Enhancing (amongst others) Rubin-*Euclid* Synergies with Robust Catalogue Cross-Matching

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National Astronomy Meeting 2023 — Euclid science exploitation in the UK, 5/Jul/23

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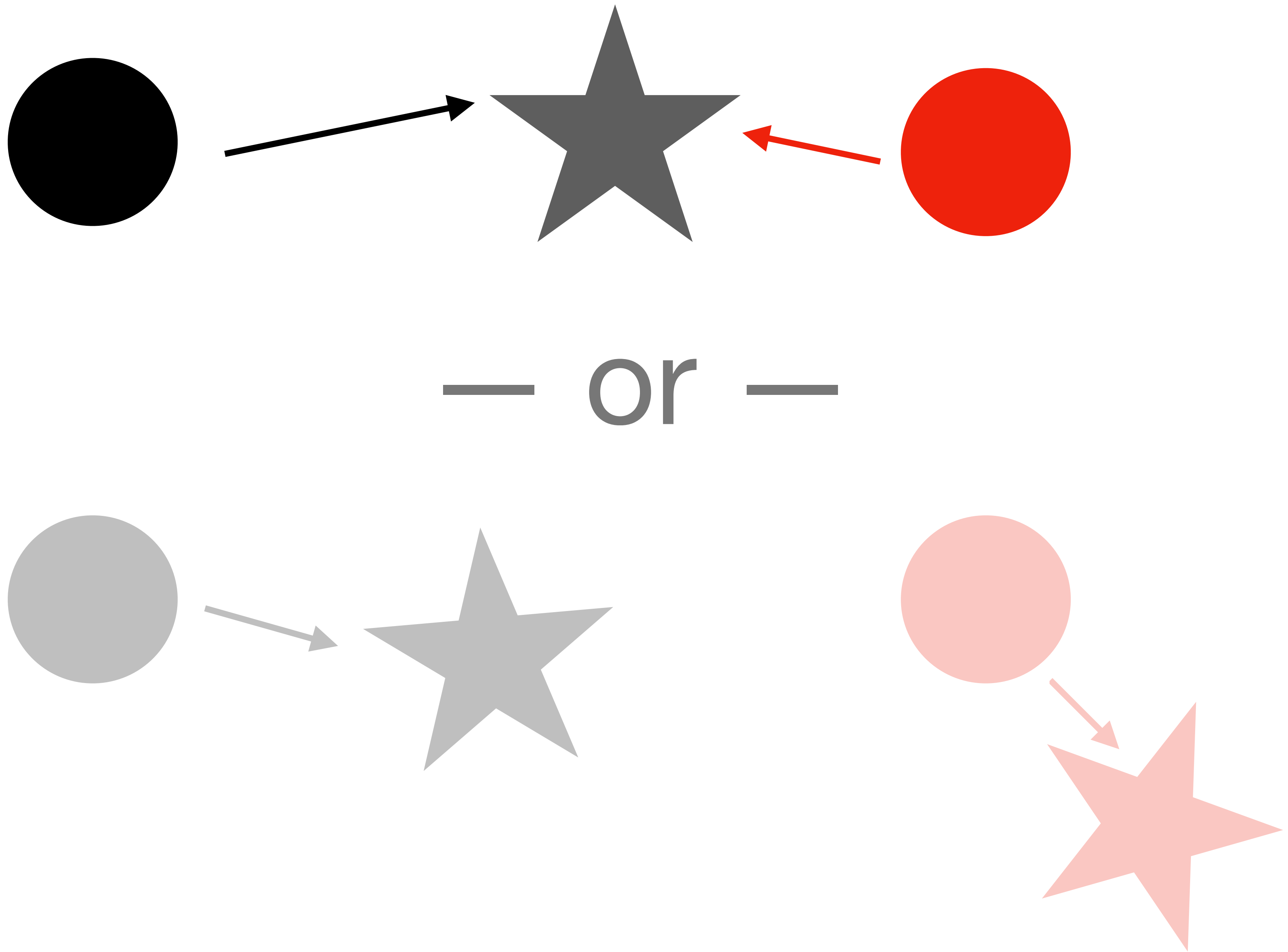
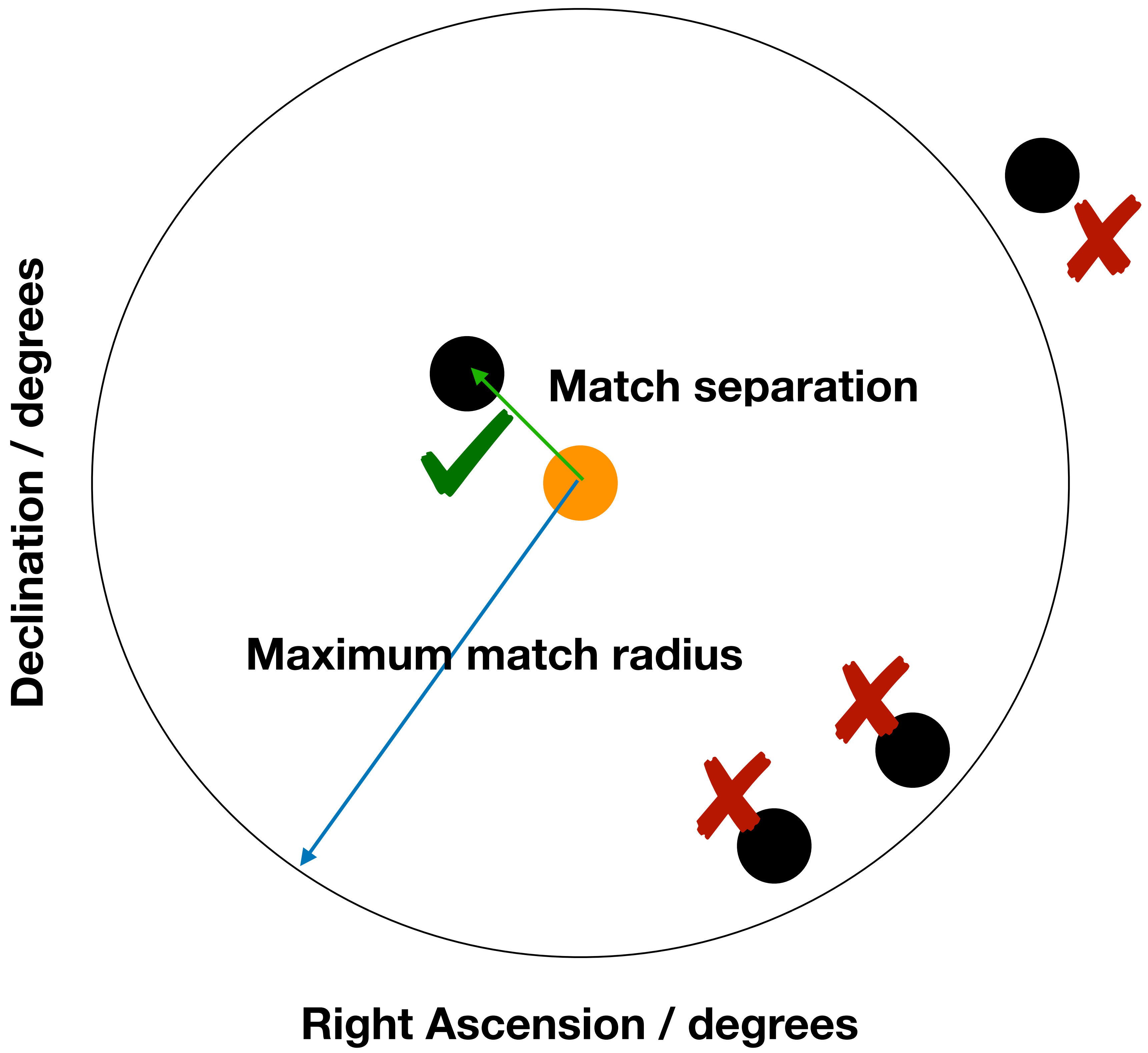
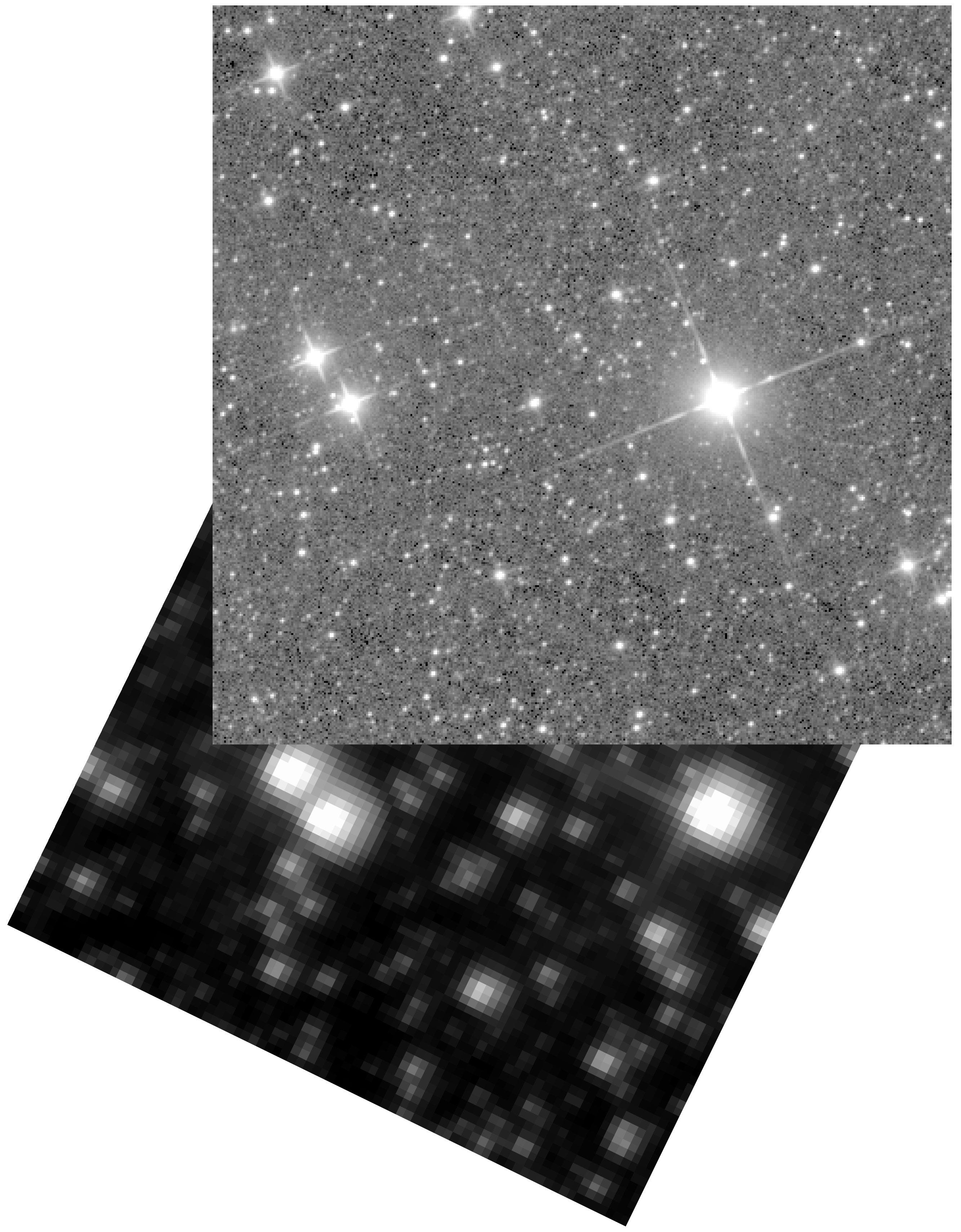
LSST:UK Consortium

Science and Technology Facilities Council

“Simple” Cross-Matching







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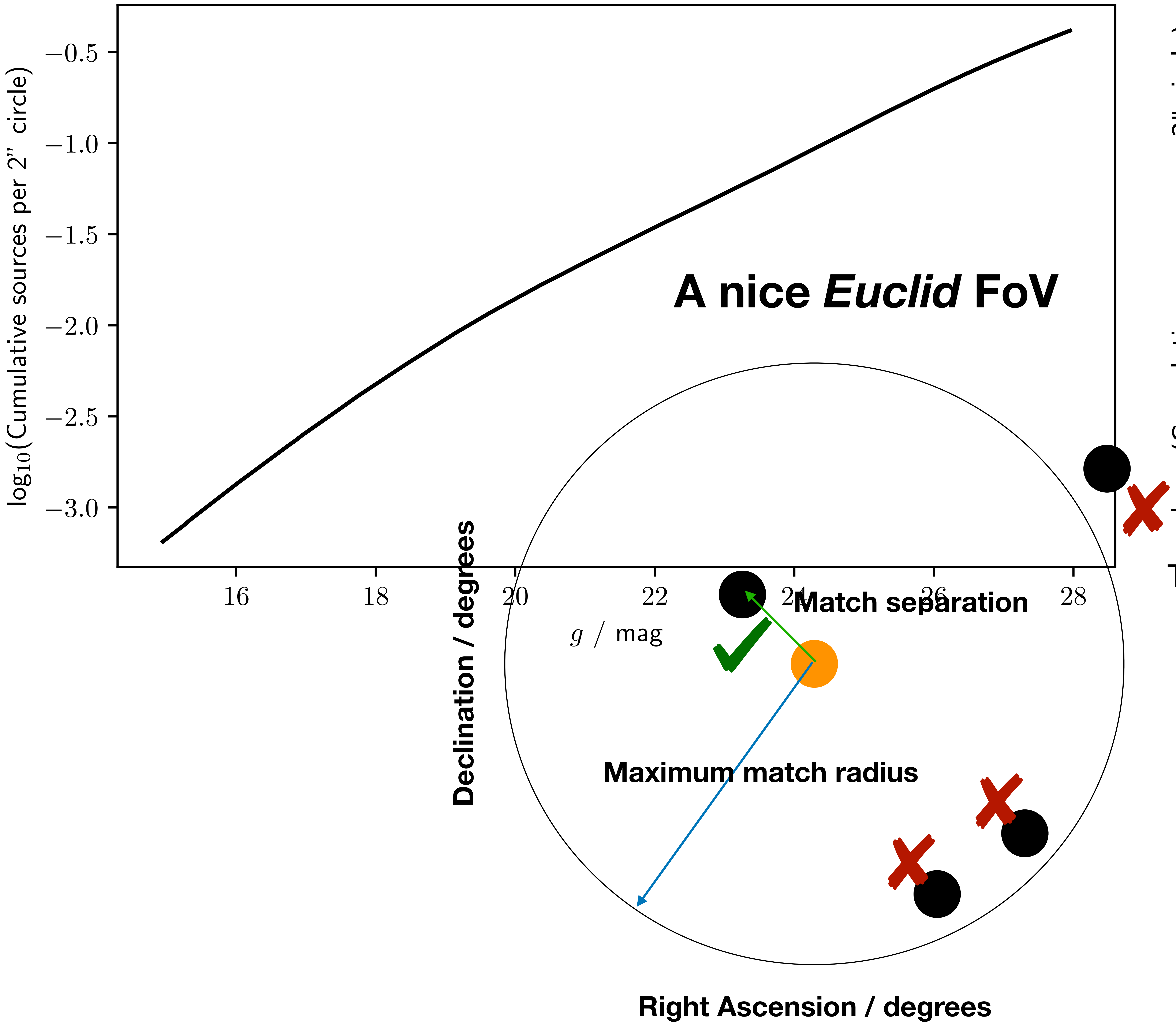
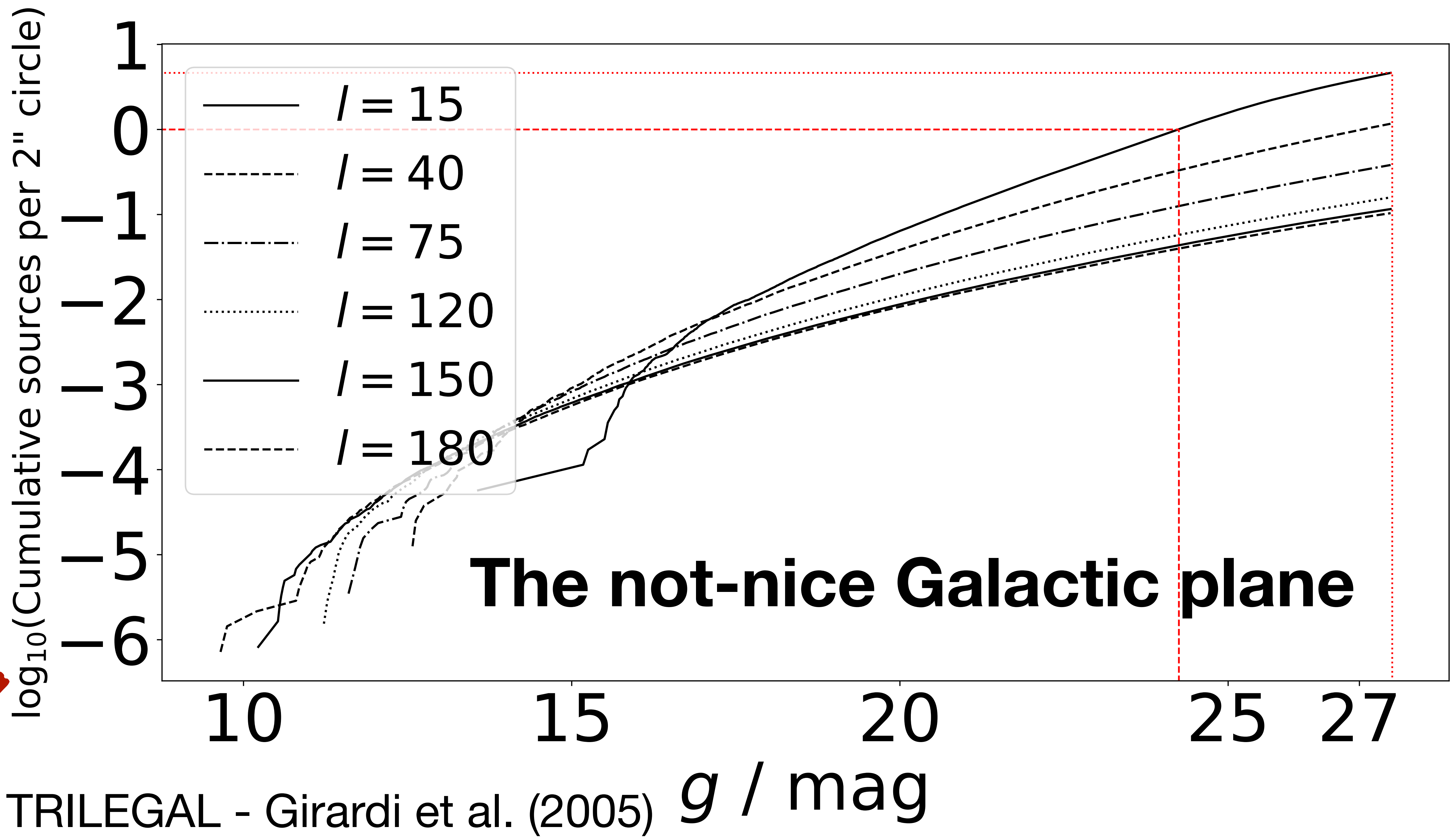
The Problem With Vera C. Rubin Obs.'s LSST





