Put me here!

Towards Solving the Catalogue Cross-Match Problem

Tom J Wilson (he/him) and Tim Naylor
t.j.wilson@exeter.ac.uk
University of Exeter

UNIVERSITY OF EXETER

LSST:UK Consortium

VERA C. RUBIN OBSERVATORY

Macauff

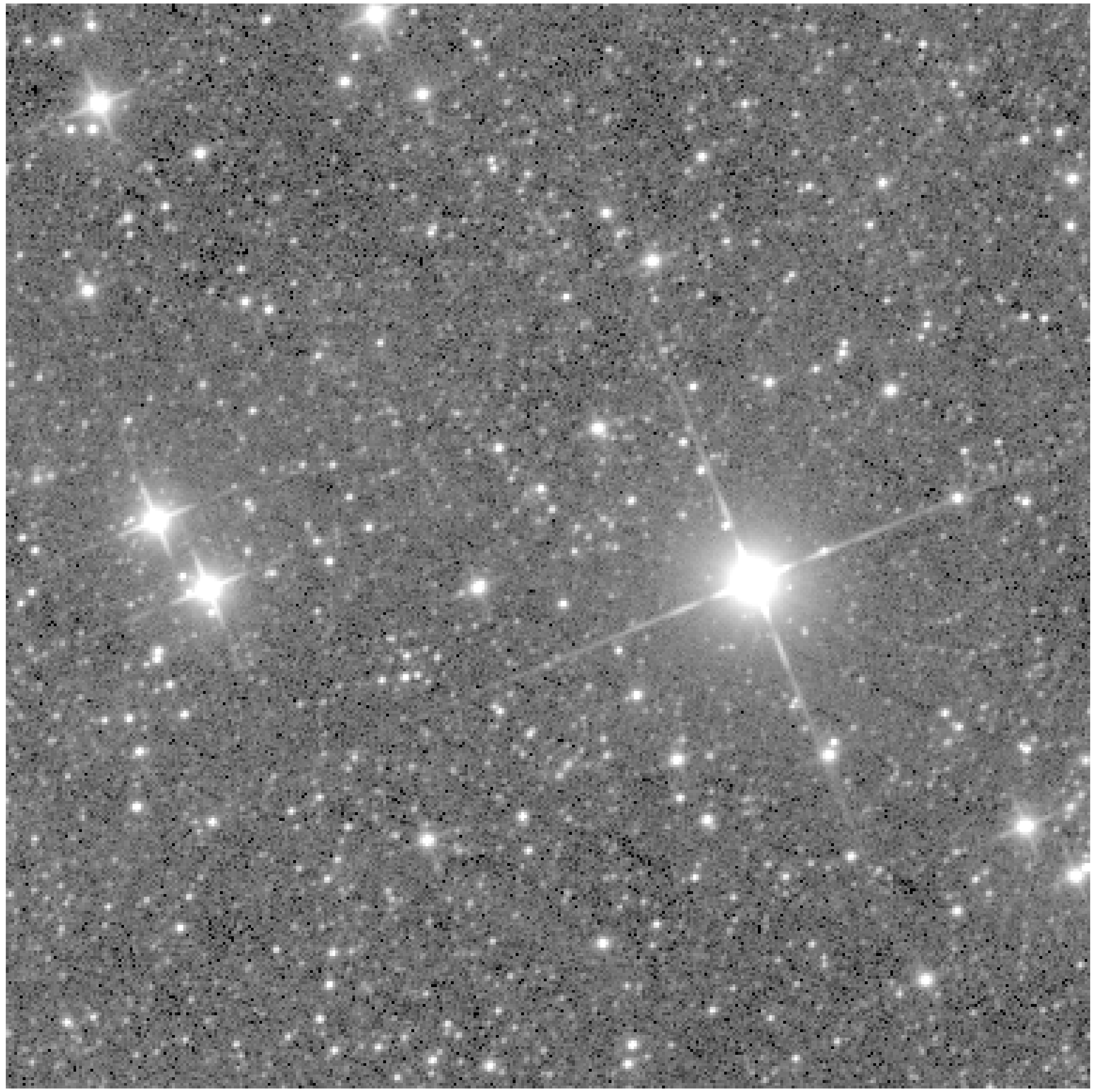
@Onoddil@pm.me
@Onoddil.github.io

What is the Cross-Match Problem?

- **We extend the probability-based catalogue cross-match schemes of others in a few key areas:**
  - **include additional descriptions of detected source deviation from “true” location**
    - **crowded fields (*WISE*, LSST) significantly affected by unresolved hidden contaminants**
    - **but we also model unknown proper motions**
  - **false matches can be solved by the use of the photometry of the objects**

- **This new framework then allows for useful, secondary information that has wide scientific application**
  - **simulations of unresolved objects allow us to estimate how much additional flux is hidden within a detection, crucial for confidence in things like IR excesses or extinction**
  - **finding “odd” objects based on whether they match or not when including photometric information; useful for rare objects, transients, variability etc.**

Photometric Observations



WISE - Wright et al. (2010)

WISE W1

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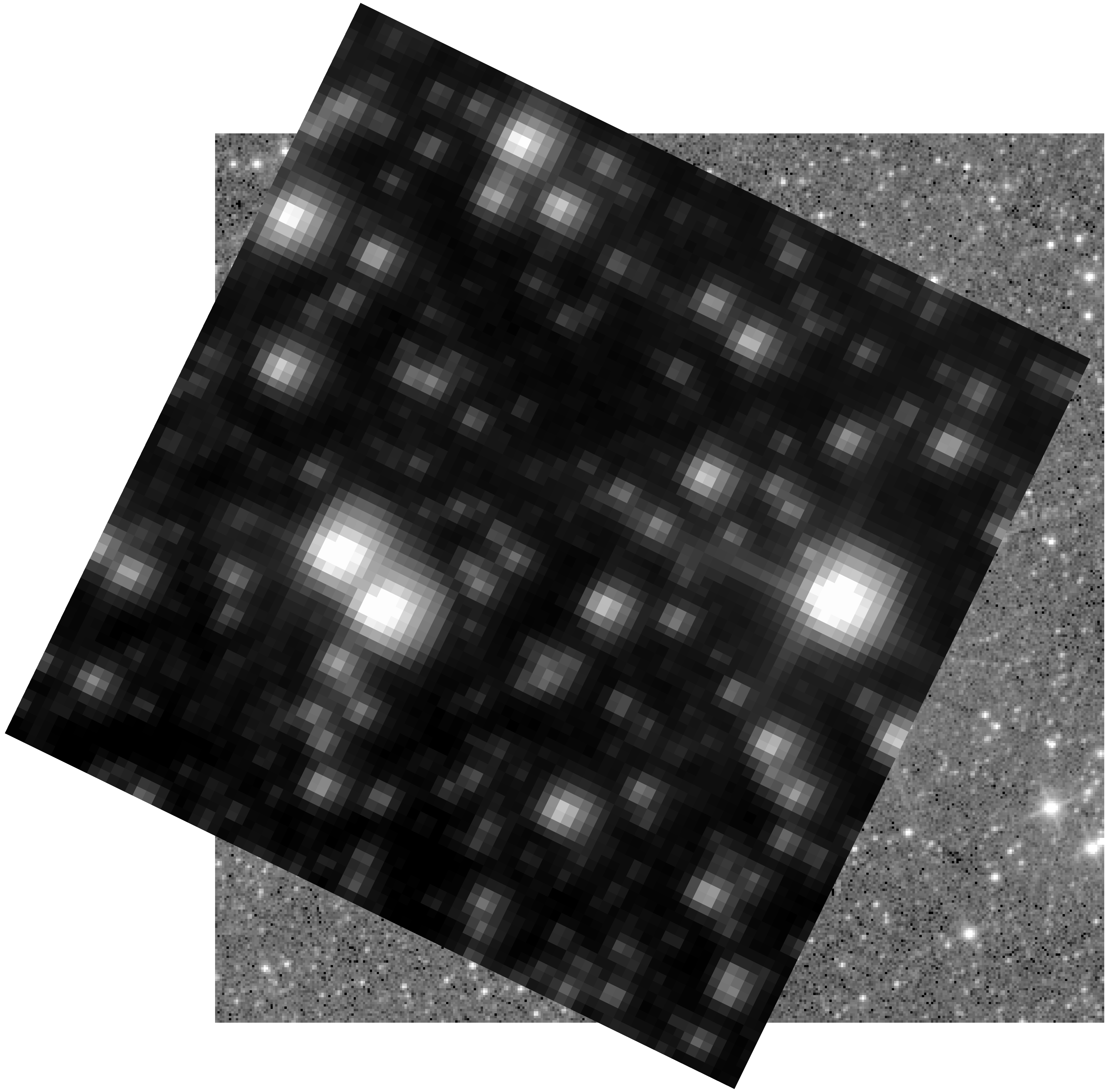
Photometric Observations



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

TESS T

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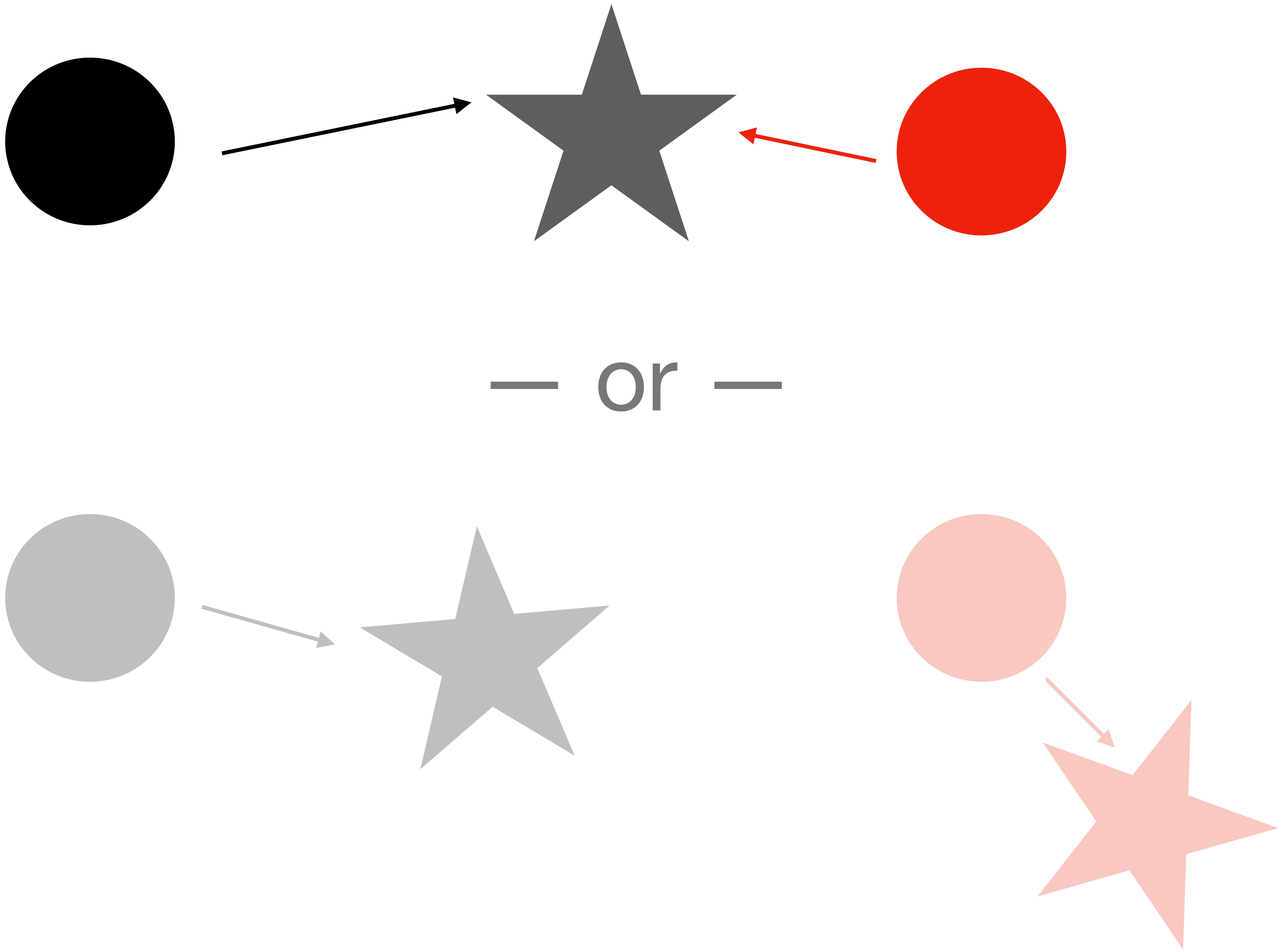
Counterpart Assignment



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Matching Constellations

Image credit: Mouser, wikimedia

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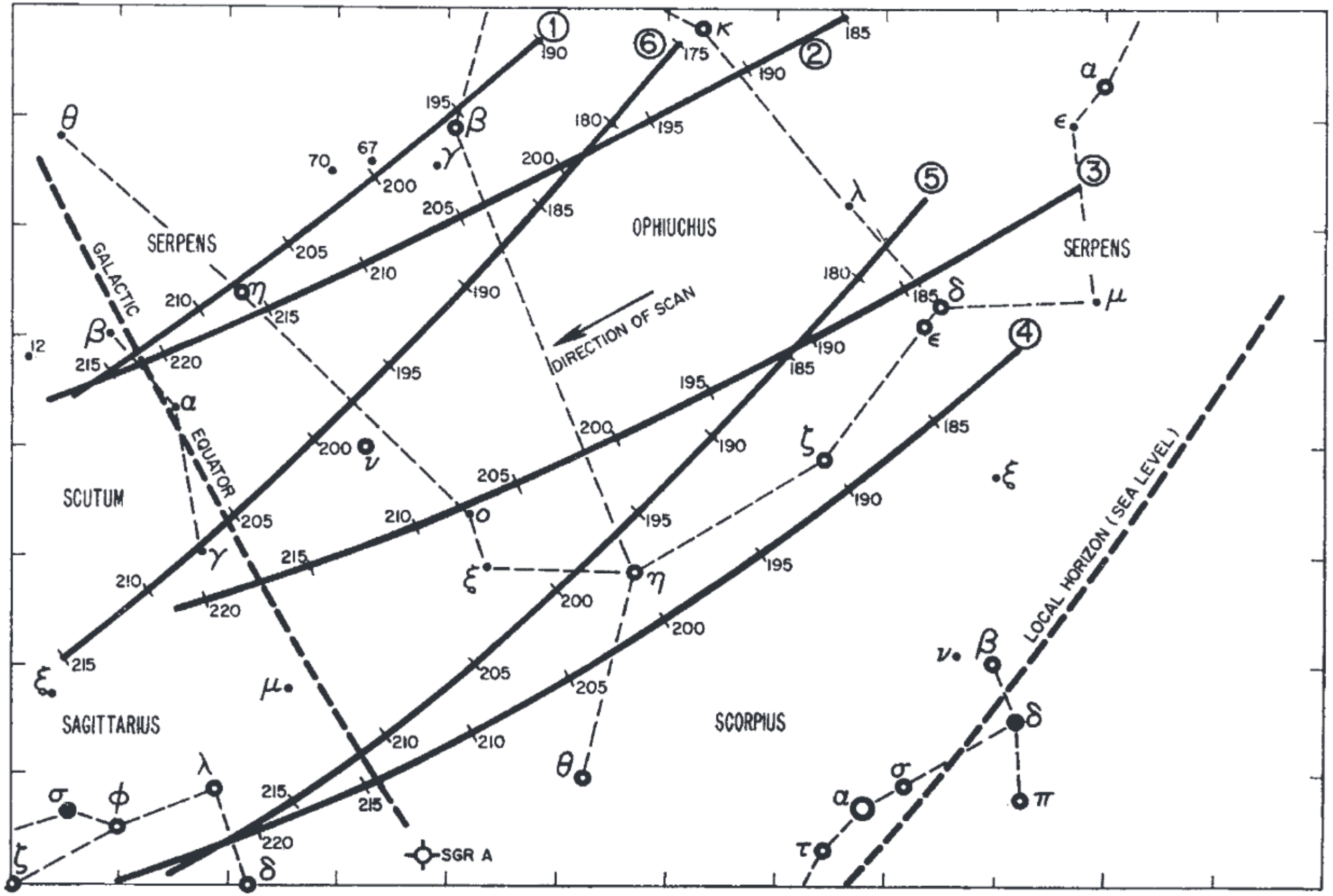
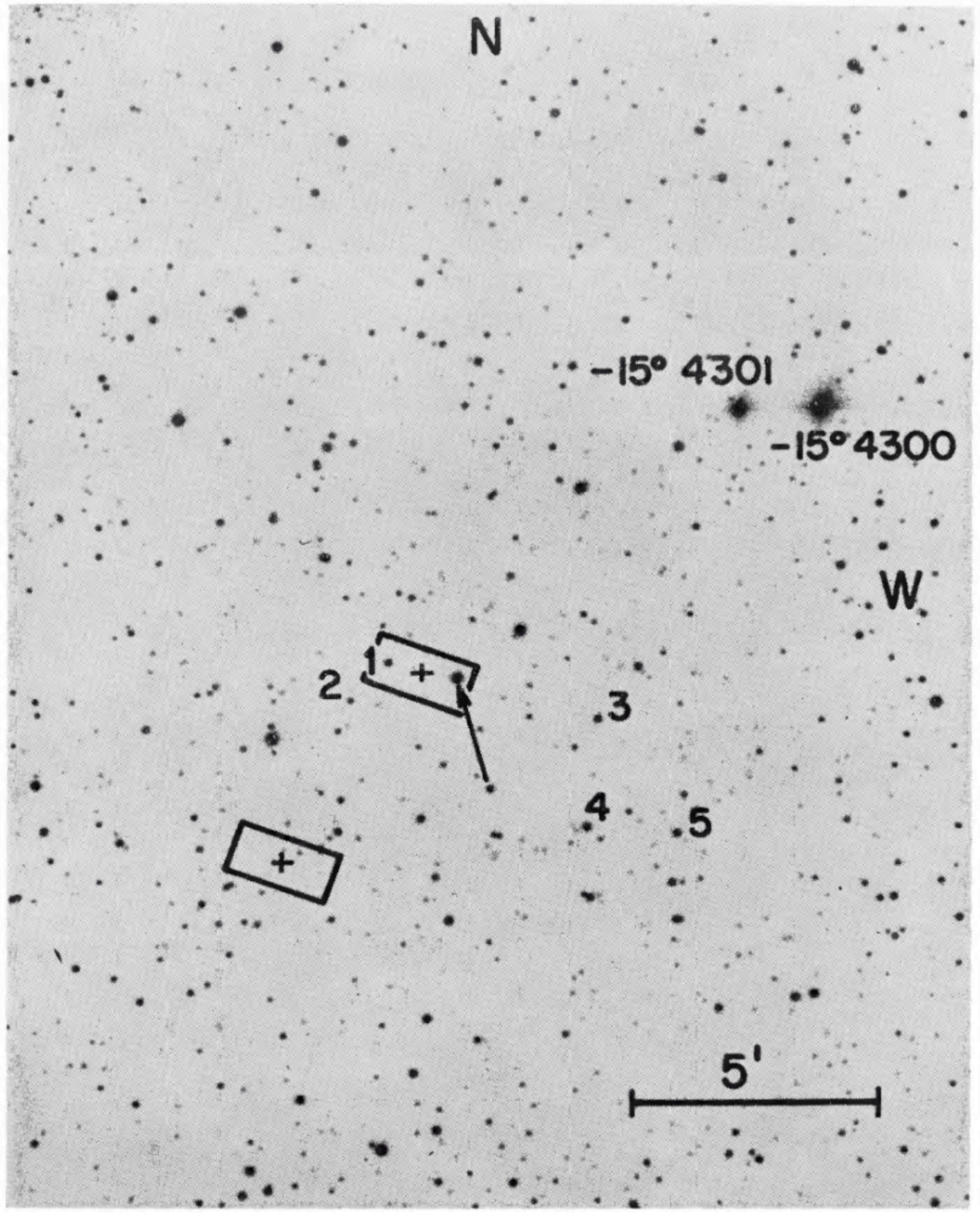
Technology Abounds

- **Ancient lists of stars (Ptolemy, 150; Brahe, 1598)**
- **Galileo invents the telescope (1610)**
- **Greenwich Observatory catalogues (e.g. Bradley, 1798)**
- **Astrophotography invented (Bond & Whipple, 1850)**
- **Harvard Observatory surveys (8th magnitude, 1882-1886)**
- **Astrographic Chart (11th magnitude; 1887-1962)**
- **Carte Du Ciel (14th magnitude; 1880s-never finished)**
- **Invention of the CCD (Boyle & Smith, 1970)**
- **InfraRed detector invented (Forrest et al. 1985)**
- **4- and 5-m class telescopes (1970s-1980s; e.g. LAT, MMT, UKIRT, CFHT, WHT)**
- **Space Telescopes (1980s-2010s; e.g. IRAS, ISO, AKARI, *WISE*, *Spitzer*)**
- **All-sky ground-based surveys (e.g. 2MASS, 1997-2001; SDSS, 2000-; Pan-STARRS, 2010-).**

X-ray Detections: Hunting for Sco X-1



Giacconi, Gursky, & Waters (1964)



Sandage et al. (1966)

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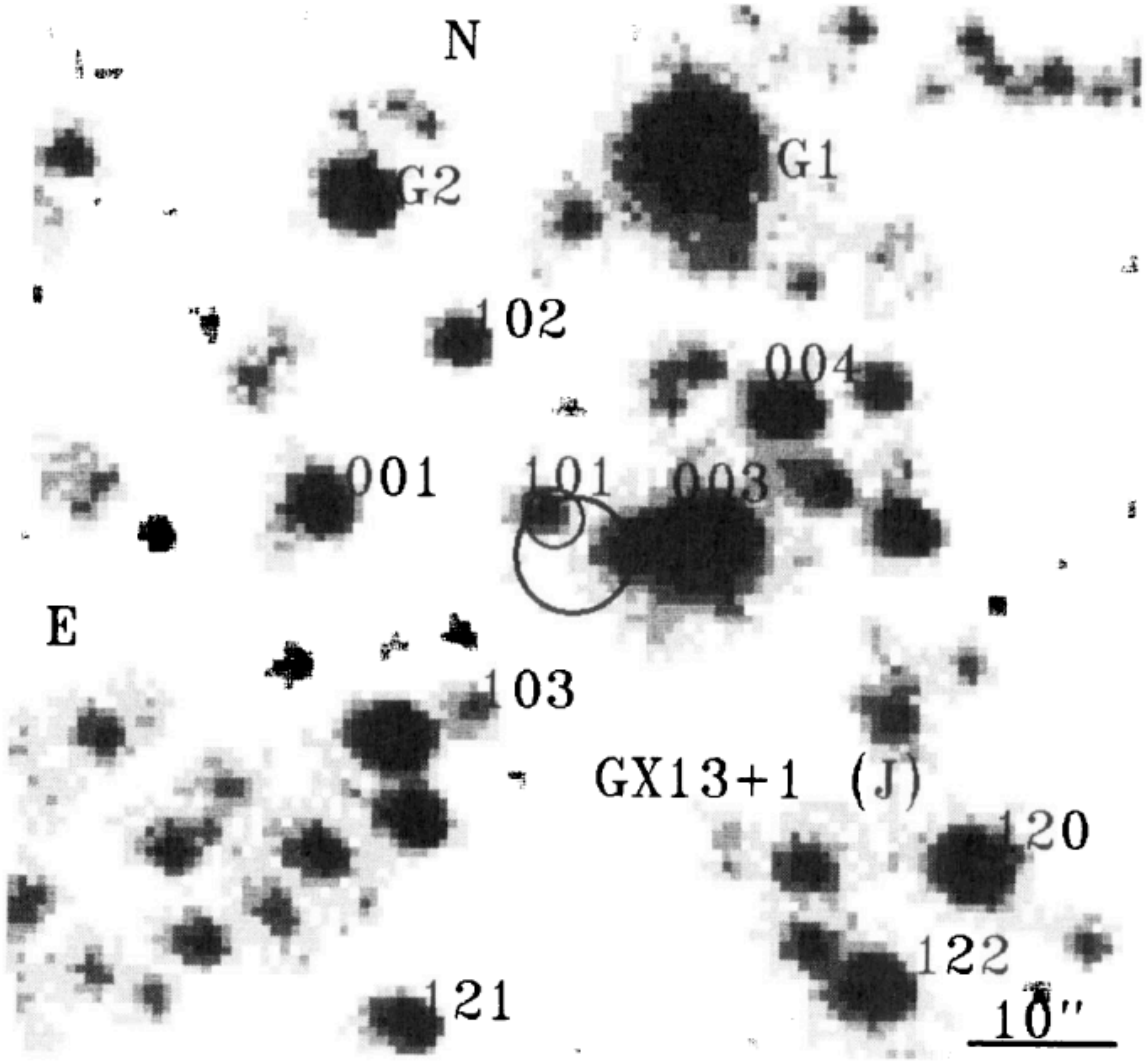
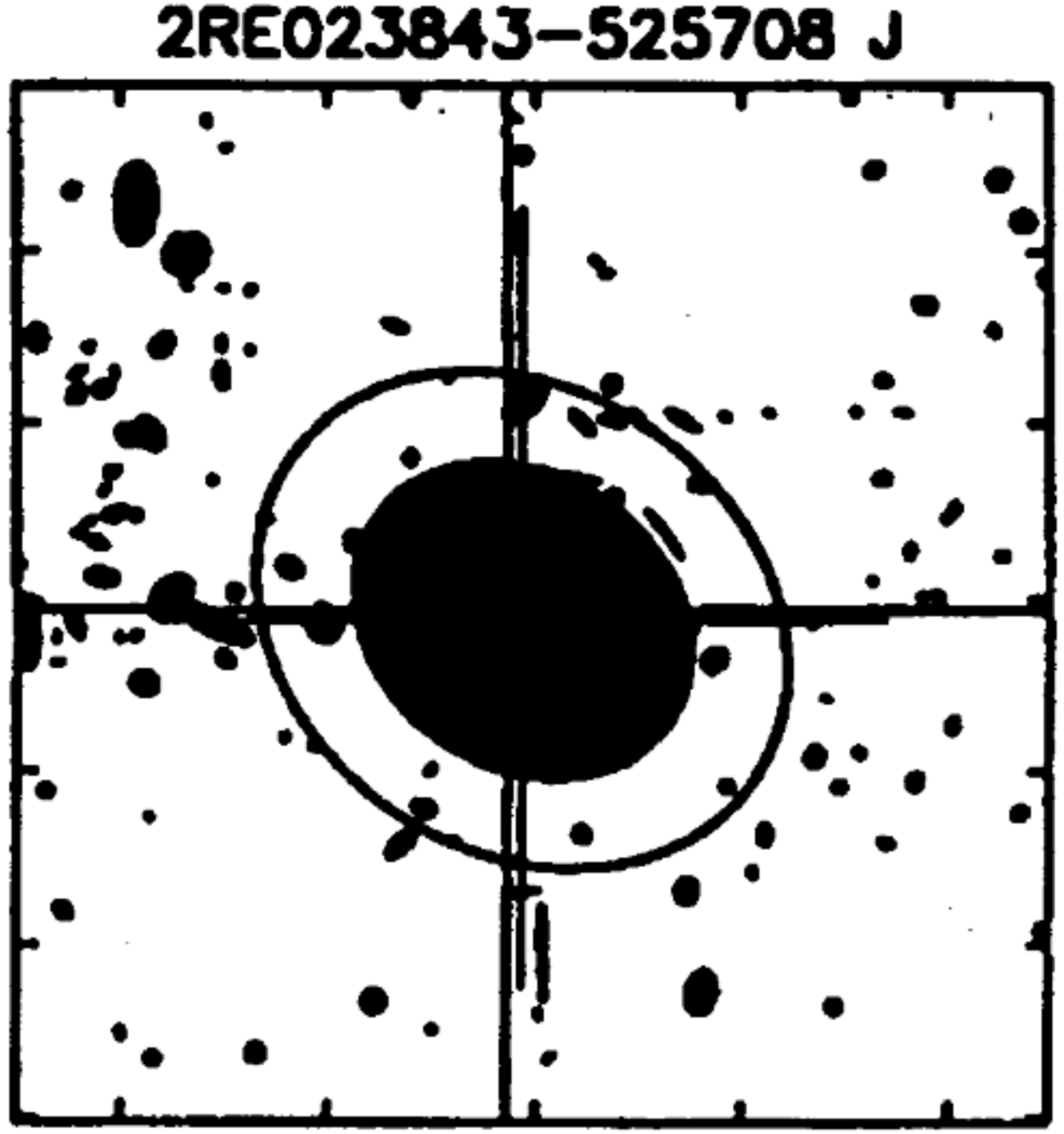
The Brightest Star in the Sky



Naylor, Charles, & Longmore (1991)



Mason et al. (1995)

"...X-ray sources are rare events; bright optical sources are also rare events, so the observation of an X-ray source and a bright optical source in the same region of the sky is considered a non-random event"

Fotopoulou et al. (2016)

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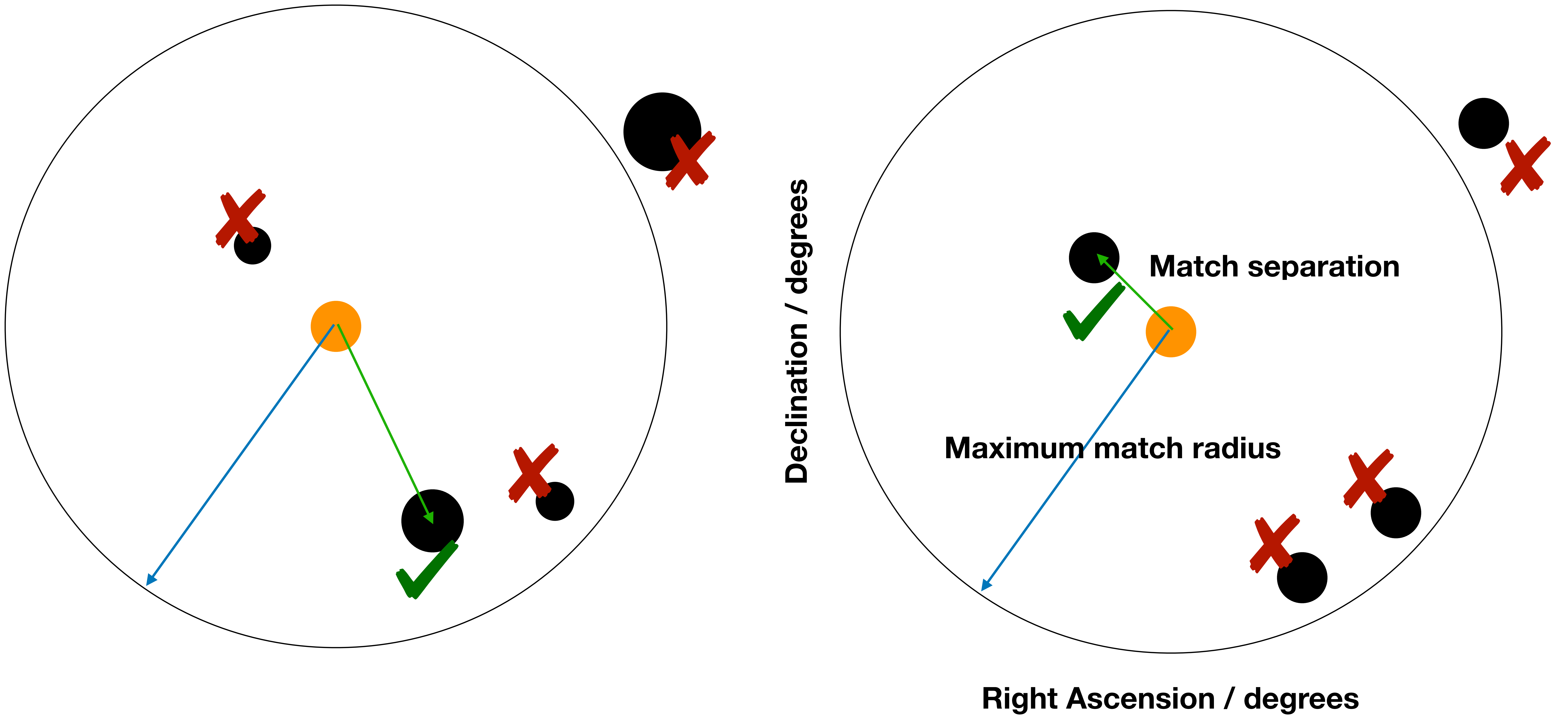
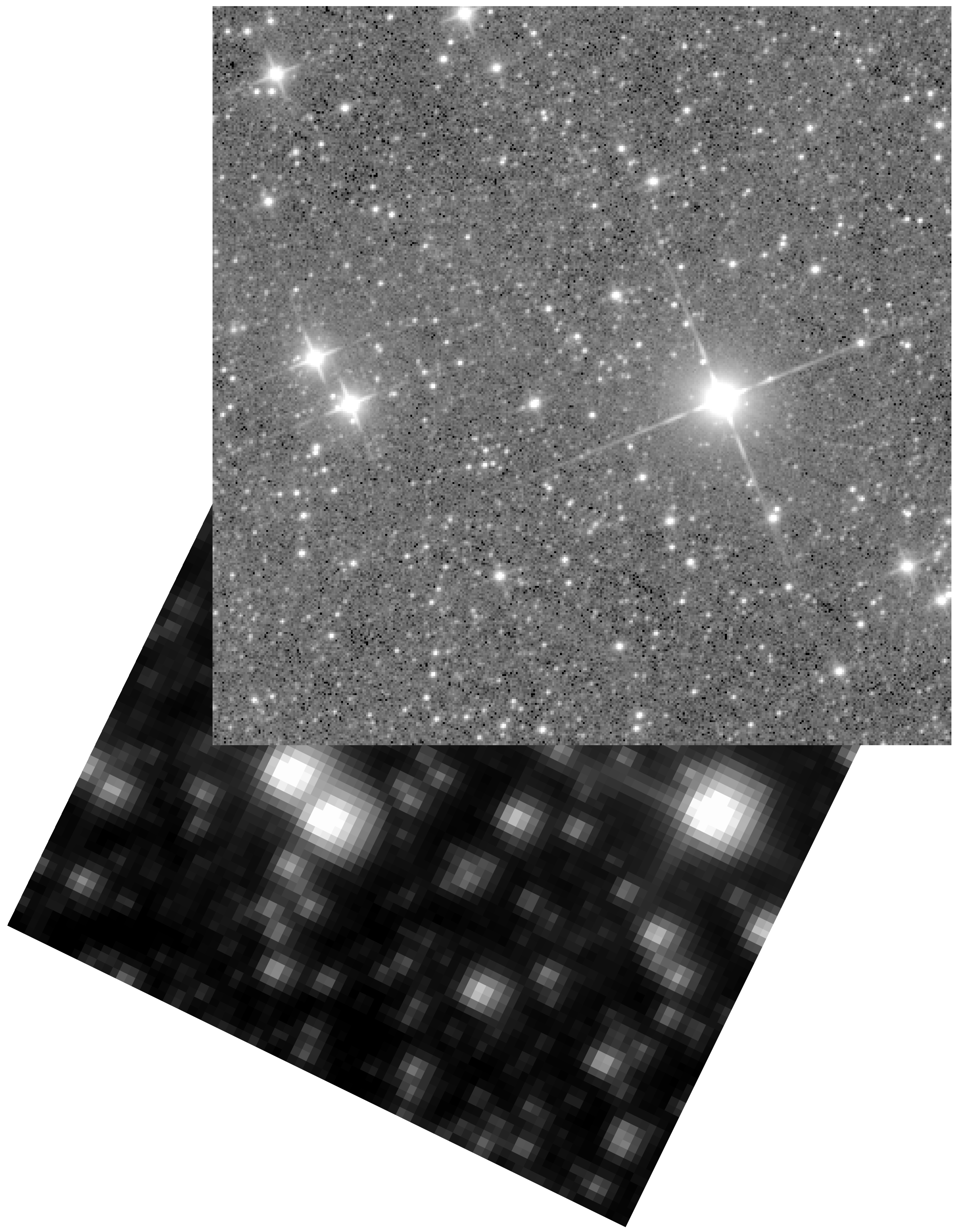
“Traditional” Cross-Matching





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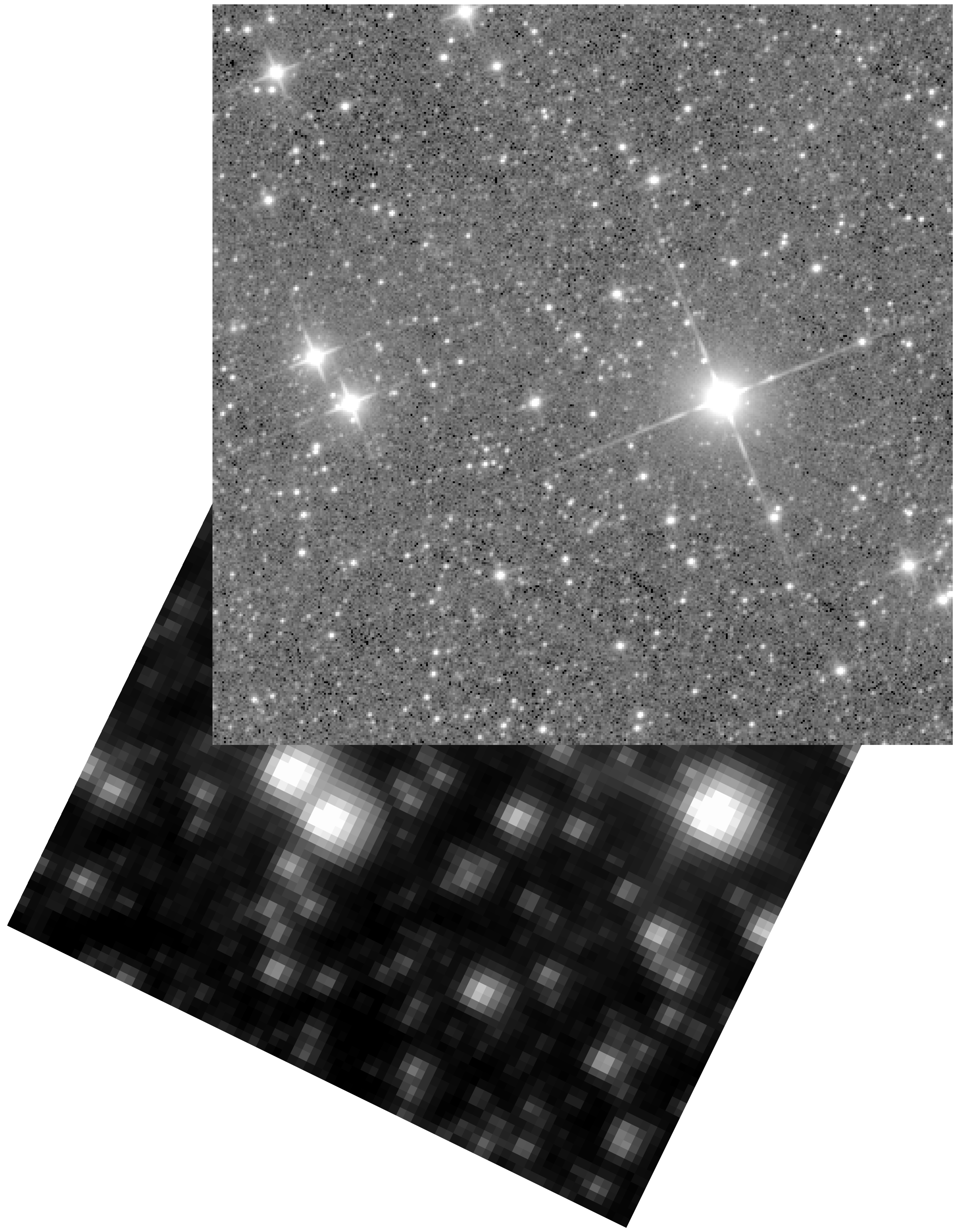
The Astronomy Error Function



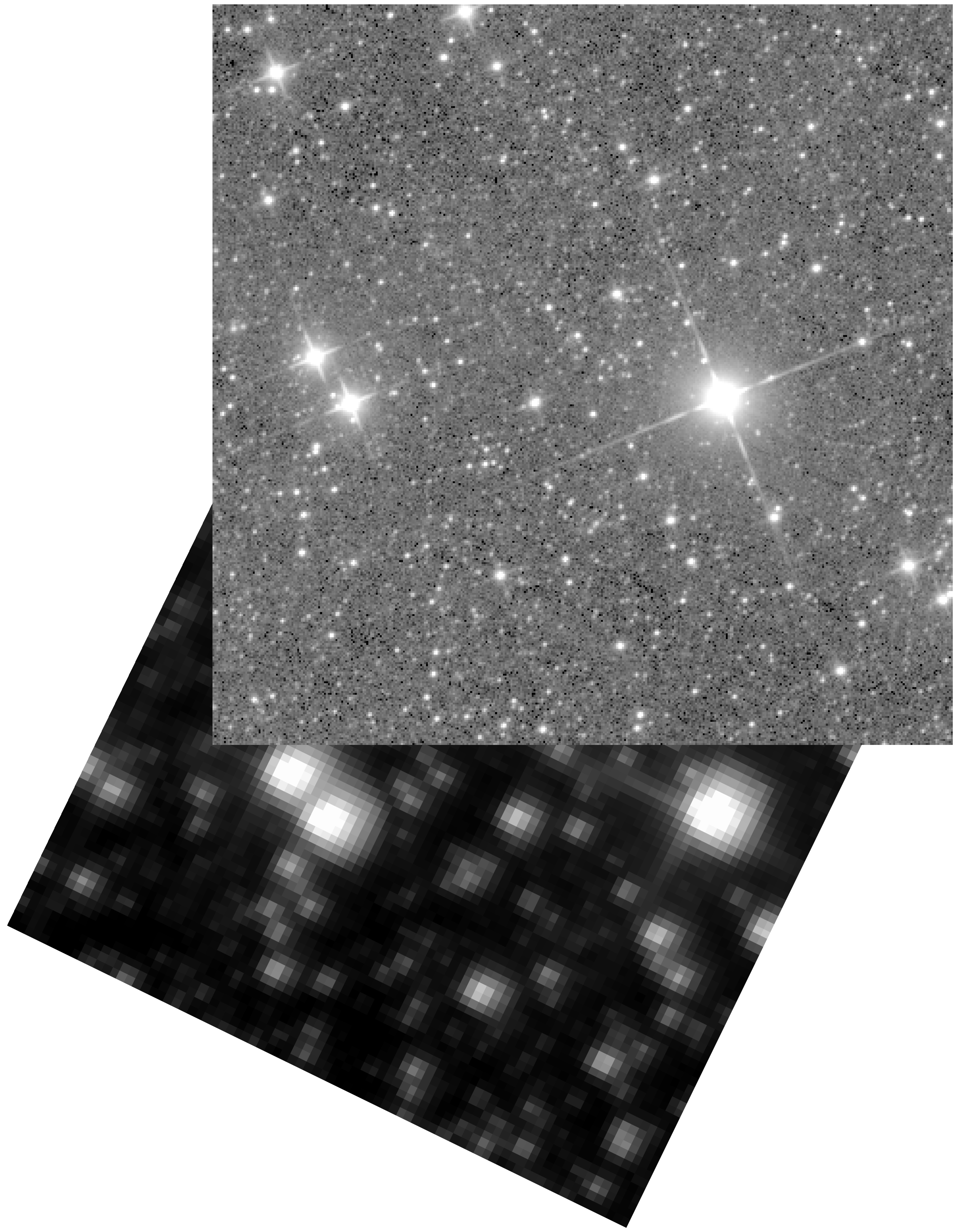
1) $p(x \text{ and } y) = p(x)p(y)$

2) $p(x)$ decreases as x increases

3) $p(x) = p(-x) \Rightarrow p(x^2)$

J. F. W. Herschel, “Quetelet on Probabilities”, 1850

The Astronomy Error Function



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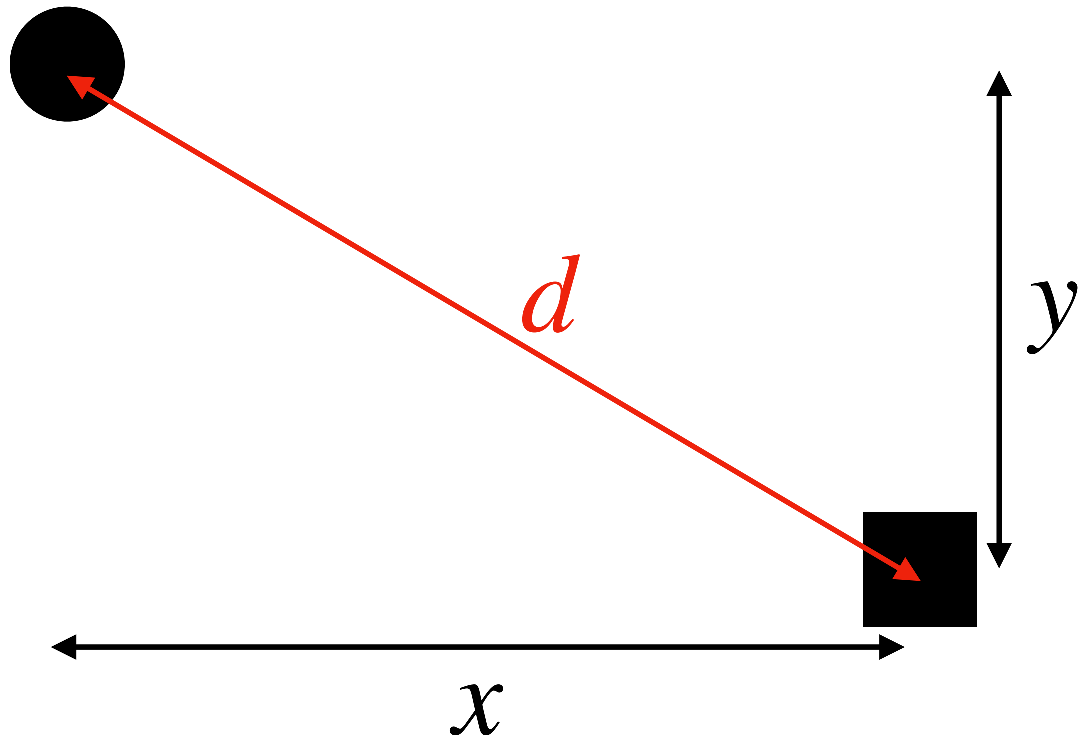

