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Data Processing for High-Contrast Imaging (HCI) with the James Webb Space Telescope (JWST)

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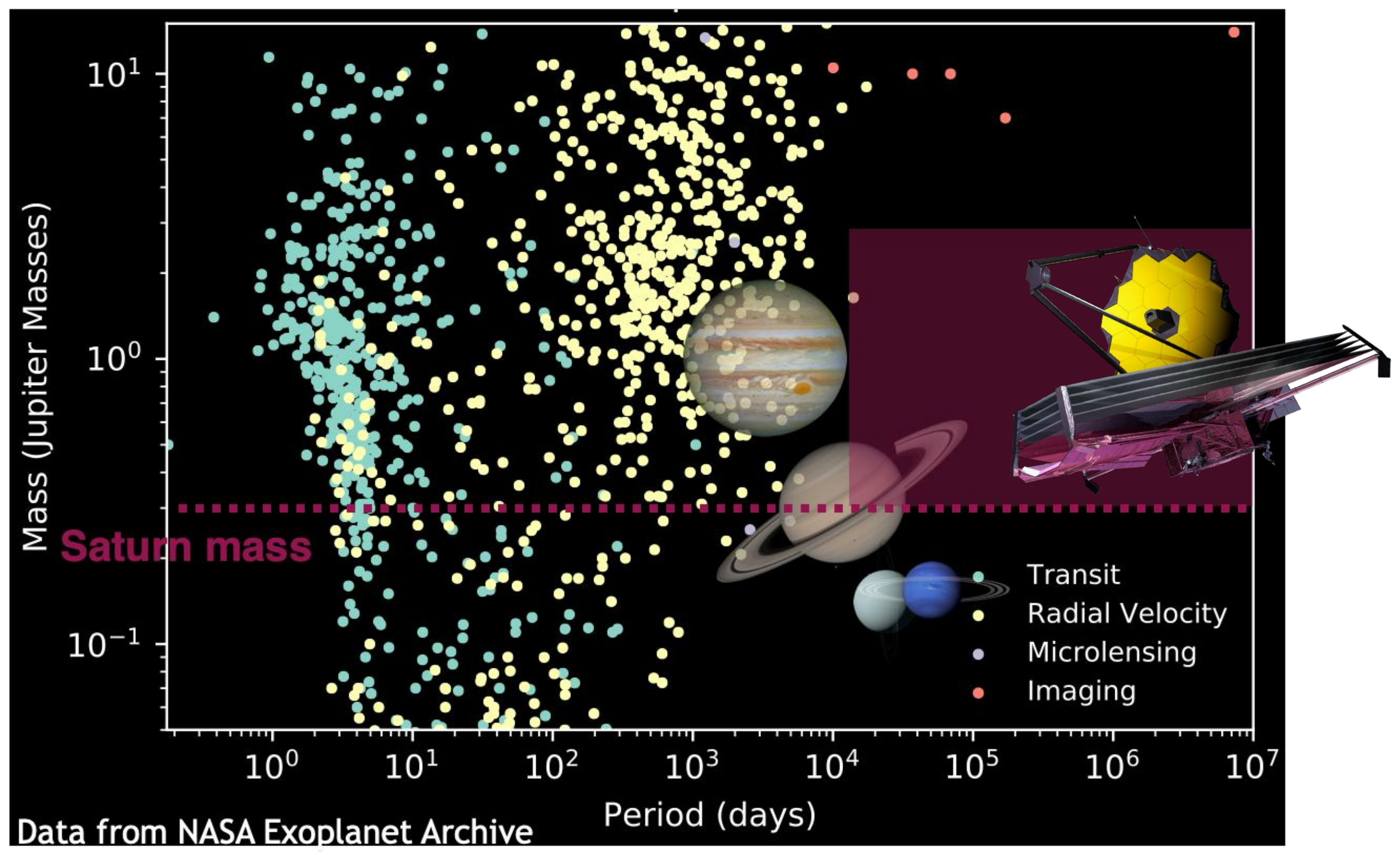
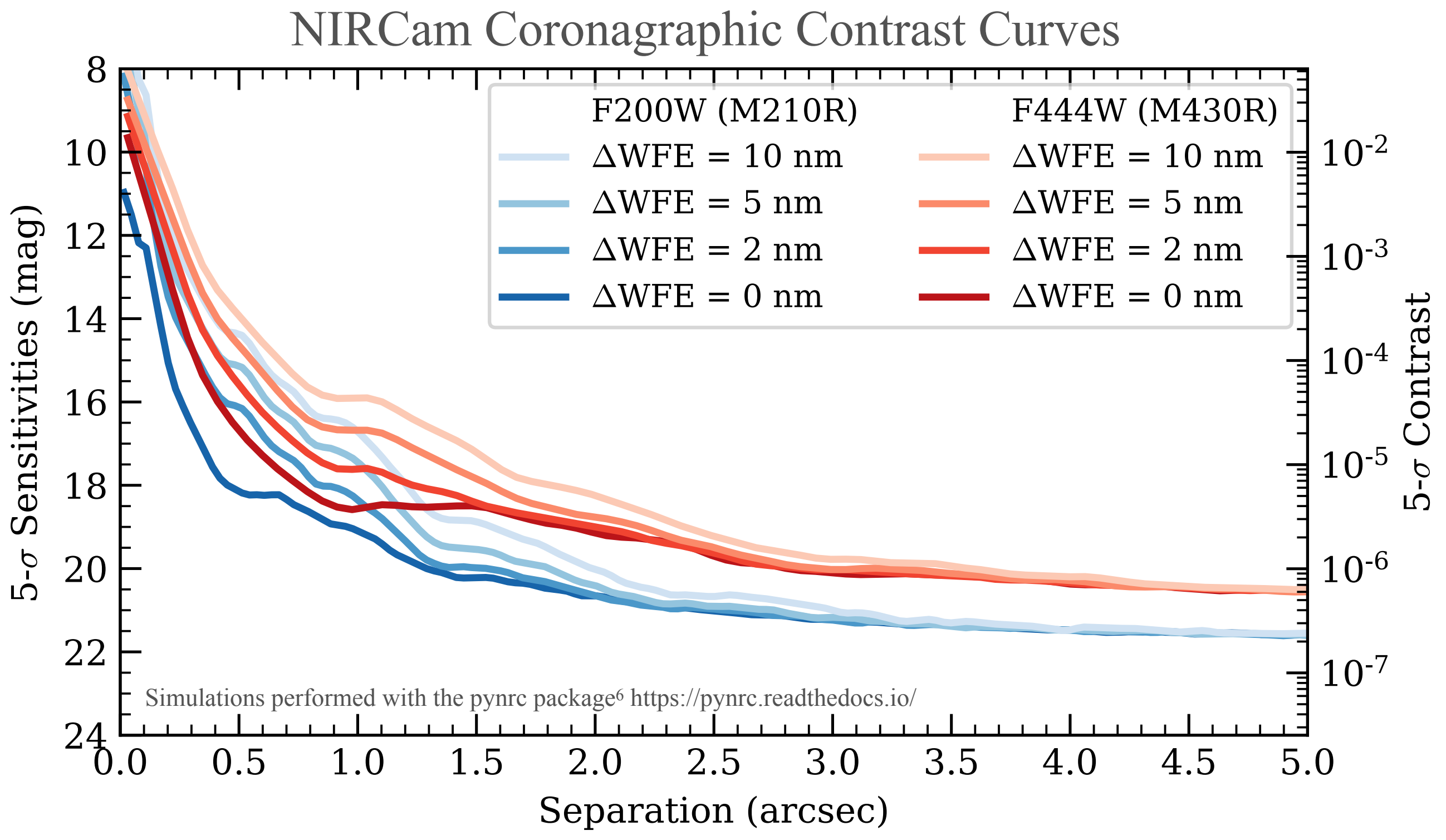
INTRODUCTION

JWST[1] will probe circumstellar environments at an unprecedented sensitivity. However, HCI's performance is limited by the residual light from the star at close separations (<2-3"), where the incidence of exoplanets increases rapidly. There is currently no solution to get rid of the residual light down to the photon noise level at those separations, which may prevent some crucial discoveries. JWST's debut is planned for October 2021 for a baseline mission lifetime of only 5 years. It is crucial to find a solution to this problem before its launch.

