On-sky Determination and Correction of Instrumental Signatures

G. Bernstein (UPenn)

18 November 2013

For the full DES collaboration

Analyses by D. Gruen, A. Bauer, R. Armstrong, P. Astier, N. Regnault, H. Lin, A. Plazas, D. James

Topics of interest

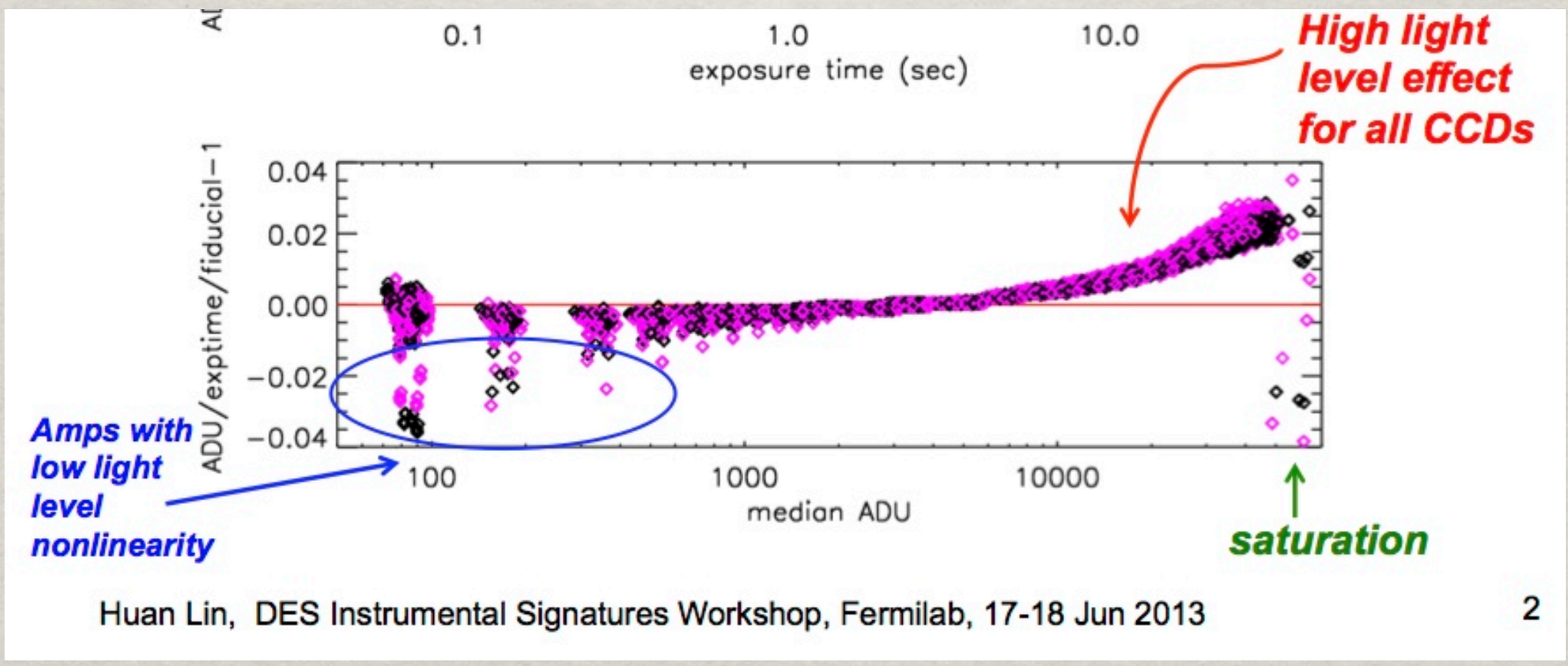
- Anomalies
  - High-light-level nonlinearity (HLLNL)
  - Low-light-level nonlinearity (LLLNL)
  - The Brighter-Fatter effect
- Precision photometry
  - The flat-field fallacies
  - Star flats and millimag photometry
  - Stability of instrument response and dome illumination
- Precision astrometry
- Sky and fringe subtraction
- Potential DES-LSST cooperative developments

Anomalies

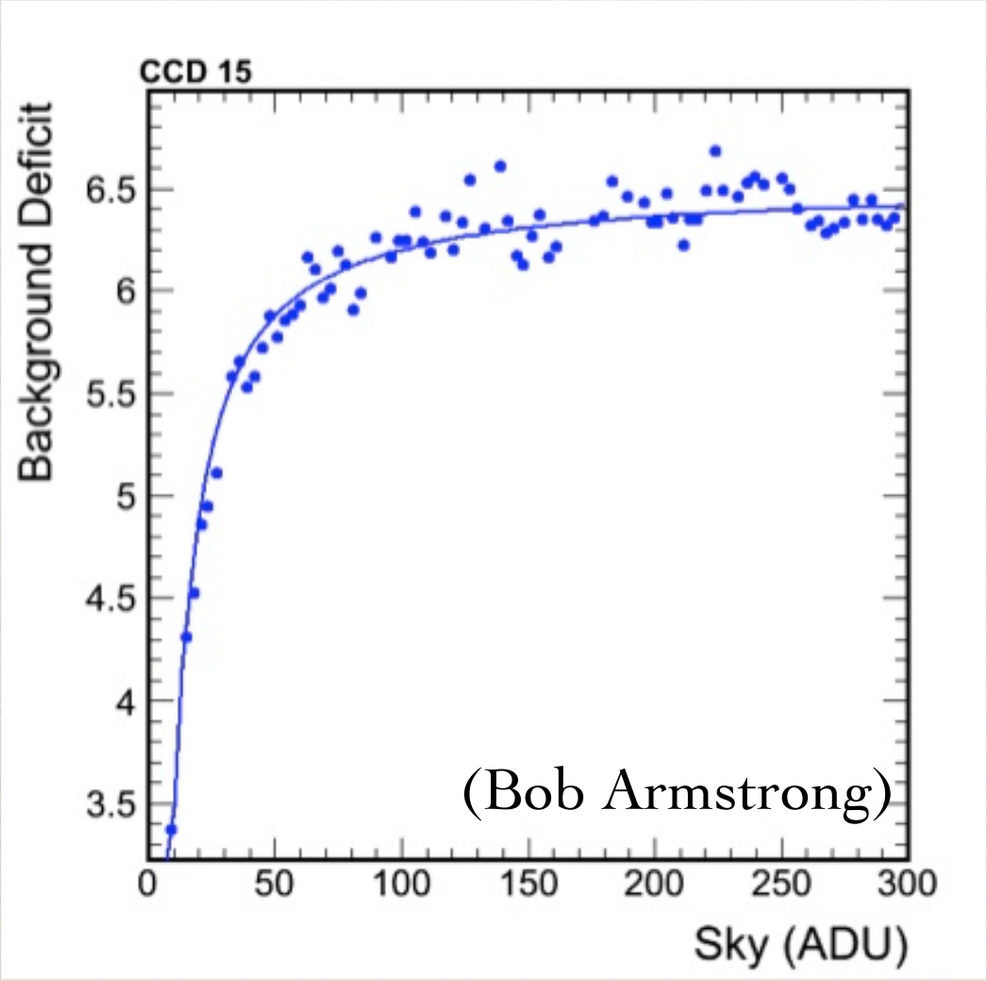
- First step of image reduction: create a value at each pixel proportional to the light incident on the pixel.
- Non-ideal behavior to correct:
  - Defects, traps (not discussed here)
  - Bias removal (not discussed here)
  - Signal-chain nonlinearities
  - “Brighter-fatter” relation: repulsion of photo-generated carriers

Signal-chain nonlinearity

- Data to collect:
  - "Photon Transfer Curve" (PTC) sequences of dome flats with varying exposure times.
  - "Linearity test": varying exposure times on rich stellar field

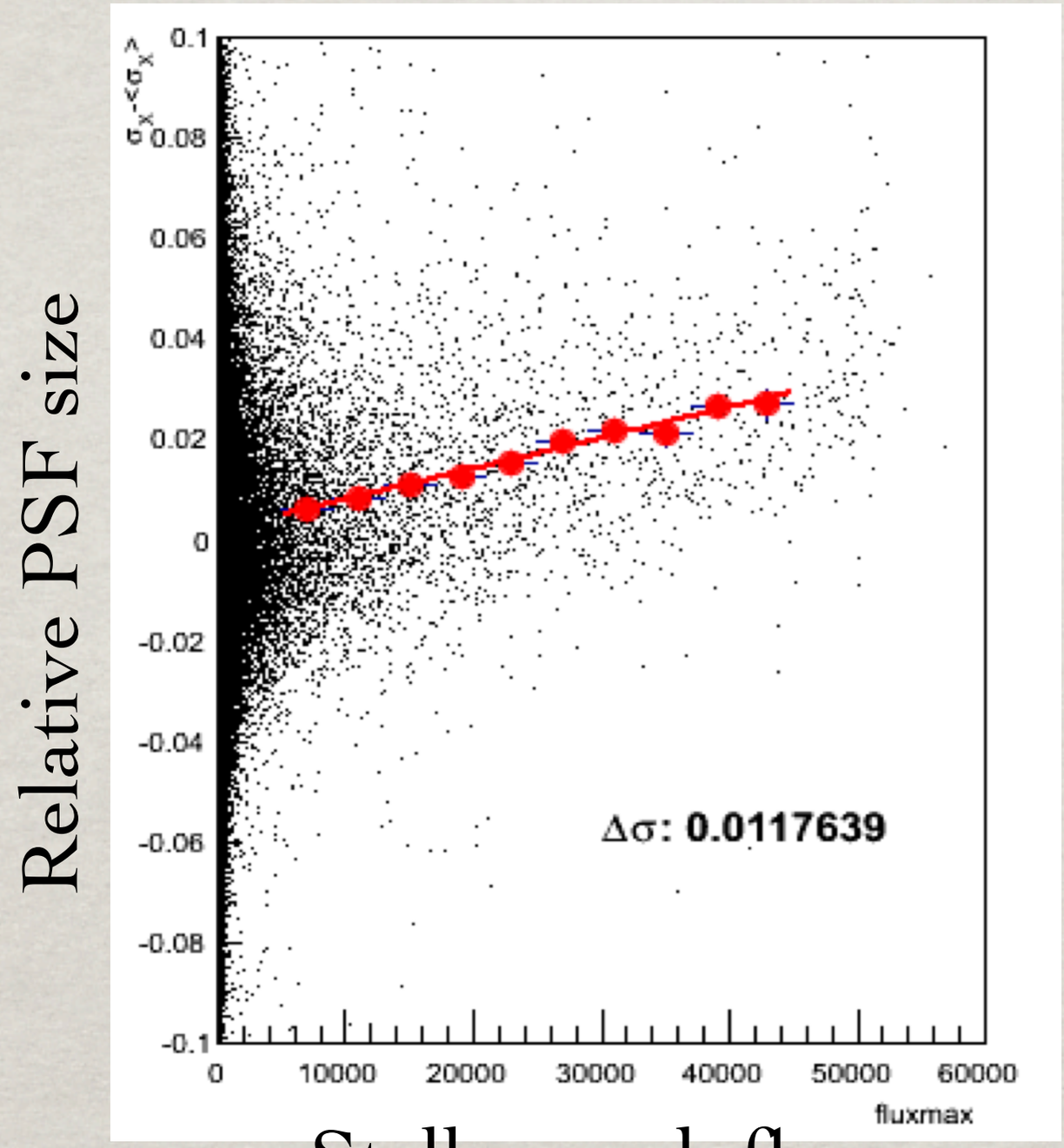


Low-light nonlinearity



- Manifests as a deficit of counts that saturates at ~100 ADU.
- Seen above 10*e* for about 10 amplifiers (out of 122).
- One amplifier has time-variable deficit and will be difficult to use for precision photometry.

The Brighter-Fatter (BF) relation



N. Regnault

- All CCDs show approx 0.5% larger PSF for bright stars than faint ones.

Charge-repulsion model for BF

- Antilogus et al., arXiv:1402.0725

$$\delta^X_{ij} = \sum_{kl} a^X_{k-i,l-j} \times q_{kl}$$

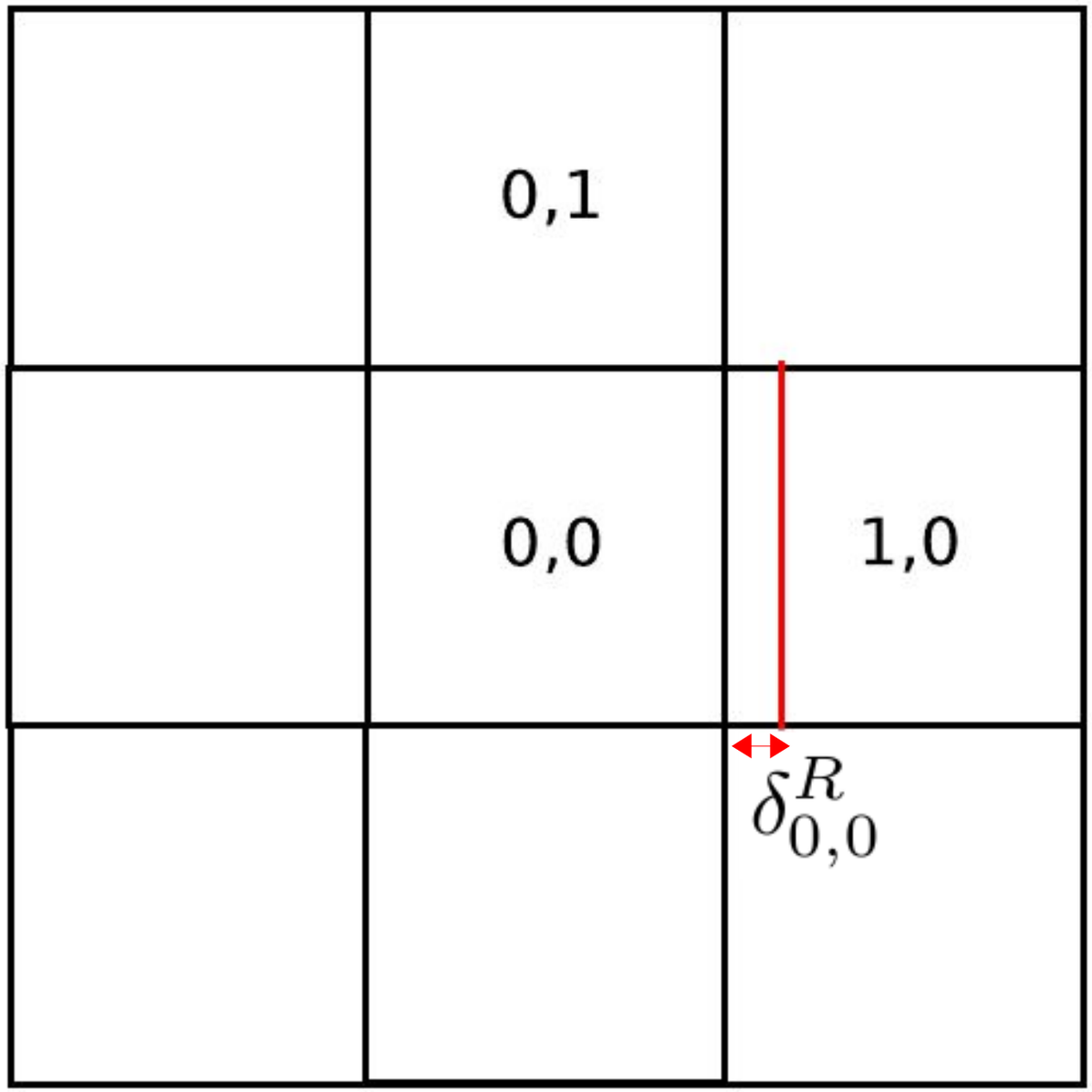
shift parameters

charge in pixel kl

- Change in flux:

