Super-Resolution Spectro-Imaging with SCExAO/ Photonic Lanterns

Olivier Guyon[a,b,c], Sebastien Vievard[a,d] , Mona El Morsy[e], Thayne Currie[a,e] , Vincent Deo[a],, Tomoyuki Kudo[a,b], Yoo-Jung Kim, Julien Lozi[a] , Christopher Hamner[d], Aidan Walk[d], Elsa Huby, Sylvestre Lacour, Manon Lallement, Sergio Leon-Saval, Michael Fitzgerald, Chris Betters, Nemanja Jovanovic, Jon Lin,

[a] *Subaru telescope,* [b] *Astrobiology Center,* [c] *University of Arizona,* [d] *SSEI Univ. of Hawaii,* [e] *University of Texas at San Antonio,*
[d] *Tohoku University,* [e] *Univ. of Tokyo,*

Contact: guyon@naoj.org

OVERVIEW

Modal Decomposition of light with a Photonic Lantern (PL)

In a PL, light transitions adiabatically (no loss) from the MMF input to multiple SMF outputs. **The PL performs a modal decomposition of the input electric field** over a small FOV.

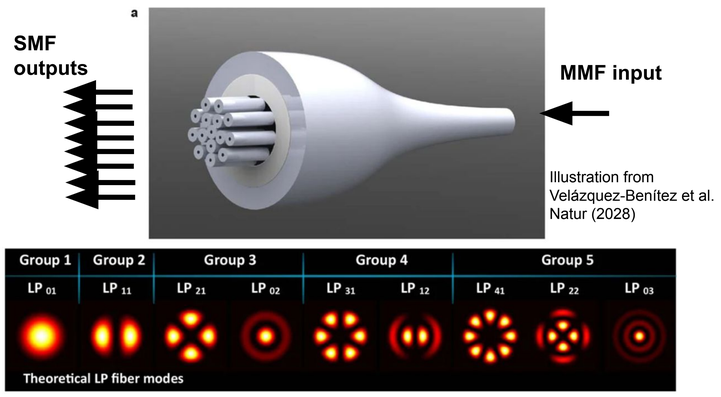


Illustration from Velázquez-Benítez et al. Natur (2028)

All-fibre photonic lantern. (**a**) Illustration of a photonic lantern fabricated using 15 fibres, and (**b**) theoretical LP fibre modes attainable with this device.

A transformative technology for astronomy

The interferences occurring within the PL **encode with high accuracy both the incoming wavefront and source image**. These can be cleanly separated, in some cases removing the effect of WFEs from high-precision measurements. *This would not be possible in a classical imaging system.*
The PL output, an array of SMFs, **can be spectrally dispersed**, allowing for spectro-imaging, spectro-astrometry, and spectro-WFSing.
The PL is an efficient way to **inject light into photonic chips/circuits** for additional processing.

PL activities @ Subaru

- **FIRST-PL is a visible light (600-800nm) spectro-imager** ar R~3000, using PL for modal decomposition of input light and image reconstructions. **FIRST-PL will be offered for open use in 26B** (goal).
- **Exo-NINJA will provide R~4000 NIR spectro-imaging** of exoplanets and compact sources using a 19-port PL. ExoNINJA is in development, open use in ~2 yr (goal).
- We operate a **near-IR PL-fed photonic spectrograph** for WFSing, nulling and image reconstruction.

These activities are integrated with an **active R&D effort** exploring the use of PL for high contrast spectroscopy (NASA-led HWO mission), and ultra-high precision radial velocity (Ultra-Doppler instrument).
Subaru Telescope is the world leading facility in on-sky use of PLs.

PL MODULES/INSTRUMENTS @ SUBARU/SCExAO

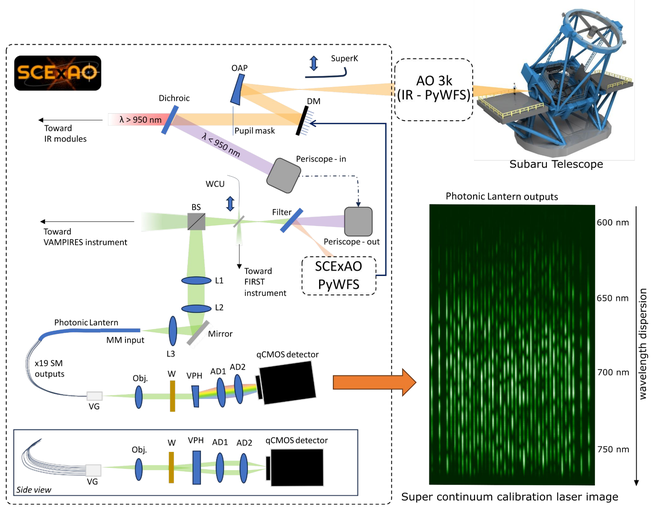
FIRST-PL

PIs : Elsa Huby, Sébastien Vievard

Spectro-imaging & spectro-astrometry, R=3000, 600-900nm
Uses 19-port PL, Includes polarization splitting; Supports off-axis pointing (companion)
Low-noise detector, RON 0.2-0.4 e-

