(transient) Enhancing Rubin Science with Robust Cross-Matches in the Crowded LSST Sky

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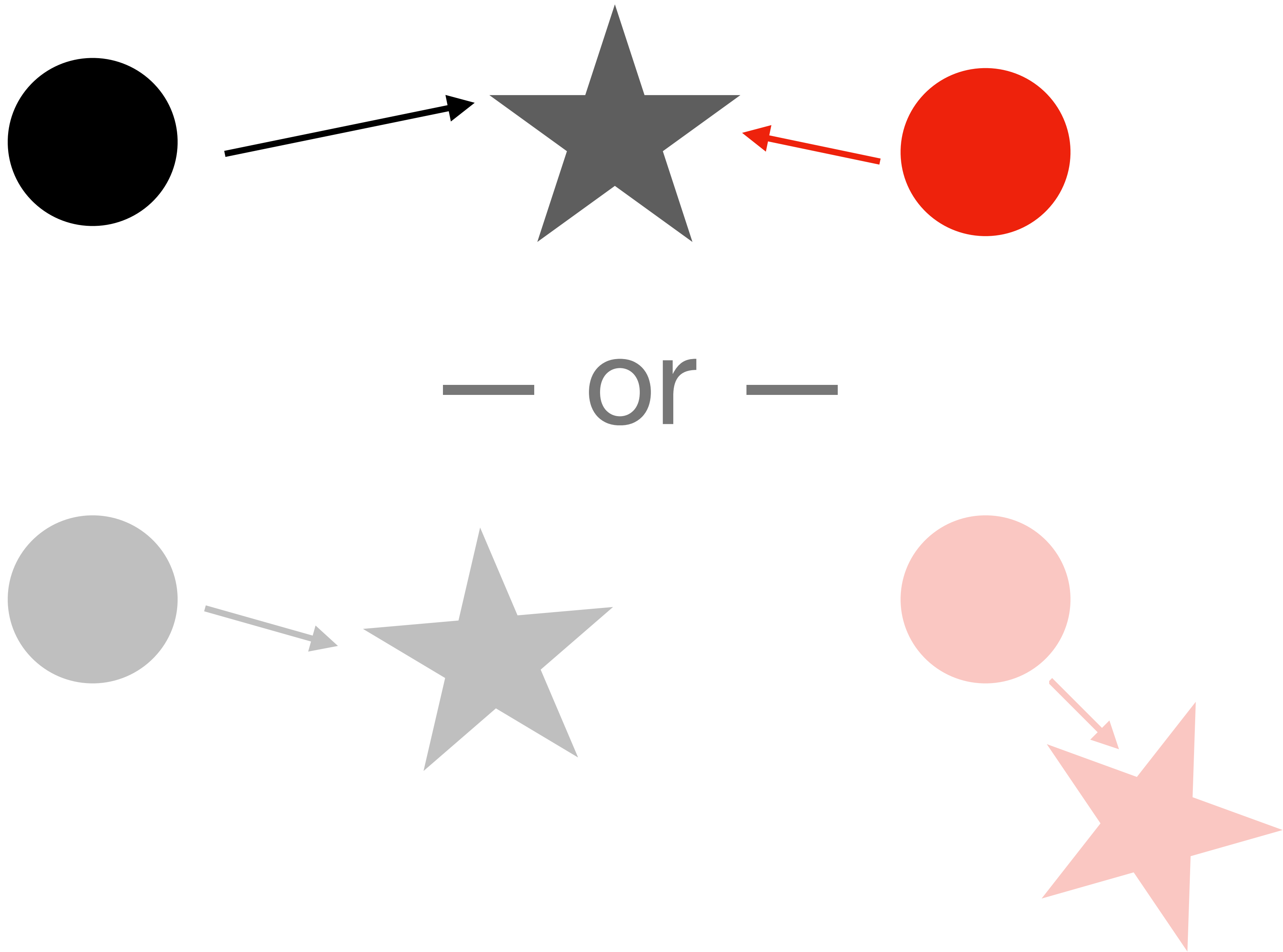
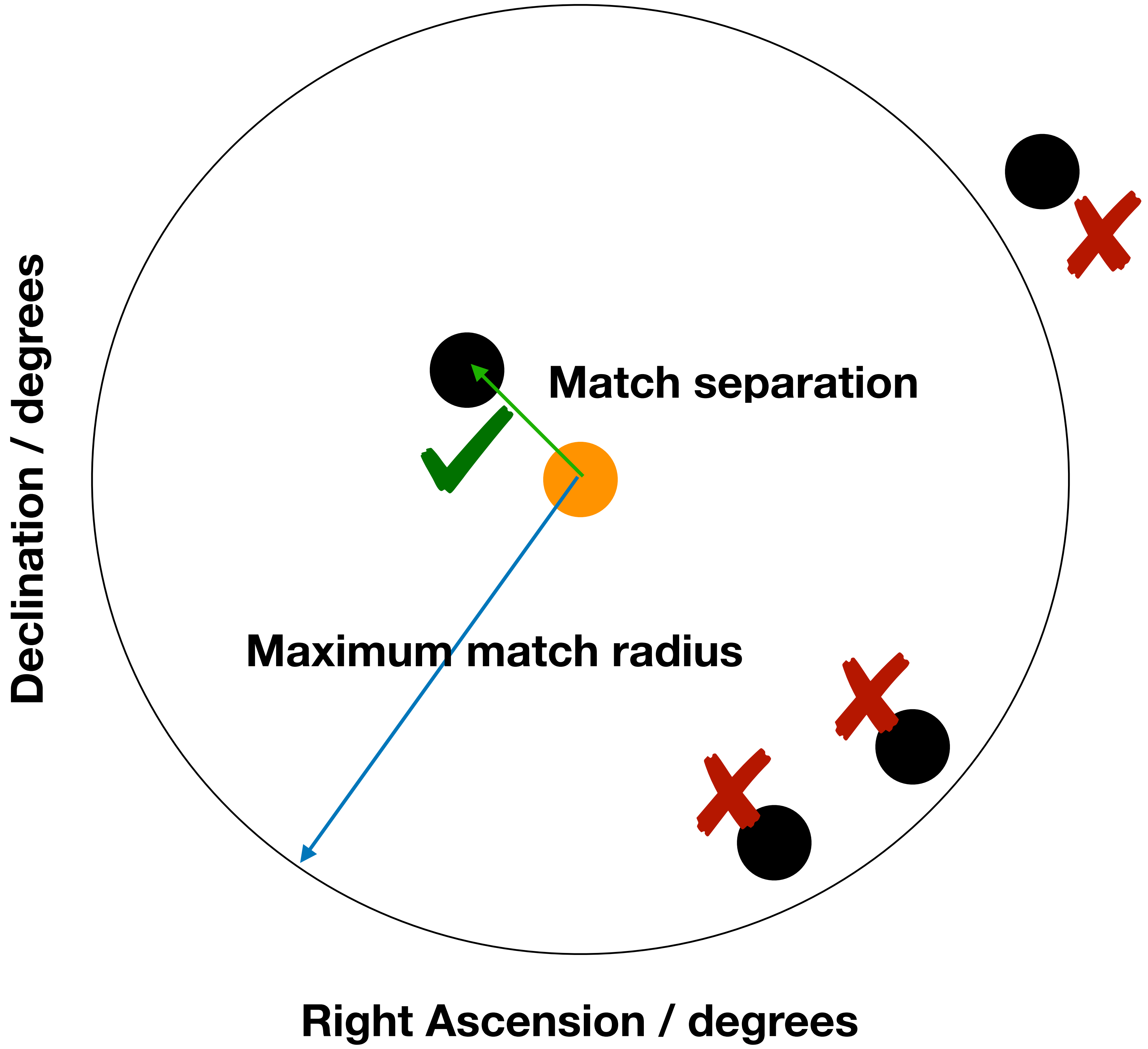
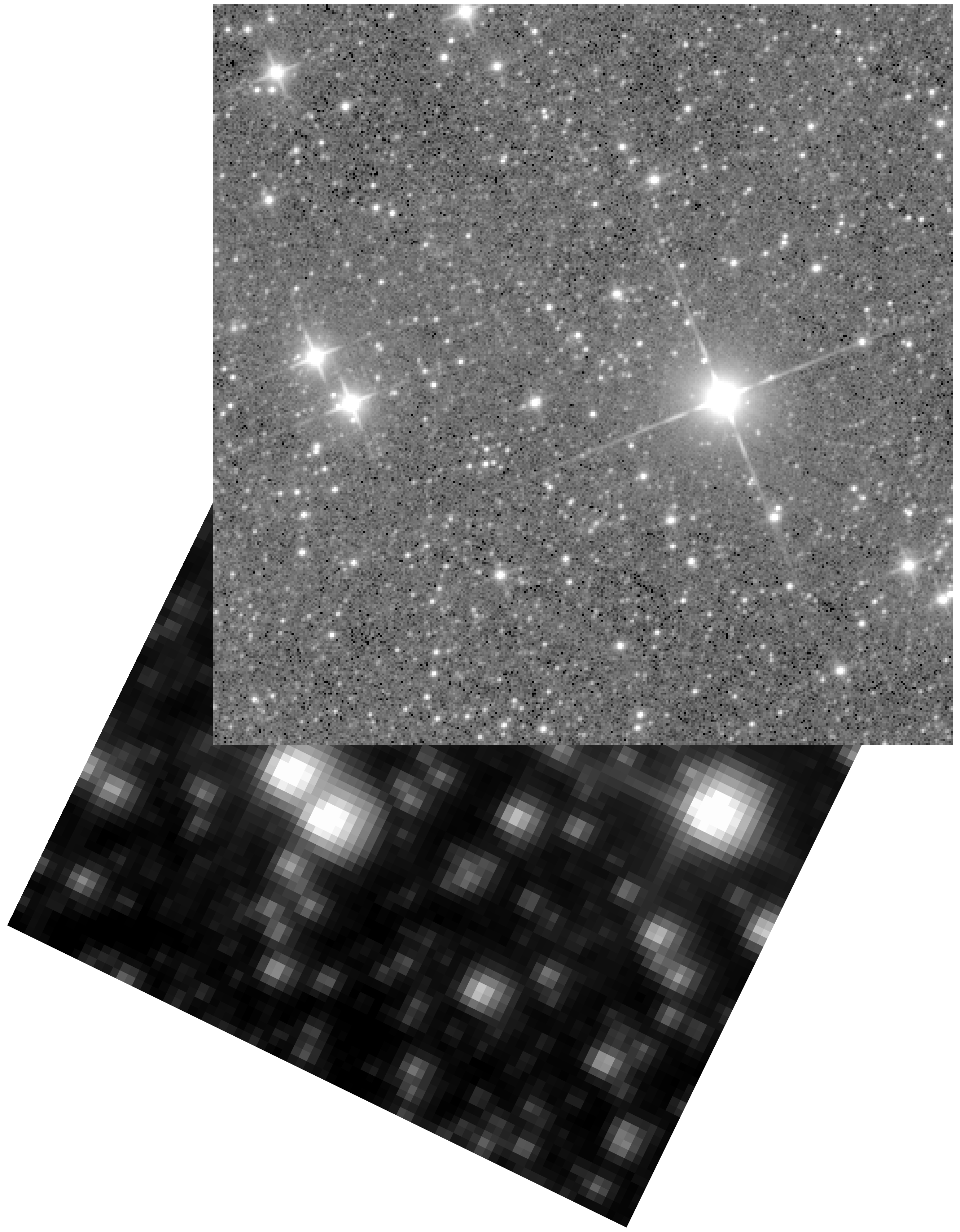
University of Exeter
LSST:UK Consortium
UKRI Science and Technology Facilities Council

