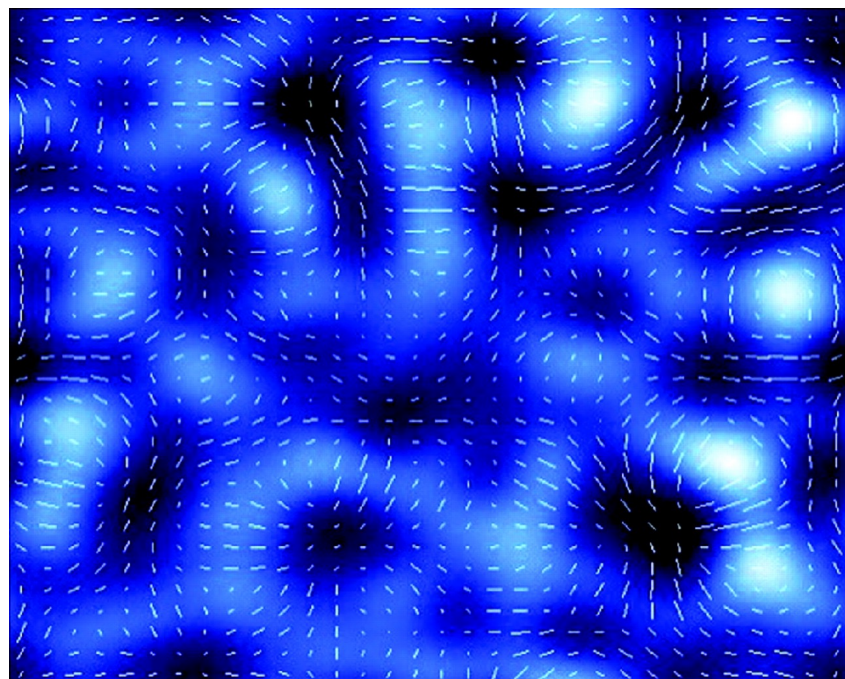


PSFs In the Full Field-of-view (Piff)

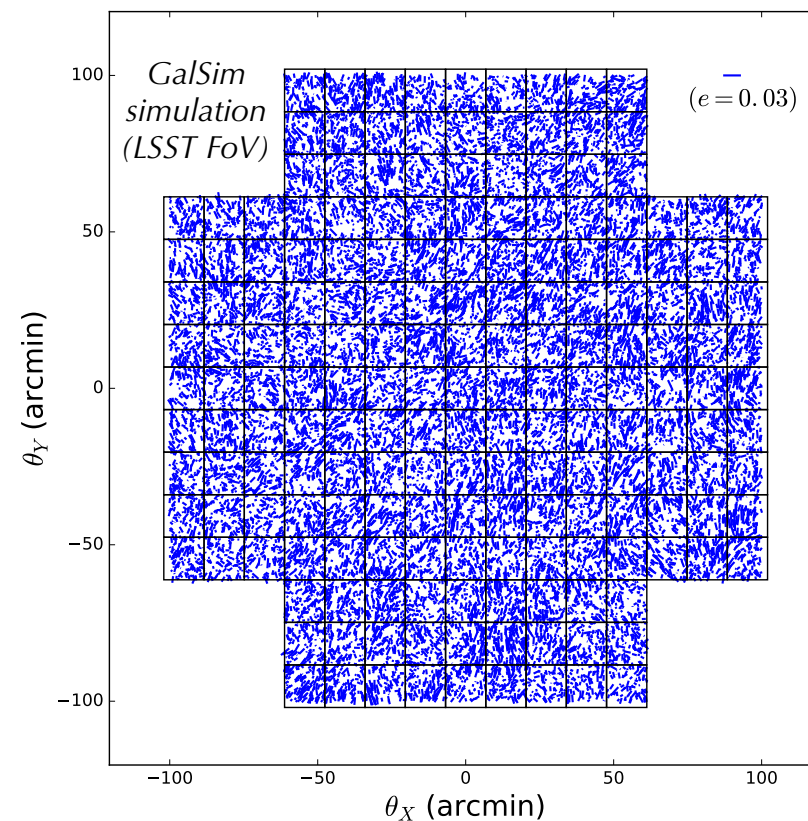
Pierre-François Léget - LPNHE

Weak lensing signal

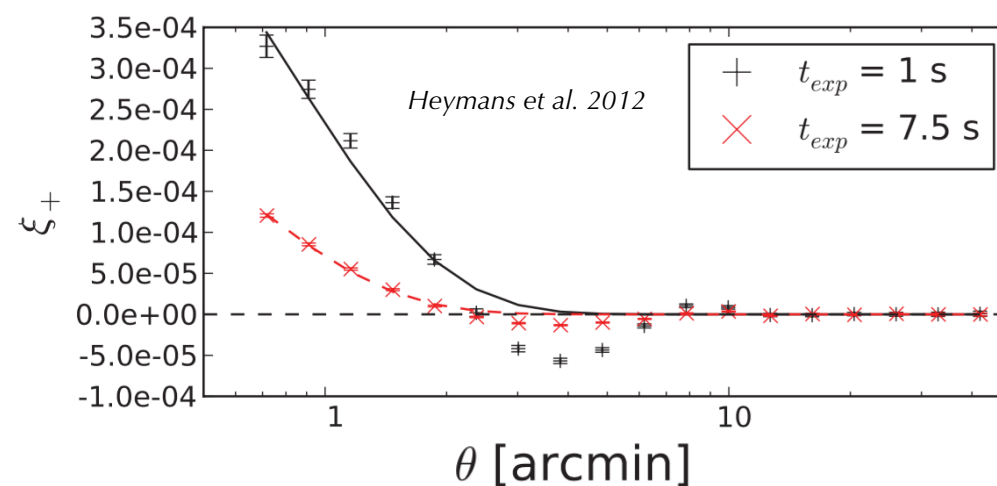
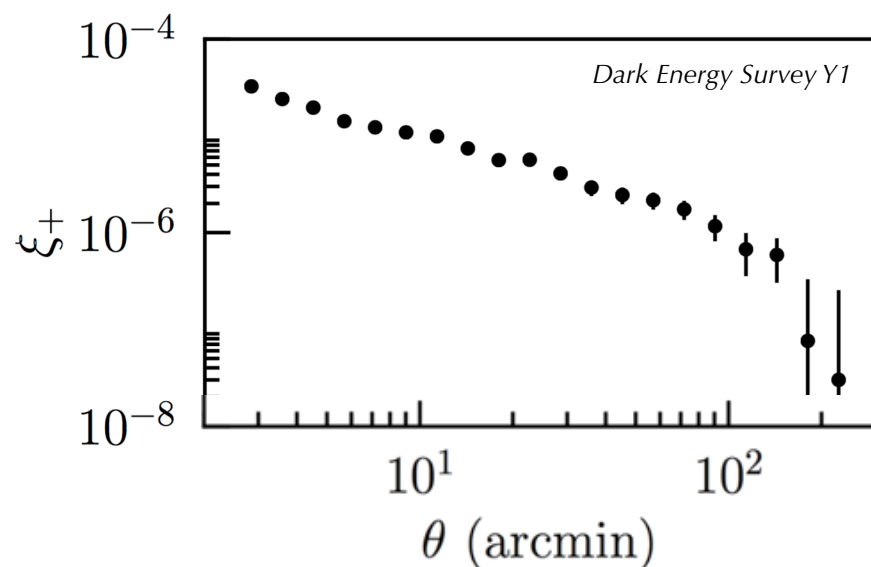
Ellis 2010 (simulation)

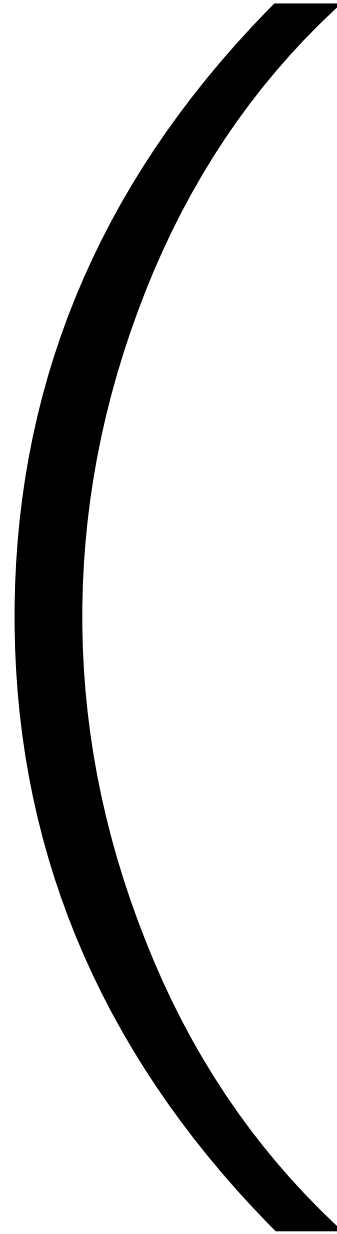


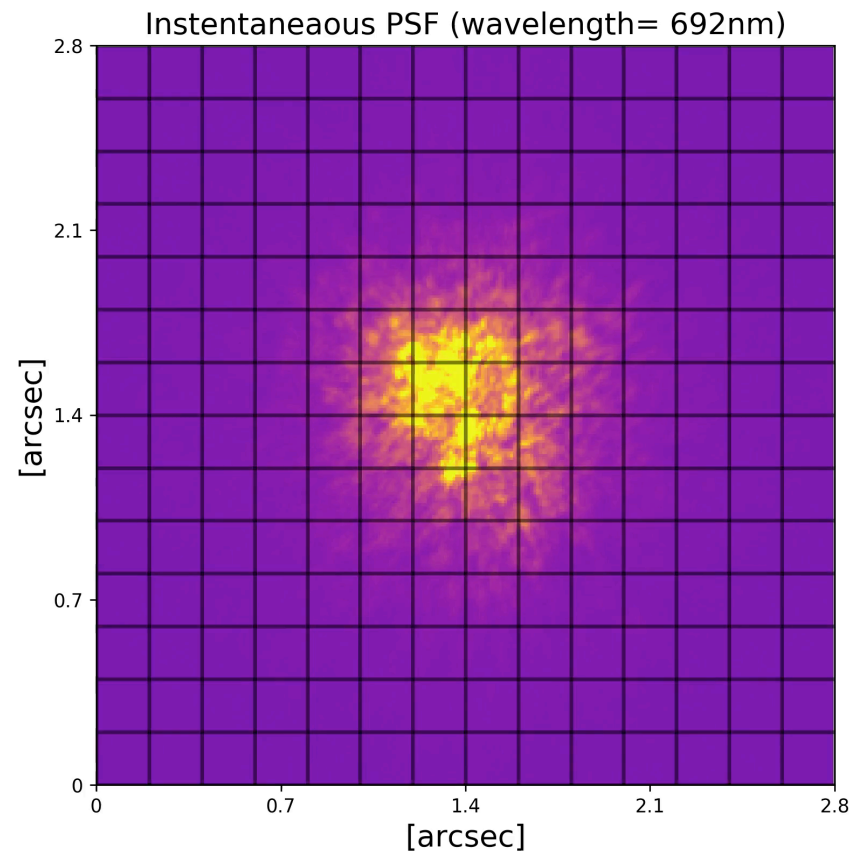
Point Spread Function ellipticity



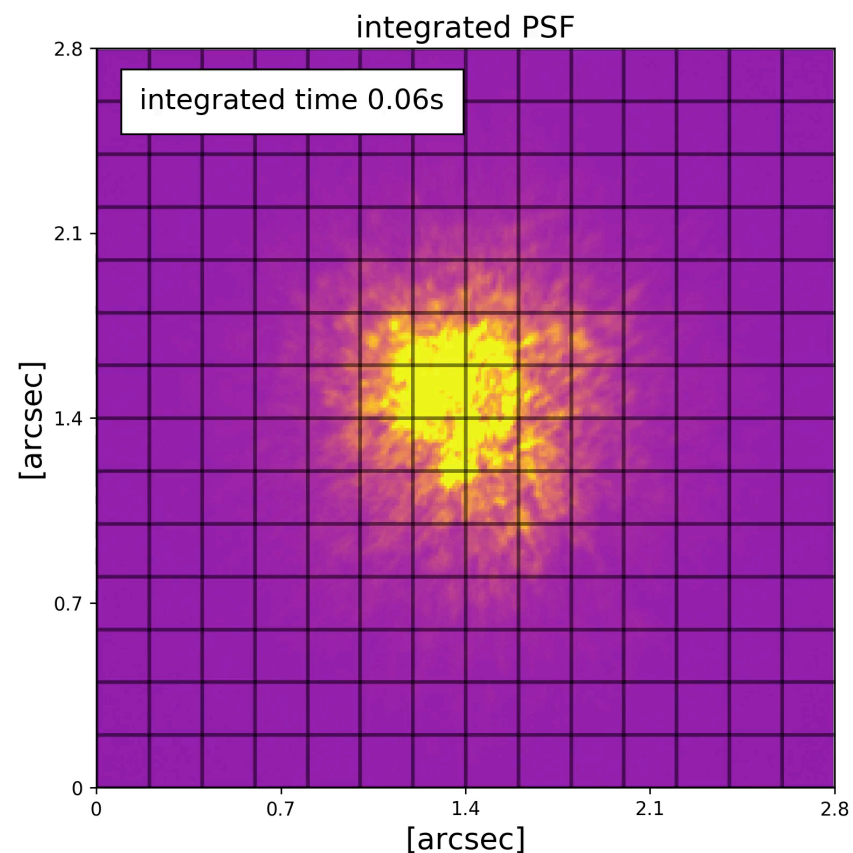
- Weak-lensing needs very accurate (unbiased) shape measurements
- PSF introduces additional ellipticity and is spatially correlated (like sheared galaxy shapes) due to atmosphere and optics
- An accurate (unbiased) model of spatial variation of the PSF is crucial for LSST cosmic shear

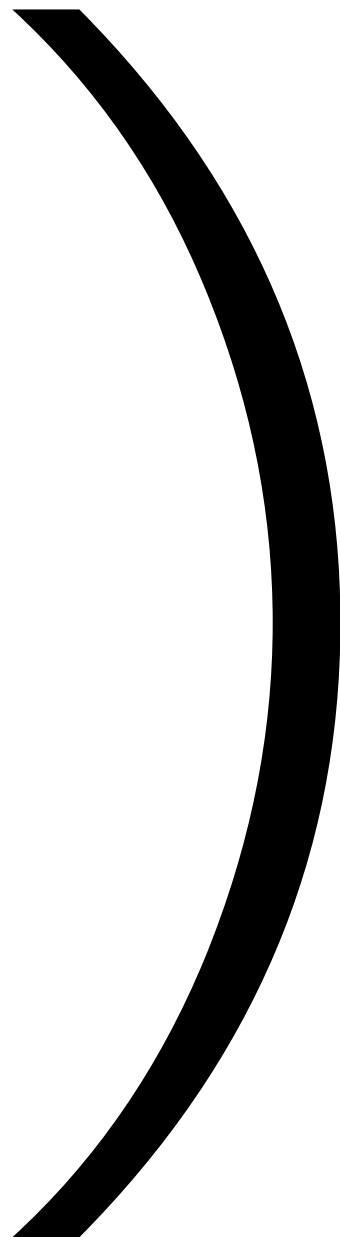






- How the PSF really looks like ?
- High definition movies of bright stars took on Gemini south with the Differential Speckle Survey Instrument
- 0.011 arcsec / pixel (LSST 0.2 arcsec / pixel)
- Exposure time of 60 ms with 2 ms of readout
- See C.-A. Hébert et al. ArXiv: 1807.09337





