Characterizing accretion signatures with photonic lantern spectro-astrometry

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Introduction

Characterizing actively forming planets around young stars is important for understanding the detailed physics of planetary accretion. Recent studies have detected gas giants embedded within circumstellar disks at relatively large separations from their host stars. To detect planet formation on solar system scales, innovations in instrumentation and techniques are necessary. The photonic lantern is a fiber-optic device that, combined with the spectro-astrometry technique, has the potential to overcome these observational challenges.

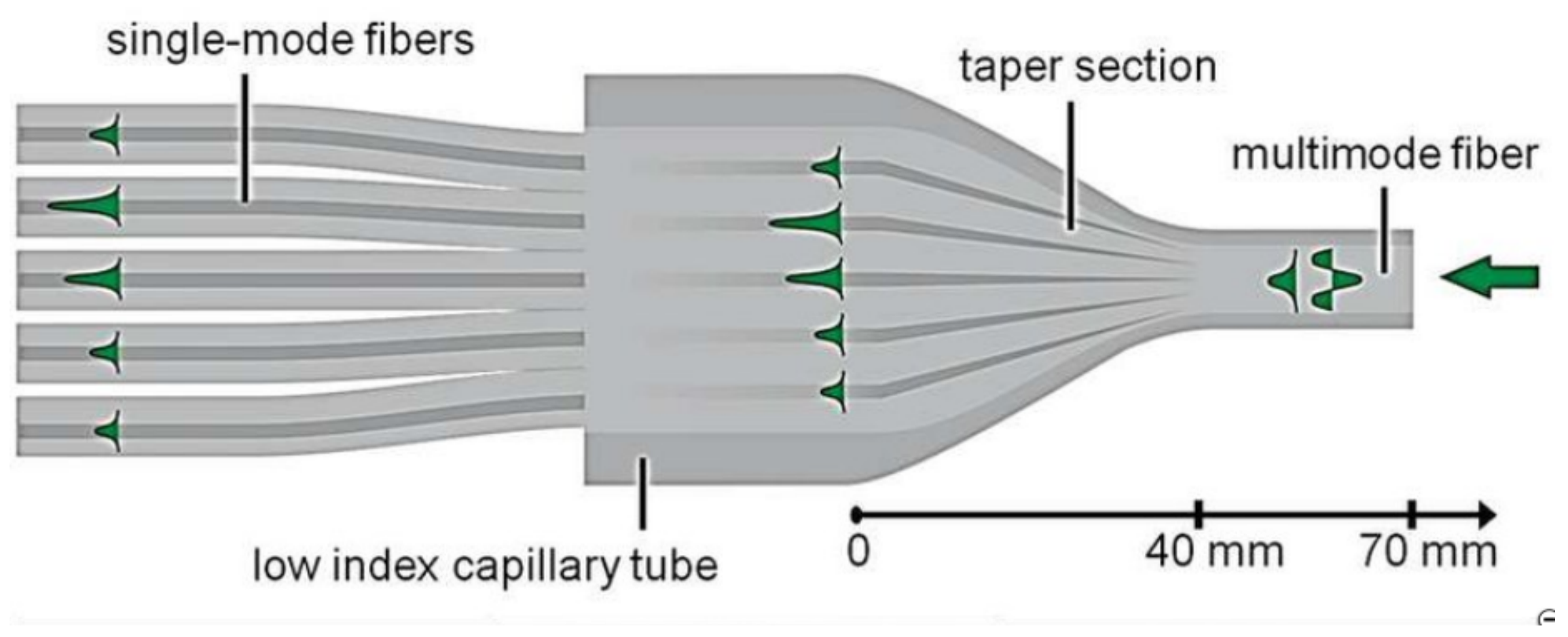

Figure 1. The photonic lantern takes multimode light into the multimode fiber end on the right, then isolates each individual mode, and outputs each mode in their own separate single mode fibers.