“Simple” Cross-Matching







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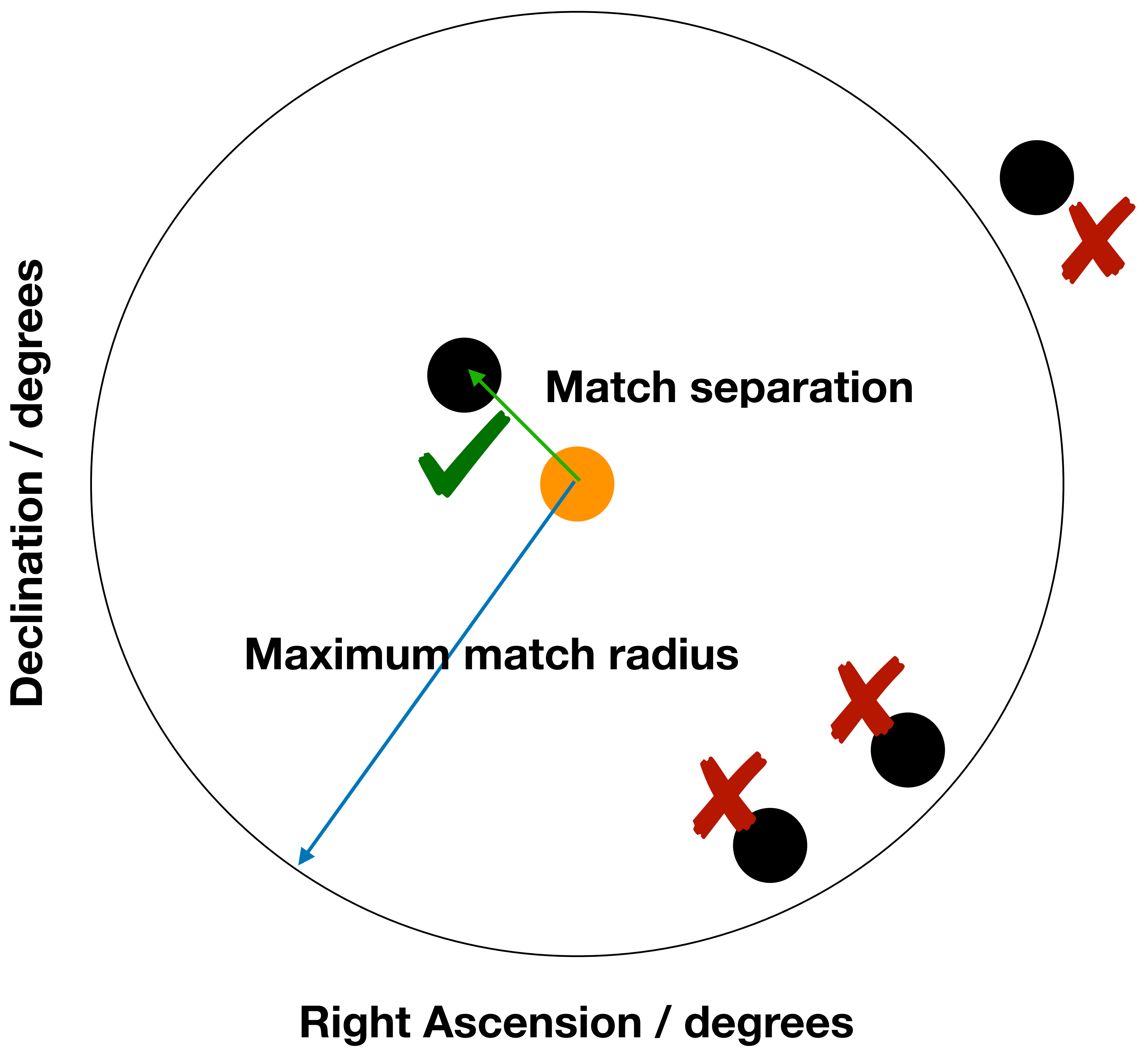
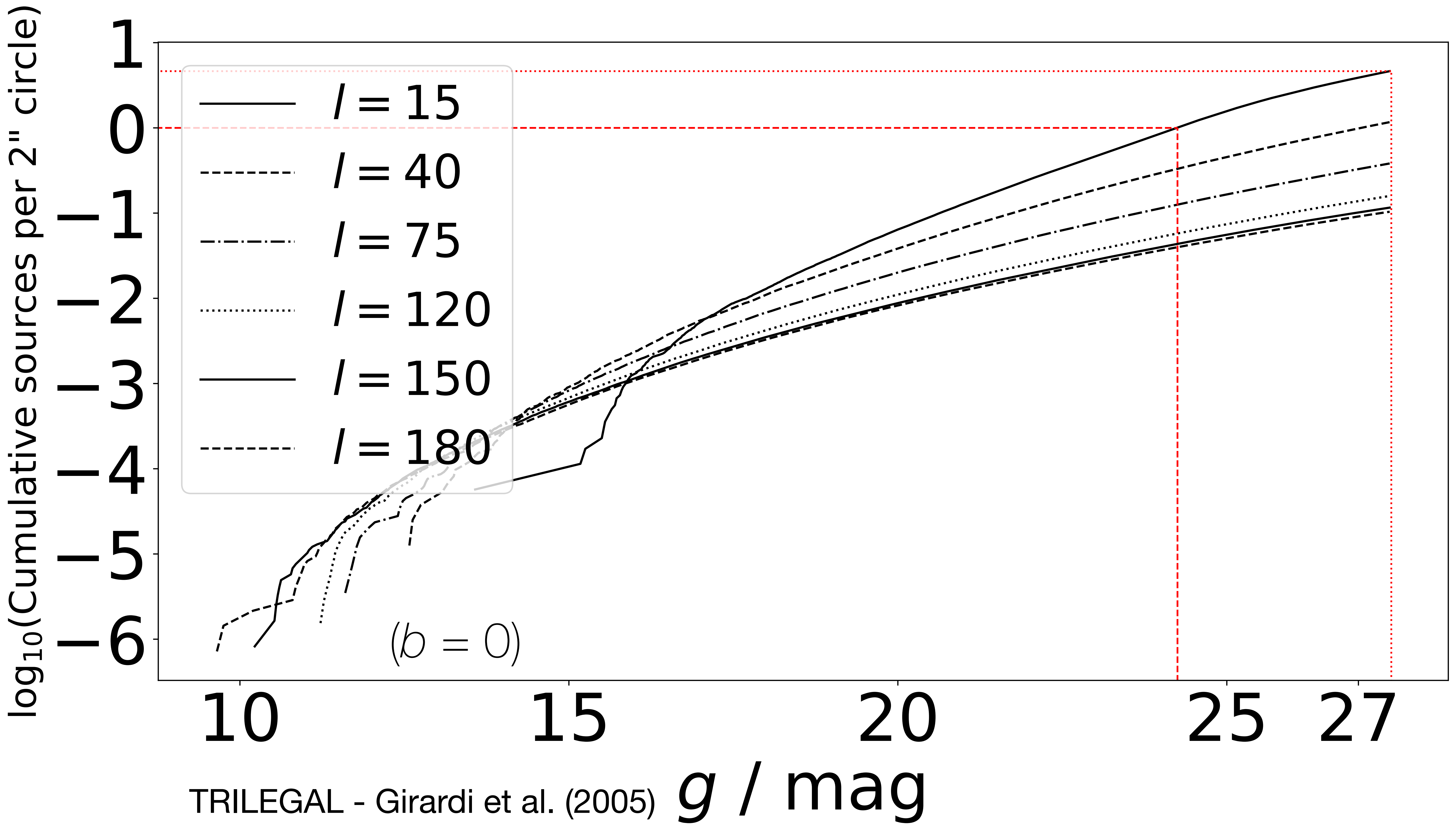
The Problem With Rubin Obs.'s LSST





TRILEGAL - Girardi et al. (2005)

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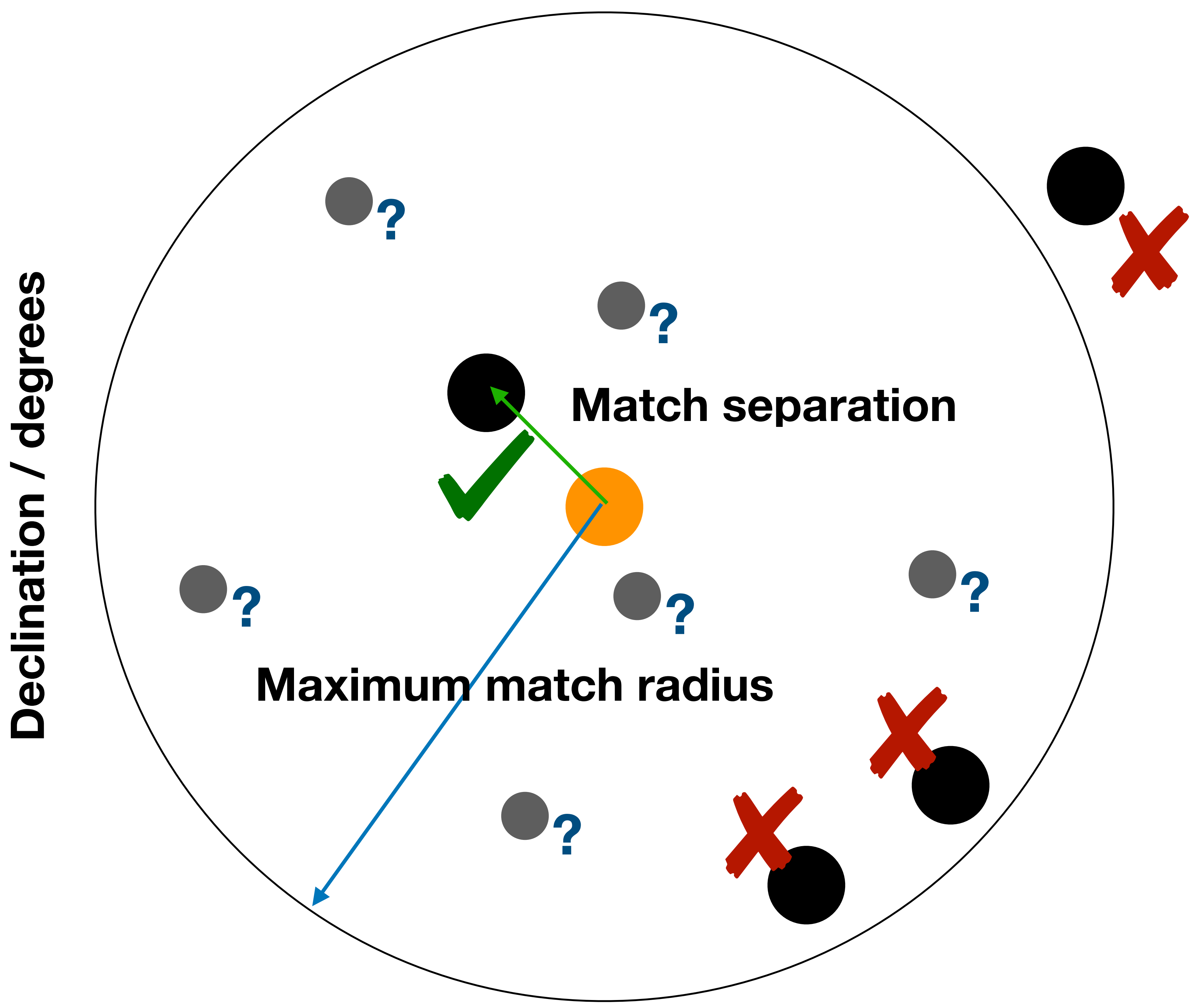

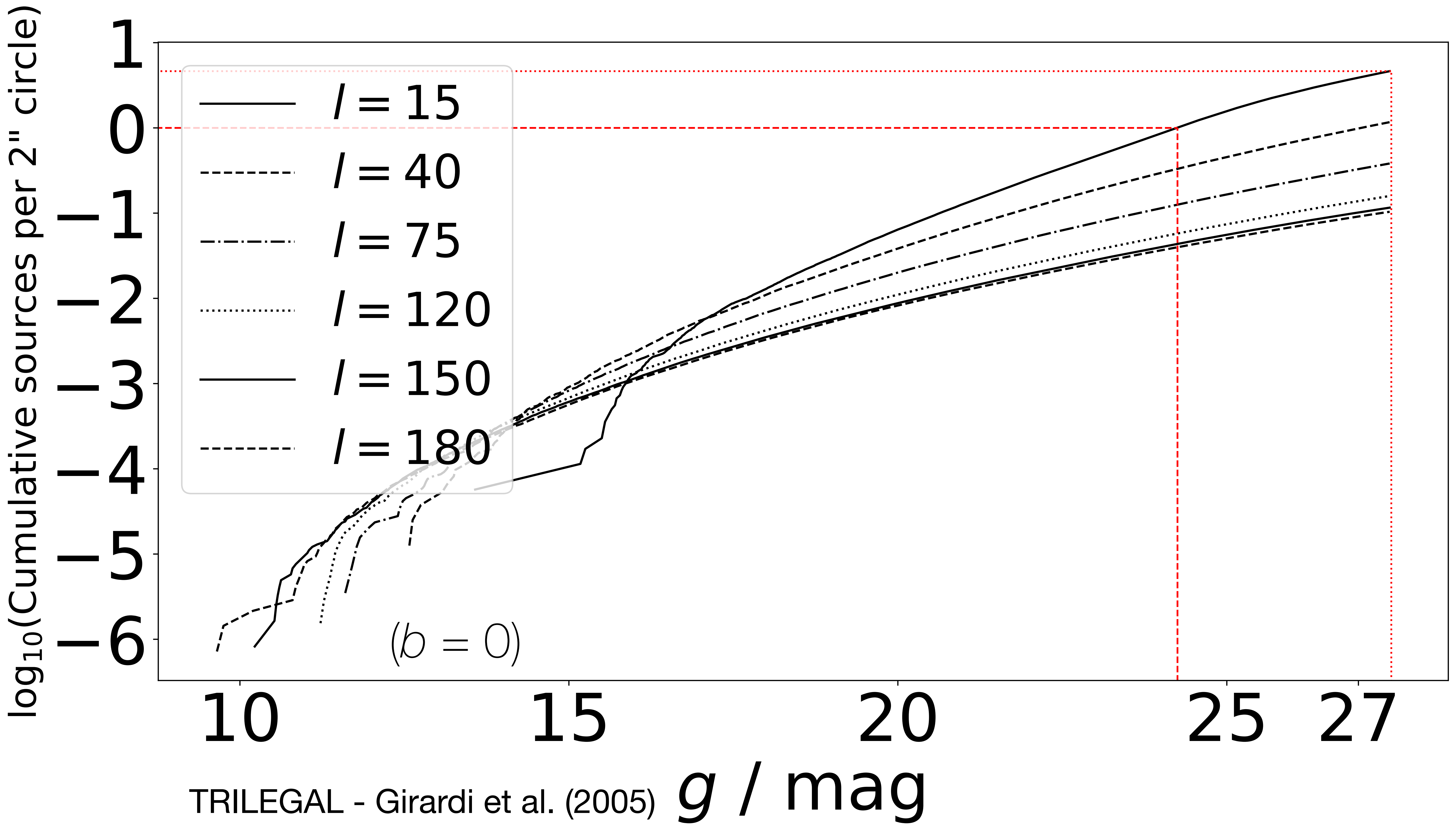

TRILEGAL - Girardi et al. (2005)

