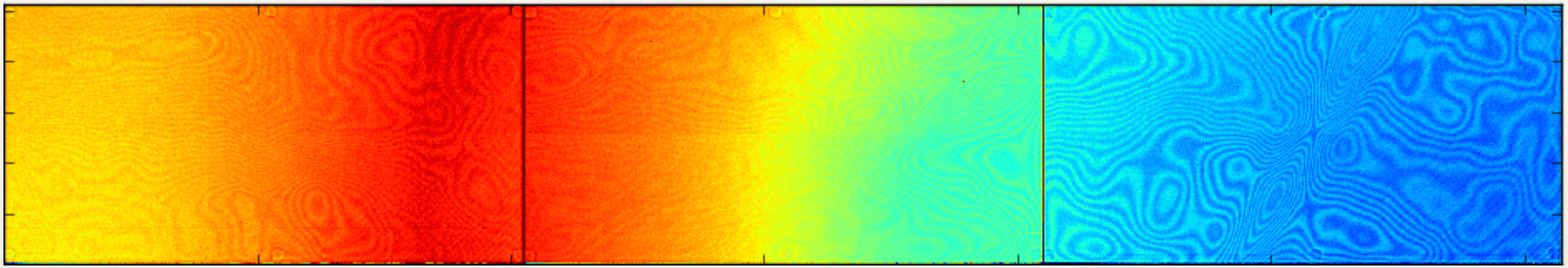


How clear is a cloudless sky?

Gary Bernstein
(University of Pennsylvania)
and the DES Collaboration

9 July 2015

Motivations

- The *Dark Energy Survey (DES)* consists of
  - WIDE survey in *grizY* of 5000 deg^2 covered 10x90s per filter over 5 years
  - SUPERNOVA survey of ~weekly imaging in *griz* of 10 fields covering 30 deg^2.
- Consistent photometry - *measuring the same magnitude for a source no matter when or where in the survey it is observed* - is critical to many survey goals, esp. galaxy clustering, photo-z's, and SN cosmology.
- State of the art for large surveys: 10-20 mmag for SDSS "ubercal" (Padmanabhan et al 2008), 8-12 mmag for PanStarrs 3pi survey (Magnier et al 2013).

Can we do better? How?

Calibration steps

1. Get the same flux for a source across the focal plane of a given exposure (“detrending”)
2. Get the same flux for sources observed in different exposures across the full time/angle span of survey (“global calibration”)
3. Extend 1 & 2 to include sources of arbitrary (but known) spectral shape (“color calibration”)
4. Place flux scale into physical units (“absolute calibration”)

Detrending model

Assuming here that we have already estimated the count rate by removing bias, correcting detector nonlinearities, and subtracting sky background:

$$\overbrace{\mathbf{Rate}_\star}^{\textit{Count rate per pixel}} = \int d\lambda\, \overbrace{r_{\mathrm{ref}}(\lambda)}^{\textit{Reference bandpass}} \overbrace{\mathbf{r}(\lambda, t)}^{\textit{Response variations}} \left[\overbrace{\mathbf{I}_\star(\lambda, t)}^{\textit{Sky brightness signal}} + \overbrace{\mathbf{I}_{\mathrm{ghost}}(\lambda, t)}^{\textit{Reflections, ghosts, etc}}\right] \overbrace{\boldsymbol{\Omega}}^{\textit{Solid angle per pixel}}$$

$$\mathbf{Dome} = \int d\lambda\, r_{\mathrm{ref}}(\lambda)\mathbf{r}(\lambda, t)\mathbf{I}_{\mathrm{LED}}(\lambda)\left[1 + \overbrace{s(\lambda, t)}^{\textit{Diffuse scattered light fraction}}\right] \boldsymbol{\Omega}$$

$$\mathrm{flux}(t) = \sum_{\mathrm{pix}} \int d\lambda r_{\mathrm{ref}}(\lambda)\mathbf{I}_\star(\lambda, t)\boldsymbol{\Omega} \neq \sum_{\mathrm{pix}} \frac{\mathbf{Rate}_\star}{\mathbf{Dome}}$$

Detrending model

$$\mathbf{Rate}_\star = \int d\lambda\, r_{\rm ref}(\lambda)\mathbf{r}(\lambda,t)\left[\mathbf{I}_\star(\lambda,t) + \xcancel{\mathbf{I}_{\rm ghost}}(\lambda,t)\right]\boldsymbol{\Omega}$$

$$\mathbf{I}_\star(\lambda,t) = f\,F(\lambda)\,\mathbf{PSF}(\lambda,t)$$

If the star has known spectral *shape F* and we want to know the flux *f*, then a correct formula for extracting the flux is:

$$f = \frac{1}{C(t)}\sum_{\rm pix}\frac{\mathbf{Rate}_\star}{\mathbf{r}(t)}$$

$$\mathbf{r}(t) = \int d\lambda\, F_{\rm ref}(\lambda) r_{\rm ref}(\lambda)\mathbf{r}(\lambda,t)$$

"Reference flat"

$$C(t) = \frac{\int d\lambda\, F(\lambda) r_{\rm ref}(\lambda)\mathbf{r}(\lambda,t)}{\int d\lambda\, F_{\rm ref}(\lambda) r_{\rm ref}(\lambda)\mathbf{r}(\lambda,t)}$$

"Color correction"

Our task:

- Determine the *reference flat* **r** giving response to a standard-spectrum star vs array position and time. Split into $\mathbf{r}=\mathbf{r}_{\mathrm{inst}}\,\mathbf{r}_{\mathrm{expo}}$
  - Instrument term is fixed in time (for each season)
  - Exposure term has only mild spatial dependence (constant, linear, or quadratic across entire array).
- Determine the color correction for non-standard-spectrum objects, requiring either many observations of such objects, or knowledge of instrument spectral response.

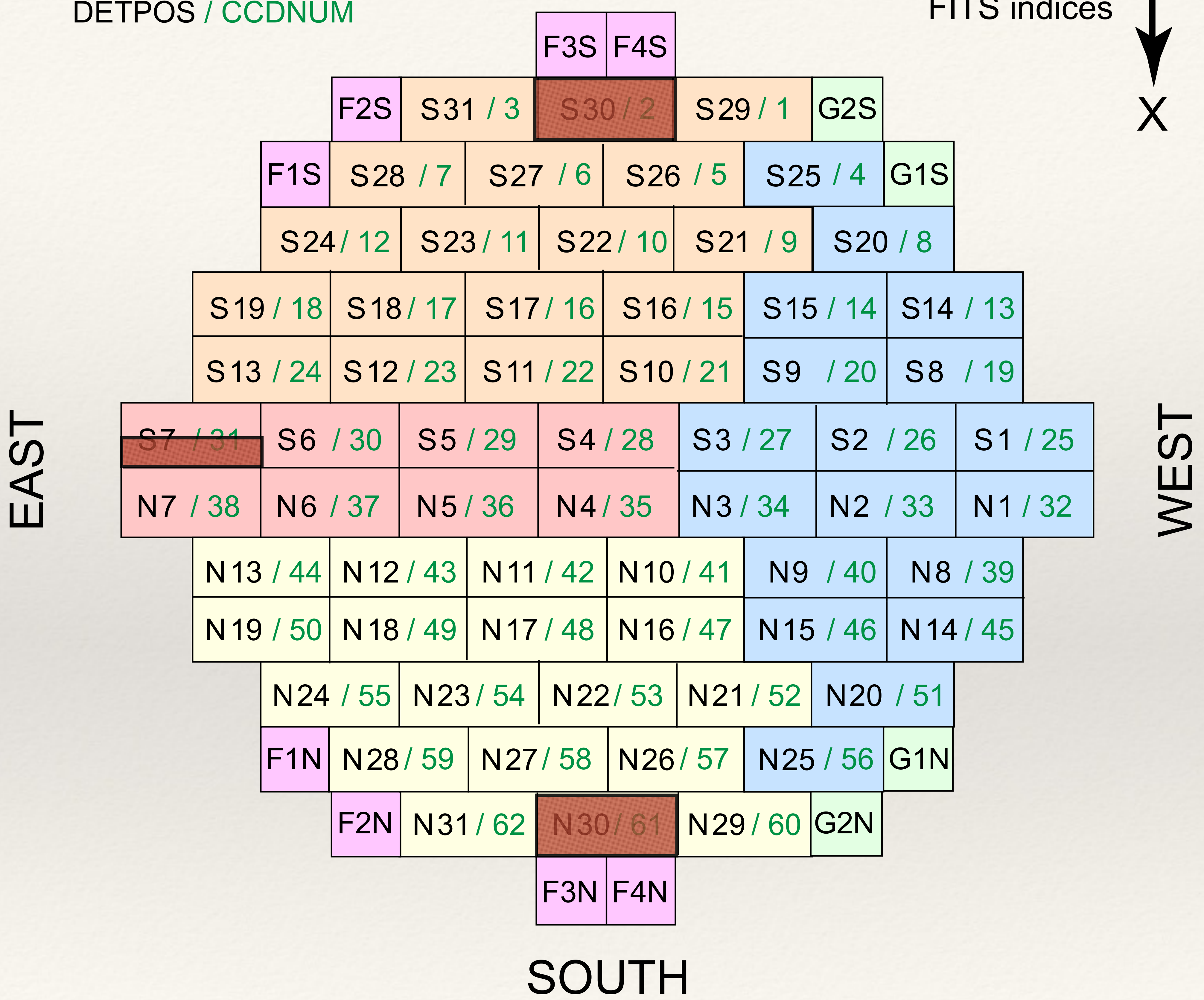
The instrument response

- The dome flat differs from the reference flat because:
  - It does not have reference spectrum
  - Illumination of pupil is slightly different
  - Contains scattered light
  - Mixes pixel-area and QE terms
- The dome flat is a good first approximation but we need to disentangle above effects to reach <=20 mmag RMS. What other information do we have?

Sky Orientation of DECam

NORTH

DETPOS / CCDNUM



Y

FITS indices

X

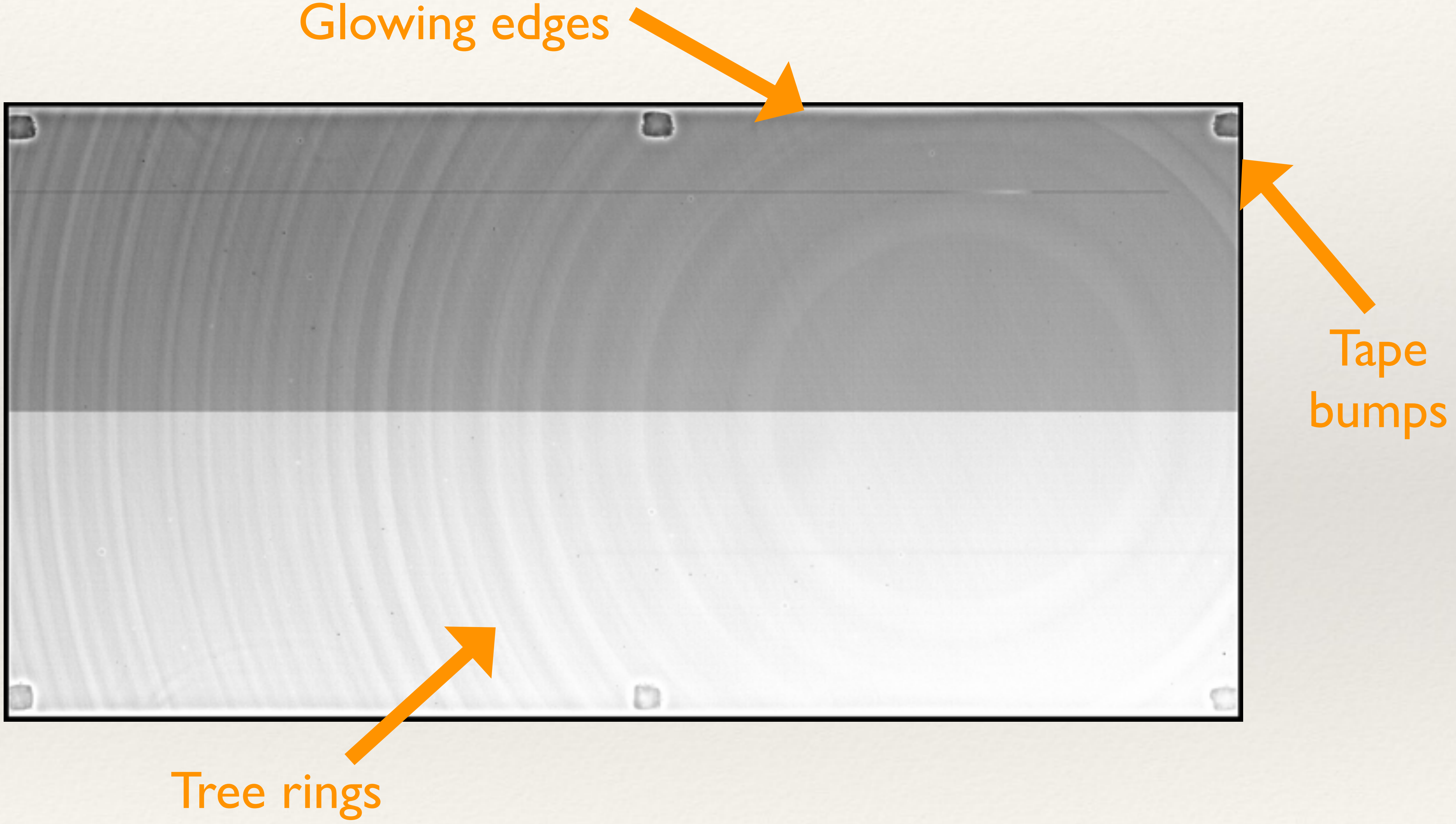
F3S F4S
F2S S31 / 3 S30 / 2 S29 / 1 G2S
F1S S28 / 7 S27 / 6 S26 / 5 S25 / 4 G1S
S24 / 12 S23 / 11 S22 / 10 S21 / 9 S20 / 8
S19 / 18 S18 / 17 S17 / 16 S16 / 15 S15 / 14 S14 / 13
S13 / 24 S12 / 23 S11 / 22 S10 / 21 S9 / 20 S8 / 19
S7 / 31 S6 / 30 S5 / 29 S4 / 28 S3 / 27 S2 / 26 S1 / 25
N7 / 38 N6 / 37 N5 / 36 N4 / 35 N3 / 34 N2 / 33 N1 / 32
N13 / 44 N12 / 43 N11 / 42 N10 / 41 N9 / 40 N8 / 39
N19 / 50 N18 / 49 N17 / 48 N16 / 47 N15 / 46 N14 / 45
N24 / 55 N23 / 54 N22 / 53 N21 / 52 N20 / 51
F1N N28 / 59 N27 / 58 N26 / 57 N25 / 56 G1N
F2N N31 / 62 N30 / 61 N29 / 60 G2N
F3N F4N

