



Photonic lanterns for image reconstruction with FIRST-PL, a demonstration with HIP81126

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 - Taking modulated data
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 - Observing companions
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1. FIRST :

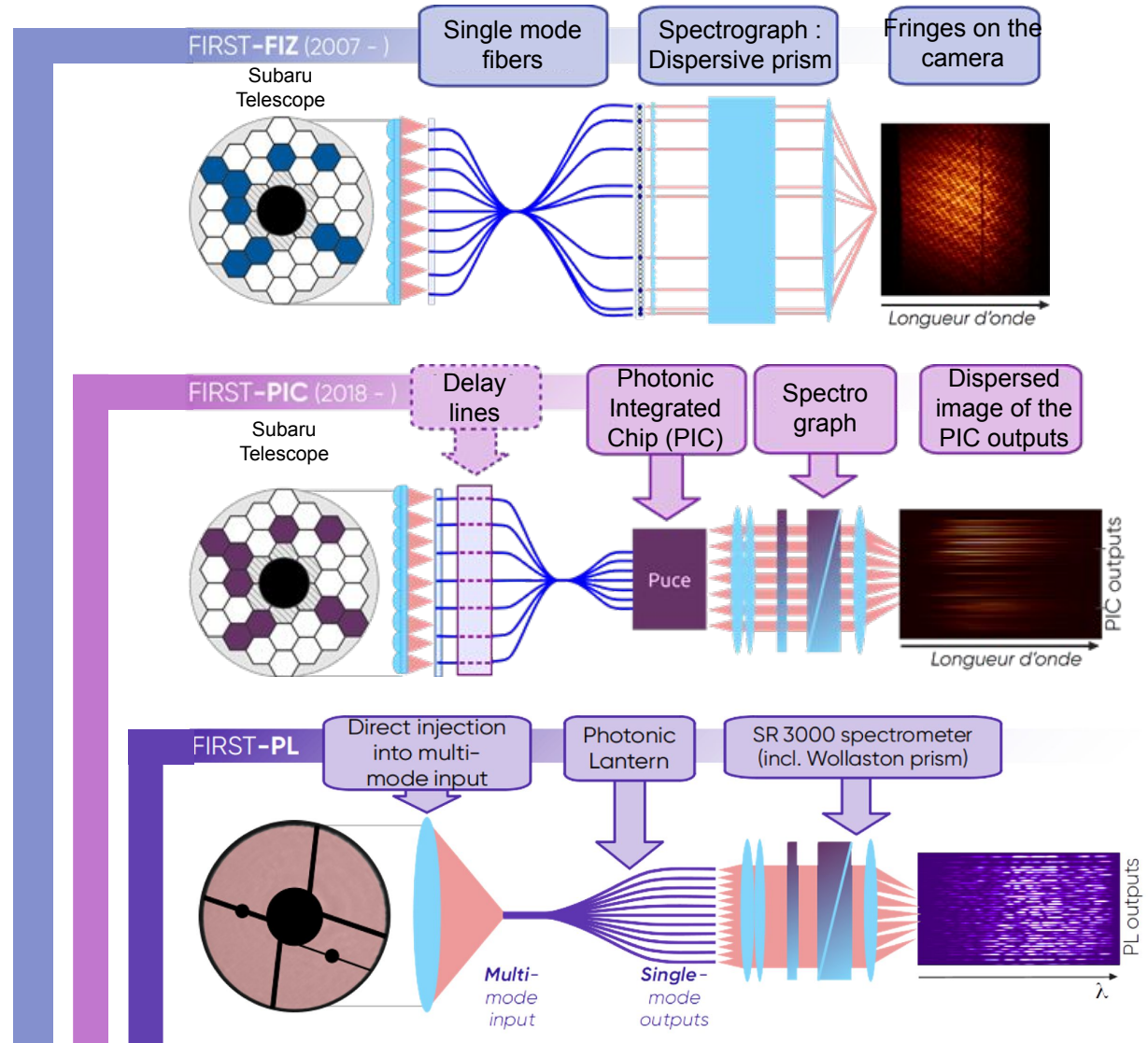
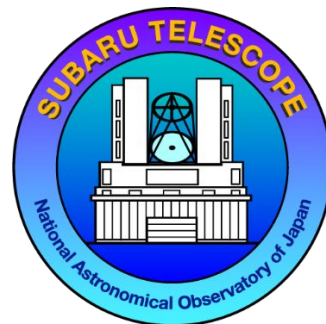
Fibered Imager for a Single Telescope

Three modes :

- **FIRST-FIZ**
- **FIRST-PIC**
- **FIRST-PL**

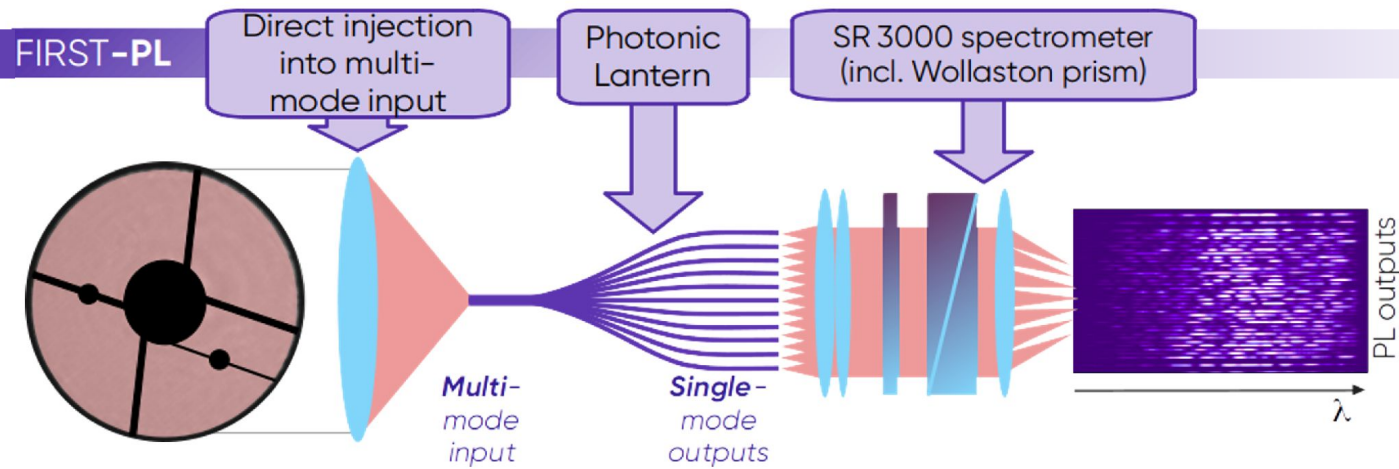
Current capacities with **FIRST-PL** :

- Wavelength range : 630-780 nm
- Resolution : 25 mas
- Spectral resolution : 3000
- Field of view : 130 to 1000 mas

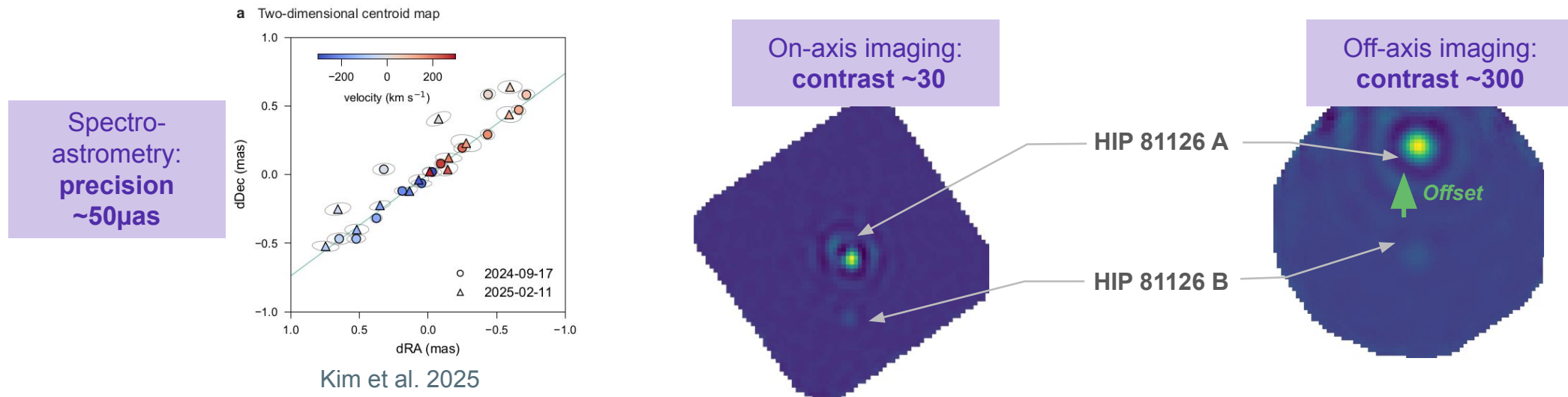


Credit: Elsa Huby

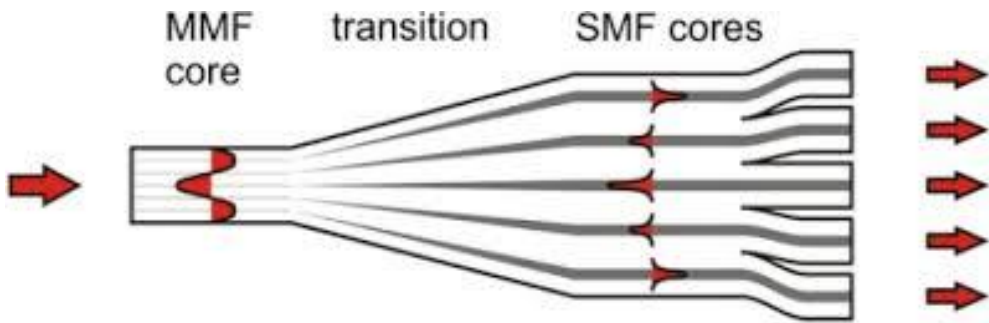
FIRST-PL : Introducing the Photonic Lantern for science operations on-sky



