A new fibered NIR spectrograph for novel wavefront sensing techniques on SCExAO

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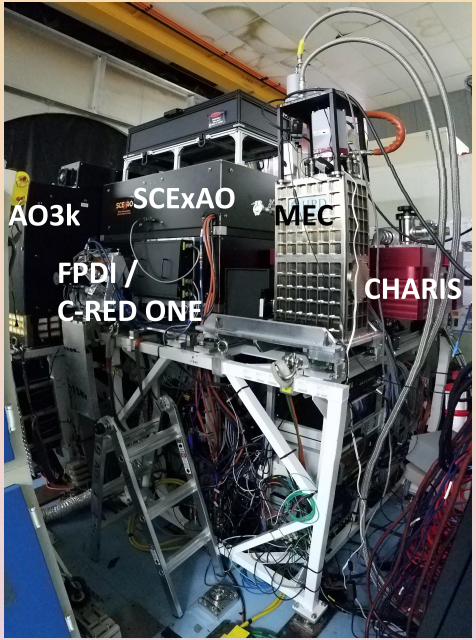
SCExAO overview

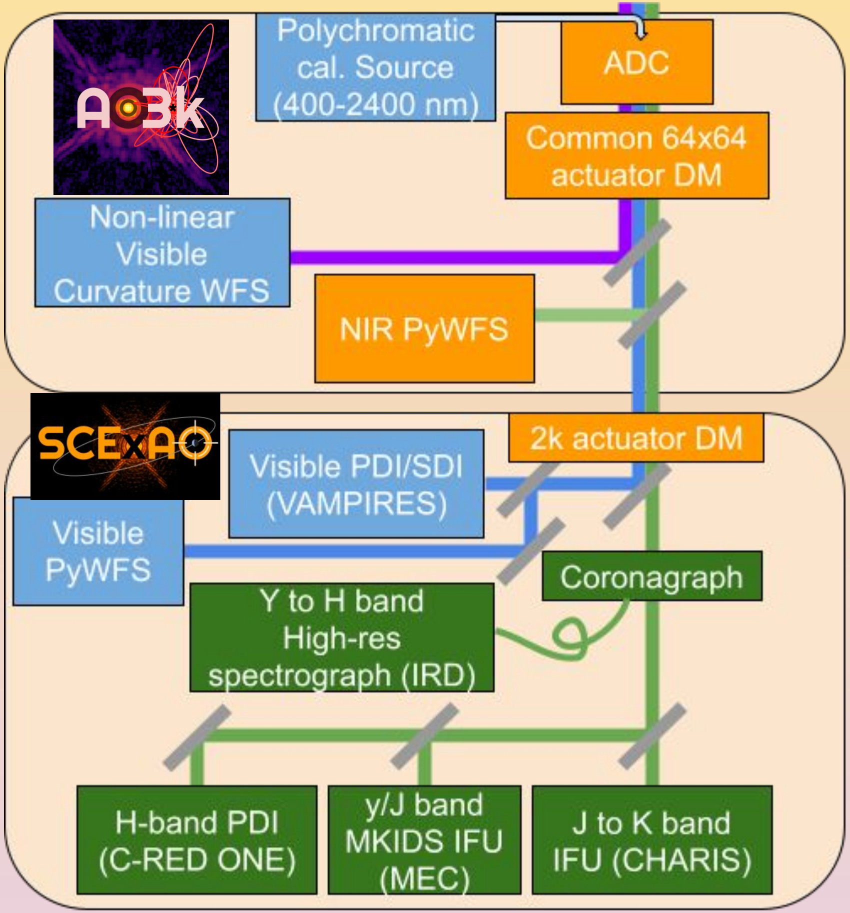
SCExAO: Subaru Coronagraphic Extreme Adaptive Optics

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.





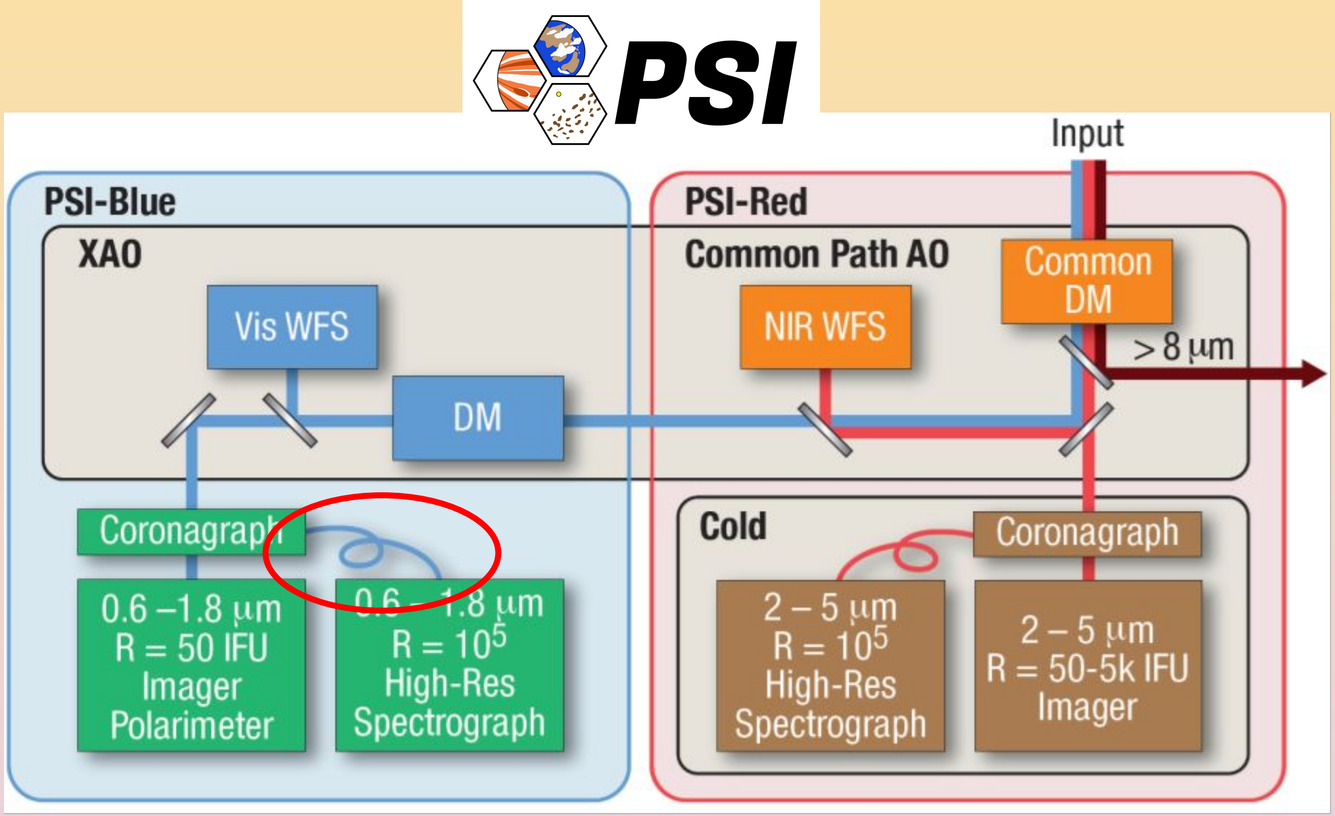
Testing critical technologies for TMT-PSI

