The COBREX project: unleashing the full potential of archival high-contrast imaging observations

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Exoplanet demographics, i.e. the statistical analysis of physical, orbital and stellar host properties of the exoplanet population, holds the key to a full understanding of the physical processes underlying planet formation. However, connecting the distinct niches probed by different techniques is a challenging task, especially in the critical 5-20 au region, where most giant planets are thought to form. Within the COBREX project, we are aggressively applying state-of-the-art post-processing algorithms to a large library of archival direct imaging (DI) data to significantly (1-2 mag) improve our ability to detect young Jupiter analogs in this region. The reanalysis of GPIES, the largest planet-hunting DI survey to date, has allowed us to place some of the tightest constraints to the occurrence frequency of substellar companions ever provided by imaging.

Scientific rationale

Despite being yet insensitive to sub-Jovian planets, direct imaging (DI) provides **crucial constraints on planet formation models** thanks to its exquisite sensitivity to wide-orbit (≳20 au) young (≲500 Myr) Super Jupiters. Conversely, radial velocity(RV) studies are sensitive to lighter planets, but struggle to draw a complete picture beyond ~5 au[1]. However, the full potential of DI data has **not yet been fully unleashed**: in addition to hardware performances, observing conditions and good calibrations, the final sensitivity of DI is dictated by the power of the **post-processing method** used to decrease noise levels – allowing for planet-to-star contrast ratios ~10^{-6-7} (Fig.1).

