The UKD-S9 In-Kind Contribution: macauff, birnam, banquo (and commissioning), oh my!

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University of Exeter

SMWLV Telecon, 22/10/24

Science and Technology Facilities Council

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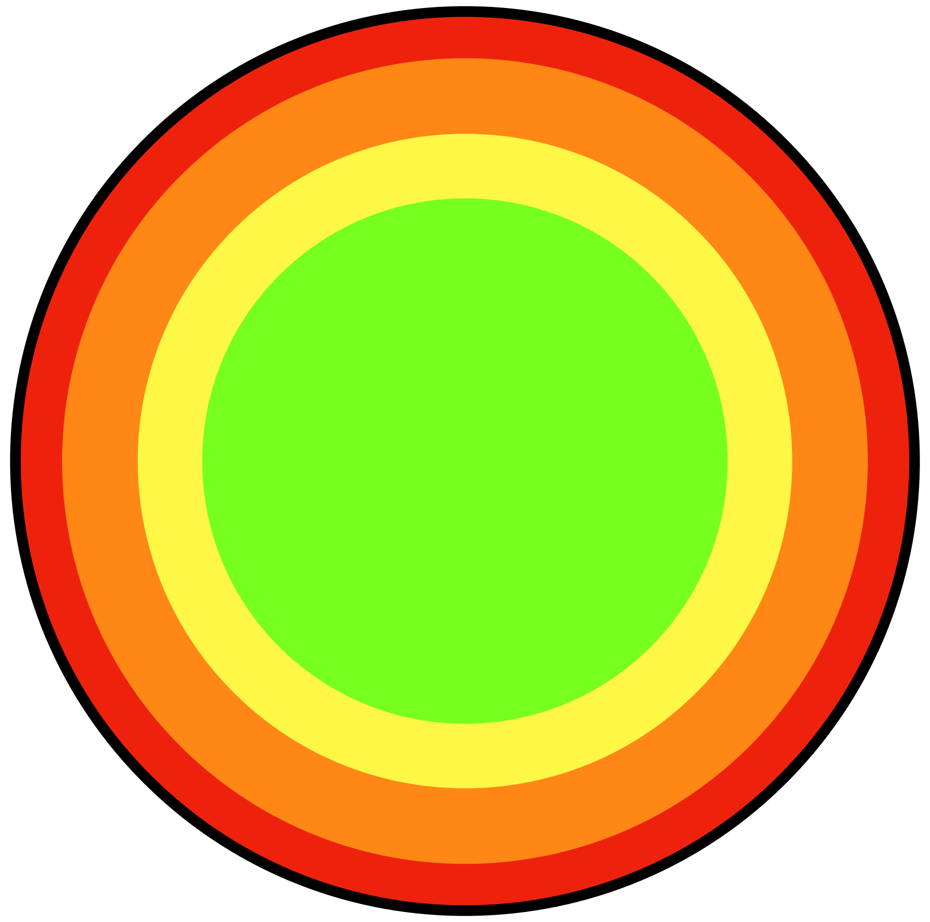
University of Exeter

LSST:UK Consortium

VERA C. RUBIN OBSERVATORY

Cross-Match Science, Methodology, Background



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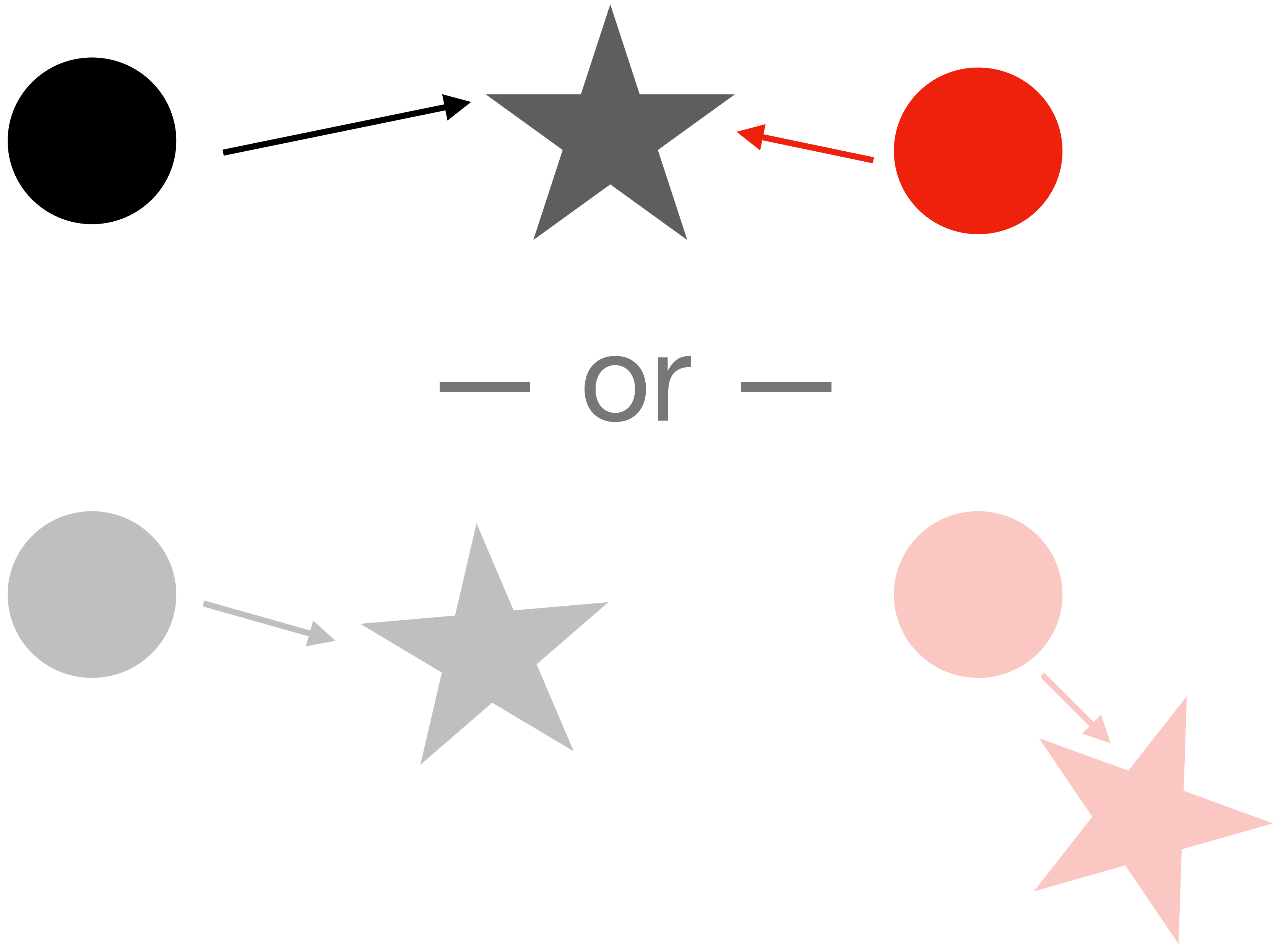
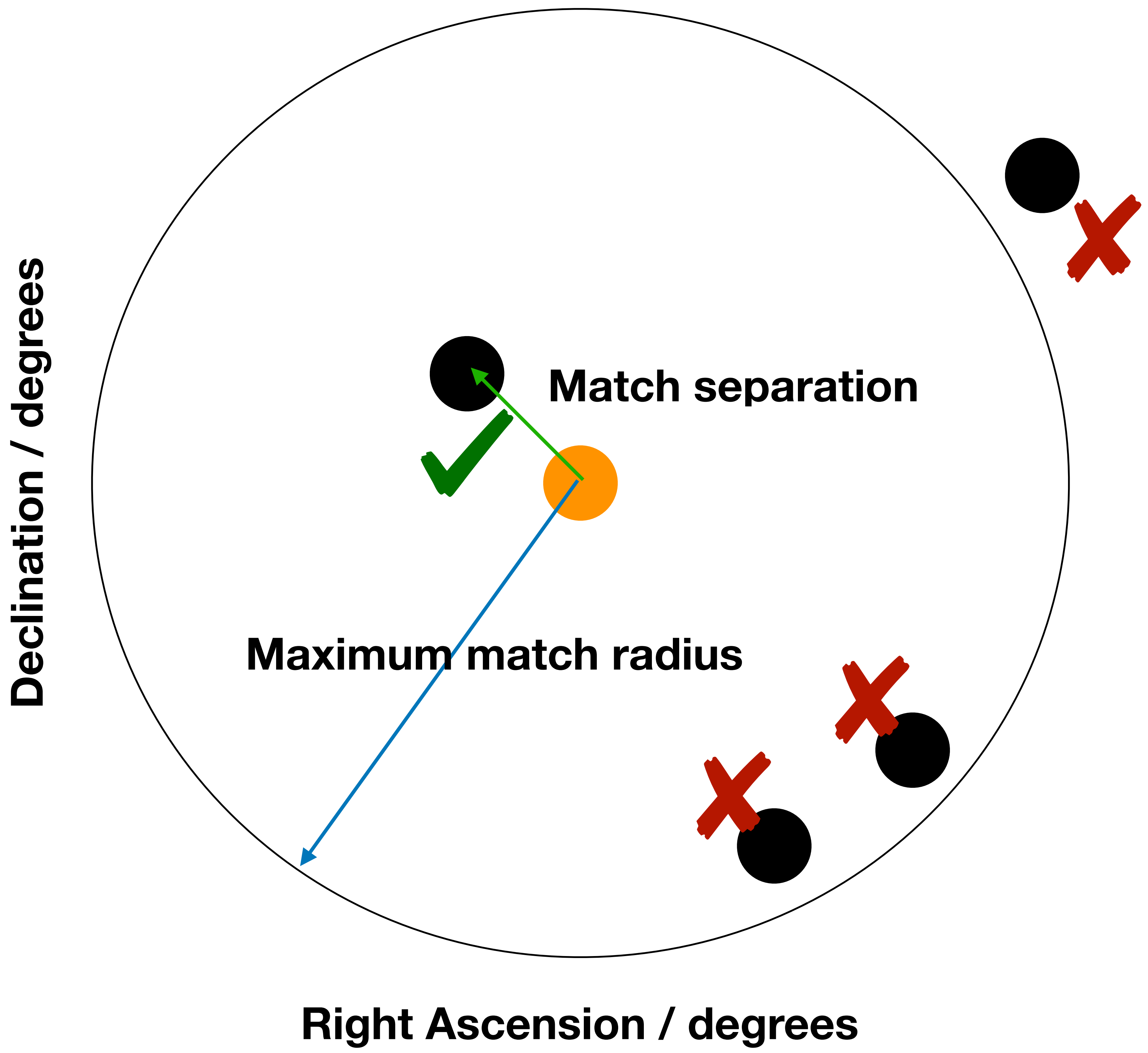
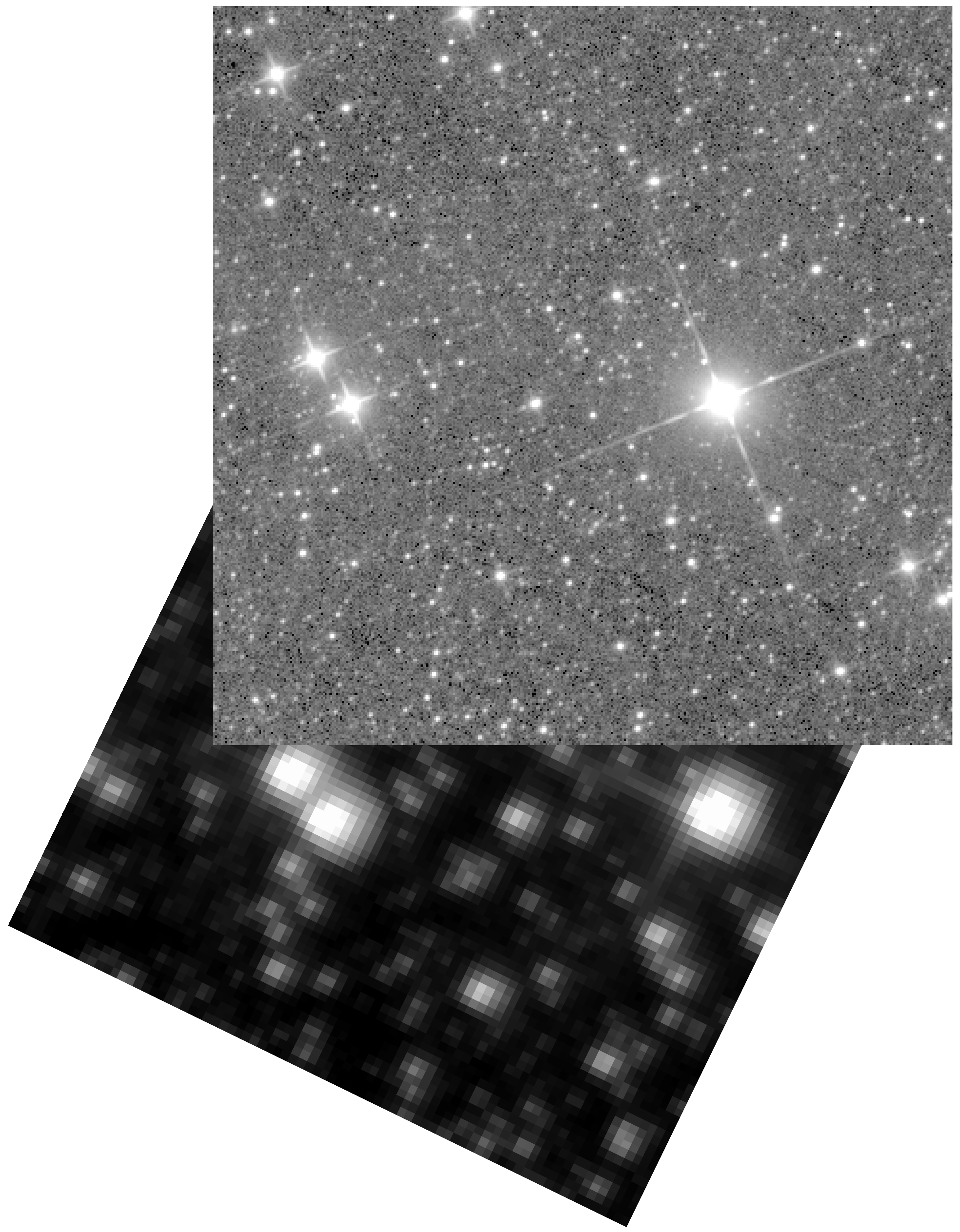
“Simple” Cross-Matching







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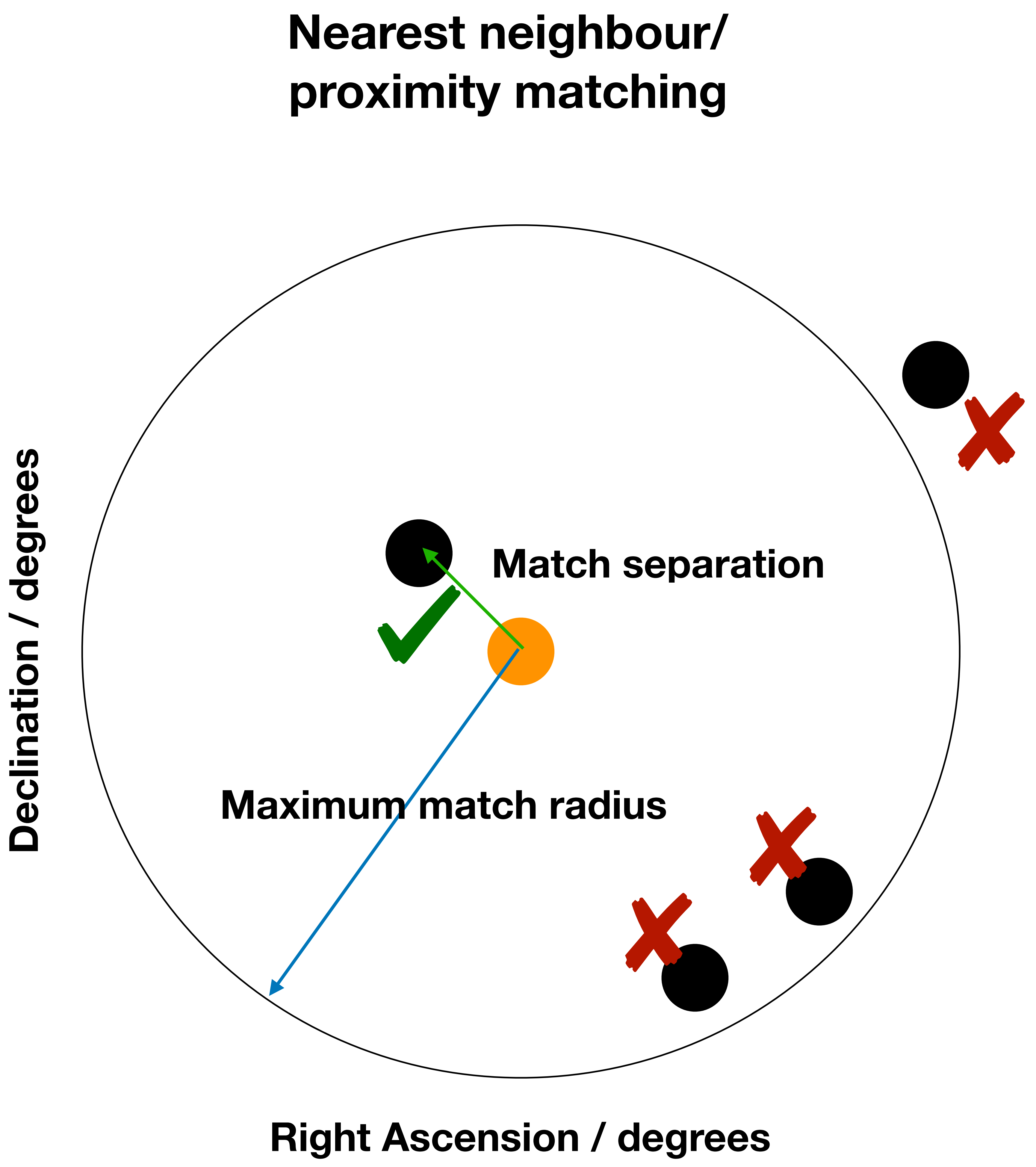
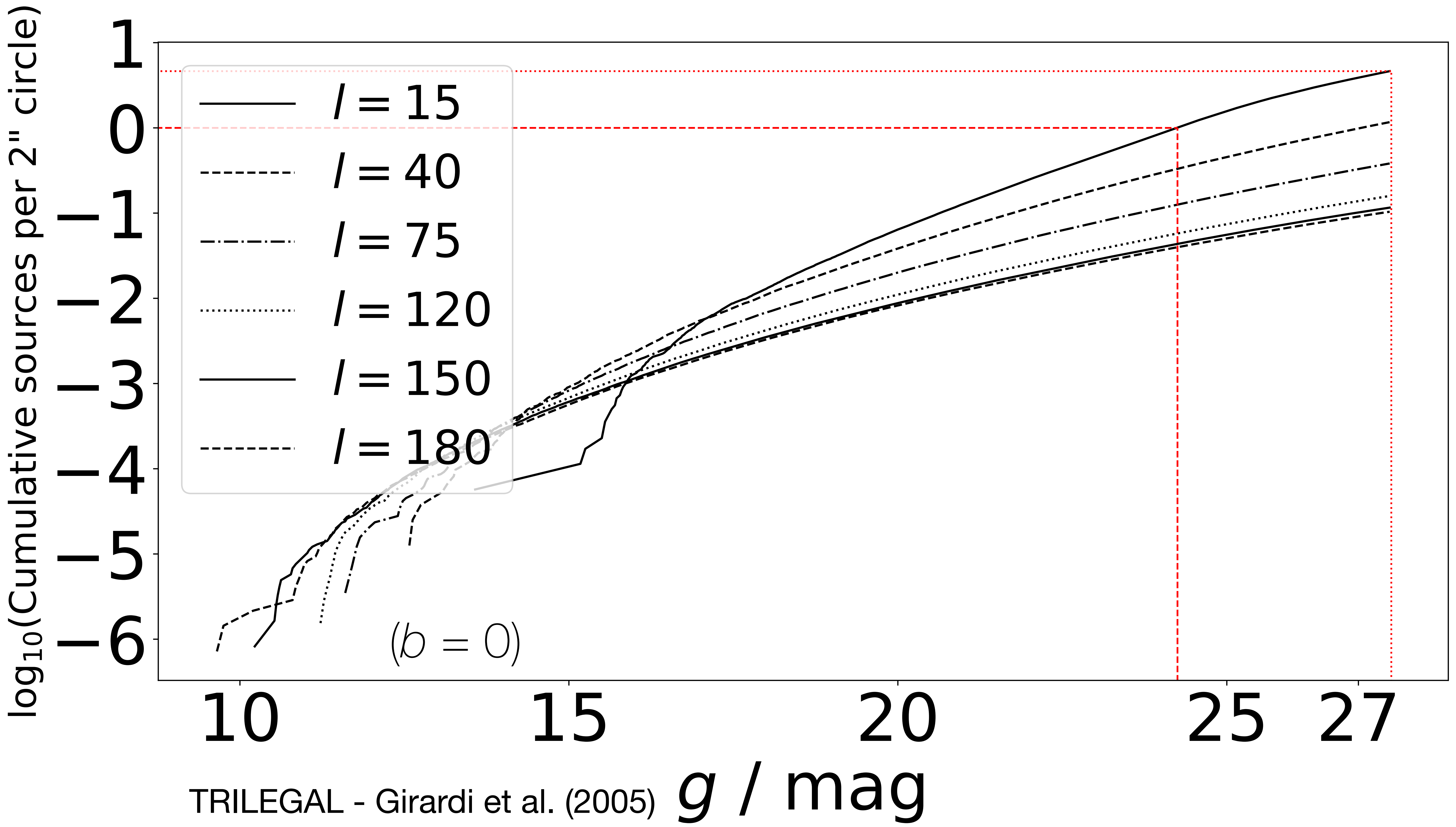
The Problem With LSST





TRILEGAL - Girardi et al. (2005)

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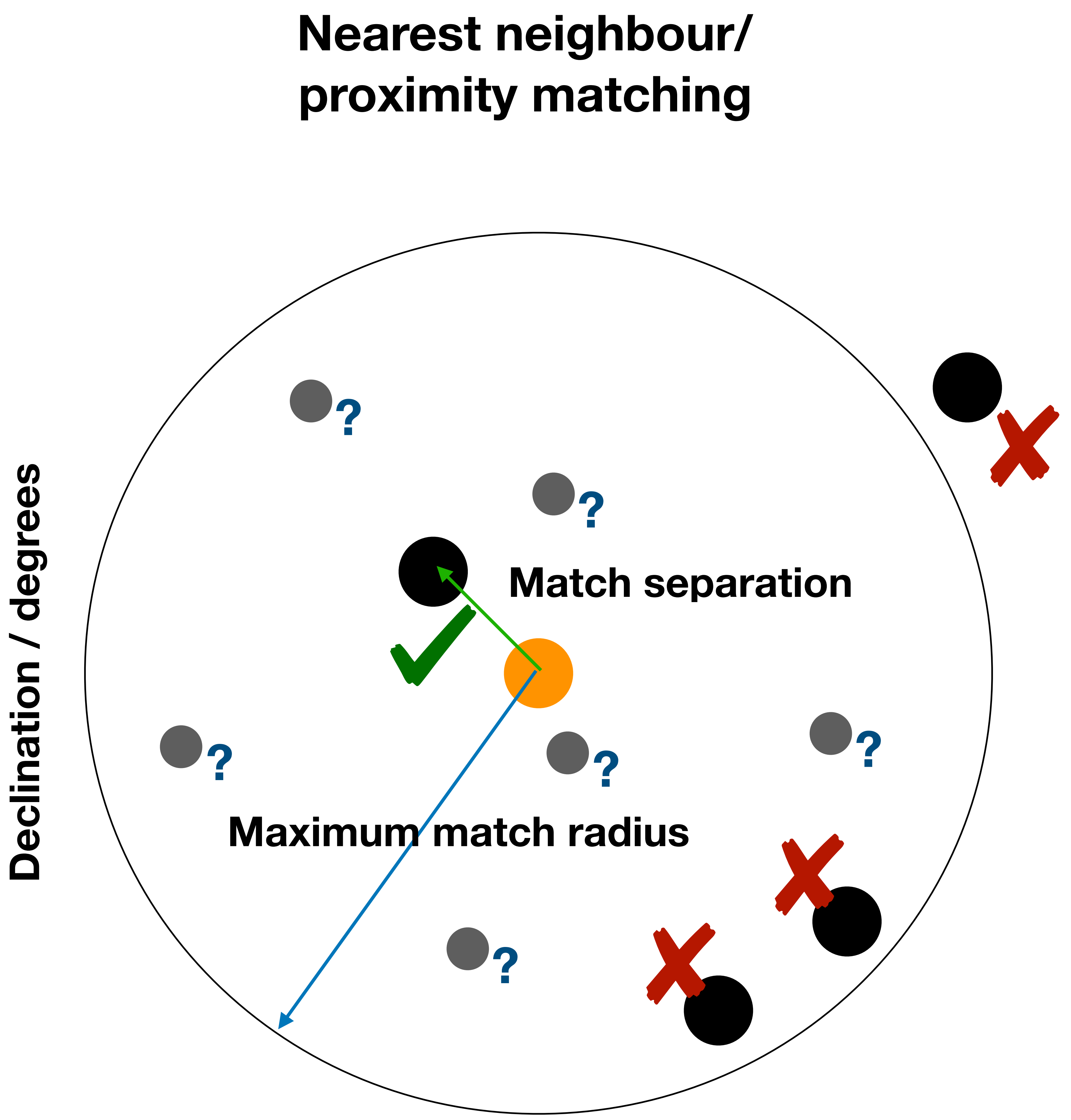
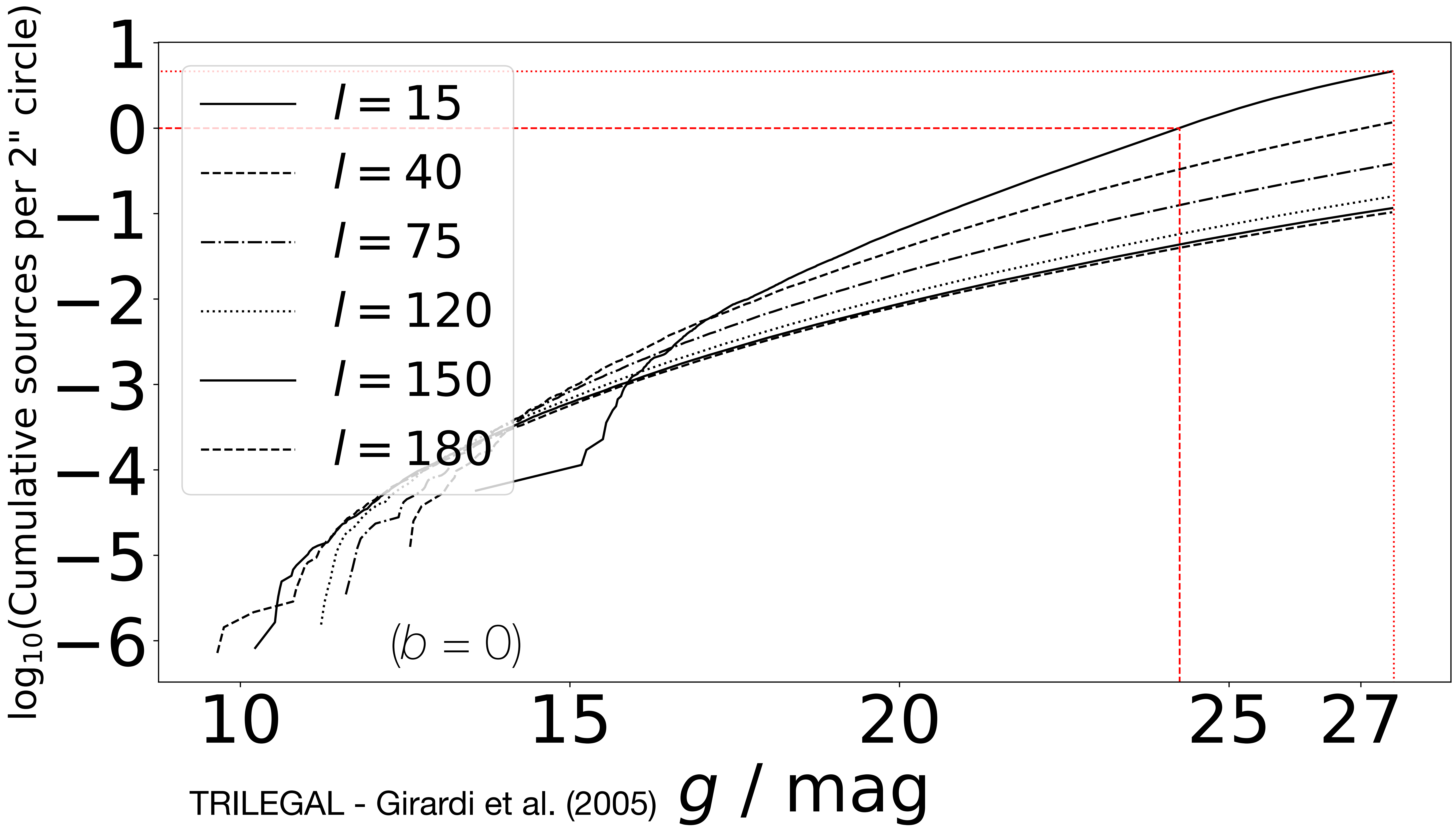
The Problem With LSST

(It's still a few randomly placed objects in every match radius at high Galactic latitudes)





TRILEGAL - Girardi et al. (2005)

Nearest-neighbour matching _will not_ work in the era of Rubin!