PSF decomposition

For a given exposure

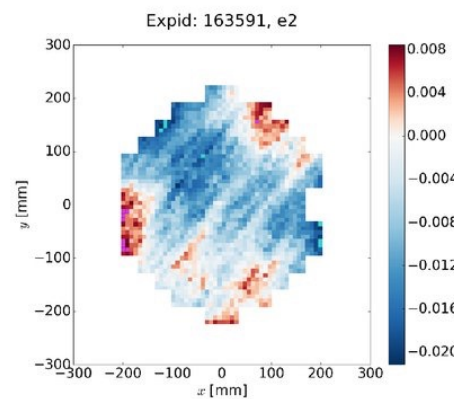
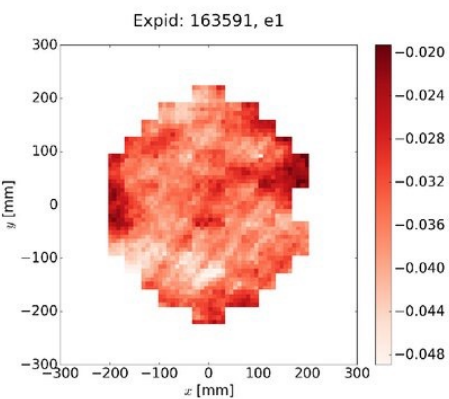
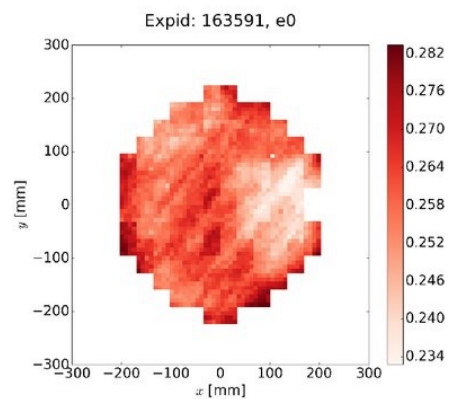
Davis et al. 2016

PSF size

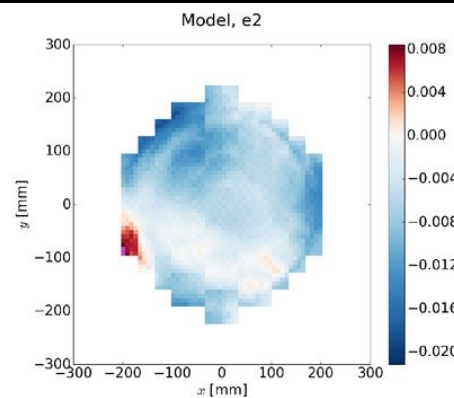
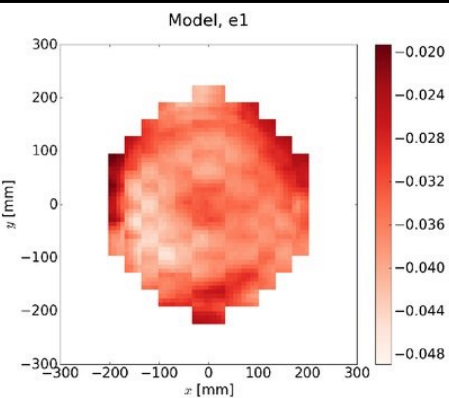
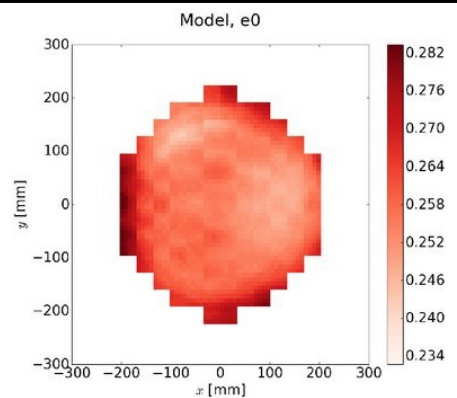
PSF ellipticity 1

PSF ellipticity 2

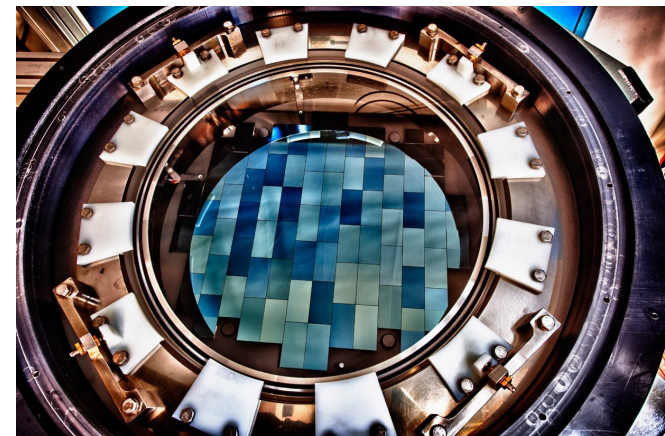
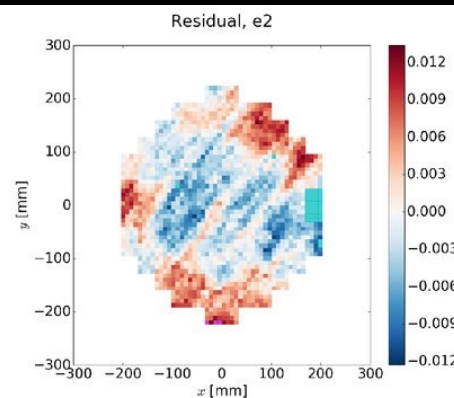
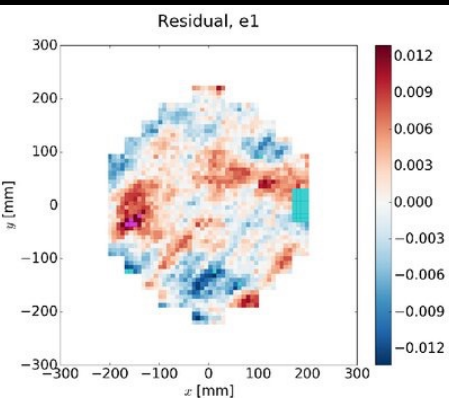
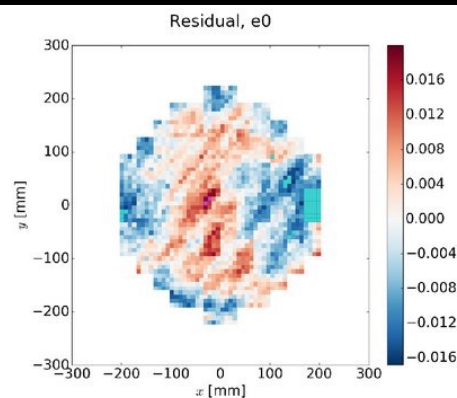
Total PSF



Optical PSF



Atmospheric PSF



Dark Energy Camera

I. 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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- 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

Rowe Statistics:

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

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

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

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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

Rowe Statistics:

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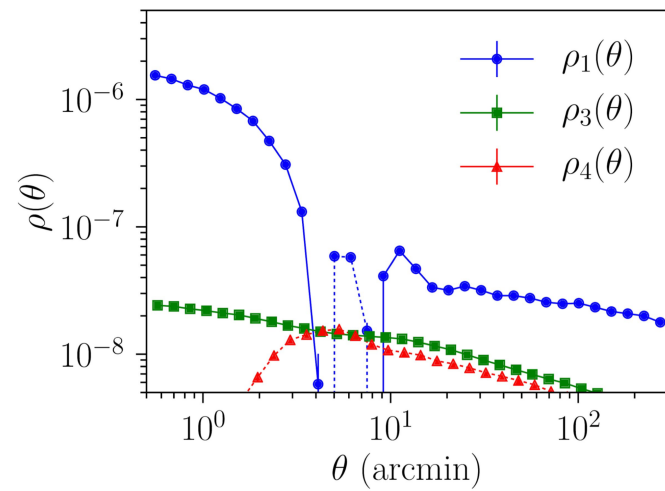
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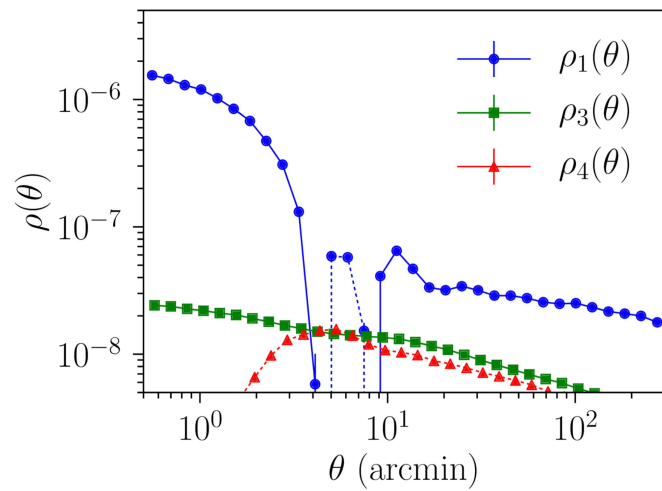
$$\Delta \xi_+ = 2 \left\langle \frac{T_{PSF}}{T_{gal}} \frac{\Delta T_{PSF}}{T_{PSF}} \right\rangle \xi_+(\theta) + \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle^2 \rho_1(\theta) - \alpha \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle \rho_2(\theta) + \left\langle \frac{T_{PSF}}{T_{gal}} \right\rangle^2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

PSFex



- Piff and PSFex are applied on $\sim 50\%$ 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

PSFex



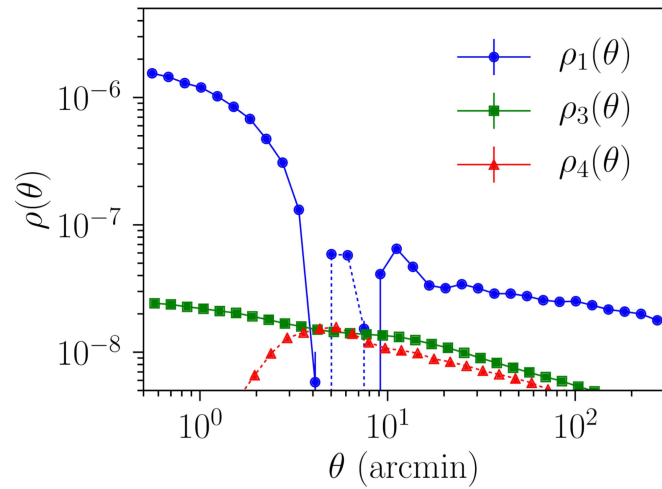
$$\rho_1(\theta) \equiv \left\langle \Delta e^*(x) \Delta e(x + \theta) \right\rangle$$

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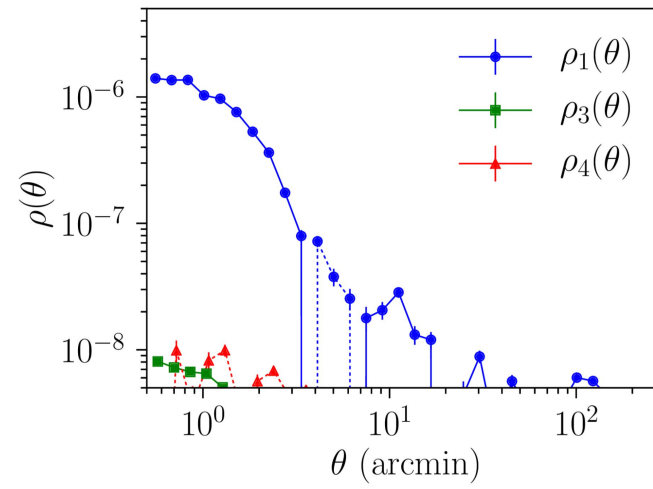
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Piff



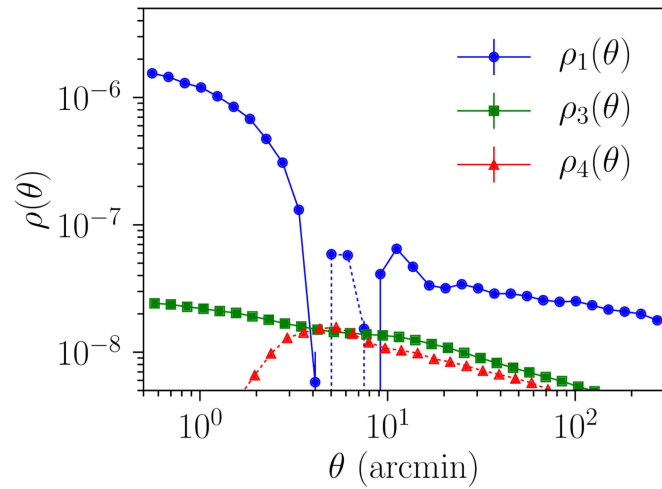
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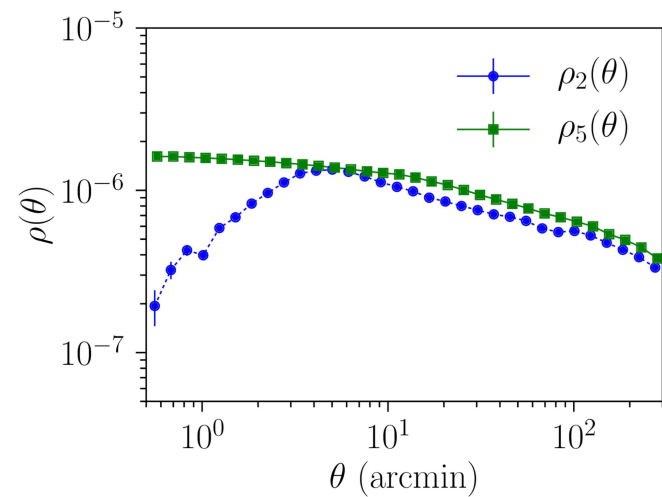
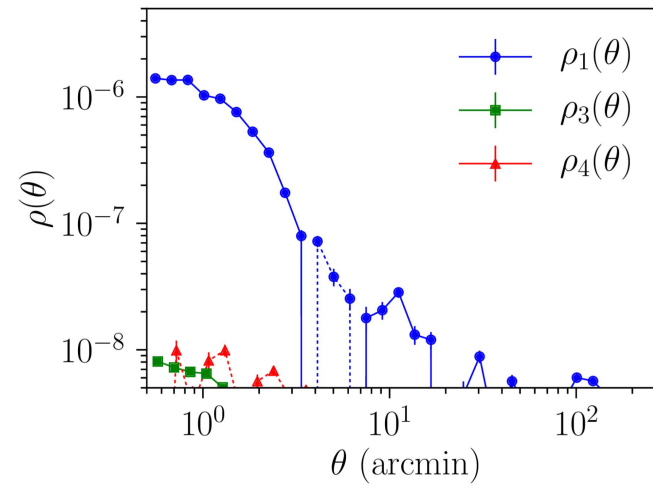
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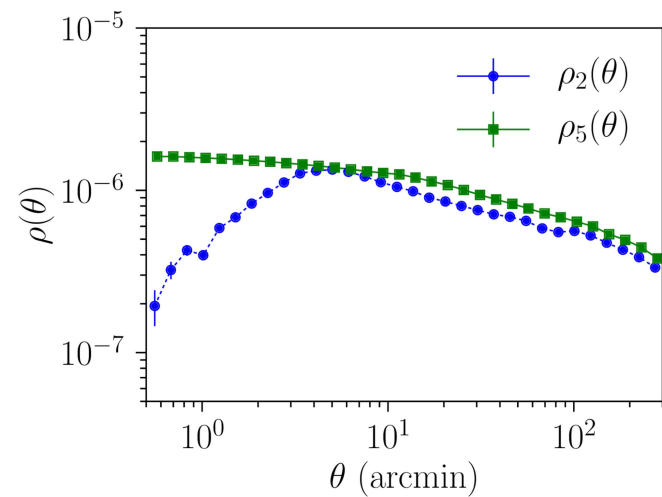
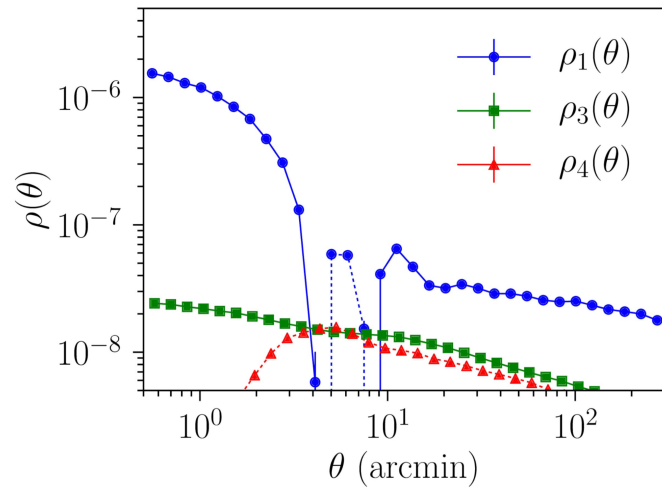
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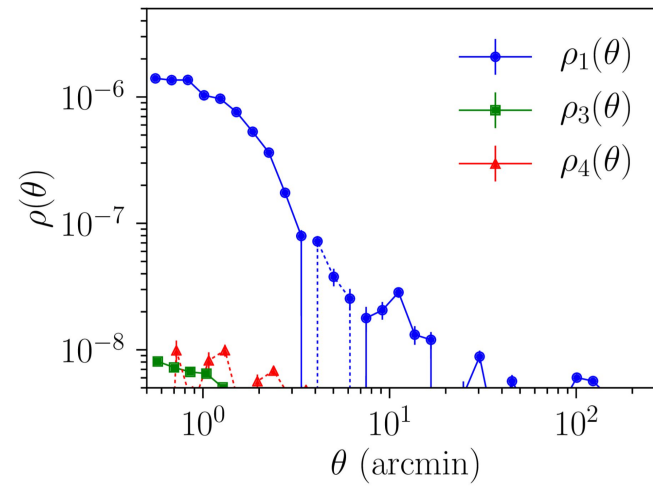
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PSFex