EAST

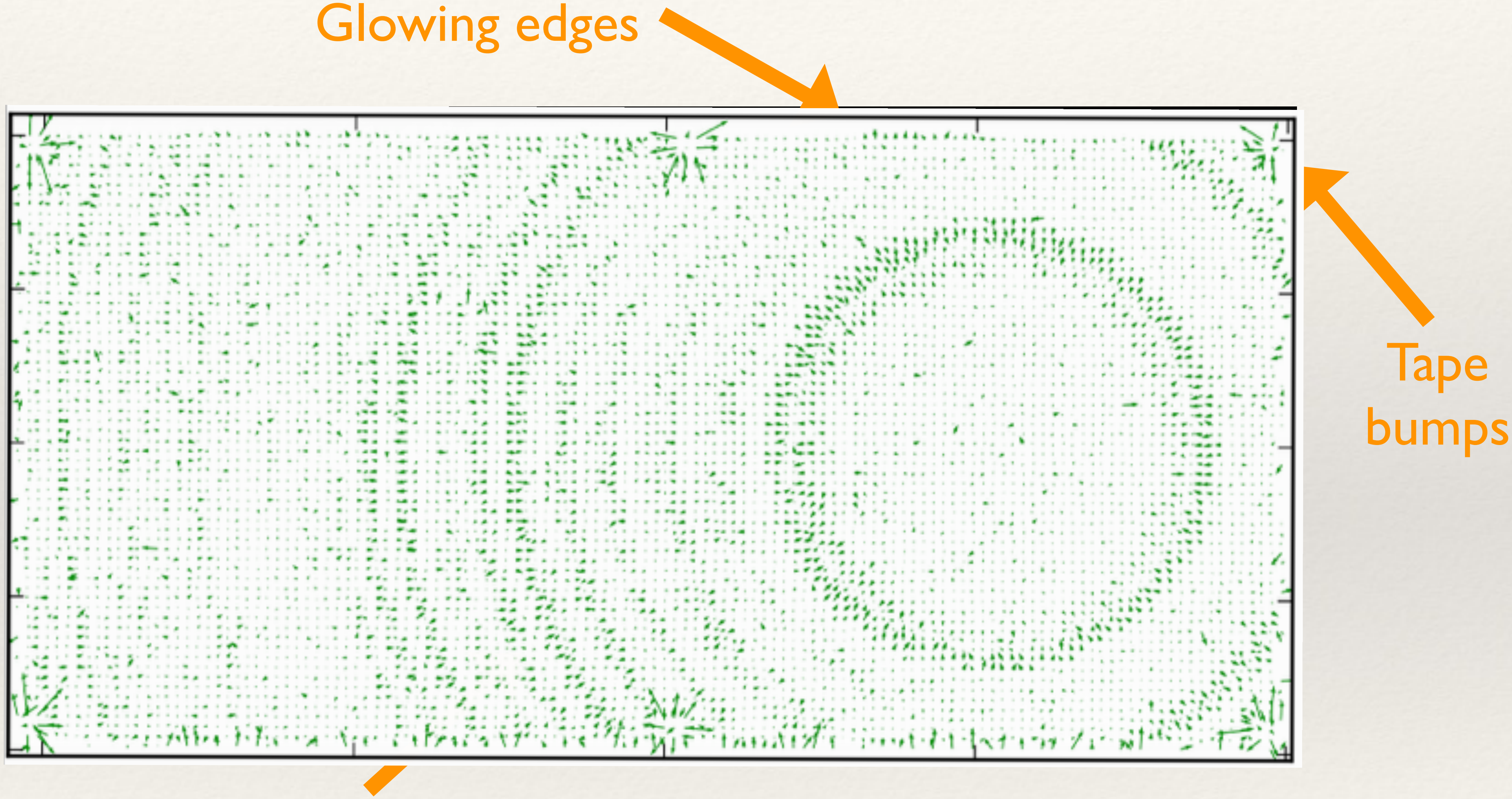
WEST

SOUTH

A typical dome flat from DECam



A typical dome flat from DECam



Glowing edges

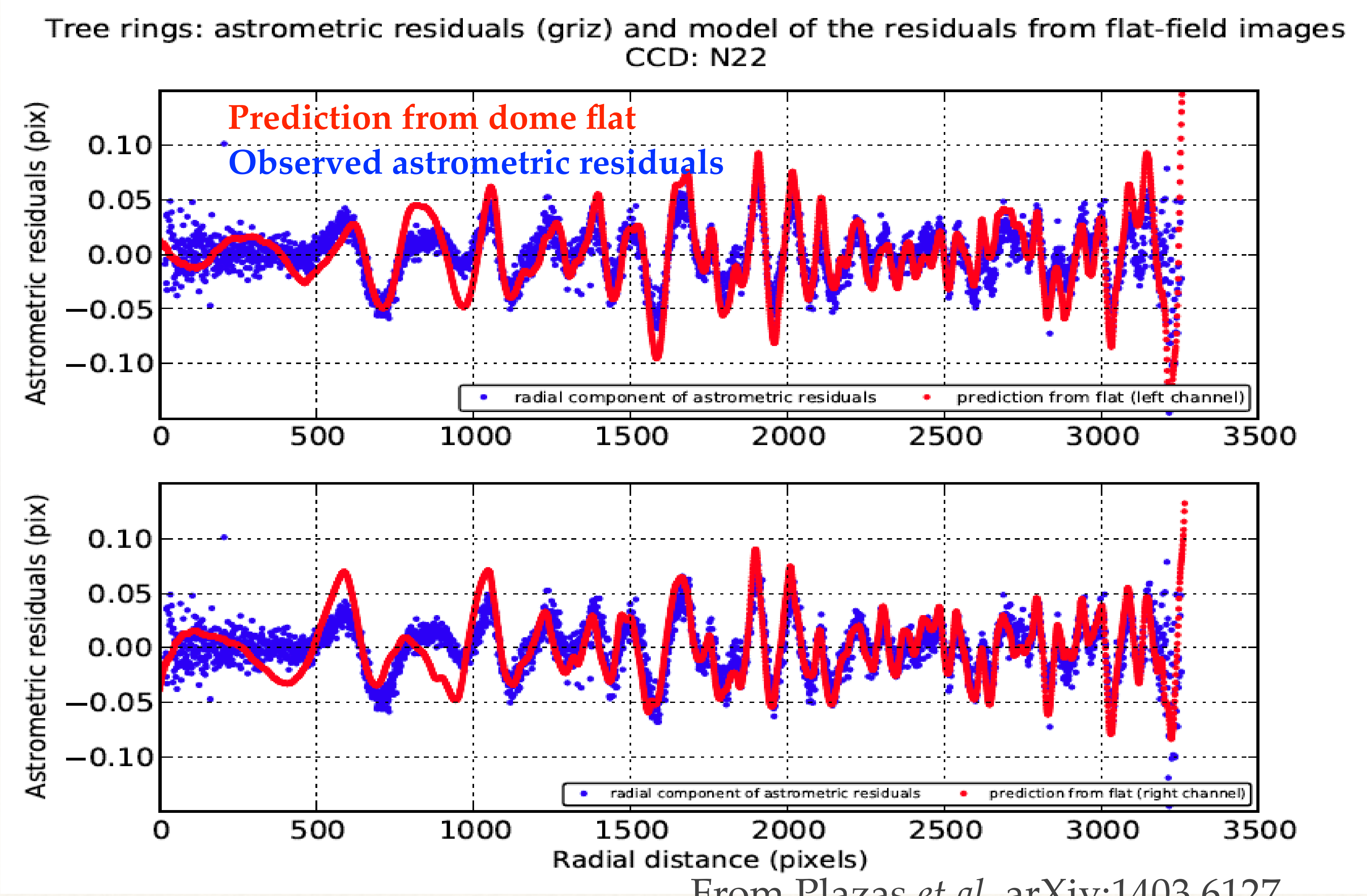
Tape bumps

Tree rings

Astrometric residuals: A. Plazas

Most of the structure in dome flats at scales 1″-10′ is pixel-scale variation!

Rings in dome flats nearly perfectly predict annular astrometric displacements

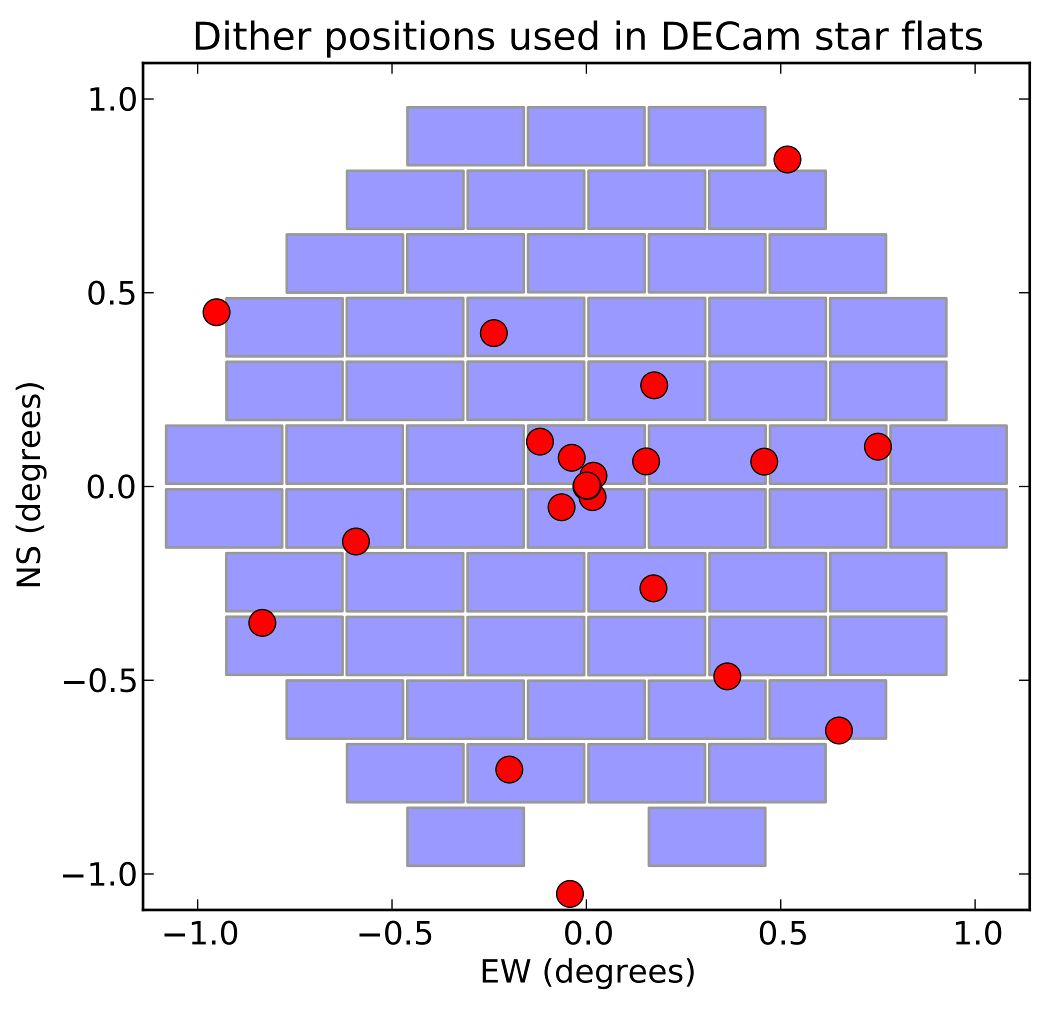


From Plazas *et al.* arXiv:1403.6127

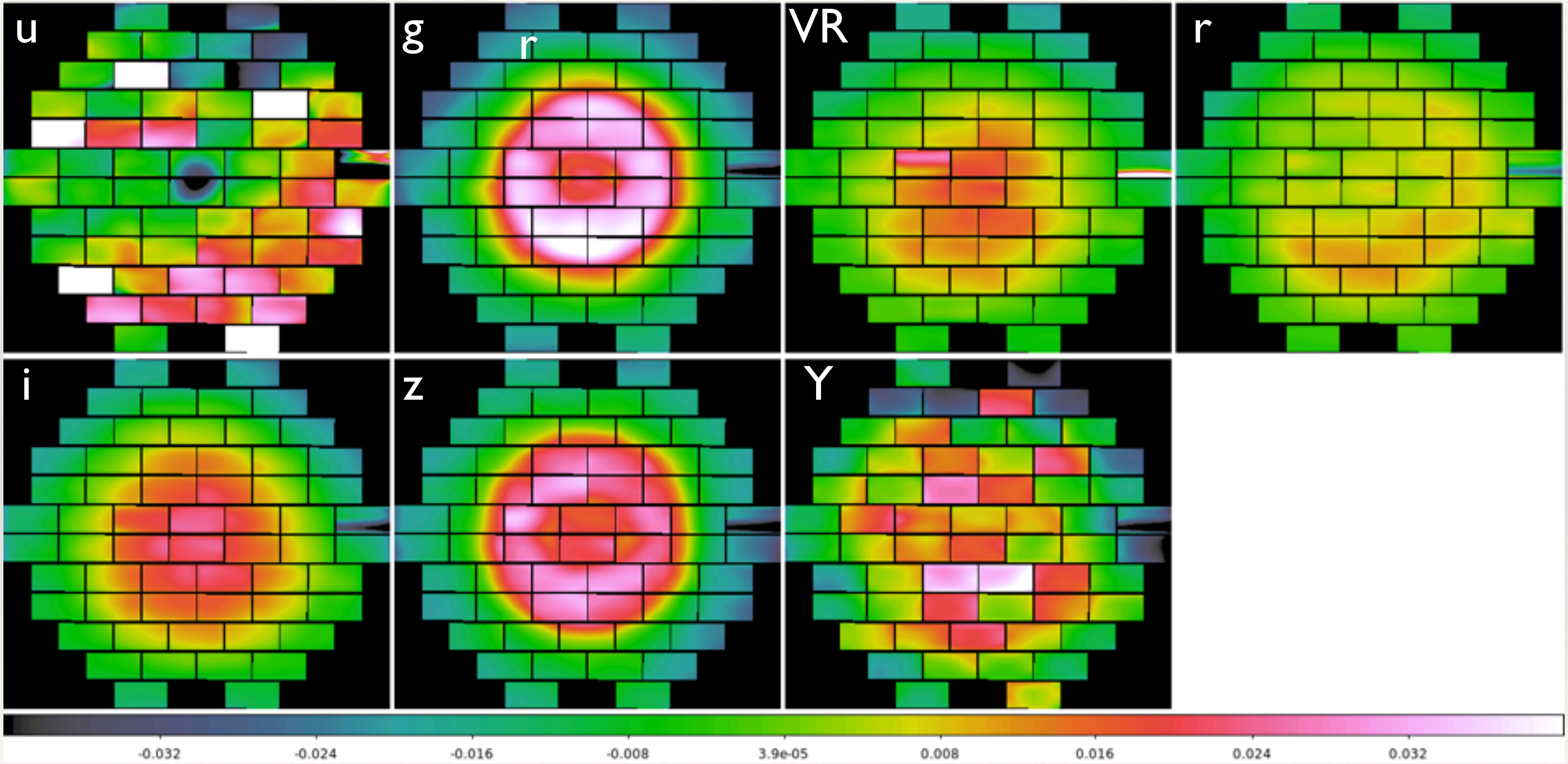
The right way to calibrate camera's response to focussed starlight

…is to measure the signals from focussed stars!

- **Star Flats** are maps of stellar response constructed by forcing signals from each star to agree for exposures on many parts of the focal plane.
- Easy to obtain >10,000 high-S/N stellar mags per DECam exposure.
- Standard DECam sequence of ~20 exposures dithered by up to FOV taken every 2-3 months in each filter and solved for camera's stellar response *after* normalization by a dome flat.



