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# Towards Solving the Catalogue Cross-Match Problem

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github.io www

Bristol&Cardiff, 1/June/22

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# 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

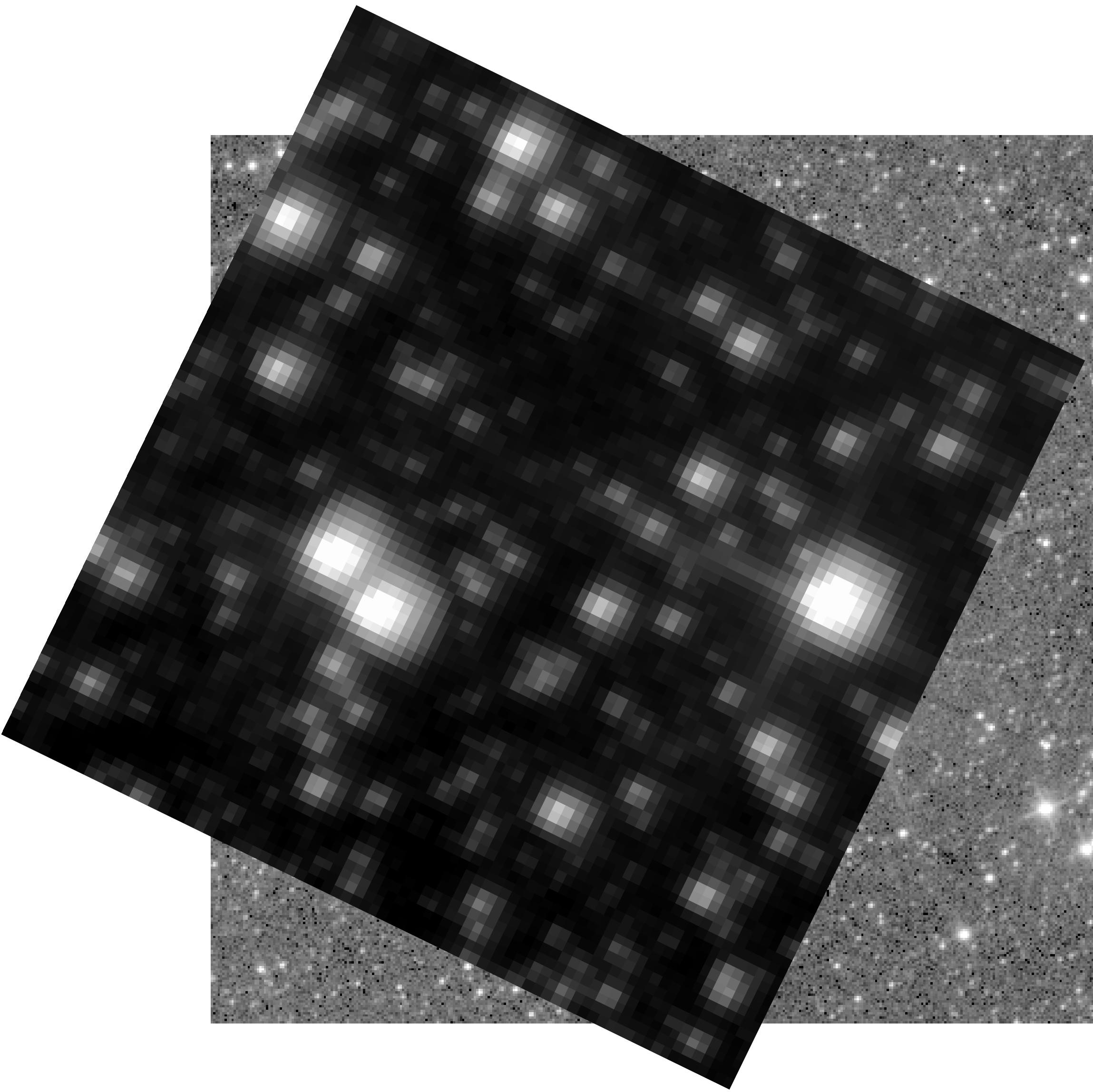


WISE - Wright et al. (2010)

WISE W1

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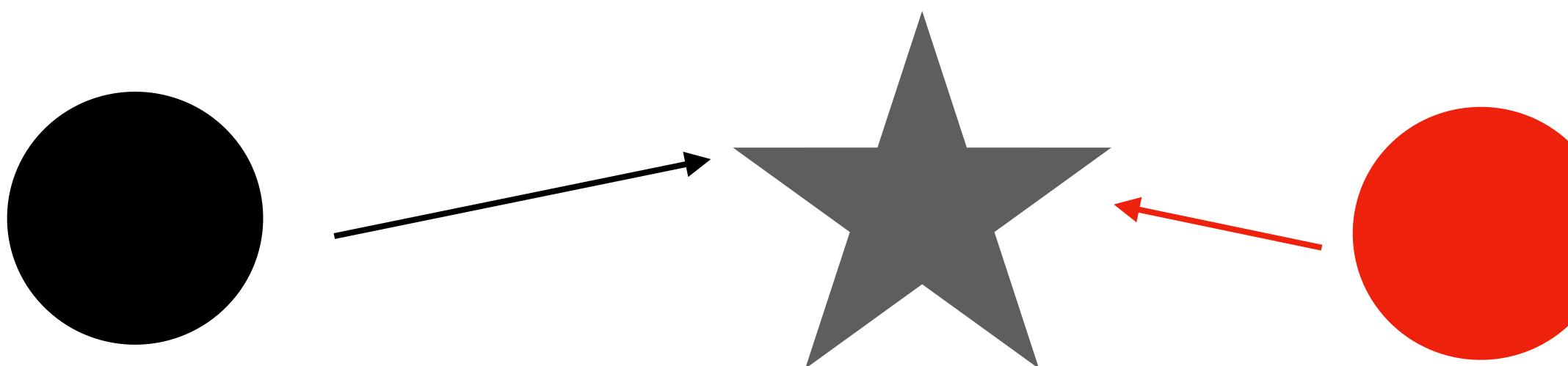
# Photometric Observations



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

TESS T  
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# Counterpart Assignment



— or —



# Matching Constellations



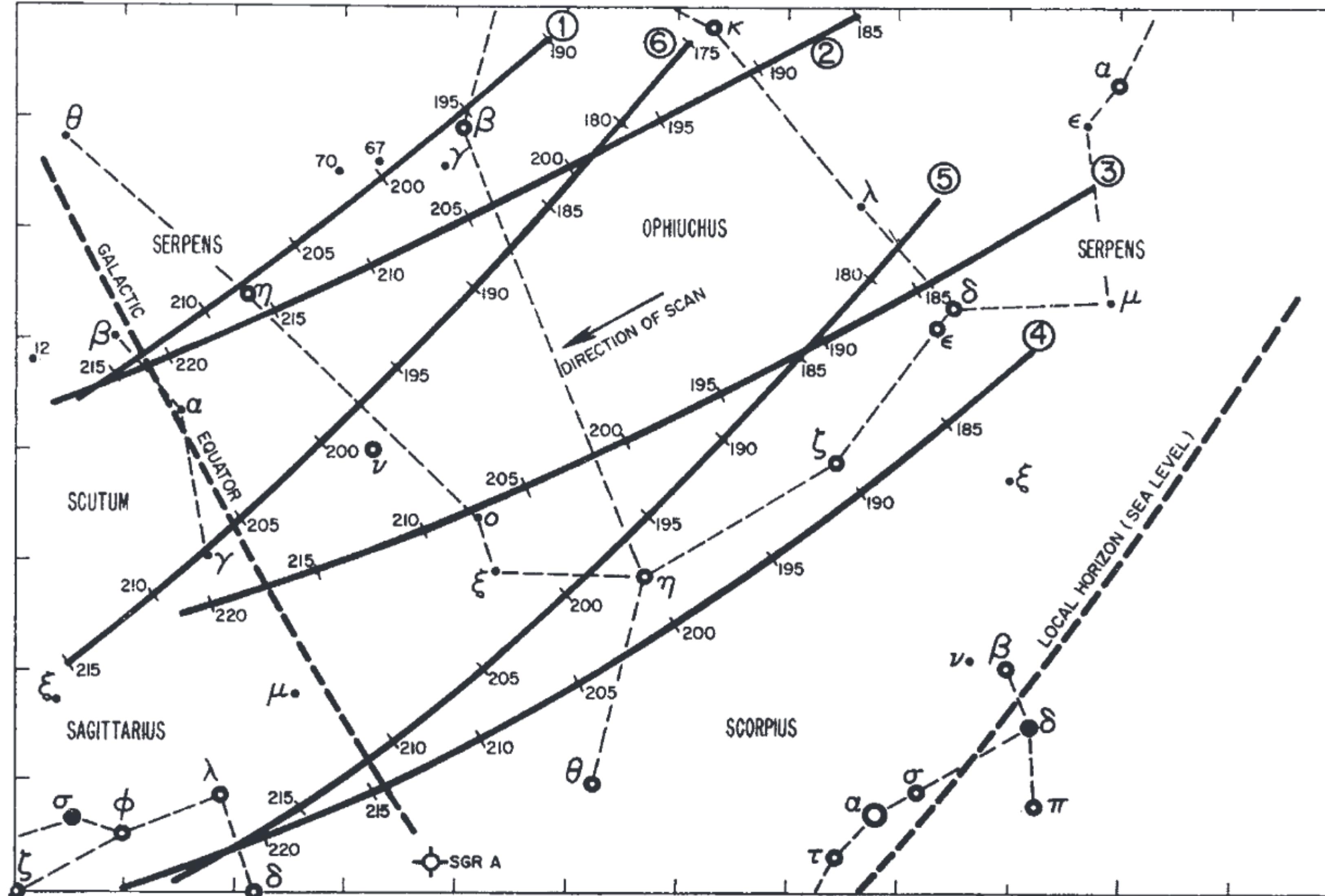
Image credit: Mouser, wikipedia

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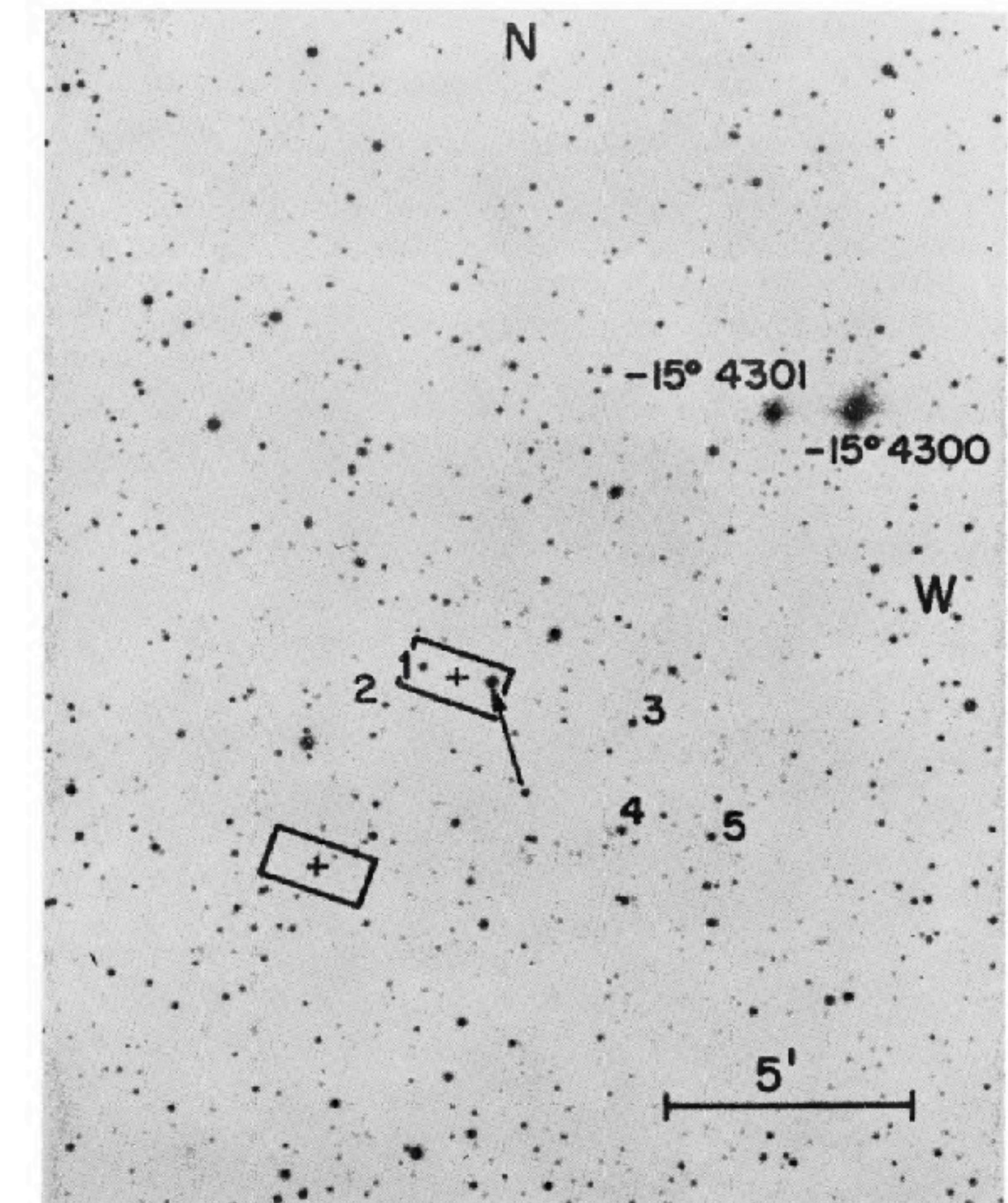
# Technology Abounds

- 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



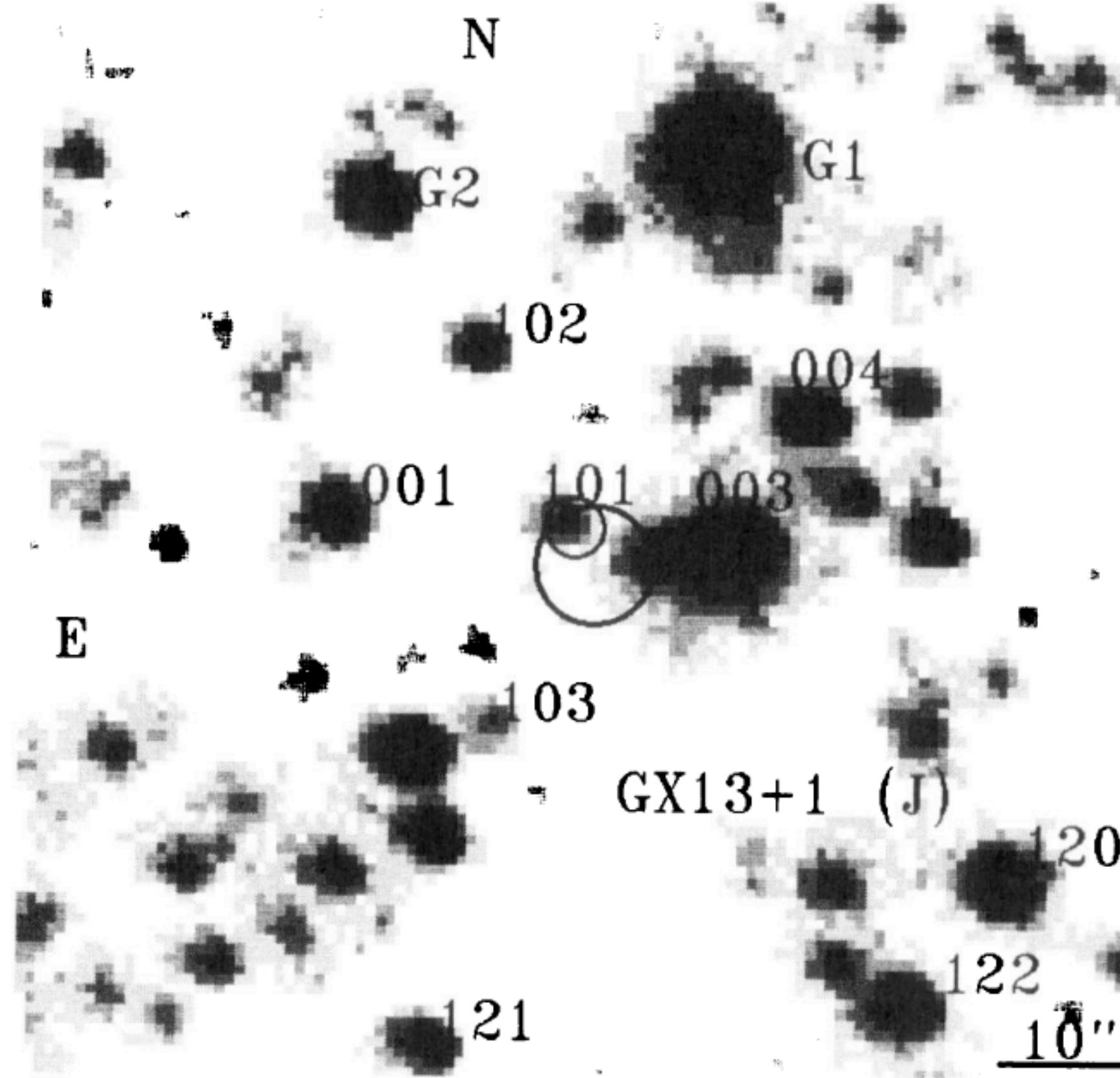
Giacconi, Gursky, & Waters (1964)



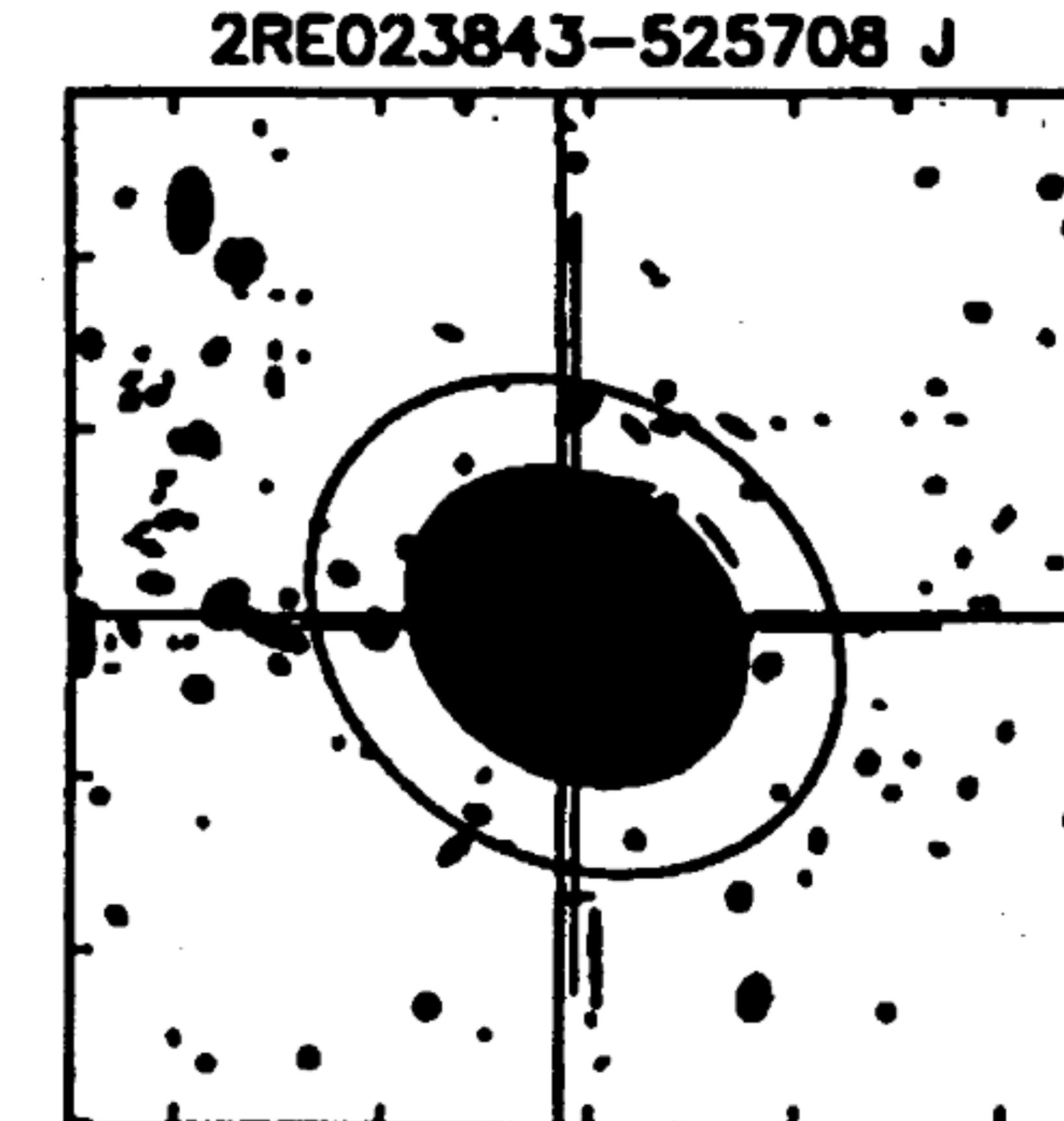
Sandage et al. (1966)

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# The Brightest Star in the Sky



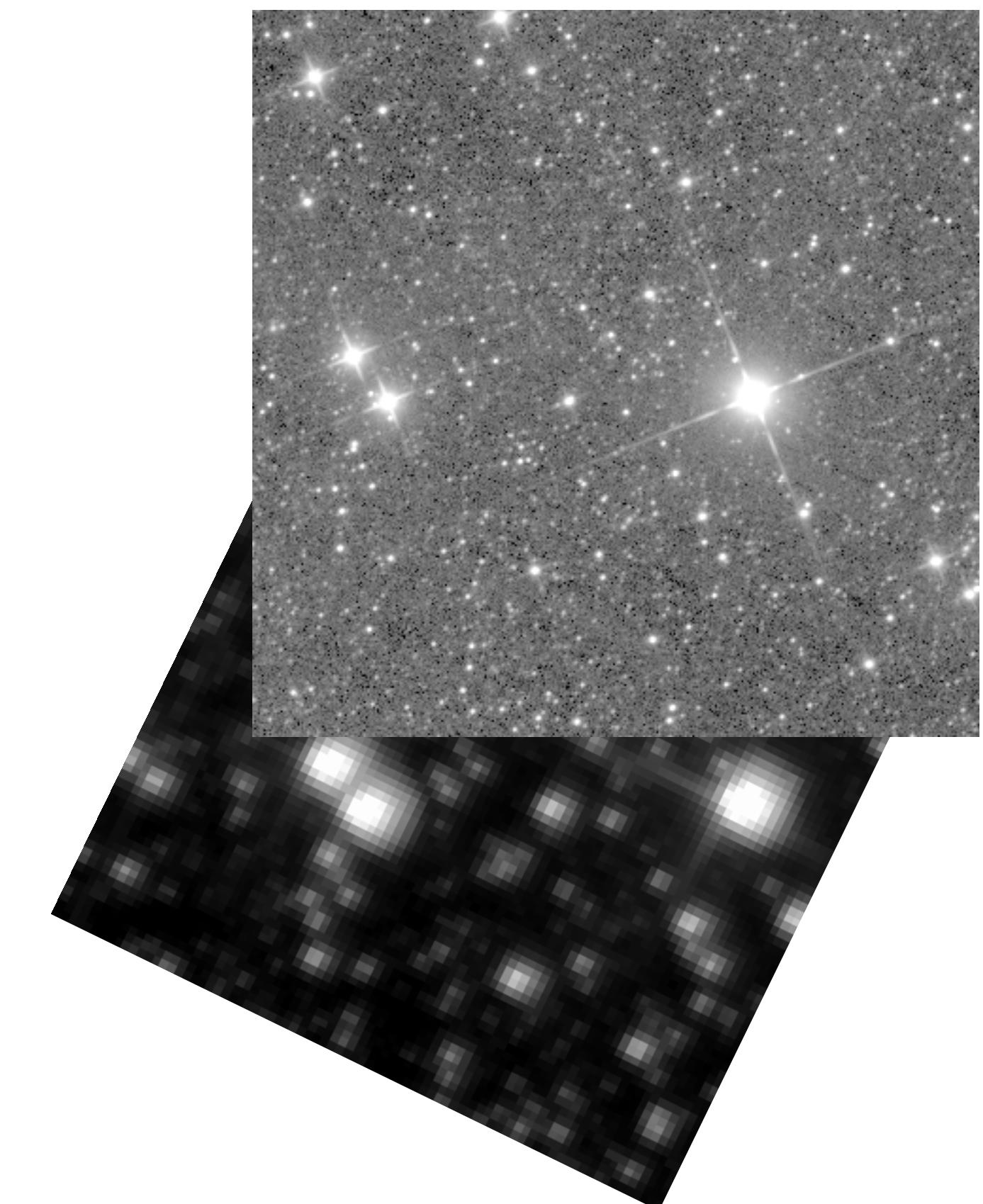
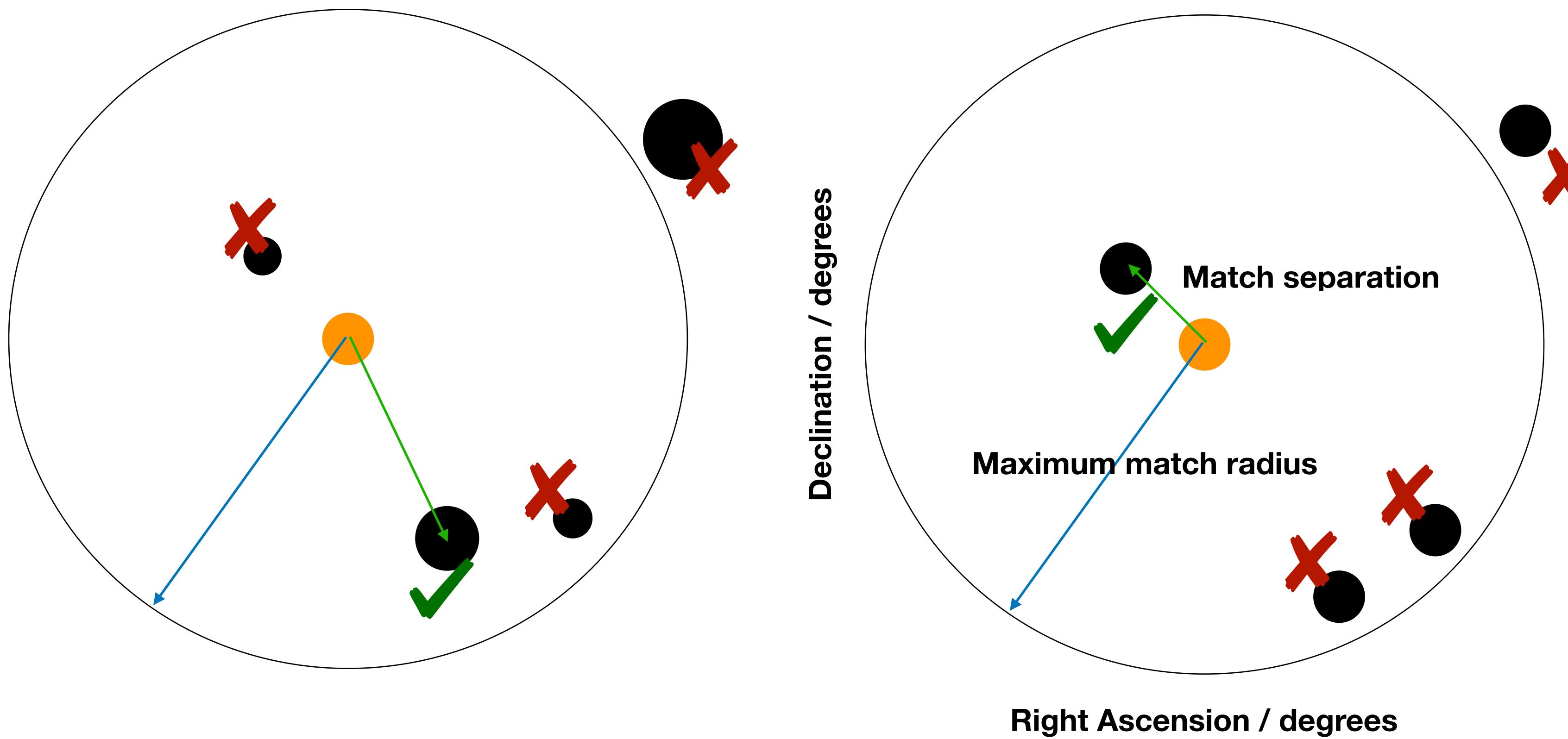
Naylor, Charles, & Longmore (1991)



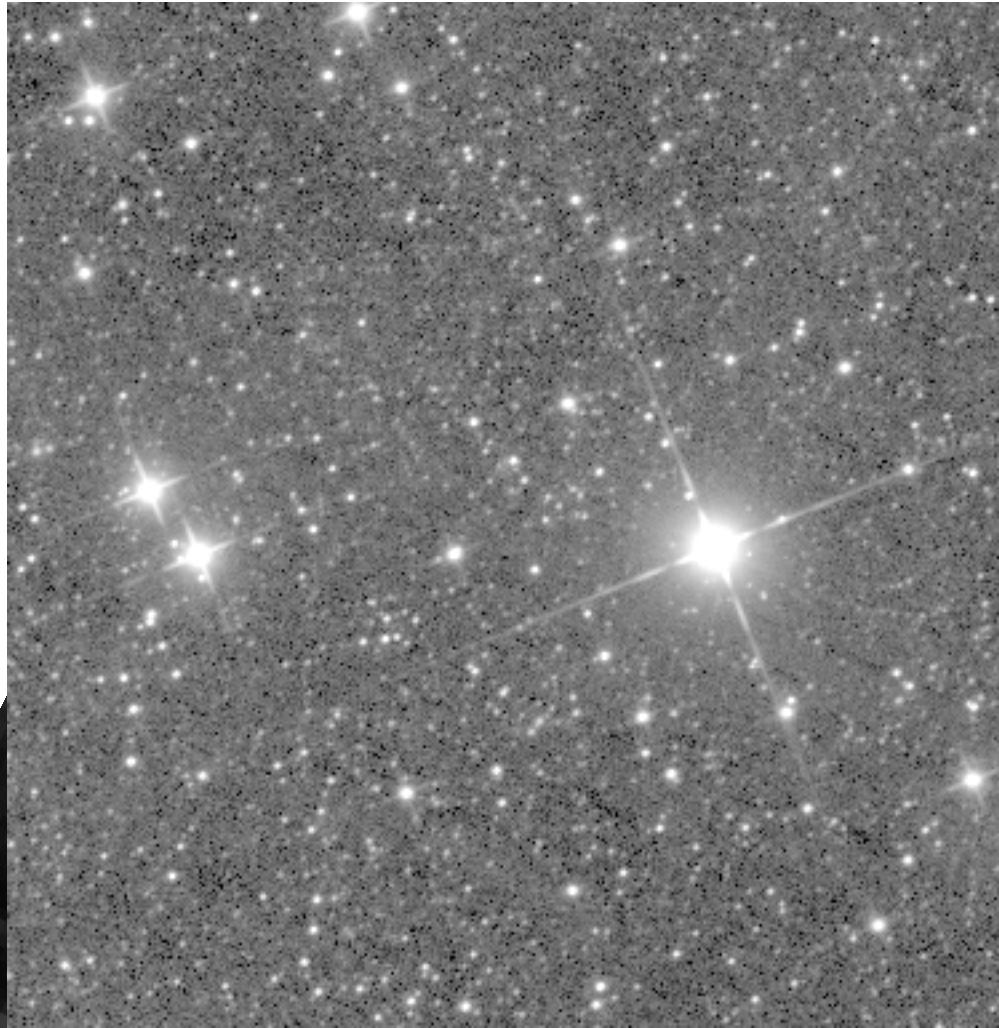
“...X-ray sources are rare events; bright optical sources are also rare events, so the observation of an X-ray source and a bright optical source in the same region of the sky is considered a non-random event”

Fotopoulou et al. (2016)

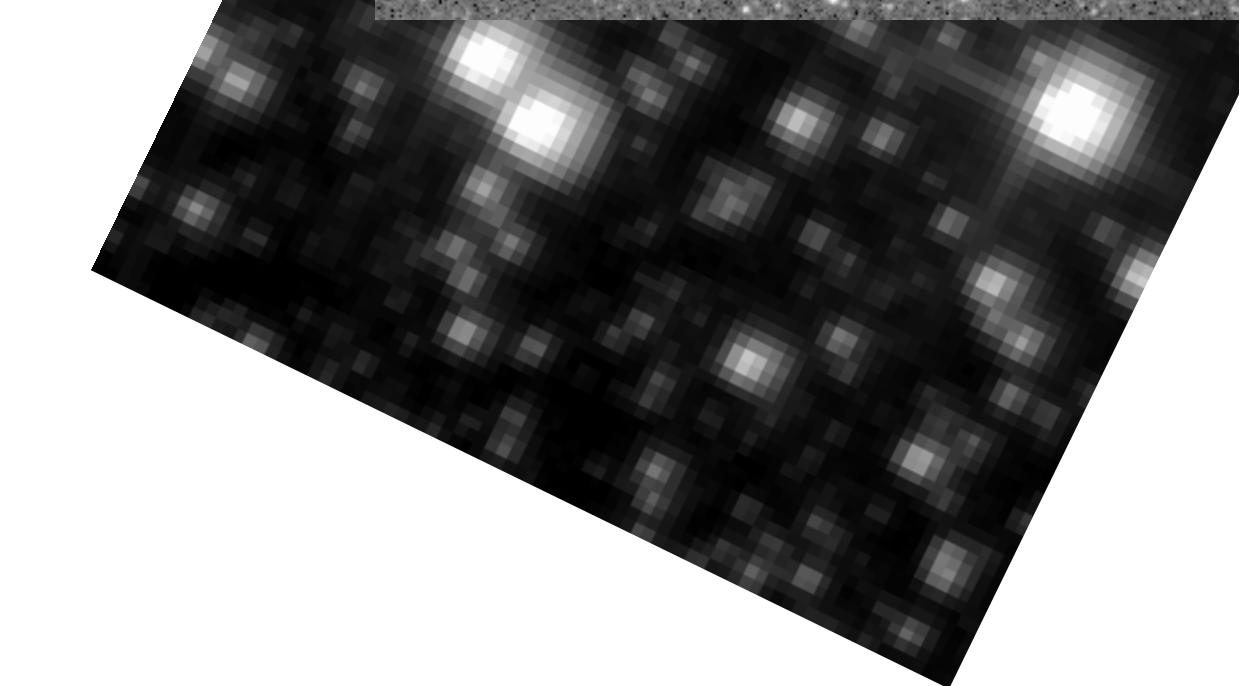
# “Traditional” Cross-Matching



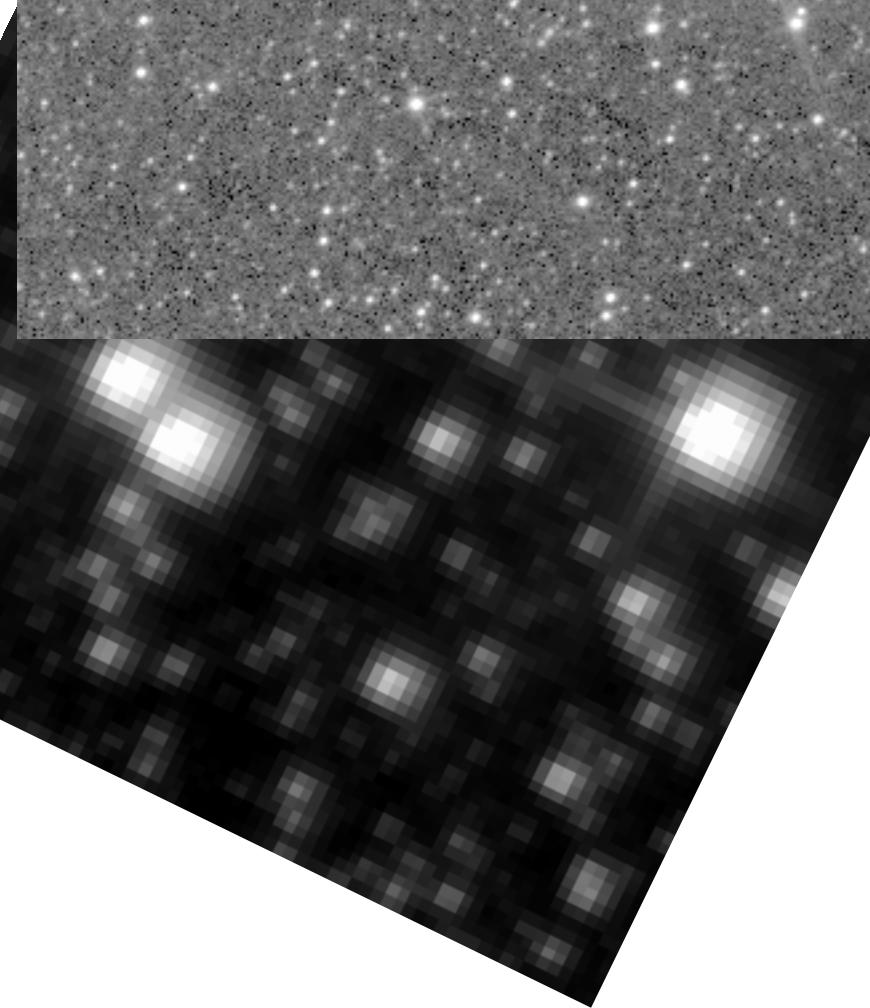
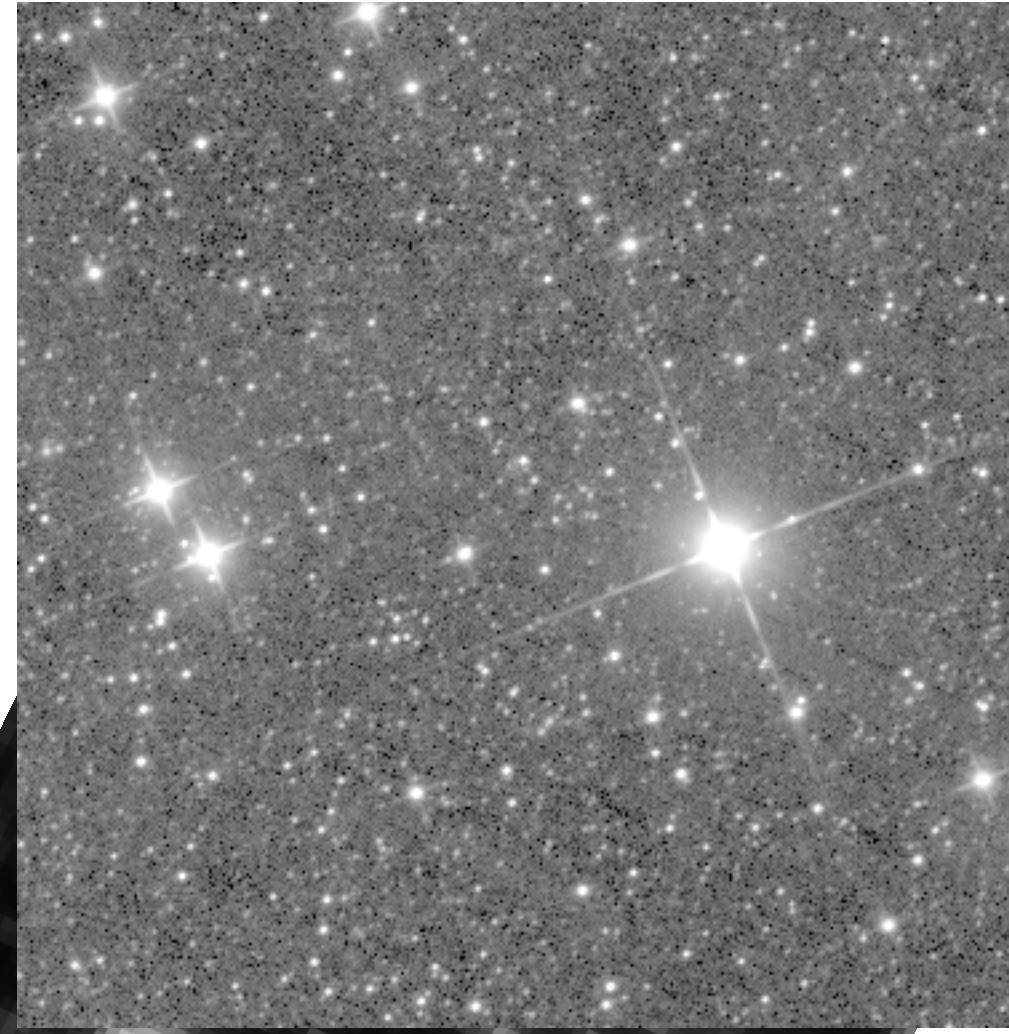
# The Astronomy Error Function



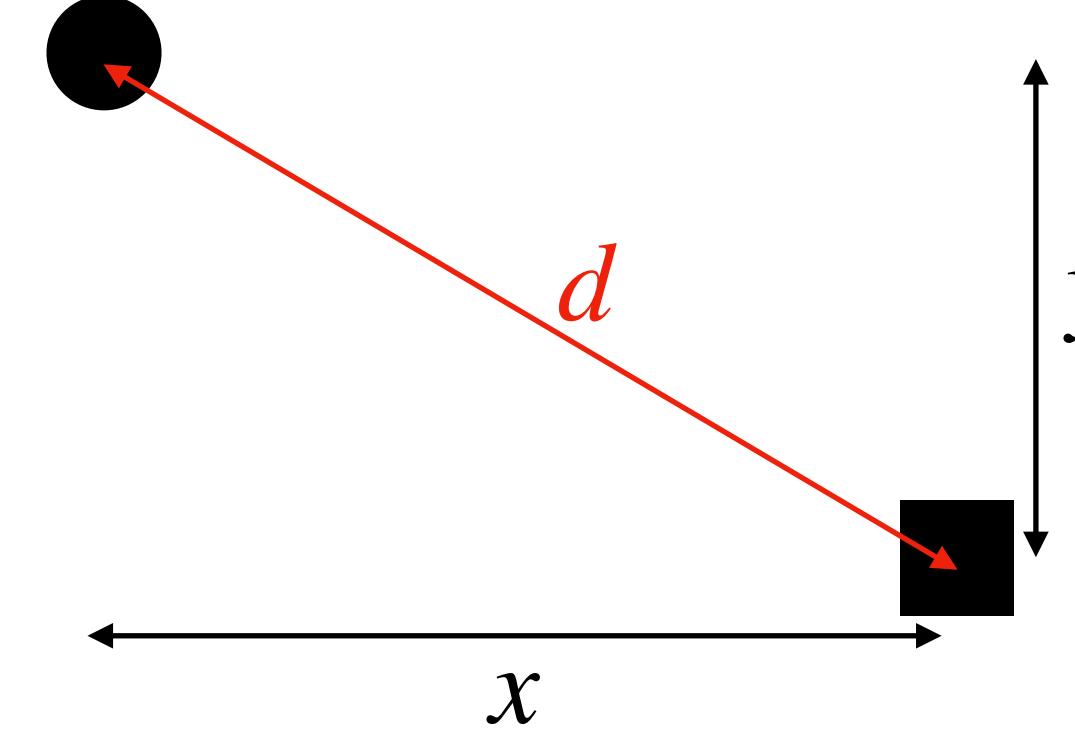
- 1)  $p(x \text{ and } y) = p(x)p(y)$
- 2)  $p(x)$  decreases as  $x$  increases
- 3)  $p(x) = p(-x) \Rightarrow p(x^2)$