TRILEGAL - Girardi et al. (2005)

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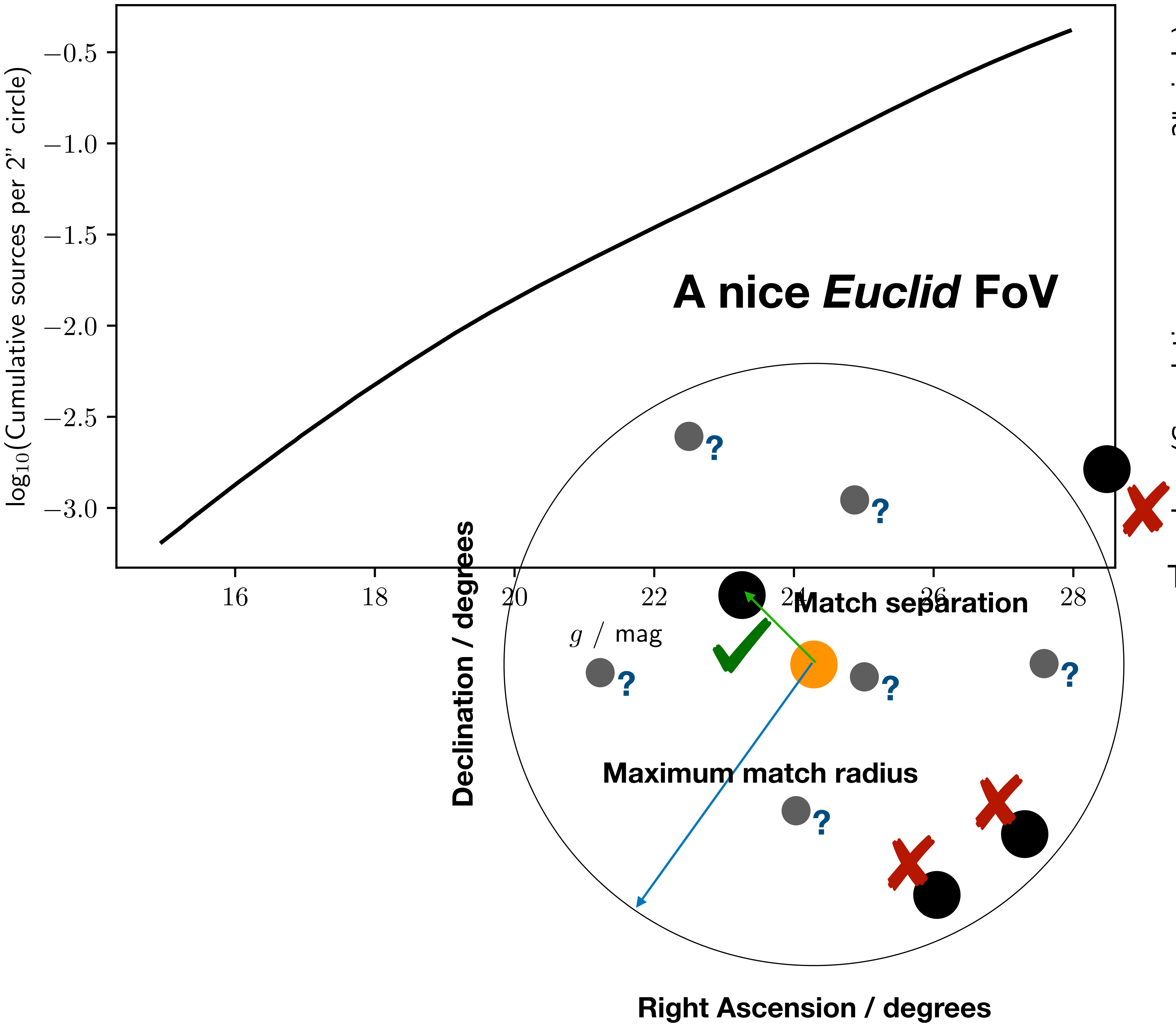
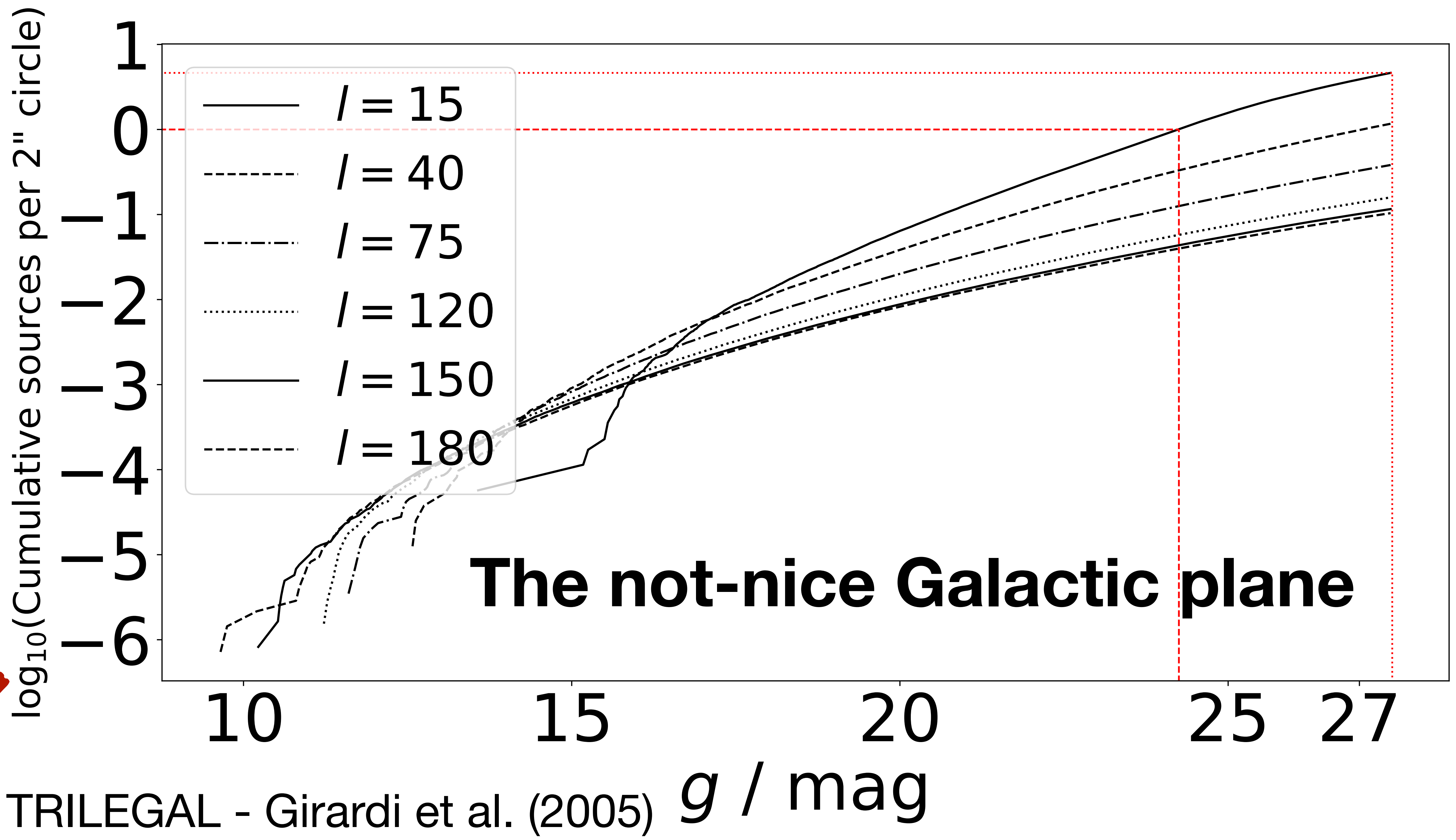
The Problem With Vera C. Rubin Obs.'s LSST





TRILEGAL - Girardi et al. (2005)

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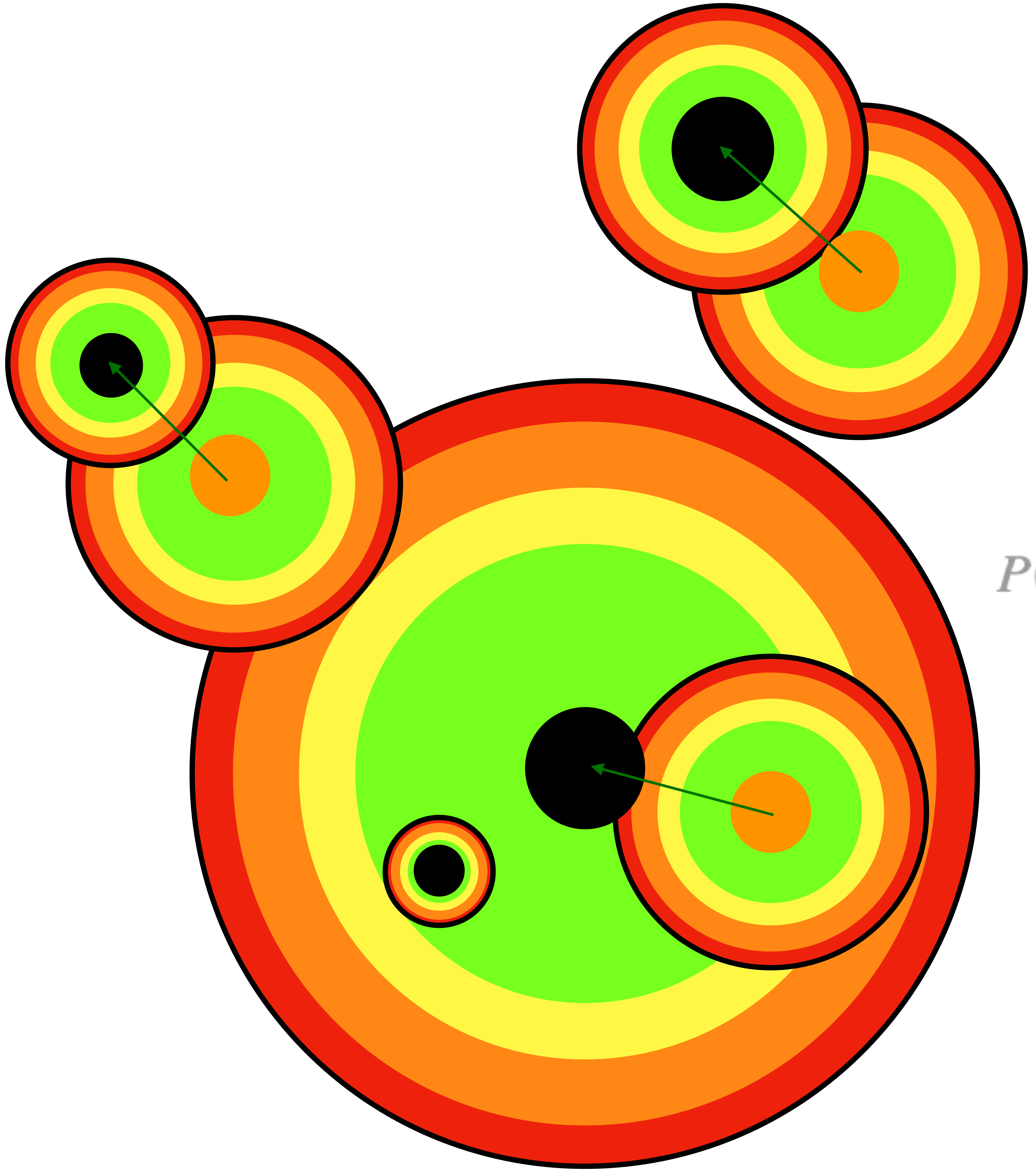
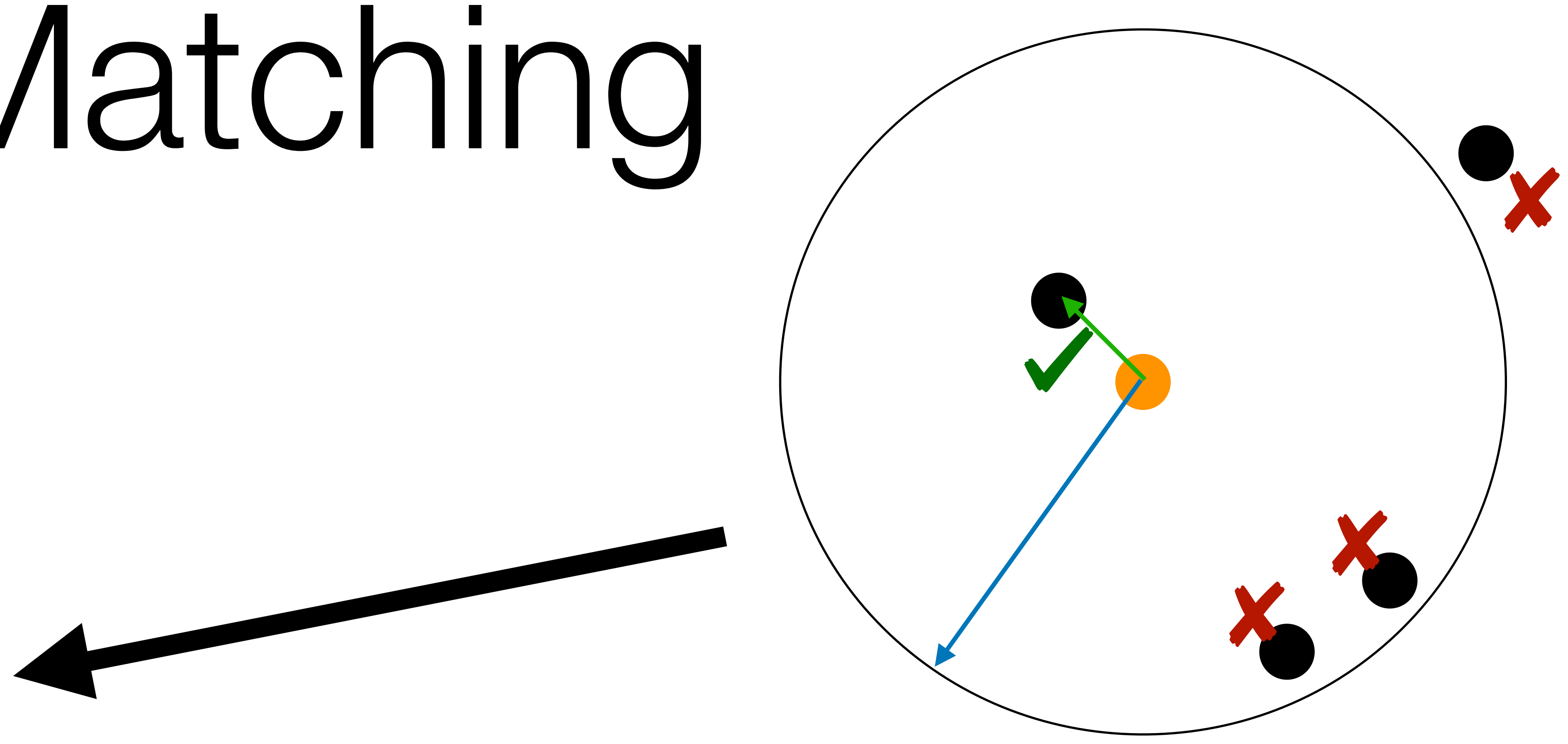
Probabilistic Cross-Matching





