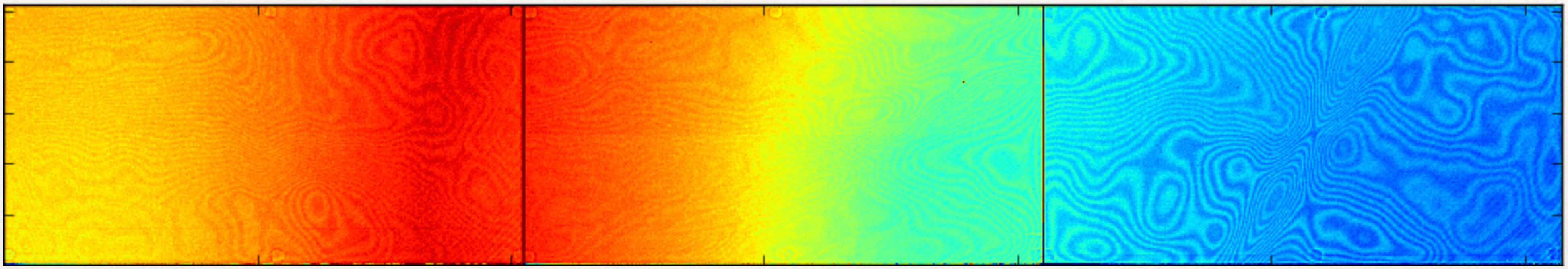


DES Photometric and Astrometric algorithms

Gary Bernstein
(virtually located at the University of Pennsylvania)
and the DES Collaboration (esp. E. Rykoff)

18 March 2020

Outline

- Astrometry & photometry:
  - Functional forms vs pixel lookup tables
  - "Fixed" vs "stochastic" components
- Algorithms for fixed components
- Algorithms for stochastic components
- Sky subtraction in DES
- Non-Poisson sky noise

DES detrending algorithms not covered include: brighter-fatter, streak finding, asteroid/satellite lookups, passband determination, absolute calibration, …

References

- Morganson et al. (2018): overview of the full DES Y1 reduction pipelines
- Bernstein et al. (2017): derivations of the operational order and algebra for all detrending steps (esp: why dome flats aren't for high-precision work). Also has PCA sky subtraction algorithms.
- Bernstein et al. (2017): photometric algorithms for DES.
- Bernstein et al. (2017): astrometric algorithms for DES *(since then: proper motion/parallax solutions integrated; full survey time dependence and lookup tables)*
- Burke et al. (2017): global photometric solutions (first version)
- Eckert et al (2020): non-Poisson noise and sky offsets (on arXiv early April)

(all are published in journals, but links are arXiv versions you can reach easier from home!)

Astrometry+Photometry overview

- We want the functions

$$\left[\begin{array}{c}\text{flux zeropoint}\\ \text{(RA, Dec)}\end{array}\right](x_{\text{pix}}, y_{\text{pix}}, t, \text{color})$$

- Why not just build a look-up table for each exposure *t* from "truth" (*e.g.* Gaia)?
  - Insufficient data - about 1 Gaia star per sq arcmin per exposure. These functions have structure on smaller scales, 10's of pixels for detector effects.
  - If some distortion is known to vary slowly over time *or* space, then we can combine many Gaia stars to gain more data per DOF.

Stochastic vs "Fixed" components

- DES photometry/astrometry divide the function into:
  - **Static** component: unchanging over many exposures (weeks), though perhaps dependent upon known time-variable parameters (airmass)
  - **Exposure** - varies exposure-to-exposure but low-order spatial dependence (telescope pointing/rotation; full-field zeropoint)
  - **Stochastic -** varies exposure-to-exposure, many DOF across focal plane

Solving for fixed components

- Assume parametric form for the static & exposure-level functions and fit them to the data of many exposures, treating stochastic terms as a noise source atop true statistical noise.

$$\chi^2 = \sum_{t \in \text{exposures}} \sum_{\alpha \in \text{stars}} \Delta \mathbf{x}_{t\alpha}^T \, \mathbf{C}_{t\alpha}^{-1} \, \Delta \mathbf{x}_{t\alpha}$$

$$\Delta \mathbf{x}_{t\alpha} = \mathbf{x}_{t,\alpha}^{\text{true}} - \mathbf{x}^{\text{model}}(\mathbf{x}_{t\alpha}^{pix}, c_\alpha, \text{static parameters, few parameters per } t)$$

$$\mathbf{x}_{t\alpha}^{\text{true}} = \mathbf{x}_\alpha^0 + \mu_\alpha (t - t_0) + \pi_\alpha \mathbf{x}_{t\perp}^{\text{Earth}}$$

(truth takes a simpler form of a truth magnitude for photometric case, or for astrometry over time periods <<1 yr)

Models and parameter counts

- For DES: Static functions require dimensional reduction compared to full 2d lookup tables (would need a LUT for color terms too!), *i.e.* tree rings are assumed azimuthally symmetric and proportional to template implied by dome flat wiggles. [LSST might have enough stellar images to solve 2d model directly.]. **Few x100 parameters per filter (1000's for LSSTCam)**
- Exposure terms are cubic or lower-order polynomials across array. **Few x10 of parameters per exposure x thousands of exposures.**
- Chisq can also include external data (Gaia). Must be aware of degeneracies (e.g. abs zeropoint)
- **Millions of stars yield millions of parameters for "truth." But all enter quadratically into chisq, and we can marginalize over them analytically on the fly to eliminate these "nuisance" parameters.**

Some computational details

- All model components are coded to deliver derivatives w.r.t. parameters, usually analytically (fast). Including compounding of model components.
- This enables fast solutions via Newton iteration, since adjustments are small and everything is close to linear in parameters.
- Chisq (and its derivatives) are trivially parallelizable over the domain of stars **except** for updates to the summed A matrix / b vector in linear solution. For these I have implemented a fine-grained lock mechanism to enable shared-memory parallelism.
- Use off-the-shelf Cholesky for solution (Eigen)
- Crucial to eliminate outliers - basic sigma-clipping algorithm used iteratively.
- ***Solution of one "zone" of the sky for all of DES has <10^5 free parameters, requires Cholesky solution of this scale for each outlier-rejection iteration. Inversion time is currently less than time to accumulate chisq and its derivations over all exposures/stars. Easily done on a single high-performance node.***

Model: photometry

Table 2. Components of the DECam photometric model

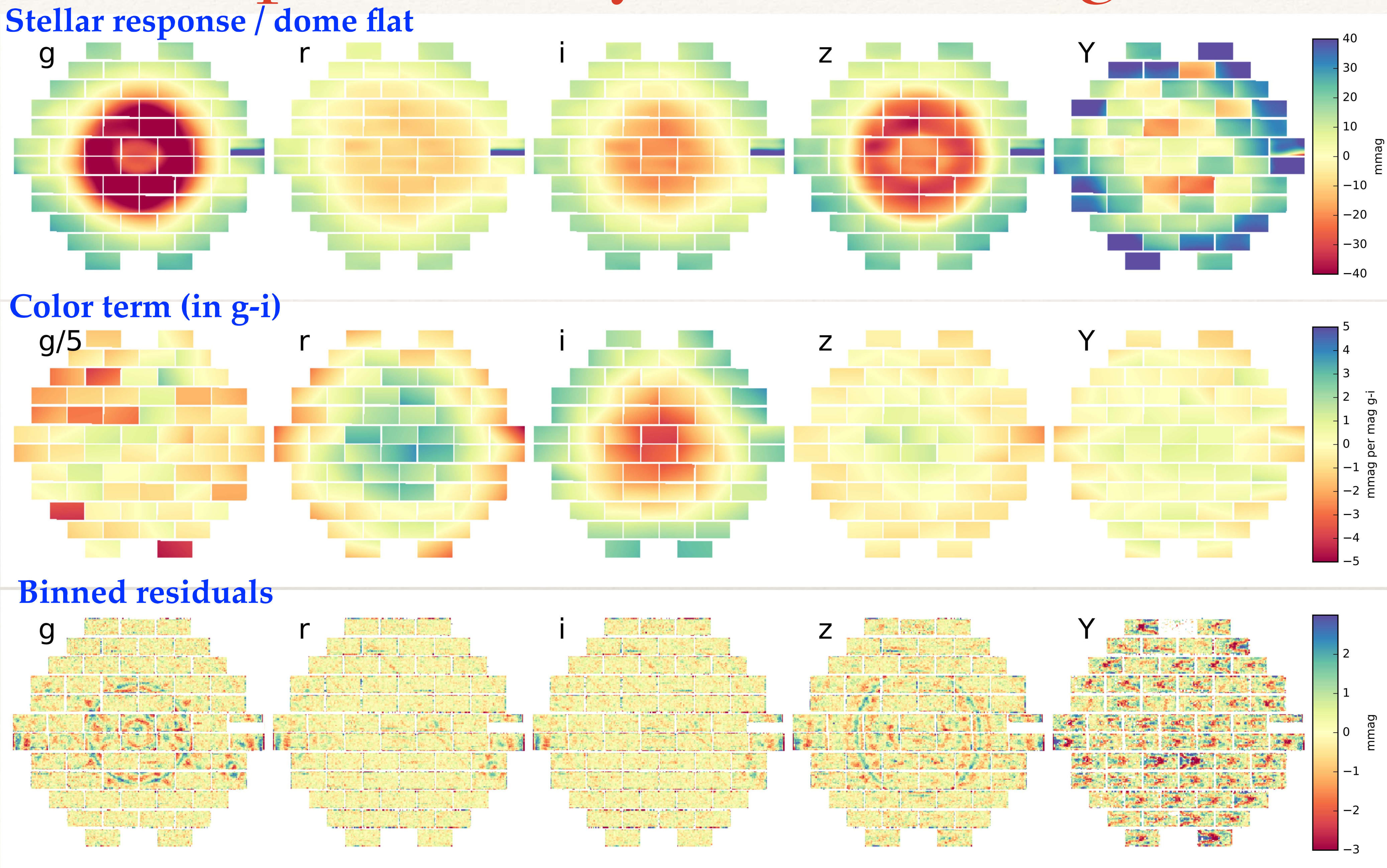
Description	Name	Type	Max. size (mmag)	RMS[a] (mmag)
Tree ring distortion	⟨*band*⟩/⟨*device*⟩/`rings`	`Template` (radial)	± 20	3
Serial edge distortion	⟨*band*⟩/⟨*device*⟩/`lowedge`	`Template` (X)	± 10	0.7
Serial edge distortion	⟨*band*⟩/⟨*device*⟩/`highedge`	`Template` (X)	± 10	0.7
Optics/CCDs	⟨*band*⟩/⟨*device*⟩/`poly`	`Polynomial` (order= 3)	± 40	24
Color term	⟨*band*⟩/⟨*device*⟩/`color`	`Color`×`Linear`	± 5 (± 20 in g)[a]	< 2 (6 in g)[a]
Exposure zeropoint	⟨*exposure*⟩	`Constant`	± 150	≈ 50
Exposure color	⟨*exposure*⟩/`color`	`Color`×`Constant`	± 4[b]	< 2[b]
Extinction gradient	⟨*exposure*⟩/`gradient`	`Polynomial` (order= 1)	± 20 (g, $X = 2$)	10 (g, $X = 2$)
Long-term drift	⟨*epoch*⟩/`drift`	`Polynomial` (order= 4)	± 9	2
CCD QE shift[c]	⟨*epoch*⟩/`ccd`	`Constant`	± 12	2

[a]RMS values are averaged over time and array position, and are given for the worst filter. Many effects are localized or sporadic.

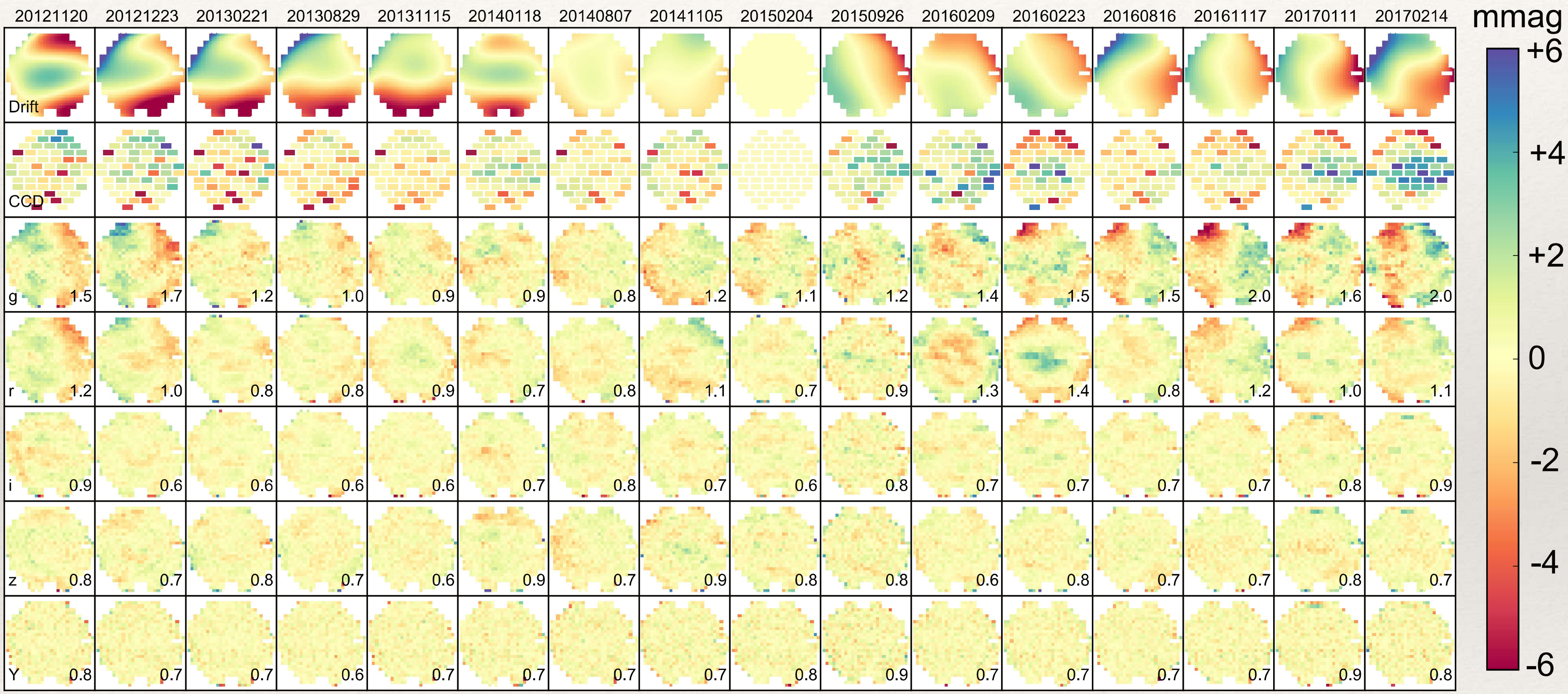
[b]The color terms are in units of mmag per magnitude of $g - i$ color.

