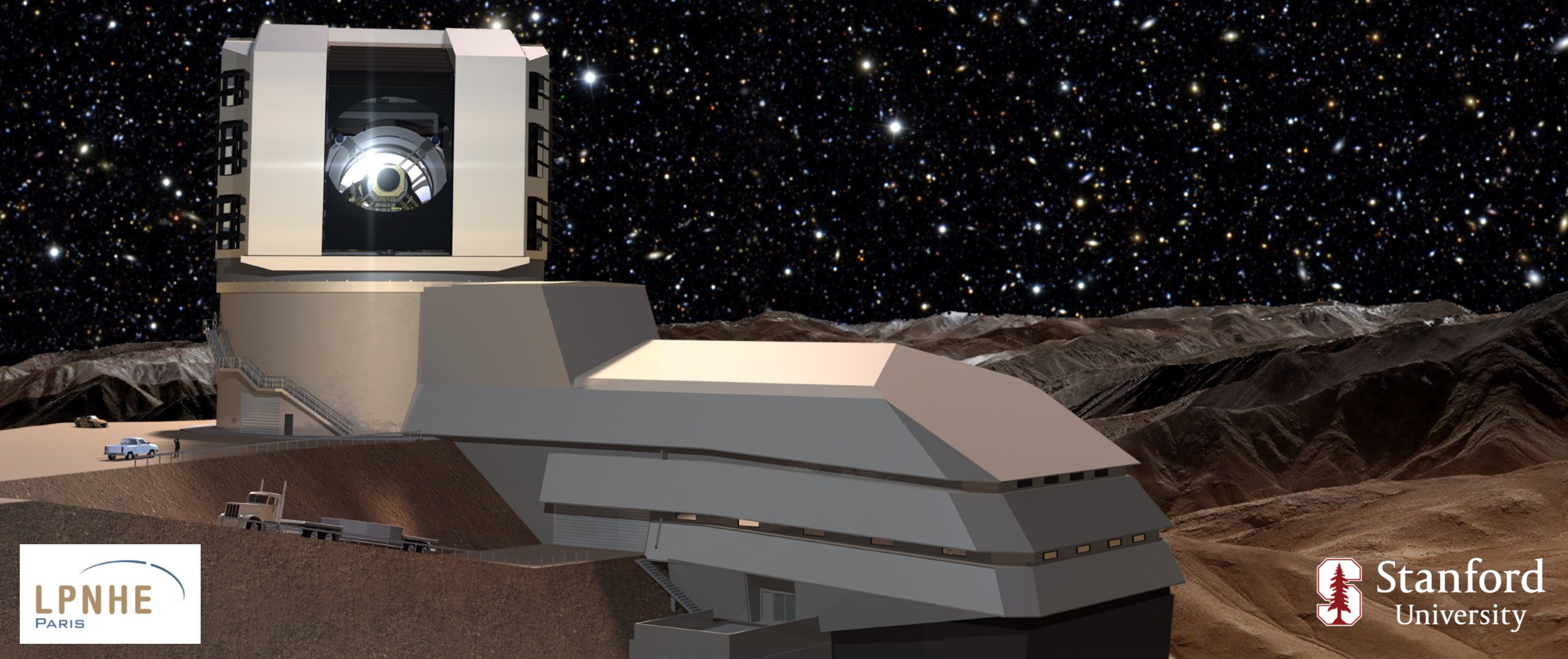
Flux estimator & PSF modeling

Pierre-François Léget, Stanford University / LPNHE

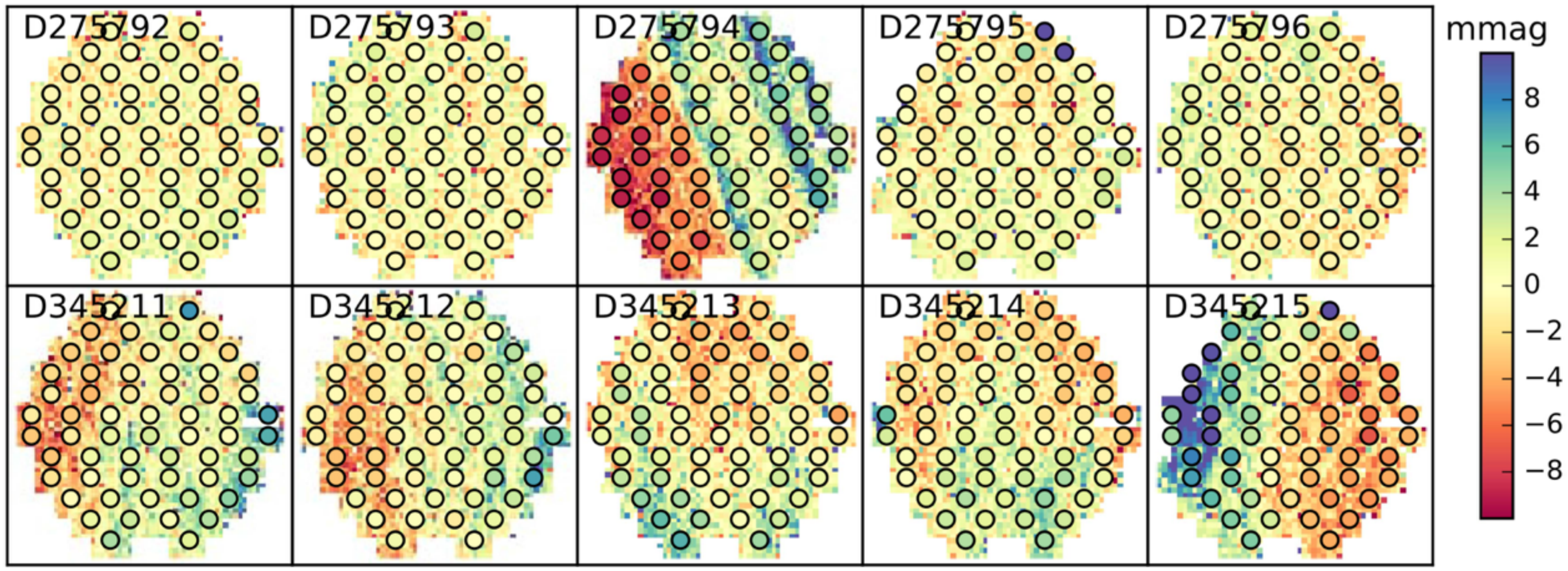


1. Photometric Residual & Atmospheric PSF
2. Current PSF modeling and Piff
3. The Optical and Atmospheric model
4. Preliminary results on the Dark Energy Survey Y3

1. Photometric Residual & Atmospheric PSF

- Two methods for extracting Flux:
  - Apperture photometry
  - PSF photometry
- Shape measurement of galaxy needs an accurate and unbiased PSF modeling
- PSF requirement for shape measurement / Weak-Lensing:
  - Need a good estimate of PSF over the full survey
  - Need spatial residuals of the PSF be un-correlated over the full survey
- A lot of effort are done in the Weak-lensing side to improve PSF modeling
- Efforts done in Weak-Lensing may help photometric calibration

Bernstein et al. 2017 (Photometric characterization of DECam)



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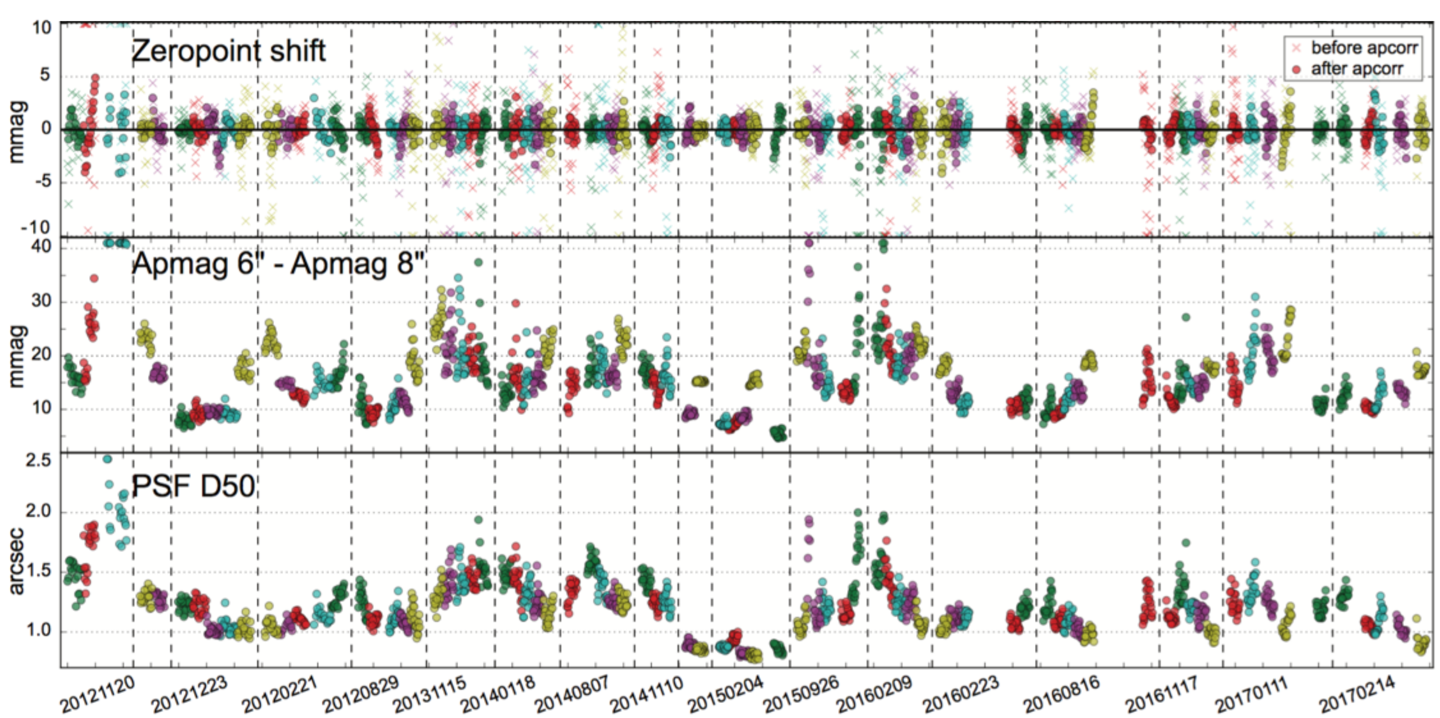