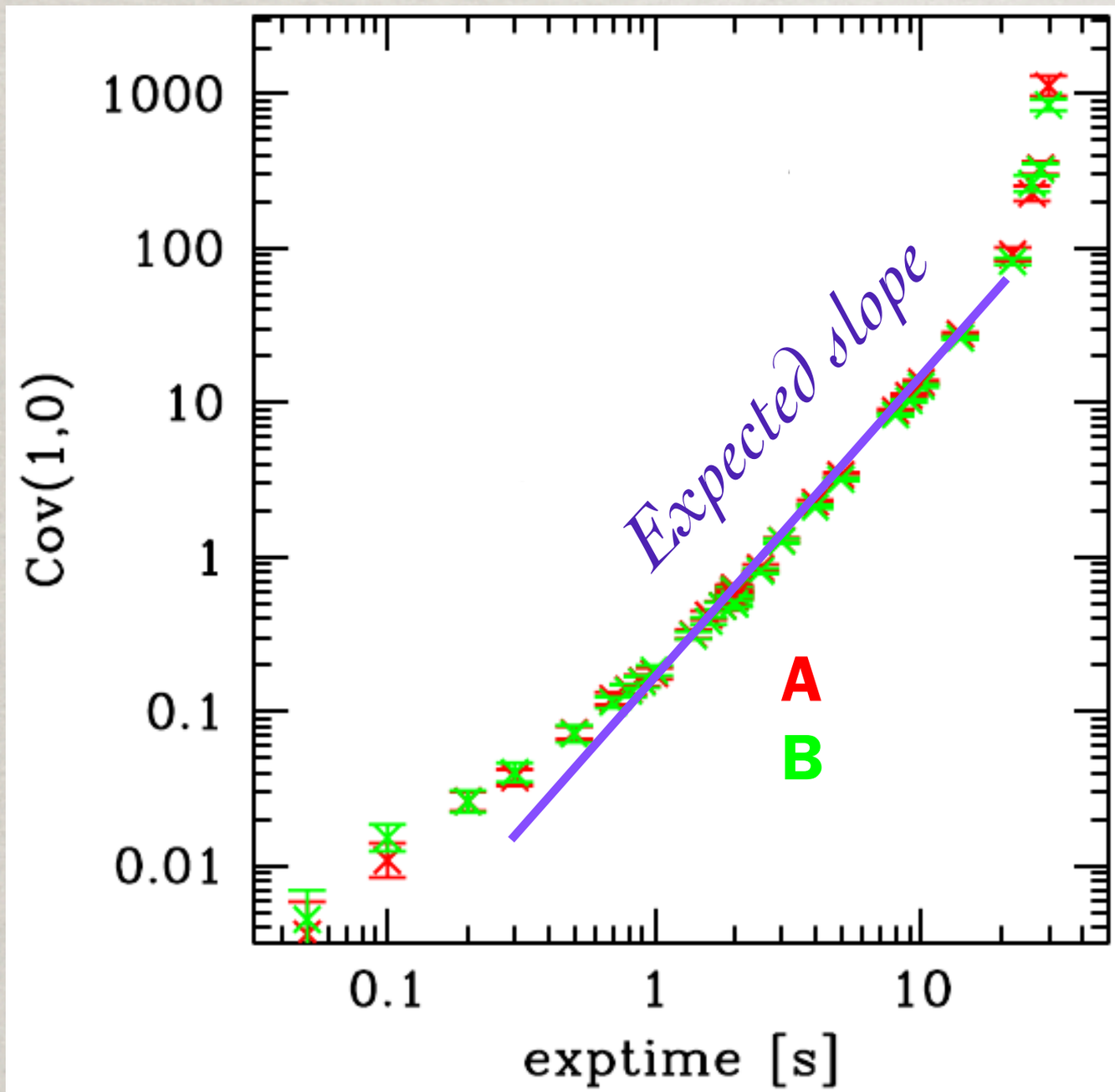
$$\delta^R_{0,0} \times \frac{q_{0,0} + q_{1,0}}{2}$$

(plus other sides)



(D. Gruen)

BF model predicts flux-dependent covariance between pixels on flat fields



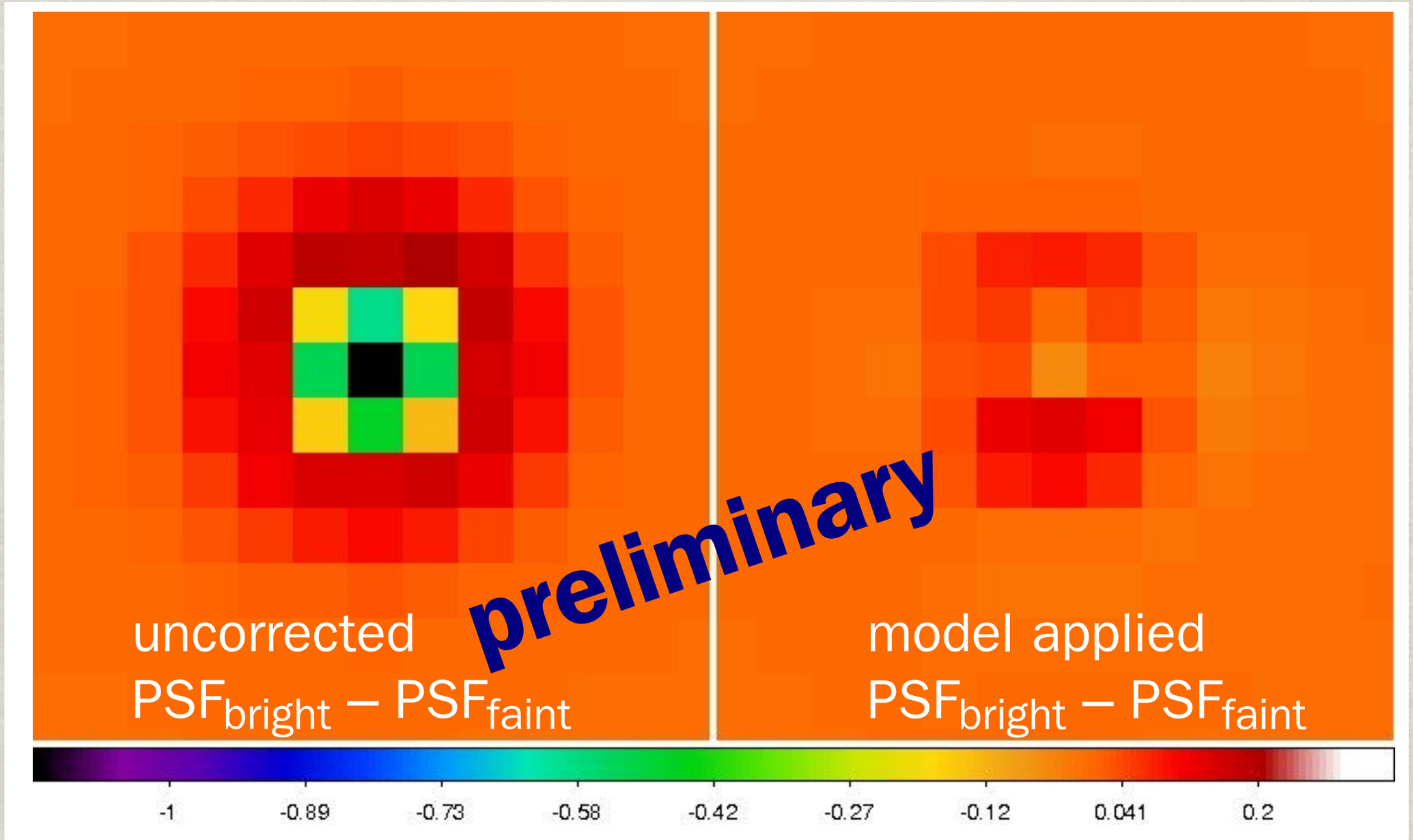
Model predicts:

$$\mathrm{cov}(Q_{00}, Q_{ij}) = 2V\mu \sum_{X=T,B,L,R} a_{ij}^{X}$$

flux^2 dependence

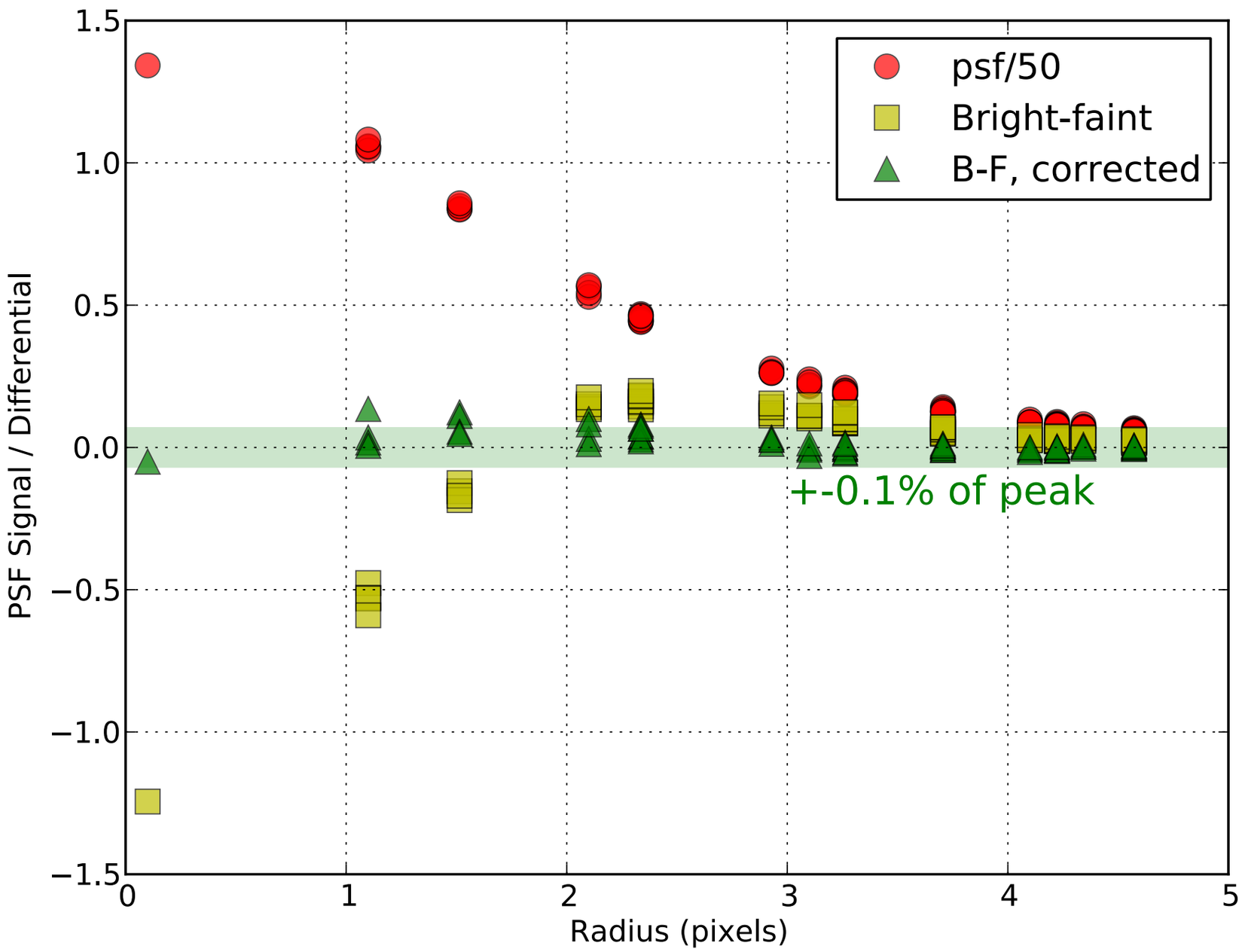
(D. Gruen)

Fit the border-shift coefficients to the pixel covariance data. Then apply reverse shifts to sky images.

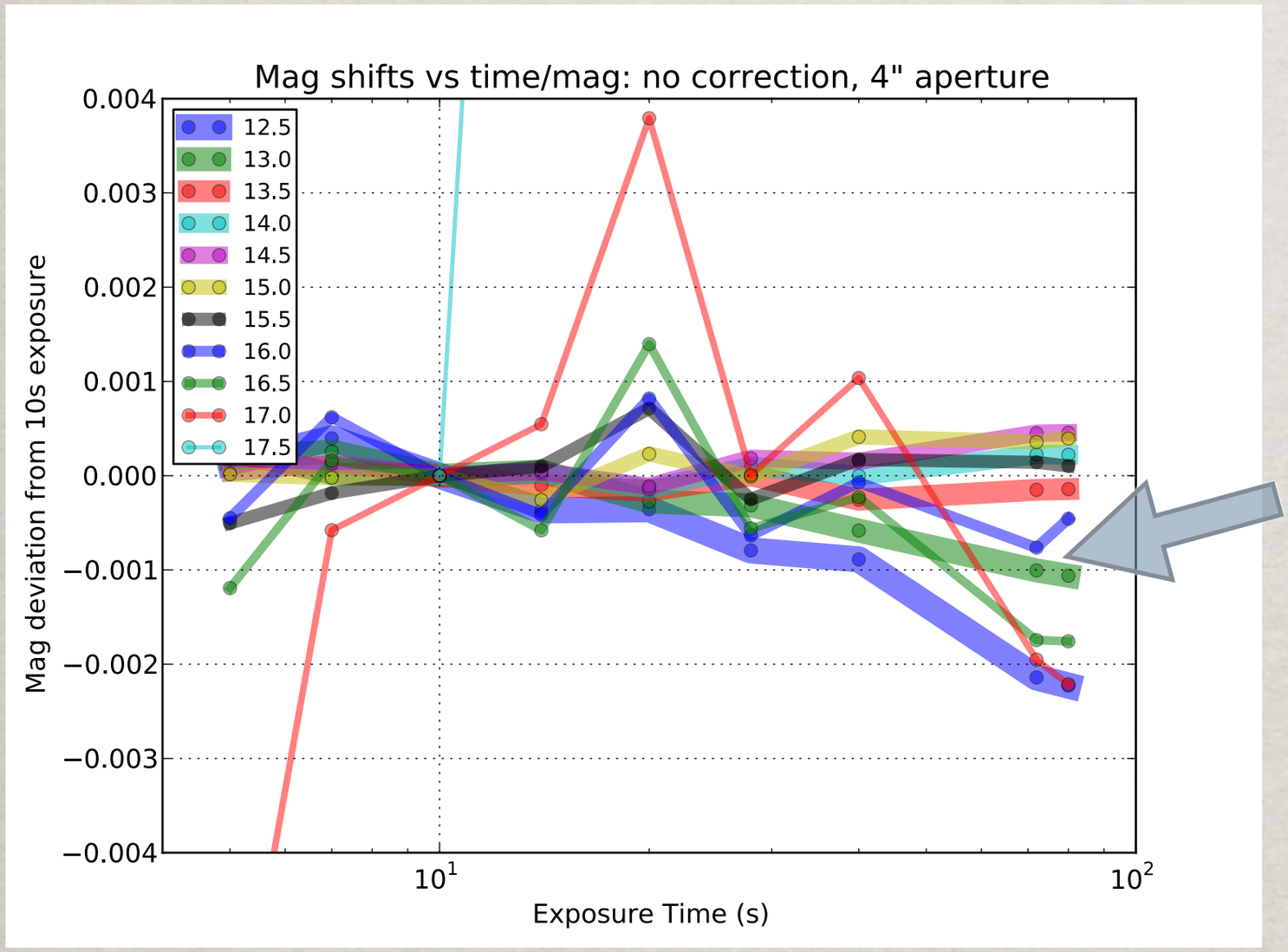


(D. Gruen)

Very first attempt at applying the anti-Antilogus correction reduces the B-F effect in stellar images by 90% !



