Brighter-Fatter effect on HyperSuprimeCam

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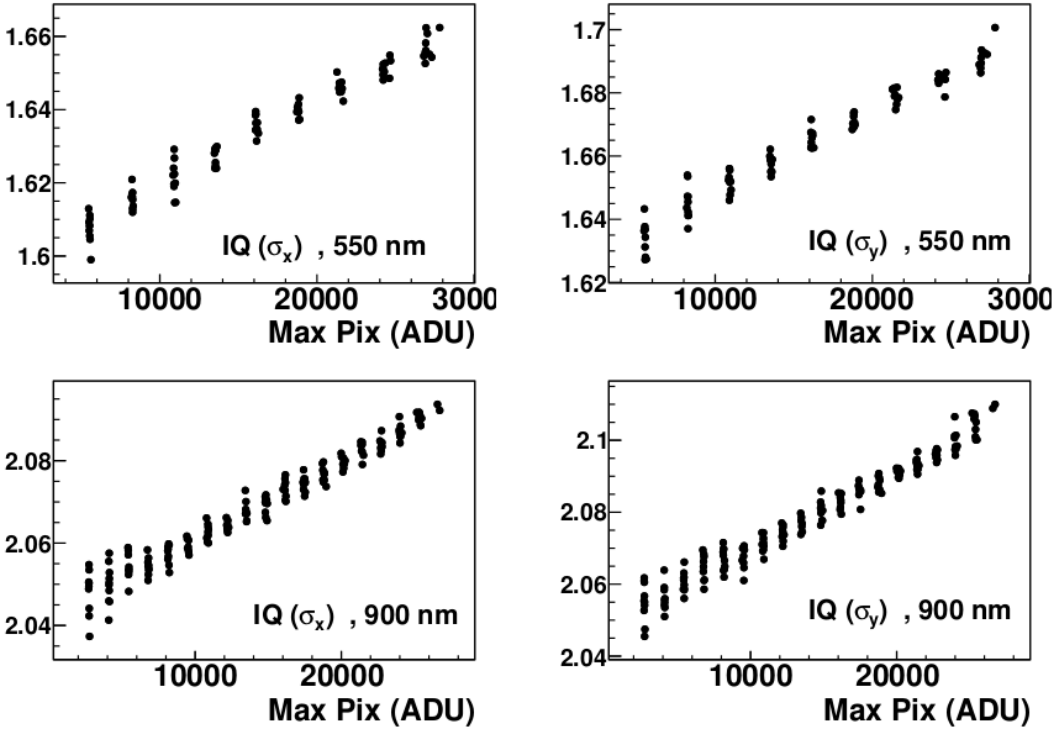
(Rubin/LSST-France, nov. 2021)

Brighter-fatter ?



1402.0725 : sizes of (lab) star as a function of its max (flux), in both directions and for two wavelengths.

The size of a spot a few pixels across increases by a few % from 0 to saturation.

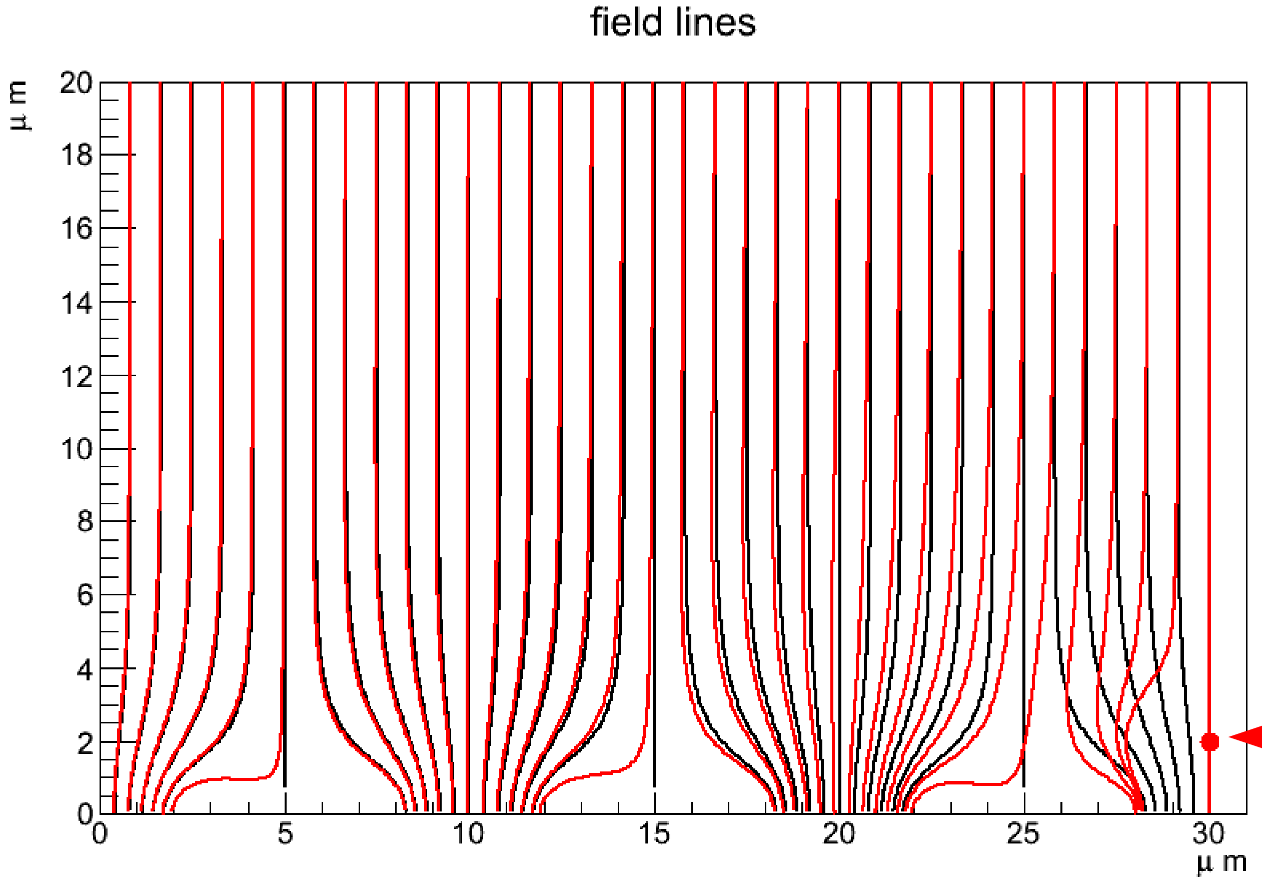
This is a genuine non-linearity unrelated to electronics.

Name :
« brighter-fatter effect»

Why bother ?

- The PSF is measured from bright stars, and is hence biased when used to describe the system response to faint astronomical objects.
- This bias potentially messes up measurements of galaxy shapes and distant supernova fluxes.
- The effect is due to electrostatics in the CCD (Guyonnet et al 2015).
- The standard (and so far unchallenged) way to cope with is to constrain the CCD electrostatics using the correlation function of flatfields, and derive a correction to be applied to raw science images.

Dynamical image distortions



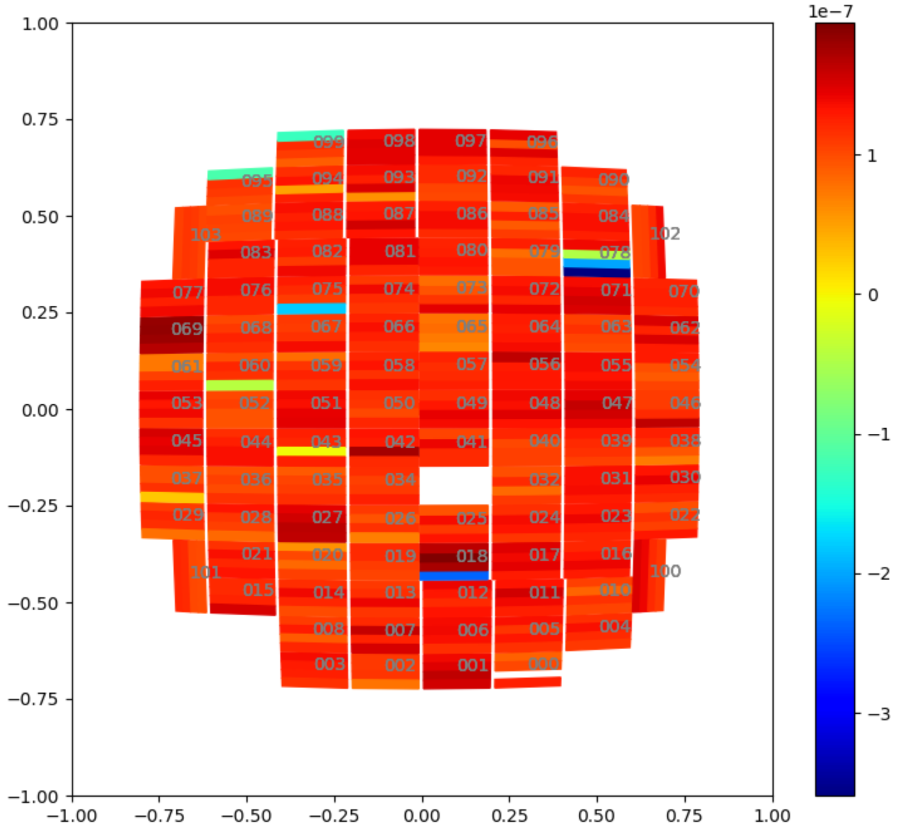
Charges stored in the CCD distort the drift lines of the forthcoming electrons.