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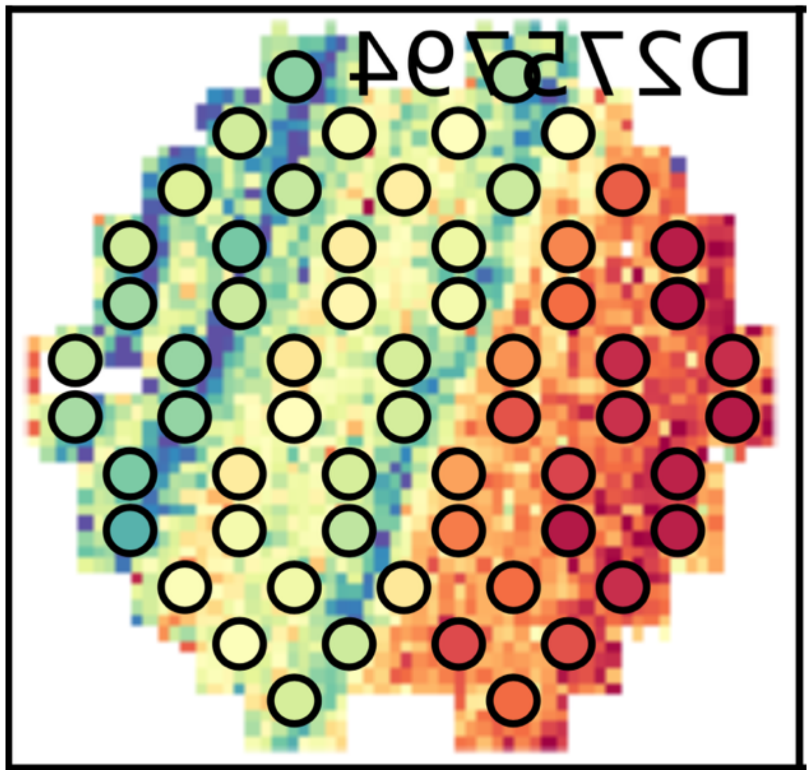

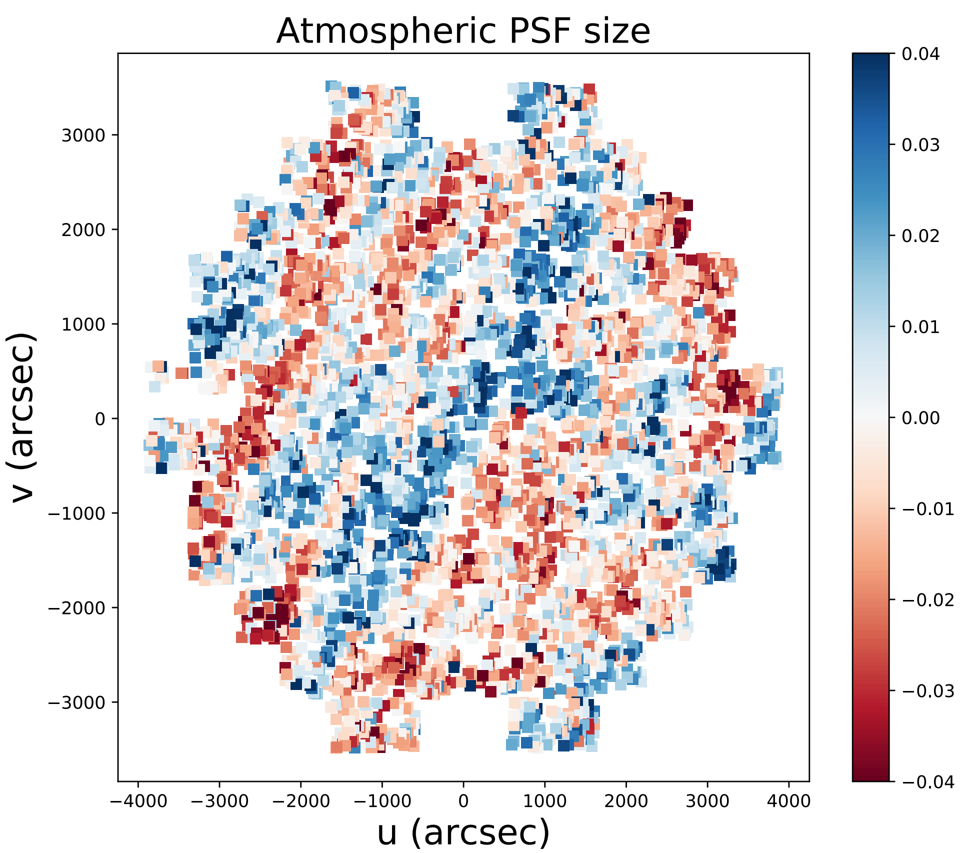

- Photometric residuals would represent what fall outside the aperture during the exposure, mainly due to the atmosphere

- Need an estimate of the Atmospheric PSF modeling

- This is something that already exist!

- We developed a physical model of the PSF that separate the PSF in two components:
  - Optical
  - Atmospheric

- Exemple on one DES exposure (510463), (not the same as in Bernstein et al.)

- Spatial variation of the atmospheric size are consistent with Atmospheric perturbation!

2. Current PSF modeling and Piff

PSFex package

- PSFex is a common used package for PSF modeling
- A ‘Pixel Basis’ model
- ‘Pixel Basis’ parameters interpolated with a polynomial interpolation per CCD chip in pixel coordinate

Limitations of PSFex:

- Working in pixel coordinate does not allow inclusion of effect such as the treerings
- Does not take into account for spatial correlations that are larger than a CCD chip size

PSFs In the Full FoV (Piff) package

- Piff is a new python software for PSF estimation developed initially to replace PSFex in DES and now also developed for LSST

- Modular package where it is easy to implement new PSF modeling and interpolation scheme over the FoV

- Package with unit testing and code review

- Will be used for the Weak-Lensing analysis of DES Y3

- Contributors:

Mike Jarvis, Chris Davis, Pierre-François Léget, Erin Sheldon, Josh Meyers, Gary Bernstein, Aaron Roodman, Pat Burchat, Daniel Gruen, Ares Hernandez, Andres Navarro, Flavia Sobreira, Reese Wilkinson, Joe Zuntz, Sarah Burnett

Piff improvements respect to PSFex:

- PSF modeling in sky coordinate instead of pixel coordinate. It allows the WCS (including treerings, …) to be removed before interpolating.
- Can modeled the PSF per CCD or in the full FoV (great to get PSF variation due to atmosphere)
- Different choices of modeling the PSF are available (Pixel basis, Optical model + Kolmogorov profile, …)
- Different choices of interpolation model are available (polynomial, gaussian process, …)
- The average PSF model over the survey can be a part of the final solution

- Needs of metrics to evaluate quality of the PSF
- Metrics already exist in weak-lensing
- Evaluate spatial correlation of second moments of the PSF (size and ellipticity)

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- T == Trace of second moments

- e == complex ellipticity

Rowe Statistics:

$$\rho_1(\theta) \equiv \left\langle \Delta e^*(x) \Delta e(x+\theta) \right\rangle$$

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- Needs of metrics to evaluate quality of the PSF
- Metrics already exist in weak-lensing
- Evaluate spatial correlation of second moments of the PSF (size and ellipticity)
- T == Trace of second moments
- e == complex ellipticity
- Those coefficient comes from the propagation of error modeling of the PSF to the cosmic shear signal
- See Jarvis et al. 2016, Rowe 2010 and Paulin-Henriksson et al. 2008

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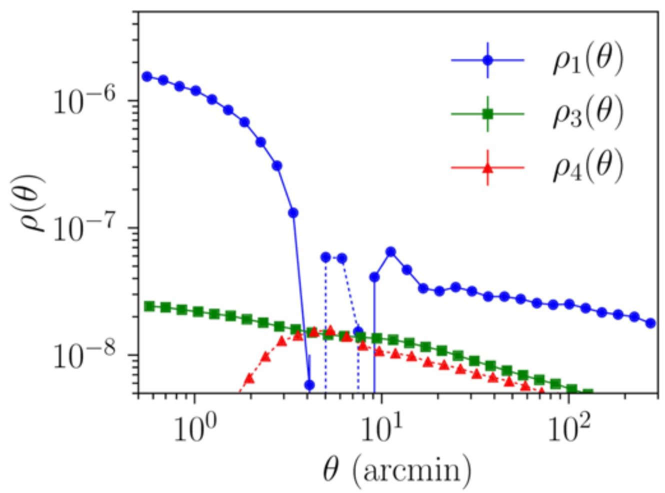
$$\Delta\xi_+ = 2\left\langle \frac{T_{PSF}}{T_{gal}} \frac{\Delta T_{PSF}}{T_{PSF}} \right\rangle \xi_+(\theta) + \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle^2 \rho_1(\theta) - \alpha \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle \rho_2(\theta) + \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle^2 \rho_3(\theta) + \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle^2 \rho_4(\theta) - \alpha \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle \rho_5(\theta)$$

PSFex



- Piff and PSFex are applied on ~50% of DES Y3 data
- Both used the same 'Pixel Basis' model of the PSF
- Both used a Polynomial interpolation per CCD chip
- The main difference is the coordinate system
- Rowe statistics is computed to compare both
- Analysis and plots done by Mike Jarvis

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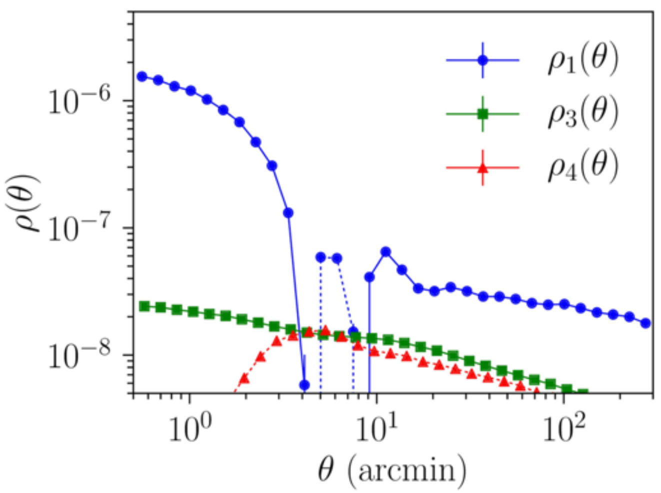

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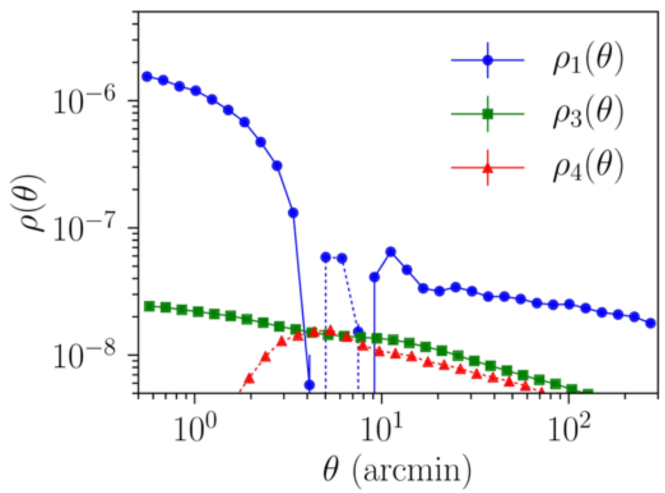