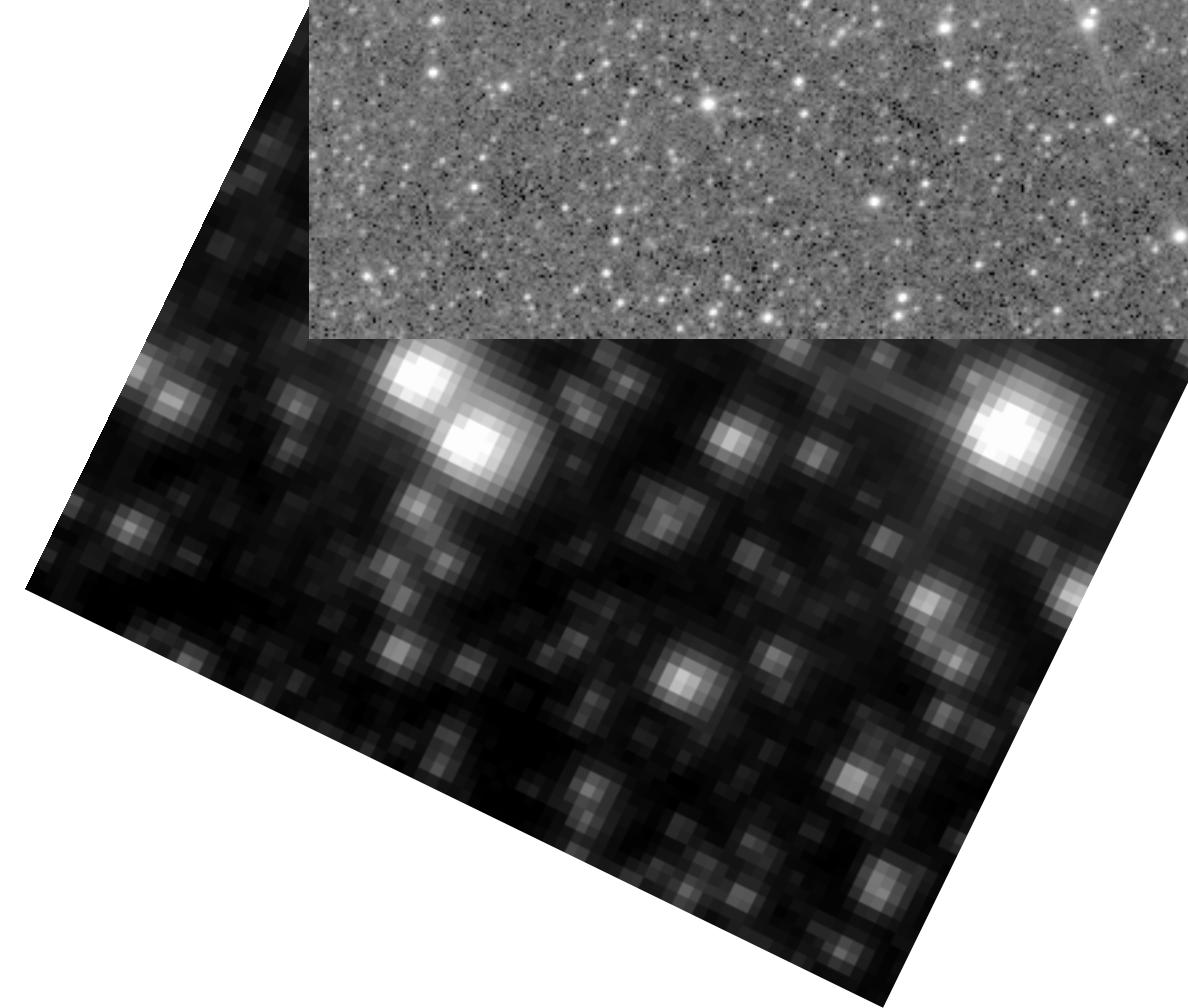
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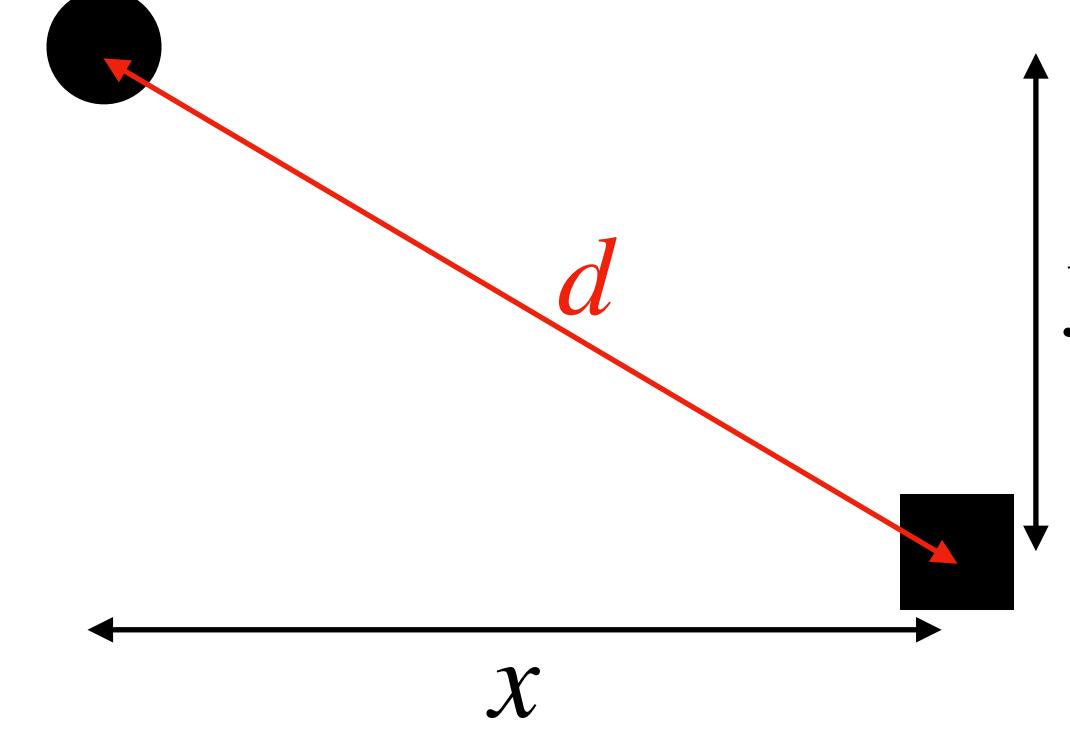
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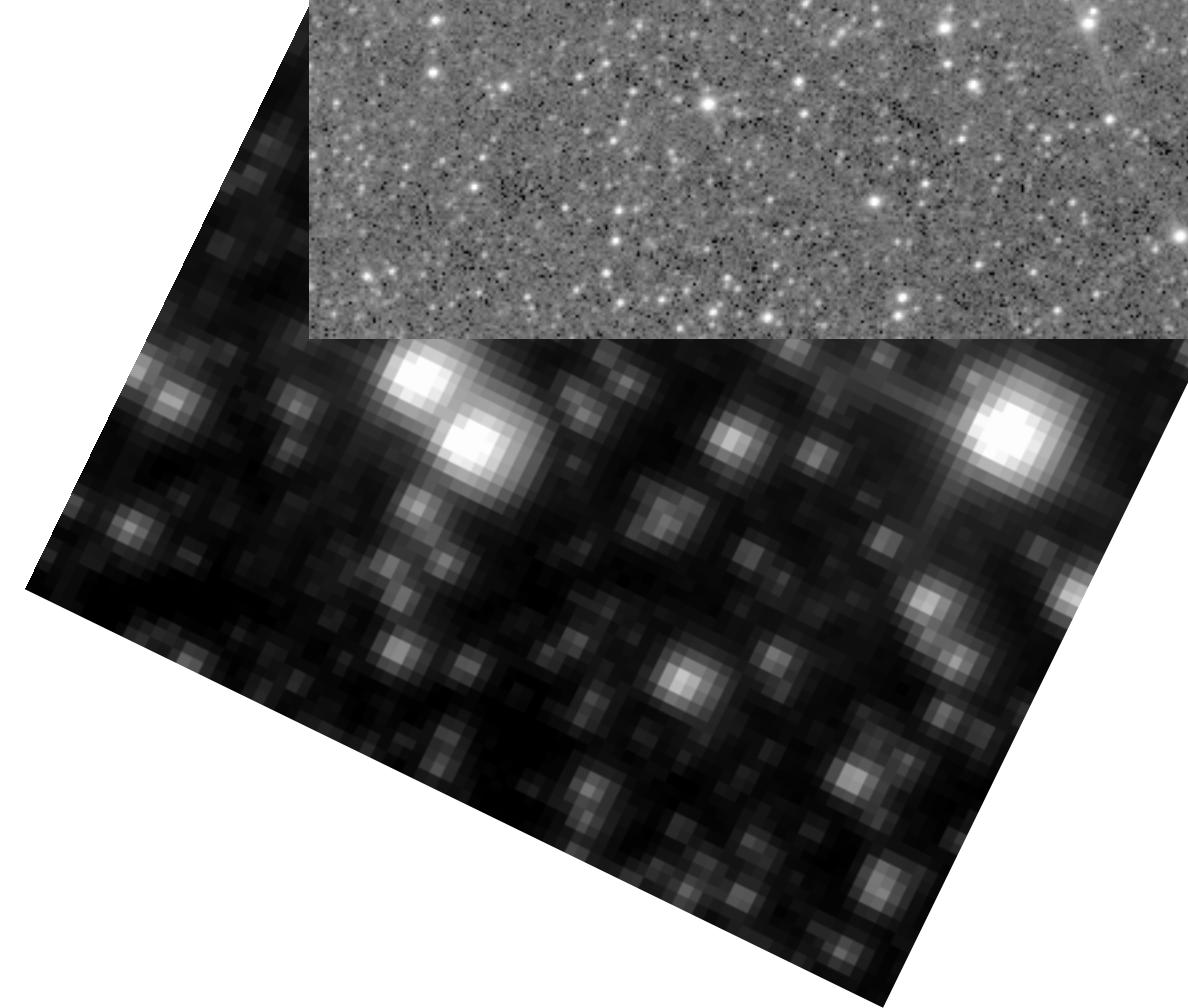


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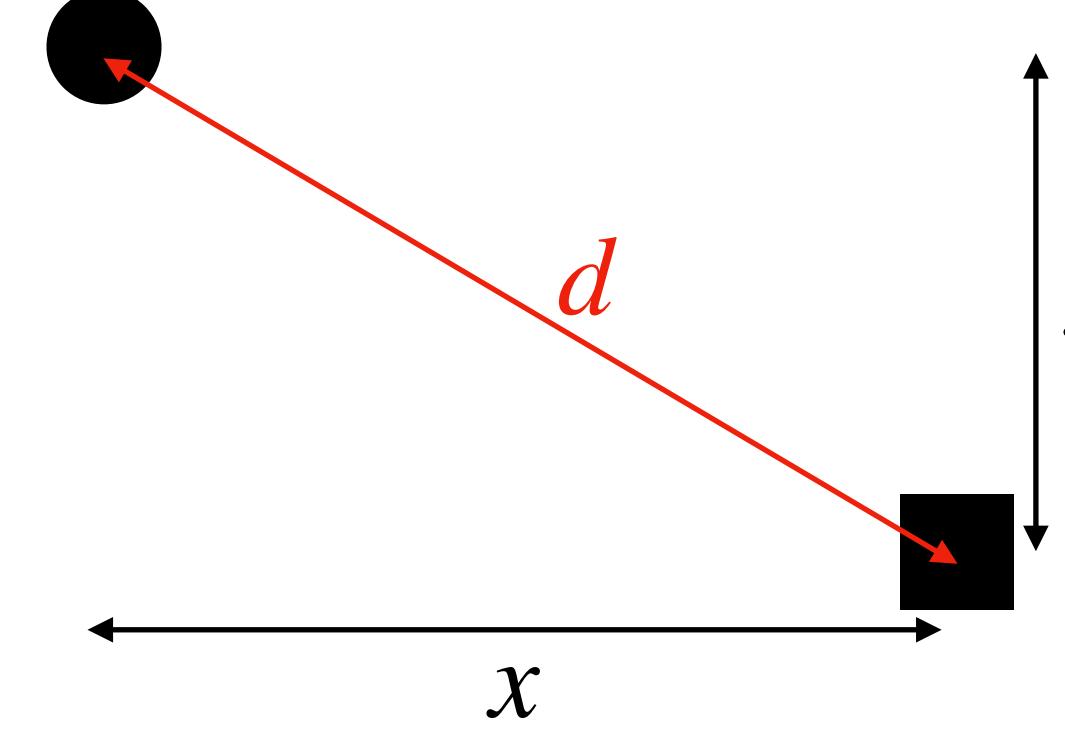


$$p(d^2) = p(x^2 + y^2) = p(x^2)p(y^2)$$

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

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

# 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)

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

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

Wolstencroft et al. (1986)

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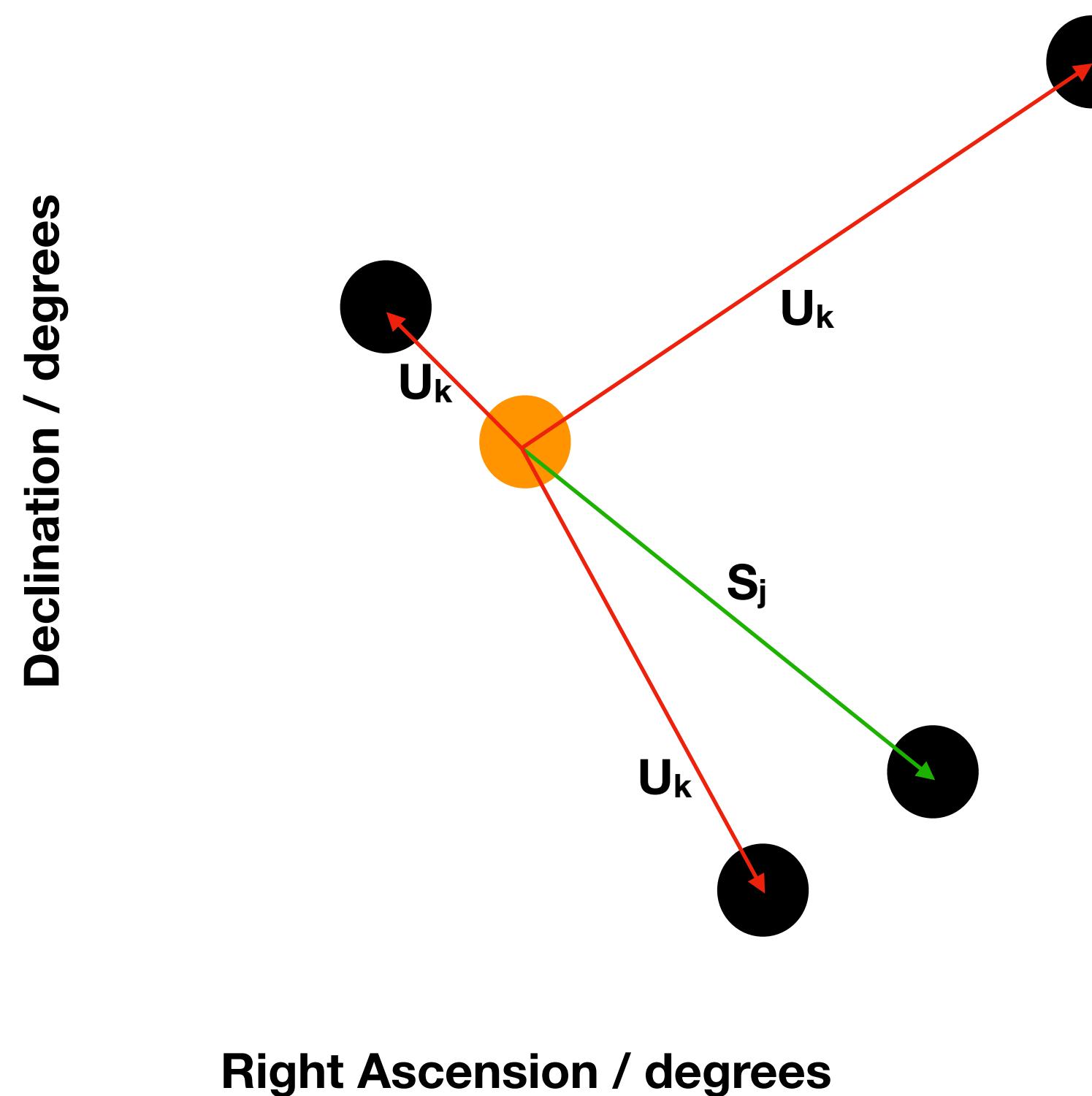
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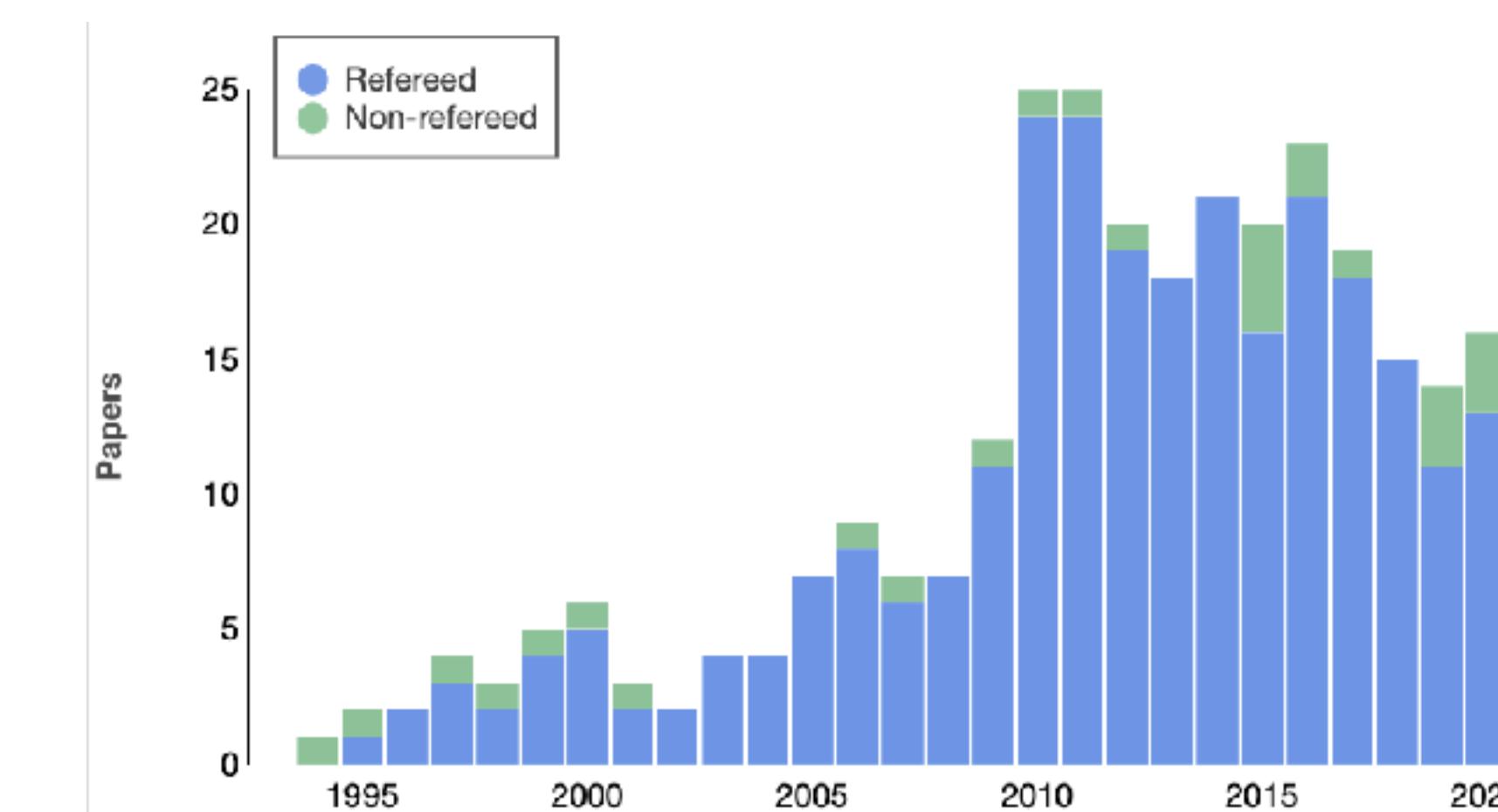
Wolstencroft et al. (1986)

## The “Reliability” – Sutherland & Saunders (1992)



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

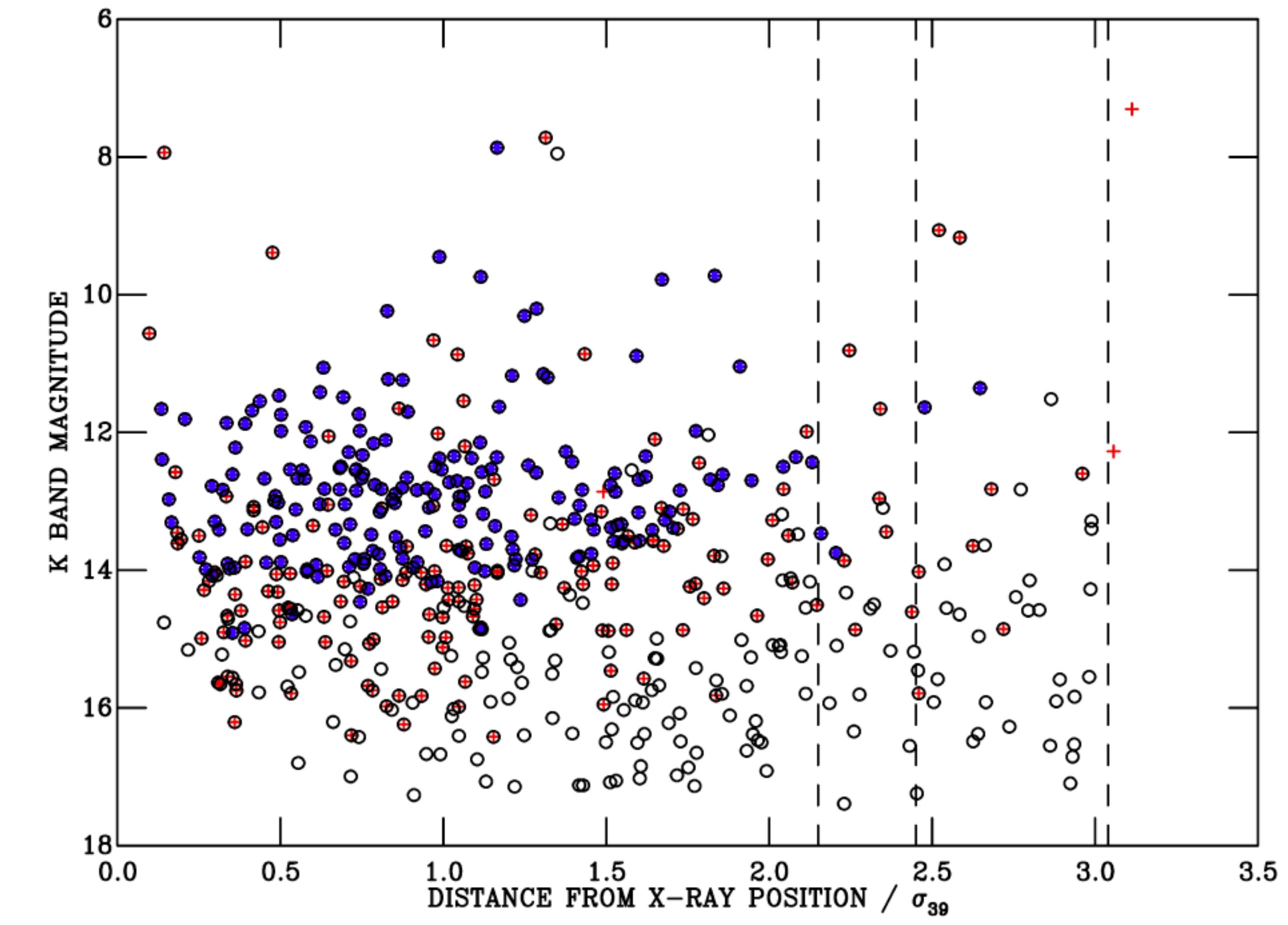
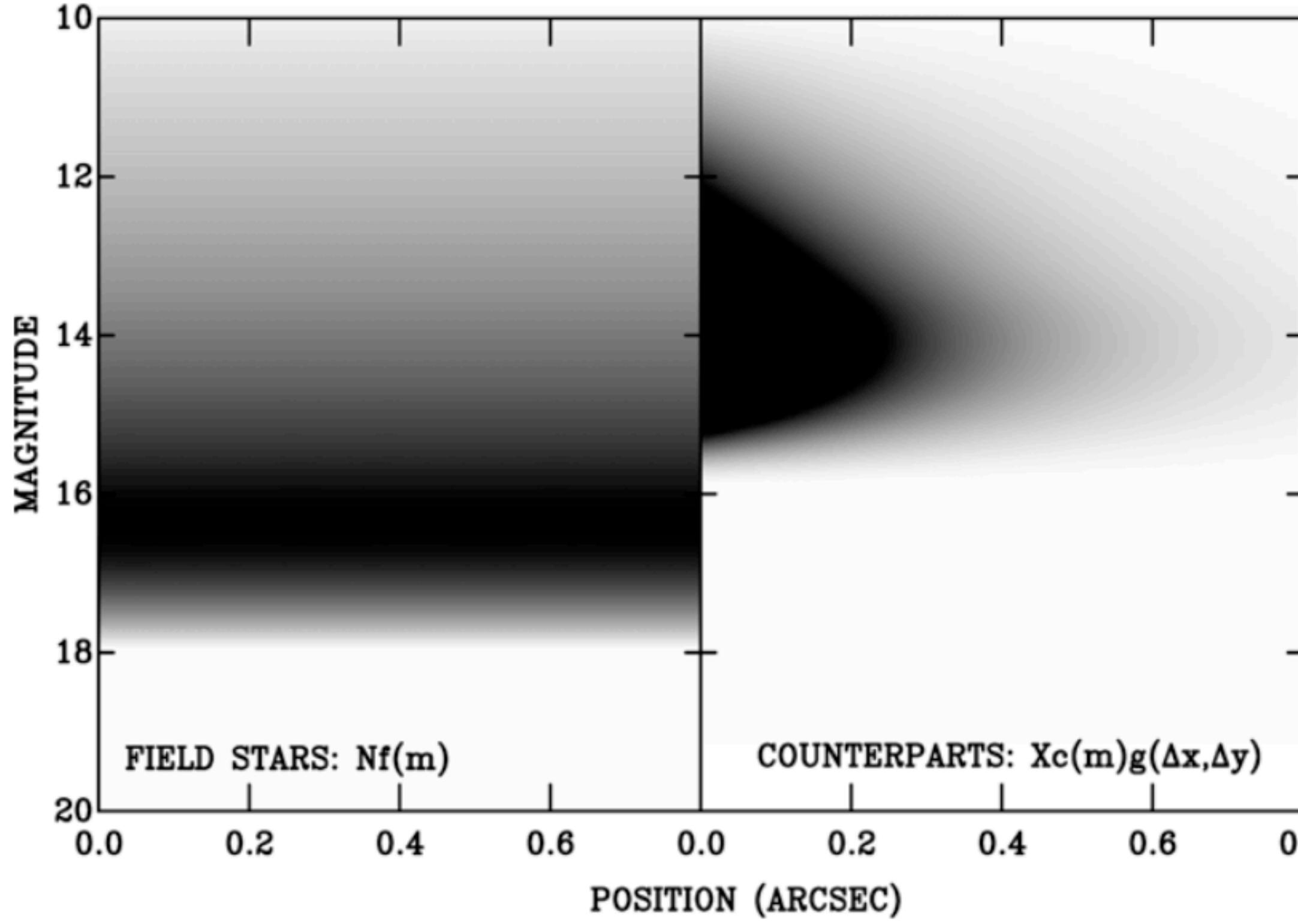
$$L = \frac{q(m, c) f(x, y)}{n(m, c)}$$



# Probabilistic Cross-Matching

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

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



# Probabilistic Cross-Matching

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

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

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

Budavári & Szalay (2008)

Includes SED model fitting to all sources

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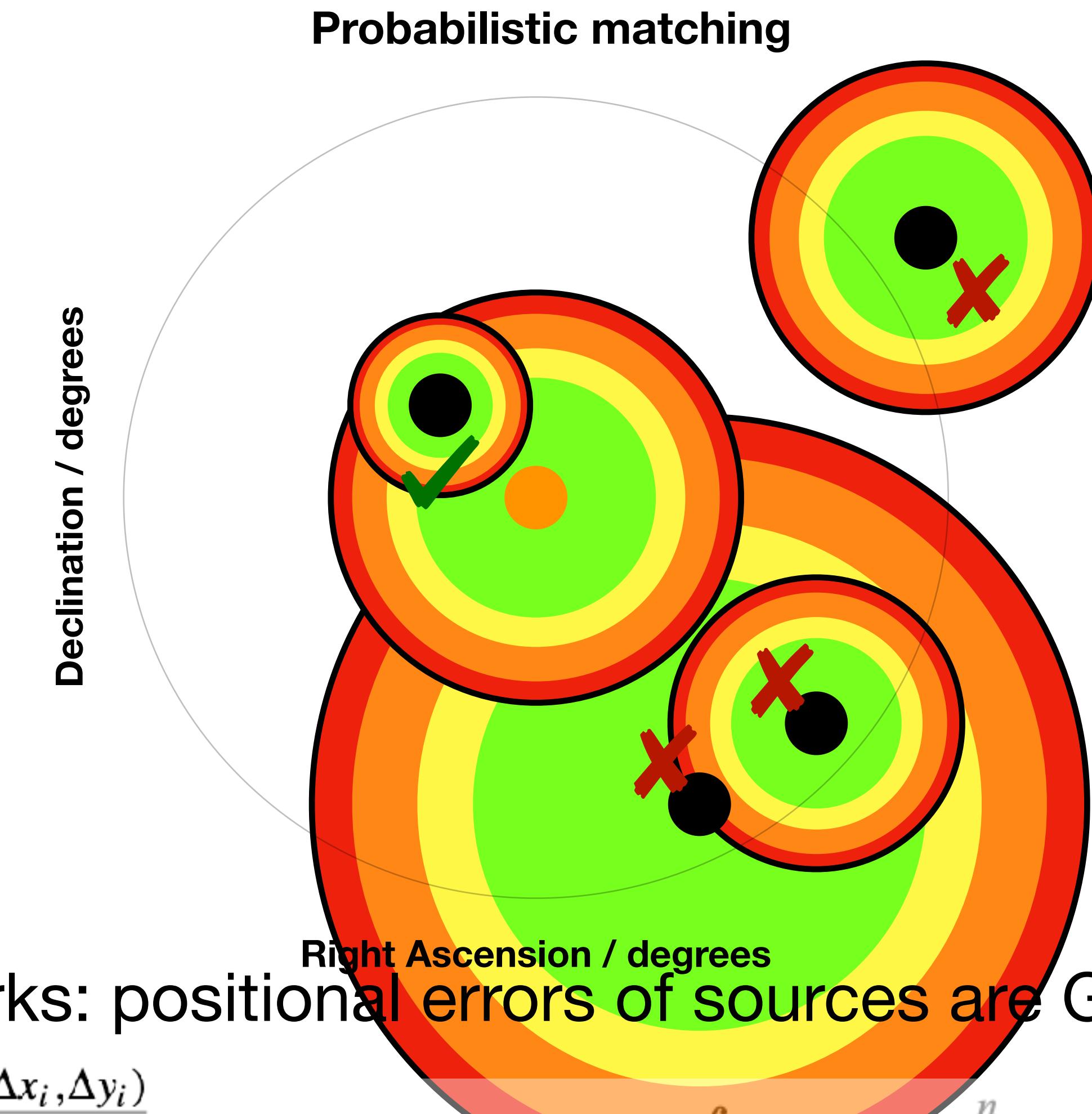
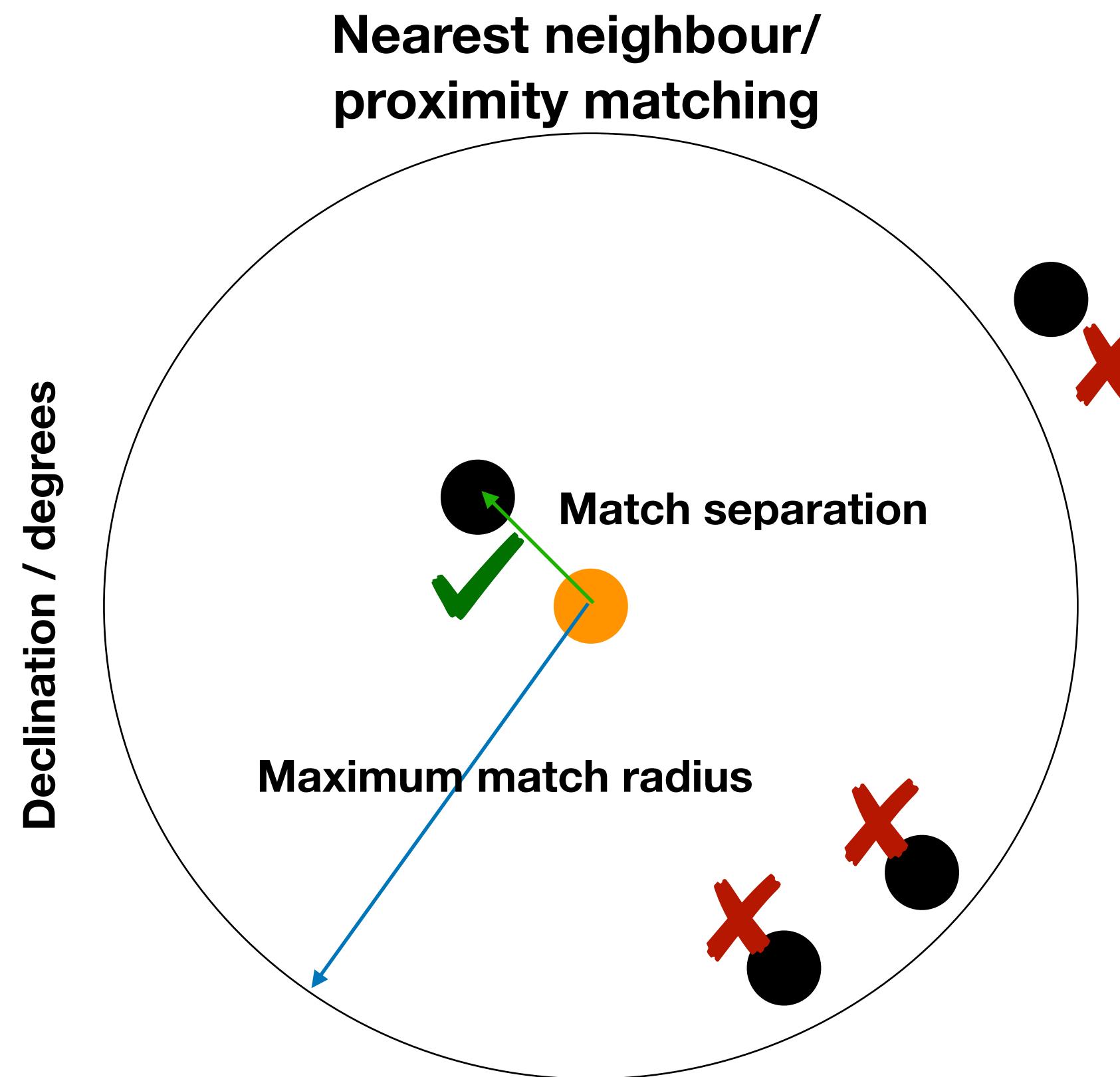
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One assumption made in all of these works: positional errors of sources are Gaussian!

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

# Probabilistic Cross-Matching



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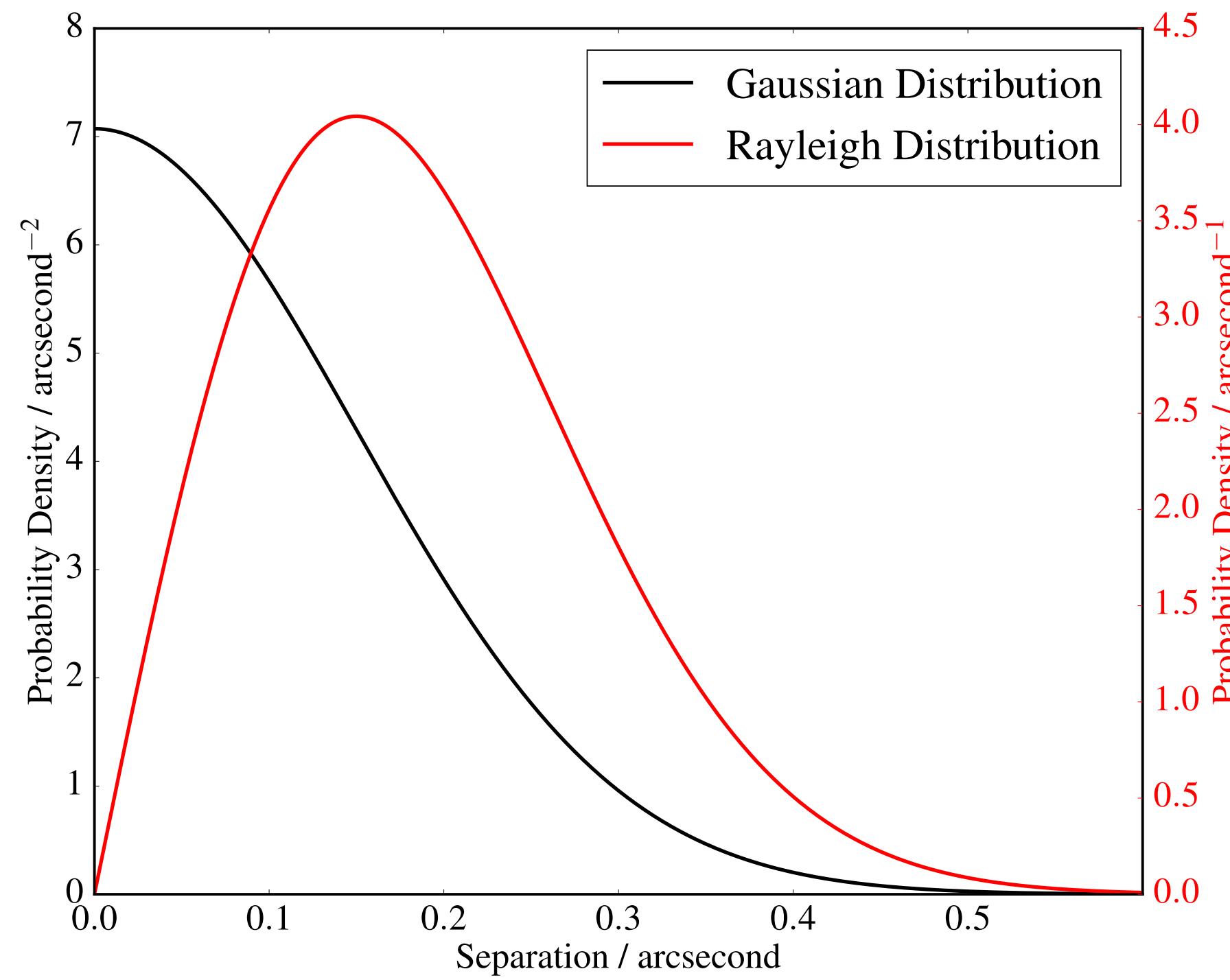
$$p(D|H) = \int p(\mathbf{m}|H) \prod_{i=1}^n p_i(\mathbf{x}_i|\mathbf{m}, H) d^3 m$$

# The Astrometric Uncertainty Function

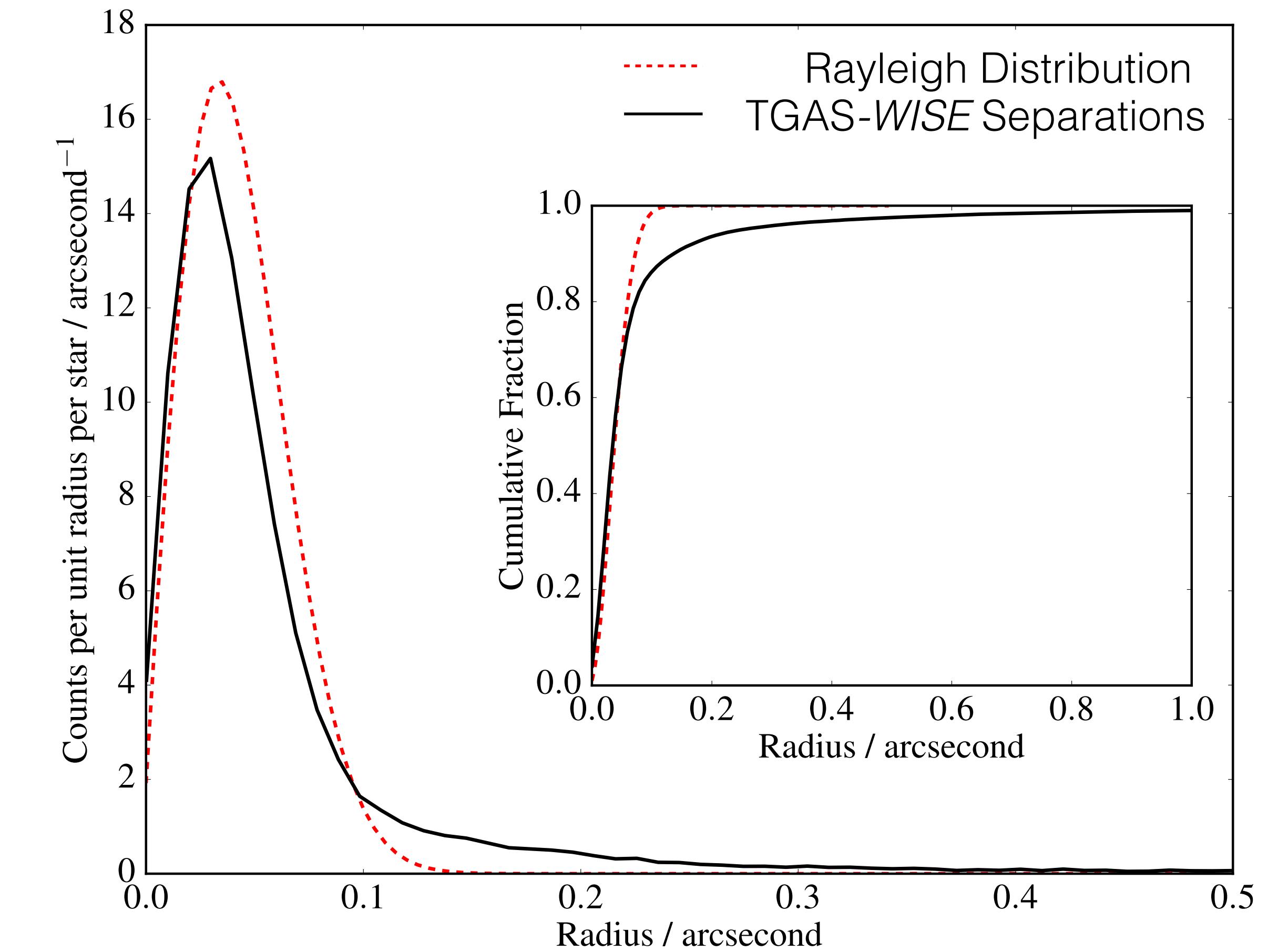
$$g(x, y, \sigma) = (2\pi\sigma^2)^{-1} \exp\left(-\frac{1}{2}\frac{x^2 + y^2}{\sigma^2}\right)$$



