

# Blind and robust reconstruction of adaptive optics point spread functions for asteroid deconvolution and moon detection

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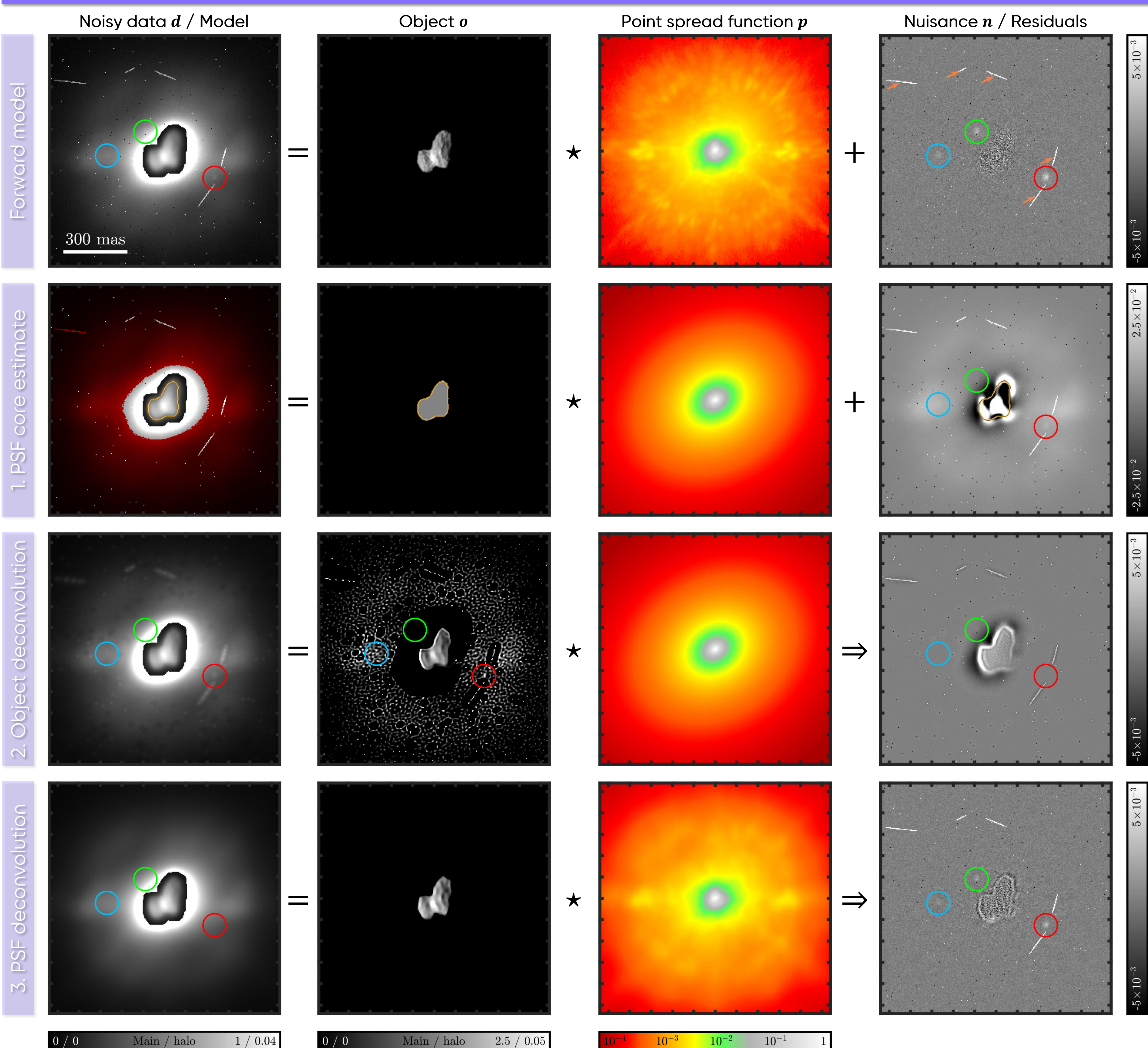
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## Abstract

