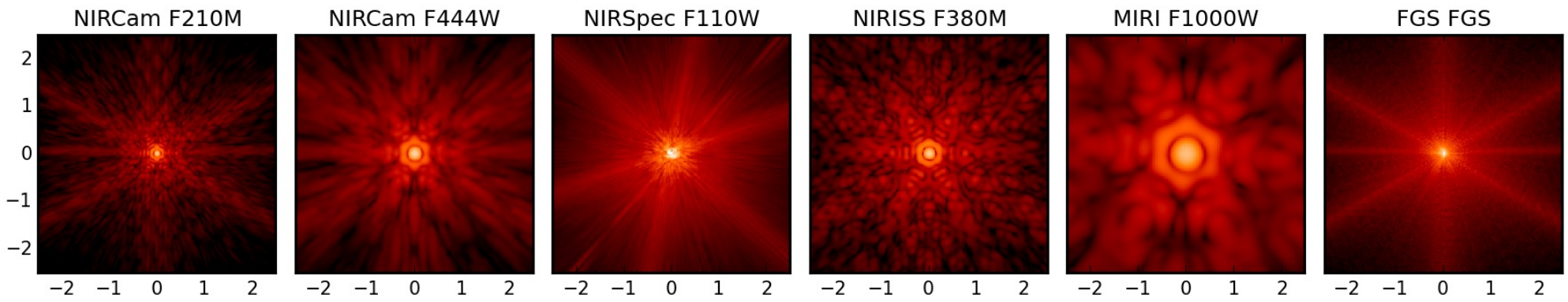


Empirical Characterization of the NIRCam Point Spread Function

Jacqueline McCleary

Northeastern University

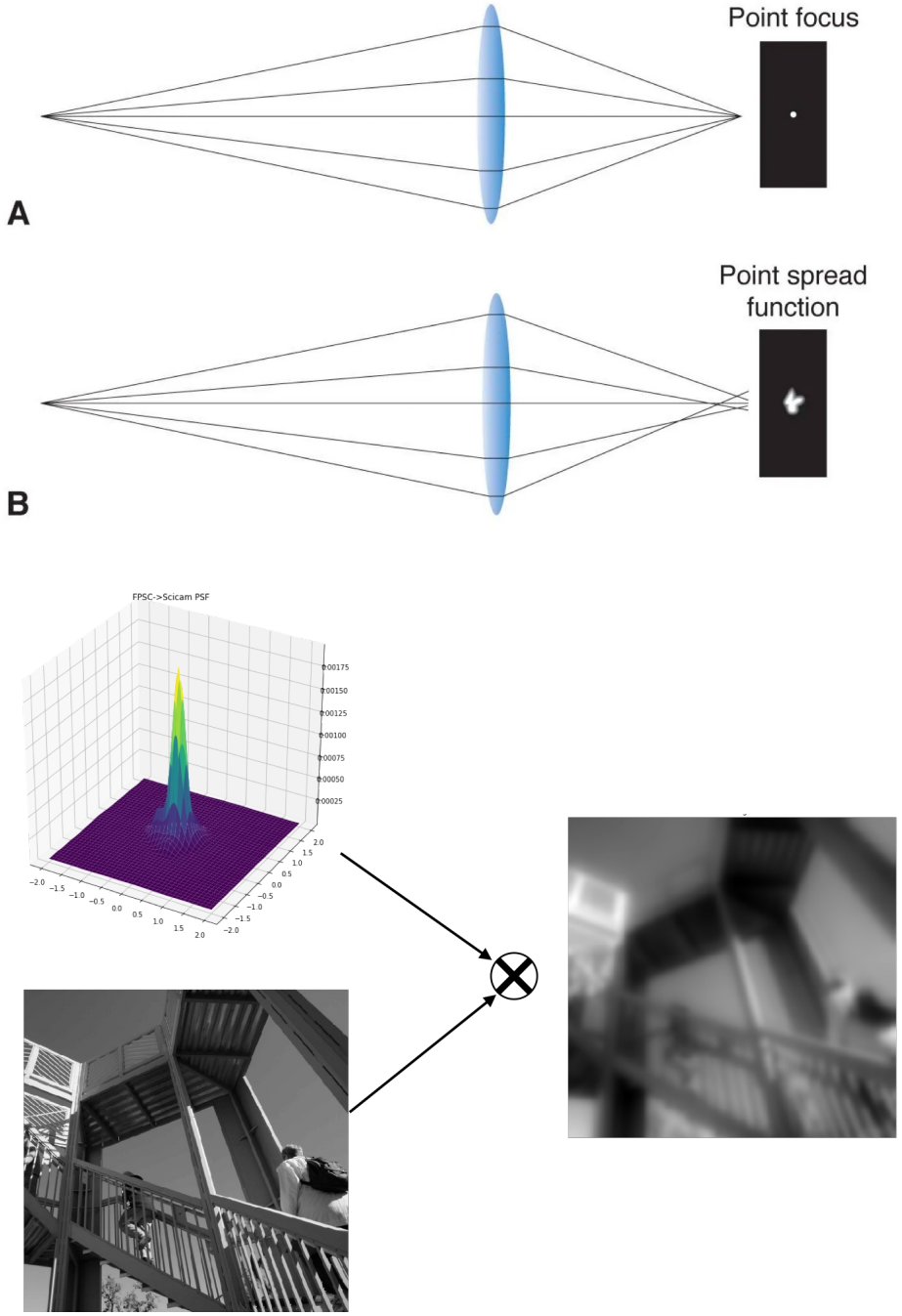


Figure credit M. Shaaban (UToronto)

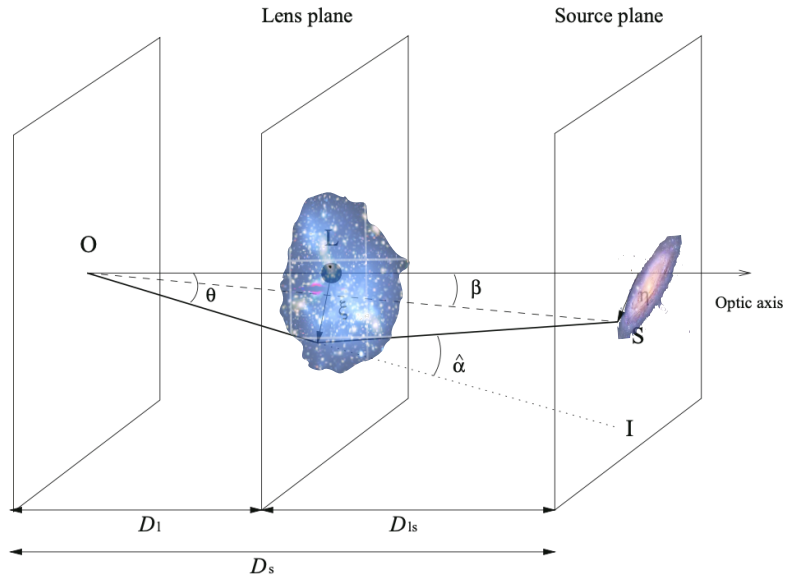
Point spread function: shears and smears

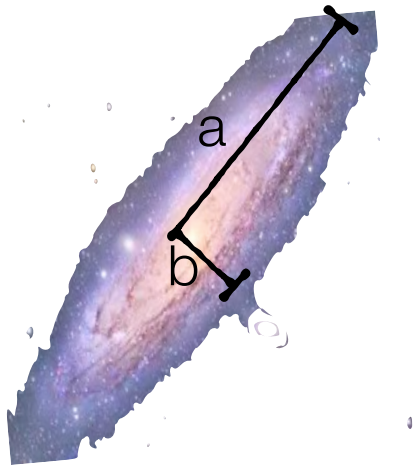
Diffraction, atmospheric turbulence, and telescope optics refract and distort incoming light.

Result: plane waves from distant object become incoherent

Gravitational Lensing

The observable





$$\boldsymbol{e} = e_1 + ie_2,$$

$$e_1 = e\,\cos(2\theta)\, e_2 = e\,\sin(2\theta),$$

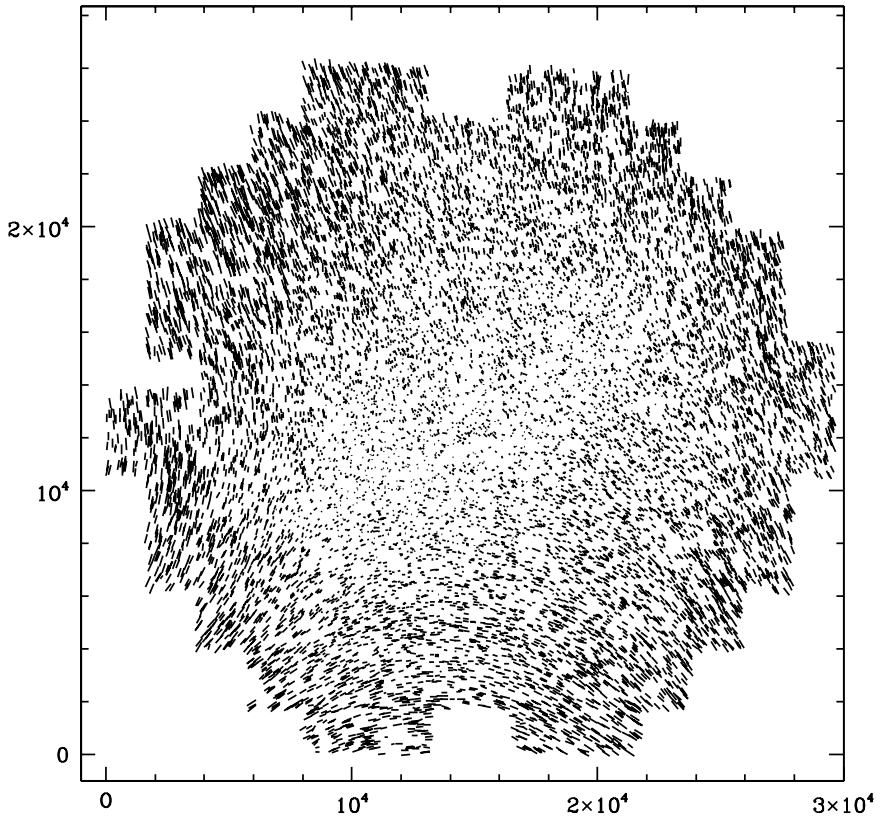
$$e = \frac{a-b}{a+b}$$

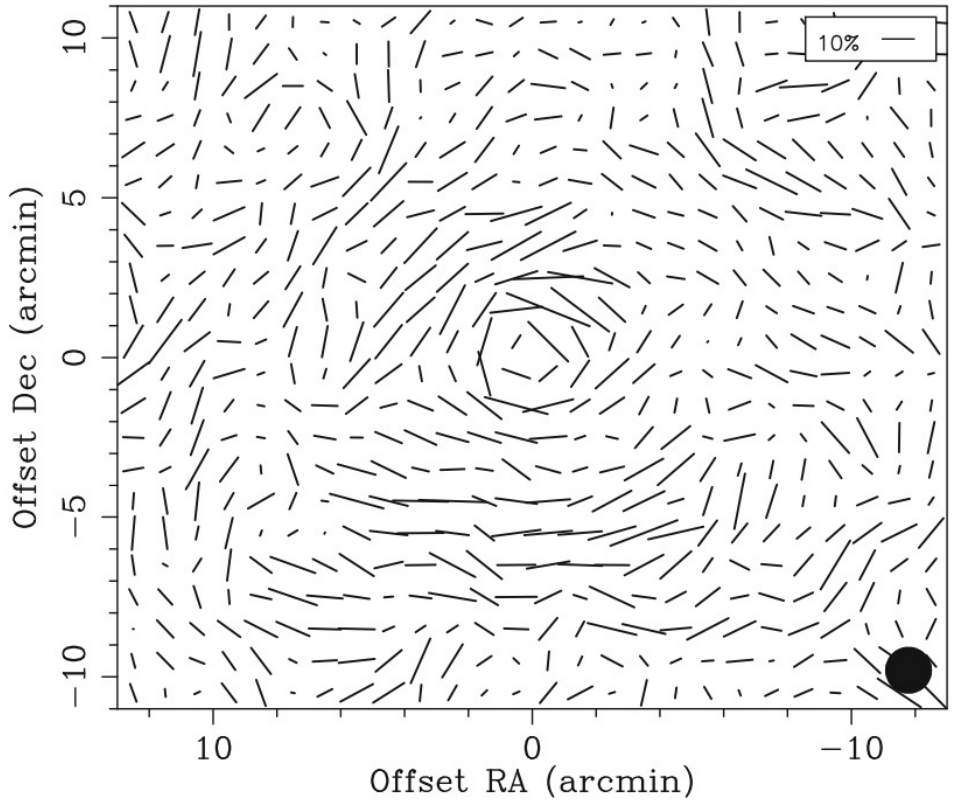
↓ Weak lensing regime

$$\gamma \simeq g \simeq \frac{\langle e \rangle}{2}$$

Observable for shear is galaxy *ellipticity* e,

which is estimator for shear γ of gravitational lens in the limit of weak lensing.