Figure 1 details how photonic lanterns take in unfiltered multimode light and filter out modal noise, allowing for observations within the diffraction limit. Here, we simulate photonic lantern observations of circumstellar disks hosting accreting protoplanets using the technique of spectro-astrometry, as shown in Figure 5.

Circumstellar Disk and Protoplanet Model

The circumstellar disk model consits of a central star, a gapped gaussian disk around the star, and a hotspot embedded within the disk representing accretion onto a protoplanet.

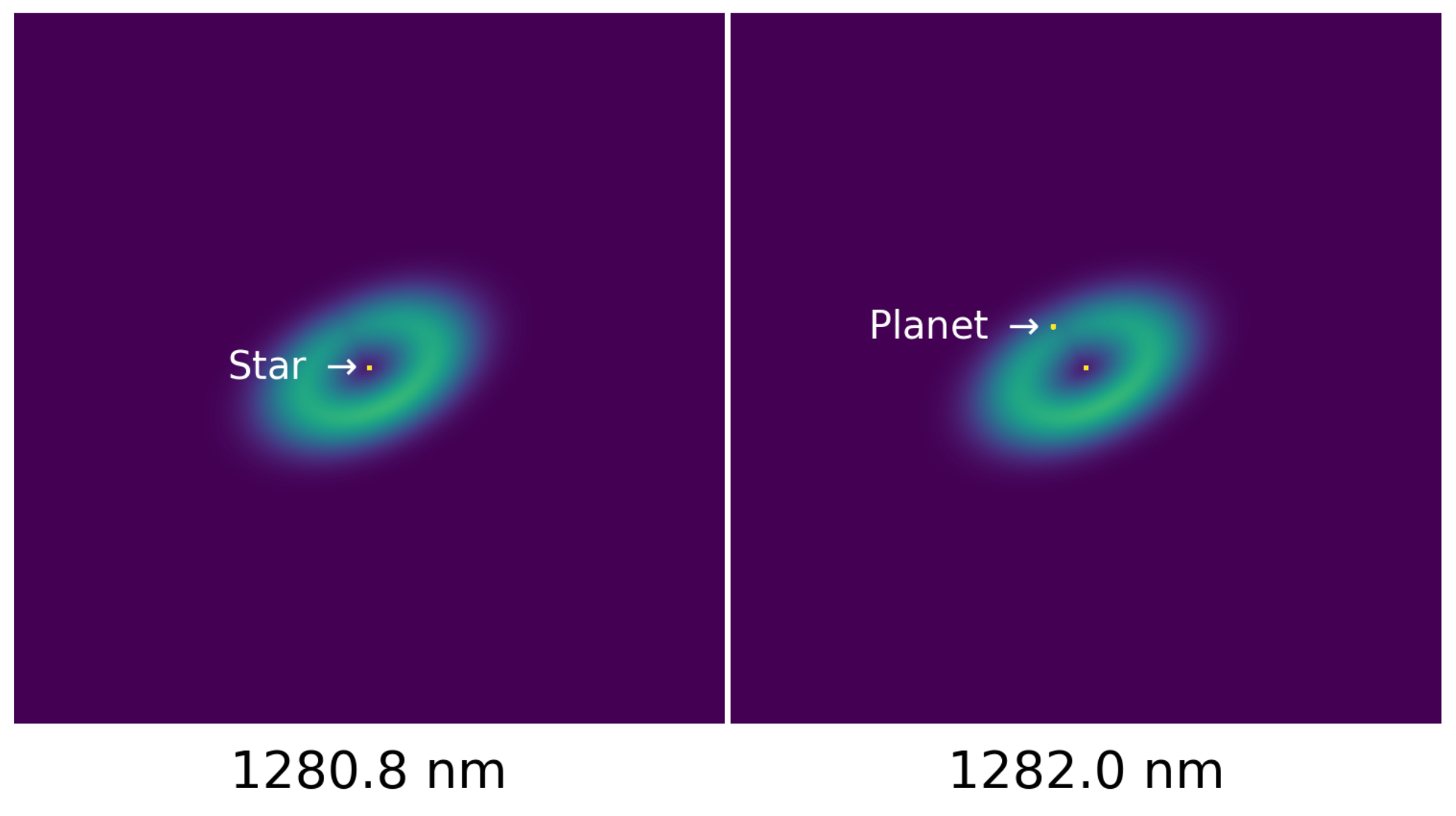

Figure 2. Circumstellar disk with an embedded accretion hotspot emitting at the Paβ line. The relative brightnesses are adjusted to enhance visibility of the disk and the hotspot.