[c]Only for Y band.

Static photometry solution - large scale



Photometric response changes few mmag over months/yrs

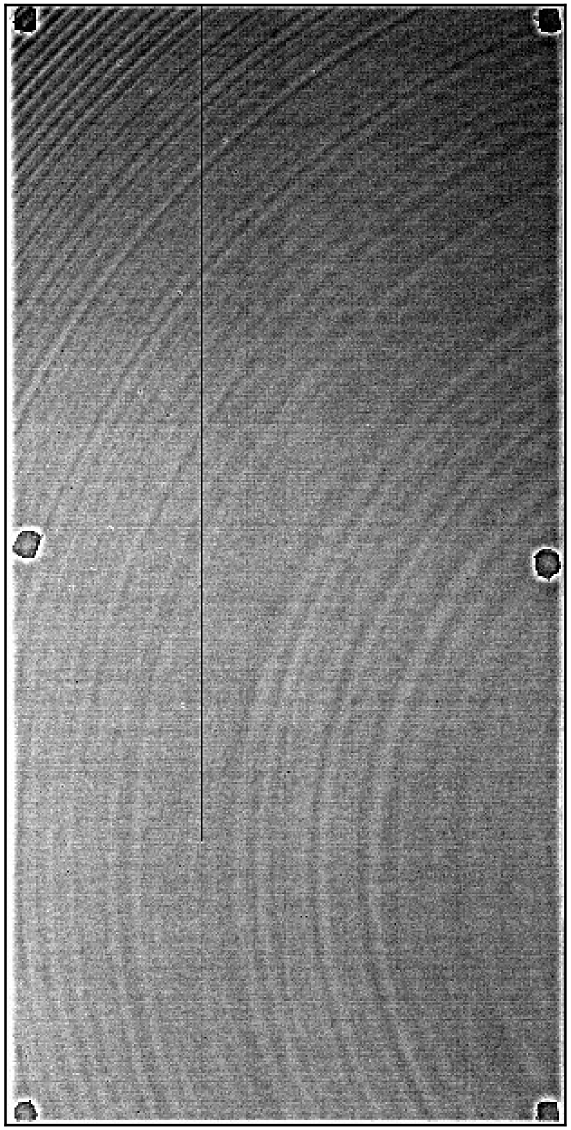


LSST will want to generate solutions on ~monthly basis

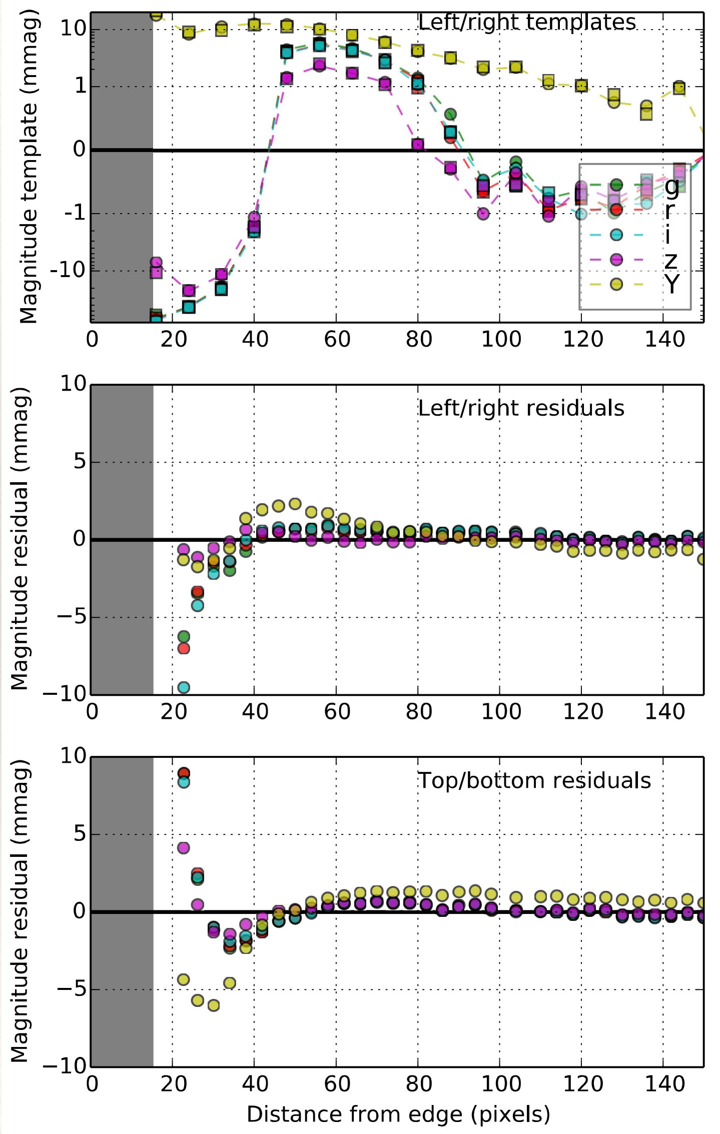
Static photometry solution - small scale

Typical dome flat

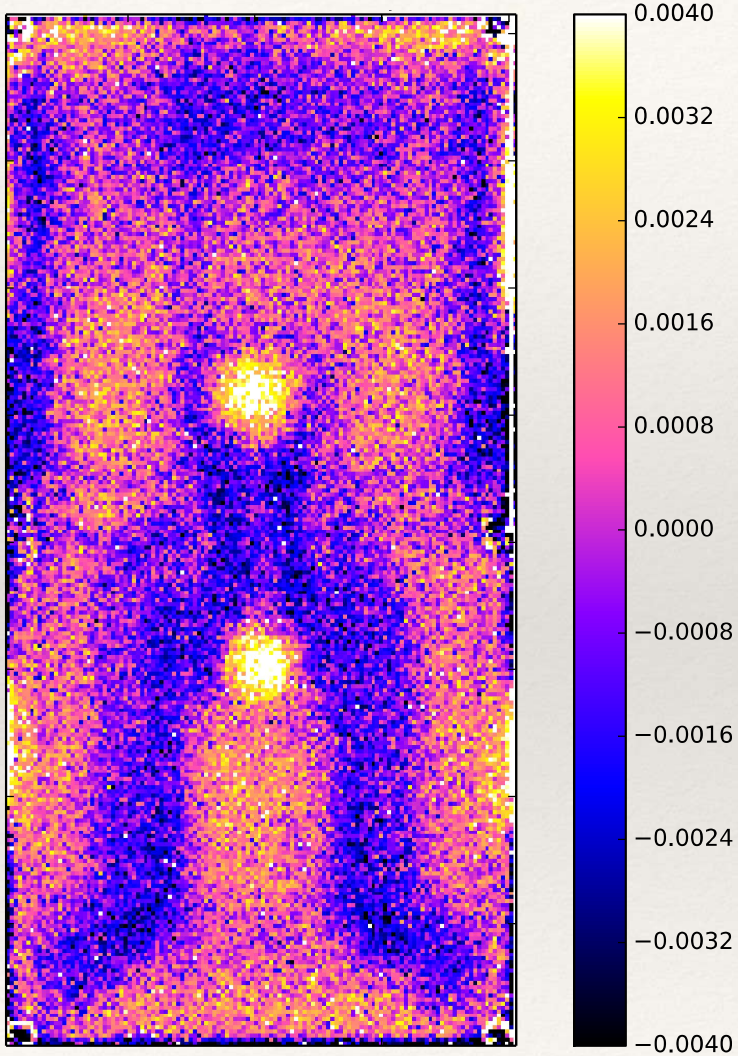
Tree rings are reduced to 1d radial function



Edge effects

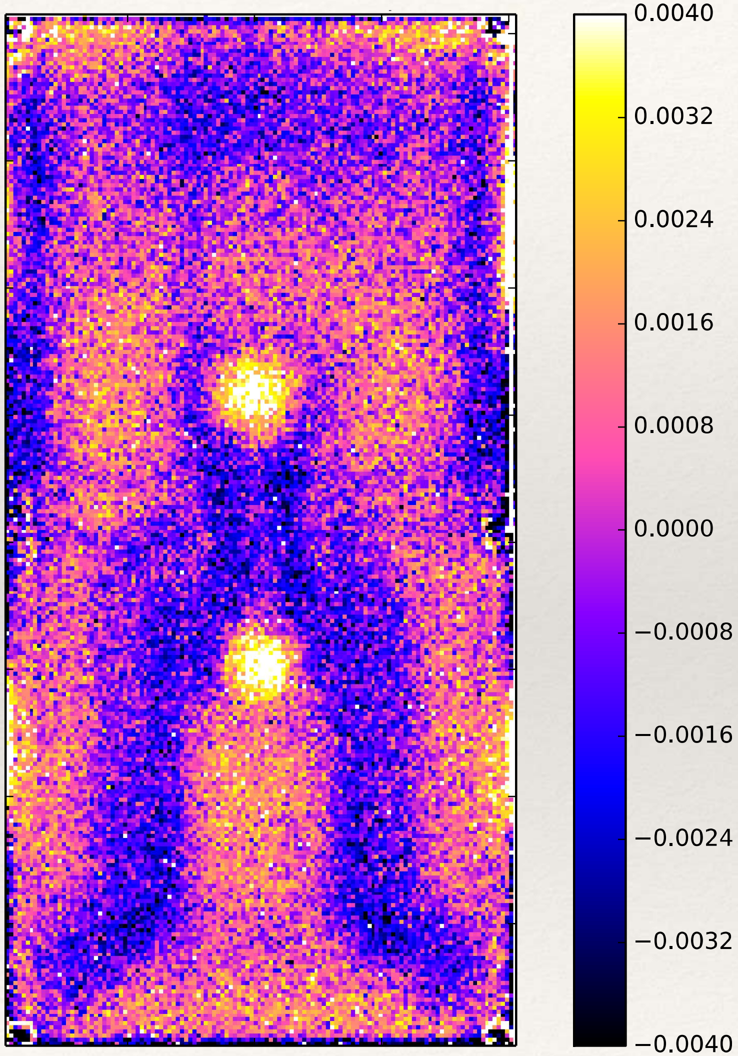


What's with Y band?



Avg mag residuals vs CCD posn

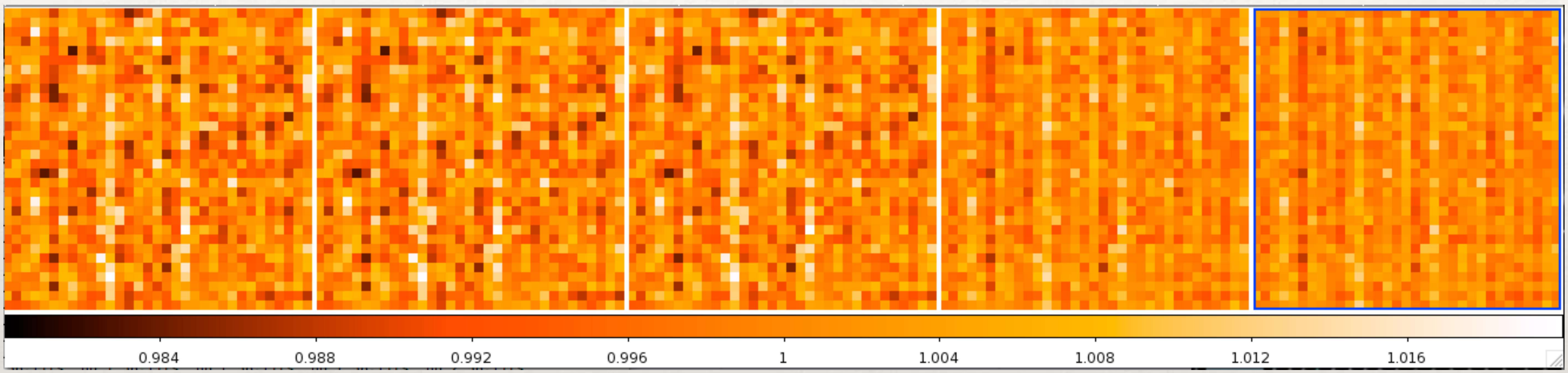
What's with Y band?



