Rubin Observatory

“Compensated Filters”

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Thanks to Nate Lust, Robert Lupton

SLAC

July 27th, 2022

What are we measuring?

Rubin Observatory

- We need to have reliable stellar fluxes in order to compute accurate and precise photometric calibrations.
  - The flux estimator need not measure the *total flux* (to infinity)
    - It can measure something that scales with total flux
  - The flux estimator should measure the same fraction of the total flux independent of flux level
  - The flux estimator should have as low noise as is possible, given these constraints.
    - More signal-to-noise please!
  - The flux estimator may vary over the detector/focal plane from the “truth”, but should vary *slowly*.

What is the problem?

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- The standard flux estimator for doing photometric calibration is a large circular aperture.
  - We use 12 pixel radius as the default (that’s big!)
  - I will call this the “Top-hat filter” because it is circular, high and flat in the middle, and low around that.
- This has some significant drawbacks…

Top-hat apertures in sims

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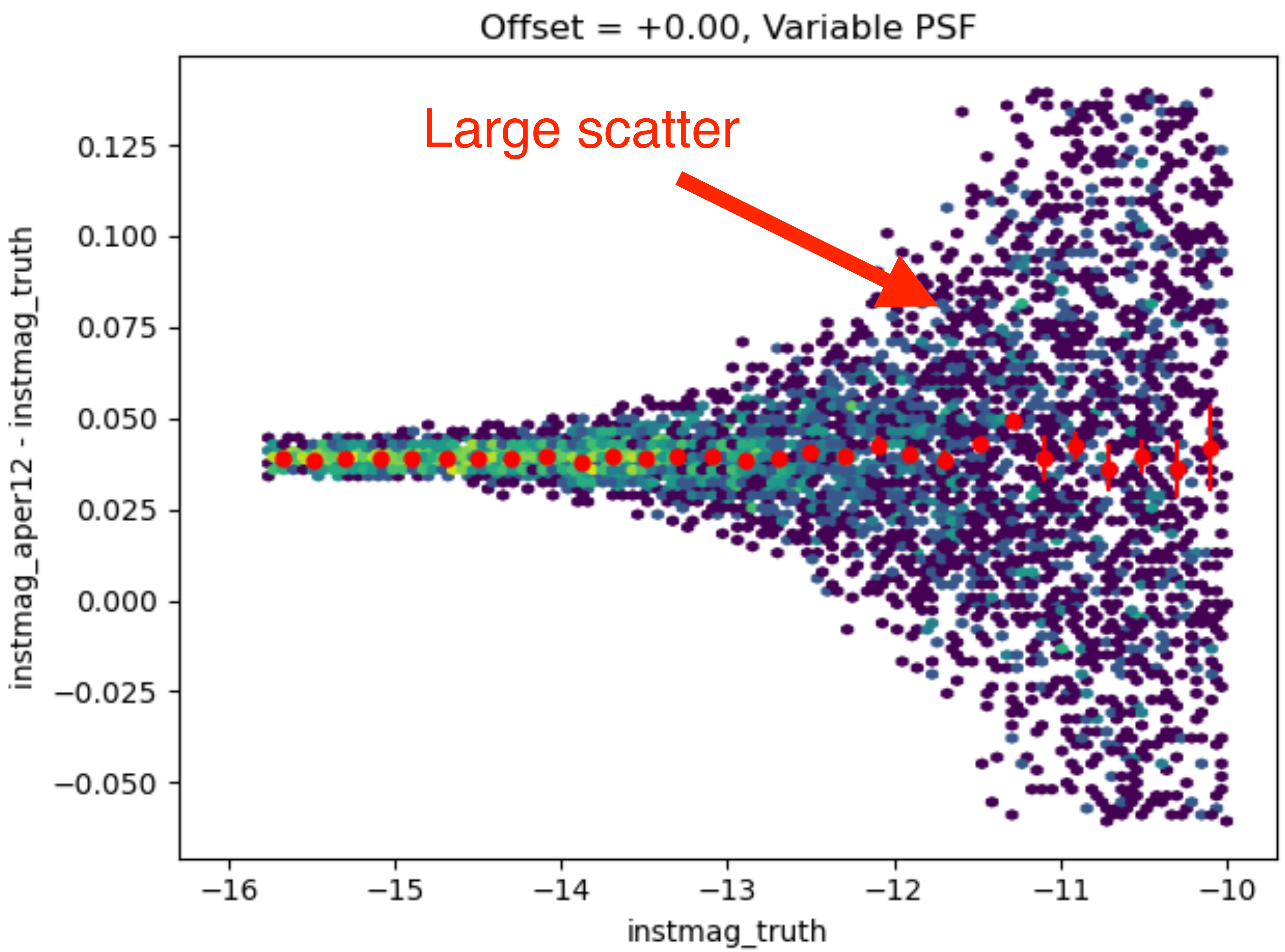
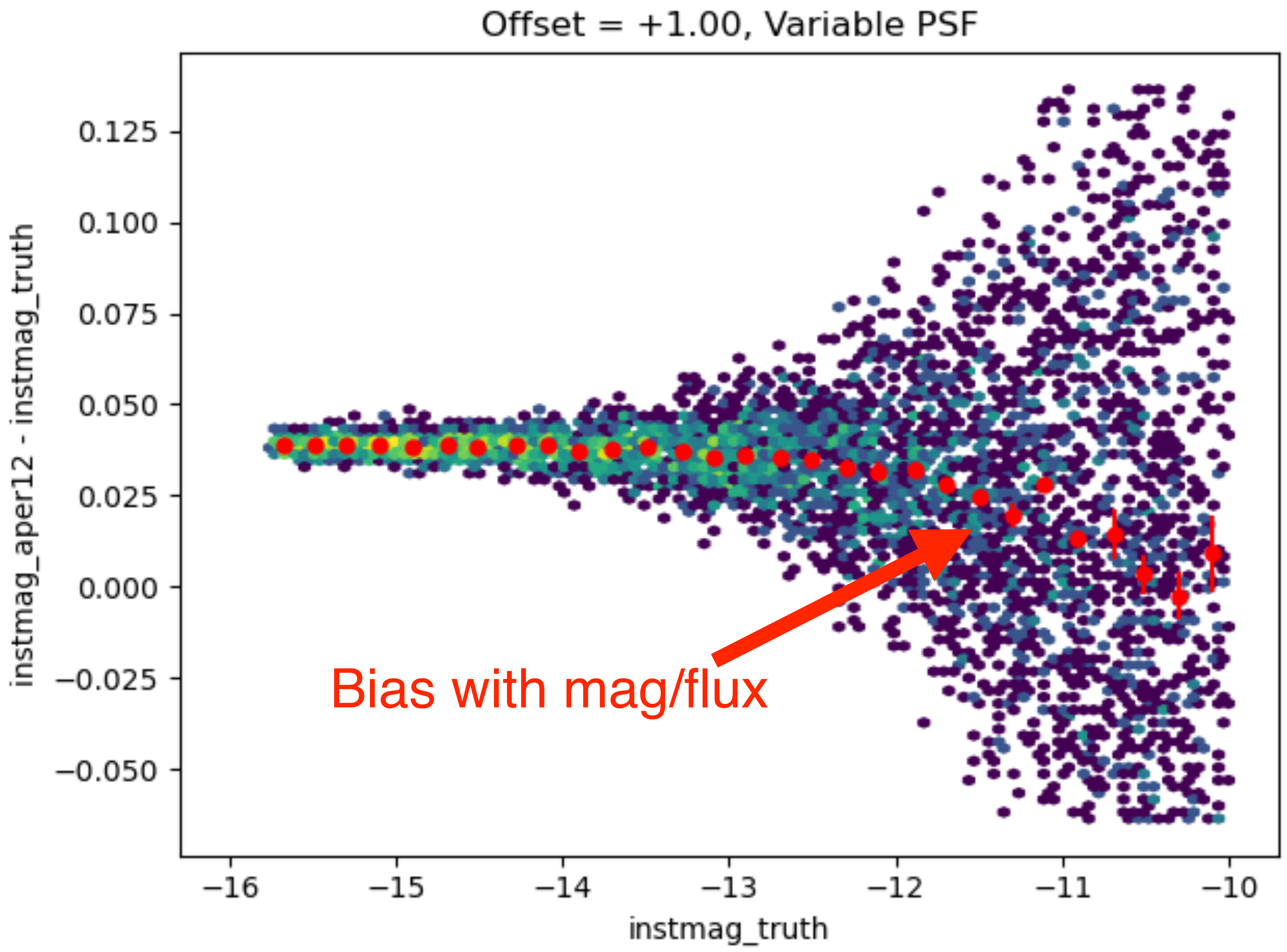
- Run a grid of realistic PSFs with galsim and run aperture measurement.
- Compare aperture mags with true mags.





Top-hat apertures in HSC data

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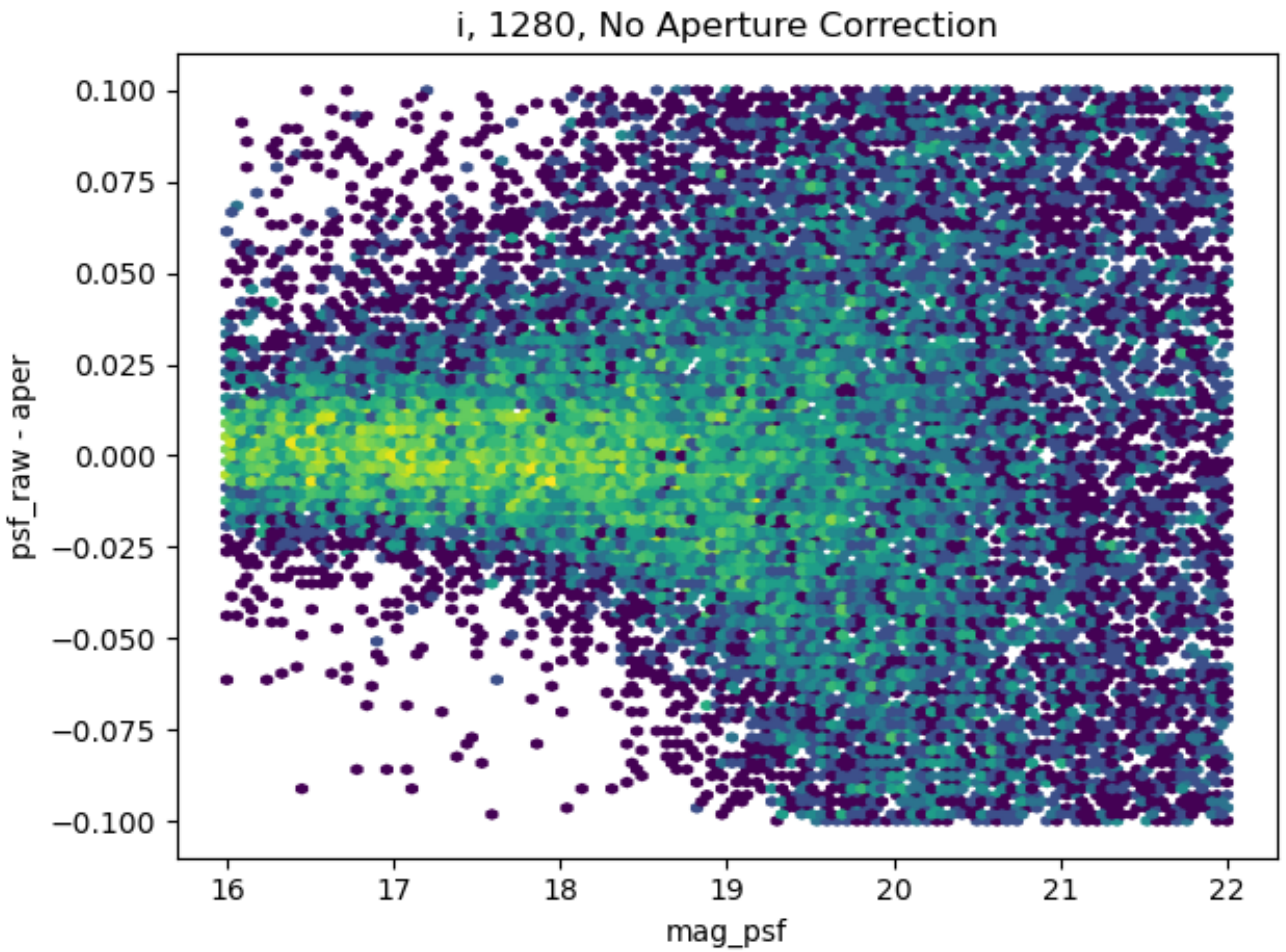
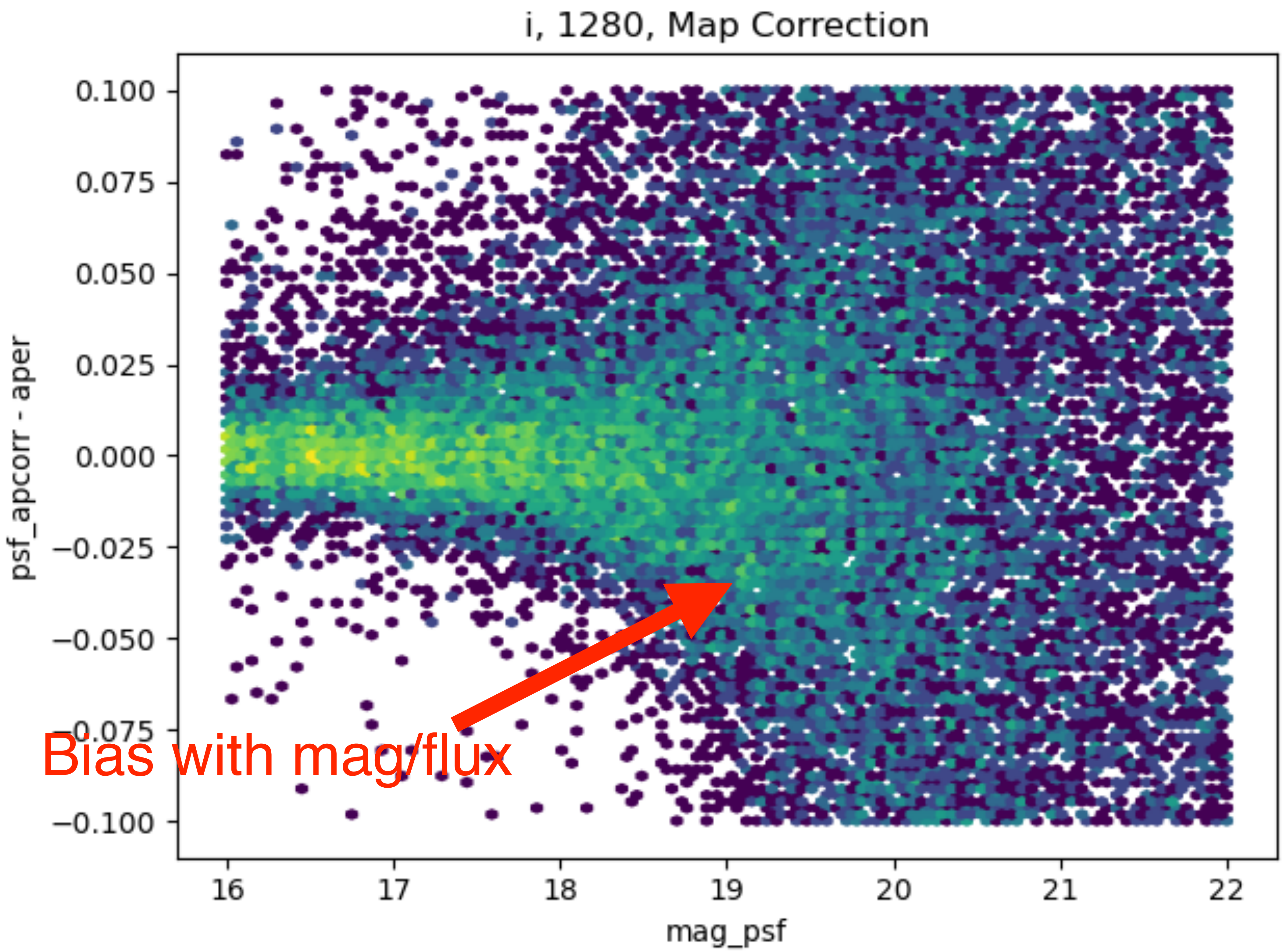
- These biases aren’t theoretical!
- Lauren’s favorite RC2 i-band visit 1280. Full focal plane



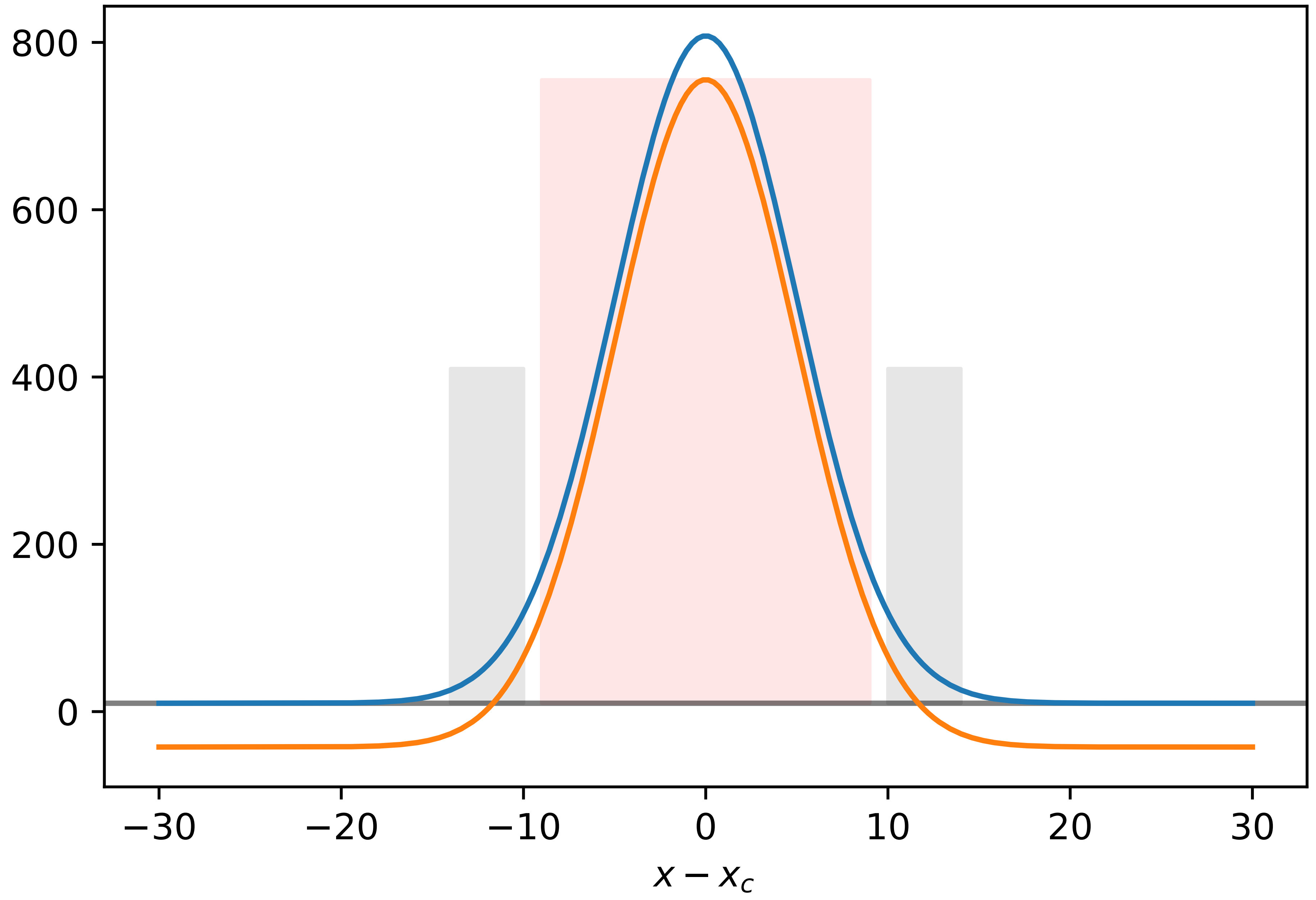


Bring On the Compensated Filters!

