Enabling Rubin Science with Robust Cross-Matches in the Crowded LSST Sky

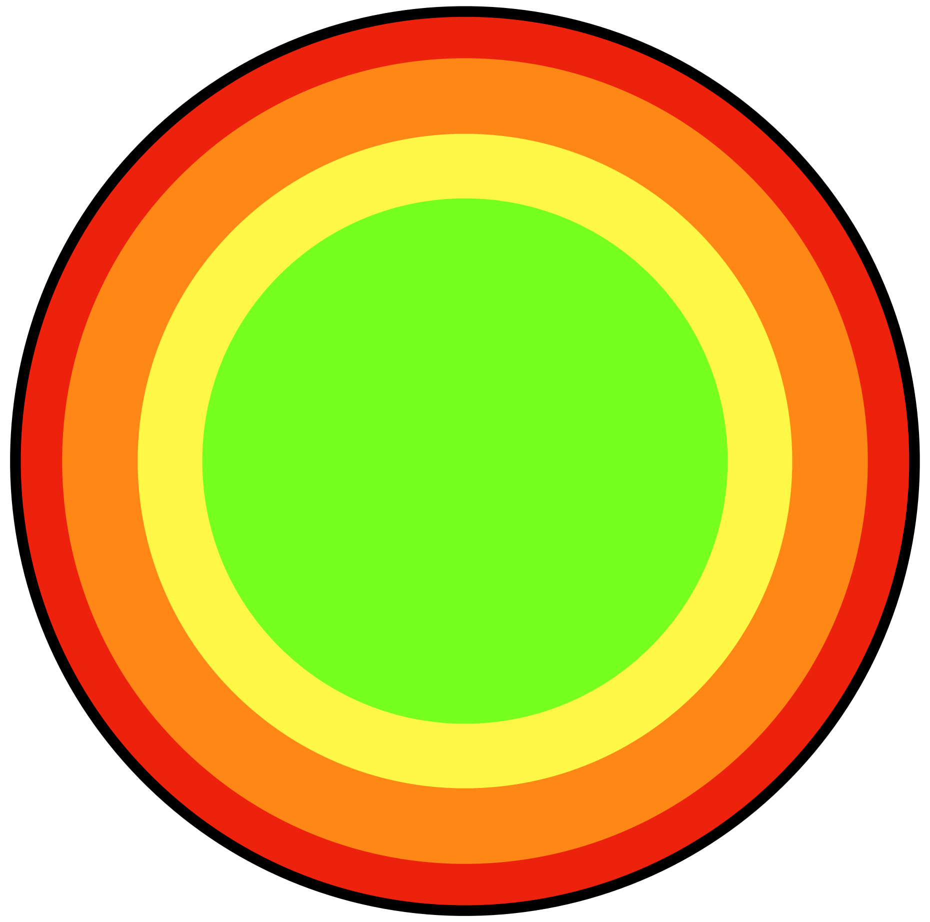
Tom J Wilson (he/him) and Tim Naylor
With George Beckett, Mike Read, and Dominic Sloan-Murphy
t.j.wilson@exeter.ac.uk
University of Exeter

National Astronomy Meeting 2023 — UK involvement in the Vera C. Rubin Observatory: Legacy Survey of Space and Time, 7/Jul/23

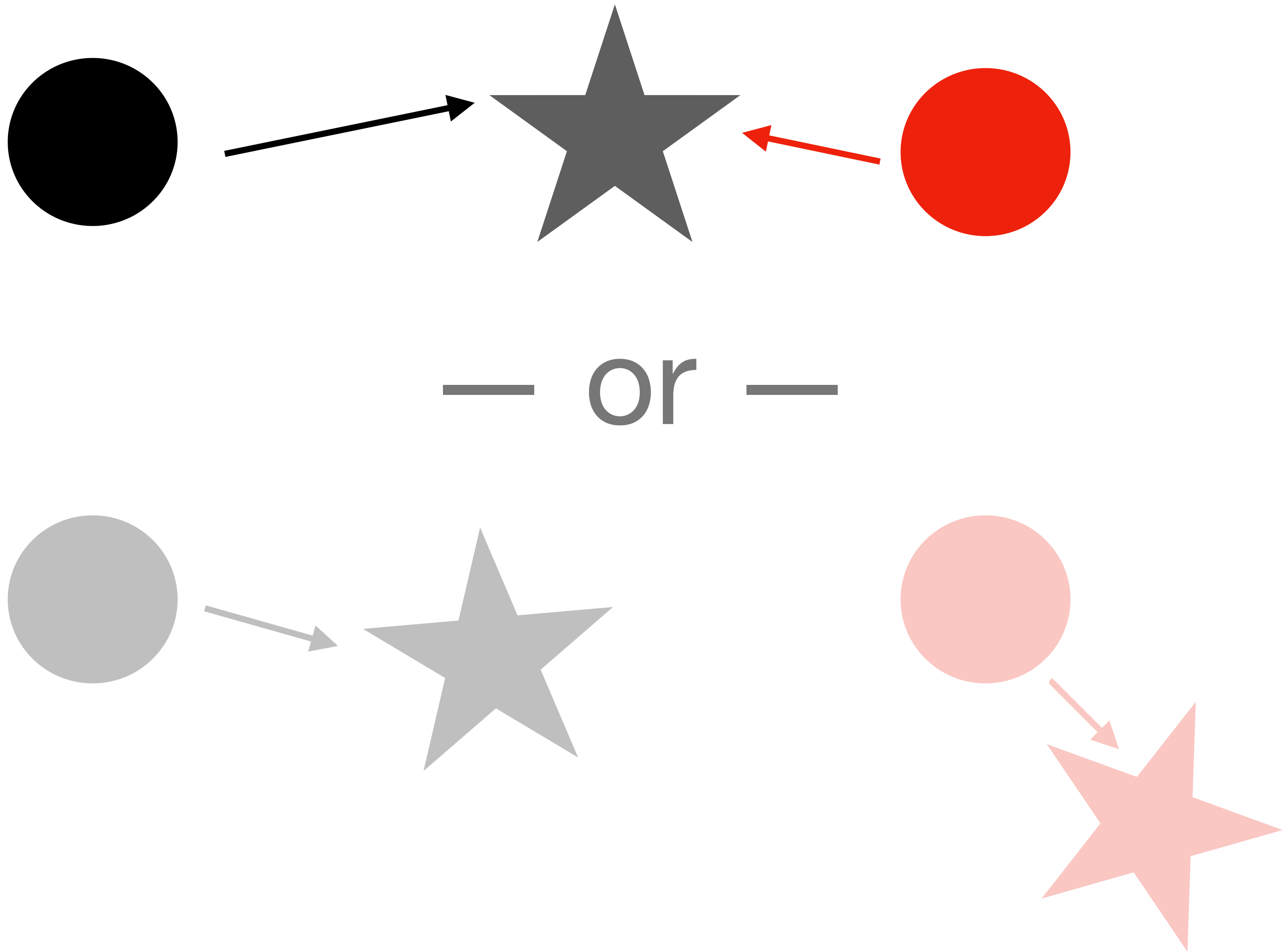
@Onoddil @pm.me .github.io

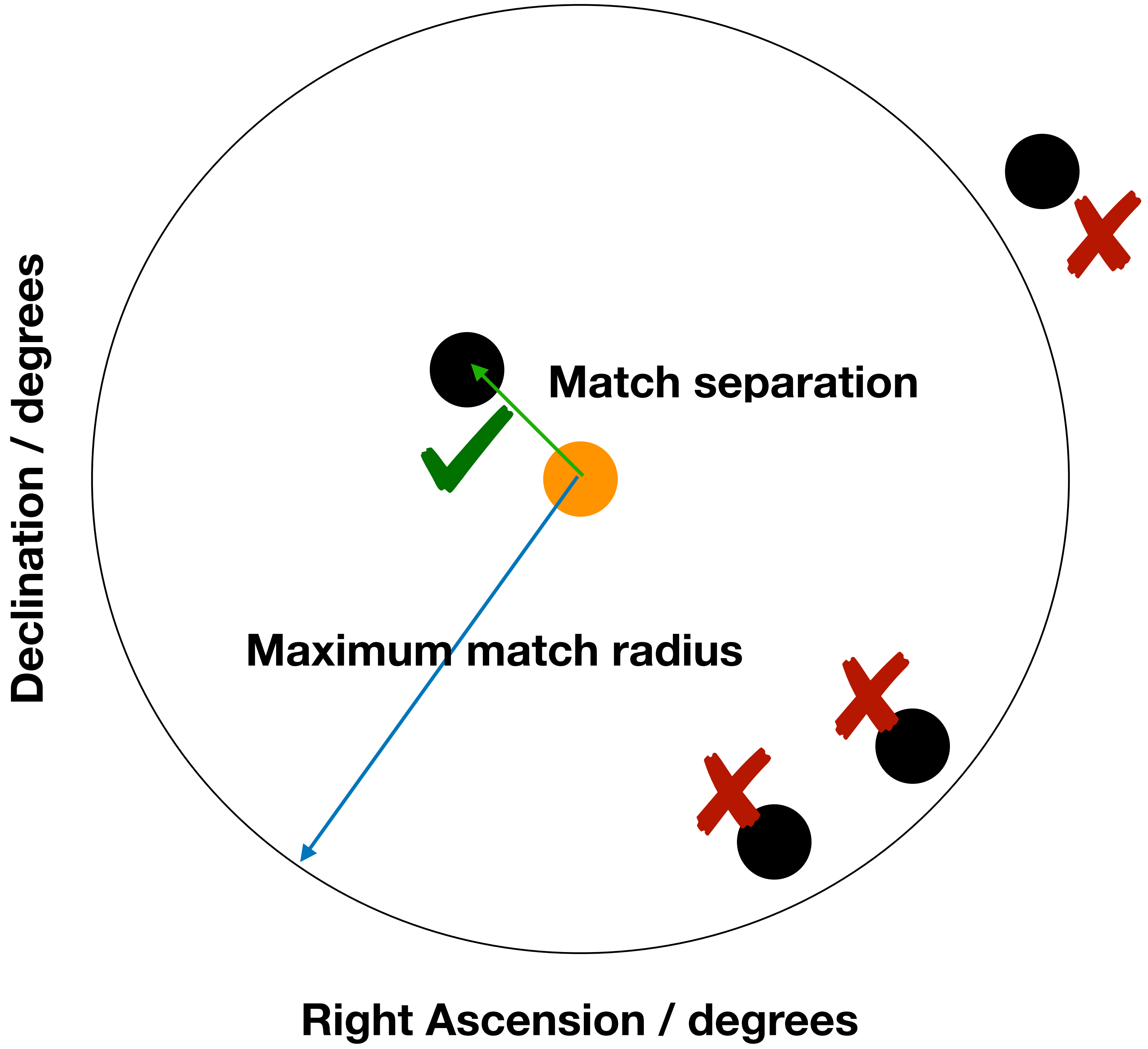
University of Exeter
LSST:UK Consortium
Science and Technology Facilities Council

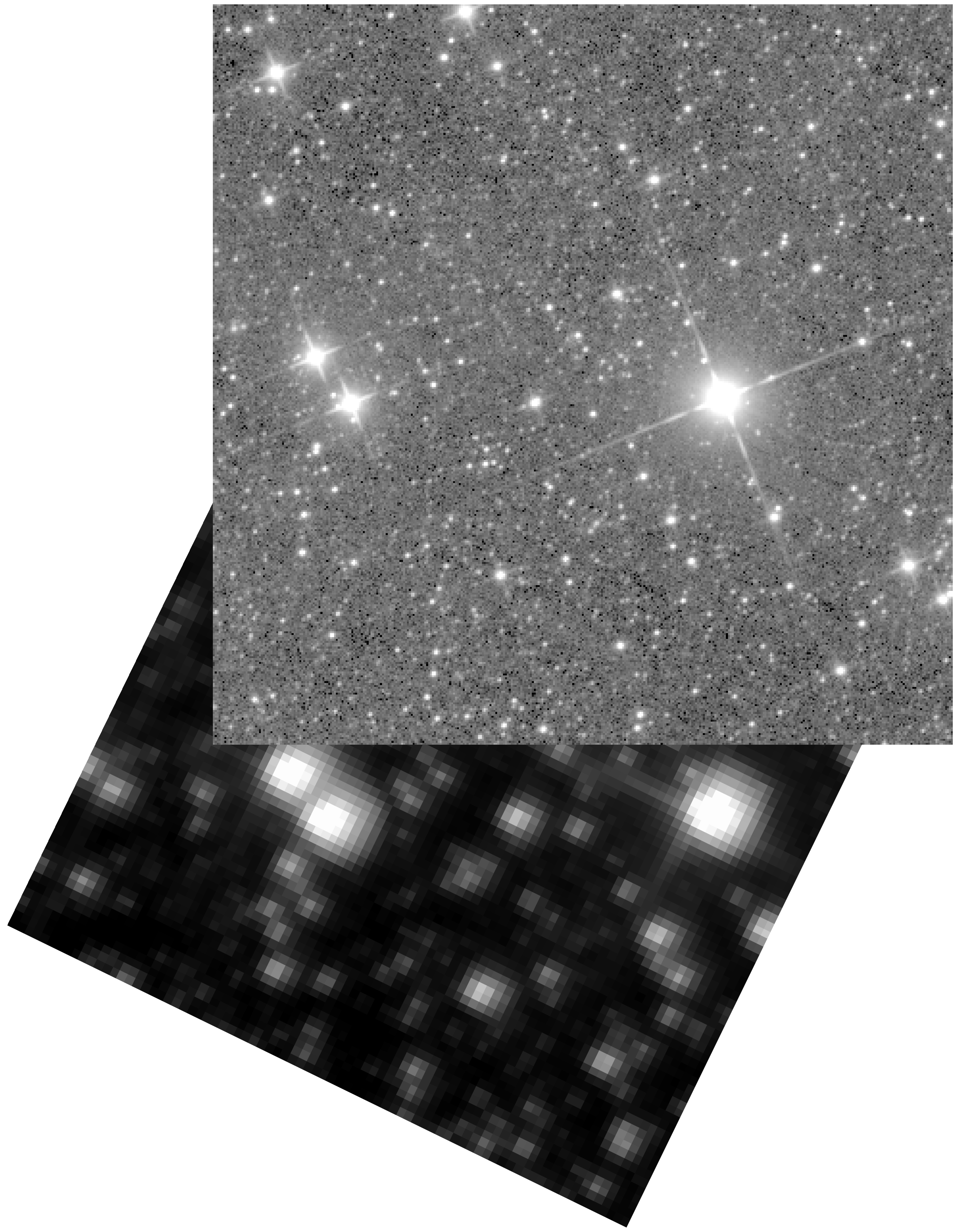
Cross-Match Science, Methodology, Background



