




# VIP: A Python package for high-contrast imaging

Valentin Christiaens<sup>1</sup>, Carlos Alberto Gómez Gonzalez<sup>2</sup>, Ralf Farkas<sup>3</sup>, Carl-Henrik Dahlqvist<sup>1</sup>, Evert Nasedkin<sup>4</sup>, Julien Milli<sup>5</sup>, Olivier Absil<sup>1</sup>, Henry Ngo<sup>6</sup>, Carles Cantero<sup>1,7</sup>, Alan Rainot<sup>8</sup>, Iain Hammond<sup>9</sup>, Faustine Cantalloube<sup>10</sup>, and Arthur Vigan<sup>10</sup>

<sup>1</sup> Space sciences, Technologies & Astrophysics Research Institute, Université de Liège, Belgium <sup>2</sup> Barcelona Supercomputing Center, Barcelona, Spain <sup>3</sup> Rheinische Friedrich-Wilhelms-Universität Bonn, Germany <sup>4</sup> Max-Planck-Institut für Astronomie, Heidelberg, Germany <sup>5</sup> Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France <sup>6</sup> NRC Herzberg Astronomy and Astrophysics, Victoria, BC, Canada <sup>7</sup> Montefiore Institute, Université de Liège, 4000 Liège, Belgium <sup>8</sup> Institute of Astronomy, KU Leuven, Belgium <sup>9</sup> School of Physics and Astronomy, Monash University, Vic 3800, Australia <sup>10</sup> Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

## Software

- [Review](#) 
- [Repository](#) 
- [Archive](#) 

Editor: [Open Journals](#) 

## Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

## License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

## Summary

Direct imaging of exoplanets and circumstellar disks at optical and infrared wavelengths requires reaching high contrasts at short angular separations. This can only be achieved through the synergy of advanced instrumentation, such as adaptive optics and coronagraphy, with a relevant combination of observing strategy and post-processing algorithms to model and subtract residual starlight. In this context, VIP is a Python package providing the tools to reduce, post-process and analyze high-contrast imaging datasets, enabling the detection and characterization of directly imaged exoplanets, circumstellar disks, and stellar environments.

## Statement of need

VIP stands for Vortex Image Processing. It is a collaborative project which started at the University of Liège, aiming to integrate open-source, efficient, easy-to-use and well-documented implementations of state-of-the-art algorithms used in the context of high-contrast imaging. The package follows a modular architecture, such that its routines cover a wide diversity of tasks, including:

- image pre-processing, such as sky subtraction, bad pixel correction, bad frame removal, or image alignment and star centering (preproc module);
- modeling and subtracting the stellar point spread function (PSF) using state-of-the-art algorithms that leverage observing strategies such as angular differential imaging (ADI), spectral differential imaging (SDI) or reference star differential imaging ([Marois et al., 2006](#); [Ruane et al., 2019](#); [Sparks & Ford, 2002](#)), which induce diversity between speckle and authentic astrophysical signals (psfsub module);
- characterizing point sources and extended circumstellar signals through forward modeling (fm module);
- detecting and characterizing point sources through inverse approaches (invprob module);
- assessing the achieved contrast in PSF-subtracted images, automatically detecting point sources, and estimating their significance (metrics module).

The features implemented in VIP as of 2017 are described in Gomez Gonzalez et al. ([2017](#)). Since then, the package has been widely used by the high-contrast imaging community for

the discovery of low-mass companions (Hirsch et al., 2019; Milli, Hibon, et al., 2017; Ubeira-Gabellini et al., 2020), their characterization (Christiaens et al., 2019, 2018; Delorme et al., 2017; Wertz et al., 2017), the study of planet formation (Maucó et al., 2020; Reggiani et al., 2018; Ruane et al., 2017; Toci et al., 2020), the study of high-mass star formation (Rainot et al., 2022, 2020), the study of debris disks (Milli, Vigan, et al., 2017; Milli et al., 2019), or the development of new high-contrast imaging algorithms (Dahlqvist et al., 2020, 2021; Gomez Gonzalez et al., 2018; Pairet et al., 2021). Given the rapid expansion of VIP, we summarize here all novelties that were brought to the package over the past five years.