- Three modes : Spectro-astrometry, **on-axis imaging**, **off-axis imaging**

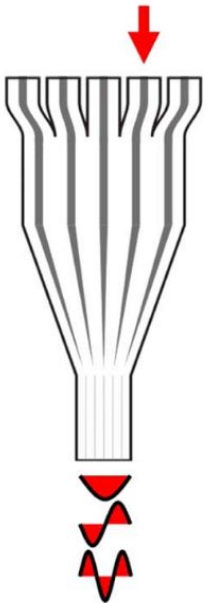
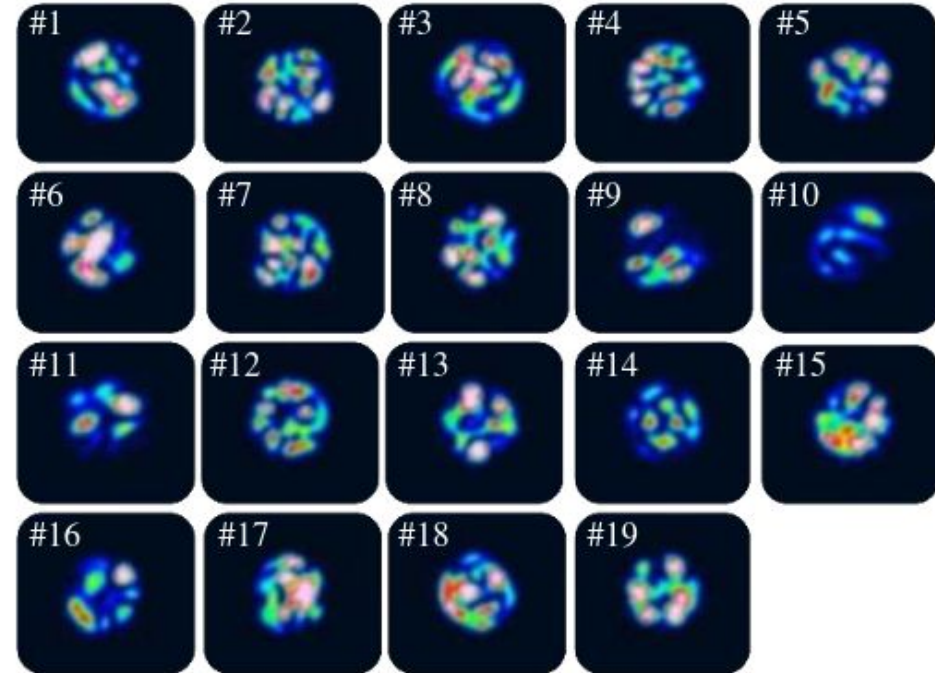


2. Photonic Lantern



Birks et al. 2015

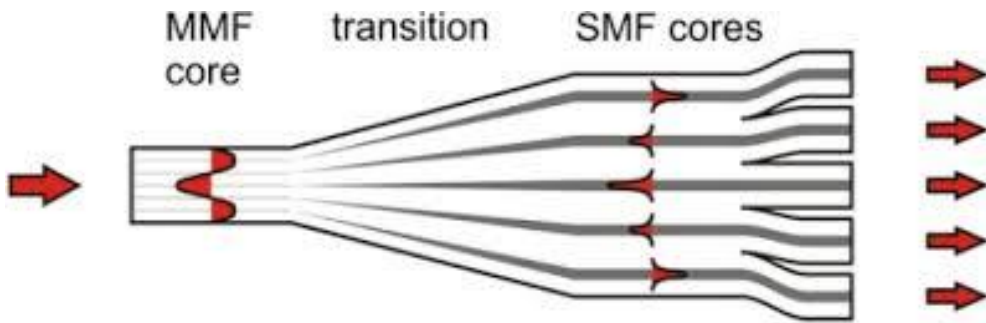
The light from the telescope is coupled into the MM fiber of the lantern, and slowly transitioned into several SM fibers.



Images obtained by injecting a laser light into the SM fibers and measured at the the MM entrance

Vievard et al. 2024

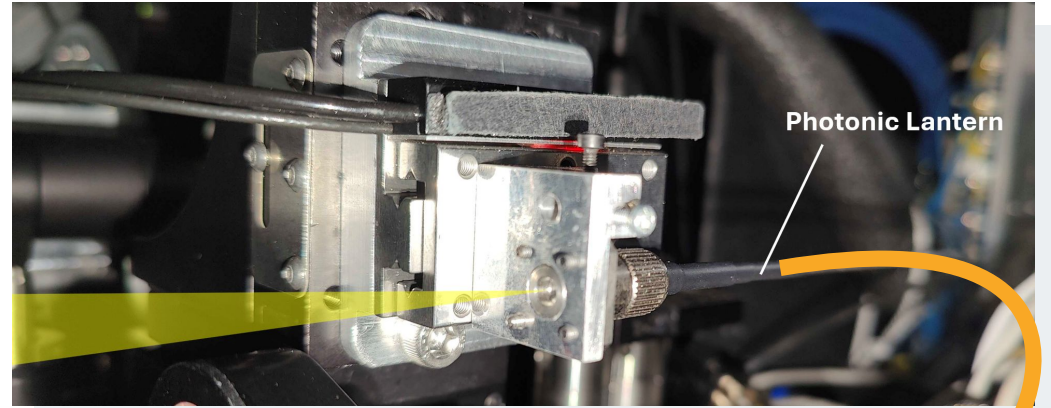
2. Photonic Lantern



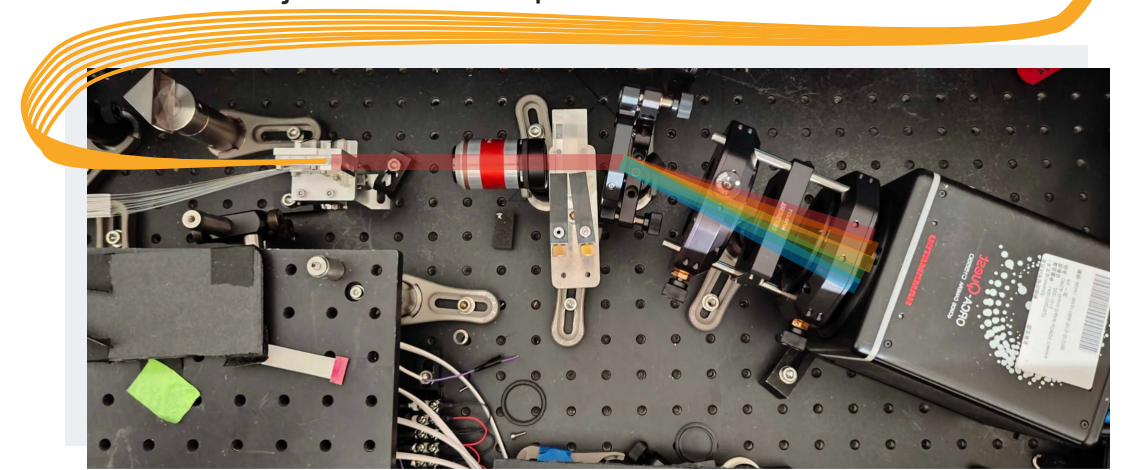
Birks et al. 2015

The light from the telescope is coupled into the MM fiber of the lantern, and slowly transitioned into several SM fibers.

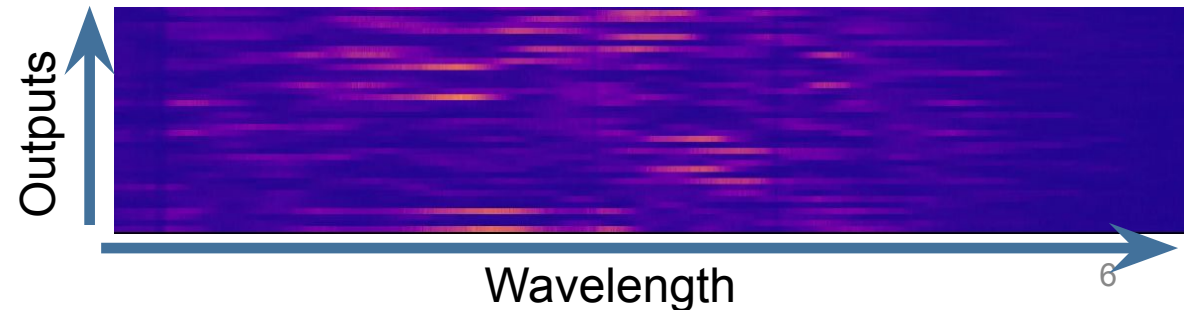
The SM fibers feeds a spectrograph : we collect both the spatial and spectral information of our target



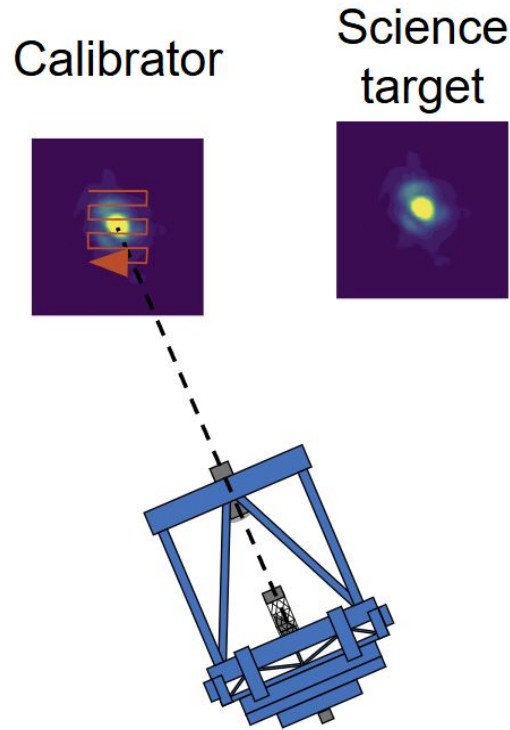
Injection into the photonic lantern MM end



Spectrograph (RS 3000)

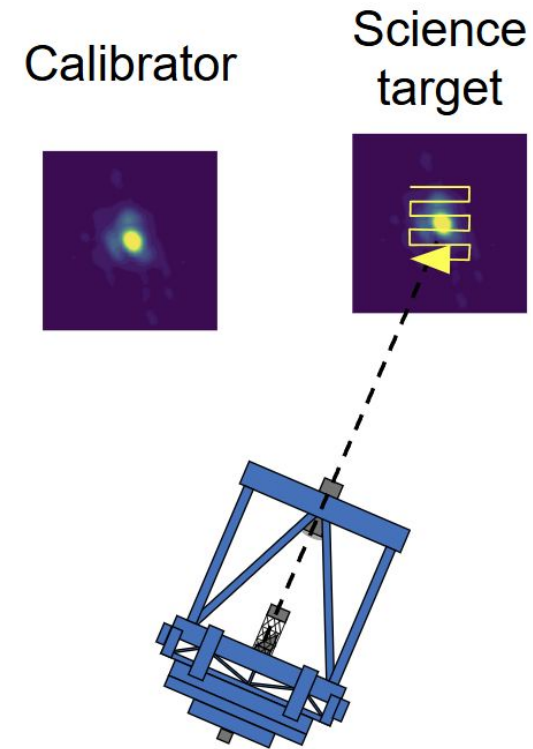


3. Utilizing the lantern for imaging



I – Calibration on a bright target

- Centering the PL
- Taking modulated data
- Building a response map of the lantern on the sky