“Simple” Cross-Matching







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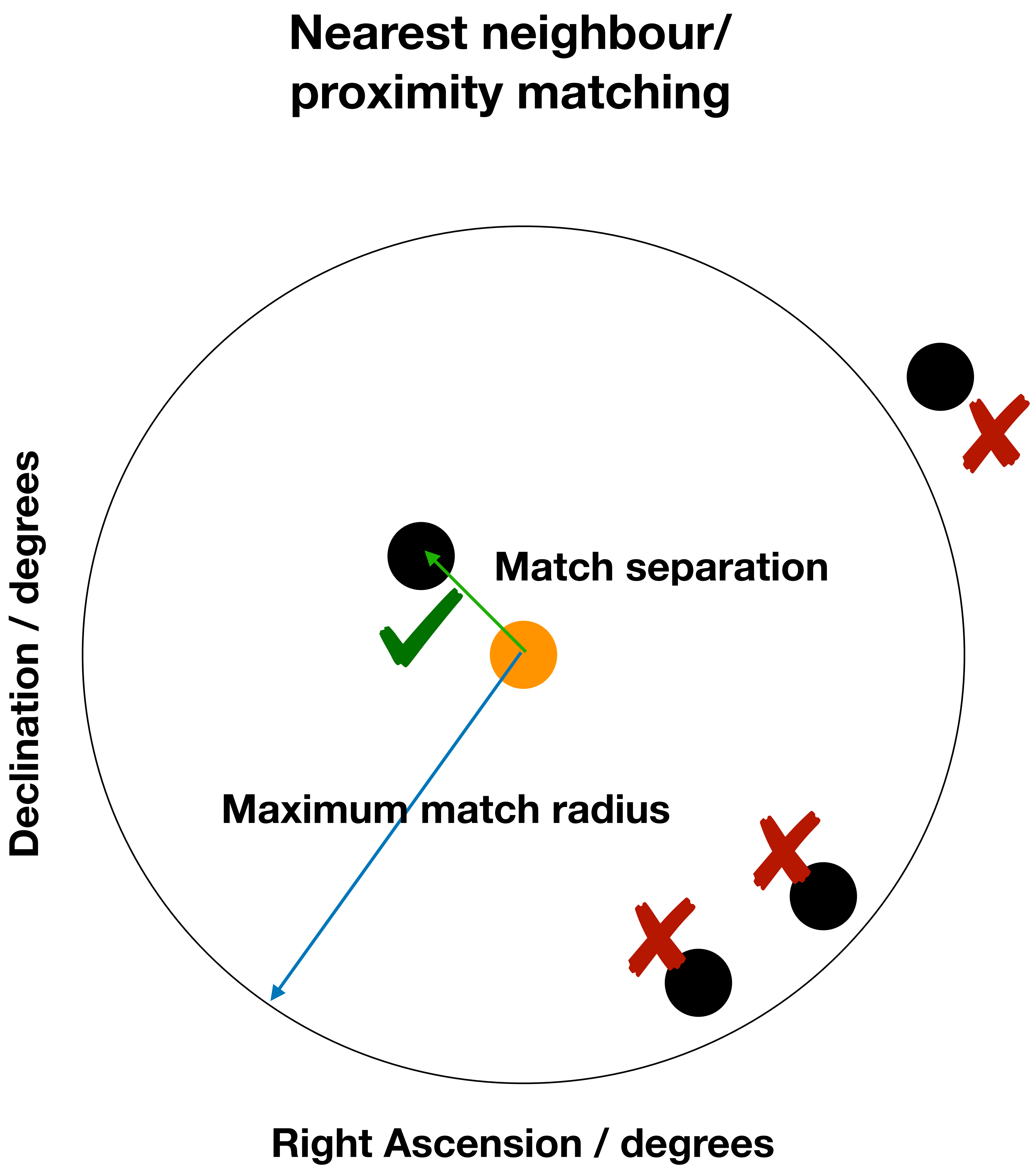
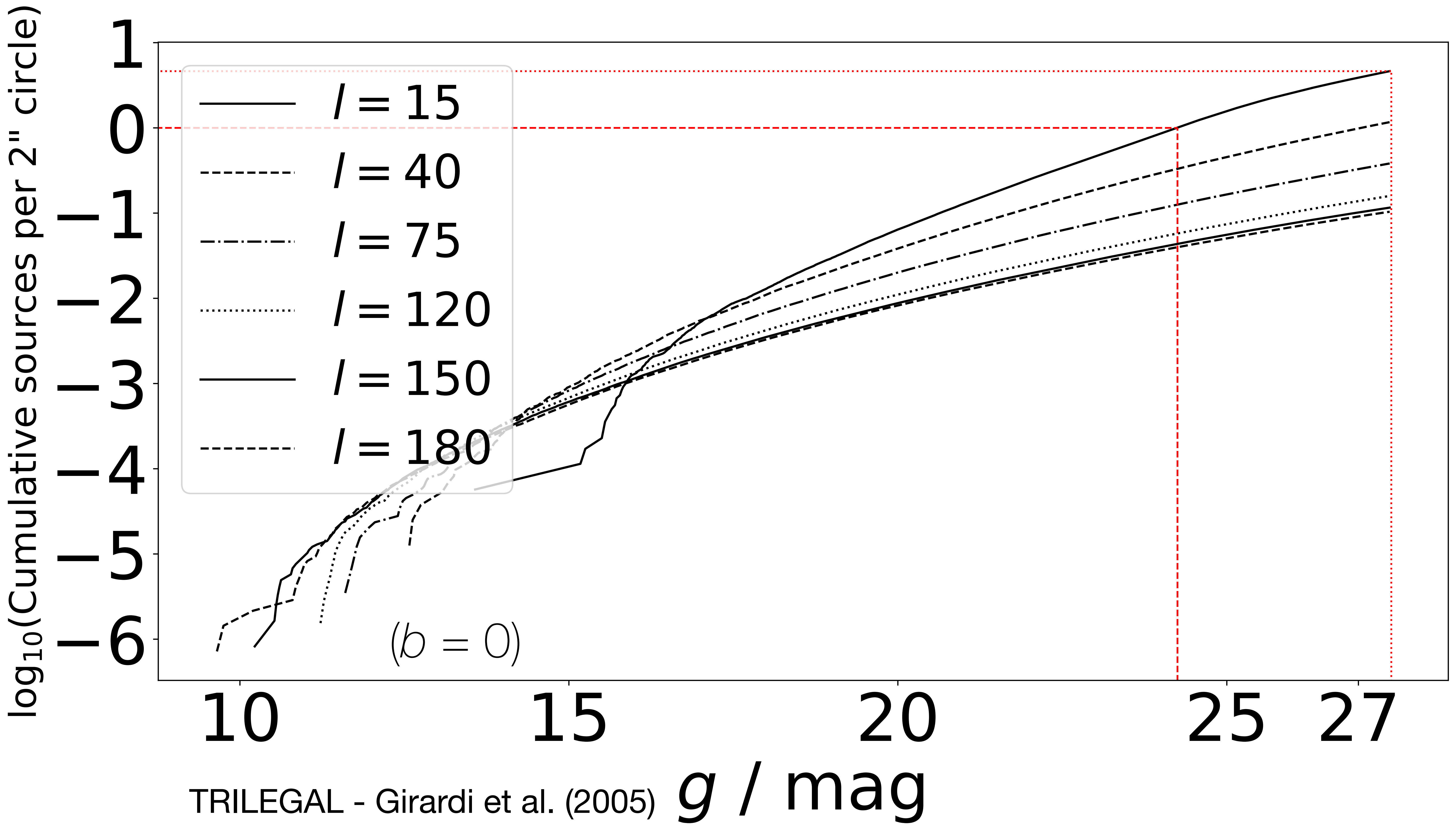
The Problem With Rubin Obs.'s LSST





TRILEGAL - Girardi et al. (2005)

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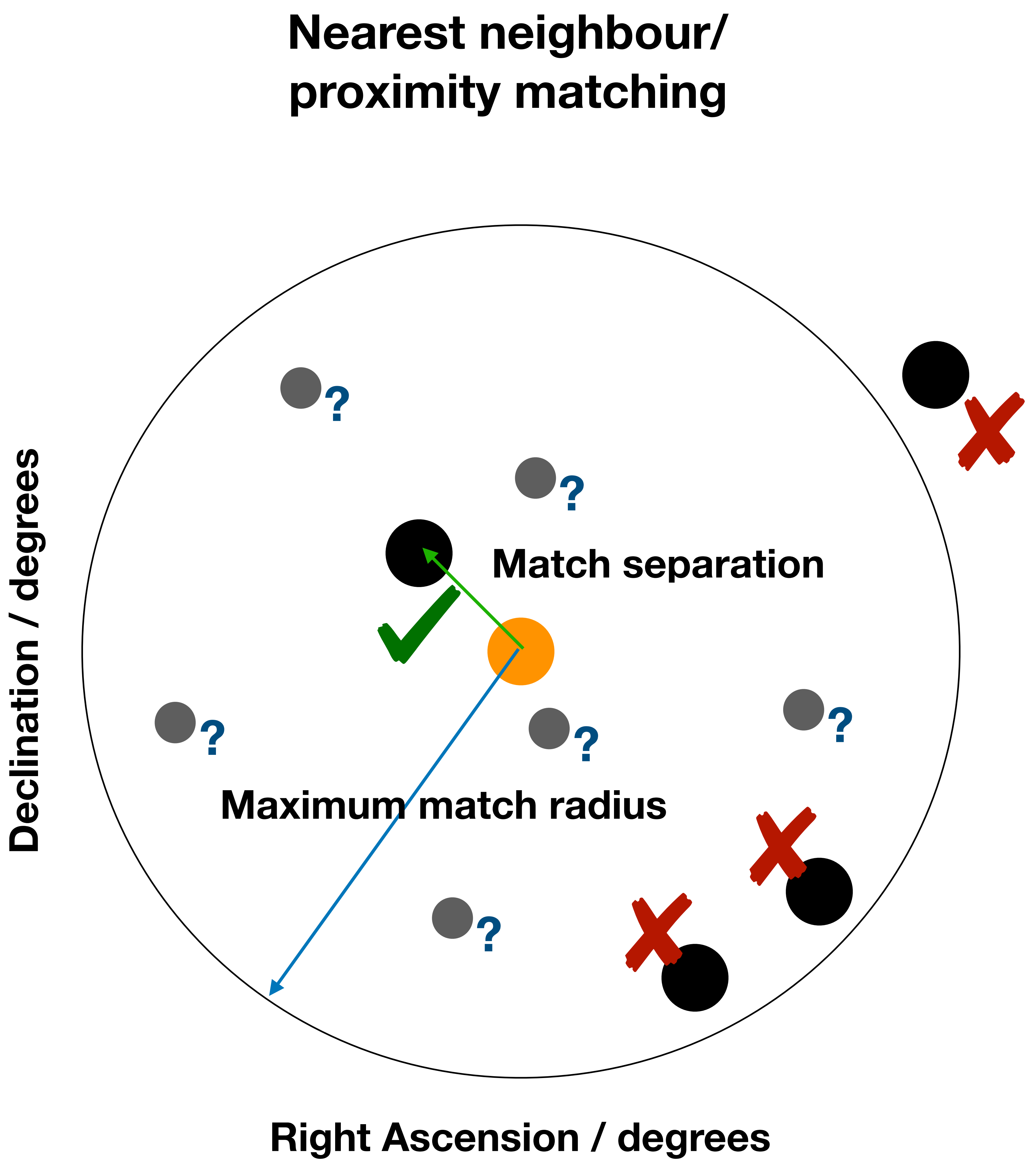

