# AstraKairos v1.0: A computational framework for the Observational Prioritization of Visual Binary Stars

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## Motivations

In the era of large data surveys like Gaia, the primary challenge in binary star research has shifted from sole discovery to target prioritization and analysis. To tackle this, we have developed AstraKairos, an open-source Python framework that aims to answer the question, "*What to observe tonight?*". Our goal isn't to provide a single set of results, but to allow new paths of research by using our tools in different contexts.

We will dive in some of the main features of AstraKairos:

- A WDS-Gaia DR3 crossmatch with potential for long-period orbital discovery and new binary-related discoveries for systems with long historical data.
- A LightGBM Machine Learning model that emulates "El-Badry's" $R$ parameter calculation [1] for any given Gaia pair that meets minimum physicality criteria.
- The Orbital Deviation Index, a metric that compares predicted ephemeris with measured positions to quantify orbital deviation.

## WDS-Gaia DR3 Crossmatch

The Washington Double Star Catalog (WDS) is the primary source for well-studied visual binary systems. However, its potential is limited by its lack of a direct relationship with modern surveys such as Gaia. Because of this, we've developed a simple yet powerful component-based crossmatch catalog between the WDS and Gaia DR3, allowing for population-scale analysis and improved observational candidate search.

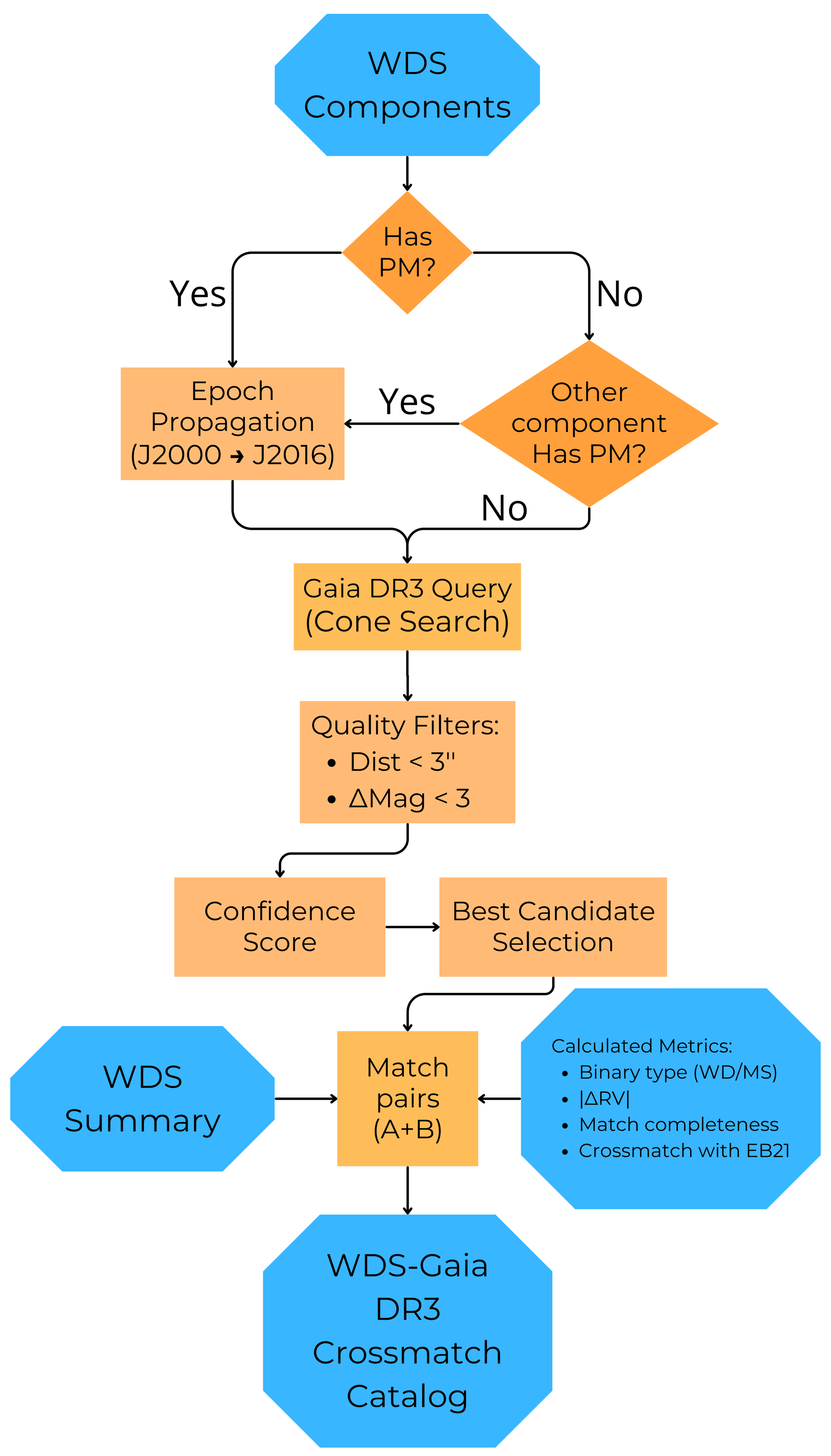


Figure 1: Flowchart showing AstraKairos' crossmatching process between the WDS and Gaia.