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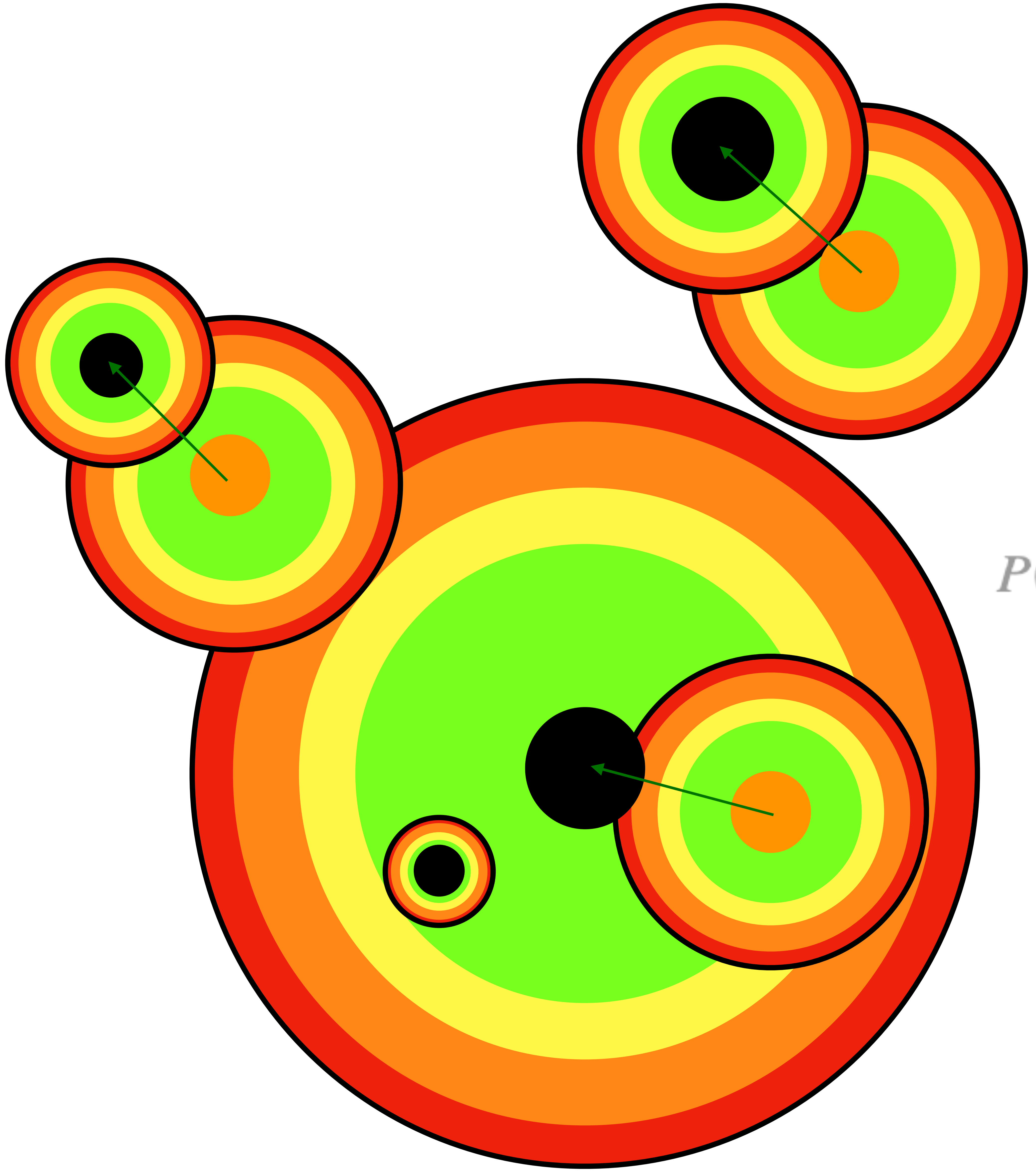
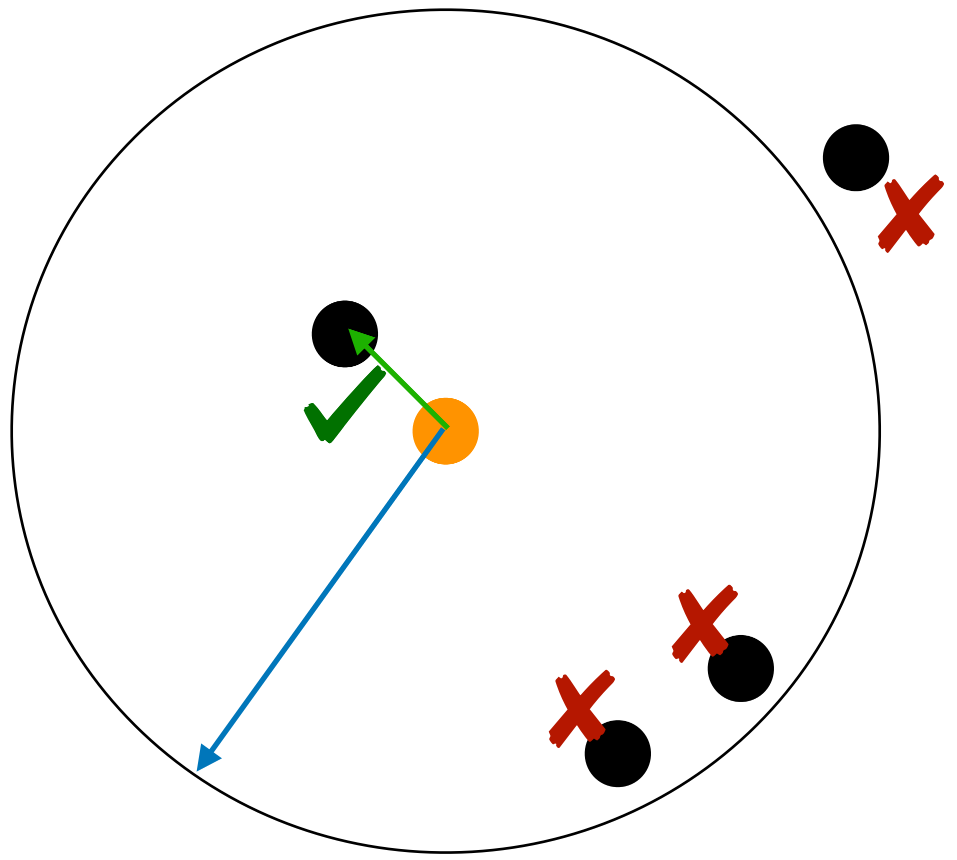
Probabilistic Cross-Matching





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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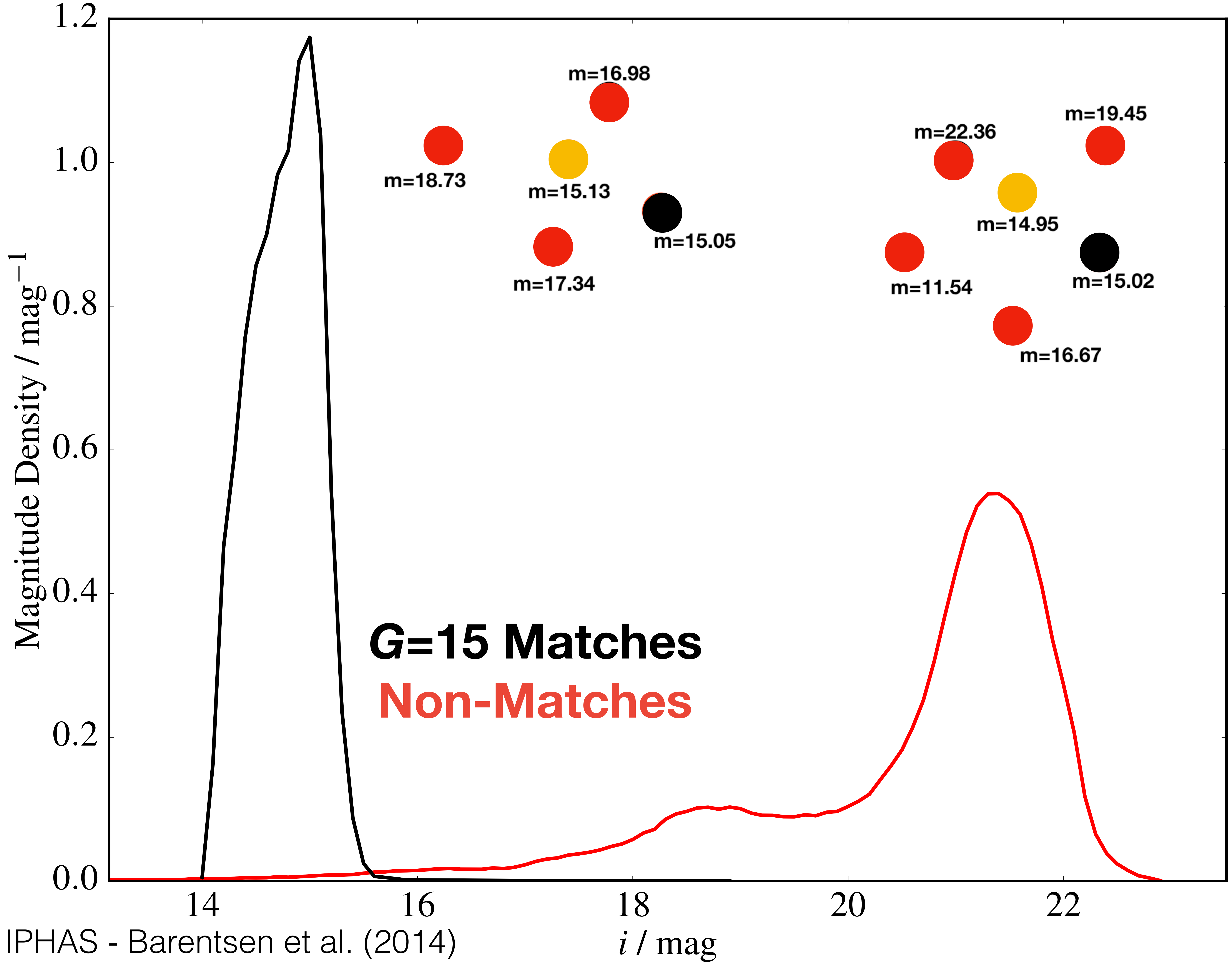
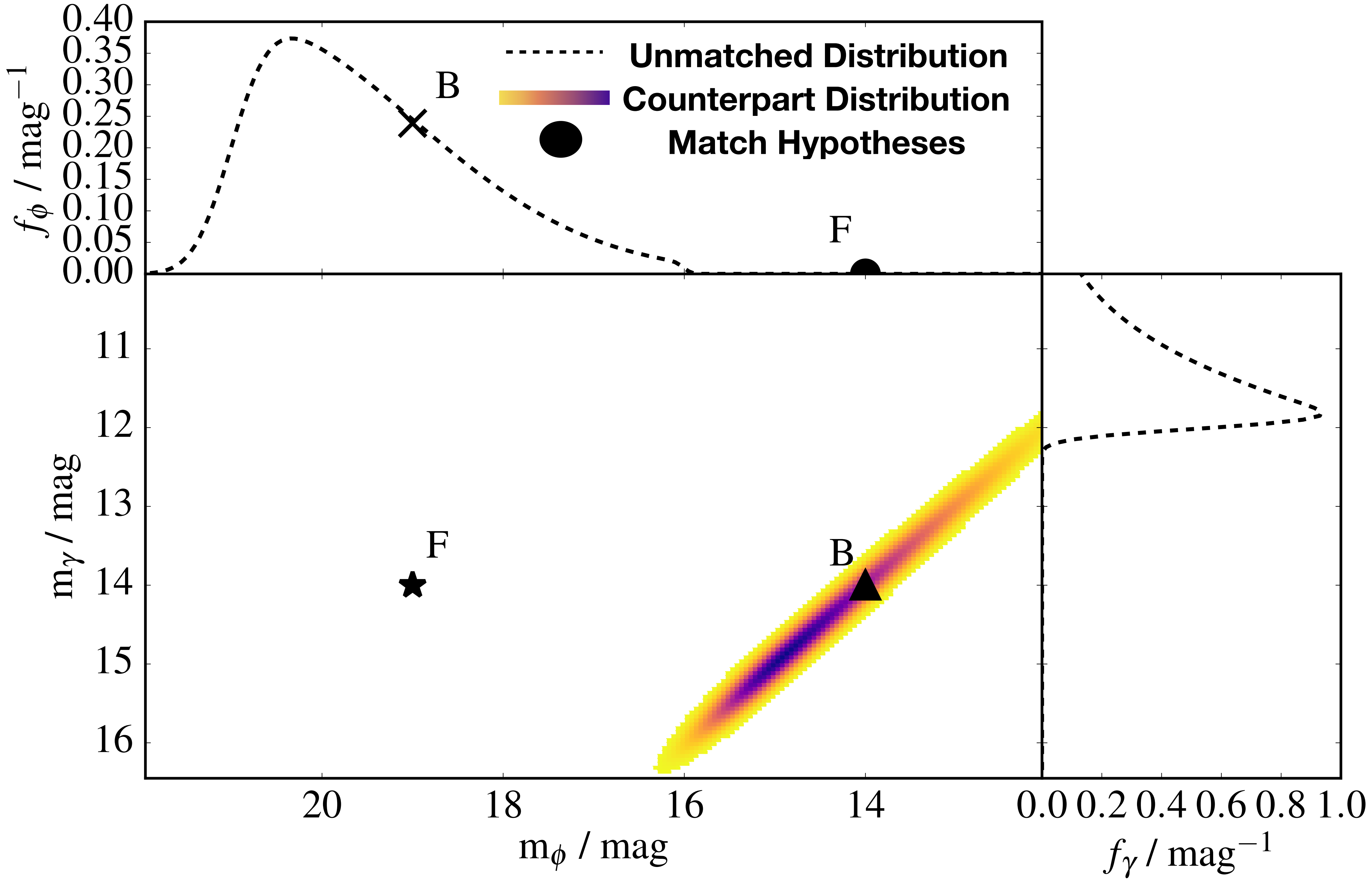
Photometry: Rejecting False Positives

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



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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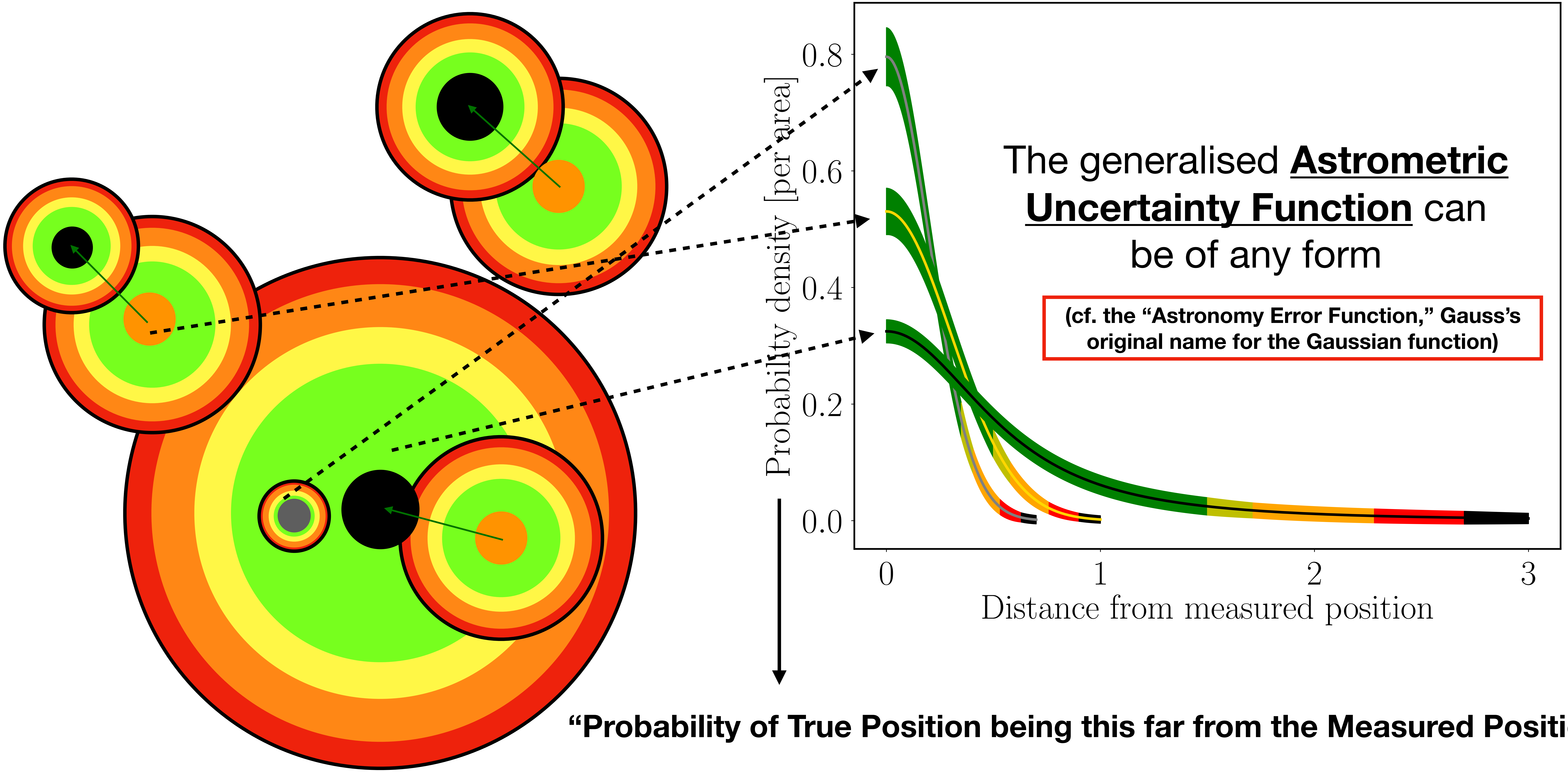
Probabilistic Cross-Matching: the AUF



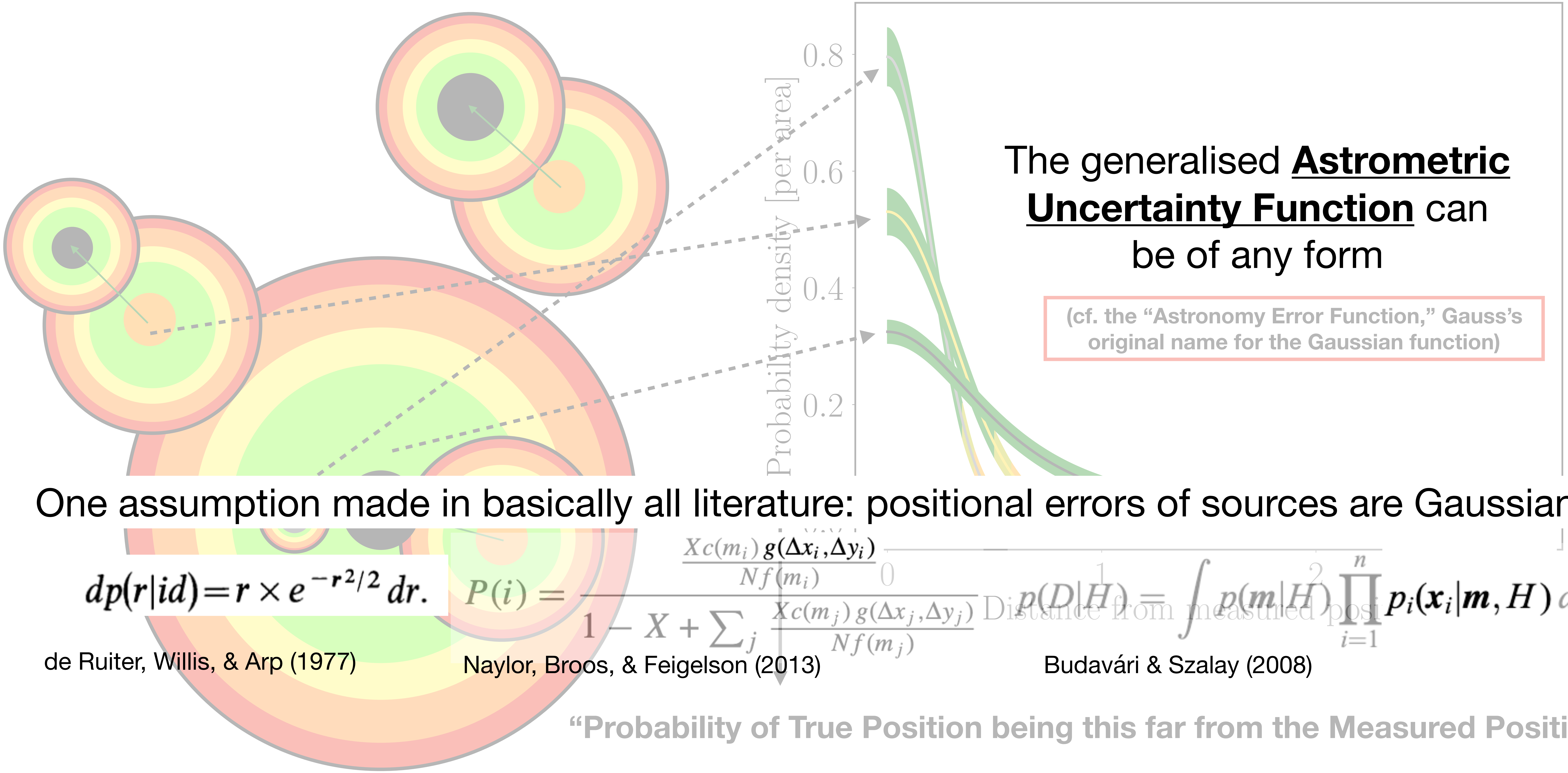
The generalised **Astrometric Uncertainty Function** can be of any form

(cf. the "Astronomy Error Function," Gauss's original name for the Gaussian function)

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

Tom J Wilson @onoddil

Probabilistic Cross-Matching: the AUF



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

(cf. the "Astronomy Error Function," Gauss's original name for the Gaussian function)

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)

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

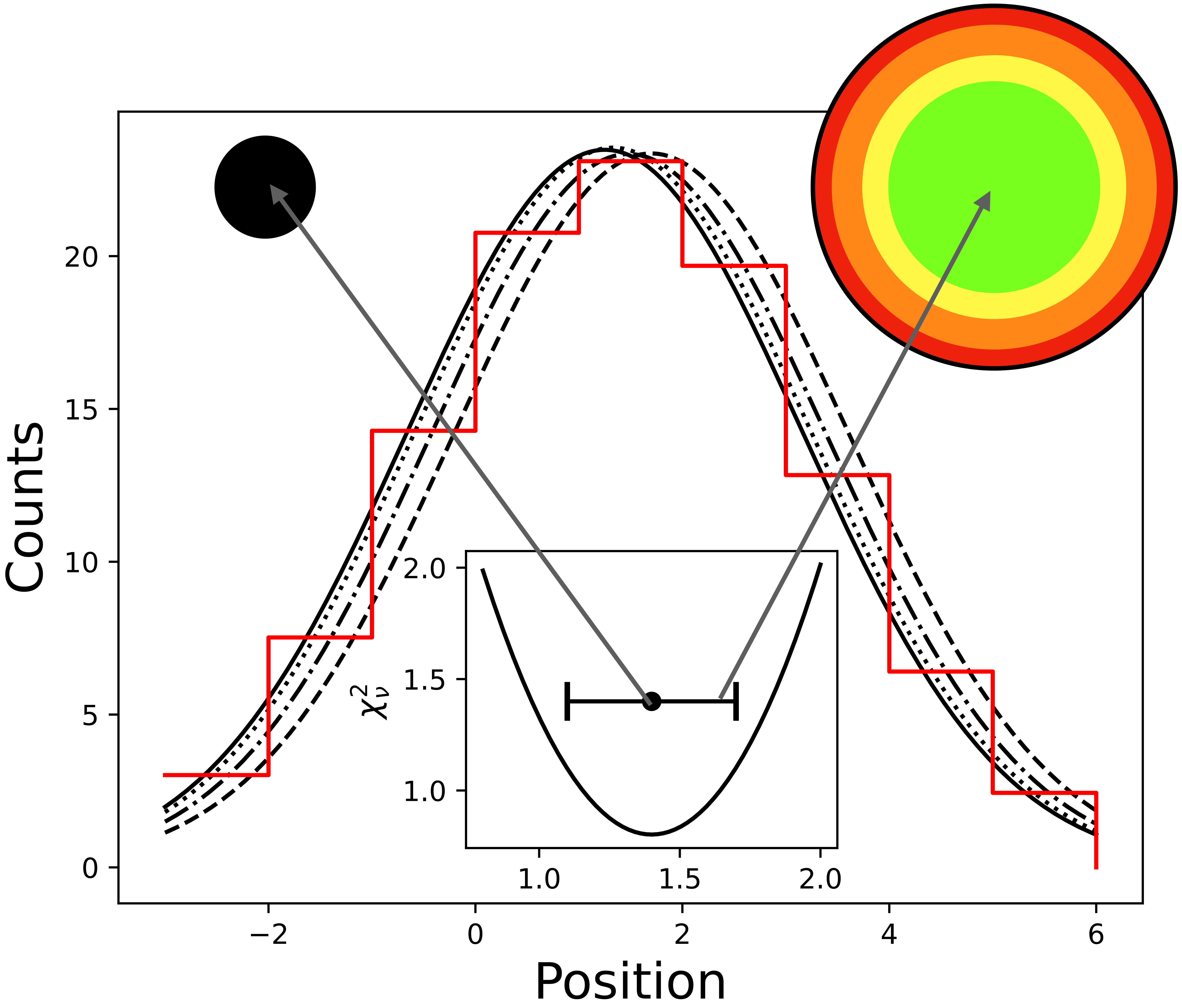
Naylor, Broos, & Feigelson (2013)

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

Budavári & Szalay (2008)

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

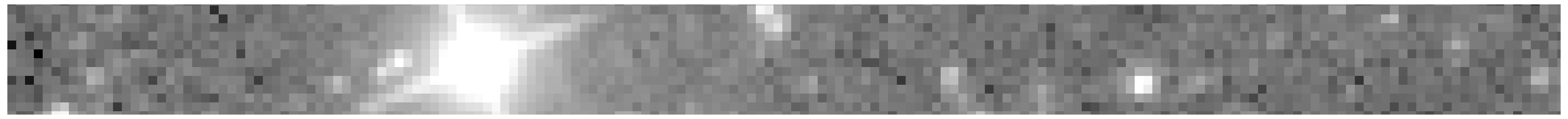
Centroid Positions and Uncertainties



$$p(D\,|\,M) \propto \frac{\exp\left(-\frac{1}{2}\left(\mathbf{x}-\boldsymbol{\mu}\right)^T \boldsymbol{\Sigma}^{-1}\left(\mathbf{x}-\boldsymbol{\mu}\right)\right)}{\sqrt{(2\pi)^k\,|\,\boldsymbol{\Sigma}\,|}}$$

$$\boldsymbol{x} = \begin{pmatrix} x \\ y \end{pmatrix}, \boldsymbol{\mu} = \begin{pmatrix} \mu_x \\ \mu_y \end{pmatrix}, \boldsymbol{\Sigma} = \begin{pmatrix} \sigma_x^2 & \rho\sigma_x\sigma_y \\ \rho\sigma_x\sigma_y & \sigma_y^2 \end{pmatrix}$$

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



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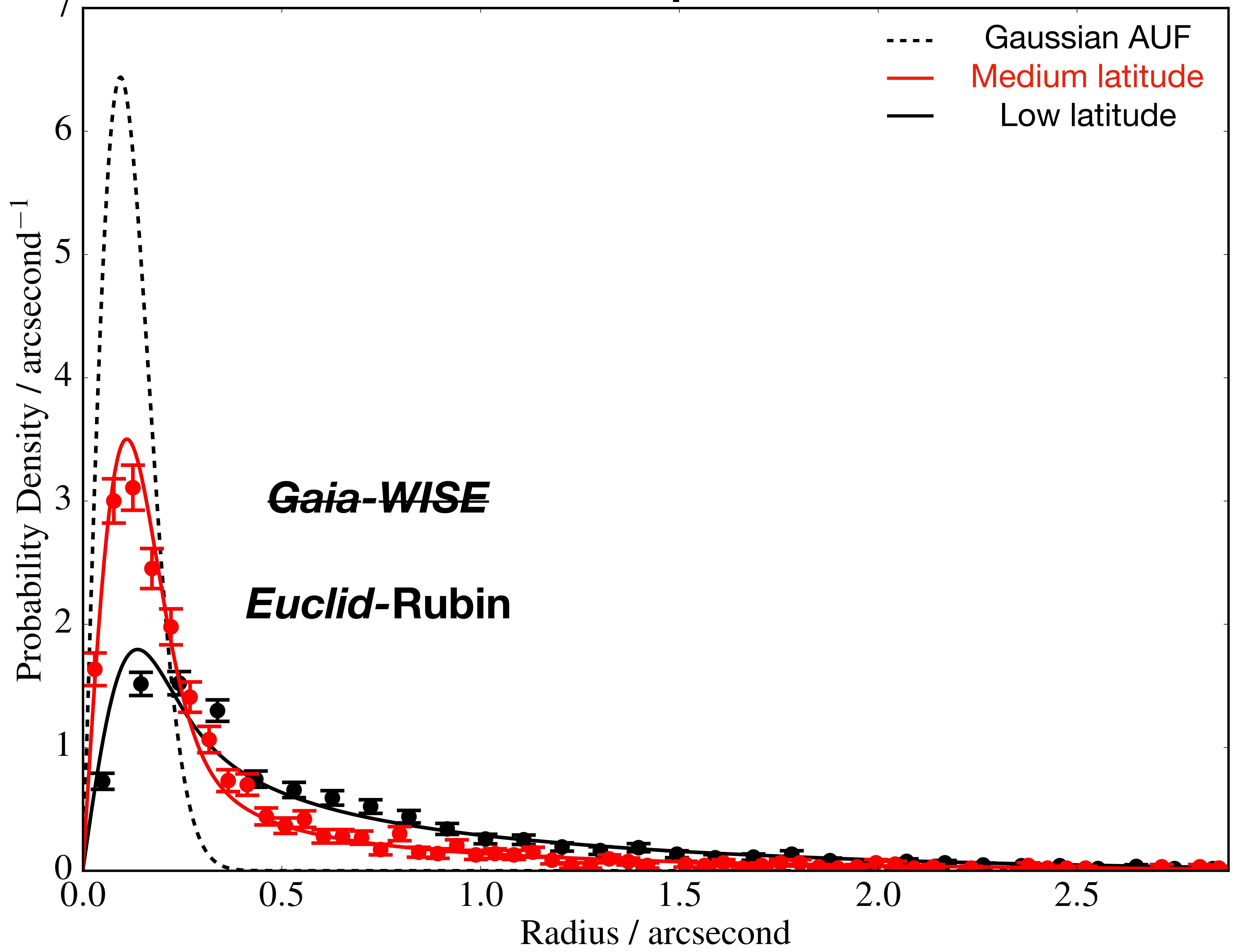
Additional Components of the AUF

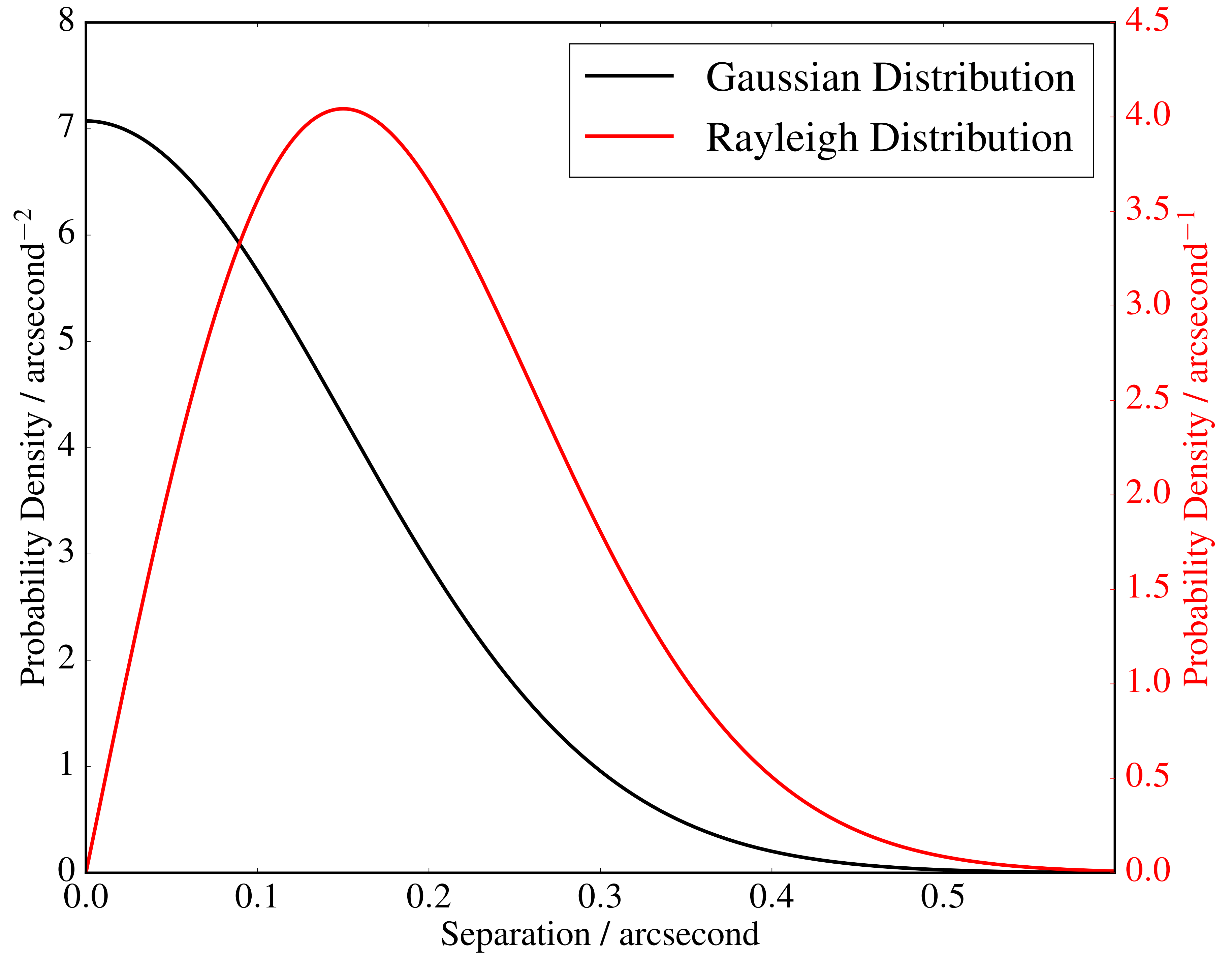
$$P(\zeta, \lambda, k|\gamma, \phi) = \frac{1}{K} \times \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i \lambda_i} c_{\gamma\phi}^{\zeta_i \lambda_i}$$