PSF characterization: crucial for weak lensing

Pros and cons of popular PSF modeling tools

PSFEx

Pro:

- Lightning fast
- Robust to WCS errors
- Widely used

Con:

- "Size bias"
- No astrometric distortion
- Opaque code

PIFF

Pro:

- Fancy diagnostics
- Python: readable
- Astrometric distortion

Con:

- Python: s l o w
- Still under active development

WebbPSF

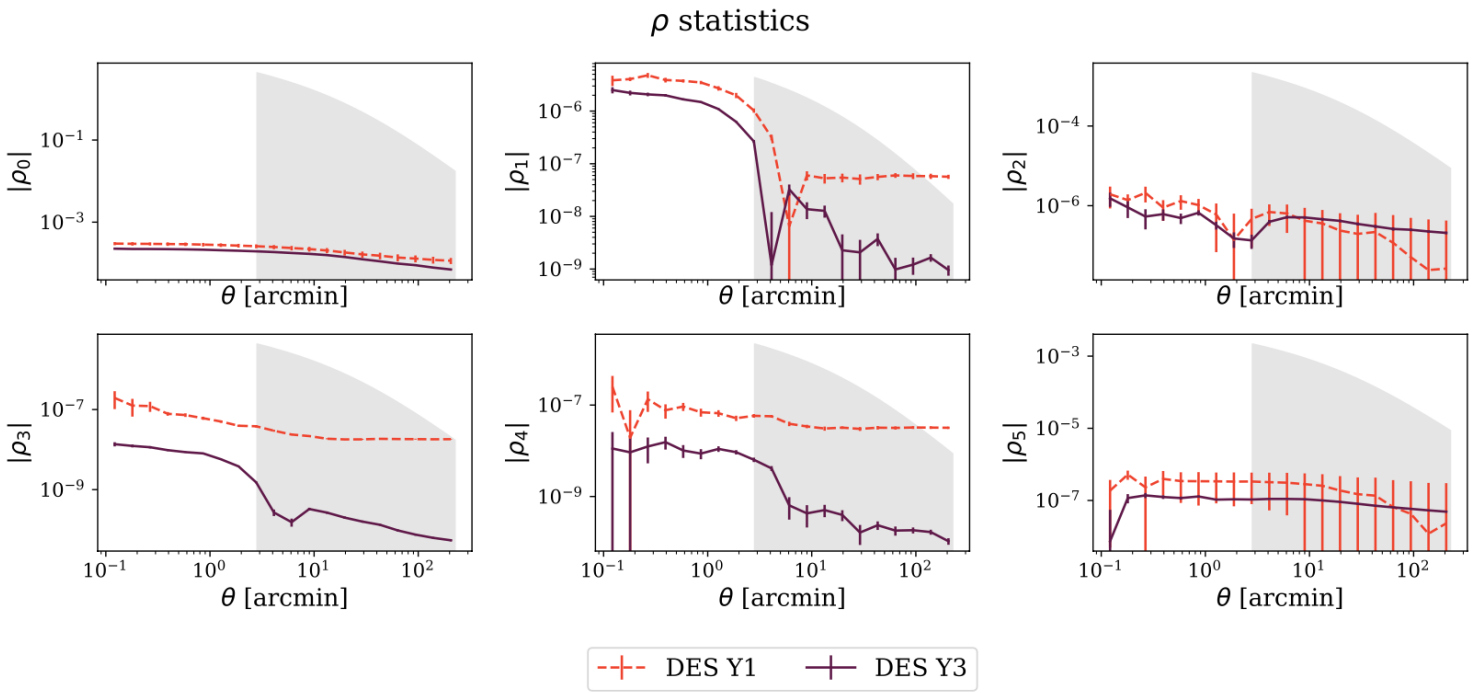
Pro:

- Deterministic, noiseless
- High detail, highly robust

Con:

- **Can miss real but unknown PSF features**
- Inflexible

PIFF: PSFs in the Full FOV



M. Jarvis et al. 2021

DES Y1 analysis conducted with PSFEx showed small but real offset between PSF model size and star size.

Residuals also showed spatial pattern related to astrometric distortion solution

PIFF implemented in DES Y3

- describes PSF in astrometric coordinates
- written in Python
- allows "multi-chip" fitting when observations are homogeneous

DES Y3 systematics < DES Y1 (PSFEx)

Rho statistics: correlation of PSF size and shape residuals

$$\rho_1(\theta) \equiv \langle \delta e^*_{\rm PSF}(\boldsymbol{x}) \delta e_{\rm PSF}(\boldsymbol{x}+\boldsymbol{\theta}) \rangle \tag{17}$$

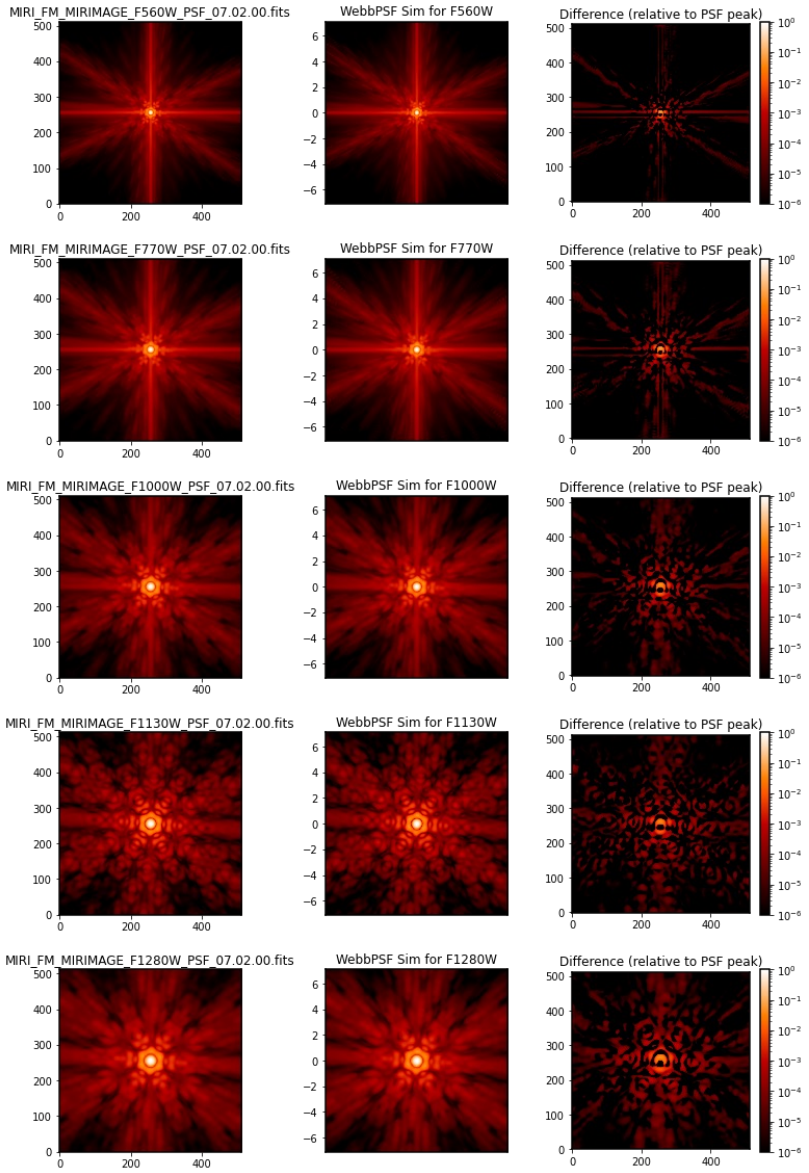
$$\rho_2(\theta) \equiv \langle e^*_{\rm PSF}(\boldsymbol{x}) \delta e_{\rm PSF}(\boldsymbol{x}+\boldsymbol{\theta}) \rangle \tag{18}$$

$$\rho_3(\theta) \equiv \left\langle \left(e^*_{\rm PSF} \frac{\delta T_{\rm PSF}}{T_{\rm PSF}} \right)(\boldsymbol{x}) \left(e_{\rm PSF} \frac{\delta T_{\rm PSF}}{T_{\rm PSF}} \right)(\boldsymbol{x}+\boldsymbol{\theta}) \right\rangle \tag{19}$$

$$\rho_4(\theta) \equiv \left\langle \delta e^*_{\rm PSF}(\boldsymbol{x}) \left(e_{\rm PSF} \frac{\delta T_{\rm PSF}}{T_{\rm PSF}} \right)(\boldsymbol{x}+\boldsymbol{\theta}) \right\rangle \tag{20}$$

$$\rho_5(\theta) \equiv \left\langle e^*_{\rm PSF}(\boldsymbol{x}) \left(e_{\rm PSF} \frac{\delta T_{\rm PSF}}{T_{\rm PSF}} \right)(\boldsymbol{x}+\boldsymbol{\theta}) \right\rangle \tag{21}$$

Here $e_{\rm PSF}$ is the ellipticity of the real PSF, i.e., the star ellipticity; $T_{\rm PSF}$ is the size of the real PSF; $\delta e_{\rm PSF}$ is the difference between the ellipticity of the real and model PSFs at position $\boldsymbol{x}$; and $\delta T_{\rm PSF}$ is the difference between the sizes of the real and model PSFs at position $\boldsymbol{x}$. Brackets denote averages over all pairs within a separation $\boldsymbol{\theta}$,



Gaussian and non-parametric diagnostics

- Typical PSF diagnostics are quantities measured from elliptical Gaussians
- Acceptable for ground-based PSFs and galaxy shears, but not for complex PSFs like NIRCam
- Consider both residual-based approaches and classic PSF metrics

Diagnostics calculated

Gaussian

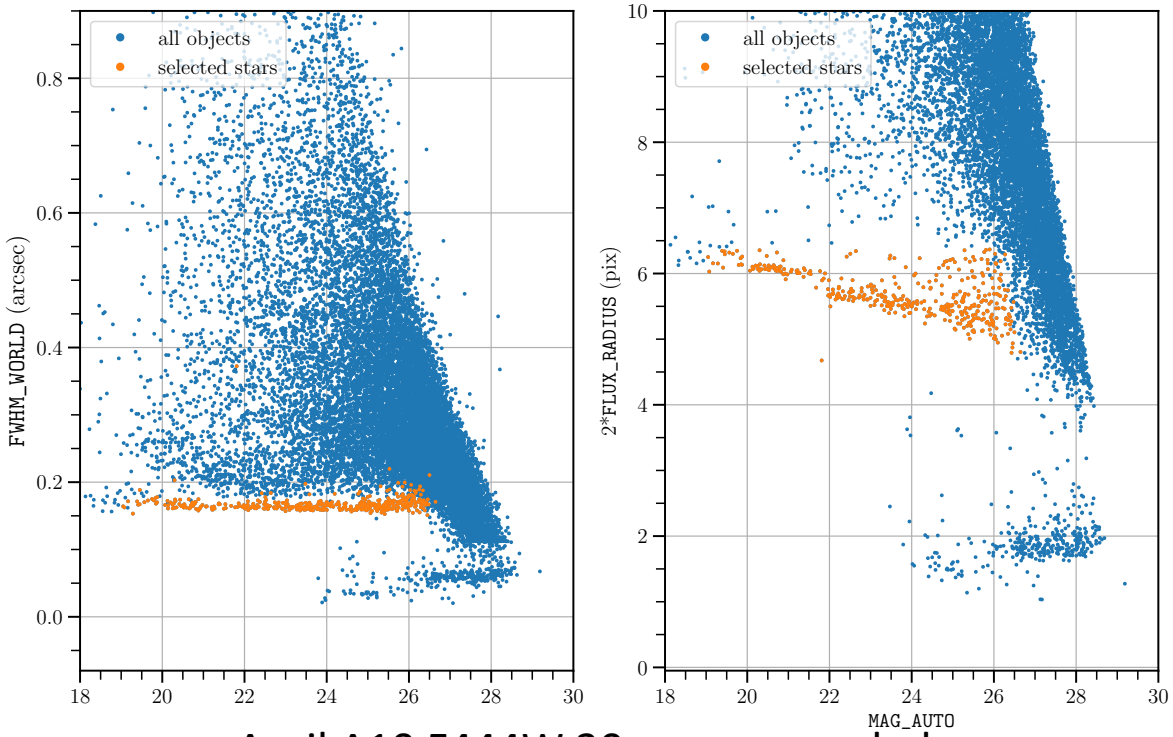
- Shear sticks (whisker) plots of star ellipticity & orientation
- ρ-statistics: correlating residuals
- FWHM & ellipticity E-mode and B-mode maps*
- FWHM & ellipticity 2-D histograms

Non-parametric

- χ^2 maps* and stacked values for all observed stars
- Star-PSF flux residuals, stacked for all observed stars
- γ_T, $\gamma_\times$ around stars*

