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# Towards Solving the Catalogue Cross-Match Problem


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Alternatively — Space Is Crowded, Or: How I Learned To Start Worrying and Hate the Mess

UNIVERSITY OF EXETER

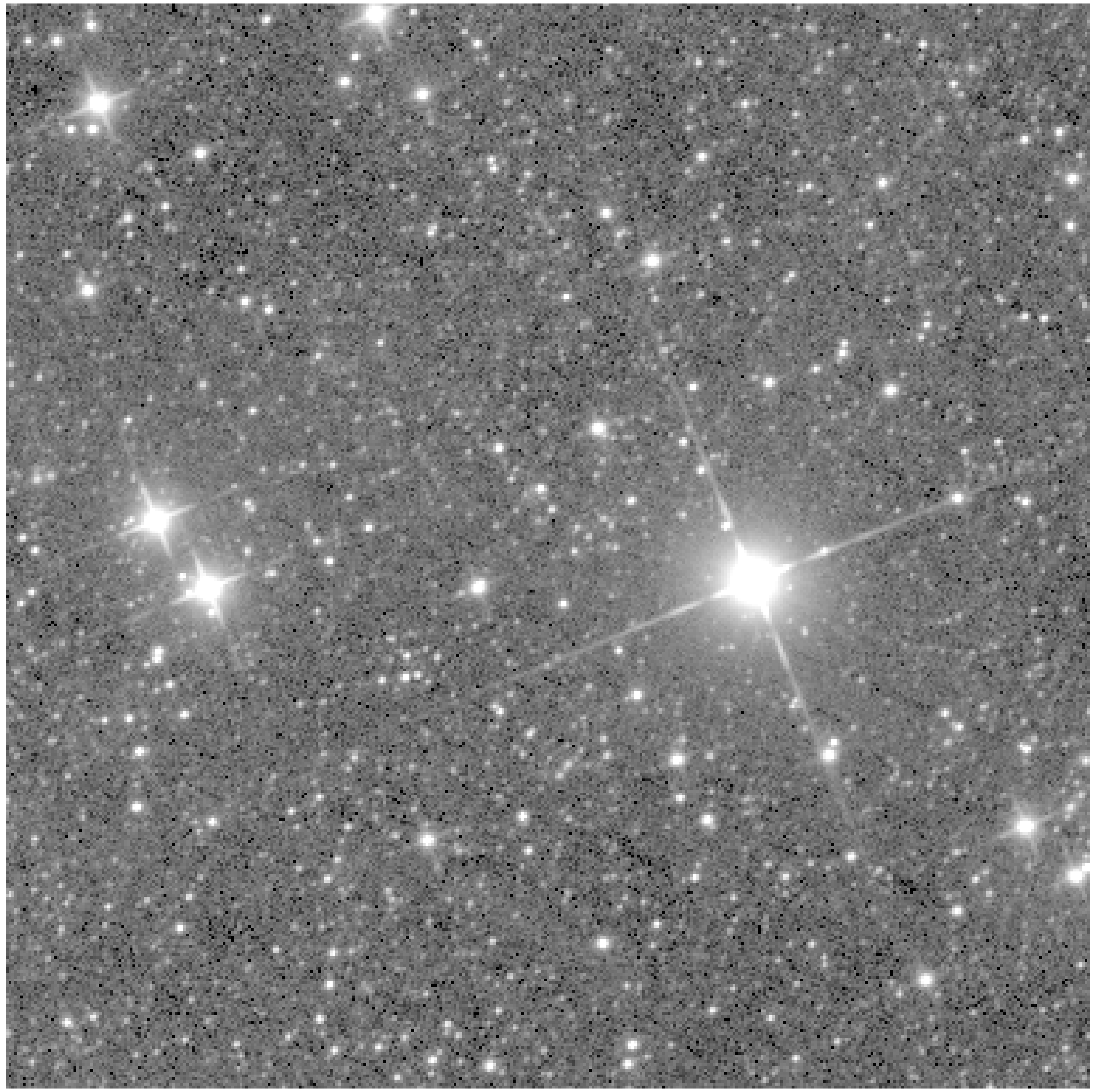
LSST:UK Consortium

VERA C. RUBIN OBSERVATORY

Macauff

@Onoddil @pm.me .github.io

# Photometric Observations



*WISE* - Wright et al. (2010)

*WISE* W1

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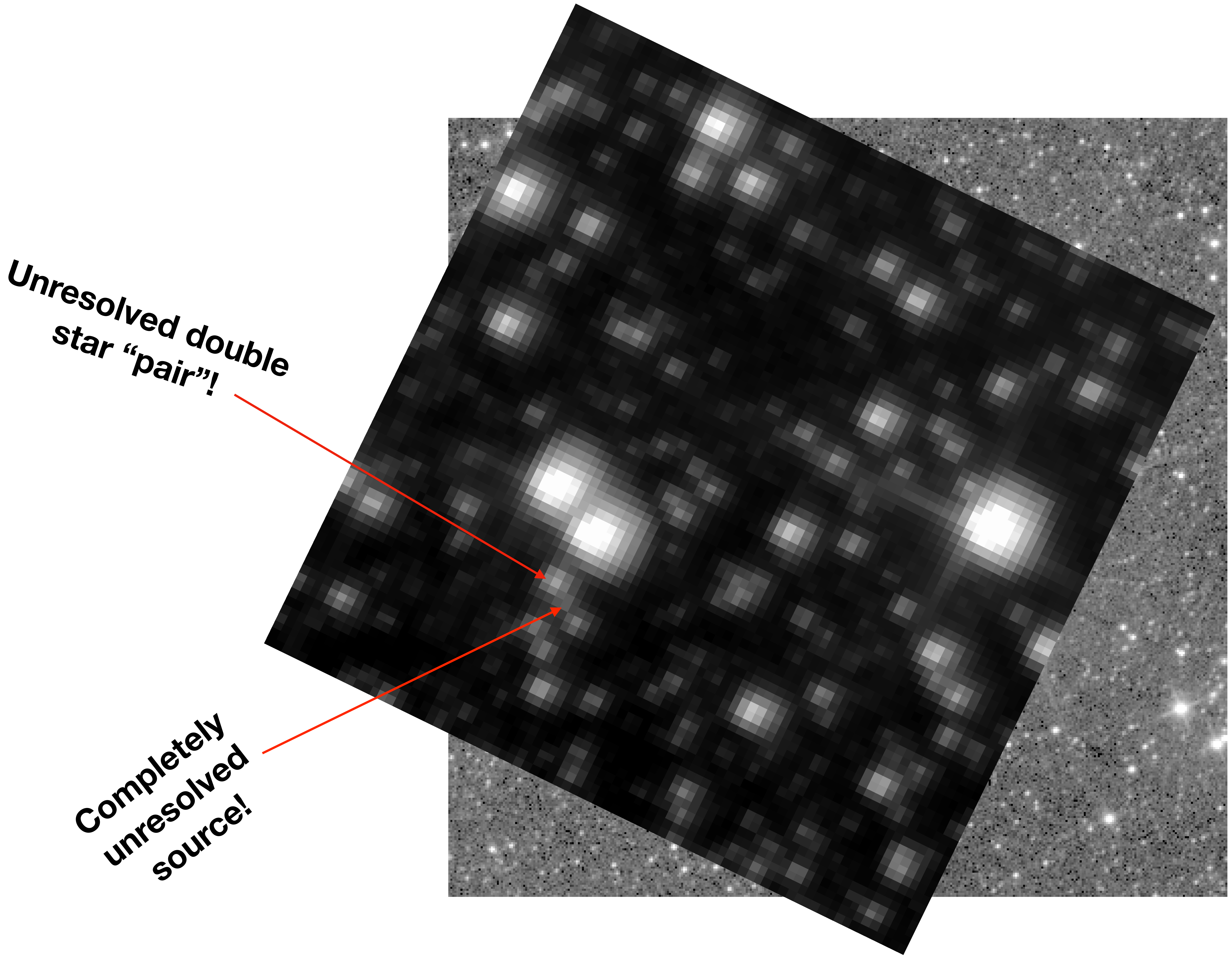
# Photometric Observations




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

*TESS* T

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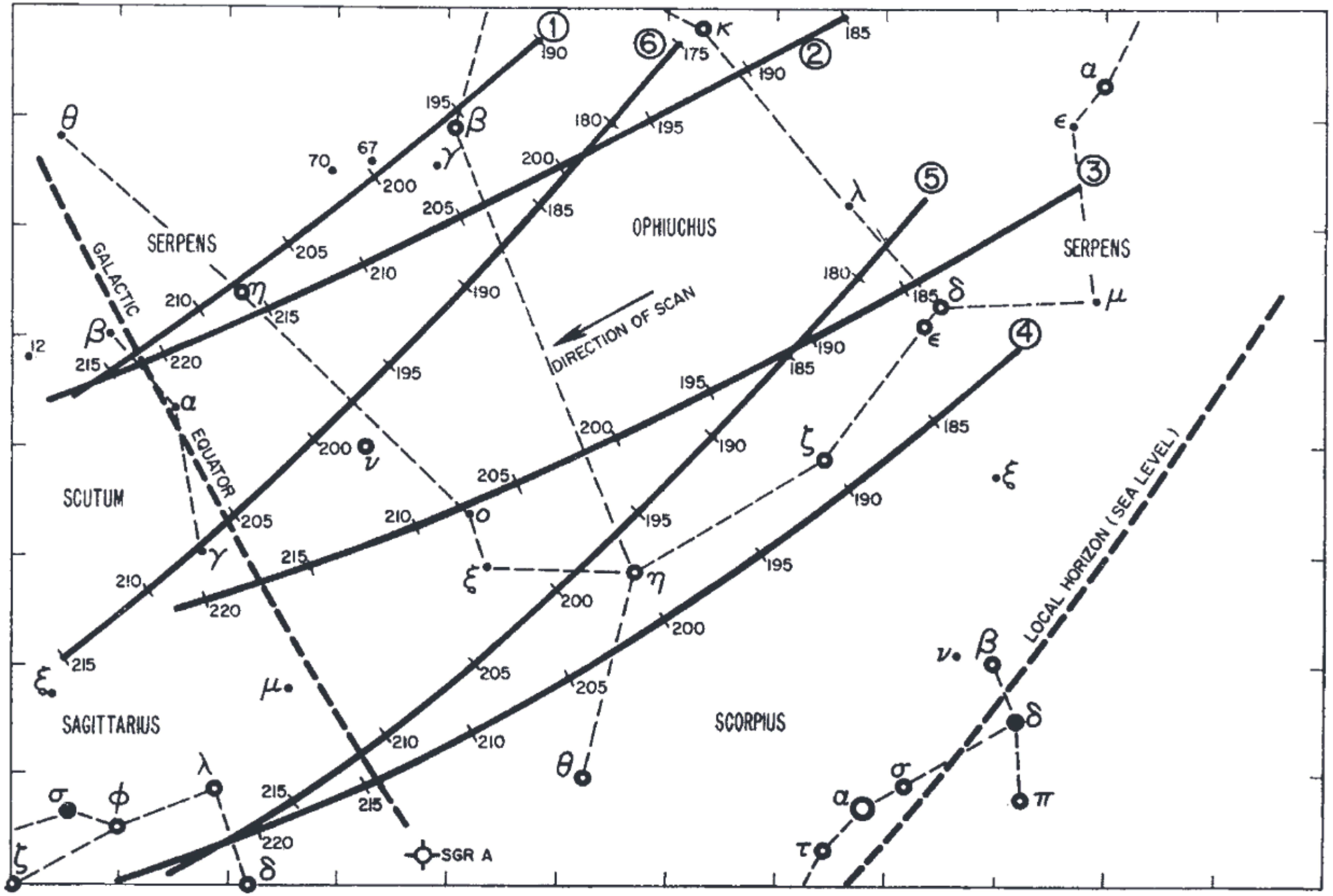
# Matching Constellations

Image credit: Mouser, wikimedia

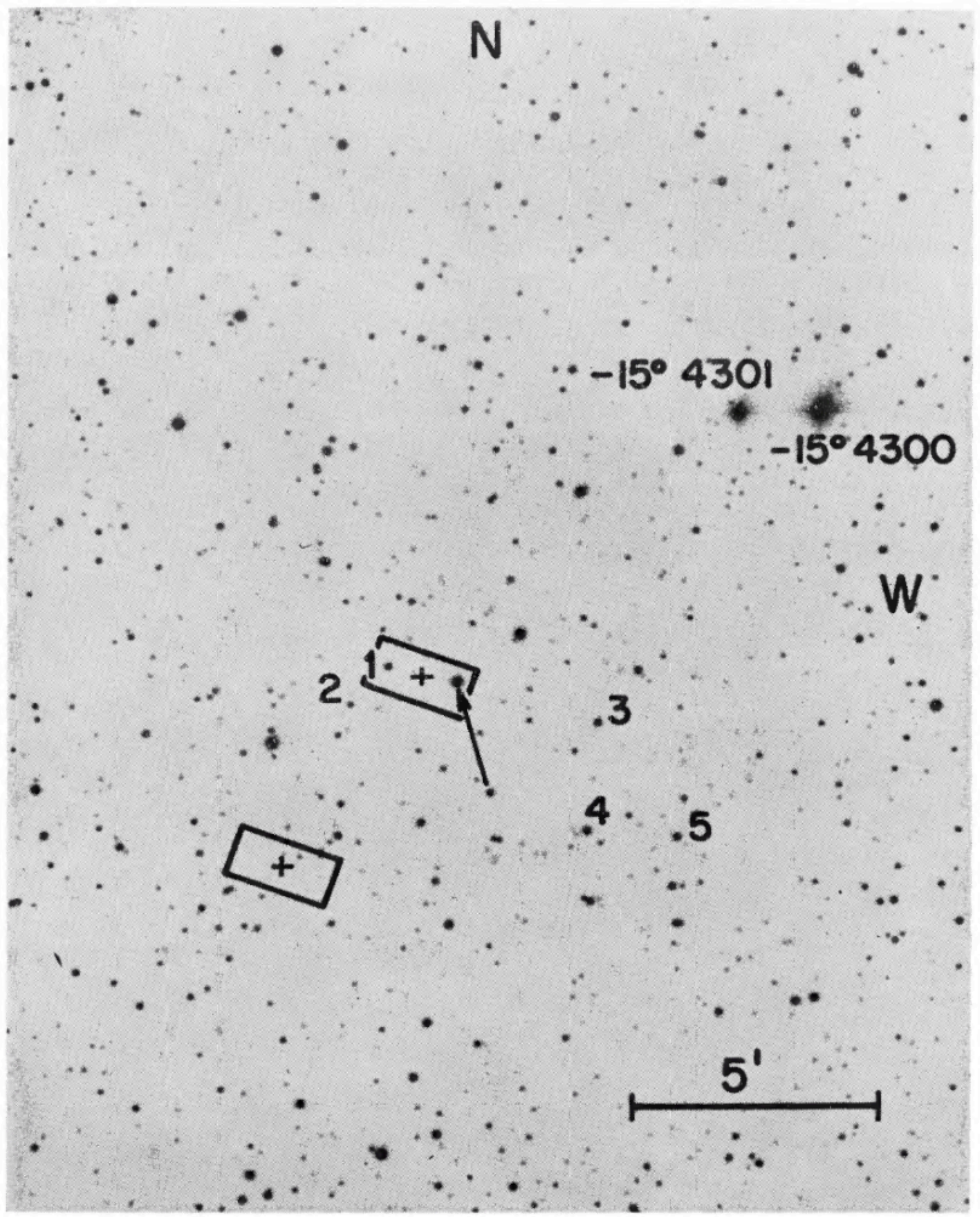
# Technology Abounds

- 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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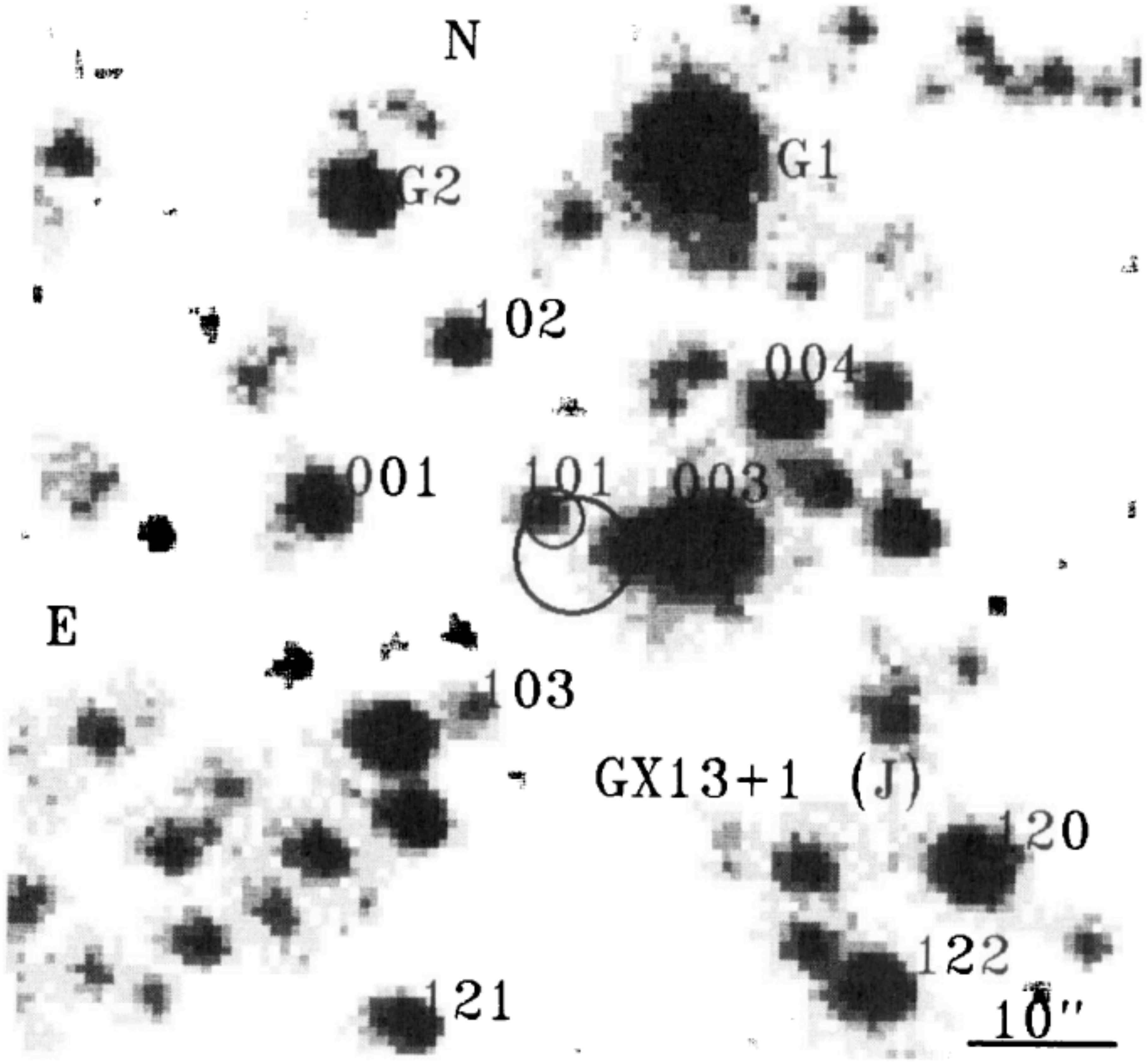
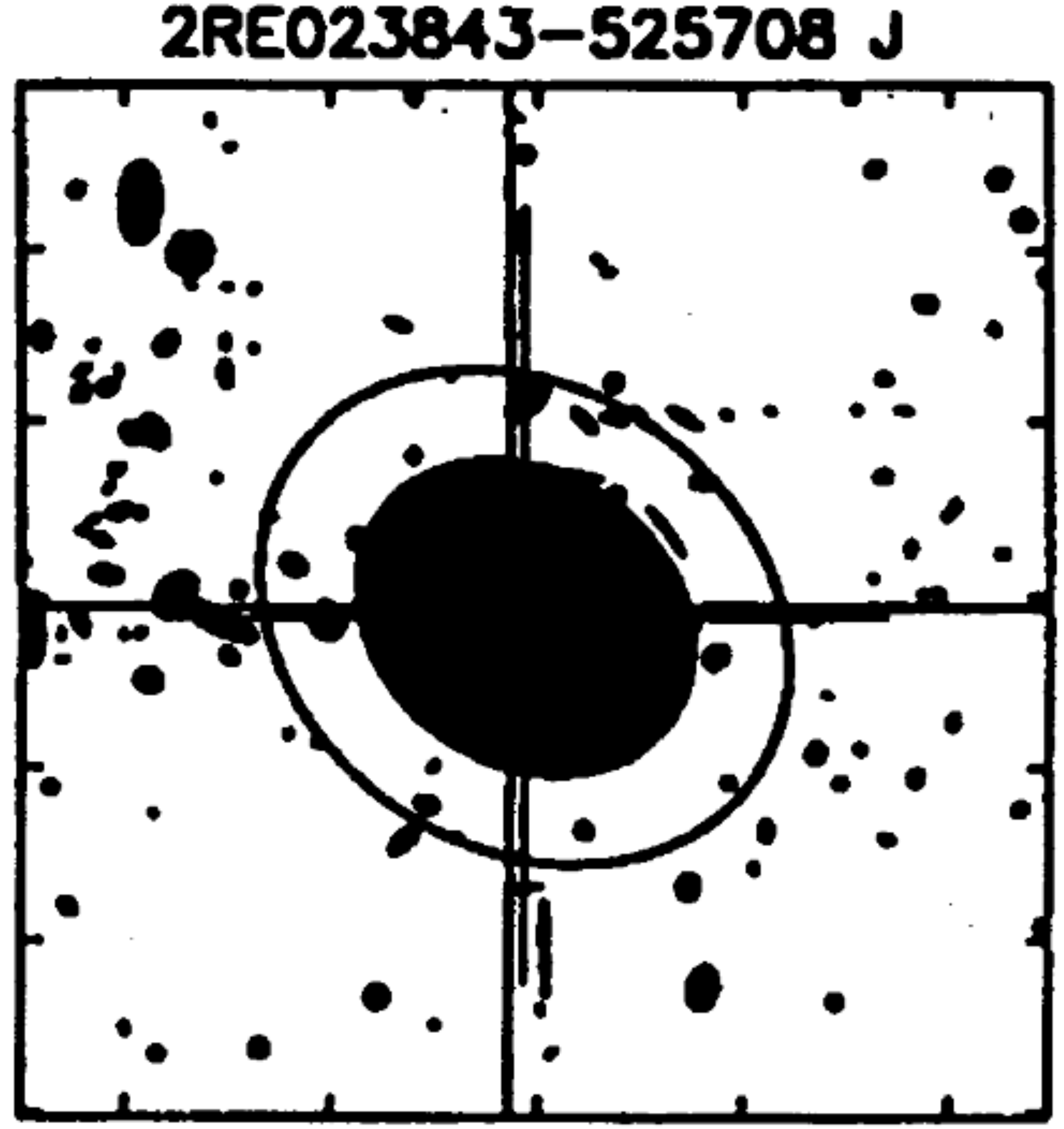
# The Brightest Star in the Sky




Naylor, Charles, & Longmore (1991)

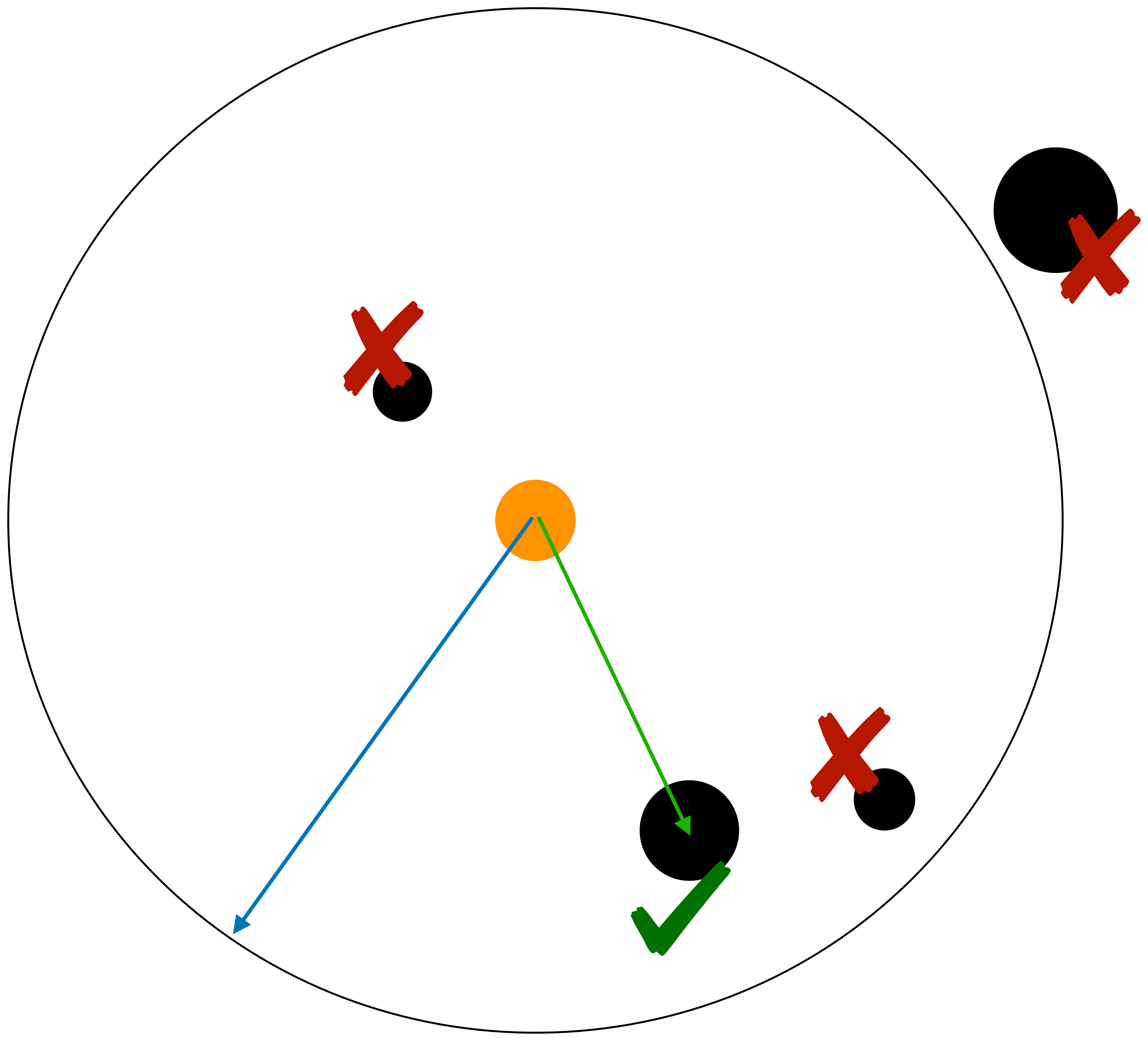


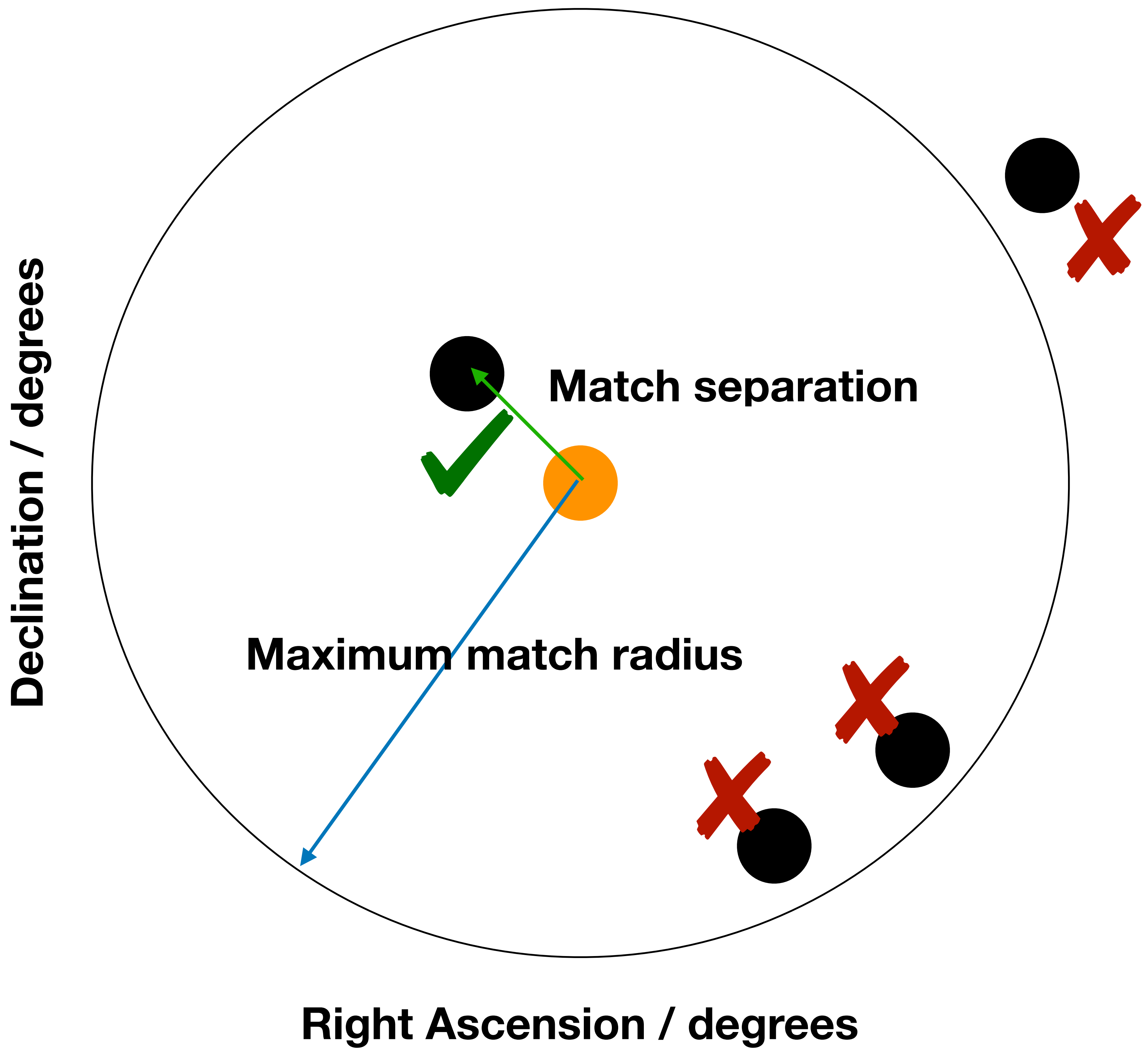

Mason et al. (1995)

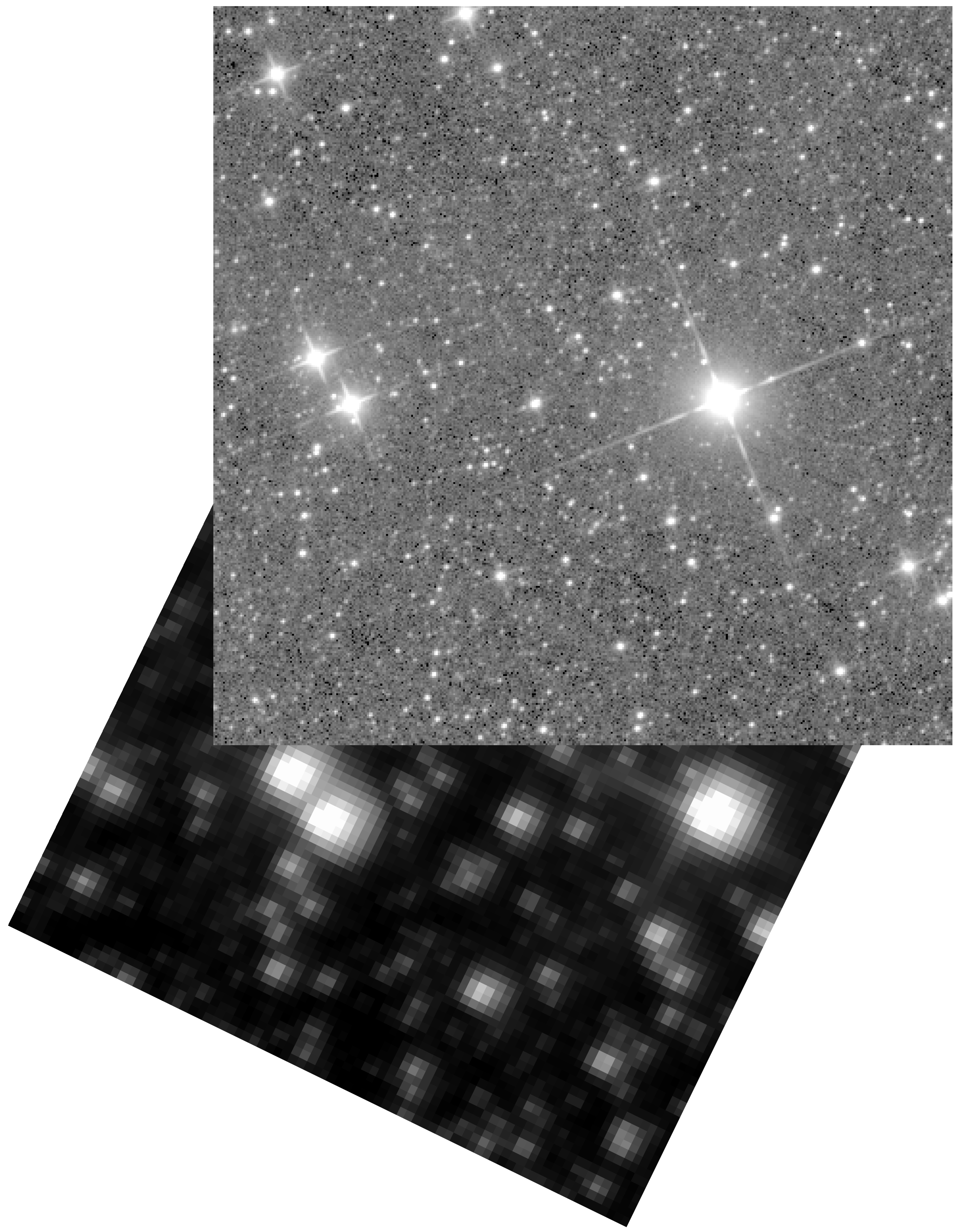
"...X-ray sources are rare events; bright optical sources are also rare events, so the observation of an X-ray source and a bright optical source in the same region of the sky is considered a non-random event"

Fotopoulou et al. (2016)

# “Traditional” Cross-Matching





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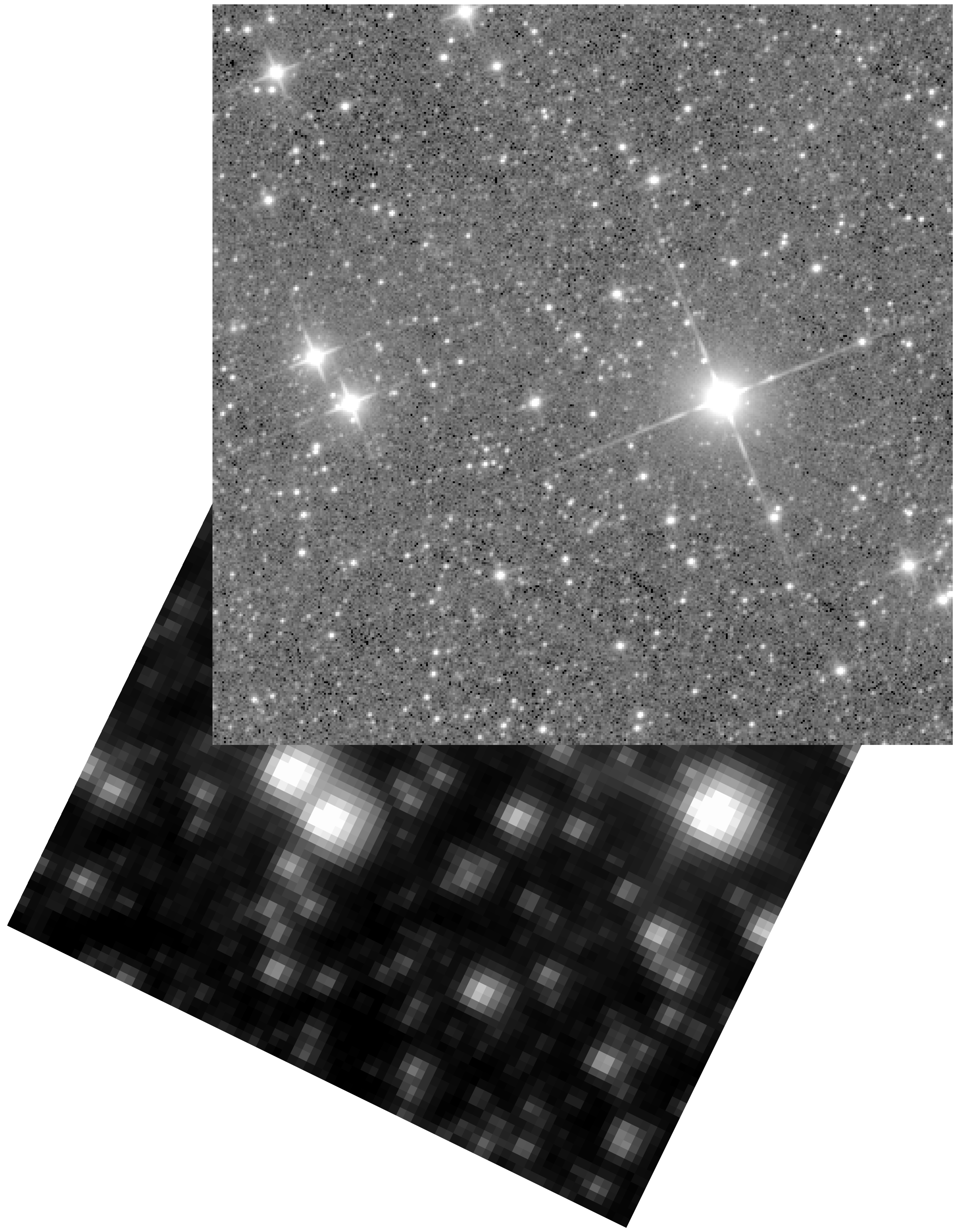
# The Astronomy Error Function