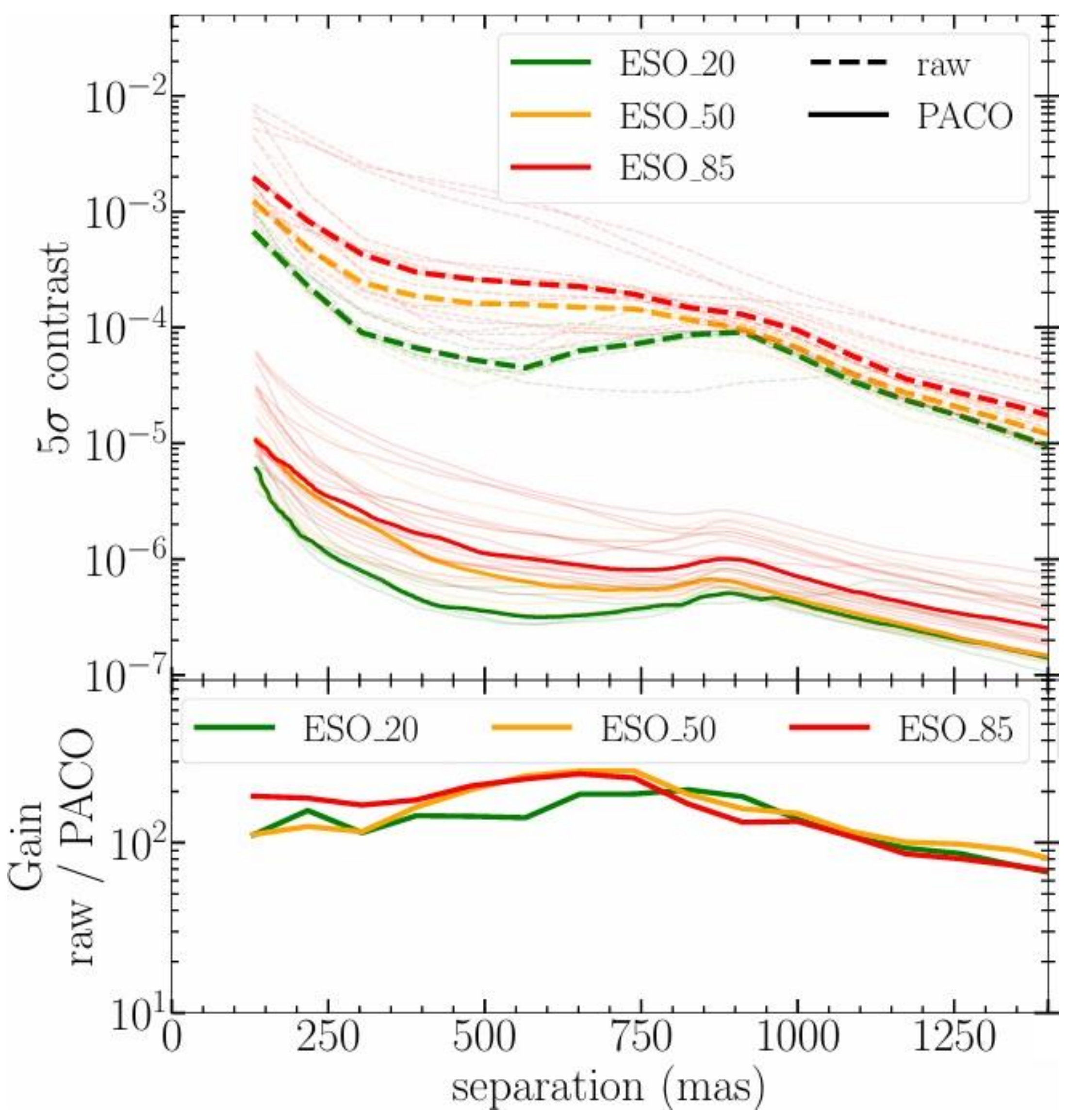

Figure 1. An example of the contrast gain achievable by post-processing (data source: SPHERE/IRDIS; Chomez et al. in prep).

Data & pre-reduction

We collected all public raw data from GPIES, an ongoing H-band (1.5-1.8 μm, R~50) survey operated by GPI@Gemini since 2013. An analysis of the first half of the survey (300 stars) was published in 2019[2]. In addition to these stars, we considered stars with a robust age determination (a key information in DI studies) derived either from the membership to young moving groups or from the SHINE survey[3]. After recovering additional non-GPIES observations targeting our stars of interest, we obtained a sample comprising **552 observations** for **400 stars** (Fig. 2). The data were pre-reduced in a two-step process involving the GPI Data Reduction Pipeline[4] and pyklip[5]. We thoroughly checked the reliability of the resulting datacubes via extensive testing[6].