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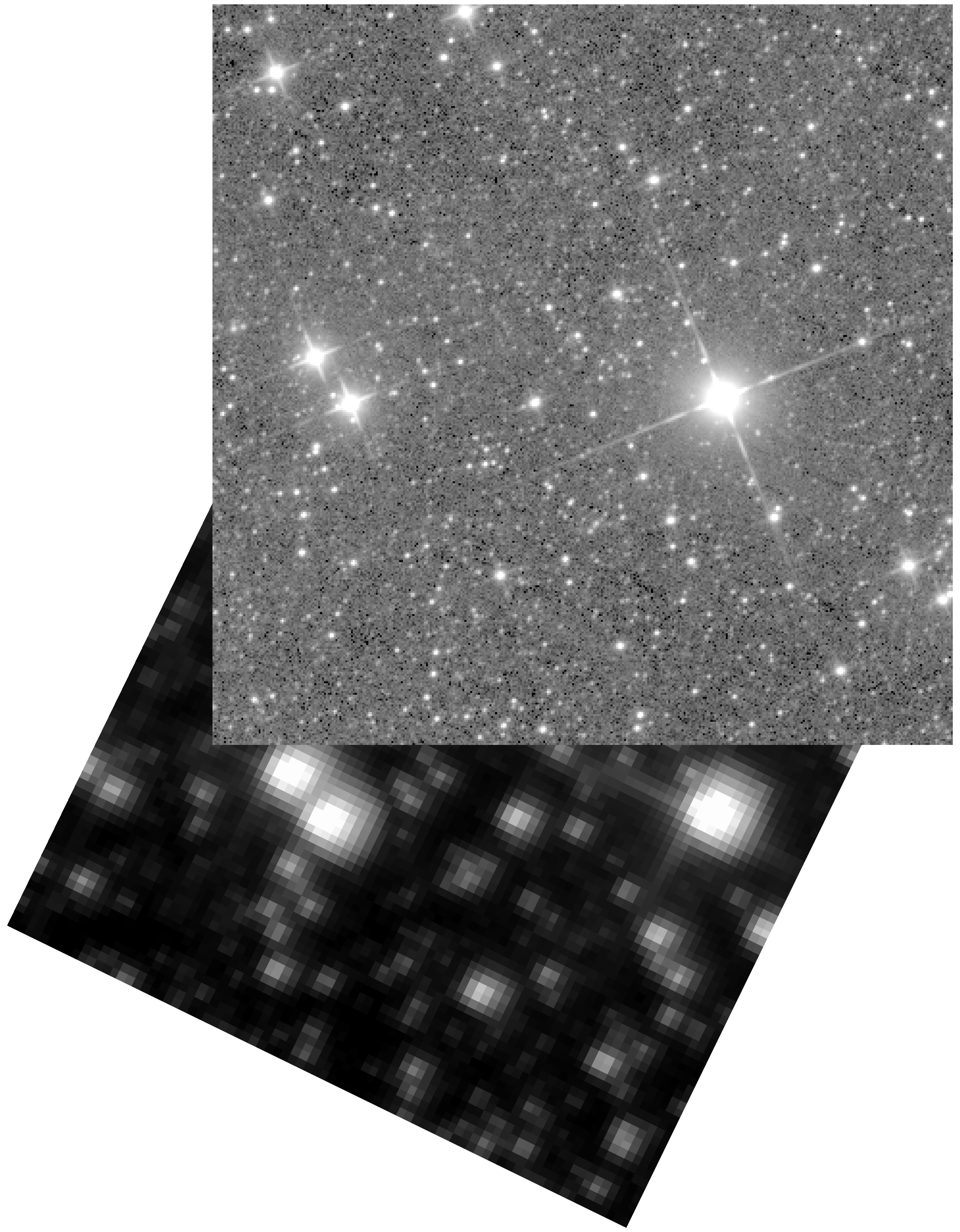

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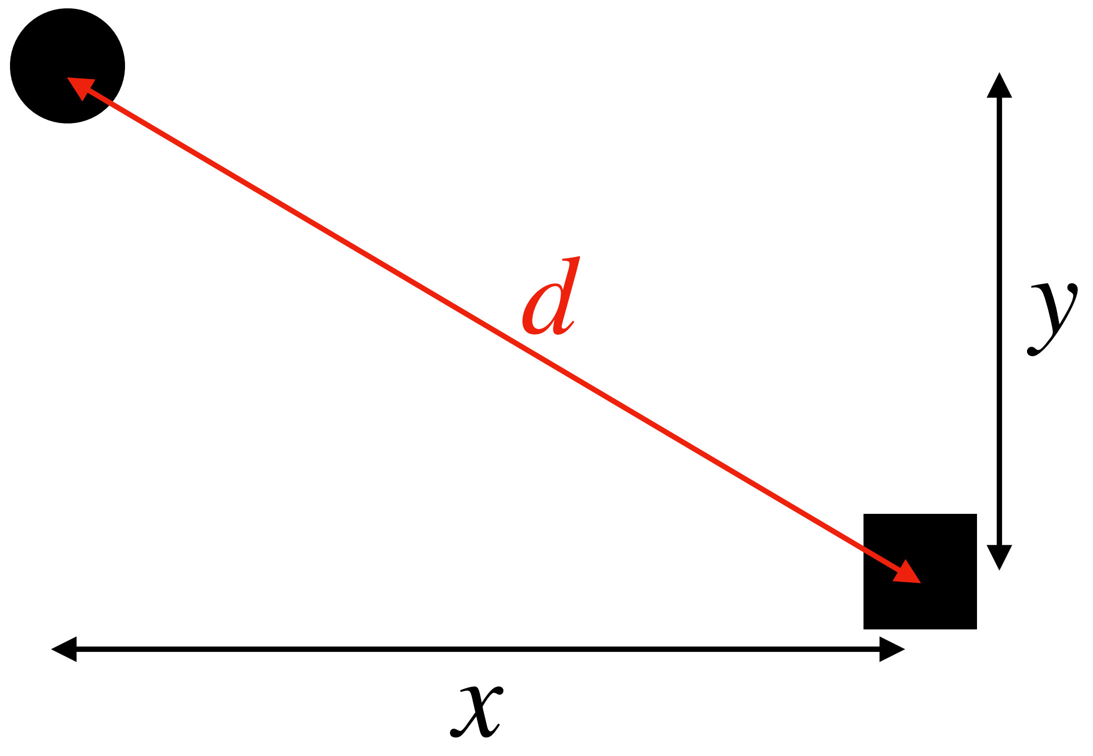

$$p(d^2) = p(x^2 + y^2) = p(x^2)\,p(y^2)$$

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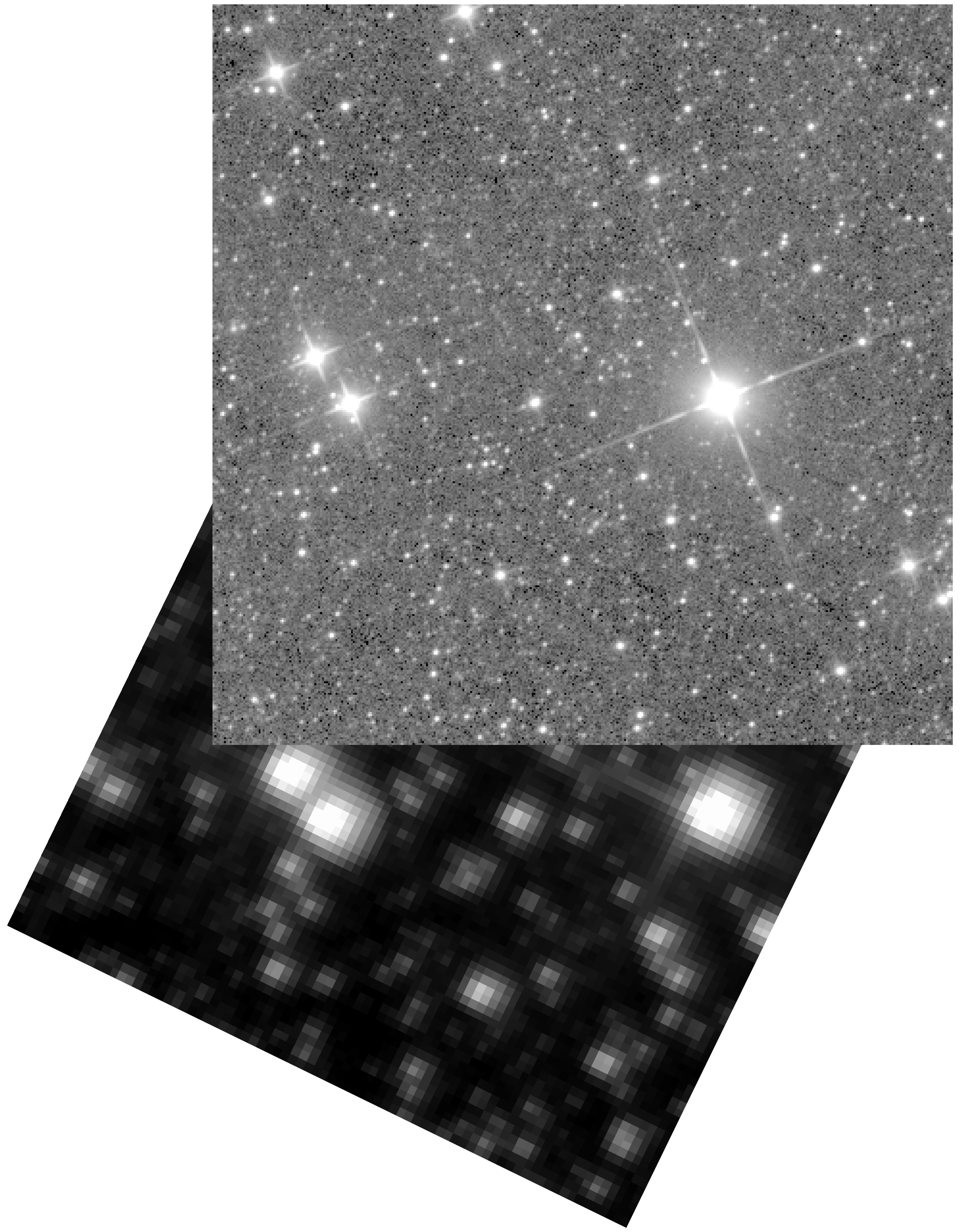

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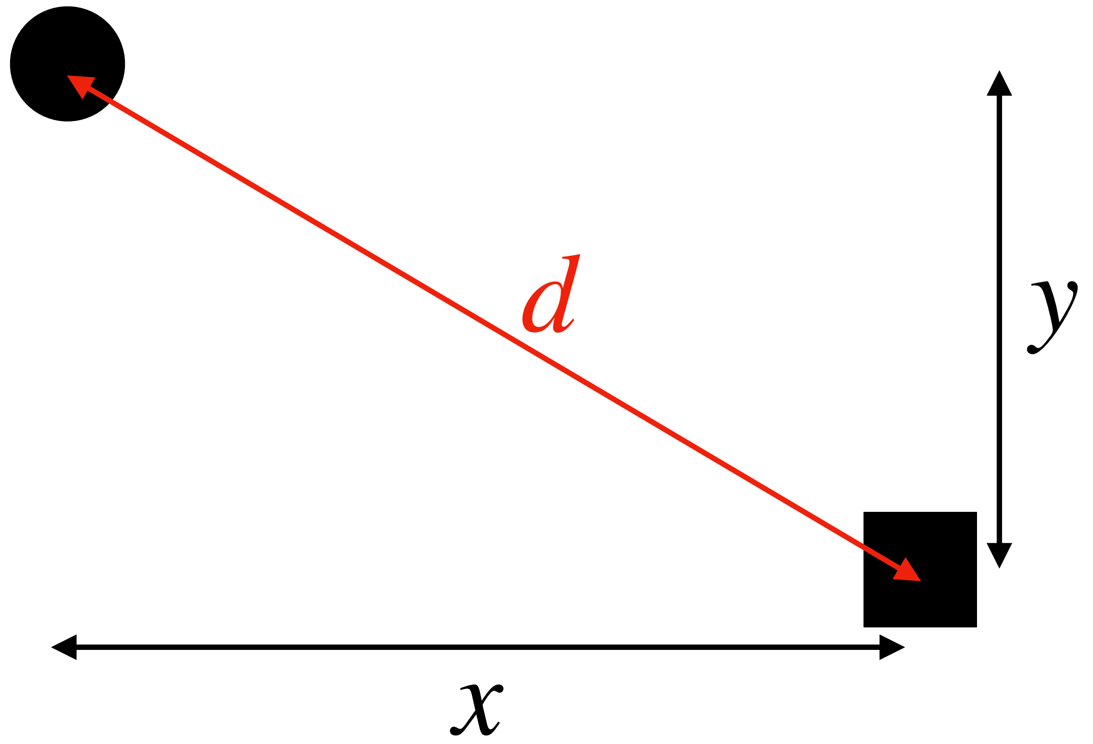

$$p(d^2) = p(x^2 + y^2) = p(x^2)\,p(y^2)$$

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

J. F. W. Herschel, “Quetelet on Probabilities”, 1850

Probabilistic Cross-Matching

The Likelihood Ratio

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

$$dp(r|c) = 2\lambda r \times e^{-\lambda r^2}\,dr$$

$$LR(r) = dp(r|id)/dp(r|c) = \frac{1}{2\lambda}\exp\left\{\frac{r^2}{2}(2\lambda - 1)\right\}$$

de Ruiter, Willis, & Arp (1977)

$$dp_{\rm id} = Qr\exp\left(\frac{-r^2}{2}\right)dr. \quad dp_{\rm uo} = 2\lambda r\,dr$$

$$LR(r) = \frac{dp_{\rm id}}{dp_{\rm uo}} = \frac{Q\exp(-r^2/2)}{2\lambda}$$

Wolstencroft et al. (1986)

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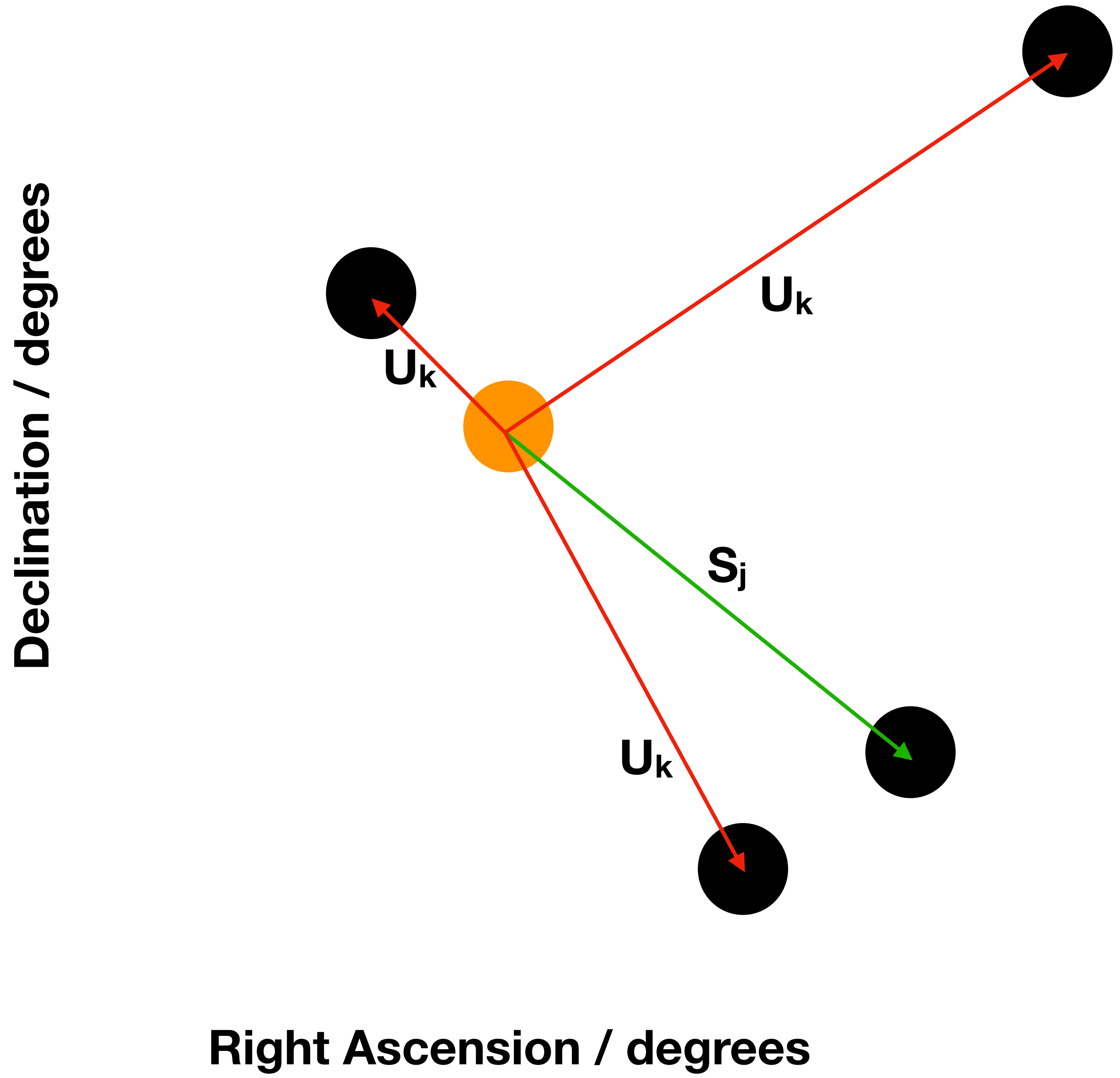
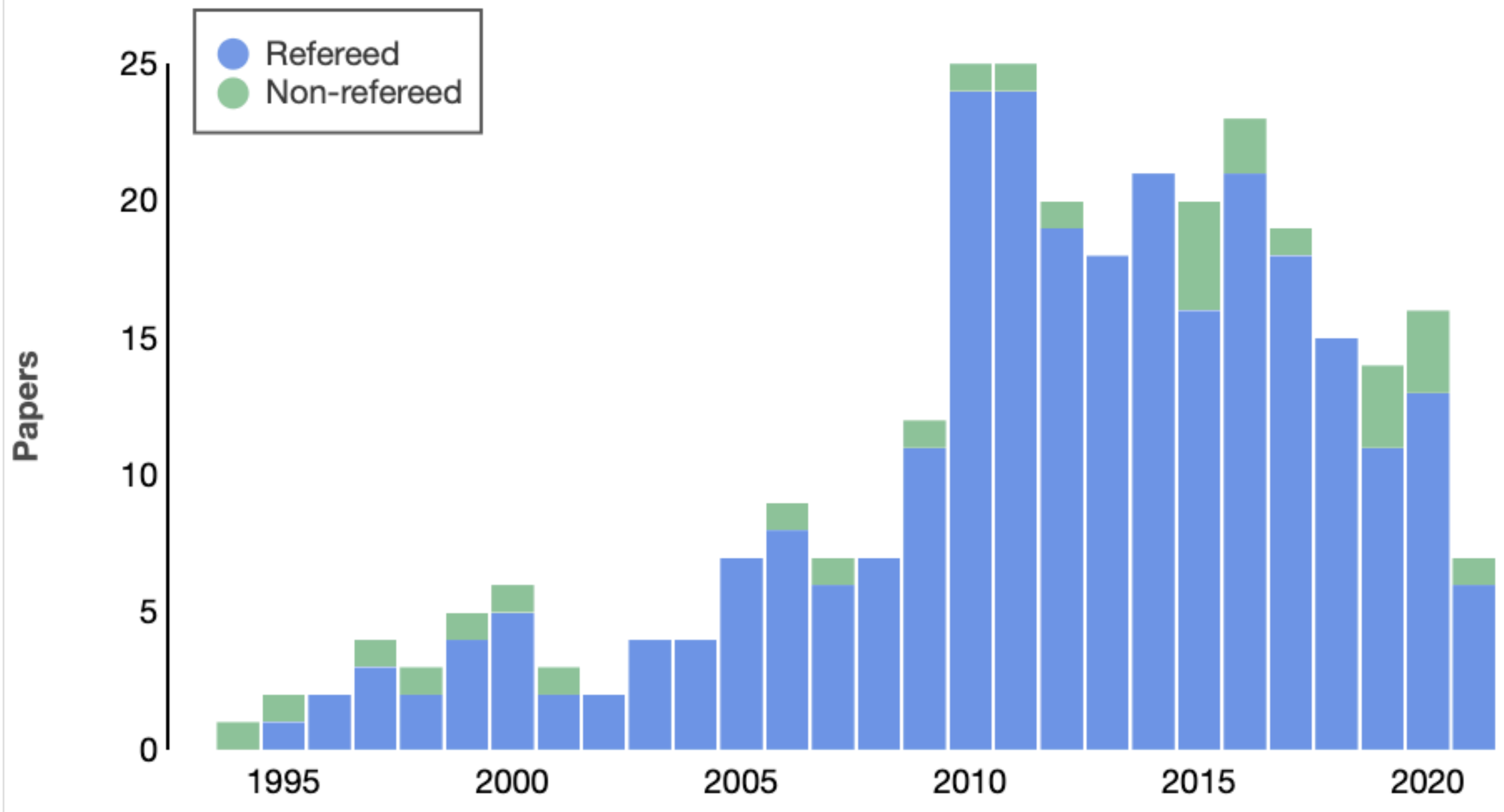
Wolstencroft et al. (1986)

The "Reliability" — Sutherland & Saunders (1992)



$$R_j = \frac{\Pr\left[S_j \cap \left(\bigcap_{k \neq j} U_k\right) \cap \left(\bigcap_{k'} E_{k'}\right)\right]}{\sum_i \Pr\left[S_i \cap \left(\bigcap_{k \neq i} U_k\right) \cap \left(\bigcap_{k'} E_{k'}\right)\right] + \Pr\left[(m_S > m_{\mathrm{lim}}) \cap \left(\bigcap_k U_k\right) \cap \left(\bigcap_{k'} E_{k'}\right)\right]} = \frac{L_j}{\sum_i L_i + (1-Q)}$$



$$L = \frac{q(m,c)\, f(x,y)}{n(m,c)}$$

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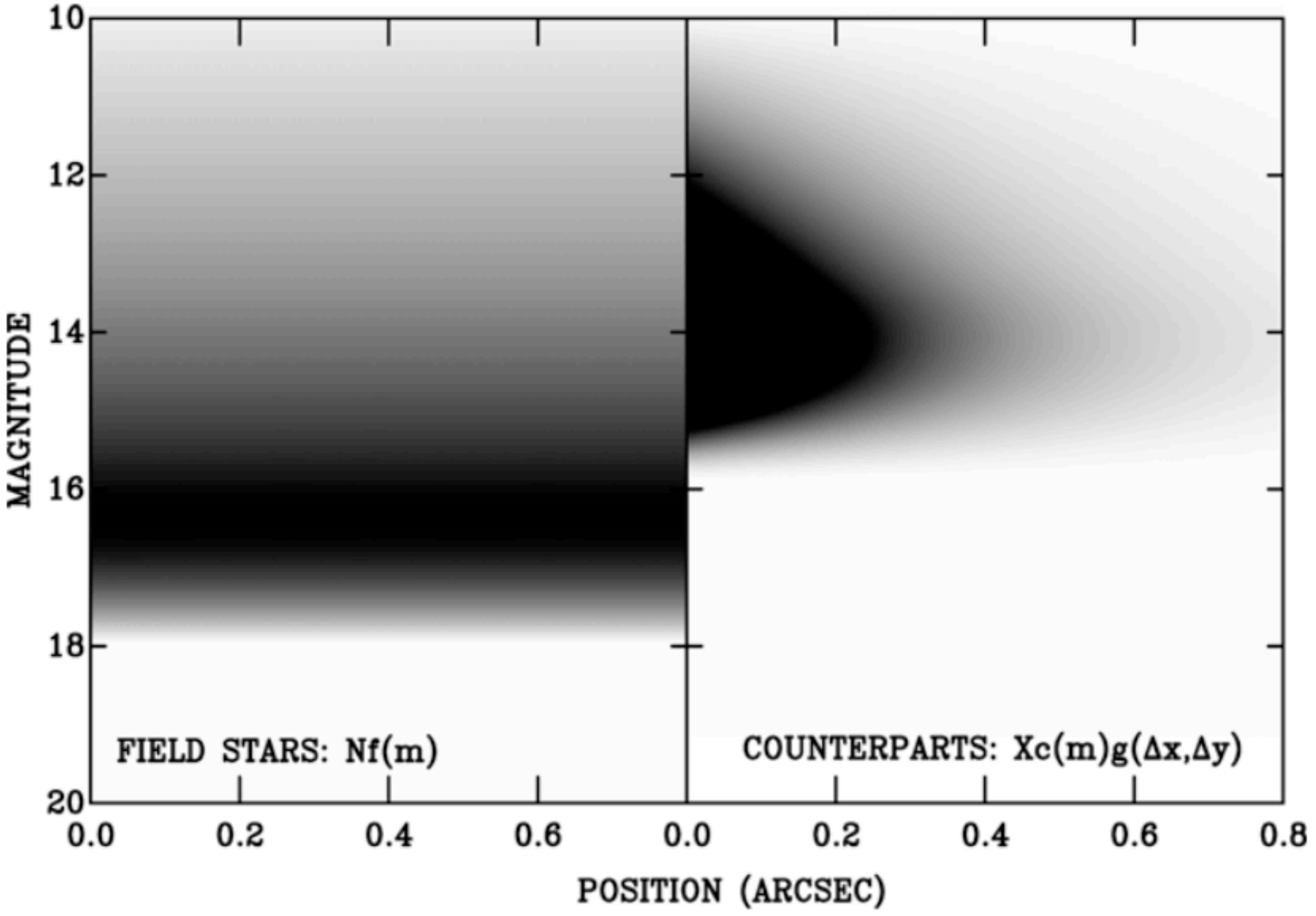
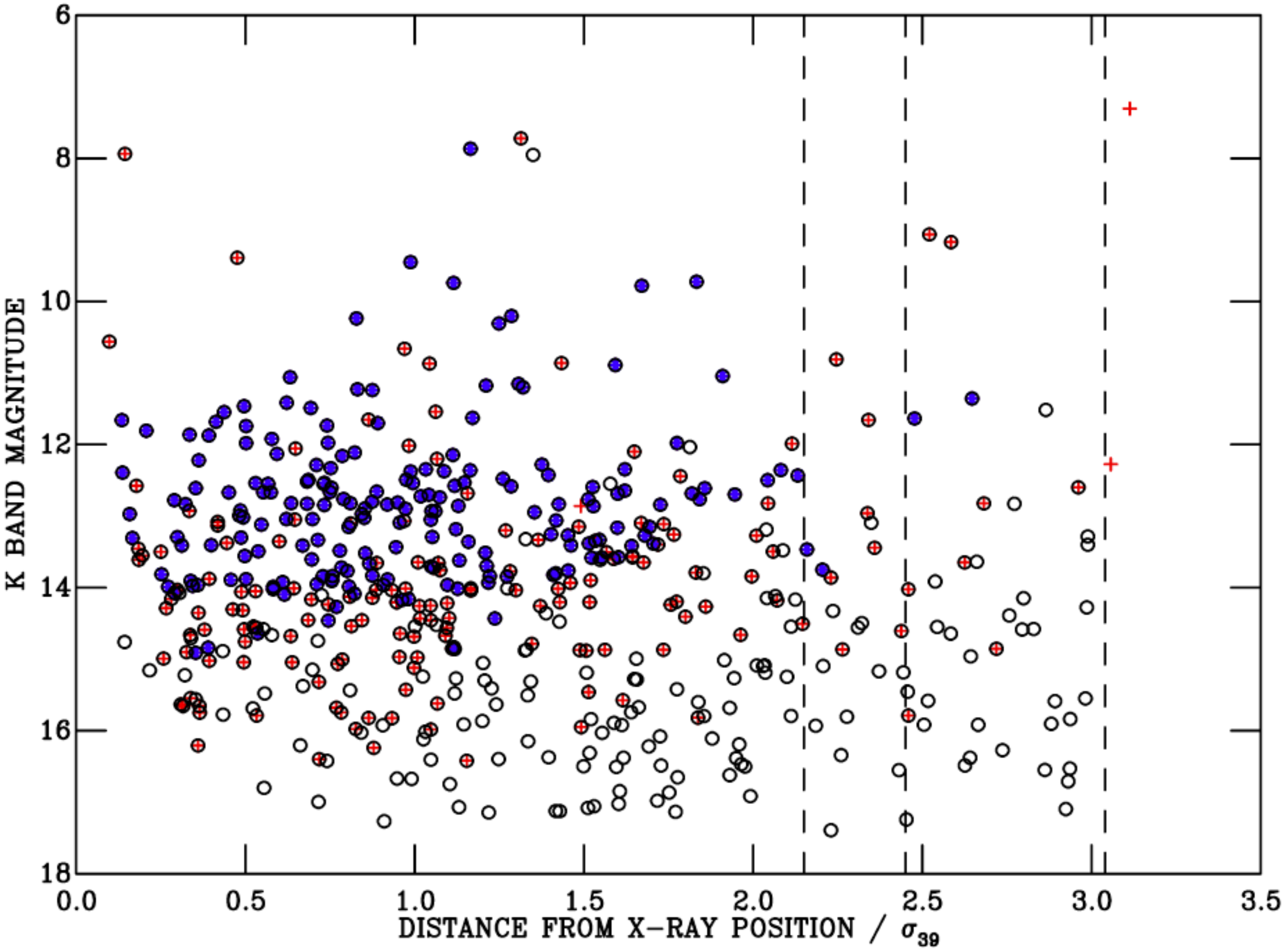
Probabilistic Cross-Matching

$$P(0) = \frac{1 - X}{1 - X + \sum_j \frac{Xc(m_j)\,g(\Delta x_j, \Delta y_j)}{Nf(m_j)}} \qquad P(i) = \frac{\frac{Xc(m_i)\,g(\Delta x_i, \Delta y_i)}{Nf(m_i)}}{1 - X + \sum_j \frac{Xc(m_j)\,g(\Delta x_j, \Delta y_j)}{Nf(m_j)}}$$





Naylor, Broos, & Feigelson (2013)

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Probabilistic Cross-Matching

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

$$p(D|K) = \prod_{i=1}^{n} \left[\int p(\boldsymbol{m}_i|K) p_i(\boldsymbol{x}_i|\boldsymbol{m}_i, K)\, d^3 m_i \right]$$

$$B(H, K|D') = \frac{\int p(\boldsymbol{\eta}|H) \prod_{i=1}^{n} p_i(\boldsymbol{g}_i|\boldsymbol{\eta}, H)\, d^r \eta}{\prod_{i=1}^{n} \left[\int p(\boldsymbol{\eta}_i|K) p_i(\boldsymbol{g}_i|\boldsymbol{\eta}_i, K)\, d^r \eta_i \right]}$$

Budavári & Szalay (2008)

Includes SED model fitting to all sources

(Apologies for the lack of nice figures in this paper!)

Probabilistic Cross-Matching

Nearest neighbour or brightest neighbour: one-to-one, either astrometry OR photometry

Likelihood ratio: one-to-one matches, mostly just astrometry (e.g., Wolstencroft et al. 1986)

Reliability: One-to-many matches, uses photometry from one dataset (e.g. Naylor et al. 2013)

Budavári & Szalay (2008): one-to-one-to-one-to… matches, include SED fitting

e.g. Pineau et al. (2017): many-to-many-to-many-to… matches, no photometry implemented

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One assumption made in all of these works: positional errors of sources are Gaussian!

$$dp(r|id) = r \times e^{-r^2/2}\,dr. \quad P(i) = \frac{\frac{Xc(m_i)\,g(\Delta x_i, \Delta y_i)}{Nf(m_i)}}{1 - X + \sum_j \frac{Xc(m_j)\,g(\Delta x_j, \Delta y_j)}{Nf(m_j)}} \quad p(D|H) = \int p(\boldsymbol{m}|H) \prod_{i=1}^{n} p_i(\boldsymbol{x}_i|\boldsymbol{m}, H)\, d^3m$$

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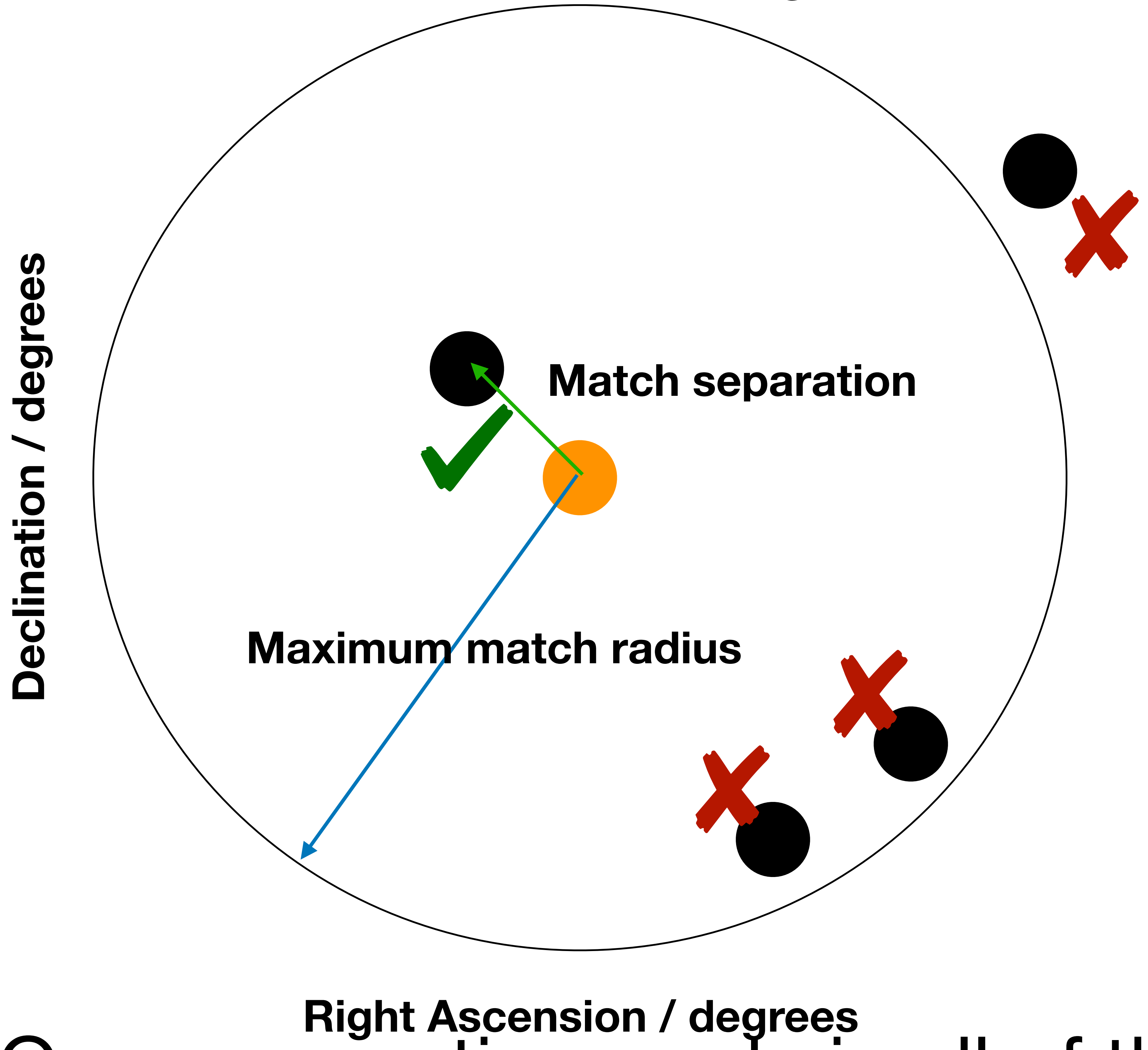
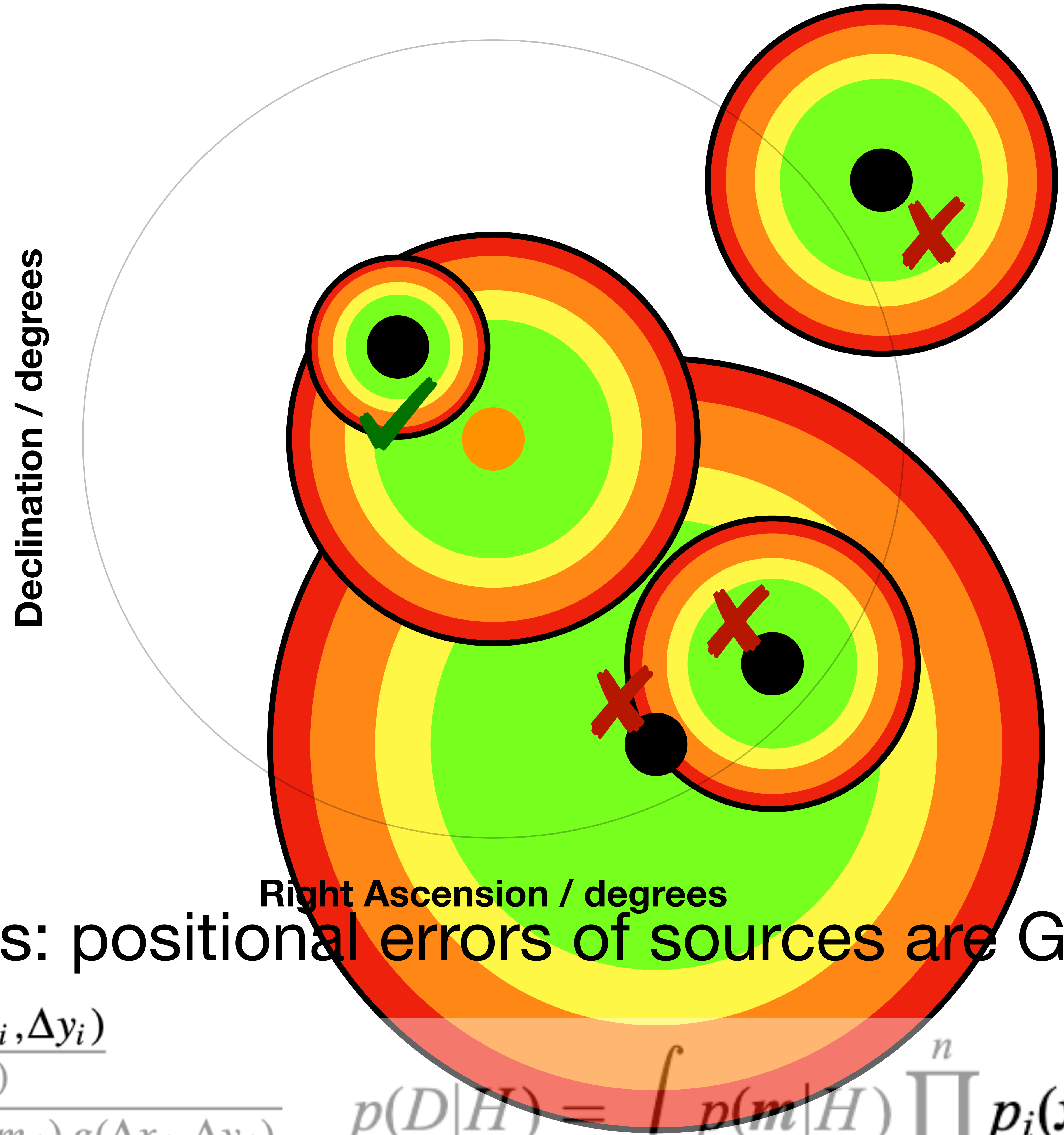
Probabilistic Cross-Matching

Nearest neighbour/ proximity matching



Probabilistic matching



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

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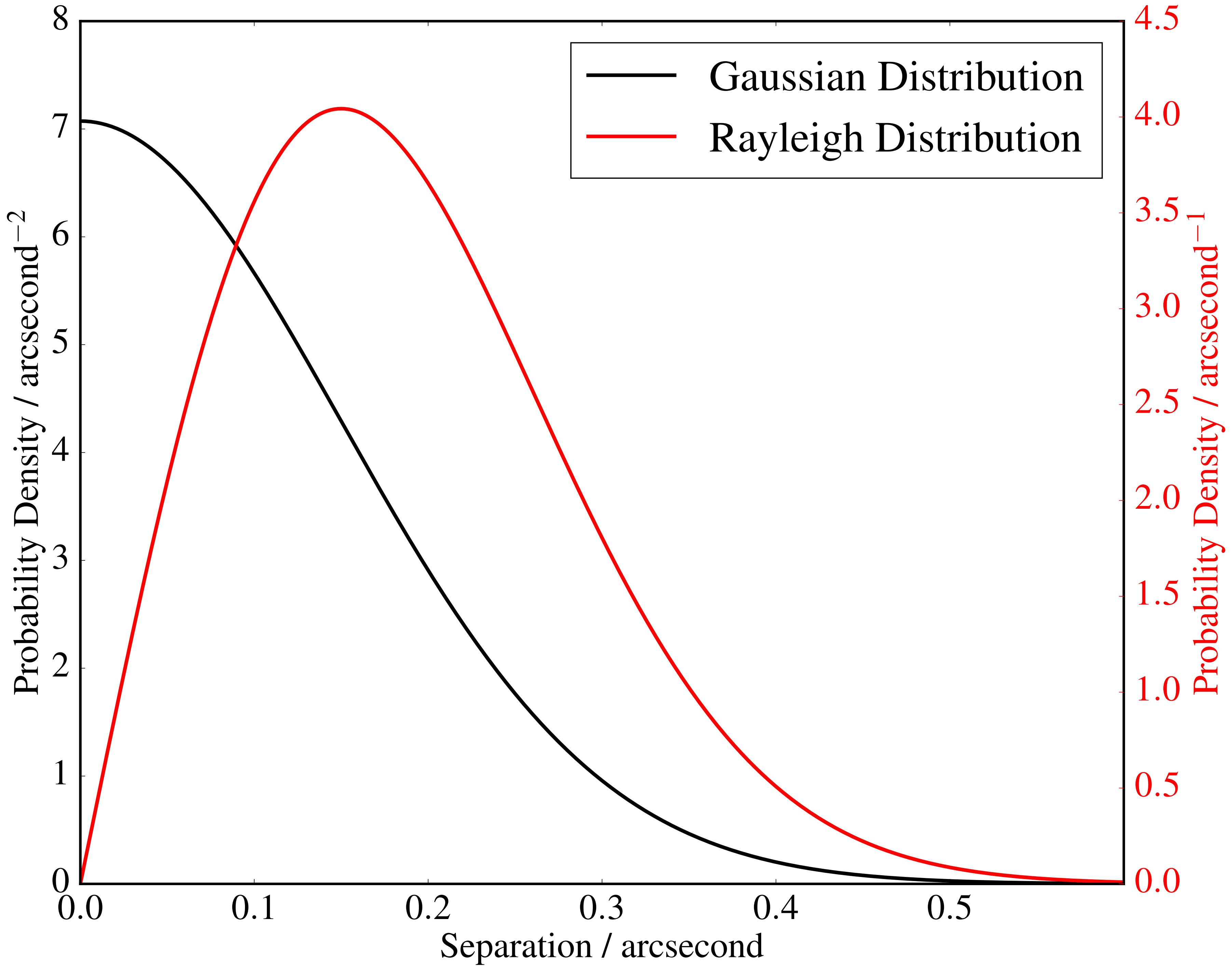
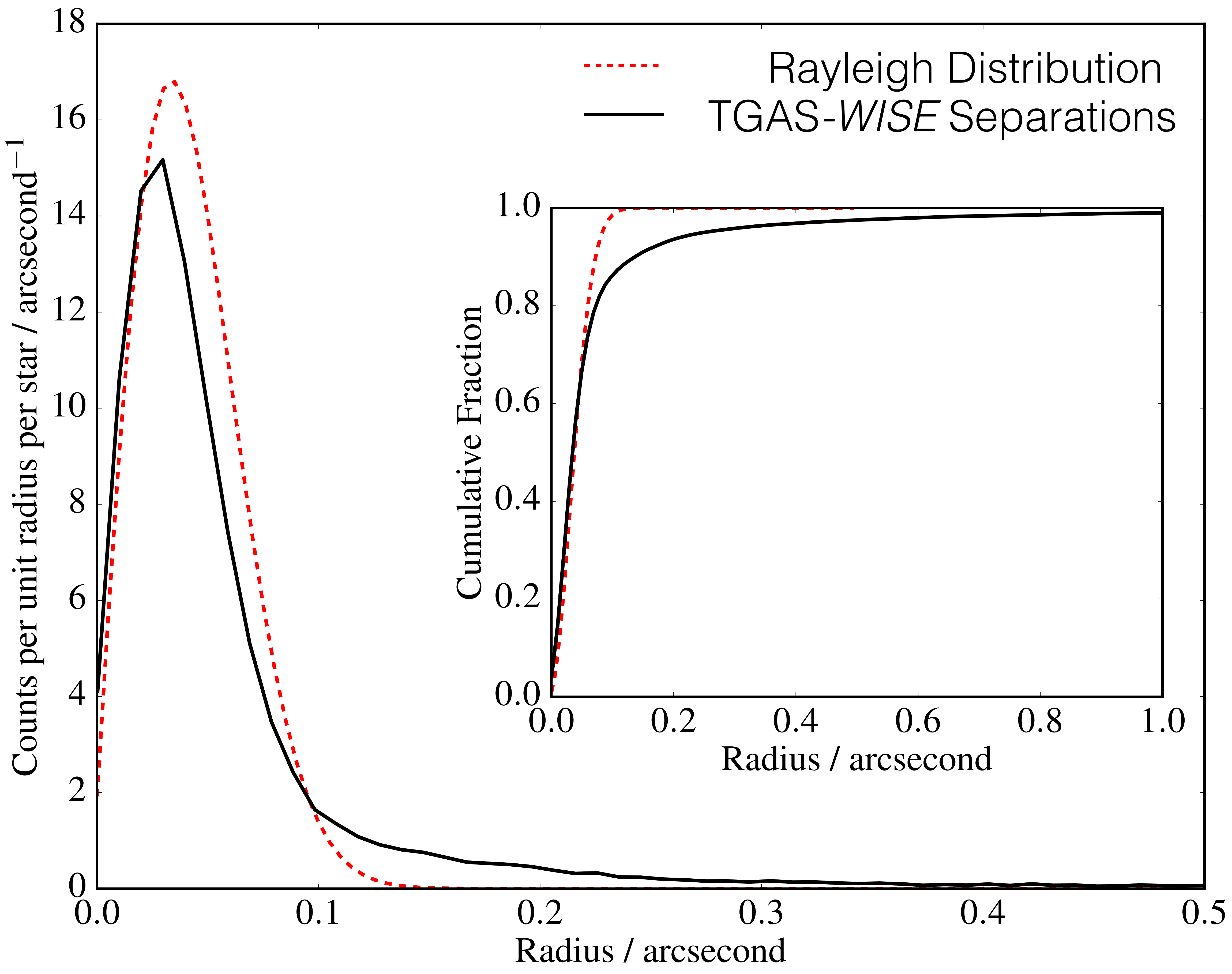
The *Astrometric Uncertainty* Function

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

↓

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





Wilson & Naylor (2017)
WISE - Wright et al. (2010)

TGAS - Michalik, Lindegren, & Hobbs (2015)
Gaia - Gaia Collaboration, Brown A. G. A., et al. (2016)

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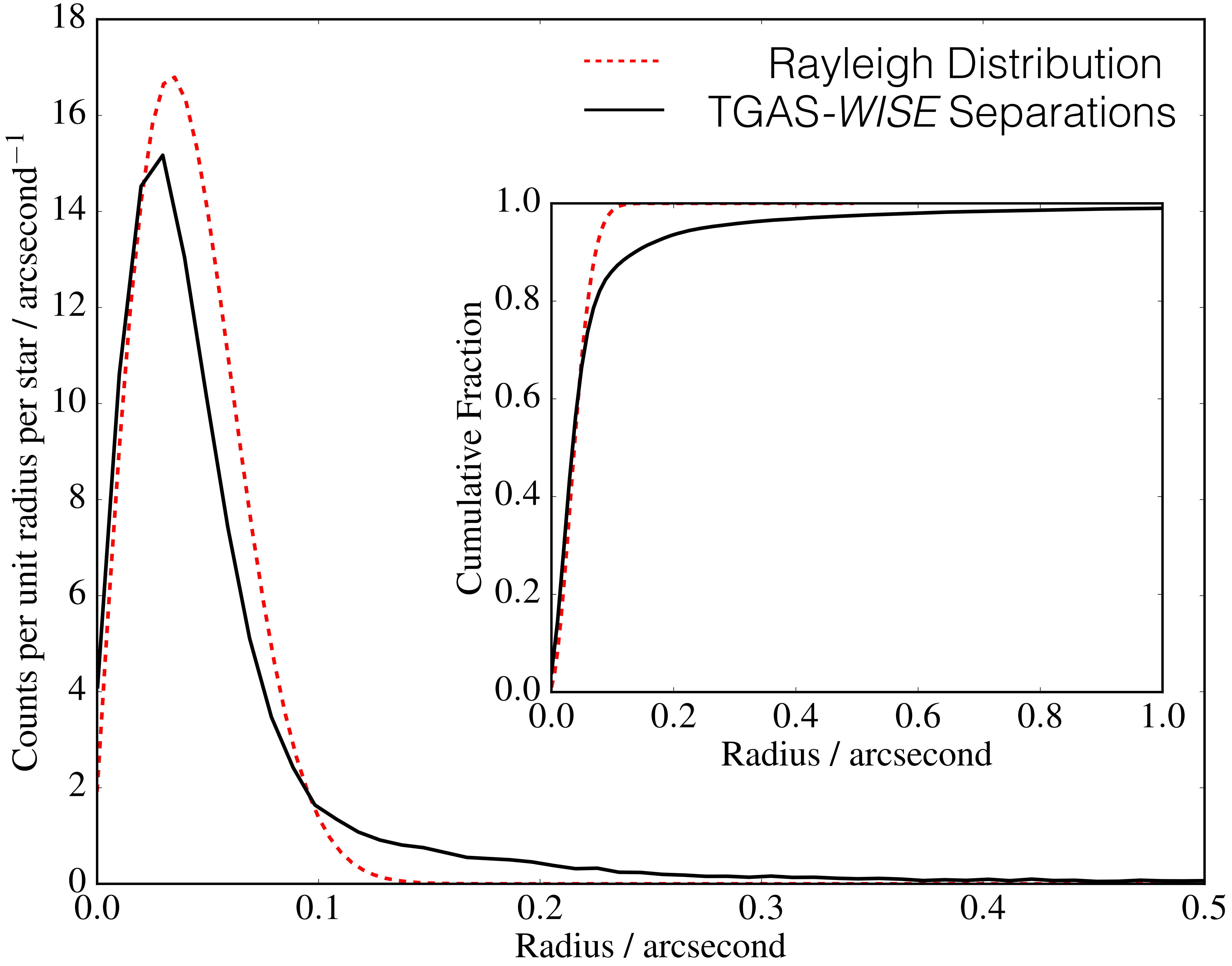
The *Astrometric Uncertainty* Function

Reasons for large separations:

1) proper motions (e.g. AllWISE Supplement 6.4, Cutri et al. 2012) — no, TGAS provided for all sources
2) false matches — no, 0.1% chance of random match within 0.5 arcseconds
3) What else could it be?



