ON-SKY PERFORMANCE OF THE DARK ENERGY CAMERA

G. Bernstein (UPenn) 18 November 2013

★ ★ ★ ★ ★ ★ ★ ★

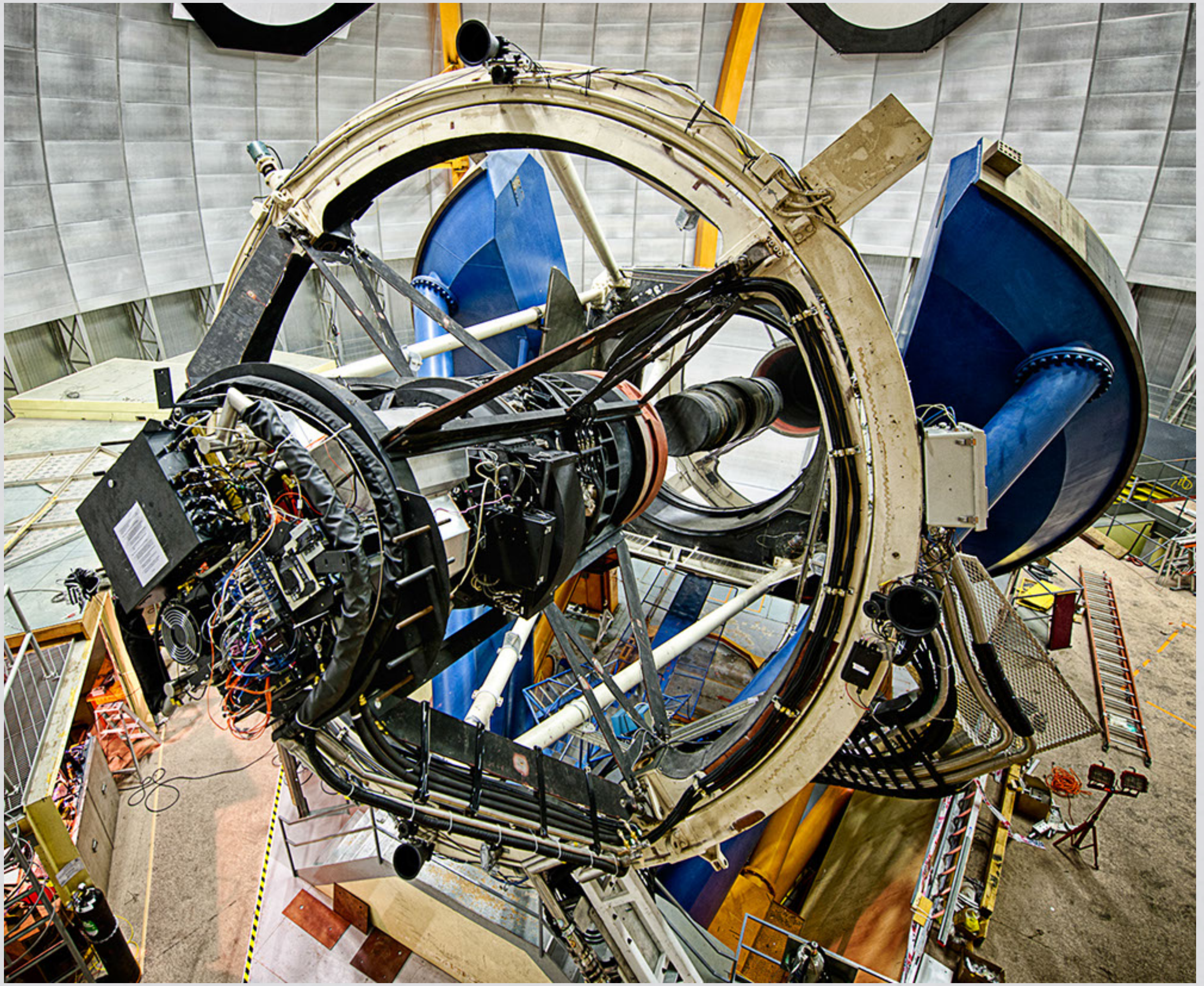
On behalf of the *Dark Energy Survey* Collaboration, the creators of *DECam*, and the creators of the LBL CCDs in the camera.
Particular analysis contributions from A. Plazas, R. Armstrong, A. Bauer, N. Regnault, P. Astier, H. Lin, D. Gruen, E. Bertin

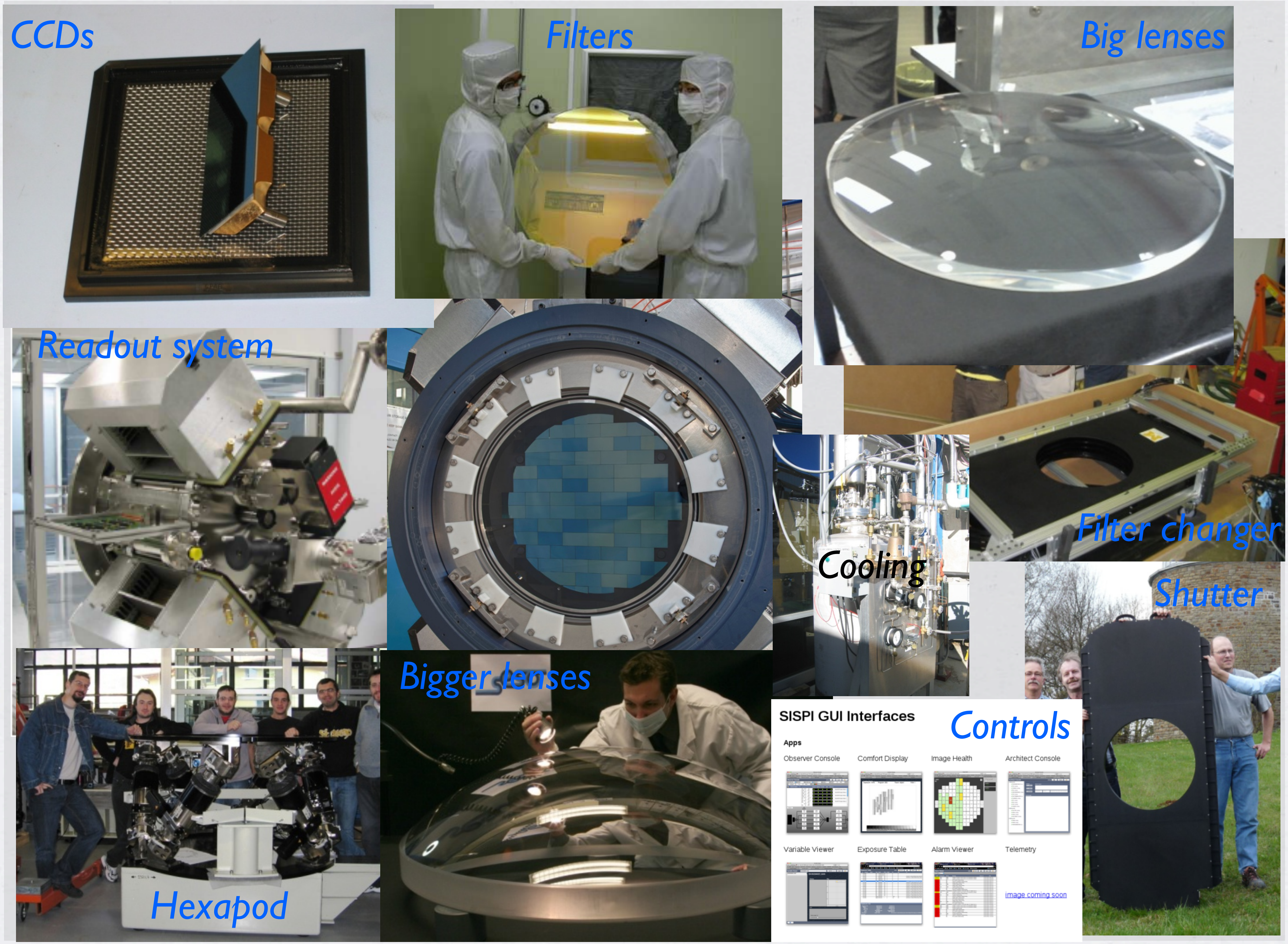
Topics of interest

* DECam Overview
* Anomalies
  * Device failures
  * High-light-level nonlinearity (HLLNL)
  * Low-light-level nonlinearity (LLLNL)
* Precision Photometry
  * The star flat formalism and technique
  * **The importance of pixel area variation** (*cf.* A. Plazas talk)
  * **Attaining millimag photometry**
  * Testing nonlinearity corrections
  * **Stability of instrument response** and dome illumination
  * **Fringes**
* Precision Astrometry
* Precision PSF characterization
  * **The brighter/fatter effect** (*cf.* P. Astier talk)
  * Frontside diffraction

Bold items most affected by deep-depletion

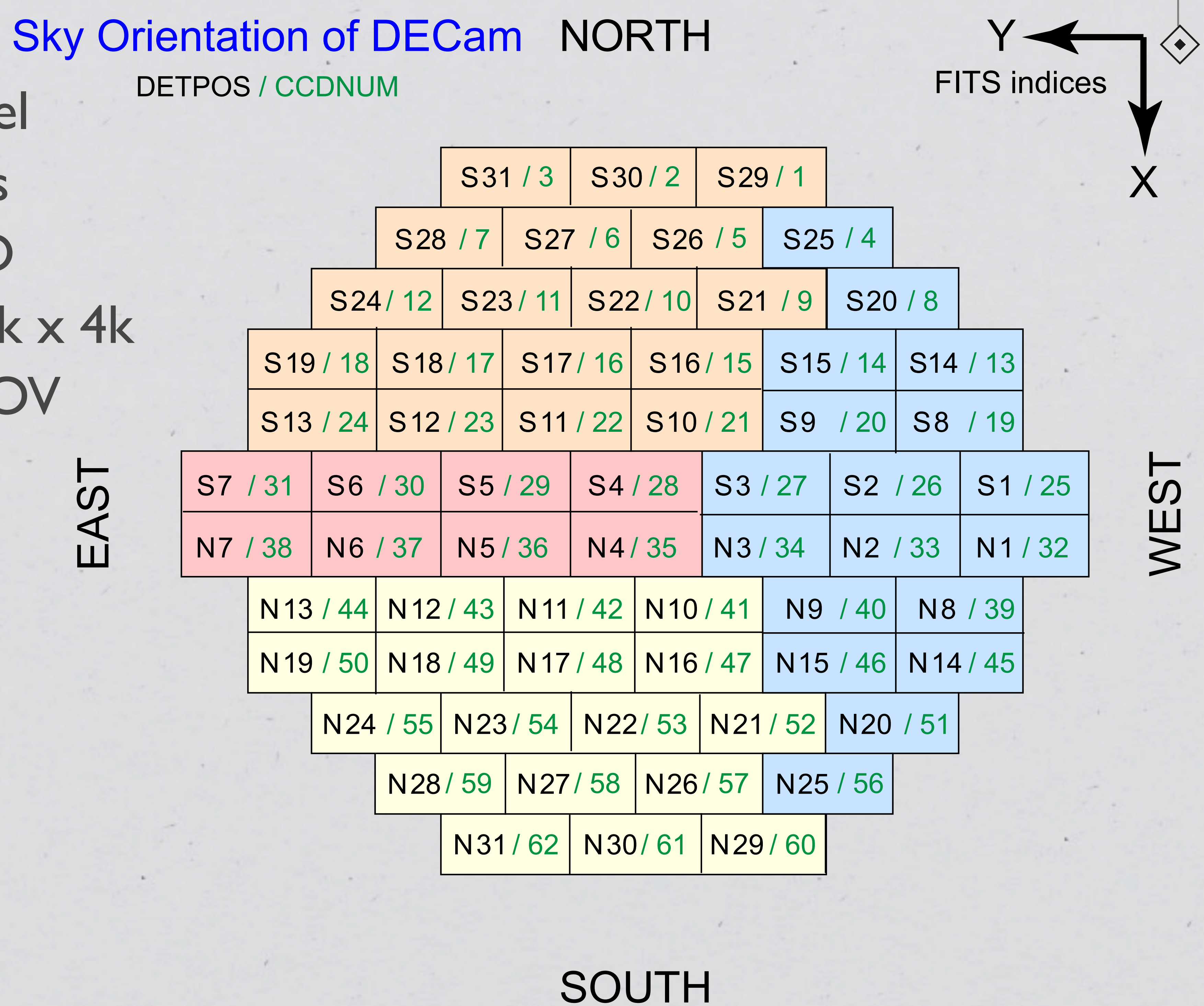
The Dark Energy Camera




CCDs
Filters
Big lenses
Readout system
Filter changer
Cooling
Shutter
Bigger lenses
SISPI GUI Interfaces
Controls
Apps
Observer Console
Comfort Display
Image Health
Architect Console
Variable Viewer
Exposure Table
Alarm Viewer
Telemetry
image coming soon
Hexapod

Scientist's view of DECam

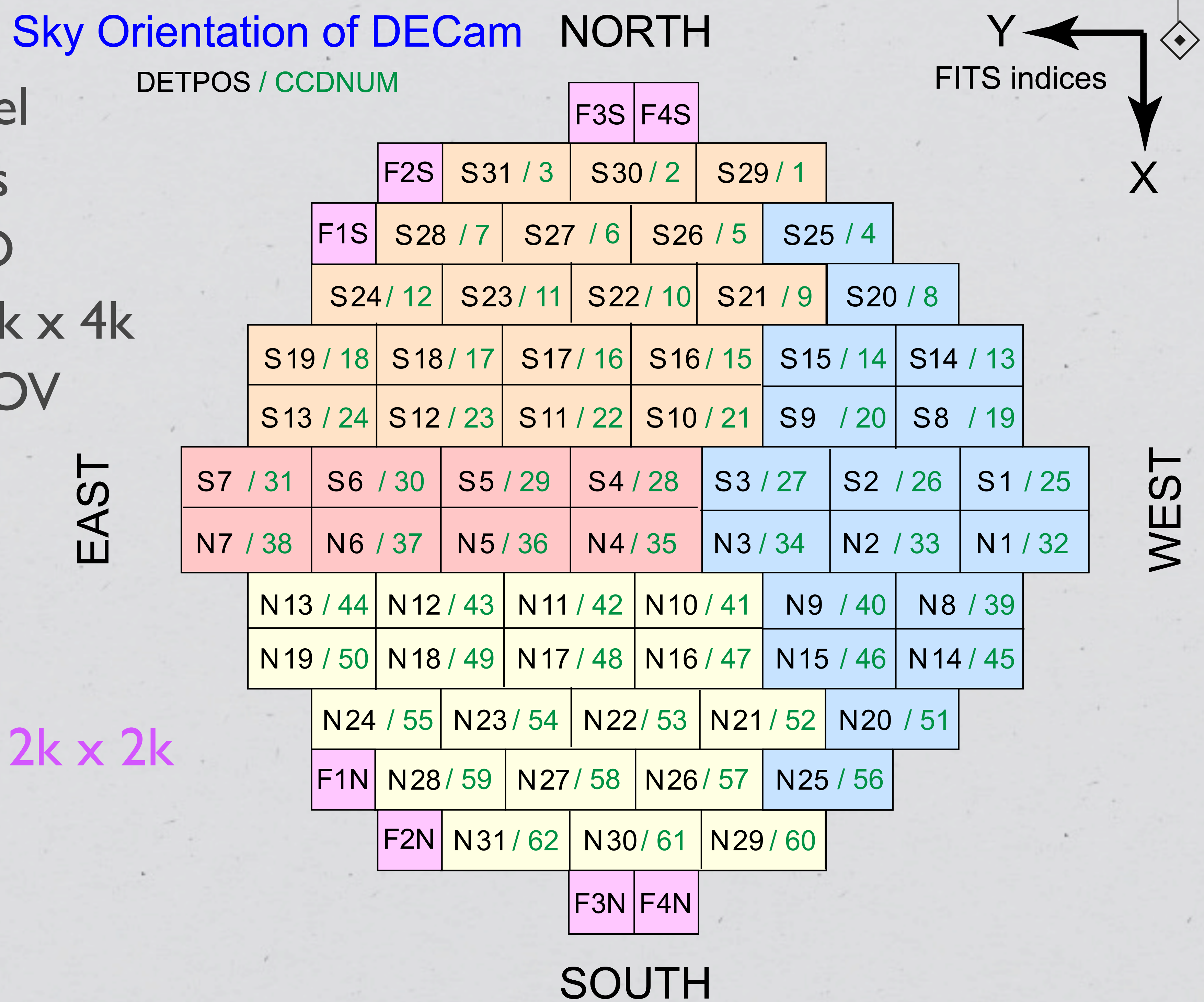
- 250 um LBL p-channel
- 15 um (0.264") pixels
- 2 amplifiers per CCD
- Science Array: 62 x 2k x 4k
- 2-degree diameter FOV



Scientist's view of DECam

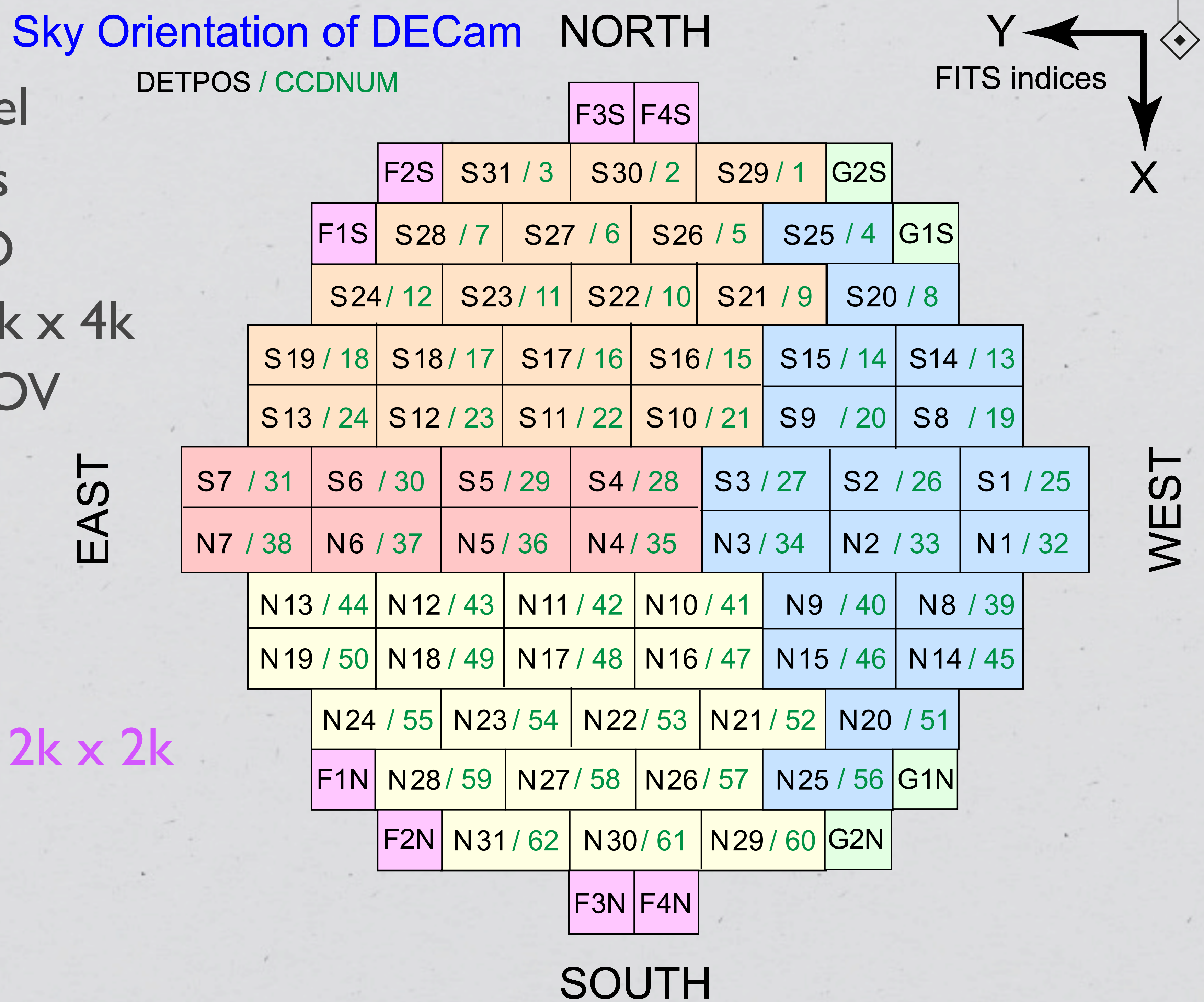
- 250 um LBL p-channel
- 15 um (0.264") pixels
- 2 amplifiers per CCD
- Science Array: 62 x 2k x 4k
- 2-degree diameter FOV