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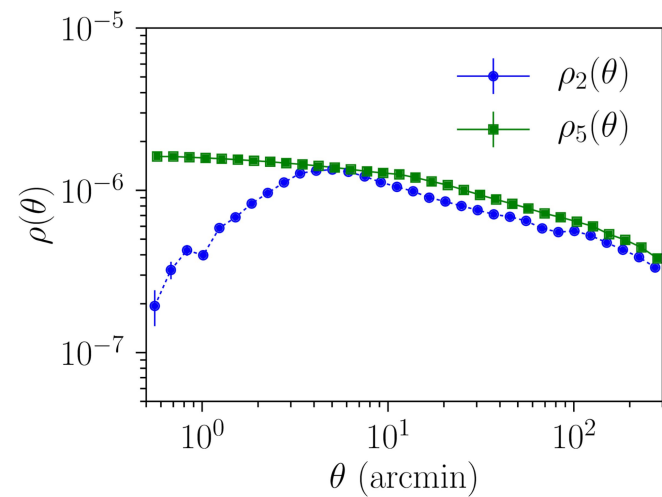
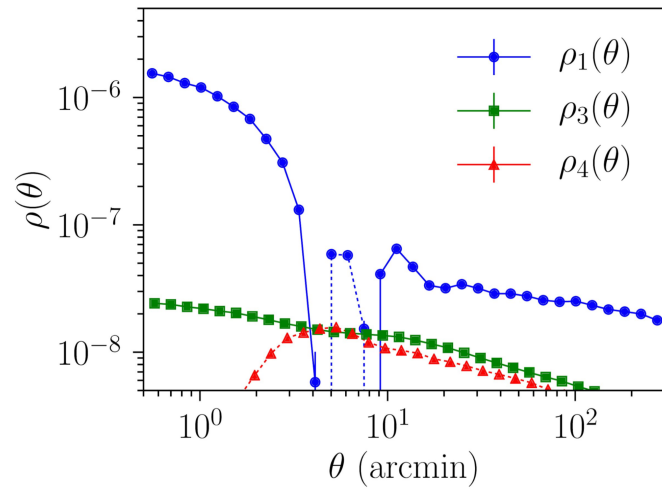
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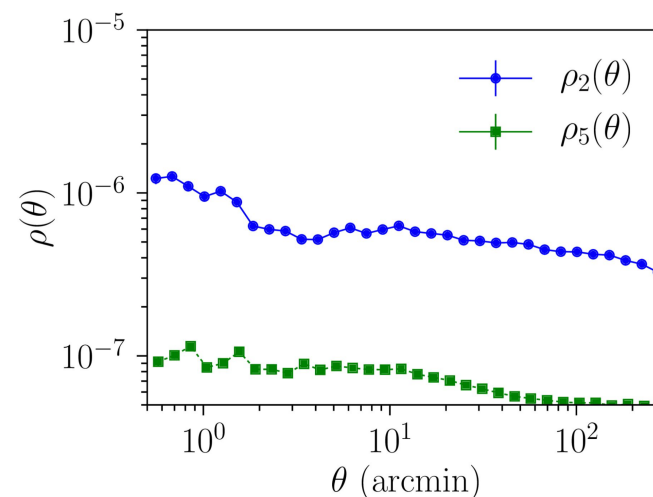
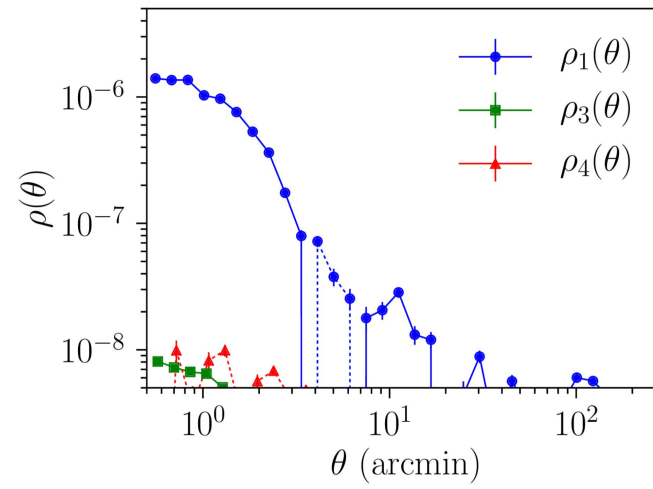
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PSFex



Piff



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2. The Optical and Atmospheric PSF model

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

2. The Optical and Atmospheric PSF model

PSF profile

~

Optical part of the PSF
as a Fraunhofer Diffraction

⊗

Atmospheric part of the PSF

$$I(u, v) \sim \left| F \left\{ \underset{\substack{\downarrow \\ \text{Pupil function}}}{P(\rho, \theta)} e^{\underset{\substack{\downarrow \\ \text{Wavefront}}}{2\pi i W(\rho, \theta)/\lambda}} \right\} \right|^2$$

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

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

$$a_{i, \text{corr}}(u, v) = \sum_j b_{i, j}(u, v) Z_j(\rho, \theta)$$

2. The Optical and Atmospheric PSF model

PSF profile

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Optical part of the PSF
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Atmospheric part of the PSF
as a Kolmogorov profile

$$I(u, v) \sim \left| F \left\{ \underset{\substack{\downarrow \\ \text{Pupil function}}}{P(\rho, \theta)} e^{\underset{\substack{\downarrow \\ \text{Wavefront}}}{2\pi i W(\rho, \theta)/\lambda}} \right\} \right|^2 \otimes K(\alpha(u, v), g_1(u, v), g_2(u, v))$$

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2. The Optical and Atmospheric PSF model

PSF profile \sim Optical part of the PSF as a Fraunhofer Diffraction \otimes Atmospheric part of the PSF as a Kolmogorov profile

$$I(u, v) \sim \left| F \left\{ \underset{\text{Pupil function}}{P(\rho, \theta)} \underset{\text{Wavefront}}{e^{2\pi i W(\rho, \theta)/\lambda}} \right\} \right|^2 \otimes K(\underset{\text{Second moment of the Kolmogorov profile (size, ellipticity)}}{\alpha(u, v)}, g_1(u, v), g_2(u, v))$$

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

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2. The Optical and Atmospheric PSF model

PSF profile

\sim

Optical part of the PSF
as a Fraunhofer Diffraction

\otimes

Atmospheric part of the PSF
as a Kolmogorov profile

$$I(u, v) \sim \left| F \left\{ P(\rho, \theta) e^{2\pi i W(\rho, \theta)/\lambda} \right\} \right|^2 \otimes K(\alpha(u, v), g_1(u, v), g_2(u, v))$$

Pupil function

Wavefront

Second moment of
the Kolmogorov profile
(size, ellipticity)

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

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

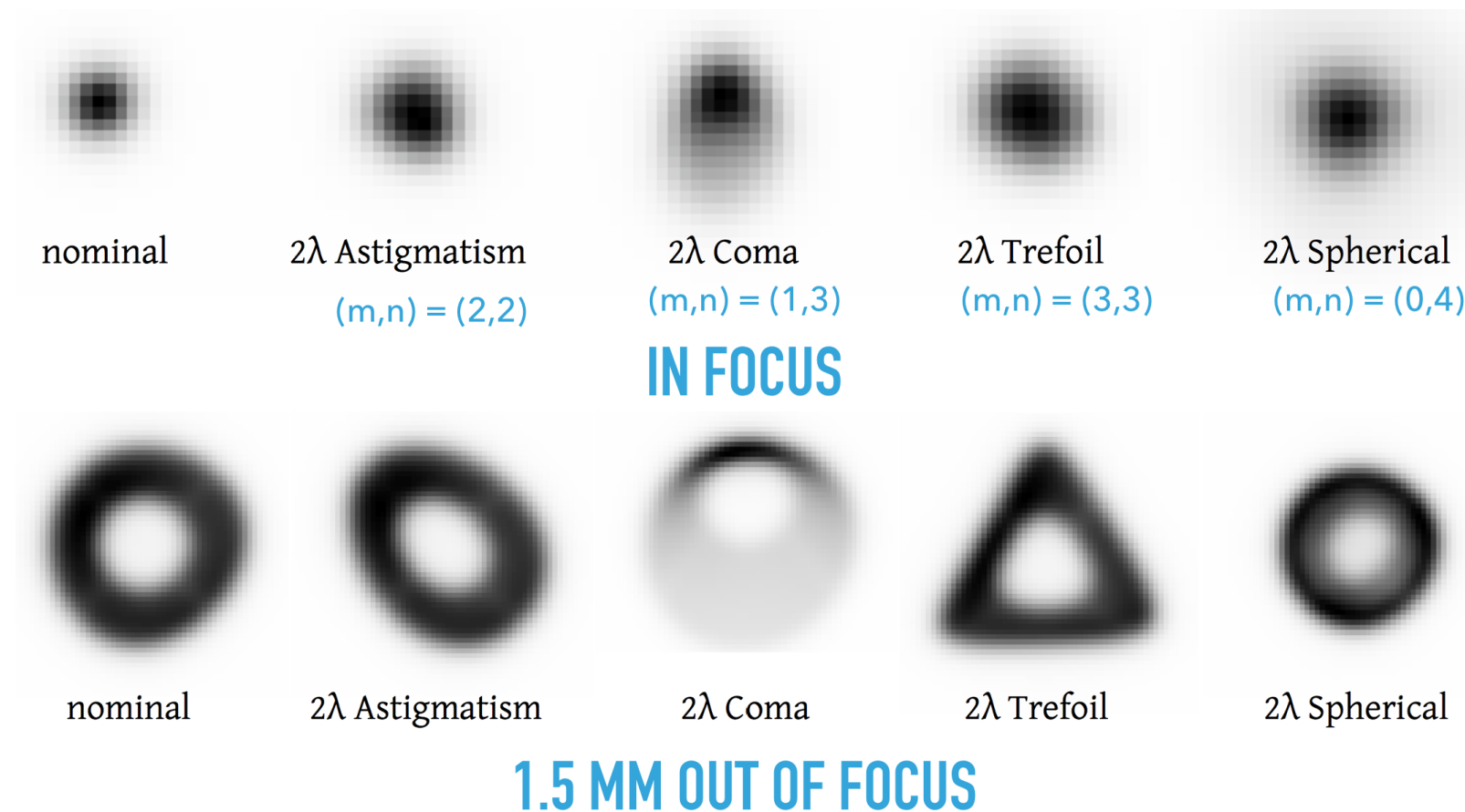
$$a_{i, \text{corr}}(u, v) = \sum_j b_{i, j}(u, v) Z_j(\rho, \theta)$$

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

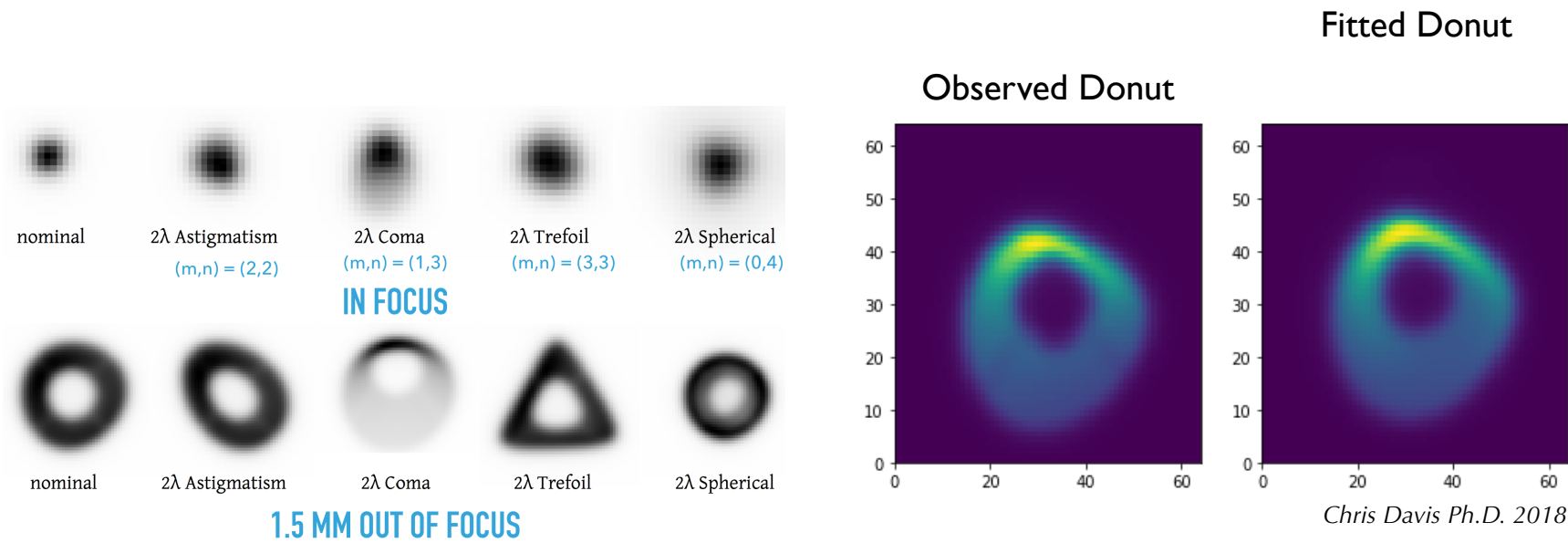
$$\alpha(u, v) \sim N(\alpha_0(u, v), \xi)$$

