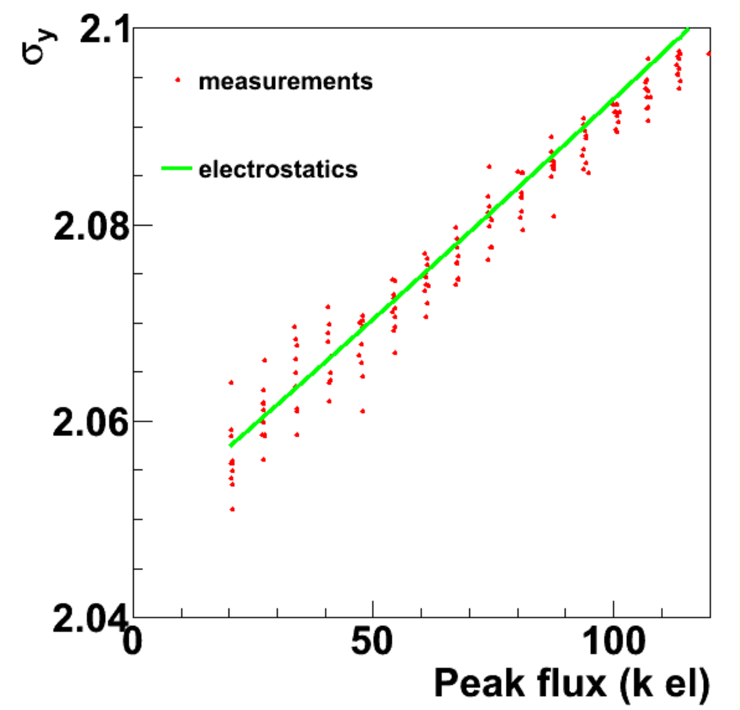
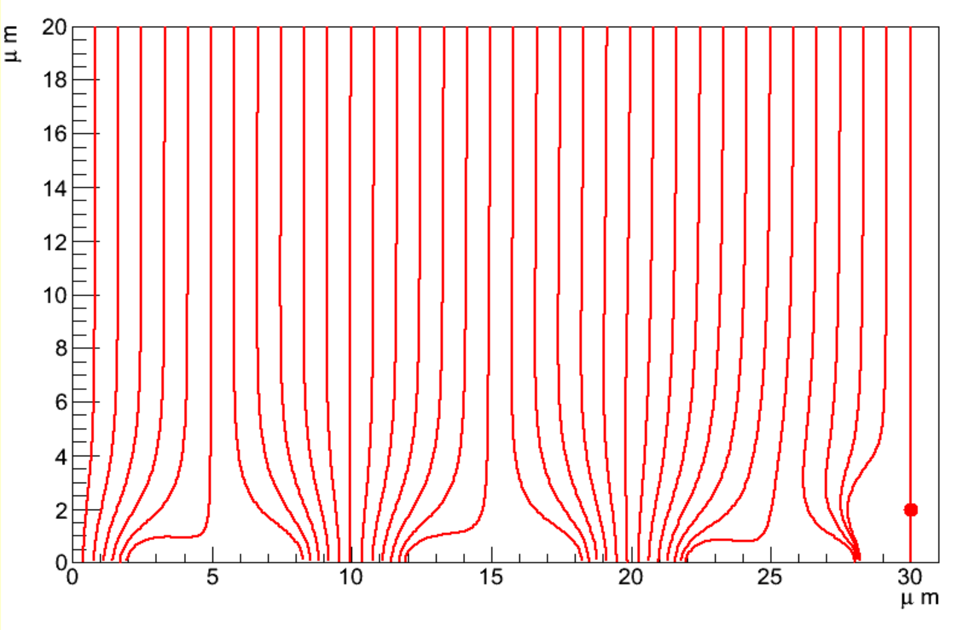
The brighter-fatter effect and pixel correlations





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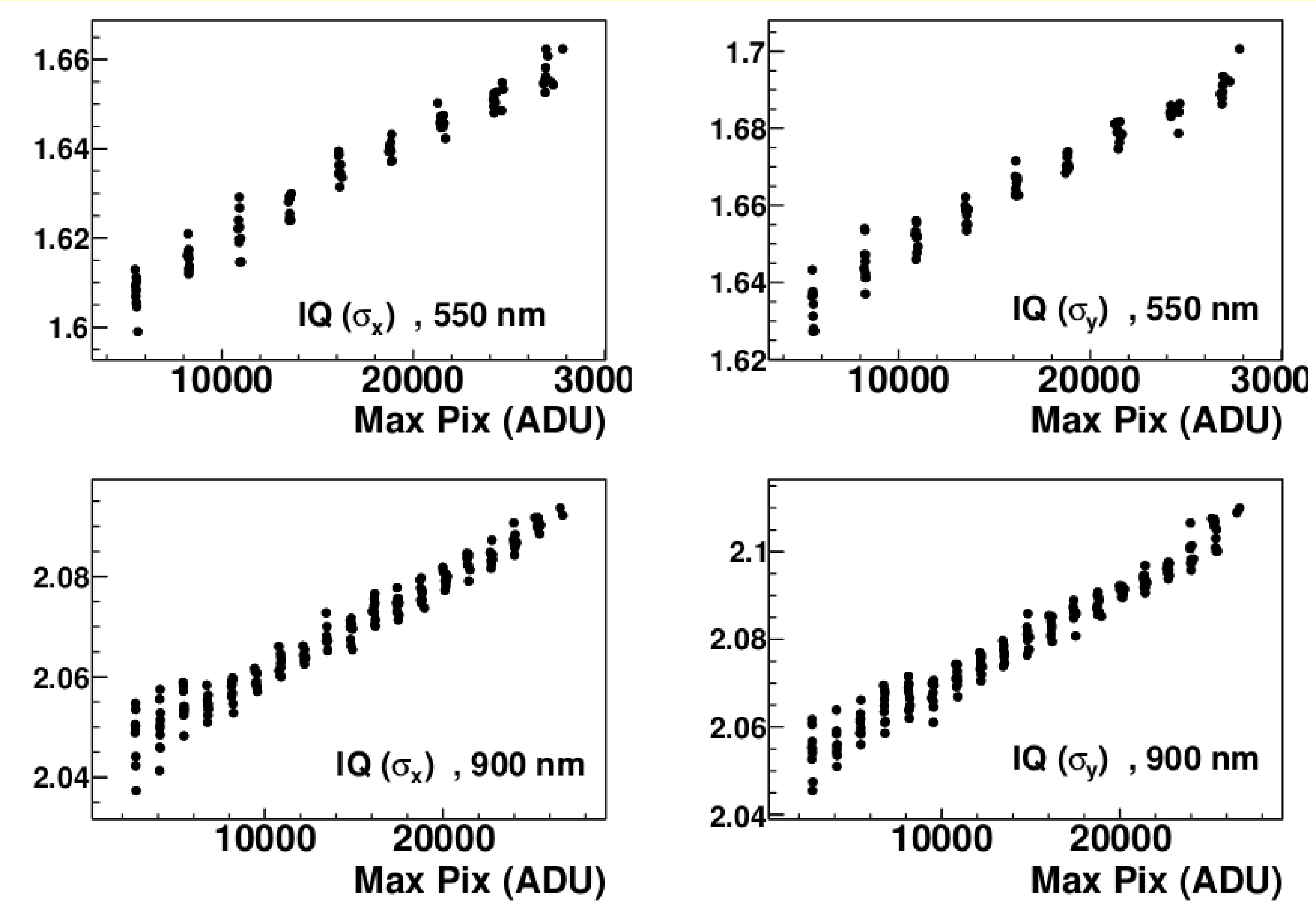
LPNHE / IN2P3 / CNRS , Universités Paris 6&7.

The brighter-fatter effect

Bright spots are broader than faint ones, by a small amount.



- Measurements by P. Doherty (Harvard) In the laboratory.

-"Lab spots" CCD E2V (LSST)

- Intensity is varied via integration time.

- typically a 2-3% increase over the full dynamic range.

Our definition for the size of stars

- We use Gaussian-weighted second moments

We solve these equations for M_g:

$$\mathrm{M}_g \equiv \begin{pmatrix} m_{xx} & m_{xy} \\ m_{xy} & m_{yy} \end{pmatrix}$$

$$\boldsymbol{M}_g = 2\frac{\sum_{pixels}(\boldsymbol{x}_i - \boldsymbol{x}_c)(\boldsymbol{x}_i - \boldsymbol{x}_c)^T W_g(\boldsymbol{x}_i) I_i}{\sum_{pixels} W_g(\boldsymbol{x}_i) I_i}$$

$$W_g(\boldsymbol{x}_i) \equiv \exp\left[-\frac{1}{2}(\boldsymbol{x}_i - \boldsymbol{x}_c)^T \boldsymbol{M}_g{}^{-1}(\boldsymbol{x}_i - \boldsymbol{x}_c)\right]$$

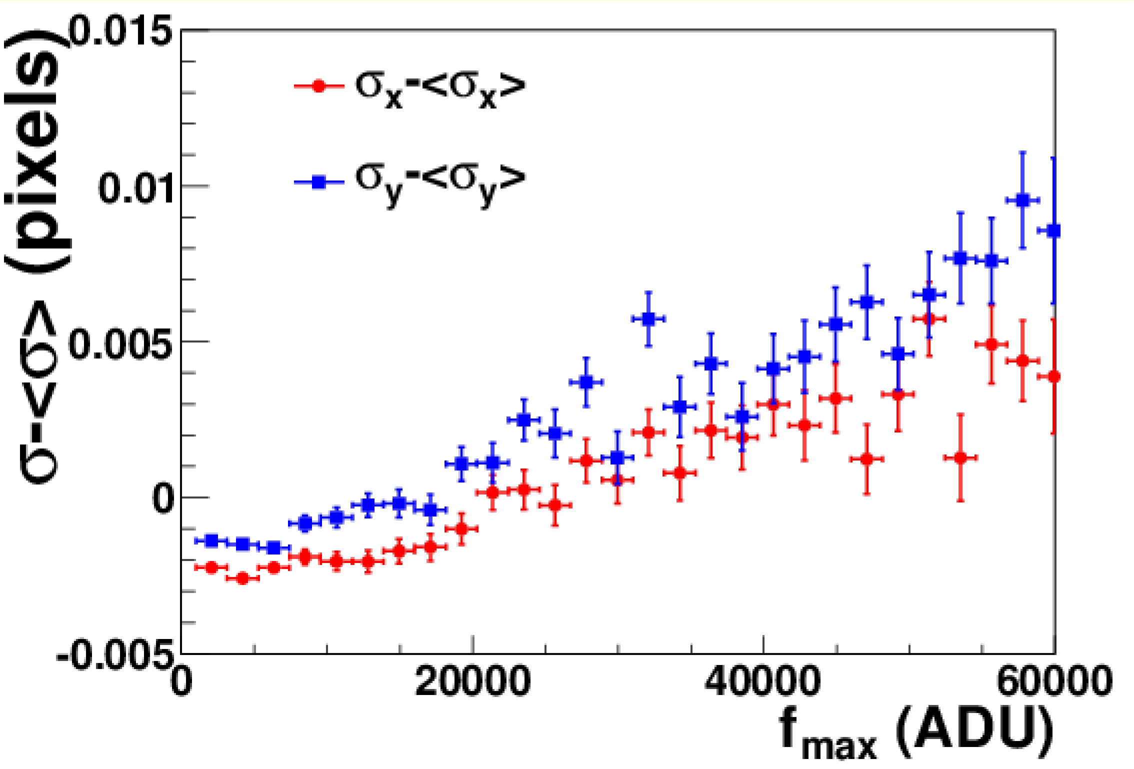
I_i: sky-subtracted image

We have checked that, even with a non-Gaussian PSF, the recovered size is independent of flux when PSF size is independent of flux.

The brighter-fatter effect

- The source of the effect has to be non-linear.
  - If it where linear, shape would not change with flux.
  - It hence cannot be due to diffusion.
- Non-linearity of overall response ?
  - Obviously possible
- What about other sensors?

The effect also shows up on MegaCam (@CFHT)...