Focus/Alignment: 8 x 2k x 2k



Scientist's view of DECam

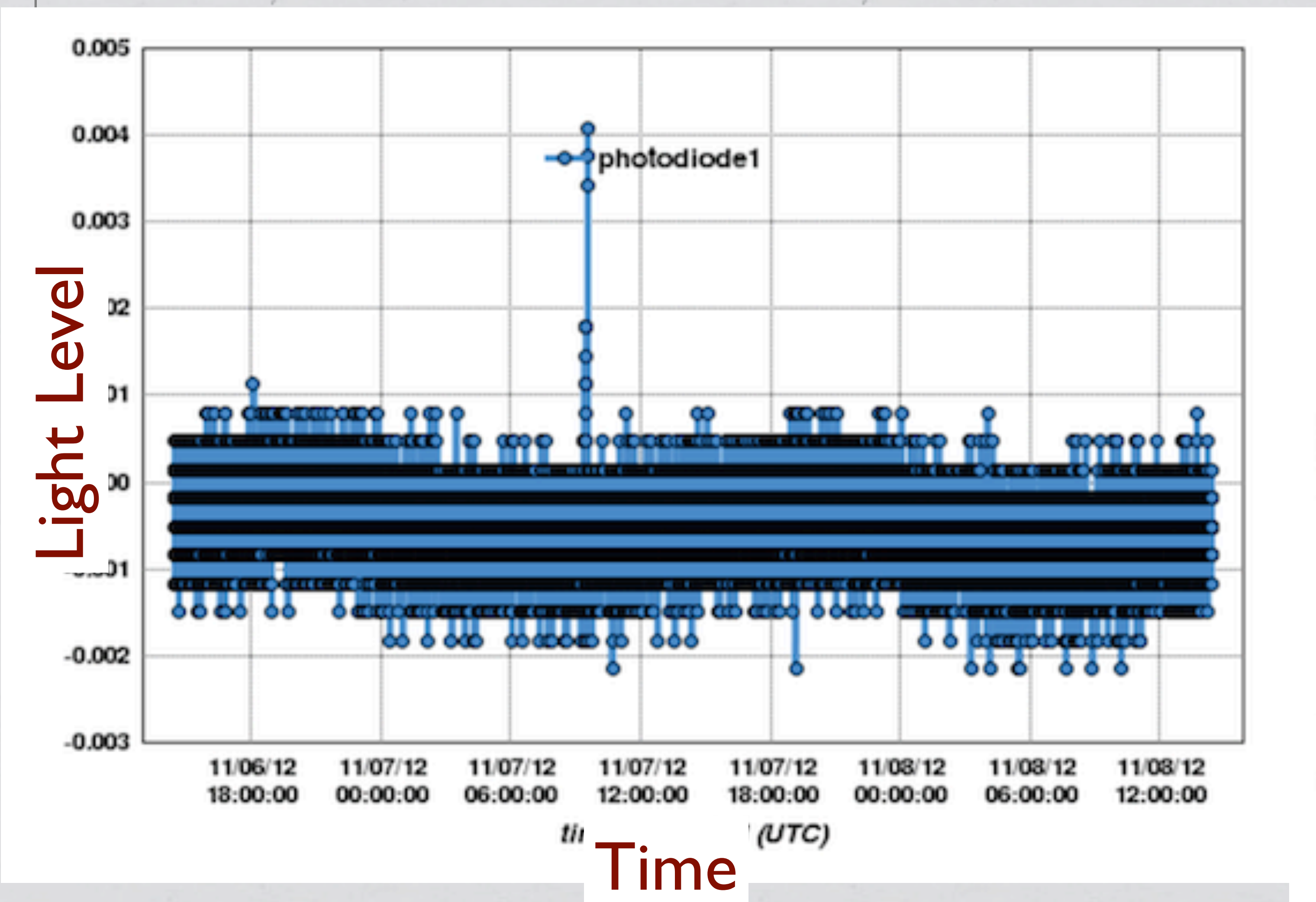
- 250 um LBL p-channel
- 15 um (0.264") pixels
- 2 amplifiers per CCD
- Science Array: 62 x 2k x 4k
- 2-degree diameter FOV

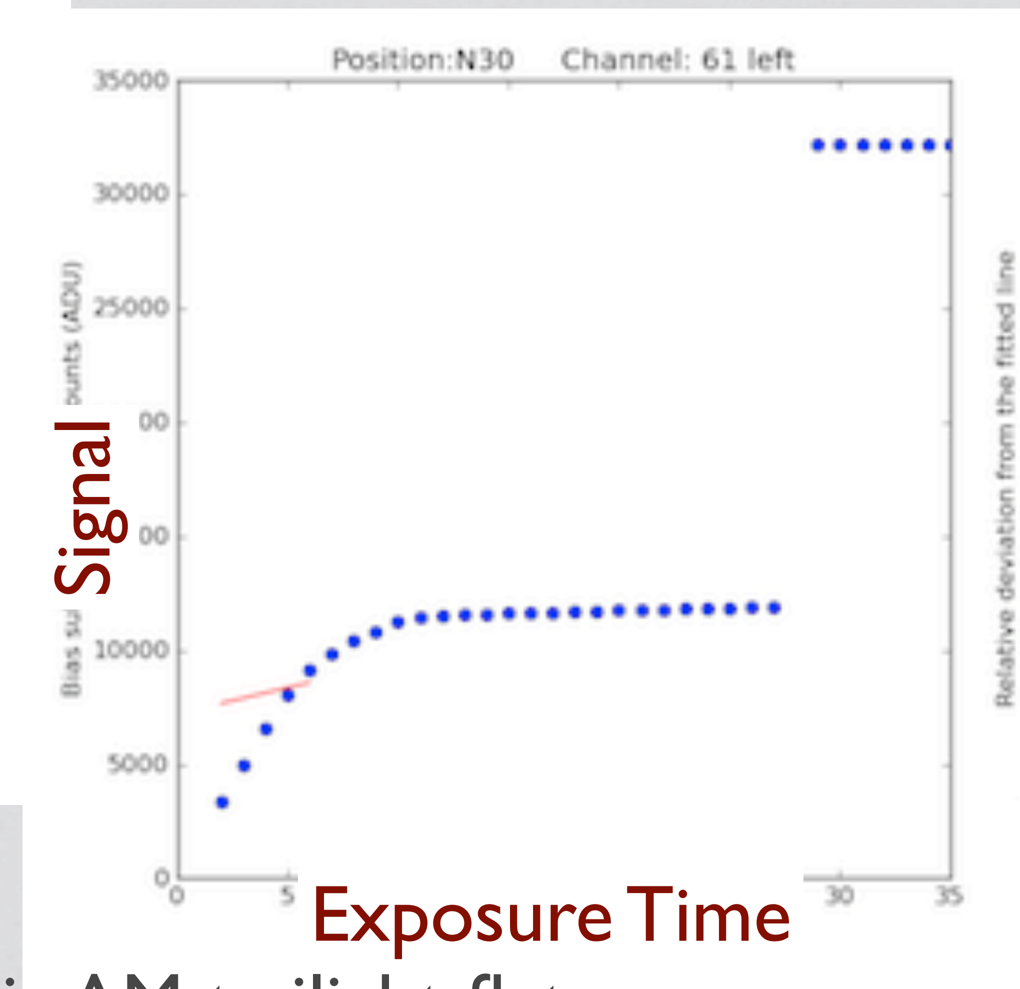


Focus/Alignment: 8 x 2k x 2k

Guiders 4 x 2k x 2k

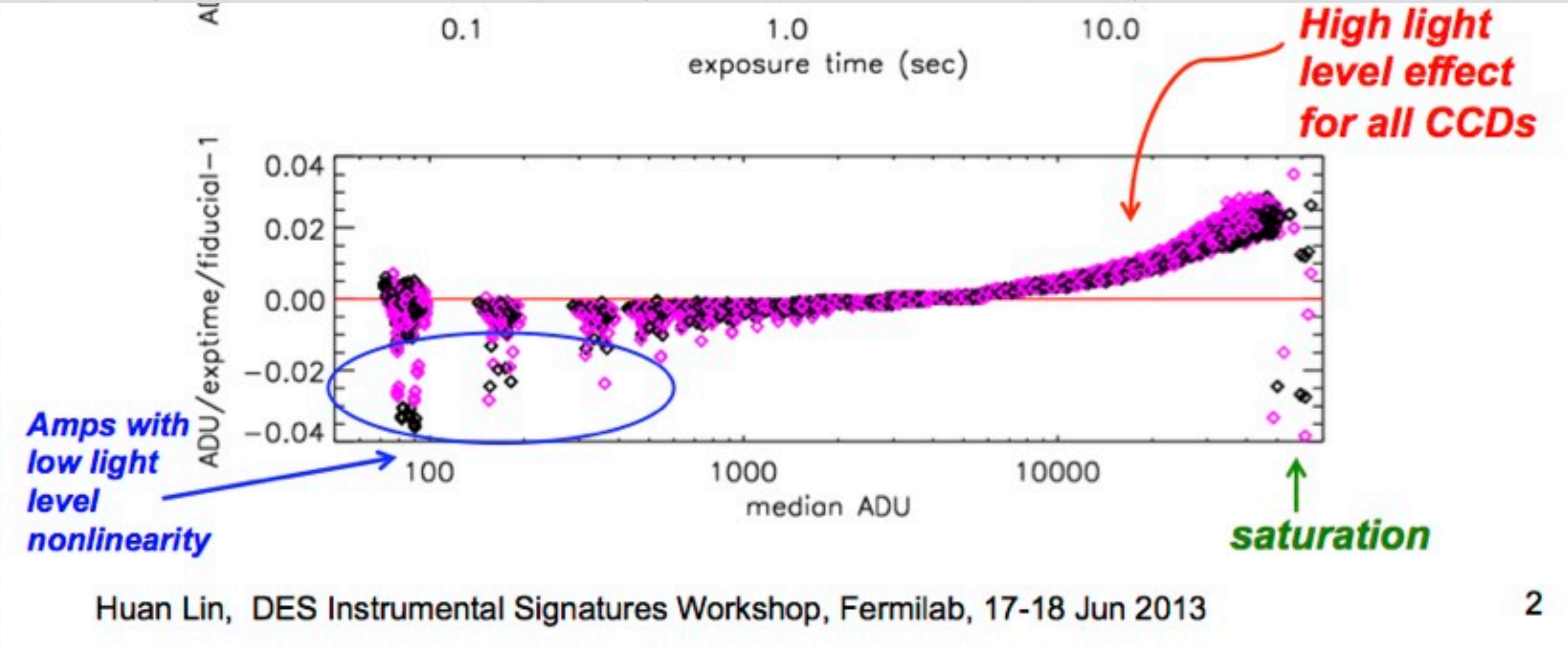
One science CCD is damaged





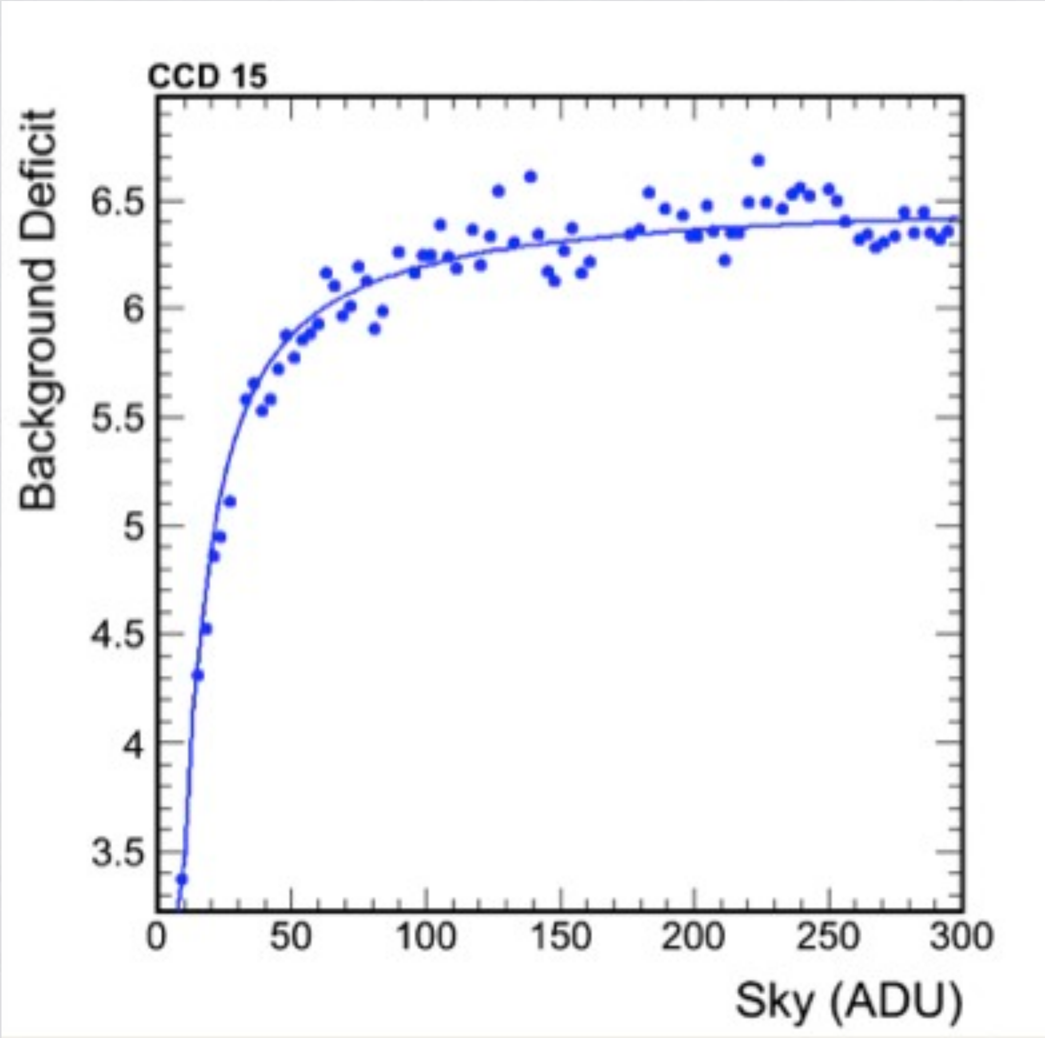
- Illumination spike during an over-enthusiastic AM twilight flat.
- Dome flats in AM ok; catastrophic loss of full well seen in PM flats.
- 100x lower illumination than lab-measured threshold for this failure mode

Nonlinearity in dome flats



- High-count nonlinearities (1-2%) seen in all channels. Consistent with quadratic response term at requirements level.
- Low-count nonlinearities (many %) seen in ~10 of the amplifiers.

Low-light nonlinearity



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

Precision relative photometry

- Just divide debiased image by dome flat, right?

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

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

  - r = response of array to focussed starlight
  - s = **scattered** or stray light, *i.e.* reflection off CCD and filter.
  - $\mathbf{\Omega}$= sky area per pixel.
  - k is dome surface brightness, might vary slowly across FOV
- Aperture photometry requires

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

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

The star flat

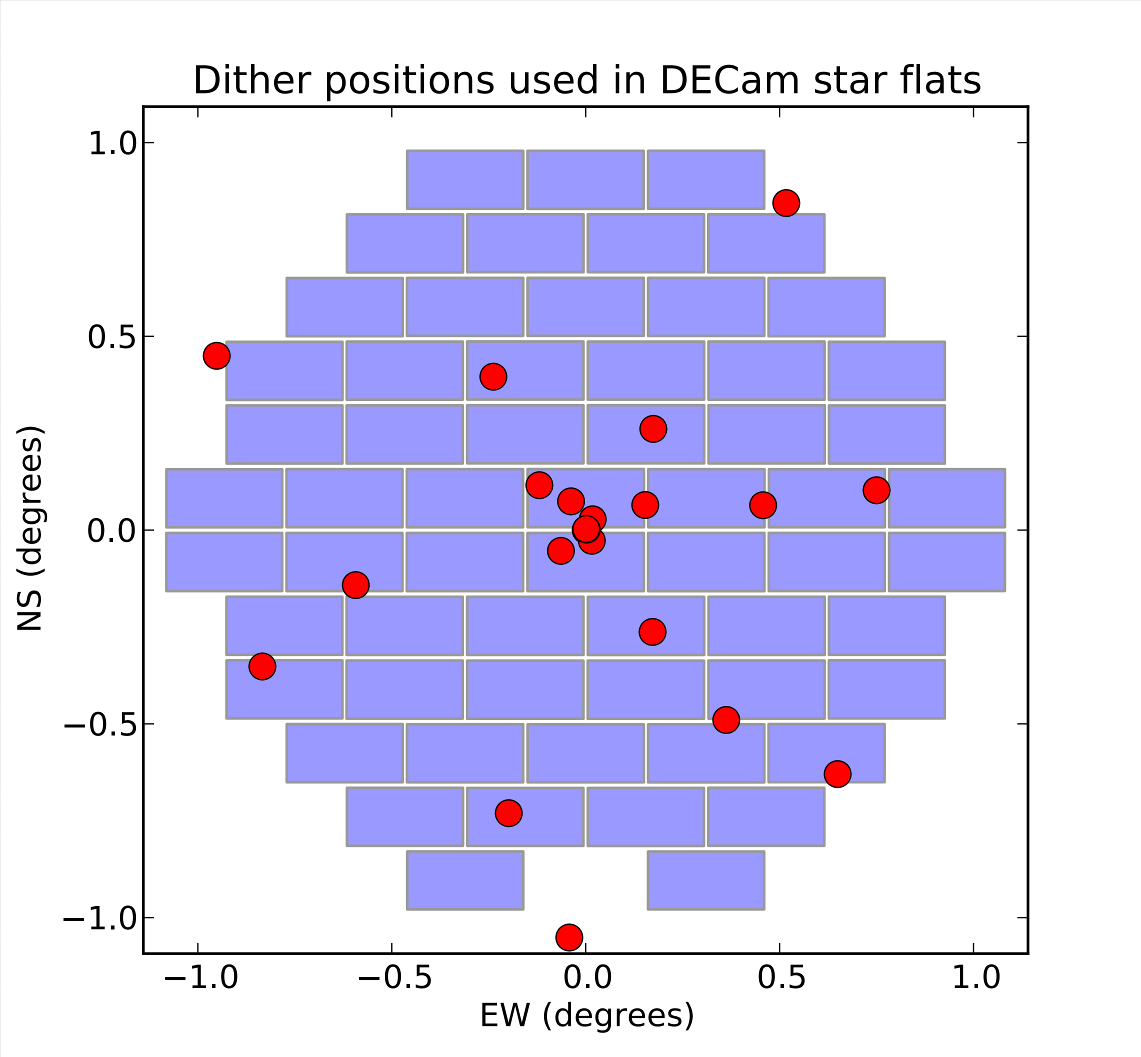
* To do proper photometry we need to know this image:

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

* And we also need the pixel-size map $\mathbf{\Omega}$ (i.e. the astrometric map) to fit surface-brightness models and do precision astrometry, registration of images.
* We derive both 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.