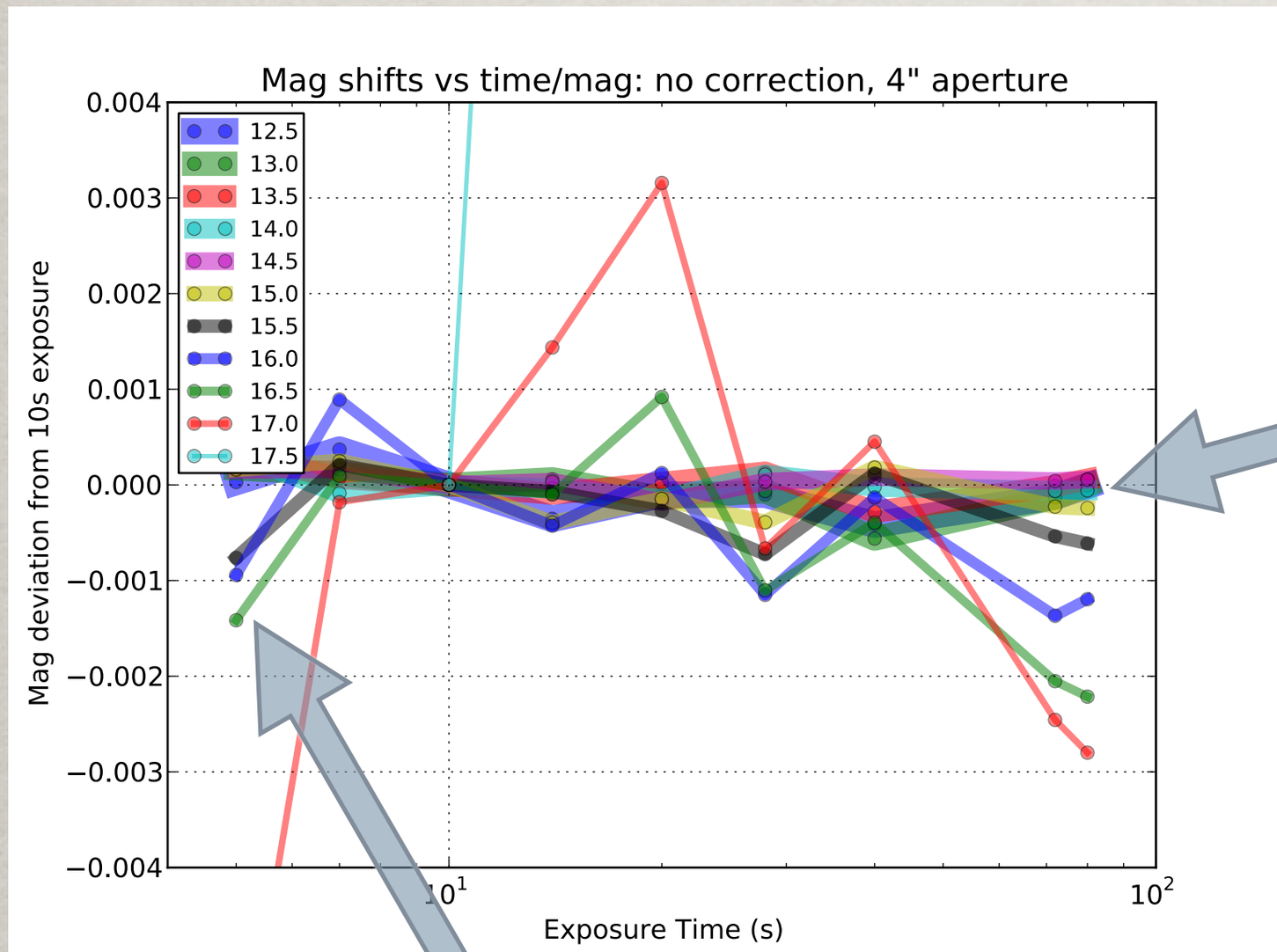
Nonlinearity and BF both change PSF centers of bright stars. But BF only rearranges charge, does not change total counts. Use stellar exposures of varying lengths to distinguish them.



Fan-out of residuals for bright-star mags vs exposure time is signature of non-linearity.

0.003 mag errors in ~1e5 ADU fluxes.

The nonlinearity correction eliminates flux-dependent residuals for bright stars



Agreement! >10x better?

Any issues at low ADU?

Flat-field fallacies

$$Raw_i = (I_i + I_{\mathrm{bg}}) * r_i$$

$$Flat_i = kr_i$$

$$\Rightarrow flux \propto \sum I_i = \sum \left(\frac{Raw_i}{Flat_i} - bg \right)$$

Real flat fields

$$Raw = \Omega \left[I_\star r + \overline{I}_{\rm bg}(r+s) \right]$$

$$Dome = k\Omega(r' + s')$$

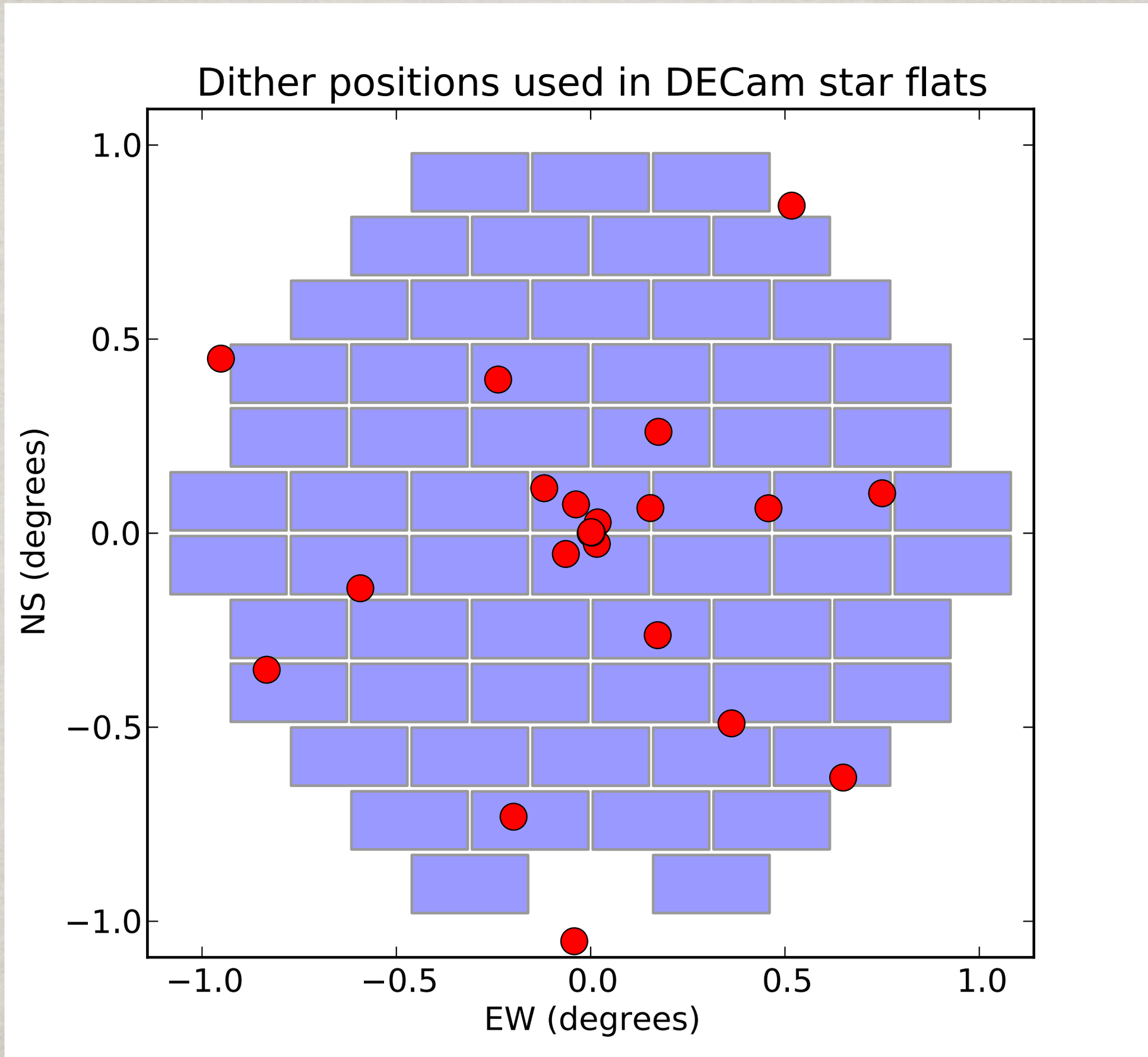
- r = response of array to **focussed** light
- s = **scattered** or stray light, *i.e.* reflection off CCD and filter.
- Ω= sky area per pixel **varies from pixel to pixel**.
- Color differences may mean r',s' for flat, even night sky, can **differ** from r,s.
- Ignoring the color difference, aperture photometry requires

$$flux = \sum_{\rm pixels} \Omega I_\star = \sum_{\rm pixels} \left(\frac{Raw}{Dome} - \overline{I}_{\rm bg}/k \right) \times \frac{\Omega(r+s)}{r}$$

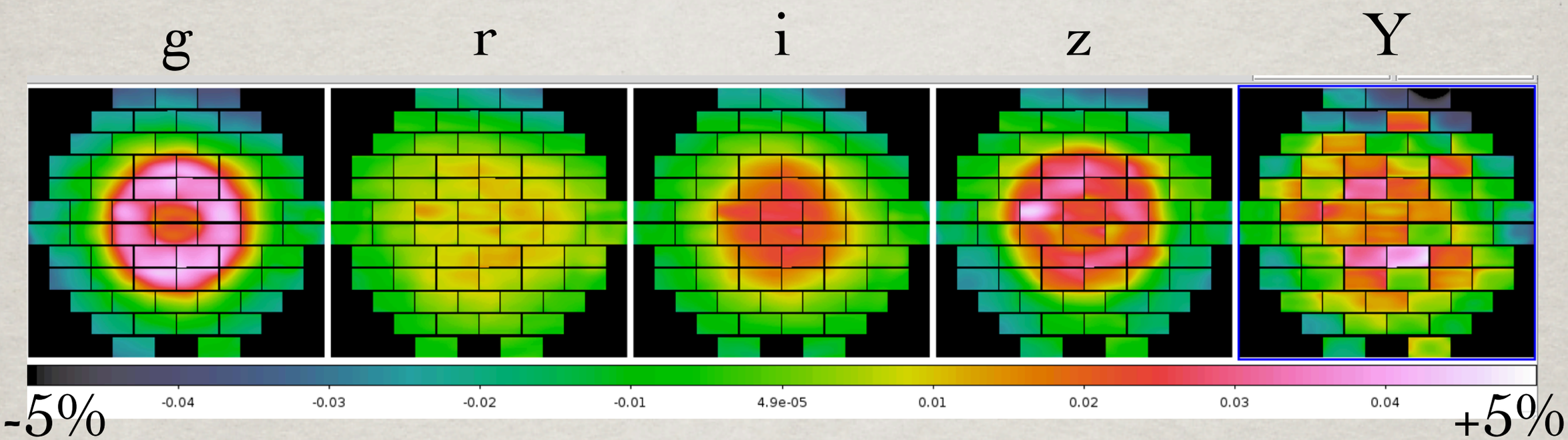
$$StarFlat = \frac{\Omega(r+s)}{r}$$

Precision relative photometry

- For each pixel, we need to know:
  - Pixel area Ω
  - Focused-light response *r*
  - Scattered-light pattern *s*
  - *(color response, both focused and scattered)*
- Acquire multiple calibration images
  - Dome (or other) flats
  - Pixel-area map - from astrometric solutions
  - Focused-light response, from *star flats*
  - *(narrow-band flat field data+???)*


Dither positions used in DECam star flats
1.0
0.5
0.0
−0.5
−1.0
NS (degrees)
−1.0
−0.5
0.0
0.5
1.0
EW (degrees)

Star flats: large scale features



★Stray light is up to 10% of photons in a pixel from diffuse (dome) source.
★Agreement on pattern from 4 codes (Bauer, Bernstein, Regnault, Kent)
★Roughly as expected from Steve Kent optical models, but strongest at filter edges.

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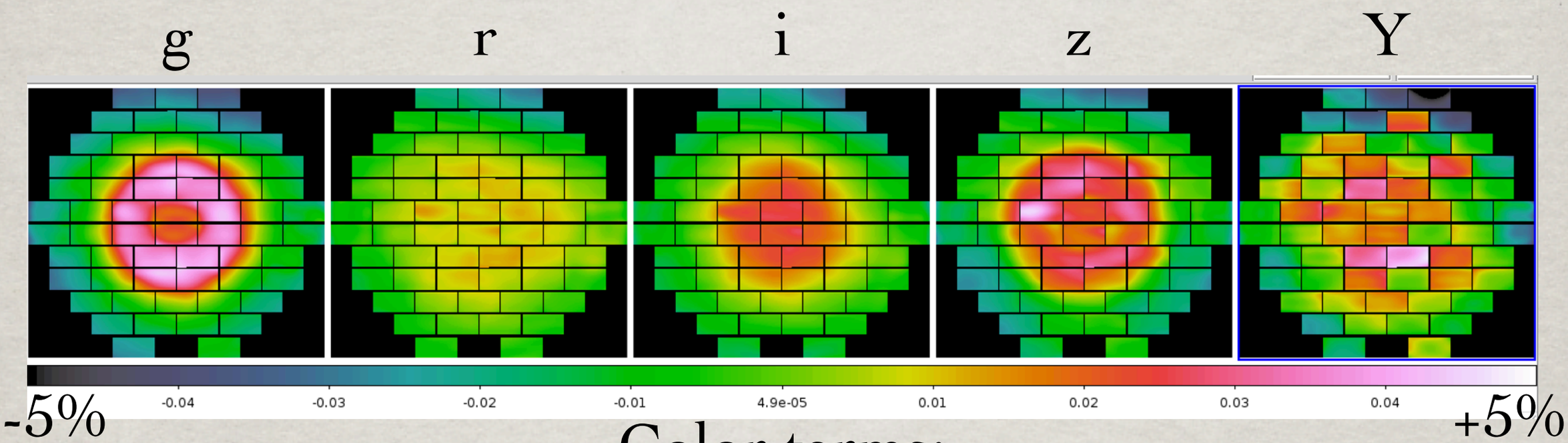

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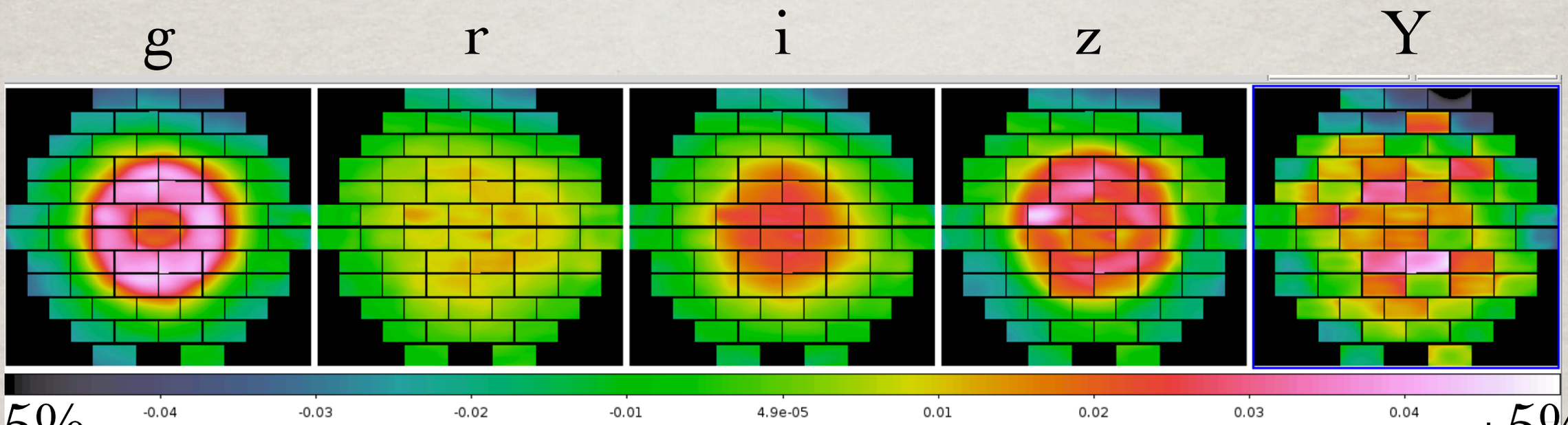
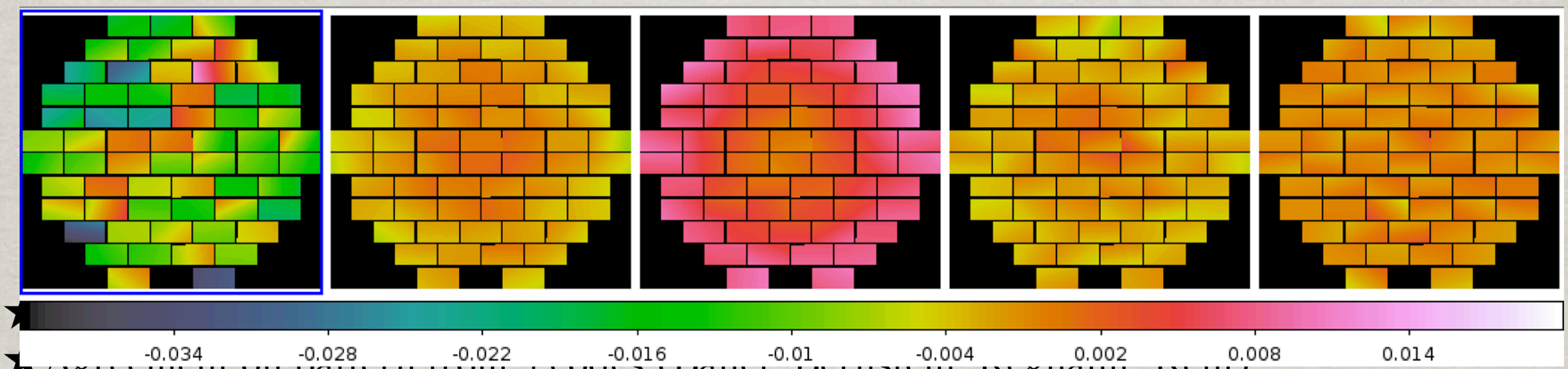


-5% +5%

Color terms:



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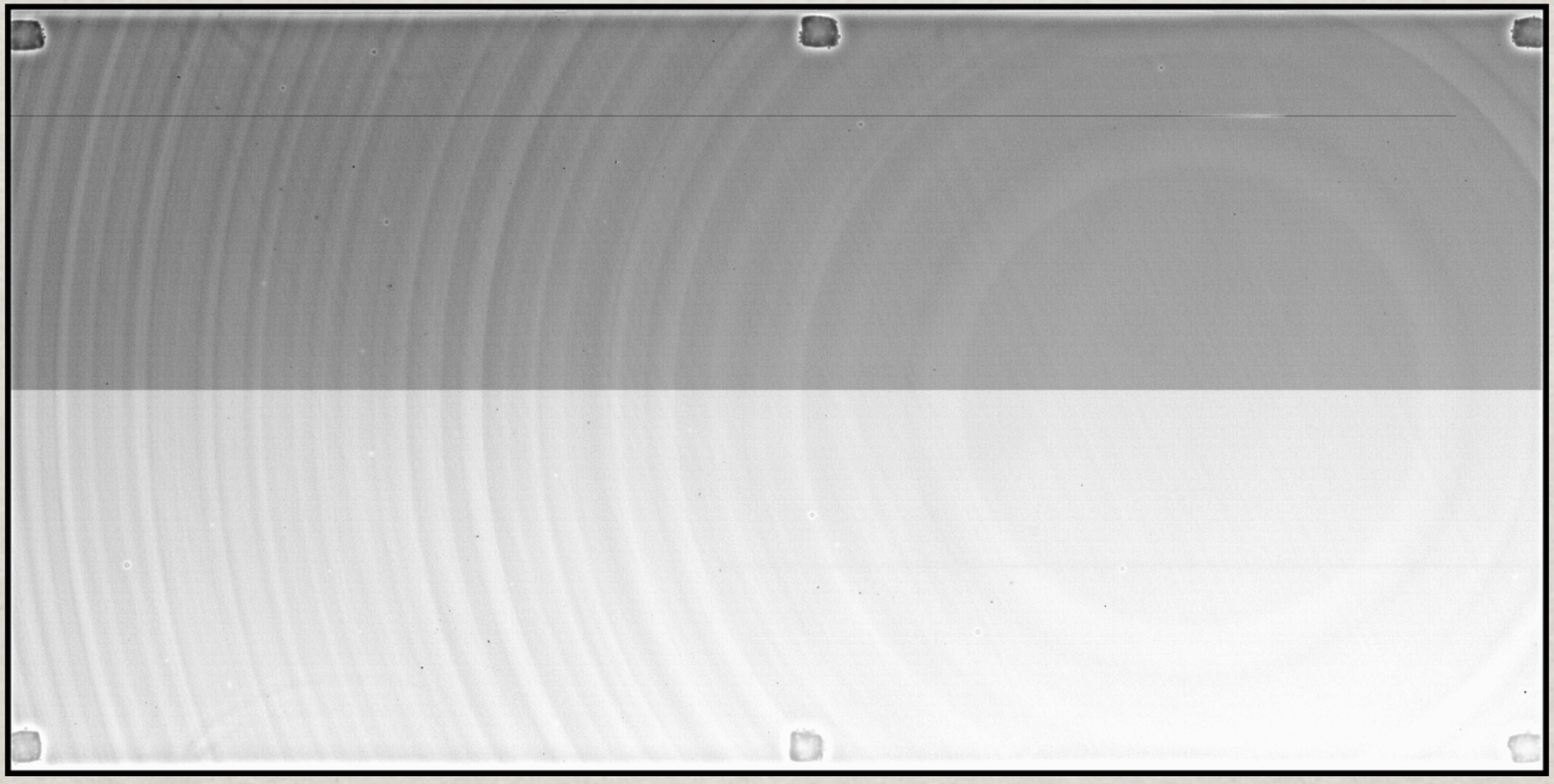
Most of the visible structure in dome flats is **pixel size variation**!



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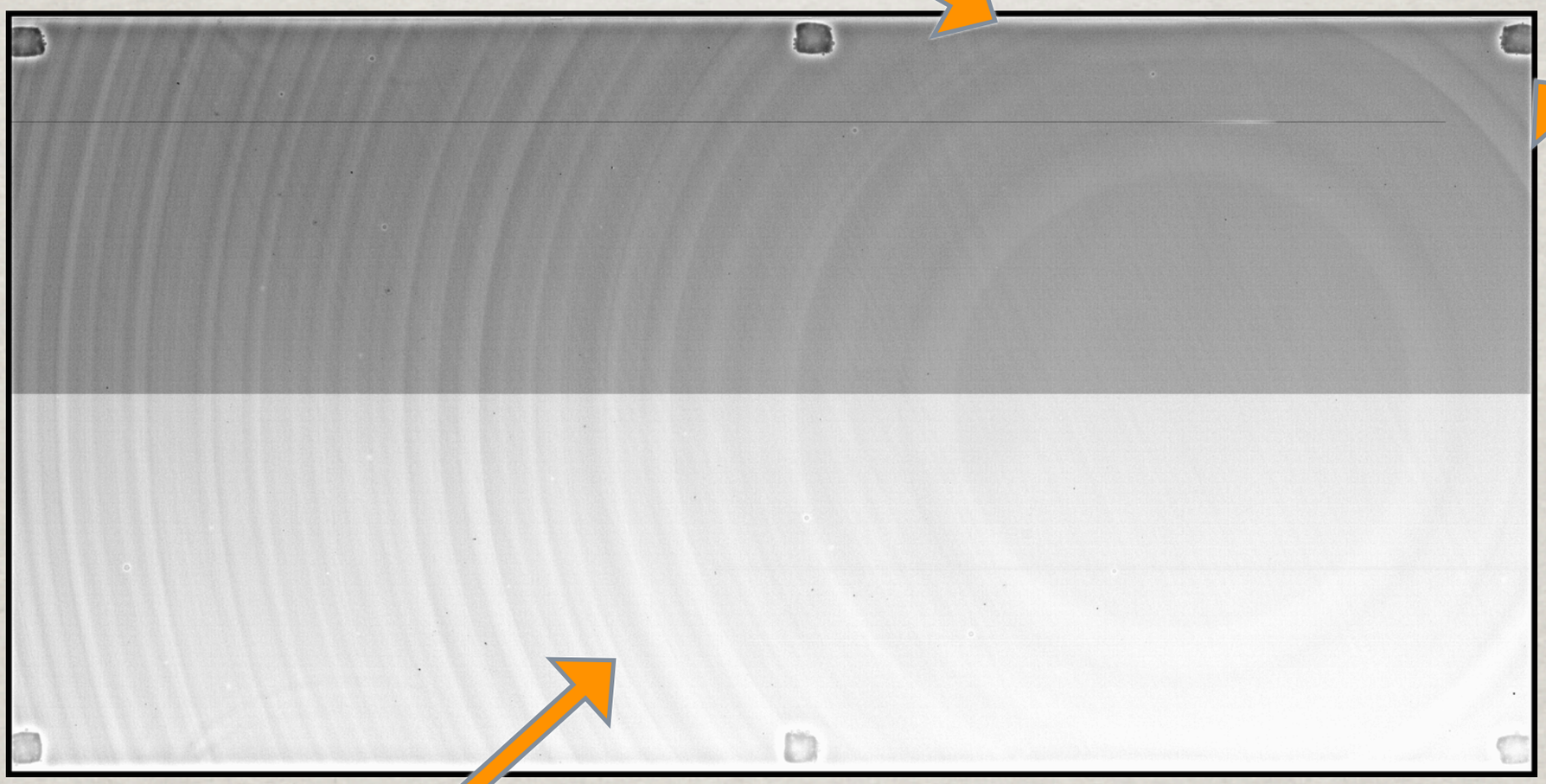

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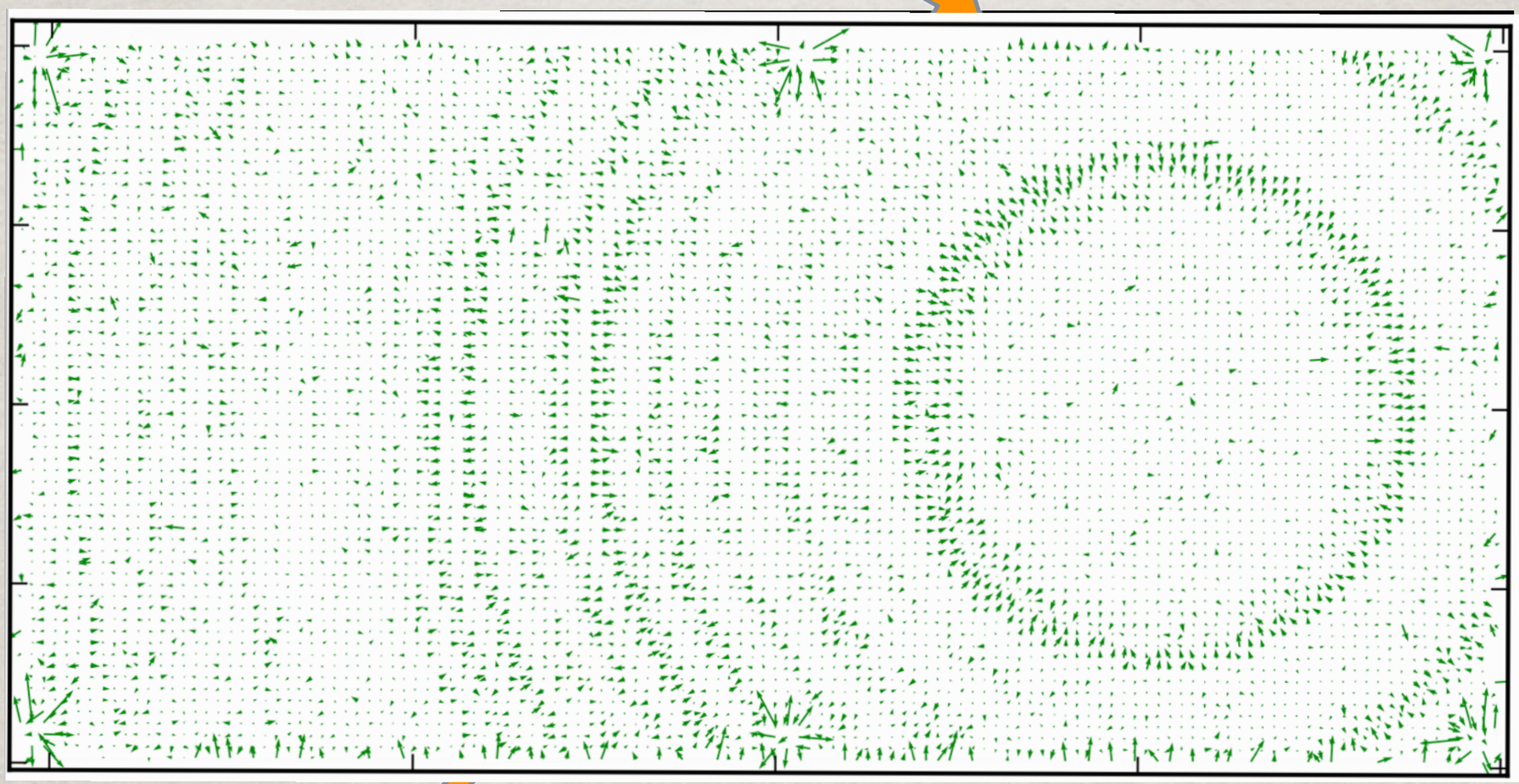
Glowing edges



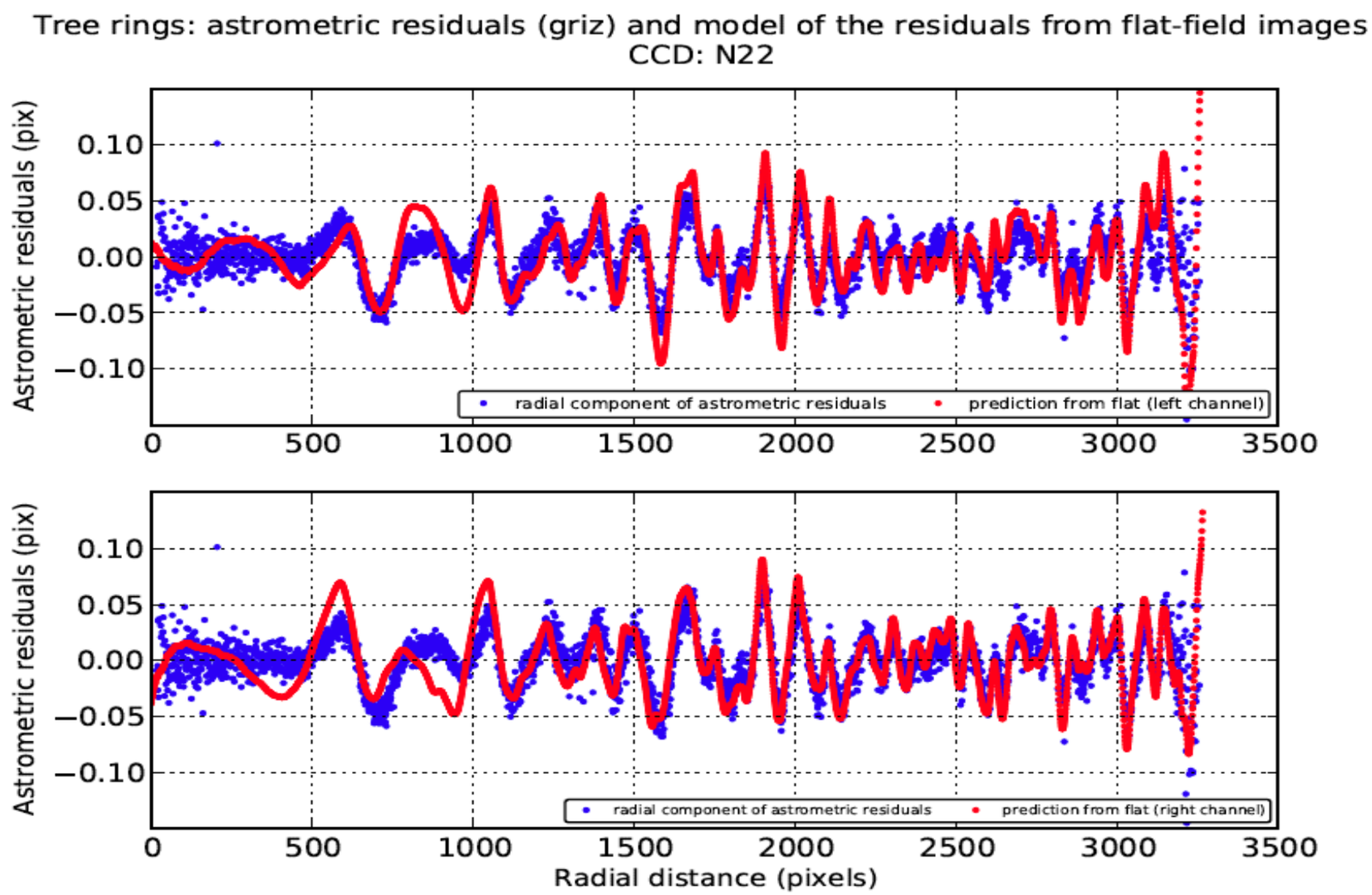
Tape bumps

Tree rings

Astrometric residuals: A. Plazas

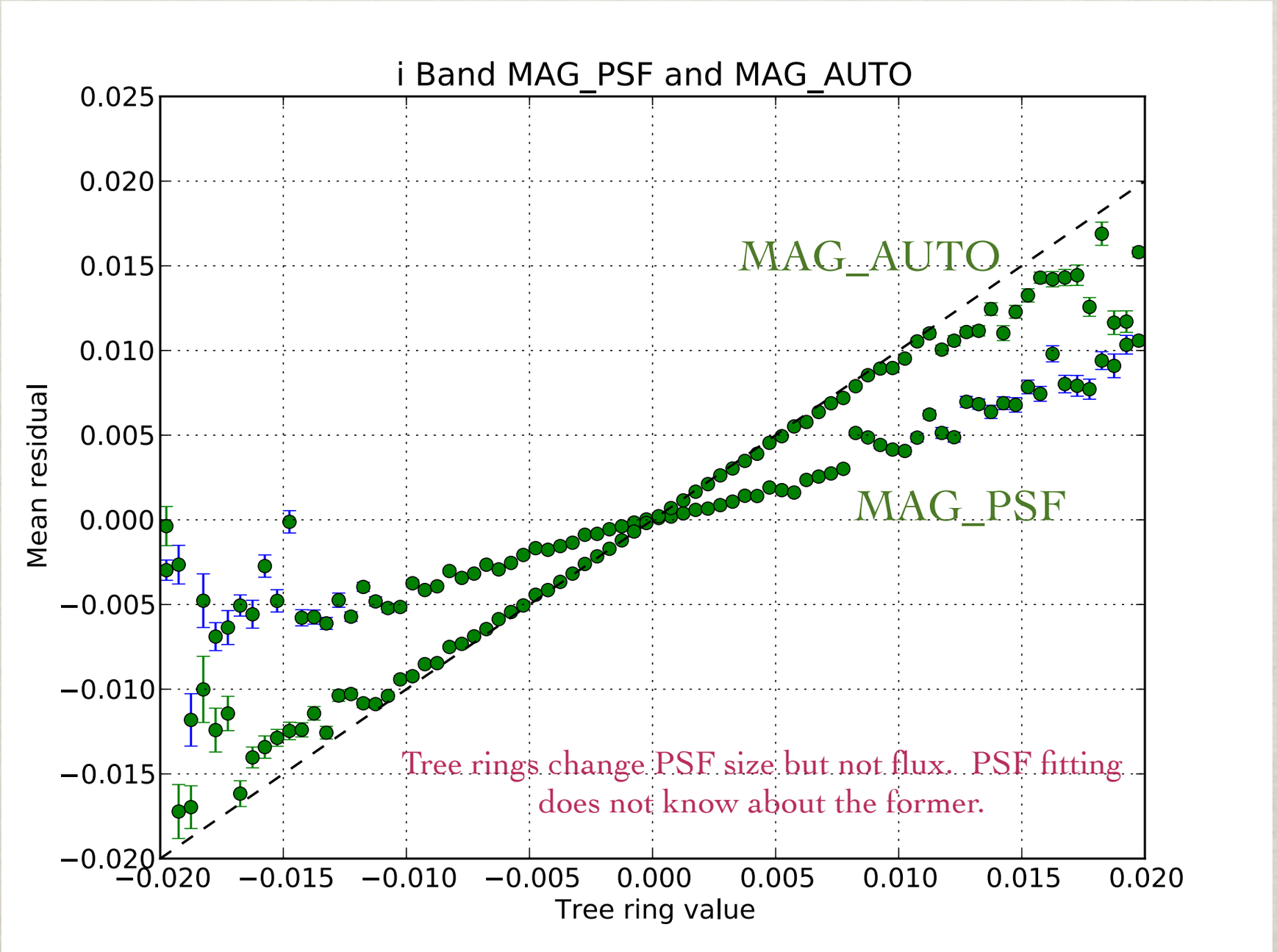
Rings in dome flats nearly perfectly predict annular astrometric displacements