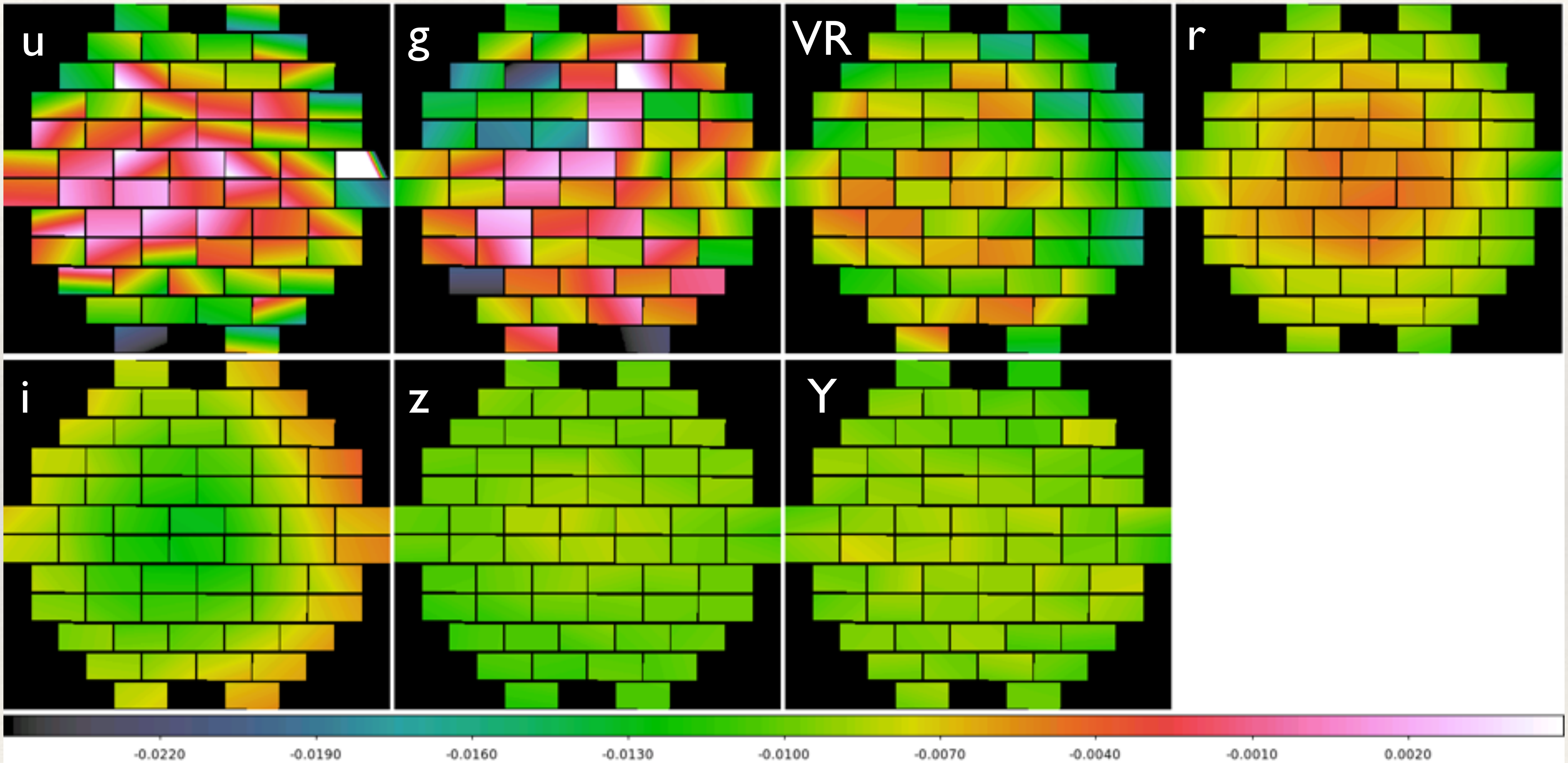
Star flats: large scale



-4%

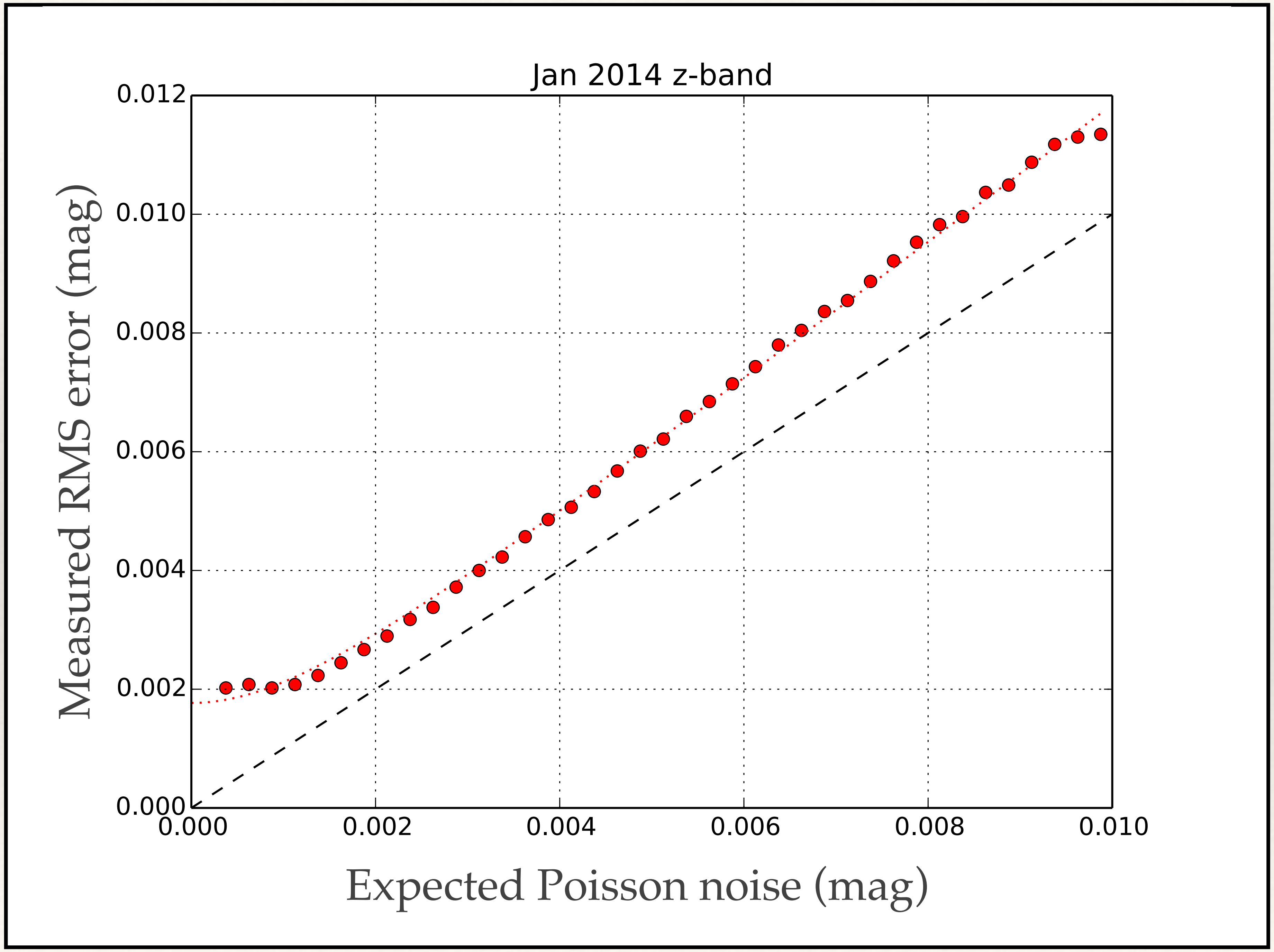
+4%

Star flats: color terms

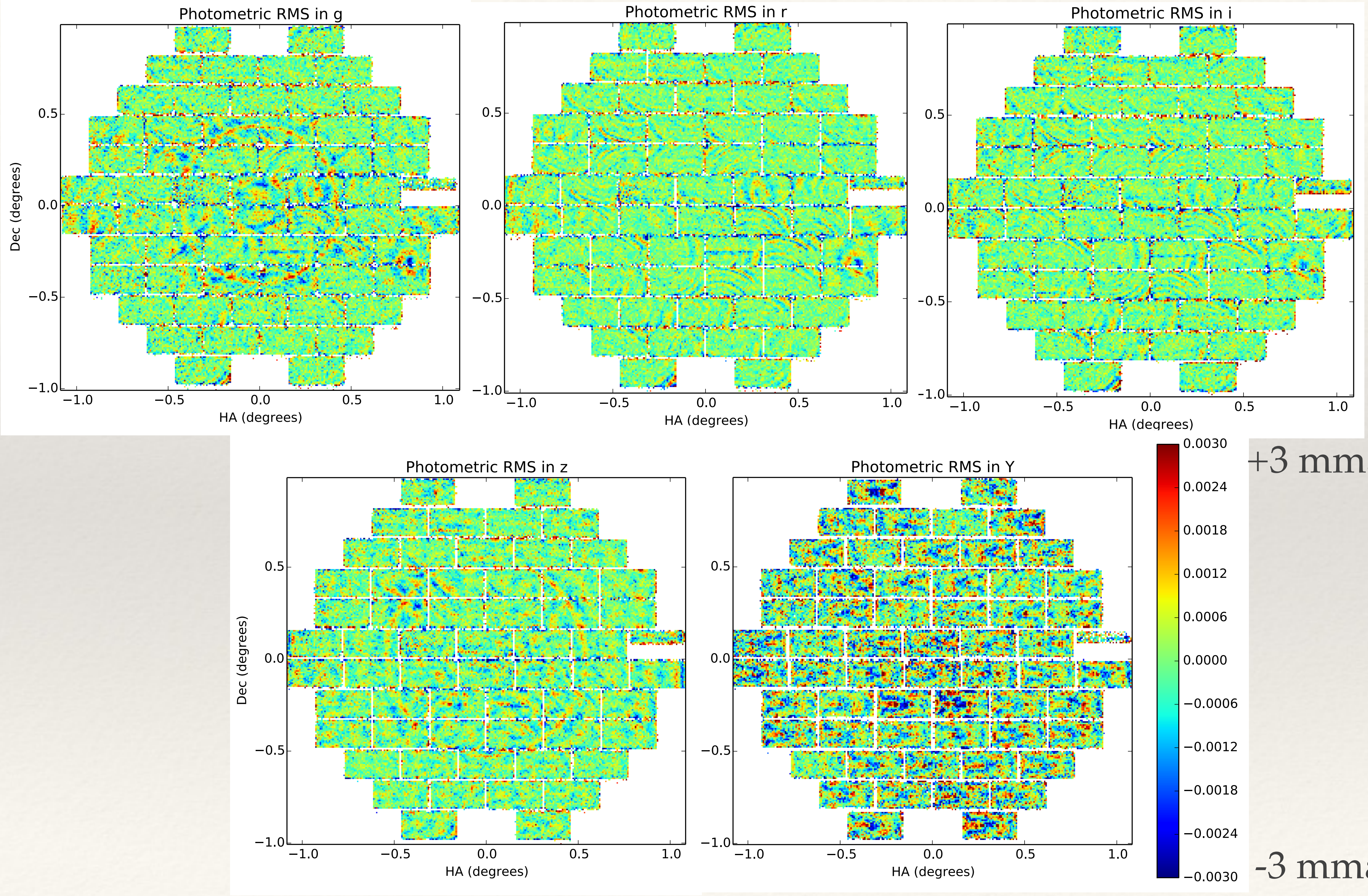


-0.025 +0.005

Precision after star-flattening



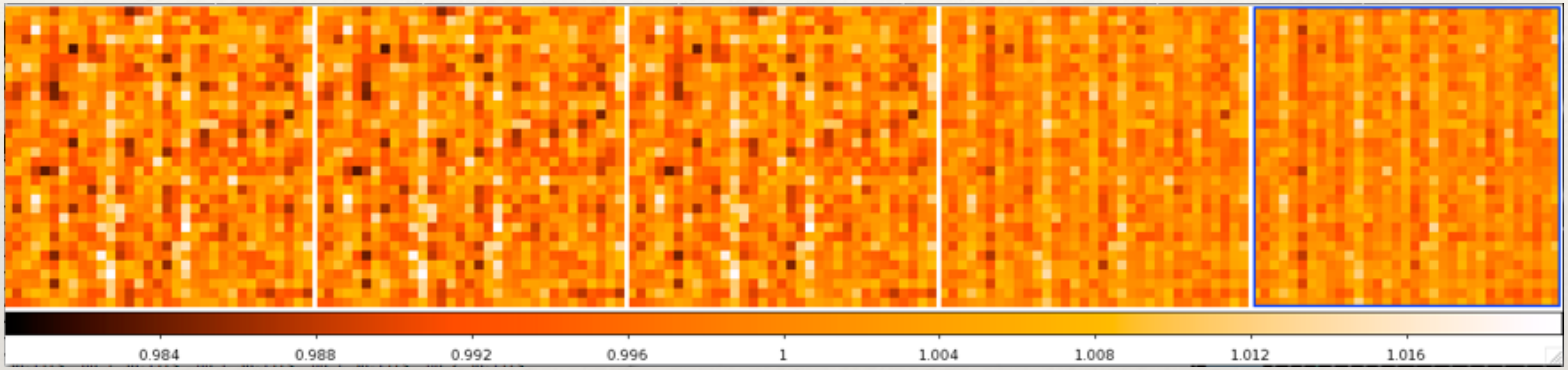
Residuals after star flattening



+3 mmag

-3 mmag

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

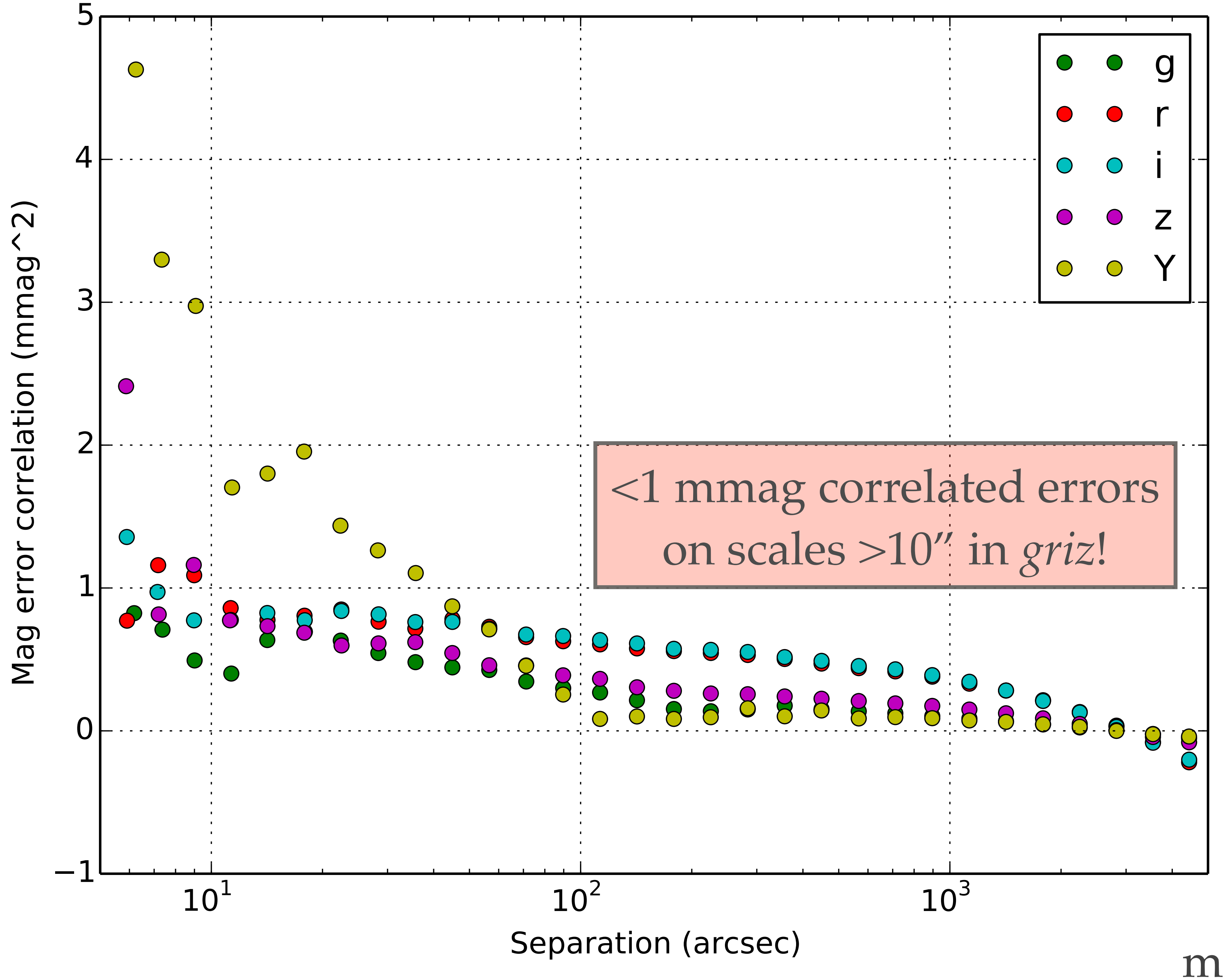


g: 0.63% RMS r: 0.62% RMS i: 0.60% RMS z: 0.47% RMS Y: 0.43% RMS

- These pixel-area variations are not corrected by star flats, might contribute ~1 mmag RMS.

Are mag errors coherent?

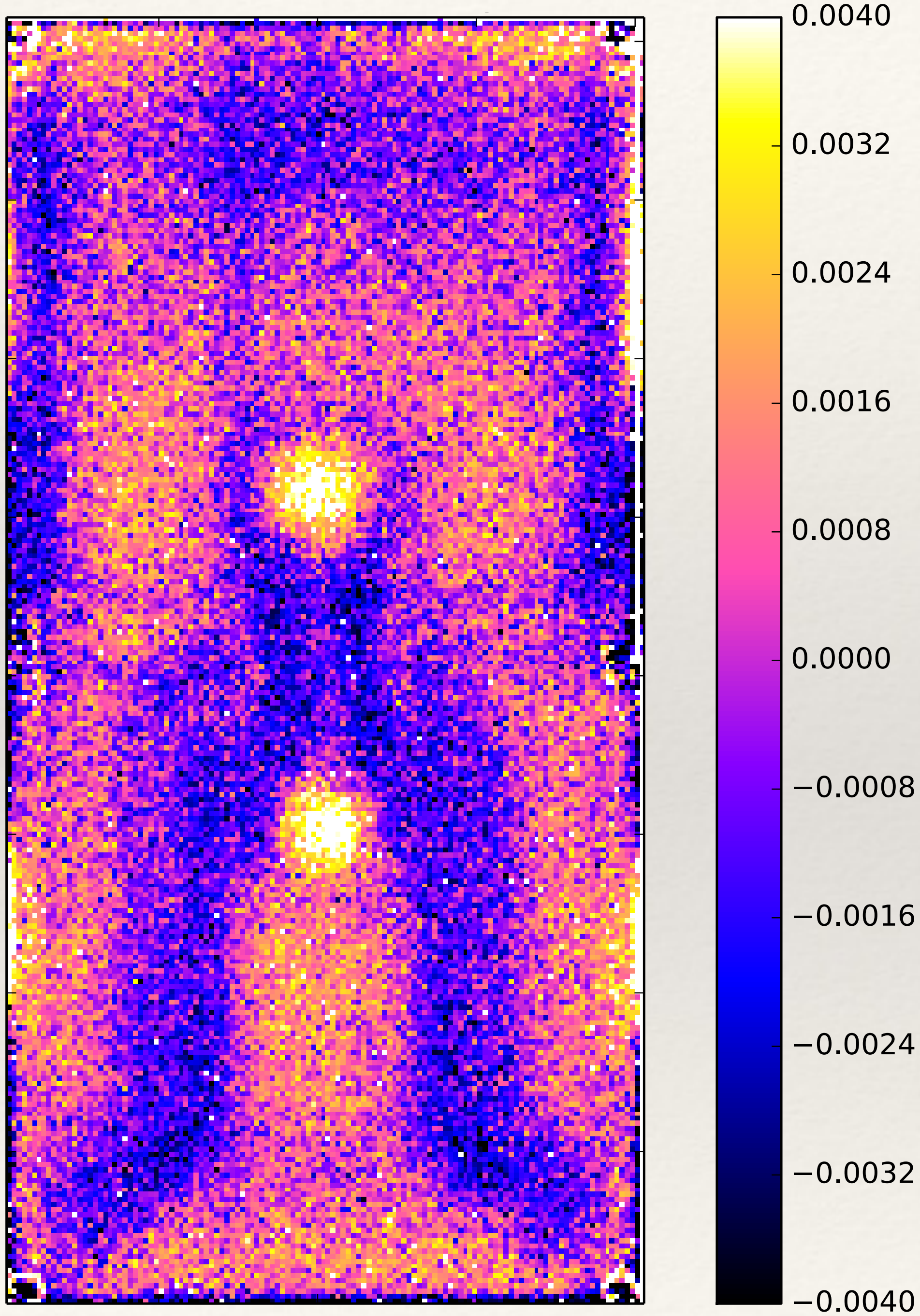
2-point correlation function of mag residuals for bright stars



<1 mmag correlated errors on scales >10″ in *griz*!

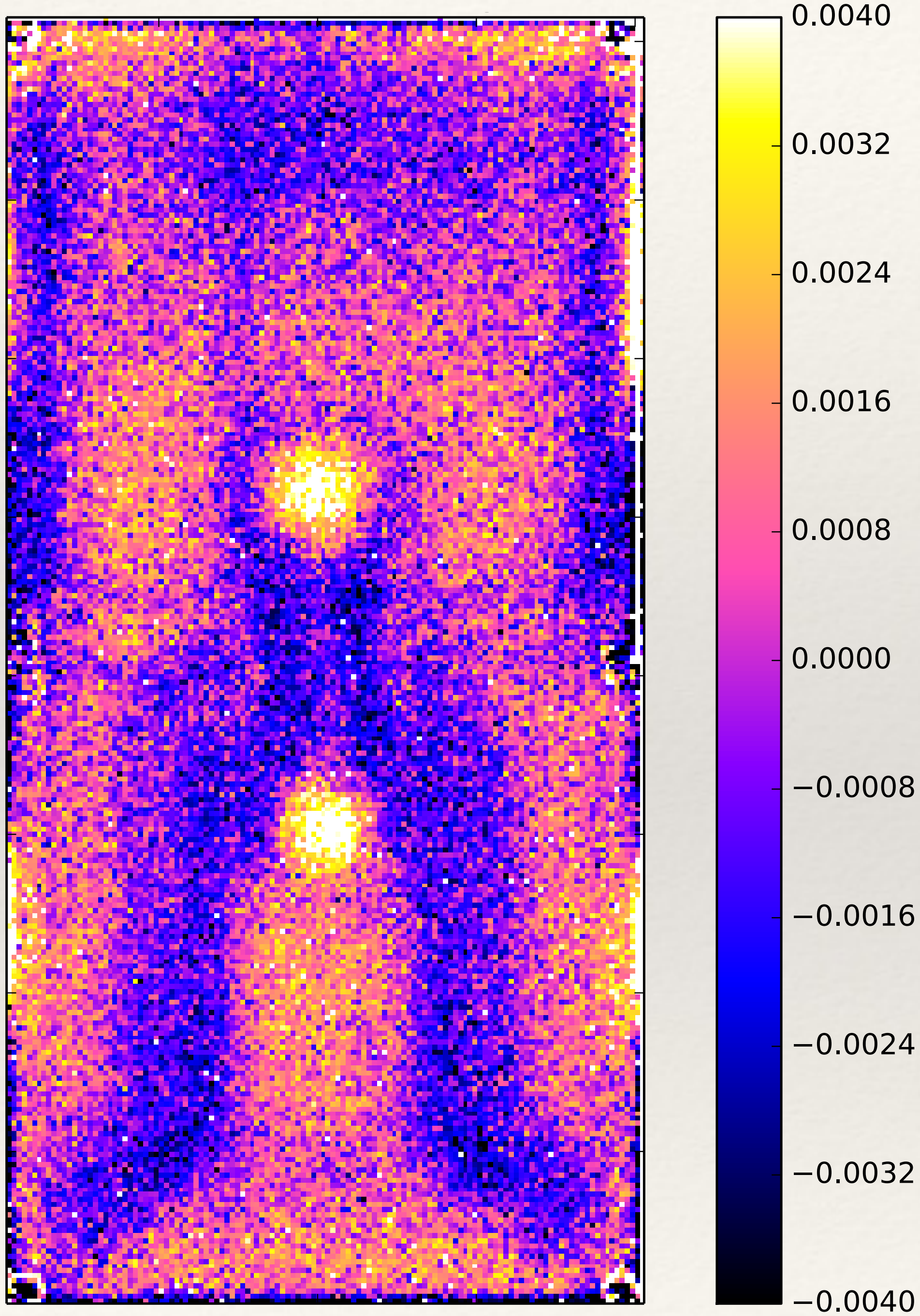
magerr<3 mmag

What's with Y band?



Avg mag residuals vs CCD posn

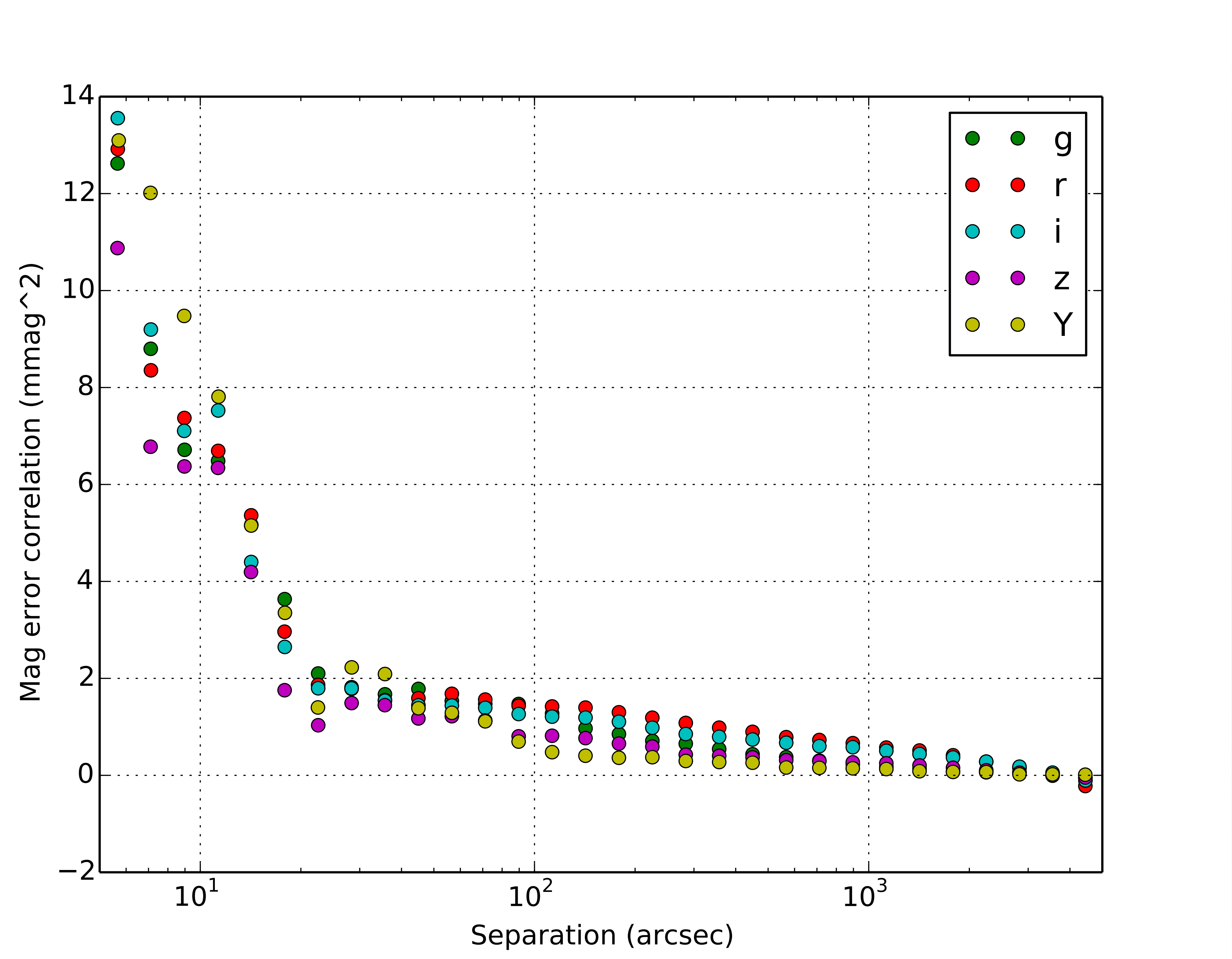
What's with Y band?