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

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

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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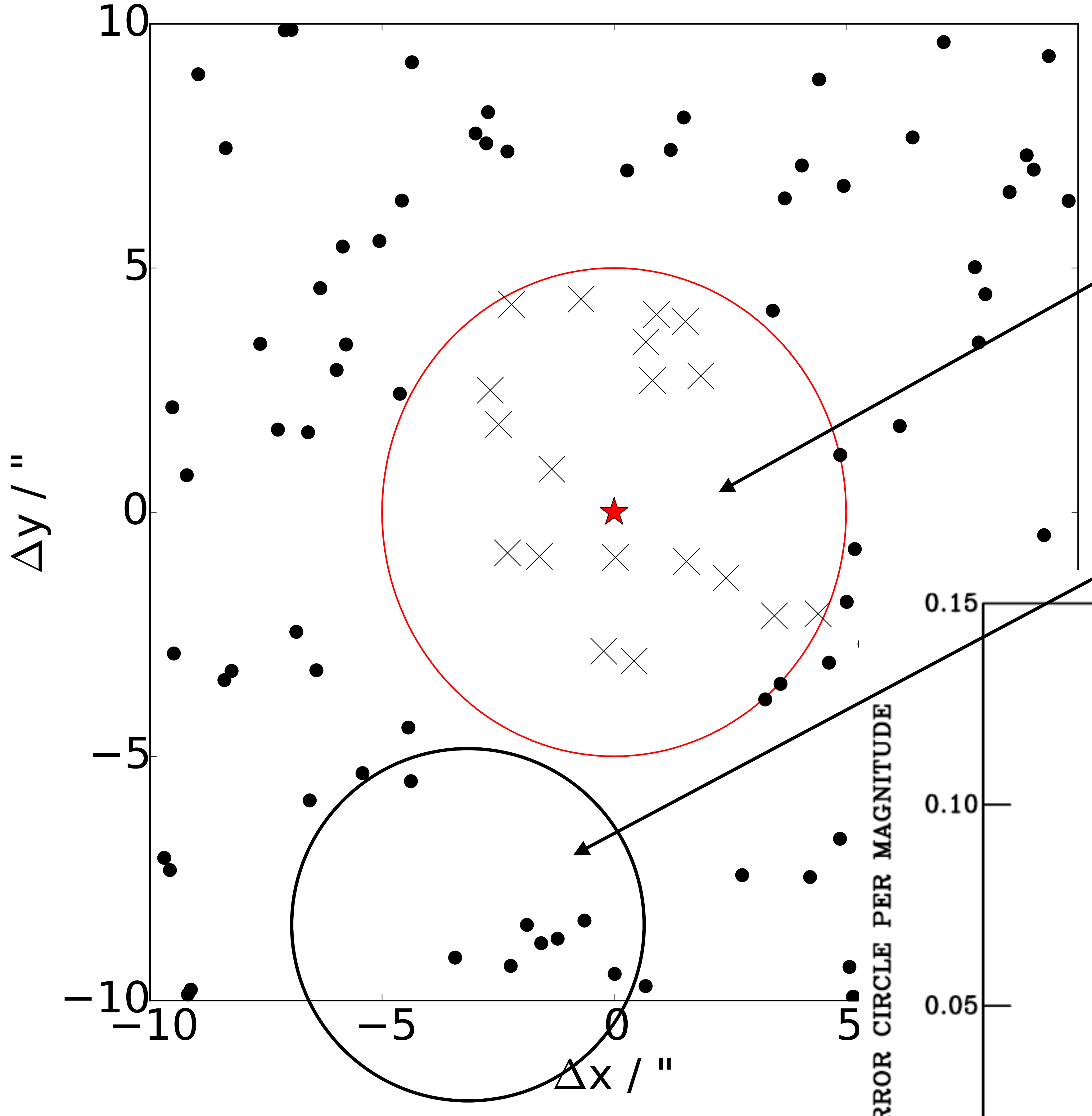
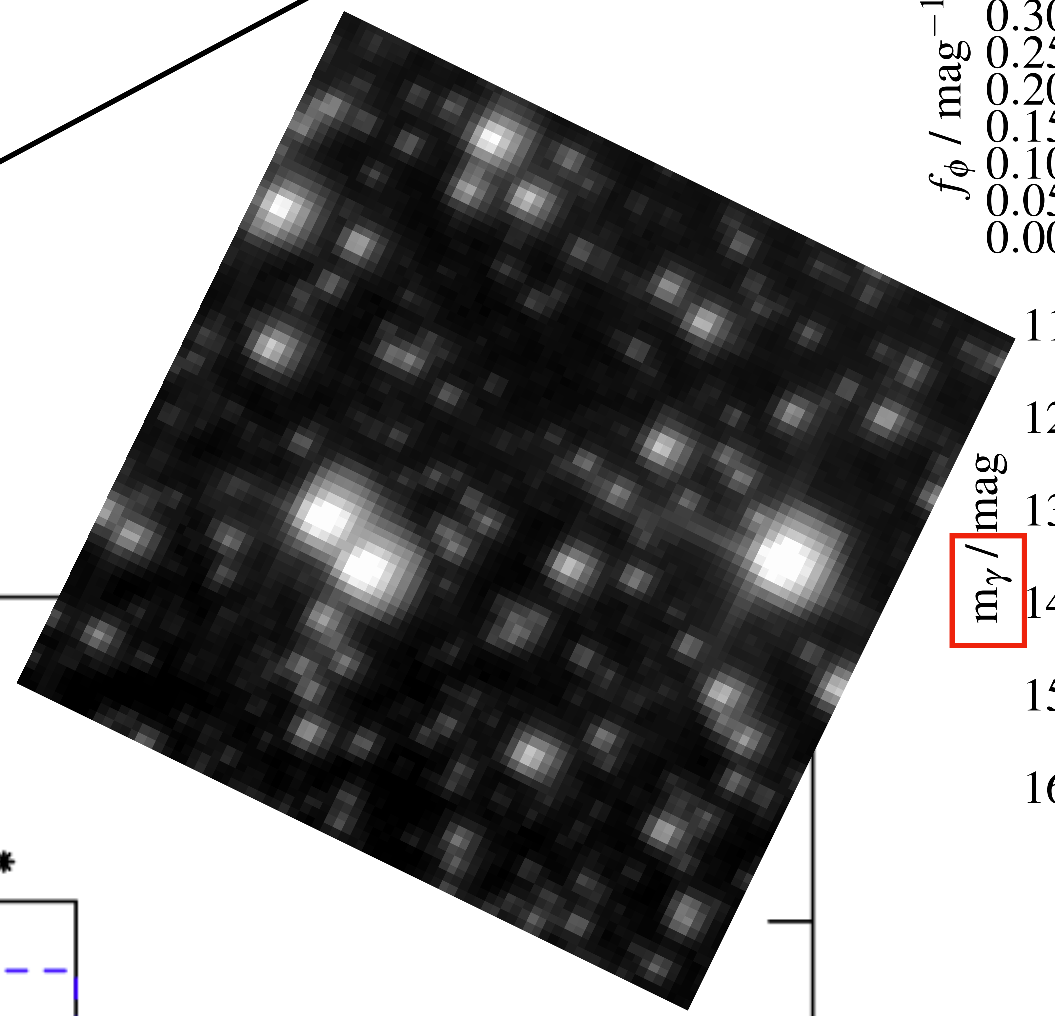
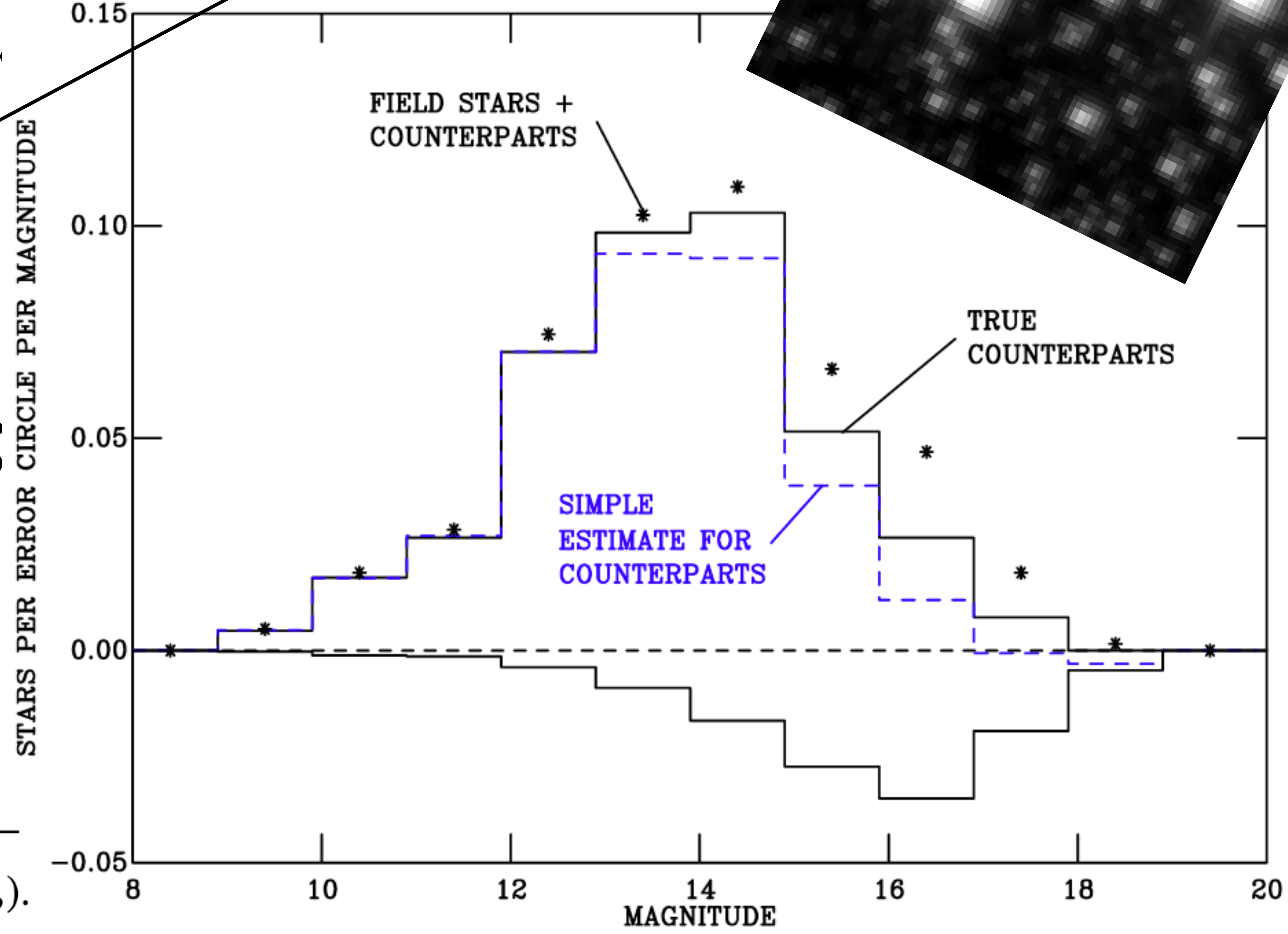
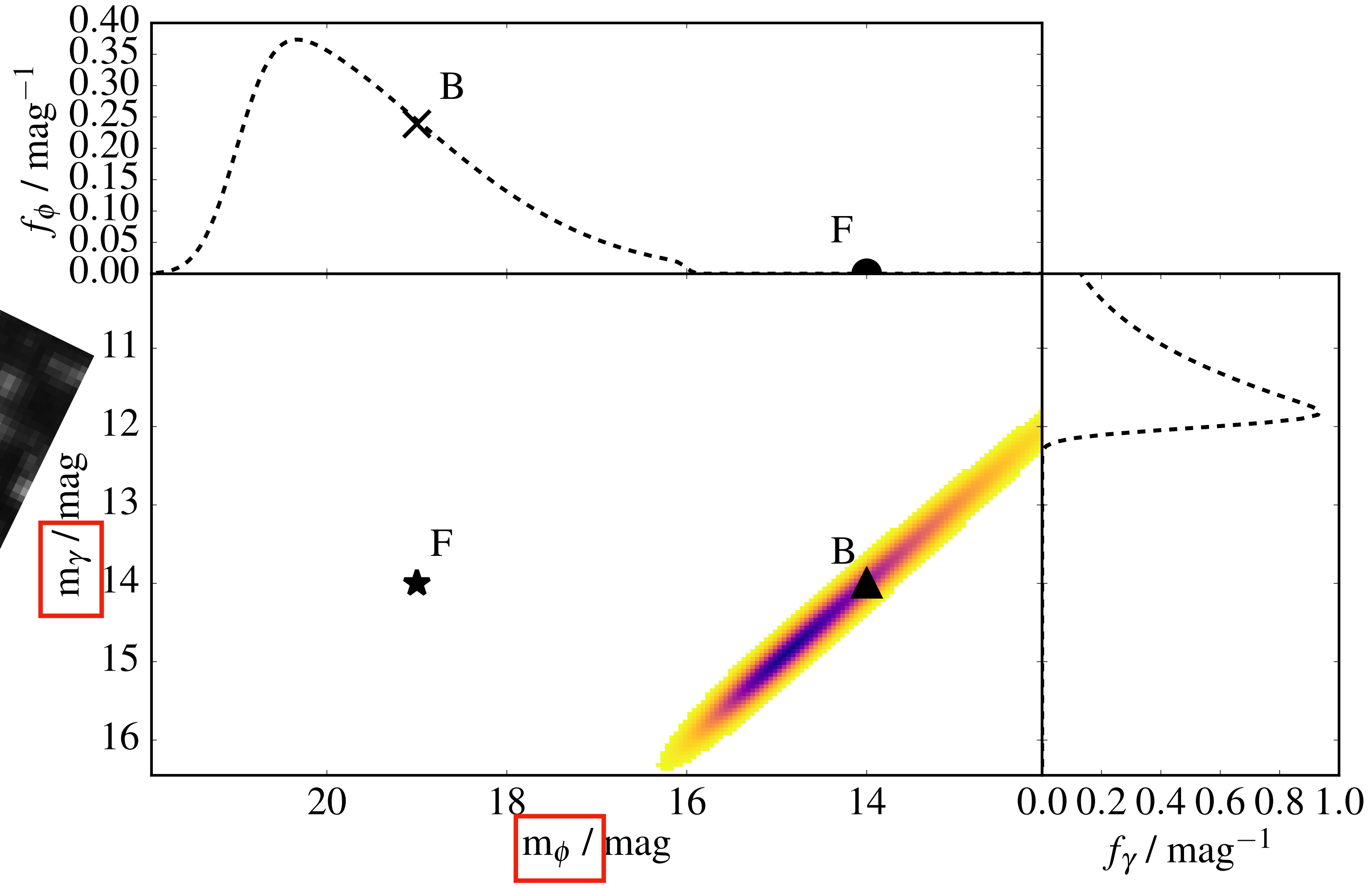
Photometry: Rejecting False Positives



Counterparts = ("Counterparts" + field) - field







Where needed, photometry-based likelihoods (c and f) allow us to mitigate high false positive rates

$$Z_{c\gamma}\cdot c_\gamma(m_\phi|m_\gamma) = Z_\gamma b_\gamma(m_\phi|m_\gamma)\exp\left(A_\gamma N_\phi F_\phi(m_\phi)\right) - \left(1 - Z_{c\gamma}C_\gamma(m_\phi|m_\gamma)\right) A_\gamma N_\phi f_\phi(m_\phi).$$

Naylor, Broos, & Feigelson (2013); Wilson & Naylor (2018a)