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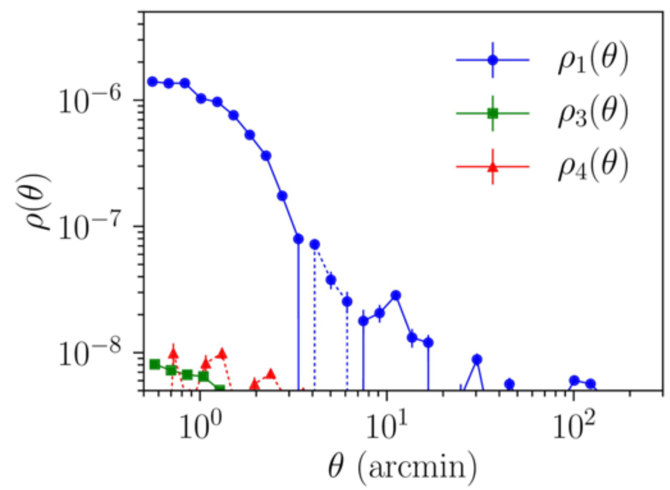

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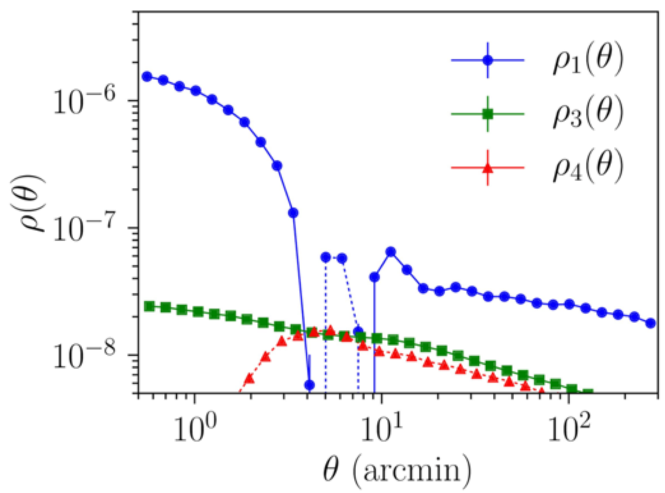

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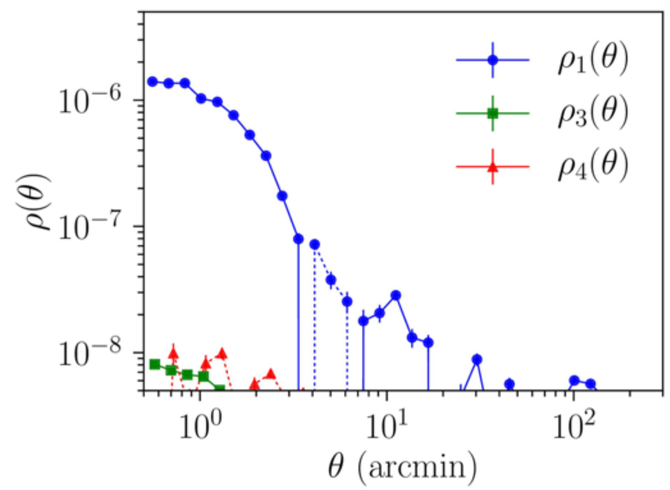

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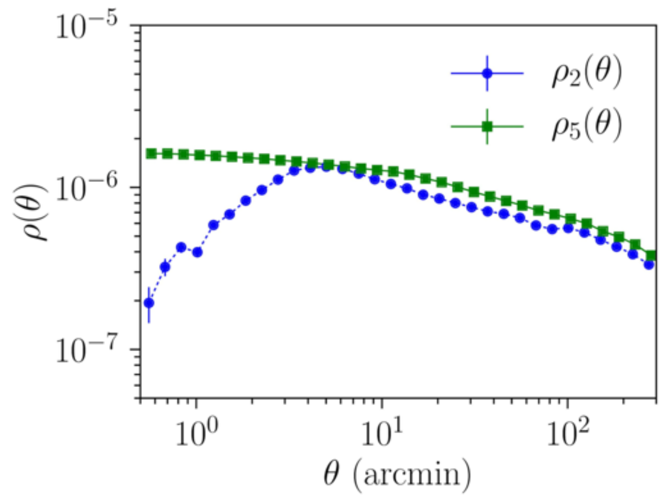

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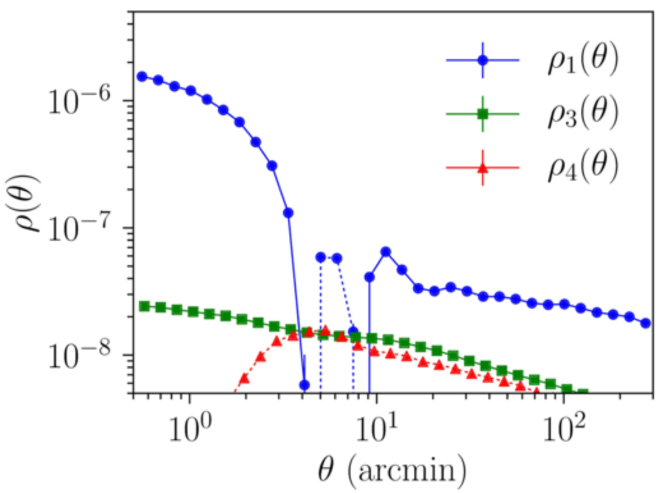

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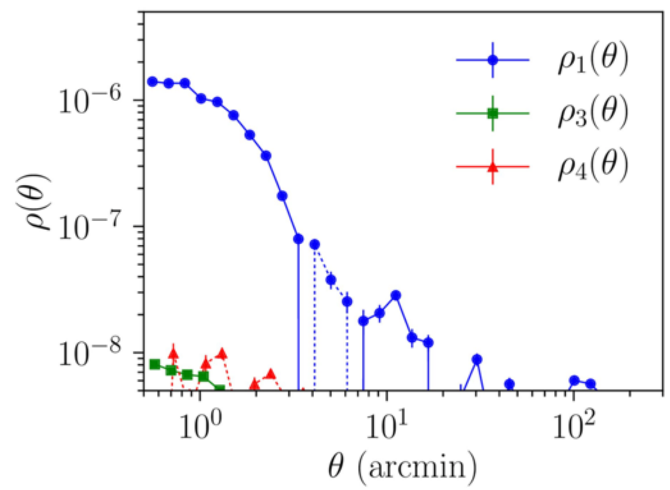

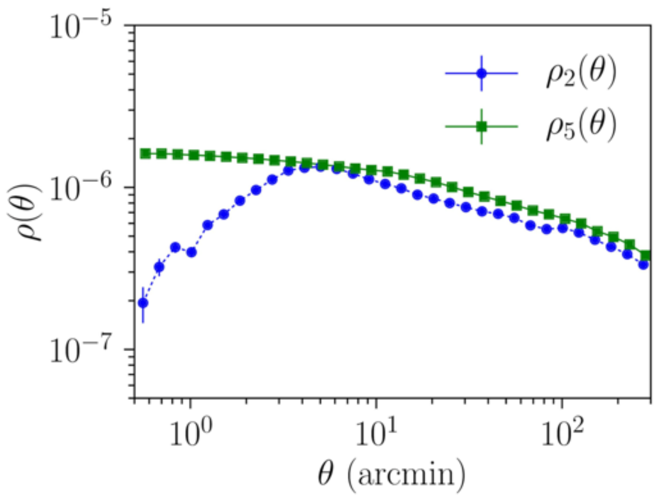

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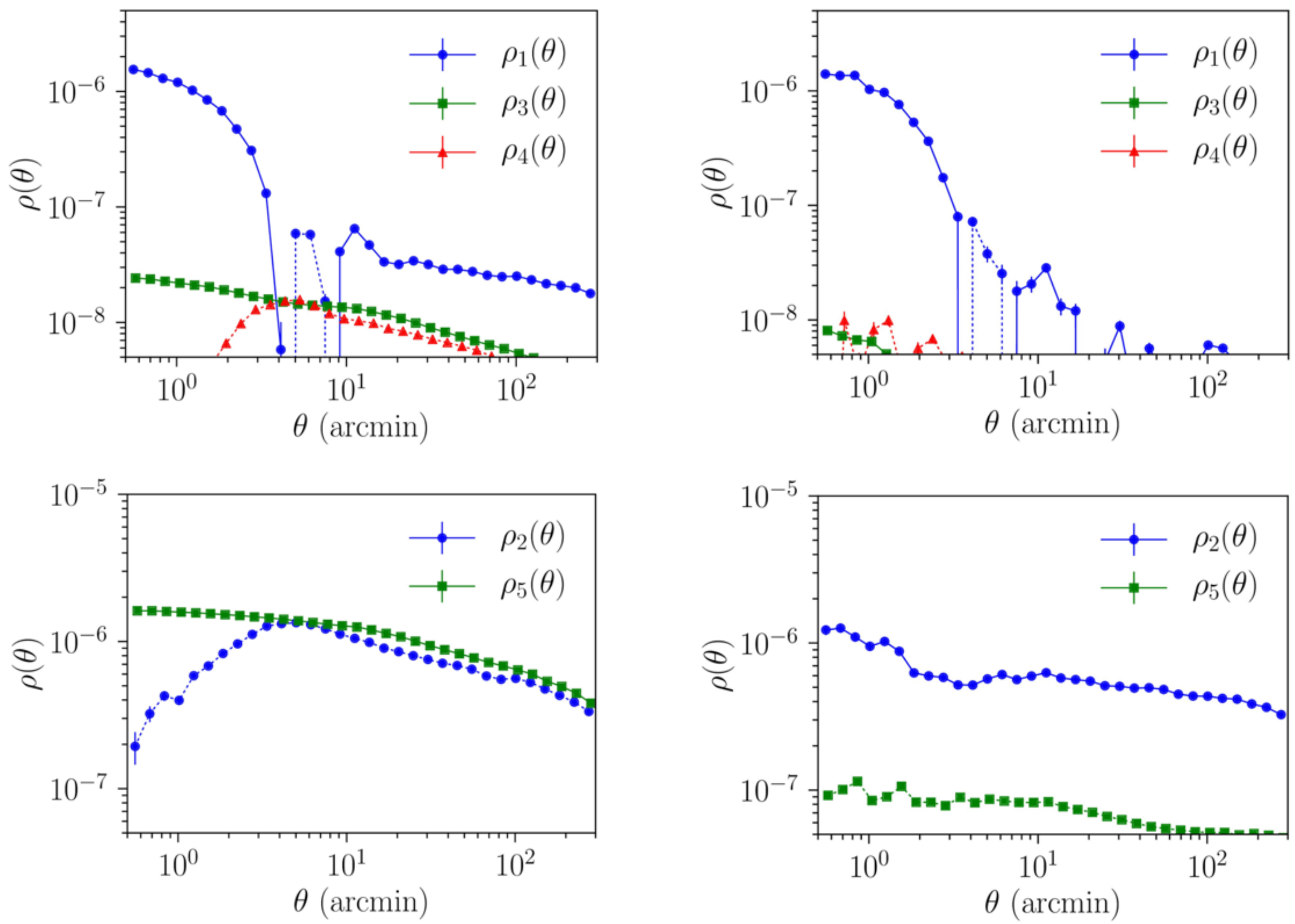
PSFex | Piff