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

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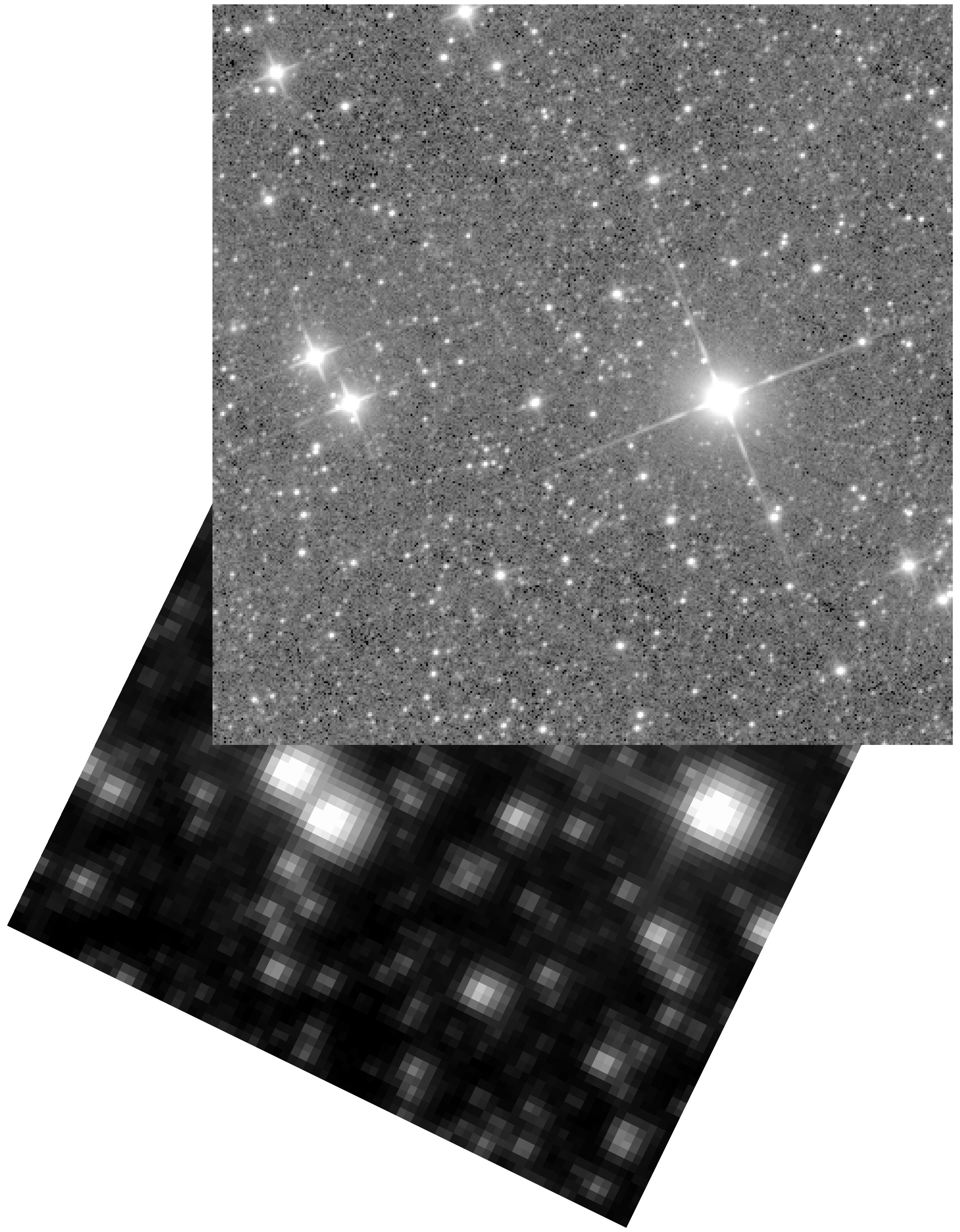

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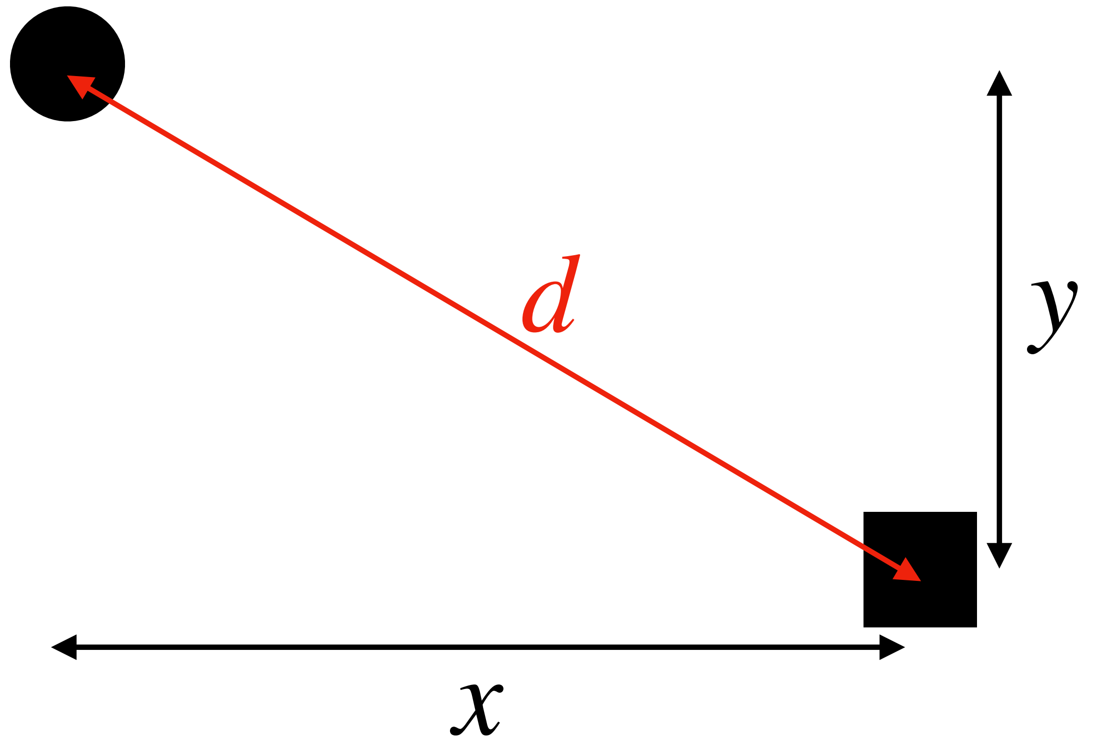


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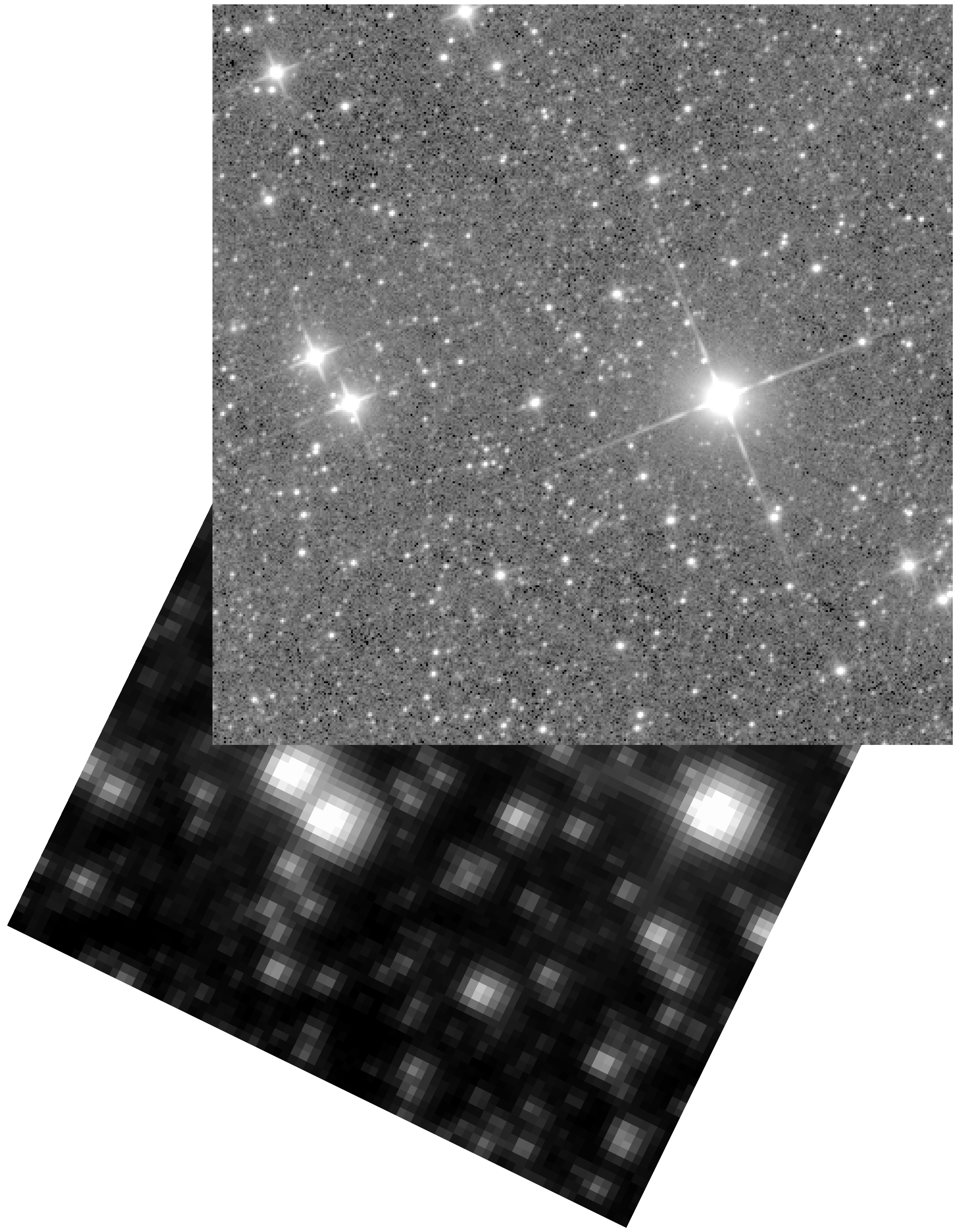

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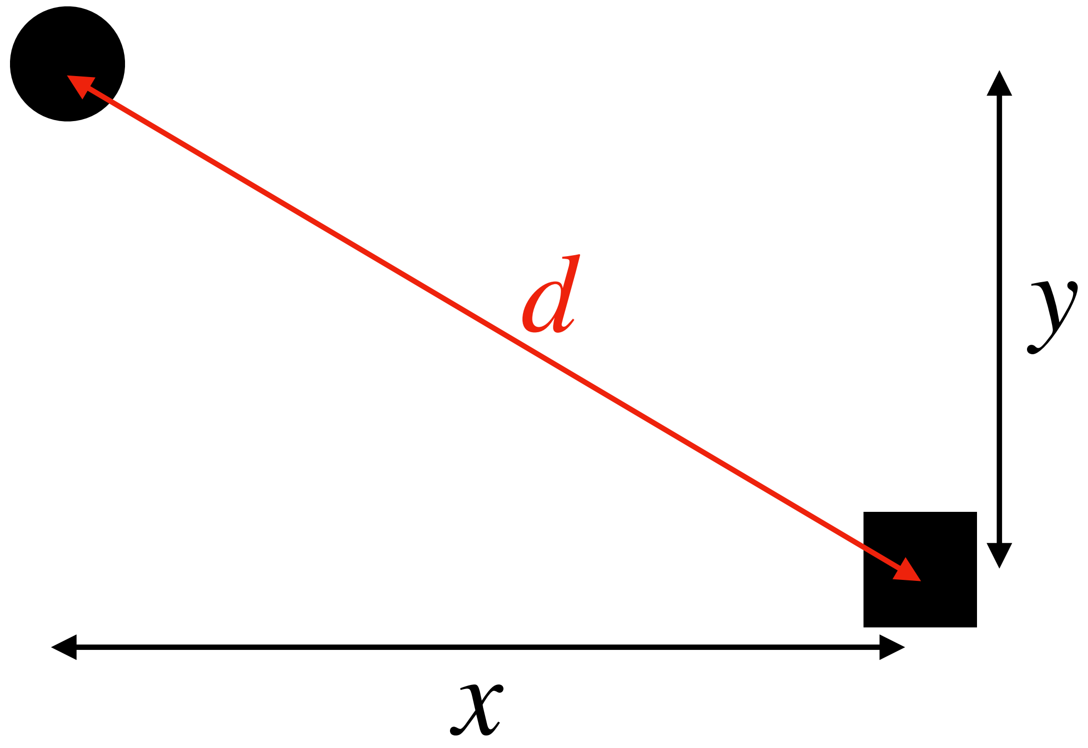


$$p(d^2) = p(x^2 + y^2) = p(x^2)\,p(y^2)$$

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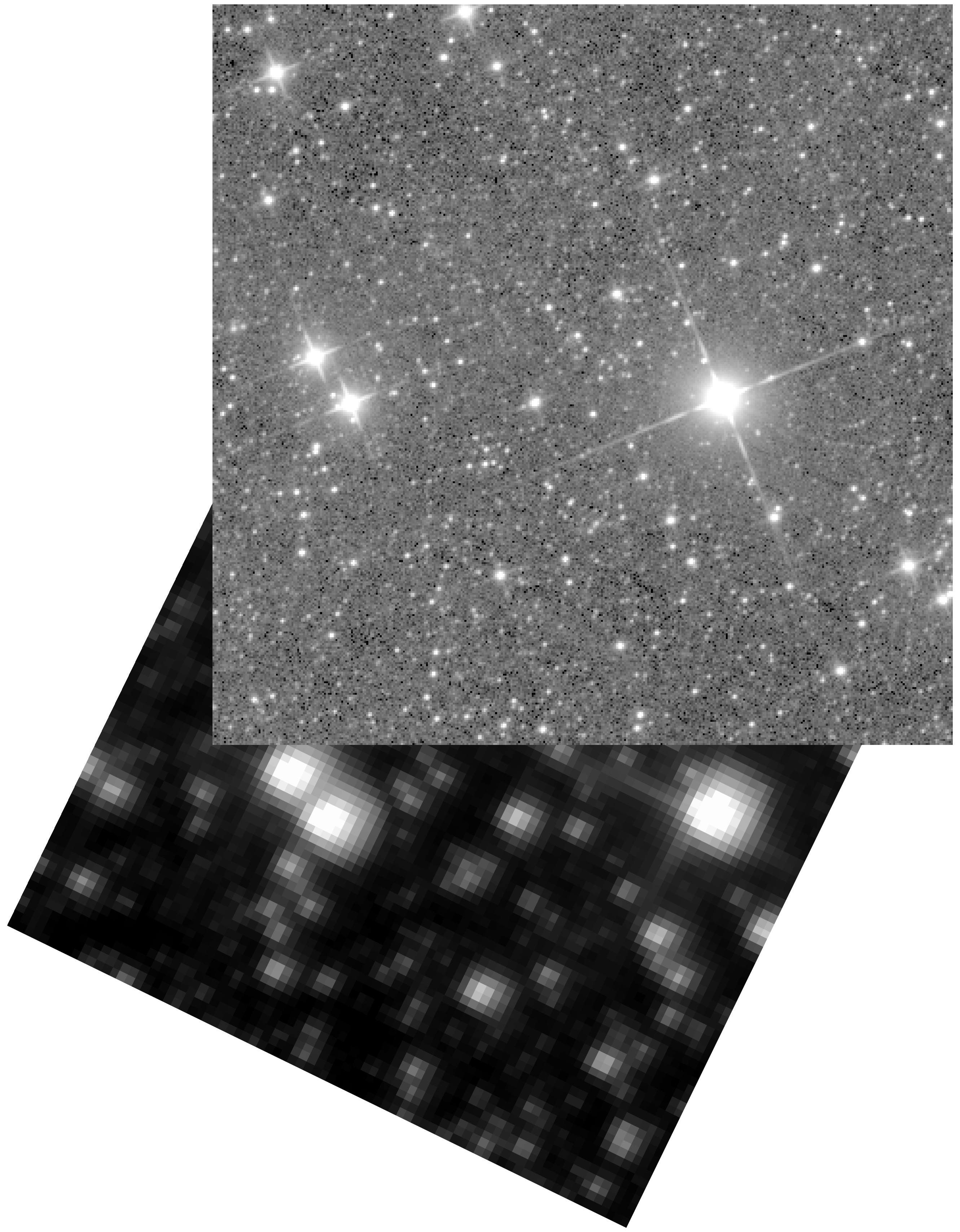

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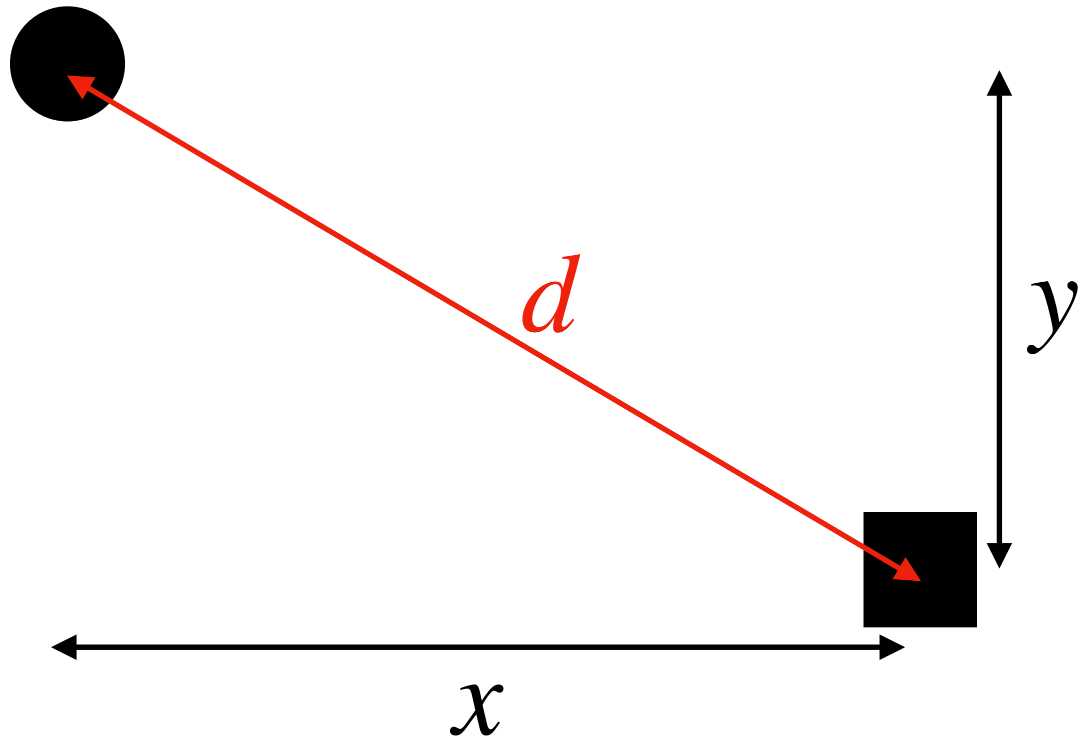


$$p(d^2) = p(x^2 + y^2) = p(x^2)\,p(y^2)$$

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

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)

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

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

Wolstencroft et al. (1986)

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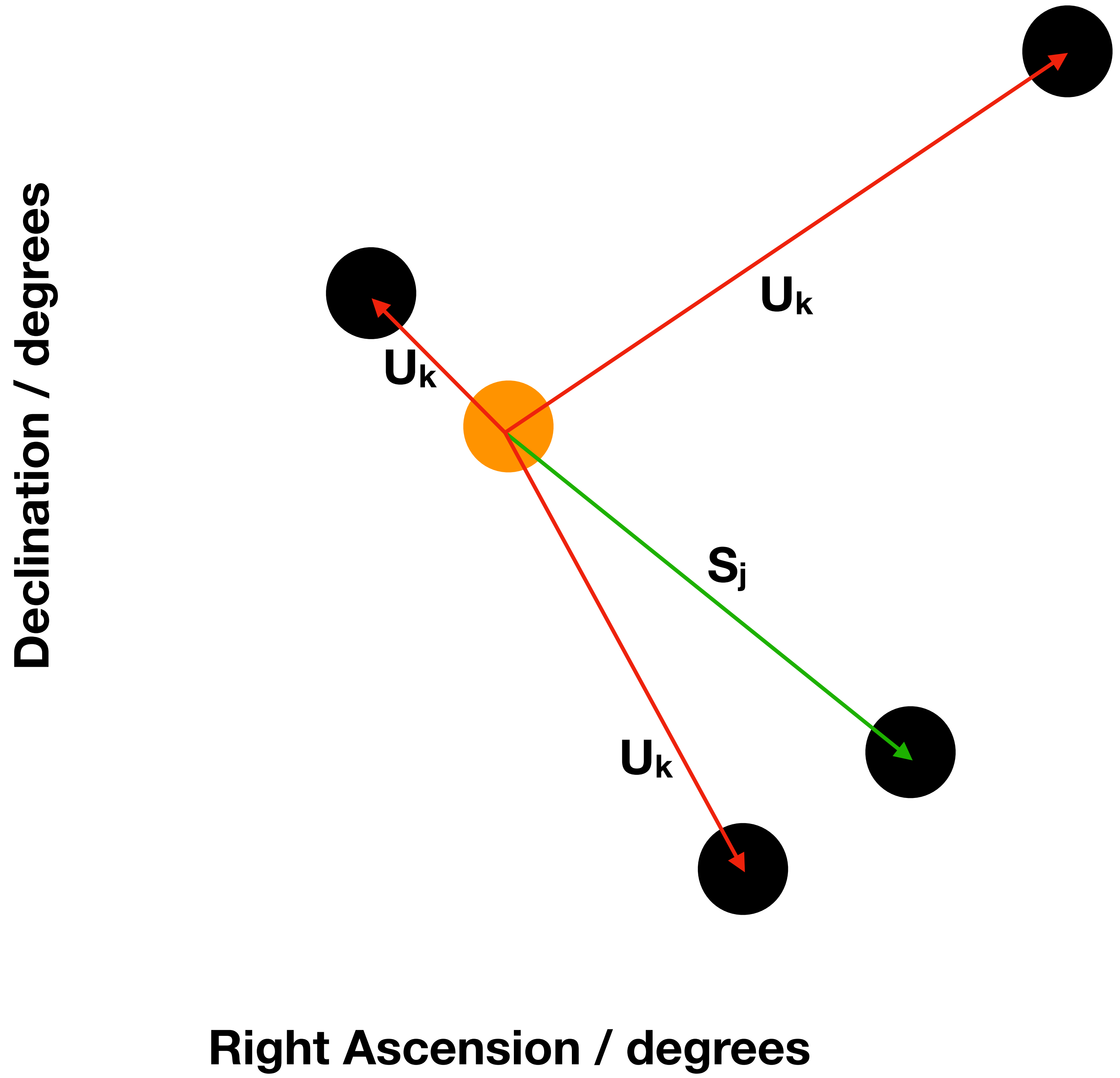
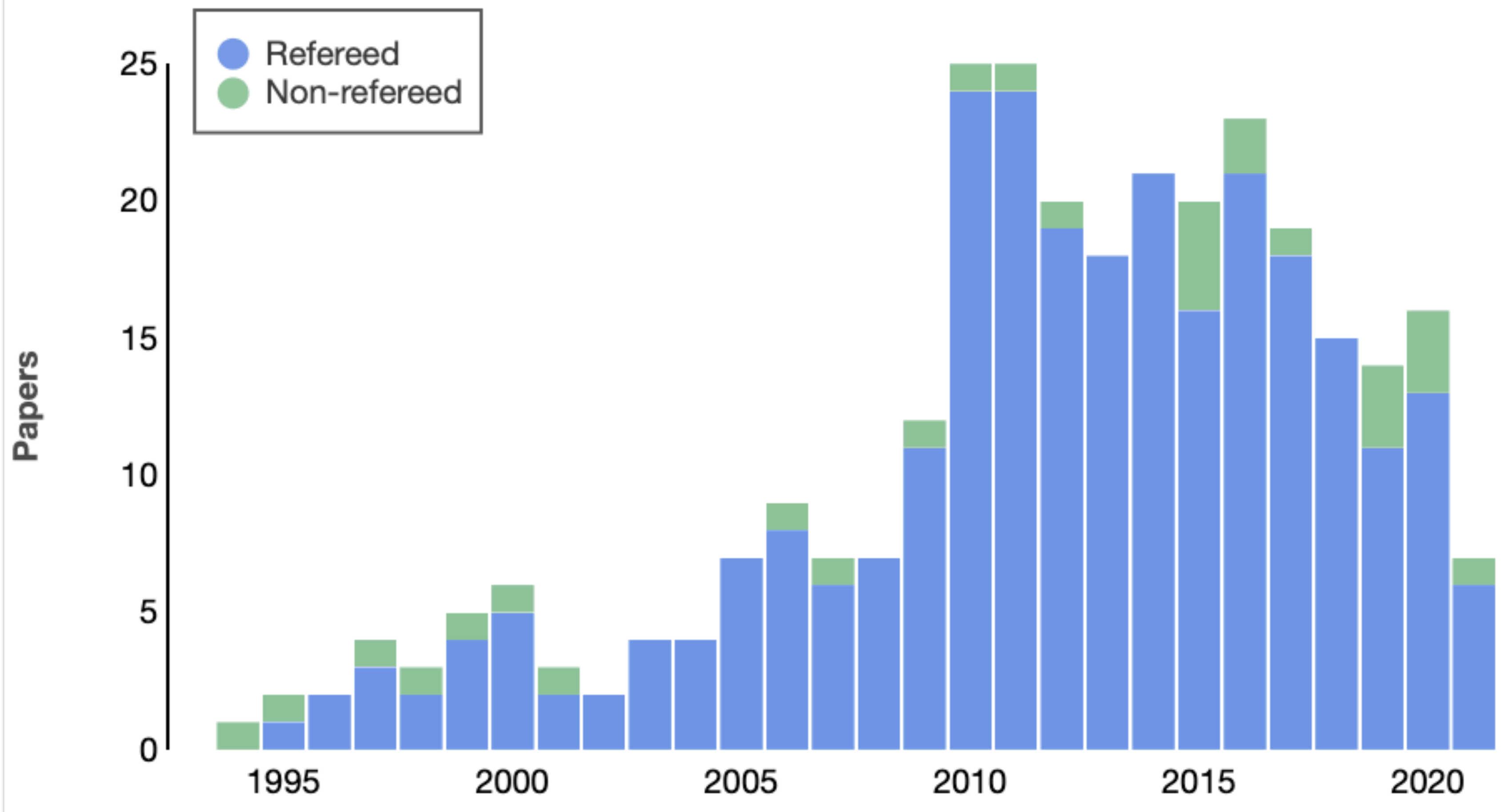
Wolstencroft et al. (1986)

## 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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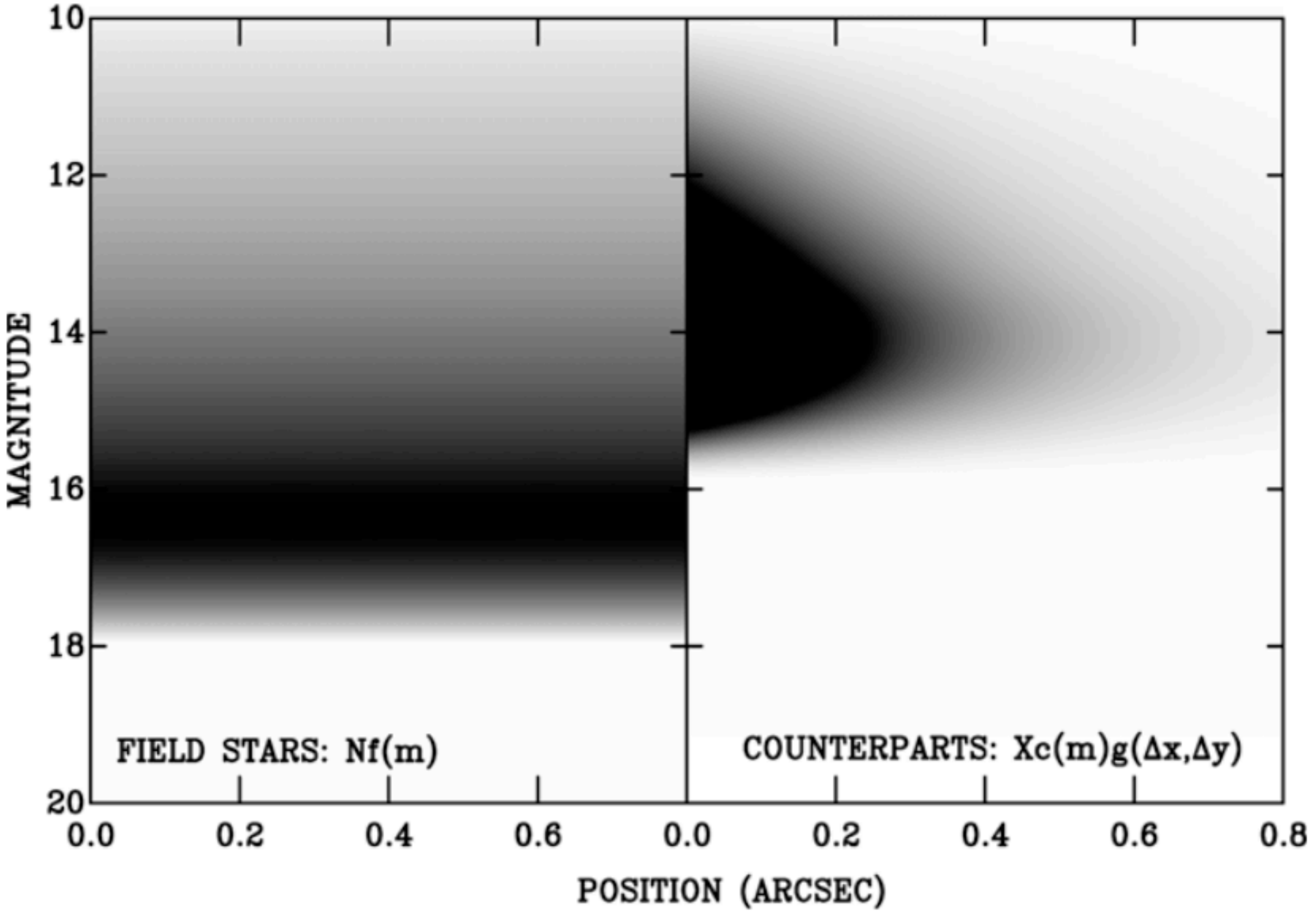
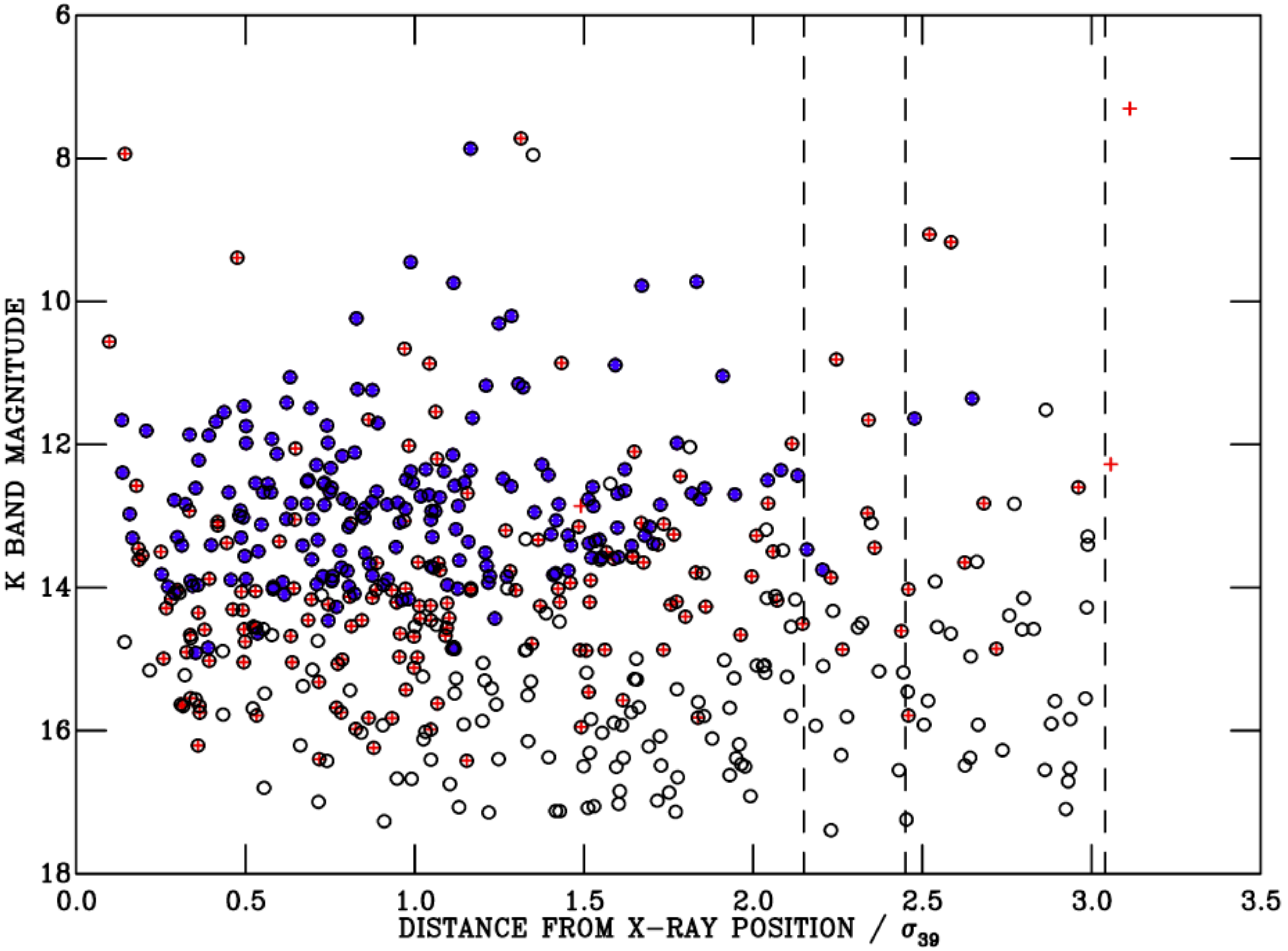
# Probabilistic Cross-Matching