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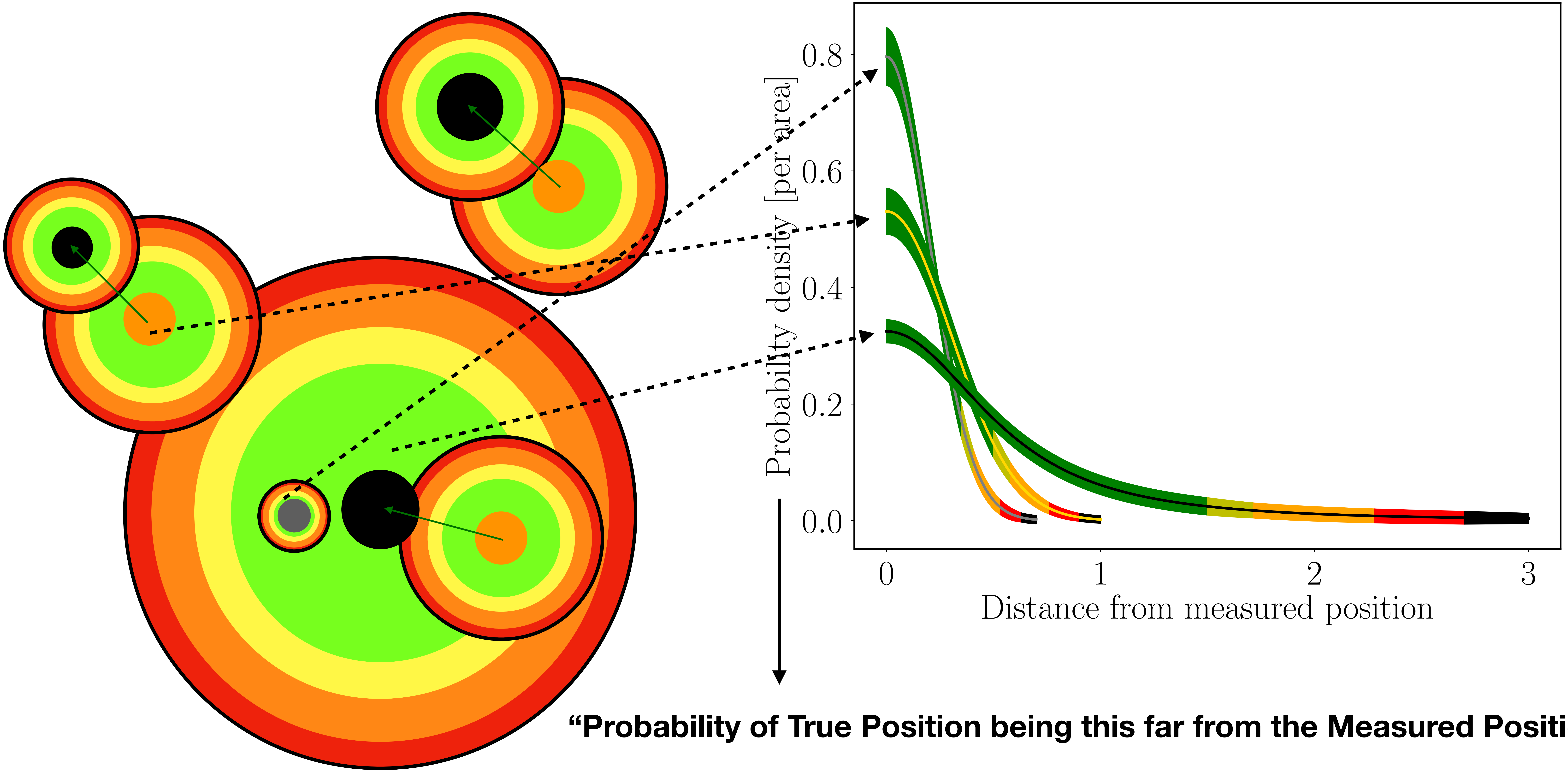
Probabilistic Cross-Matching: the AUF



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

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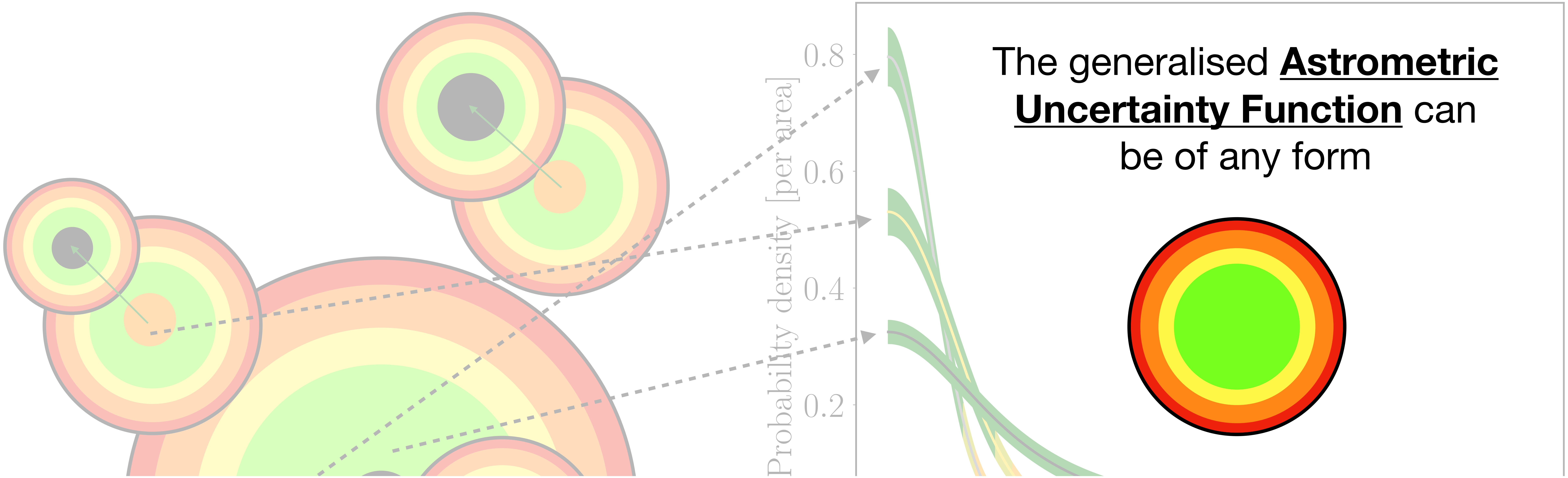
Probabilistic Cross-Matching: the AUF



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)

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

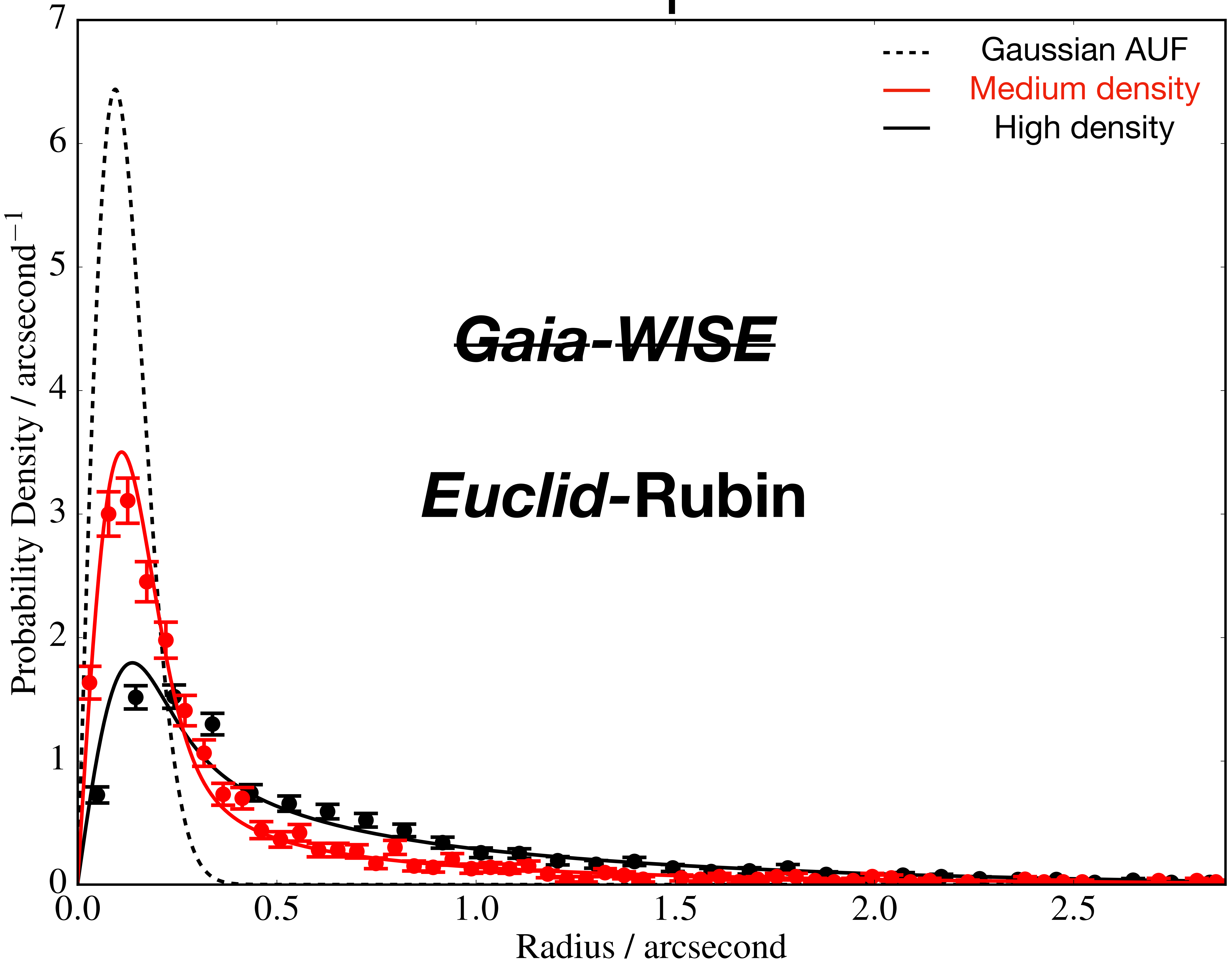
Naylor, Broos, & Feigelson (2013)

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

Budavári & Szalay (2008)

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

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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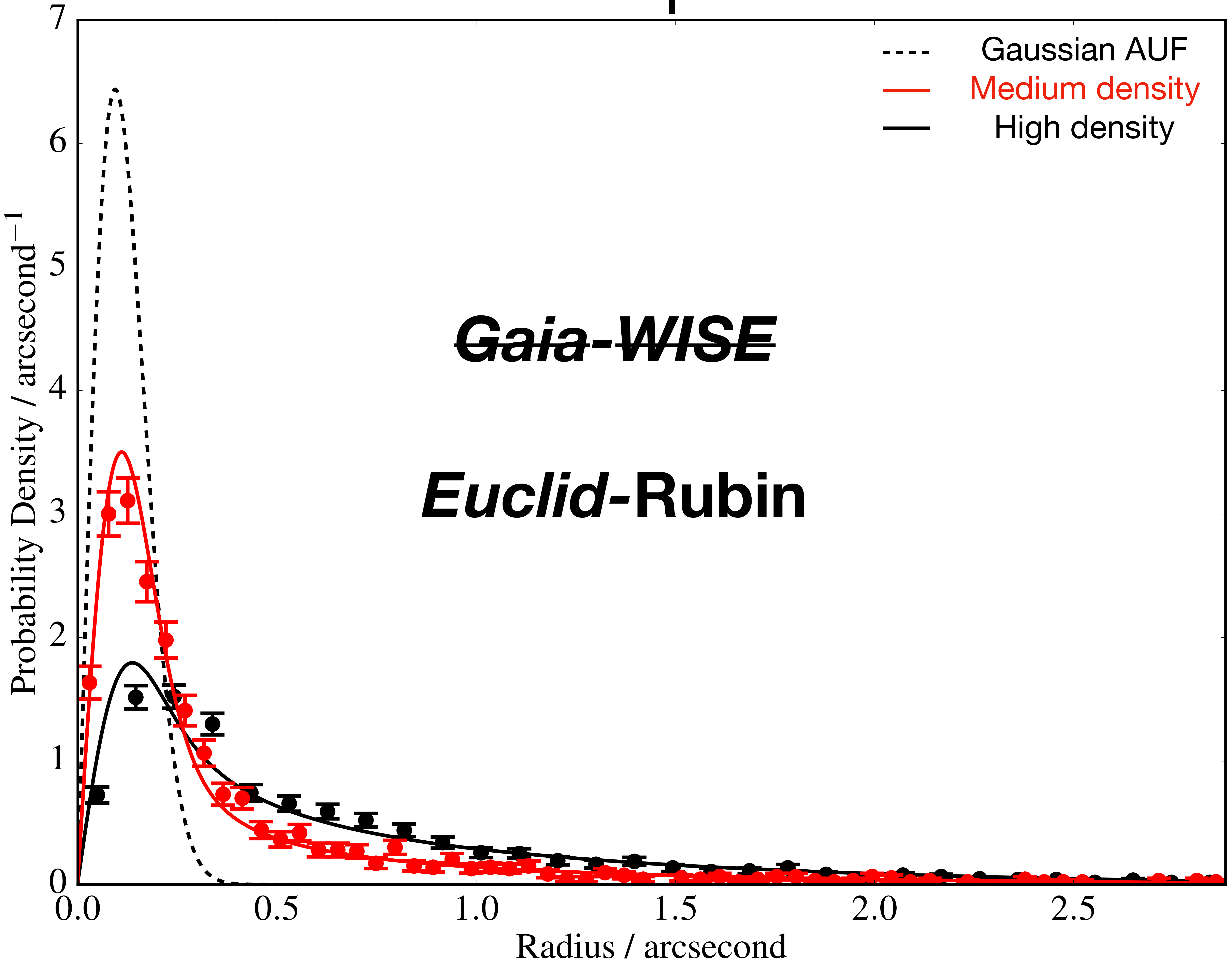

