IAUGA 2022 FM7 @Busan, Aug 11. 2022

Spectro-astrometry with **Photonic Lanterns**

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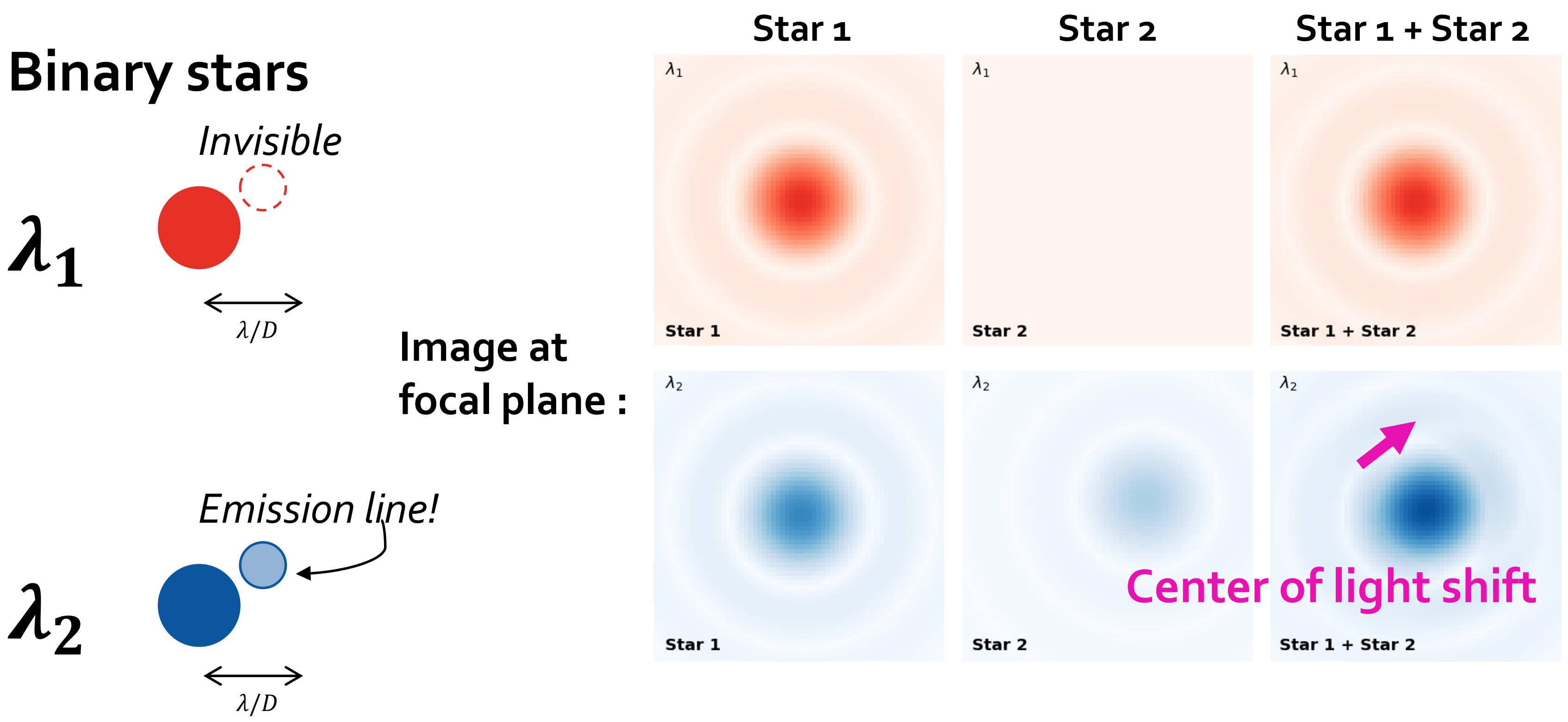
NSF ATI 2109232

Overview

1. Spectro-astrometry and artifacts
2. Photonic lanterns
3. Spectro-astrometry with photonic lanterns
4. Application & mock observation: Binary model

Spectro-astrometry measures light centroid as a function of wavelength, a technique for studying angular scales smaller than the PSF size



Spectro-astrometric signal = wavelength-dependent centroid shift

A method for studying scales smaller than the PSF size, where morphology changes with wavelength

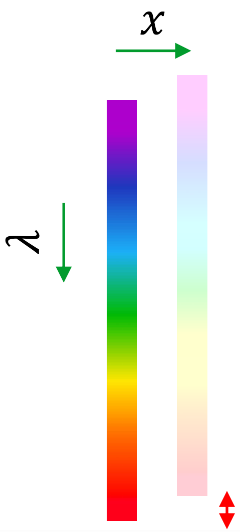
Examples: young binaries, stellar outflows, broad-line region of quasars

Slit-based spectro-astrometry suffers from artifacts due to asymmetry in PSF

Most spectro-astrometric studies used long-slit spectroscopy or image slicer-based IFU spectroscopy.

