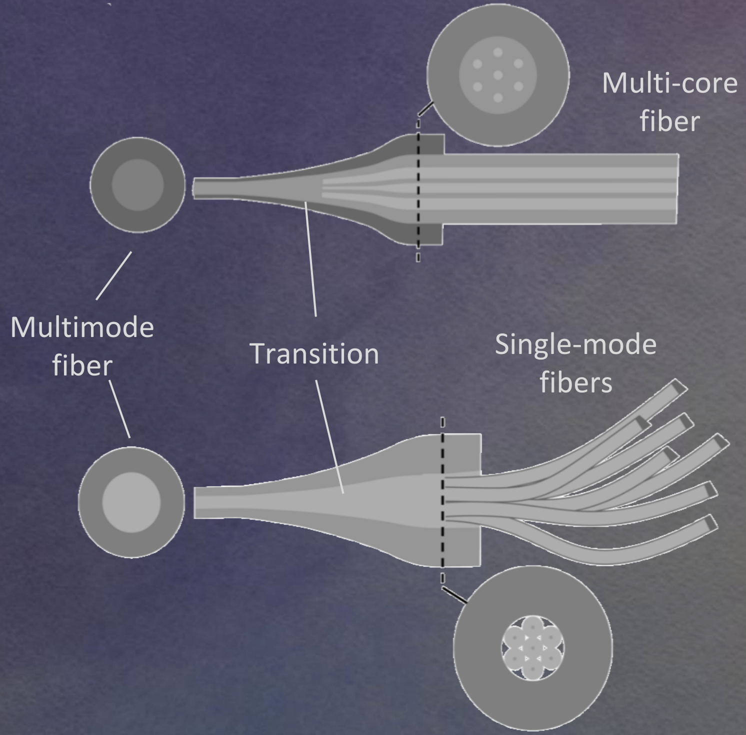
Enhancing scientific discoveries using Photonic Lanterns on the SCExAO system

Sébastien Vievard (Subaru Telescope, Astrobiology Center),
M. Lallement, S. Leon-Saval, O. Guyon, N. Jovanovic, E. Huby, S. Lacour, J. Lozi, V. Deo, K. Ahn, YJ Kim, D. Levinstein, J. Lin, M. Fitzgerald, B. Norris, S. Sallum, P. Gatkine, T. Kotani, M. Tamura, E. Spalding, Y. Xin

2023 Subaru Users Meeting

What is a Photonic Lantern ?

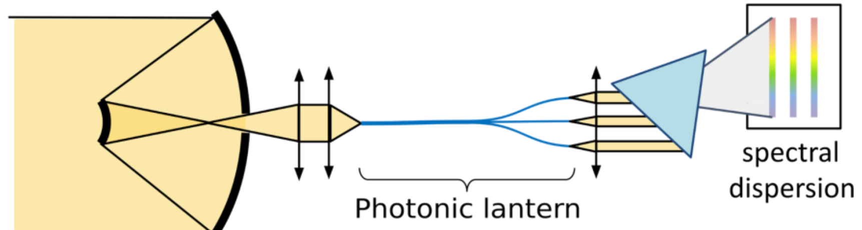


Schematics representation of two different approaches for the fabrication of Photonic Lanterns; Top: Multicore fibre approach; and Bottom: Standard single-mode fiber combiner/splitter technique.

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

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

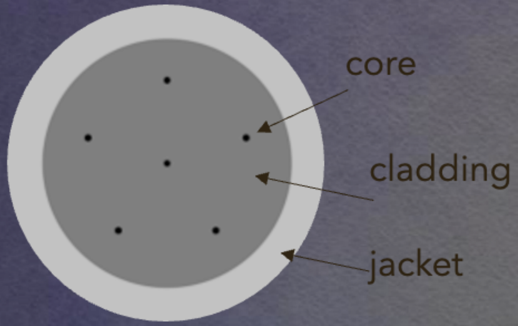
- ❖ Adiabatic transition between MM to SM mode very efficient (>90%, Birks et al. 2015)
- ❖ Allows for SMF-fed spectroscopy with high throughput



Photonic Lantern spectroscopy instrument concept

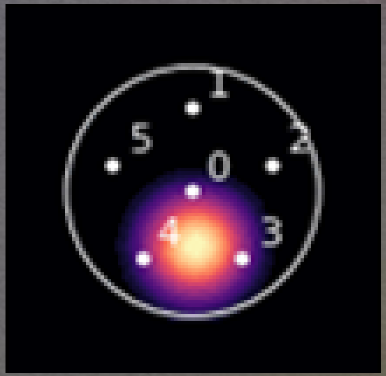
Properties of Photonic Lanterns

The intensity distribution at the SMF outputs depends on the **input scene**



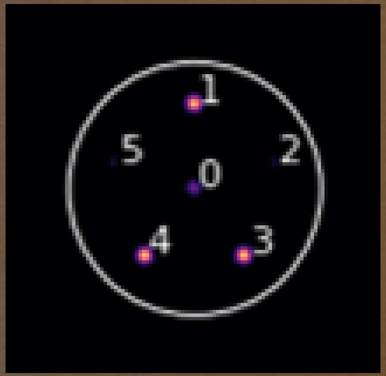
Photonic Lantern with
6 SMF outputs

PSF at the multi mode input



Photonic Lantern

Intensities at the single mode outputs

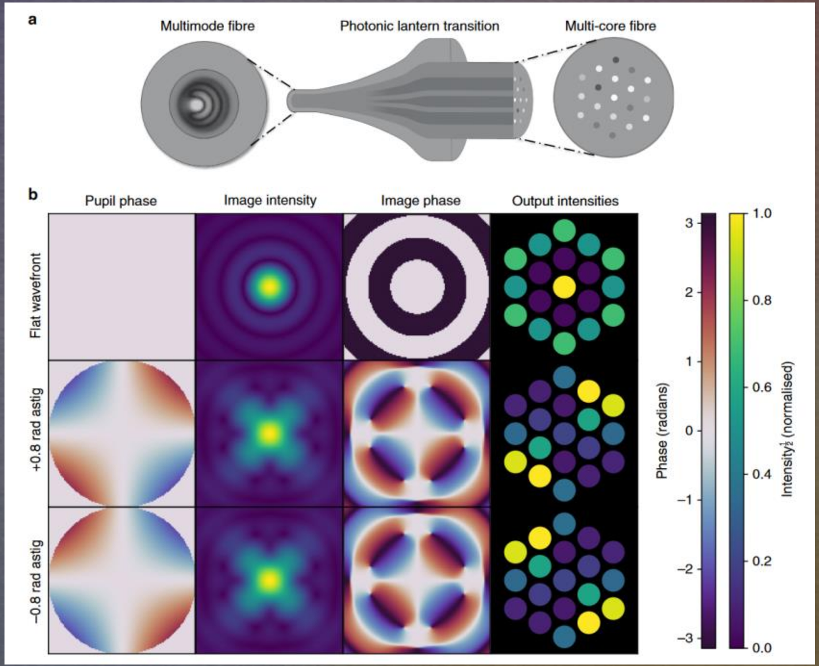


Simulation by Yoo-Jung Kim

→ PL outputs can be used **for constraining the input scene for science applications**.

Properties of Photonic Lanterns

The intensity distribution at the SMF outputs depends on the **input wavefront**

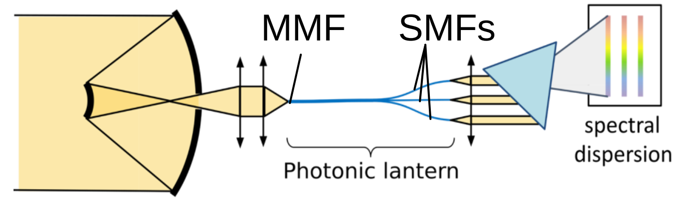


B. Norris et al, Nature, 2020

→ PL outputs can be used for **wavefront control**

Photonic Lanterns capabilities in a nutshell

High throughput
Enabling SMF-fed spectroscopy with high efficiency (especially in the Visible)



Photonic Lantern spectroscopy instrument concept

Photonic Lanterns capabilities in a nutshell

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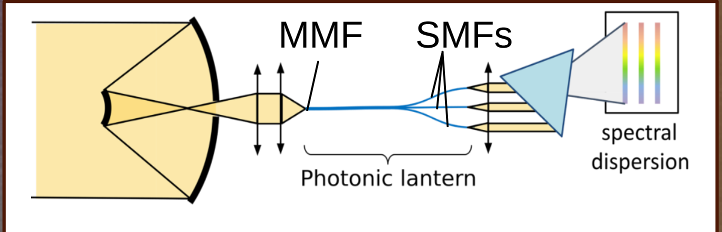
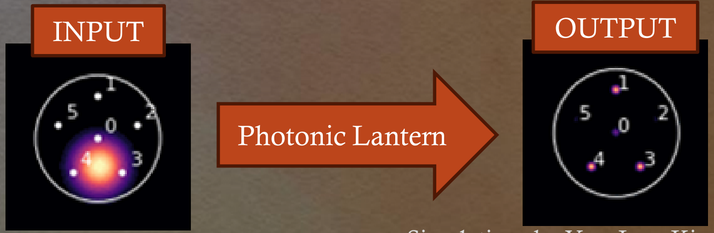
Sensitive to input scene
Output flux distribution depends on the observed object