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



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



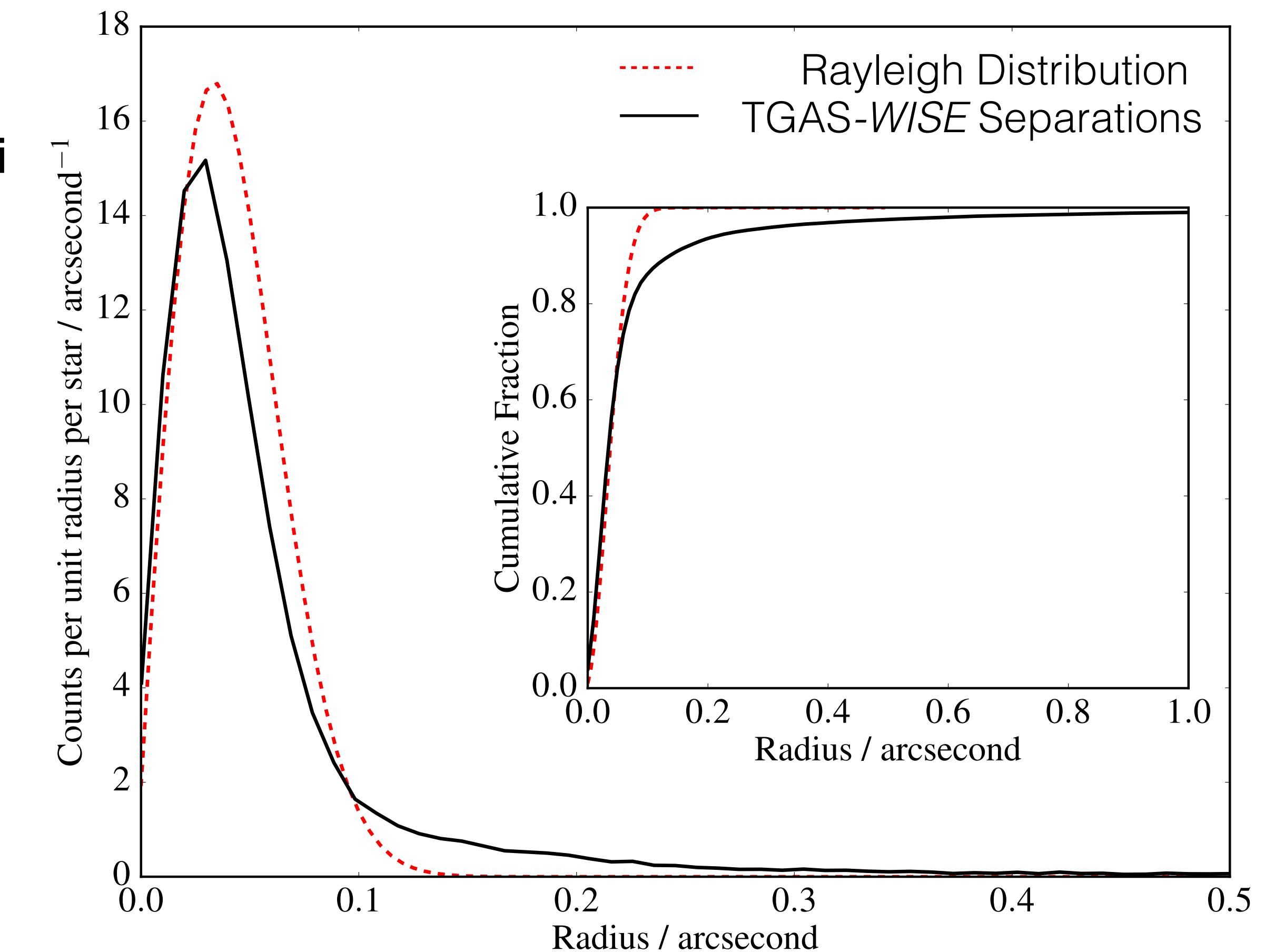
TGAS - Michalik, Lindegren, & Hobbs (2015)  
Gaia - Gaia Collaboration, Brown A. G. A., et al. (2016)

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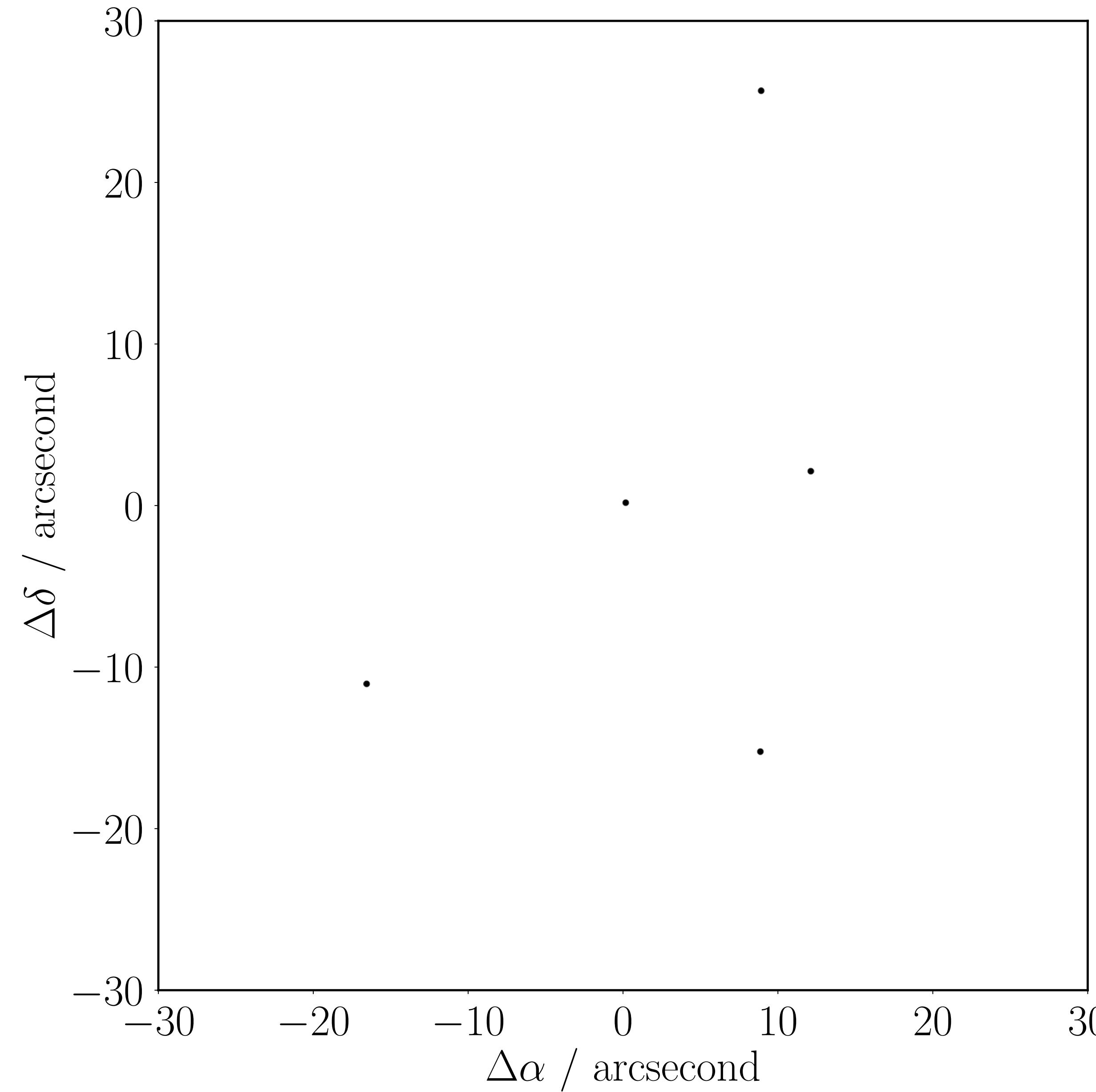
# The Astrometric Uncertainty Function

Reasons for large separations:

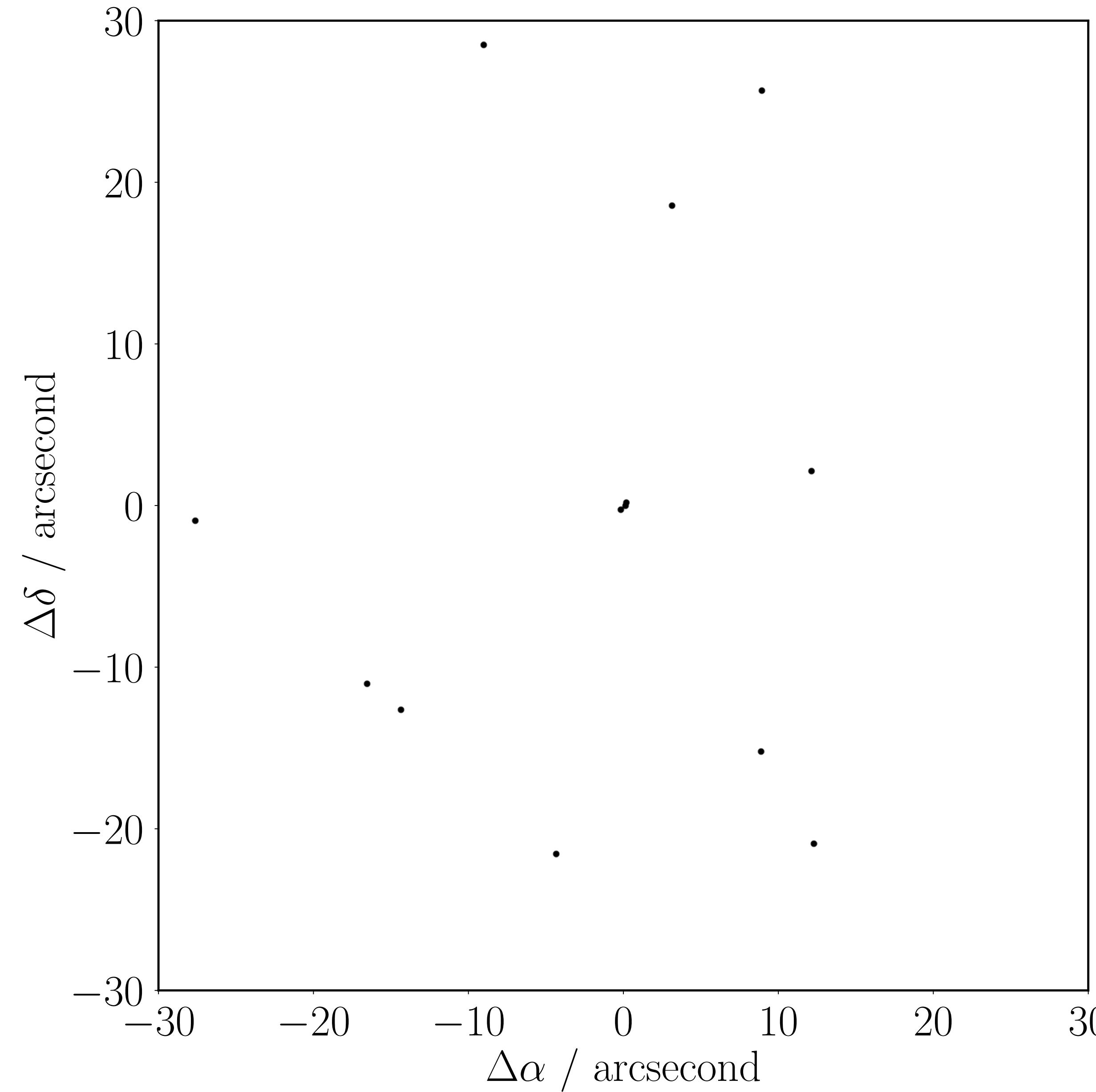
- 1) proper motions (e.g. AllWISE Supplement 6.4, Cutri et al. 2012) – no, TGAS provided for all sources
- 2) false matches – no, 0.1% chance of random match within 0.5 arcseconds
- 3) What else could it be?



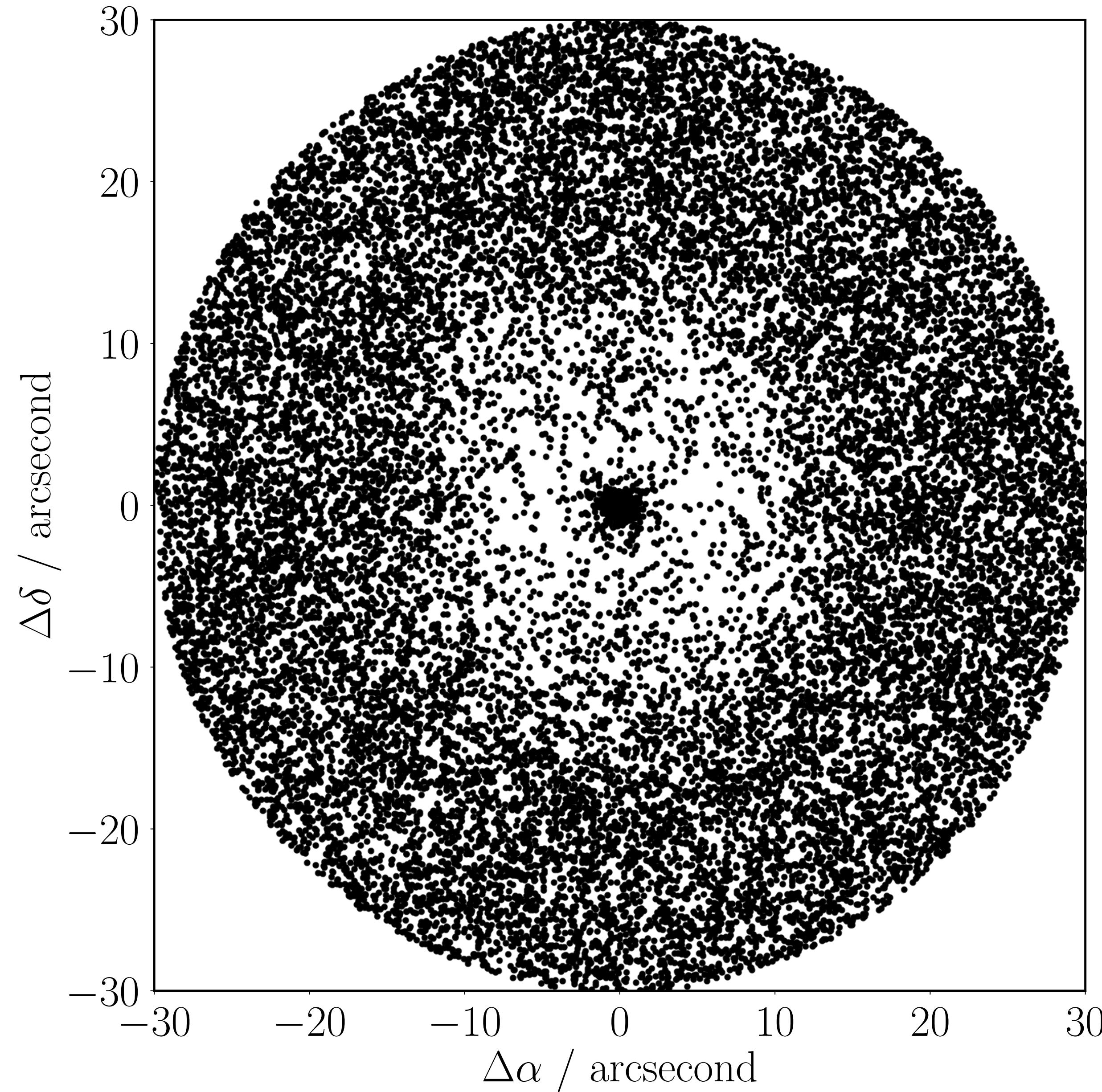
# The AUF: Crowding



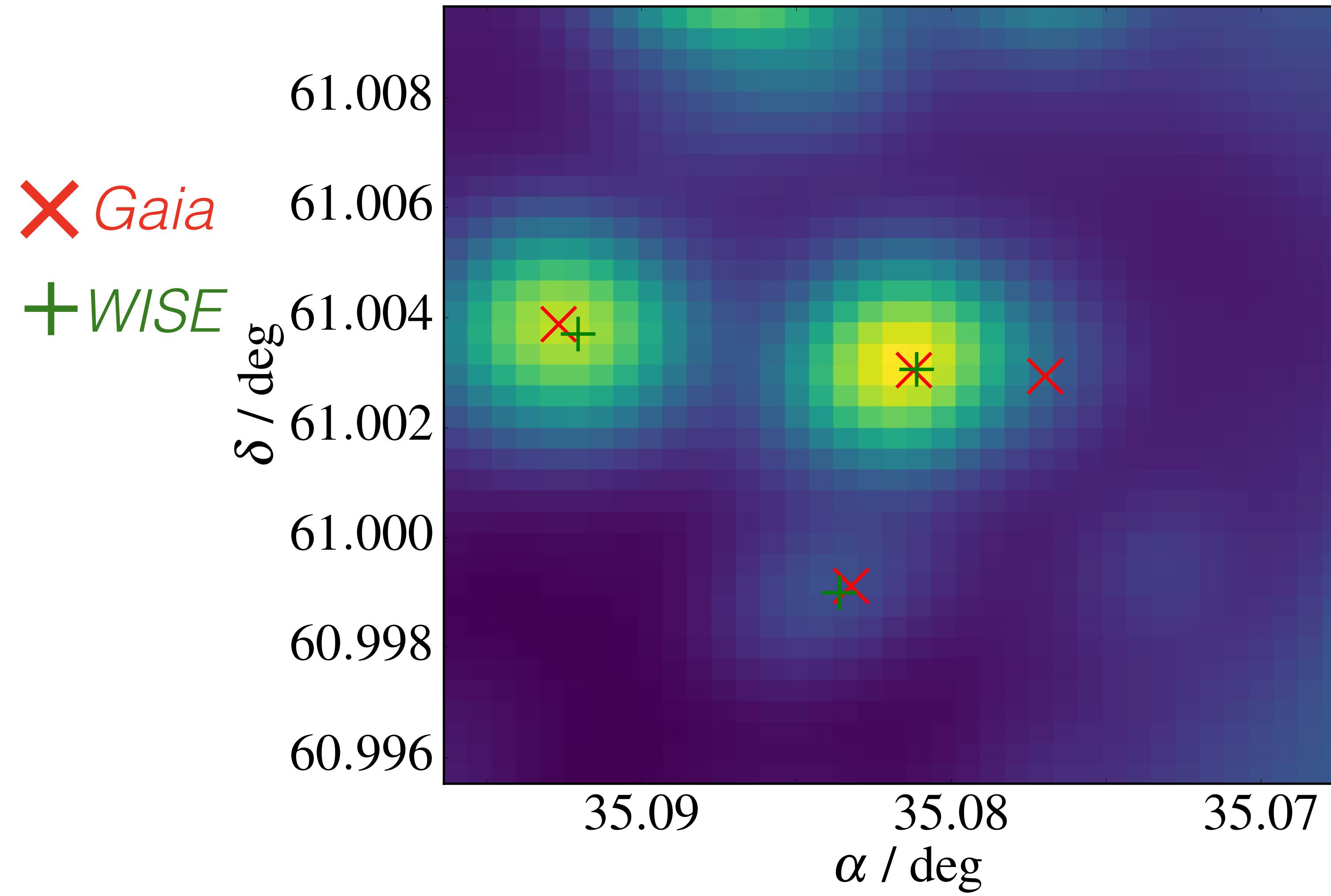
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# Resolving *Gaia*-*WISE* Blends



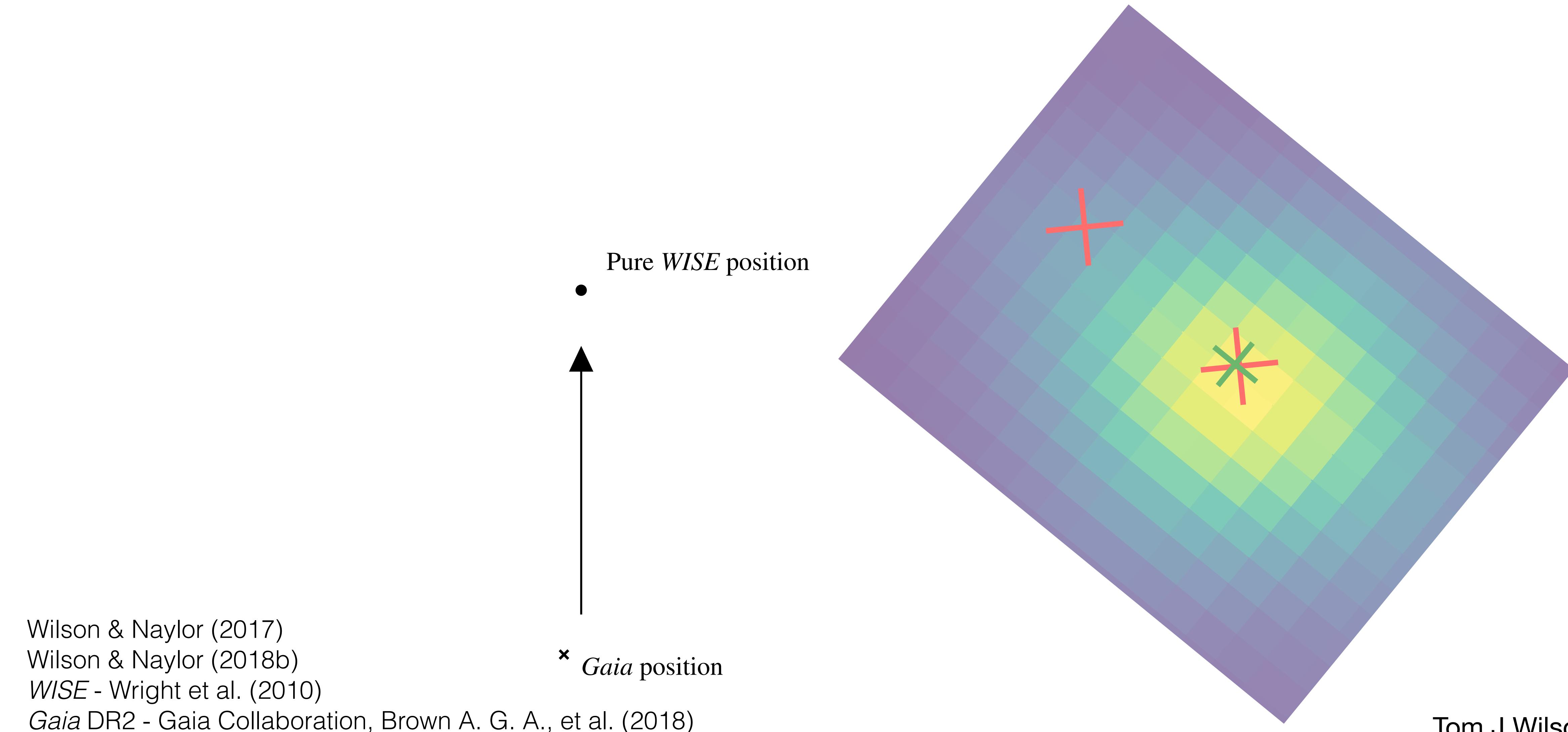
Wilson & Naylor (2018b)

*WISE* - Wright et al. (2010)

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

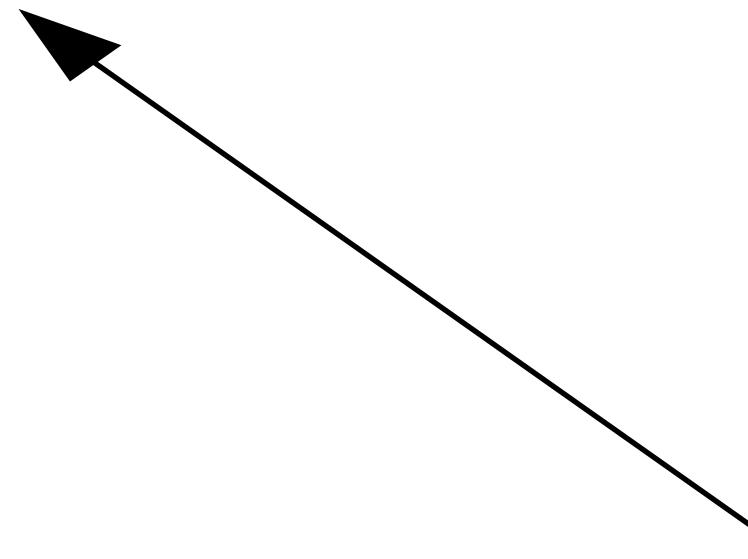
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# The AUF: Perturbation



# The AUF: Perturbation

To *WISE* contaminant



Pure *WISE* position



*Gaia* position

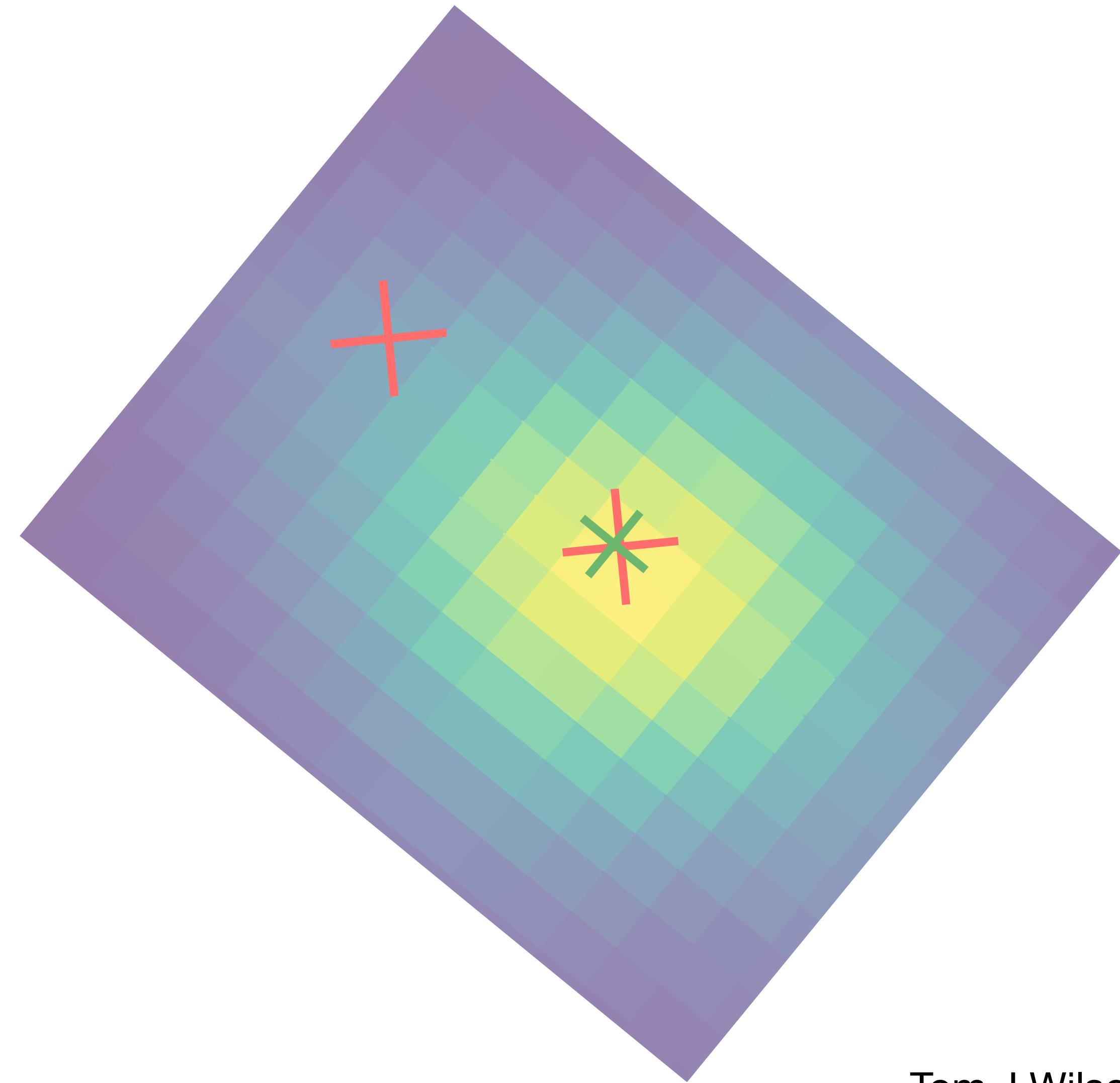


Wilson & Naylor (2017)

Wilson & Naylor (2018b)

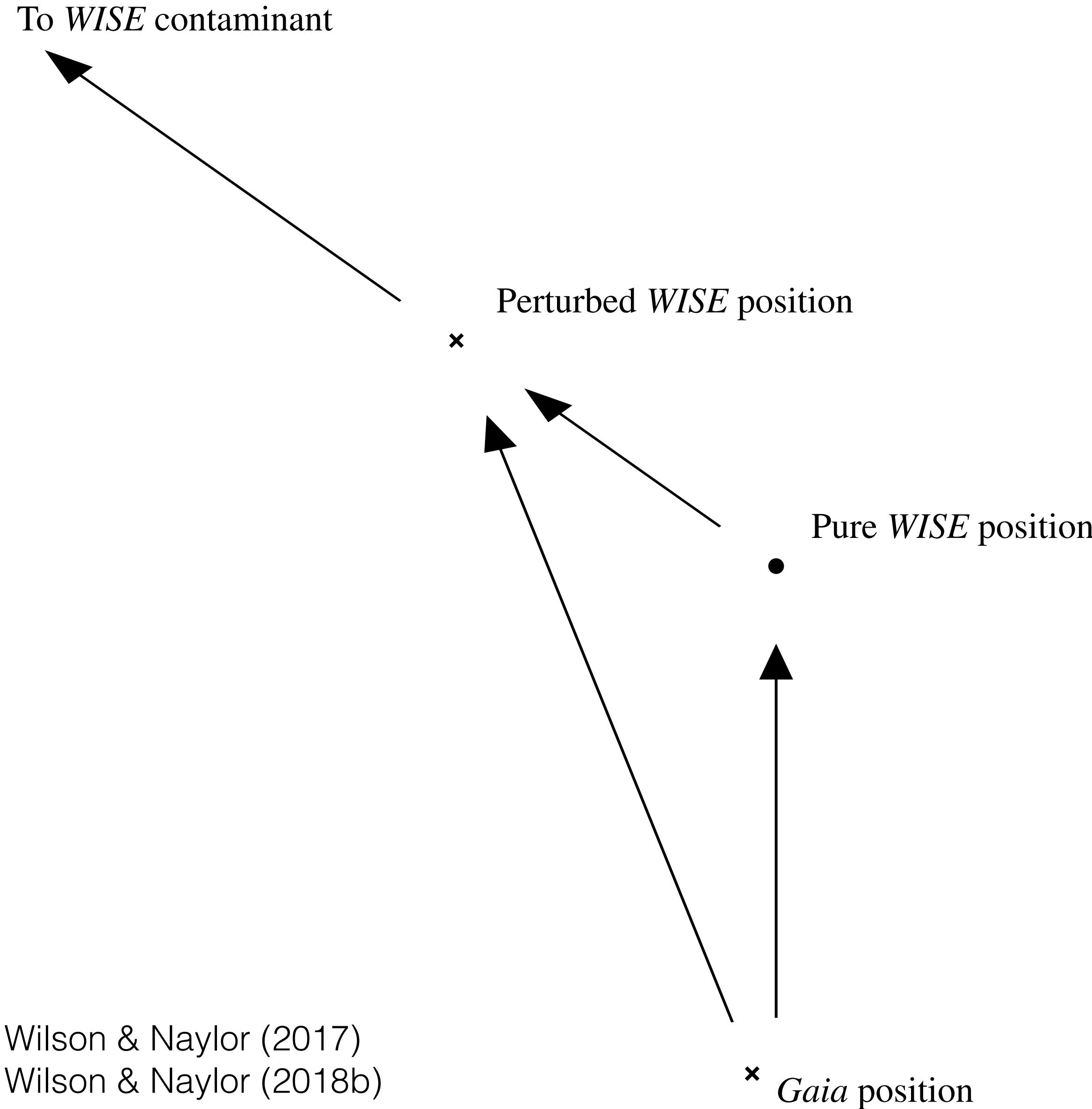
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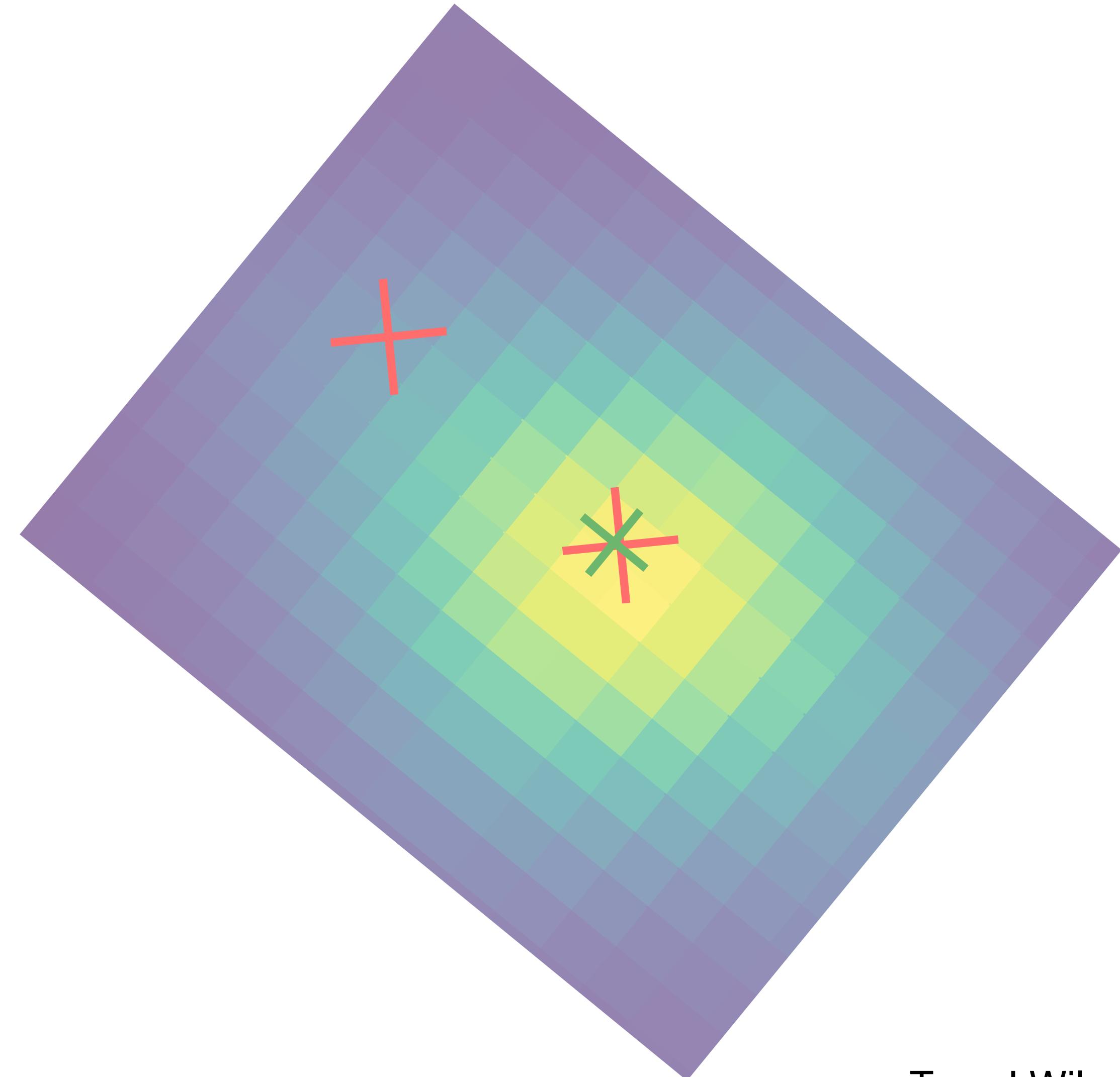


Wilson & Naylor (2017)

Wilson & Naylor (2018b)

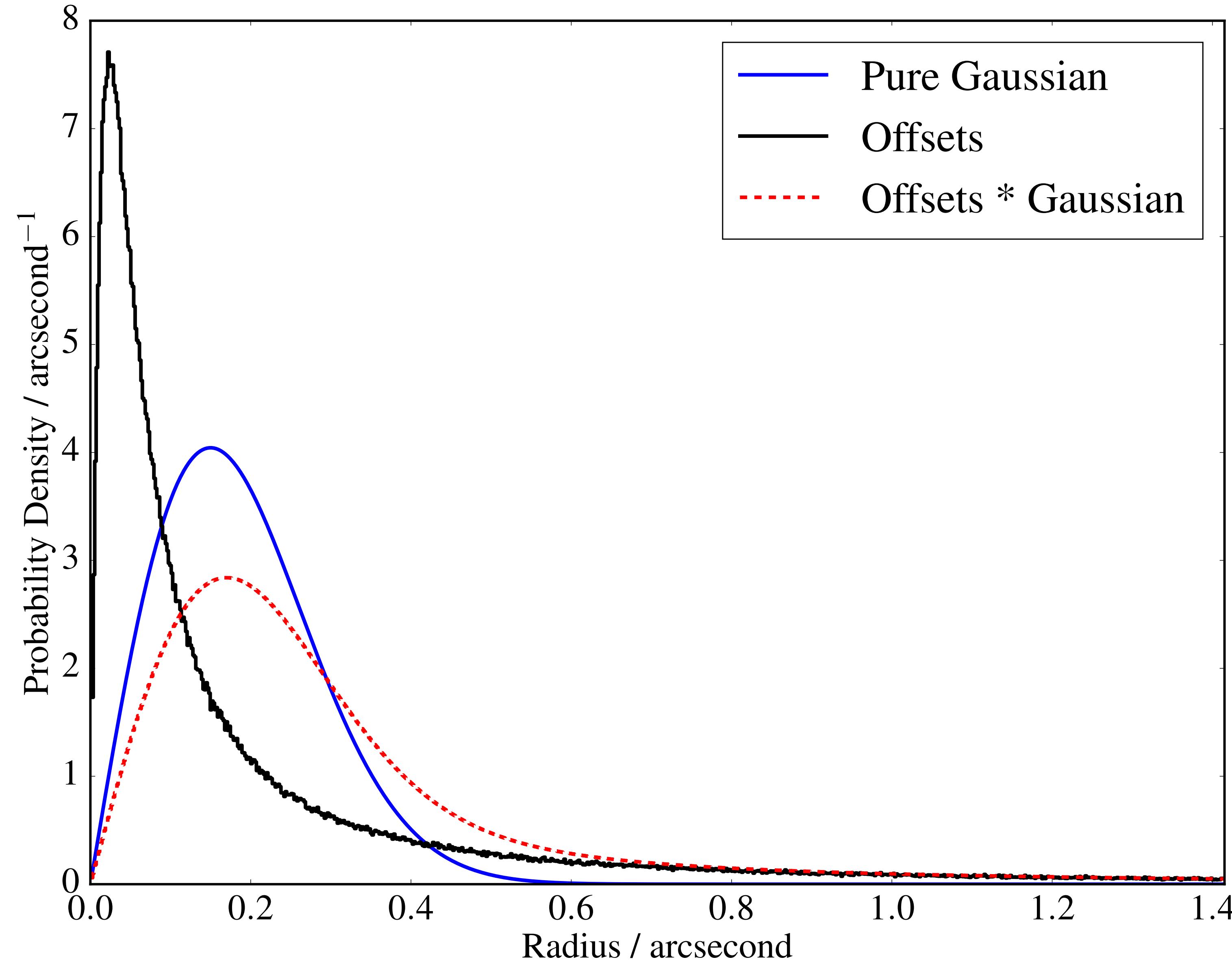
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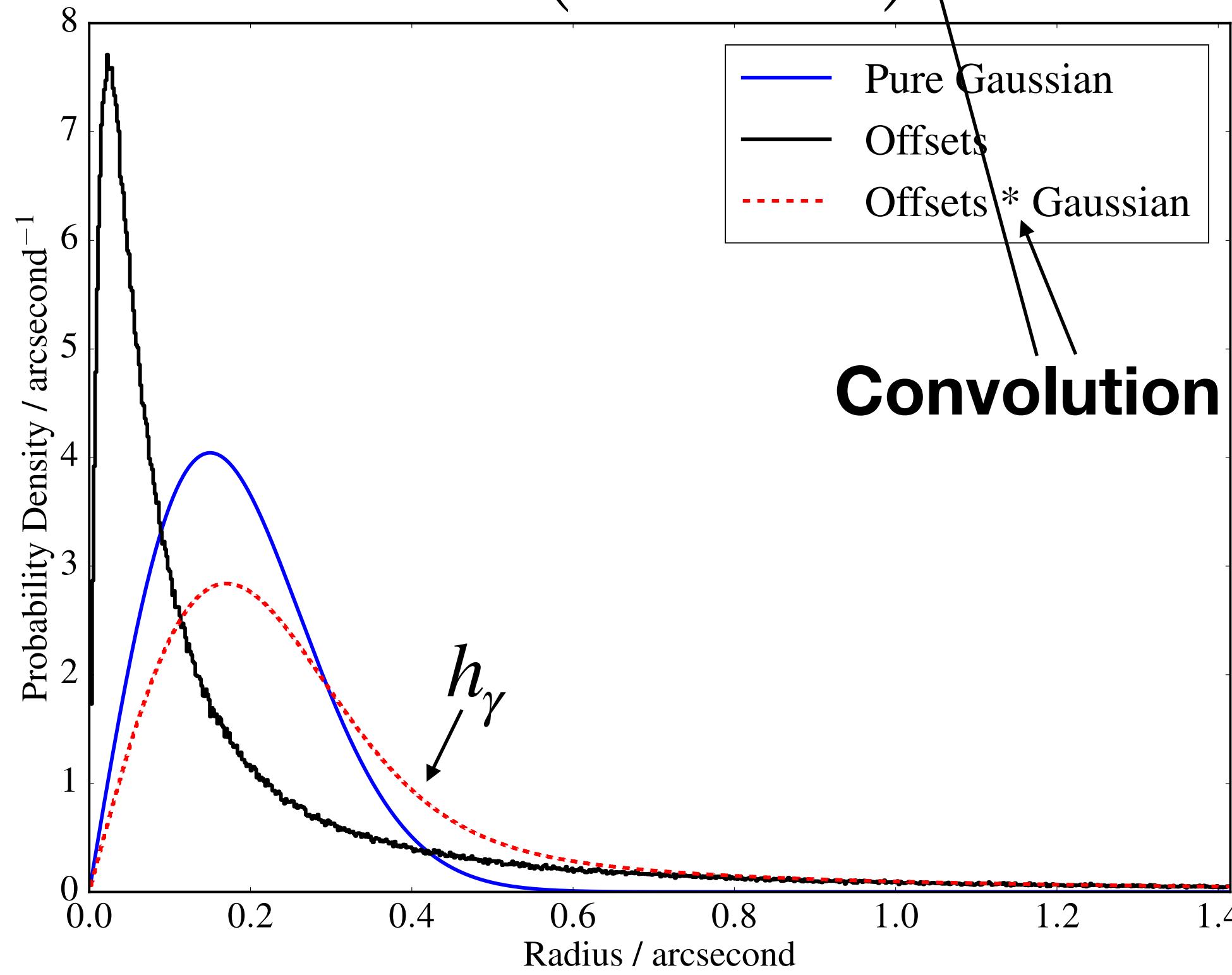
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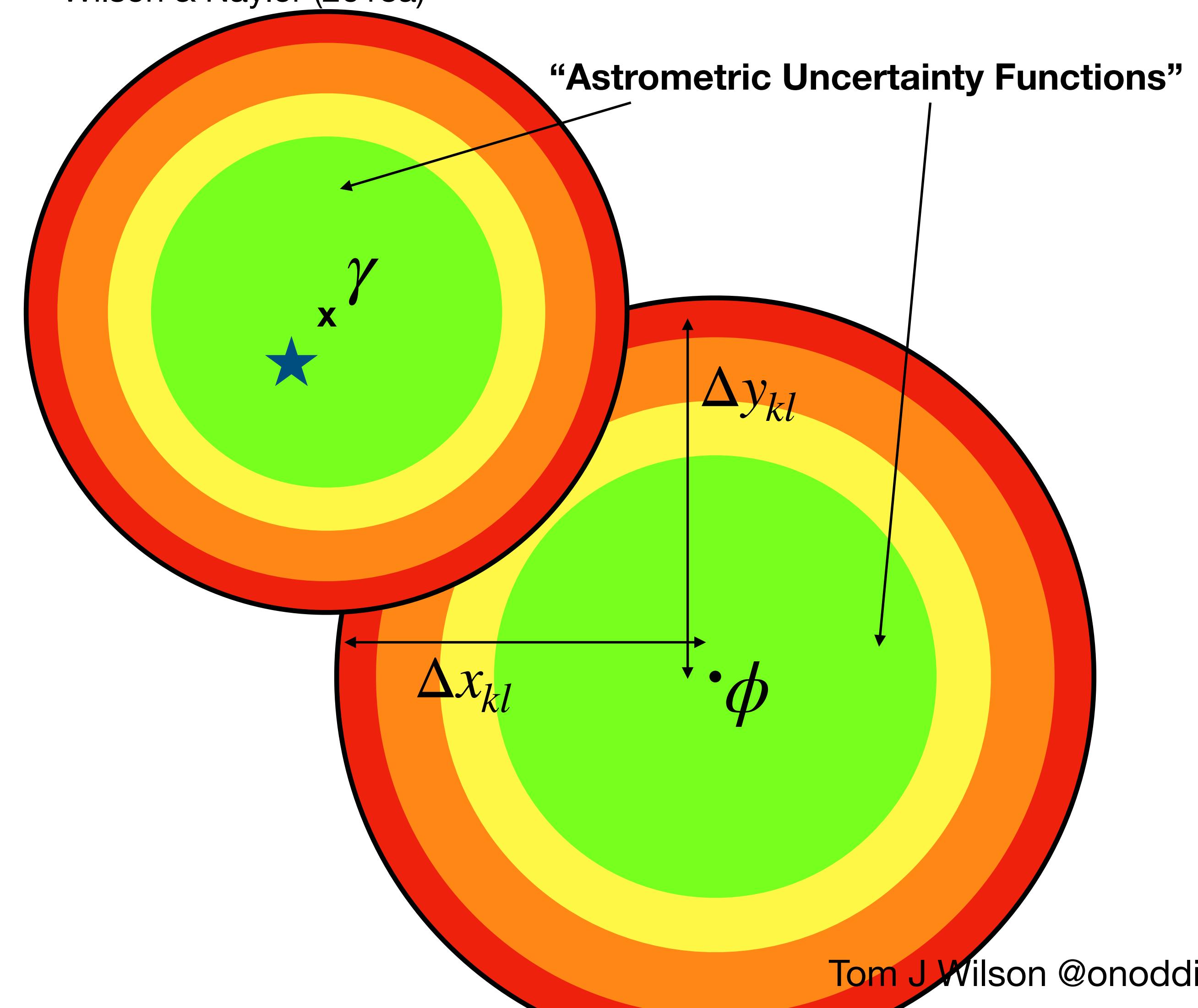
# Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0) dx_0 dy_0$$
$$= N_c \times (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl})$$