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

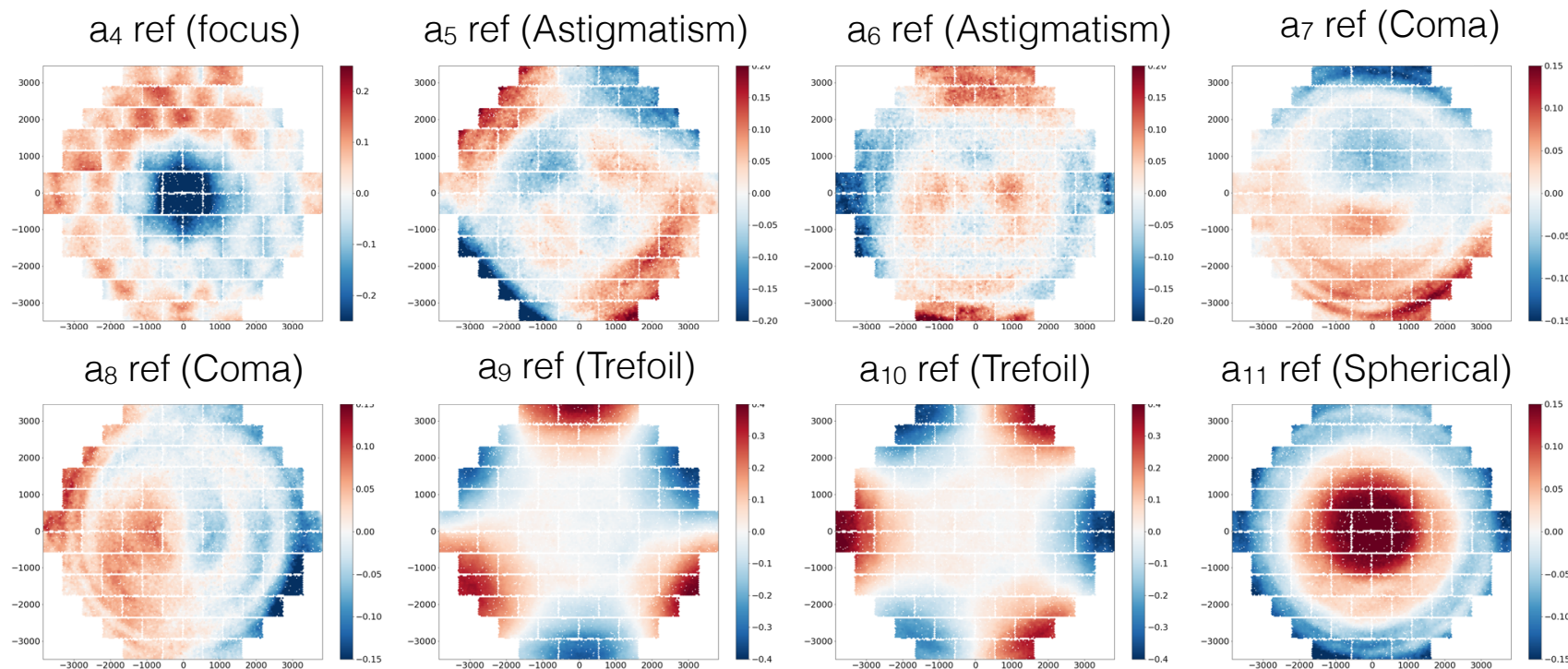
$$g_2(u, v) \sim N(g_{2,0}(u, v), \xi)$$



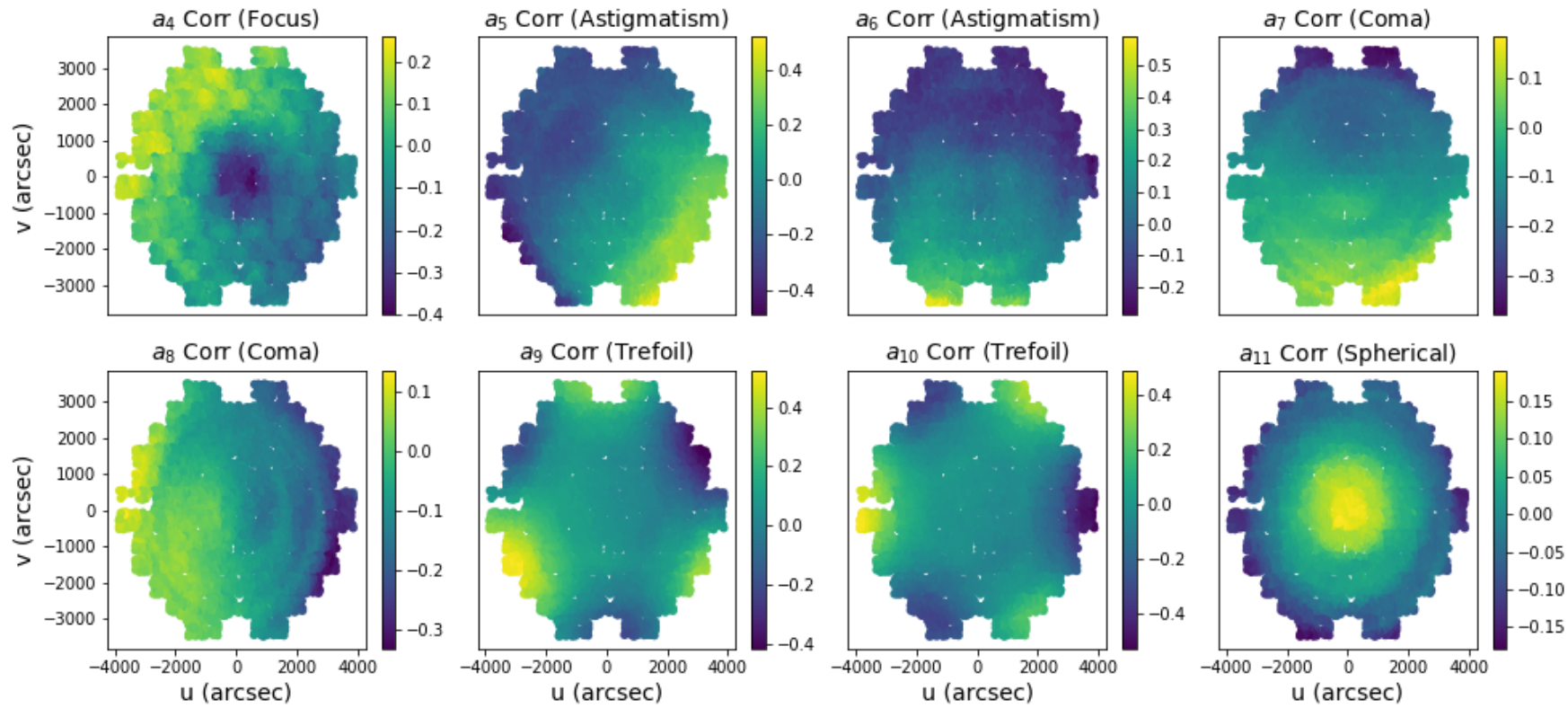
- Each optical aberration is really easy to get with out of focus images (« donuts » images)
- Each Zernike coefficient is associated with an optical aberration



- 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)

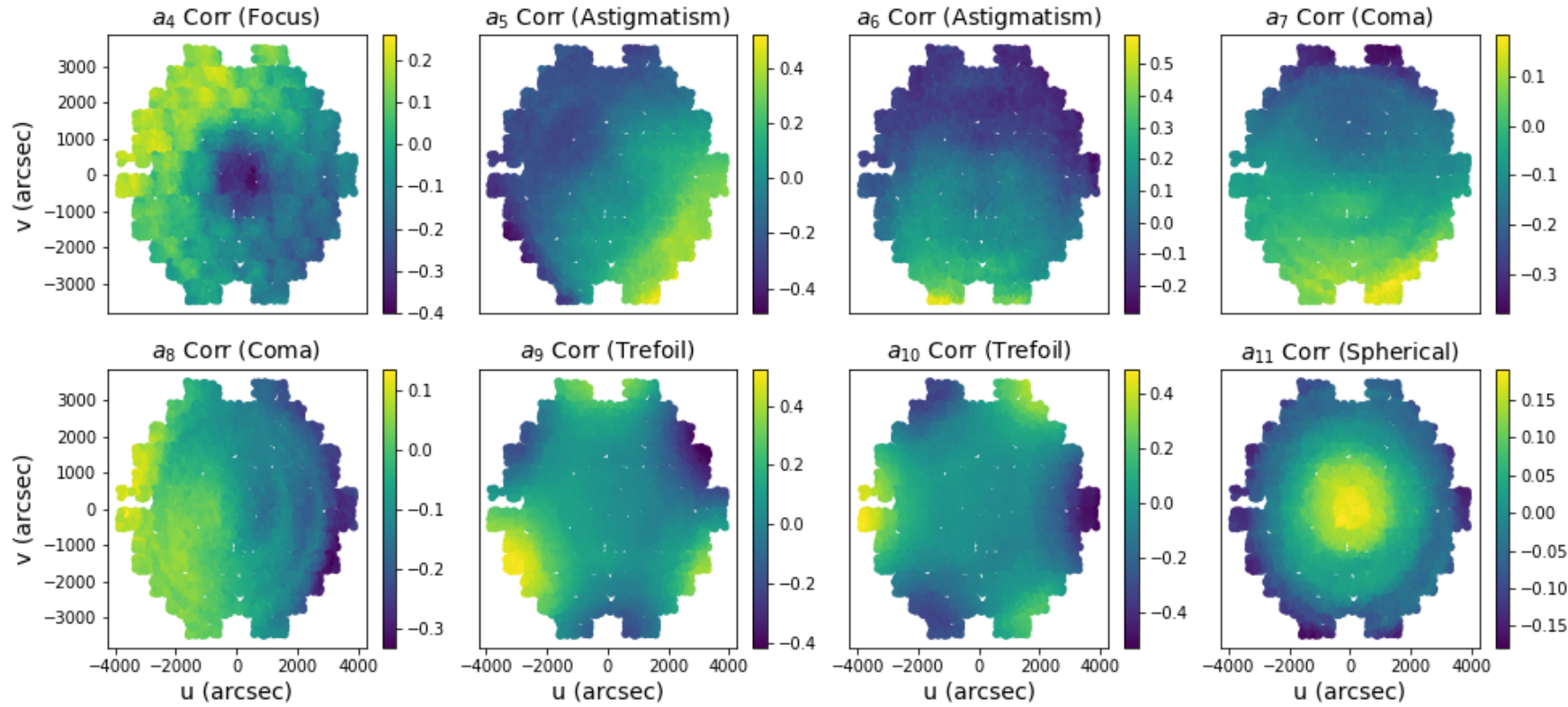


Exposure n°510463 (12/01/2016)

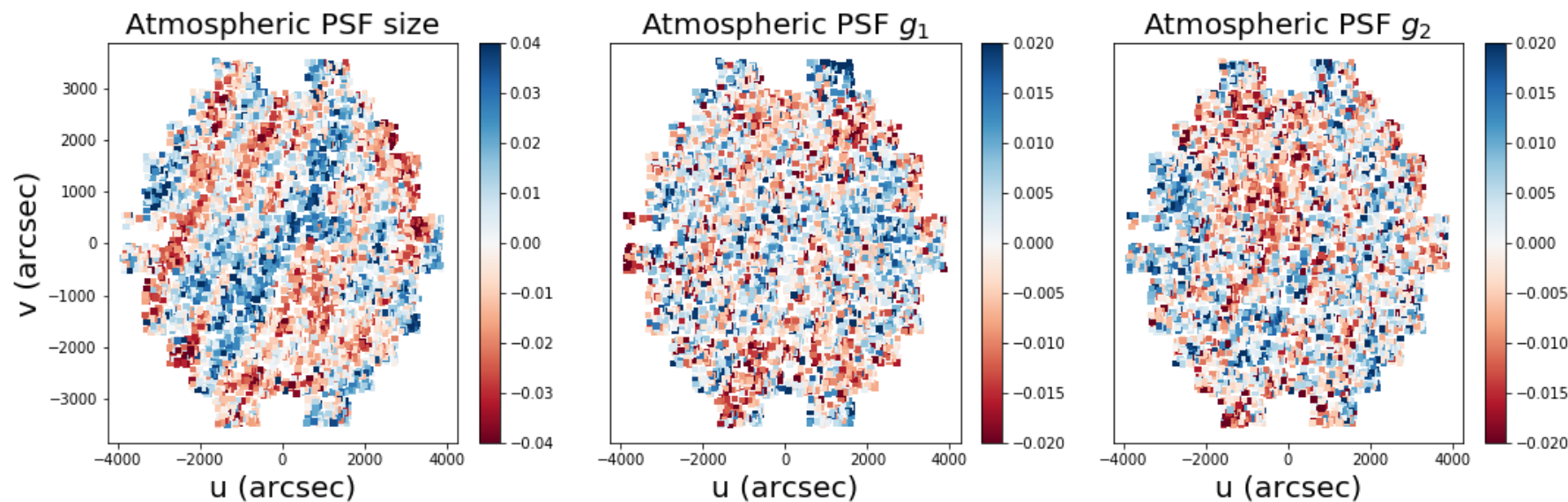


- Deviation from reference image could be fit on focused stars for an individual exposure

Exposure n°510463 (12/01/2016)