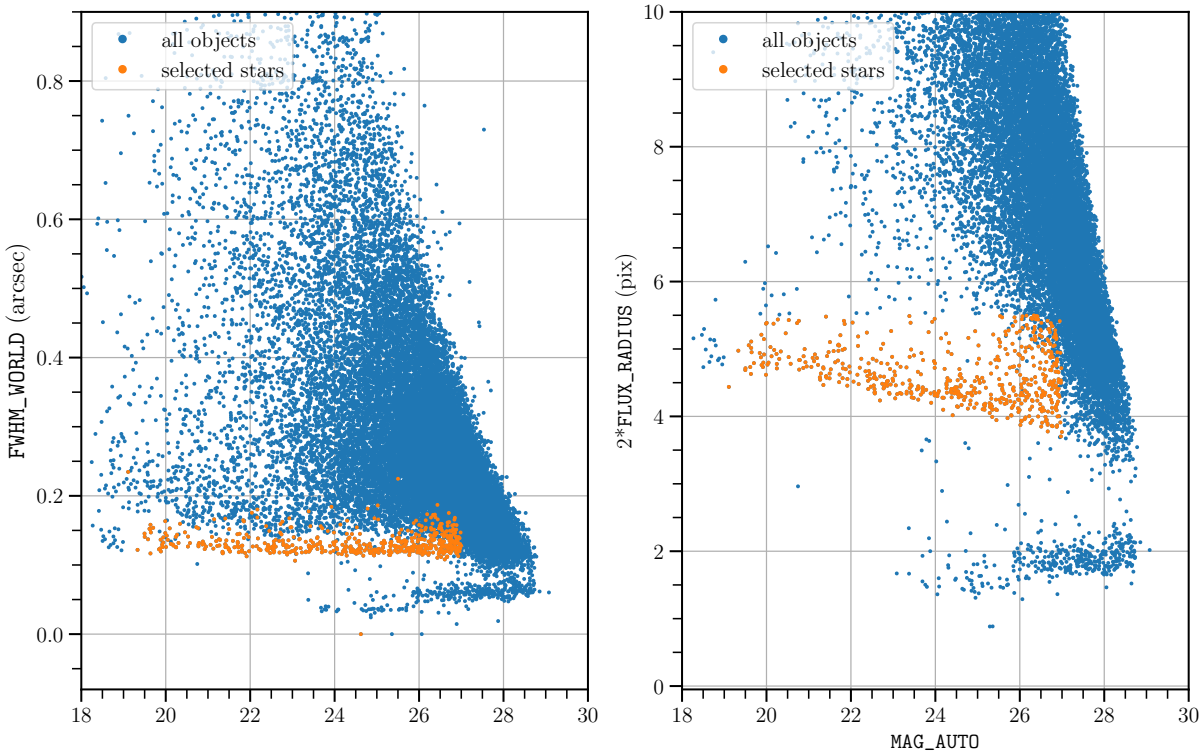
Empirical approach to making PSF models

- Take set of NIRCam exposures or mosaics, *empirically* identify stellar locus and create star catalog
- Run PSFEx and PIFF on stellar locus with range of parameters (allow cleaning)
- Create renderings of models at star locations
- Evaluate models against detected stars using pre-determined diagnostics