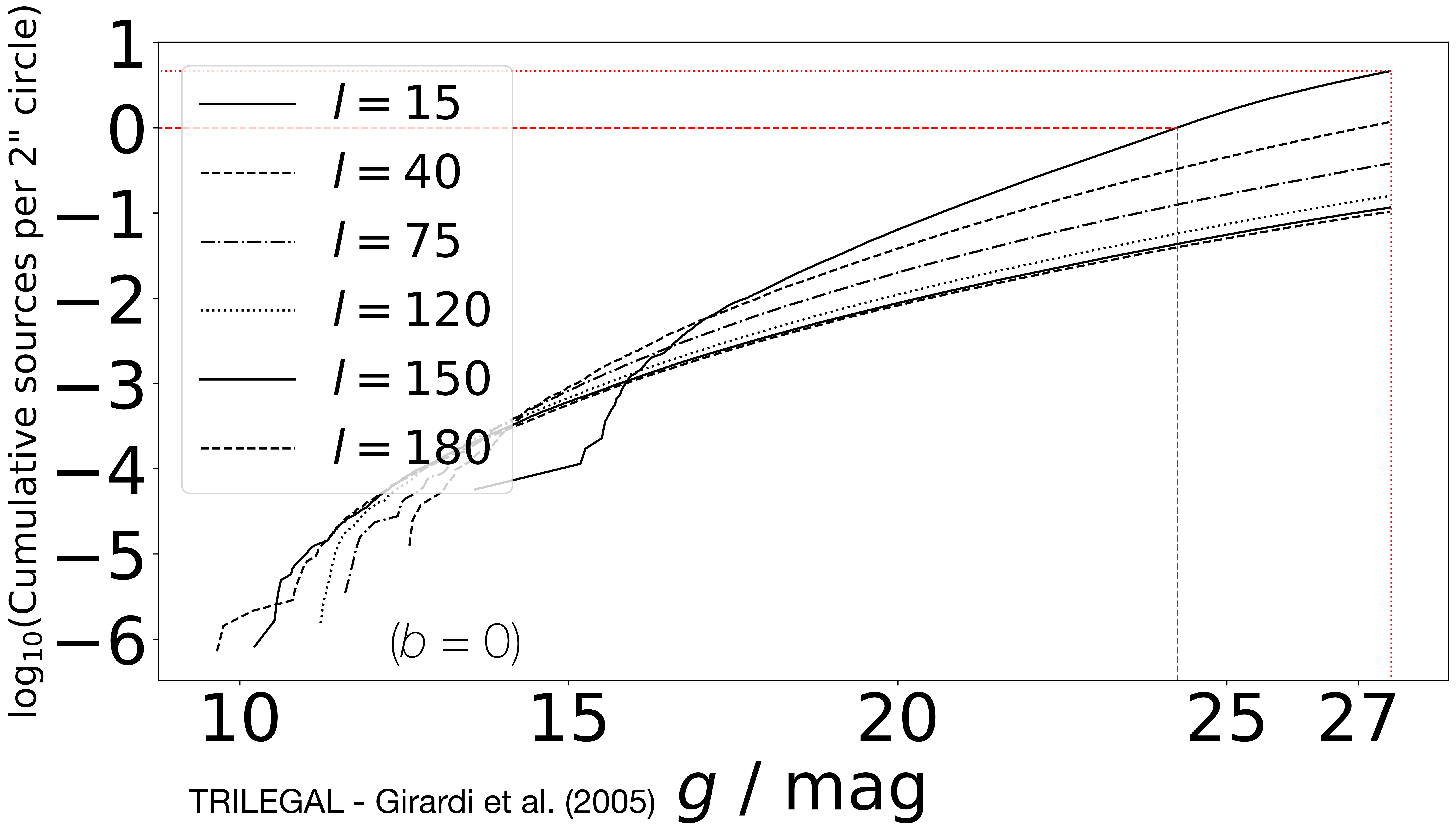

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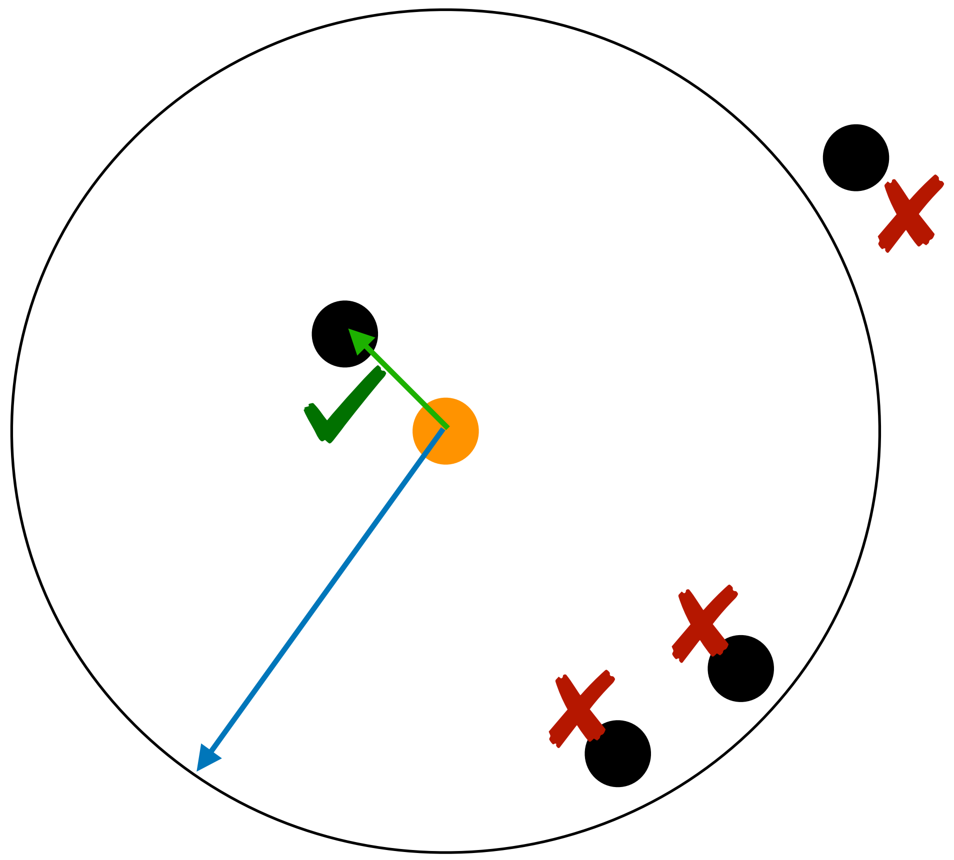
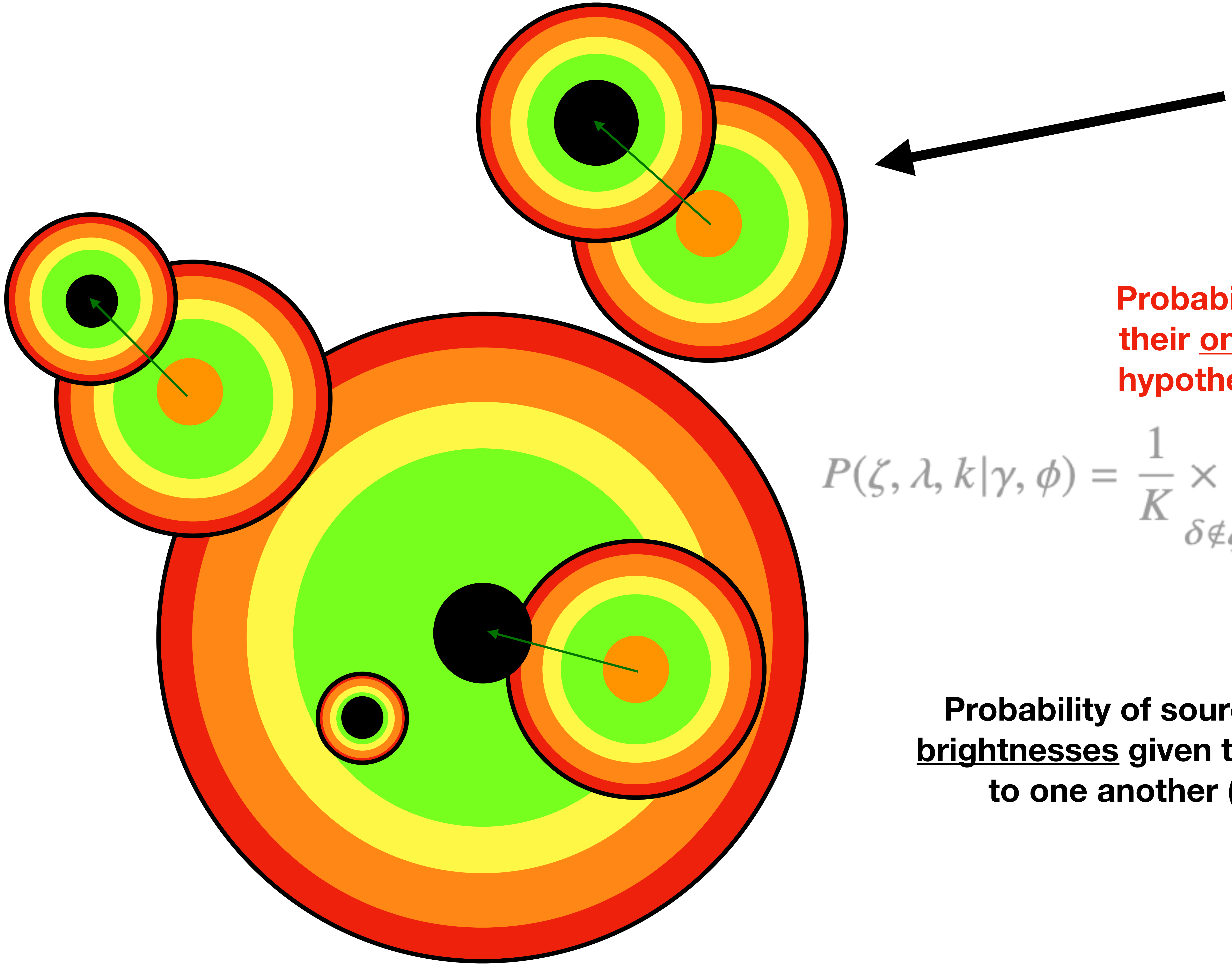
Probabilistic Cross-Matching





Probability of two sources having their <u>on-sky separation</u> given the hypothesis they are counterparts

$$P(\zeta,\lambda,k|\gamma,\phi) = \frac{1}{K} \times \prod_{\delta\notin\zeta\cap\delta\in\gamma} N_\gamma f_\gamma^\delta \prod_{\omega\notin\lambda\cap\omega\in\phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i\lambda_i} c_{\gamma\phi}^{\zeta_i\lambda_i}$$

Probability of sources having their <u>brightnesses</u> given they are unrelated to one another ("field stars")

Probability of sources having their <u>brightnesses</u> given they are counterparts

Wilson & Naylor (2018a)

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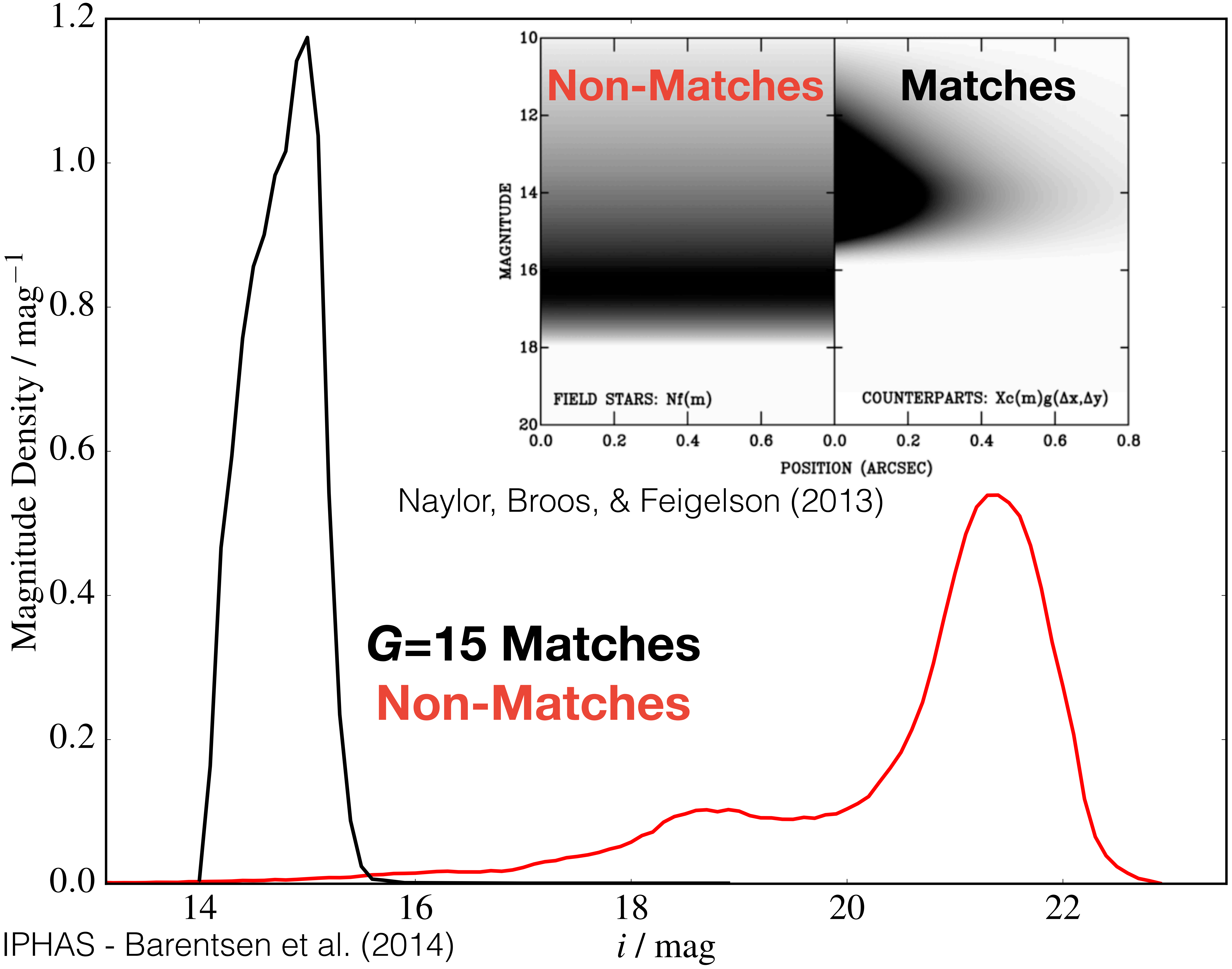
Including Magnitude Information: Rejecting False Positives

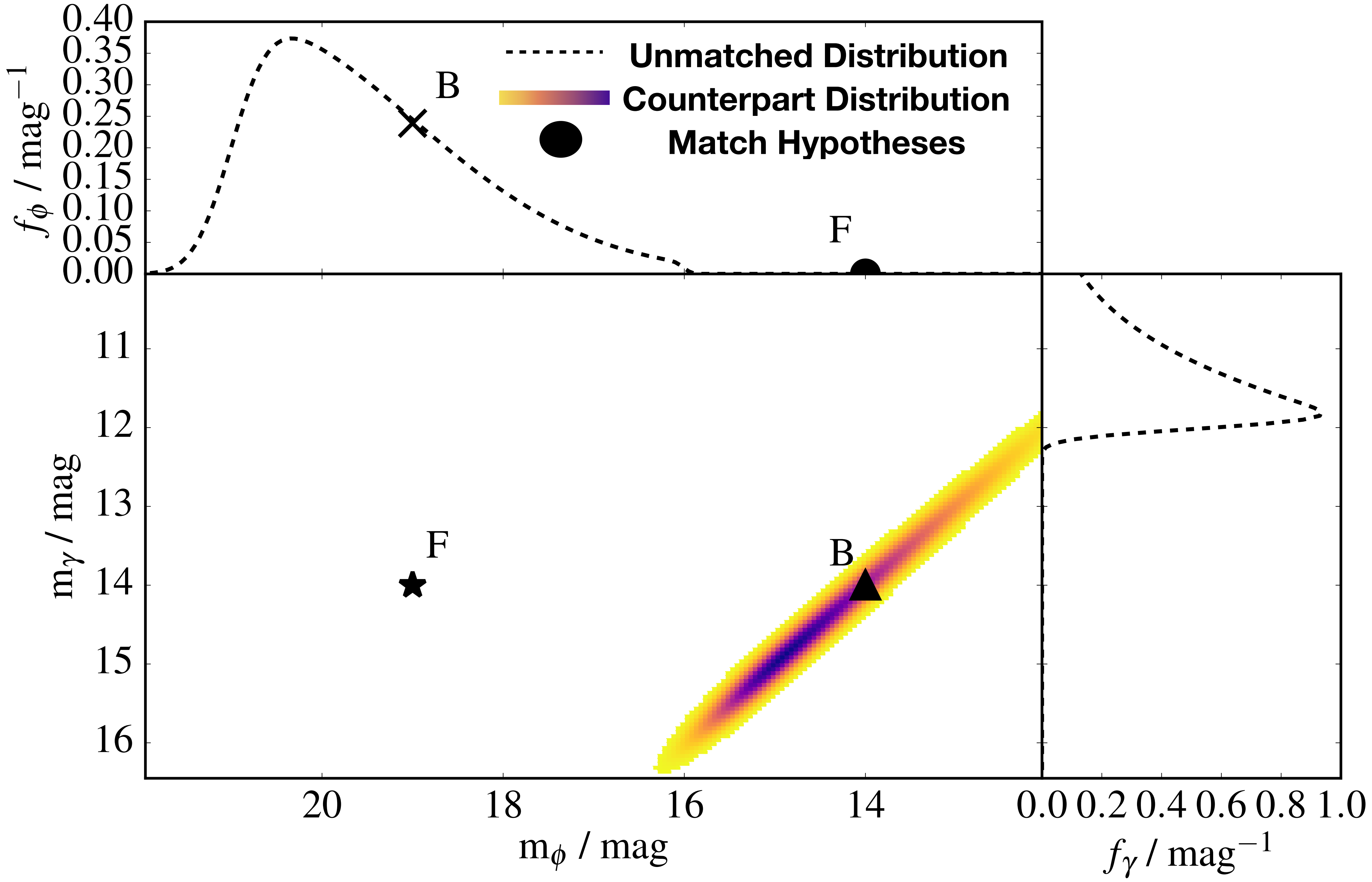
$$P(\zeta, \lambda, k|\gamma, \phi) = \frac{1}{K} \times \prod_{\delta\notin\zeta\cap\delta\in\gamma} N_\gamma f_\gamma^\delta \prod_{\omega\notin\lambda\cap\omega\in\phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i\lambda_i} c_{\gamma\phi}^{\zeta_i\lambda_i}$$



Naylor, Broos, & Feigelson (2013)

IPHAS - Barentsen et al. (2014)

Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)



Wilson & Naylor (2018a)

The photometry-based likelihoods (c and f) allow us to mitigate high false positive rate in crowded fields, but now we need the position-based likelihood G

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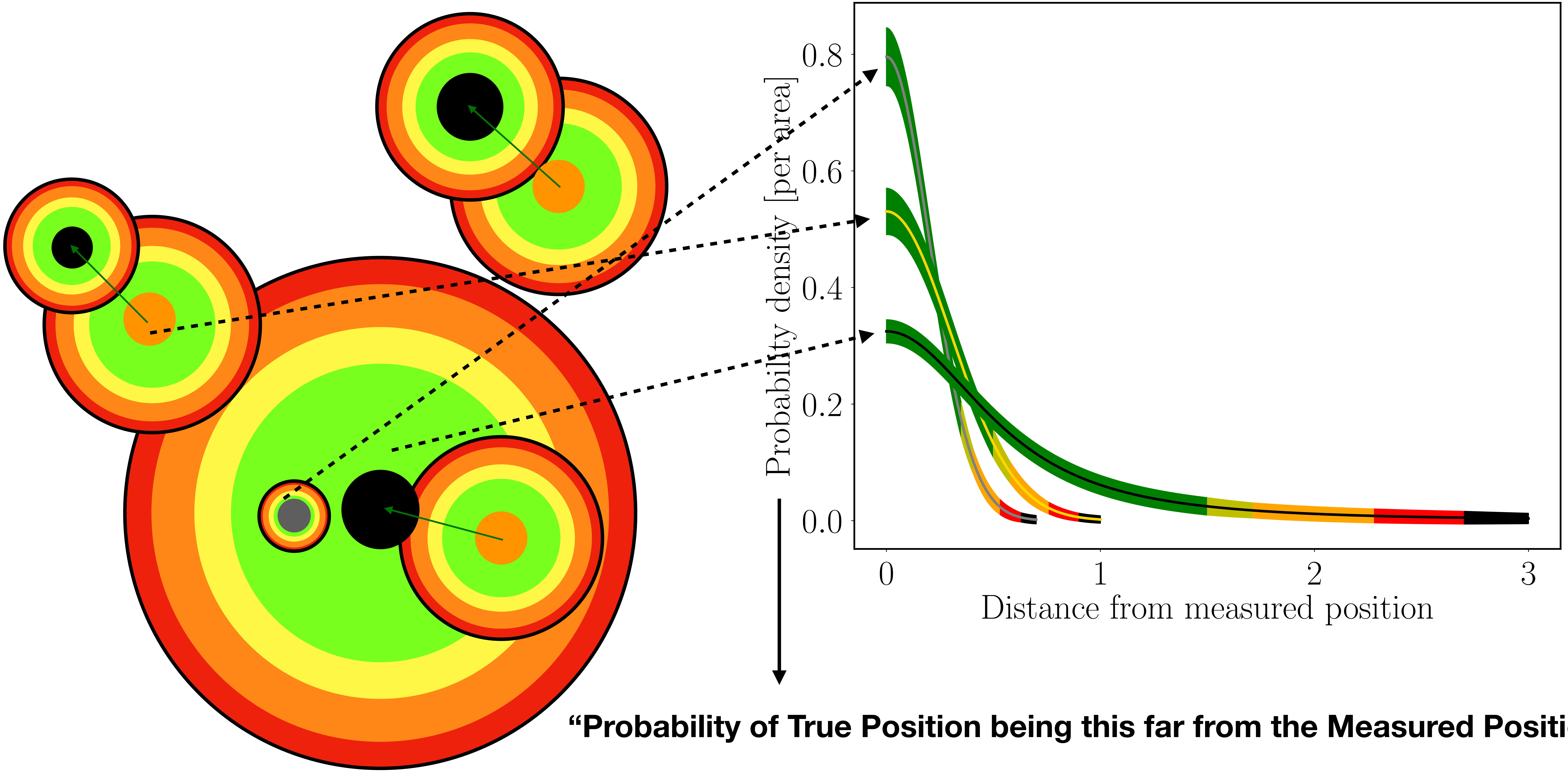
Probabilistic Cross-Matching: the AUF