- See Robert's talk from January 2021 (!)
  - Nate L. has done great work implementing an initial version of this on DM-32994.
  - I'm finally putting a bunch of it together.

$$S = \frac{1}{\pi(R_2^2 - R_1^2)} \int_{R_1}^{R_2} I(\boldsymbol{x}) 2\pi r \, dr$$

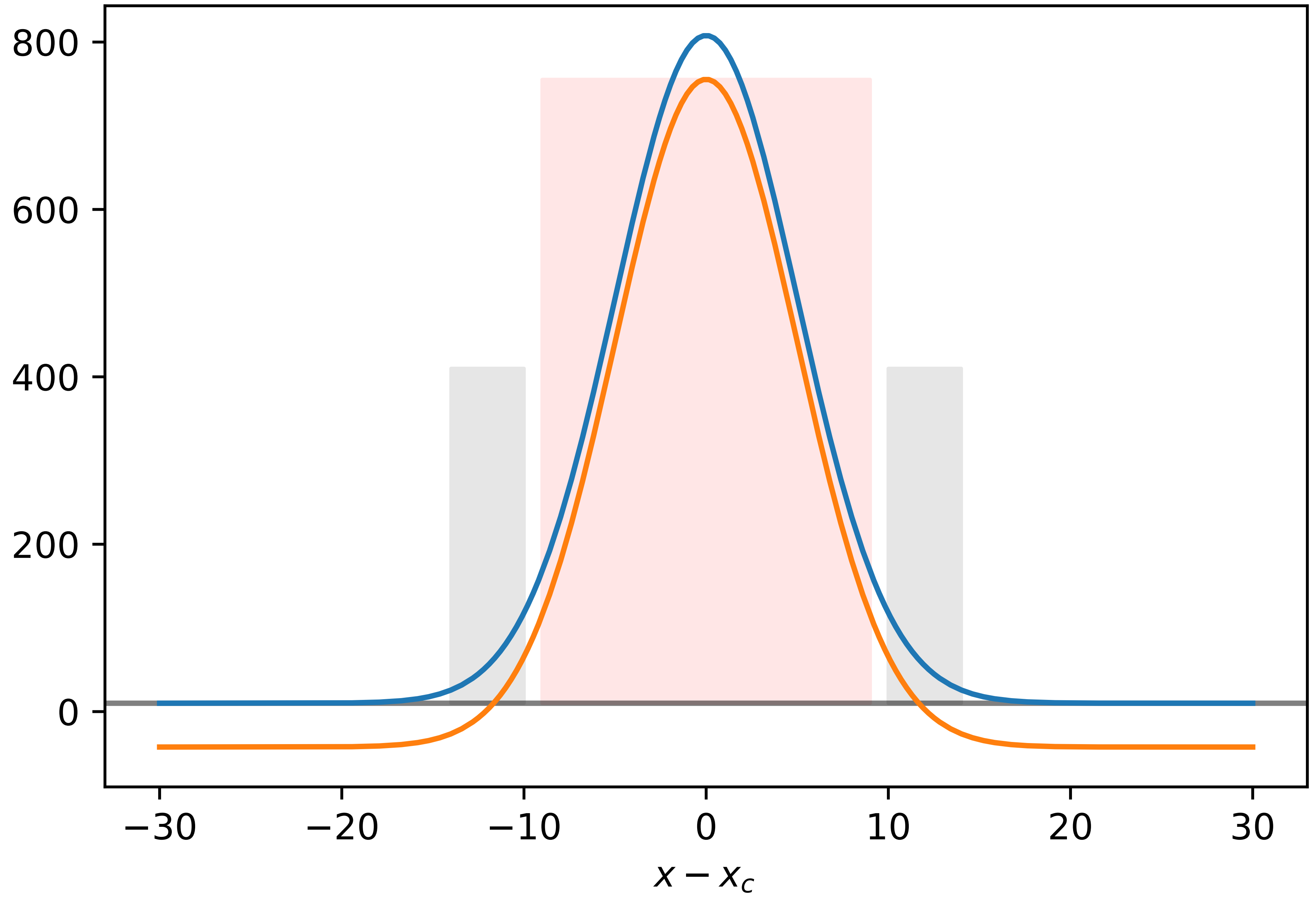
  - The term "compensated filter" is in some ways just a fancy name for "local background subtraction."
  - Because the PSF is (?) the same for bright and faint objects, you subtract off a constant fraction of the flux.
    - This is fine!



Compensated top-hat

- For the top-hat: (Note that this has the same noise problems as the regular top-hat)

$$S = \frac{1}{\pi(R_2^2 - R_1^2)} \int_{R_1}^{R_2} I(\boldsymbol{x}) 2\pi r \, dr$$



We can rewrite this as a measurement filter:

$$\chi(\boldsymbol{x}; R_ap, R_1, R_2) = c \begin{cases} 1 & r \le R_{ap} \\ -\frac{R_{ap}^2}{R_2^2 - R_1^2} & R_1 \le r \le R_2 \end{cases}$$

where c is chosen so that $\langle \int \chi\phi \, d^2\boldsymbol{x} \rangle = 1$, *i.e.* that $\int \chi I \, d^2\boldsymbol{x}$ is an unbiased estimator of F.
The works because $\int \chi S \, d^2\boldsymbol{x} = 0$ for $S = S_0 + xb \cdot d\boldsymbol{S}$.

Compensated Gaussian

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- Can also use a Gaussian filter … with better noise properties.

It's easy enough to analyse this filter, but instead let's look at a filter based on Gaussians.

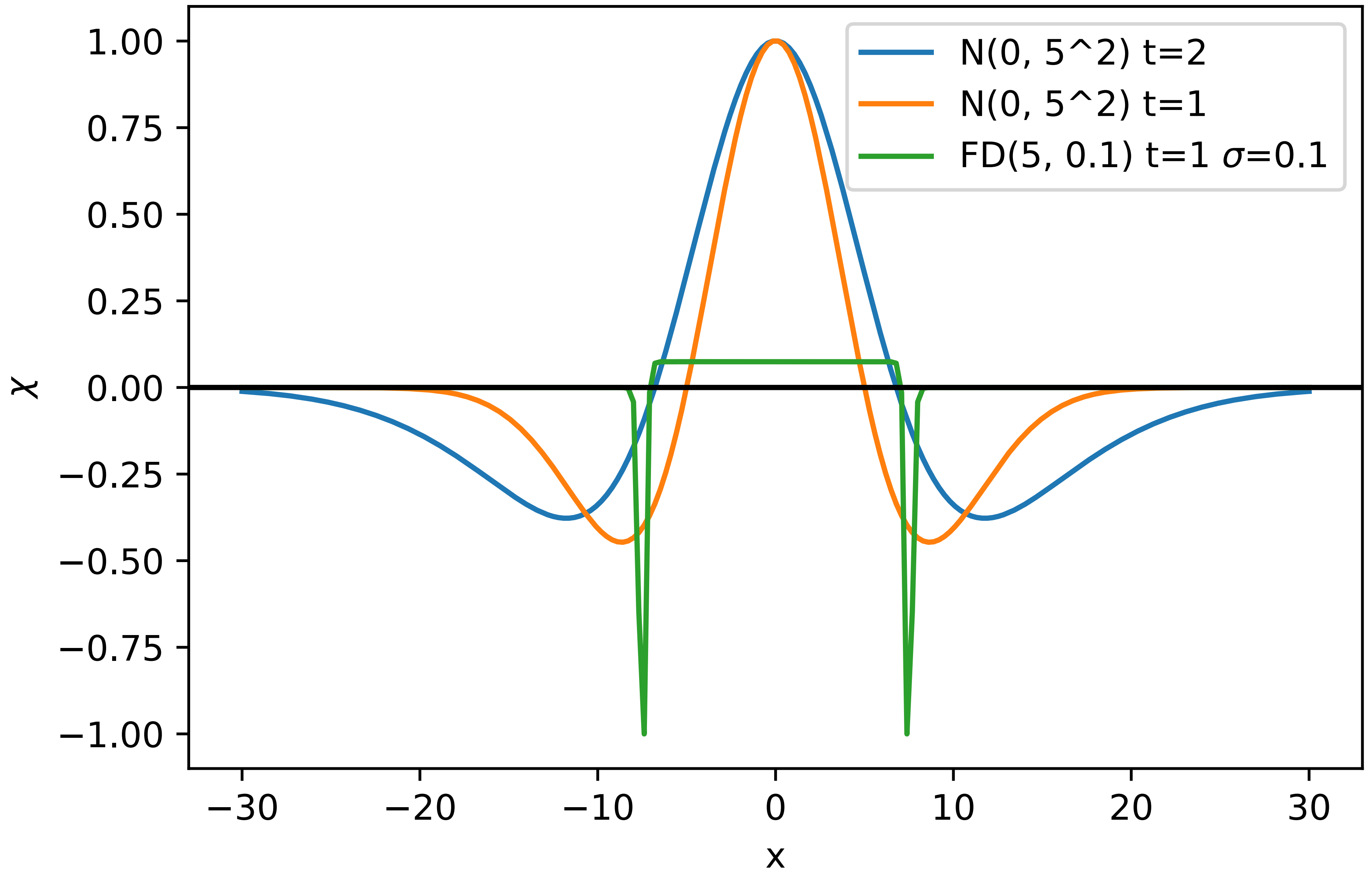
- a Gaussian is more statistically efficient than a top-hat aperture
- it's easier to parameterise sensibly
- it's more fun

Let's write

$$\chi(\boldsymbol{x}; t, \beta) = c(t, \beta)\left(N(\boldsymbol{x}_c, \beta^2) - N(\boldsymbol{x}_c, t^2\beta^2)\right)$$

$$c(t, \alpha) = 4\pi\alpha^2\left(\frac{t^2+1}{t^2-1}\right)$$

$$\mathrm{var}(\hat{F}_\chi) = 4\pi\alpha^2\sigma^2\left(\frac{t^2+1}{t^2}\right)$$



Top-hat apertures on Sims

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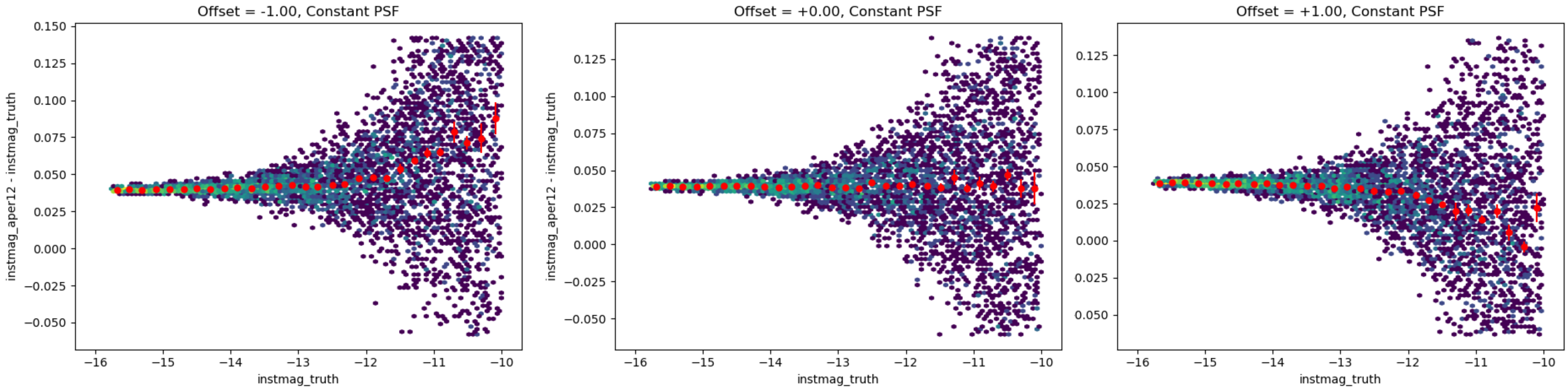
- Back to the galsim grid sims, using a spatially constant PSF.
- Aperture mags are biased at the faint end when the background is offset by 1 ADU/pix (we see this all the time…)



Top-hat aperture errors on Sims

Rubin Observatory

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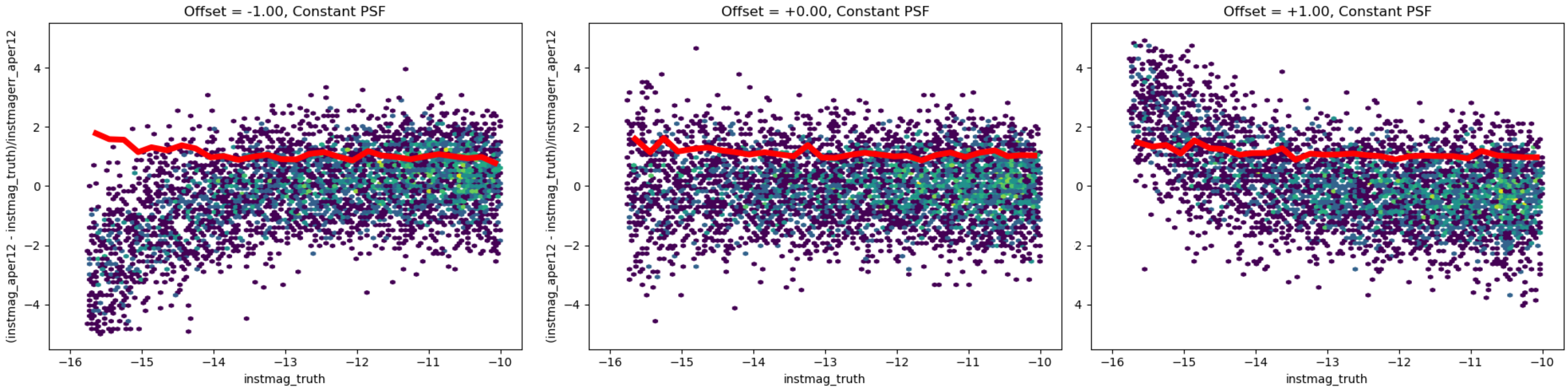

Compensated Gaussians on Sims

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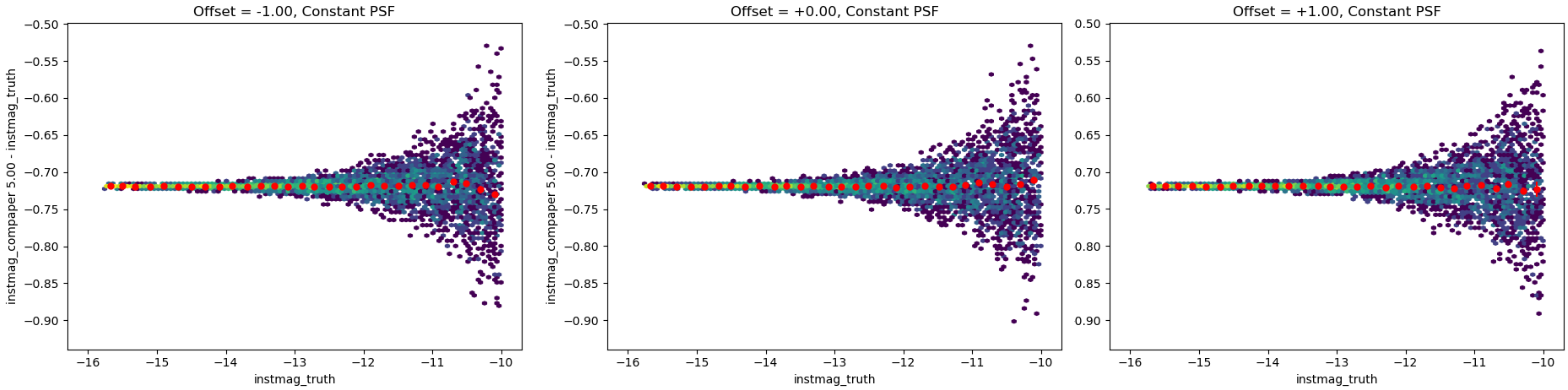
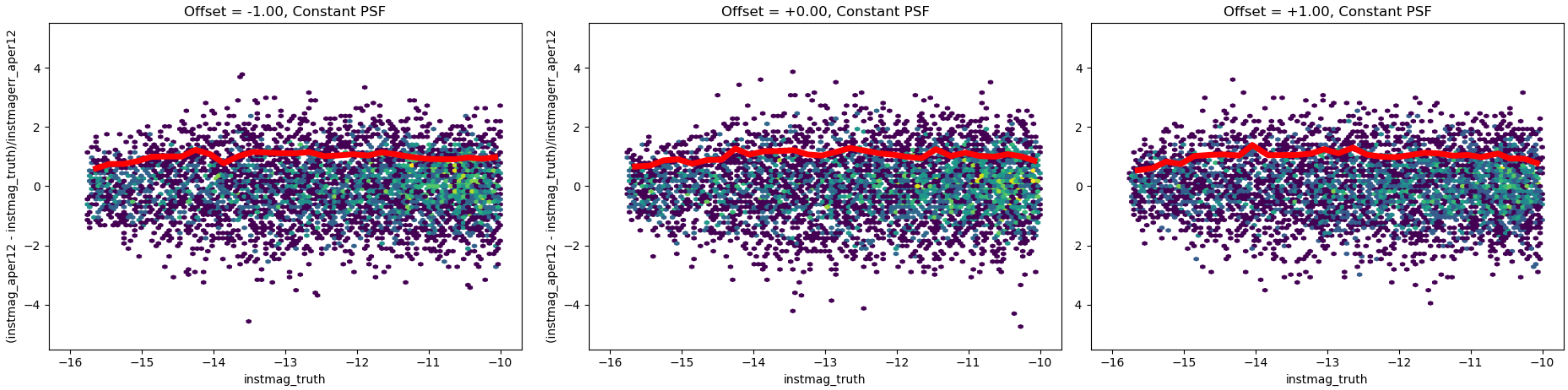
- Back to the galsim grid sims, using a spatially constant PSF.
- CG mags are virtually unbiased with background shifts, have much less noise…
  - … but notice the normalization. This is hard to get correct with first principles.
  - (Note: this was with width=5 pixels, t=1.2)



Compensated Gaussian Errors on Sims

- Back to the galsim grid sims, using a spatially constant PSF.
- The error performance of the CG is good, using Robert’s prescription that Nate implemented.