Initially designed to detect and characterize exoplanets, extreme adaptive optics systems (AO) open a new window on the solar system by resolving its small bodies. Nonetheless, despite the always increasing performances of AO systems, the correction is not perfect, degrading their image and producing a bright halo that can hide faint and close moons. Using a reference point spread function (PSF) is not always sufficient due to the random nature of the turbulence. In this work, we present our method to overcome this limitation. It blindly reconstructs the AO-PSF directly in the data of interest, without any prior on the instrument nor the asteroid's shape. This is done by first estimating the PSF core parameters under the assumption of a sharp-edge and flat object, allowing the image of the main body to be deconvolved. Then, the PSF faint extensions are reconstructed with a robust penalization optimization, discarding outliers on-the-fly such as cosmic rays, defective pixels and moons. This allows to properly model and remove the asteroid's halo. Finally, moons can be detected in the residuals, using the reconstructed PSF and the knowledge of the outliers learned with the robust method. We show that our method can be easily applied to different instruments (VLT/SPHERE/ZIMPOL-IFS-IRDIS, Keck/NIRC2), efficiently retrieving the features of AO-PSFs. Compared with state-of-the-art moon enhancement algorithms, moon signal is greatly improved and our robust detection method manages to discriminate faint moons from outliers.

## Blind and Robust Deconvolution of AO-PSFs [1]



**Forward model:** the nuisance term  $n$  includes noise, moons, cosmic rays, dead and hot pixels, ...  
$$d = (o * p) + n$$

First guess (Step 1.) obtained with a **binary threshold** of the data convolved with a **parametric PSF** (2D elongated Moffat), discarding pixels emphasized in red.

**2D deconvolution of the object** (Step 2.) **and the PSF** (Step 3.) by alternating the minimization on  $o$  and  $p$  of the cost function:

$$\mathcal{C}(o, p) = \mathcal{D}^{wls}(d, o * p, w) + \mu^{obj} \mathcal{R}^{obj}(o) + \mu^{psf} \mathcal{R}^{psf}(p),$$

with

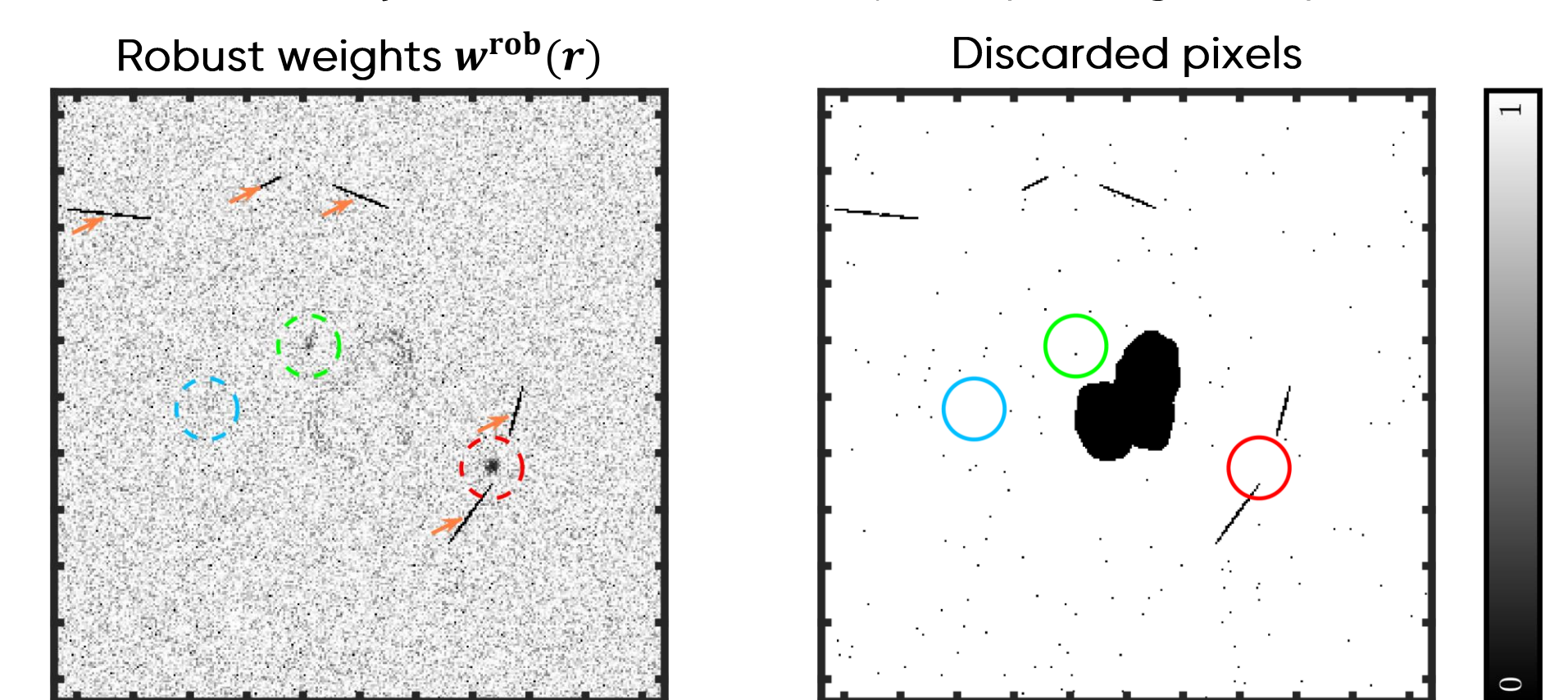
- $\mathcal{D}^{wls} \rightarrow$  Iterative reweighted Least Square of weights  $w$
- $\mathcal{R}^{obj} \rightarrow$  Hyperbolic norm on object gradients  $\nabla o$  (total variation)
- $\mathcal{R}^{psf} \rightarrow \ell^2$ -norm on PSF gradients  $\nabla[\log p]$  (dynamics whitening)