Chips : E2V CCD42-90
(thinned chips)

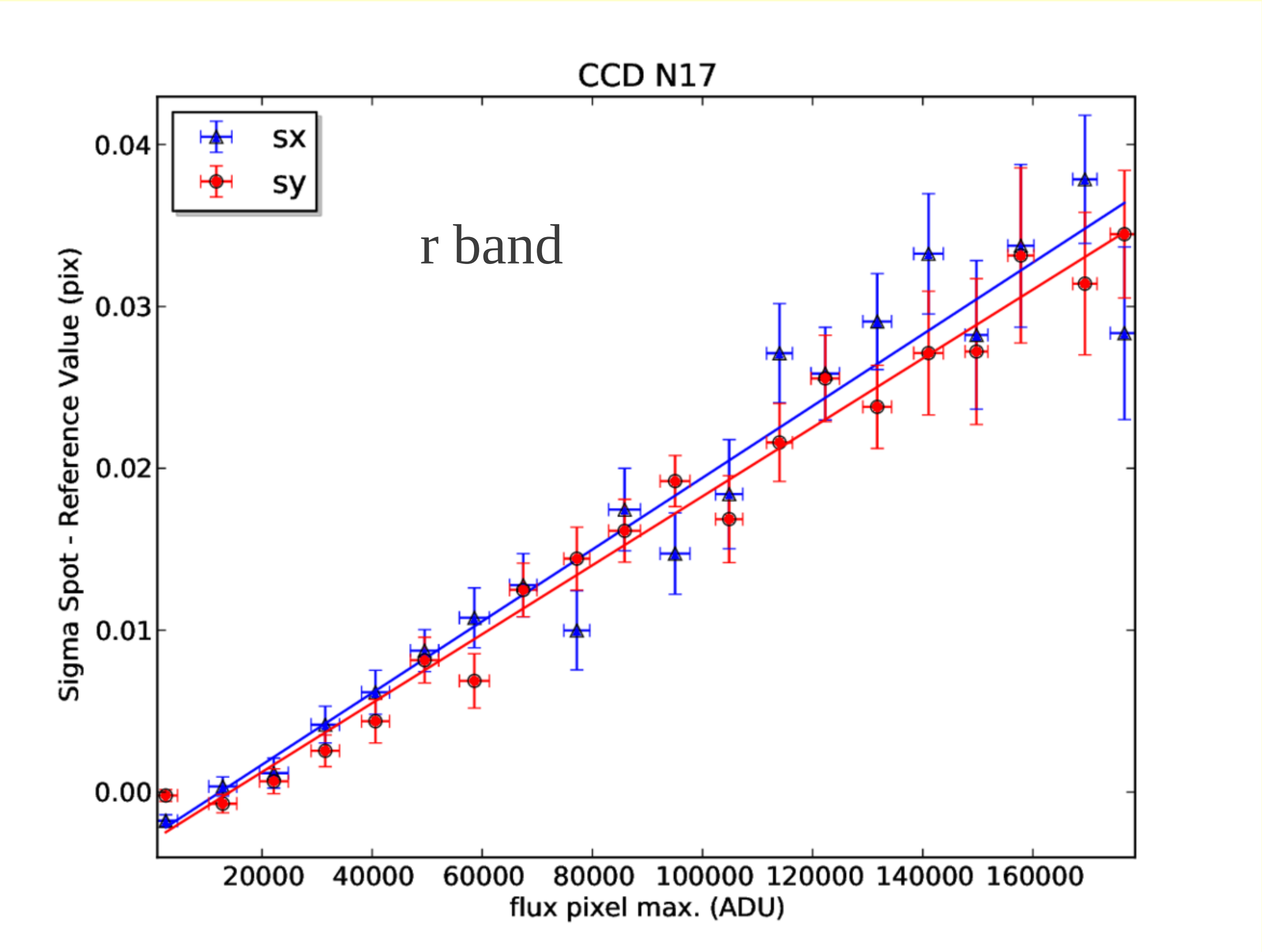
(CFHTLS data)

Less than 0.5% over the whole range.

And it is pretty much achromatic

(SNLS photometry technical paper, A&A 557, A.55 2013)

… and on DECam (@CTIO-4m)



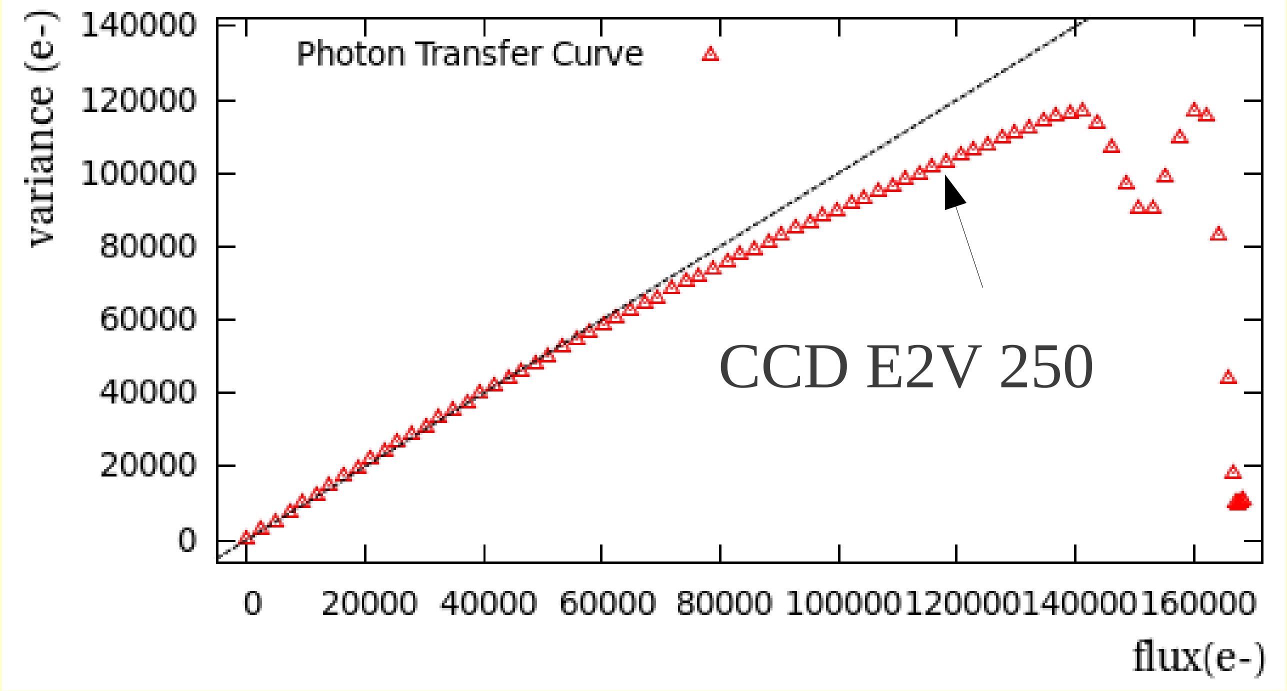
LBL/DALSA chips
high-rho
250 μm thick

Measurements from
Science Verification
Data (i.e. on sky)
with a tiny
color correction

Other strange effects on CCDs (1)

Variance of flat fields is not exactly proportional to their average

Photon Transfer Curve (PTC) :
variance=f(average)



??

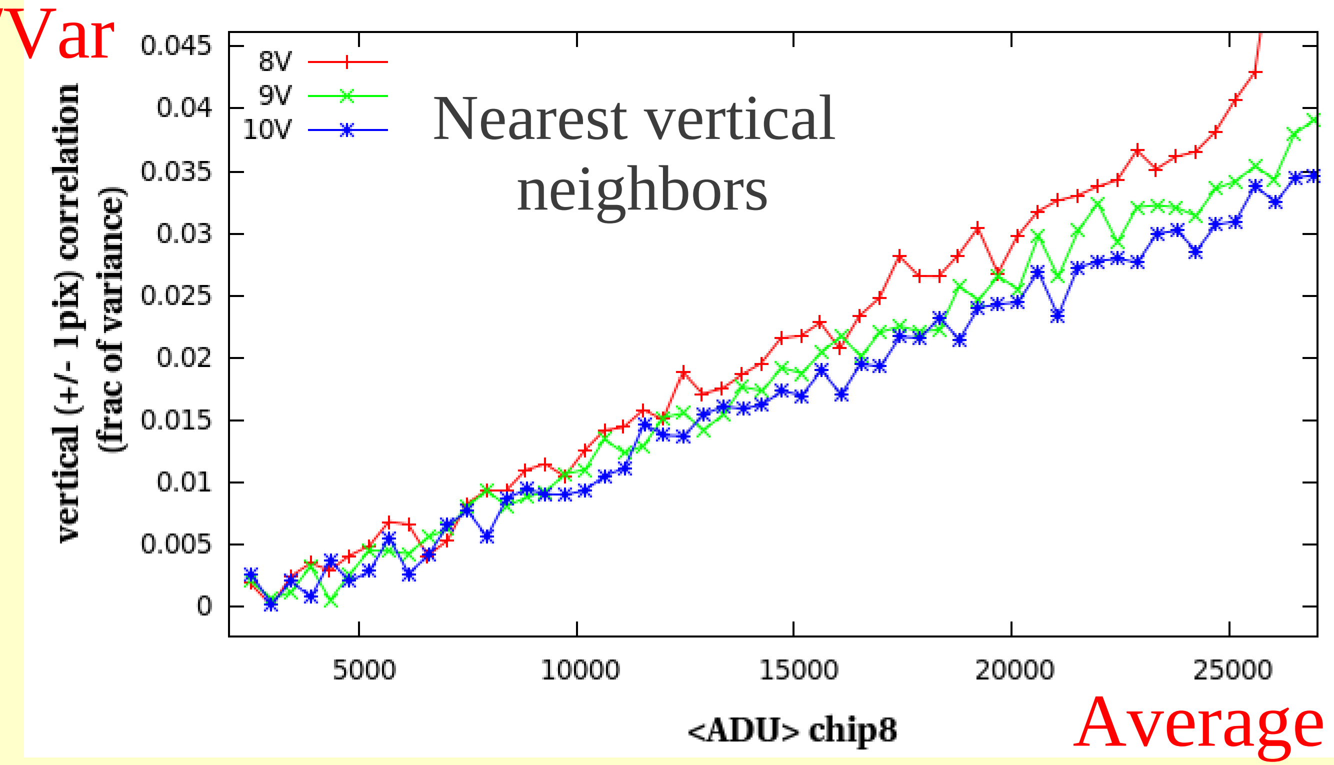
Siméon Denis Poisson

Non-linearity of PTC tends to go down when re-binning the image.

Other strange effects on CCDs (2)

Flat-field pixels are not statistically independent.
Their correlations increase (linearly) with illumination.

Cov/Var



Average

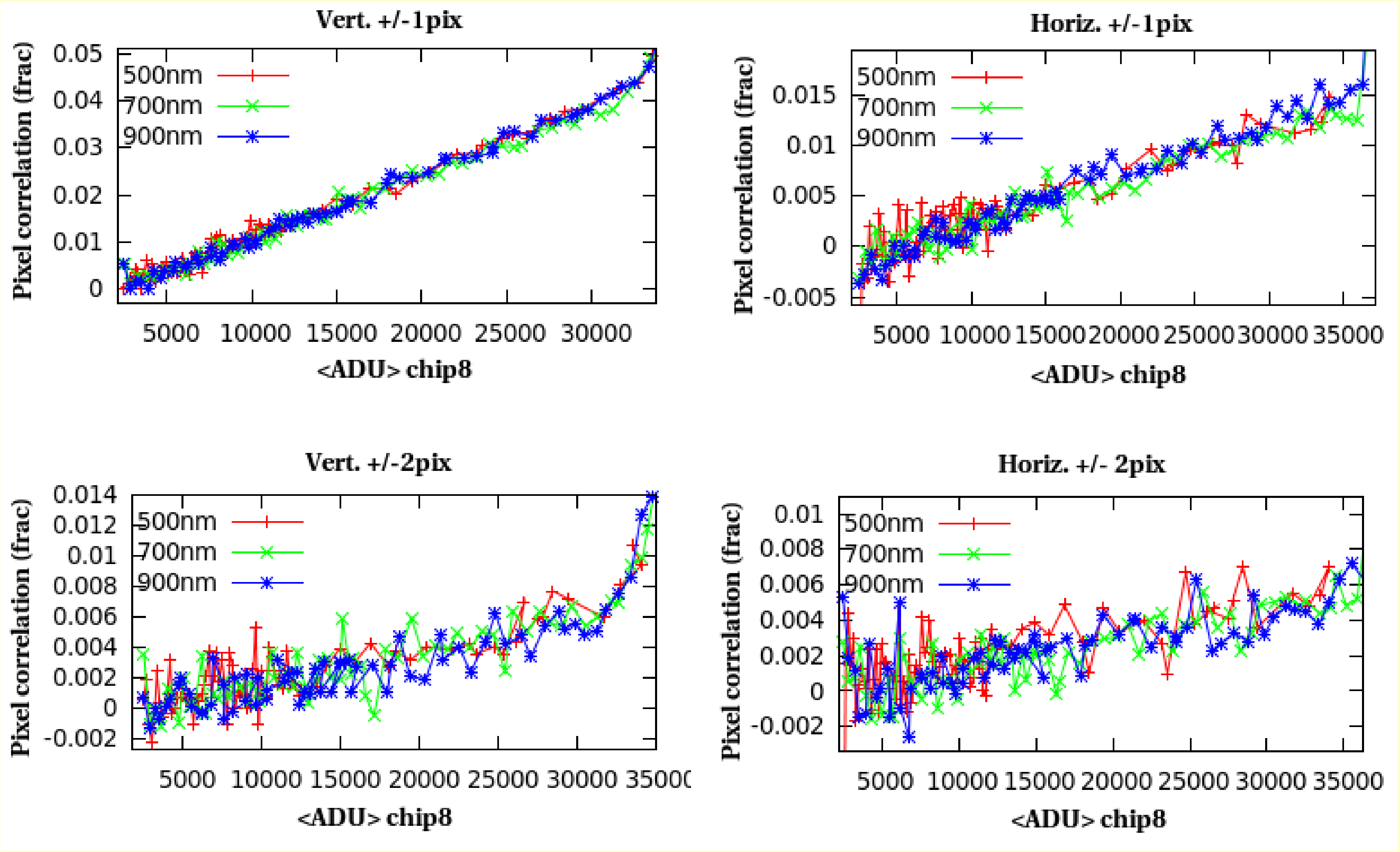
- E2V CCD

-Measurements by P.Doherty (Harvard)