...and then we can compare the prediction to the measurements:



From A. Plazas

Binning residuals vs tree ring value shows that tree rings should be removed from *r* flats



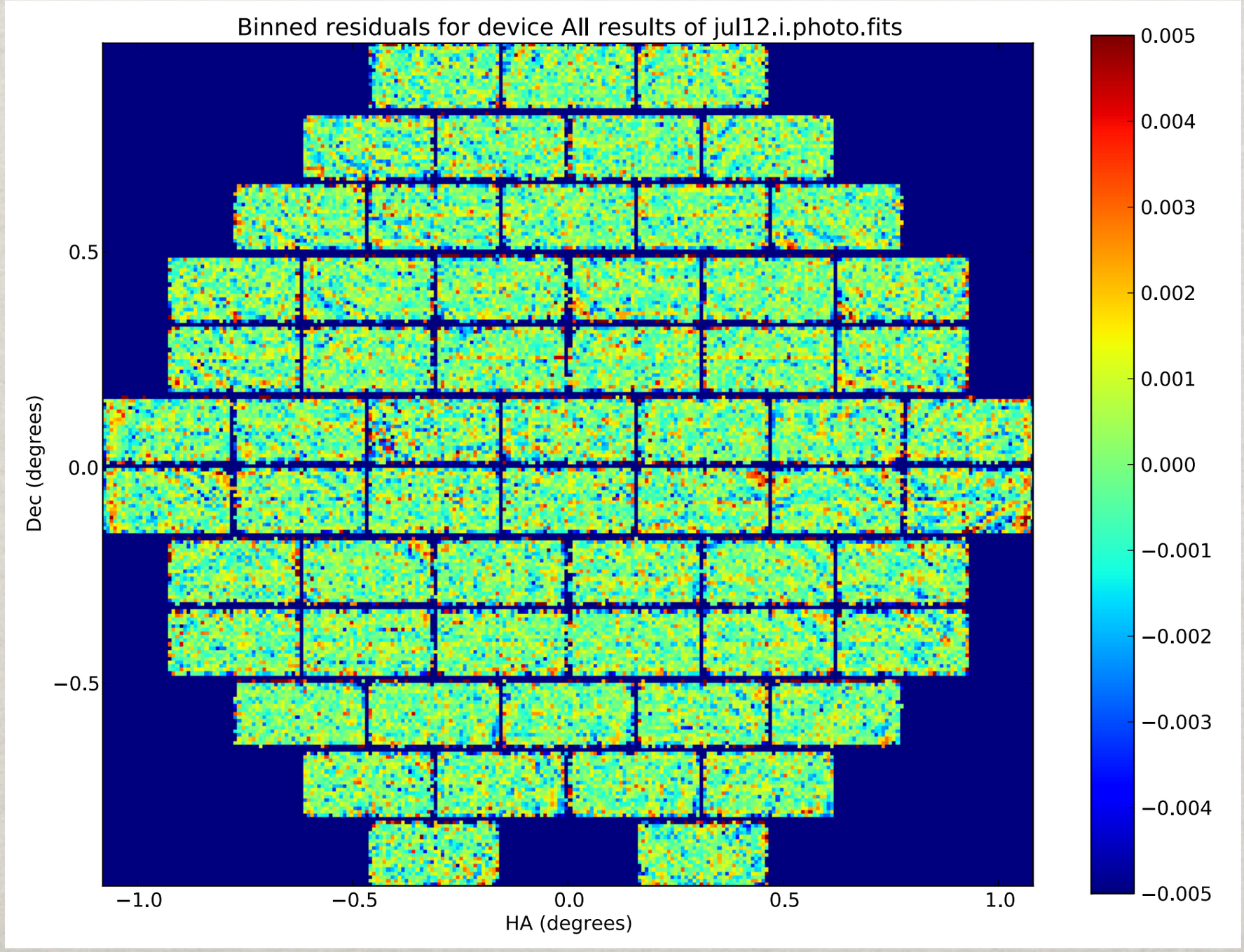
Photometric response model allows removal of small-scale rings, edge structures from the flat field.

$$ADU = brightness \times Dome \times Instrument \times Exposure$$

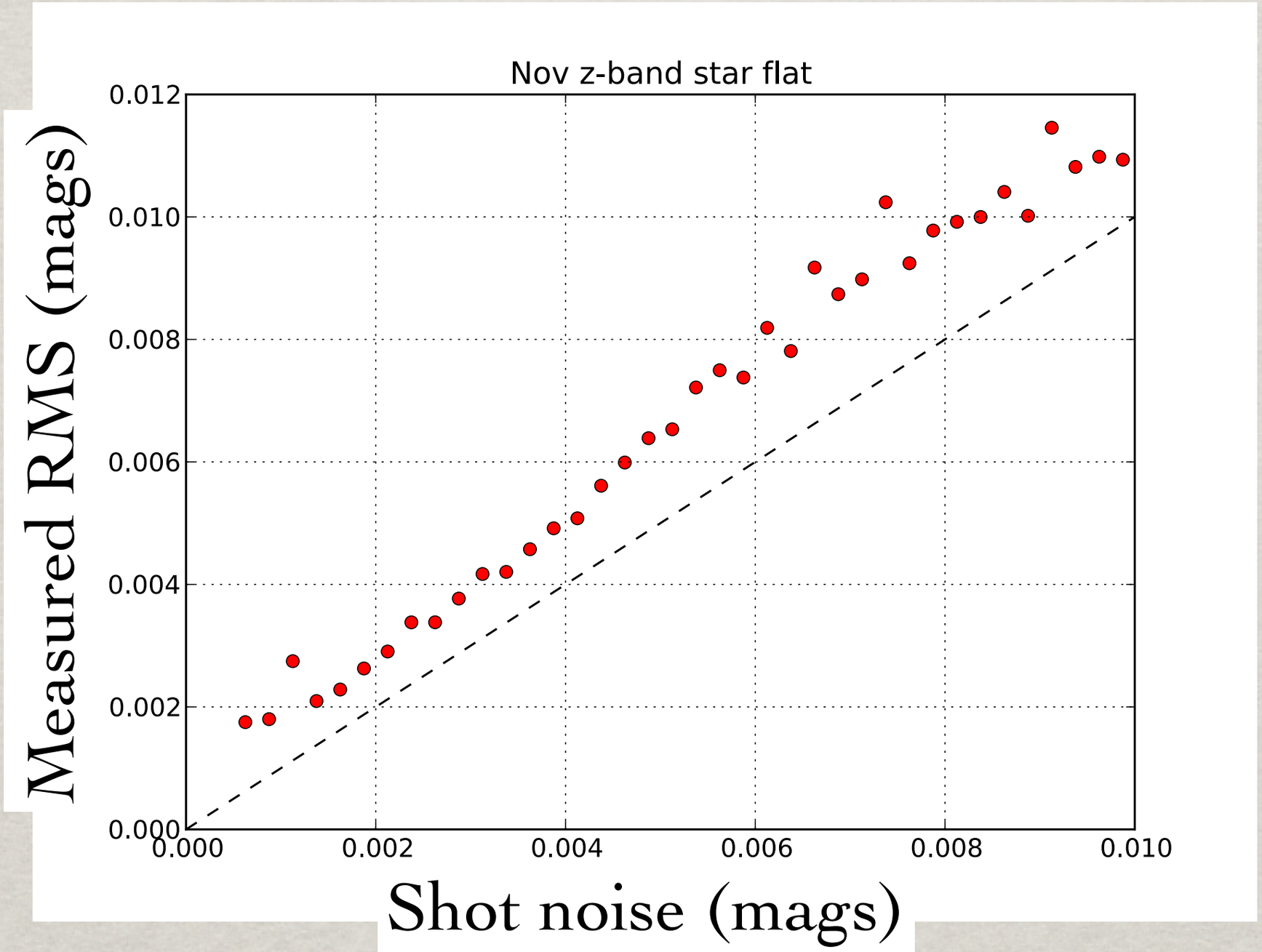
$$Exposure = Const(exposure)$$

$$\begin{aligned} Instrument = {} & Poly_4(x_{\mathrm{pix}}, y_{\mathrm{pix}}) \\ & \times Poly_1(x_{\mathrm{pix}}, y_{\mathrm{pix}}, color) \\ & \times k_1 \cdot Edge(x_{\mathrm{pix}}, y_{\mathrm{pix}}) \\ & \times k_2 \cdot Rings(x_{\mathrm{pix}}, y_{\mathrm{pix}}) \end{aligned}$$

No discernible patterns of residuals across focal plane.

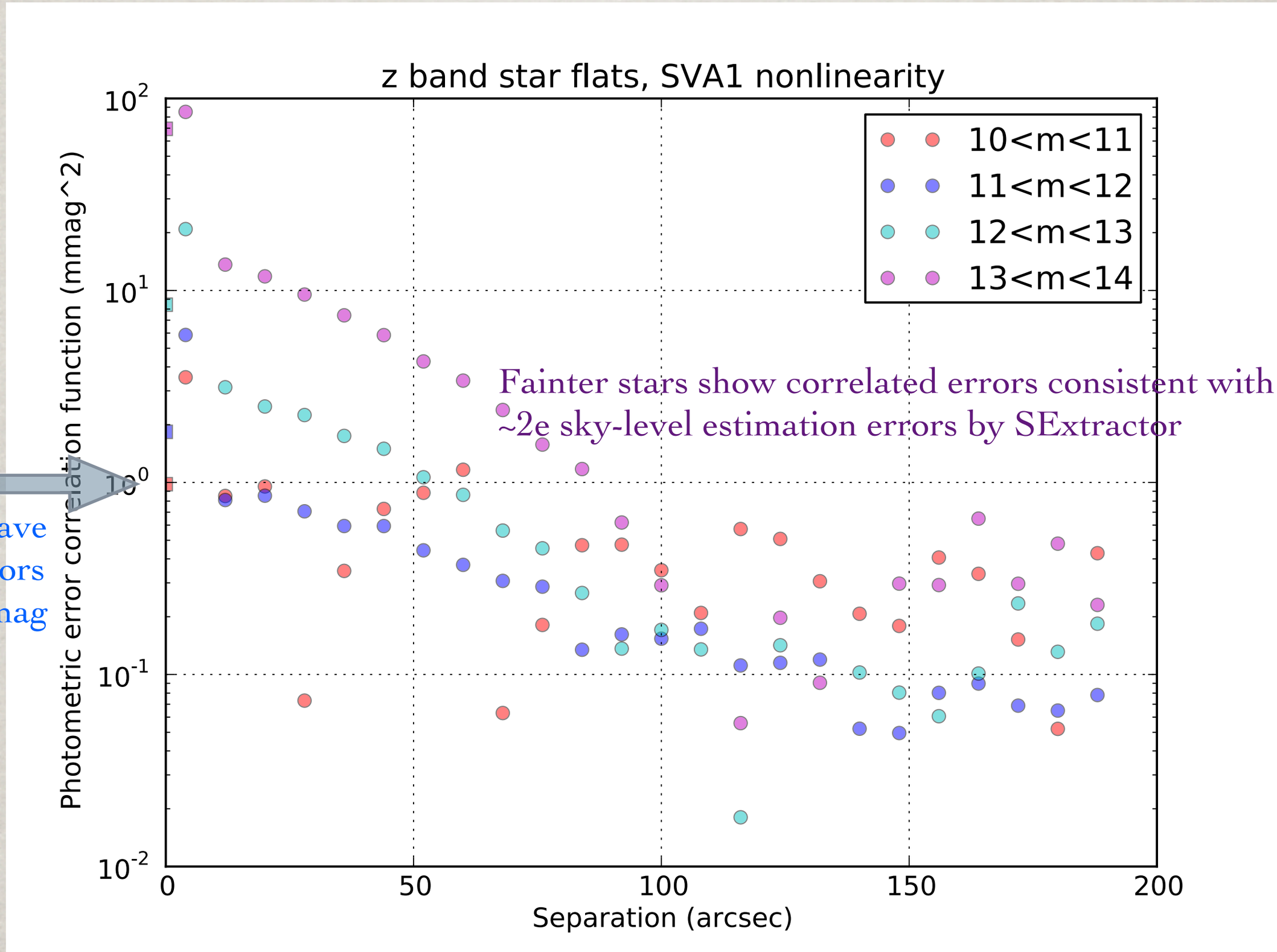


Photometric repeatability using full photometric model is close to shot noise.



