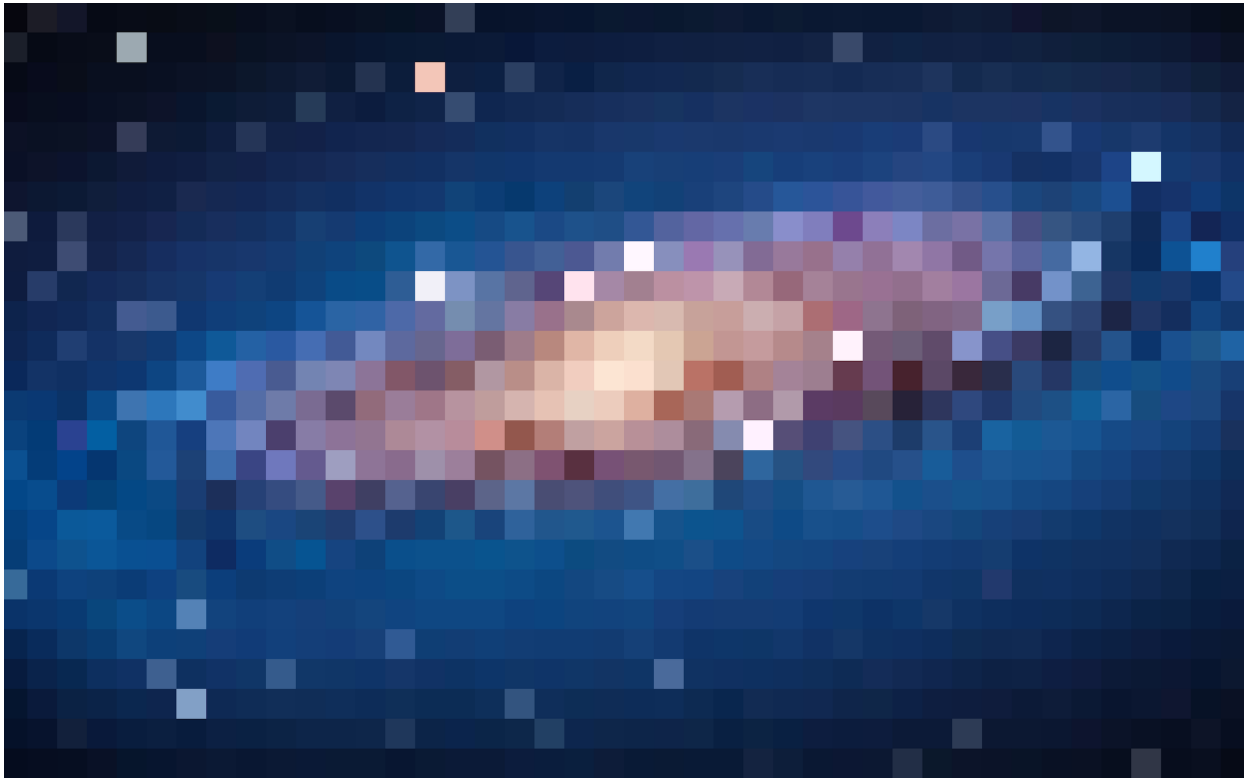
Brighter-fatter and other sensor effects in simulations

CHRIS WALTER, DUKE UNIVERSITY



Precision Astronomy with Fully Depleted CCDs / December 2014

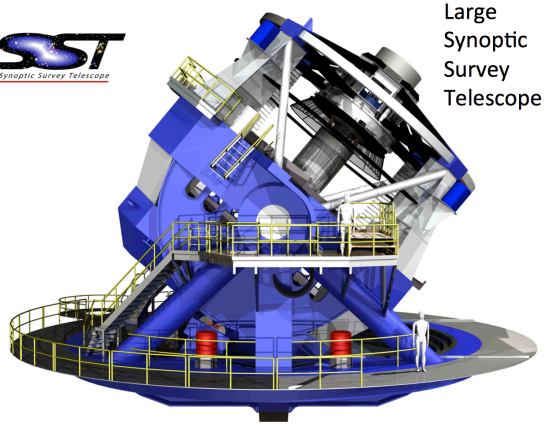
Contributions from: A. Nomerotski, J. Peterson, M. Duncan, B. Beamer, R. Lupton

Introduction

In LSST we are using the PhoSim package to try to simulate the physical effects in the CCD image sensors in order to understand and control instrument based systematic errors.

- We are working to validate the main sensor effects in PhoSim:
  - Tree rings and edge effects (BNL – Nomerotski et al)
  - Brighter-Fatter effect (Duke – Walter et al)
  - Others to come later
- Simulations of lab setups
  - We want to use data from the LSST CCD test stands (BNL and SLAC) along with the optical simulators (UC Davis LSST Simulator) to compare with simulations and quantify the systematic effects.
- The eventual goal is to tune the simulation well enough to evaluate the effects on weak lensing science.

LSST Strategy

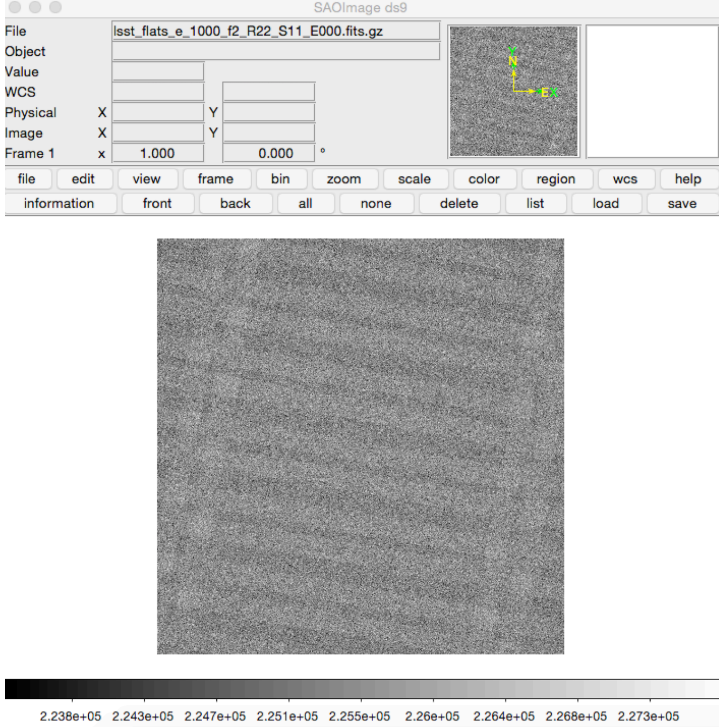


While testing our pipeline
and attempting to either correct or account for effects like tree-rings and the brighter fatter effect, it is important that we do not introduce effects and then trivially remove them with the same algorithms and techniques.

When possible we will always have a physics based model for the effects in the instrument including electron-by-electron tracking.

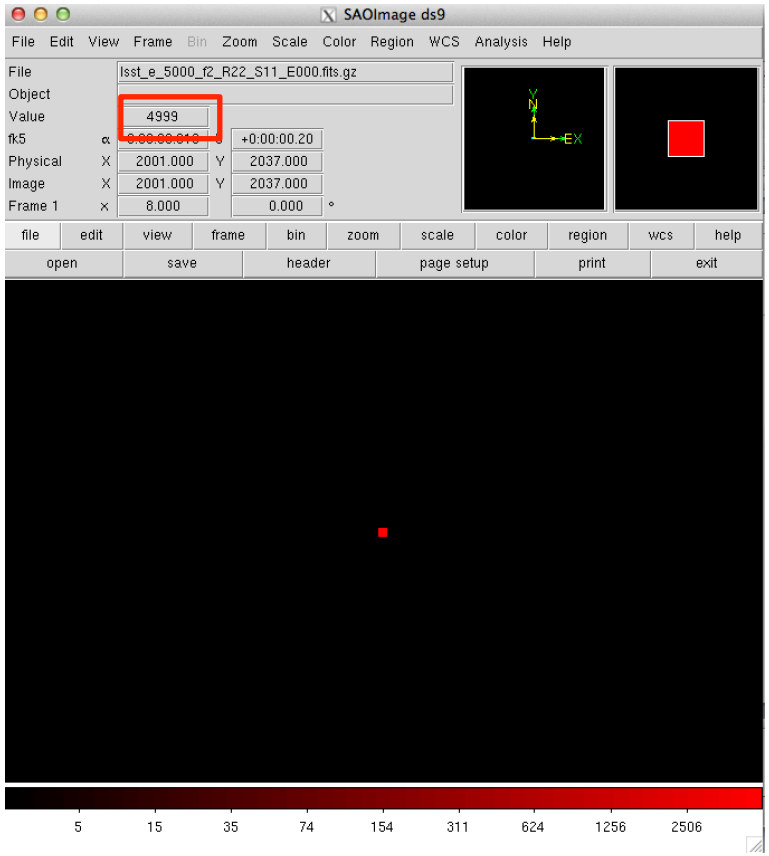
Current PhoSim Tests

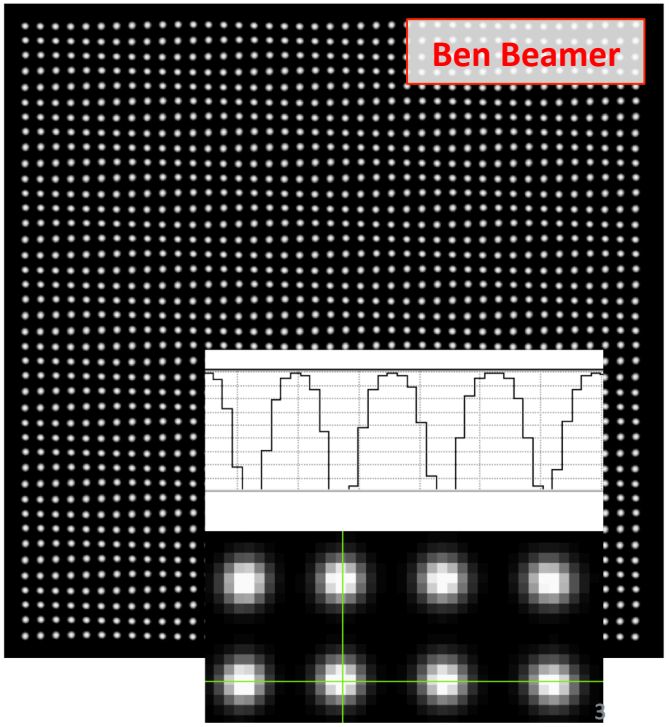
- Currently we turn one effect on at a time with everything else turned off.
- The effects are sometimes magnified in order for us to understand them.
- We are running in photon-by-photon mode and sometimes reduce the chip size for speed.



Simulated full-well flat with annealing pattern.

We use calibrated spots, flats, and grids of stars for tree rings and edge effects.

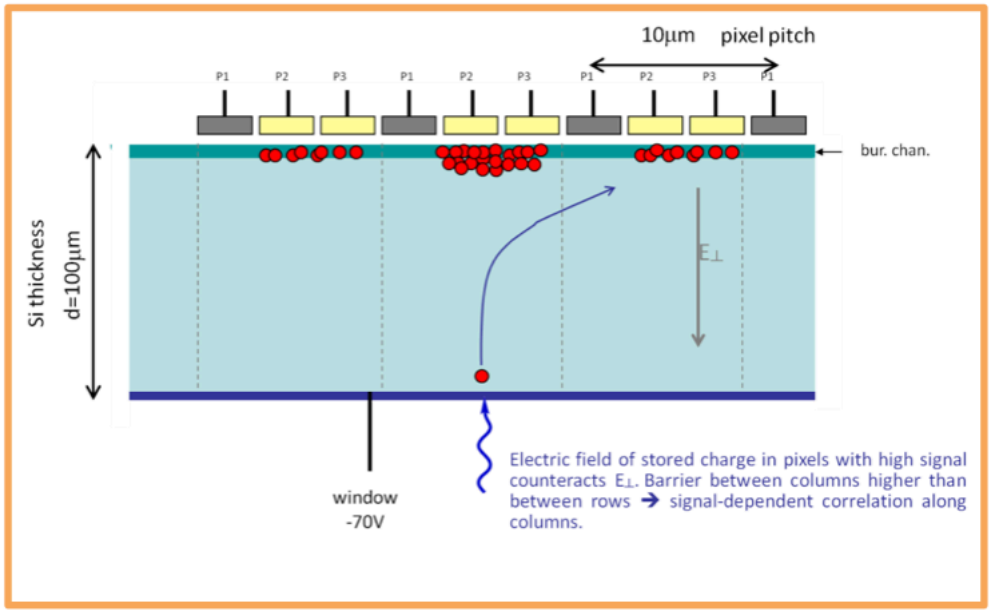




A magnitude 20 star results in 366545 electrons (no saturation)
m1 = 2.5 log_10(num_e/366545) – 20