Photonic Lantern spectroscopy instrument concept



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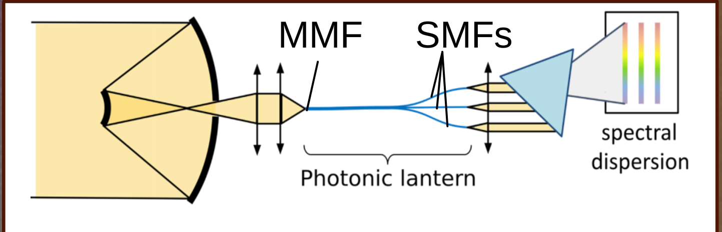
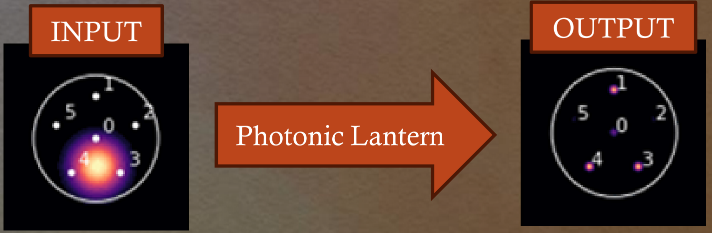
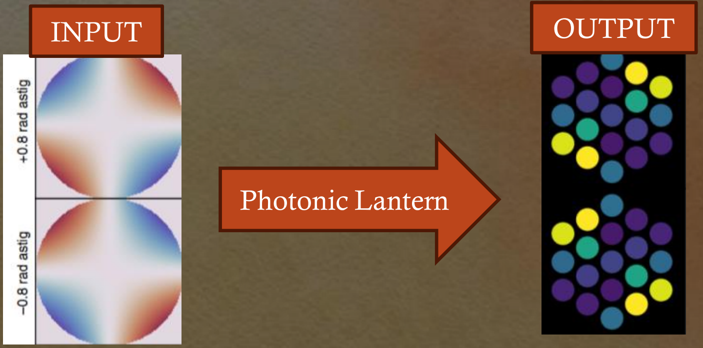
Sensitive to input wavefront
Output flux distribution depends on the input wavefront



Photonic Lantern spectroscopy instrument concept





Science applications – SMF-fed spectroscopy

- **Spectrally dispersed wavefront sensing and close-loop control (Island Effect)**
  J. Lin

- **Image reconstruction, spectro-imaging**
  Y-J Kim, B. Norris, O. Guyon

- **Efficient injection into photonic devices (FIRST)**
  E. Huby, S. Lacour + FIRST team, Y-J Kim

- **Emission line source detection (H-alpha accreting planets)**
  M. Lallement, S. Vievard, O. Guyon

- **Emission line source characterization (H-alpha accreting planets - injection into RHEA R~60,000)**
  S. Vievard, O. Guyon

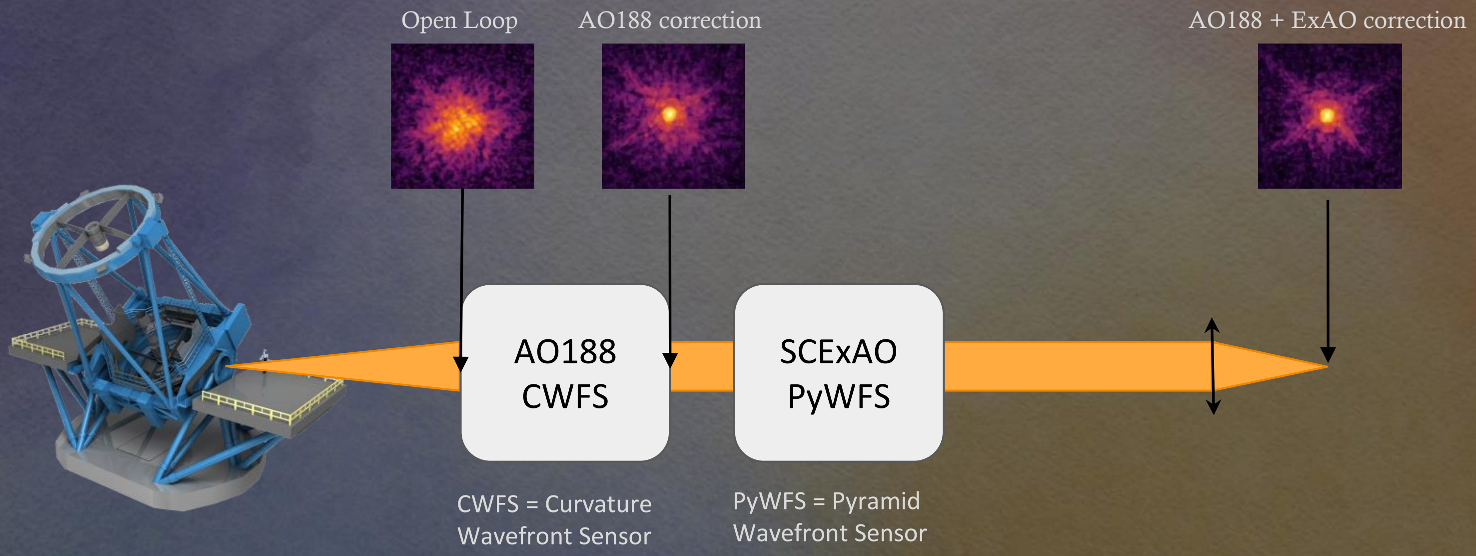
- **Spectro-astrometry**
  D. Levinstein

- **Extreme Precision Radial Velocity (EPRV)**
  T. Kotani, M. Tamura, O. Guyon

Photonic Lanterns on SCExAO

SCExAO = Subaru Coronagraphic Extreme Adaptive Optics

→ High contrast imaging instrumentation

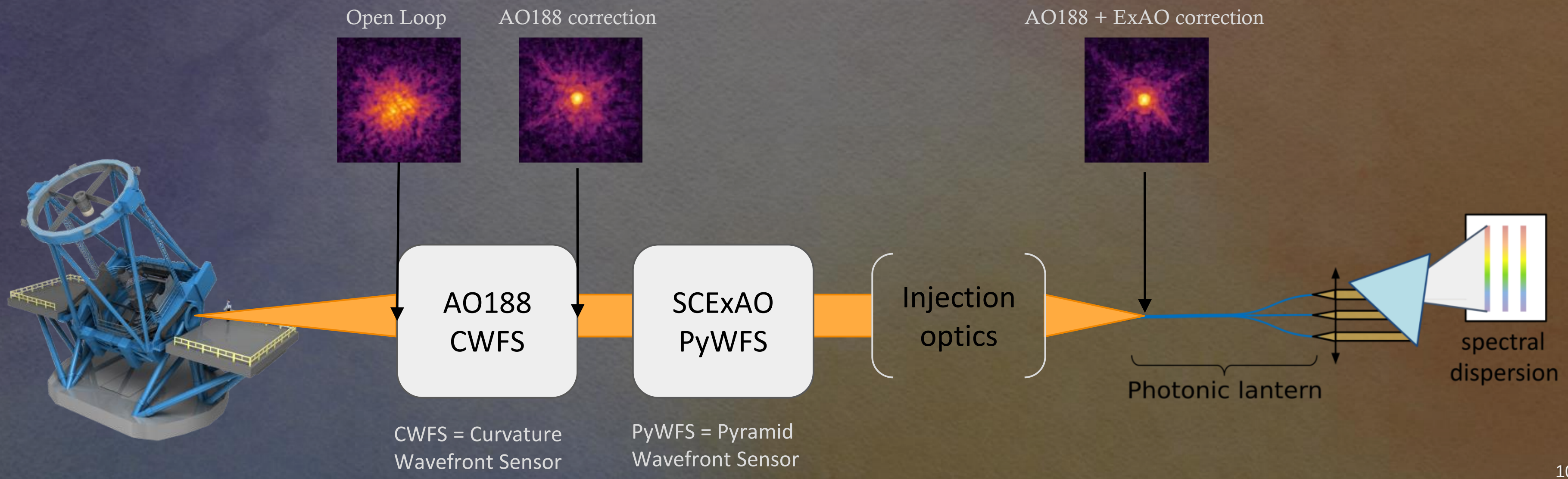


Photonic Lanterns on SCExAO

SCExAO = Subaru Coronagraphic Extreme Adaptive Optics

→ High contrast imaging instrumentation

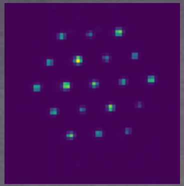
→ High Strehl PSF injected into the multi-mode photonic lantern input + single-mode fiber-fed spectroscopy

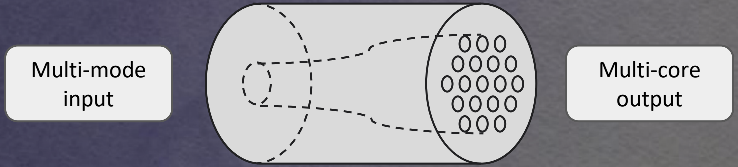


Photonic Lanterns on SCExAO

Near InfraRed

- 19-port photonic lantern (No dispersion)





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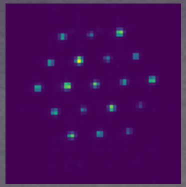
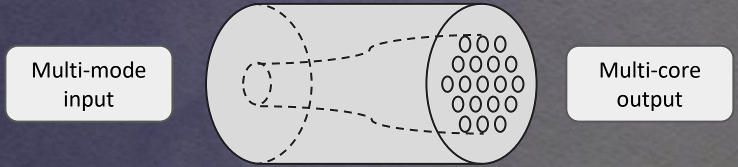
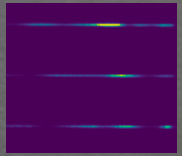
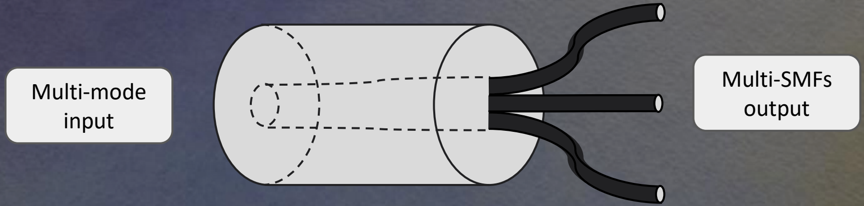




- 3-port photonic lantern (R~300 spectro.)