Avg mag residuals vs CCD posn

DECam CCD mount (J. Estrada)

Small-scale structure in dome flats is mostly pixel-size variation

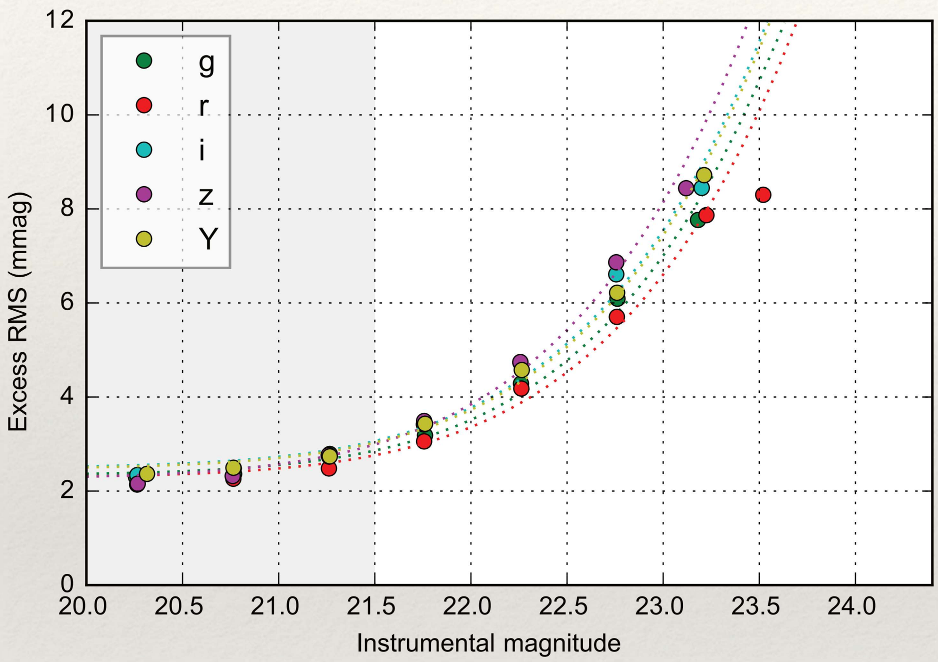


g: 0.63% RMS r: 0.62% RMS i: 0.60% RMS z: 0.47% RMS Y: 0.43% RMS

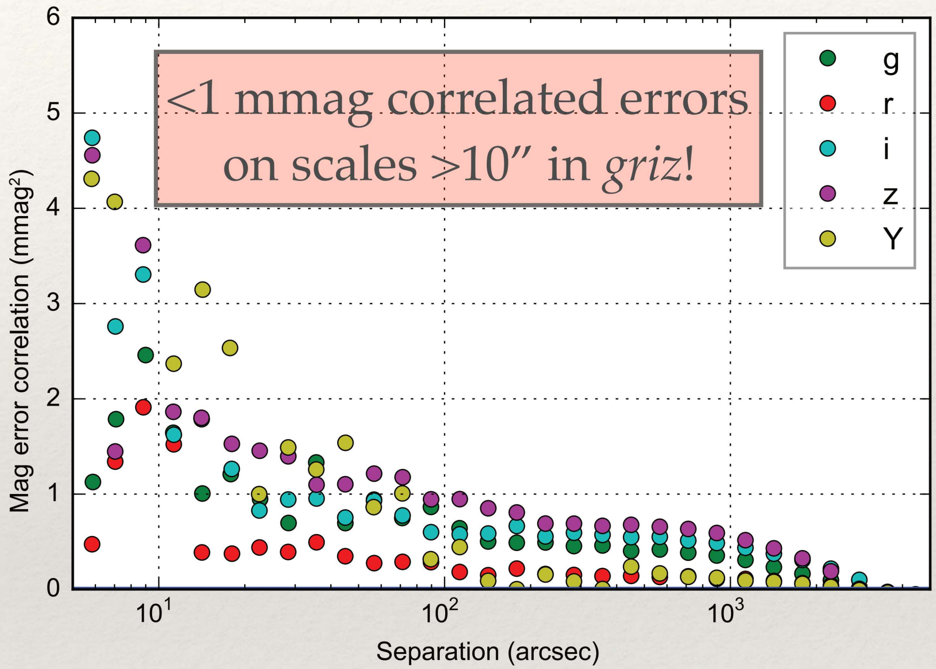
- We are **not** correcting photometry for this “lithography noise,”, might contribute ~1 mmag RMS.

Results: photometry

RMS above shot noise vs mag



2-pt correlation function of residuals



Variance of photometry in excess of expected shot noise is consistent with:

* **multiplicative error** of 2 mmag RMS, plus
* **additive error** equivalent to getting sky level wrong by a few electrons. Shot noise in the sky annulus?

We are shot-noise limited for any star with S/N<500!

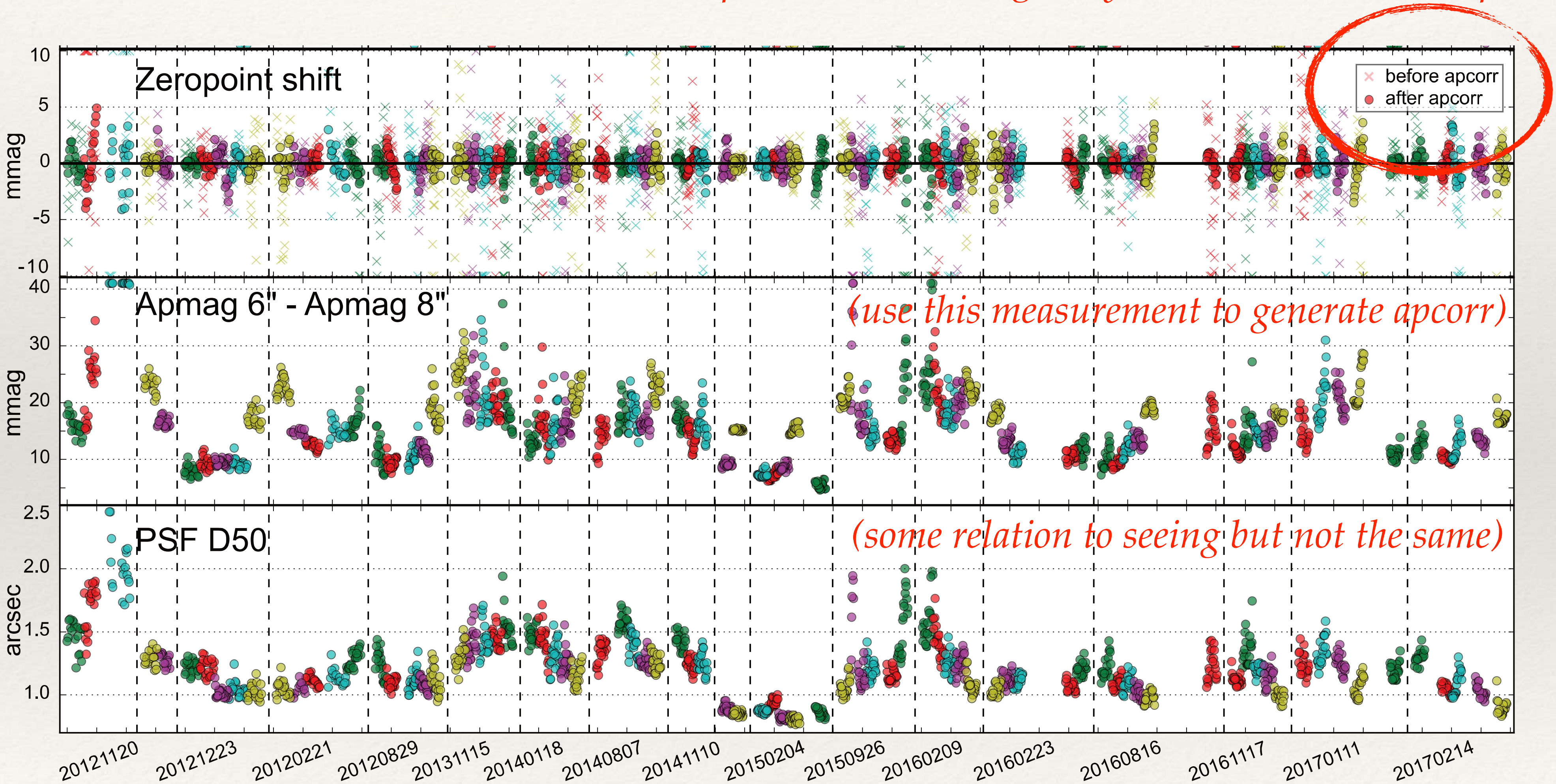
Photometry: exposure and stochastic variations

- Each exposure is expected to have an overall zeropoint and color term that depends on airmass and atmospheric conditions (note that we must account for gradient of airmass across DECam or LSSTCam FOV).
- These are solved with nightly atmospheric models and multi-season consistency solution (ubercal) as marvelously executed by Burke, Rykoff, *et al.* "Forward Global Calibration Model"
- But there are observable photometric zeropoint fluctuations that occur within short time scale (minutes) and across the FOV of a single exposure on cloudless nights.

These "stochastic" terms correlate very closely with the amount of flux in an outer annulus around the PSF - the dominant stochastic effect is variation in light outside the 3" aperture.

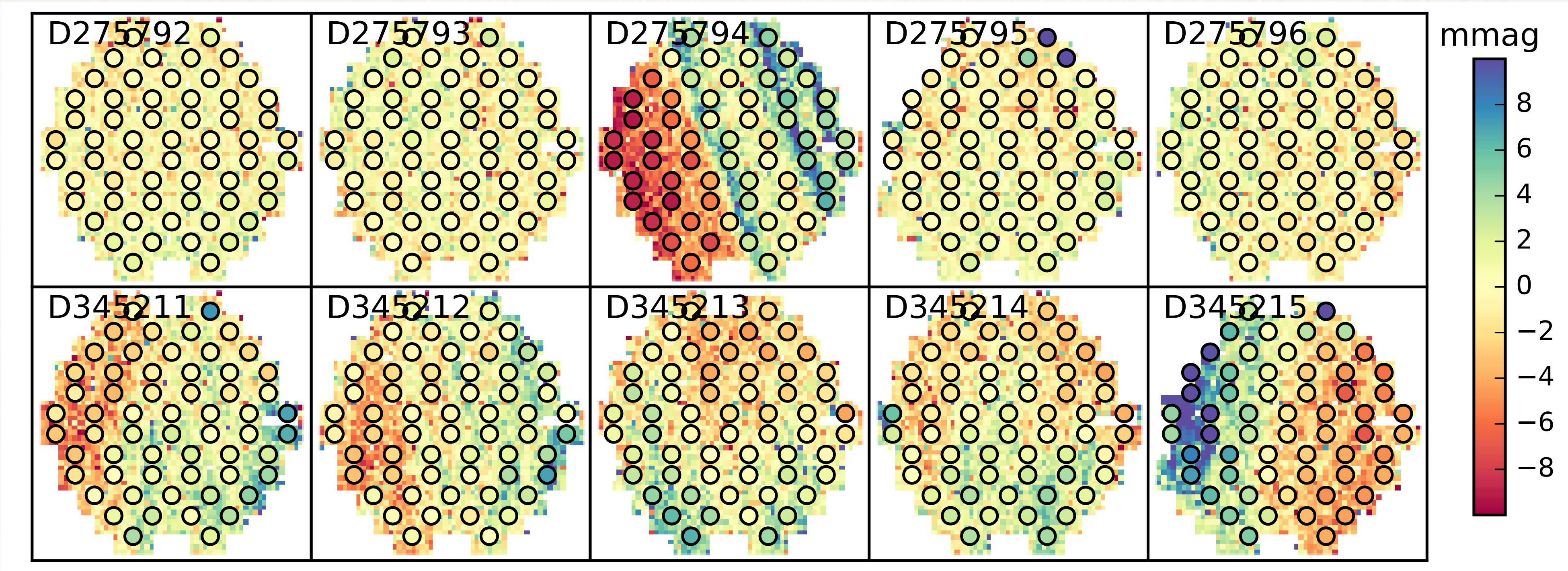
Atmospheric variation: time

Estimated aperture correction greatly reduces "stochastic" zpts



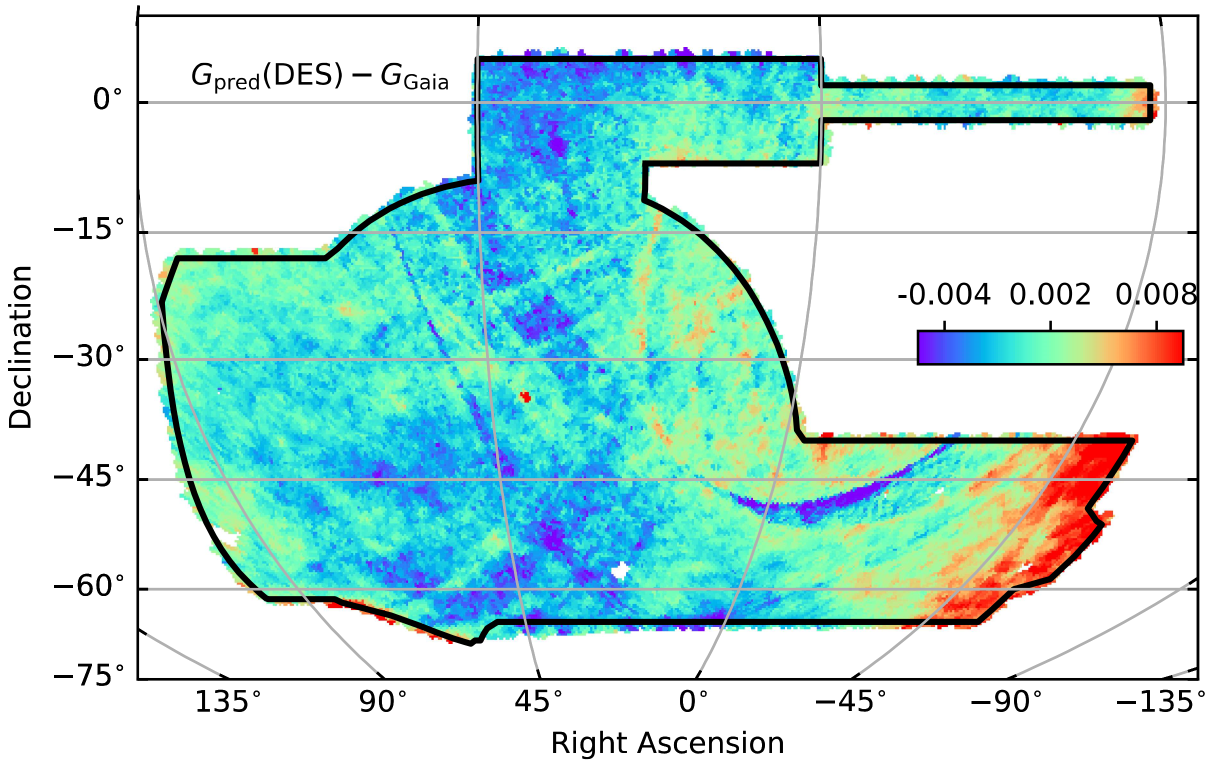
Time (ticks are 1 hr)