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PSF profile $\sim$ Optical part of the PSF $\otimes$ Atmospheric part of the PSF

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PSF profile ~ Optical part of the PSF as a Fraunhofer Diffraction ⊗ Atmospheric part of the PSF

$$I(u,v) \sim \left| F\left\{ P(\rho,\theta) e^{2\pi i W(\rho,\theta)/\lambda} \right\} \right|$$

$P(\rho,\theta)$ → Pupil function

$W(\rho,\theta)$ → Wavefront

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Wavefront decomposed as a double Zernike polynomial that depend on the focal plane coordinate

$$W(\rho,\theta) = \sum_i \left[a_{i,reference}(u,v) + a_{i,corr}(u,v) \right] Z_i(\rho,\theta)$$

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$\alpha(u,v)$, $g_1(u,v)$, $g_2(u,v)$: Second moment of the Kolmogorov profile (size, ellipticity)

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Pupil function ($P(\rho,\theta)$)

Wavefront ($W(\rho,\theta)$)

Second moment of the Kolmogorov profile (size, ellipticity) ($\alpha(u,v)$, $g_1(u,v)$, $g_2(u,v)$)

Wavefront decomposed as a double Zernike polynomial that depend on the focal plane coordinate

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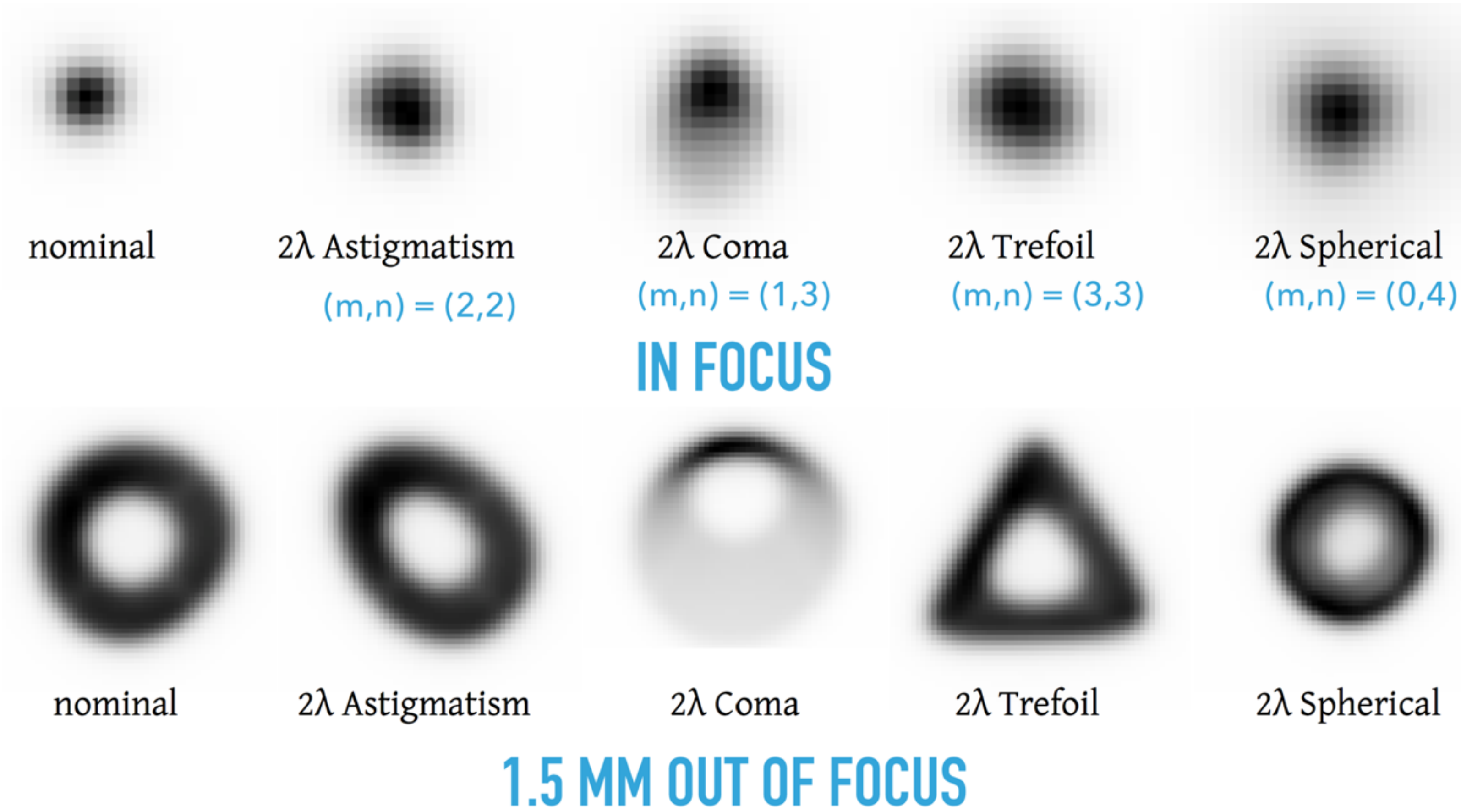
Kolmogorov parameters modeled as a Gaussian Process drive by a Von-Karman correlation function

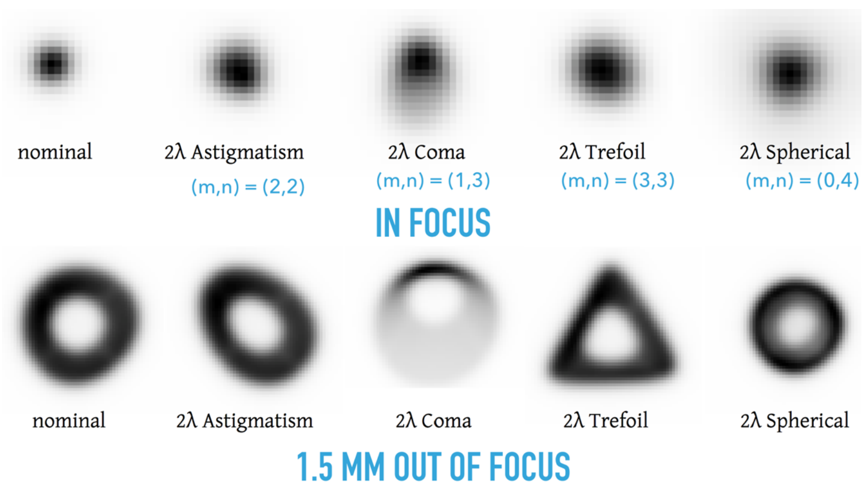
$$\alpha(u,v) \sim N(\alpha_0(u,v), \xi)$$

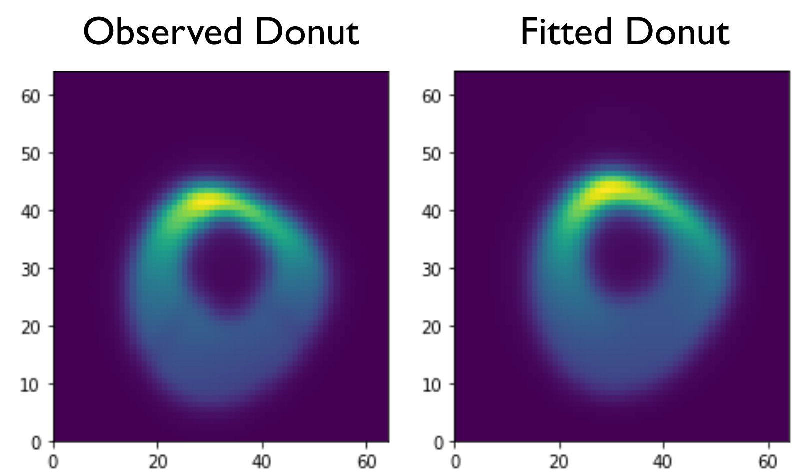
$$g_1(u,v) \sim N(g_{1,0}(u,v), \xi)$$

$$g_2(u,v) \sim N(g_{2,0}(u,v), \xi)$$



- Each optical aberration is really easy to get with out of focus images (« donuts » images)
- Each Zernike coefficient is associated with an optical aberration





