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PSF modeling plans

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Existing DM PSF framework

- Most widely used algorithm is PSFex
- Limited to running 1 sensor at a time
- We know we'll need to iterate for chromatic effects:
  - Initial PSF -> photometry -> better chromatic PSF
- Intend to include differential chromatic refraction as part of PSF (as opposed to WCS, where only DCR 1st moment could ever be included).

The goal for the future: a modular PSF

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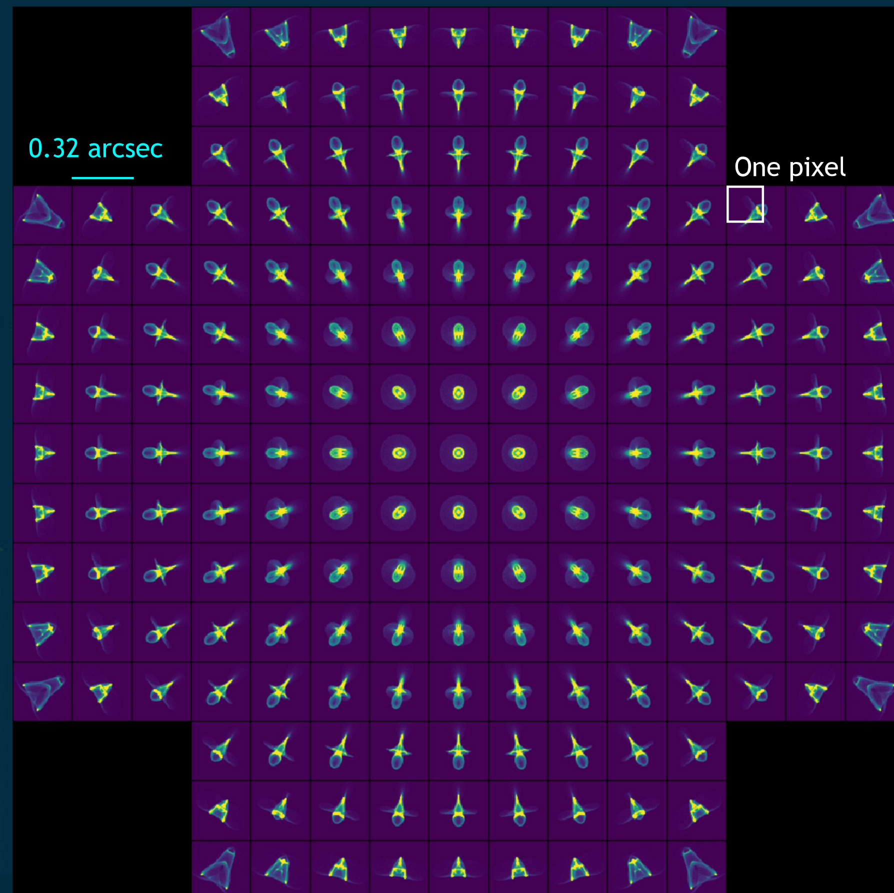
- PSF = Convolve(atmosphere, optics, CCD)
- Advantages:
  - ***Robust***: small number of variables to describe full-field optics variations
  - Capture ***chip discontinuities*** in static optics PSF, allowing atmospheric PSF to be interpolated across entire focal plane
  - Easier modeling of PSF ***chromaticity***, we have good models for how individual components behave chromatically.

A challenge: discontinuities

- Current PSF packages: fit individual stars using parametric model, interpolate coefficients
- CCD gaps => discontinuities
  - Limits packages to working one CCD at a time.
- Uniform distribution of heights between +/- 5 microns leads to size discontinuities of ~1% after convolution with atmosphere, sensor PSF contributions.

Fiducial Rubin Obs optical PSF



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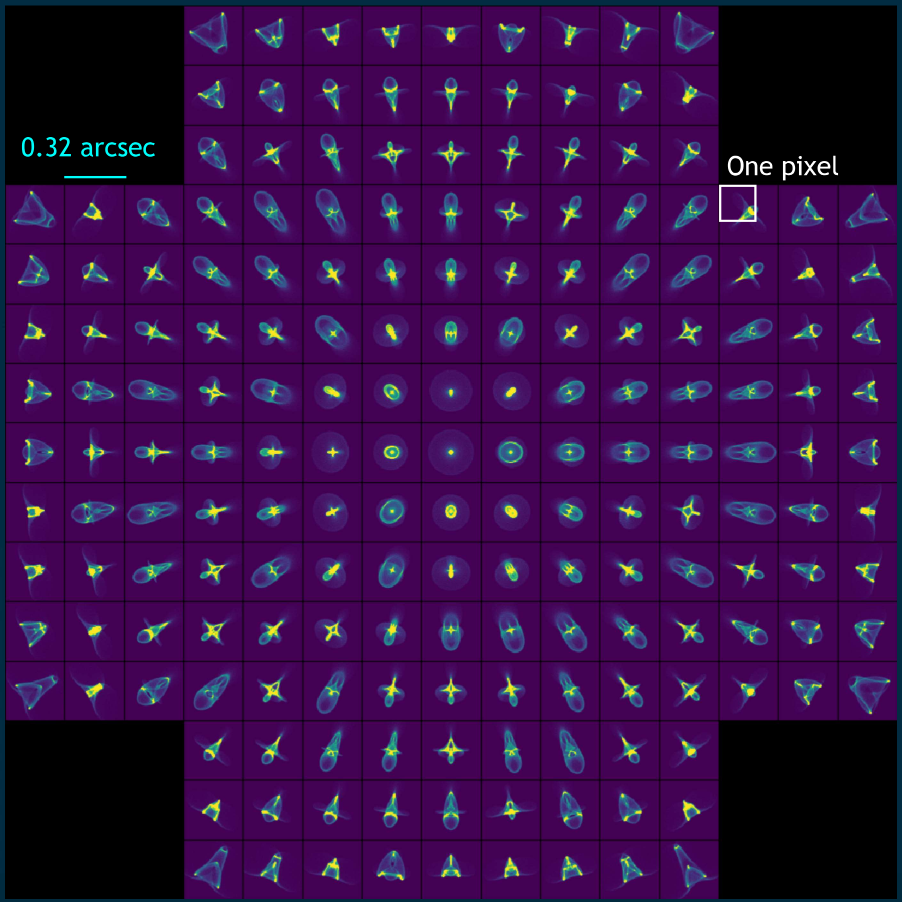
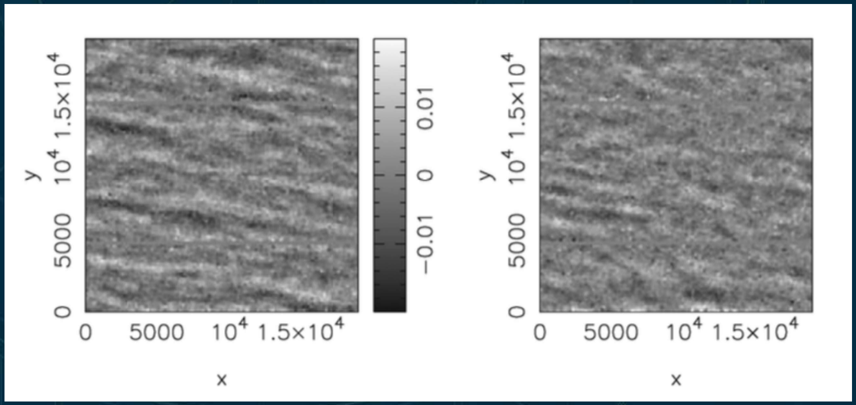
Fiducial Rubin Obs optical PSF with height variations



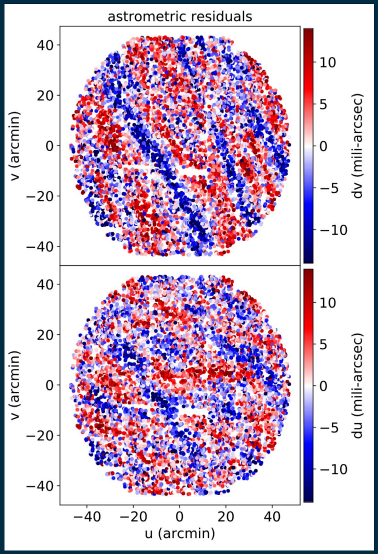
An opportunity: long range correlations

- Atmospheric PSF often contains interesting anisotropic spatial correlations
- Most interpolation algorithms can't take advantage of this.
- Proposal is to use a Gaussian process with anisotropic kernel to model this.
  - Initially interpolate parameters of Von Karman surface brightness profile, but other parameterizations also possible.