The star flat from PhotoFit

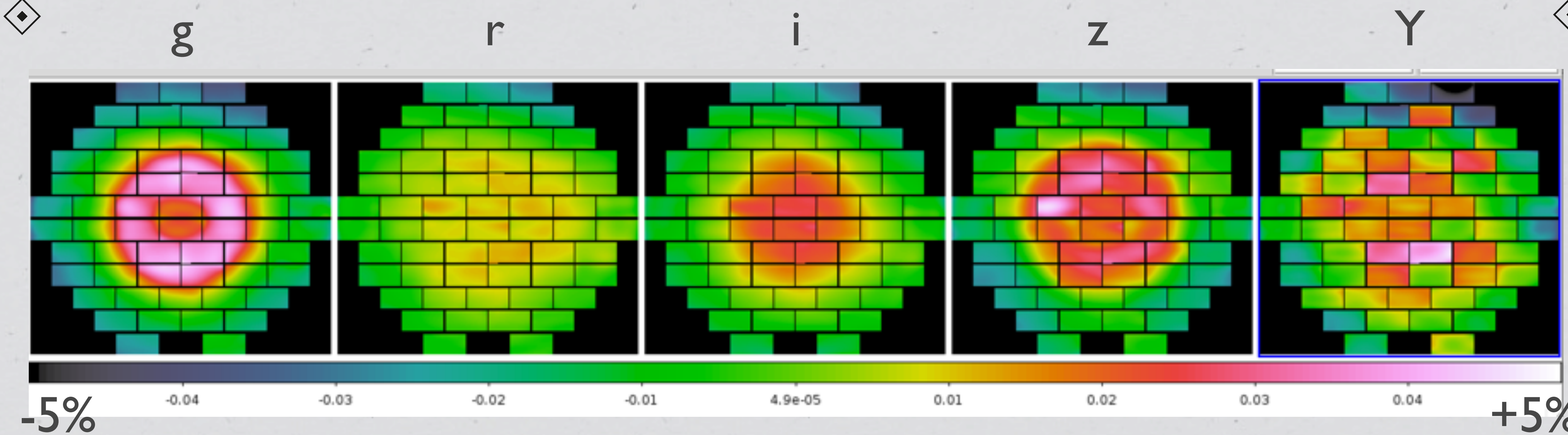
$$m = -2.5\log_{10}(ADU/T) + Inst_{\mathrm{CCD}}(x_{\mathrm{pix}}, y_{\mathrm{pix}}) + Exposure_{\mathrm{expo}}(x_{\mathrm{fp}}, y_{\mathrm{fp}})$$



$$Exposure = Const(exposure)$$

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

Star flats

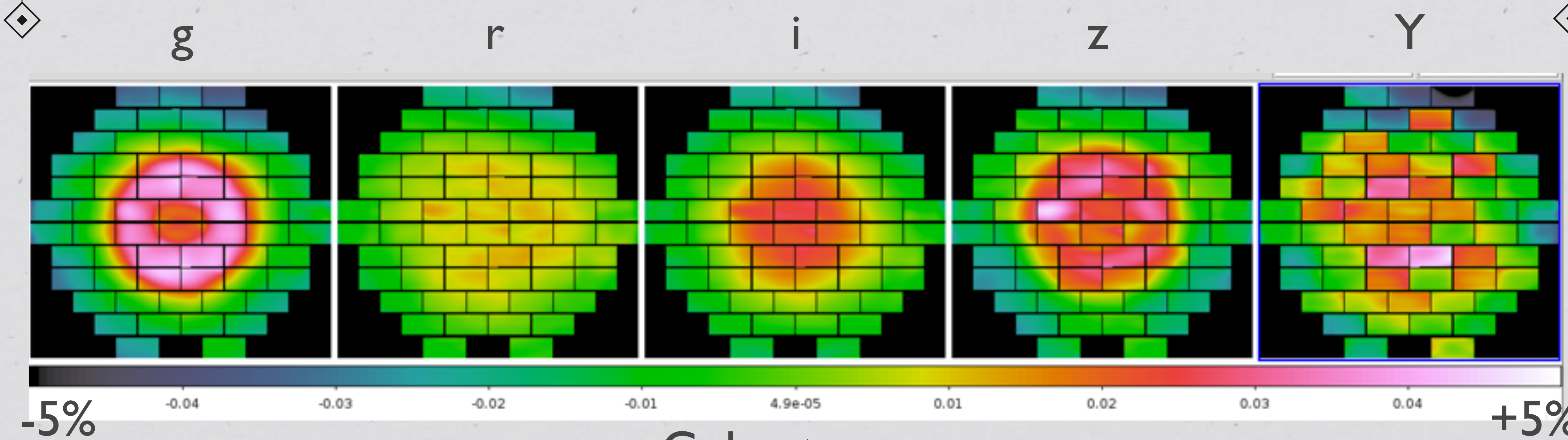


★Stray light is up to 10% of photons in a pixel from diffuse (dome) source.

★Agreement on pattern from 4 codes (Bauer, Bernstein, Regnault, Kent)

★Roughly as expected from Steve Kent optical models, but strongest at filter edges.

Star flats



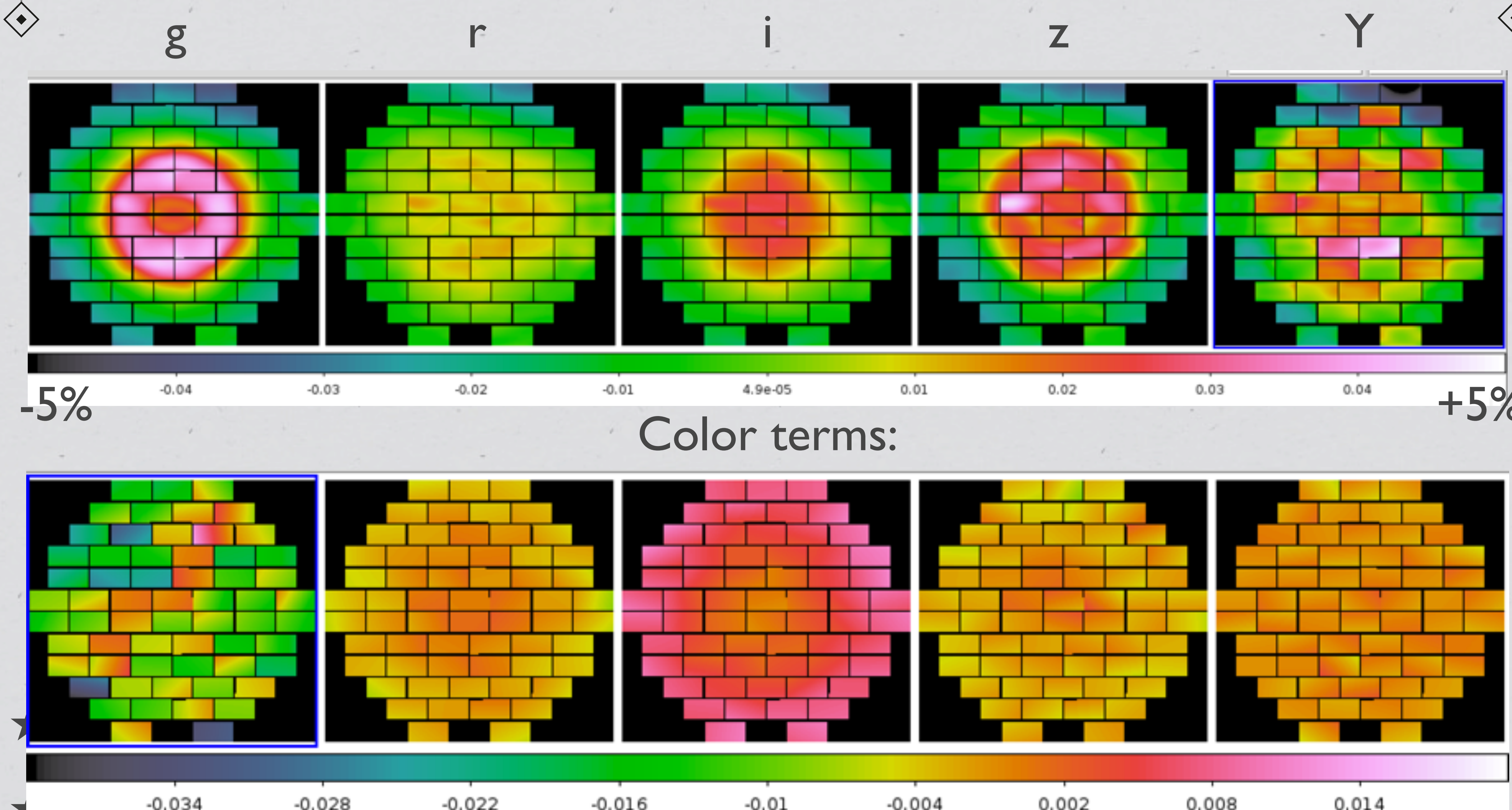
Color terms:

★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.

Star flats



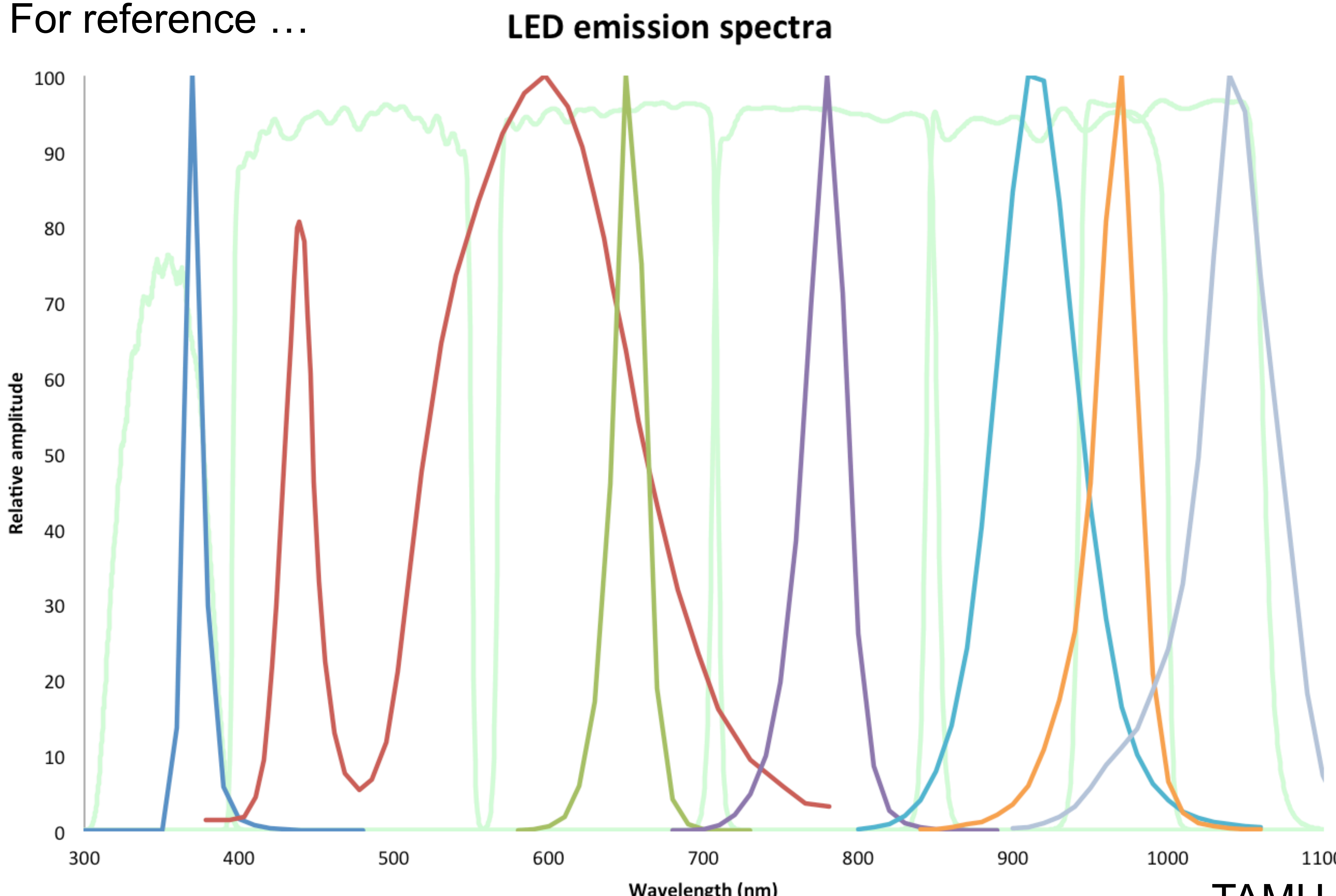
★Agreement on pattern from 4 codes (Bauer, Bernstein, Regnault, Kent)

★Roughly as expected from Steve Kent optical models, but strongest at filter edges.

