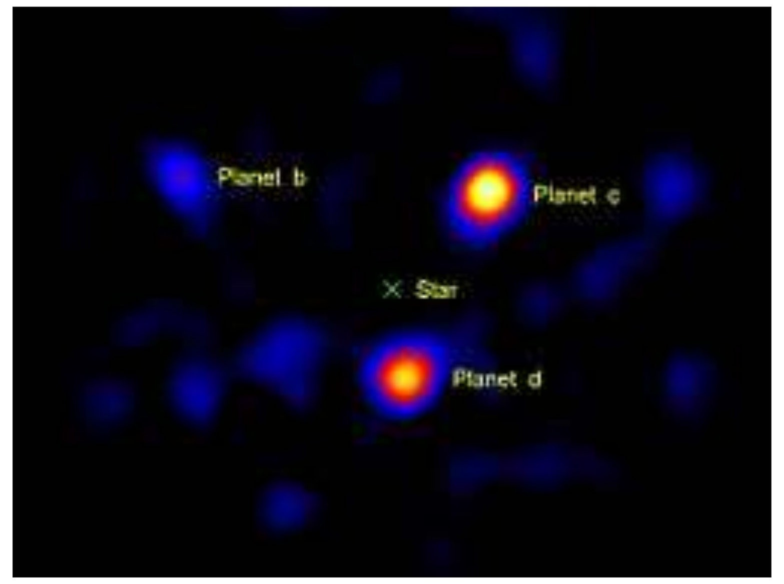
Analysis of Angular-Differential Post-Processing Algorithms for Exoplanet Direct Detection Using a Photonic Lantern Nuller

Suvinay Goyal (UIUC), Yinzi Xin (Caltech), Dimitri Mawet (Caltech), Nemanja Jovanovic (Caltech)

Direct Imaging

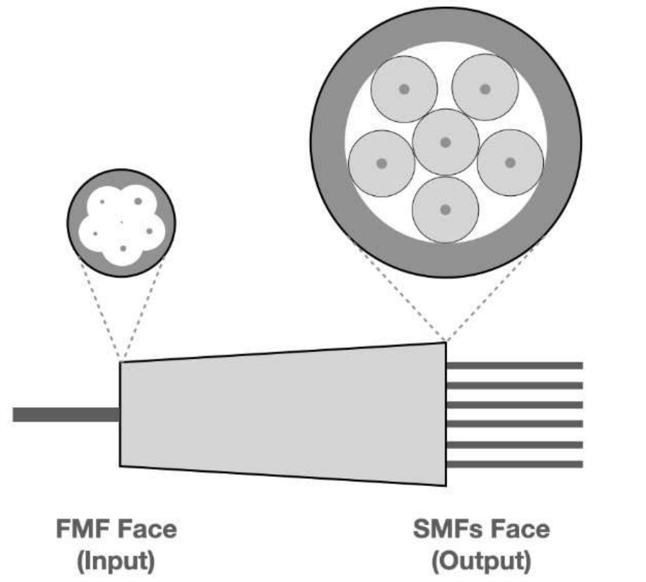
Direct imaging enables the detection of exoplanets by suppressing the overwhelming glare of their host stars, allowing the much fainter off-axis planetary signal to be observed. This is achieved using a coronagraph, an optical instrument that blocks on-axis starlight while preserving the surrounding planetary light. Advanced wavefront control techniques and post-processing algorithms are crucial for mitigating the residual stellar speckles, pushing the limits of direct imaging toward the characterization of exoplanet atmospheres and potential biosignatures.

Direct Imaging has mostly been successful for observing self luminous, massive bodies (Hot Jupiters) at distances >10 AU from their stellar host, in typically the NIR (Near Infrared), MIR (Mid Infrared) and the Visible Spectrum.