Avg mag residuals vs CCD posn

DECam CCD mount (J. Estrada)

Fainter stars have higher correlations, probably sky estimation errors.

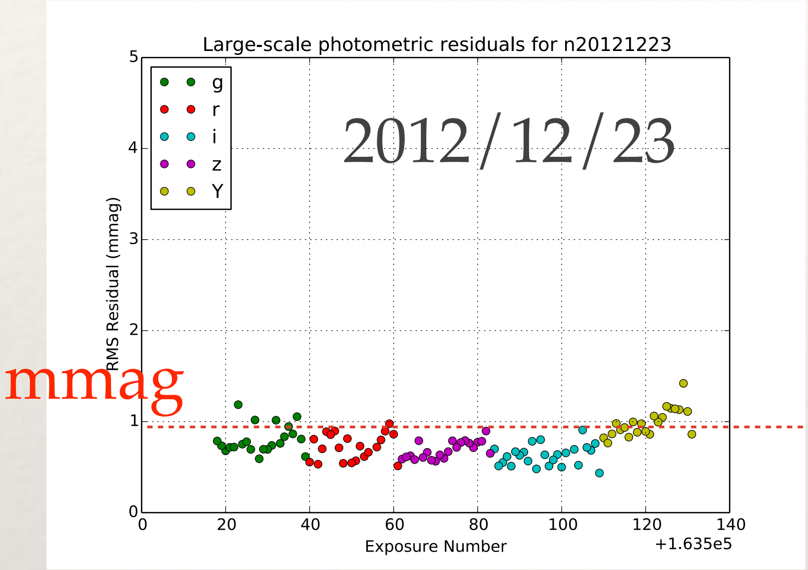


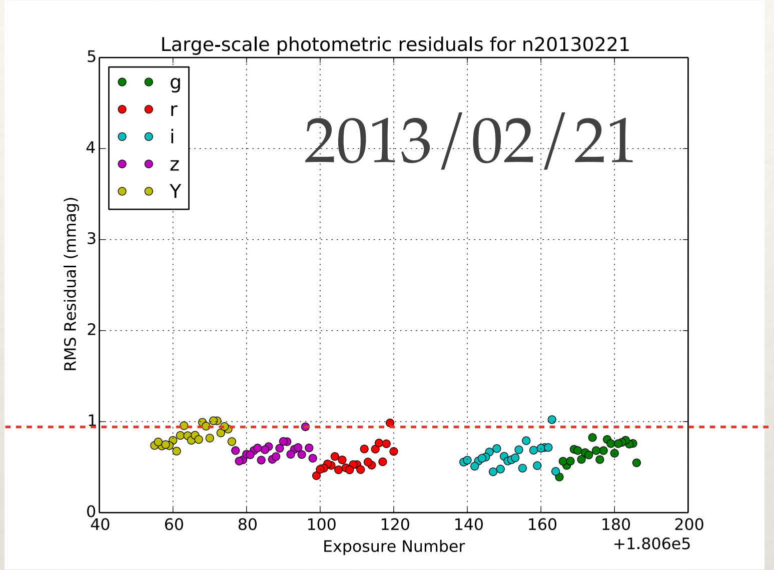
5 mmag<magerr<10 mmag

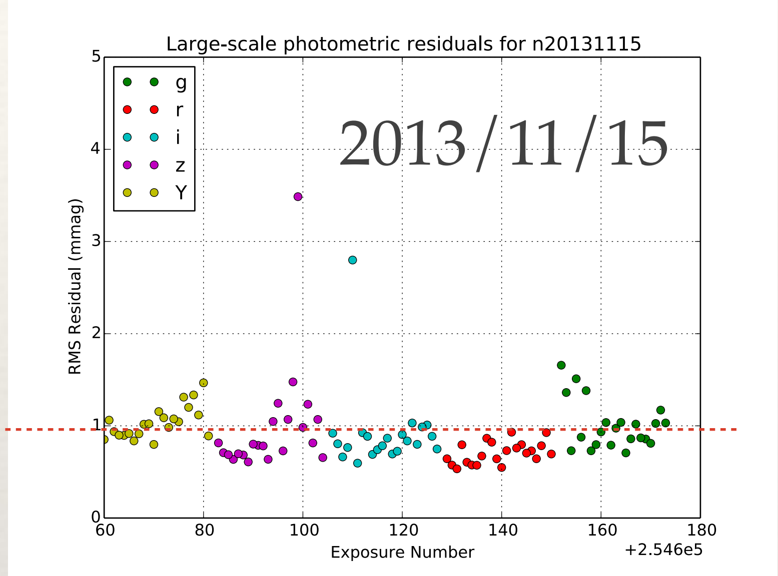
Response stability: hours

These plots show the large-scale RMS variation of stellar mags on each exposure of star flats.

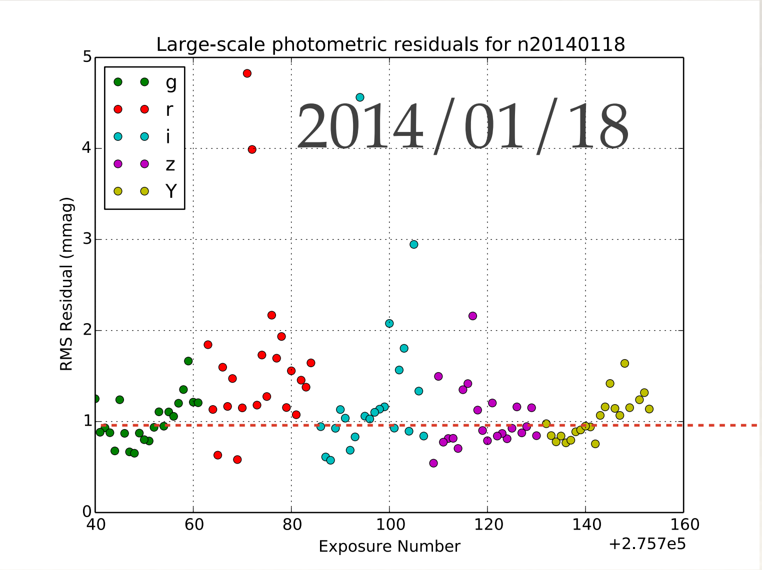
1 mmag

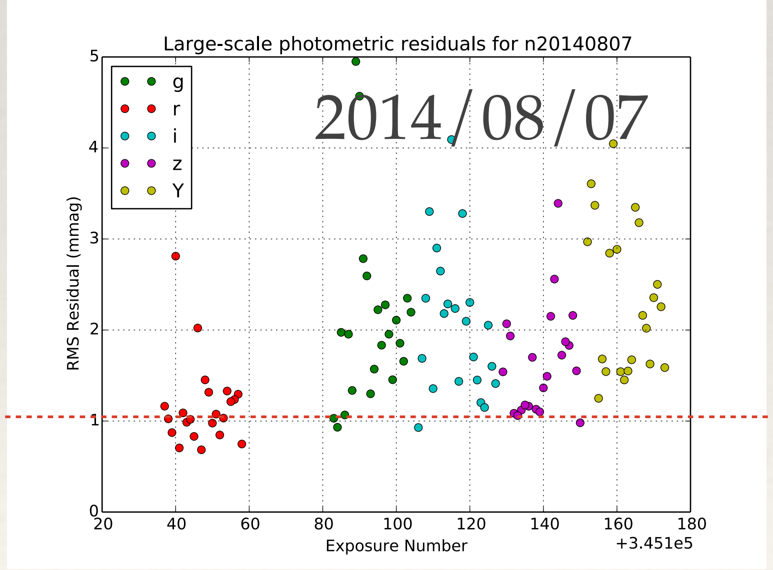

Large-scale photometric residuals for n20121223

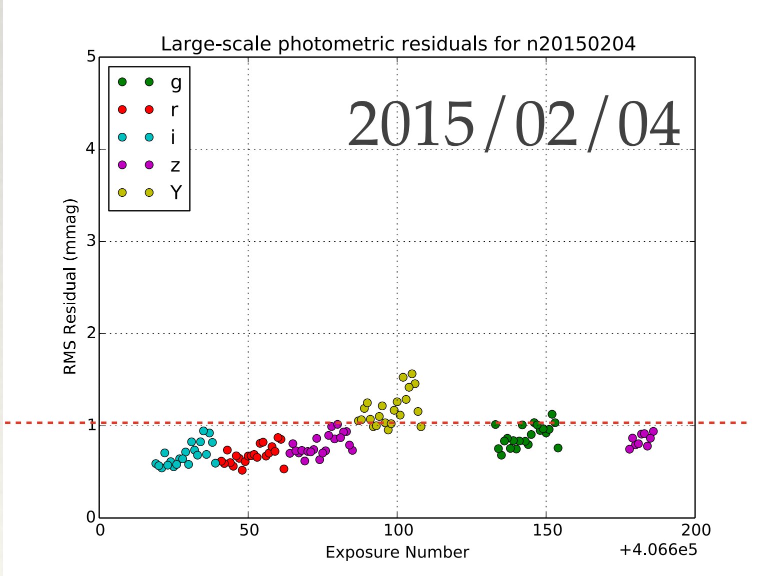

Large-scale photometric residuals for n20130221


Large-scale photometric residuals for n20131115

[RASICAM video for 20140807]


Large-scale photometric residuals for n20140118

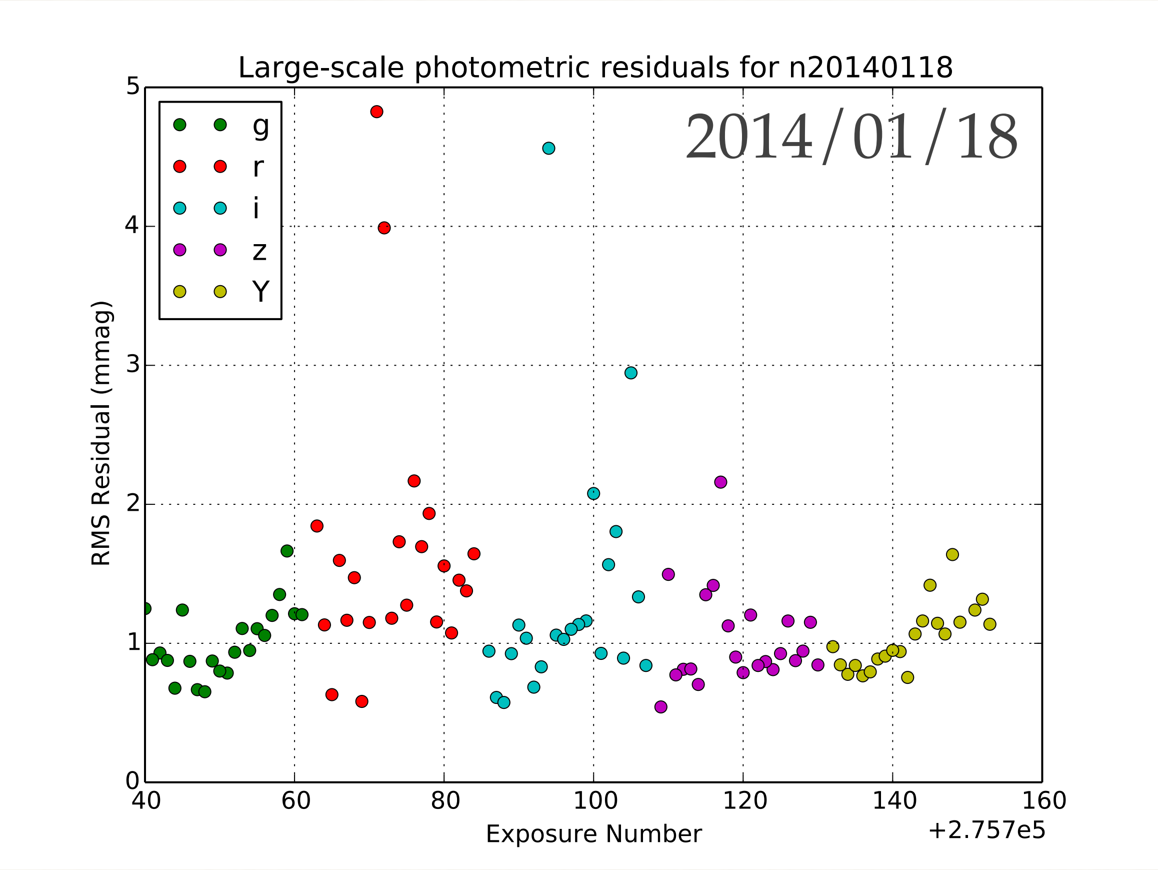

Large-scale photometric residuals for n20140807

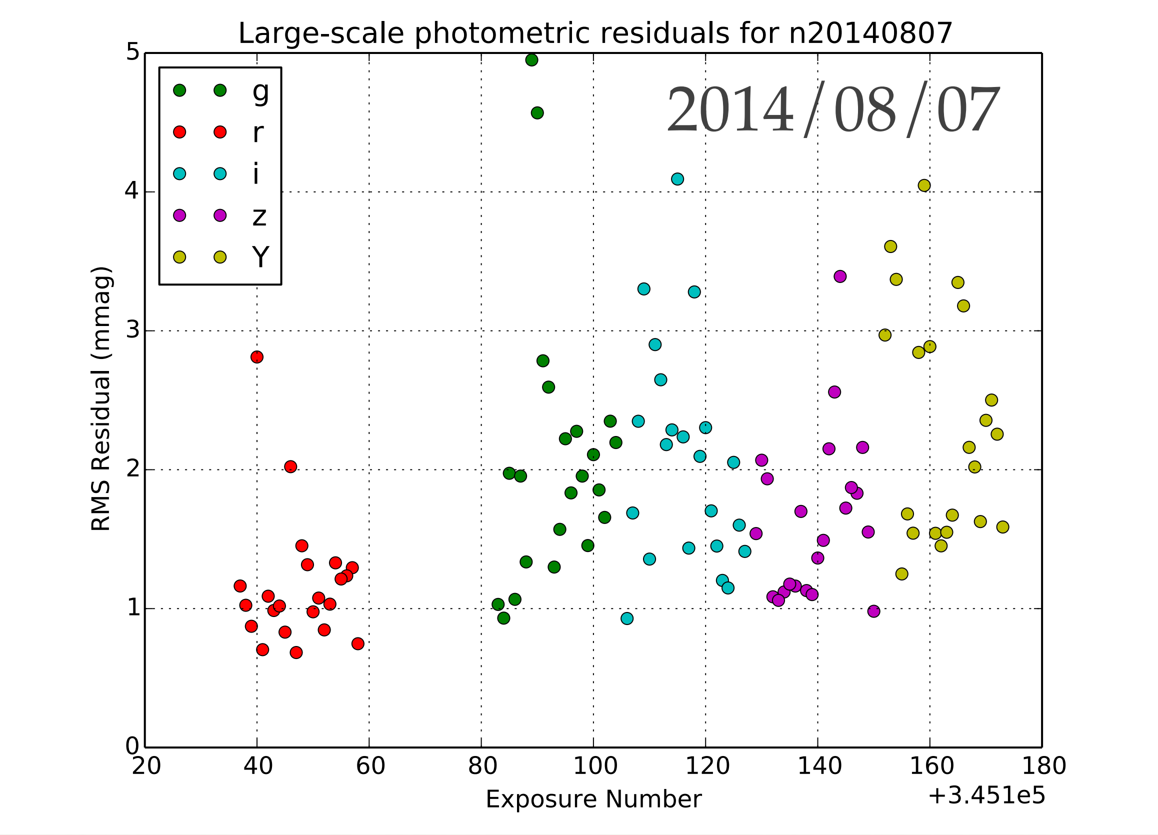

Large-scale photometric residuals for n20150204

Some "cloudless" nights have several-mmag patchy extinction variation!

“Patchy” nights

The 2 nights (of ~10) showing spatial response variation >1 mmag show no signs of clouds on the *RASICAM* all-sky thermal-IR cloud monitor! RASICAM video for 20140807





