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

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Science and Technology Facilities Council

LSST@Europe4, 26/Oct/22

University of Exeter

LSST:UK Consortium

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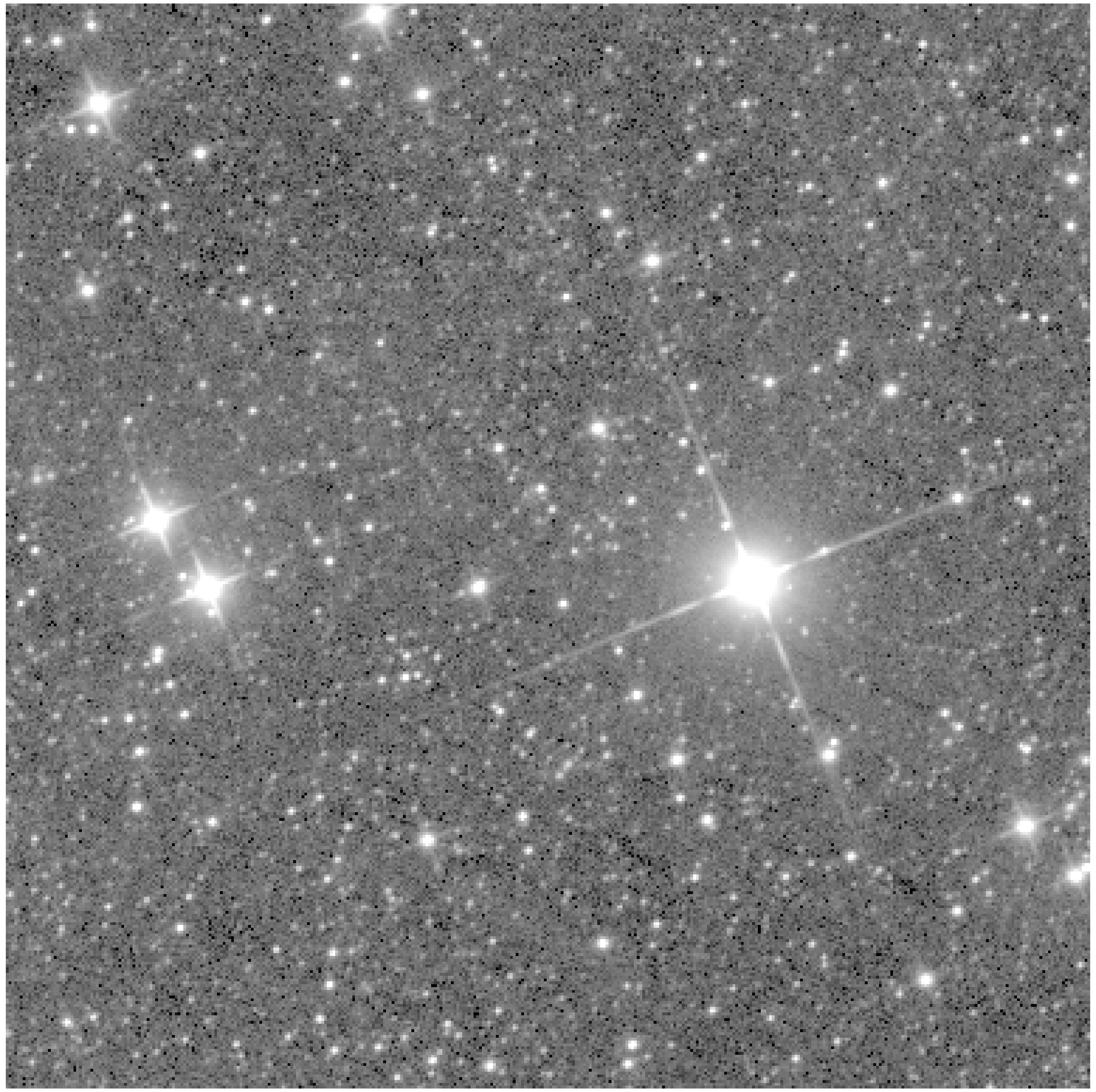
Photometric Observations



WISE - Wright et al. (2010)

WISE W1

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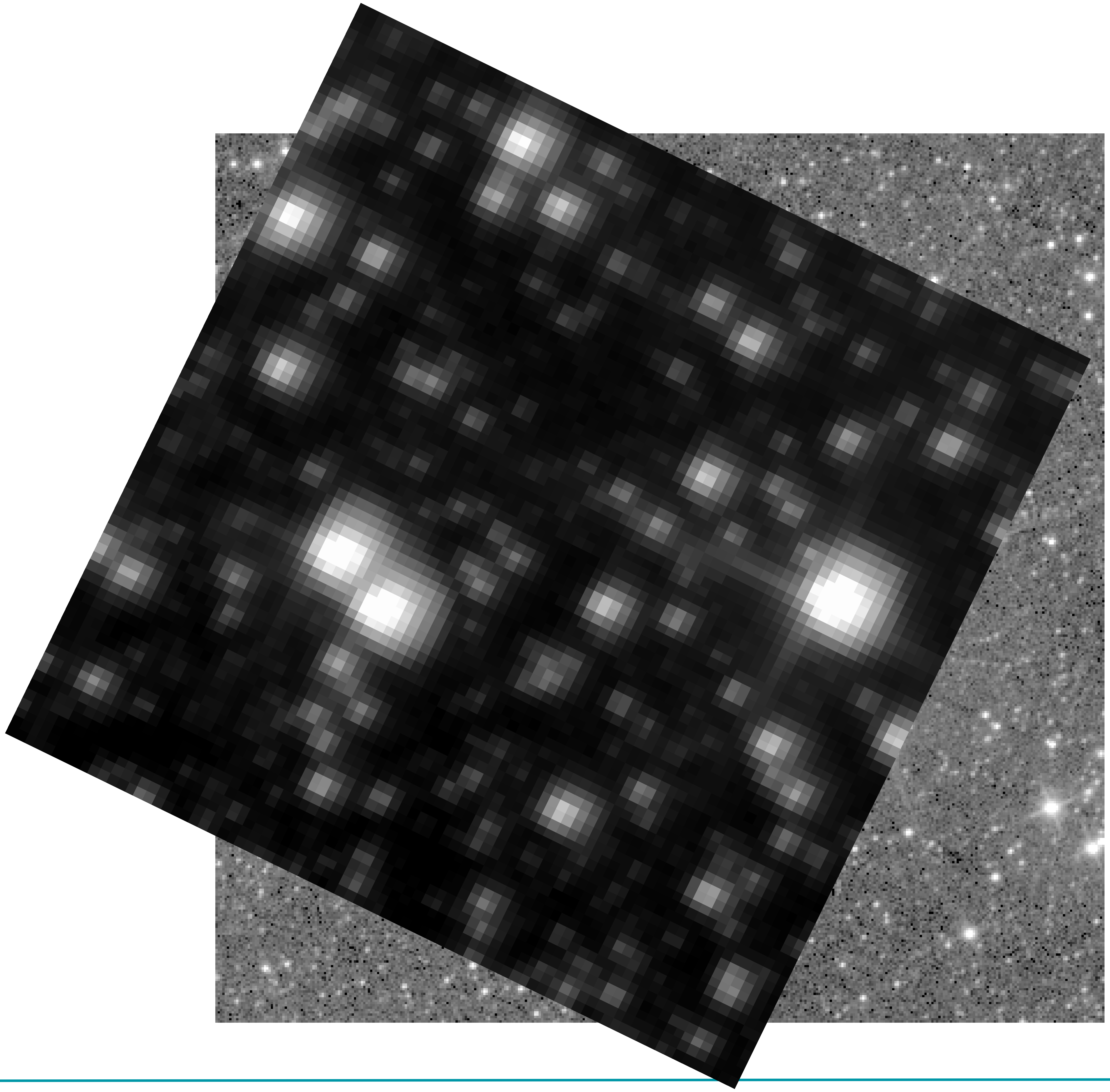
Photometric Observations



WISE - Wright et al. (2010)
TESS - Ricker et al. (2015)

TESS T

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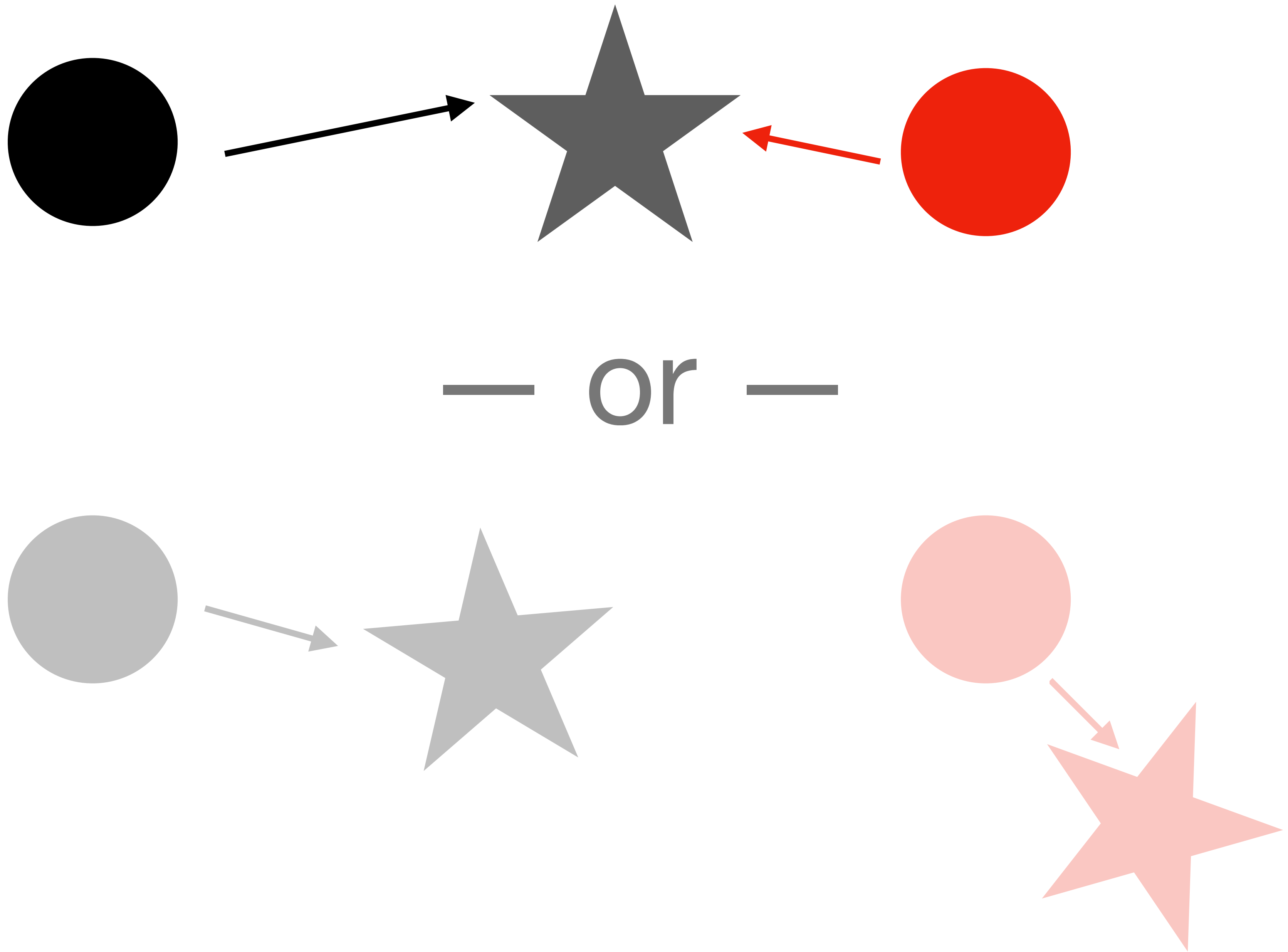
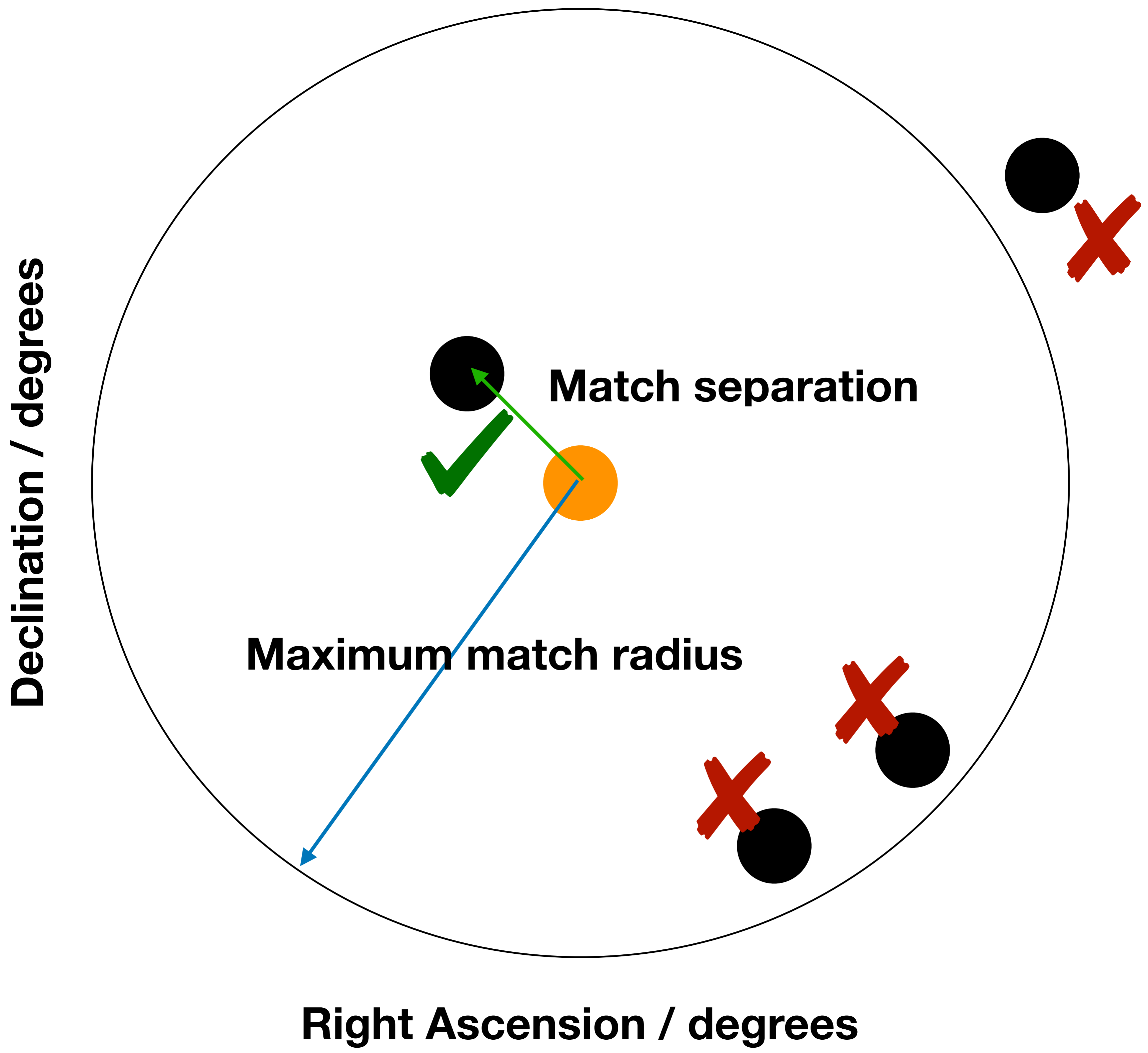
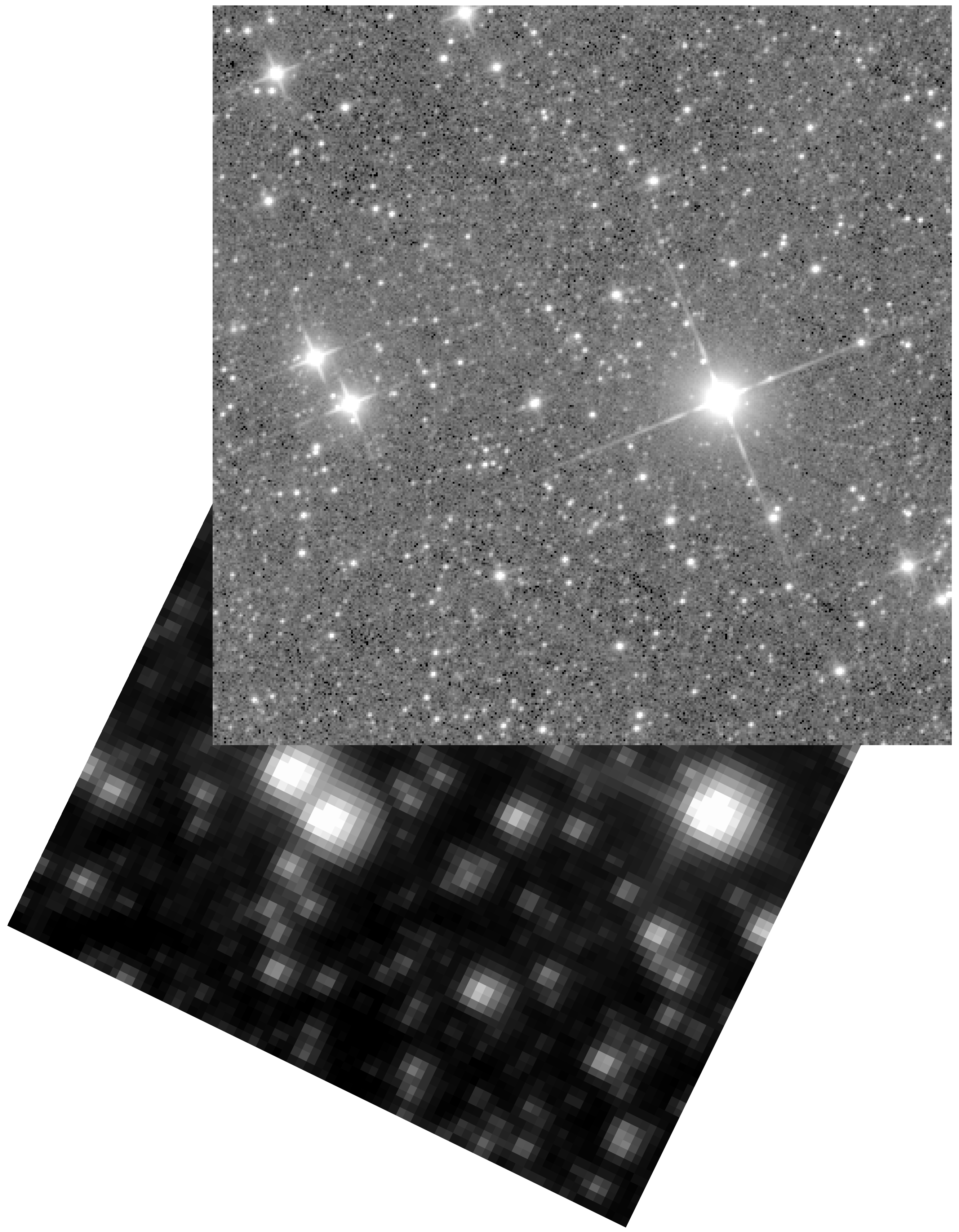
“Simple” Cross-Matching