apologies, labels are wrong, these are compensated gaussian comparisons

But … there's always a but…

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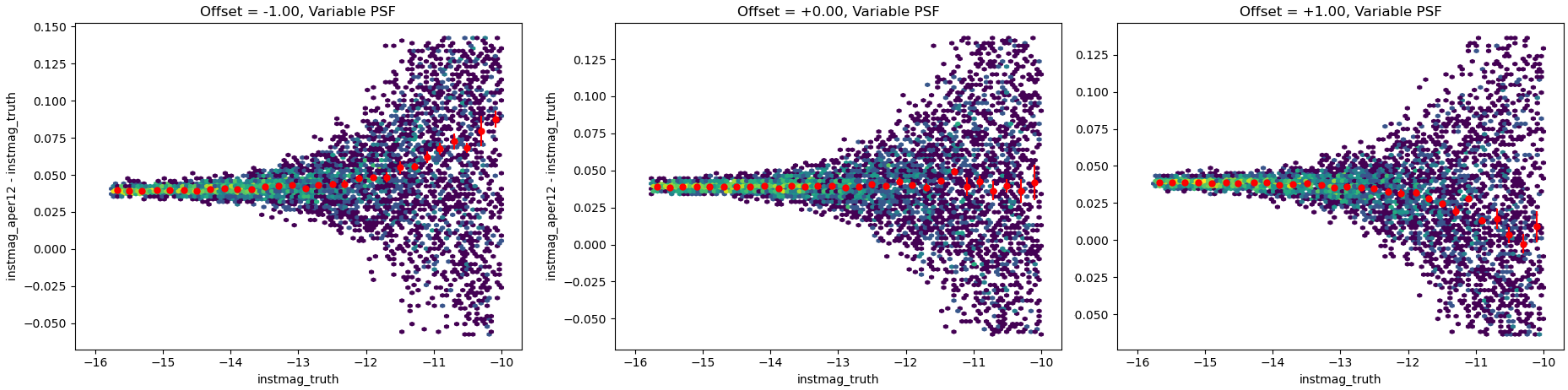
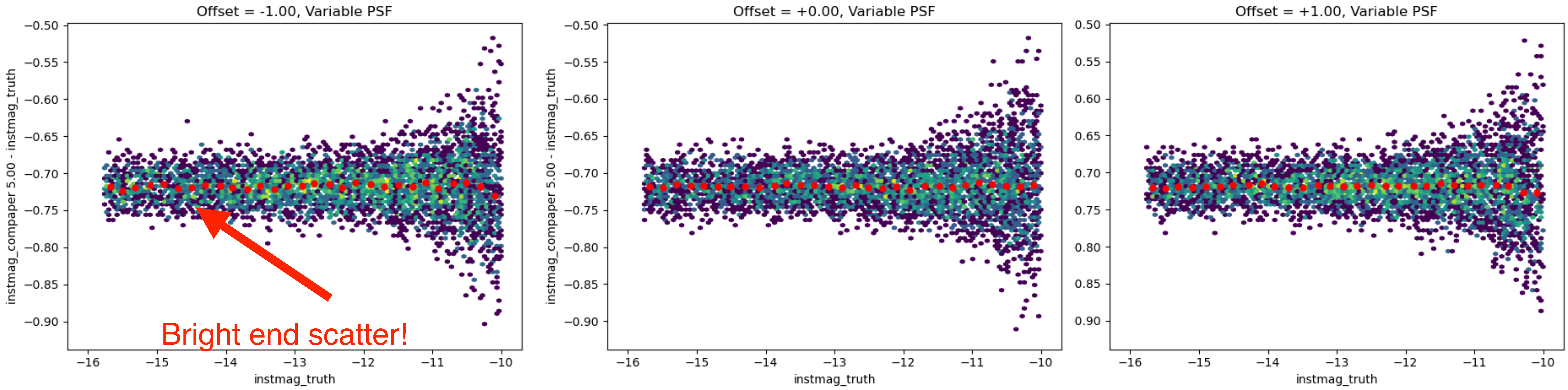
- That normalization offset? It changes with PSF size. And the PSF varies.
- Redo grid sims with a realistic (?) spatially varying PSF.
- Large apertures are basically unperturbed by variations in PSF size.



But … there's always a but…

Rubin Observatory

- That normalization offset? It changes with PSF size. And the PSF varies.
- Redo grid sims with a realistic (?) spatially varying PSF.
- Gaussians are annoyed by variations in PSF size.



What is the proper normalization?

- The normalization of the filter varies with position (via the PSF).

- This is functionally the “aperture correction”…

Robert on Aperture Corrections

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We usually define an aperture correction to a fixed circular aperture (12 pixels for HSC, *c.* 1.6"). For stellar photometry this is fine; the spatial structure in the PSF is reflected in the spatial structure of the aperture correction.

Historically *aperture corrections* were taken to large radii to allow us to calibrate data taken *now* with standard stars taken *then*; but with deep omnipresent catalogues such as PS1 and DES this is no longer necessary.

Galaxies are tricky. In theory you need to deconvolve and sort out what fraction of the flux you'd have included in the canonical calibration. In practice we assume that galaxies are as centrally-concentrated as stars. If we use compact compensated filters, this is not likely to be an acceptable approximation.

How should we calibrate compensated measurements? One approach would be to use compensated measurements for stars, then transfer that measurement to *e.g.* 12-pixel apertures using bright stars and proceed as before.

I'm not sure if this is what we want to do.

Pros and Cons of different flux measurements

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- Top-hat filter (circular aperture)
  - Pro: varies smoothly and slowly with PSF variations
  - Pro: Simple!
  - Con: Serious background problems.
  - Con: Noisy
- PSF model
  - Pro: varies minimally with PSF variations
  - Pro: small footprint -> small background problems.
  - Pro: High s/n
  - Con: complicated model!
  - Con: Still need to tie to top-hat aperture
- Compensated Gaussian
  - Pro: Background fixed!
  - Pro: High s/n
  - Con: varies significantly with PSF variations (but handleable?)
  - Con: Still need to tie to top-hat aperture

Let’s Look at Real Data

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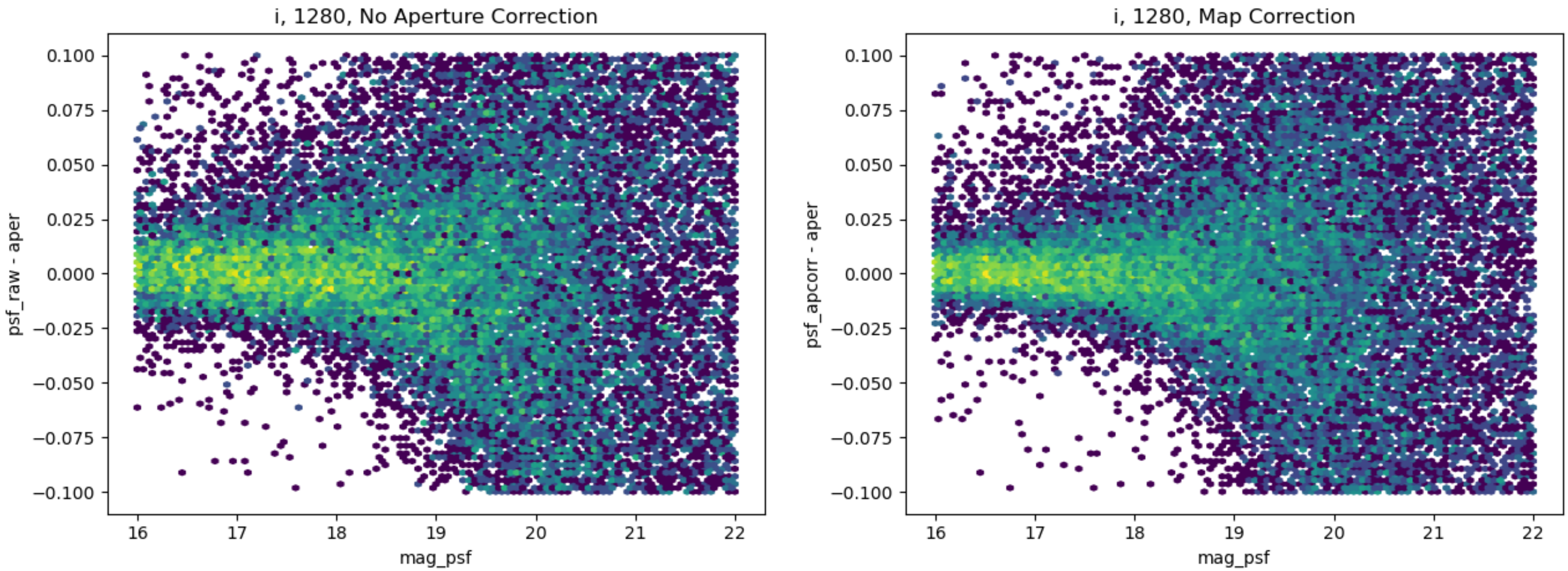
- Comparing PSF mags to aper12, with and without aperture corrections.



Let's Look at Real Data

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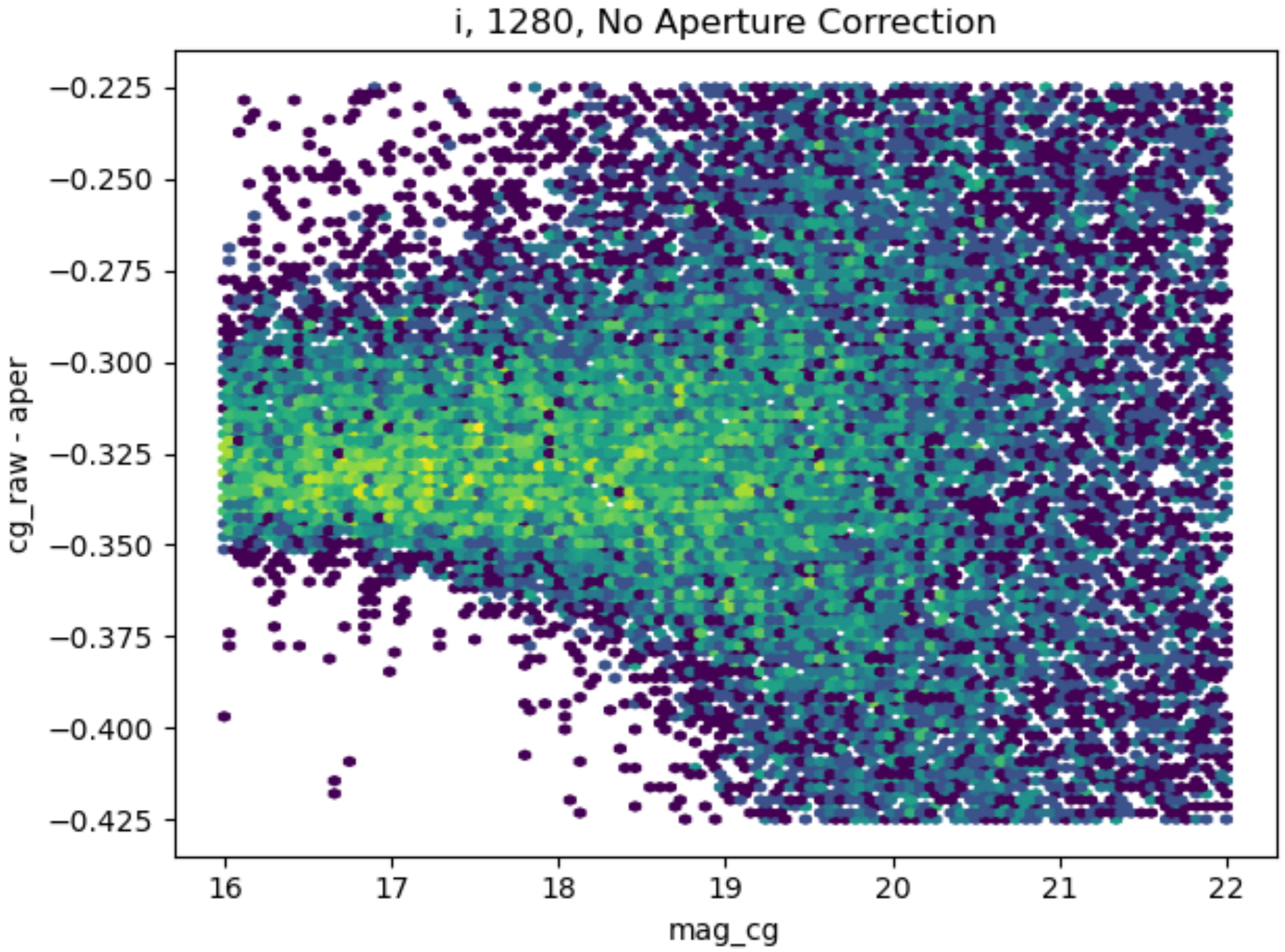
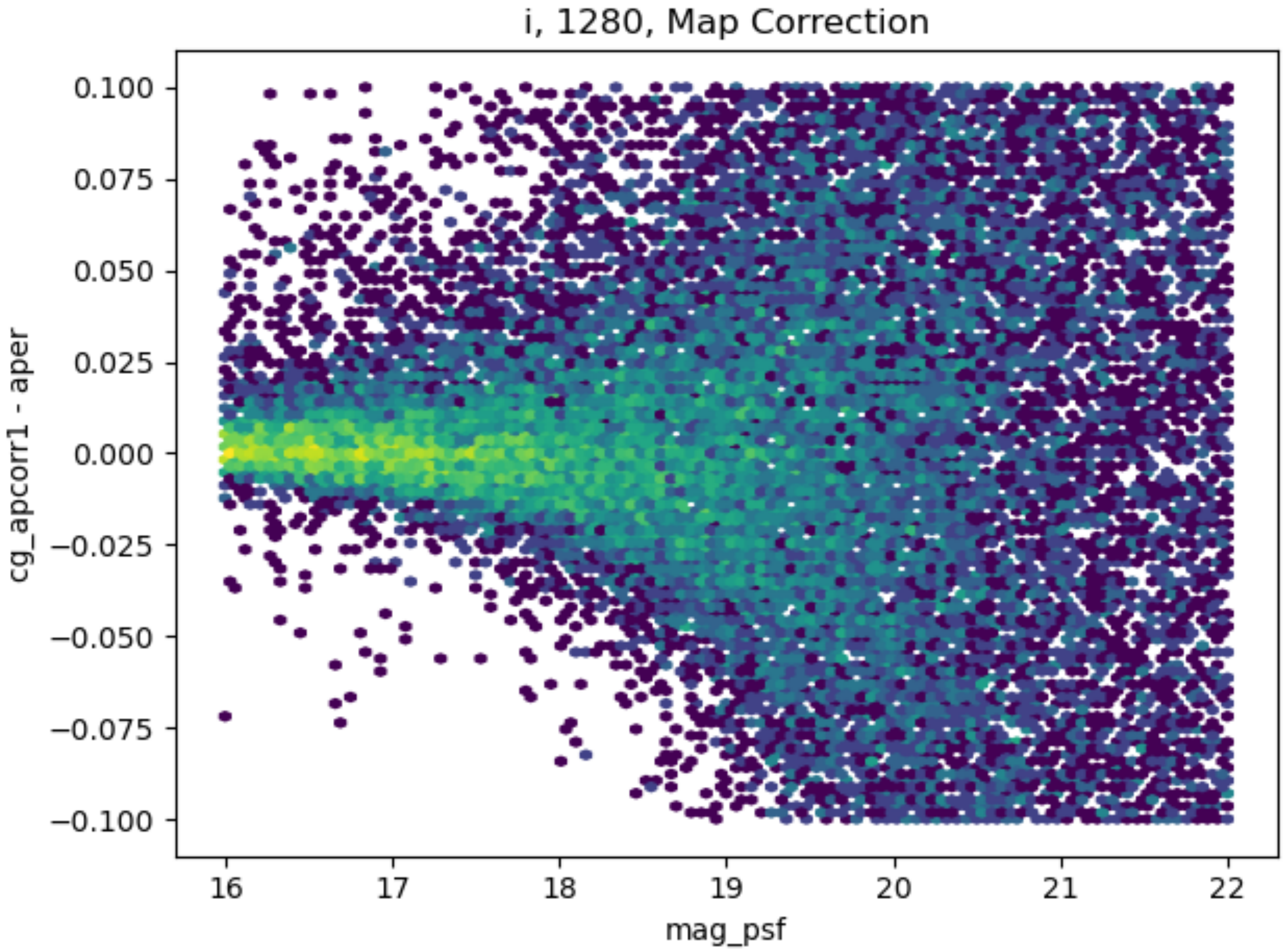
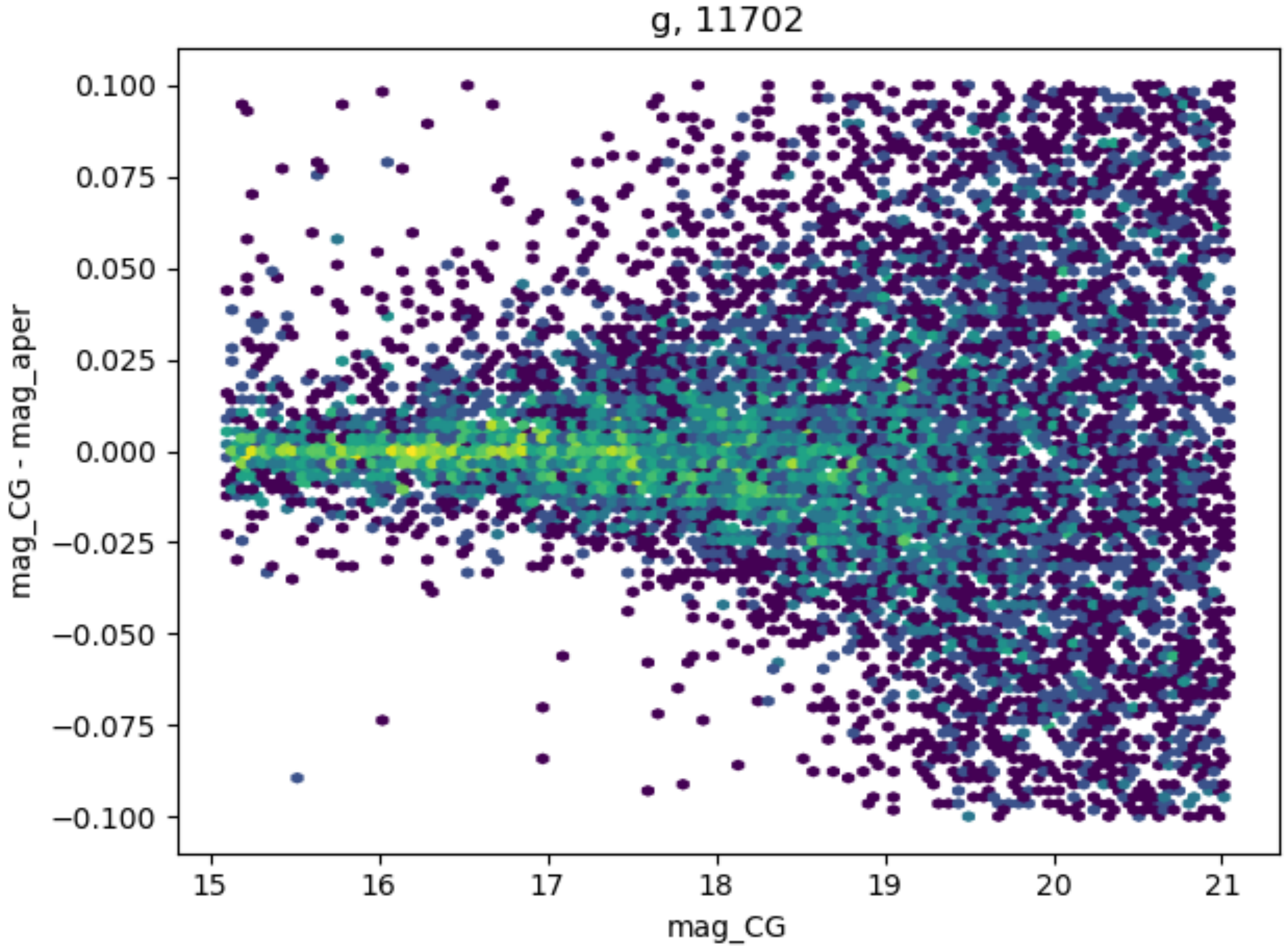
- Comparing CG mags to aper12, without aperture corrections (left) and (right) using a simple 1 correction-per-detector, computed from 25% brightest stars