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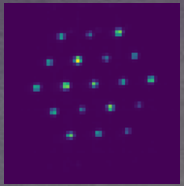

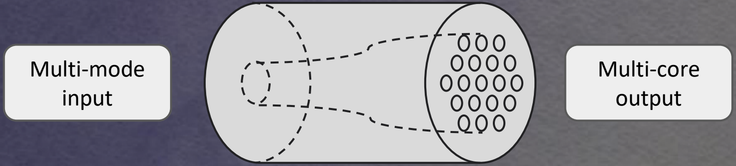

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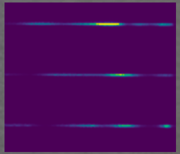
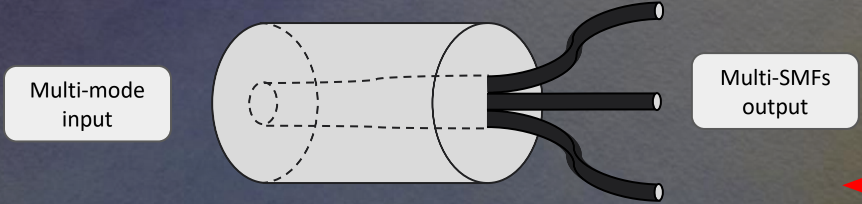
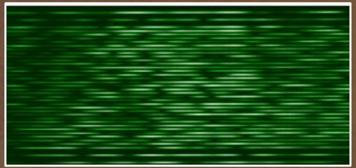
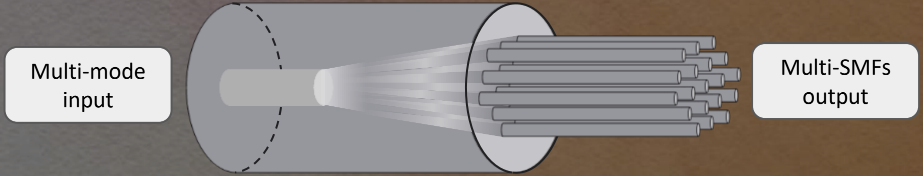


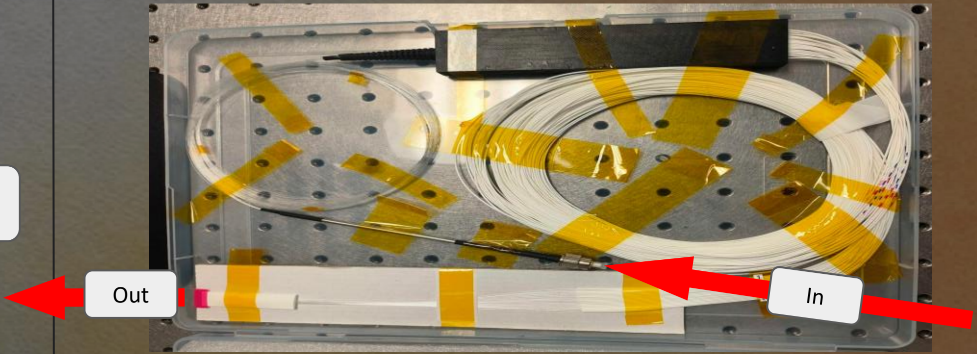


Visible

- 19-port photonic lantern
(R~4000 + polarization splitting)

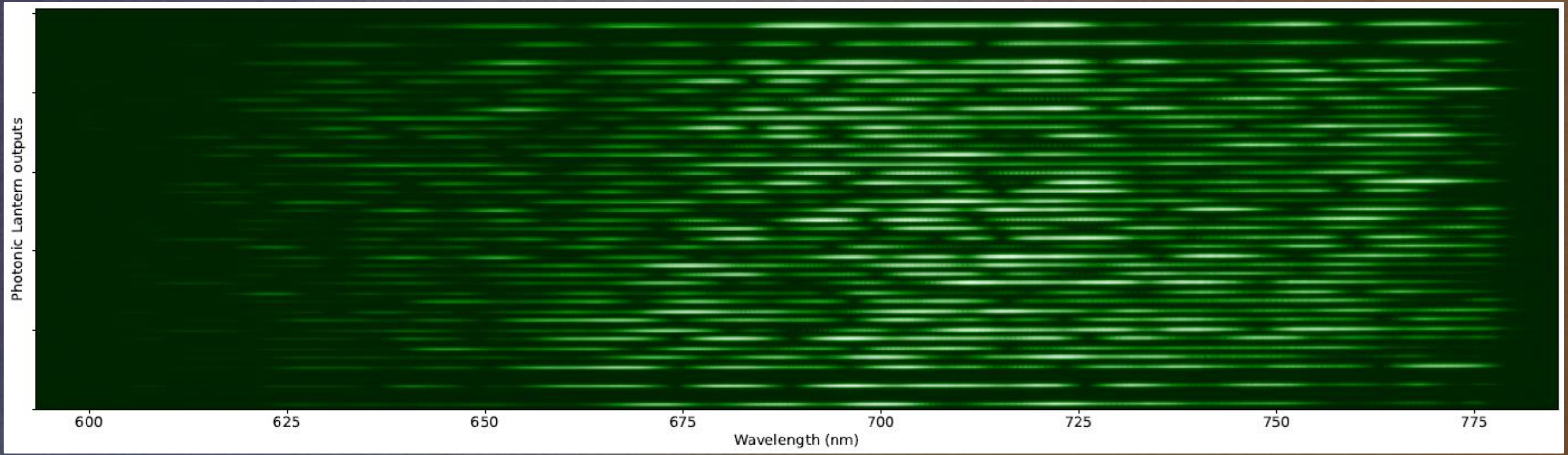






Visible Photonic Lantern – Data acquisition

38 spectra on the detector (19 x 2 polarizations)
→ **Flux repartition** between the PL outputs depends on **the source position/shape** and the **injected wavefront**
→ Spectral structures appear depending on the injected PSF size (~injected beam focal ratio or F#)



PL imaging the SCExAO internal super continuum source (F#4)

→ **How to properly inject light into the Photonic Lantern ?**

Visible Photonic Lantern – Coupling maps

To efficiently couple light into the PL, the PL core (~25um) must be centered on the injected PSF.
This optimal position of the PL is found using **coupling maps**.

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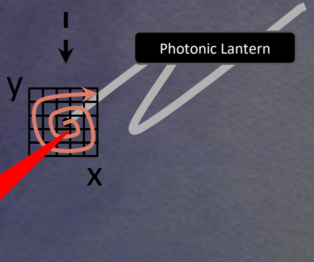
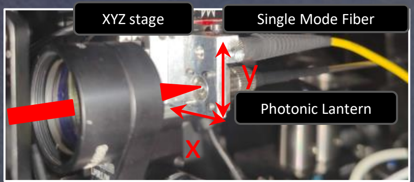
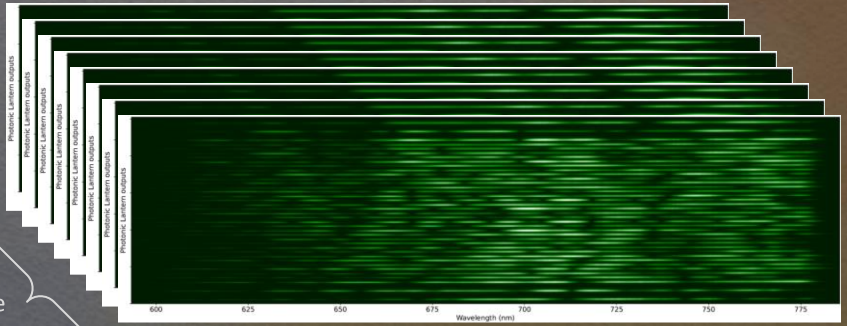
Move PL mount to position (x,y) → Record PL image → Scan done ? — No → Move PL mount to position (x,y); Yes → **Coupling maps**

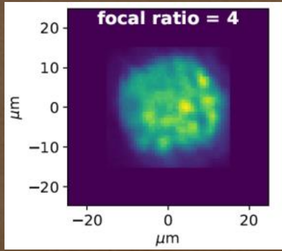


Converging beam (F#) from the injection bench



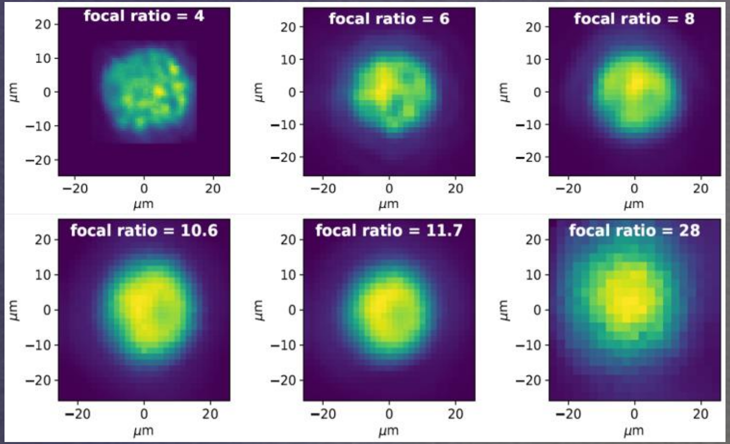


One image per position



Visible Photonic Lantern – Coupling maps

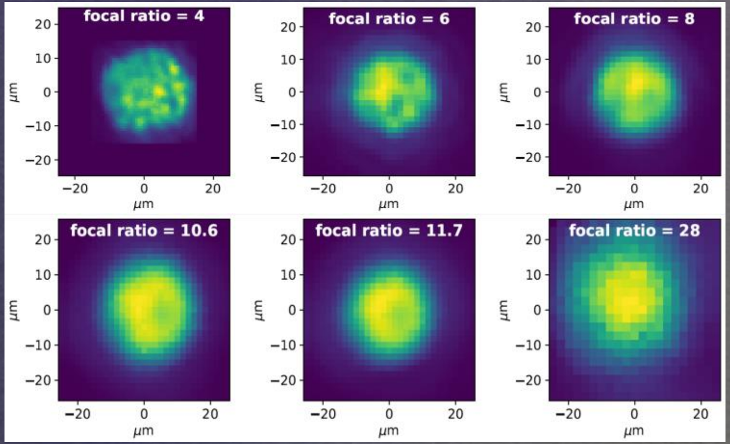
- Coupling maps for various focal ratios (or PSF size)