The rest of this manuscript summarizes all major changes since v0.7.0 (Gomez Gonzalez et al., 2017), that are included in the latest release of VIP (v1.3.0). At a structural level, VIP underwent a major change since version v1.1.0, which aimed to migrate towards a more streamlined and easy-to-use architecture. The package now revolves around five major modules (fm, invprob, metrics, preproc and psfsub, as described above) complemented by four additional modules containing various utility functions (config, fits, stats and var). New Dataset and Frame classes have also been implemented, enabling an object-oriented approach for processing high-contrast imaging datasets and analyzing final images, respectively. Similarly, a HCIPostProcAlgo class and different subclasses inheriting from it have been defined to facilitate an object-oriented use of VIP routines.

Some of the major changes in each module of VIP are summarized below:

- fm:
  - new routines were added to create parametrizable scattered-light disk models and extended signals in ADI cubes, in order to forward-model the effect of ADI post-processing (Christiaens et al., 2019; Milli et al., 2012);
  - the log-likelihood expression used in the negative fake companion (NEGFC) technique was updated, and the default convergence criterion for the NEGFC-MCMC method is now based on auto-correlation (Christiaens et al., 2021);
  - the NEGFC methods are now fully compatible with integral field spectrograph (IFS) input datacubes.
- invprob:
  - a Python implementation of the ANDROMEDA algorithm (Cantalloube et al., 2015) is now available as part of VIP;
  - the KLIP-FMMF and LOCI-FMMF algorithms (Dahlqvist et al., 2021; Pueyo, 2016; Ruffio et al., 2017) are now also available in the invprob module.
  - a Python implementation of the PACO algorithm (Flasseur et al., 2018) is now also available, including both the planet detection and flux estimation algorithms.
- metrics:
  - calculation of standardized trajectory maps (STIM) is now available (Pairet et al., 2019);
  - functions to calculate completeness-based contrast curves and completeness maps, inspired by the framework in Jensen-Clem et al. (2018) and implemented as in Dahlqvist et al. (2021), have now been added to the metrics module.
- preproc:
  - the module now boasts several new algorithms for (i) the identification of either isolated bad pixels or clumps of bad pixels, leveraging on iterative sigma filtering (cube\_fix\_badpix\_clump), the circular symmetry of the PSF (cube\_fix\_badpix\_a\_nnull), or the radial expansion of the PSF with increasing wavelength (cube\_fix\_badpix\_ifs), and (ii) the correction of bad pixels based on either median replacement (default) or Gaussian kernel interpolation (cube\_fix\_badpix\_with\_kernel);
  - a new algorithm was added for the recentering of coronagraphic image cubes based on the cross-correlation of the speckle pattern, after appropriate filtering and log-scaling of pixel intensities (Ruane et al., 2019).
- psfsub:
  - all principal component analysis (PCA) based routines (Amara & Quanz, 2012;

- 94 [Soummer et al., 2012](#)) have been re-written for improved efficiency, and are now  
 95 also compatible with 4D IFS+ADI input cubes to apply SDI-based PSF modeling  
 96 and subtraction algorithms;  
 97 – an implementation of the Locally Optimal Combination of Images algorithm  
 98 ([Lafrenière et al., 2007](#)) was added;  
 99 – an annular version of the non-negative matrix factorization algorithm is now available  
 100 ([Gomez Gonzalez et al., 2017](#); [Lee & Seung, 1999](#));  
 101 – besides median-ADI, the medsub routine now also supports median-SDI.

102 We refer the interested reader to release descriptions and GitHub [announcements](#) for a more  
 103 complete list of all changes, including improvements not mentioned in the above summary.

104 Two major convention updates are also to be noted in VIP. All image operations (rotation,  
 105 scaling, resampling and sub-pixel shifts) are now performed using Fourier-Transform (FT)  
 106 based methods by default. These have been implemented as low-level routines in the preproc  
 107 module. FT-based methods significantly outperform interpolation-based methods in terms  
 108 of flux conservation ([Larkin et al., 1997](#)). However, given the order of magnitude slower  
 109 computation of FT-based image rotations, the option to use interpolation-based methods is  
 110 still available in all relevant VIP functions. The second change of convention concerns the  
 111 assumed center for even-size images, which is now defined as the top-right pixel among the  
 112 four central pixels of the image - a change motivated by the new default FT-based methods  
 113 for image operations. The center convention is unchanged for odd-size images (central pixel).