# electrons	Magnitude…
5000	24.663

Brighter- Fatter: A Model and Some Data



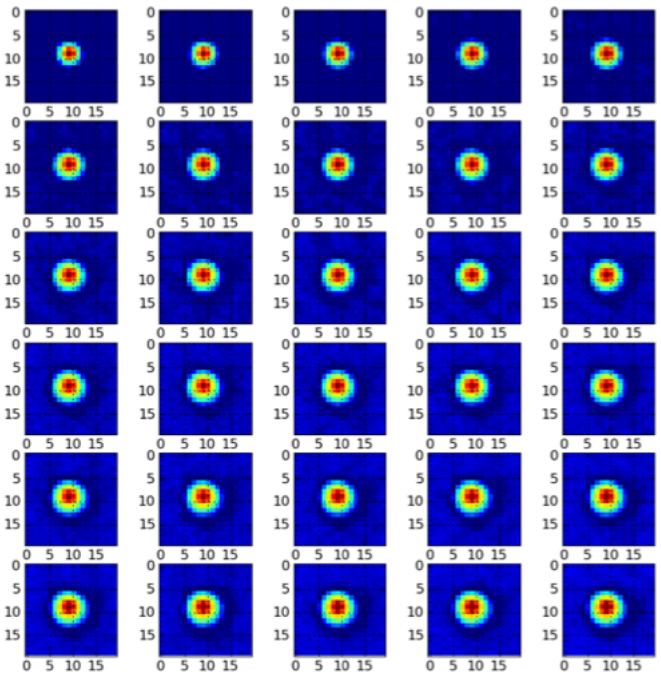
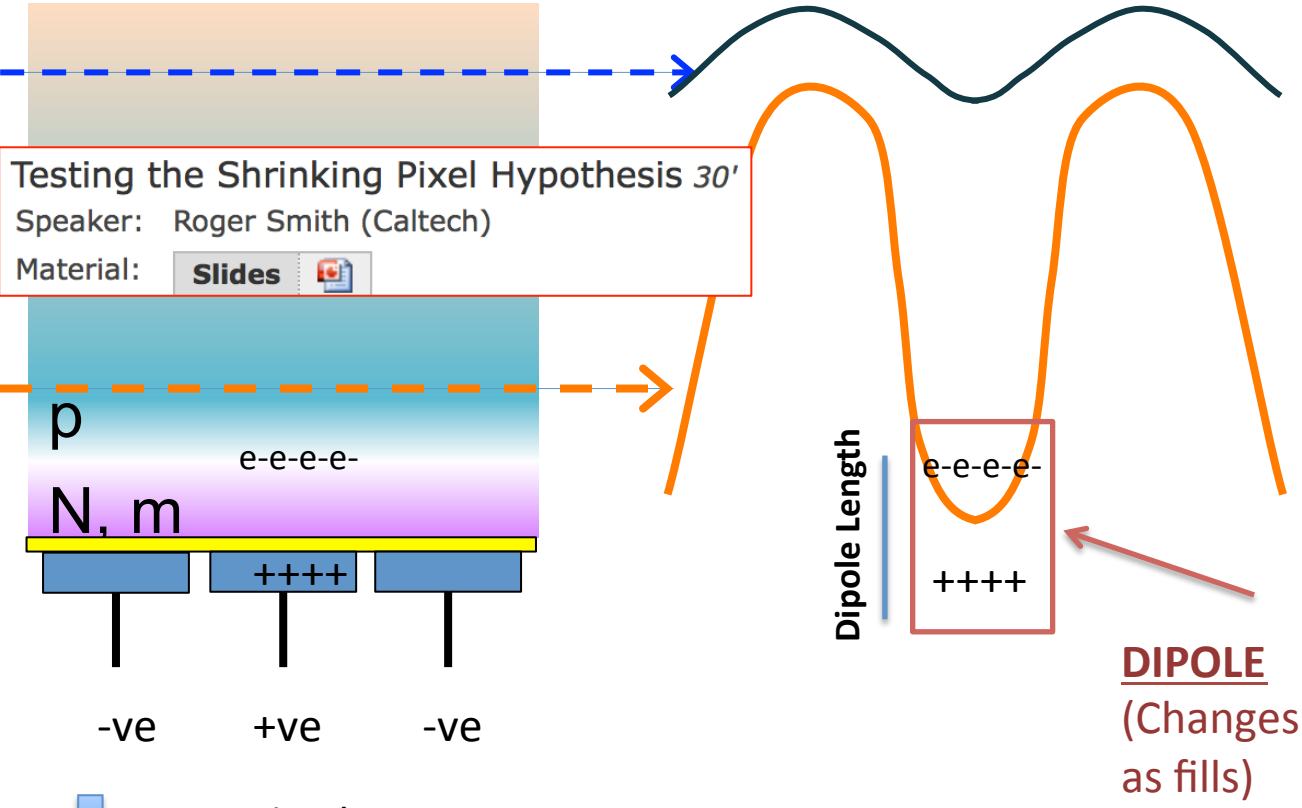


Figure from Paul O'Conner.: Drift should happen in the bulk.

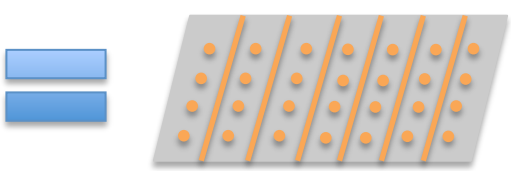
Data taken by Paul O'Conner.

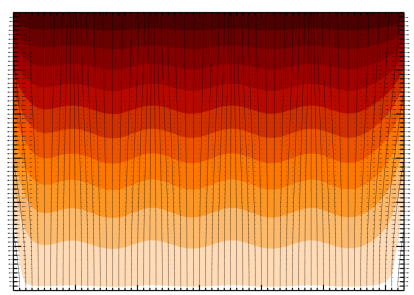
I think there is more than one model for calculating fields "in the field".

PhoSim

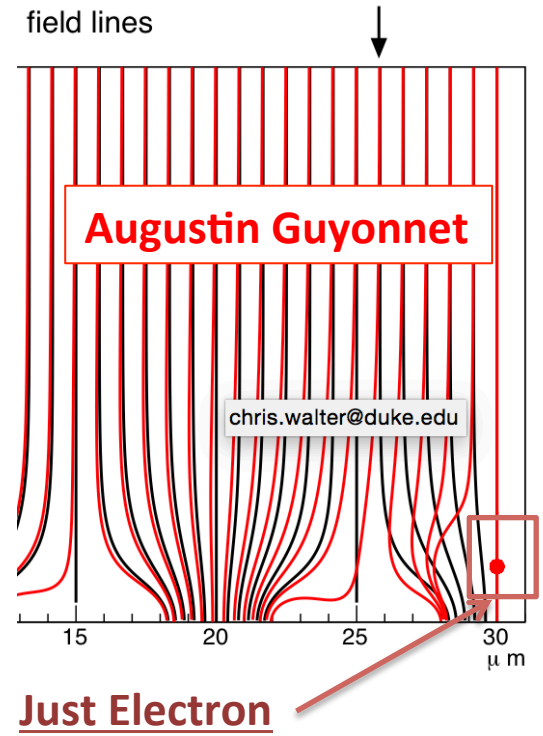


Static Charges
(Calculated Once)



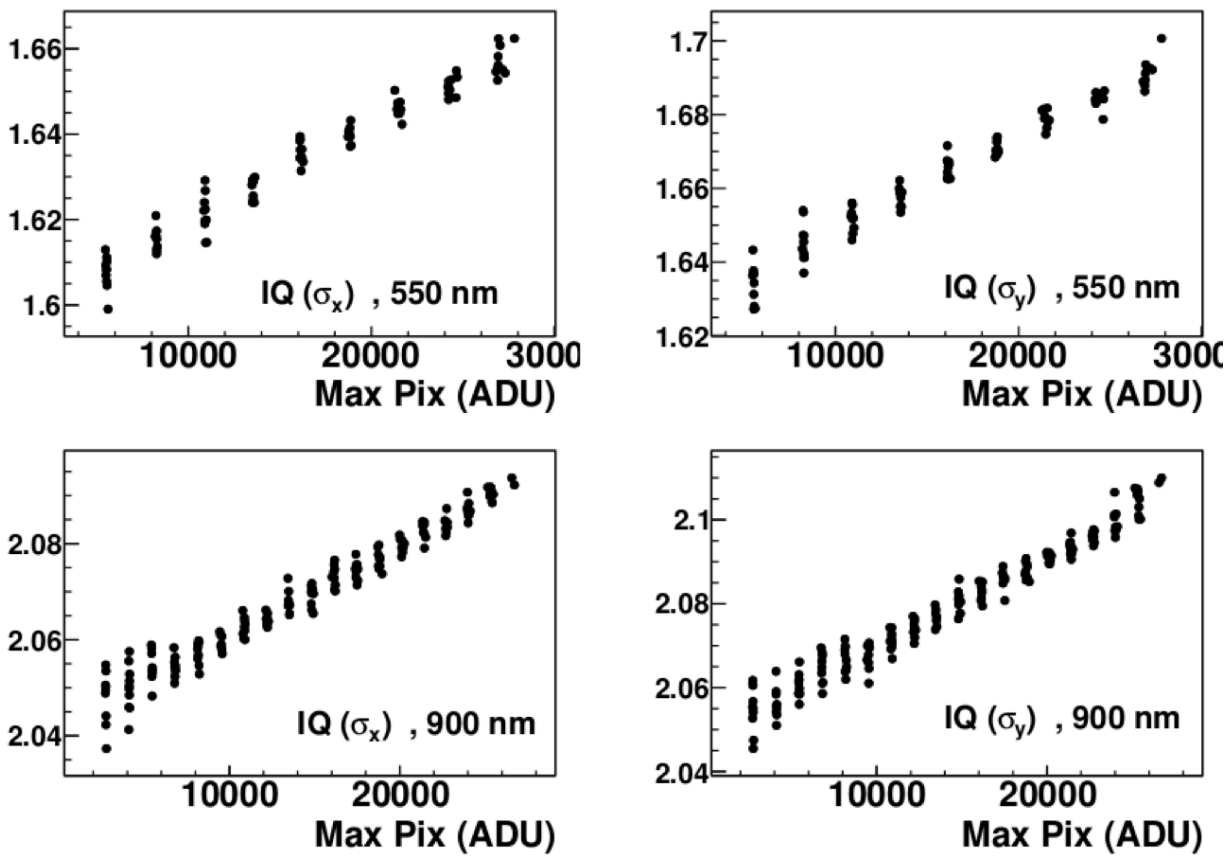


CNRS



Static Charges

Data taken by P. Doherty @ Harvard for e2v



2-3% change over range. Notice comparable changes in both X and Y.

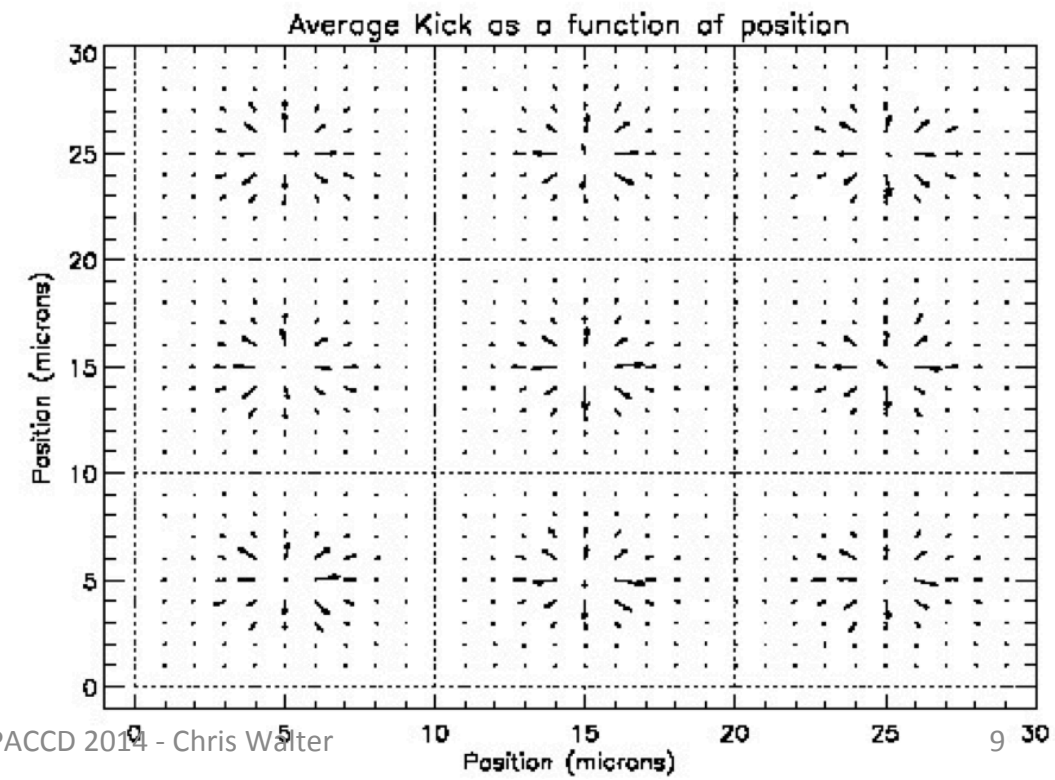
Note: scale in ADU ranges to about 150000 electrons

From Astier et al paper/talk from PACCD 2013 conference.

Expected charge movement in PhoSim

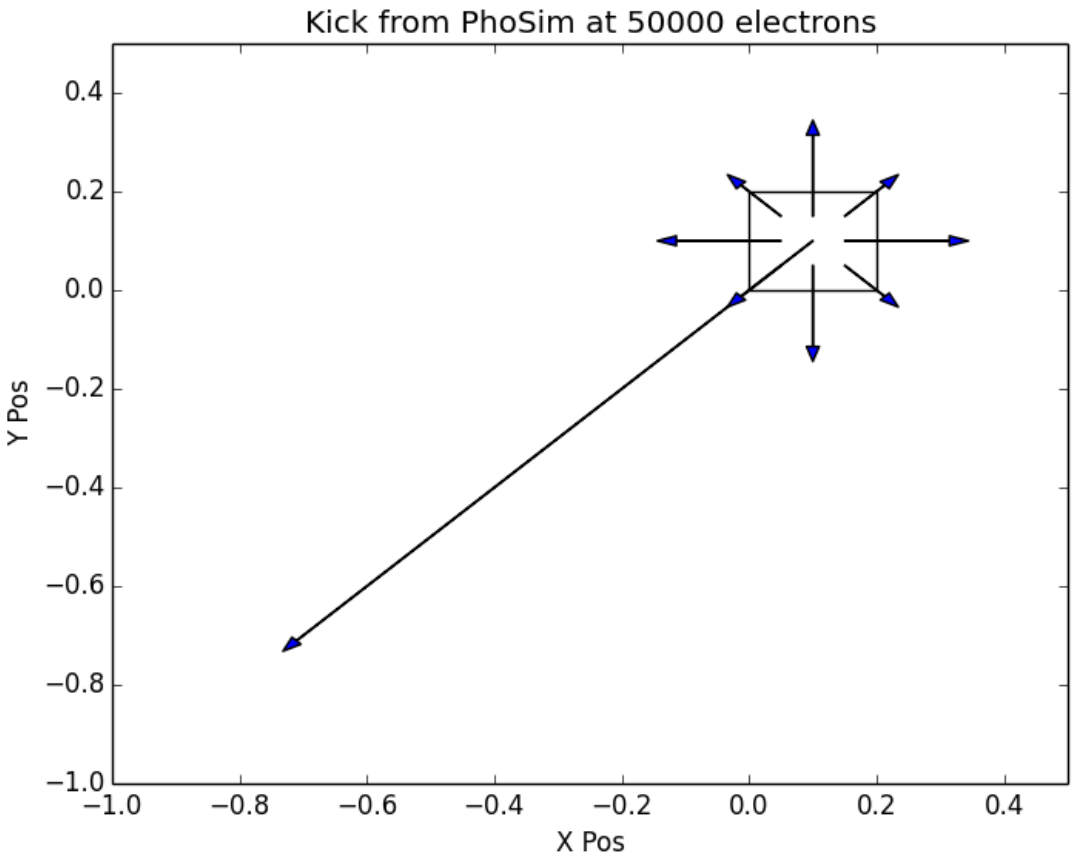
- The kick from electric fields is calculated from the
  - Charge in pixel
  - Charge in nearest neighbor four pixels
  - Charge Stops
- Next check one of these in detail.

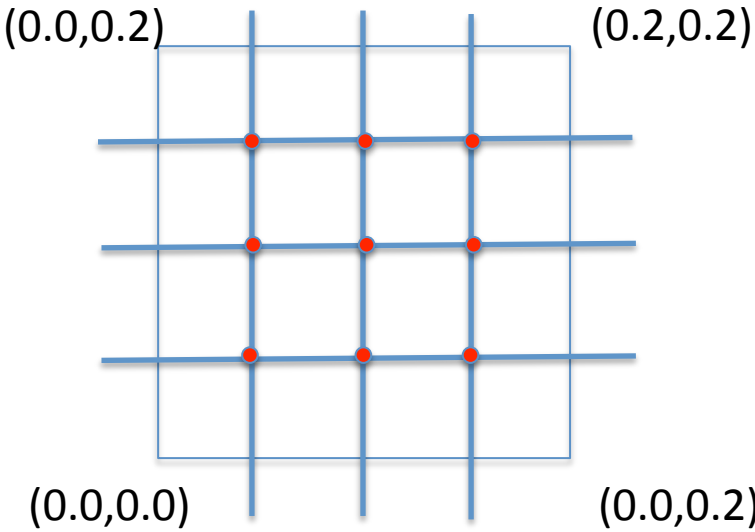
$$dr_{xy}(x,y) = \text{integral}\,(E_{xy}(x,y,z)/Ez(z) * dz)$$



Sum of kicks made by John P.