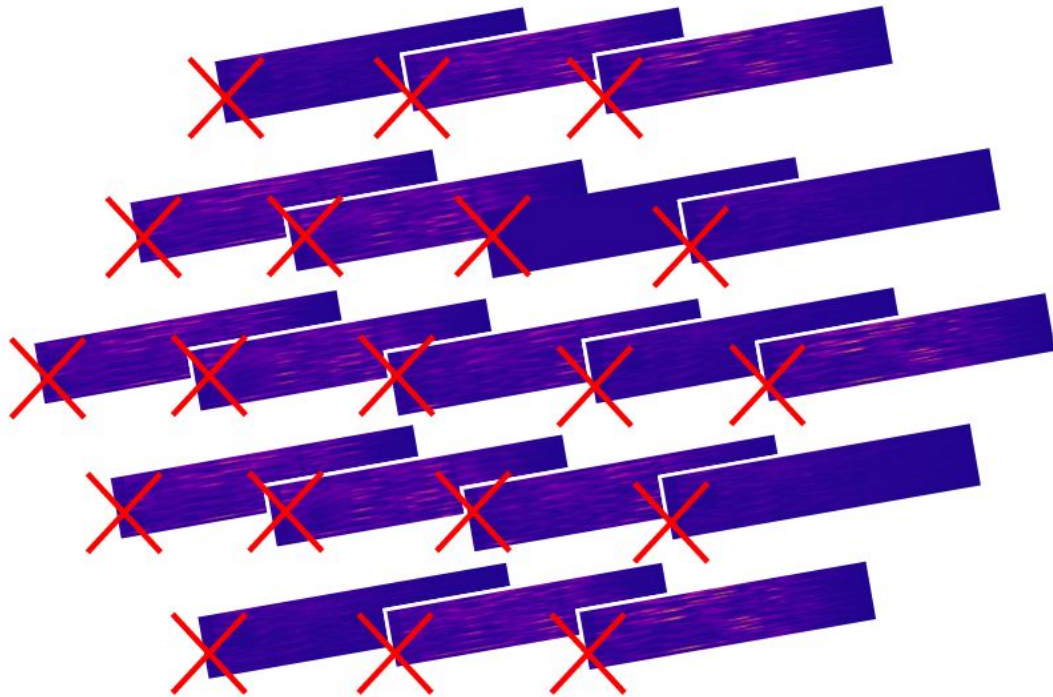


II – Imaging a science target

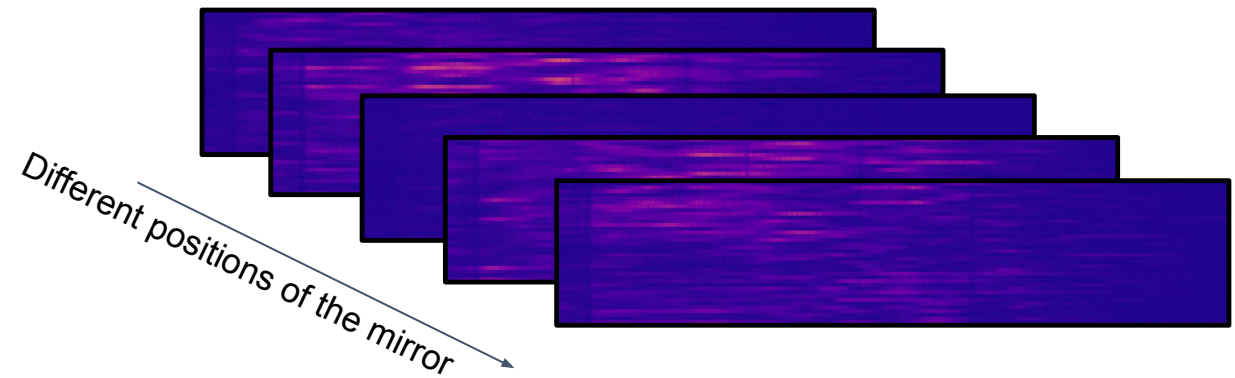
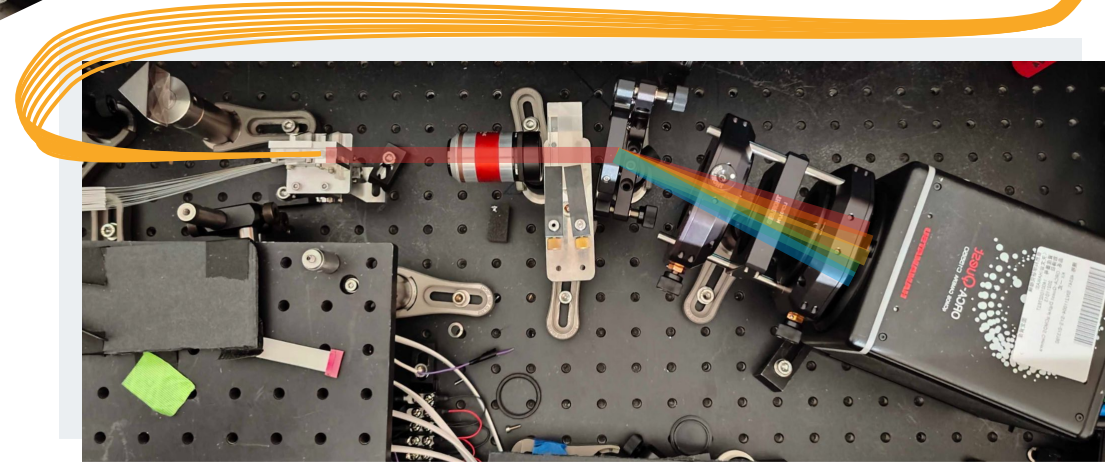
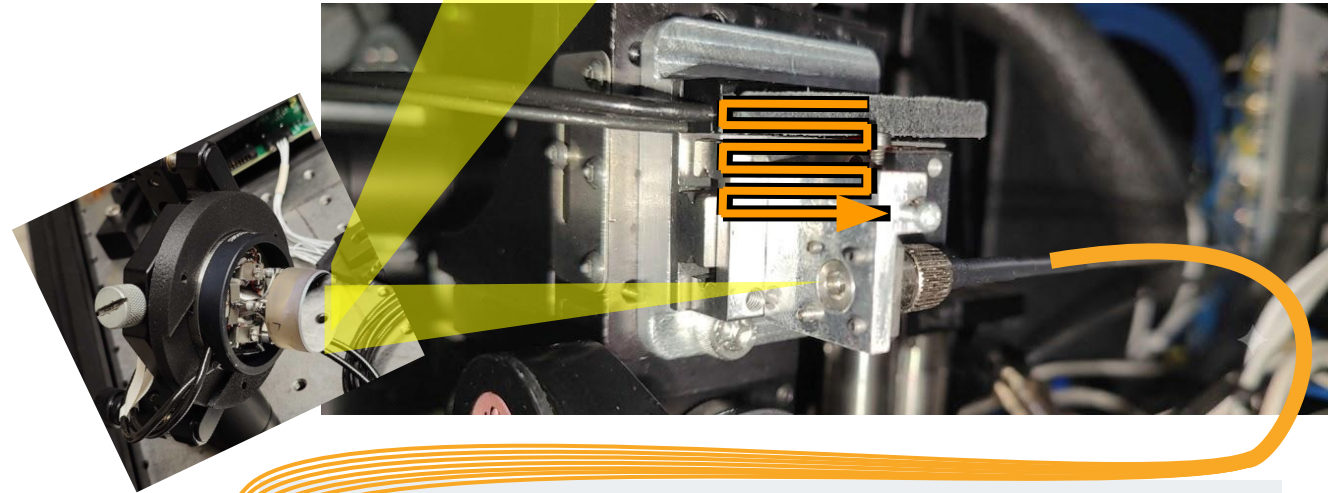
- Centering the PL
- Taking science data
- Reconstructing the input image thanks to the response map

Taking modulated data

A fast piezo tip-tilt mirror is used to capture images at different points in the sky following a modulated pattern

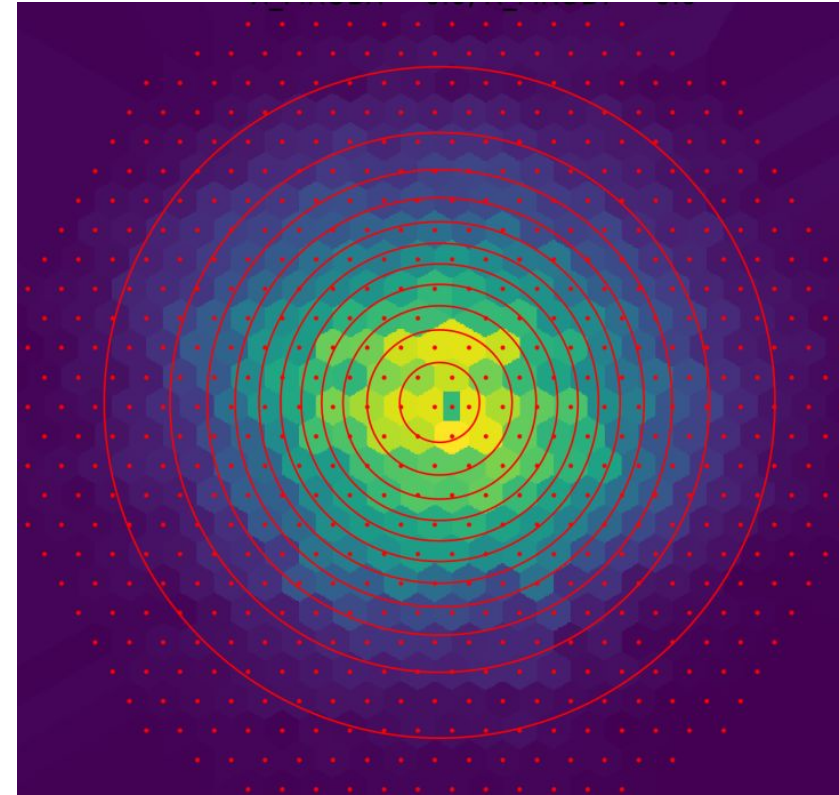
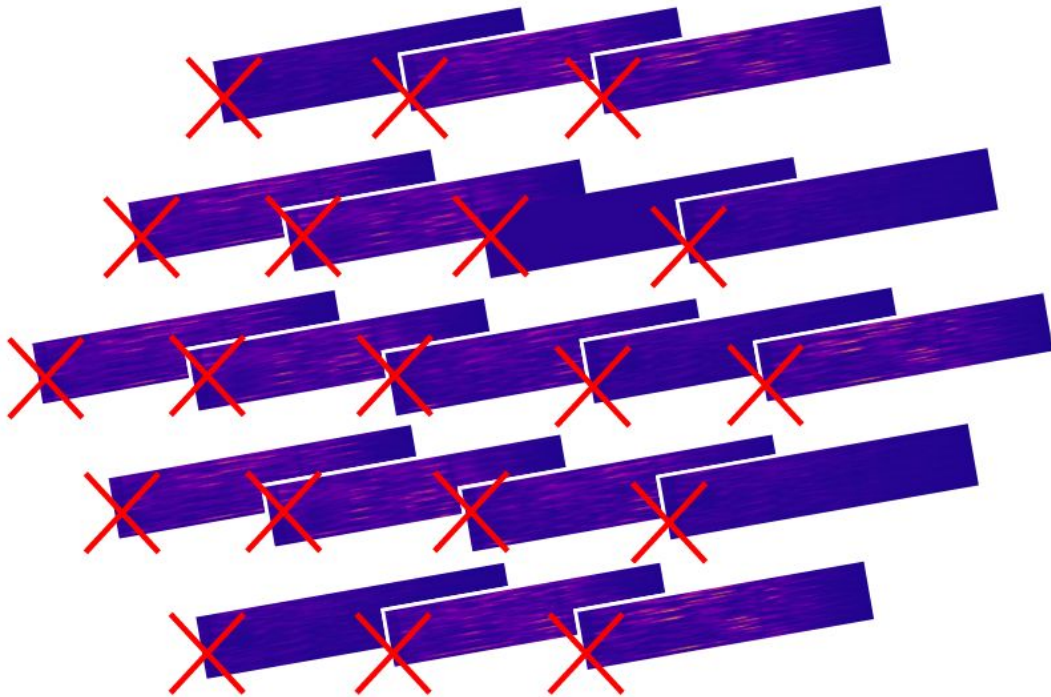