LED emission

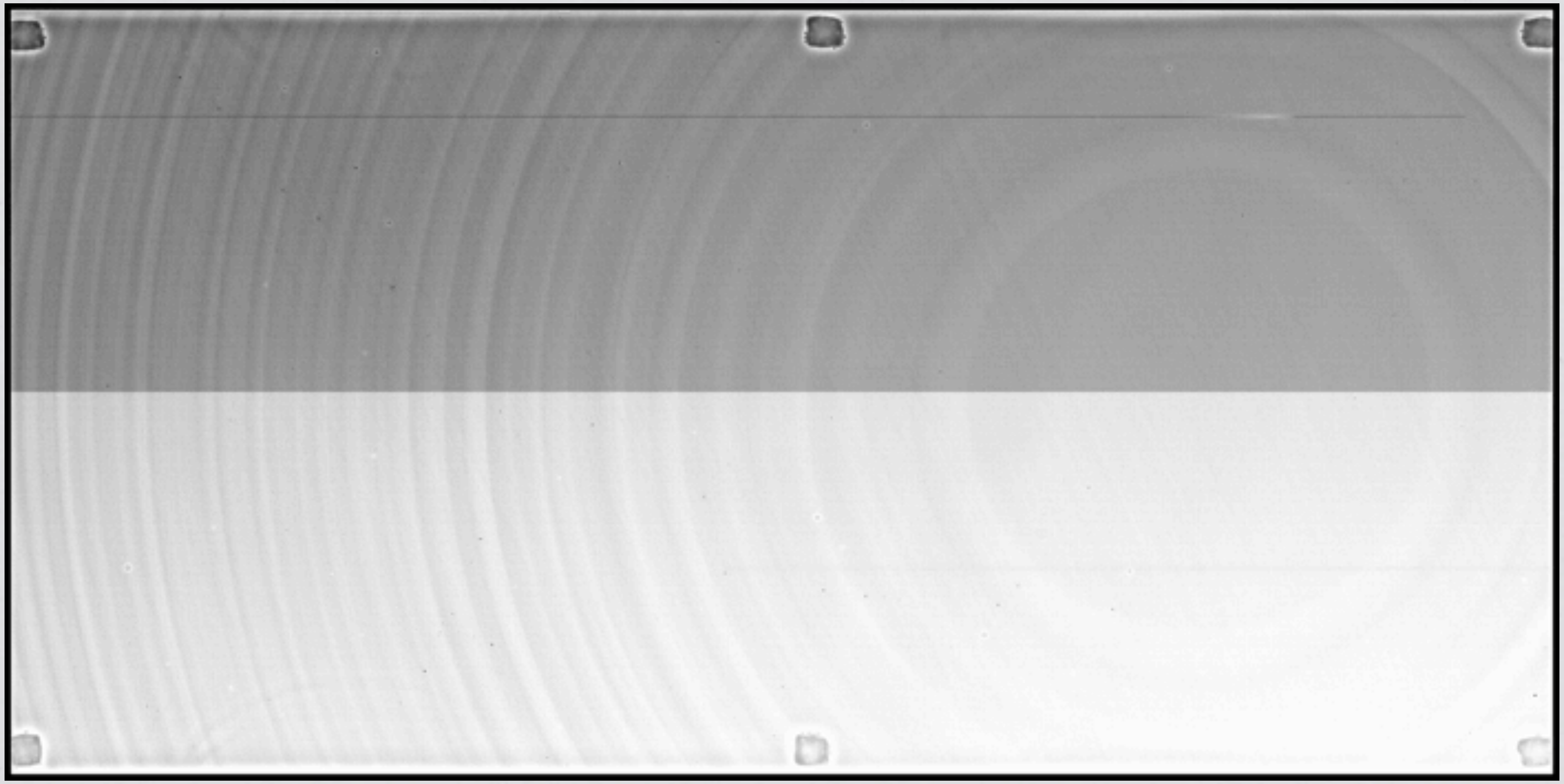
DARK ENERGY SURVEY

For reference …

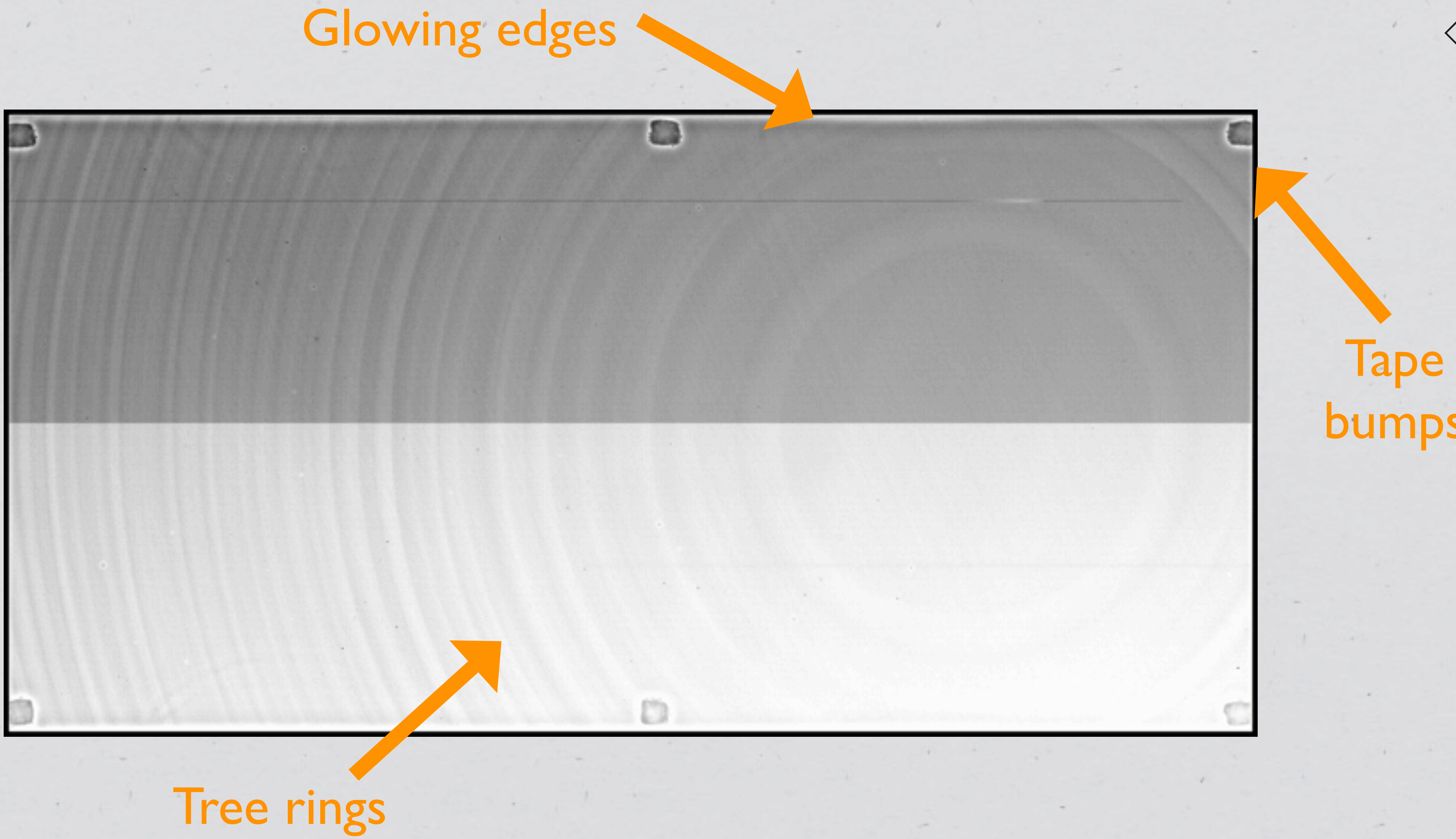


TAMU

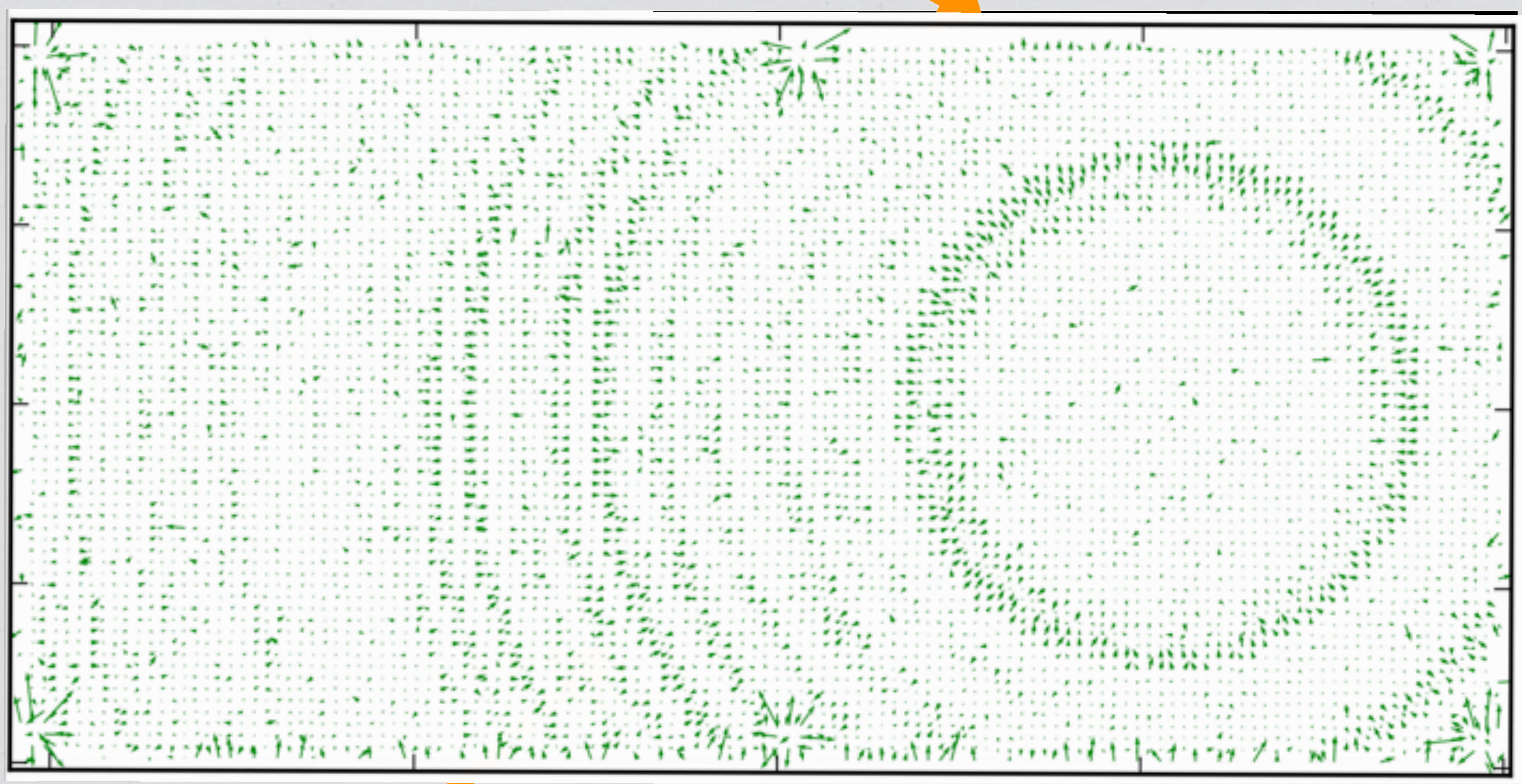
Most of the visible structure in domes is pixel size variation!



Most of the visible structure in domes is pixel size variation!

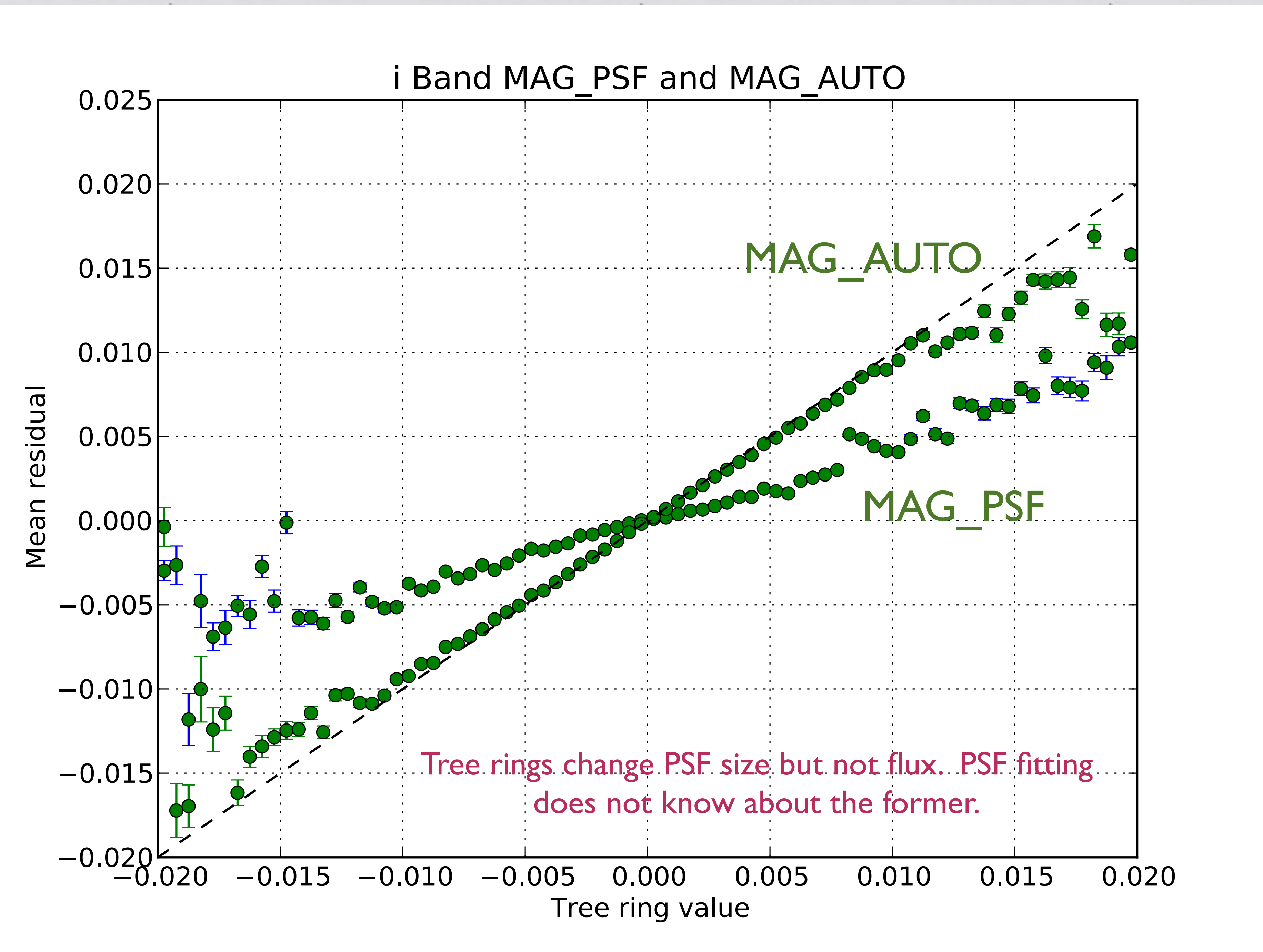


Most of the visible structure in domes is pixel size variation!



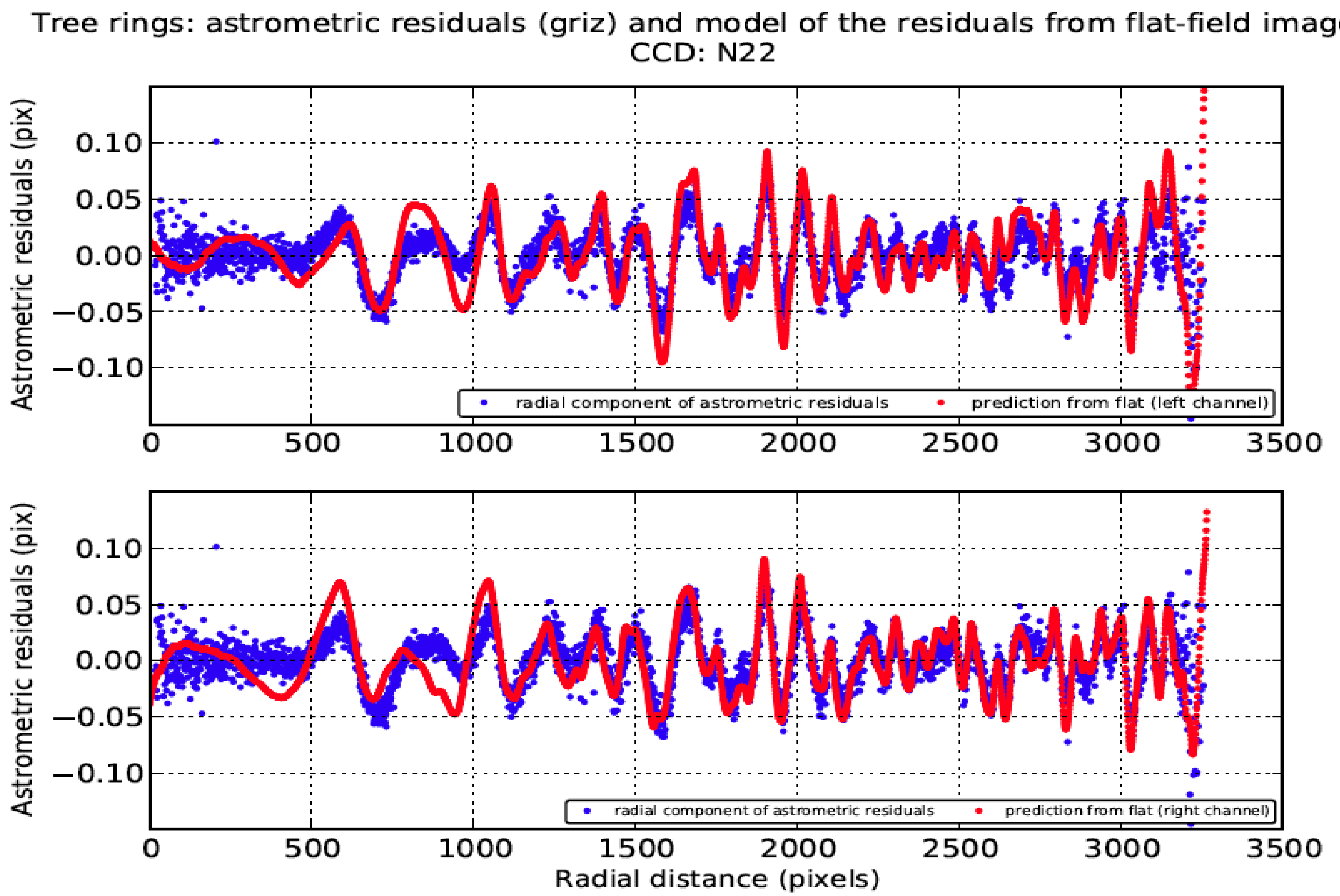
Astrometric residuals: A. Plazas

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



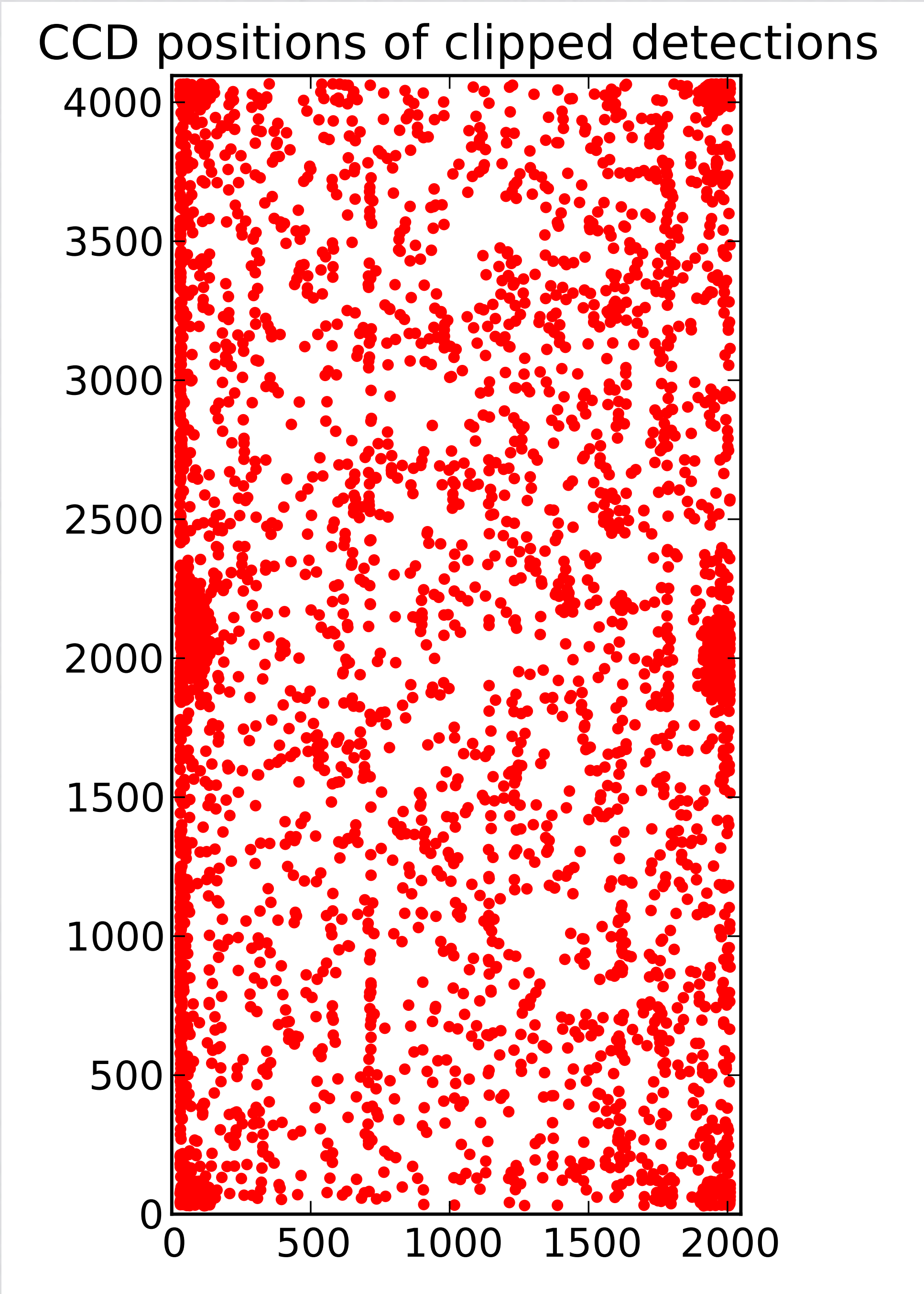
Rings in dome flats nearly perfectly predict annular astrometric displacements