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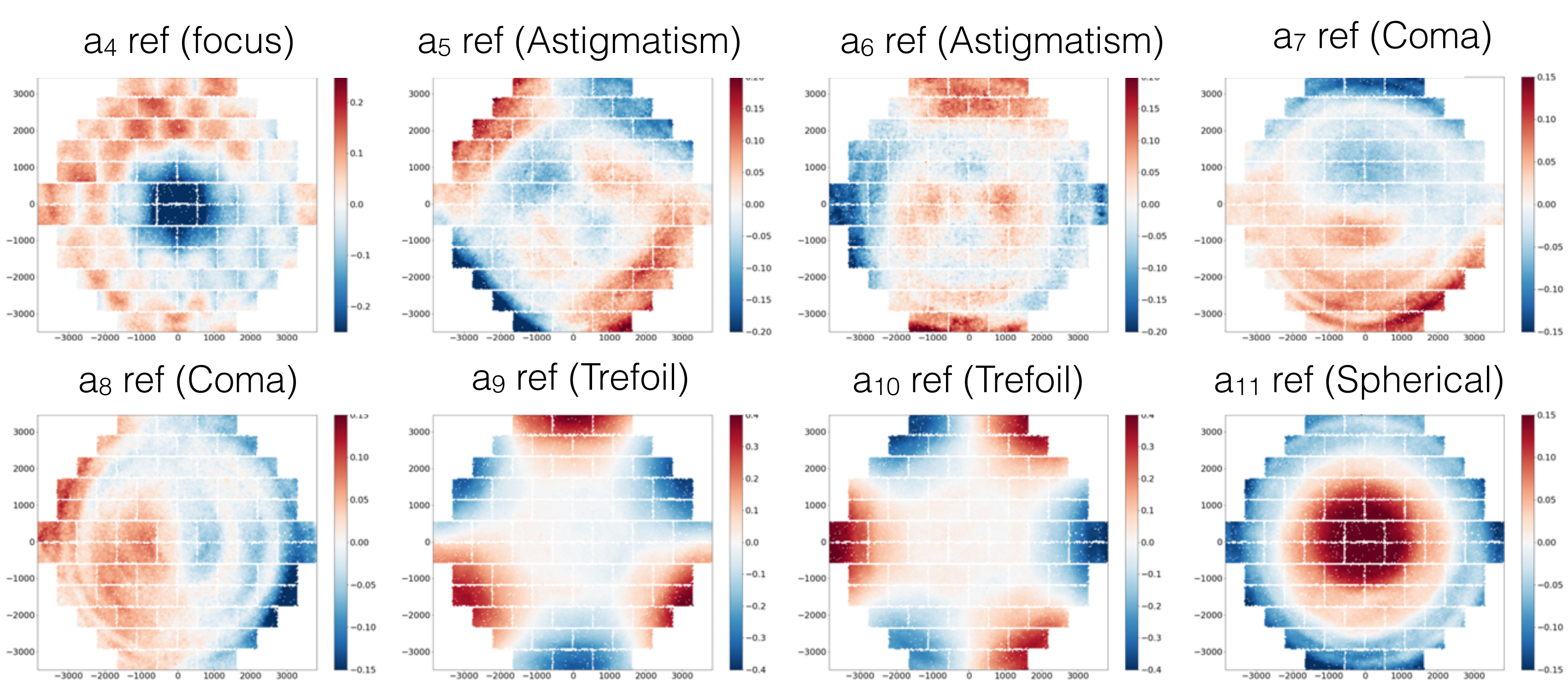
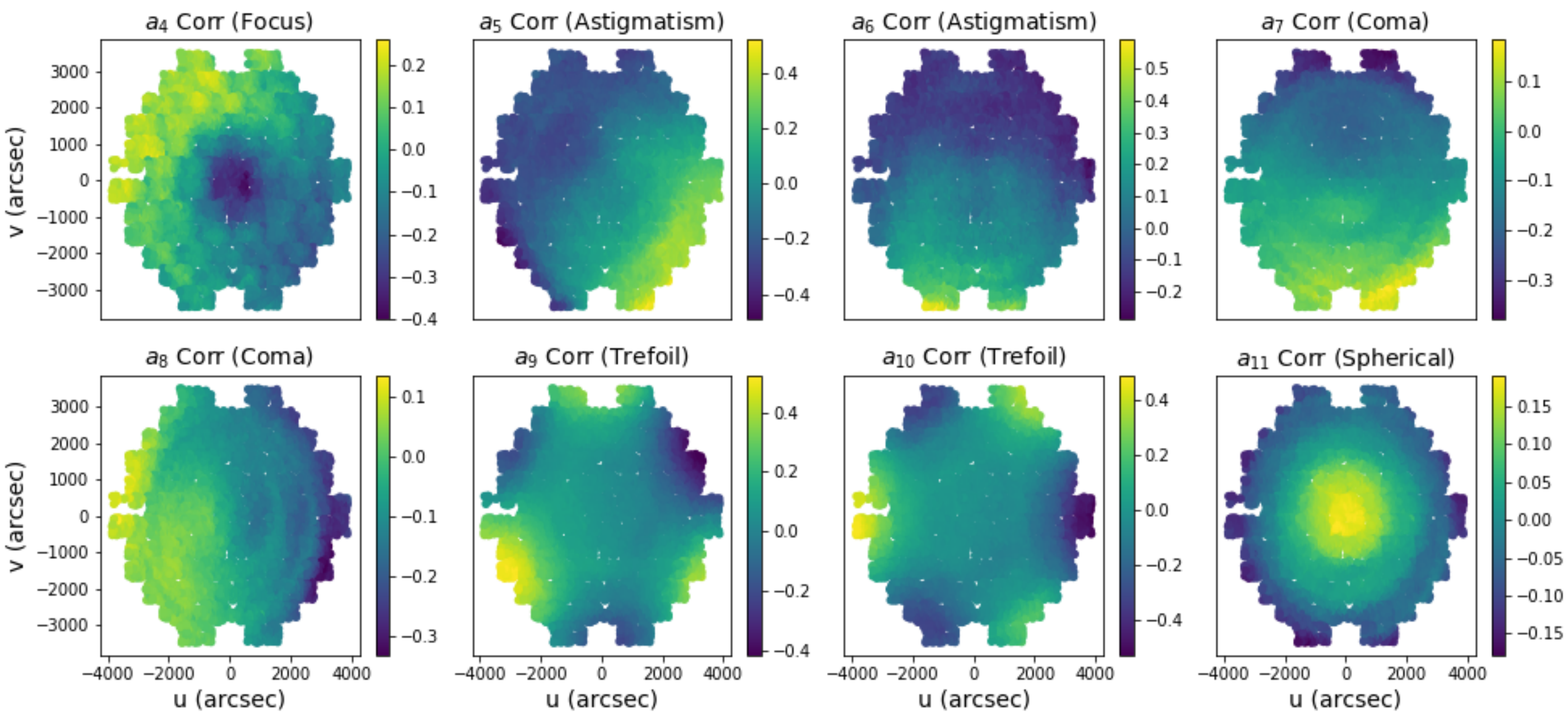


Chris Davis Ph.D. 2018

- Each optical aberration is really easy to get with out of focus images (« donuts » images)
- Each Zernike coefficient is associated with an optical aberration
- By turning the focal plane out of focus, it becomes a wavefront sensor where it is possible to get the reference optical aberration (work done by Aaron Roodman for DES)

Exposure n°510463 (12/01/2016)



- Deviation from reference image could be fit on focused stars for an individual exposure

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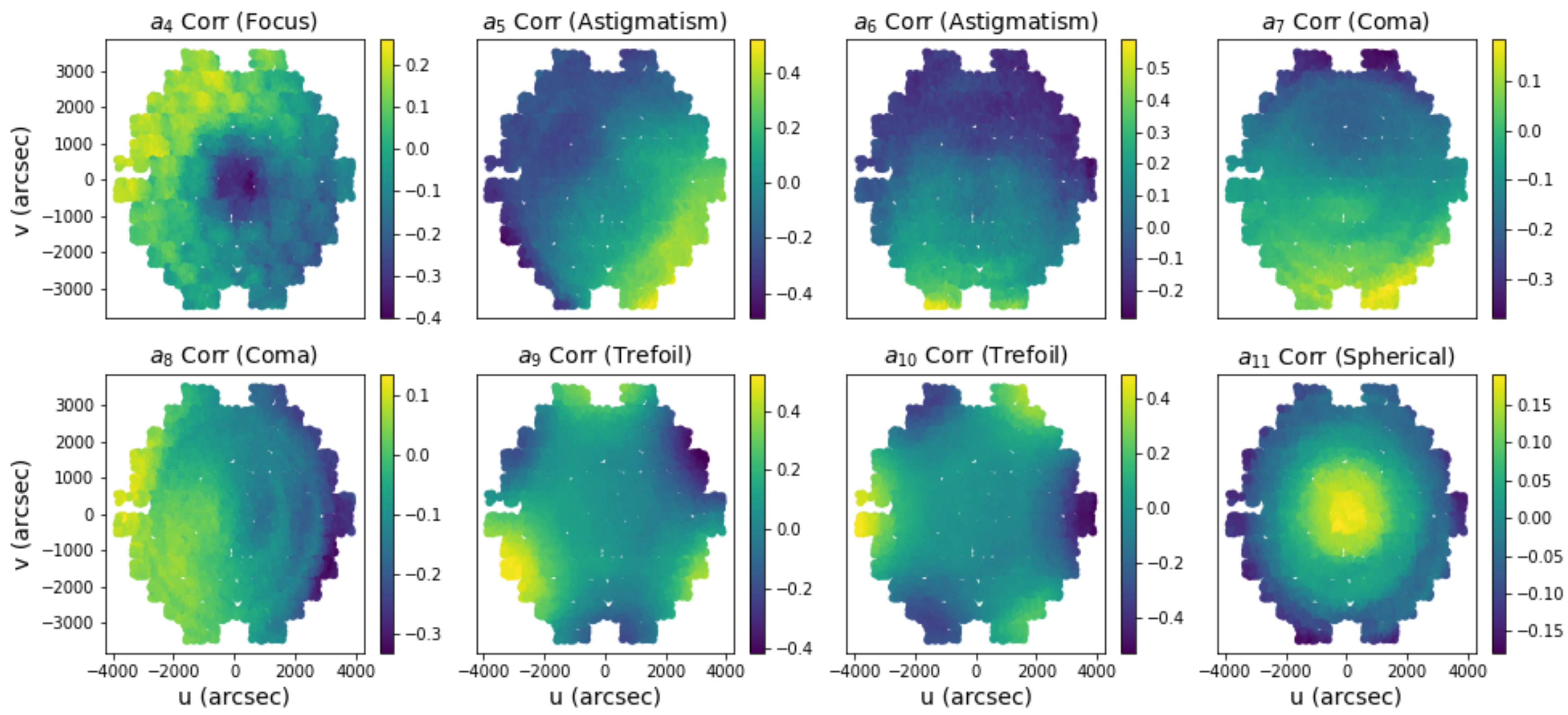