The disk is defined by parameters including the relative brightnesses of the hotspot and the disk to the star, major axis position angle, axis ratio, disk uniformity, disk thickness, hotspot separation, and hotspot position angle. The model in Figure 2 shows a thick, gapped, nearly uniform disk with a protoplanet embedded in the inner edge of the disk. The simulated observation assumes a total integration time of 5 hours incorporating random photon noise and zernike tip/tilt jitter.

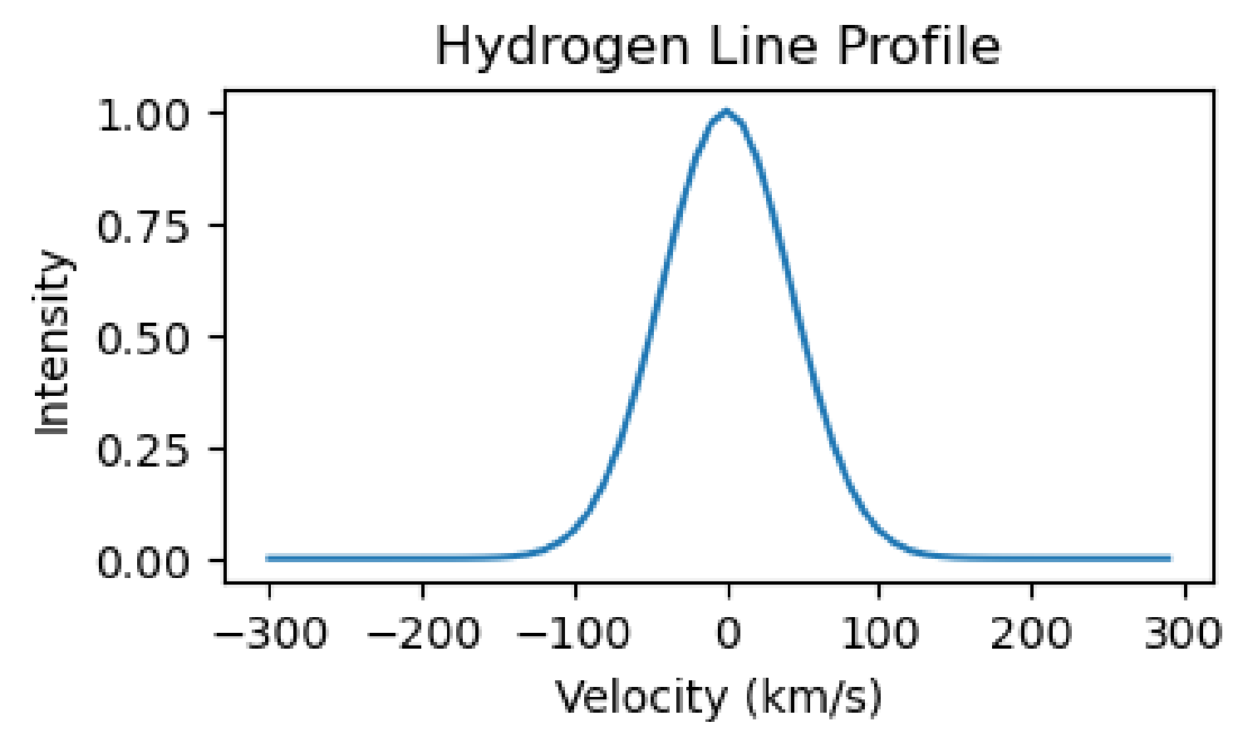

Figure 3. Hydrogen line profile centered on the Paschen-beta emission line with an free-fall velocity of ∼100 km/s.