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



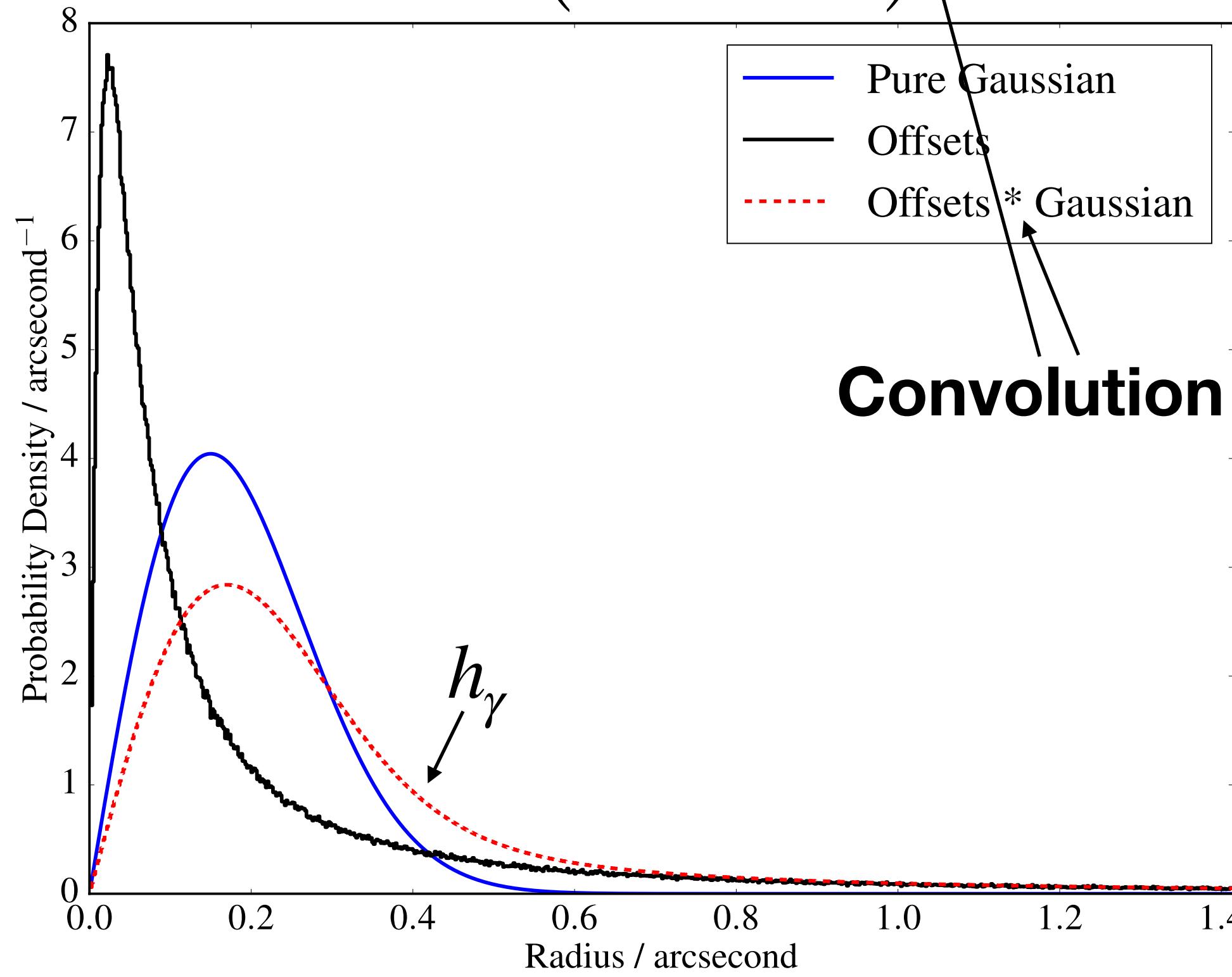
Wilson & Naylor (2018a)



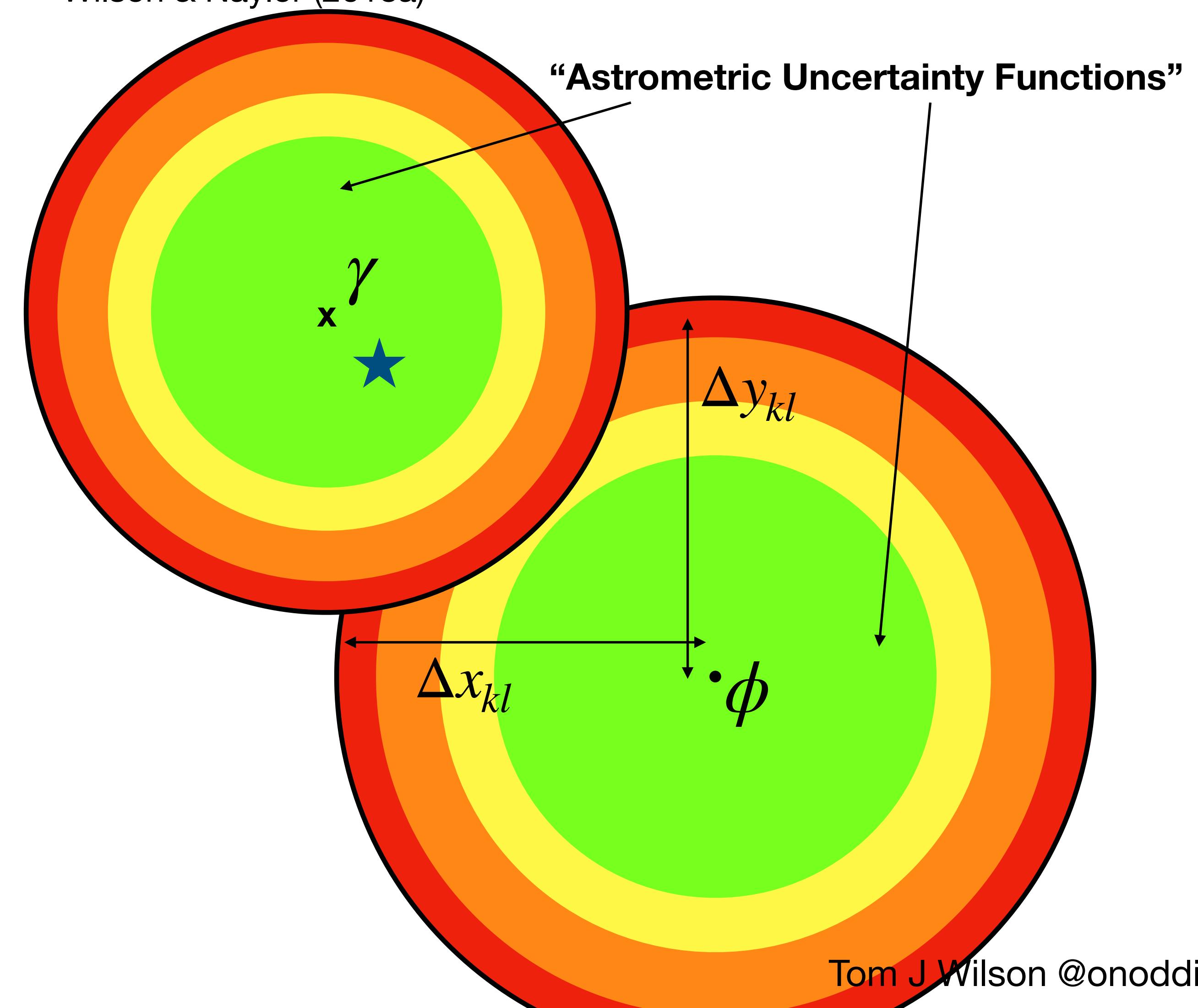
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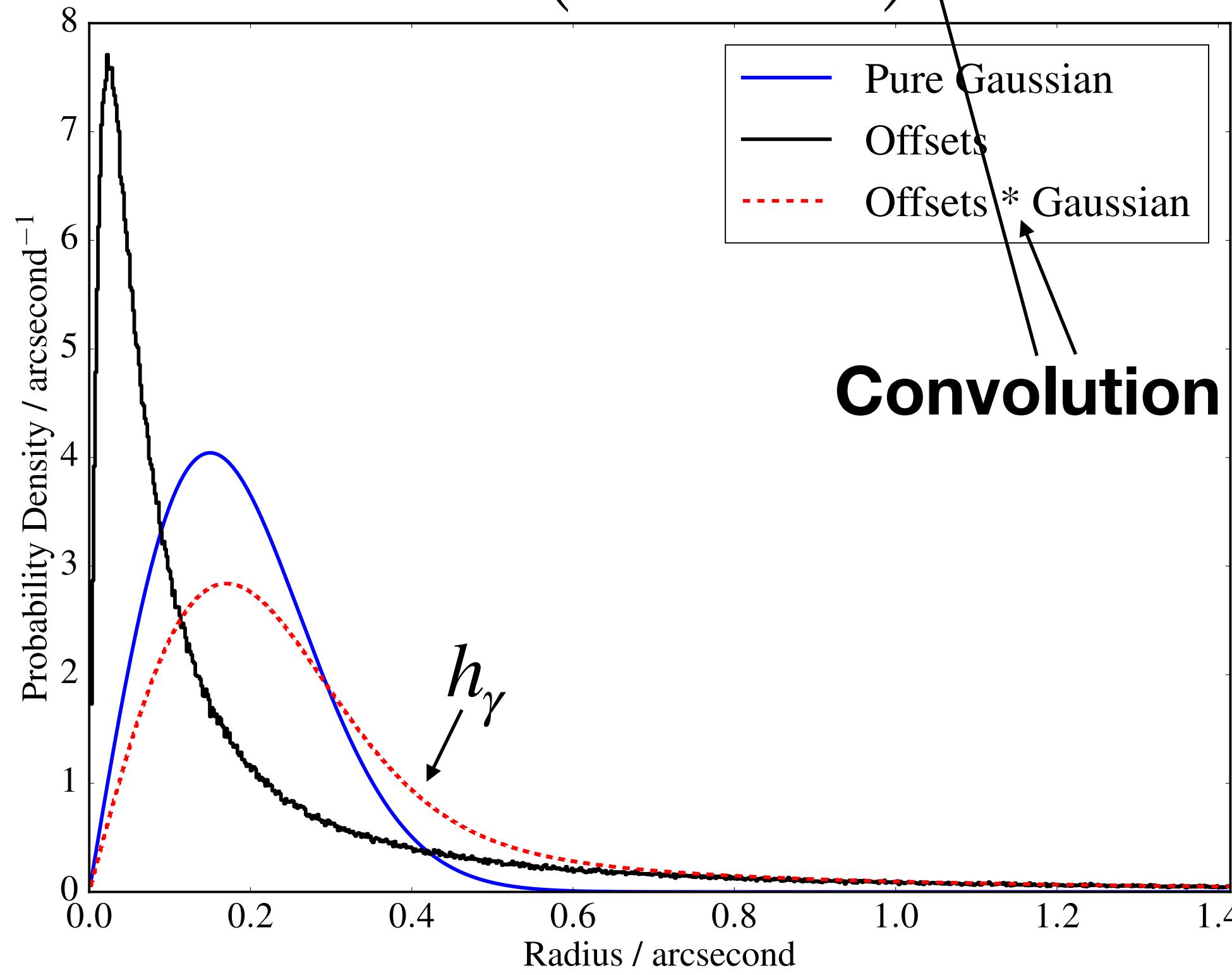
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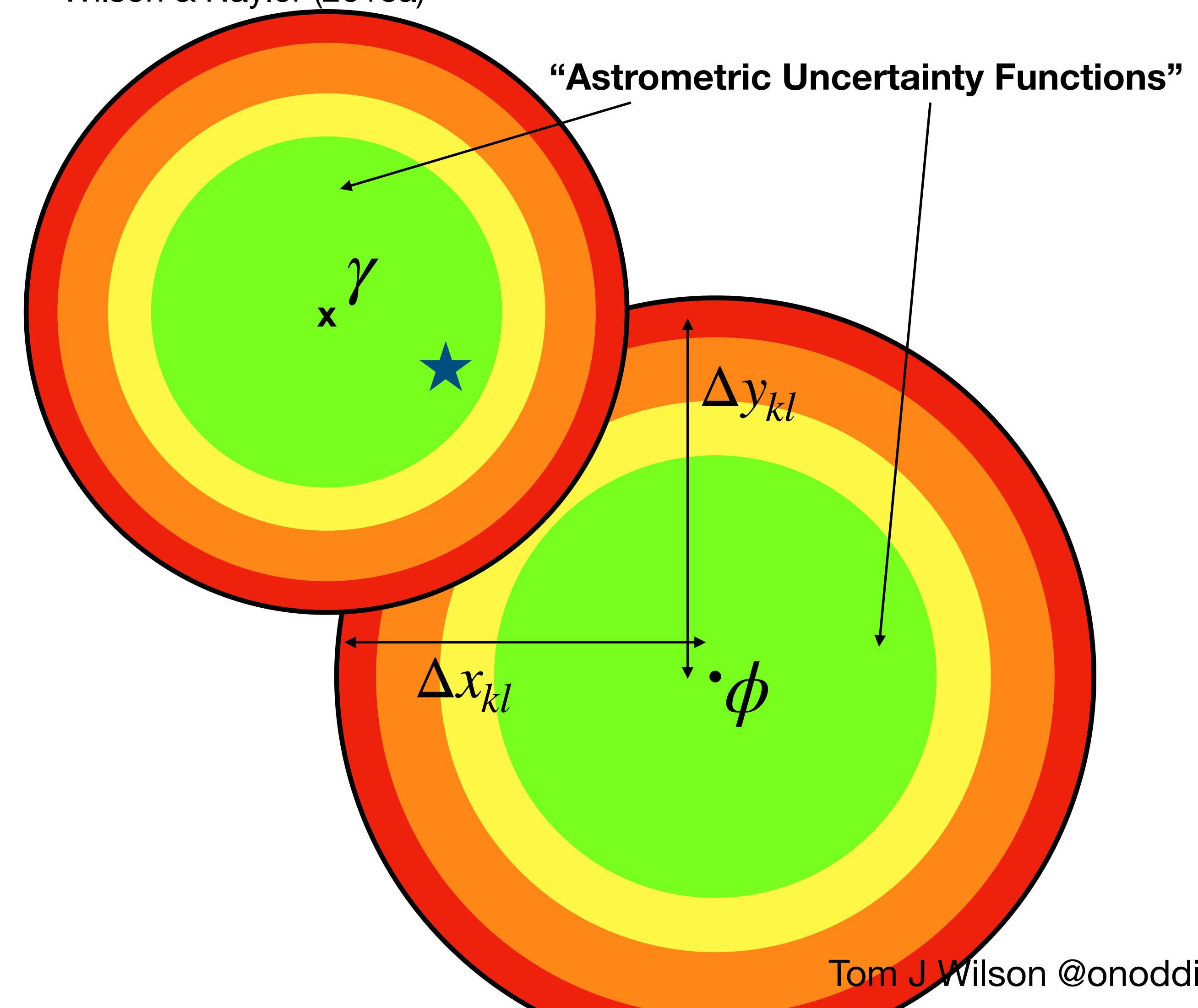
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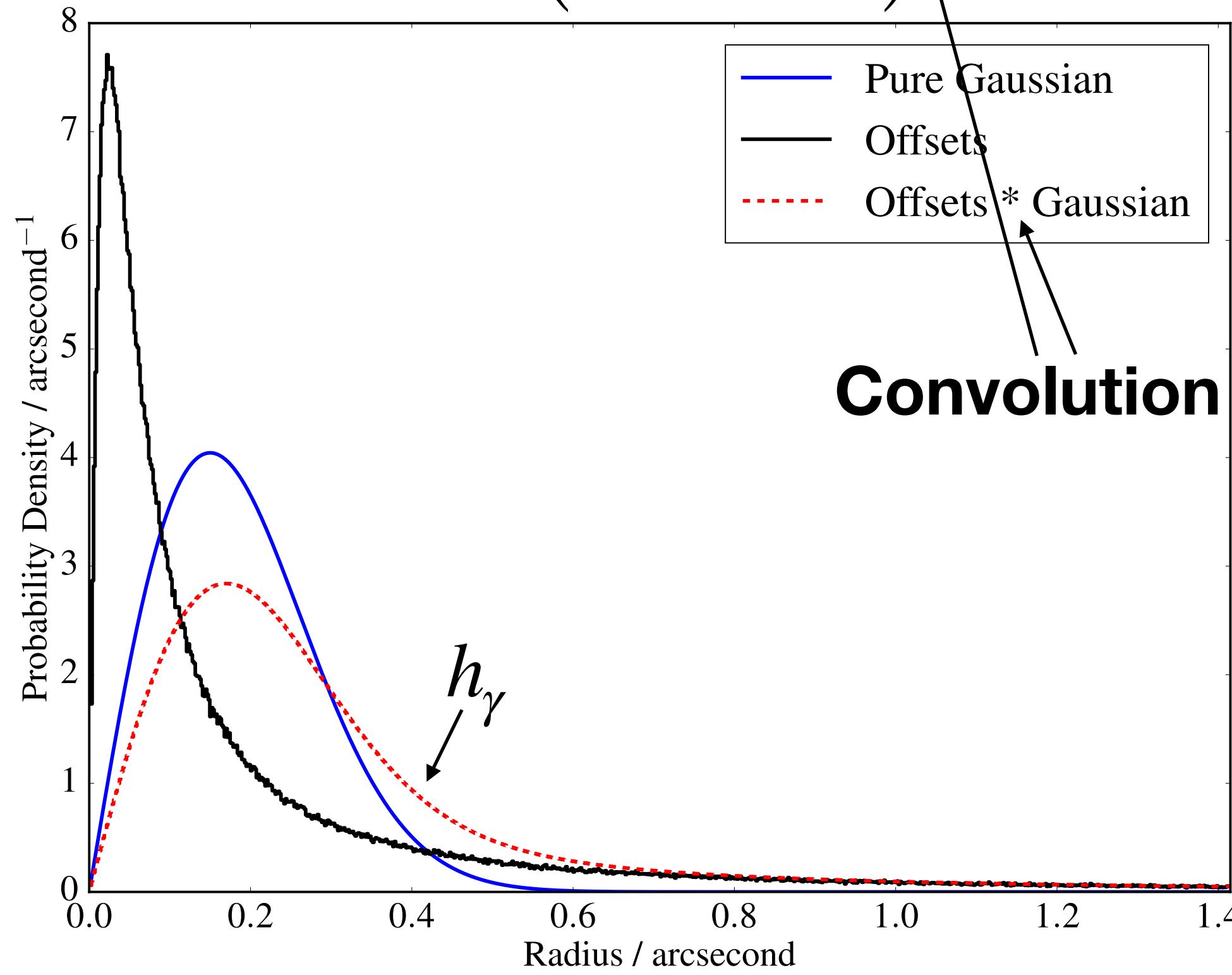
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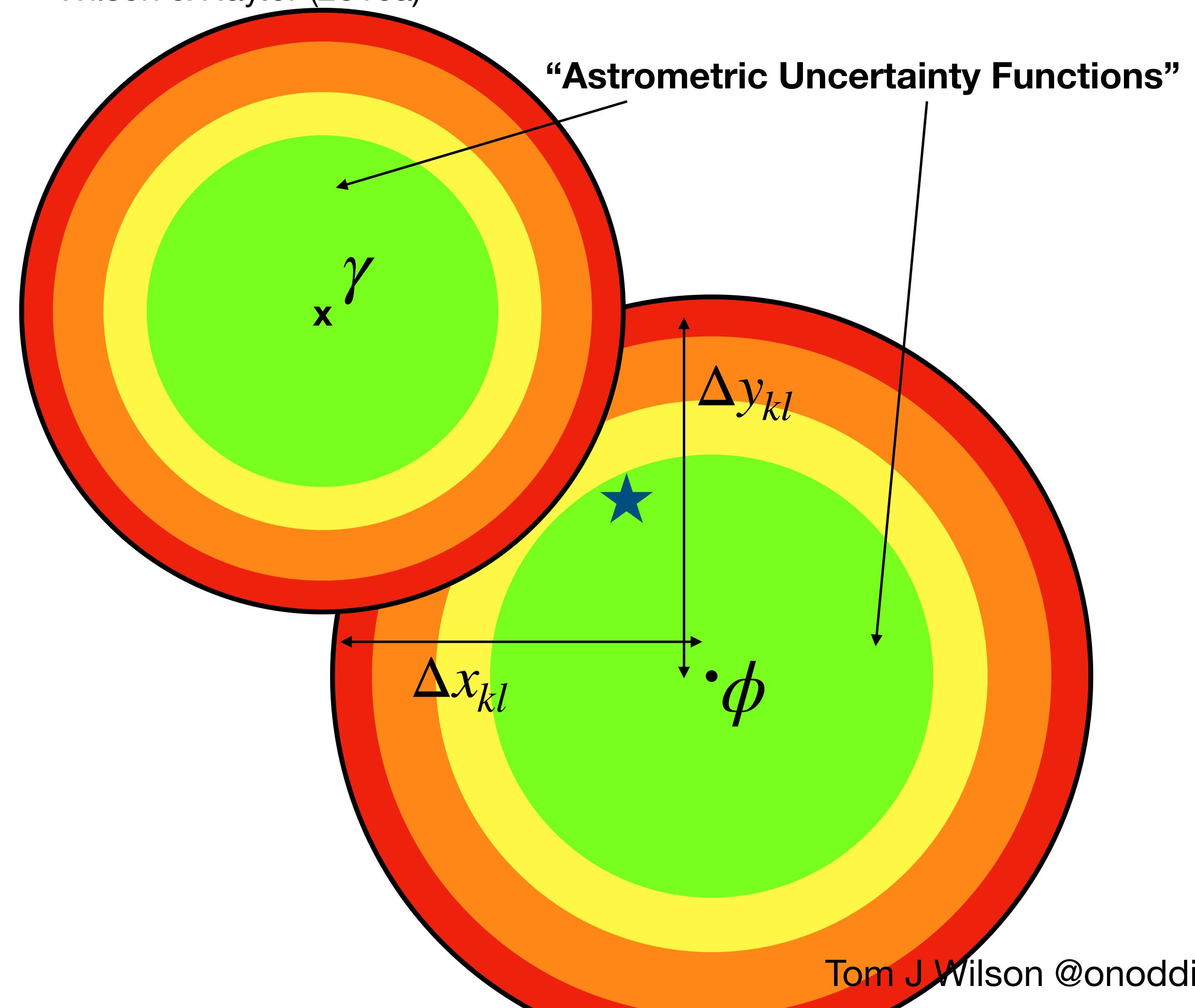
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Wilson & Naylor (2018a)

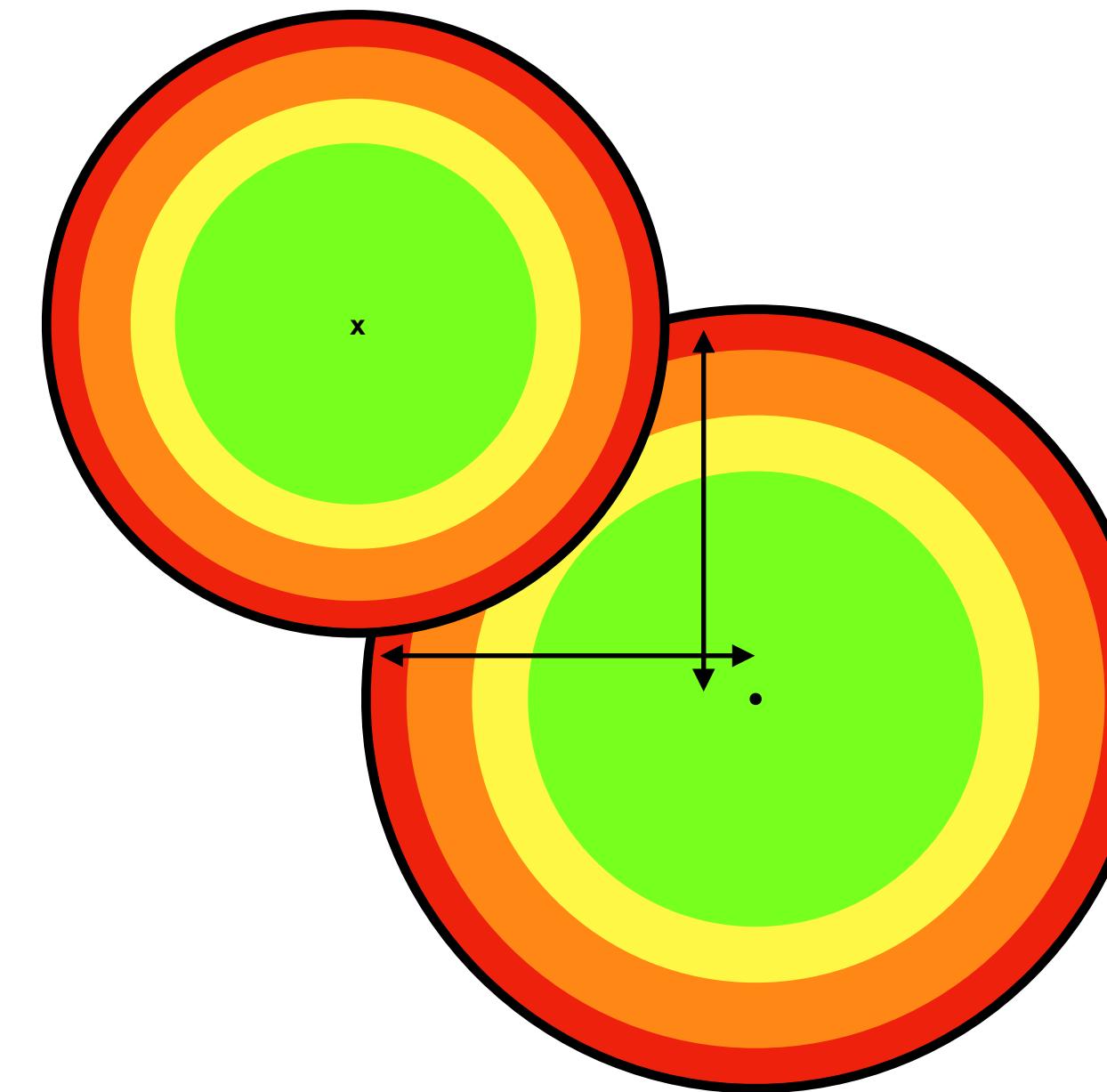
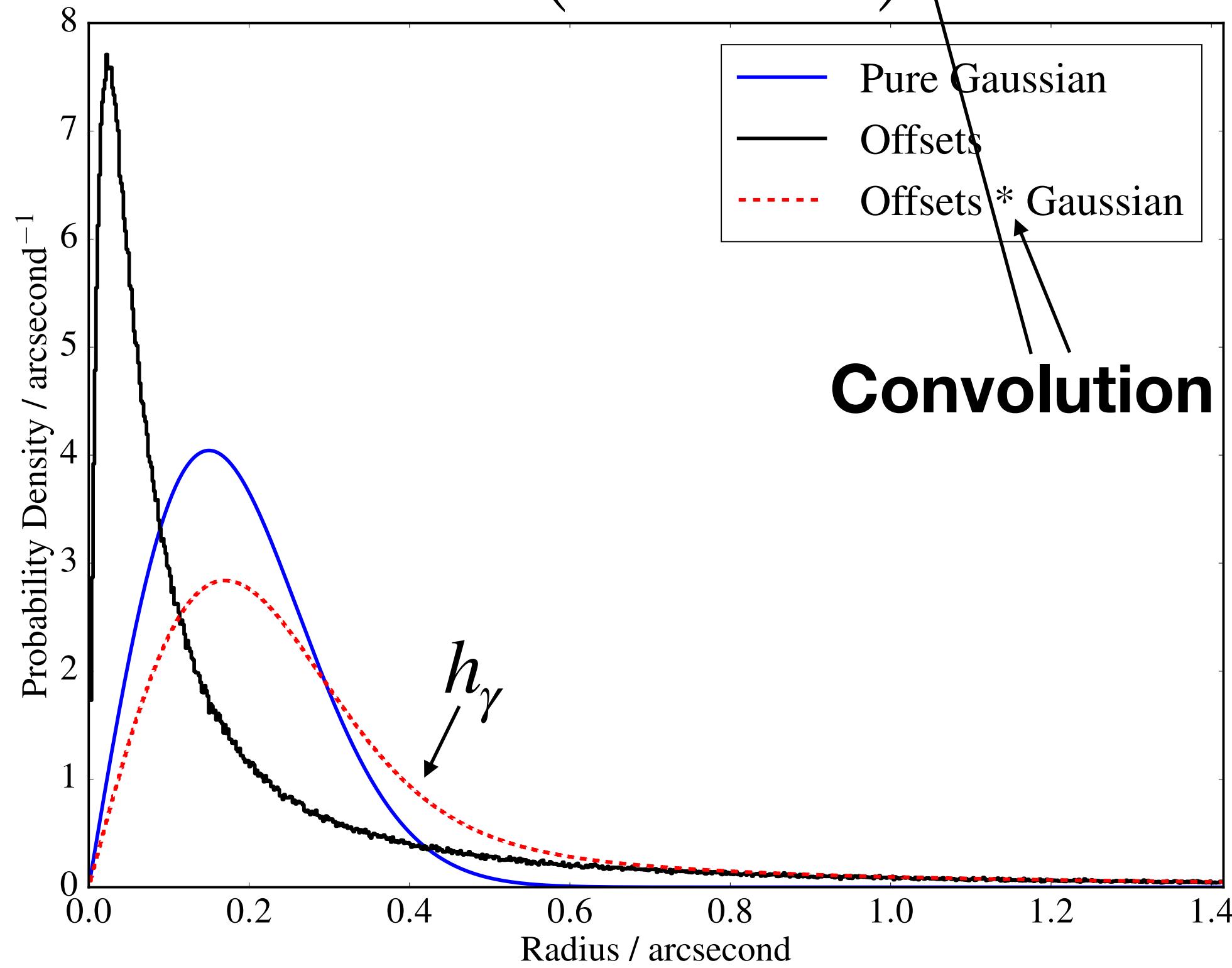


# Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0) dx_0 dy_0$$
$$= N_c \times (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl})$$

Wilson & Naylor (2018a)

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



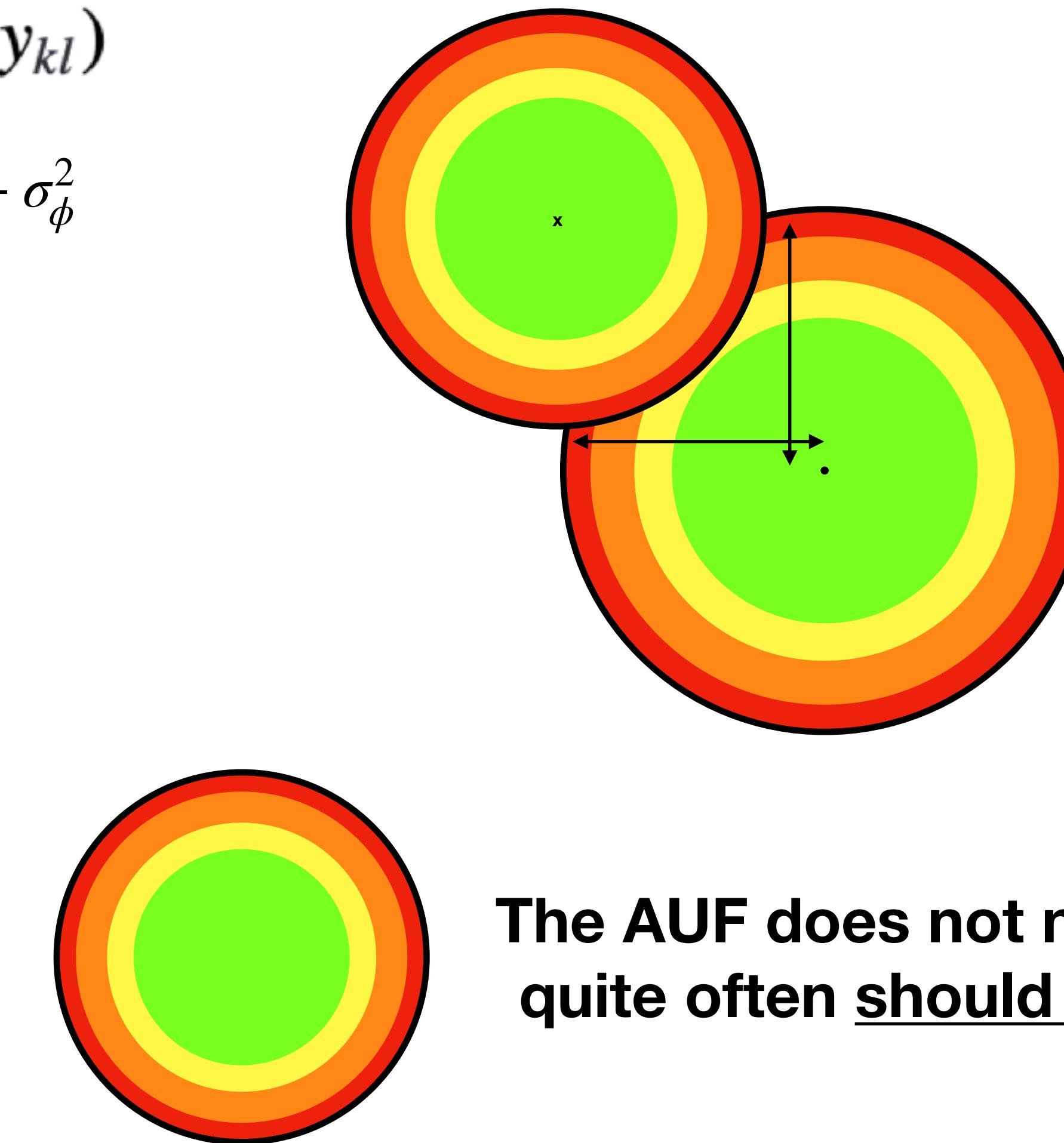
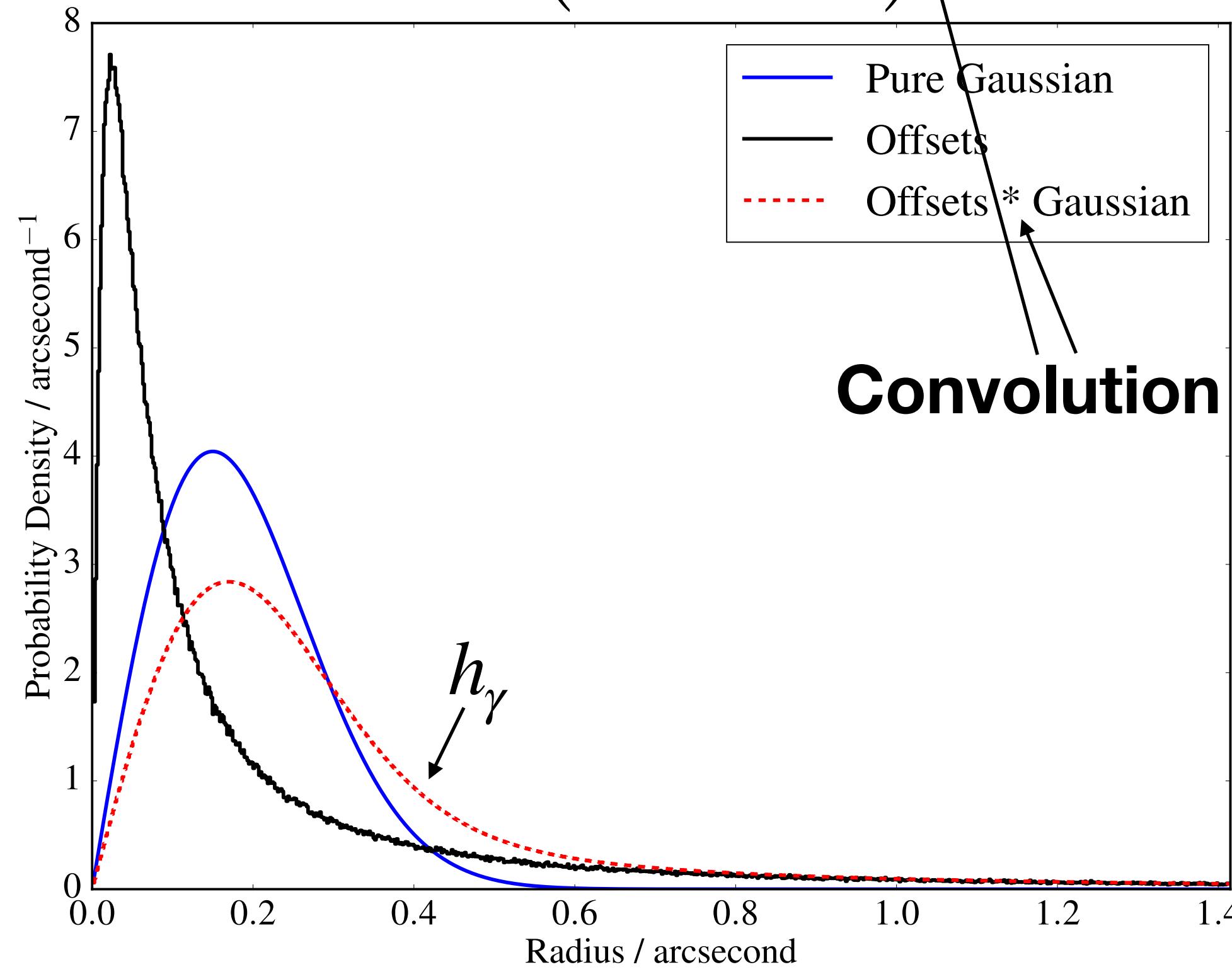
“Were the succession of stars endless... there could be absolutely no point, in all that background, at which would not exist a star.”  
— Edgar Allan Poe, Eureka (1848)

# Separation Likelihood Function

$$g(x_k, y_k, x_l, y_l) = \iint_{-\infty}^{+\infty} h_\gamma(x_0 - x_k, y_0 - y_k) h_\phi(x_l - x_0, y_l - y_0) p(x_0, y_0) dx_0 dy_0$$
$$= N_c \times (h_\gamma * h_\phi)(\Delta x_{kl}, \Delta y_{kl})$$

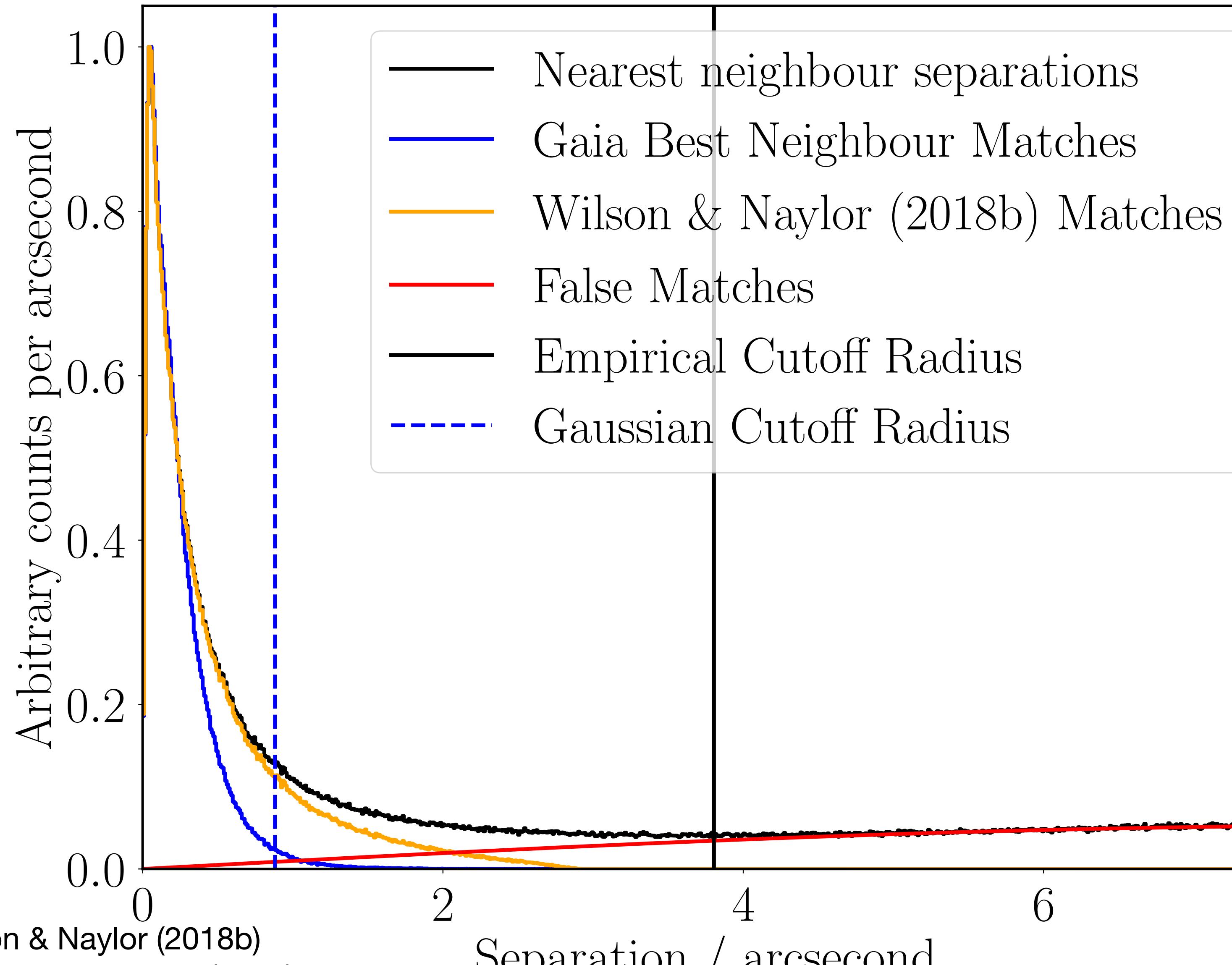
Wilson & Naylor (2018a)

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

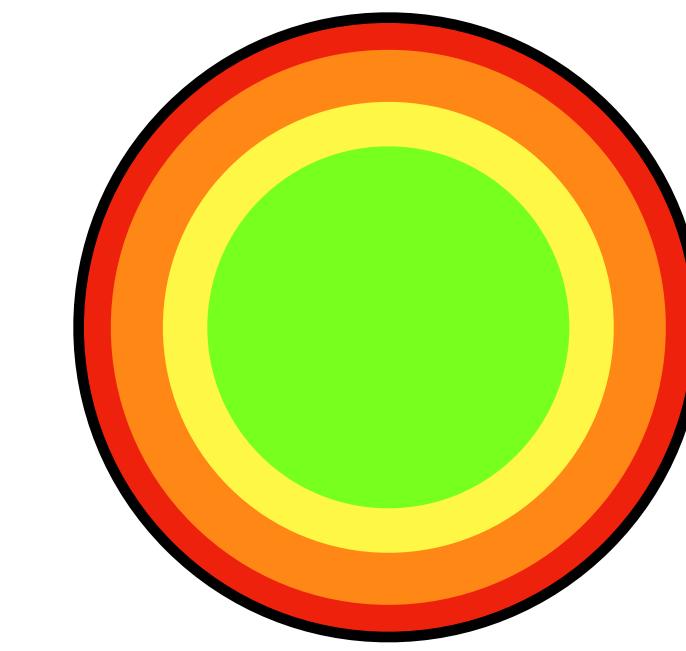


The AUF does not need to, and in fact quite often should not, be Gaussian!