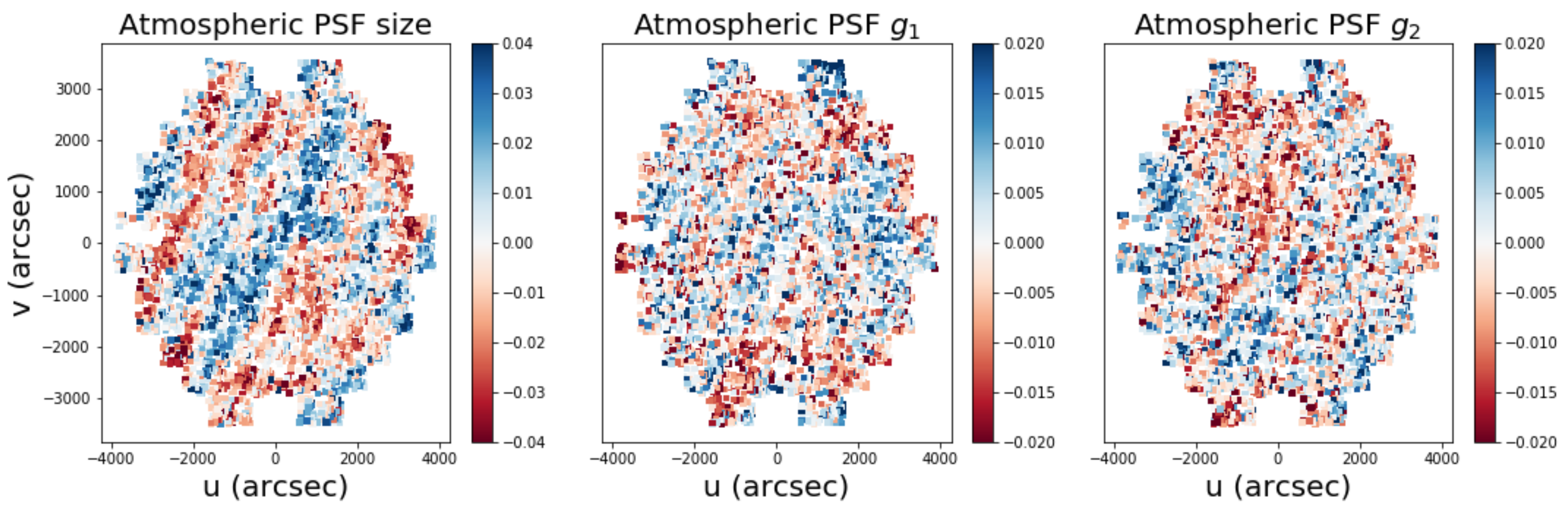

- Deviation from reference image could be fit on focused stars for an individual exposure

- Once the Optical part is removed, the atmospheric part can be estimated

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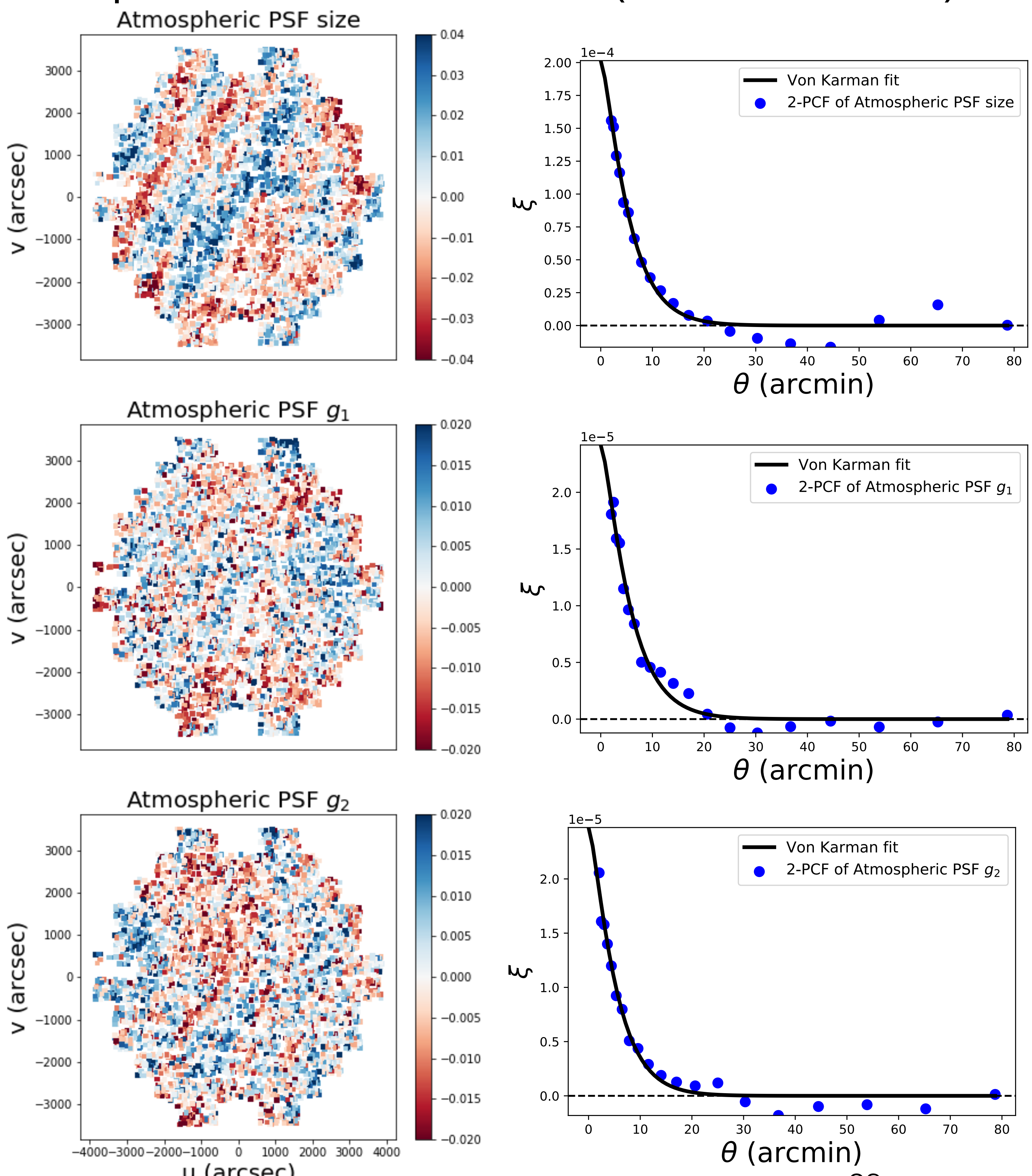


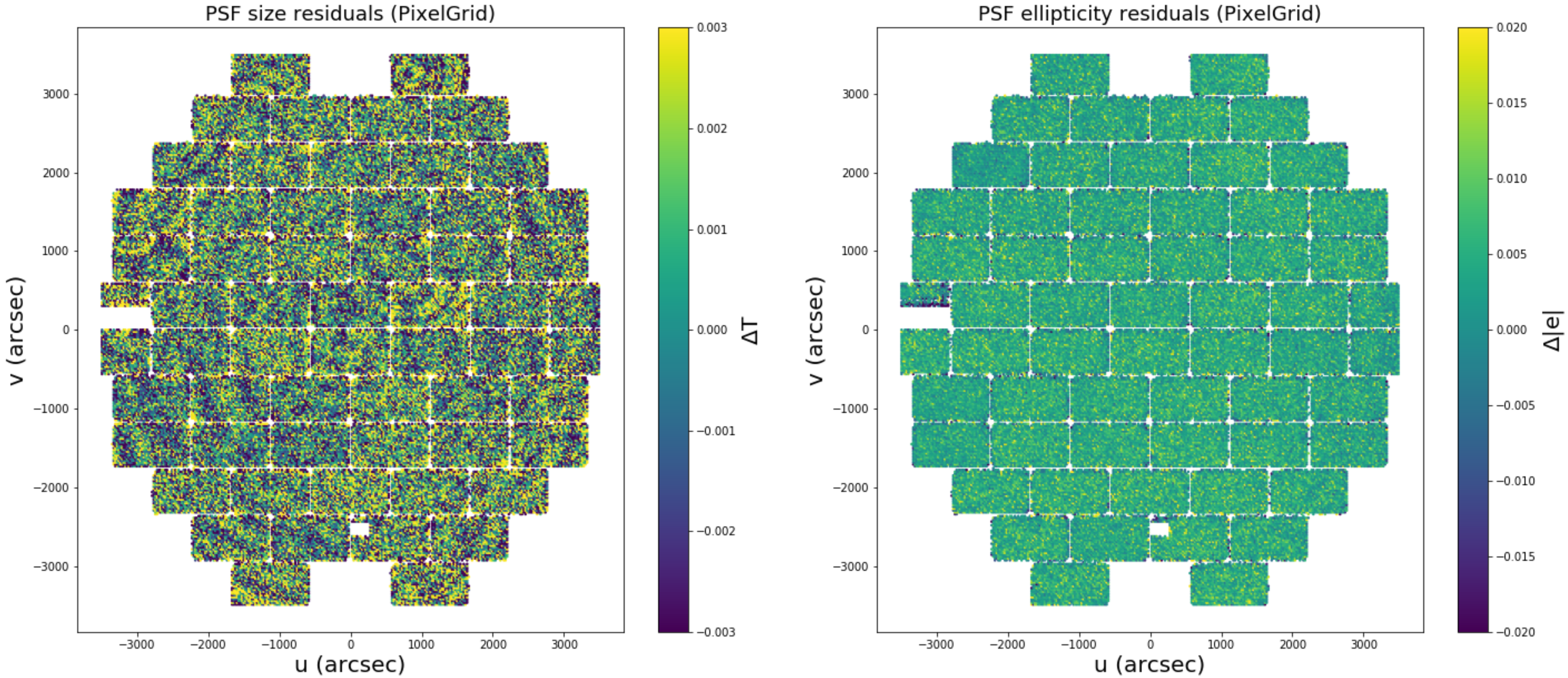
- Atmospheric PSF parameters are interpolated on the full FoV (and not per CCD chip)
- Gaussian Process interpolation
- Use of a Von Karman correlation function for interpolation:

$$\xi(D,\sigma,\ell)=\sigma^2\left[\left(\frac{D}{\ell}\right)^{\frac{5}{12}}K_{\frac{5}{6}}\left(2\pi\frac{D}{\ell}\right)\right]$$