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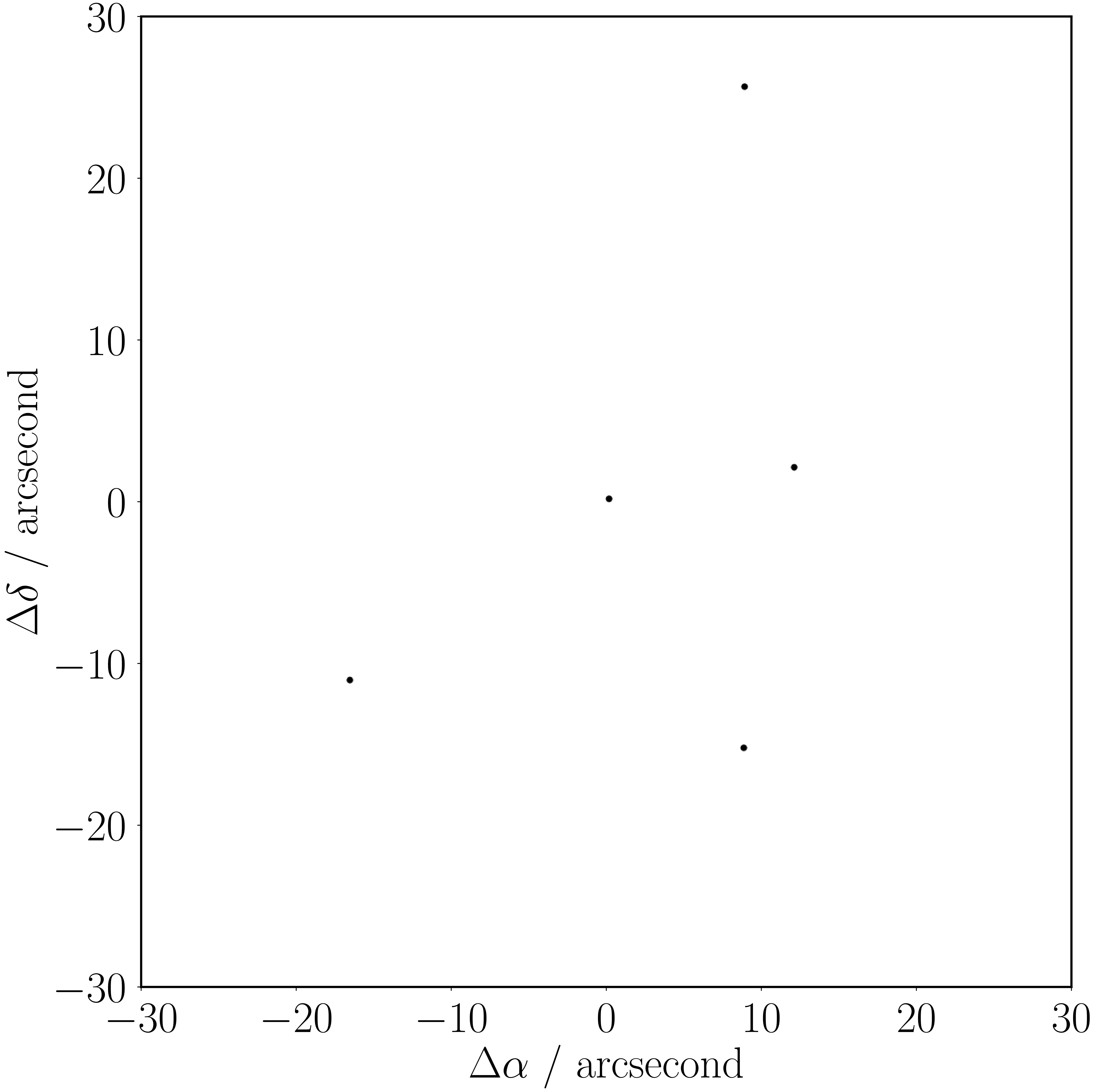
The AUF: Crowding



Wilson & Naylor (2017)

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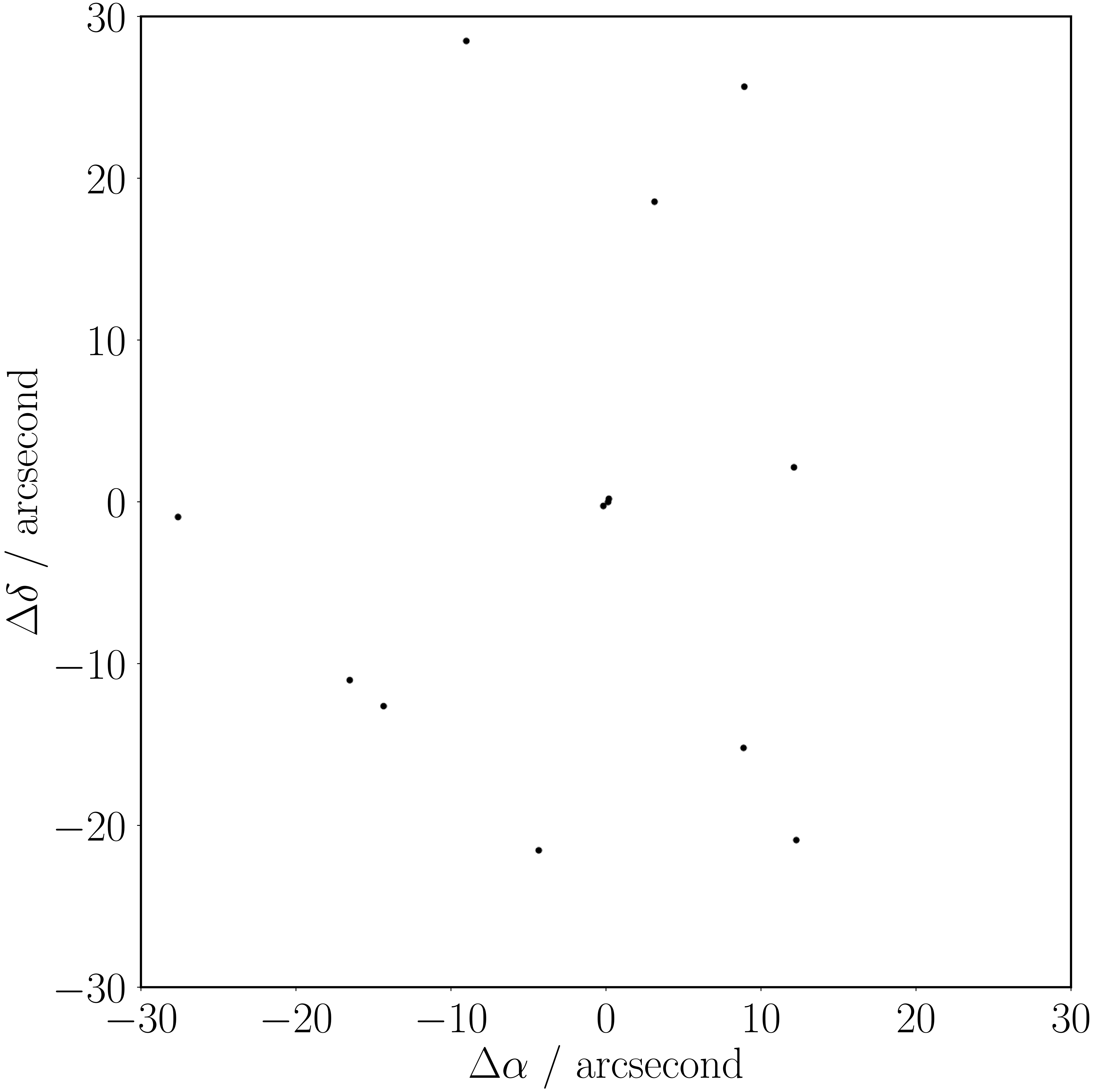

Wilson & Naylor (2017)

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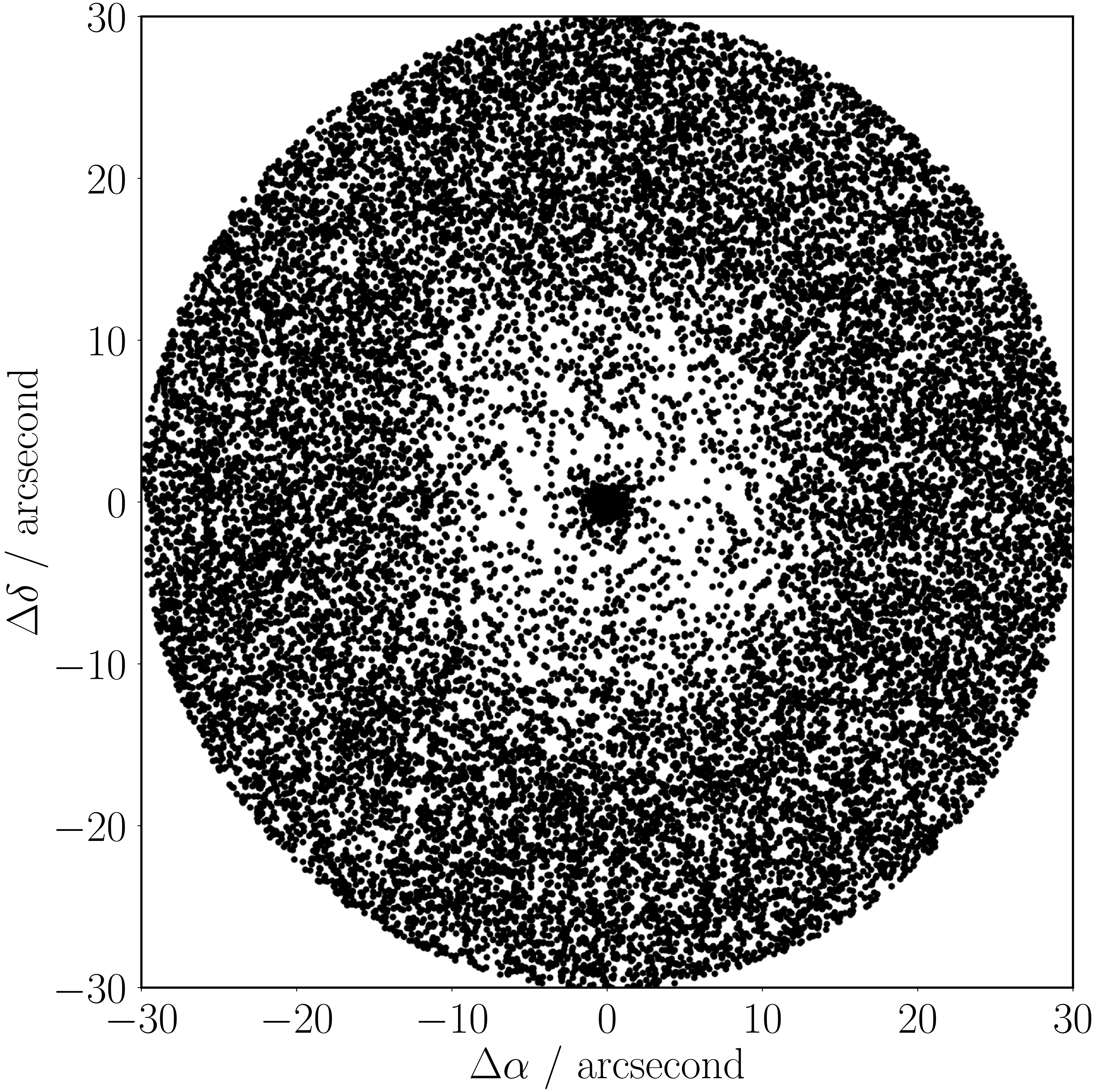
The AUF: Crowding



Wilson & Naylor (2017)

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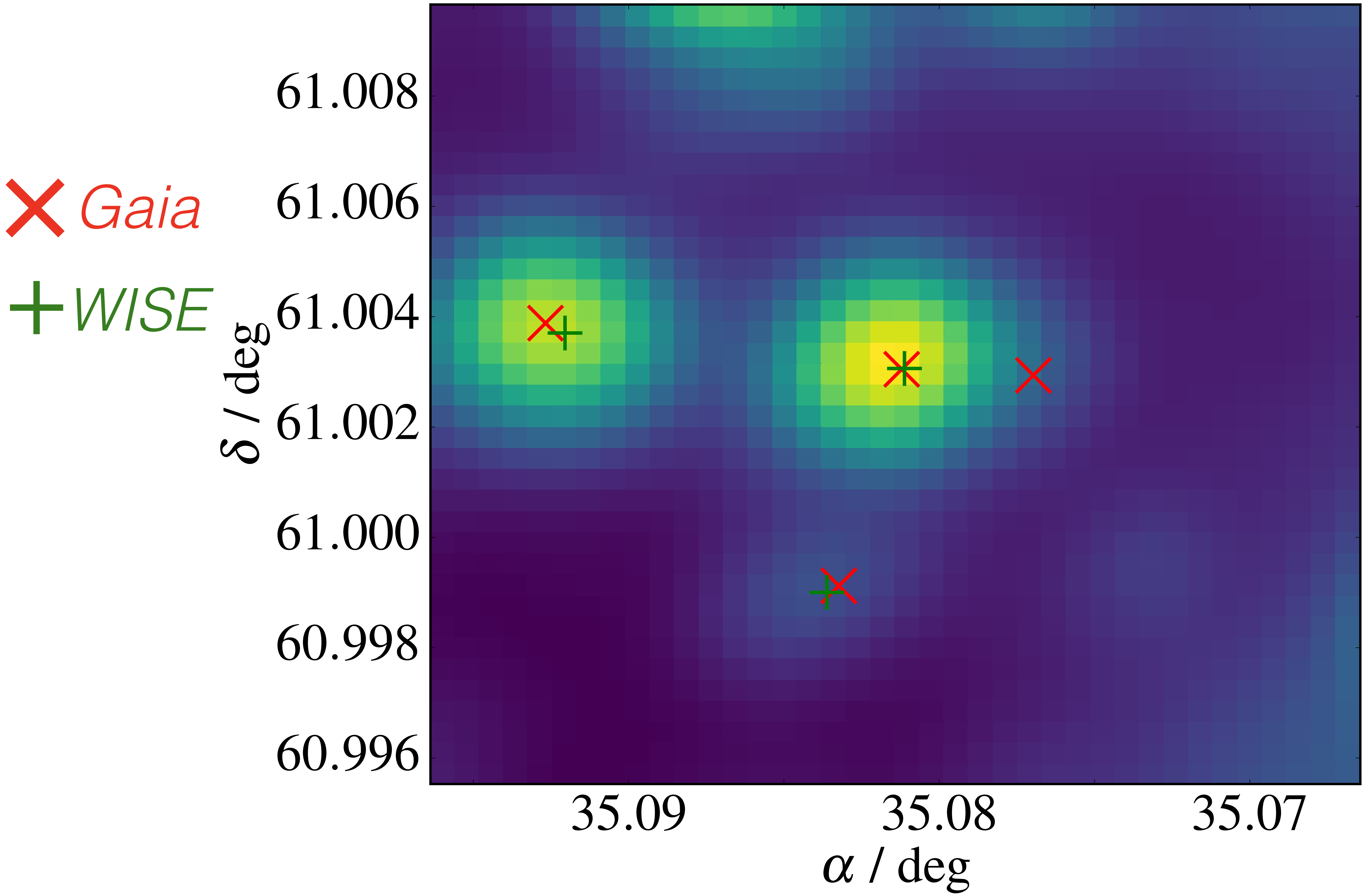
Resolving *Gaia*-*WISE* Blends



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

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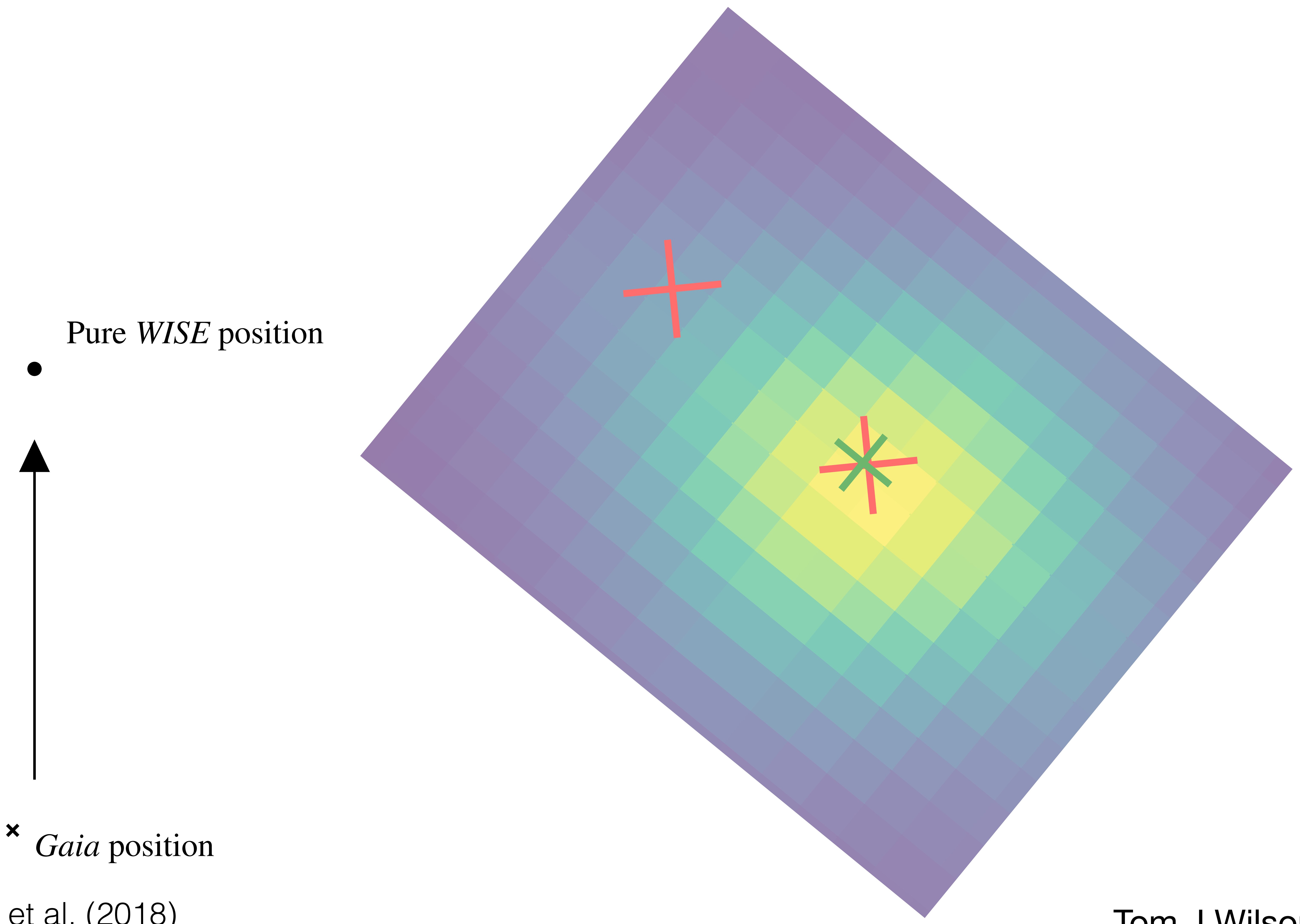
The AUF: Perturbation



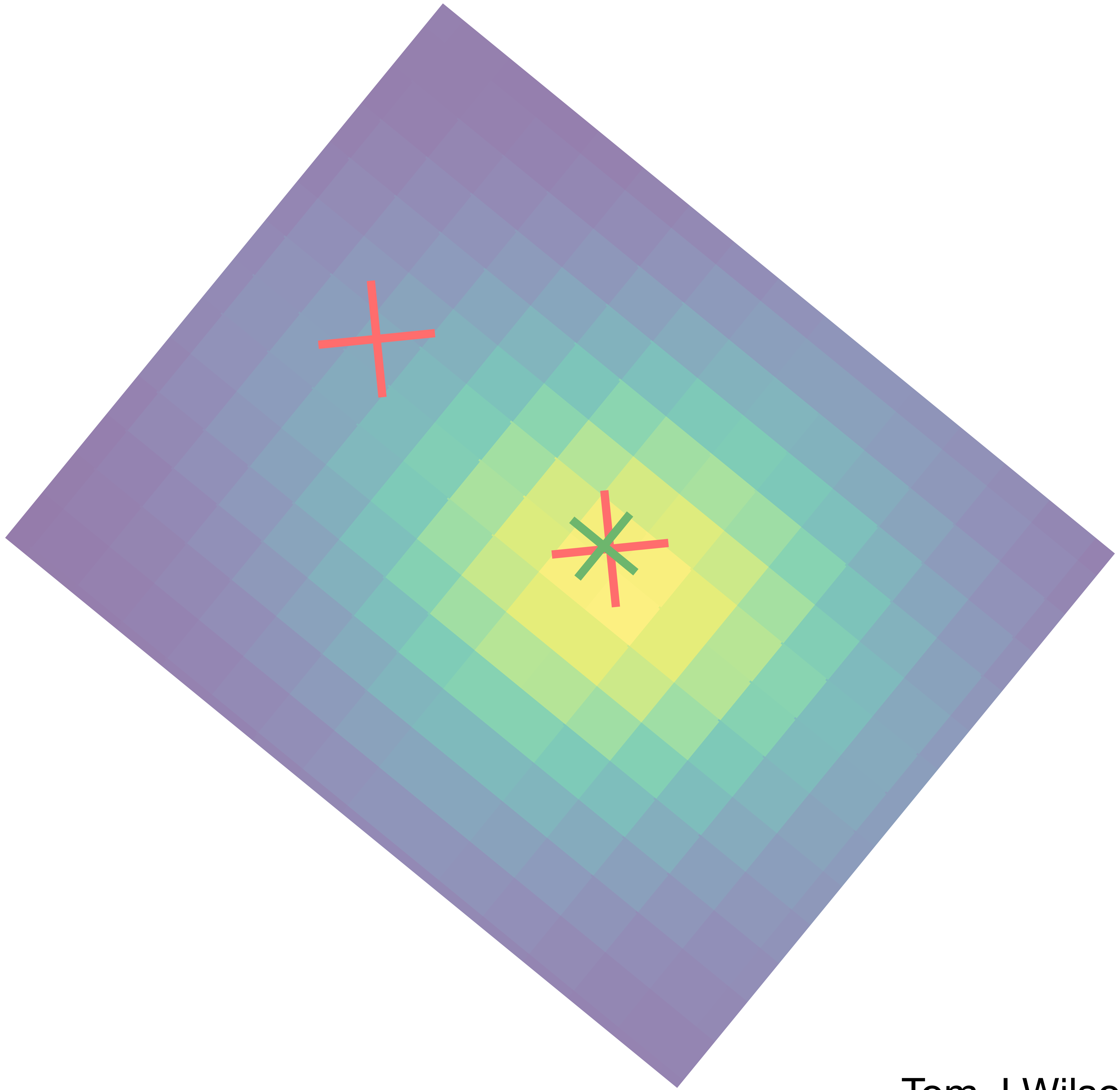
Wilson & Naylor (2017)
Wilson & Naylor (2018b)
WISE - Wright et al. (2010)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

The AUF: Perturbation

To *WISE* contaminant

Pure *WISE* position

Gaia position



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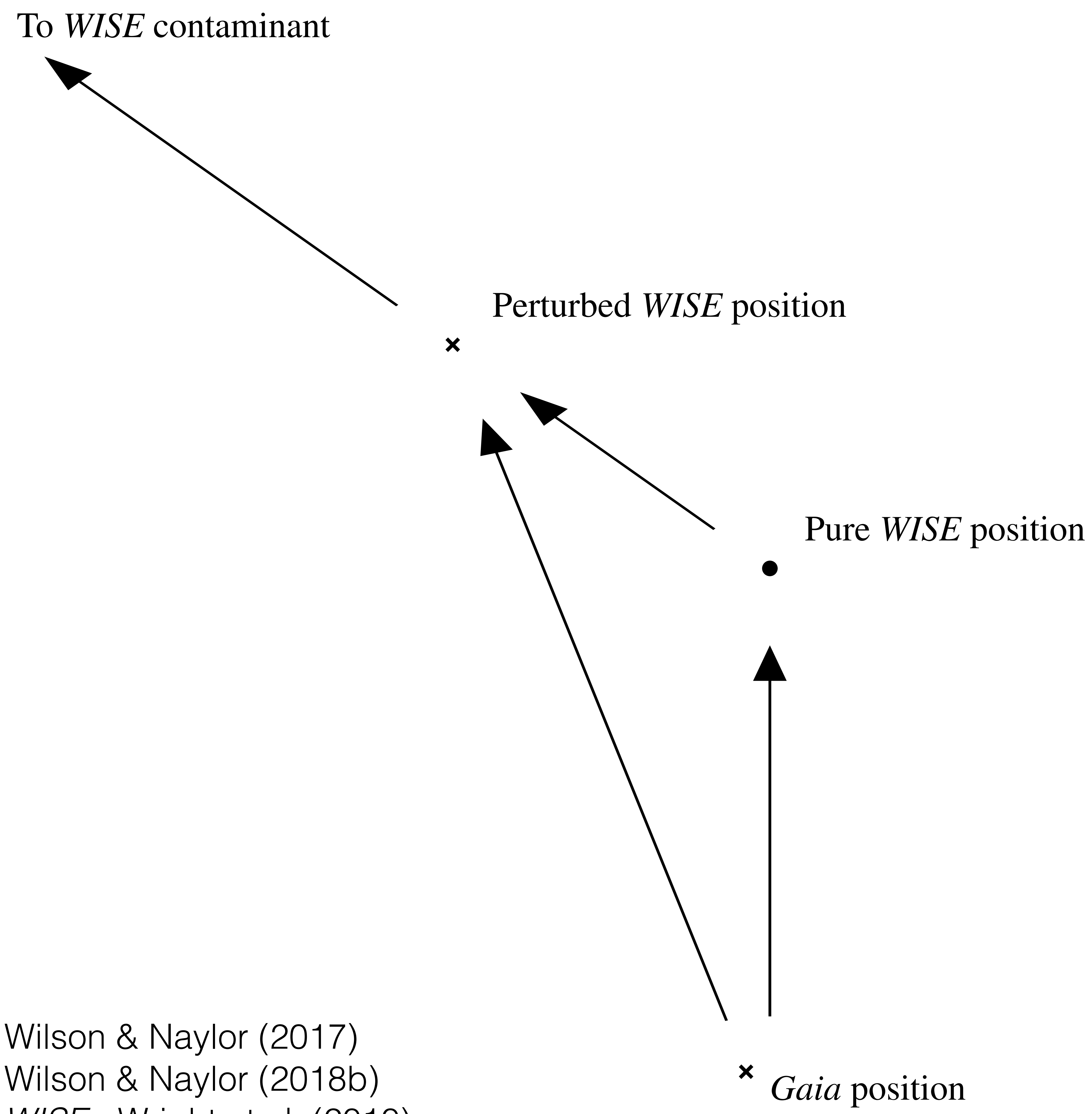

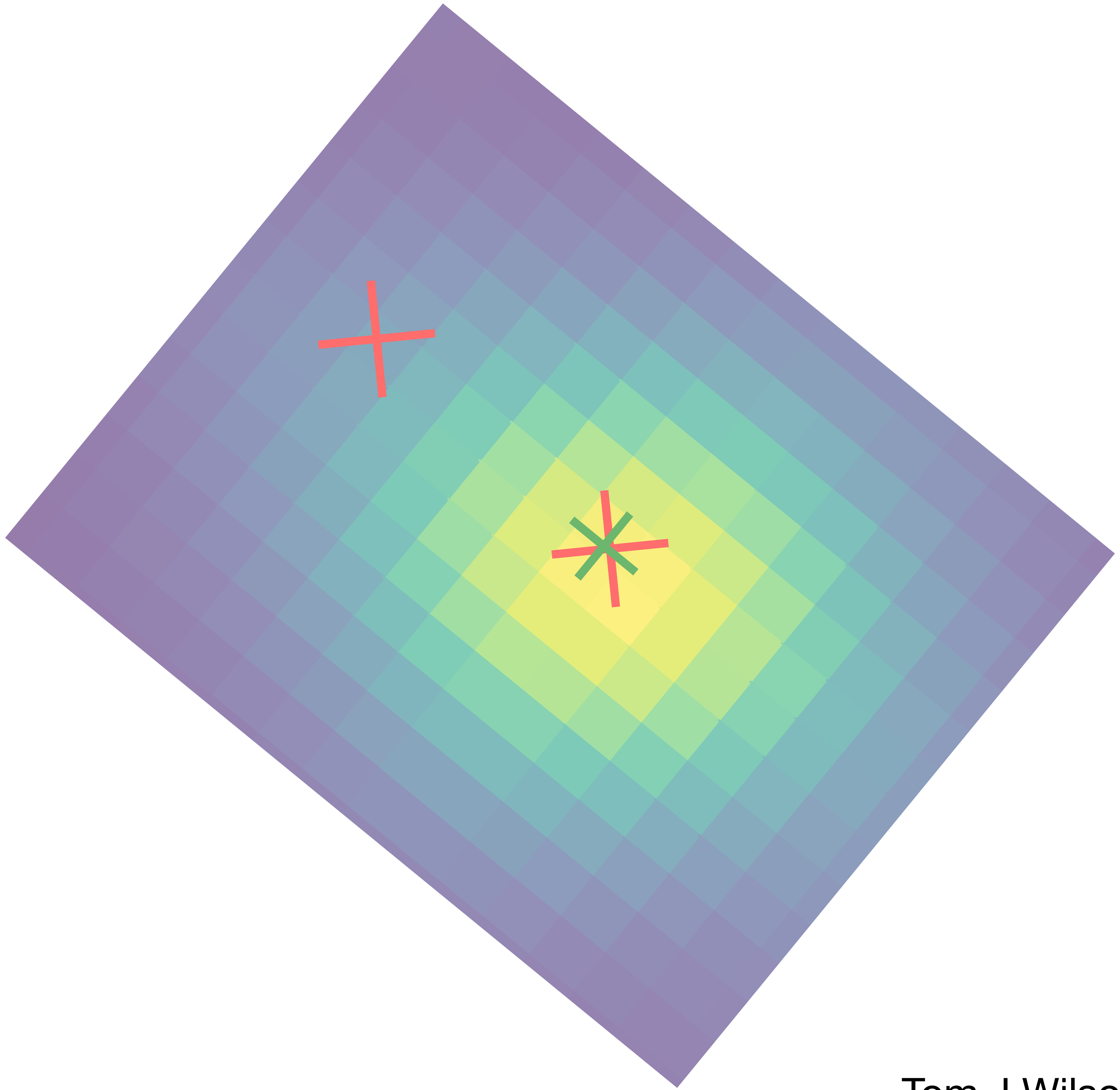

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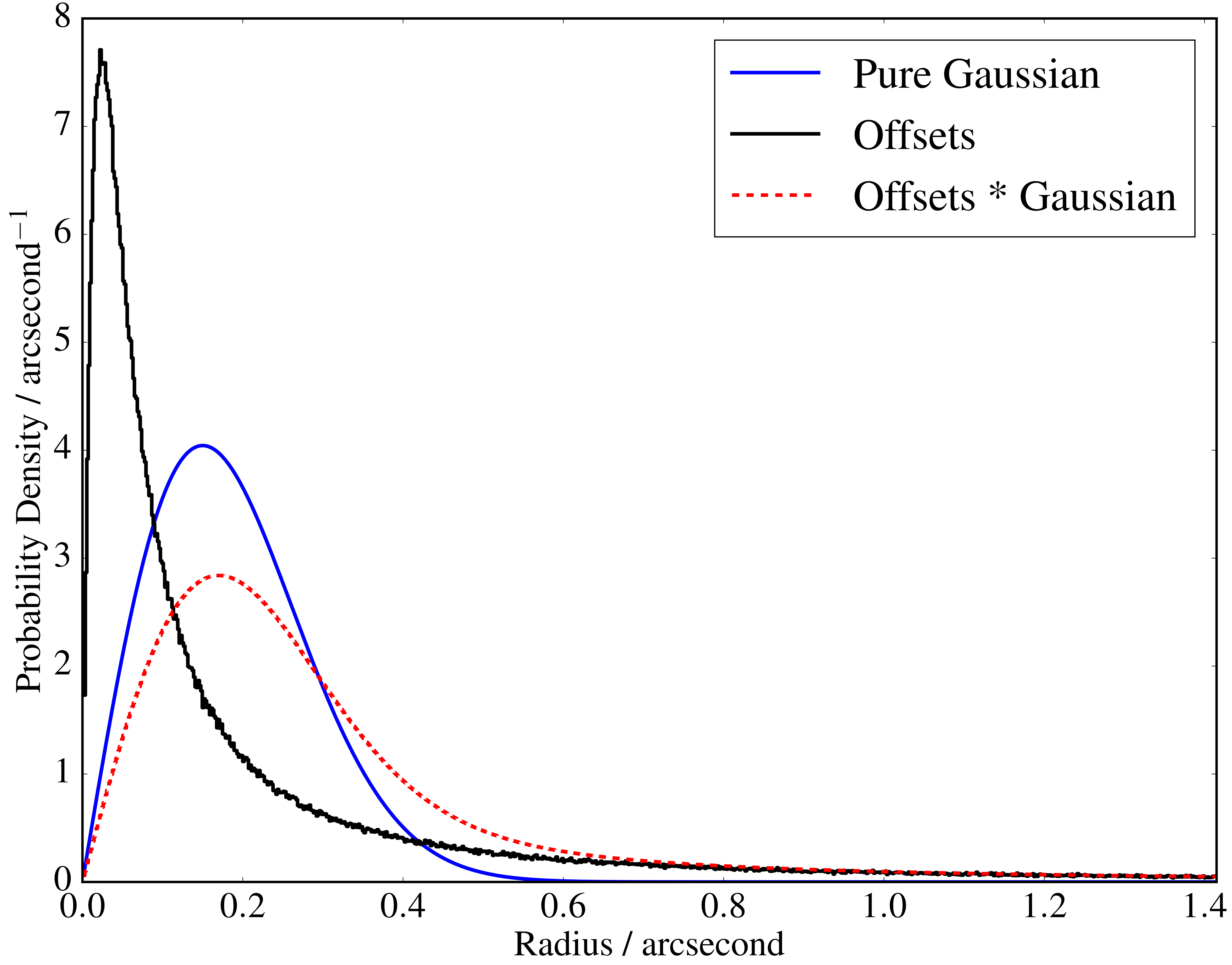

Wilson & Naylor (2018b)

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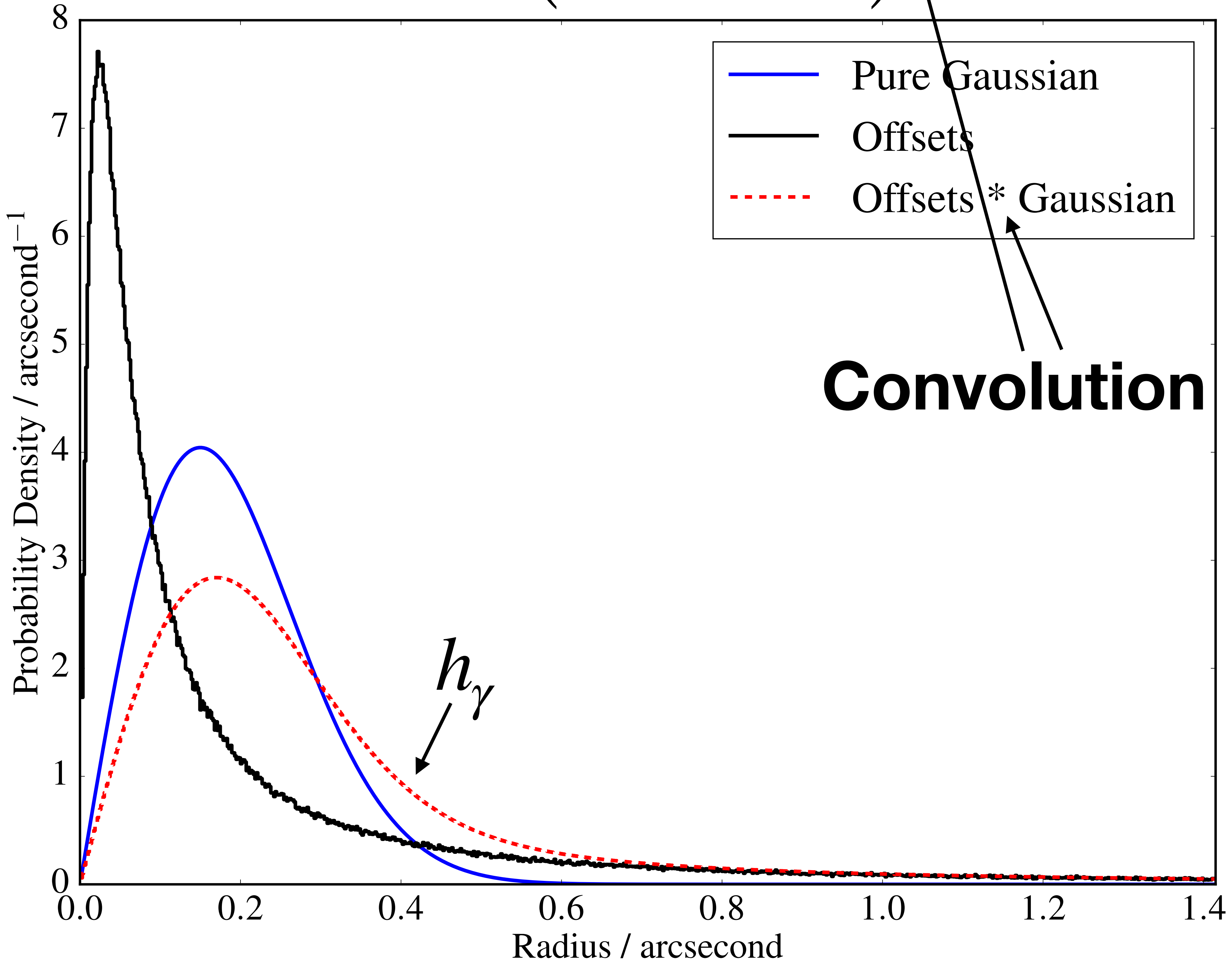
Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

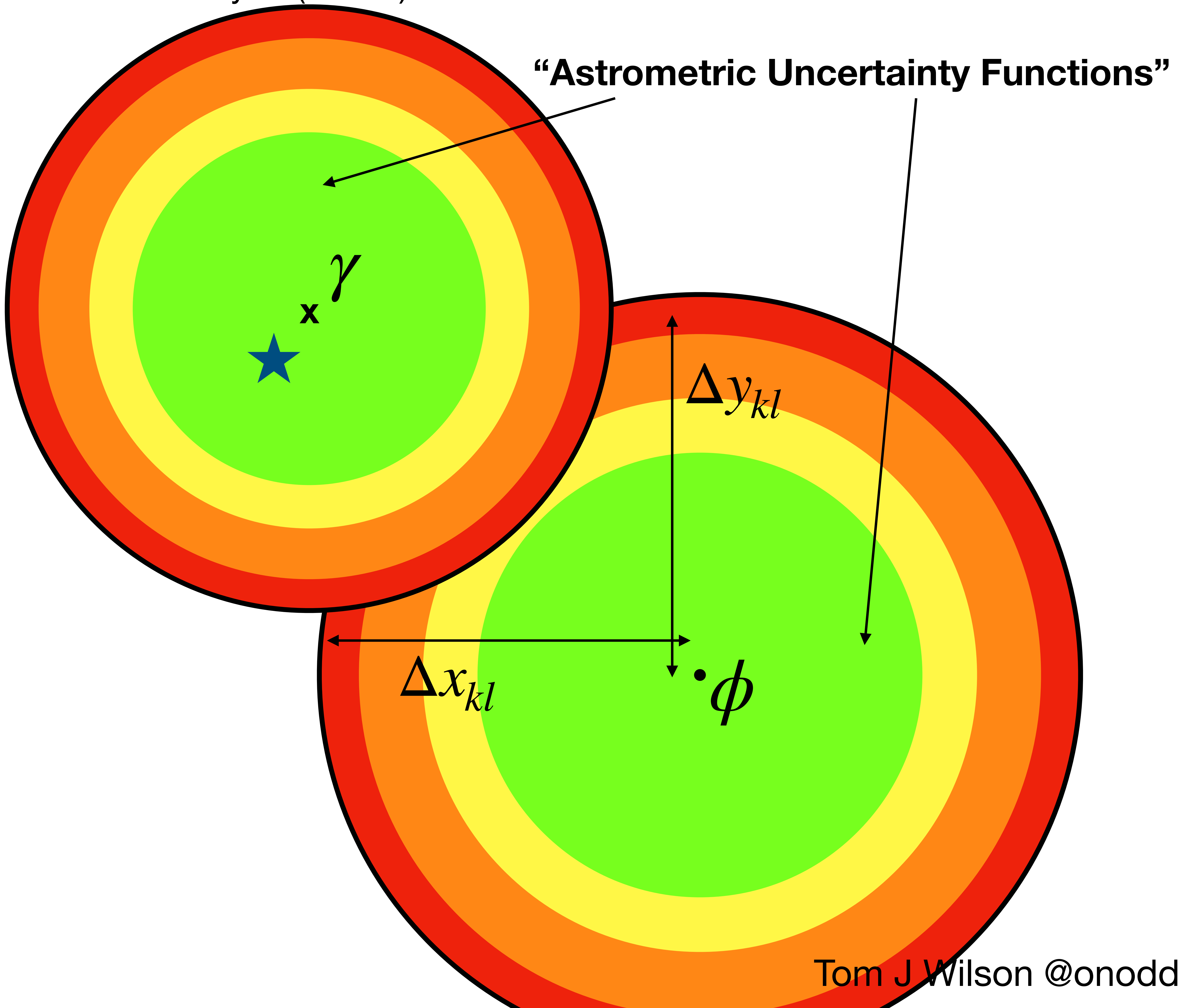
$$= N_\mathrm{c} \times (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl})$$