AO3k+SCExAO is now close to the architecture of TMT-PSI.

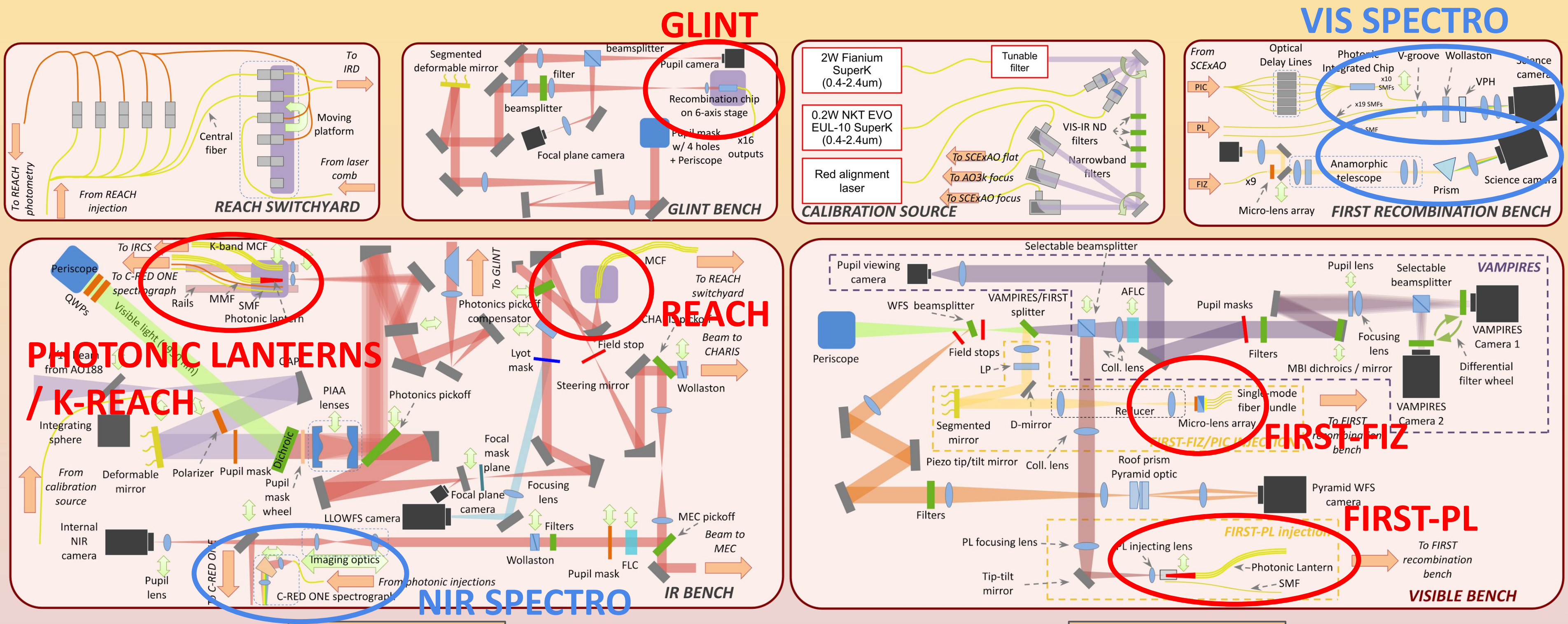
We are now demonstrating key technologies for astrophotonics (injecting light into single mode fibers, photonic integrated chips or photonic lanterns).