Further advances in post-processing techniques are required to enhance the detectability of planets hidden in the instrumental noise as well as to improve their characterization.



Data from NASA Exoplanet Archive

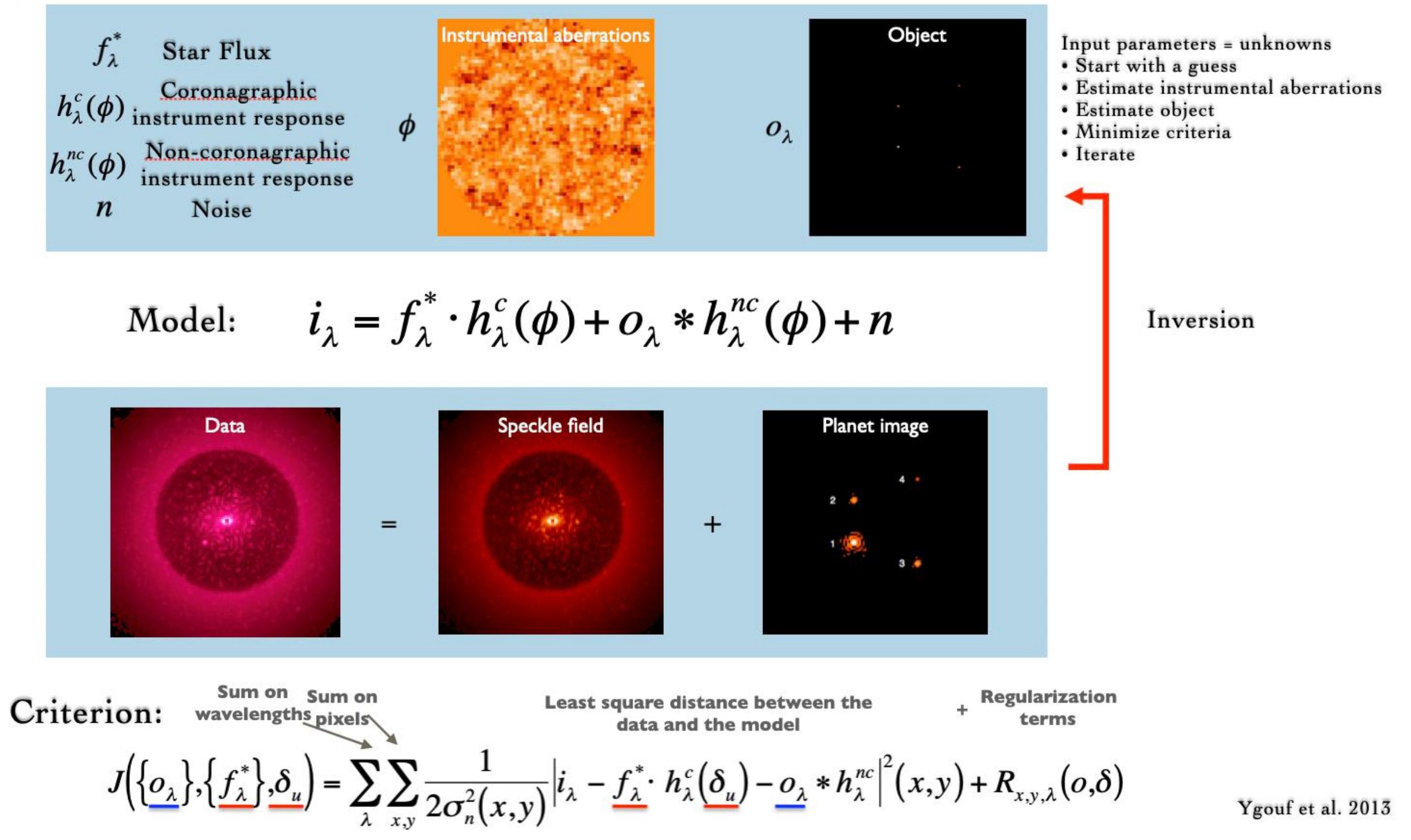


Simulations performed with the pynrc package[6] https://pynrc.readthedocs.io/

Contrast curves after post-processing for wavefront drifts ranging from 0 to 10nm in the ideal case of a reference star of the same spectral type as the target star (G stars with K=5.2mag). For this particular case, WFE drift=0nm corresponds to the photon noise limit. This limit is reached at separations >2–3" but conventional post-processing techniques do not reach the limit at closer separations.

METHODS

We are further developing and implementing an innovative approach to model HCI instruments that takes advantage of information, such as Wavefront Sensing (WFS) data on JWST, to estimate simultaneously instrumental aberrations and the object scene (*Medusae* Approach[2,3,4]) and provide a more robust determination of faint astrophysical structures around a bright source.