Asymmetries in the dispersion axis introduce spectro-astrometric **artifacts**

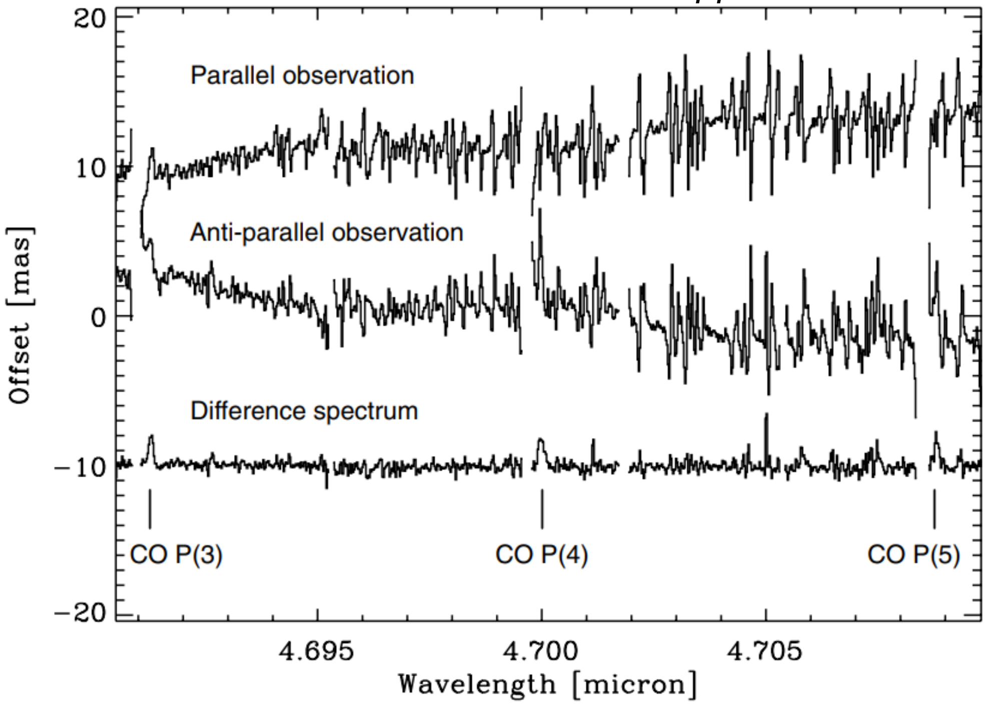
180° rotated spectra must be obtained to correct for the artifacts

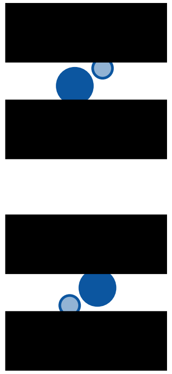


We measure center of light shift in the spatial axis (spectro-astrometric signal)

At least two observations of different position angles needed to obtain 2D spectro-astrometric signals

Pontoppidan et al. 2011



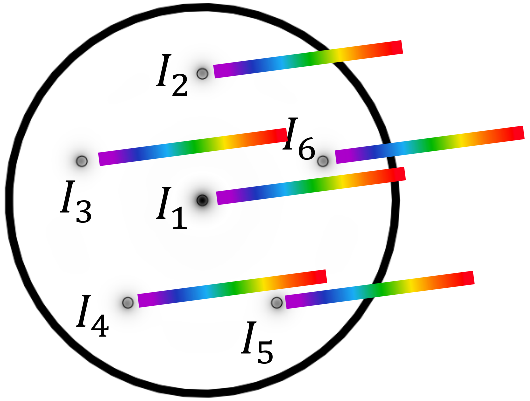


Spatial filtering of unwanted aberrations is crucial!

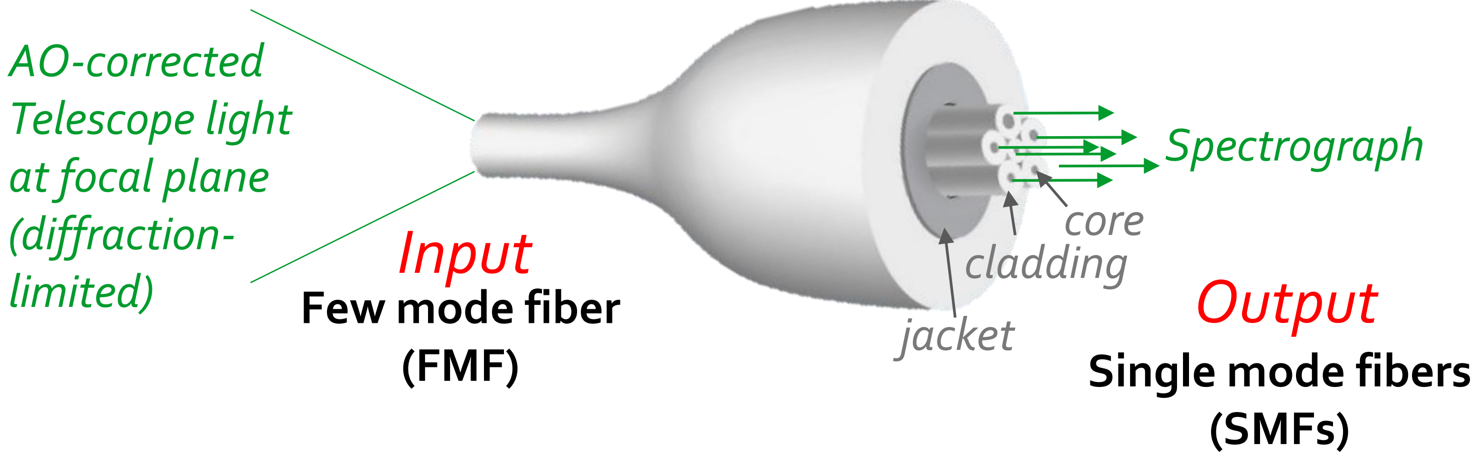
Photonic Lantern (PL)

