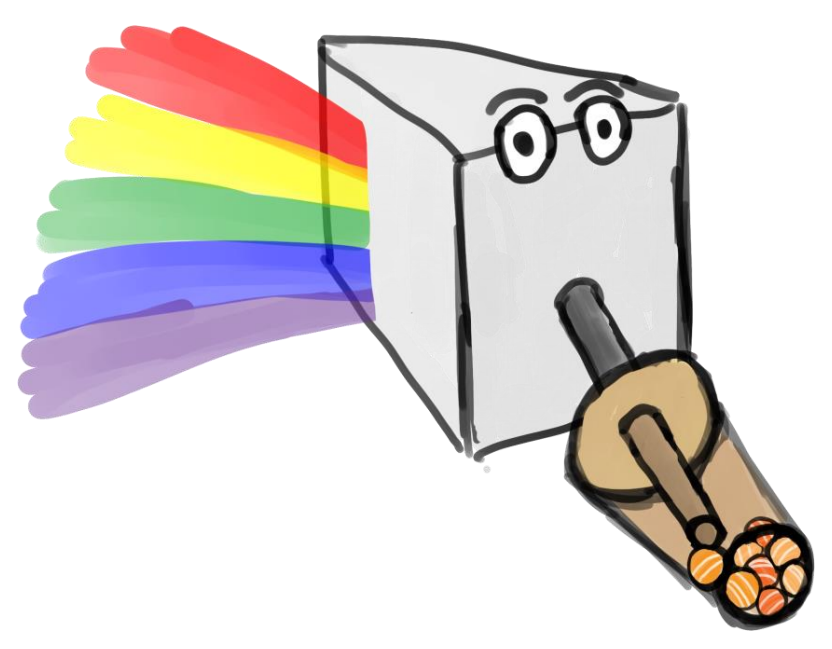

Differentiable Optical Modelling for Exoplanet Direct Imaging with JWST

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Abstract

Direct-imaging is an essential technique to discover and characterize exoplanets. Given that the host star is orders-of-magnitude brighter than the planets we wish to observe, **the main challenge of direct-imaging is to remove as much starlight as possible while keeping as much planet signal as possible** in our images. Doing this more effectively allows the study of fainter planets, which translates into access to new exoplanet populations. In particular, the James Webb Space Telescope (JWST) allows for the first-time sensitivity to directly-image sub-Jupiter mass planets. While commonly used methods consist of performing Principal Component Analysis (PCA) on reference images to remove starlight, **this work introduces a new forward-modelling approach to starlight subtraction using a differentiable coronagraph model**. Leveraging the extraordinary stability of JWST, we test our method on simulated JWST images, fitting simultaneously for the stellar Point Spread Function (PSF) and the Optical Path Difference (OPD) map at the entrance of the telescope. Our method successfully recovers the planet signal at a wide range of challenging contrast levels.

The fainter, the better

- Exoplanet imaging probes a unique region of exoplanet parameter space (Fig. 1).
- By **imaging fainter planets**, we reach new planet populations (e.g., younger, smaller planets).
- **Current and future instruments**, such as JWST, the Roman Space Telescope, the Extremely Large Telescope and the Habitable Worlds Observatory show a **promising future for direct-imaging.**
- Equally innovative **post-processing methods are fundamental** to directly-image new exoplanet populations.