e_1 CFHT data e_2



Heymans++12



HSC data

Credit: PF Leget

Modeling Strategy

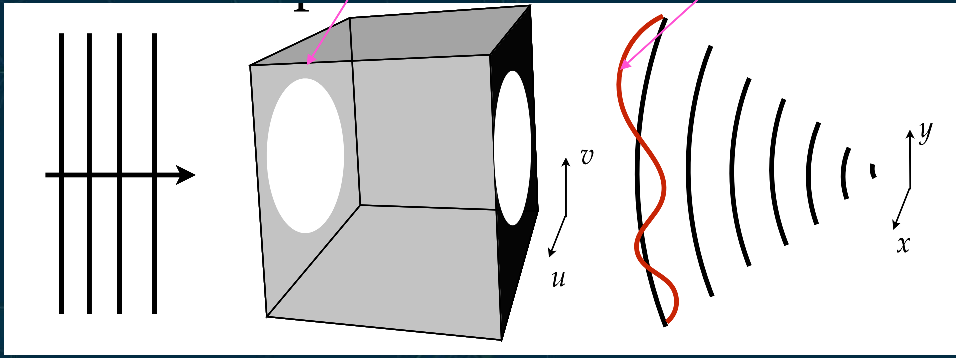
- PSF = convolve(optics, atm, ccd)
  - optics = static + dynamic
  - Forward model: fit via chi-square minimization or related.
- Preprocessing: using many donut exposures, fit for static and dynamic optics terms.
  - (Atmosphere is relatively less important for donuts)
- Holding static optics terms fixed, fit an in-focus exposure iteratively:
  - First iteration: degrees of freedom are dynamic optics + uniform atm.
  - Second iteration: hold optics terms fixed and fit individual star atm components.
  - Interpolate atm components (GP?)
  - Repeat as desired.

Optics model - Fourier optics

$$I(\vec{\theta};\vec{x}) \propto \left| \mathcal{F}\left[P(\vec{\theta};\vec{u}) \exp\left(\frac{-2\pi i}{\lambda} W(\vec{\theta};\vec{u}) \right) \right] \right|^2$$

pupil illumination

wavefront



$\vec{\theta}$ = sky

$\vec{x}$ = image

$\vec{u}$ = pupil

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Wavefront model

Exposure index

Rotation operator

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

"reference" wavefront

- Wavefront is the sum of contributions from:
  - Telescope
    - static; continuous; may vary quickly over focal plane due to figure errors
  - CCD height variations
    - static; contains discontinuities; needs to de-rotate wrt telescope
  - Per-visit aberrations
    - dynamic; continuous; slow variation over focal plane; kinds of variations are predictable

Express wavefront as double Zernike series

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For one star, pupil wavefront is Zernike series

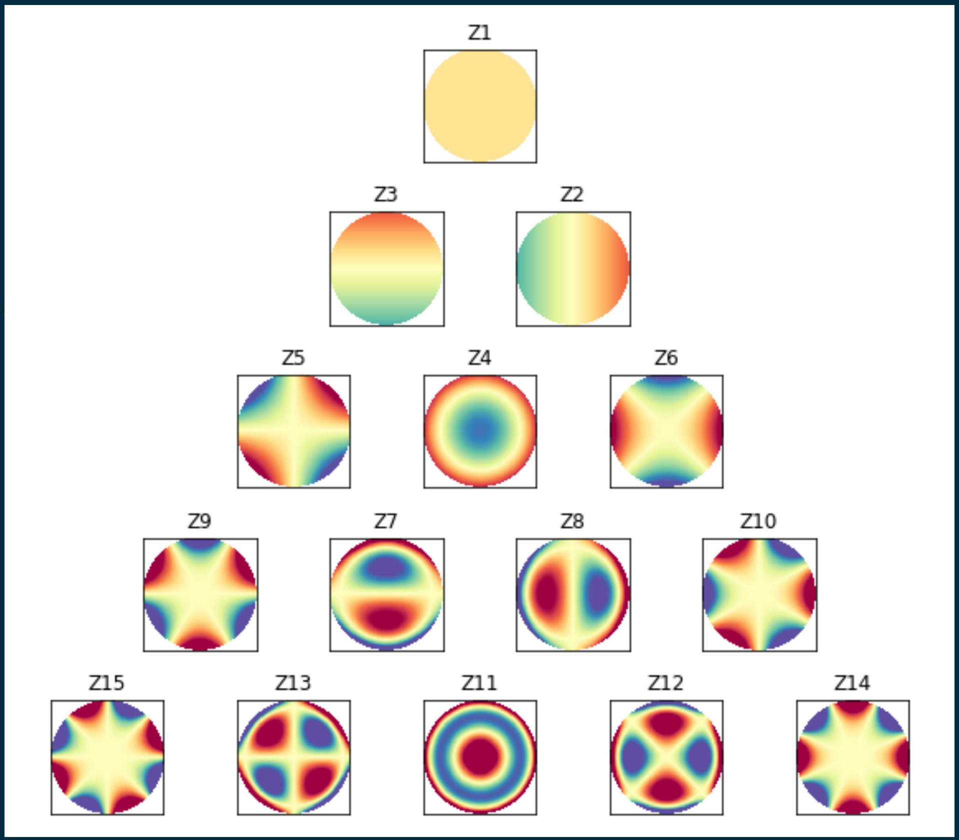
$$W^*\left(\vec{u}\right) = \sum_{j=4} a_j^* Z_j\left(\vec{u}\right)$$

For entire field of view, let coefficient also be Zernike series

$$a_j\left(\vec{\theta}\right) = \sum_{k=1} a_{jk} Z_j\left(\vec{\theta}\right)$$

Double Zernike series

$$W\left(\vec{u}, \vec{\theta}\right) = \sum_{j=4} \sum_{k=1} a_{jk} Z_j\left(\vec{u}\right) Z_k\left(\vec{\theta}\right)$$



Misalignments, bending modes introduce low-order patterns

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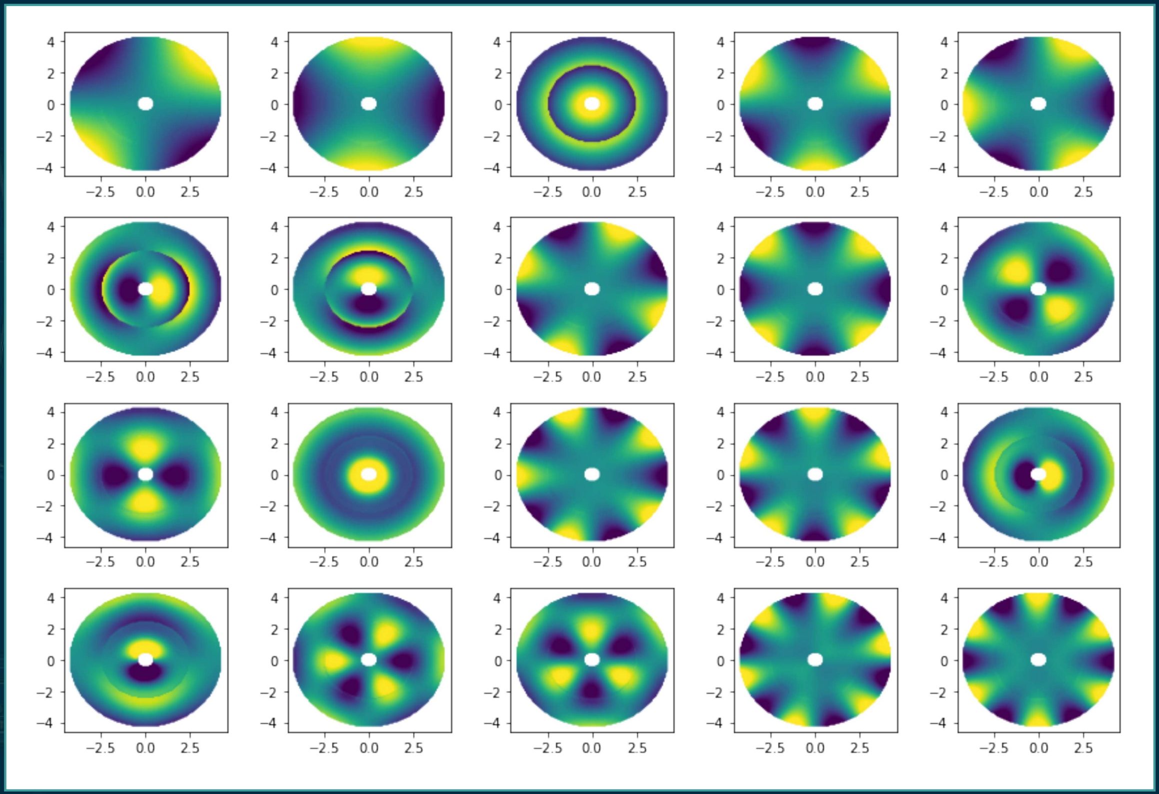
- Dynamic part of optics (flexure) is modelable using only a few low-order double Zernike terms.
- Rigid body of Camera + M2:
  - ~9 DZ terms
- Rigid body + 10 M1M3 modes:
  - ~17 DZ terms
- Rigid body + 20 M1M3 modes:
  - ~34 DZ terms