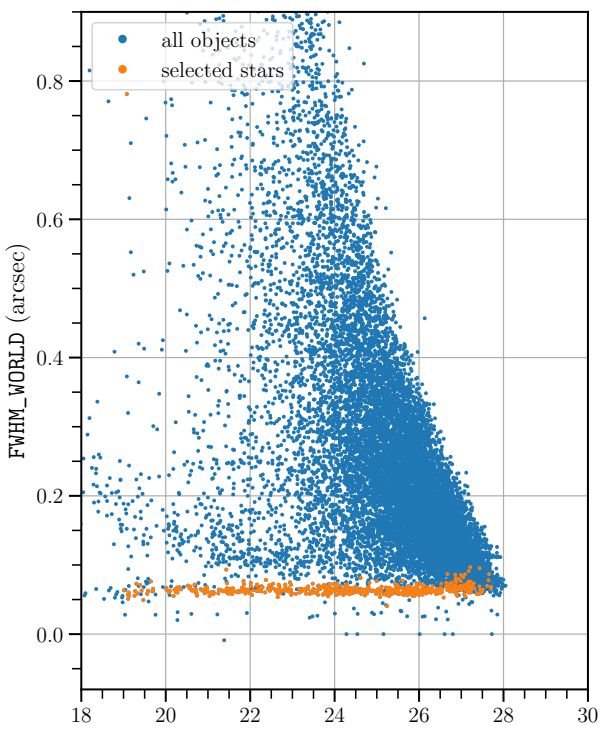


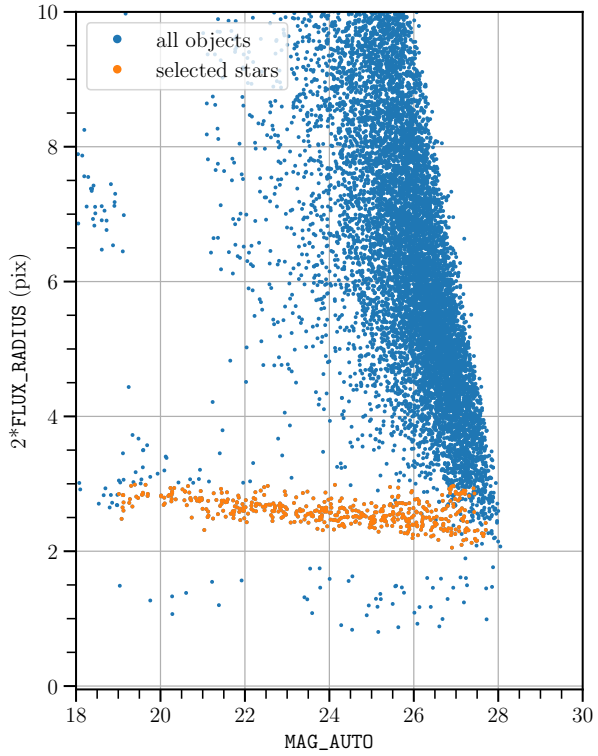
April A10 F444W 30 mas resampled

Check out `cweb_psf` here: https://github.com/mcclearyj/cweb_psf

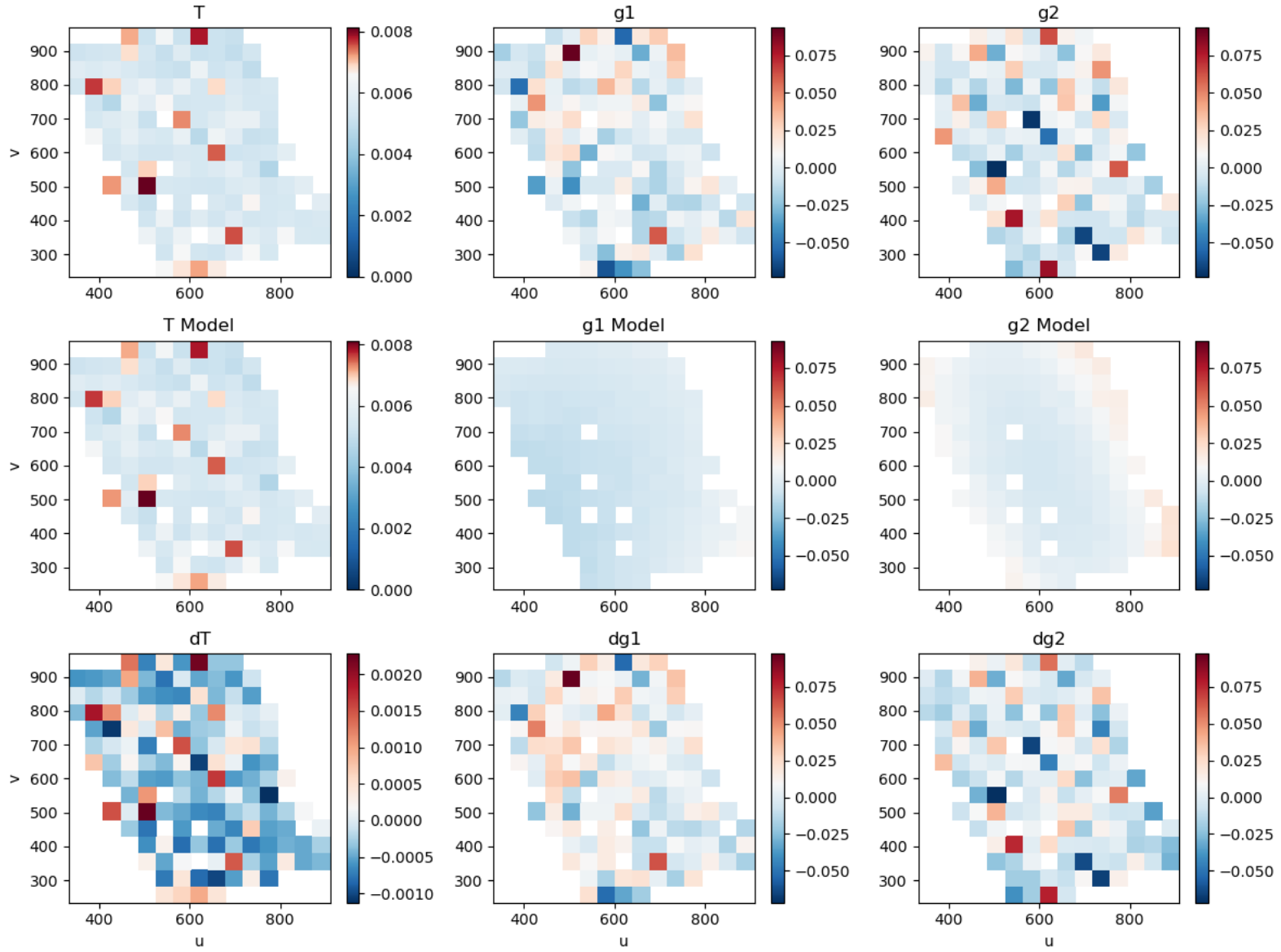


April A10 F277W 30 mas resampled

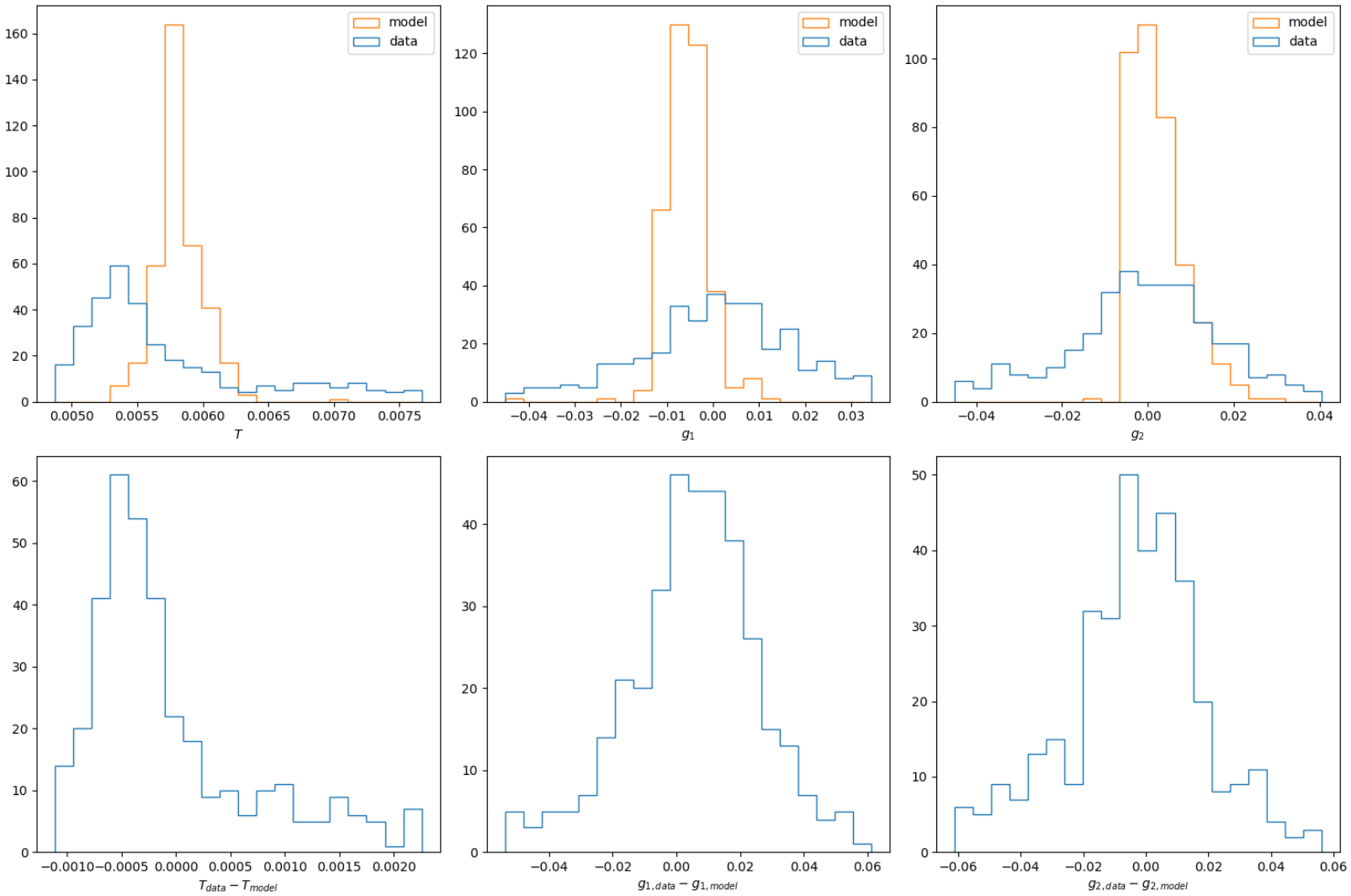




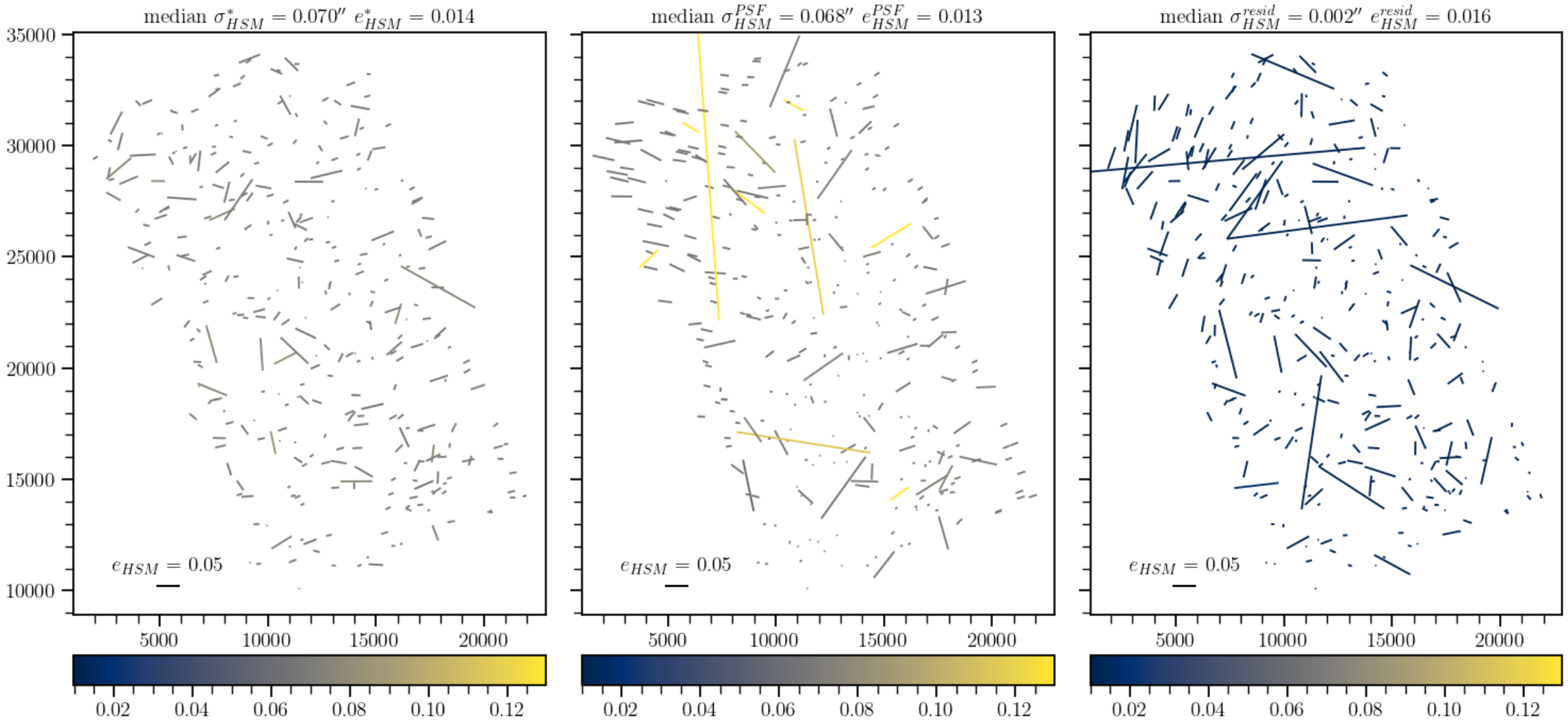
April A10 F150W



Size (T) and ellipticity component (g1/g2) 2D histograms for PIFF fit

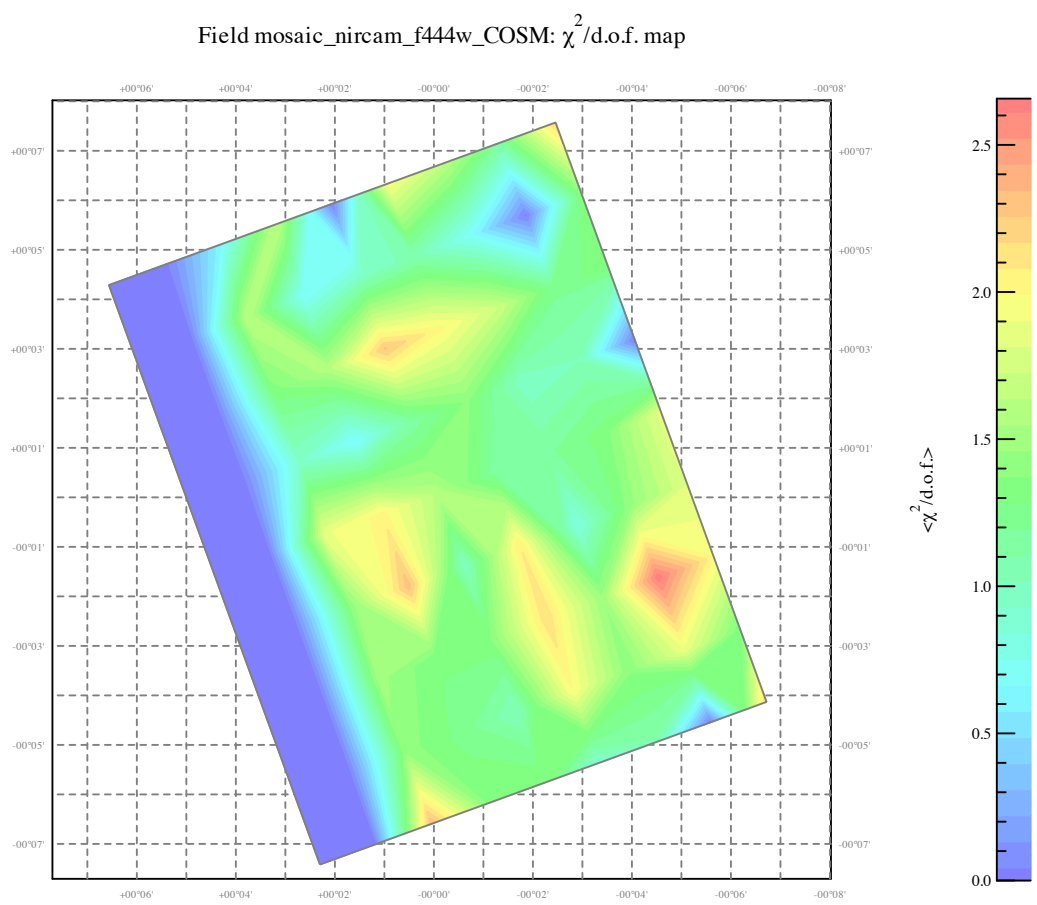


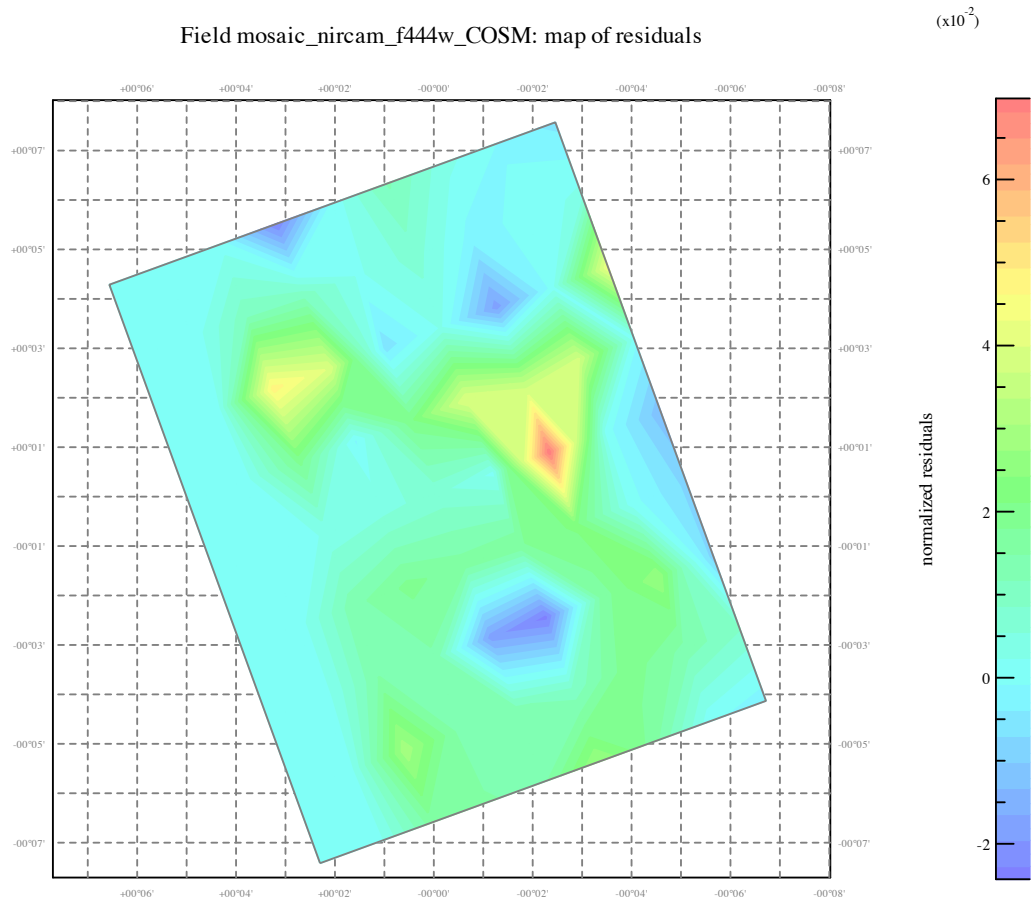
Size (T) and ellipticity component (g1/g2) histograms for PIFF fit



Shear sticks:

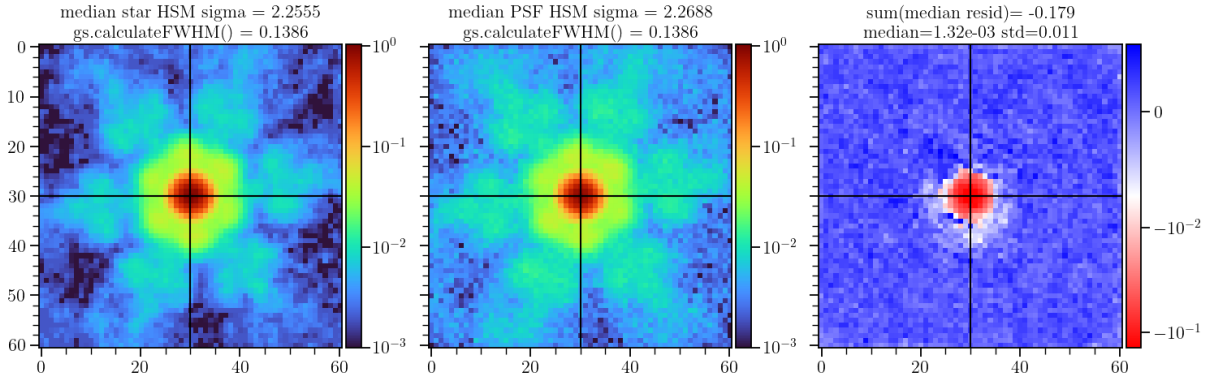
- Stick length = ellipticity, orientation = angle of ellipse.
- Left to right: stars, PSF model, residuals