❖ Photonic lantern:

- A waveguide that gradually transitions from few-mode fiber geometry to a bundle of single-mode fiber geometry.
- High throughput, high stability (spatial filtering)
- Considered for future fiber-fed spectrograph
- Uses: OH line suppression, Focal-plane wavefront sensing, high contrast imaging with vortex fiber nuller



6-port Photonic lantern



Photonic Lantern (PL) for spectro-astrometry

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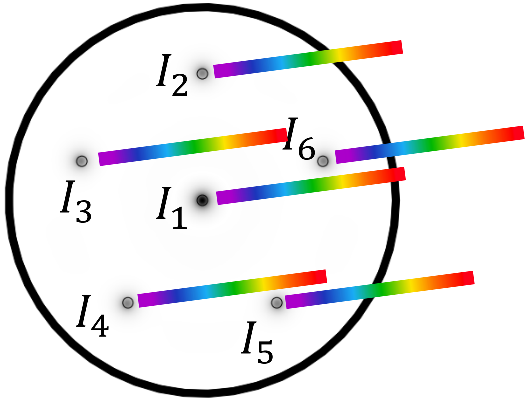
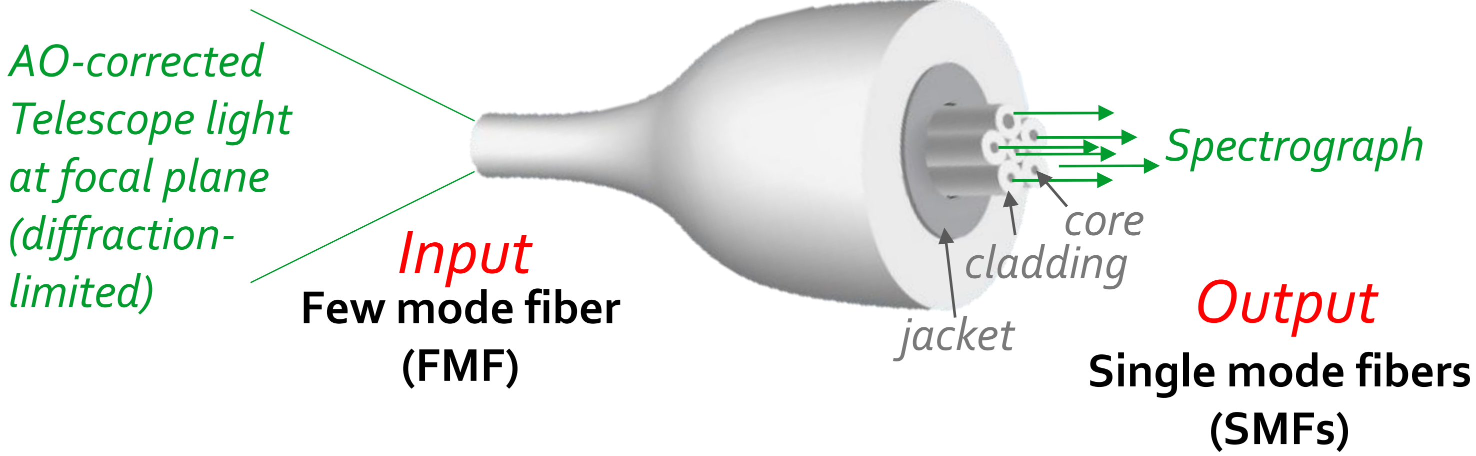