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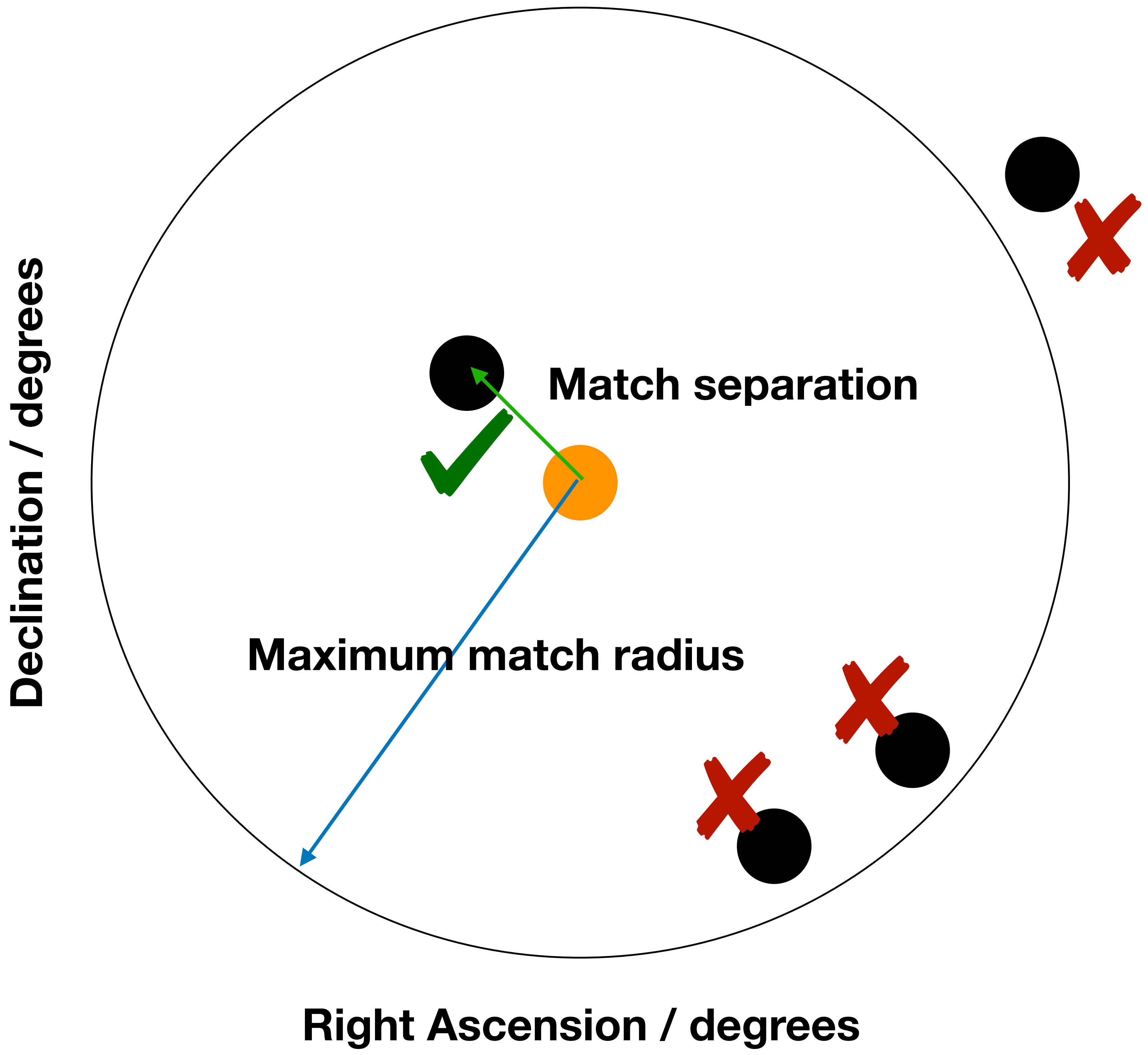
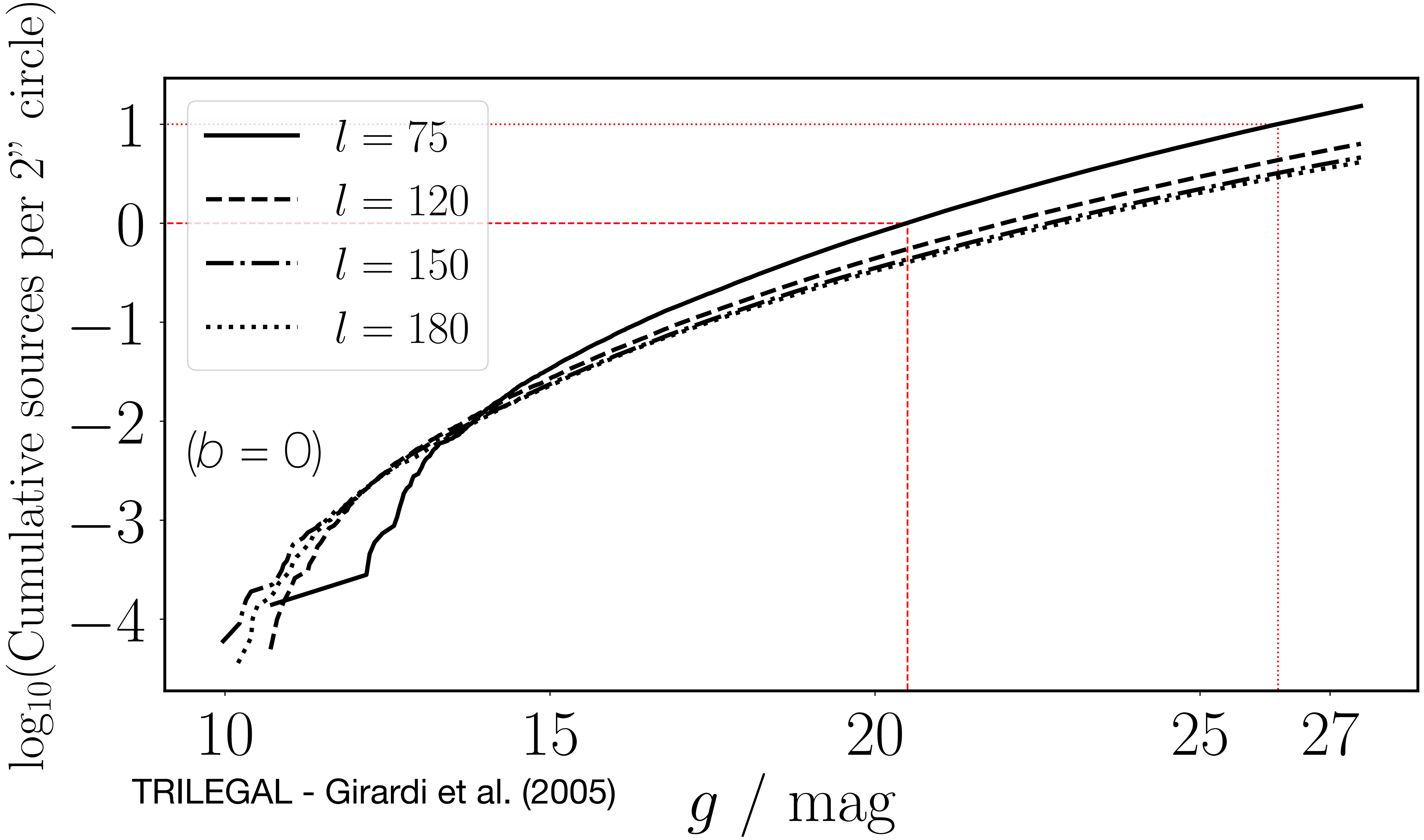
The Problem With Vera C. Rubin Obs.'s LSST





TRILEGAL - Girardi et al. (2005)