114 Finally, a total of nine jupyter notebook tutorials covering most of the available features in VIP  
 115 were implemented. These tutorials illustrate how to (i) load and post-process an ADI dataset  
 116 (quick-start tutorial); (ii) pre-process ADI and IFS datasets; (iii) model and subtract the stellar  
 117 halo with ADI-based algorithms; (iv) calculate metrics such as the S/N ratio ([Mawet et al.,  
 118 2014](#)), STIM maps ([Pairet et al., 2019](#)) and contrast curves; (v) find the radial separation,  
 119 azimuth and flux of a point source; (vi) create and forward model scattered-light disk models;  
 120 (vii) post-process IFS data and infer the exact astro- and photometry of a given point source;  
 121 (viii) use FT-based and interpolation-based methods for different image operations, and assess  
 122 their respective performance; and (ix) use the new object-oriented framework for VIP.

## 123 Acknowledgements

124 An up-to-date list of contributors to VIP is available [here](#). VC acknowledges financial support  
 125 from the Belgian F.R.S.-FNRS. This project has received funding from the European Research  
 126 Council (ERC) under the European Union's FP7 and Horizon 2020 research and innovation  
 127 programmes (grant agreements No 337569 and 819155), and from the Wallonia-Brussels  
 128 Federation (grant for Concerted Research Actions).

## 129 References

- 130 Amara, A., & Quanz, S. P. (2012). PYNPOINT: an image processing package for finding  
 131 exoplanets. *MNRAS*, 427, 948–955. <https://doi.org/10.1111/j.1365-2966.2012.21918.x>  
 132 Cantalloube, F., Mouillet, D., Mugnier, L. M., Milli, J., Absil, O., Gomez Gonzalez, C.  
 133 A., Chauvin, G., Beuzit, J.-L., & Cornia, A. (2015). Direct exoplanet detection and  
 134 characterization using the ANDROMEDA method: Performance on VLT/NaCo data.  
 135 *Astronomy and Astrophysics*, 582, A89. <https://doi.org/10.1051/0004-6361/201425571>  
 136 Christiaens, V., Casassus, S., Absil, O., Cantalloube, F., Gomez Gonzalez, C., Girard, J.,  
 137 Ramírez, R., Pairet, B., Salinas, V., Price, D. J., Pinte, C., Quanz, S. P., Jordán, A.,  
 138 Mawet, D., & Wahhaj, Z. (2019). Separating extended disc features from the protoplanet  
 139 in PDS 70 using VLT/SINFONI. *MNRAS*, 486(4), 5819–5837. <https://doi.org/10.1093/mnras/stz1232>  
 140