Astrophotonics enables ultra-precise measurements in a miniaturized format

- single mode spectroscopy
- wavefront sensing at the photon noise limit
- imaging and spectro-astrometry at and below the diffraction limit
- nulling interferometry



AO3k+SCExAO Photonic injections & Spectrographs



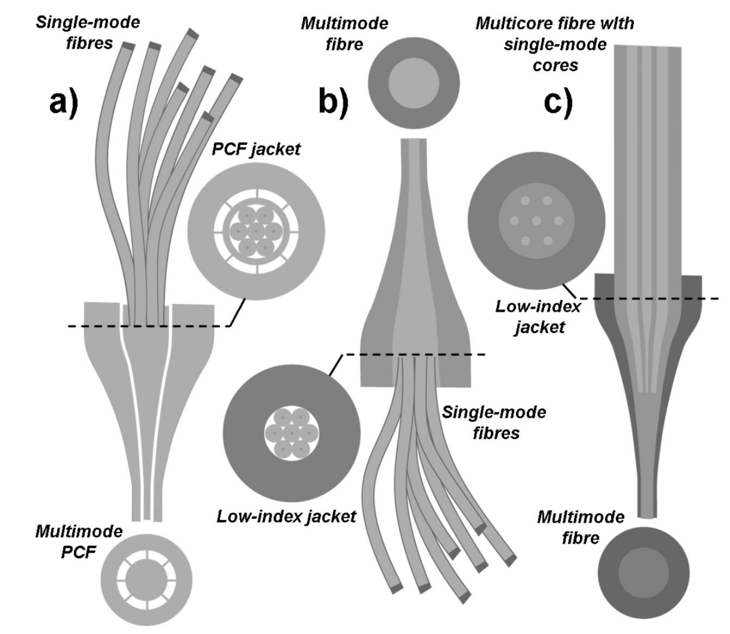
IR BENCH
950-2400 nm

Photonic Injections

Fibered spectrographs

VISIBLE BENCH
600-950 nm

What is a Photonic Lantern

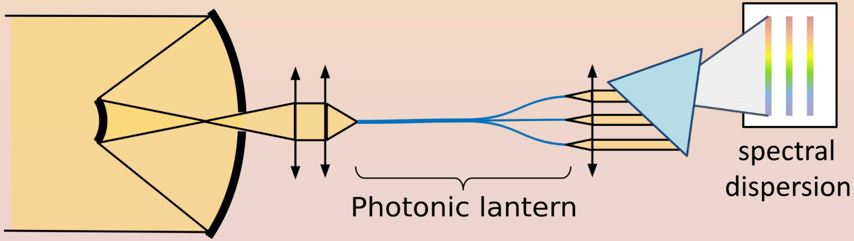


Schematics representation of three different approaches for the fabrication of Photonic Lanterns; a) PCF technique; b) Standard single-mode fiber combiner/splitter technique; and c) Multicore fibre approach.

From Leon-Saval et al. "Photonic Lanterns: a study of light propagation in multimode to single-mode converters" *OSA 2010*

Photonic Lantern = Fibered device with Multi-Mode input and several Single-Mode outputs

- Adiabatic transition between MM to SM mode
- very efficient (>90%, Birks et al. 2015)
- Allows for SMF-fed spectroscopy with high throughput



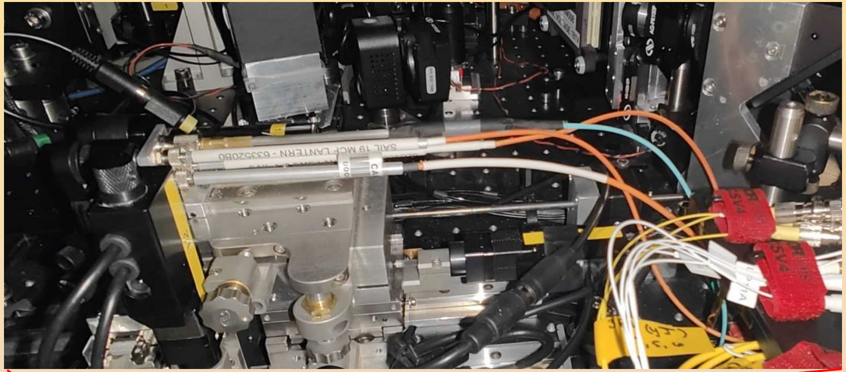
Photonic Lantern spectroscopy instrument concept

Photonic Lantern testing efforts

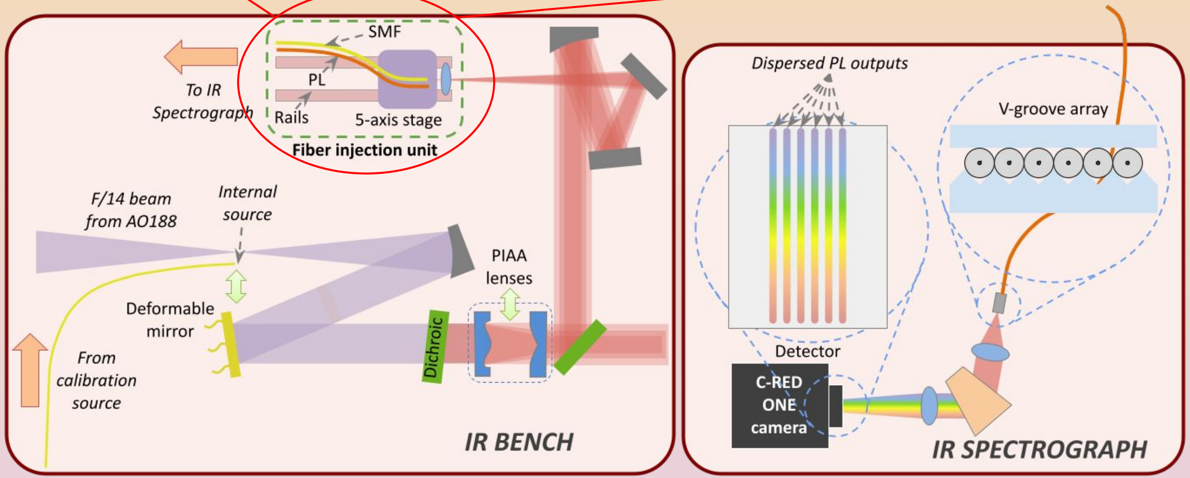
Effort mainly financed by two NSF ATIs (PI Nem Jovanovic)
→ Four Photonic Lanterns installed (made in Australia/Florida, tested by PhD students from UCLA/CalTech):