Bending modes of M1M3



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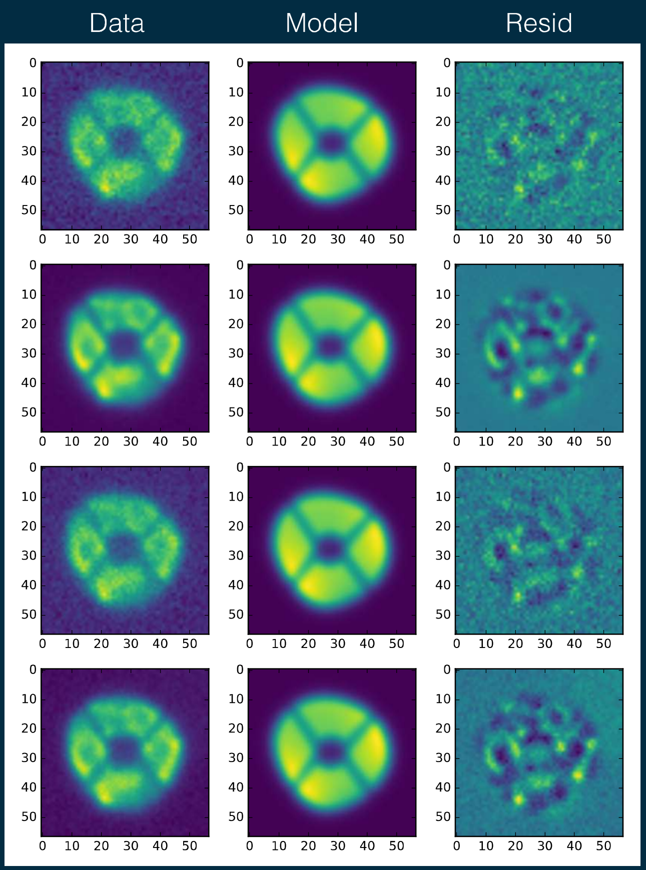
Building the reference wavefront

- Use metrology obtained during construction, or measure directly from donuts.
- DECam reference wavefront obtained by low-order detrending to remove flexure followed by taking mean of all donut exposure Zernike coefficients.
- Rubin Obs reference wavefront requires two pieces b/c of presence of rotator.
- Can solve a large linear algebra problem to obtain.



HSC donuts

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Separating wavefront components

- We can take series of donut measurements at different rotator angles to tease apart different contributions to reference wavefront.
- (Don't need to grok this slide now, just here for reference and to show general idea…)

geometry

Note leaving out CCD term

$$\sum_{j=4}^{\text{jmax}} a_j^i(\vec{\theta}_*) Z_j(\vec{u}) = \sum_{jk} b_{jk}^{\text{tel}} Z_k(\vec{\theta}_*) Z_j(\vec{u}) + \sum_{jk} c_{jk}^i Z_k(\vec{\theta}_*) Z_j(\vec{u})$$

have these

want these

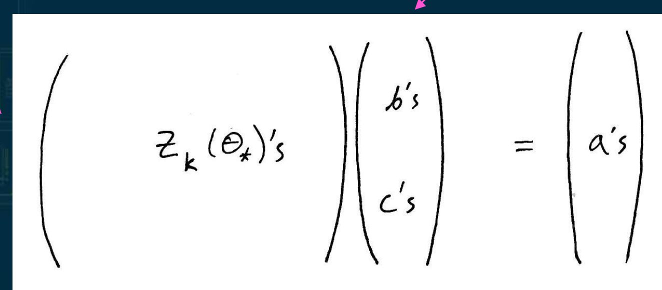
- Can solve this for the b's and c's term-by-term (indep for each j)

$$a_j^i(\vec{\theta}_*) = \sum_k b_{jk}^{\text{tel}} Z_k(\vec{\theta}_*) + \sum_k c_{jk}^i Z_k(\vec{\theta}_*)$$

want these

- Matrix equation roughly:

geometry



have these

Also require

$$\sum_i c_{jk}^i = 0$$

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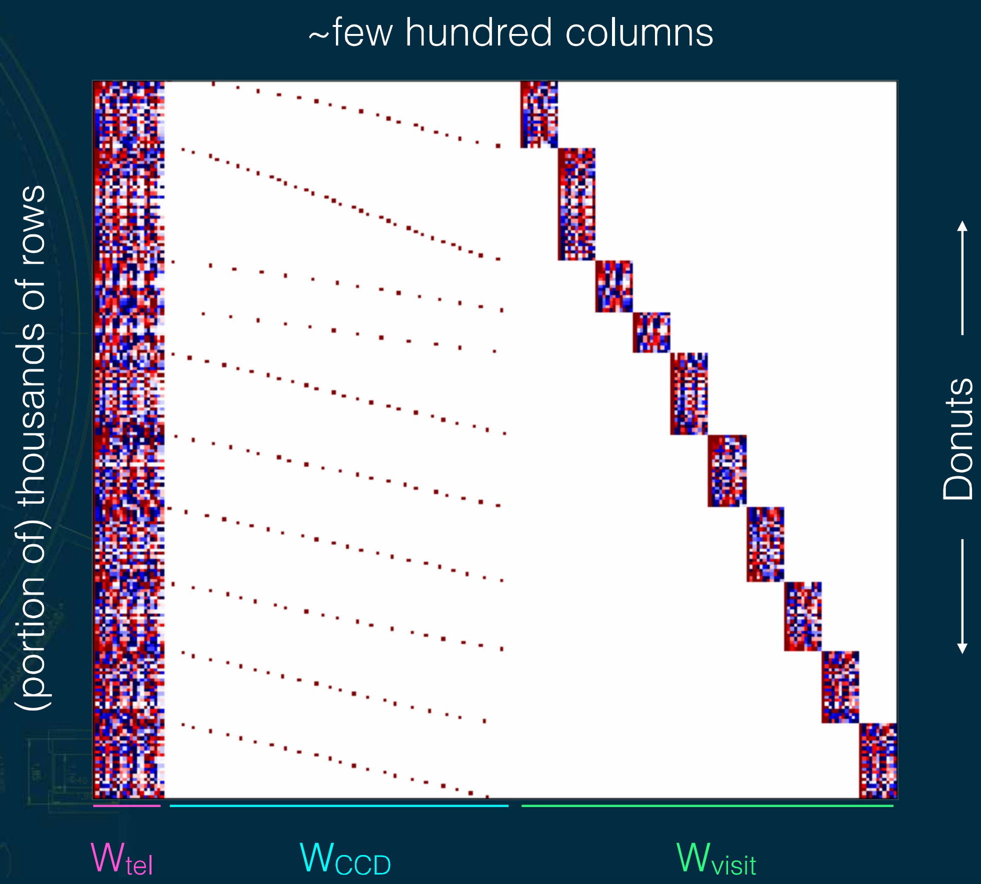
HSC design matrix example

- Color of filled in cells determined by rotator angle and position of * in focal plane.
- All stars contribute to our knowledge of telescope.
- Each star contributes to one CCD term and one per-visit term.
- Visit solutions only good for particular training exposures, but CCD and telescope terms are useful for ***all*** Rubin obs exposures.
- Repeat for each pupil Zernike coefficient (or pair of related coefficients).



W_{tel} results for HSC

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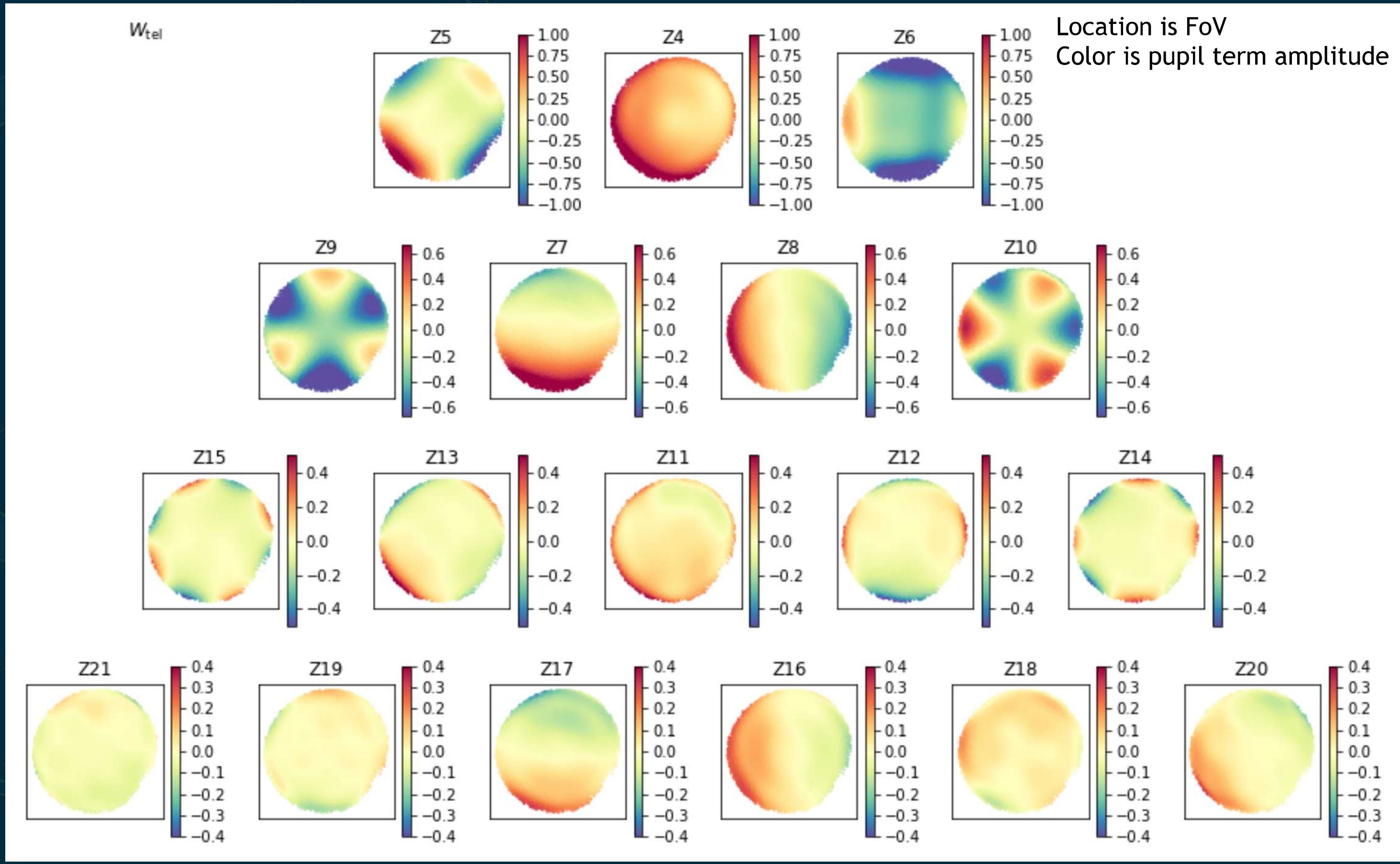