The weights  $w$  are updated using a **robust Cauchy estimator** on the residuals  $r$  to discard outliers on-the-fly:

$$w^{rob}(r) = (1 + r^2/2.385^2)^{-1}$$

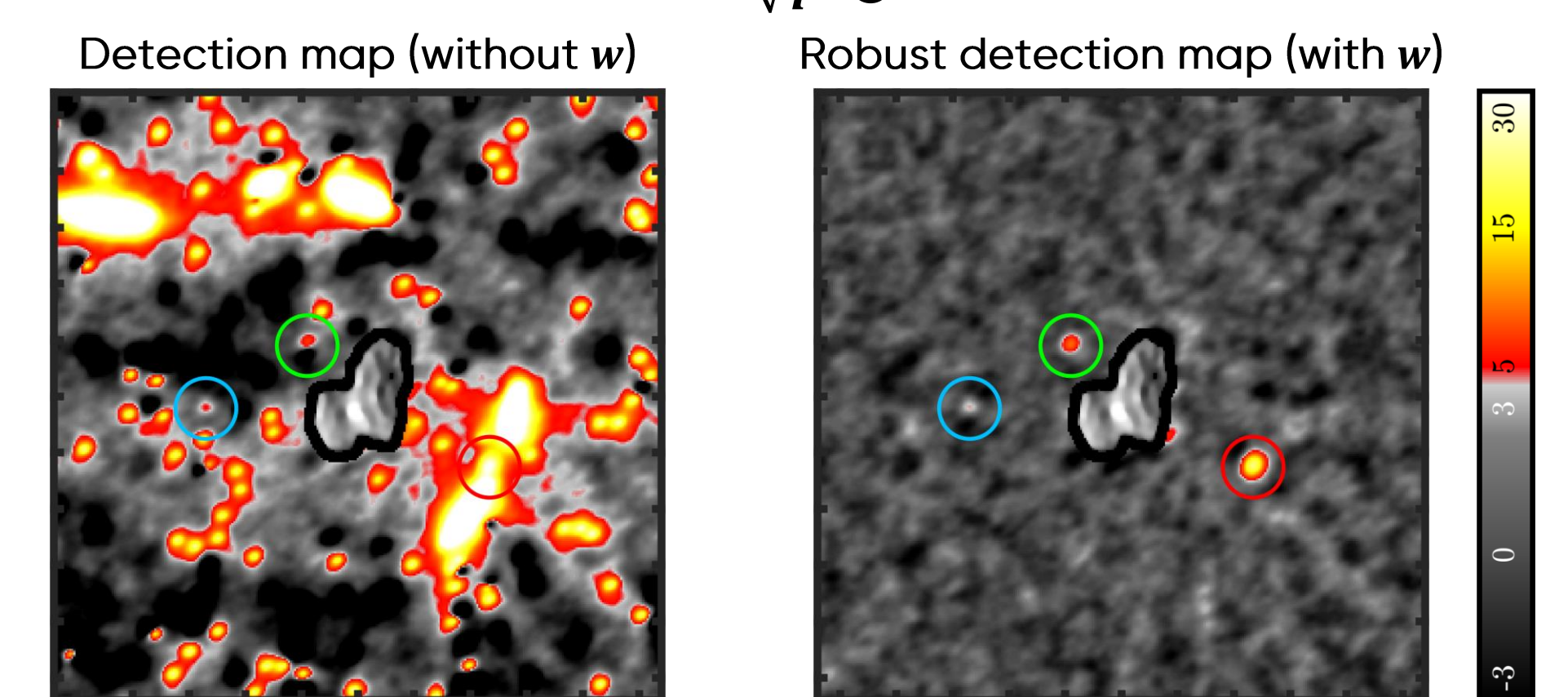
## Moon detection [2]