- Christiaens, V., Casassus, S., Absil, O., Kimeswenger, S., Gonzalez, C. A. G., Girard, J., Ramírez, R., Wertz, O., Zurlo, A., Wahhaj, Z., Flores, C., Salinas, V., Jordán, A., & Mawet, D. (2018). Characterization of low-mass companion HD 142527 B. *Astronomy and Astrophysics*, 617, A37. <https://doi.org/10.1051/0004-6361/201629454>
- Christiaens, V., Ubeira-Gabellini, M.-G., Cánovas, H., Delorme, P., Pairet, B., Absil, O., Casassus, S., Girard, J. H., Zurlo, A., Aoyama, Y., Marleau, G.-D., Spina, L., van der Marel, N., Cieza, L., Lodato, G., Pérez, S., Pinte, C., Price, D. J., & Reggiani, M. (2021). A faint companion around CrA-9: protoplanet or obscured binary? *MNRAS*, 502(4), 6117–6139. <https://doi.org/10.1093/mnras/stab480>
- Dahlqvist, C.-H., Cantalloube, F., & Absil, O. (2020). Regime-switching model detection map for direct exoplanet detection in ADI sequences. *Astronomy and Astrophysics*, 633, A95. <https://doi.org/10.1051/0004-6361/201936421>
- Dahlqvist, C.-H., Cantalloube, F., & Absil, O. (2021). Auto-RSM: An automated parameter-selection algorithm for the RSM map exoplanet detection algorithm. 656, A54. <https://doi.org/10.1051/0004-6361/202141446>
- Delorme, P., Schmidt, T., Bonnefoy, M., Desidera, S., Ginski, C., Charnay, B., Lazzoni, C., Christiaens, V., Messina, S., D'Orazi, V., Milli, J., Schlieder, J. E., Gratton, R., Rodet, L., Lagrange, A.-M., Absil, O., Vigan, A., Galicher, R., Hagelberg, J., ... Wildi, F. (2017). In-depth study of moderately young but extremely red, very dusty substellar companion HD 206893B. *Astronomy and Astrophysics*, 608, A79. <https://doi.org/10.1051/0004-6361/201731145>
- Flasseur, O., Denis, L., Thiébaud, É., & Langlois, M. (2018). Exoplanet detection in angular differential imaging by statistical learning of the nonstationary patch covariances. The PACO algorithm. 618, A138. <https://doi.org/10.1051/0004-6361/201832745>
- Gomez Gonzalez, C. A., Absil, O., & Van Droogenbroeck, M. (2018). Supervised detection of exoplanets in high-contrast imaging sequences. *Astronomy and Astrophysics*, 613, A71. <https://doi.org/10.1051/0004-6361/201731961>
- Gomez Gonzalez, C. A., Wertz, O., Absil, O., Christiaens, V., Defrère, D., Mawet, D., Milli, J., Absil, P.-A., Van Droogenbroeck, M., Cantalloube, F., Hinz, P. M., Skemer, A. J., Karlsson, M., & Surdej, J. (2017). VIP: Vortex Image Processing Package for High-contrast Direct Imaging. *The Astronomical Journal*, 154, 7. <https://doi.org/10.3847/1538-3881/aa73d7>
- Hirsch, L. A., Ciardi, D. R., Howard, A. W., Marcy, G. W., Ruane, G., Gonzalez, E., Blunt, S., Crepp, J. R., Fulton, B. J., Isaacson, H., Kosiarek, M., Mawet, D., Sinukoff, E., & Weiss, L. (2019). Discovery of a White Dwarf Companion to HD 159062. *The Astrophysical Journal*, 878(1), 50. <https://doi.org/10.3847/1538-4357/ab1b11>
- Jensen-Clem, R., Mawet, D., Gomez Gonzalez, C. A., Absil, O., Belikov, R., Currie, T., Kenworthy, M. A., Marois, C., Mazoyer, J., Ruane, G., Tanner, A., & Cantalloube, F. (2018). A New Standard for Assessing the Performance of High Contrast Imaging Systems. 155, 19. <https://doi.org/10.3847/1538-3881/aa97e4>
- Lafrenière, D., Marois, C., Doyon, R., Nadeau, D., & Artigau, É. (2007). A New Algorithm for Point-Spread Function Subtraction in High-Contrast Imaging: A Demonstration with Angular Differential Imaging. *The Astrophysical Journal*, 660, 770–780. <https://doi.org/10.1086/513180>
- Larkin, K. G., Oldfield, M. A., & Klemm, H. (1997). Fast Fourier method for the accurate rotation of sampled images. *Optics Communications*, 139(1-3), 99–106. [https://doi.org/10.1016/S0030-4018\(97\)00097-7](https://doi.org/10.1016/S0030-4018(97)00097-7)
- Lee, D. D., & Seung, H. S. (1999). Learning the parts of objects by non-negative matrix factorization. *Nature*, 401(6755), 788–791. <https://doi.org/10.1038/44565>