Photonic Lantern Nuller

The Photonic Lantern Nuller (PLN) is an instrument concept which aims to help observe closer and fainter off-axis exoplanets to their stellar hosts, at separations that coronagraphs can't effectively reach. The Photonic Lantern instrument type that uses 4-6 spatially varying coupling ports to put limits on the planet's on sky position and capture a smaller field of view around the star. They then further cancel out the central starlight through destructive interference and increase the contrast between the stellar host and nearby planets, a process called "nulling" of the starlight, allowing for us to see fainter exoplanets at closer separations



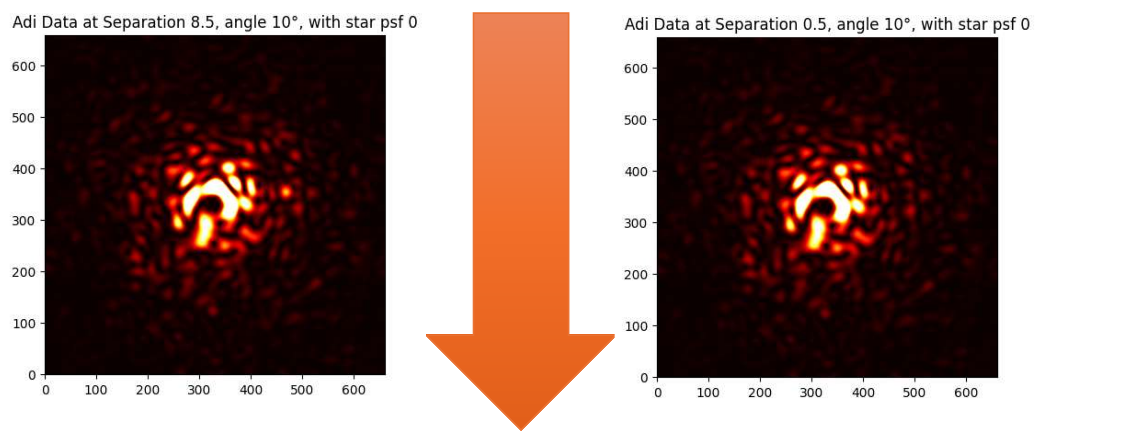
For a 6-port mode-selective photonic lantern spatial-multiplexer fiber (SMF) system. Each mode at the few mode fiber(FMF) face is mapped to one of the six single-mode ports of the SMF face. The device is bi-directional, so light injected into one of the SMF ports will propagate into the mode corresponding to that port at the FMF face.

Angular Differential Imaging

ADI is a high contrast imaging technique mostly suitable for ground-based instruments, relying on the rotating field of view with respect to the instrument due to the rotation of Earth. The images then taken, are used to make reference Point Spread Functions (PSF) with respect to other chosen images and are subtracted to remove the quasi-static speckles. The algorithms that are used for this include classical ADI median subtraction, the Locally Optimized Combination of Images (LOCI)and the Karhunen-Loève Image Projection (KLIP).

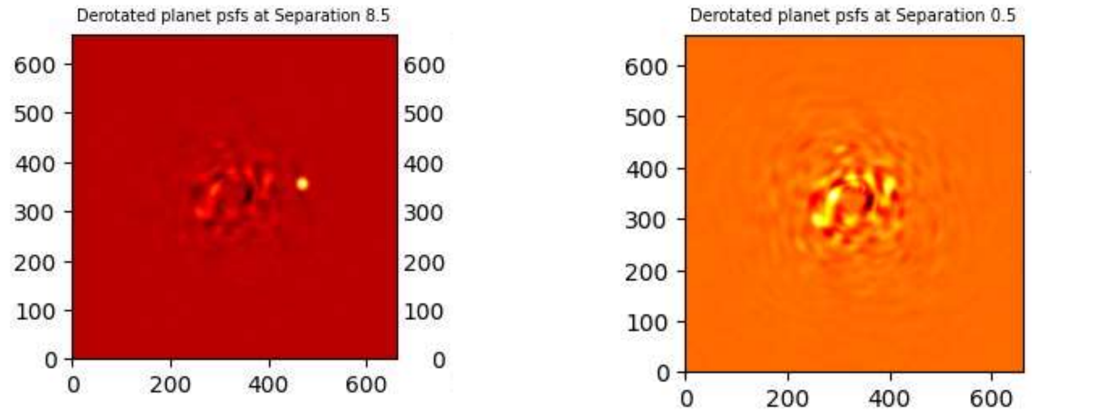
The classical ADI subtraction technique was developed on the principle of taking a median between the PSF of all images. From the algorithms that came later, LOCI works on the principle of assigning relevant weights to a sequence of images to create a final combined image, while KLIP relies on Principal Component Analysis techniques to efficiently achieve a higher exoplanet contrast.