6-port Photonic lantern

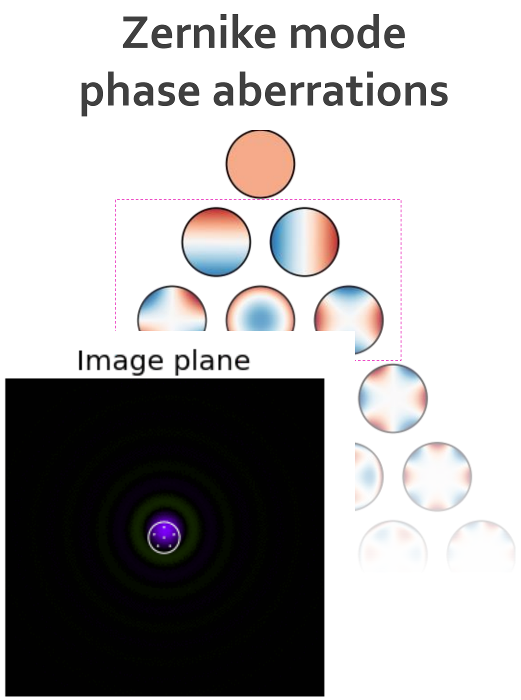


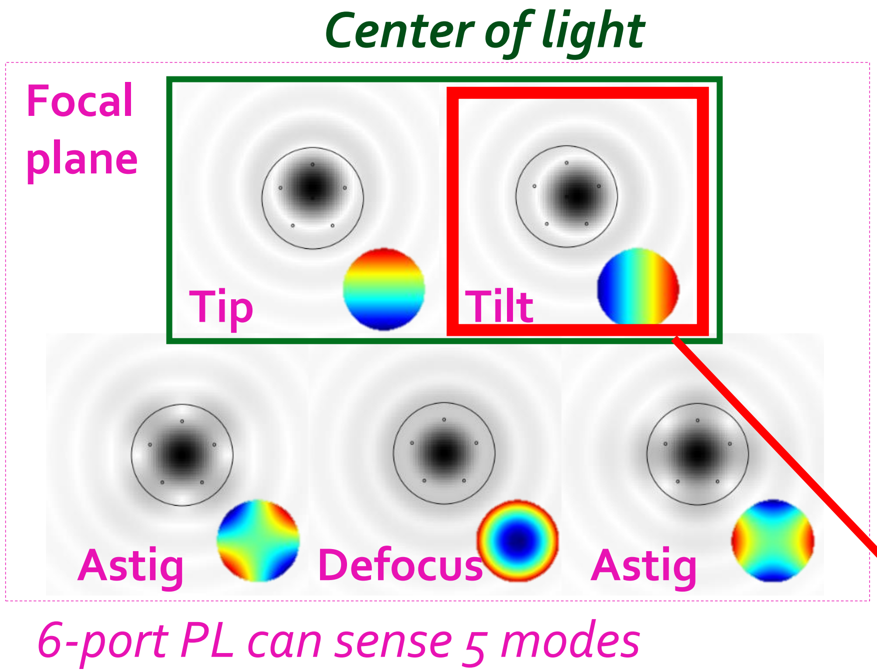
For spectro-astrometry:

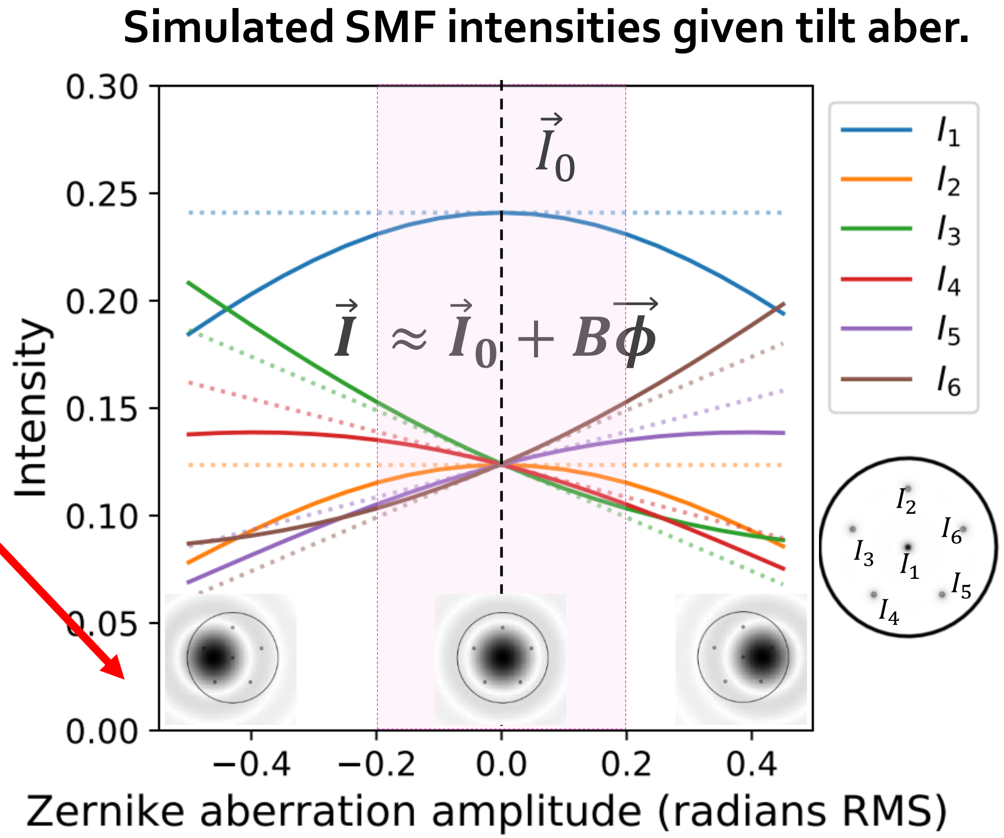
Relative intensities in each single mode fiber can be used to determine the light centroid precisely!

Linearity of the PL response makes it ideal for spectro-astrometry

- Photonic lanterns respond linearly to low-order aberrations.





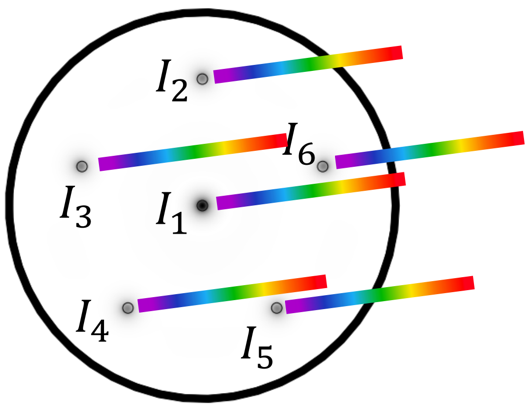


- The linear relation can be inverted to recover phase aberrations ($\vec{\phi} \approx B^{-1}(\vec{I} - \vec{I}_0)$) – tip/tilt, defocus, astigmatism.
- In the linear regime, random errors are averaged out (example: AO-residual tip-tilt jitter)

PLs can measure 2D spectro-astrometric signals, do not suffer from artifacts, and are insensitive to random errors.