→ Less structures when focal ratio increases

Visible Photonic Lantern – Coupling maps

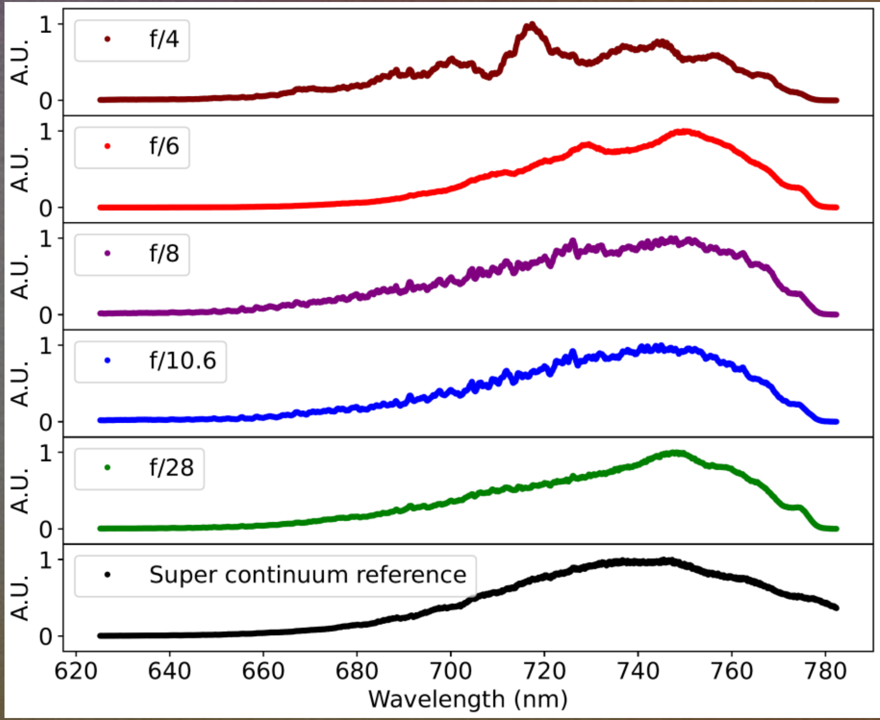
- ❖ Coupling maps for various focal ratios (or PSF size)



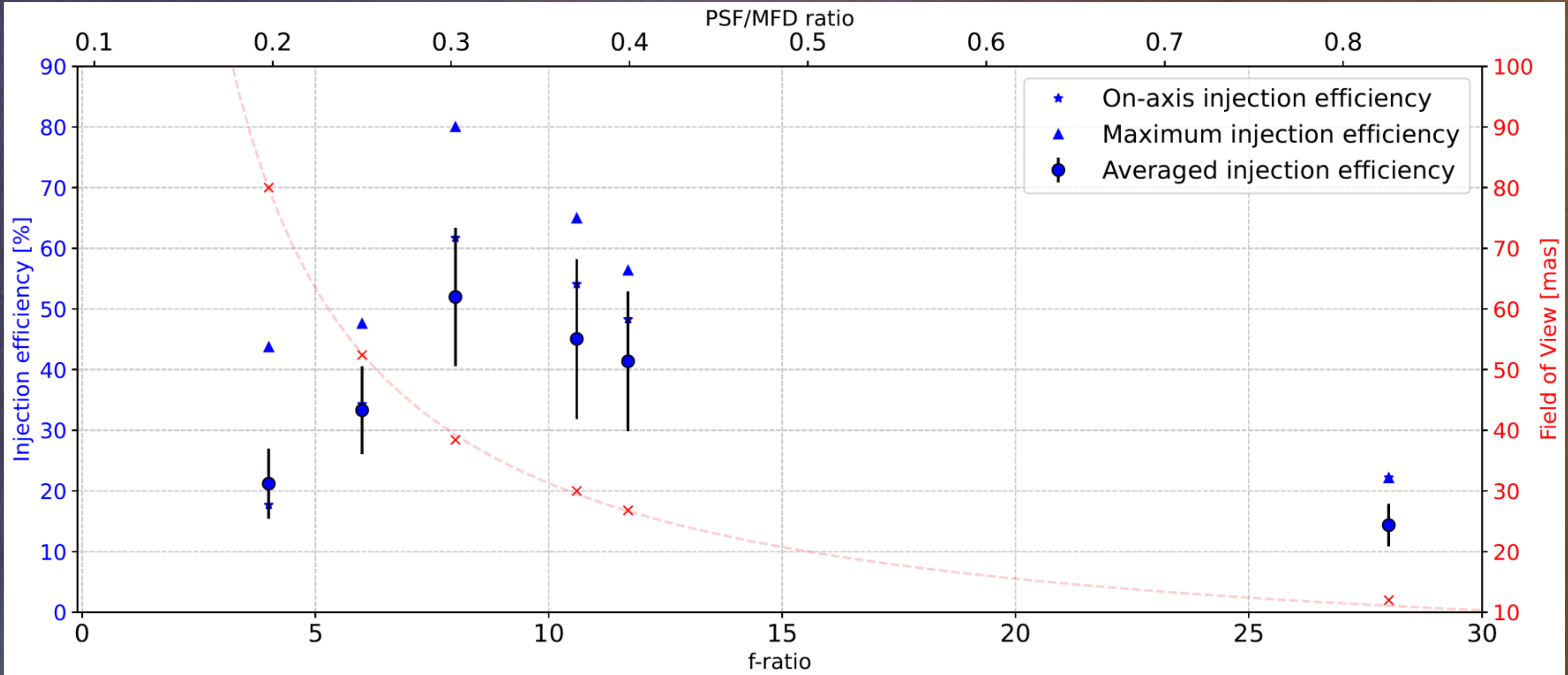
→ Less structures when focal ratio increases

- ❖ Spectrum reconstruction at various focal ratios

→ Spectral information loss for low focal ratios



Visible Photonic Lantern – Injection efficiency



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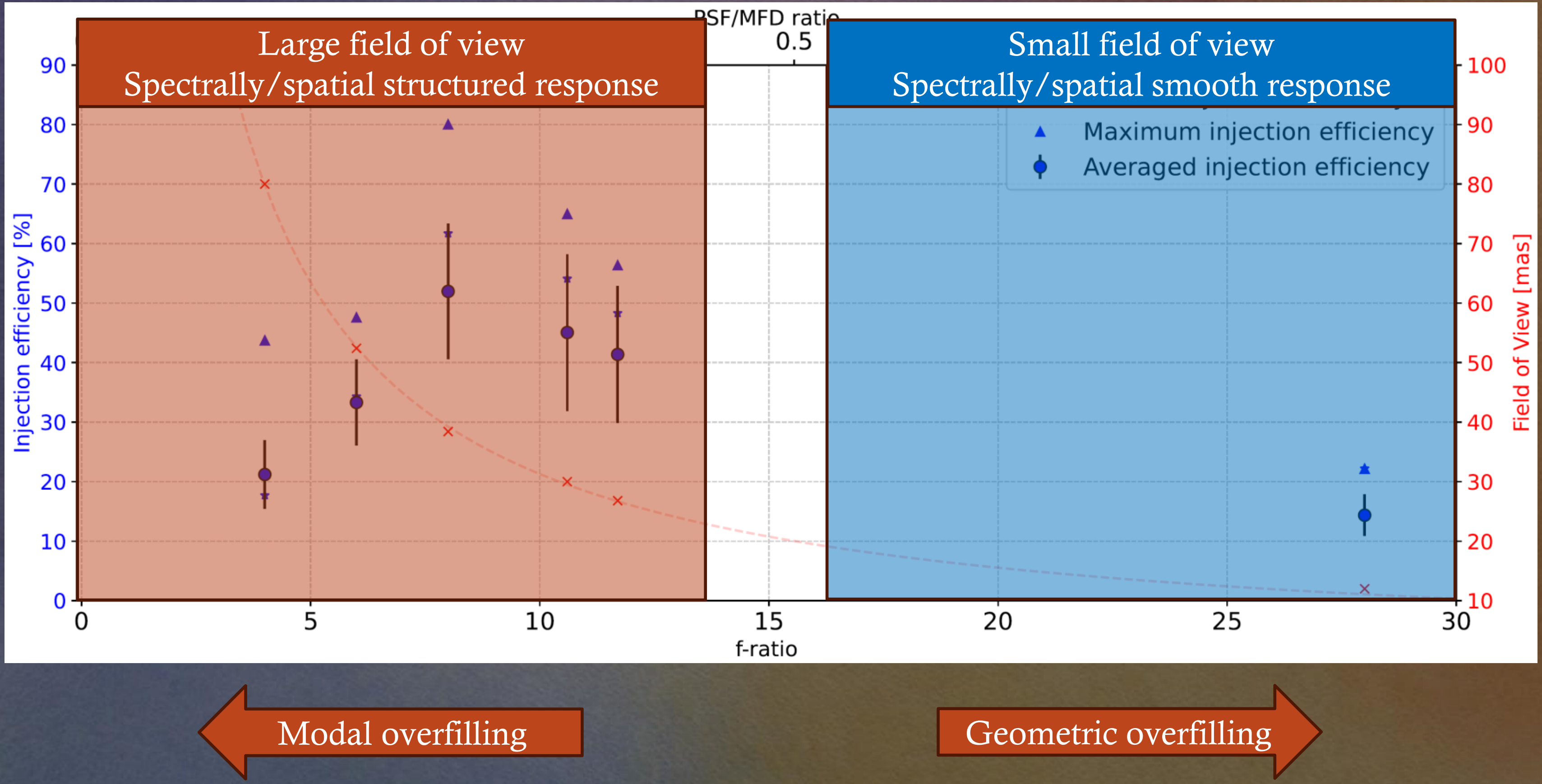