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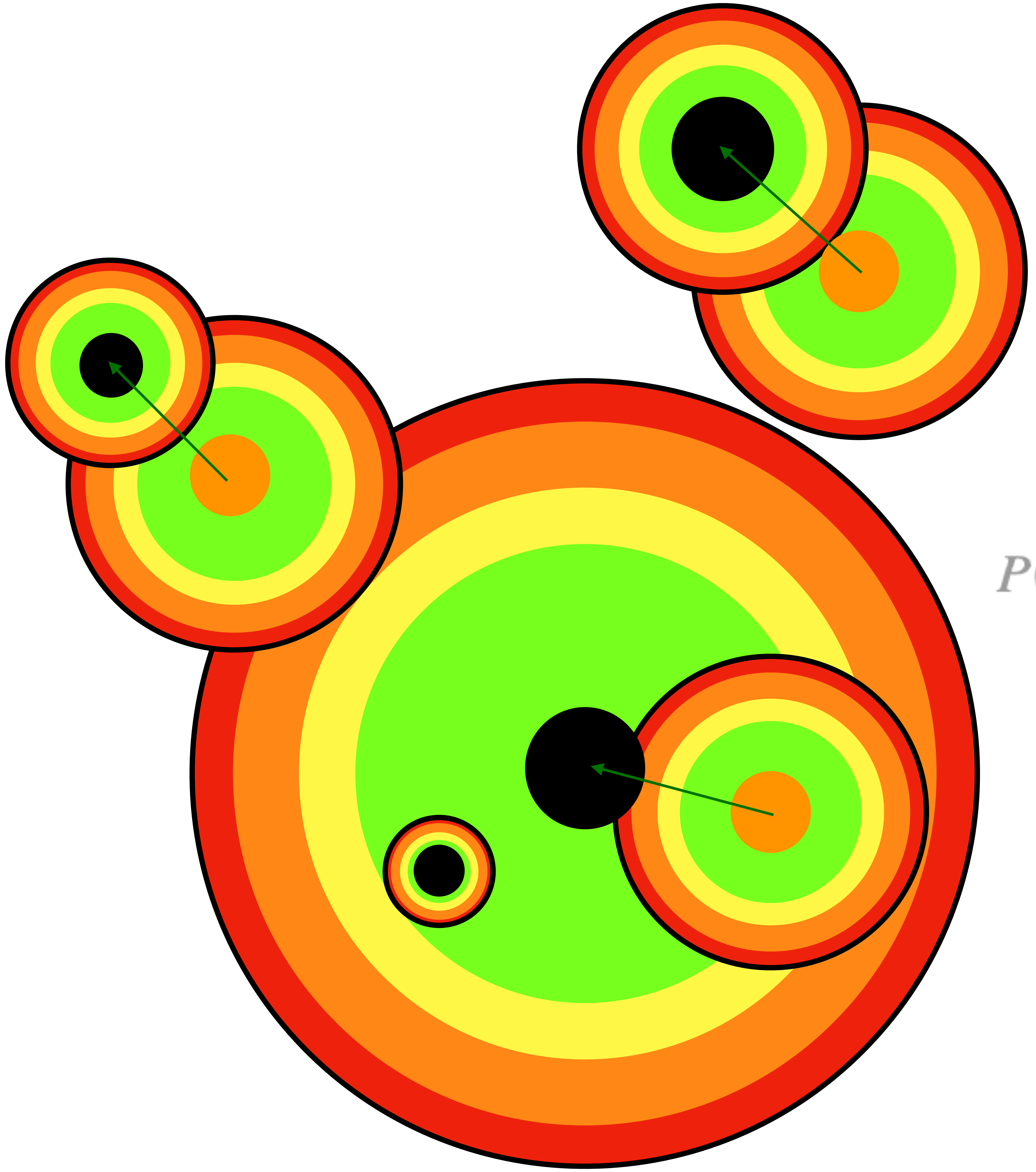
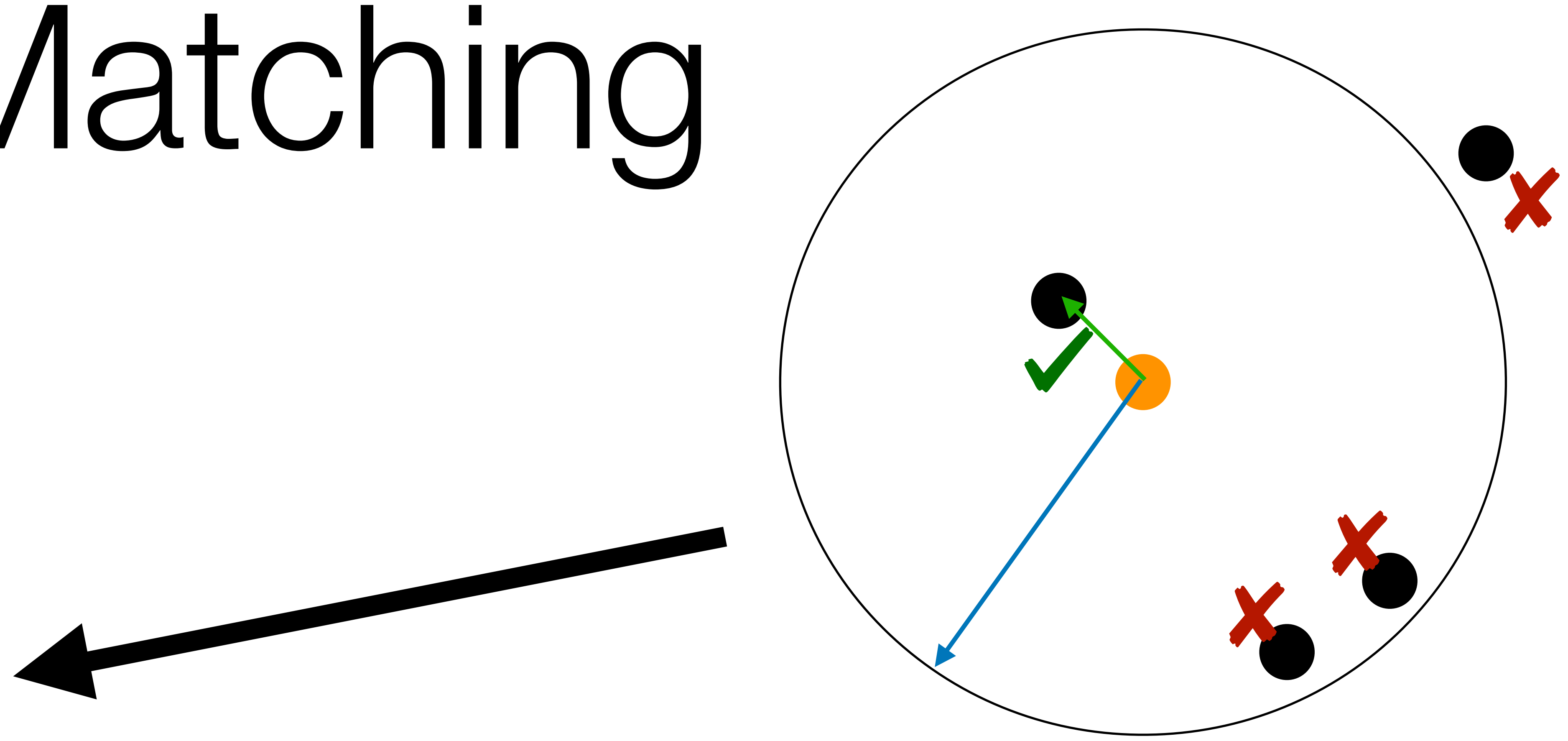
Probabilistic Cross-Matching





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

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

Wilson & Naylor (2018a)

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

(Although for transient matching, by definition, we probably want to skip this part of the equation, given that the colours won’t make sense anymore!)

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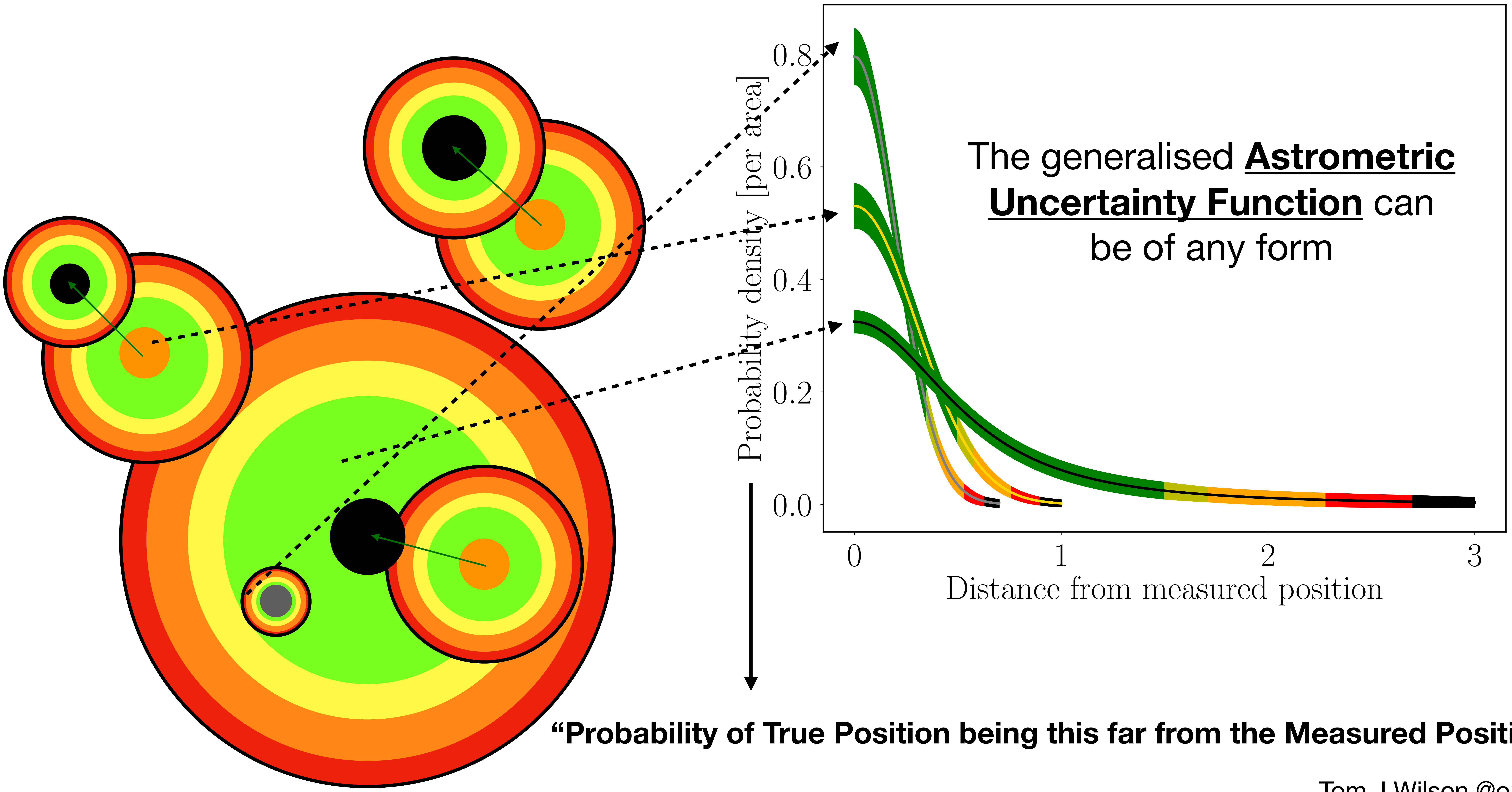
Probabilistic Cross-Matching: the AUF



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

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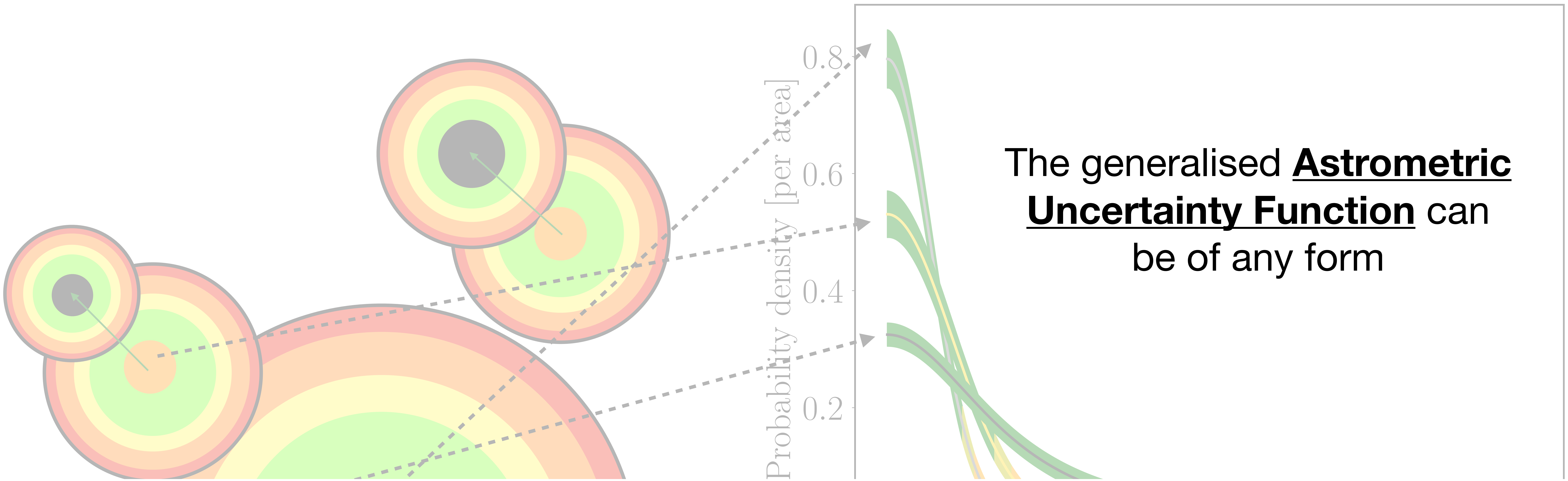
Probabilistic Cross-Matching: the AUF