- **19-port multi-core output**
- **3-port YJ optimized**
- **3-port H optimized**
- **6-port mode selective PL**

→ All lanterns feed the C-RED one spectrograph



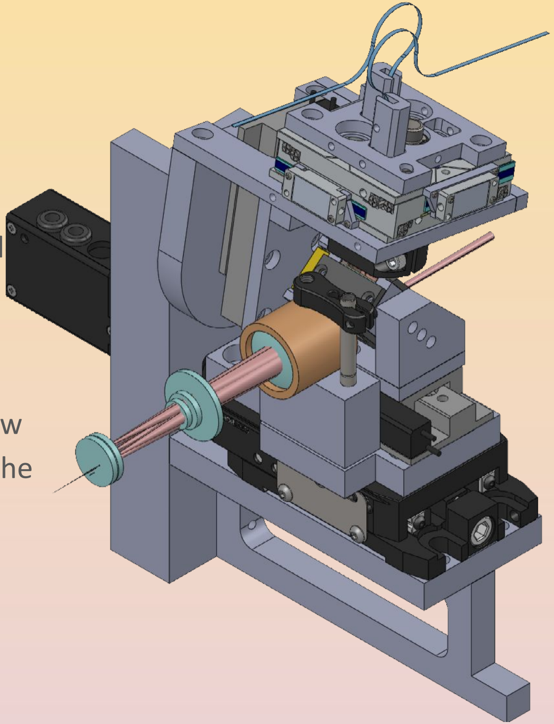
C-RED ONE of the FPDI mode, repurposed for a NIR fiber-fed spectrograph

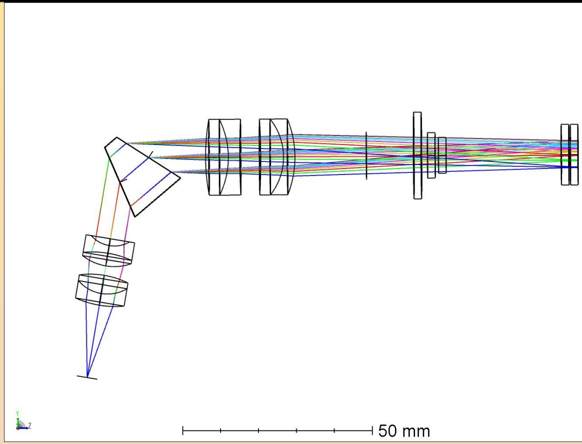


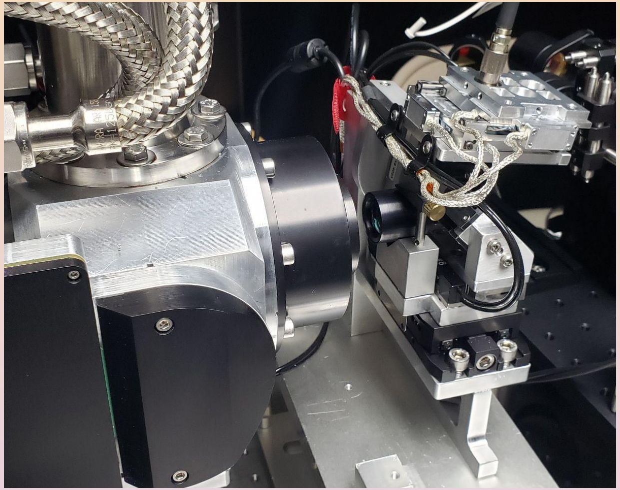
NIR Spectrograph design

→ Optical design by Chris Betters (University of Sydney) and Julien Lozi (Subaru Telescope)
→ Mechanical design by Julien Lozi
→ Financed by NSF ATI and TMT strategic R&D fund (dispersion prism)

- Diffraction limited over 1-1.8 um
- Very compact thanks to a single high-ind NIR prism (AMTIR2)
- Dispersion between 800 @1um to 200 @1.8 um
- Challenging due to the necessity of a slow beam to go through all the windows of the C-RED ONE camera
- Can image 13 fibers in a typical v-groove
- Fully motorized to switch between
  - FPDI mode (no spectrograph)
  - Photometric mode
  - Spectroscopic mode
  - Selectable v-grooves & fibers