50 k electrons

What is new w.r.t the first HSC science papers

- New series of flat fields acquired at fall 2019
  - firstly to measure non-linearity
  - but can be used also measure the 2-point function
- These flat fields are much more stable than the legacy data, and allow to disentangle the lamp intensity variation from non-linearity.
- They allow to actually measure non-linearity
  - The average non-linearity on HSC is sizable and affects the PTC curvature (~10%).
- Revisiting the BF effect on HSC is worth it.

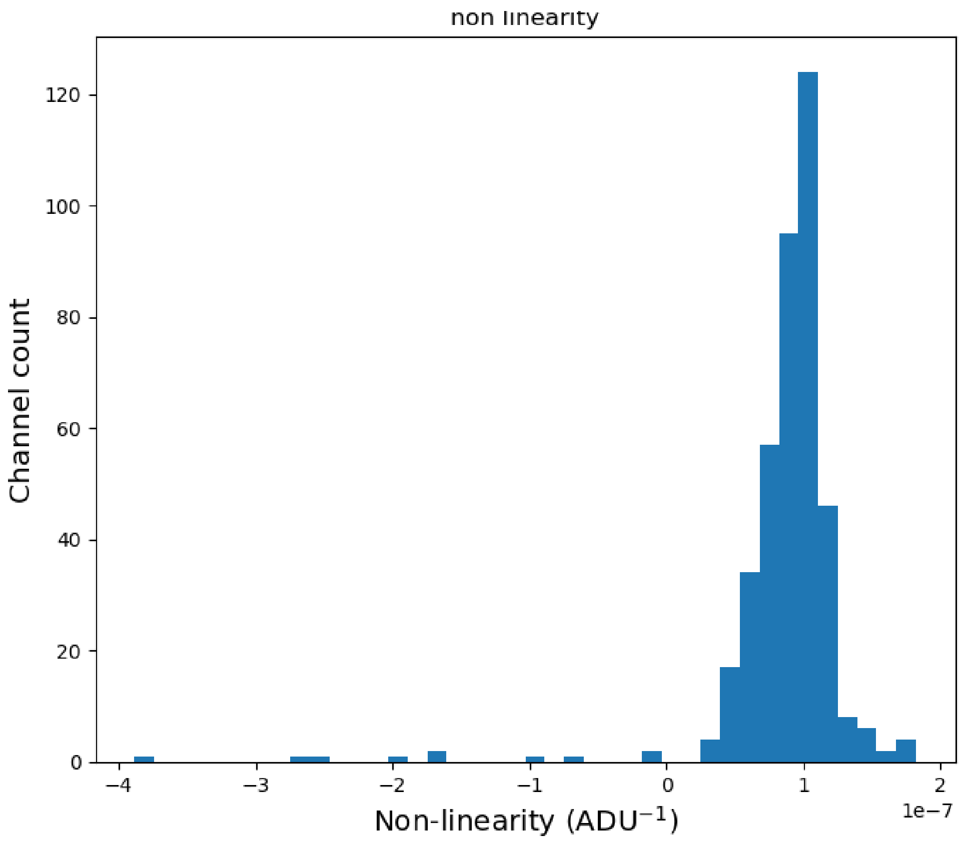
All channels nonlinearity map



$$I_{corr} = I_{raw} + k\, I_{raw}^{2}$$

Fairly homogeneous over the focal plane, with some odd chips.

All channels non linearity



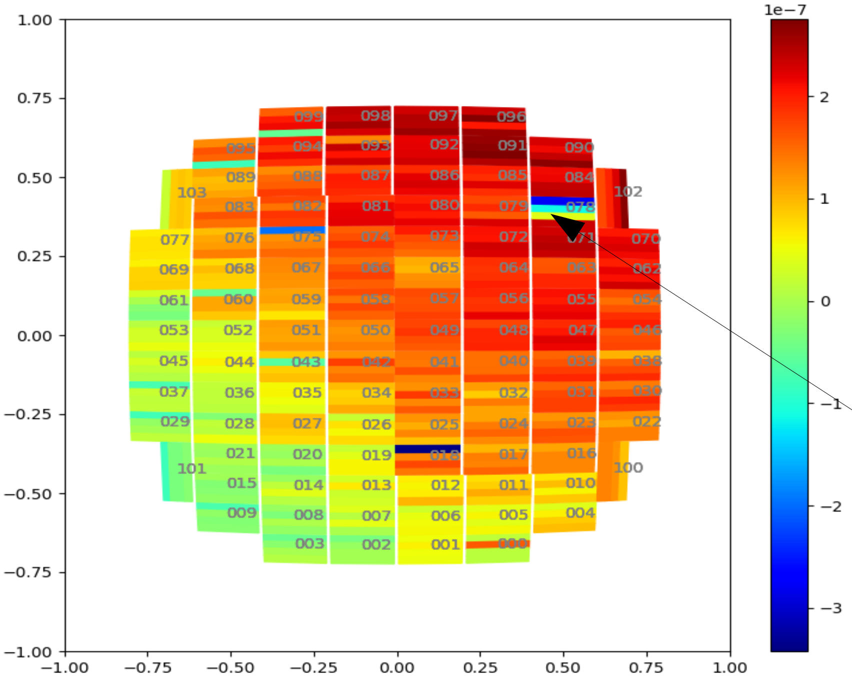
$I_{corr} = I_{raw} + k\, I_{raw}^2$

k is expressed in ADU^{-1}

Amounts to ~0.4% at full scale (~ 40 kADUs).

DM non-linearity corrections

k values in the focal plane



$$I_{true} = I_{obs} + k\ I_{obs}^2$$

This may be due to lamps varying differently as the sequence goes.

Chip 78 covers the whole range

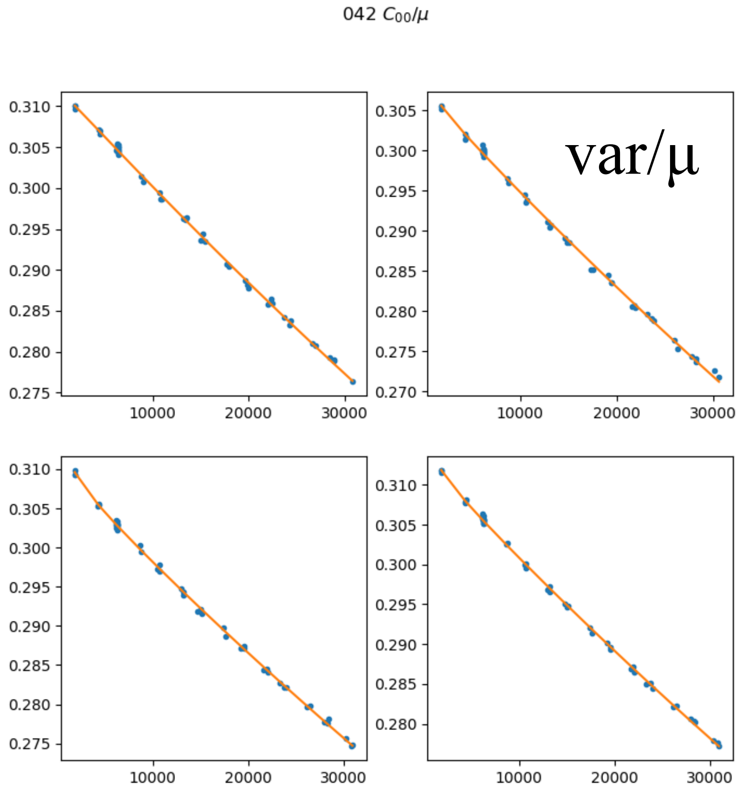
Two-point function of flats

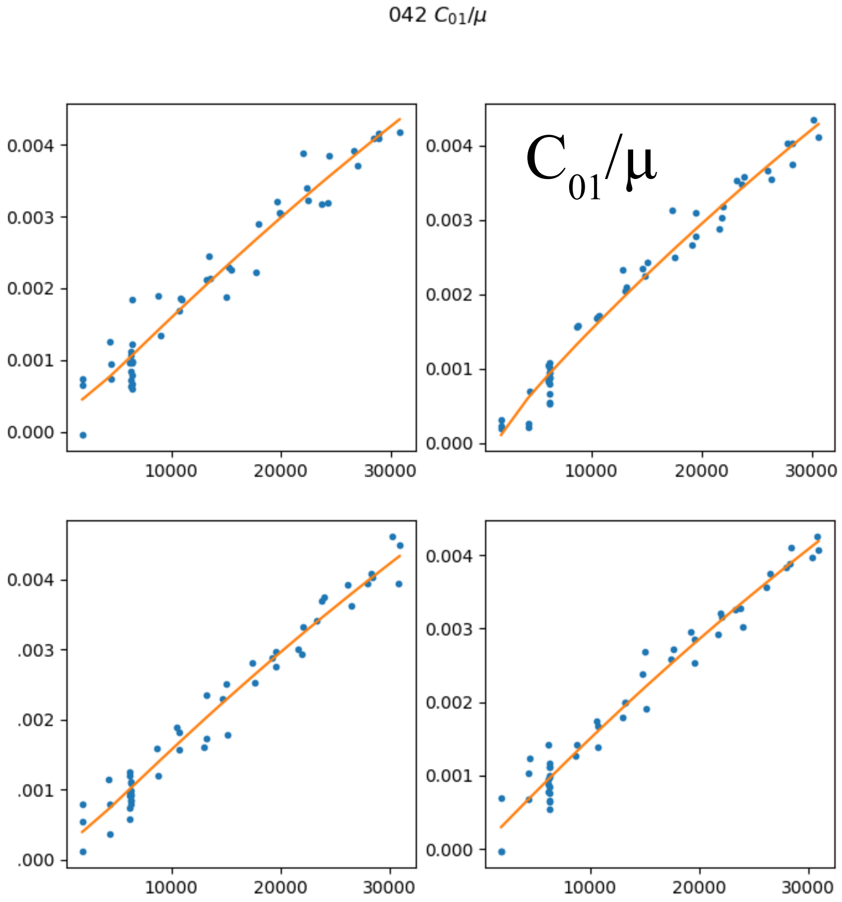
- This is the core ingredient to the brighter-fatter correction.
- 104 CCDs, 4 channels/chip, with a handful of dead channels
- All calculations are done at the video channel level.
- Evaluate 10x10 co-variances
- 62 flat pairs in total in this 2019 data.
- g band.