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

$\downarrow$

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



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

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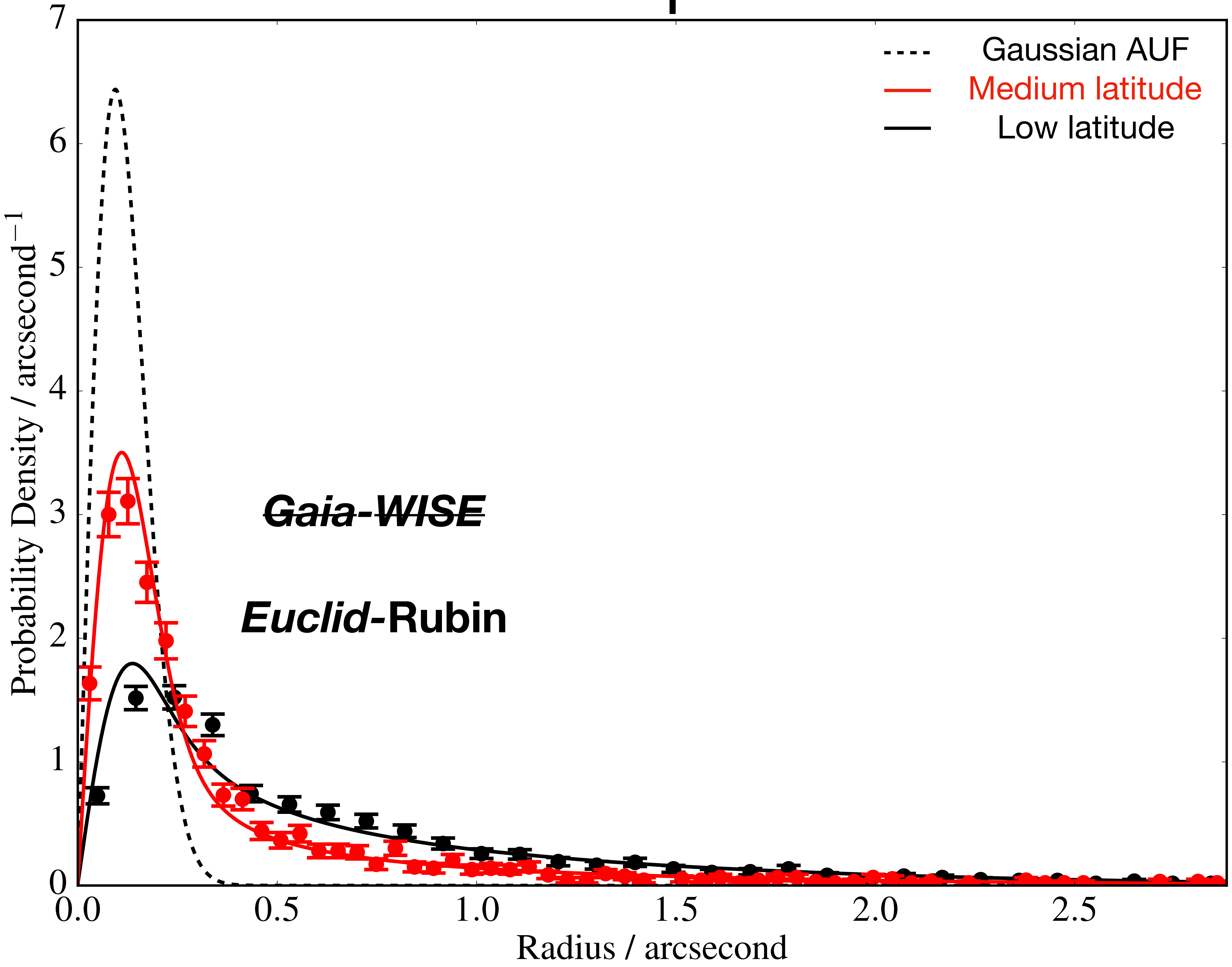

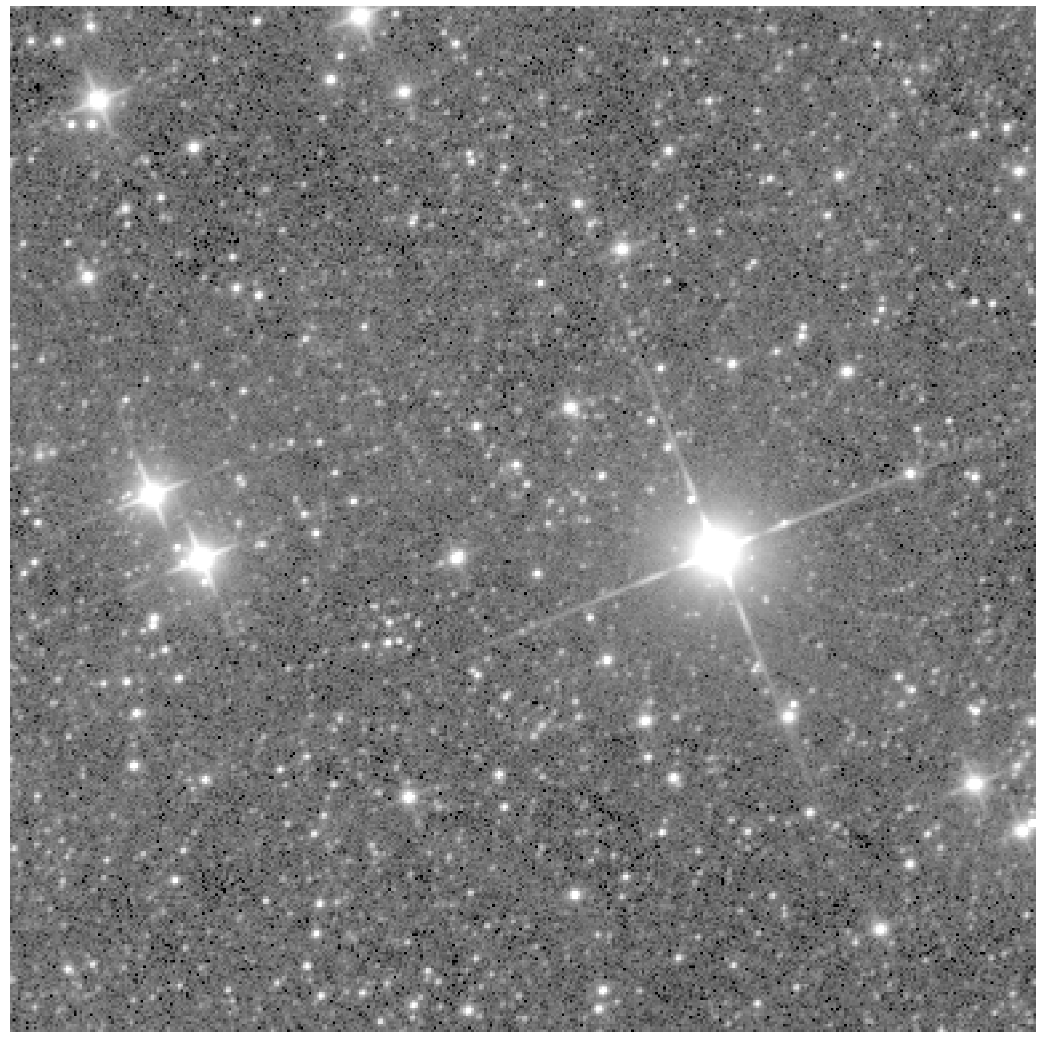

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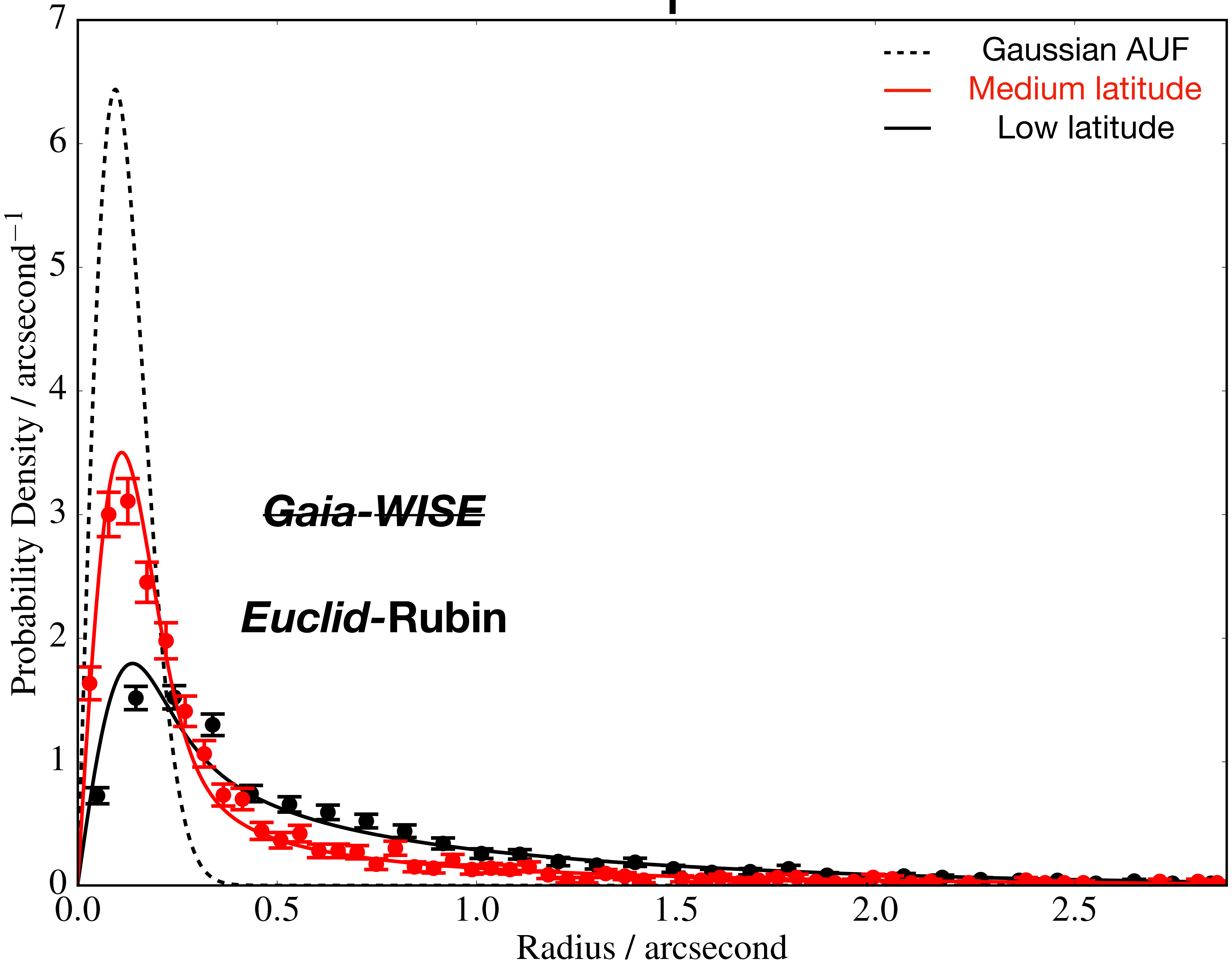
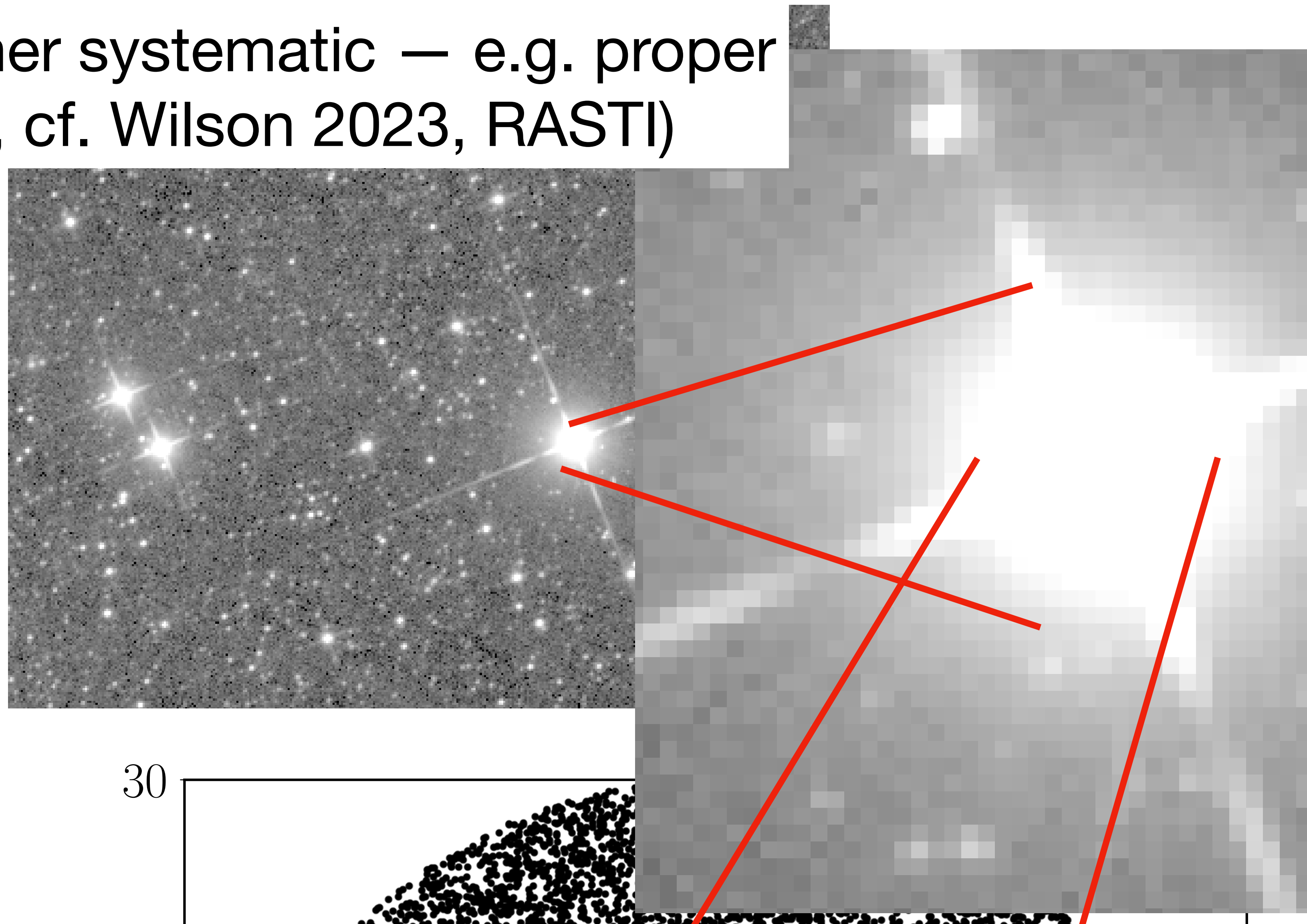
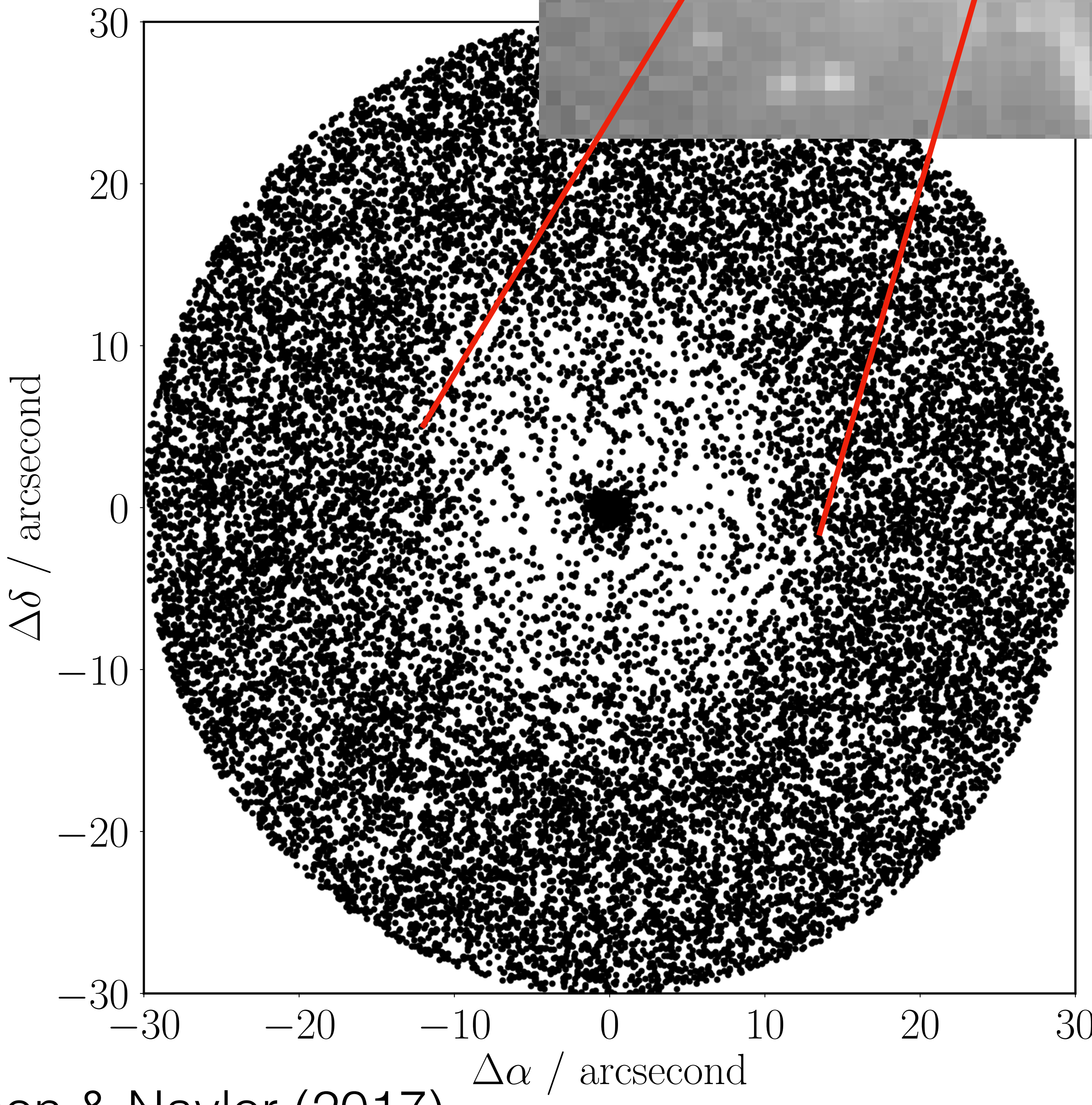


(and any other systematic — e.g. proper motions, cf. Wilson 2023, RASTI)





Wilson & Naylor (2017)

WISE - Wright et al. (2010)
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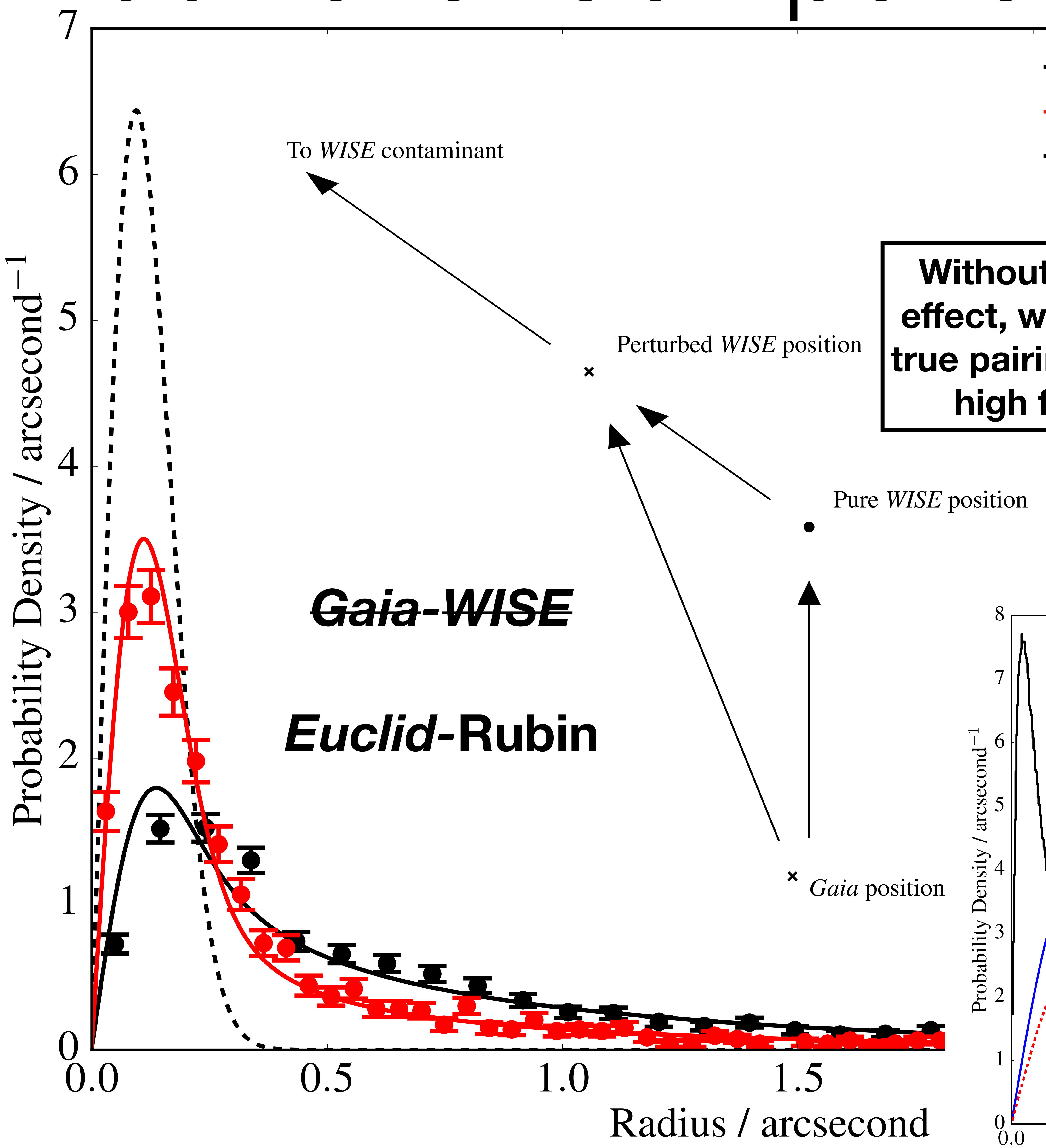

Without modelling this extra effect, we fail to recover many true pairings, with an artificially high false negative rate!

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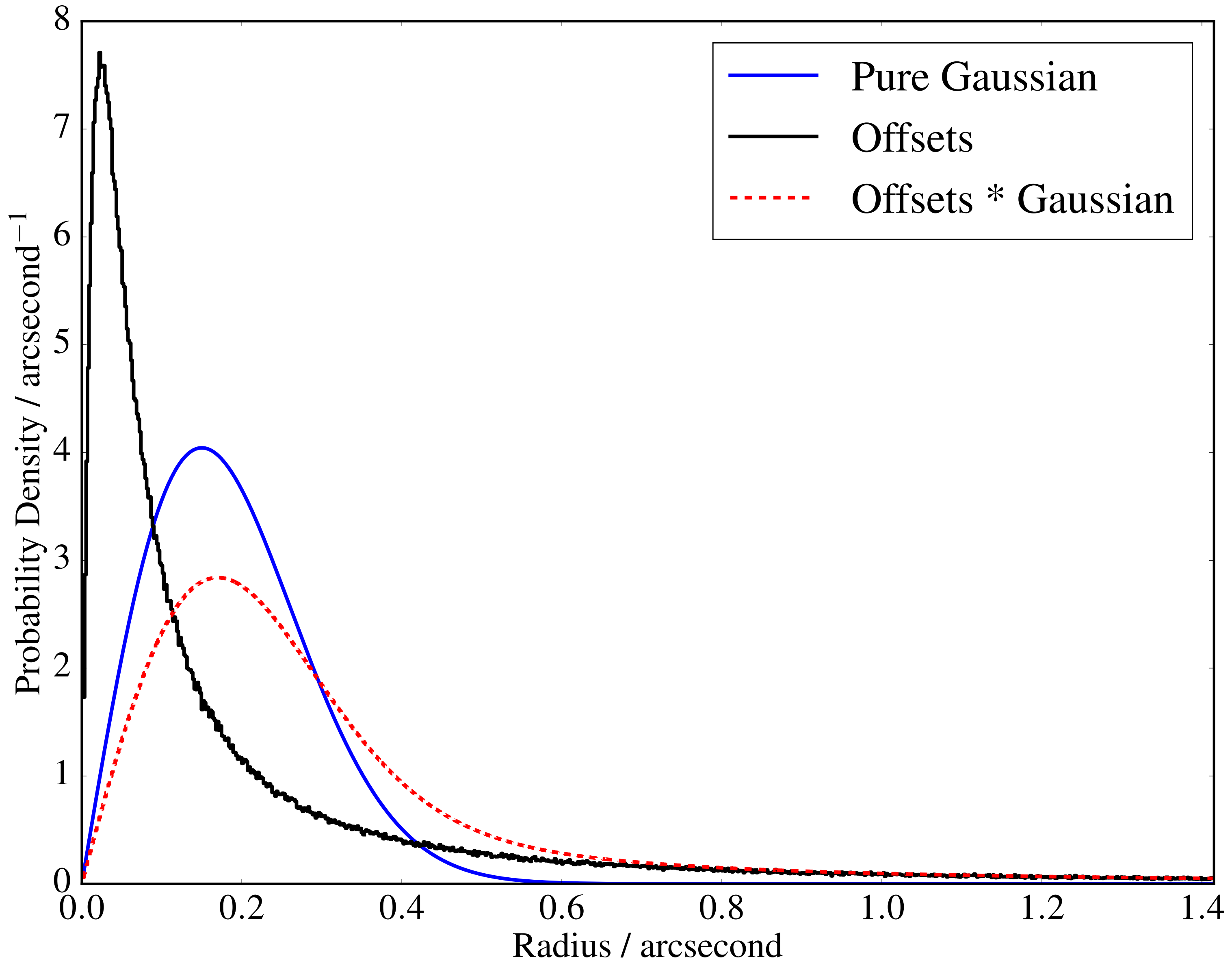
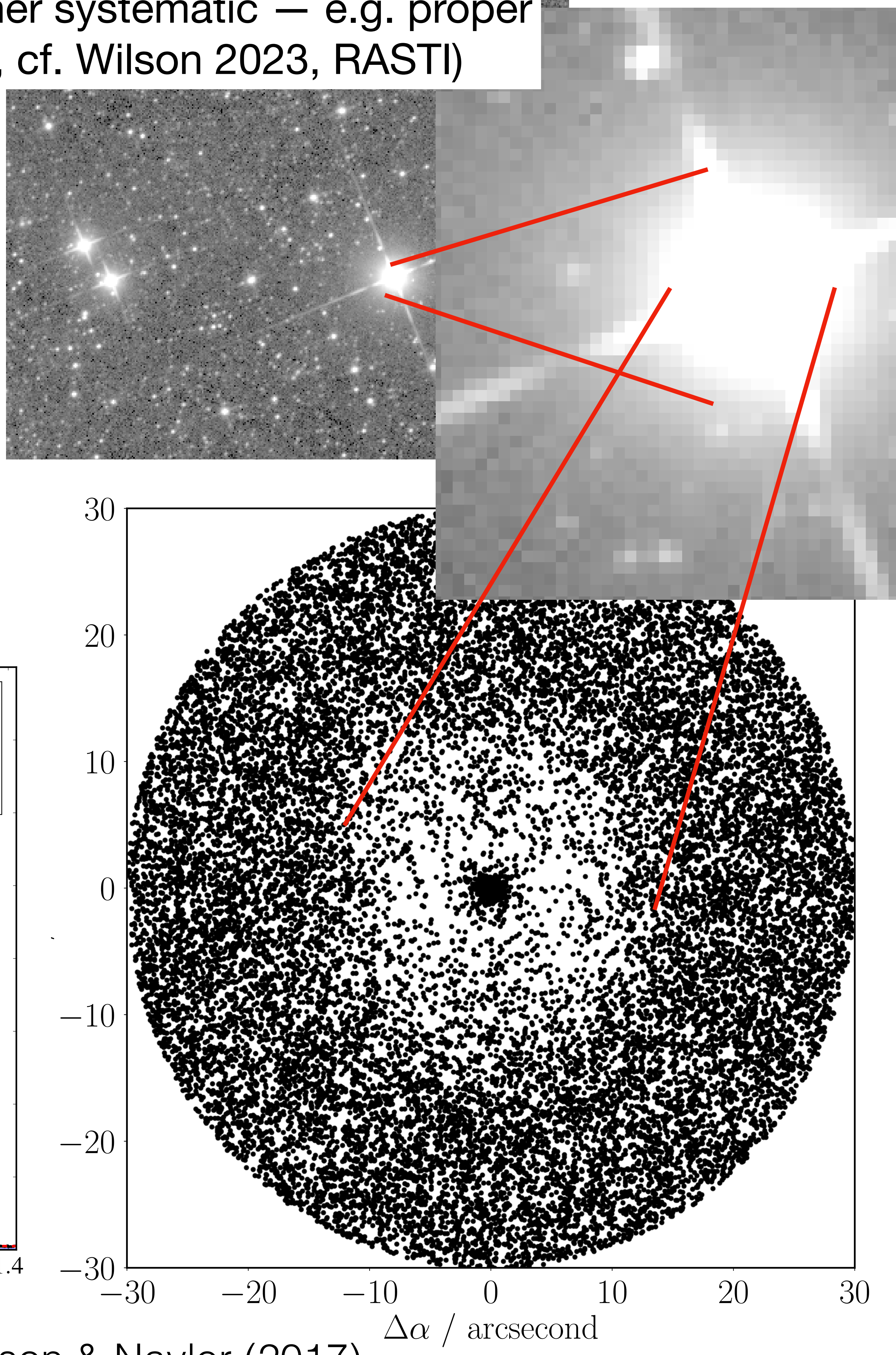


Wilson & Naylor (2018b)



Wilson & Naylor (2017)

WISE - Wright et al. (2010)