Map of all positions taken on sky



Centering the PL

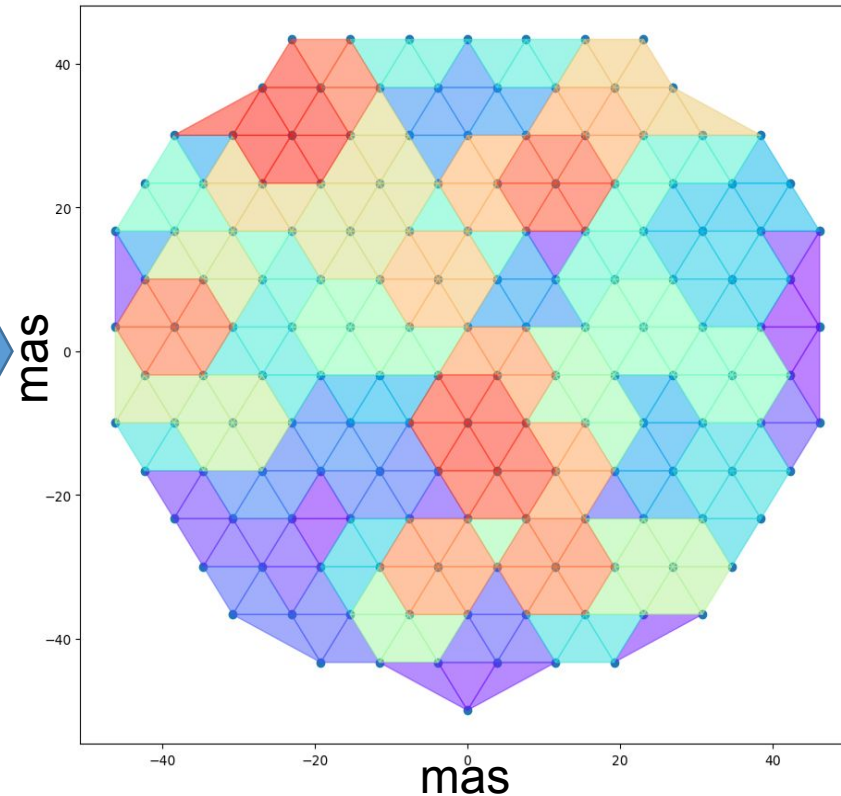
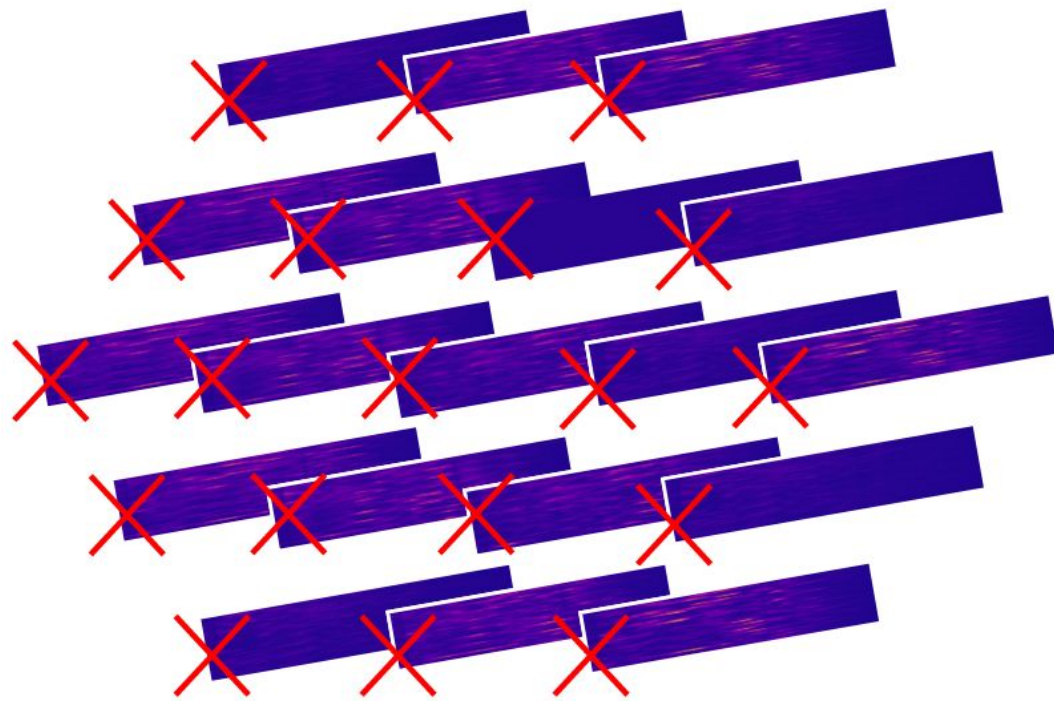
A fast piezo tip-tilt mirror is used to capture images at different points in the sky following a modulated pattern



Summing the total flux at each position gives us an « optimization map » to center the mirror on the target for the next modulation.

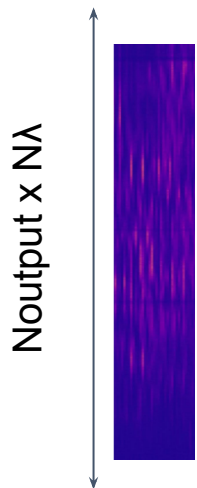
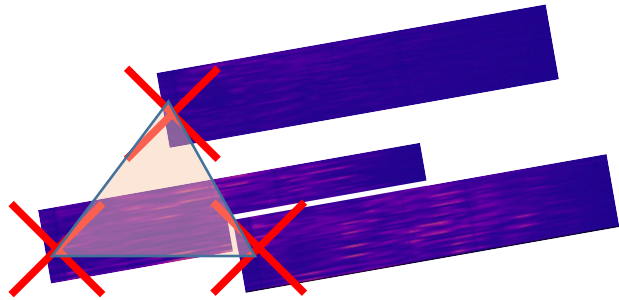
4. Image reconstruction : Calibration

A set of data with a fine modulation grid is taken on a bright point-like source.



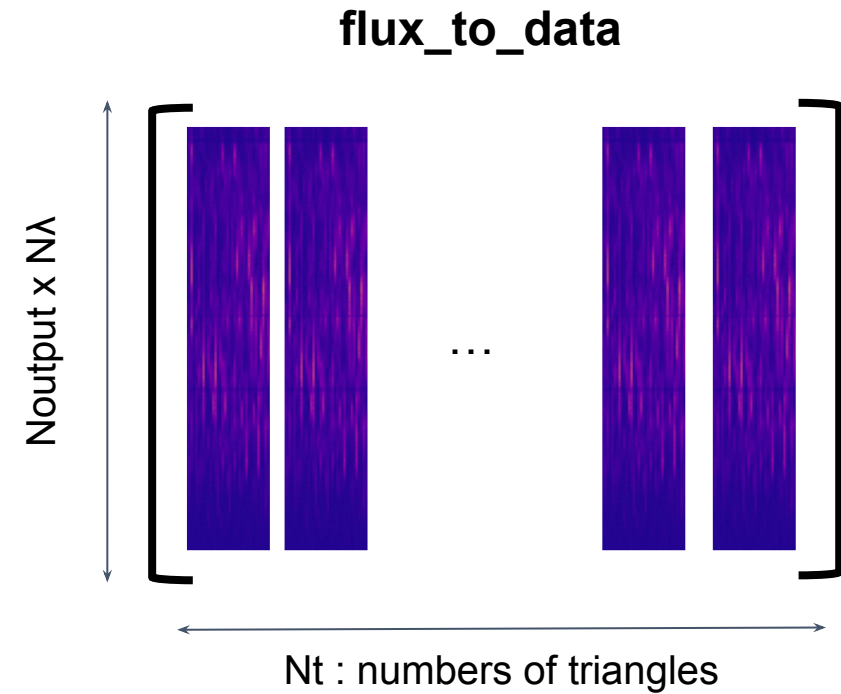
- 1) We construct a mesh of triangles from the points. This will have 2 purposes :
 - Calibrate the mean response of each triangle for image reconstruction (first order calibration)
 - Interpolate the response within each triangle to find the best fit model of a point-like source (second order calibration)

2) For each triangle of the mesh, we calculate the average flux among its three points :



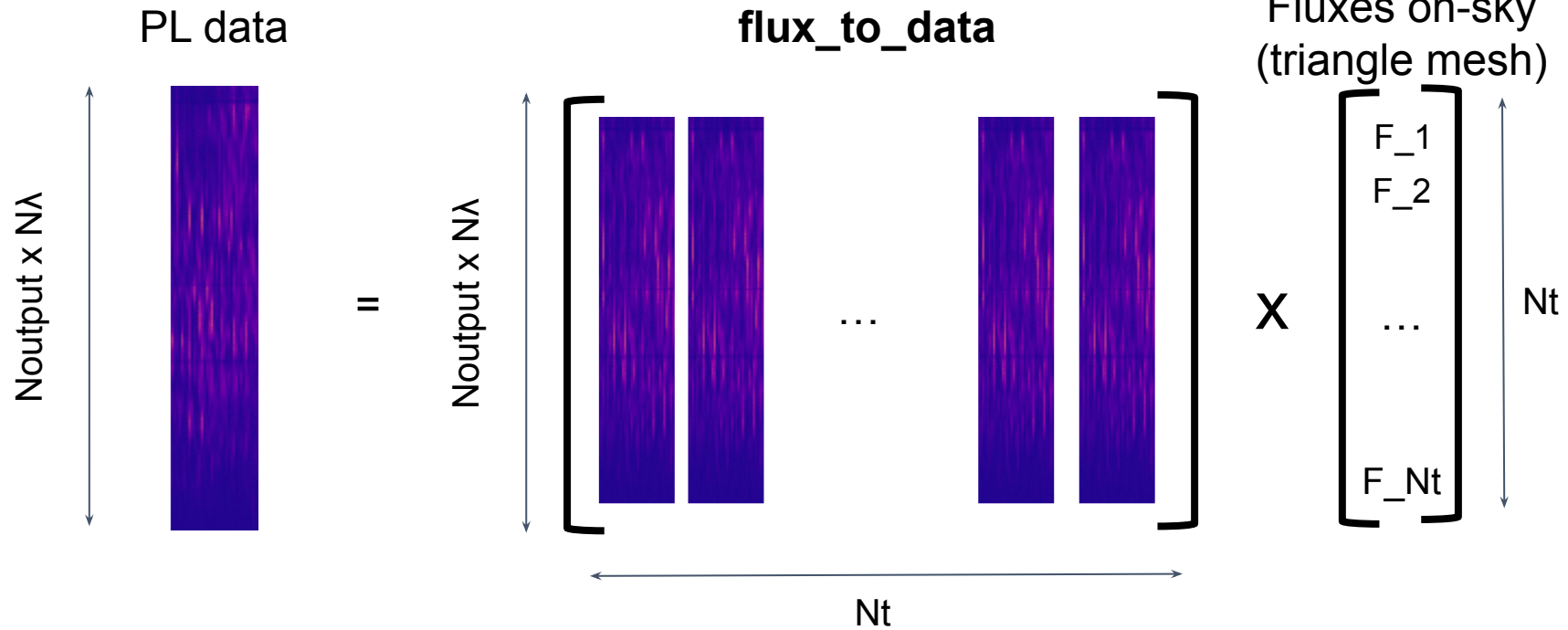
Each triangle's response is calibrated

(First order calibration)