"Probability of True Position being this far from the Measured Position"

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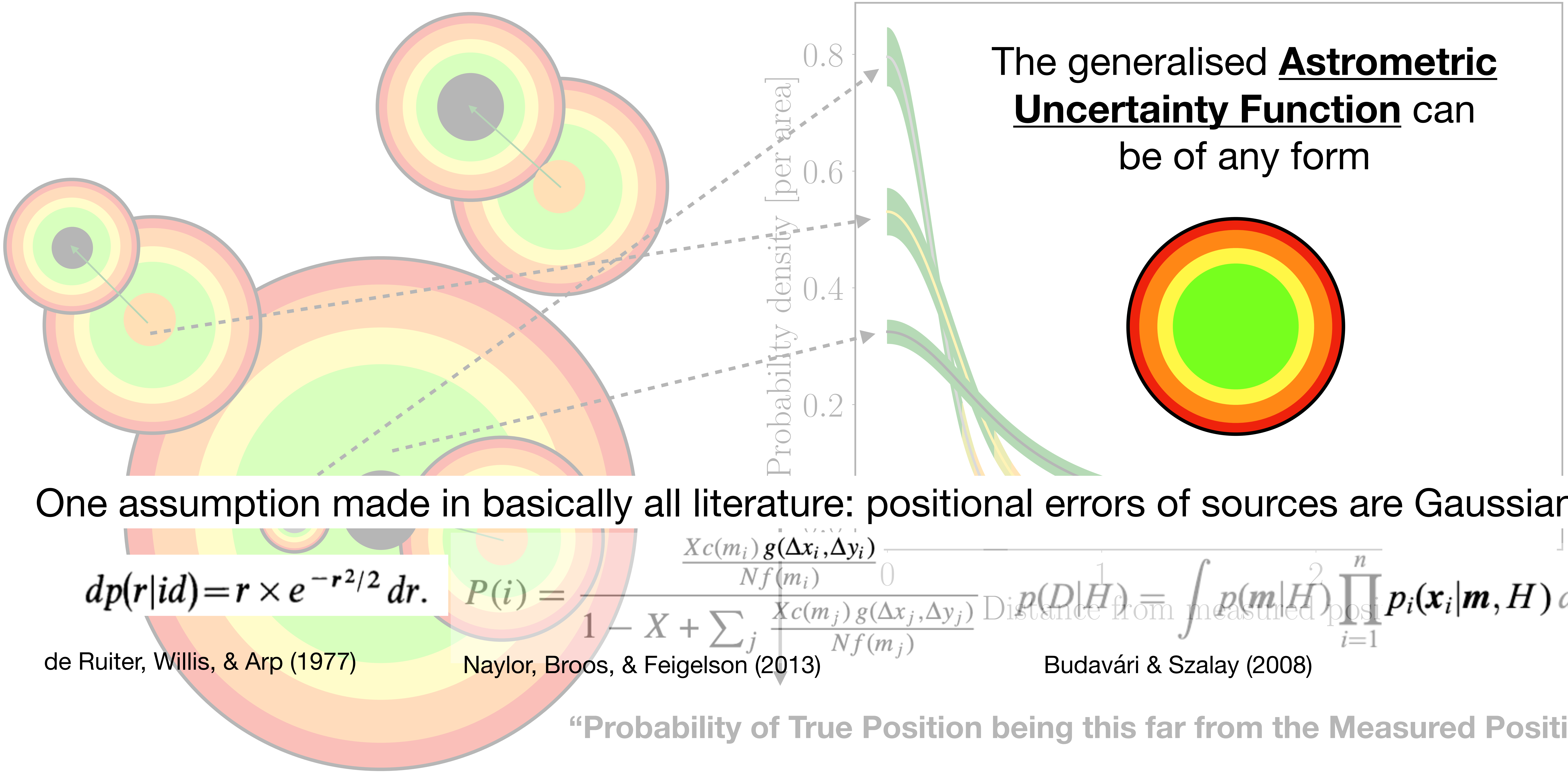
Probabilistic Cross-Matching: the AUF



The generalised **Astrometric Uncertainty Function** can be of any form

One assumption made in basically all literature: positional errors of sources are Gaussian!

$$dp(r|id) = r \times e^{-r^2/2}\, dr.$$

de Ruiter, Willis, & Arp (1977)

$$P(i) = \frac{\frac{Xc(m_i)\,g(\Delta x_i, \Delta y_i)}{Nf(m_i)}}{1 - X + \sum_j \frac{Xc(m_j)\,g(\Delta x_j, \Delta y_j)}{Nf(m_j)}}$$

Naylor, Broos, & Feigelson (2013)

$$p(D|H) = \int p(\boldsymbol{m}|H) \prod_{i=1}^{n} p_i(\boldsymbol{x}_i|\boldsymbol{m}, H)\, d^3m$$

Budavári & Szalay (2008)

"Probability of True Position being this far from the Measured Position"

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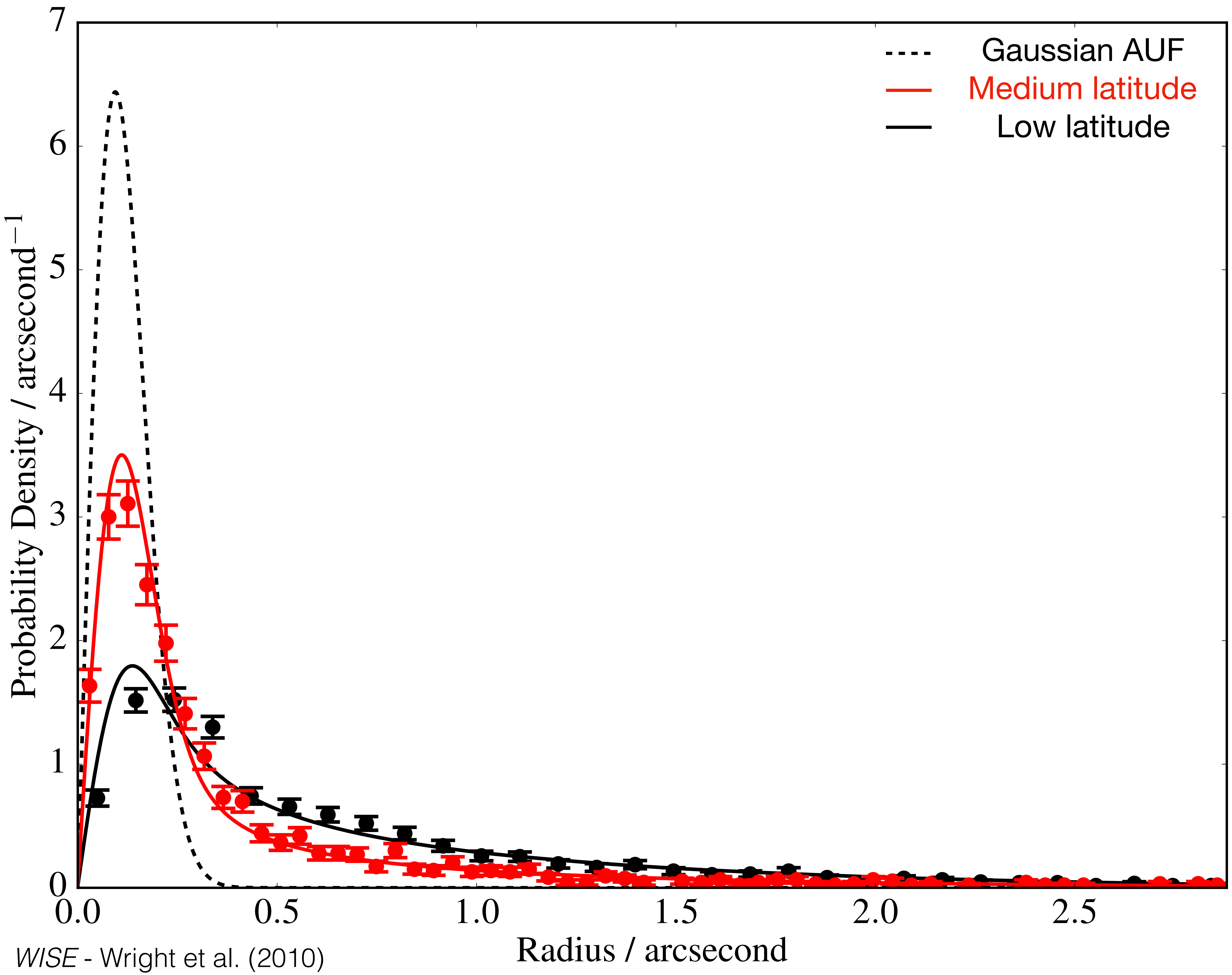
Additional Components of the AUF

$$P(\zeta, \lambda, k | \gamma, \phi) = \frac{1}{K} \times \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_\mathrm{c} \boldsymbol{G}_{\boldsymbol{\gamma\phi}}^{\boldsymbol{\zeta_i \lambda_i}} c_{\gamma\phi}^{\zeta_i \lambda_i}$$



WISE - Wright et al. (2010)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

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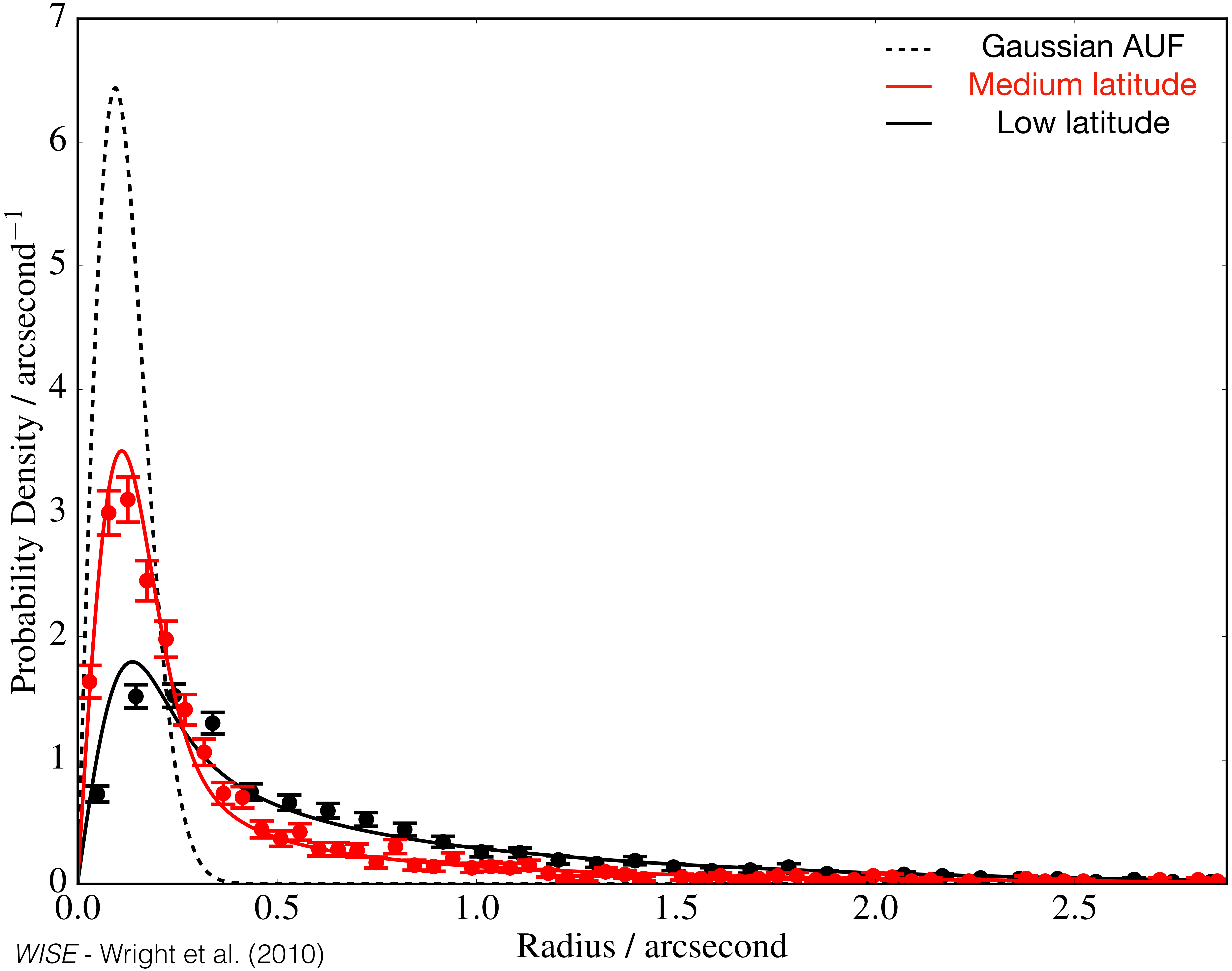