# Match Separations



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



Wilson & Naylor (2018b)

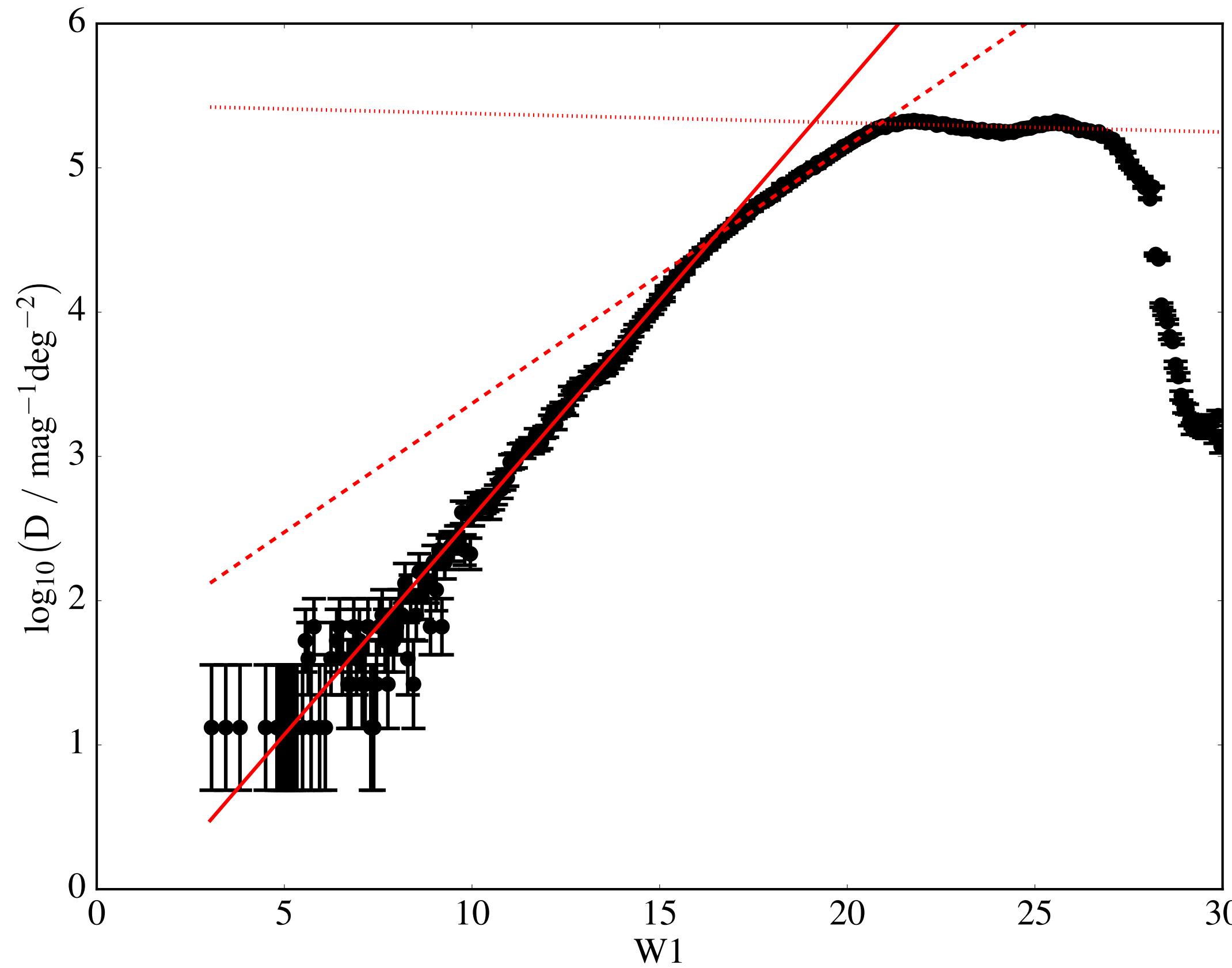
WISE - Wright et al. (2010)

Gaia matches - Marrese et al. (2019)

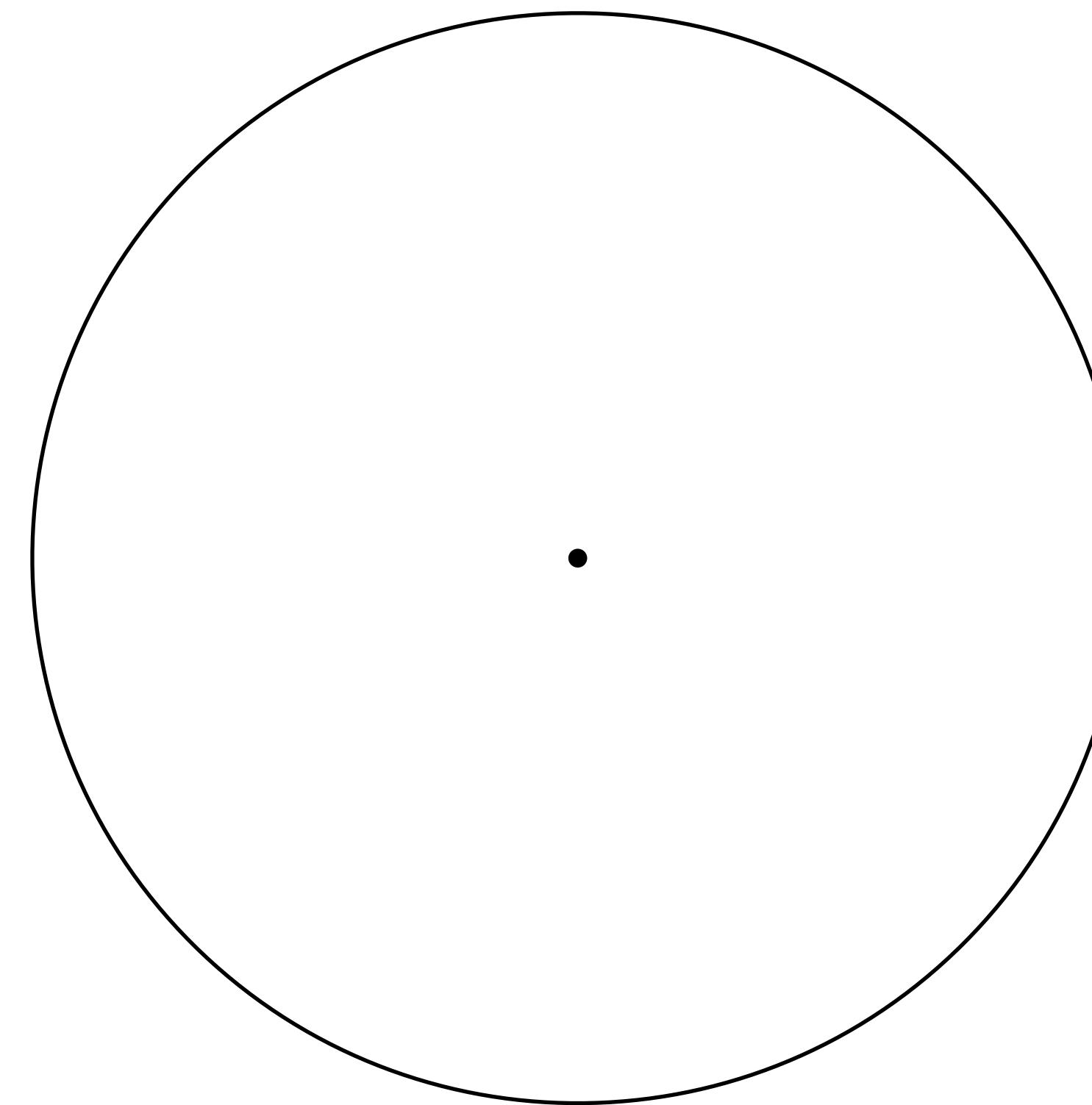
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

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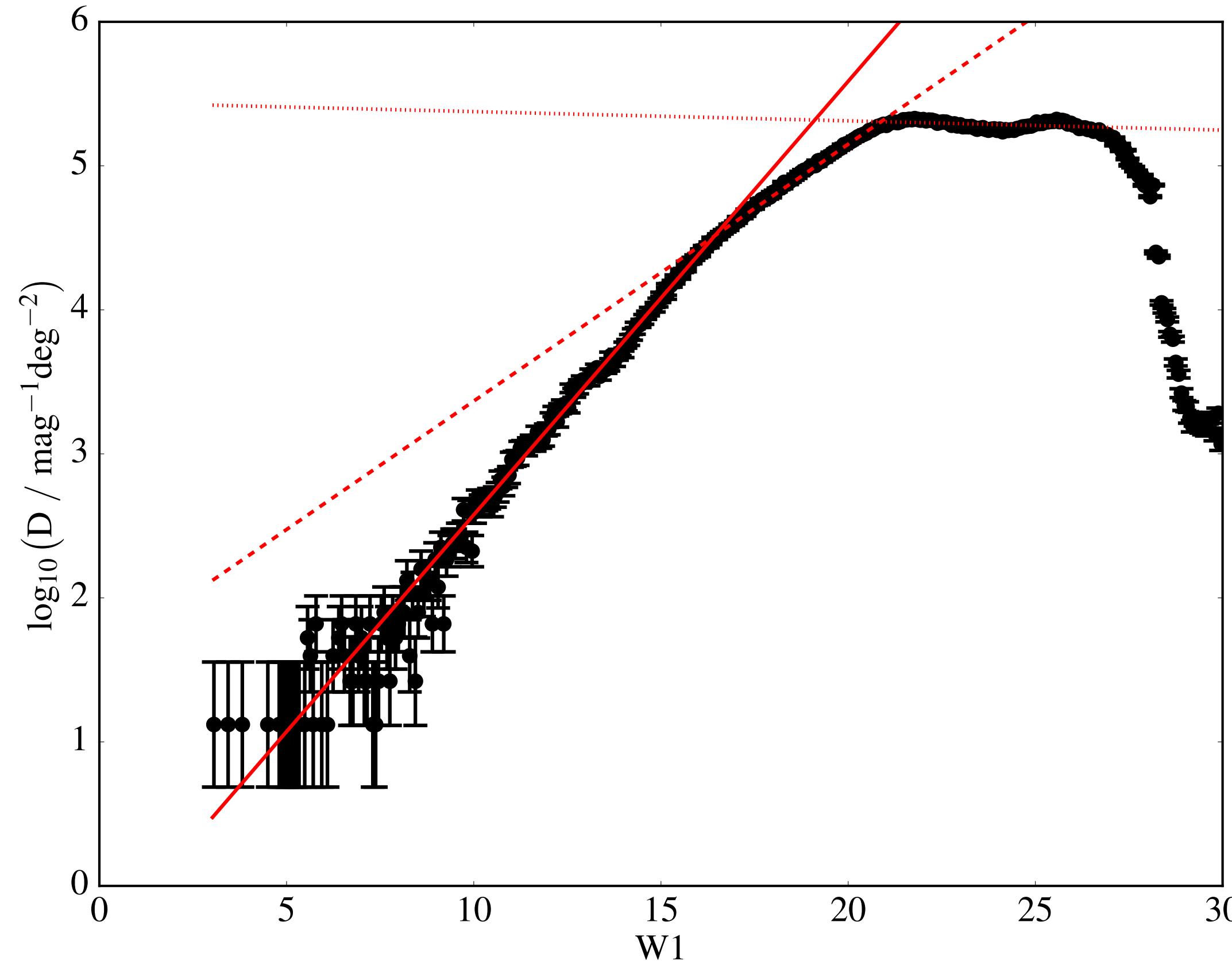
# Building Empirical AUFS



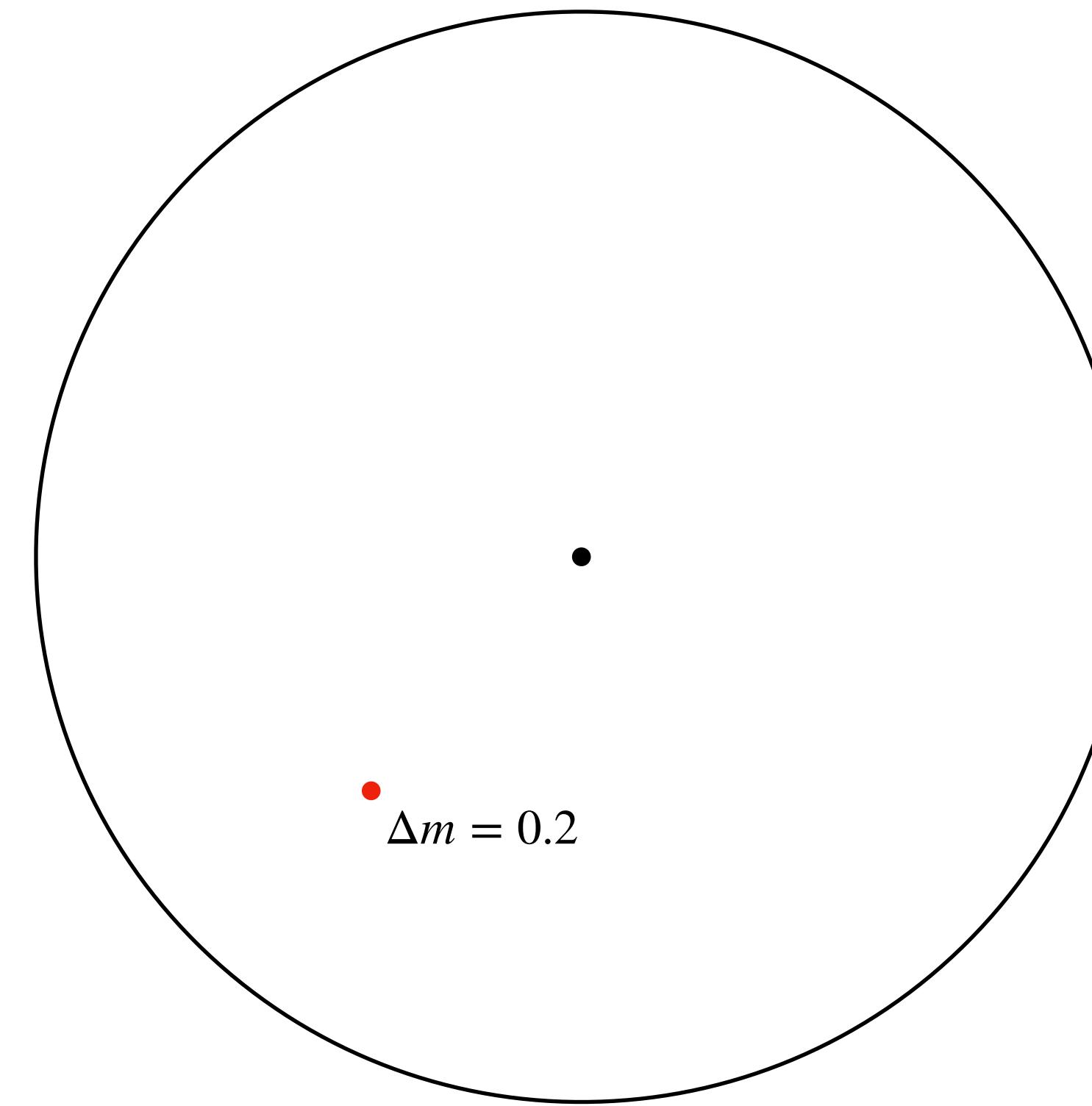
**PSF radius  $\sim 1.2$  FWHM (Rayleigh criterion)**



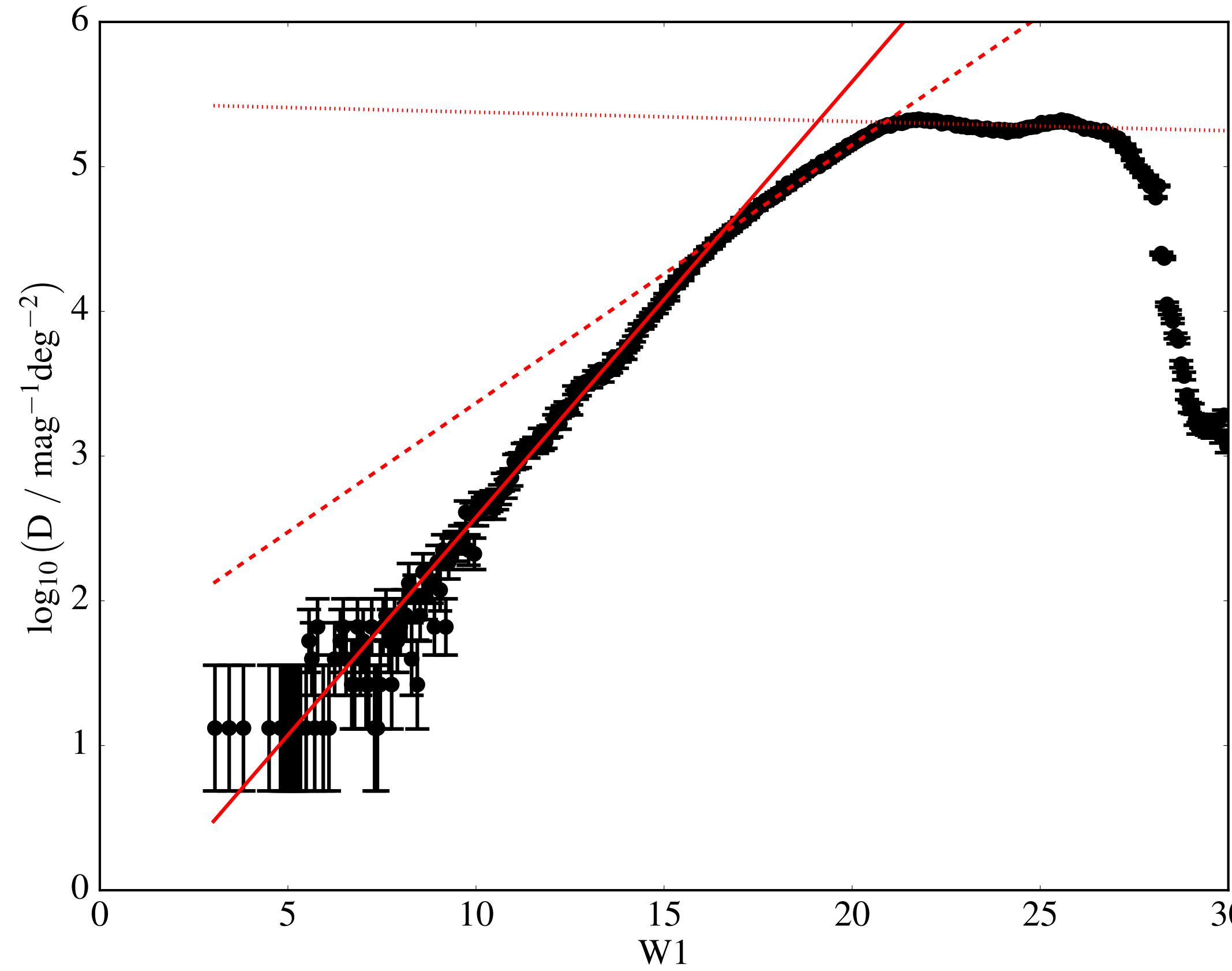
# Building Empirical AUFS



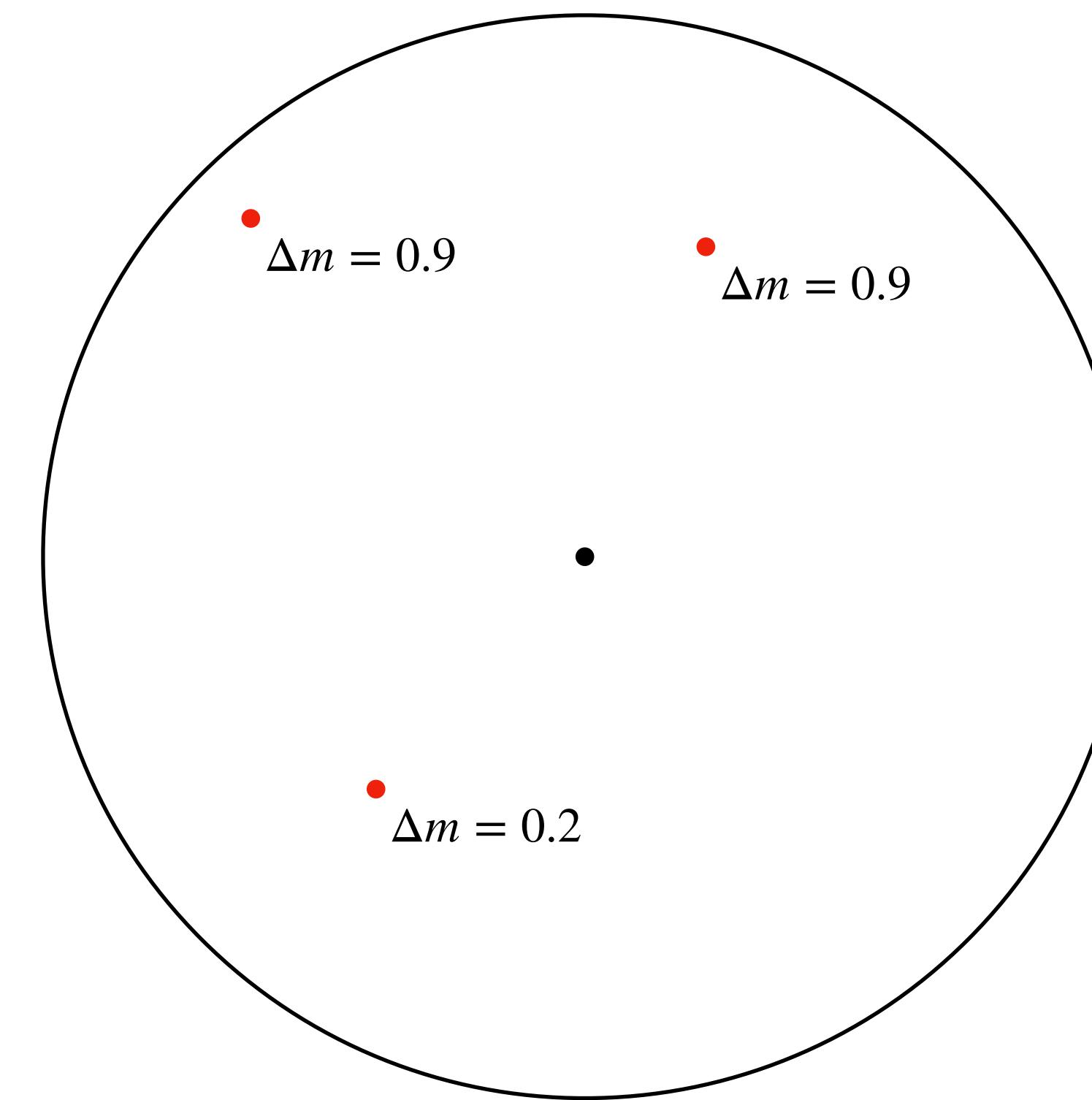
**PSF radius  $\sim 1.2$  FWHM (Rayleigh criterion)**



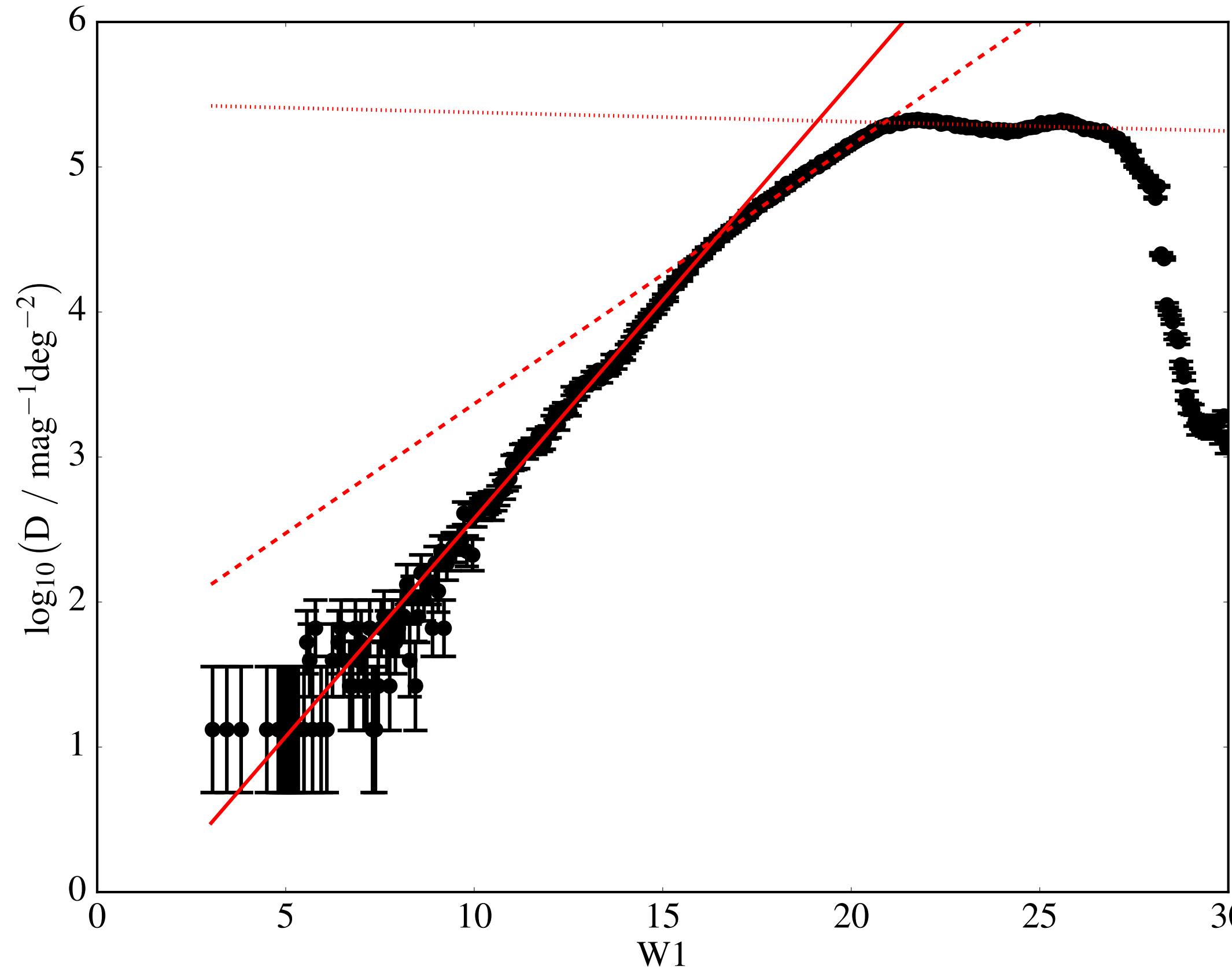
# Building Empirical AUFS



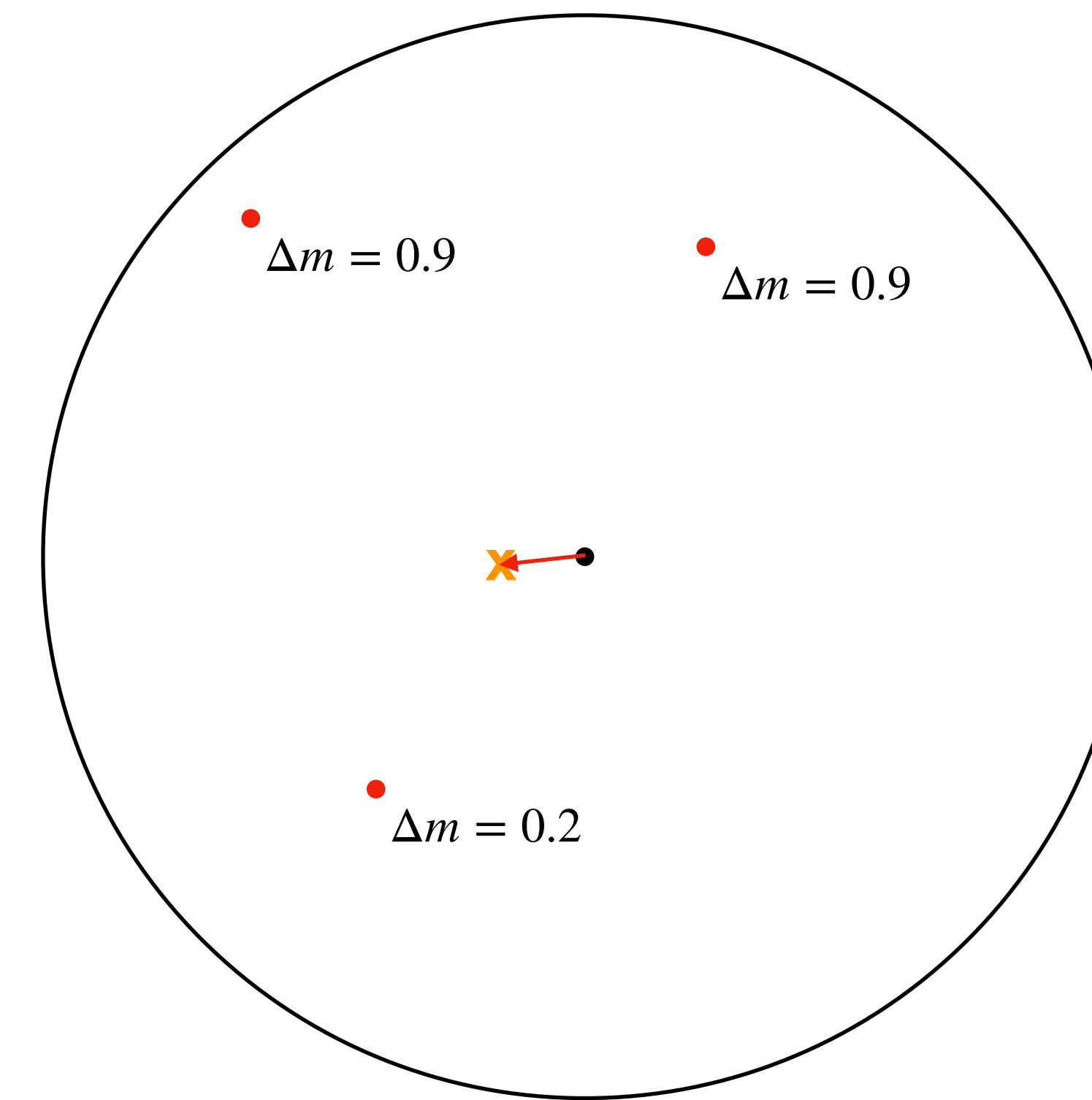
**PSF radius  $\sim 1.2$  FWHM (Rayleigh criterion)**



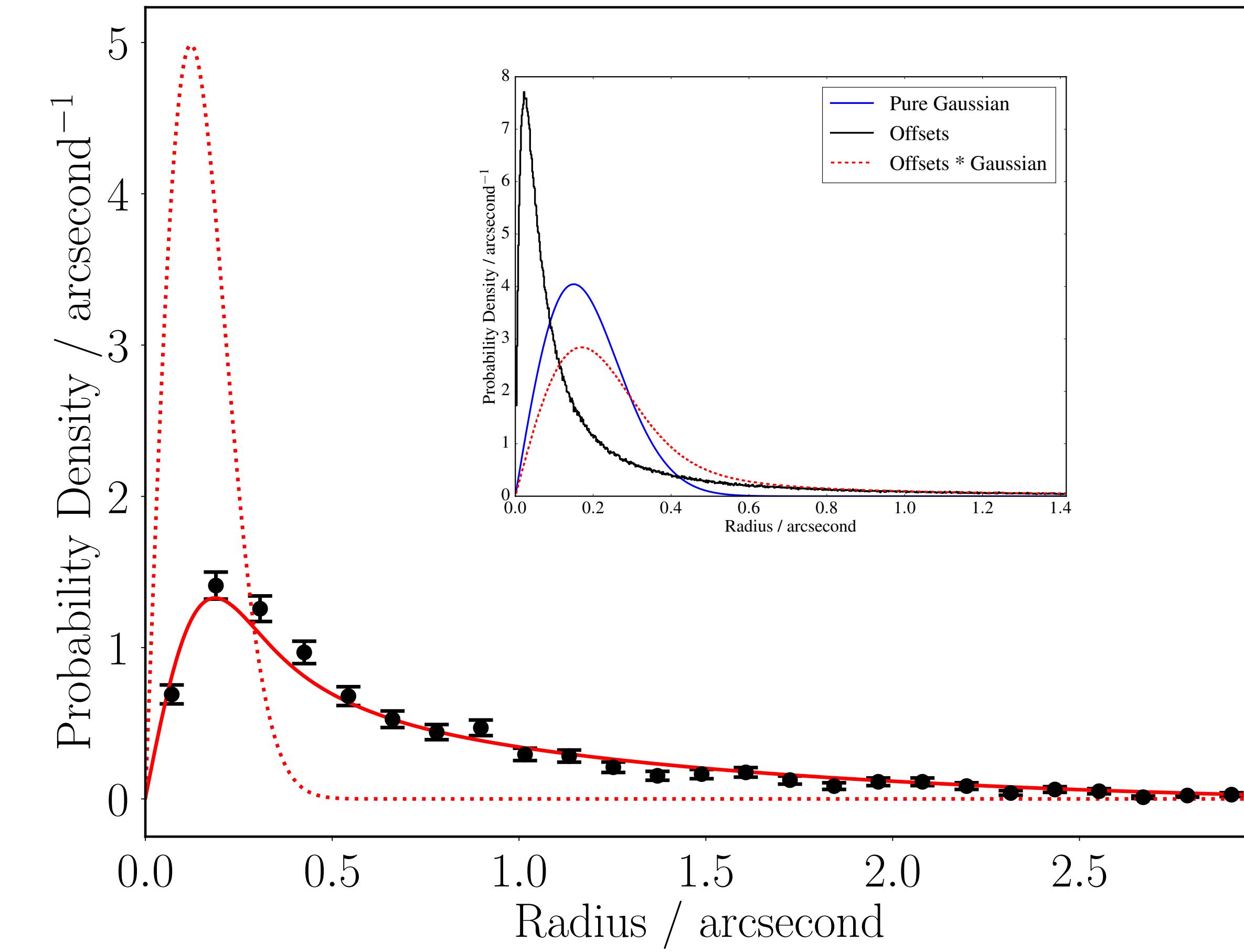
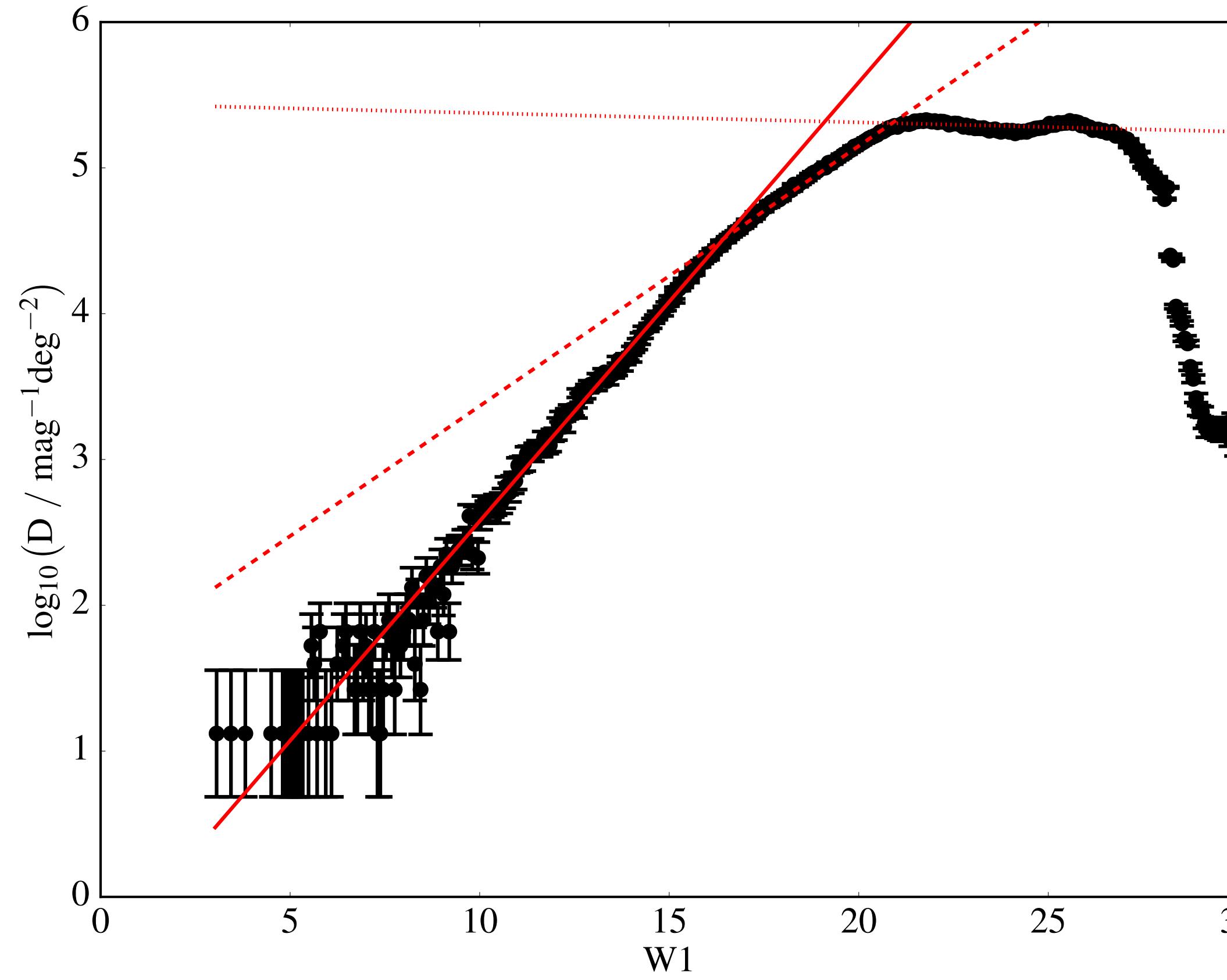
# Building Empirical AUFS



**PSF radius  $\sim 1.2$  FWHM (Rayleigh criterion)**



# Building Empirical AUFS

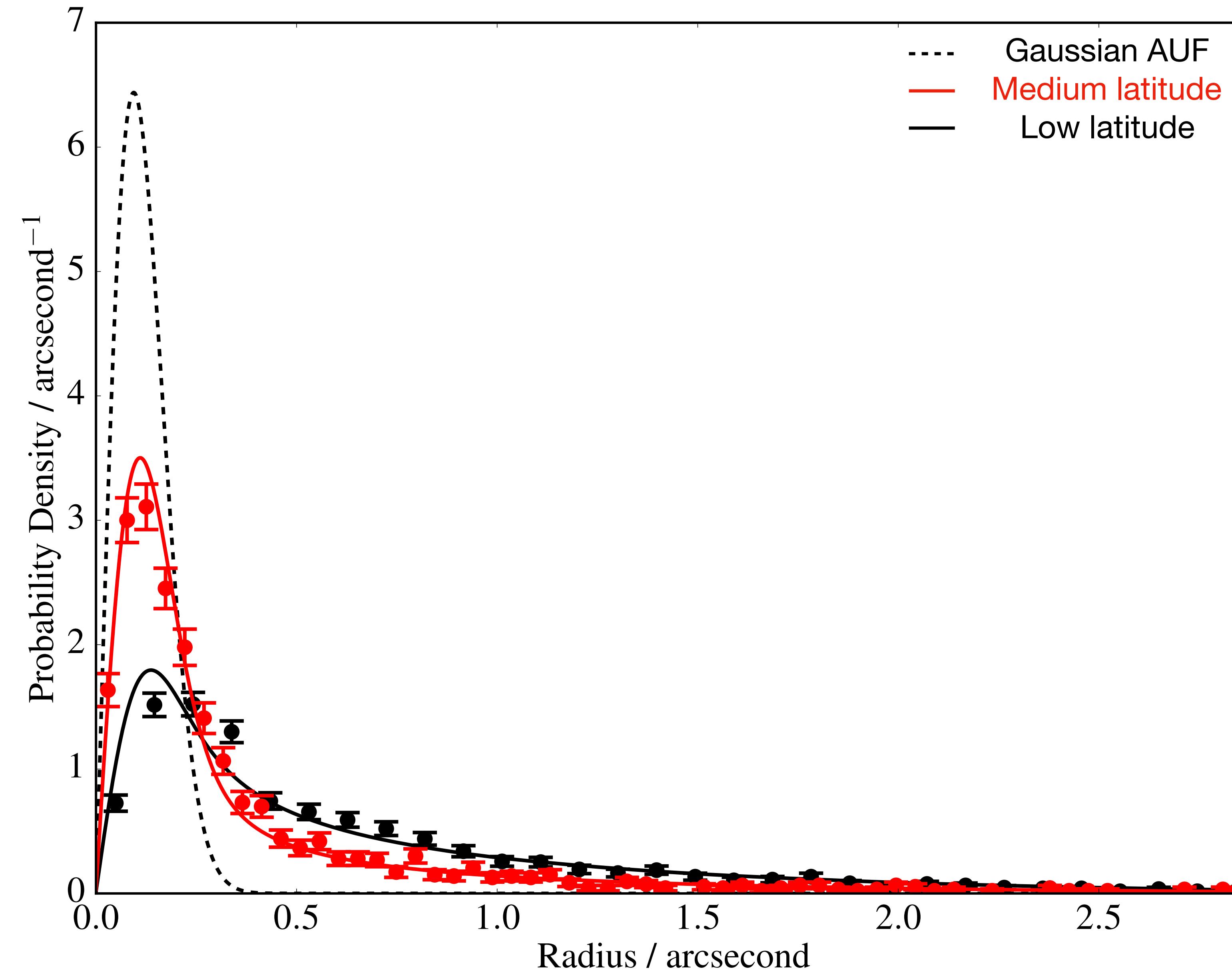


Wilson & Naylor (2018b)

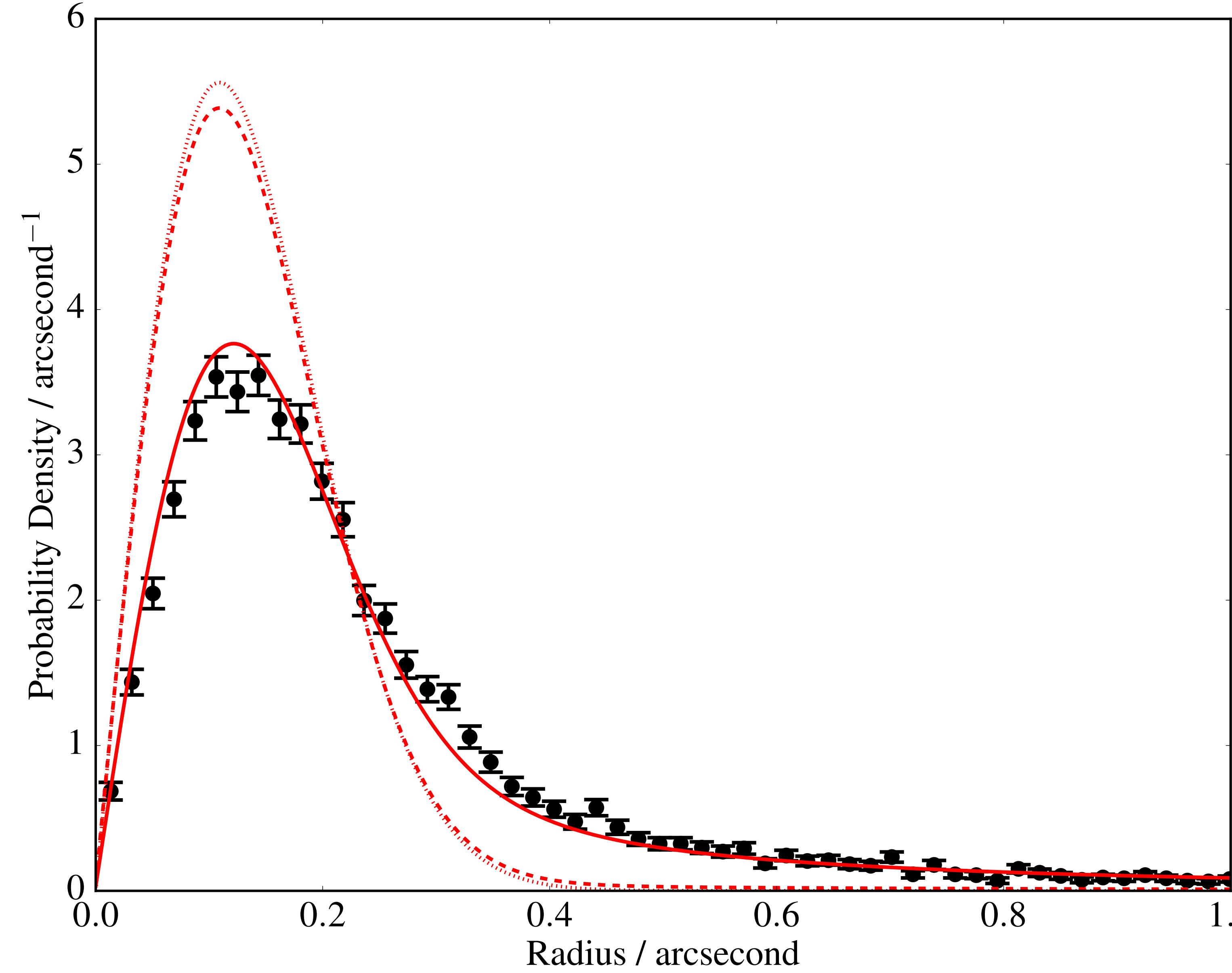
TRILEGAL - Girardi et al. (2005)