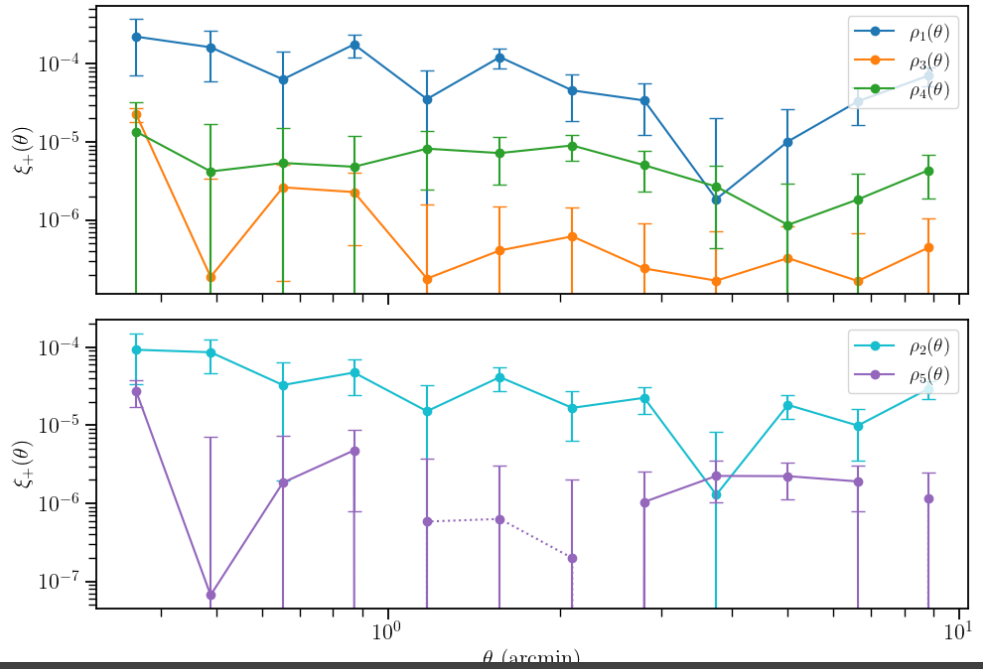


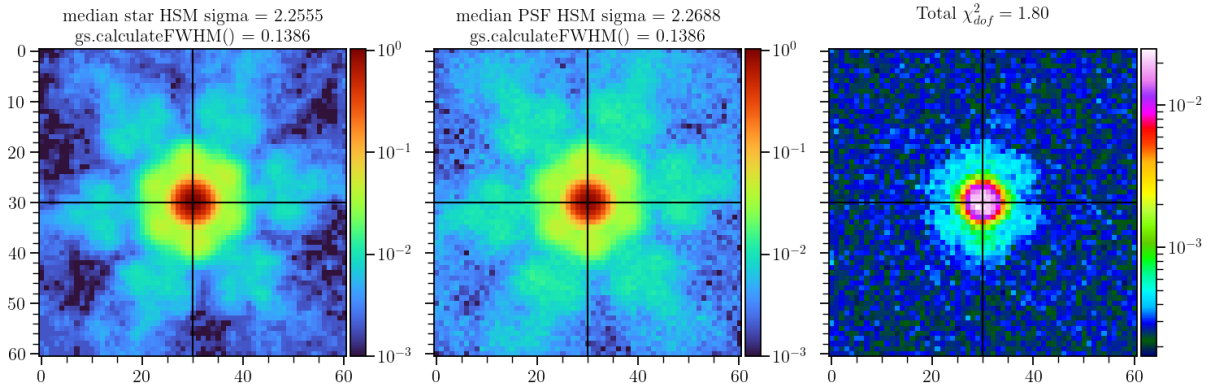


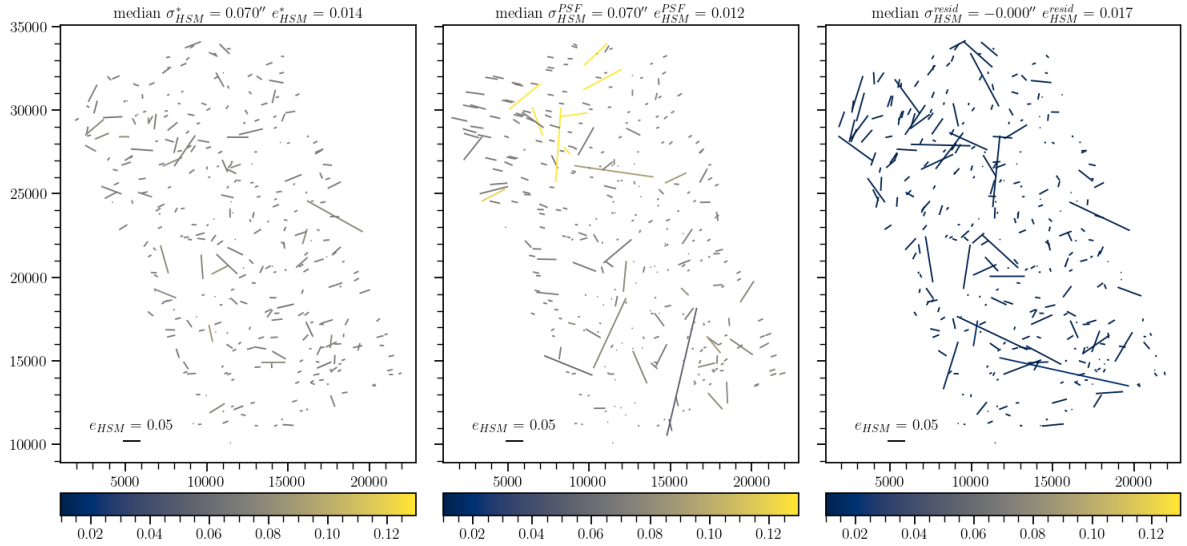
χ^2 and norm. residuals map over FOV, output by PSFEx

Example of a “better” psfex fit for f444w: esheldon/psfex rendering

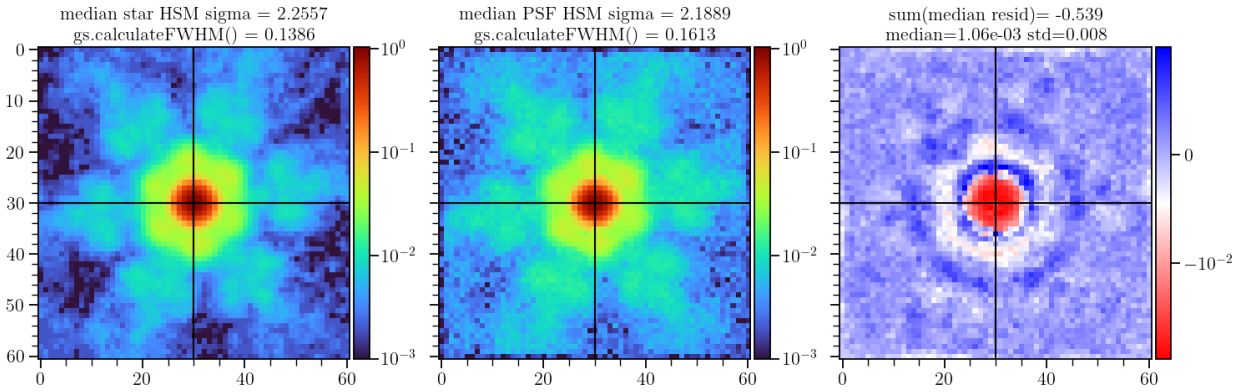


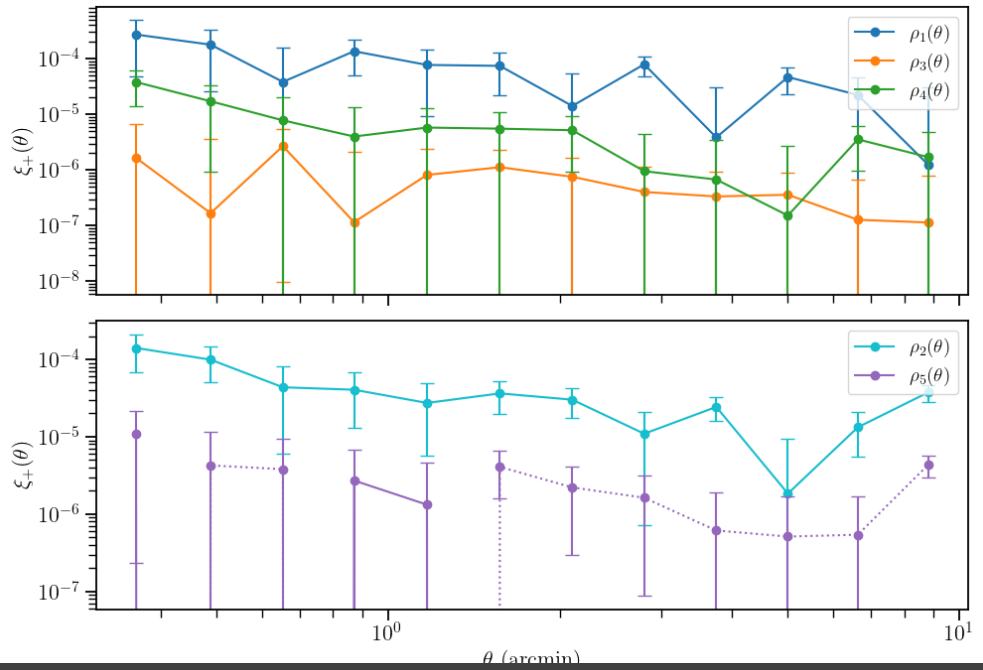


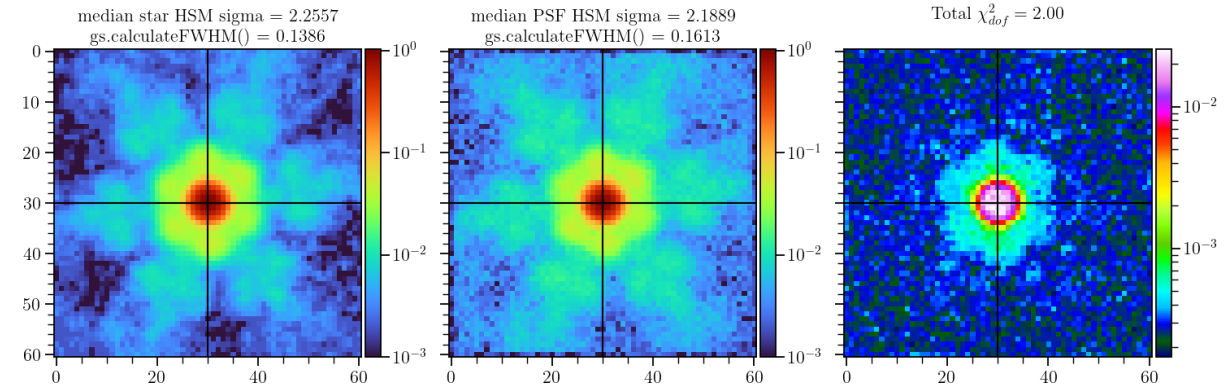


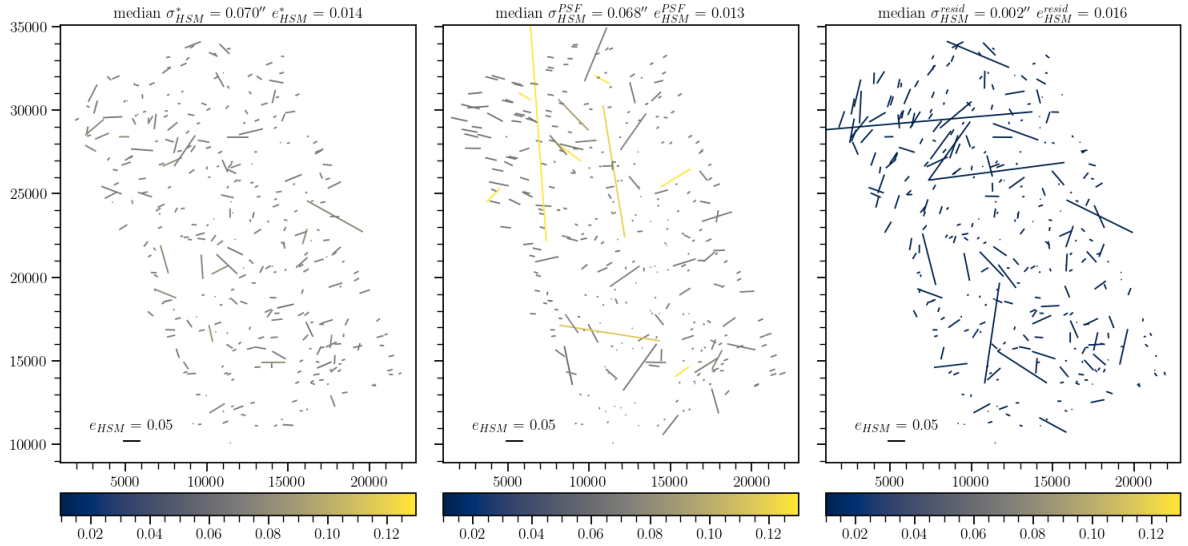


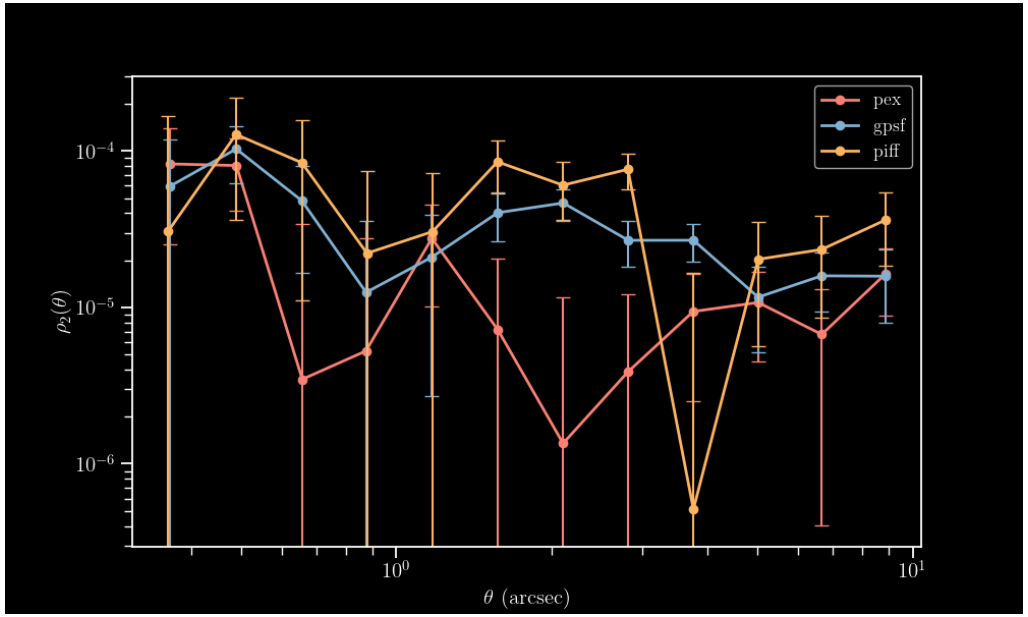
Example of a “better” psfex fit for f444w: galsim.DES_PSFEx rendering