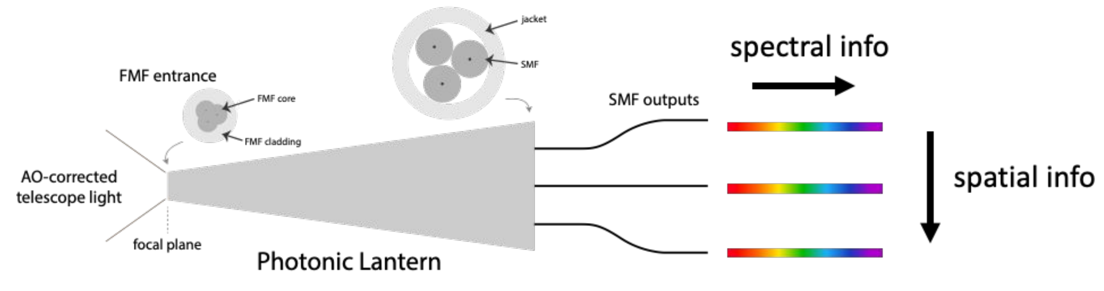




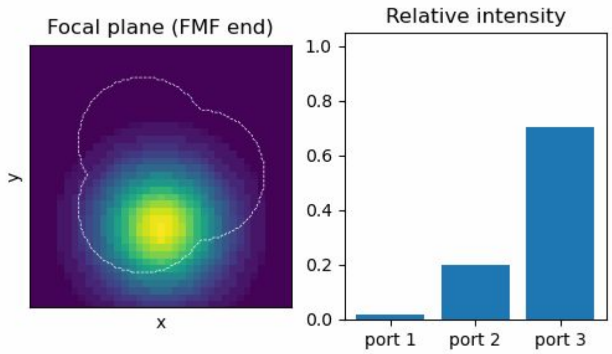
Spectroscopy with PLs

High angular resolution spectroscopy with photonic lanterns (PLs)

- Spectrally dispersed PL outputs can act like a small **integral field unit (IFU)**, containing *both* **spectral** information and high angular resolution **spatial** information (within FoV of ~ λ/D).
- PL-fed high-resolution spectrograph can enable **high-throughput** observation of high angular and high spectral resolution measurements.



Kim et al. 2024



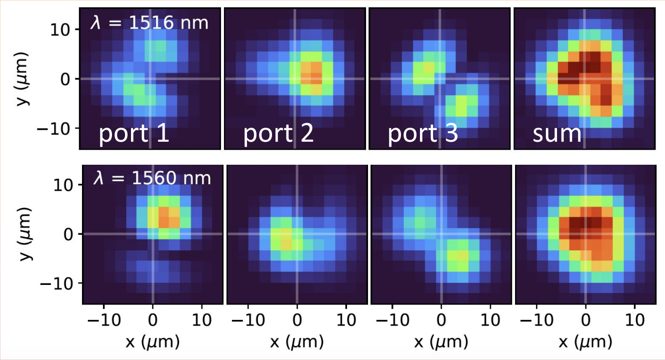
numerically simulated intensity responses of a standard 3-port PL to astrometric displacements

Science objectives: < λ/D spectro-astrometry and spectro-imaging

- detection and characterization of accreting protoplanets
- resolving stellar rotation, kinematic structures of circumstellar disks and AGNs

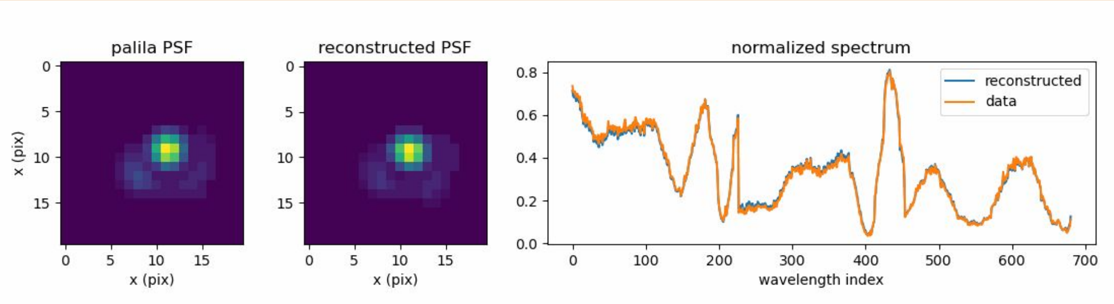
Development status and future plans

- **Two standard 3-port PLs, optimized for yJ- and H-bands**, are installed and characterized for astrometric measurements.
- SCExAO provides a unique ExAO platform to test the capabilities of PL-fed spectrographs for astrometric measurements and imaging in lab and on-sky, and to develop calibration strategies with various telemetry data and concurrent observations in the Visible.
- Spectroastrometric signal recovery is **demonstrated in lab**, with simulated turbulence **similar to on-sky condition**.
- Future plans include **on-sky demonstration** of spectroastrometric signal recovery.
- We are currently limited by spectral resolution (R~300 in H-band, ~500 in J-band) but an upgrade to a **high-resolution spectrograph** (such as Exo-NINJA?) will enable broader science applications.



Kim et al. 2024

Coupling maps for two different wavelengths, for H-band 3-port PL. Asymmetries of the coupling maps indicate sensitivity to astrometric displacements. Wavelength diversity can be utilized for simultaneous spectroastrometry and wavefront sensing.



For spectroastrometry calibration, we need a data-driven model mapping the PSF and the PL spectrum. We demonstrated that this approach works, using on-sky data taken on Sep 17, 2024.
Kim et al. in prep

Photonic Lantern Nulling (PLN)

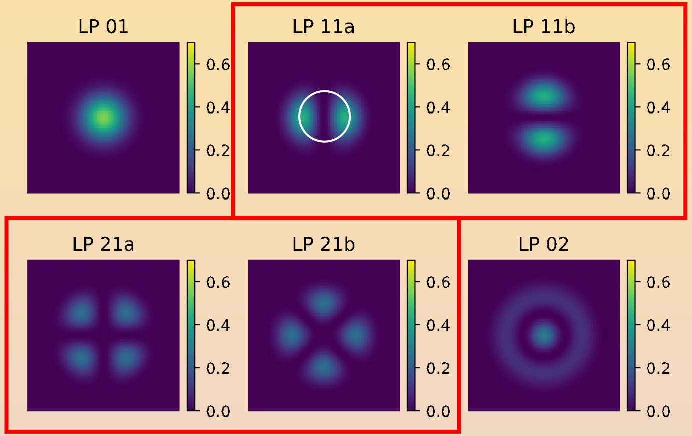
Nulling interferometry with a mode-selective photonic lantern