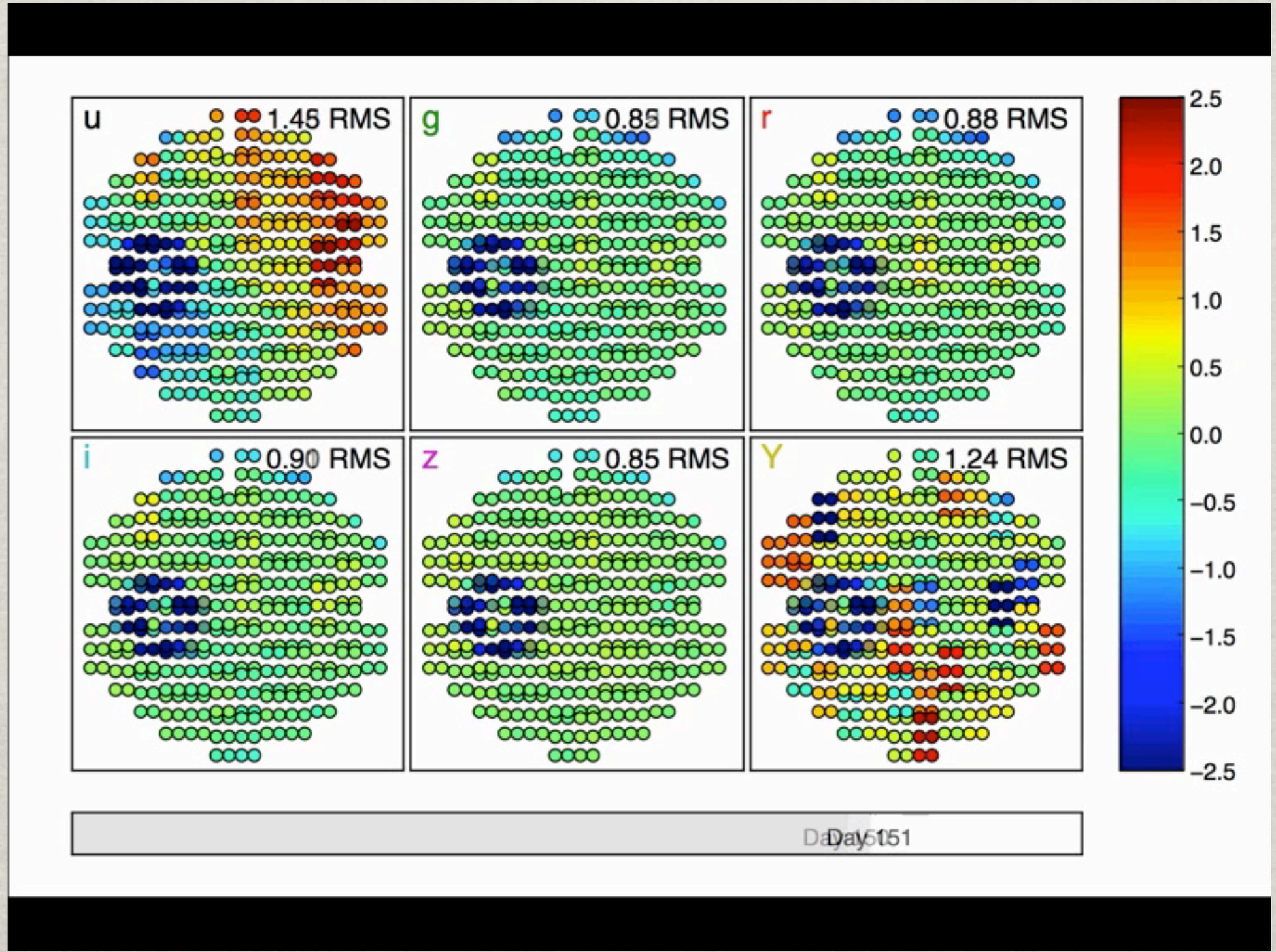
Consistent with (shot noise) + (1.5 mmag RMS) + (fixed-ADU noise)

Correlated photometric errors are <1 mmag

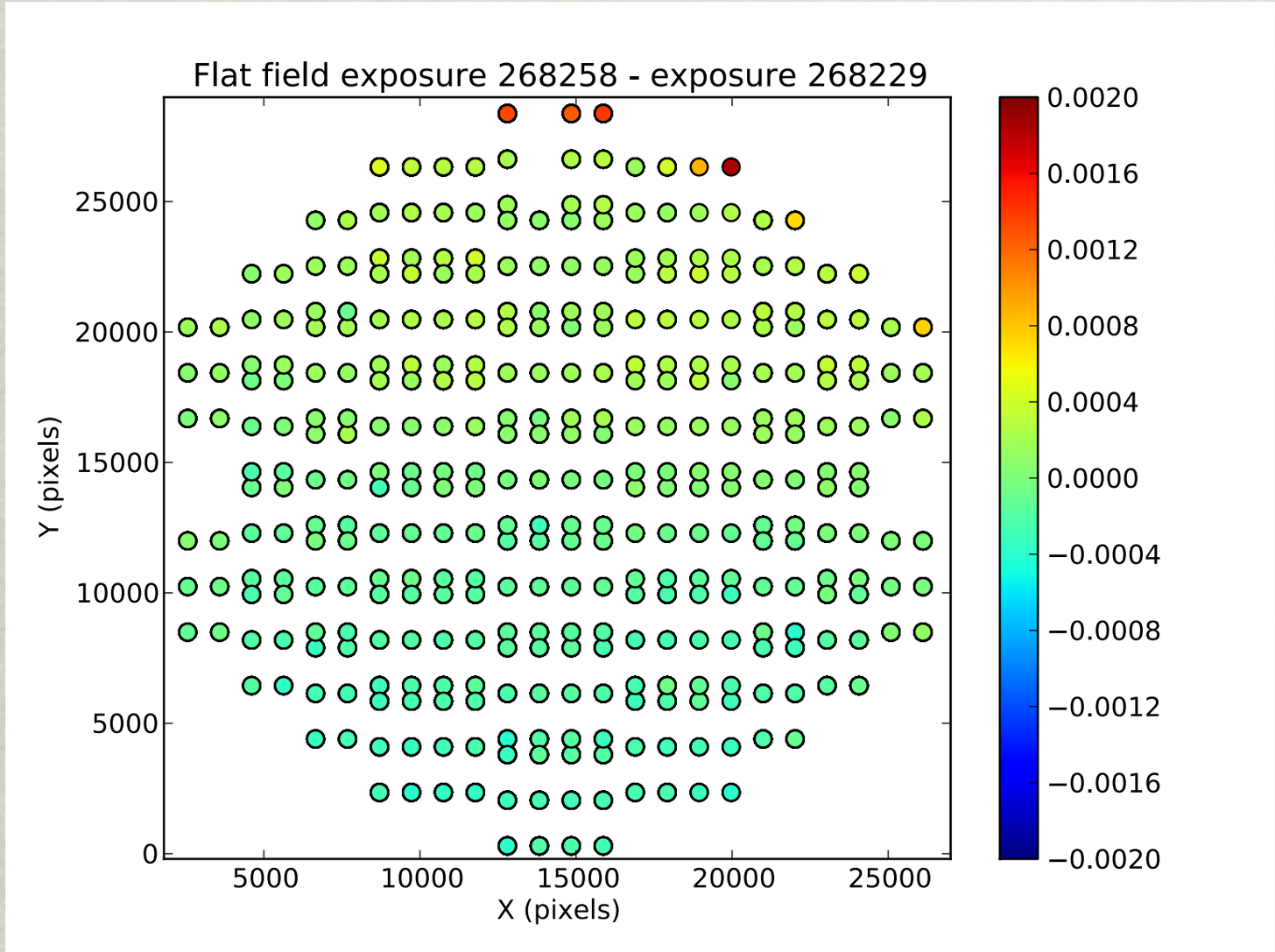


Bright stars have correlated errors <1 mmag

Dome flats vary by 3 mmag over weeks, percent changes at "incidents"



Dome flats are sensitive to alignment at 1-2 mmag level



Tests by D. James, photo & shoes by Phil Rooney

Camera response to **stars** (not dome) stable to 1-2 mmag over season, more between seasons?

Nov12/Dec12 Feb13/Dec12 Sep13/Dec12

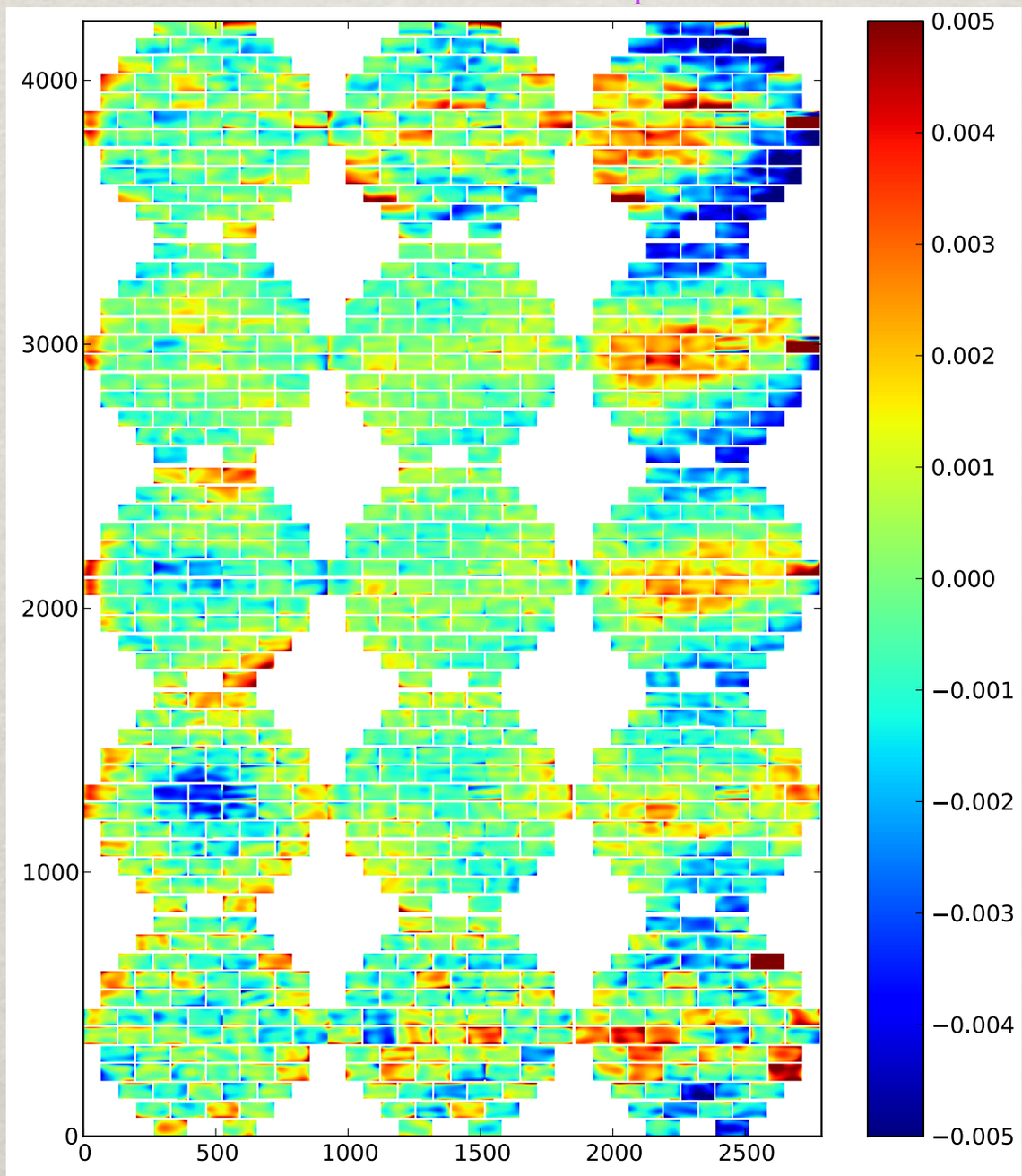
g

r

i

z

Y

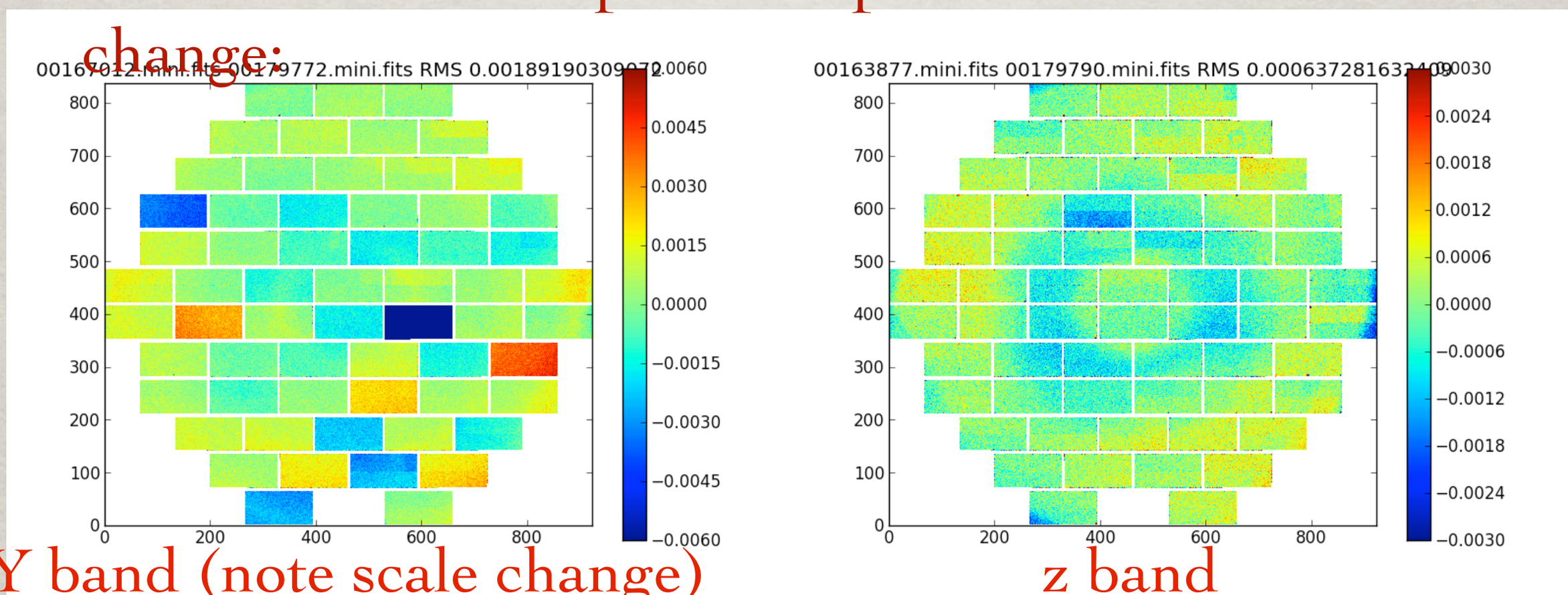


Dome x Star Flat

relative to Dec 2012

Except that temperature excursions affect Y-band response, hysteretically

Fractional change in dome flats on days before/after a focal plane temperature change:



Y band (note scale change)

z band

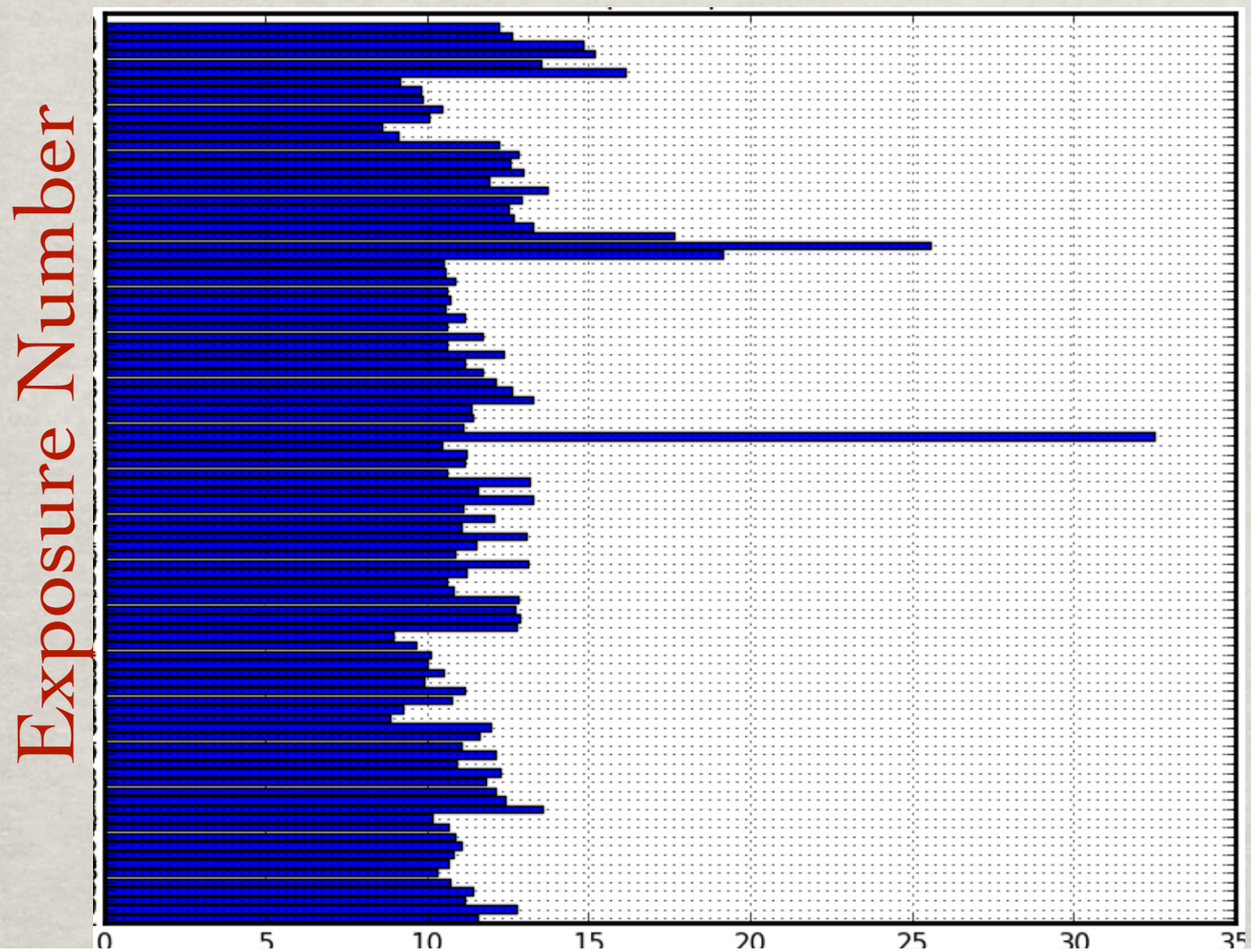
Effect is stronger in the dome flats than in stellar response

Occurs for temperature excursions as small as 5K!