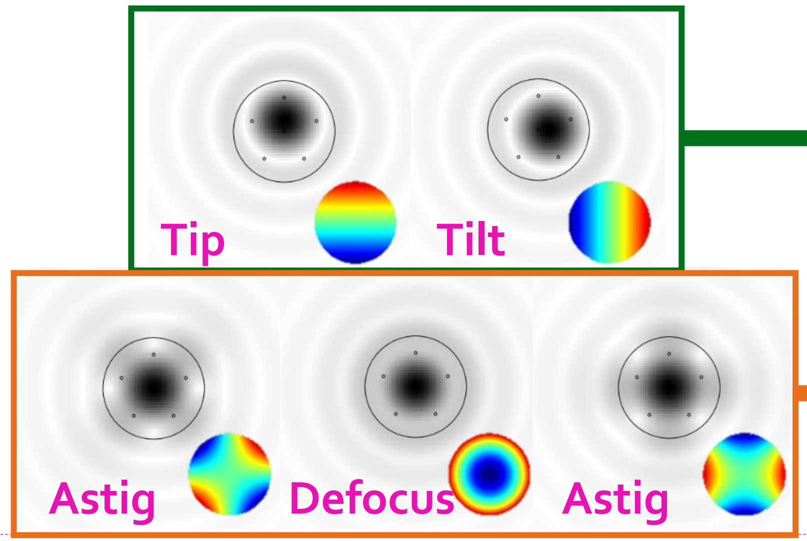
Summary: PL spectro-astrometry

Measure



Linear operation

Aberration amplitudes

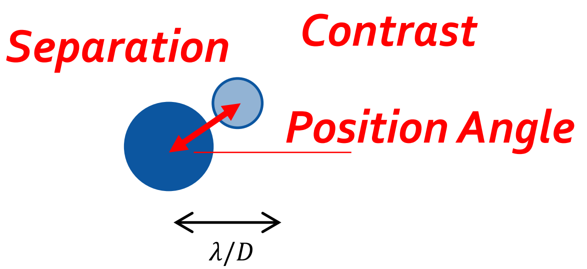


Center of light as a function of wavelength

(spectro-astrometric signal)