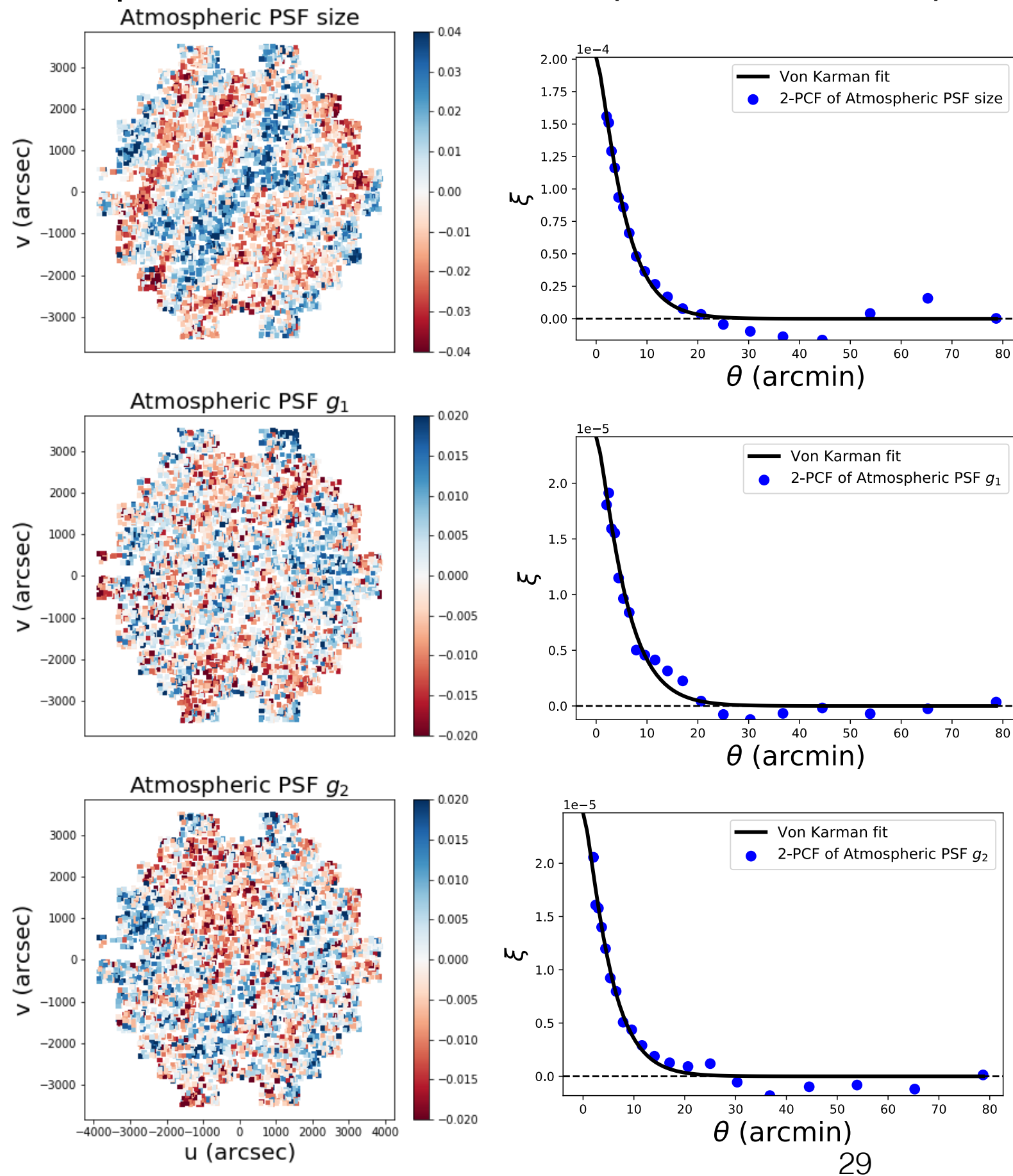


- Deviation from reference image could be fit on focused stars for an individual exposure



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

Exposure n°510463 (12/01/2016)



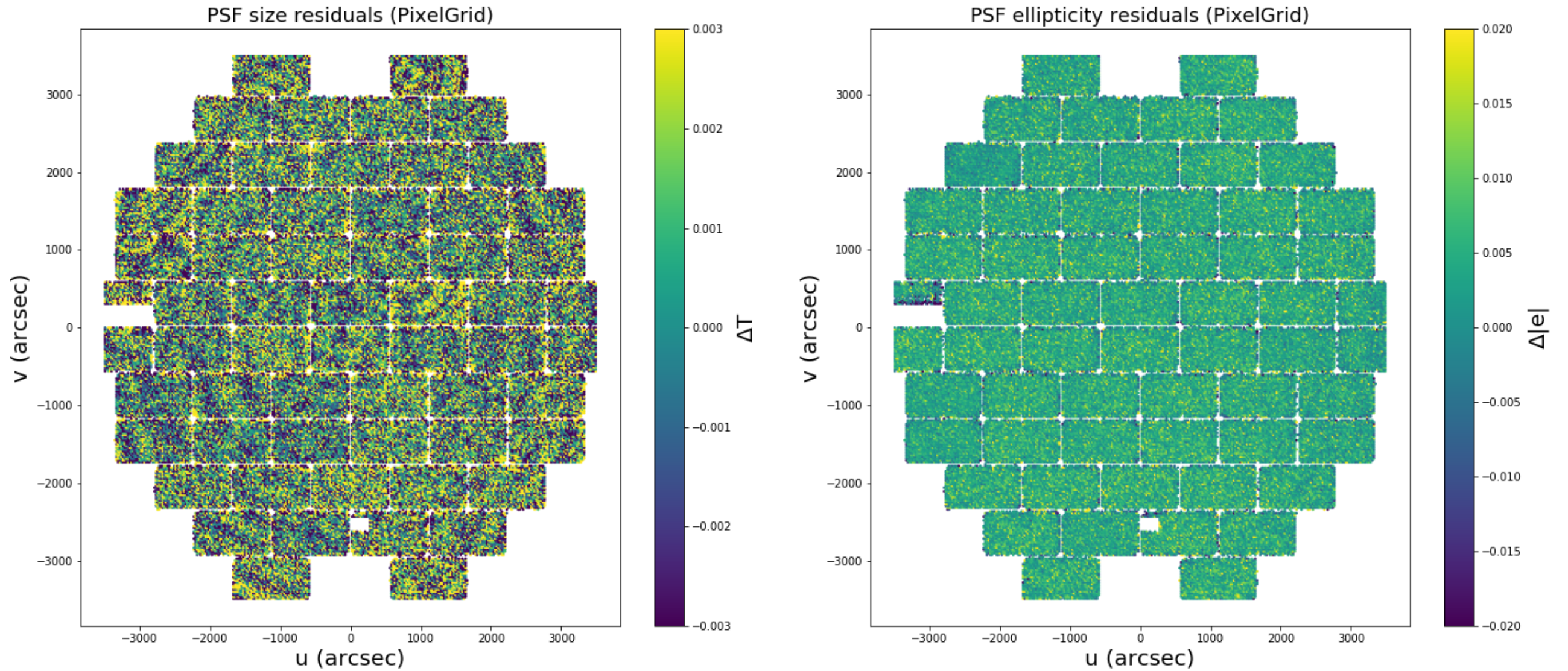
- Atmospheric PSF parameters are interpolated on the full FoV (and not per CCD chip)
- Gaussian Process interpolation
- Use of a Von Karman correlation function for interpolation:

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

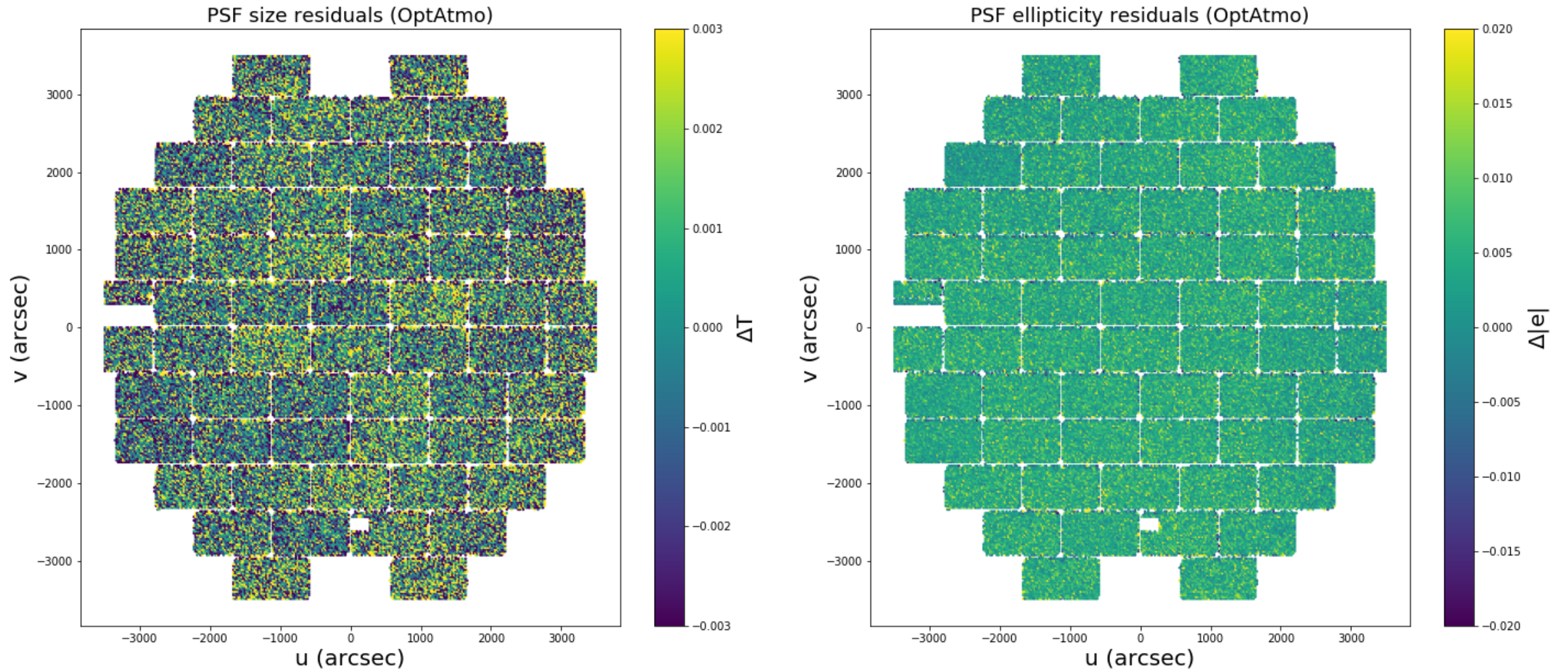
- Observed correlation function are consistent with a Von Karman correlation function

4. Preliminary results on the Dark Energy Survey Y3

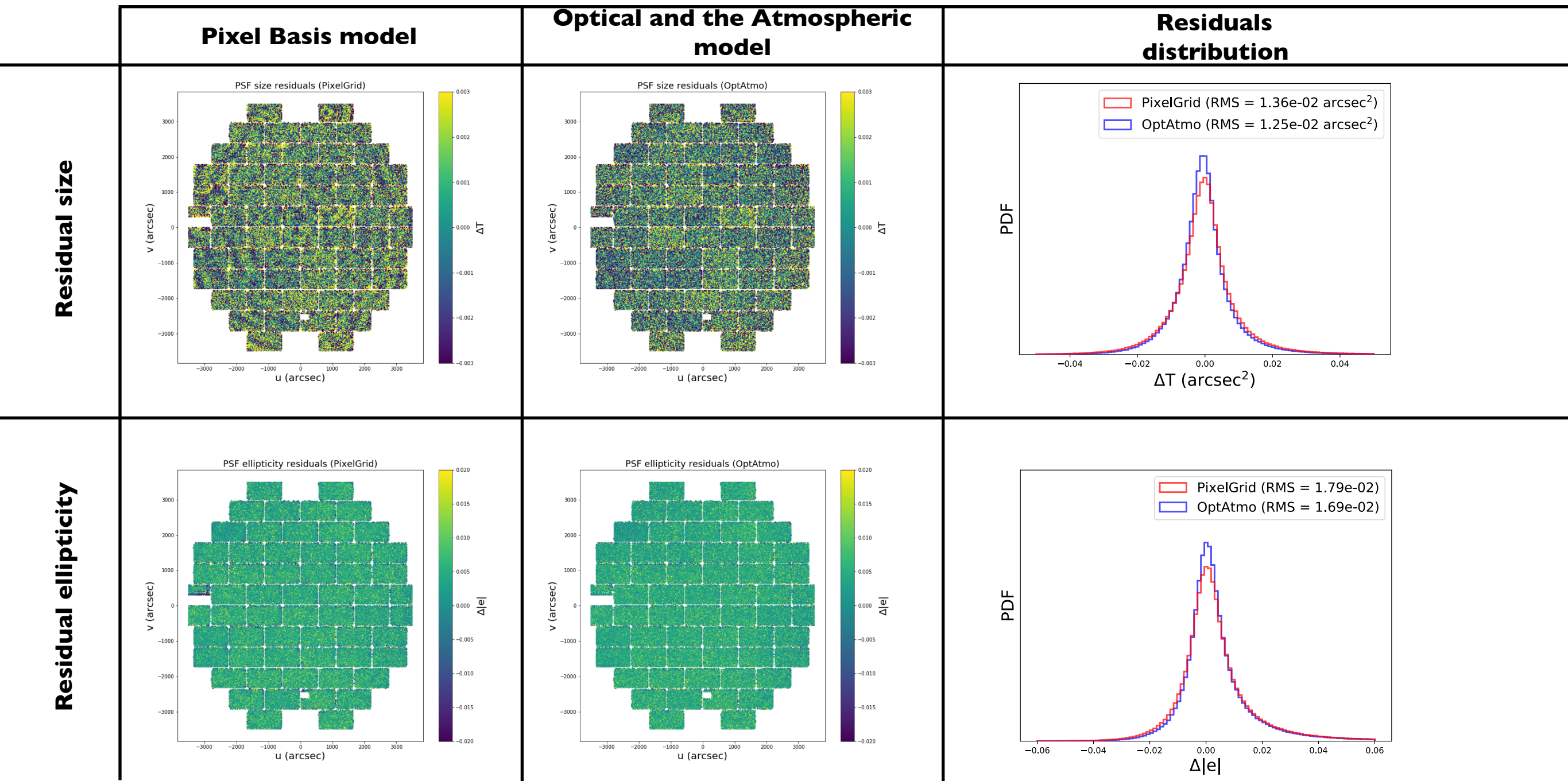
- Method applied on DES Y3
- On ~ 1000 exposures in grizY
- Compare the optical & atmosphere model to the Pixel Basis model (that will be used for Y3 Weak-lensing analysis) \longrightarrow Both from Piff
- Training (modeling + interpolation) on 80% of stars
- 20% of stars kept for validation
- Results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

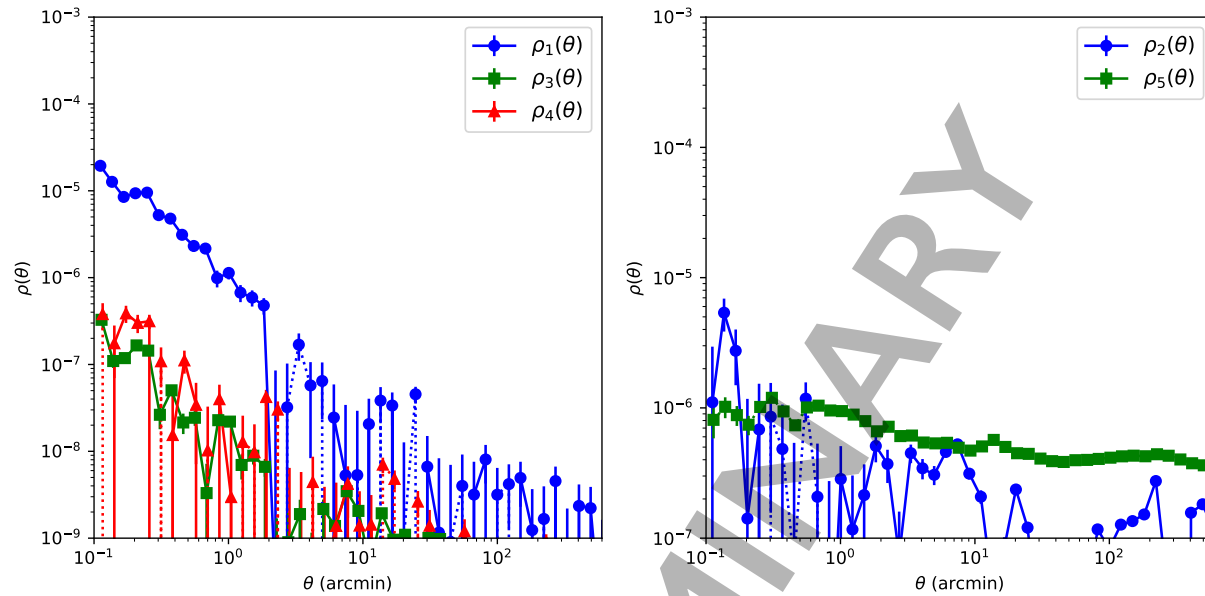


- Residual size (Trace of second moments matrix) and ellipticity averaged across the DES FoV
- For the **Optical and the Atmospheric model** using Piff and an **interpolation done on the full FoV**