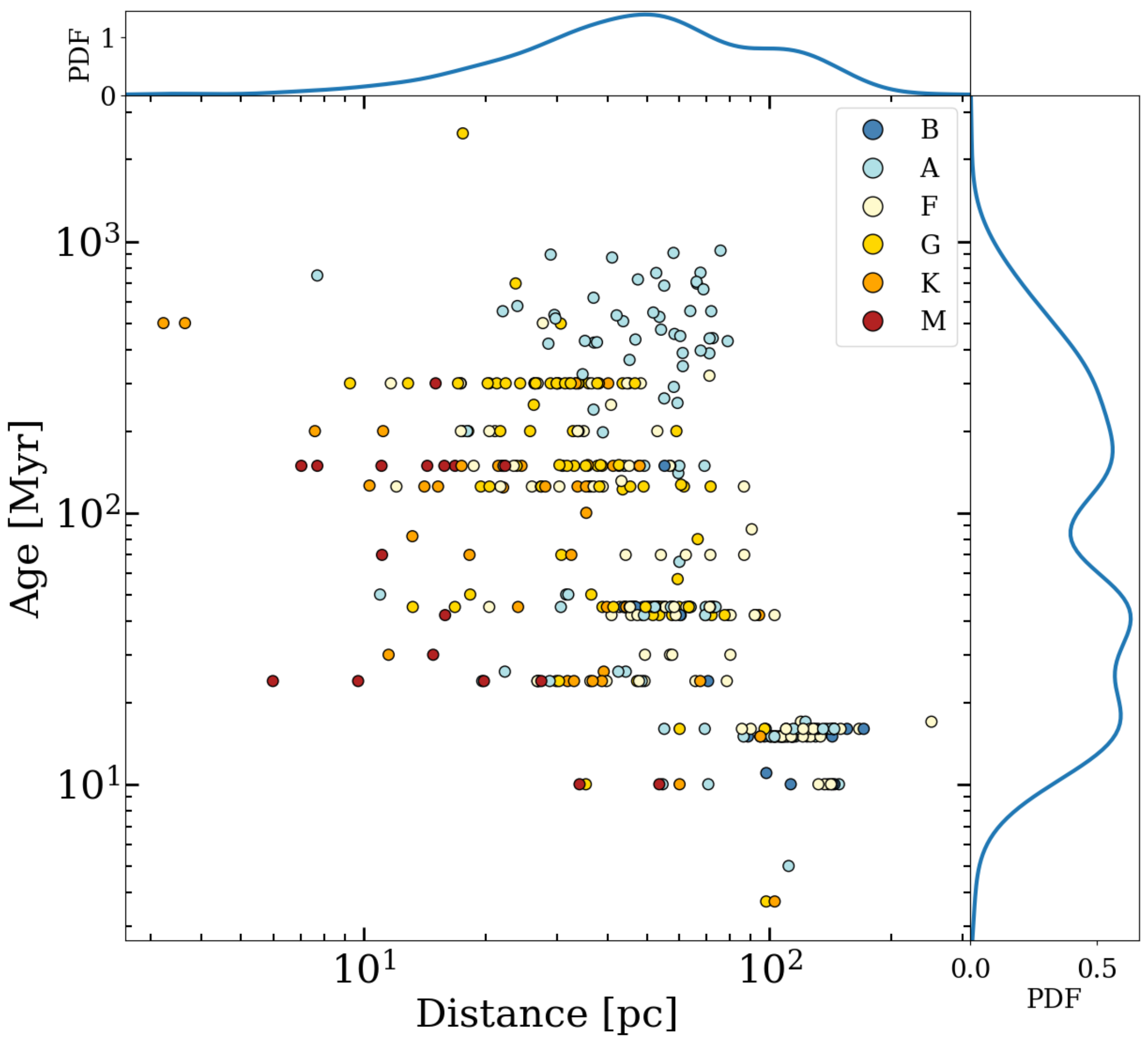

Figure 2. Distances, ages and spectral types for the stars in the sample.

PACO

PACO[7] is a post-processing algorithm that employs angular and spectral differential imaging to model, inside small patches, the spatial and temporal fluctuations of noise; the Gaussianity of residual noise maps, upon which >5σ detections are performed, allows for reliable SNR and false positive rate assessment. The detection capability is further enhanced by the use of physically-informed spectral weights.

As a first test, we **reanalyzed** with PACO the 300 stars discussed in Nielsen+19: under the same input parameters and assumptions, we obtained a **significant improvement** of detection capabilities (Fig. 3). We therefore applied PACO to the entire 400-star sample.