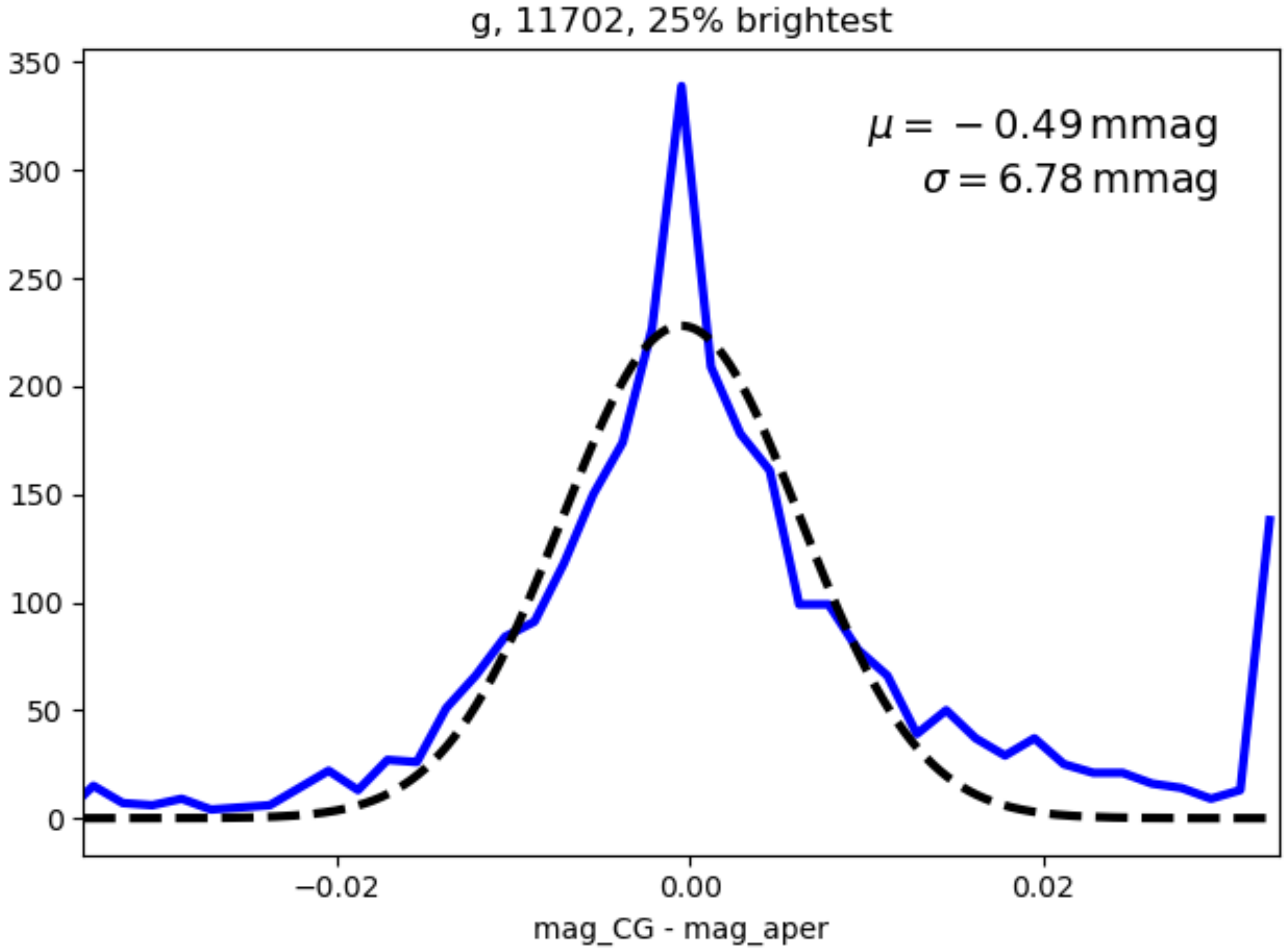




Comparing CG to PSF mags, RC2

- Compare CG (1-#-per-detector aperture correction) to PSF mags (standard aperture corrections).





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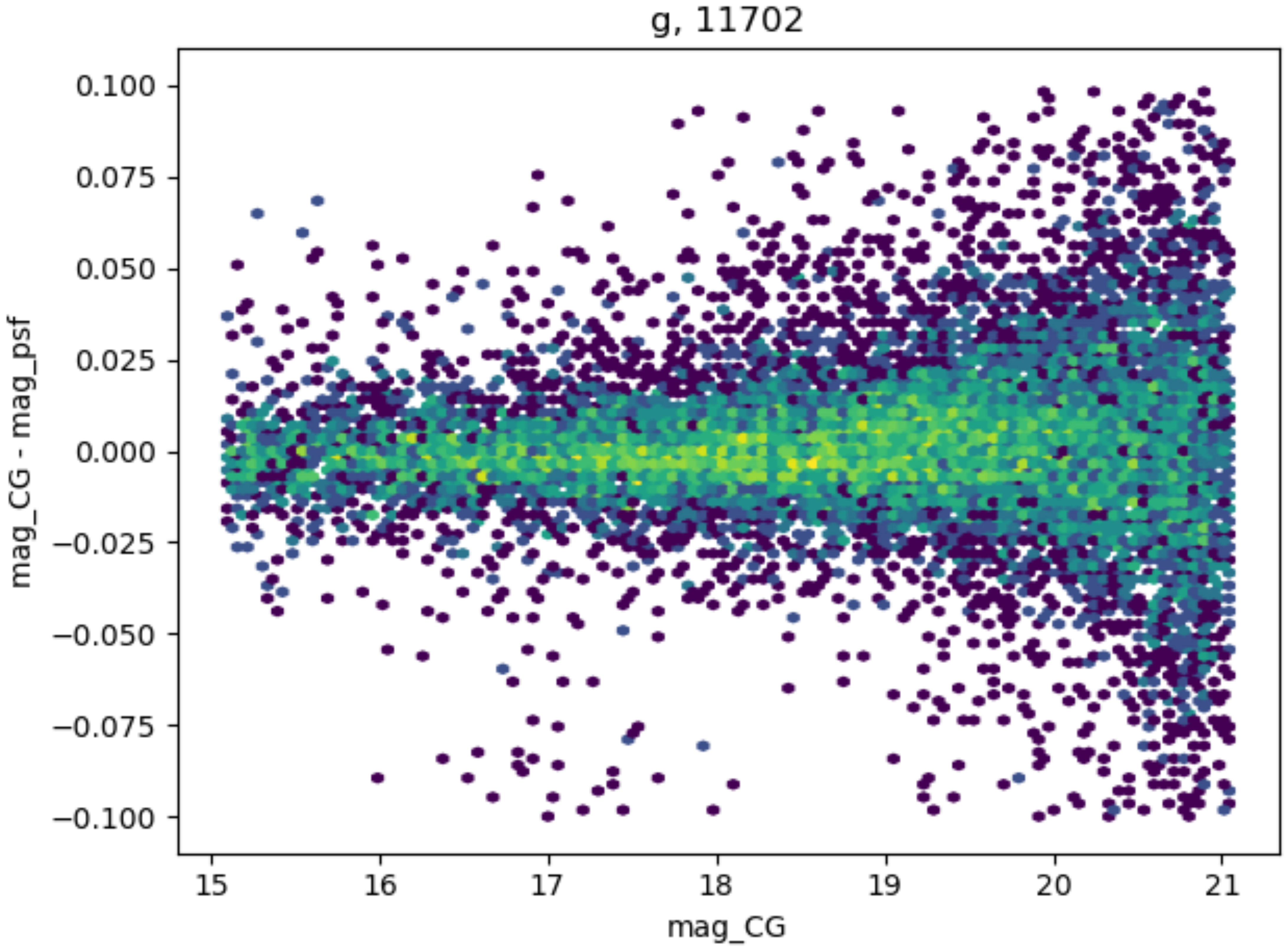

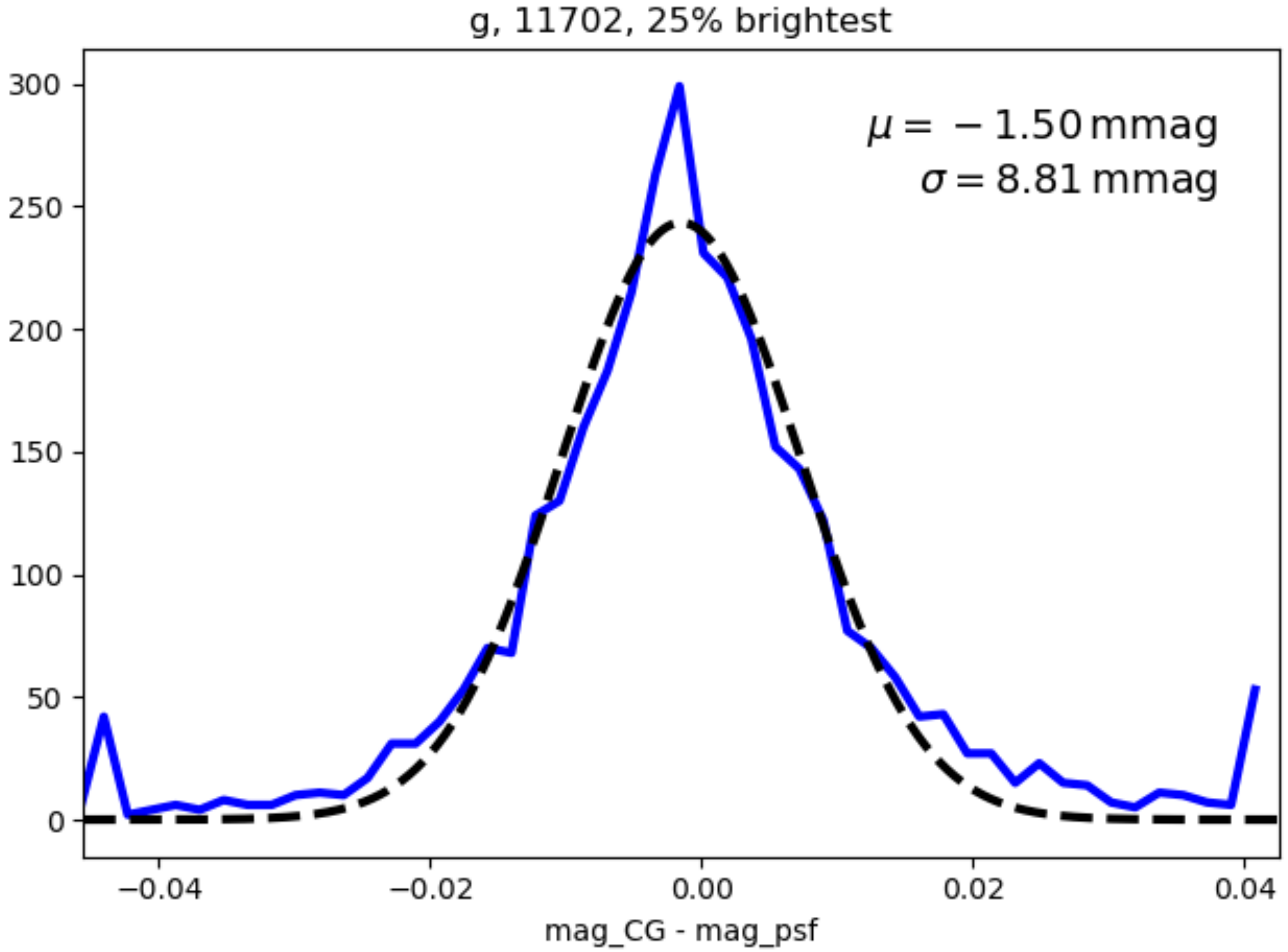

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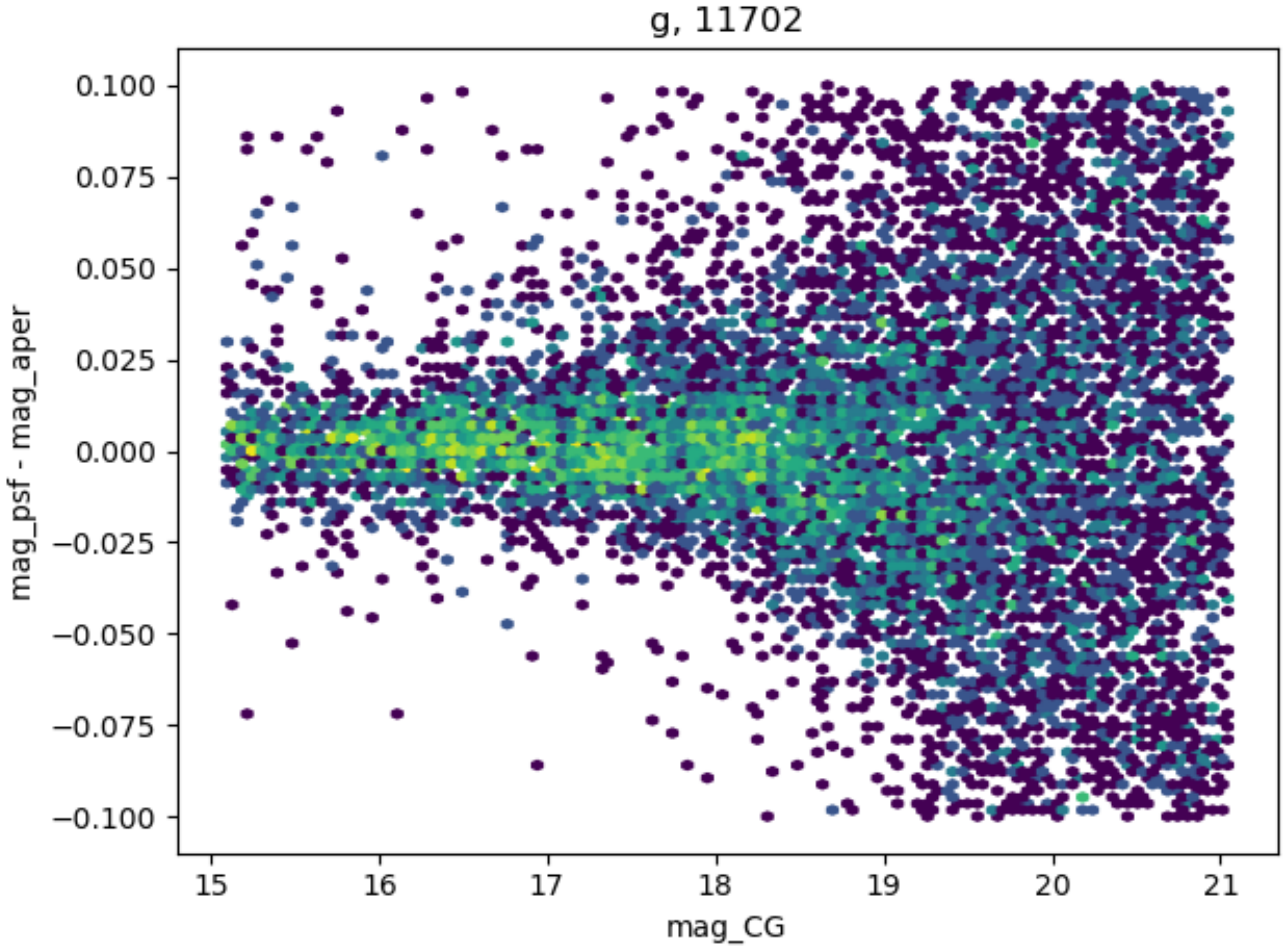