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

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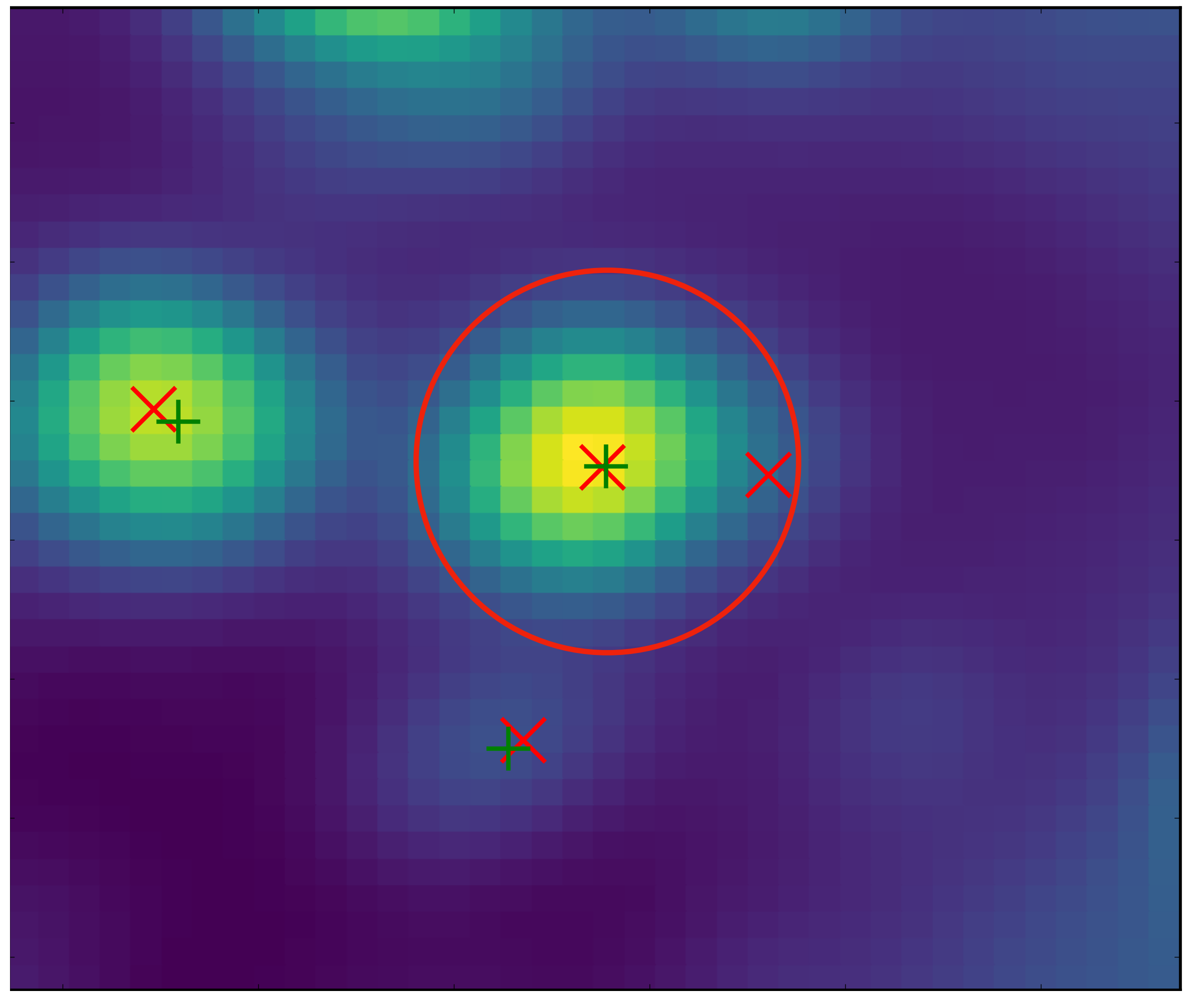
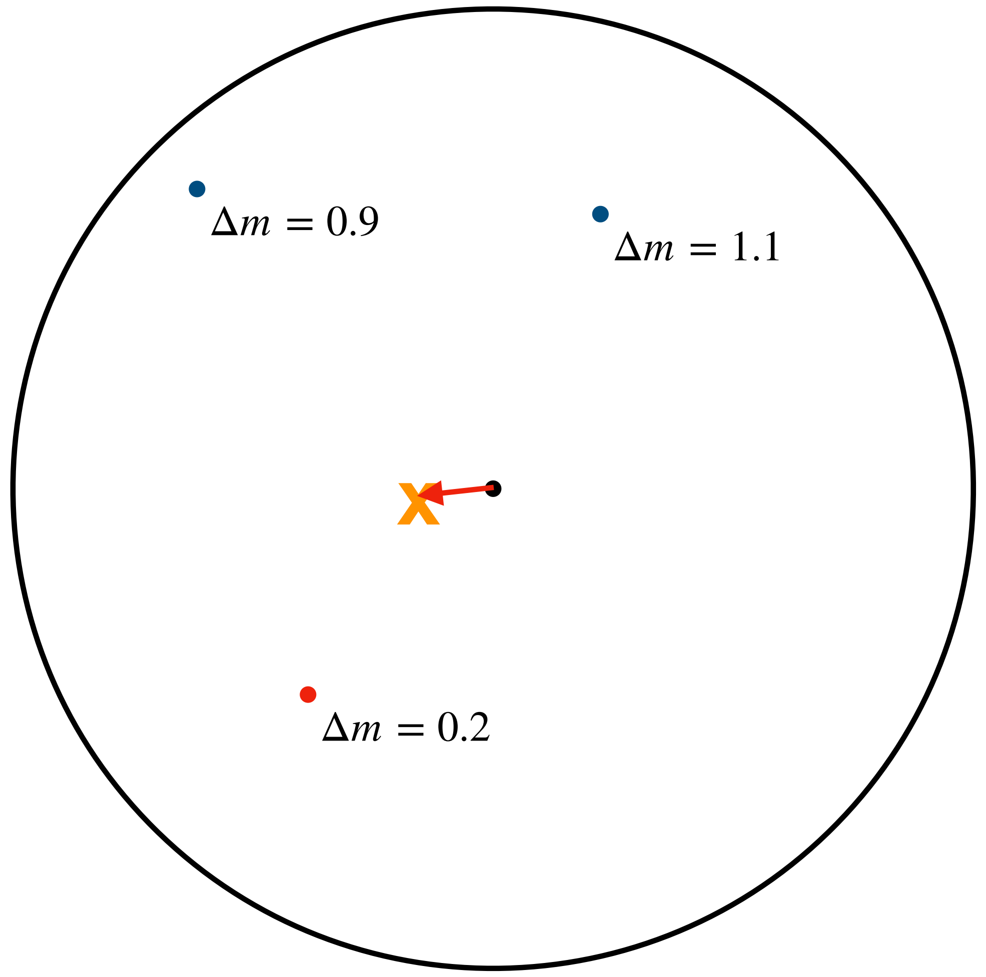
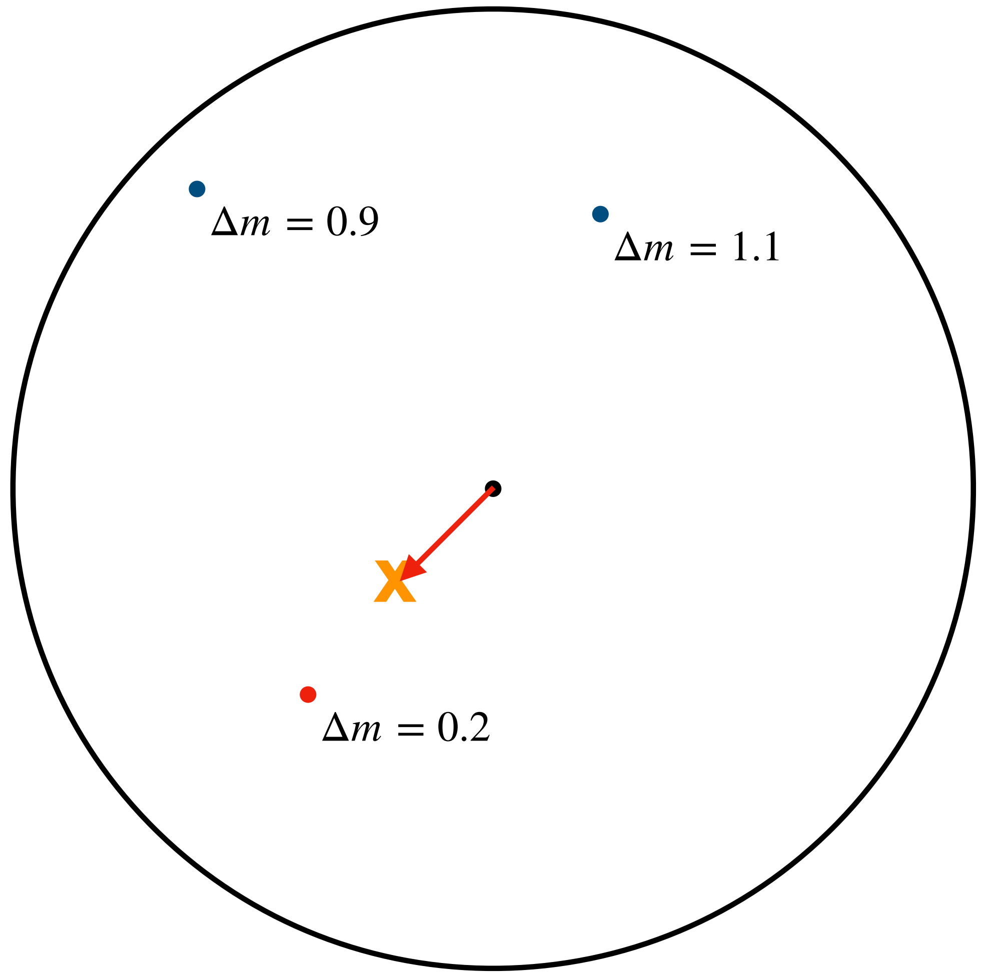
Modelling Crowded-Field Flux Brightening

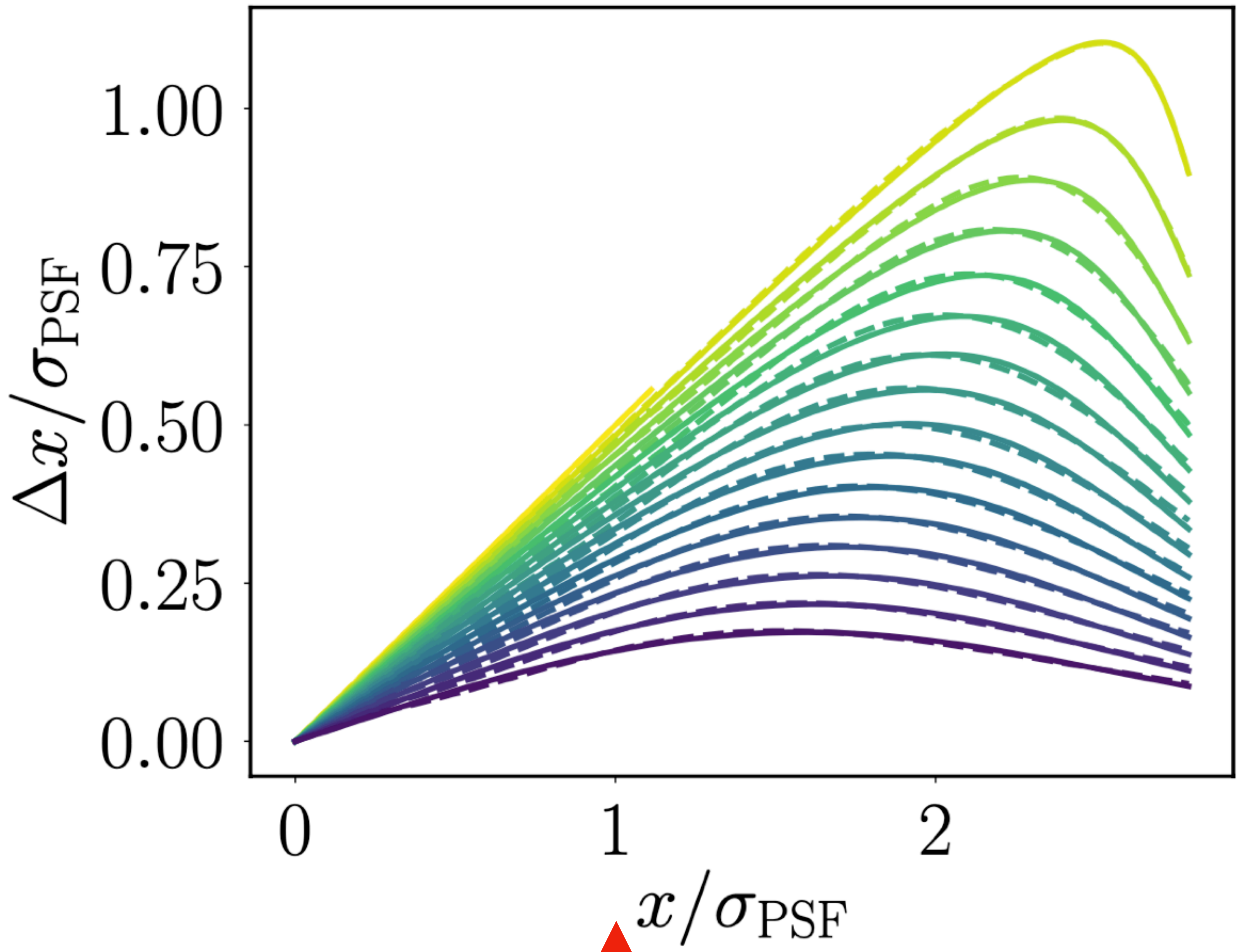
High SNR PSF or Aperture Photometry

Low SNR PSF Photometry









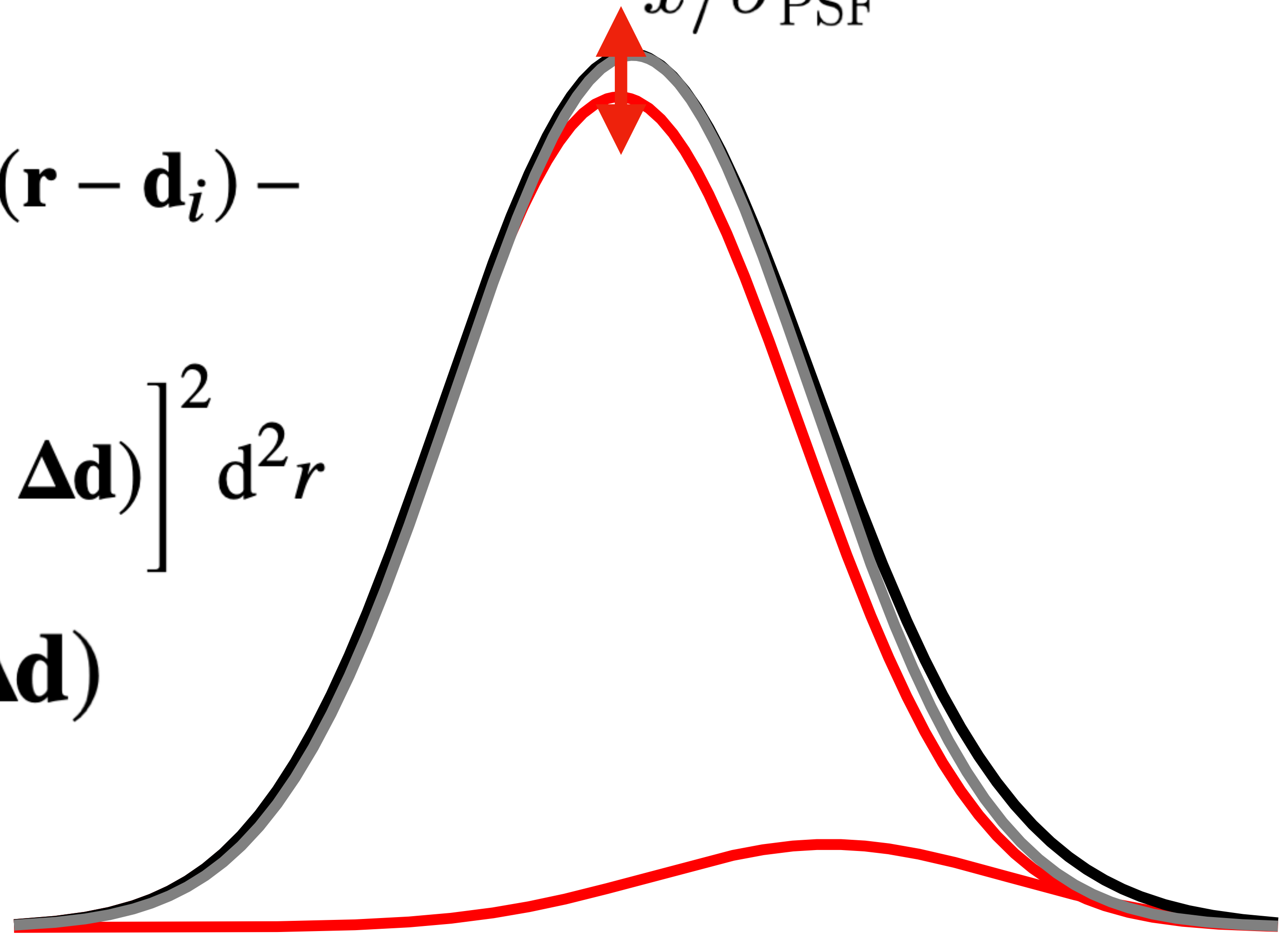
(This raises questions about the validity of quoting photometric statistical precisions if objects are systematically biased, and SED fitting in general in crowded fields)

$$\Delta x = \frac{\sum_i f_i x_i}{1 + \sum_i f_i}$$

$$\Delta f = \sum_i f_i$$

$$\log \mathcal{L} = -\frac{1}{2} \times L \int_{-\infty}^{\infty} \left[\phi(\mathbf{r}) + \sum_i f_i \phi(\mathbf{r} - \mathbf{d}_i) - (1 + \Delta f)\phi(\mathbf{r} - \mathbf{\Delta d}) \right]^2 \mathrm{d}^2 r$$

$$\Delta f = \psi'(\mathbf{\Delta d}) - 1 + \sum_i f_i \psi'(\mathbf{d}_i - \mathbf{\Delta d})$$



Wilson & Naylor (2018b; in prep.)
Plewa & Sari (2018)

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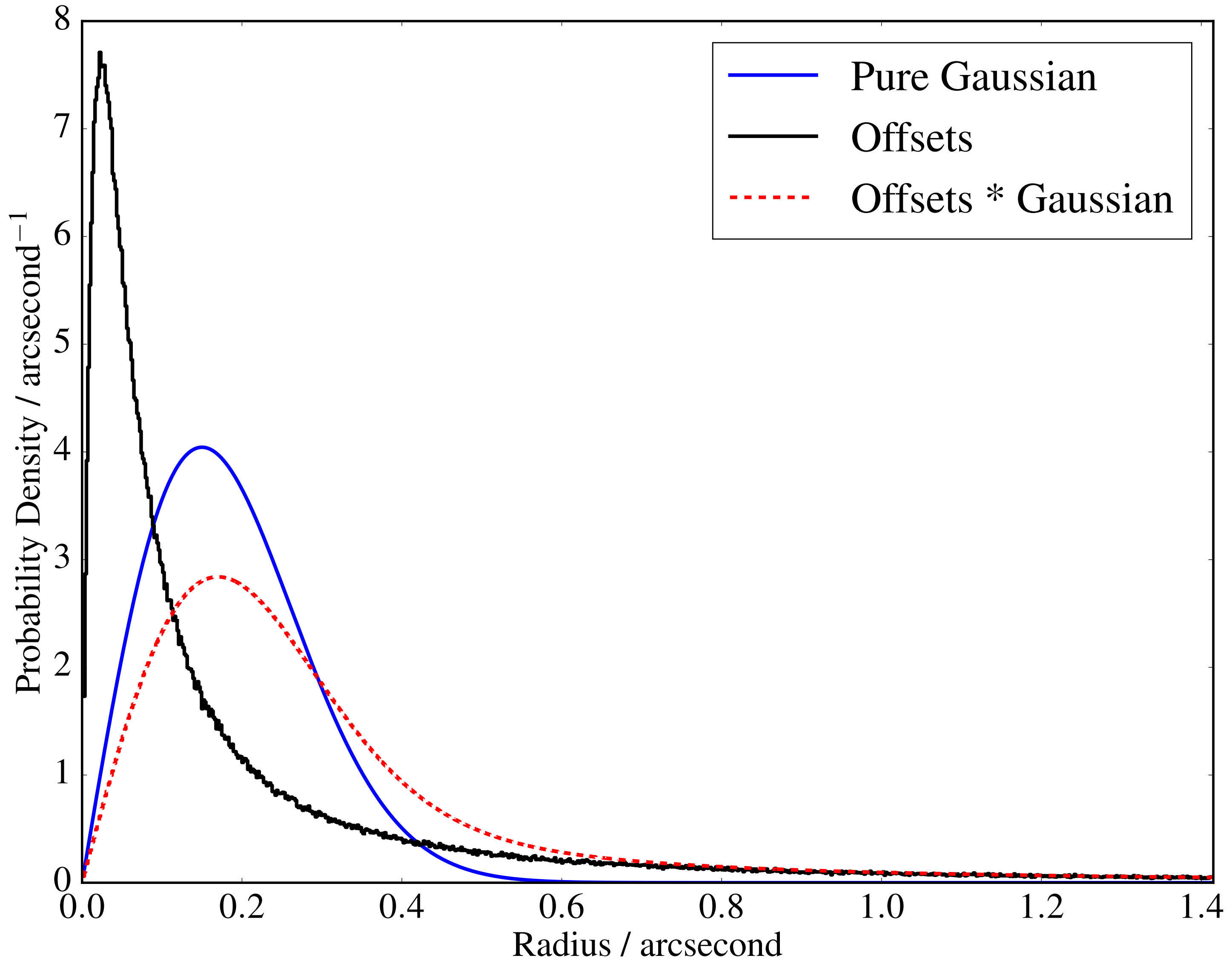
Photometric Contamination Rates and Amounts



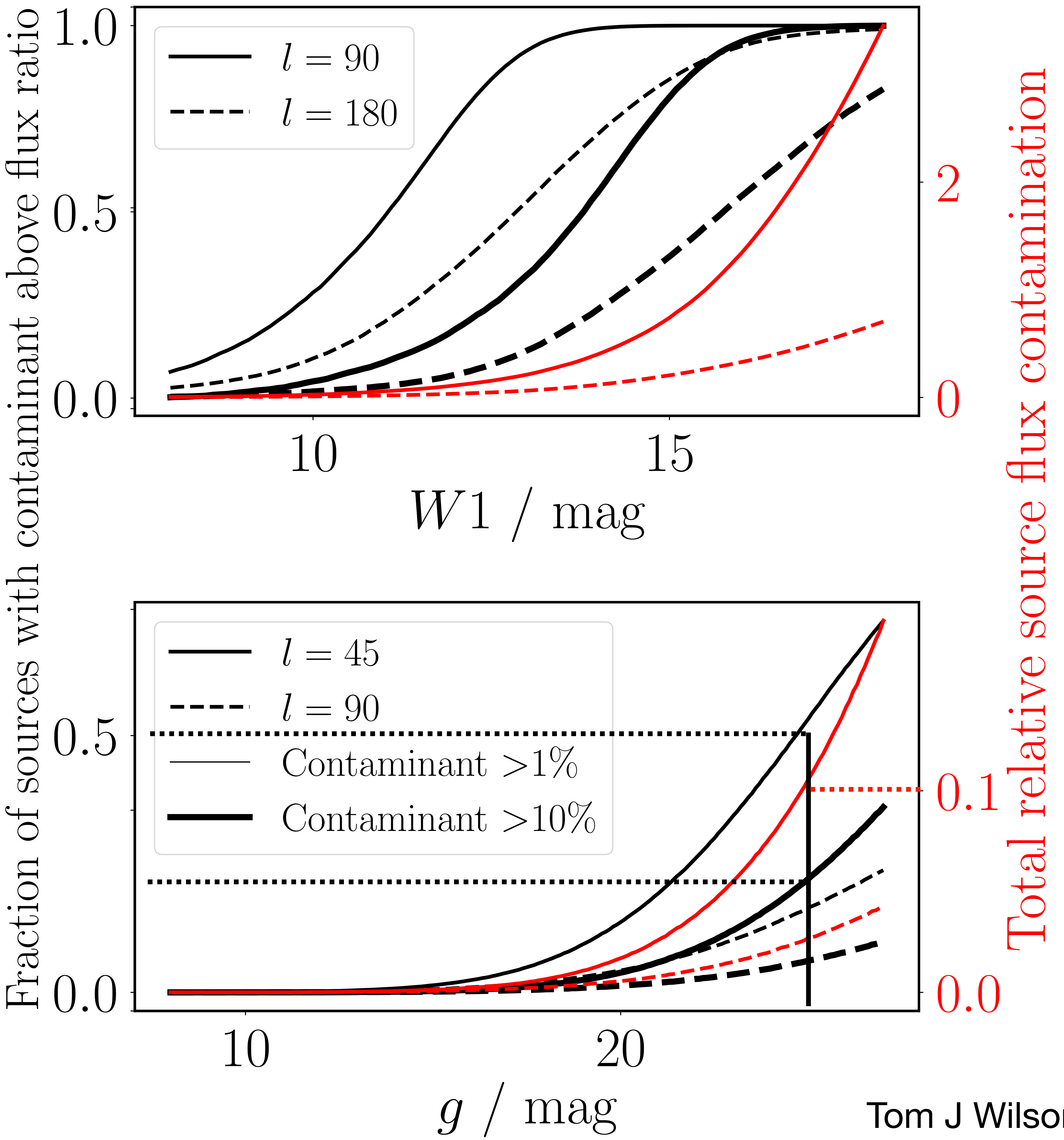
Typical, single visit images in near-Bulge regions of the Plane will have:

- 50% of objects with at least one >1% flux object in their PSF

- 20% of objects with a >10% relative flux object contaminating them

- an average 10% total "extra" flux

(the Bulge will be much more crowded! Nearest-neighbour matching won't work there, but neither will probabilistic matching without taking this effect into account…)



TRILEGAL - Girardi et al. (2005)
Wilson & Naylor (2018b)

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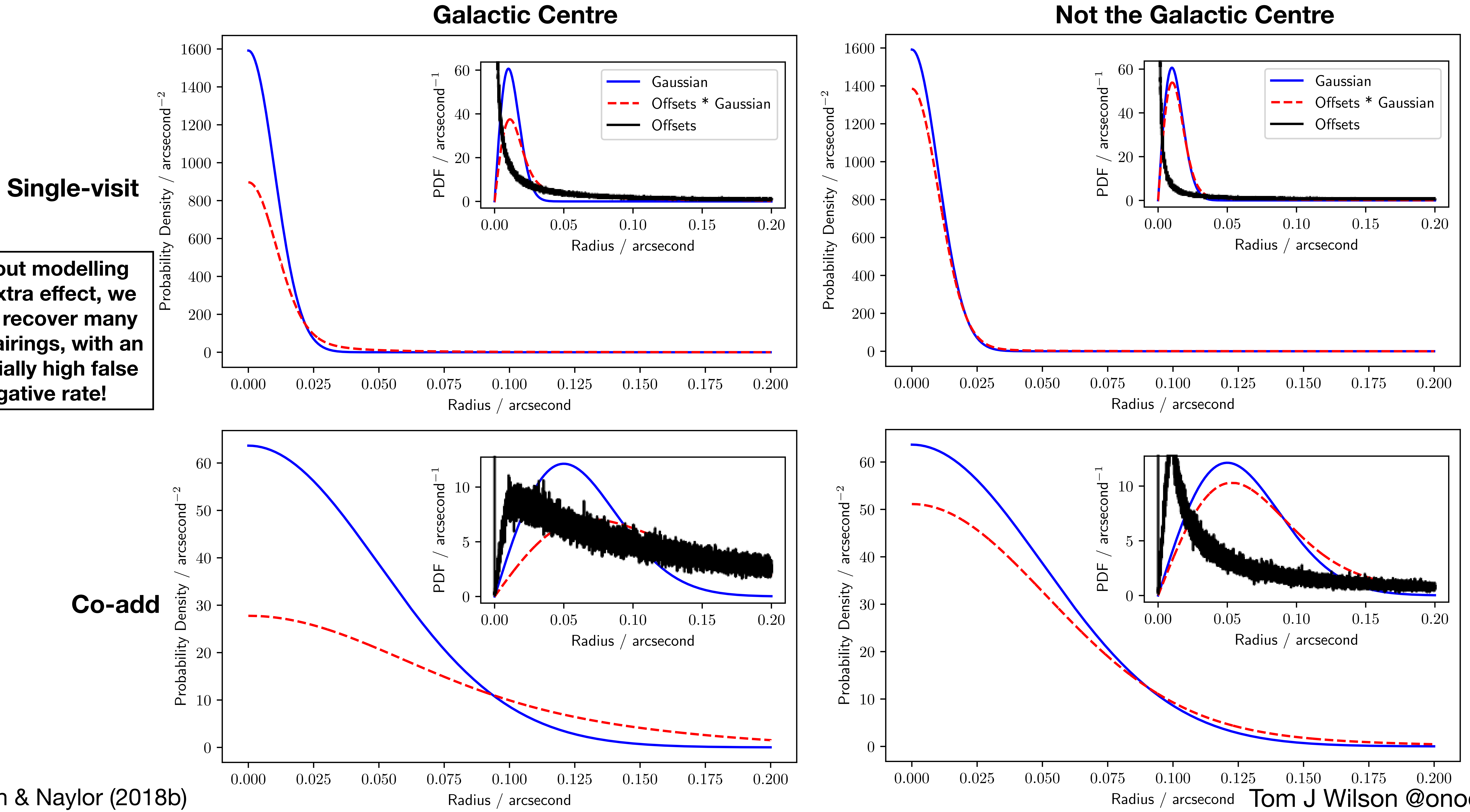
The Rubin AUF: Galactic Plane



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

Wilson & Naylor (2018b)

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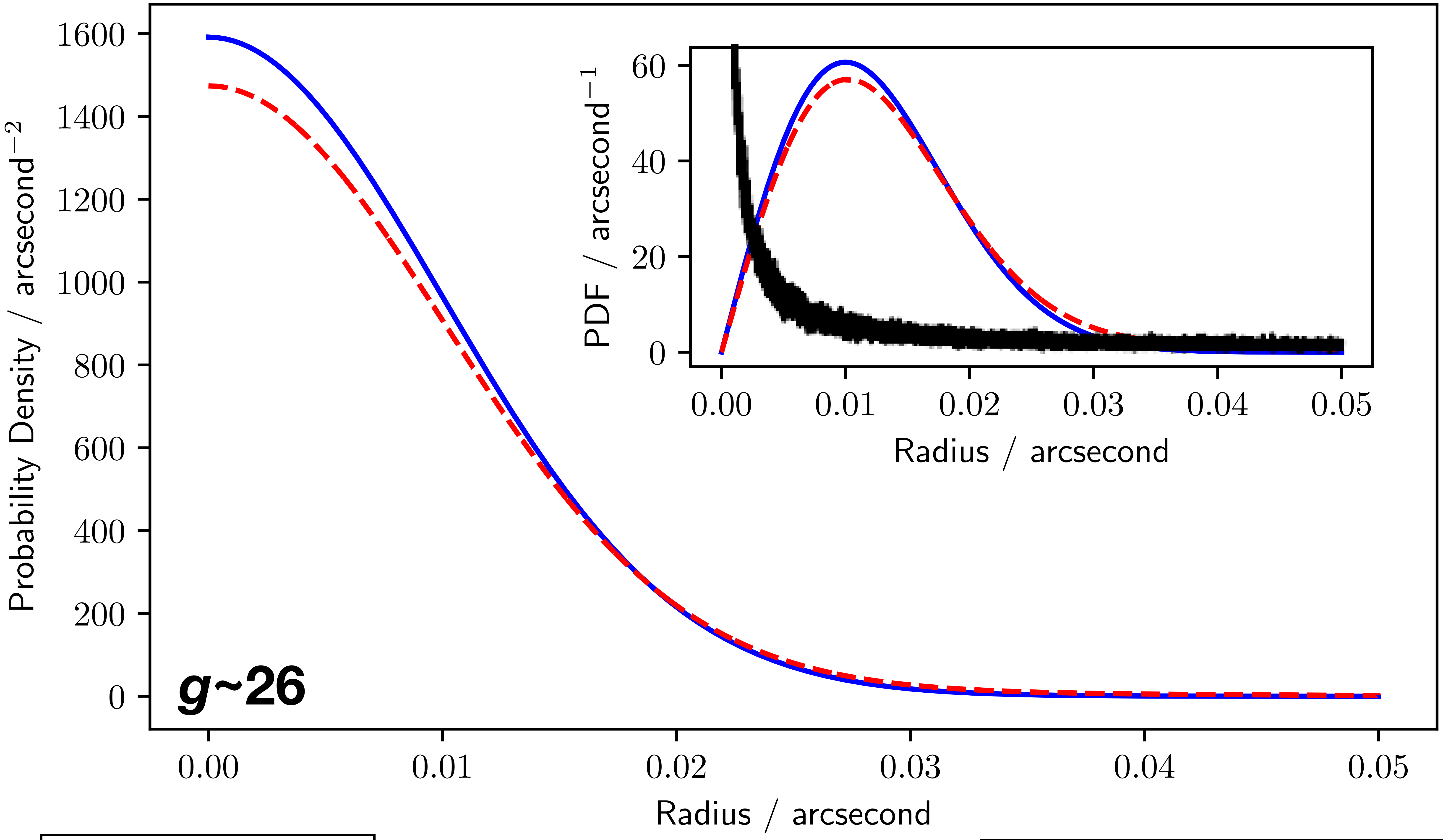
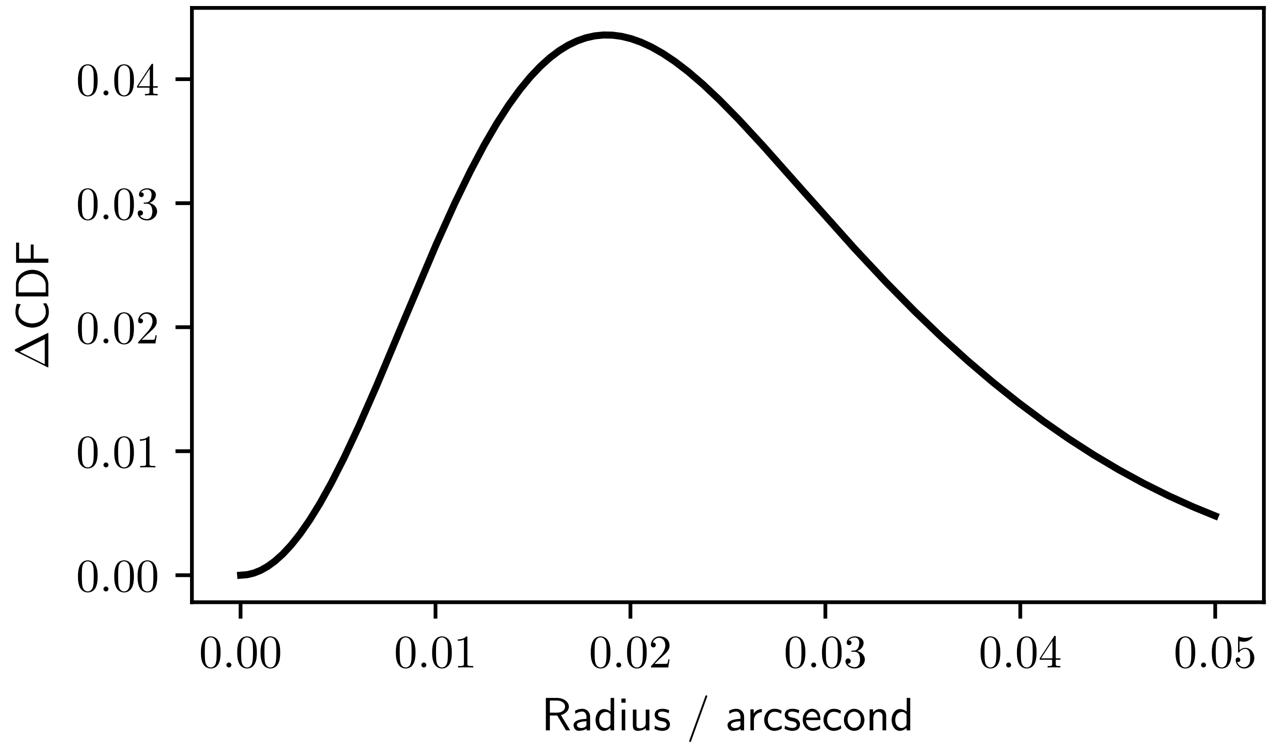
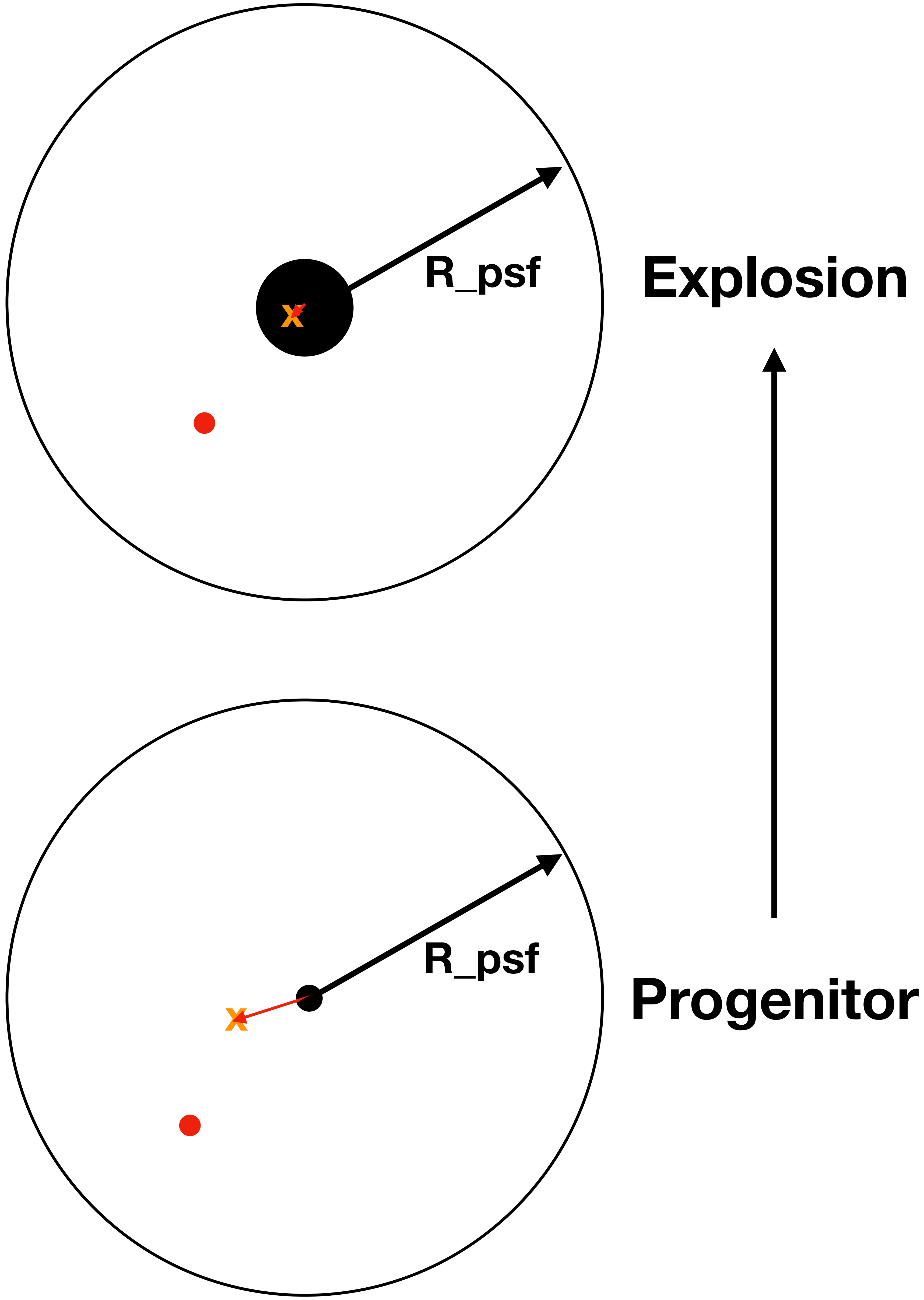
The Rubin AUF: Extra-Galactic, Transients