PhoSim kick at 50,000 electrons

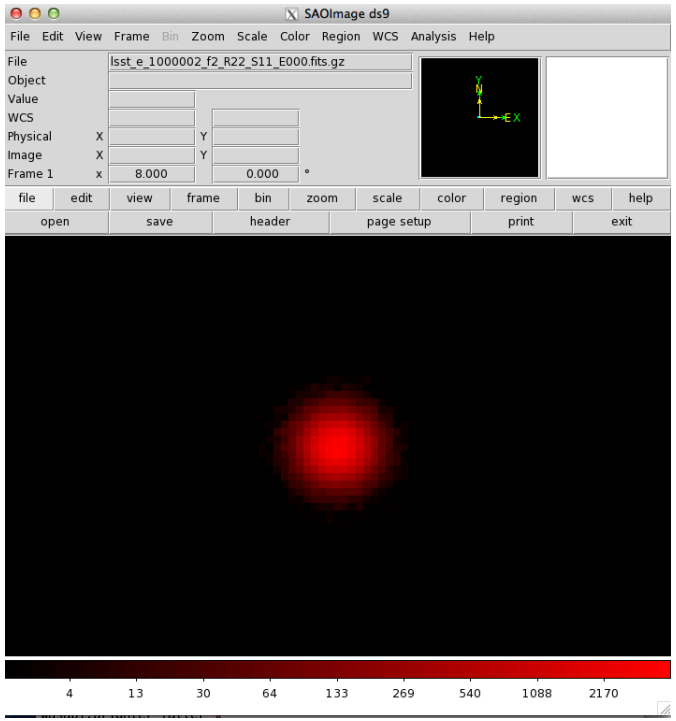


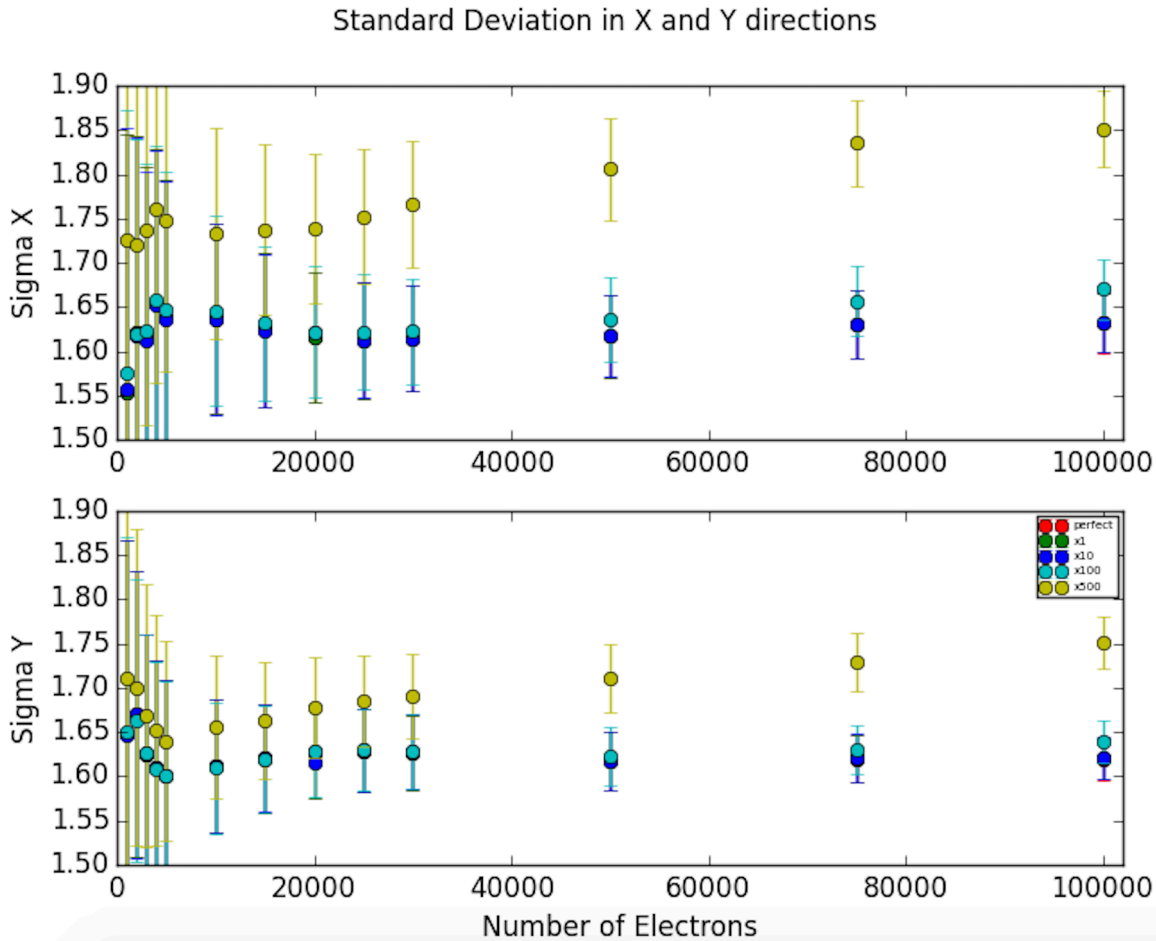


Note: All charged assumed to be at center point.

<u>This is only for the charge in the pixel itself. It is summed with 6 other contributions.</u>

Make a Gaussian Spot





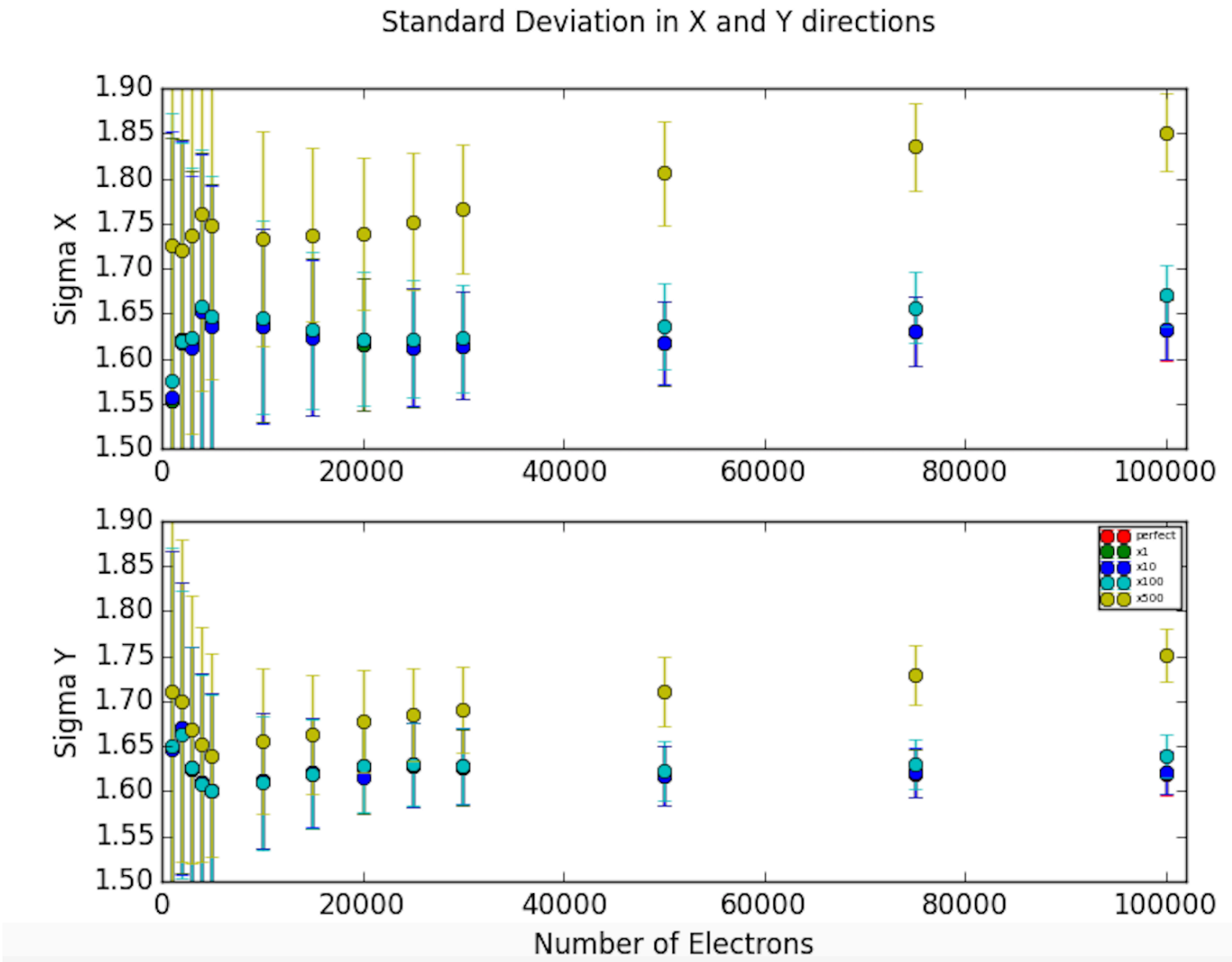
The result of a Gaussian spot with sigma of ~1.6 (log scale).

<u>I modified PhoSim to run with varying BF strengths.</u>

X&Y sigma as measured by the LSST SDSS shape algorithm.

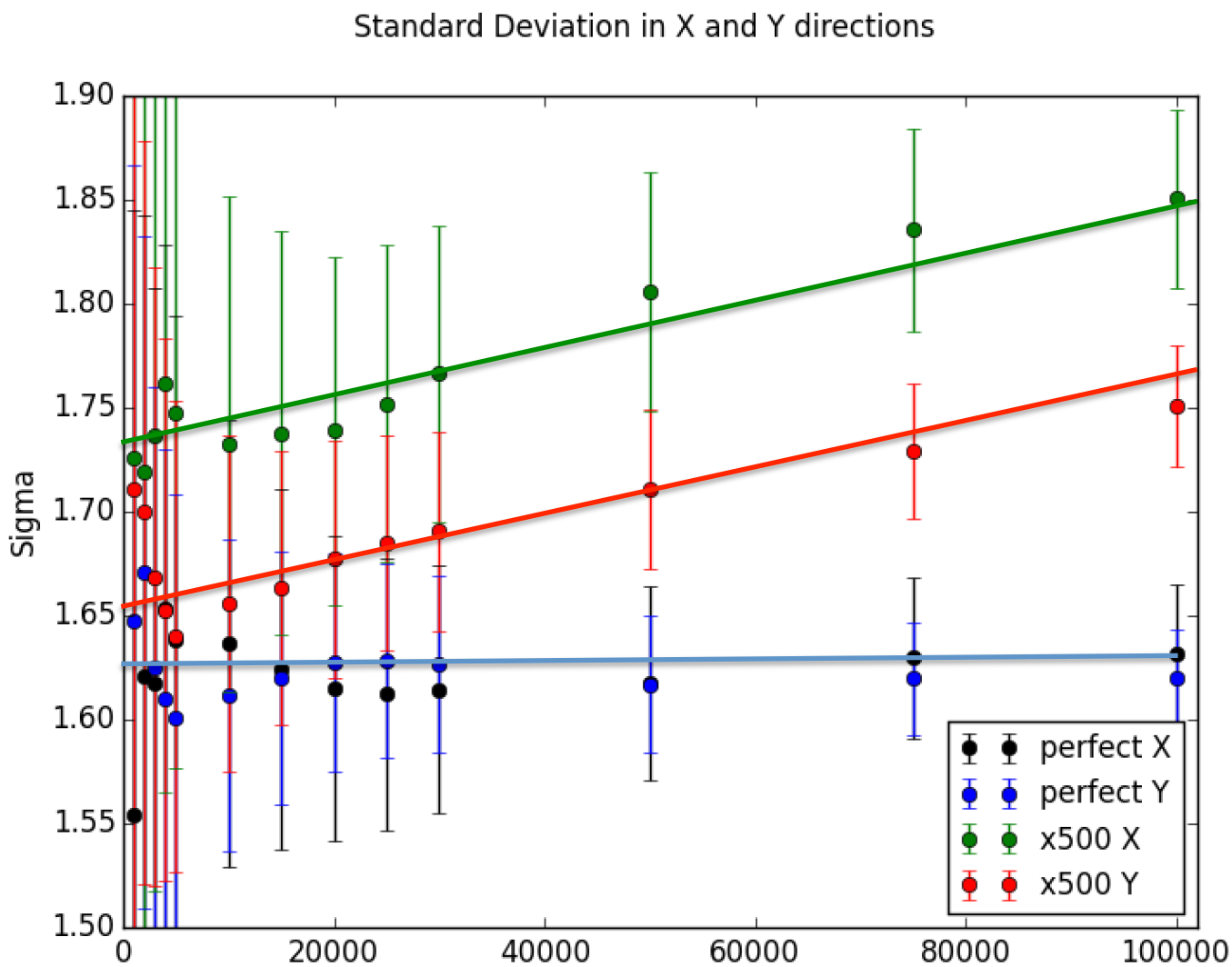
<u>Main conclusion is that you need to increase the effect a lot to get the spreading you need.</u>

Measured spot size



This is a 5-7% increase. Astier et al 2-3%. But for 100-500x times effect

Overlay X & Y for x500



Similar slope in X and Y

But overall shift.