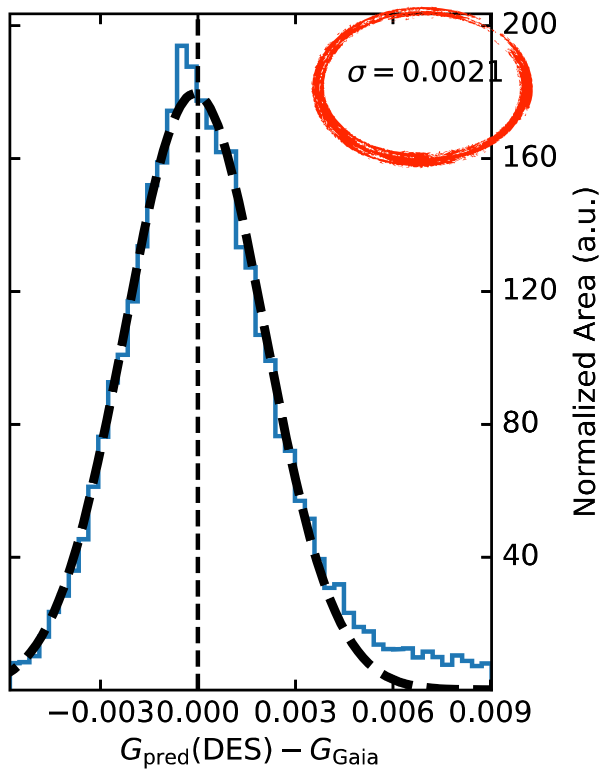
Atmospheric variation: space



Maps of mean mag residual across array for 10 individual DES exposures. The circles are filled with the estimated local apcorr - very close match to residuals! Rubin may wish to institute such local corrections, DES FGCM has something like this on per-CCD level.

Large-scale DES FGCM vs Gaia





Comparison of two *completely independent* large-area photometric catalogs.

At least one of them has large-scale systematic variation below 1.4 mmag!

Astrometric solutions: fixed

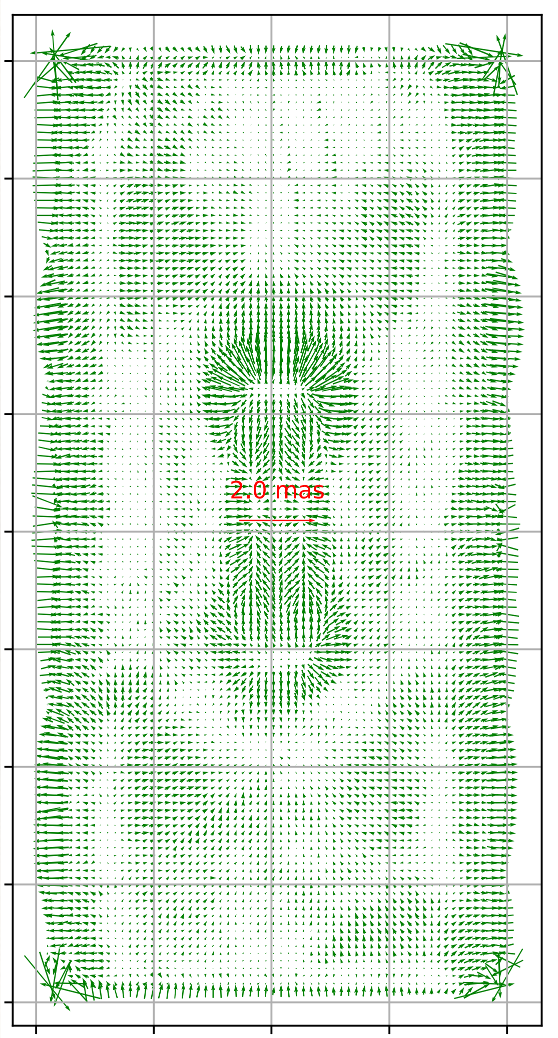
Table 2. Components of the DECam astrometric model

Description	Name	Type	Max. Size
Tree ring distortion	⟨*band*⟩/⟨*device*⟩/`rings`	`Template` (radial)	$\approx 0''.05$
Serial edge distortion	⟨*band*⟩/⟨*device*⟩/`lowedge`	`Template` (X)	$0''.03$
Serial edge distortion	⟨*band*⟩/⟨*device*⟩/`highedge`	`Template` (X)	$0''.03$
Optics	⟨*band*⟩/⟨*device*⟩/`poly`	`Polynomial` (order= 4)	$\gg 1''$
Lateral color[a]	⟨*band*⟩/⟨*device*⟩/`color`	`Color`×`Linear`	$\approx 0''.04$
CCD shift	⟨*epoch*⟩/⟨*device*⟩/`ccdshift`	`Linear`	$\approx 0''.1$
Exposure	⟨*exposure*⟩	`Linear`	$\gg 1''$
Differential chromatic refraction	⟨*exposure*⟩/`dcr`	`Color`×`Constant`	$\approx 0''.05$

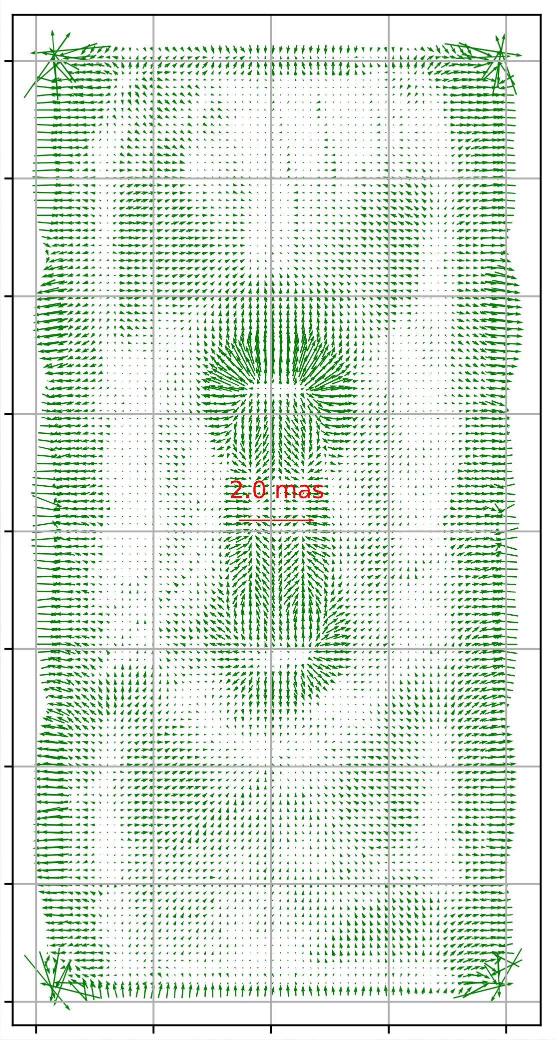
[a]The lateral color correction is set to `Identity` transformation for *izY* bands.

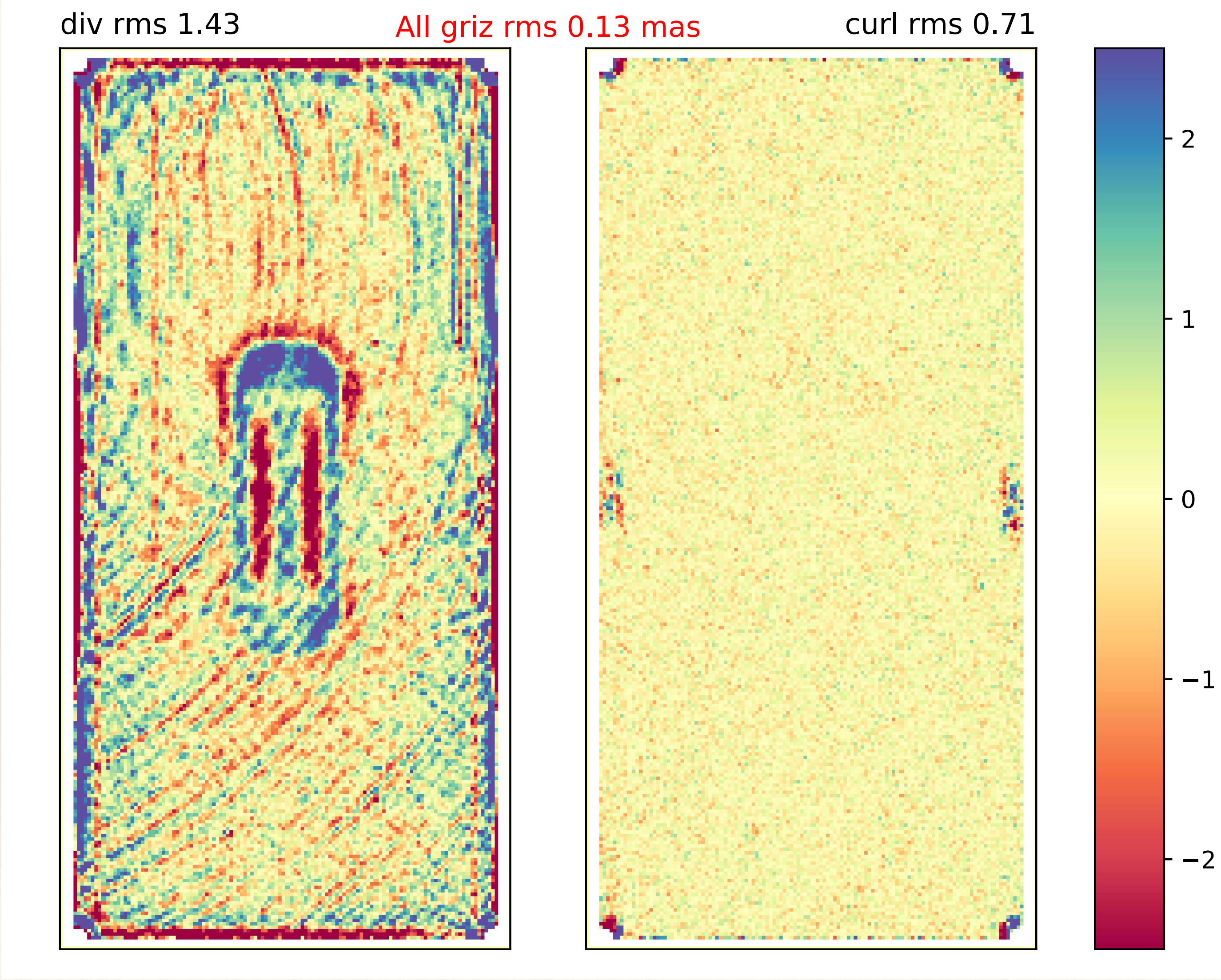
- Astrometric solution follows parallel algorithm (with more dimensions) to photometry, similar set of physical effects, although:
- There is an absolute reference (Gaia, for all 5d), unlike photometry.
- There is a much stronger stochastic component: atmospheric turbulence

Mean astrometric residuals vs CCD position



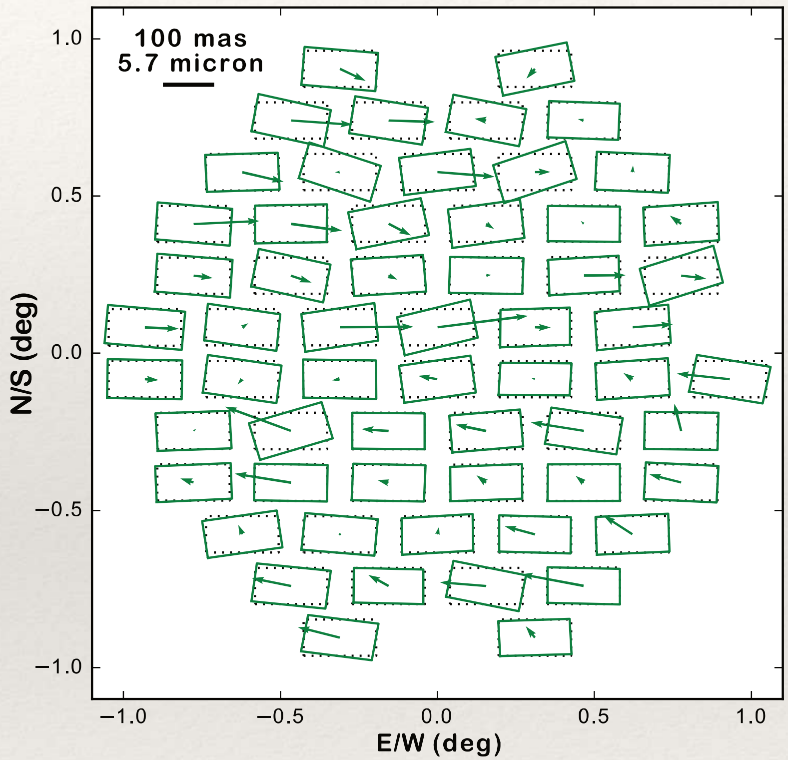
Mean astrometric residuals vs CCD position