Location is FoV
Color is pupil term amplitude

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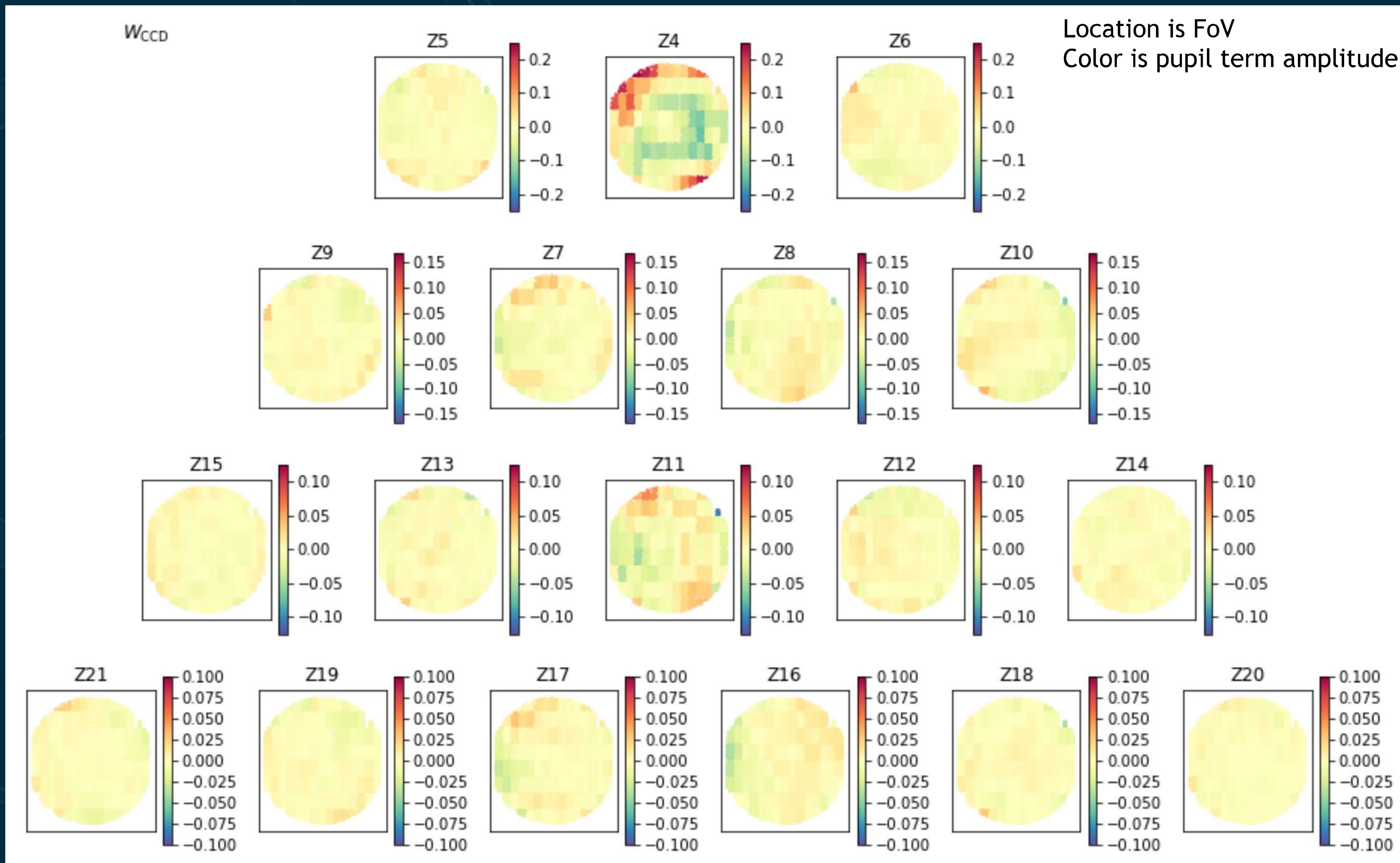
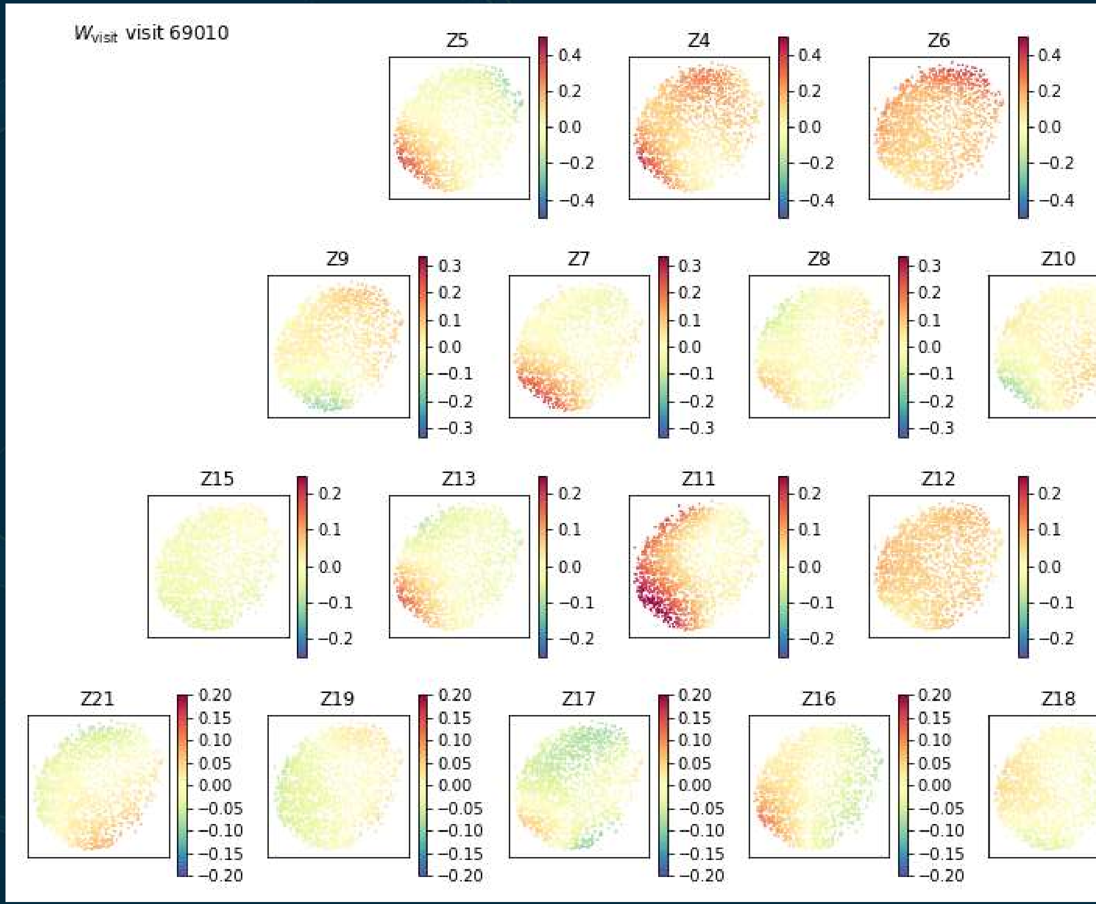
W_{CCD} results for HSC