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

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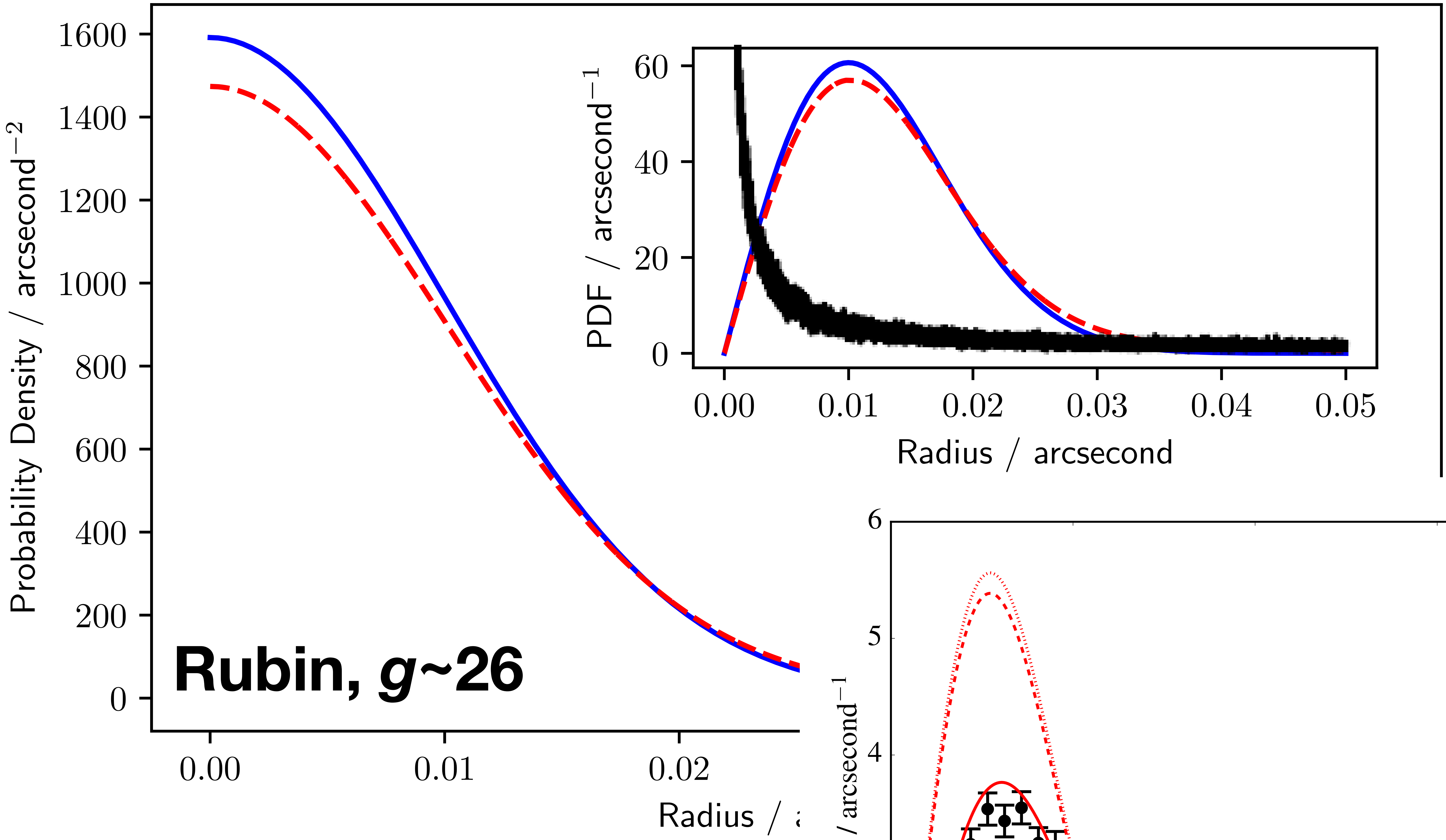

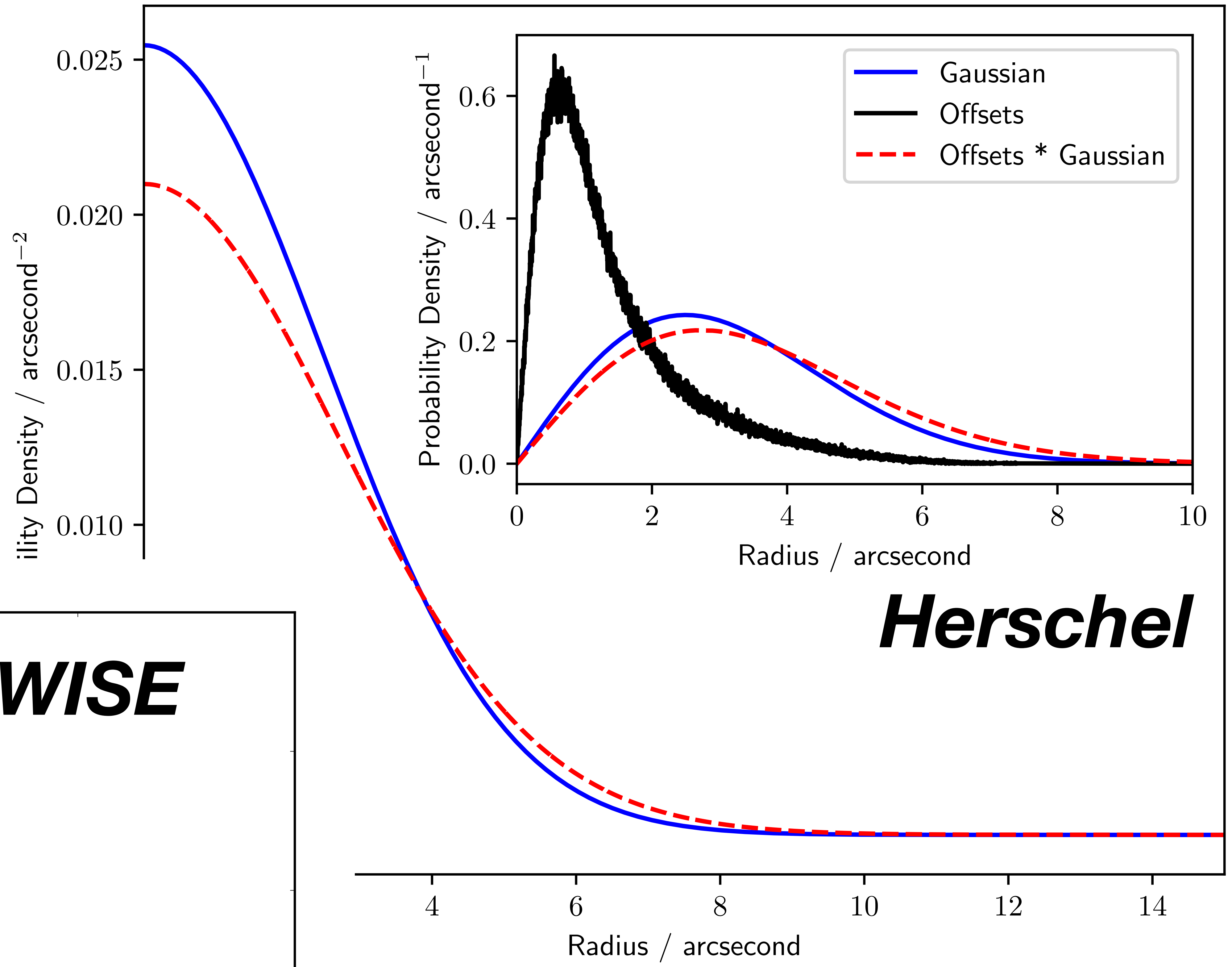

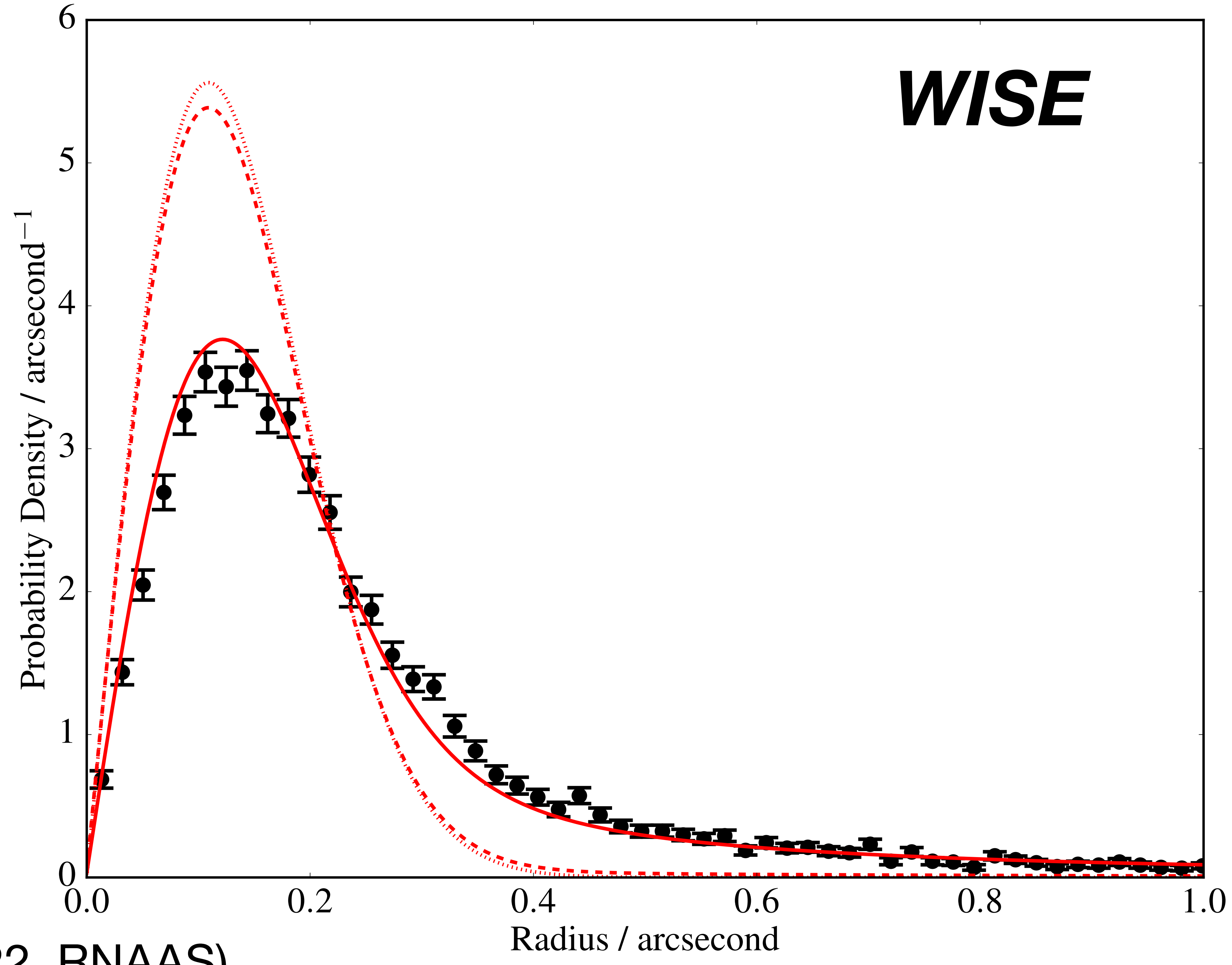

Without modelling this extra effect, we fail to recover many true pairings, with an artificially high false negative rate!

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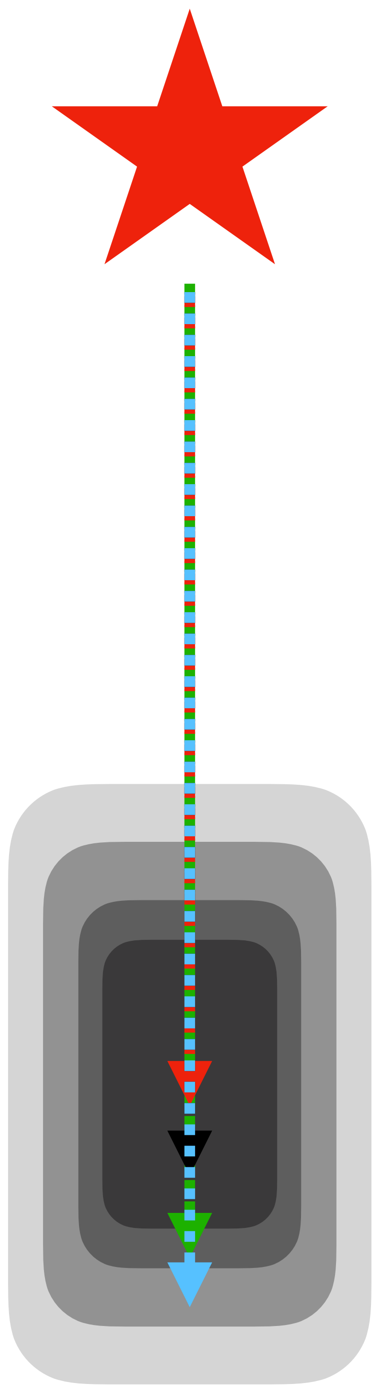
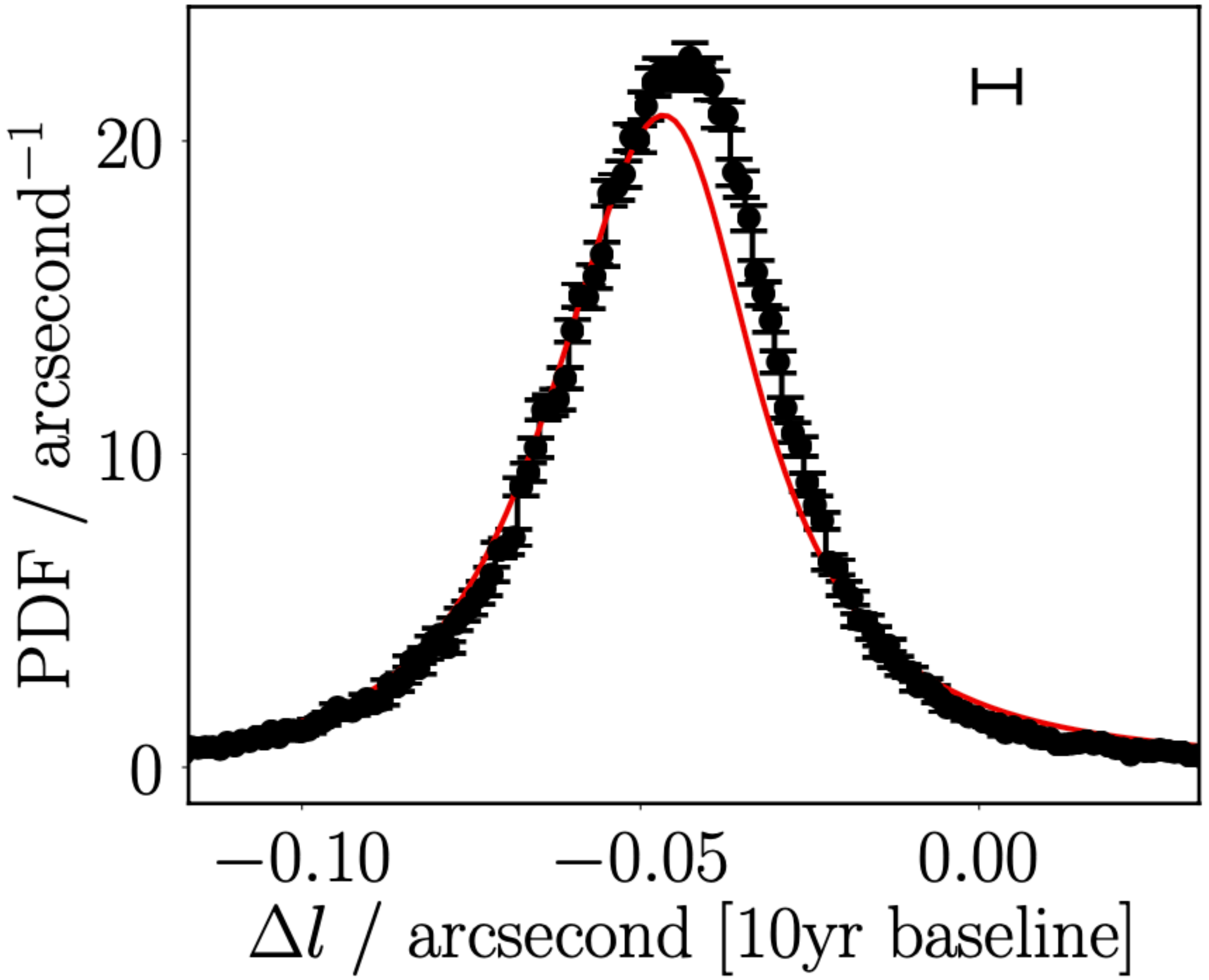
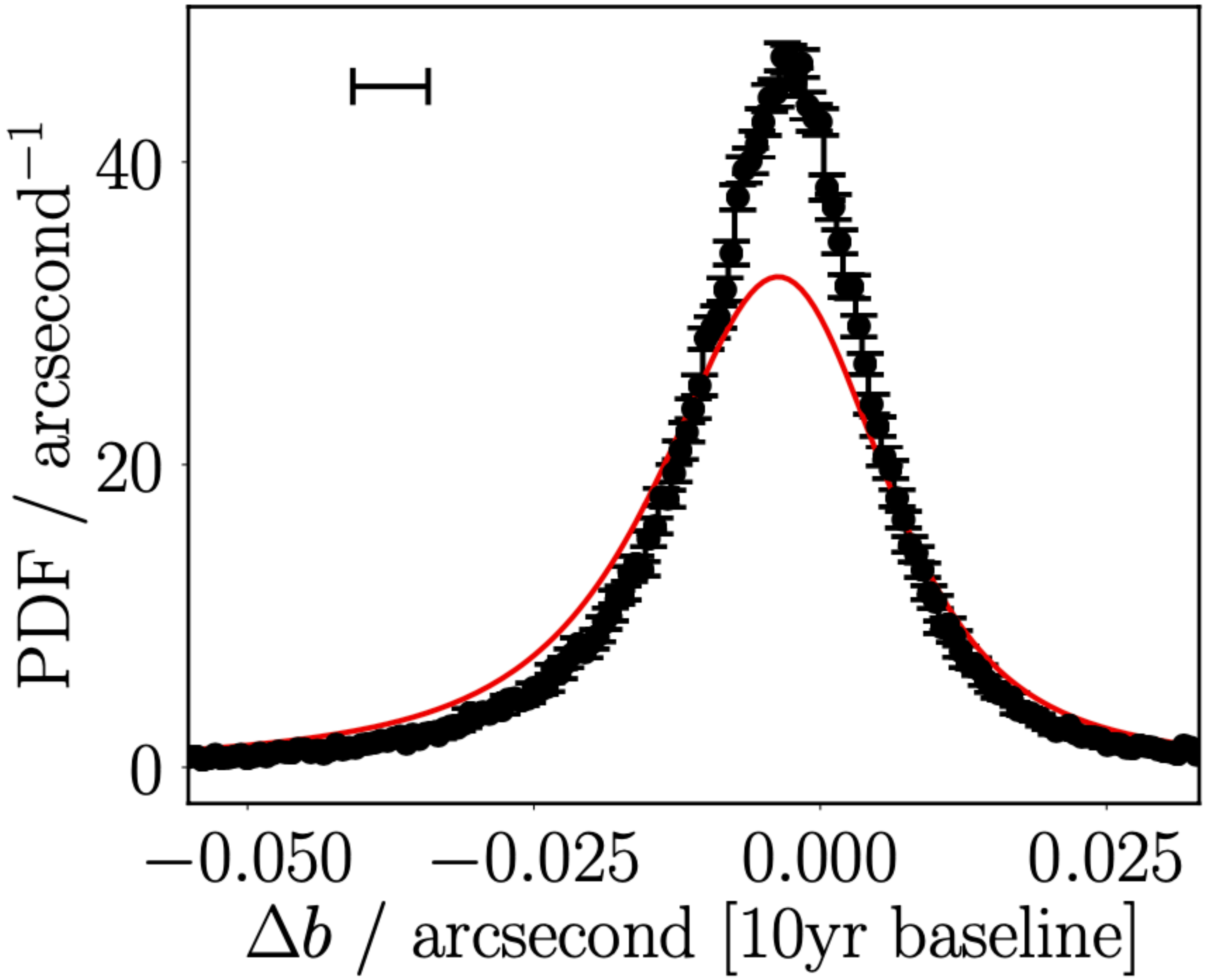
Unknown Proper Motions

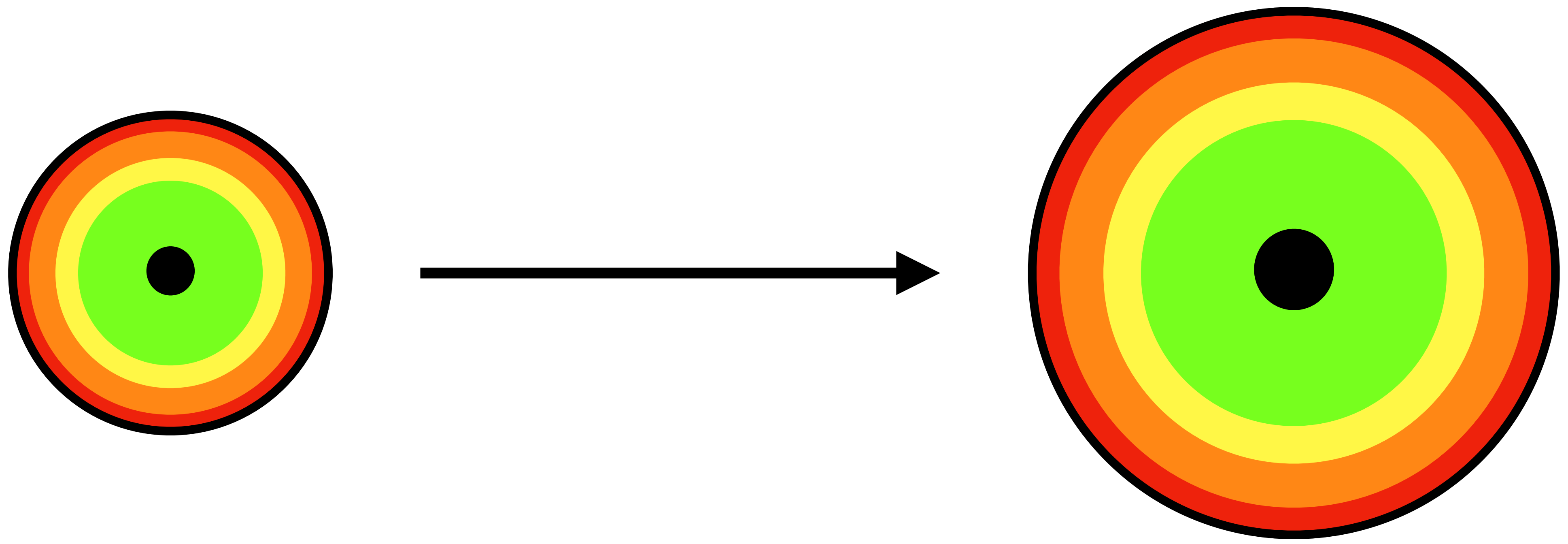
Object in 2015



Projected to 2025



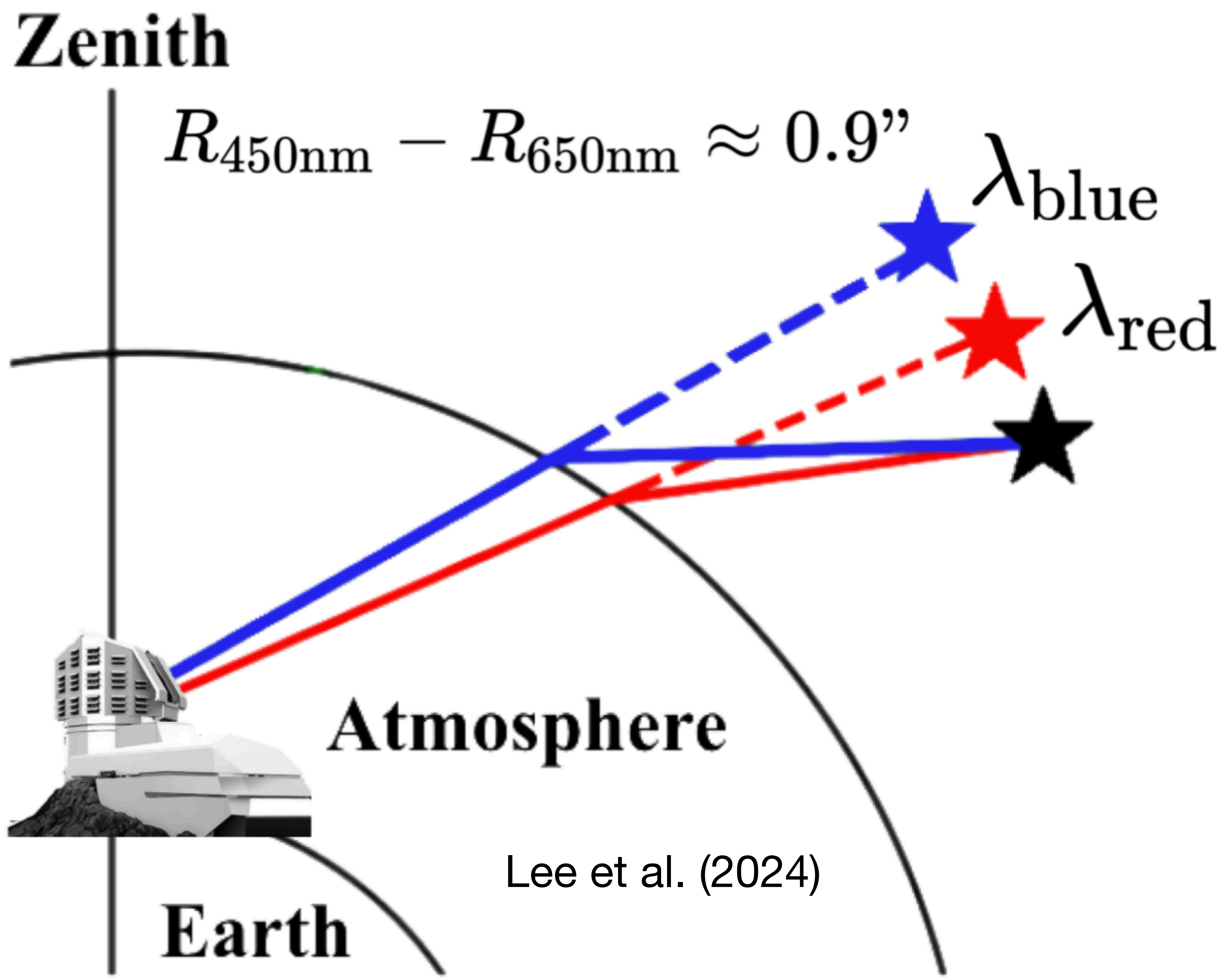




(This also applies to *uncertain* proper motions, where we can incorporate the covariance matrix of weakly-constrained proper motions, e.g. just above the single-visit LSST limit)

Wilson (2023, RASTI, 2, 1)
Gaia eDR3 - Gaia Collaboration et al. (2021, A&A, 649, A1)