We generated a Gaussian line profile centered on the PaB emission line assuming a FWHM of 100 km/s, representative of the expected free-fall velocity of a giant protoplanet in a circumstellar disk. We made 60 images of the circumstellar disk model spaced equally across the hydrogen line profile, with the hotspot brightness given by the intensity of the line.

Photonic Lantern

Optical propagation of light in a photonic lantern is linear in the complex electric field, so we can use a transfer matrix to simulate the propagation of the disk image through the photonic lantern.

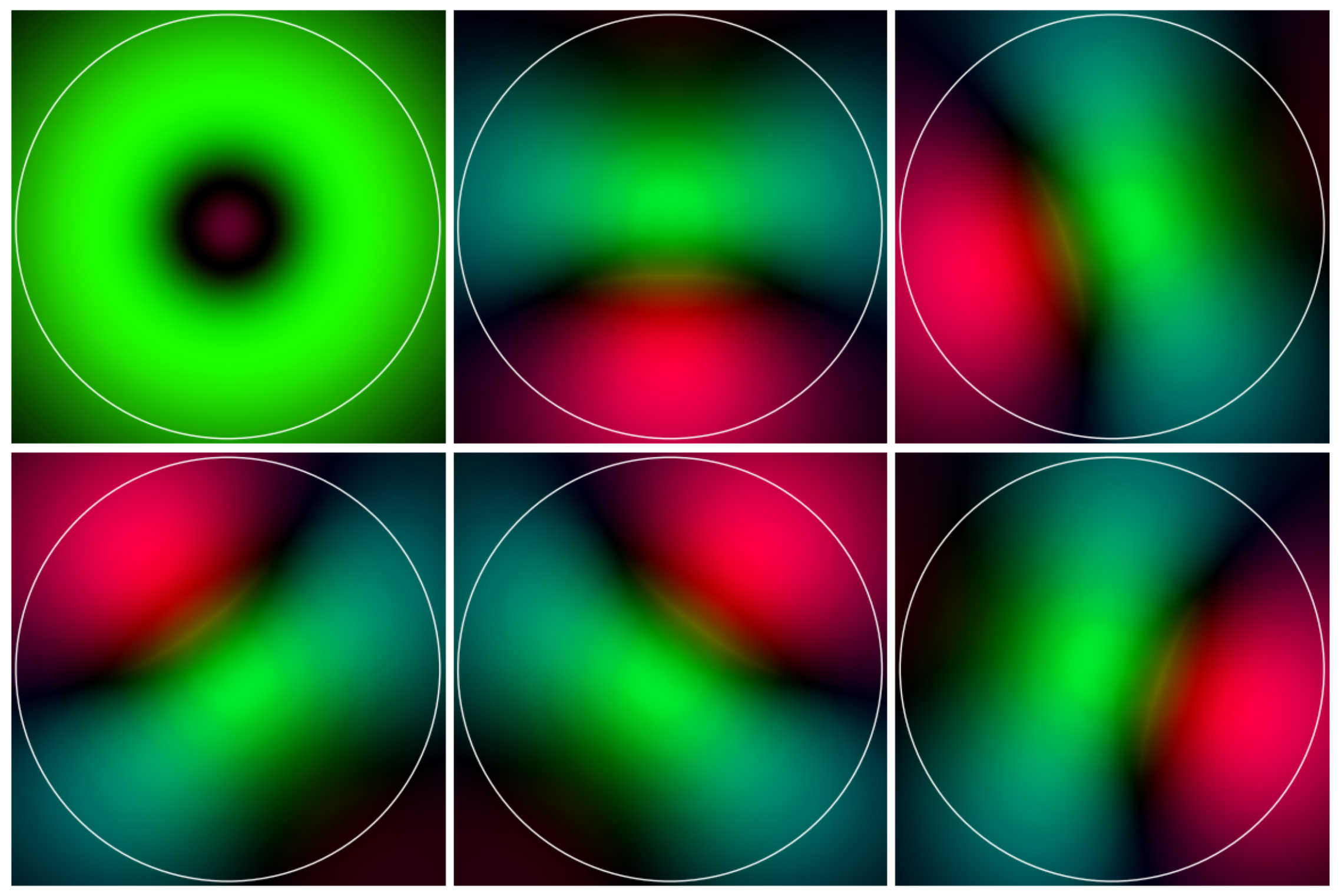

Figure 4. Visualization of the pupil plane complex electric fields of each of the six ports of the photonic lantern. Only light of the shape of each mode will pass through each of the ports.

The pupil plane image of the disk model is multiplied by the transfer matrix to get the intensity response of each port. Each of the six ports in Figure 4 only allows light of the mode shown to pass through and rejects all other light.

Spectro-astrometry

Spectro-astrometry utilizes the spatially-resolved spectra of a known object to determine the wavelength-dependent position of the object beyond the diffraction limit. Objects with separations smaller than the diffraction limit are unresolvable with traditional imaging techniques, but they can be clearly identified using spectro-astrometry. The hydrogen Paβ emission line at 1282 nm is a good indicator of protoplanetary accretion, so we simulate spectro-astrometric observations across that line.