What determines the flat-field co-variances?

- The pixel area change due to a (1 electron) charge put in a pixel
- The area is changed by $(1+a_{ij})$ for a pixel located i columns and j rows away from the source.
- a_{00} is negative ("self interaction" shrinks a pixel)
- For almost all reasonable configurations all the other a_{ij} are positive.
- because of area conservation, $$\sum_{-\infty<i,j<\infty} a_{ij} = 0$$
- See 1905.08677 for details

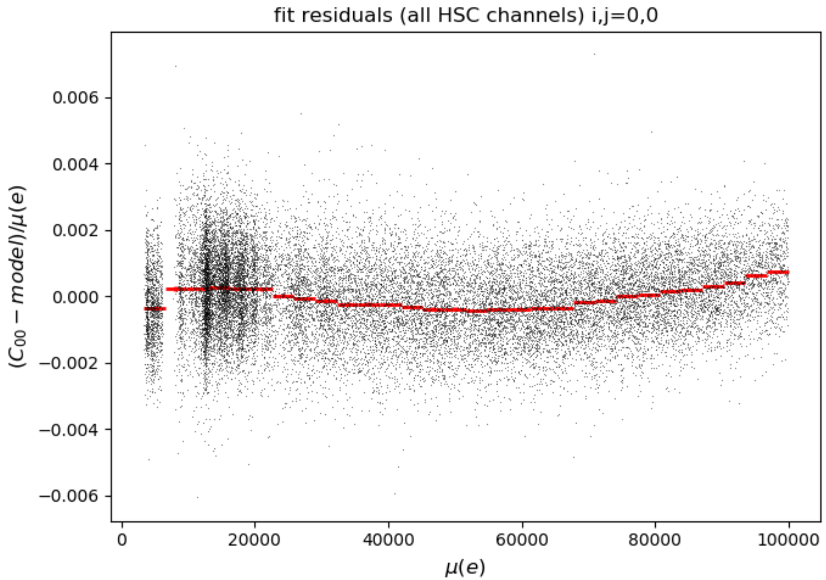
Data and fits

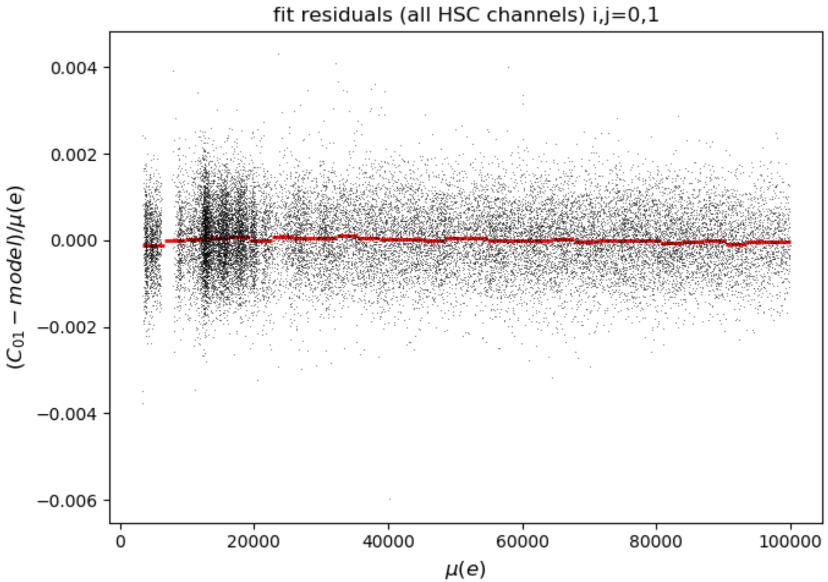


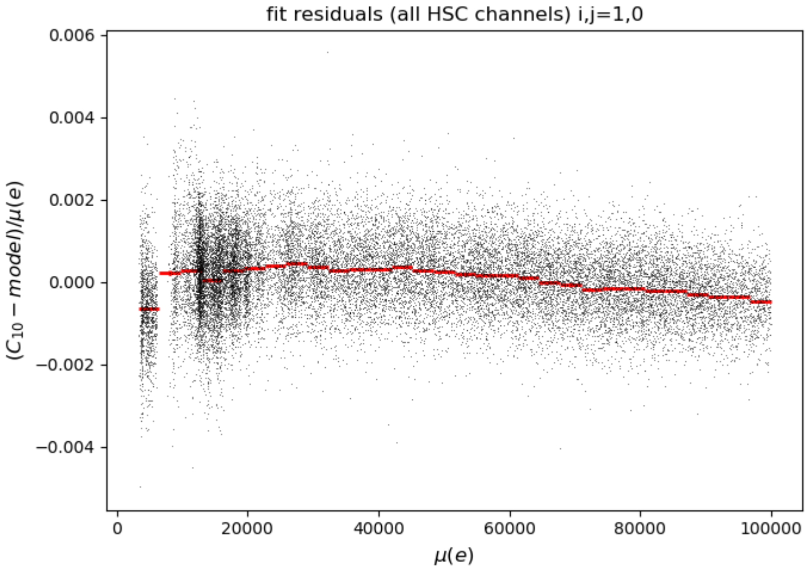


$$C_{ij}(\mu) = \frac{\mu}{g}\left[\delta_{i0}\delta_{j0} + a_{ij}\mu g + \frac{2}{3}[\boldsymbol{a}\otimes\boldsymbol{a}]_{ij}(\mu g)^2 + \frac{1}{3}[\boldsymbol{a}\otimes\boldsymbol{a}\otimes\boldsymbol{a}]_{ij}(\mu g)^3 + \cdots\right] + n_{ij}/g^2, \quad (15)$$

PTC fits residuals

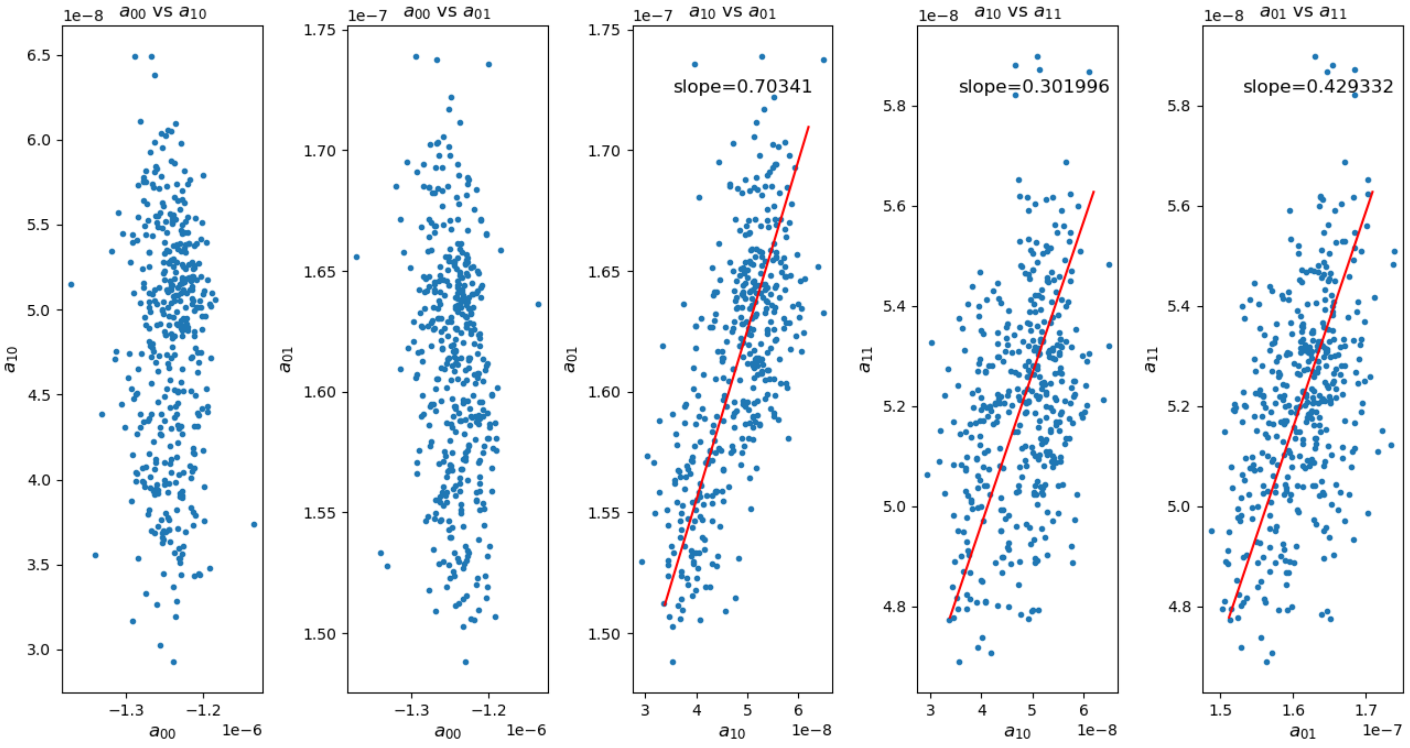






- There is some sort of next-to-leading order effect.
- An imperfect non-linear correction is an unlikely explanation because
  - non-linearity does not affect covariances
  - the non-linearity residuals are too small to accommodate the size of the effect.
- There are strange problems at low flux.
- Size is significant: about 10% of covariances.