Differential Chromatic Refraction



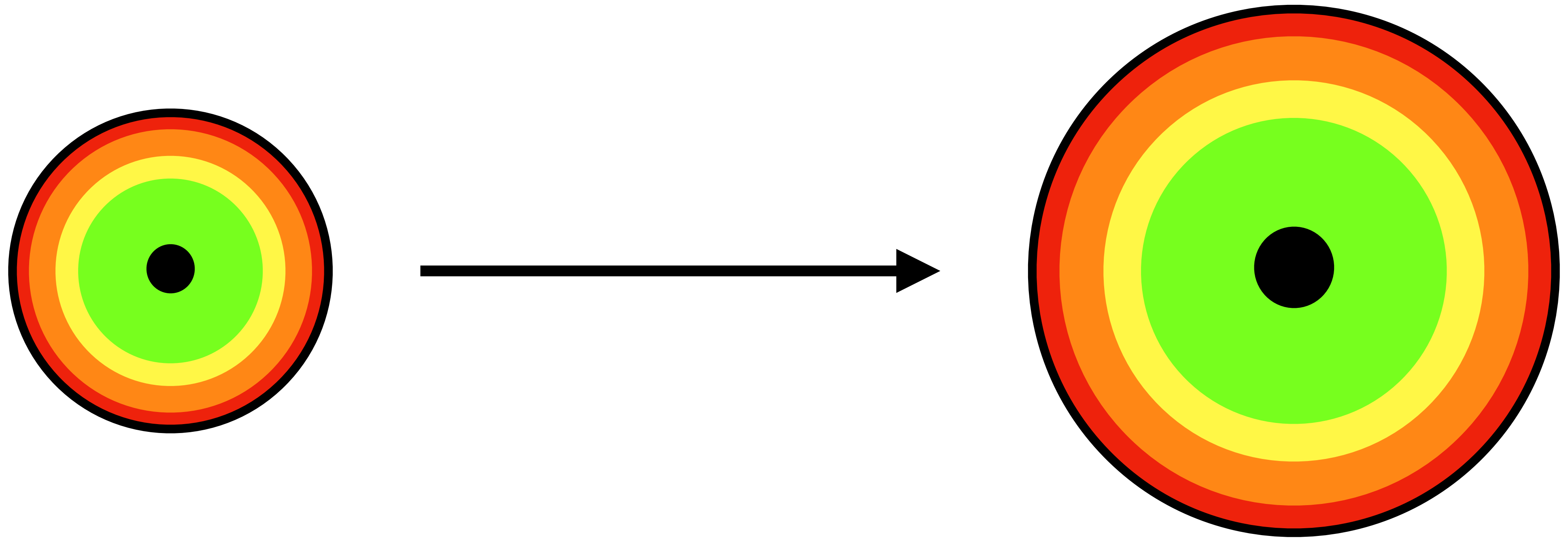
Lee et al. (2024)

e.g. gbdes, Bernstein et al. (2017)

$$\Delta \mathbf{x}^{w} = K_{b} c \tan z \, \hat{\mathbf{p}}$$

Unknown/uncertain per-band (*b*) scaling factor

Unknown/uncertain photometric colour *c*



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Matching Across Catalogues using the Astrometric Uncertainty Function and Flux

https://github.com/macauff/macauff

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Macauff

Cross-Match Tools, Framework, Usage

birnam

banquo

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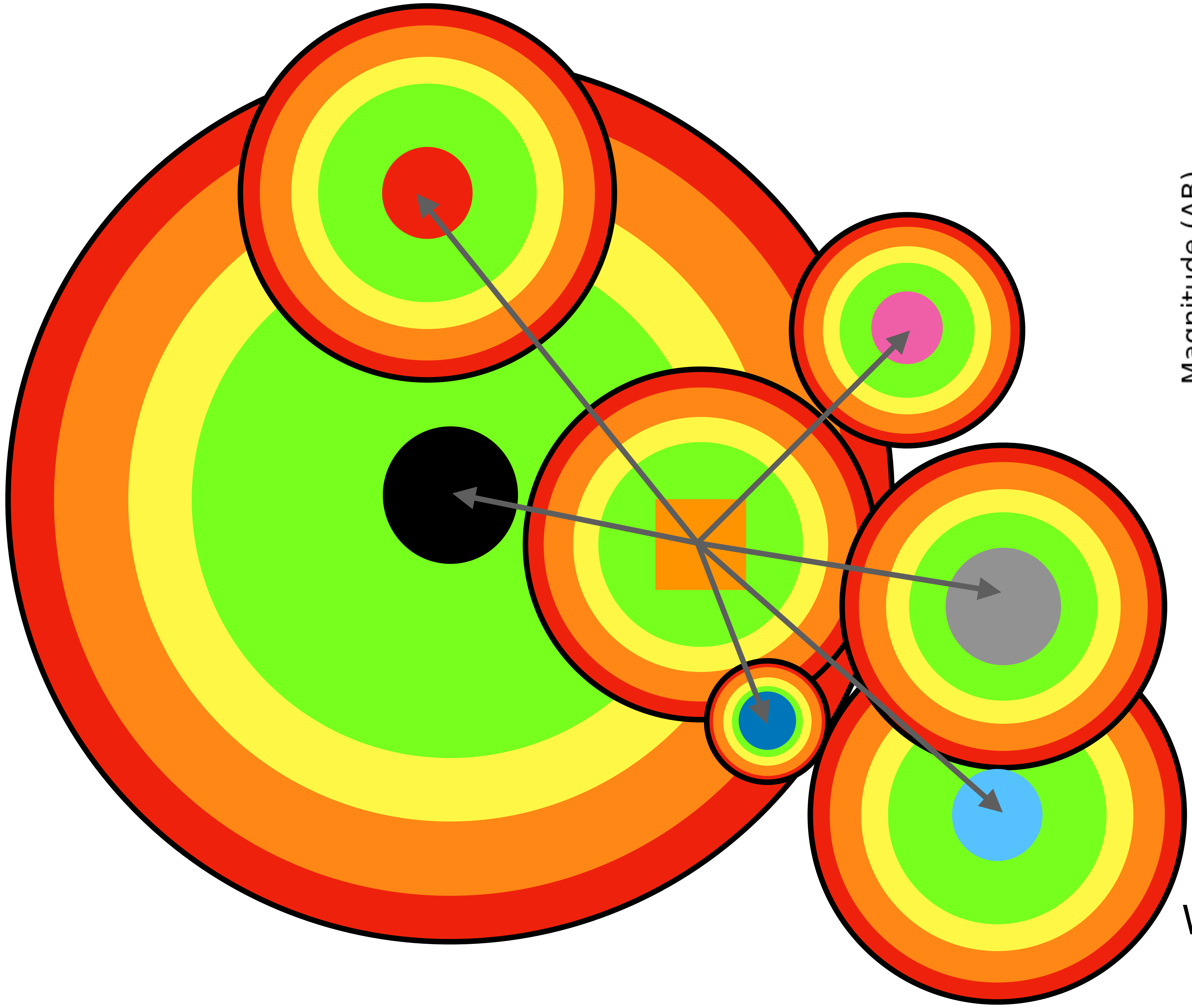
The Rubin "Super-Match"

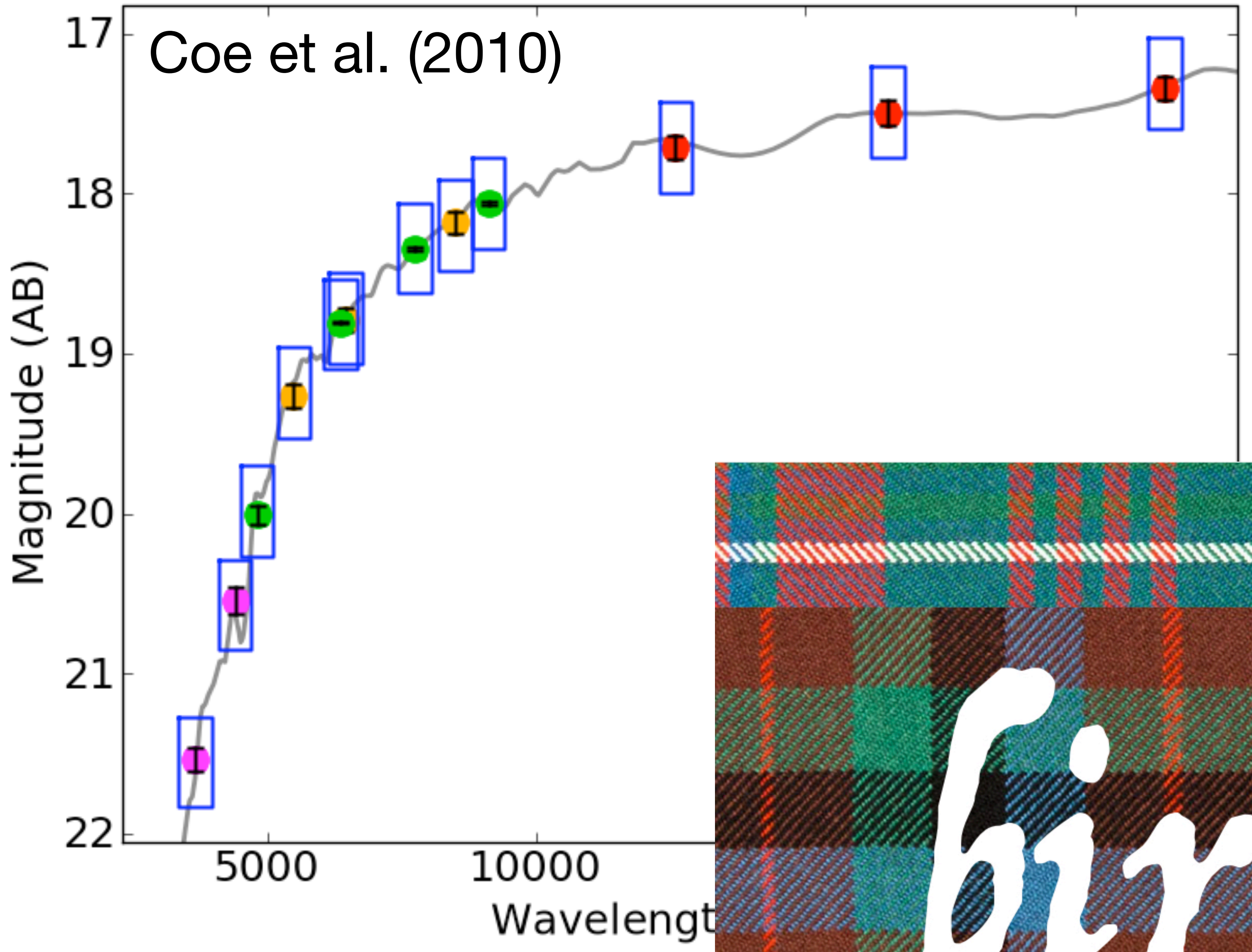
Bringing Independent Results together to Notify of Associations across Multiple catalogues

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.





https://github.com/macauff/macauff
https://github.com/macauff/birnam

Wilson & Naylor (in prep.)
Pineau et al. (2017)

Tom J Wilson @onoddil

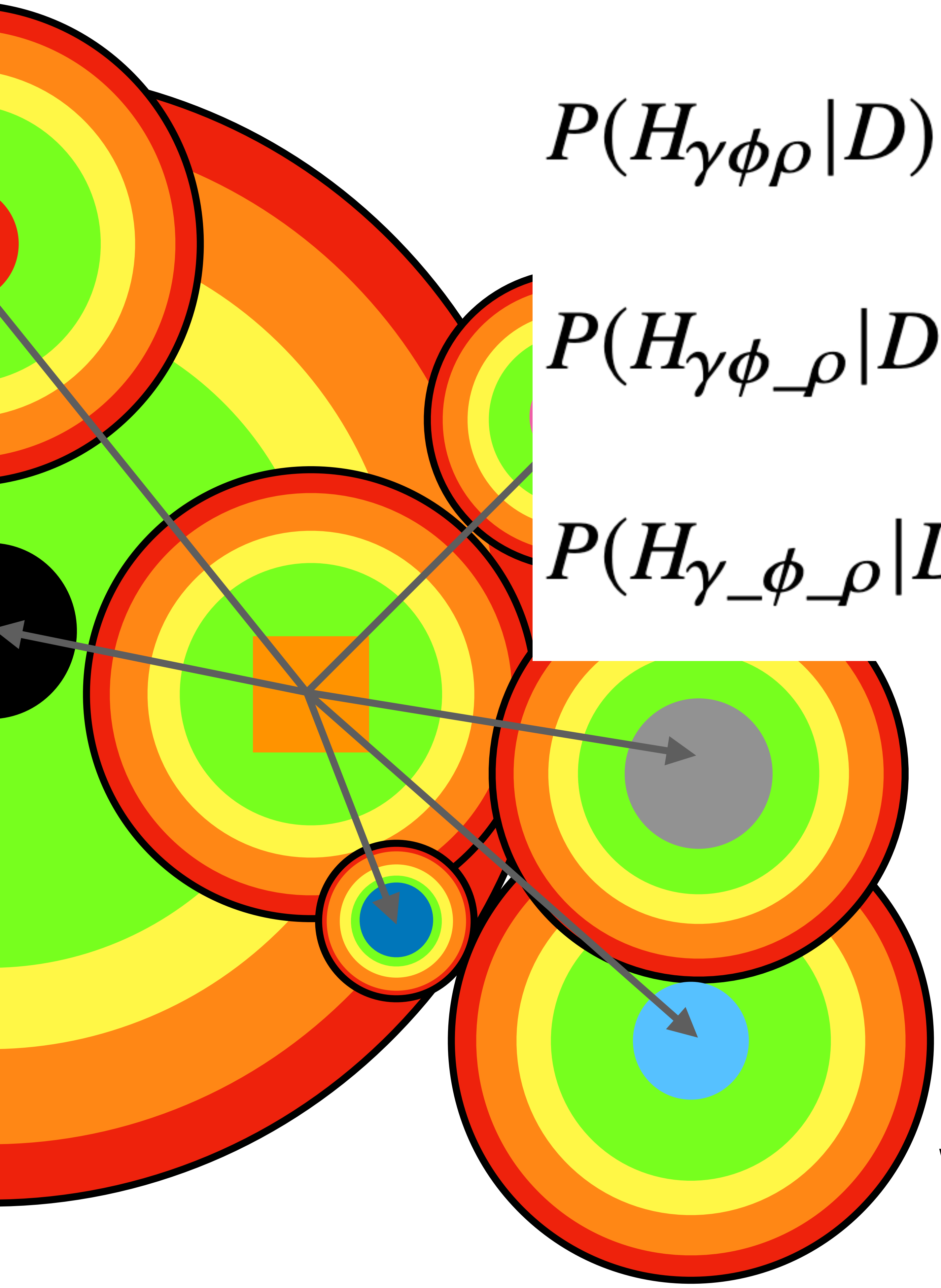
The Rubin "Super-Match"

Bringing Independent Results together to Notify of Associations across Multiple catalogues

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.



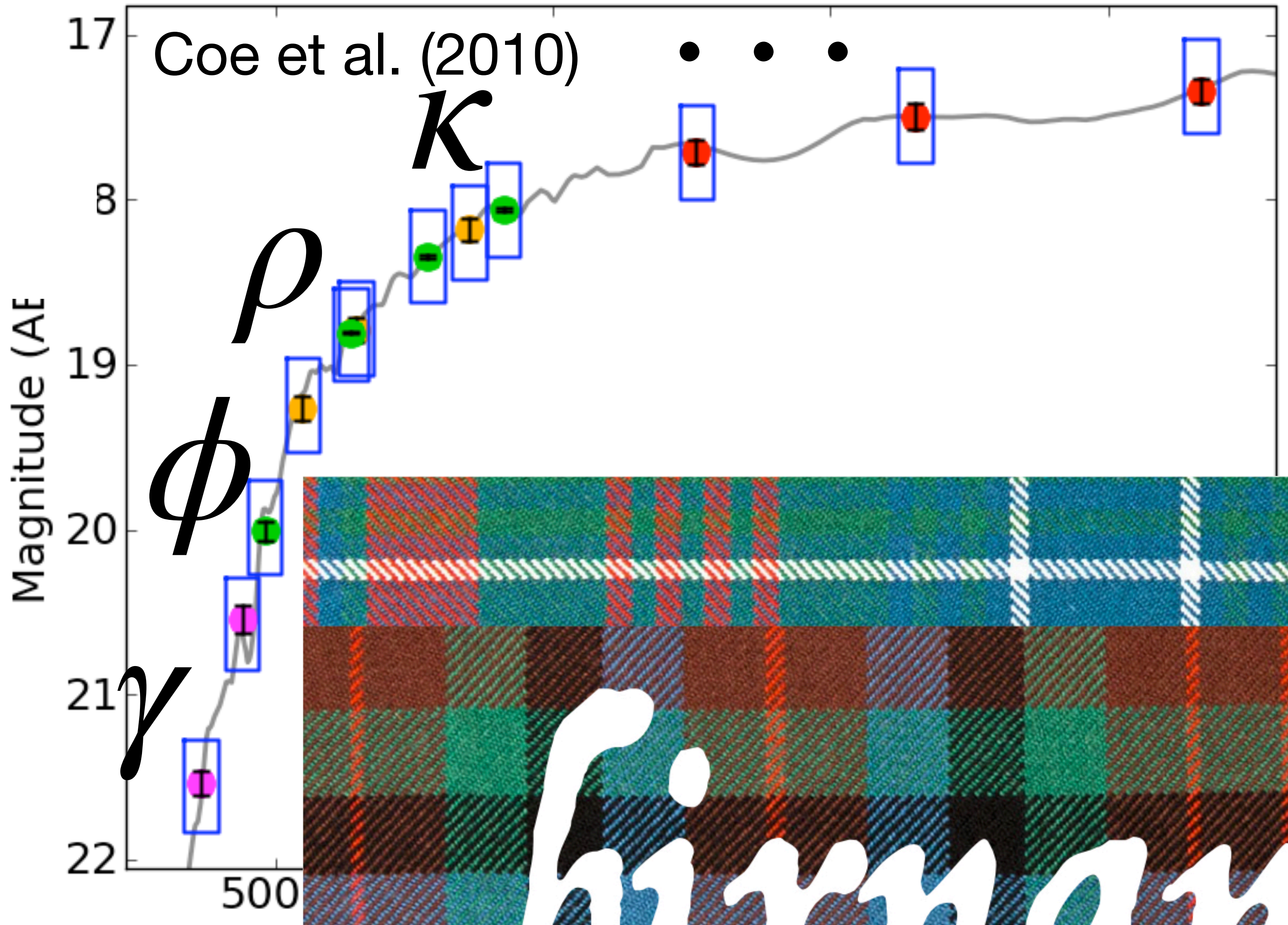
$$P(H_{\gamma\phi\rho}|D) = \frac{1}{K} N_{\gamma\phi} G_{\gamma\phi} N_{\gamma\rho} G_{\gamma\rho} = A_{\gamma\phi} A_{\gamma\rho},$$

$$P(H_{\gamma\phi\_\rho}|D) = \frac{1}{K} N_{\gamma\phi} G_{\gamma\phi} N_{\gamma} N_{\rho} = B_{\gamma\phi} A_{\gamma\rho},$$

$$P(H_{\gamma\_\phi\_\rho}|D) = \frac{1}{K} N_{\gamma} N_{\phi} N_{\gamma} N_{\rho} = B_{\gamma\phi} B_{\gamma\rho},$$

$$A_{\gamma\phi} = \frac{N_{\gamma\phi} G_{\gamma\phi}}{N_{\gamma} N_{\phi} + N_{\gamma\phi} G_{\gamma\phi}}$$

$$B_{\gamma\phi} = \frac{N_{\gamma} N_{\phi}}{N_{\gamma} N_{\phi} + N_{\gamma\phi} G_{\gamma\phi}}$$



Wilson & Naylor (2018a)

Wilson & Naylor (in prep.)
Pineau et al. (2017)

https://github.com/macauff/macauff
https://github.com/macauff/birnam

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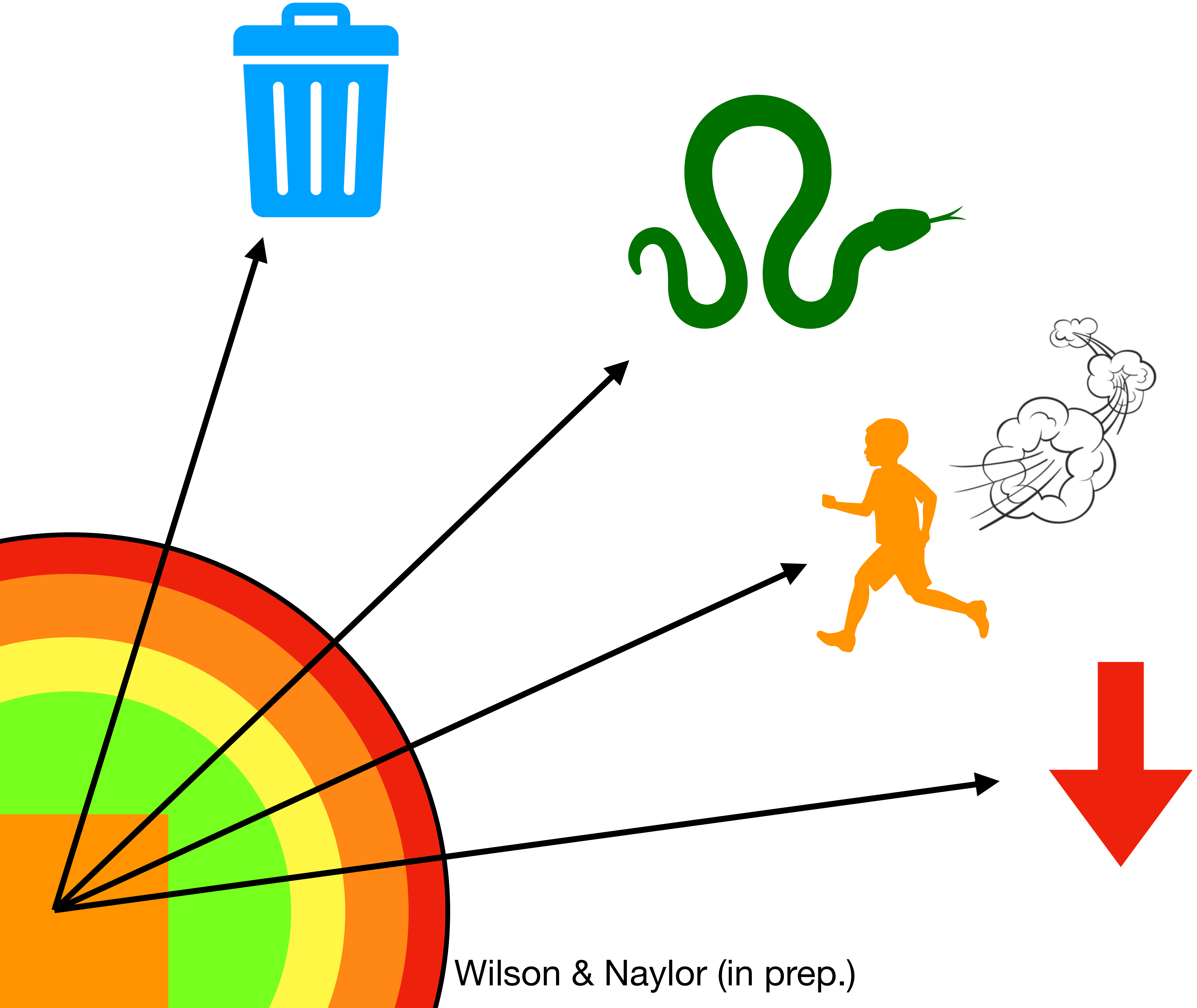
Confirming Lonely Rubin Sources

Blanks And Near-misses, Questionable sources, Upper-limits, and Objects of varying brightness



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

Wilson & Naylor (in prep.)

Tom J Wilson @onoddil

Confirming Lonely Rubin Sources

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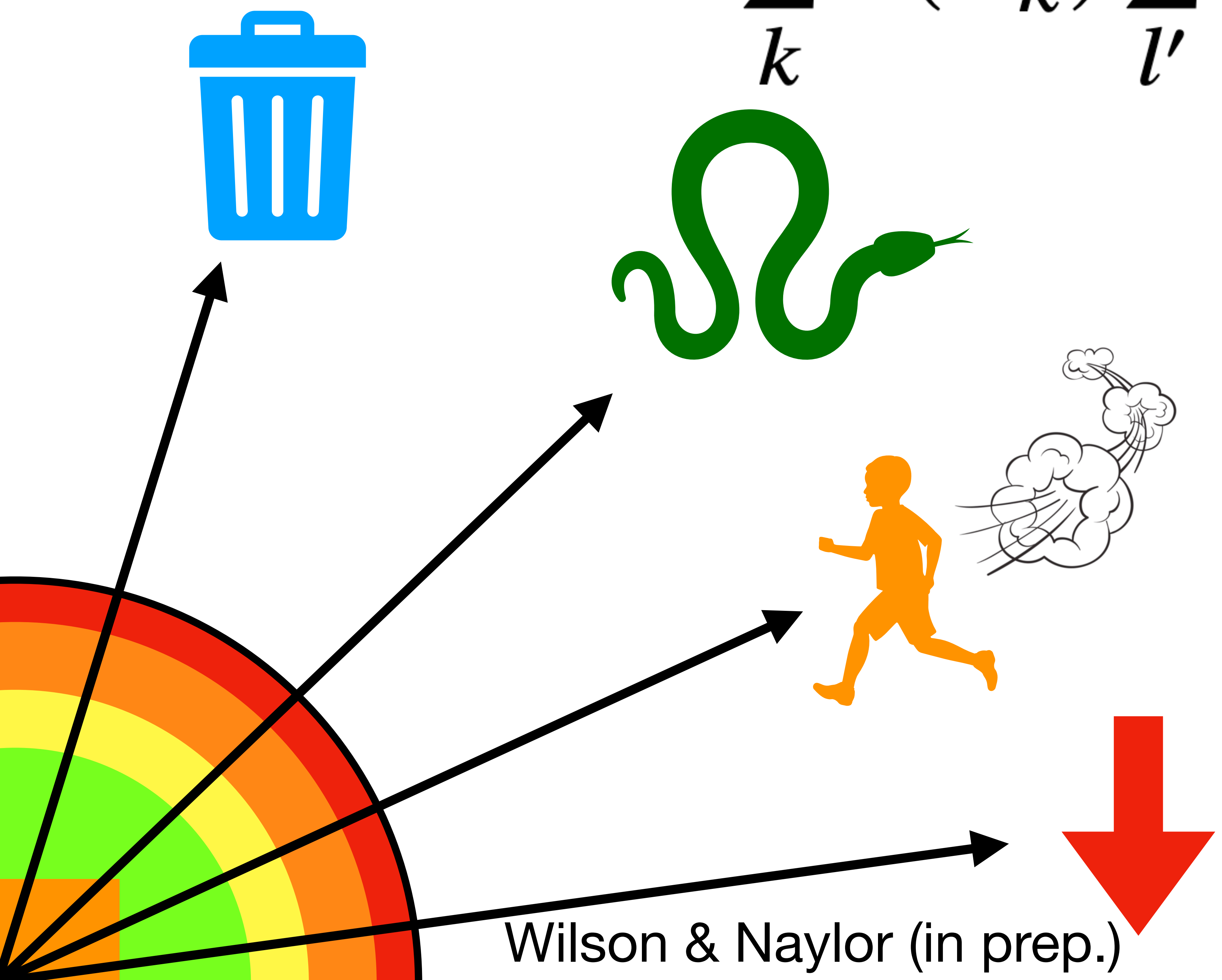
$$P(H_i, M_j|\mathbf{D}) = \frac{P(H_i)P(M_j|H_i)p(\mathbf{D}|H_i, M_j)}{p(\mathbf{D})}$$

$$P(H_i, M_j|\mathbf{D}) = \frac{P(H_i)L_j}{\sum_k P(H_k) \sum_{l'} L_{l'} + \sum_{k'} P(H_{k'})}$$

$$L = \frac{Gc}{Nf}$$



Wilson & Naylor (in prep.)

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- Image artefacts
- Astrophysically variable objects
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Tom J Wilson @onoddil

Verifying Astrometry: Accounting For Systematics

In each sightline (10s of sq deg for good bright source counting N):

1. **Cross-match your high angular resolution, high astrometric precision data to LSST to obtain separation distributions**
2. **Create systematics model for all non-centroid astrometric components of uncertainty**
3. **Fit full AUF to data, allowing centroid Gaussian uncertainty to be fit**
4. **Repeat for each brightness (and effectively different astrometric uncertainty)**
5. **Derive fit-quoted astrometric uncertainty relations**

Create crowding-caused perturbation model, for example:

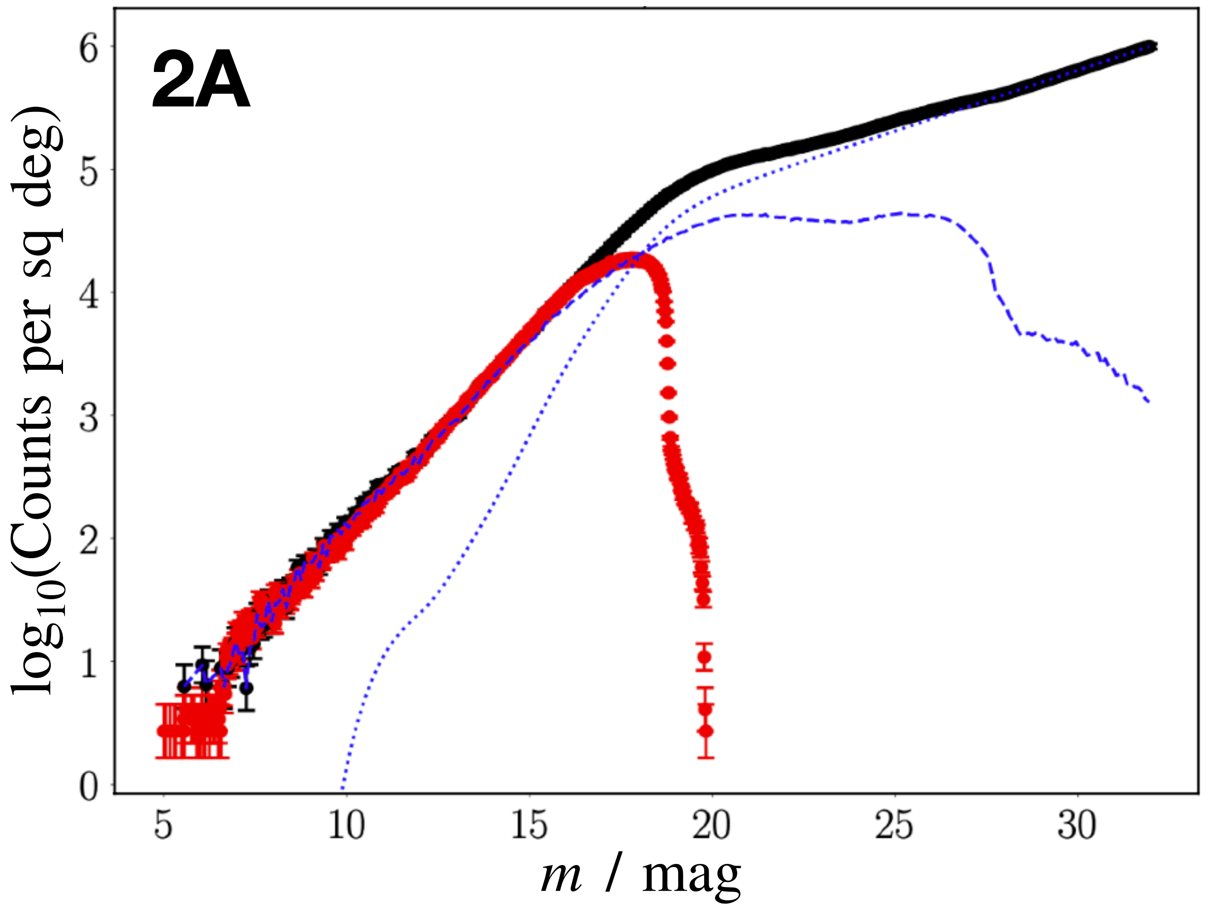
A. Verify model source count densities match observed data