-Analysis by A. Guyonnet (Paris)

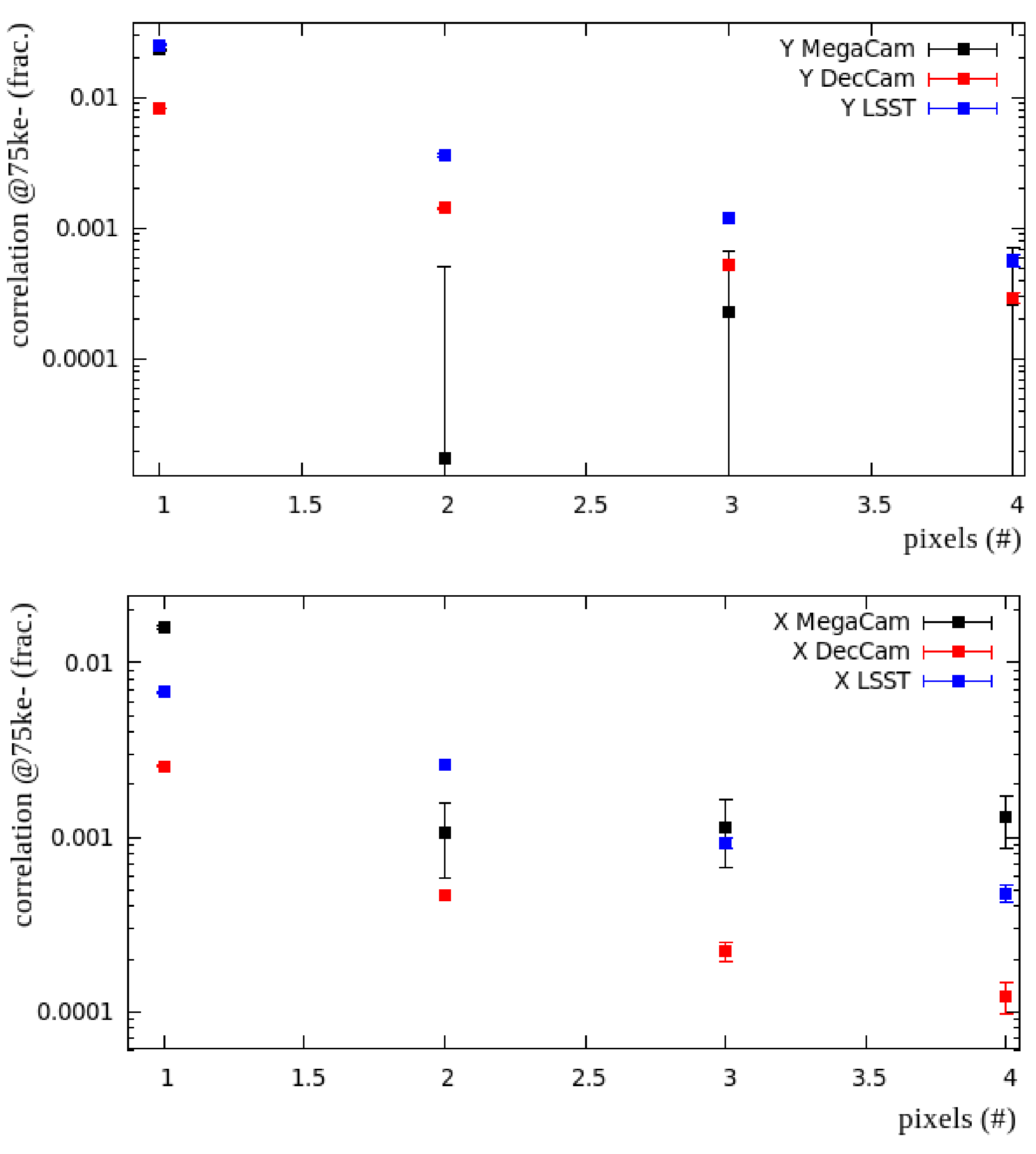
- Linear increase with flat-field average
- Depends on some electrostatic boundary condition.

These correlations seem to be achromatic



So, the effect does not depend on how deep photons convert.

These correlations decay with distance



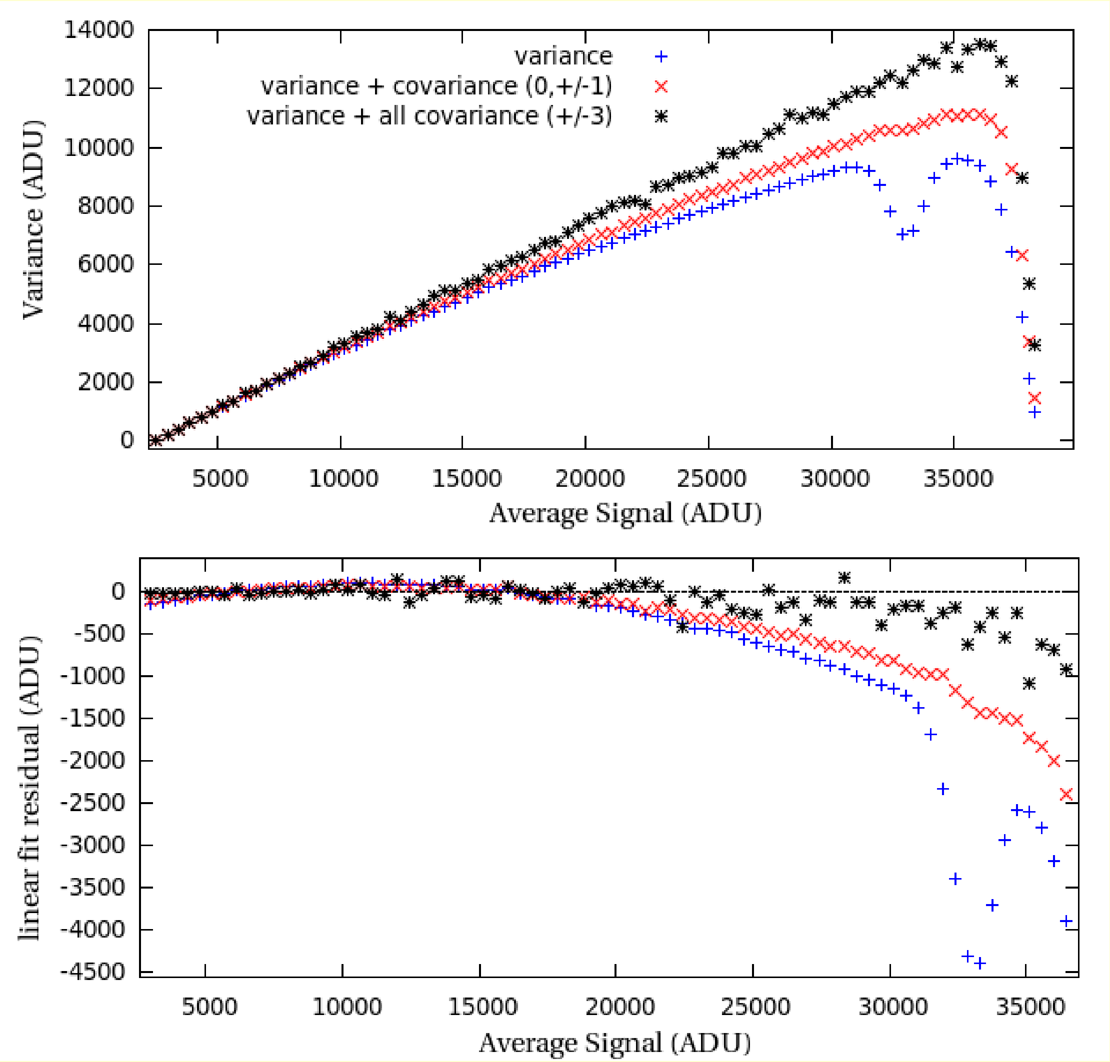
- correlations decrease roughly exponentially with separation.

- They are larger along Y than along X.

Non-linear PTC and correlations

Unsurprisingly, when accounting for pixel correlations, the PTC becomes more linear

PTC for ccd e2v 250



About non-linearity of PTC

With correlations increasing linearly with illumination, we have:

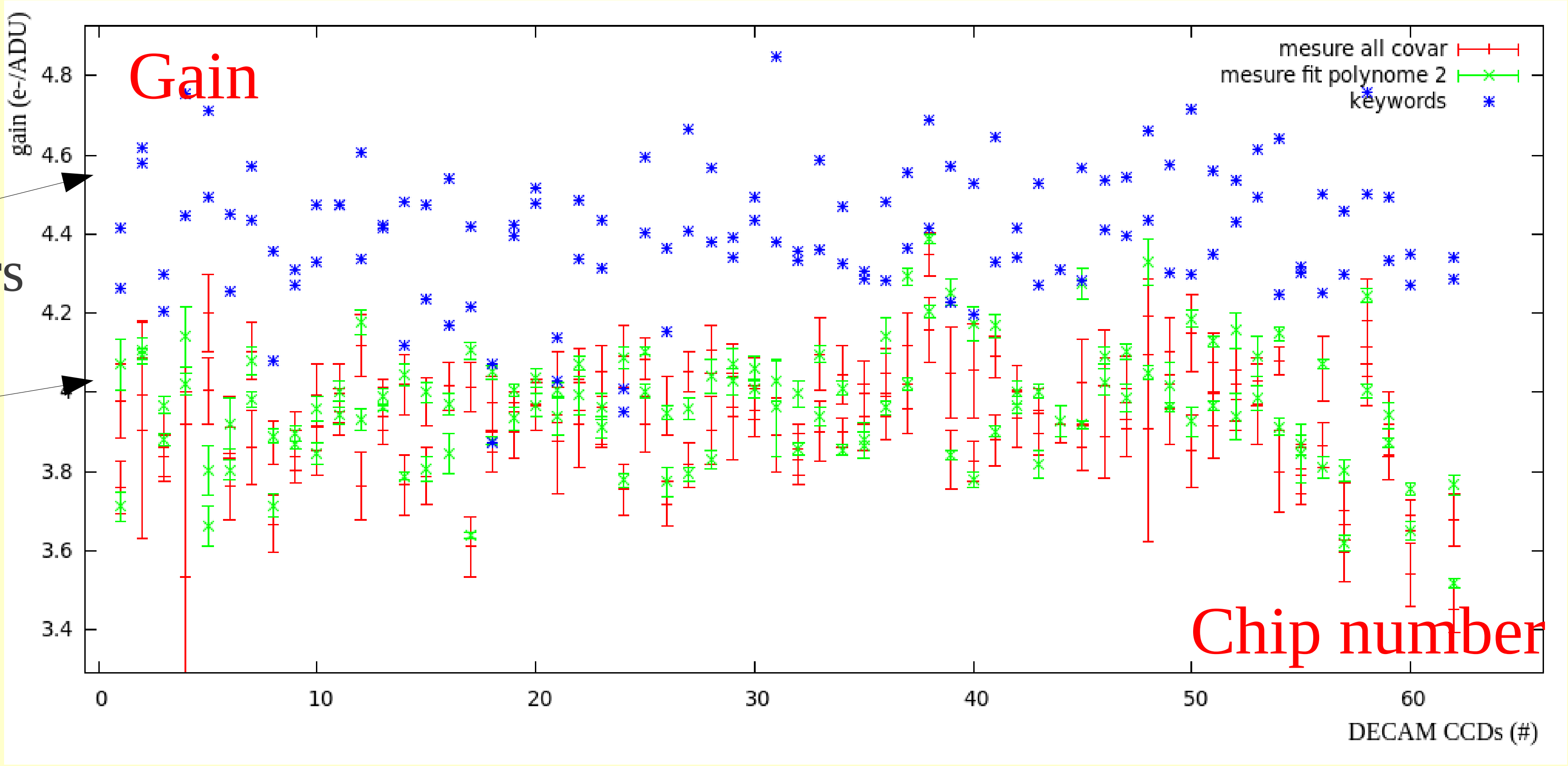
$$V = a\mu^2 + b\mu + c$$

a : correlations
b = 1/Gain
c : readout noise

DECam Science Verification data

Values in FITS headers

Parabolic fit to PTC



So,

We detect 3 effects :