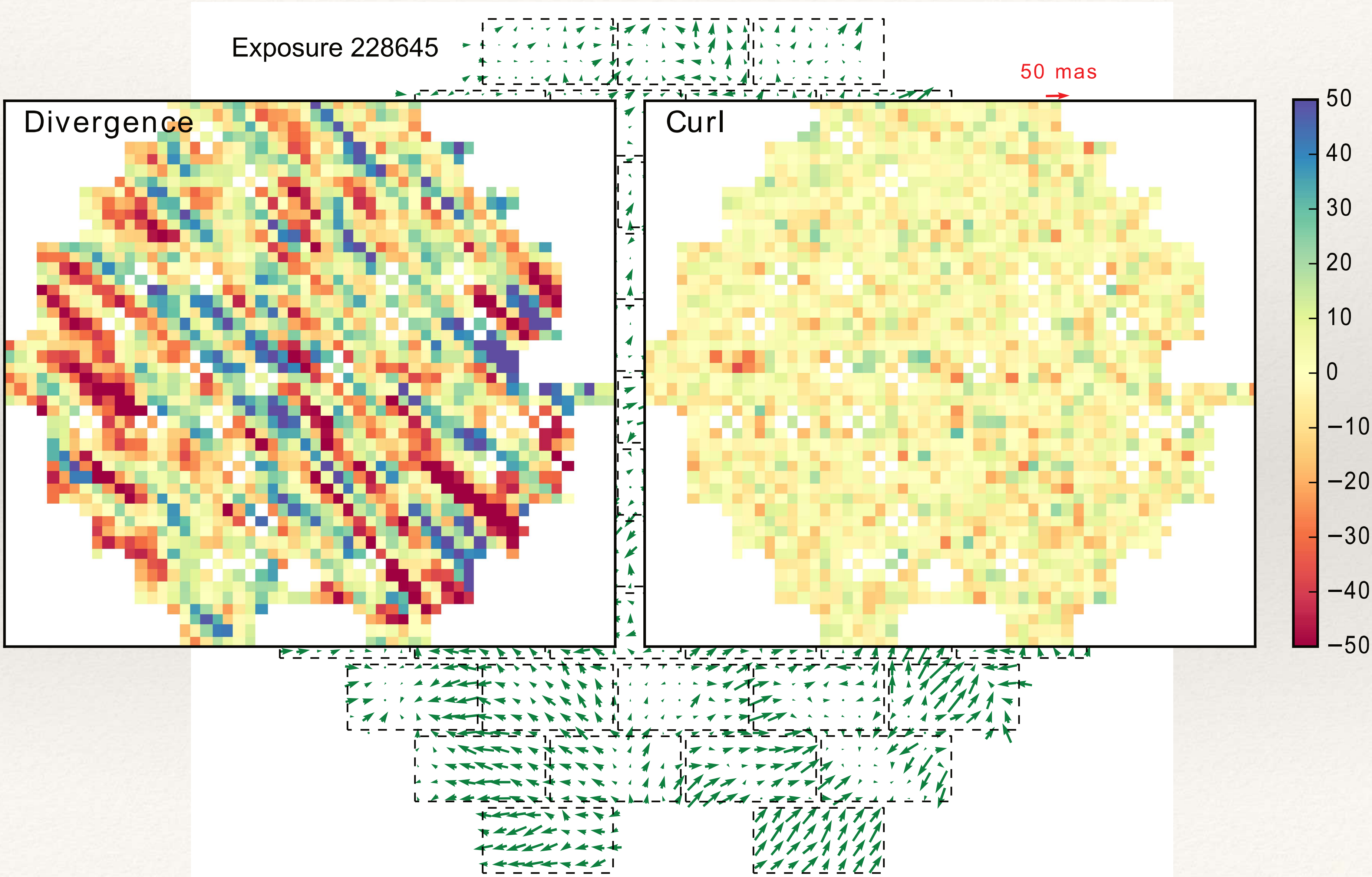
Astrometry wrinkles

- The CCD's move over time (esp. with camera temperature cycles) so ~weekly solution adjustments needed.
- Introduction of field rotation may complicate things quite a bit for LSSTCam
- Stochastic signals are significantly larger than shot noise or residual errors in fixed solutions
- Combining full survey's residuals yields higher-res correction maps.
- Full 5d stellar solutions are a byproduct.

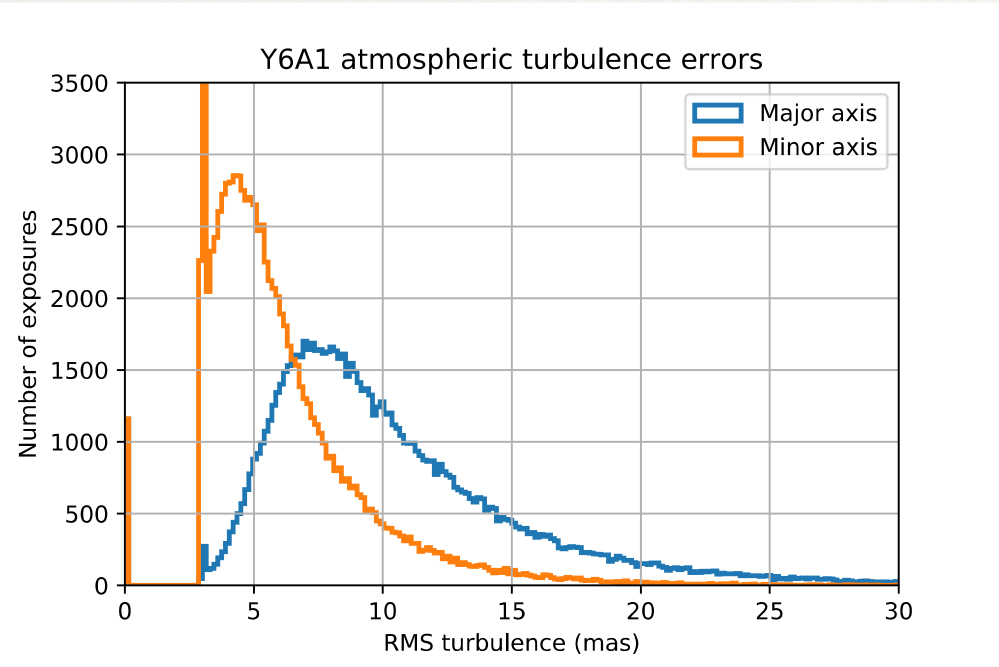


Stochastic atmospheric signals

Stochastic atmospheric signals



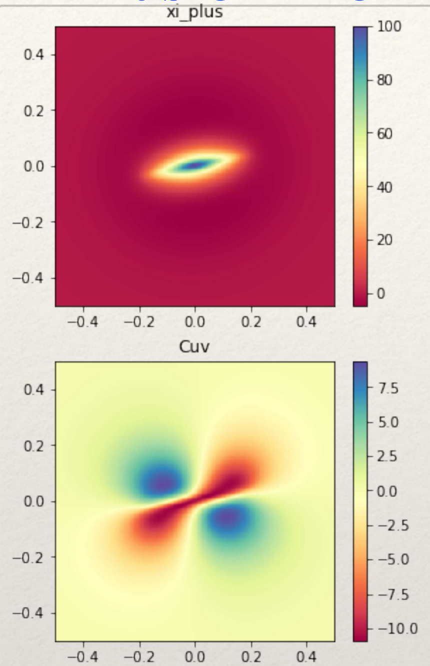
Size of astrometric errors



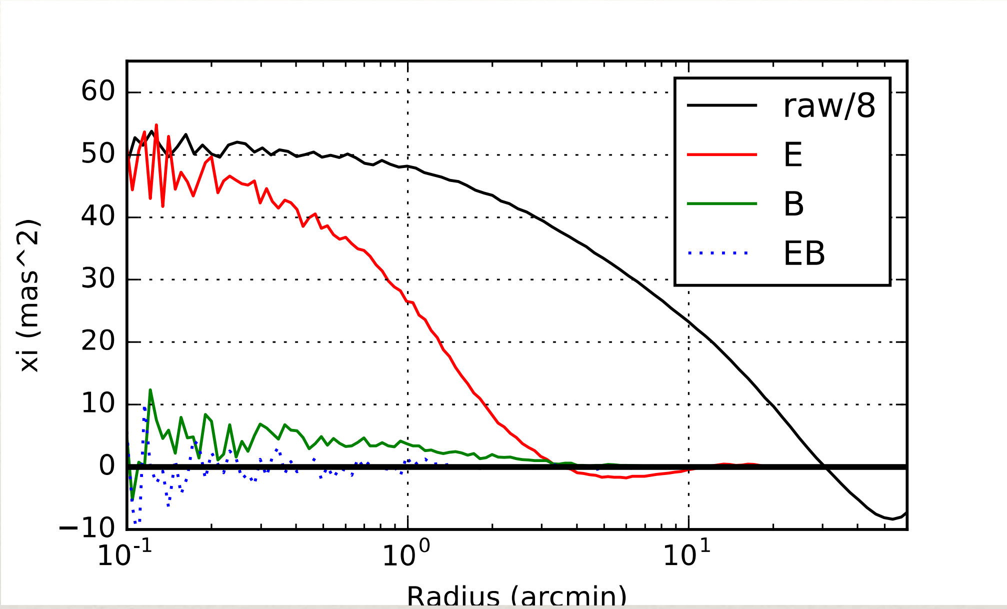
- Windblown turbulence creates anisotropic error covariance matrices
- Also seen in HSC data (PF Leget)
- Typical exposure for DES: 5/8 mas RMS in minor/major axis directions
- Expect ~3-fold reduction from interpolation techniques described below, **1-3 mas RMS**?
- LSST will be better (4m->8m aperture) and worse (90s -> 30s exposures) so similar per visit? (plus shot noise of course)

Reducing stochastic errors

Theoretical correlation functions from windblown von Karman turbulence



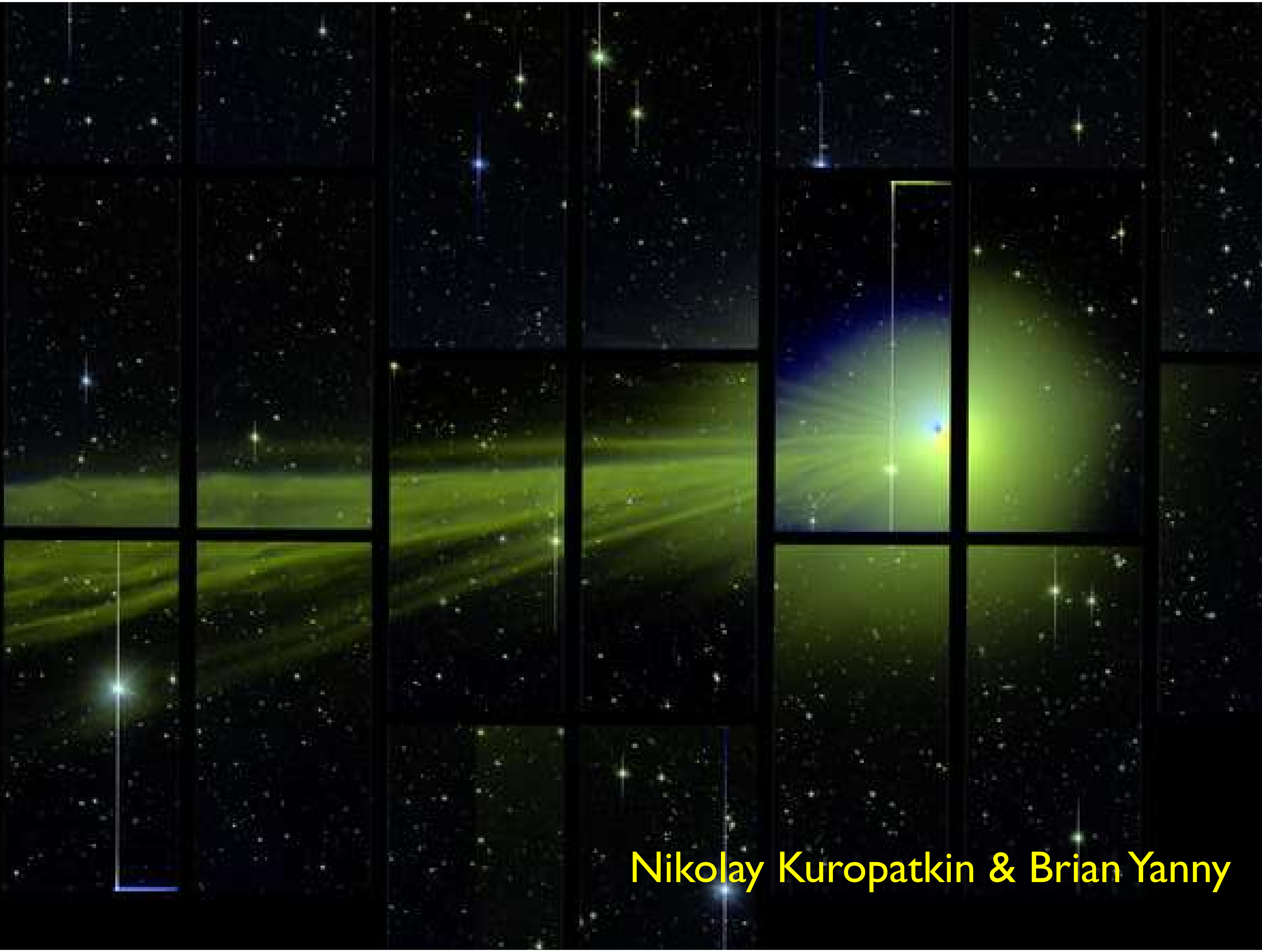
Azimuth-averaged astrometric correlation functions before and after simple GP interp