W_{visit} results for a few HSC exposures



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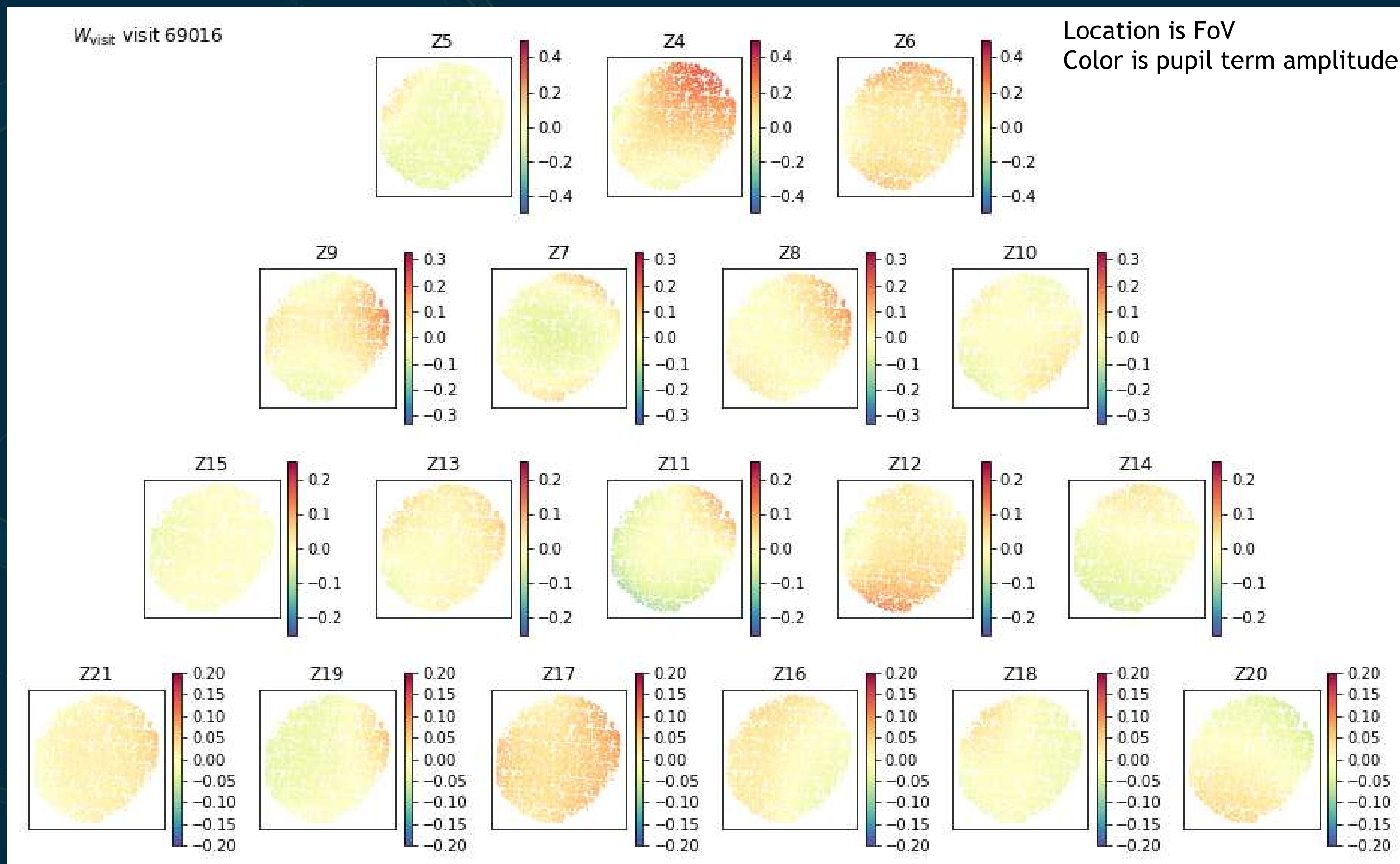

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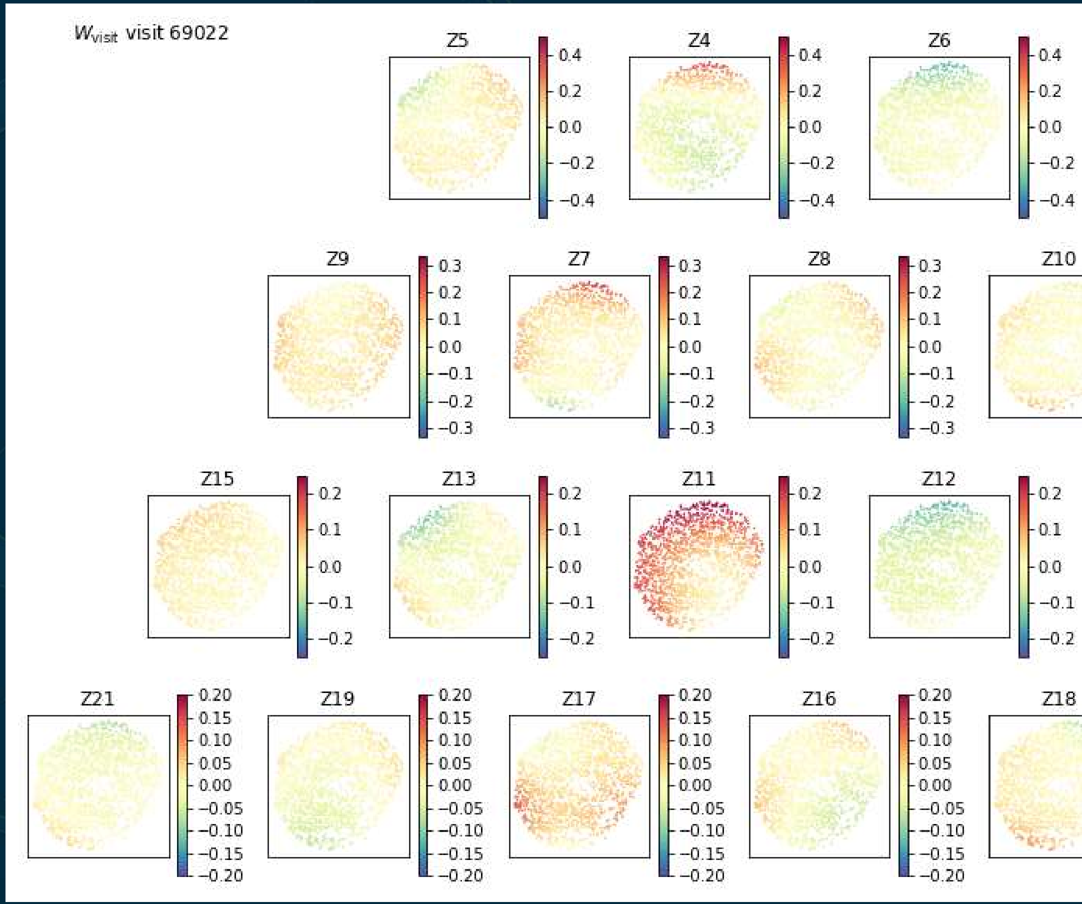