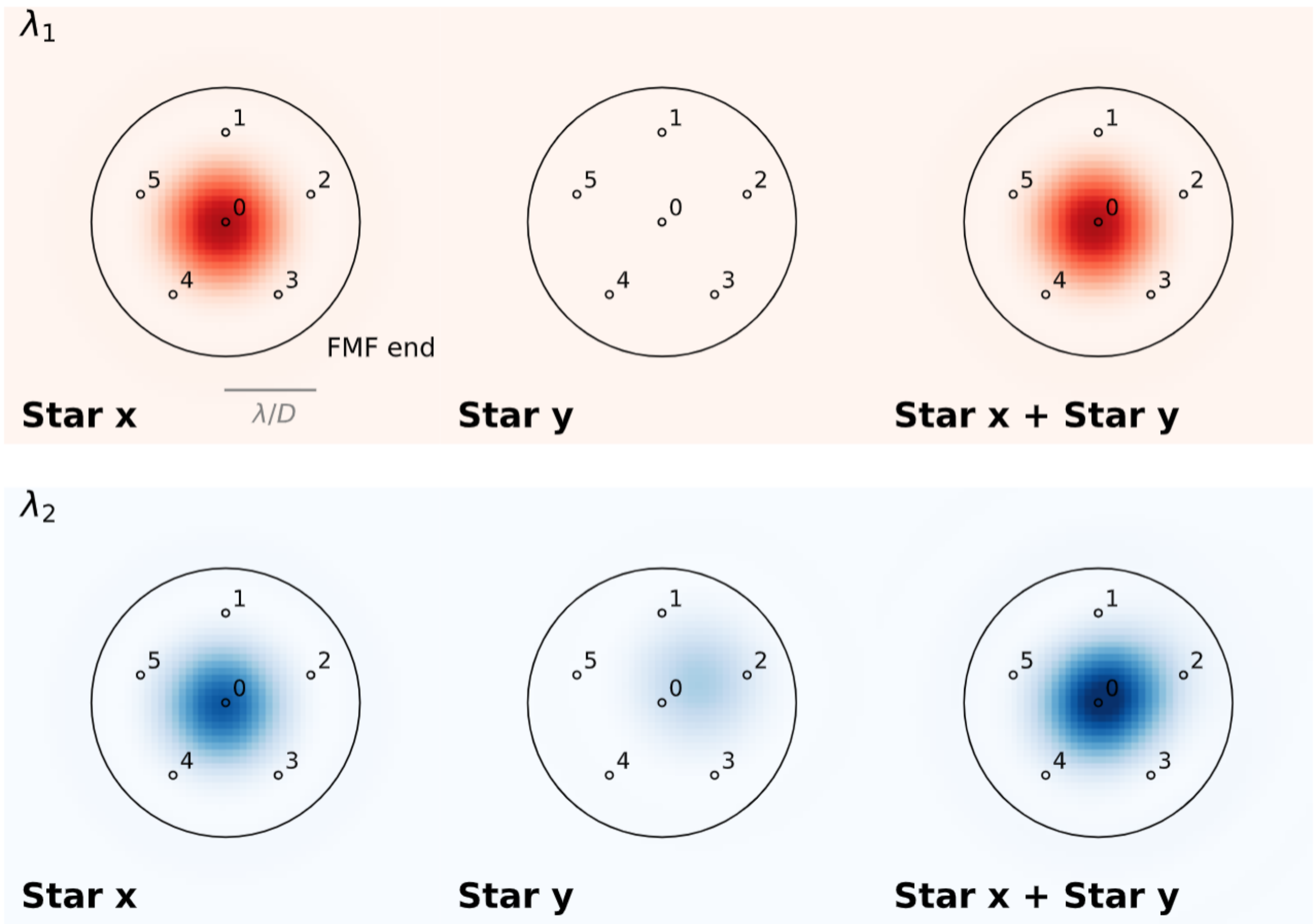

Figure 5. Focal plane intensity maps for an example binary consisting of a bright star (Star x) with no spectral features, and a dim star (Star y) with an emission line at λ_2.

At λ_1 in the example in Figure 5, the focal plane image of the binary is centered on the photonic lantern. Star y is too dim to detect at λ_1 so the centroid is dominated by Star x. At λ_2, Star y has excess emission, which causes the centroid to shift toward Star y, away from the center of the lantern outputs. This shift causes the relative intensities at the outputs of the lantern to change, allowing us to identify the presence of the second star in the binary. The simulations shown here include a more complex scene than that shown in Figure 5, with a central star plus a disk and an accretion hotspot, all with different spectral features.

References & Acknowledgements

[1] Schwab et al., 2012 [2] Kim et al., 2022 [3] Foreman-Mackey, 2016

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Parameter Recovery Results with MCMC

We use a parallel tempered Markov chain Monte Carlo algorithm to recover the parameters that define the model used in the simulated observations.