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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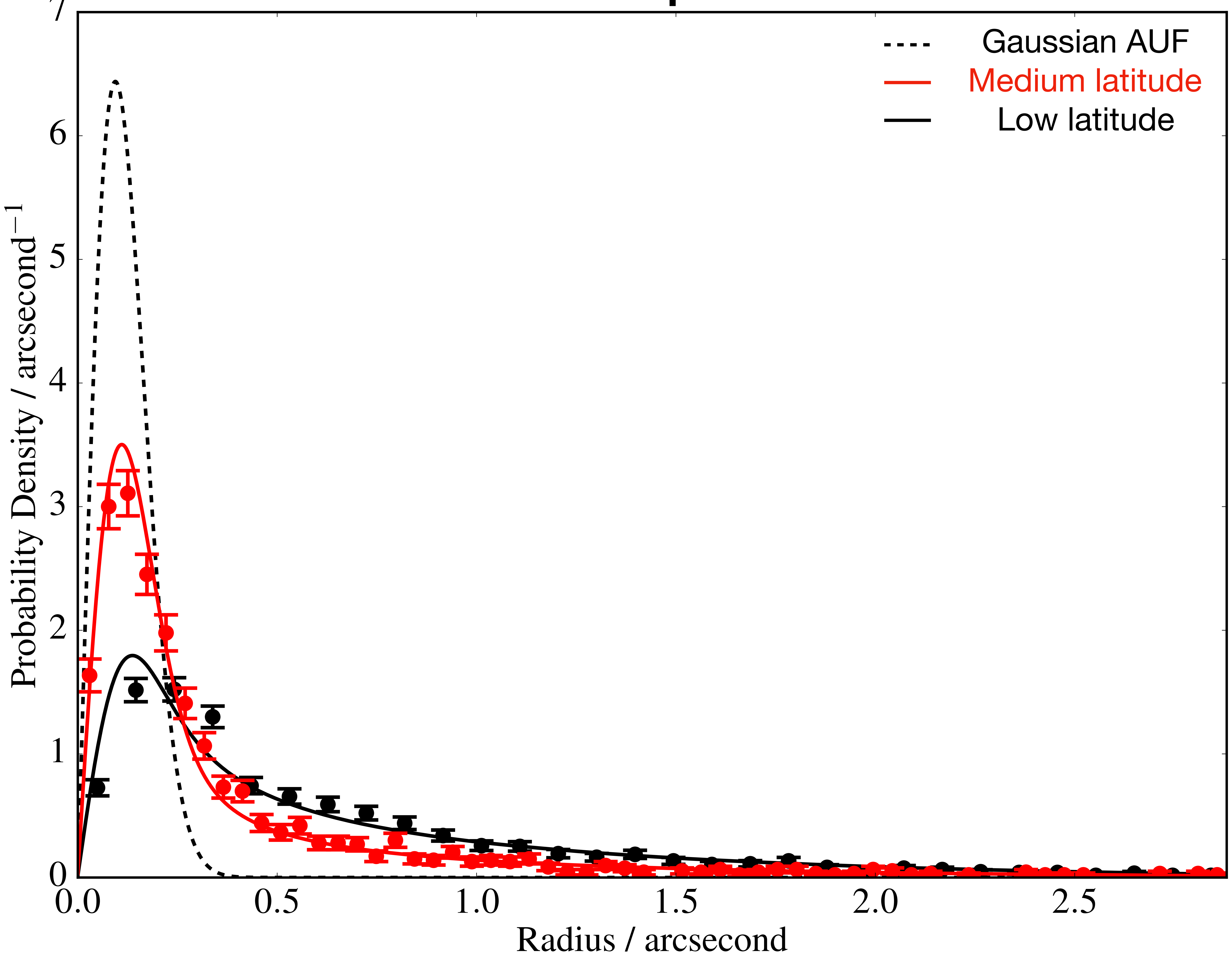
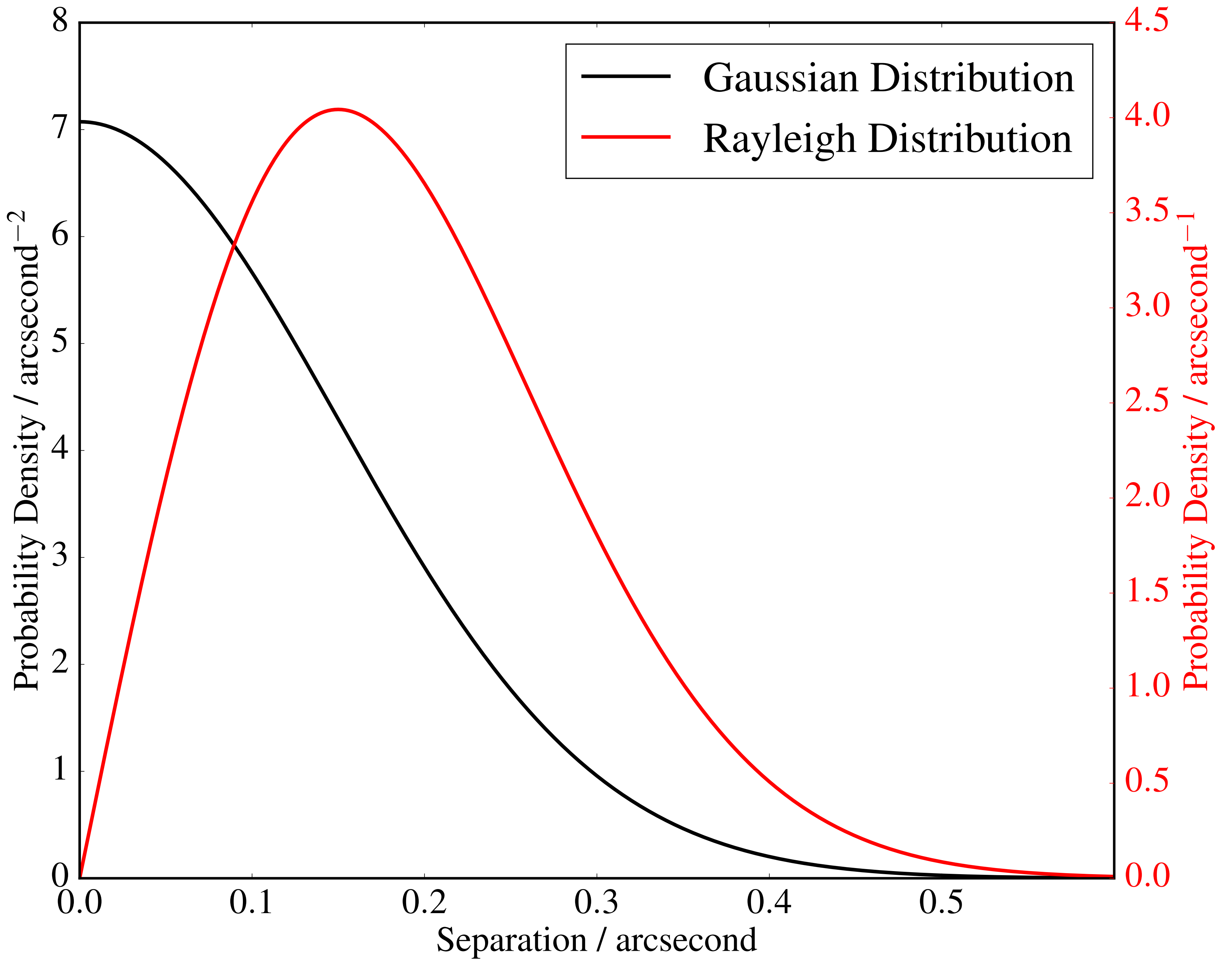
Additional Components of the AUF



$$g(x, y, \sigma) = (2\pi\sigma^2)^{-1} \exp\left(-\frac{1}{2}\frac{x^2+y^2}{\sigma^2}\right)$$

$$\downarrow$$

$$g(r, \sigma) = \frac{r}{\sigma^2} \exp\left(-\frac{1}{2}\frac{r^2}{\sigma^2}\right)$$



WISE - Wright et al. (2010)

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

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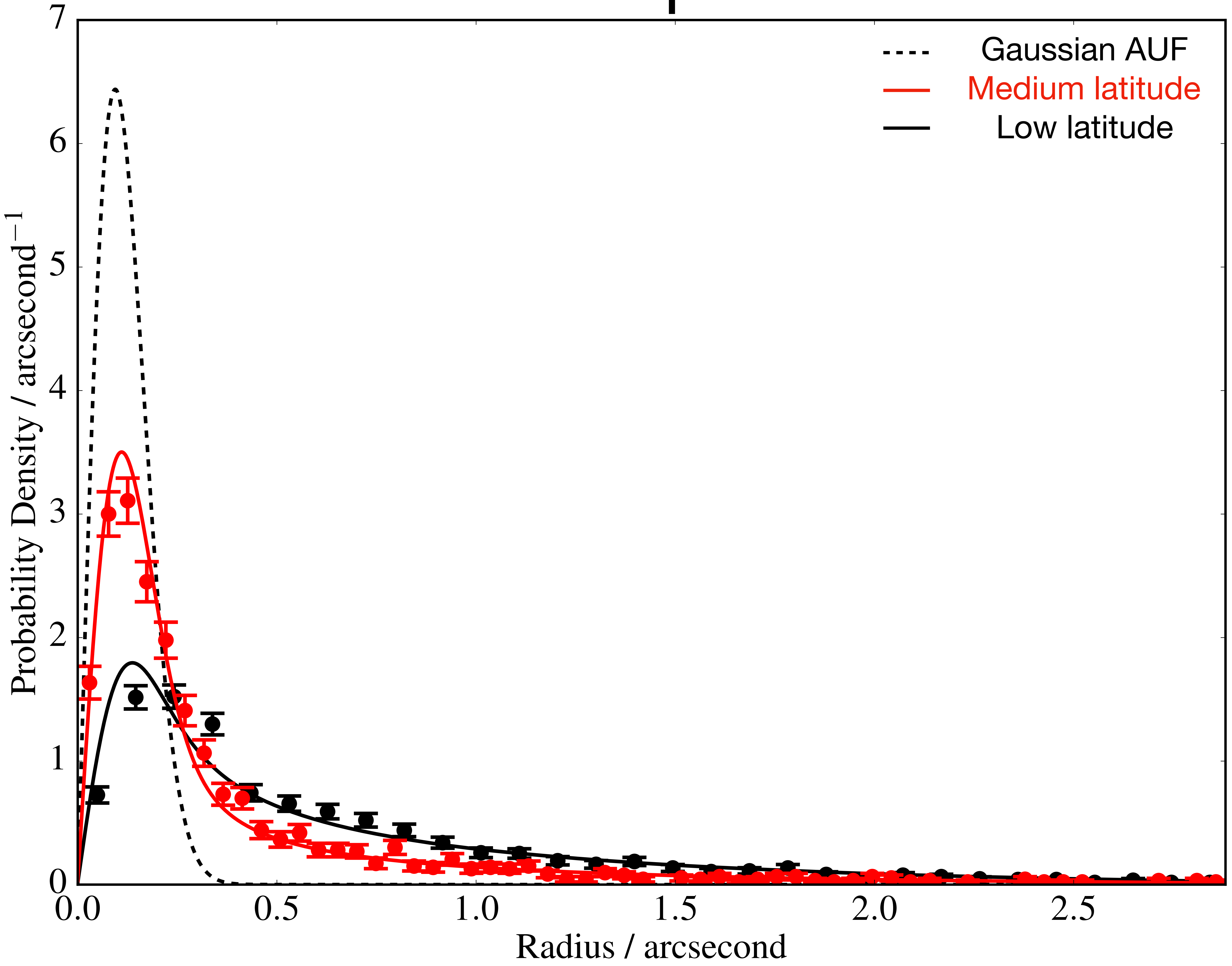