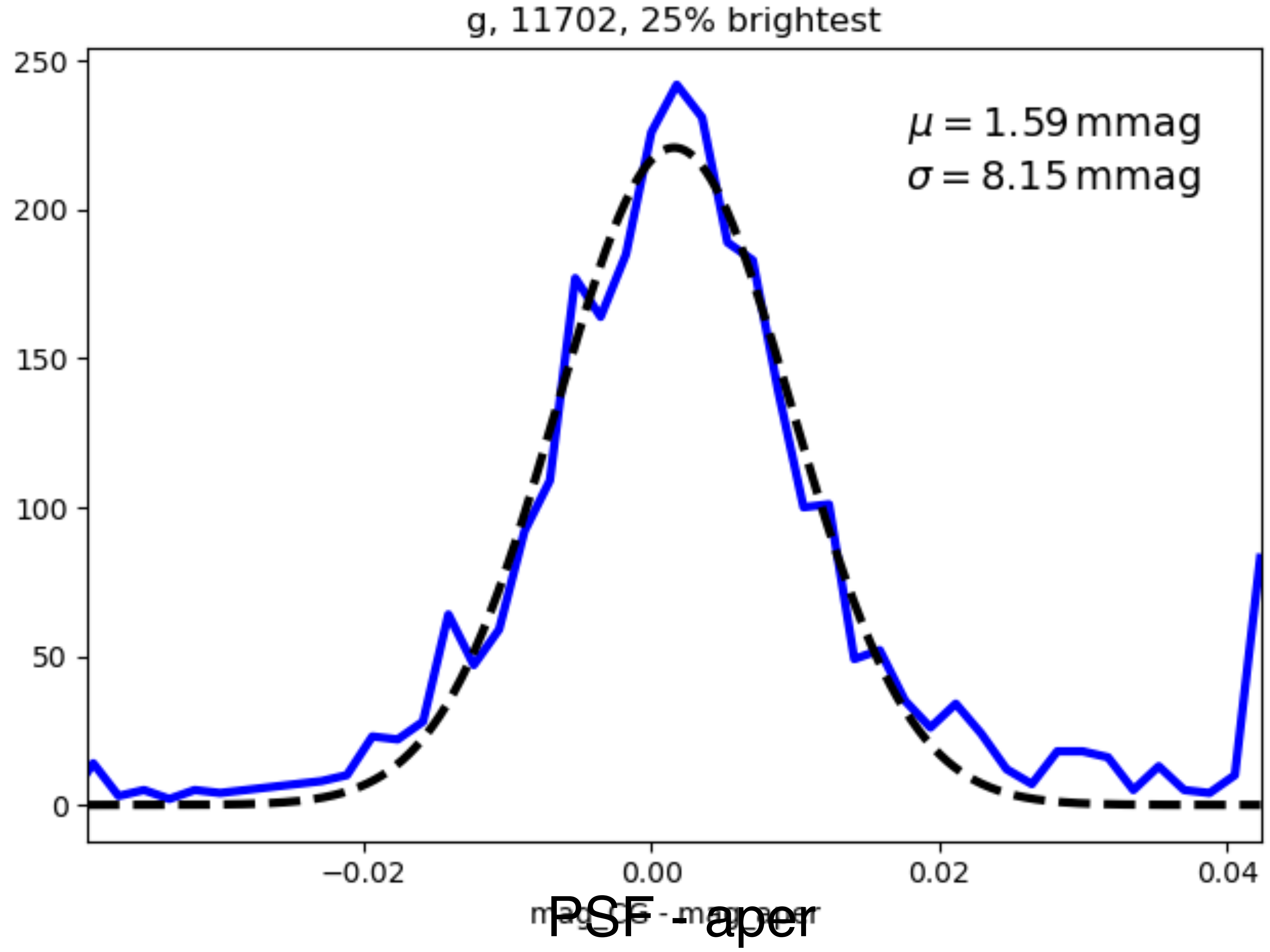

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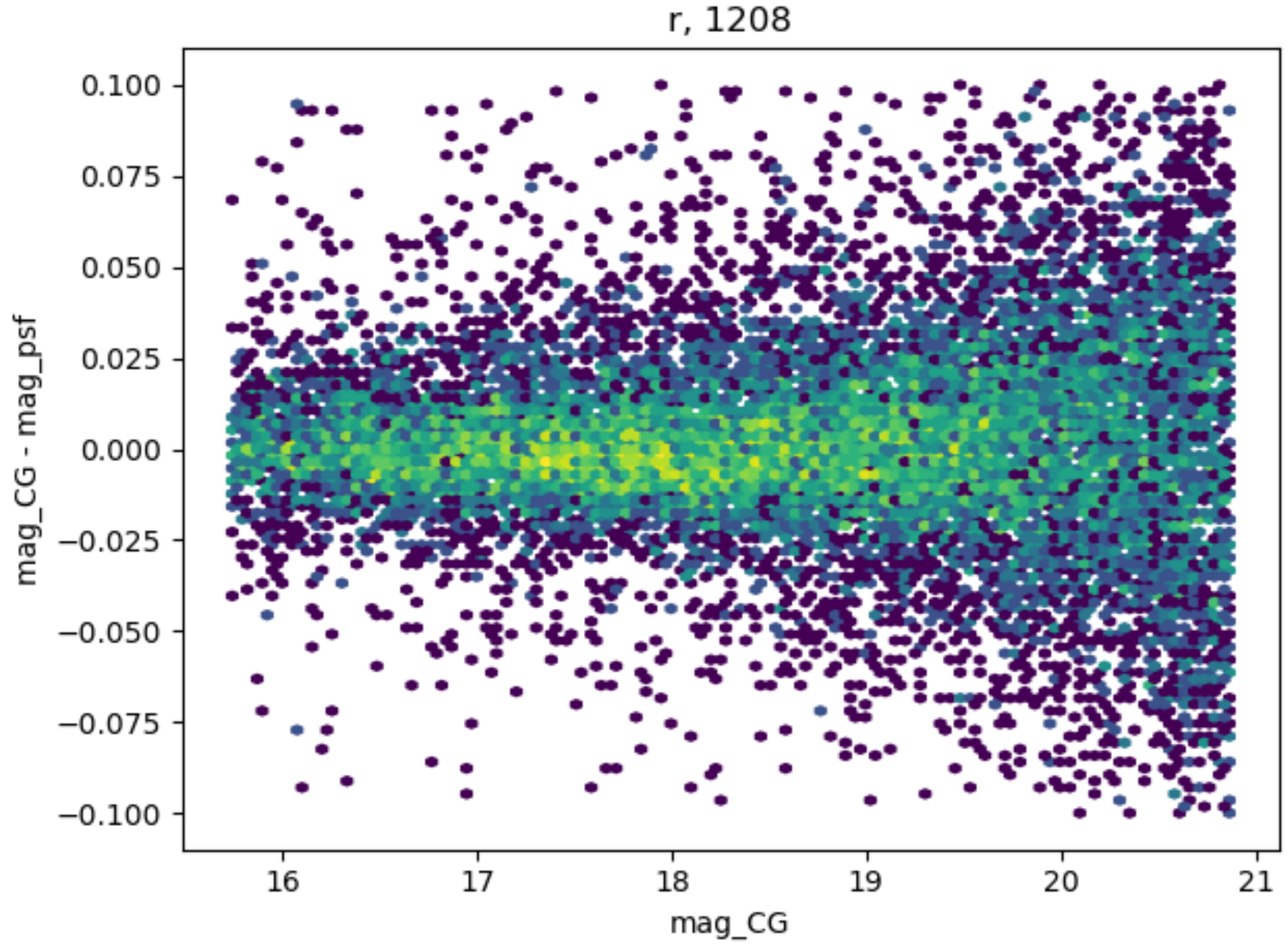

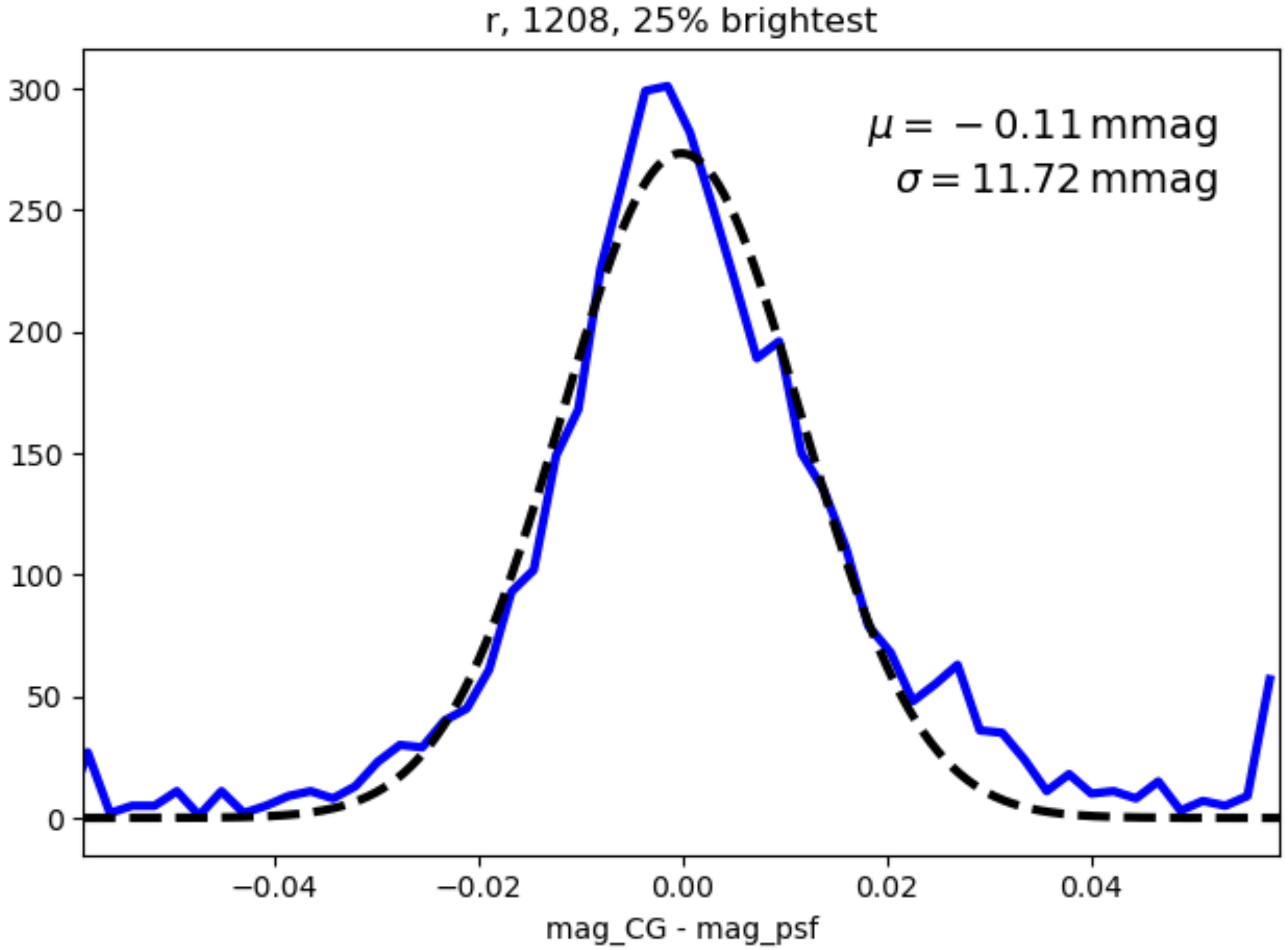

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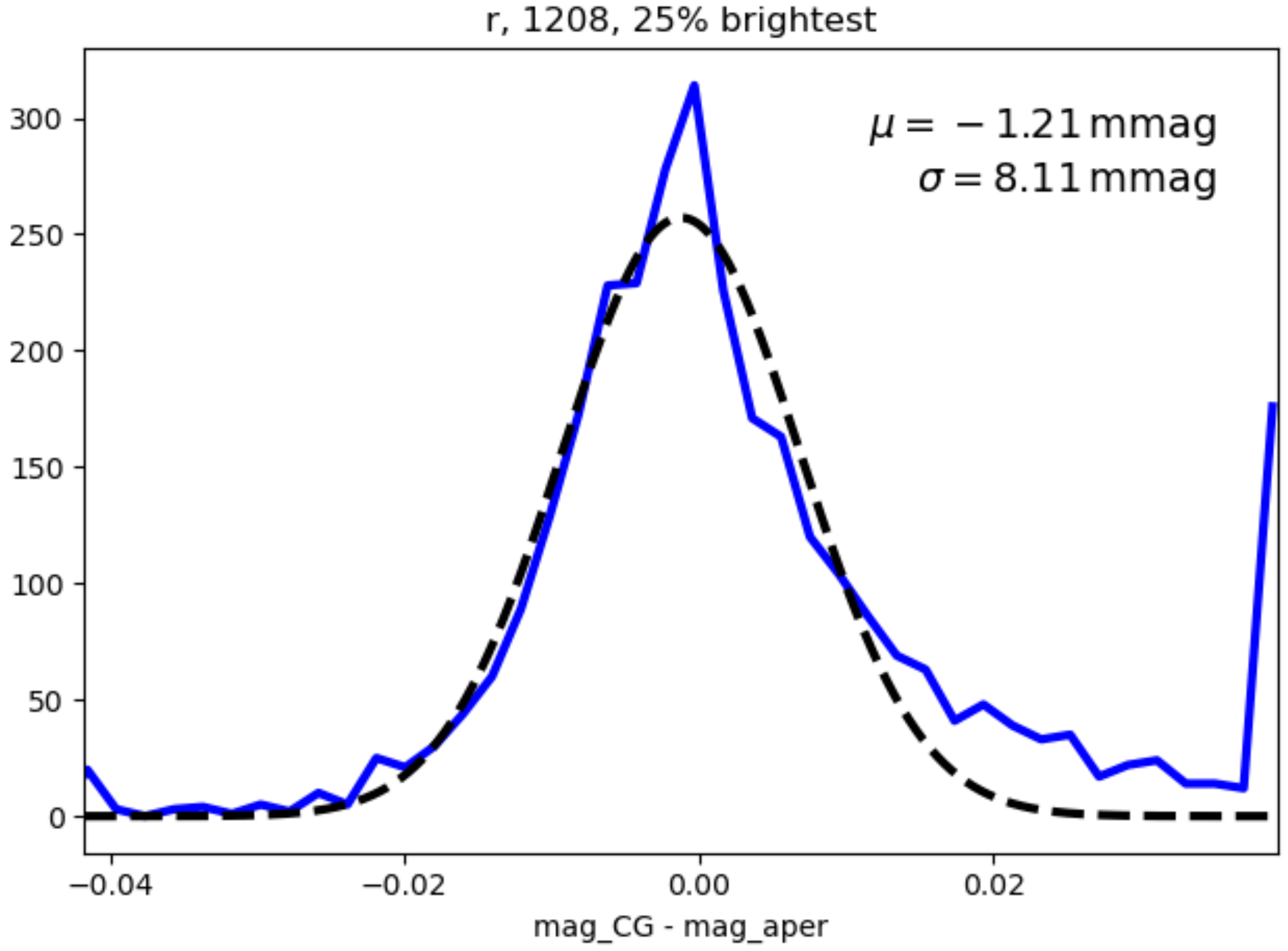

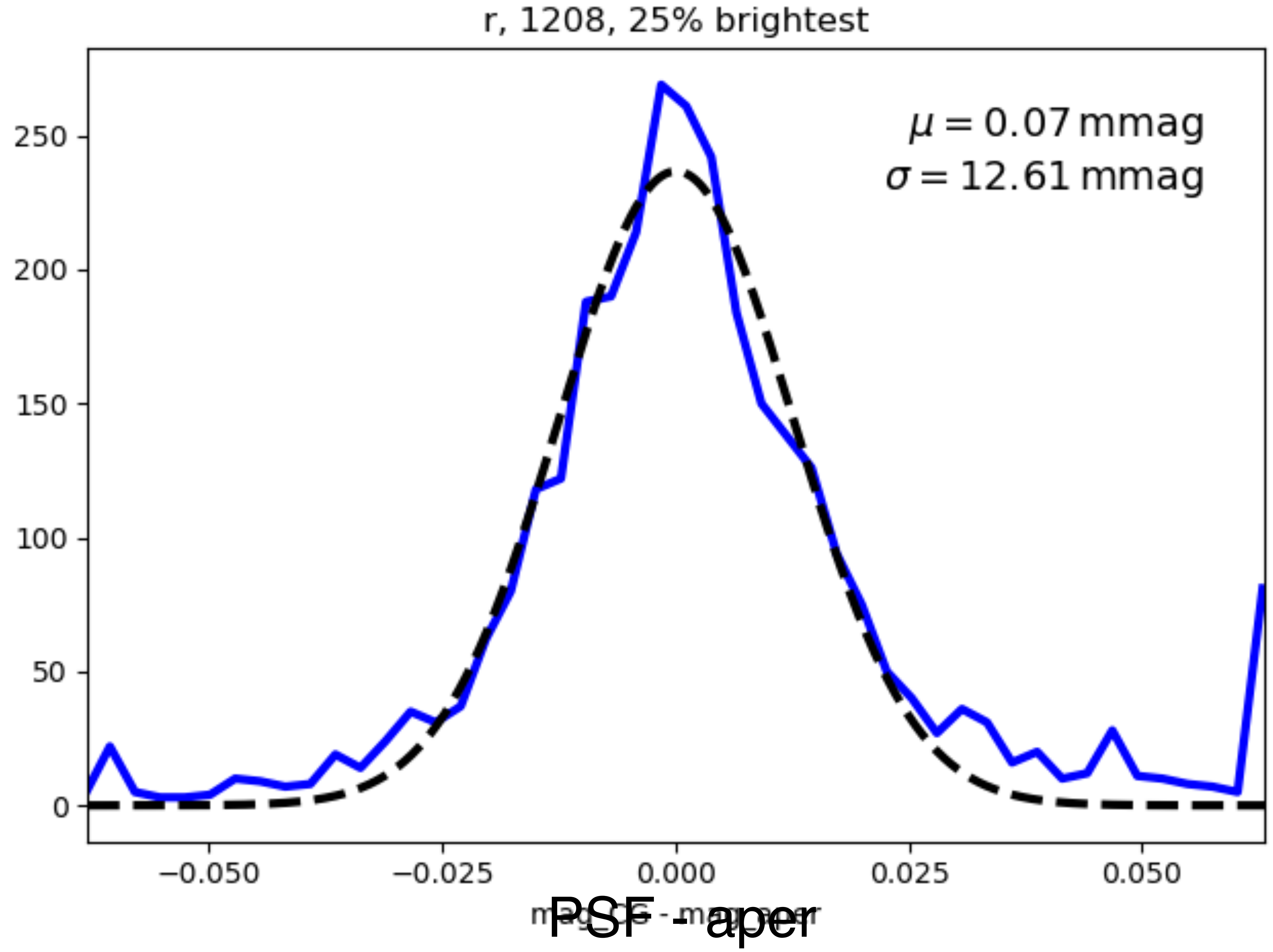

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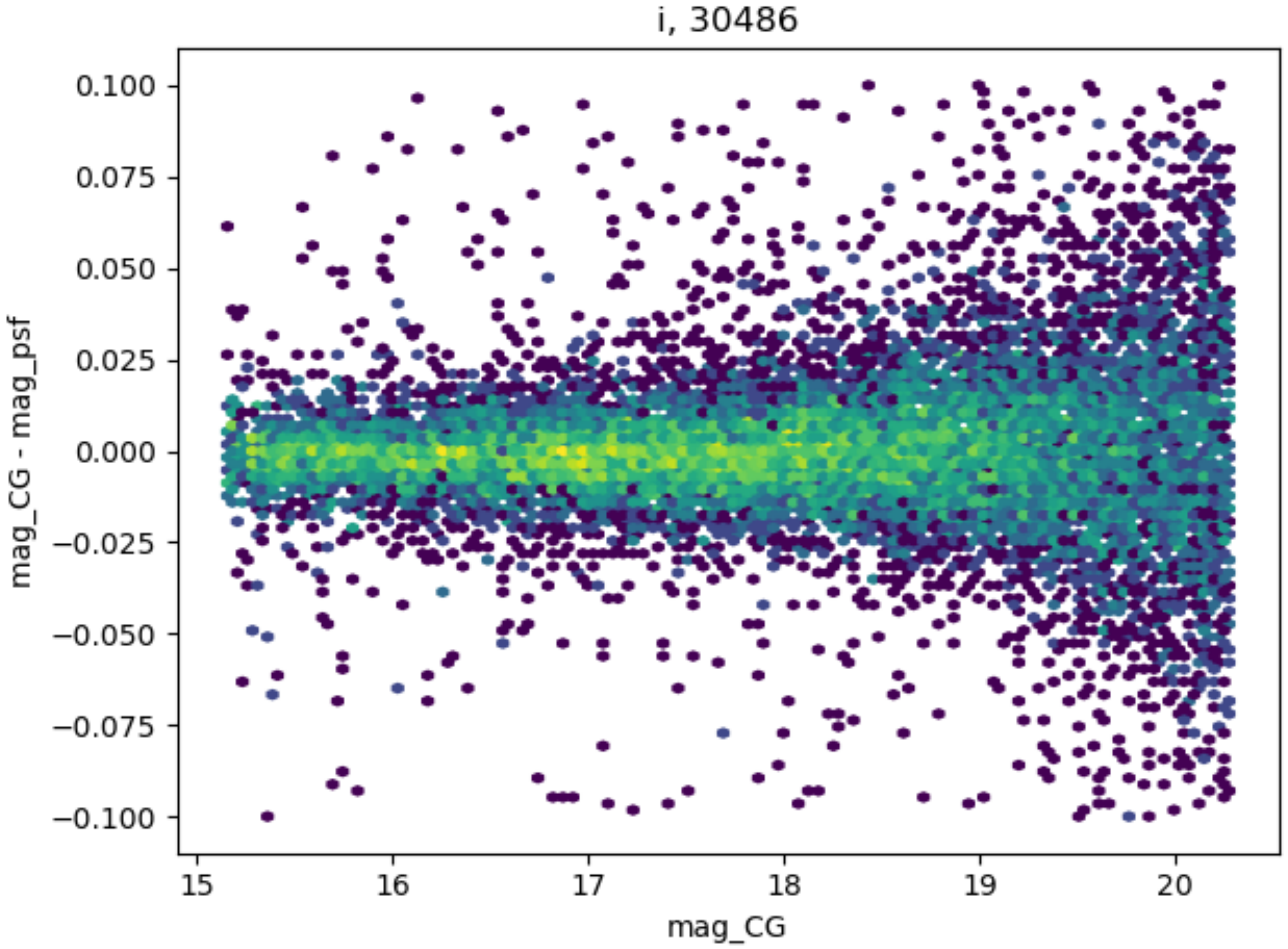