Distributions of a_{ij} over (~400) channels



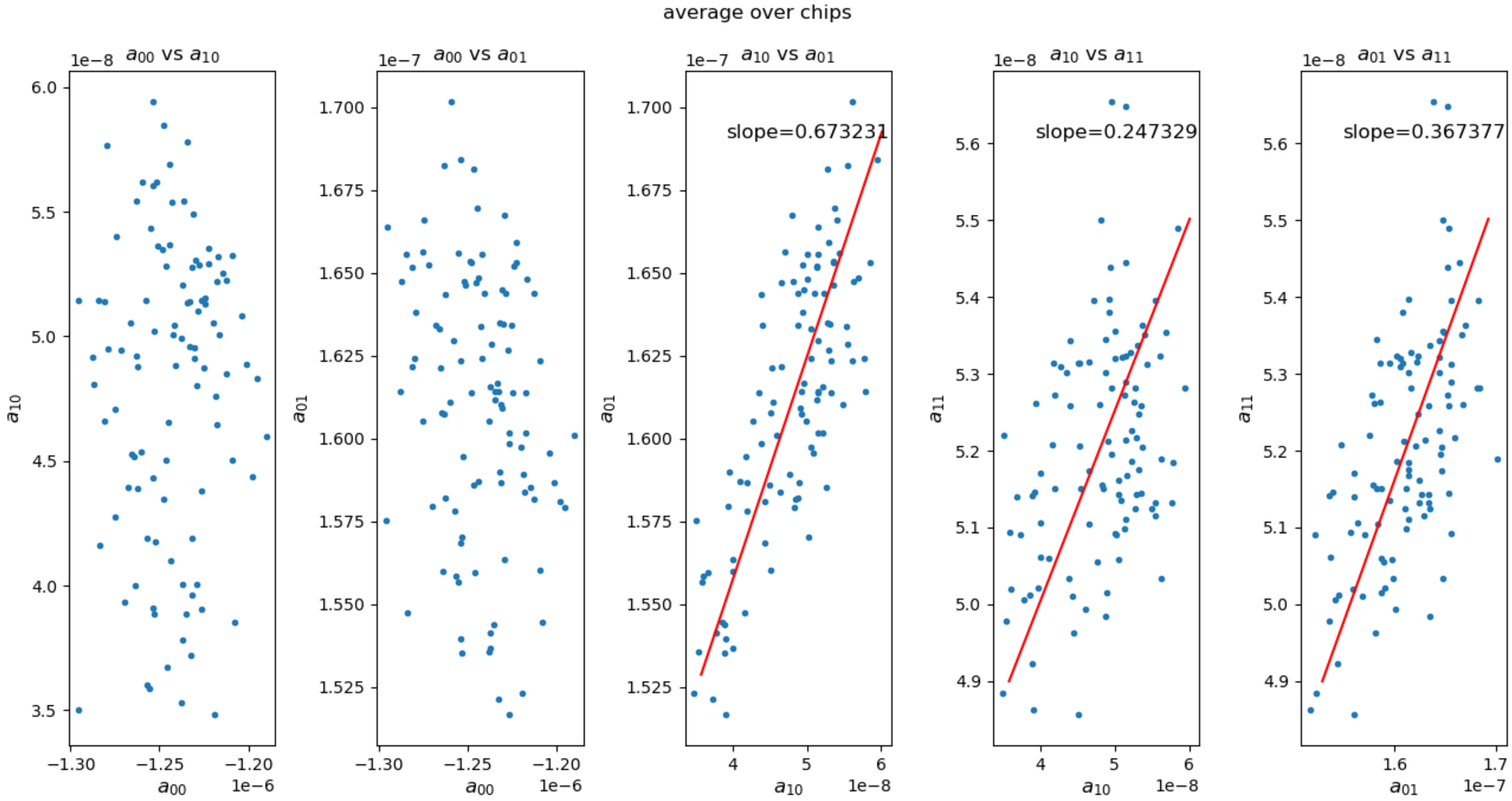
The a_{ij} are independent of the gain.

Spreads are larger than expected from shot noise

Covariances expected from fits are expected to go the other way

Variability is probably real.