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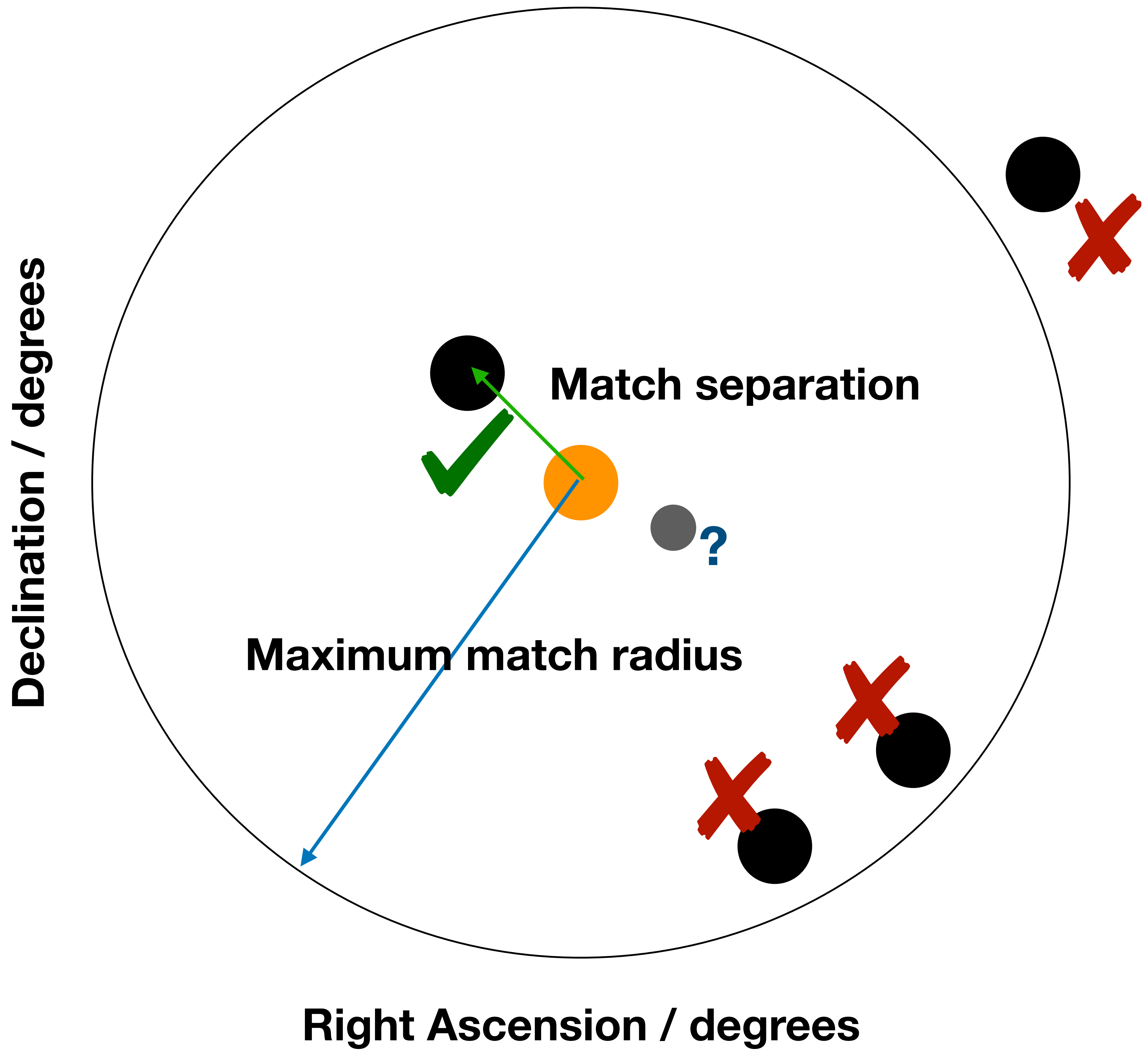

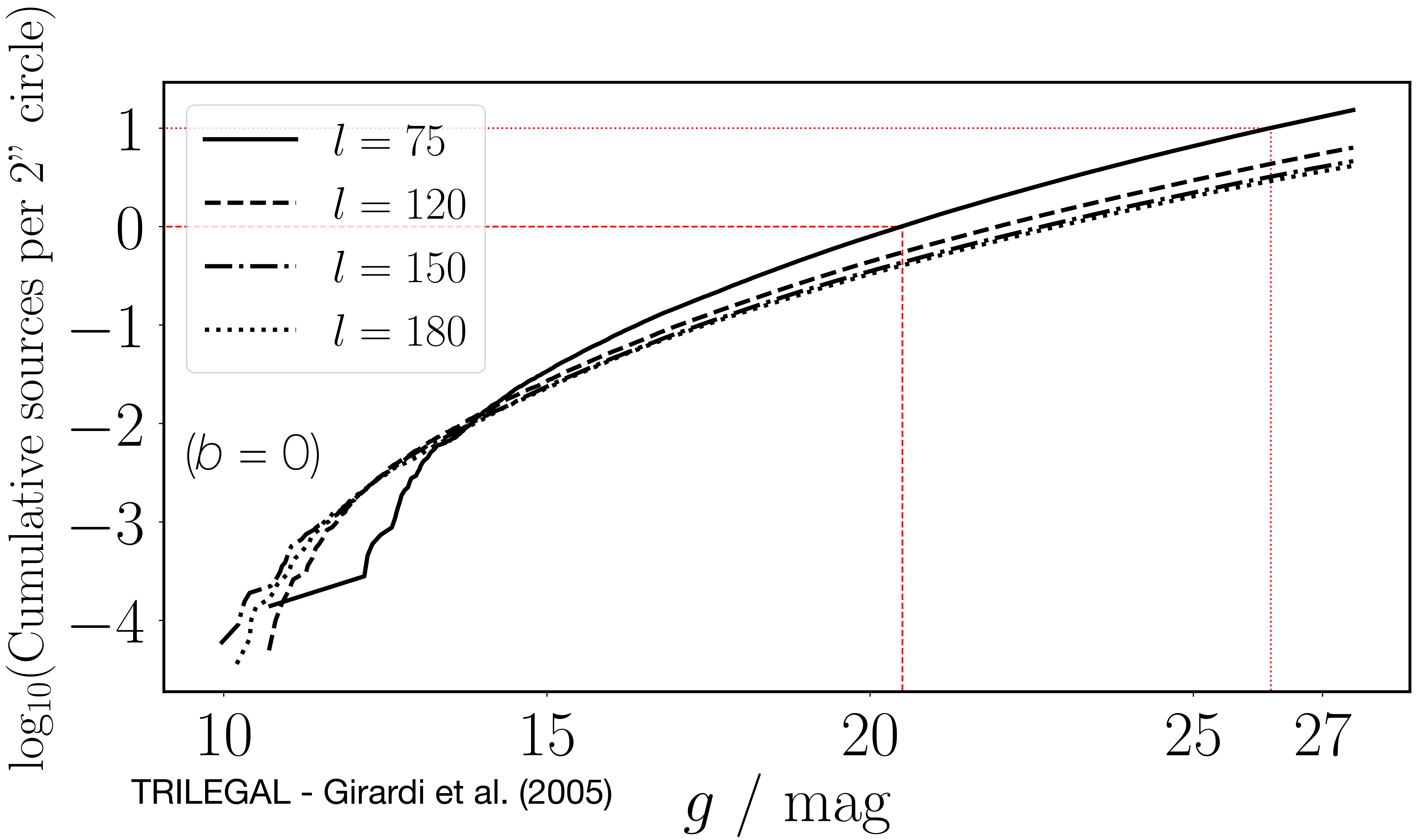

TRILEGAL - Girardi et al. (2005)

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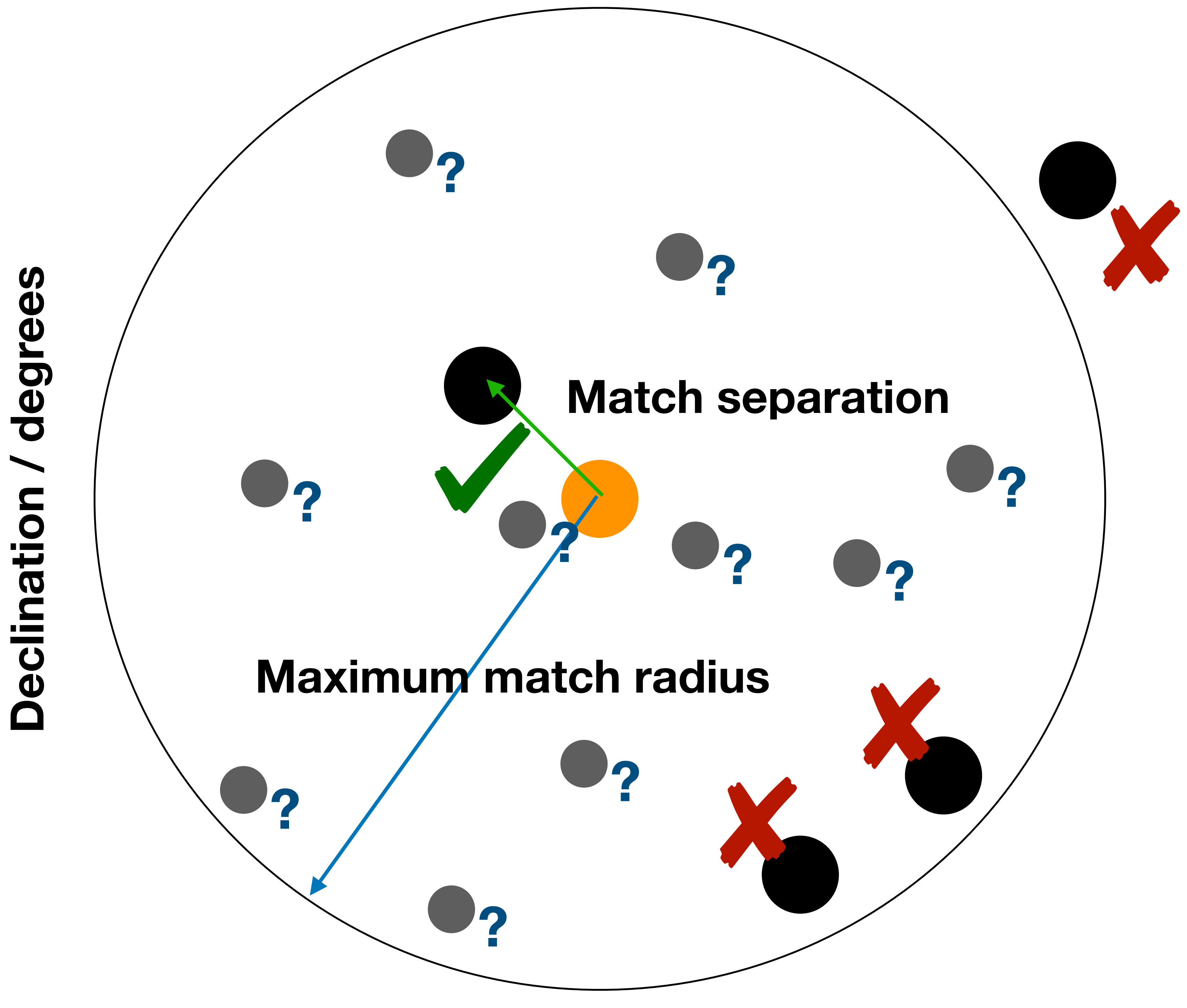
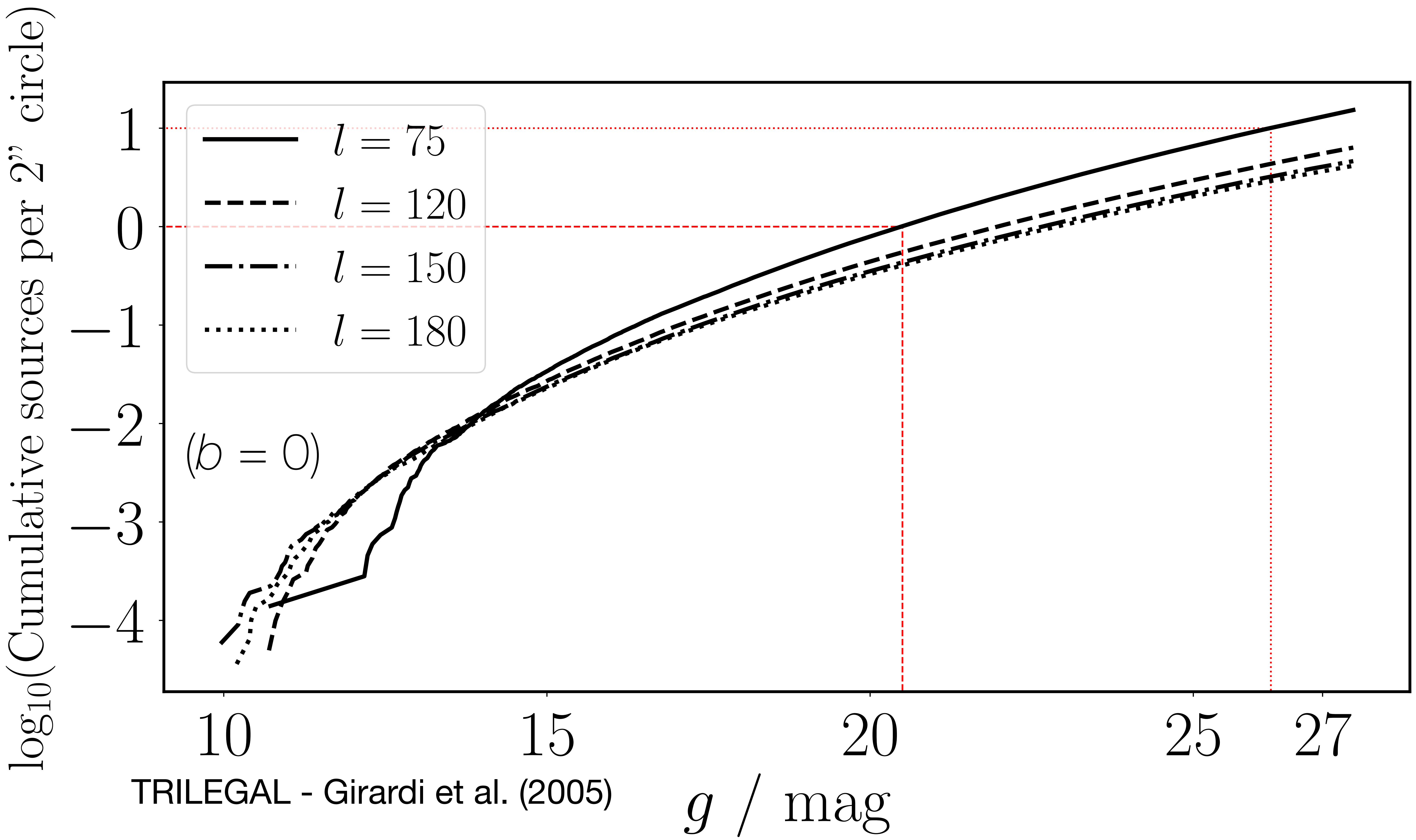
The Problem With Vera C. Rubin Obs.'s LSST





TRILEGAL - Girardi et al. (2005)