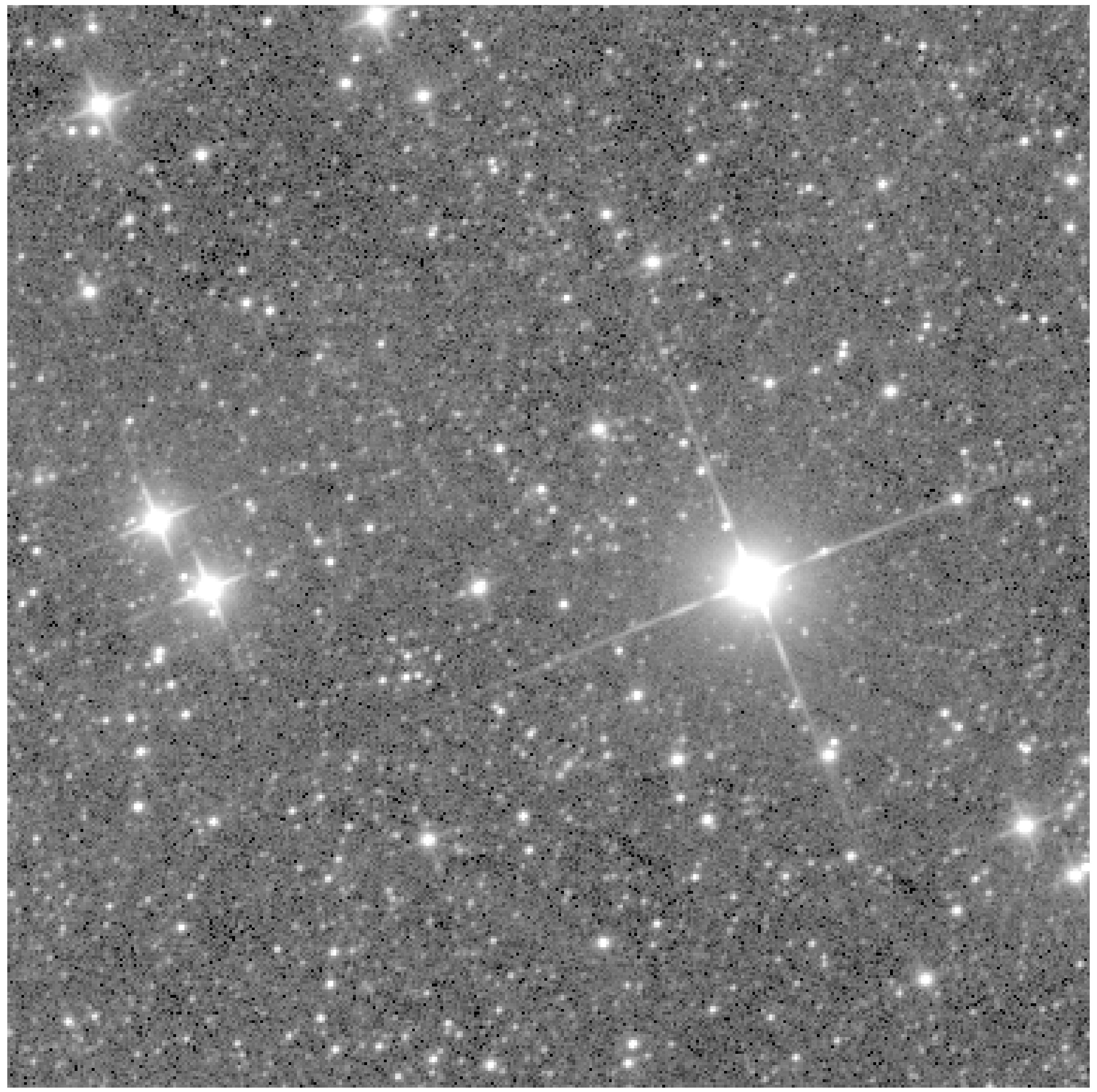

WISE - Wright et al. (2010)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

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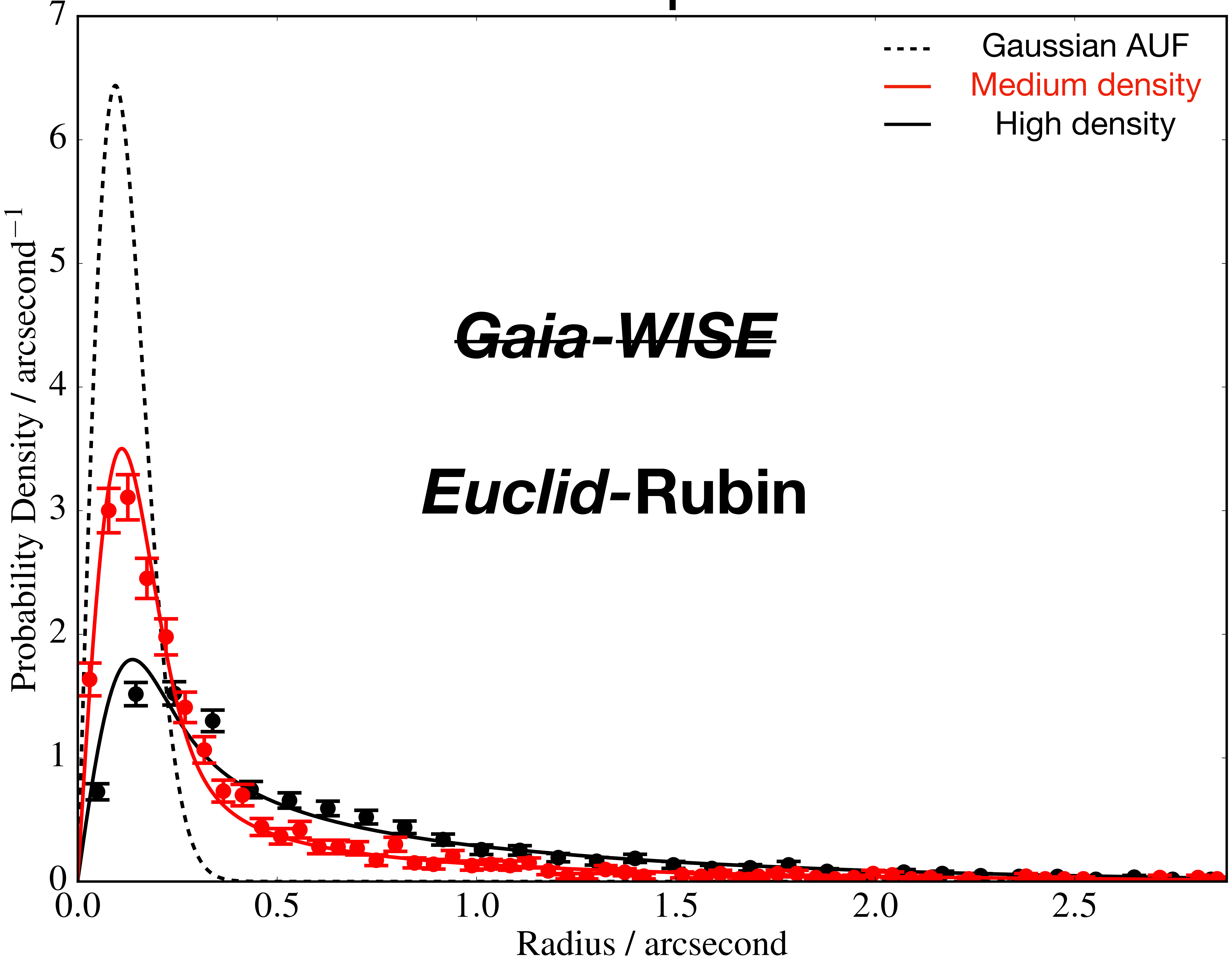
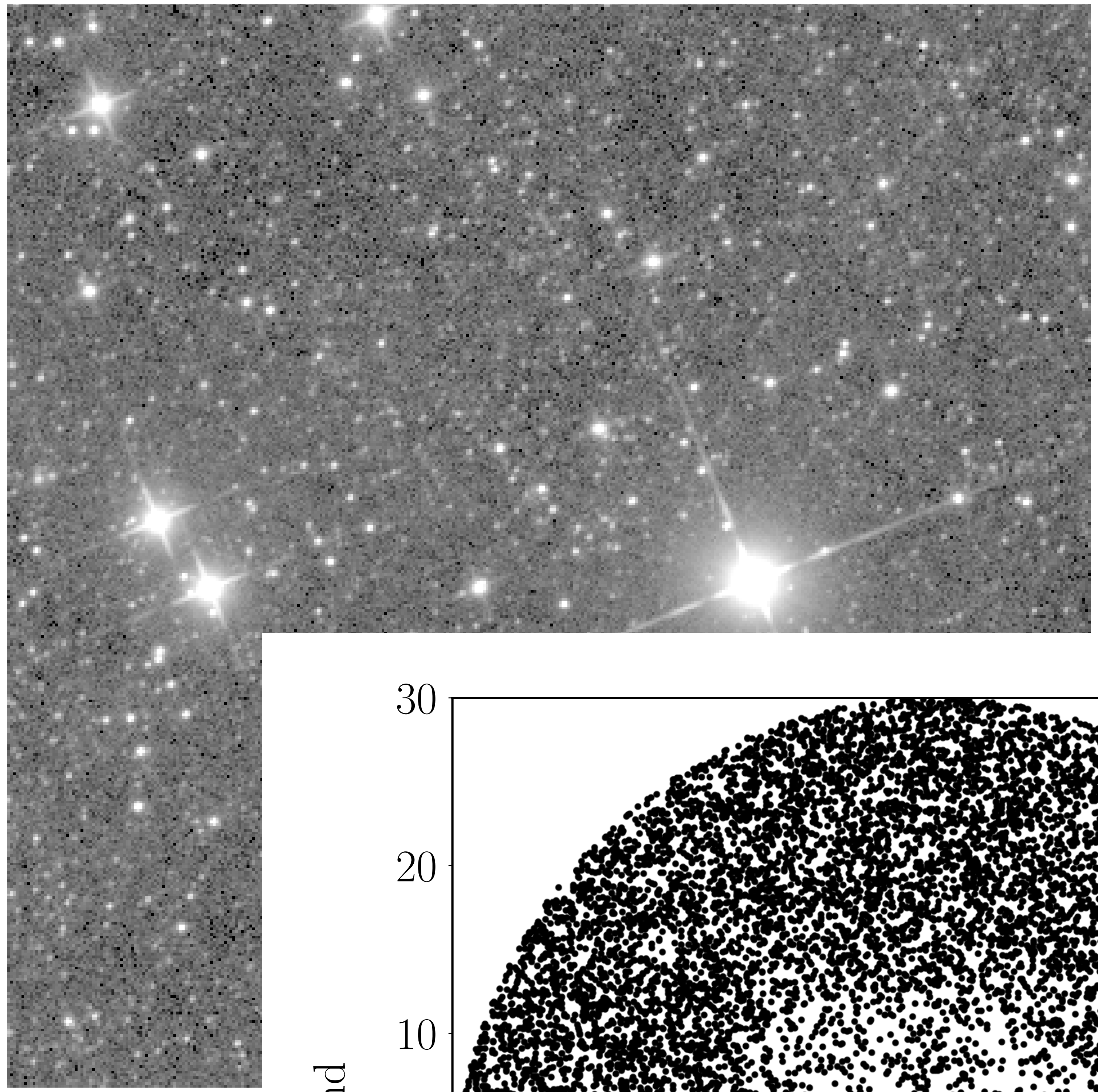
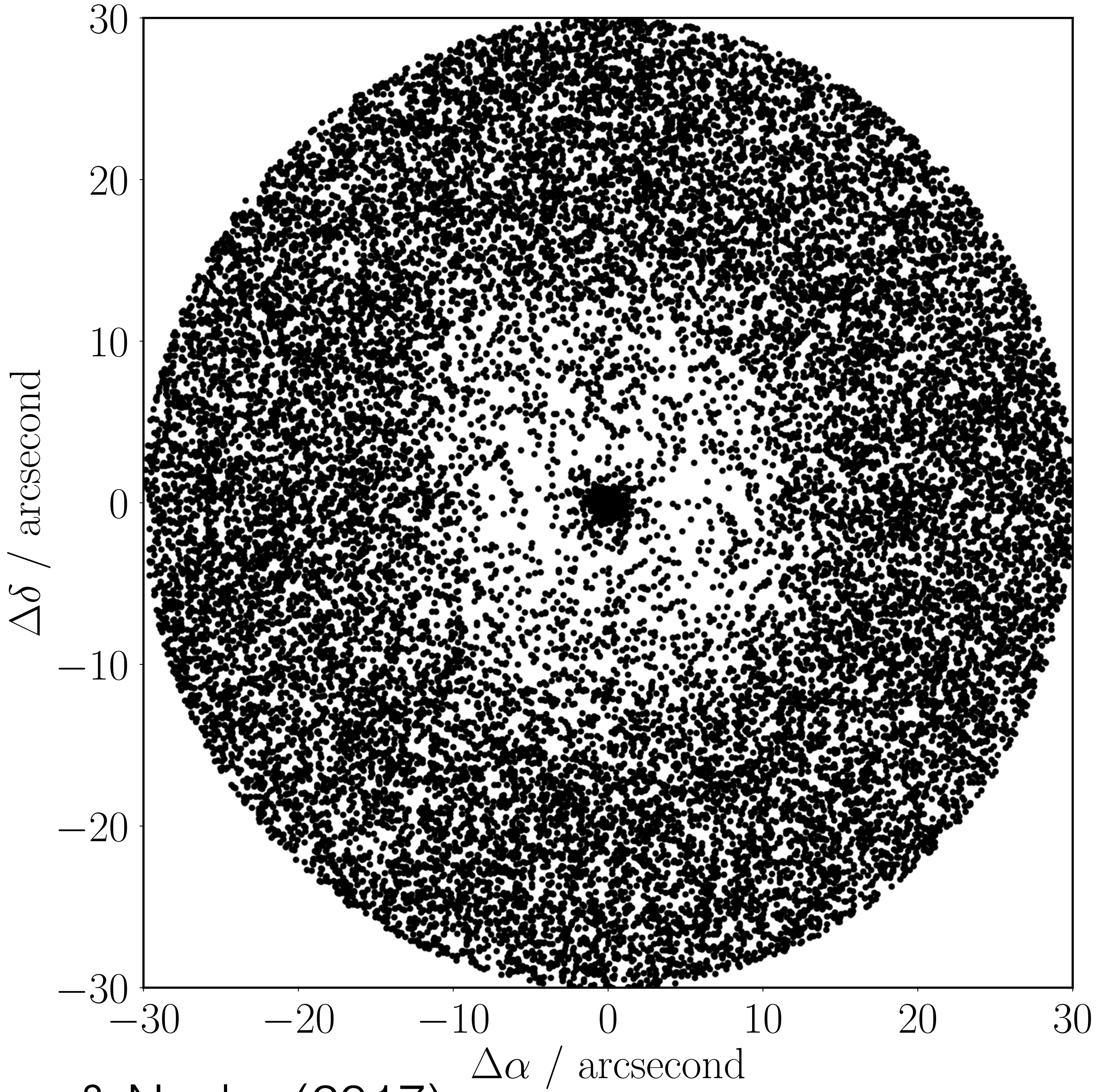
Additional Components of the AUF

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







Wilson & Naylor (2017)

WISE - Wright et al. (2010)