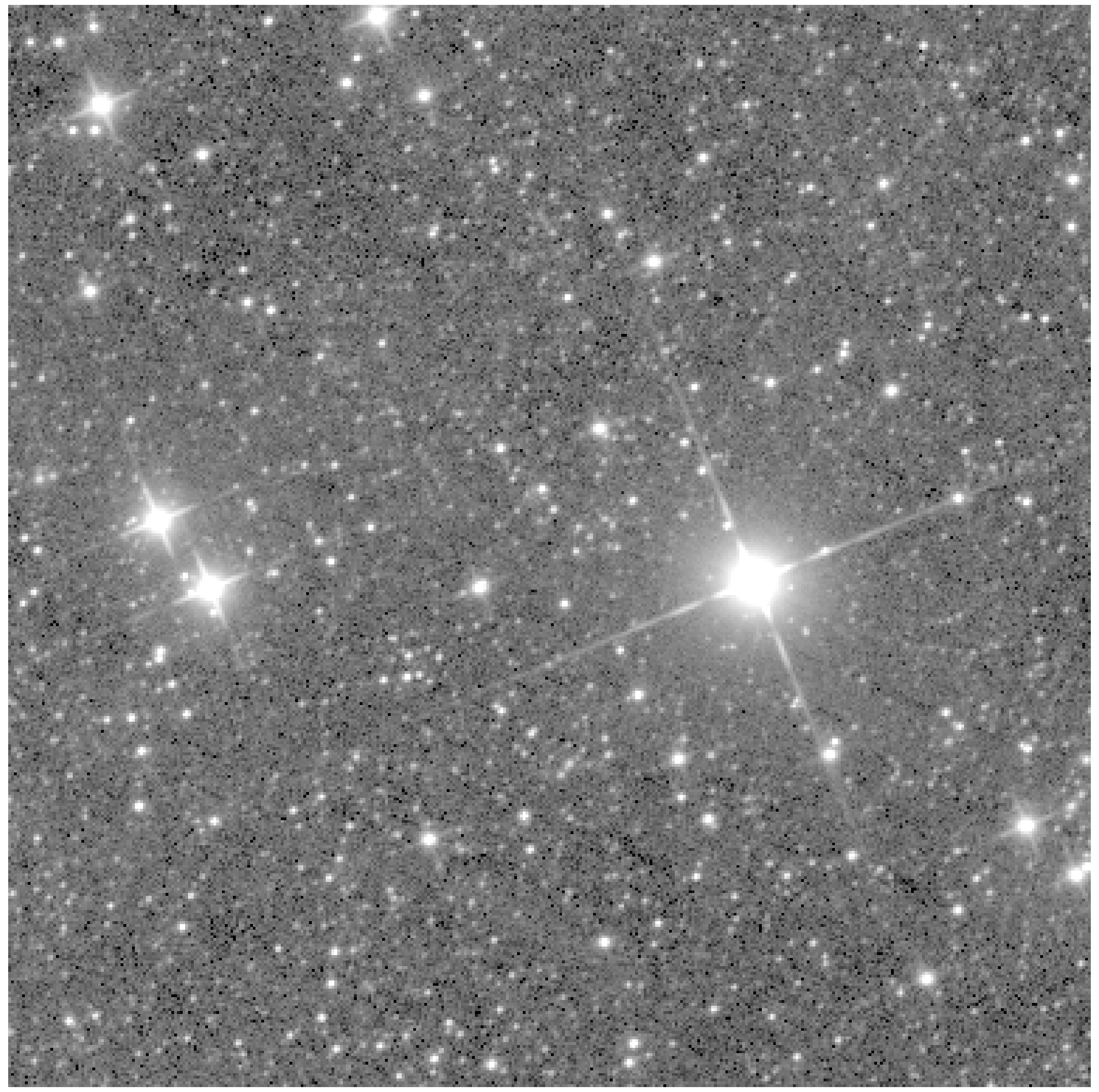

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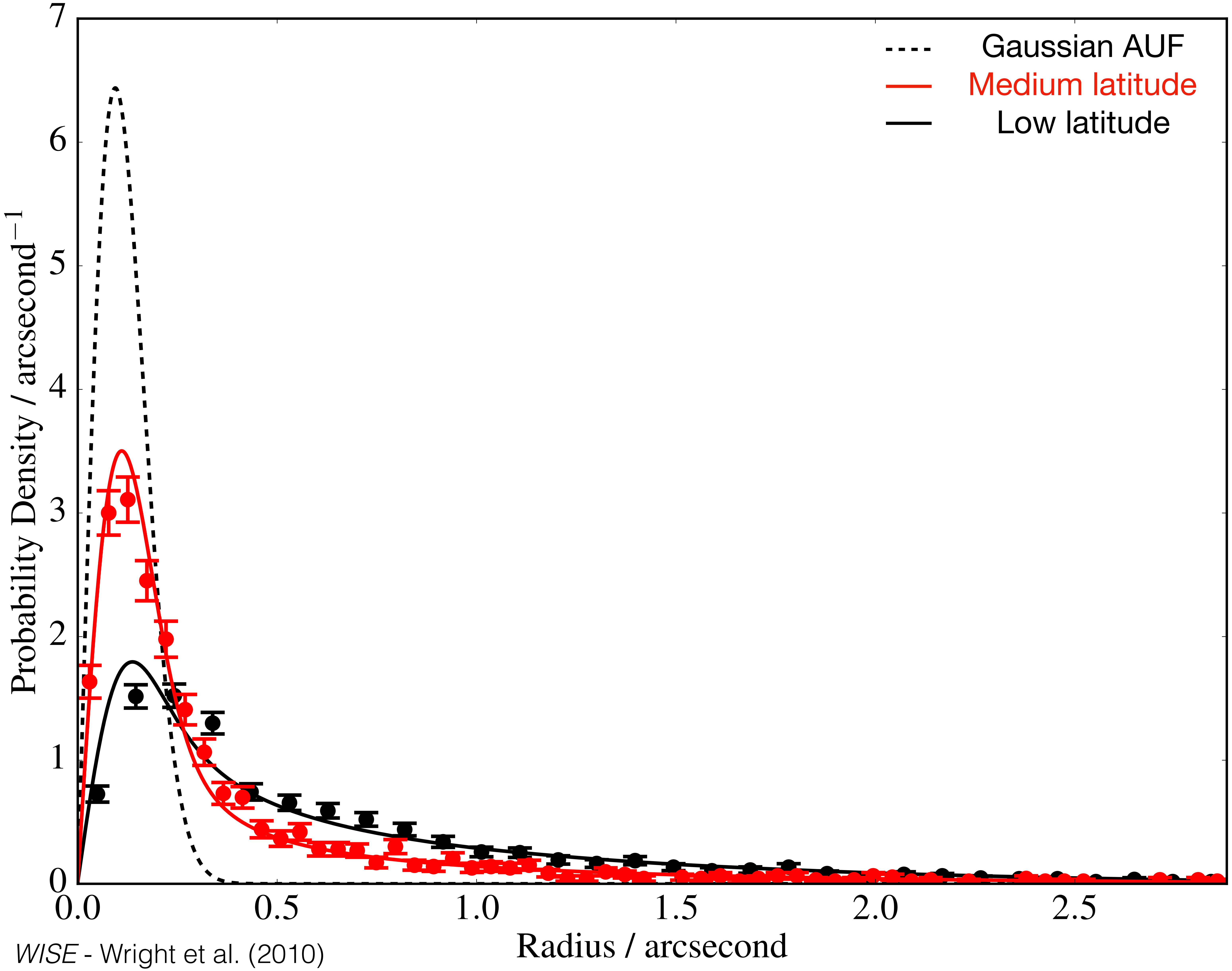

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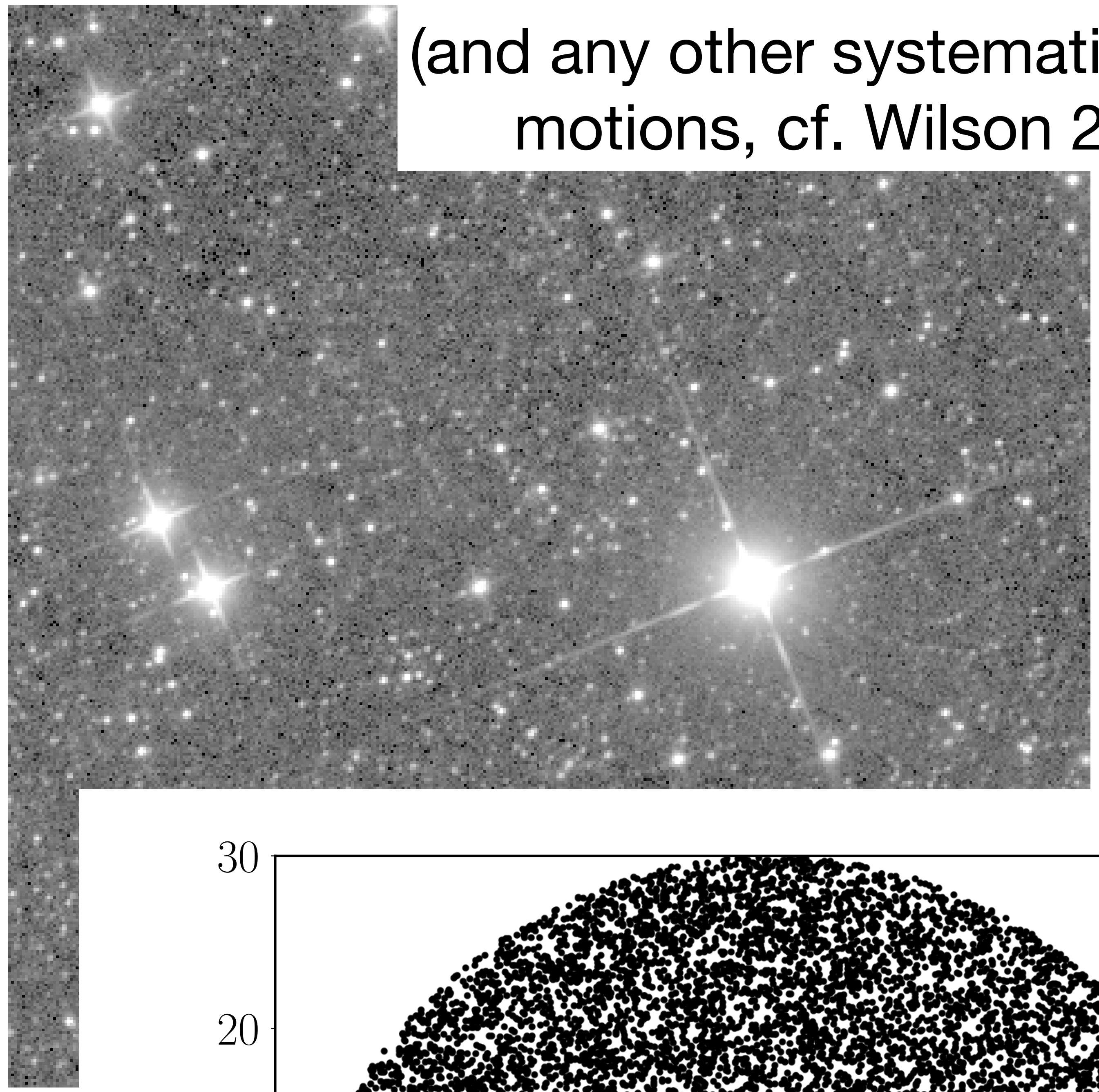
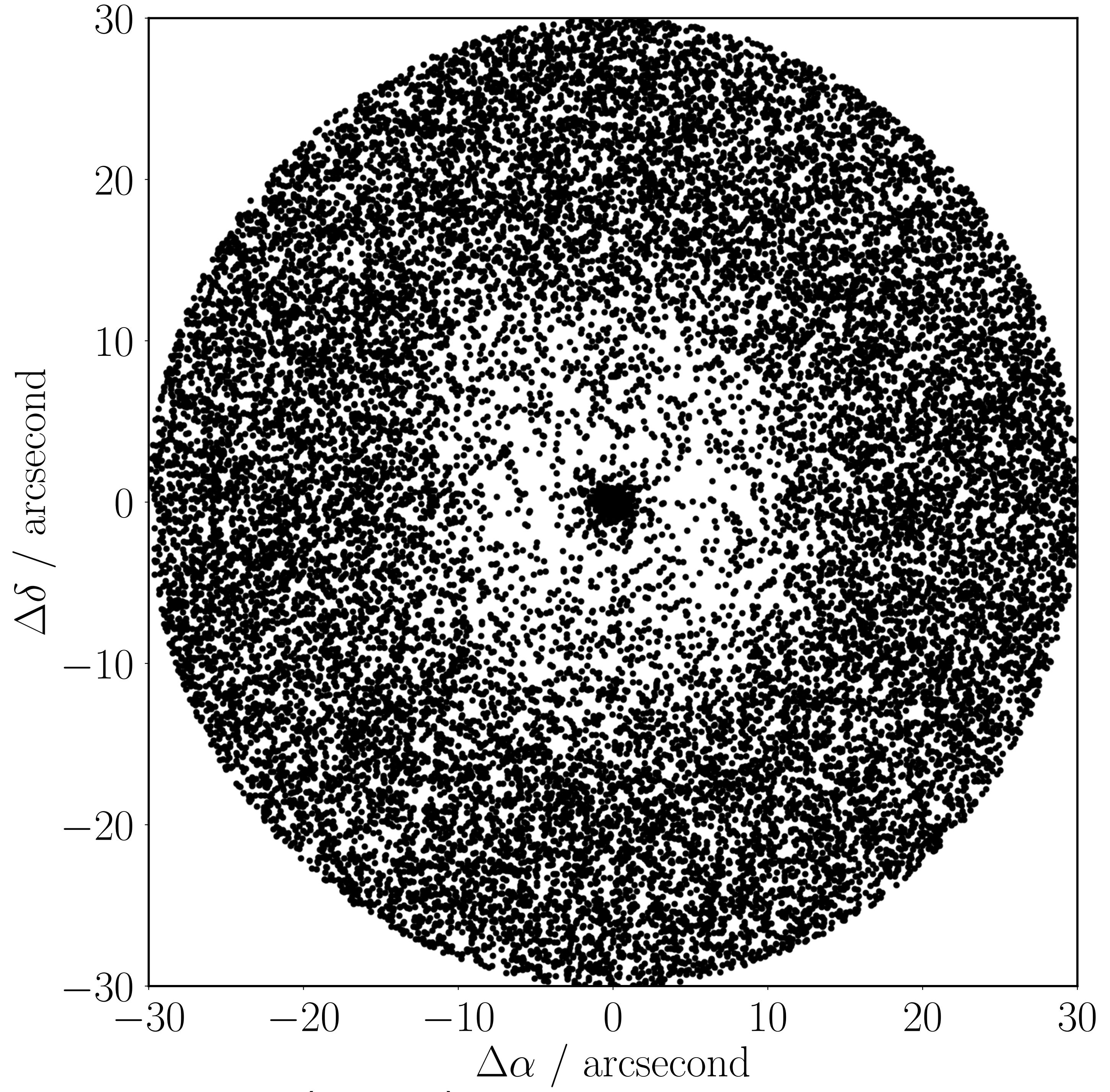
(and any other systematic — e.g. proper motions, cf. Wilson 2023, RASTI)





Wilson & Naylor (2017)

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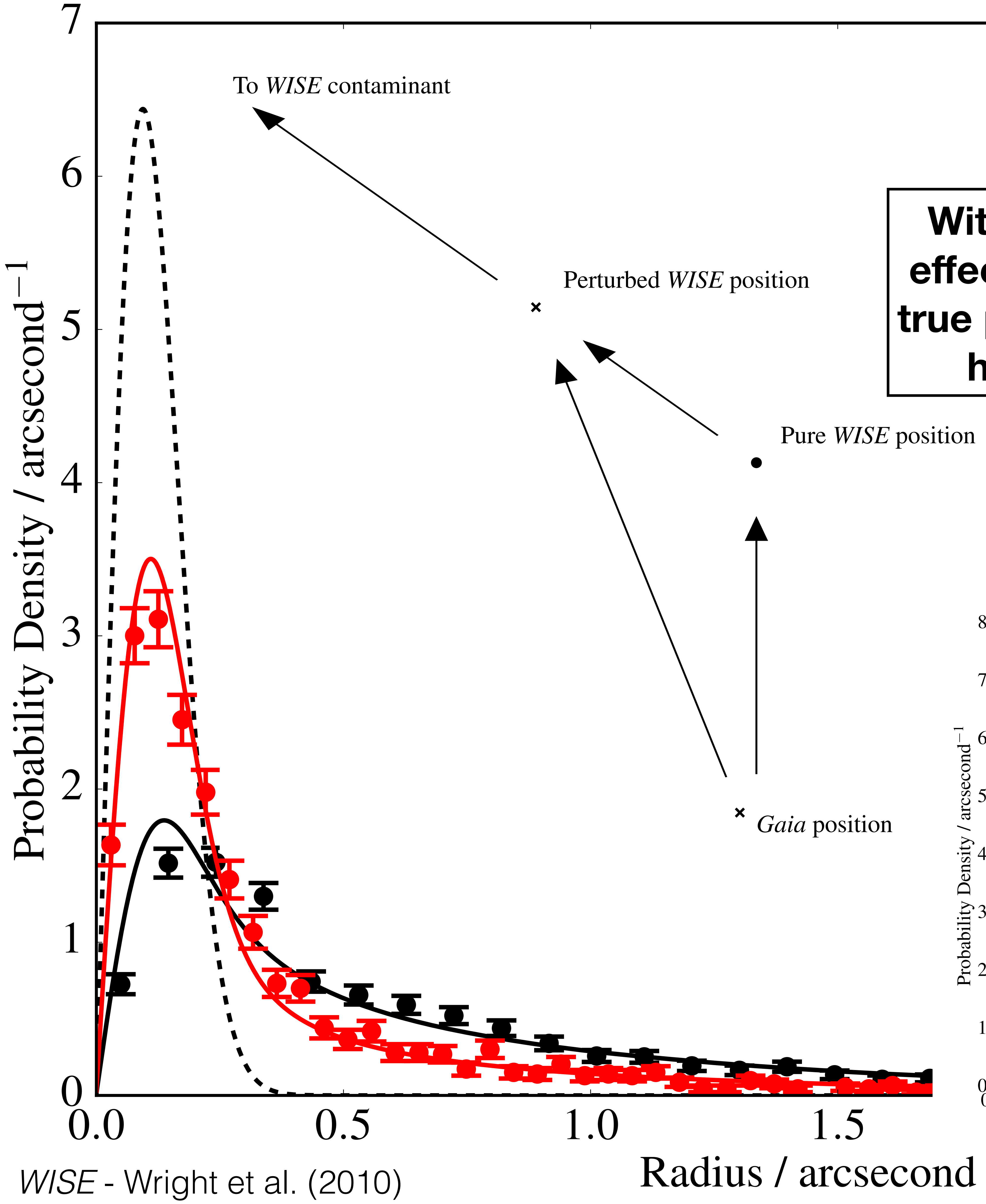