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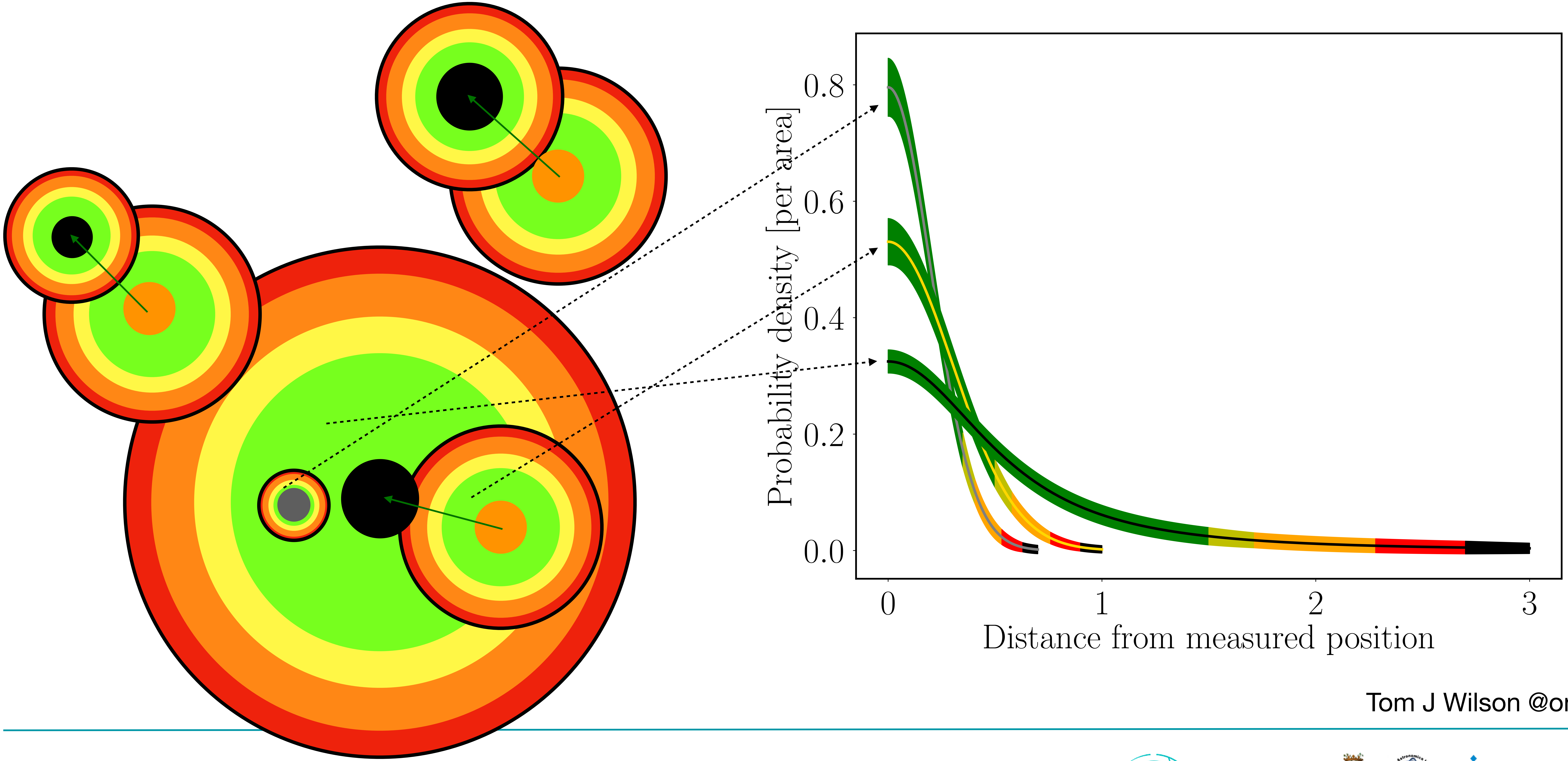
Probabilistic Cross-Matching



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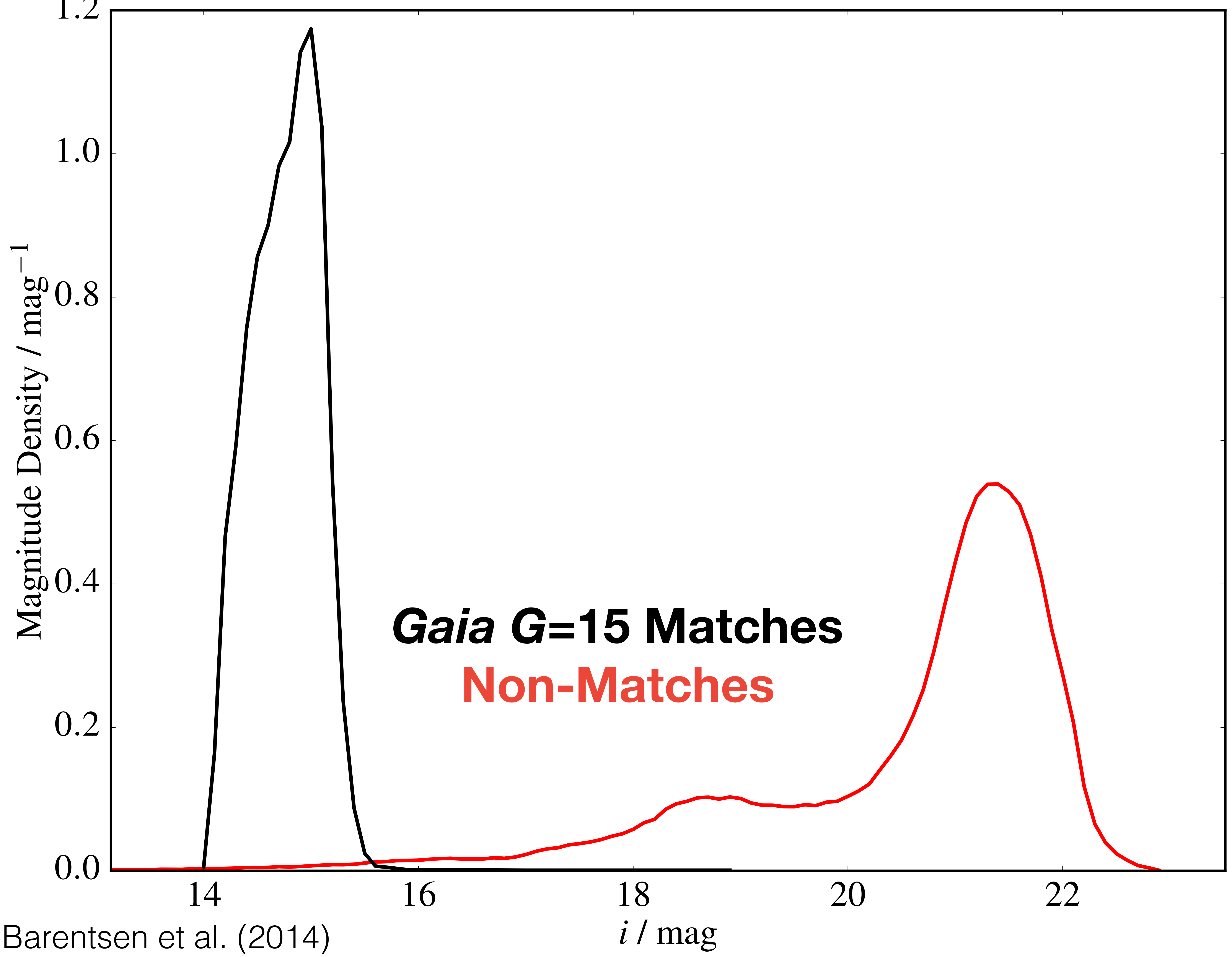
Including Magnitude Information



IPHAS - Barentsen et al. (2014)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

The photometry-based likelihoods (c and f) allow us to mitigate high false positive rate in crowded fields

Wilson & Naylor (2018a)

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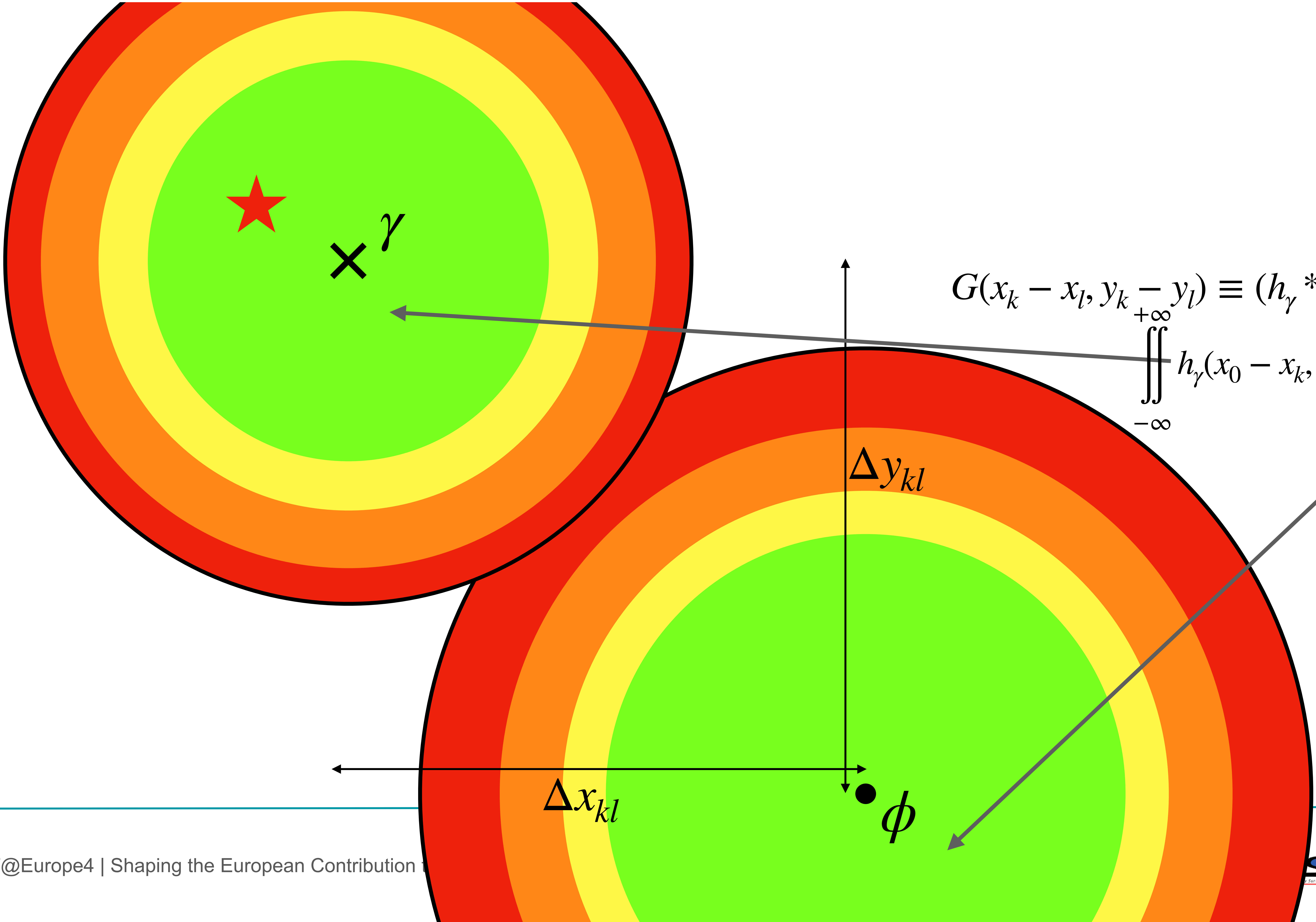
Match Separation Probability



$$G(x_k - x_l, y_k - y_l) \equiv (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl}) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

Wilson & Naylor (2018a)

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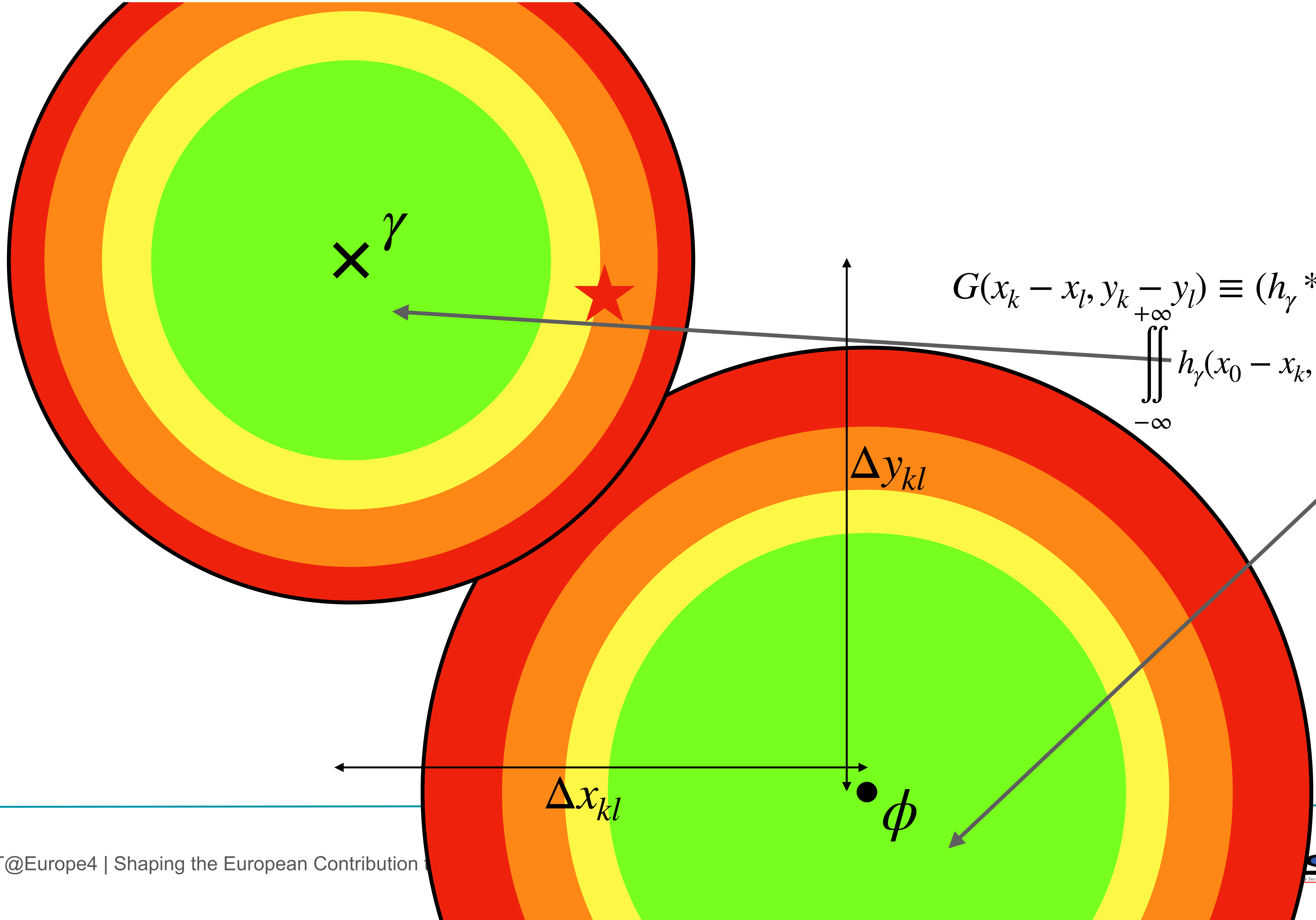
Match Separation Probability



$$G(x_k - x_l, y_k - y_l) \equiv (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl}) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