- 189 Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. (2006). Angular Differential  
190 Imaging: A Powerful High-Contrast Imaging Technique. *The Astrophysical Journal*, 641,  
191 556–564. <https://doi.org/10.1086/500401>
- 192 Maucó, K., Olofsson, J., Canovas, H., Schreiber, M. R., Christiaens, V., Bayo, A., Zurlo, A.,  
193 Cáceres, C., Pinte, C., Villaver, E., Girard, J. H., Cieza, L., & Montesinos, M. (2020). NaCo  
194 polarimetric observations of Sz 91 transitional disc: a remarkable case of dust filtering.  
195 *MNRAS*, 492(2), 1531–1542. <https://doi.org/10.1093/mnras/stz3380>
- 196 Mawet, D., Milli, J., Wahhaj, Z., Pelat, D., Absil, O., Delacroix, C., Boccaletti, A., Kasper, M.,  
197 Kenworthy, M., Marois, C., Mennesson, B., & Pueyo, L. (2014). Fundamental Limitations  
198 of High Contrast Imaging Set by Small Sample Statistics. *The Astrophysical Journal*, 792,  
199 97. <https://doi.org/10.1088/0004-637X/792/2/97>
- 200 Milli, J., Engler, N., Schmid, H. M., Olofsson, J., Ménard, F., Kral, Q., Boccaletti, A.,  
201 Thébault, P., Choquet, E., Mouillet, D., Lagrange, A.-M., Augereau, J.-C., Pinte, C.,  
202 Chauvin, G., Dominik, C., Perrot, C., Zurlo, A., Henning, T., Beuzit, J.-L., ... Pragt,  
203 J. (2019). Optical polarised phase function of the HR 4796A dust ring. 626, A54.  
204 <https://doi.org/10.1051/0004-6361/201935363>
- 205 Milli, J., Hiben, P., Christiaens, V., Choquet, É., Bonnefoy, M., Kennedy, G. M., Wyatt,  
206 M. C., Absil, O., Gómez González, C. A., del Burgo, C., Matrà, L., Augereau, J.-C.,  
207 Boccaletti, A., Delacroix, C., Ertel, S., Dent, W. R. F., Forsberg, P., Fusco, T., Girard,  
208 J. H., ... Wahhaj, Z. (2017). Discovery of a low-mass companion inside the debris ring  
209 surrounding the F5V star HD 206893. *Astronomy and Astrophysics*, 597, L2. <https://doi.org/10.1051/0004-6361/201629908>
- 210 Milli, J., Mouillet, D., Lagrange, A.-M., Boccaletti, A., Mawet, D., Chauvin, G., & Bonnefoy,  
211 M. (2012). Impact of angular differential imaging on circumstellar disk images. *Astronomy  
212 and Astrophysics*, 545, A111. <https://doi.org/10.1051/0004-6361/201219687>
- 213 Milli, J., Vigan, A., Mouillet, D., Lagrange, A.-M., Augereau, J.-C., Pinte, C., Mawet, D.,  
214 Schmid, H. M., Boccaletti, A., Matrà, L., Kral, Q., Ertel, S., Chauvin, G., Bazzon, A.,  
215 Ménard, F., Beuzit, J.-L., Thalmann, C., Dominik, C., Feldt, M., ... SPHERE Consortium.  
216 (2017). Near-infrared scattered light properties of the HR 4796 A dust ring. 599, A108.  
217 <https://doi.org/10.1051/0004-6361/201527838>
- 218 Pairet, B., Cantalloube, F., Gomez Gonzalez, C. A., Absil, O., & Jacques, L. (2019). STIM  
219 map: detection map for exoplanets imaging beyond asymptotic Gaussian residual speckle  
220 noise. *MNRAS*, 487(2), 2262–2277. <https://doi.org/10.1093/mnras/stz1350>
- 221 Pairet, B., Cantalloube, F., & Jacques, L. (2021). MAYONNAISE: a morphological components  
222 analysis pipeline for circumstellar discs and exoplanets imaging in the near-infrared. *MNRAS*,  
223 503(3), 3724–3742. <https://doi.org/10.1093/mnras/stab607>
- 224 Pueyo, L. (2016). Detection and Characterization of Exoplanets using Projections on Karhunen  
225 Loeve Eigenimages: Forward Modeling. 824(2), 117. <https://doi.org/10.3847/0004-637X/824/2/117>
- 226 Rainot, A., Reggiani, M., Sana, H., Bodensteiner, J., & Absil, O. (2022). Carina High-contrast  
227 Imaging Project for massive Stars (CHIPS). II. O stars in Trumpler 14. *Astronomy and  
228 Astrophysics*, 658, A198. <https://doi.org/10.1051/0004-6361/202141562>
- 229 Rainot, A., Reggiani, M., Sana, H., Bodensteiner, J., Gomez-Gonzalez, C. A., Absil, O.,  
230 Christiaens, V., Delorme, P., Almeida, L. A., Caballero-Nieves, S., De Ridder, J., Kratter,  
231 K., Lacour, S., Le Bouquin, J.-B., Pueyo, L., & Zinnecker, H. (2020). Carina High-contrast  
232 Imaging Project for massive Stars (CHIPS). I. Methodology and proof of concept on QZ  
233 Car ( $\equiv$  HD 93206). *Astronomy and Astrophysics*, 640, A15. <https://doi.org/10.1051/0004-6361/201936448>
- 234  
235  
236