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




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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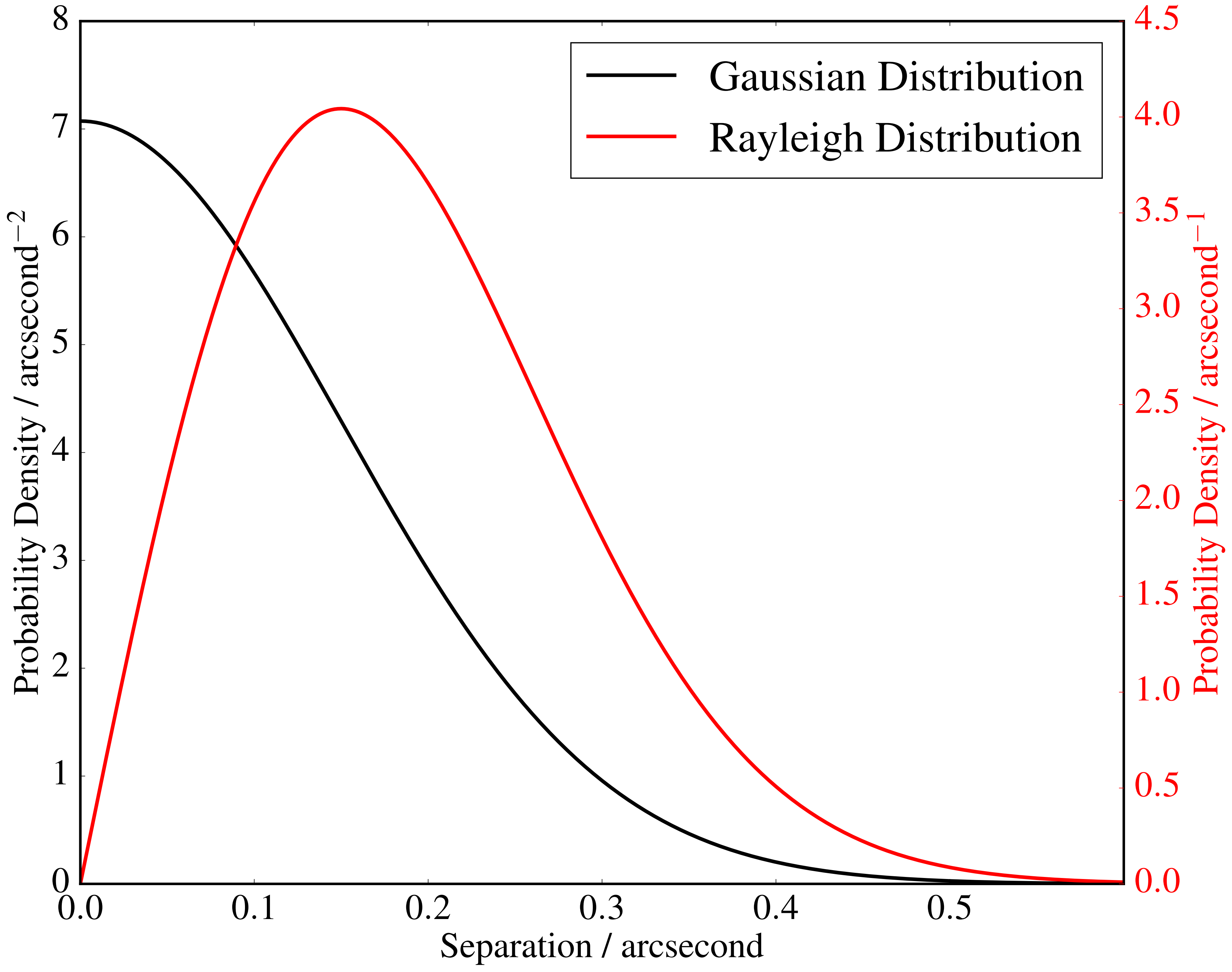
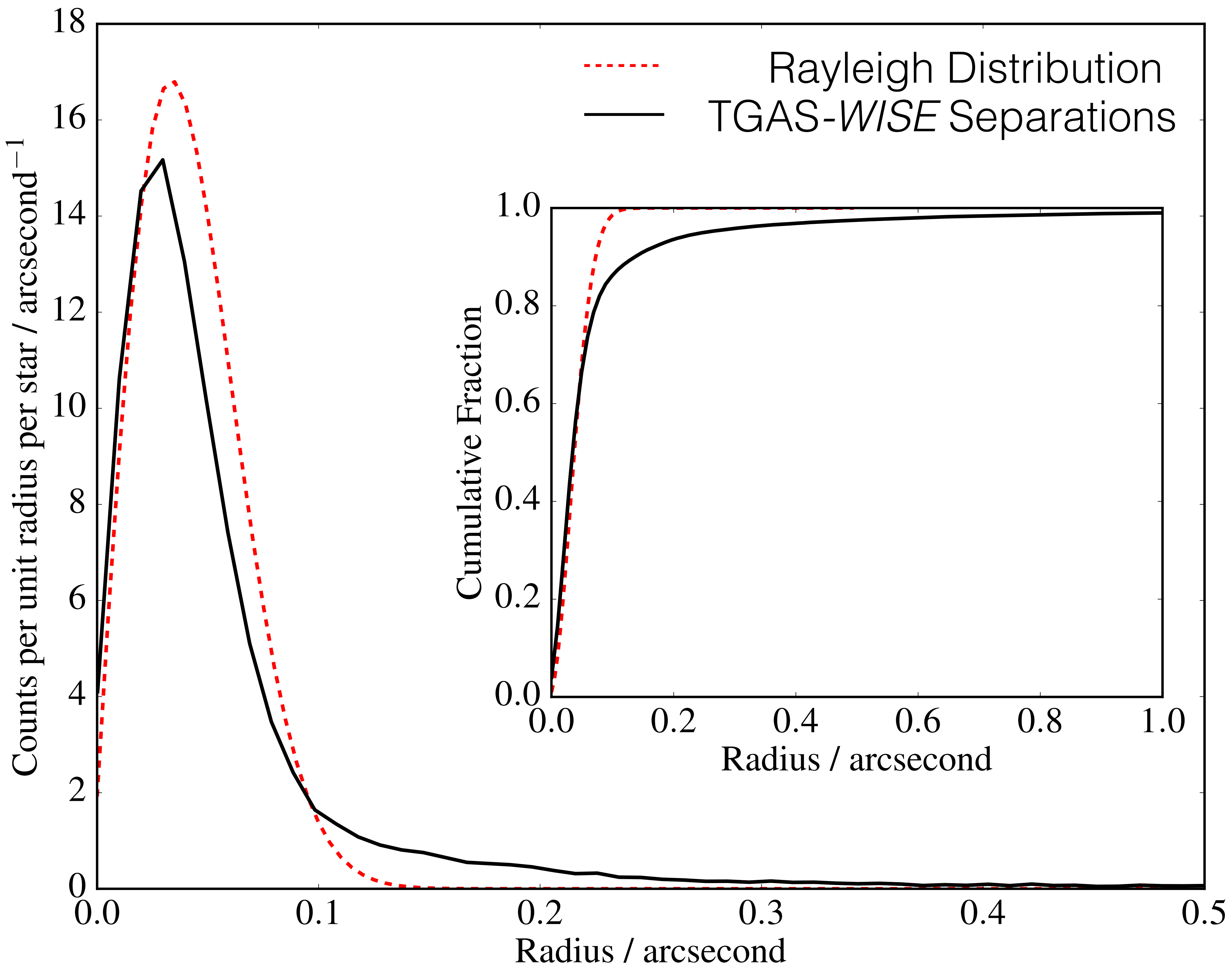
# The *Astrometric Uncertainty* Function

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

$$\downarrow$$

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




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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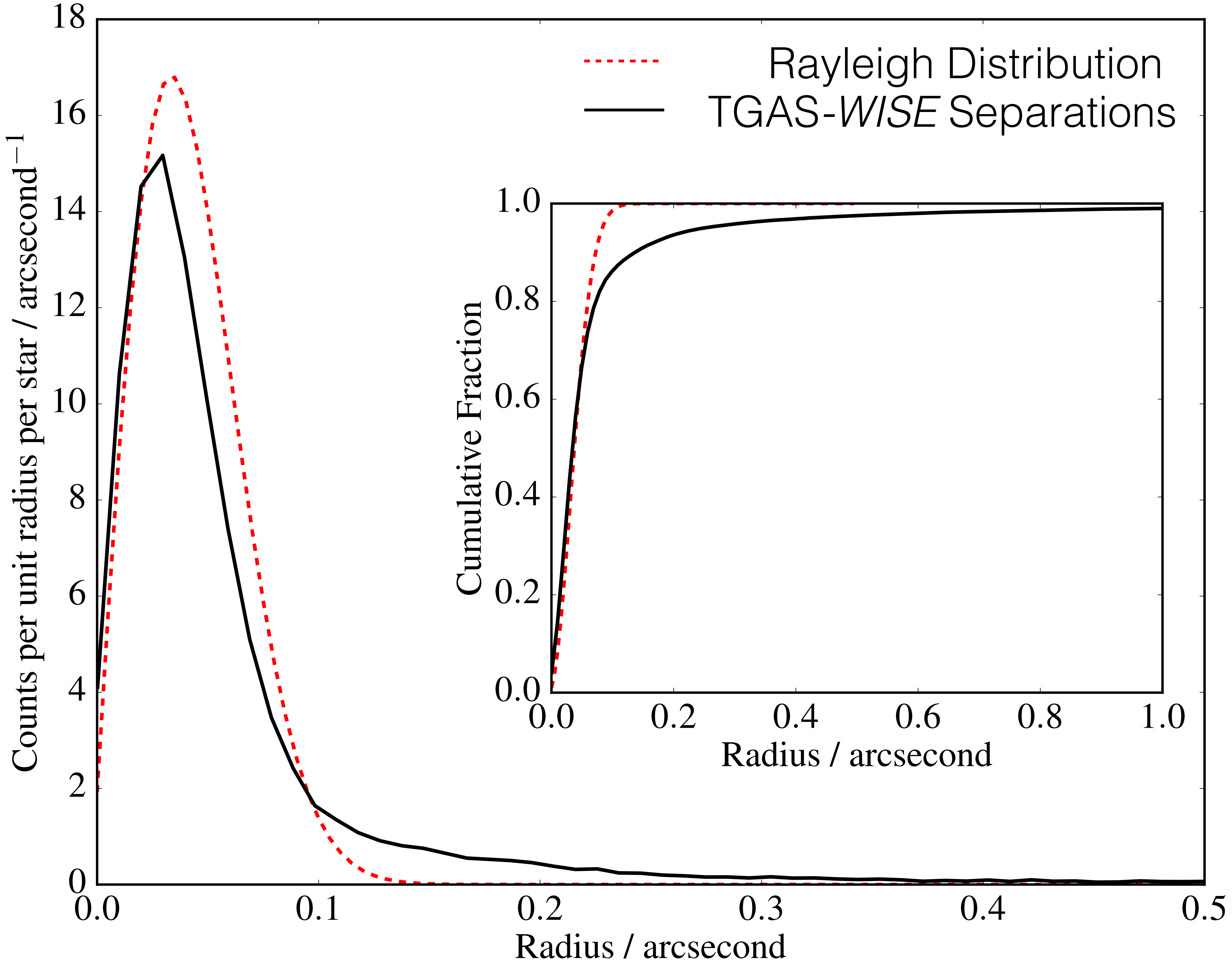
# The *Astrometric Uncertainty* Function

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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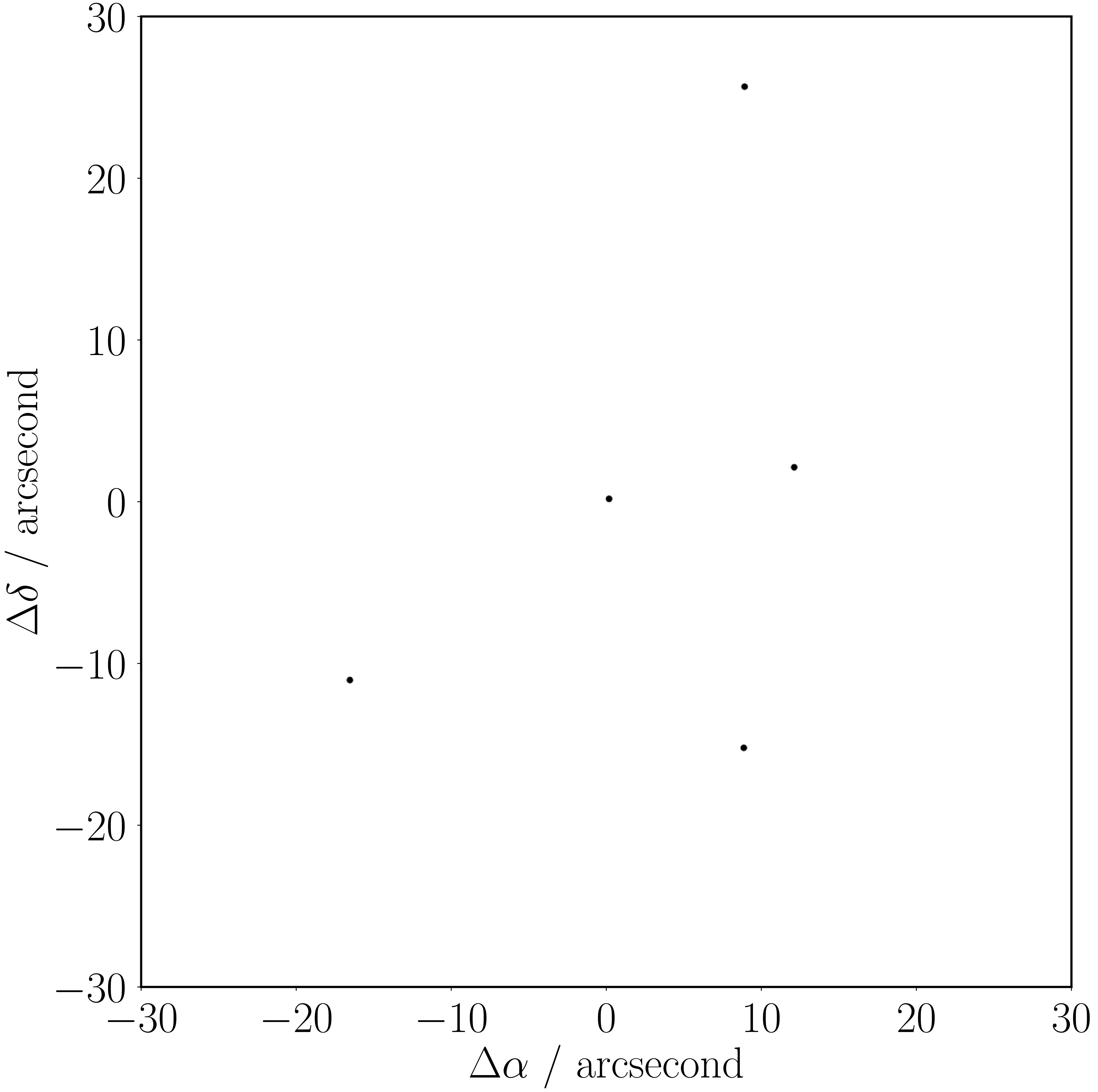
# The AUF: Crowding




Wilson & Naylor (2017)

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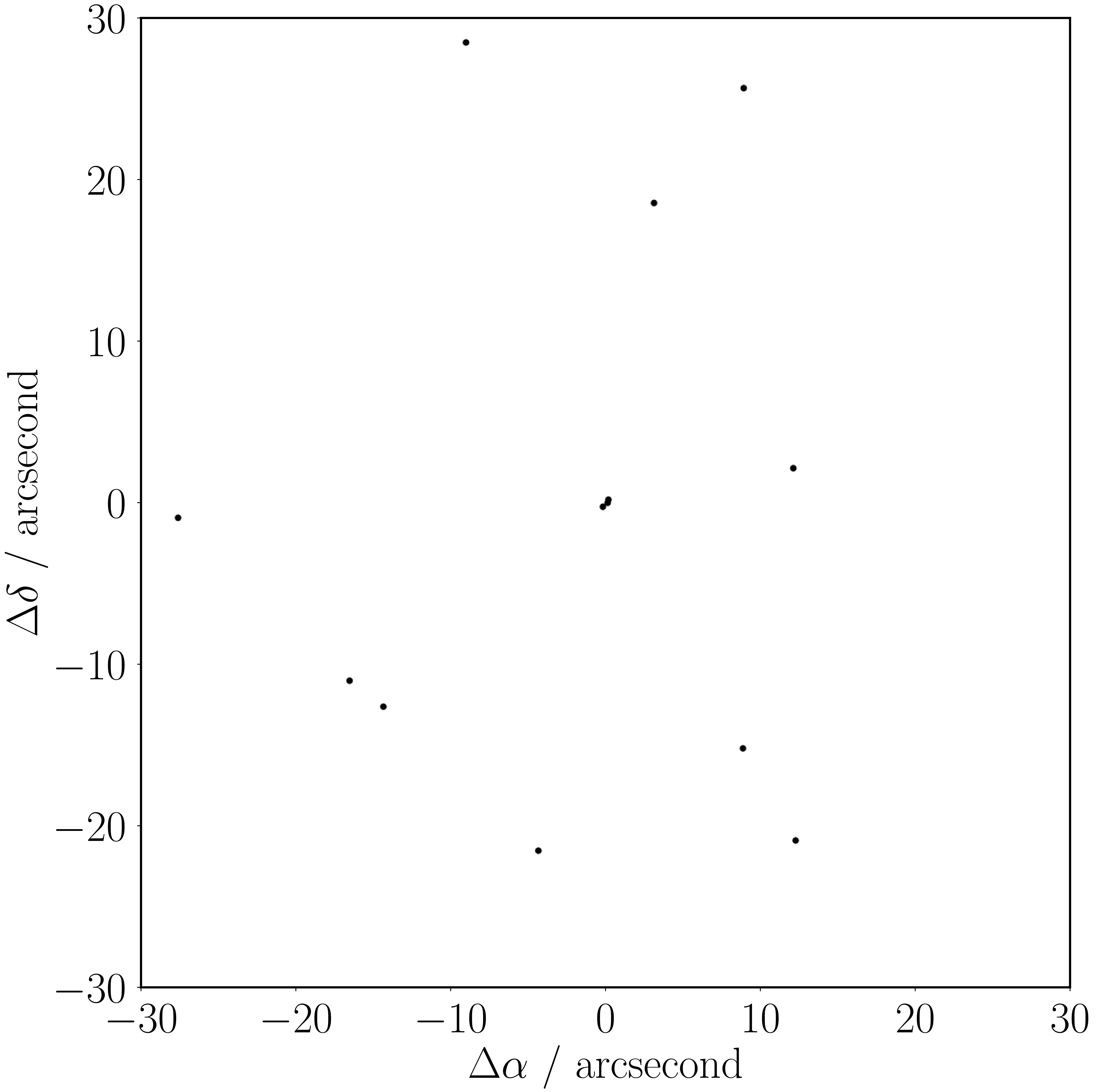


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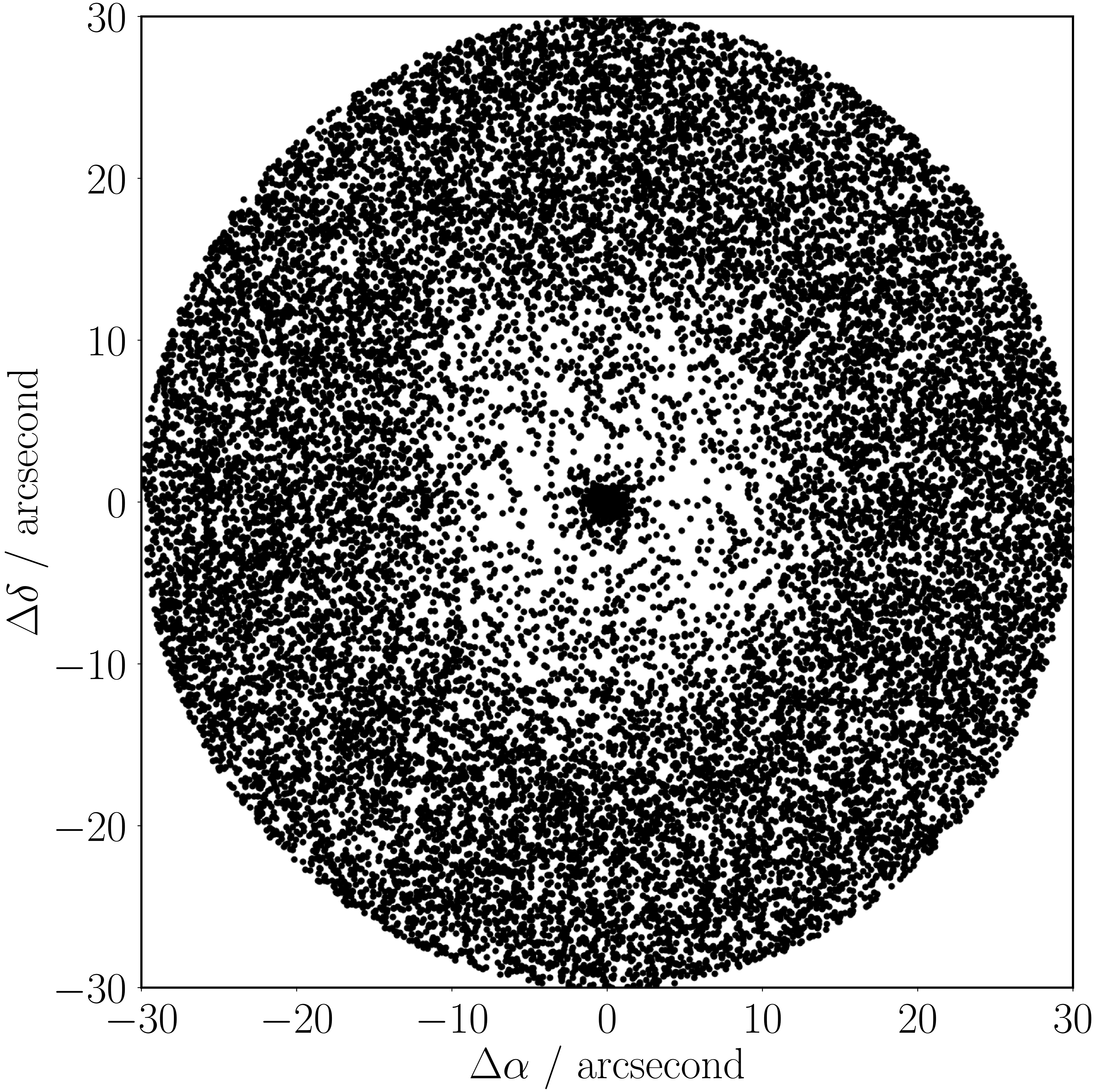
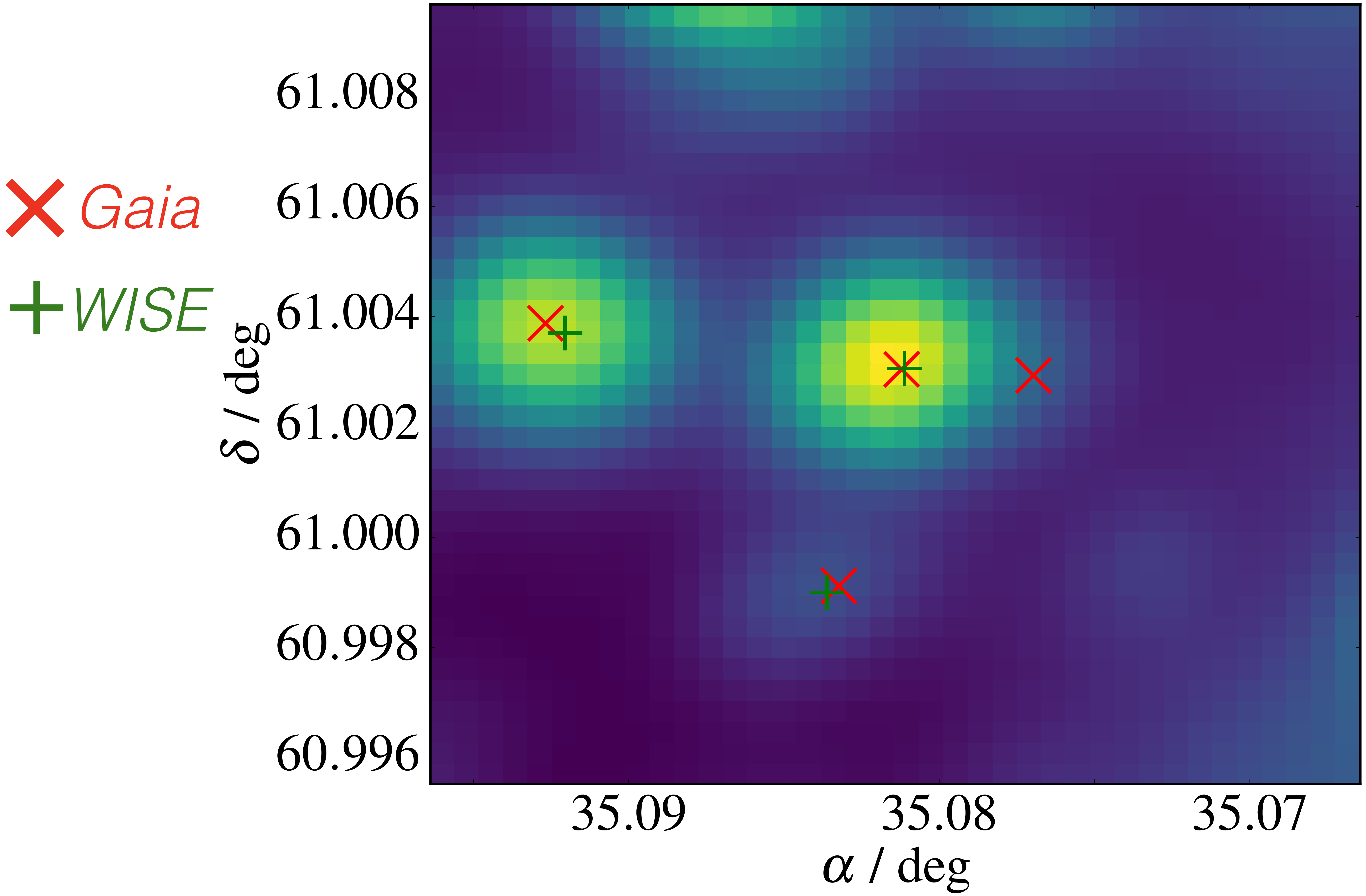



Wilson & Naylor (2017)

# 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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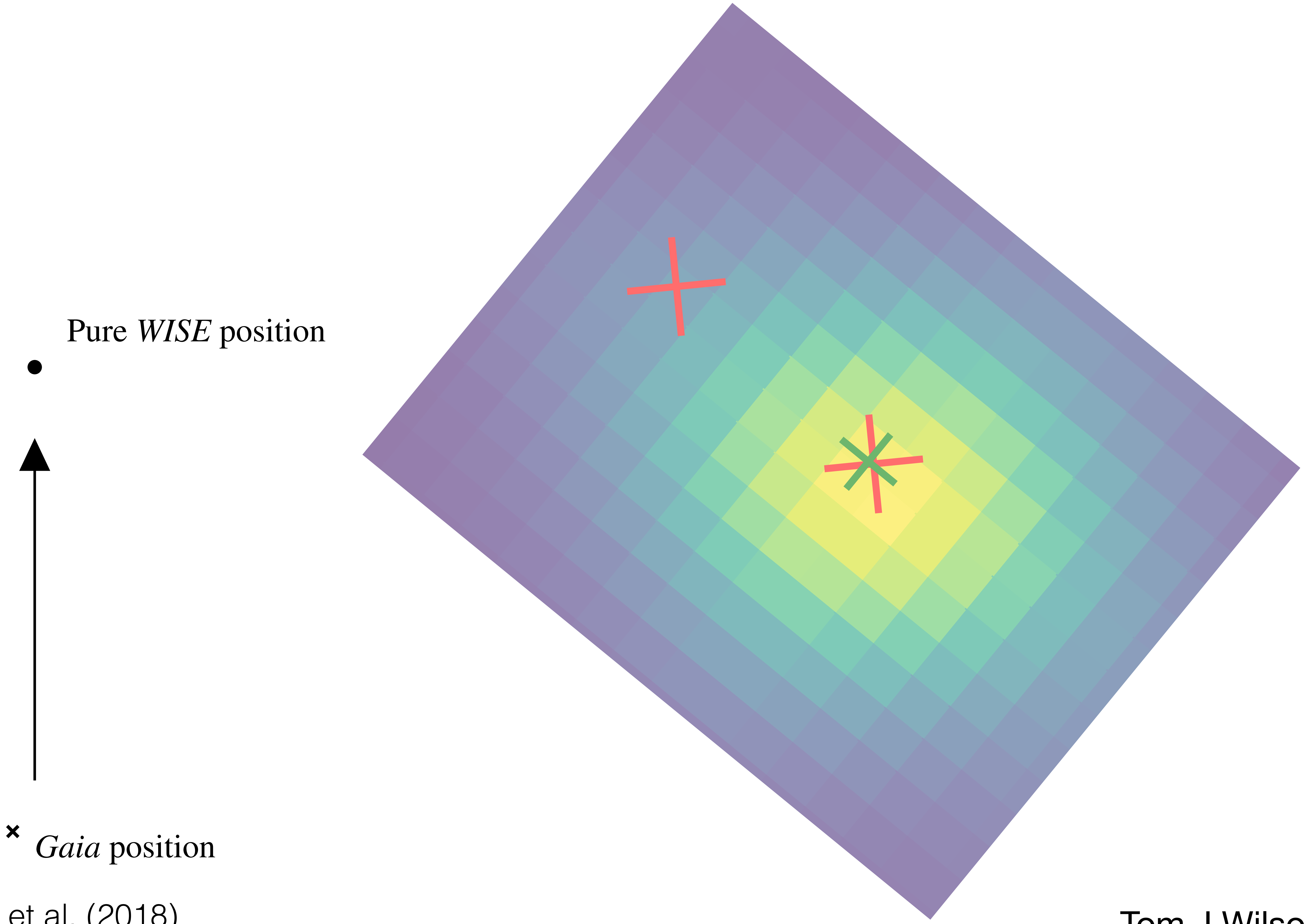
# The AUF: Perturbation




Wilson & Naylor (2017)
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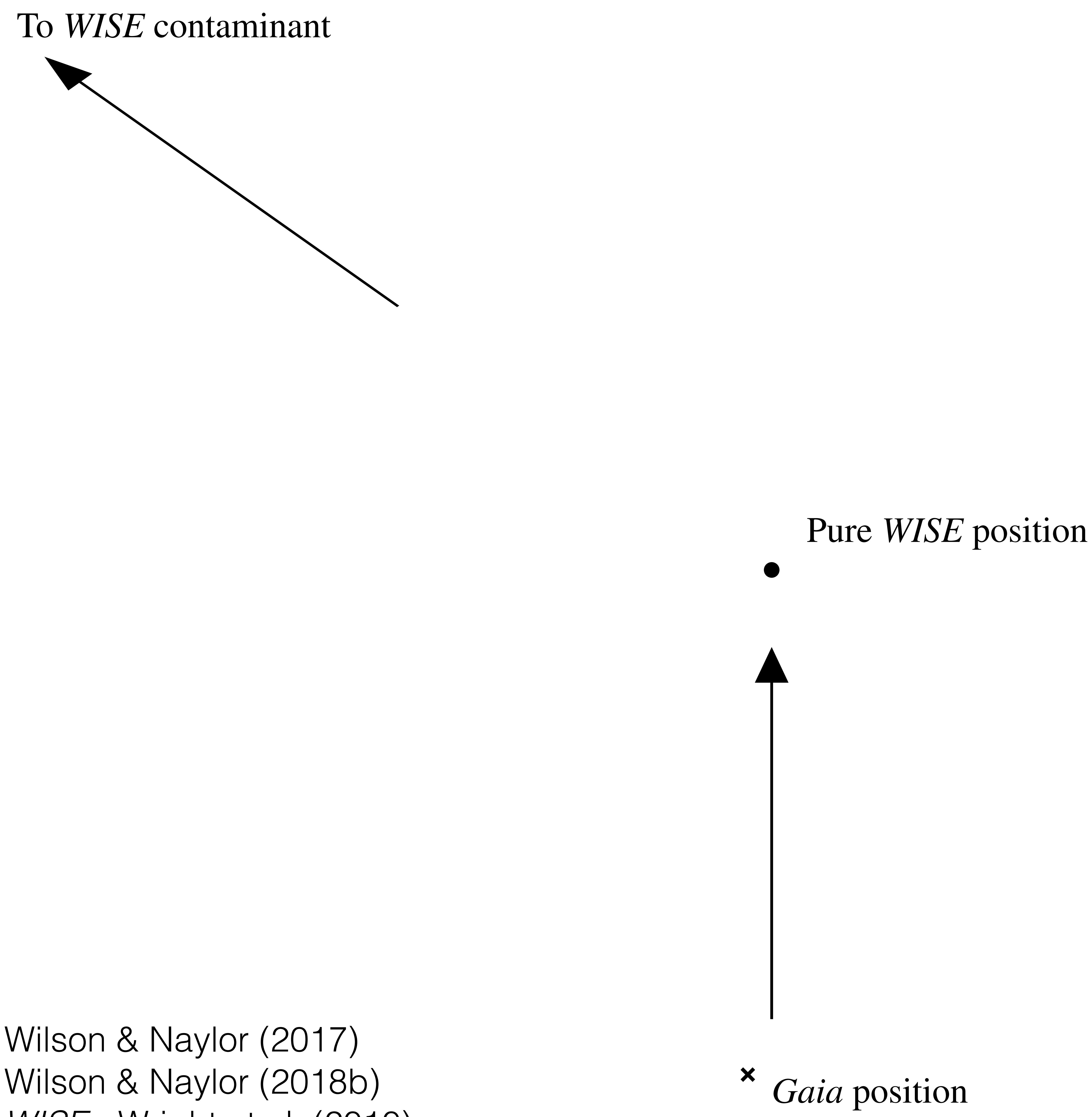


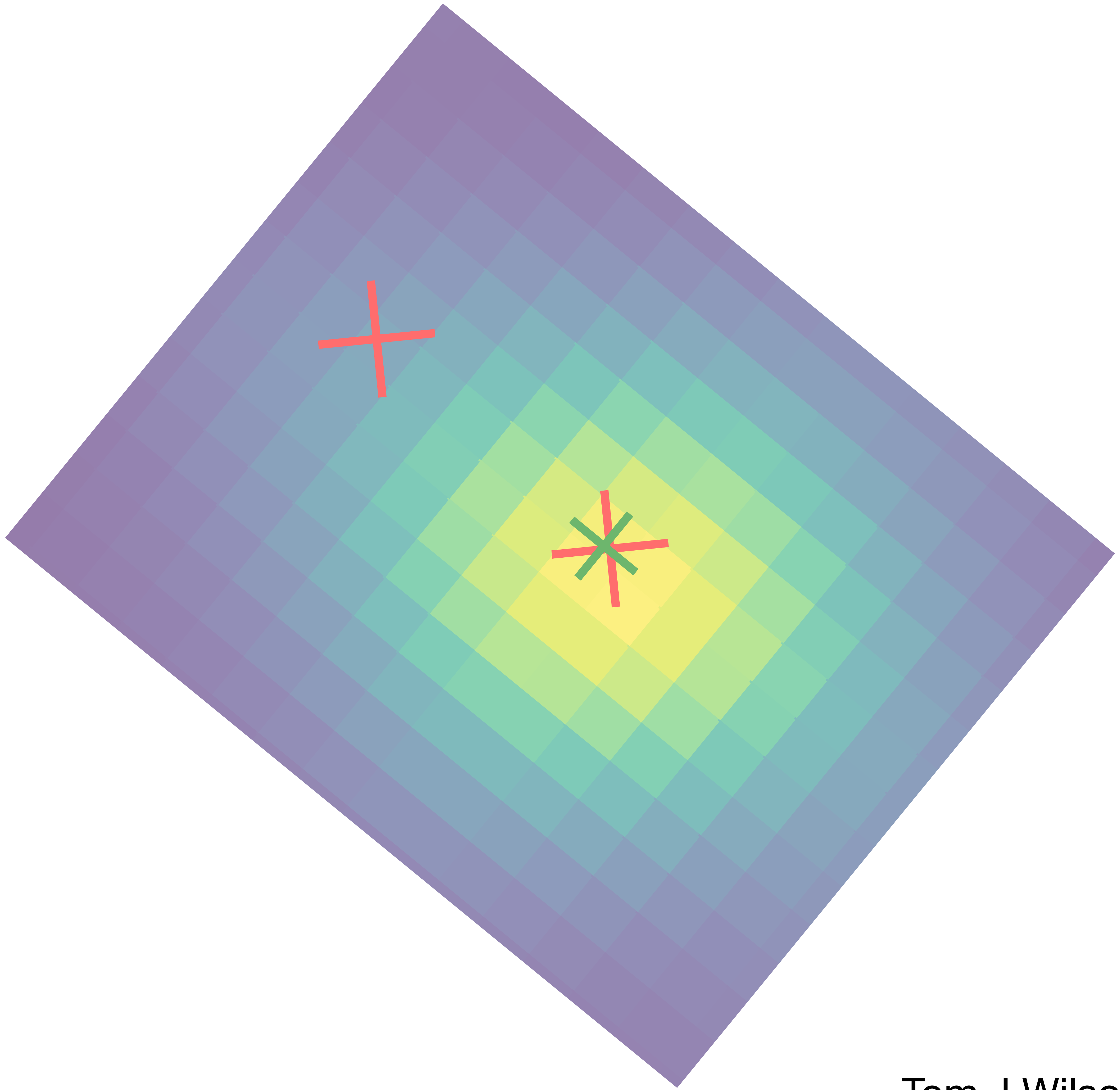

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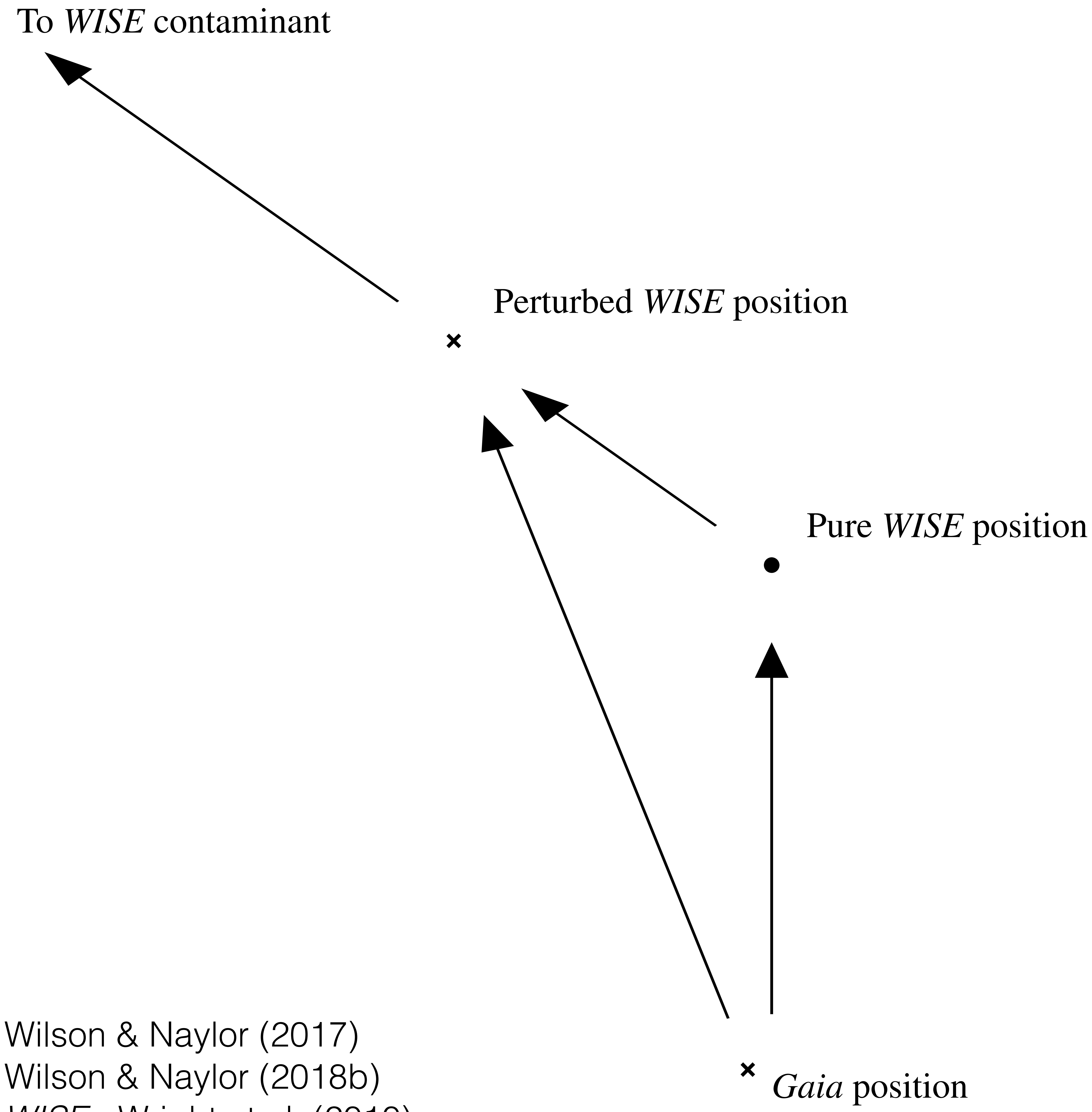