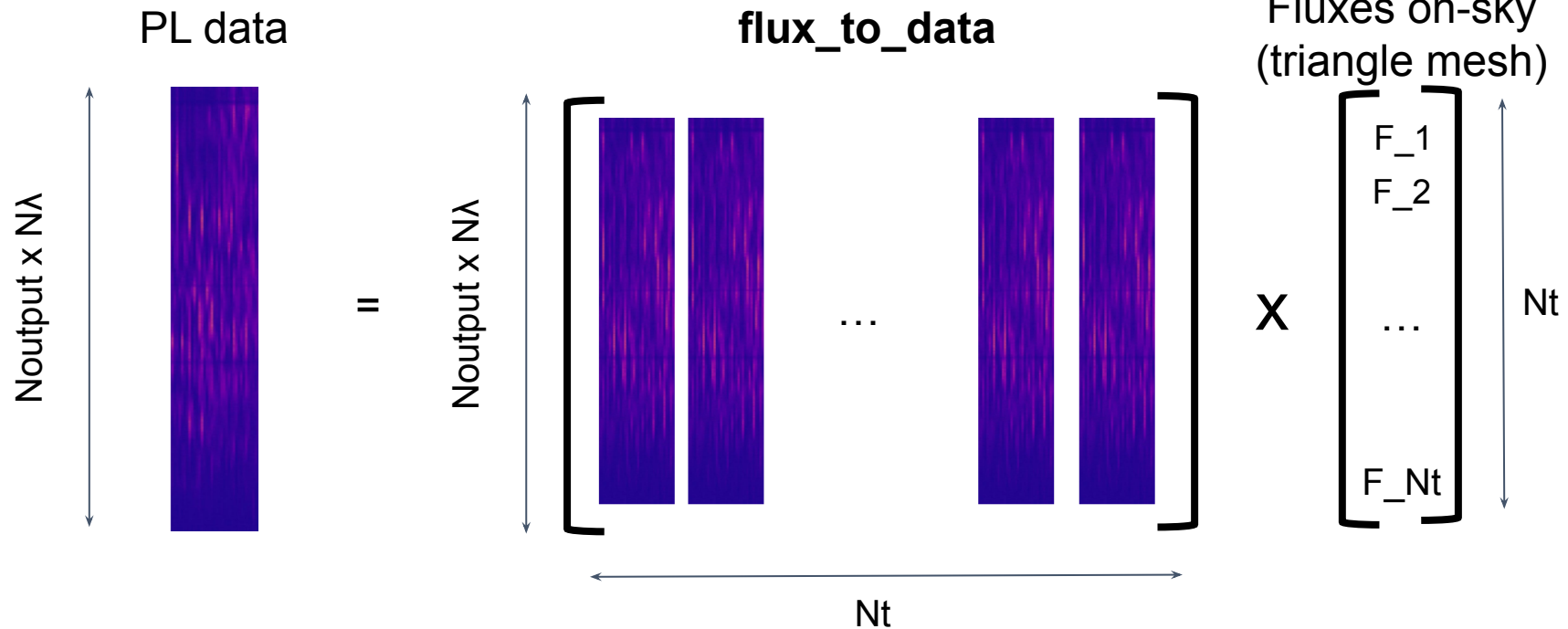


When we combine the response of all triangles, we construct a **flux_to_data** matrix, corresponding to the global response map of the lantern over the mesh

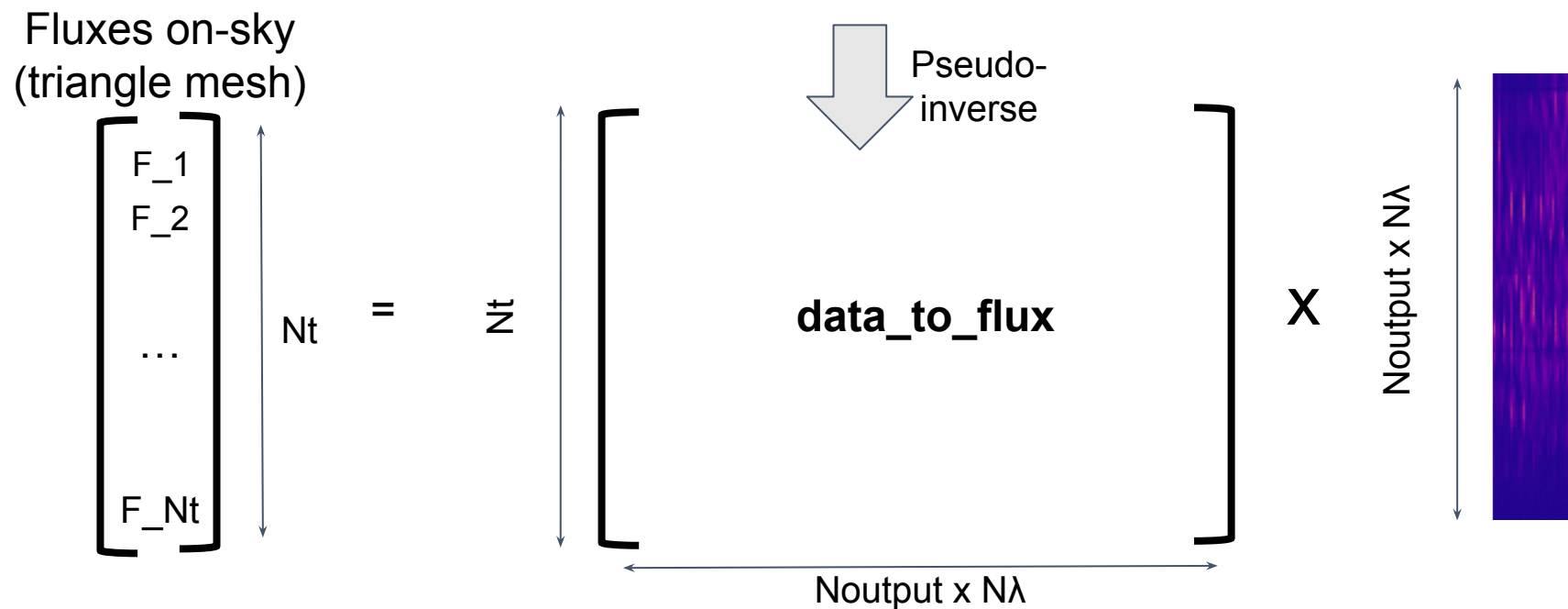
Linearity assumption:
each PL data is a linear combination of the spatial modes measured on a grid (calibration)



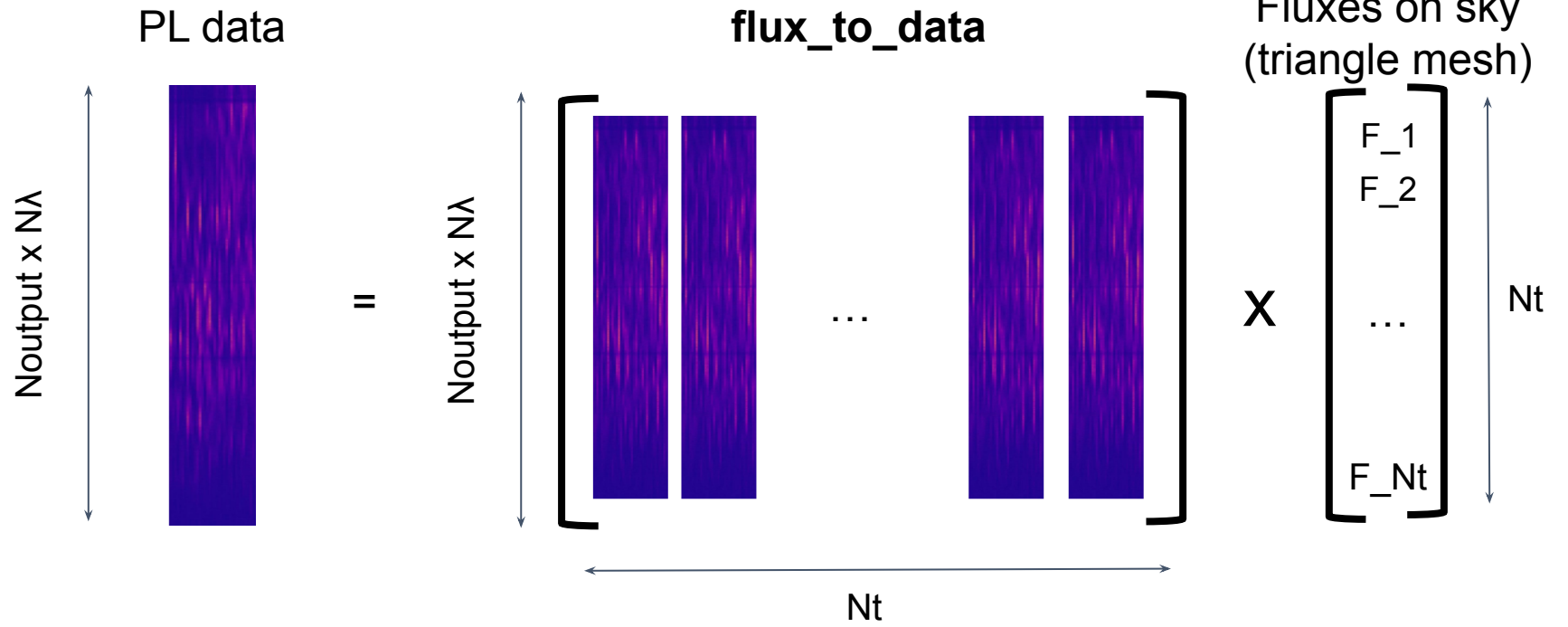
Linearity assumption:
 each PL data is a linear combination of the spatial modes measured on a grid (calibration)



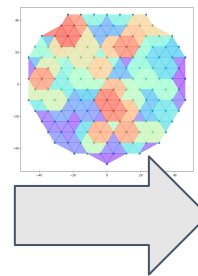
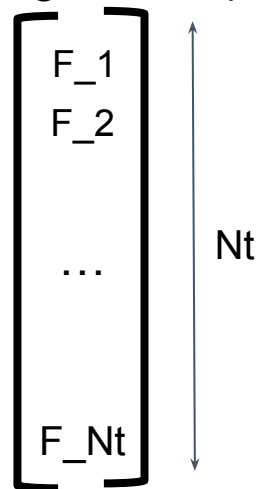
Model inversion:
 the on-sky fluxes are estimated by projecting any PL data on the modes



Linearity assumption:
 each PL data is a linear combination of the spatial modes measured on a grid (calibration)



Fluxes on sky (triangle mesh)