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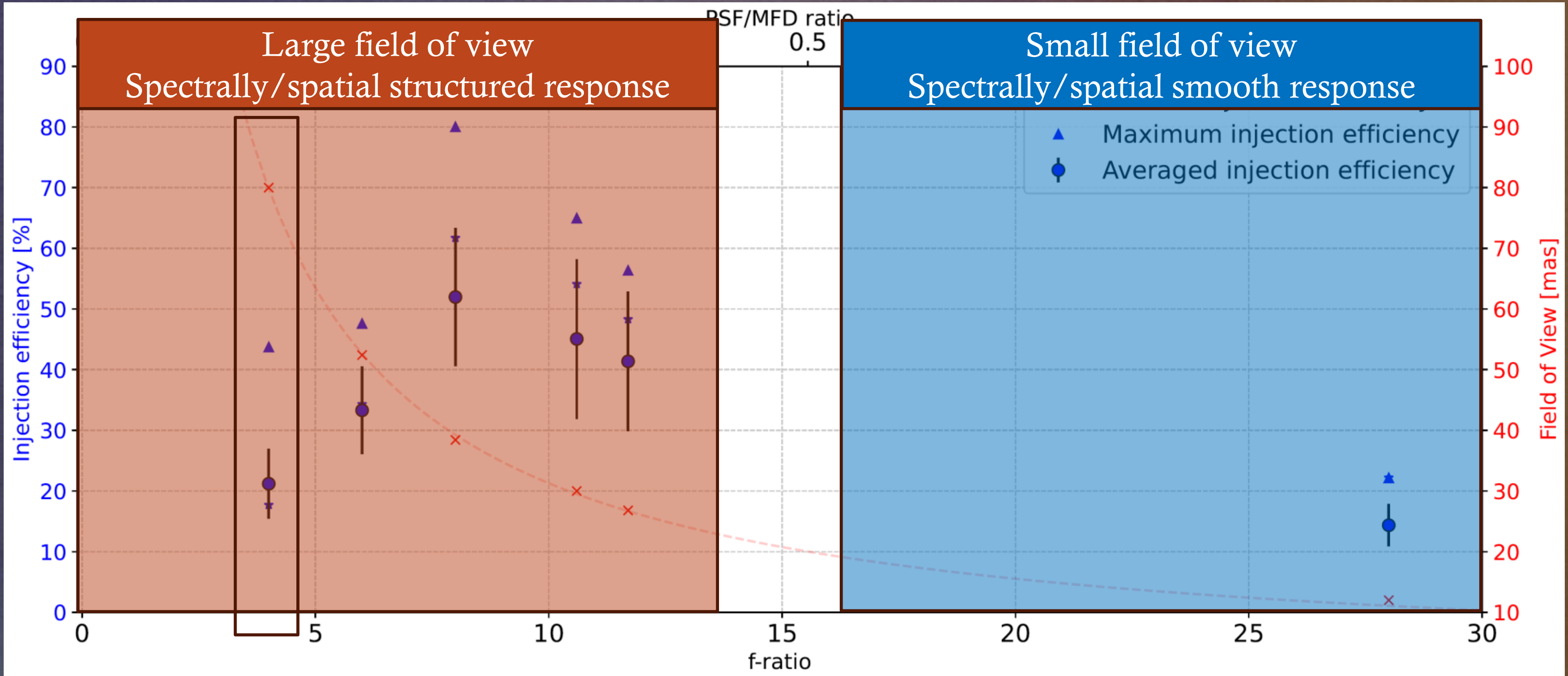
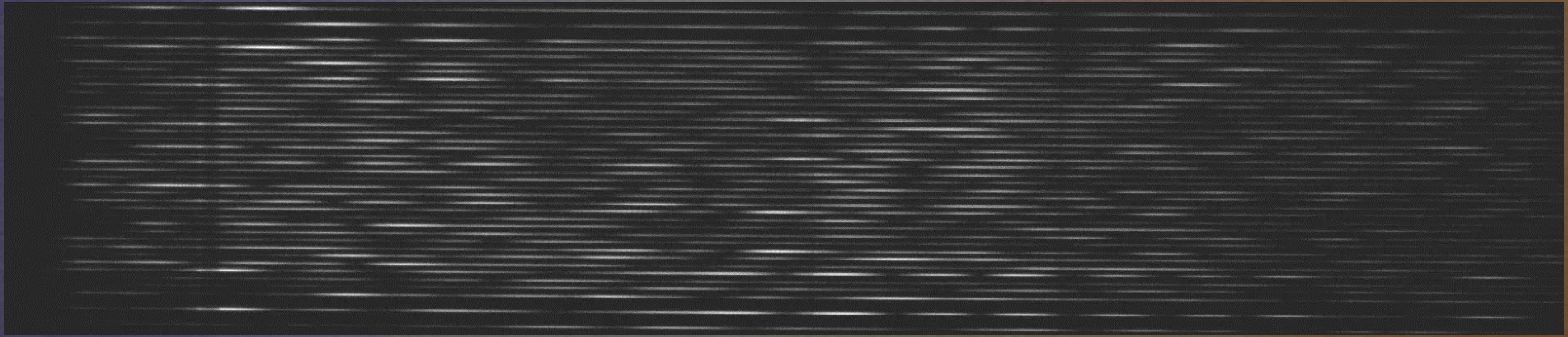


Modal overfilling

Geometric overfilling

Visible Photonic Lantern – On-sky testing on **Humu**

- Observation of Humu [*Altair*]
- Raw data – 5 ms exposure
- Medium seeing conditions (0.6 arcsec reported)

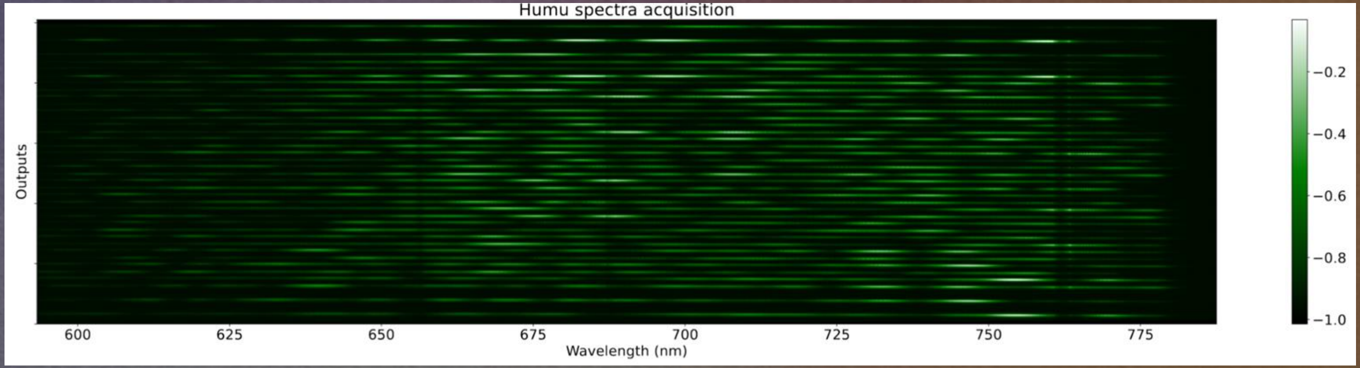


- Fast residual wavefront error (~100Hz) redistributes light among the 38 spectra → Fast chromatic modulations

Visible Photonic Lantern – On-sky testing on **Humu**

Humu [*Altair*] test on-sky:

- **Large FoV - f-ratio ~ 4**
- **Medium seeing conditions**
- 5ms exposure
- 12000 frames averaged
- 1D spectrum extraction : **Extract each row (A)** and **co-add spectra (B)**



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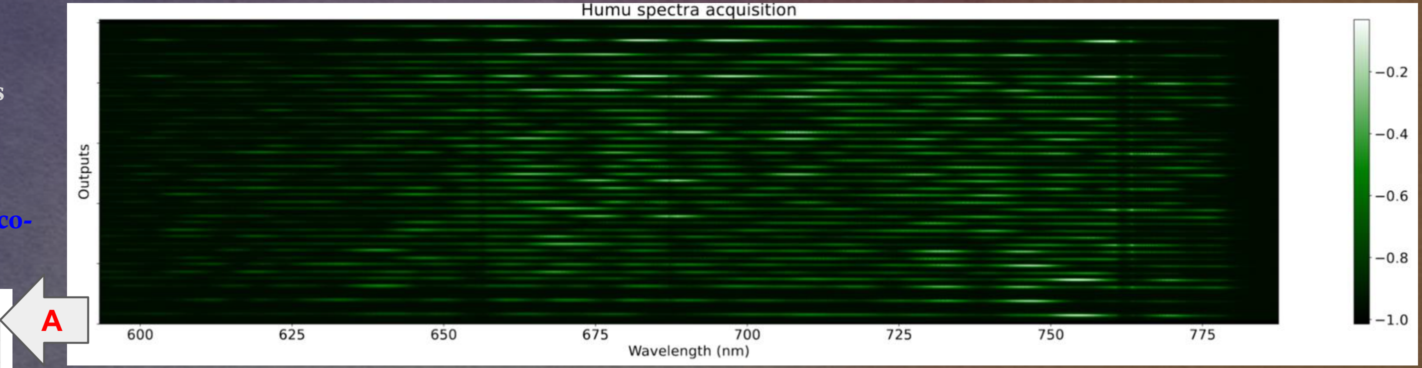