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



Wilson & Naylor (2018b)

Wilson & Naylor (2018a)



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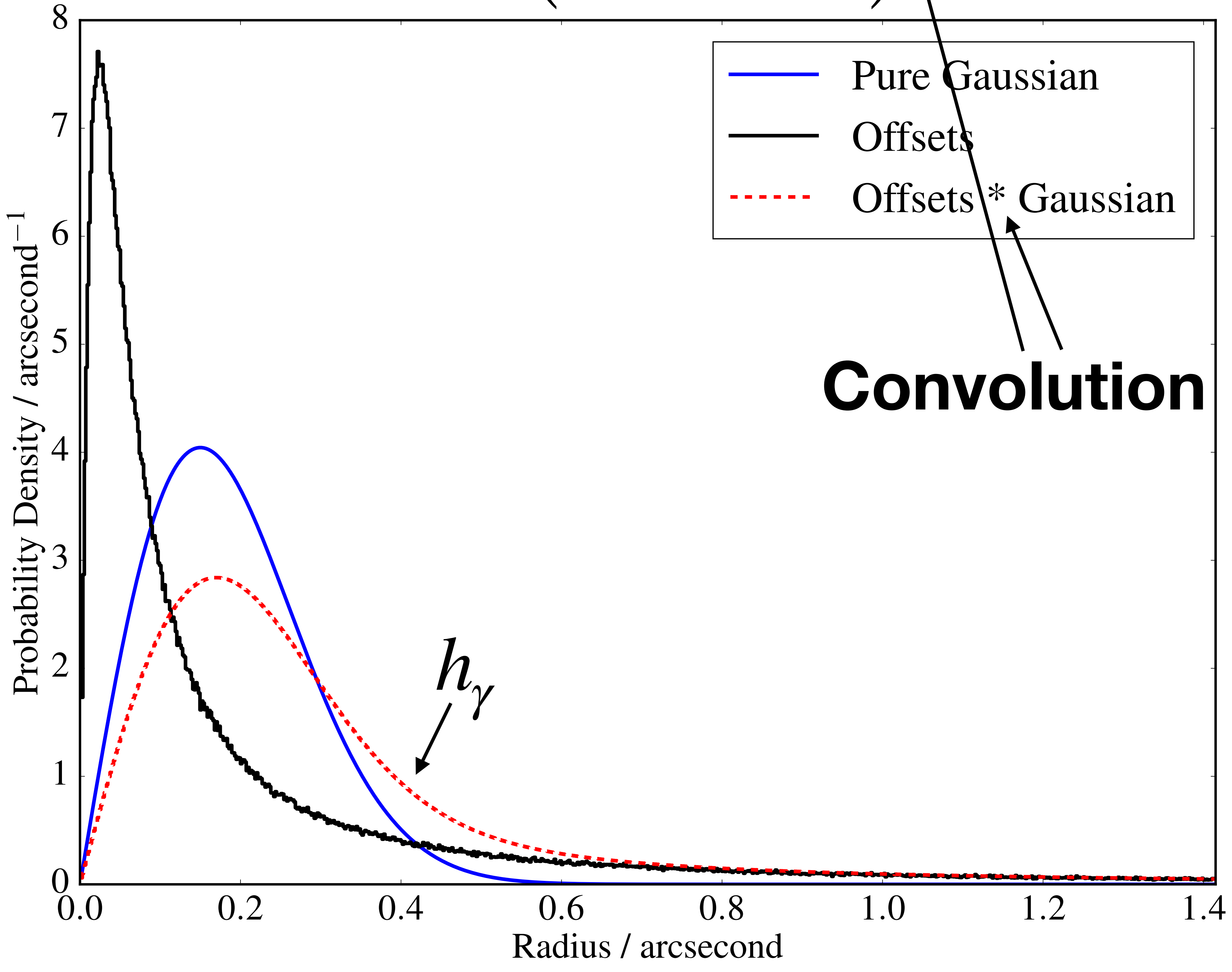
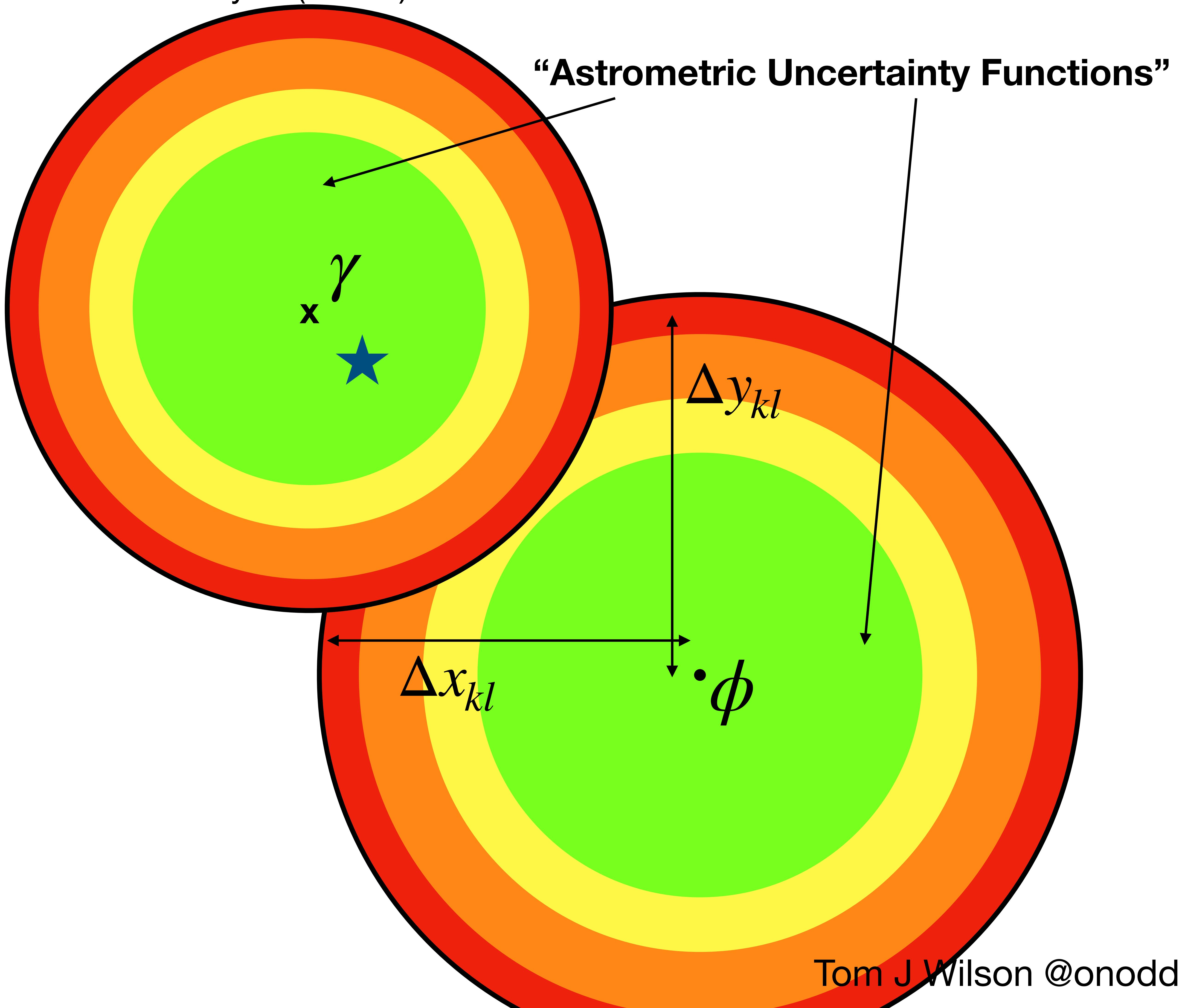


Wilson & Naylor (2018b)

Wilson & Naylor (2018a)



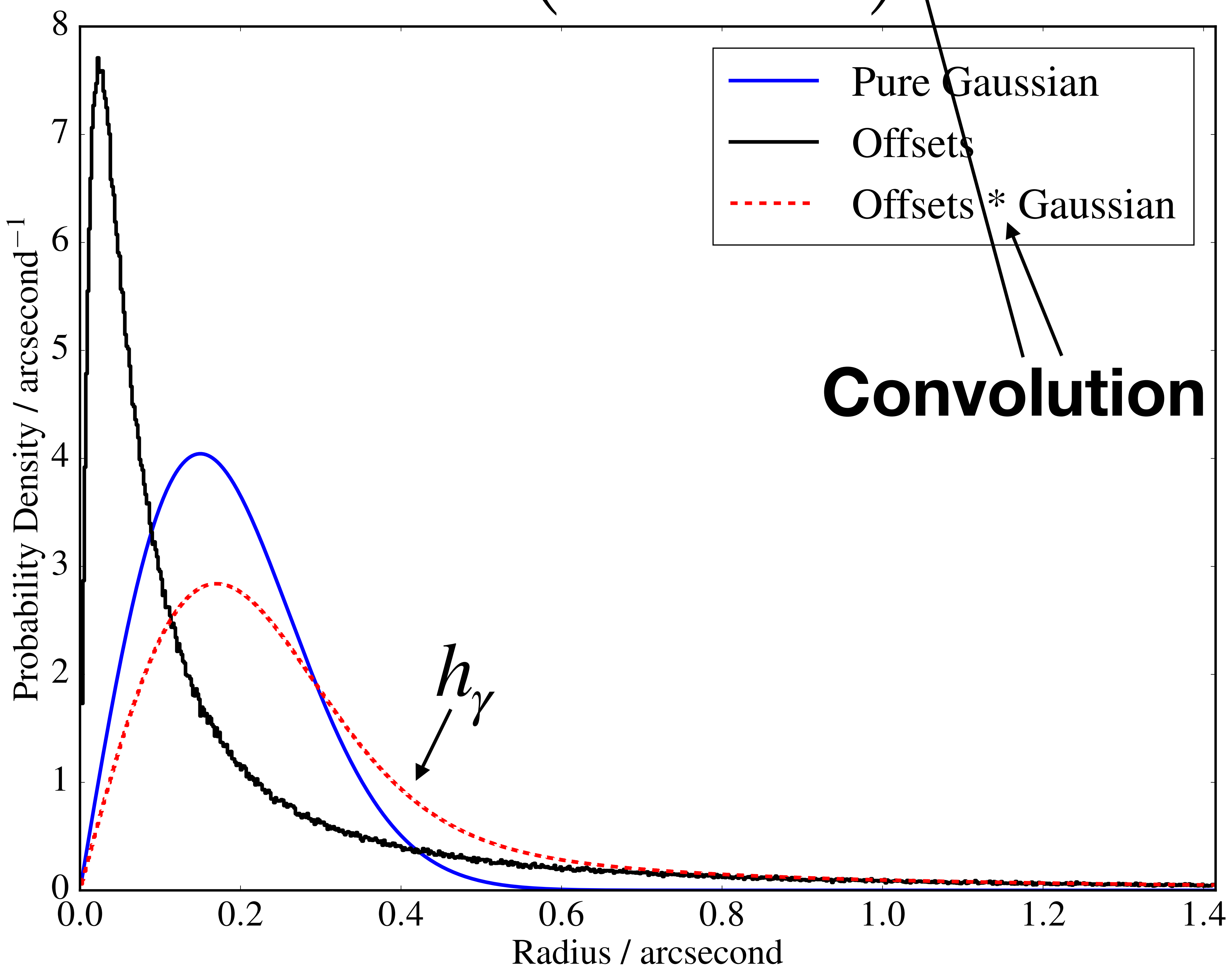
Tom J Wilson @onoddil

Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

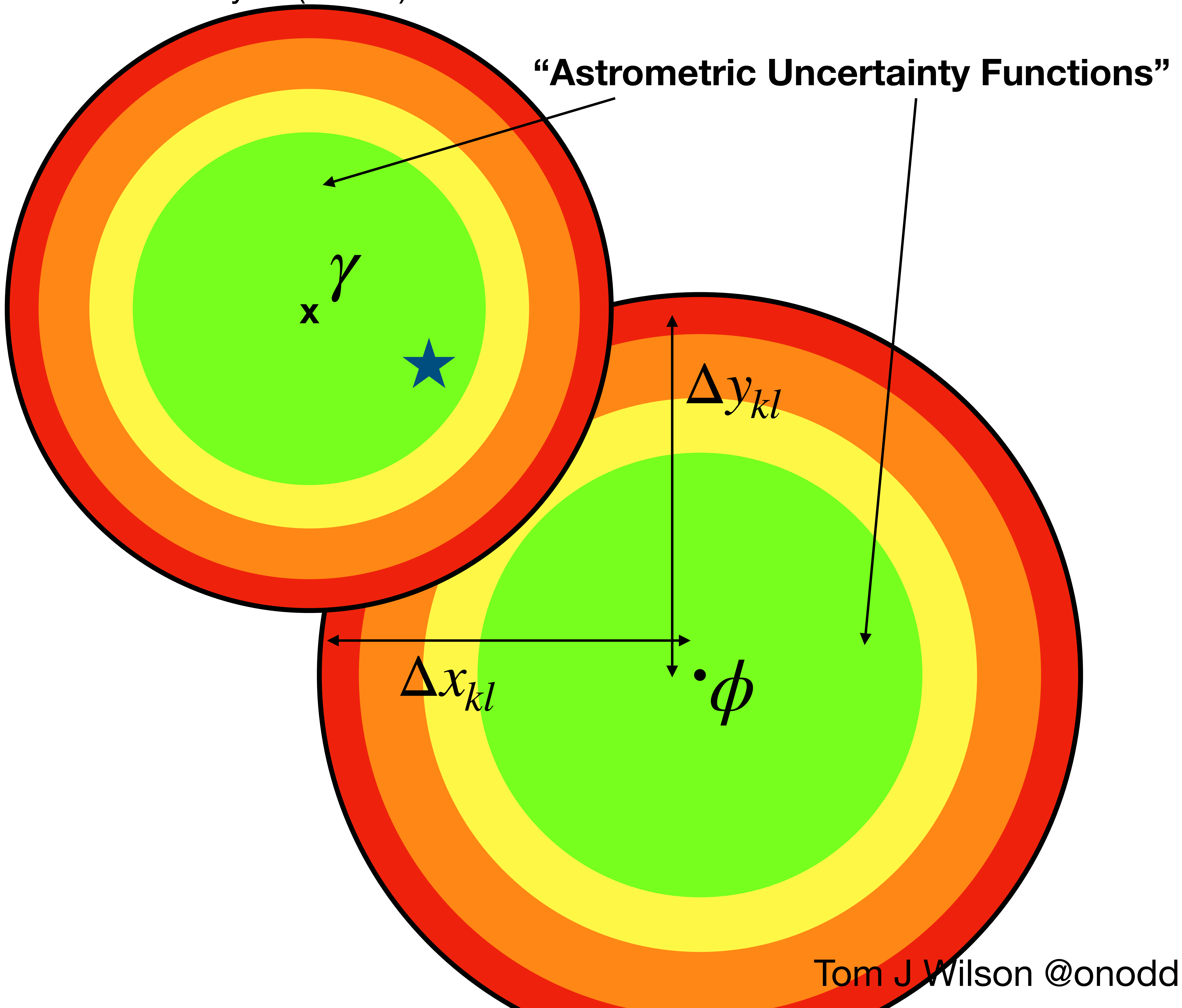
$$= N_\mathrm{c} \times (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl})$$

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



Wilson & Naylor (2018b)

Wilson & Naylor (2018a)



Tom J Wilson @onoddil

Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

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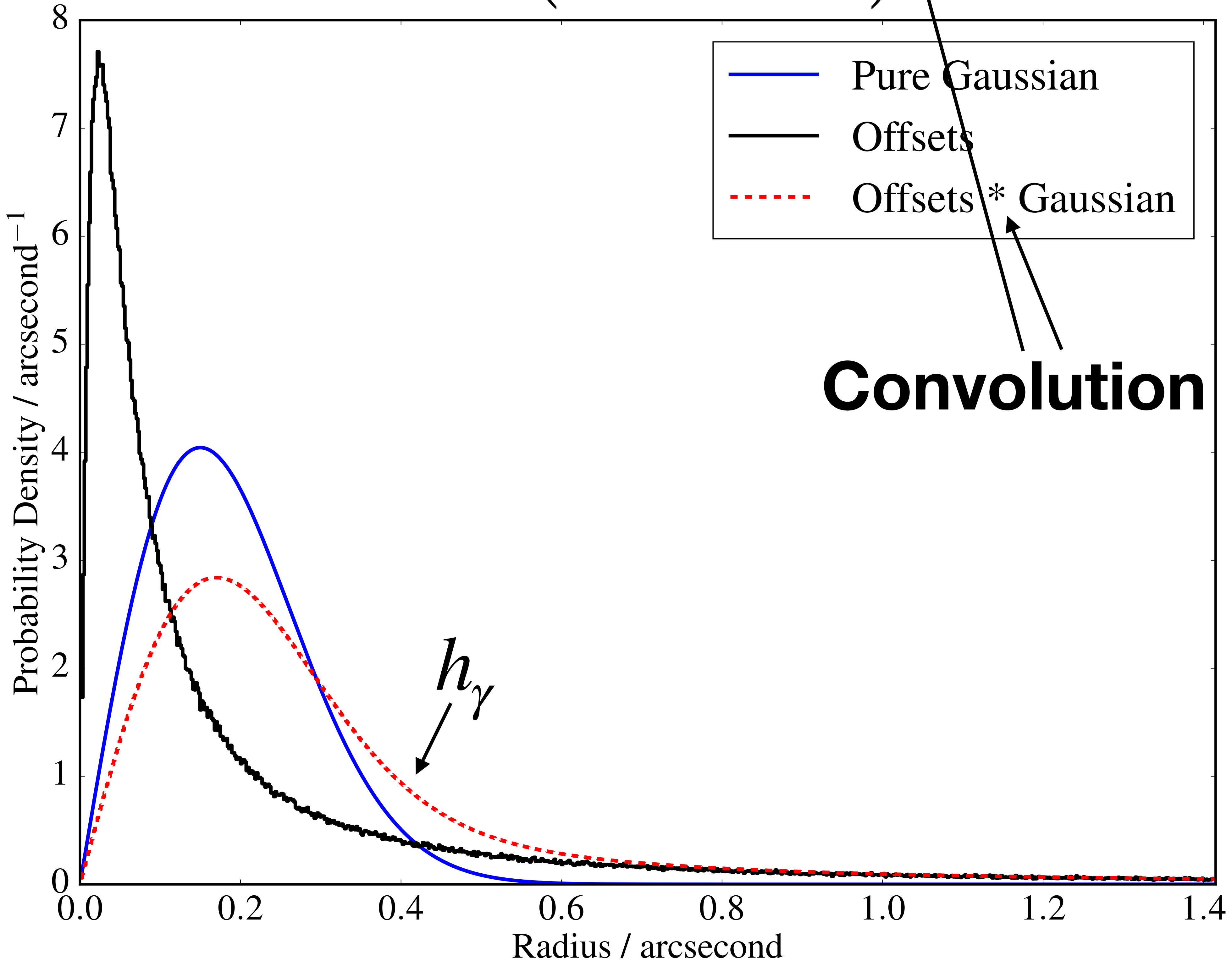
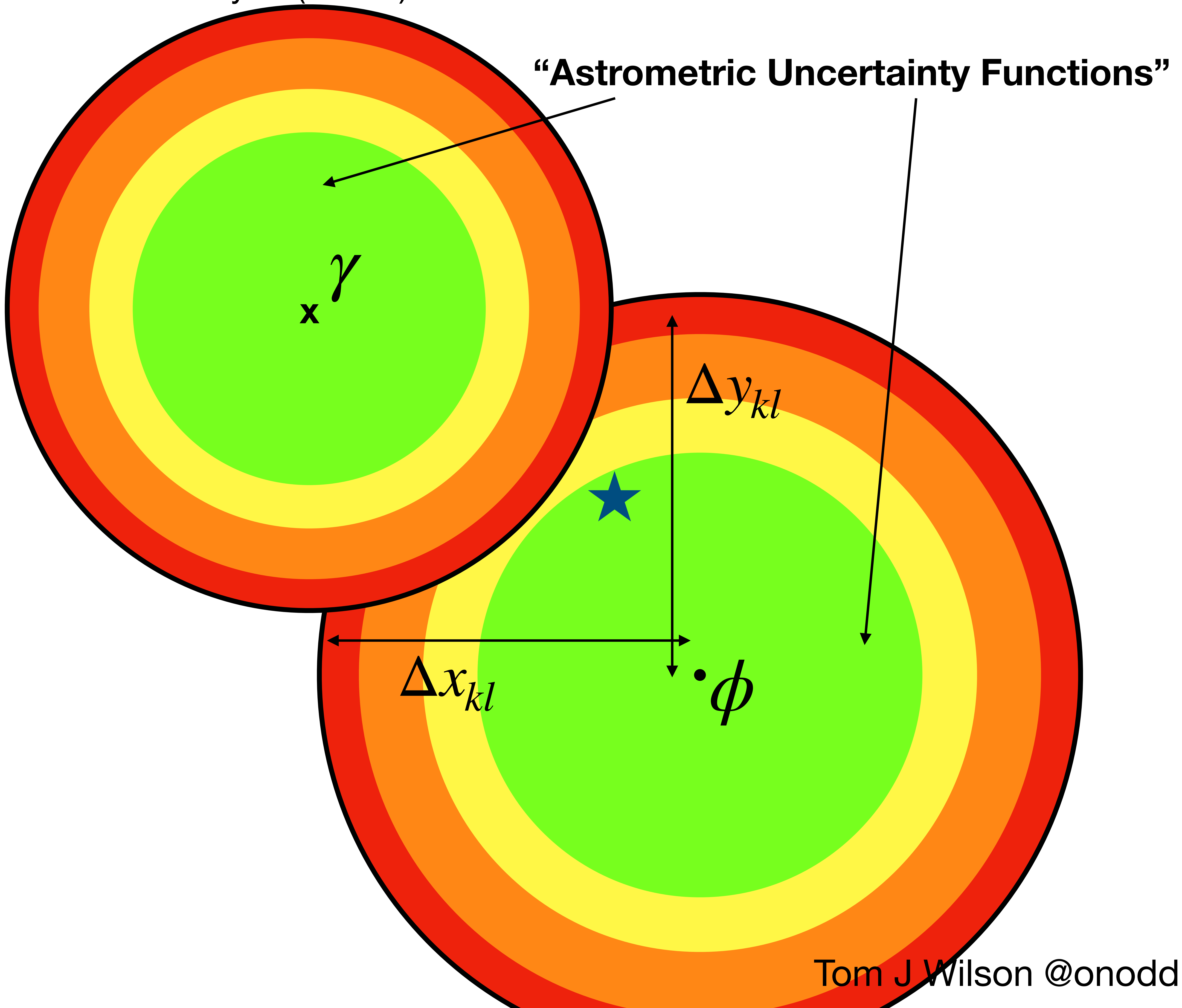


Wilson & Naylor (2018b)

Wilson & Naylor (2018a)



Tom J Wilson @onoddil

Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$
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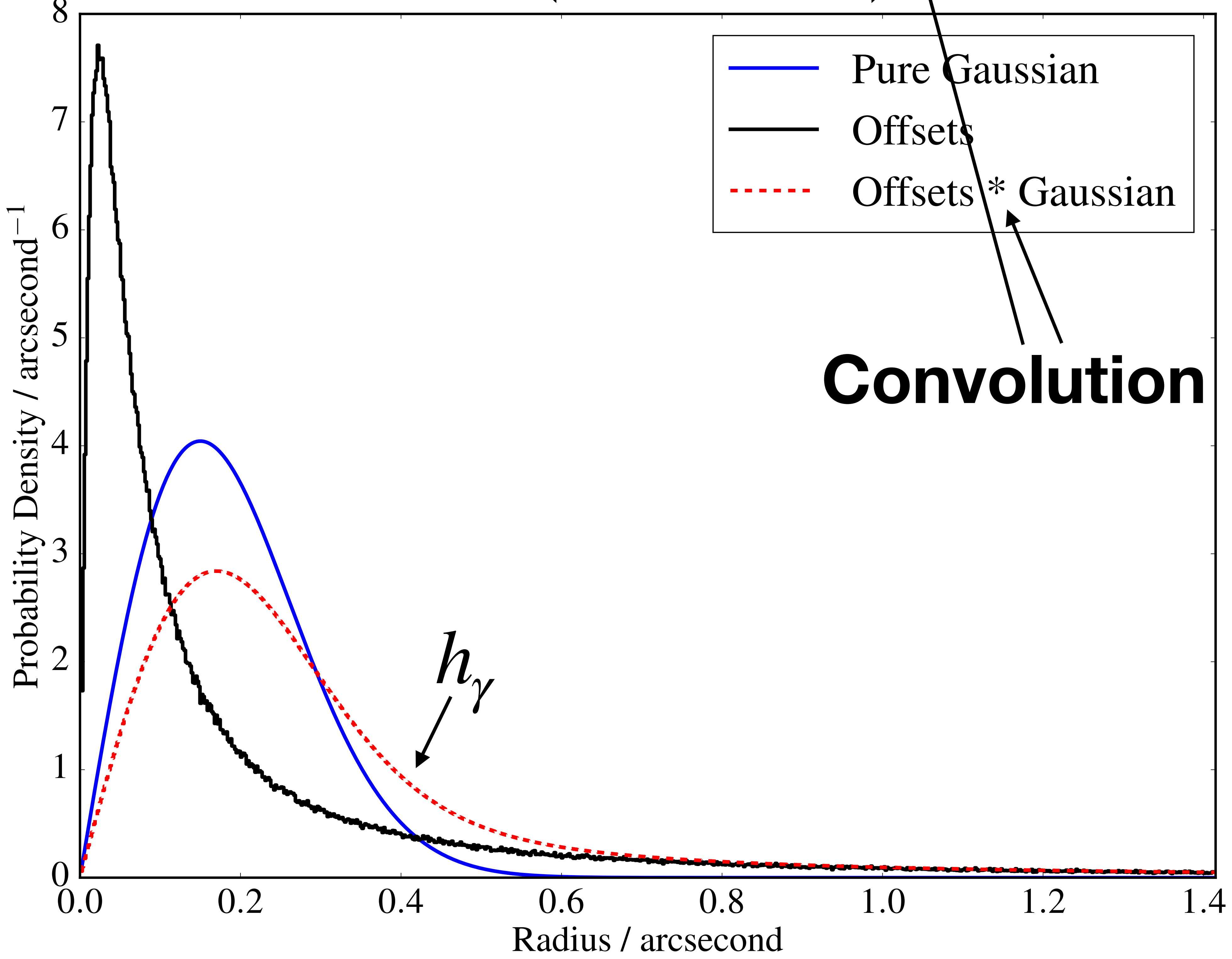
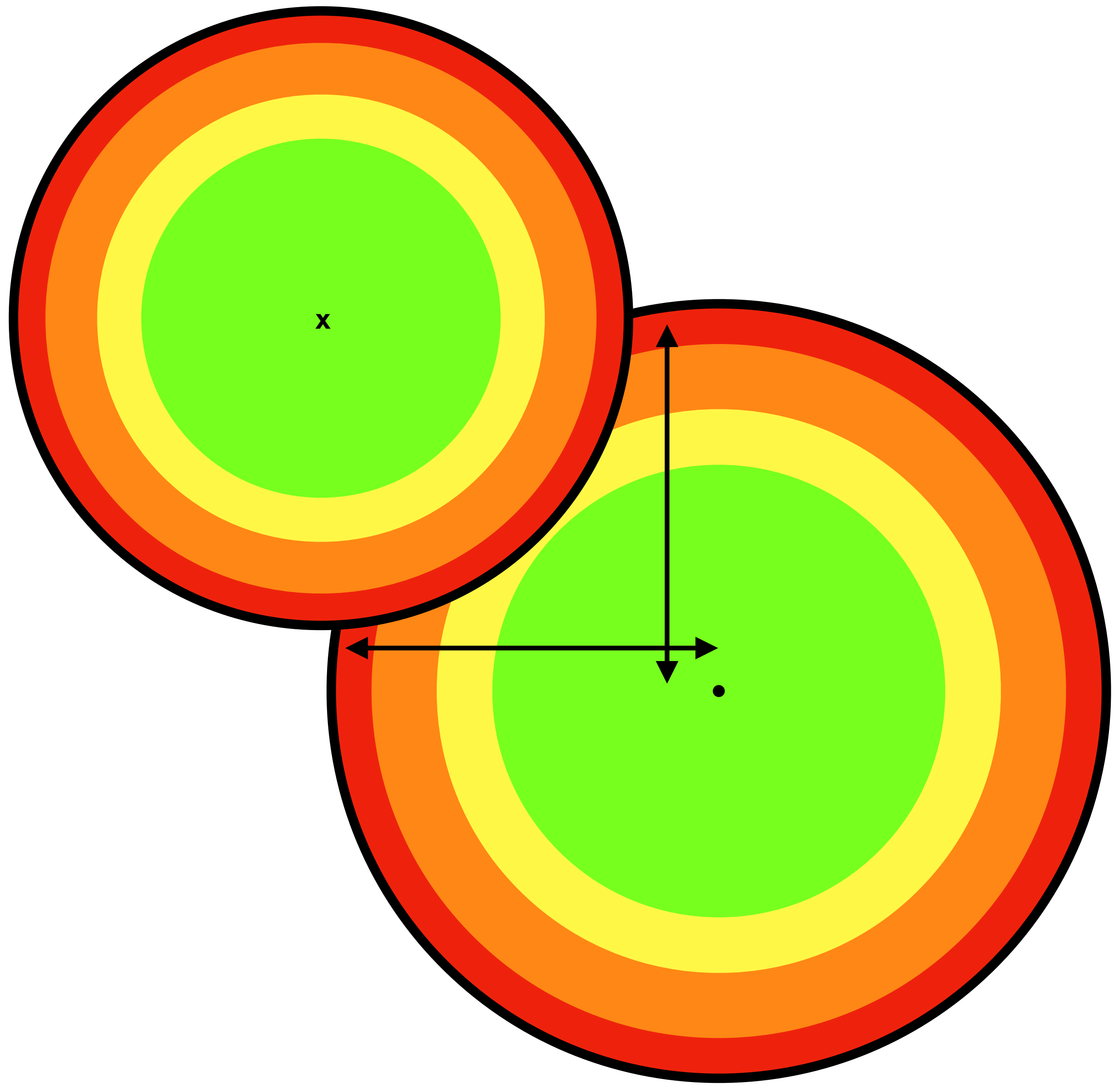
Convolution



Wilson & Naylor (2018b)

Wilson & Naylor (2018a)



“Were the succession of stars endless... there could be absolutely no point, in all that background, at which would not exist a star.”
— Edgar Allan Poe, Eureka (1848)

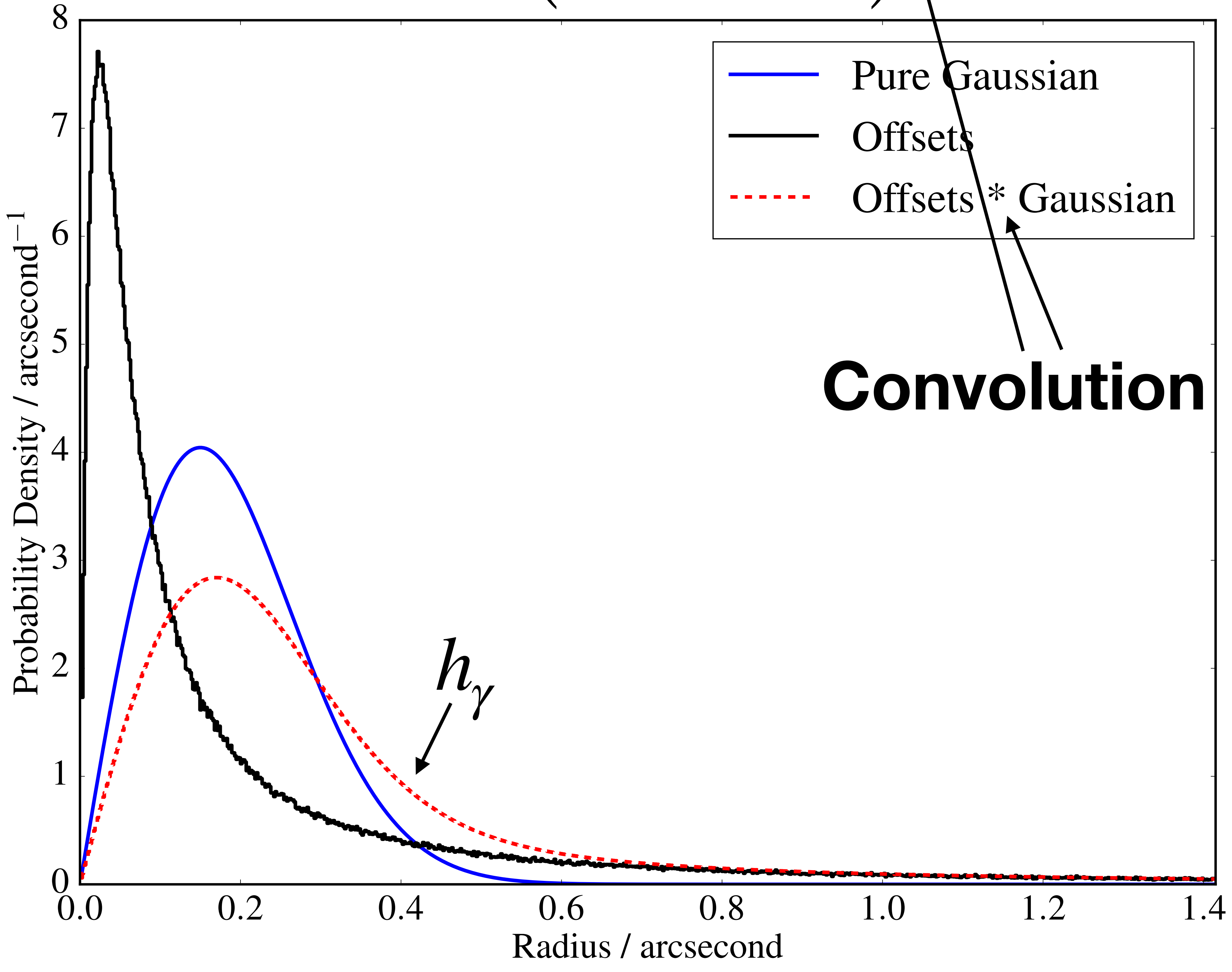
Tom J Wilson @onoddil

Separation Likelihood Function

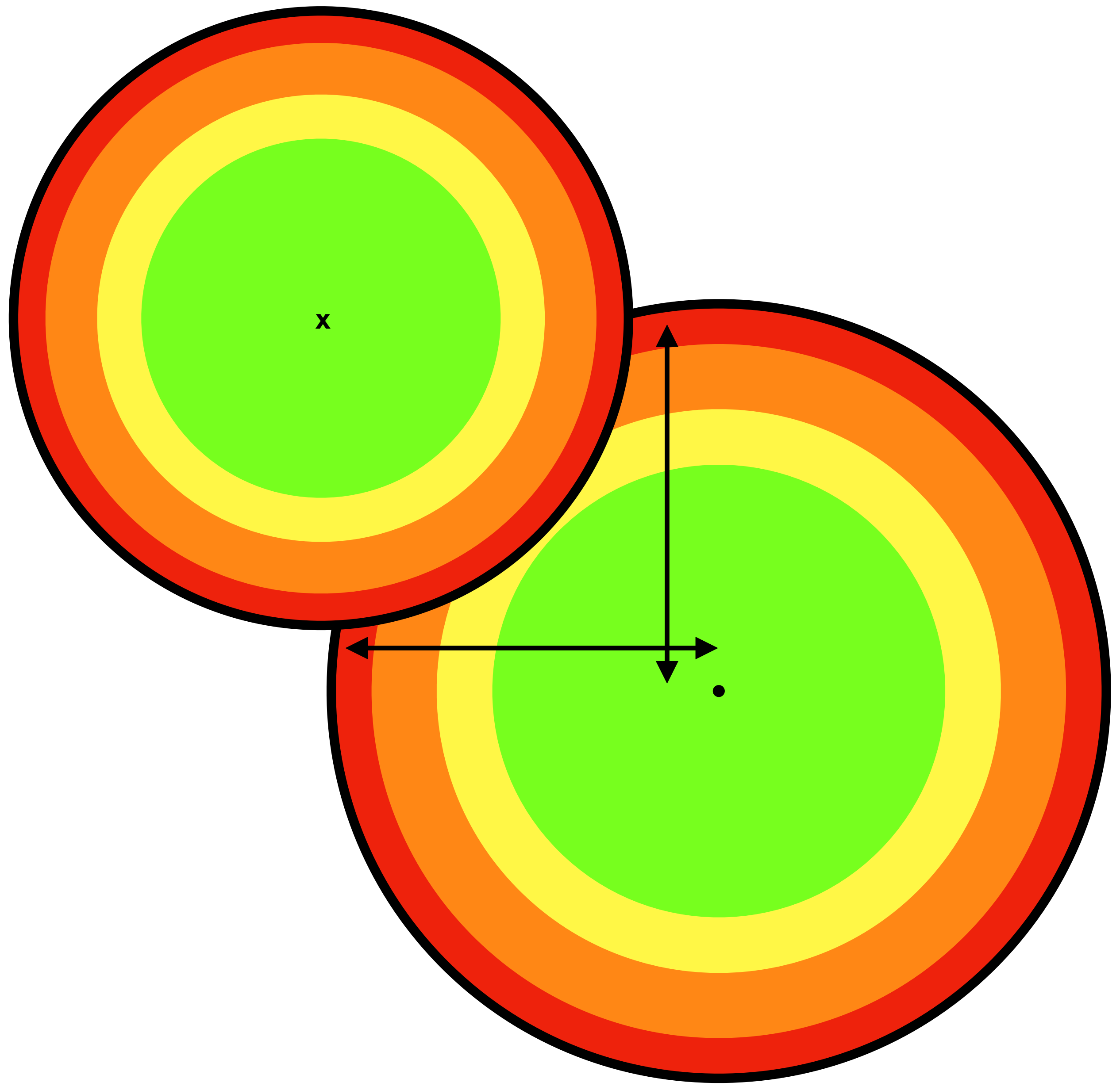
$$g(x_k, y_k, x_l, y_l) = \iint\limits_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$
$$= N_\mathrm{c} \times (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl})$$

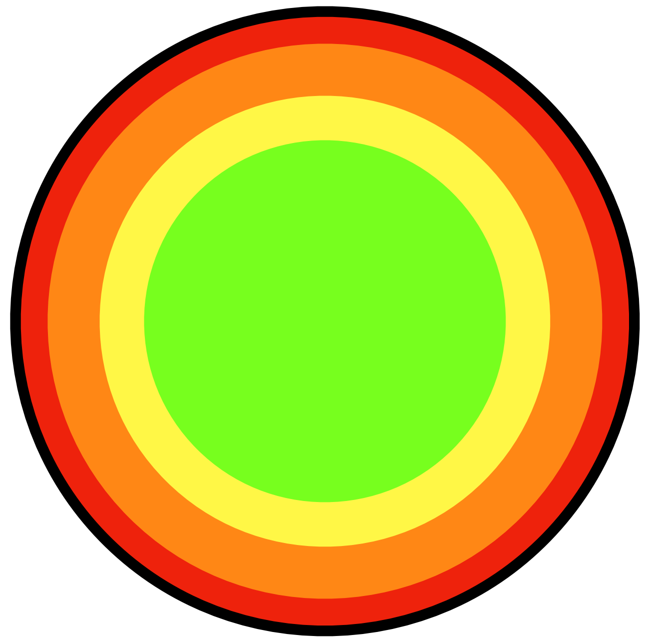
Wilson & Naylor (2018a)

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



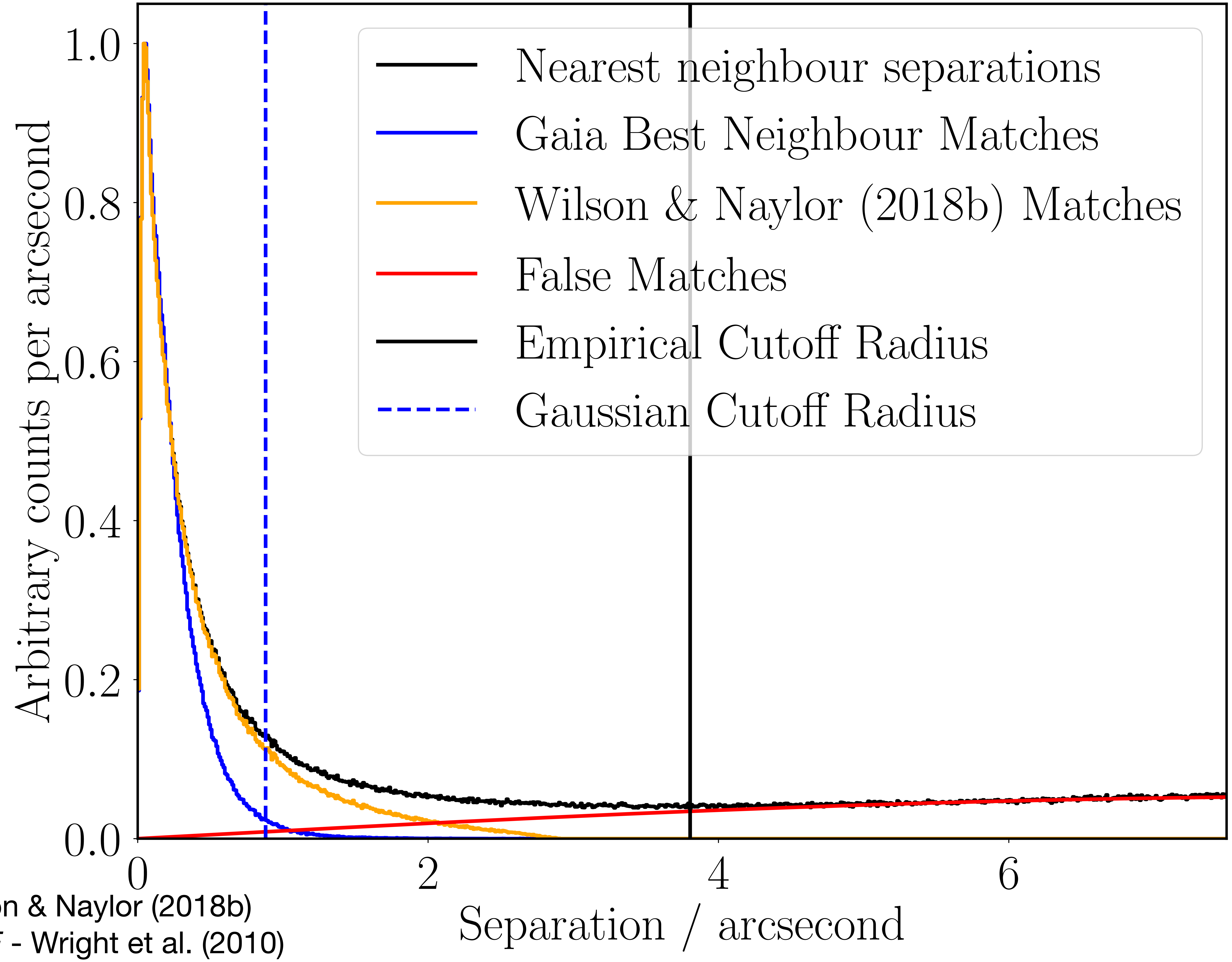
Wilson & Naylor (2018b)

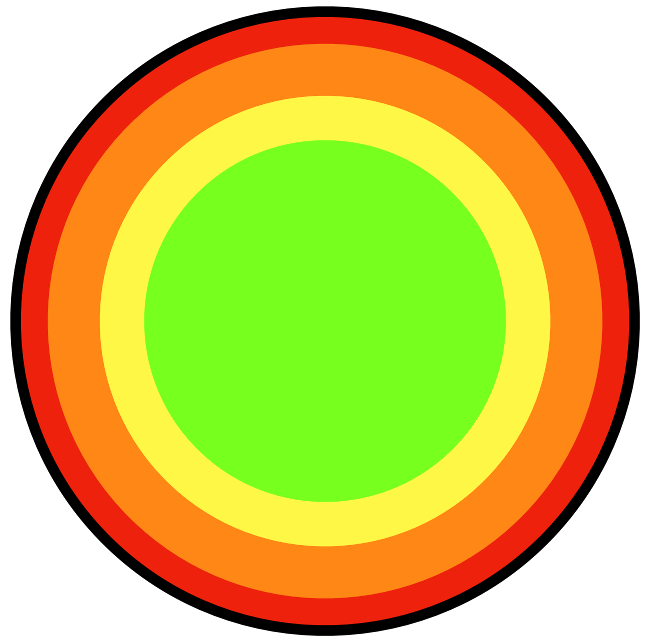




The AUF does not need to, and in fact quite often <u>should *not*</u>, be Gaussian!