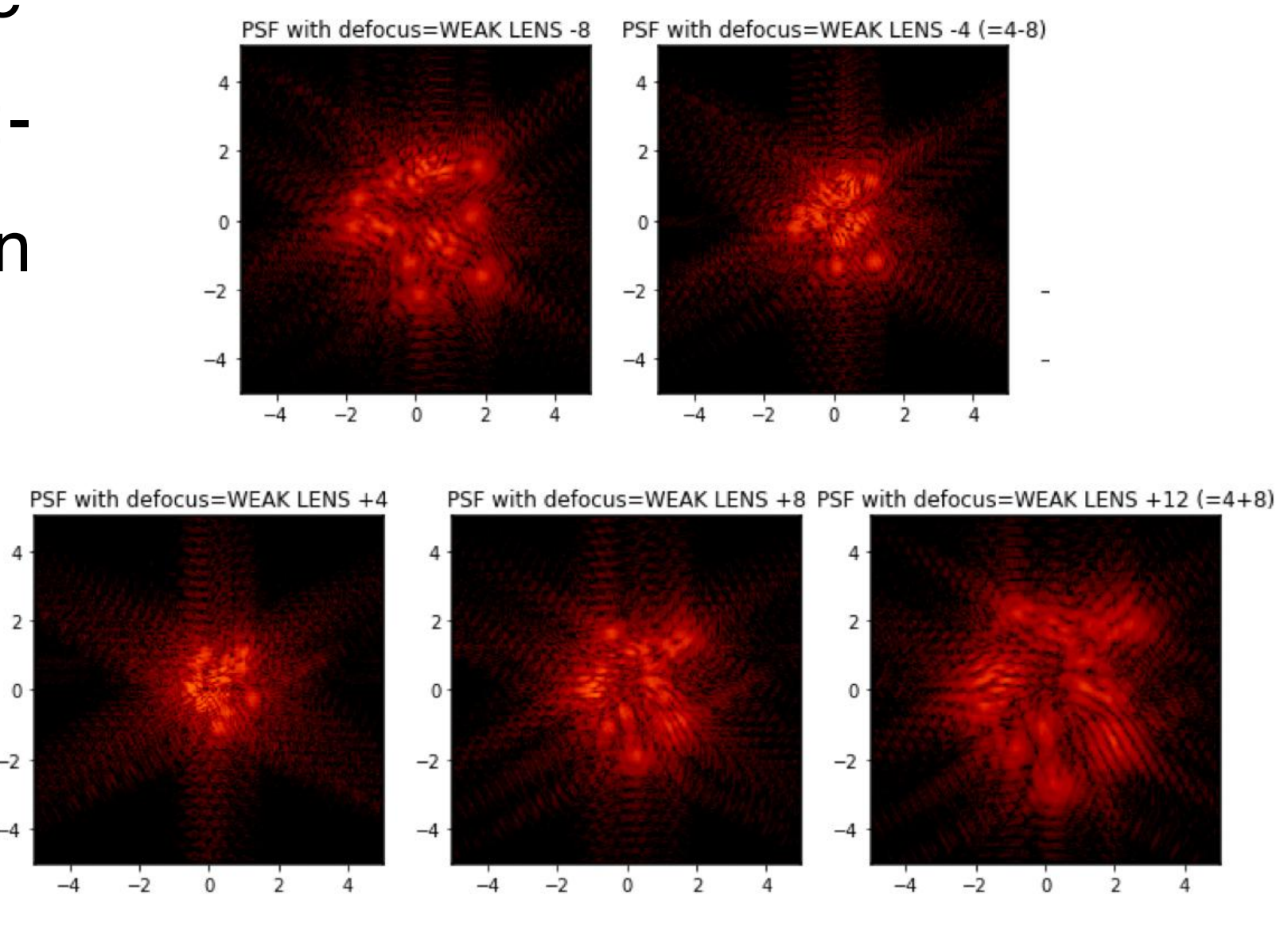


Model: $$i_\lambda = f_\lambda^* \cdot h_\lambda^c(\phi) + o_\lambda * h_\lambda^{nc}(\phi) + n$$

Criterion: $$J\left(\{\underline{o_\lambda}\},\{\underline{f_\lambda^*}\},\underline{\delta_u}\right) = \sum_\lambda \sum_{x,y} \frac{1}{2\sigma_n^2(x,y)} \left| i_\lambda - \underline{f_\lambda^*} \cdot h_\lambda^c(\underline{\delta_u}) - \underline{o_\lambda} * h_\lambda^{nc} \right|^2 (x,y) + R_{x,y,\lambda}(o,\delta)$$

Ygouf et al. 2013

JWST will provide bidiurnal instrumental aberrations measurements thanks to its WFS system. Those measurements can be used to build a good description of the instrument mode that will be crucial to inform post-processing in the mitigation of residual starlight.



JWST wavefront sensing data simulated with WebbPSF

The Bayesian framework that we are implementing offers the possibility to make use of the library of wavefront maps from the JWST wavefront sensing operations that will be publicly available. In particular, we reconstruct the wavefront by minimizing a metric that is based on the model of instrument.