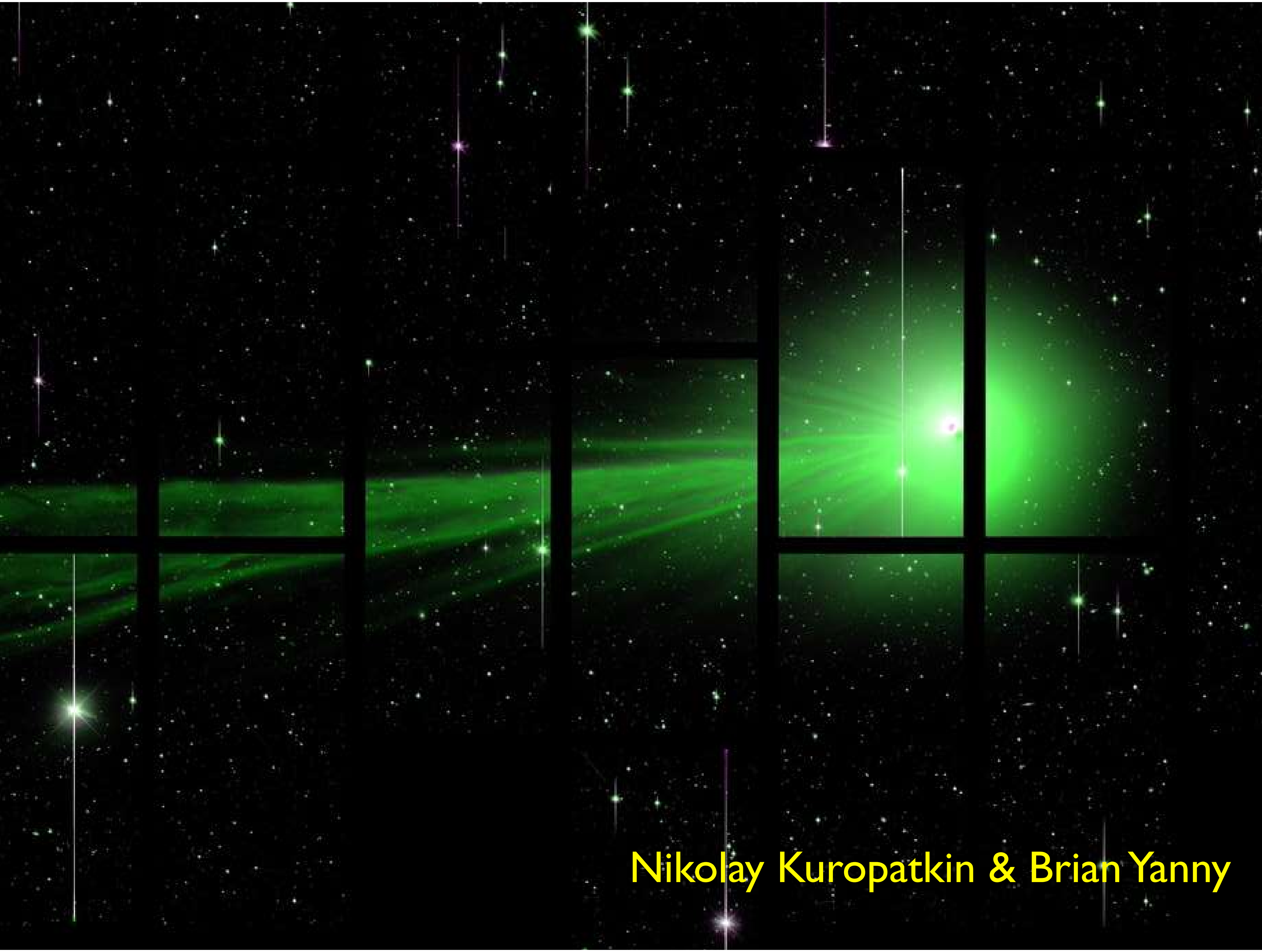


- Correlation length of the turbulence signal is ~10′, so interpolation from Gaia stars should be effective.
- Stochastic astrometric signals arise from atmospheric turbulence, so likely to be well described by a scalar Gaussian field. So a GP interpolator should be nearly optimal.
- We have developed a variant of GP that exploits the curl-free nature of the field (x and y displacements form a single coupled covariance matrix). Senior thesis of Willow Fortino.
- Expect ~3-5x reduction in RMS turbulence - here is an early attempt.
- We have also developed formalism for simultaneous solution of full stack of exposures to simultaneously solve the turbulence estimation and the 5d stellar solutions, reinforcing each other. Not yet implemented (anyone interested?).
- All of this will likely be post-processing after the "static" astrometric solutions have been derived and applied.

Critical to photometry: sky subtraction

- DES distinguishes 2 kinds of sky subtraction:
  - The part that comes from truly diffuse (uniform) sky emission / scattering. This we assume is driven by a few physical variables (moon phase, observation angles, excitation levels of airglow).
  - The scattered light from individual light sources. The worst ghosts of bright stars are pre-masked using ray tracing models (S. Kent). Otherwise we rely on SExtractor algorithms.
- Images of diffuse objects (large galaxies, dust reflection nebulae, LSBG's) are much easier to see without step 2!

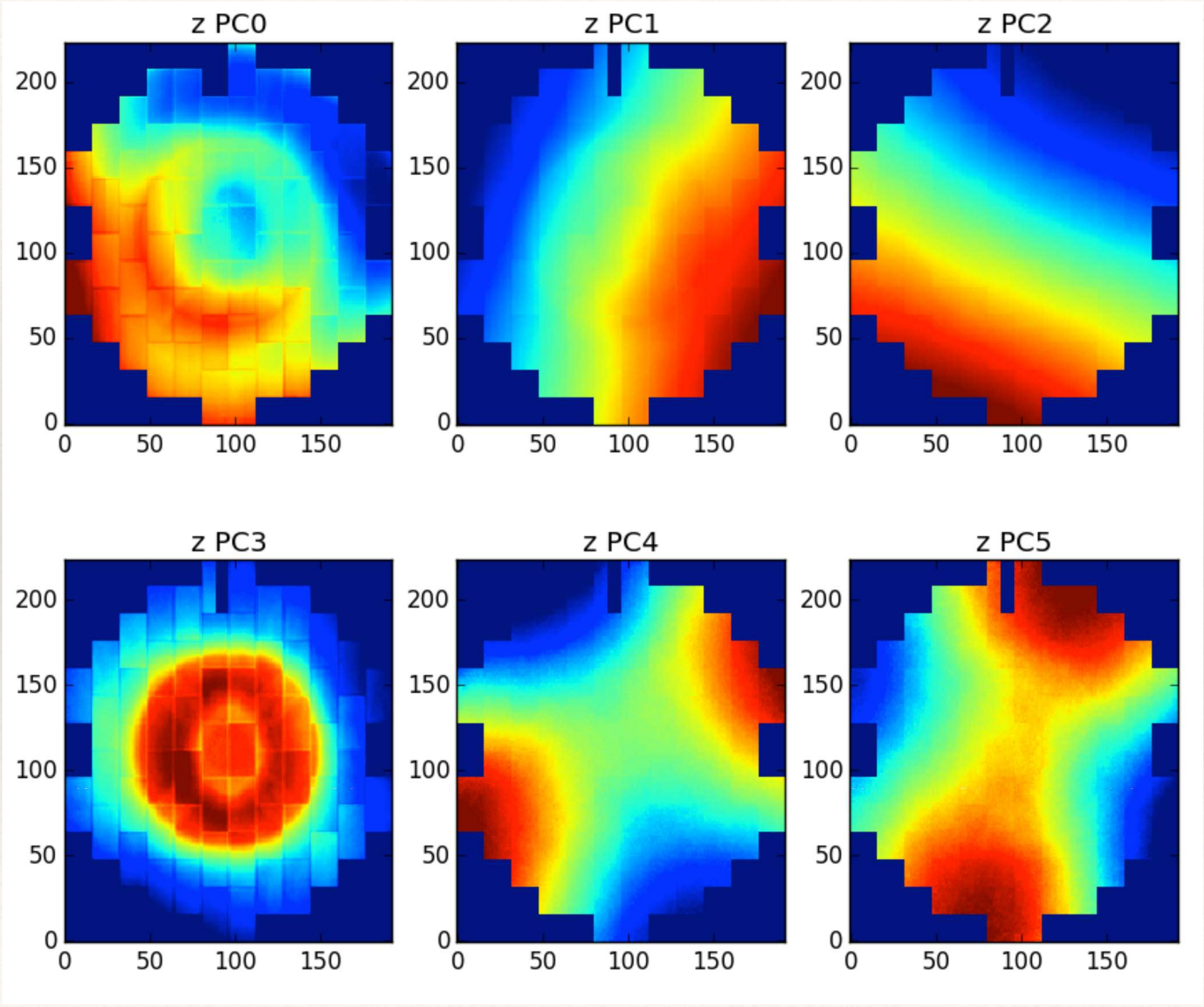

Nikolay Kuropatkin & Brian Yanny


Nikolay Kuropatkin & Brian Yanny

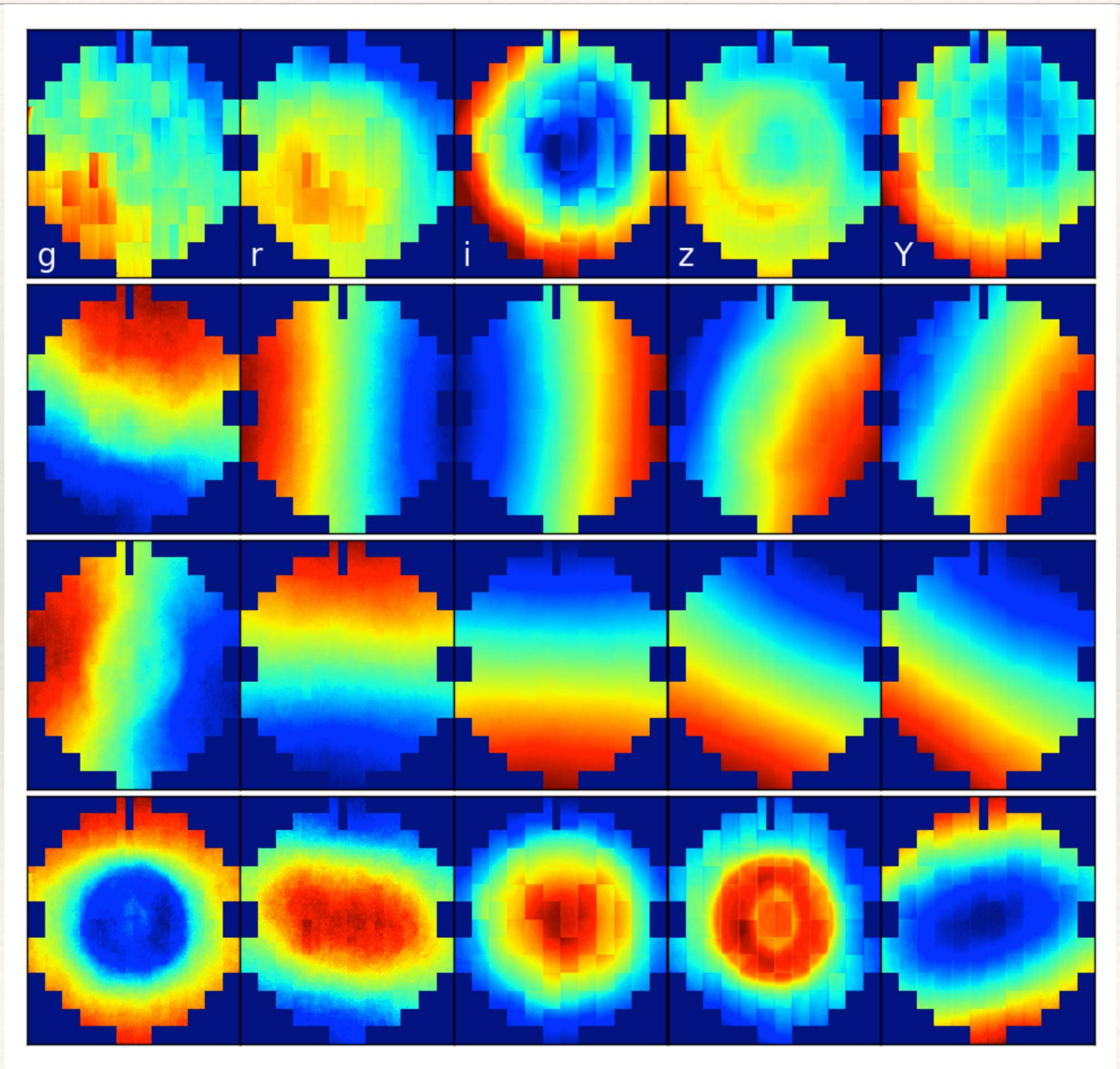
"True" sky subtraction

- Identify the first few principal components of sky signals from stack of ~1000 or more exposures in a filter (once or twice per season).
  - Algorithm to derive PC's must be robust (ignore astronomical sources) Require large dimensional reduction for PCA, cannot do 1000 x 2 billion PCA.
  - Use 32x32 median decimation, do a 1000 x ~1 million PCA to extract top PC coefficients for 1000 exposures. Then do 2 billion robust linear regressions, each 1000x4, to re-densify the PC's.
  - Now for each target exposure: execute decimation, determine PC coefficients, and build / subtract full sky model.