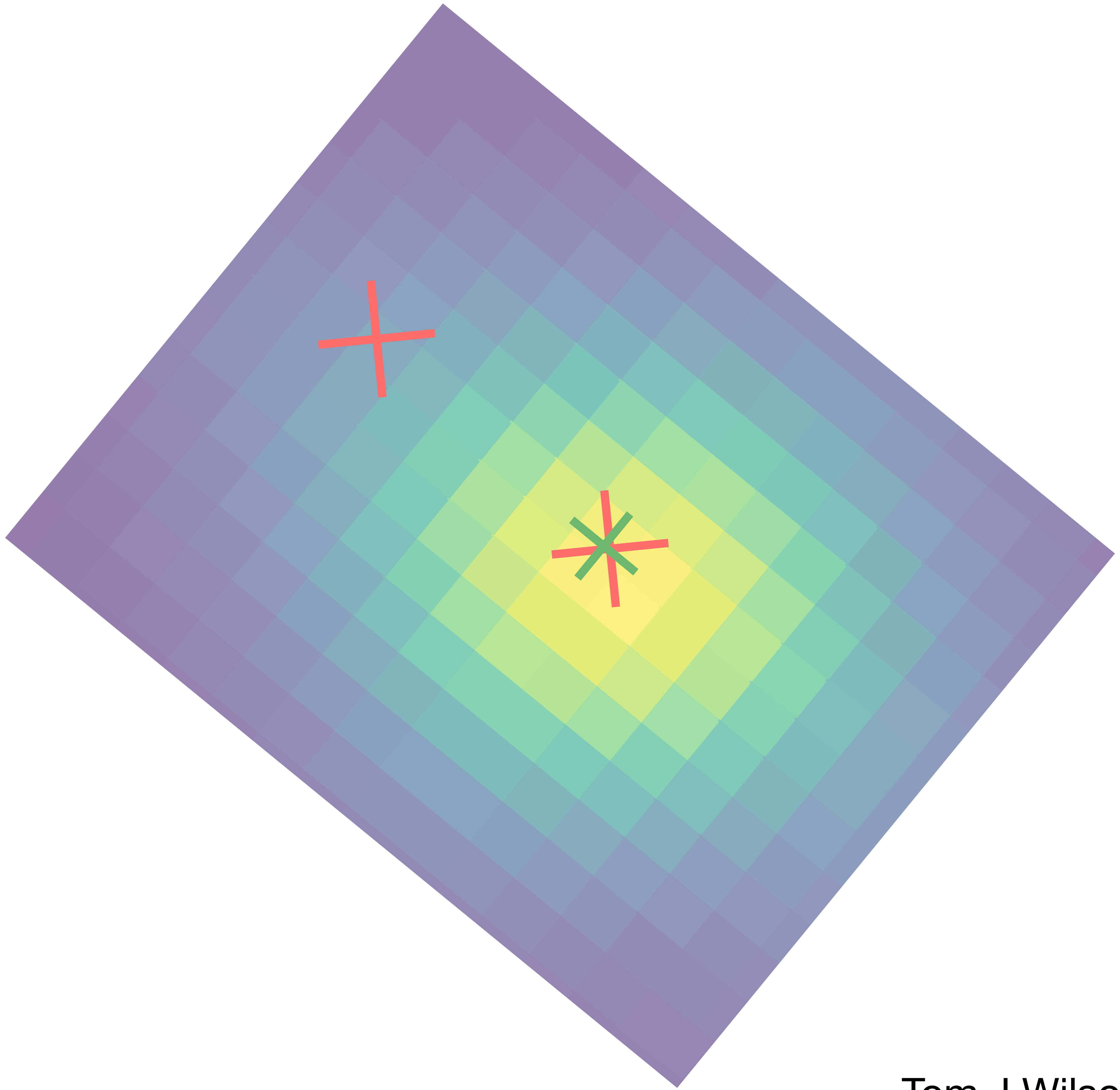

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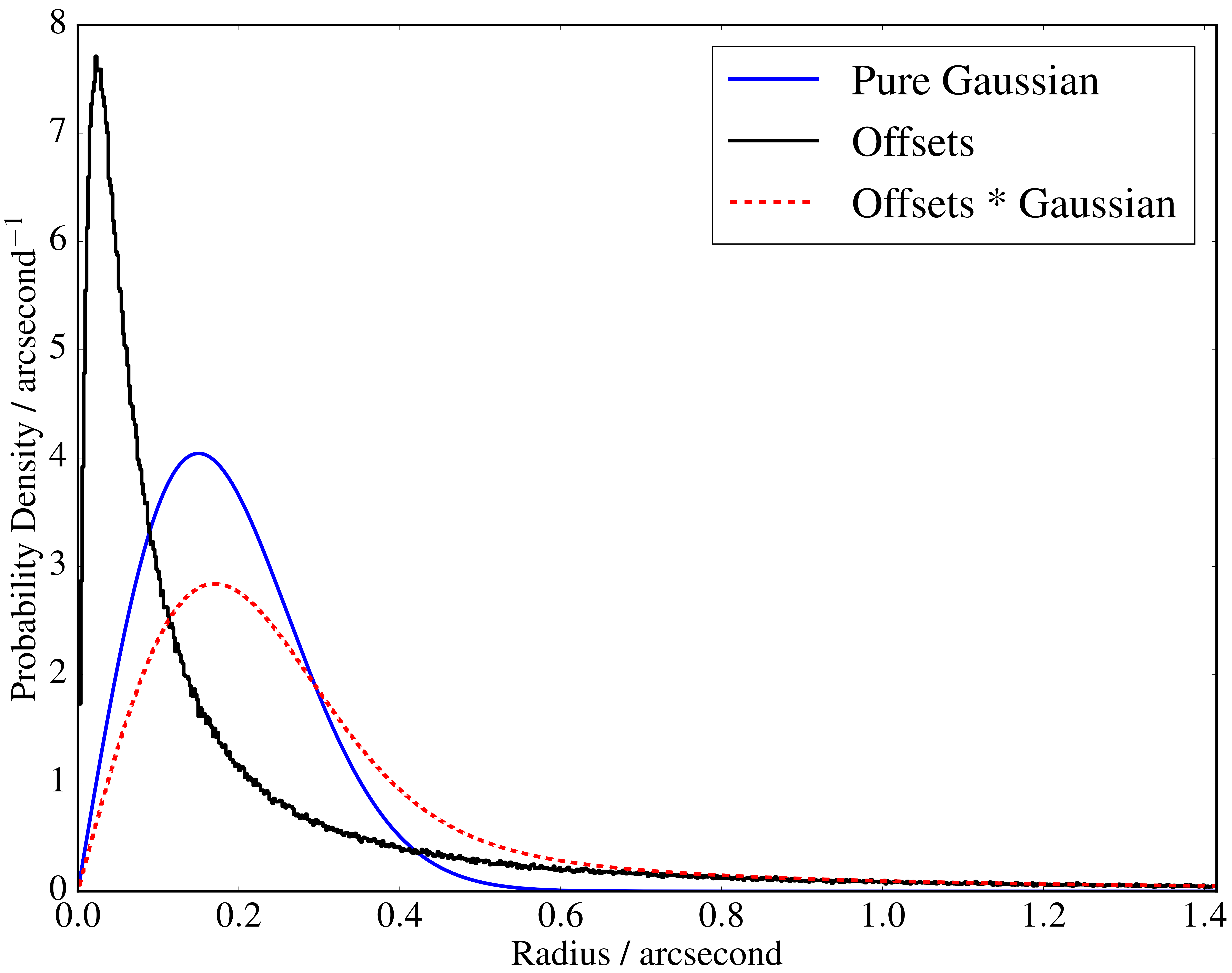



Wilson & Naylor (2018b)

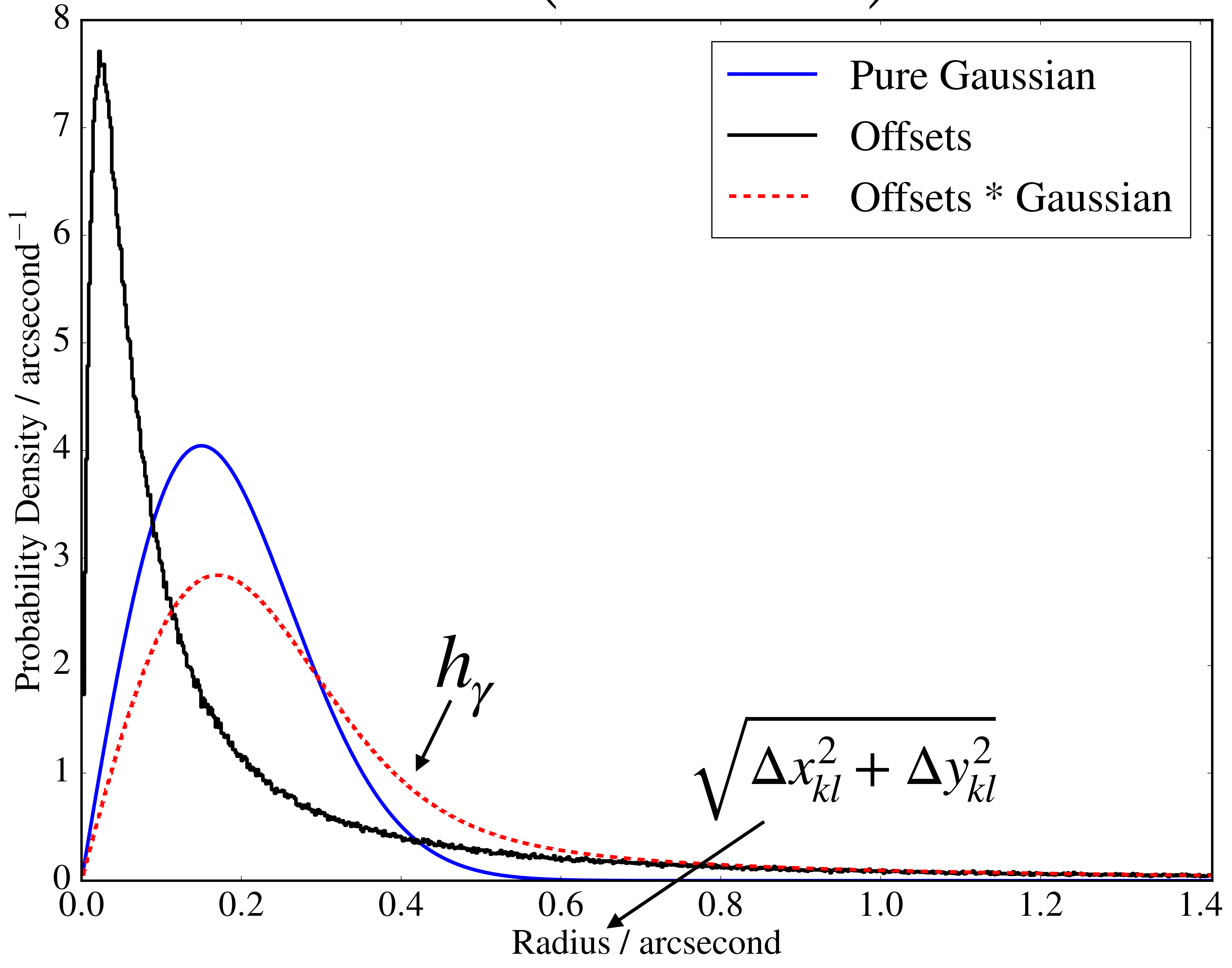
# Separation Likelihood Function

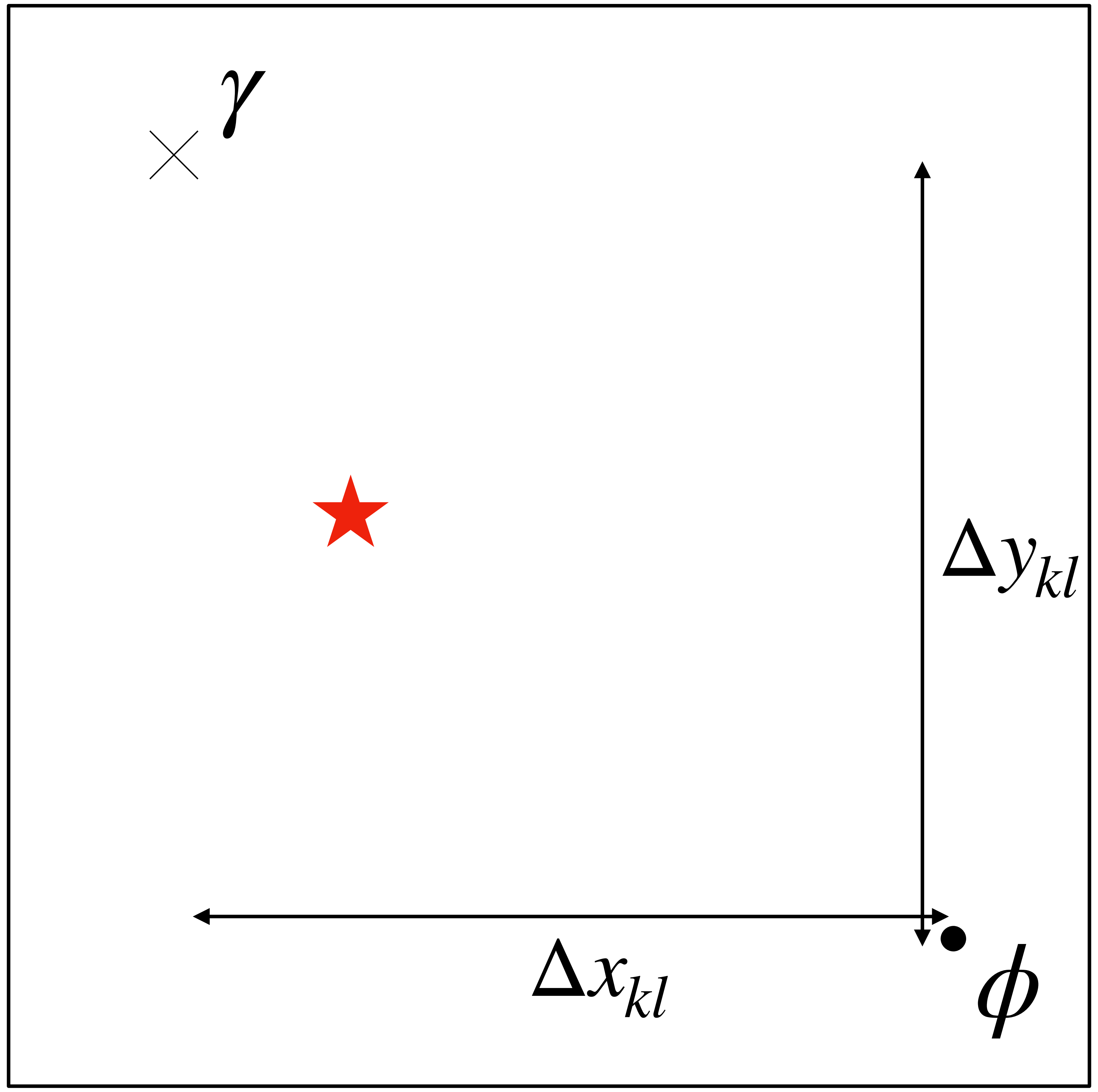
$$g(x_k, y_k, x_l, y_l) = \iint\limits_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\,\mathrm{d}x_0\,\mathrm{d}y_0$$

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

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 $\sigma^2 = \sigma_1^2 + \sigma_2^2$




Wilson & Naylor (2018b)

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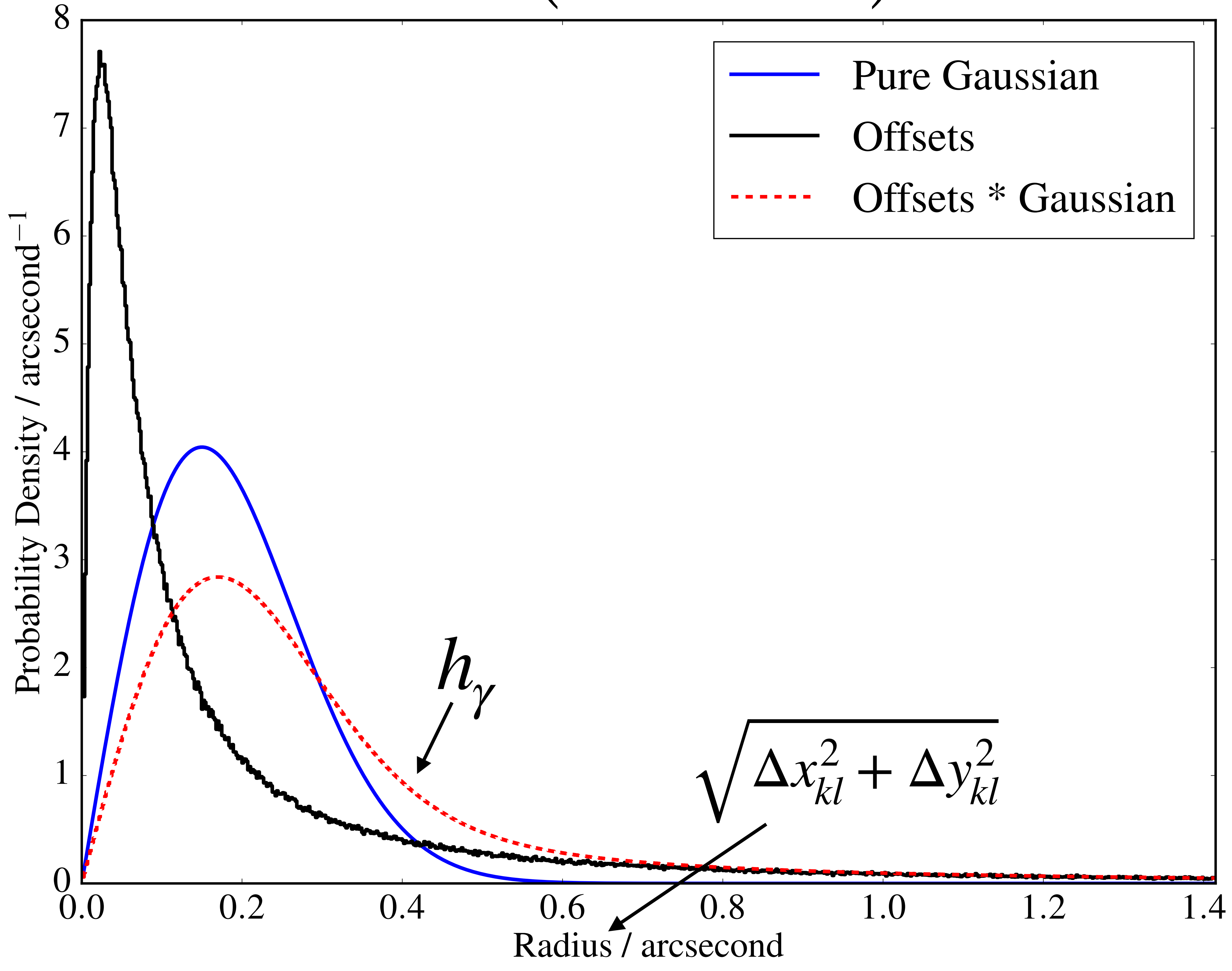


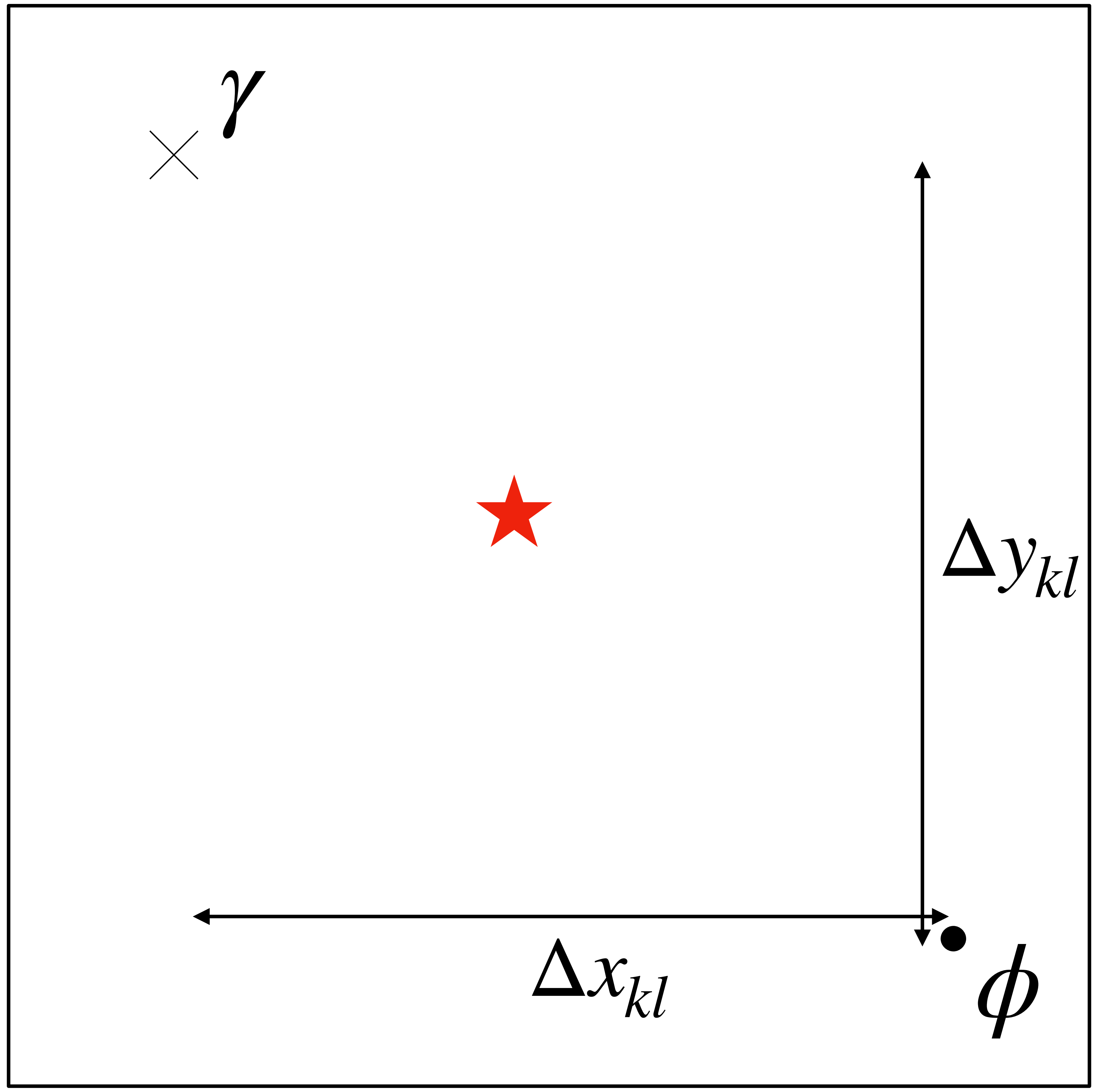


Wilson & Naylor (2018b)

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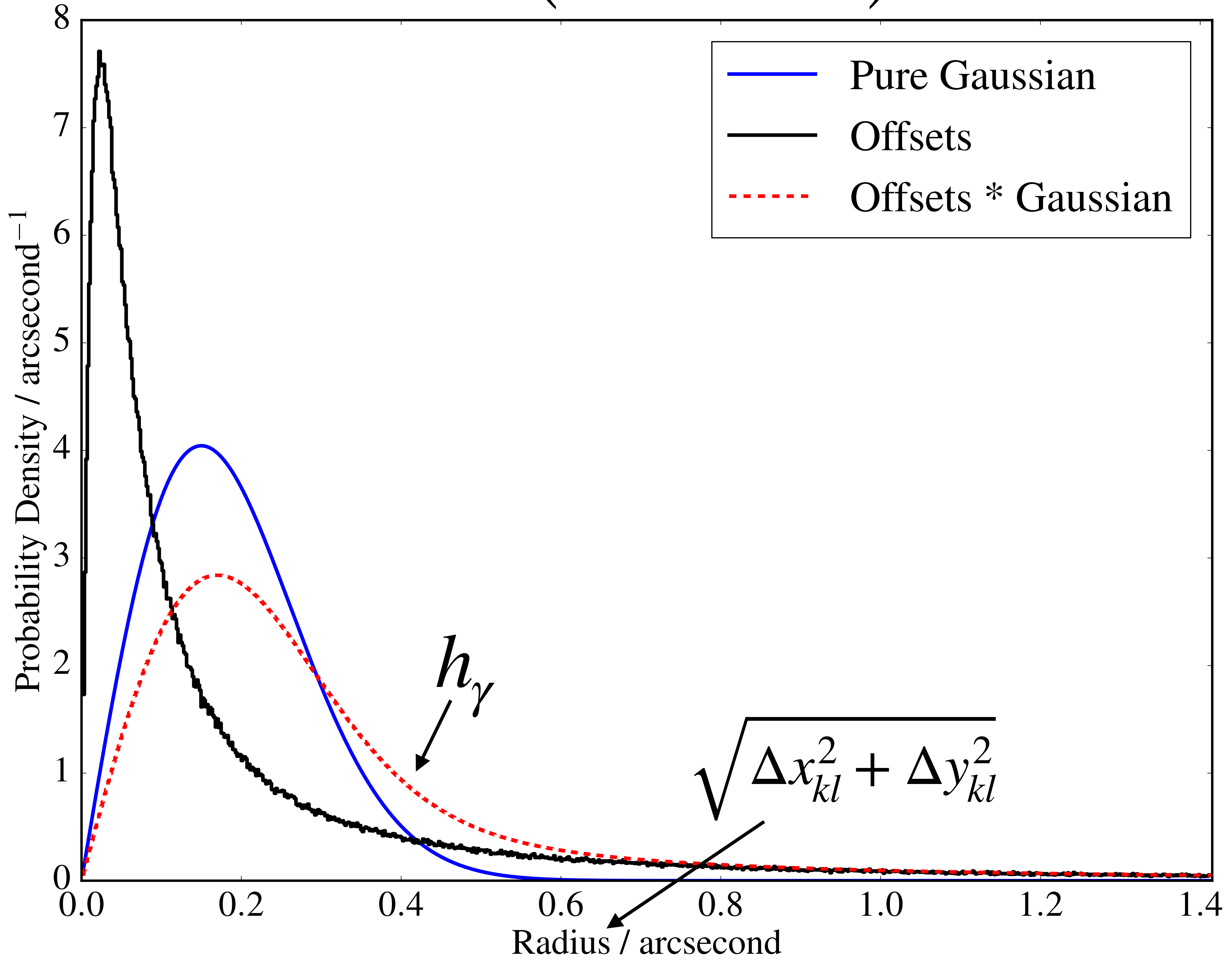
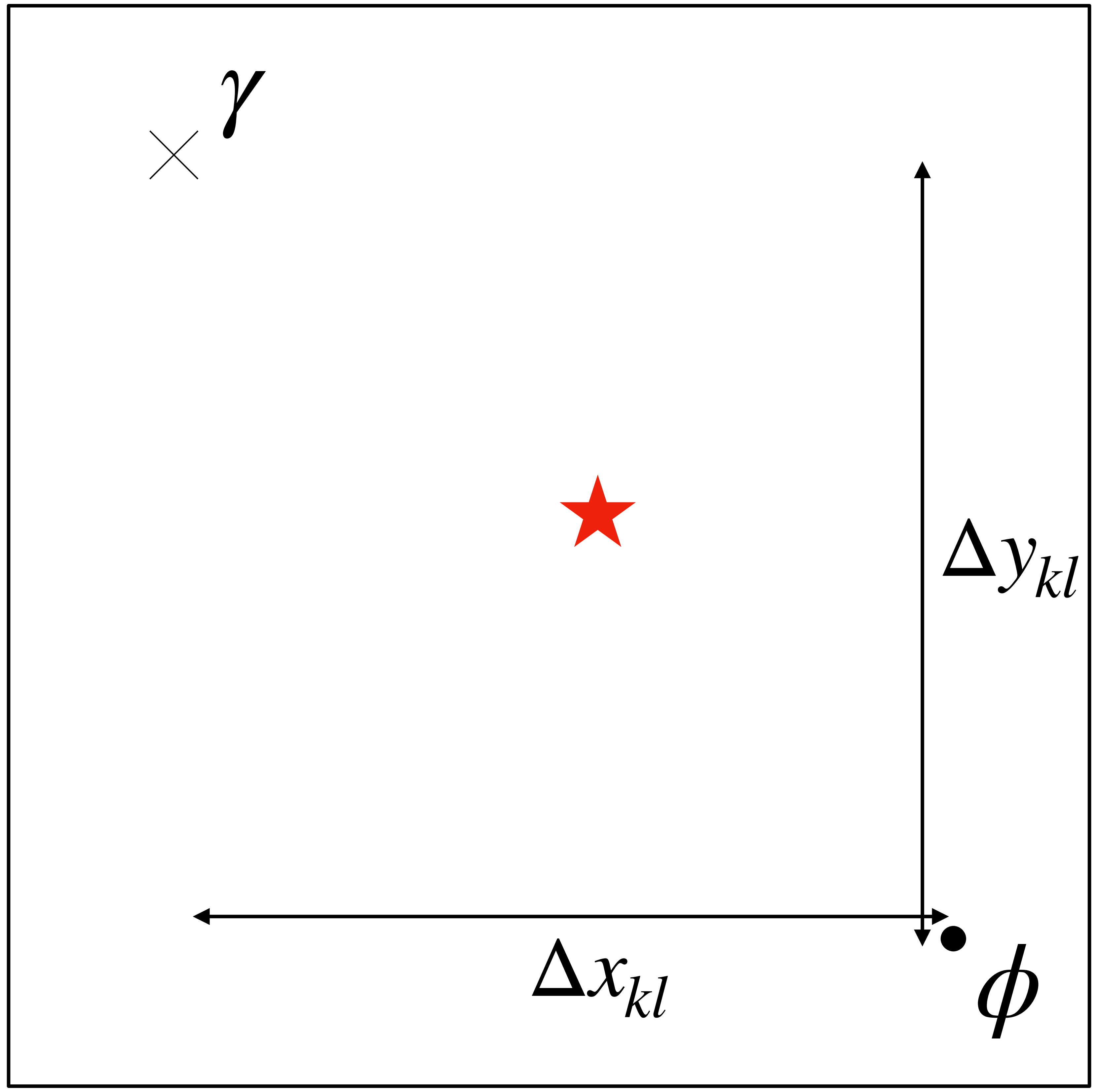
Wilson & Naylor (2018a)

$$g(\Delta x, \Delta y, \sigma) = (2\pi\sigma^2)^{-1} \exp\left(-\frac{1}{2}\frac{\Delta x^2 + \Delta y^2}{\sigma^2}\right) \text{ where } \sigma^2 = \sigma_1^2 + \sigma_2^2$$




Wilson & Naylor (2018b)

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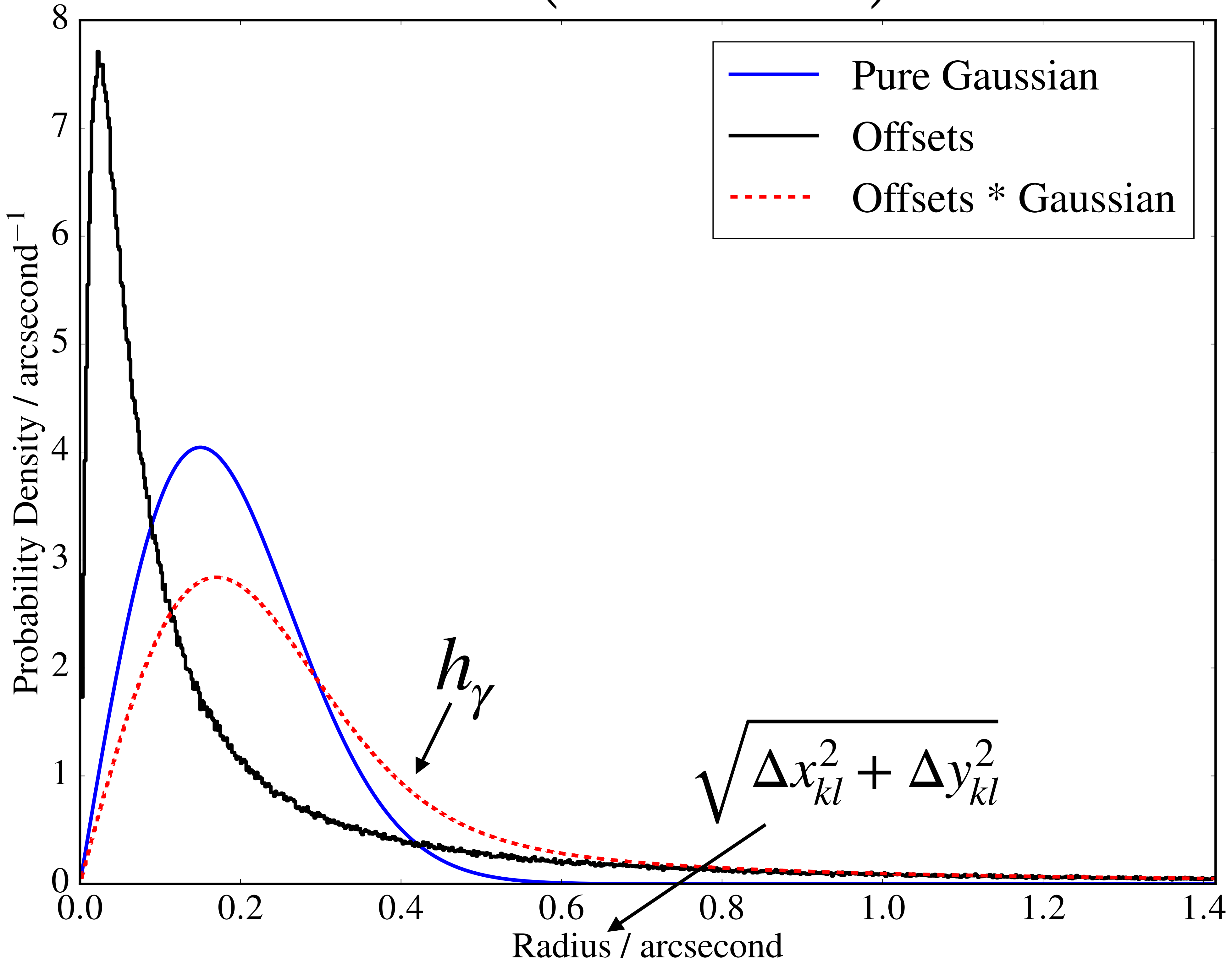
# Separation Likelihood Function

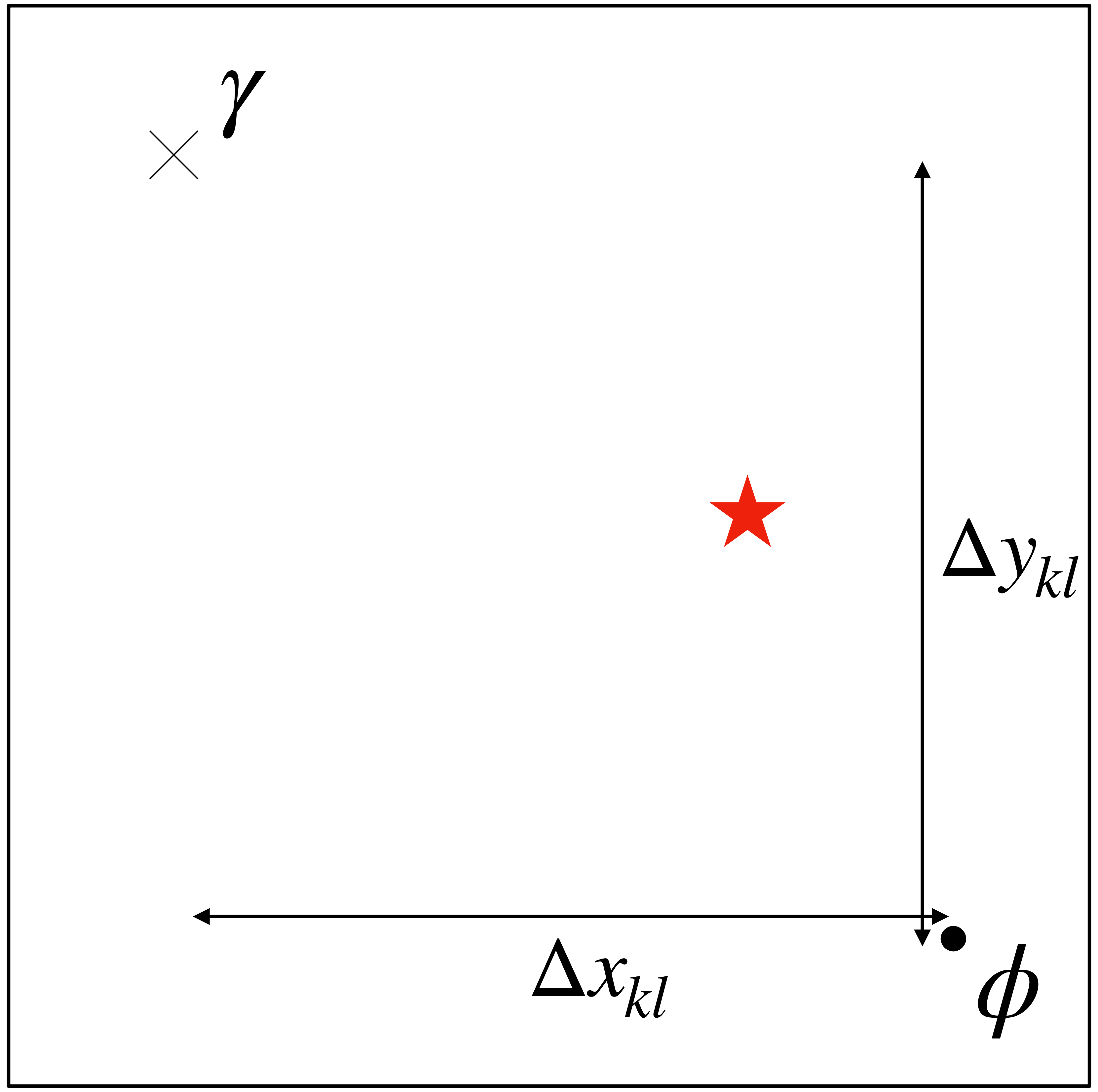
$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0)\, \mathrm{d}x_0\, \mathrm{d}y_0$$