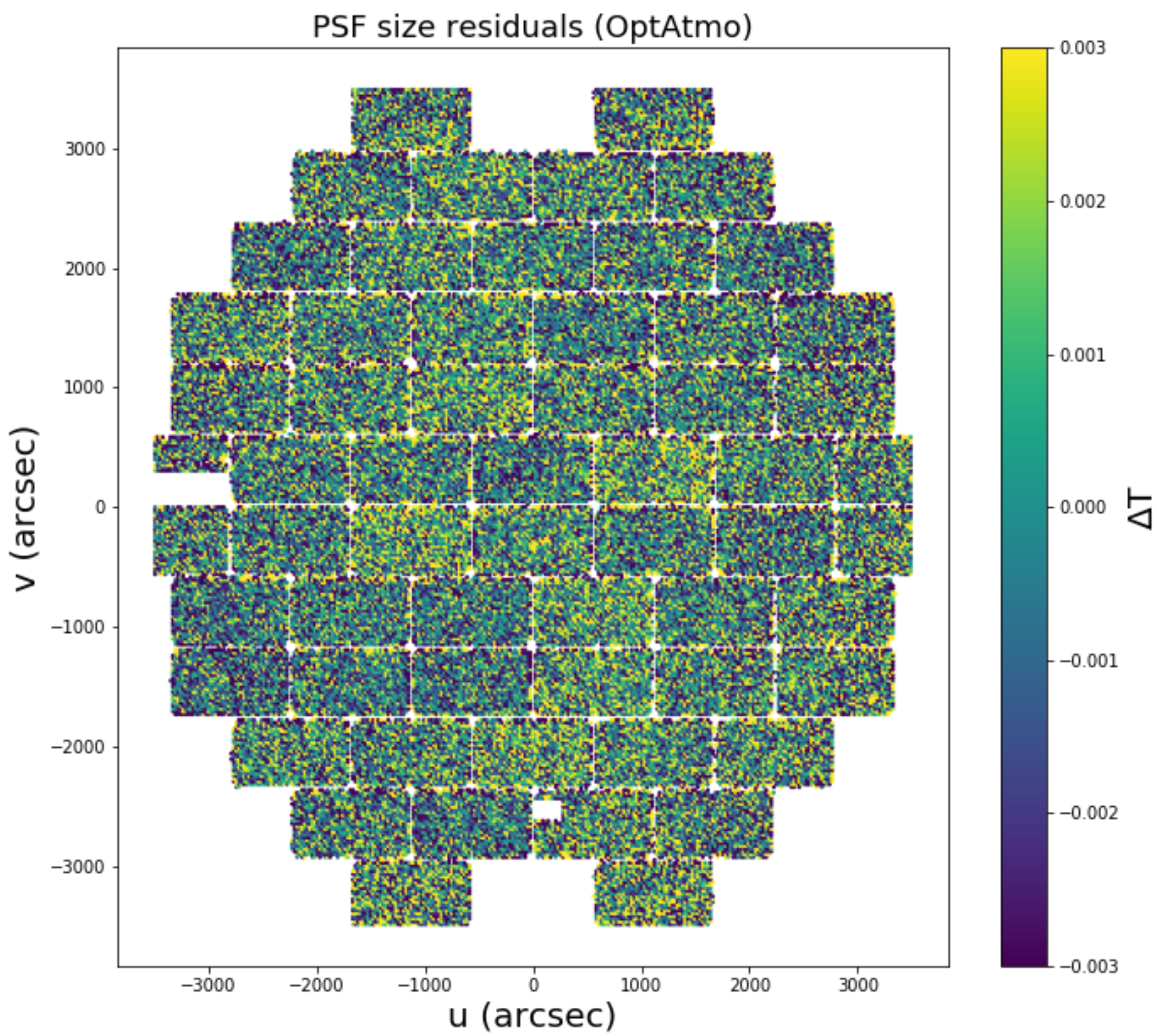
- Observed correlation function are consistent with a Von Karman correlation function

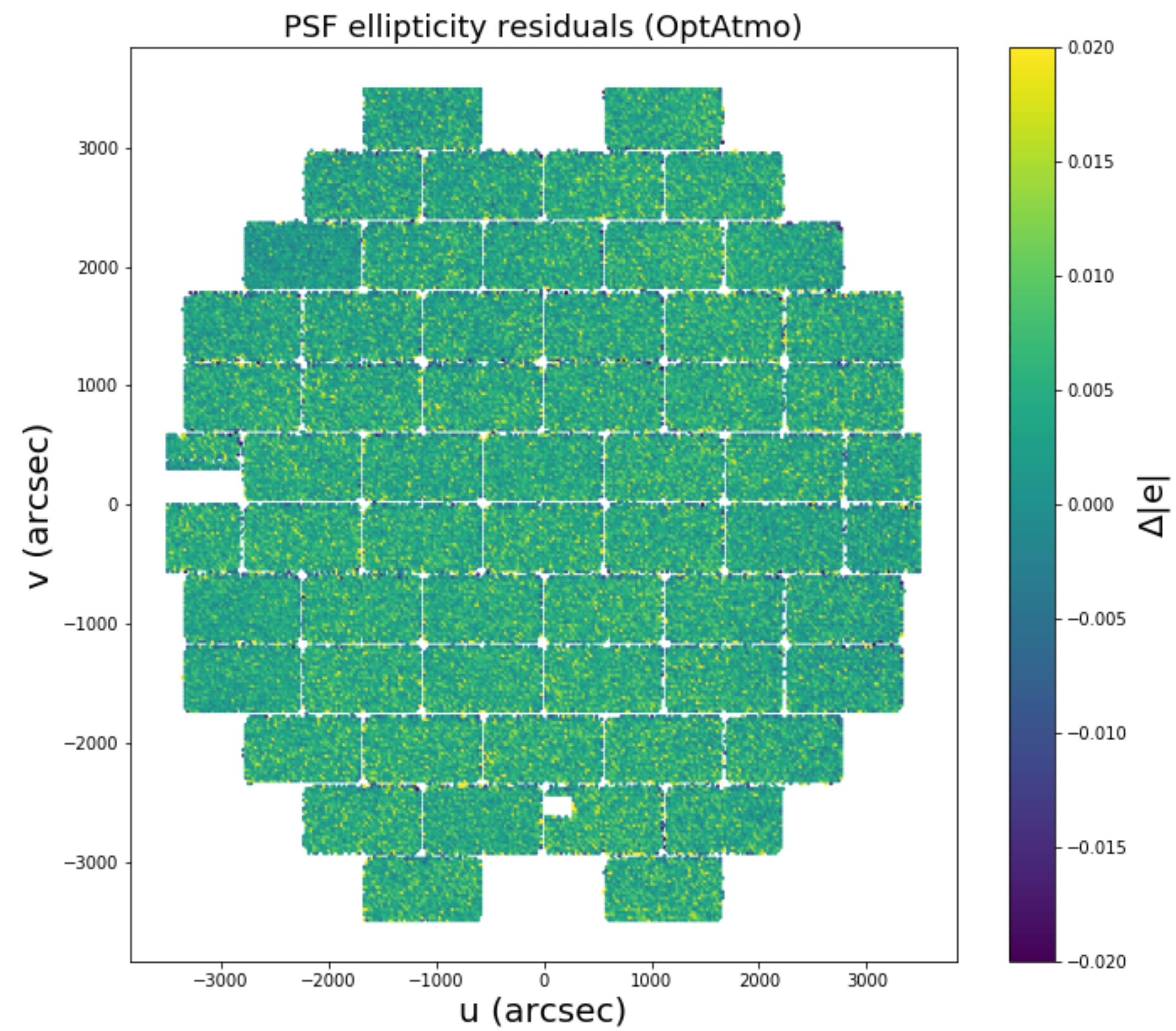
4. Preliminary results on the Dark Energy Survey Y3

- Method applied on DES Y3
- On ~1000 exposures in grizY
- Compare the optical & atmosphere model to the Pixel Basis model (that will be used for Y3 Weak-lensing analysis) —> Both from Piff
- Training (modeling + interpolation) on 80% of stars
- 20% of stars kept for validation
- Results shown on the validation sample only

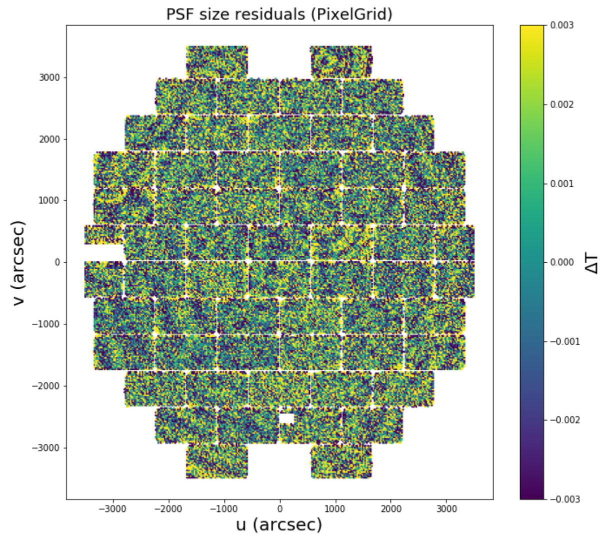
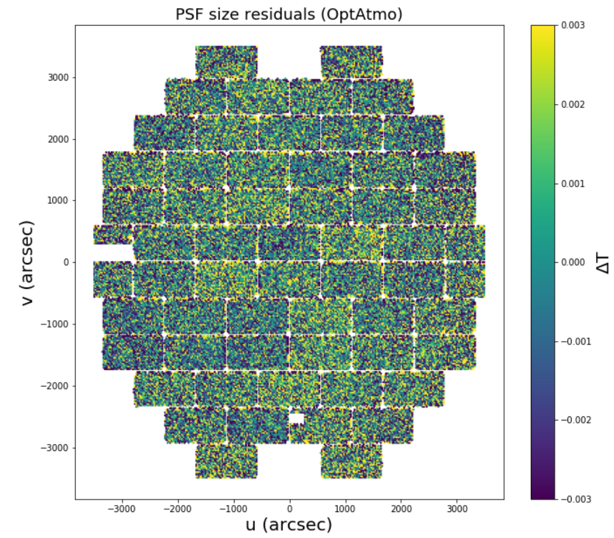
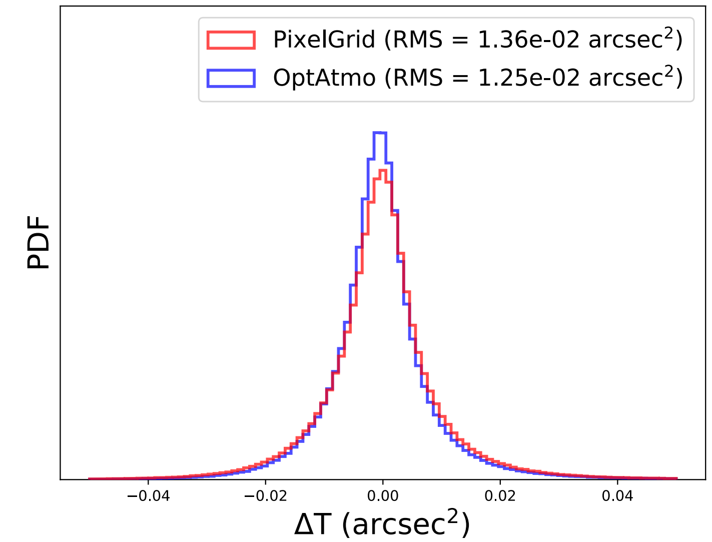


- Residual size (Trace of second moments matrix) and ellipticity averaged across the DES FoV
- For the **Pixel Basis** model using Piff and an **interpolation done per CCD chip**





- Residual size (Trace of second moments matrix) and ellipticity averaged across the DES FoV
- For the **Optical and the Atmospheric model** using Piff and an **interpolation done on the full FoV**