## Angular separation bias

As expected, considering Gaia's angular resolution of $\sim$0.5 arcsec [3], we have found that systems below $\sim$1 arcsec of separation have, by far, the highest proportion of "UNRESOLVED" completeness flags (Figure 2). However, a good portion of these systems have published orbital solutions in the Sixth Catalog of Orbits of Visual Binary Stars (ORB6), so filtering by the UNRESOLVED flag can be of particular interest for those seeking to compute new orbits, especially if Gaia shows that the matched component holds Gaia Non-Single-Star (NSS) data.

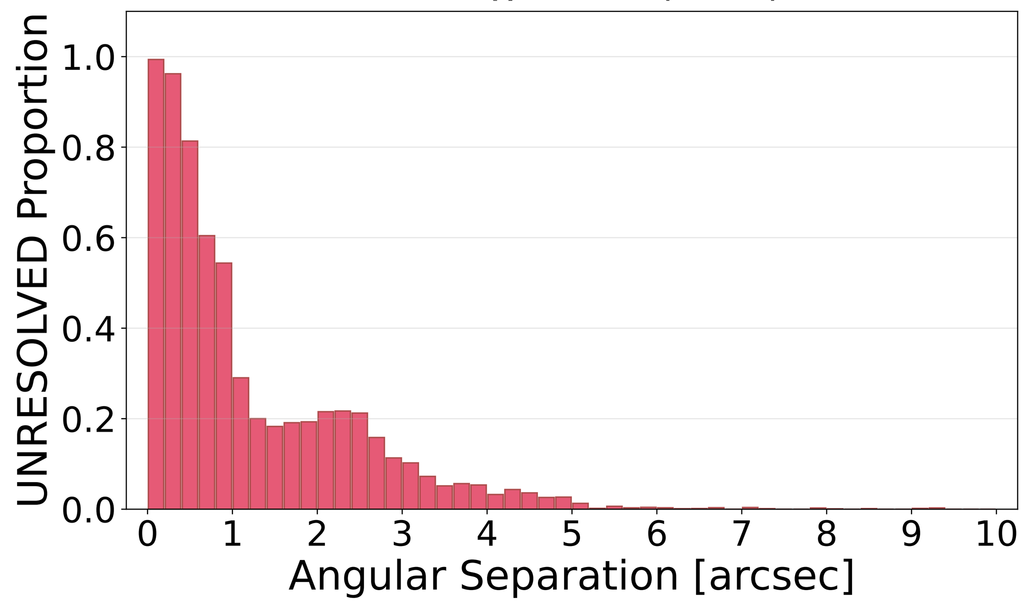


Figure 2: Proportion of UNRESOLVED systems vs Angular Separation

## Physical candidates

After applying simple astrometric cuts based on "El-Badry's" criteria [1] [2] for all "FULL" systems in the crossmatch, we've found $\sim$37,000 candidates for physically-bound binary systems. Bound systems are expected to have a close to one-to-one ratio between their components' Radial Velocities. Only 7.79$\%$ of phtsical systems deviate from $|\Delta RV| > 3\sigma$, while 39.46$\%$ of optical systems do not meet this criterion. Out of this list, we identified $\sim$32,000 MSMS, $\sim$350 WDMS, and $\sim$70 WDWD systems.