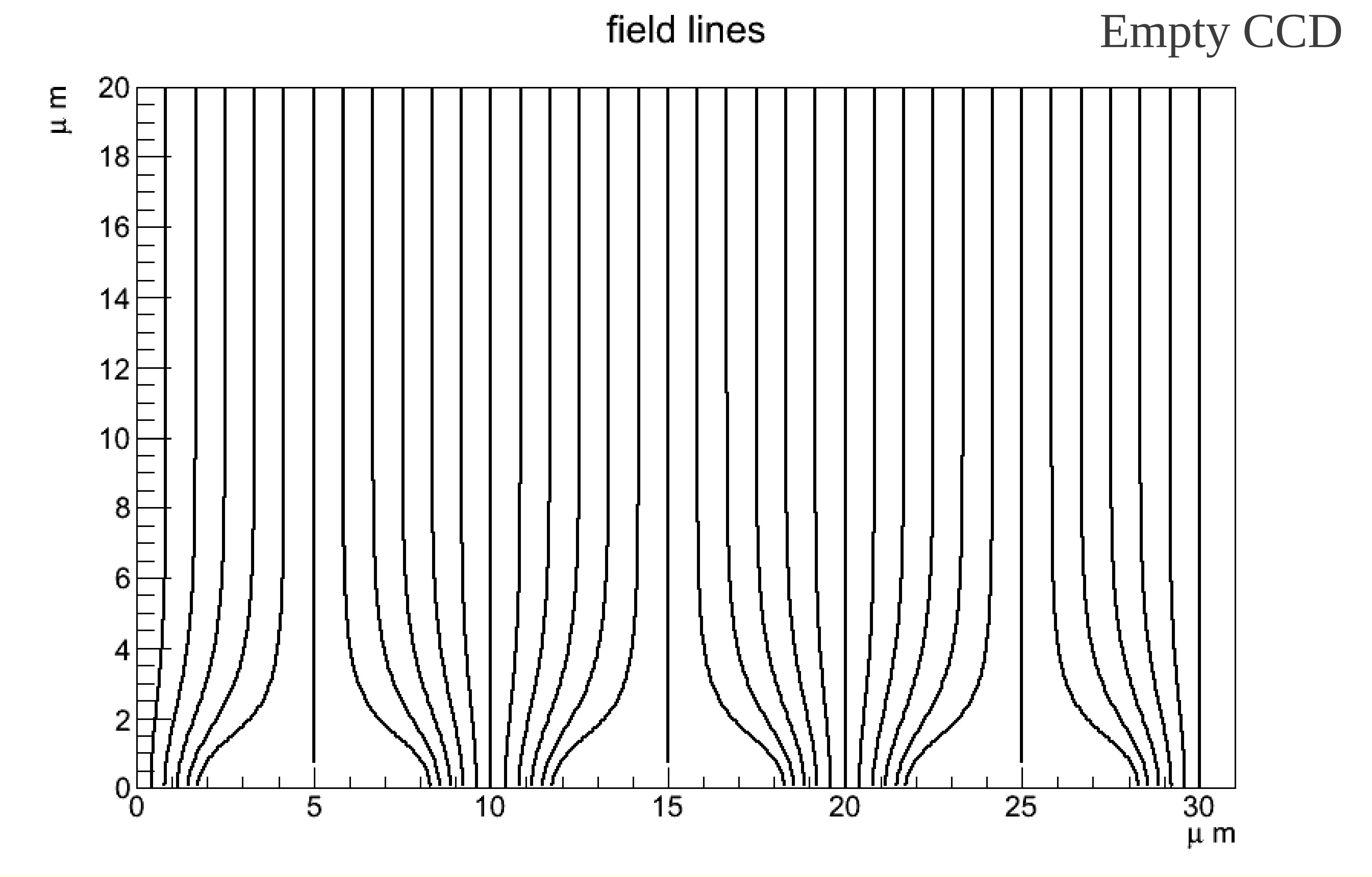
- brighter-fatter for stars/spots
- Variance of flatfields is smaller than Poisson
- Flatfields exhibit correlations

Linearly increasing with illumination.

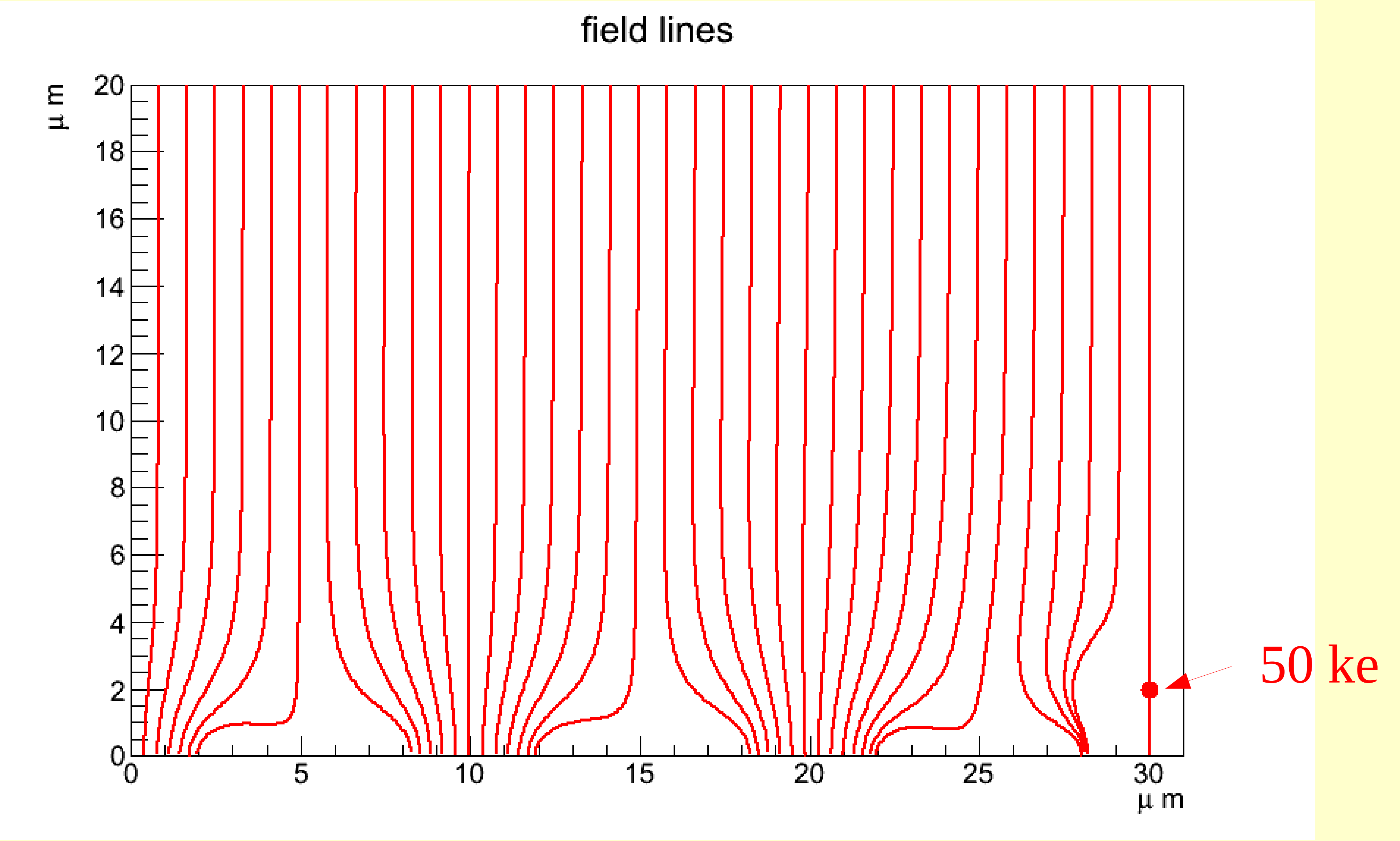
- The two last effects are trivially related.
- Smoothing of flatfields and stars might share the same origin.