Match Separations

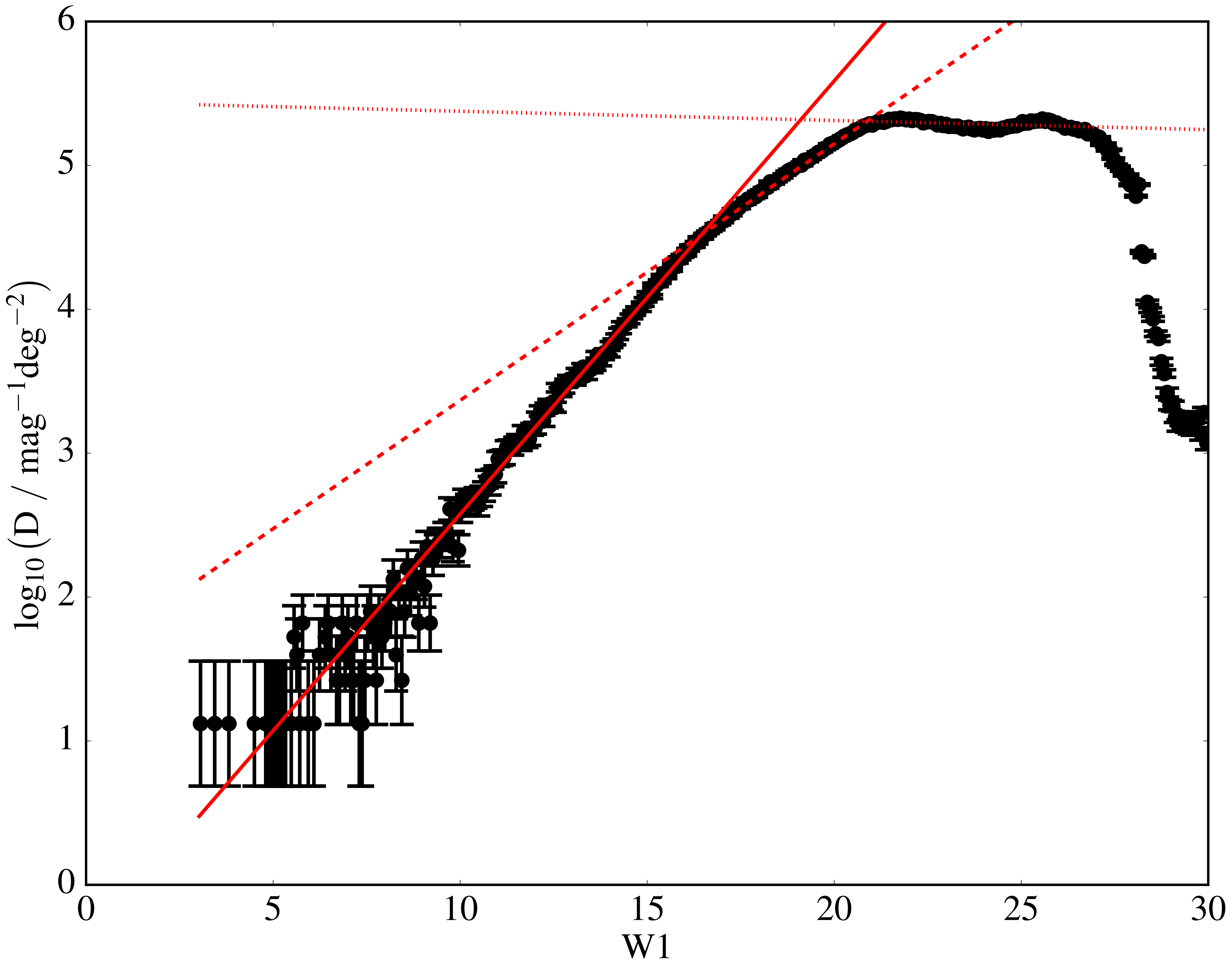




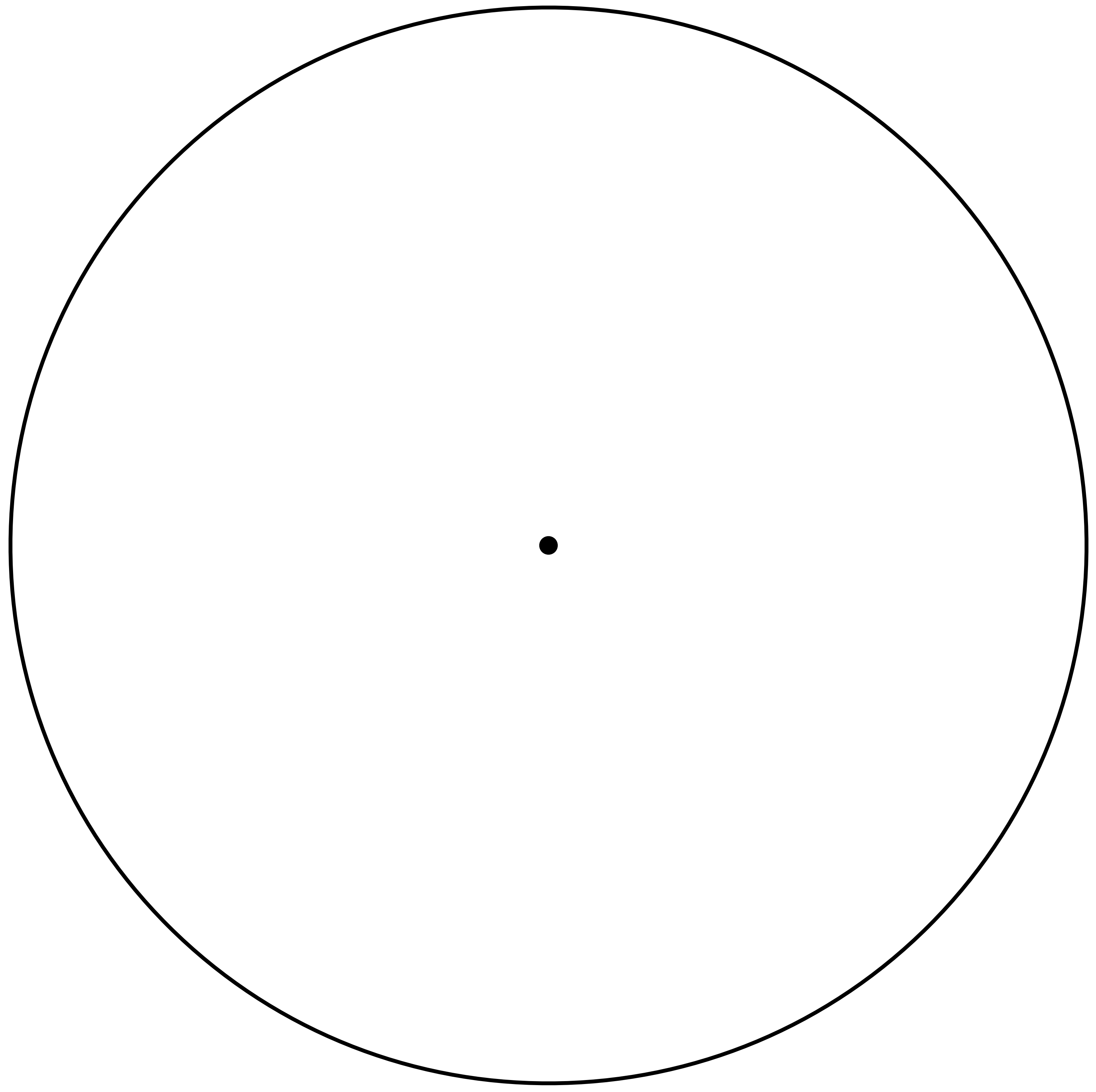
The AUF does not need to, and in fact quite often <u>should *not*</u>, be Gaussian!

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)

Building Empirical AUFs



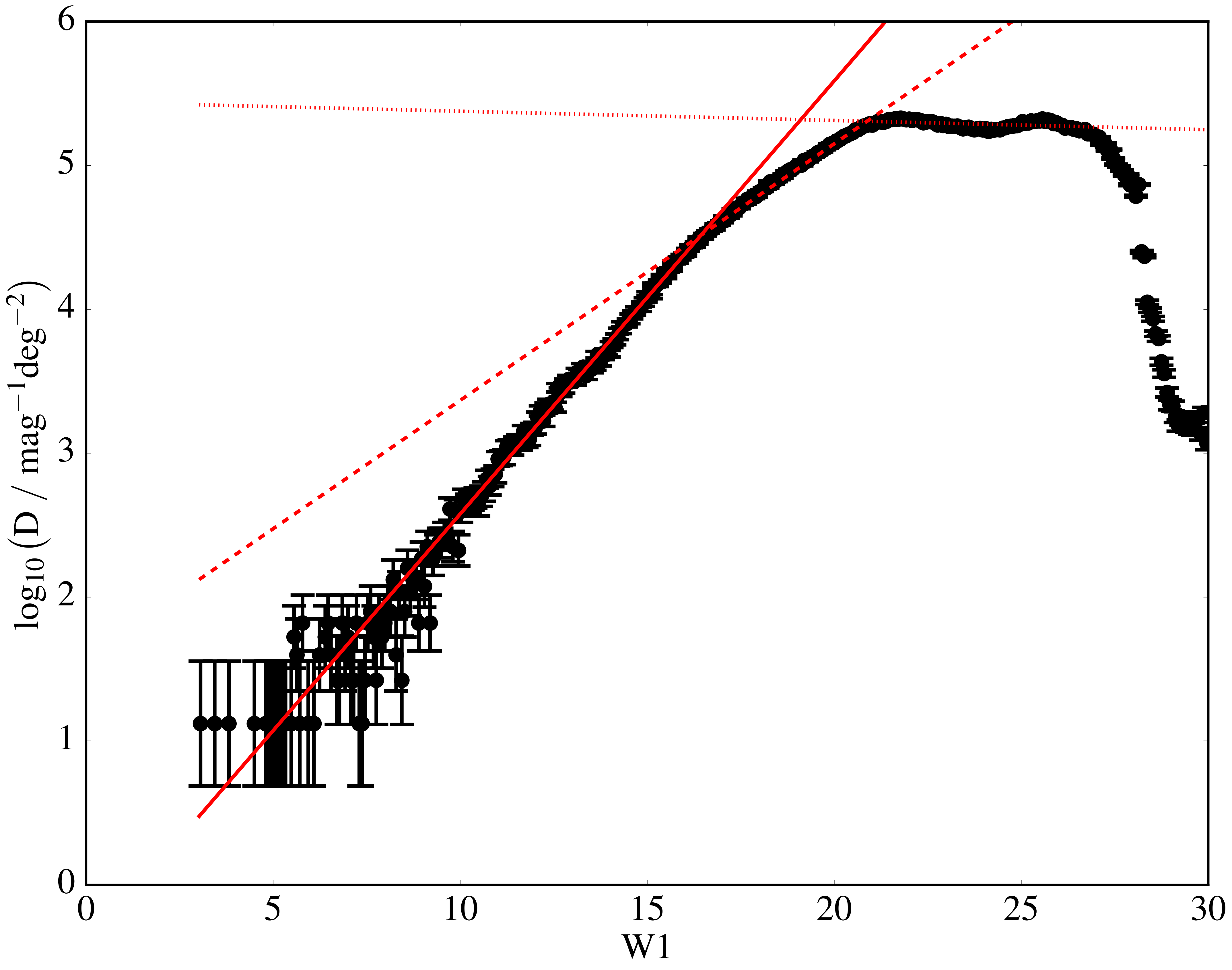
PSF radius ~ 1.2 FWHM (Rayleigh criterion)



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

Tom J Wilson @onoddil

Building Empirical AUFs



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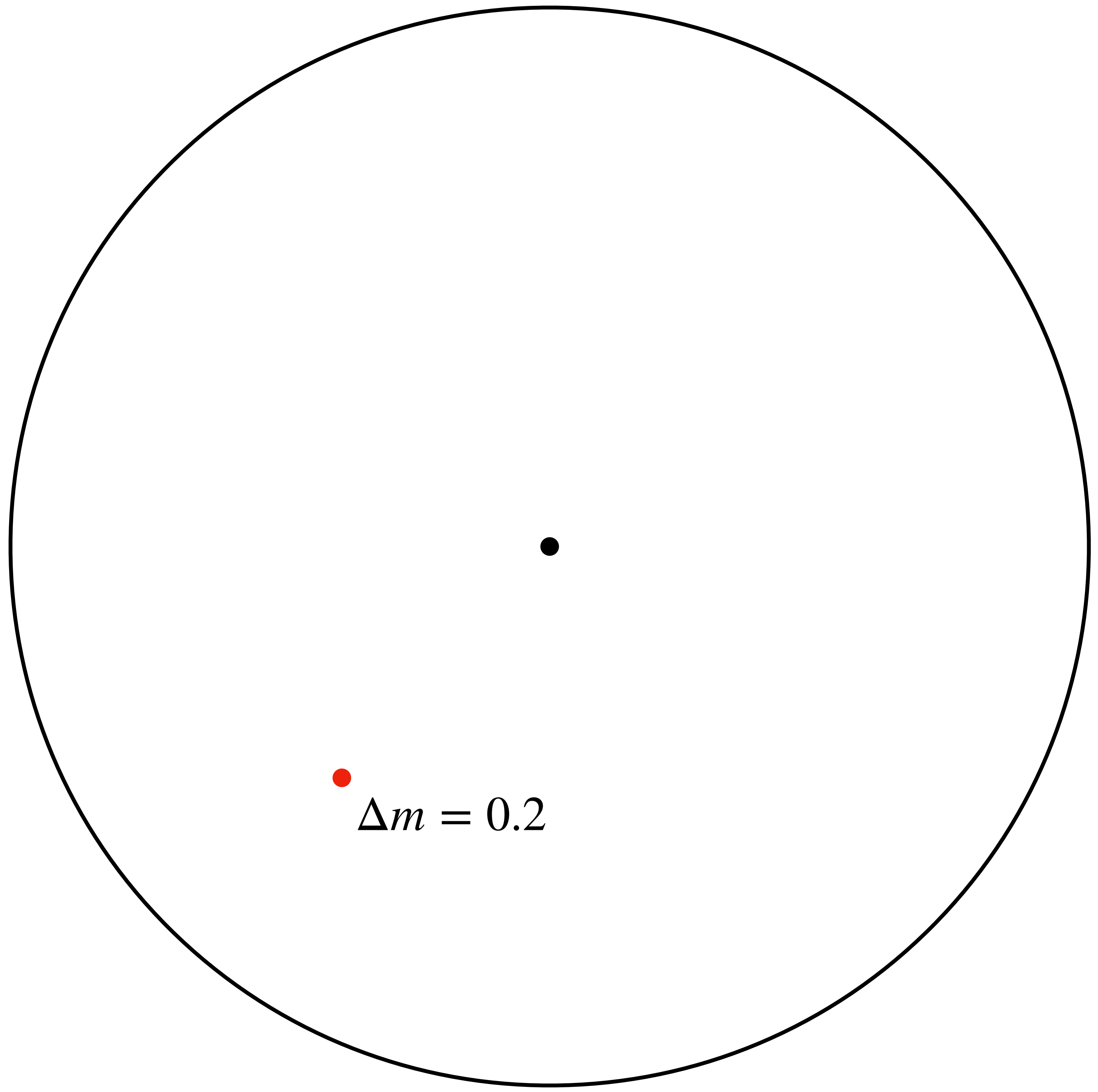
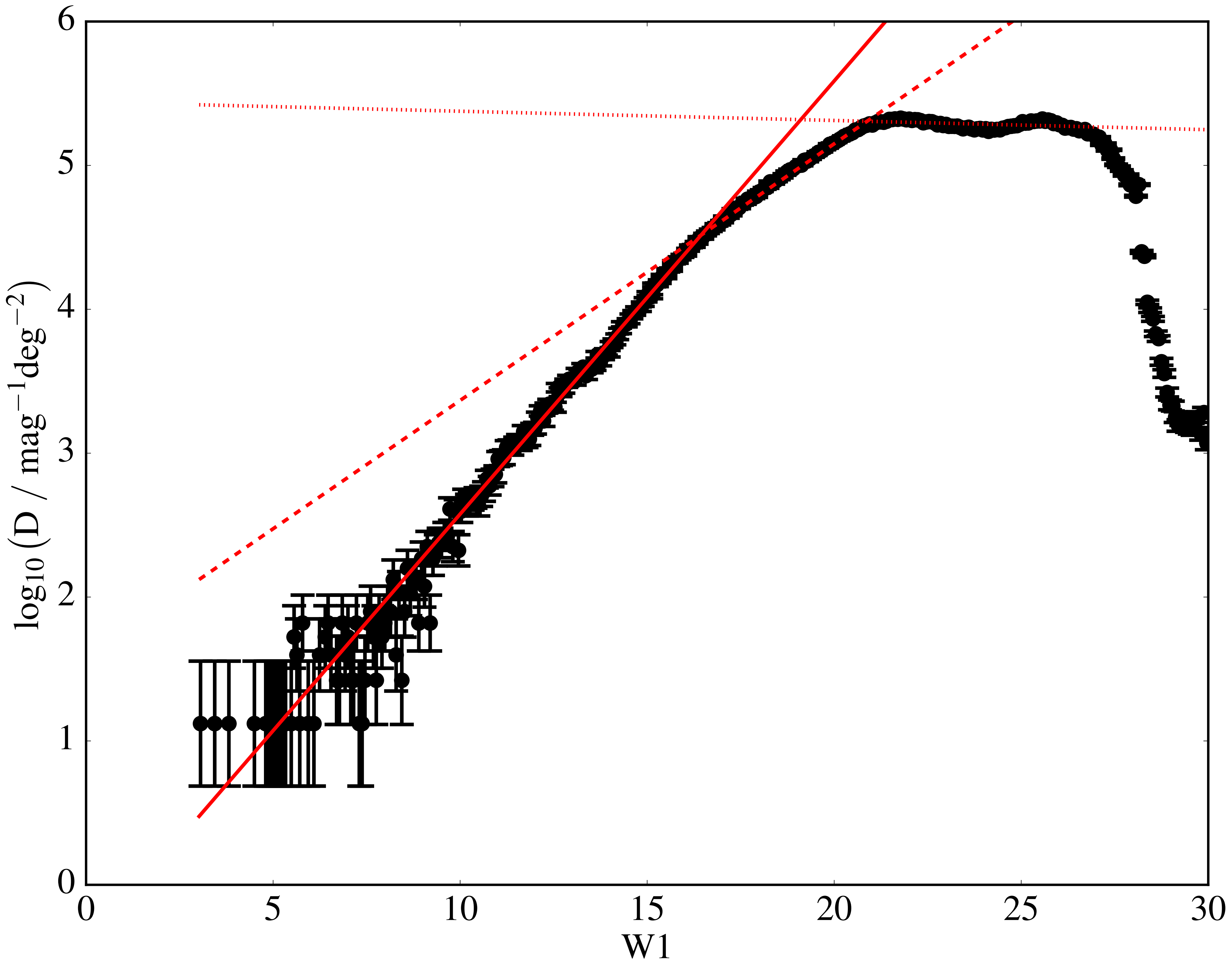


Wilson & Naylor (2018b)
TRILEGAL - Girardi et al. (2005)

Tom J Wilson @onoddil

Building Empirical AUFs



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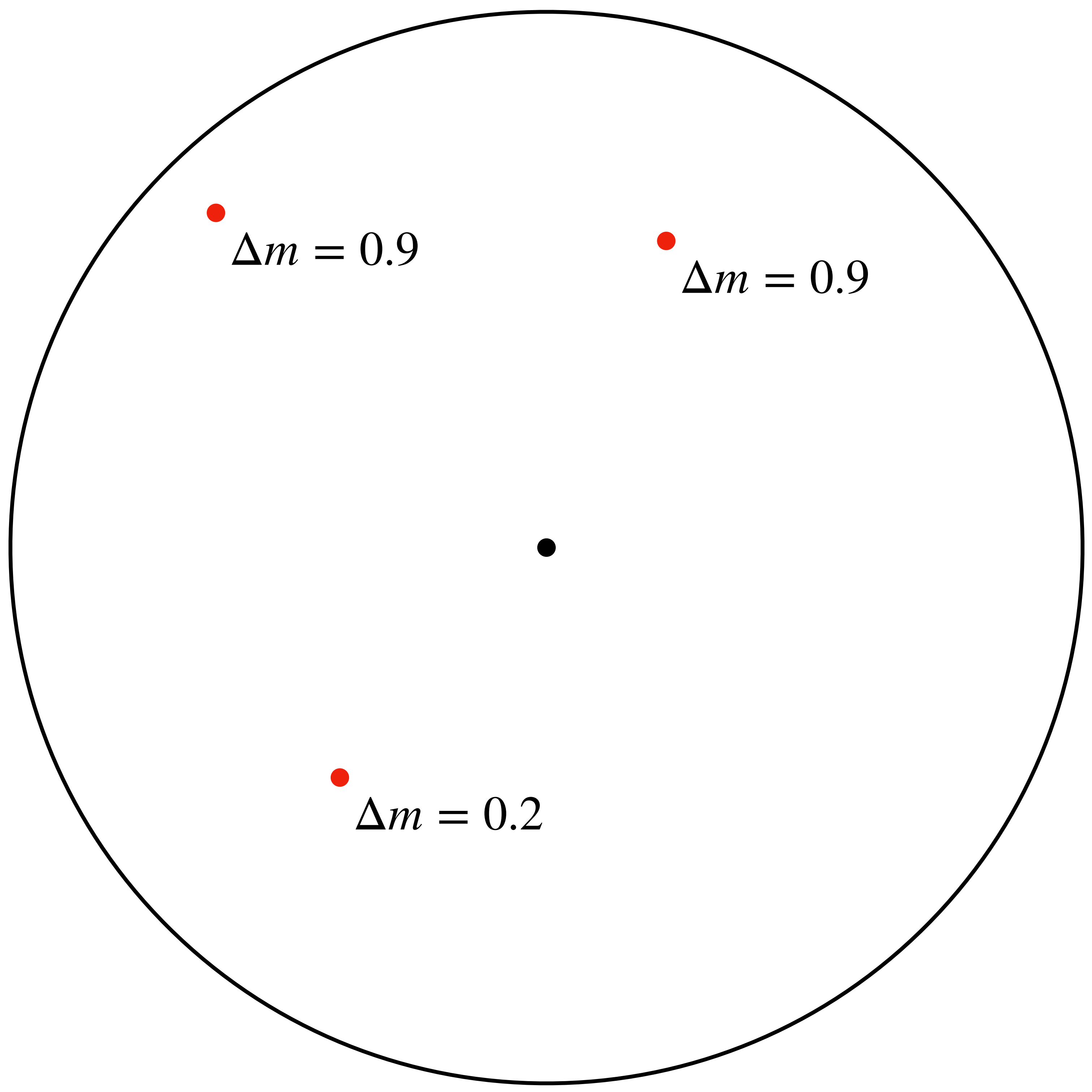
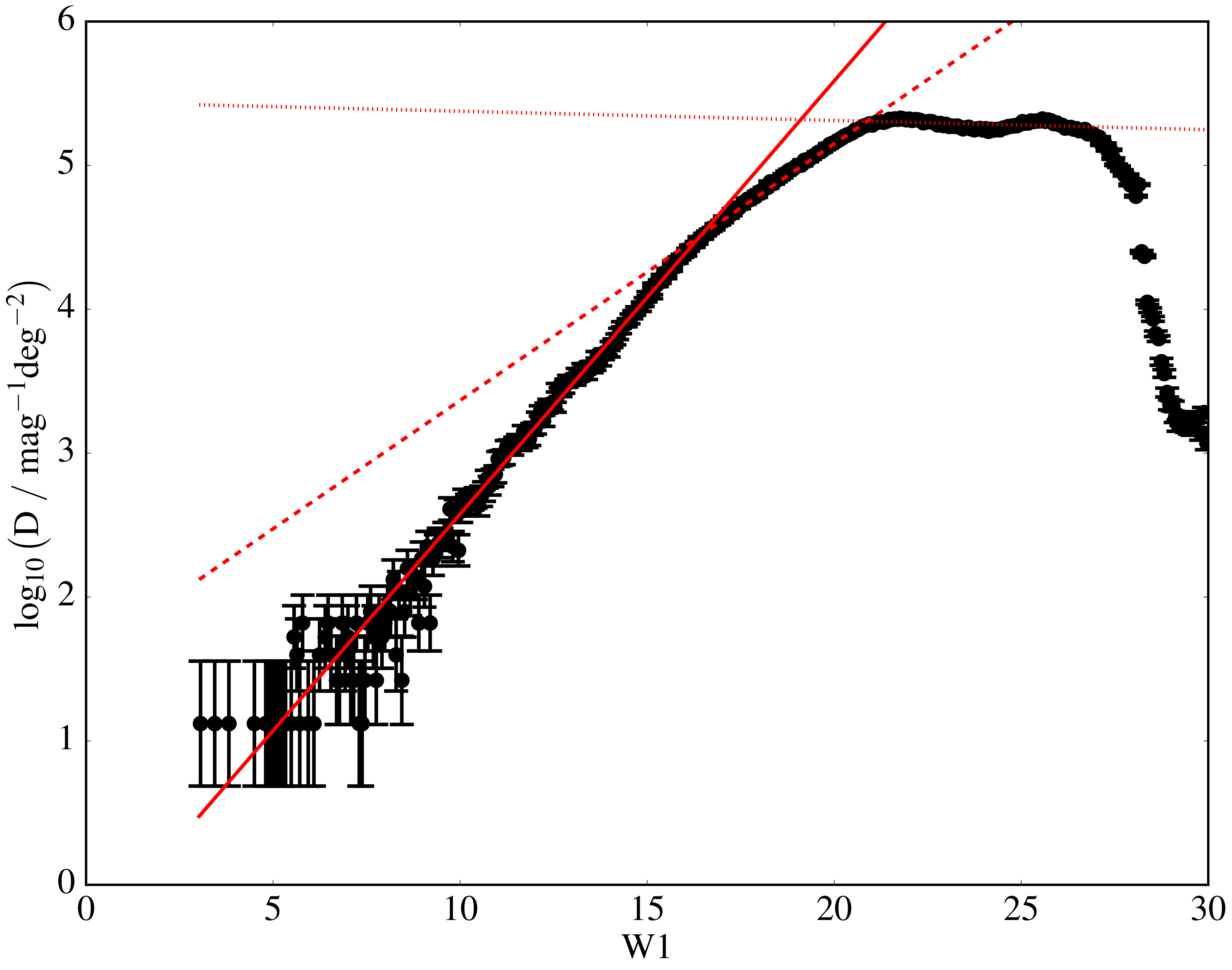


Wilson & Naylor (2018b)
TRILEGAL - Girardi et al. (2005)

Building Empirical AUFs



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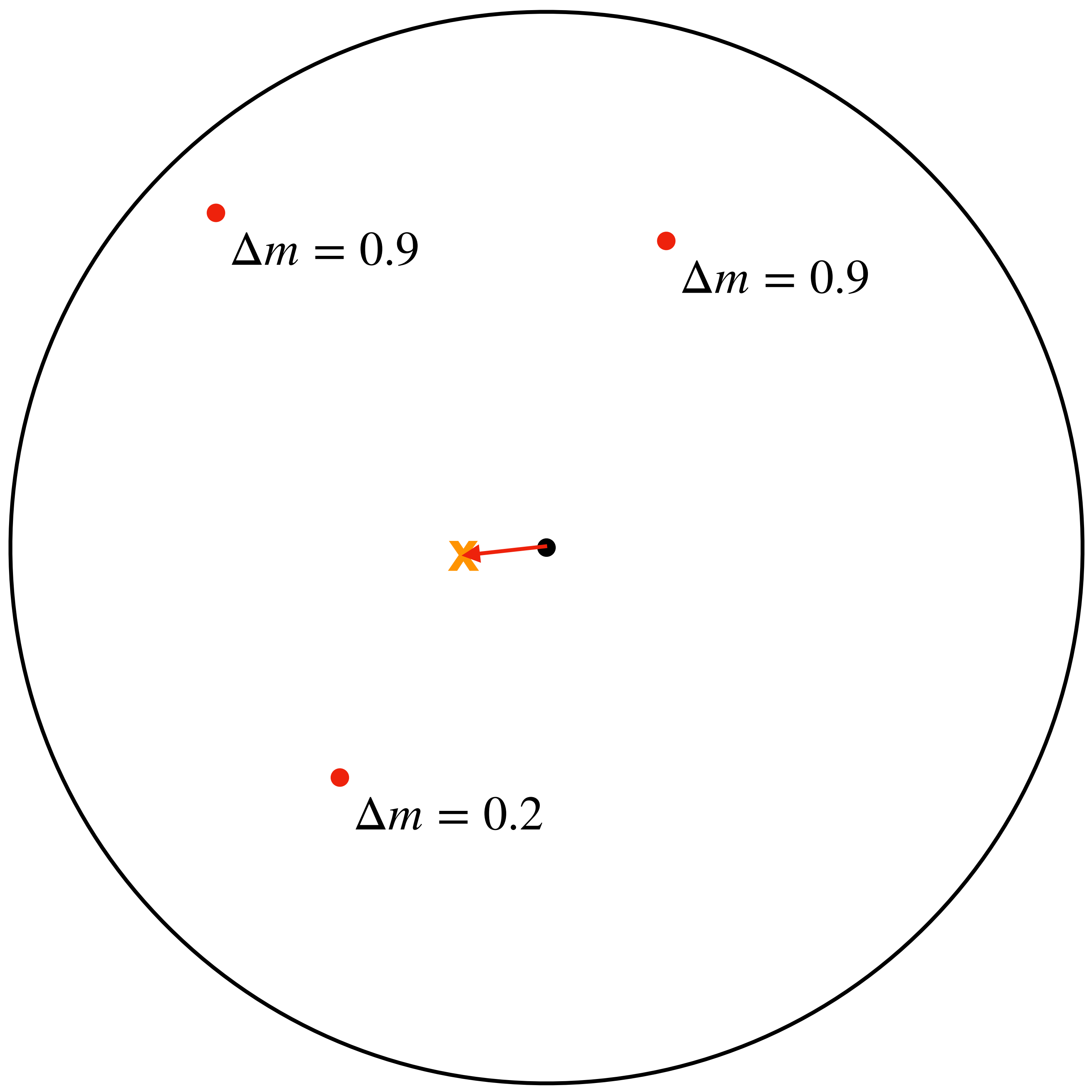
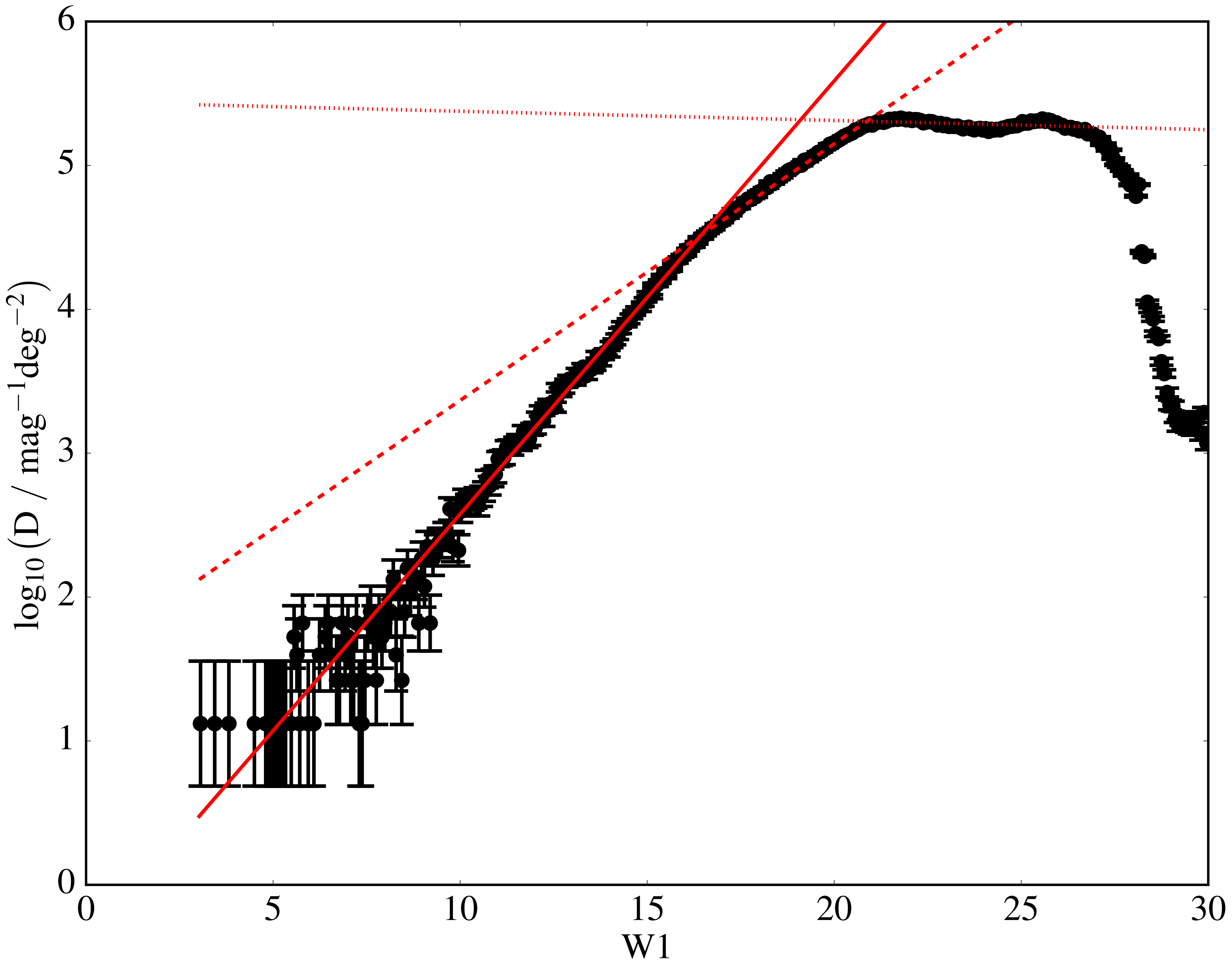
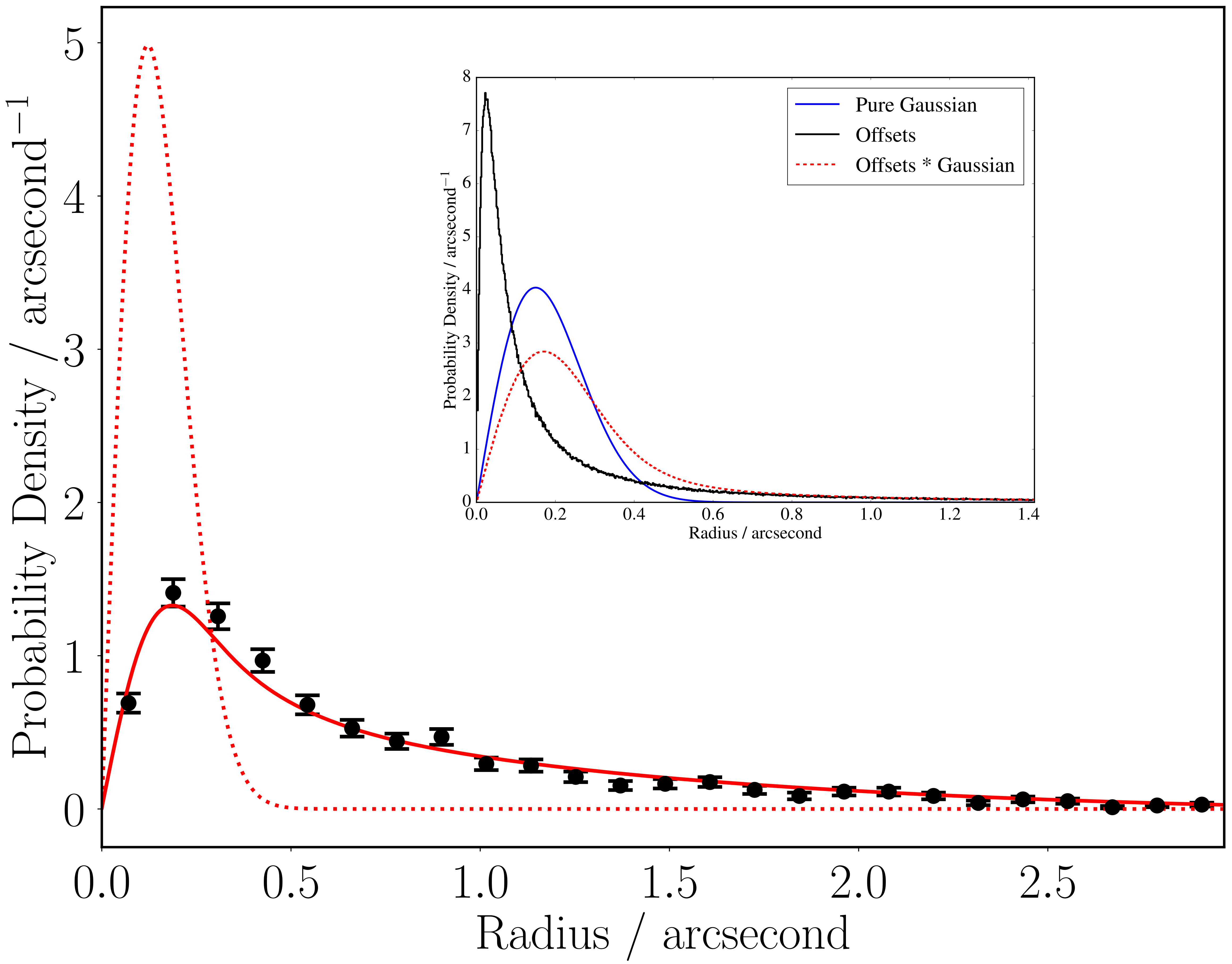


Wilson & Naylor (2018b)
TRILEGAL - Girardi et al. (2005)

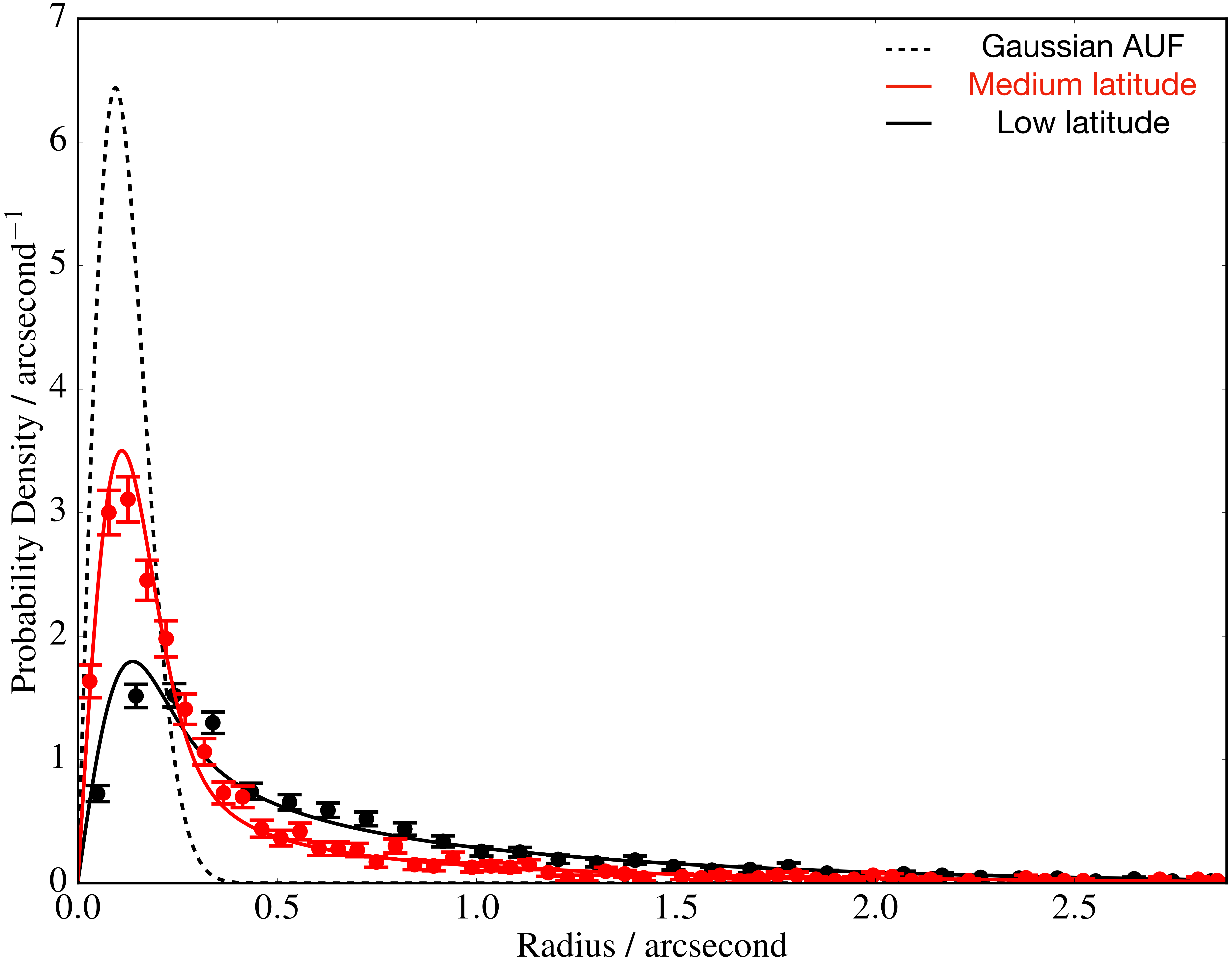
Building Empirical AUFs



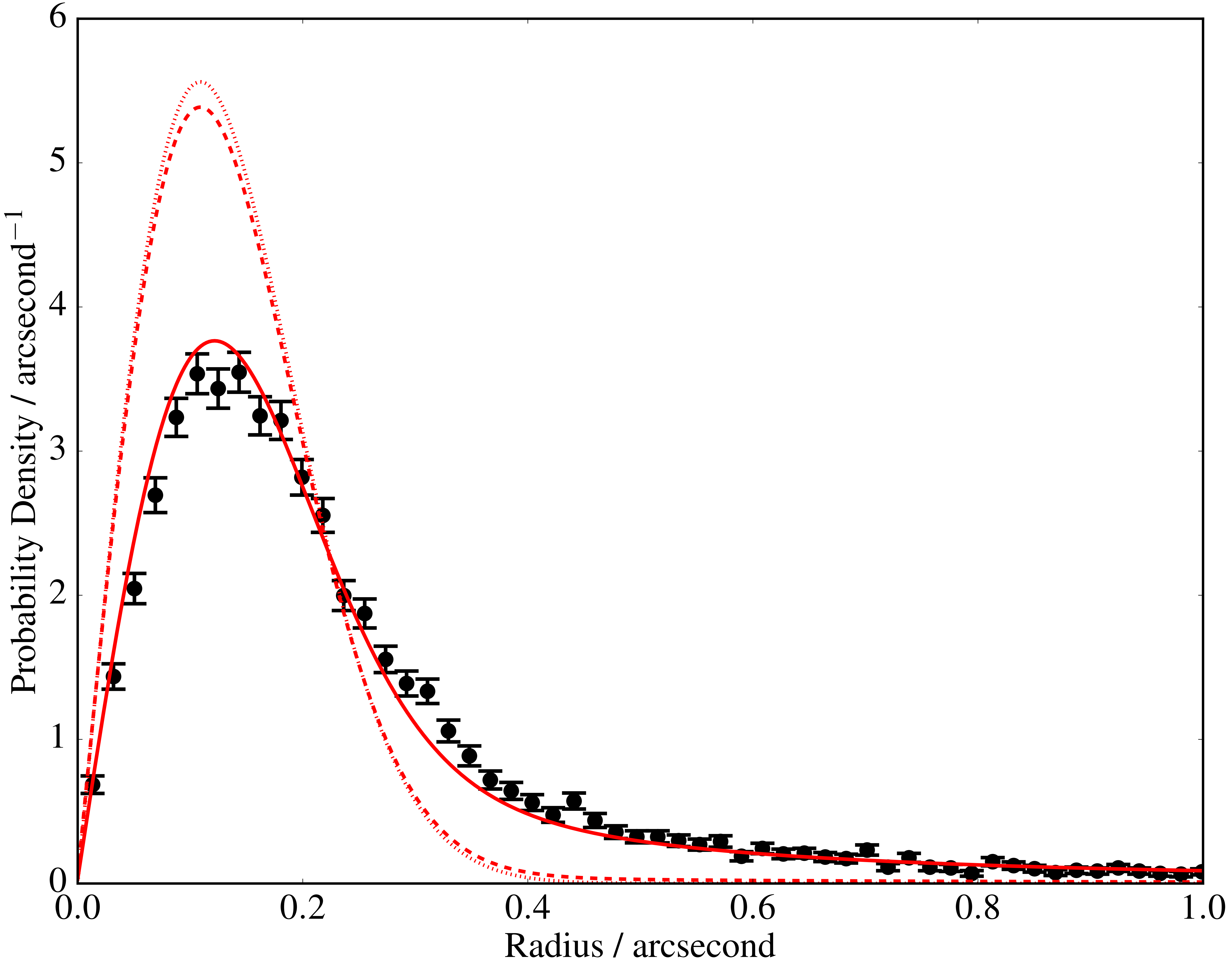


Wilson & Naylor (2018b)
TRILEGAL - Girardi et al. (2005)