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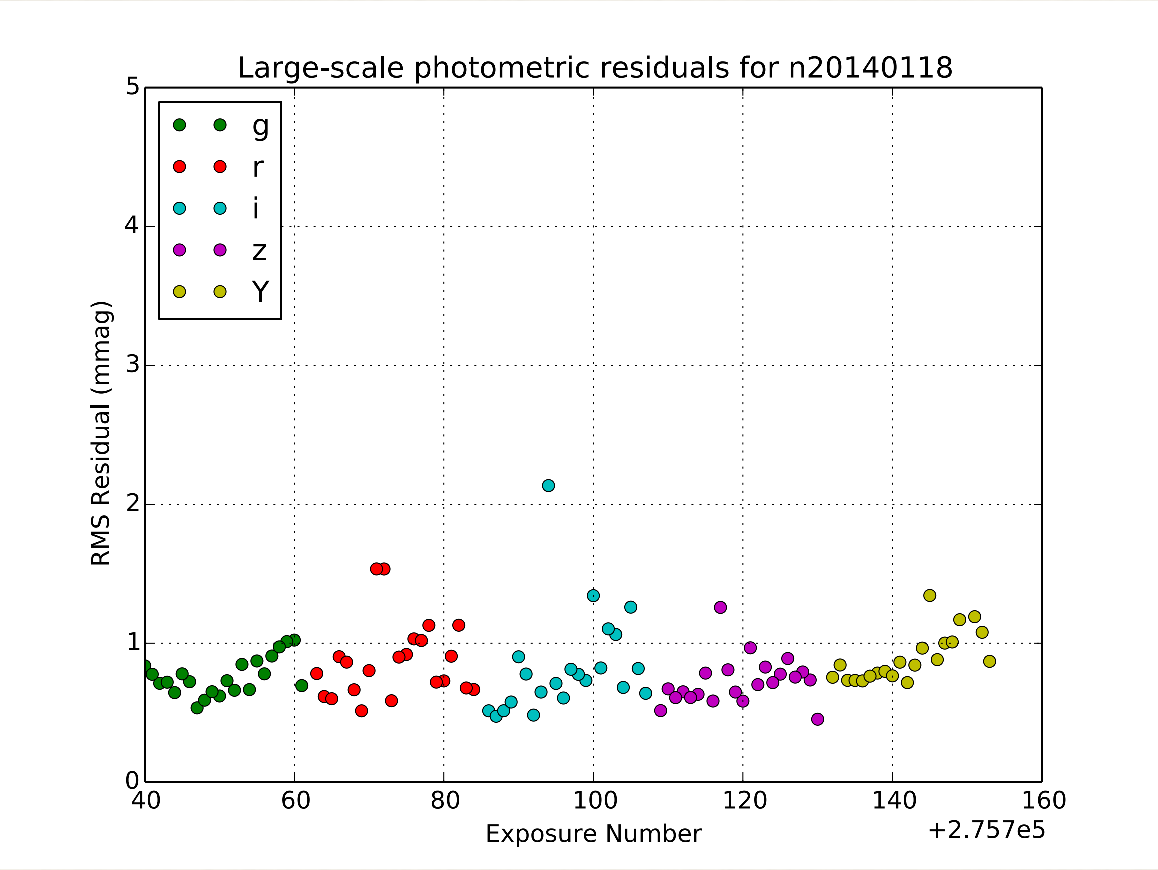
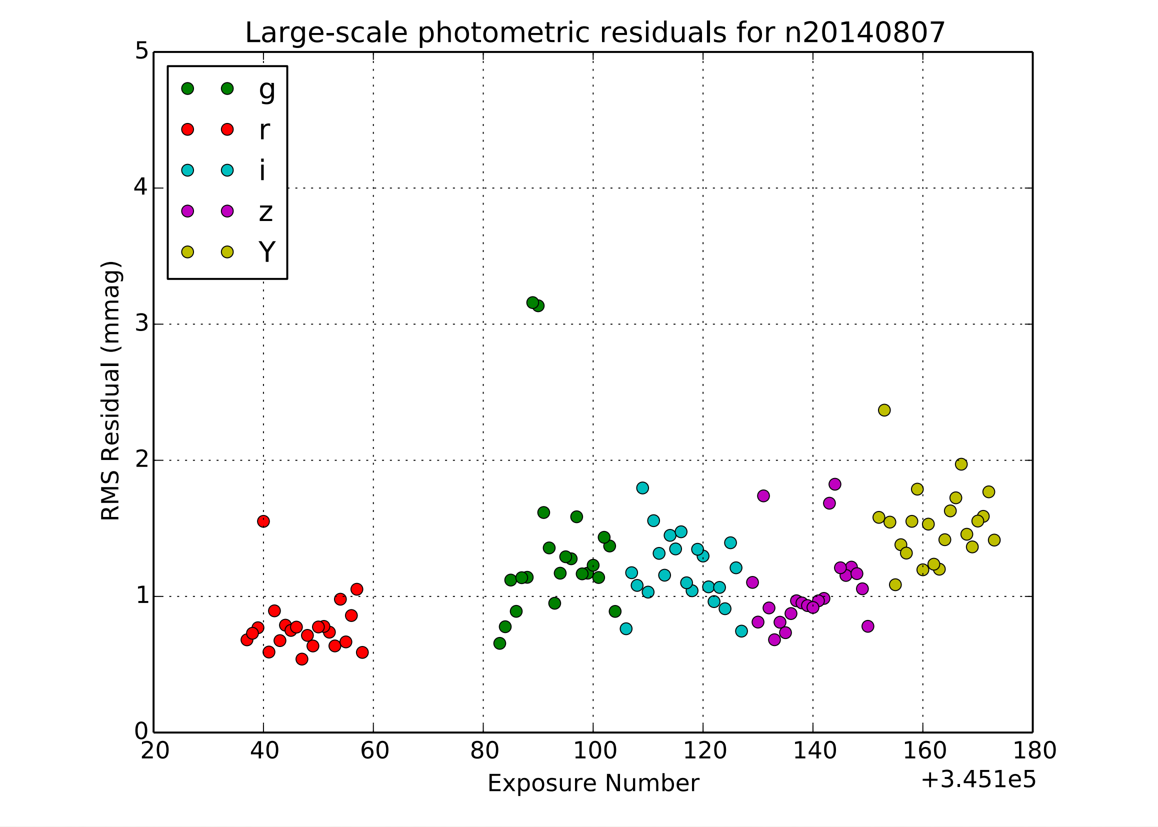
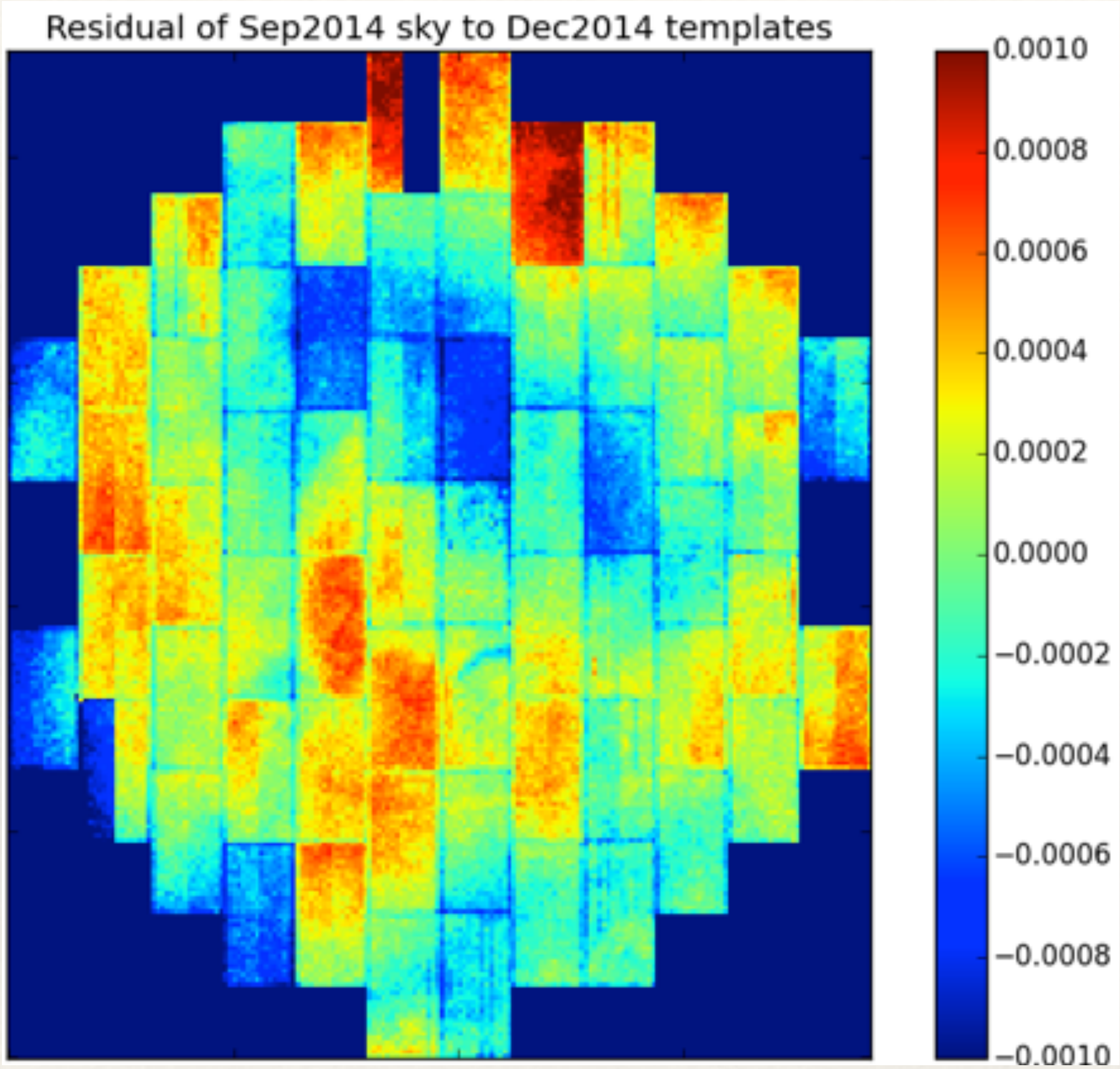
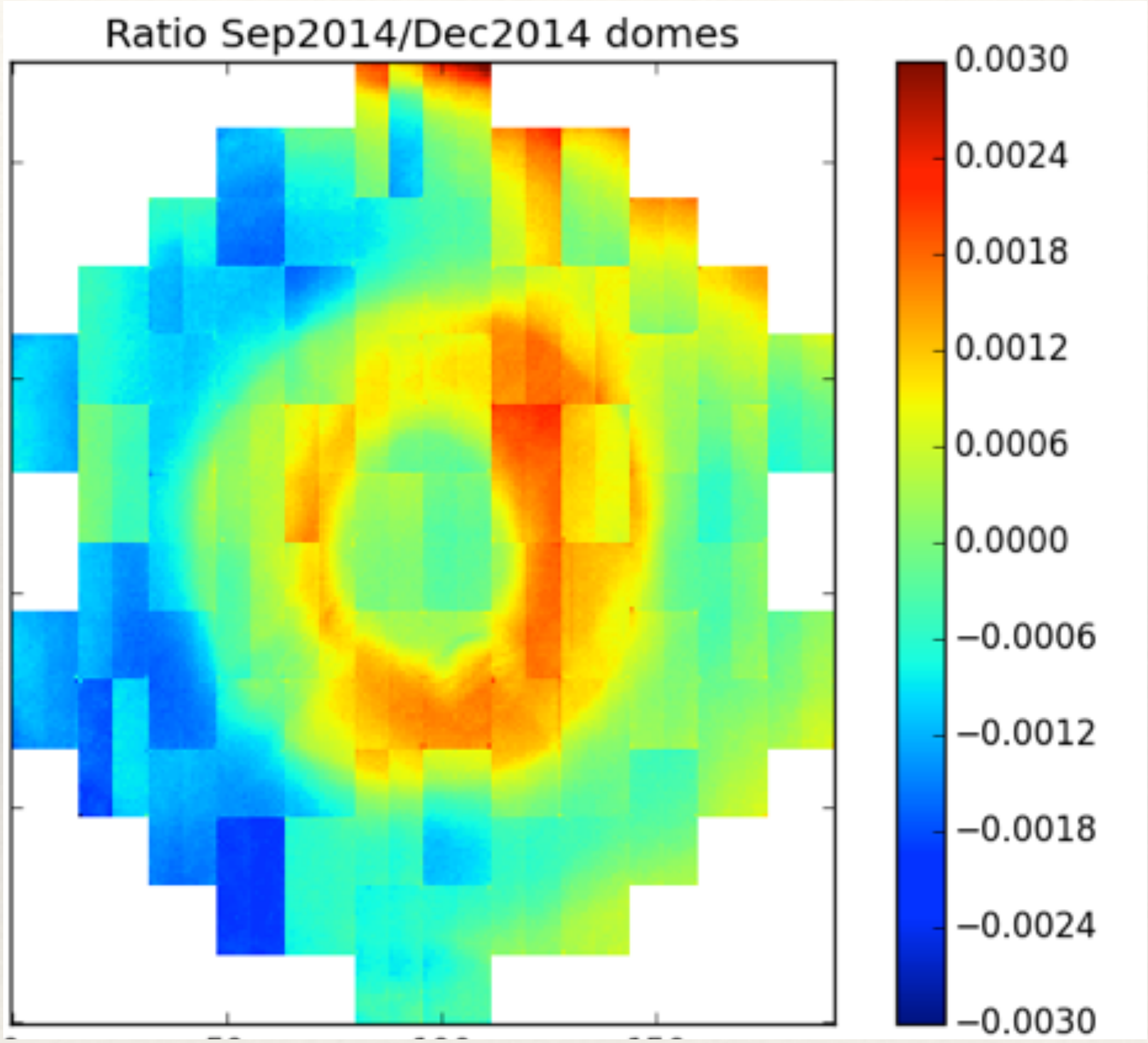




Letting “exposure solution” have quadratic variation across FOV eliminate most of RMS

Response stability: days/months

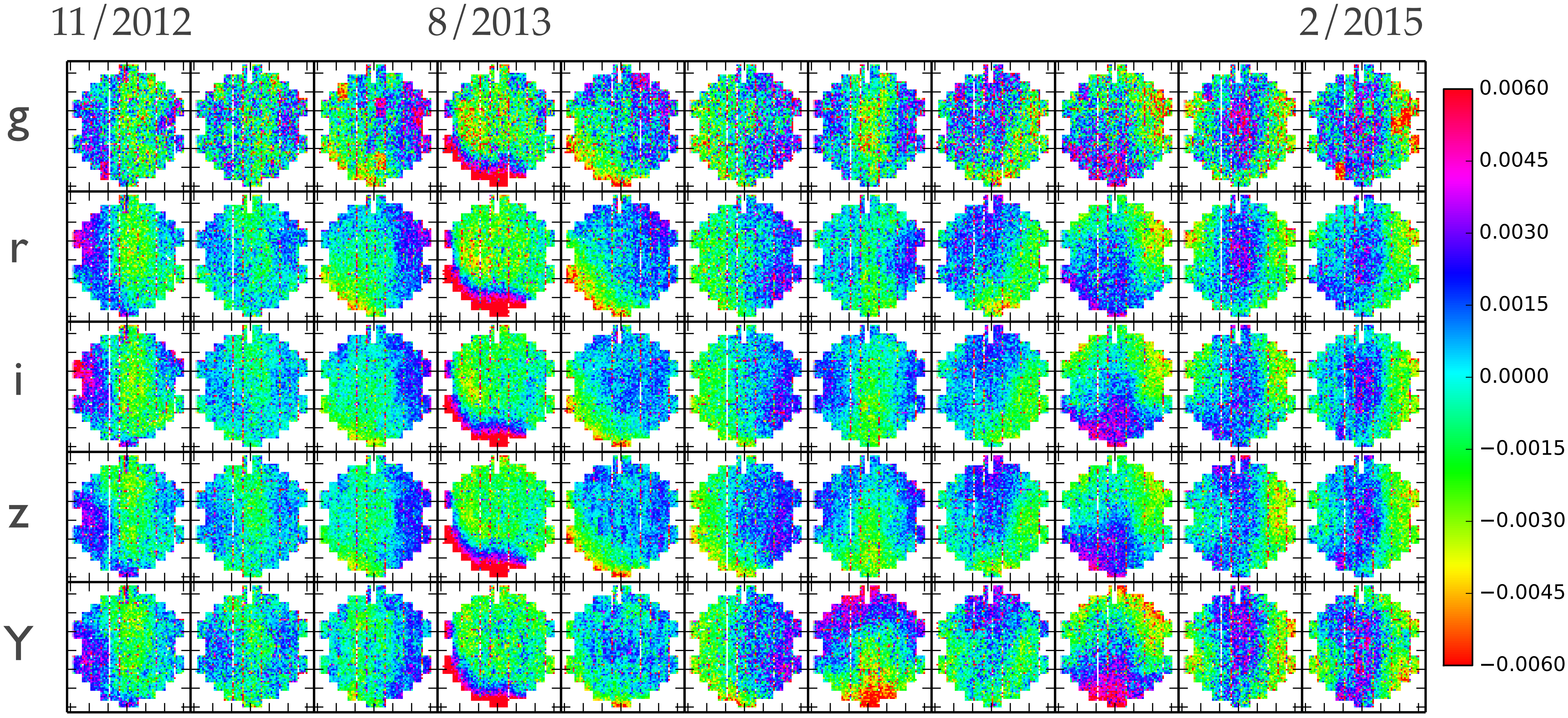




The sky pattern is stable to <0.1%… while the dome pattern changes +-0.3%!

The dome flats are not a good way to measure long-term changes in response.

Photometric response changes few mmag over months

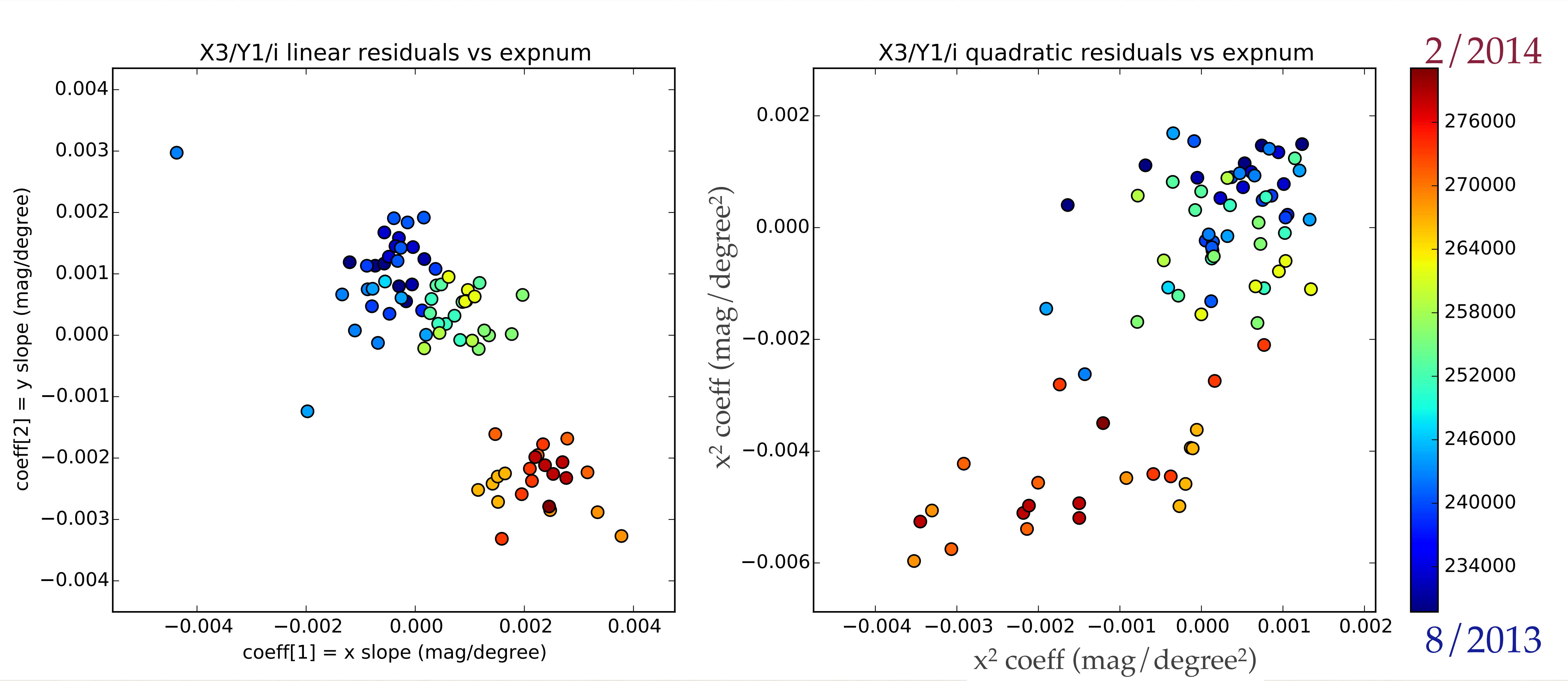


What varies over months but is wavelength-independent and coherent across CCDs??

Response stability using the stars in SN fields

- Supernova survey is great place to monitor the stability of the instrument over weeks/months.
- SN fields use essentially the same pointing for every epoch, making it easy to track variation in response vs array position.
- Processed all of Y1 data for SN X3 field using a fixed dome flat and star flat.
- Subtract mean of all measures for each star to get residuals, and fit quadratic function of sky position to residuals in each exposure.