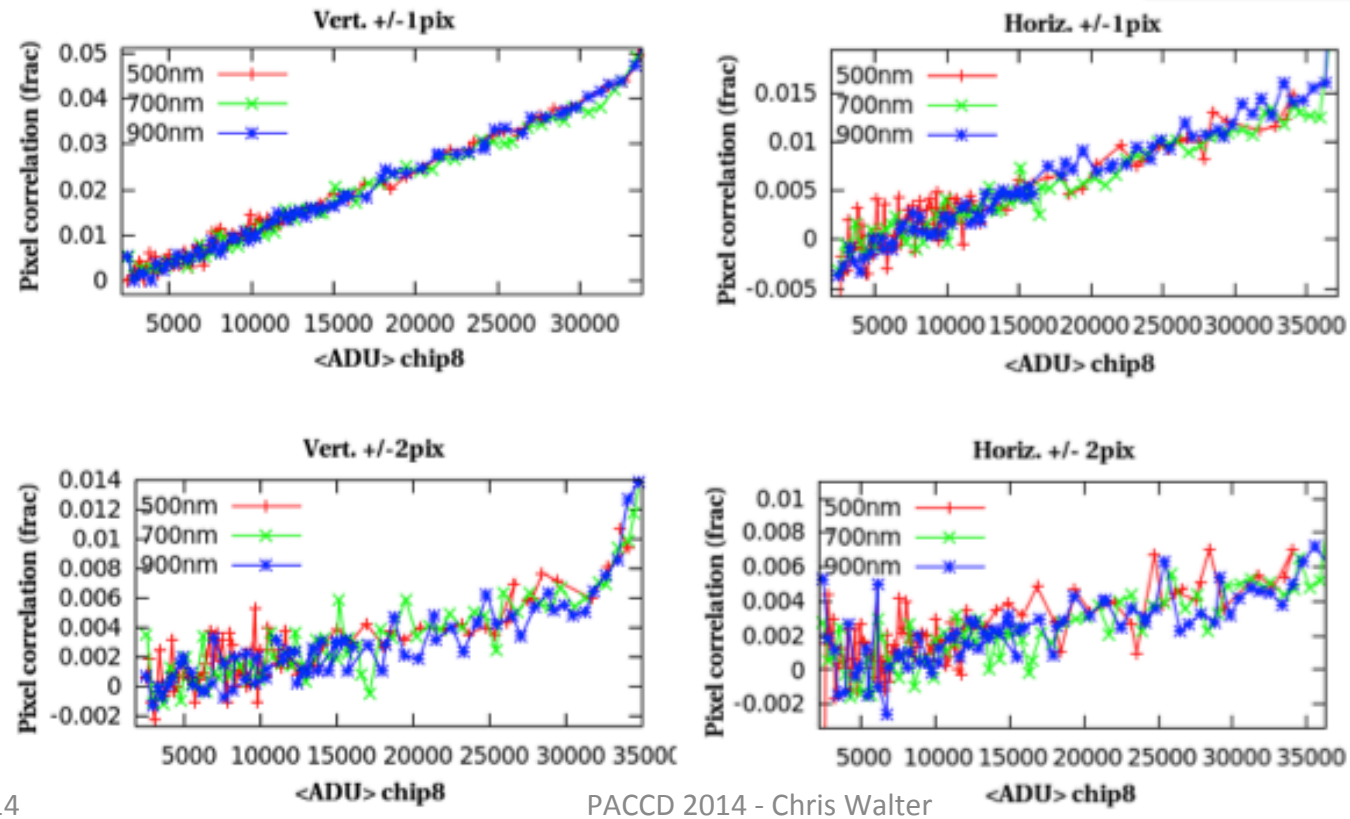
Then: make flats to check for PTC and spatial auto-correlations

For these tests for speed use a 400x400 sensor.

All optimizations are turned off and this is a true photon-by-photon simulation.

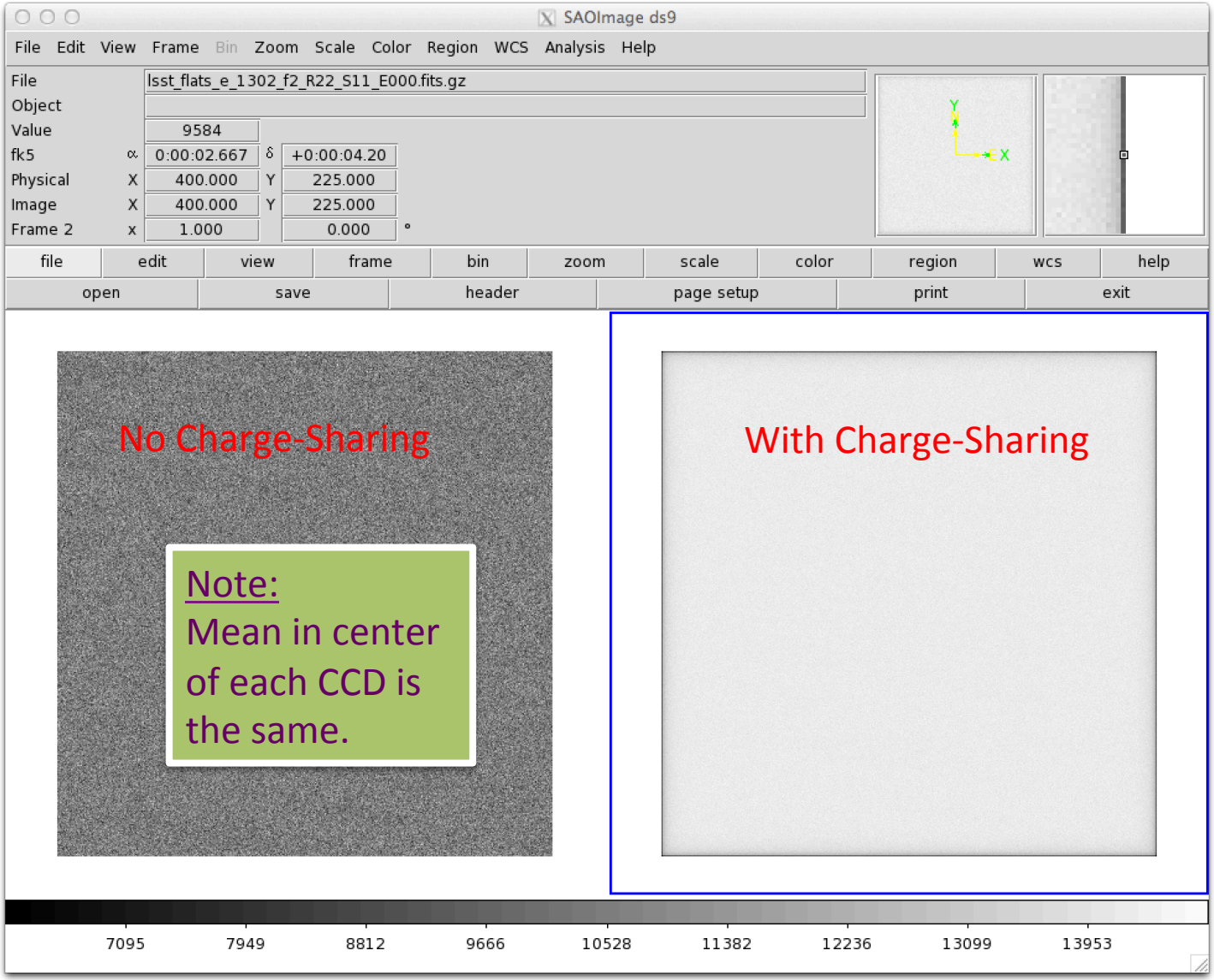
Astier
1 to 5% correlation coef

Note larger y-correlation

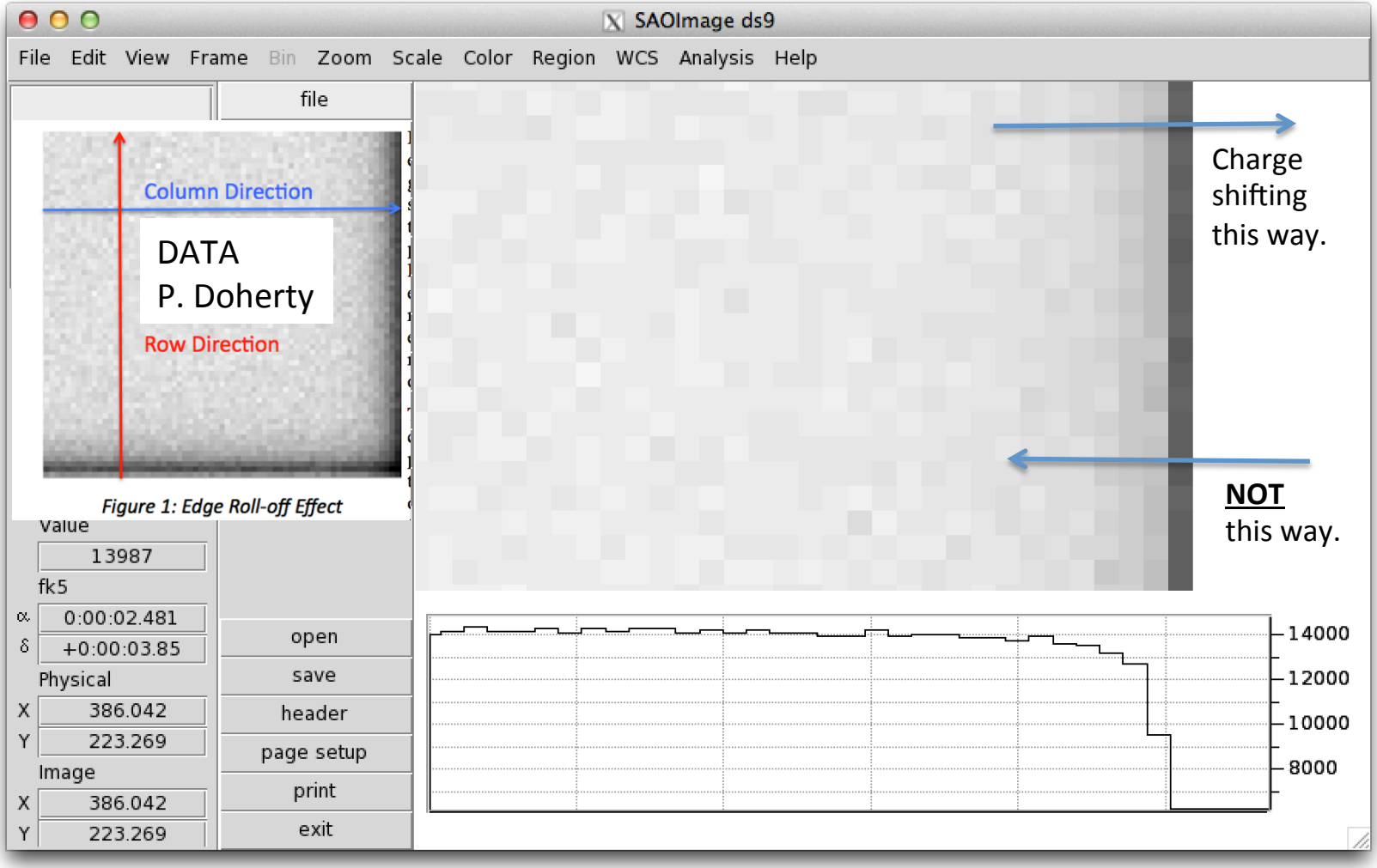


BF only edge effect

Only from charge at center of pixel.



Charge is moving off the edge.



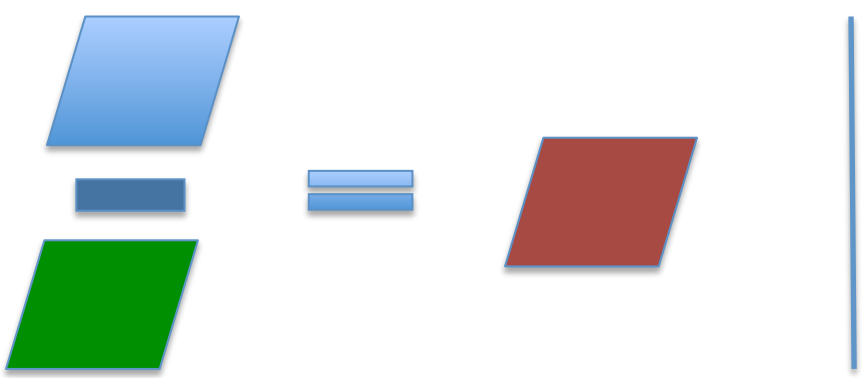
There is no corresponding charge outside of the active silicon area of the CCD to shift back in. <u>Need to be careful near edges!</u>

Calculate statistics on the flats (following Downing et al.)

The **Photon Transfer Curve (PTC)** [Mean/Variance] checks whether or not the statistics in each pixel follows a Poisson distribution. There ways to check for both the effect of charge spreading distribution and common mode variations:

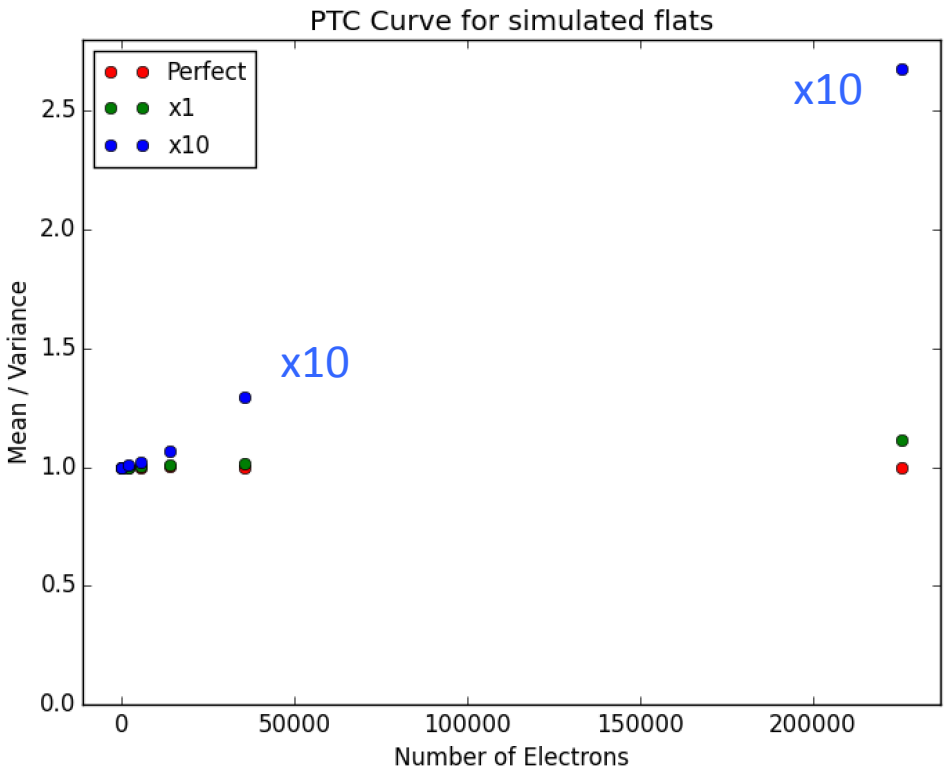
- Make two simulated exposures and subtract them. This should remove any common mode variations just like with real data. <u>Also trim outer 20 pixels.</u>

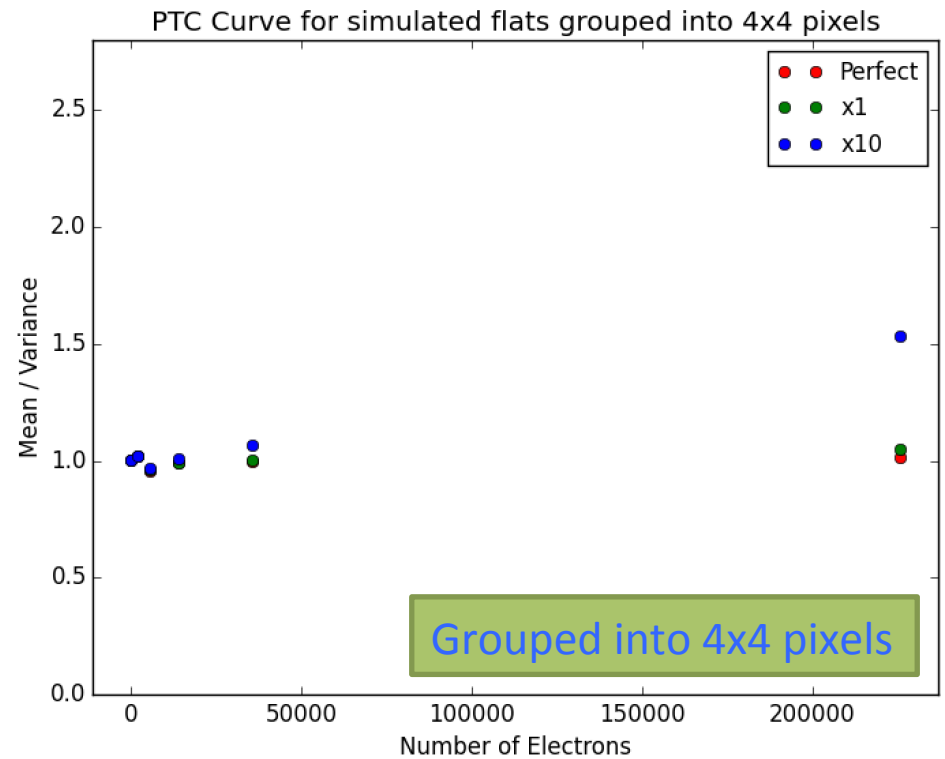
- Also, group pixels into to 4x4 blocks this should recover the Poisson statistics.