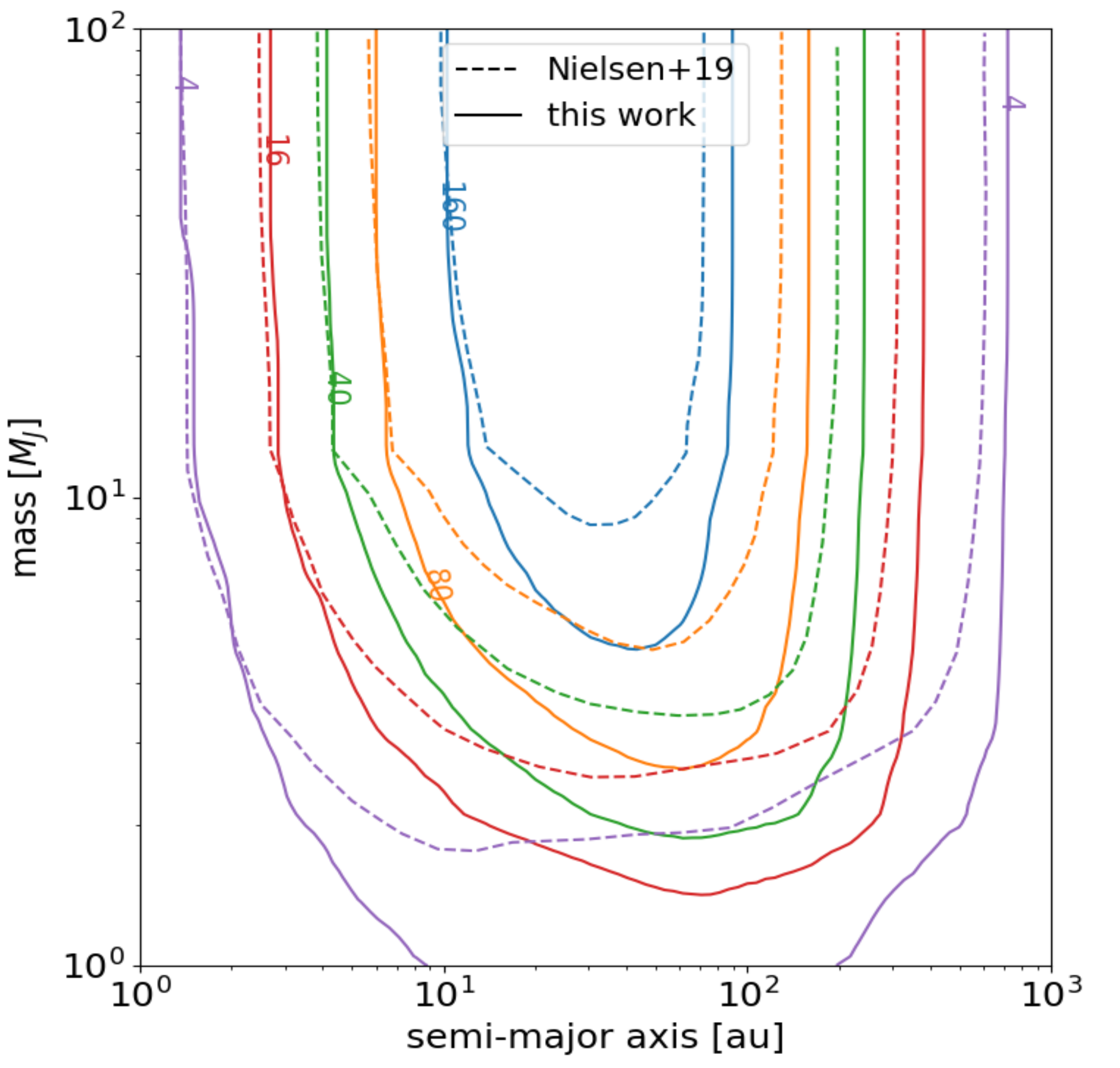

Figure 3. Completeness map for the 300 stars analyzed in Nielsen+19. Each curve N connects the (sma, mass) points for which a detection is possible around N stars.

Results

More than 200 sources were detected during the analysis. Whenever multiple observations were available, astrometric displacements with respect to the target could be used to assess common proper motion. The position of candidates on a color-magnitude diagram allowed us to reject as background contaminants almost all the remaining sources. By suitably degrading the detection limits so as to exclude the few **interesting candidates requiring dedicated follow-up**, we were able to estimate the occurrence frequency of giant planets and brown dwarf companions and its dependence on stellar mass in a more precise way than ever before[6] (Fig. 4).