Wilson & Naylor (2018a)

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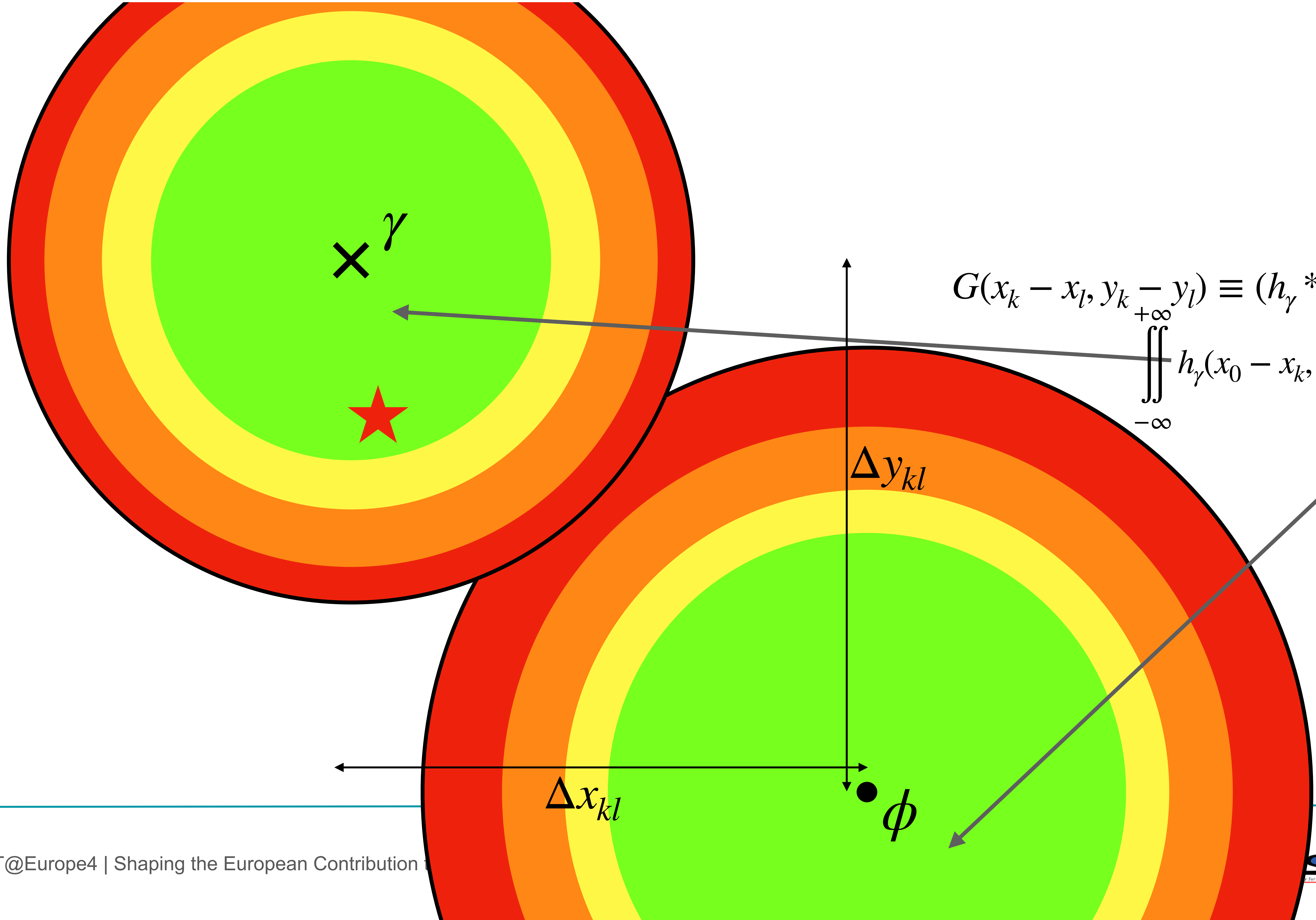

$$G(x_k - x_l, y_k - y_l) \equiv (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl}) =$$
$$\iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

Wilson & Naylor (2018a)

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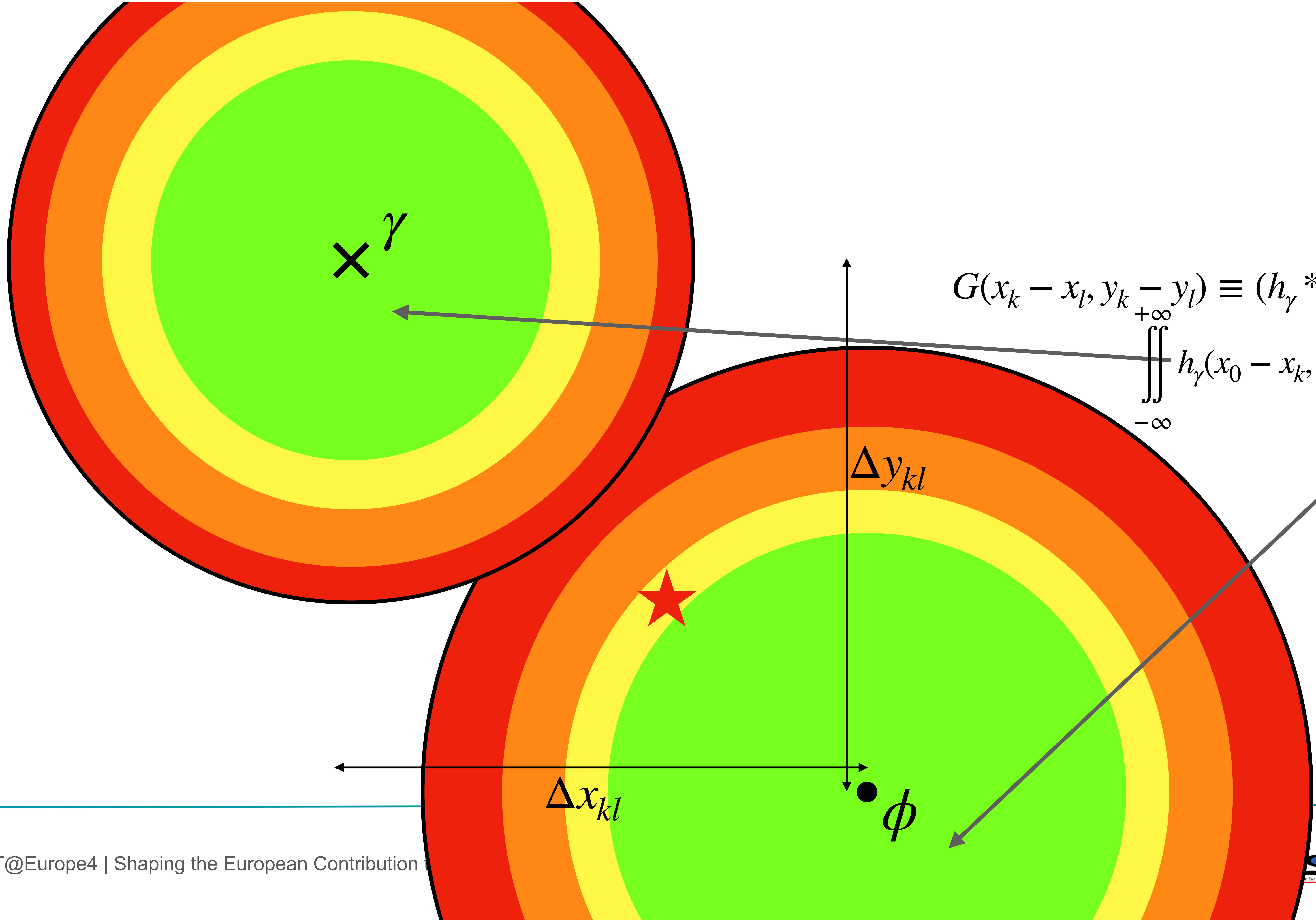

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Wilson & Naylor (2018a)

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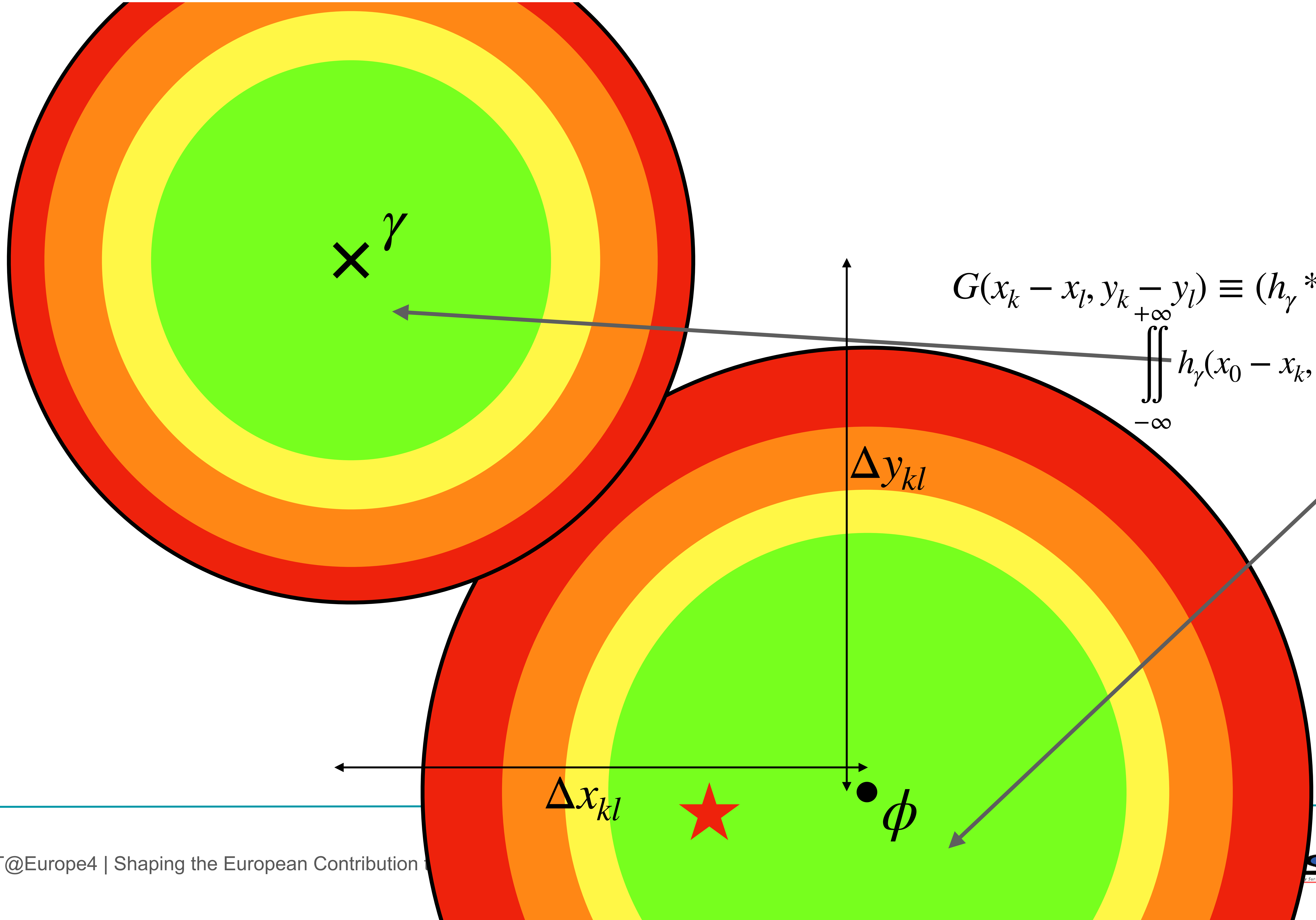
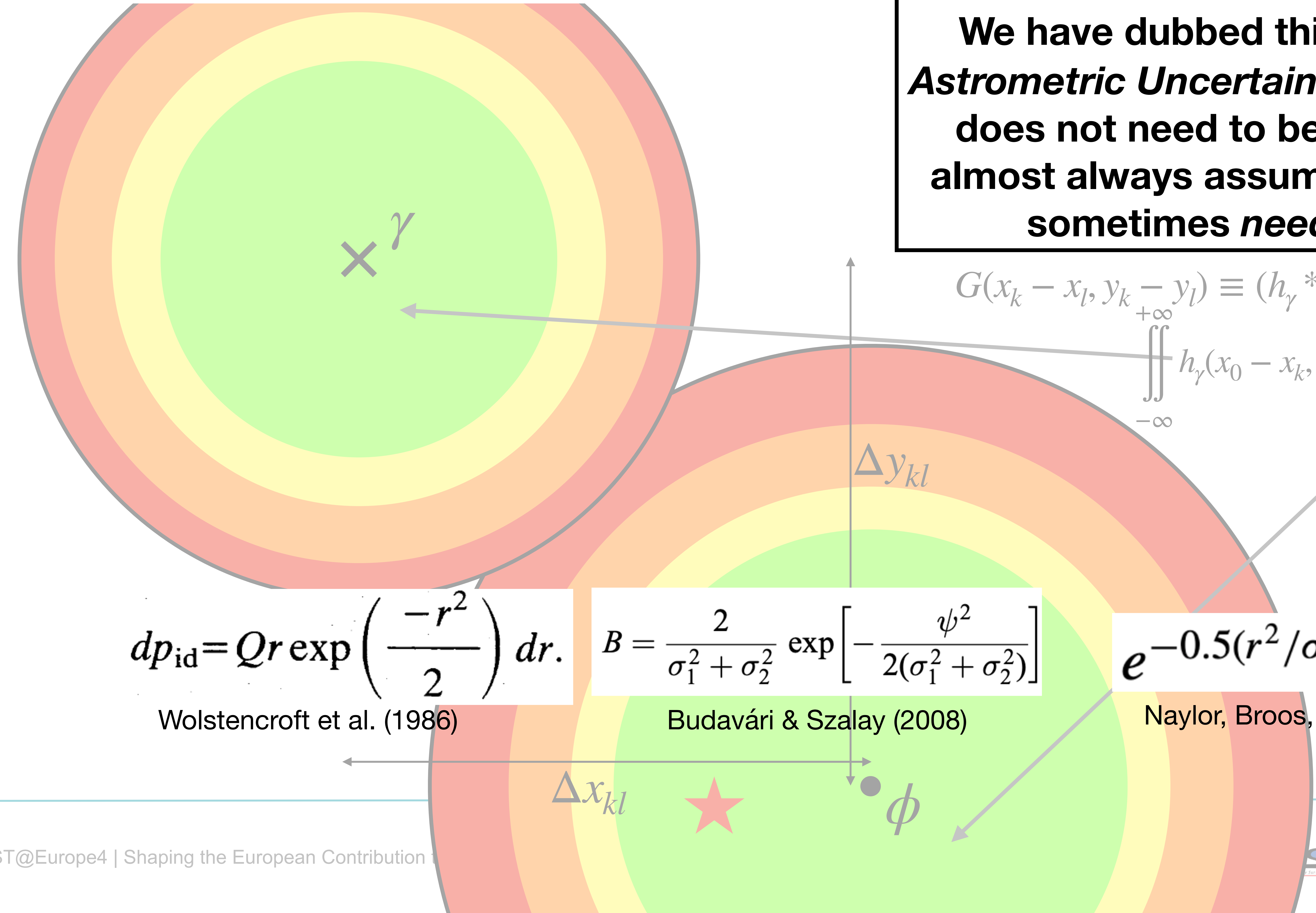