1	2	3	1	2	3
4	5	6	4	5	6
7	8	9	7	8	9

PTC curve for 3 BF strengths

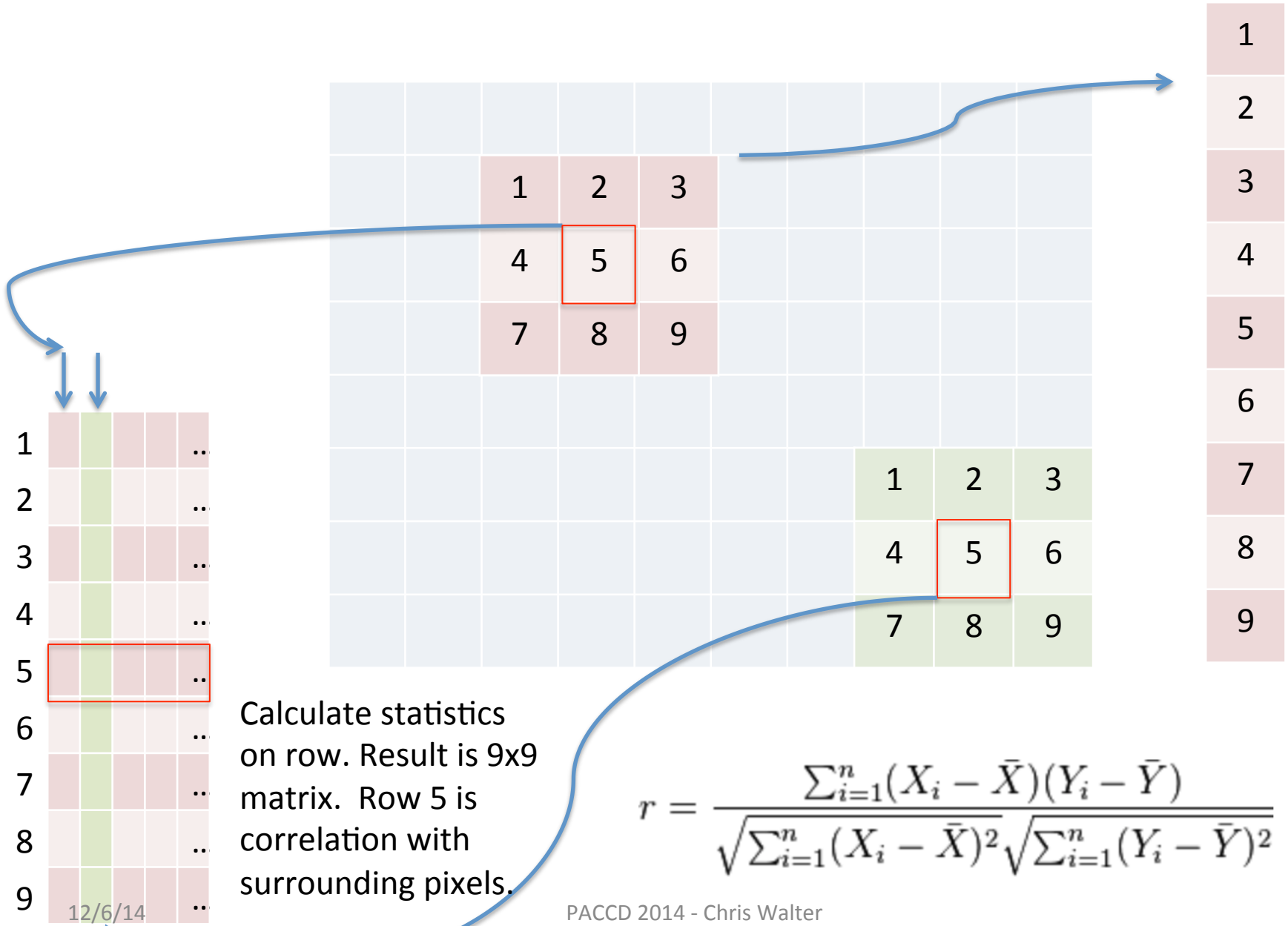




x1 to x10 shows strong effect. 4x4 grouping reduces effect as expected.

Note: differencing needed. Also, x100 and x500 show pathological effects.

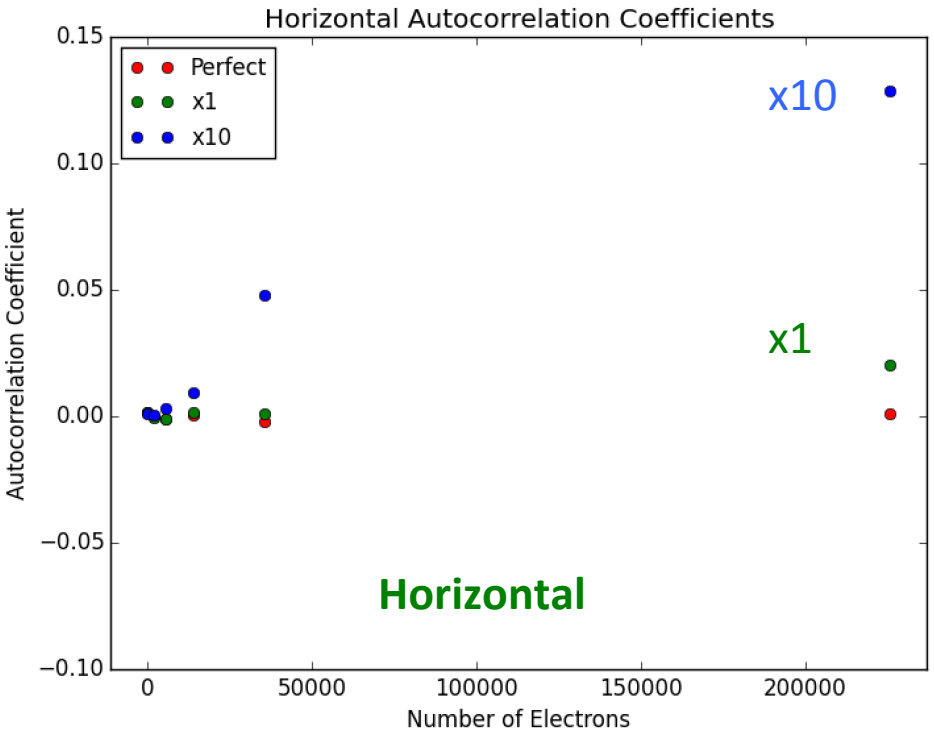
Also: Spatial 2D autocorrelation function

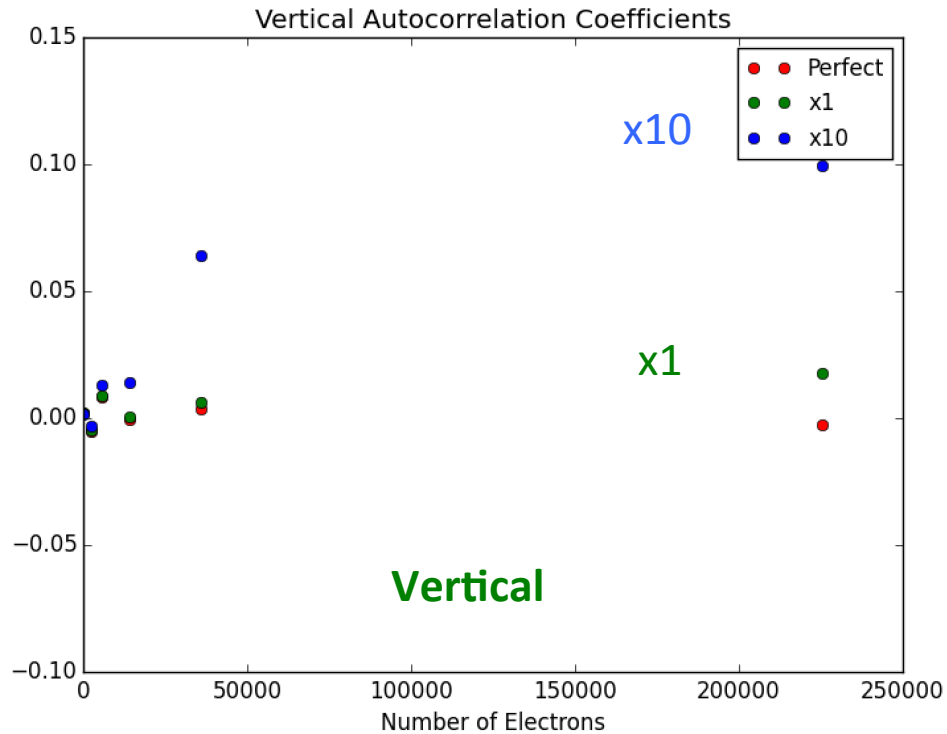


Calculate statistics on row. Result is 9x9 matrix. Row 5 is correlation with surrounding pixels.

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

Correlation Coefficients for 4 cases





<u>Astier and all measure 1-5% effect. Very close!</u>
(At x1 we see about 2%)
Note: Currently, only measured in nearest neighbors

Summary of Brighter-Fatter Results

- Spots produced with flat SEDs/ Flats at 550 nm
- BF effect does not seem large enough for spots (compared to previous data results).
- Flat PTC and correlations look reasonable. Note: only checked 1st nearest neighbor so far.
- -> Need to run real test data through the same algorithms to make a fair comparison.

CODE: https://github.com/cwwalter/brighter-fatter

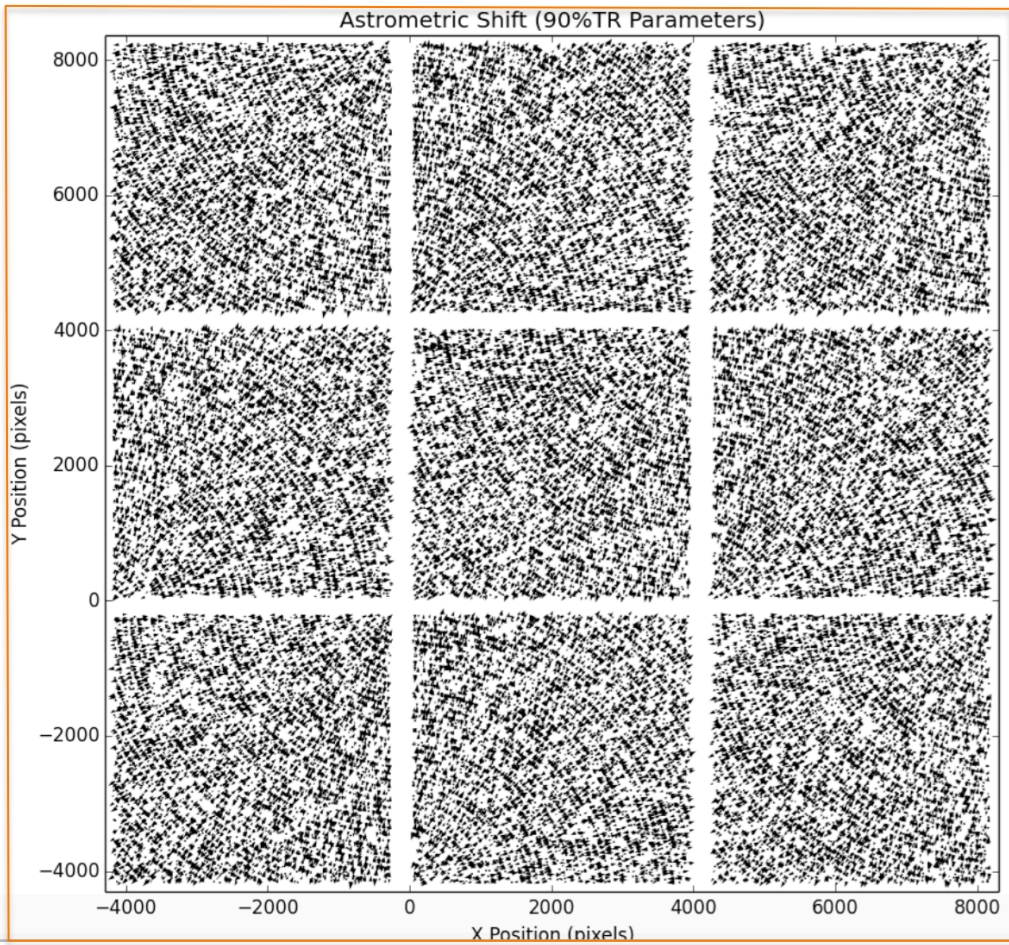
Simulation of tree rings

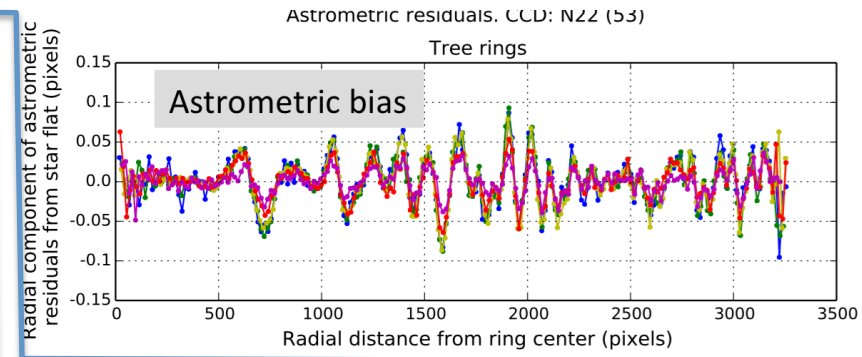
Andrei Nomerotski
Ben Beamer

DES

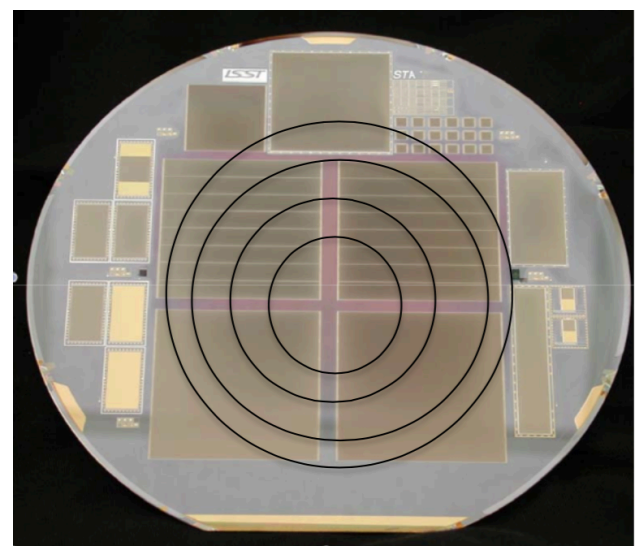
Transverse electric fields' effects in the Dark Energy Camera CCDs