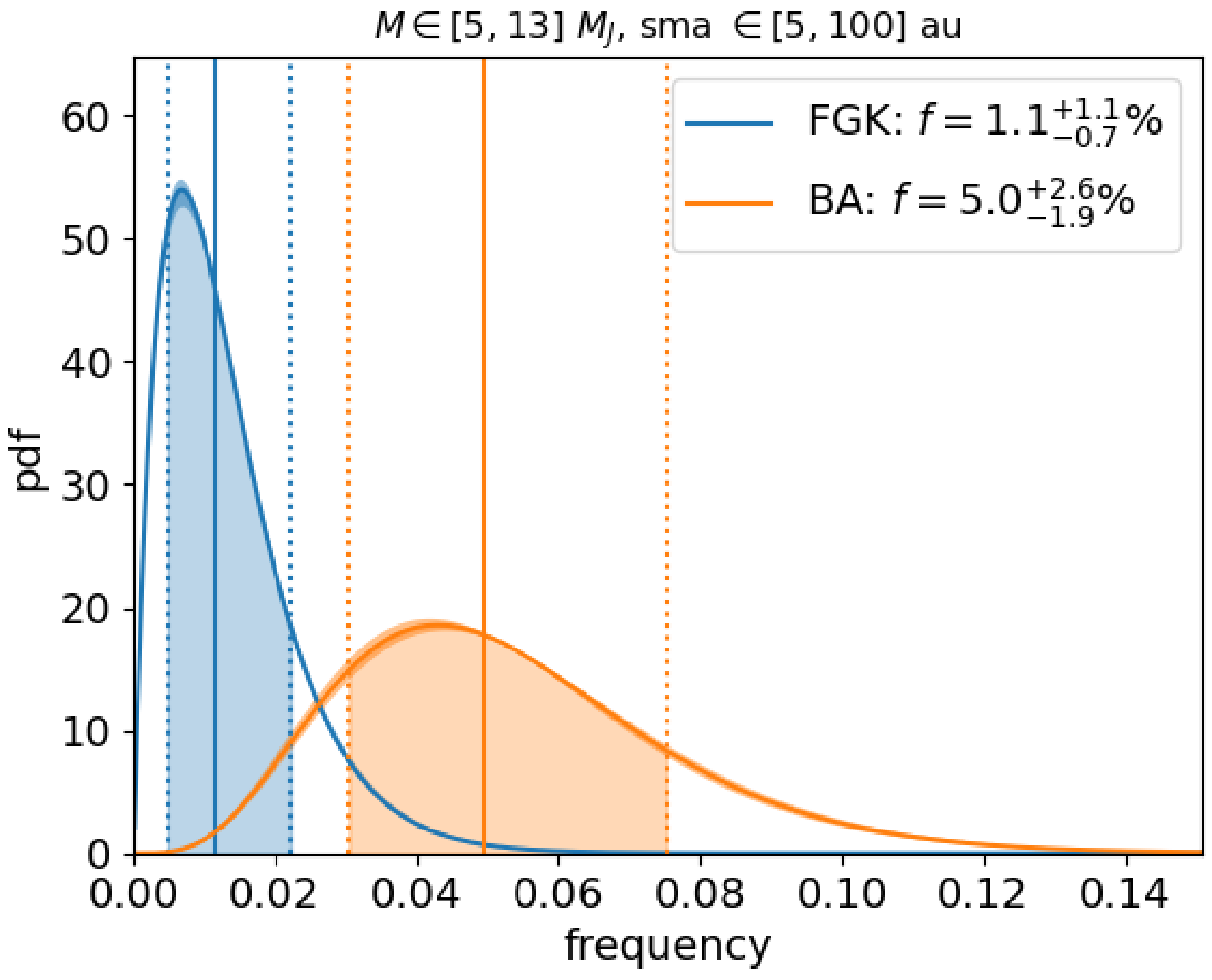

Figure 4. Occurrence rates of 5-13 M_J planets in the [5, 100] au region for $0.5<M/M_{sun}<1.5$ stars (blue) and $M>1.5\ M_{sun}$ (orange).

Future prospects

Besides GPIES, PACO was selected by the SHINE consortium to process the observations of their 400-star sample (talk by A. Chomez). By merging the two samples and additional sets of archival data, we will be able to obtain **the most stringent constraints** on the occurrence of the giant planet population ever provided by direct imaging. These results, in turn, will pave the way to **joint demographic studies** involving DI, RV and astrometric data.

The planet candidates detected by PACO are going to be followed-up by dedicated programs. Every new confirmed planet detection will be pivotal in shedding light on the mechanisms underlying planet formation, and a priority target for follow-up atmospheric studies with JWST, GRAVITY, ERIS and/or ELT.

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