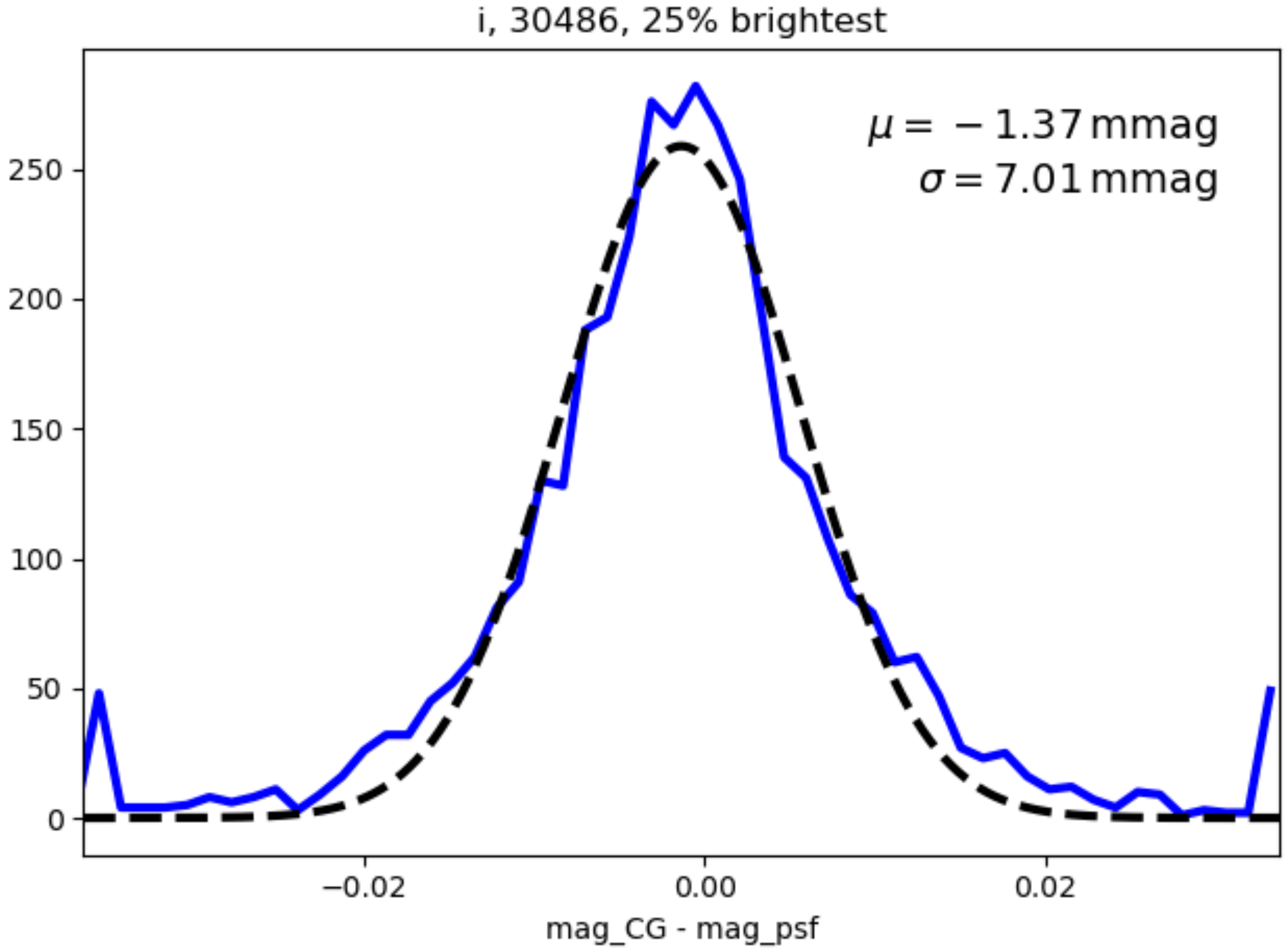

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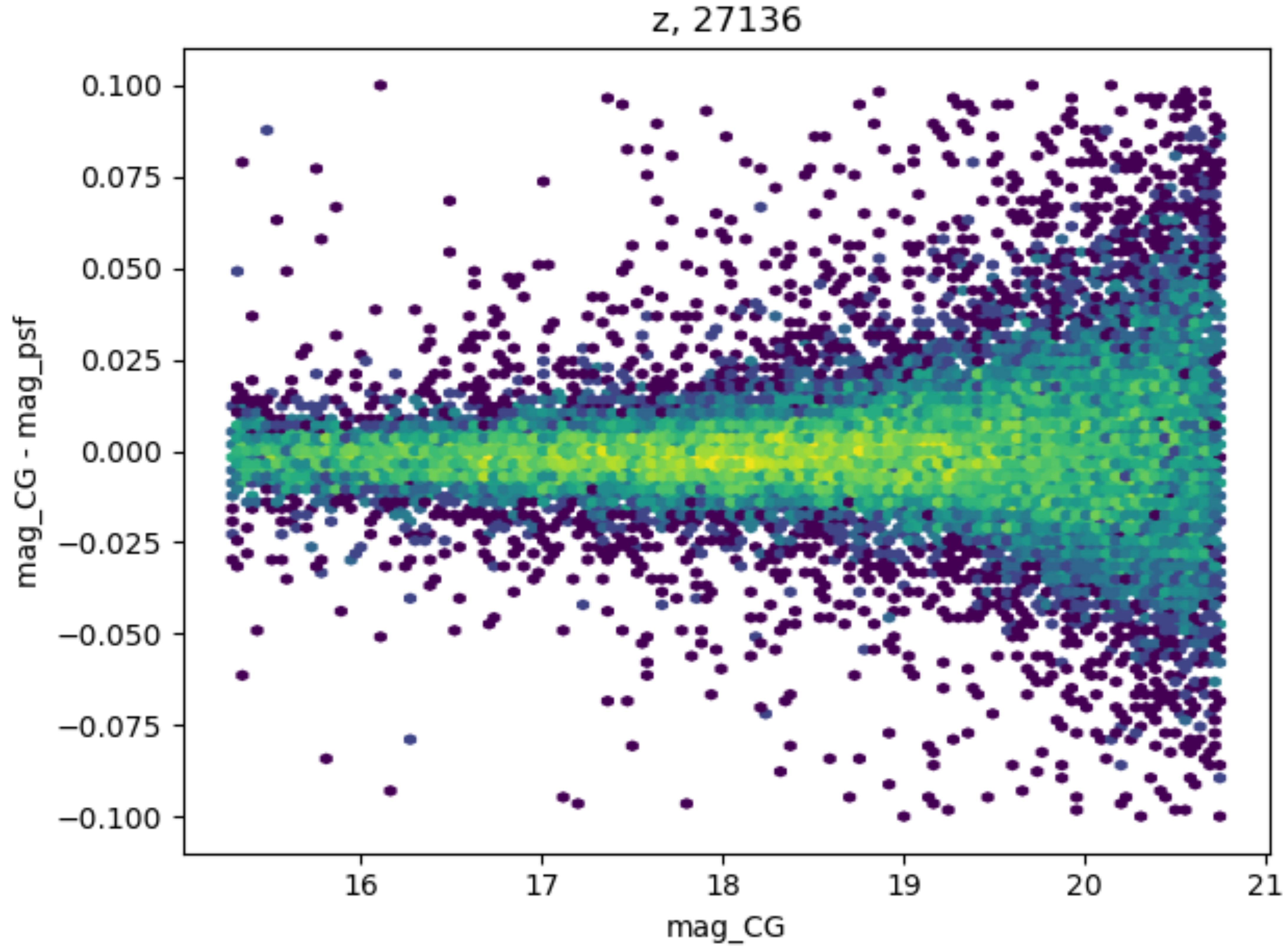

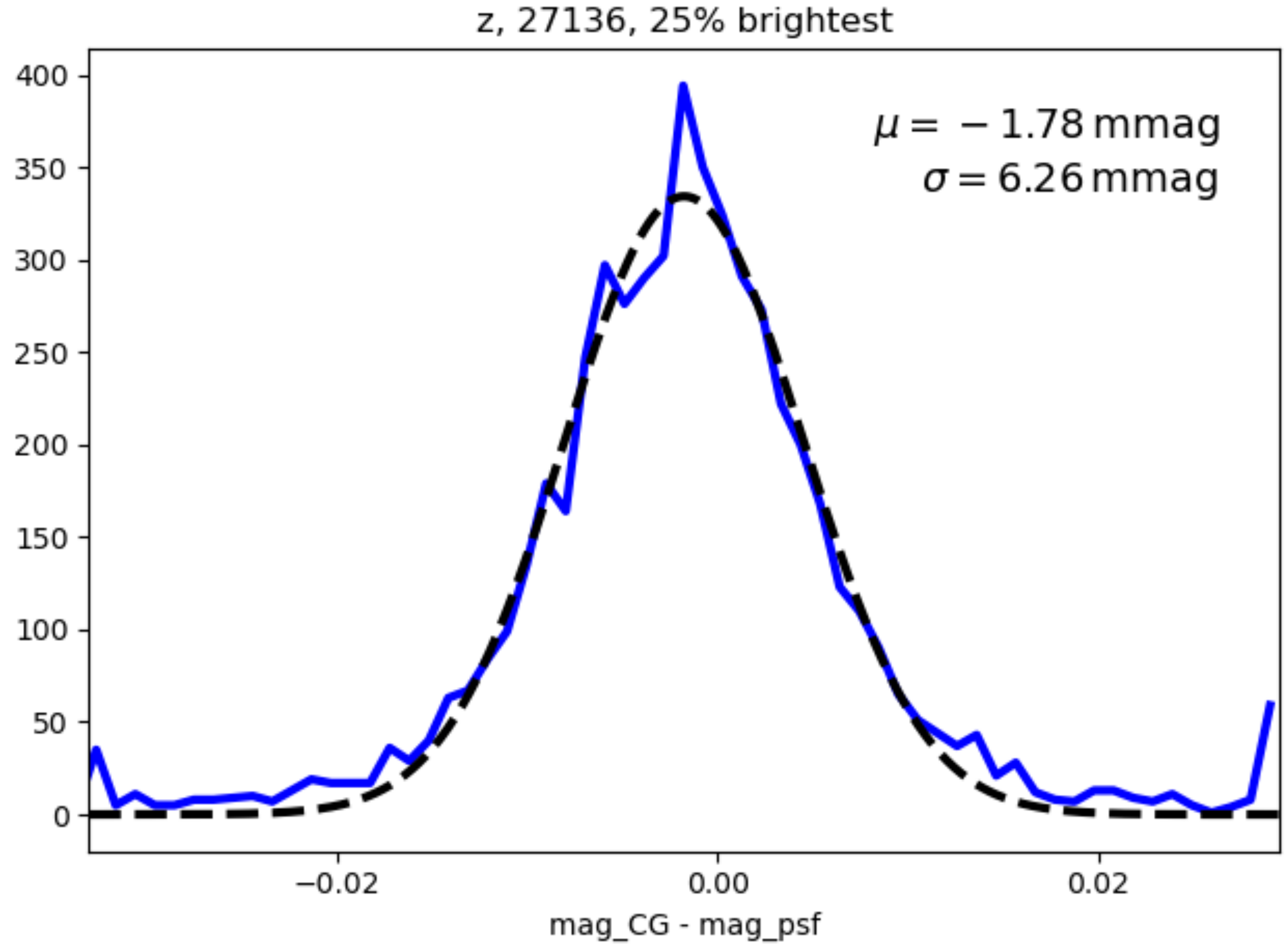

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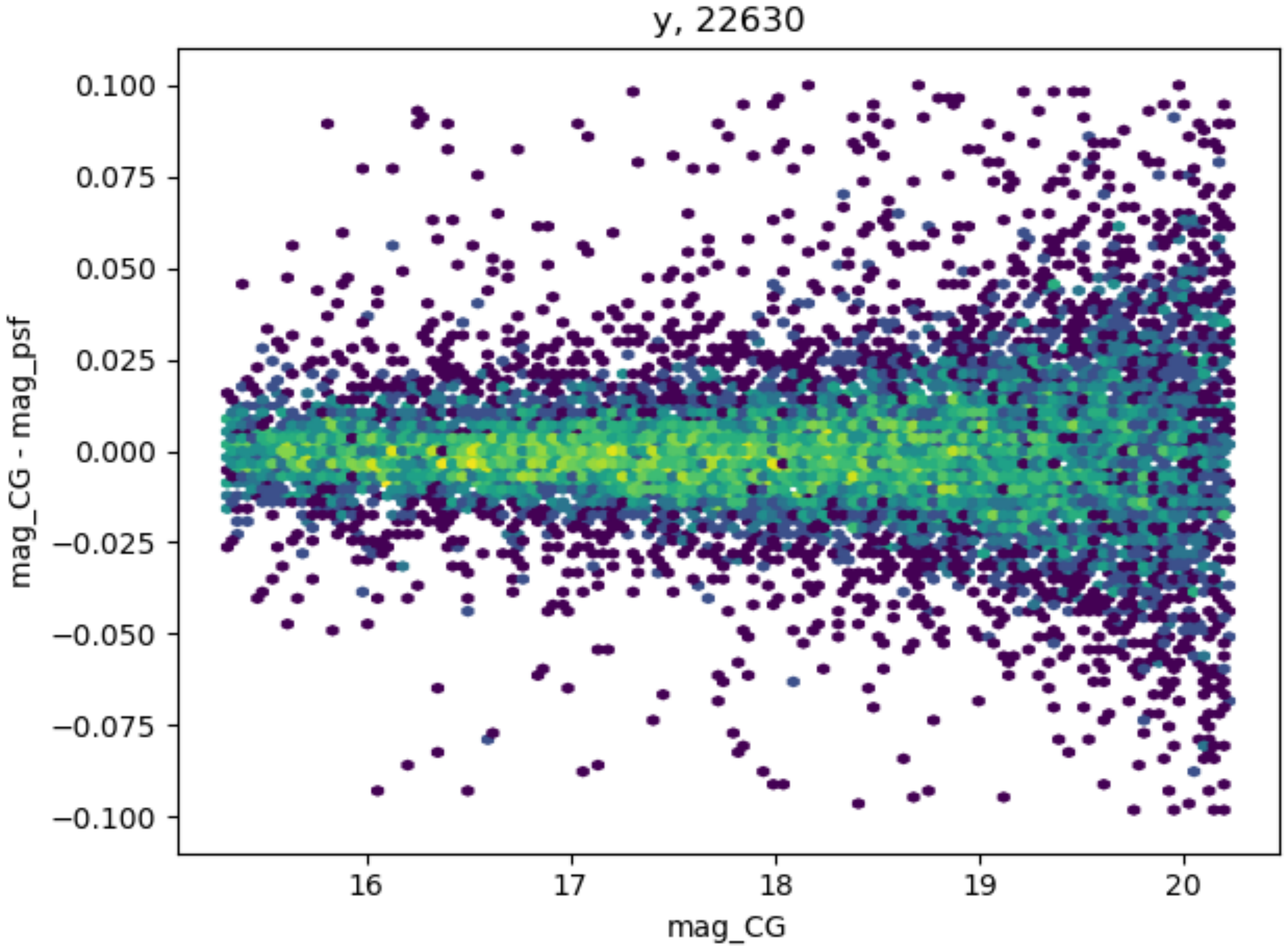