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



From A. Plazas

Outlier photometric measurements are on tape bumps and glowing edges



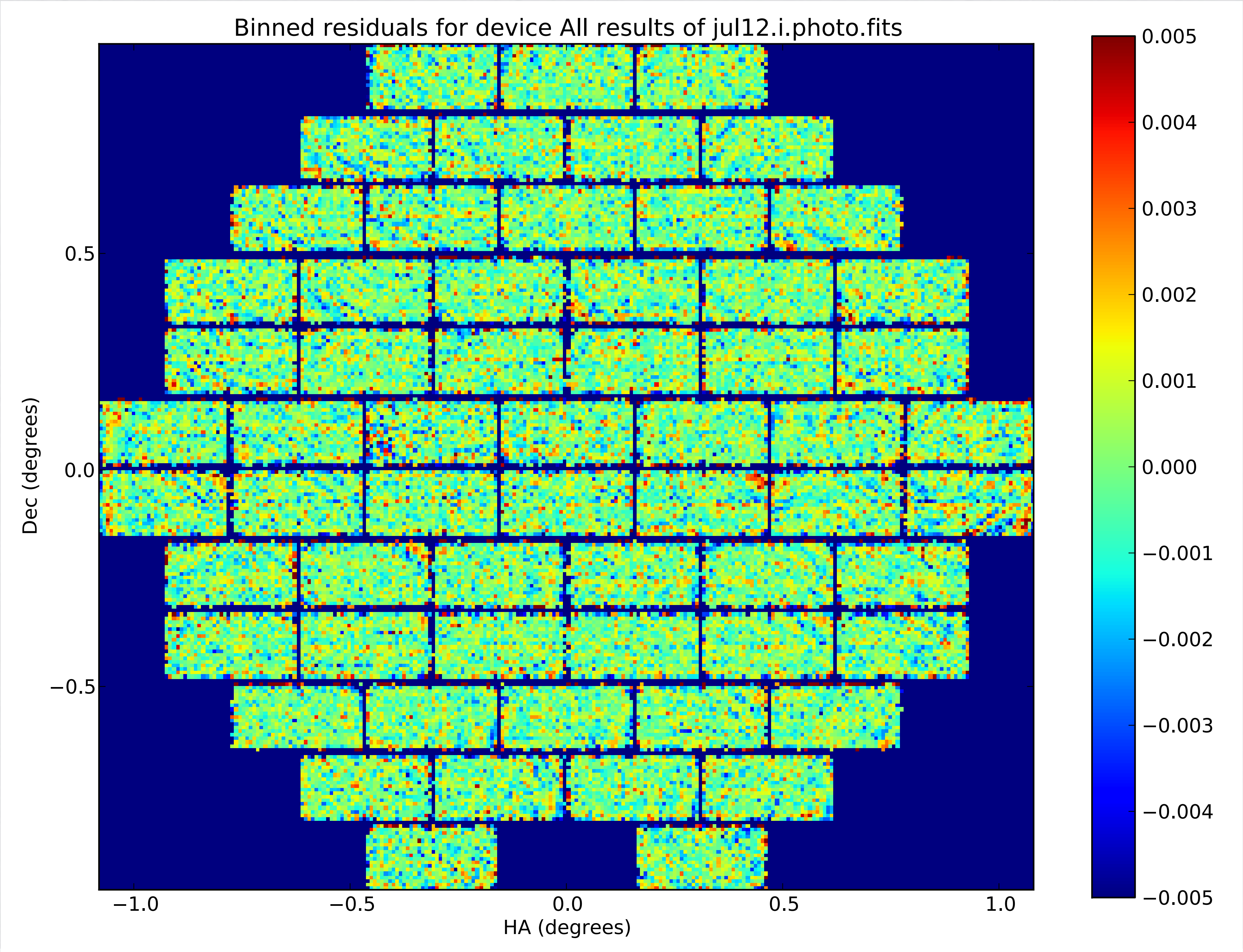
The photometric model

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

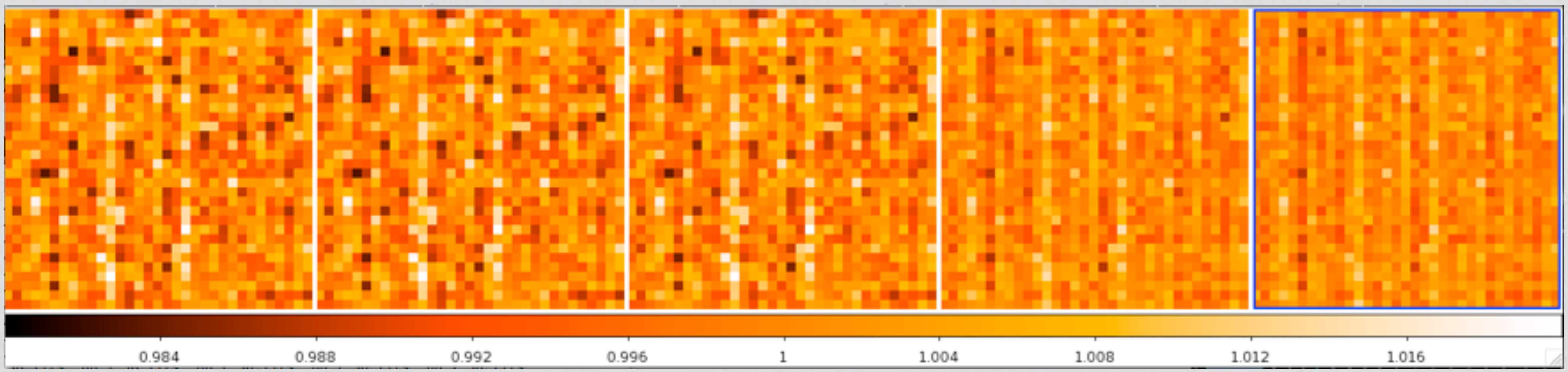
$$Exposure = Const(exposure)$$

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

No discernible patterns of residuals across focal plane.



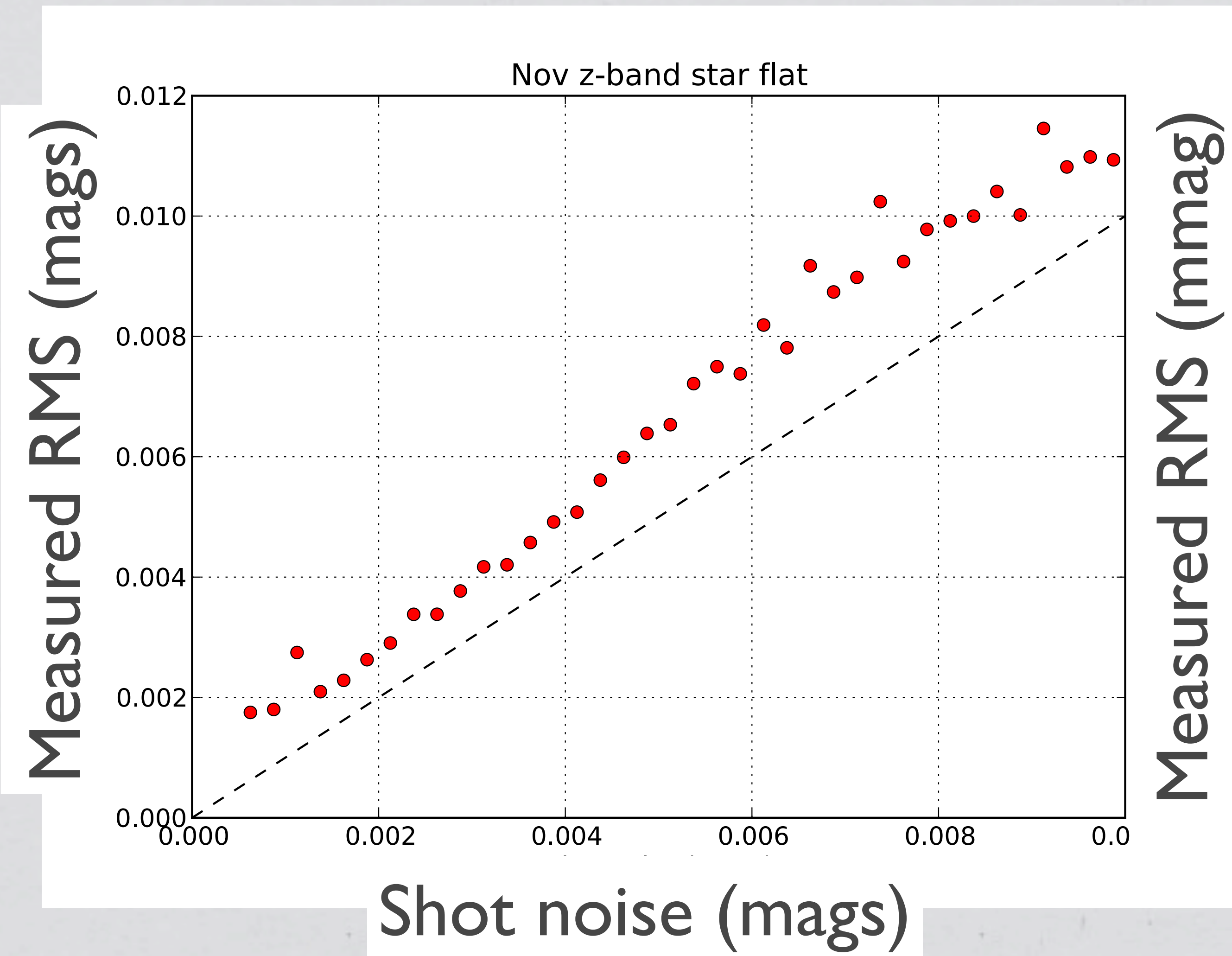
Small-scale structure in flats is also mostly pixel-size variation

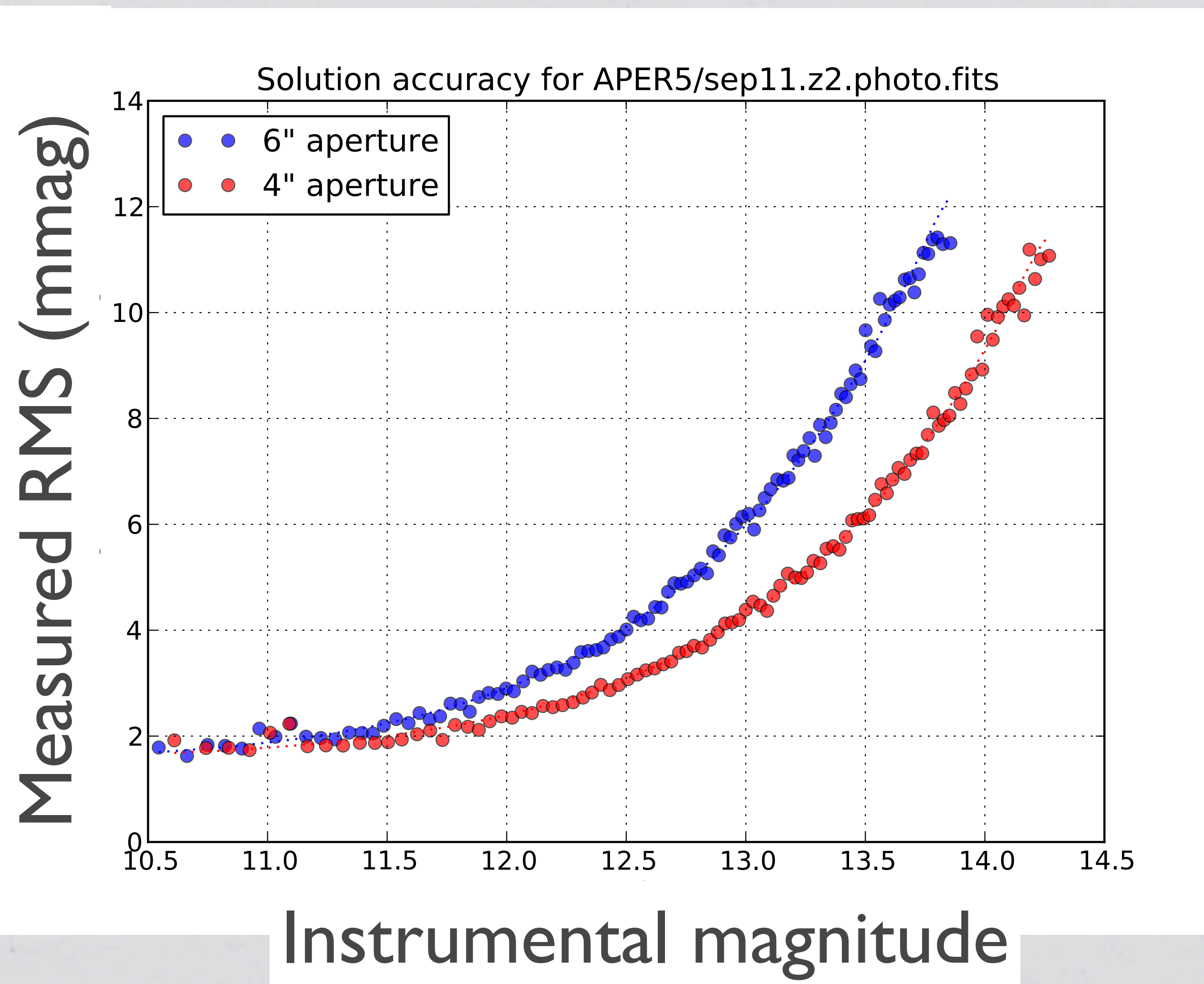


g: 0.63% RMS r: 0.62% RMS i: 0.60% RMS z: 0.47% RMS Y: 0.43% RMS

- 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.

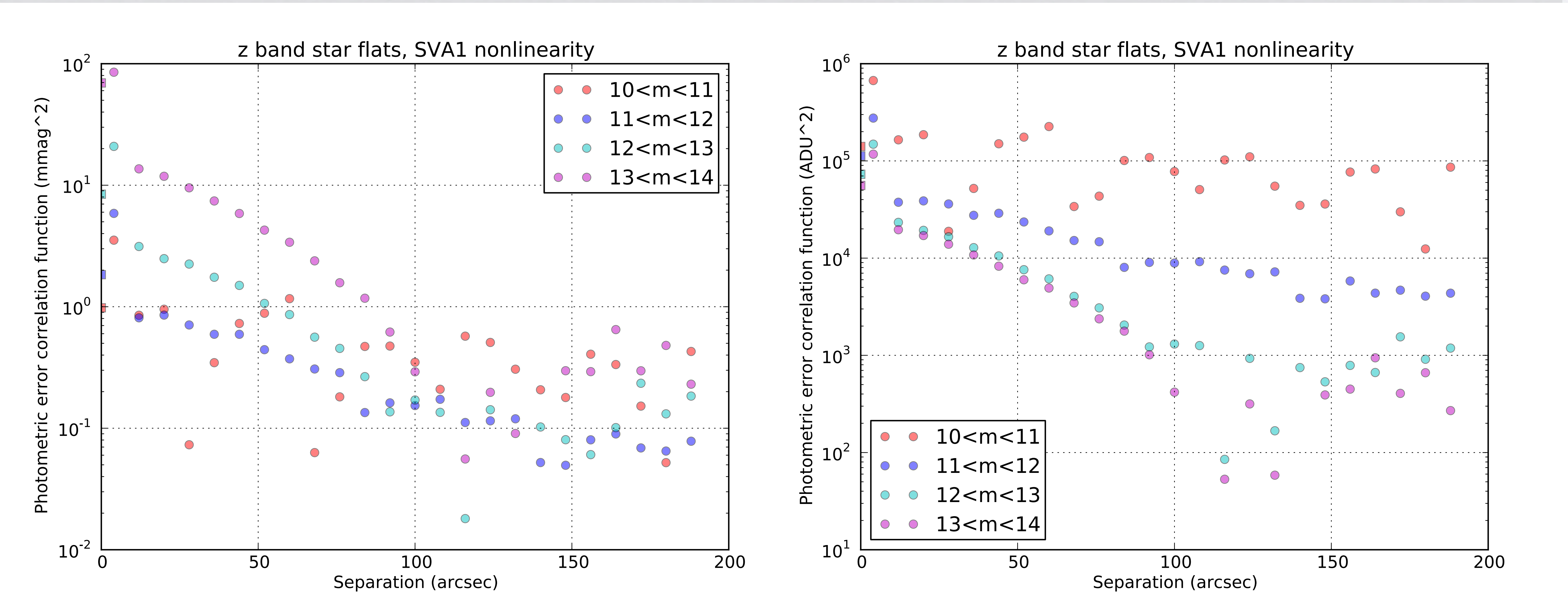
Photometric repeatability using full photometric model is close to shot noise.





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

Correlated photometric errors are < 1 mmag



Consistent with **correlated errors < 1 mmag** (nonlinearity?) + arcmin-scale error roughly 150 ADU in 300 pixel aperture (sky estimation error?)

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	✗	✗	✔	✗	✗

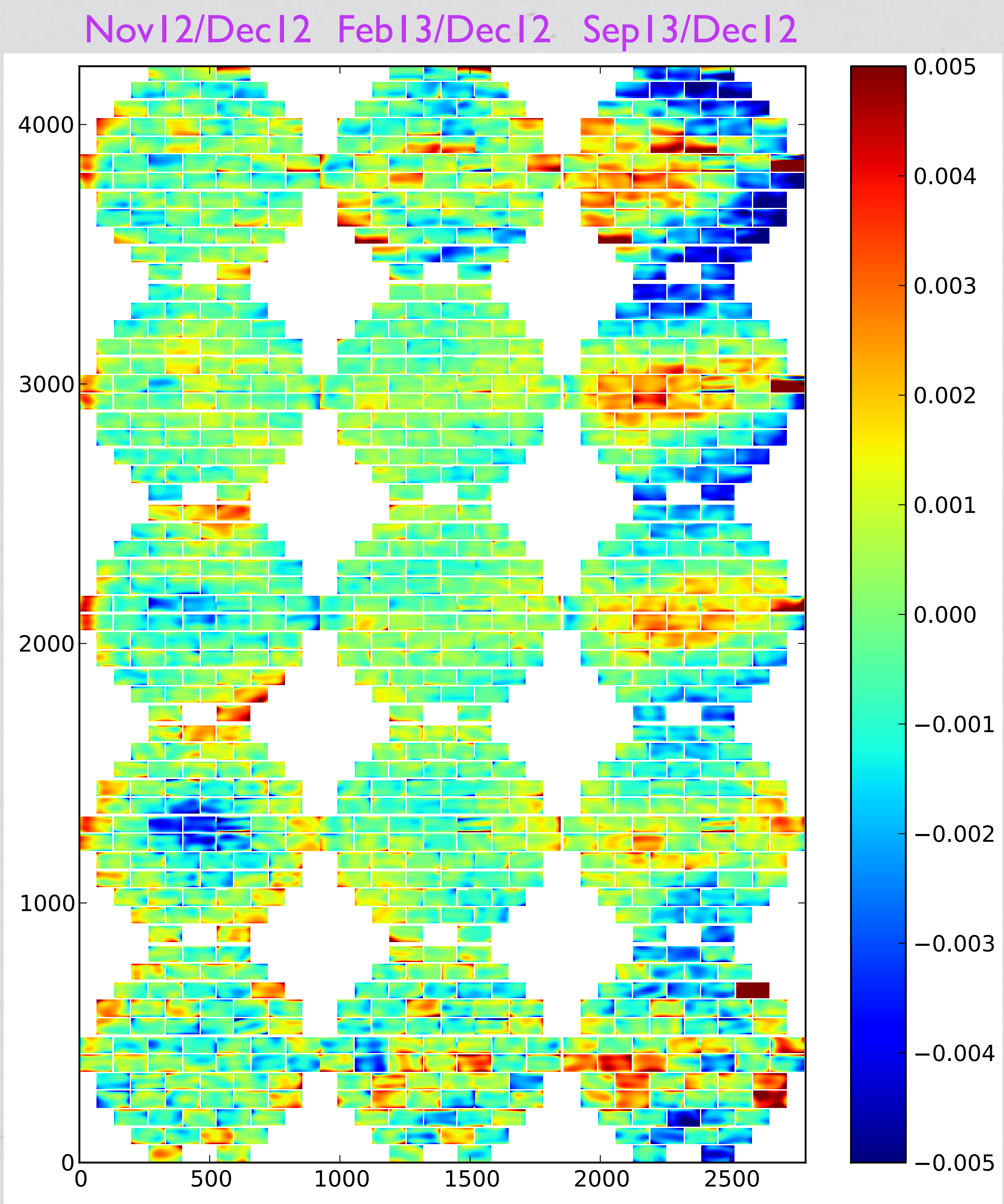
It takes one of these to characterize an instrumental distortion:

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	✗	✗	✔	✗	✗

Can we live with ~0.003 pixel astrometric “noise”?