$$G(x_k - x_l, y_k - y_l) \equiv (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl}) = \iint\limits_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

Wilson & Naylor (2018a)

Match Separation Probability

We have dubbed this function h the *Astrometric Uncertainty Function,* which does not need to be Gaussian, as is almost always assumed — and indeed sometimes *needs* not to be!



$$G(x_k - x_l, y_k - y_l) \equiv (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl}) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

Wilson & Naylor (2018a)

$$dp_{\text{id}} = Qr \exp\left(\frac{-r^2}{2}\right) dr.$$

Wolstencroft et al. (1986)

$$B = \frac{2}{\sigma_1^2 + \sigma_2^2} \exp\left[-\frac{\psi^2}{2(\sigma_1^2 + \sigma_2^2)}\right]$$

Budavári & Szalay (2008)

$$e^{-0.5(r^2/\sigma_{39}^2)}$$

Naylor, Broos, & Feigelson (2013)

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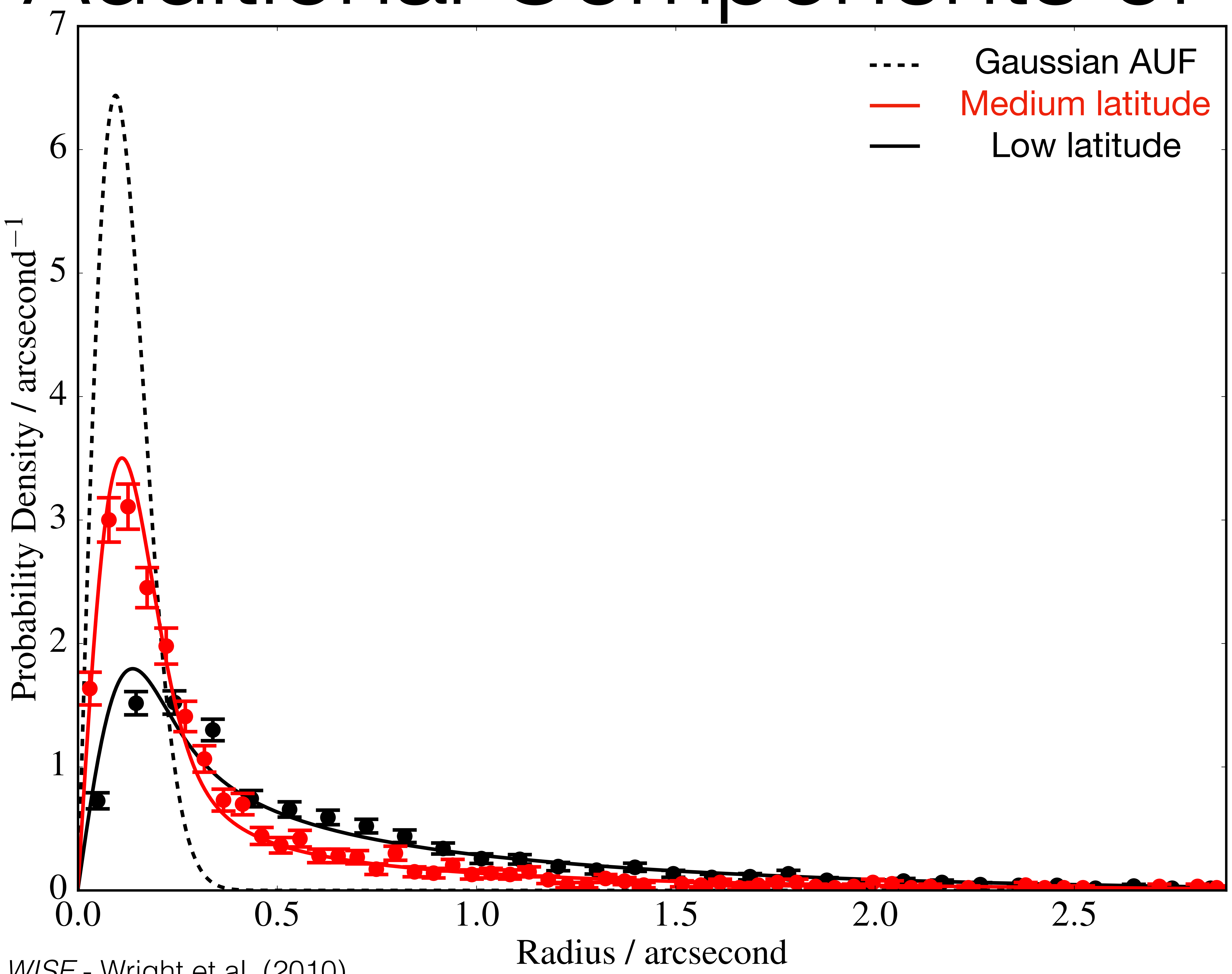
Additional Components of the AUF



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

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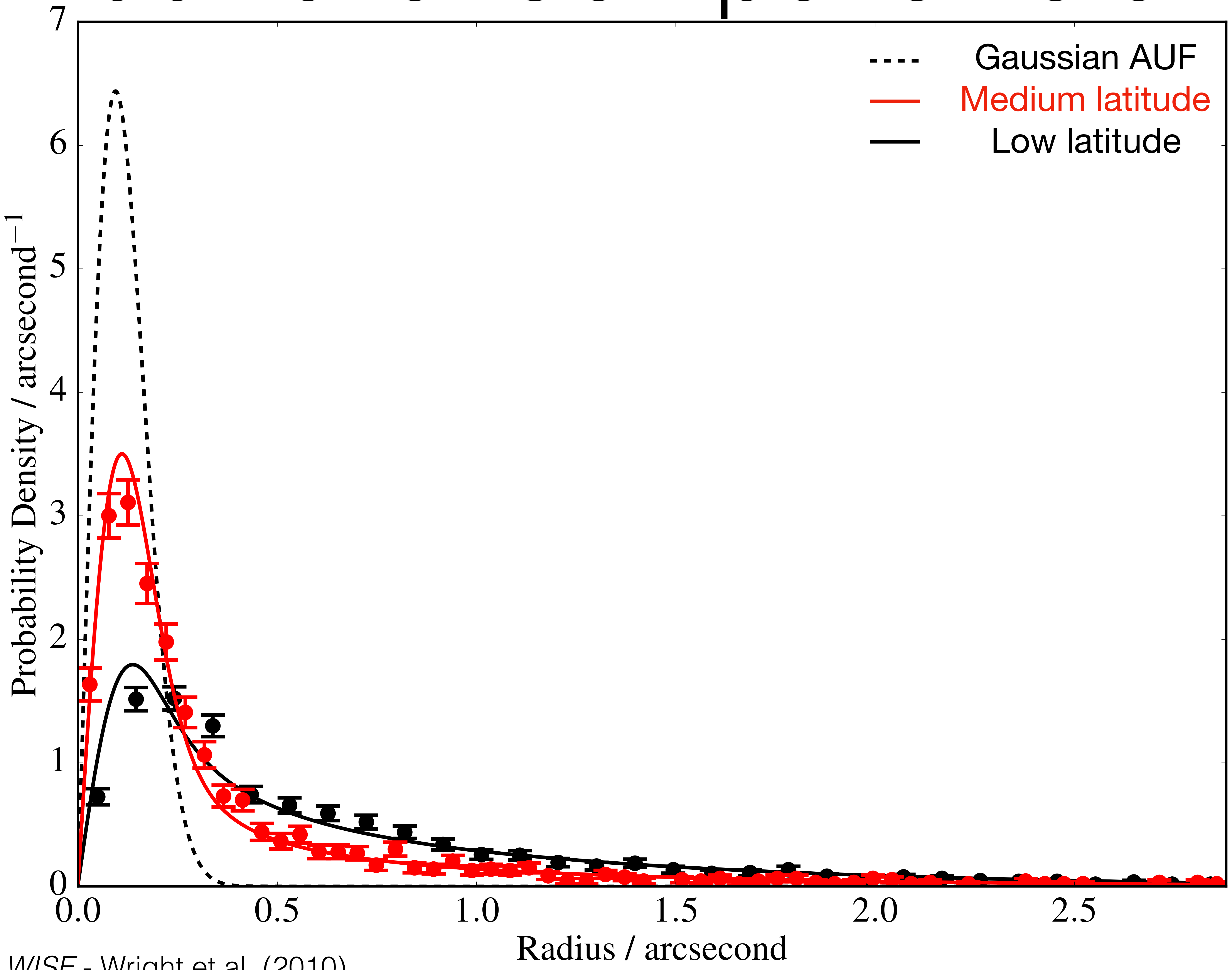
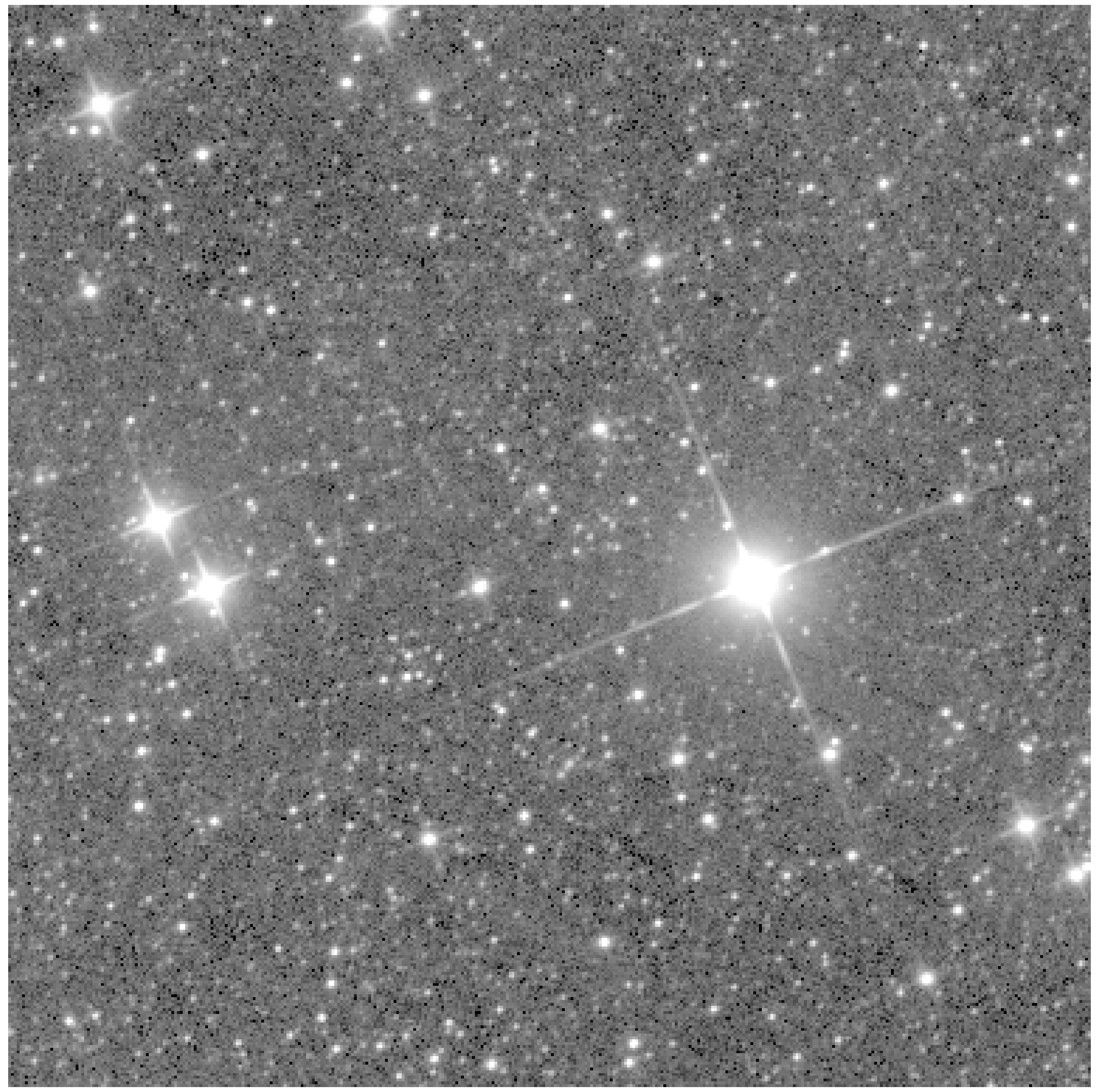
Additional Components of the AUF