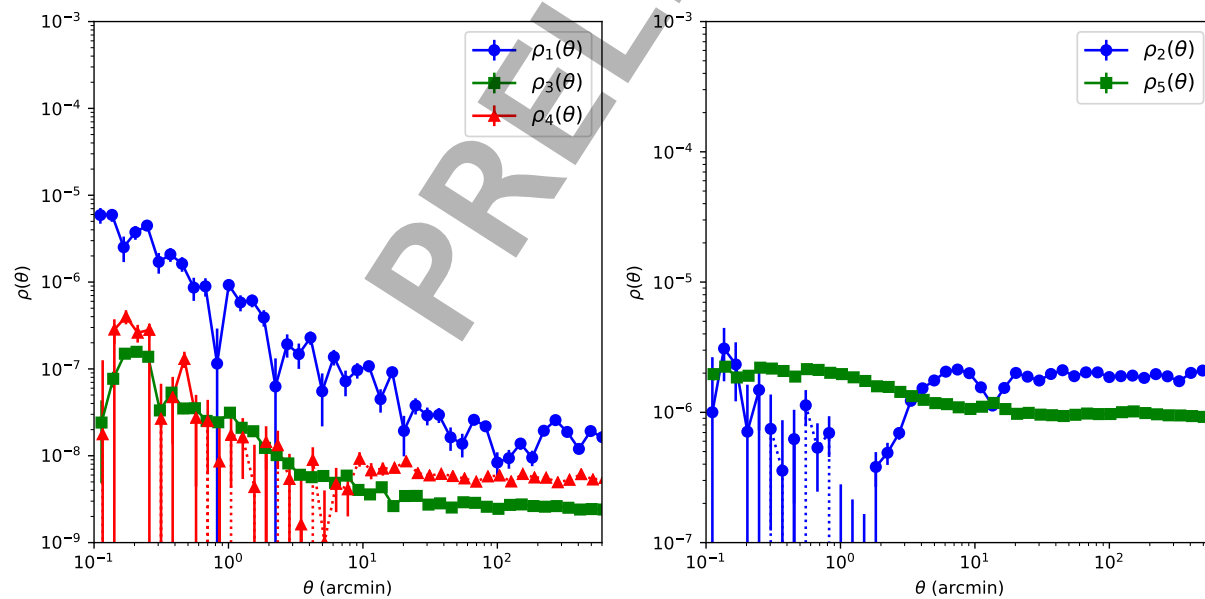


- Residual size (Trace of second moments matrix) and ellipticity averaged across the DES FoV
- The **Optical and the Atmospheric model** seems to do a better job to reconstruct the second moments compared to the **Pixel Basis model**

Pixel Basis model



Optical and the Atmospheric model



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

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

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

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

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

- 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!)

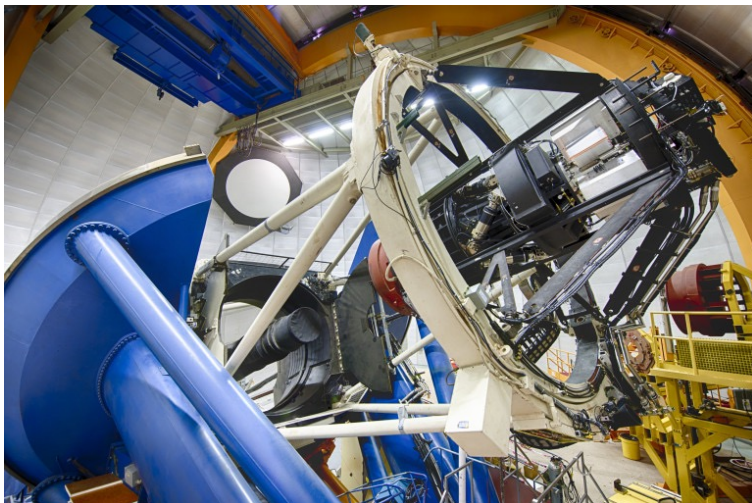
Ongoing improvement of the PSF modeling:

- 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)

Ongoing improvement of the PSF modeling:

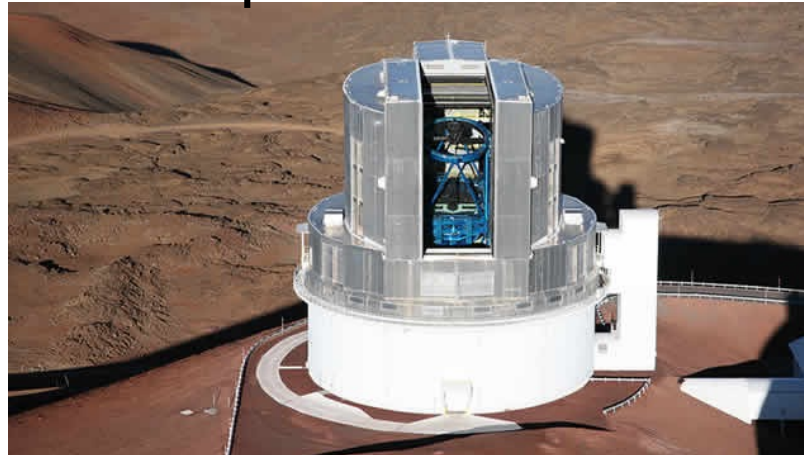
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The near terms goals is to
make work the physical
model for DES Y5



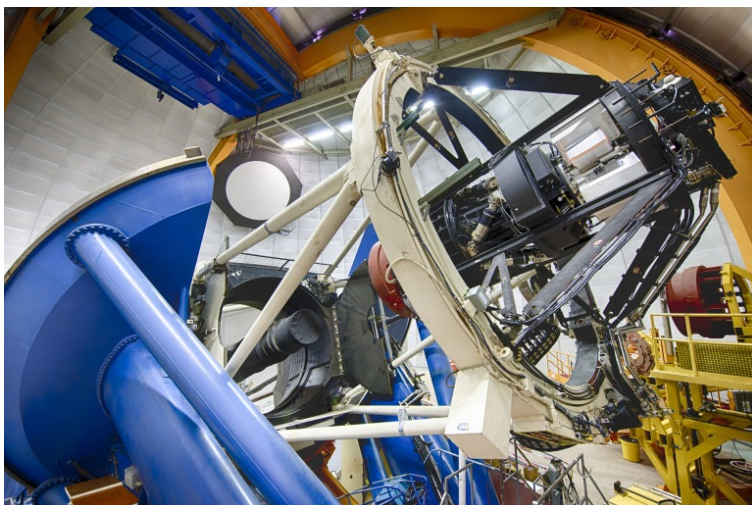
DES

The next stage for PSF modeling: HSC.
More complicated optical system on an 8 meters telescope



Subaru / HSC

The near terms goals is to make work the physical model for DES Y5

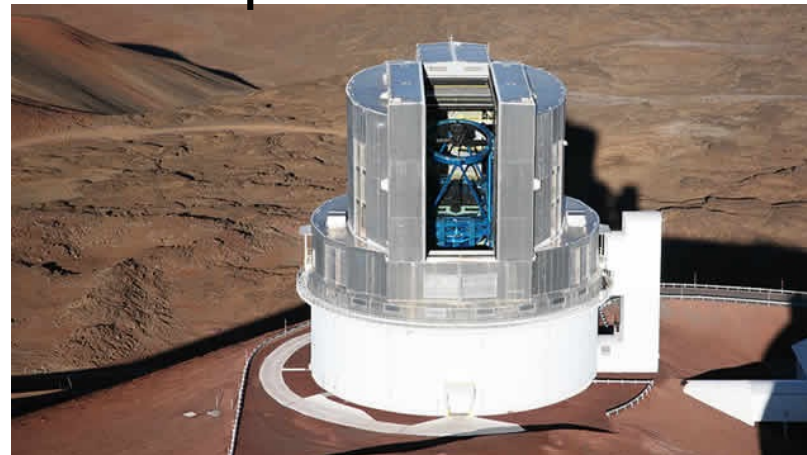


DES

LSST

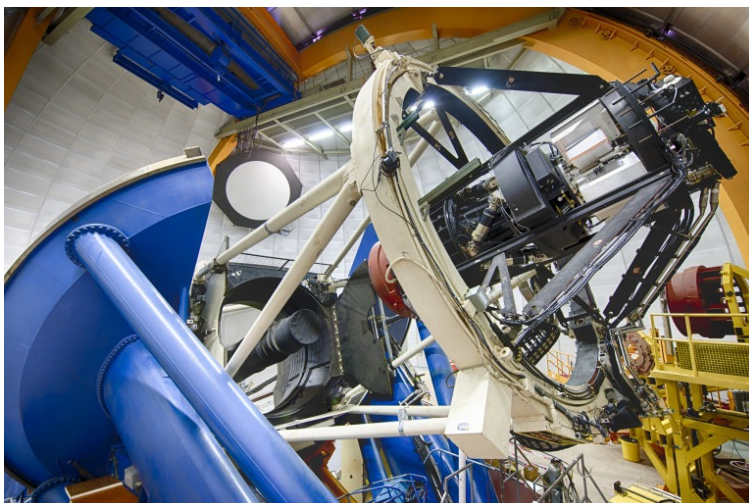


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Subaru / HSC

The near terms goals is to make work the physical model for DES Y5

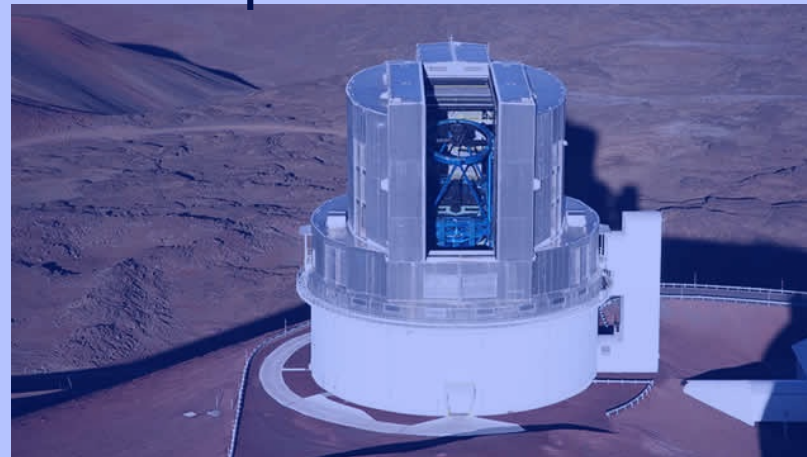


DES

LSST

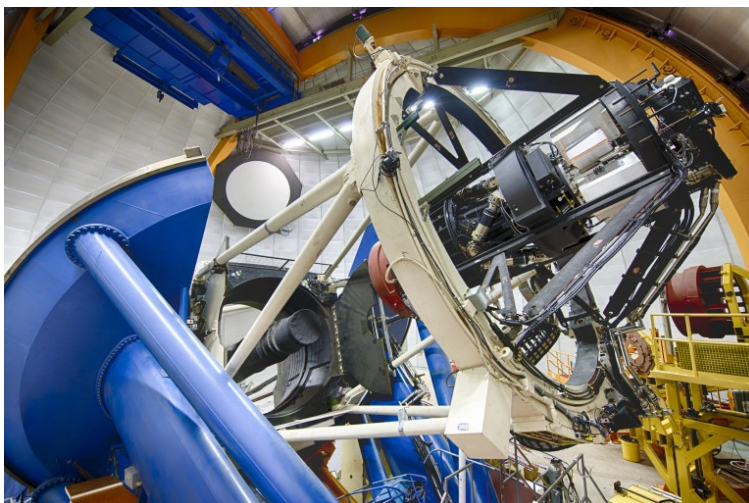


The next stage for PSF modeling: HSC.
More complicate optical system on an 8 meters telescope



Subaru / HSC

The near terms goals is to make work the physical model for DES Y5



DES

The model for HSC

- Wavefront is sum of contributions from:
 - Telescope (static; continuous; may vary quickly over focal plane)
 - CCD height variations (static; need to de-rotate; discontinuities)
 - Per-visit aberrations (dynamic; continuous; low order)

i = visit index

θ = field coord

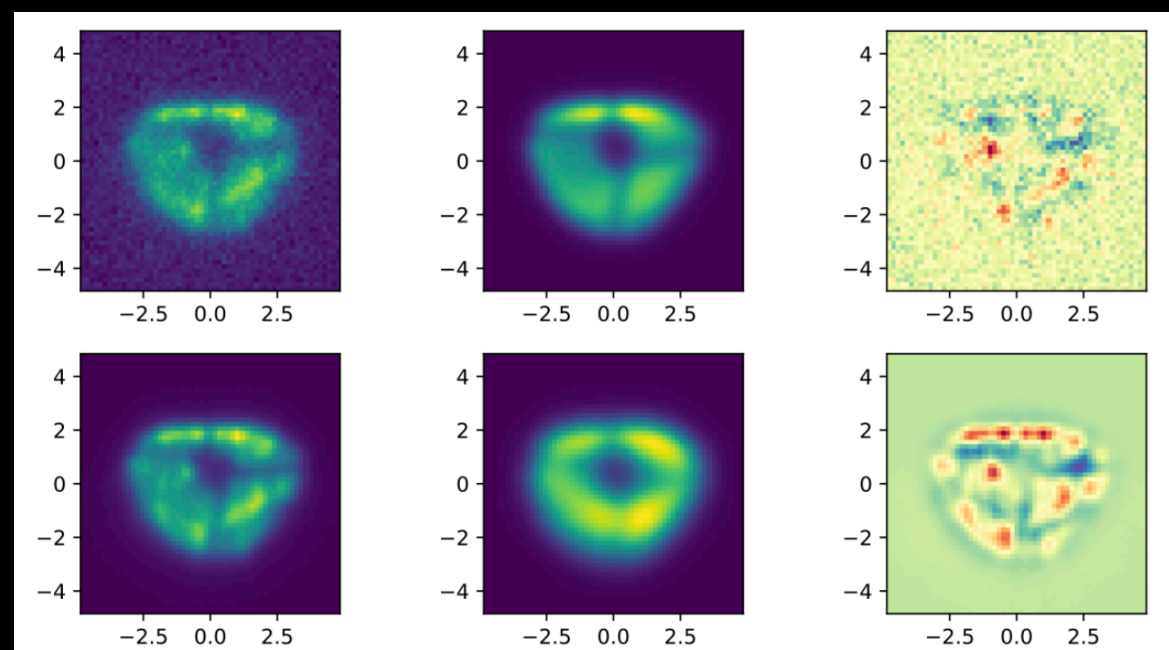
u = pupil coord

$$W^i(\vec{u}; \vec{\theta}) = W_{\text{tel}}(\vec{u}; \vec{\theta}) + W_{\text{CCD}}(R^i \vec{u}; R^i \vec{\theta}) + W_{\text{visit}}^i(\vec{u}; \vec{\theta})$$

- Someday include wavelength, but not today...