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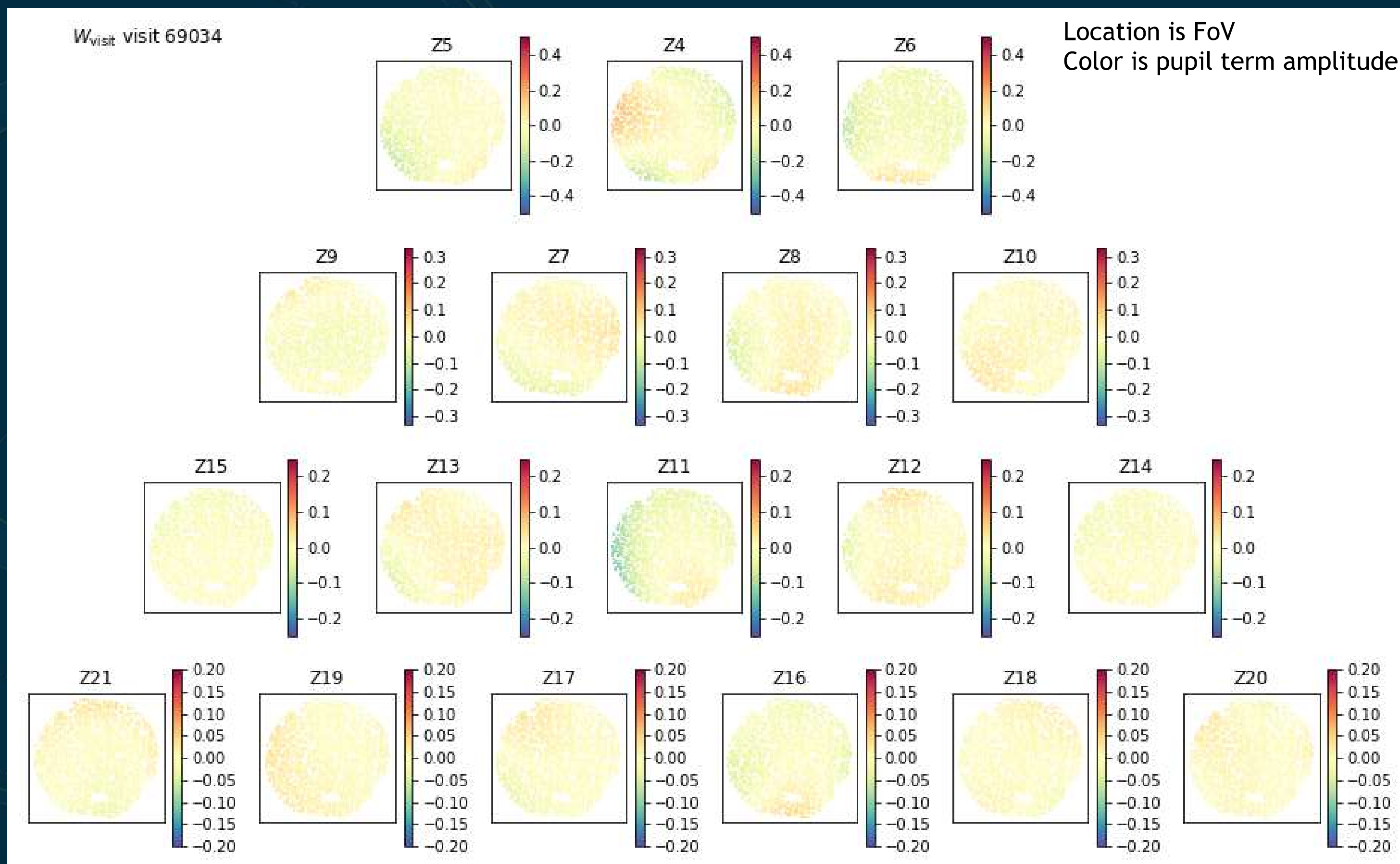

Results for HSC

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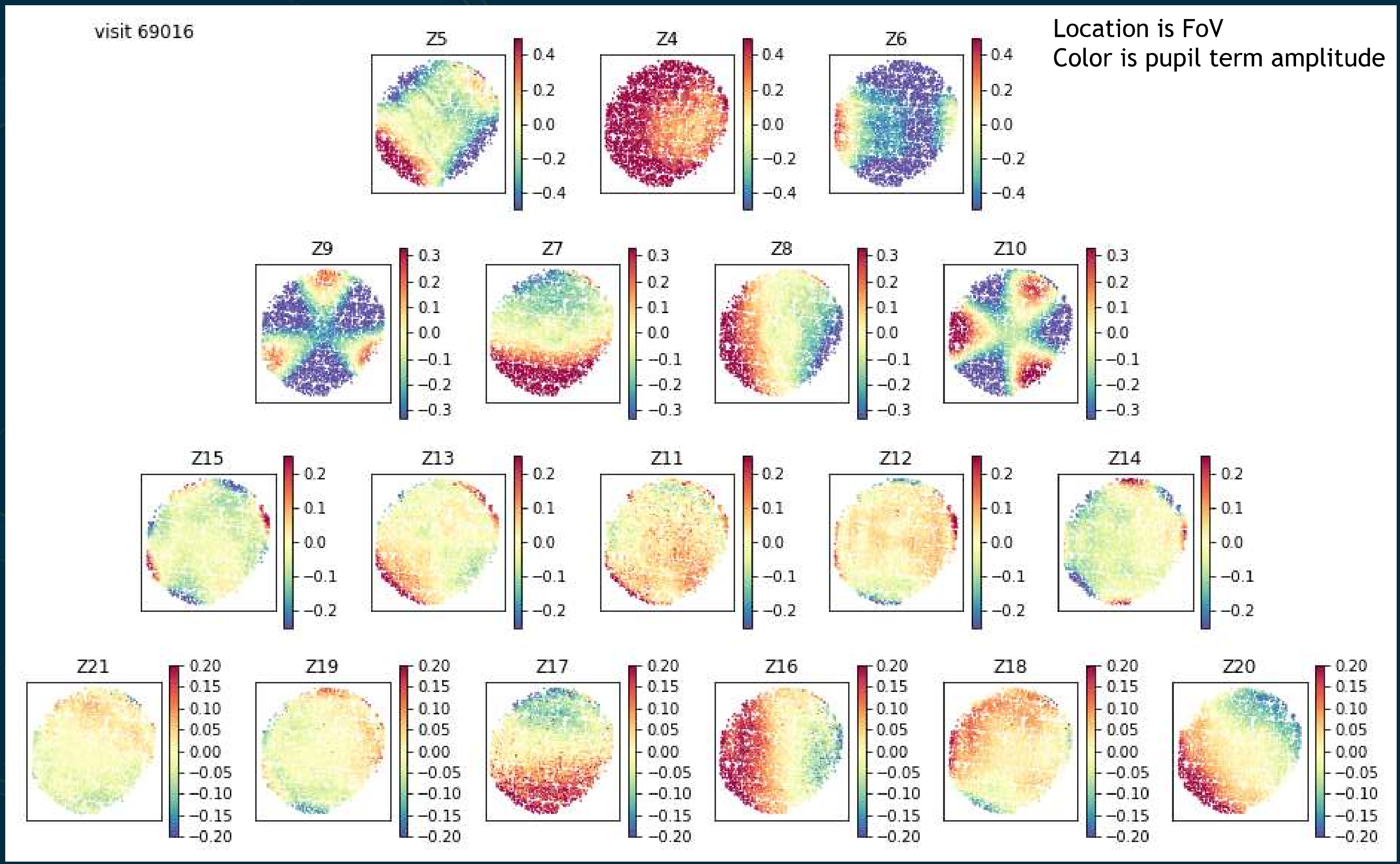

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Results for HSC

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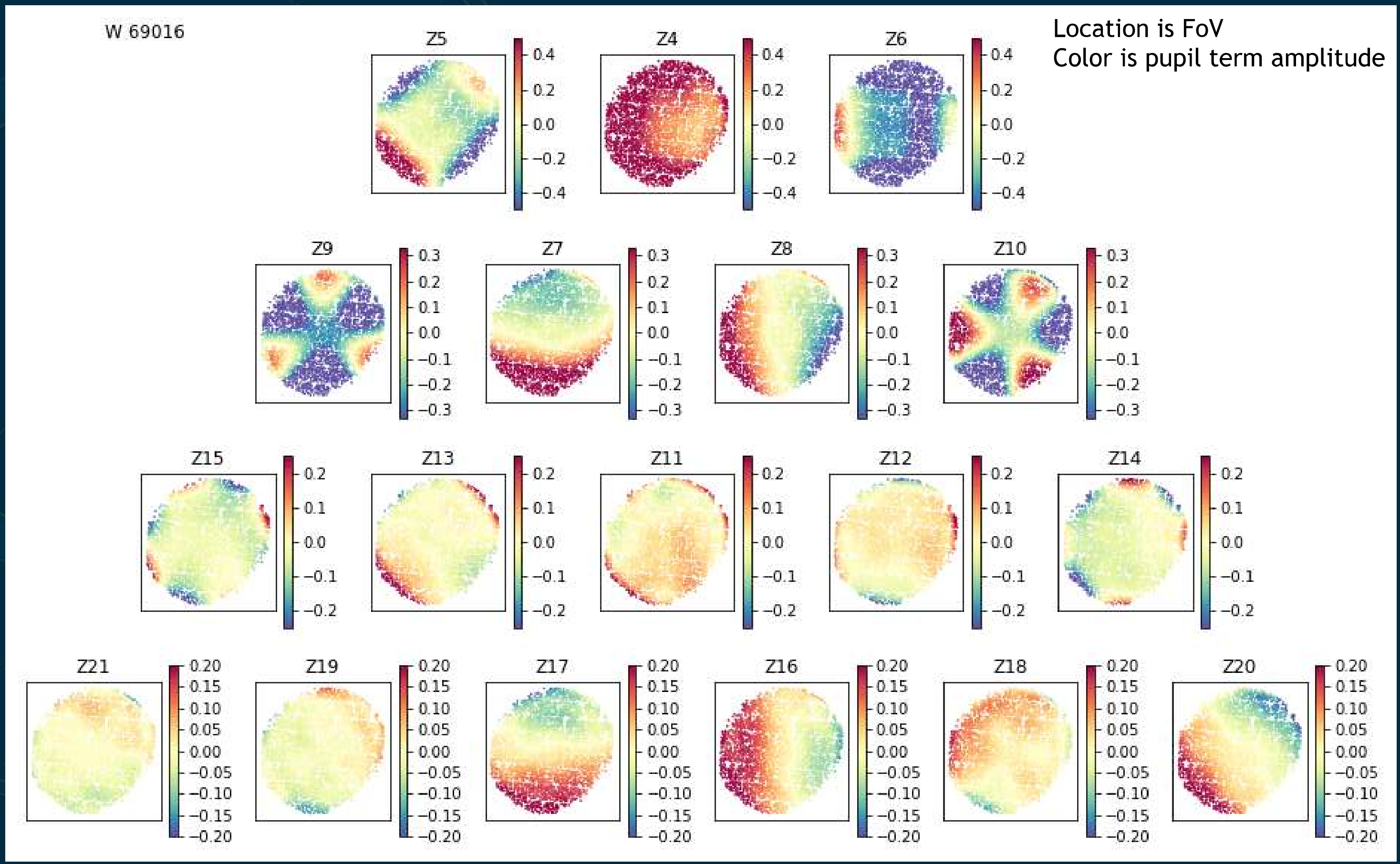

