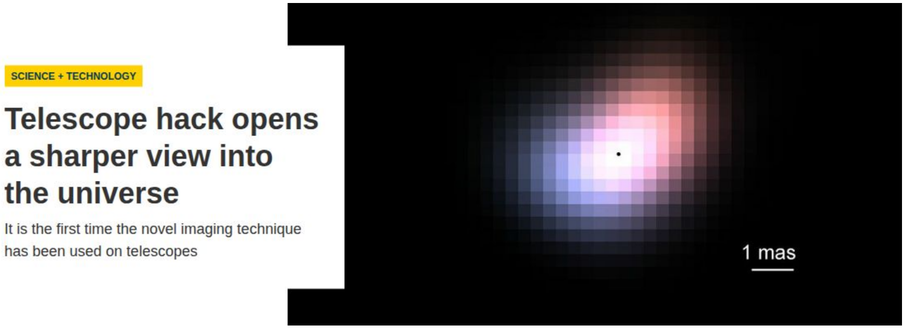
GLINT team (Rossini-Bryson et al. 2025), in prep

Self-Calibration

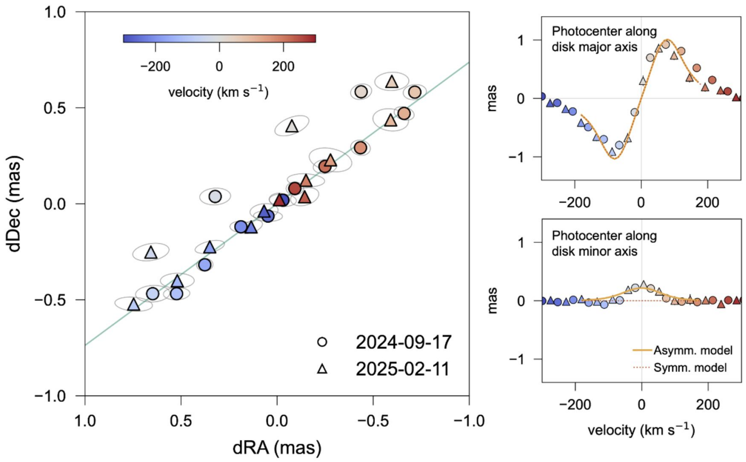
Efficiency
Optimal pixel use
Starlight suppression
Self-calibrating



Thanks to the **modal decomposition**, the photonic spectrograph should **disambiguate true signal (exoplanet) from WF errors** (starlight leaking into science fiber)



"On-sky Demonstration of Subdiffraction-limited Astronomical Measurement Using a Photonic Lantern" Yoo Jung Kim *et al* 2025 *ApJL* 993 L3



50 uas precision per spectral bin

Key Subaru Contributions to HWO's NIR Coronagraph

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(Precursor) observations

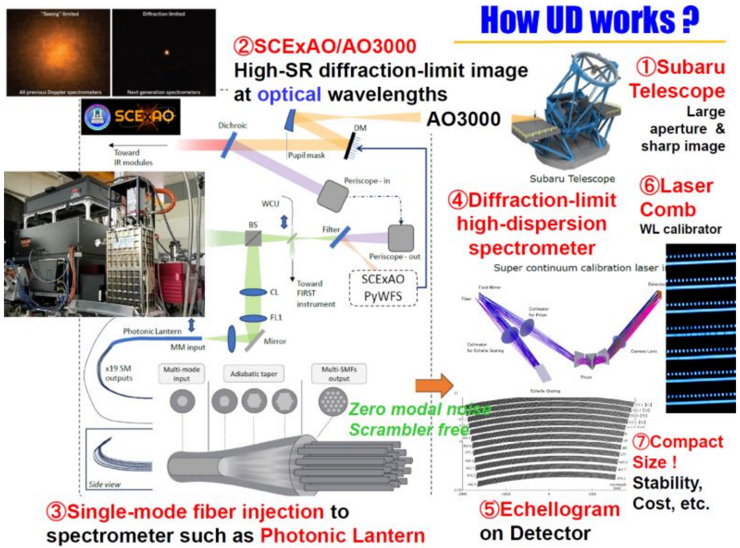
HWO targets:

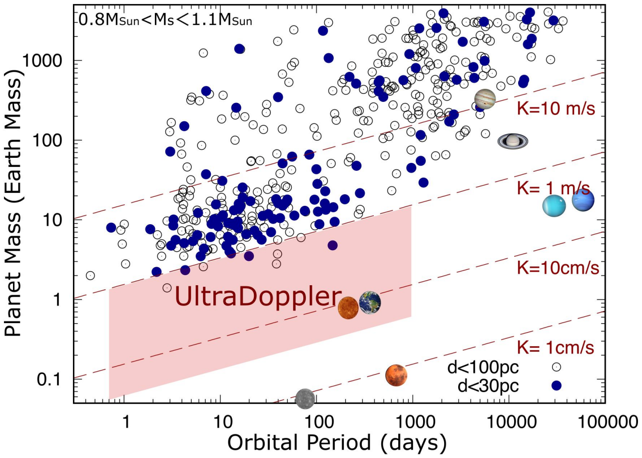
- Ultra-Doppler -> Targets, masses
- SCExAO -> Companions, dust, spin axis

Precursor Observations - Ultra-Doppler

Ultra-Doppler will **identify habitable planets before HWO** (targets) and measure stars spin axis -> <u>estimate planet position and mass</u>.

RV+direct imaging data will unambiguously measure **planet masses**





UD Goal: 3 cm/s

Possible targets

- SpT: F7–K9
- vsin(i) < 5 km/s

-> Selected 101 stars

- V = 2.8~7.7
- <20pc

Next steps / Recommendations (near term)

Allocate 1 FTE for HWO/SCExAO testbed

Current ABC/NAOJ staff @ Subaru is focused on science operation. Cannot efficiently support HWO development program.

-> Need 1 FTE to:

- Operate/optimize SCExAO as a HWO development platform
- Support Japan-based scientists to validate key technologies
- Help support/grow community of young researchers/engineers necessary for sustained development

Increase young researchers participation

Student-led HWO-related experiments/projects

Improve SCExAO testbed contrast

SCExAO measured stability at ~1e-8. Can be improved by thermal management (to ~1e-9?). Supporting deep broadband contrast requires additional out-of-plane DM.

-> Improve thermal stability (temperature control + airflow)
-> Add 2nd DM (USD $200k for electronics only, $1M for electronics + DM)

Improving & understanding contrast limit of SCExAO is essential to optimize and accelerate vacuum testing plans in Japan (& US ?)

Cost-effective, flexible, rapid testing should be done at SCExAO when possible.
Vacuum testing will be more focused for the deepest contrast, and will take more time to start.

Conclusions

Subaru is well positioned to contribute to HWO's NIR coronagraph instrument, as a **community testbed**, for **training young researchers** in both science and technology dev, and for **precursor observations**.

Even though HWO is scheduled for launch in ~20yr, there is no time to waste to develop key technology. **Early validation of high-risk high-gain technologies is critical** and will guide/focus further development activities.

We have unique expertise in **photonic nulling spectroscopy**, leveraging recent technical evolutions (photonics) to provide ~10x in sensitivity and enable NIR spectroscopy of habitable planets. The same approach can **revolutionize AO-fed spectroscopy for Subaru & TMT**.