Science objectives : ~1 λ/D high-resolution spectroscopy with limited imaging

- **Detection and atmospheric characterization** of exoplanets and brown dwarfs
  - Targets separations of 20-60 mas in H-band, where the giant planet population peaks
- **Nulling spectroastrometry**
  - Reduced photon noise compared to conventional spectroastrometry

Unique capabilities :

- **High planet throughput** (~40% coupling efficiency at 1 λ/D with the current device, with a theoretical maximum of >60%)
- **Broadband nulls** from lantern geometry
- Second and fourth order nulls **simultaneously** available
- Out-of-band short-wavelength light potentially useful for **WFS** and **null calibration in post-processing**



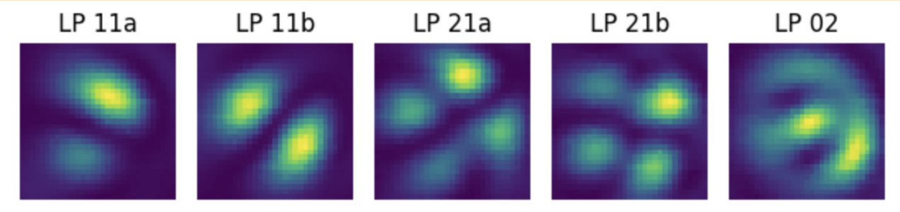
Theoretical transmission profiles for the 6 ports of the mode-selective lantern. The ports outlined in red null the central star but couple off-axis planet light. A white circle with a radius of 1 λ/D is shown for scale.

PLN : Initial Development and Engineering

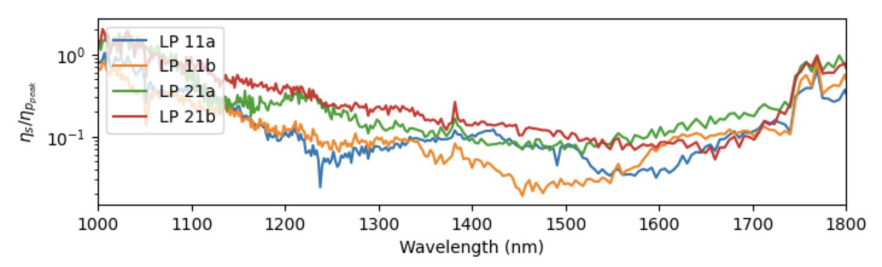
September 2024

- Mode-selective photonic lantern installed on SCExAO bench
- Preliminary daytime characterization and calibration (with unoptimized wavefront)
- Preliminary on-sky tests 9/16-9/17

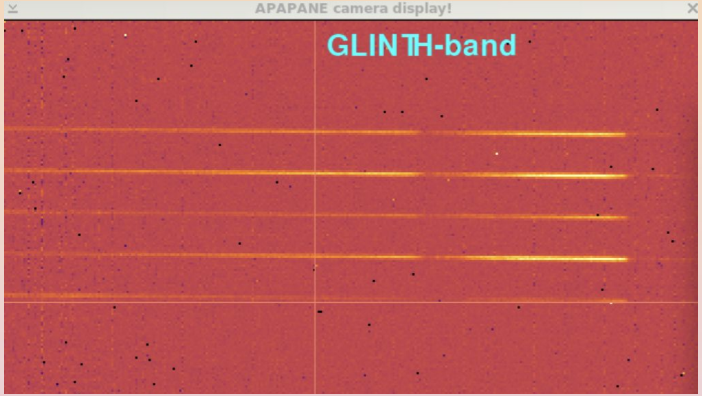
Coupling maps with calibration source



Spectrally dispersed null depth measurements



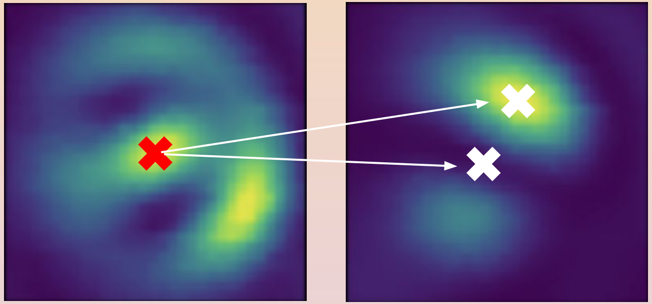
On-sky spectral traces (September 16, 2024)



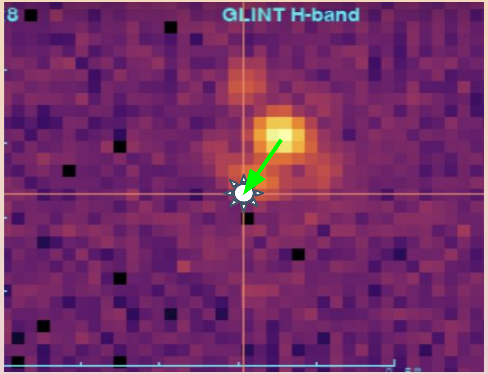
PLN : Future Development Plans

- **Engineering Observations** identified the need for a **more precise and repeatable calibration procedure**, including running a centroid tip-tilt loop on-sky to align the PSF to the lantern null
- **2025 engineering time** requested to test the PLN with tip-tilt control and measure on-sky null depths
- Additional development activities and path to open use:
  - Implement wavefront optimization techniques to improve null depths (already demonstrated in the lab at Caltech)
  - Investigating compatibility and science capabilities with IRD and NINJA spectrographs

Lab (LP 02) Lab (LP 11a)