All 3 effects require some non-linear mechanism

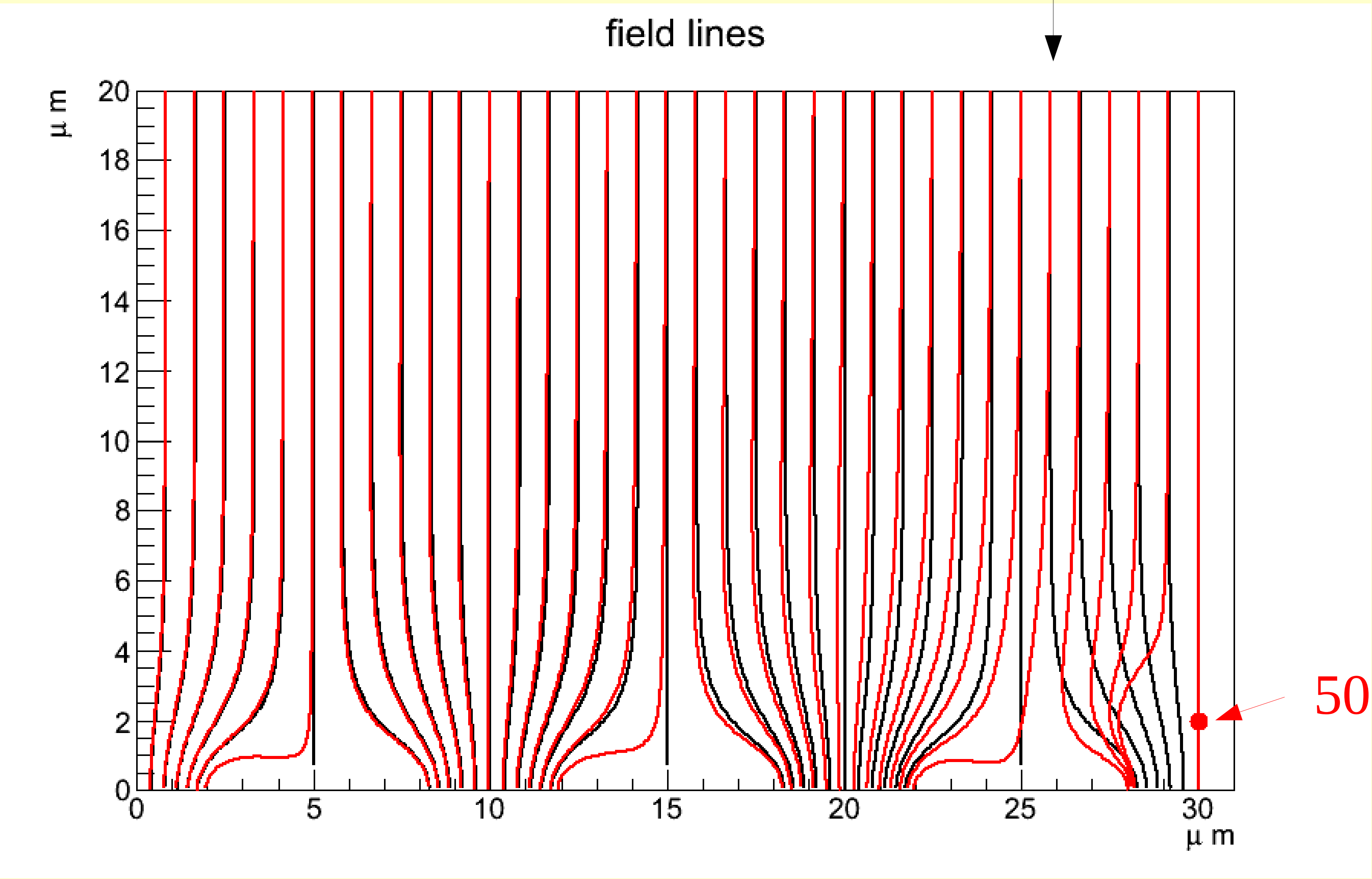
Coulomb forces in a CCD



Coulomb forces in a CCD



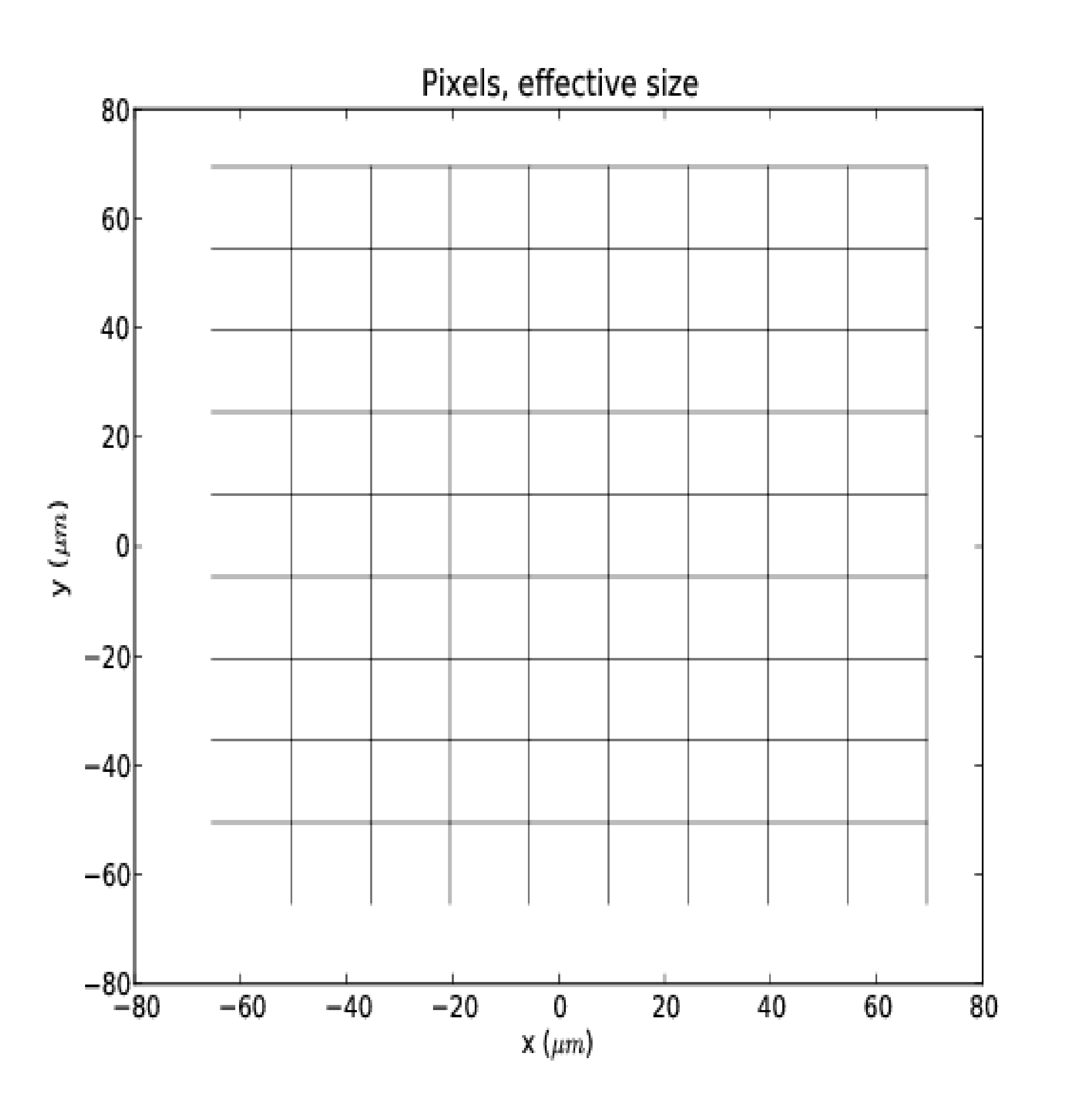
Depending on the stored charge, electrons drifting here go left or right



50 ke

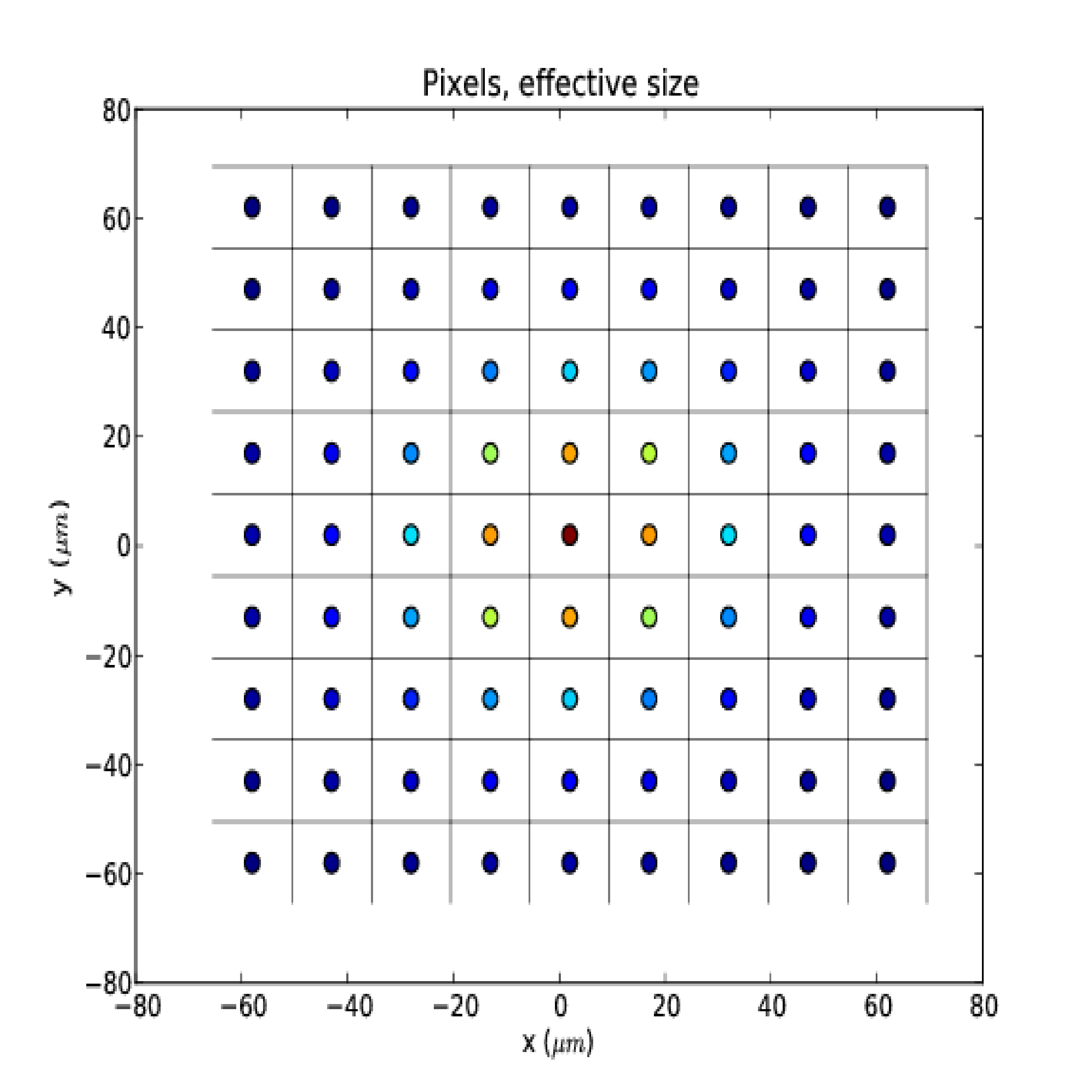
Top view

Empty CCD



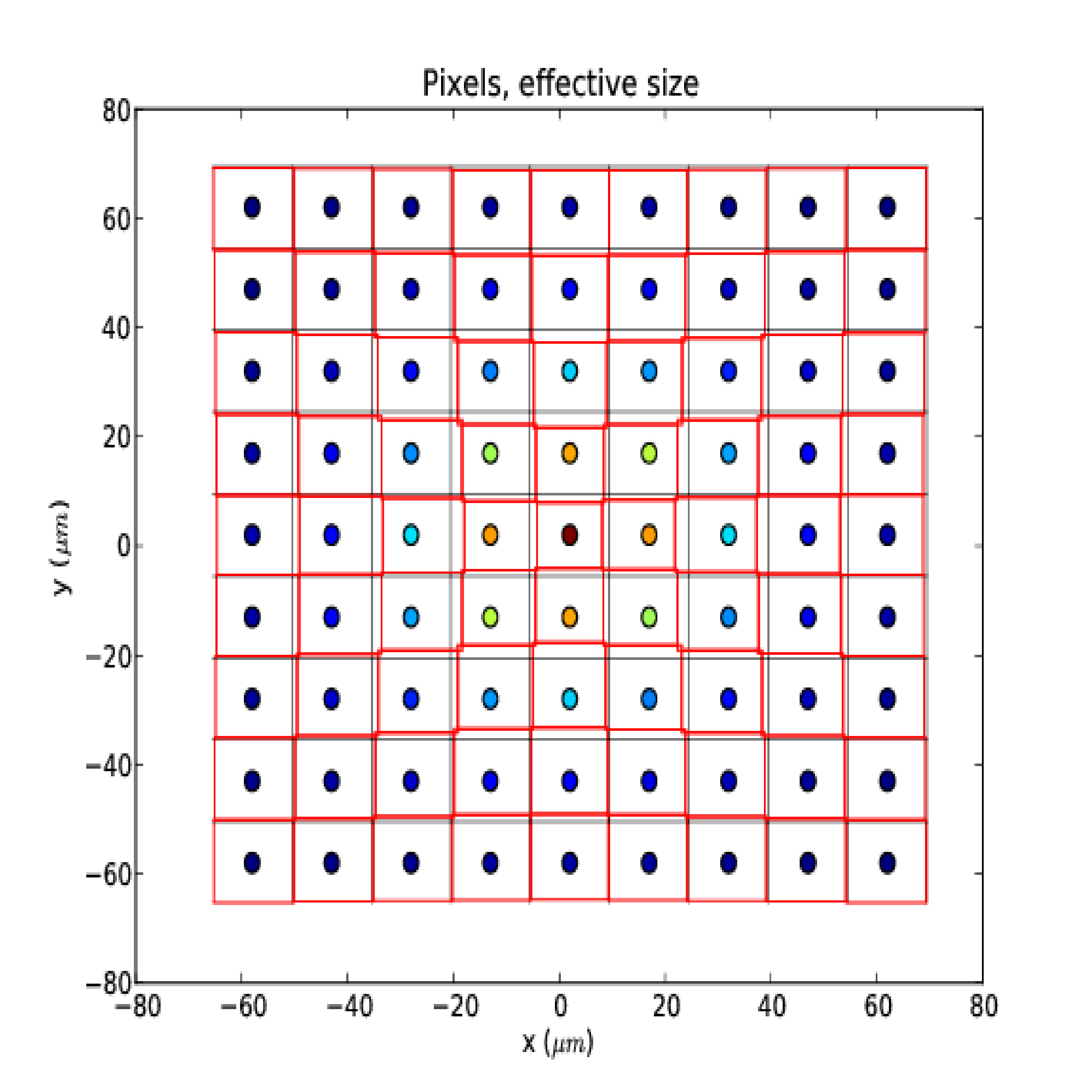
Top view

Add a bright star



Top view

Shifted pixel boundaries (shifts x 5)



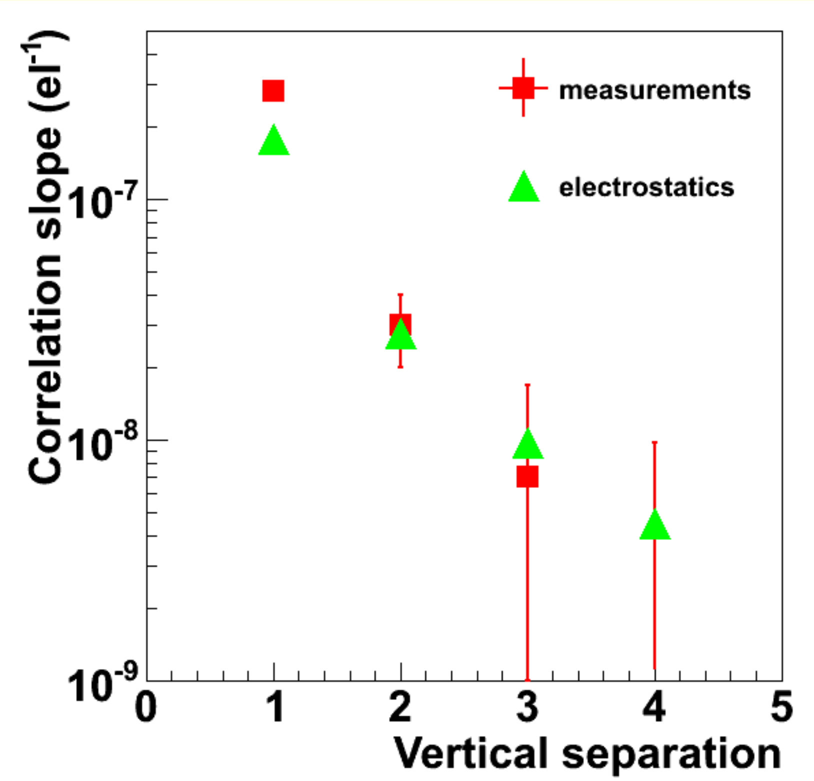
So,

Due to Coulomb forces, overfilled pixels get smaller w.r.t the average pixel size. This effect:

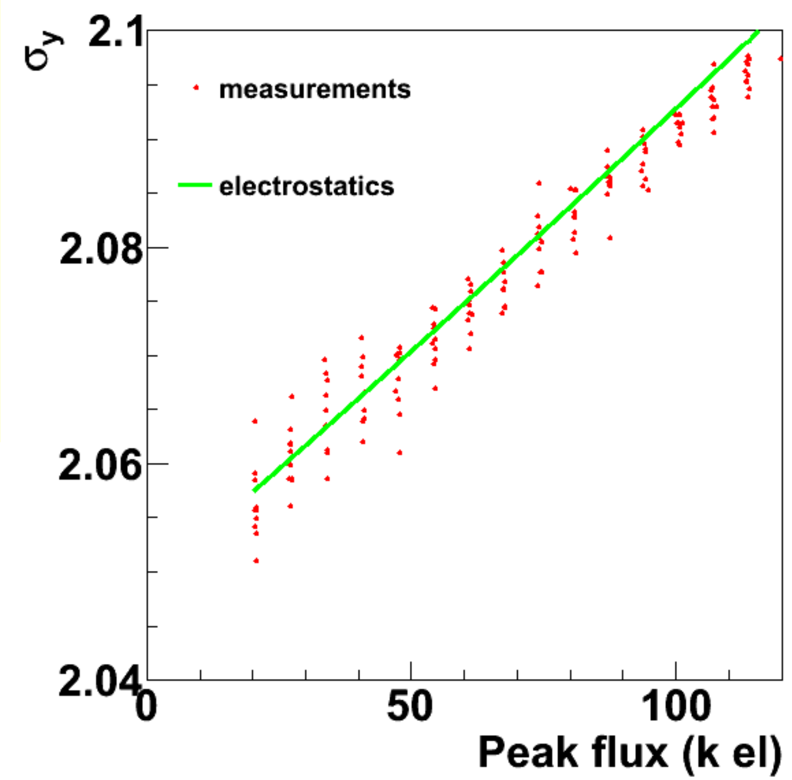
- Reduces spatial variance of flat-fields w.r.t Poisson
- Causes positive correlations in flat fields (sourced by Poisson fluctuations)
- Broadens bright spots w.r.t fainter ones

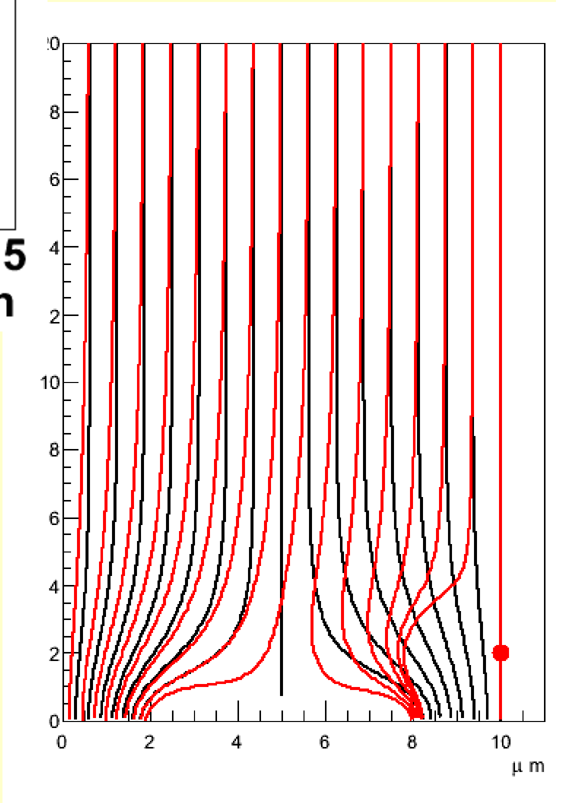
Charles-Augustin de Coulomb

Can Coulomb forces cause the observed size of effects ?



E2V CCD





A sketchy simulation roughly reproduces the size of the observed correlations and of the brighter-fatter slope.

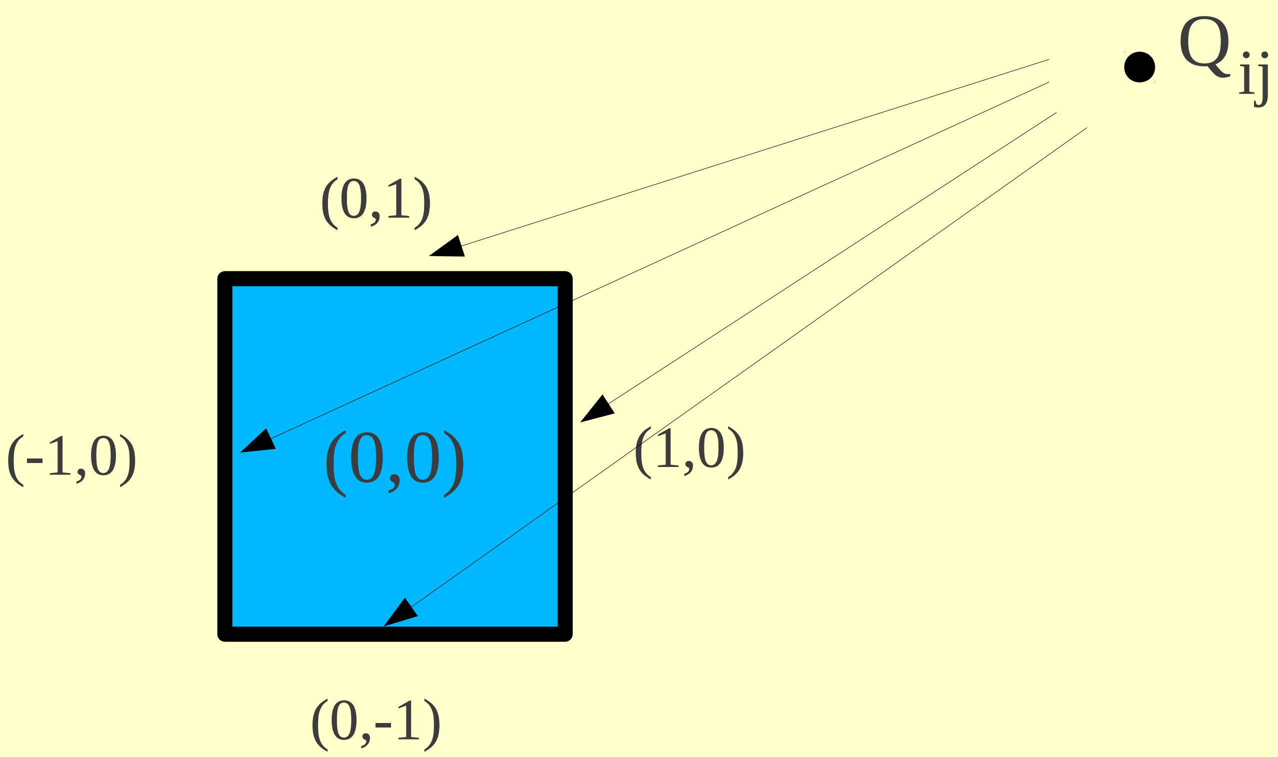
An empirical model

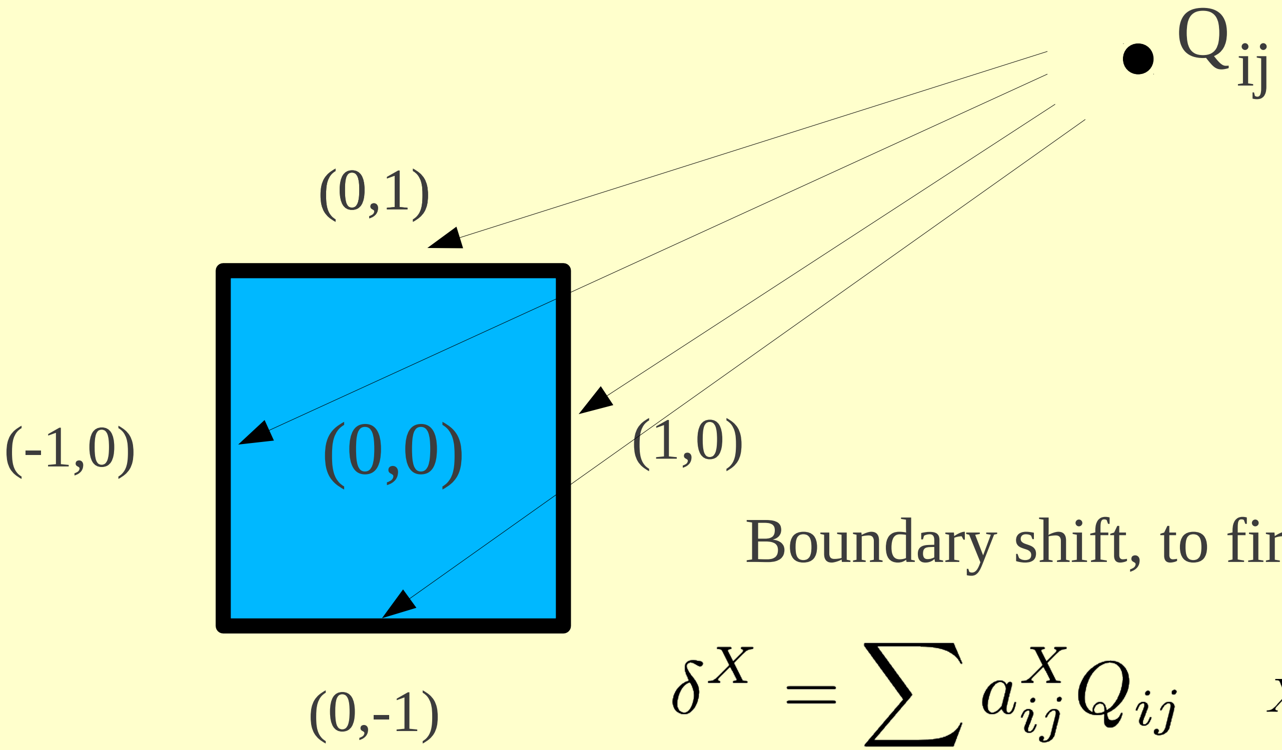
- We do not know the details of how CCDs are made
- Most vendors would not answer our questions.
- The effect is small and hence Taylor expansions should hold
- Rather than making quantitative predictions from electrostatics, we make a general first order model and (try to) derive its unknowns from data.

A simplistic model

- Charges stored in a CCD source an electric field
- Drift trajectories are perturbed by this additional electric field
- Pixels boundaries are affected by these perturbations.

→ Effective pixel boundaries are (marginally) dynamical





Boundary shift, to first order in source charges:

$$\delta^X = \sum_{ij} a_{ij}^X Q_{ij} \qquad X \in \{(0,1),(1,0),(0,-1),(-1,0)\}$$

Charge "transfer" (induced by all Q_{ij}):

$$\delta Q_{0,0}^X = \delta^X (Q_{00} + Q_X)/2 = \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)/2$$

Sum over the 4 sides

$$\delta Q_{00} = \sum \delta Q_{00}^X$$

This is a non-linear effect

$$\boxed{\delta Q_{0,0} = \sum_X \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)}$$

To be determined:

- Integrates all numerical factors from the previous slide
- Characteristic of a device (+ operating conditions)

Source charge

Test charge.
<u>Assumes the image is well sampled.</u>

Charge shuffling : no charge gets lost

Correlations in flats

$$Q'_{0,0} = Q_{00} + \sum_X \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)$$

For a flat-field (average μ, variance V) one gets :

$$Cov(Q'_{00}, Q'_{ij}) = 4\mu V \sum_X a_{ij}^X$$

Sum over 4 sides

So :

- correlations (Cov/V) increase linearly with illumination
- variance of flat-fields : Poisson term minus a quadratic correction

Do the brighter-fatter effect and flat-field correlations share the same origin ?

TEST:

$$Q'_{0,0} = Q_{00} + \sum_X \sum_{ij} a_{ij}^X Q_{ij}(Q_{00} + Q_X)$$

Derive coefficients from flat-field correlations

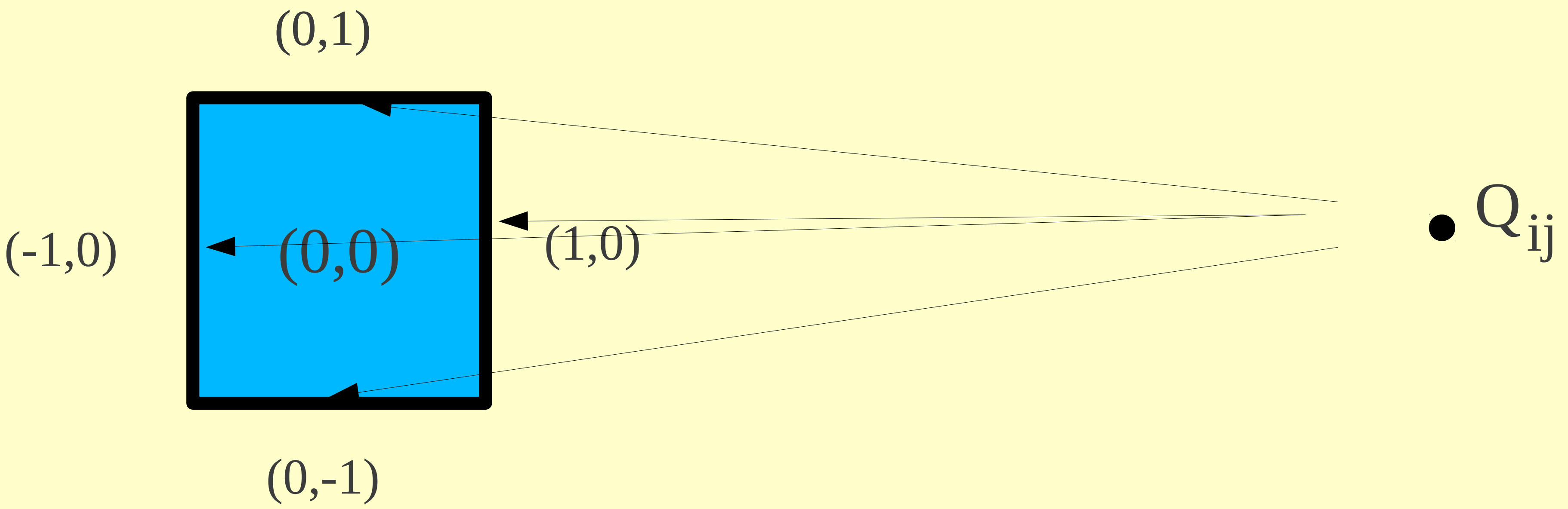
$$Cov(Q'_{00}, Q'_{ij}) = 4\mu V \sum_X a_{ij}^X$$

Scramble faint spots (or stars) and compare to bright ones

From correlations to coefficients.

$$Cov(Q'_{00}, Q'_{ij}) = 4\mu V \sum_X a_{ij}^X$$

At “large” distance, correlations vary mostly as the derivative of the boundary displacement with position.