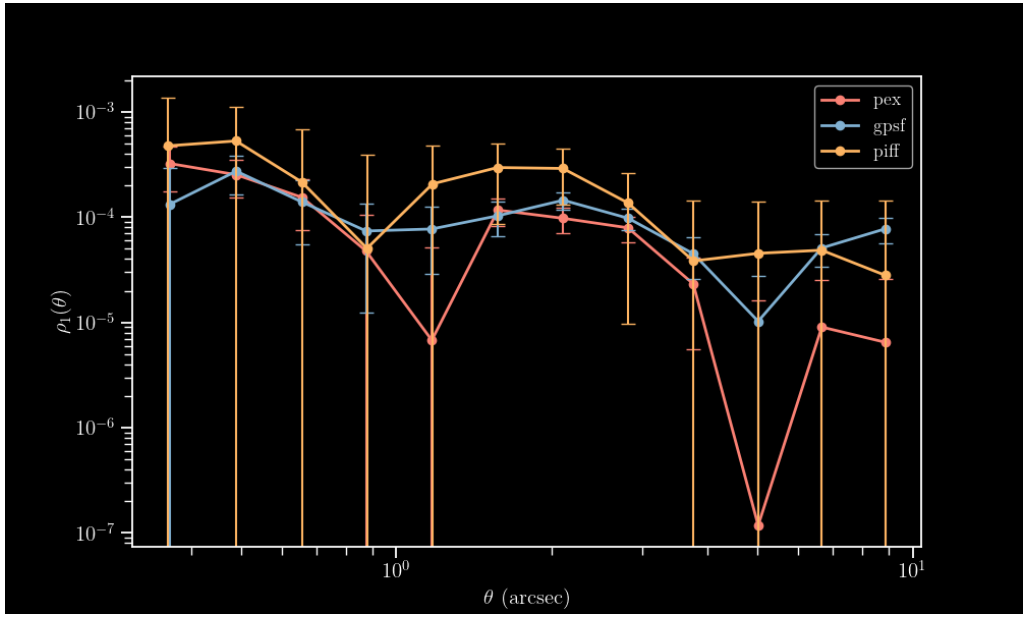


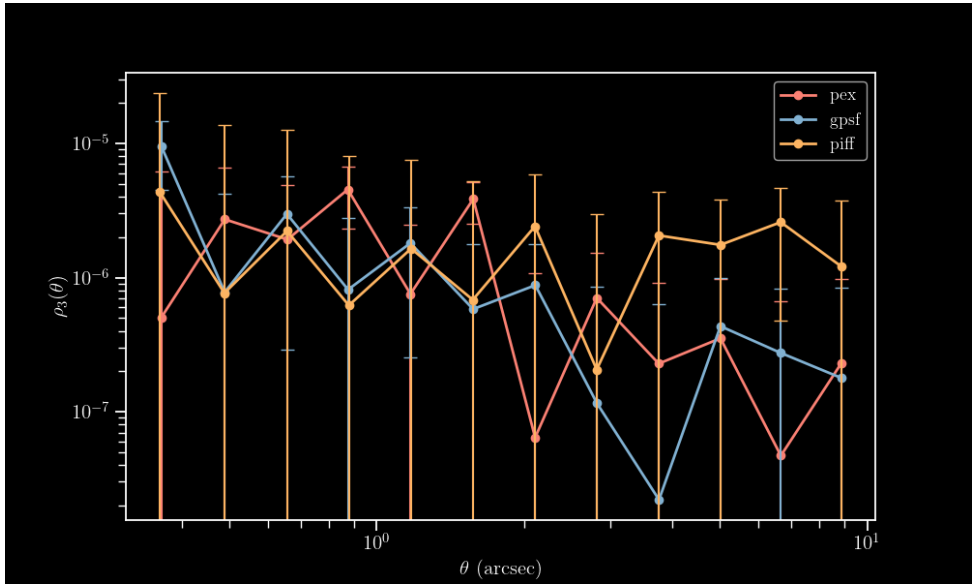


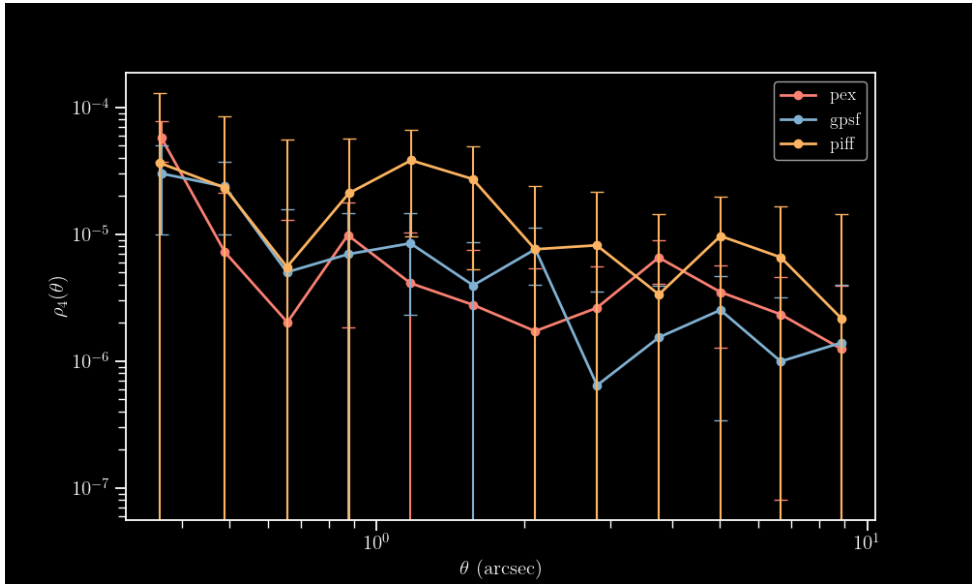




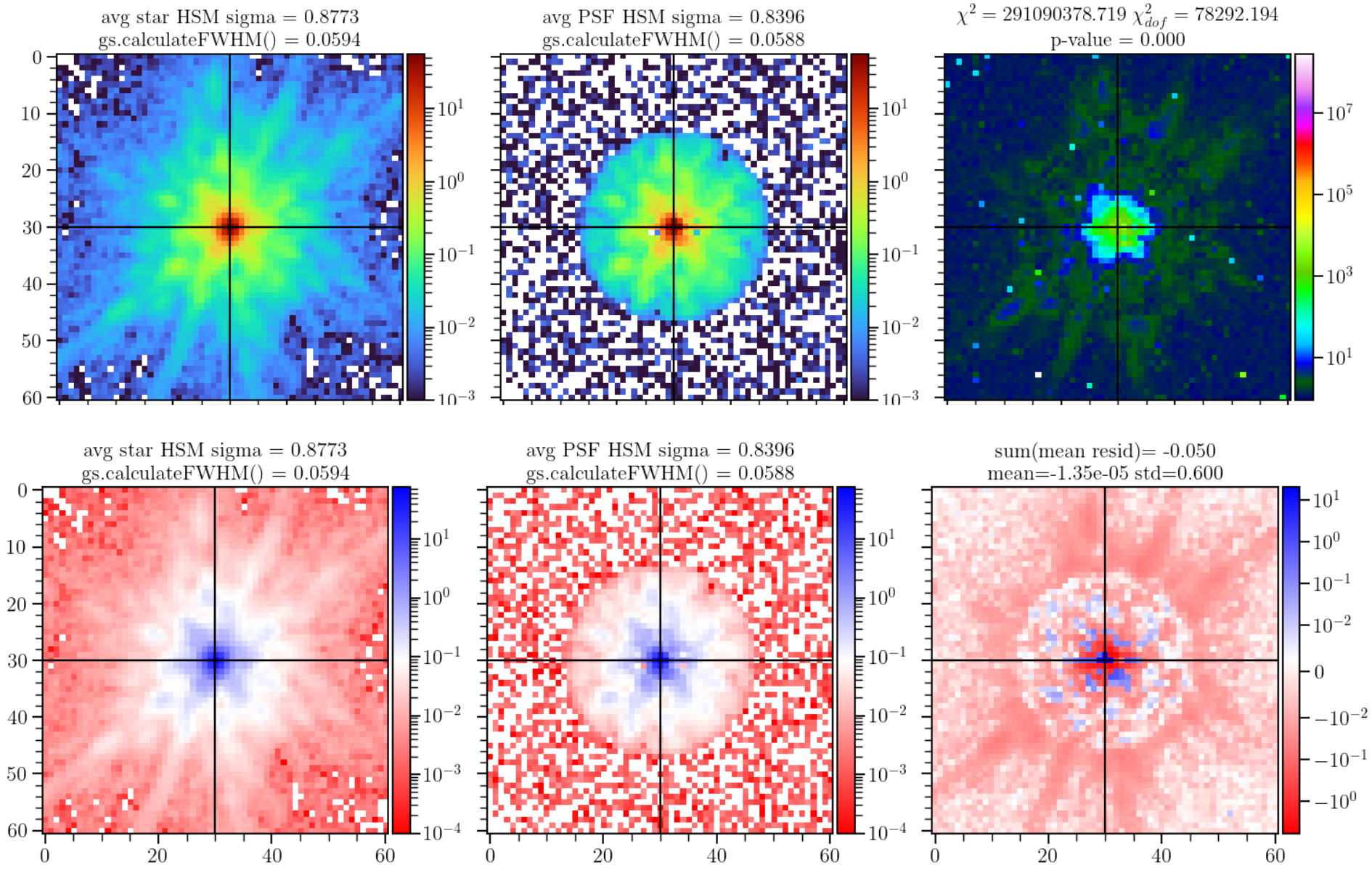

pex
gpsf
piff
$\rho_2(\theta)$
θ (arcsec)


pex
gpsf
piff
$\rho_1(\theta)$
θ (arcsec)

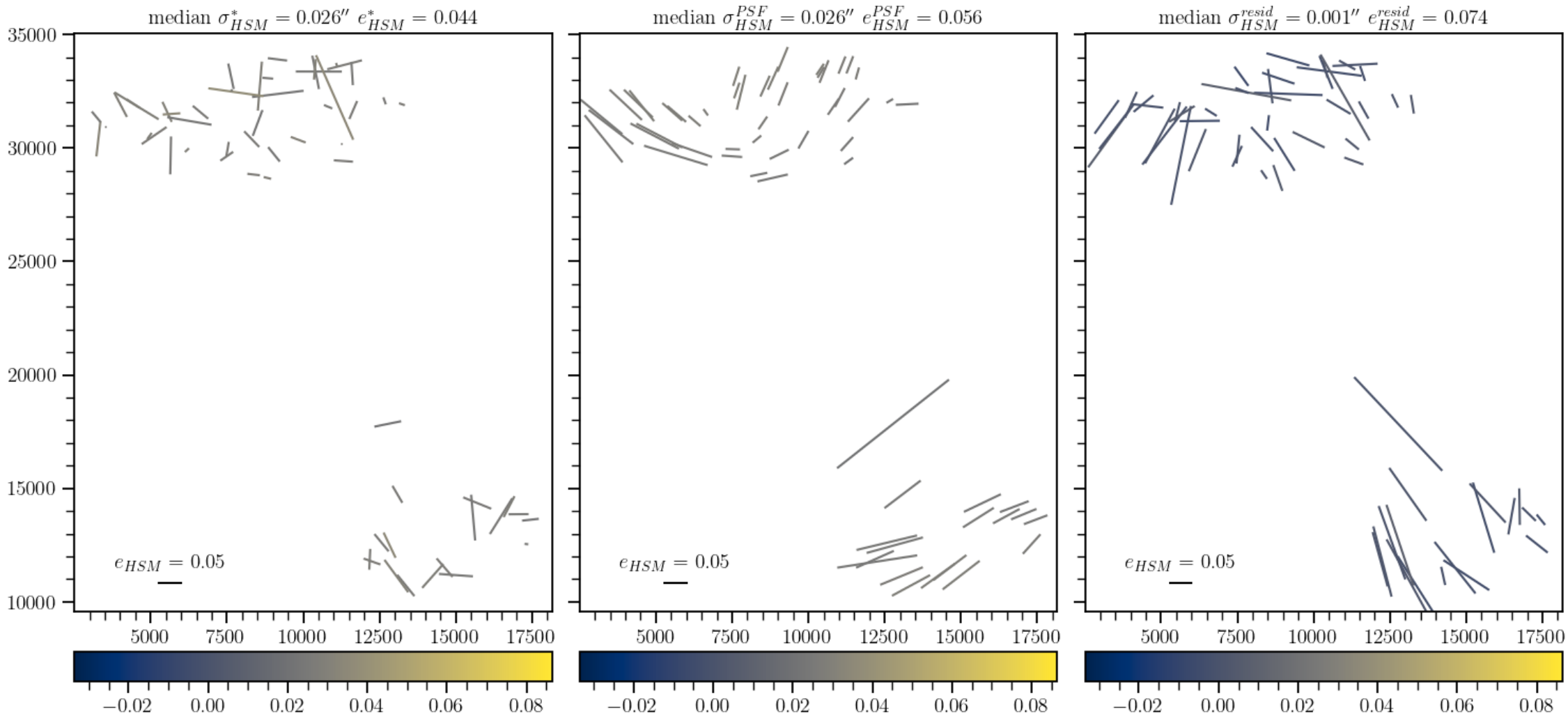

pex
gpsf
piff
$\rho_3(\theta)$
θ (arcsec)


pex
gpsf
piff
$\rho_4(\theta)$
θ (arcsec)