Old alignment procedure attempted to apply offsets as measured in the lab to align to the coupling maximum and central null, which was unsuccessful in on-sky conditions



New alignment procedure involves calibrating the lantern to a fixed pixel position on the PSF monitoring camera, and running a tip-tilt loop on-sky to drive the PSF to the calibrated position

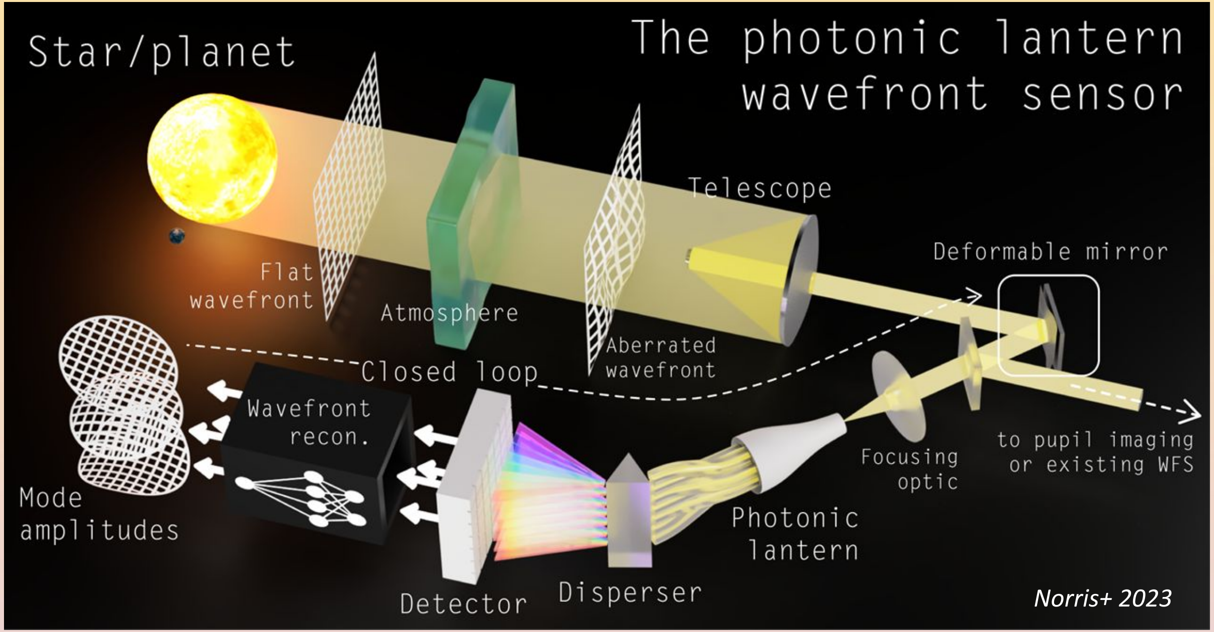
Wavefront sensing with PLs

PL outputs **encode** information about pupil-plane **phase**.

⇒ the PL can provide low-order WFSing from the **focal plane**.

Simultaneous w/ PL science.

PL outputs may be **dispersed** to gain even more phase information ⇒ better **correction fidelity** & **dynamic range**.

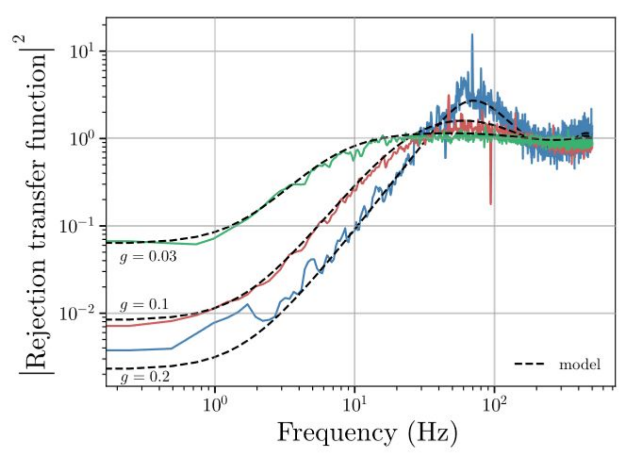


Norris+ 2023

AO3k + SCExAO Scientific & technical benefit

1. Sense and drive correction of **LWE** (top right).
2. 2nd-stage WFSing behind AO3K, to drive correction of low-order **NCPA** (bottom right).
3. Simultaneous w/ PL science ⇒ **self-calibration** for nulling, spectroscopy, spectroastrometry.
4. Provides a platform to test **novel** nonlinear **WFSing techniques** (wavelength diversity, machine learning).
5. **Uniqueness**: to my knowledge, there is no other facility with access to the same combination of PL WFSing, on-sky capability with xAO, and spectral dispersion.

Closed-loop control using SCExAO 2K DM + 19-port IR PL
Lin+ 2023



Transfer functions for closed-loop control of artificial NCPA w/ IR PL, *Lin+ 2023*