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

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 $$\sigma^2 = \sigma_1^2 + \sigma_2^2$$




Wilson & Naylor (2018b)

Tom J Wilson @onoddil

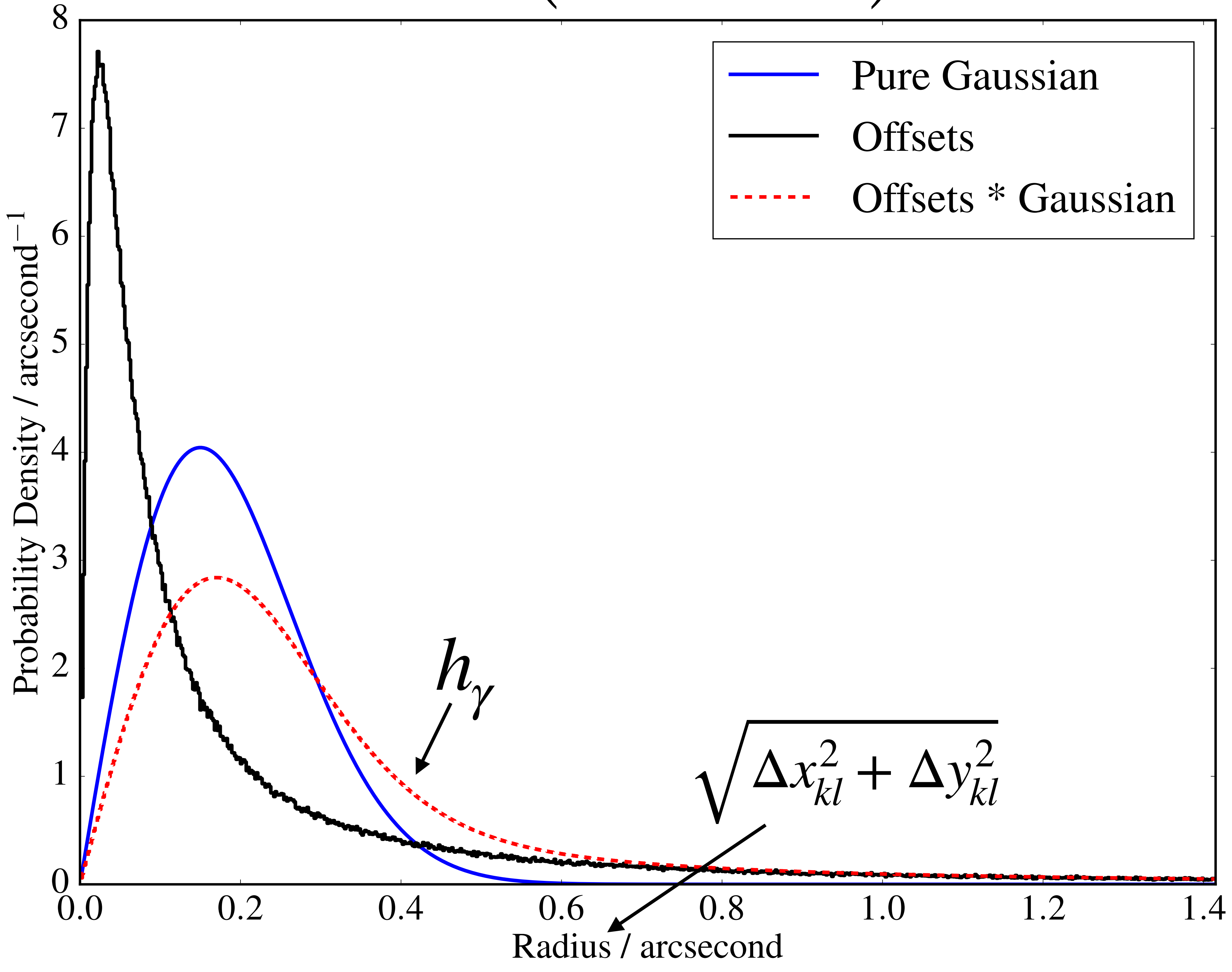
# Separation Likelihood Function

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

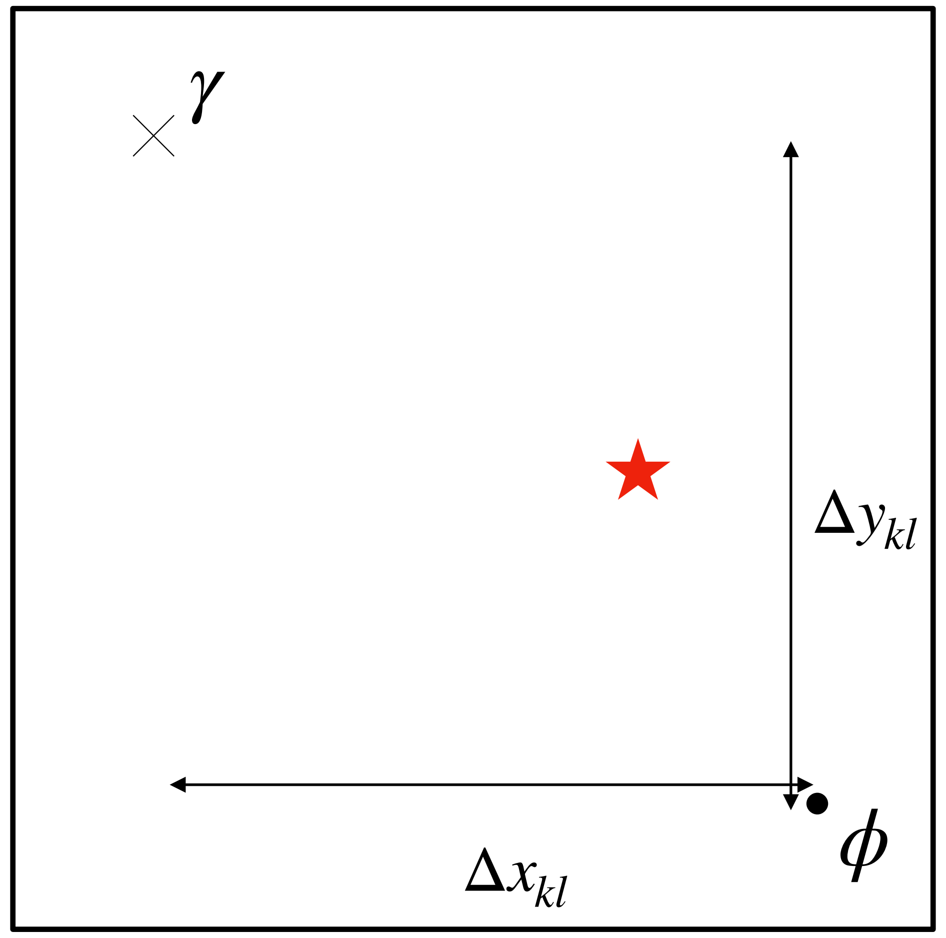
Wilson & Naylor (2018a)

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

$$g(\Delta x, \Delta y, \sigma) = (2\pi\sigma^2)^{-1} \exp\left(-\frac{1}{2}\frac{\Delta x^2 + \Delta y^2}{\sigma^2}\right)$$ where $\sigma^2 = \sigma_1^2 + \sigma_2^2$




Wilson & Naylor (2018b)




**John Herschel's result, 170 years on, appears wrong, but only because the universe got in the way.**
**"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)**

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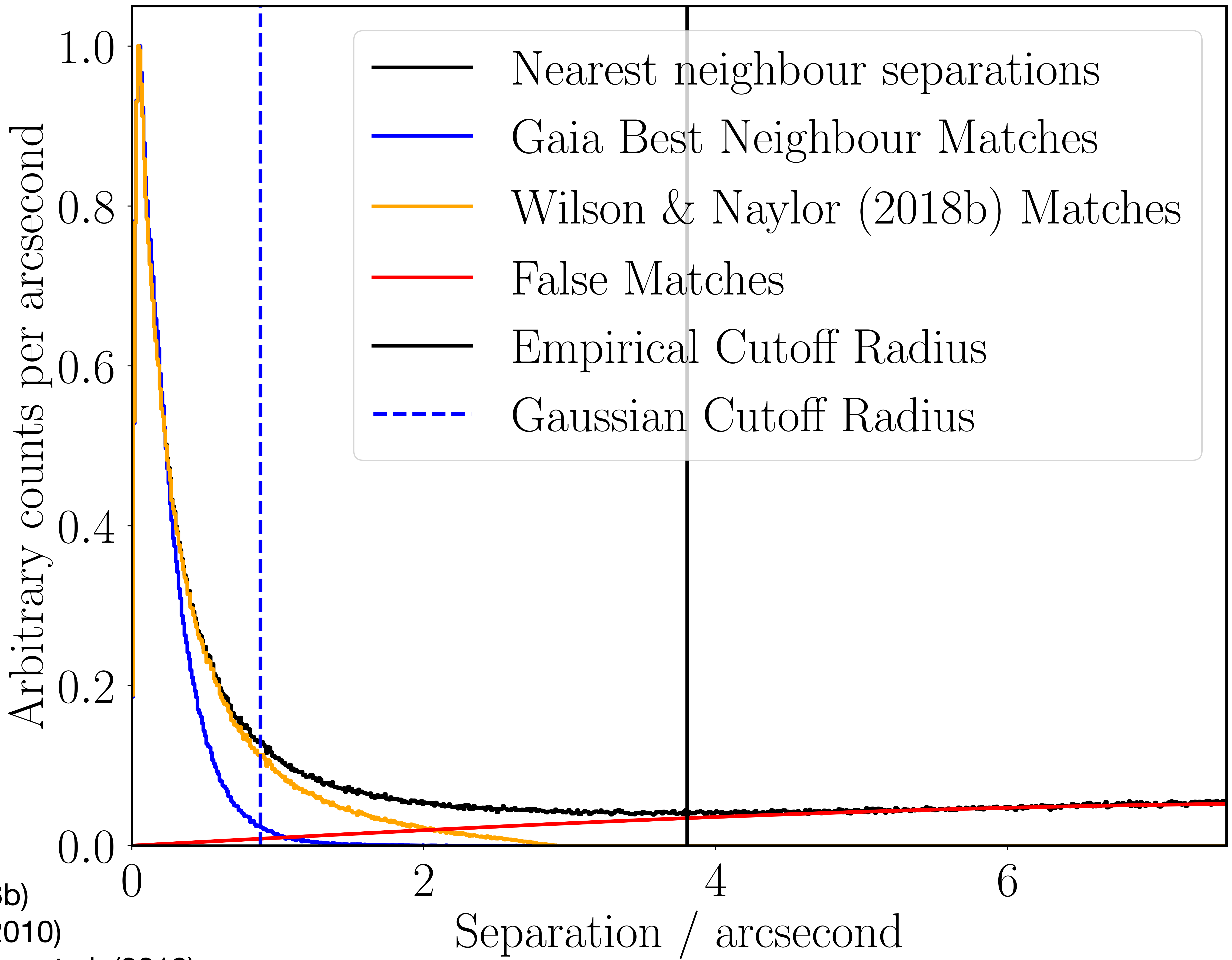
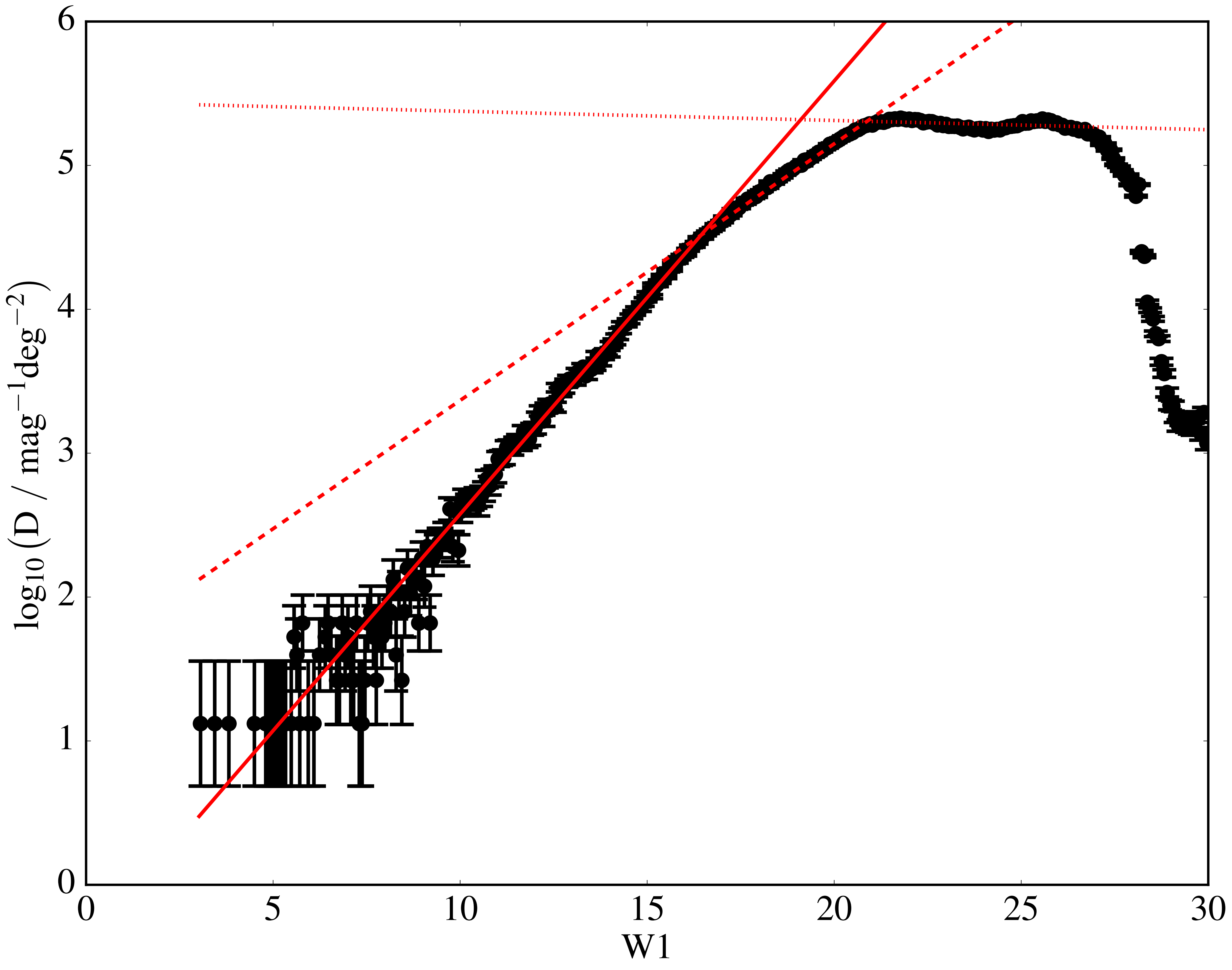
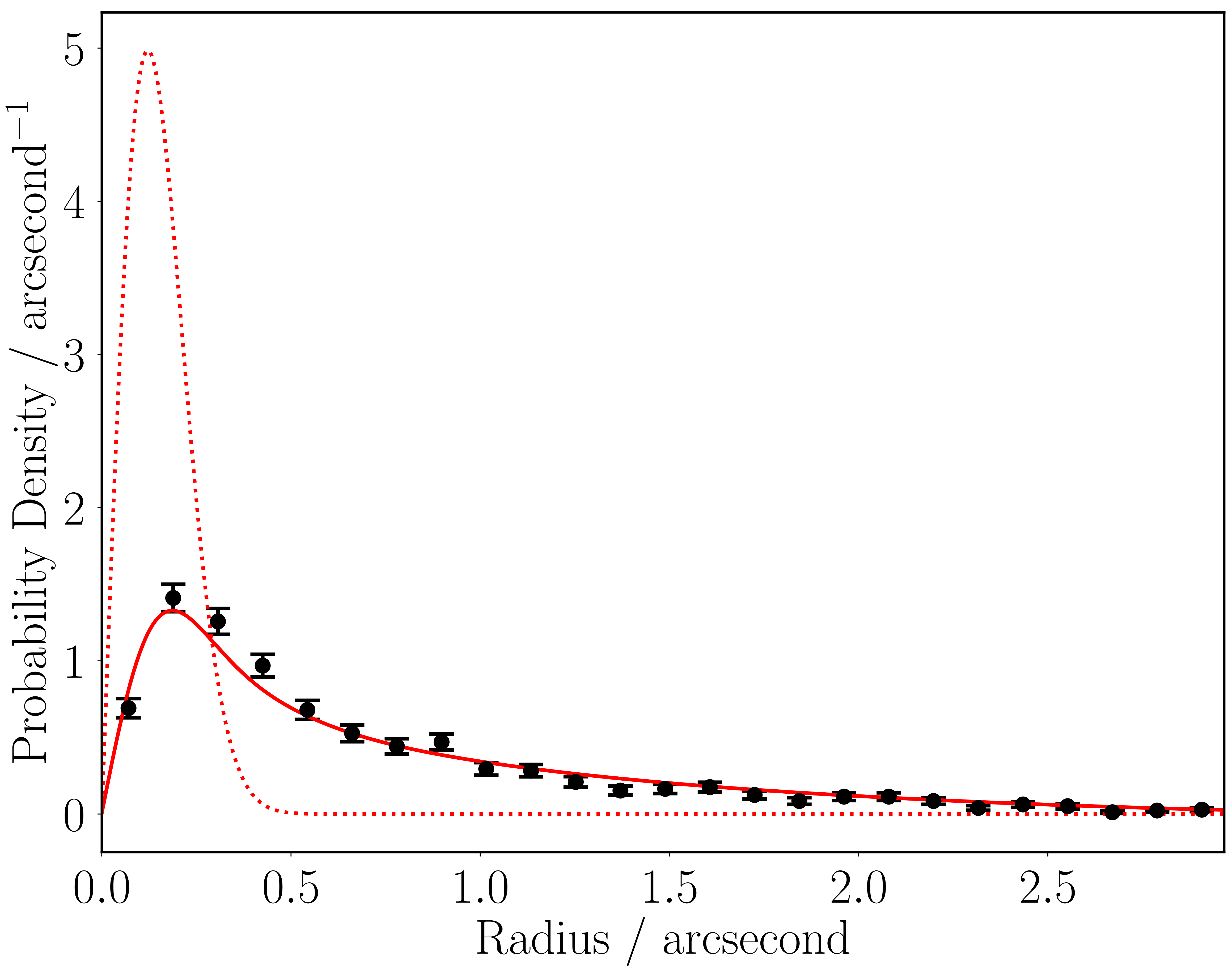
# Match Separations




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




Wilson & Naylor (2018b)

TRILEGAL - Girardi et al. (2005)

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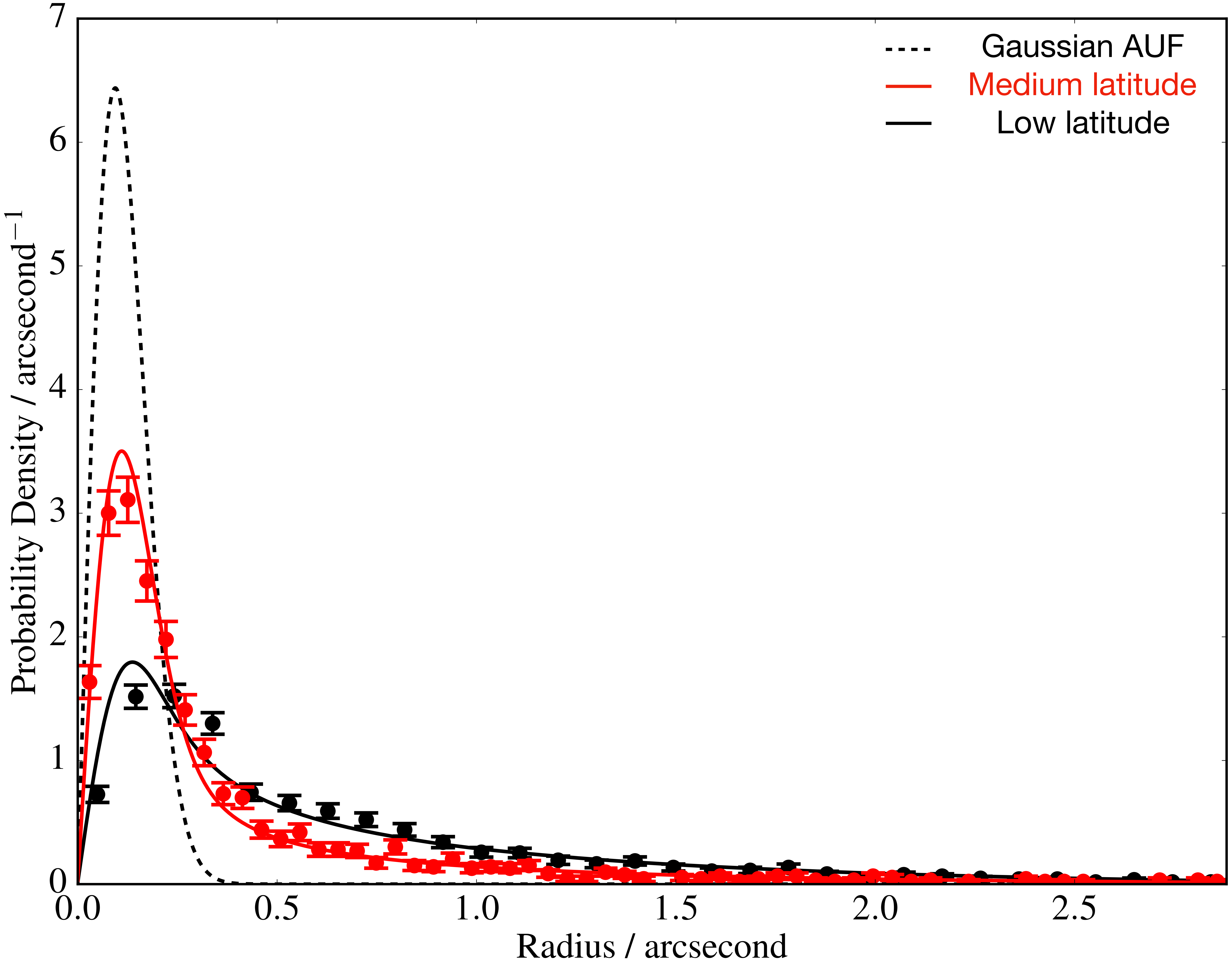
# Crowding Normalisation

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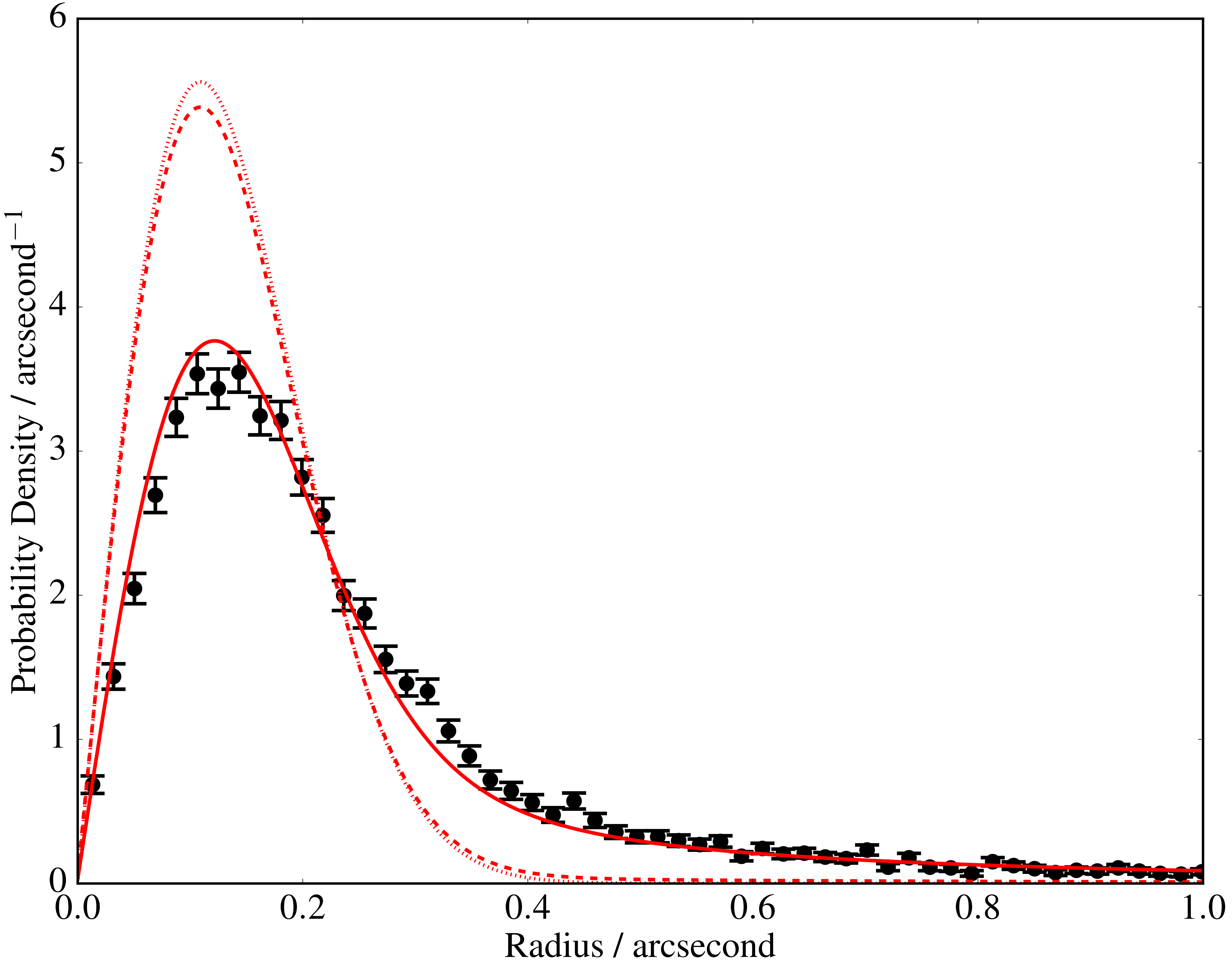
# Extra-galactic Effects of Crowding




Wilson & Naylor (2018b)

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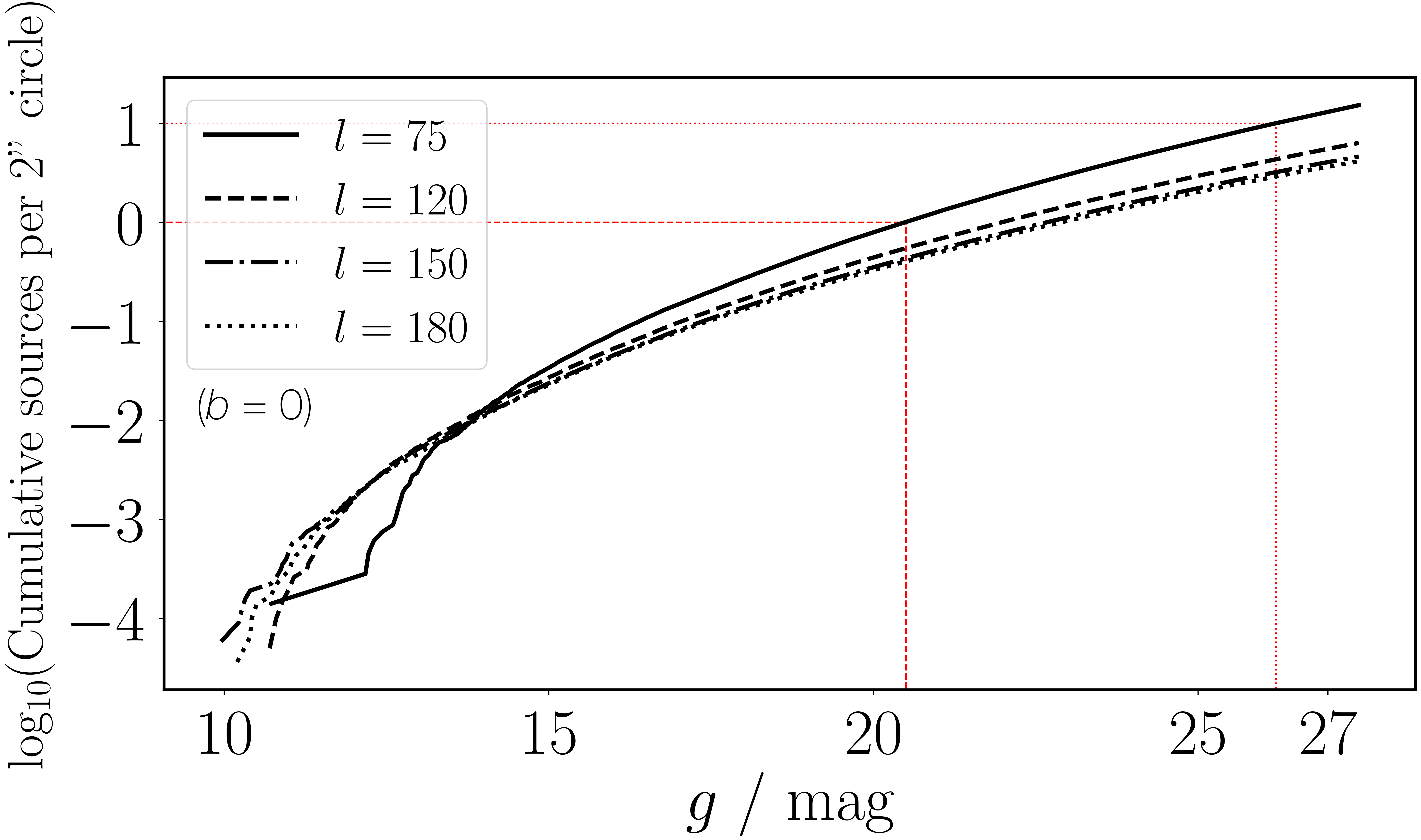
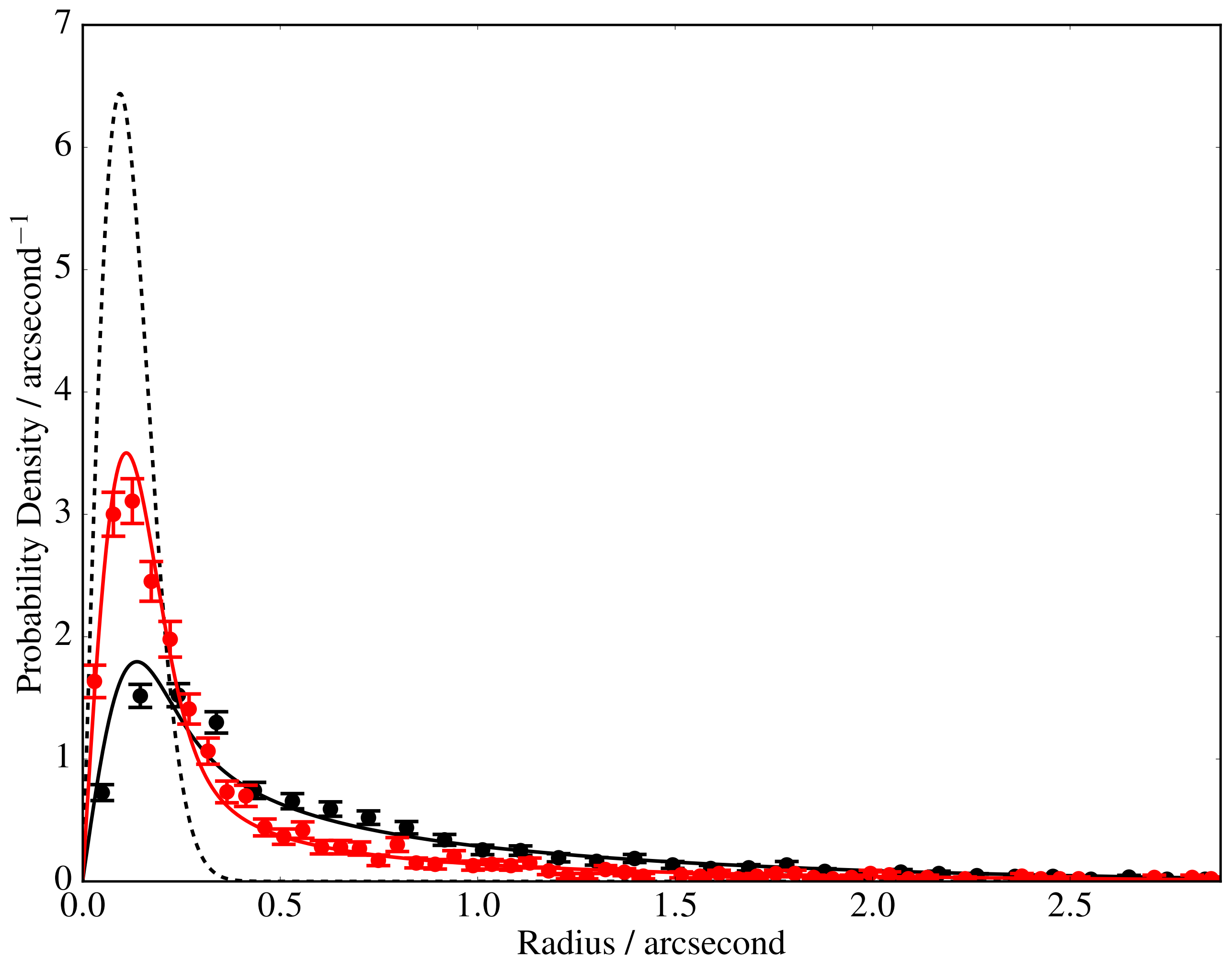
# Vera C. Rubin Observatory's LSST




TRILEGAL - Girardi et al. (2005)

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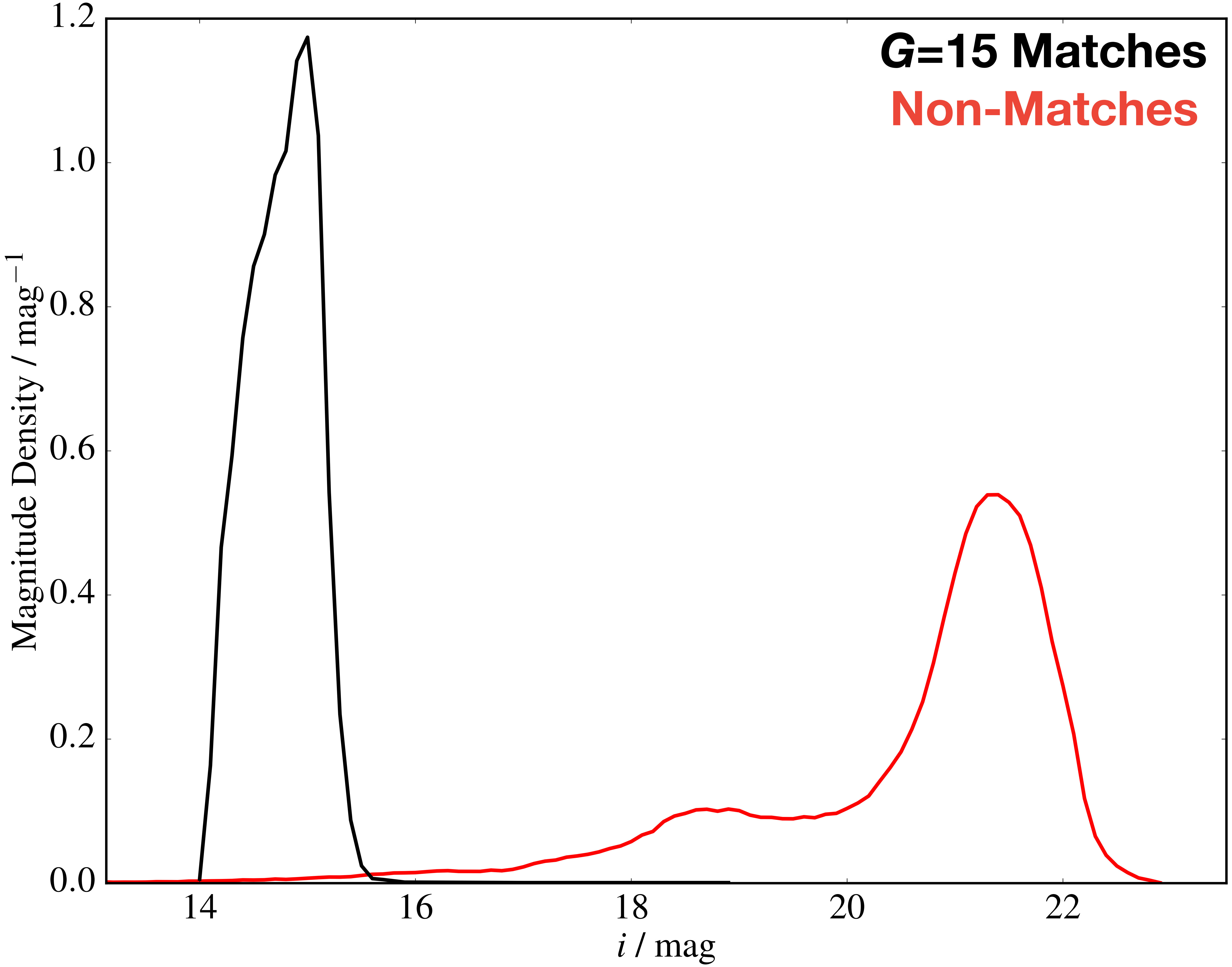
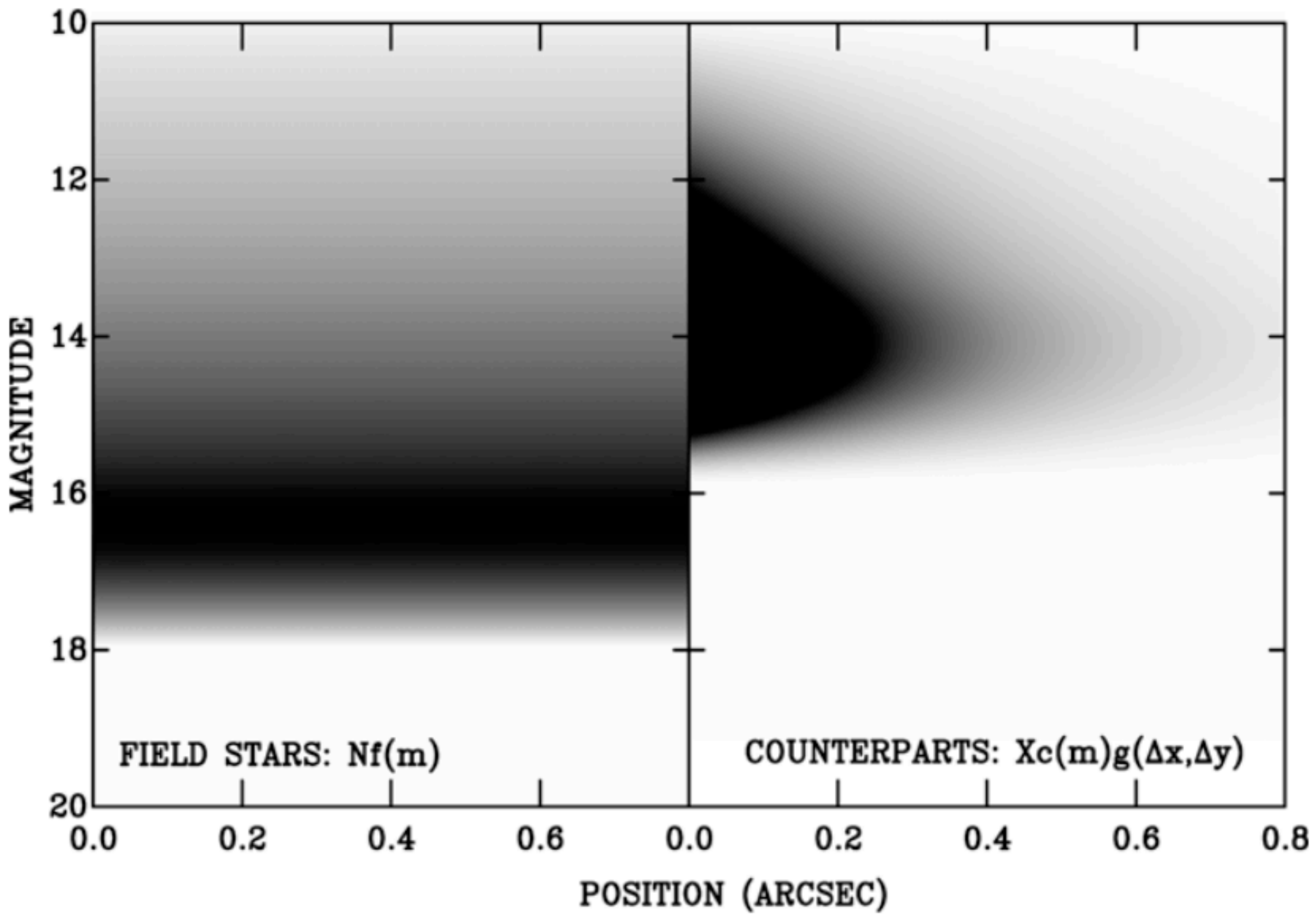
# Including the Magnitude Information