Additional information to constrain model parameters & correct for non-linearity

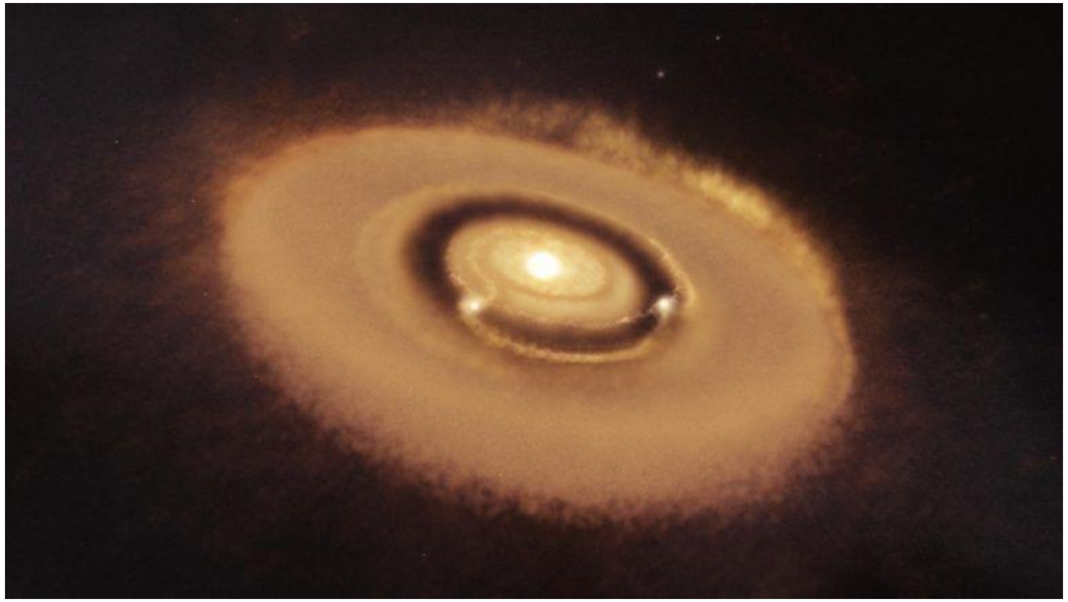
Application: Binary Model



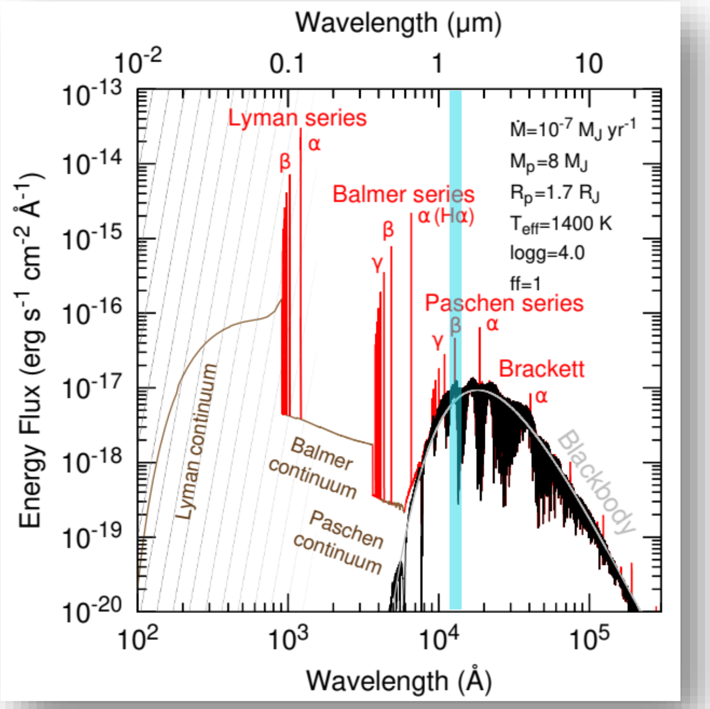
Can we recover binary parameters with PL spectro-astrometry?

Mock observation:

Accreting planets show strong hydrogen emission lines

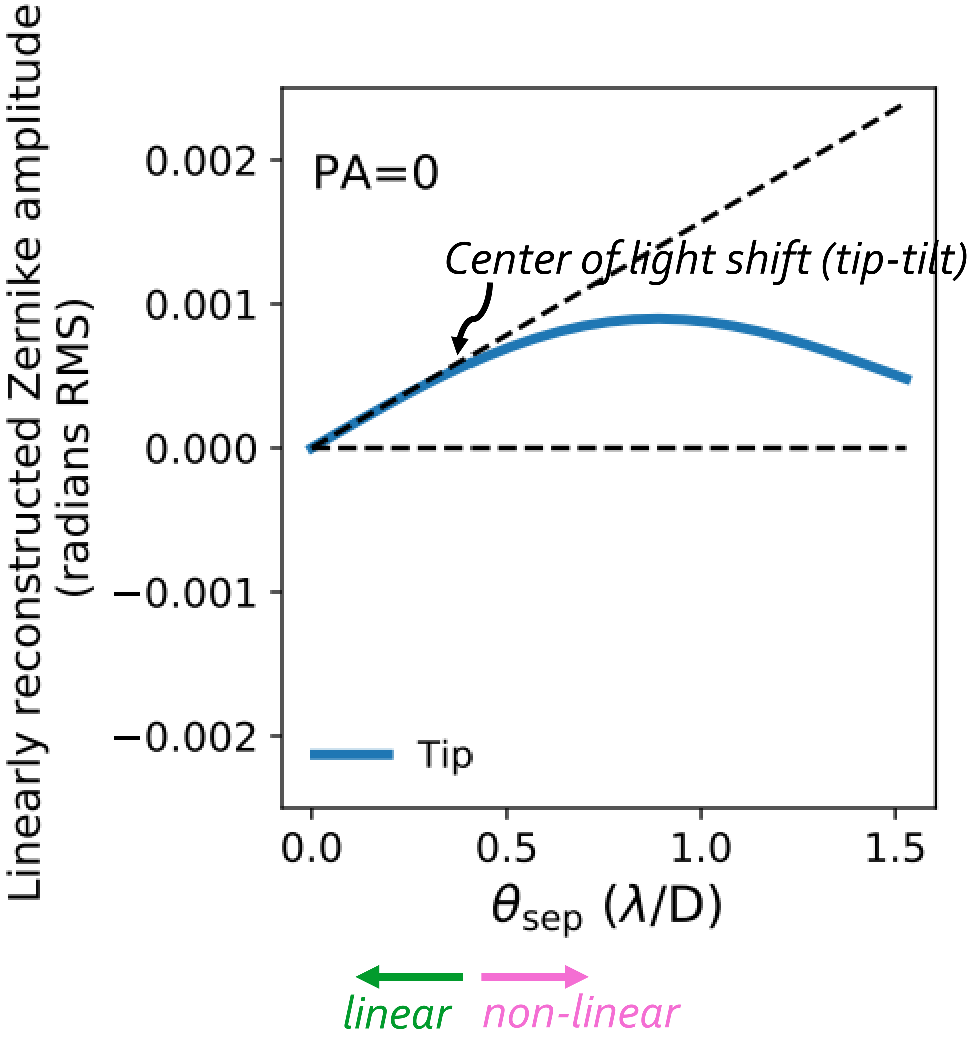


Artist's impression of PDS70 system. W. M. Keck Observatory/Adam Makarenko

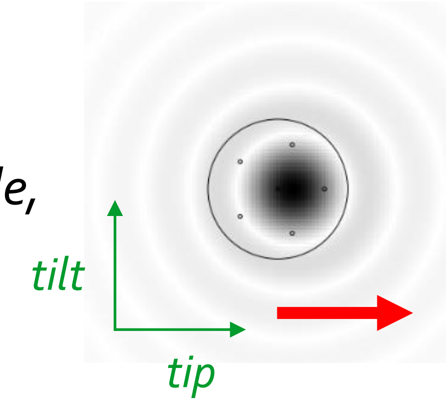


Aoyama et al. 2021

Linearly reconstructed aberration amplitudes (tip, tilt, defocus, astig) can be used to constrain binary parameters (cont., sep., PA)