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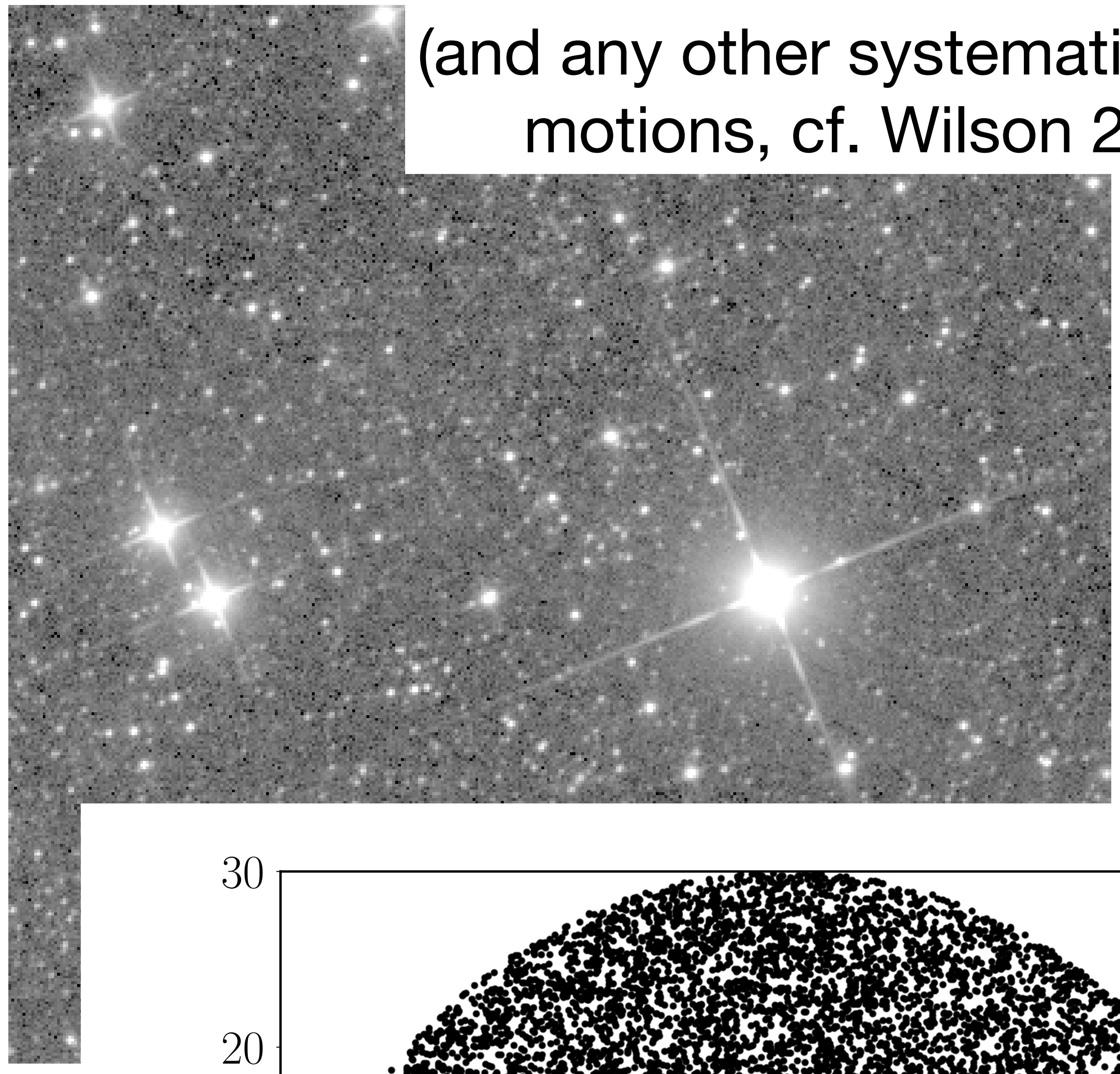
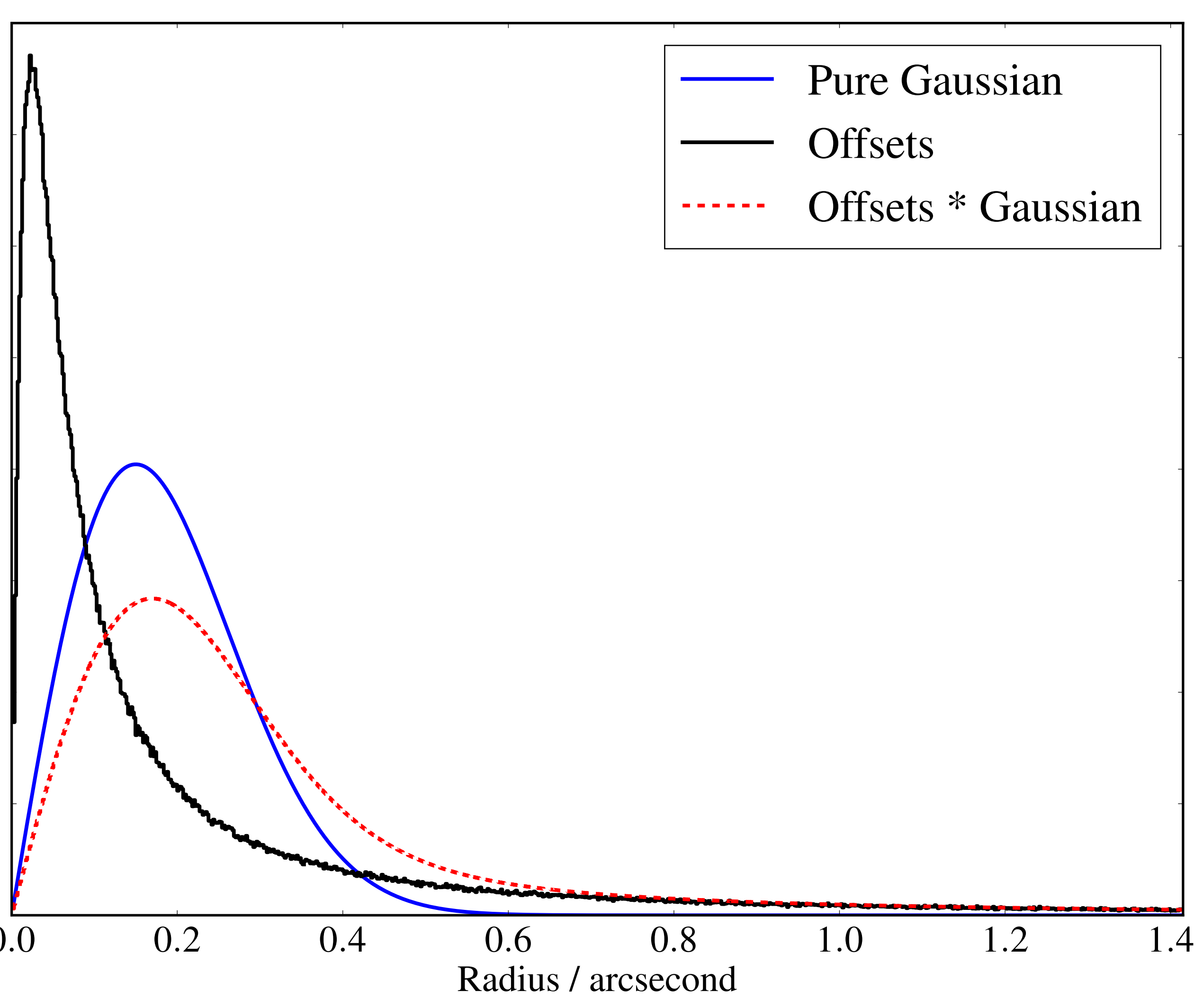
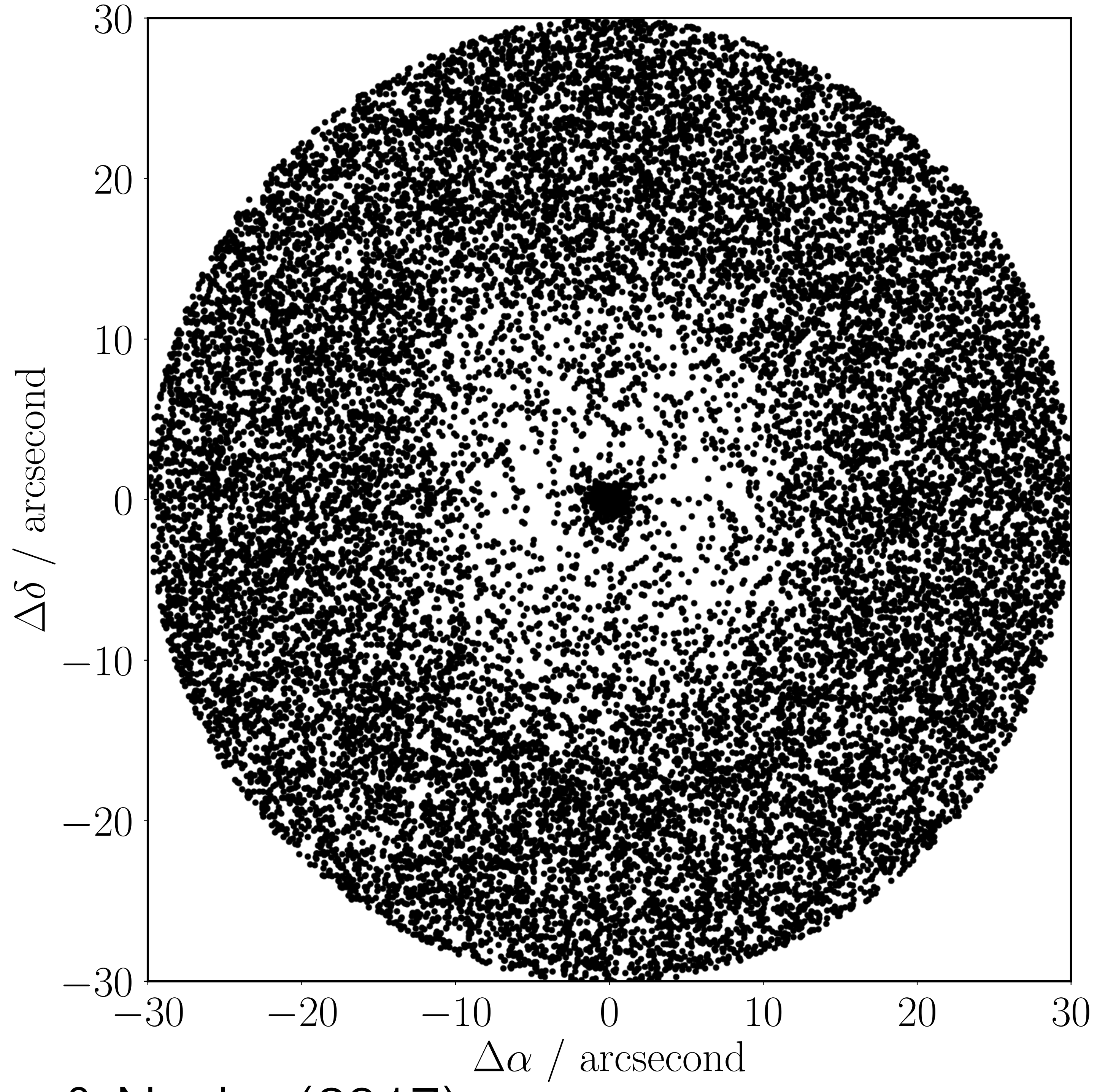




Wilson & Naylor (2018b)



Wilson & Naylor (2017)

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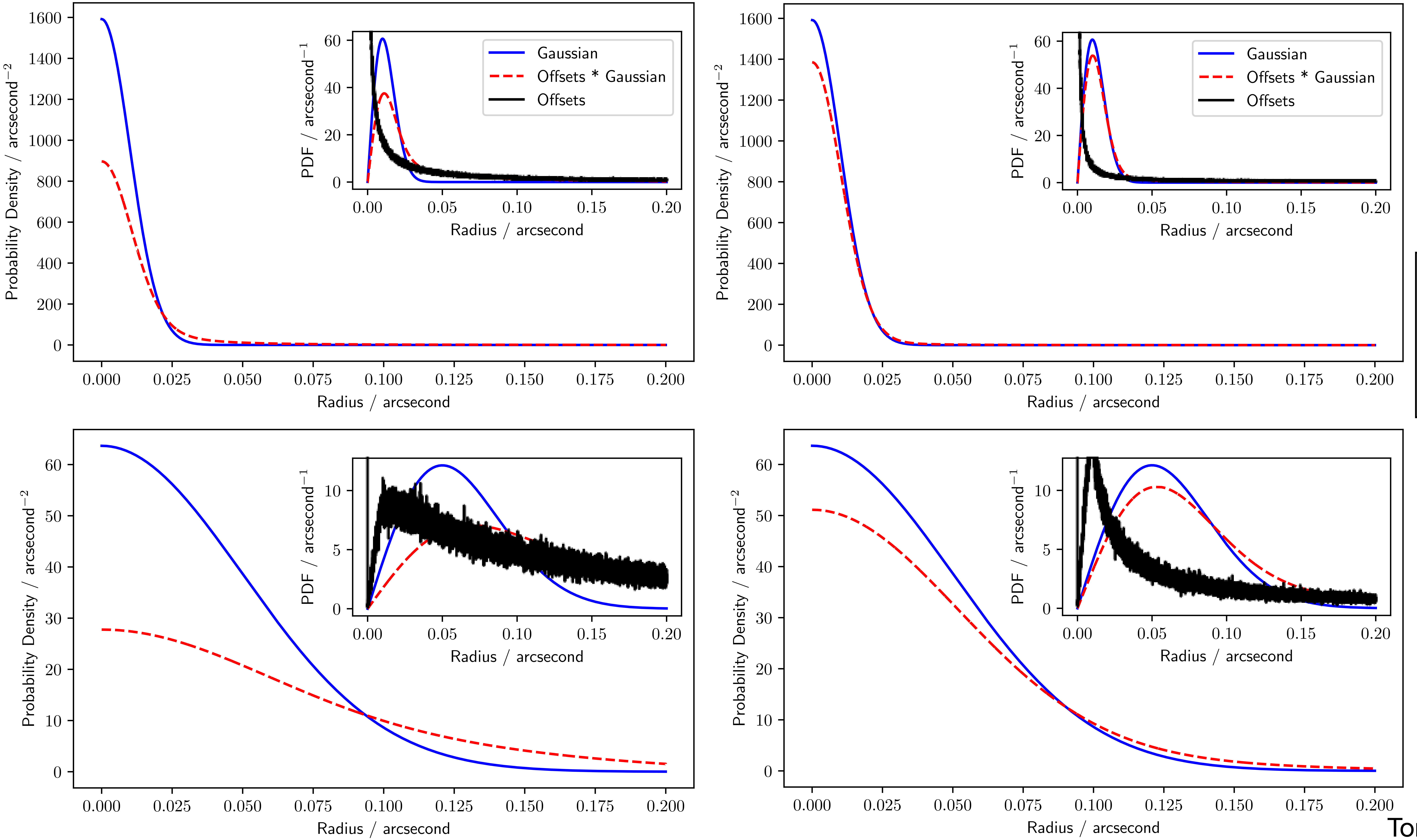
The Rubin AUF

Wilson & Naylor (2018b)



Without modelling this extra effect, we fail to recover many true pairings, with an artificially high false negative rate!