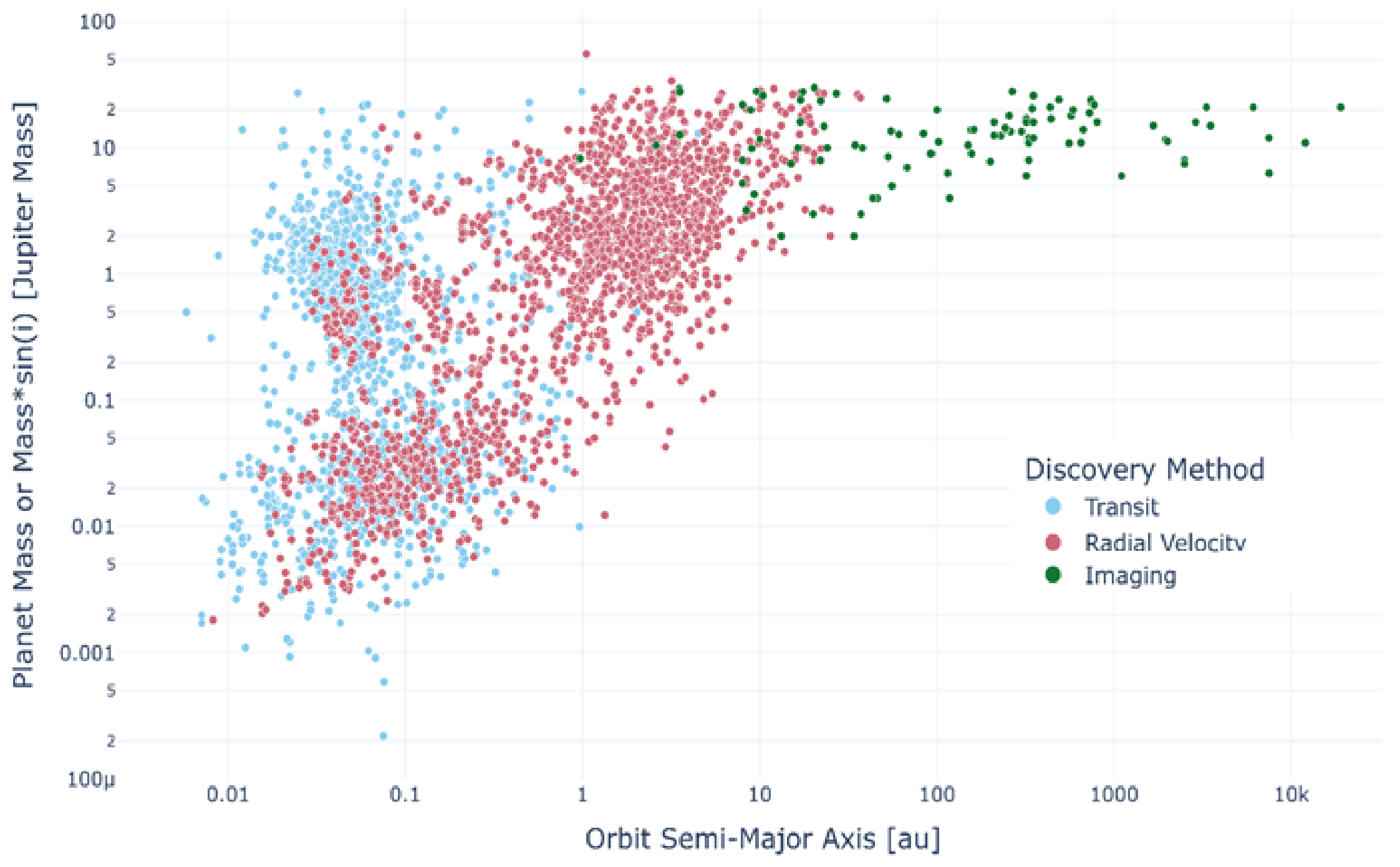


Figure 1. Planets discovered by transit, radial velocity and direct-imaging as a function of mass and semi-major axis. New instruments and post-processing methods are essential to expand the sensitivity of direct-imaging to dimmer, smaller, closer-in planets. [1]

- The fundamental data analysis problem: **high-quality stellar point-spread function (PSF) subtraction.**
- Current PSF subtraction methods rely on collecting reference images (e.g., observations of a different star) and using principal component analysis (PCA) to remove components of the PSF.
- **The effectiveness of these methods depends on the availability of a suitable and large enough library of reference images**, which are costly to obtain.
- With the extraordinary stability of instruments like JWST, **a forward-modelling approach to PSF subtraction becomes feasible.**
- A forward-modelling approach, apart from **saving resources**, has the potential to simultaneously fit the stellar PSF and other variables of interest, such as the **wavefront error** or the **precise position of the star** behind the coronagraph.