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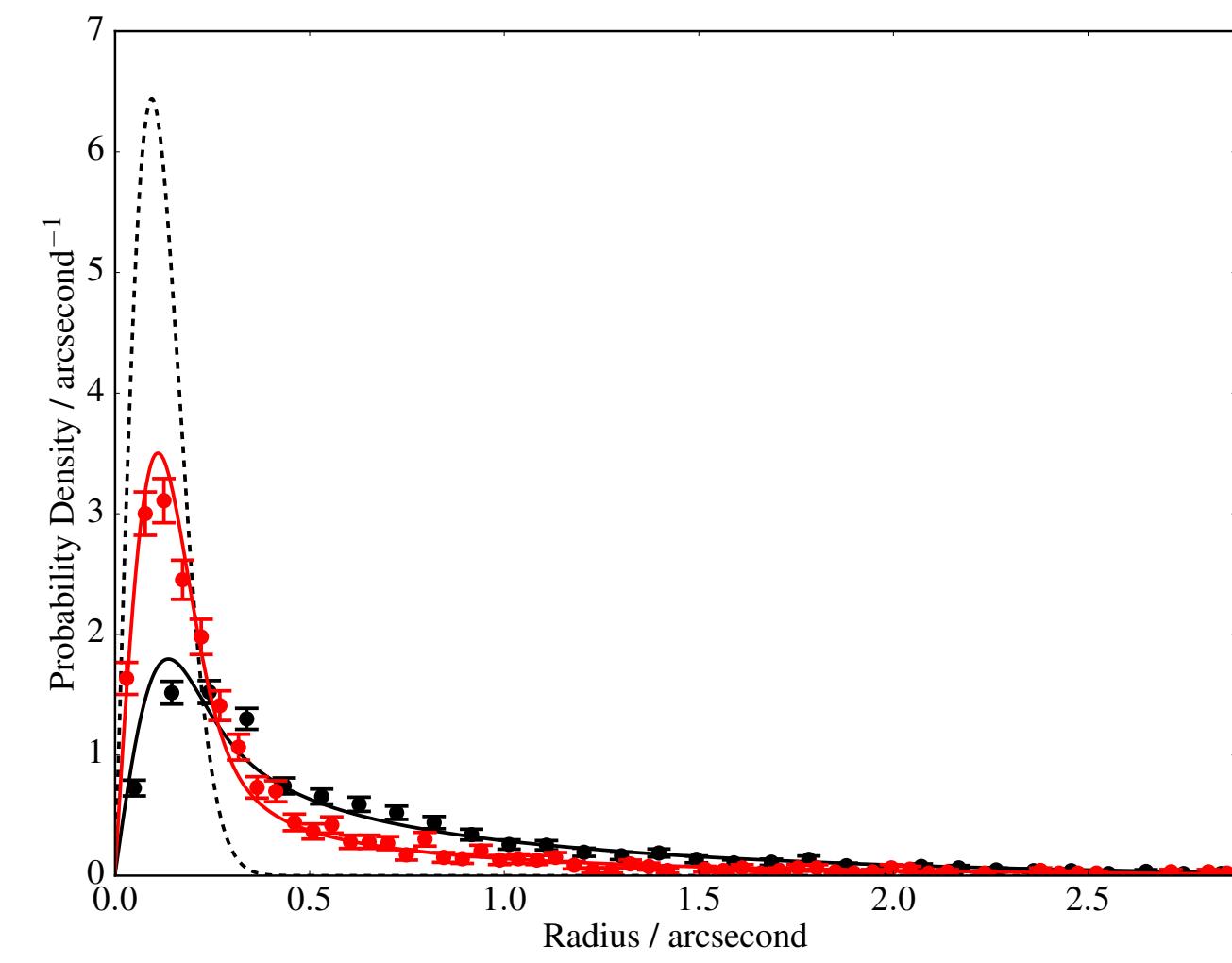
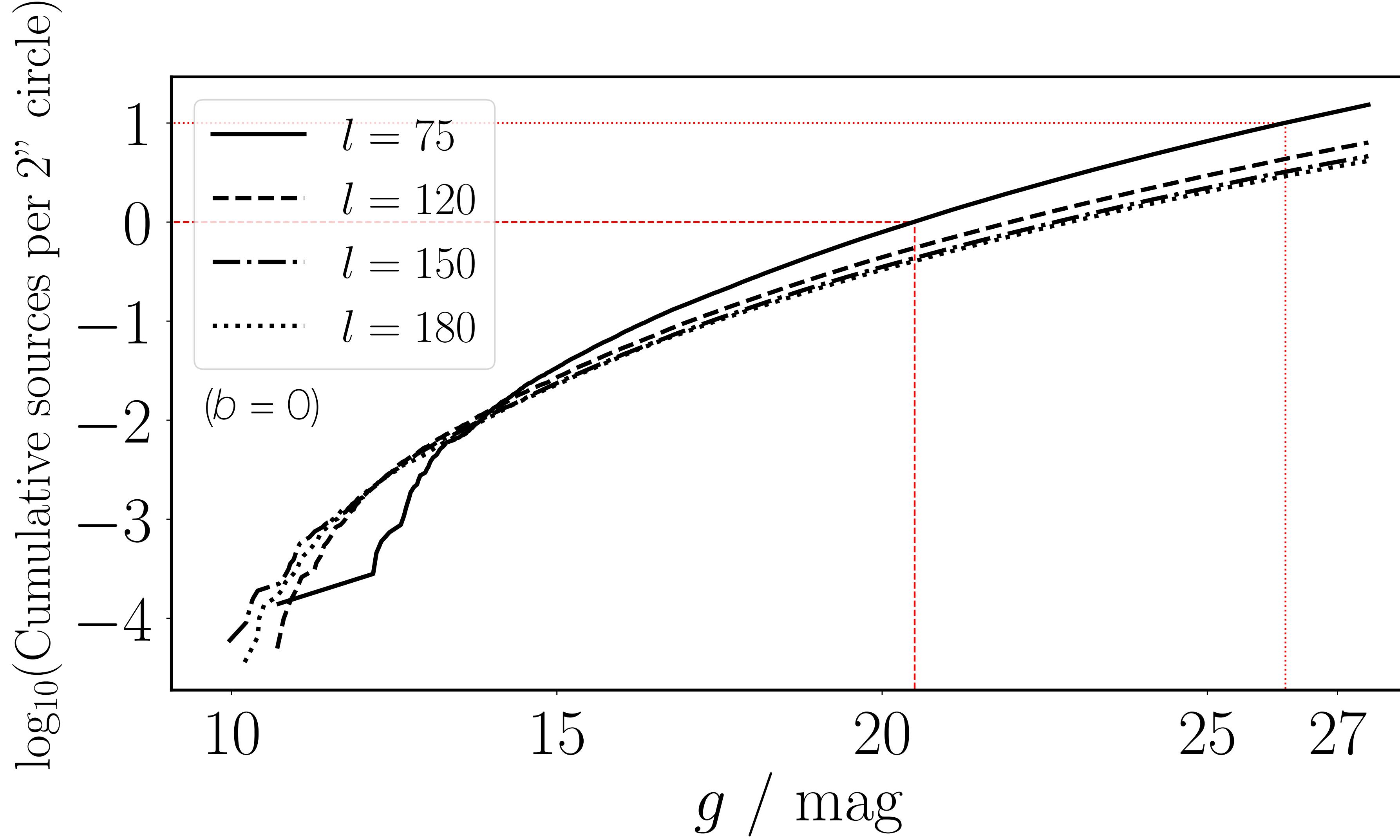
# Crowding Normalisation



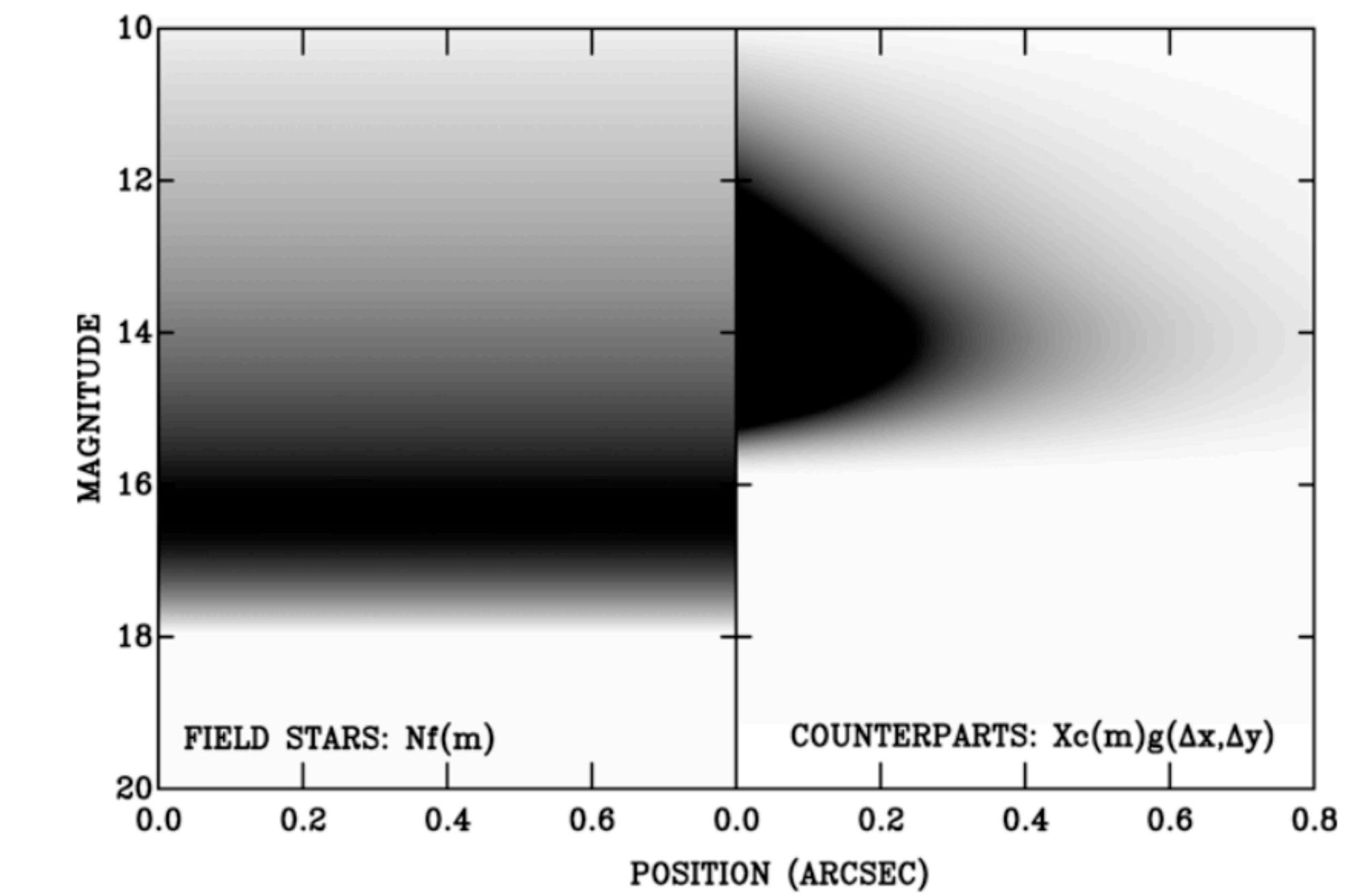
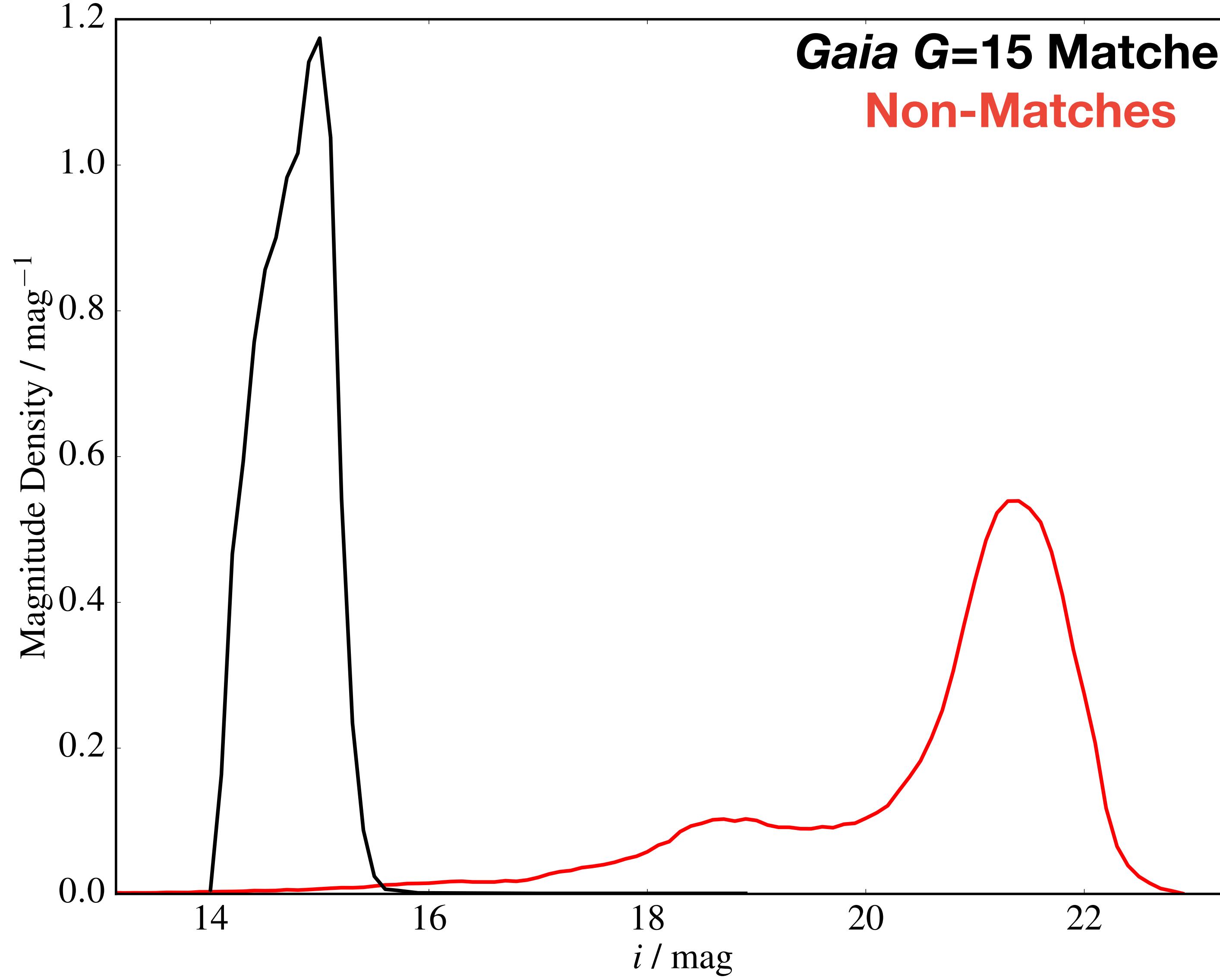
# Extra-galactic Effects of Crowding



# Vera C. Rubin Observatory's LSST



# Including the Magnitude Information



Naylor, Broos, & Feigelson (2013)

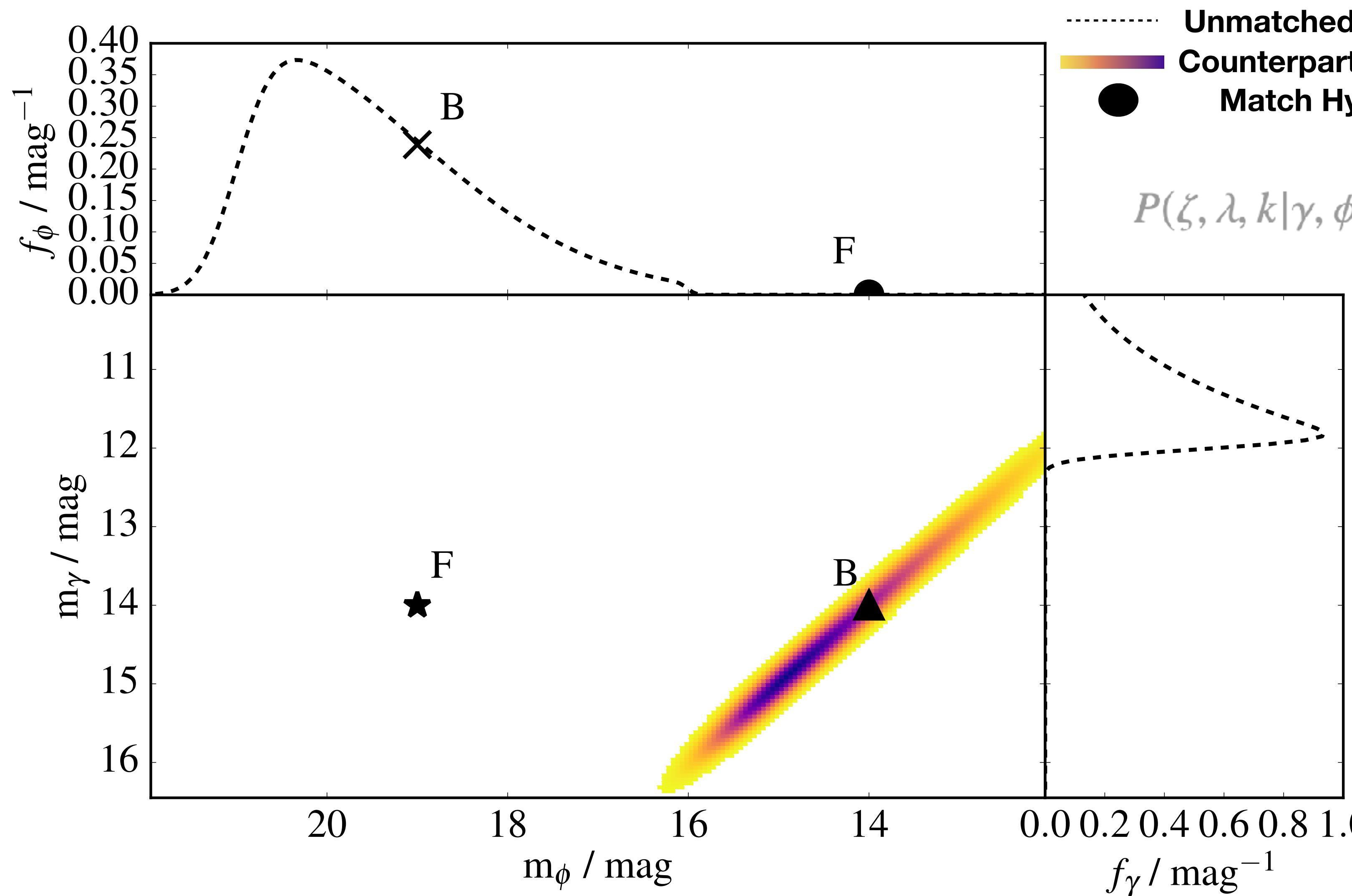
Wilson & Naylor (2018a)

IPHAS - Barentsen et al. (2014)

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

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# Including the Magnitude Information

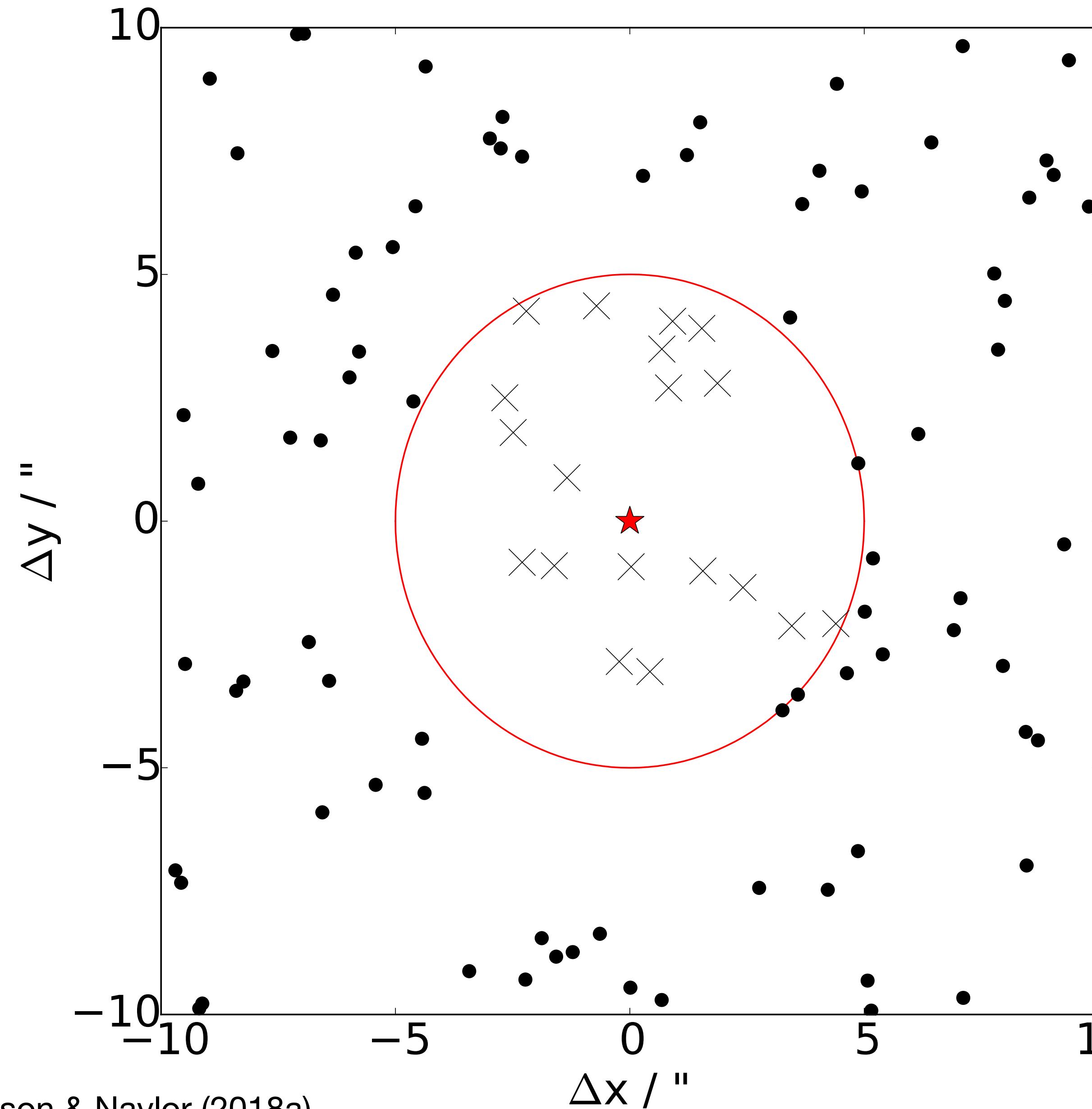


Unmatched Distribution  
Counterpart Distribution  
Match Hypotheses

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

Unmatched      Matched

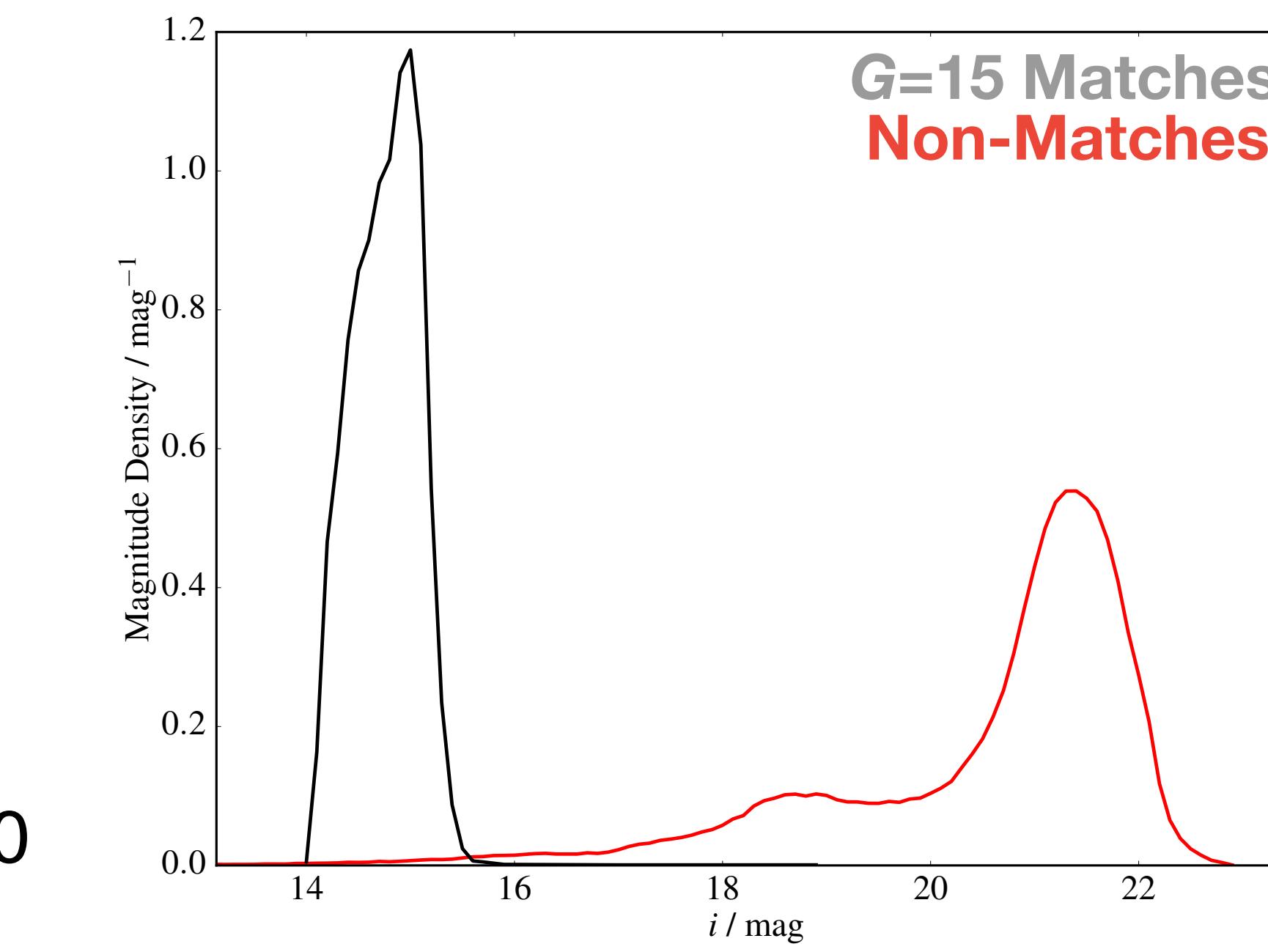
# The “Field Star” Distribution



Wilson & Naylor (2018a)

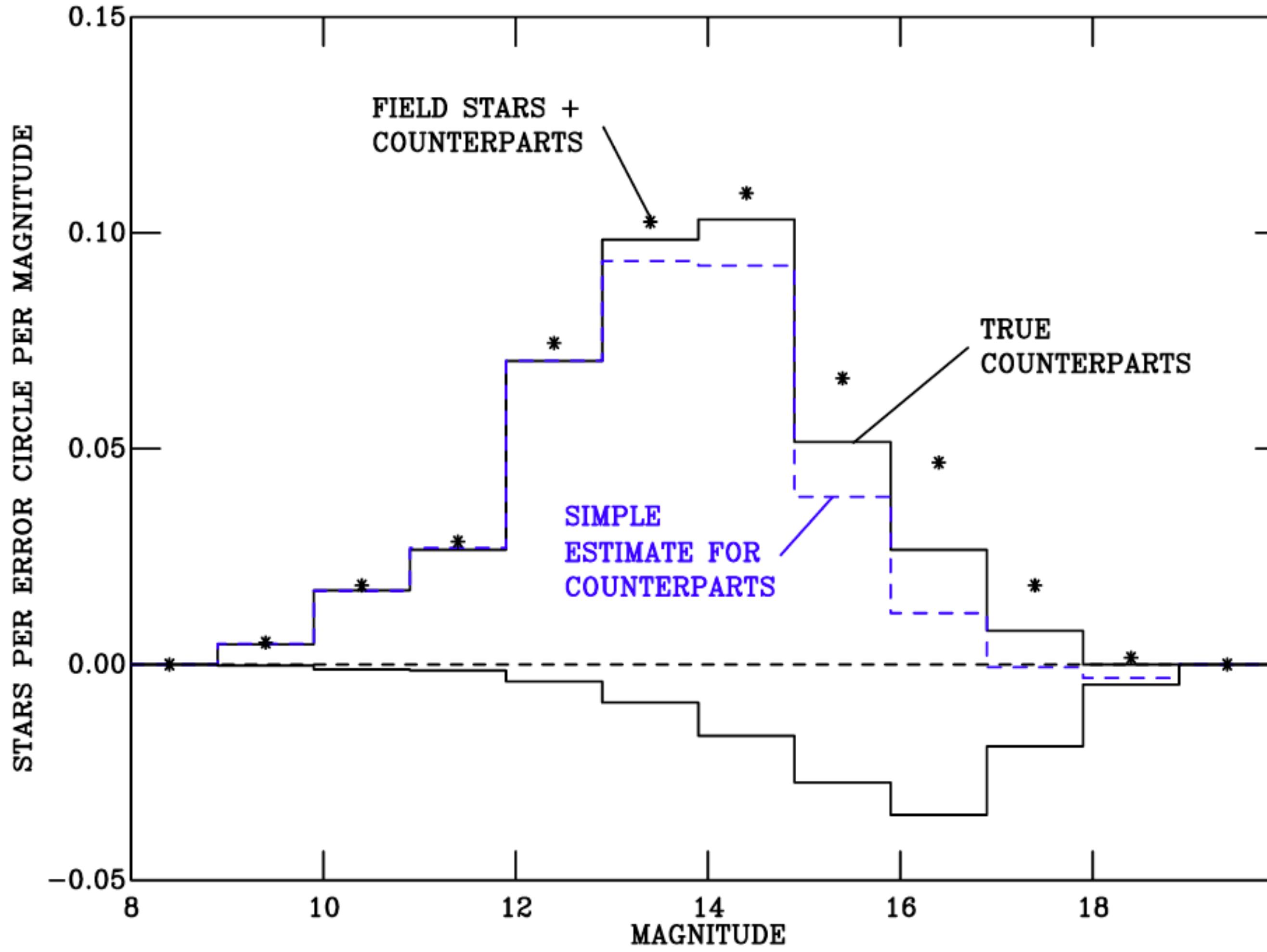
$$P(\zeta, \lambda, k | \gamma, \phi) = K^{-1} \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^k N_c G_{\gamma\phi}^{\zeta_i \lambda_i} c_{\gamma\phi}^{\zeta_i \lambda_i}$$

Unmatched      Matched

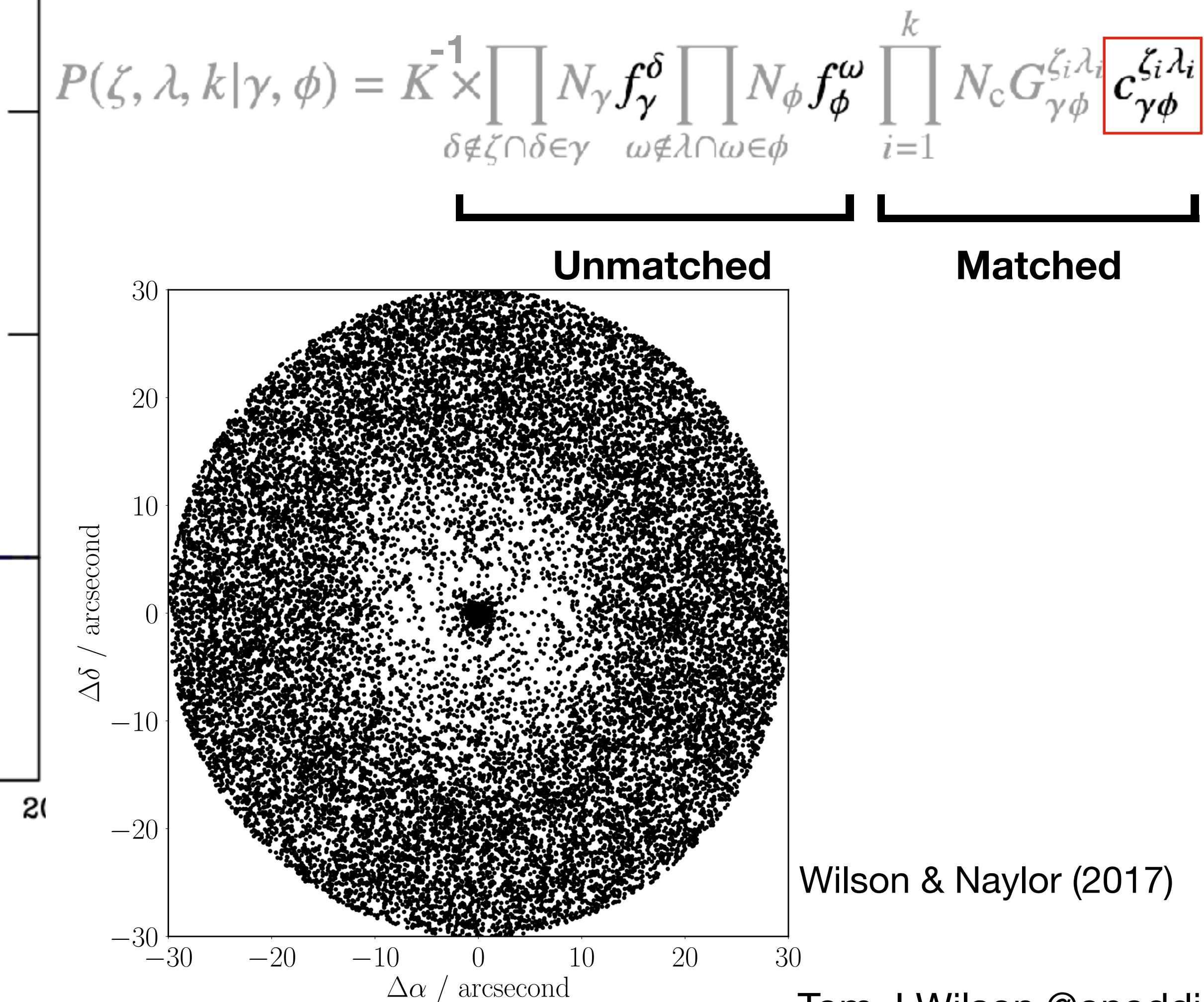


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# The Counterpart Source Distribution

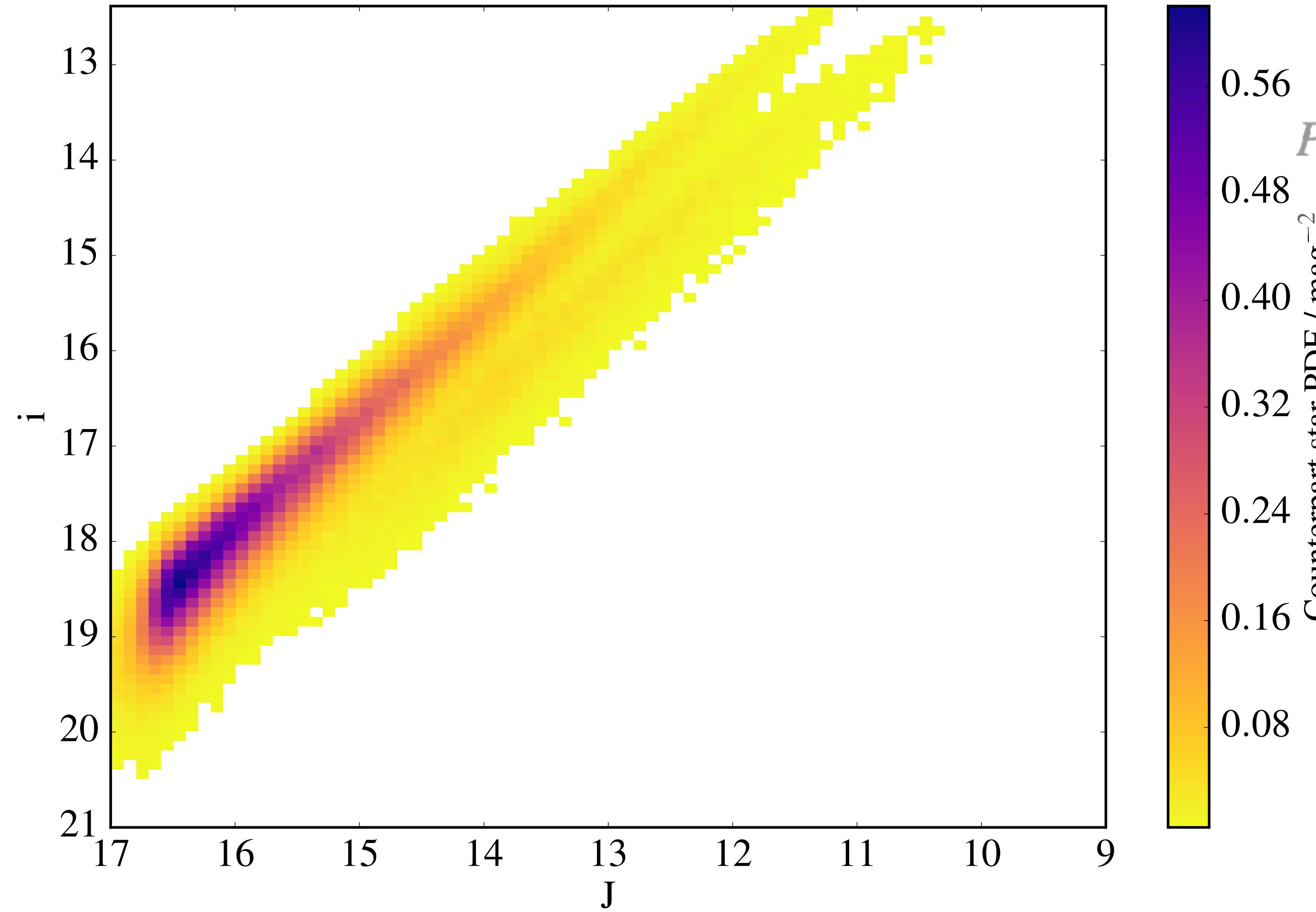


Naylor, Broos, & Feigelson (2013); also see Wilson & Naylor (2018a)



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# The Counterpart Source Distribution

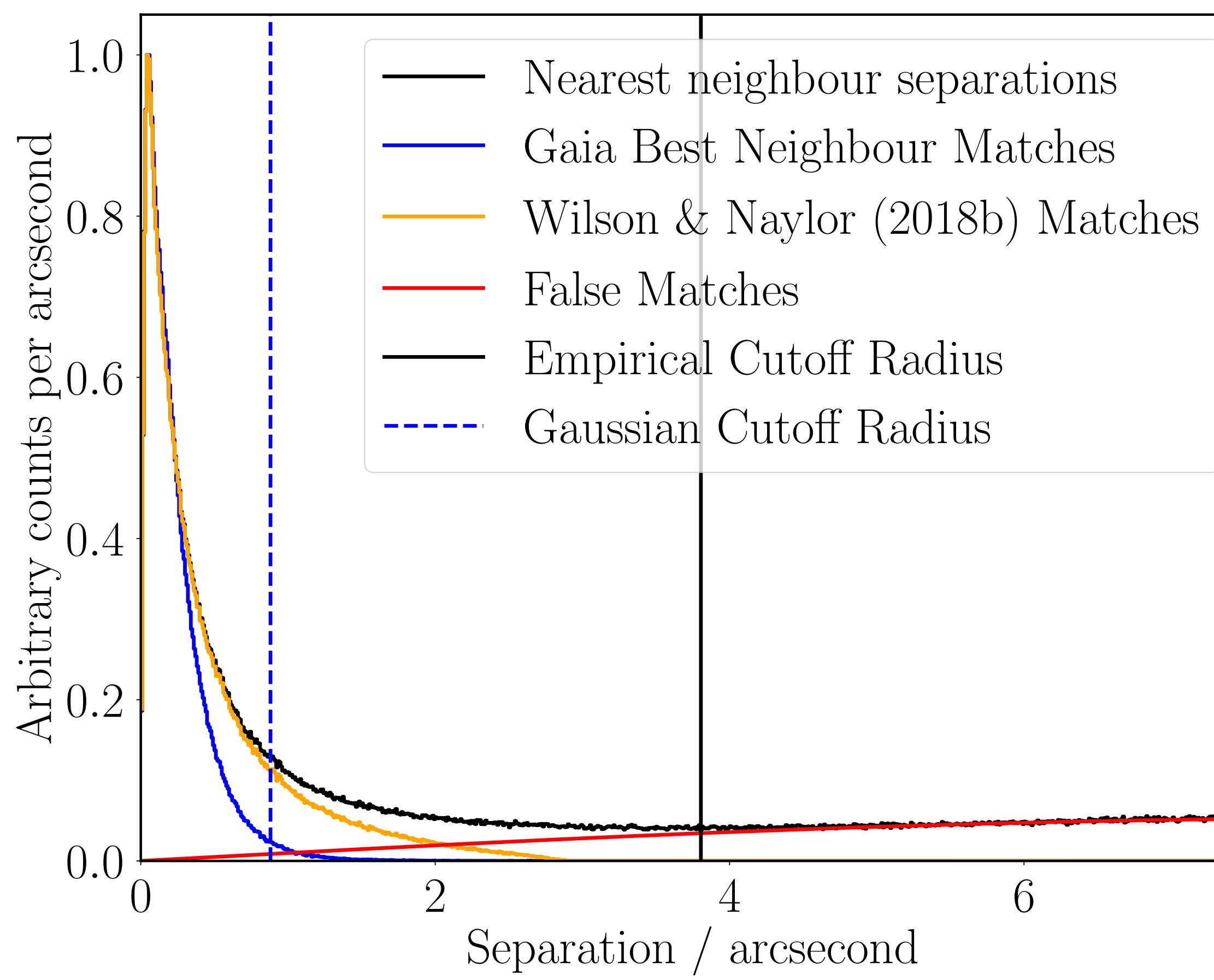


Counterpart star PDF /  $\text{mag}^{-2}$

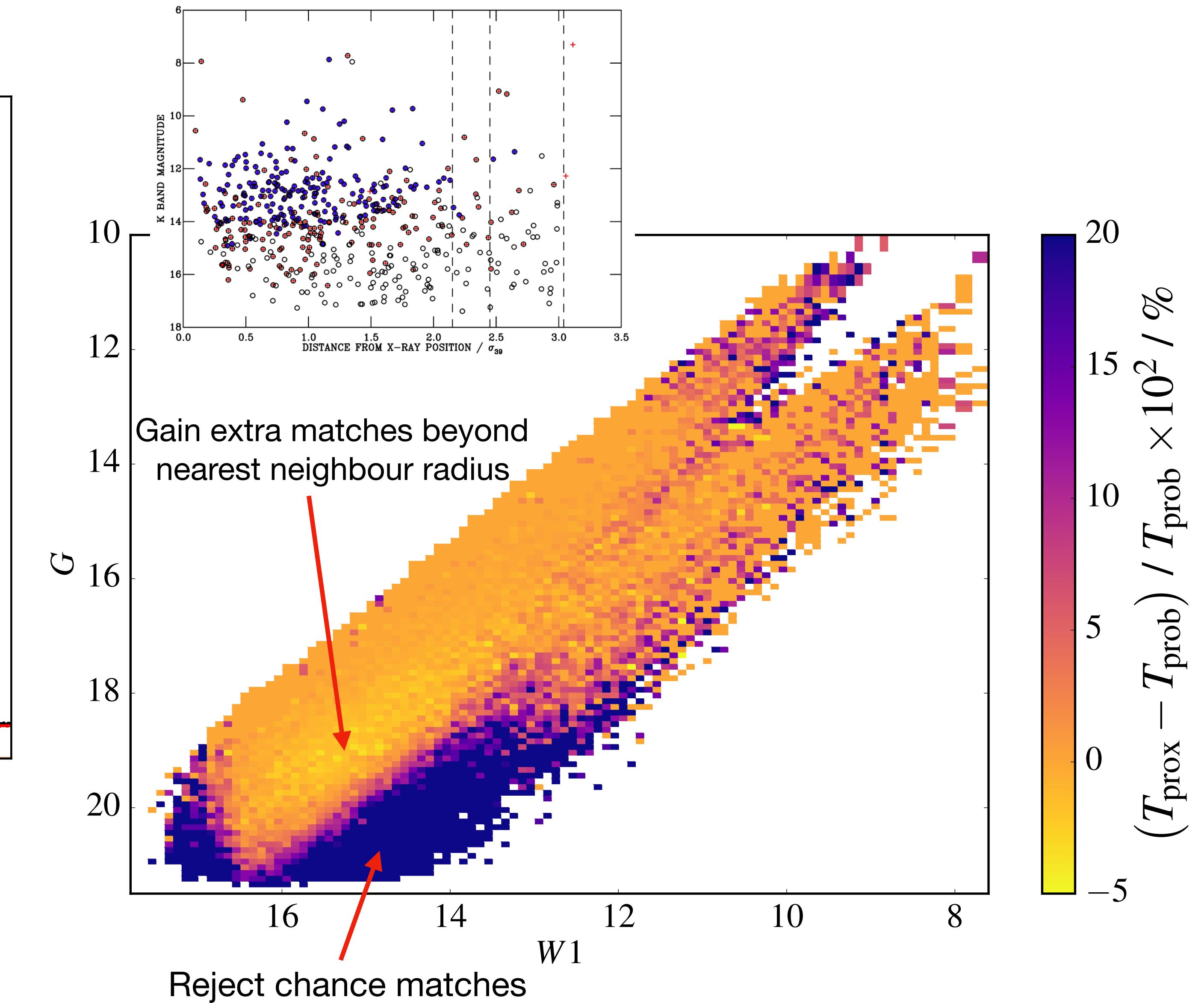
$$P(\zeta, \lambda, k | \gamma, \phi) = K^{-1} \times \prod_{\delta \notin \zeta \cap \delta \in \gamma} N_\gamma f_\gamma^\delta \prod_{\omega \notin \lambda \cap \omega \in \phi} N_\phi f_\phi^\omega \prod_{i=1}^k N_c G_{\gamma\phi}^{\zeta_i \lambda_i} c_{\gamma\phi}^{\zeta_i \lambda_i}$$