GLINT Overview

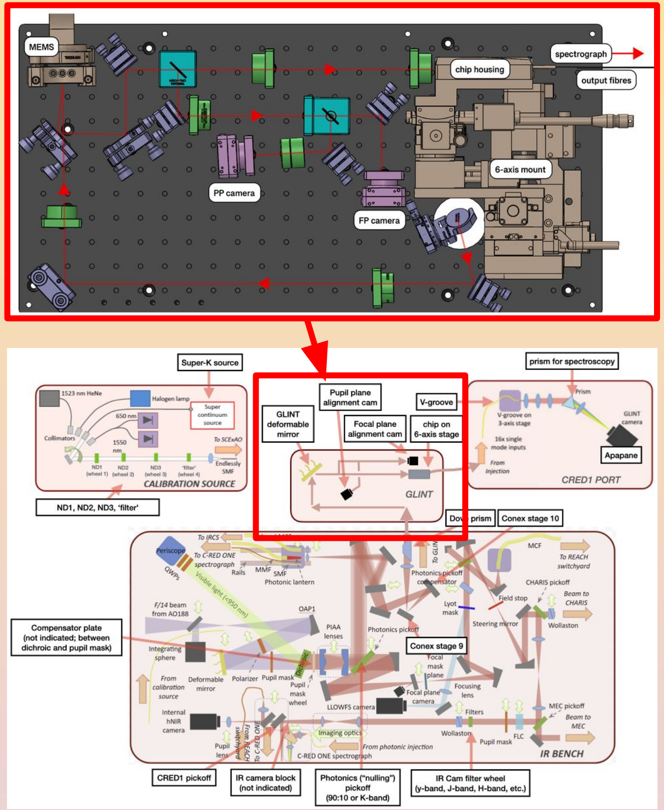
Nulling interferometry with a photonic chip

Science objectives : <λ/D spectroscopy

- Nulling of bright on-axis host stars to resolve ~10s mas off-axis science light
- Stellar noise subtracted and sent down different channel (in contrast to stellar/Fizeau interferometry)
- Science cases include YSOs, circumstellar disks, exoplanets, AGNs

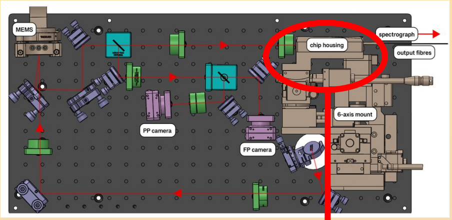
Unique capabilities :

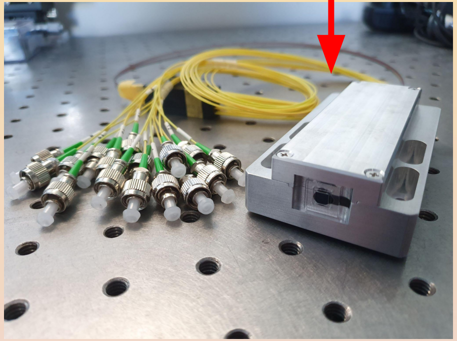
- Demonstrated <λ/D resolution (Norris et al. 2020 MNRAS)
- First and only on-chip nuller which is on-sky (until L-band VLT/NOTT in ~2025)
- Currently the only active H-band nuller
- Photonic chip with waveguides made with ultra-fast laser inscription (ULI)
- ULI-based achromatic phase shifter

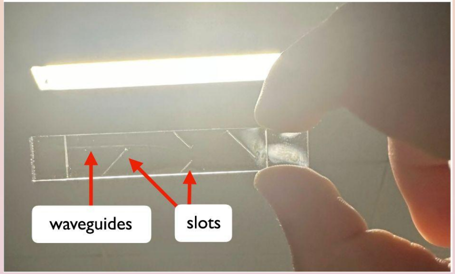


GLINT as a backend to the SCExAO IR bench

GLINT progress



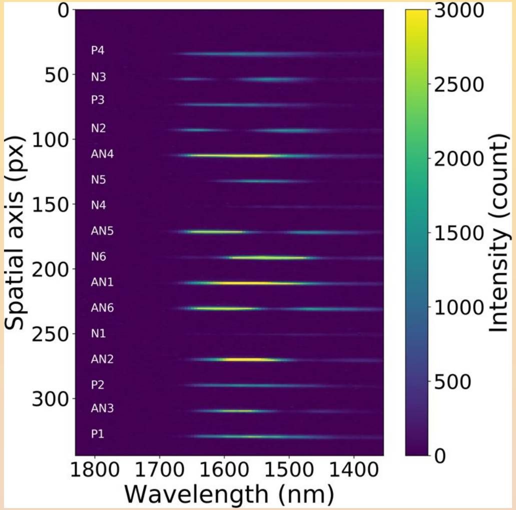


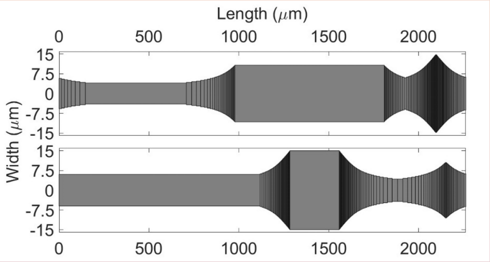


H-band chip upgrade for deeper and more broadband nulls

- New implementation of achromatic phase shifters, tricouplers
- First chip installed at Subaru Jan. 2024
- Second version installed July 2024
- User information on SCExAO Wiki [Link]
- Data is archived on SCExAO computers
- No internal cooling required, electrical needs limited to chip mount and DM for static path length offsets

Waveguides arranged as tricouplers to enable phase control





Waveguides have achromatic phase shifters for a more broadband null

Summary

- Astrophotonics is an emerging field that can provide the means to **characterize exoplanets close to their host star**, especially on TMT.
- Photonic lanterns can be the key for ultra-Doppler spectrographs (~10 cm/s precision) and high-throughput spectrographs with no modal noise.
- Thanks to the TMT strategic R&D funds, **Subaru Telescope is the first and only major telescope to have a multi-channel photonic spectrograph**
- This project is generating significant R&D at Subaru, and we are now **leading on-sky testing for astrophotonics projects** with few USD $M of investment (2 NSF ATIs and Australian funds).

  - For the visible counterpart of this effort, see Sebastien's poster on FIRST (P26).

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.