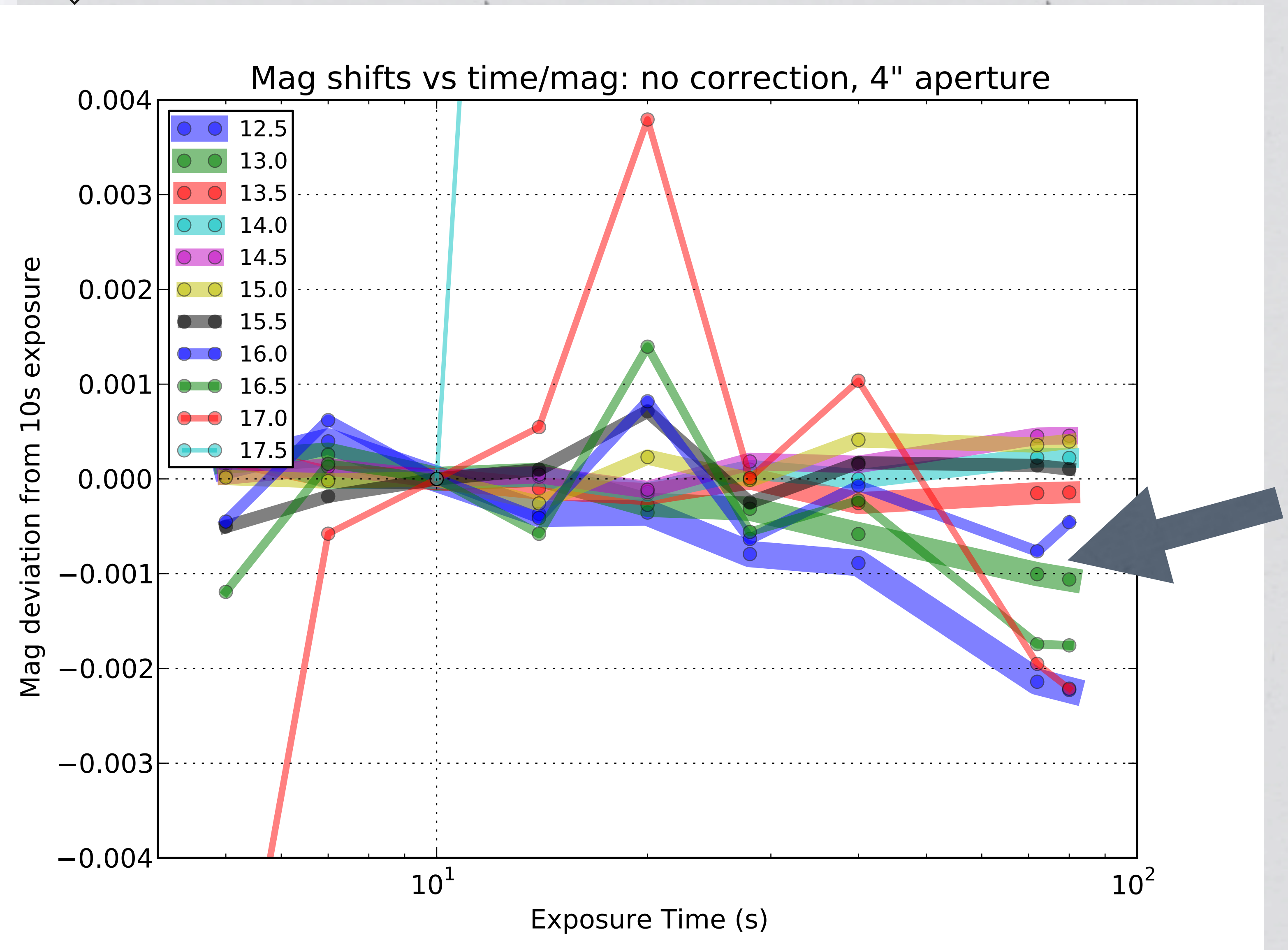
Stellar response changes few mmag over months

g
r
i
z
Y



Dome x Star Flat relative to Dec 2012

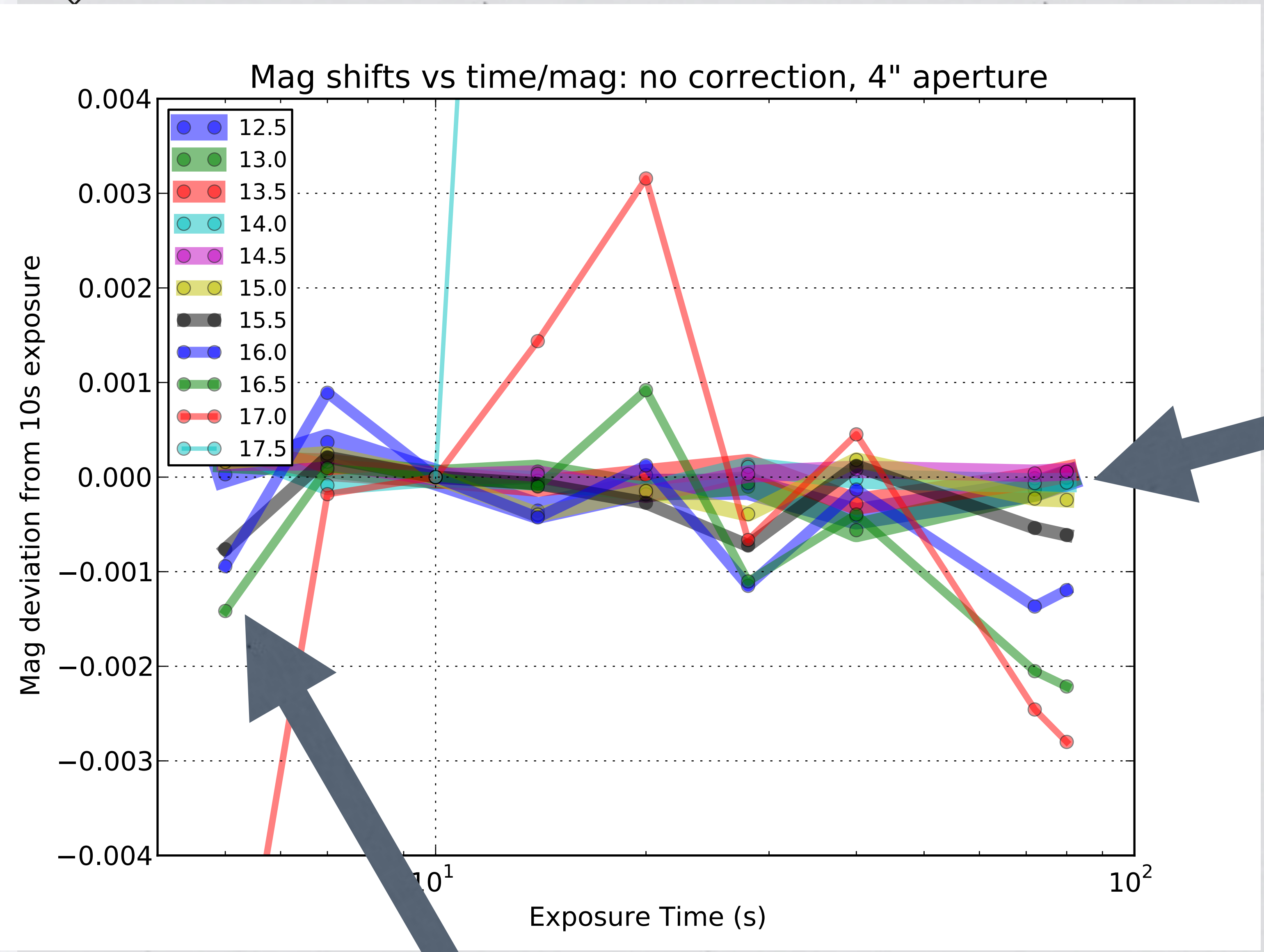
The nonlinearity correction eliminates flux-dependent residuals for bright stars



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

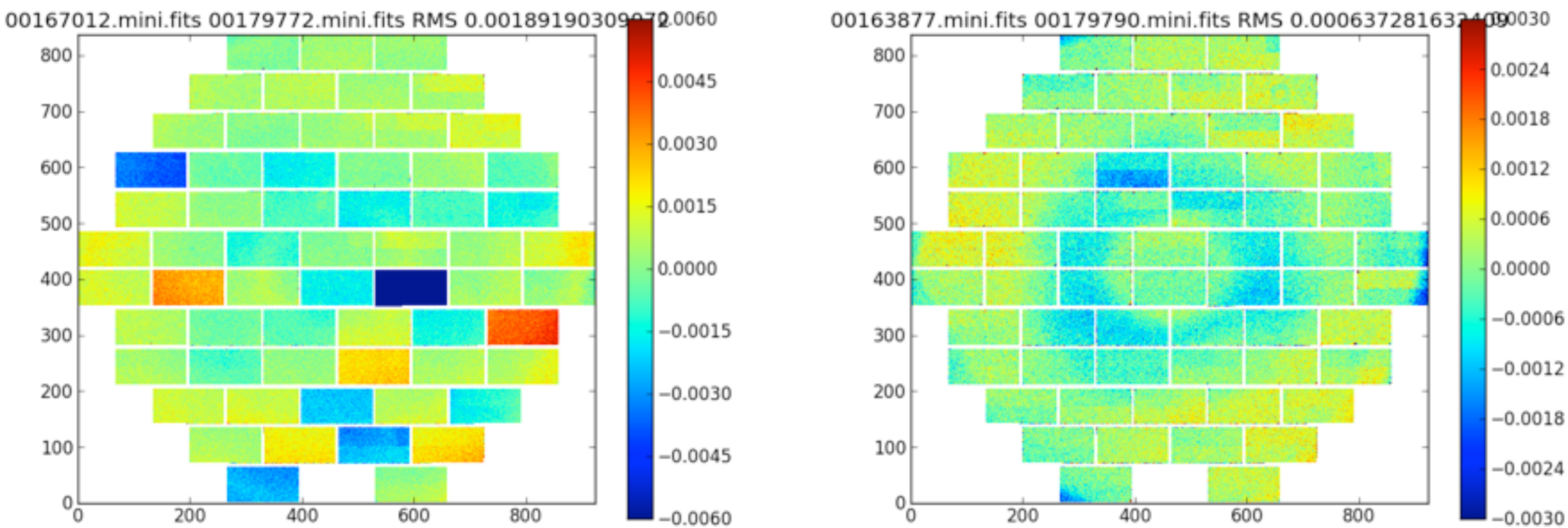


Agreement! >10x better?

Any issues at low ADU?

Focal-plane temperature cycles cause changes in Y-band domes

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

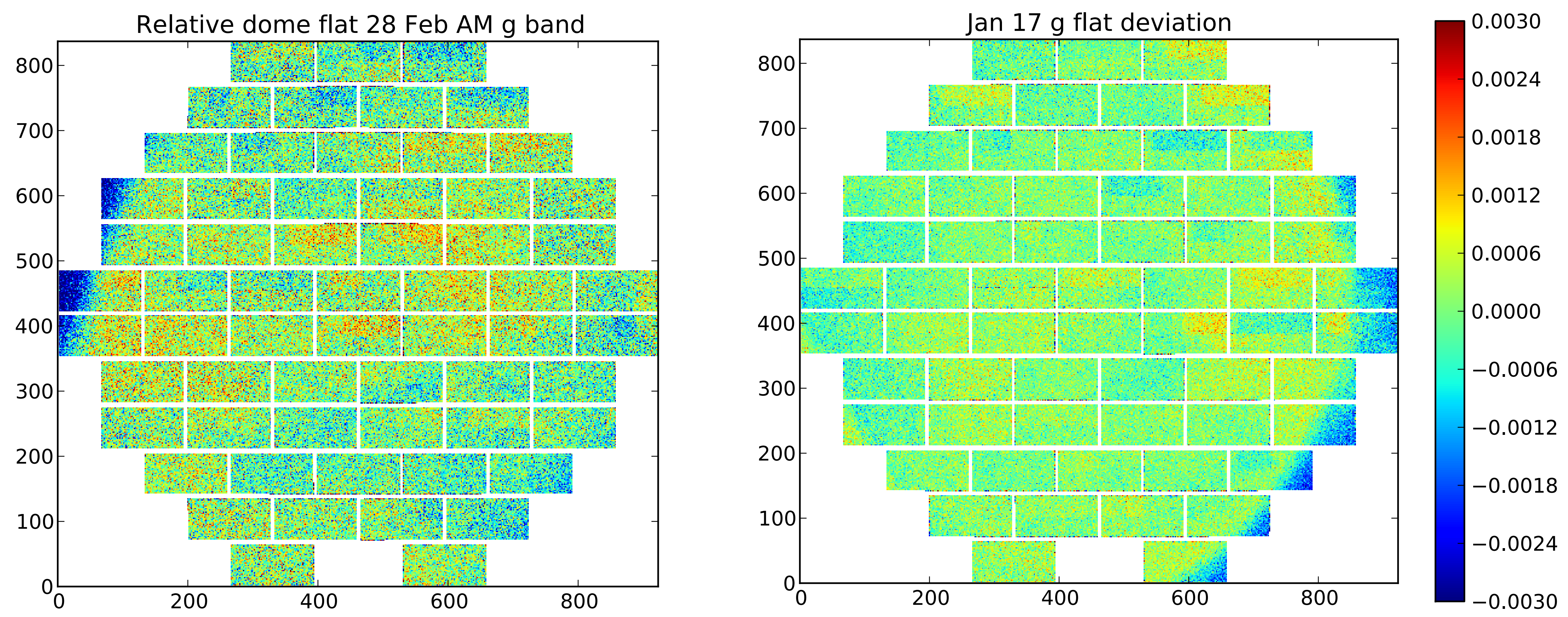


Y band (note scale change) z band

Effect is stronger in the dome flats than in stellar response

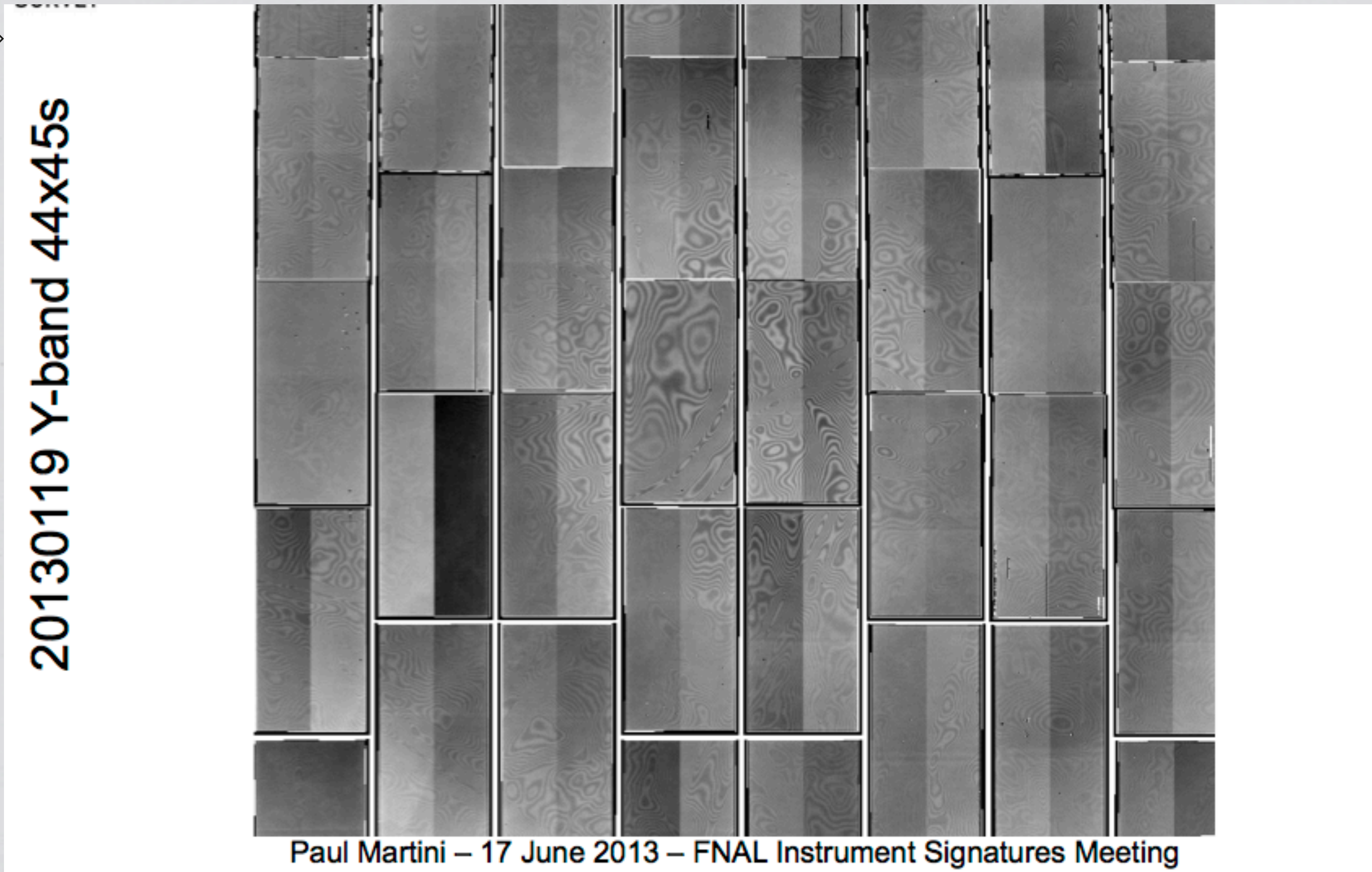
Occurs for temperature excursions as small as 5K!