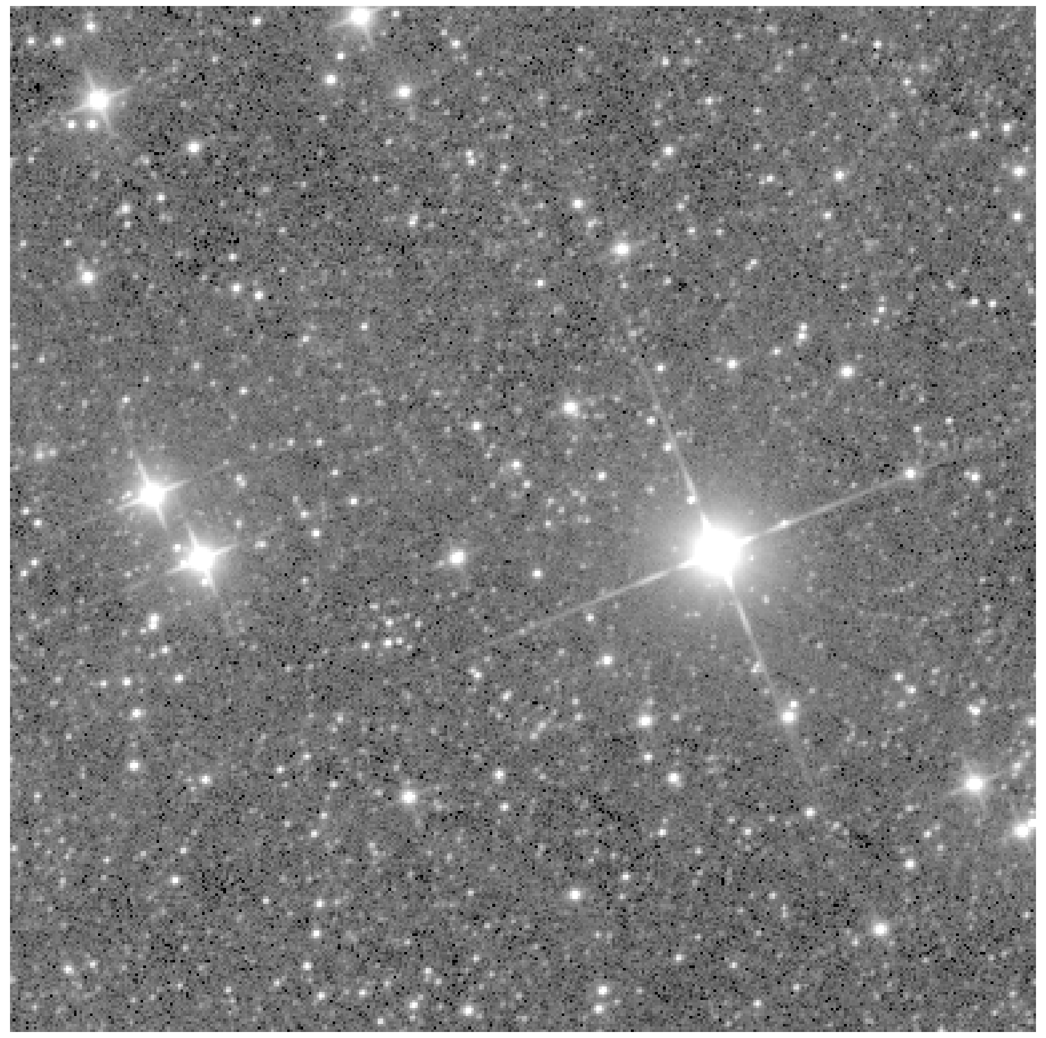

WISE - Wright et al. (2010)
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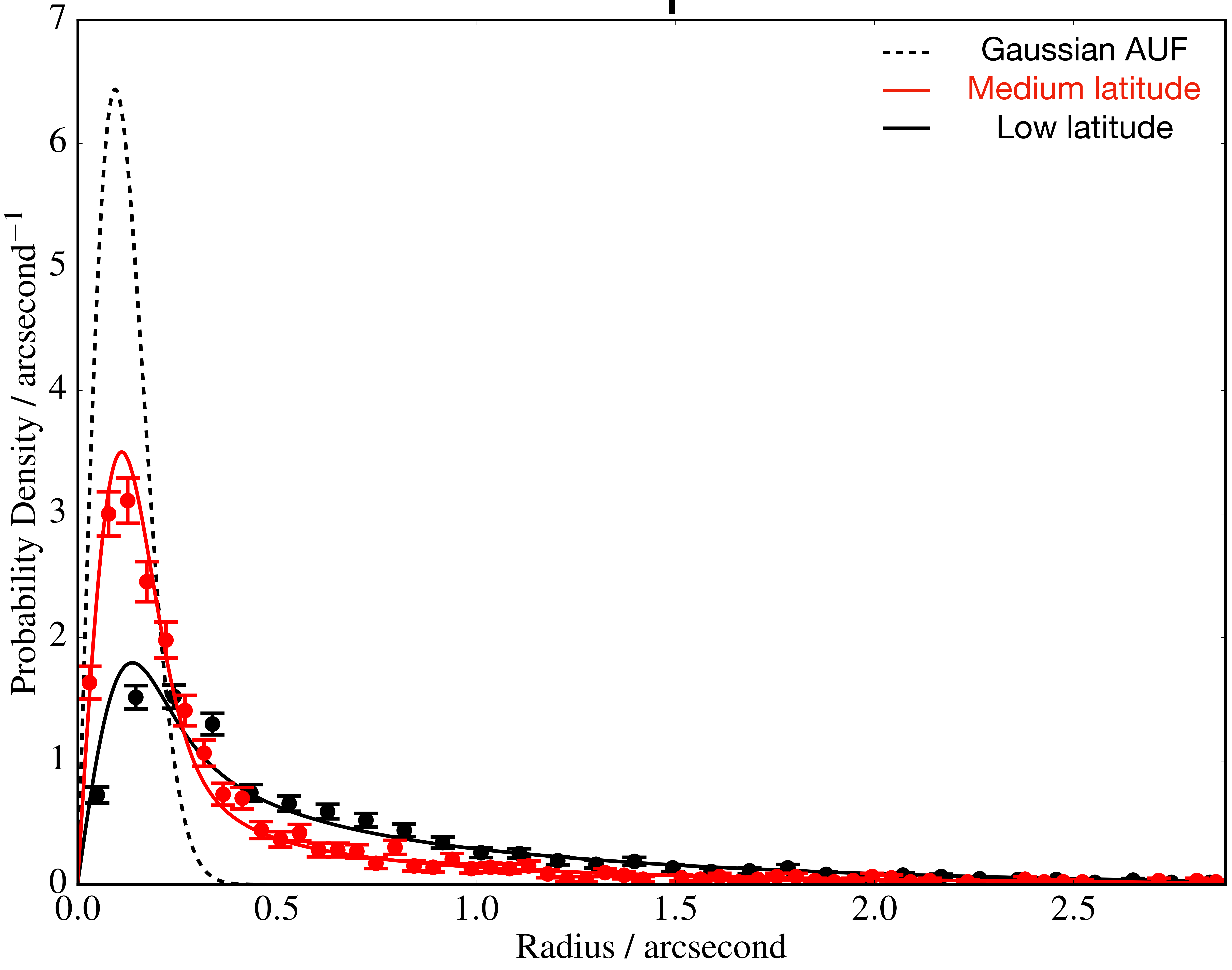
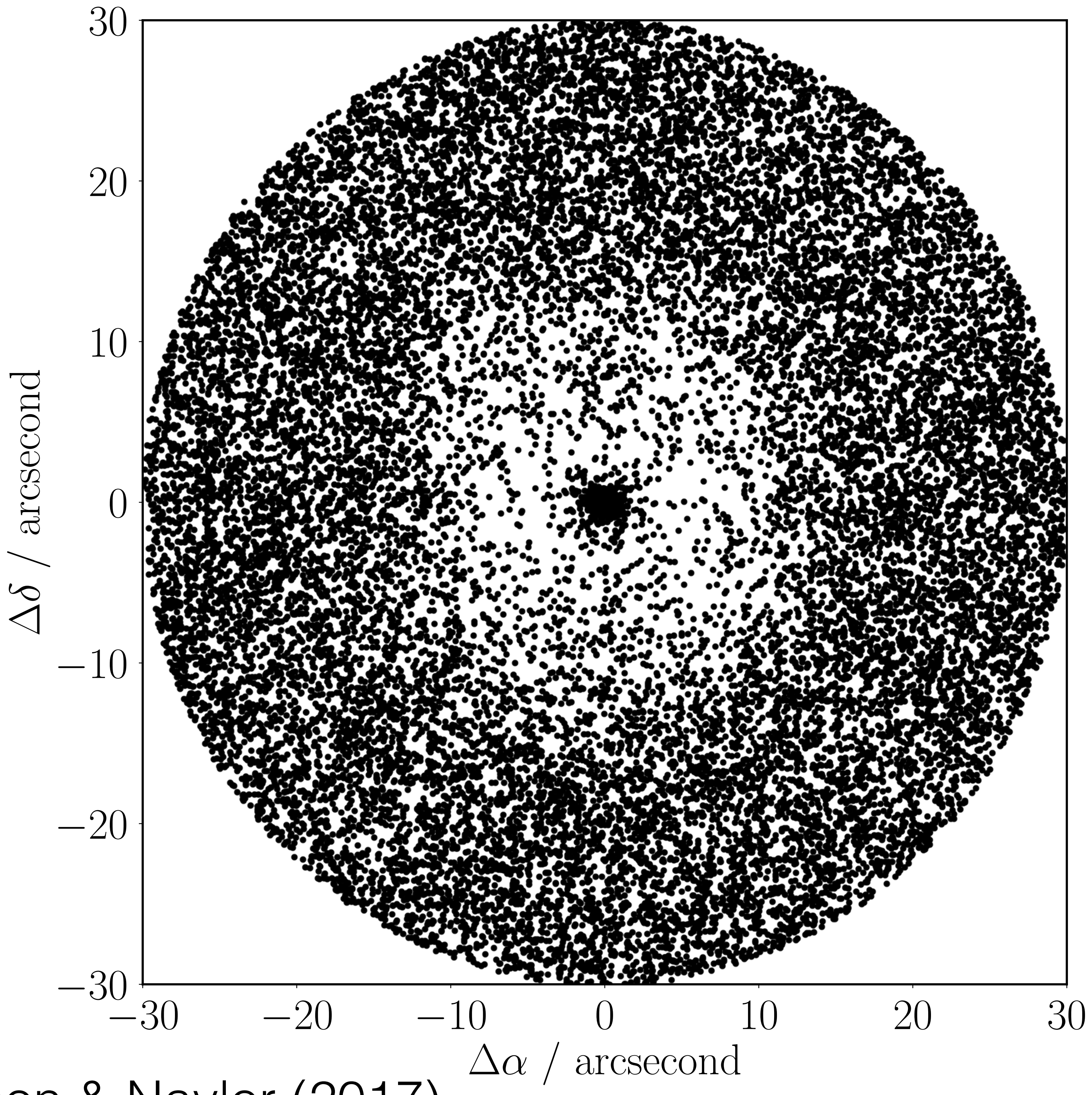
Additional Components of the AUF

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





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Wilson & Naylor (2017)