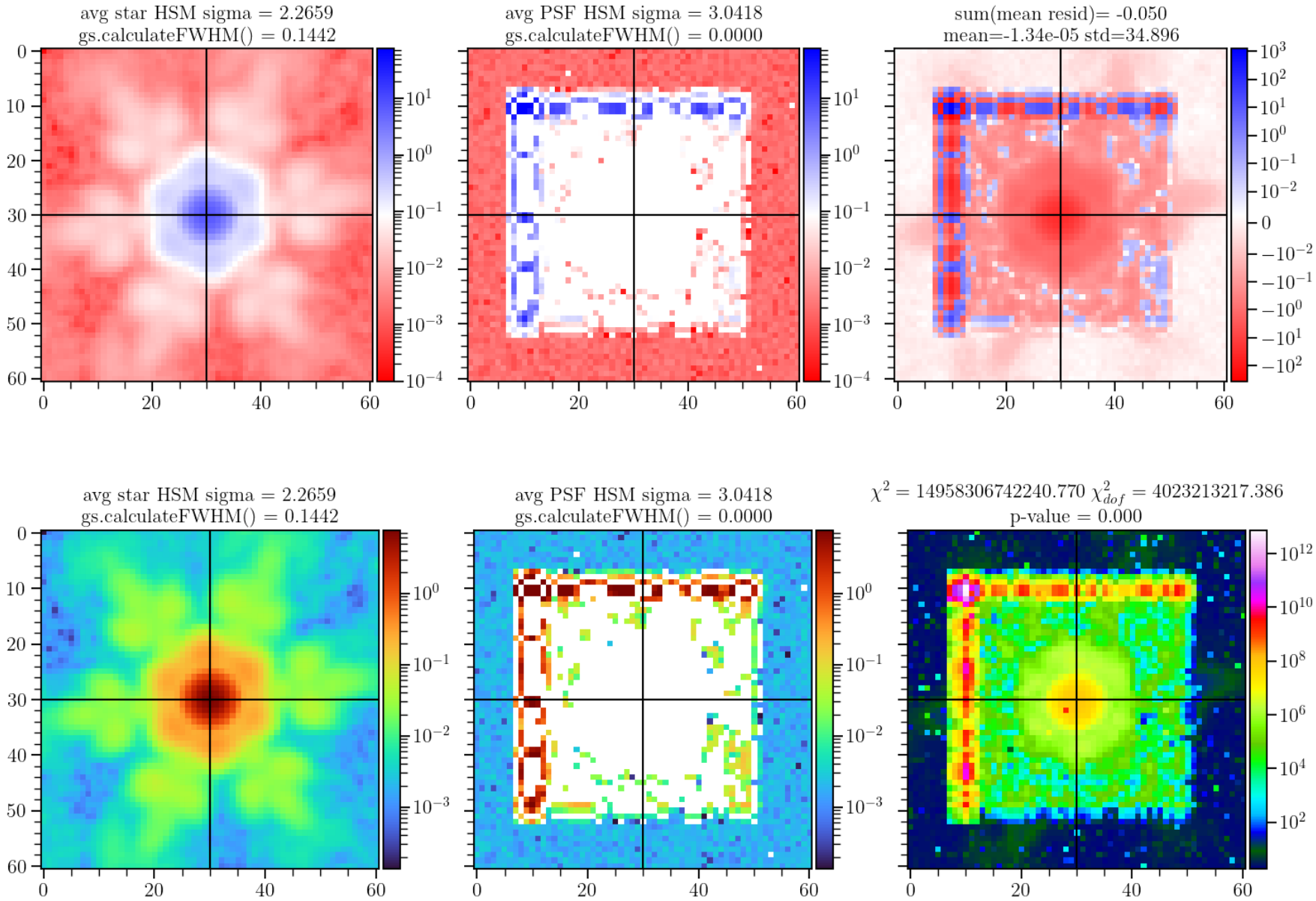
Example of a “bad” psfex fit for f115w



Example of a “bad” psfex fit for f115w

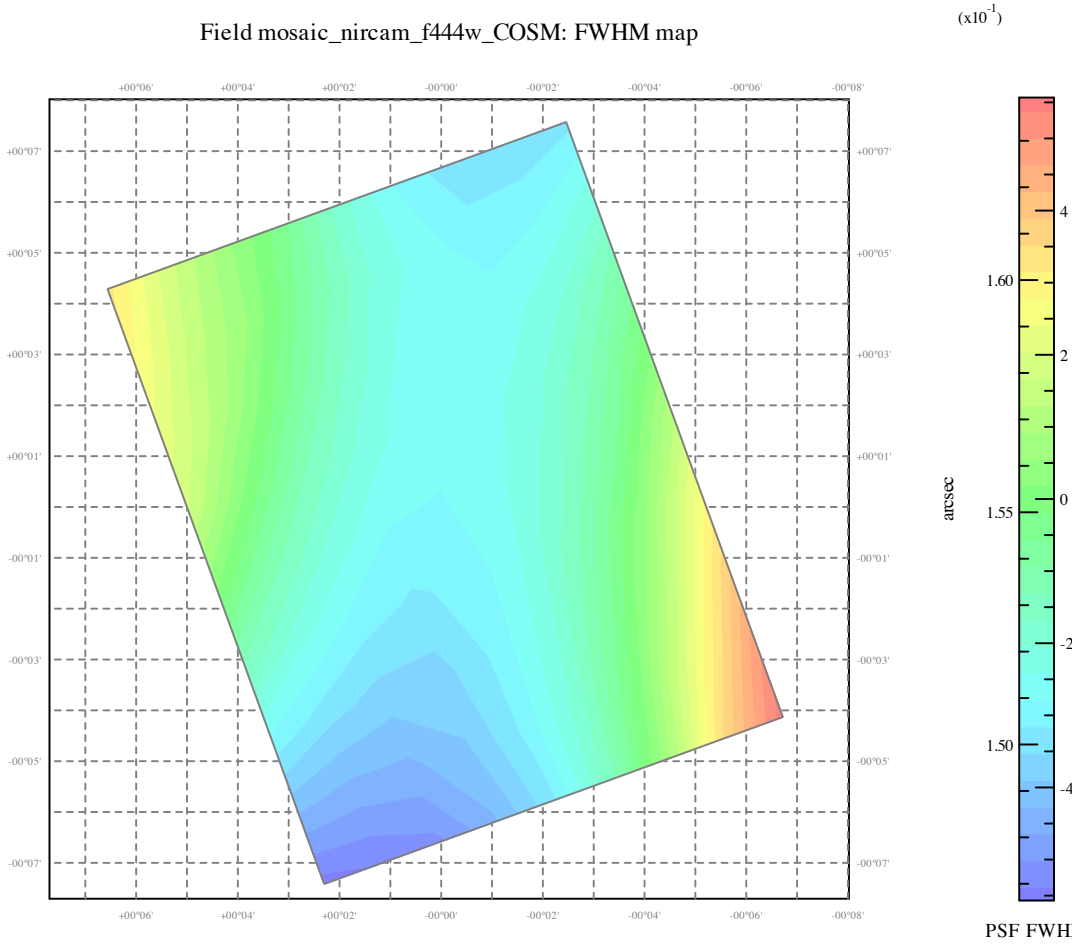


Example of a “bad” PIFF fit for f444w

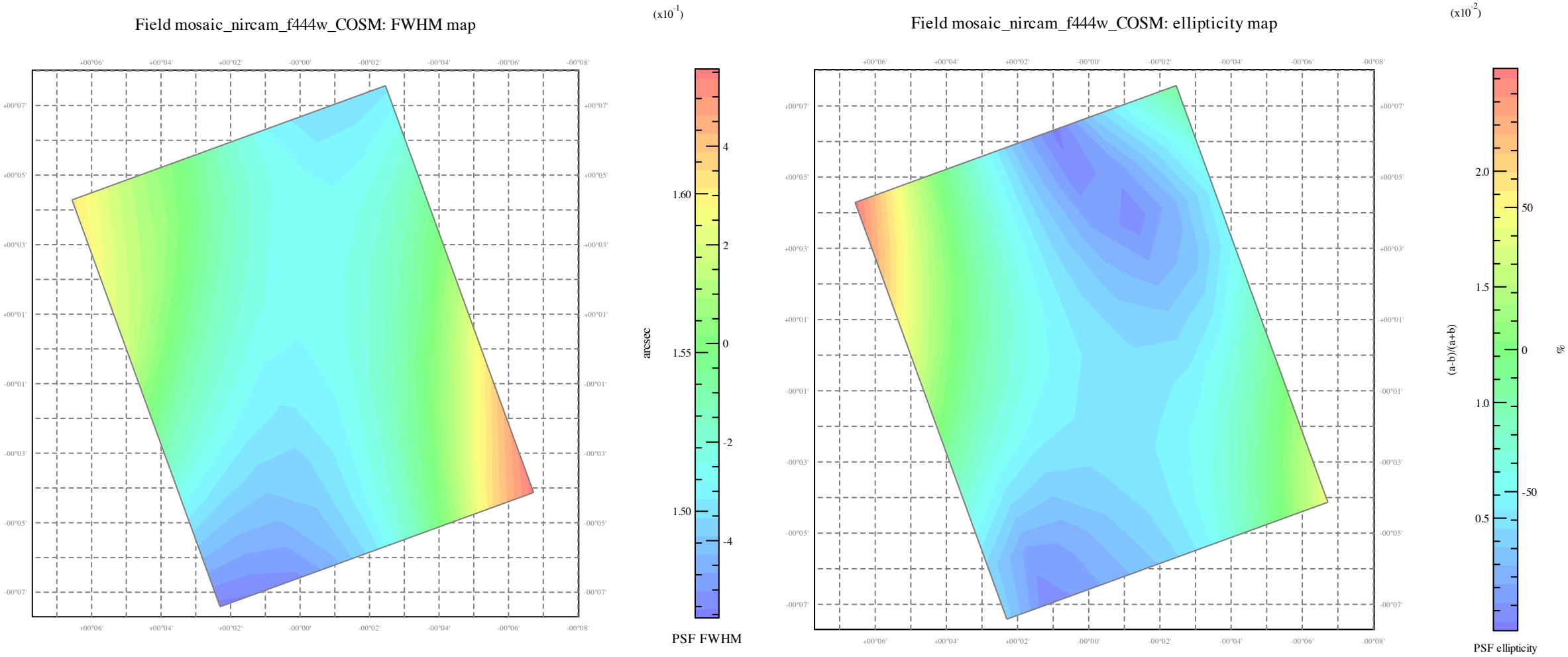


Takeaways from initial analysis

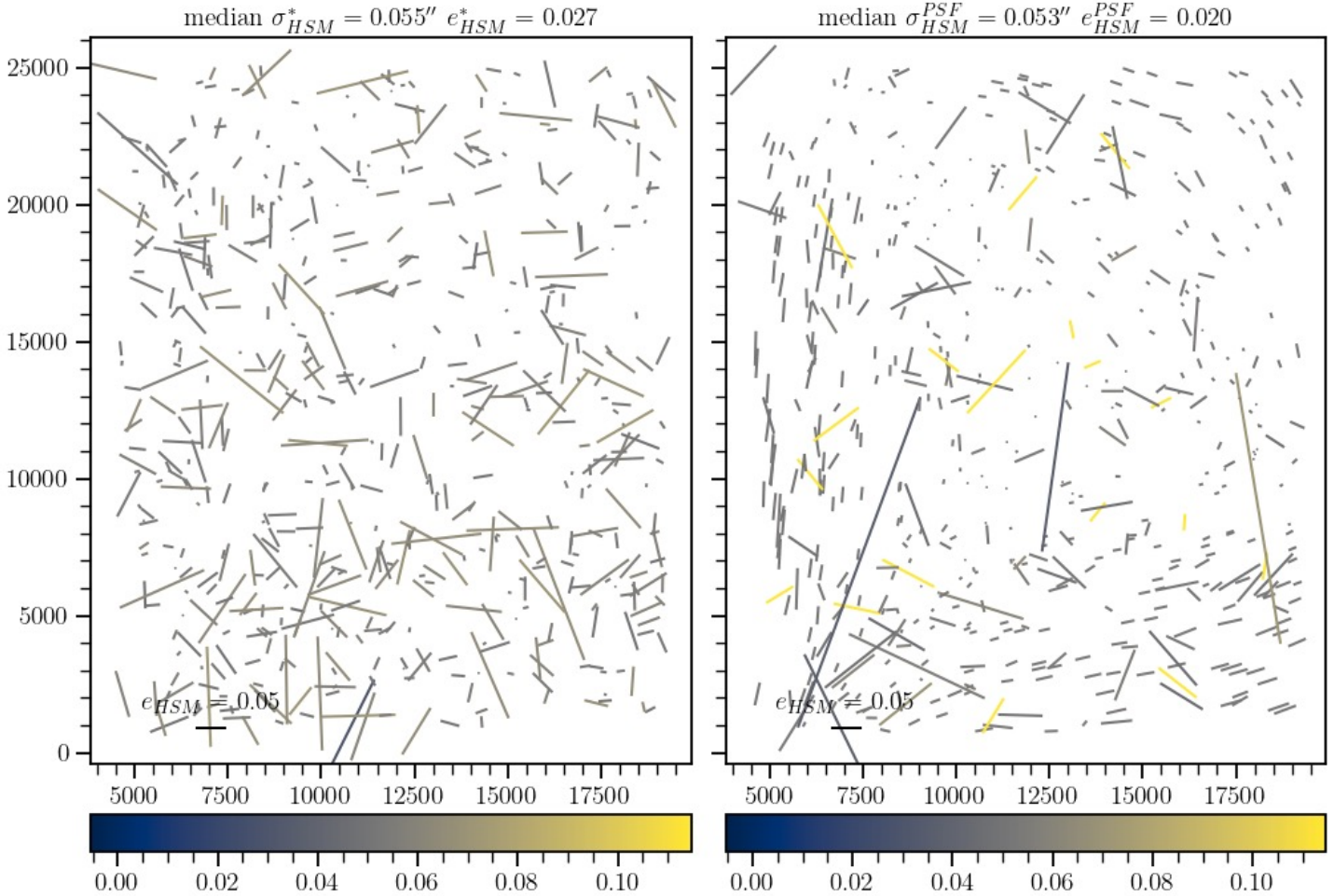
- Resampled long-wavelength data (F277W and F444W) seems to yield better PSF models than short-wavelength data
- No clear advantage to PIFF models *at this stage*
- PSFEx believes there variation in PSF size and ellipticity across the FOV of a single tile – remains to be confirmed