- 237 Reggiani, M., Christiaens, V., Absil, O., Mawet, D., Huby, E., Choquet, E., Gomez Gonzalez,  
238 C. A., Ruane, G., Femenia, B., Serabyn, E., Matthews, K., Barraza, M., Carlomagno,  
239 B., Defrère, D., Delacroix, C., Habraken, S., Jolivet, A., Karlsson, M., Orban de Xivry,  
240 G., ... Wertz, O. (2018). Discovery of a point-like source and a third spiral arm in the  
241 transition disk around the Herbig Ae star MWC 758. *Astronomy and Astrophysics*, 611,  
242 A74. <https://doi.org/10.1051/0004-6361/201732016>
- 243 Ruane, Mawet, D., Kastner, J., Meshkat, T., Bottom, M., Femenía Castellá, B., Absil,  
244 O., Gomez Gonzalez, C., Huby, E., Zhu, Z., Jensen-Clem, R., Choquet, É., & Serabyn,  
245 E. (2017). Deep Imaging Search for Planets Forming in the TW Hya Protoplanetary  
246 Disk with the Keck/NIRC2 Vortex Coronagraph. *The Astronomical Journal*, 154, 73.  
247 <https://doi.org/10.3847/1538-3881/aa7b81>
- 248 Ruane, Ngo, H., Mawet, D., Absil, O., Choquet, É., Cook, T., Gomez Gonzalez, C., Huby,  
249 E., Matthews, K., Meshkat, T., Reggiani, M., Serabyn, E., Wallack, N., & Xuan, W. J.  
250 (2019). Reference Star Differential Imaging of Close-in Companions and Circumstellar  
251 Disks with the NIRC2 Vortex Coronagraph at the W. M. Keck Observatory. 157(3), 118.  
252 <https://doi.org/10.3847/1538-3881/aafec2>
- 253 Ruffio, J.-B., Macintosh, B., Wang, J. J., Pueyo, L., Nielsen, E. L., De Rosa, R. J., Czekala,  
254 I., Marley, M. S., Arriaga, P., Bailey, V. P., Barman, T., Bulger, J., Chilcote, J., Cotten,  
255 T., Doyon, R., Duchêne, G., Fitzgerald, M. P., Follette, K. B., Gerard, B. L., ... Wolff, S.  
256 (2017). Improving and Assessing Planet Sensitivity of the GPI Exoplanet Survey with a  
257 Forward Model Matched Filter. 842, 14. <https://doi.org/10.3847/1538-4357/aa72dd>
- 258 Soummer, R., Pueyo, L., & Larkin, J. (2012). Detection and Characterization of Exoplanets  
259 and Disks Using Projections on Karhunen-Loève Eigenimages. *The Astrophysical Journal*,  
260 755(2), L28. <https://doi.org/10.1088/2041-8205/755/2/L28>
- 261 Sparks, W., & Ford, H. (2002). Imaging Spectroscopy for Extrasolar Planet Detection. *The*  
262 *Astrophysical Journal*, 578, 543–564. <https://doi.org/10.1086/342401>
- 263 Toci, C., Lodato, G., Christiaens, V., Fedele, D., Pinte, C., Price, D. J., & Testi, L. (2020).  
264 Planet migration, resonant locking, and accretion streams in PDS 70: comparing models  
265 and data. *MNRAS*, 499(2), 2015–2027. <https://doi.org/10.1093/mnras/staa2933>
- 266 Ubeira-Gabellini, M. G., Christiaens, V., Lodato, G., Ancker, M. van den, Fedele, D., Manara,  
267 C. F., & Price, D. J. (2020). Discovery of a Low-mass Companion Embedded in the Disk of  
268 the Young Massive Star MWC 297 with VLT/SPHERE. *The Astrophysical Journal*, 890(1),  
269 L8. <https://doi.org/10.3847/2041-8213/ab7019>
- 270 Wertz, O., Absil, O., Gómez González, C. A., Milli, J., Girard, J. H., Mawet, D., & Pueyo, L.  
271 (2017). VLT/SPHERE robust astrometry of the HR8799 planets at milliarcsecond-level  
272 accuracy. Orbital architecture analysis with PyAstrOFit. *Astronomy and Astrophysics*, 598,  
273 A83. <https://doi.org/10.1051/0004-6361/201628730>