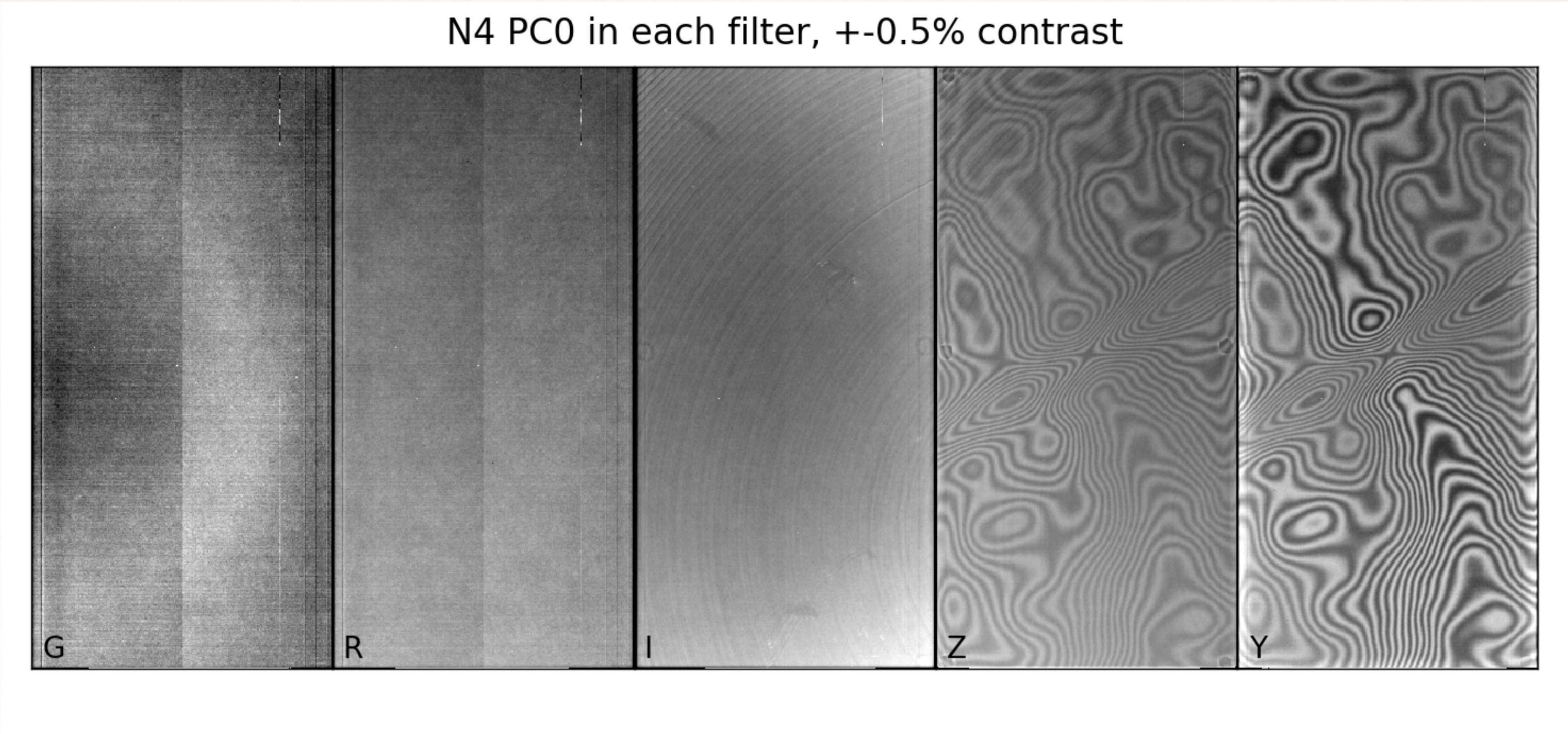
Large-scale view of z-band sky components



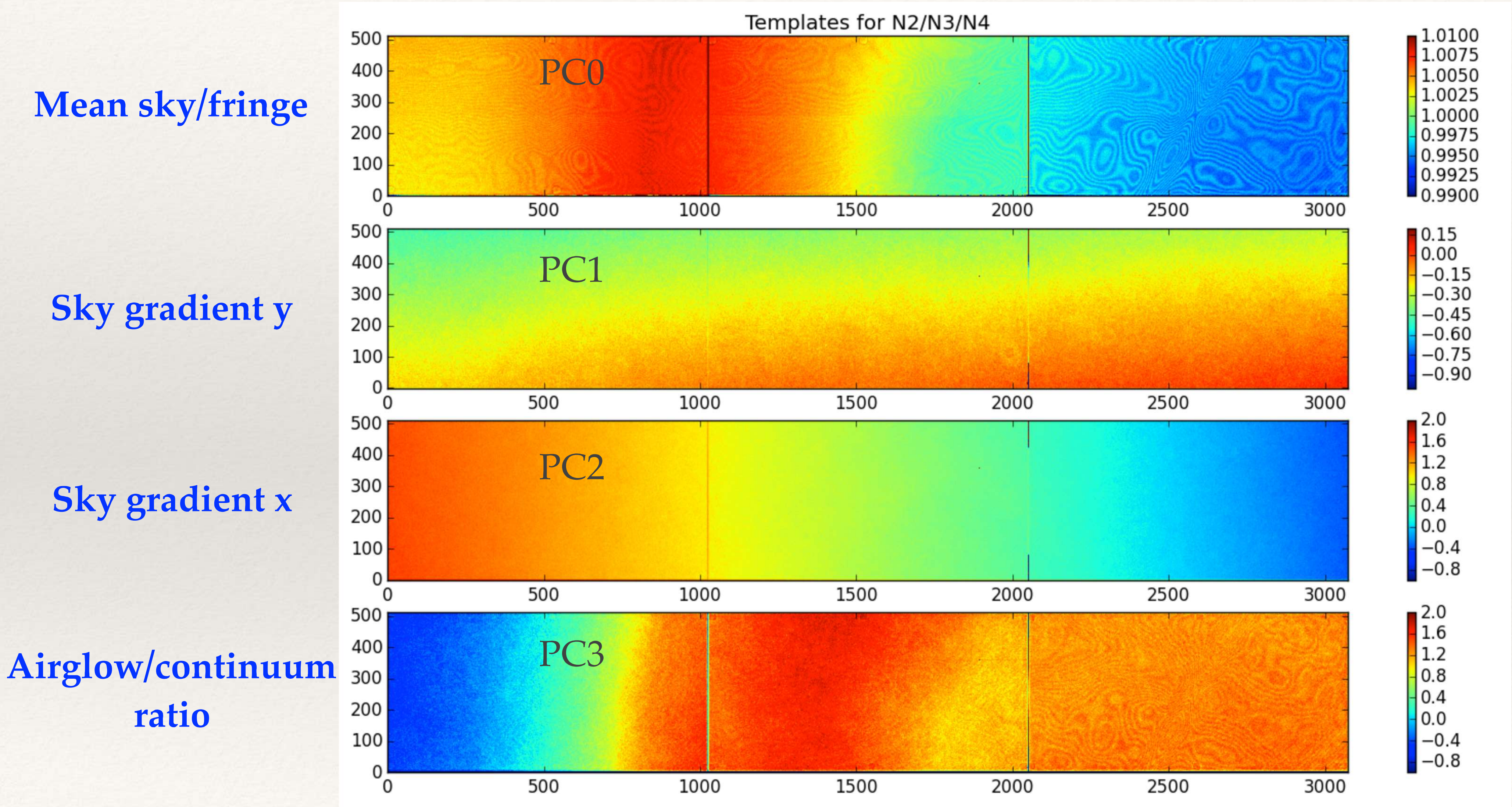
Top 4 sky components *grizY*



PC0 for CCD N4 in *grizY*



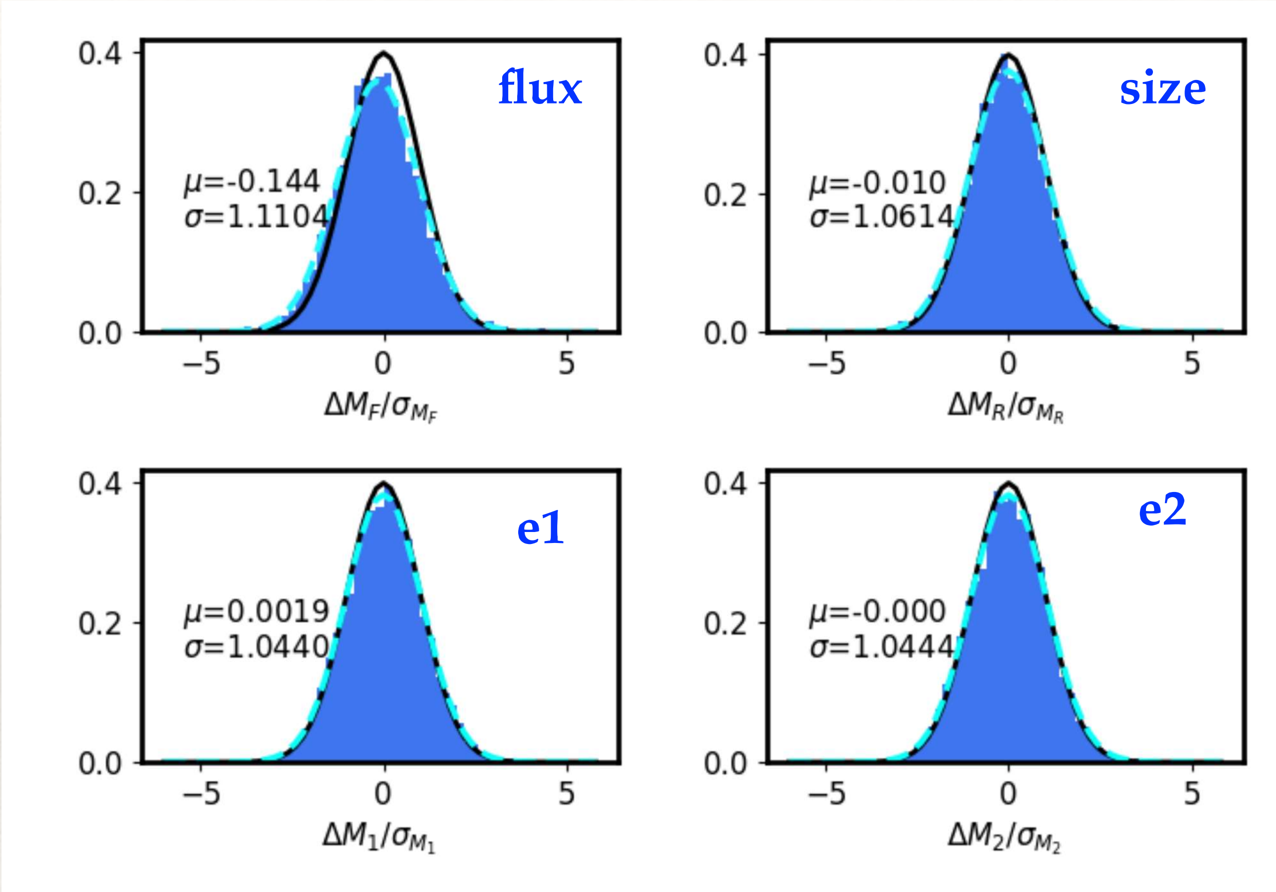
Small-scale behavior of z-band sky components



Sky noise and bias (*cf.* Eckert *et al.* forthcoming)

- Using Balrog image-injection pipeline, we can compare the mean and variance of flux and other low-order image moments to the predictions from sky noise.