Precision relative astrometry

- Solve using star flat stellar positions.
- Current *instrumental* distortion model: Cubic polynomial per CCD, plus templates for tree rings and glowing edges.
- Current *exposure* distortion model: Quadratic polynomial for FOV
- **Quickly attain accuracy dominated by wave-like displacement patterns per exposure, presumably atmospheric in origin.**
- Easily detect milliarcsec distortions due to CCD geometry.

Relative astrometric errors are about 10 mas



RMS astrometric disagreement (mas) From Bob Armstrong

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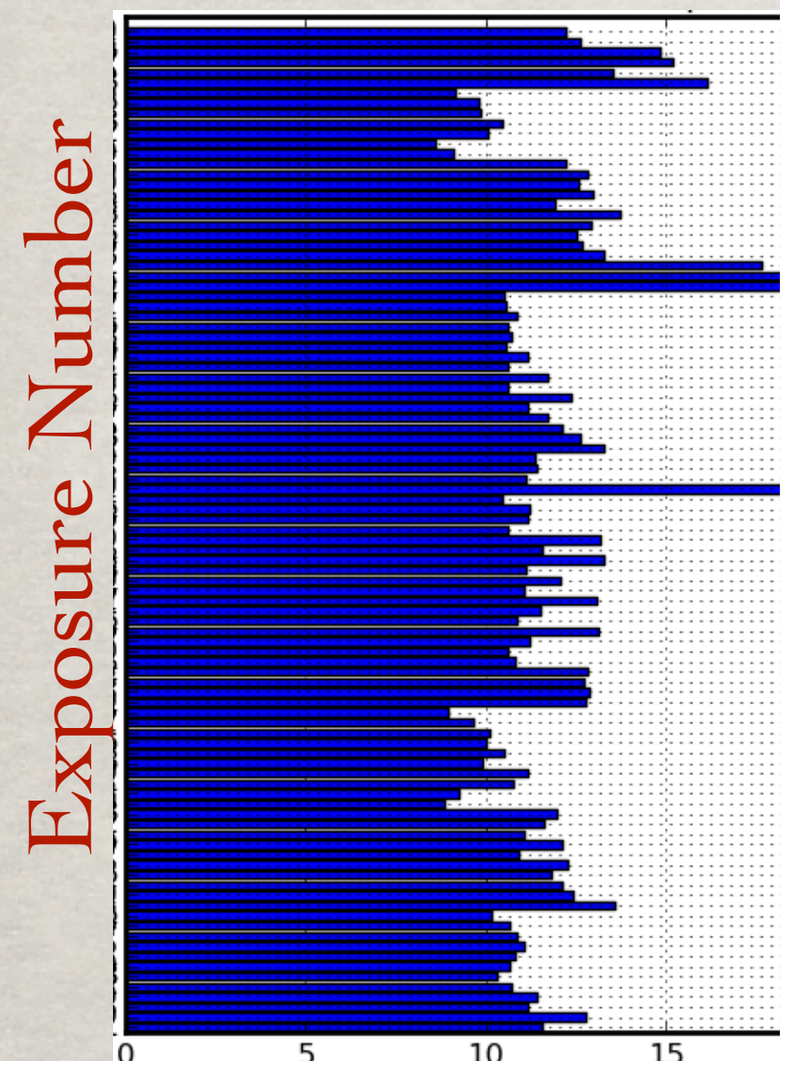

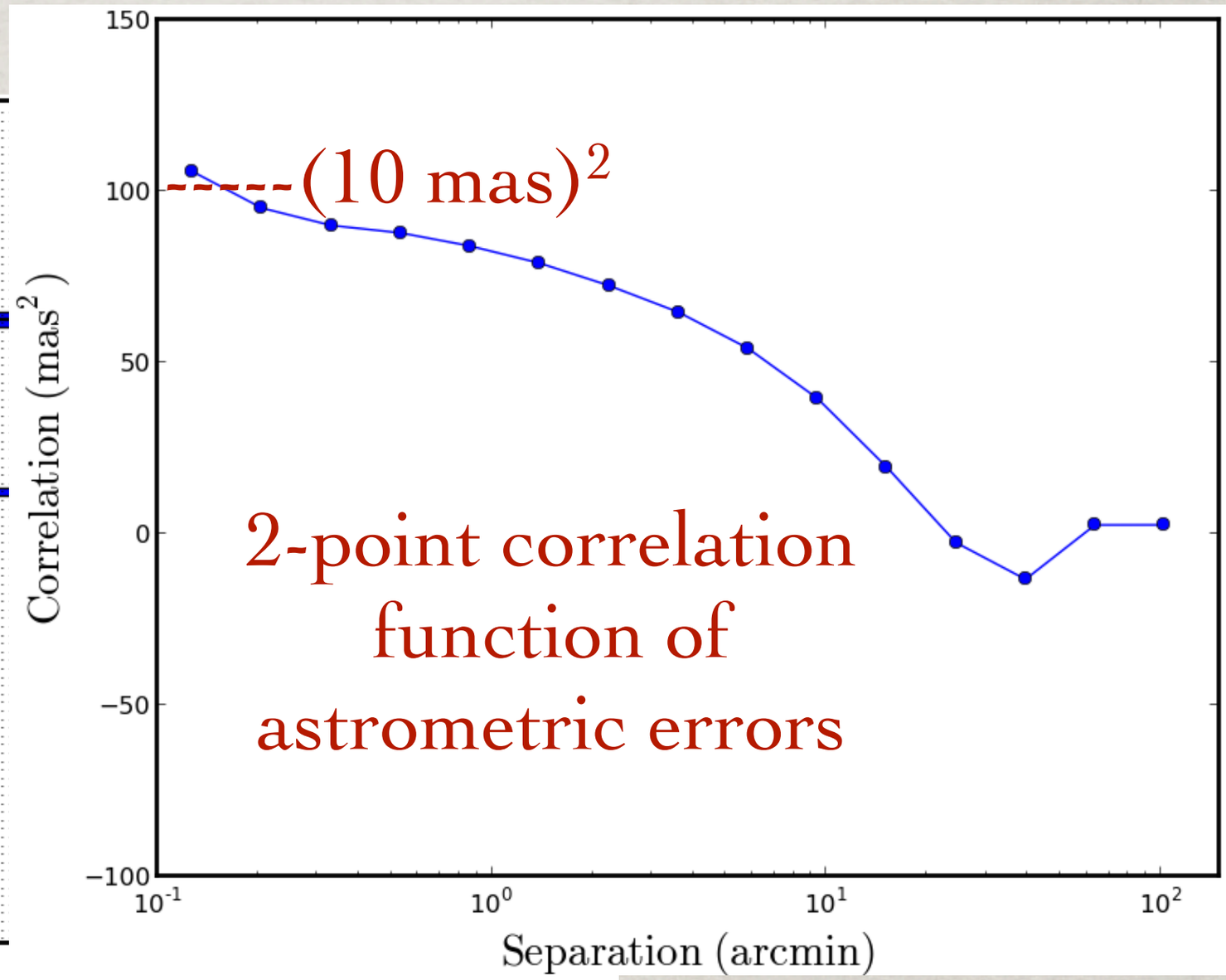

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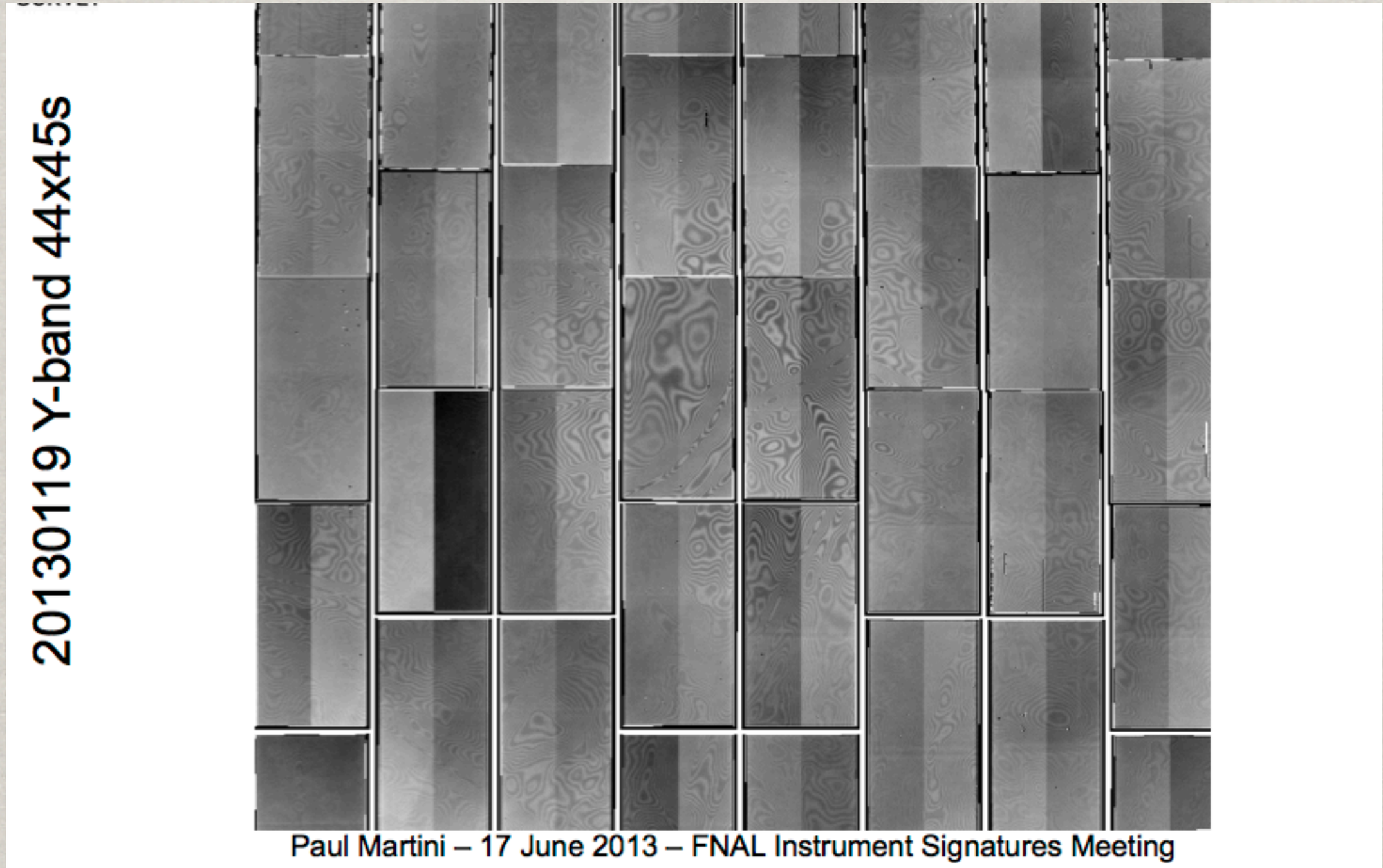
Fringing (via P. Martini)



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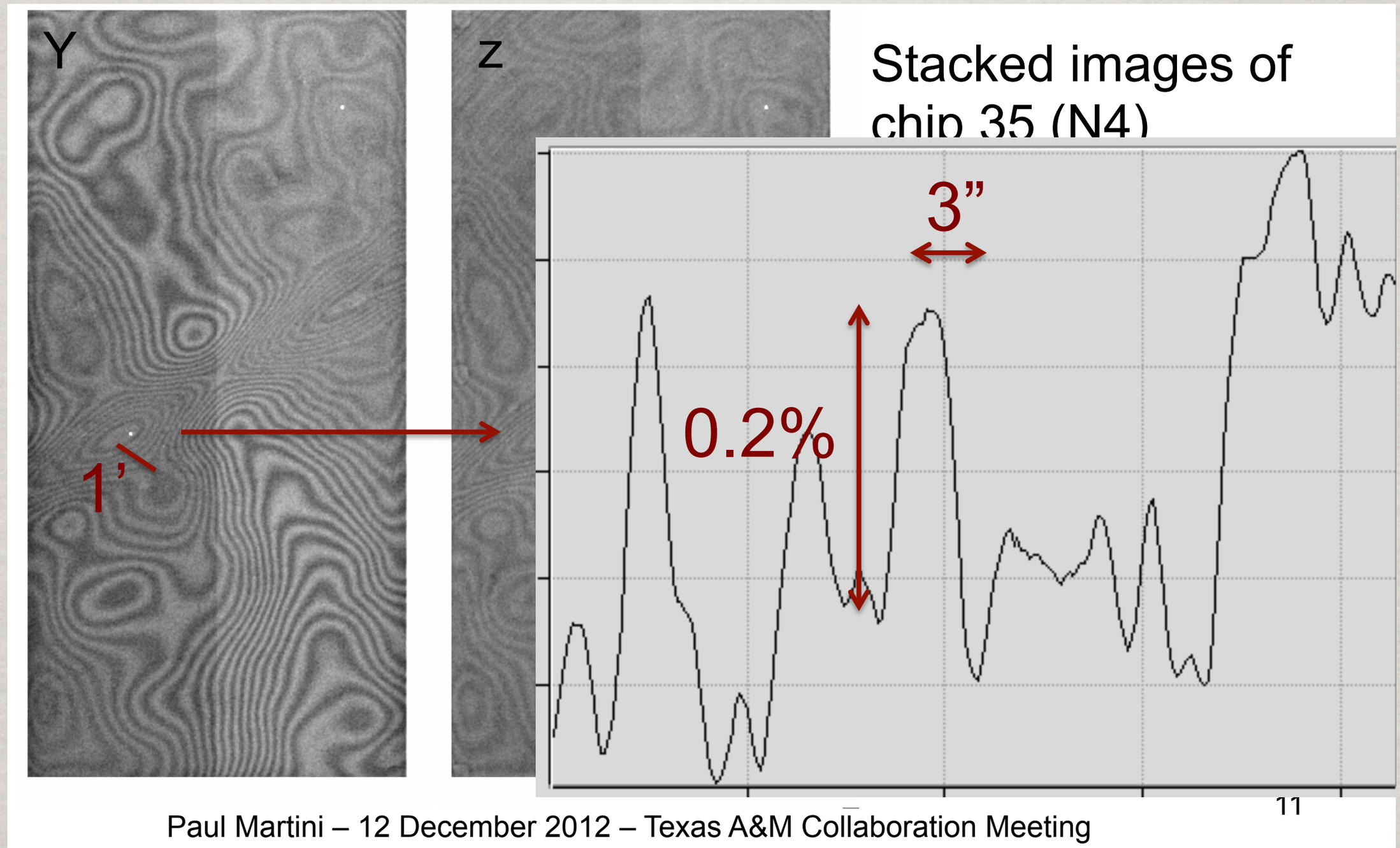


DES lessons so far

- We can perform exquisite calibration with the camera on the telescope, using biases, darks, and observations of dome and star fields of varying exposure time.
- The "star flat" on-sky observations use dither patterns that do not occur naturally during the survey, so a small amt. of engineering time is needed to maintain calibrations.
- *DECam is a very stable instrument with very little "personality" to be medicated away.*
- Nonlinearities and BF effect are clearly present. The simplest pixel-level corrections appear to pass the tests we have so far conducted.
- The relative response across the array can be put on a common scale to mmag accuracy. Use of dome flats can cause more harm than good if not careful.
- Astrometric and photometric calibration are limited by atmospheric variations.
- Photometric response seems stable at mmag level between configuration changes. Dome flats are less stable with time than sky response.
- High-precision astro/photometry not fully implemented in *DESDM* pipeline (particularly need an audit of the treatment of pixel sizes).

LSST and DES

- **Instrument rotation** on LSST will make these calibrations more complex than DES!
- Some areas where cooperative development would be useful:
  - A format for astrometric distortions with more structure than FITS WCS can offer
  - Code for deriving multivariate sky+fringe components, and removal from images.