**Moons and outliers** (dead pixels, cosmic rays) are visible in the robust estimator equivalent weights. Isolated pixels and the deconvolved object are discarded by morphological operation.



**Significance maps** are obtained by robust weighted correlation:

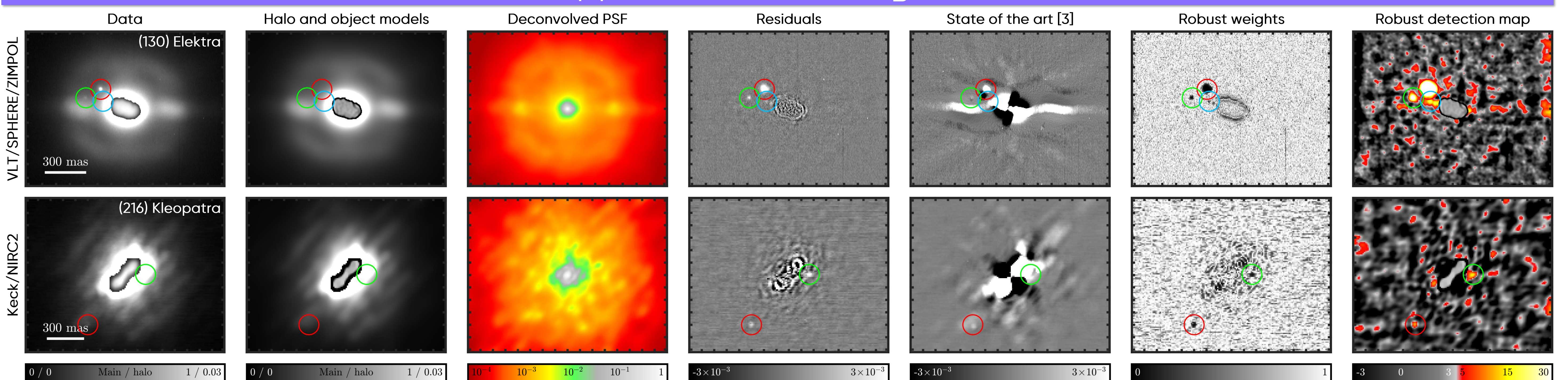
$$\sigma = \frac{p \otimes [w(d - p * o)]}{\sqrt{p^2 \otimes w}}$$



Simulated data based on a photo of 67P/Churyumov-Gerasimenko (European Space Agency). Dead pixels are simulated with "pepper & salt" noise on top of the photon and readout noises. 3 moons (colored circles) and 5 cosmic rays (orange arrows) are injected. After the alternate deconvolution: (i) the **object's shape**

**and surface texture** are retrieved, (ii) the **PSF structures** (AO cutoff frequency, main speckles, multi-lobbed core) are correctly estimated with the correct dynamics. **The moons and outliers are visible in the residuals.** The robust discarding of outliers cleans the detection maps from false positive. **The three moons are detected.**

## Application on On-Sky Data



**Conclusions:** (i) Robust to a large variety of instruments and turbulence conditions. (ii) Faint and close moon detection. (iii) Asteroid surface deconvolution. (iv) Prepare ELT complex PSFs.

**Perspectives:** (i) Improve the sensor noise model (detection map). (ii) Multi-frame and multi-epoch detection. (iii) Quantify the contrast performances. (iv) Process archival data.

## References & Acknowledgments

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