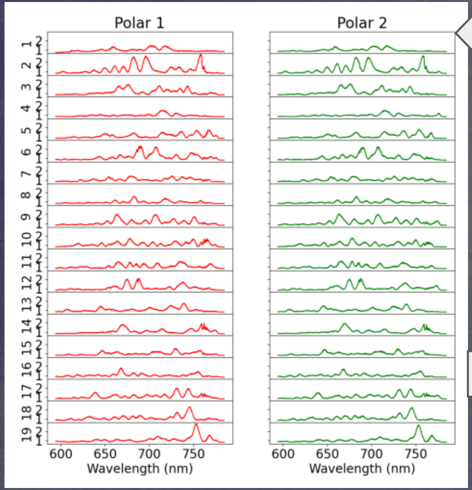

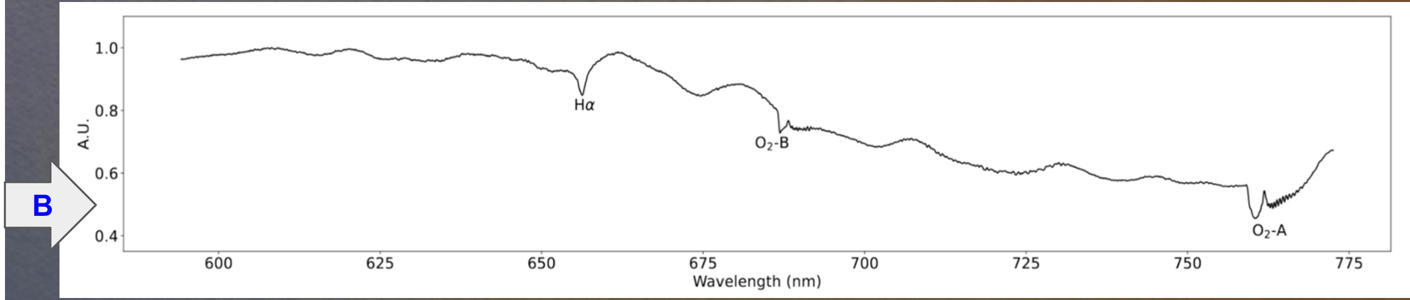

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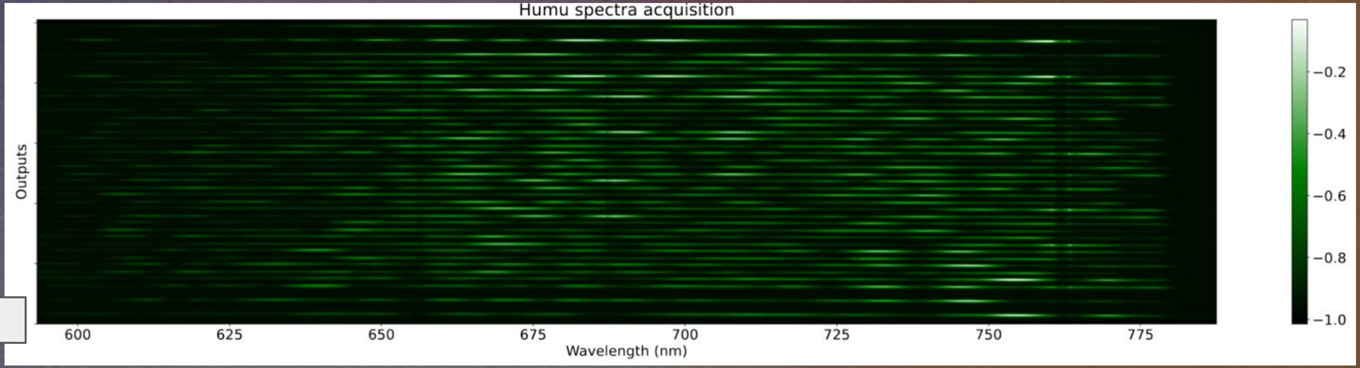
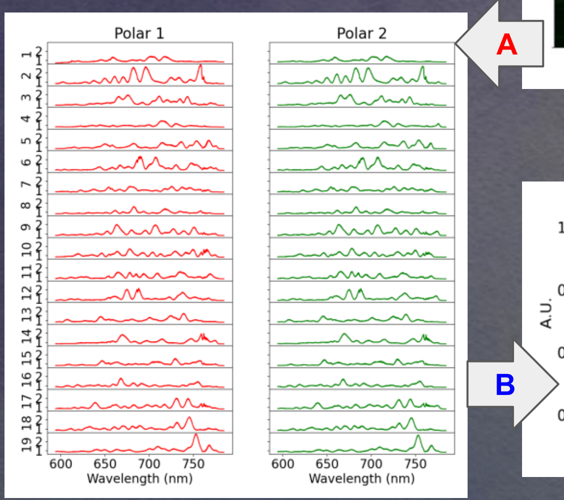
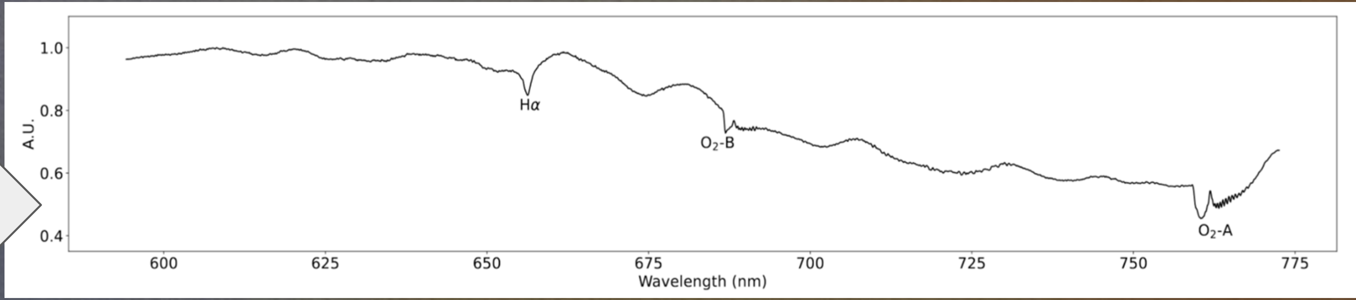


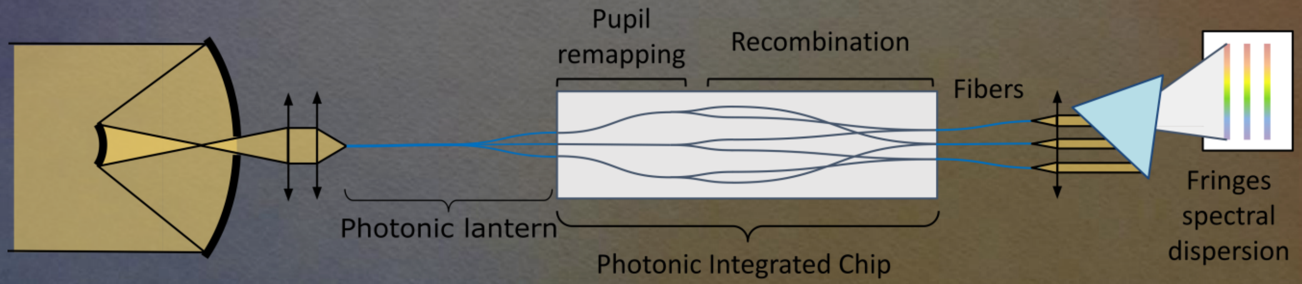




→ **Coupling efficiency estimation : 6% average - ~11% at best (in lab, 18% obtained)**

Conclusion & Perspectives

- Photonic Lanterns can enable self calibrated **high efficiency spectroscopy** with SMFs (deployable mini IFUs, radial velocity…) → various applications depending on the selected focal ratio
- More tests to come on-sky for instrument commissioning
- **Key perspectives for the future :**
  - **Coupling with high resolution spectrograph (R-60,000)** for H-alpha line characterization
  - **Enabling Extreme Precision Radial Velocity measurments**
  - **Combination with photonic chips**



  - **Waverfont sensing** (petalling, cophasing, NCPAs, Self calibration)

Properties of Photonic Lanterns

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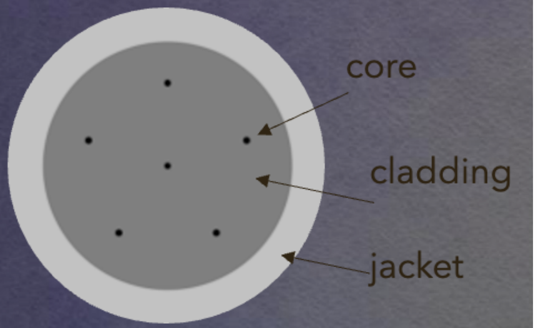
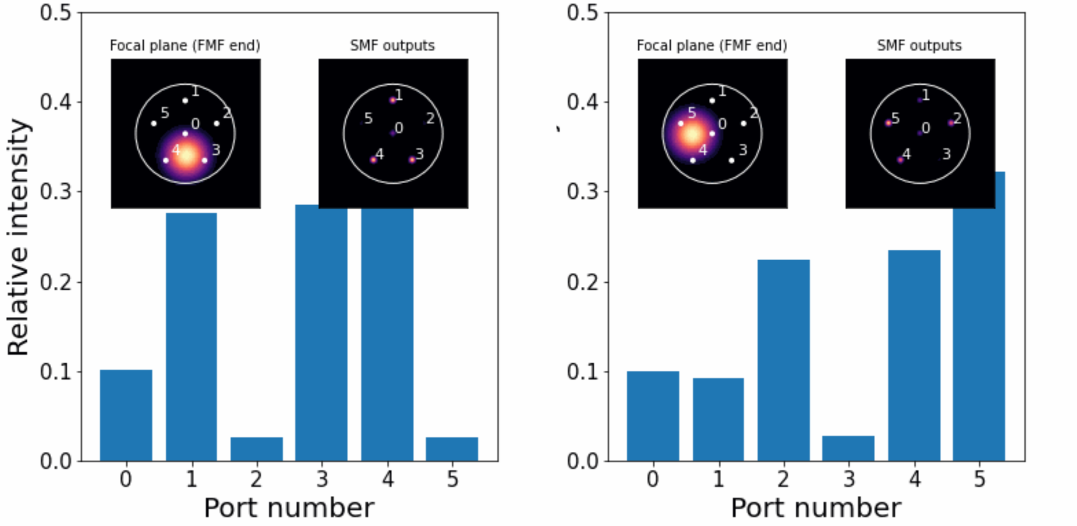


Photonic Lantern with
6 SMF outputs

Numerically simulated intensity responses for a standard 6-port PL

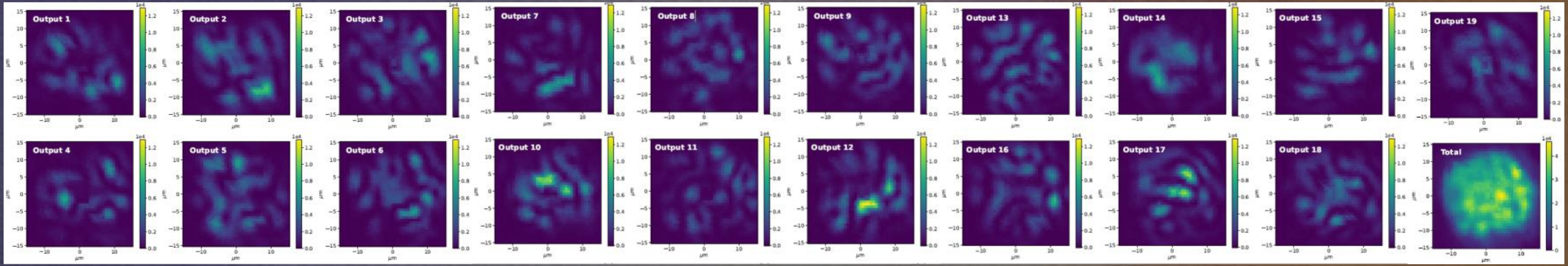


Simulations by Yoo-Jung Kim

→ PL outputs can be used **for constraining the input scene for science applications**.