WISE - Wright et al. (2010)
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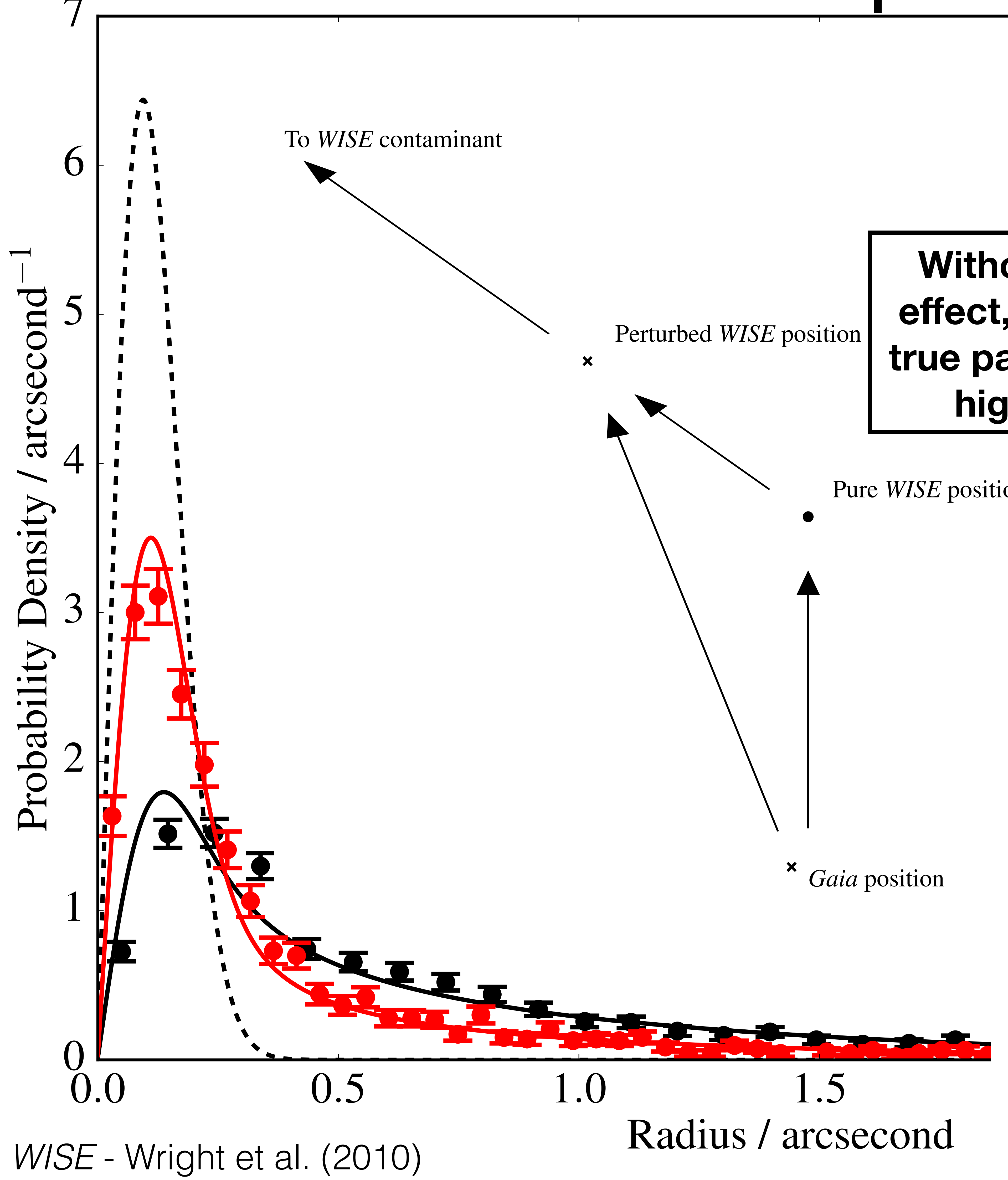
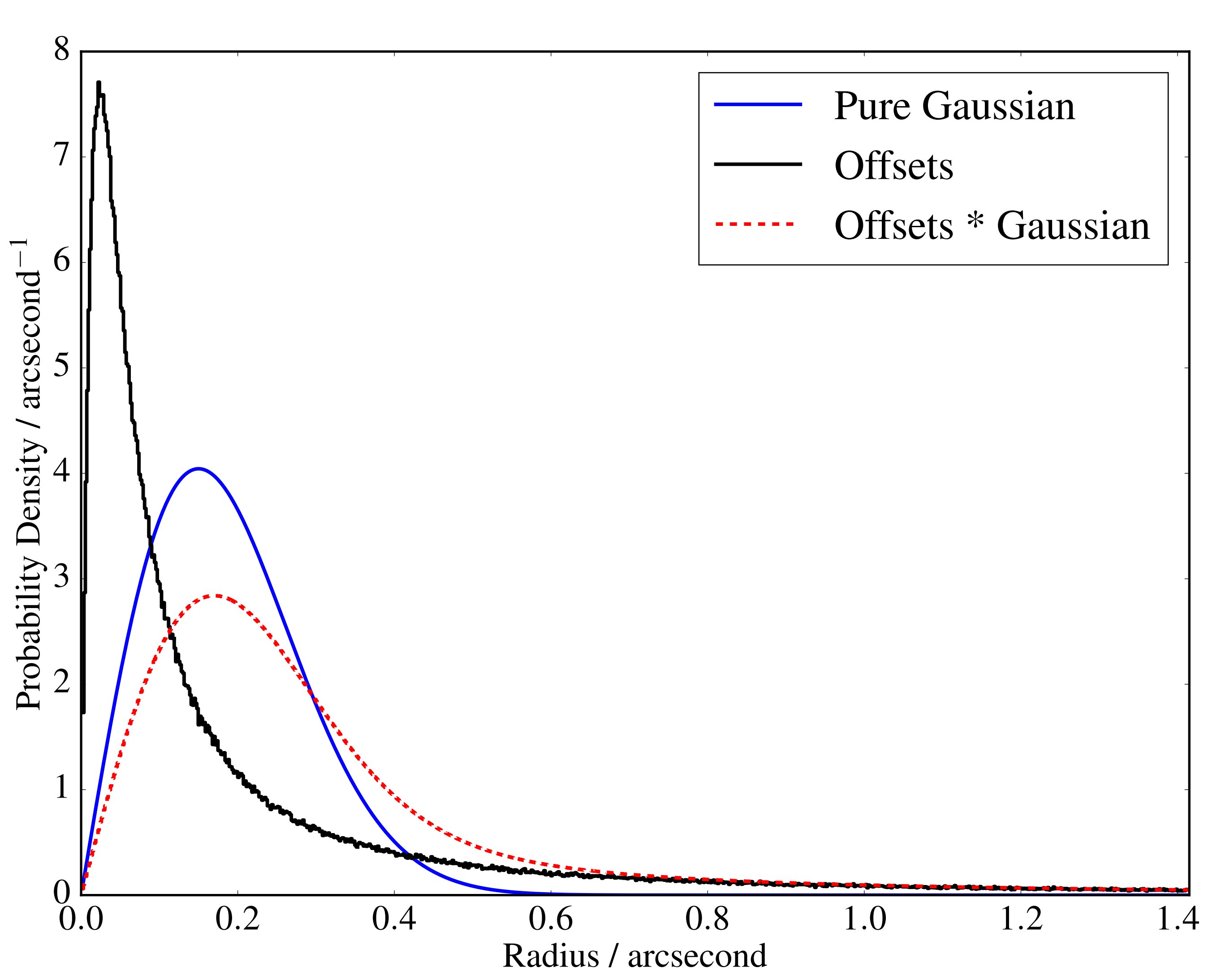
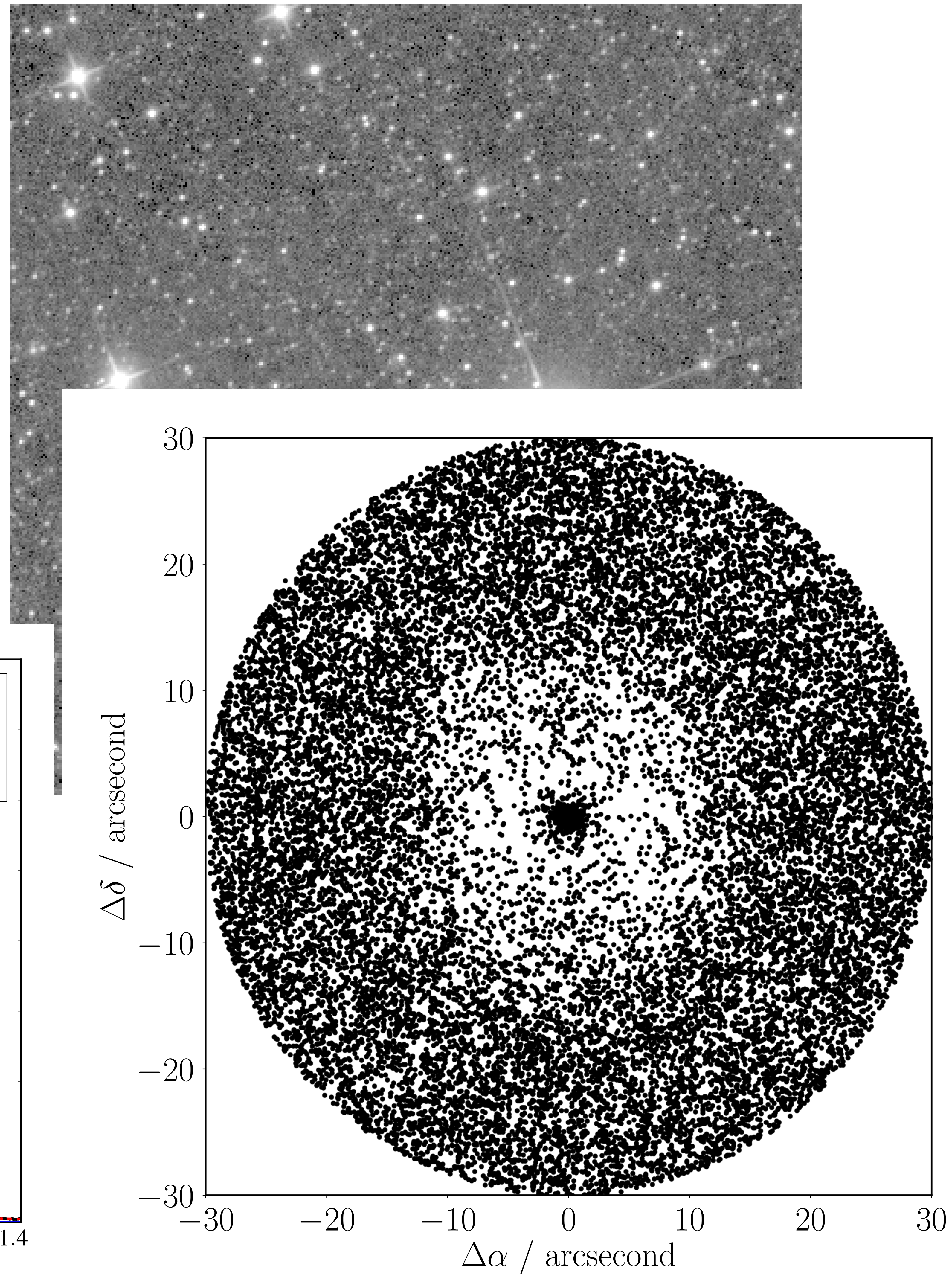


WISE - Wright et al. (2010)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)



Wilson & Naylor (2018b)



Wilson & Naylor (2017)