Average over chips

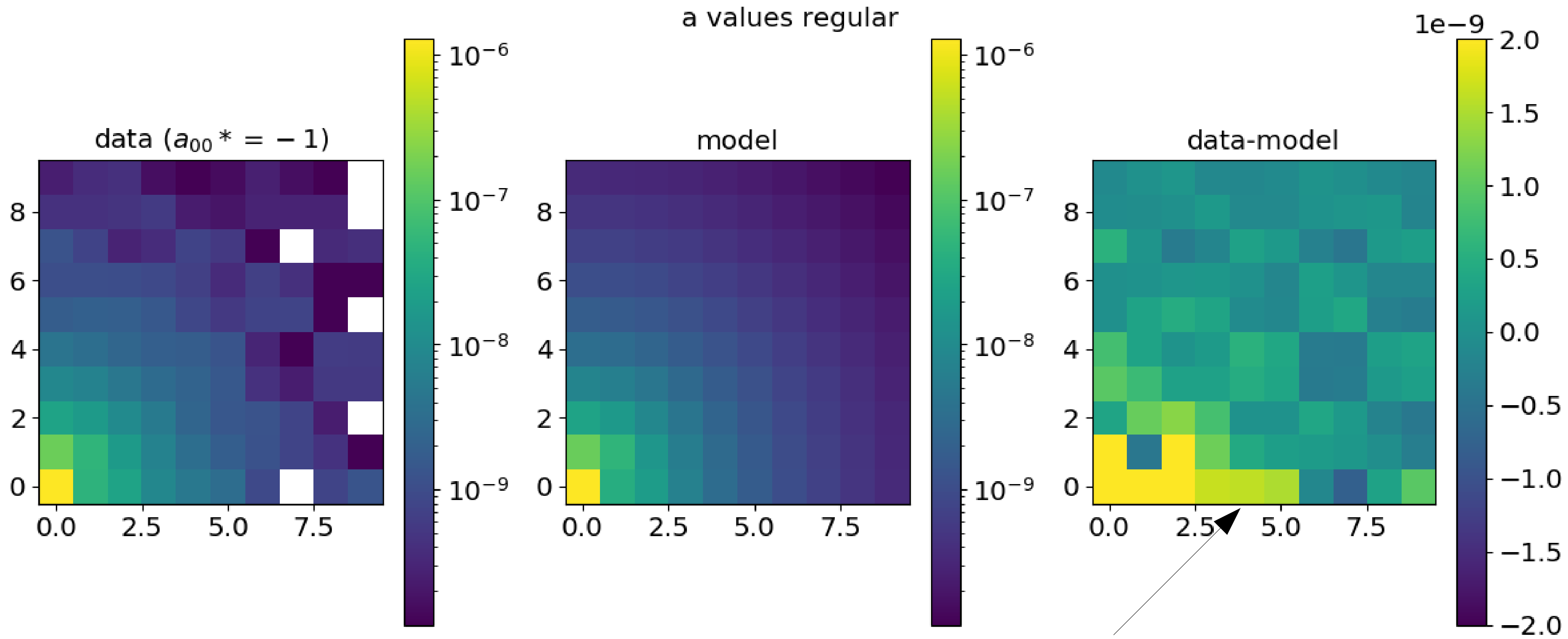


Both trends and ranges are similar to the amp-level data

Average over all channels

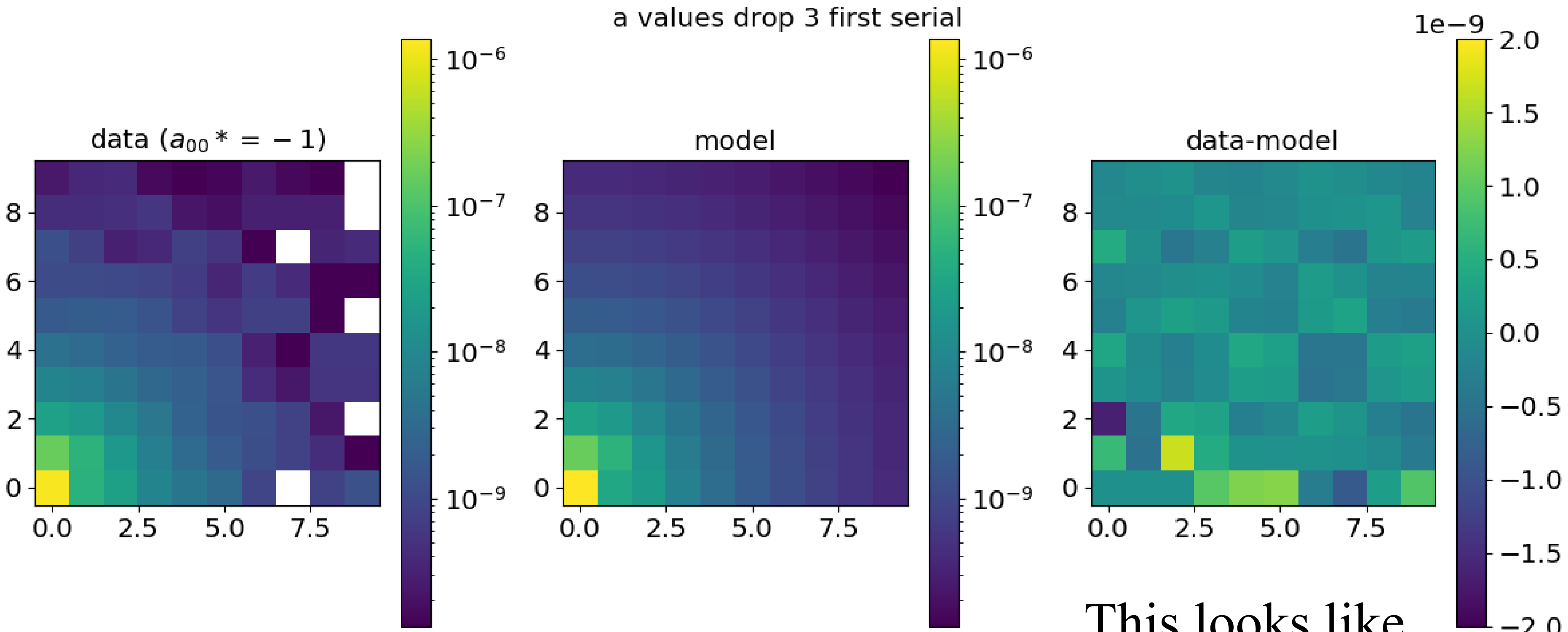
- The spread over channels is a at most 5 to 10% rms
- We decide to average the a_{ij} over all channels in order to get a significant measurement at a distance of a few pixels.
- We perform an electrostatic fit to the (average) data.
- The sum rule of the fitted a_{ij} coefficients is enforced $\sum_{i,j} a_{ij} = 0$
- We measure : $a_{00} = -1.26\ 10^{-6}$ and sum(|i,j|<10) = $7\ 10^{-8}$
- Since we evaluate that $\sum_{|i,j|>9} a_{ij} \simeq 7\ 10^{-8}$, we have an excess of ~10% of $|a_{00}|$ in the data

Electrostatic fit



Electrostatics cannot accommodate the x/y asymmetry of data.

Electrostatic fit without the first 3 serial pixels

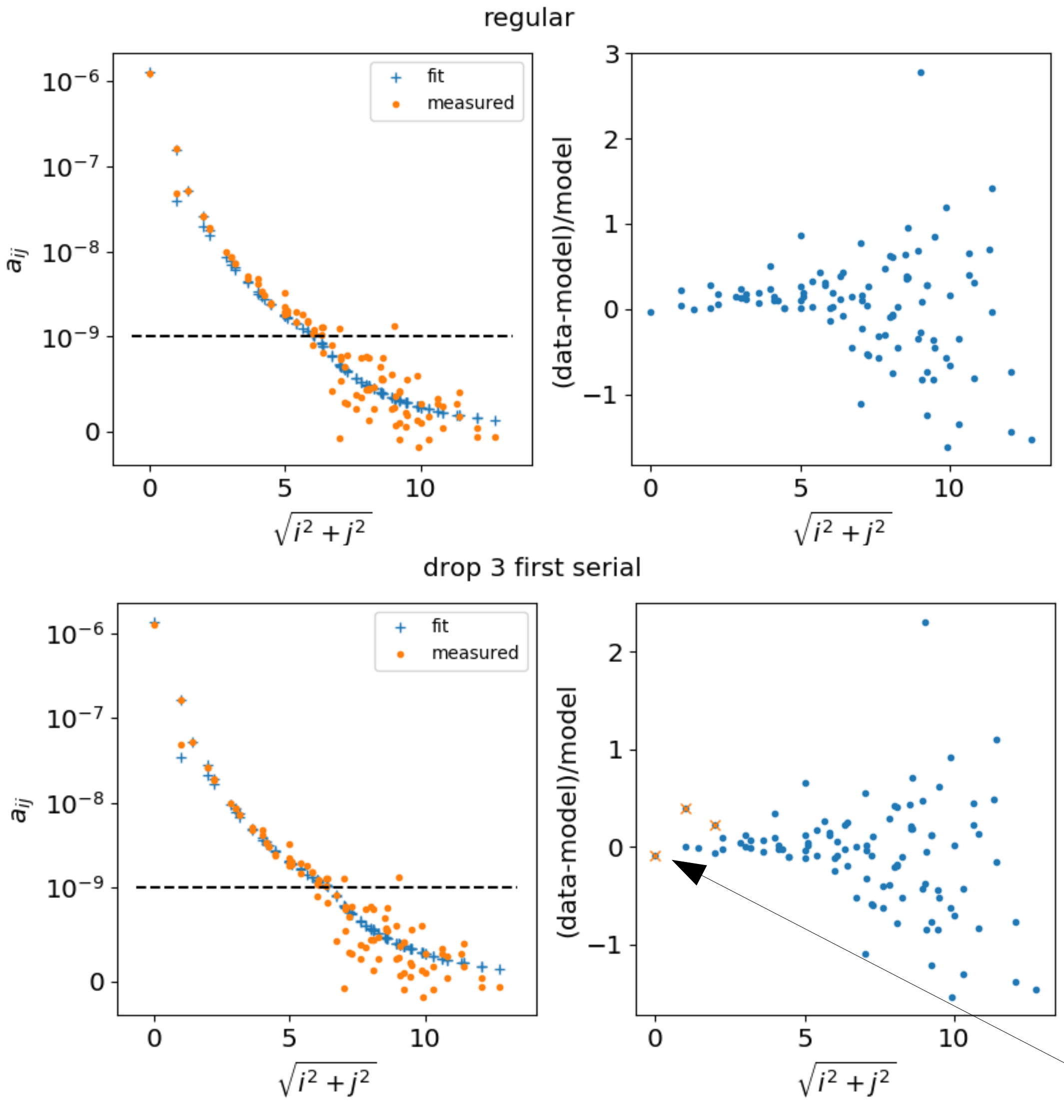


a_{00} = -1.28 10^{-6}

a_{00} = -1.37 10^{-6}

This looks like a good fit

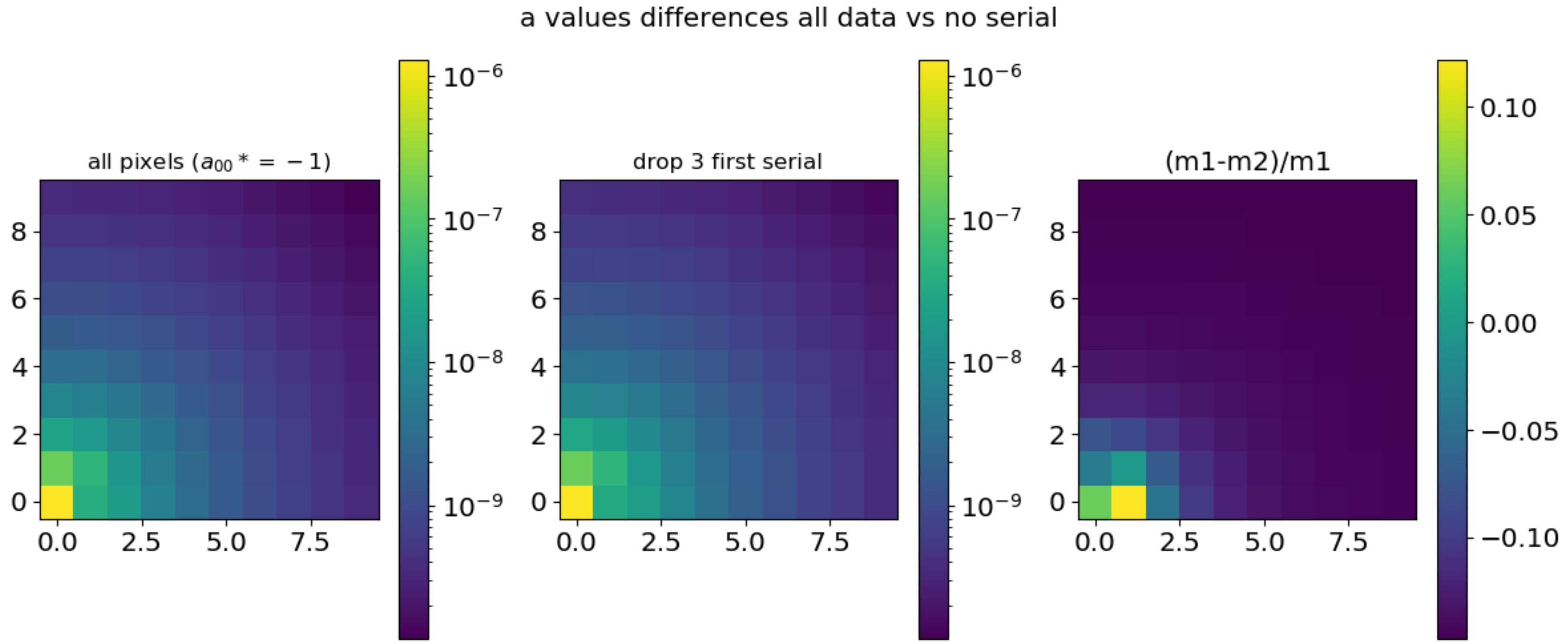
Comparison



- All data points carry roughly the same uncertainty
- The bottom fit is much better than the top one

flipped sign

Comparing the two models



The large-distance scale difference is about 15%

Serial noise excess : which source ?