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Extra-galactic Effects of Crowding

Wilson & Naylor (2018b); also see Wilson (2022, RNAAS)

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Macauff

Cross-Match Tools, Framework, Usage

birnam

banquo

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Matching Across Catalogues using the Astrometric Uncertainty Function and Flux

https://github.com/Onoddil/macauff

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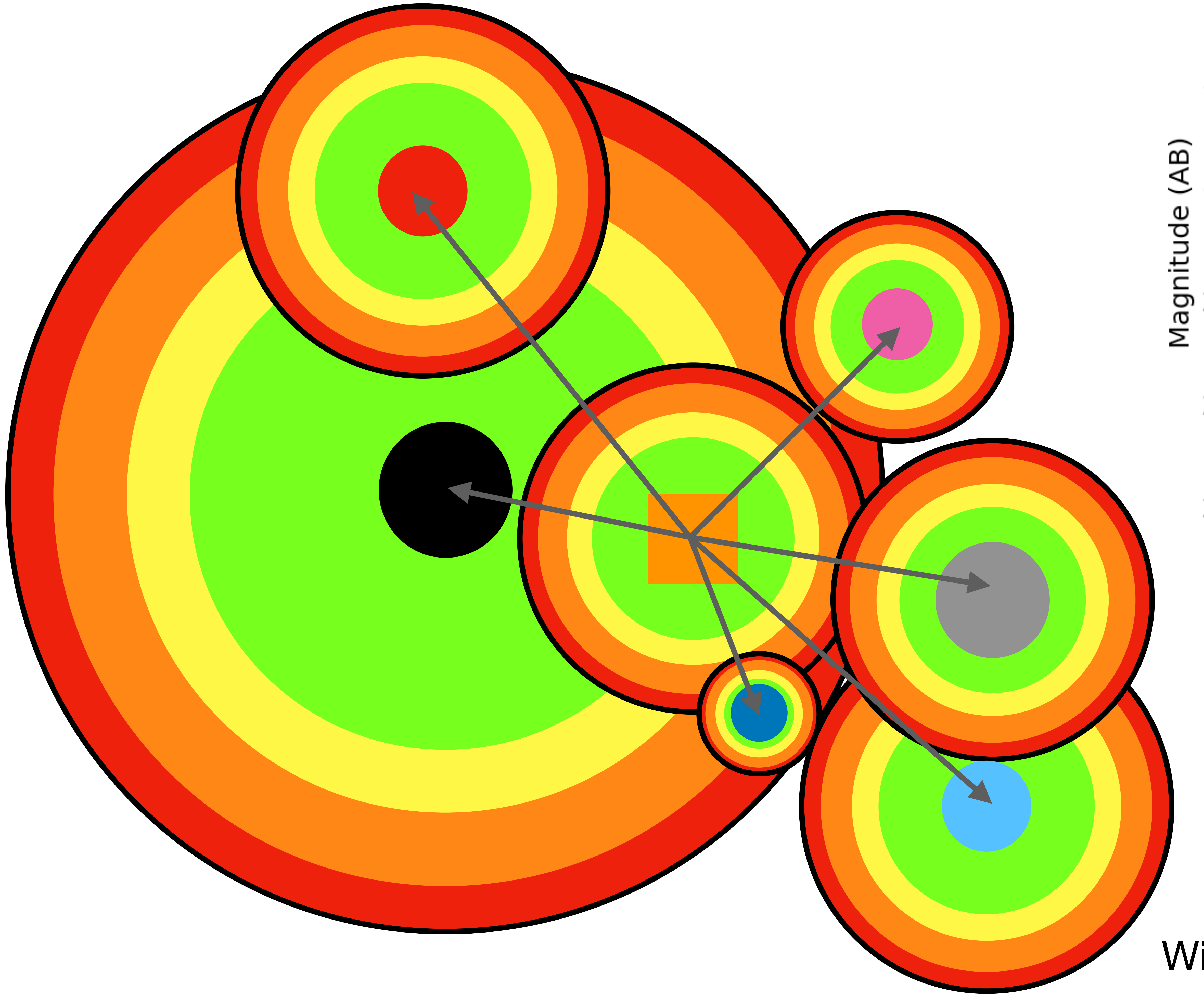
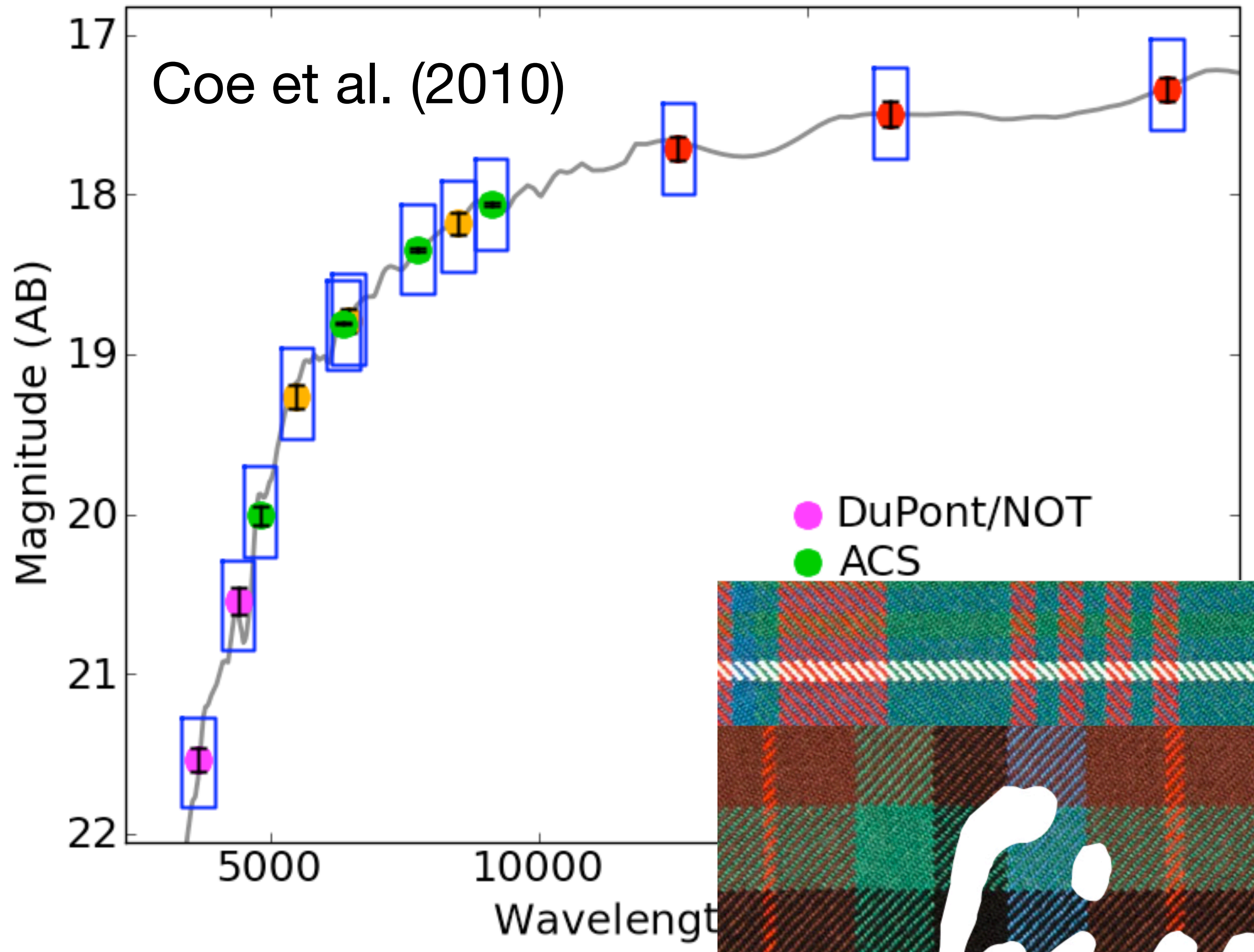
The Rubin "Super-Match"

LSST -> *Gaia*, *WISE*, VISTA, *Euclid*, SDSS, … matches

Quick and easy construction of spectral energy distributions for each LSST source

Includes SED probabilities, individual match reliability, contamination statistics etc.





Wilson & Naylor (in prep.)

https://github.com/Onoddil/macauff

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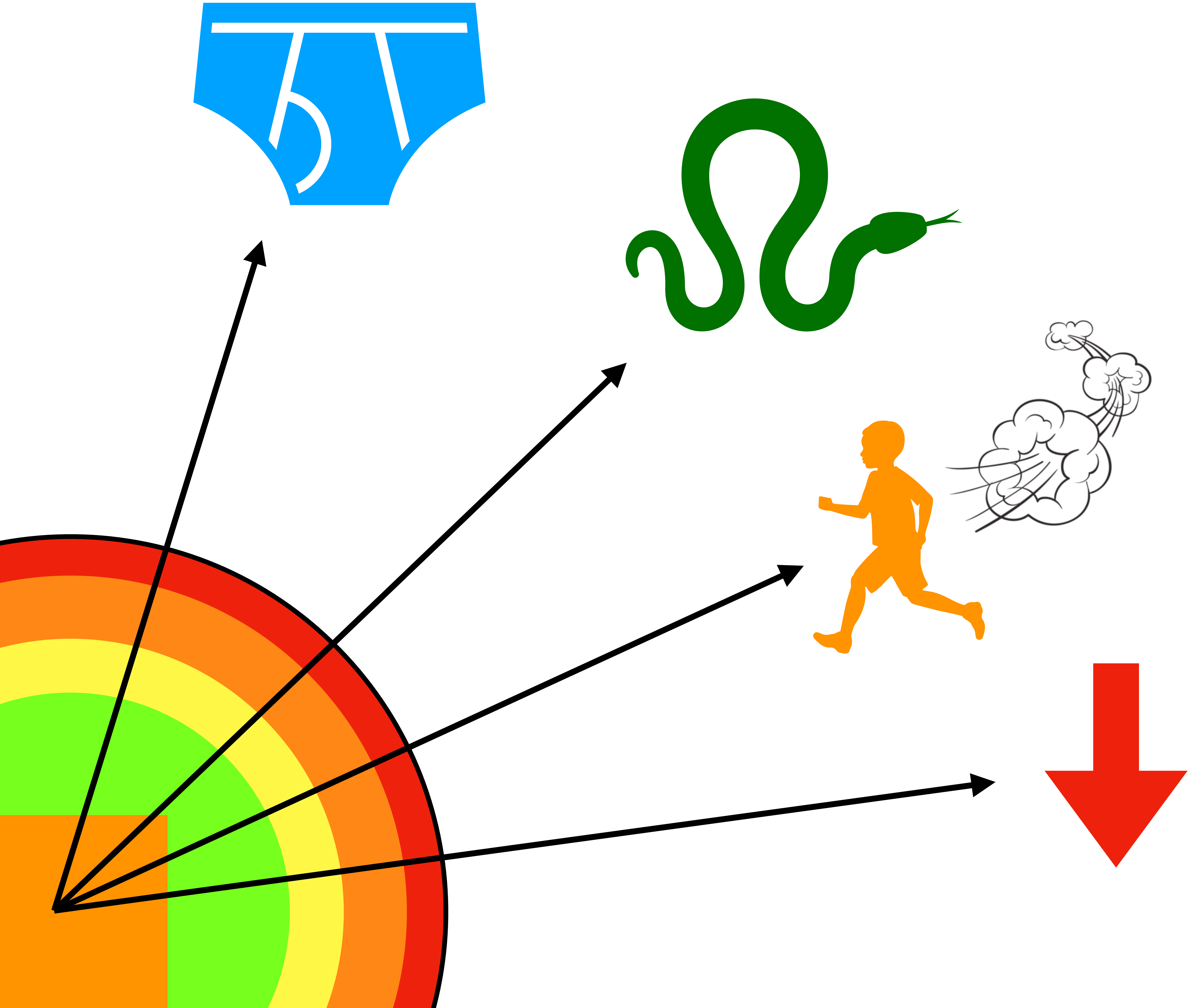
Confirming Lonely Rubin Sources



Most LSST sources will be "lonely" with 15x as many sources as the next dataset. We will follow up all non-matches, and confirm whether these objects are:

- Image artefacts
- Astrophysically variable objects
- High proper motion sources
- Regular objects that are simply too faint to be seen in the opposing catalogue

https://github.com/Onoddil/macauff

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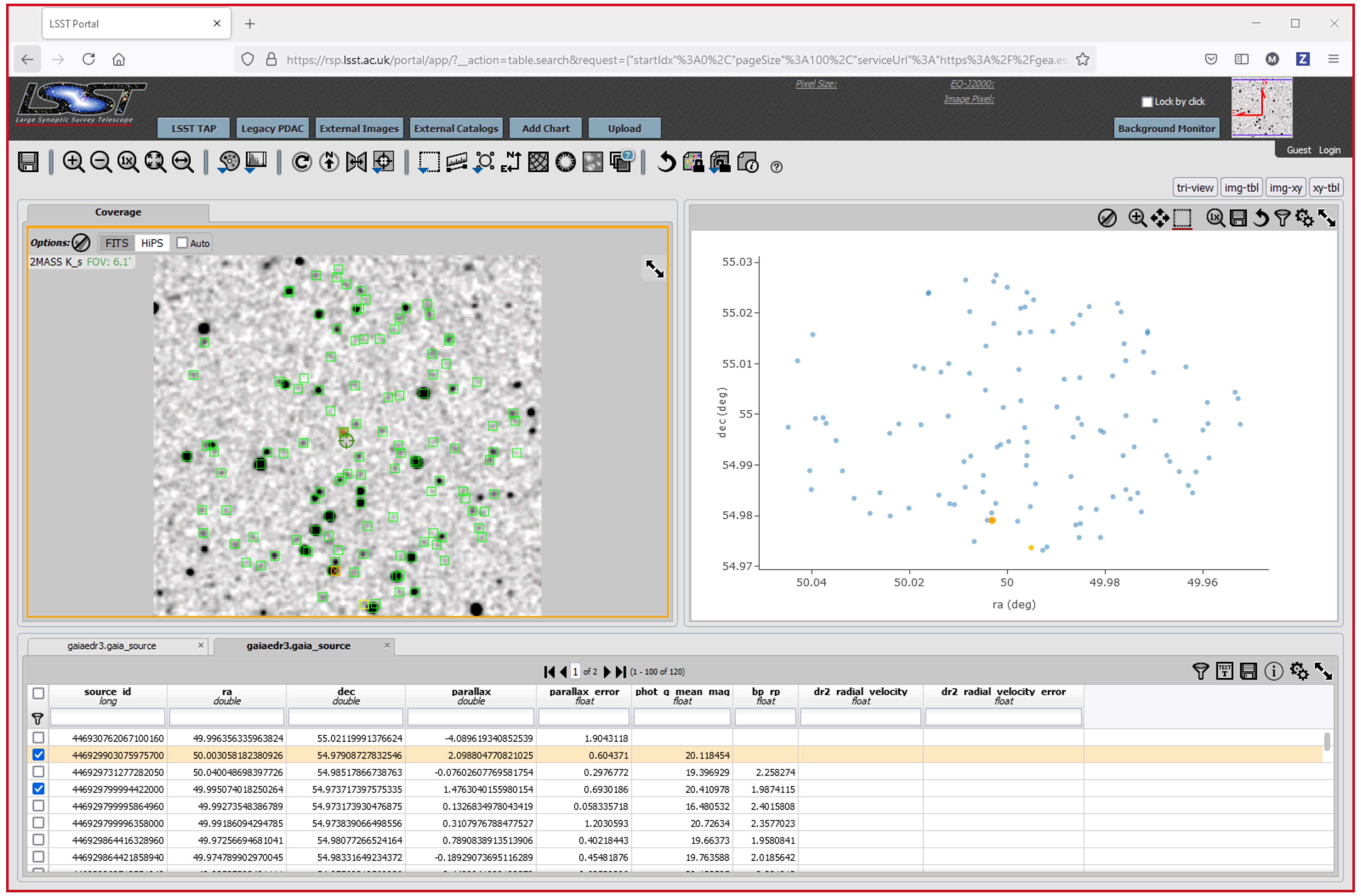
How To Use Our Cross-Matches