PSF modelling via differentiable optical simulation

- To test this forward-modelling approach, we built an **optical model in PyTorch for PSF simulation and efficient gradient computation.**
- As a case study, we simulate the Lyot coronagraph in the **NIRCam instrument of JWST**.
- In our experiments, we fit the stellar PSF by **updating the optical path difference (OPD)** at the entrance of the telescope (Fig. 2).

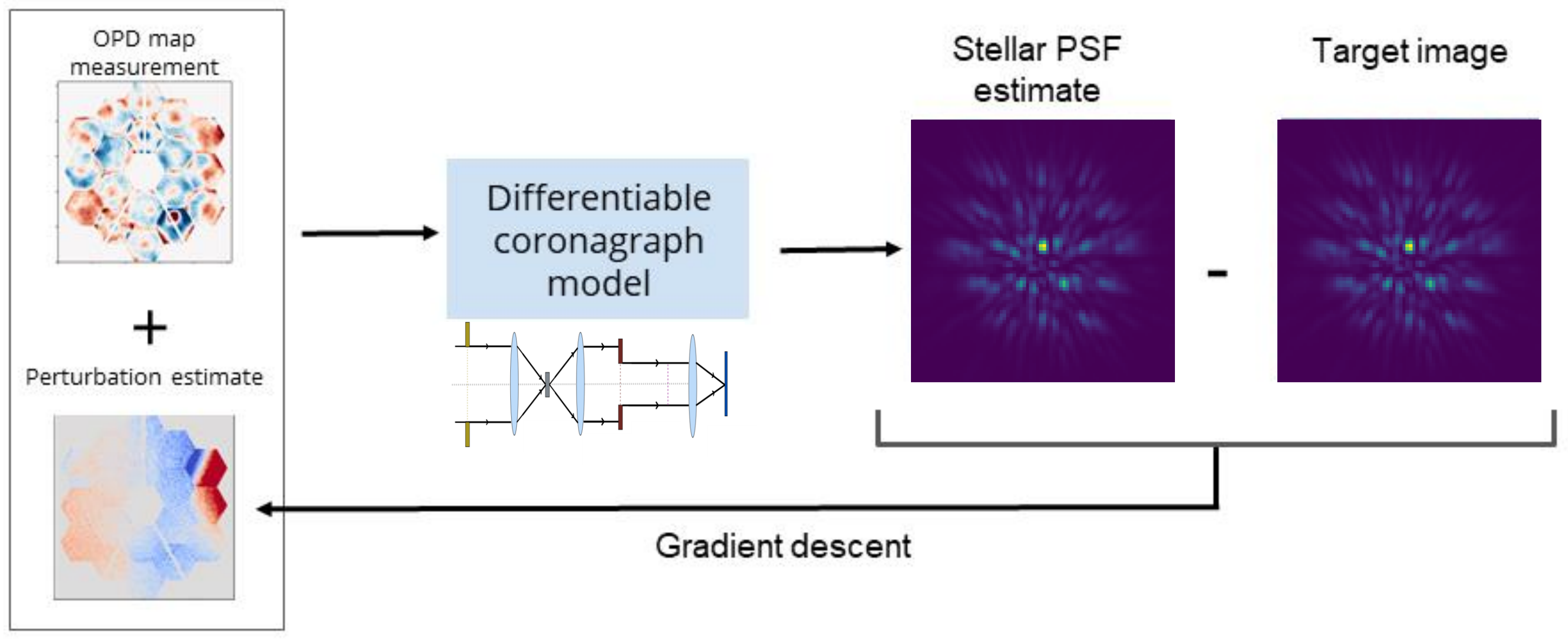


Figure 2. Schematic showing the method for stellar PSF modelling through a differentiable coronagraph model of the NIRCam instrument in JWST. A target image (right) containing both starlight and planet signals of interest is simulated, and through an iterative update of the optical path difference (OPD) map estimate, the model updates the stellar PSF model to better match the target image[2].