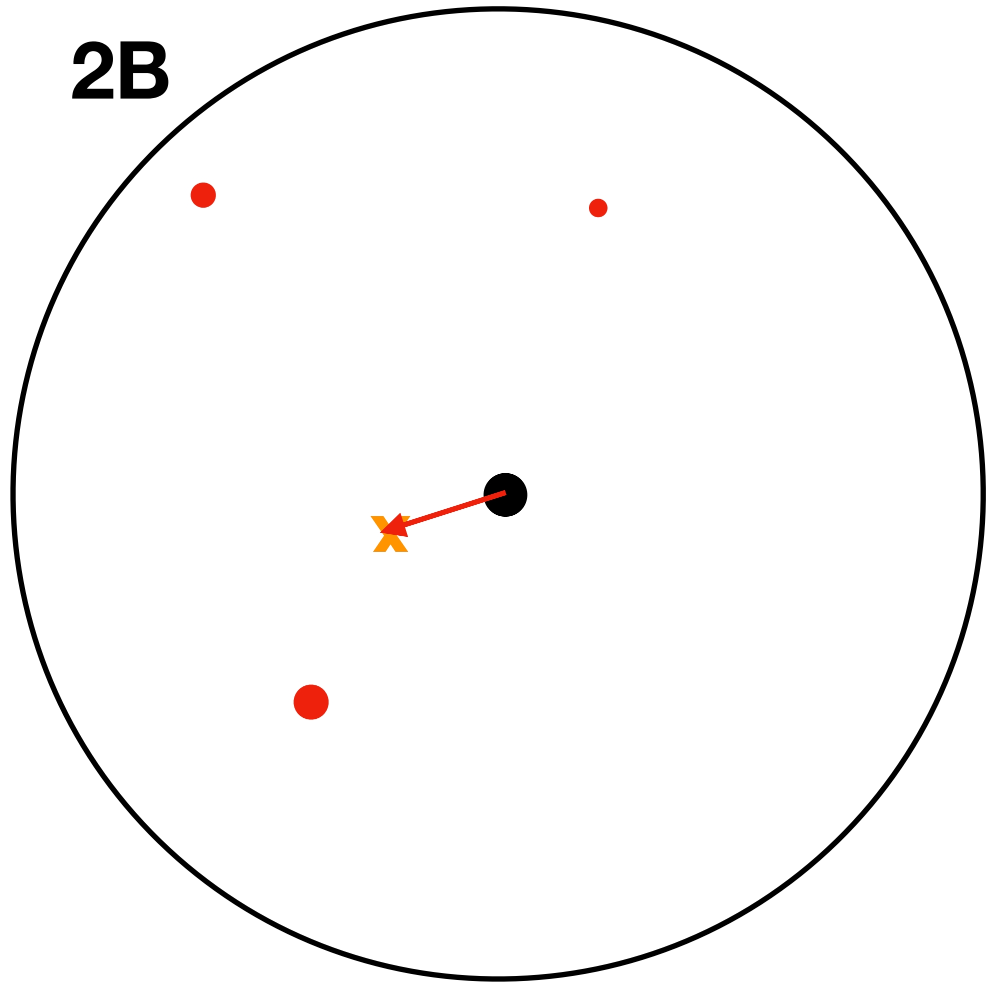
B. Randomly draw perturbing sources within your PSF (“darts at a dartboard”)

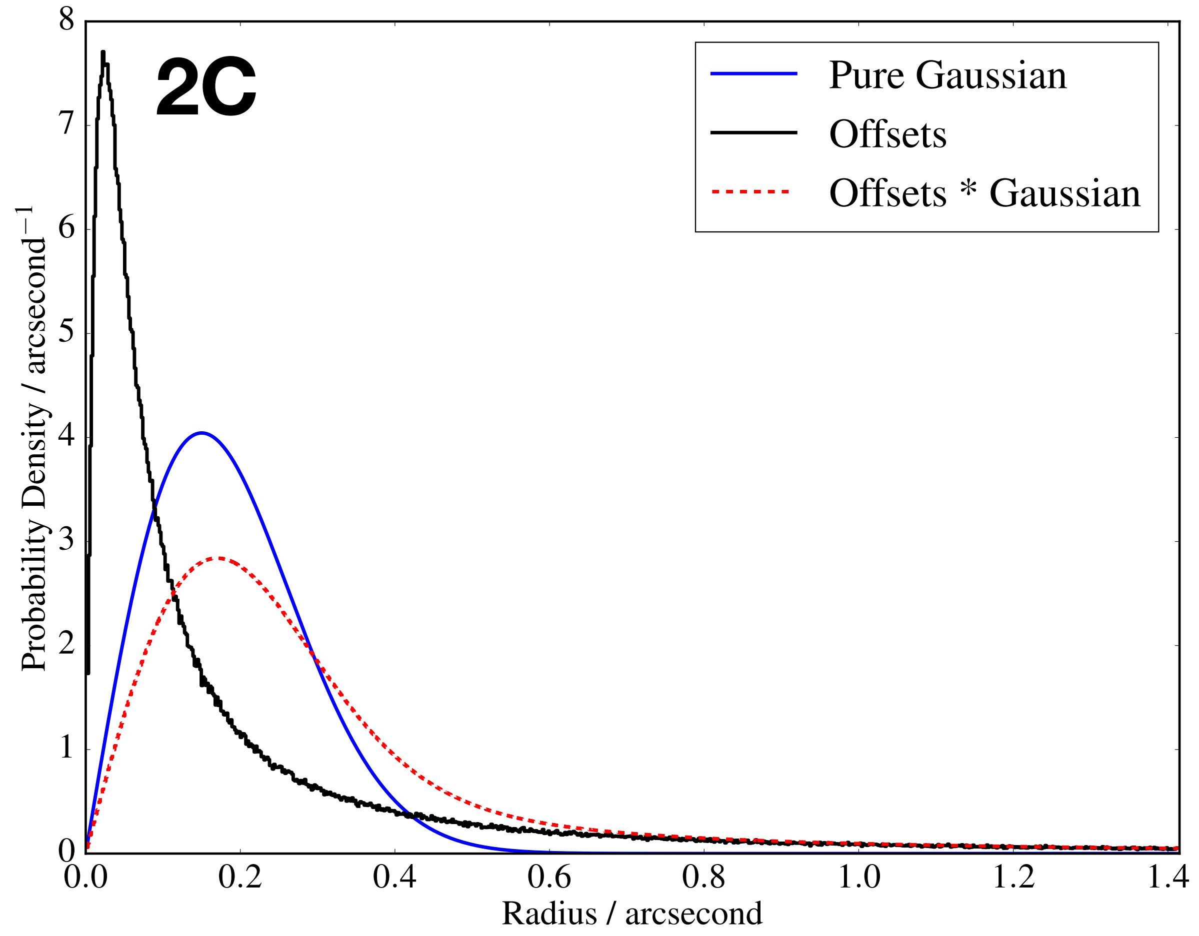
C. Repeat lots of times to get a distribution of perturbation offsets

D. Repeat however many times you have different perturbation algorithms

E. Combine your perturbation algorithms







2D

$$\bar{x} = \frac{1 \times 0 + \sum_i f_i x_i}{1 + \sum_i f_i}$$

- or -

$$\log \mathcal{L} = -\frac{1}{2} \times L \int_{-\infty}^{\infty} \left[\phi(\mathbf{r}) + \sum_i f_i \phi(\mathbf{r} - \mathbf{d}_i) - (1 + \Delta f)\phi(\mathbf{r} - \mathbf{\Delta d}) \right]^2 \mathrm{d}^2 r$$

$$\Delta x(x, y, f) = \begin{cases} f\, x \exp\left(-\frac{1}{4}\frac{x^2+y^2}{\sigma_\psi^2}\right) & f < 0.15 \\ \Omega(x, f) & f \geq 0.15, \end{cases}$$

where

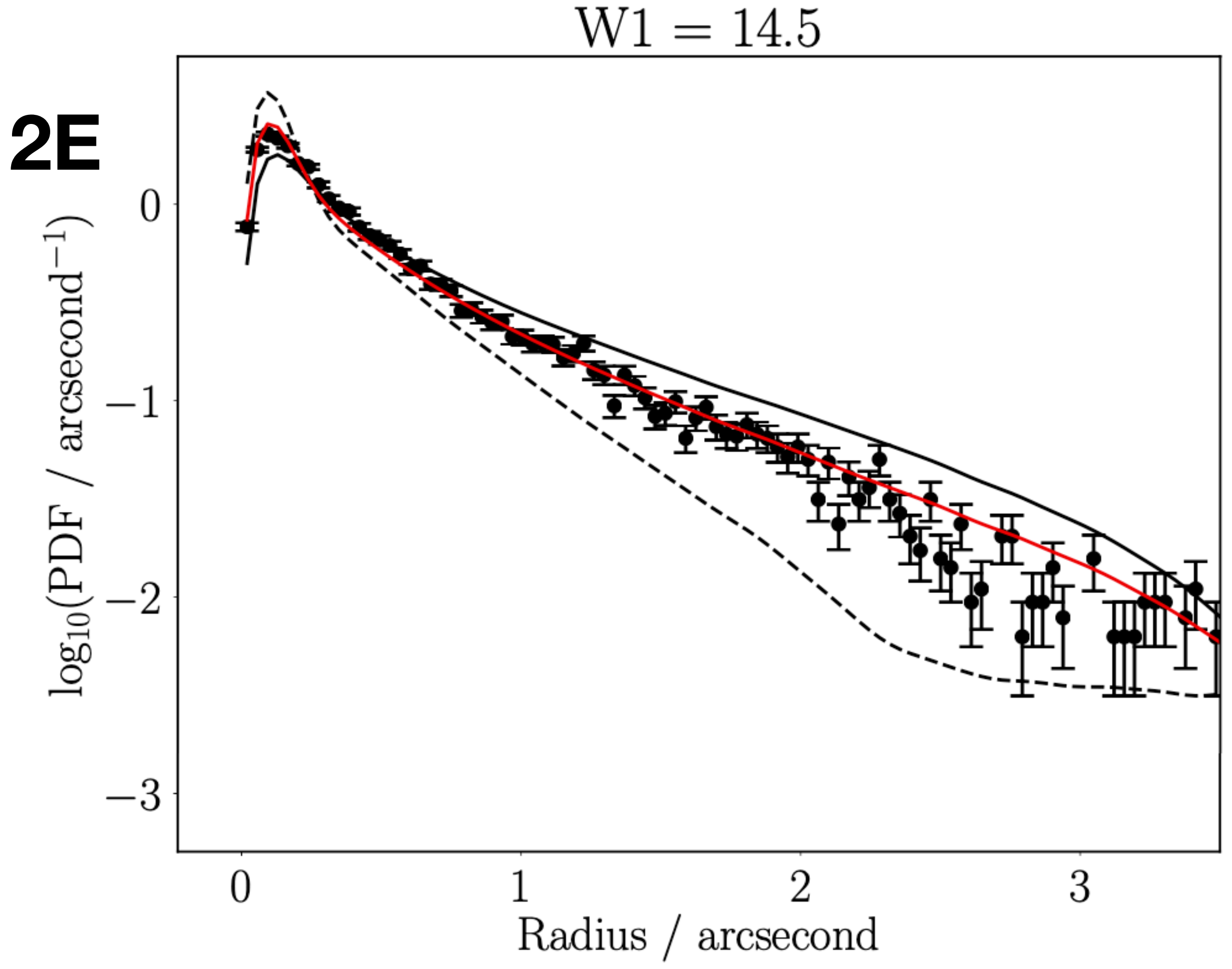
$$\Omega(x, f) = \Omega(x, f, \sigma, \mu, \alpha, T, r_c)$$

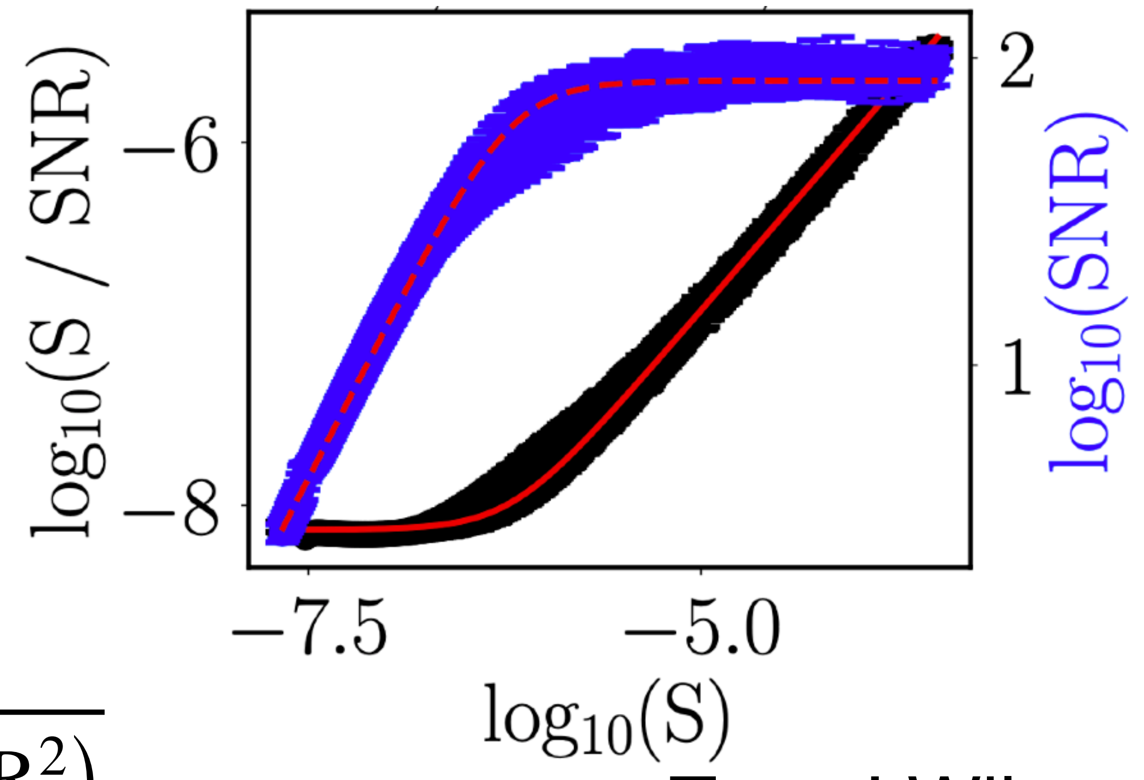
$$= \begin{cases} x f/(1+f) & x < r_c \text{ or } f > 0.9975 \\ 2f\frac{T}{\sigma}\lambda\left(\frac{x-\mu}{\sigma}\right)\Lambda\left(\alpha\frac{x-\mu}{\sigma}\right) & x > r_c \text{ and } f \leq 0.9975 \end{cases}$$

Wilson & Naylor (in prep.)
cf. Plewa & Sari (2018)

$$\mathrm{SNR} = \frac{S}{\sqrt{c \times S + b + (a \times S)^2}}$$

$$H = 1 - \sqrt{1 - \min\left(1,\, a \times \mathrm{SNR}^2\right)}$$





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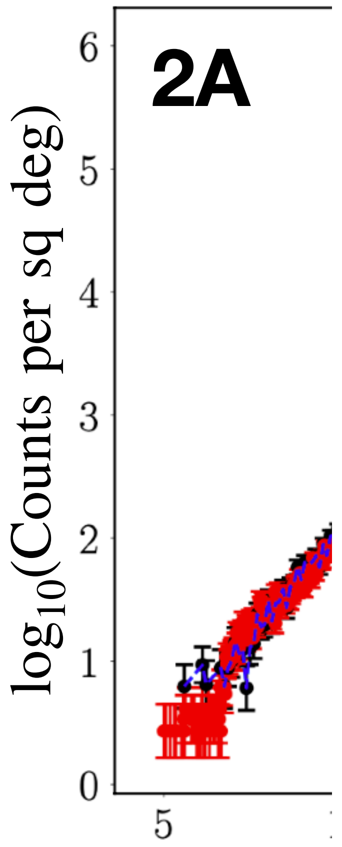
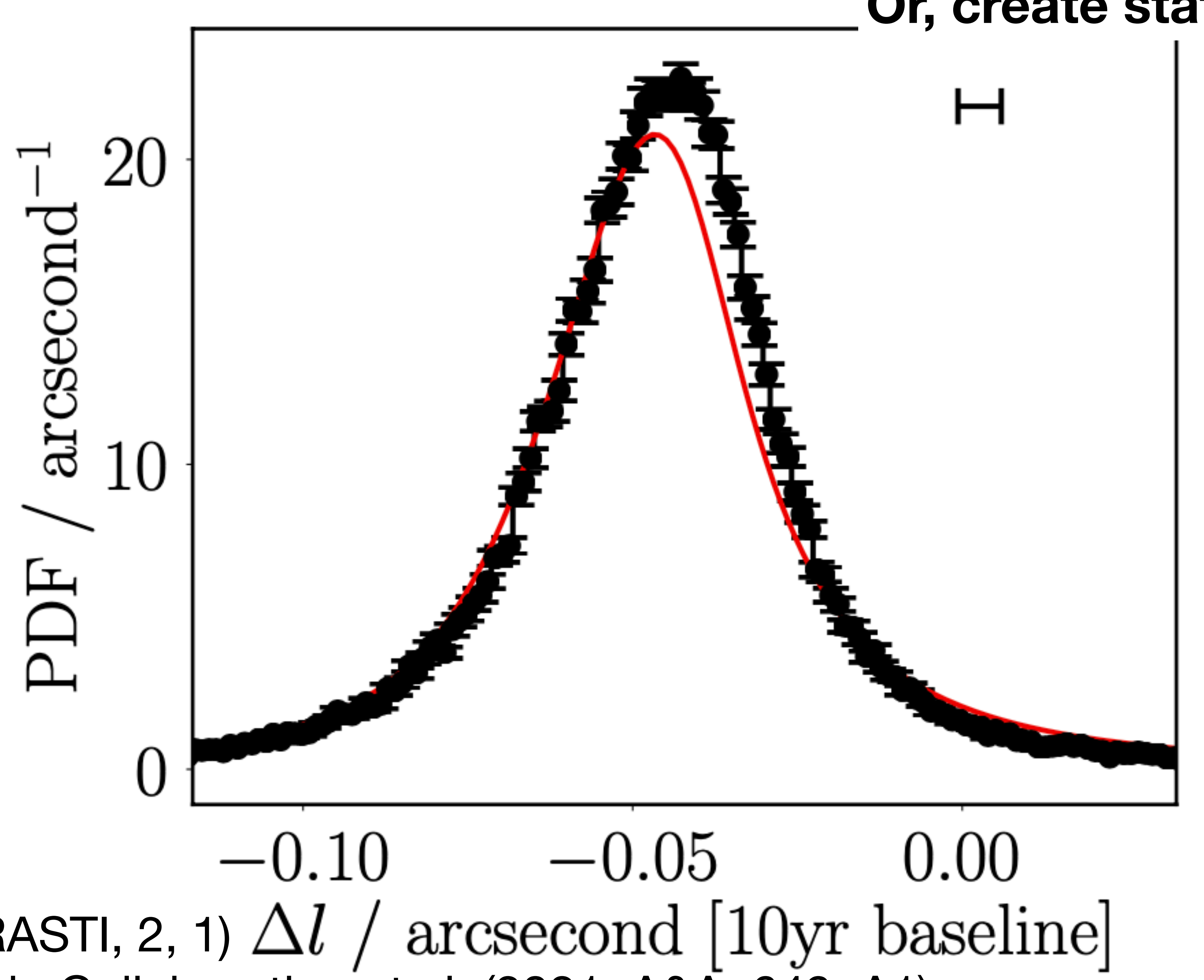
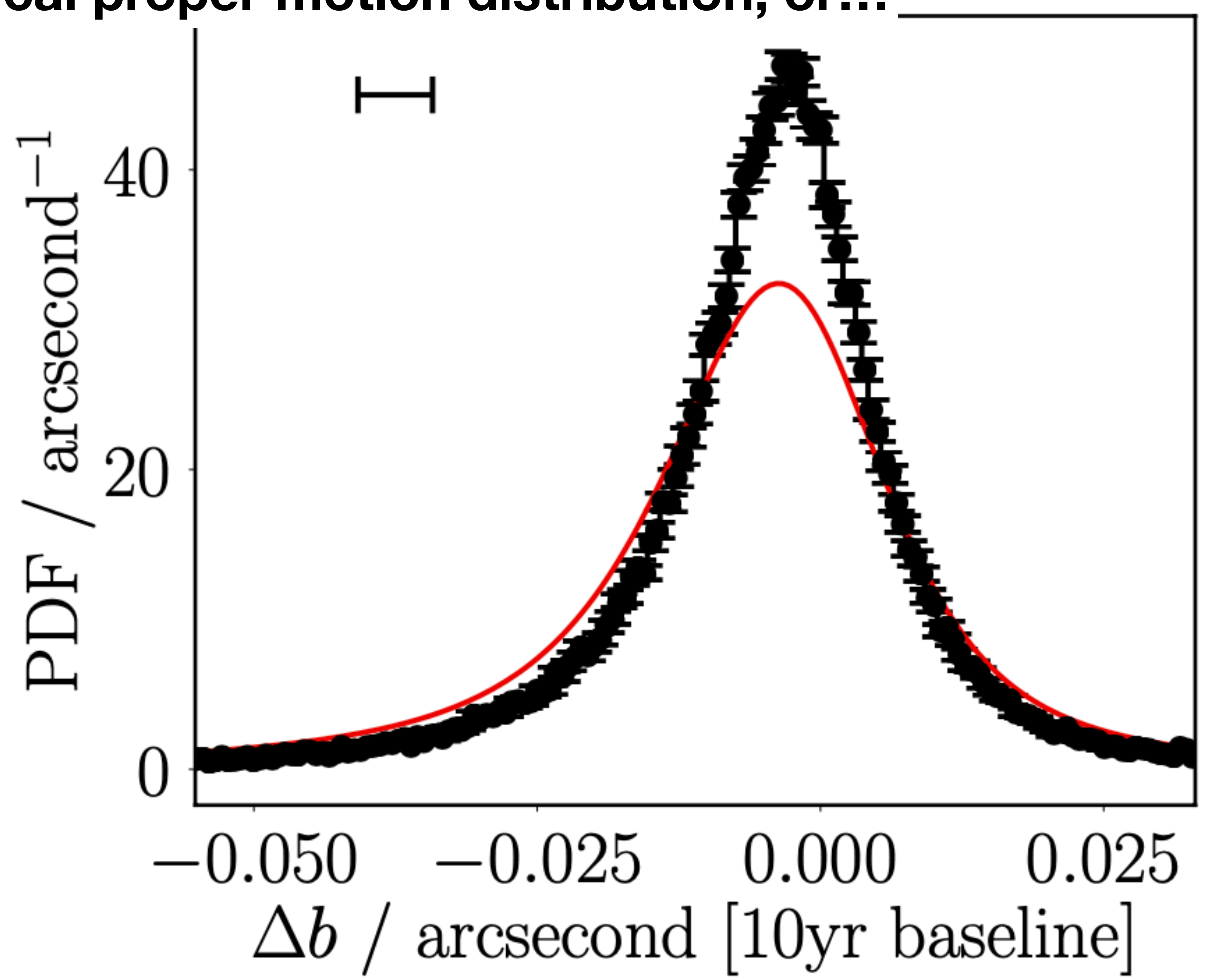
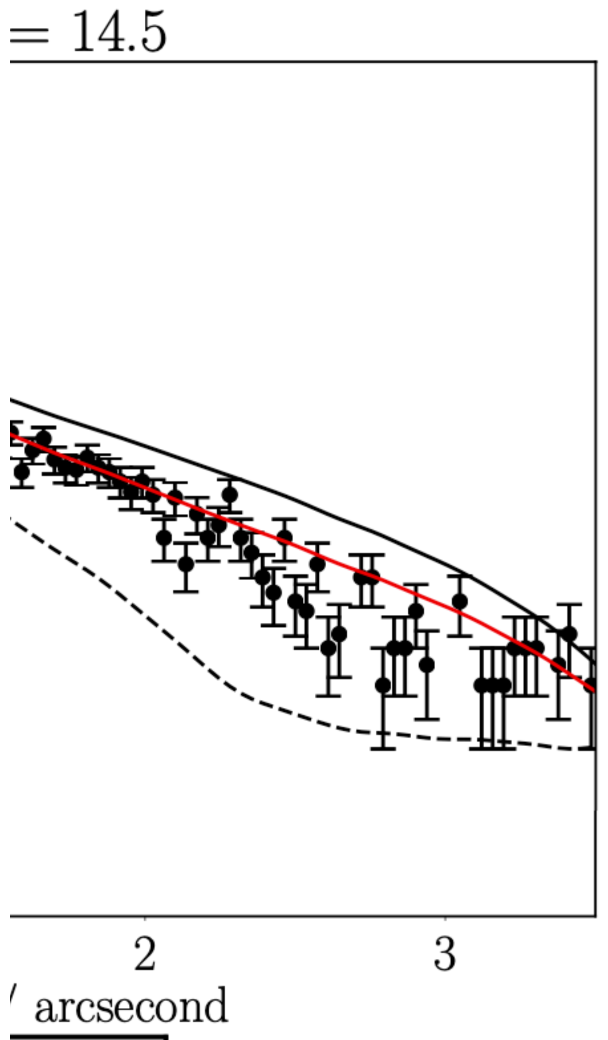
D. **Repeat however many times you have different perturbation algorithms**
E. **Combine your perturbation algorithms**

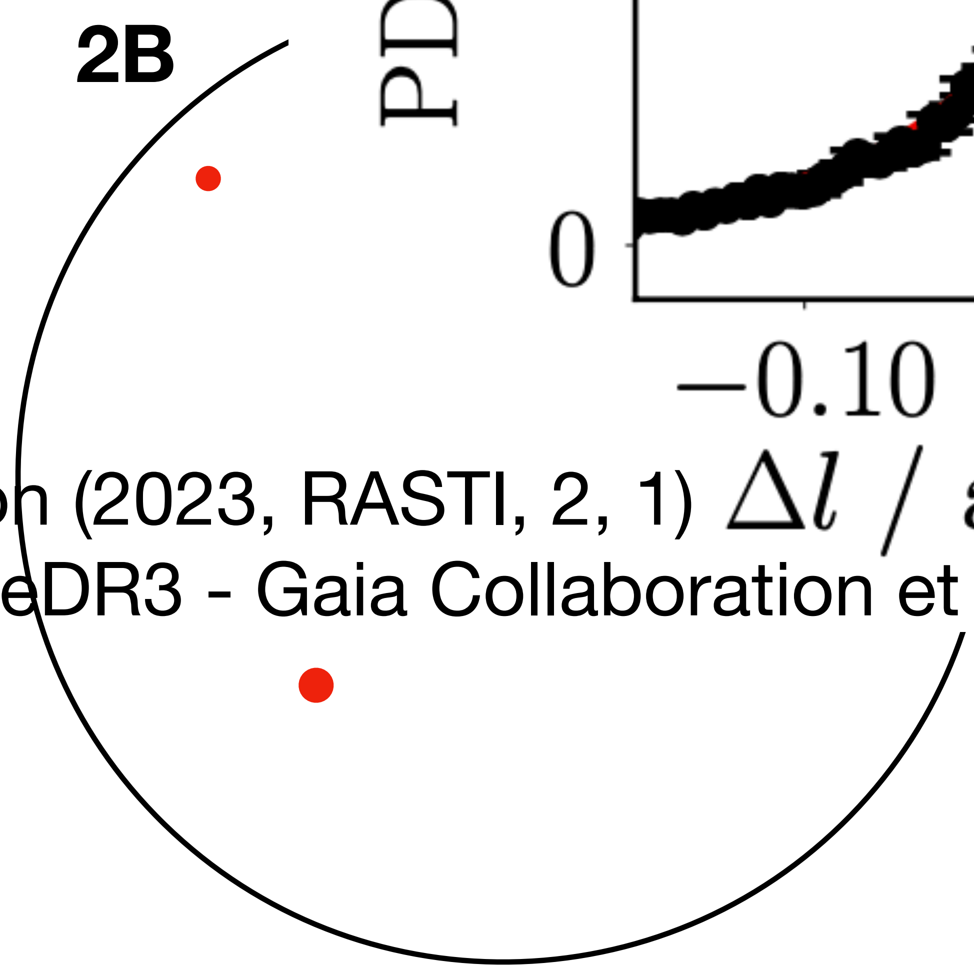
Or, create statistical proper motion distribution, or…

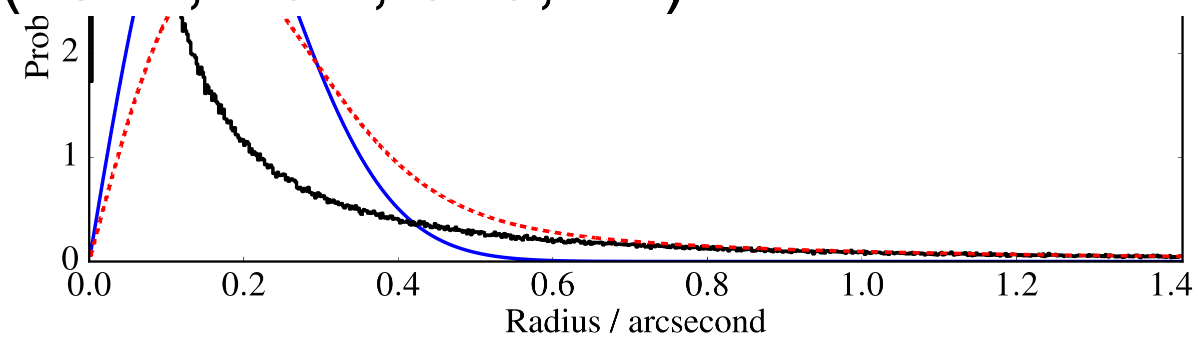


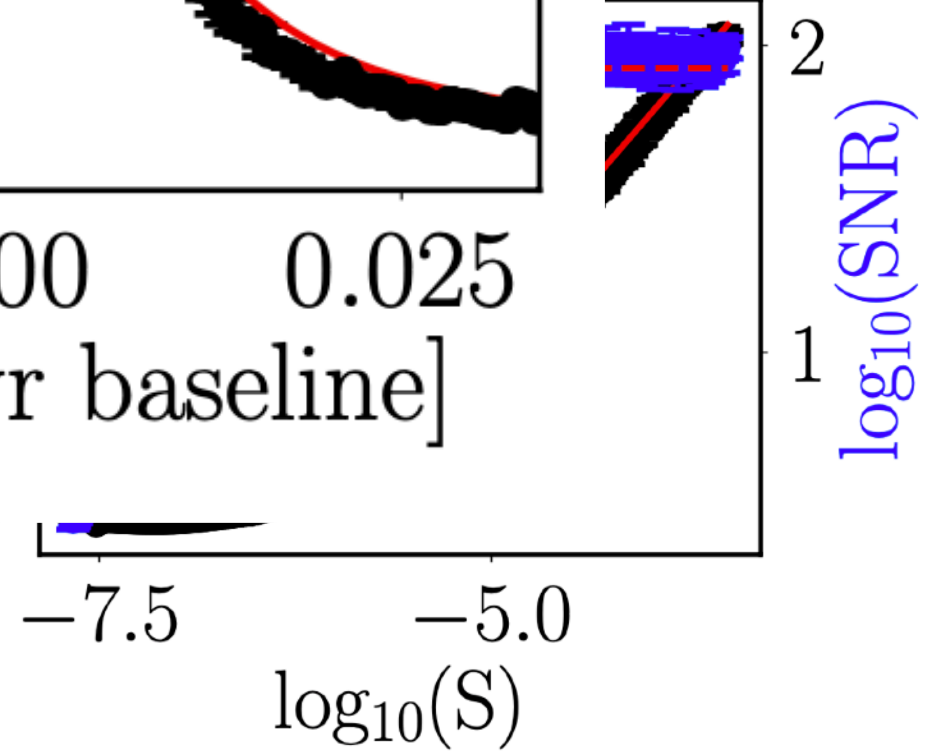












Wilson (2023, RASTI, 2, 1)

Gaia eDR3 - Gaia Collaboration et al. (2021, A&A, 649, A1)

$$\mathrm{SNR} = \frac{\ldots}{\sqrt{c \times S + b + (a \times S)^2}}$$

$$H = 1 - \sqrt{1 - \min\left(1,\ a \times \mathrm{SNR}^2\right)}$$

Tom J Wilson @onoddil

Verifying Astrometry: Fitting Centroid Uncertainty

In each sightline (10s of sq deg for good bright source counting N):