**Unmatched**      **Matched**

# Comparing Match Distributions

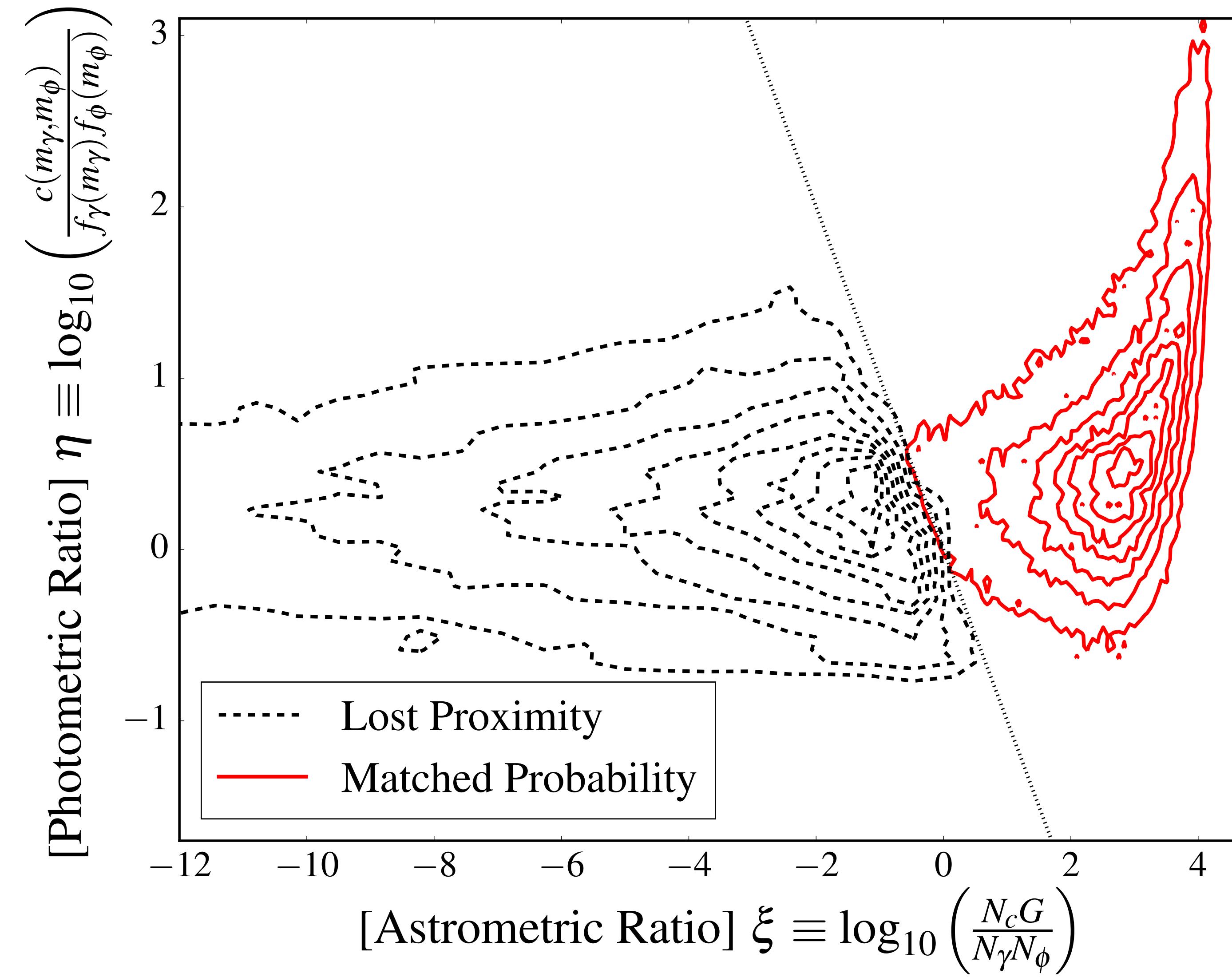


Wilson & Naylor (2018b)  
WISE - Wright et al. (2010)  
Gaia matches - Marrese et al. (2019)  
Gaia DR2 - Gaia Collaboration, Brown A. G. A., et al. (2018)

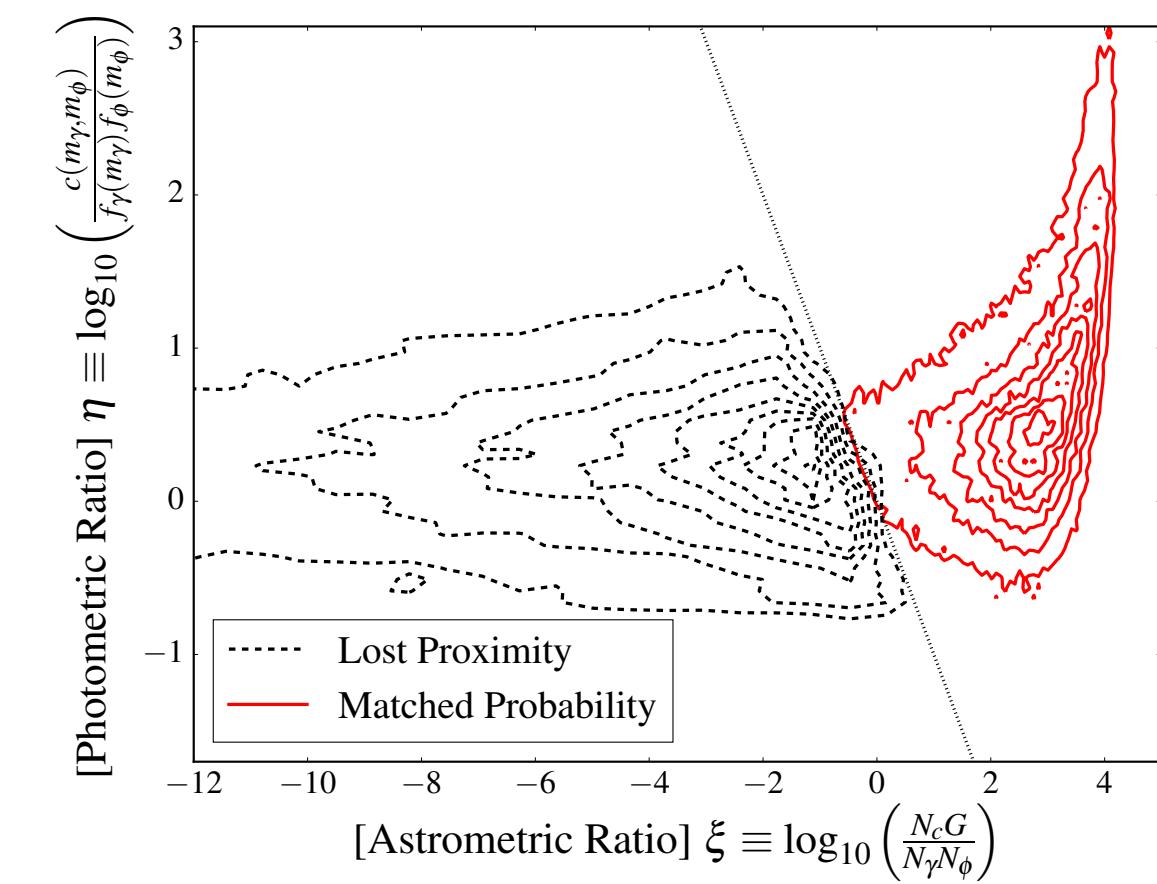
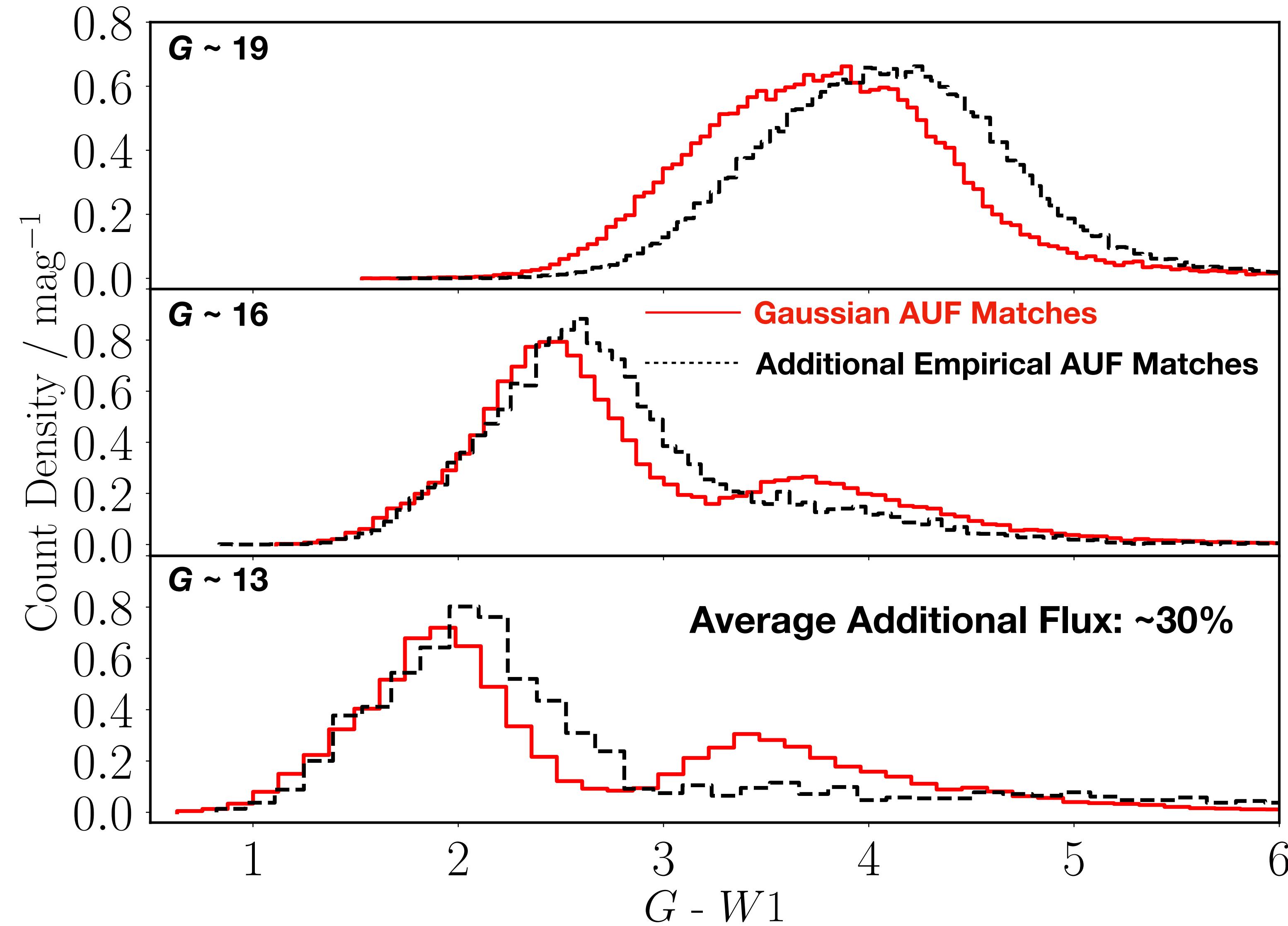


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# Lost Gaussian-Only Matches

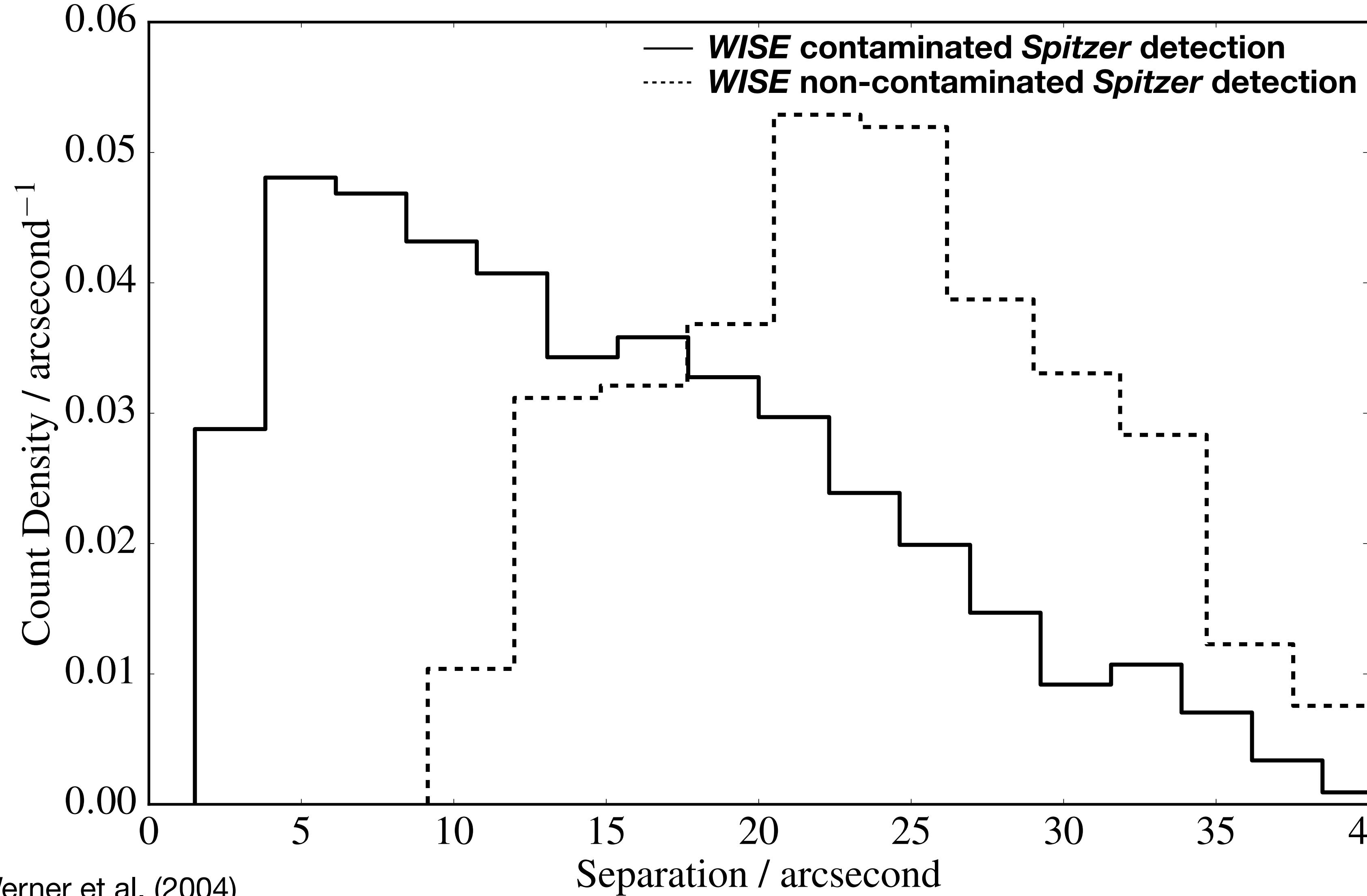


# Perturbation-Colour Correlation



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

# Resolving Contaminants



Spitzer - Werner et al. (2004)

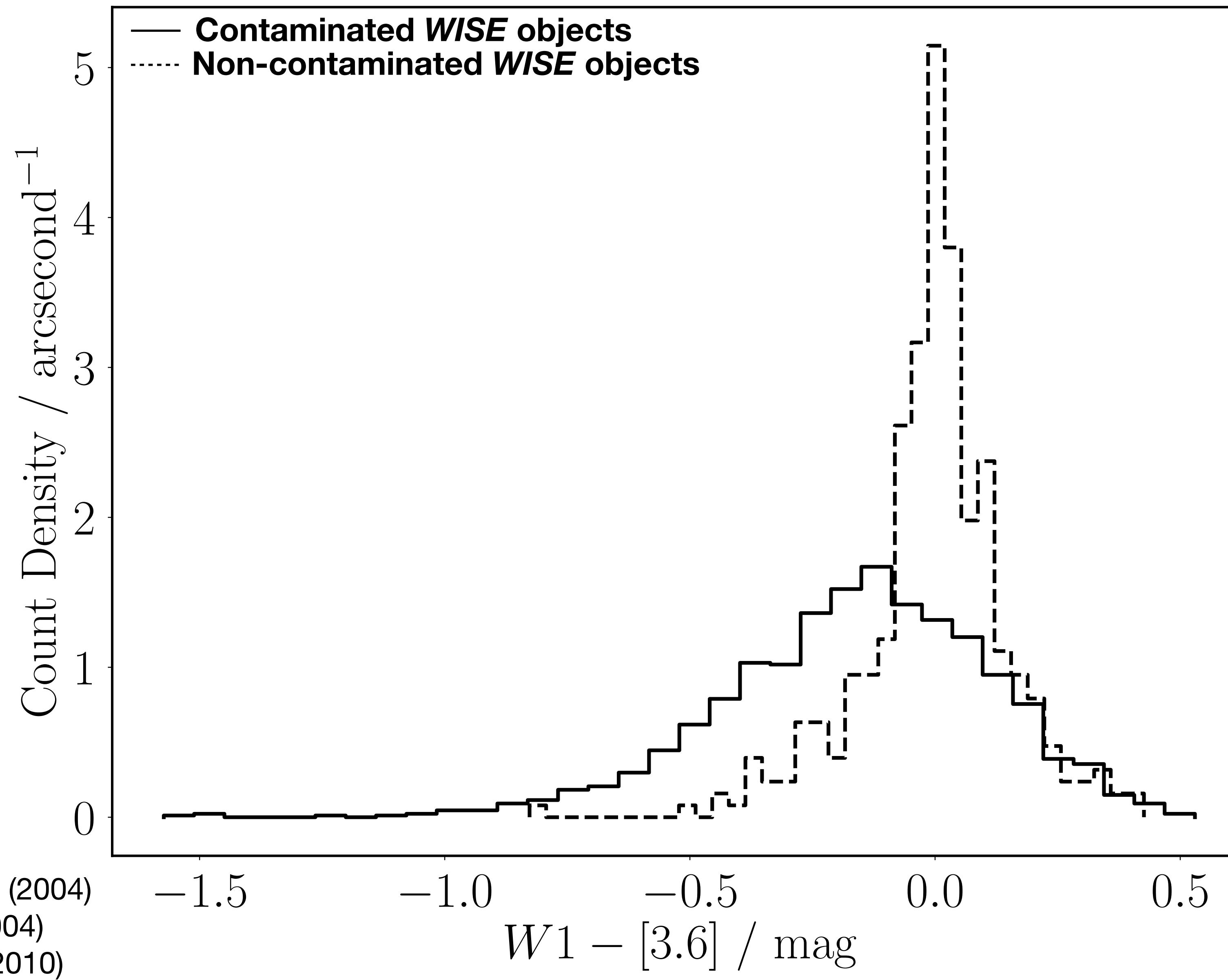
IRAC - Fazio et al. (2004)

WISE - Wright et al. (2010)

Wilson & Naylor (2018b)

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# Resolving Contaminant Flux

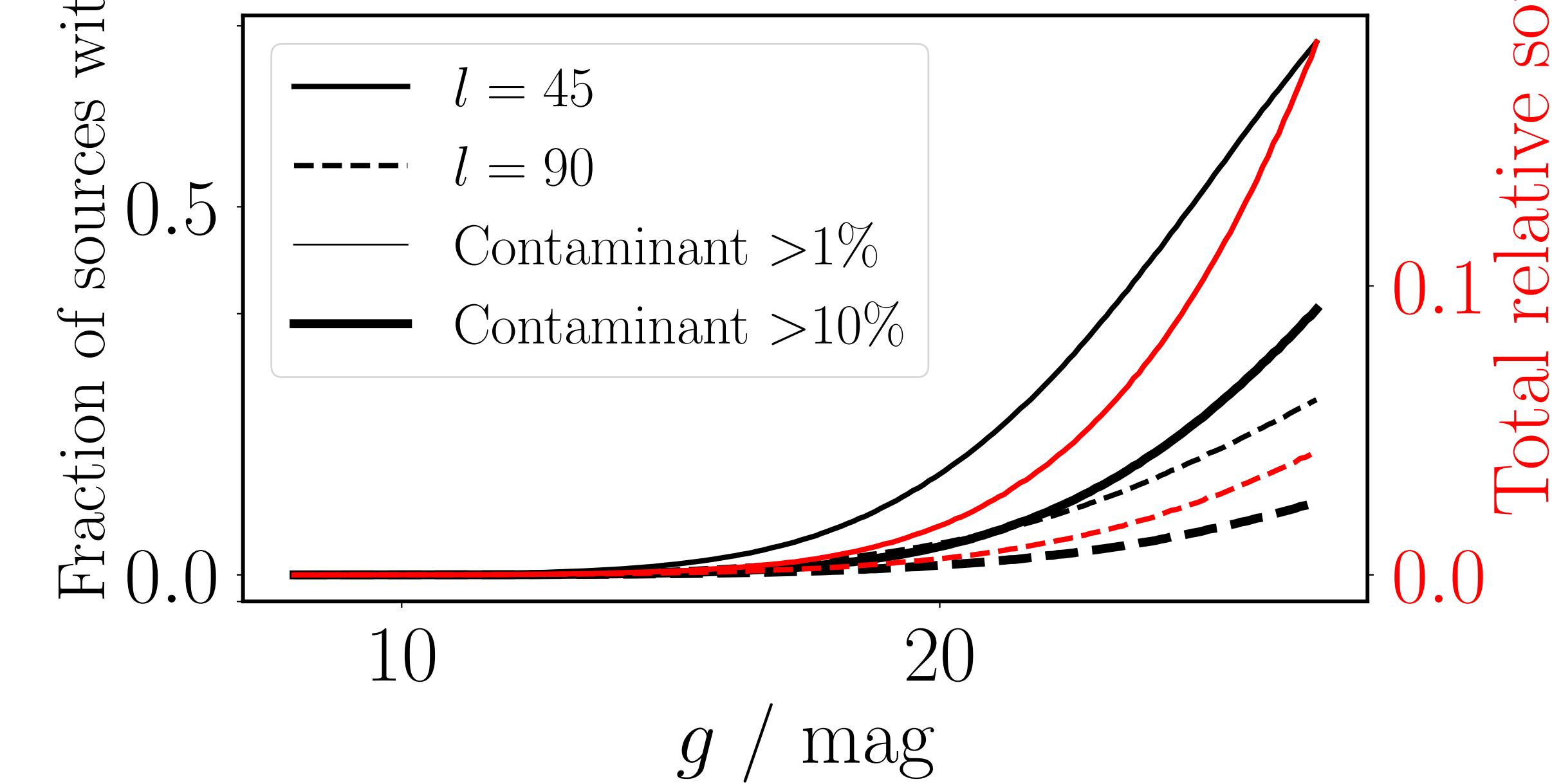
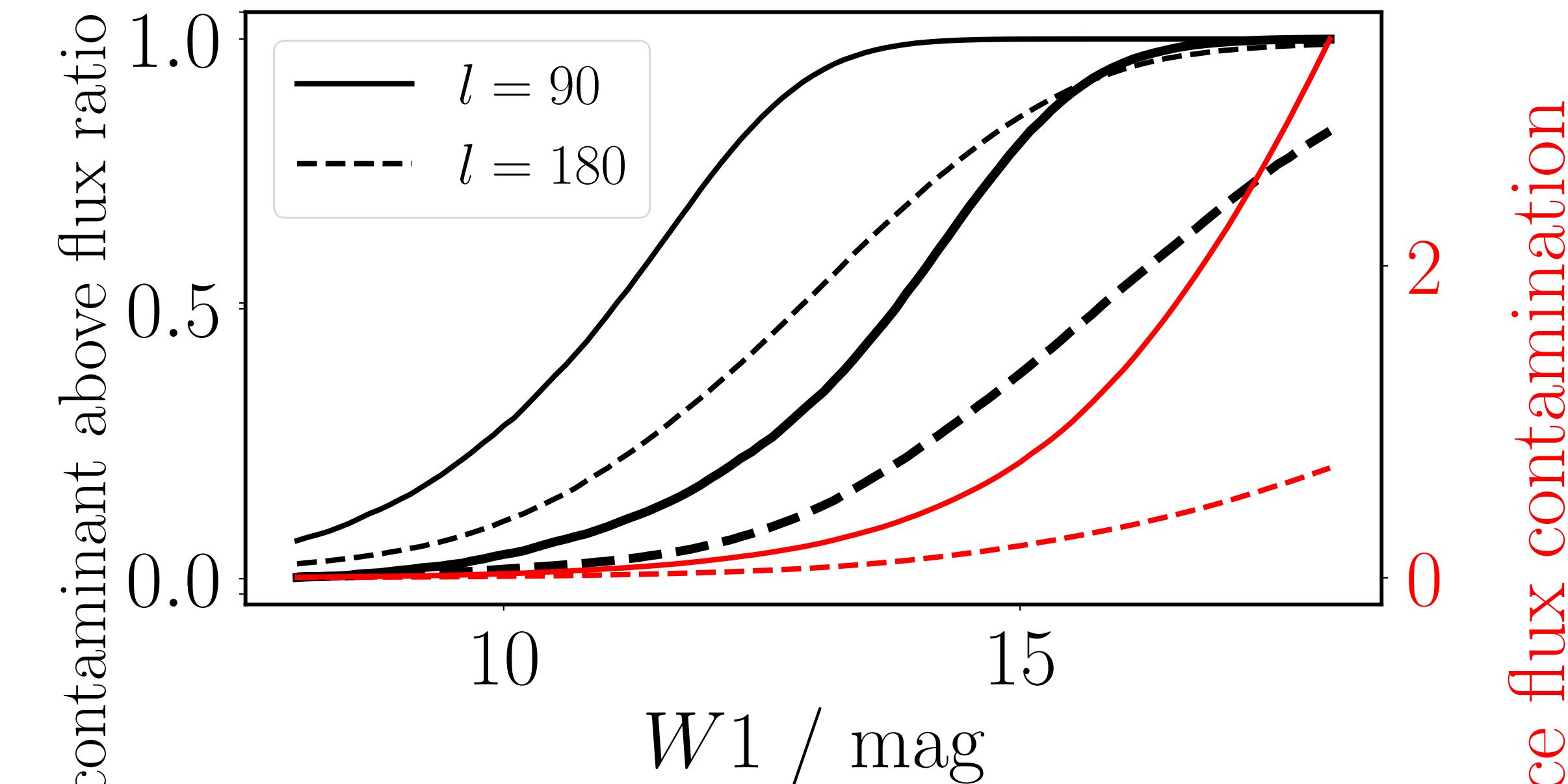
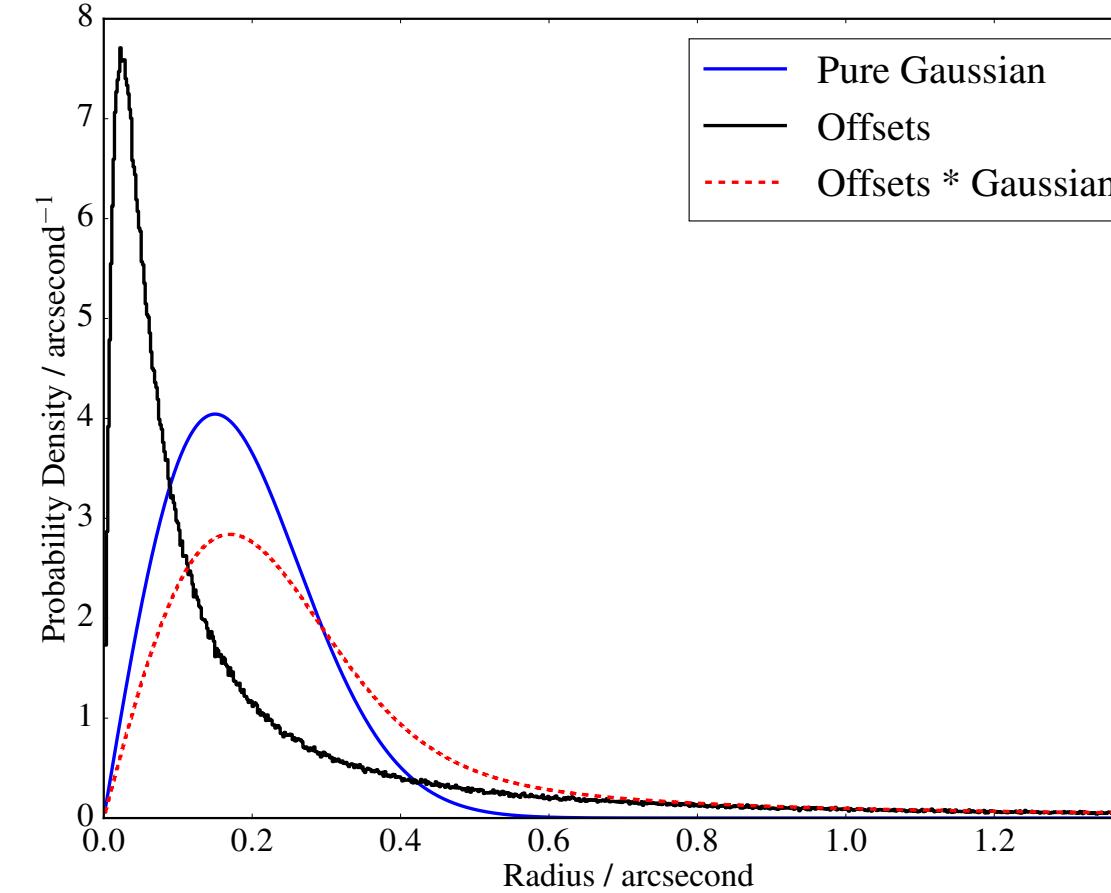


Spitzer - Werner et al. (2004)  
IRAC - Fazio et al. (2004)  
WISE - Wright et al. (2010)  
Wilson & Naylor (2018b)

$W1 - [3.6]$  / mag

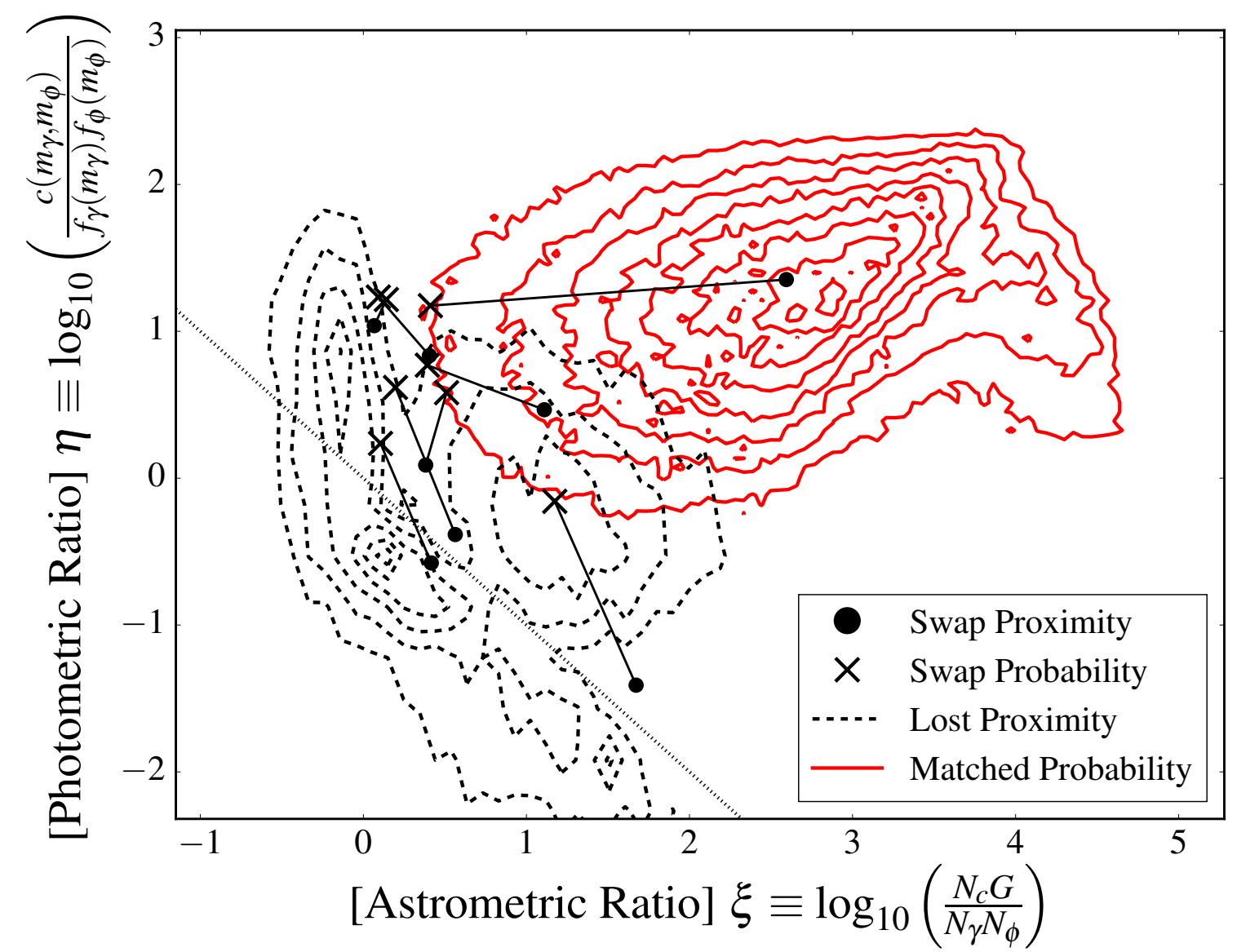
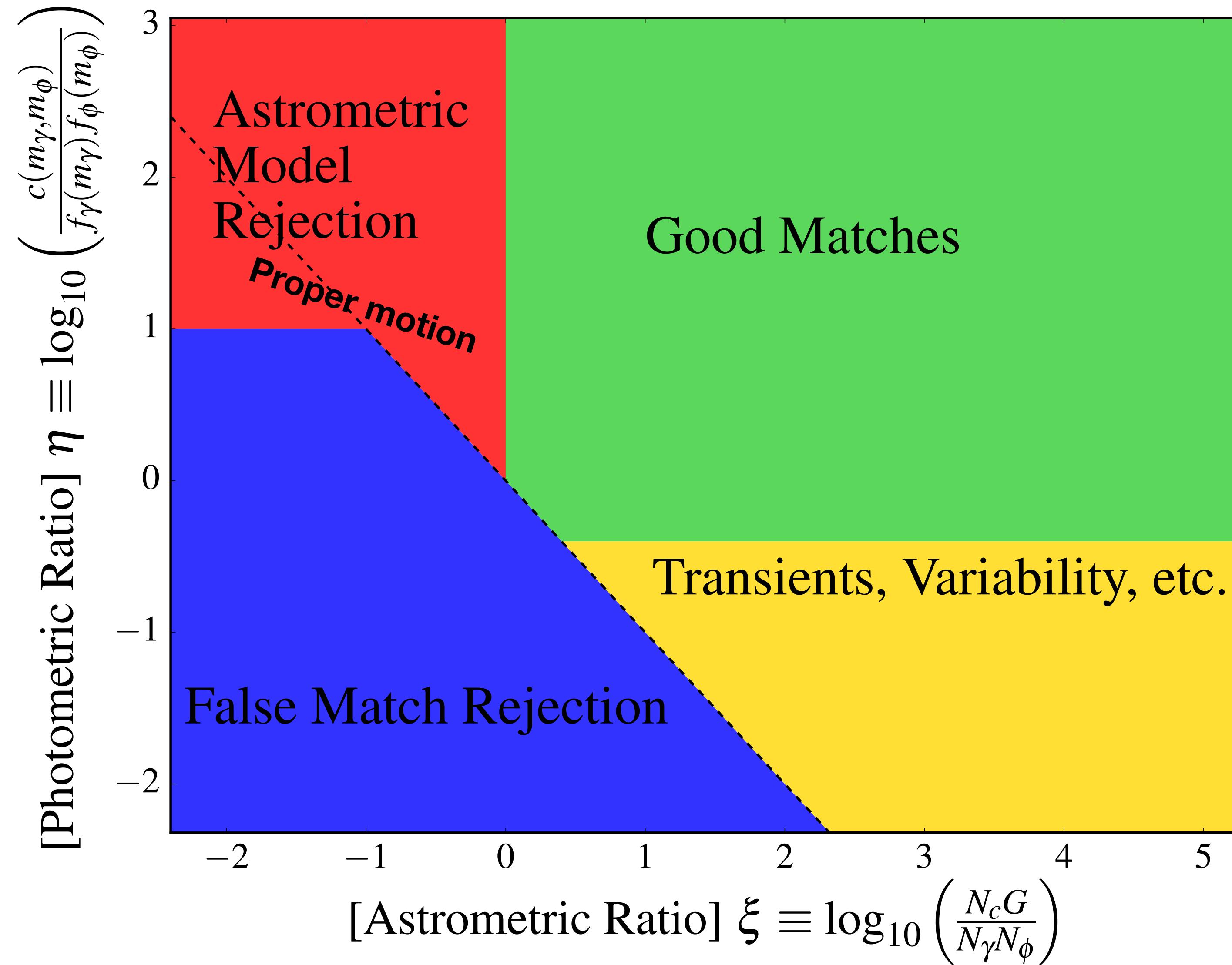
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# Contamination Rates and Amounts



Total relative source flux contamination

# The Likelihood Ratio Space



# Open Source Code: macauff

**Matching Across Catalogues using the Astrometric Uncertainty Function and Flux**



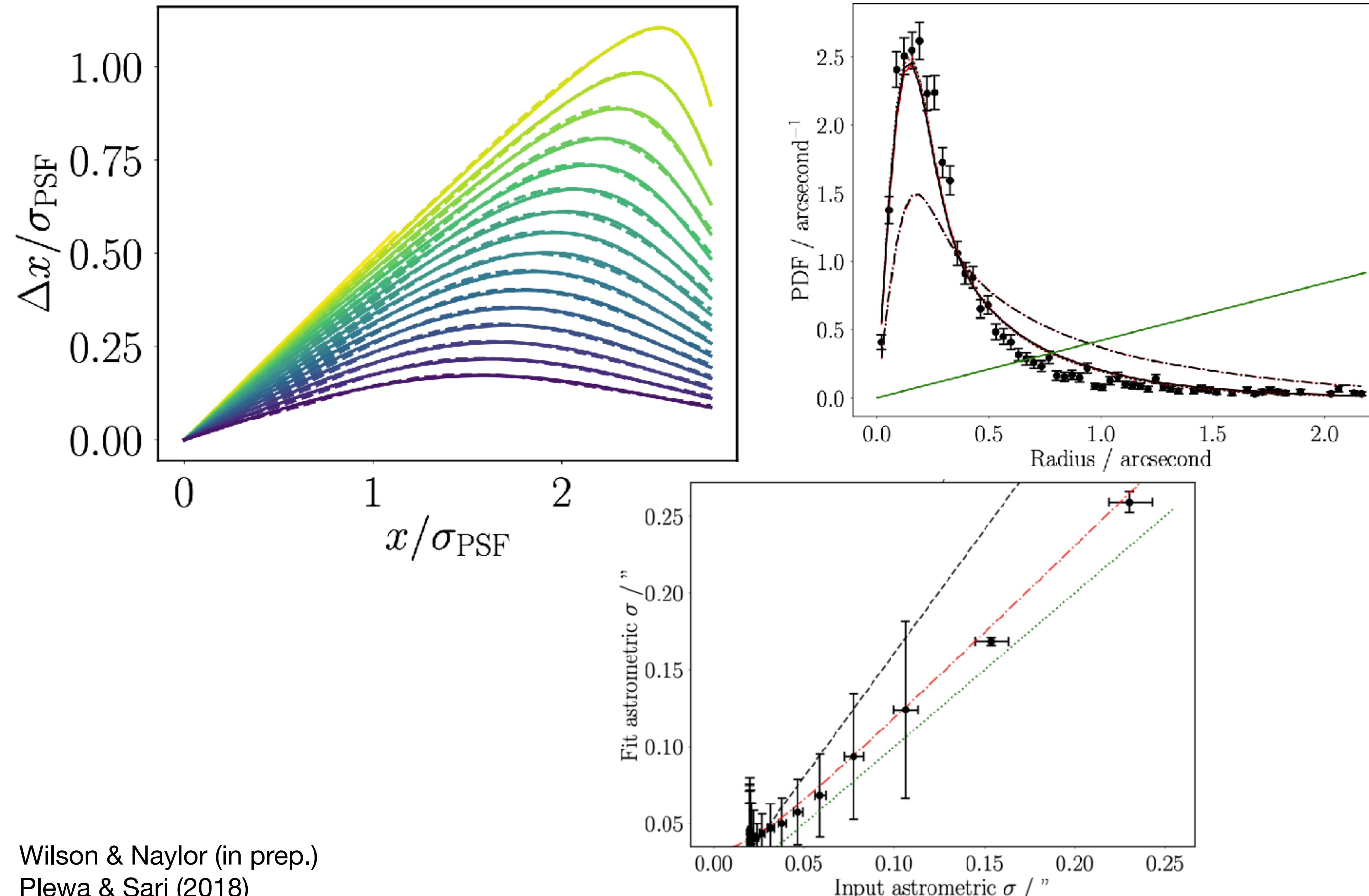
<https://github.com/Onoddil/maauff>



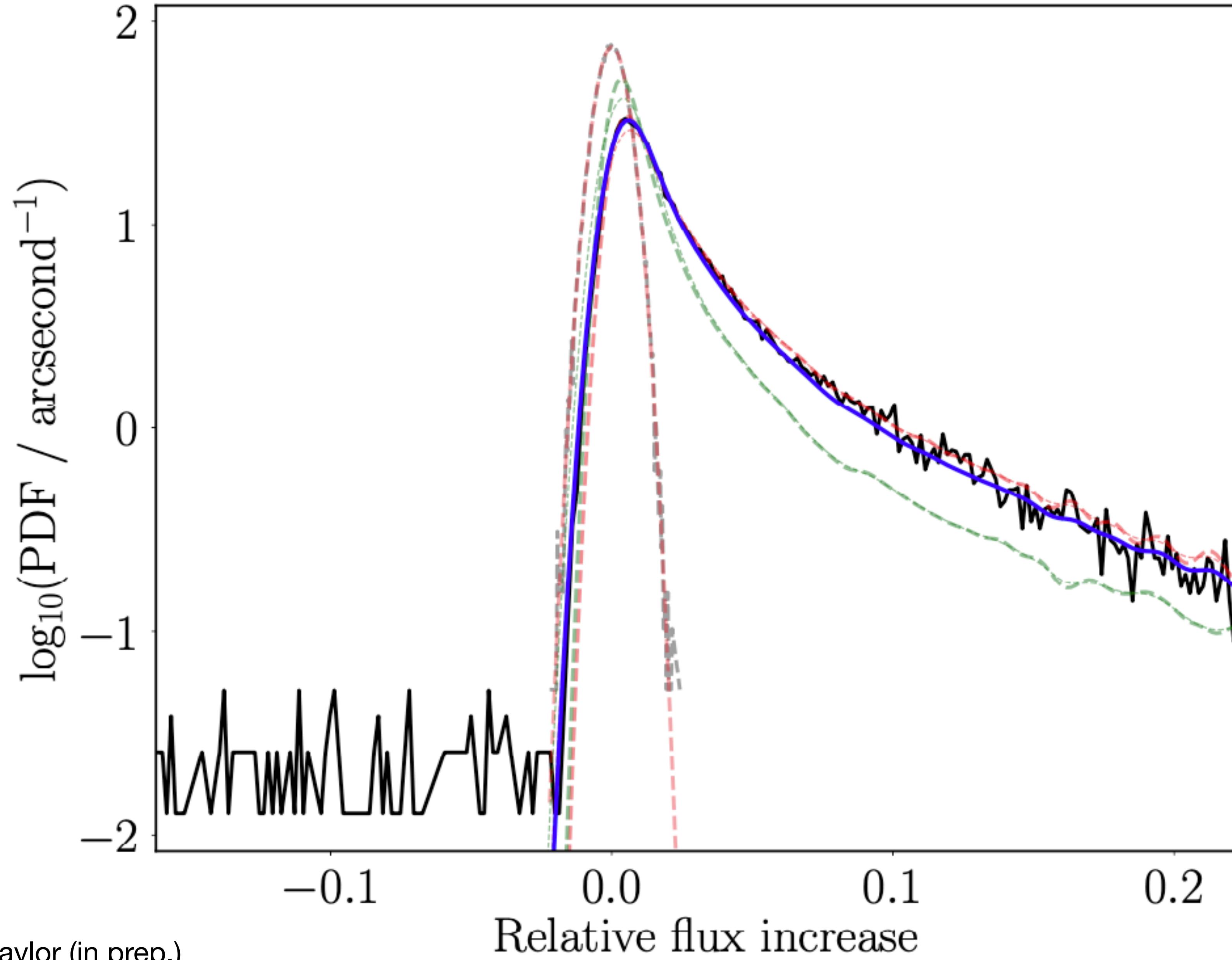
(Points if you know your tartans!)