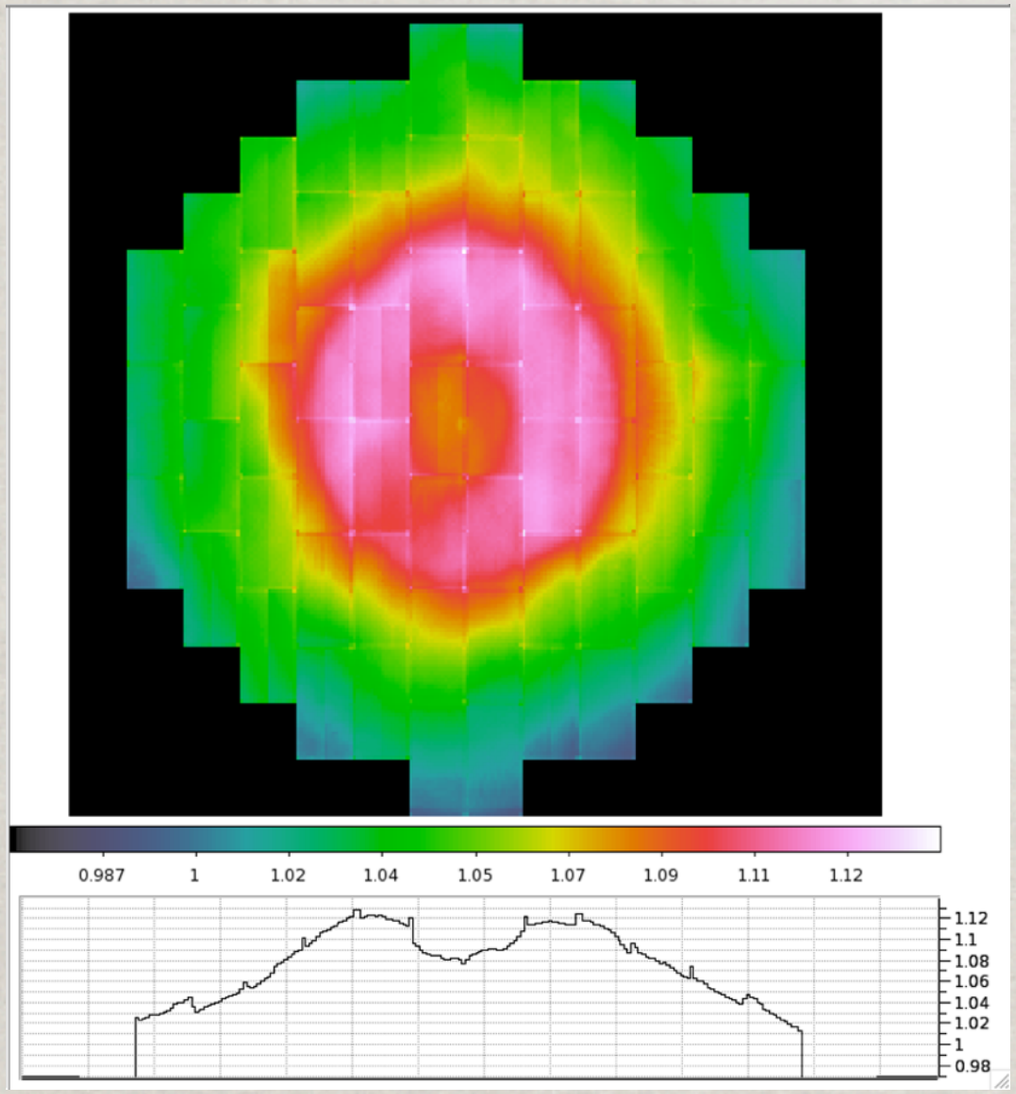
Extra slides

The star flat

$$StarFlat = \frac{\Omega(r+s)}{r}$$

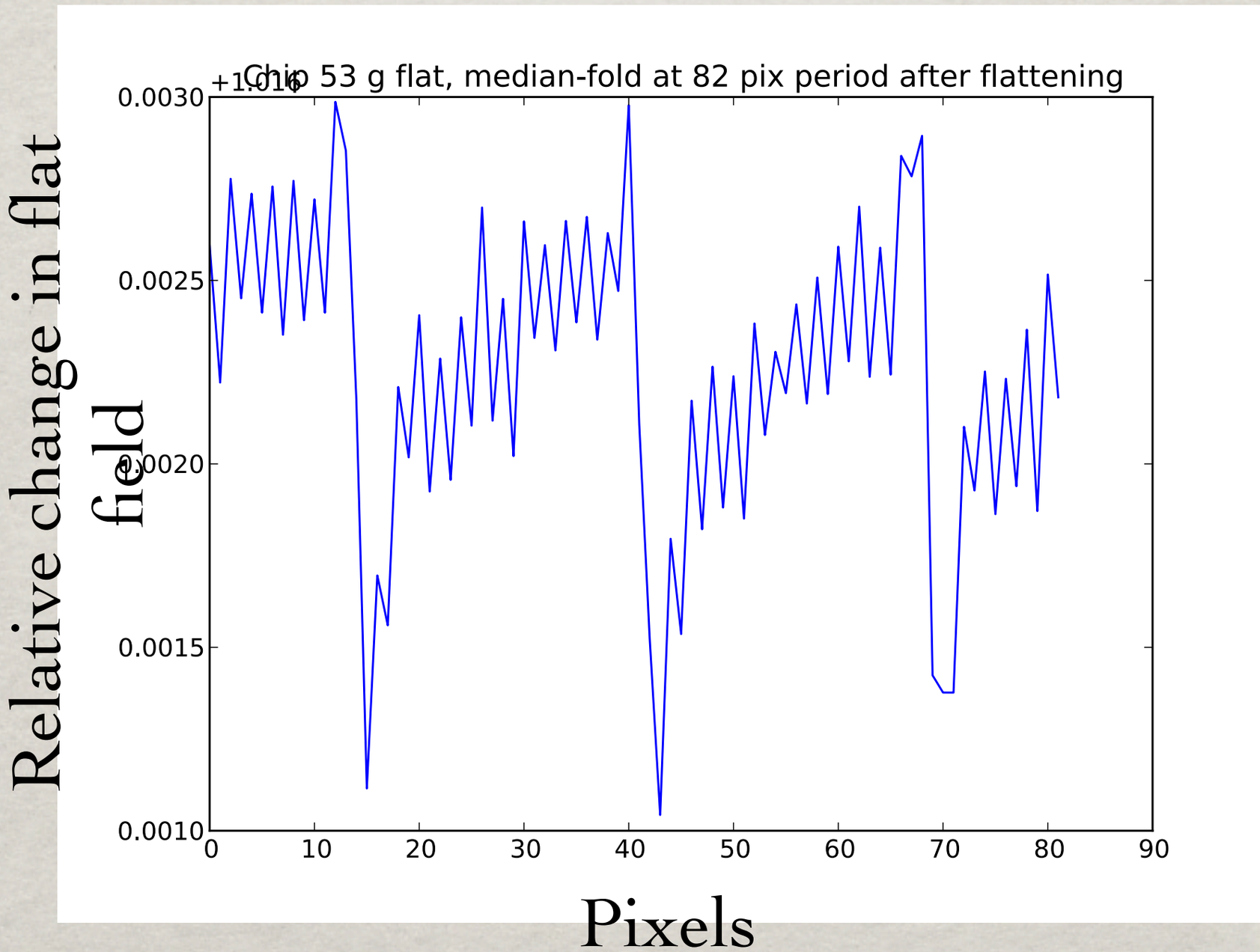
- We derive both the star flat and the astrometric solution from a sequence of 20-25 exposures (per filter) dithered to move a star around the array.
- Posit a functional form for the star flat and adjust its parameters to minimize dispersion of magnitudes of a given star as it moves around the array.
- Multiple codes in DES to accomplish this (my *PhotoFit*, also Bauer, Regnault, Kent). Agreement at <3 mmag RMS.

Instrumental Signatures: photometric response

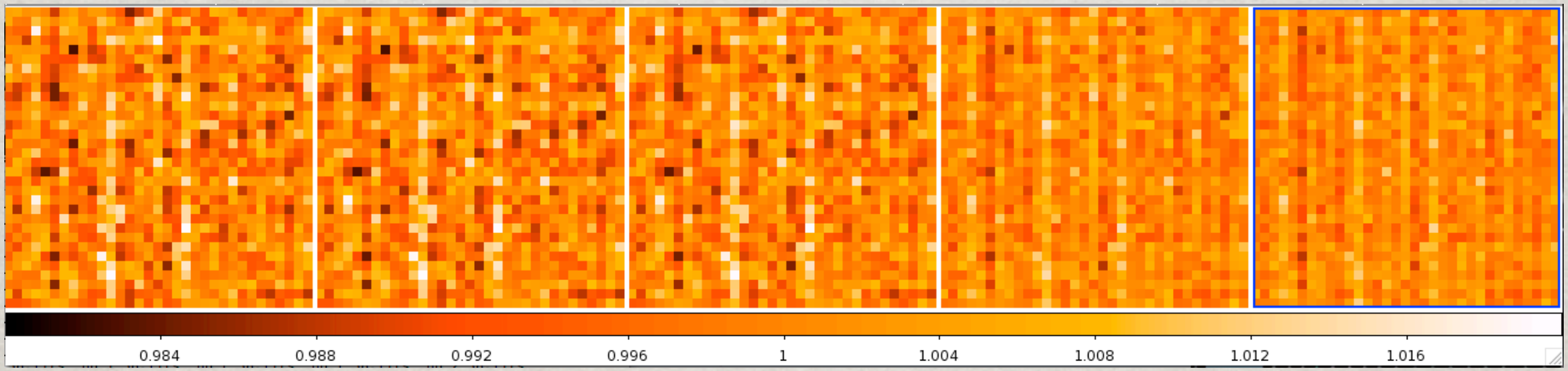


- This is the full-field g-band flat after matching gains/ QE's.
- *The donut pattern is out-of-focus light reflecting off the CCDs!*

Periodic signal along DECam rows



Small-scale structure in flats is also



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

- Removing small-scale structure from the dome flats **improves** the error floor for aperture photometry but does not **eliminate** it.
- Some, but not all, of the variation has coherence on rows/columns
- Amplitude weakens near silicon red edge.
- Consistent with most but not all of small-scale structure being variation in the shape of gates/channel stops, 0.003 pixel @45 nm RMS, fields extend substantially into depletion region.

It takes one of these to characterize an instrumental distortion:

Property:	Method:	Tree rings	Glowing edges	Tape bumps	QE/ optical effects	Ragged gates
Can be reduced to a 1d function?	Derive astrometry from dome flats.	✔	✔	✗	✗	✗
Low # DOF?	Constrain distortion with star flat data	✗	✗	✗	✔	✗
Small fraction of FOV?	Ignore region	✗	✗	✔	✗	✗

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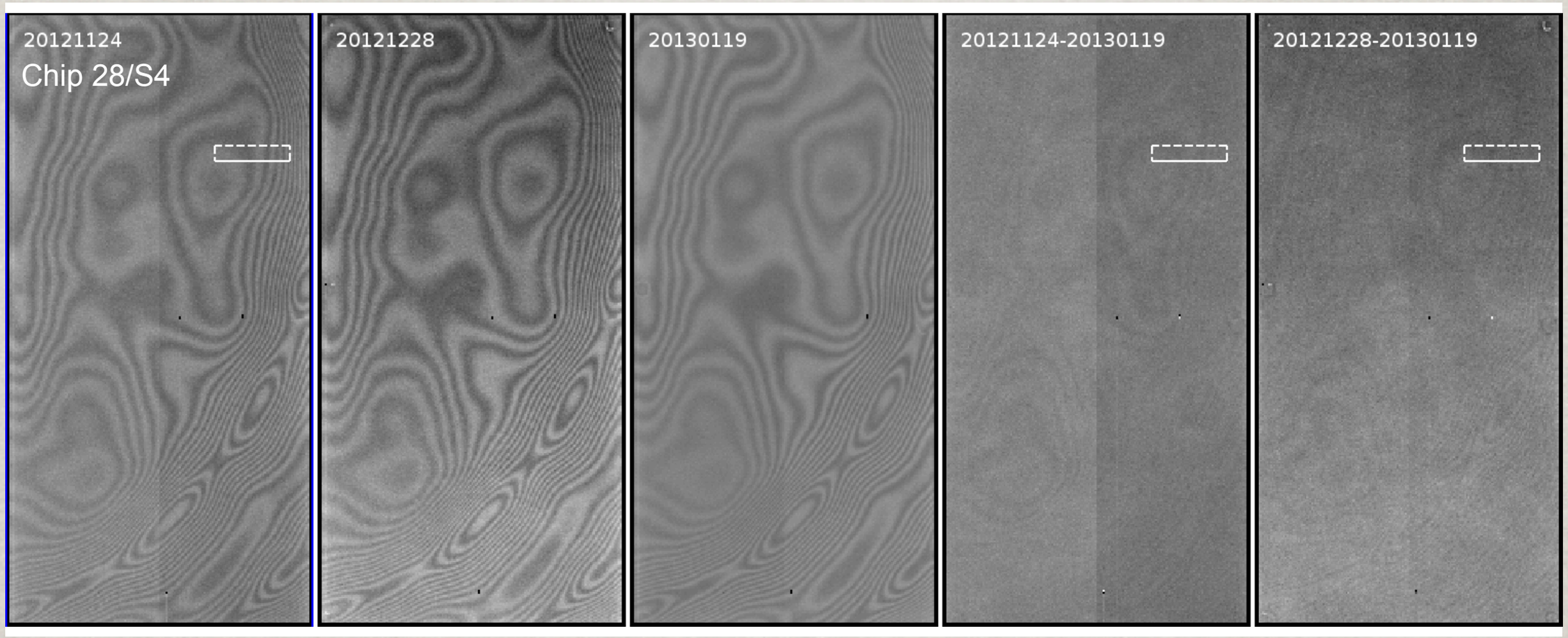
Can we live with ~0.003 pixel astrometric "noise"?

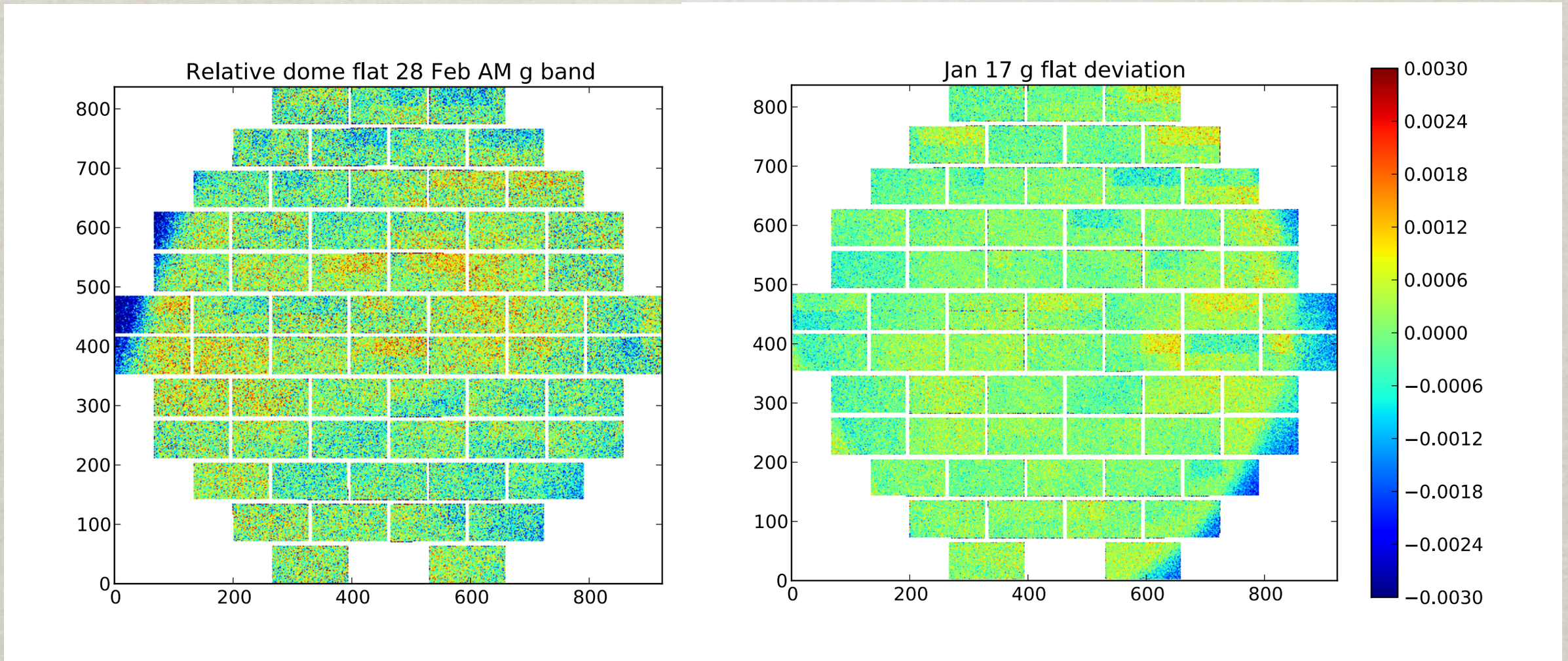
Fringe amplitude varies with time, which is not treated currently in DESDM



Paul Martini – 17 June 2013 – FNAL Instrument Signatures Meeting

To accuracy of current tests, the fringe pattern is ***constant!***

Stability of dome flats



See few-mmag changes over days/weeks/months