Science Cases:

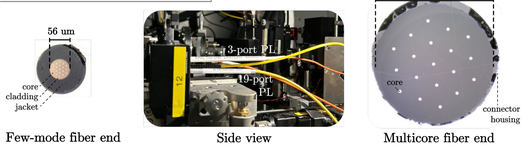
- **Planet accretion Mapping**: Mapping gas accretion on young planets at small angular separations, by observing the Hα line, and precisely locating its source
- **Stellar mass loss and evolved stars**: Mapping mass loss from evolved stars, discretion from Ae/Be stars, dust formation around evolved stars. Measuring convection cells, temperature and chemical gradients across stellar disk for evolved stars.
- **Exoplanets:** Measure stellar spin axis to place constraint on exoplanet orbit inclination and mass. Reveal the on-sky orientation of orbits, so that planet(s) positions can be constrained.
- **Close Binaries**: Resolving spectroscopic binaries, differential spectroscopy between the components.
- **AGNs**: Map inflows/outflows and circum-AGN starburst activity.

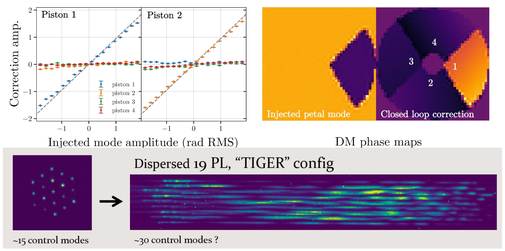


NIR-PL

IR Photonic Lantern
(J. Lin, YJ Kim, N. Jovanovic, M. Fitzgerald, B. Norris, J. Lozi, O. Guyon et al…)
Wavelength range : 900 - 1400 nm
Device throughput : 80%
Nb of outputs : 19

IR Photonic Lantern (2/2)
(J. Lin, YJ Kim, N. Jovanovic, M. Fitzgerald, B. Norris, J. Lozi, O. Guyon, S. Vievard et al…)
Wavelength range : 900 - 1400 nm
Device throughput : 89.5% average
Nb of outputs : 3
Spectral resolution : 300





Exo-NINJA

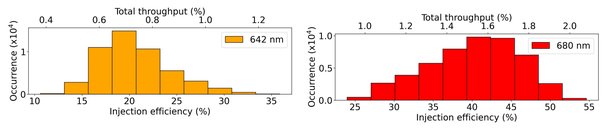
ECoupling SCExAO and medium-resolution spectrograph NINJA (R=4000 at JHK bands) using optical fibers *(PIs: M. El Morsy/ T. Currie | Subaru: O. Guyon/ J. Lozi/ S. Vievard)*

Science objectives

- Exoplanet Spectroscopy: Atmosphere Characterization
- Detecting and Measuring Gas Accretion onto Forming Planets
- Spectro-Astrometry
- Imaging narrow field objects like galaxies

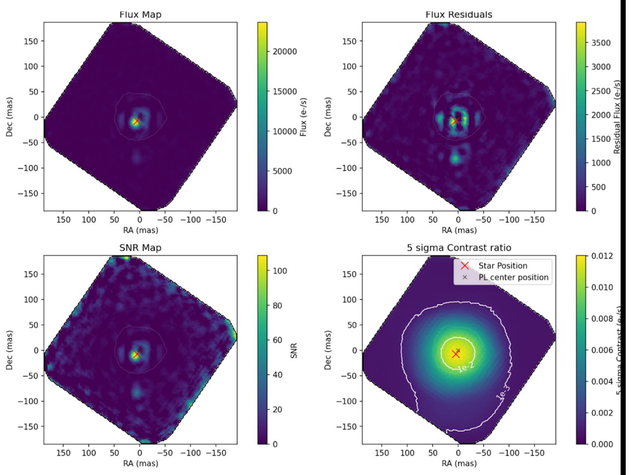
FIRST-PL - Instrument performance

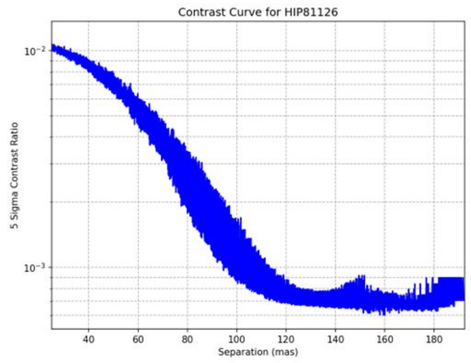
→ **On-sky Injection efficiency** (20-30% Strehl @ 750 nm) :
@ 642 nm : average **21% injection efficiency (max 36%)** (~60% in-lab)
@ 680 nm : average **40% injection efficiency (max 55%)**