Final Image = Star PSF + Flux Ratio (FR) * Planet PSF



$$R_{ij} = I_{ij} - MEDIAN(I_{ik}|k \neq j)$$

After Derotation and Stacking

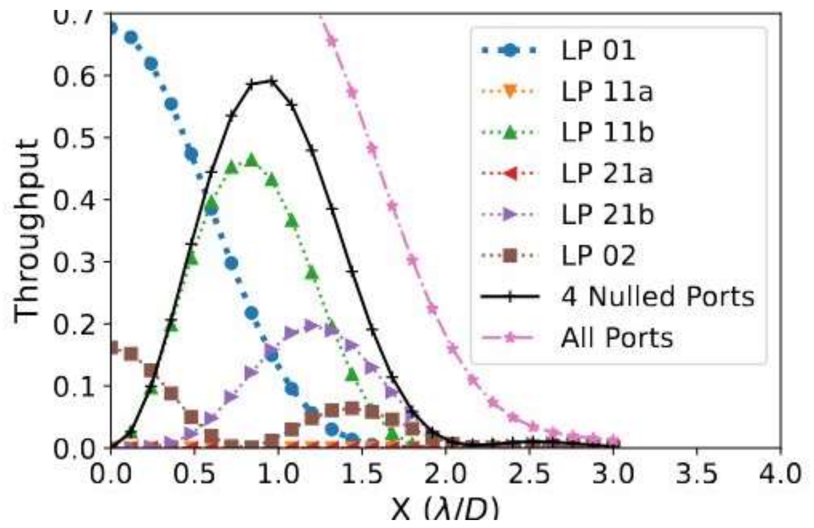


3 Main Takeaways:

- Despite extreme adaptive optics, wavefront control and post processing, coronagraphs can only effectively image planets down to 3 λ/D.
- ADI assumes that the planets' optical signals don't significantly overlap with the stellar hosts' signals to avoid self-subtraction.
- ADI also assumes that planets' optical signals are rotationally invariant.

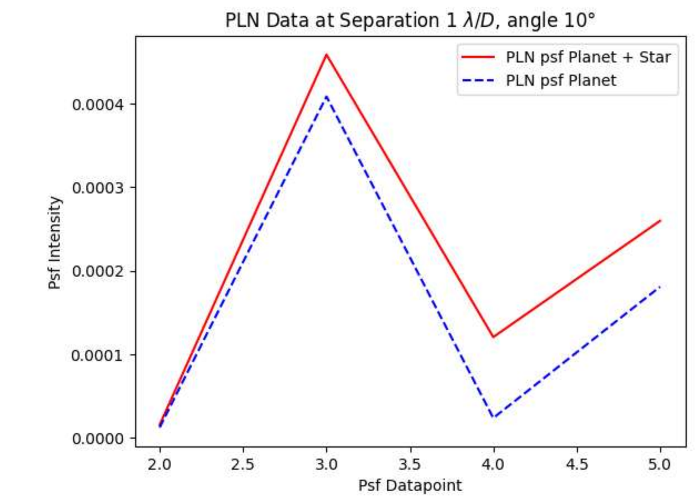
None of these hold true for the PLN, hence necessitating a need for ADI reformulation for the PLN.

PLN Signal Characterization



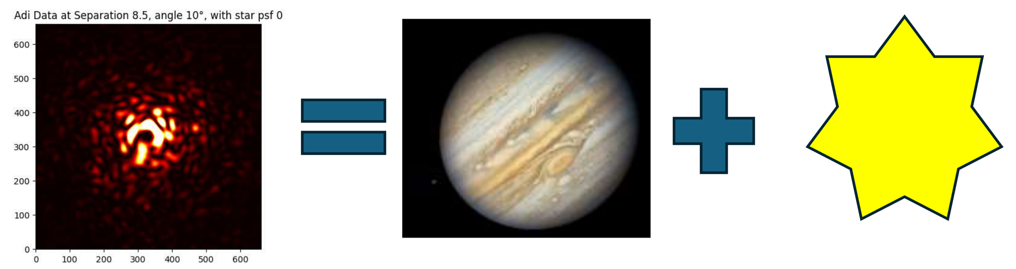
PLN Signals:

- Are 1 Dimensional representing 4 optical intensities (Not Rotationally Invariant)
- Have dependence on the angles with respect to the instrument rotation
- Give us the ability to access closer-in exoplanets and also help develop future technologies that could potentially detect biosignatures!