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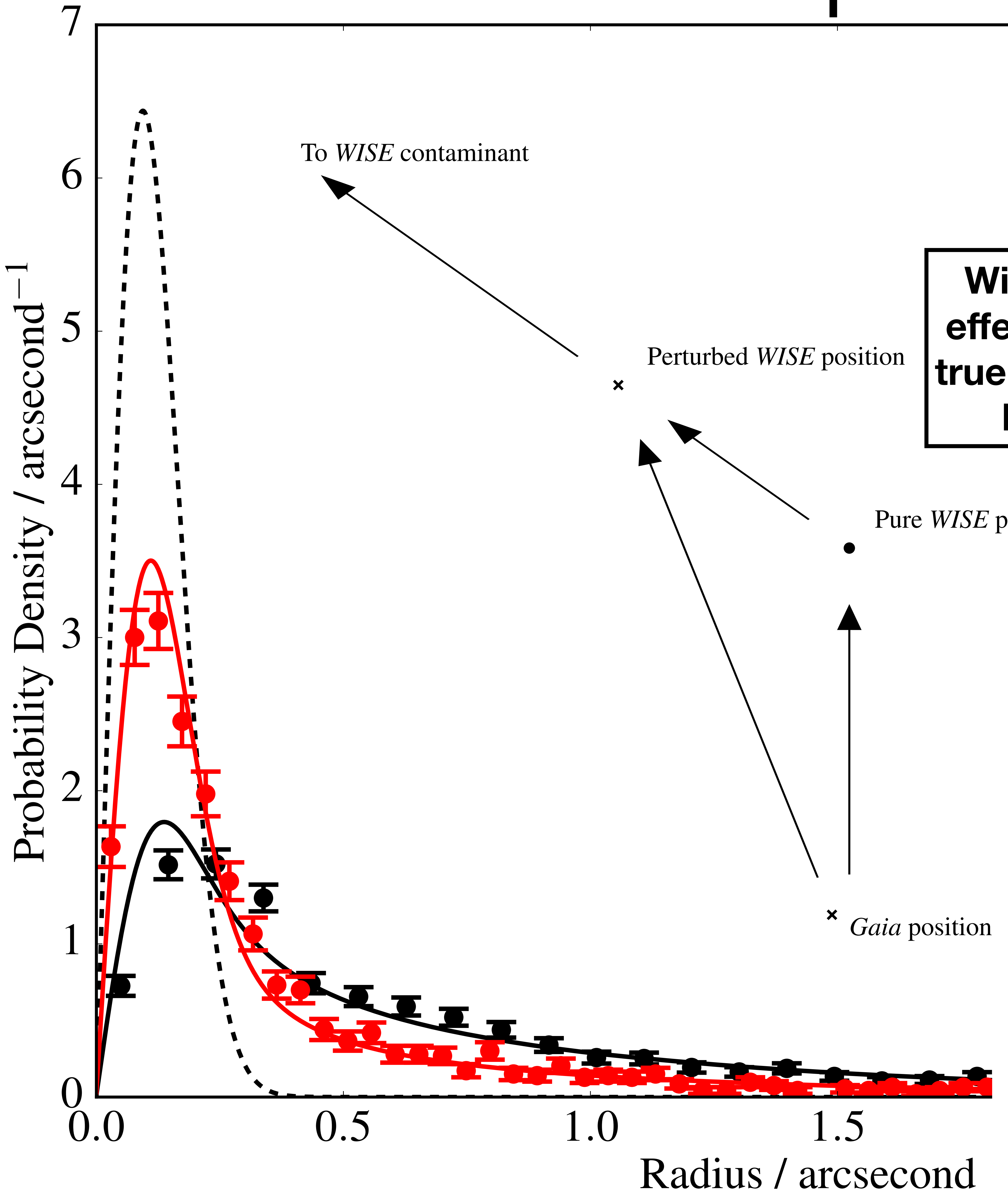
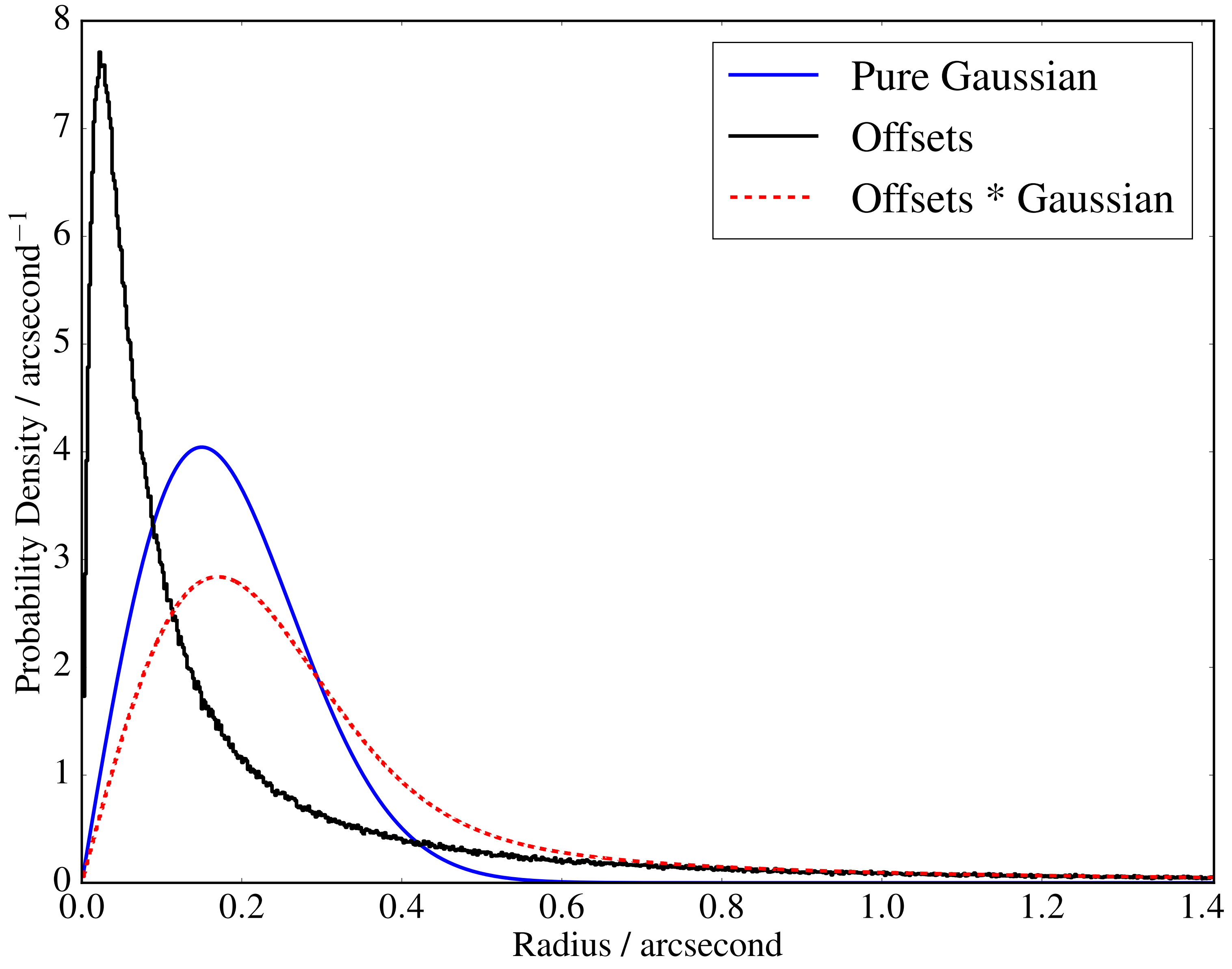
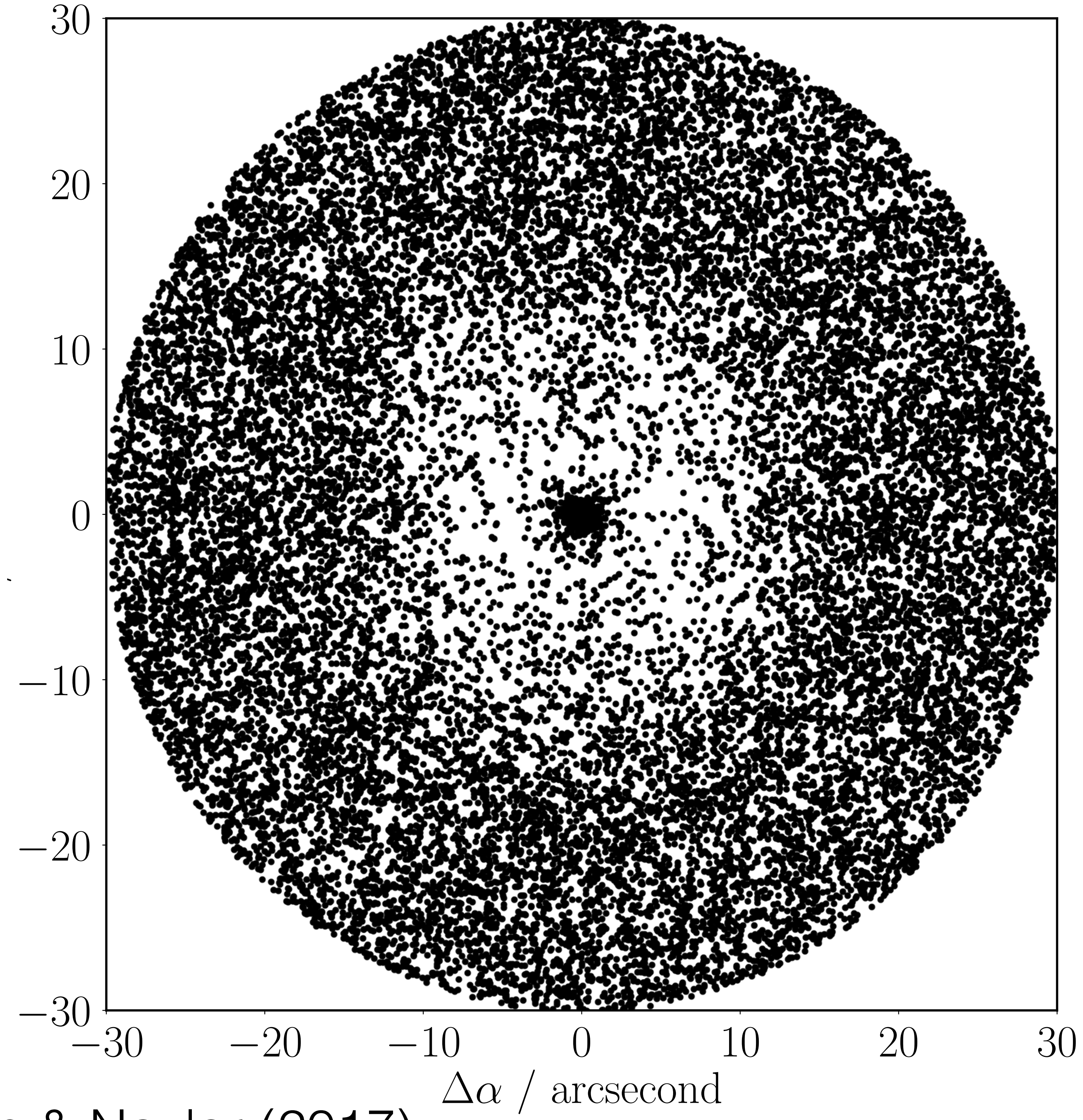


Without modelling this extra effect, we fail to recover many true pairings, with an artificially high false negative rate!



Wilson & Naylor (2018b)



Wilson & Naylor (2017)

WISE - Wright et al. (2010)

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

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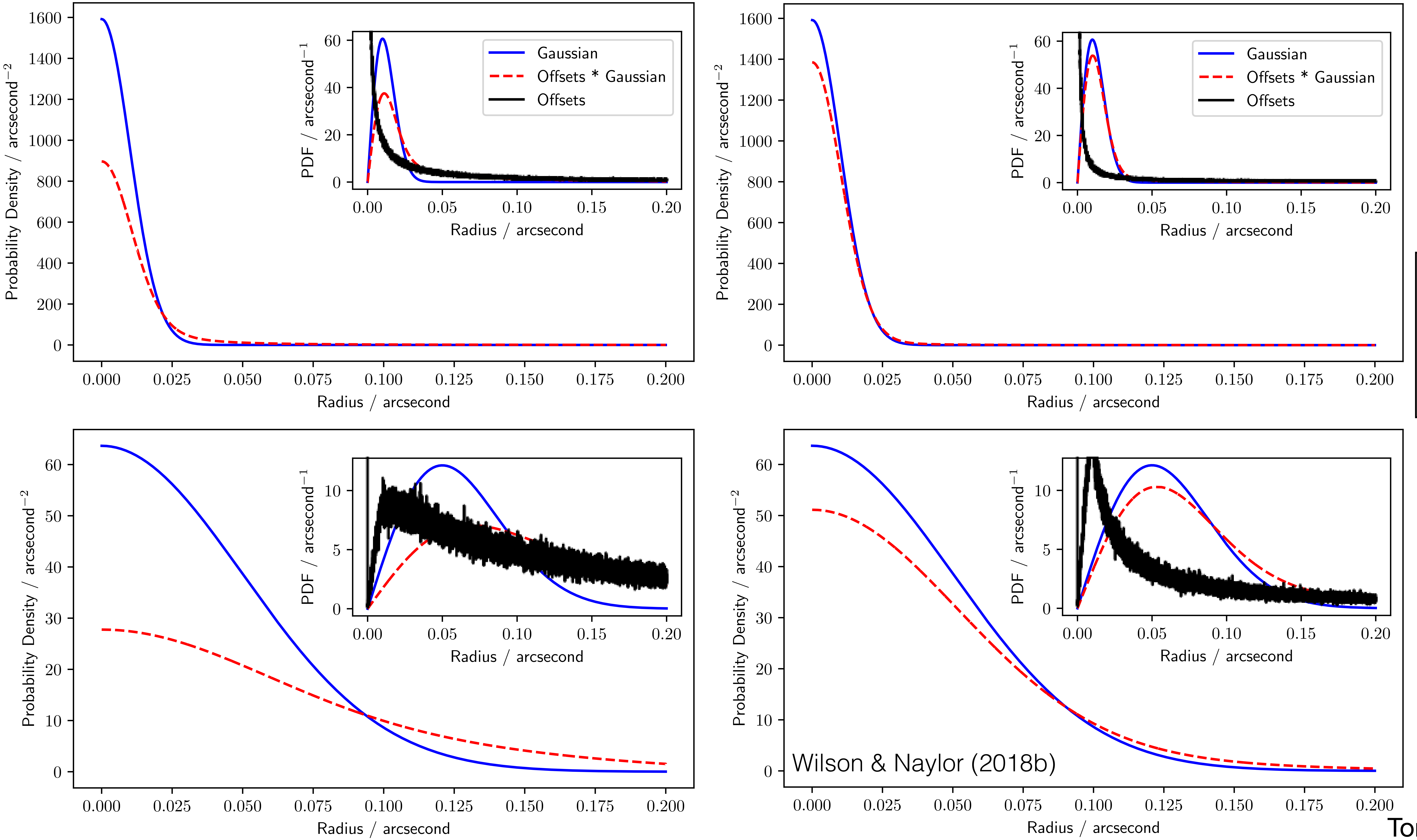
The Rubin AUF: Galactic Plane