→ **Observation of HIP81126** (work led by Sylvestre Lacour)

- Binary, separation 70 mas
- Successful image reconstruction at every wavelength
- Achievable contrast : **~10^{-3} at 100 mas**



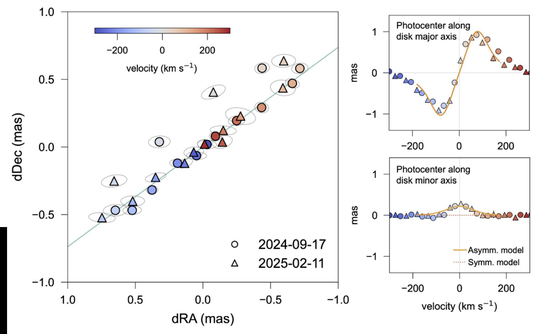


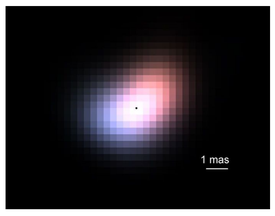
RECENT HIGHLIGHT

Observation of β-CMi

(work led by Yoo Jung Kim @ UCLA)

- **β-CMi** is a Be star with an Hα decretion disk
- Spectro-astrometry well below the diffraction limit of the Subaru Telescope (~20 mas at 656 nm)
- Disk asymmetry shown for the first time
- Spectro-astrometry below the milliarcsecond scale, with a **precision of 50µas**





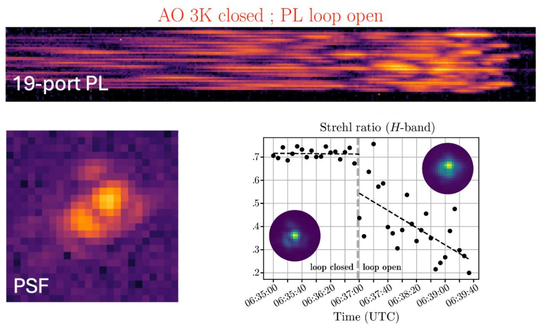
Reconstructed H-alpha image
Color indicates radial velocity, relieving the spinning disk

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

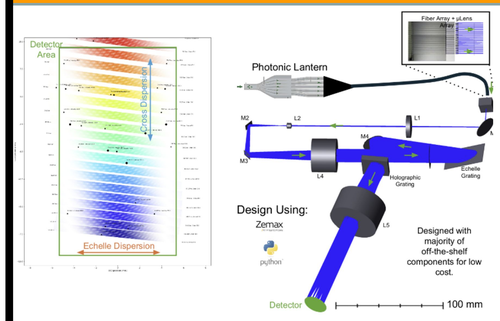
Closed AO loop with the Photonic Lantern

(work led by Jon Lin @ UCLA)

- **Demonstration of closed loop following AO3k**
- **Clear correction of the PSF**



FIRST-PL FUTURE PLANS



Design of a « compact » Echelle spectrometer architecture with 46 parallel SM fiber imputs. R~65,000, covering 620-780 nm, applied to radial velocity measurements. Credit : C. Hamner

Commissioning targeted for S26B open use

FIRST-PL will initially support open use observers for spectro-astrometry and spectroimaging of bright targets.

New science capabilities to unlock :
- Stellar spin axis (grad student at University of Hawaii)
- Image reconstruction
- Fainter targets (AGNs, faint companions)
- Polarization Differential Imaging mode
- Integration with WFS/C

New high resolution mode (R~63,000).
Development in progress at University of Hawaii, collaboration with Astrobiology Center of Japan. Prototype for Ultra-Doppler instrument.

Acknowledgements

The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.
The development of SCExAO was supported by the National Astronomical Observatory of Japan (NAOJ), the Astrobiology Center of the National Institutes of Natural Sciences, Japan, the Subaru Telescope, the Japan Society for the Promotion of Science (Grant-in-Aid for Research #23340051, #26220704, #23103002, #19H00703 & #19H00695), and the Mt Cuba Foundation.
Wavefront control R&D activities received support from the Heising-Simons foundation and NASA (Grant #80NSSC19K0336). LDFC development is supported by NASA Strategic Astrophysics Technology grant #80NSSC19K0121. NS acknowledges support from the PSL Iris-OCAV project.