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# Probing the Faintest Sources

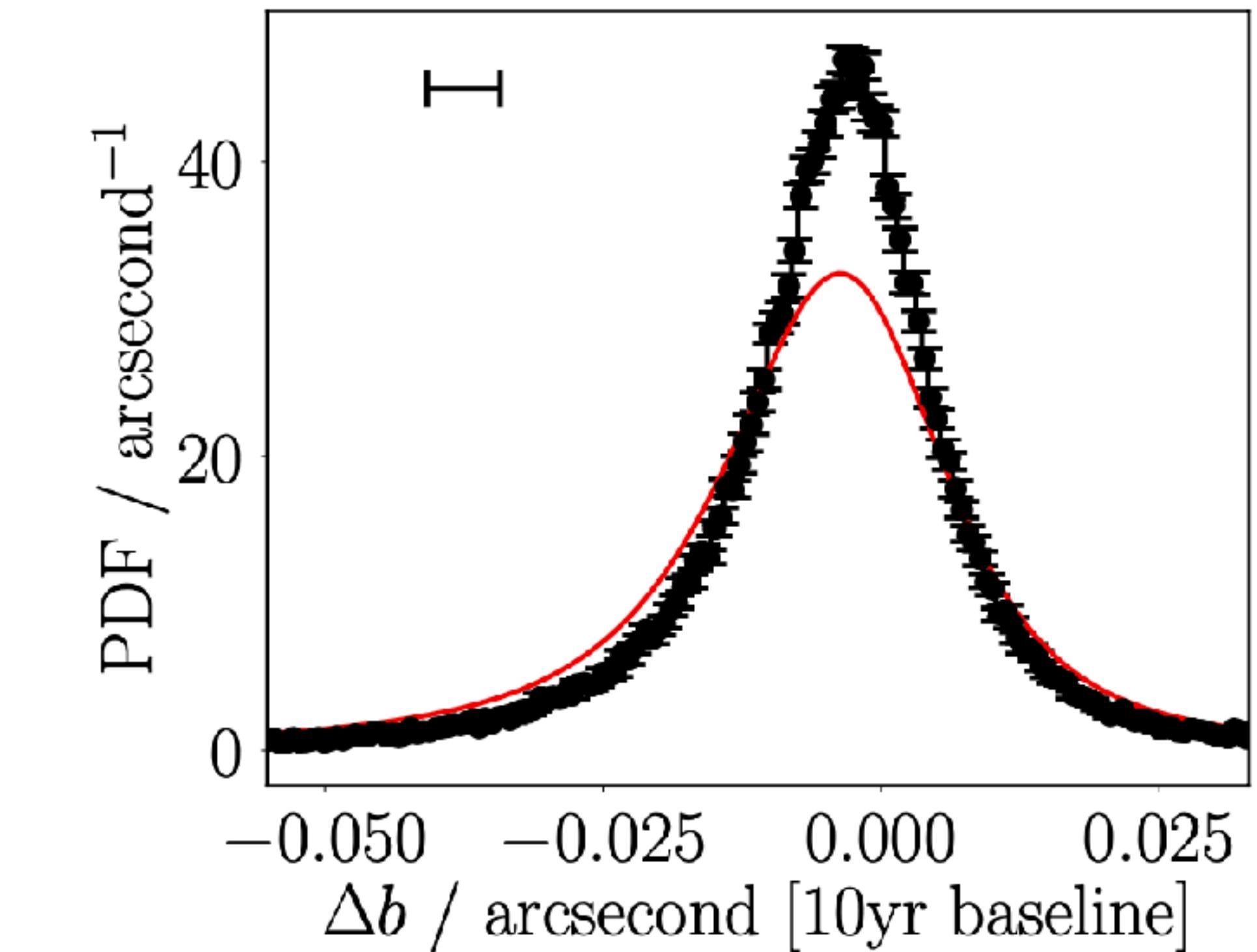
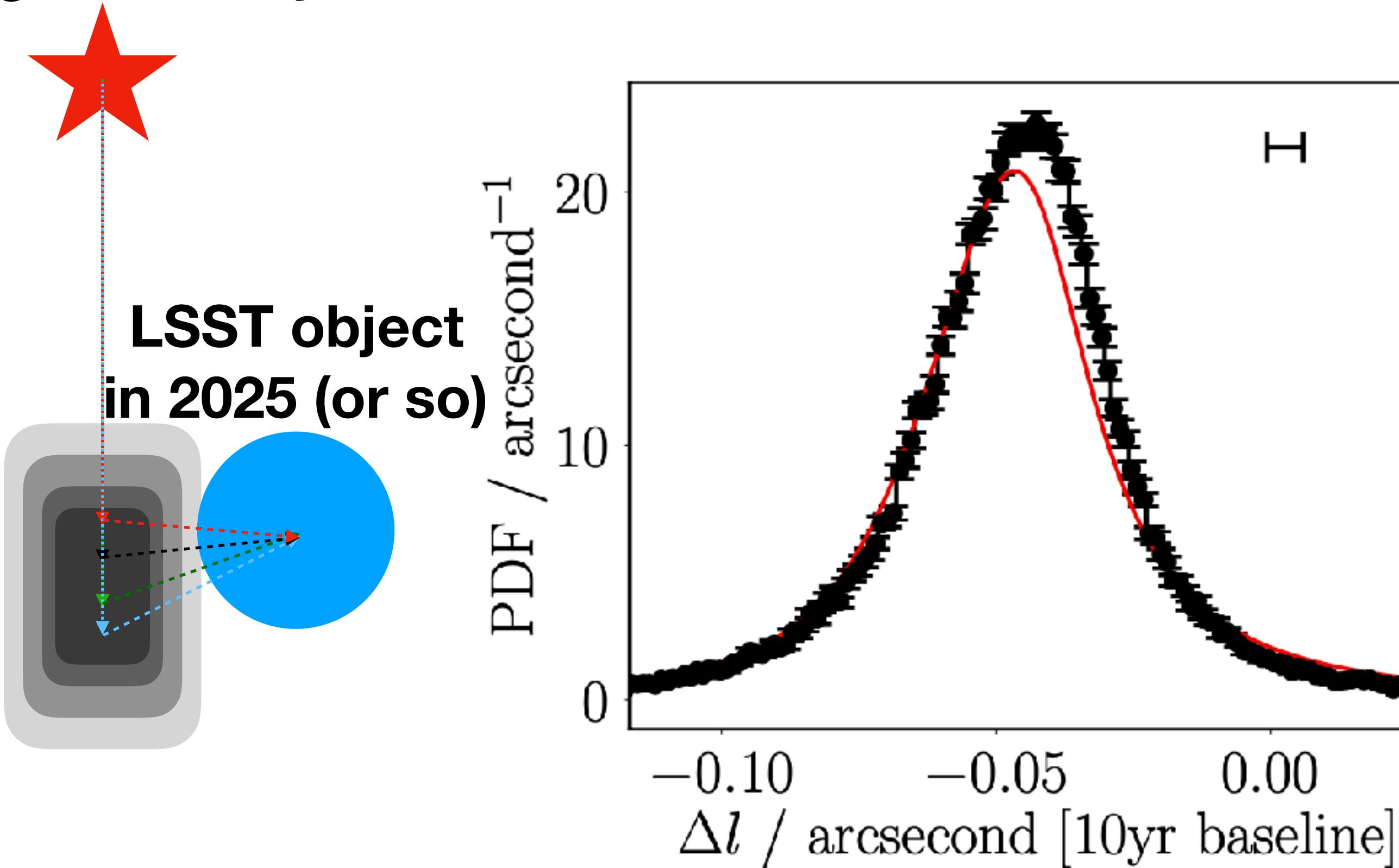


# Photometric Contamination Function



# 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  $G$ .

$$G' = G * h_{\text{pm}}' \quad G = h_\gamma * h_\phi$$
$$h_\gamma = h_{\gamma, \text{centroiding}} * h_{\gamma, \text{perturbation}} * \dots$$

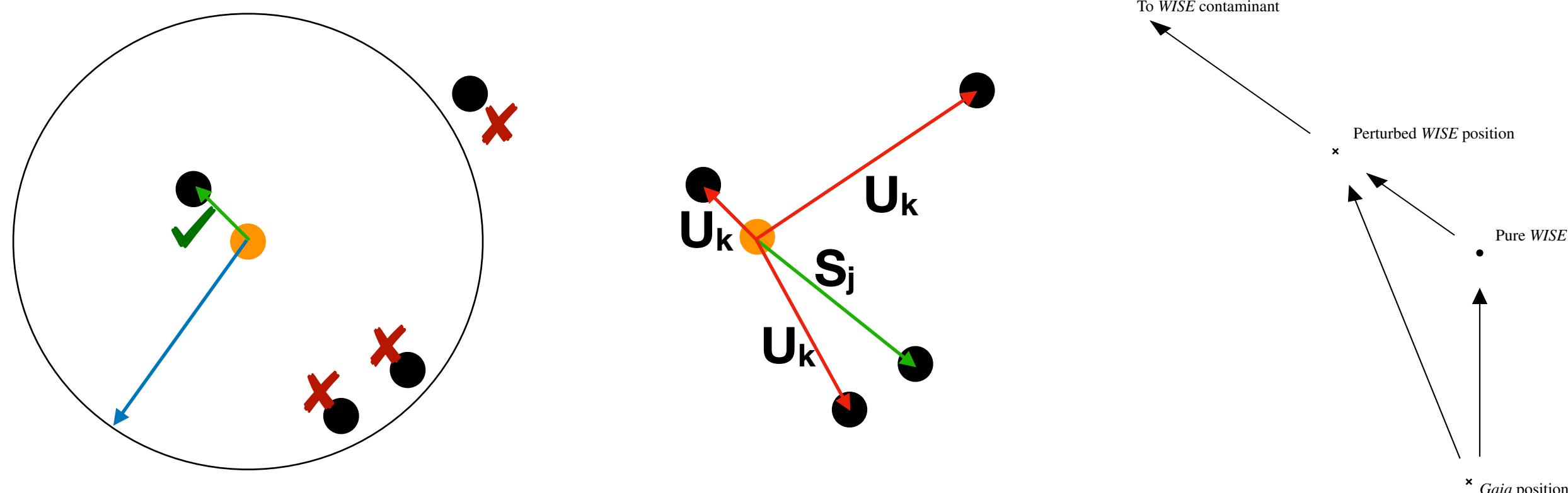
# What does this mean for you?

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

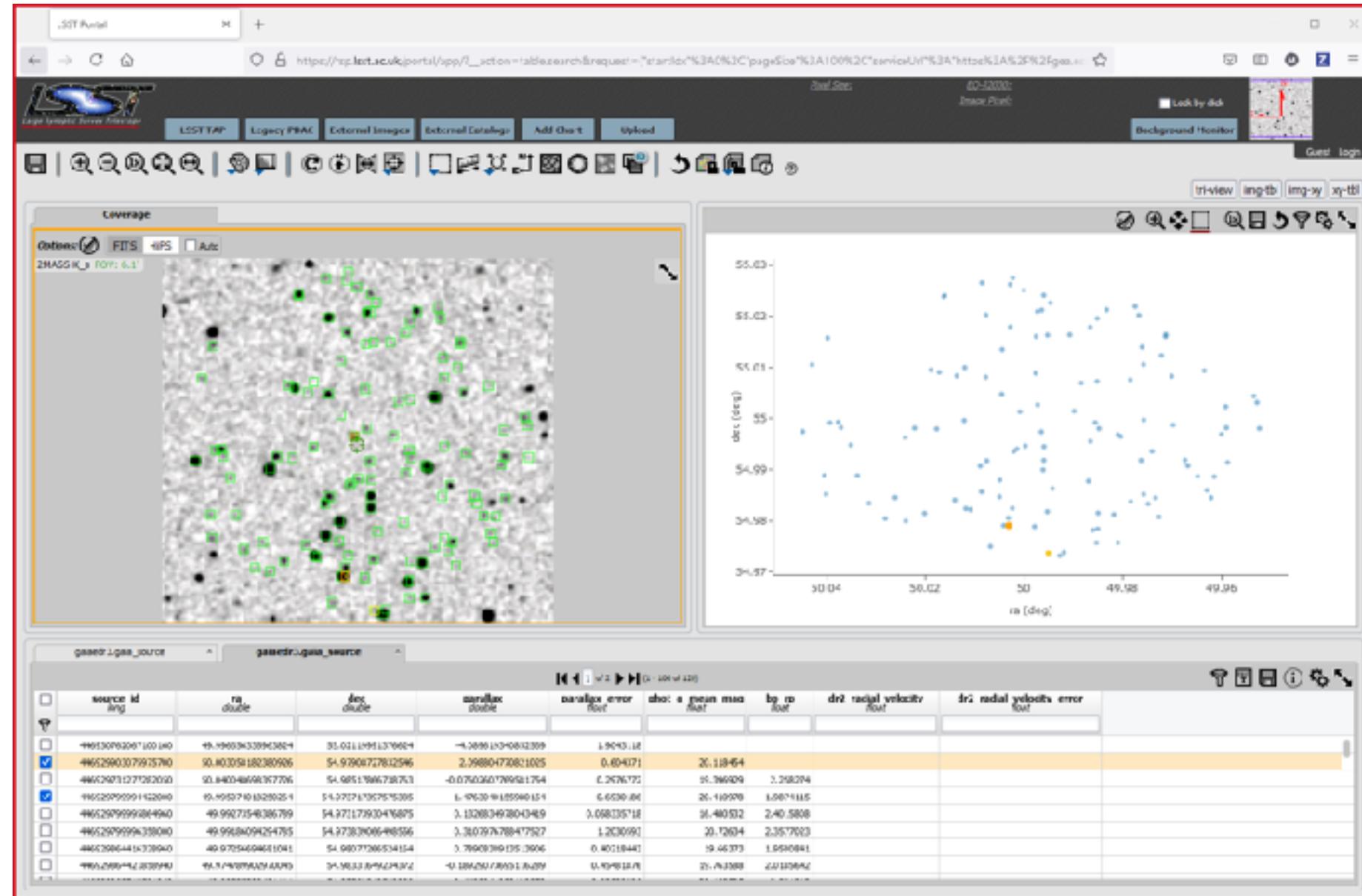
**The “smart” astronomer: uses our cross-matches to get the correct number of matches  
and information on how much flux contamination is affecting their object!**



you downloading your favourite  
cross-matches, probably

# 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

# 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

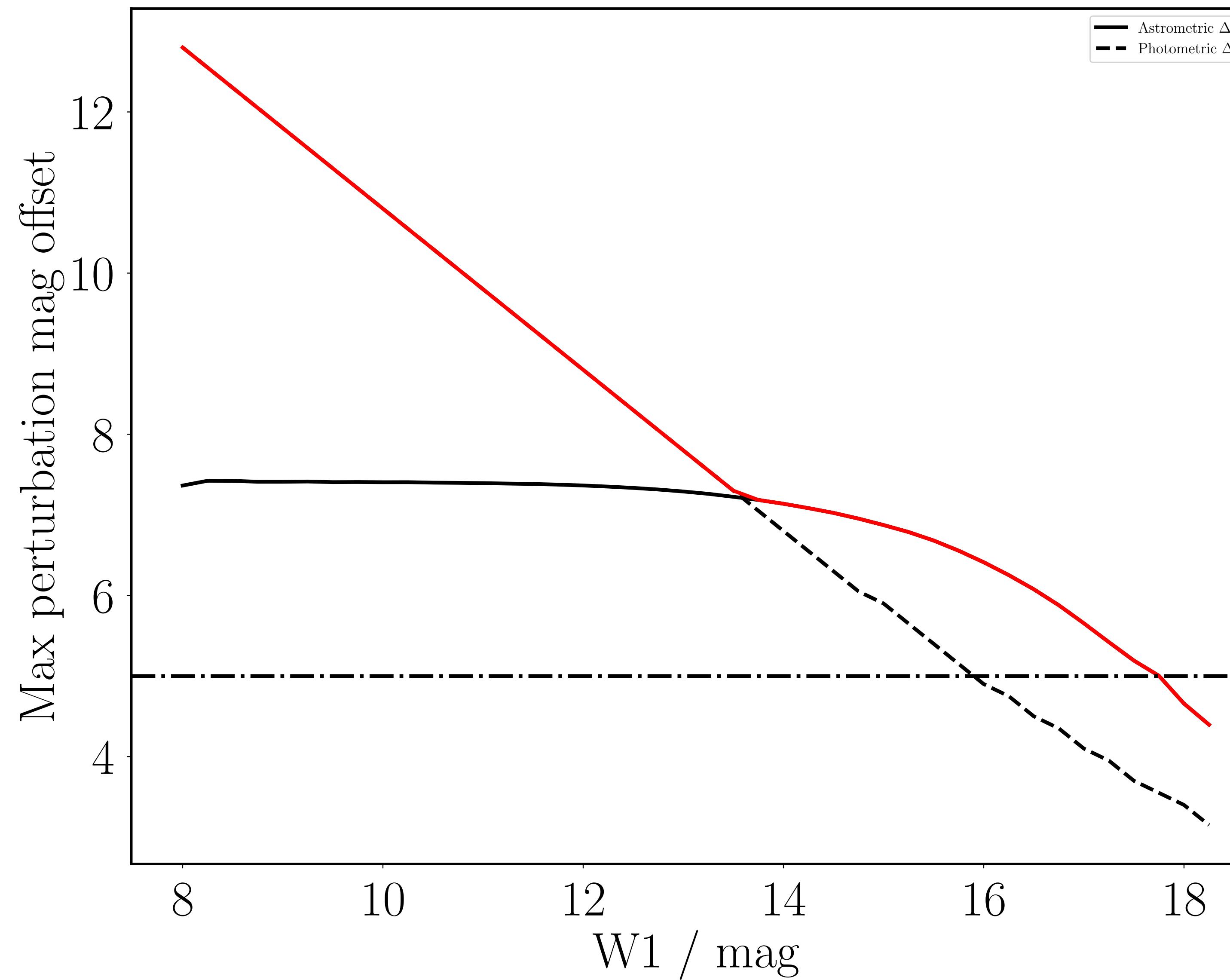
Wilson (2022, RNAAS)

Wilson (2022, RASTI, in review)

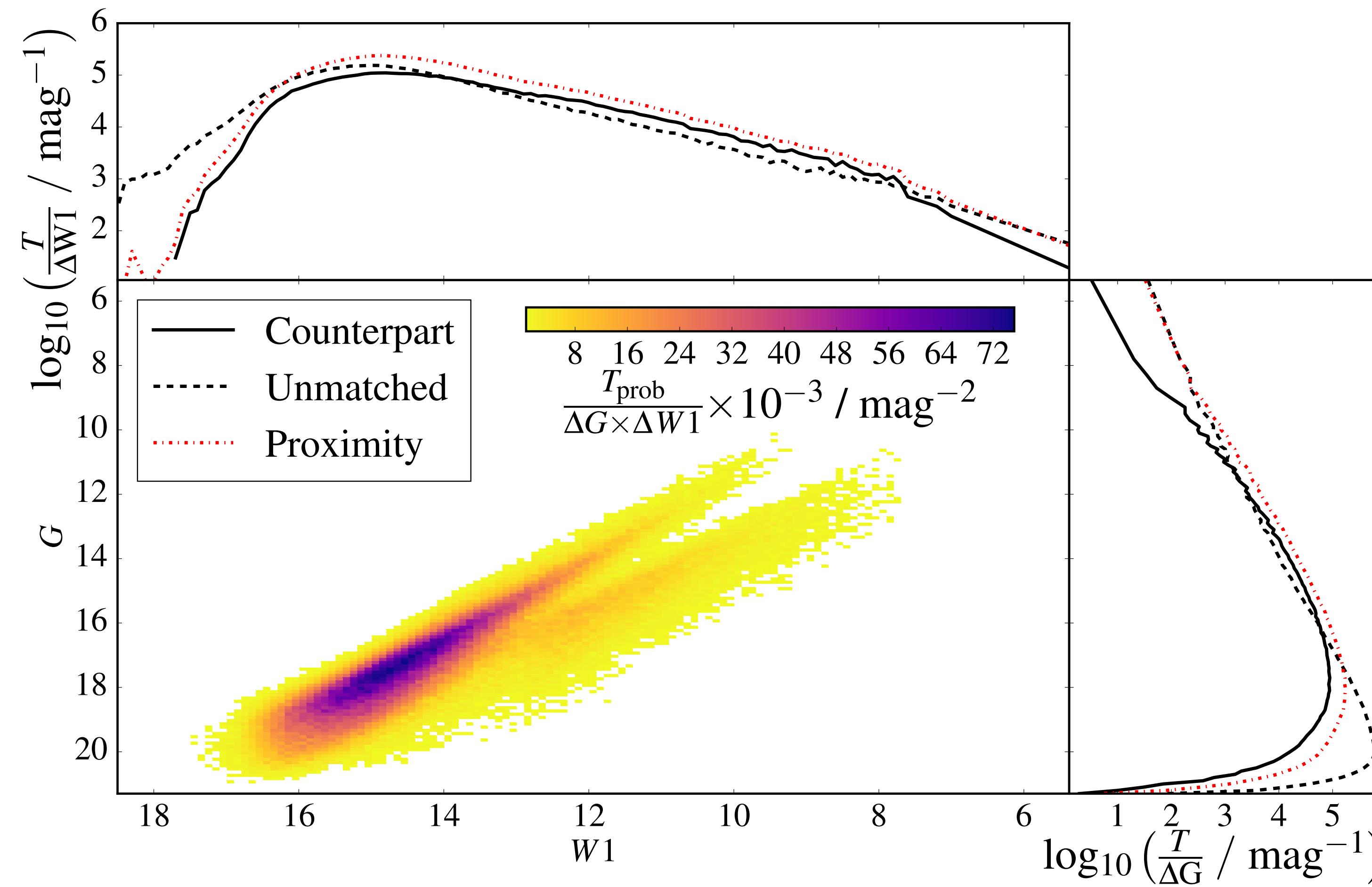
<https://github.com/Onoddil/macauff>



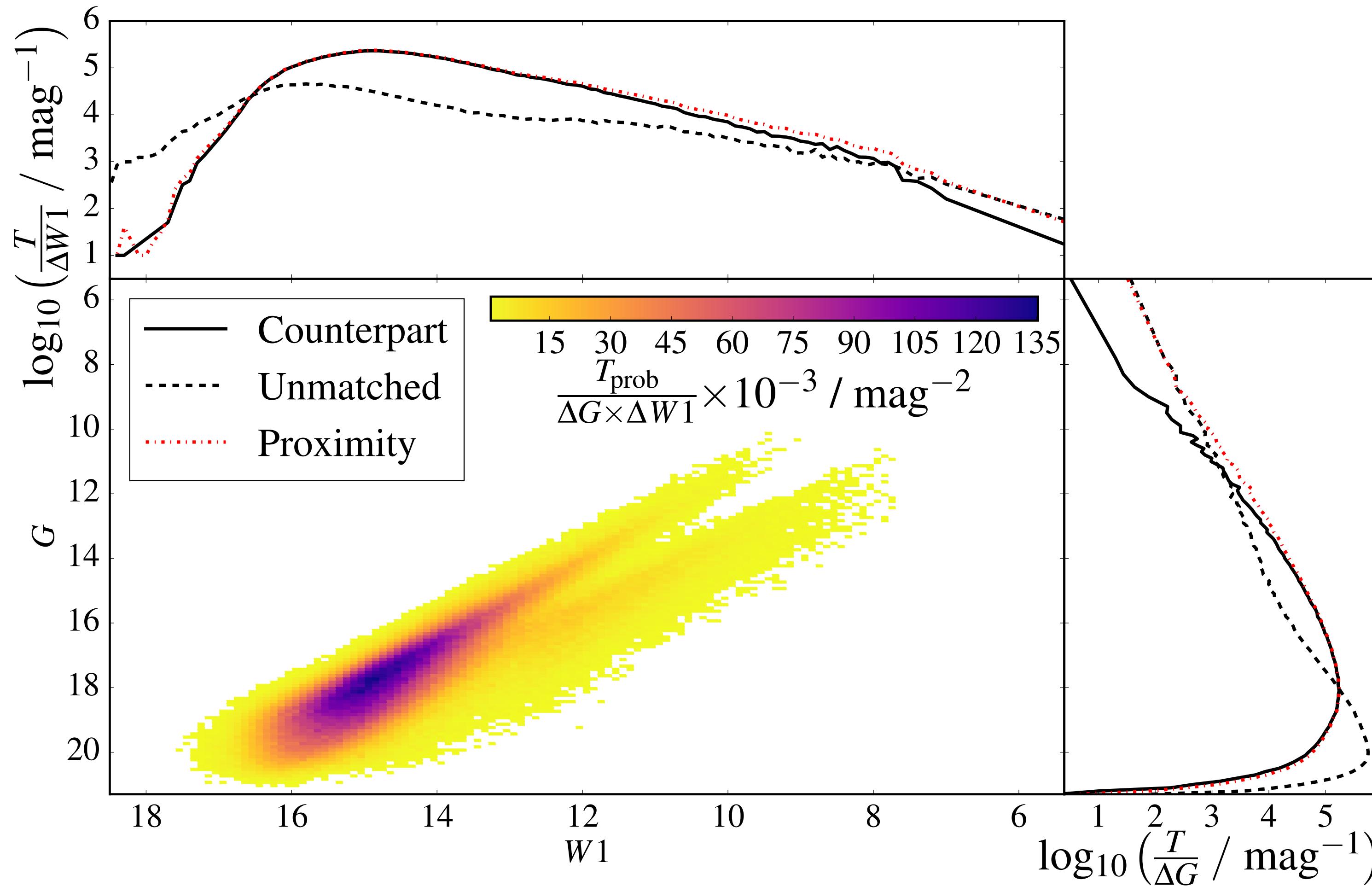
# The Astrometric Uncertainty Function and LSST: A Crisis of Completeness Limit



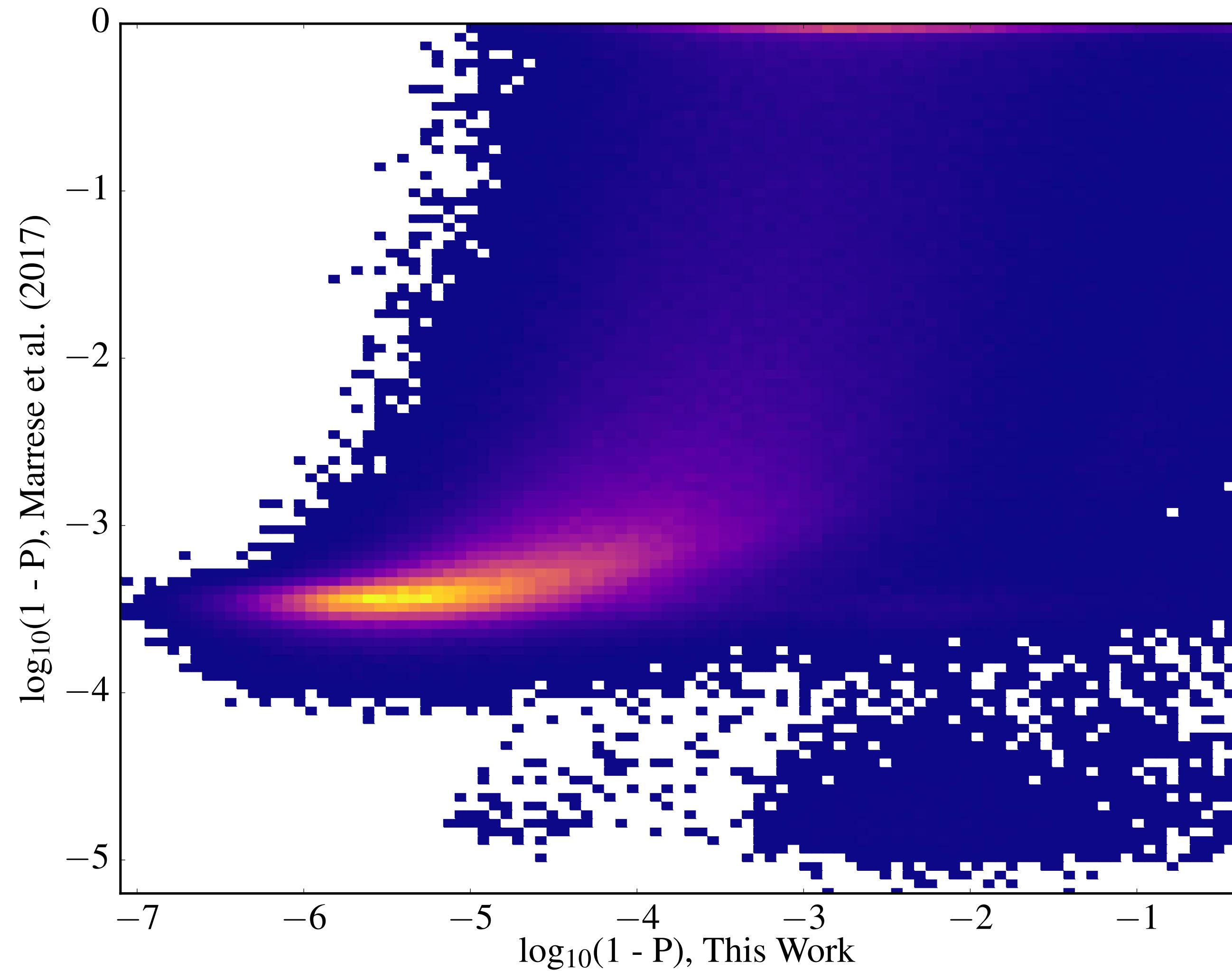
# Contamination Effects: Gaia-WISE Gaussian Matches



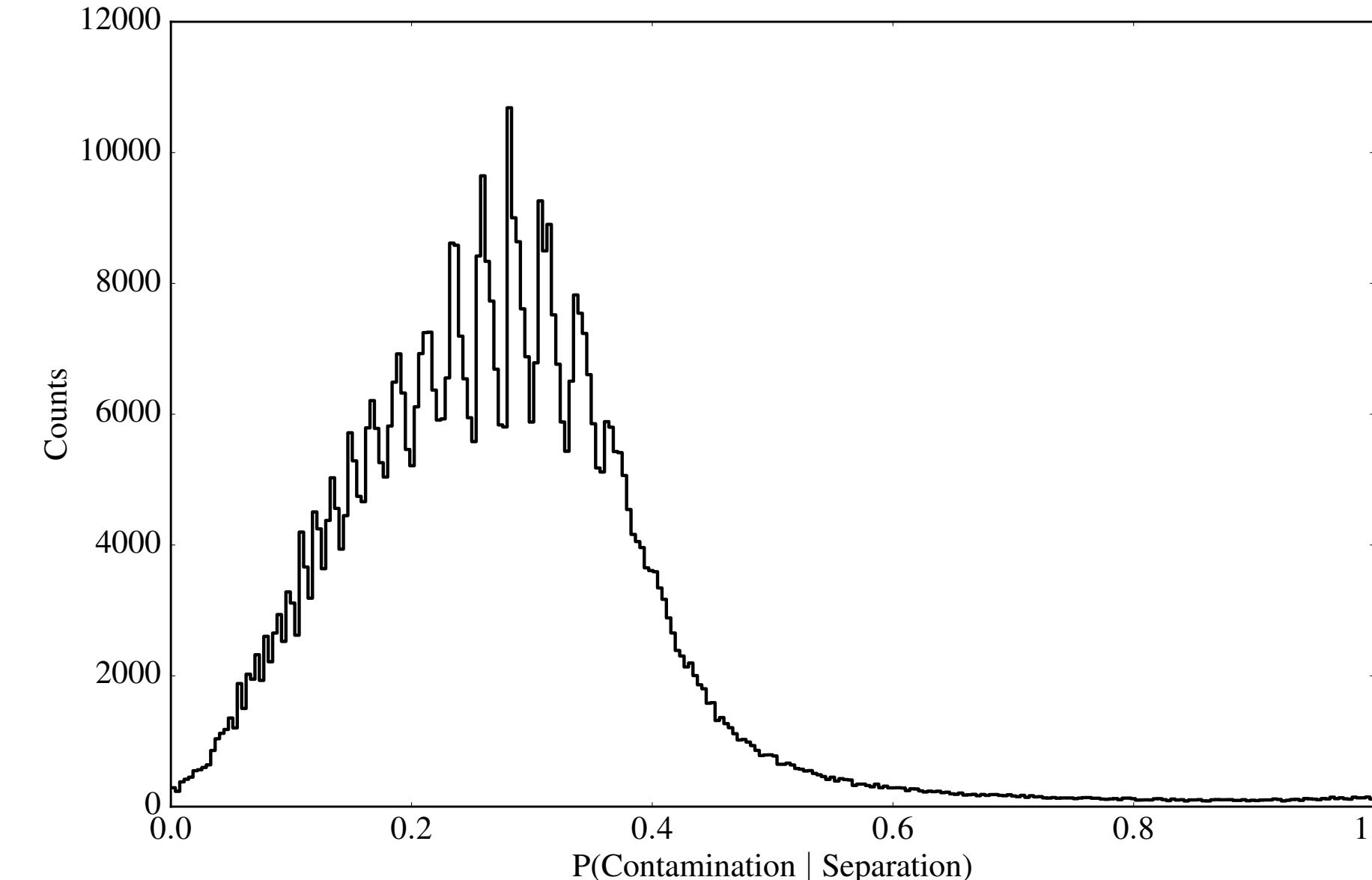
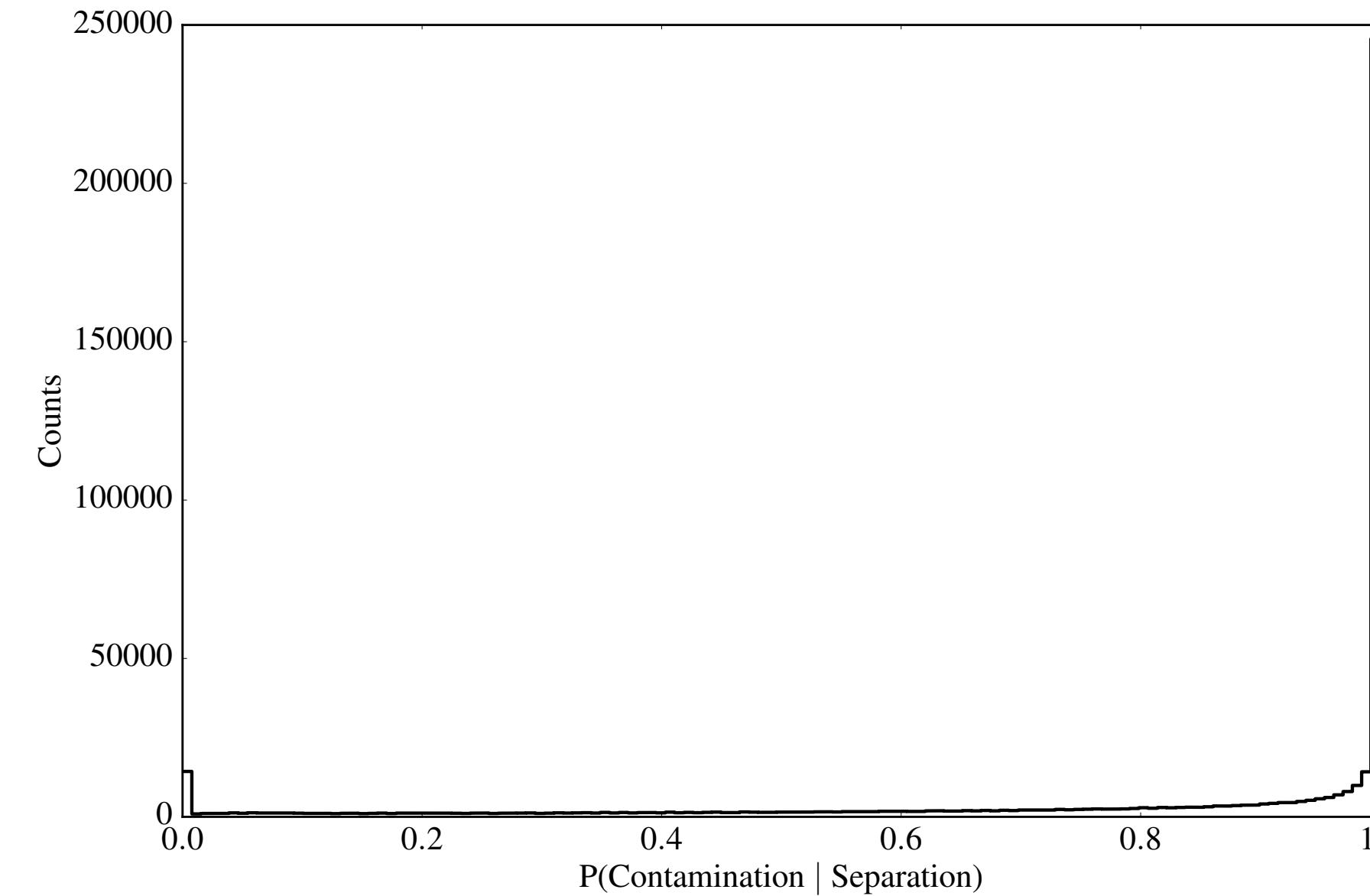
# Contamination Effects: Gaia-WISE Empirical Matches



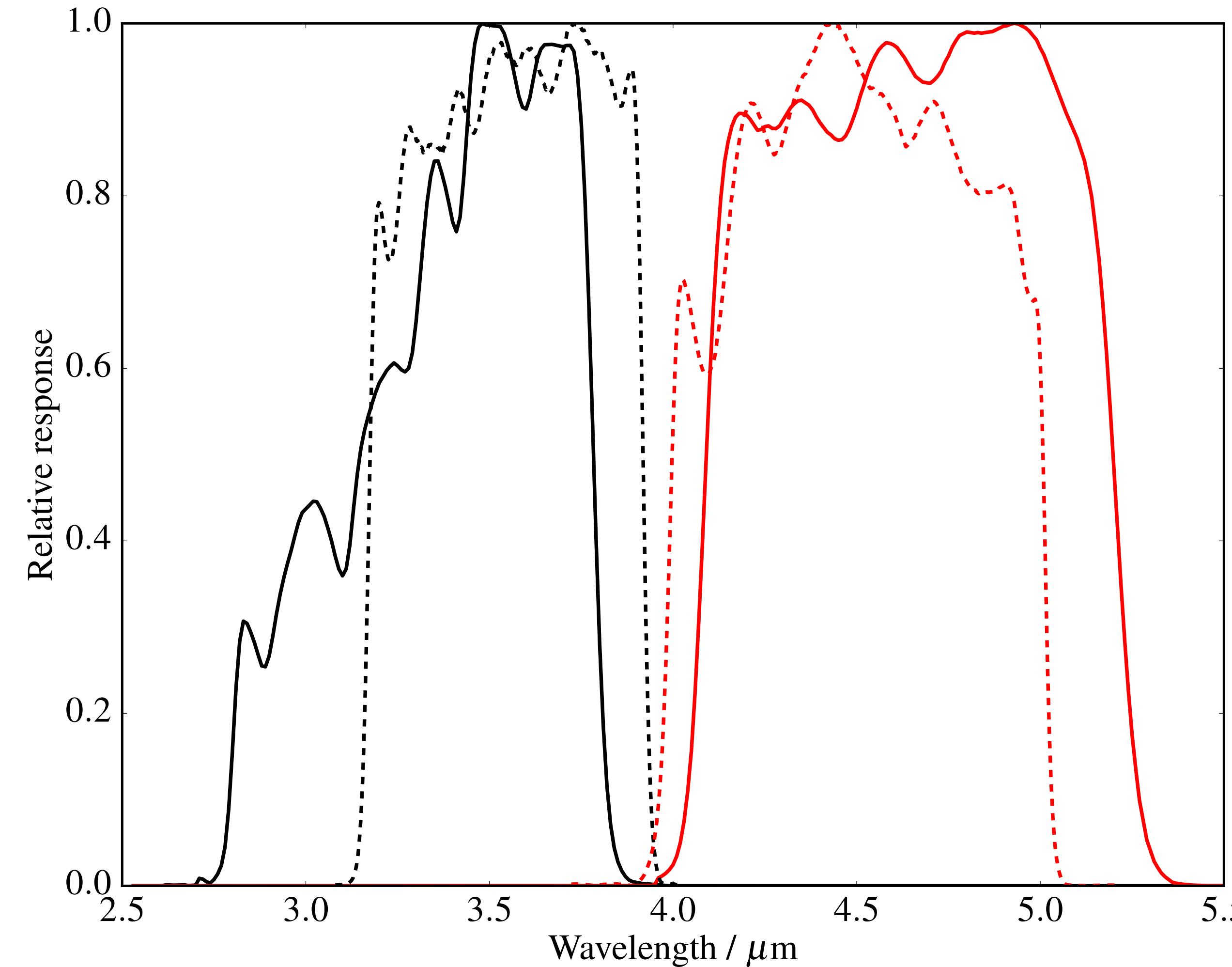
# Contamination Effects: Gaia Lost Matches



# Photometric Contamination: WISE/Spitzer Contamination %



# Contamination Effects: Wavelength Coverage



# The Astrometric Uncertainty Function: Analytical perturbations