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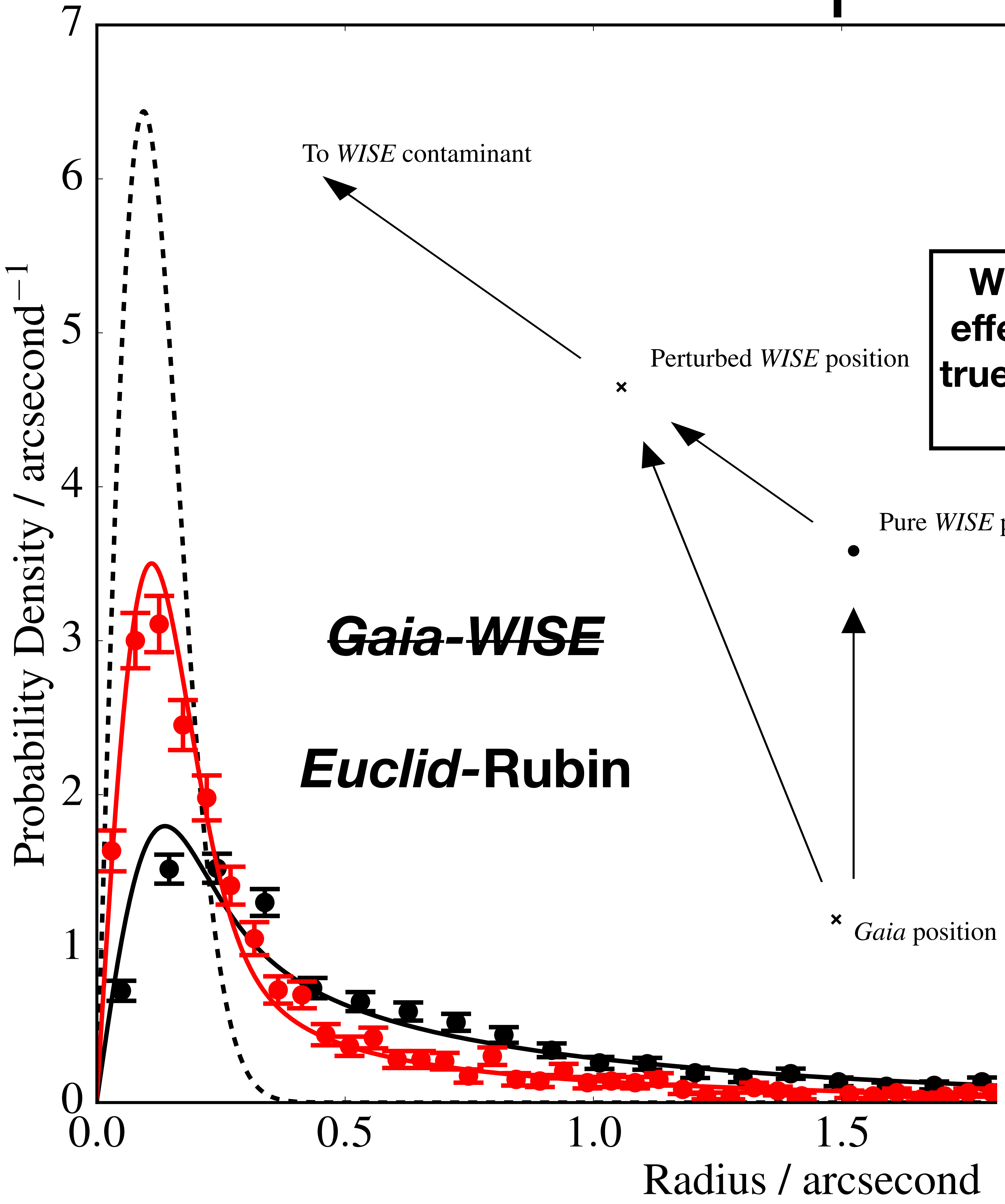
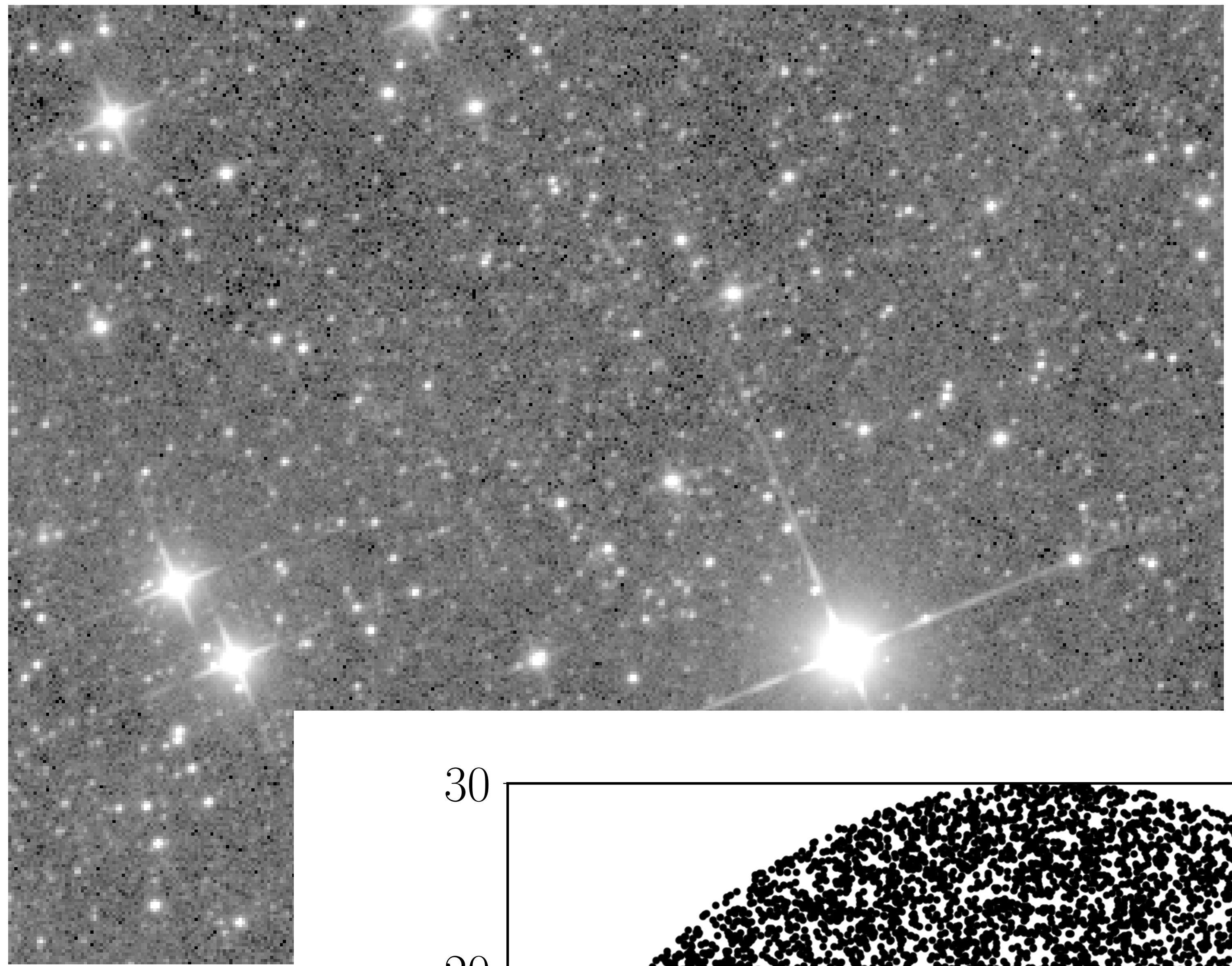
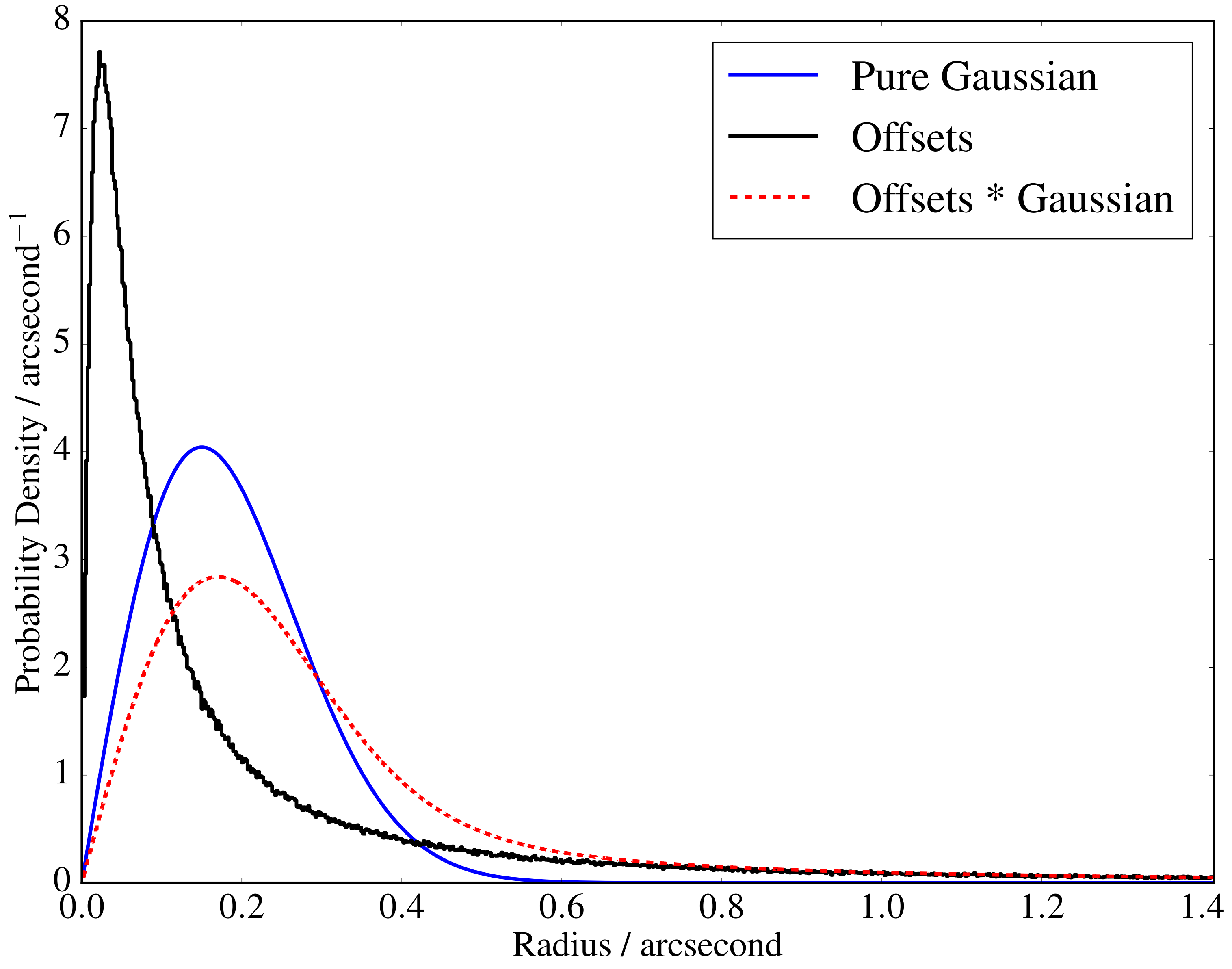
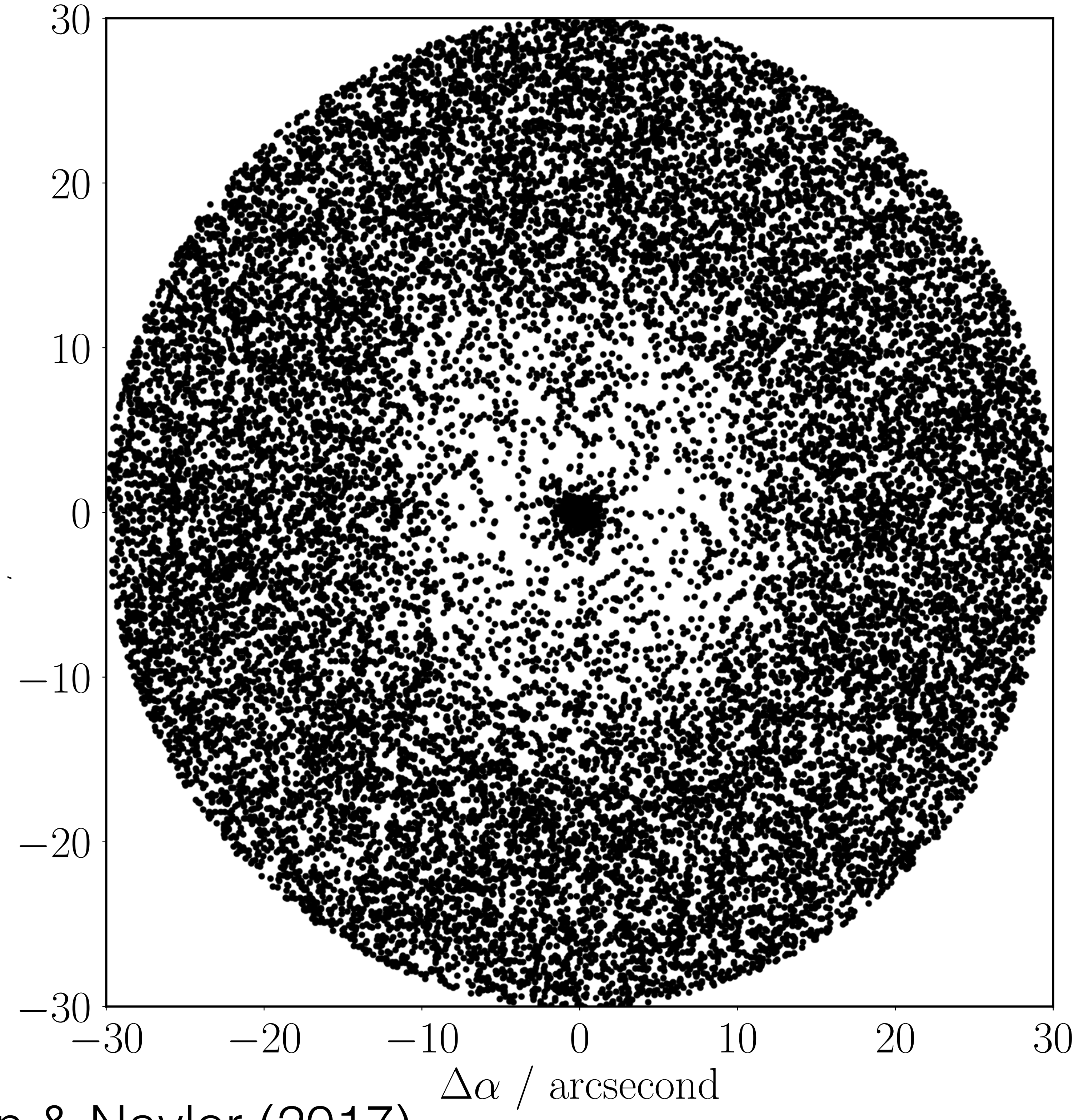


Without modelling this extra effect, we fail to recover many true pairings, with an artificially high false negative rate!





Wilson & Naylor (2018b)



Wilson & Naylor (2017)

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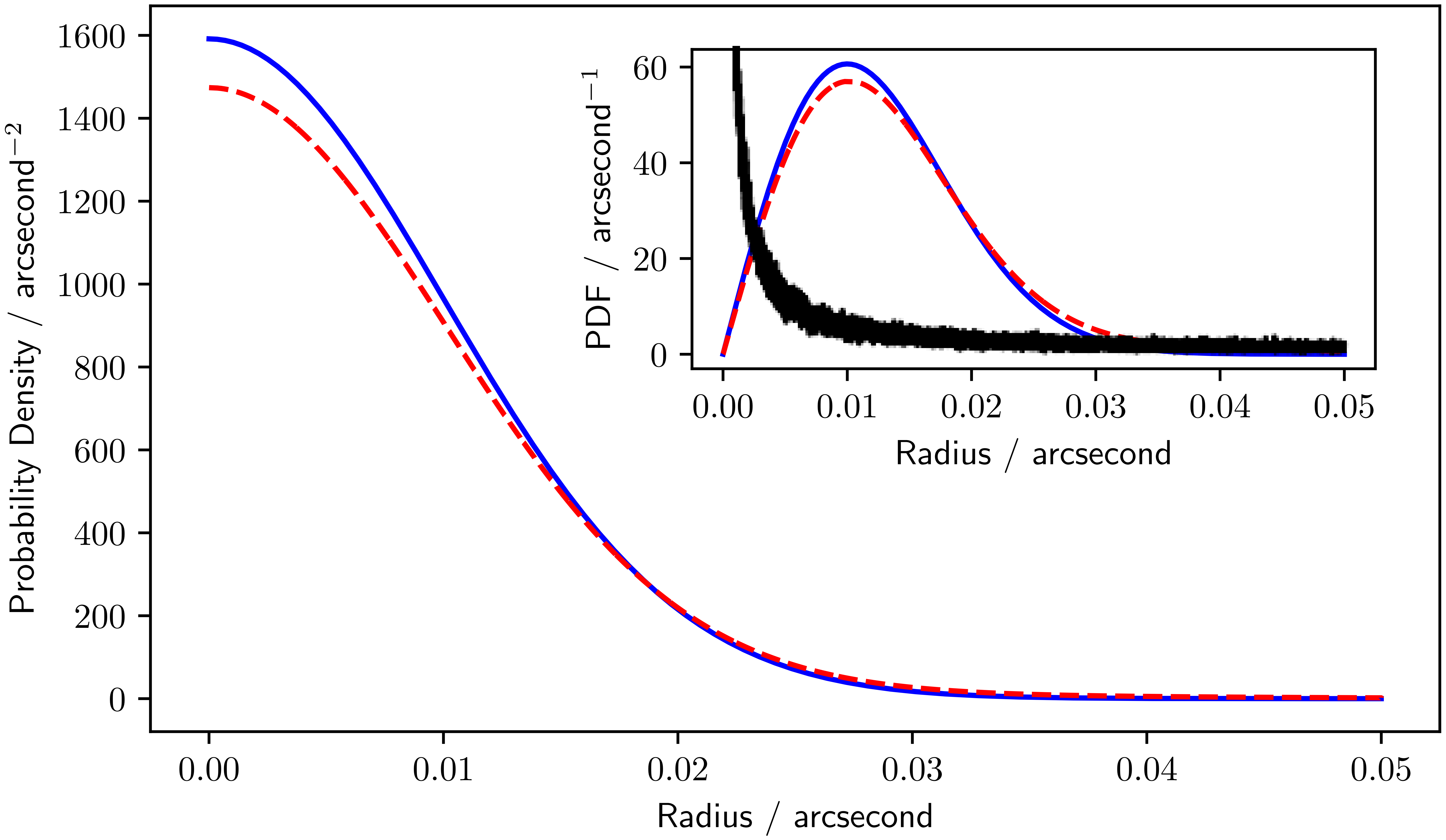
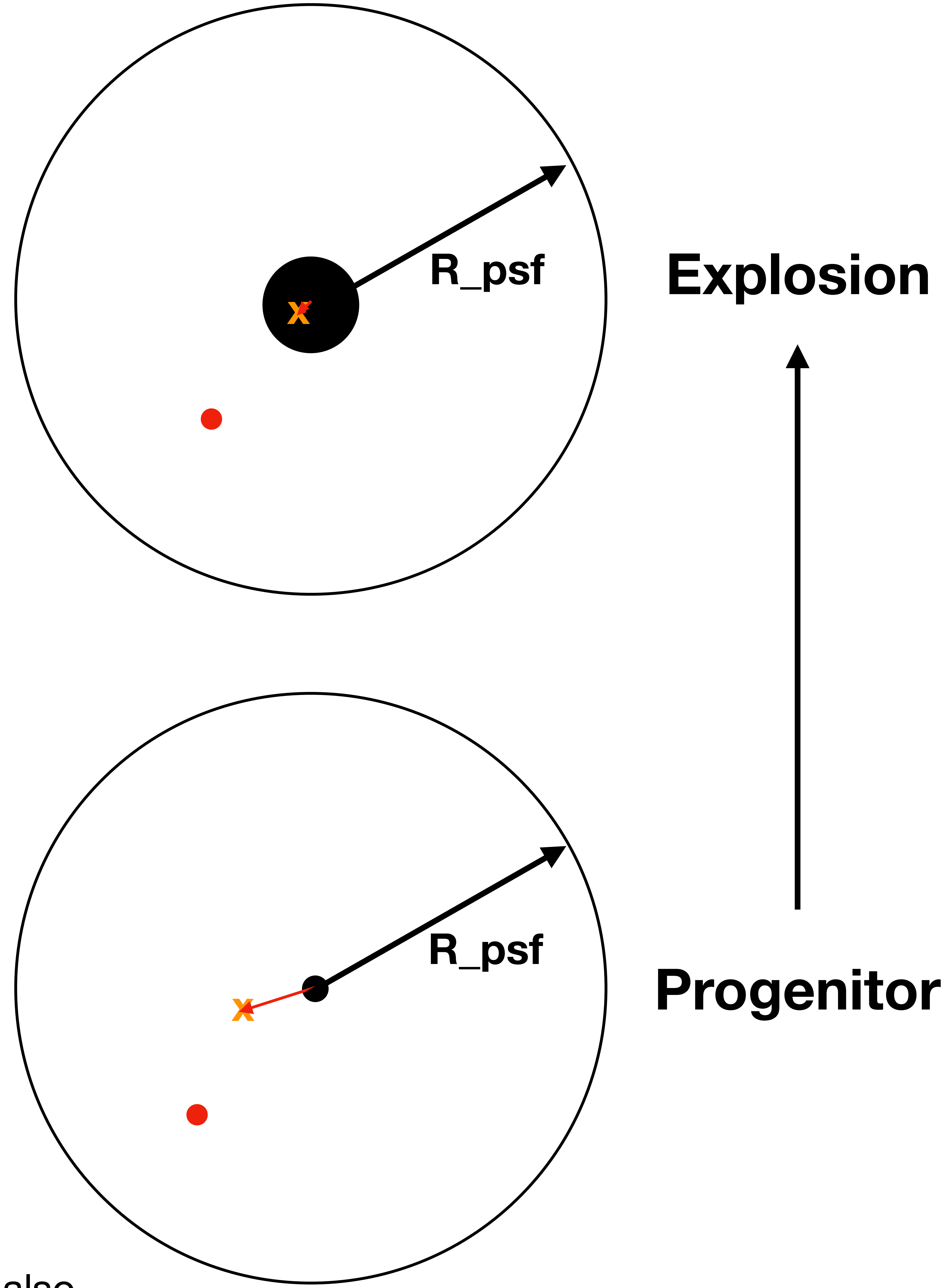
Effects of Crowding: Transients