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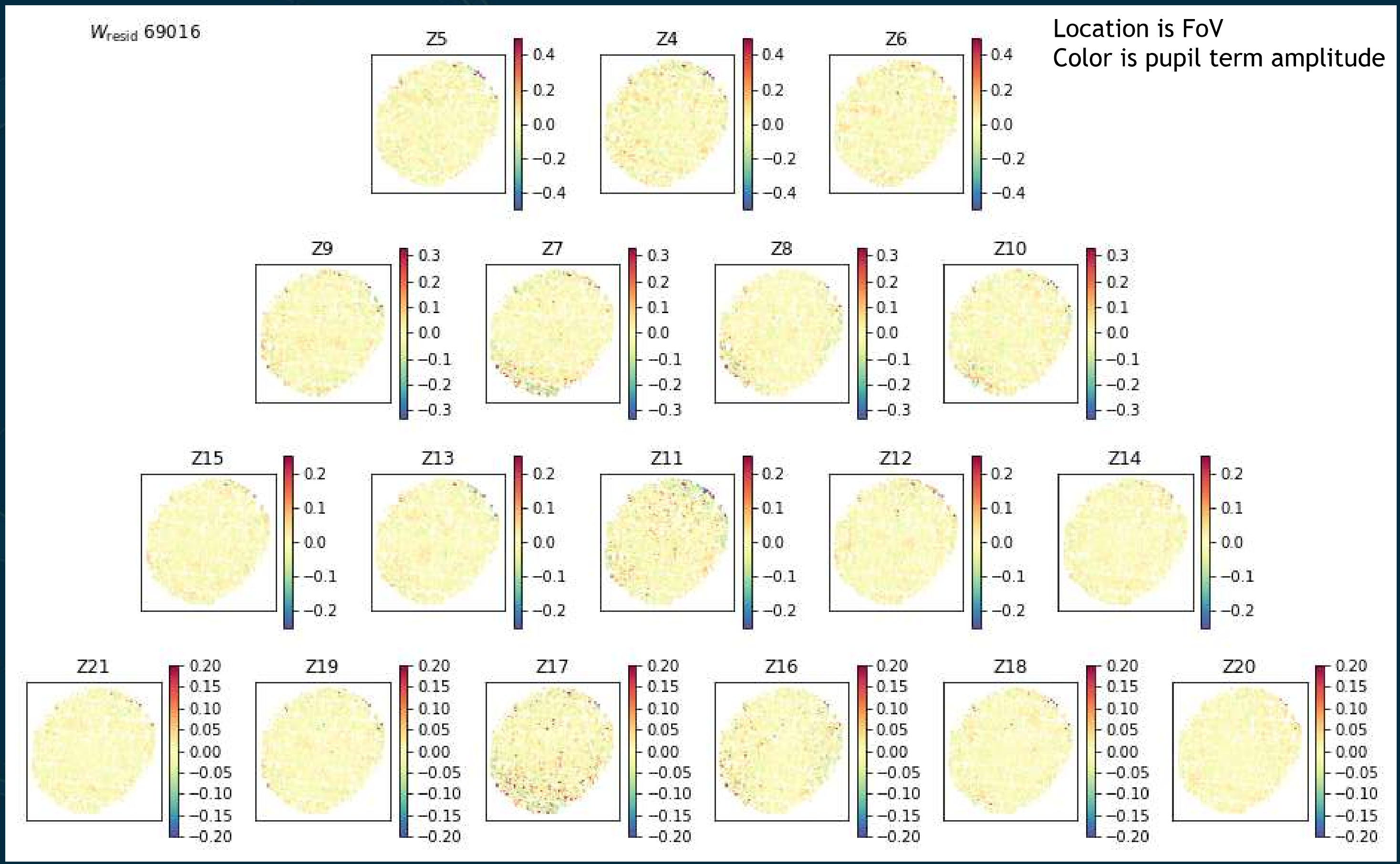
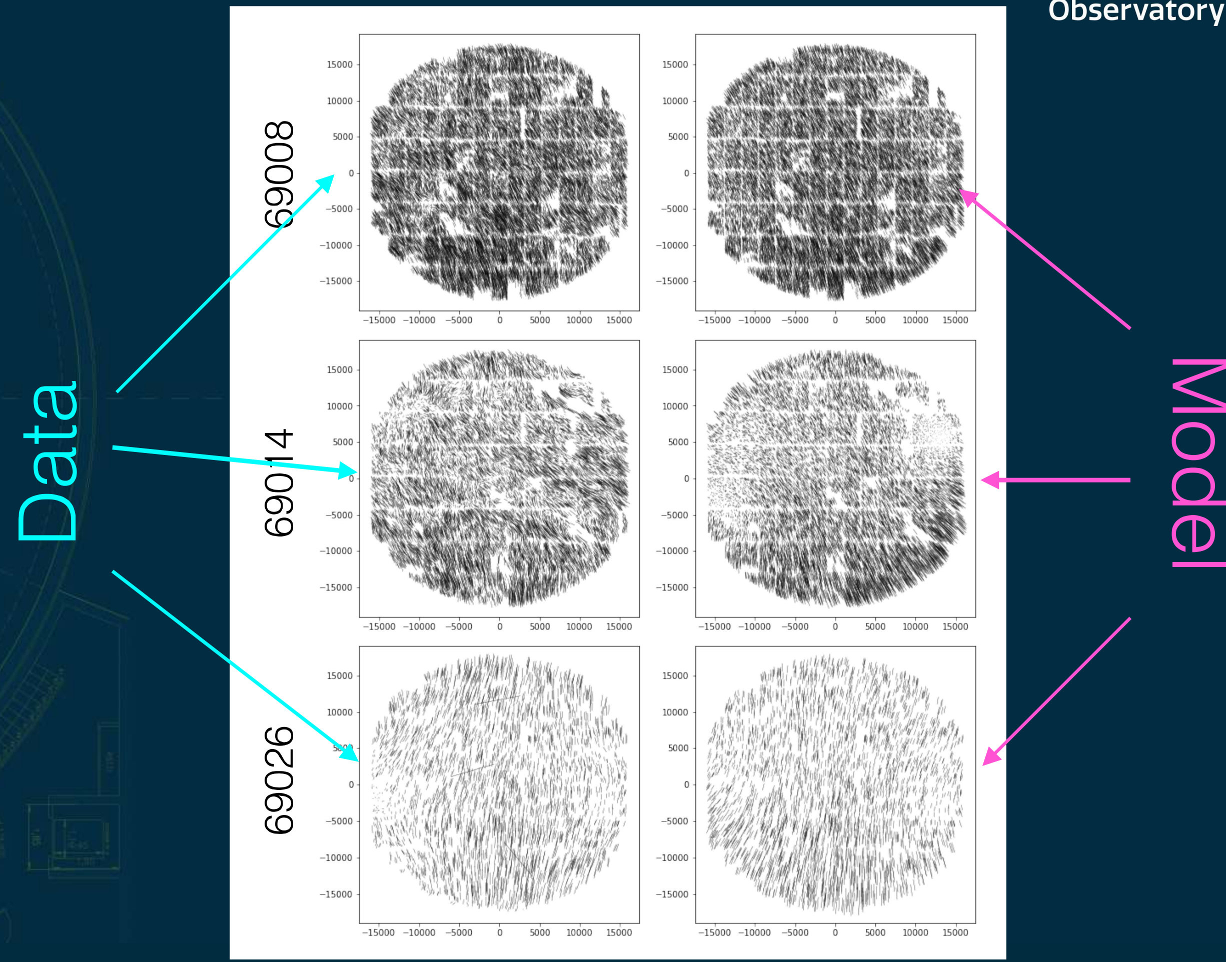


Results for HSC

- Fitting to new ***in-focus*** exposures is accomplished by fixing the static degrees of freedom inferred from donuts, but allowing the dynamic degrees of freedom to vary.
- Can even learn per-visit degrees of freedom from principle components of donut exposures.
  - This is model on right: simple uniform-across FoV model for Atm PSF here…
- Generally reasonable output, but HSC limited by small number of donut exposures.
- For Rubin Obs, should also investigate using WF sensors to infer dynamical state.



Results for DECam

- Dynamic degrees of freedom are a handful of low-order Zernikes here.
- Atm PSF is uniform-across-FoV vonKarman surface brightness profile.
- Capture most of the PSF using ~dozen numbers.