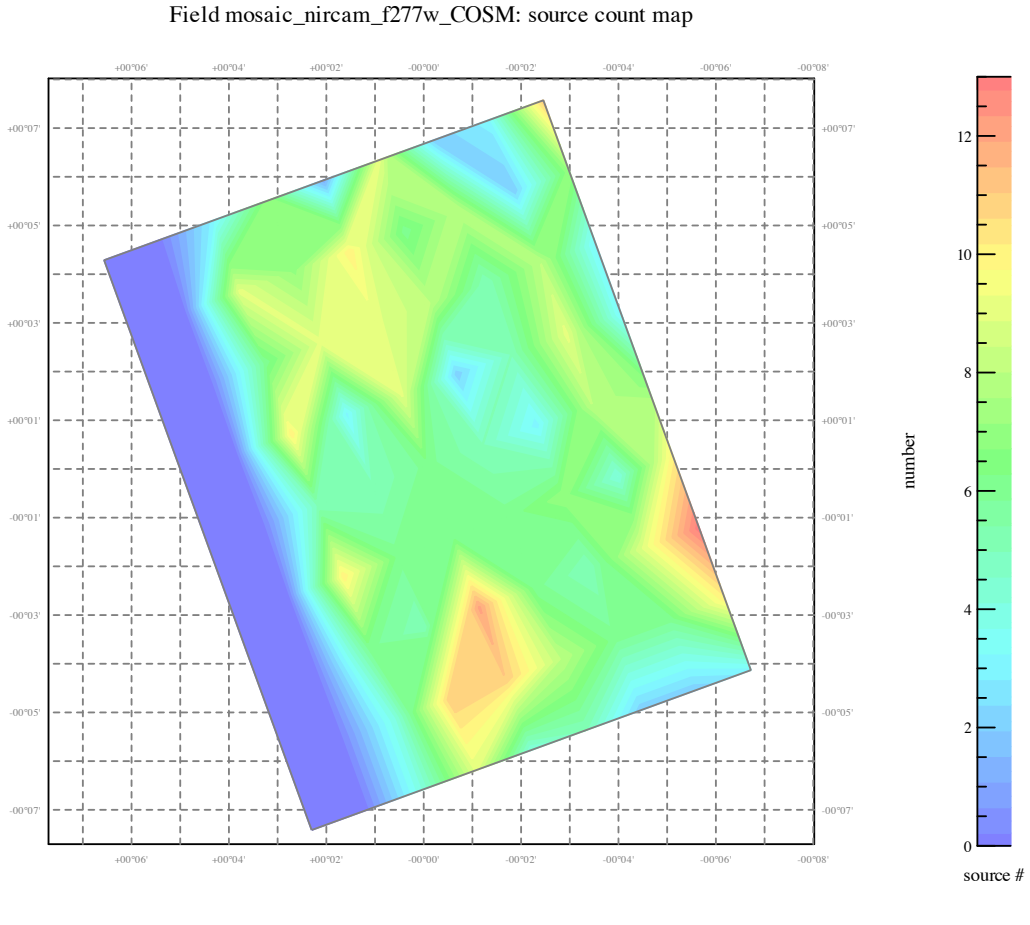


April 2023 A10 tile FWHM map



Size and ellipticity variation across FOV? PSFEx thinks so, but this is probably an edge effect


median $\sigma^*_{HSM} = 0.055''$ $e^*_{HSM} = 0.027$
median $\sigma^{PSF}_{HSM} = 0.053''$ $e^{PSF}_{HSM} = 0.020$
$e_{HSM} = 0.05$
$e_{HSM} = 0.05$
25000
20000
15000
10000
5000
0
5000 7500 10000 12500 15000 17500
0.00 0.02 0.04 0.06 0.08 0.10


Field mosaic_nircam_f277w_COSM: source count map
number
source #
0
2
4
6
8
10
12

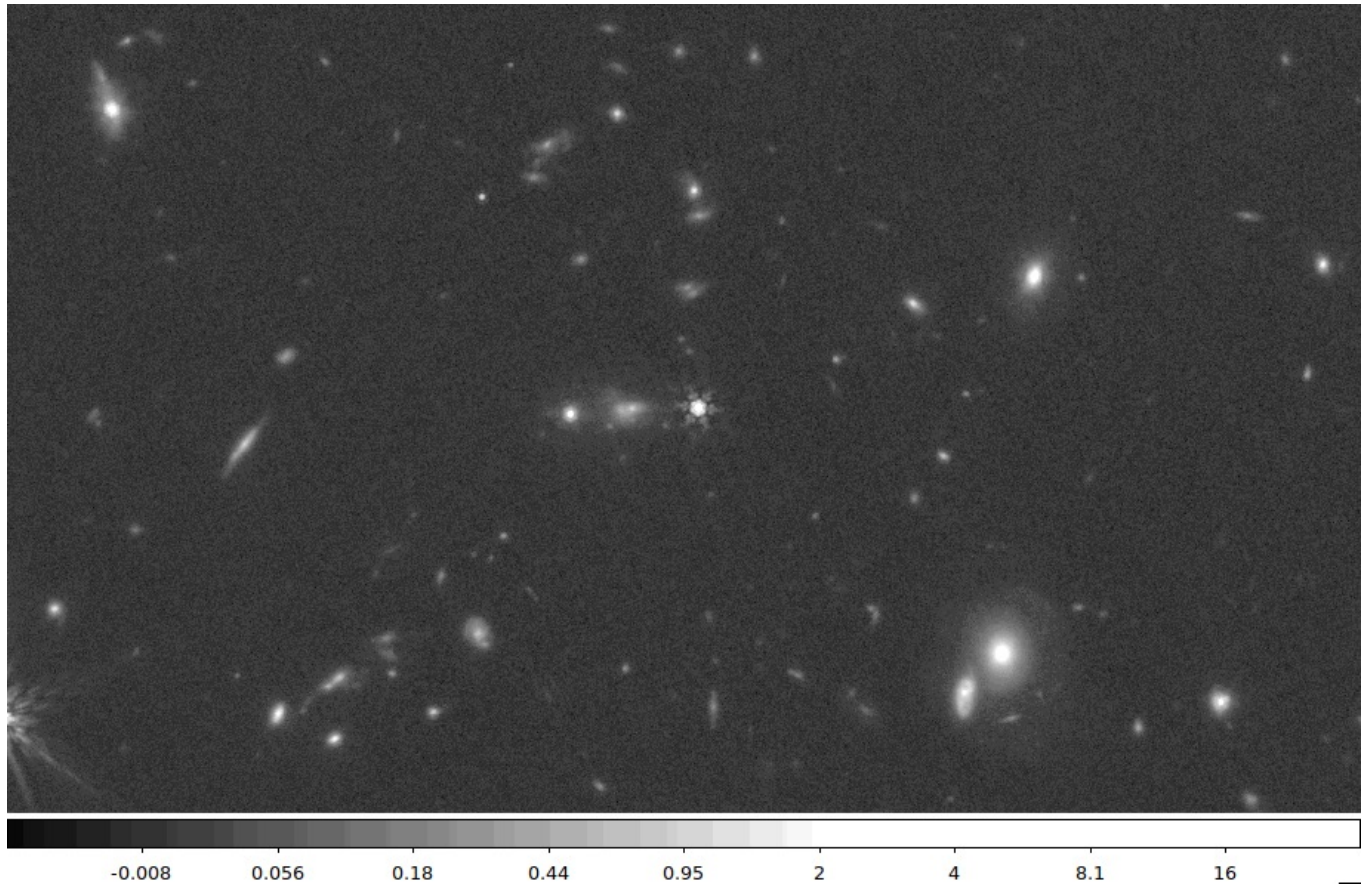
End game

Fundamental science driver: **what is the shear calibration requirement for stellar-mass-to-halo-mass measurement?**

- Determines shear calibration requirements…
- Which determines acceptable PSF mismodeling bias

Things that keep me up at night

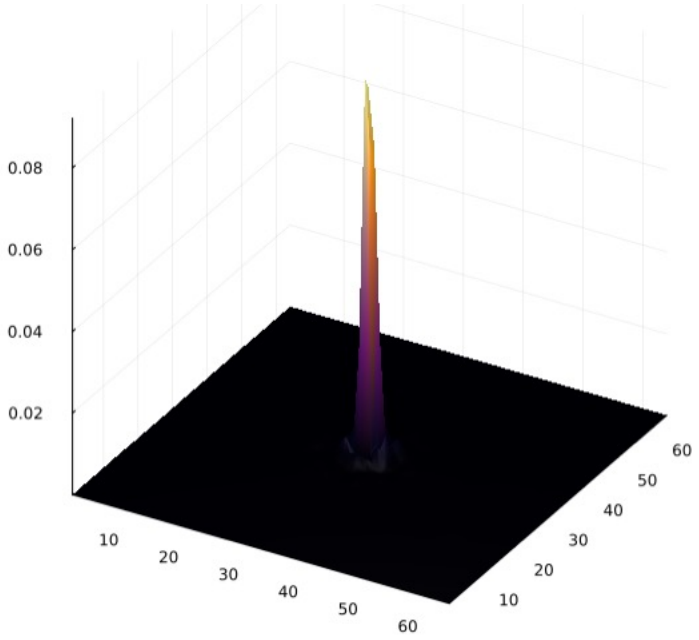
- Is our astrometry good enough? Do we need to go a step farther?
- Are resampled LW data going to bias our shapes?
- Will my PIFF fits ever converge?
- Are my models biased or wrong in a way that won't be clear until the final shear analysis?
- How bad is it to use a WebbPSF?

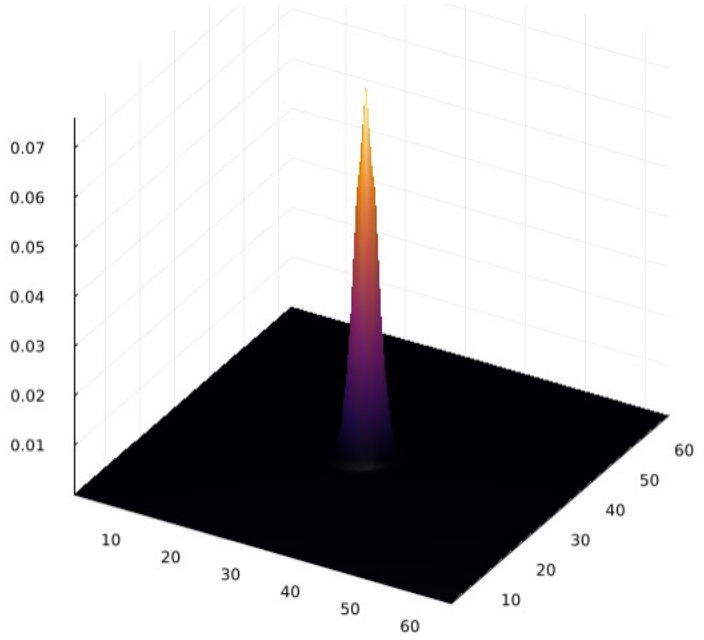


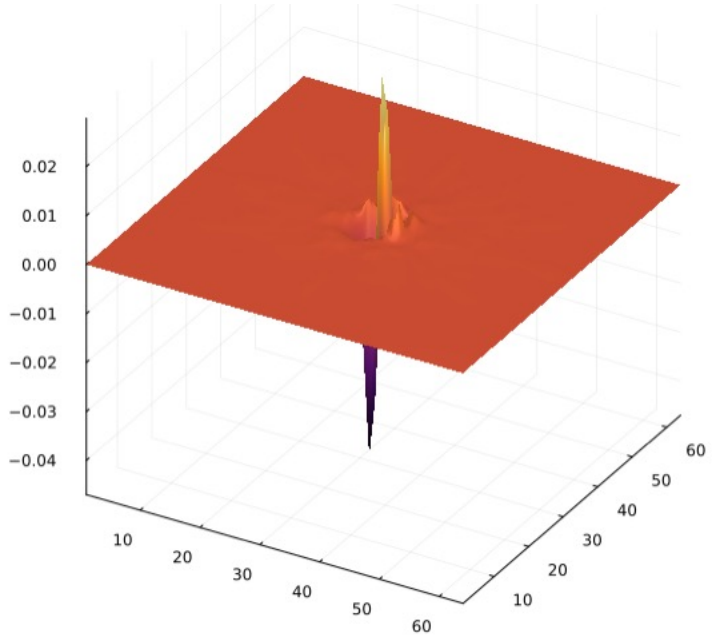
`shopt`: PSF modeling in Julia

Work-in-progress
by Edward Berman
(Northeastern U.)

https://github.com/EdwardBerman/shopt





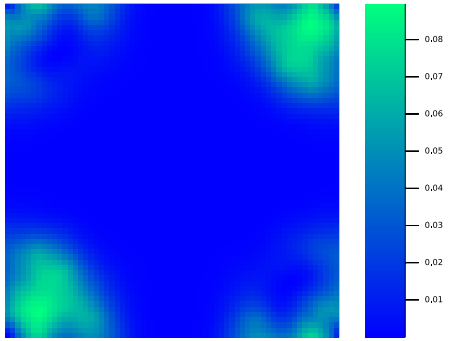


The philosophy of `shopt`

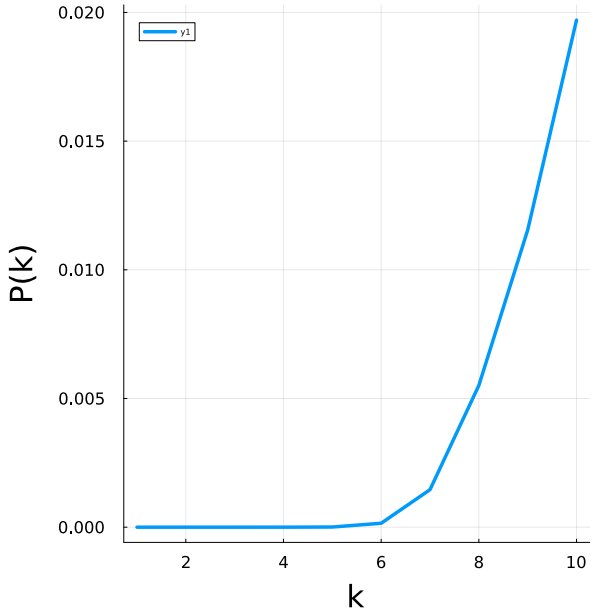
- PSF modeling is parameter estimation
- *Analytic* profile fitting is constrained optimization problem being treated as an unconstrained in the literature
- `Shopt` reparametrizes problem fitting to ensure model parameters remain in constraint (gradient descent takes excursions outside)
- `Shopt` is written in Julia, balancing readability and performance

`shopt` diagnostics galore

FFT Residuals



Power Spectrum



Analytic Profile Loss Vs Iteration (Data)