A. A. Plazas[a†], G. M. Bernstein[b], & E. S. Sheldon[a]

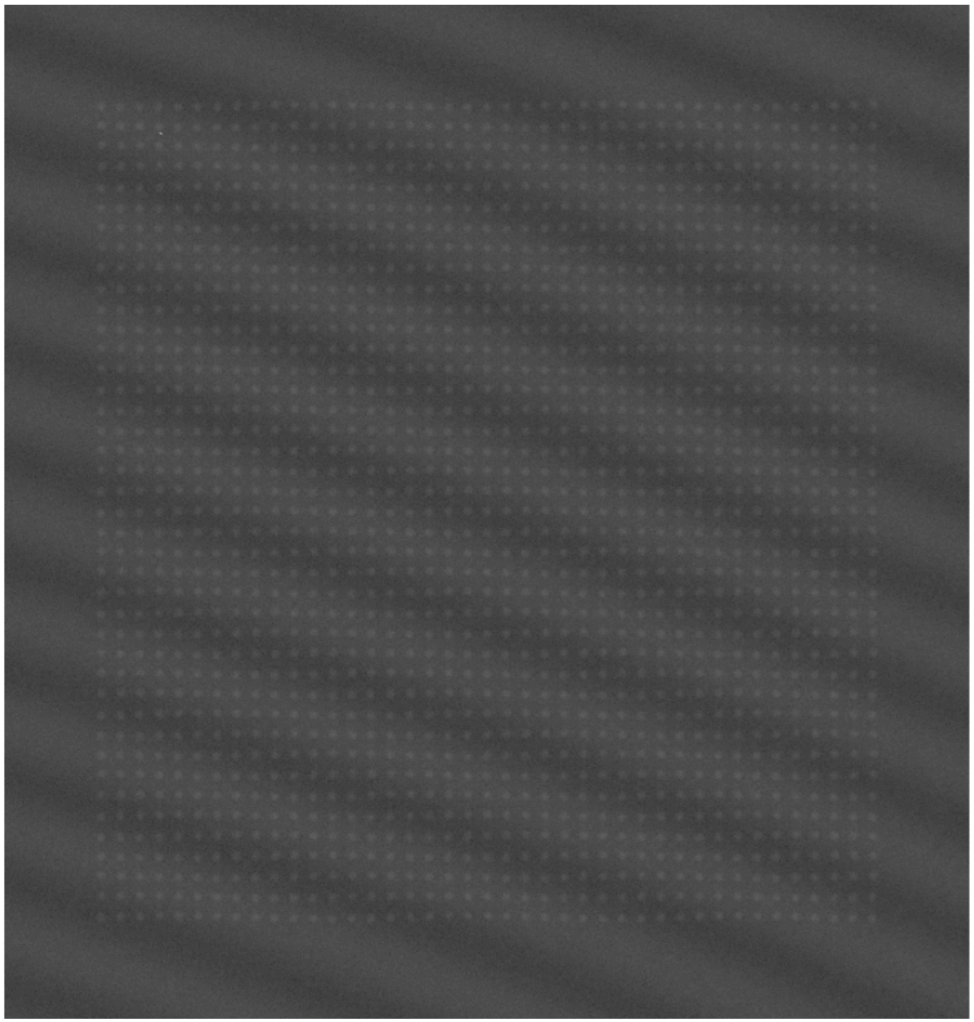


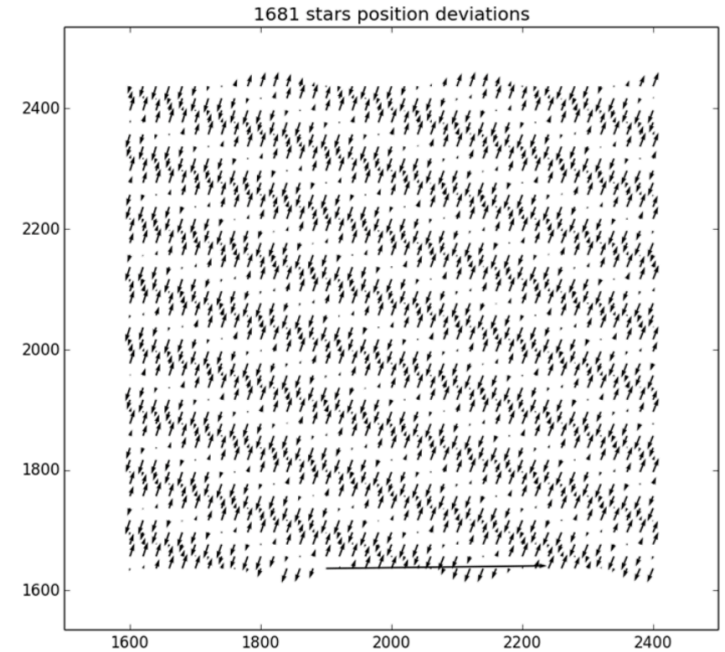


LSST

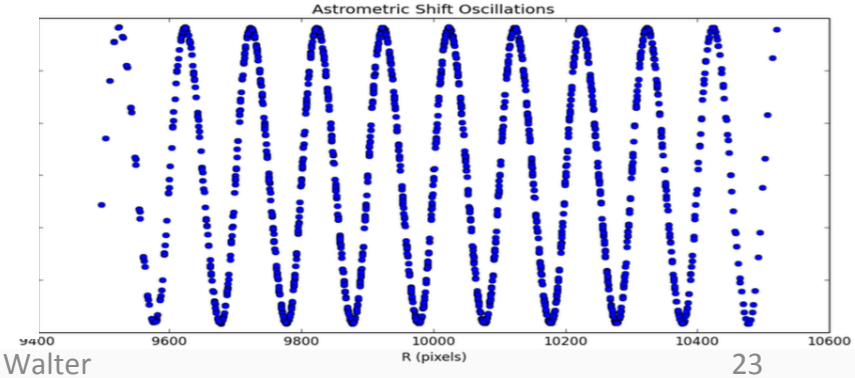


Applying a tree rings to the star grid

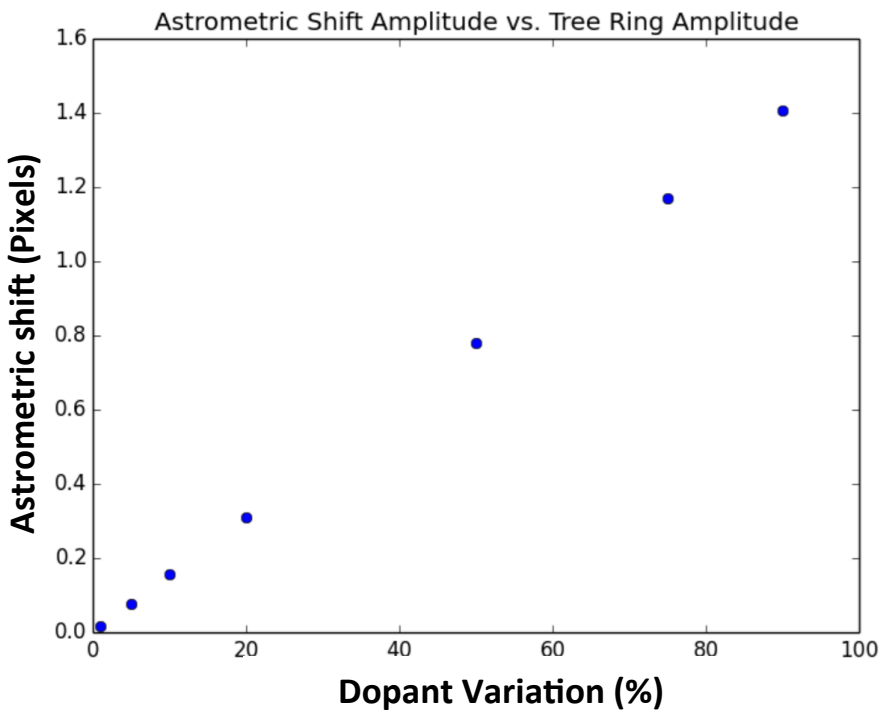


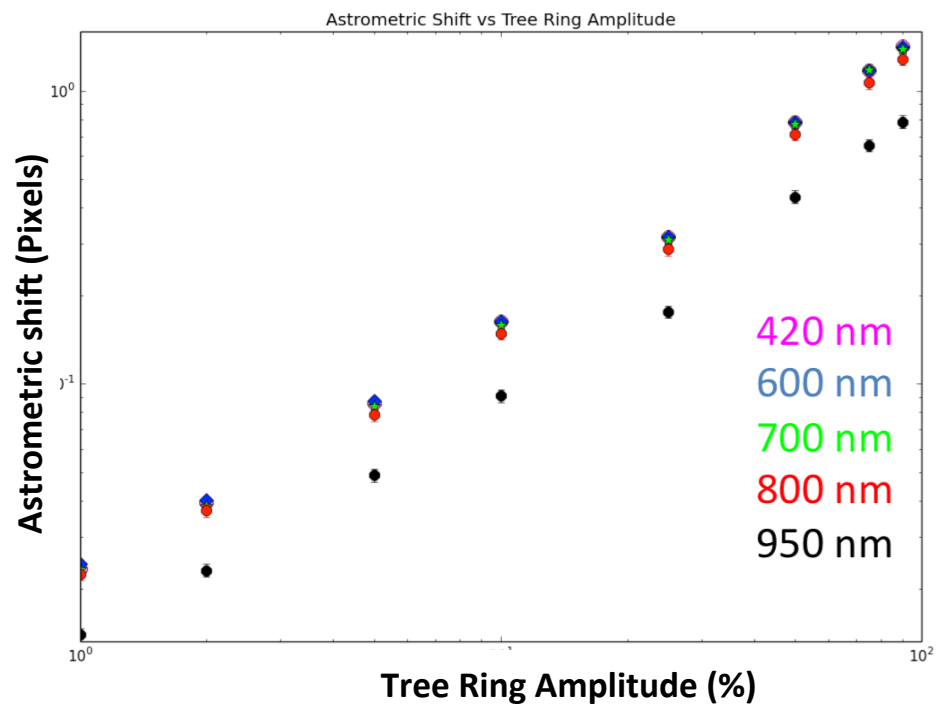


Astrometric shift measured by sextractor



The effect scales as expected with parameters

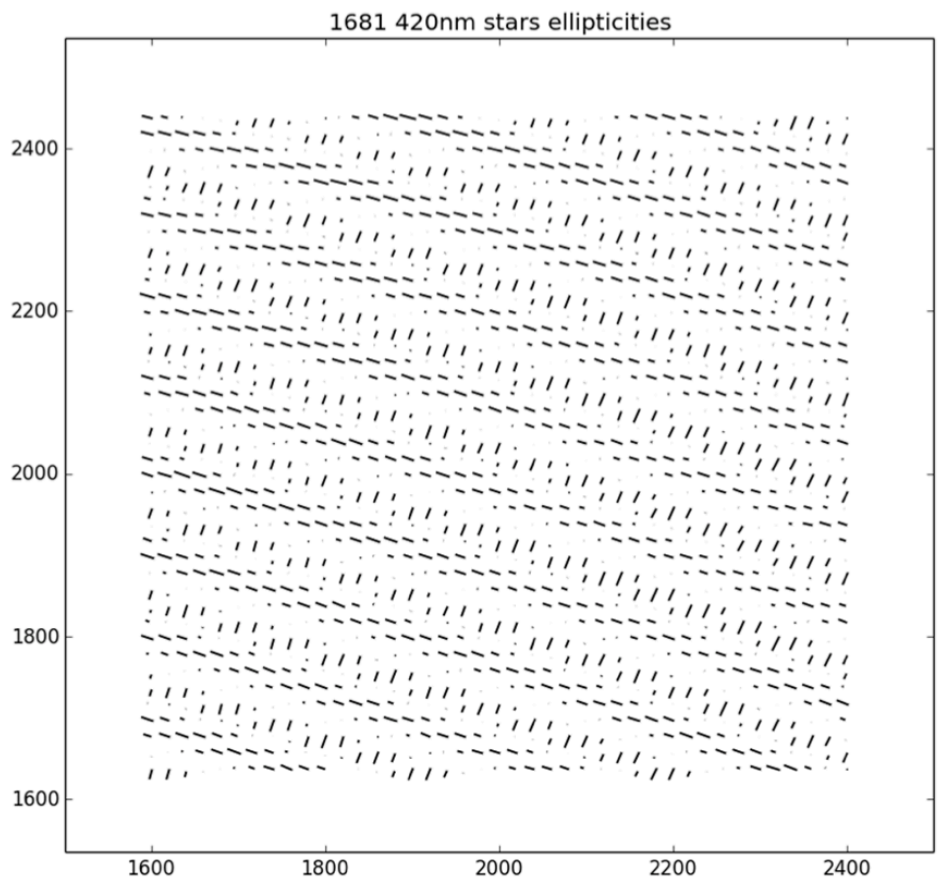


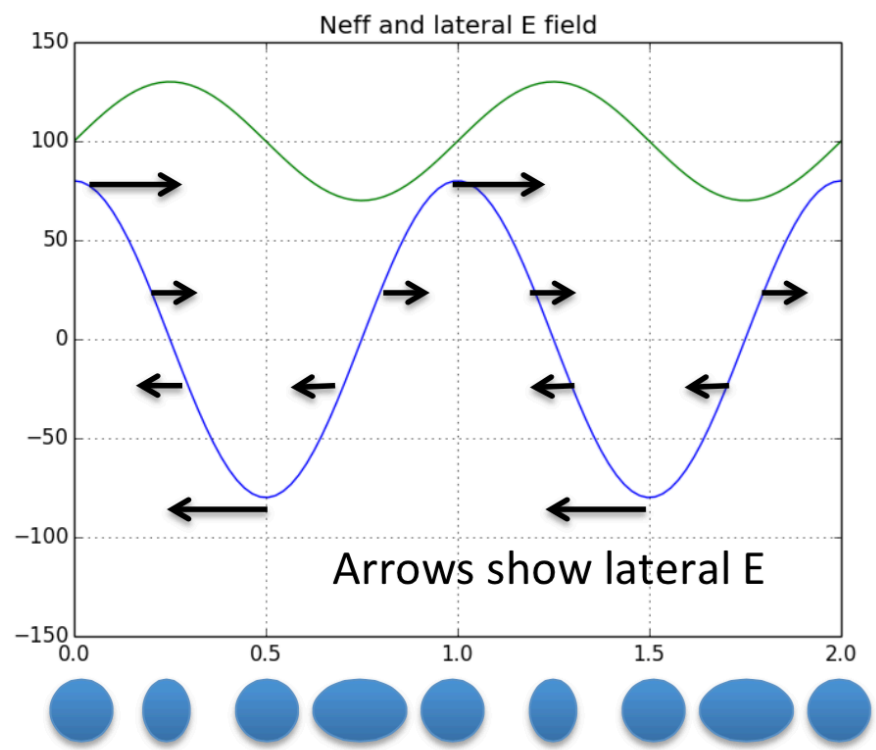


Shift increases with doping.