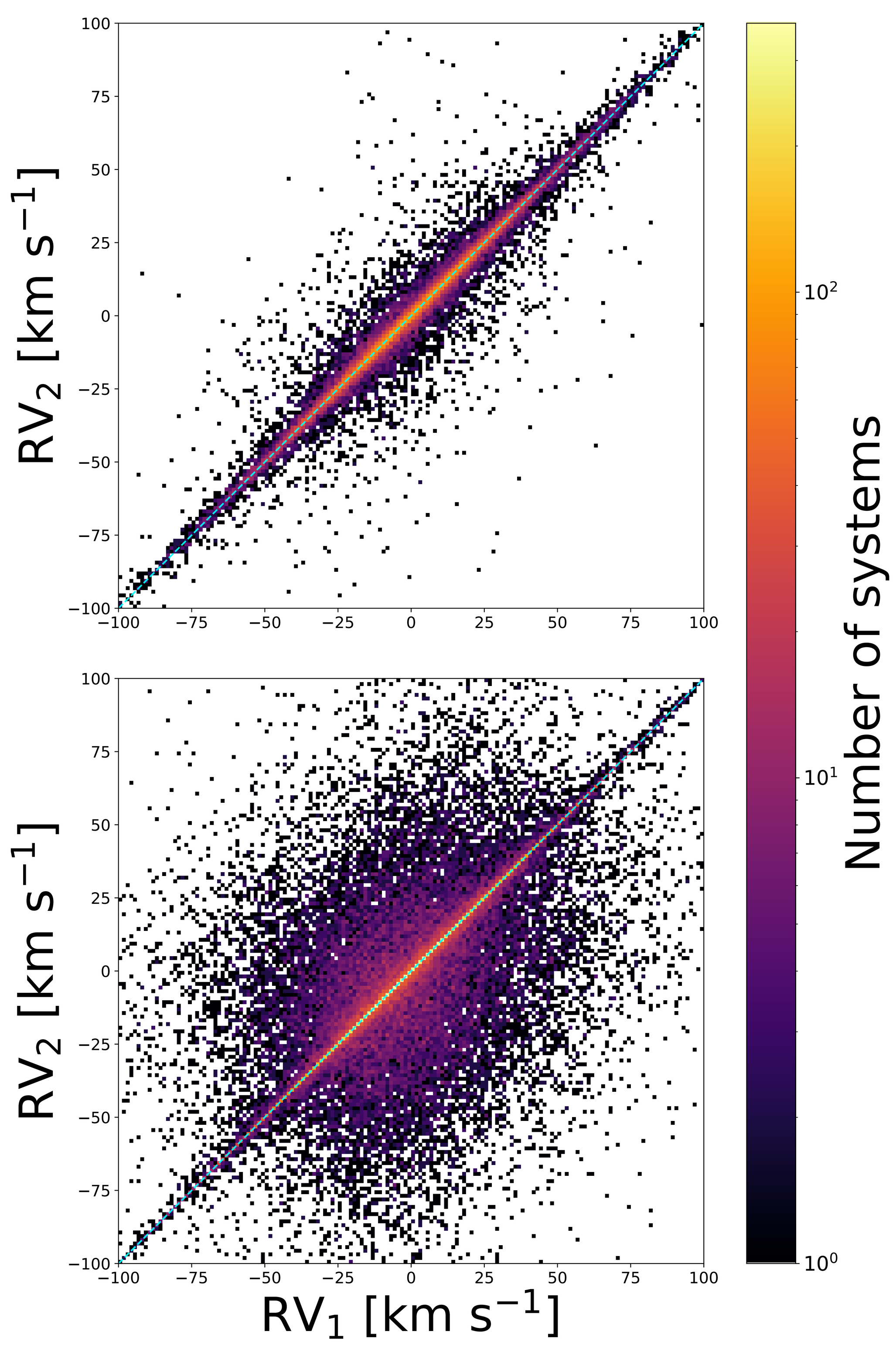


Figure 3: Plotting Radial Velocities for all Physical (above) and Optical (below) candidates.

## Chance Alignment Probability with Machine Learning

As demonstrated in "A million binaries from Gaia eDR3" [1], a "shifted catalog" that by design only contains optical pairs, combined with a 7-dimensional Gaussian kernel density estimation (KDE), can be used to estimate the probability of a given double star system being a chance alignment ($R$). This approach, however, is highly computationally expensive, which is why we have trained a Regression LightGBM model that predicts the $R$ value for systems that pass the previously mentioned physicality cuts.

Optuna was used to find the best weight combination between the 7 feature parameters. We aimed for the highest accuracy as well as the lowest cross-contamination possible. As seen in Figure 4, the accuracy percentage of the model can vary significantly from different ranges of $R$. However, the cross-contamination (when the prediction falls further than $\pm$0.1 units from each range's limits) rate stays notably low for all ranges.