- The first covariance measurements along the serial direction cannot be described by an electrostatic model, because they are too large w.r.t their neighbor (same i, j=1) and their X/Y symmetric (i↔j)
- This can be the explanation for the "sum rule excess".
- Since the HSC electronics uses Dual Slope Integration, (correlated) clock noise could be the culprit. But there are absolutely no cross-amp covariances ?!
- The dominant (variance) gain fluctuation would be $\sim 3\ 10^{-4}$ and decaying with distance.
- There is a lab measurement of this noise (Miyake et al),

Gain noise on HSC front end, measured in the lab

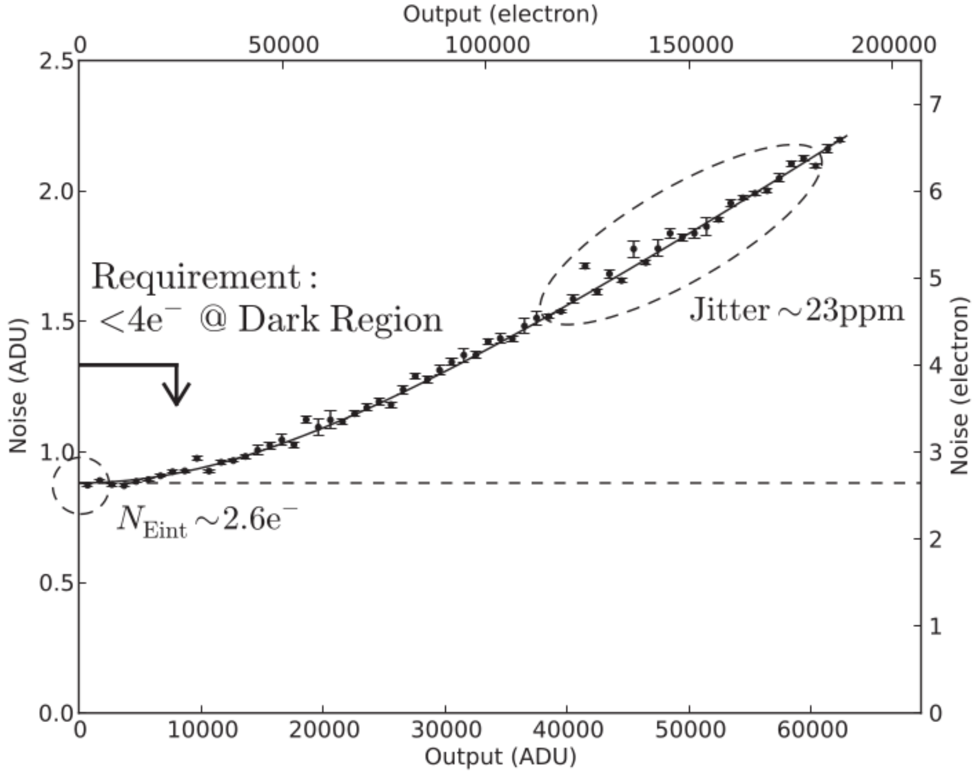


Fig. 8. Result of noise measurement.

Miyake et al, 2011

"gain noise":
$\sim 2\ 10^{-5}$

It could be larger in the actual instrument, with probably different power supplies and environment.

No channels cross-correlations in this test.

Chapter 2 : stars in science data.

- We have reduced (mostly Nicolas…) all the Ultra Deep data from the Subaru Strategic Program. This means Cosmos and SXDS (~1 pointing each), in 5 bands (grizy) over a few seasons, in order to detect and measure high-z SNe Ia. There are a few 100s events in this data, and (host) redshifts are being collected.
- The data covers a huge range in observing conditions.
- We use the code developed for SNLS, with a few modifications.
- What follows only depends on very simple algorithms, mostly the "Gaussian moments measurement", similar if not identical to Galsim and DM.

Gaussian moments measurements

- This is an unweighted least-squares fit of a Gaussian to a "spot", with 6 parameters (flux, position, moments). There is a (large) speed-up trick for the Gaussian shape that we use (as Galsim).
- This is called "SDSS moments in DM", adaptive moments in Galsim.
- Should be independent of flux if star images are free of BF…
- … but because color and brightness are not independent (generally) in star samples, and because star sizes depend on color, I am using color measurements averaged in order to correct for the PSF chromaticity.

Three processings

- No BF correction
- With BF correction from “fit 1” (all separations): model1
- With BF correction from “fit 2” (uses all separations but the 3 first serials): model2
- All corrections evaluate “charge on pixel frontiers” using a quadratic interpolator.
- There are ~20 millions star measurements in each processing.

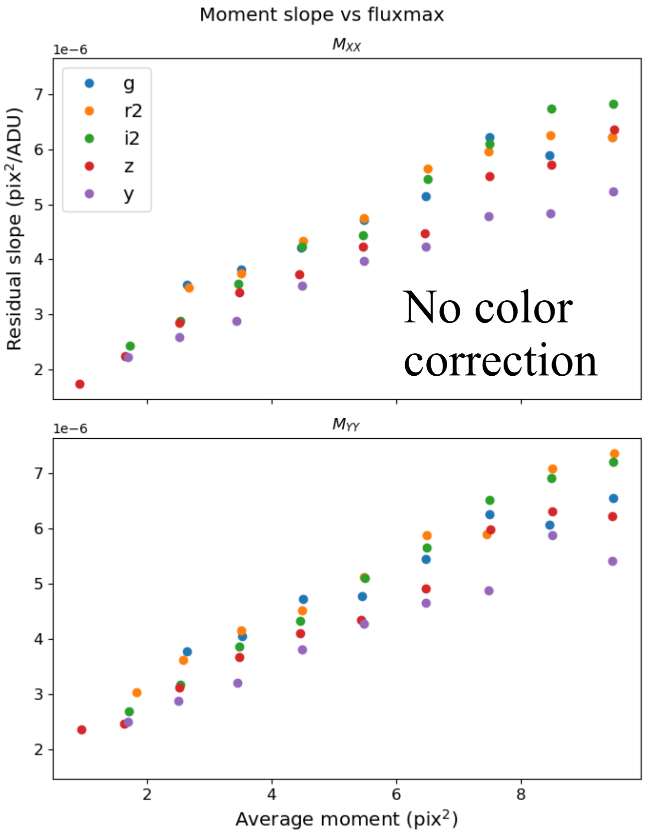
Analysis

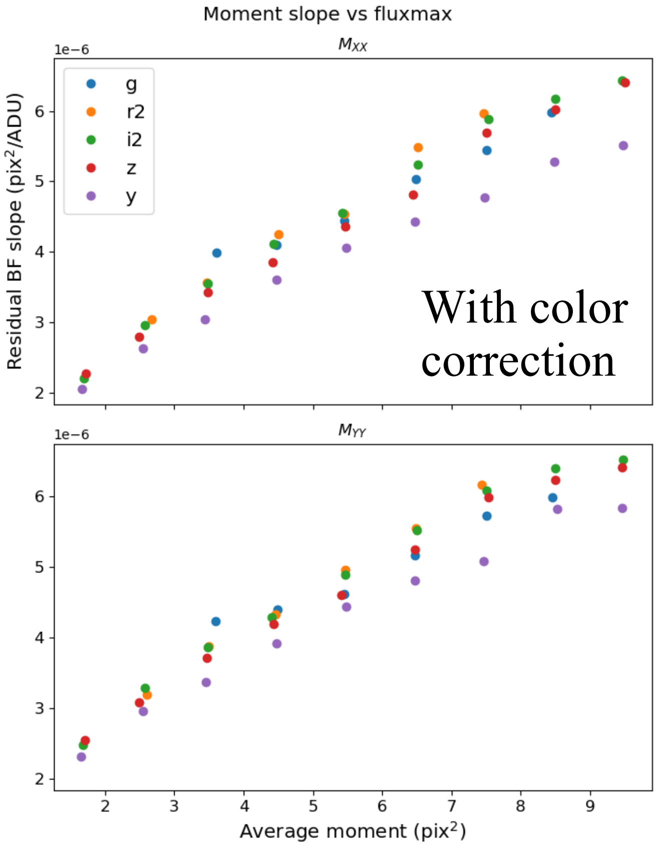
- For each CCD, we fit a 2D quadratic interpolator of the measured moments as a function of position in CCD, with outlier rejection.
- We then analyze the difference of the measurement to the smoothing, as a function of f_{max} and color:

$$M_{ab} - \hat{M}_{ab} = \alpha f_{max} + \beta c + \gamma$$

- We consider separately M_{xx} and M_{yy}
- f_{max} is measured on flat-fielded images and the flats vary by ~30% on HSC from chip to chip. Since we have to average over chips, this smears the BF relation.