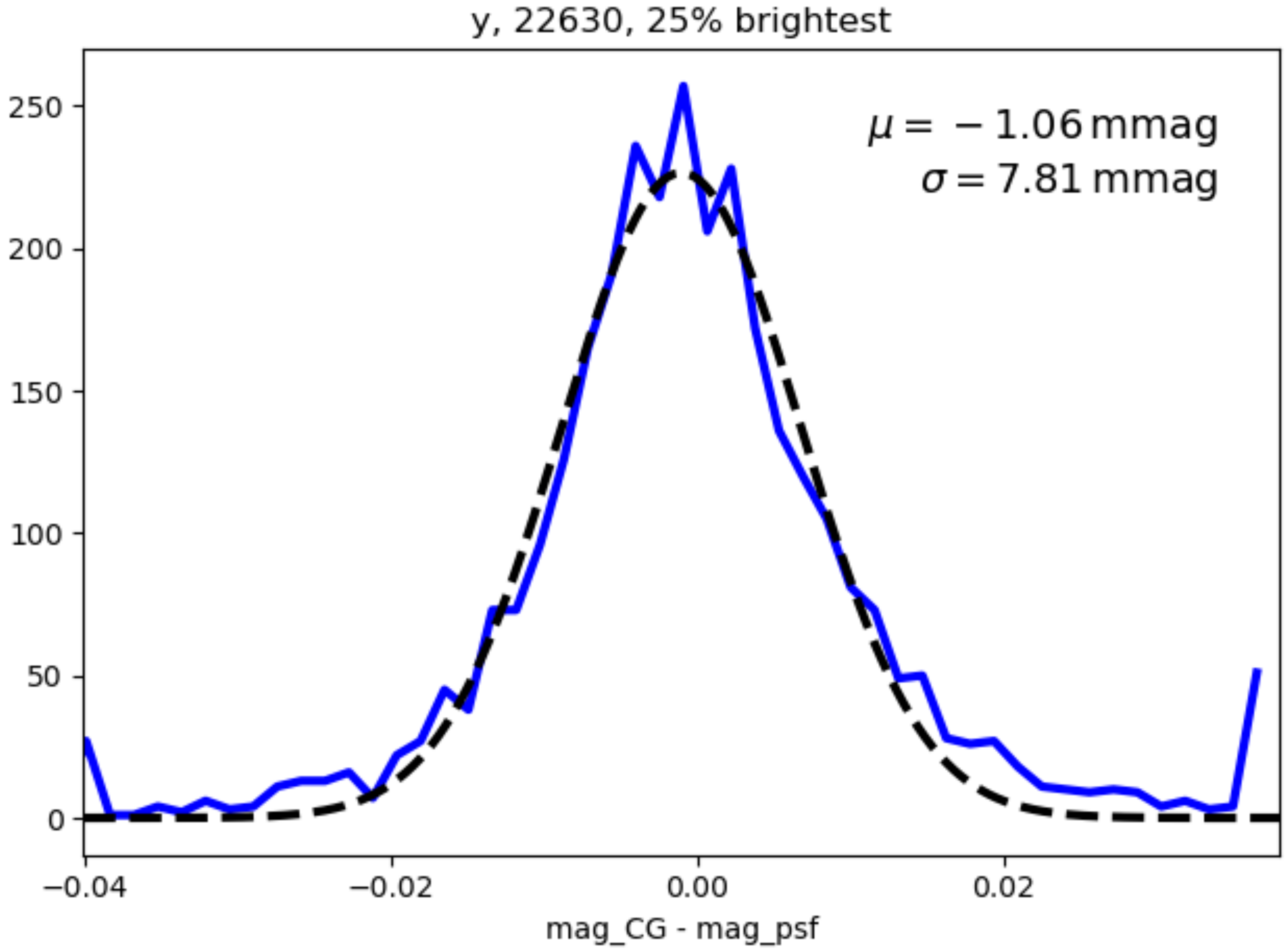

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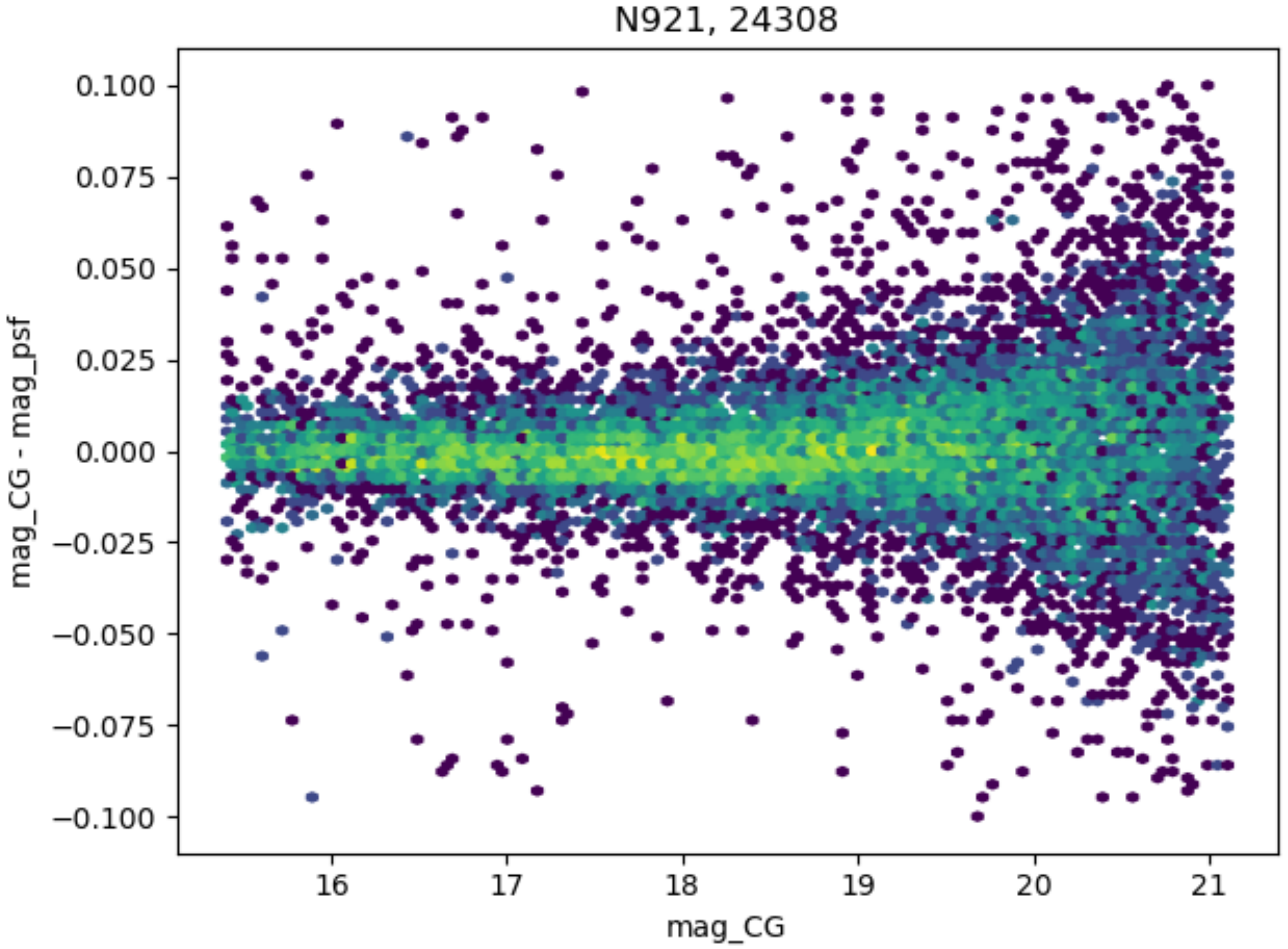

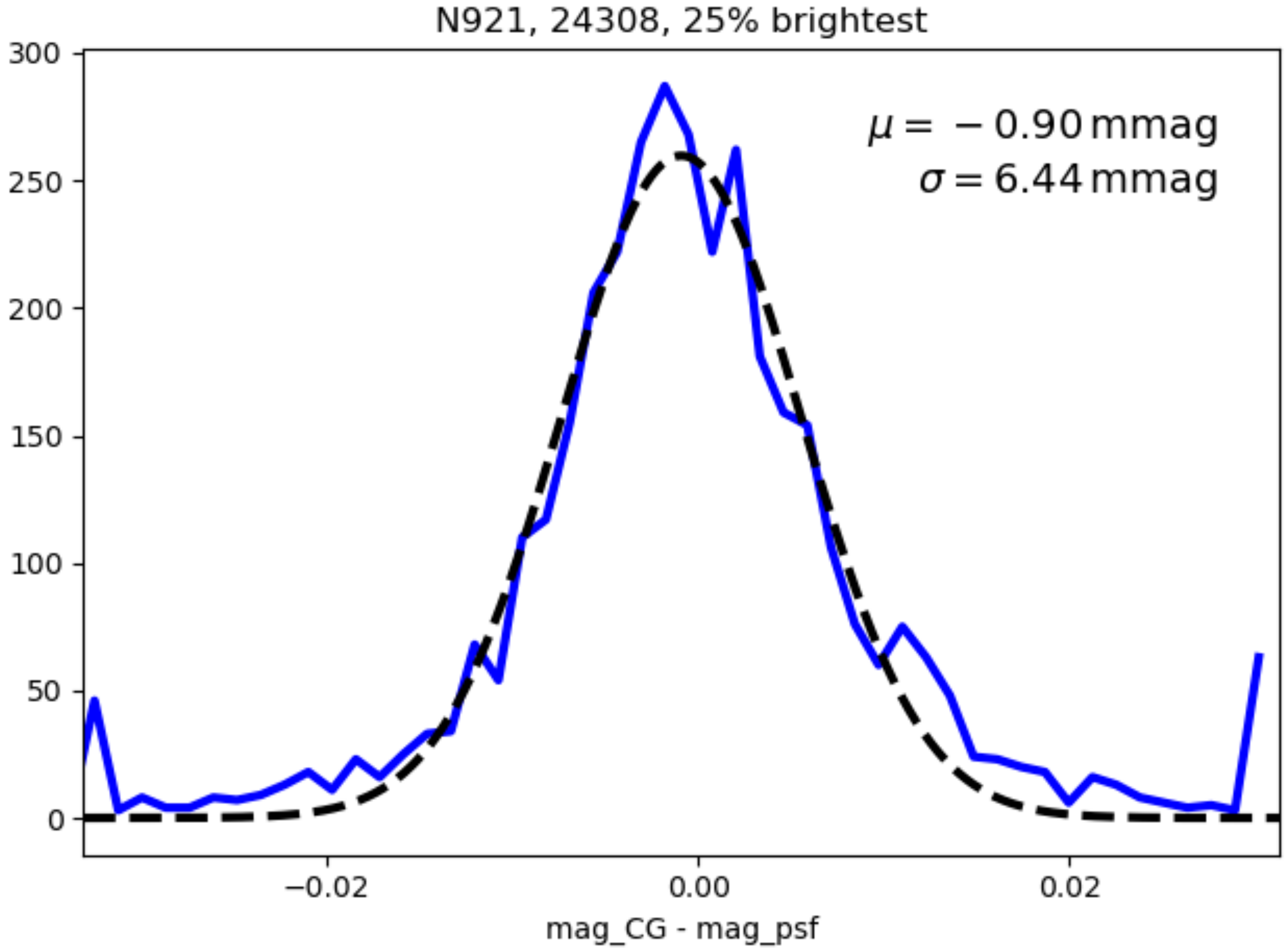

Are There Other Aperture Correction Options?

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- I looked, but couldn’t find any.
  - Using Compensated Top-hats (aperture - annulus) gives a variable amount of light loss depending on PSF wings, so is not a good reference. It’s noisy, so it’s not a great calibrator. But it does help with backgrounds!
    - Currently in fgcmcal I use a poor-person’s compensated top-hat. Fixing the background is an improvement, at least, but we still have to be careful to tie it to the reference.
  - Using the psf model and measuring the spatial variability there? (The “Rykoff Dream”)
    - Robert says this was done in SDSS but didn’t work well.
    - I tested it with HSC. Robert’s right. It doesn’t work well.
      - (Happy to discuss later)

Are There Other Aperture Correction Options?

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- I looked, but couldn't find any.
  - What about using the PSF fluxes for calibration?
    - They don't have large background issues (small footprint).
    - They don't have large spatial aperture corrections because they model the PSF.
    - We used PSF fluxes for DES and they worked a lot better than apertures.
    - But they still need to get tied to the large aperture, and the attendant problems with the background in that connection.
  - I'm at a loss.
    - Huh, decades of astronomers aren't wrong.
    - The large aperture is the simplest way of getting something that scales with total flux.

Are There Other Aperture Correction Options?

- I looked, but couldn’t find any.
  - But if you use the apertures … you have to stick to the brightest stars, and that just absolutely kills your density of calibrators.

- Proposal:
  - Compensated Gaussian
    - Can tune parameters, but 5/1.2 seems to work fine.
      - Too small and you get more spatial variation.
      - Too large and your integration footprint is unwieldy.
    - Tie to uncompensated top-hat aperture for brightest stars.
    - One number per detector to get normalization.
    - Let FGCM figure out the rest.

Performance with FGCM on HSC RC2

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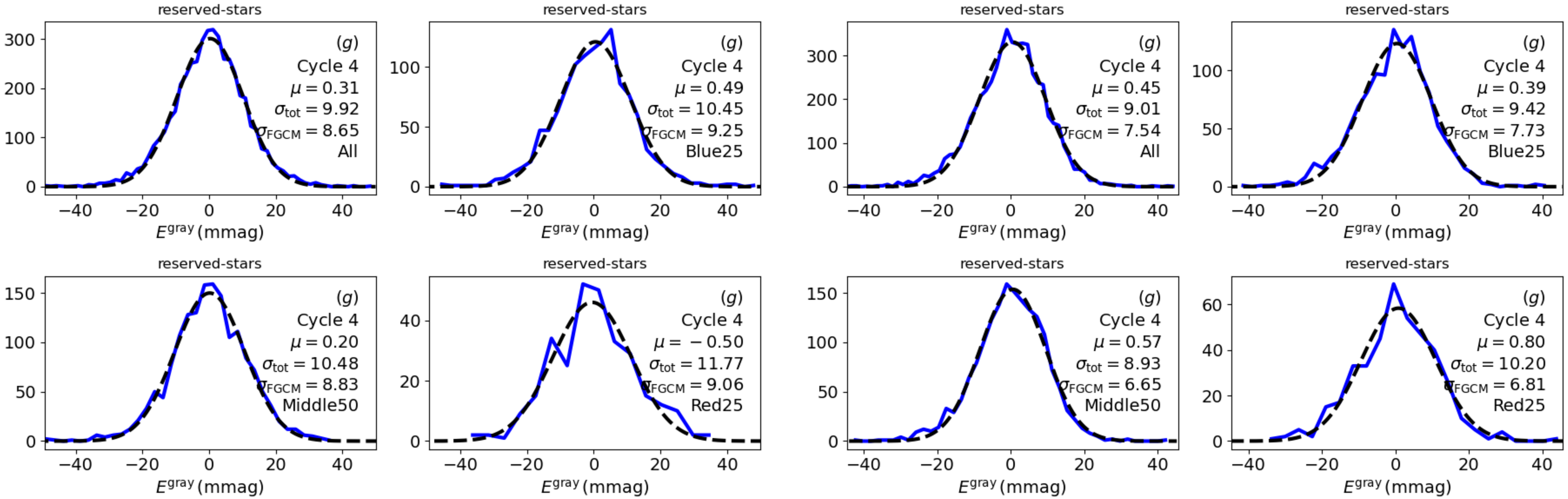
- Model repeatability is improved!



Aperture (bkg corrected)

Compensated Gaussian

Performance with FGCM on HSC RC2

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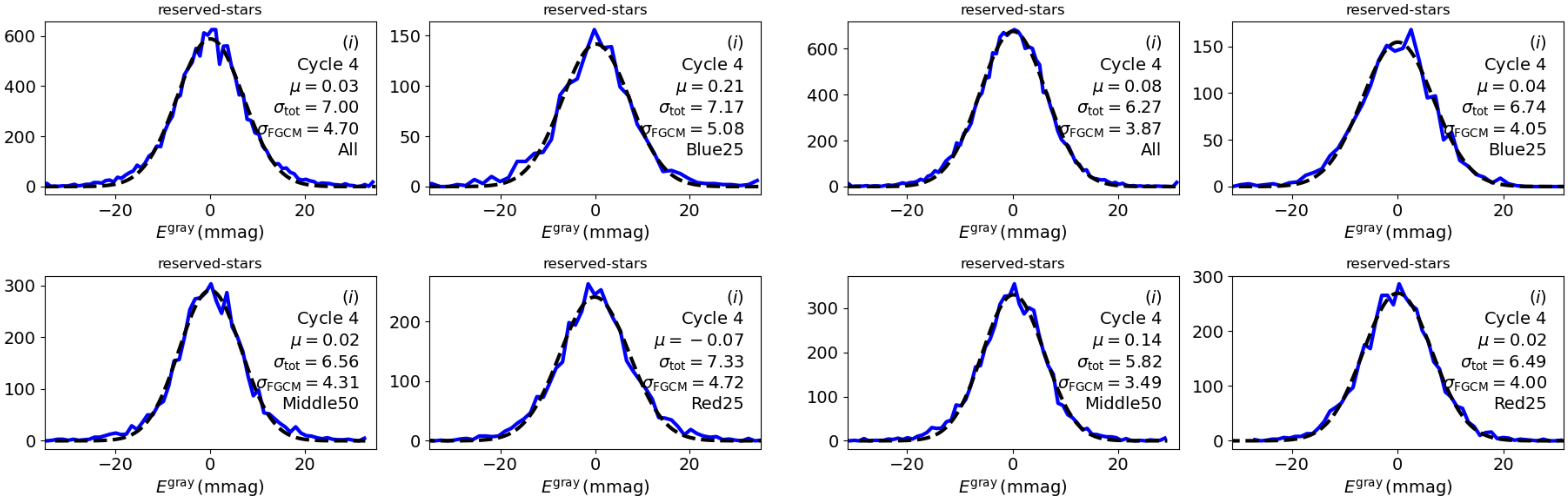


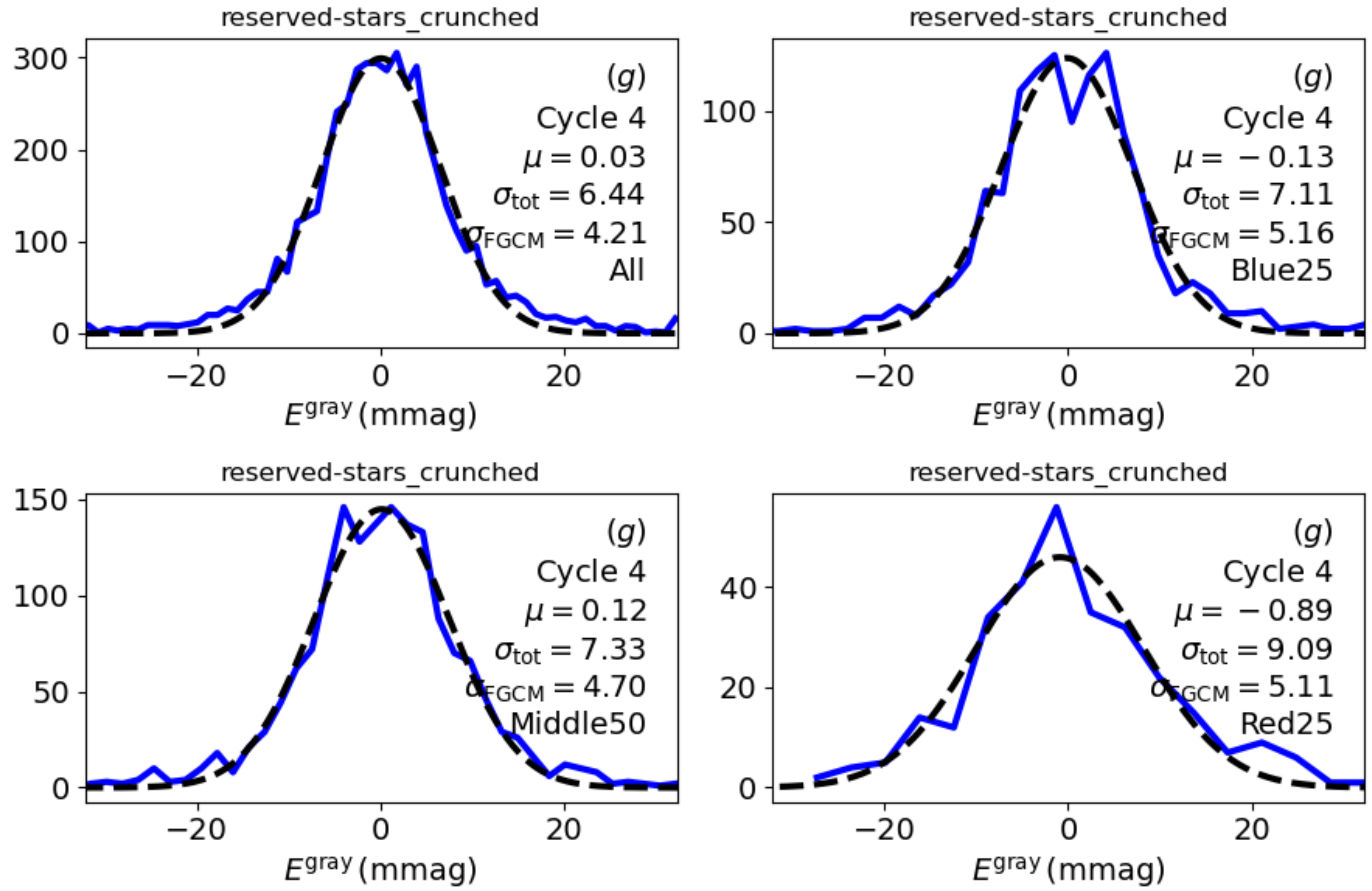
Aperture (bkg corrected)

Compensated Gaussian

Performance with FGCM on HSC RC2

Rubin Observatory

- Final repeatability is improved!