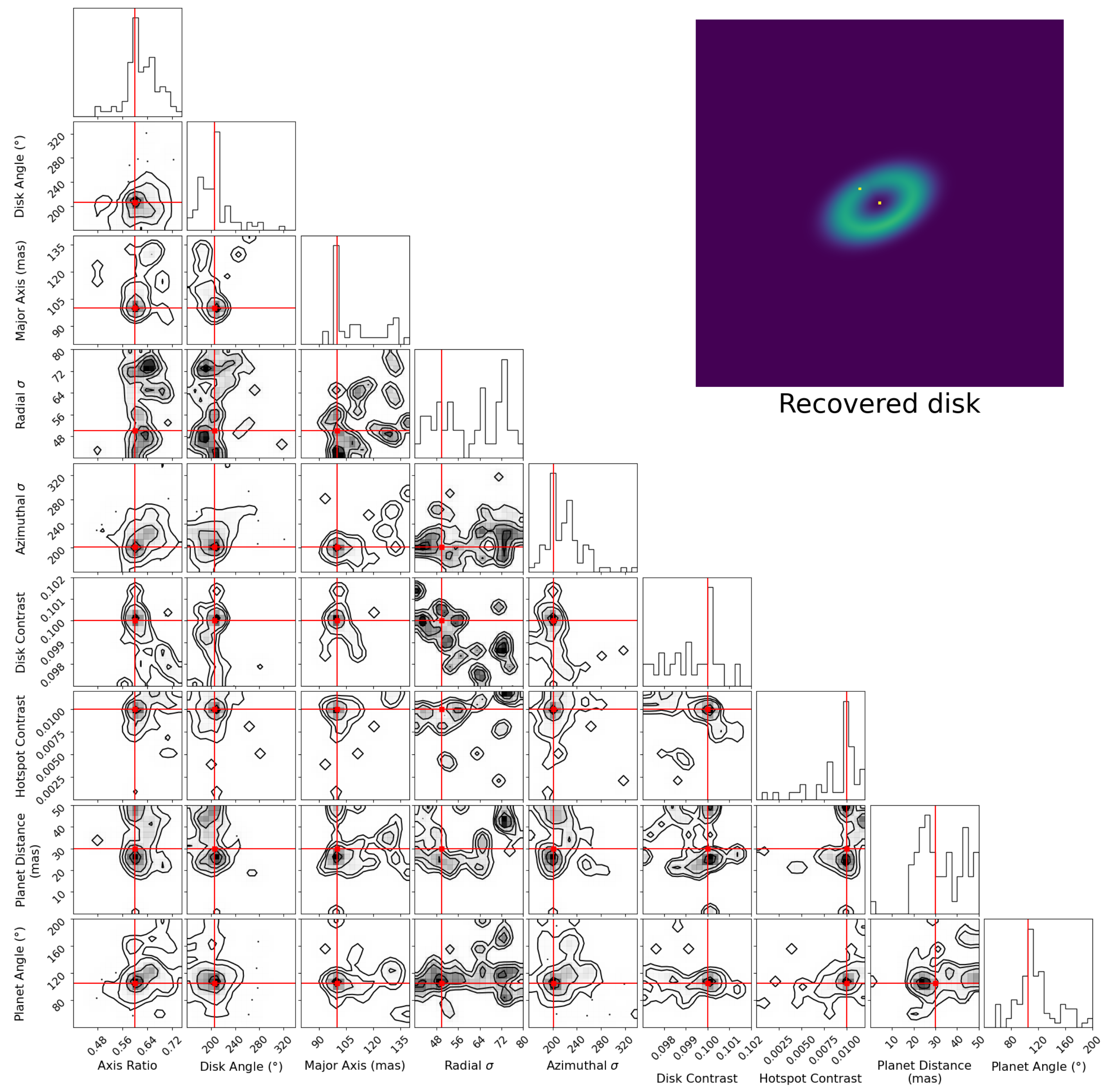

Figure 6. This corner plot shows the paremeter contraints from a short series of steps in a fit to the simulated data. The injected values are shown in red.

The corner plot in Figure 6 is a snapshot of the algorithm's progress after ∼20 steps. Currently, the recovered disk is similar to the injected disk, but could benefit from an increase in overall thickness. The companion is characterized nicely as well, but may need slight adjustments to its location.