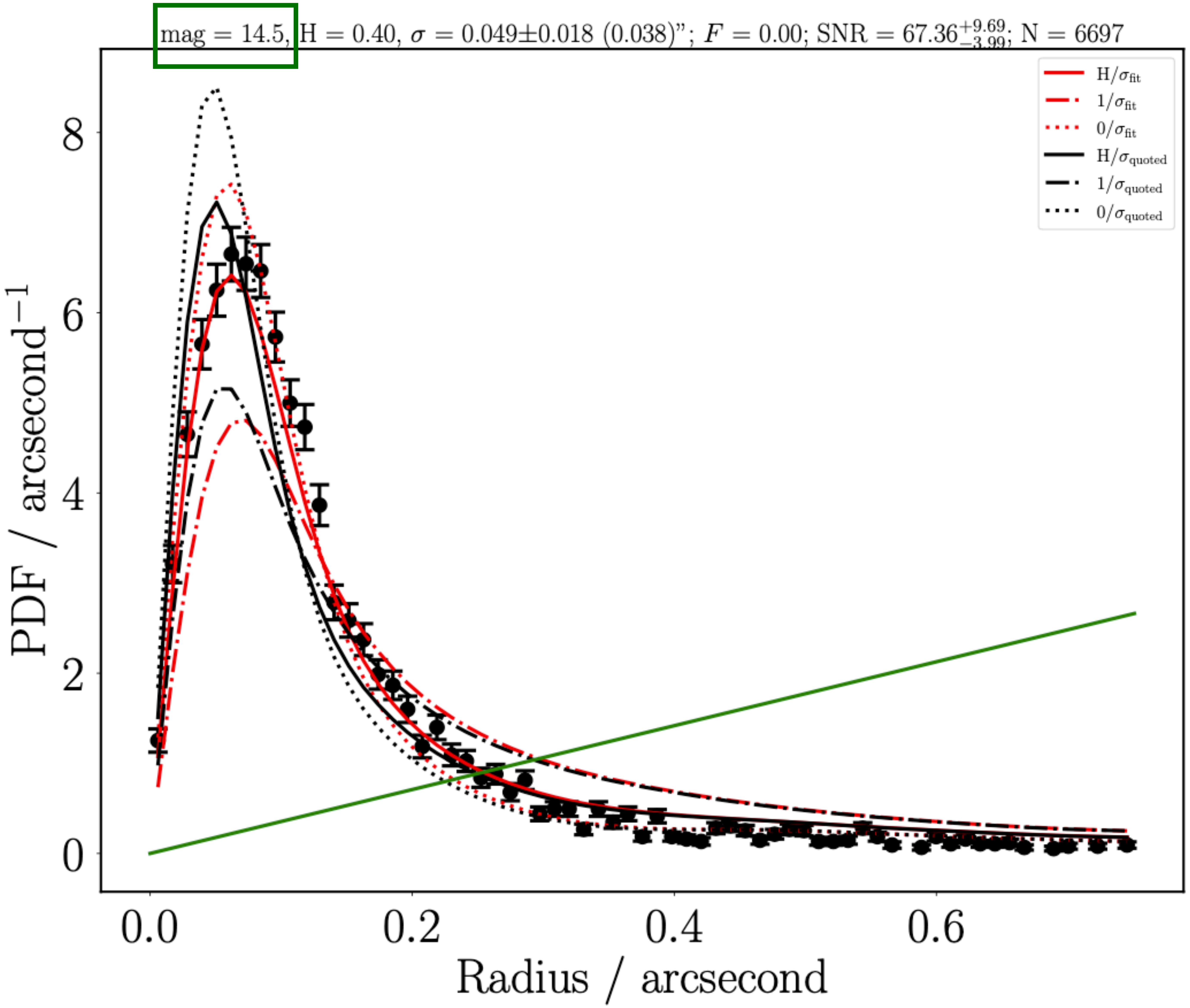
1. **Cross-match your high angular resolution, high astrometric precision data to LSST to obtain separation distributions**
2. **Create systematics model for all non-centroid astrometric components of uncertainty**
3. **Fit full AUF to data, allowing centroid Gaussian uncertainty to be fit**
4. **Repeat for each brightness (and effectively different astrometric uncertainty)**
5. **Derive fit-quoted astrometric uncertainty relations**

For each magnitude (uncertainty) slice in a given sightline, combine centroid uncertainty (Gaussian) and other AUF components (empirical) and fit for best-fitting sigma-value.

$$h_\gamma = \boxed{h_{\gamma,\mathrm{centroiding}}} * h_{\gamma,\mathrm{perturbation}} * \ \dots$$

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

Also include false positive match rate (*F*) in case simple match case was not perfect



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

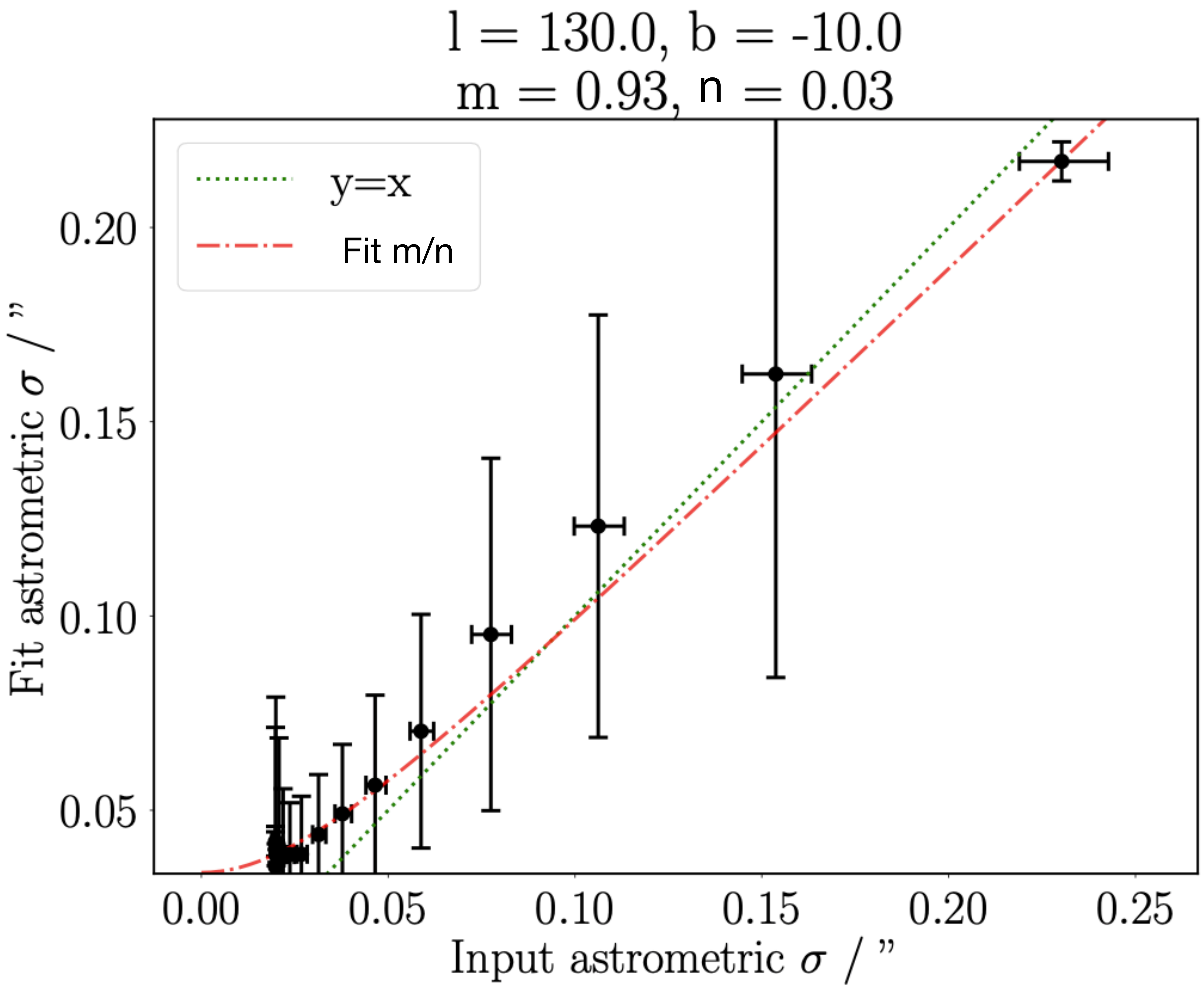
Tom J Wilson @onoddil

Verifying Astrometry: Characterisation

In each sightline (10s of sq deg for good bright source counting N):

1. **Cross-match your high angular resolution, high astrometric precision data to LSST to obtain separation distributions**
2. **Create systematics model for all non-centroid astrometric components of uncertainty**
3. **Fit full AUF to data, allowing centroid Gaussian uncertainty to be fit**
4. **Repeat for each brightness (and effectively different astrometric uncertainty)**
5. **Derive fit-quoted astrometric uncertainty relations**

Fit for $y = \sqrt{(mx)^2 + n^2}$ (or, optionally, $y = mx + n$) to account for simple systematic bias n missing and compensating scaling factor m at lower SNR data



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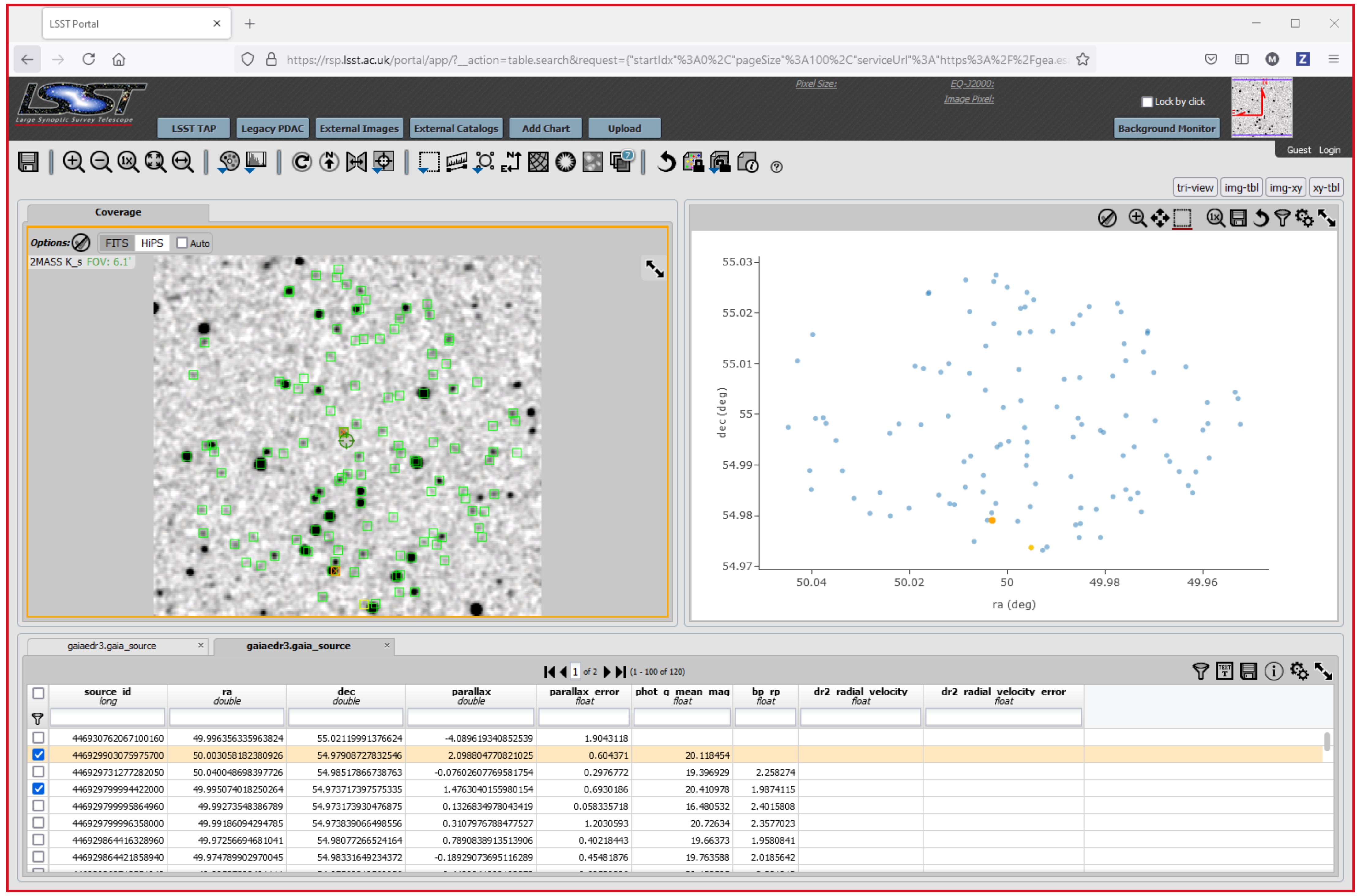
How To Use Our Cross-Matches

(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)

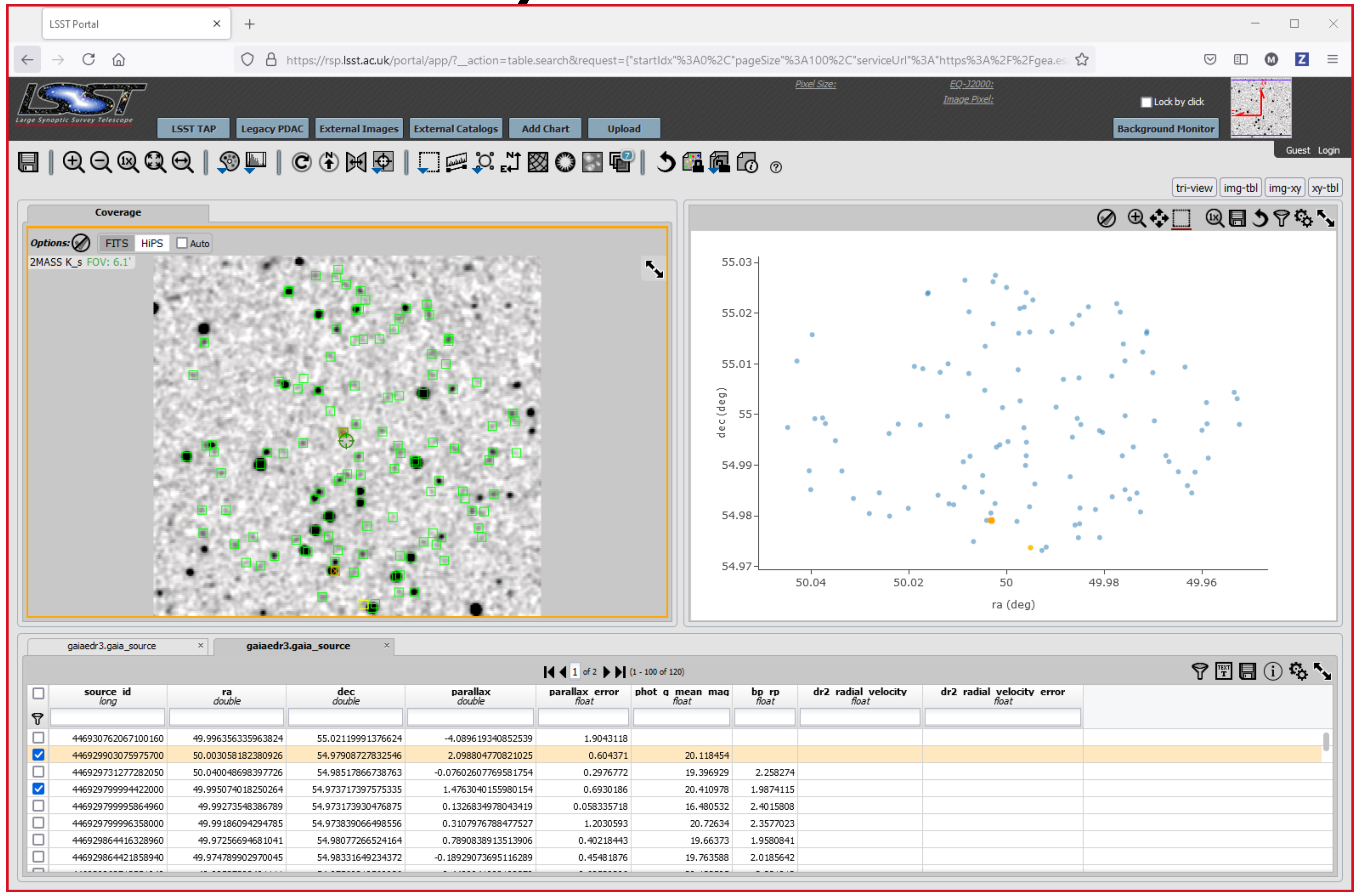
Example columns:

- **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

How To Use Our Super- and Lonely-Matches

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



Example columns:

- **Designations of *N* sources (e.g., WISE J…, *Gaia* EDR3…, 2MASS J…)**
- **Super-match probability — probability of the given permutation**

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 in all bandpasses for both objects**
- **Match probability — different to that from a macauff cross-match!**
- **Hypothesis of non-match (proper motion, artifact, transient, …)**

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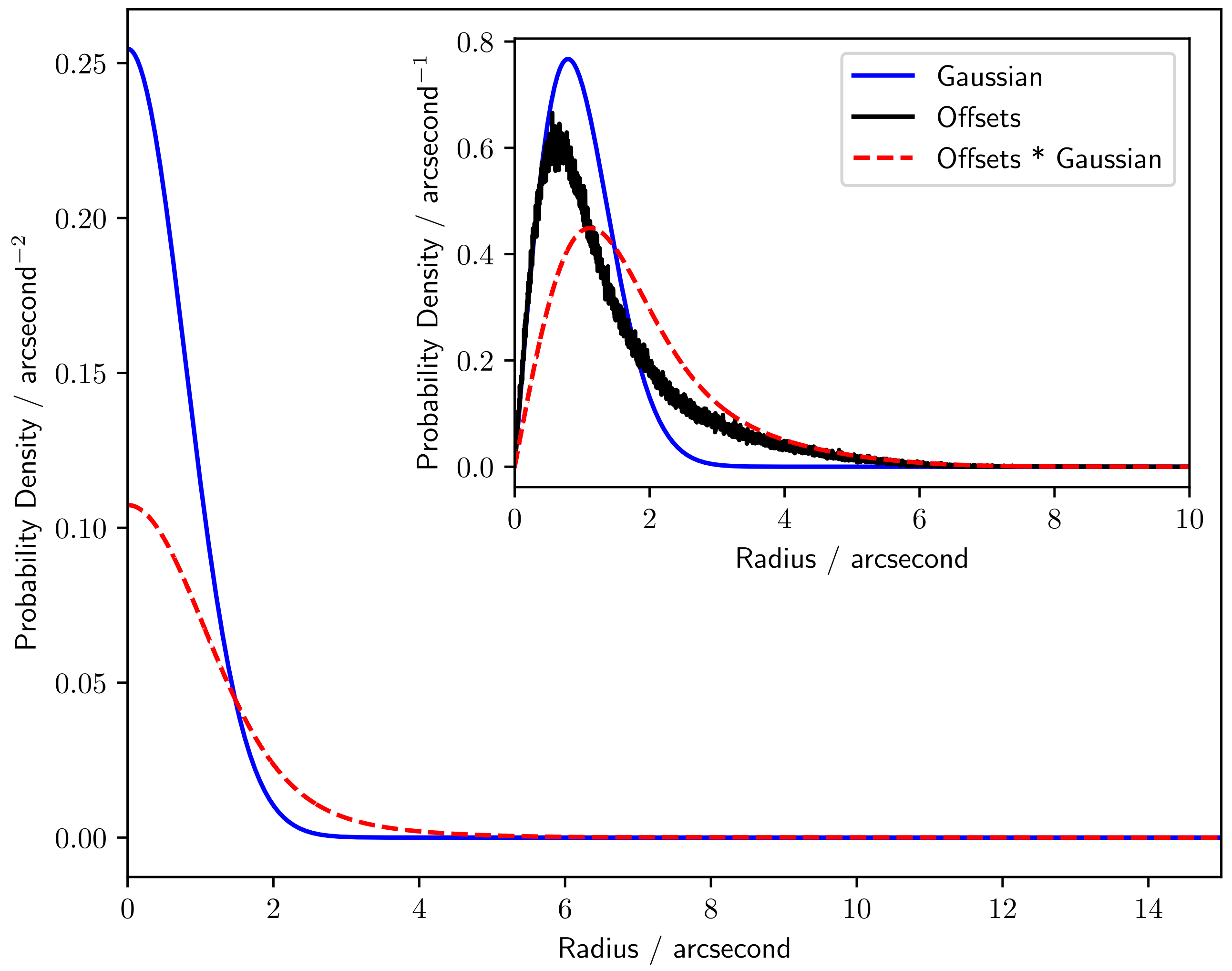
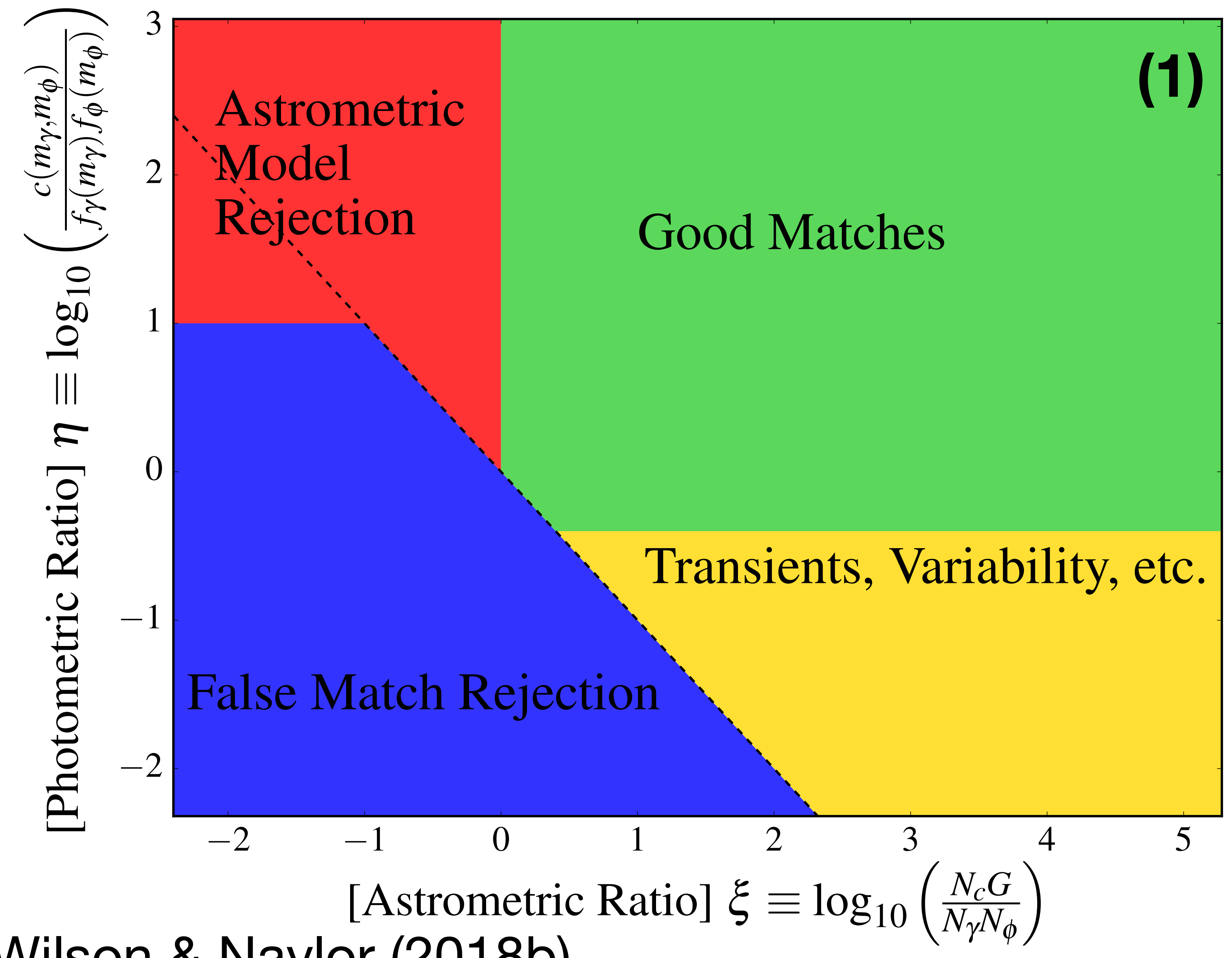
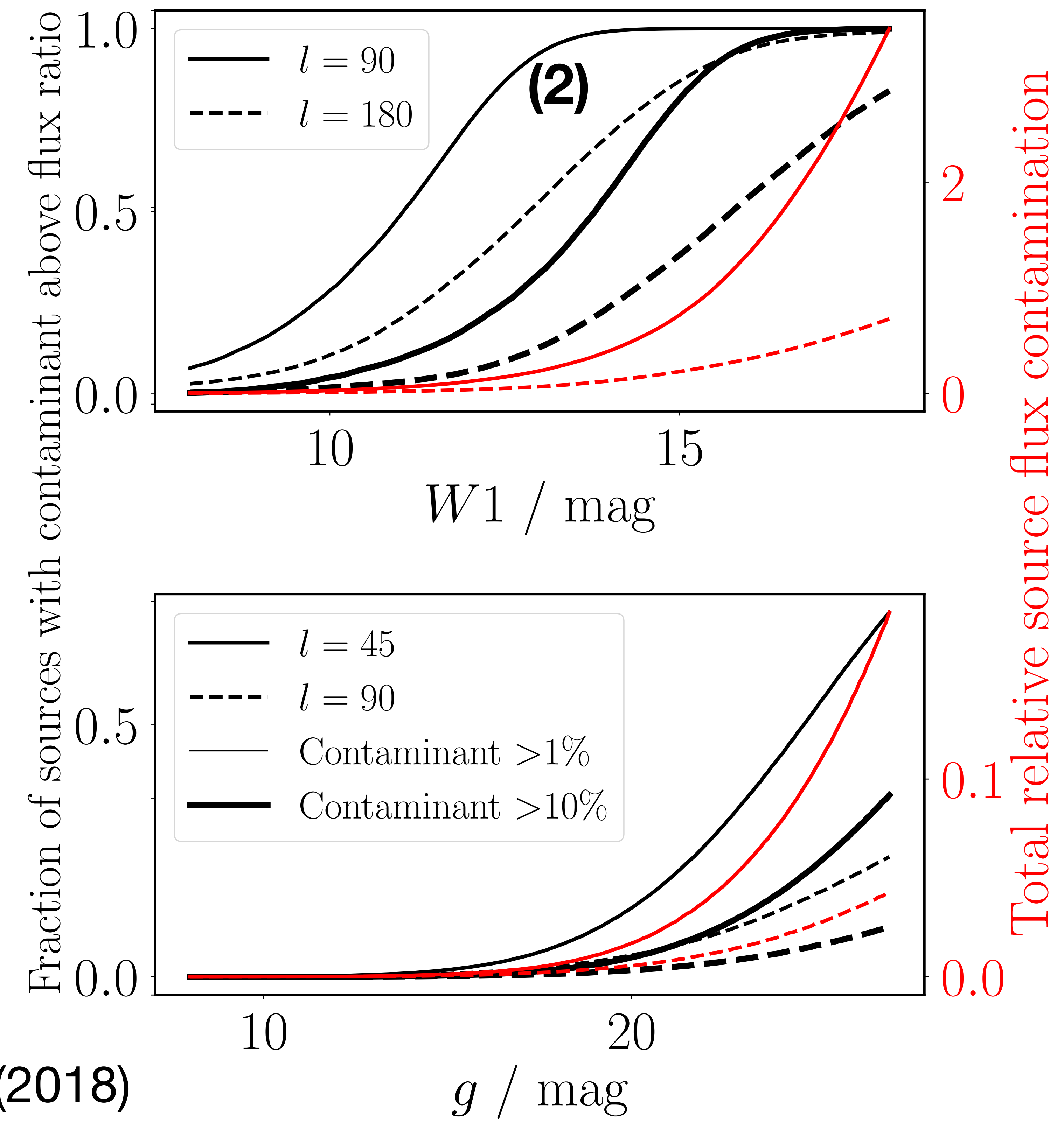
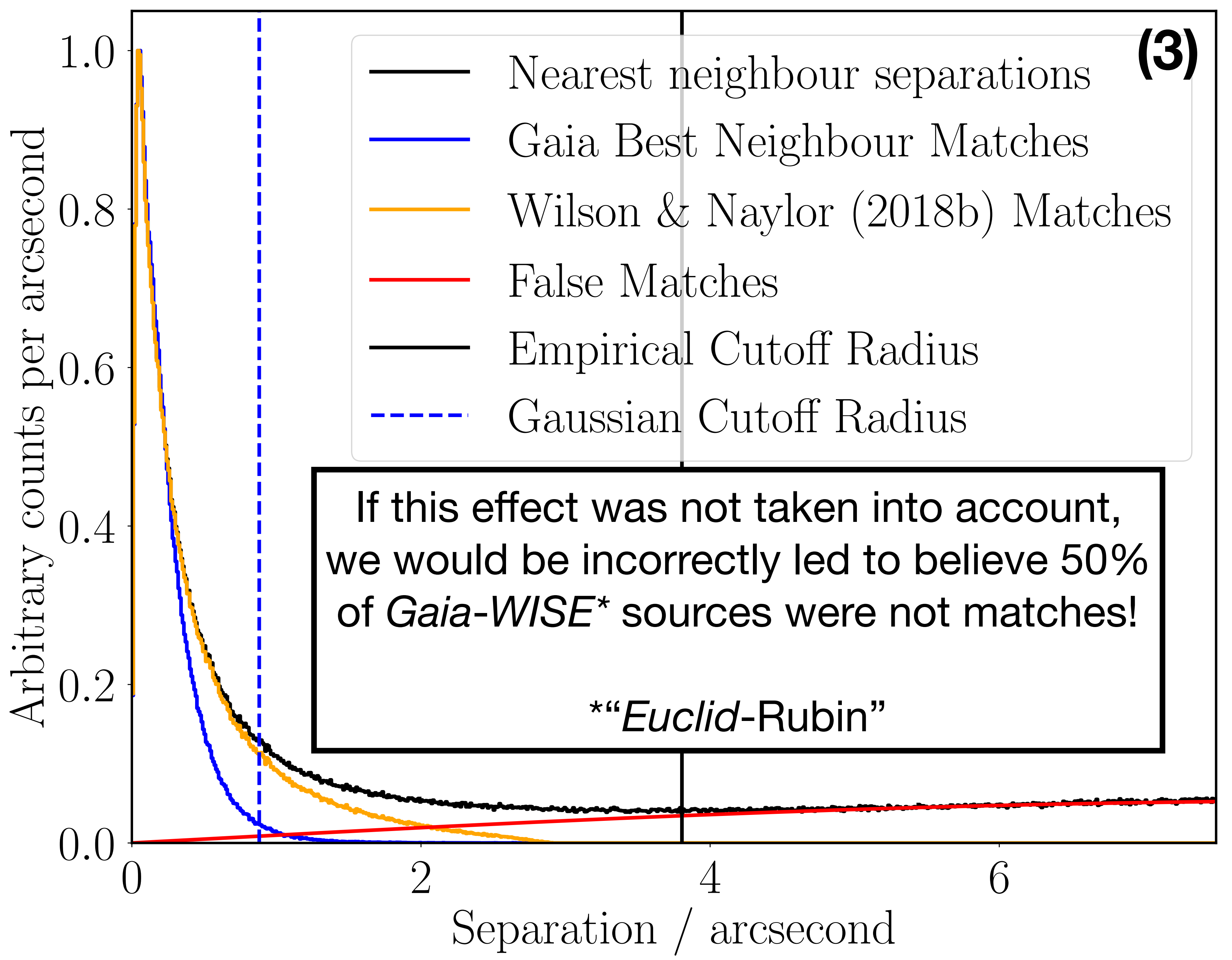
Why Use Our Cross-Matches (and Extensions)?

0) Getting cross-matches, even for "well behaved" fields
1) Finding "odd" objects, either using the inclusion vs non-inclusion of the photometry in the two match runs, or via the likelihood ratio space — separately-planned "real time" matching service for transient objects
2) Removing e.g. IR excess or correcting for extinction-like crowding brightening, through Average Contamination; crucial for "1% photometry" in both precision *and* accuracy
3) 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 extension to unknown proper motion modelling as an extra systematic









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)

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Re-Focussing UKD-S9 Efforts

We have (mostly) completed two of our stated packages, macauff and birnam. However, due to a lack of Rubin testing and timescales for the effort (i.e., me!), we are starting to question what to do with the time that is given to us, thinking about whether it would be better to focus on:

- Improving documentation — a few people other than me have tried to use the code, and are surprised at how much prep work is required. We can decrease barriers to entry and allow the community to pick up the codes after dedicated effort ceases.
- Running a large-scale “legacy” survey cross-match database for crowded fields. This would shake out the code (and the Rubin Science Platform, from which users would obtain the matches) but also provide useful early science for the community.
- Starting up a cross-match coordination group to optimise efforts and ensure algorithms are correctly paired with the right catalogues.

- Alternatively — or as well as — continue to dedicate effort to the missing sources work; we may be able to get additional effort to juggle outstanding commitments and the above.

At this stage we are looking to get opinions from the recipient groups — i.e., you lot — on where people feel it is most important to spend our time.

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!>
  - Re-evaluation of UKD-S9's effort also requires community input — what should we be focusing on?

- 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 sky) — 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
- We can use these models for systematic contributions to the AUF to validate and verify centroid precisions in photometric catalogues in extreme parts of the sky, avoiding incorrect assumptions about our precisions!

- 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 ~93% of non-matched Rubin objects to confirm flux upper limits in other surveys

University of Exeter

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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

https://github.com/macauff/macauff

LSST:UK Consortium

Science and Technology Facilities Council

VERA C. RUBIN OBSERVATORY

Macauff

Tom J Wilson @onoddil