Measure: $\vec{I}$, calculate: $\vec{\phi}_{(tip,tilt,defocus, astig)}$

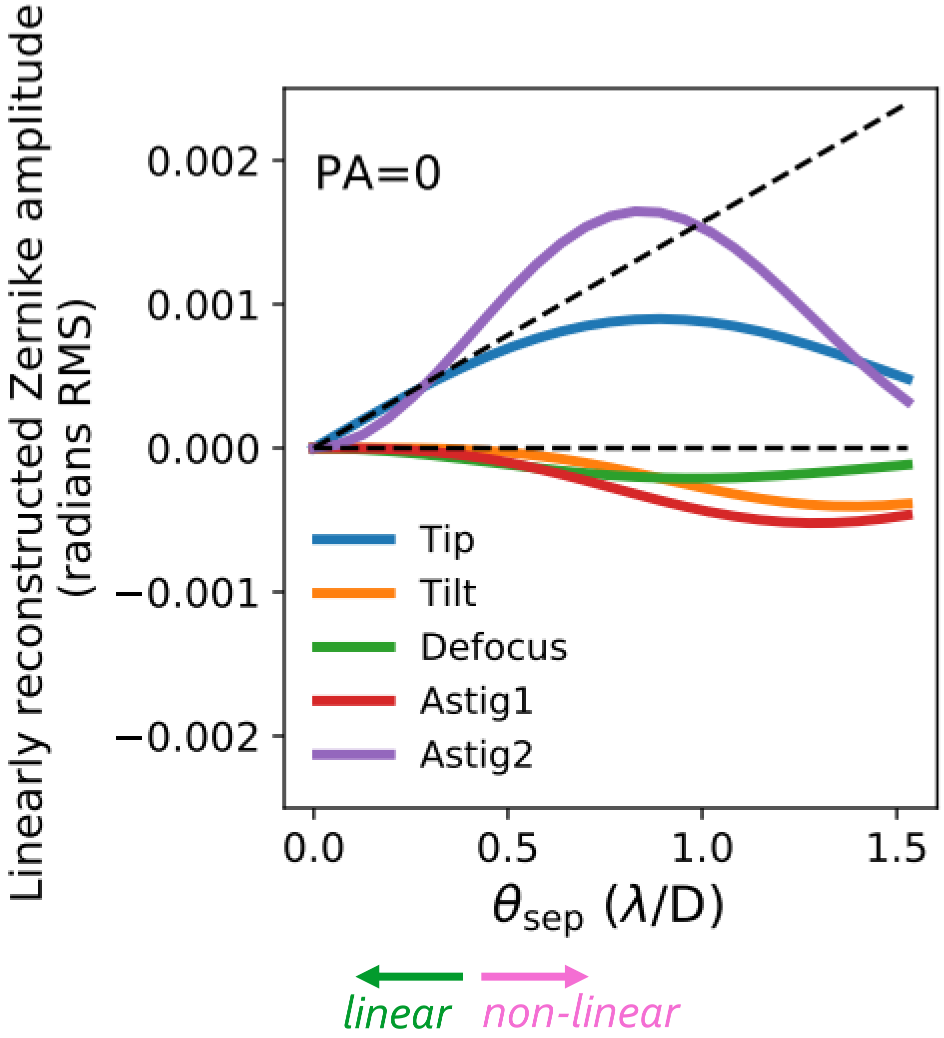


Example case for zero position angle,
Contrast = 0.001

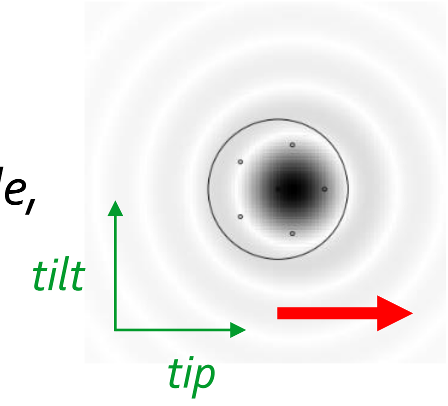
In the linear regime, the tip-tilt = center of light

At large separations, the reconstructed tip-tilt deviates from the center of light

Linearly reconstructed aberration amplitudes (tip, tilt, defocus, astig) can be used to constrain binary parameters (cont., sep., PA)