Response stability using the stars in SN fields

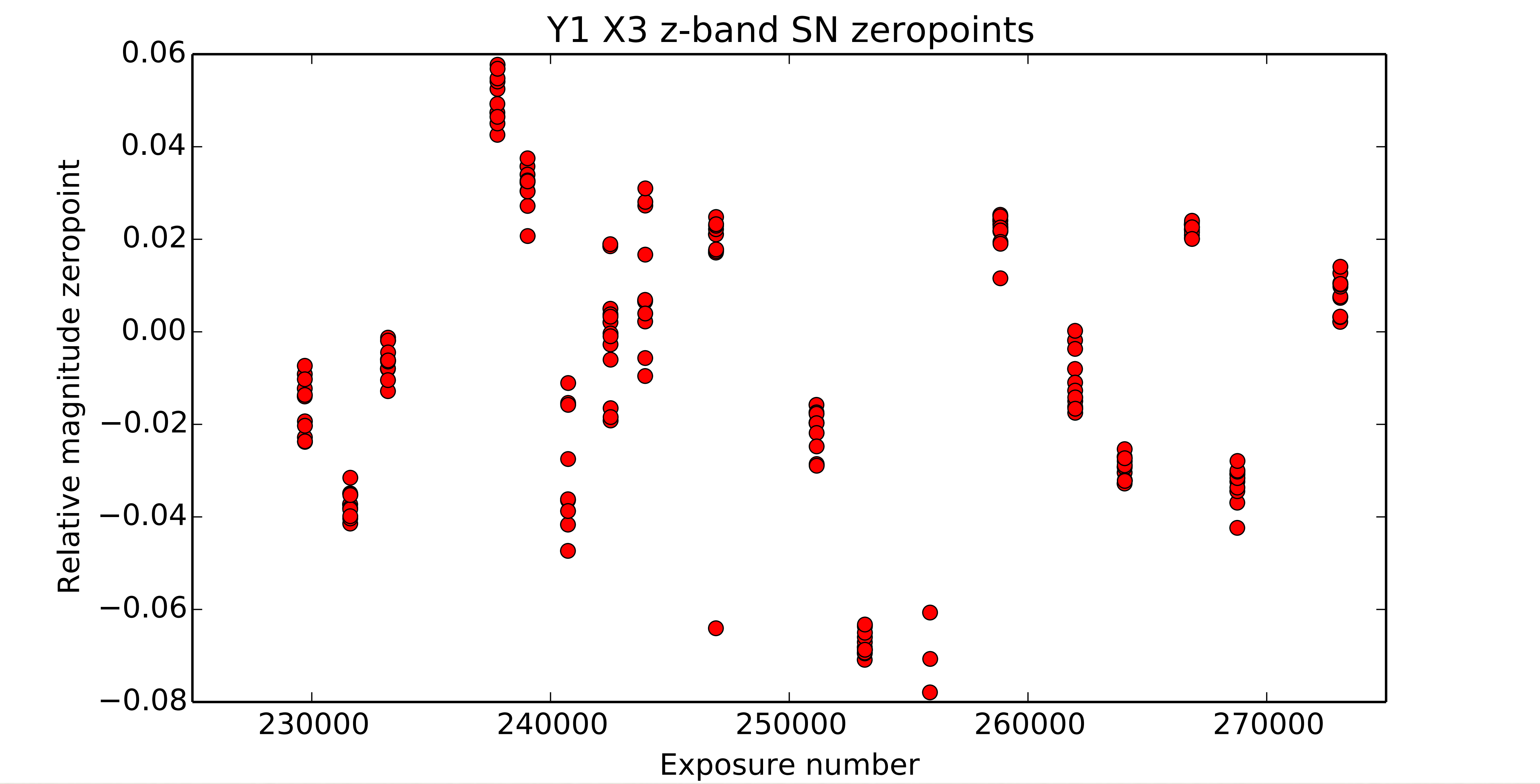


Both linear (left) and quadratic (right) coefficients of response variation show **smooth drift with time**, with a jump in early December 2013.

Global calibration

- Conclude that on any clear night, we can calibrate across FOV with accuracy of ~1 mmag, as long as we allow separate mag zeropoint (or linear/quadratic function) for each exposure.
- The *Global calibration* challenge is to tie all the exposures onto one system.
- The traditional method:
  - observe *standard stars* each night;
  - derive zeropoints for each exposure
  - if zeropoints follow constant + k*(airmass), it's a *photometric night.*
  - Apply zeropoints to all exposures for that night.

Zeropoint drifts in SN field X3



- zp varies by ~10 mmag with ~1 hr on many cloudless nights.
- Shouldn't expect standards transfer to yield zeropoints any better than this!

Global calibration: modern versions

- Enforce *internal consistency* of multiple measurements of the same star, solve for zeropoints of each exposure.
- SDSS “ubercal” is limited by minimal exposure overlap in the SDSS survey.
- DES survey strategy is heavily interlaced to make internal calibration powerful.

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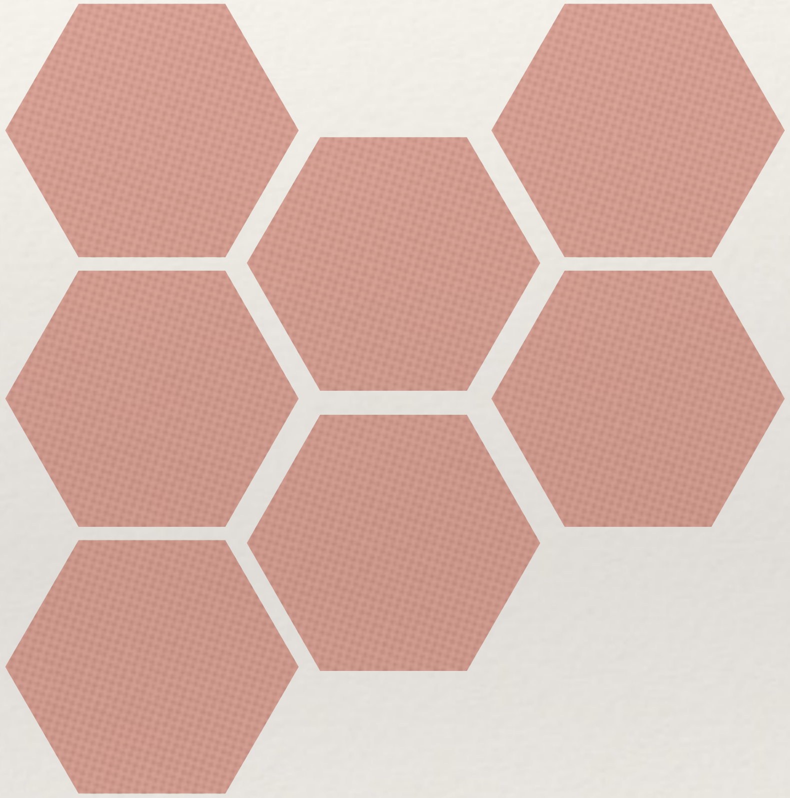

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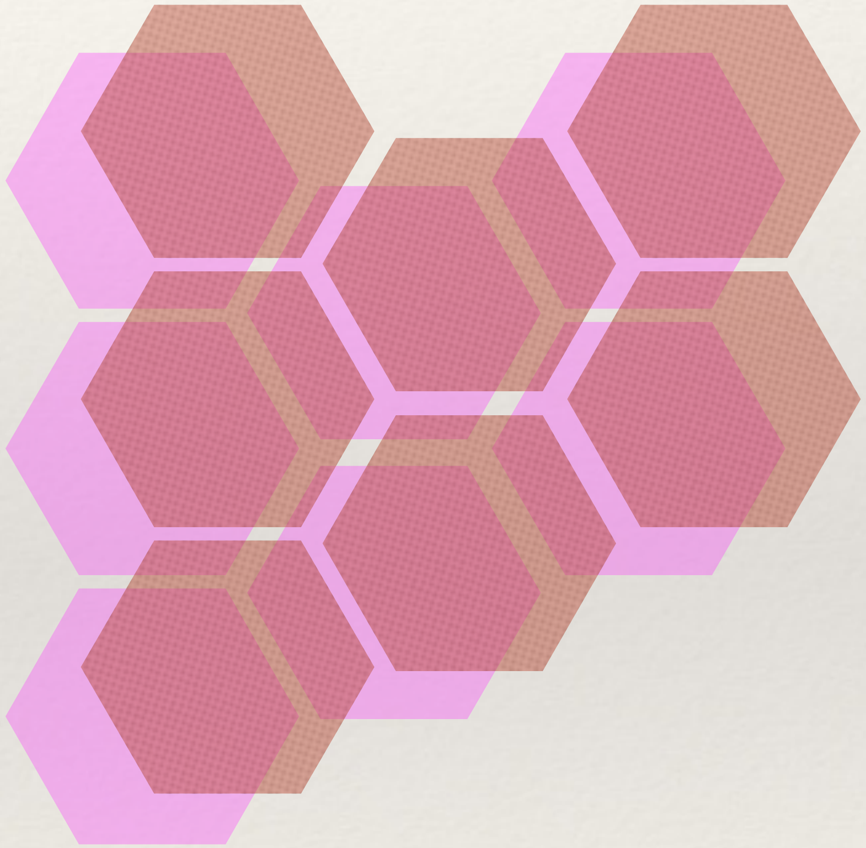

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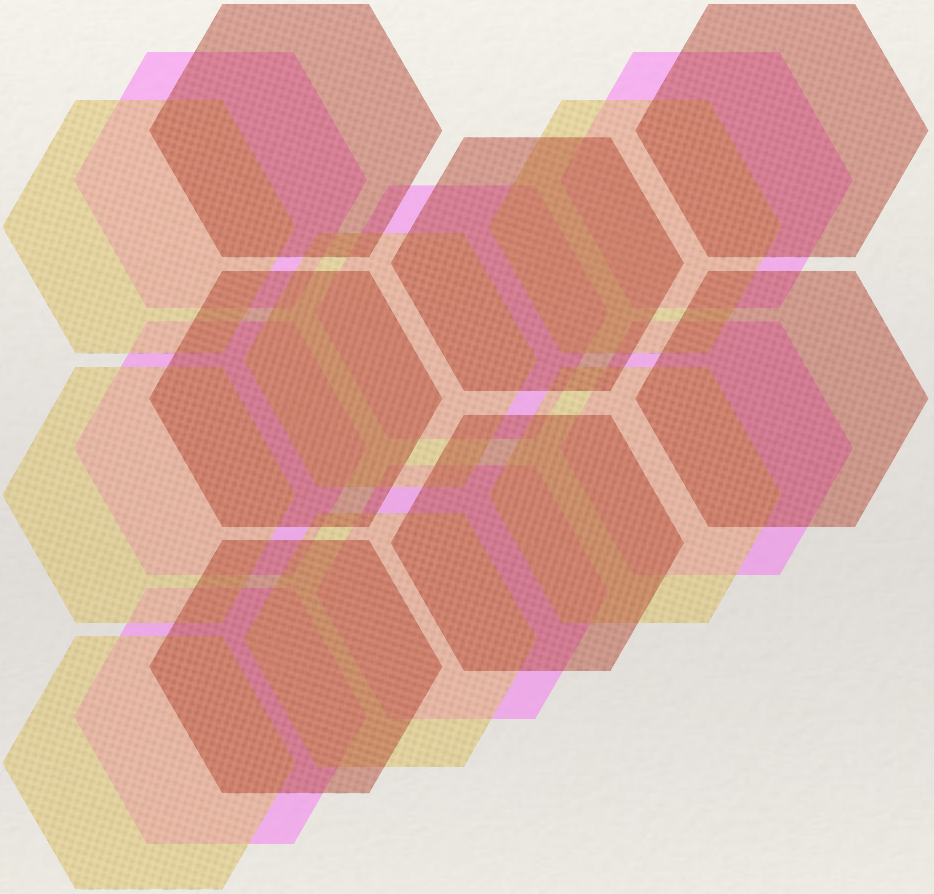

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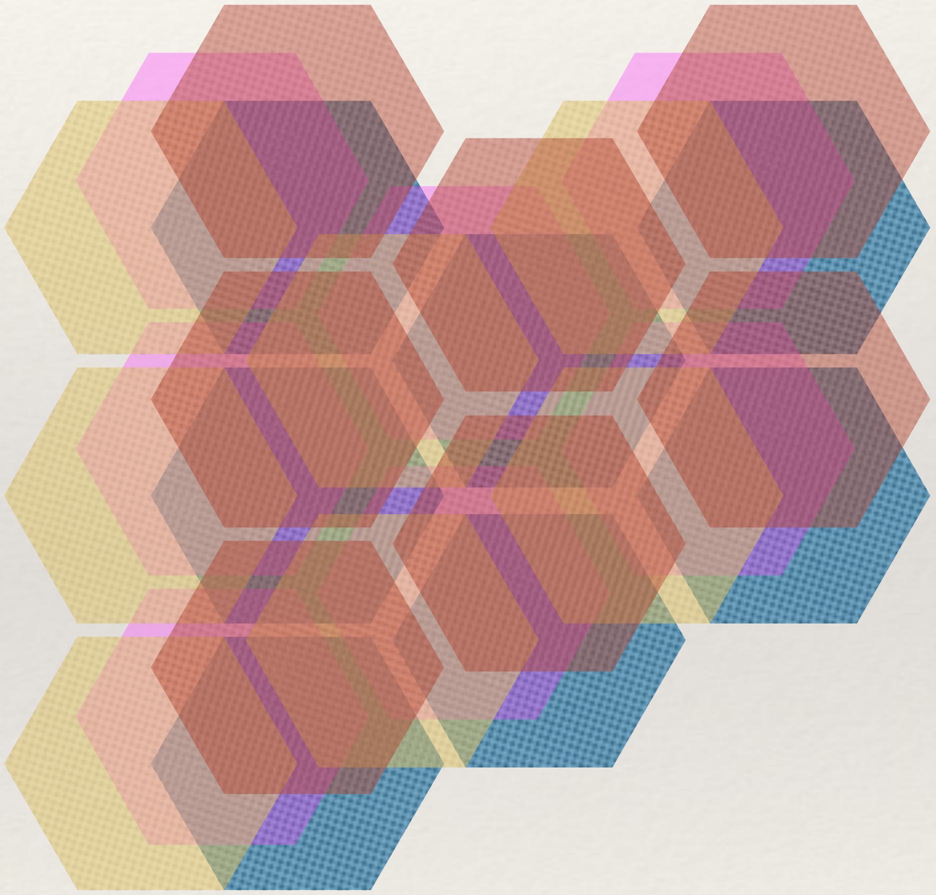
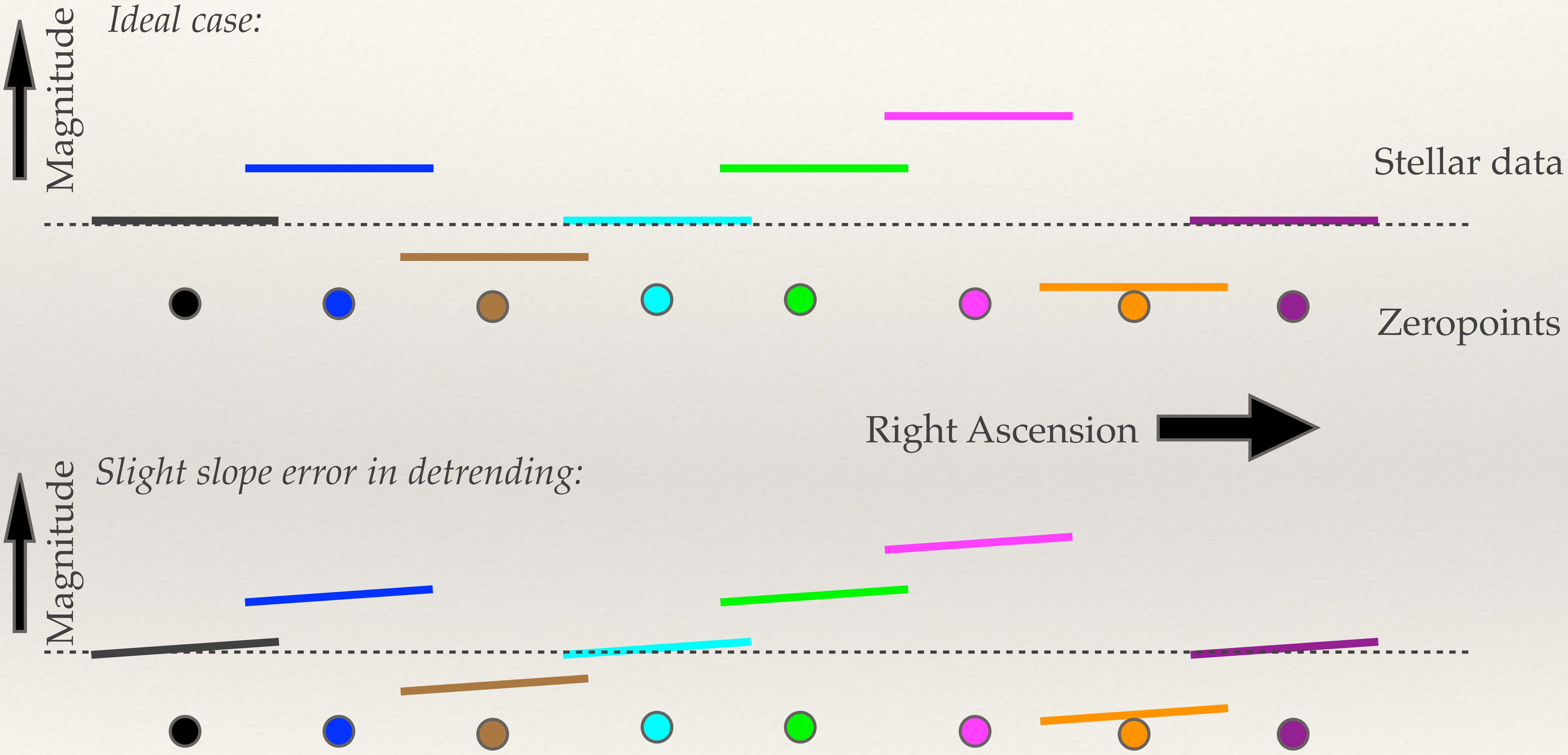


Global calibration “drift”



Ideal case:

Magnitude

Stellar data

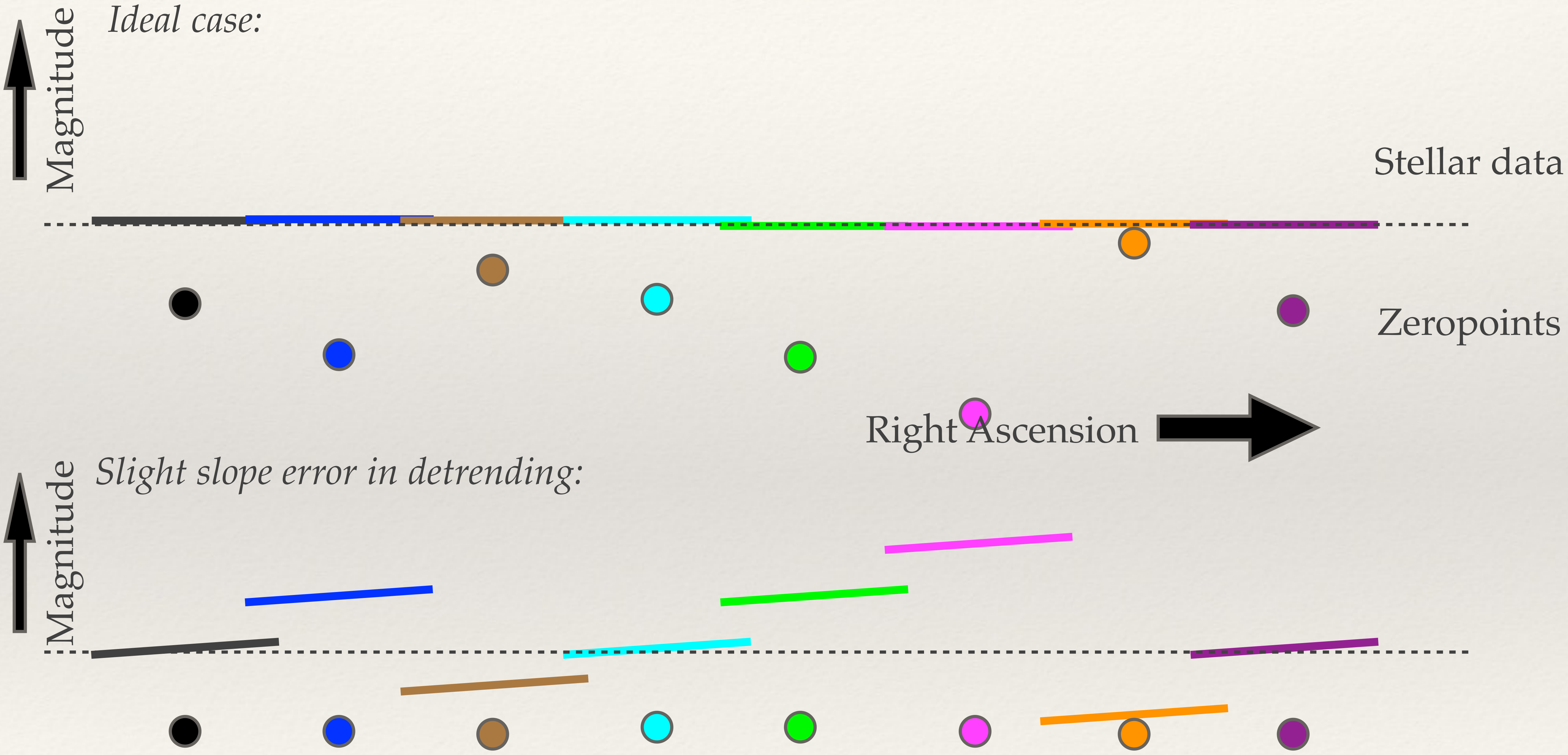
Zeropoints

Right Ascension

Slight slope error in detrending:

Magnitude

Global calibration “drift”



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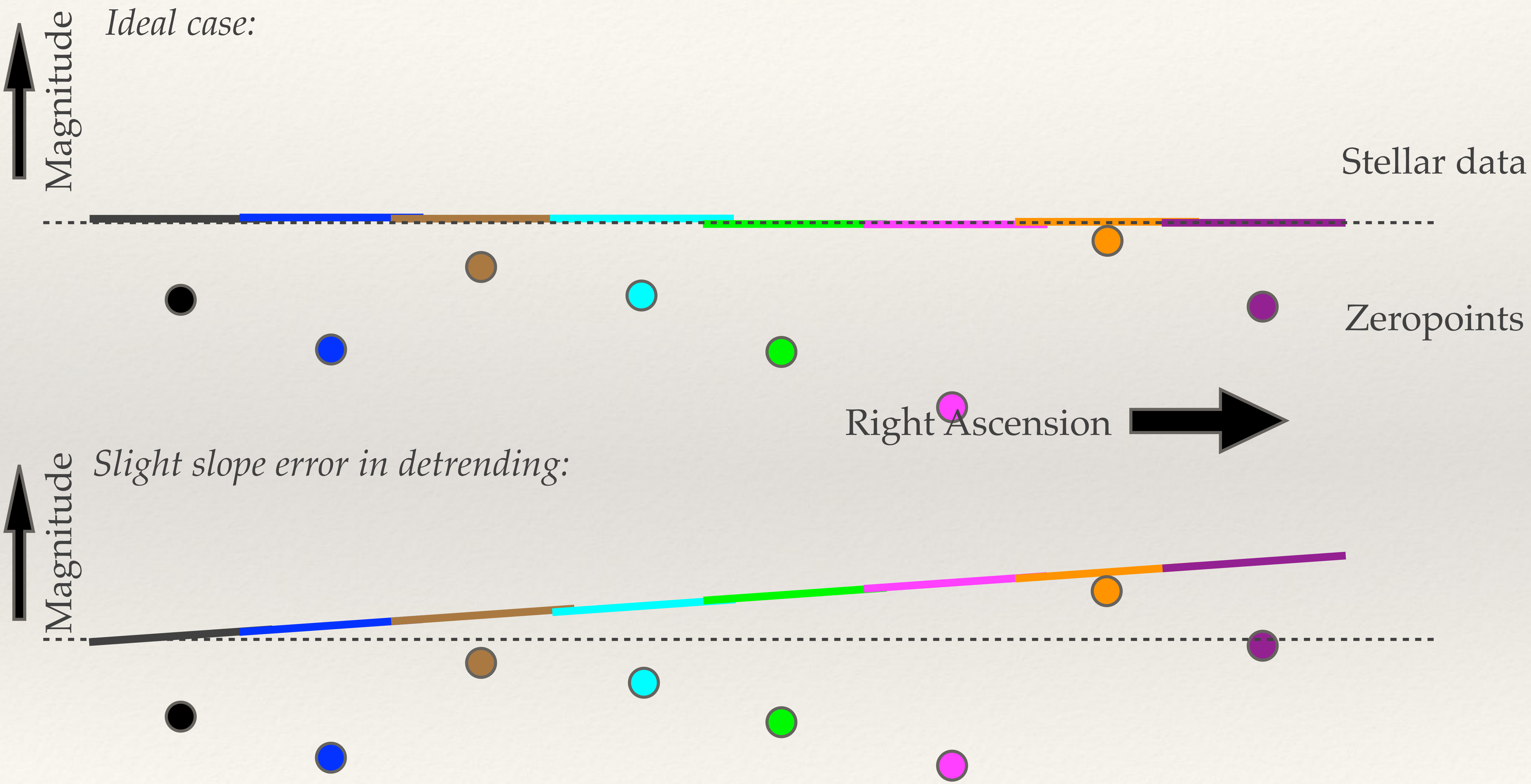
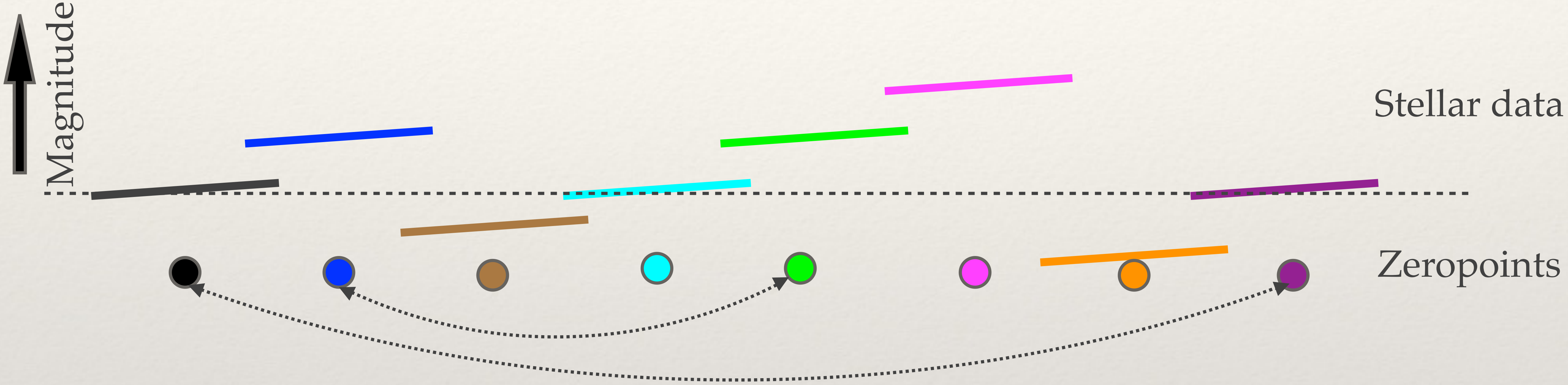


Ideal case:

Slight slope error in detrending:

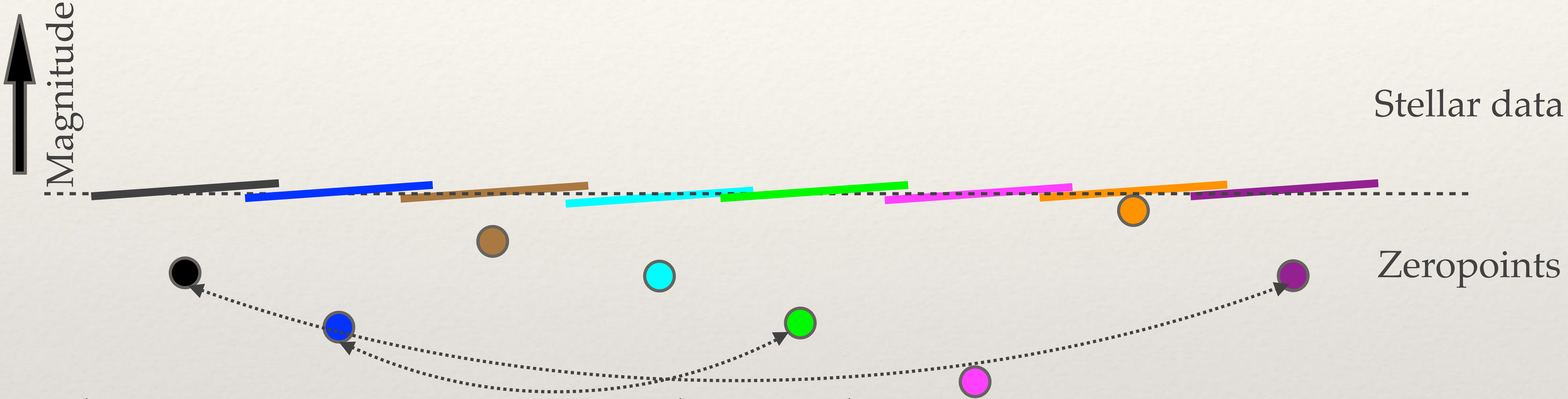
“Photometric prior” to damp drift



If these pairs of points were taken on the same photometric night, we have prior expectation they have same zp

Combination of internal consistency constraints and demanding similar zp’s for exposures close in time can constrain the system (up to an overall shift = absolute calibration) as long as the observing on photometric nights is not localized.
Can this extend our mmag nightly precision to full season? Stay tuned, still in progress!

“Photometric prior” to damp drift



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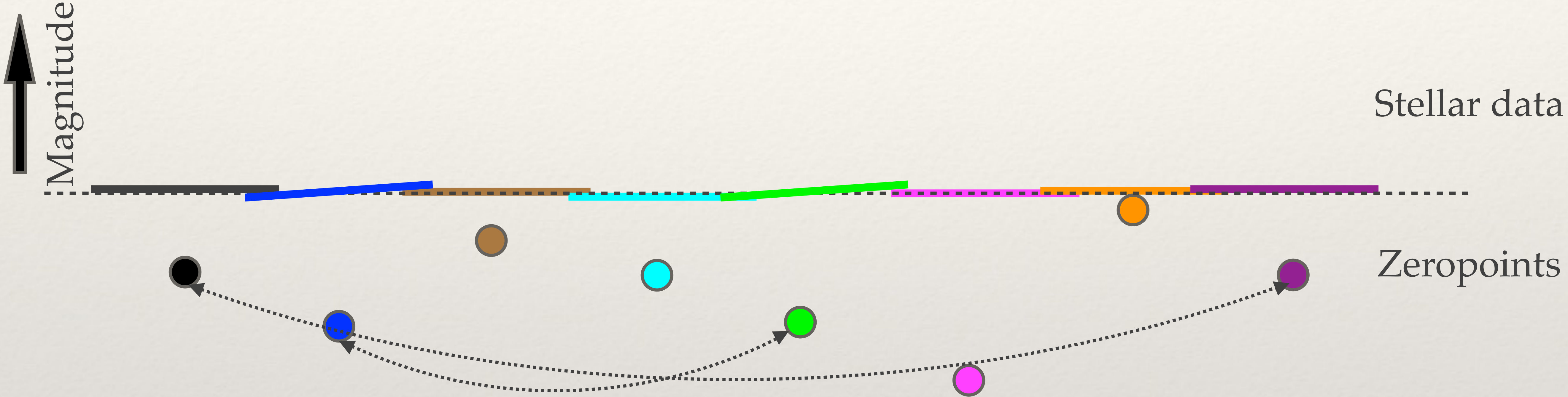

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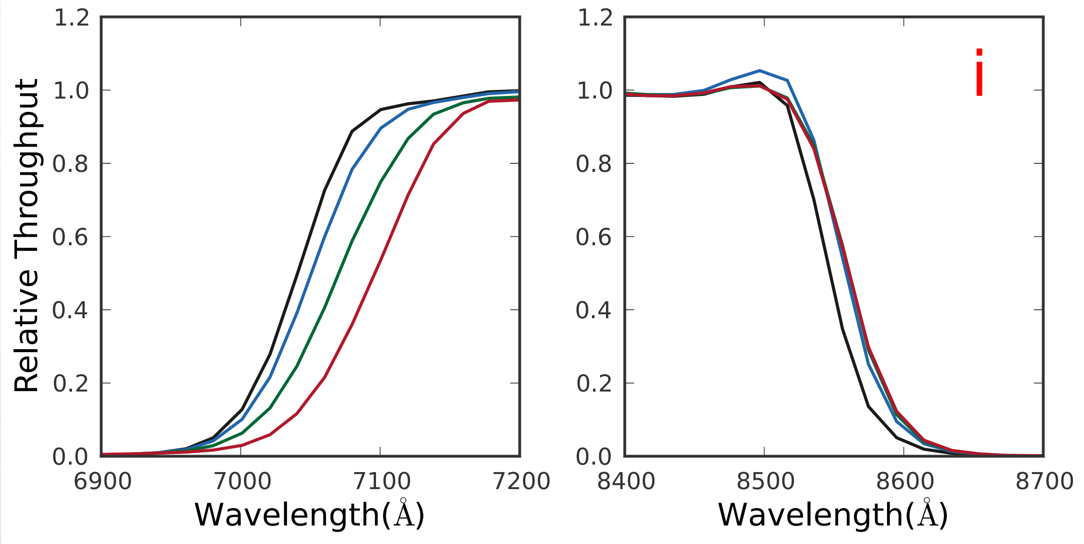
Can this extend our mmag nightly precision to full season? Stay tuned, still in progress!

Color calibration

- Color calibration requires that we understand the time/angle variation of the detection bandpass. Following proposals by Stubbs & Tonry, this is divided into two parts, using auxiliary equipment described in forthcoming papers from J. Marshall and T. Li:
  - *Instrument* bandpass varies across FOV but has no measurable change in time. Measured using the ***DECal*** narrowband dome illumination system.
  - *Atmospheric* bandpass is (nearly) constant across FOV, varies in time as modelled by atmospheric transmission model. The ***ATMCam*** determines 4 relevant atmospheric parameters by continuous monitoring of bright stars in custom narrow bands:
    - Precipitable water vapor (also monitored by dual-band GPS)
    - Atmospheric aerosol optical depth
    - Atmospheric aerosol spectral index
    - Grey extinction component (actually determined by the Global Cal process)
- An even better scheme: conduct *Global Calibration* using priors on *atmospheric model* for each evening derived from *ATMCam* and other monitors, instead of just a prior on zeropoint agreement. This will combine all sources of information into the best global response model (*cf.* D. Burke)

DECal

From Marshall *et al:*



Red & blue edges of *i*-band filter at different field radii, measured *in situ* by DECal.

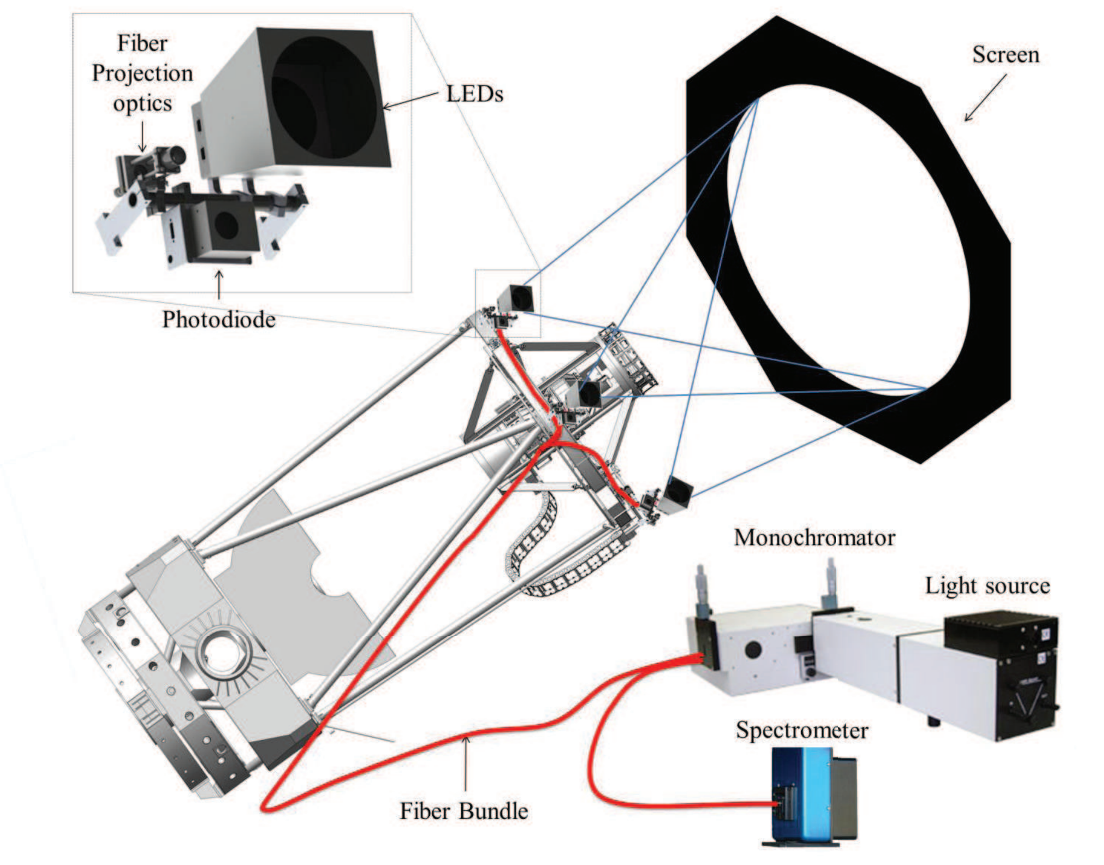


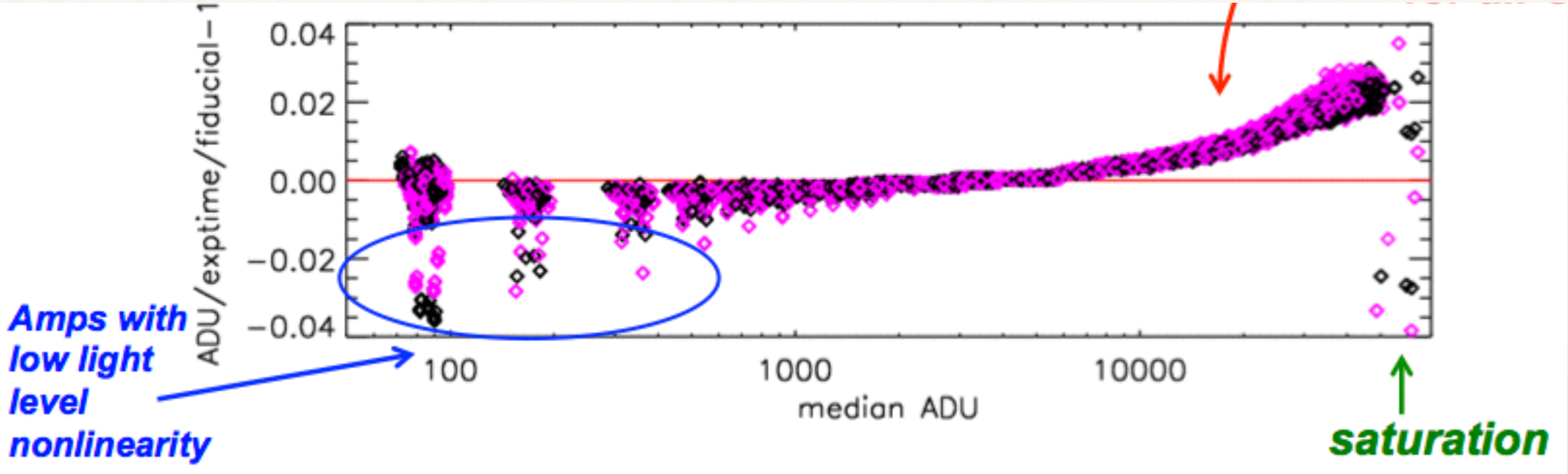
Fig. 1.— Schematic drawing of the DECal system.