Reconstructed image

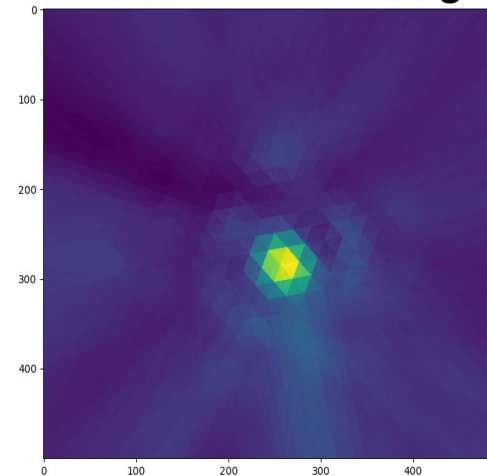
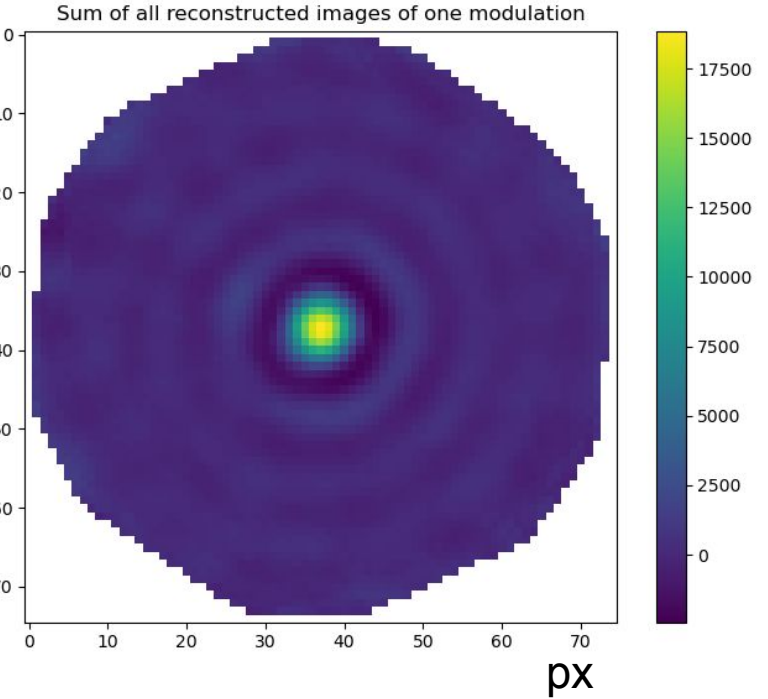
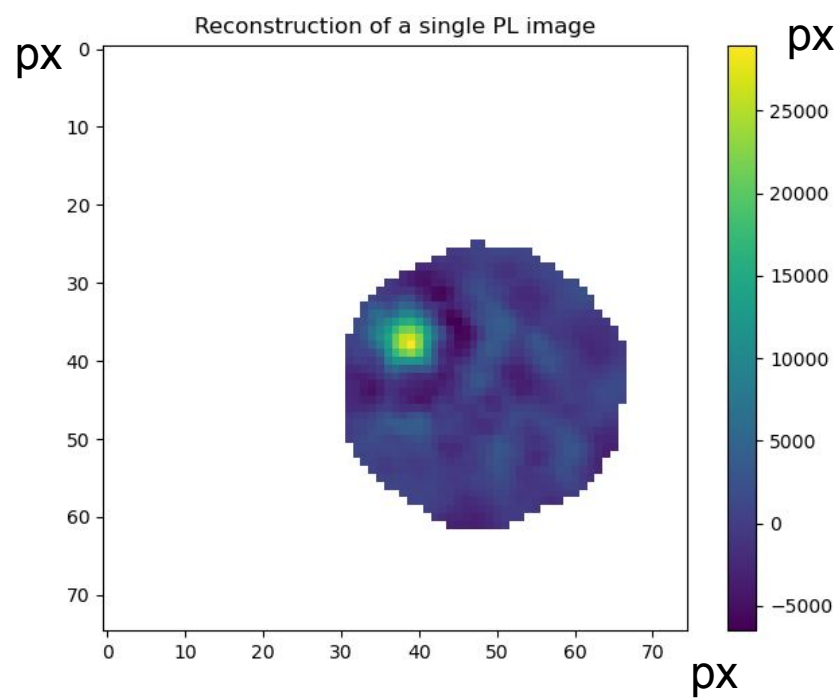
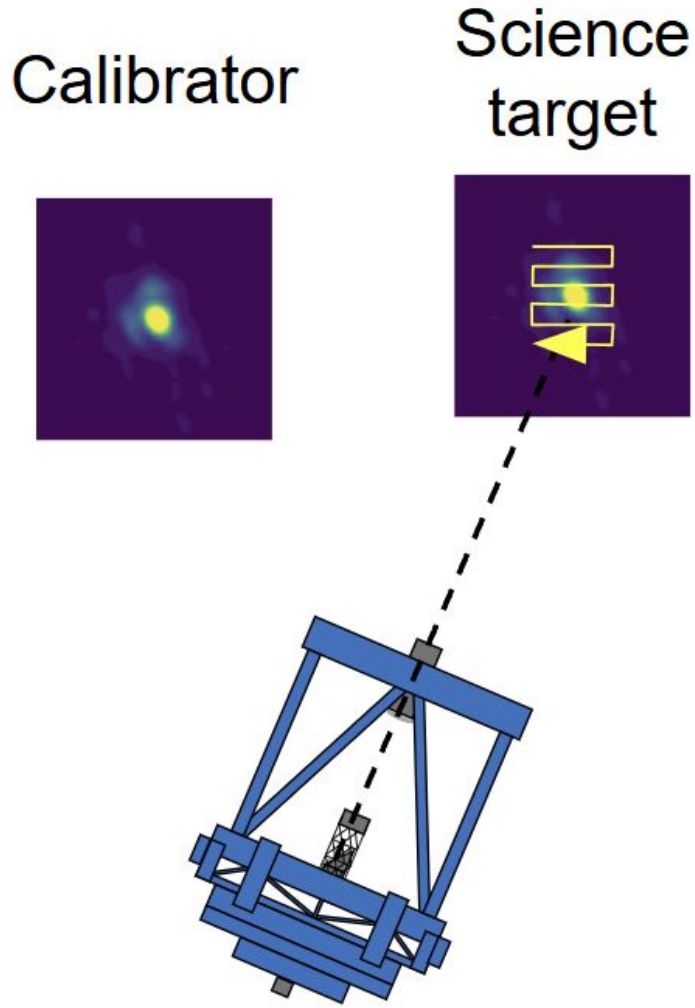


Image visualization:
 the fluxes are represented on the 2D mesh by triangles

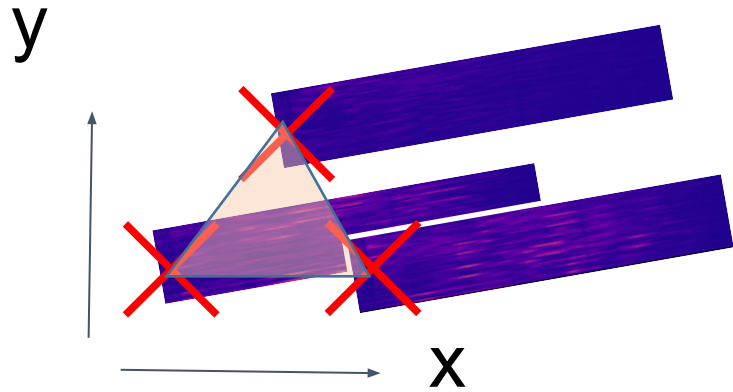
Imaging - Reconstruction



- Each single PL data is reconstructed on a field of view corresponding to the **PL FoV**, i.e. **~ 75 mas**.

- By **combining** the reconstructed images taken with a spatial modulation, the final image is **reconstructed over a wider field of view**.

Observing companions

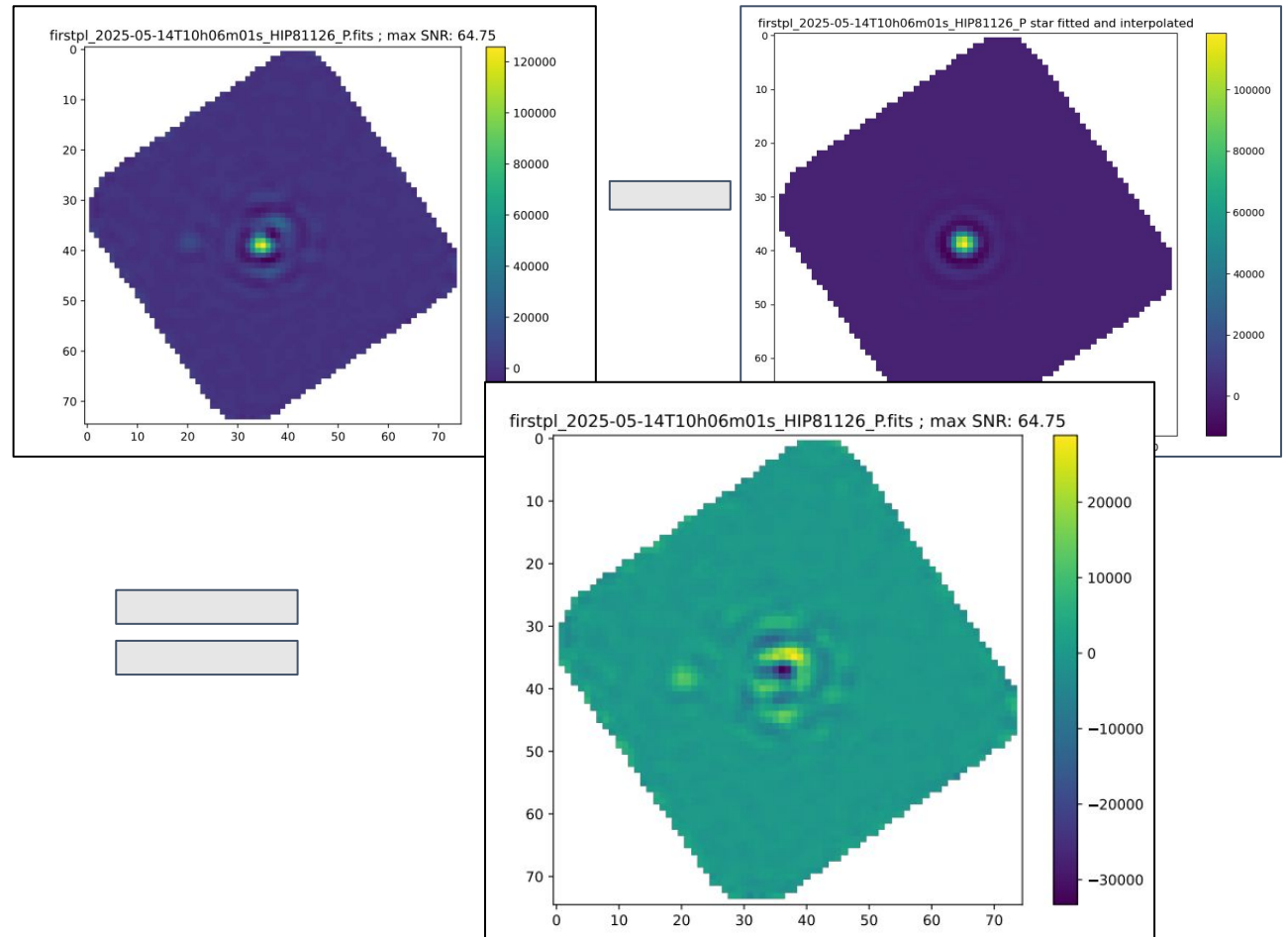


The relation of each point of the triangles with each others and with the flux can also be calibrated to calculate the answer of the lantern **within** the triangles on the mesh.