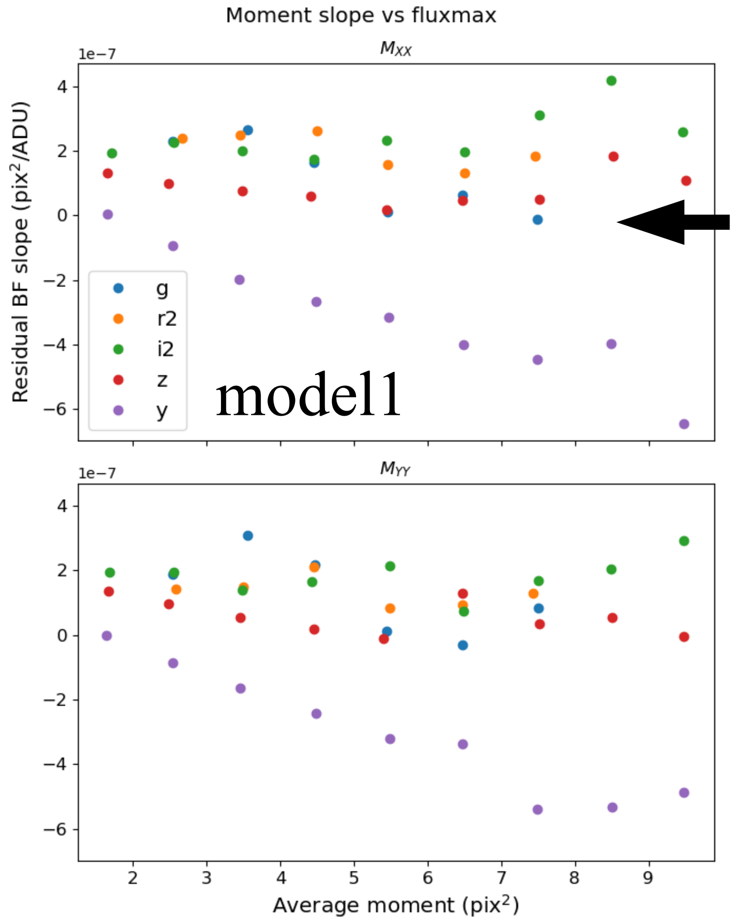
BF slopes on uncorrected data





- At full scale (~35k ADUs), the second moment increase is ~3%
- The slope increases ~linearly with moment
- X/Y asymmetry 10 to 20%
- Almost achromatic except for y and perhaps z bands.
- Color correction reduces the apparent slopes by ~10%

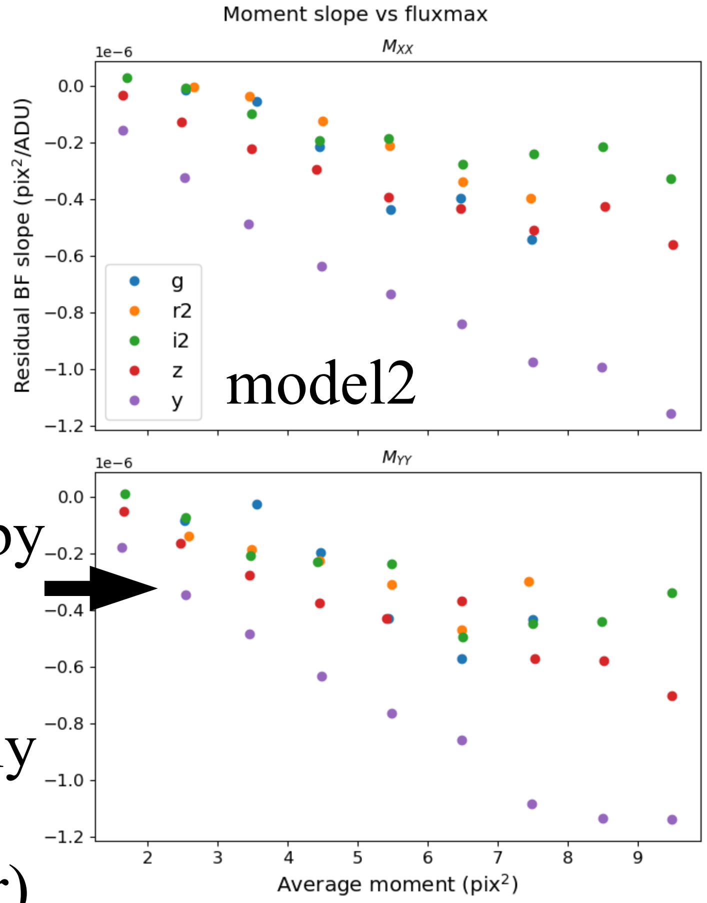
Corrected data: BF slopes



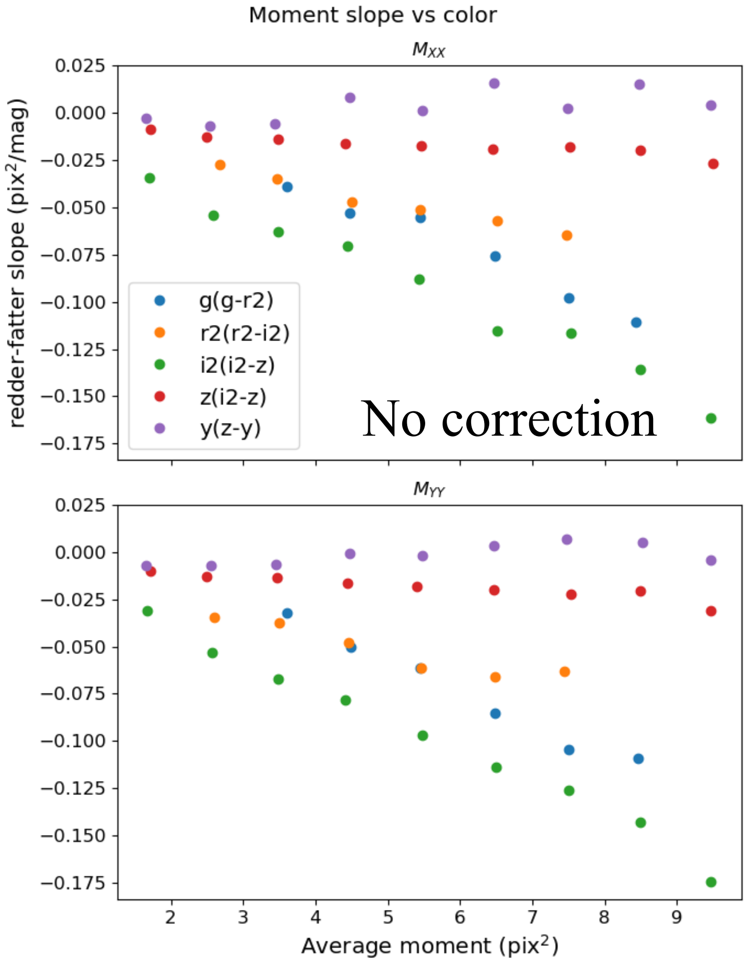
Let us ignore y for the time being.

- Effect reduced by much more than 10
- Residual slope independent of IQ (?!)

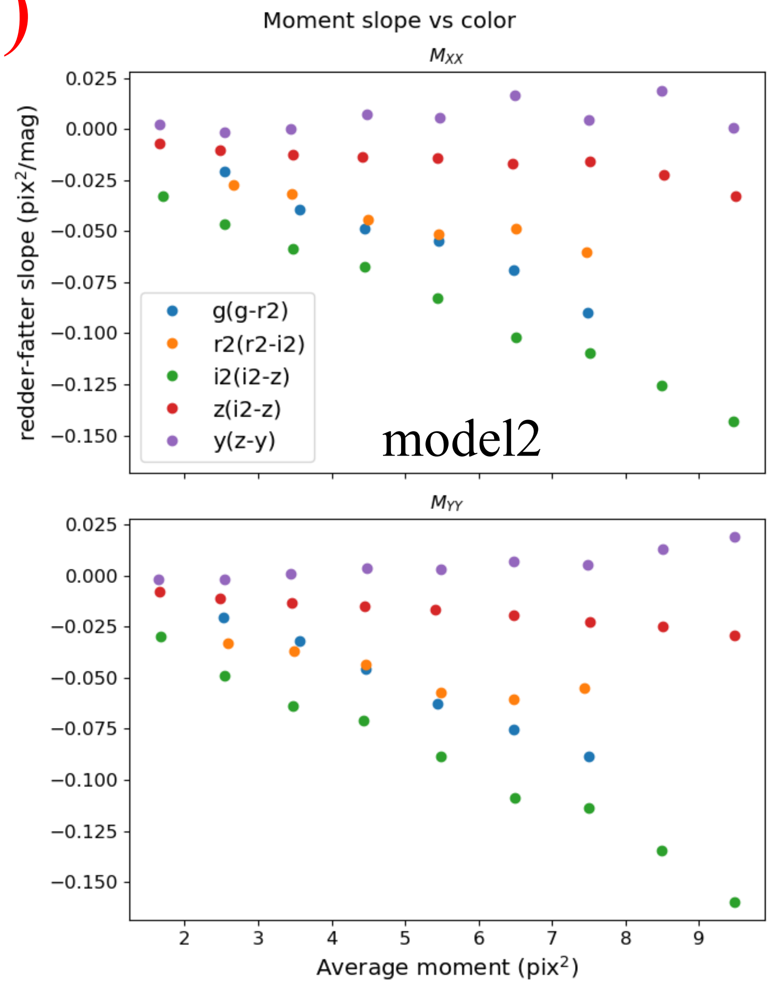
- Effect also reduced by much more than 10
- Looks like a slight over correction, mildly better than model1 (best IQs in particular)



Color slopes (1)