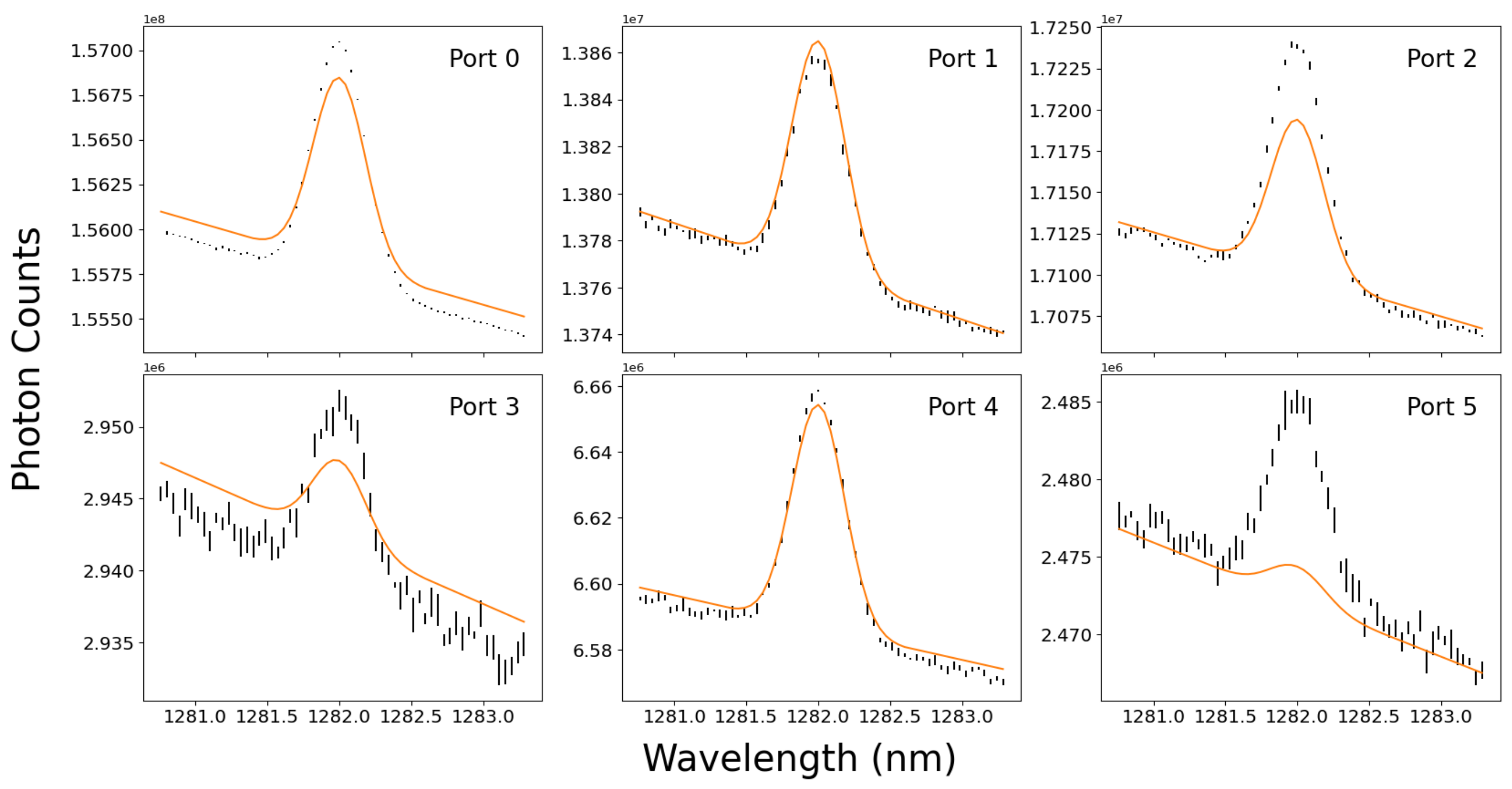

Figure 7. These plots show the lantern output as a function of wavelength, with each panel showing the output of a single port. Each of the outputs has a peak at the wavelength corresponding to the accretion hotspot, indicating a detection of the protoplanet.

Figure 7 shows the lantern intensity response for both the simulated observation (black error bars) and the recovered model (orange line). The bases of the injected and recovered signals in Ports 1, 2, 4, and 5 are all aligned nicely, and the peaks of Ports 1 and 4 show a good fit as well. The disparities in the peaks and bases of the rest of the ports will improve as the disk thickens and the hotspot location is more accurately recovered.

Future Work

The next step is to simulate more observations to constrain the limitations of photonic lantern spectro-astrometry. Understanding the capabilities of this method in detecting accreting protoplanets within disks of varying brightness will help inform on-sky observations in the near future.

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