Stability of dome flats



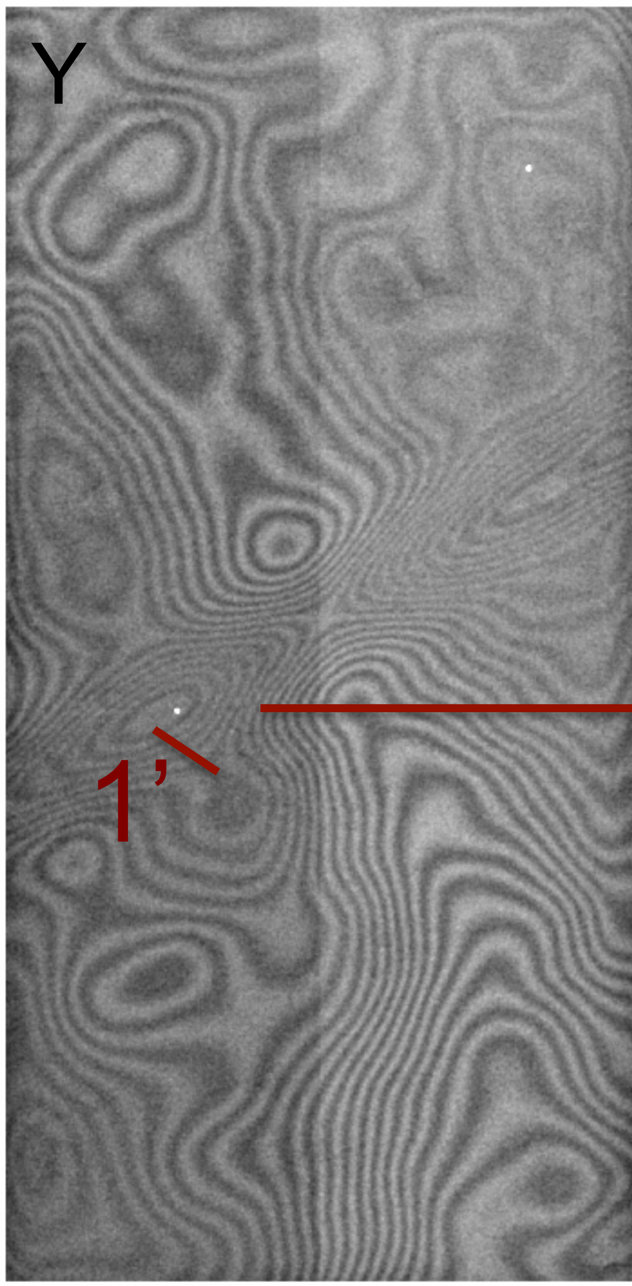
See few-mmag changes over days/weeks/months

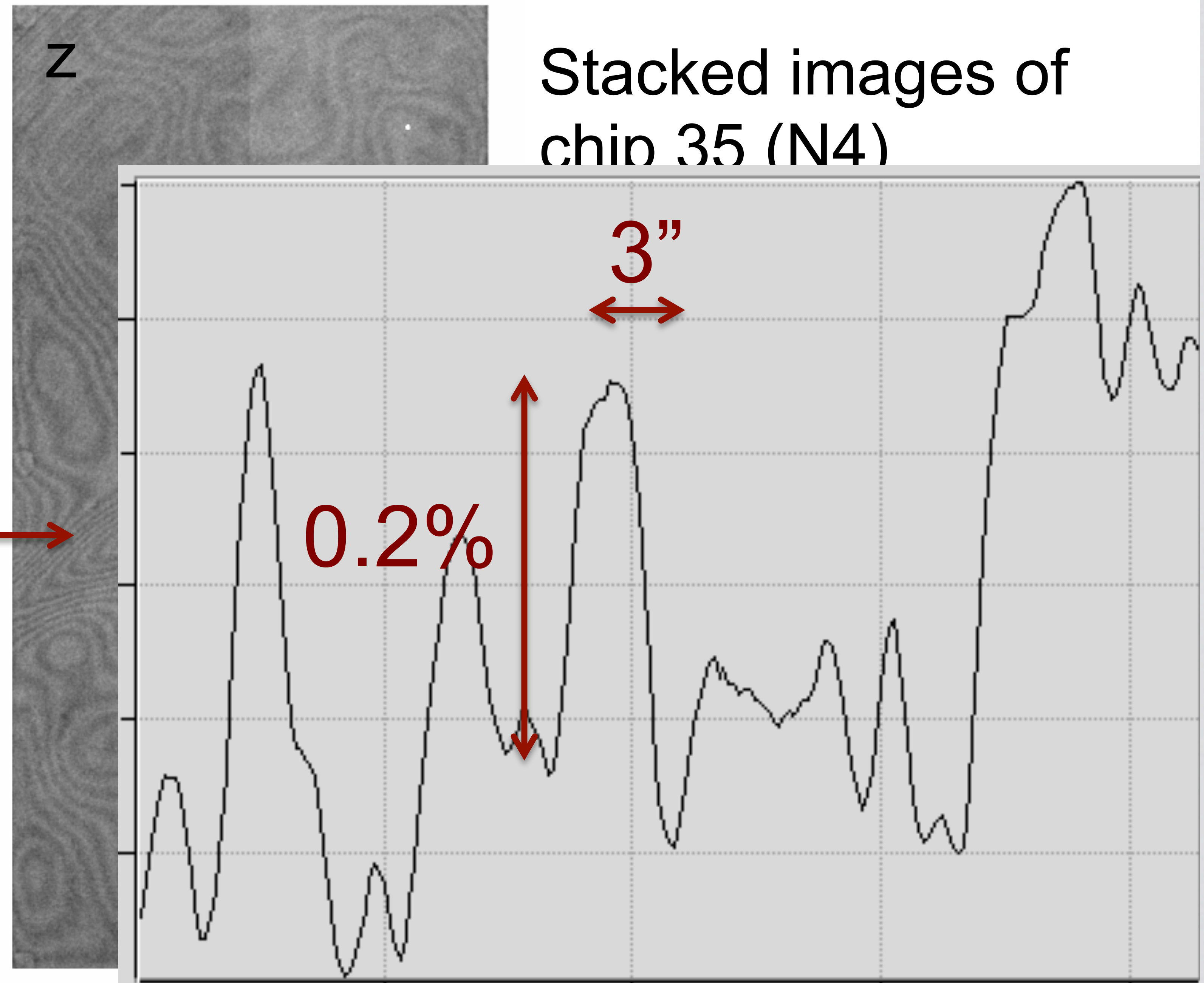
Fringing (via P. Martini)



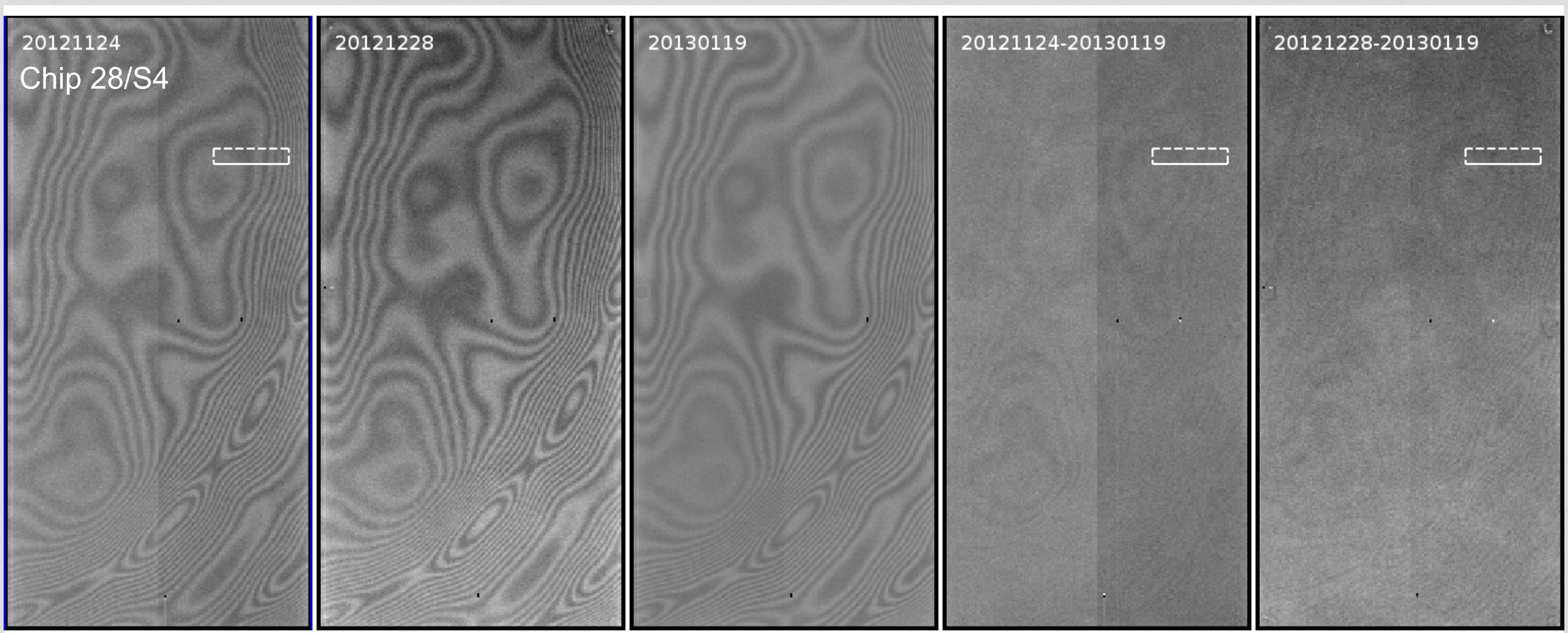
Fringing (via P. Martini)

Stacked images of chip 35 (N4)





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



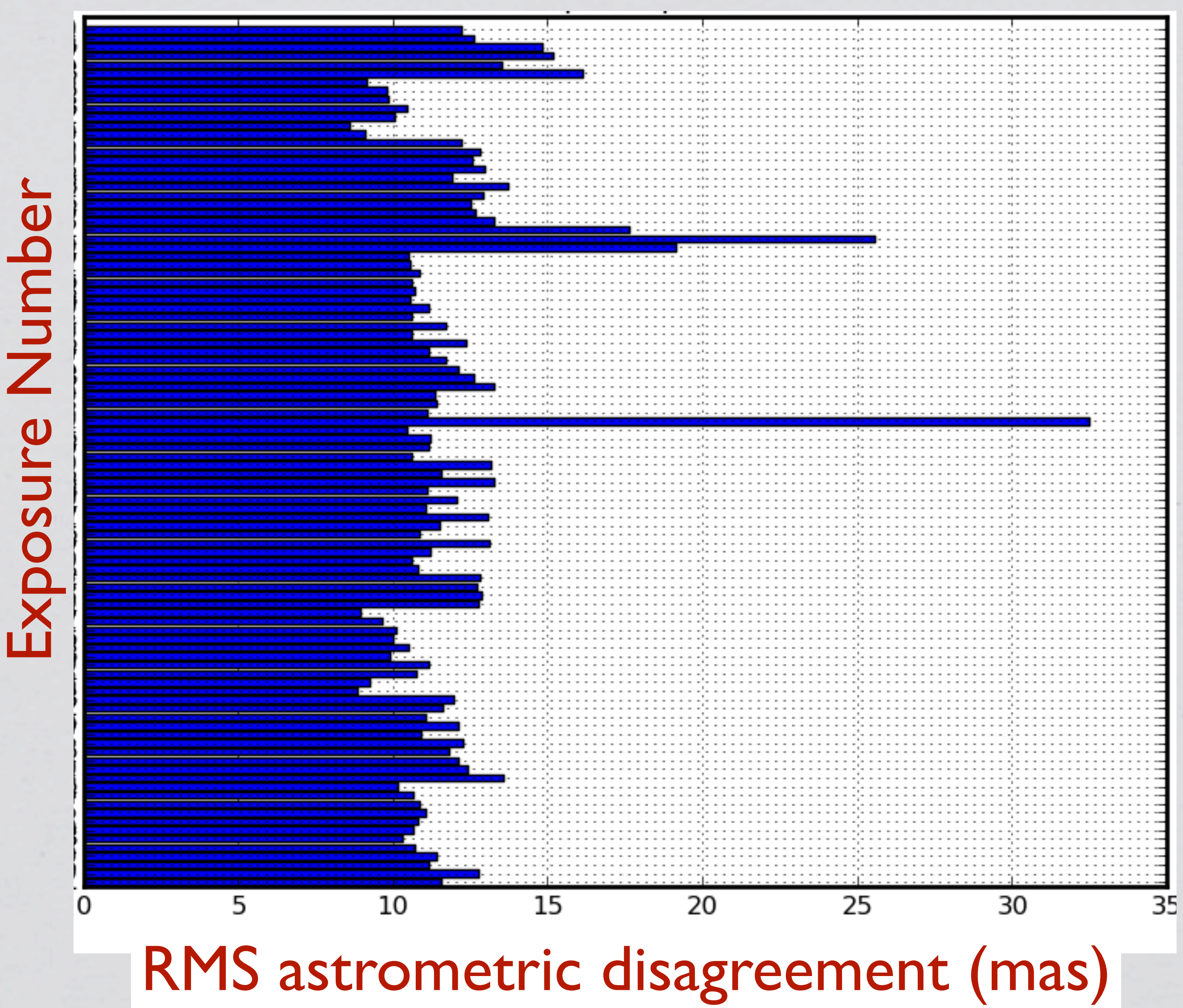
Paul Martini – 17 June 2013 – FNAL Instrument Signatures Meeting

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

Precision relative astrometry

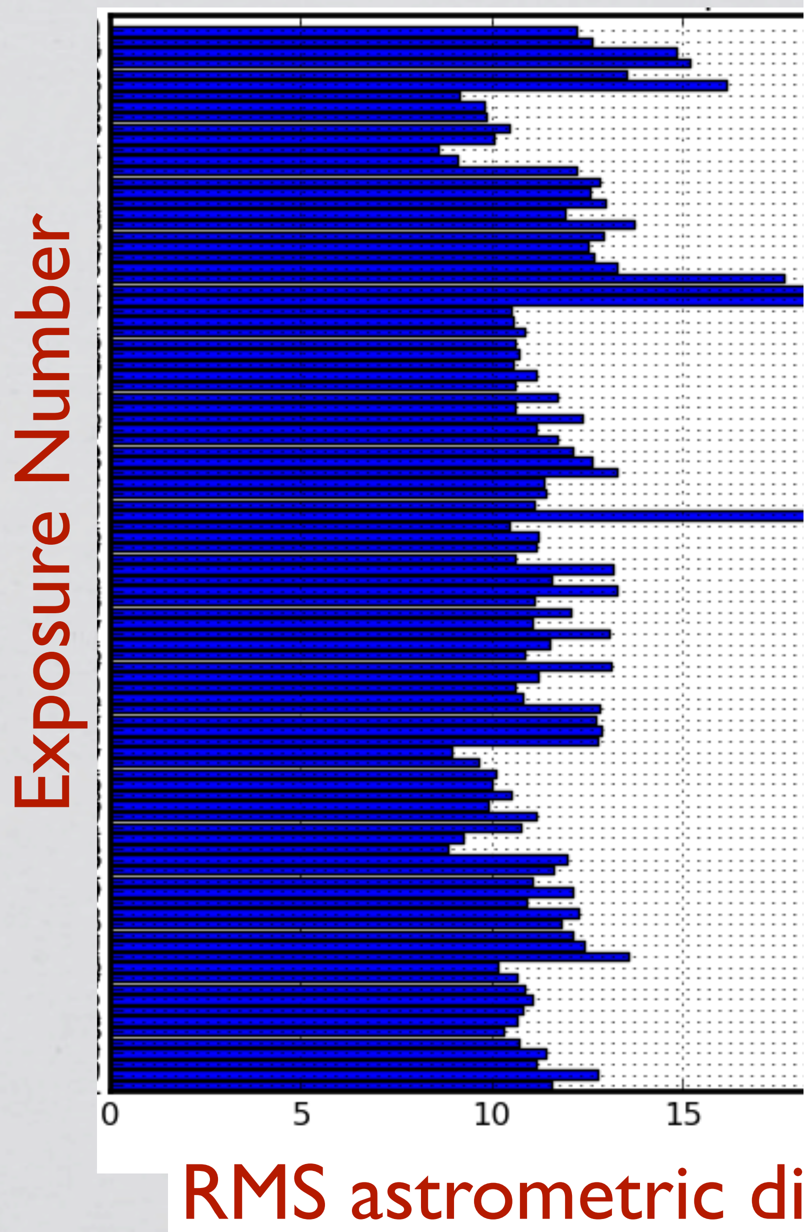
- Analagous to the photometric solution, use star flat data to derive an astrometric solution: *exposure* distortion followed by *instrumental* distortion.
- Current *instrumental* distortion model: Cubic polynomial per CCD, plus templates for tree rings and glowing edges.
- Current *exposure* distortion model: Quadratic polynomial for FOV
- Optimize parameters by minimizing sky-position dispersion among different observations of common stars in star flat exposure sequences.
- Stabilize orientation and scale of solution with external reference catalogs
- Quickly attain accuracy dominated by wave-like displacement patterns per exposure, presumably atmospheric in origin.
- Easily detect milliarcsec distortions due to CCD geometry.

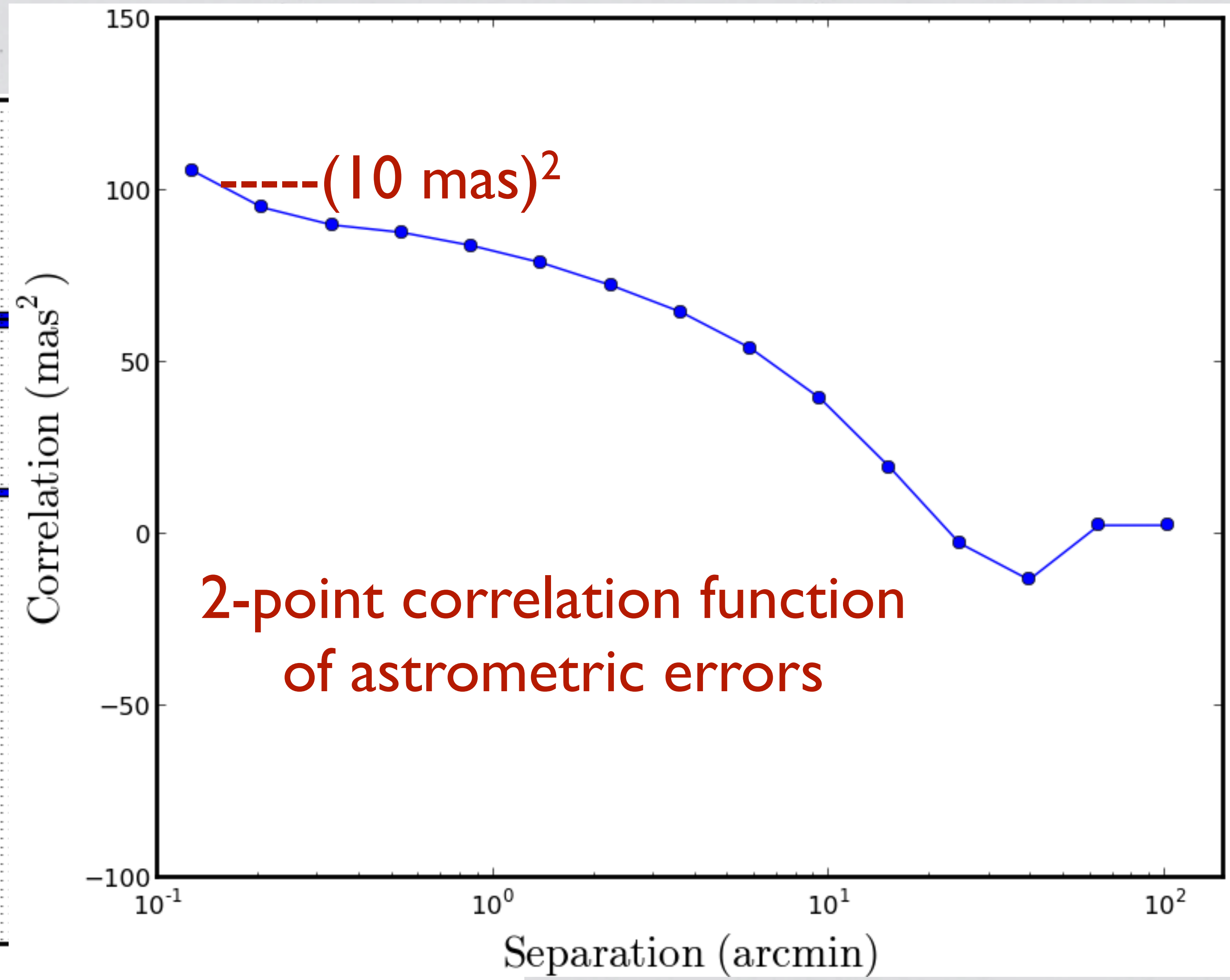
Relative astrometric errors are about 10 mas RMS