Donuts

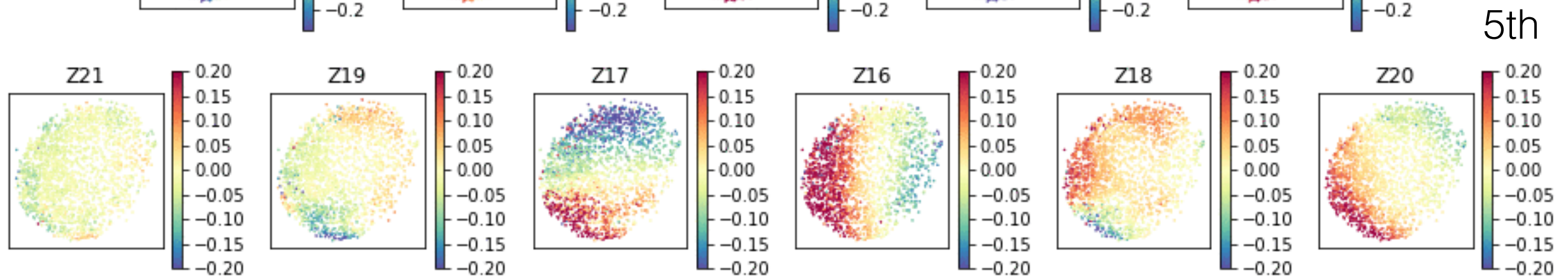
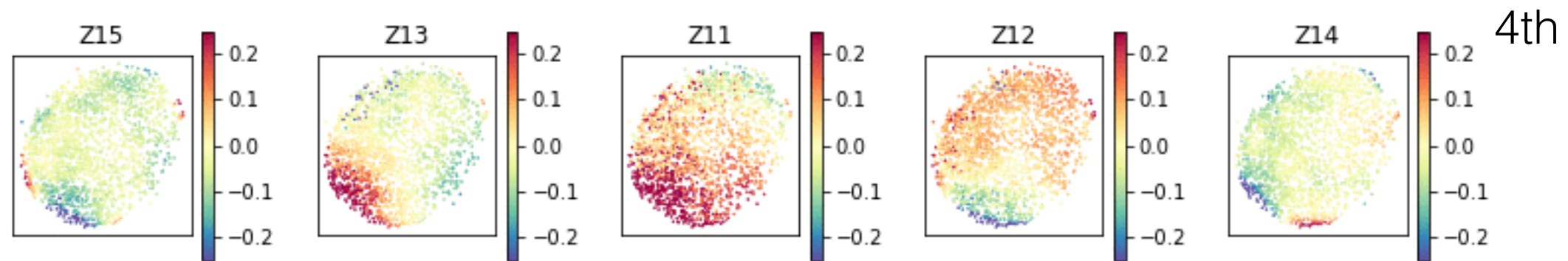
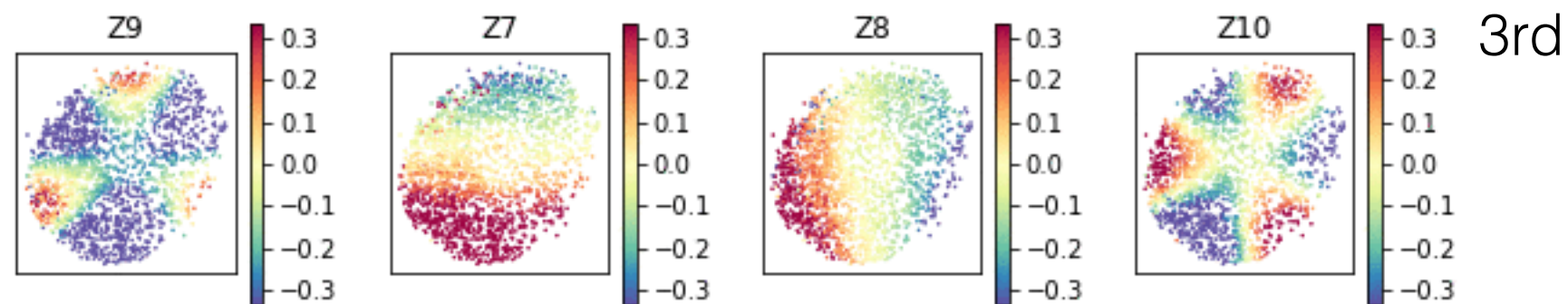
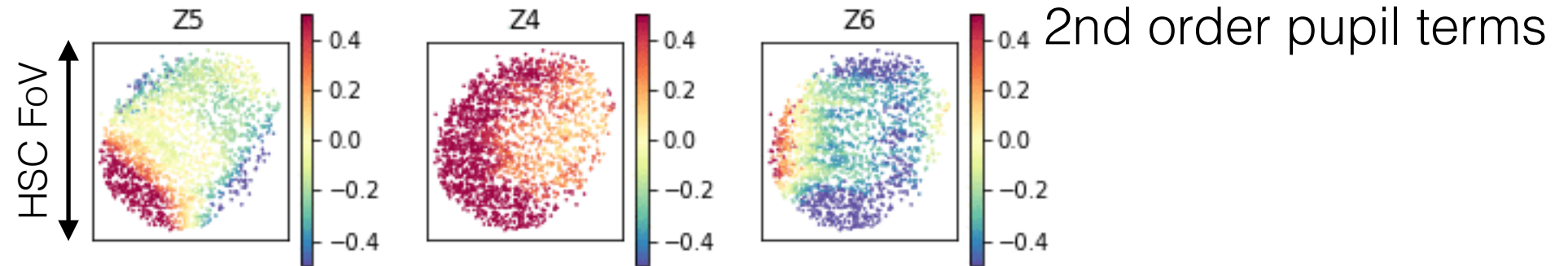
- We need to constrain W_{CCD} and W_{tel} somehow.
 - From metrology during construction?
 - In situ, from deliberately out-of-focus “donut” images.
 - Enhances optical effects compared to atmosphere and sensor effects
- HSC commissioning data includes (~ 10) donut visits at different rotations and elevations.



Measured wavefronts

Color is amplitude of Zernike *in pupil*

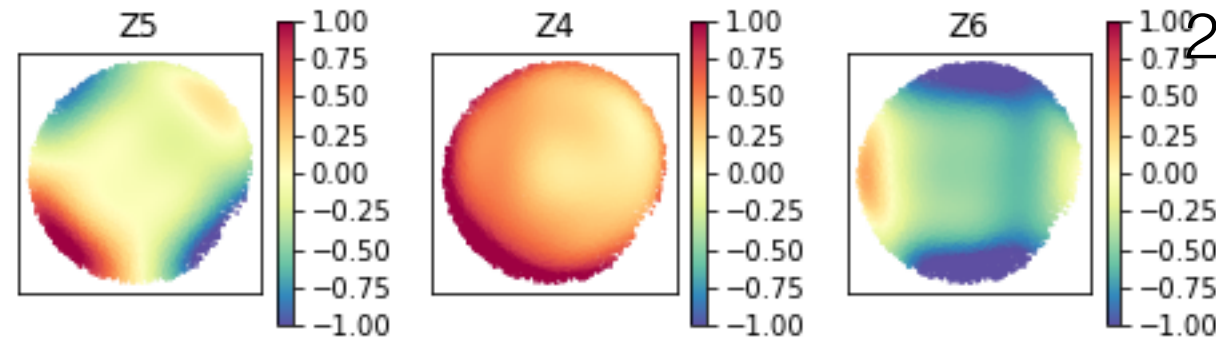
visit 69010



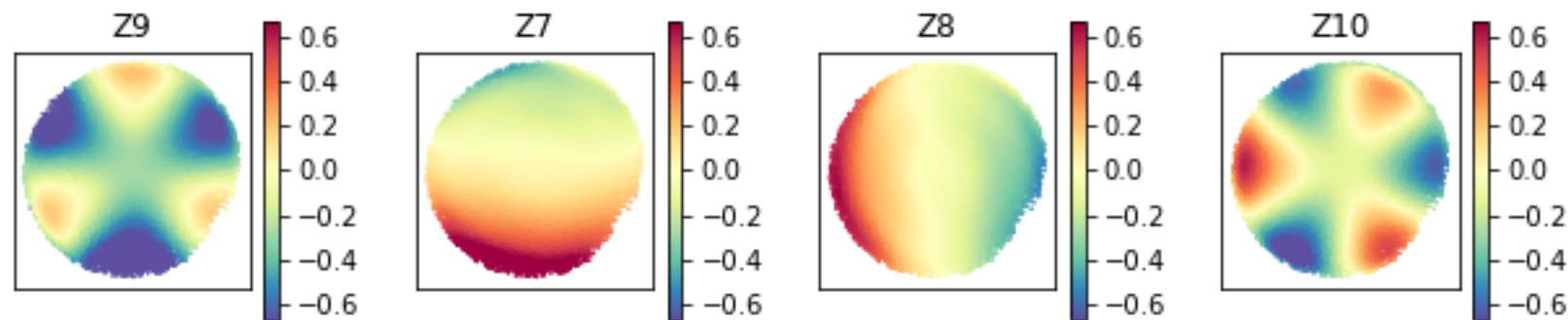
- Solve a set of *linear* equations...

W_{tel} results

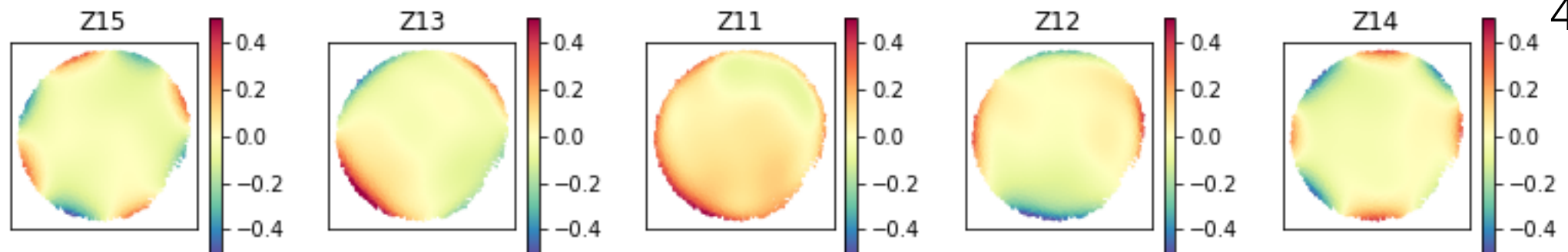
W_{tel}



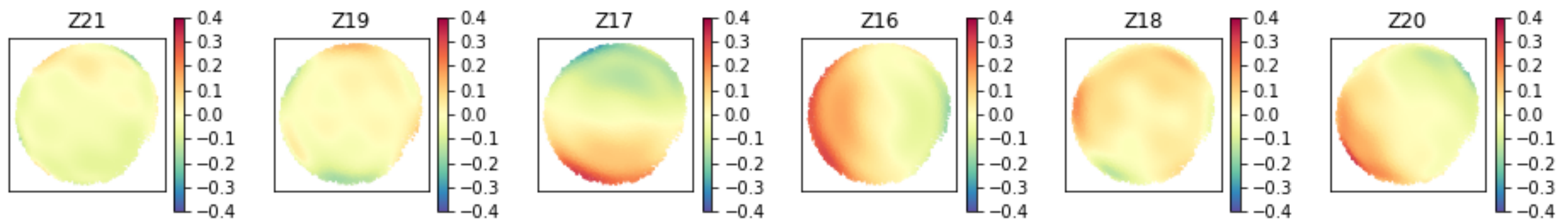
2nd order pupil terms



3rd

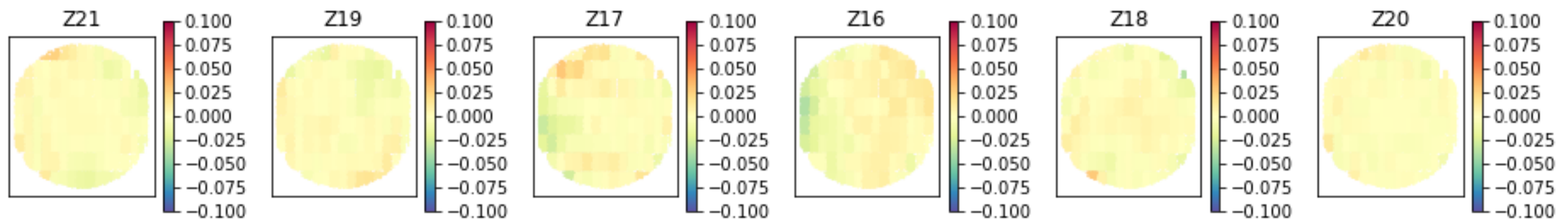
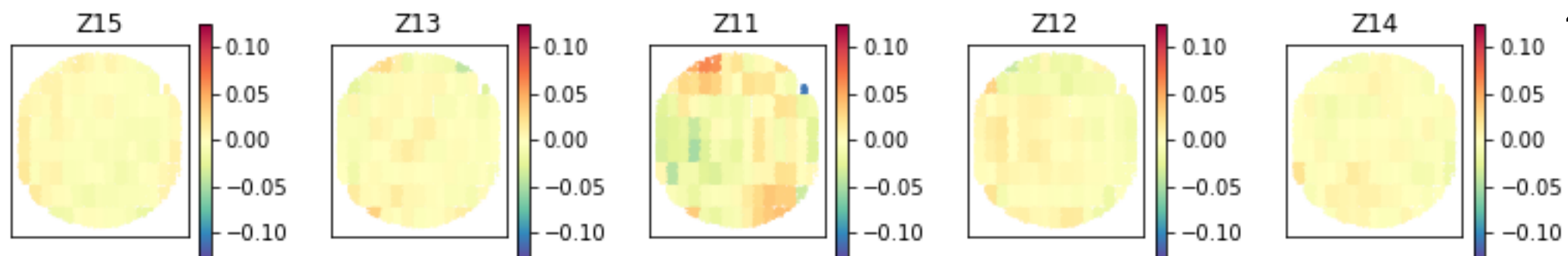
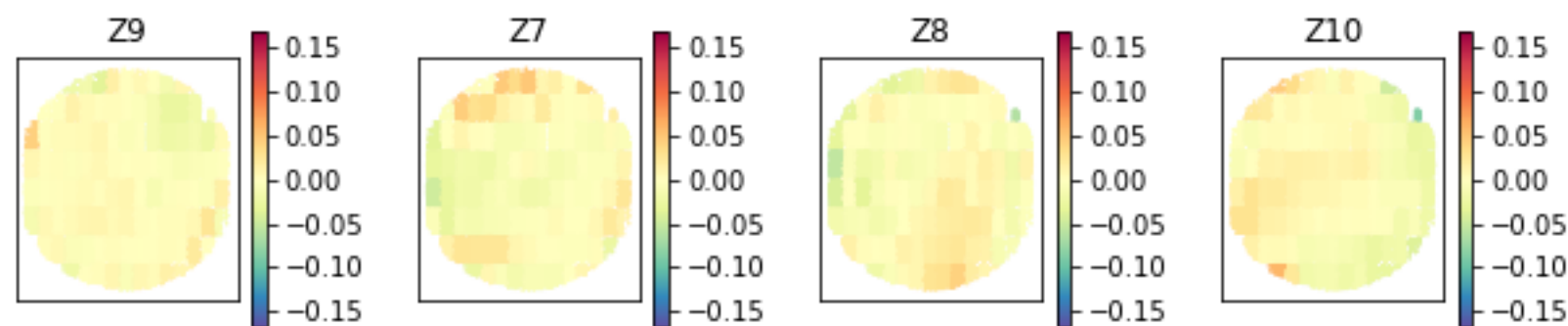
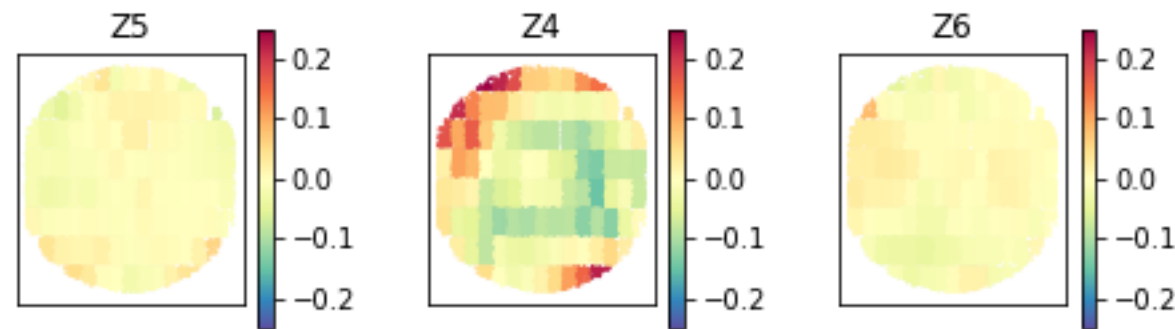