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

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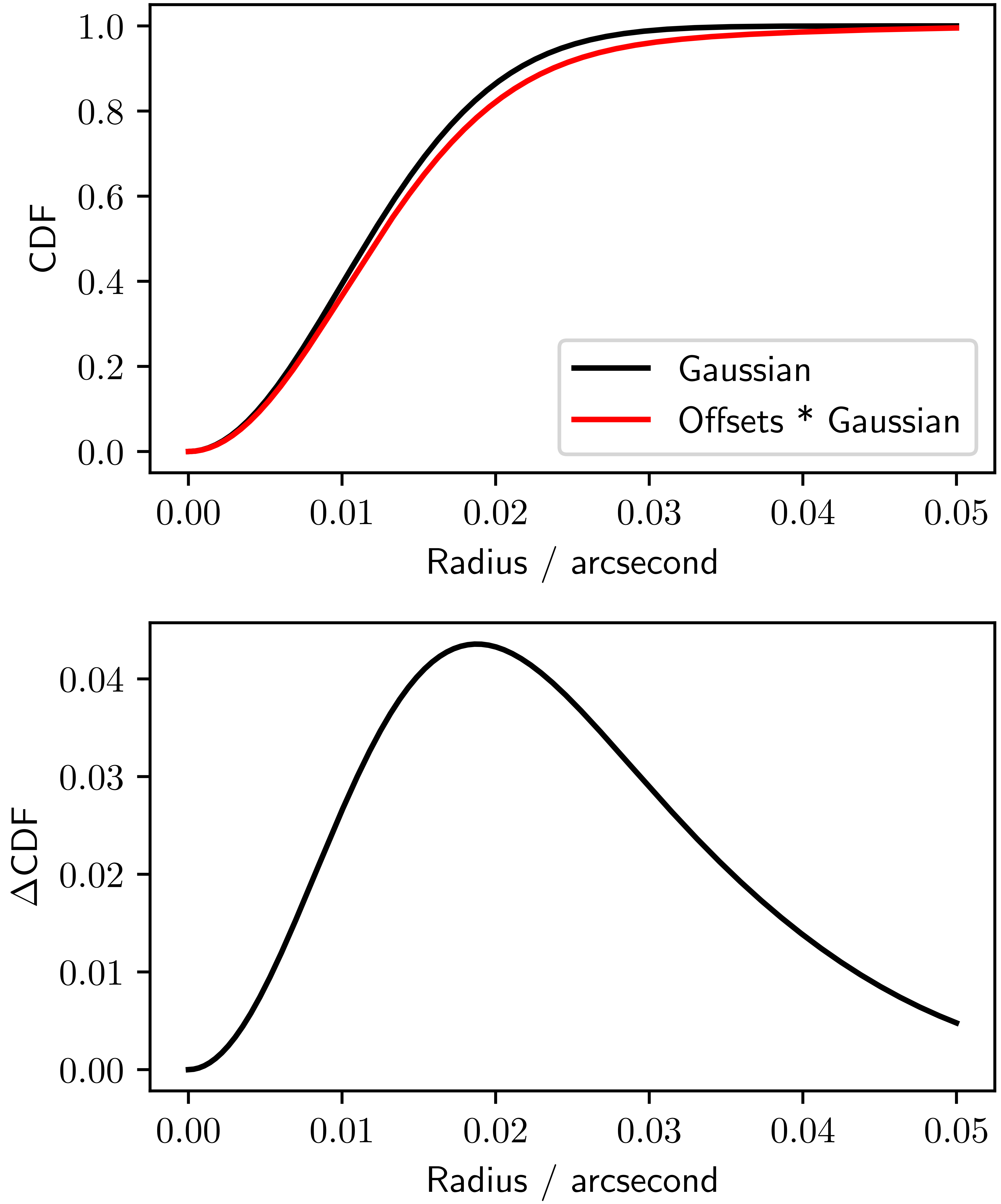
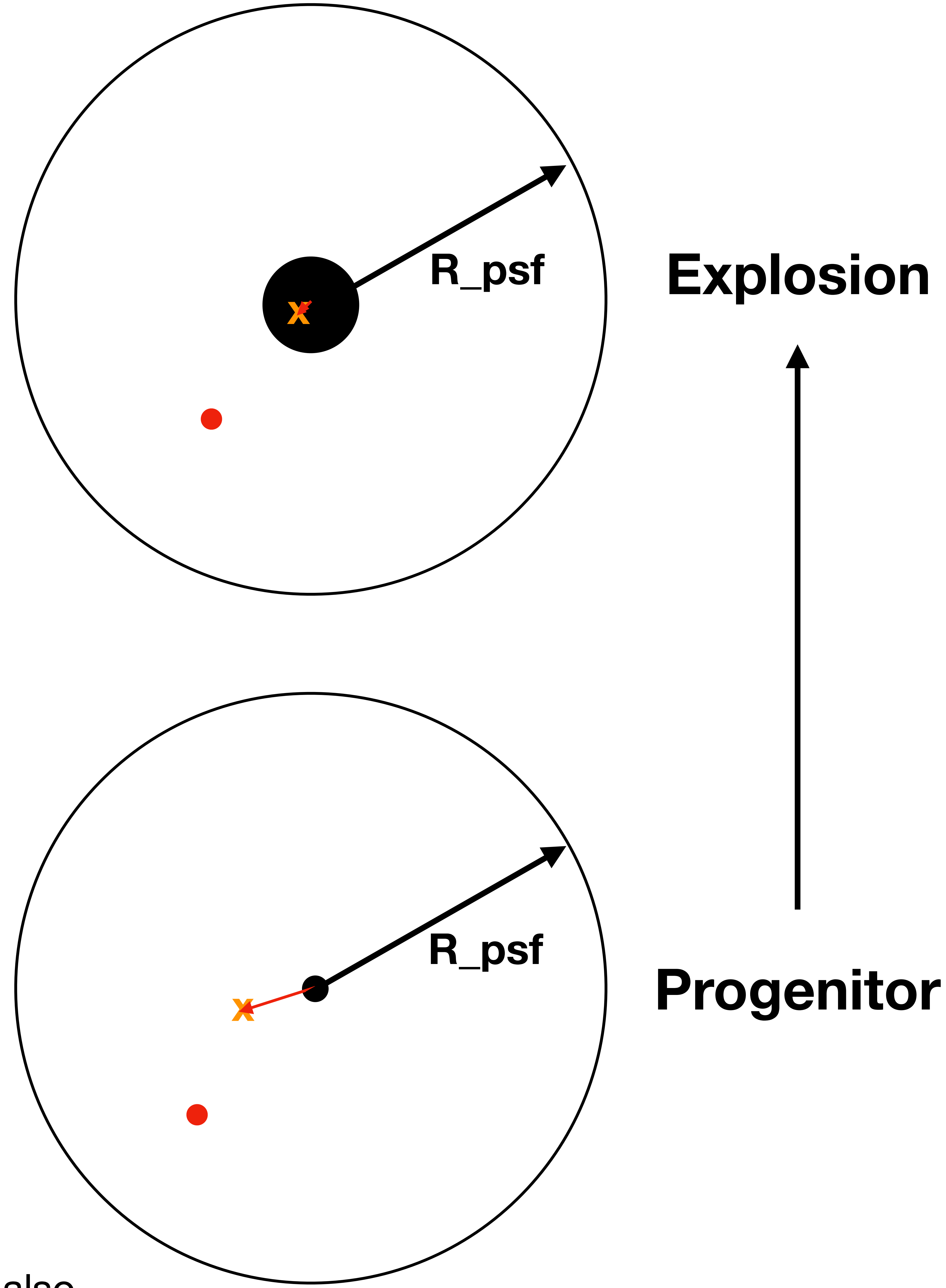
Effects of Crowding: Transients





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

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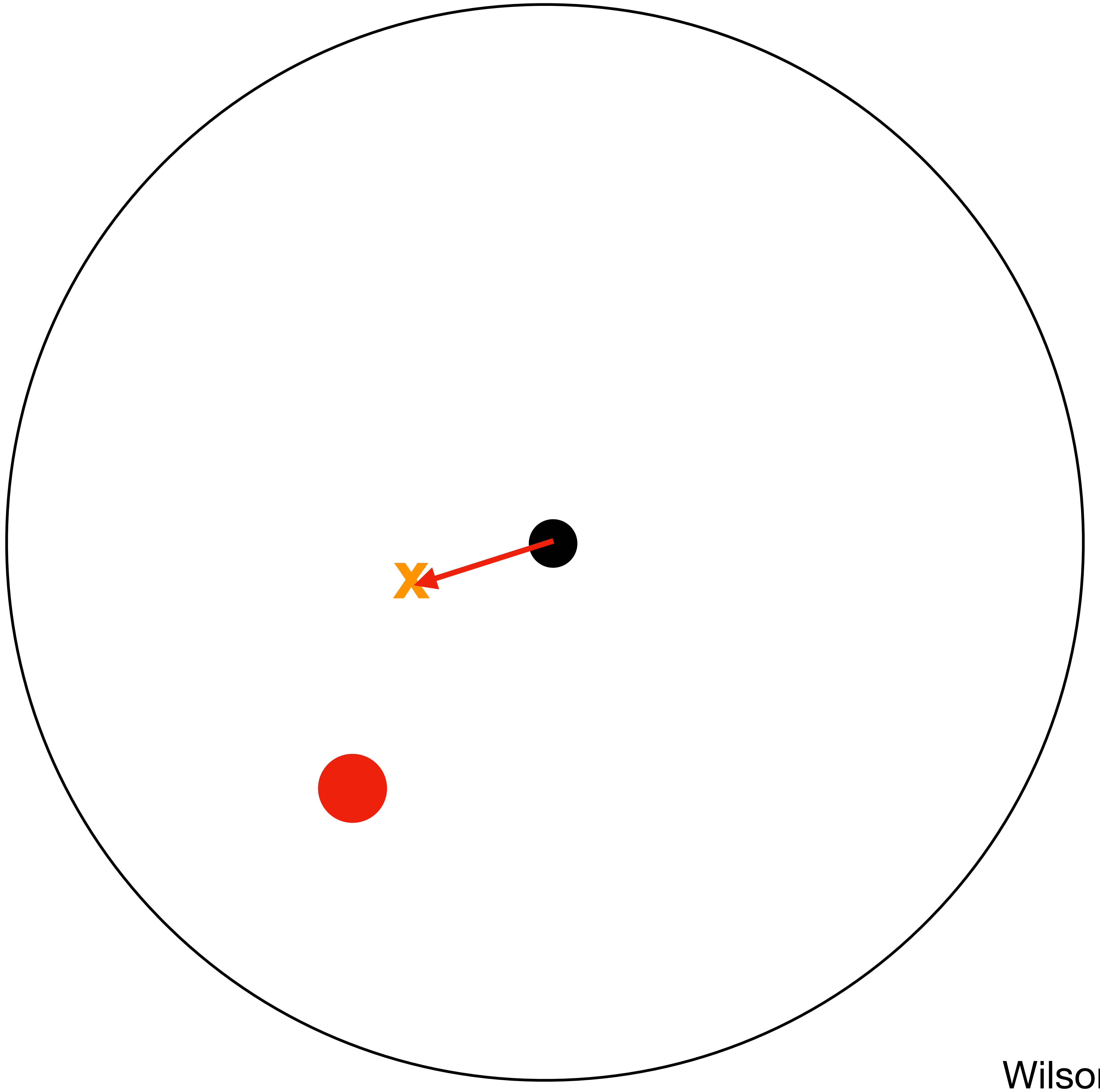
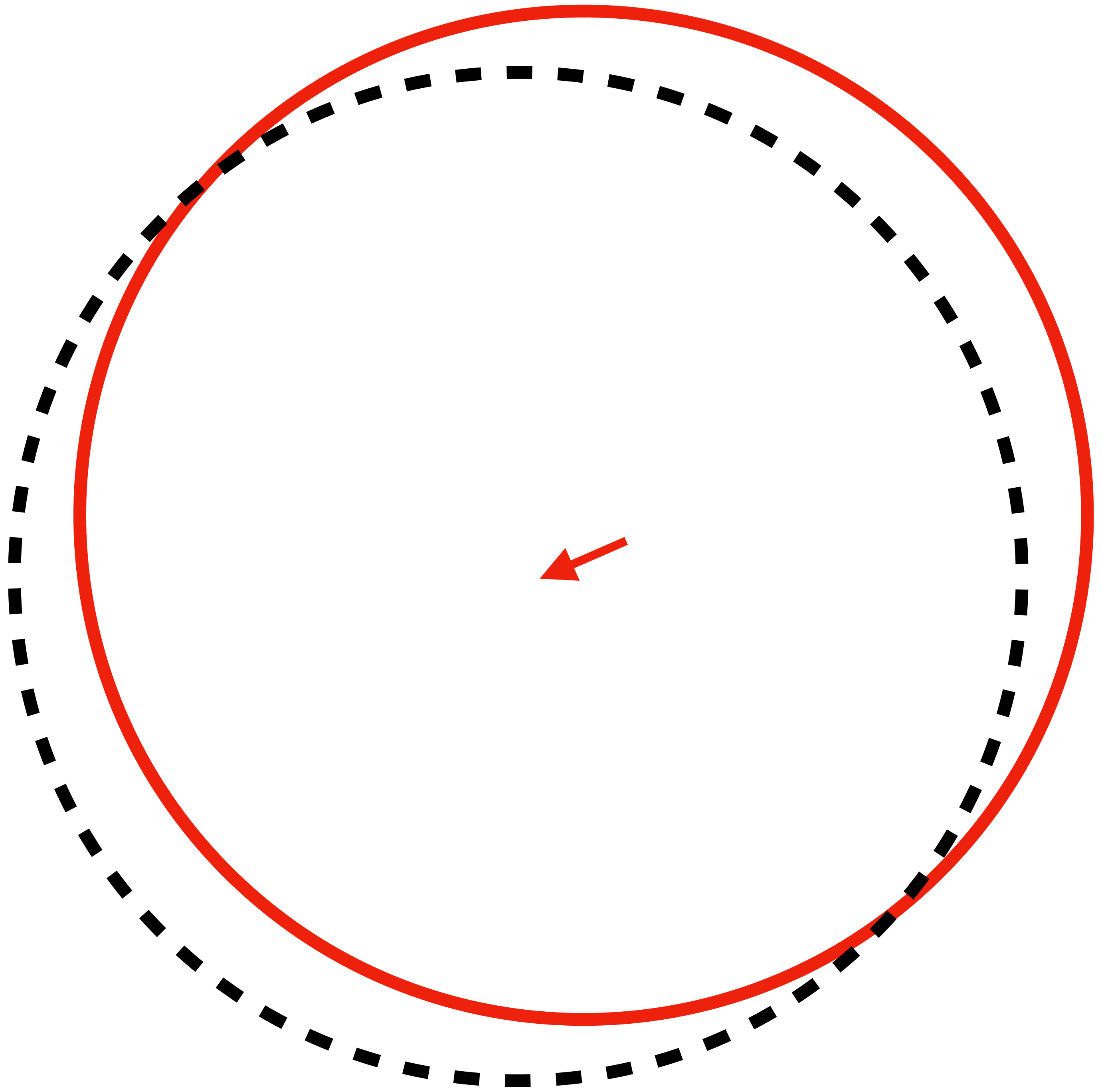
Why Not (Always) Forced Photometry?

1. *Euclid* positions may not be perturbed (although still subject to some centroid noise), but (e.g.) Rubin positions will be noisy and biased





Can get around this by folding the full AUF into the forced photometry framework instead of forcing only the maximum likelihood position

Wilson & Naylor (2017, 2018a,b, in prep)