- Currently, **JWST takes measurements of the OPD** (caused e.g., by misalignments of the hexagonal mirrors) **every couple of days**.
- **The true OPD during any given science observation is expected to be close to the OPD measurements** taken closest in time to the observation (Fig. 3).
- To emulate this setting, we **take an in-flight OPD measurement from JWST**, and add to it a realistic perturbation obtained by interpolating with the next OPD measurement closest in time. **We use this "perturbed" OPD map to simulate our target image** (star PSF, planet signals of the desired contrast level, and photon and read noise).
- Using the OPD measurement as an initial condition, we **use the coronagraph model to iteratively simulate a stellar PSF that minimizes the difference with the target image,** updating the estimate of the OPD map.
- Wsimulated images in the F444W filter, including field-of-view- and wavelength-dependent aberrations, as previously computed with *webbPSF* [3].
- For effective photon noise, we assume an effective 2-hour integration time observing β Pictoris, which determines the fundamental noise detection limit (Fig. 5).

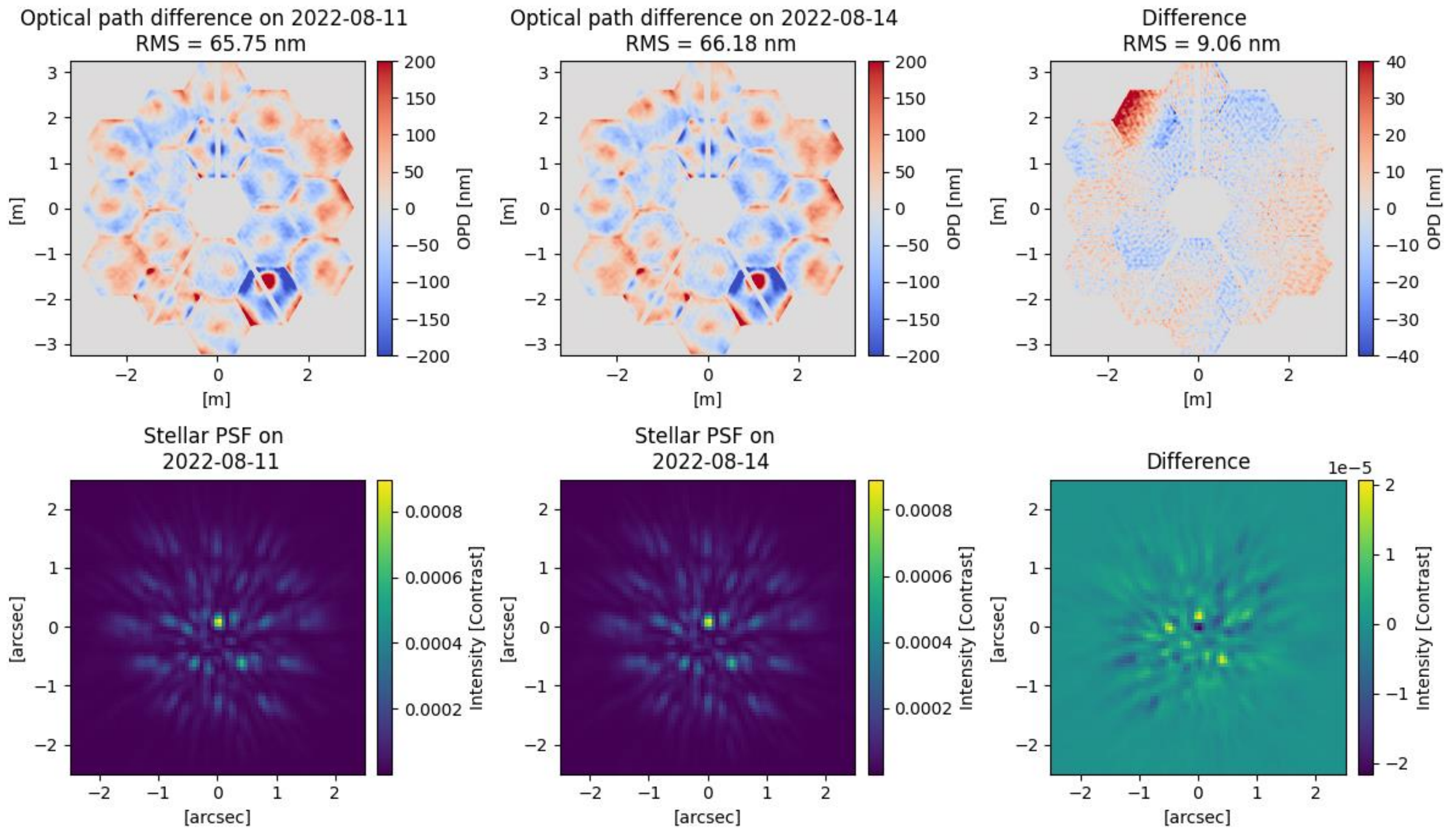
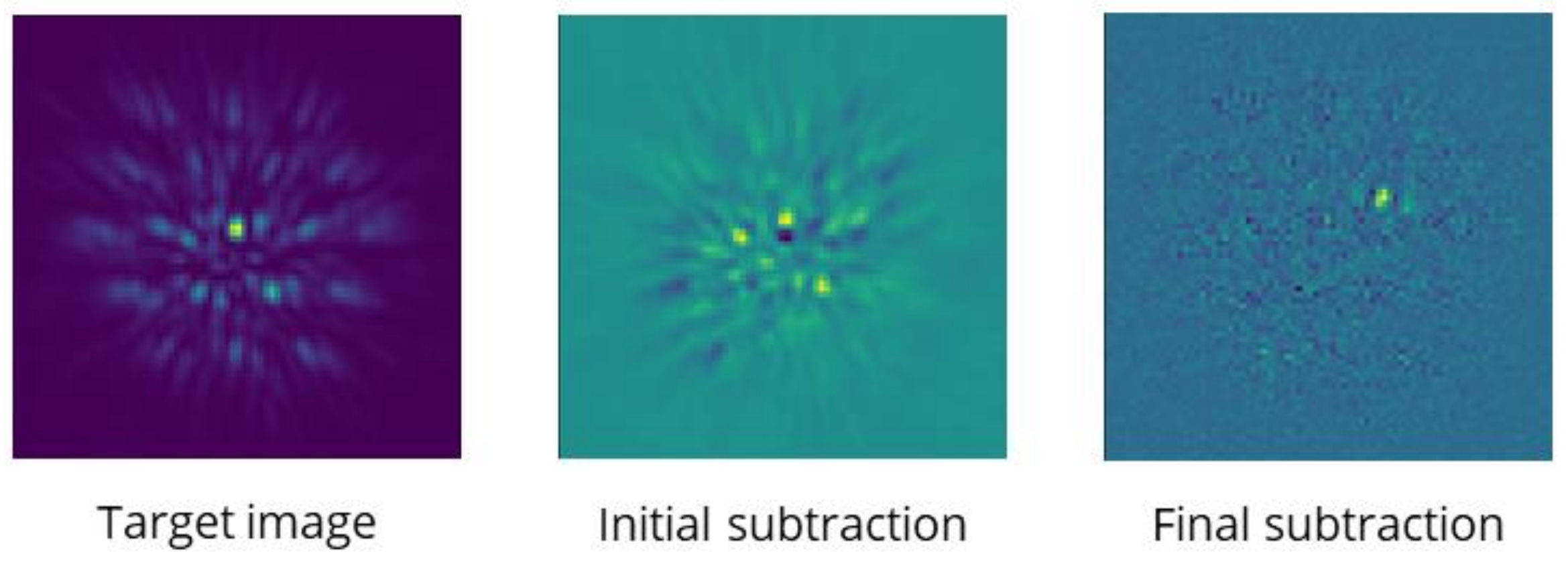


Figure 3. Two OPD measurements and their difference, along with their resulting stellar PSFs and their difference. Even though the level of drift between OPD maps over a few days in normal conditions is relatively small (RMS around 9 nm), and their resulting PSFs look identical by eye, the lower right panel shows that even that small drift is enough to cause changes in the PSF larger than many planet signals of interest (see Results section) [2].

Results

The PSF subtraction successfully revealed the planet signal at a wide variety of challenging contrast levels and separations, two of which are shown in Fig. 4. Fig. 5 shows these detections relative to the fundamental noise floor set by photon noise.