(Or, how this impacts you on a day-to-day basis)



Three tables per cross-match: merged catalogue dataset, and 2x non-match dataset (one per catalogue)

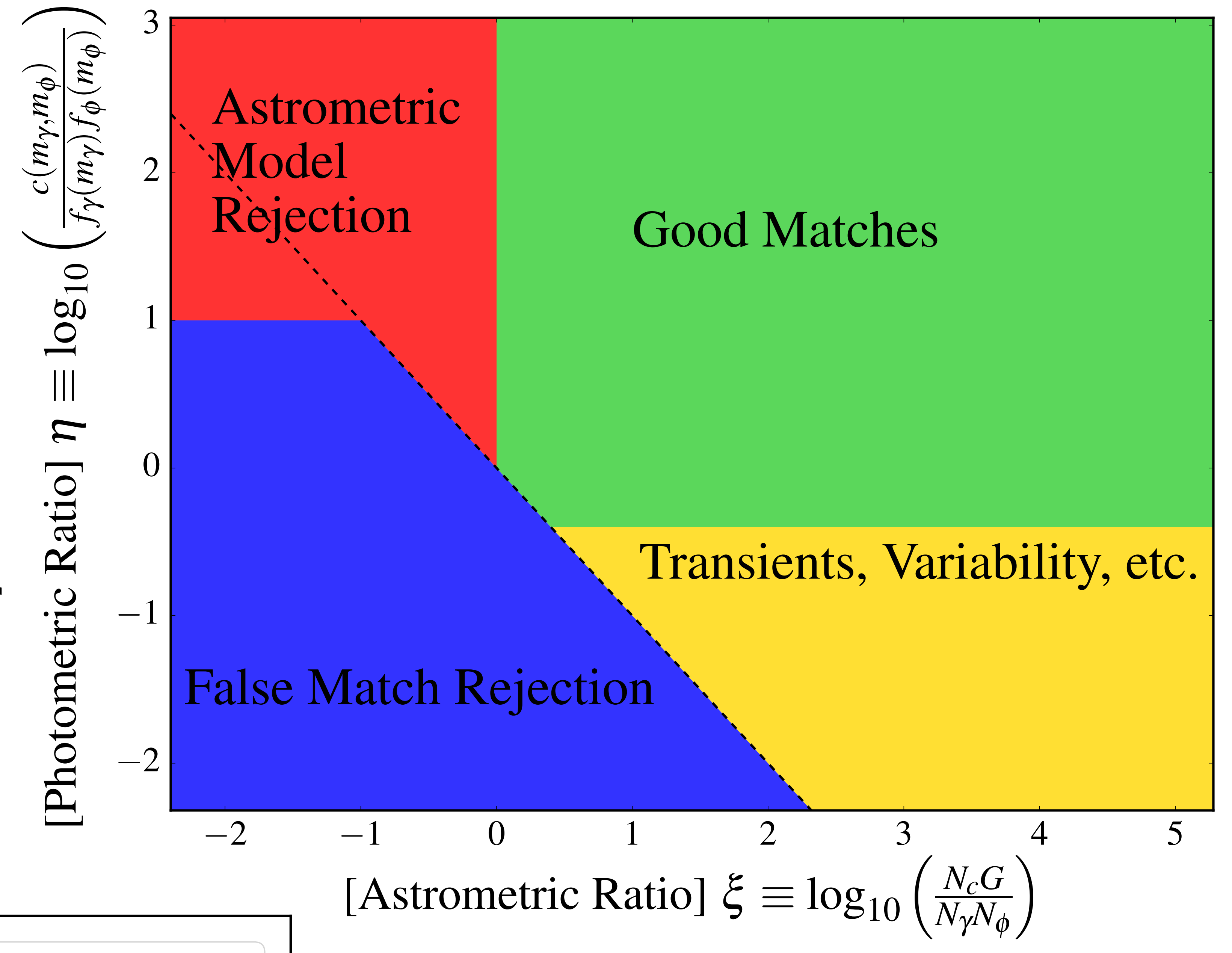
Example columns:

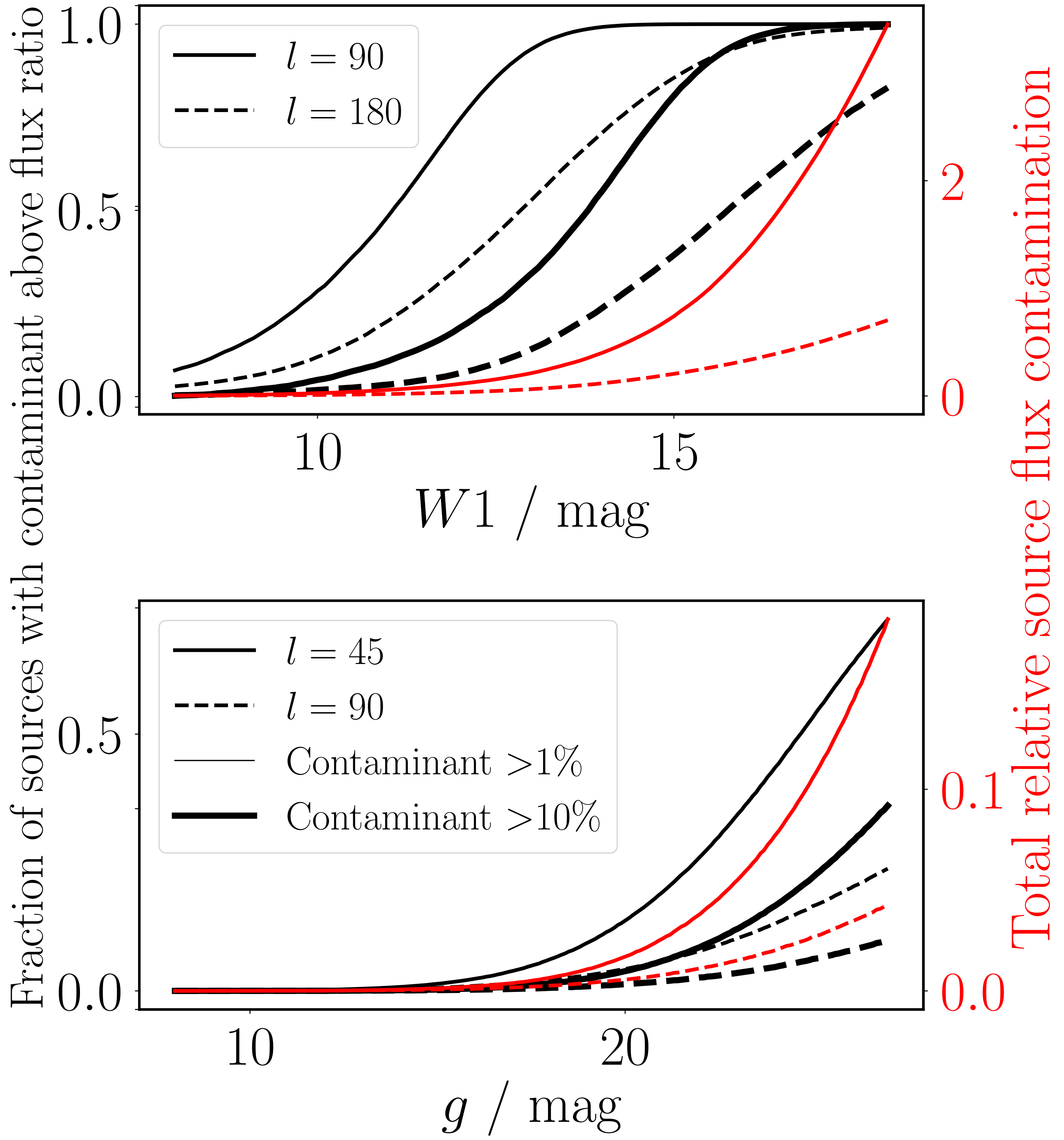
- **Designations of the two sources (e.g., WISE J… and *Gaia* EDR3…)**
- **RA and Dec (or Galactic l/b) of the two sources**
- **Magnitudes (corrected for necessary effects, such as e.g. *Gaia*) in all bandpasses for both objects**
- **Match probability — probability of the most likely permutation (see equation 26 of Wilson & Naylor 2018a)**
- **Eta - Photometric likelihood ratio (counterpart vs non-match probability, just for brightnesses; see eq37 of WN18a)**
- **Xi - Astrometric likelihood ratio (just position match/non-match comparison; see eq38 of WN18a)**
- **Average contamination - simulated mean (percentile) brightening of the two sources, based on number density of catalogue**
- **Probability of sources having blended contaminant above e.g. 1% relative flux**

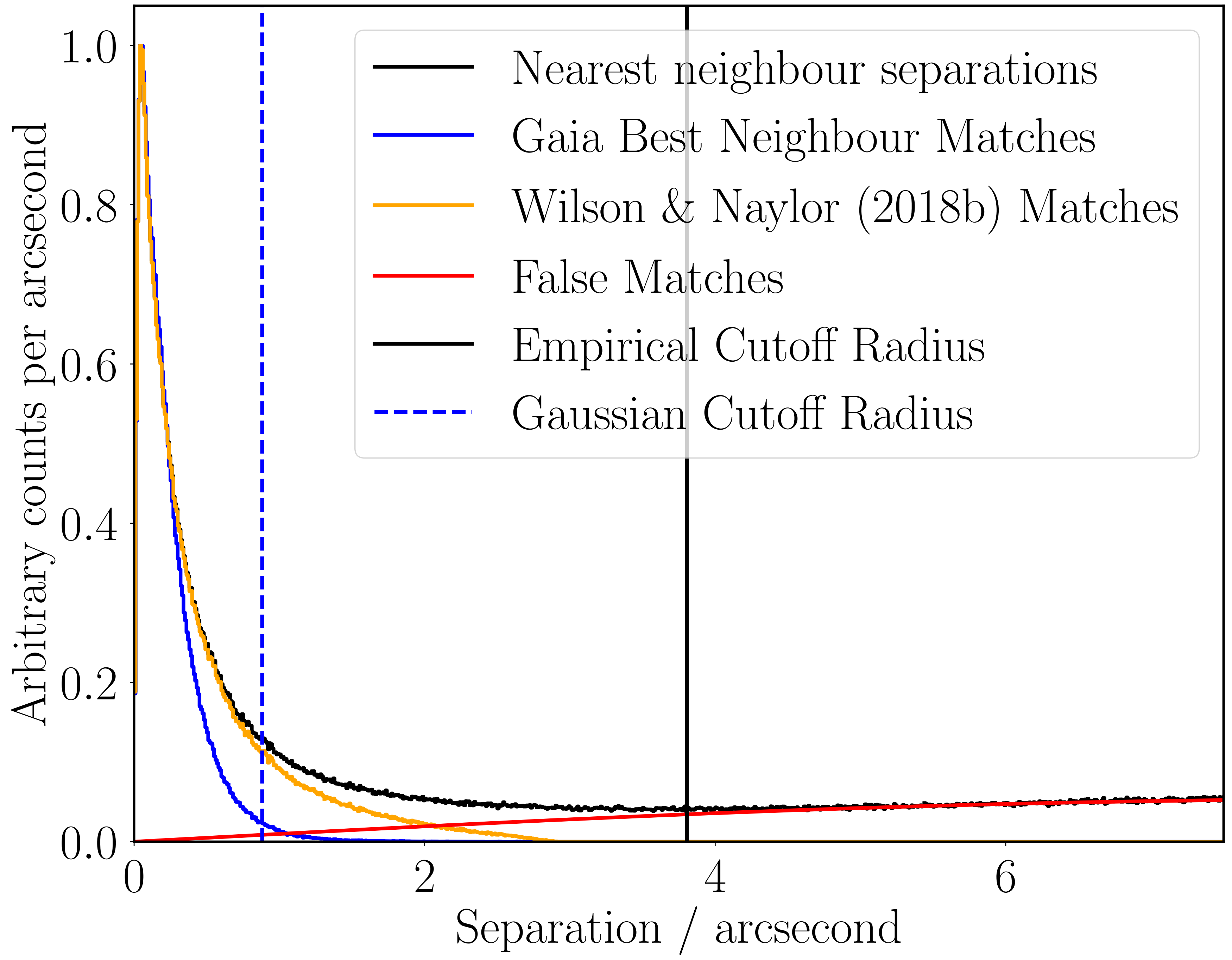
We will provide two match runs per catalogue pair match: one with, and one without, the photometry considered, to allow for the recovery of sources with “weird” colours but otherwise agreeable astrometry

Why Use Our Cross-Matches?

- **Getting cross-matches, even for "well behaved" fields**
- **Finding "odd" objects, either using the inclusion vs non-inclusion of the photometry in the two match runs, or via the likelihood ratio space — planned "real time" matching service for transient objects**
- **Removing e.g. IR excess or correcting for extinction-like crowding brightening, through Average Contamination; crucial for removing completely unknown crowding of catalogues using aperture photometry**
- **Recovering additional sources missed by other match services — either in crowded fields (we recover up to twice as many *Gaia-WISE* matches than the *Gaia* best neighbour matches), or with our in-progress extension to unknown proper motion modelling**







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Conclusions

- **Upcoming LSST:UK cross-match service macauff — let me know your thoughts/needs/hopes/dreams**
    - **Provide tables of cross-matches between LSST and <your favourite catalogue here!>**

- Our cross-matches include two key elements for avoiding issues with the crowded LSST sky
    - A generalised approach to the Astrometric Uncertainty Function allows for the inclusion of the effects of perturbation due to blended sources and unknown proper motions — reduce false -ves!
    - Use of the photometry of sources allows for the rejection of false matches (with >1 "extra" source per 2 arcsecond circle in most of the LSST Galactic plane) — reduce false +ves!
- Will include additional information on the crowding of sources, allowing for selection of uncontaminated objects, or modelling of excess flux — crucial for removal of red excess in SEDs
    - LSST will suffer of order 10% flux contamination, which could be confused with extinction

- **macauff cross-match tools are being extended currently**
    - **We will provide an easy-to-use "SED grabber" tool for each LSST source**
    - **And follow up the $\gtrsim$93% of non-matched Rubin objects to confirm flux upper limits in other surveys**

University of Exeter

@Onoddil@pm.me
@Onoddil.github.io

Wilson & Naylor, 2017, MNRAS, 468, 2517
Wilson & Naylor, 2018a, MNRAS, 473, 5570
Wilson & Naylor, 2018b, MNRAS, 481, 2148
Wilson, 2022, RNAAS, 6, 60
Wilson, 2023, RASTI, 2, 1

https://github.com/Onoddil/macauff

LSST:UK Consortium

Science and Technology Facilities Council

Macauff

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