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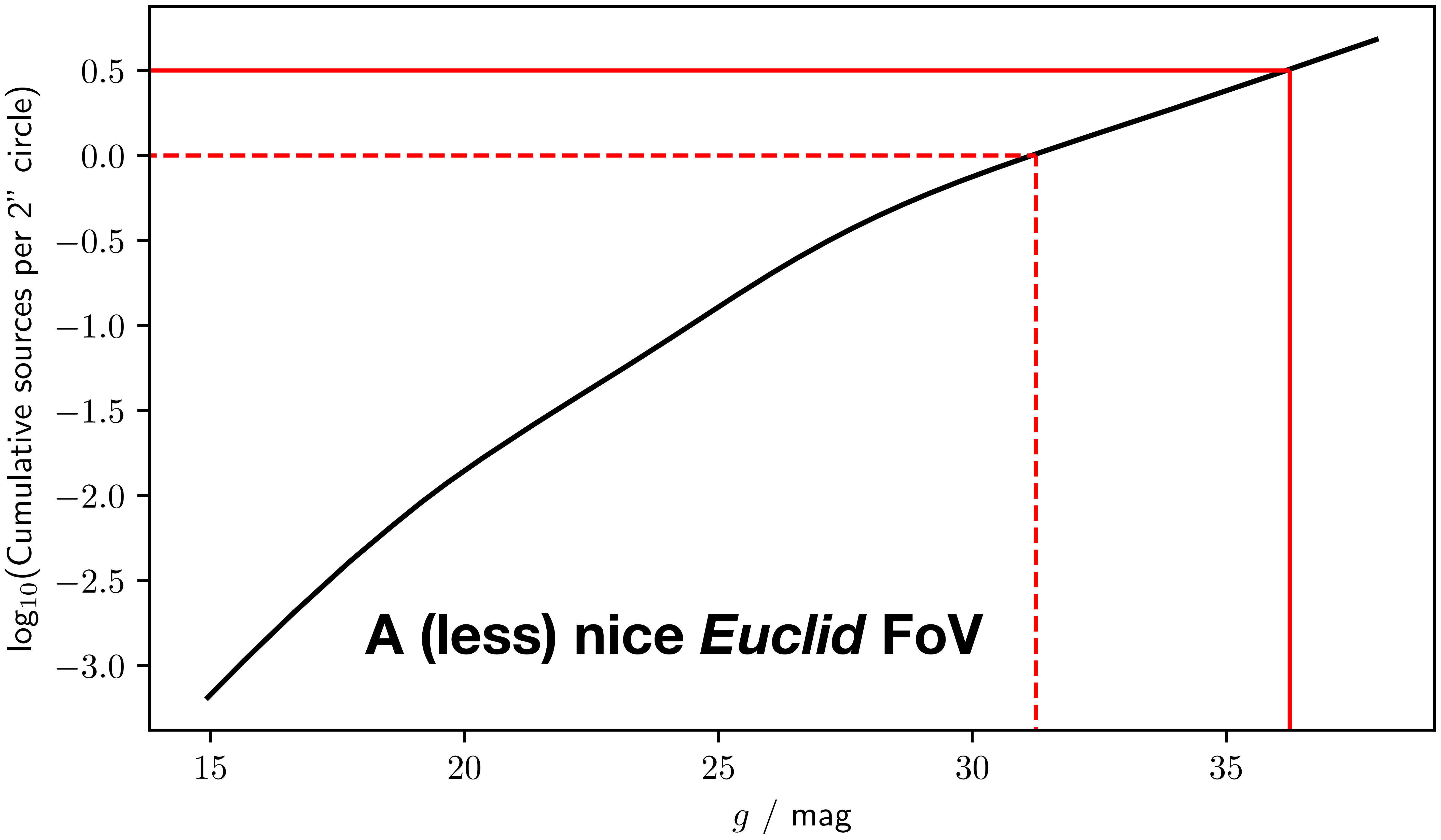
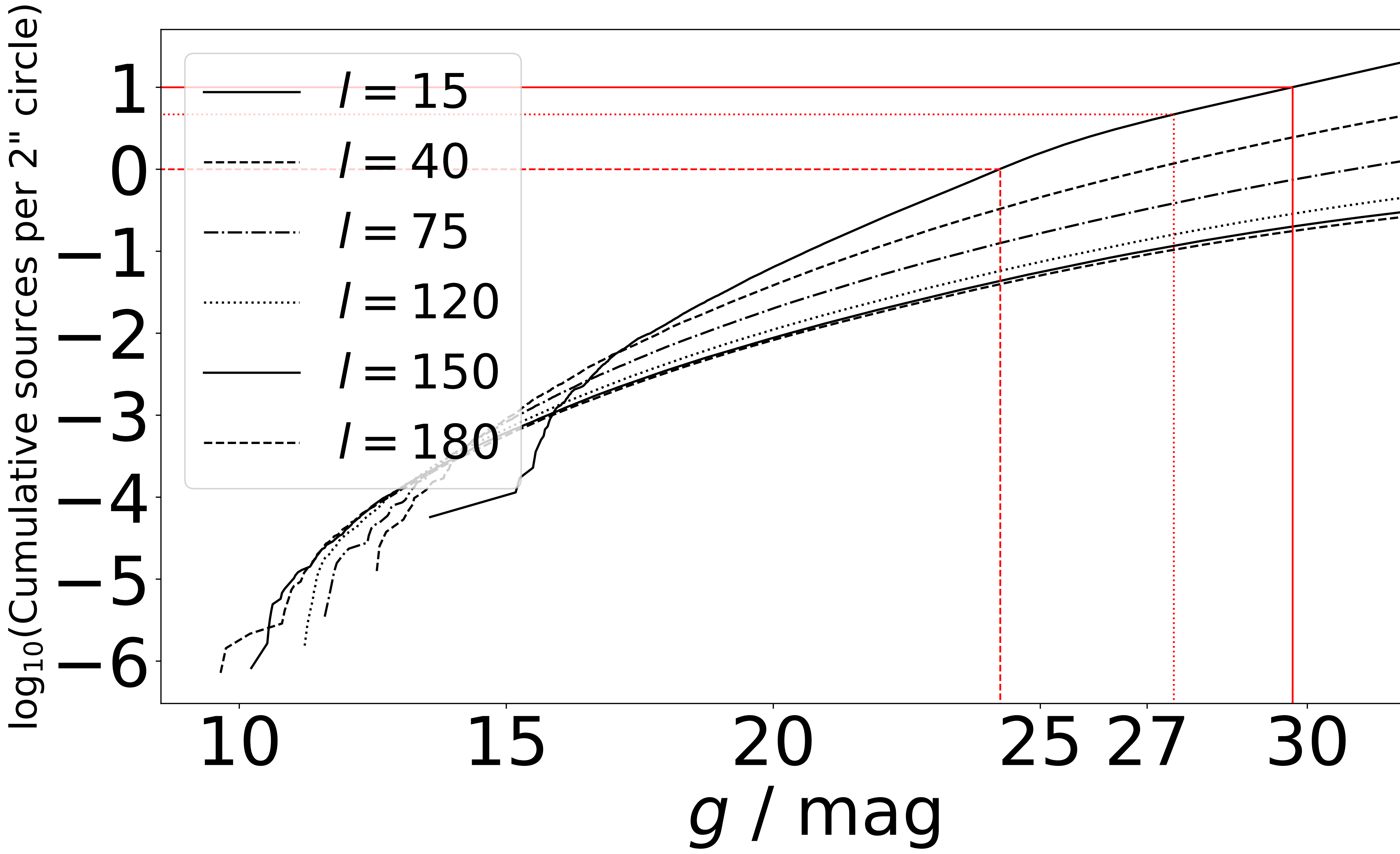
Why Not (Always) Forced Photometry?

2. The AUF allows us to probe for systematic effects below the completeness limit of either (and both!) surveys





The (even more) not-nice Galactic plane

Wilson & Naylor (2018b)

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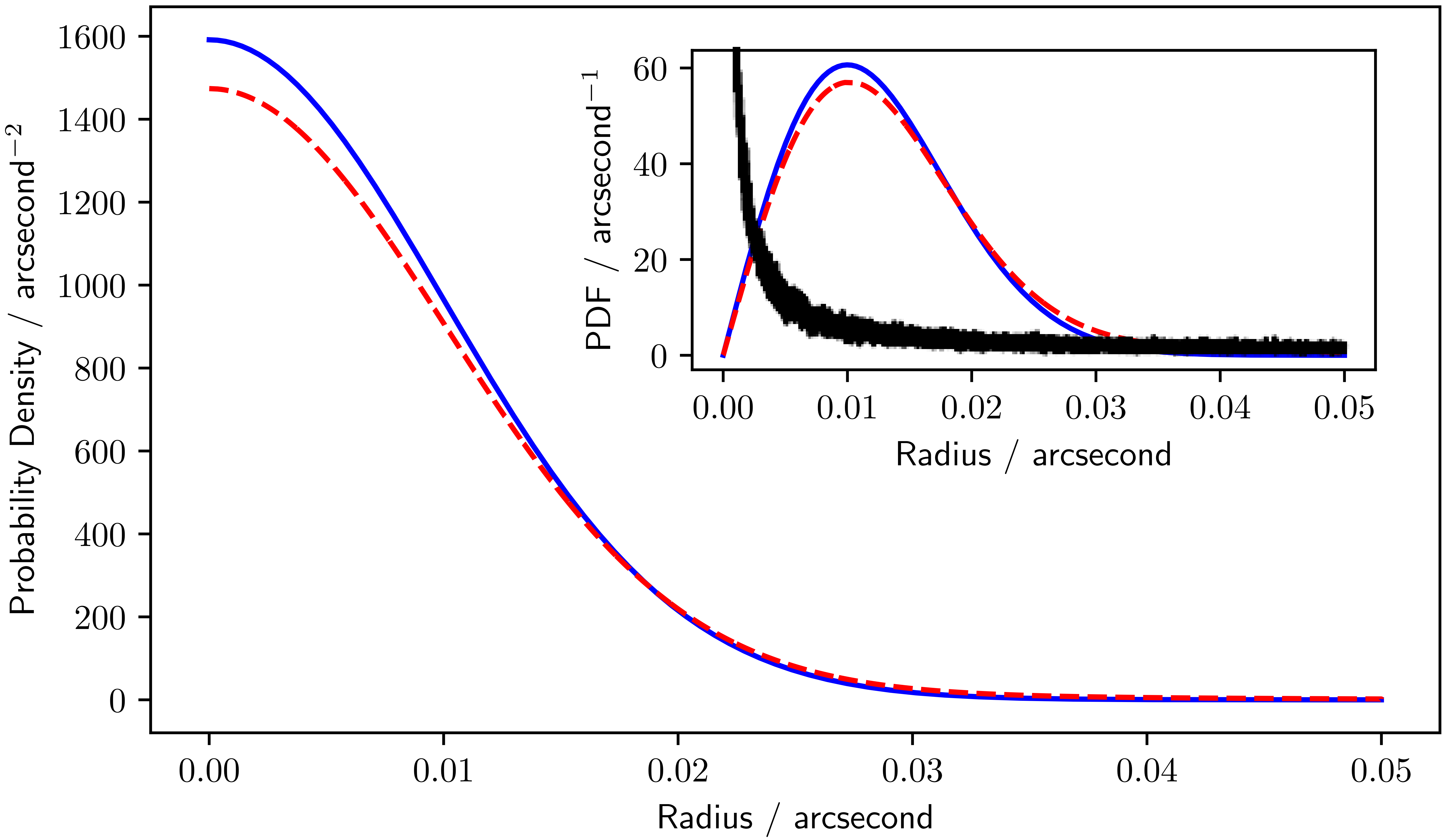
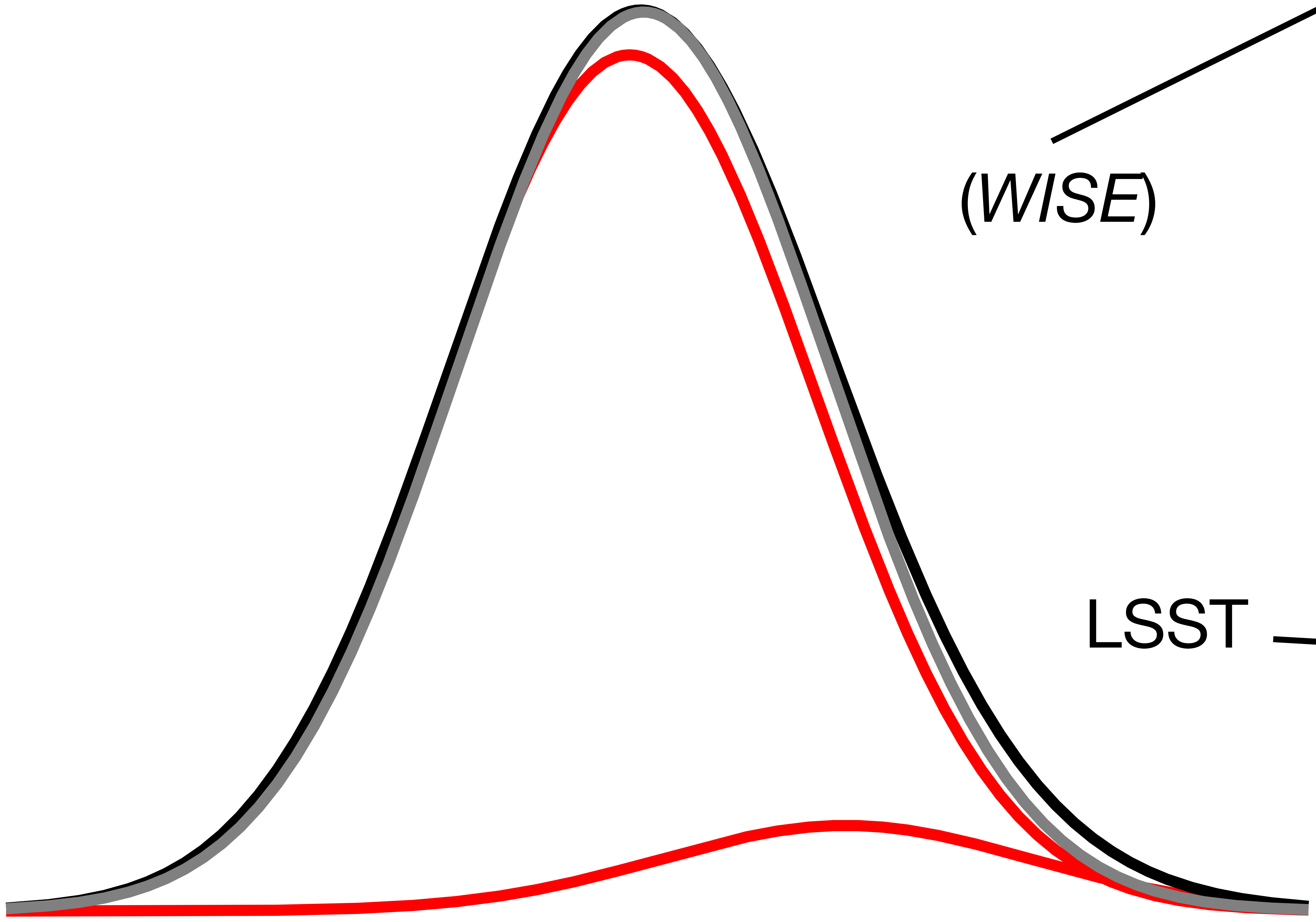
Why Not (Always) Forced Photometry?

3. Forced photometry largely works if you assume all of your objects are detected in the 'base' dataset, and the effects of "invisible" perturbers will therefore be missed



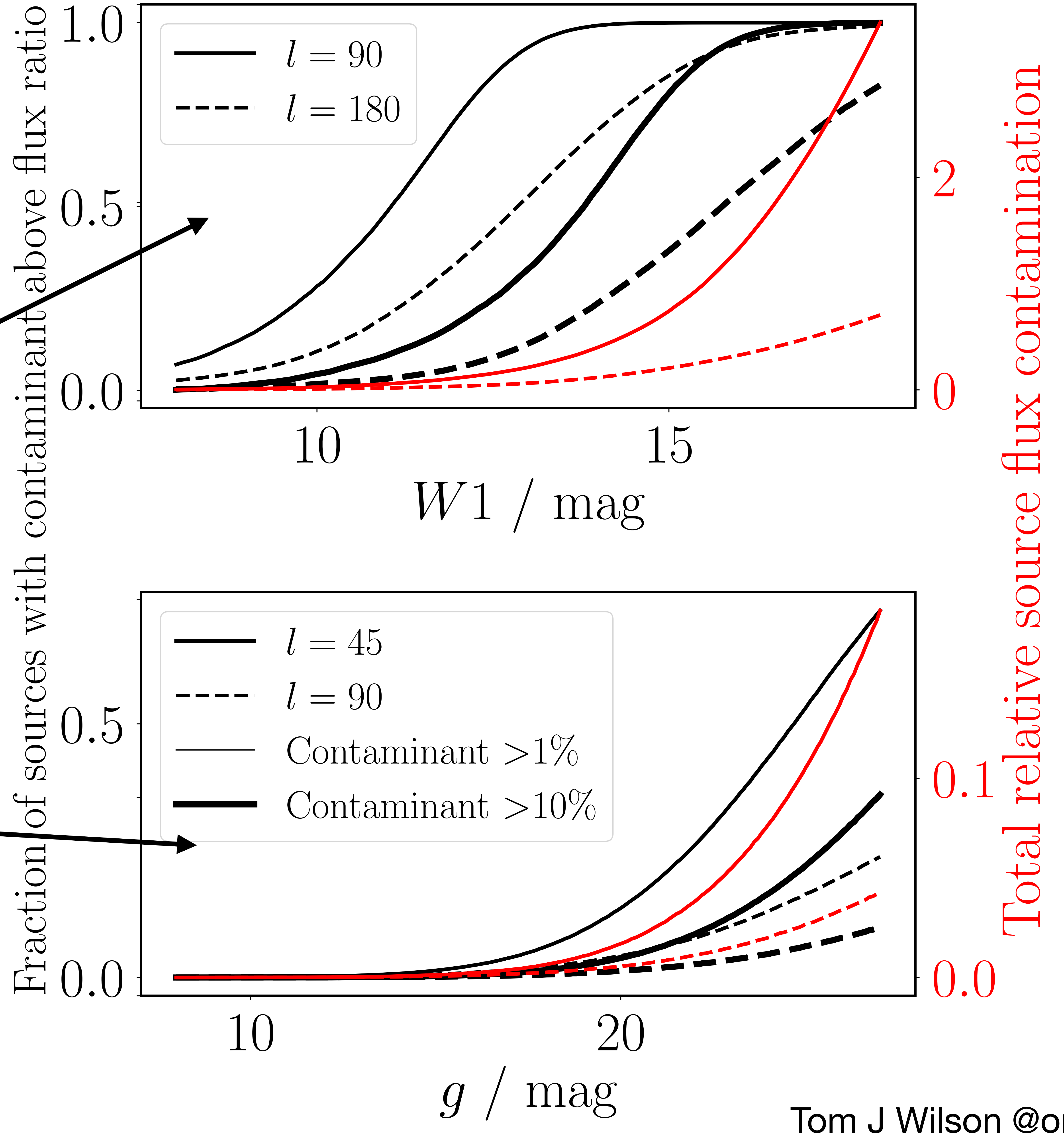
Why Not (Always) Forced Photometry?

4. If objects are missed, even "good" *Euclid* forced photometry (and in fact for non-forced photometry!) fluxes can be wrong if there are hidden perturbers!



(*WISE*)

LSST



Wilson & Naylor (2018b)

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Conclusions

- **The Astrometric Uncertainty Function is crucial to correctly understanding the true positions of sources in crowded fields — & unfortunately almost all of Rubin counts as "crowded" to some level!**
- **Using the AUF reduces the false negative rate from probabilistic cross-matching**
- **Can also use in-situ photometry and colours to reject interlopers and reduce false positive matches**

- **Where significant biases in positions are expected (or precision is required) forced photometry should be used with care**
- **Direct cross-matching should also be used over forced photometry in cases where significant number of sources are "missing" from one or other dataset — either due to simple survey completeness limits or e.g. colour selection effects**
- **Use of simulations of the perturbation component of the AUF can assist in the removal of flux biases — both for forced and non-forced photometry**

- **Software package <u>macauff</u> developed to robustly cross-match photometric catalogues in crowded fields — let me know what catalogues you would like to see robustly matched to one another!**

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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, 6, 60
Wilson, 2023, RASTI, 2, 1

Macauff

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https://github.com/Onoddil/macauff