4th

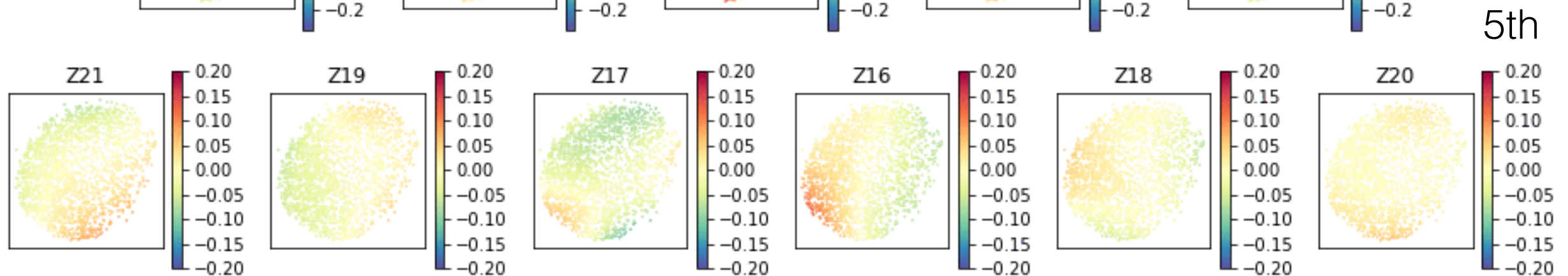
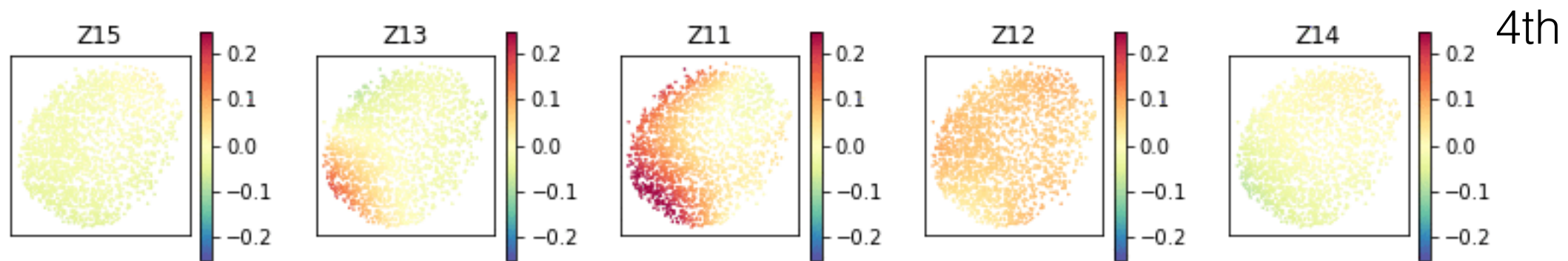
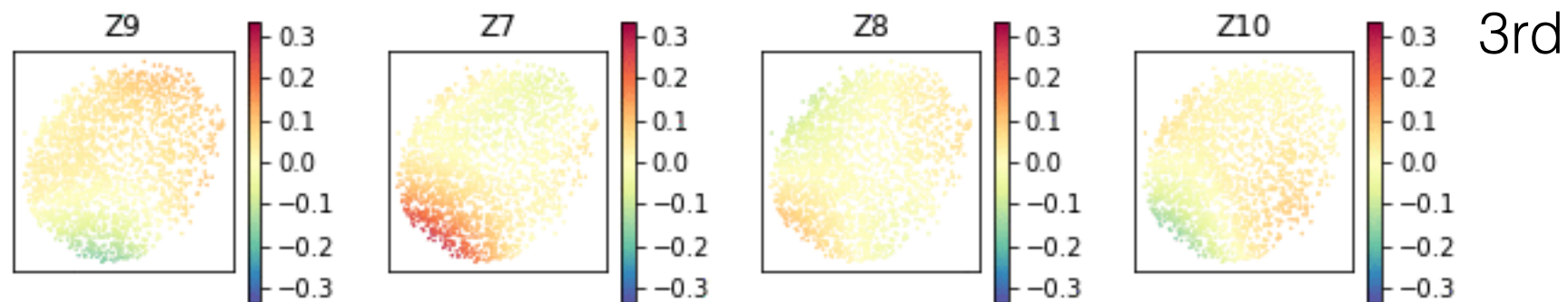
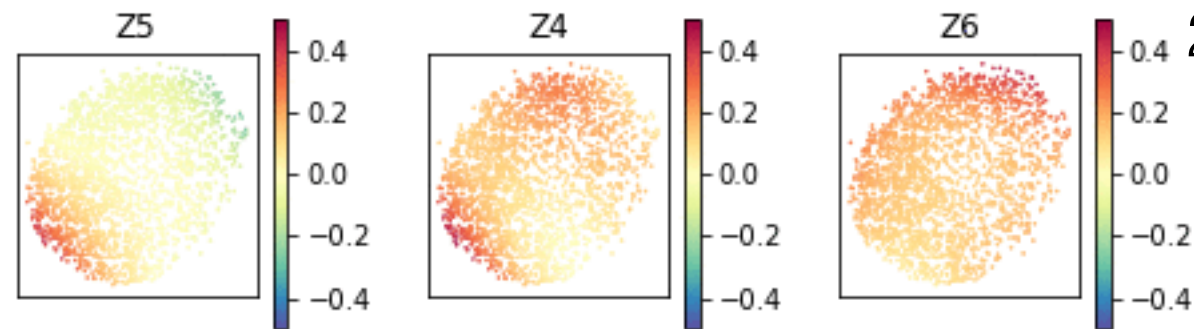


5th

W_{CCD} results

 W_{CCD} 

W_{visit} results

 W_{visit} visit 69010

Preliminary extension to in-focus exposures

- Fix W_{tel} and W_{CCD} to values found from donuts.
- PCA decompose W_{visit}^i of donut images, use 4 components (84% of variance) as parameters.
- Convolve by constant elliptical Kolmogorov profile (3 more parameters)
- Do 7 parameter fit.

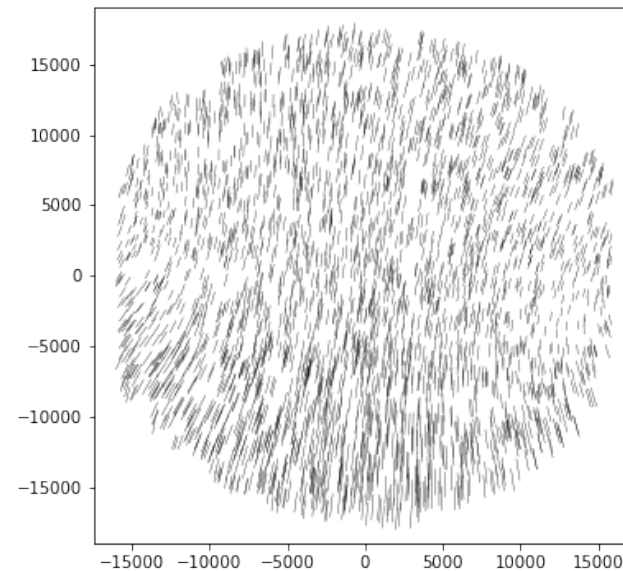
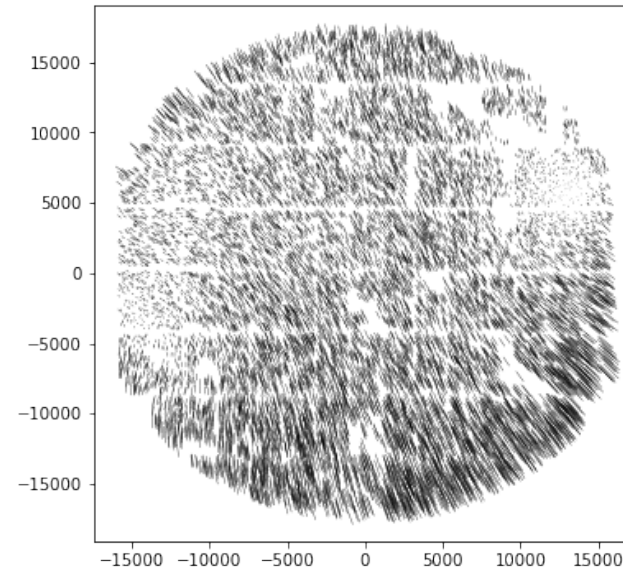
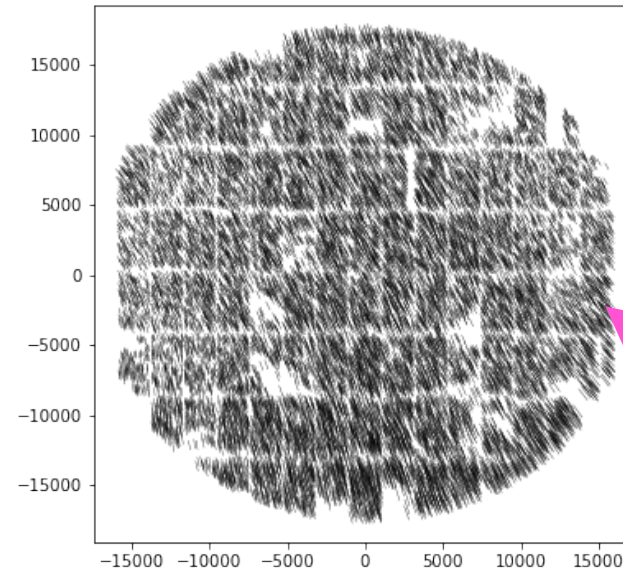
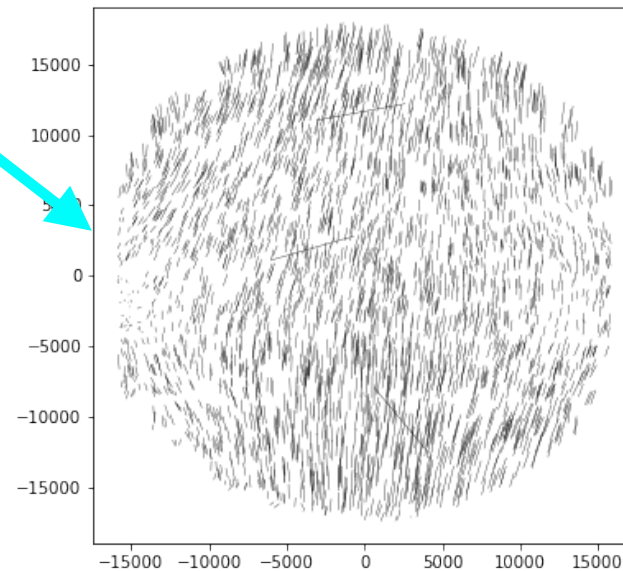
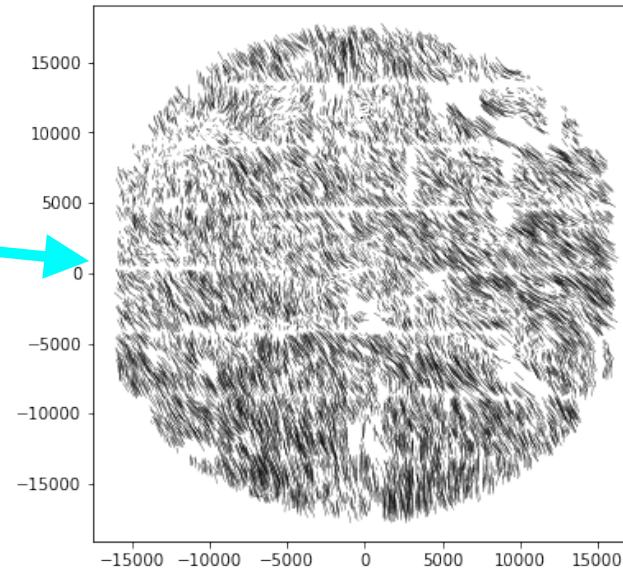
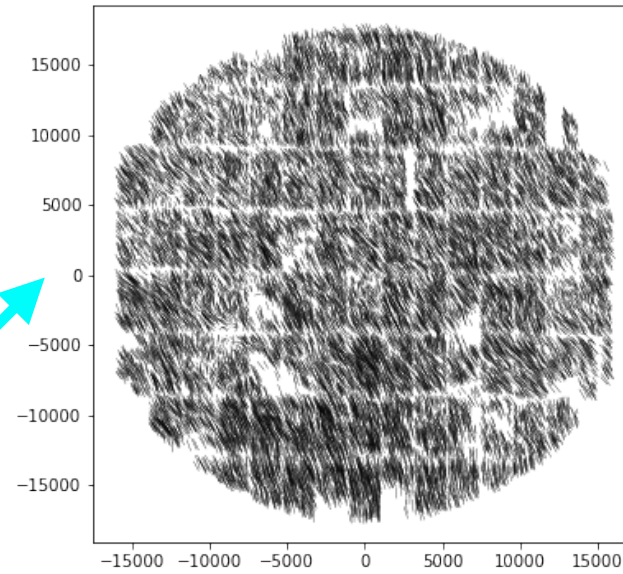
Results

Data

69008

69014

69026



Model

What's next

- (aside) implementing more detailed donut-fitting model now.
- Include fewer CCD and visit degrees of freedom.
- Add a more detailed atmosphere model.
- Thinking more about the wavelength.
- Get more donut data?

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 view the PSF problem

Merci !