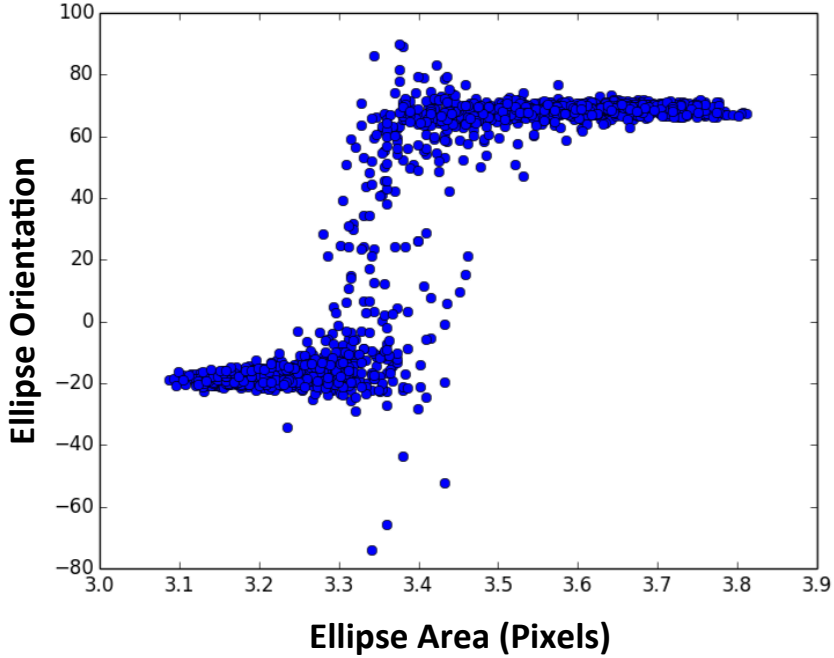
Infrared light converts later and has less time to drift.

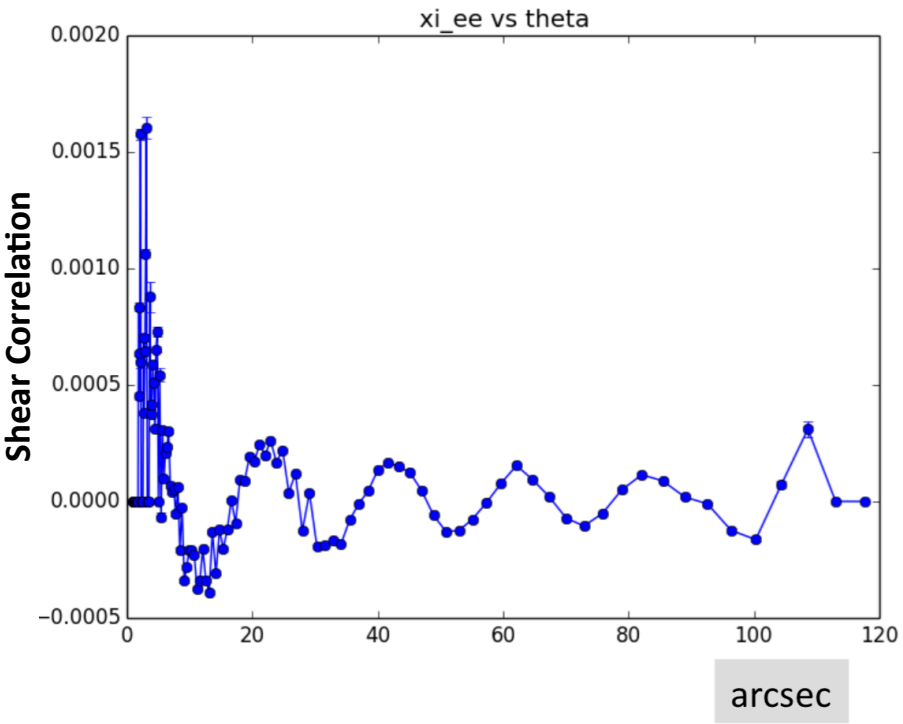
Ellipticity changes as you move through the rings.





This also causes the area and orientation to oscillate!

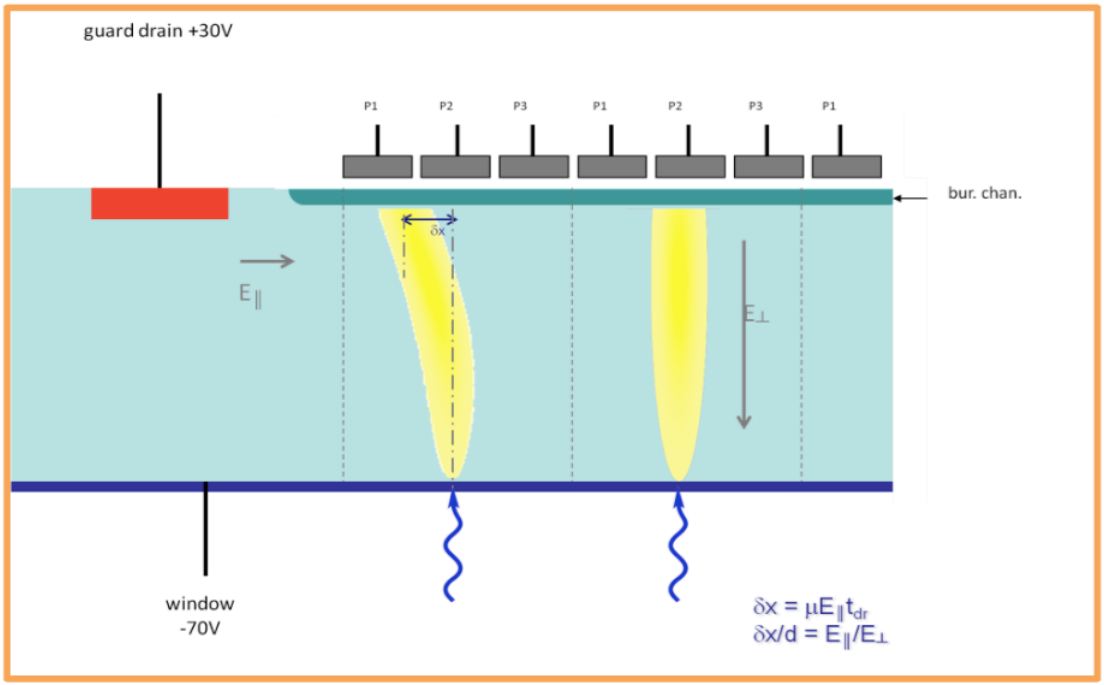




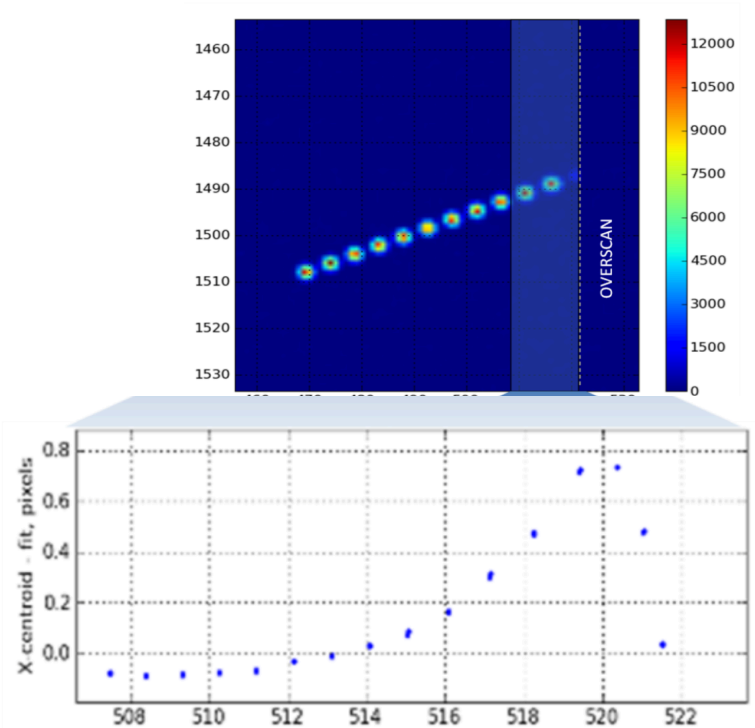
Which is also seen in the shear correlation function (calculated by corr2 by Mike Jarvis) as there is a pattern of aligned and orthogonal stars.

Andrei Nomerotski
Max Duncan

Edge roll-off effects



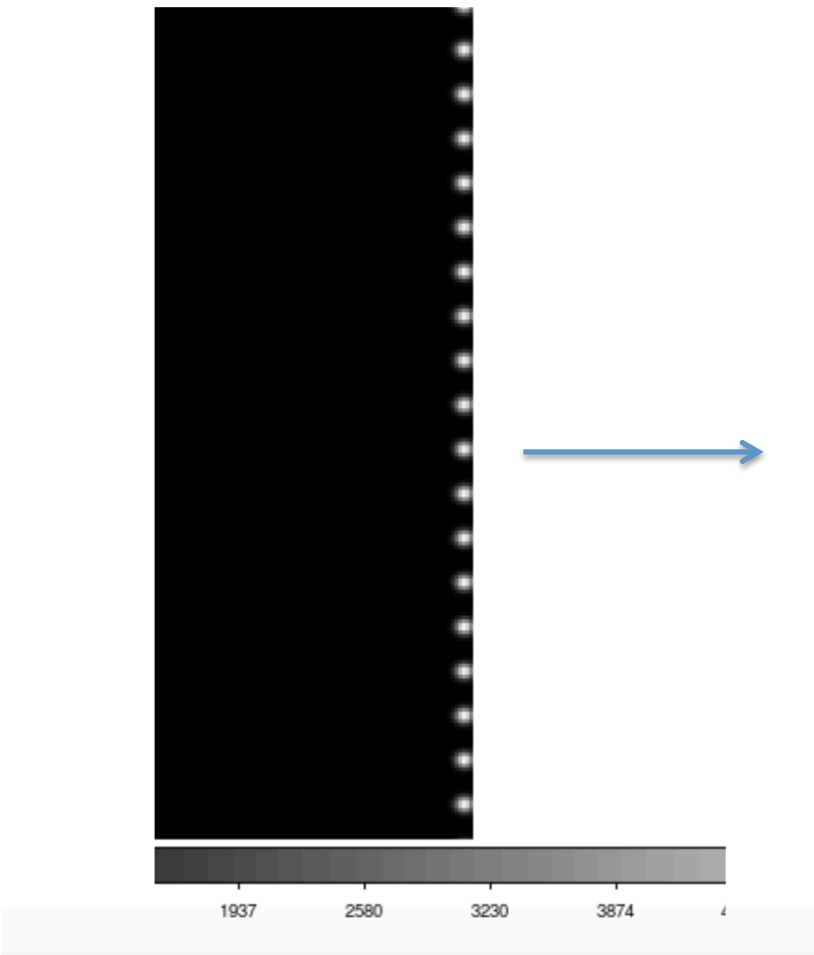
P.O'Connor

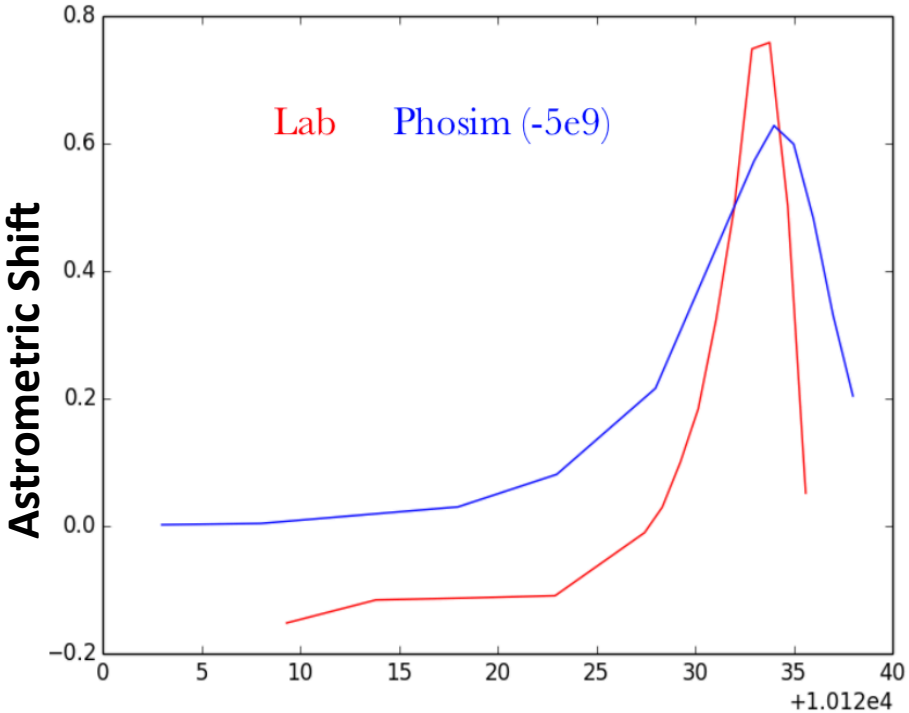


Astrometric Shift

In PhoSim

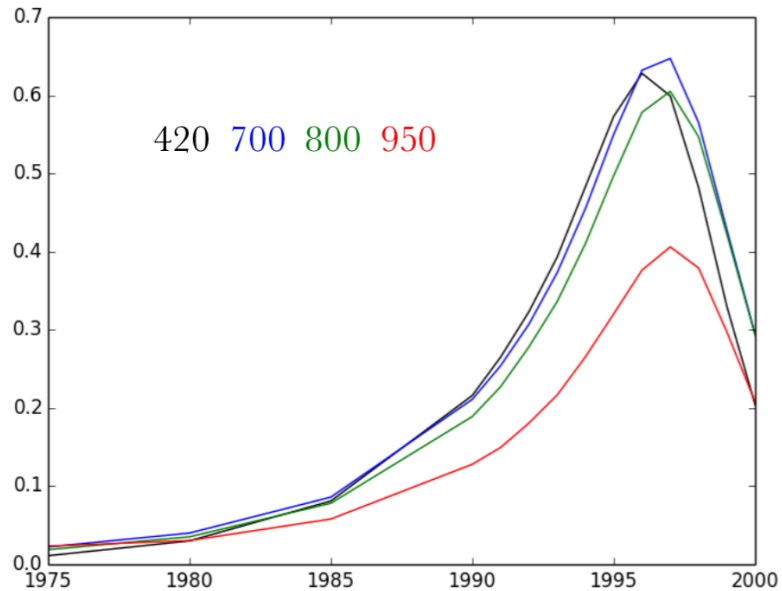
Move the line of stars off the edge.