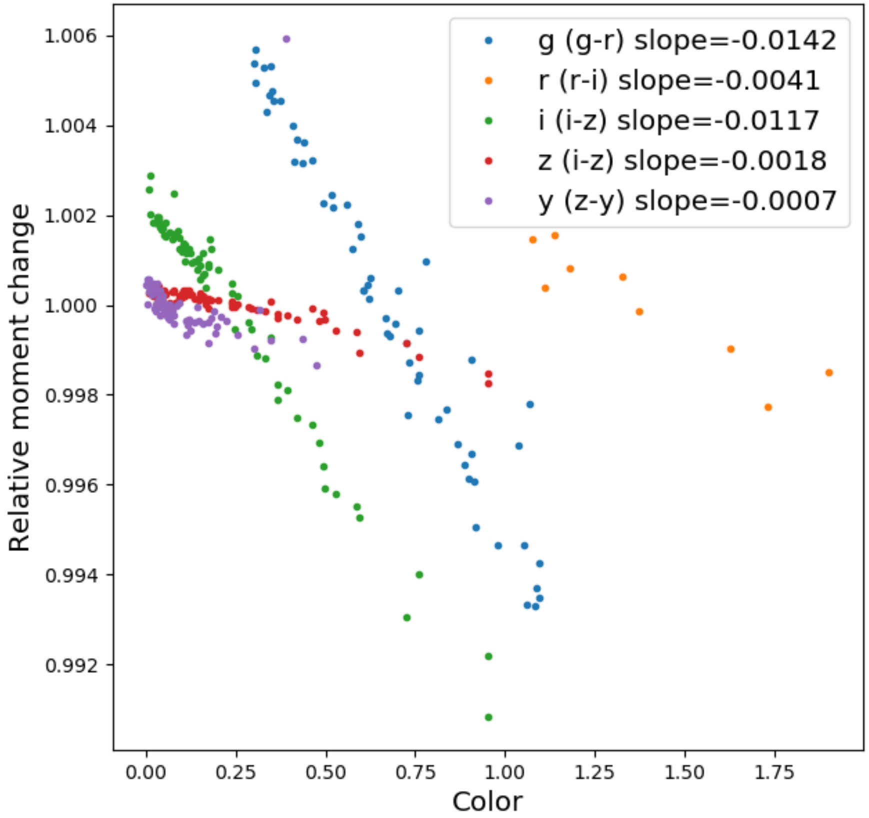


- The two plots are extremely similar
- Beware: the color index varies from band to band
- Surprised by the largest effect in i2
- No effect in y: compensating CCD effect ?
- The ~linear increase with size² is compatible with an atmospheric origin.



Color slopes(2)

- On real data, the measured color slopes in g and i are of the order of 1 to 1.5% variations of second moments per unit color.
- Assuming the variation of PSf size**2 goes as $\lambda^{-0.4}$ provides the right order of magnitude, and essentially the same band ordering as observed.
- Need r2 and i2 bandpasses.

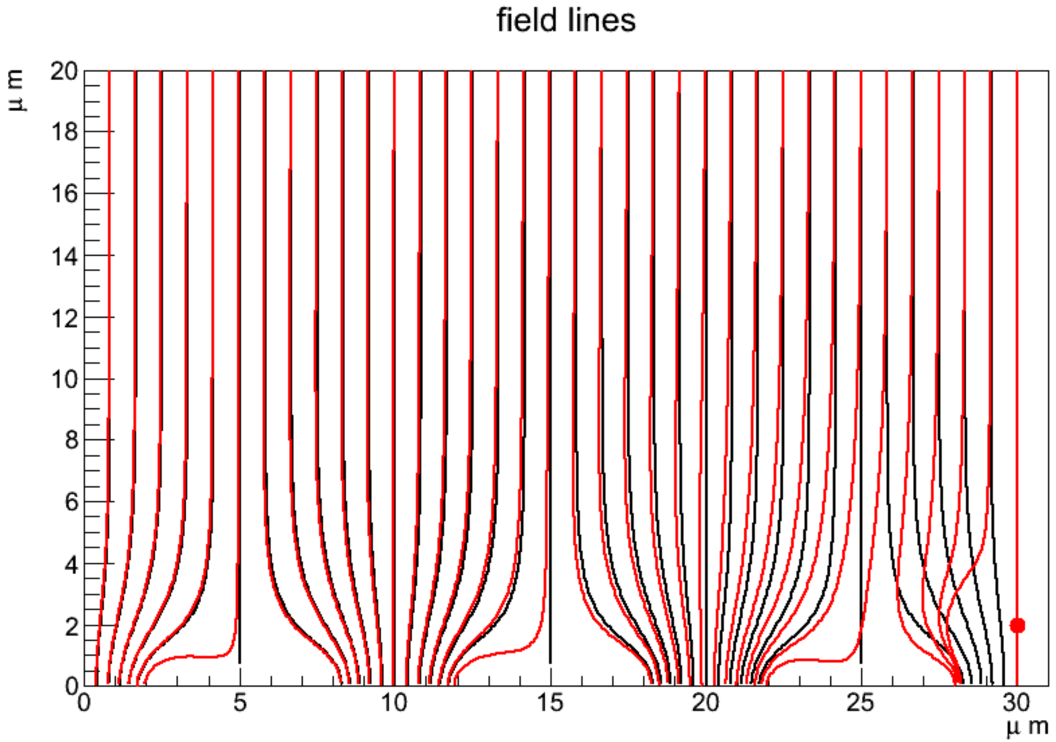


Color slopes(3)

- The range of moment variation due to color is one half or less of the one due to BF.
- Regarding the measurement of BF effect on stars, the chromaticity of PSF acts as a sizable correction to the BF slope, because of a small covariance between flux and color in practical star samples.
- On BF-corrected data, the moments variations with color have become larger than the ones with flux.

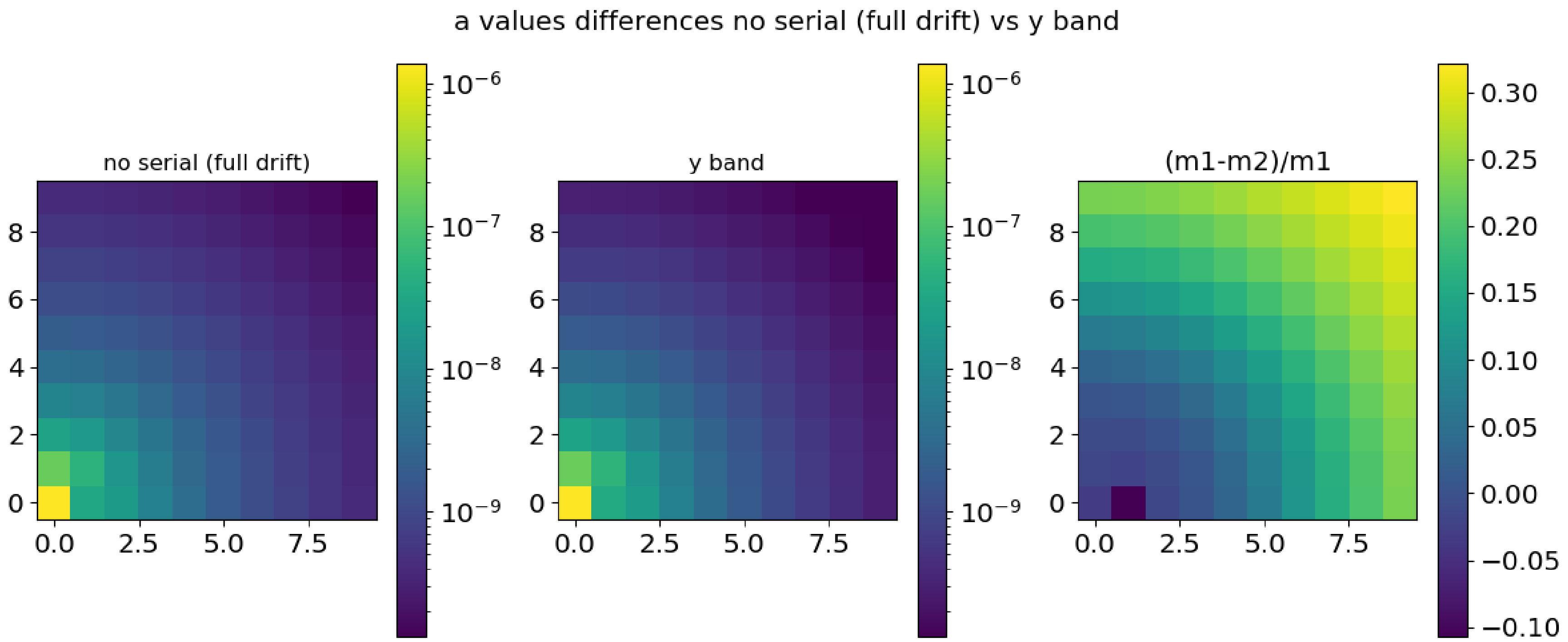
Chromaticity of brighter-fatter ?

- The achromaticity of BF is more a principle than a fact.
- There are very few chromatic comparisons, if any.
- The physics indicates that it should be achromatic...
- ...but perhaps for large distances.



All the action happens near the bottom, so how could the conversion depth matter?

Differences due to conversions in the bulk



Differences actually increase with distance.

What's next?

- The quality of the correction is good enough to measure distant SNe.
- The full scale variation of star sizes is ~0.14% after correction,which presumably allows one to measure a PSF size accurate to the 10^{-3} level.
- Apply this reduced correction to y data and see if it explains the difference of y data as compared to other bands.
- Having to ignore variance and serial covariances is a concern. I am not sure that LSST is immune to this "gain noise" problem.
- I am starting to think that deriving the correction from the correlation function of flats is perhaps not the best way to go.