Crowding Normalisation



Extra-galactic Effects of Crowding



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

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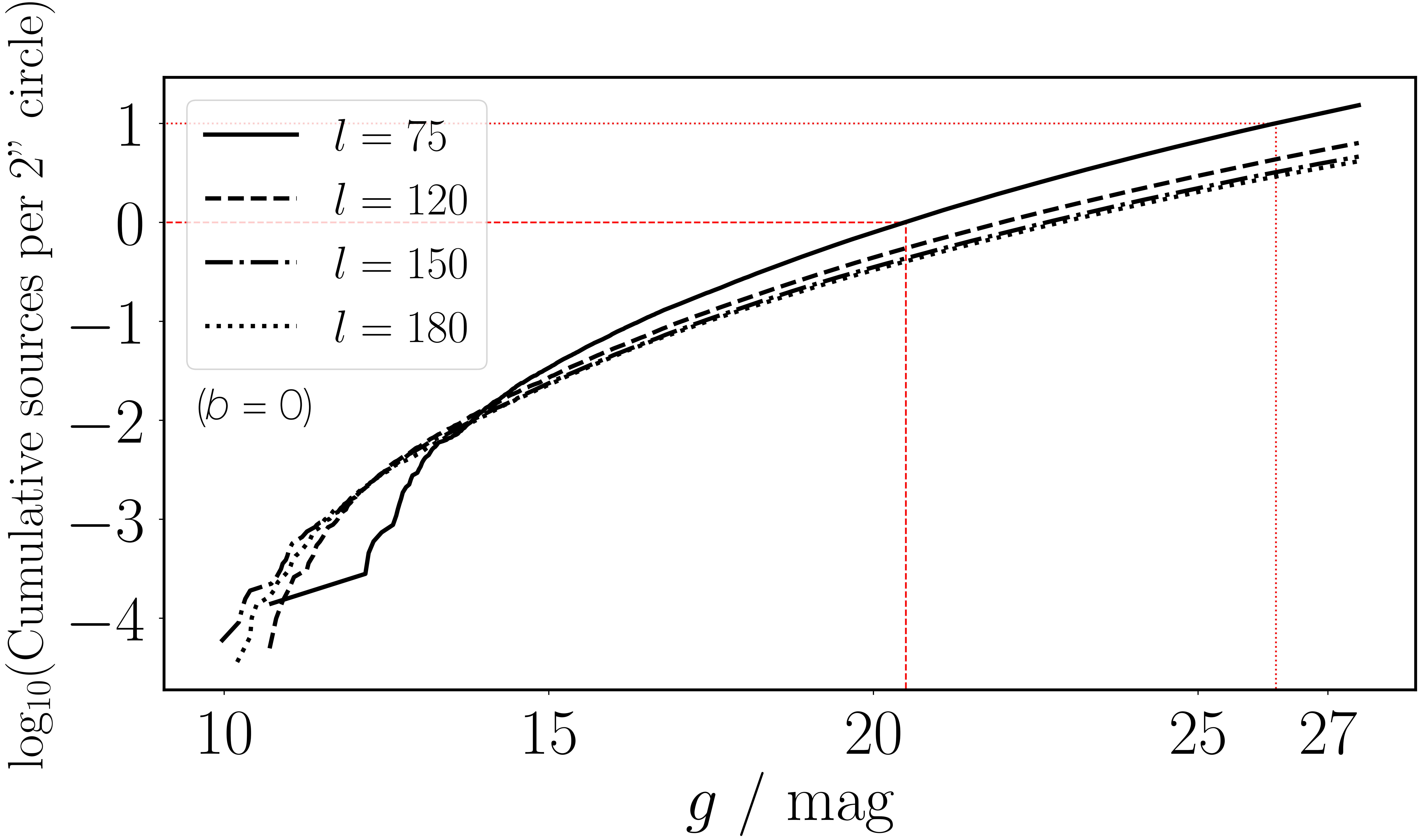
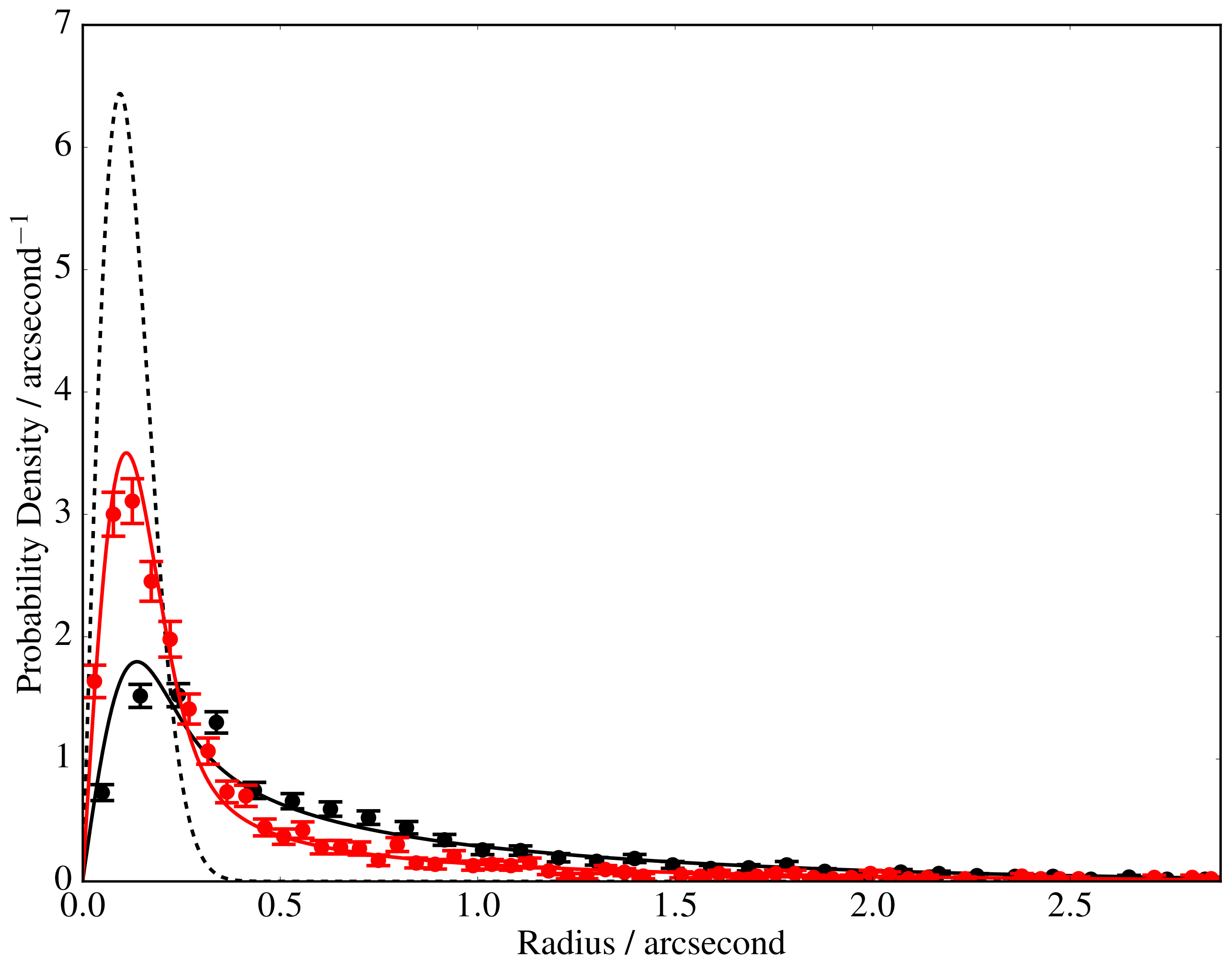
Vera C. Rubin Observatory's LSST





TRILEGAL - Girardi et al. (2005)

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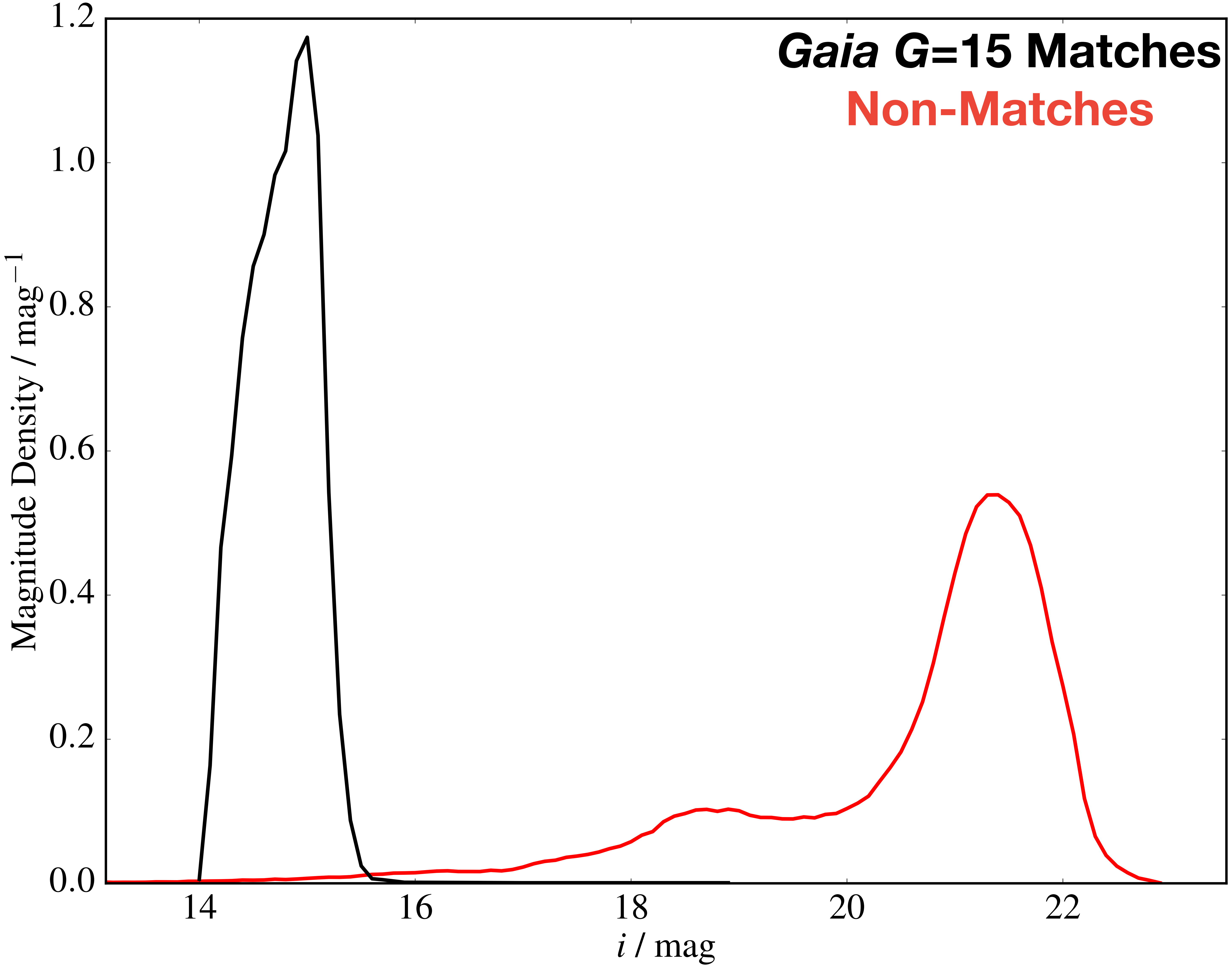
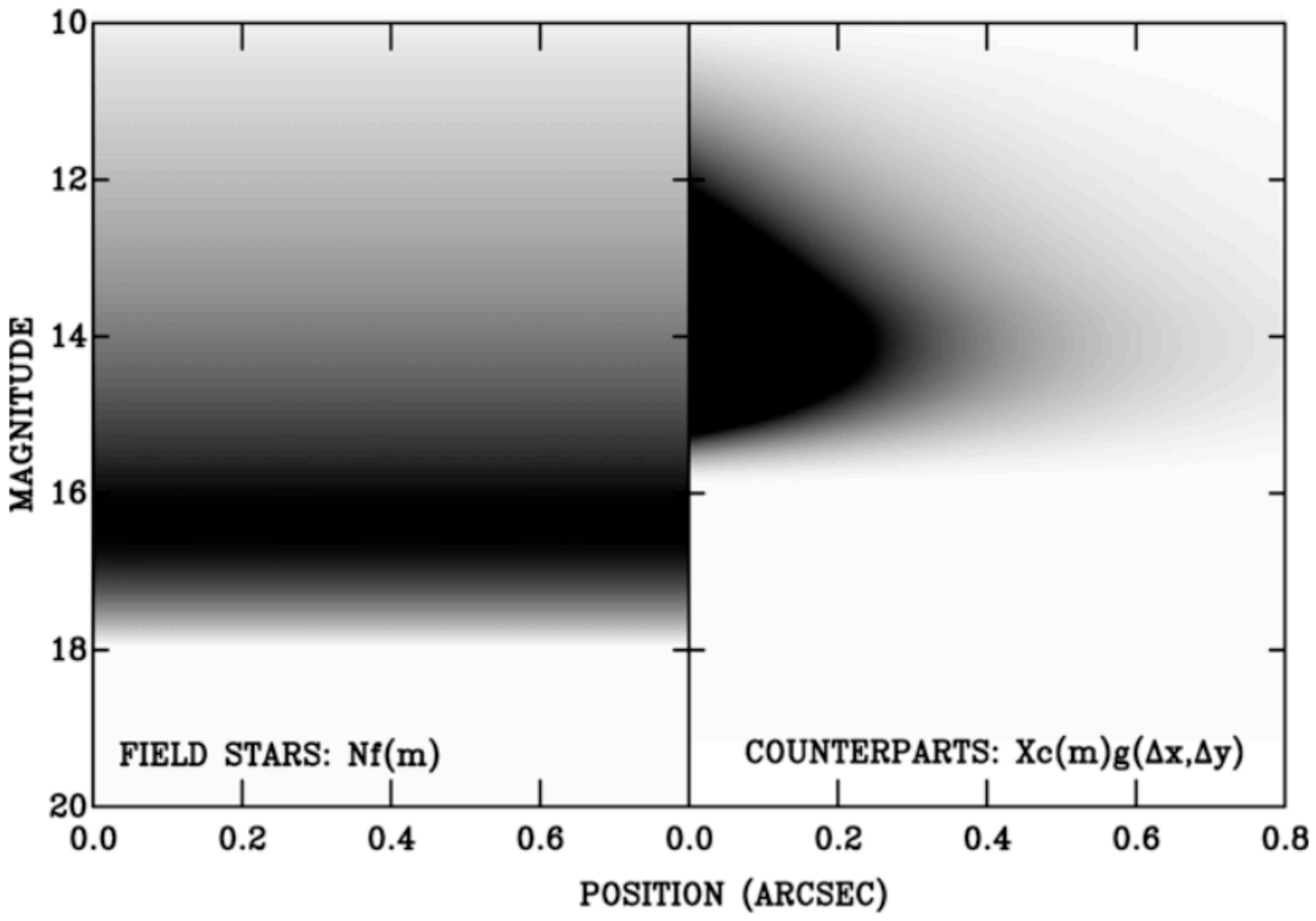
Including the Magnitude Information





Naylor, Broos, & Feigelson (2013)

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

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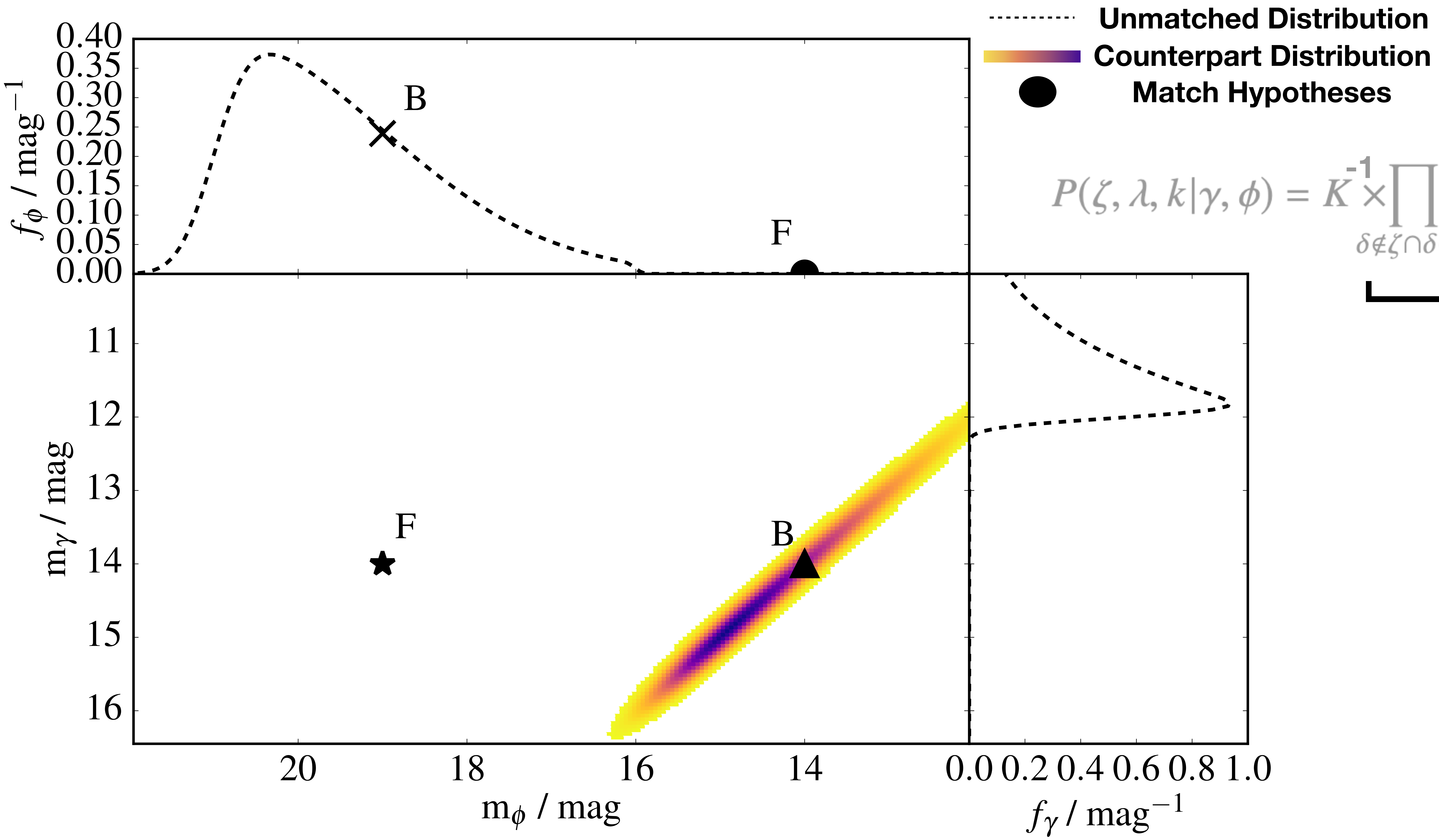
Including the Magnitude Information

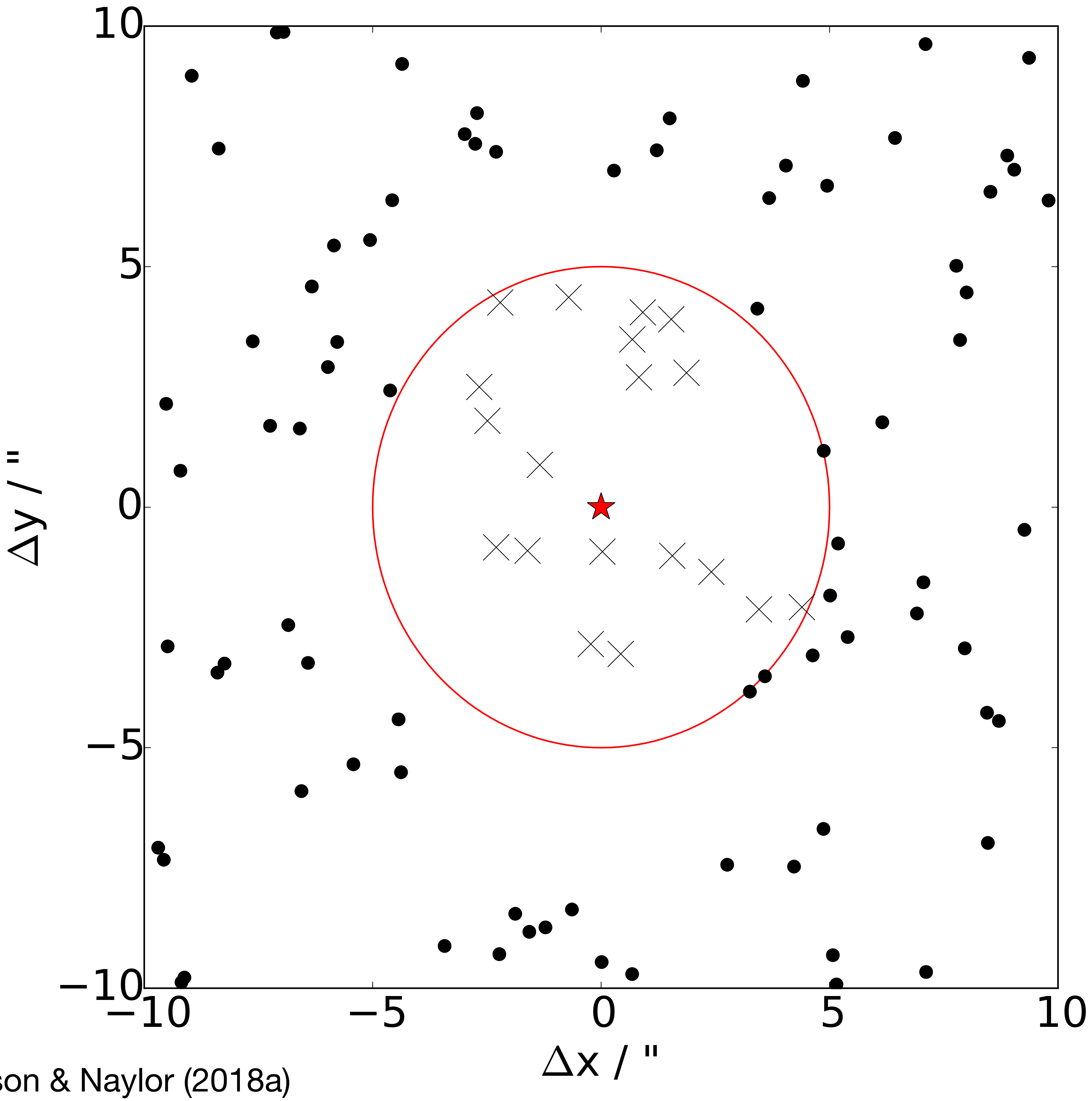


$$P(\zeta, \lambda, k|\gamma, \phi) = K^{-1} \times \prod_{\delta\notin\zeta\cap\delta\in\gamma} N_\gamma \boldsymbol{f}_{\boldsymbol{\gamma}}^{\boldsymbol{\delta}} \prod_{\omega\notin\lambda\cap\omega\in\phi} N_\phi \boldsymbol{f}_{\boldsymbol{\phi}}^{\boldsymbol{\omega}} \prod_{i=1}^{k} N_{\mathrm{c}}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

Unmatched **Matched**

Wilson & Naylor (2018a)

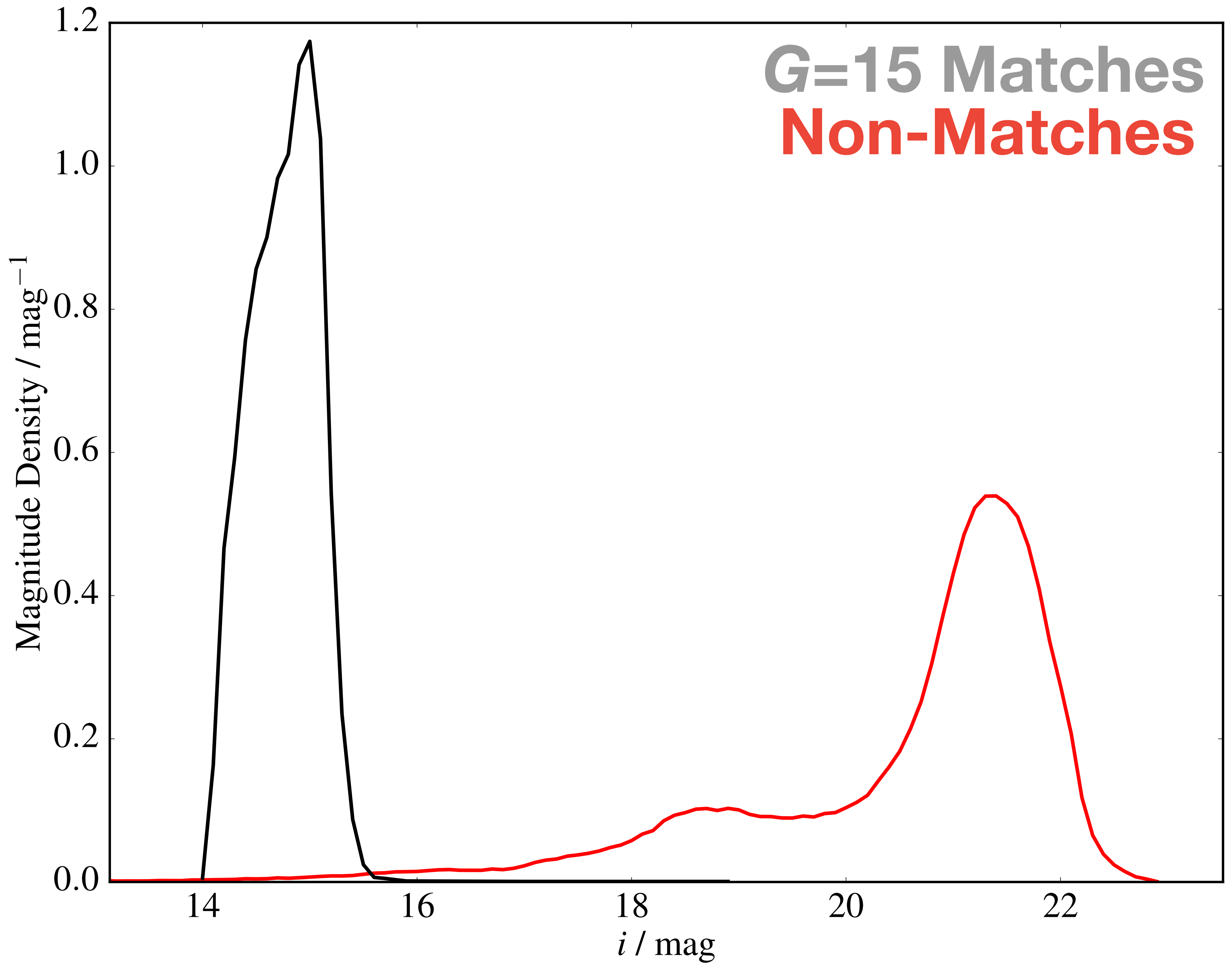
The “Field Star” Distribution



Wilson & Naylor (2018a)

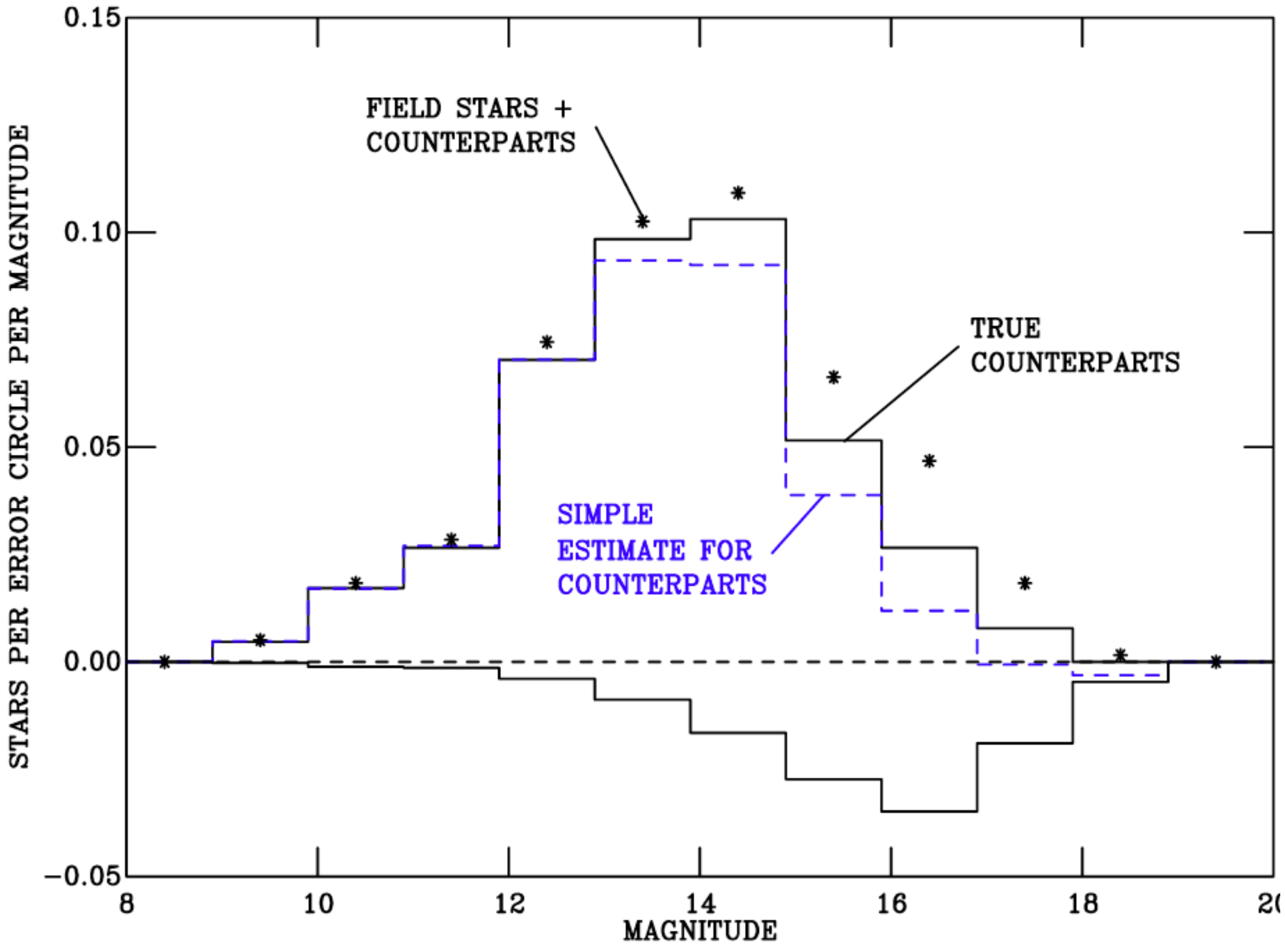
$$P(\zeta, \lambda, k|\gamma, \phi) = K^{-1} \times \prod_{\delta\notin\zeta\cap\delta\in\gamma} N_\gamma f_\gamma^\delta \prod_{\omega\notin\lambda\cap\omega\in\phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i\lambda_i} c_{\gamma\phi}^{\zeta_i\lambda_i}$$

Unmatched **Matched**



Tom J Wilson @onoddil

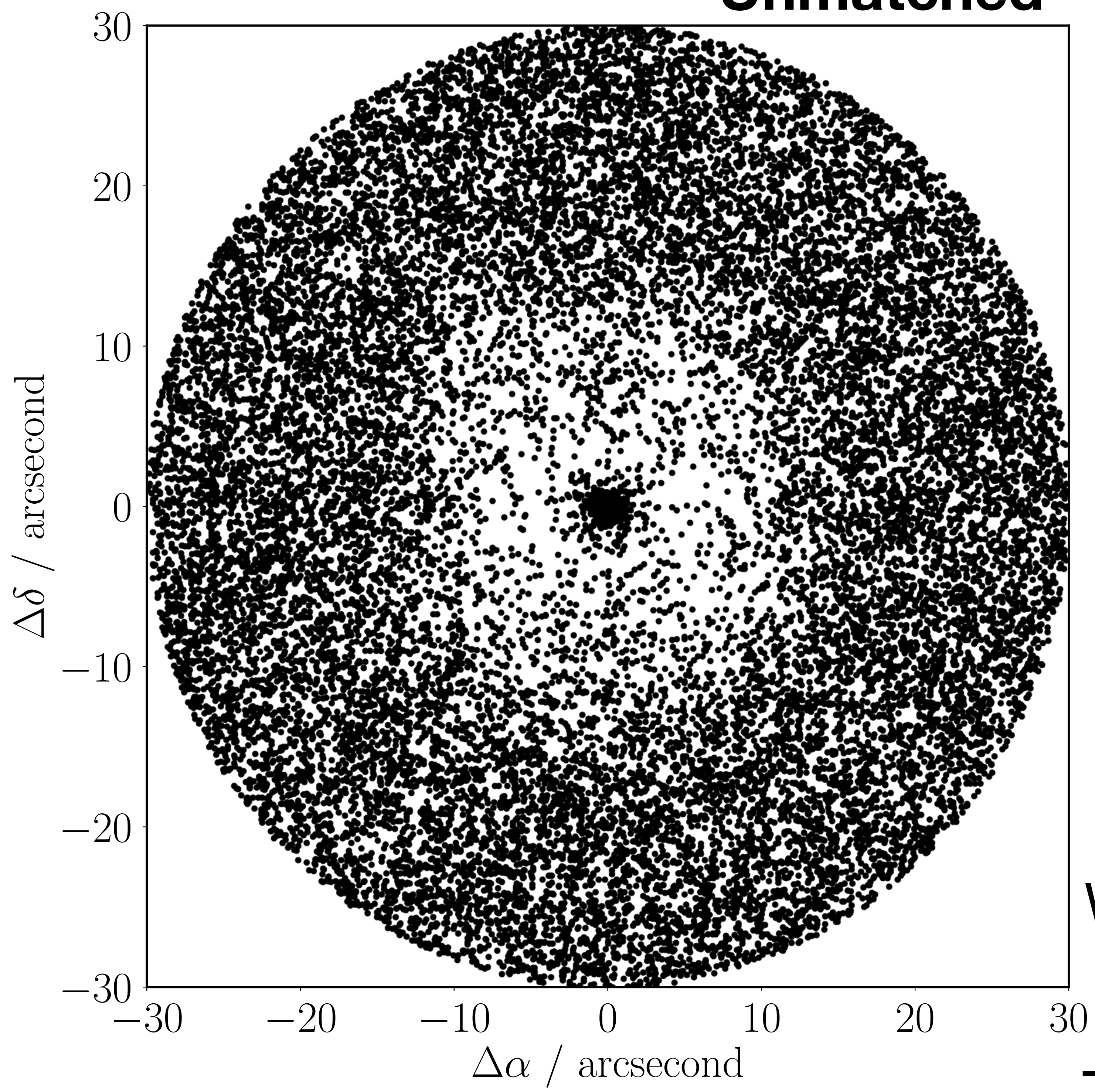
The Counterpart Source Distribution



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

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

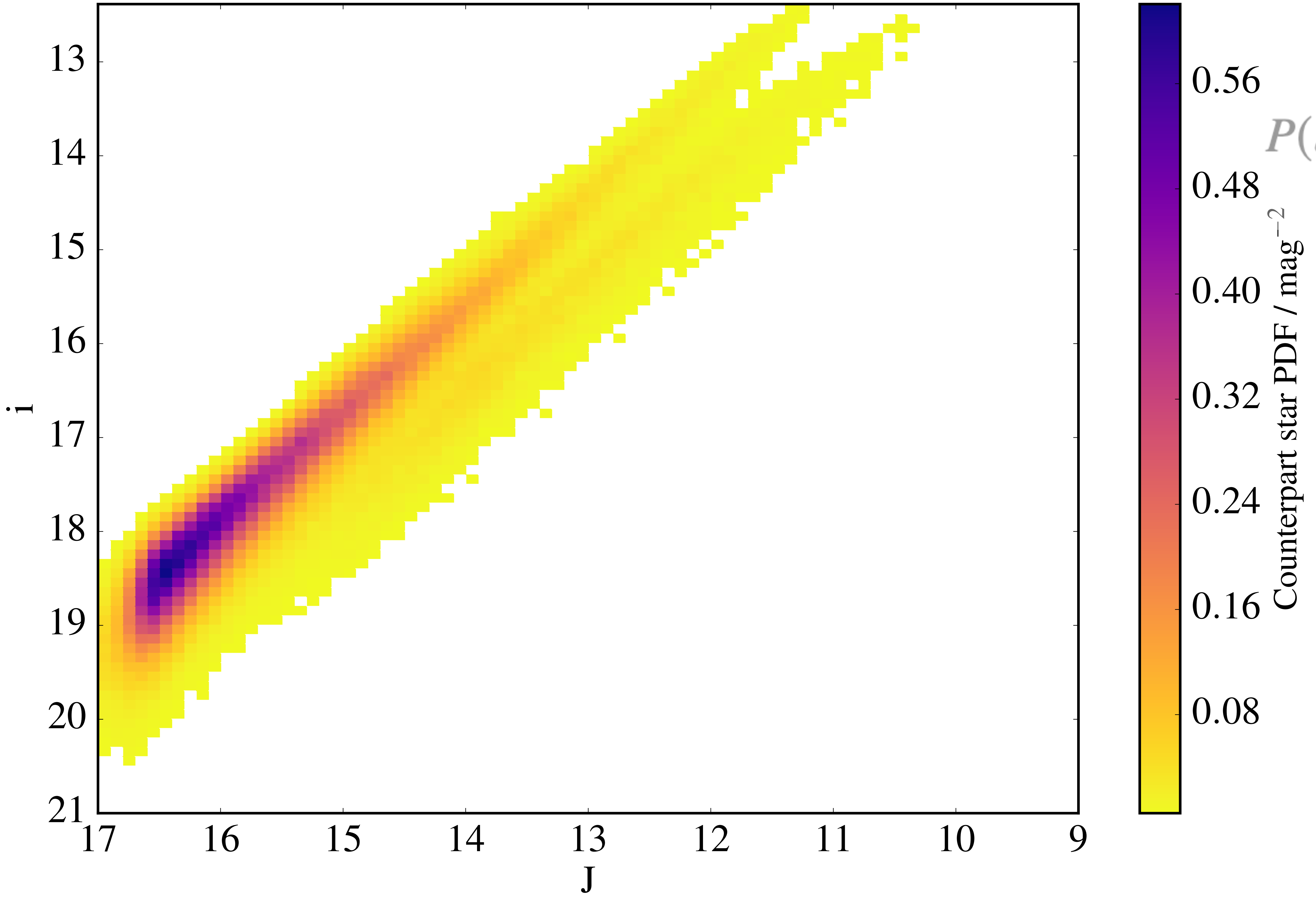
Unmatched **Matched**



Wilson & Naylor (2017)

Tom J Wilson @onoddil

The Counterpart Source Distribution



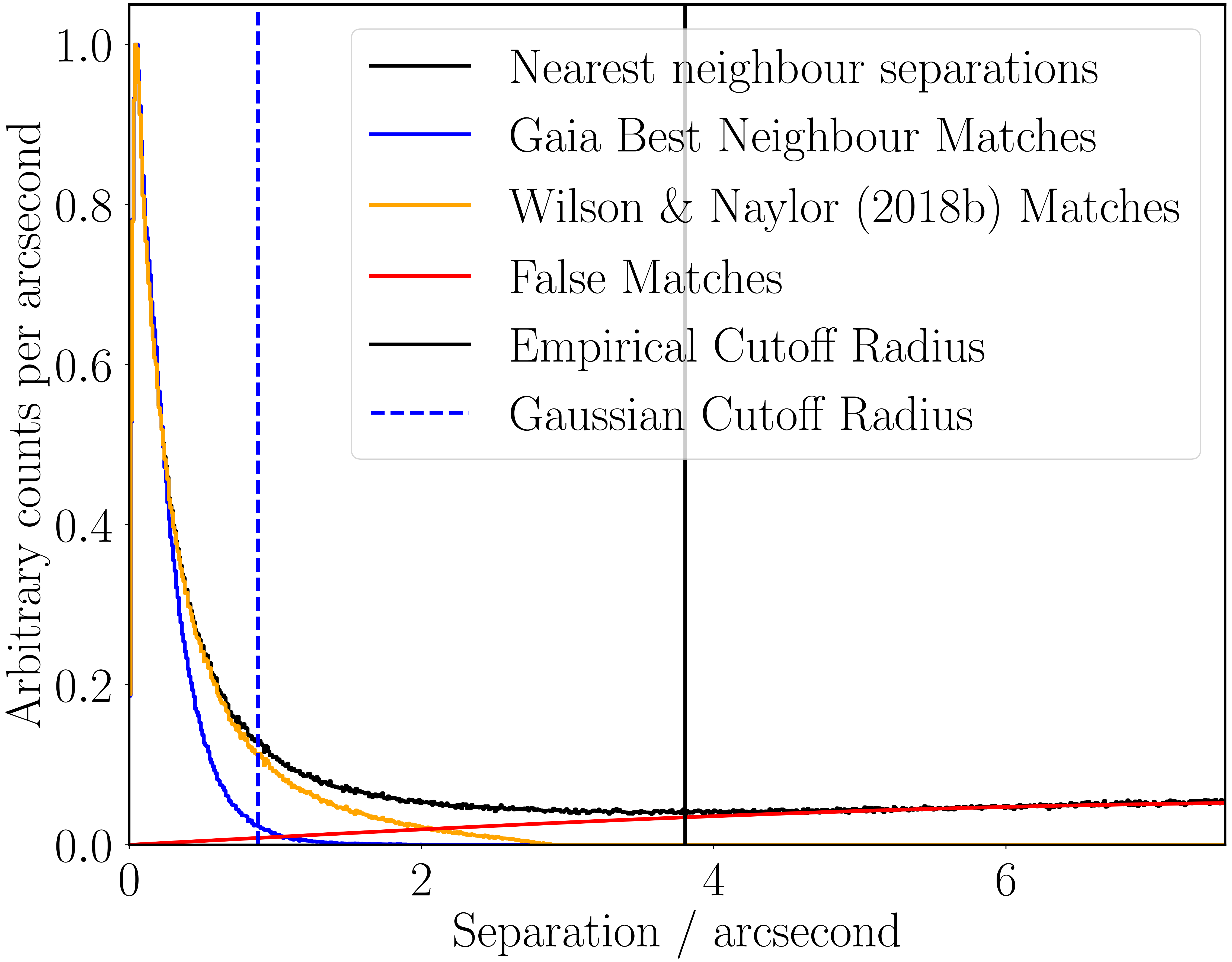
$$P(\zeta, \lambda, k|\gamma, \phi) = K^{-1} \times \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i \lambda_i} c_{\gamma\phi}^{\zeta_i \lambda_i}$$

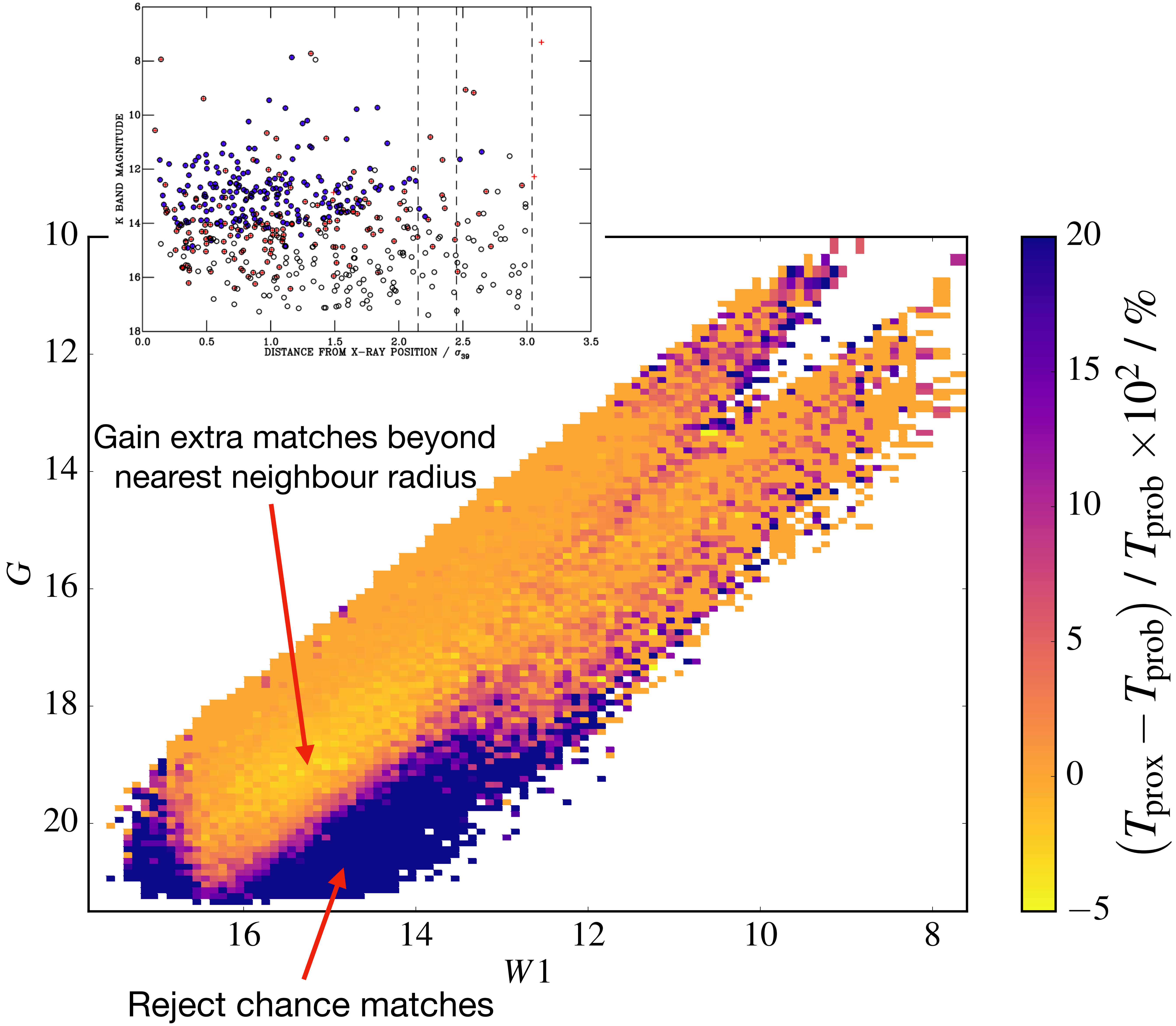
Unmatched **Matched**

Wilson & Naylor (2018a)