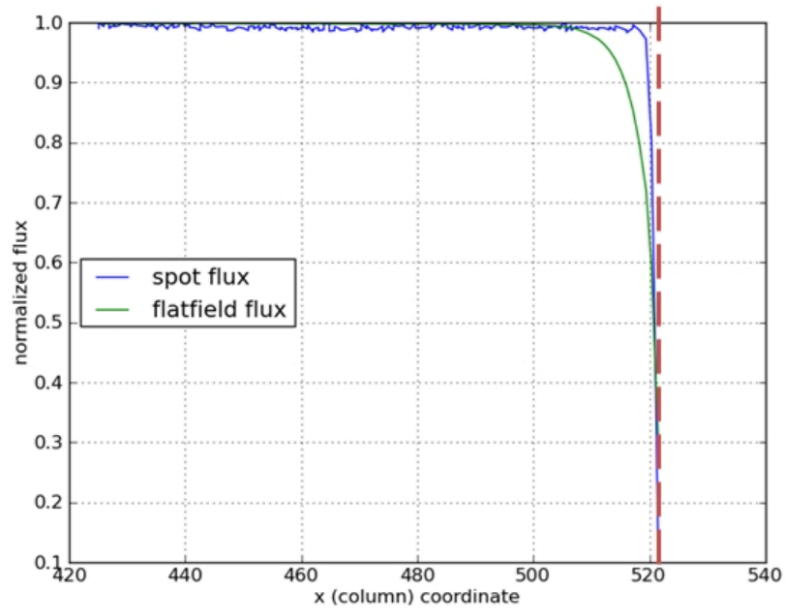




We may need to tune the surface charge configurations.

Also exhibits the expected wavelength dependence.





Currently no lab data to test this behavior.

The lab data shows a difference between the roll off for flats and spot data. Related to BF? Also need to simulate and test.

Conclusions & Future Work

- We have a concerted research program to simulate and validate these effects using PhoSim and real data.
- Validation Status:
  - Tree rings, working well and now will tune parameters. In a few months we will have a 1st pass model for the science groups.
  - The brighter-fatter model still needs work. Direct comparison with bench lab data will happen soon.
  - Other effects will come later.
- Eventually we will study the impact on the WL shear analysis from these instrumental systematics.

Backup

Calibrated PhoSim sources in electrons.

A magnitude 20 star with these settings
Results in 366545 electrons (no saturation)

We can calculate the magnitude for a given electron level:

m1 = 2.5 log_10(num_e/366545) - 20

Which gives

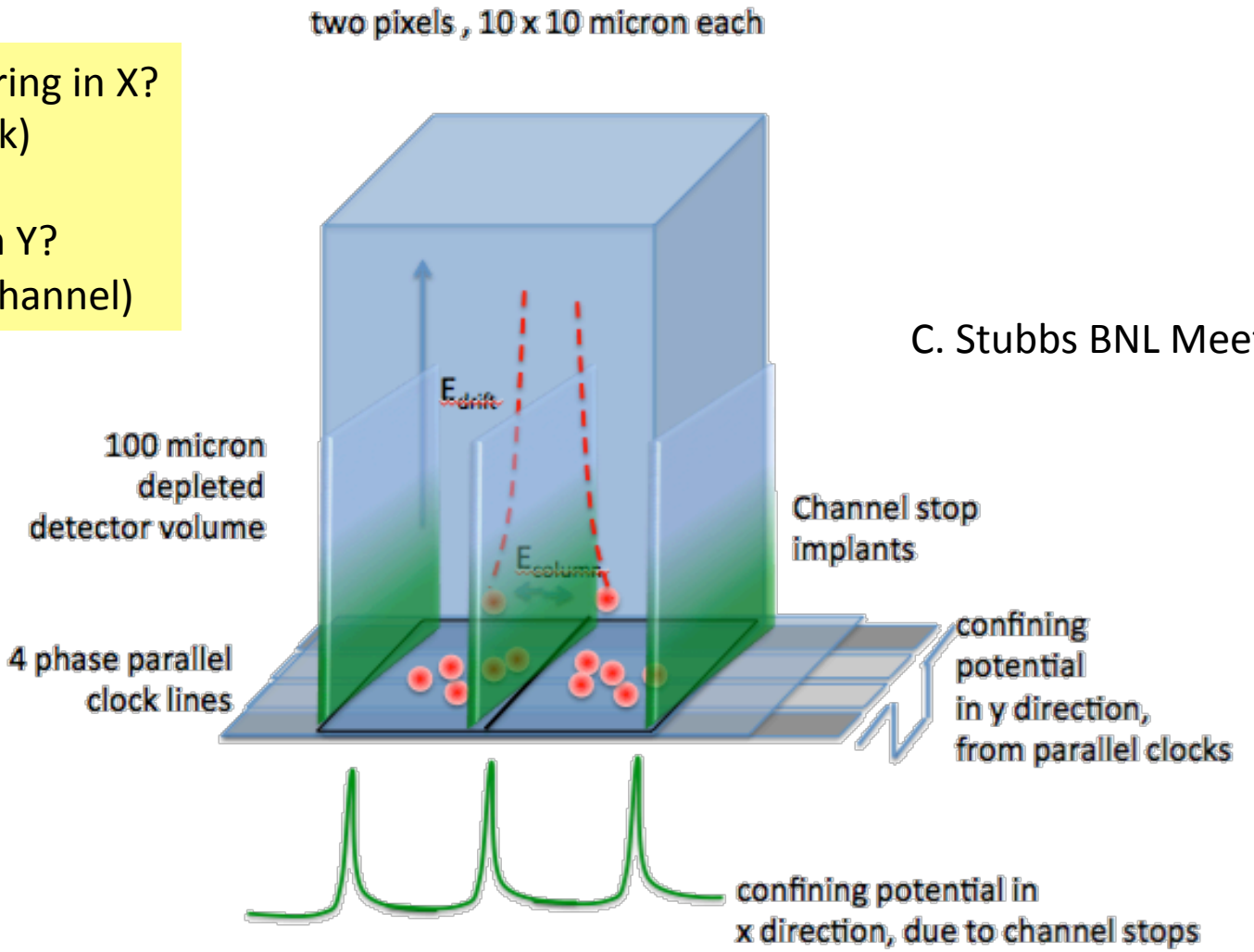
# electrons	Magnitude
1000	26.410
2000	25.658
3000	25.218
4000	24.905
5000	24.663
10000	23.910
…	
100000	21.410

Expected charge movement

Charge sharing in X?
(Drift in bulk)

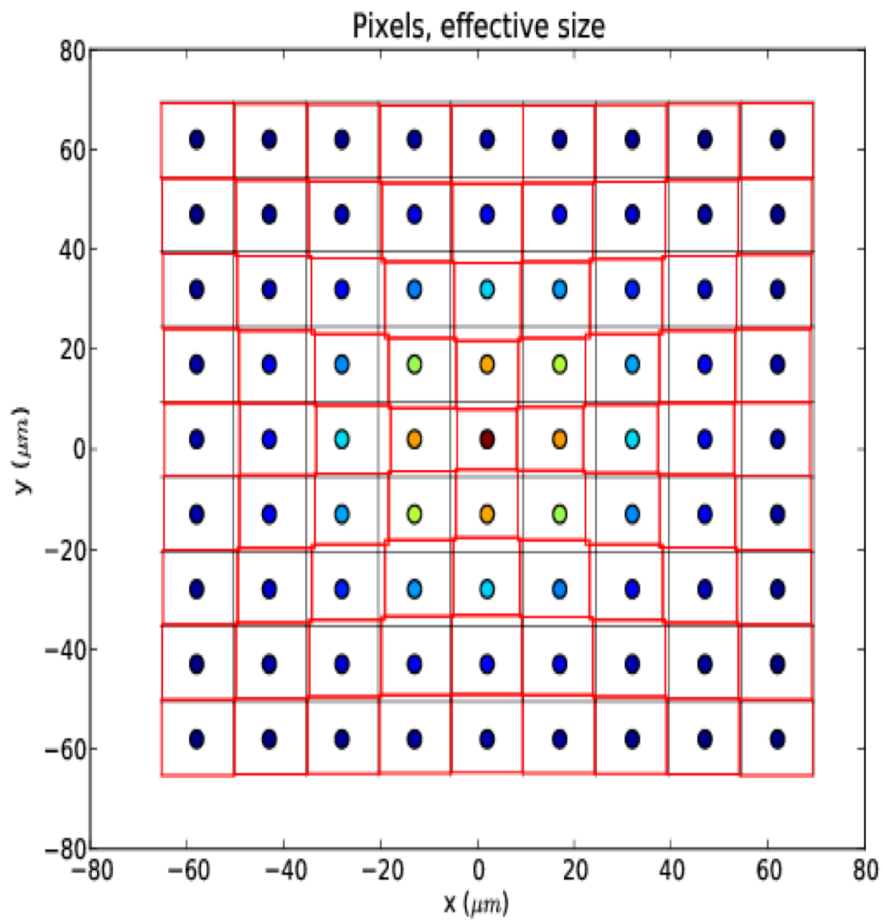
Spill-over in Y?
(in buried channel)

C. Stubbs BNL Meeting



Astier et all model

- In this model we view the distortion of edges as an effective change of pixels size as the collecting area is modified by the field for each pixel.



From Astier et al talk from PACCD 2013.

Default source puts spot at (0,0)

```
Astrophysical m=23          1          29,991   (   0, 11,   9, 80)        0.11
```

Offsets in radians

```
object 0 0.0 0.0 23.072 ../sky/sed_flat.txt 0 0 0 0 4.848e-7 4.848e-7 star none none
object 0 0.0 0.0 23.072 ../sky/sed_flat.txt 0 0 0 0 2.424e-6 4.848e-7 star none none
object 0 0.0 0.0 23.072 ../sky/sed_flat.txt 0 0 0 0 4.363e-6 4.848e-7 star none none
```

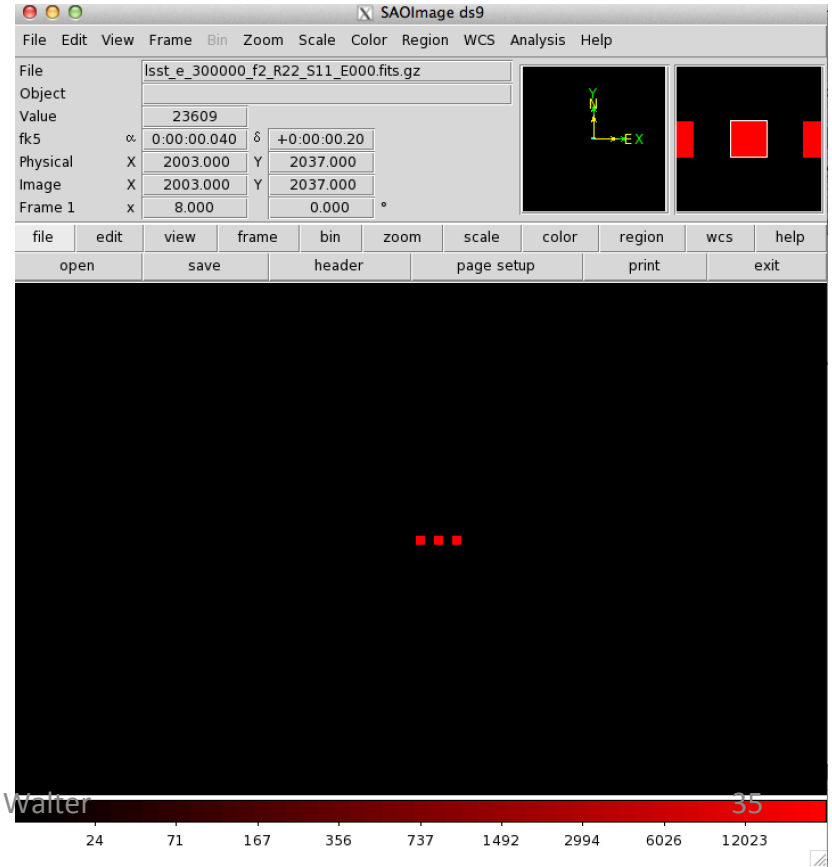
Pixels 0.2” on a side. 0,0 at corner of pixels

Make spots at:

(0.1”, 0.1”),

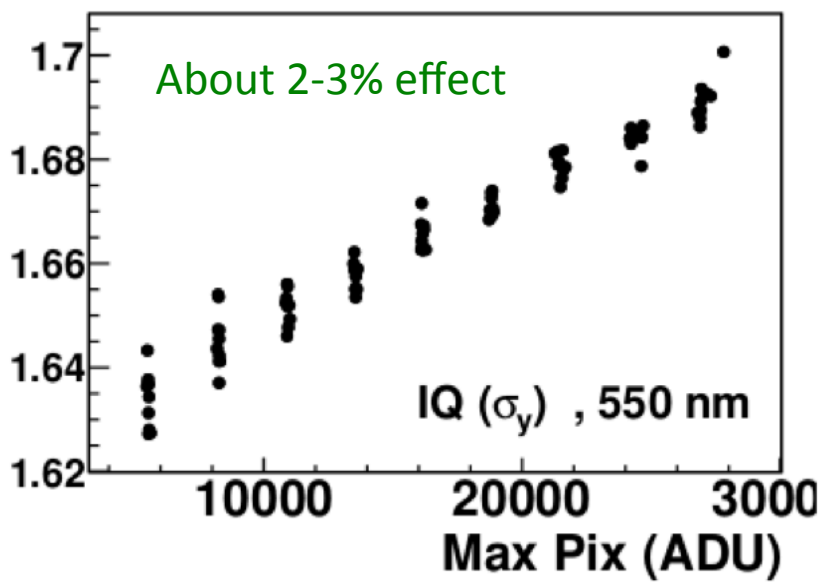
(0.5”, 0.1”),

(0.9”,0.1”)



Can control the position of the spots (good!)
→ I will use this to place a spots at 9 postions inside of a pixel

Now: want to measure the sigma as a function of electrons



Remember: Variance of a square is 1/12 = .083
stdDev = sqrt(1/12) = 0.29

I wrote a short DM program to analyze the output.

The SDSS Shape algorithm failed on a reference 1 pixel "Peak".

So I calculated both a RMS and the SDSS shape outputs.

I want to match this output so made a spot with sigma of ~1.6.

Note: Let's still be careful

CCD riddle: a) signal vs time: linear; b) signal vs variance: non-linear

Mark Downing[a], Dietrich Baade[a], Peter Sinclaire[b], Sebastian Deiries[a], Fabrice Christen [c].

[a]European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching Munich, Germany;
[b]ESO La Silla Observatory, Casilla 19001 Santiago 19, Chile;
[c]Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands.

A possible simple explanation of this interaction (charge sharing or spreading) between neighboring pixels is that the charge collected in the potential well of the pixel somehow migrates (diffuse) to their neighbors. The likelihood of this migration occurring is increased by the mutual electrostatic repulsion force of electrons. The more charge in a potential well, the greater the repulsion force and the greater chance of migration. This process could be assisted by thermal diffusion (*kT* energy). This explanation is show graphically in the right of Fig. 11. **The evidence does not fully support this explanation as the number of migrated electrons should increase with time and be dependent on temperature. This has not been observed (refer to Fig. 6 and Fig. 9 and accompanying text)**. In addition, the thermal energy (*kT*) is about 0.015 eV at -120 °C and the probability of surmounting a potential barrier even as low as 1 volt would be extremely low
at ~ $e{-}V\,kT = e{-}66$.