Example case for zero position angle, Contrast = 0.001



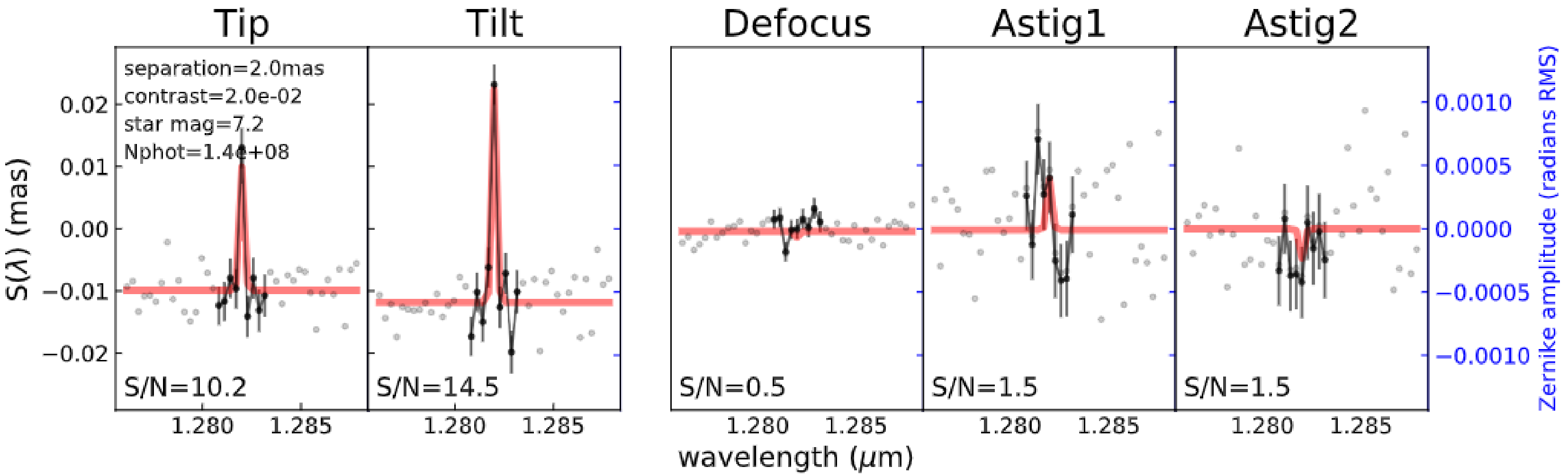
In the linear regime, the tip-tilt = center of light

At large separations, the reconstructed tip-tilt deviates from the center of light

At large separations, astigmatism & defocus signals can be used to constrain the separation
➔ contrast & separation degeneracy breaks!

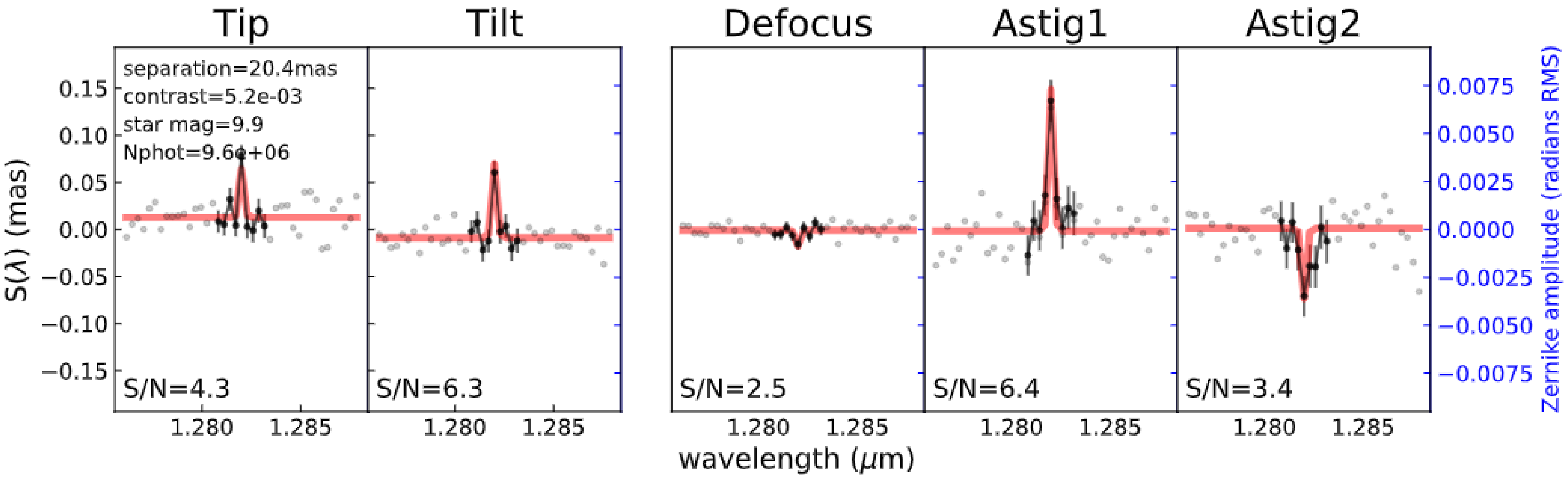
Mock observations

1 hour observation
R ~ 4000
Tip-tilt jitter 0.2mas



Distance = 40pc, separation ~ 0.1 AU, PA=60 deg, Accretion rate = $10^{-8} M_\odot/yr$

Small separation



Distance = 140pc, separation ~ 3 AU, PA=60 deg, Accretion rate = $10^{-8.5} M_\odot/yr$

Large separation

Next steps

- Experiments and on-sky verification
- SMF outputs can be interferometrically combined for spectro-interferometry and coherent imaging

Lin et al. in prep

Summary

- ❖ Spectro-astrometry is a useful technique for studying scales smaller than the PSF size, but care is needed due to artifacts.
- ❖ A photonic lantern, with its spatial filtering property and its linearity, is ideal for a stable measurement of spectro-astrometry.
- ❖ We explored the application on the binary model, in particular on observing accreting planets with hydrogen emission lines. The spectro-astrometry with photonic lantern can constrain binary parameters.