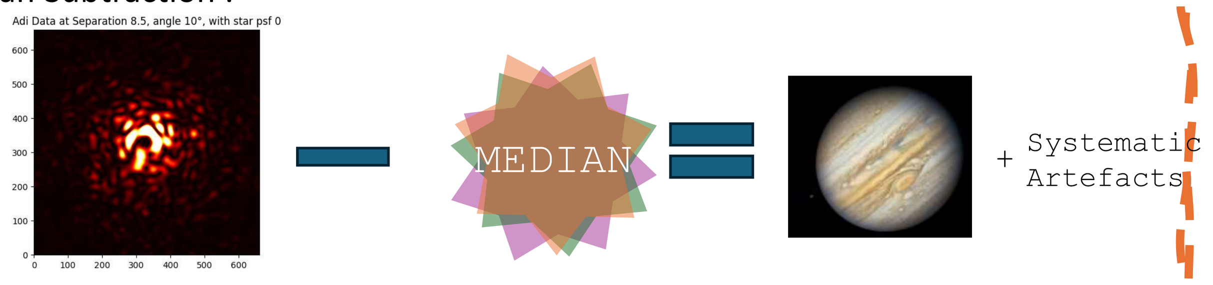


Signal Optimization Techniques

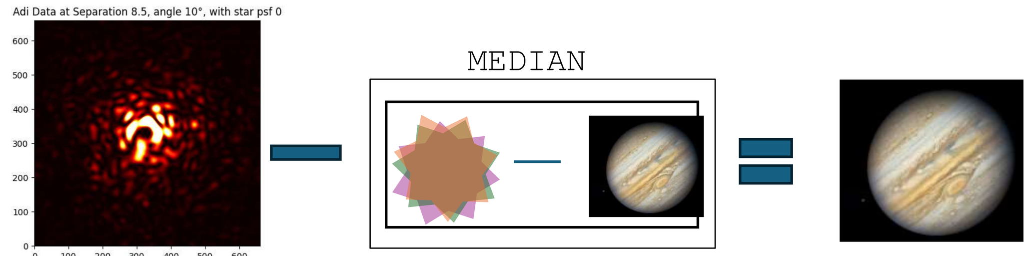
- Direct Fit :



- Median Subtraction :



- Antiplanet Median Subtraction :



Cost Function Detection Testing And Optimization

We compare seven different methods for the statistical reliability of estimating the planet signal from a signal with the following form:

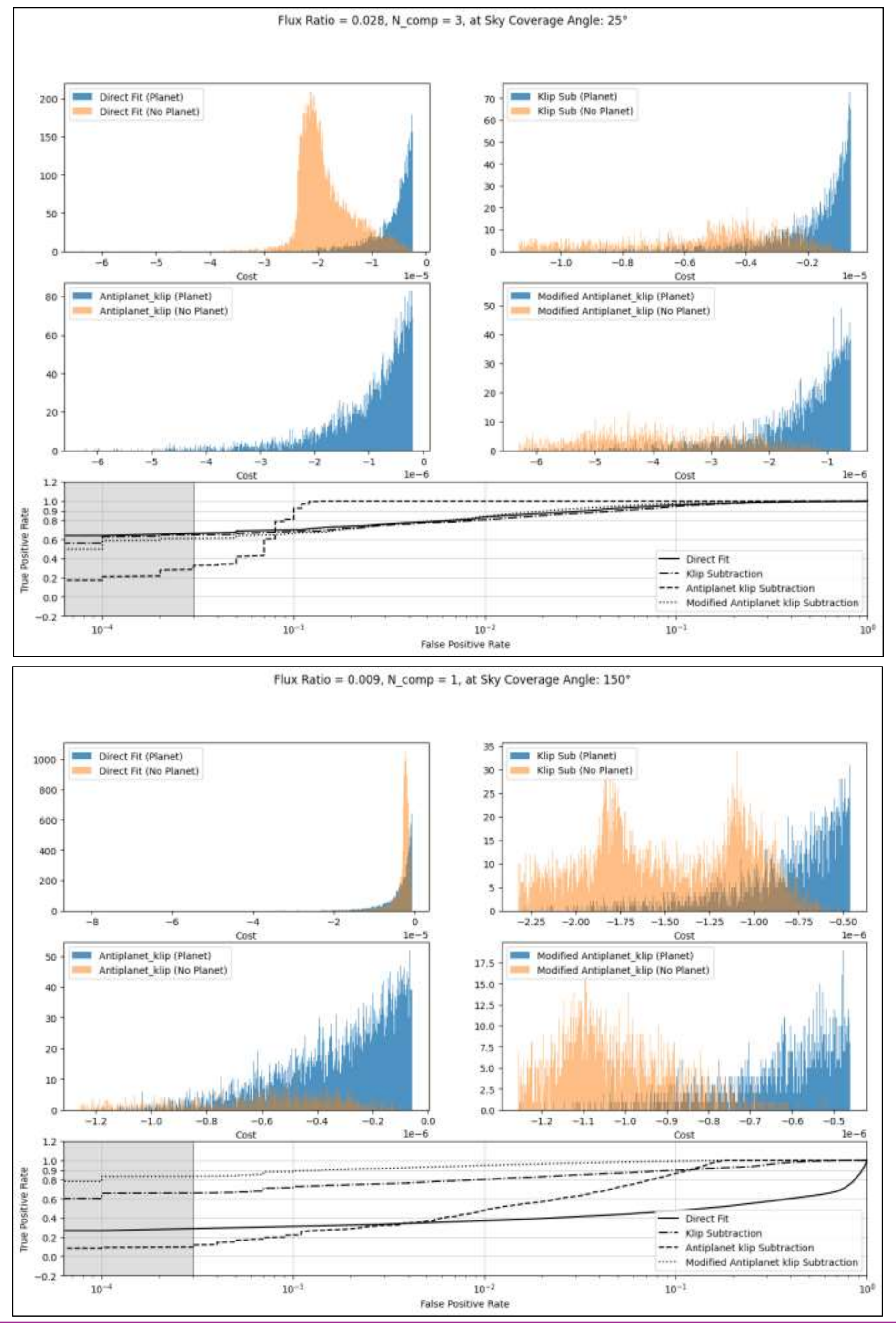
$$Signal_{PLN} = PSF_{Star}(r,\theta) + FluxRatio(FR) * PSF_{Planet}(r,\theta)$$

The PSF_{Planet} signal, is a function of FR, r and θ.

This is done through detection testing, a form of hypothesis testing which singles out the lowest FR at which the optimization method can detect a planet reliably. Detection tests are done with frames sampled across 1.25 °/frame for a total of 20, 80 and 120 frames.

$$H_0: Signal\ dataset\ with\ no\ planets\ in\ them$$
$$H_1: Signal\ Datasets\ with\ planets\ in\ them$$

We aim to achieve a 4σ detection limit at 10^{-3} False Positive Rate and 0.9 True Positive Rate, by performing a Monte Carlo on 10000 datasets.



The KLIP subtraction performs best at a lower sky coverage modified method performs best at a higher sky coverage!

Accompanying And Future Work

Accompanying Work

- Characterizing the complete localizations of the planets with different cost functions.
- Showcasing localization capabilities with joint distribution corner plots over the three parameters (FR, r and θ).
- **Publication in prep!**

Future Work

- Implement this using multi-wavelength data.
- Using this for PLN on-sky data in future.
- Characterizing the behaviour of these methods over changing angular separations, as the detection tests change over that dimension as well.

References

- Photonic Lantern Nulling (Xin et al)
- HCIPy (High Contrast Imaging for Python
- HR8799 System using Hale telescope

Acknowledgements

I would like to thank Yinzi Xin, Nemanja Jovanovic and Dimitri Mawet for their invaluable support and guidance throughout this research. I am also grateful to the California Institute of Technology for providing the SURF Fellowship that was crucial to the completion of this study.

This work was supported by National Science Foundation under Grant No. 2308360.