Pull distributions for i-band moments



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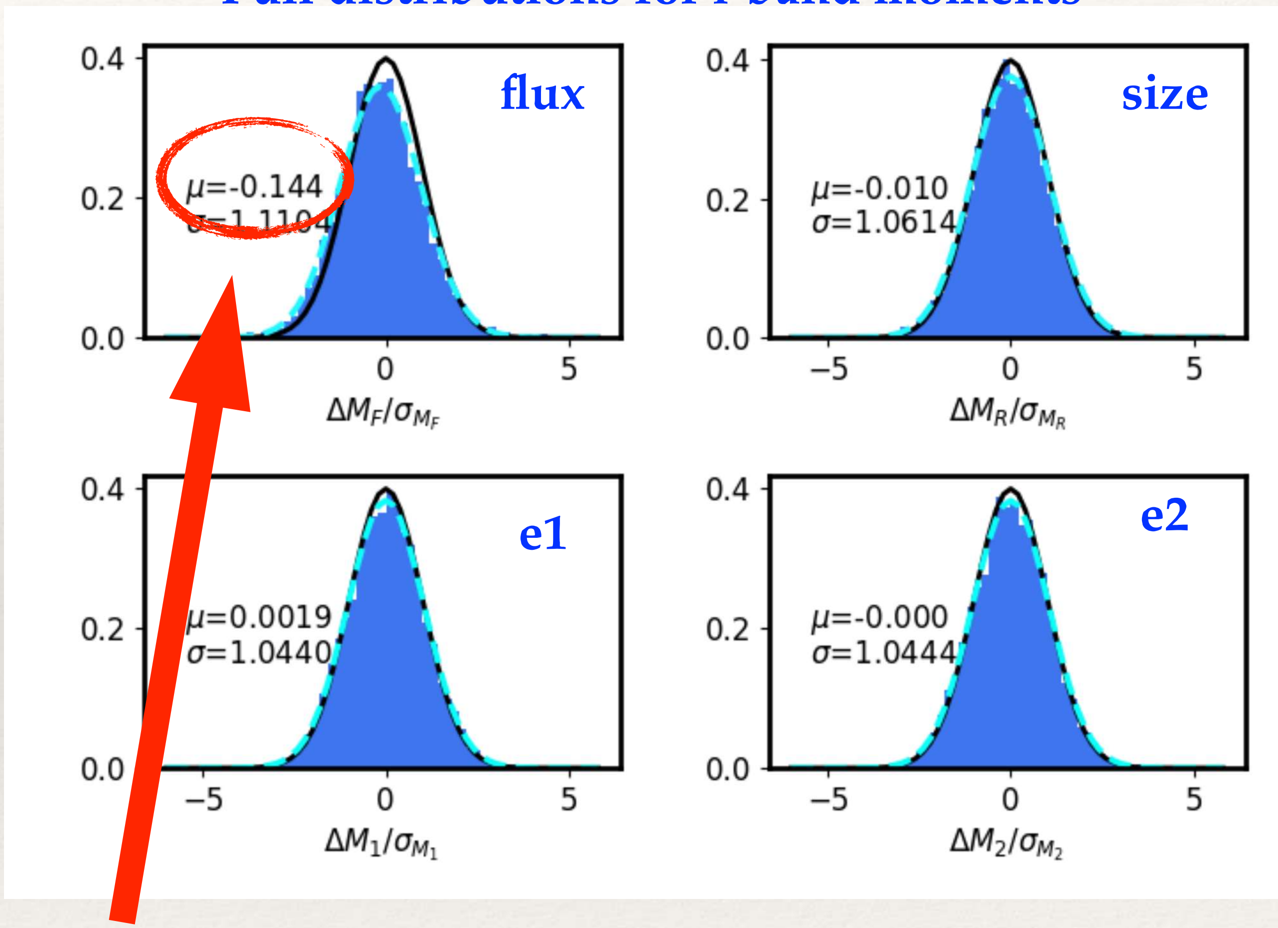
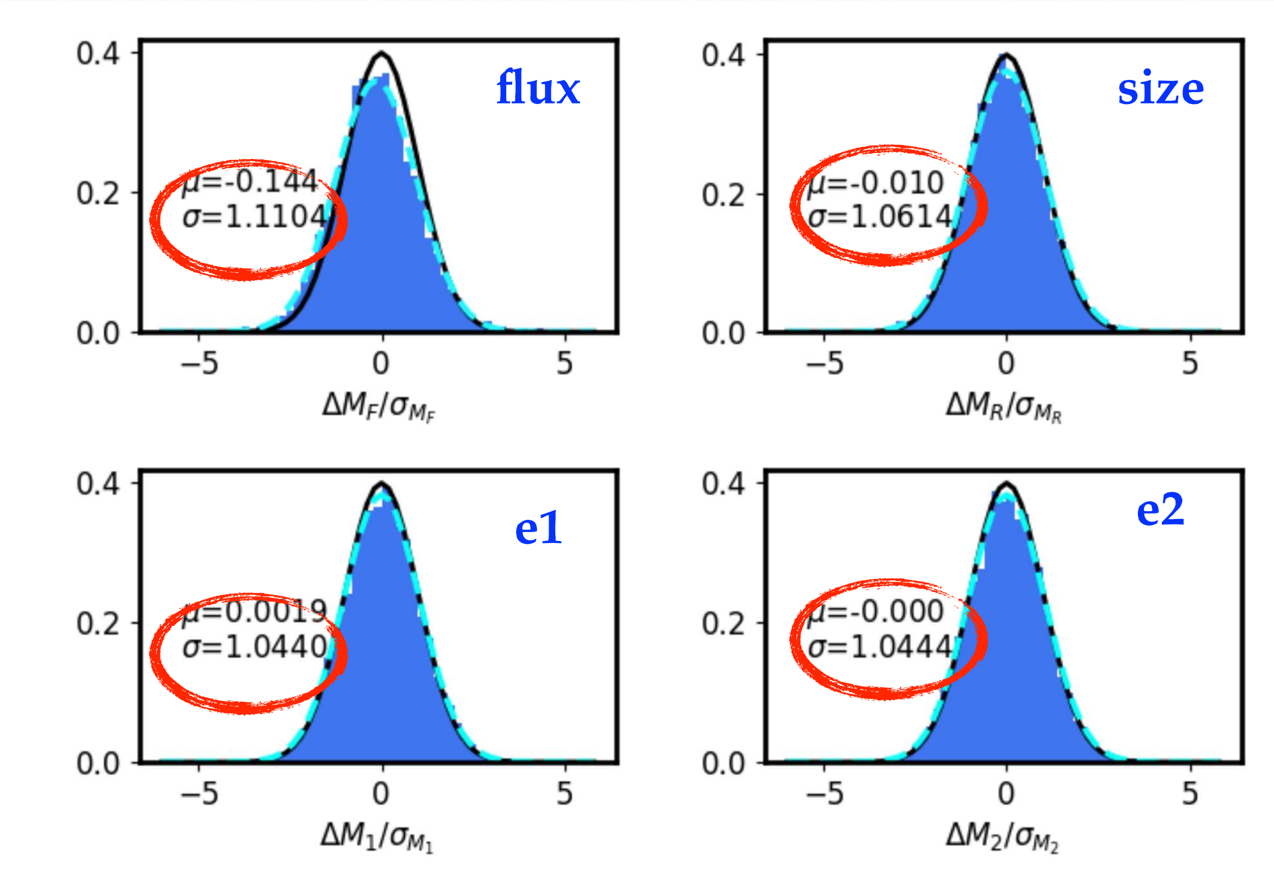


Significant bias in flux moments - sky over-subtraction! Improves when using a local sky annulus.

Undetected-source noise

- Cross-correlate distinct exposures of the same sky region, so all shot noise, sky noise, read noise cancels.

Pull distributions for i-band moments



Excess noise in all moments - what's it from?

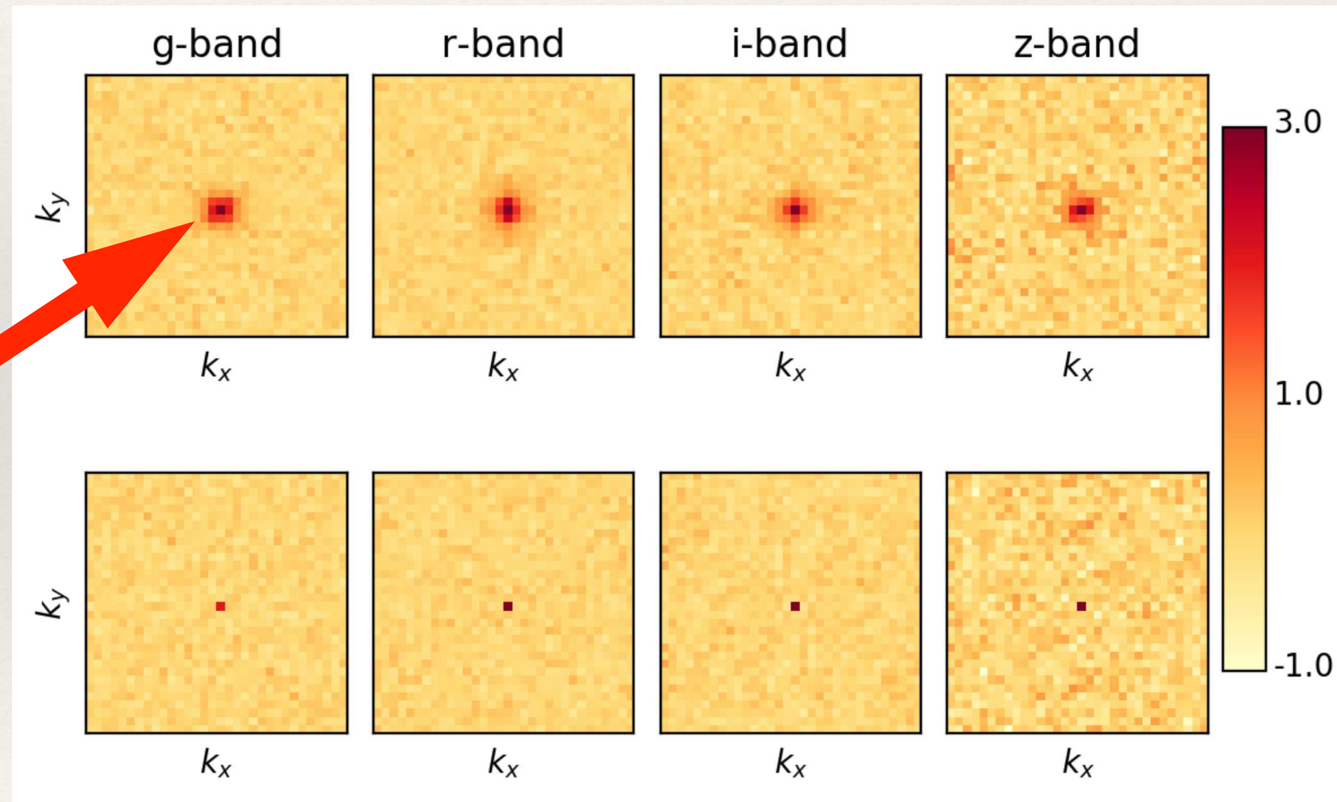
Undetected-source noise

- Cross-correlate distinct exposures of the same "blank"sky region, so all shot noise, sky noise, read noise cancels.

Registered on sky

US noise!

Scrambled on sky



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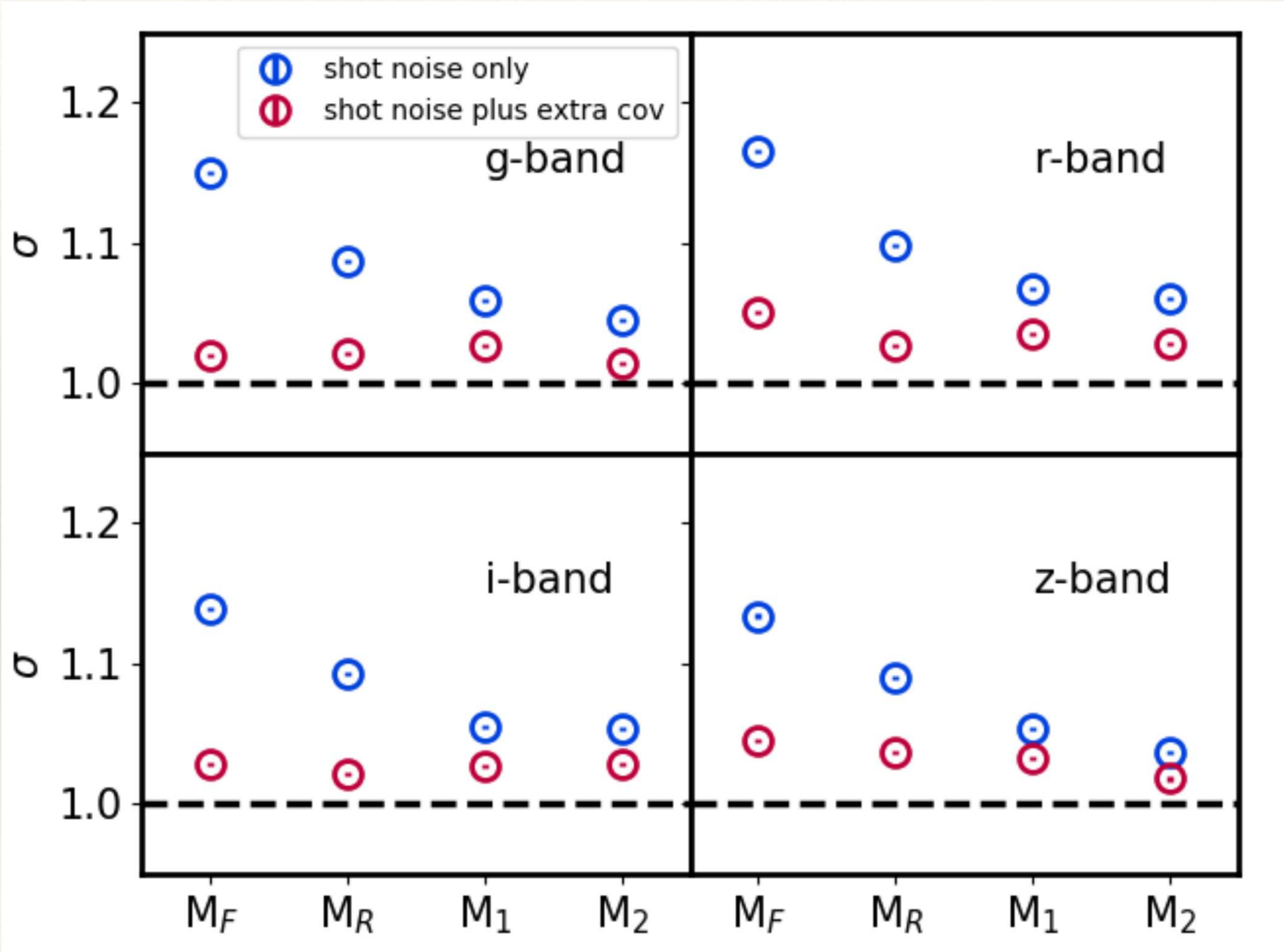
US noise estimation

From the blank-field cross-correlation we can calculate the amplitude of US noise and add it to Poisson noise and read noise. Now the variance of measurements is within 1-2% of what it should be (red points near 1.0 sigma pull).



Conclusions

- DES Astrometry/photometry calibration algorithms reduce systematic errors to ~2 mmag, 2 mas RMS. This is below shot noise for almost every unsaturated source.
- Algorithms are pretty straightforward modelling and chisquared minimization, carefully controlling DOF.
- Stochastic atmospheric effects dominate photometry and astrometry errors for bright objects. These can be reduced with "ubercal" (photometry) or GP interpolation (astrometry)
- Sky subtraction and noise need more attention at ~10% of sky noise level.
- All of this should be readily applicable to LSST, scaling in most cases as FOV x #exposures relative to DES. Field rotation is the main added complication.