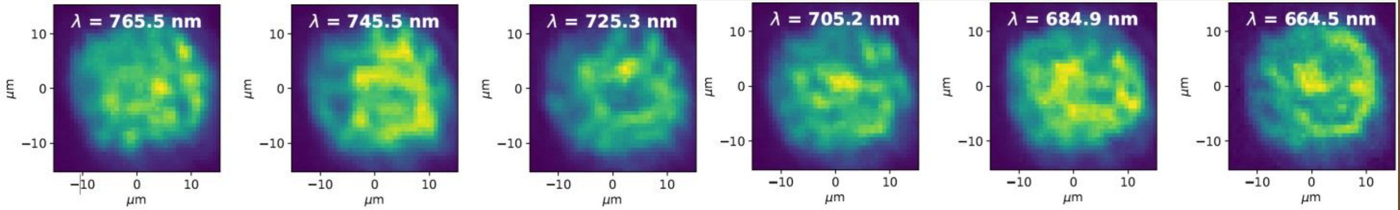
Visible Photonic Lantern – Coupling maps

- Coupling maps for 19 outputs + Total @ 765nm



→ **High order structures** on each output maps - smoother on the total (ratio darkest/brightest ~ 0.4)

- Coupling maps at various wavelengths

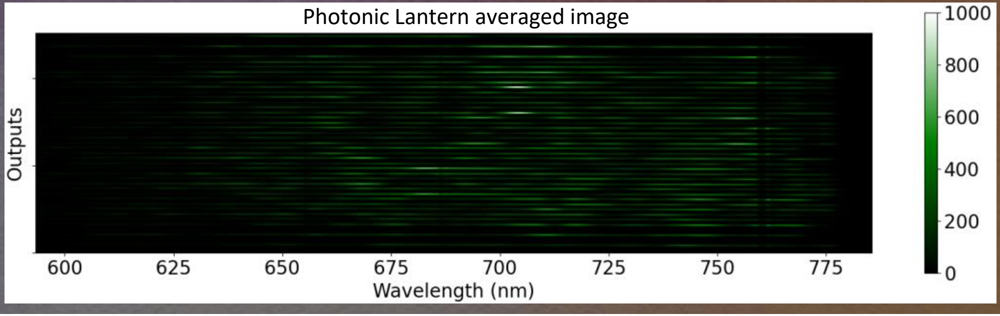


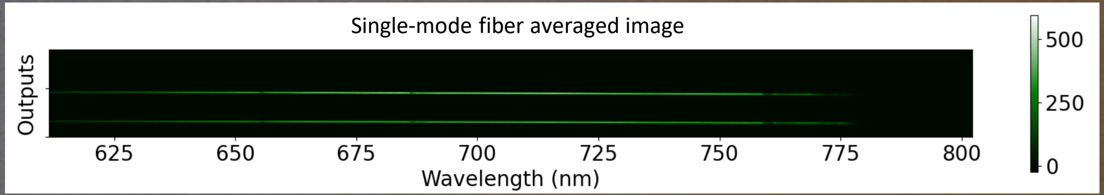
→ **Pattern changes with the wavelength**

Visible Photonic Lantern – On-sky testing on **Pōʻā**

Pōʻā [*Algol*] :

- 20ms exposure
- 3000 frames averaged
- 1D spectrum extraction : Extract each row and co-add spectra





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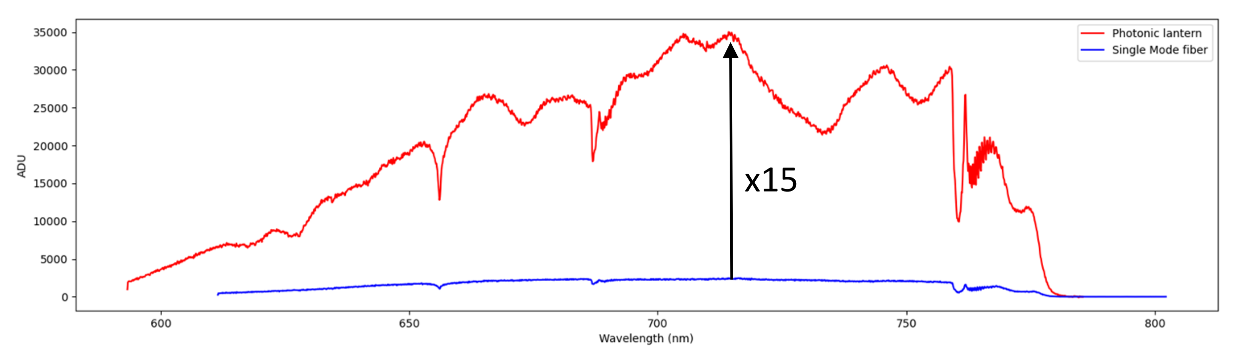
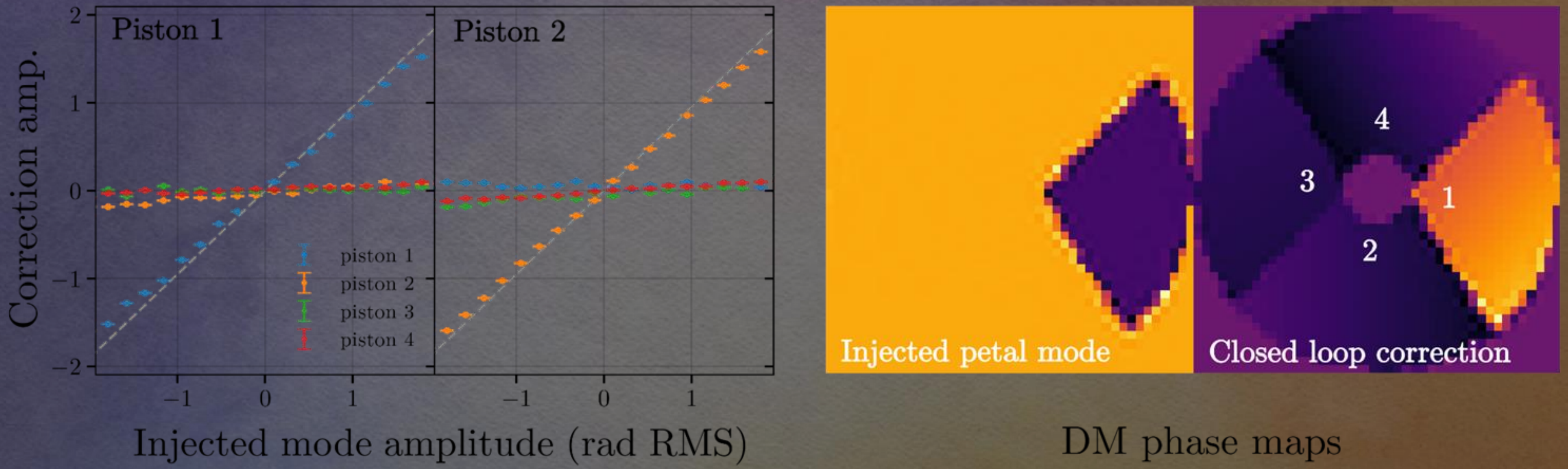


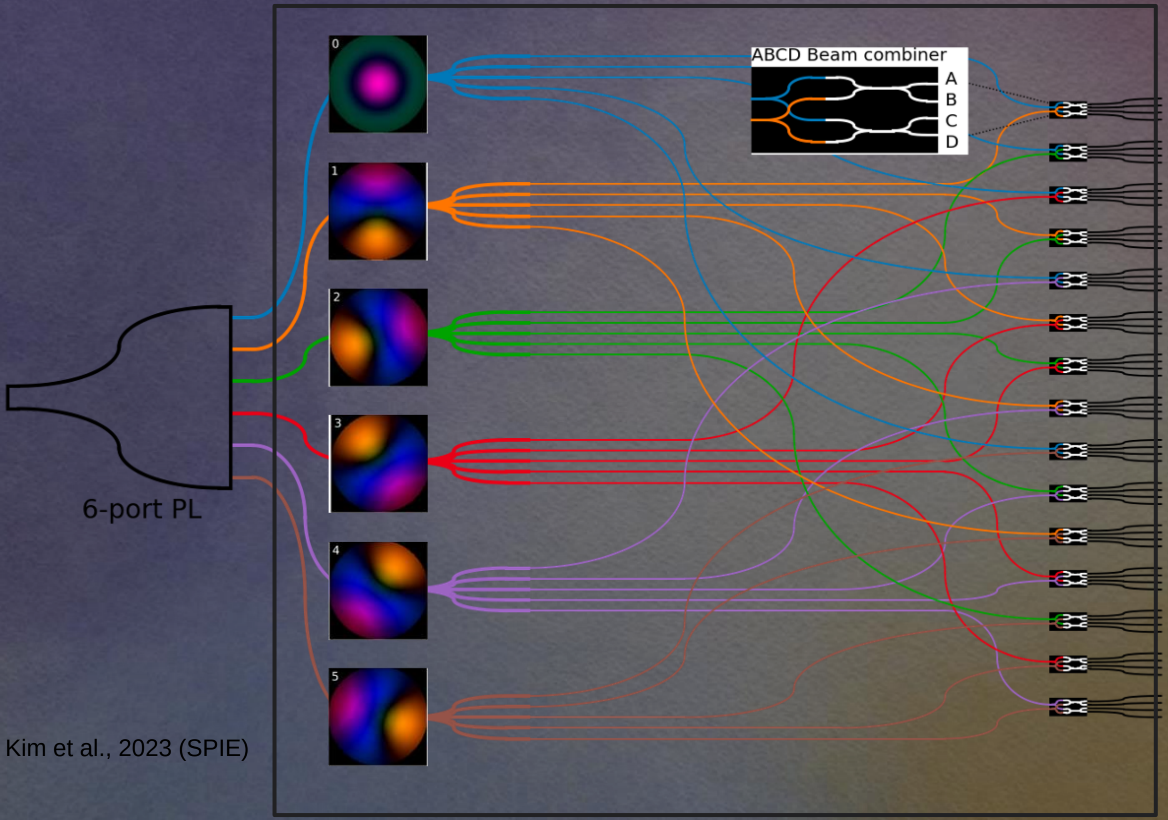
- Comparison with SMF spectroscopy (same exposure time, spectrum extracted from 3000 averaged frames)
- At best, gain x15
- Overall, x12.5 more flux