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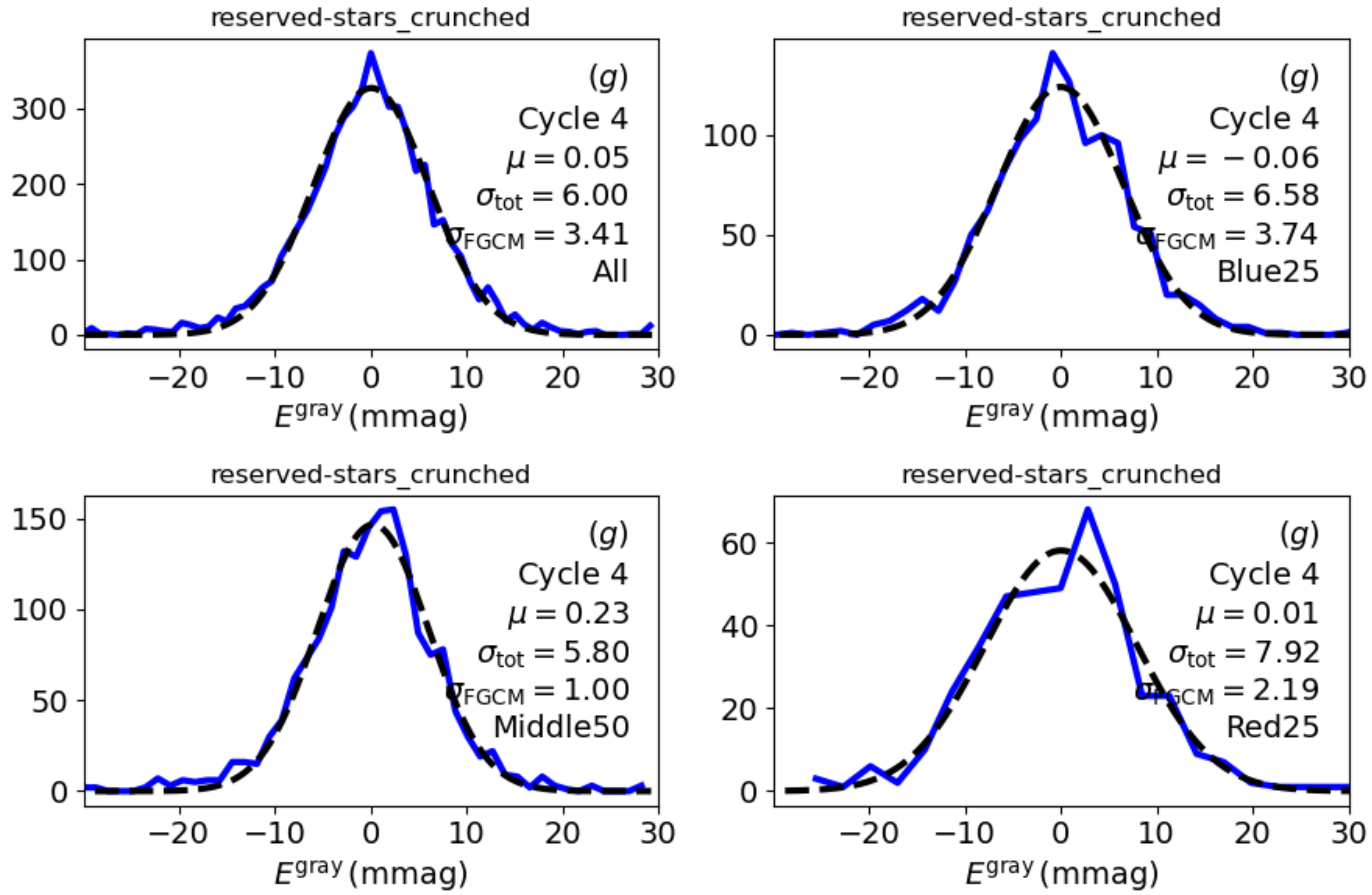

Compensated Gaussian

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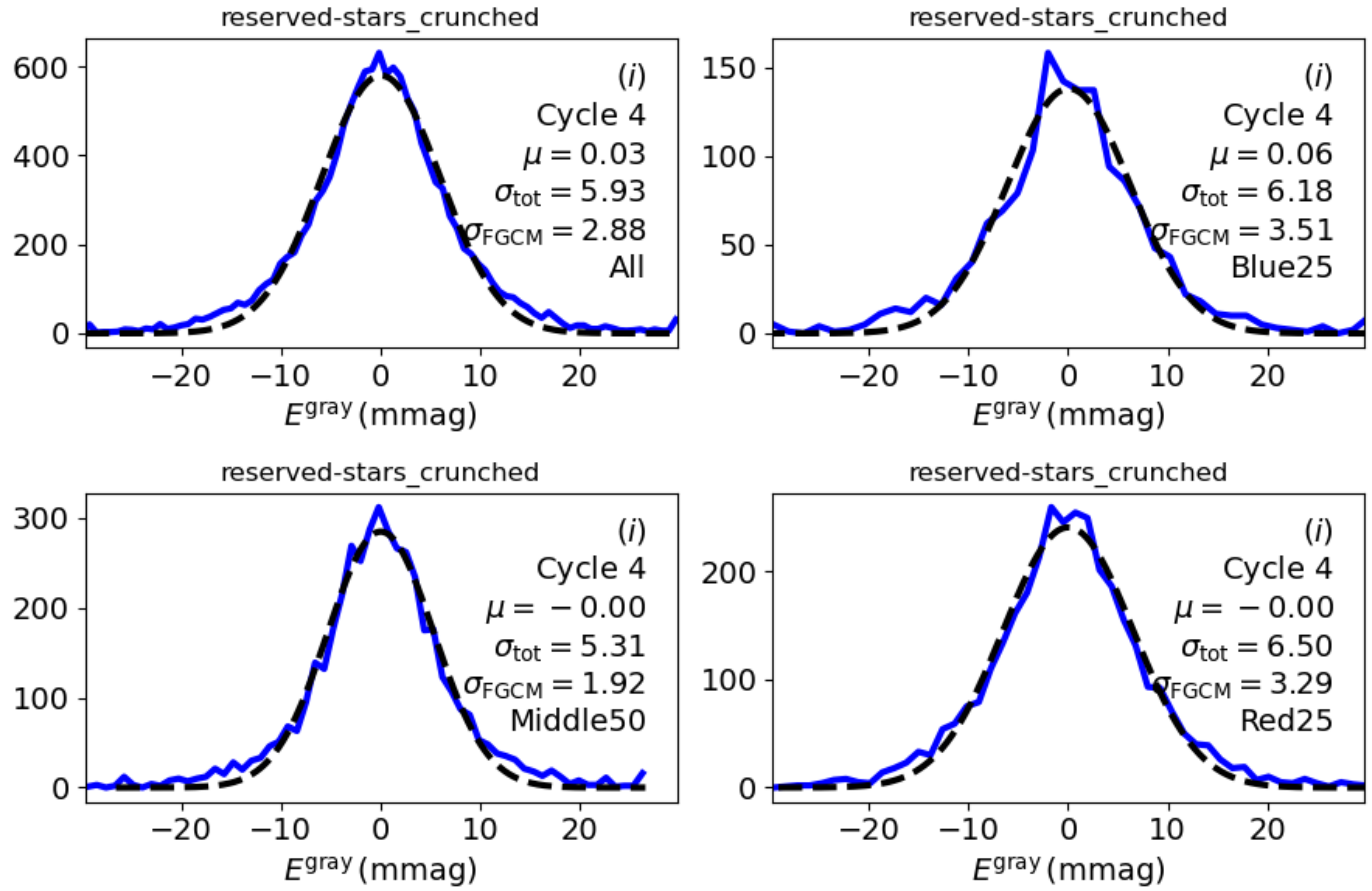

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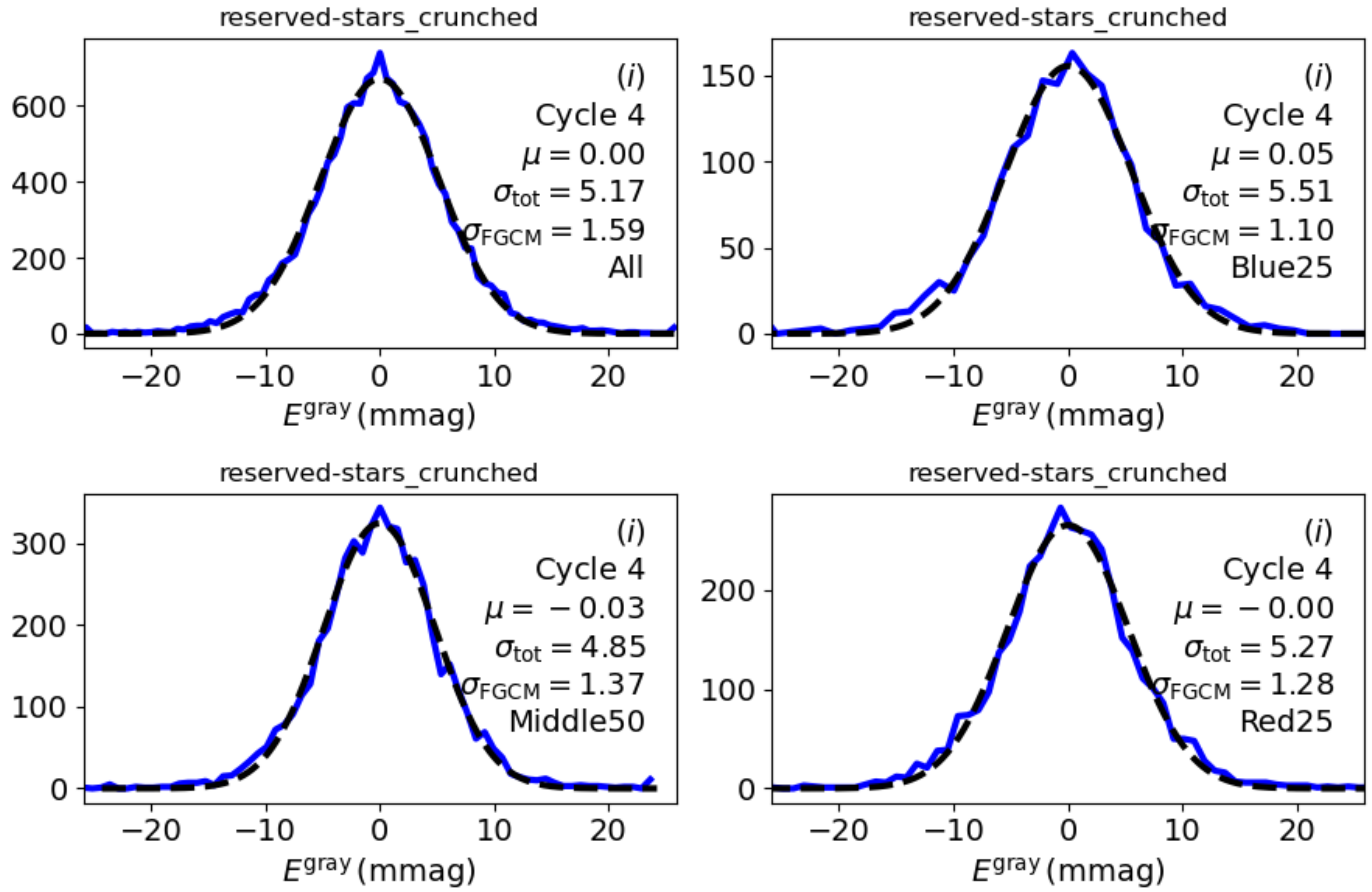

Compensated Gaussian

Performance with FGCM on HSC RC2

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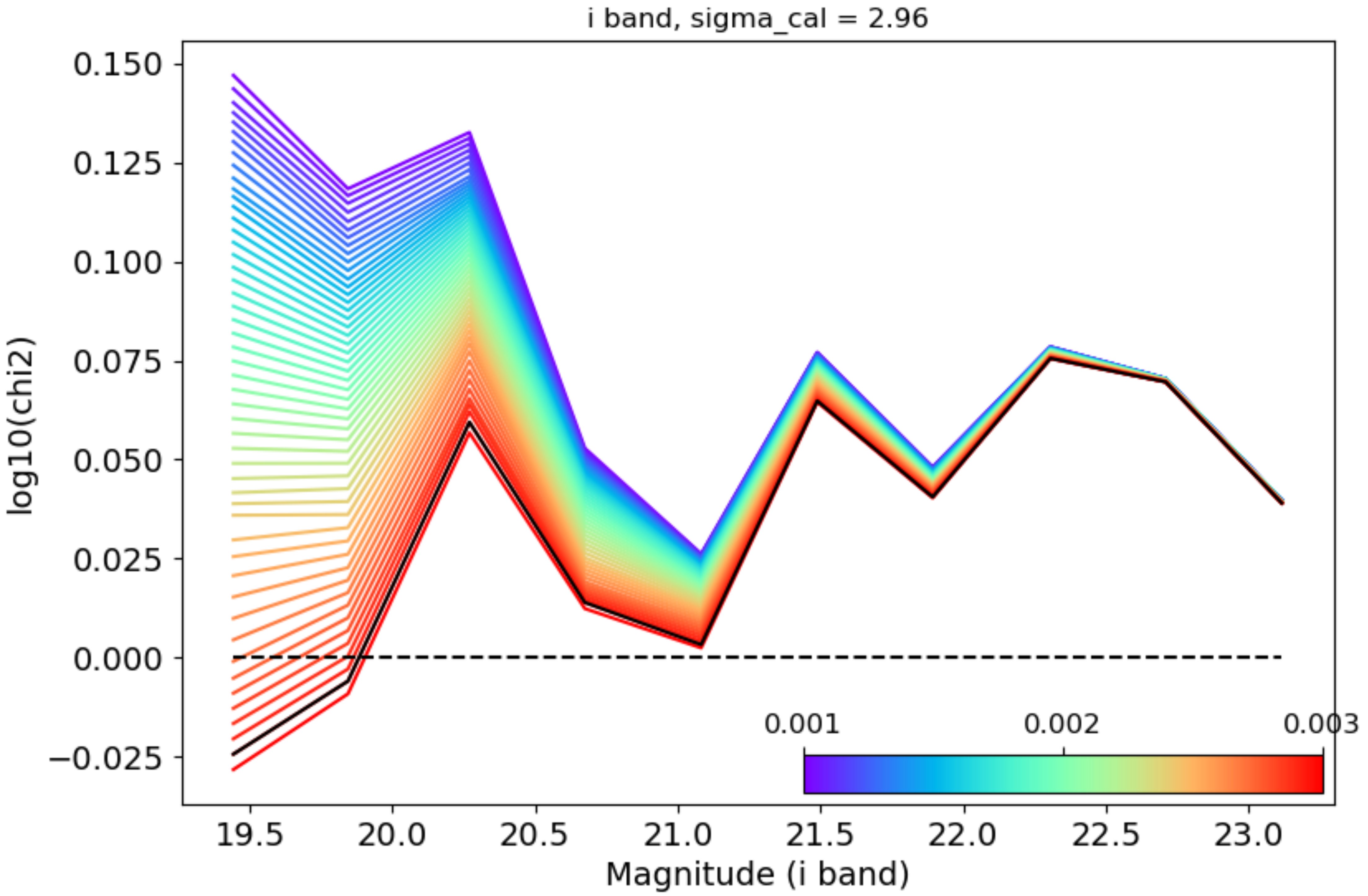
- But something about the quoted errors is not right.



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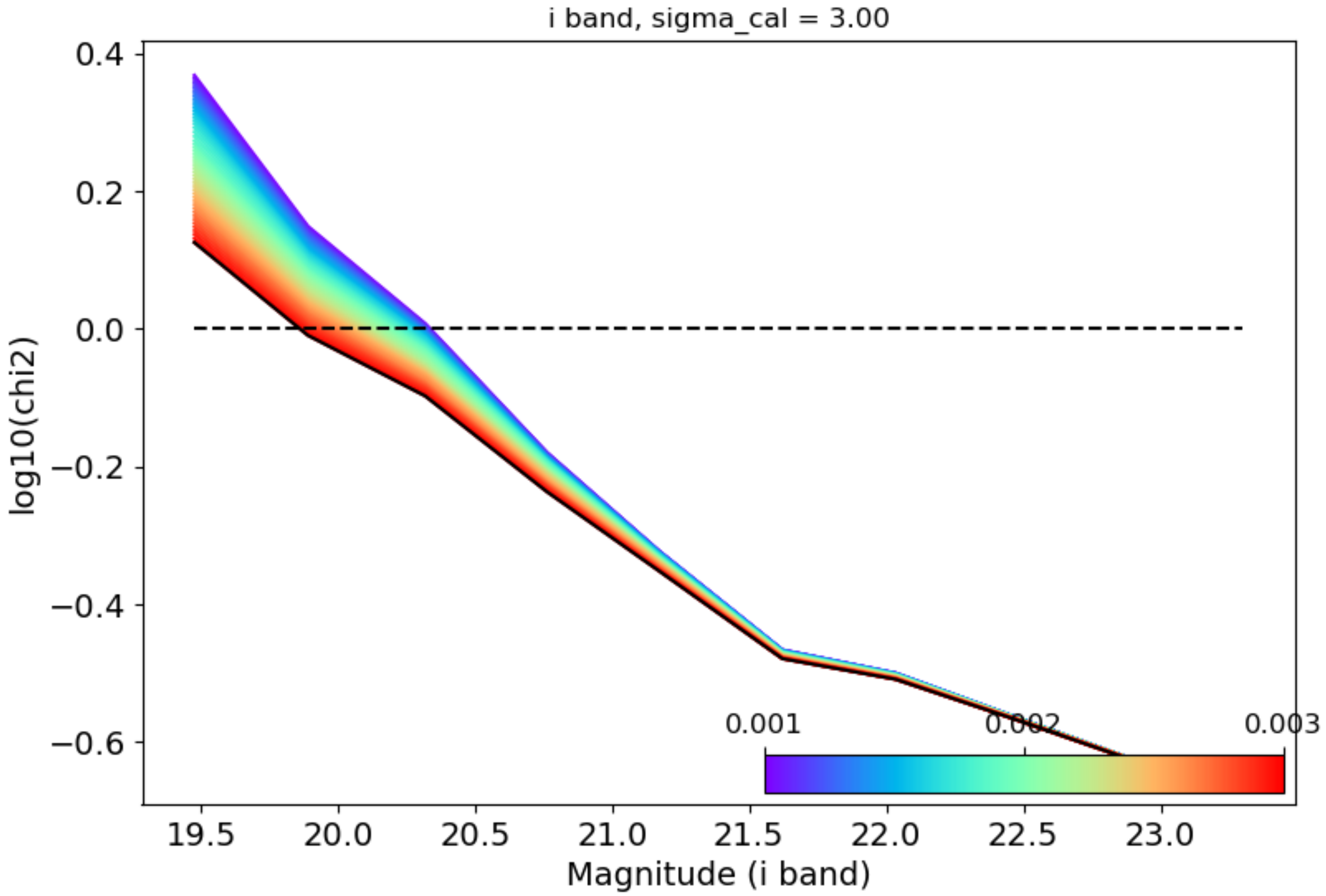

Compensated Gaussian

Next Steps

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- Figure out what's up with the error estimation according to FGCM
  - The sims seem to say the error is "basically" correct, but need to concentrate on fainter stars I think. (I checked for obvious bugs, didn't find any.)
- Investigate other parameters for the CG
  - I don't think it will matter too much, but worth a small investigation
- Work out implementation
  - We would want to run CG on each detector and then normalize it using bright stars with large aperture measurements. New normalization task I guess?
  - The "Normalized Compensated Gaussian" would then be the basis for the photometric calibration (SFM and global)
    - Aperture corrections will use NCG fluxes
    - We don't have to worry about the background issues when computing aperture corrections, which doubles number of stars used!