Contrast: 2×10^{-6}, Separation: 0.66 arcsec



Contrast: 1×10^{-6}, Separation: 1.12 arcsec

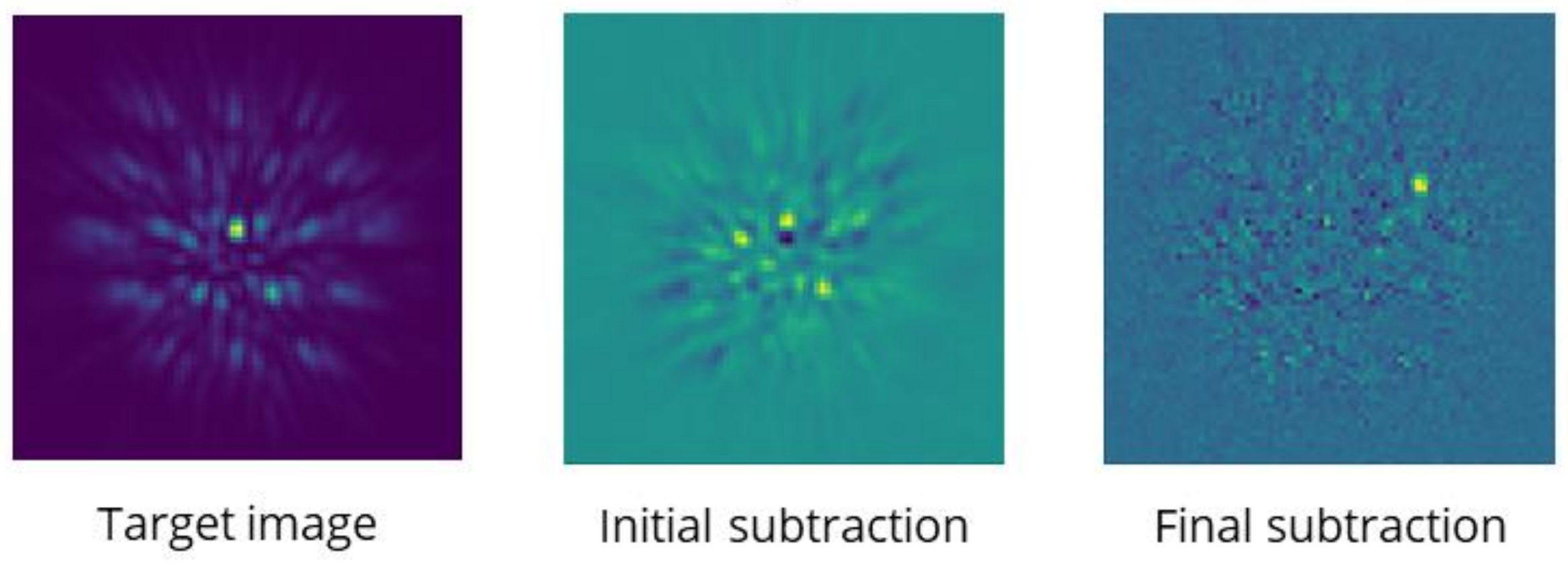


Figure 4. Examples of subtraction achieved via differentiable optical modelling. The left panels shown the target image, with a planet signal; the middle panel is the subtraction with the initialized OPD estimate (like bottom right panel in Fig. 3); and the right panels show the final subtraction, clearly revealing faint planets [2].