Getting the “a” coefficients from flat-fields (1)

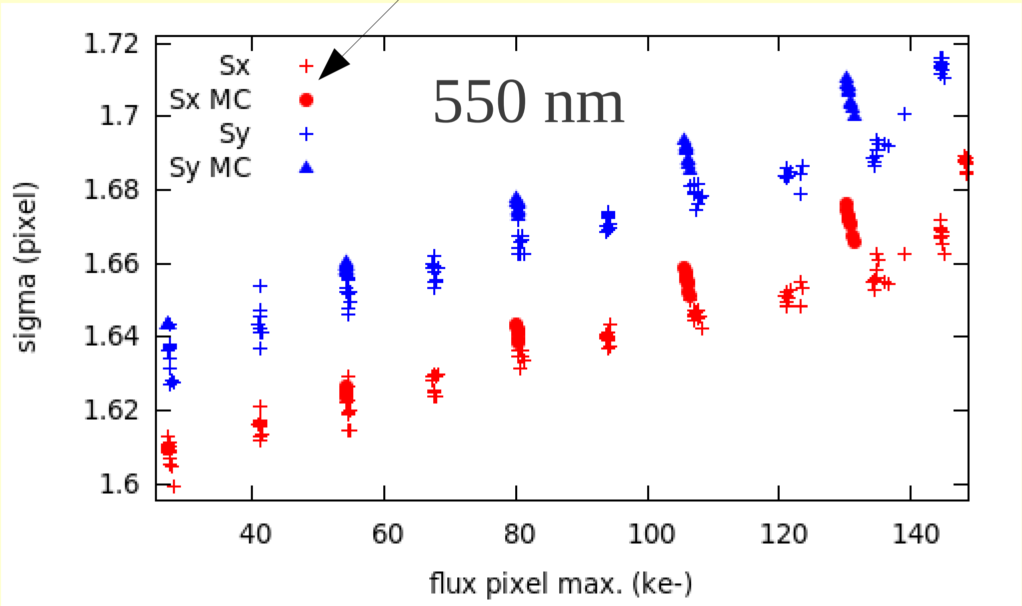
- If one wants to measure the “a” coefficients up to separation of n pixels, there are ~4 n^2 such coefficients.
- With symmetries, it drops to ~2n^2
- There are only ~n^2 correlations to be measured
- We hence have to cook-up ~n^2 constraints.

Getting the “a” coefficients from flat-fields (2)

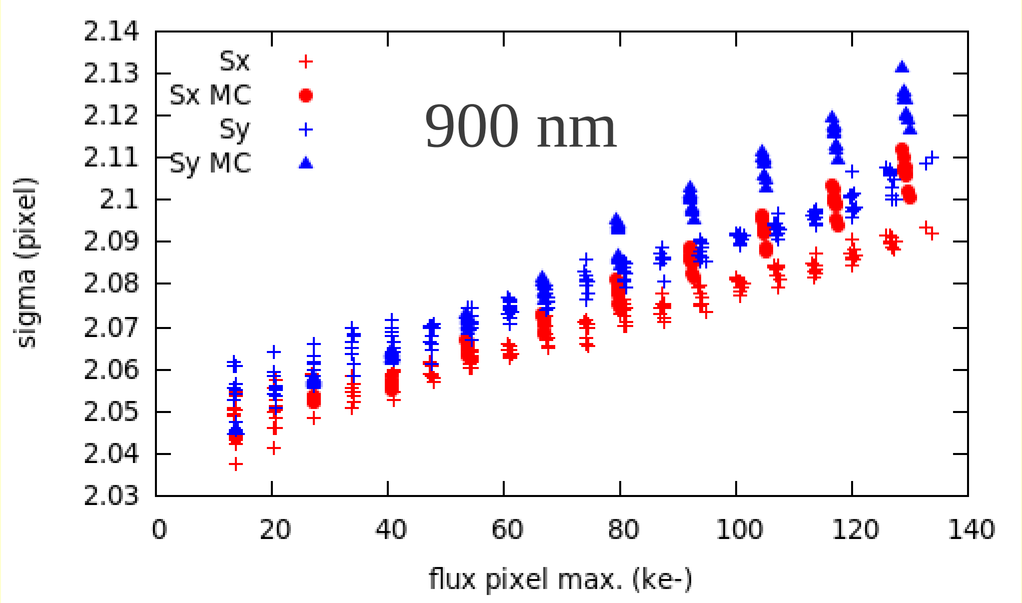
- Impose ratios of coefficients at similar distances using the overall shape of the decay.
- Results are reasonably independent of the used analytical shape.
- Any better suggestion ?

Applying the "a" coefficients (LSST/E2V)

MC propagation of correlation measurement uncertainties



Scale up faint spots and scramble them.



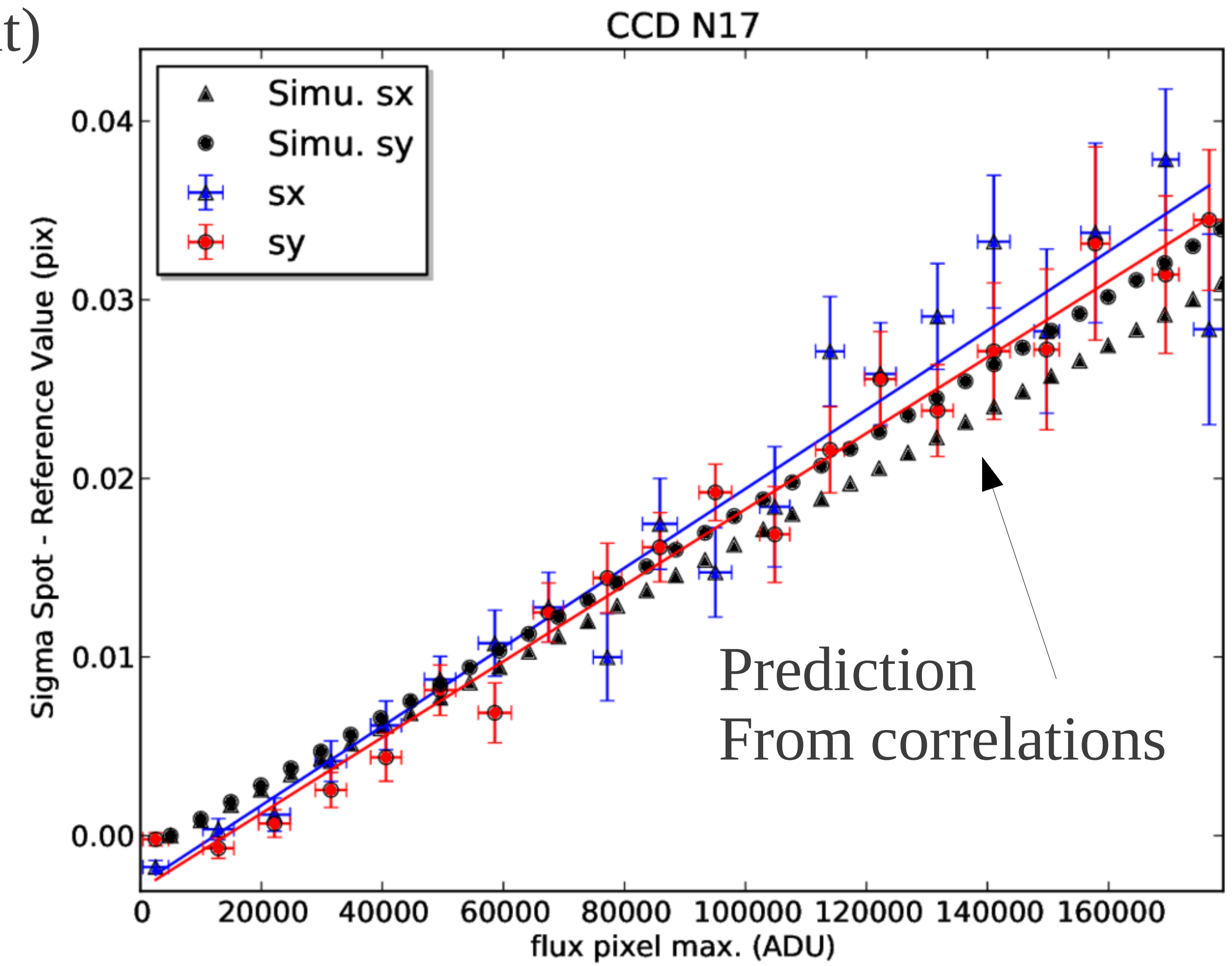
- Predicted brighter-fatter slopes are ~20% larger than measurements.
- consistently for both x and y and 550 and 900 nm

Applying the “a” coefficients

DECam

“Simulations” here proceed from the (flux-independent) PSF.

Only CCD 17.
The comparison
is limited by statistics
of flatfields and stars.



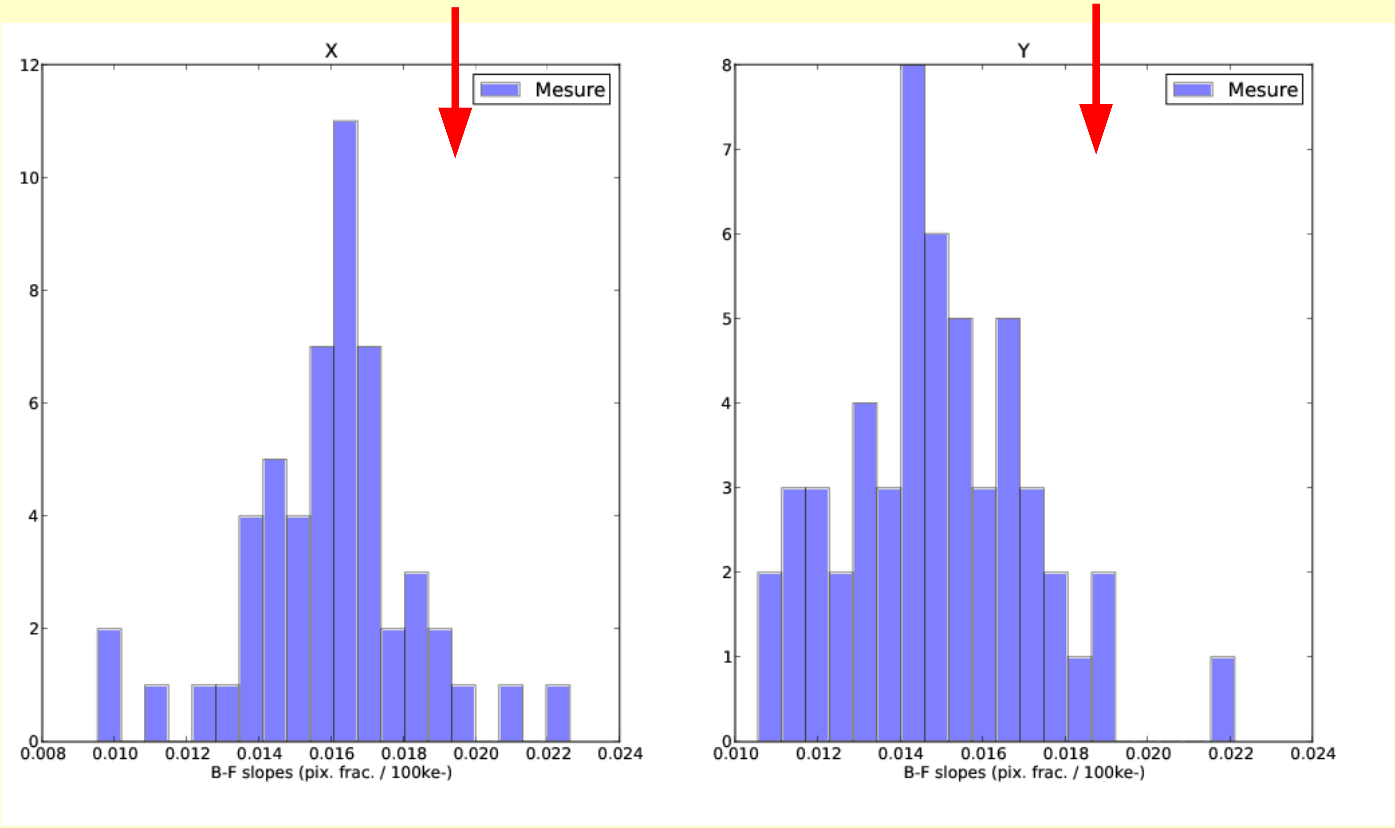
Applying the “a” coefficients

• The measured brighter-fatter slopes seem marginally compatible between chips
• The correlations seem compatible, but the statistics is low though.