Tom J Wilson @onoddil

Comparing Match Distributions

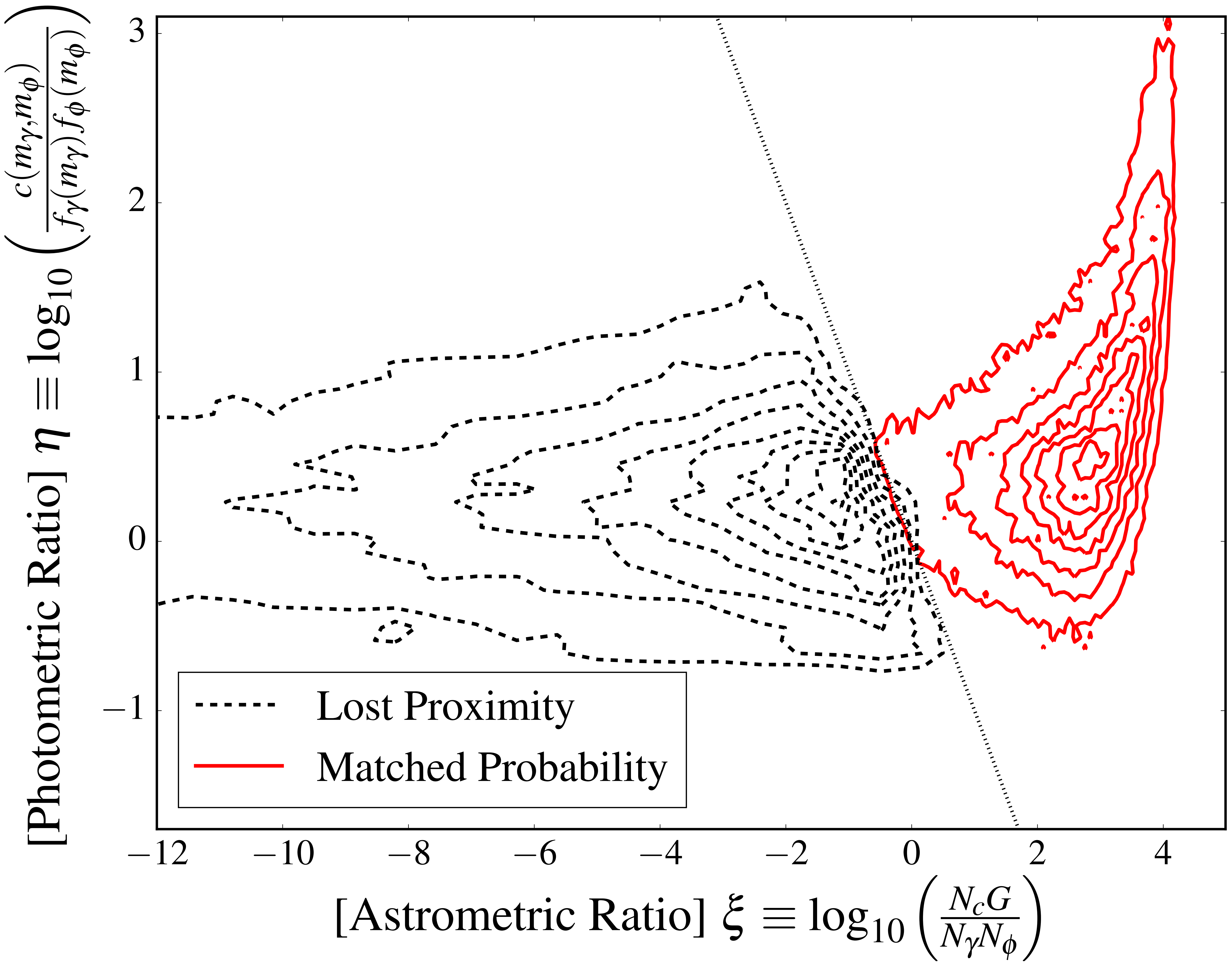




Wilson & Naylor (2018b)
WISE - Wright et al. (2010)
Gaia matches - Marrese et al. (2019)
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

Tom J Wilson @onoddil

Lost Gaussian-Only Matches



Wilson & Naylor (2018b)

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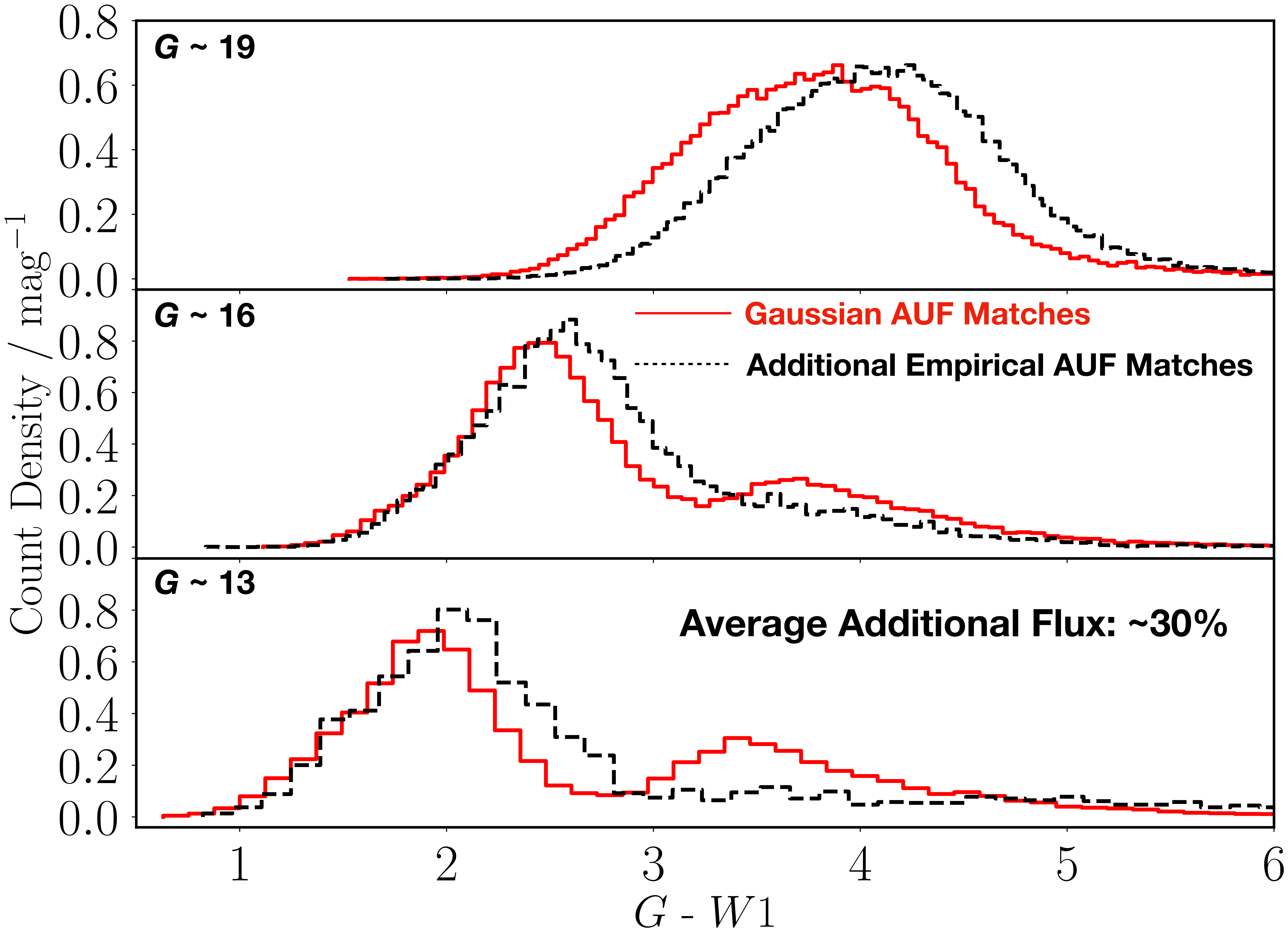
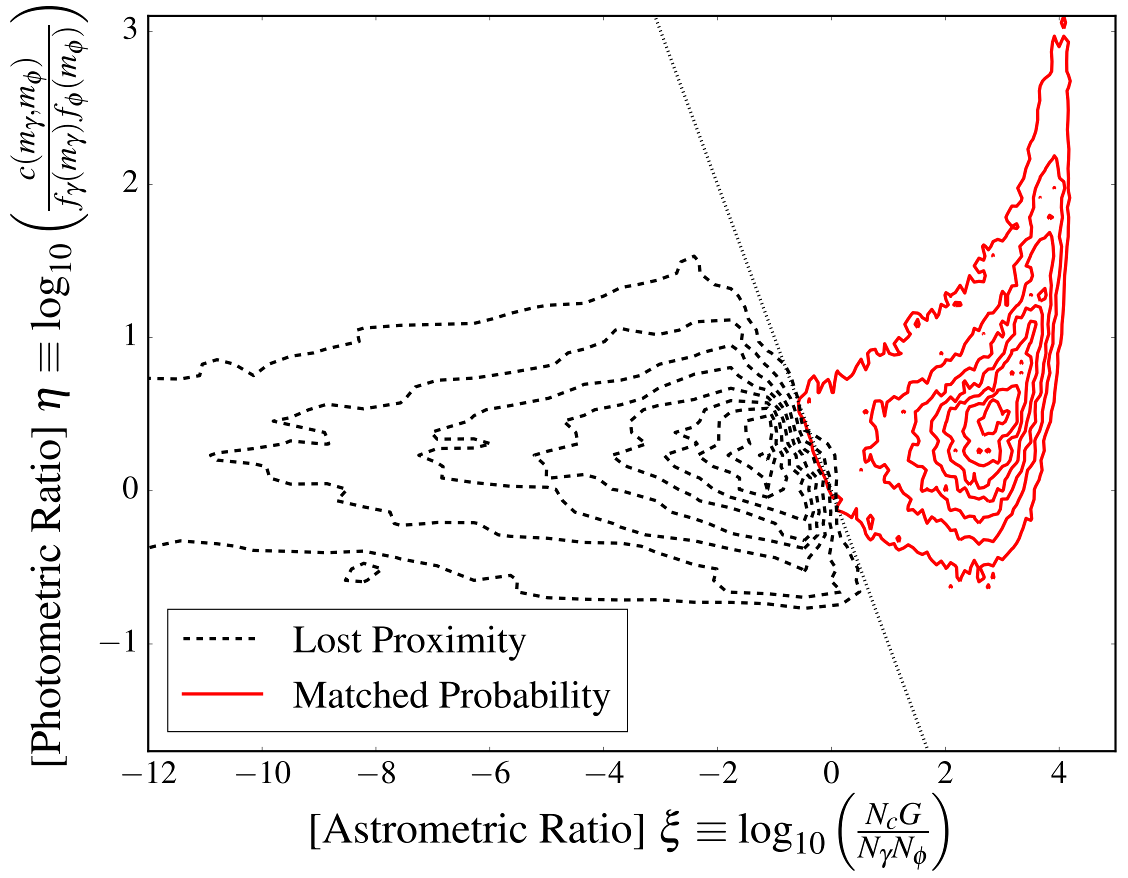
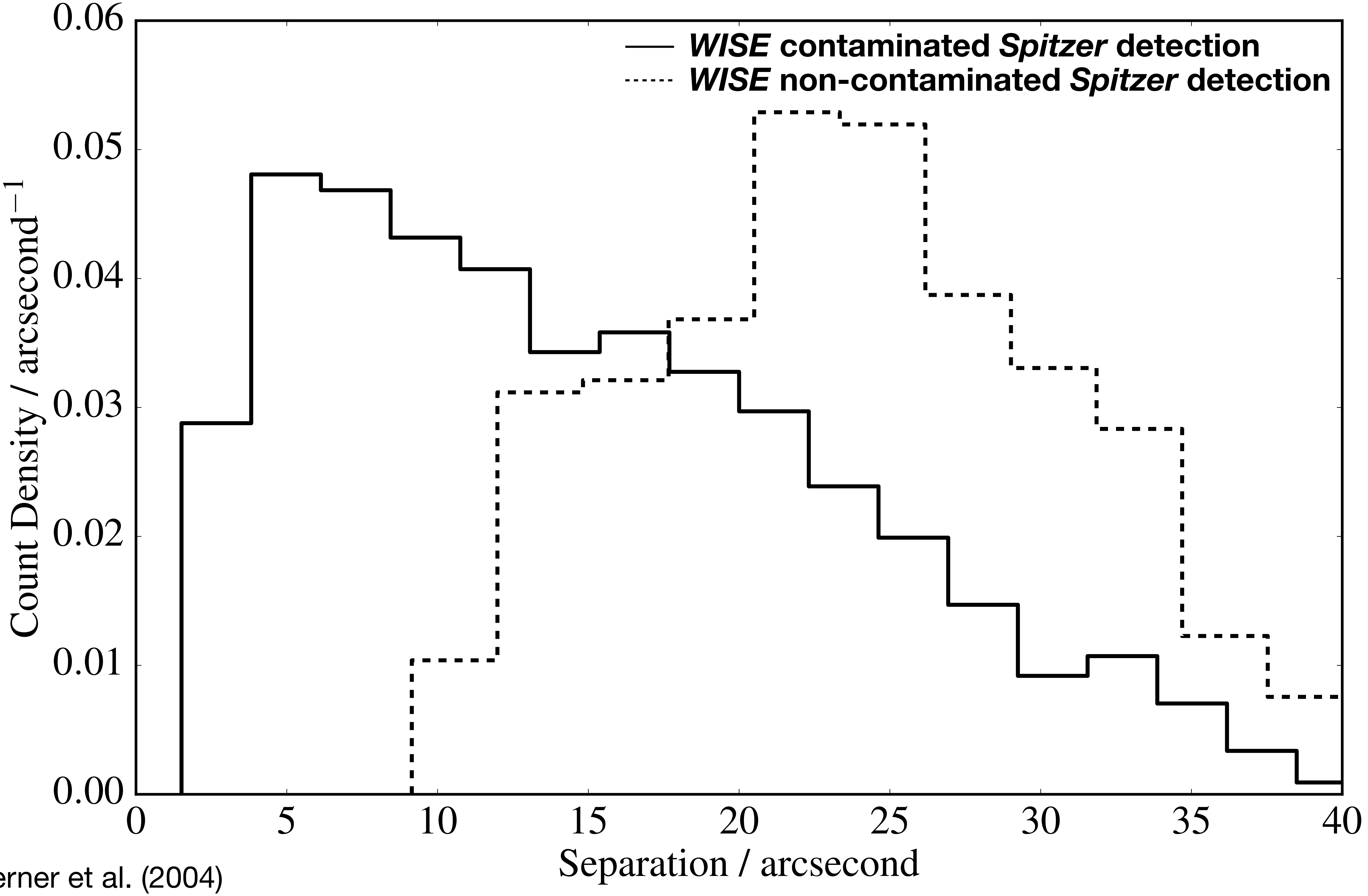
Perturbation-Colour Correlation





"Extra flux" has an impact on derived proper motions and parallaxes, and IR excesses!

Resolving Contaminants



Spitzer - Werner et al. (2004)
IRAC - Fazio et al. (2004)
WISE - Wright et al. (2010)
Wilson & Naylor (2018b)

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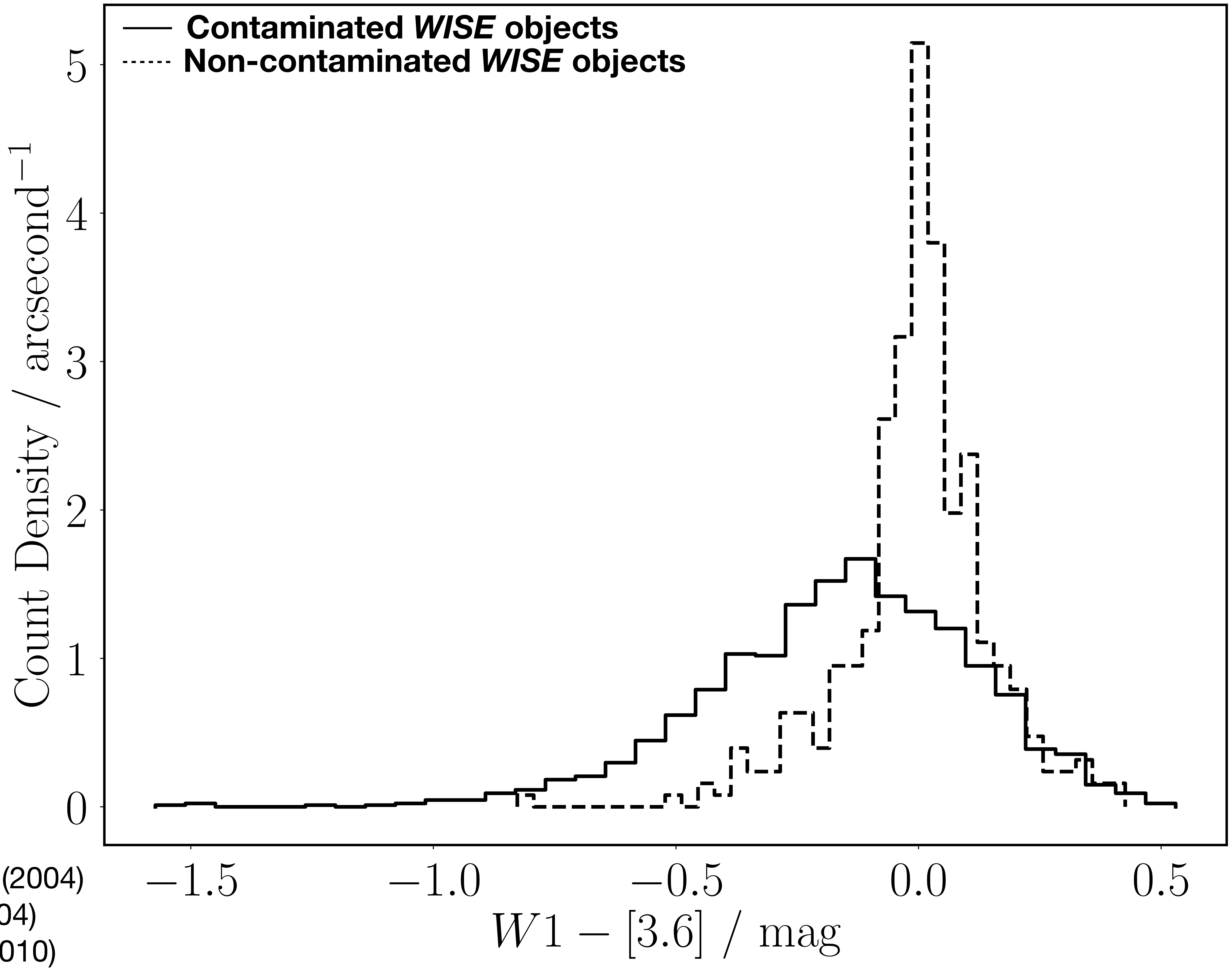
Resolving Contaminant Flux



Spitzer - Werner et al. (2004)
IRAC - Fazio et al. (2004)
WISE - Wright et al. (2010)
Wilson & Naylor (2018b)

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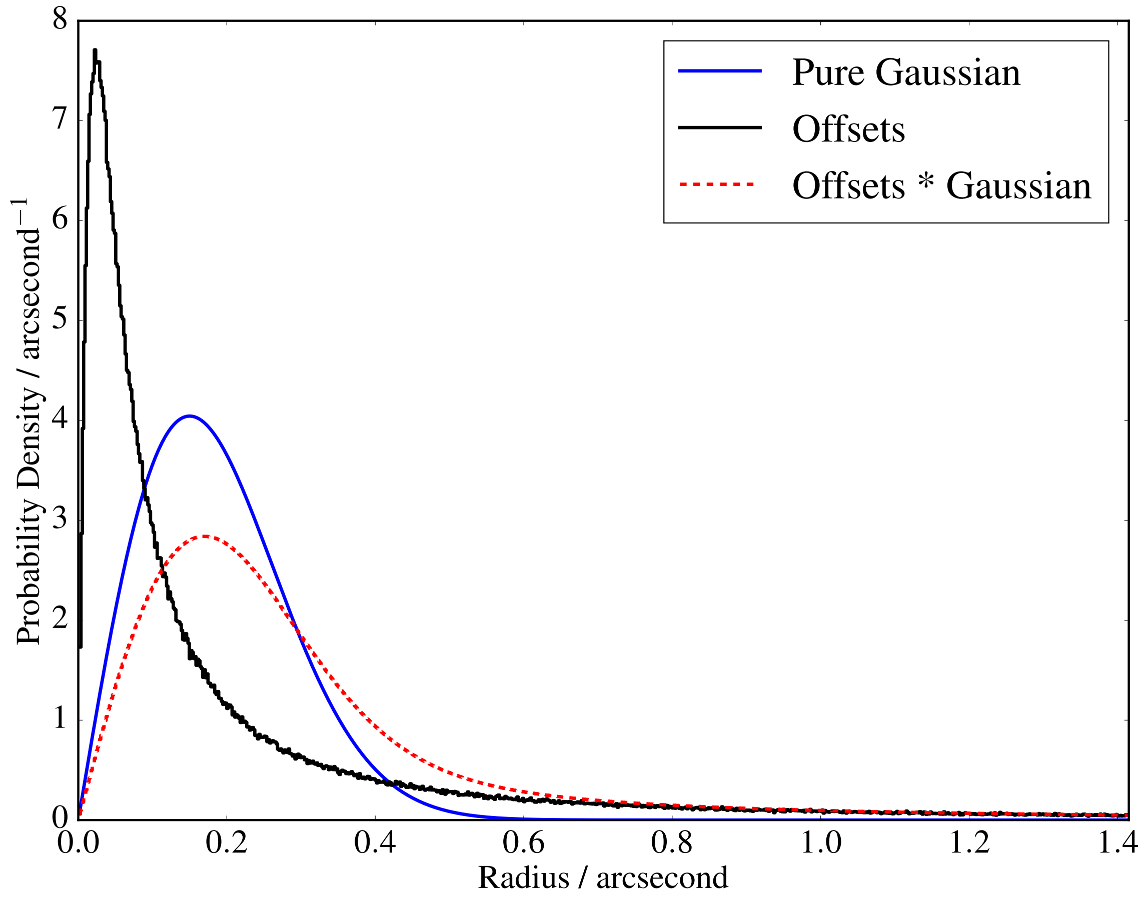
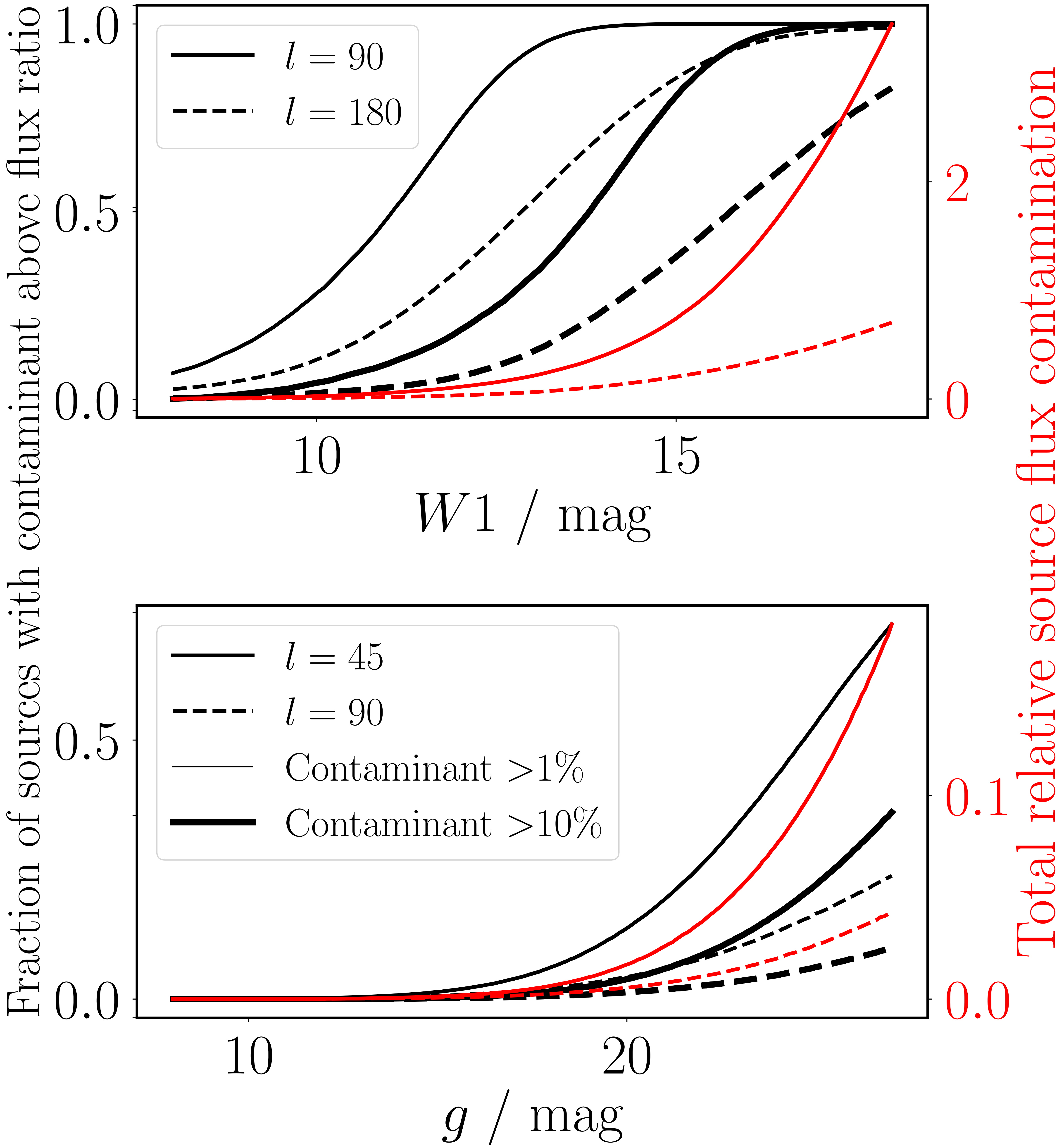
Contamination Rates and Amounts





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

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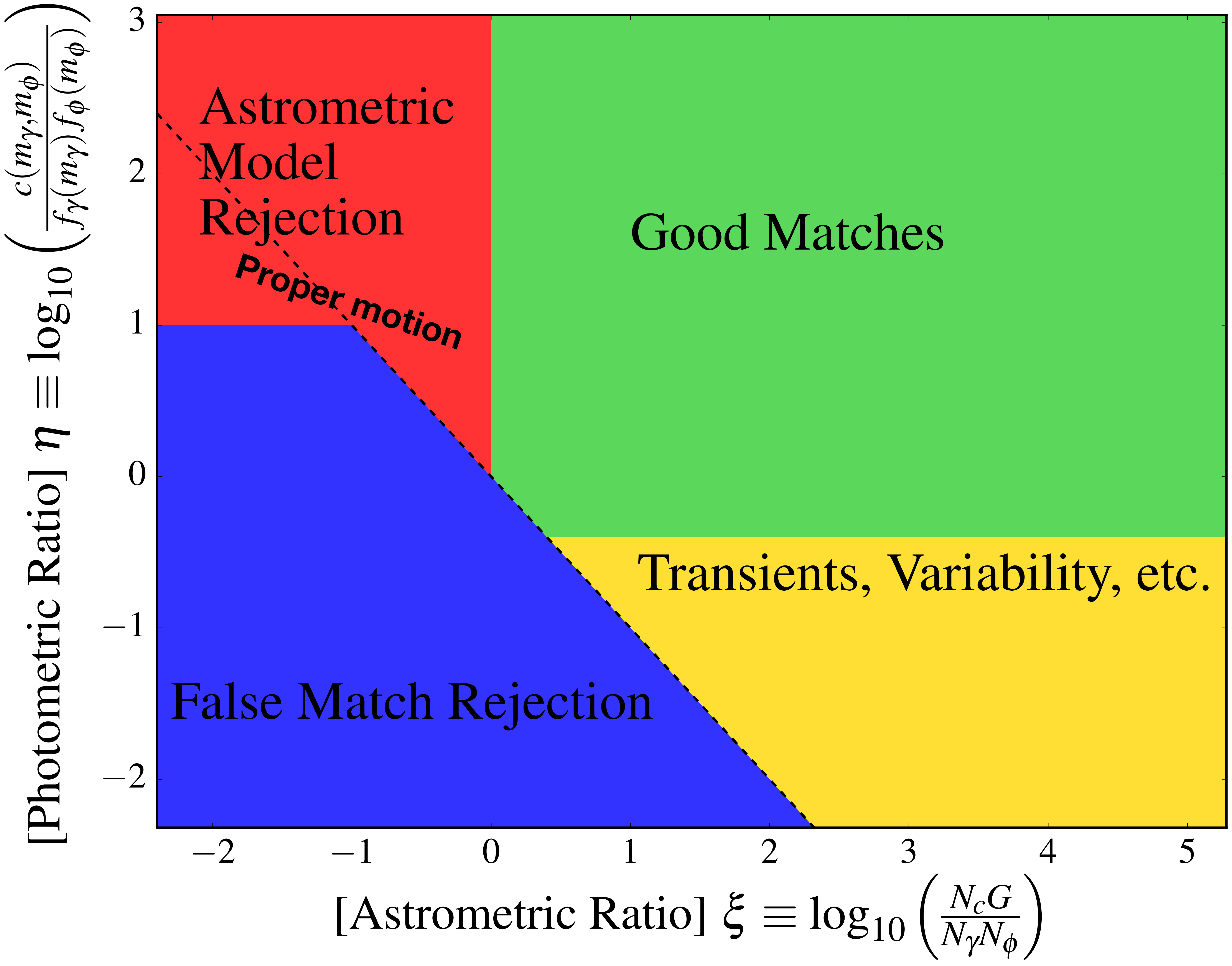
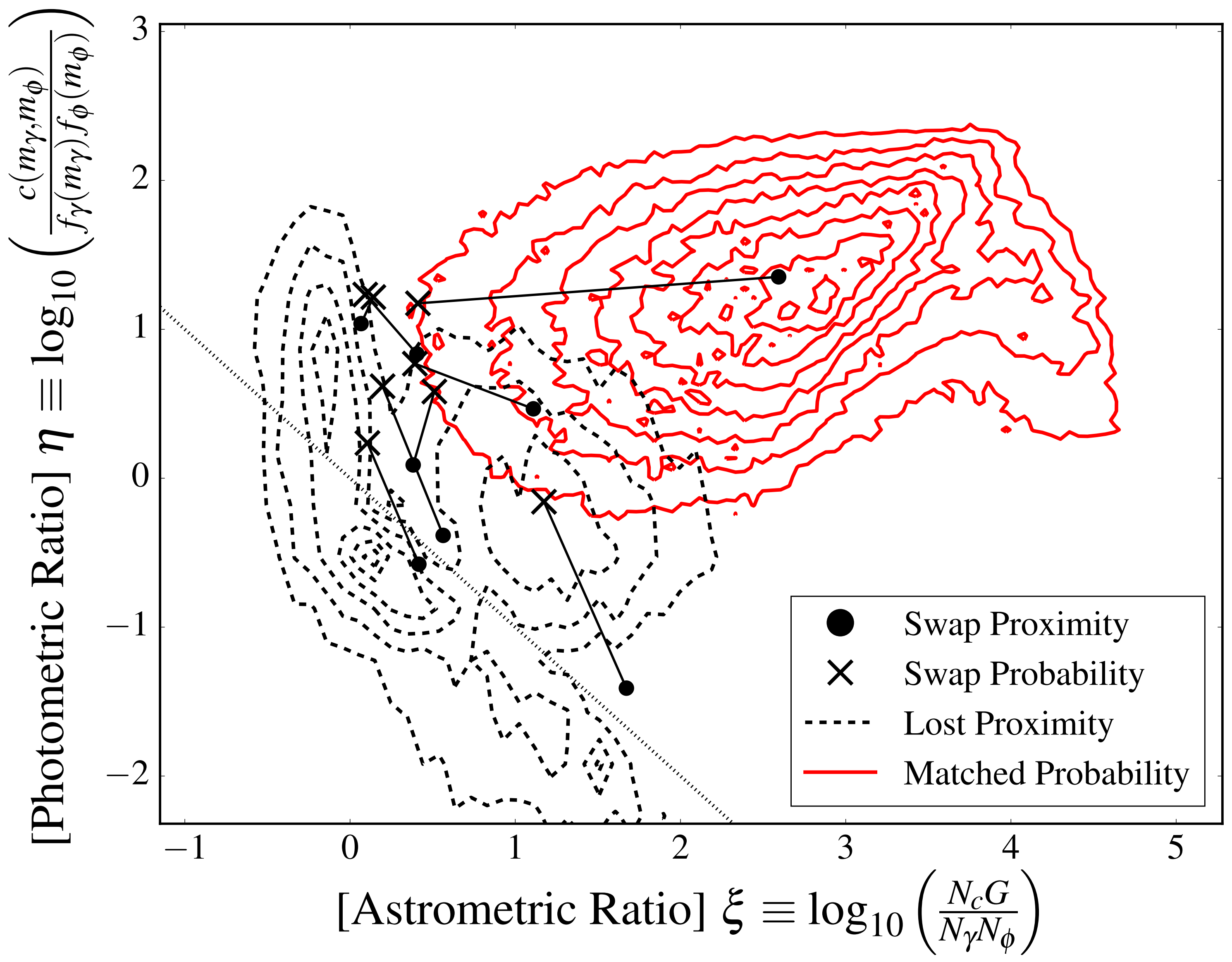
The Likelihood Ratio Space





Open Source Code: macauff

Matching Across Catalogues using the Astrometric Uncertainty Function and Flux

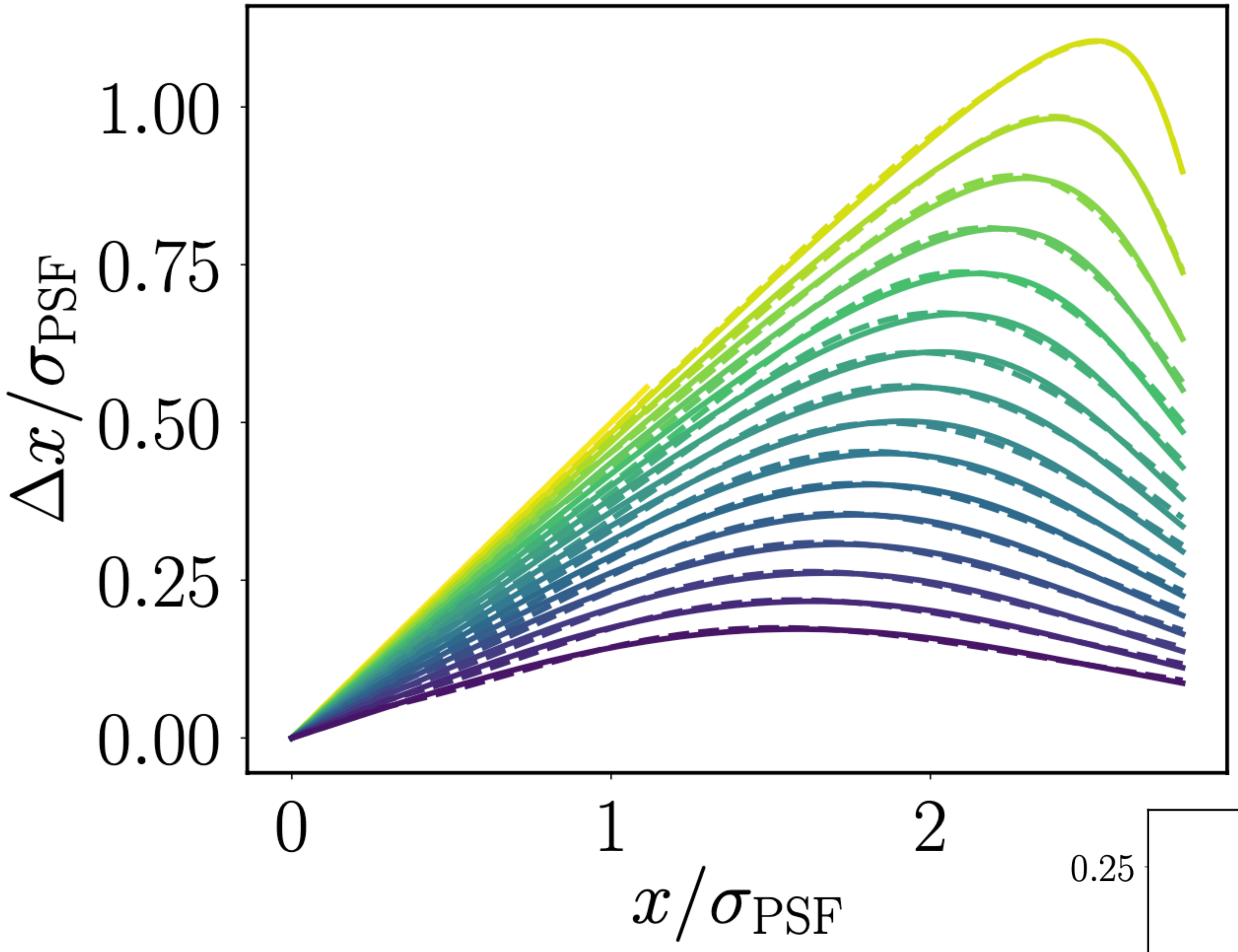
https://github.com/Onoddil/macauff

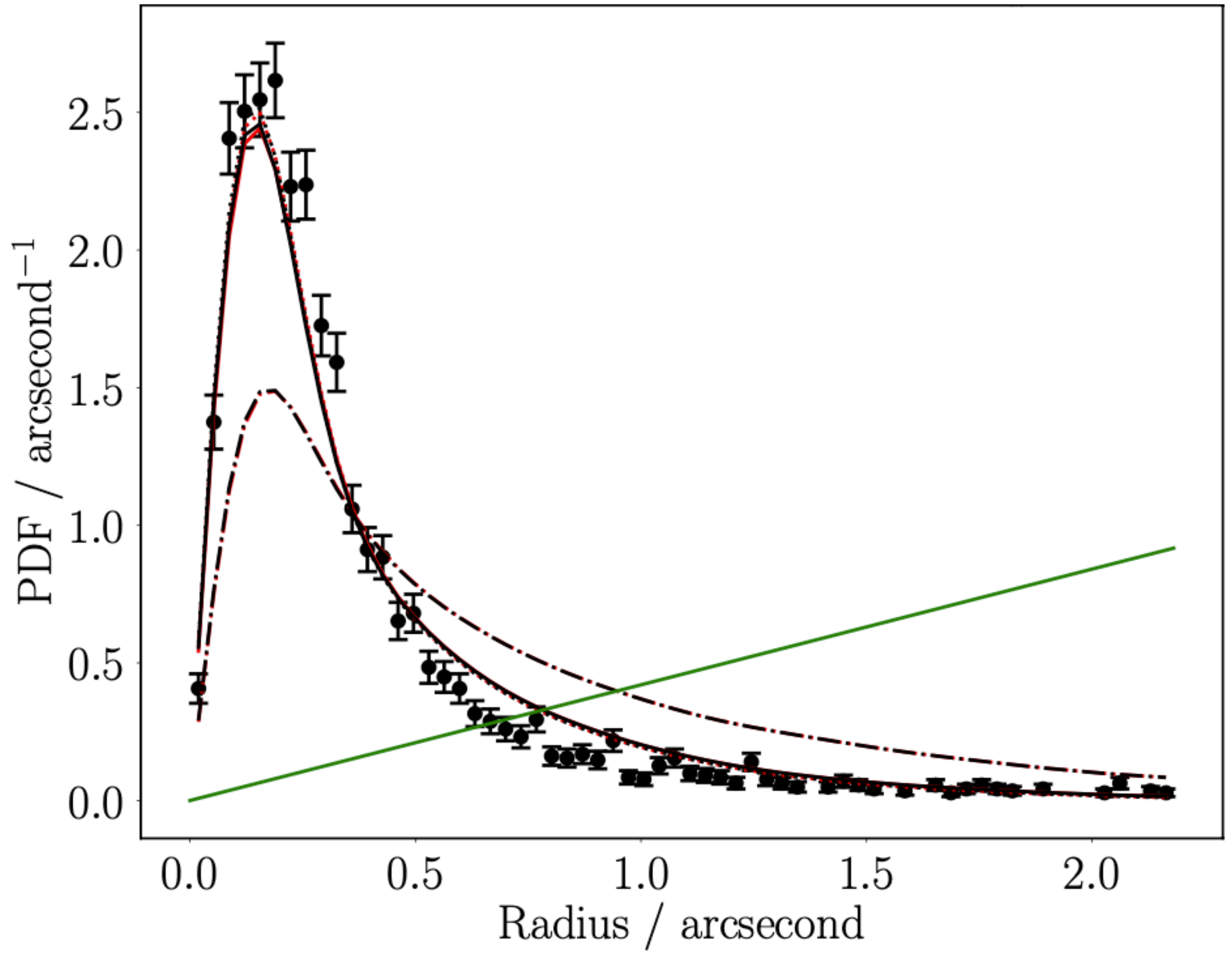
LSST:UK Consortium

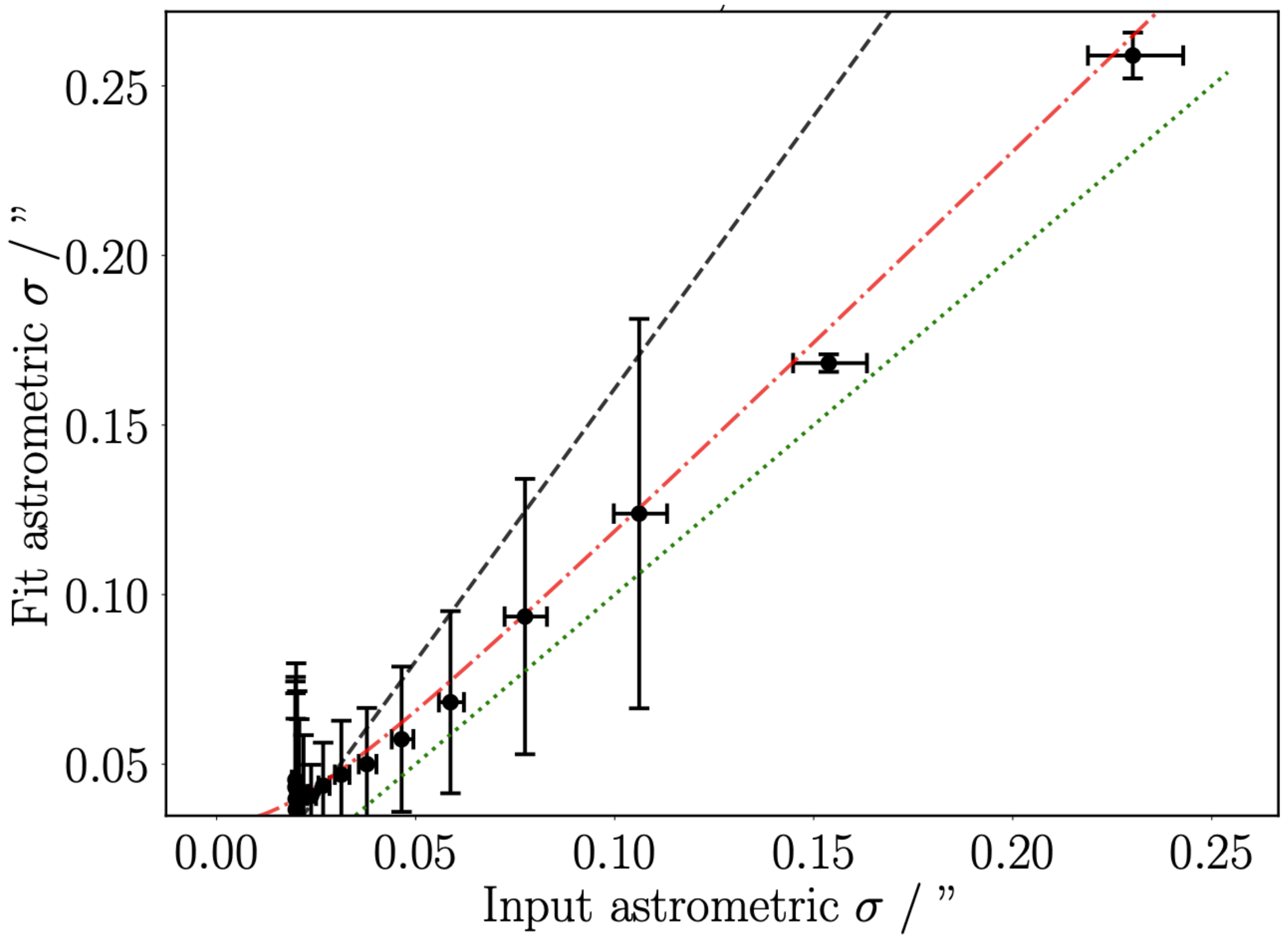
(Points if you know your tartans!)