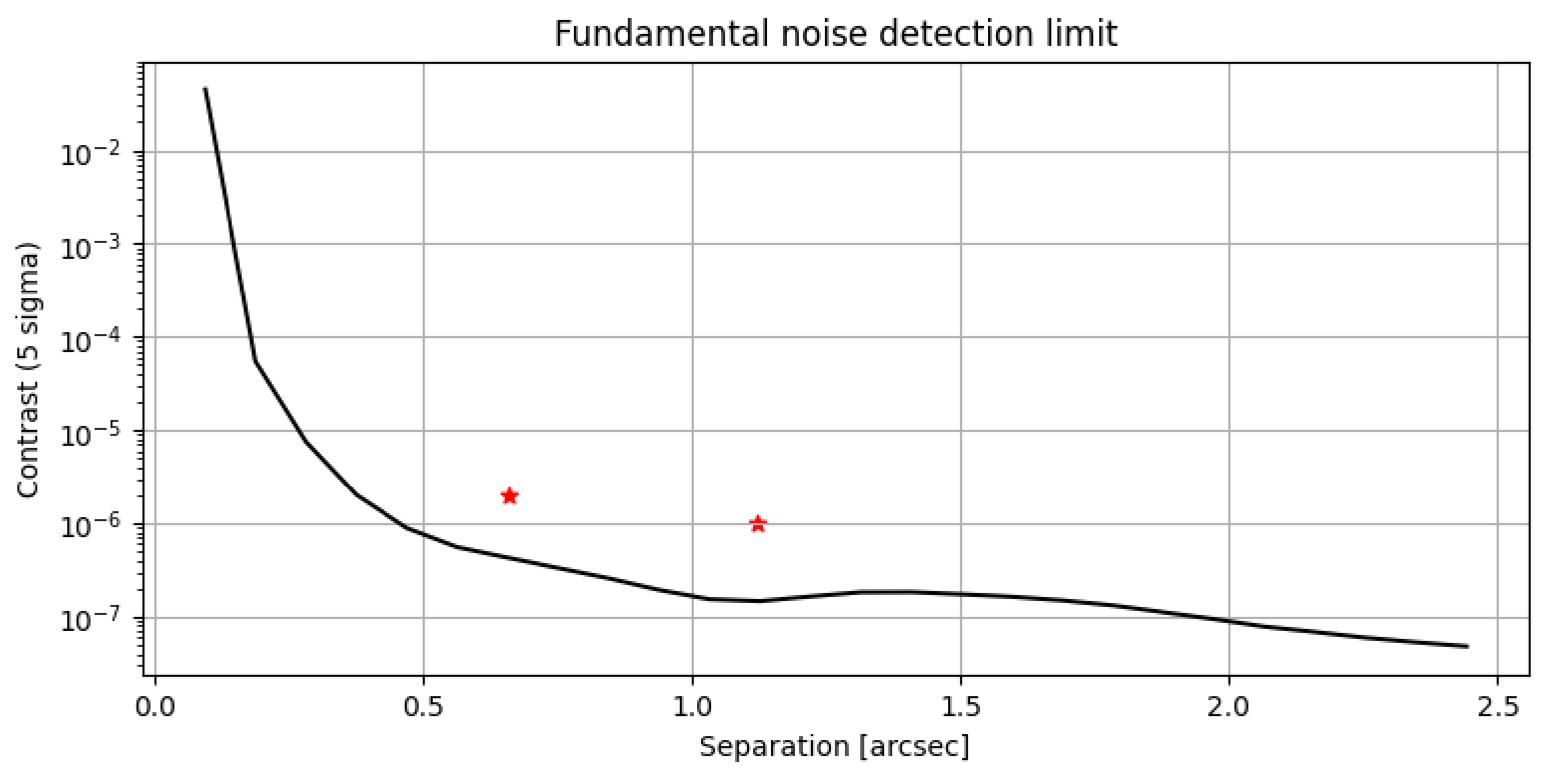


Figure 5. 5-σ detection limit set by photon noise in our simulation (solid black line), with the two detections from Fig. 4 shown with red markers. Very clear detections were achieved for contrast levels very close to photon noise [2].

Discussion and future work

These results in simulated data show the potential of this technique to be used in real astronomical observations. While in practice the optical simulation of the telescope will never be perfect, our method was also tested under conditions of moderate model mismatch, still achieving good results. **Therefore, a perfect optical simulation might not be necessary to perform high quality PSF subtractions via forward-modelling, just like perfectly identical reference stars are not necessary to perform high quality subtractions with PCA-based methods**. Future work will explore the effectiveness of this framework on real astronomical data and its performance relative to state-of-the-art methods such as KLIP [4].

References

1. NASA Exoplanet Archive (June 6th, 2024).
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