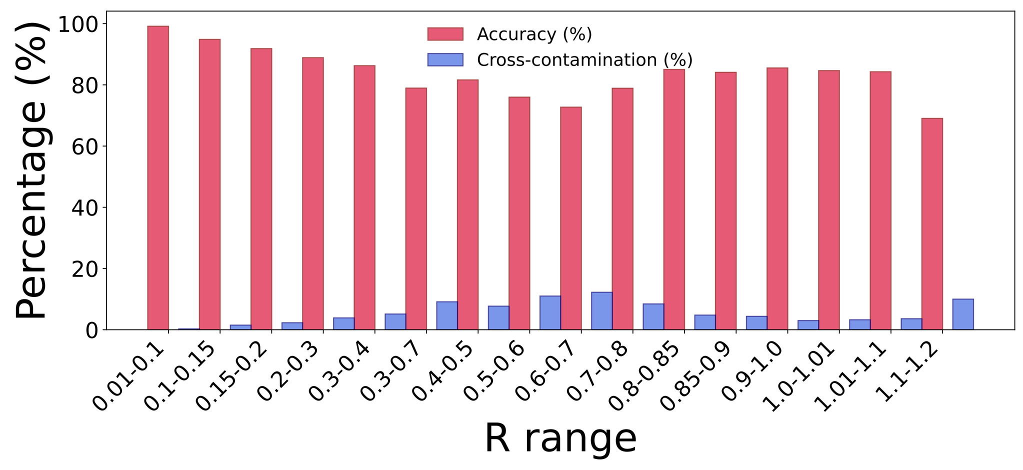


Figure 4: Bar diagram showing the accuracy and cross-contamination % for each 'true' $R$ range. Each bin is 0.1 units wide.

## Orbital Deviation Index

As a result of Gaia's limited angular resolution (Figure 2), that prevents pair-level analysis for UNRESOLVED systems, we've designed the Orbital Deviation Index (ODI), a metric that uses the Sixth Catalog of Orbits of Visual Binary Stars (WDS-ORB6)'s orbital parameters to compare the latest observation in the WDS for each ORB6 system with their respective predicted position at the same epoch as the last measurement. We calculated the ODI for $\sim$3300 ORB6 systems and found a median deviation of 0.0403 arcsec with a 90th percentile of 0.4275 arcsec. Values notably higher than this are likely the result of miscataloged measurements, such as the WDS' limit of 999.9 arcsec in angular separation.

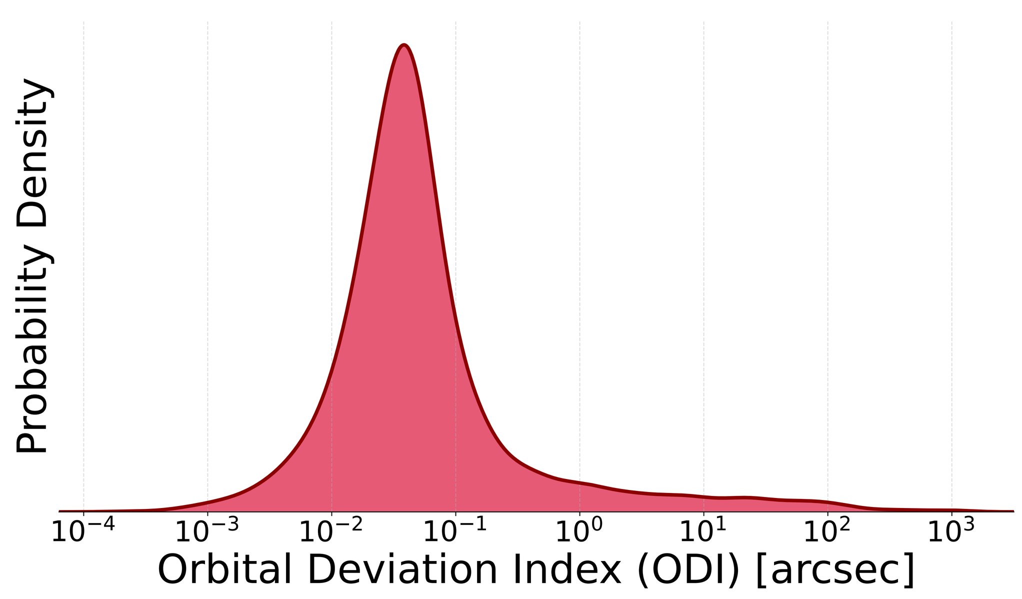


Figure 5: Distribution of the ODI for $\sim$3300 ORB6 systems.

## Conclusions & Future Work

AstraKairos provides many useful tools for the observational prioritization and analysis of Binary Stars. Our goal isn't to provide a single set of results, but to allow new paths of research by using our tools in different contexts such as: Hunting double and triple White Dwarf Systems; Orbital refinements and new orbit calculations; Searching for hierarchical triple and quadruple binary stars; Improving the quality of "Amateur" double star research.

## References

[1] Kareem El-Badry et al. "A million binaries from Gaia eDR3: sample selection and validation of Gaia parallax uncertainties". In: *Monthly Notices of the Royal Astronomical Society* 506.2 (2021), pp. 2269–2295. DOI: 10.1093/mnras/stab323.

[2] Kareem El-Badry et al. "Imprints of white dwarf recoil in the separation distribution of Gaia wide binaries". In: *Monthly Notices of the Royal Astronomical Society* 480.4 (2018), pp. 4884–4902. DOI: 10.1093/mnras/sty2186.

[3] Tristan Cantat-Gaudin et al. "An empirical model of the Gaia DR3 selection function". In: *Astronomy & Astrophysics* 669 (2023), A55. DOI: 10.1051/0004-6361/202244784.

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