Correction of static aberrations: petalling / low wind effect – Work by Jon Lin



Correction of the **four petal-piston modes** out to ~2 radians RMS

Interferometric imaging with Photonic Lanterns



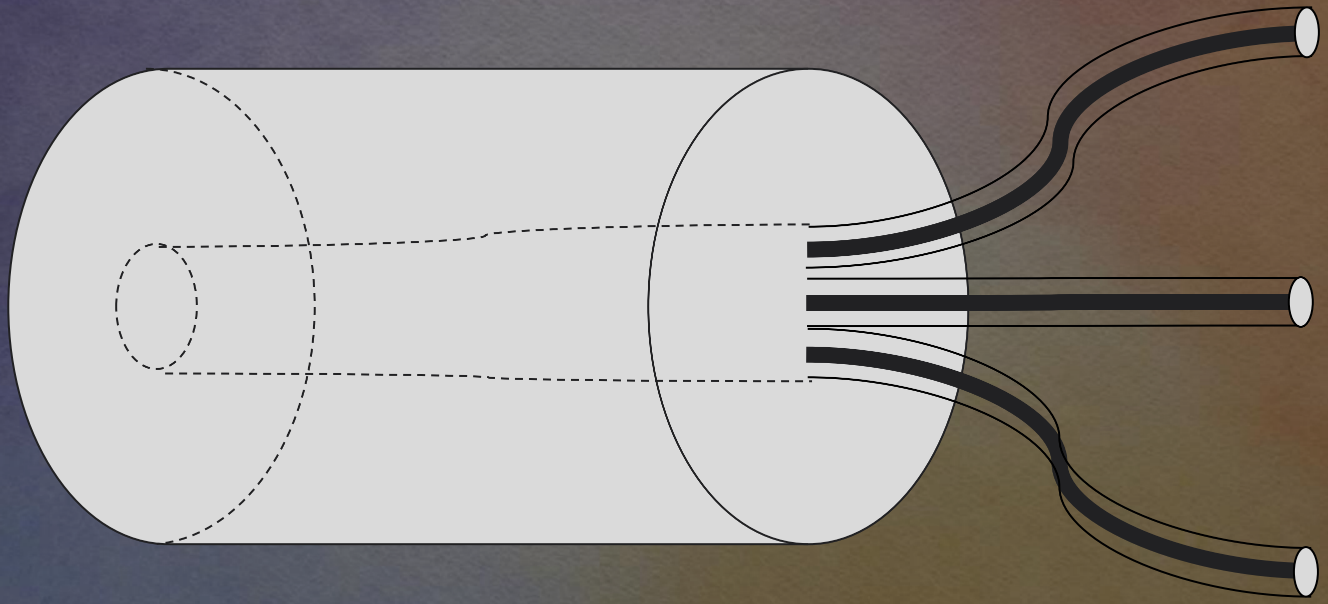
Kim et al., 2023 (SPIE)

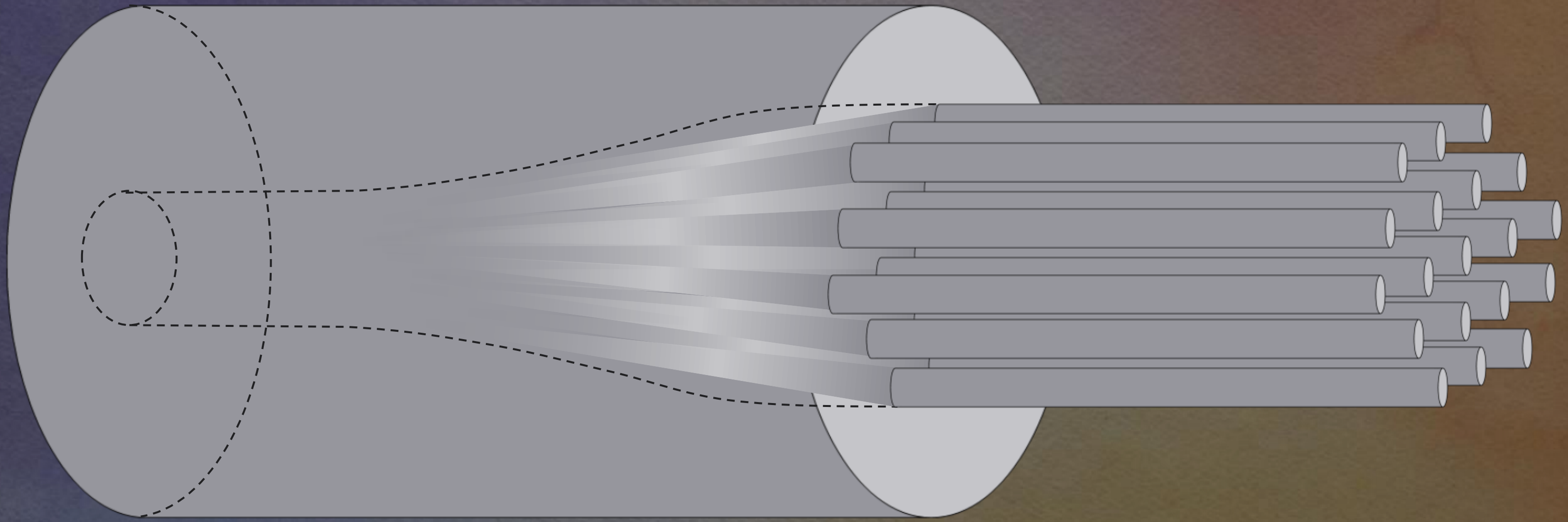
Backend photonic chip beam combiner

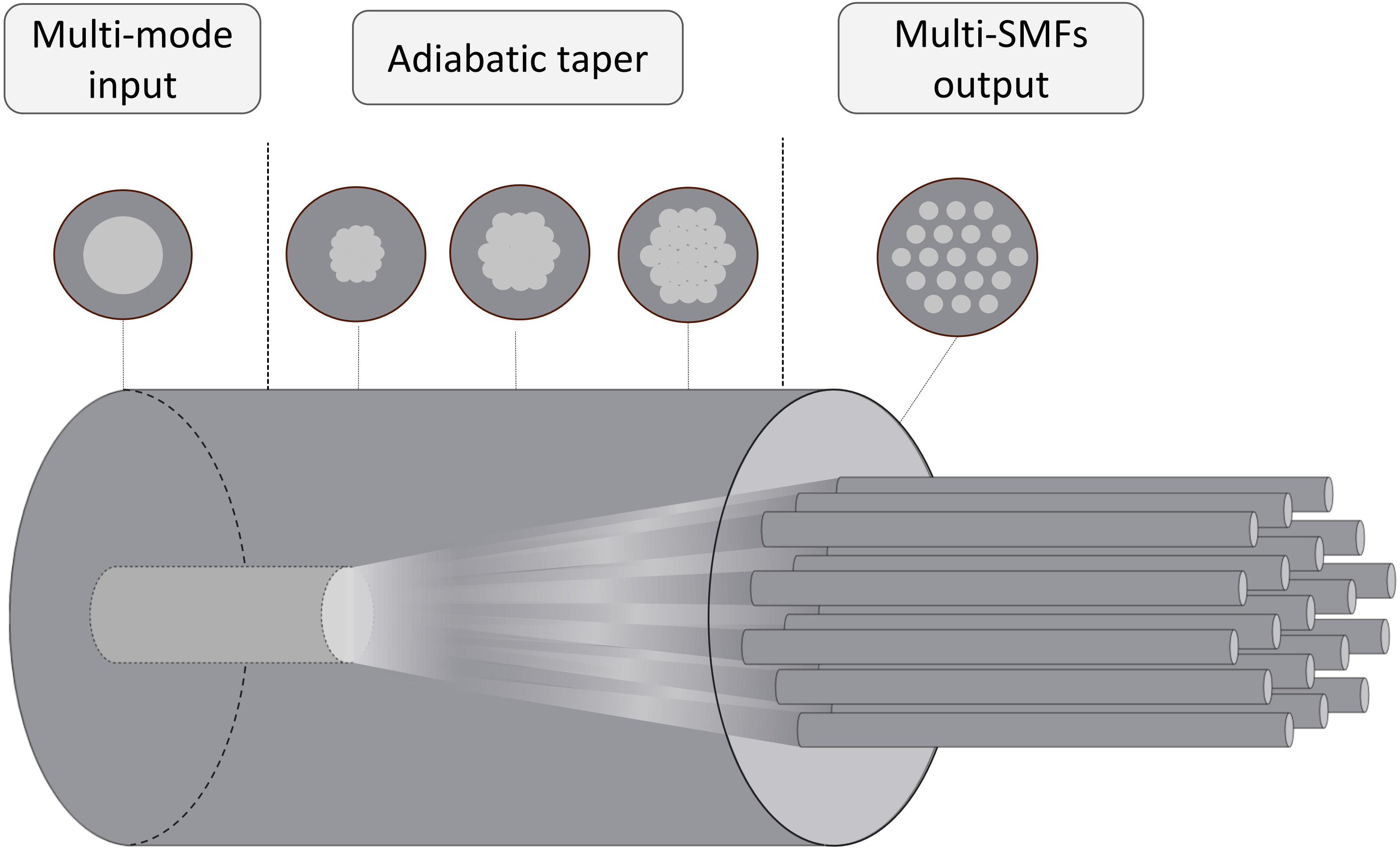
A **pairwise beam combination** of PL outputs (e.g., ABCD beam combiner) to measure coherence properties in the incoming wavefront filtered by different apertures (PLPMs).

(Single telescope interferometry)

$$\mathcal{V}_{ij} = \frac{(I_{ij,A} - I_{ij,B}) + (I_{ij,C} - I_{ij,D})i}{I_{ij,A} + I_{ij,B} + I_{ij,C} + I_{ij,D}}$$






Multi-mode input
Adiabatic taper
Multi-SMFs output