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

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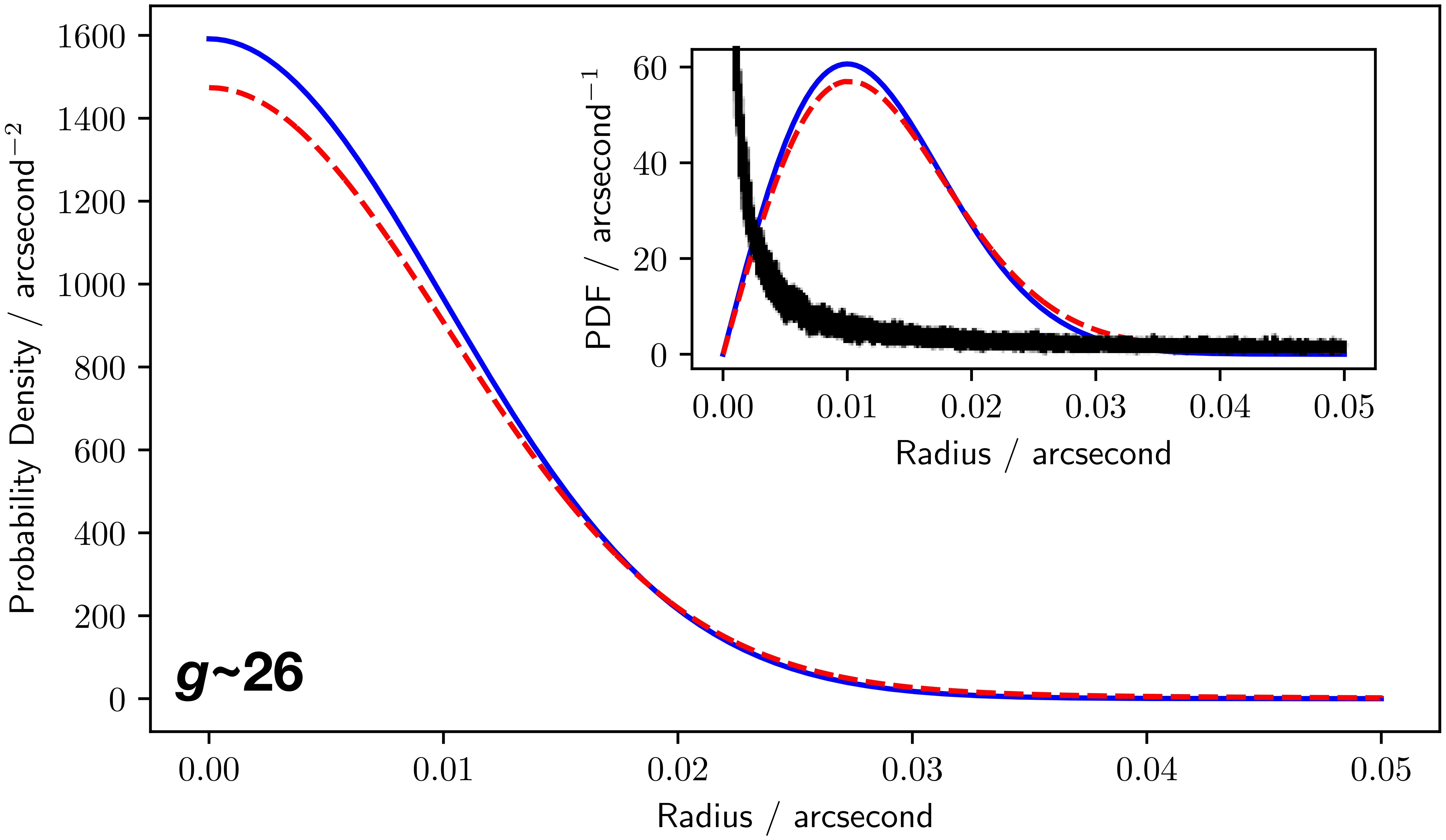
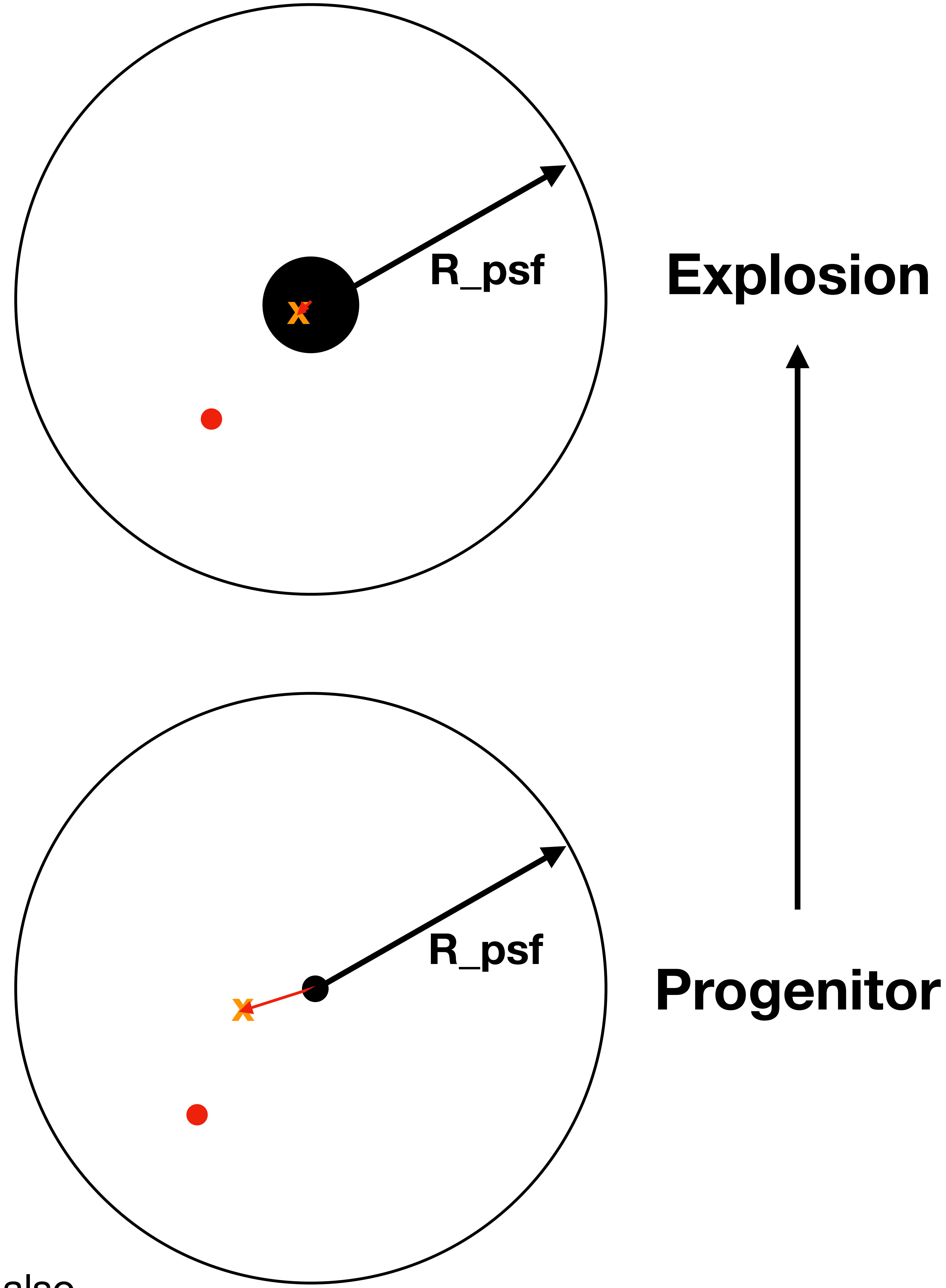
The Rubin AUF: Extra-Galactic Transients

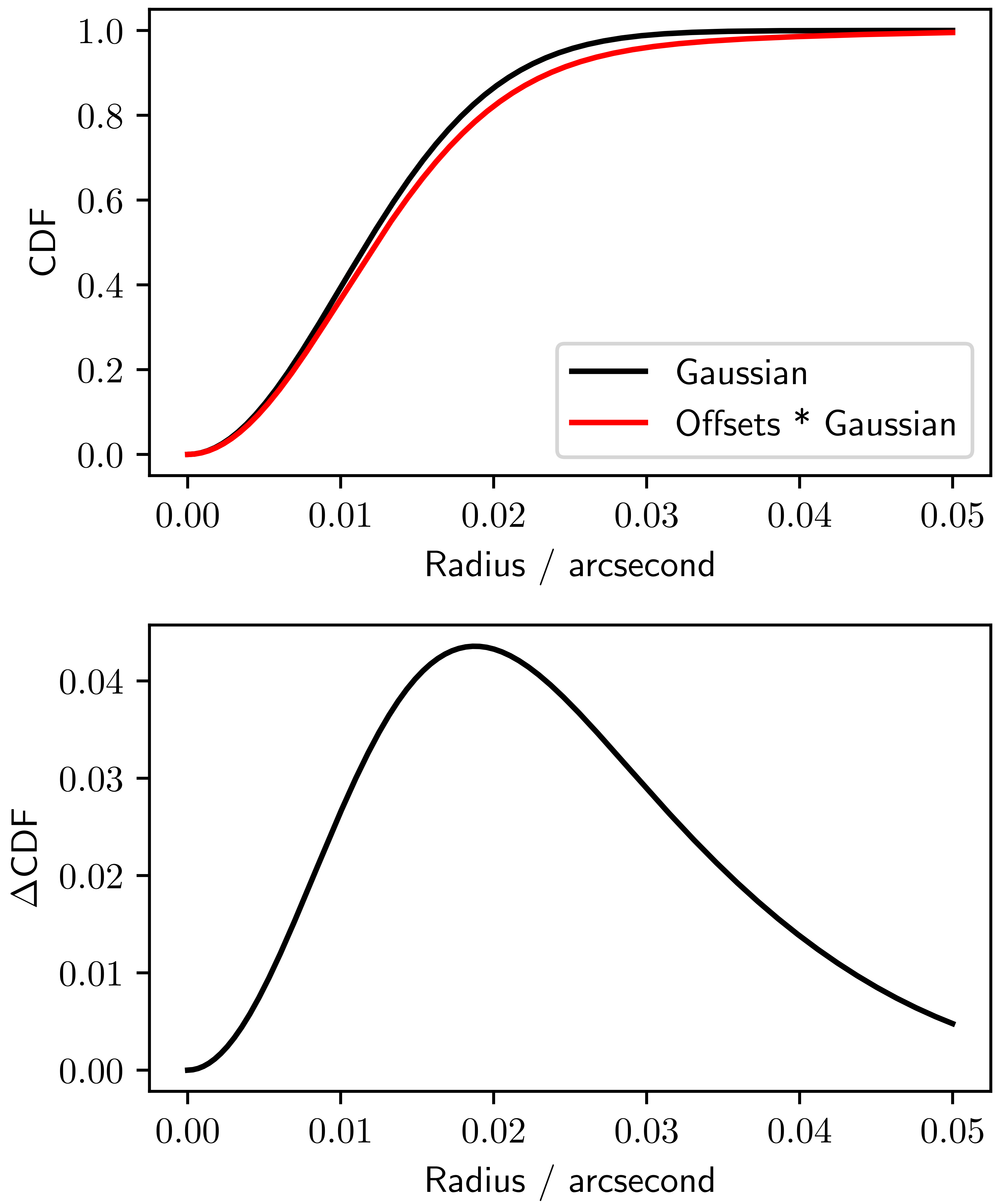
(very well-behaved!)

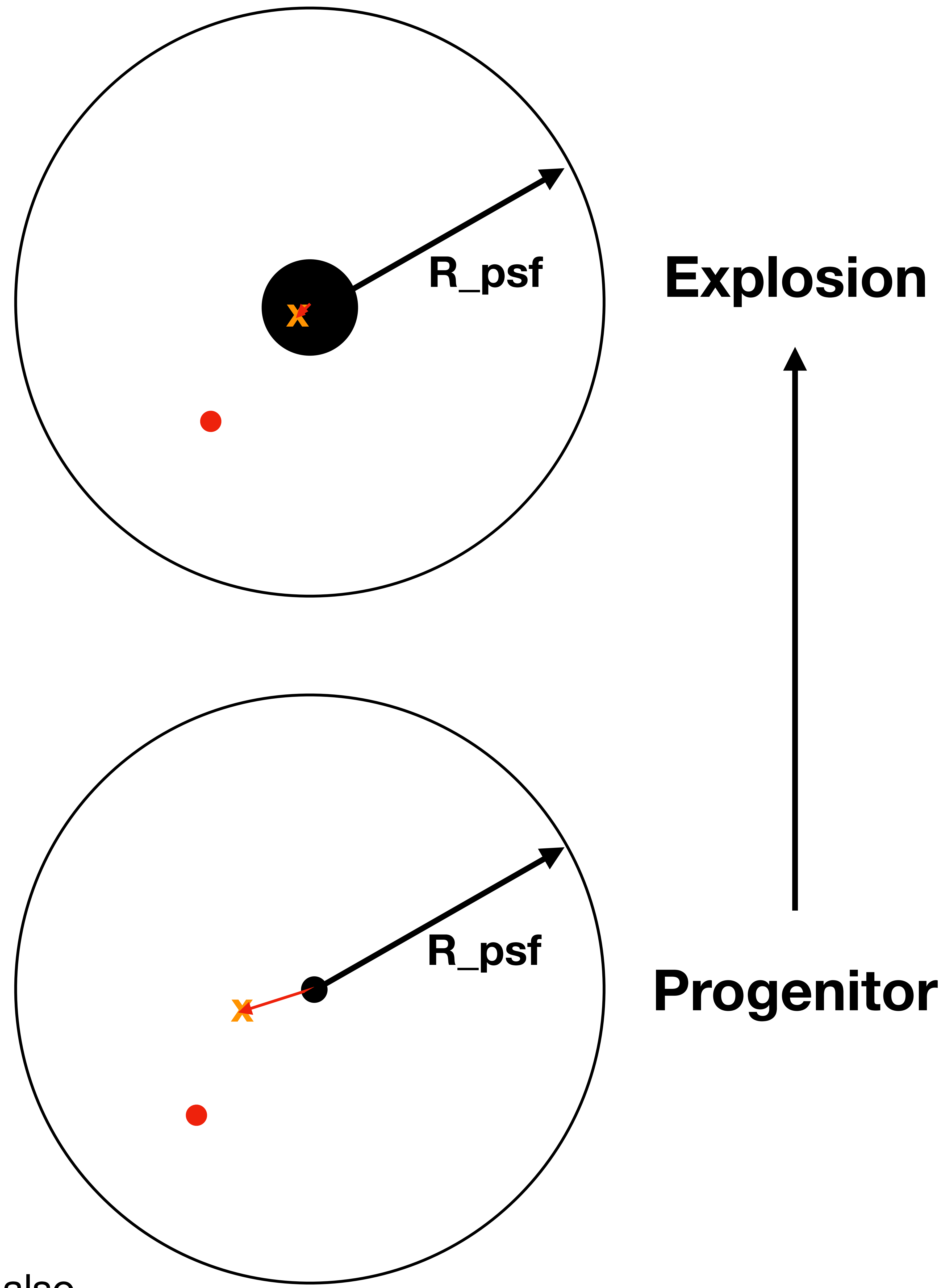




Wilson & Naylor (2018b); also see Wilson (2022, RNAAS)