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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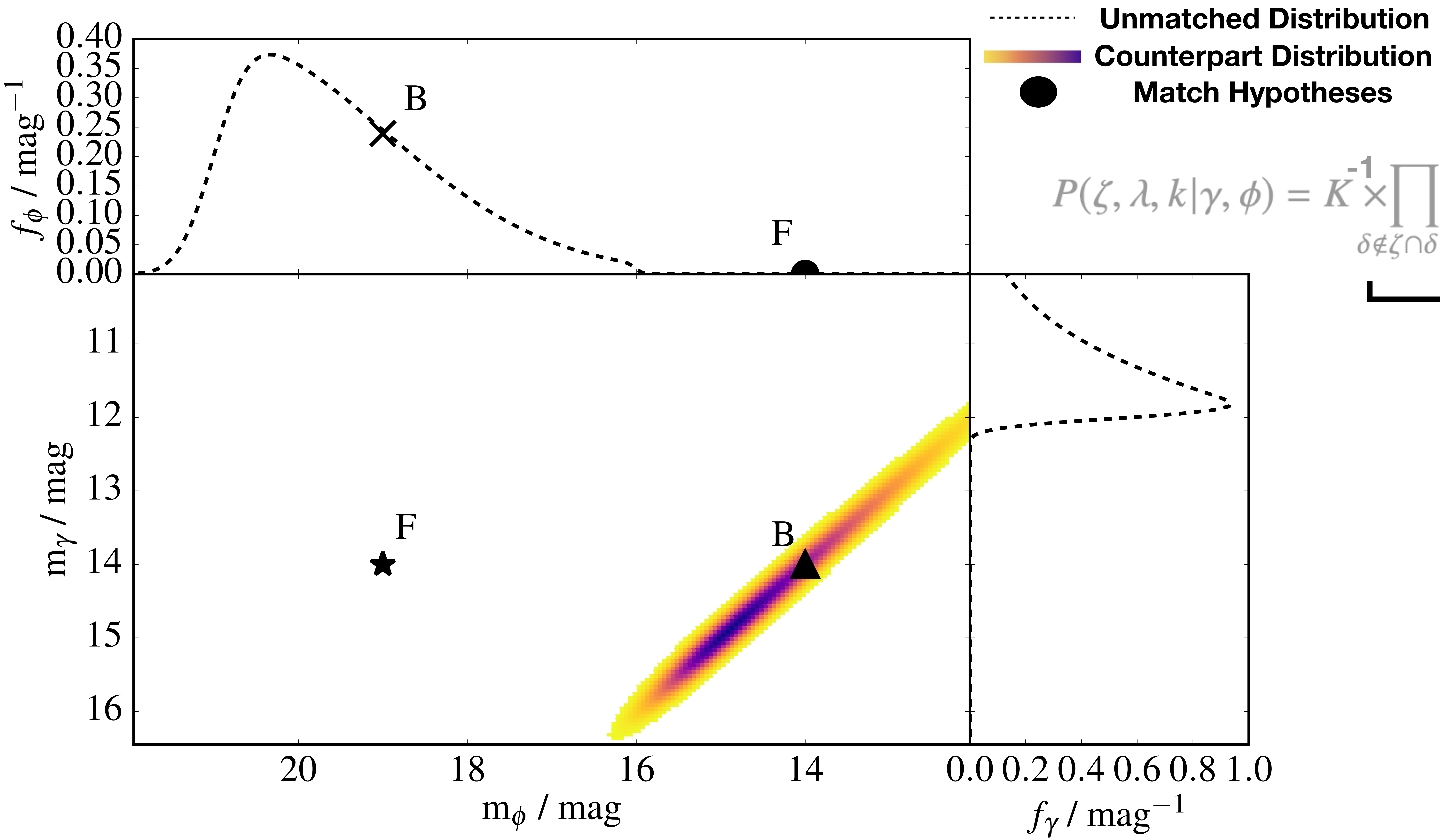
# Including the Magnitude Information



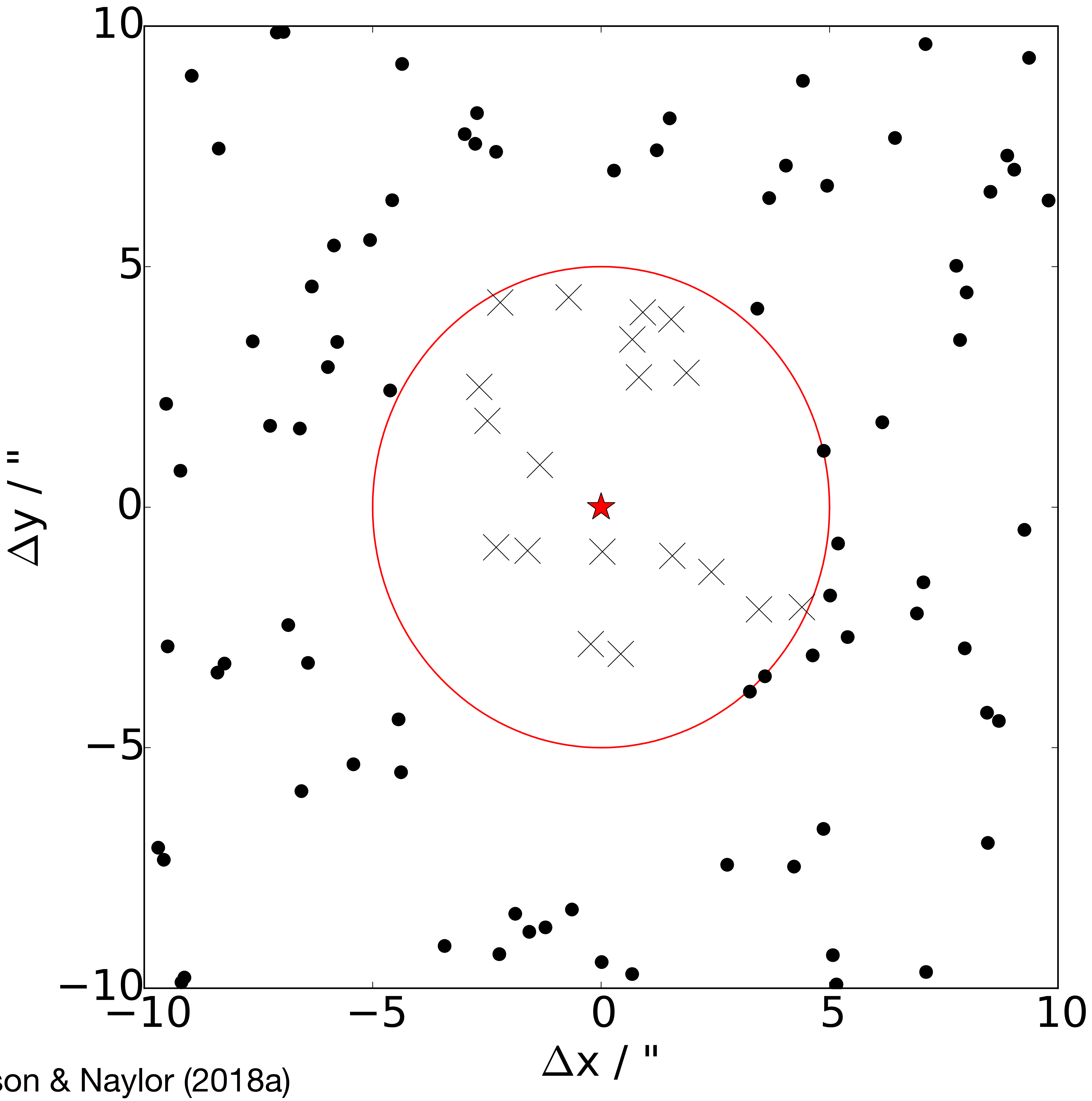

$$P(\zeta, \lambda, k|\gamma, \phi) = K^{-1} \times \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i \lambda_i} c_{\gamma\phi}^{\zeta_i \lambda_i}$$

**Unmatched** **Matched**

Wilson & Naylor (2018a)

**Tom J Wilson @onoddil**

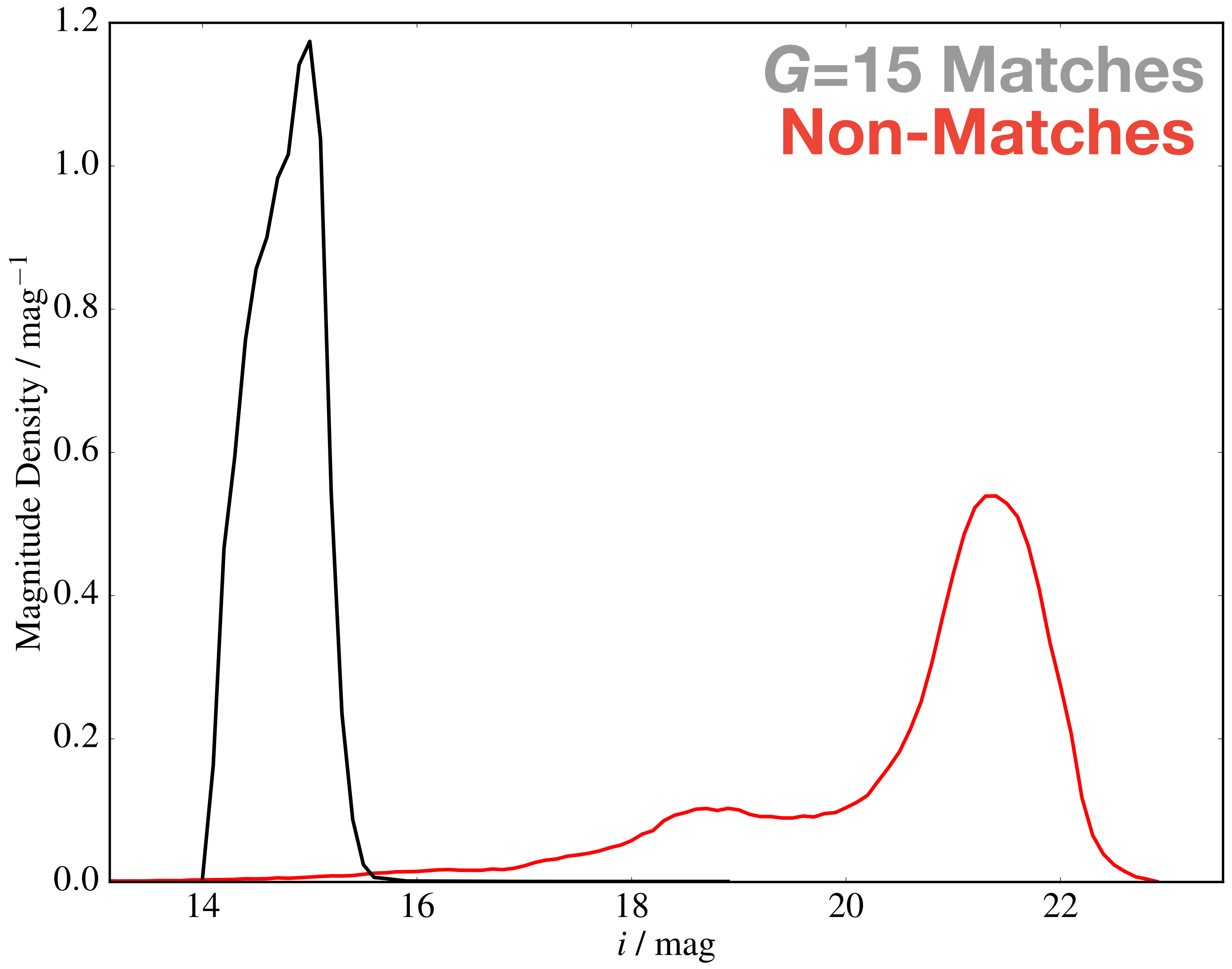
# The “Field Star” Distribution




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**

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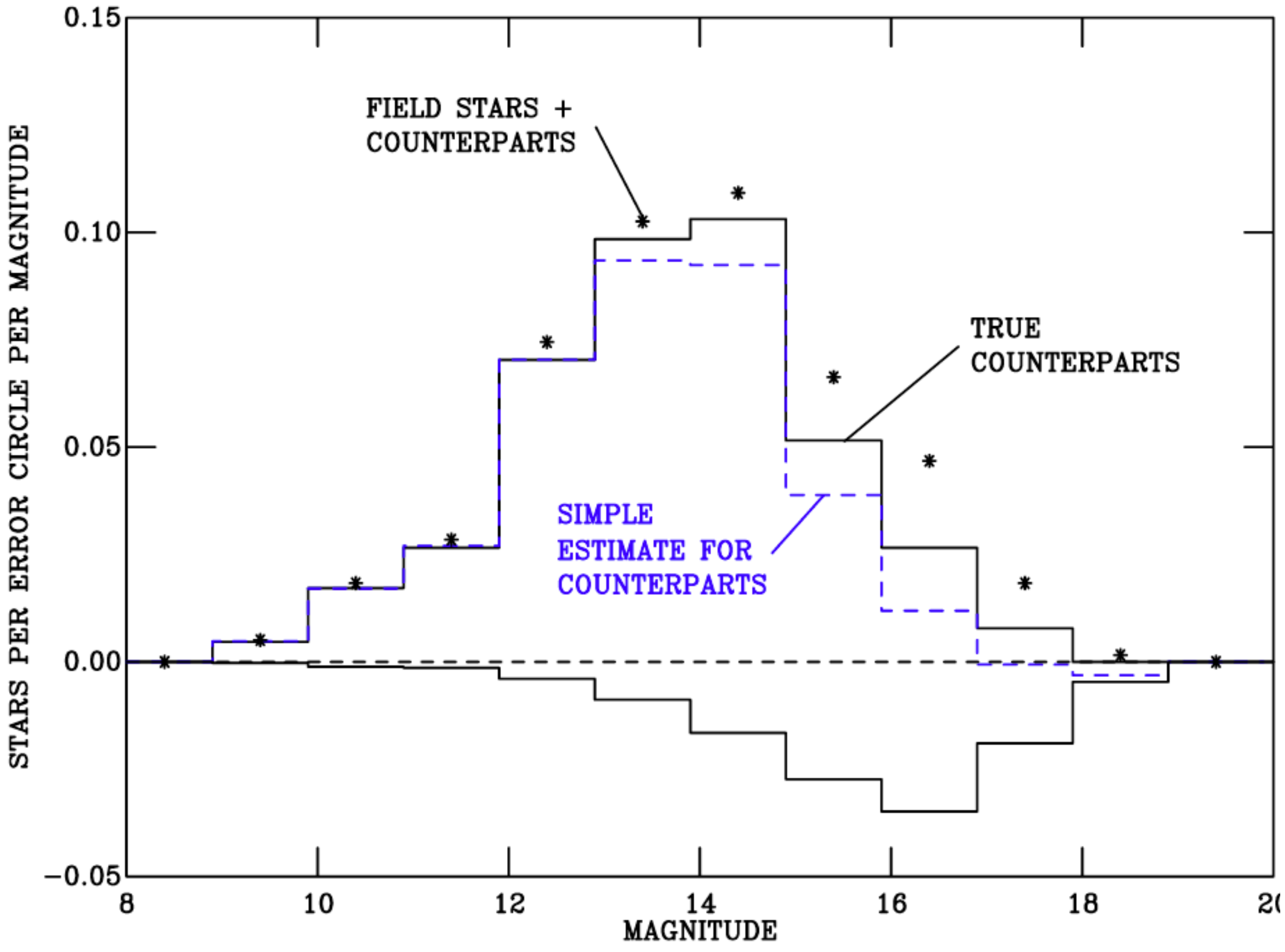
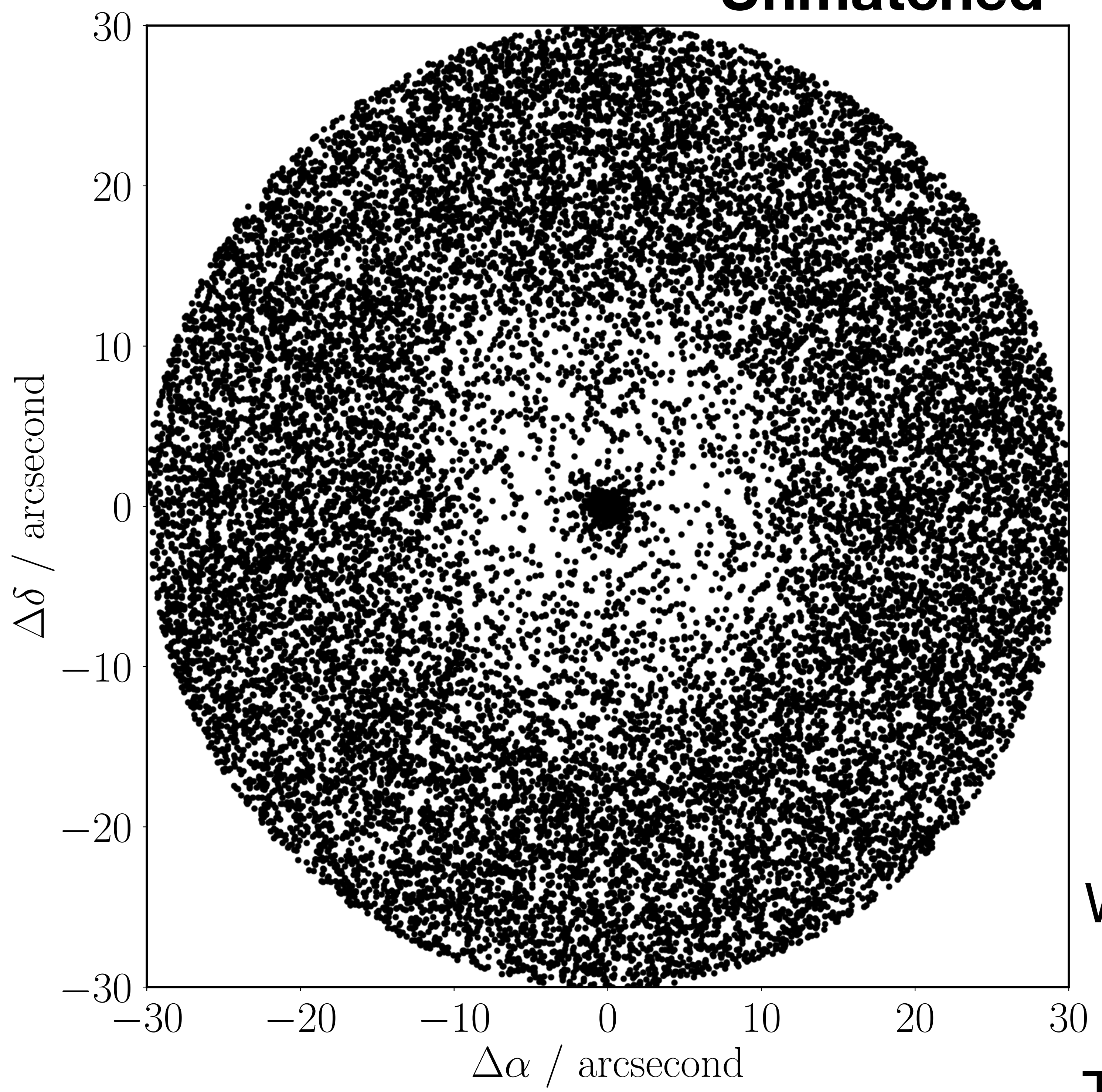
# The Counterpart Source Distribution




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)

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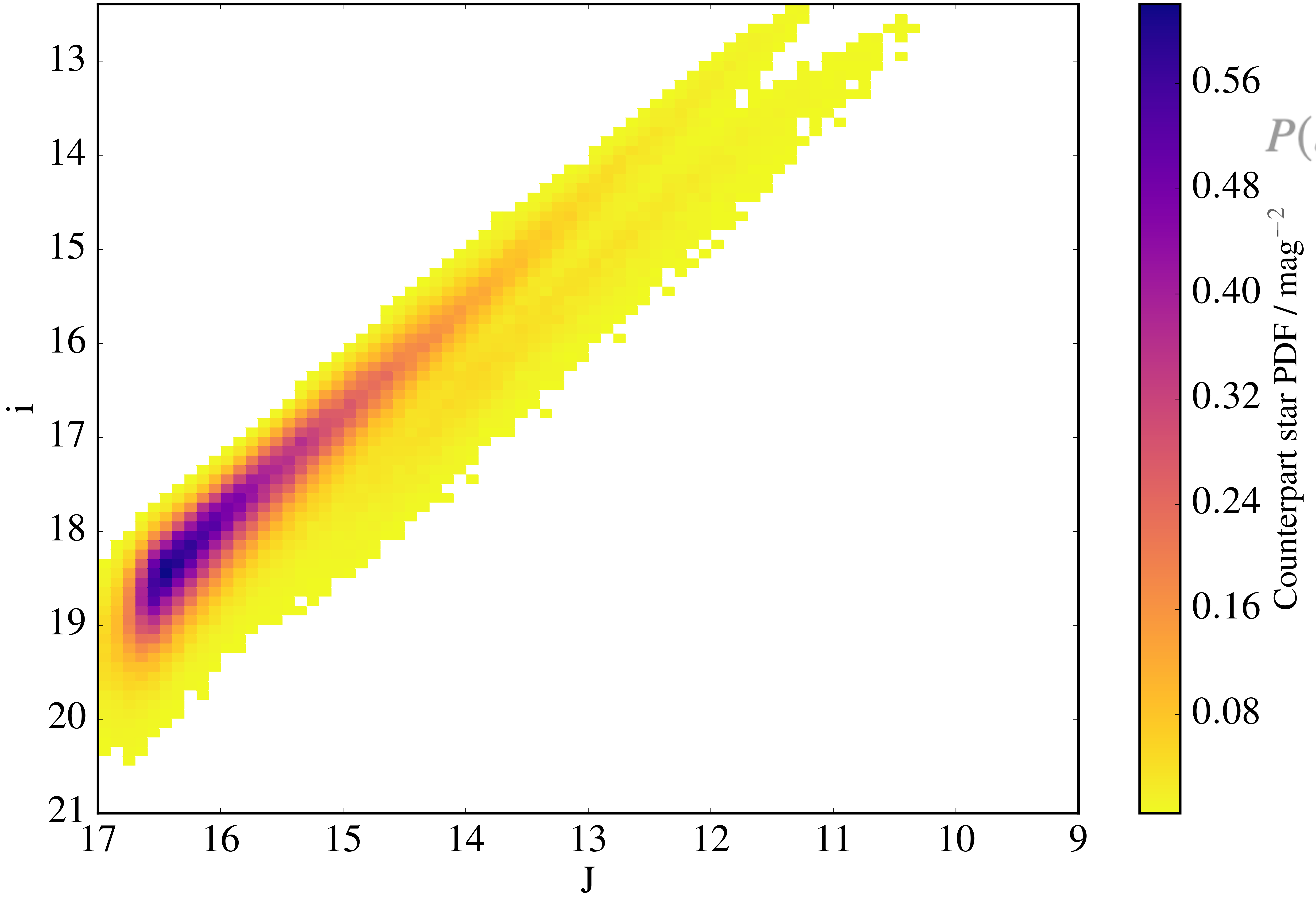
# The Counterpart Source Distribution

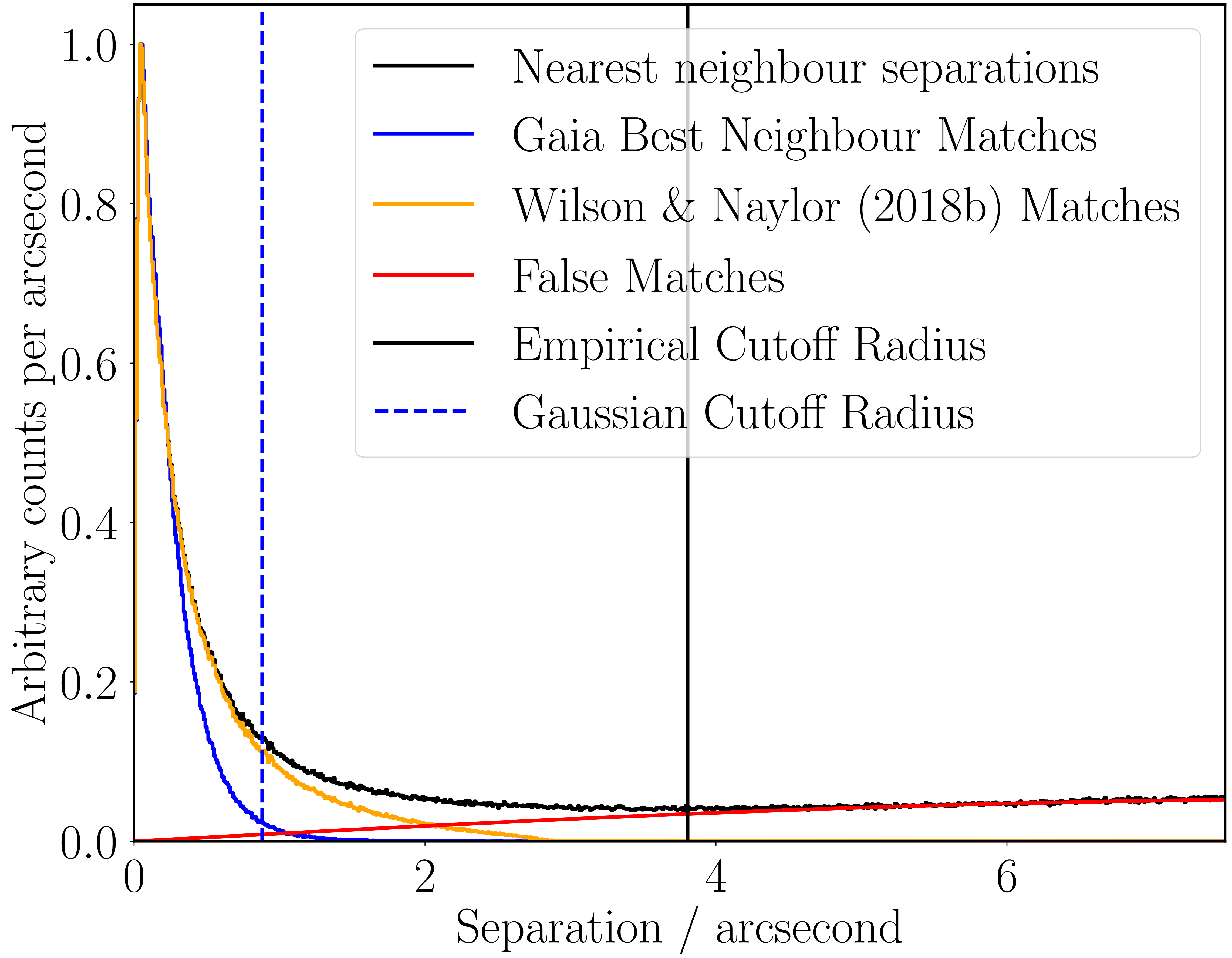


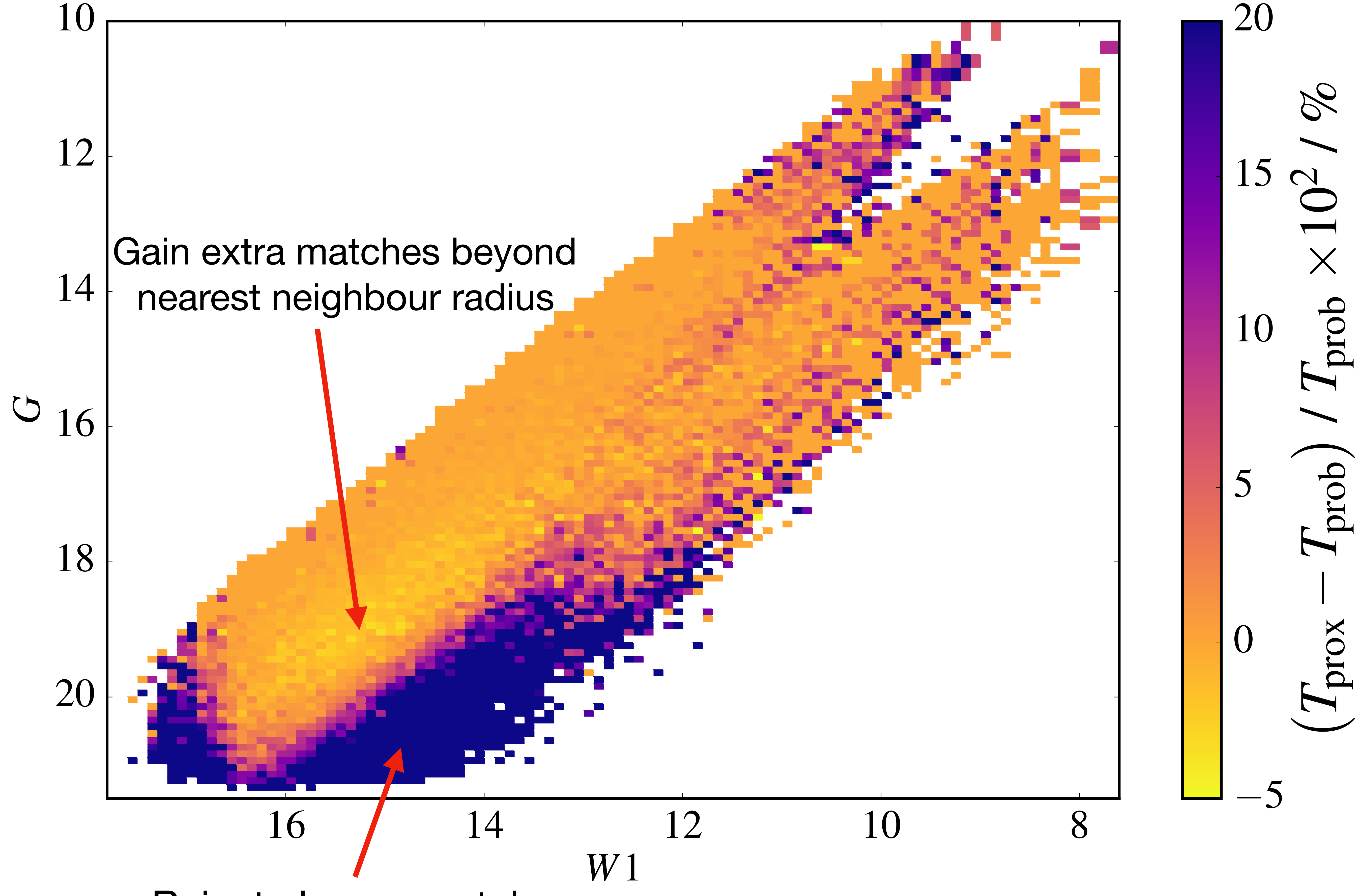

$$P(\zeta, \lambda, k|\gamma, \phi) = K^{-1} \times \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^{k} N_c G_{\gamma\phi}^{\zeta_i \lambda_i} c_{\gamma\phi}^{\zeta_i \lambda_i}$$

**Unmatched** **Matched**

Wilson & Naylor (2018a)

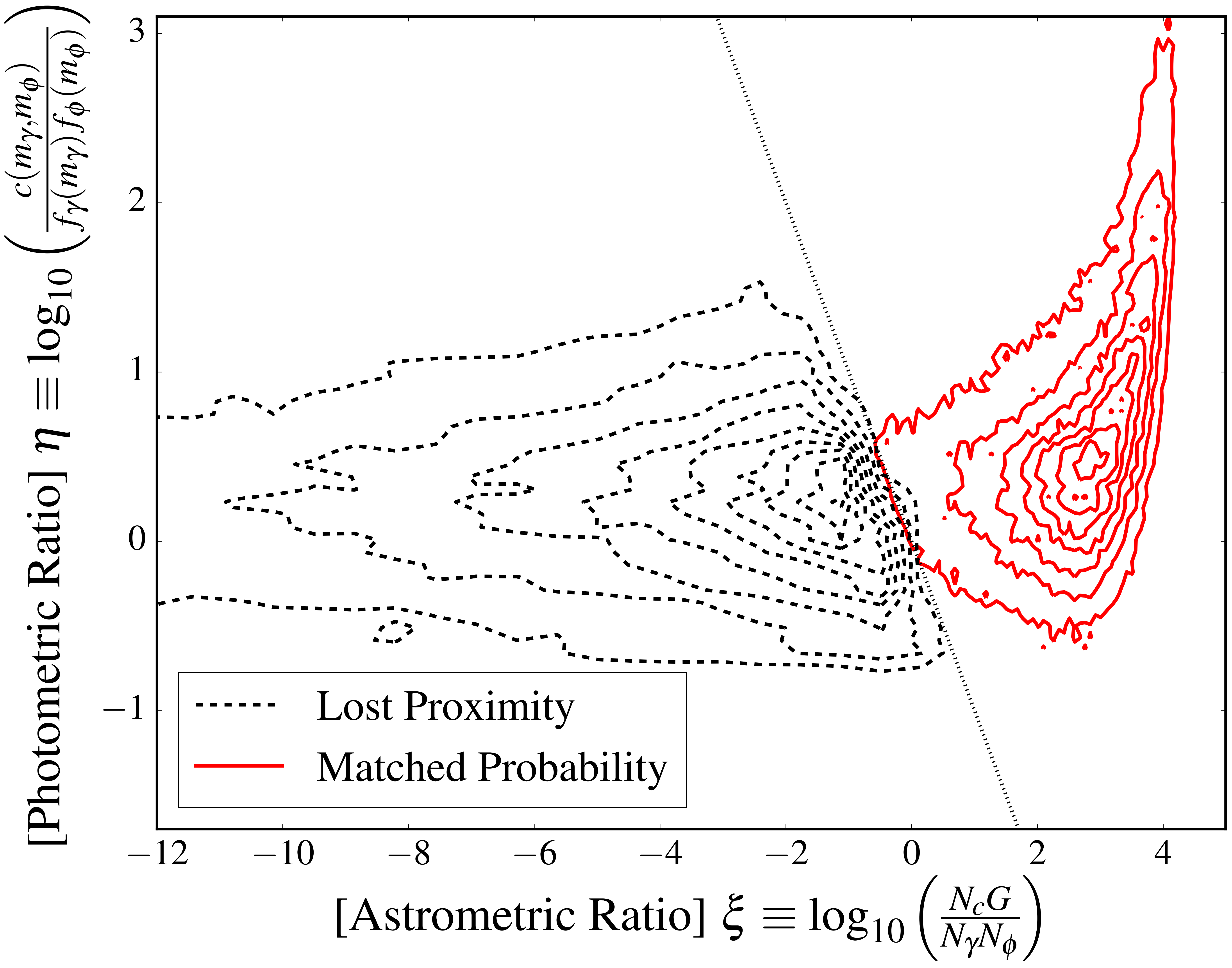
# Comparing Match Distributions




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)

# Lost Gaussian-Only Matches




Wilson & Naylor (2018b)