From Bob Armstrong

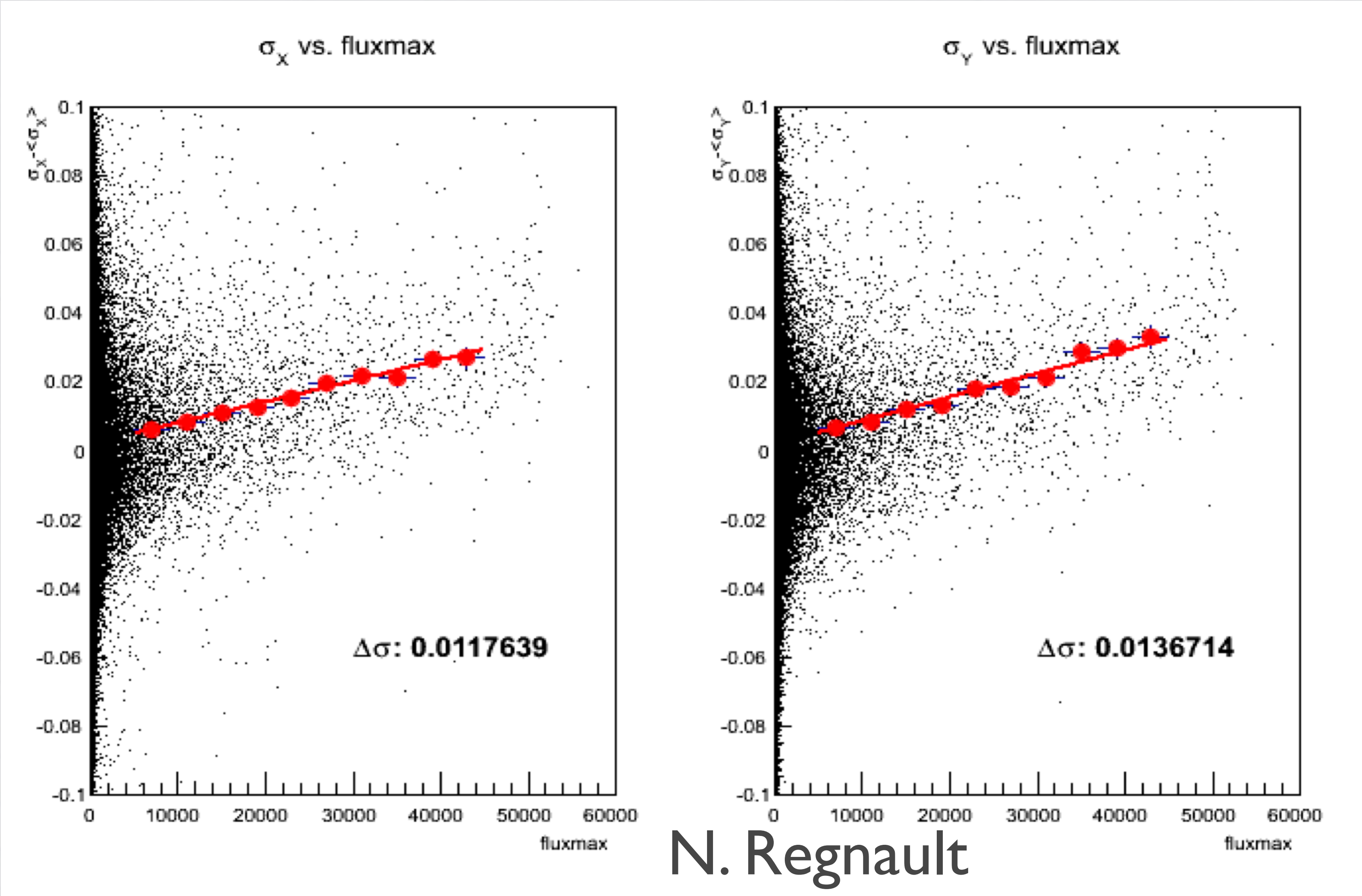
Relative astrometric errors are about 10 mas RMS





From Bob Armstrong

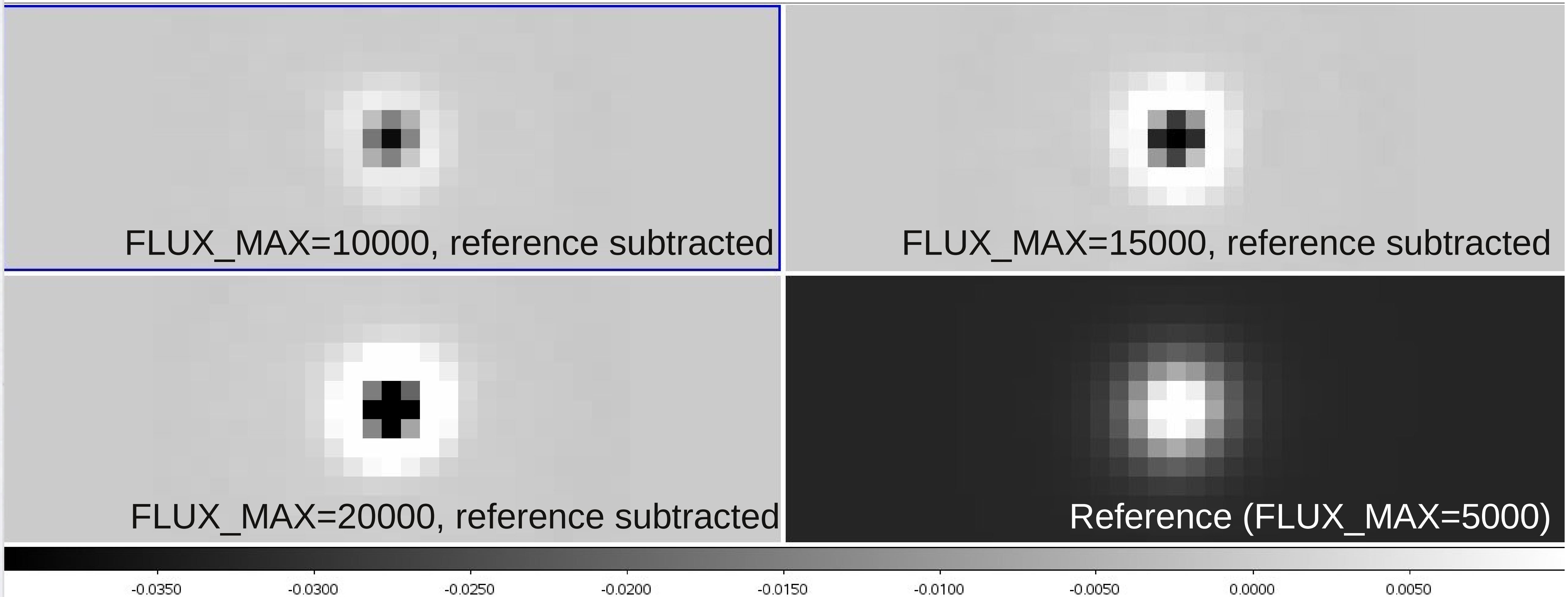
Brighter stars are observed to have broader PSFs



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

From Daniel Gruen:

A PSFEx view



- Clear flux dependence
- Counts are removed from the center and deposited on a ring (normalization doesn't matter since nonlinearity-corrected frames show consistent photometry between long and short exposures)

From Daniel Gruen:

Questions answered

- Is it linear in flux?

  yes!

- Does it depend on exposure time?

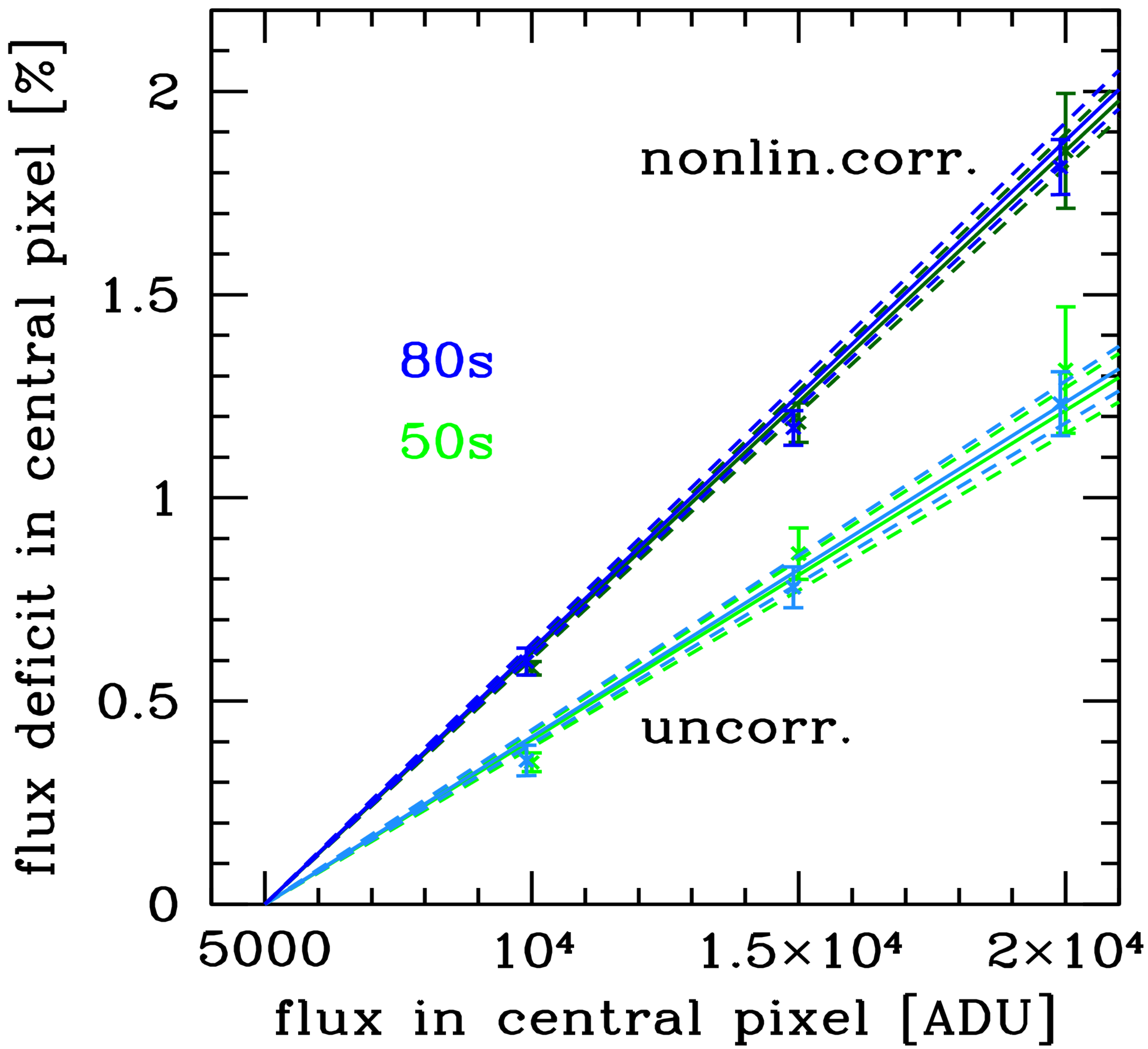
  no!

- Is this just Huan's large-ADU nonlinearity?

  no, opposite!

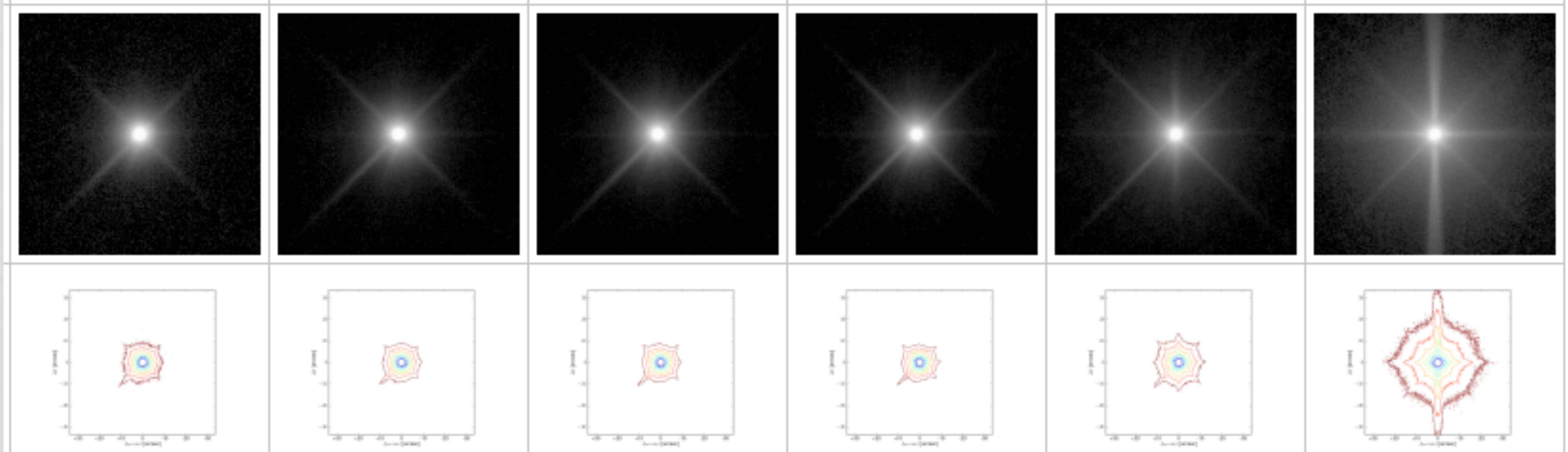
- Is it relevant?

  probably!



PSF shows extended tails and pixel-aligned spikes at red edge

	u	g	r	i	z	Y



	u	g	r	i	z	Y
	psf_u.fits.gz	psf_g.fits.gz	psf_r.fits.gz	psf_i.fits.gz	psf_z.fits.gz	psf_Y.fits.gz
FWHM:	0.99"	0.92"	0.83"	0.75"	0.77"	0.77"
	0.0061	0.0049	0.0041	0.0040	0.0116	0.0516

Last row: mag shift from 6" to 60" OD aperture

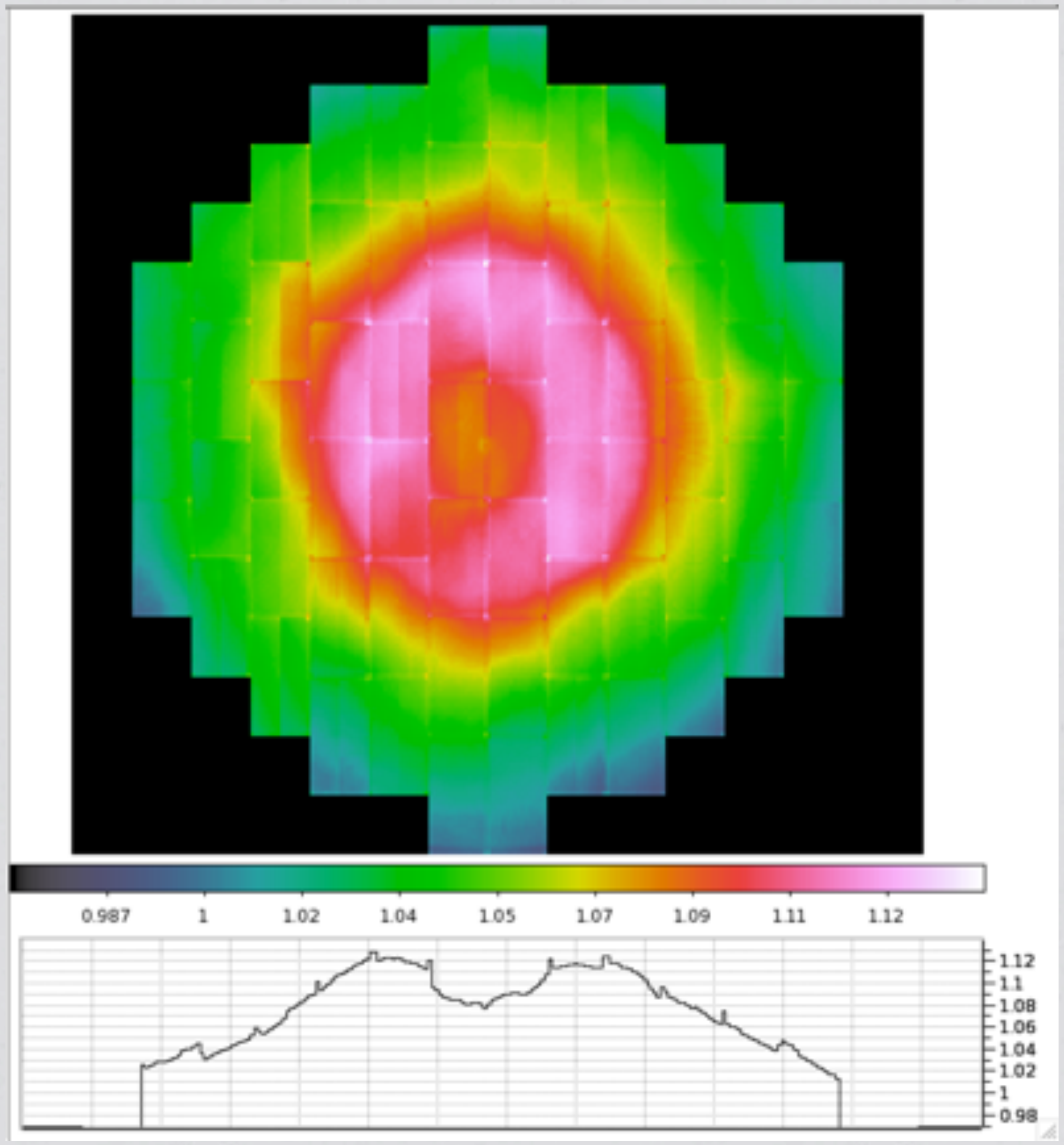
PSF maps out to 60" from Emmanuel Bertin

Highlights

* Great devices with few “features”!
* Weak fringing, as expected from deep-depletion. Stable pattern.
* Deep-depletion CCDs more susceptible to pixel-area variations.
  * We characterize and remove 2 known patterns, mask 1.
  * Constant response is better approximation to QE than are the dome flats!
  * No method available to map the small-scale 0.003-pixel astrometric shifts.
* With proper treatment of scattered light & pixel-size variations: Attain 1.5-2 mmag photometric repeatability across array (+sky estimation errors)
* Few-mmag p-p response variation over a season.
* Stellar response more stable than dome flats!
* Astrometry limited to10 mas by probable atmospheric effects
* Brighter-fatter relation exists, likely correctable at pixel level.

Extra slides

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!*
- But the center-to-edge gradient is a real feature of the filter (we think).

Periodic signal along DECam rows