(Second order calibration)

Subtraction of a point-like source:

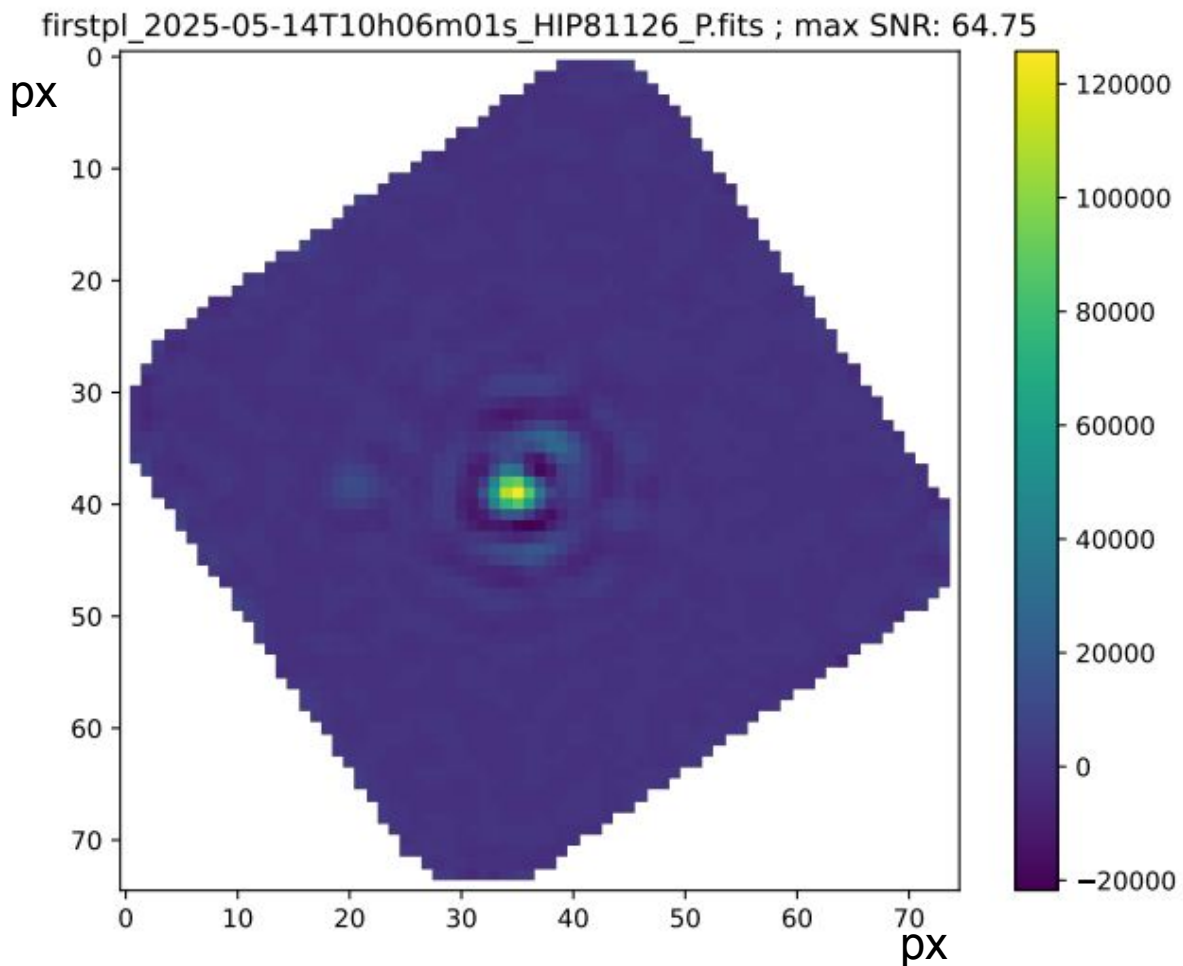
- assuming that the central star is a **point-like source**, a **fit is performed** to model its contribution (flux, x & y positions)
- the best model is **subtracted** from the data to improve off-axis companions detectability



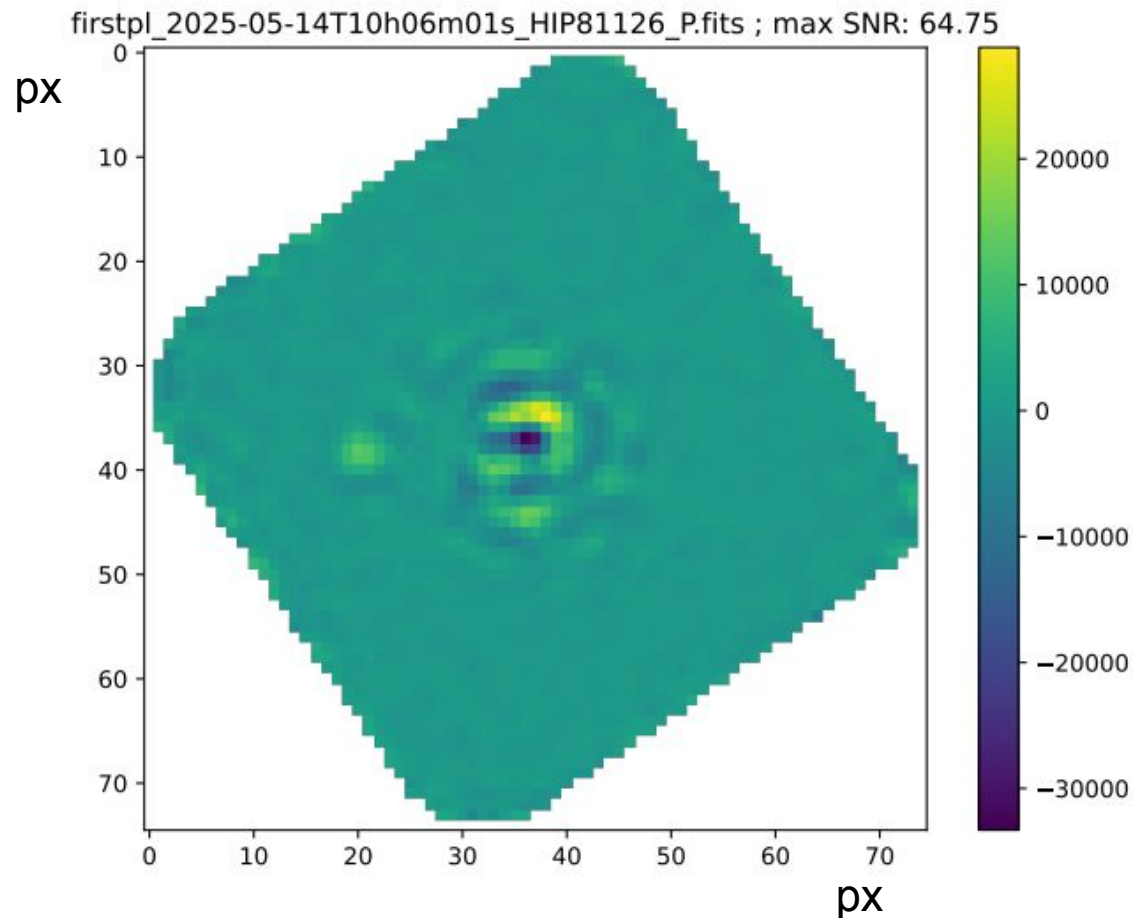
5. Results: image reconstruction

On axis – HIP81126 (binary star)

Sep = 70 mas



Reconstructed image

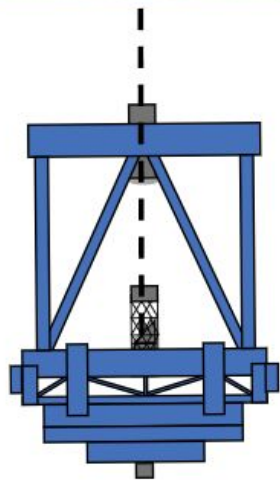
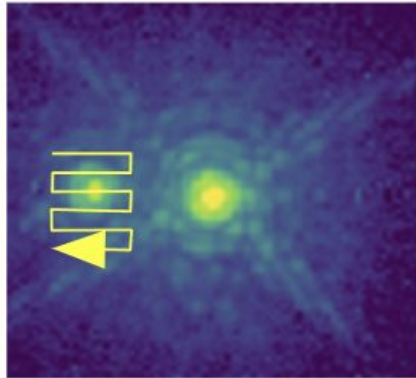