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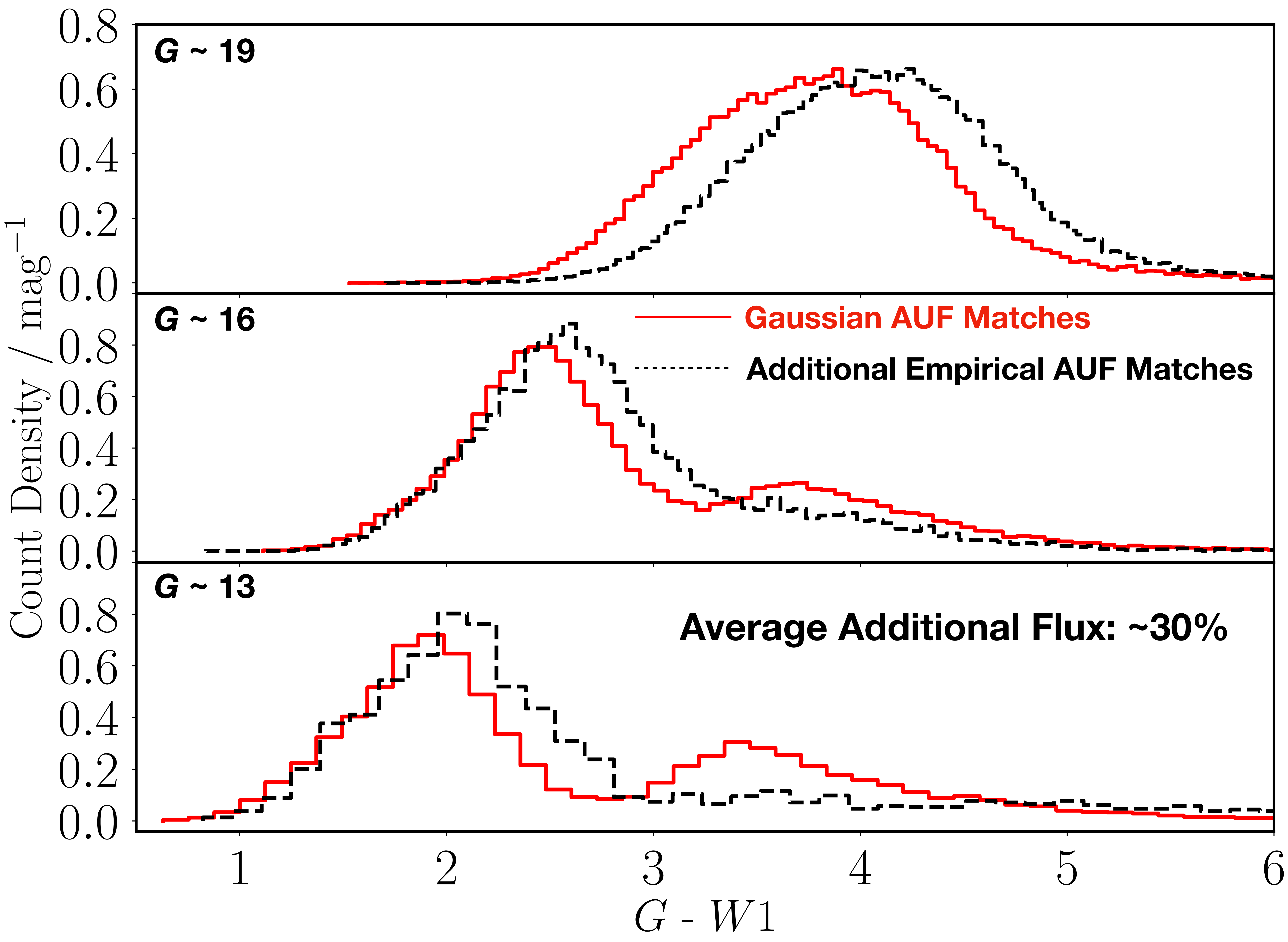
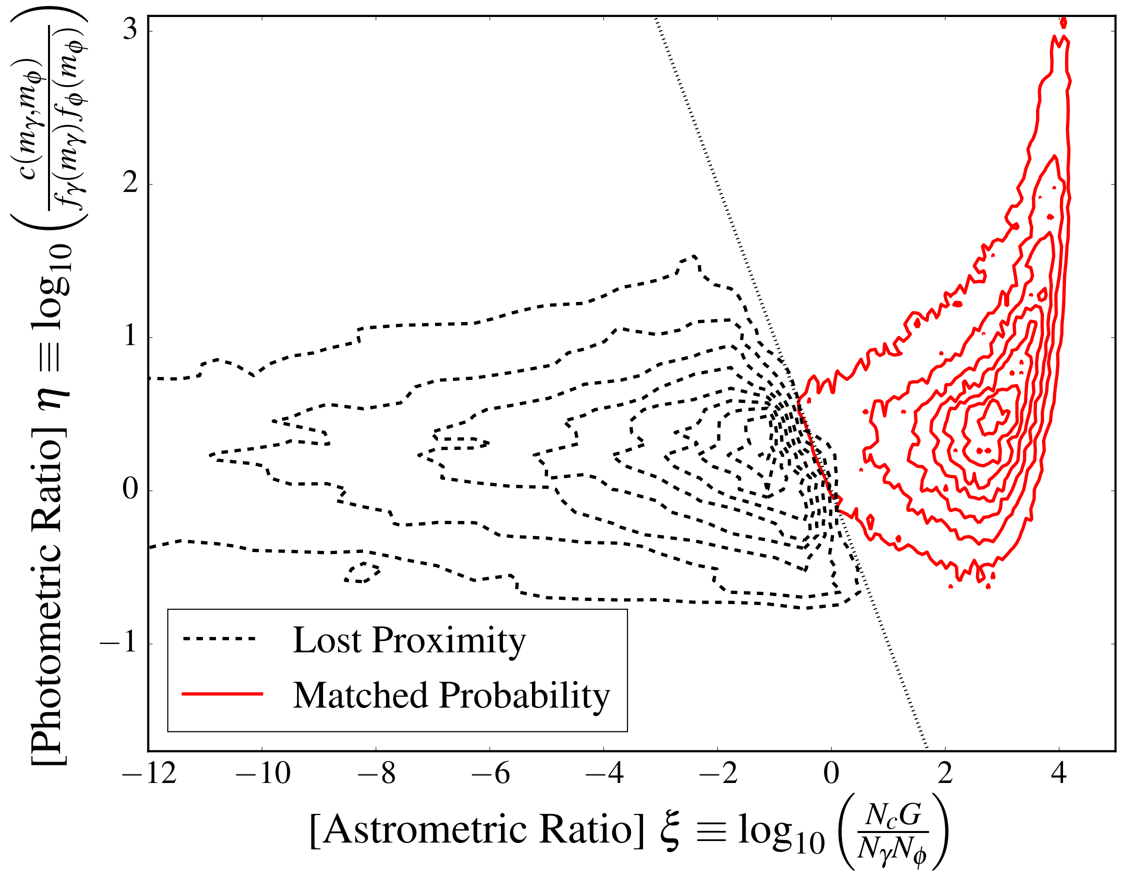
# Perturbation-Colour Correlation




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

Wilson & Naylor (2018b)

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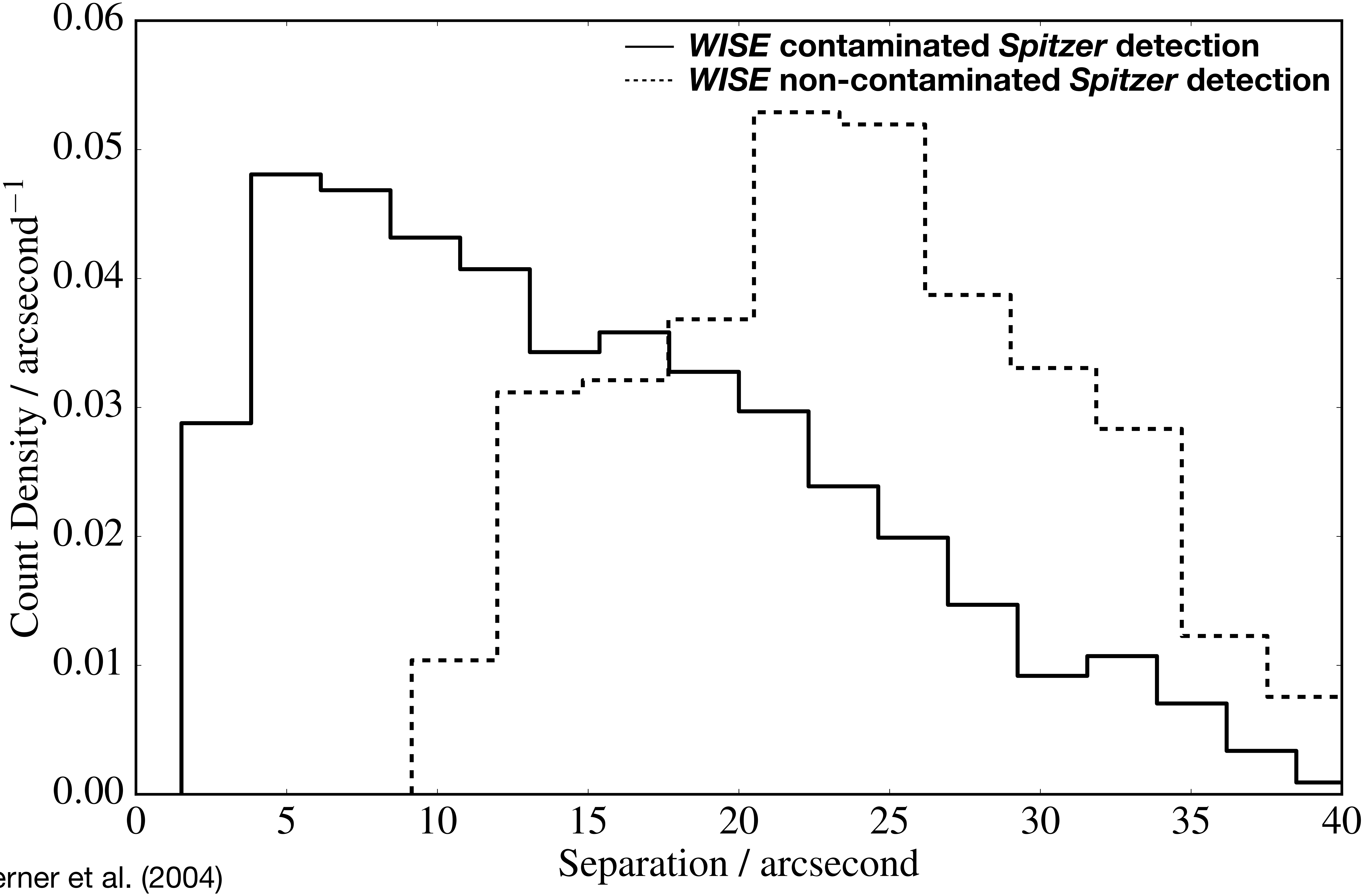
# Resolving Contaminants




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

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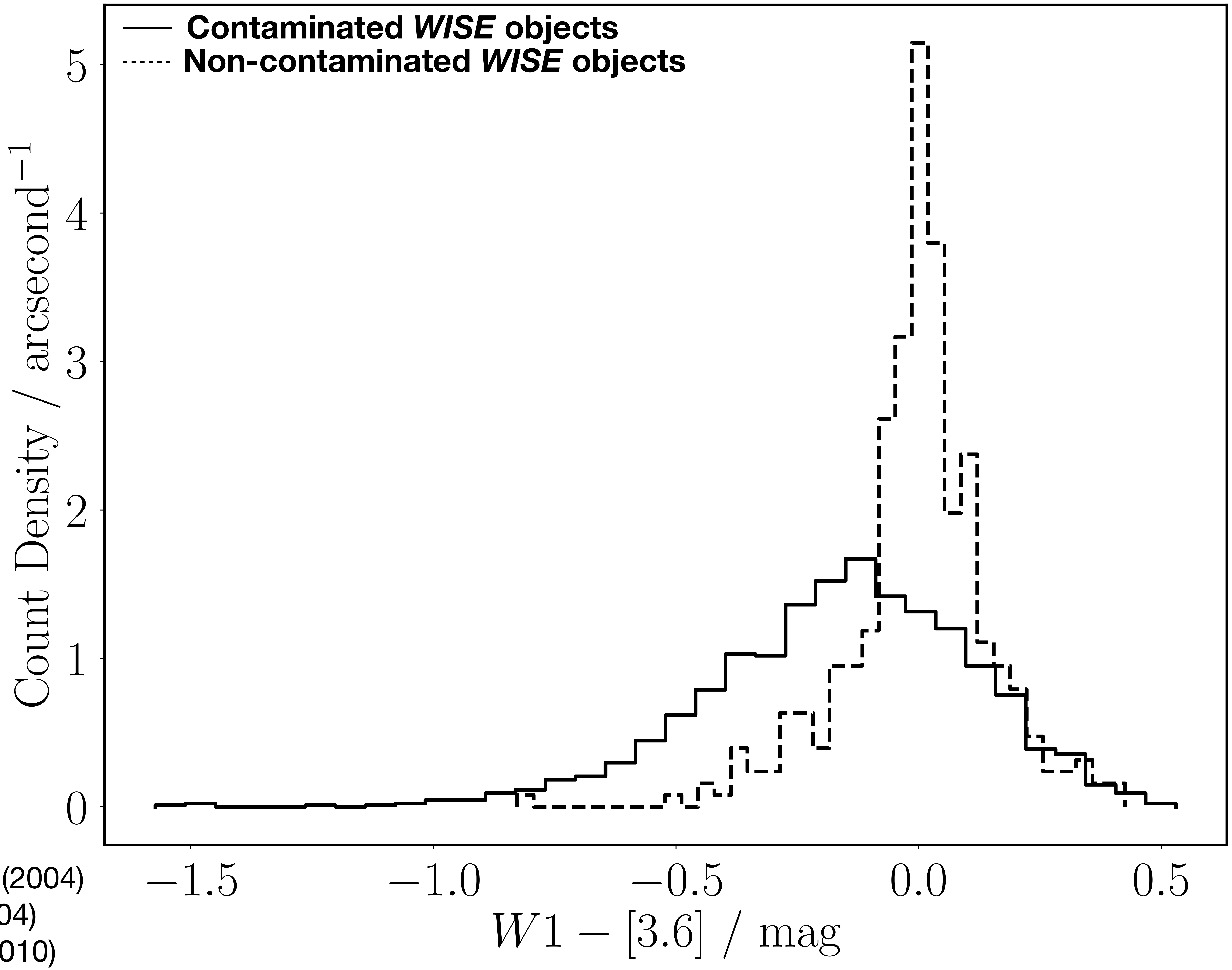
# Resolving Contaminant Flux




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

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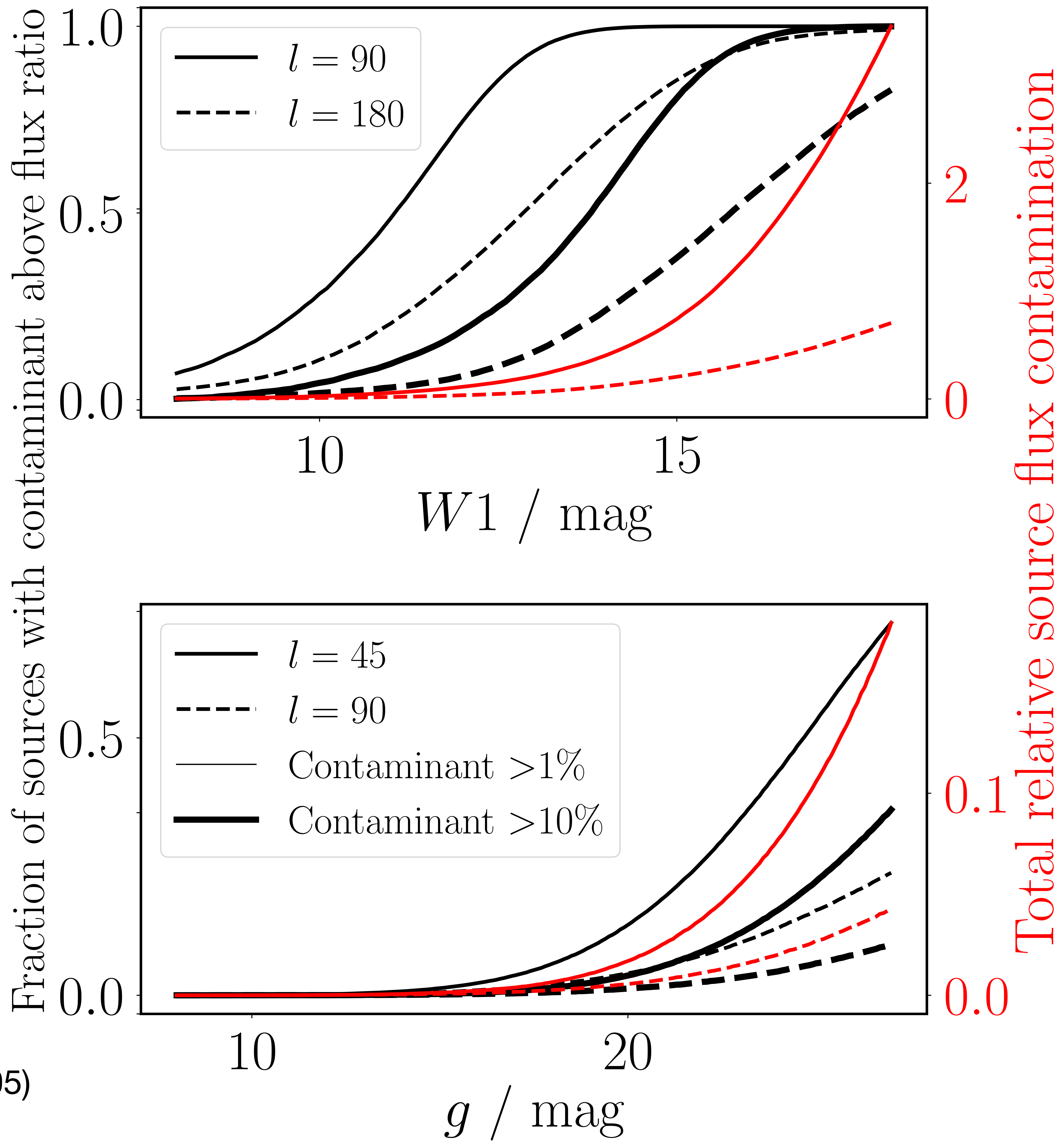
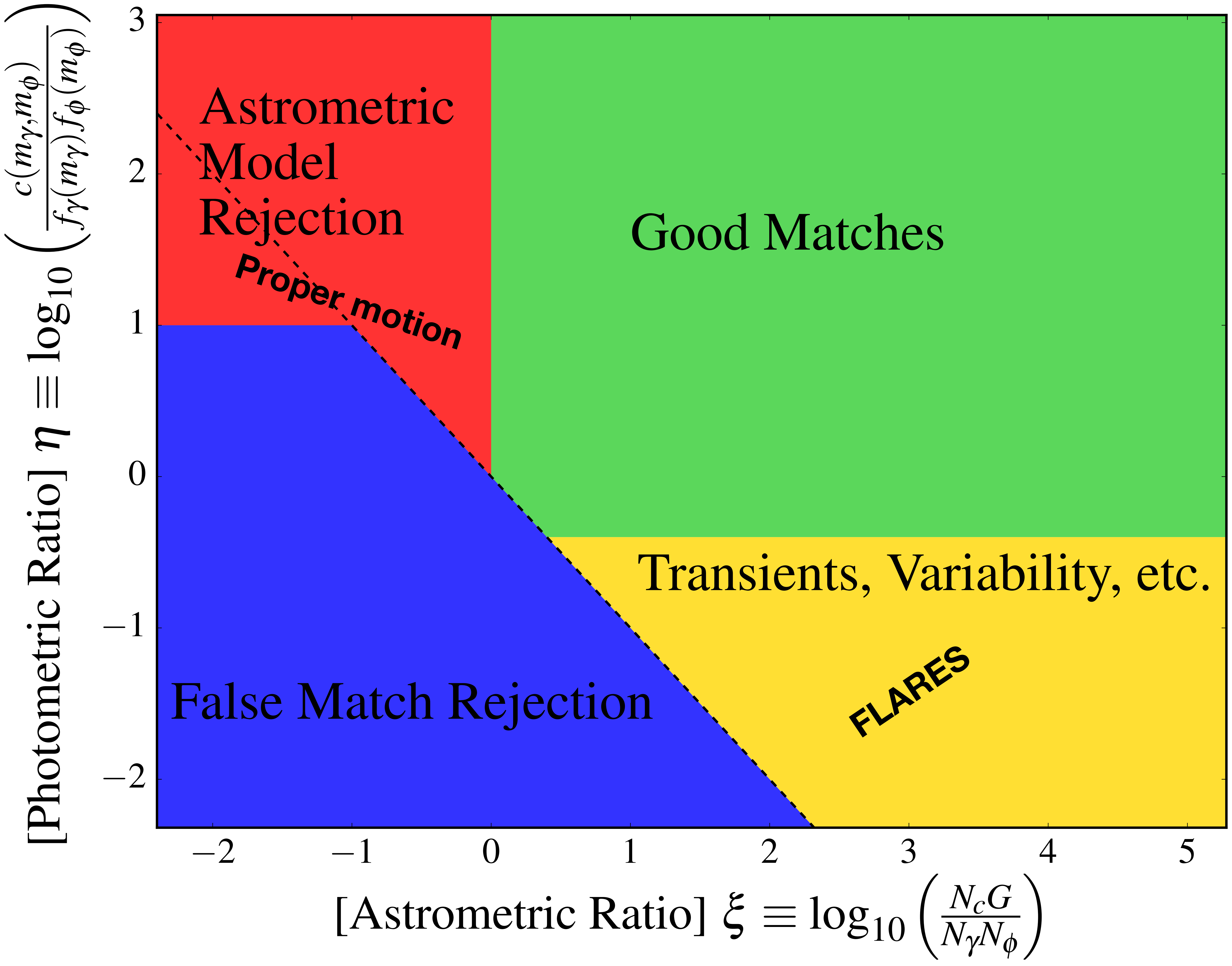
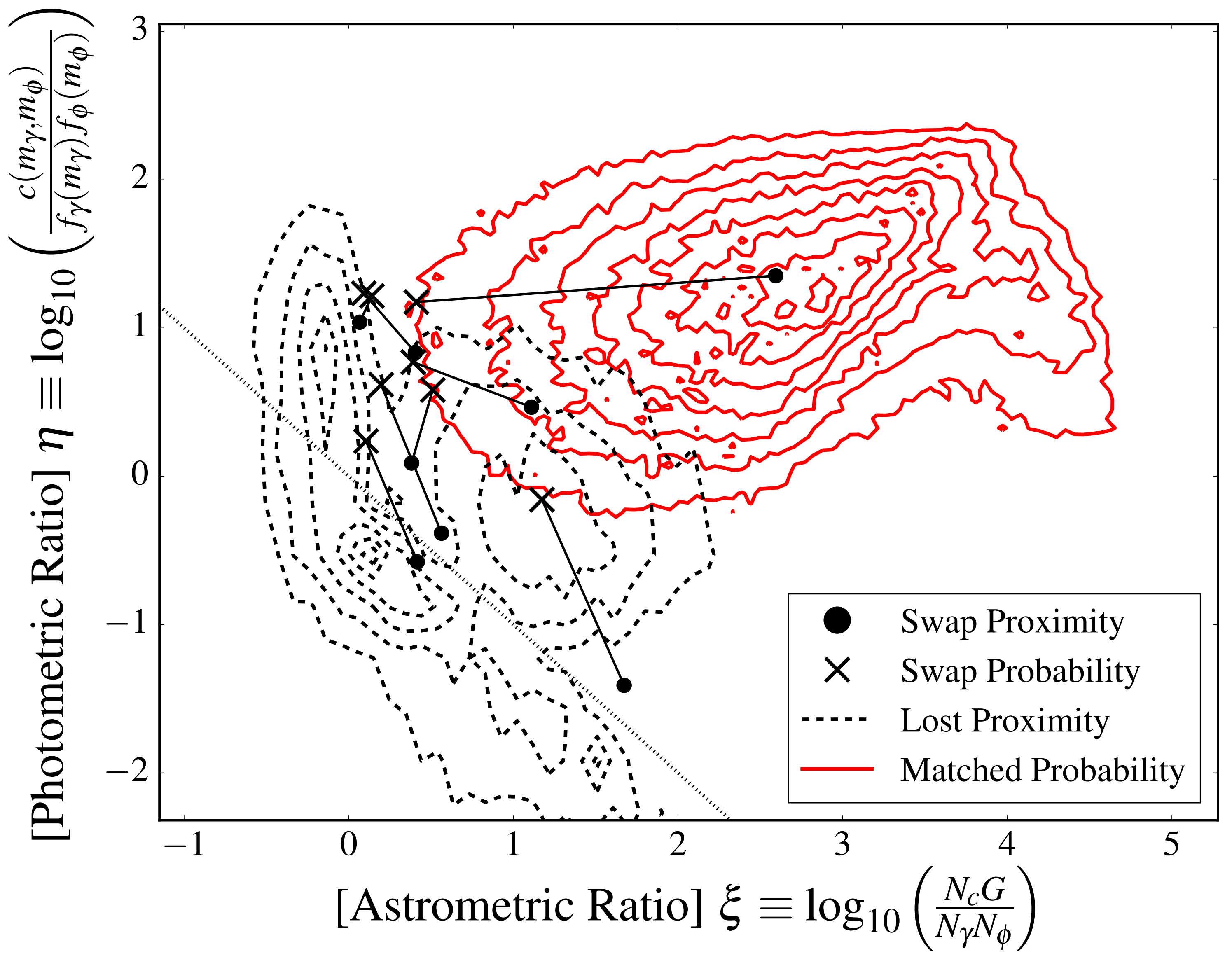
# Contamination Rates and Amounts




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

# The Likelihood Ratio Space




Wilson & Naylor (2018b)

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# 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!)

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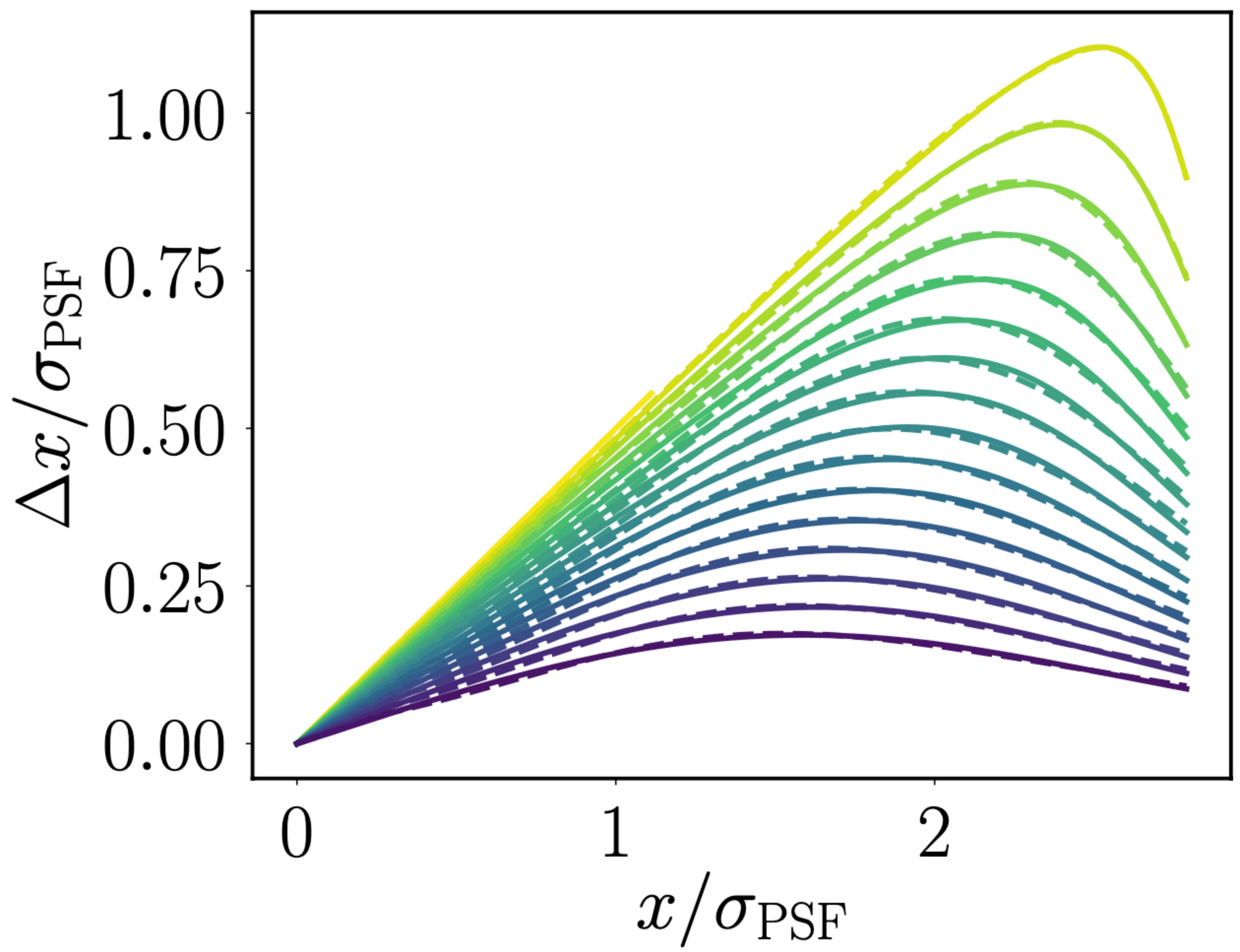
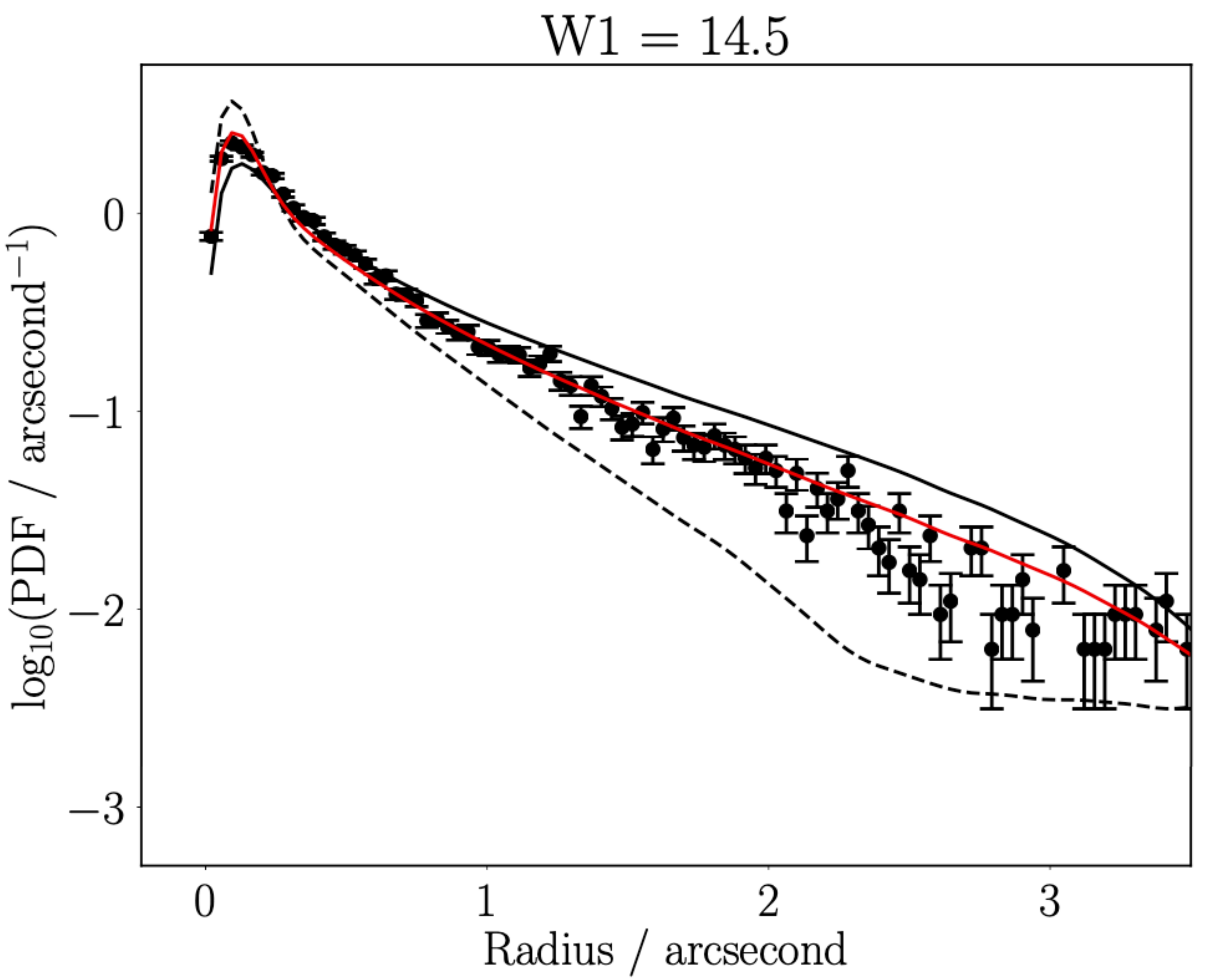
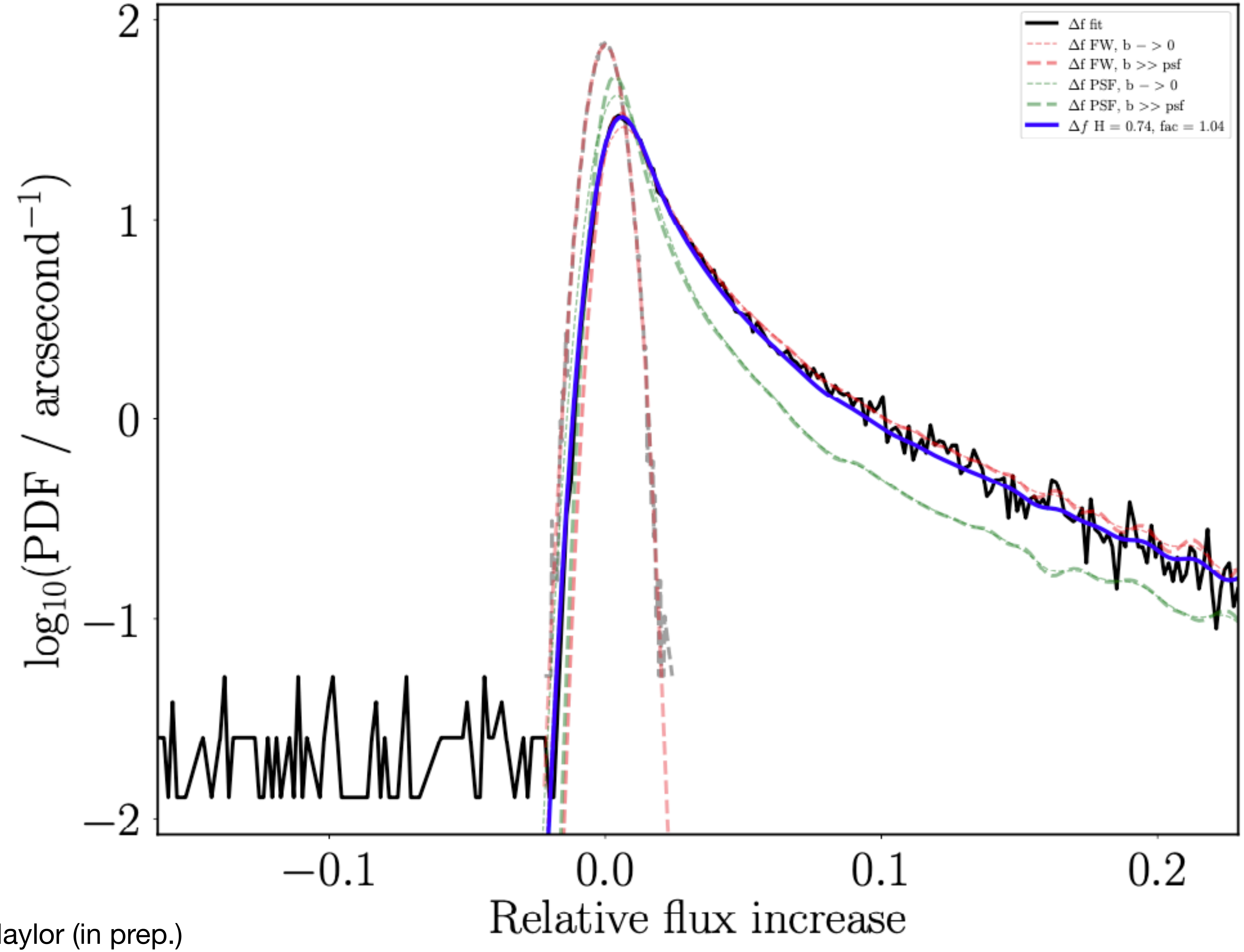
# Probing the Faintest Sources




Wilson & Naylor (in prep.)

# Photometric Contamination Function




Wilson & Naylor (in prep.)