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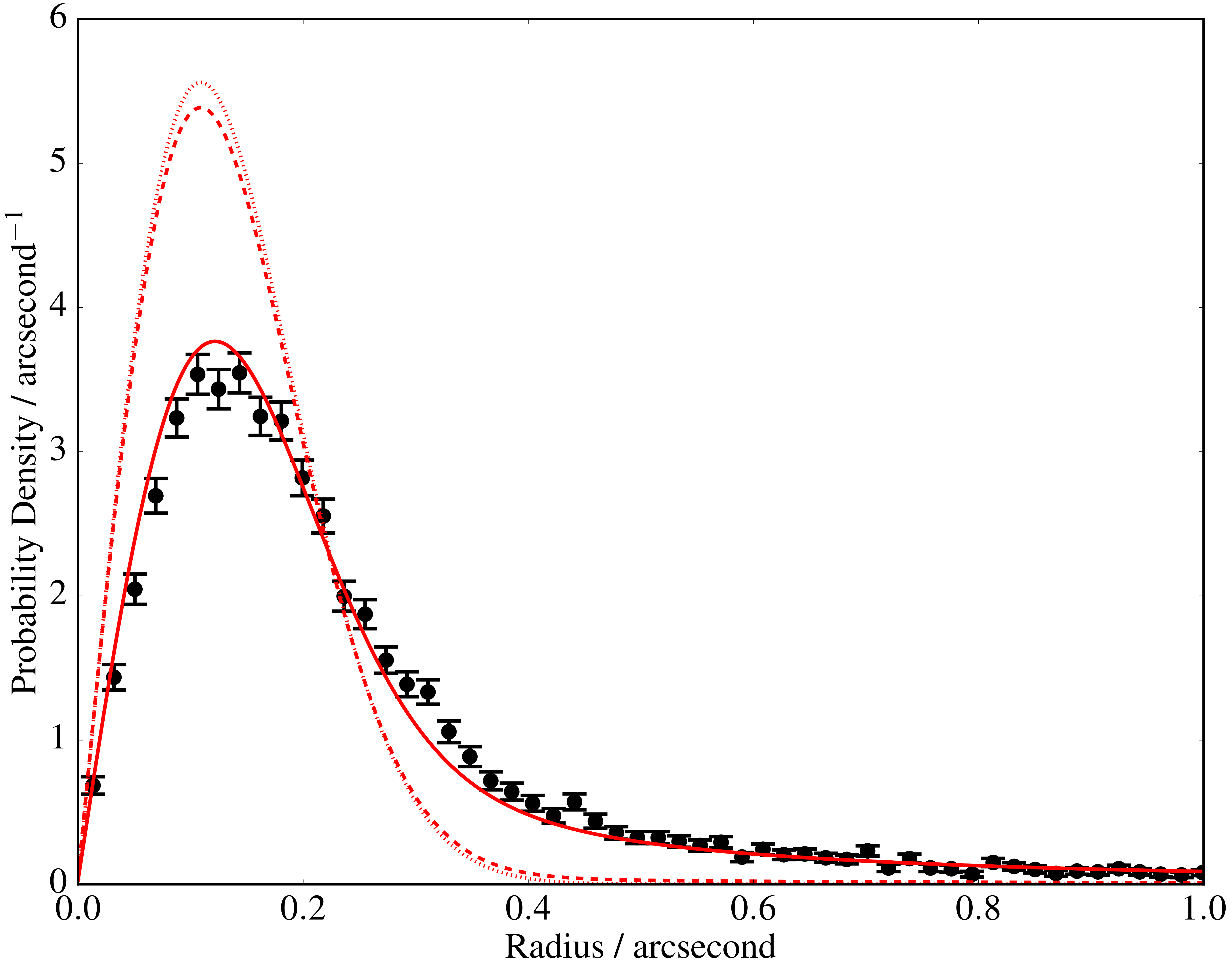
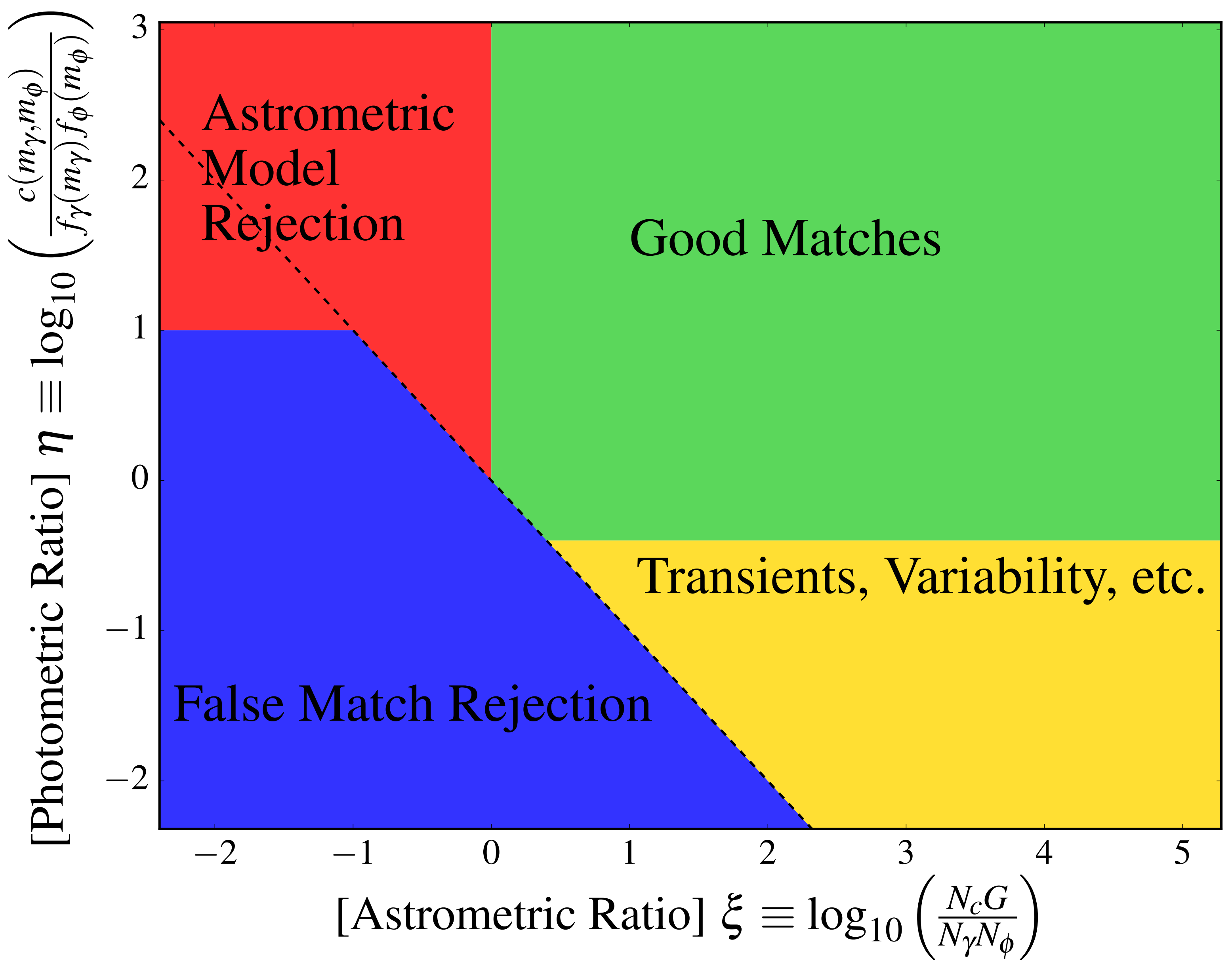
Extra-galactic Effects of Crowding



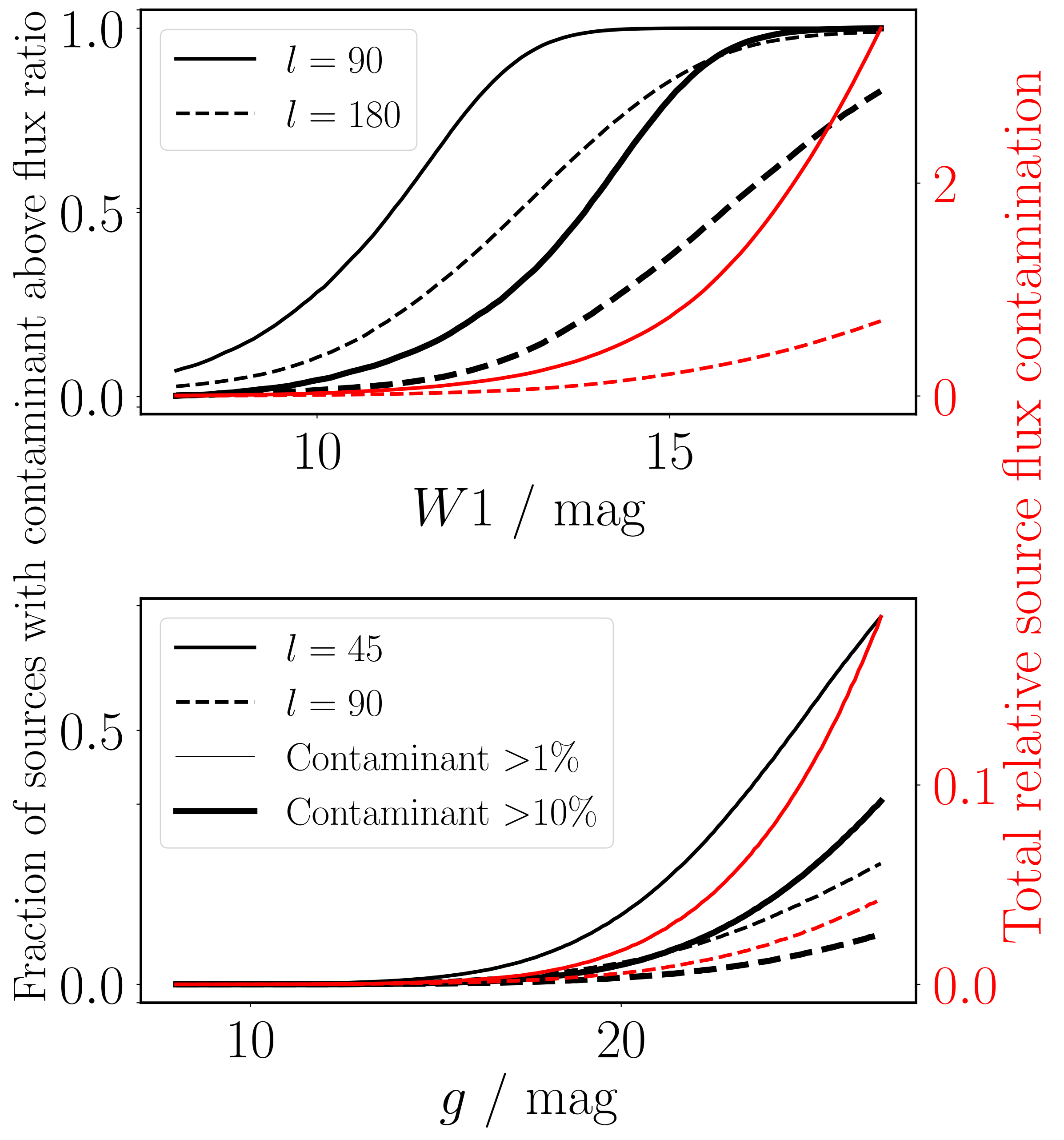
Wilson & Naylor (2018b); also see Wilson (2022, RNAAS)

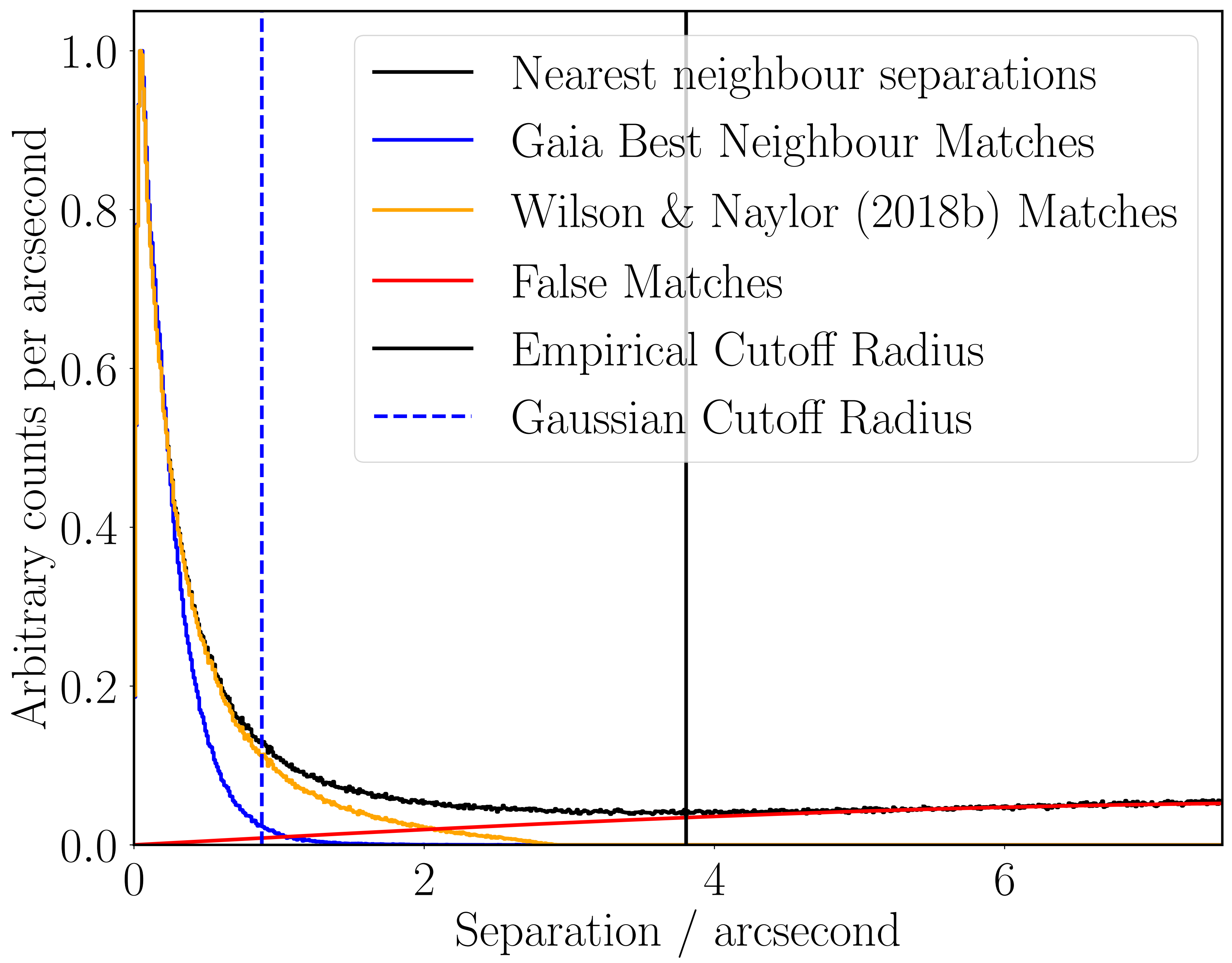
Why Use Our Cross-Matches?

- 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 from matching process; 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
- **We will provide a cross-match table service through the LSST:UK DAC**



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





Example columns from cross-match service:

- **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**
- **Re-derived “centroid” uncertainty, if necessary due to e.g. missing terms or measurement bias**
- **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

Conclusions

- **Upcoming LSST:UK cross-match service macauff — let me know your thoughts/needs/hopes/dreams**
    - **Provide *robust* 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 photometry of sources to reject of false interlopers (with >1 "extra" source per 2" circle in most of the LSST Galactic plane, and many spurious galactic matches) — 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 ~10% flux contamination, which could be confused with e.g. extinction, distance**

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LSST:UK Consortium

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Wilson & Naylor, 2017, MNRAS, 468, 2517
Wilson & Naylor, 2018a, MNRAS, 473, 5570
Wilson & Naylor, 2018b, MNRAS, 481, 2148
Wilson (2022, RNAAS)
Wilson (2022, RASTI, in review)

https://github.com/Onoddil/macauff

Macauff