<table>
<tr><th></th><th>Pixel Basis model</th><th>Optical and the Atmospheric model</th><th>Residuals distribution</th></tr>
<tr><td>Residual size</td><td>
</td><td>
</td><td>
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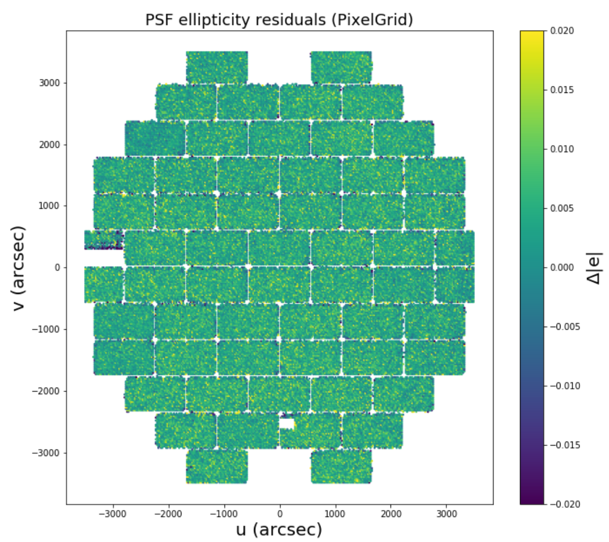
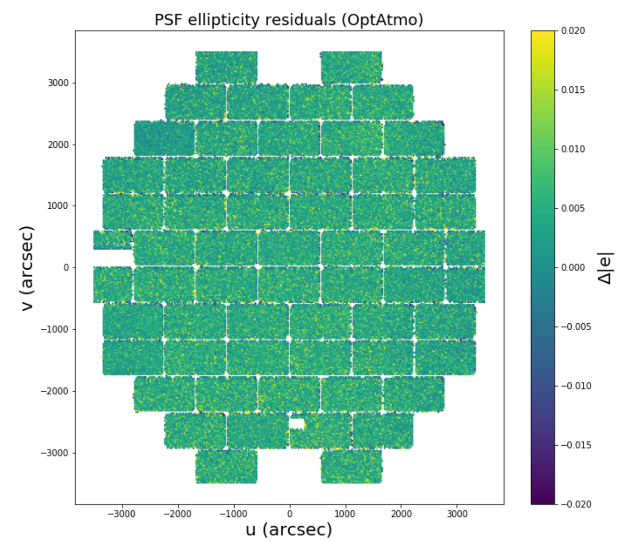
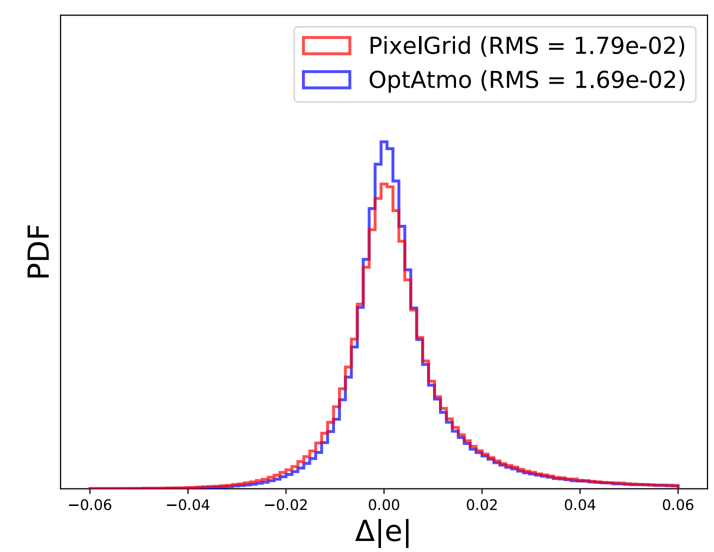
<tr><td>Residual ellipticity</td><td>
</td><td>
</td><td>
</td></tr>
</table>

- Residual size (Trace of second moments matrix) and ellipticity averaged across the DES FoV
- The **Optical and the Atmospheric model** seems to do a better job to reconstruct the second moments compared to the **Pixel Basis model**

$$\rho_1(\theta) \equiv \left\langle \Delta e^*(x)\Delta e(x+\theta) \right\rangle$$

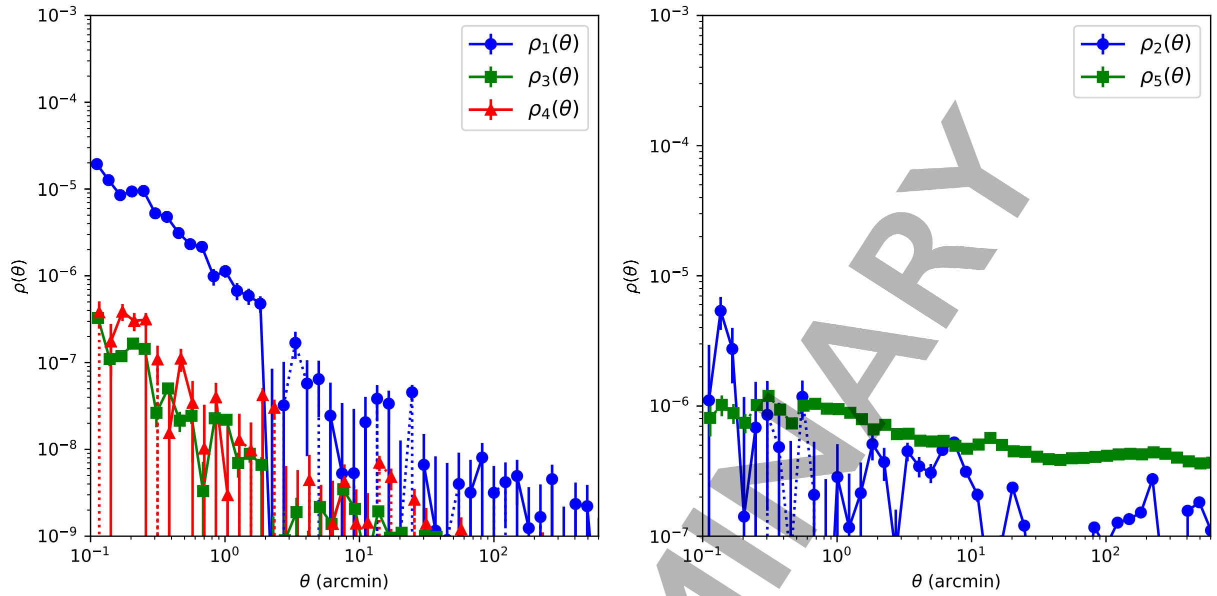
$$\rho_2(\theta) \equiv \left\langle e^*(x)\Delta e(x+\theta) \right\rangle$$

$$\rho_3(\theta) \equiv \left\langle \left(e^* \frac{\Delta T}{T} \right)(x) \left(e \frac{\Delta T}{T} \right)(x+\theta) \right\rangle$$

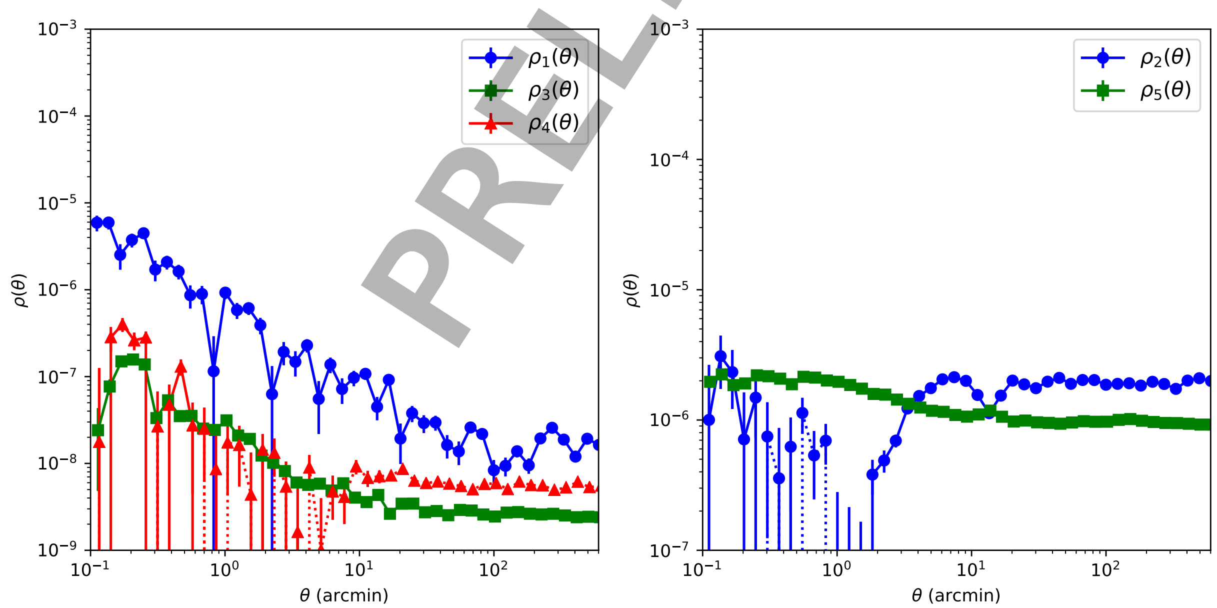
$$\rho_4(\theta) \equiv \left\langle \Delta e^*(x) \left(e \frac{\Delta T}{T} \right)(x+\theta) \right\rangle$$

$$\rho_5(\theta) \equiv \left\langle e^*(x) \left(e \frac{\Delta T}{T} \right)(x+\theta) \right\rangle$$

Pixel Basis model



Optical and the Atmospheric model



- Rowe statistic are compatible for both modeling
- **Optical and the Atmospheric model** is better at small angular separation
- Can be improve on larger scale (and we know how!)

Ongoing improvement of the PSF modeling:

- Average function of the atmosphere done per filter instead of across all filter
- Anisotropic Gaussian Processes instead of isotropic
- Add more Zernike coefficient, especially more spherical component
- Add third moment in the procedure of fitting for the optical part
- Adjust wavelength dependence in the optical model (set at 700nm currently)

4. Conclusion & Perspective

- Piff is an improvement in comparison of PSF and it will be the PSF model used for all Weak-Lensing analysis of DES Y3 (with the Pixel basis and the polynomial interpolation done per CCD)

- In going development of the optical and atmospheric model of the PSF within Piff that gave promising results on DES data (Would be used for Weak-Lensing analysis in DES Y5)

- The PSF matter so much for the Weak-Lensing but not only —> Could help on Flux estimation

- I guess this is important to see in a broader point of vue the PSF problem

Merci !