Main star subtracted

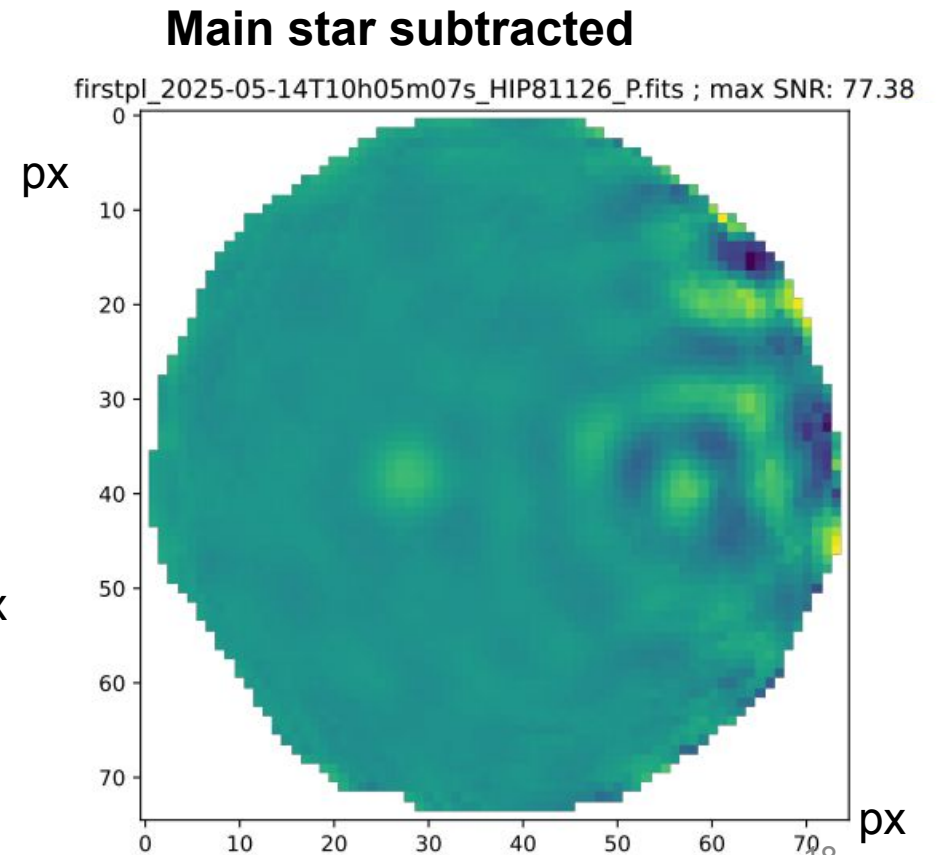
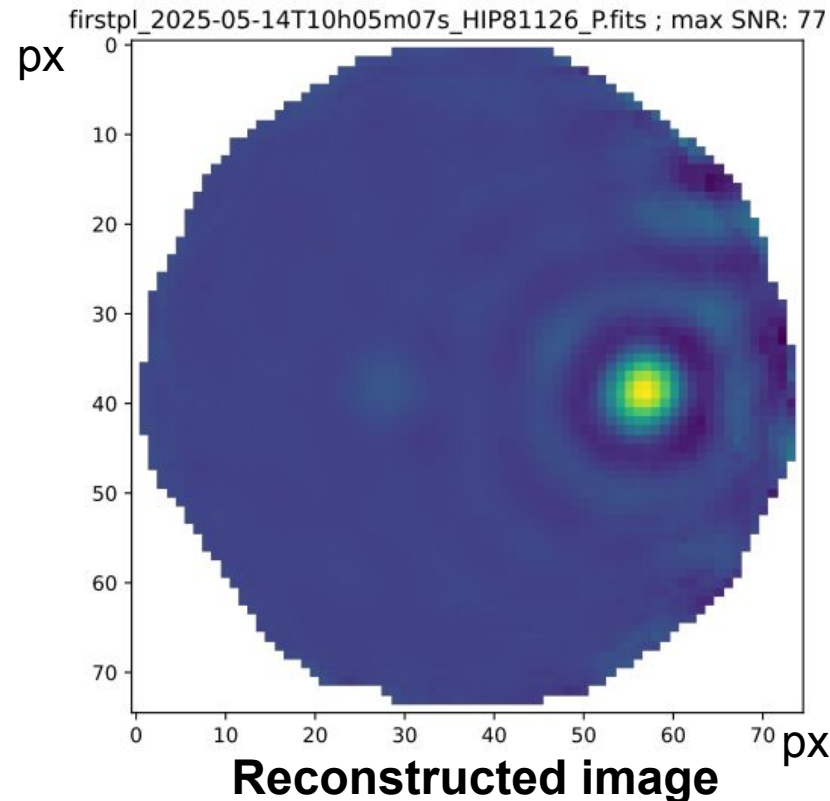
5. Results: image reconstruction

Off axis – HIP81126 (binary star)

Sep = 70 mas



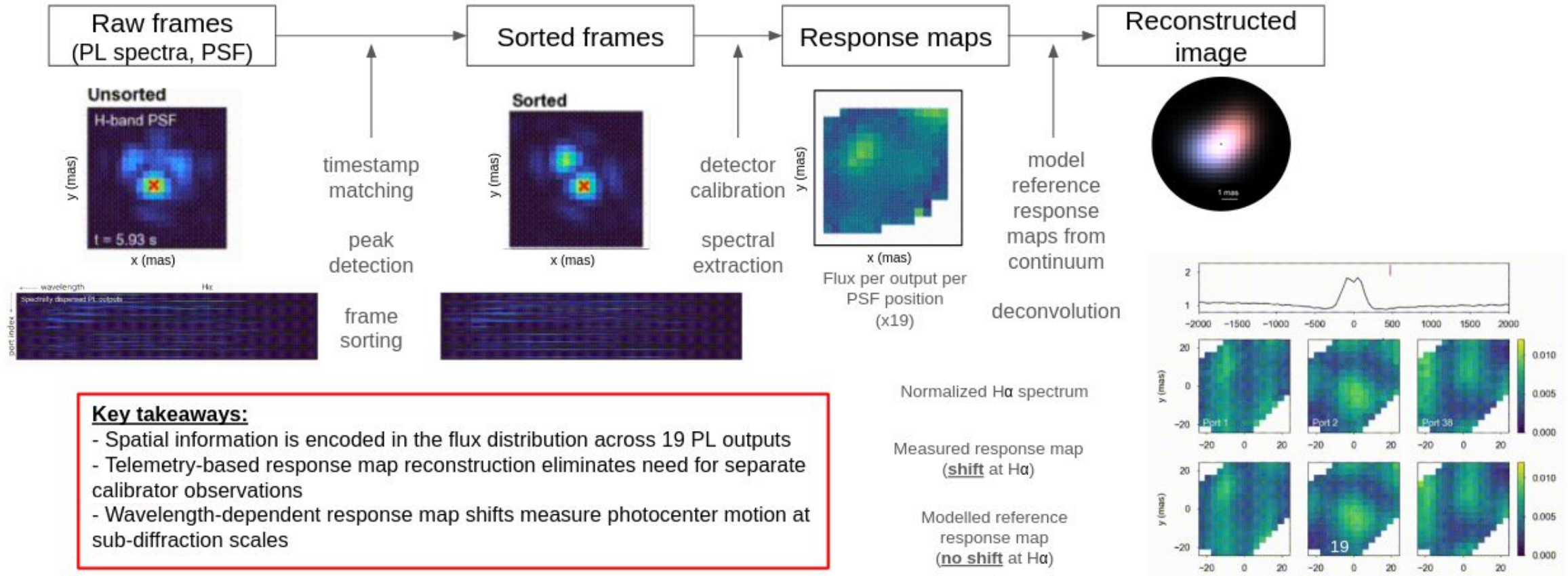
The piezo mirror is moved to center the companion



Calibration on HIP85819

5. Results: spectro-astrometry

Spectro-astrometric observing mode

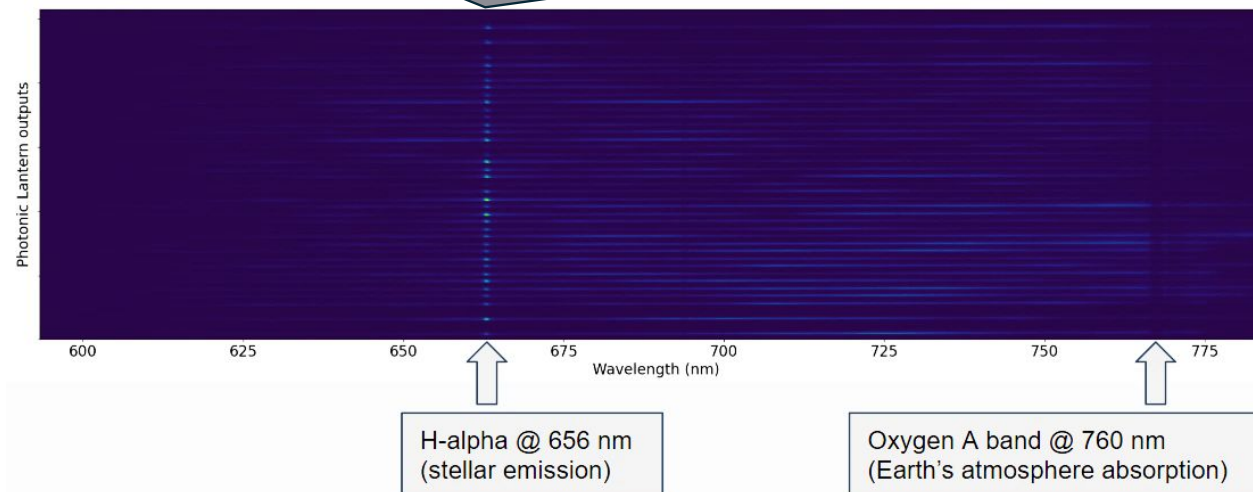
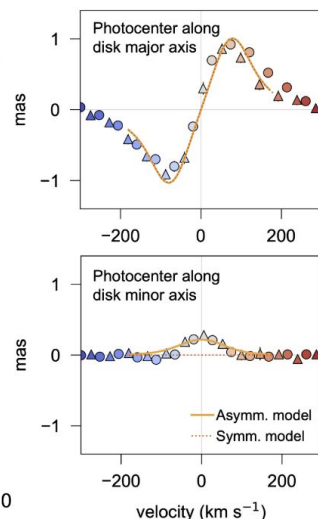
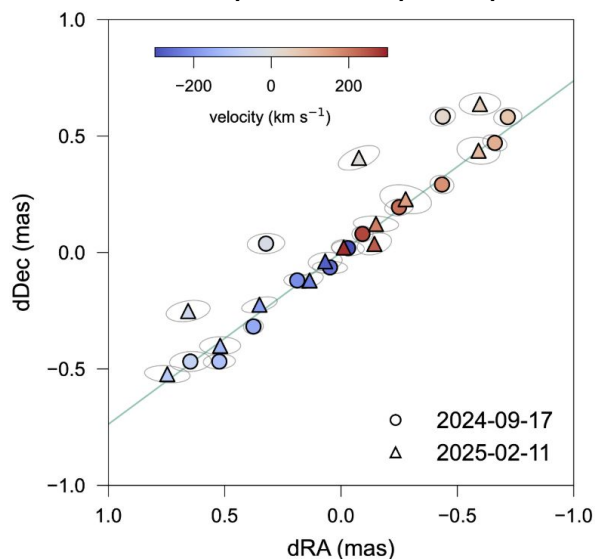
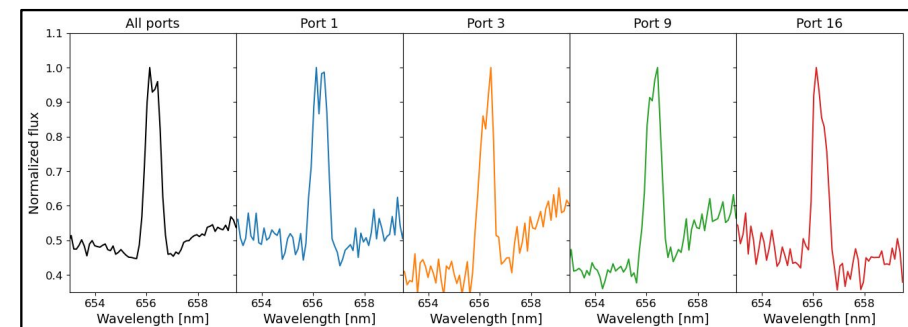


Credit : Yoo Jung Kim
Sébastien Vievard

Observation of β -CMI

(work led by Yoo Jung Kim @ UCLA)

- β -CMI is a Be star with an H α decretion disk
- The H α peak shape differs from one PL output to the other
- Sub-milliarcsecond spectro-astrometry with a precision of **50 μ as**
- Discovery of an assymetry in the disk



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

Credit : Yoo Jung Kim
Sébastien Vievard

Conclusion

FIRST-PL is an instrument for spectro-imagery **opened for scientific observations.**

Current capabilities with **FIRST-PL** :

- Wavelength range : 630-780 nm
- Resolution : **25 mas for imaging,**
50 μ as for spectro-astrometry
- Spectral resolution : 3000
- Field of view : 130 to 1000 mas

Exciting results in both spectro-astrometry and imaging using FIRST-PL !