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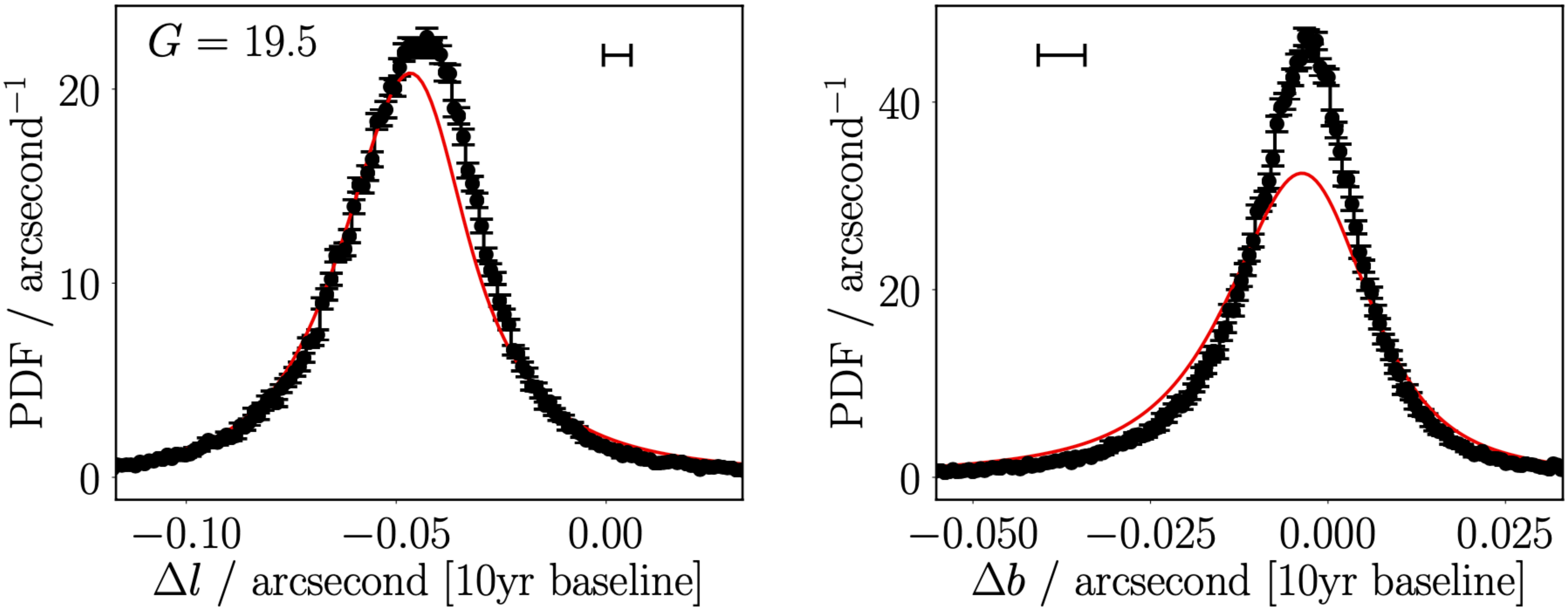
# Including Unknown Proper Motions




Wilson (2022, RASTI, submitted)
*Gaia* eDR3 - Gaia Collaboration et al. (2021, A&A, 649, A1)

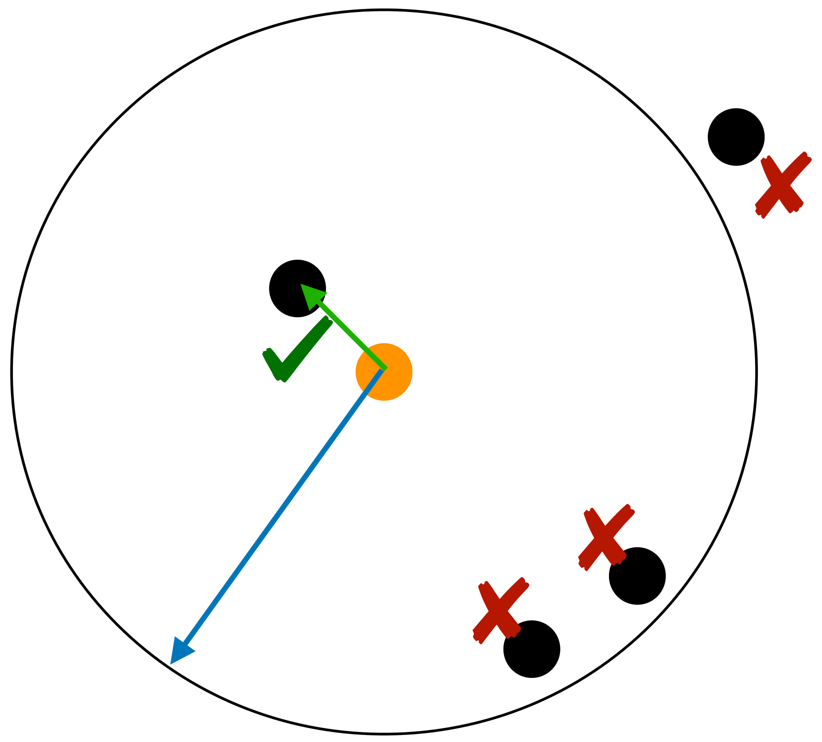
# What does this mean for you?

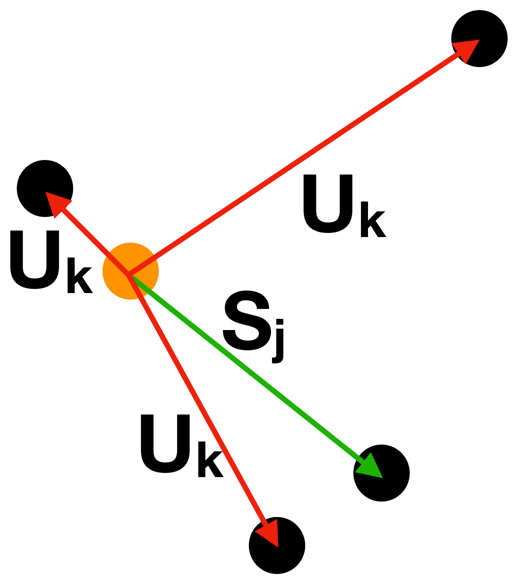
**The “busy” astronomer: uses a quick and simple 2” match -> Too many matches**

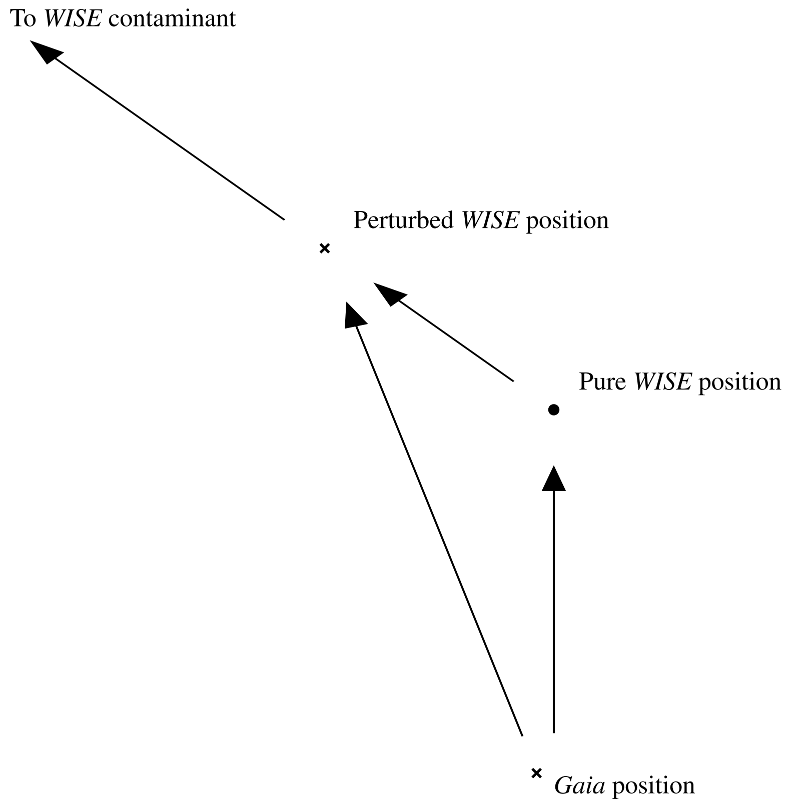
**The “Bayesian” astronomer: uses astrometric centroid uncertainty to reduce match radius -> Too few matches**

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

**The “smart” 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

Tom J Wilson @onoddil

# 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"?**
- **Can include unknown proper motions easily in AUF**
- **Modelling of statistical flux contamination allows for the recovery of "true" fluxes**
- **High dynamic range matches must account for differential crowding matching to ancillary or historic data**

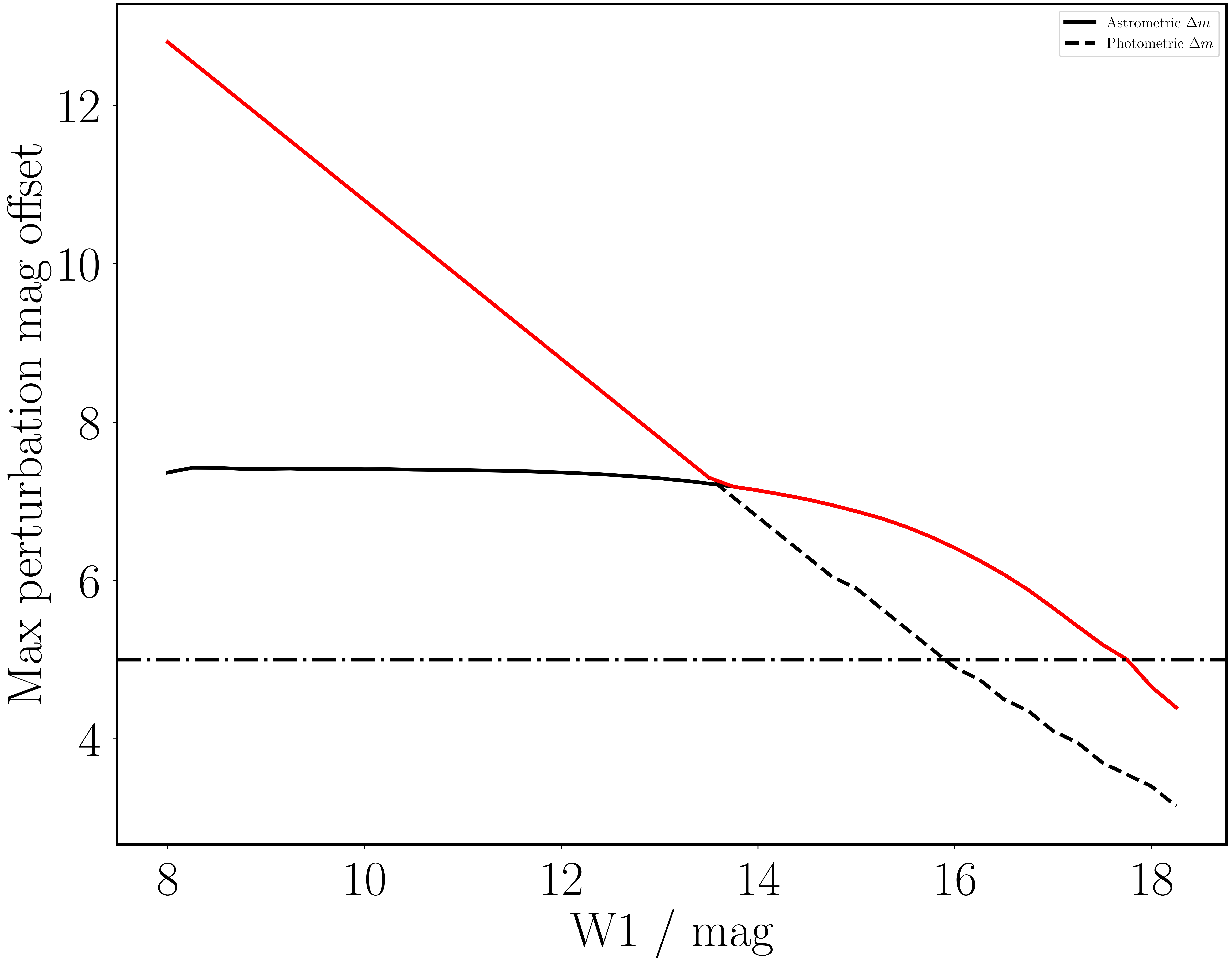
- **Upcoming LSST:UK cross-match service macauff — let me know your thoughts/needs/hopes/dreams**

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

**Wilson & Naylor, 2017, MNRAS, 468, 2517**
**Wilson & Naylor, 2018a, MNRAS, 473, 5570**
**Wilson & Naylor, 2018b, MNRAS, 481, 2148**

**https://github.com/Onoddil/macauff**

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

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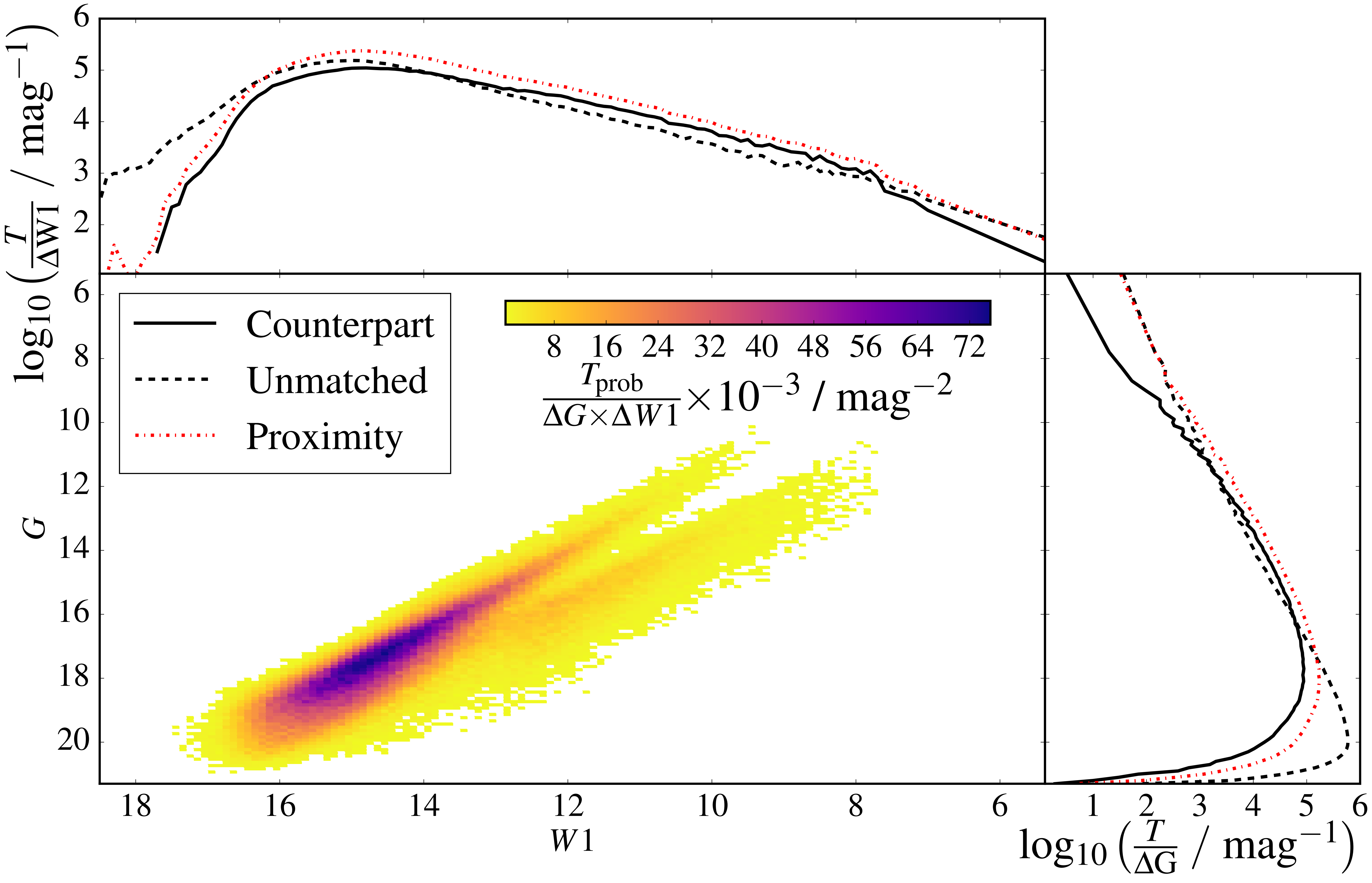
# Contamination Effects: Gaia-WISE Gaussian Matches




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

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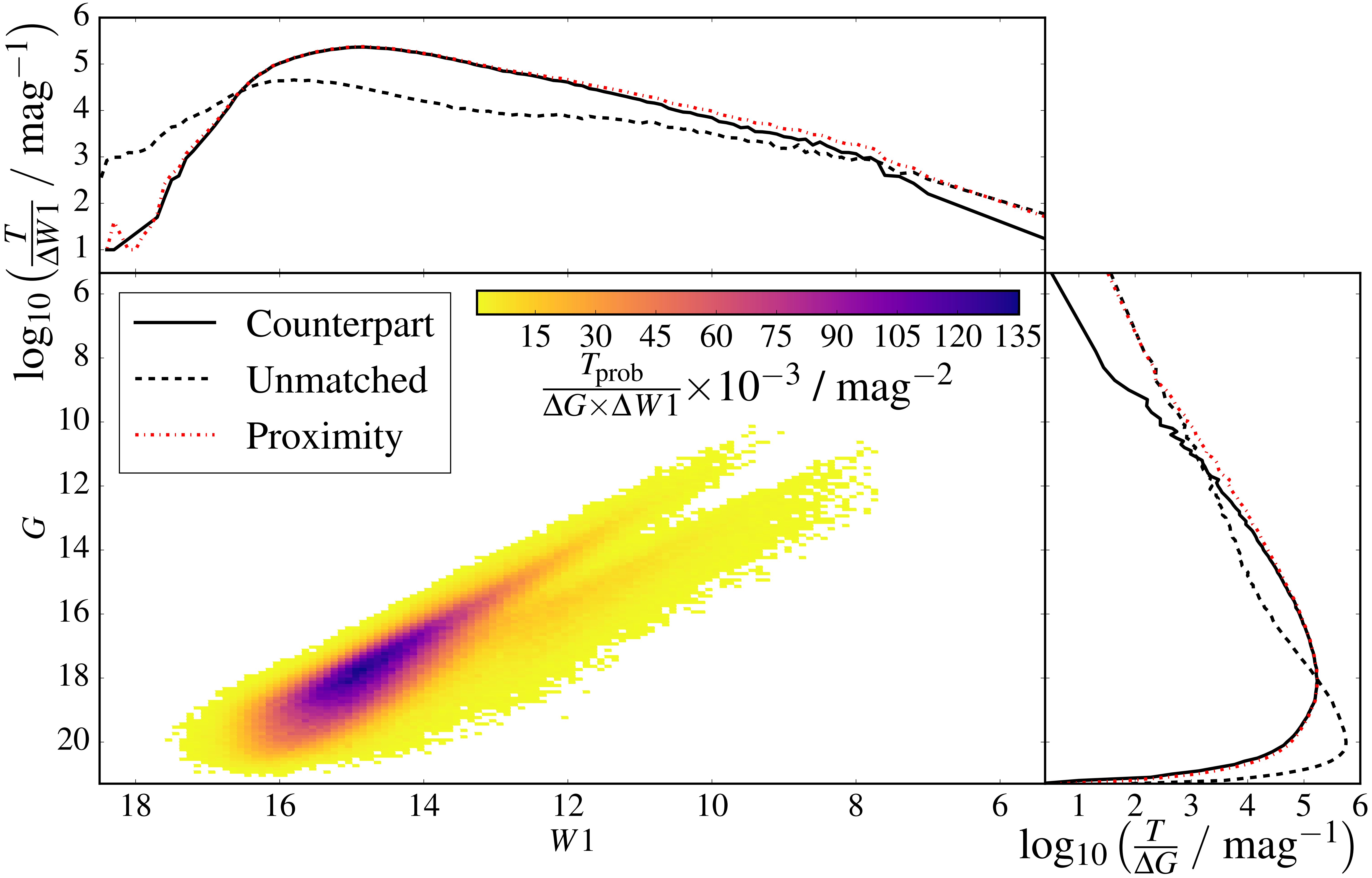
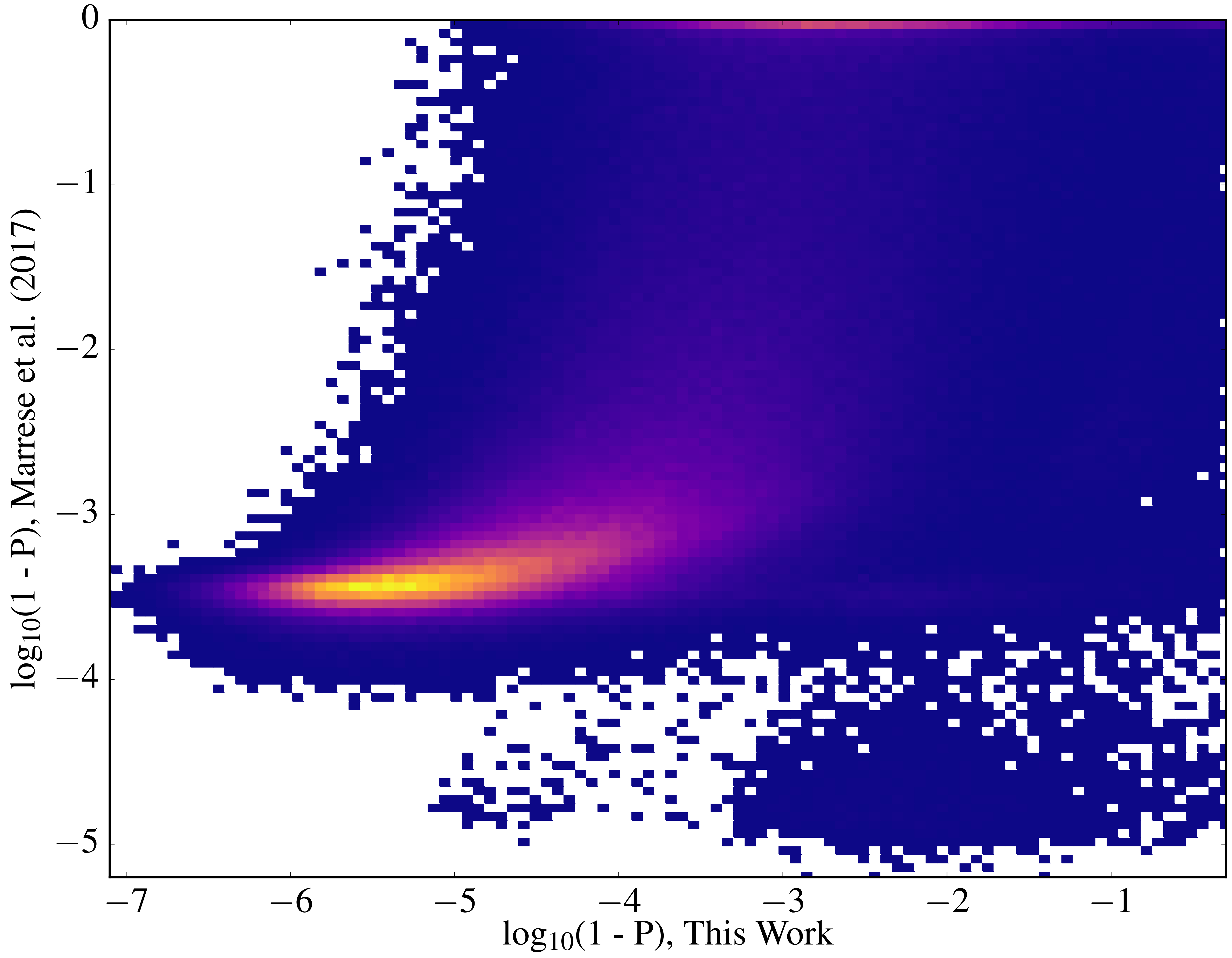
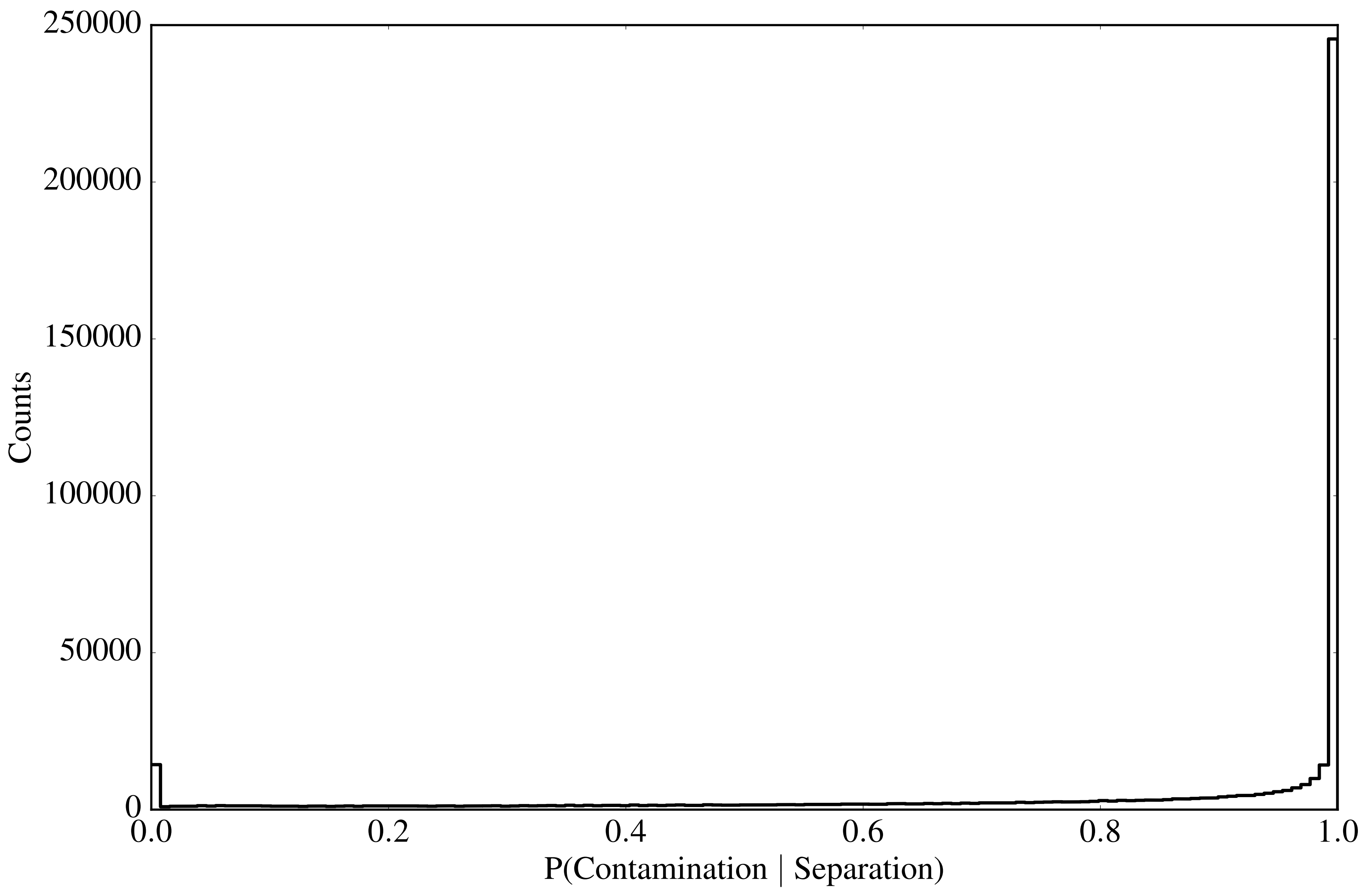
# Contamination Effects:
# Gaia-WISE Empirical Matches

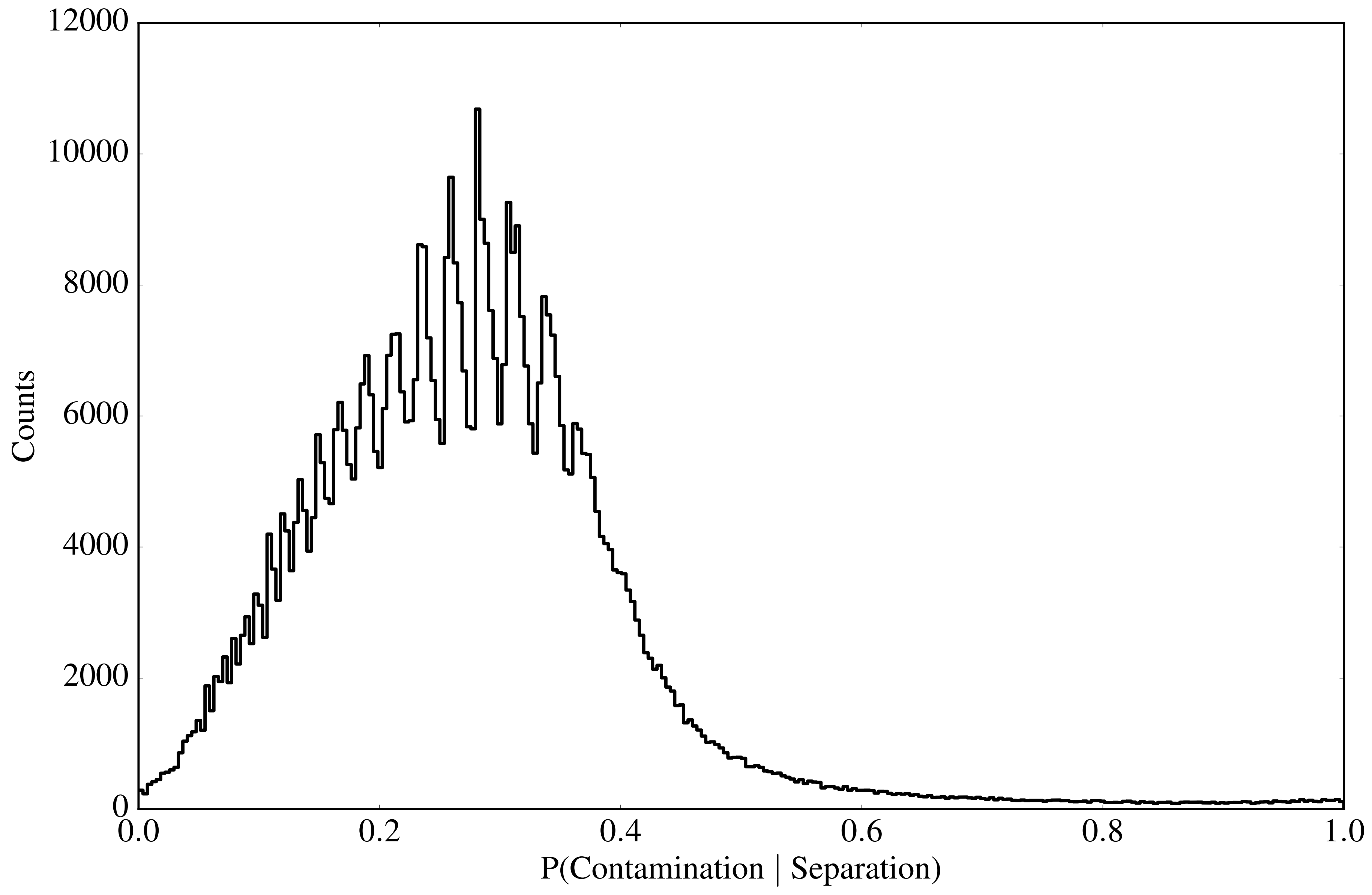


# Contamination Effects: Gaia Lost Matches



# Photometric Contamination: WISE/Spitzer Contamination %

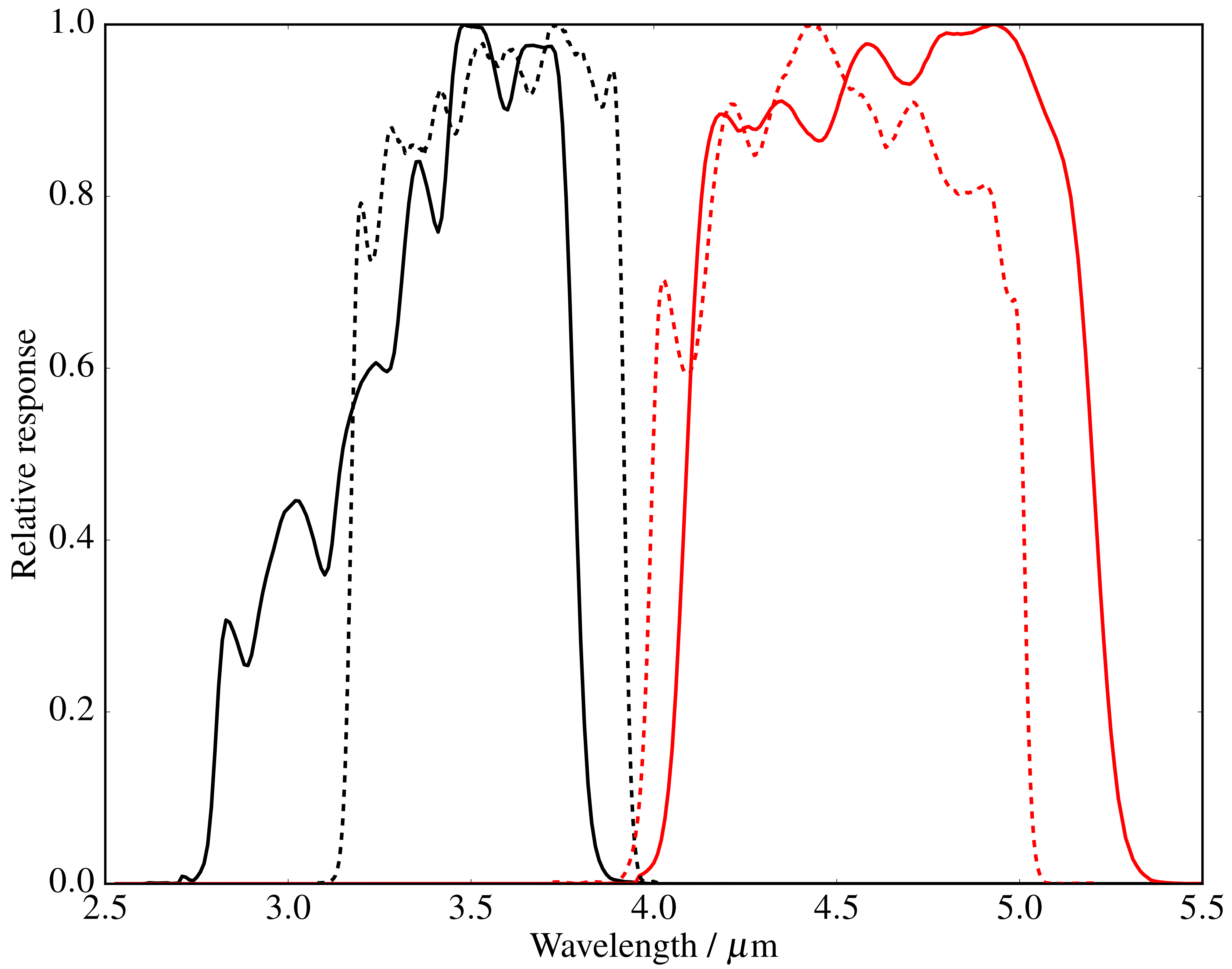



UNIVERSITY OF EXETER

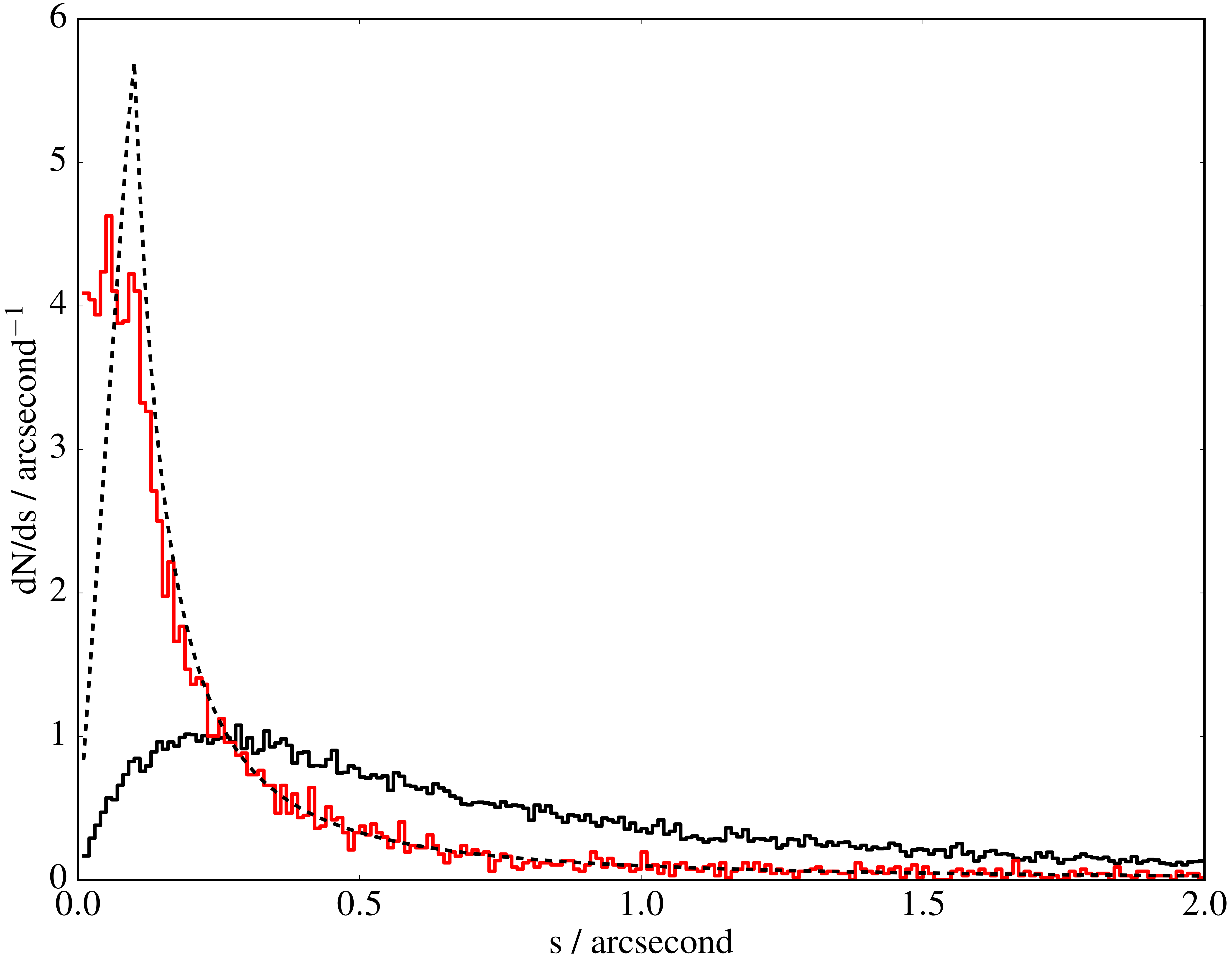
Wilson T., Naylor T., in prep…

# Contamination Effects: Wavelength Coverage




Tom J Wilson @onoddil

# The Astrometric Uncertainty Function: Analytical perturbations




Wilson & Naylor, 2017, MNRAS, 468, 2517

Tom J Wilson @onoddil