DECam : all chips

Predicted from correlations

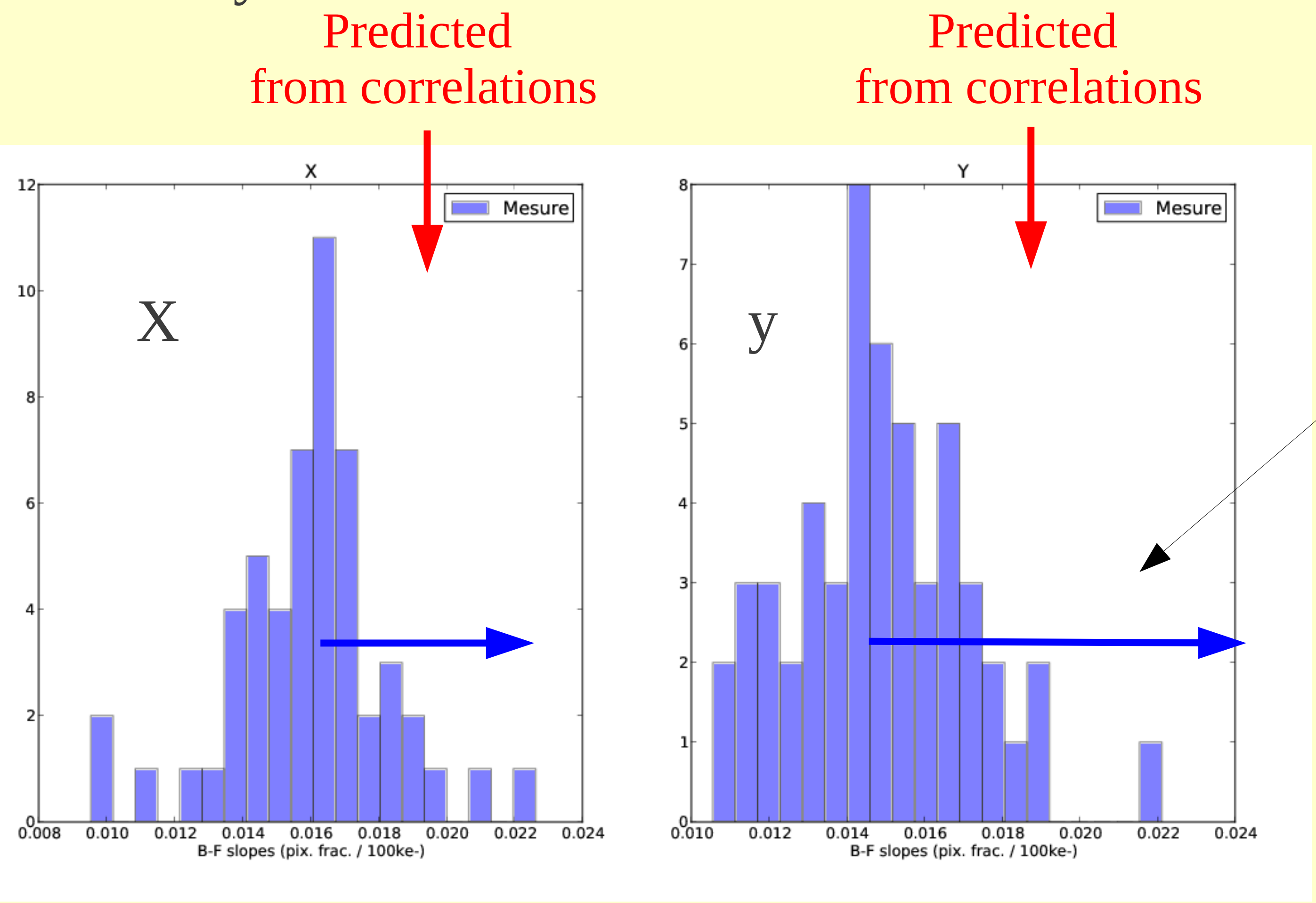
Predicted from correlations



Agreement at the 15-20% level

DECam : non-linearity of response

- DECam is suspected to exhibit non-linearities of response (see Gary's talk)
- This contributes to the brighter-fatter effect.
- With the non-linear corrections, the observed brighter-fatter effect increases by ~60 % .



Shift due to non-linearity correction

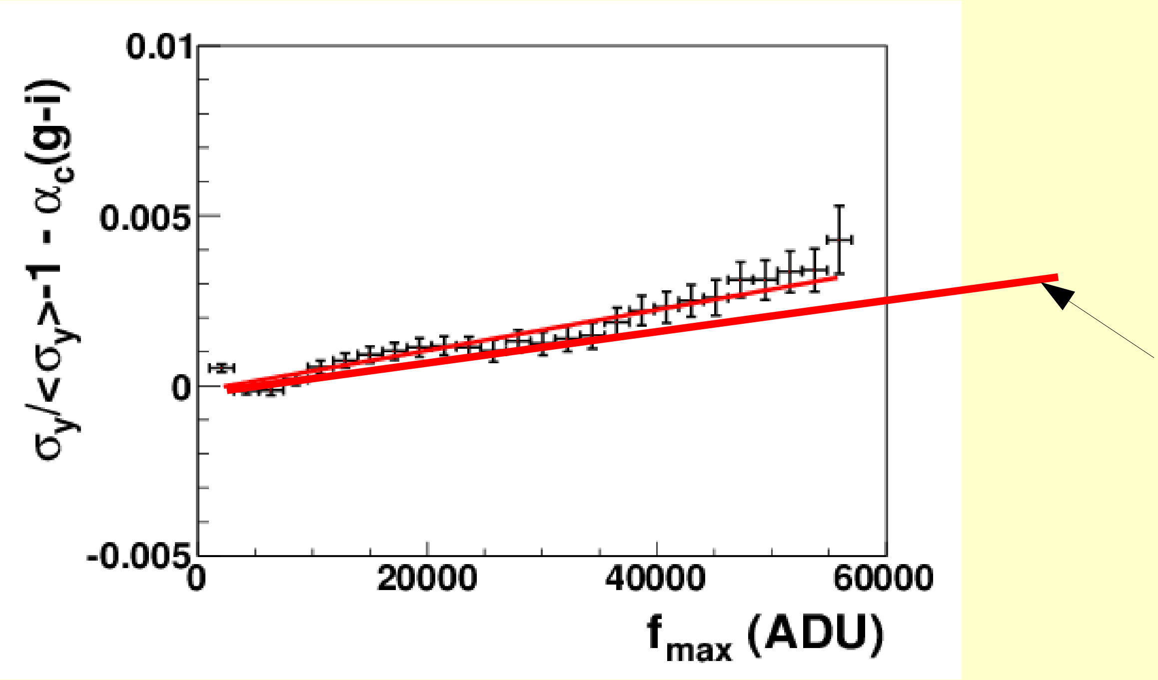
DECam non-linearity : https://cdcvs.fnal.gov/redmine/projects/des-sci-verification/wiki/AB_Ratio_Variation

Applying the “a” coefficients : DECam

- Agreement between measurements and predictions from flat-field at the
  - ~20% level (ignoring NL corrections)
  - ~30 % level (with nonlinear corrections)
- Our measurements of correlations are statistics limited.
- Non-linearity of response strongly affects the observed brighter-fatter slope.

Applying the “a” coefficients

Megacam
(thinned CCDs)

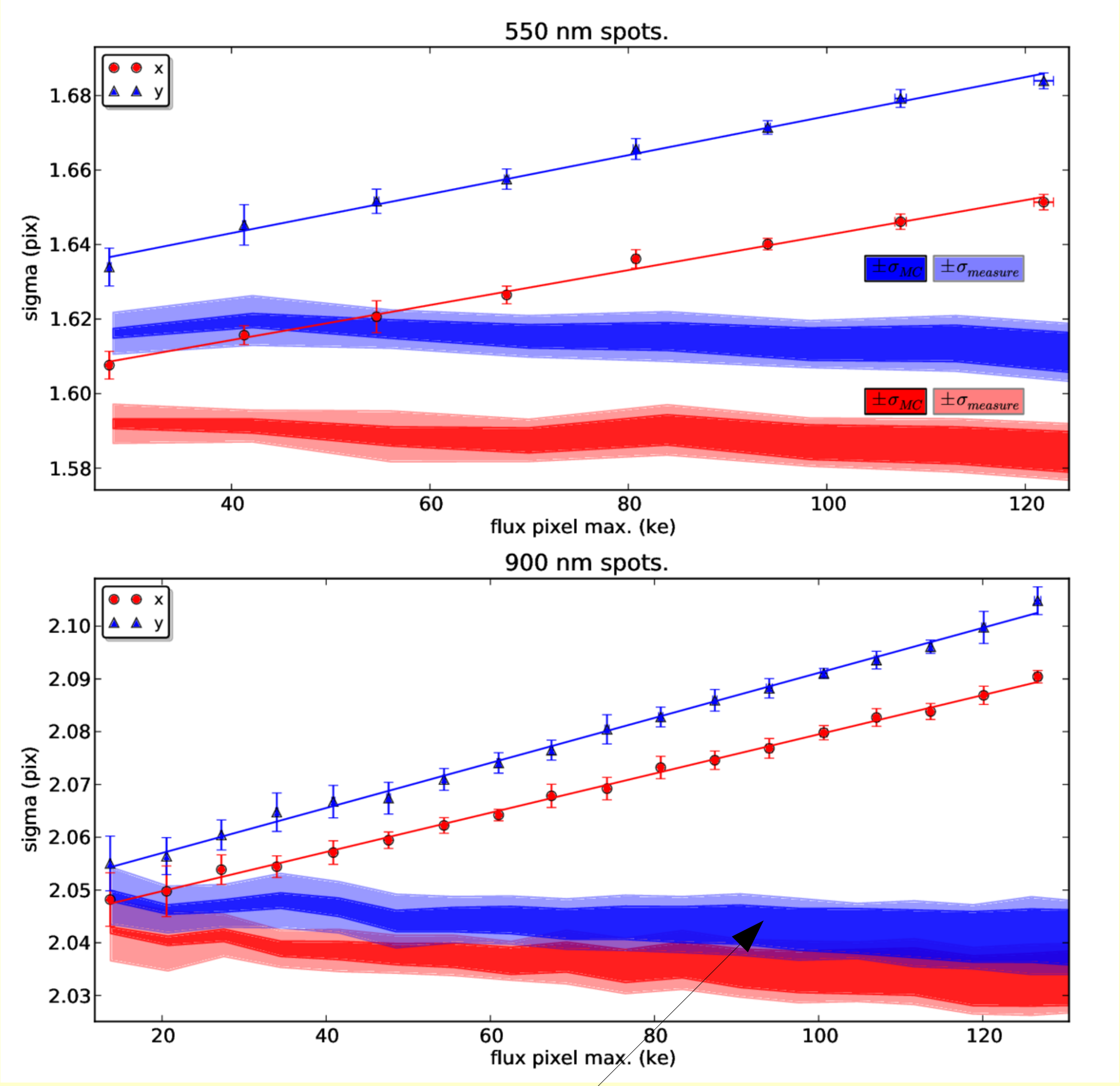


Measurement:
slope ~ 0.5

Prediction from flat-fields
slope ~ 0.34 +/- 0.15
(measured distant correlations are “in the noise”)

Unscrambling : correction at the pixel level

- The “a” coefficients are small:
- Correct for the effect by applying flipped-sign coefficients at the pixel level
- Remeasure star sizes as a function of flux



Uncertainties of correlations

Practical difficulties

- Measuring small correlations
  - Statistics needed (100 Mpix to reach 10^{-4})
  - Beware of other correlation sources (need a ramp)
- Non-linearity of response contributes to the BF effect
  - Non-linearity difficult to measure
- More coefficients than measurements
  - Improve electrostatics?
- Correction
  - Pixels level?
  - Or PSF model ?

Distortions without assuming good sampling

Pixel level:

Assumes the image is well sampled.

$$\delta Q_{0,0} = \sum_X \sum_{ij} a_{ij}^X Q_{ij} (Q_{00} + Q_X)$$

Source charge

Test charge.

Correction to PSF model:

$$\delta Q_{0,0} = \sum_X \sum_{ij} a_{ij}^X Q_{ij} \times flux \times PSF((x_{00} + x_X)/2)$$

Conclusions

- We think to have compelling evidence that the brighter-fatter effect and correlations in flat fields share the same origin : the Coulomb law.
- Correlations are the key to constrain the brighter-fatter effect.
- Non-linearity of response and other sources of correlations make the link tricky.
- Practical handling of the effect still to be settled.
- Handling the brighter-fatter effect at the ~10% level is probably not too difficult.
- We are not quite at understanding the slop at the 1% level.