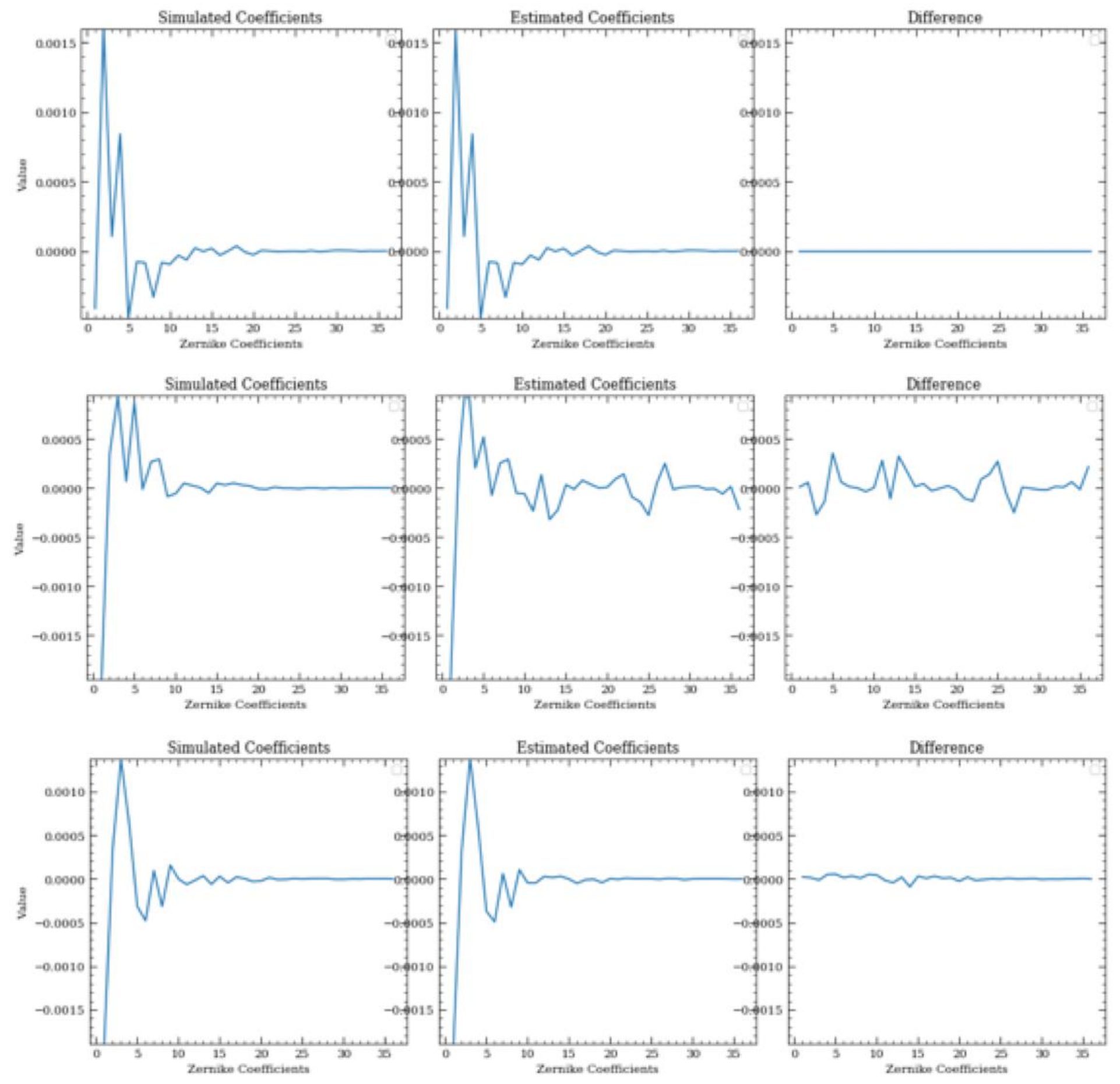
This process is degenerate and thus any prior information to help constraining the optimization algorithm is useful. The library of wavefront maps can be used to obtain such prior information.

We developed a complete python framework to simulate JWST NIRCam images and estimate wavefront maps from those images. We have a plan to further test and validate our technique on both simulated and real NIRCam JWST data.

RESULTS

We demonstrated that making use of a prior information gathered from WFS to inform post-processing improves the wavefront reconstruction from NIRCam simulated images.

The figure below demonstrates how a model-based phase retrieval algorithm can estimate wavefront aberrations in the form of 35 Zernike polynomials coefficients (orthogonal-basis representation the aberration maps) directly from a monochromatic non-coronagraphic NIRCam image. This estimation is improved when information about the power spectral density of the aberrations is used as an input of the reconstruction algorithm. When applied to coronagraphic images, this will enable to optimally reconstruct the circumstellar environment and enable its unbiased characterization.



Estimation of 35 first Zernike coefficients from NIRCam-like images. [Top panel] Without noise, the coefficients are perfectly estimated. [Center panel] With noise and unknown wavefront error budget (without no prior knowledge), coefficients are poorly estimated. [Bottom panel] With noise, known wavefront error budget (with prior knowledge), the estimation is greatly improved by adding prior information about the wavefront error (same wavefront error budget as the simulated wavefront).

This result is significant because this is the first time that some knowledge about the wavefront is used to inform and improve data processing.

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