Tom J Wilson @onoddil

Probing the Faintest Sources



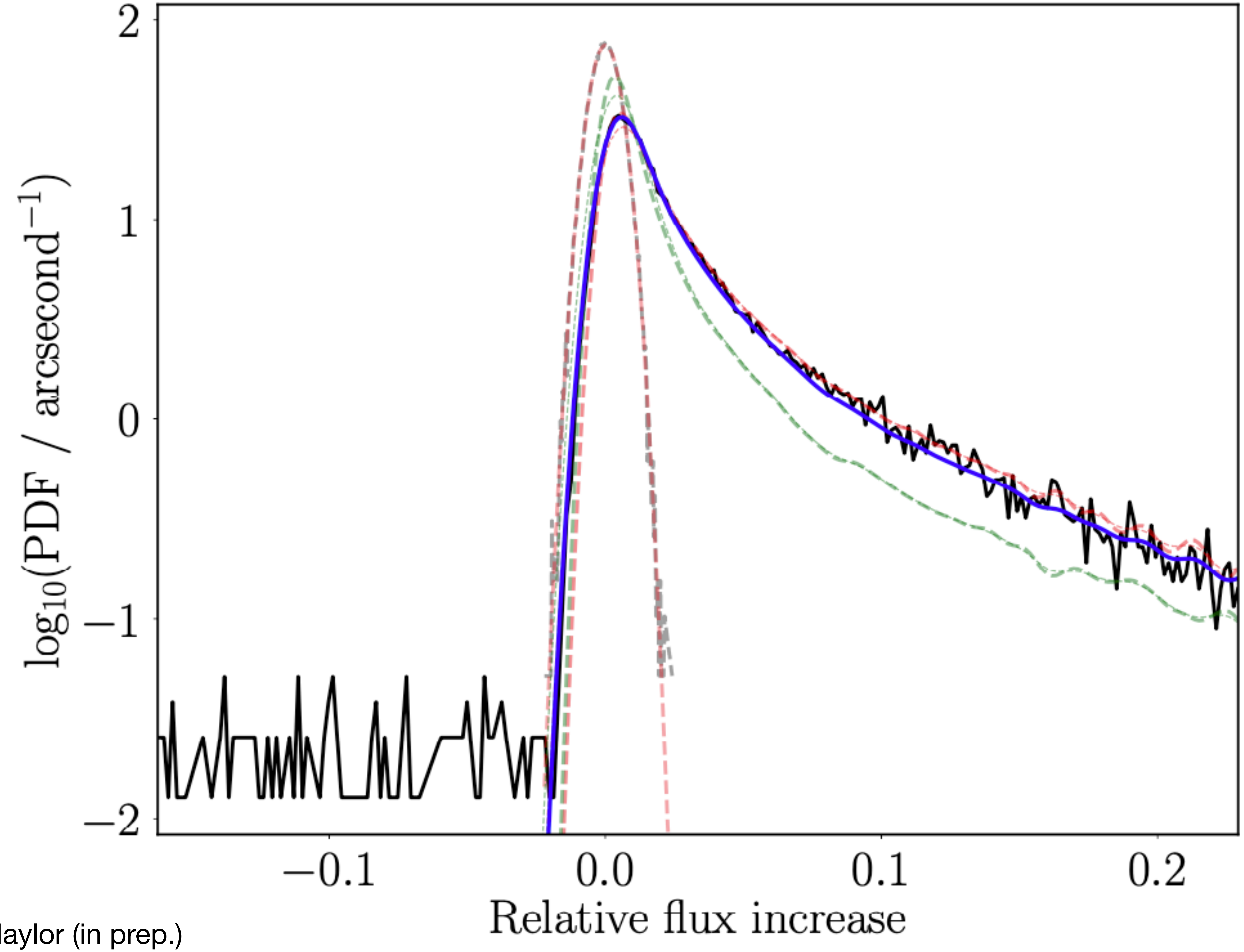




Wilson & Naylor (in prep.)
Plewa & Sari (2018)

Tom J Wilson @onoddil

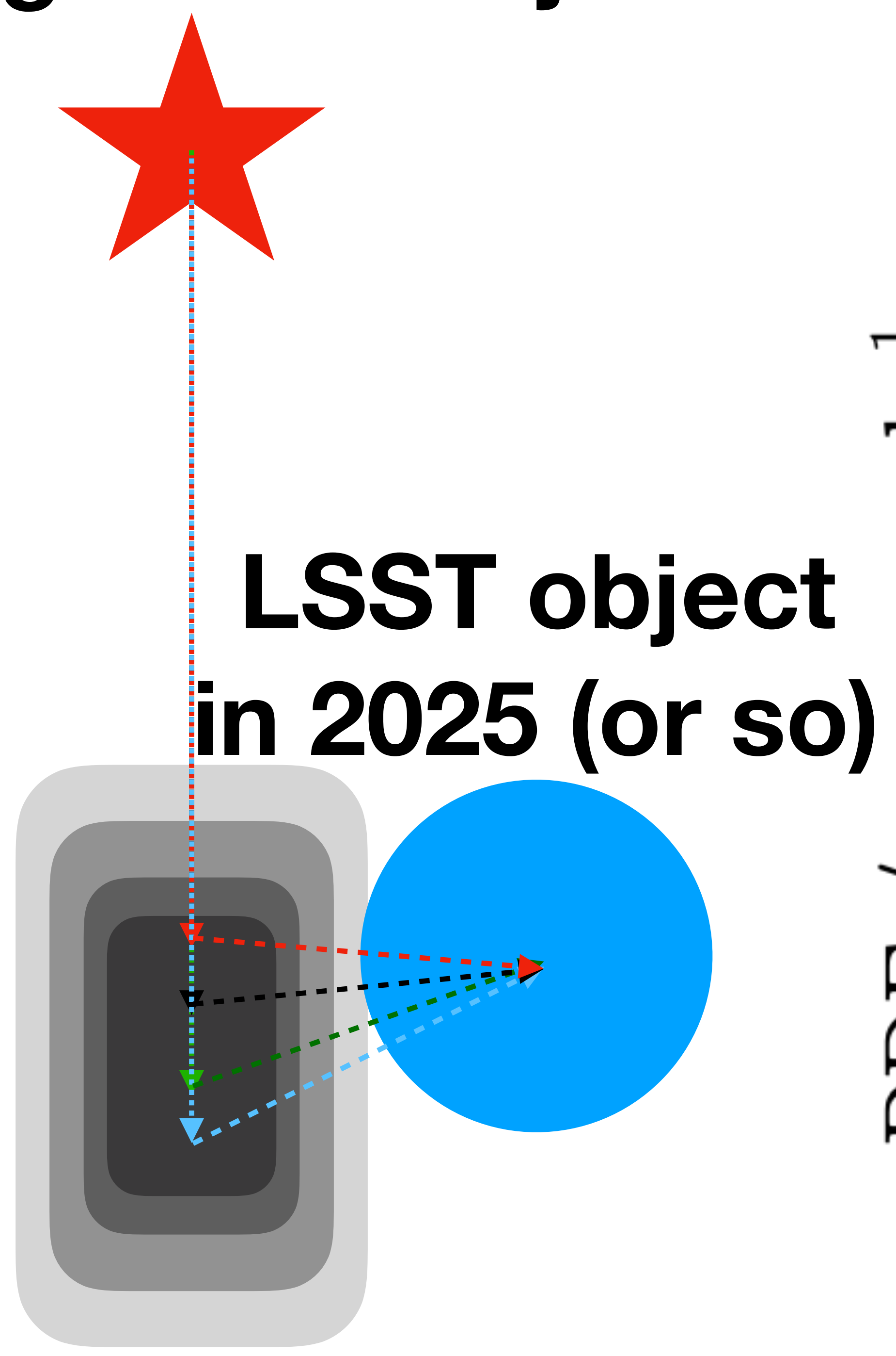
Photometric Contamination Function

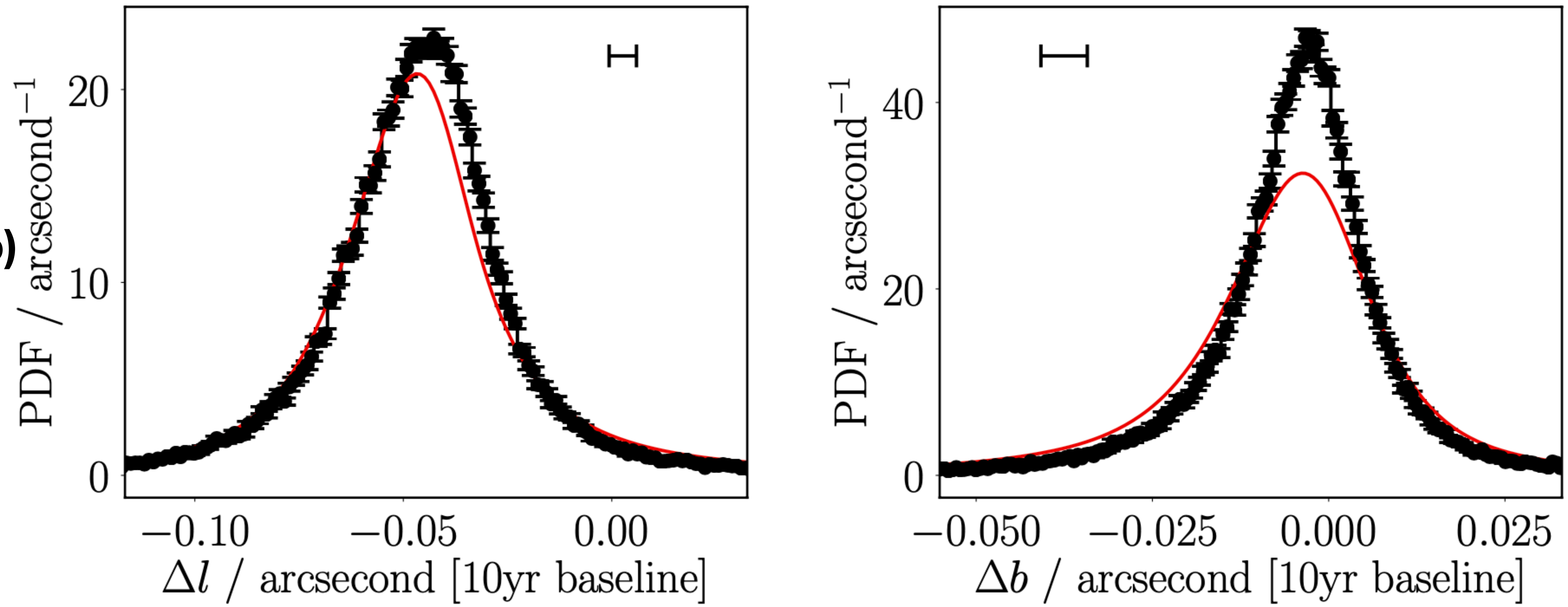


Wilson & Naylor (in prep.)

Including Unknown Proper Motions

e.g. *WISE* object in 2010





Because this function works in *separation*, rather than pure *position*, space, we apply the distribution after calculating G.

$$G' = G * h^{'}_{\mathrm{pm}} \qquad G = h_\gamma * h_\phi$$

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

Wilson (2022, RASTI, in review)

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

Tom J Wilson @onoddil

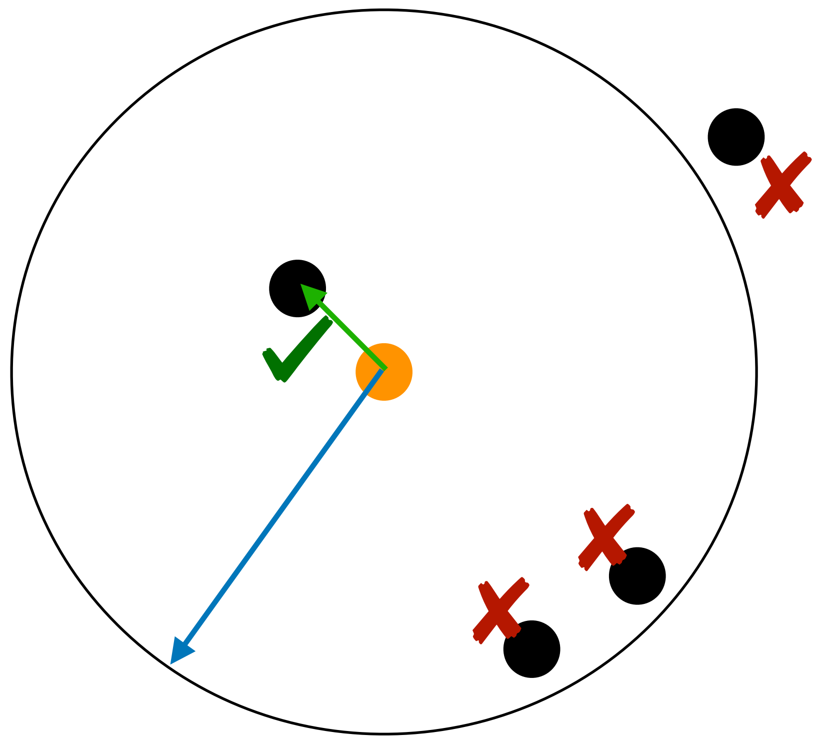
What does this mean for you?

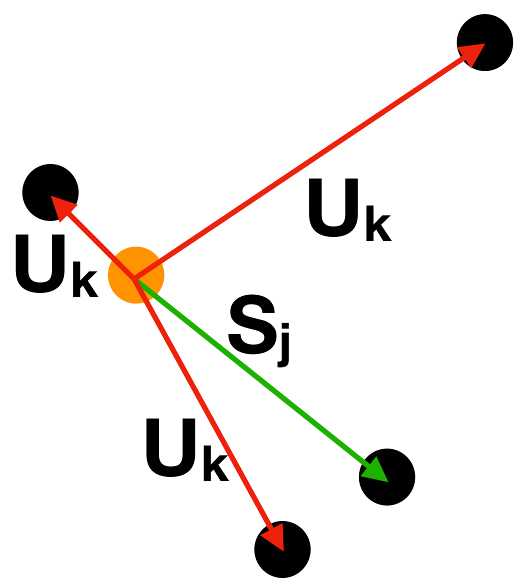
The "busy" astronomer: uses a quick and simple 2" match -> Too many matches

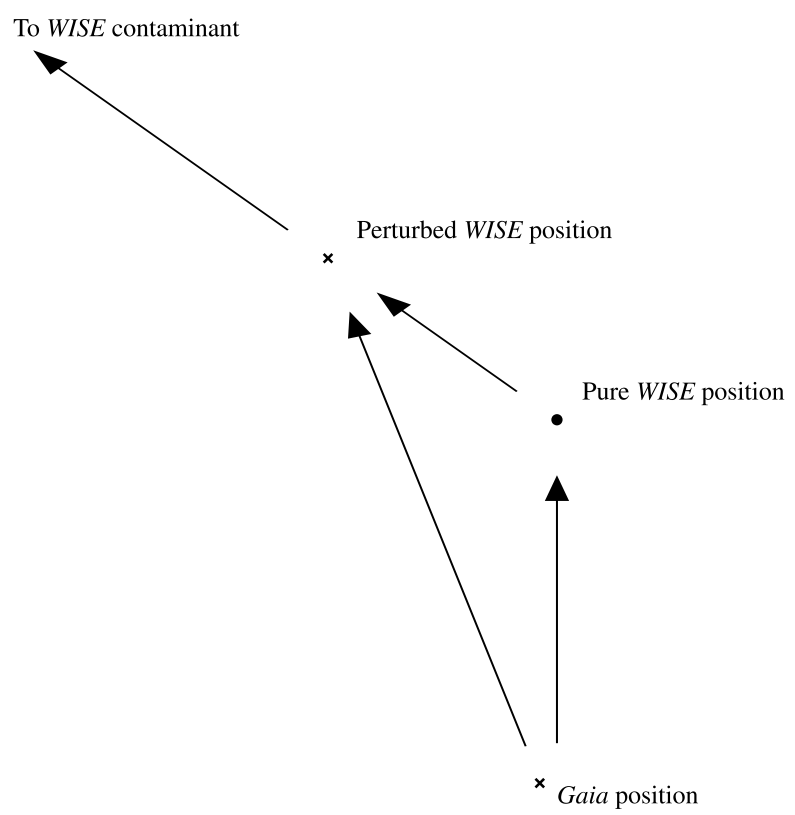
The "Bayesian" astronomer: uses astrometric centroid uncertainty to reduce match radius -> Too few matches

The "careful" astronomer: includes perturbation from blended objects in the AUF -> Correct number of matches

The "<u>smart</u>" astronomer: uses our cross-matches to get the correct number of matches *and* information on how much flux contamination is affecting their object!







you downloading your favourite cross-matches, probably

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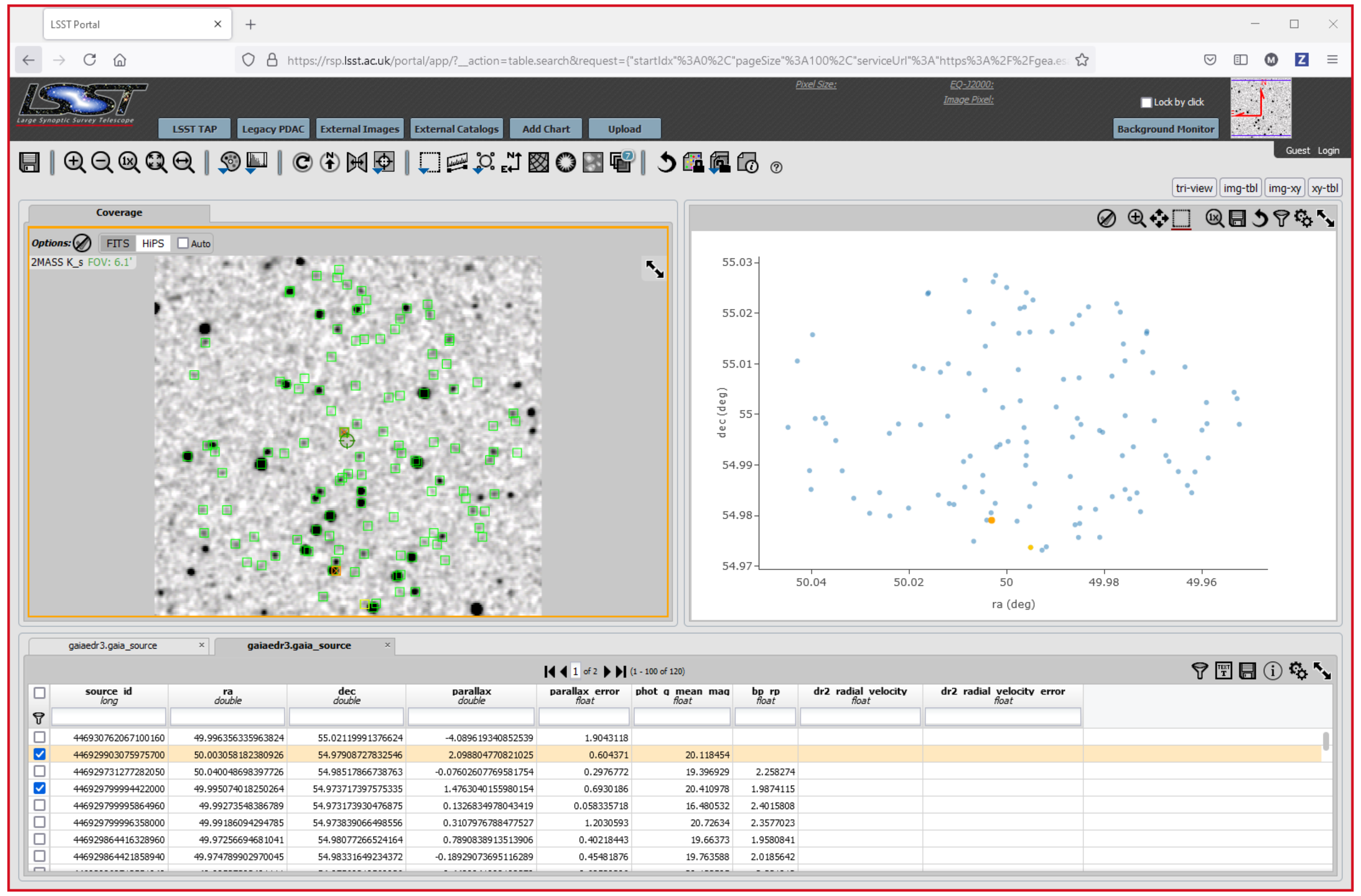
How To Use Our Cross-Matches

(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 a 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

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Conclusions

- **Blended star contamination causes positional shifts, now modelled robustly for the first time in the AUF**
- **Symmetric data-driven photometric likelihood now possible**

- ***WISE* objects are up to 30% flux contaminated**
- **LSST will suffer of order 10% flux contamination in the future**
  - **Important for extinction/distance; “1% photometry”?**
  - **Modelling of statistical flux contamination allows for the recovery of “true” fluxes**
- **LSST will suffer at least one extra source (possibly up to 10!) in each 2” matching circle**
  - **Can use photometry in catalogues to break these false match degeneracies**
- **Can include unknown proper motions easily within AUF match framework**
- **High dynamic range matches must account for differential crowding matching to ancillary or historic data**

- **Upcoming LSST:UK cross-match service macauff — let me know your thoughts/needs/hopes/dreams**

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

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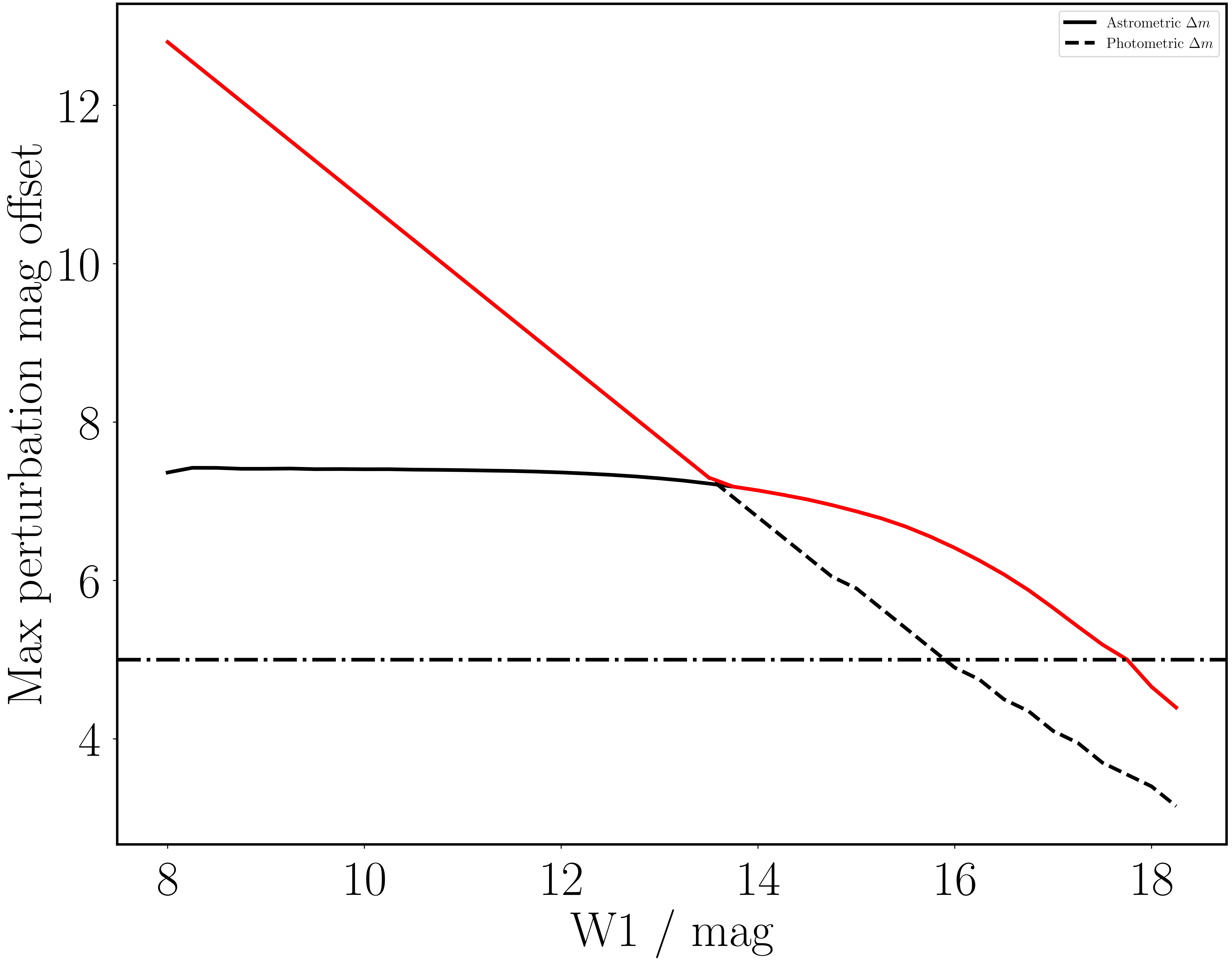
LSST:UK Consortium

VERA C. RUBIN OBSERVATORY

Macauff

@Onoddil @pm.me .github.io

The Astrometric Uncertainty Function and LSST: A Crisis of Completeness Limit



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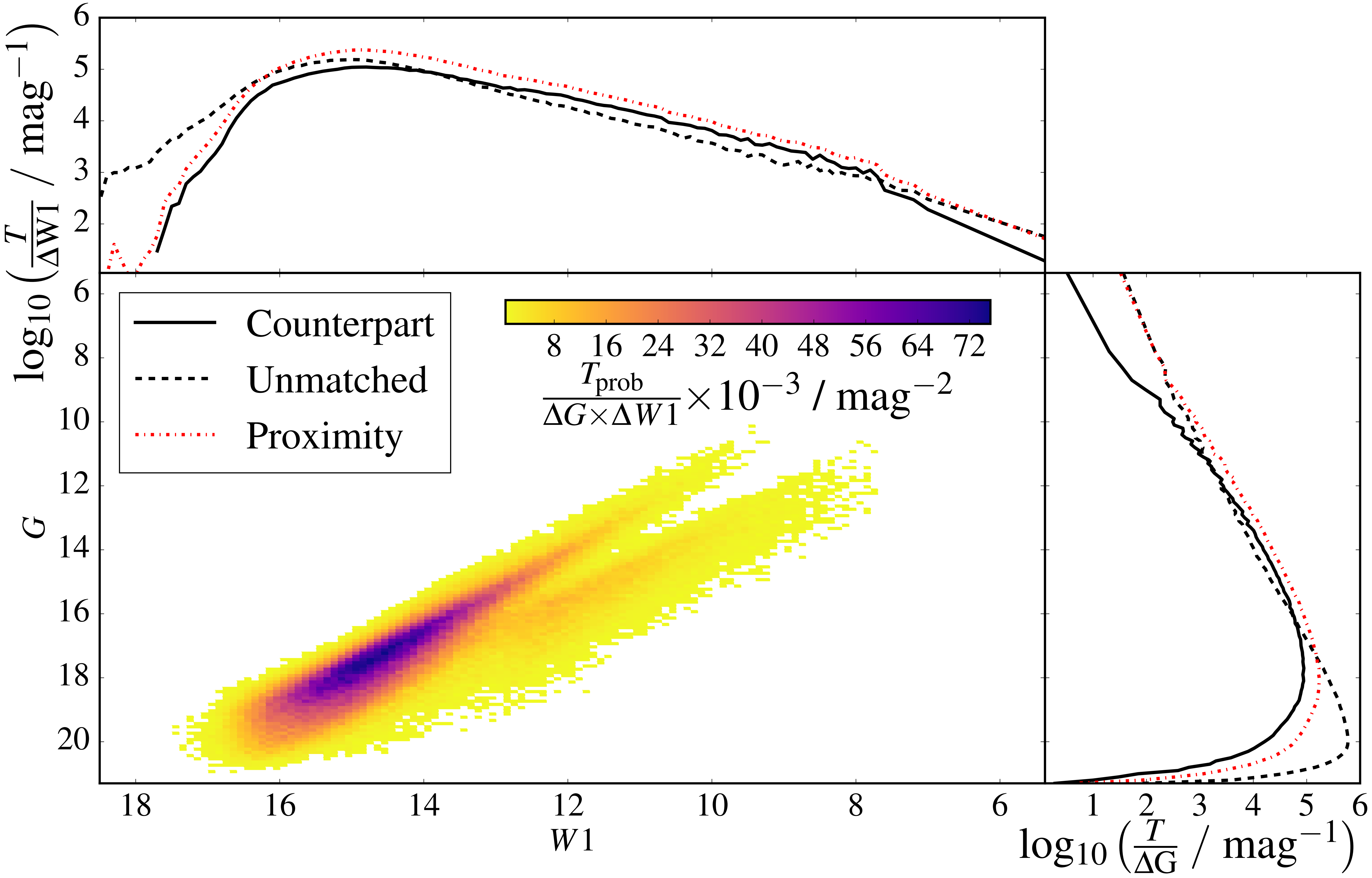
Contamination Effects: Gaia-WISE Gaussian Matches



Wilson & Naylor, MNRAS, 2018b, 481, 2148

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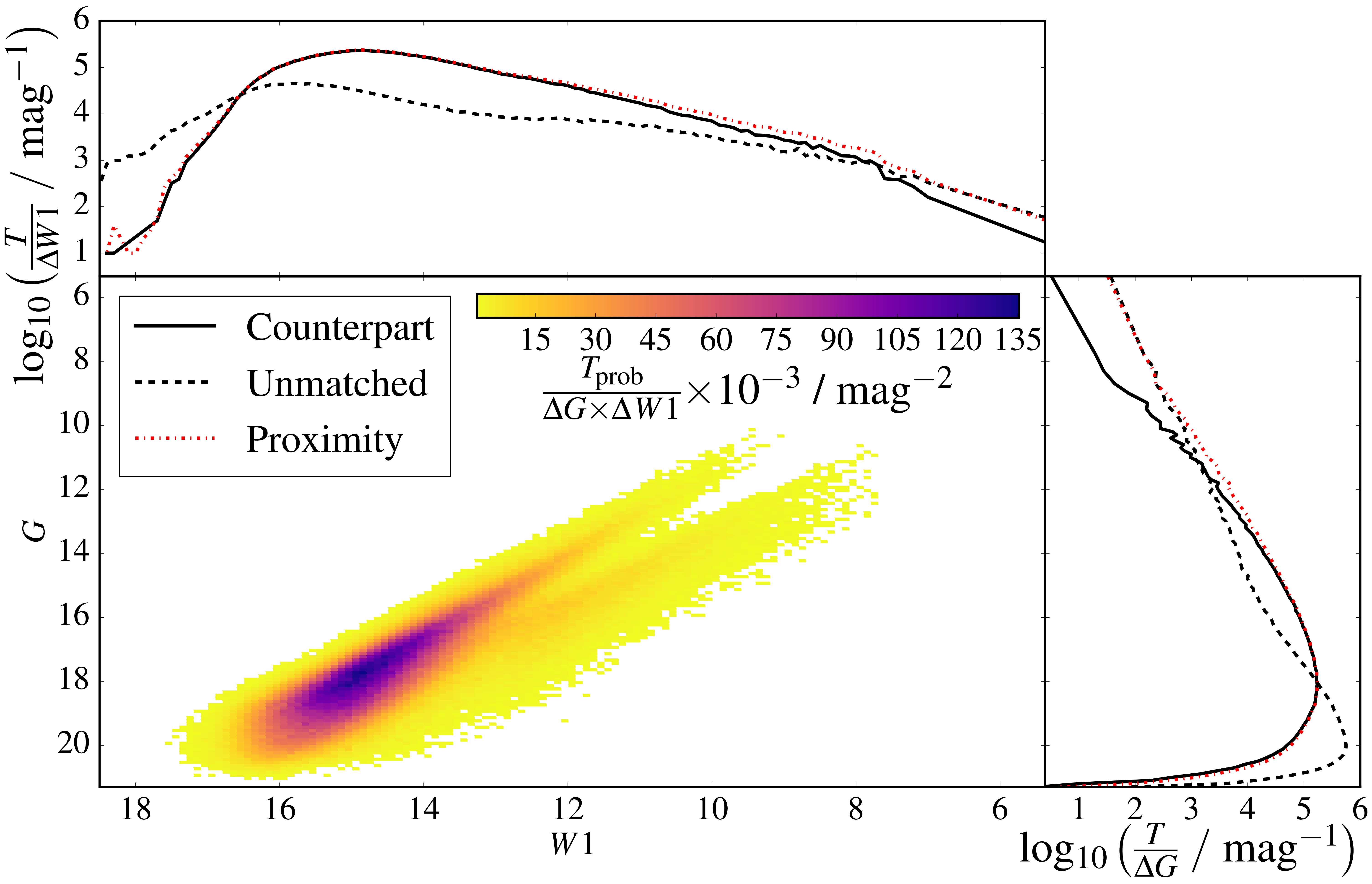
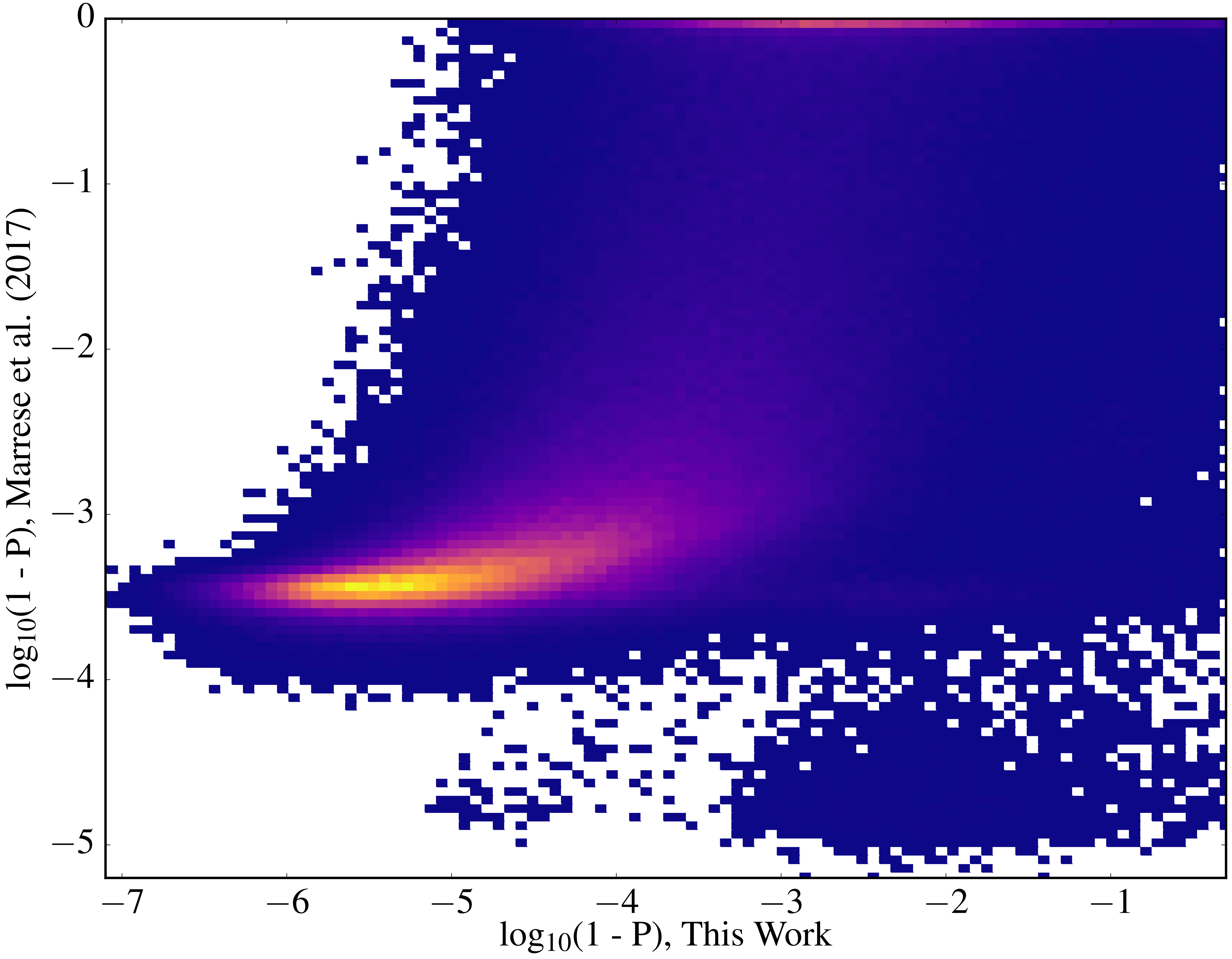
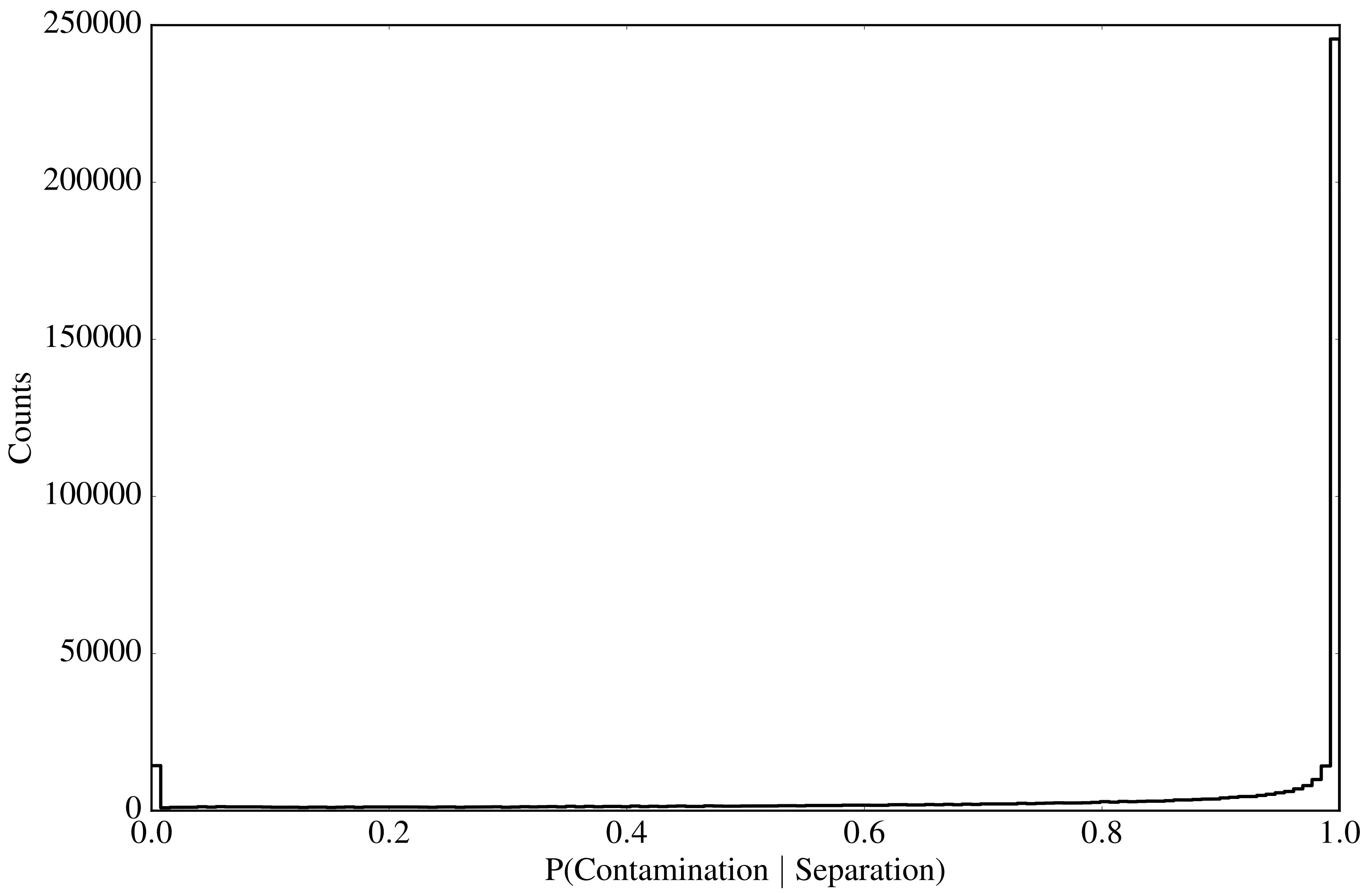
Contamination Effects: Gaia-WISE Empirical Matches

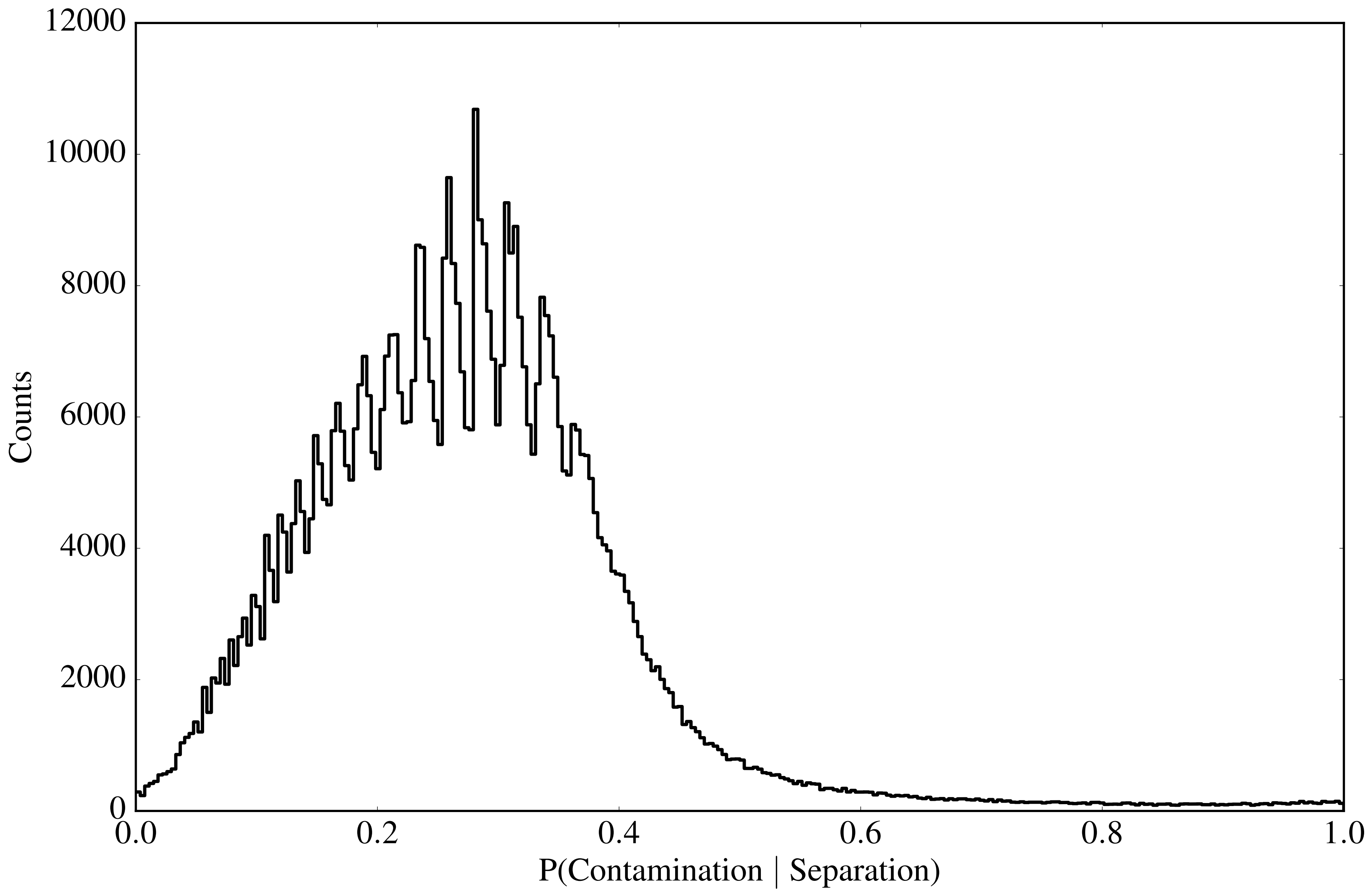


Contamination Effects: Gaia Lost Matches



Photometric Contamination: WISE/Spitzer Contamination %





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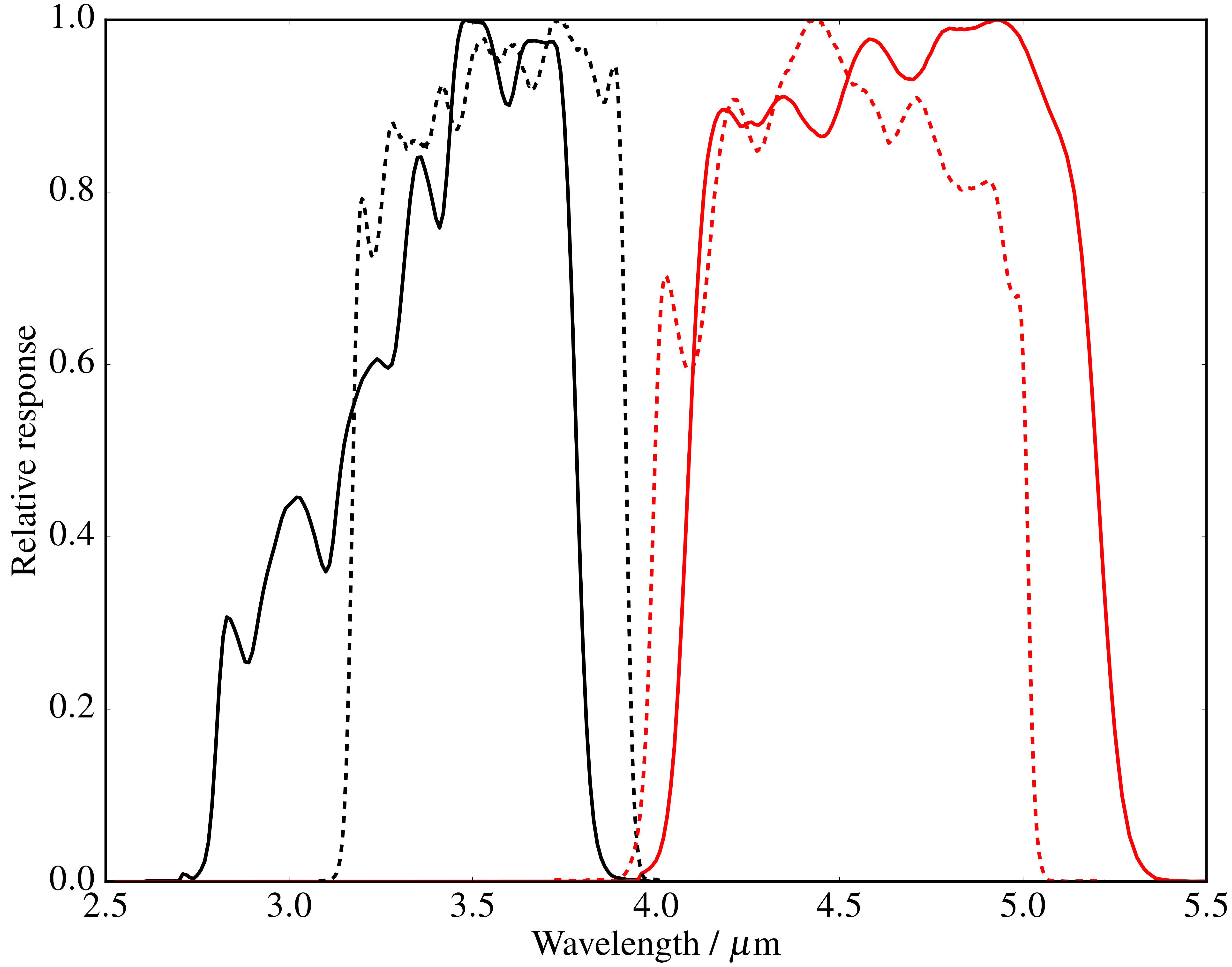
Contamination Effects: Wavelength Coverage



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The Astrometric Uncertainty Function: Analytical perturbations