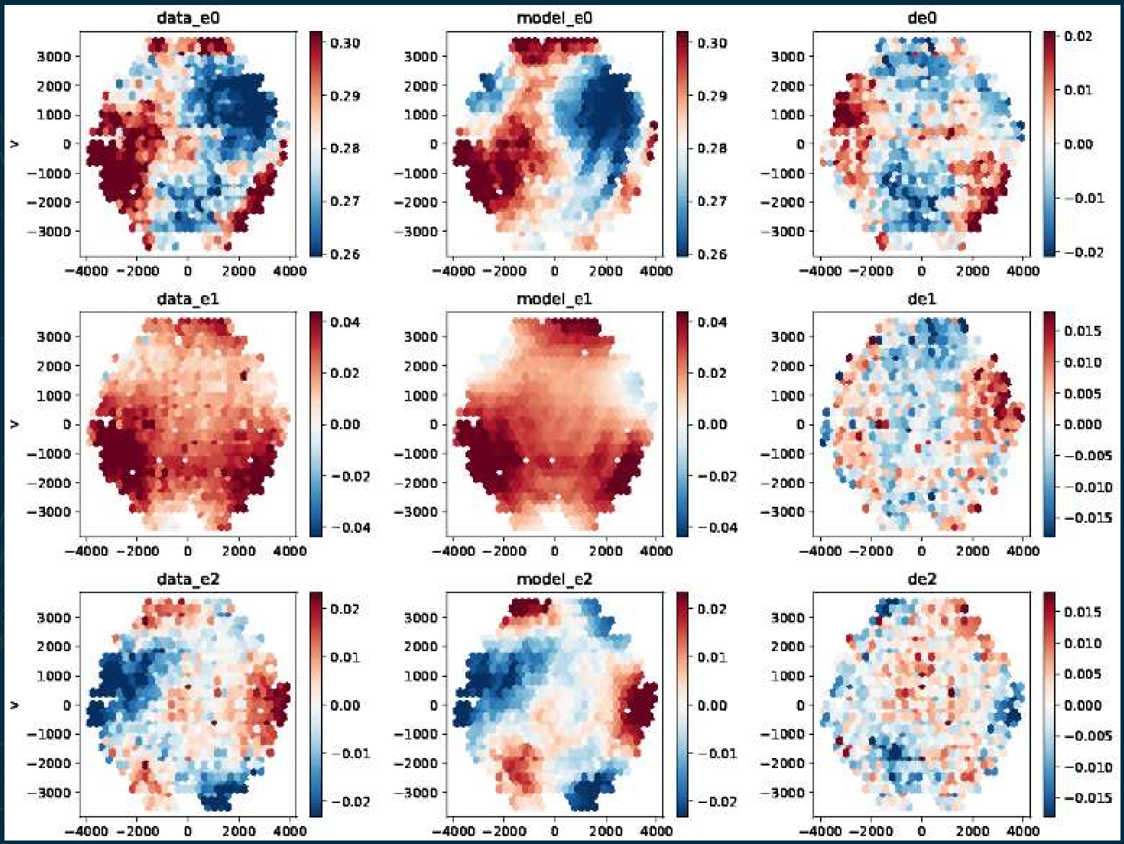


Figure credit: Ares Hernandez

Interpolate atmospheric component with Gaussian Process

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- After optics PSF inference:
  - Refit PSF stars, holding optics fixed, allowing atm params to vary independently for each star.
  - Interpolate parameters of atm component using Gaussian Process.
- Gaussian process:
  - Models directly the (potentially anisotropic) correlations in a function instead of the function itself.
    - Pierre-Francois Leget has made significant progress in rapidly modeling correlations.
  - With correlation model in hand, can interpolate from data.
    - Every prediction is a linear combination of data, with relative weights set by model correlation of prediction point with data point (set by displacement between prediction and data point)
    - Many approximate GPs exist with speedier maths.

Piff

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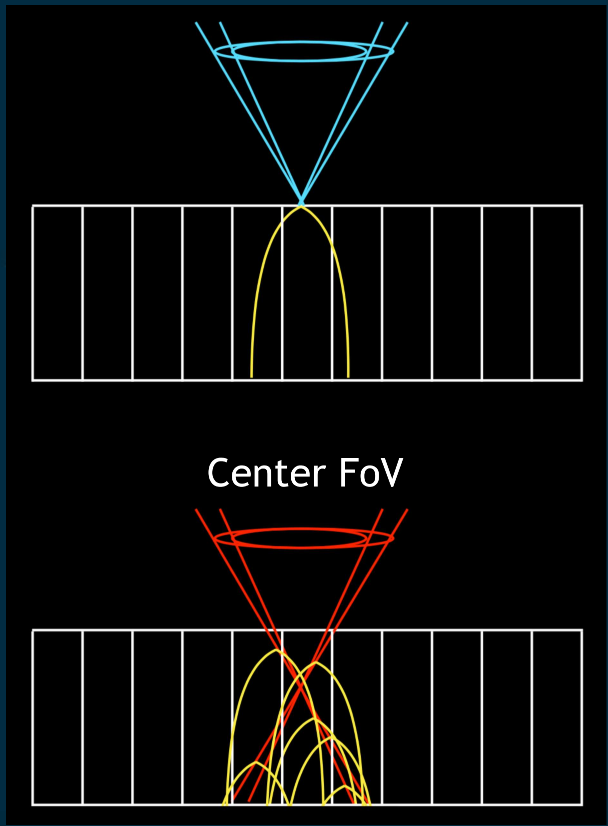
- Mike showed earlier that Piff is already superior to PSFex for DES
- Framework for modular PSF is now being developed in Piff
- We are planning to integrate Piff into the DM stack.
- Two tasks:
  - 1) Ability to run Piff on Rubin Obs images (already demonstrated by Mike with DC2 images)
  - 2) Ability to use Piff PSF outputs in subsequent stack measurement algorithms.

Chromatic effects

- PSF = PSF(λ)
- There are many:
  - Differential chromatic refraction
  - Chromatic seeing
  - Dispersive optics
  - Diffraction
  - Absorption length of silicon coupled with:
    - fast beam
    - charge diffusion
    - lateral electric fields
  - Reflections off backside of silicon.

Josh's favorite chromatic effect: silicon absorption length + fast beam



In blue, all photons convert at surface

In red, redder photons convert deeper, and b/c converging beam, over different range laterally.

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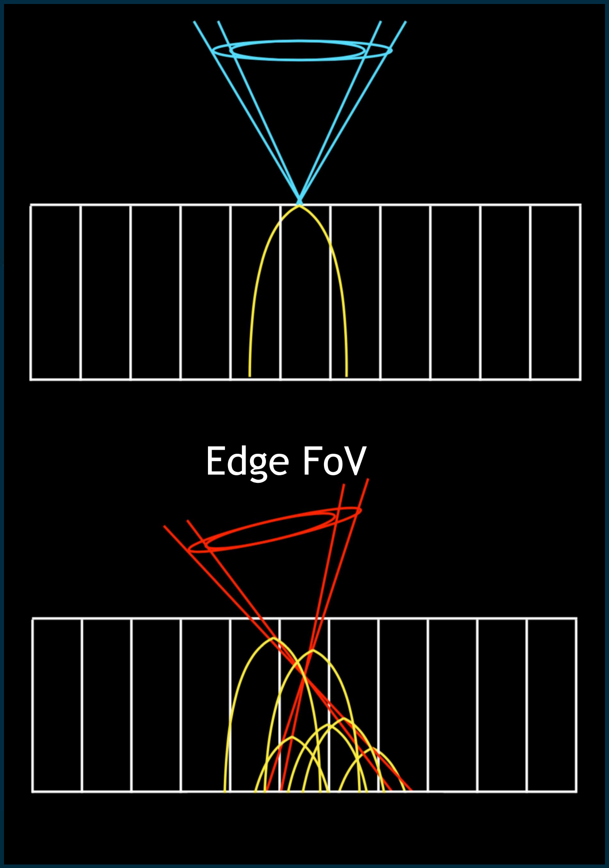

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In red, redder photons convert deeper, and b/c converging beam, over different range laterally.

Modeling chromatic effects

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- Keep in mind that stars are "easy." Their SEDs are essentially a one-parameter family (temperature).
- We have good models for many individual components of PSF(λ) (optics/atm/ccd/etc).
- I have confidence we can infer PSF(λ).
  - Fallback option: Piff PixelGrid regressed on color. (2x params; enough stars?)
- Hard part is inferring galactic SEDs from photometry to construct PSF to use in galaxy measurements.
  - This is similar to photo-zs, except no catastrophic outliers.
- The zero-order solution is to model SEDs linearly across bands using neighboring bands' colors.
- There's an interesting question for meta-detection, part of which uses a single PSF by which to deconvolve a small scene of objects with potentially disparate SEDs.

Conclusions

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- Let's adopt Piff!
  - Better than PSFex
  - Has room for baseline chromatic PSF

- Making progress with wavefront model, but still work to be done.

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