Summary

- With care to distinguish pixel-area variation and scattered light from true efficiency variation using "star flat"observations, we can calibrate the focal plane to ***2 mmag RMS accuracy, <1 mmag correlated errors*** over the span of a few hours.
- Even on cloudless evenings, atmospheric transmission can very >10 mmag between exposures and several mmag across the FOV of a single exposure. So we'll need free parameters per exposure, not just per night.
- Instrument response pattern drifts over time by several mmag, mostly smooth & trackable.
- Combining internal calibrations with prior expectation that the atmosphere is stable on the best nights will give much improved *global* matching of exposures onto a common system. Results TBD but prospects for <1% are excellent. DES survey strategy is well suited to this.
- Atmospheric model + narrowband flatfields give sufficient info on spectral response variation to allow homogenization of survey fluxes for any hypothesized spectral shape - results also TBD, but especially important for SN cosmology.

Extras

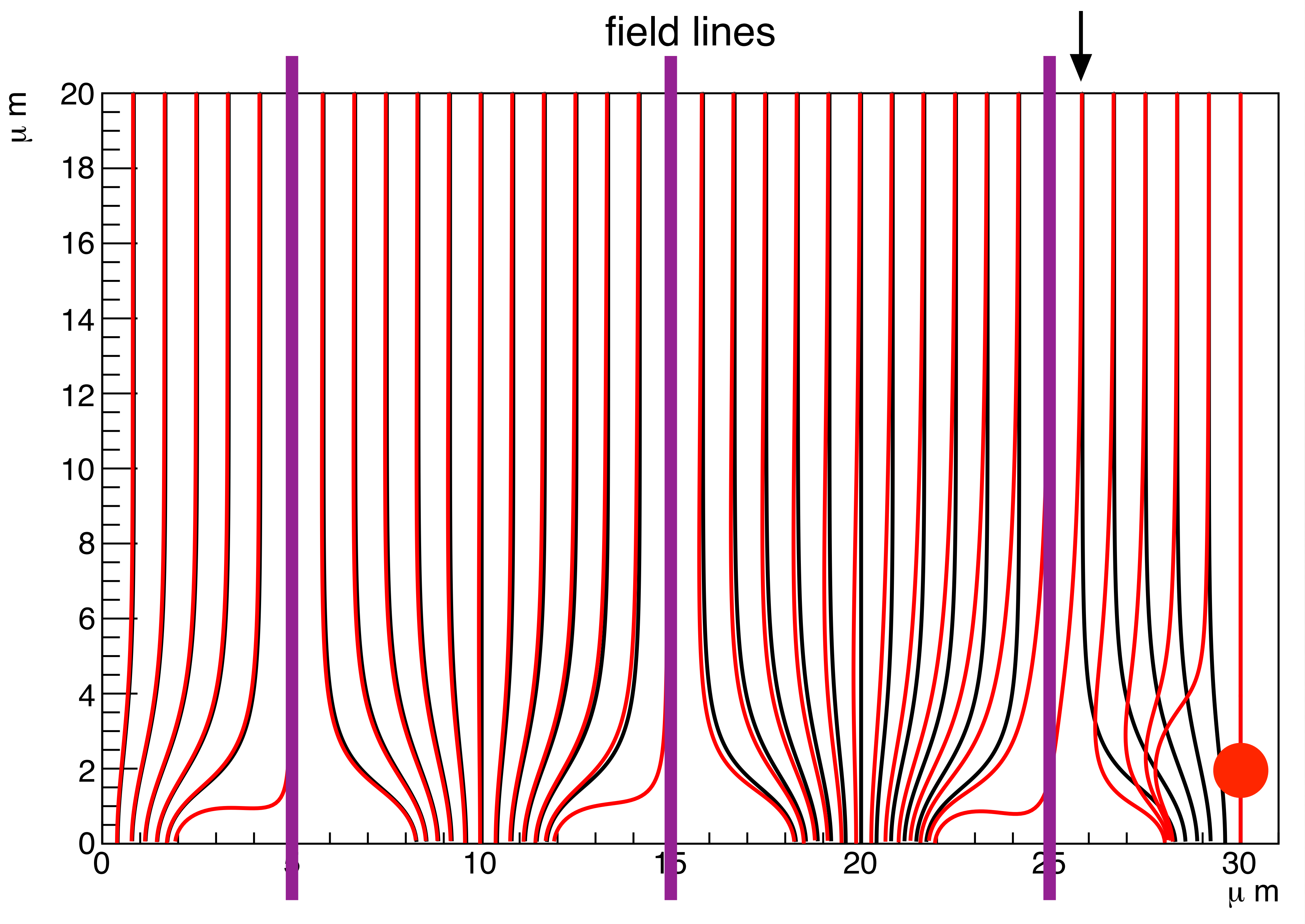
“Classical” nonlinearity



Huan Lin, DES Instrumental Signatures Workshop, Fermilab, 17-18 Jun 2013

- Tests from dome flats of varying exposure time, analysis by Huan Lin
- All amps have high-light-level nonlinearity consistent with quadratic response term
- No evidence of change from continued monitoring
- Easily fixed by remapping ADU’s after bias subtraction.

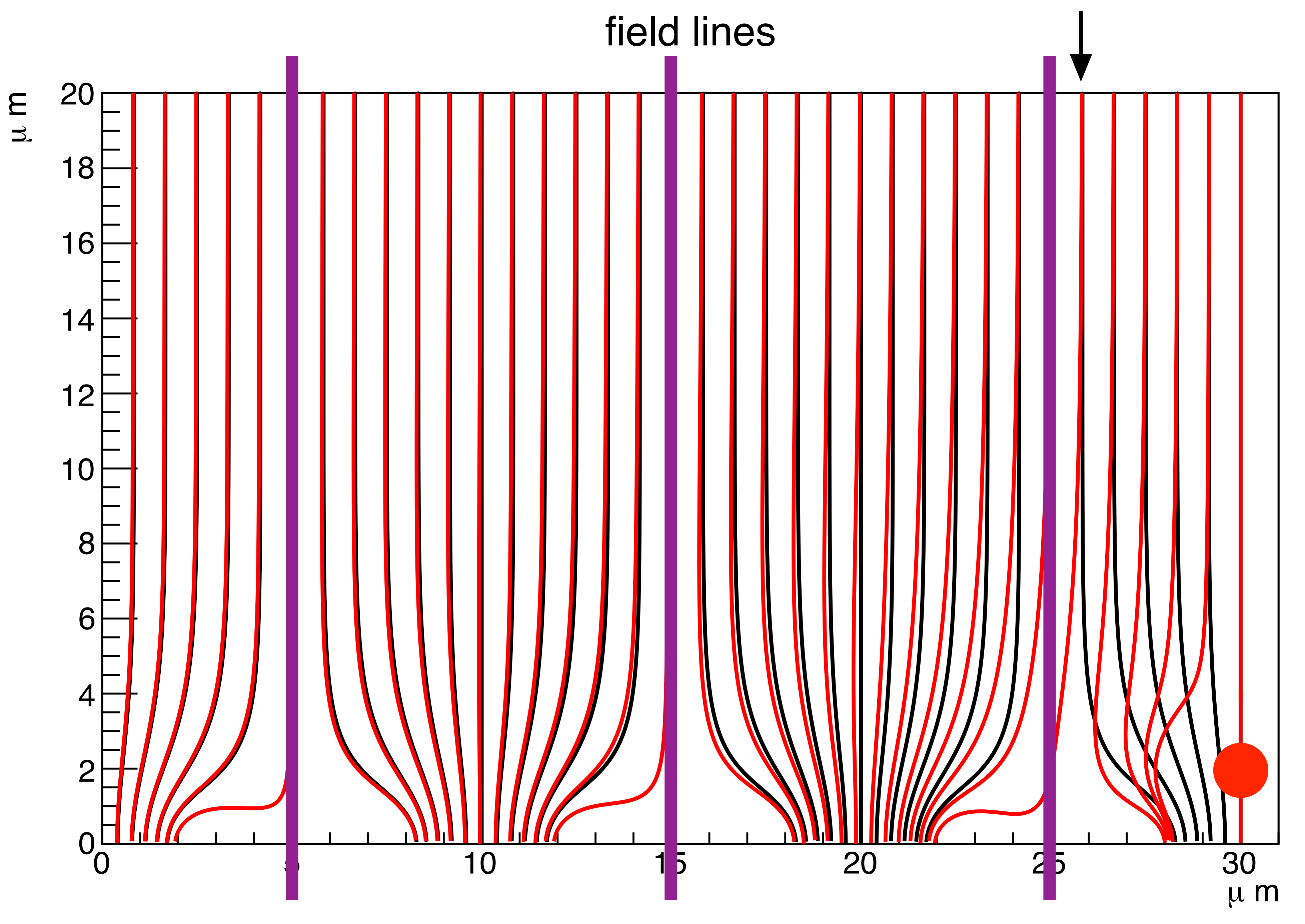
Brighter-fatter effect



Charge collected in this pixel…

Figure from Antilogus *et al*, arXiv 1402.0725

Brighter-fatter effect

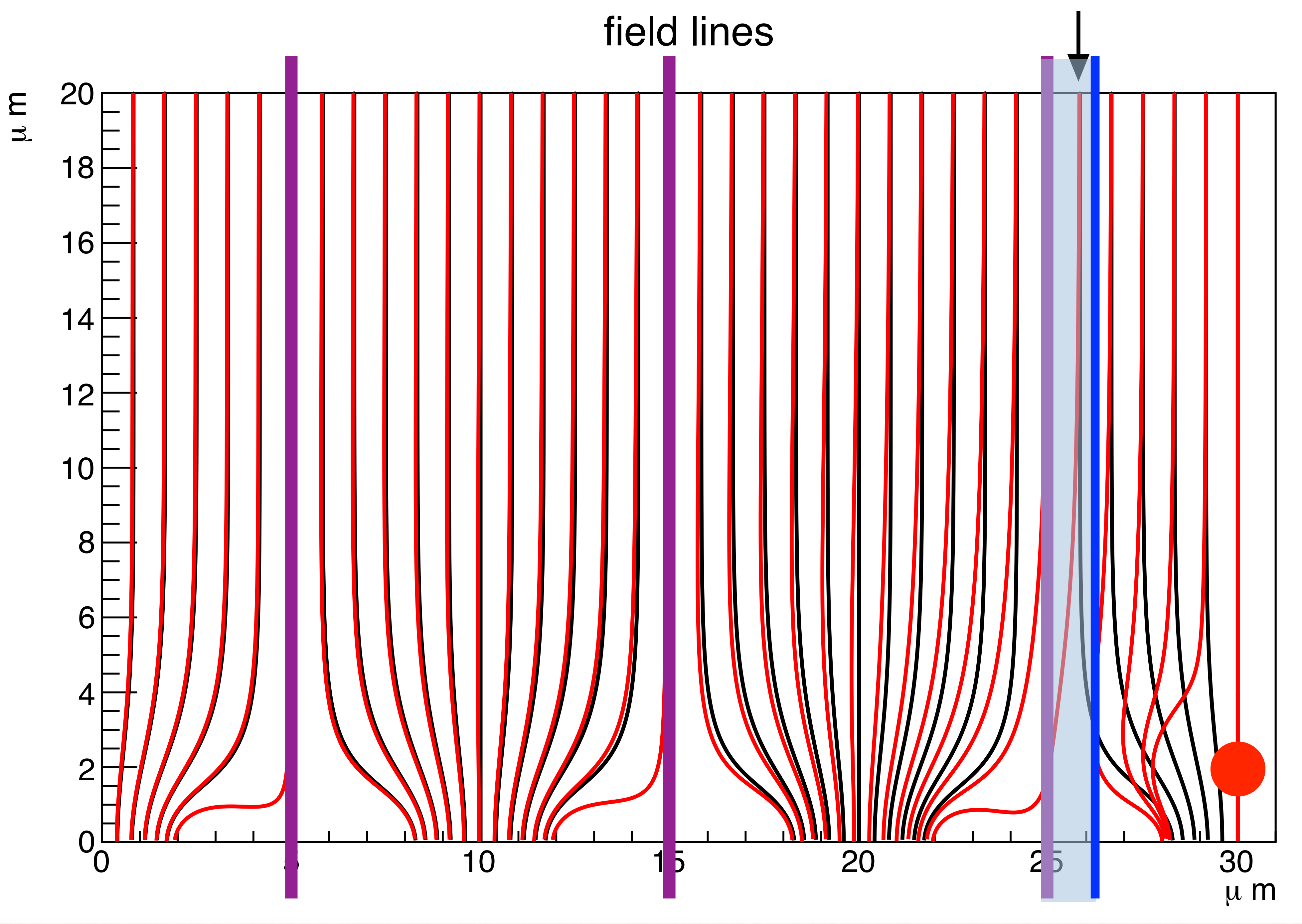


Repels further charge…

Charge collected in this pixel…

Figure from Antilogus *et al*, arXiv 1402.0725

Brighter-fatter effect



Shifts pixel boundary.

Repels further charge…

Charge collected in this pixel…

Figure from Antilogus *et al*, arXiv 1402.0725

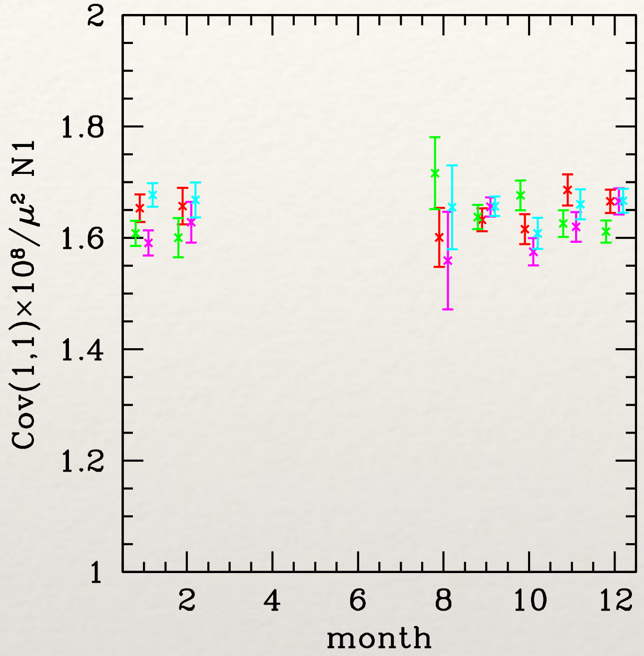
B/F behavior

- Object sizes (and shapes) depend on flux
- Image is quadratic function of illumination: charge shifts are the image convolved with some kernel.
- Pixel-size changes are manifested as noise covariances in flat fields, which can be measured to constrain the kernel (but still need to make some guesses to solve).
- Caused standard gain estimates to be wrong by ~10%!
- If you know the kernel, you can revert the effect on the image to good accuracy.
- Likely to be present on all CCD cameras, other integrating detectors too?

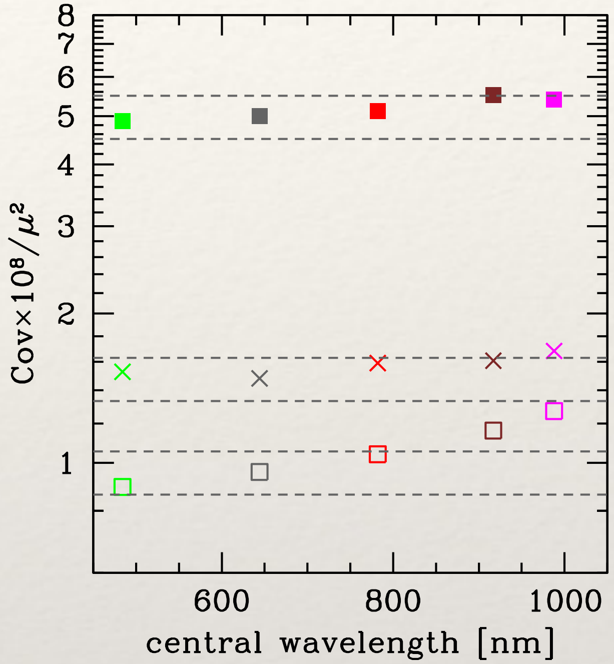
DECam’s B/F

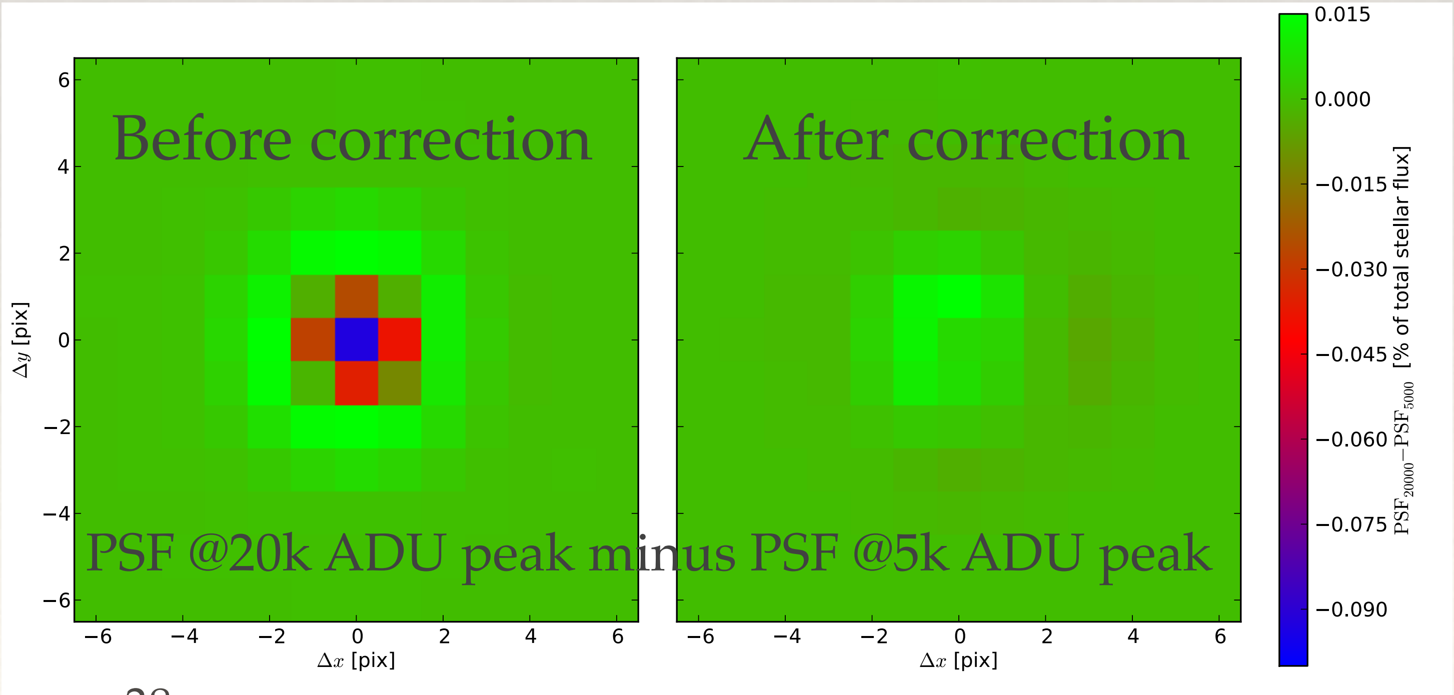
- Characterized by Daniel Gruen *et al.* (arXiv 1501.02802)
- Stars near saturation lose 2% of their signal in central pixel.
- Nearly independent of wavelength
- Same effect on both amps, amplitude varies between CCDs
- No sign of change with time
- Correction reduces effect on stars by ~10x

N1 B/F strength vs time



…vs wavelength





PSF @20k ADU peak minus PSF @5k ADU peak