The Rubin AUF: Extra-Galactic Transients





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

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The Rubin AUF: Extra-Galactic Transients

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

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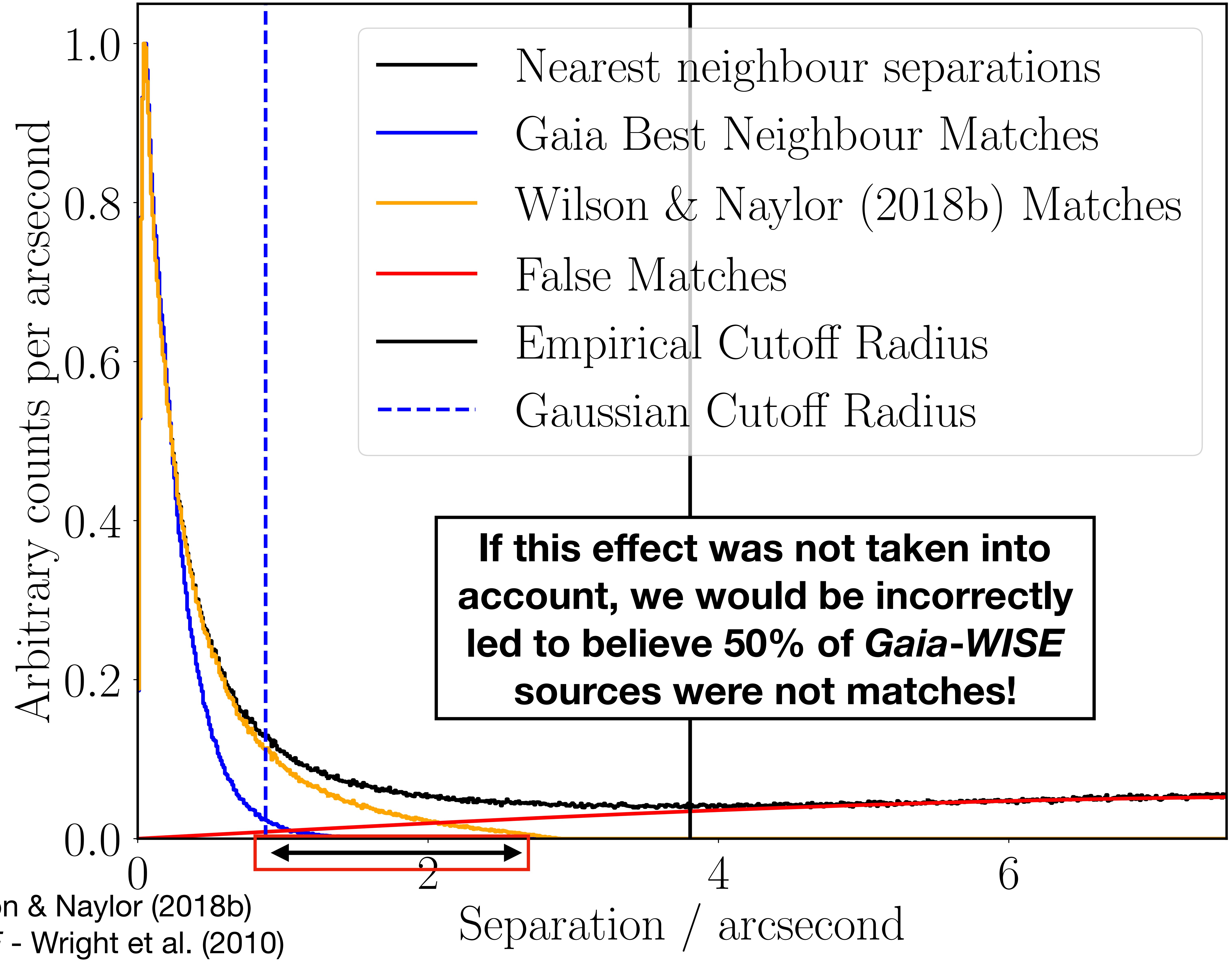
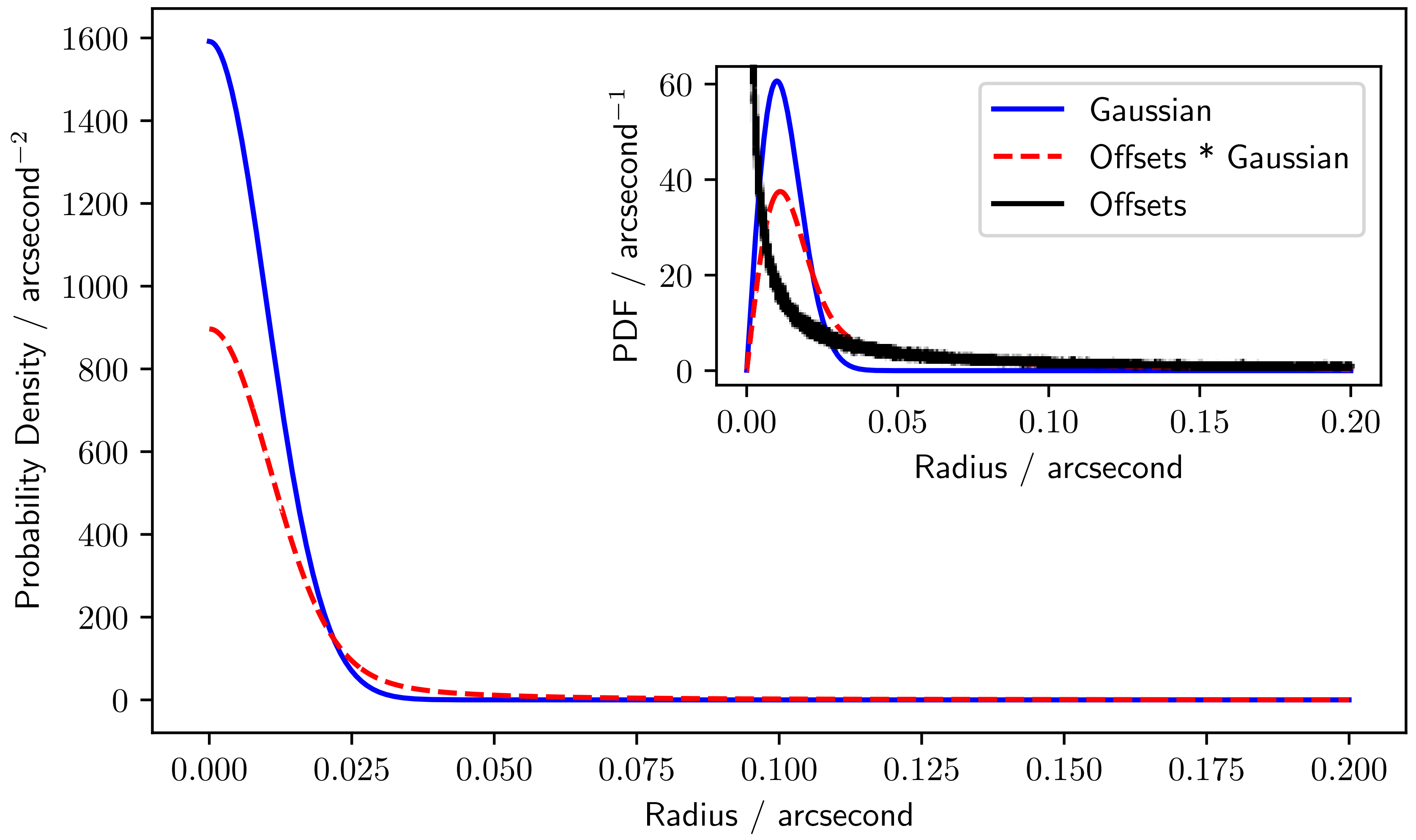
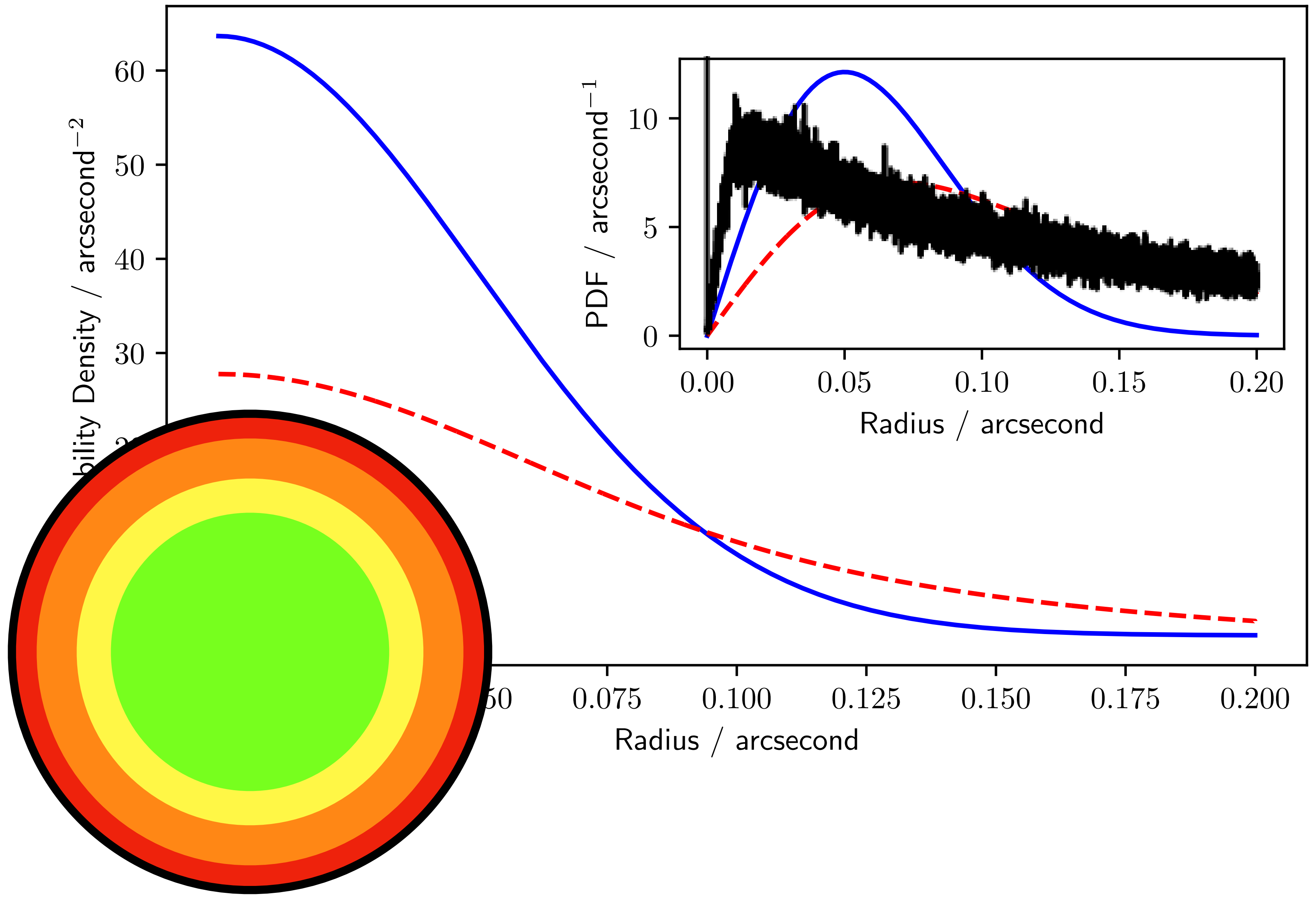
Match Separations



If this effect was not taken into account, we would be incorrectly led to believe 50% of *Gaia*-*WISE* sources were not matches!





Wilson & Naylor (2018b)
WISE - Wright et al. (2010)
Gaia matches - Marrese et al. (2019)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

The AUF does not need to, and in fact quite often <u>should *not*</u>, be Gaussian!

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Conclusions

- **Our cross-match algorithms include two key elements to avoid issues with crowded & confused data**
  - **A generalised approach to the Astrometric Uncertainty Function allows for the full inclusion of the effects of perturbation due to blended sources — reduce false -ves!**
  - **Where it can be applied (i.e., the static sky) use of (two-sided) photometry to sort out multiplicity of higher resolution data — reduce false +ves!**

- **Software package macauff developed to cross-match catalogues, including the effect of unresolved contaminant sources (and rejection of interloper objects using photometry in the static sky)**
  - **Developed through Rubin/LSST:UK, with plans to match LSST to *Gaia*, *WISE*, VISTA, SDSS, …**
  - **We have compute time to cross-match datasets — let me know your favourite combo, and what you need matched (to LSST or otherwise)!**

- **Incorporating this extension of position uncertainty into real-time matches allows for more robust counterpart identification in the alert stream and a more accurate and precise transient SED**
  - **Furthermore, we can provide *statistical* information on the level of photometric contamination unresolved contaminant sources cause, which can be subtracted in a probabilistic framework!**

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LSST:UK Consortium

Science and Technology Facilities Council

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

Macauff