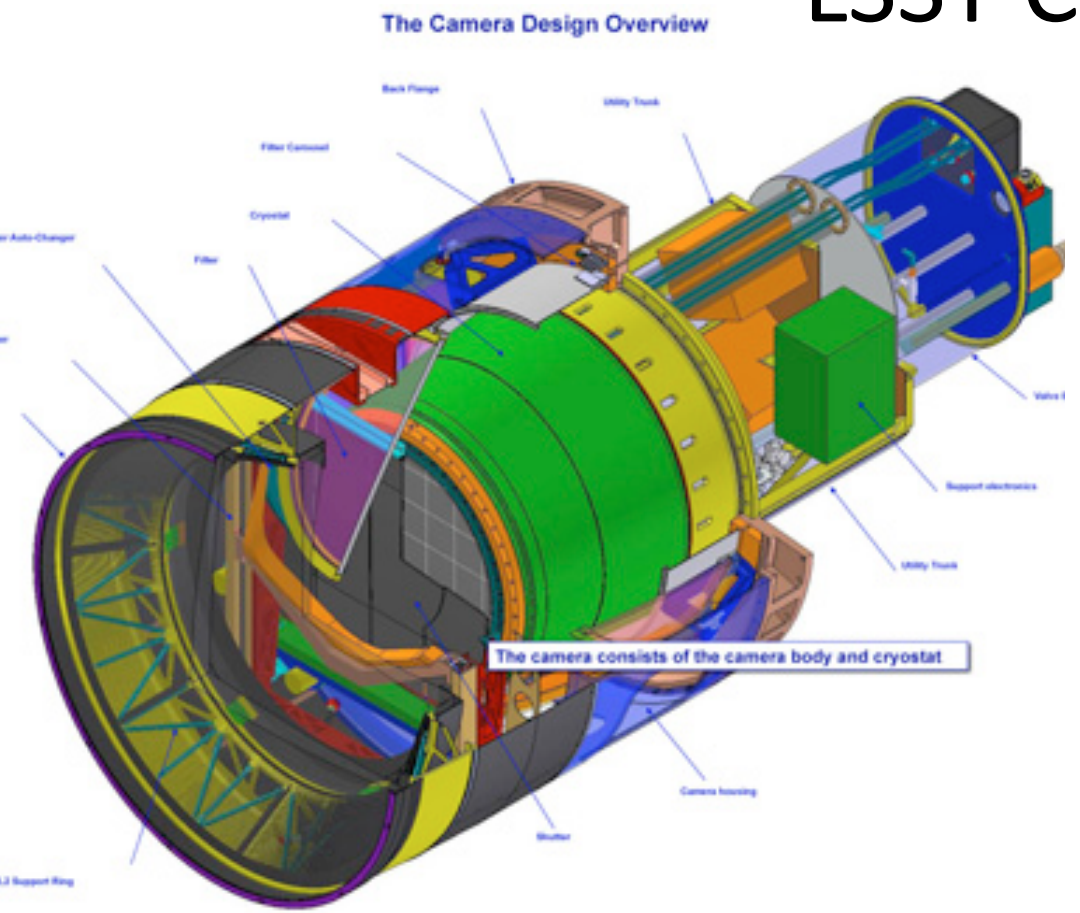
LSST Sensors

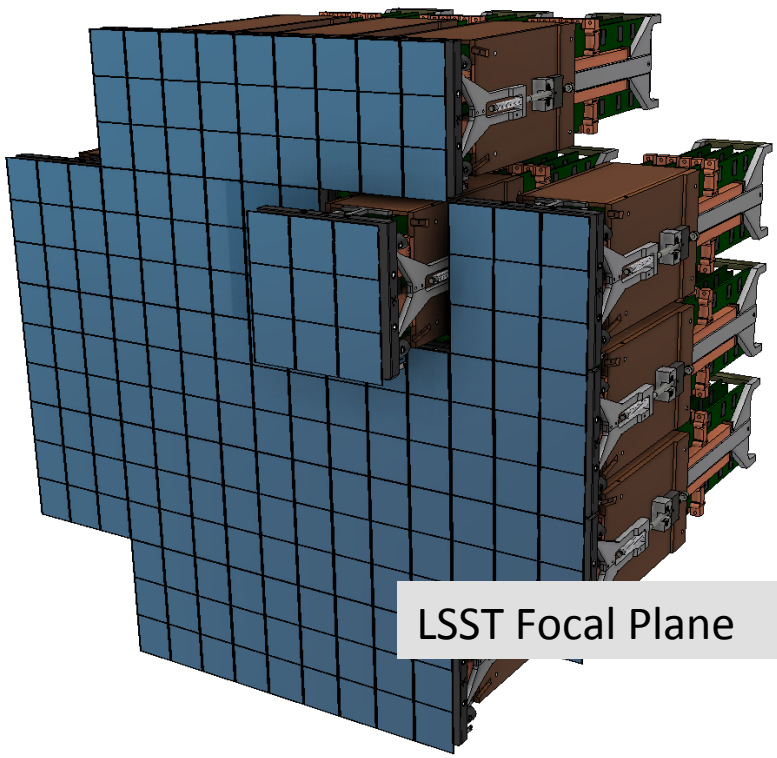
Andrei Nomerotski, BNL

PACCD2014

BNL, 4 December 2014

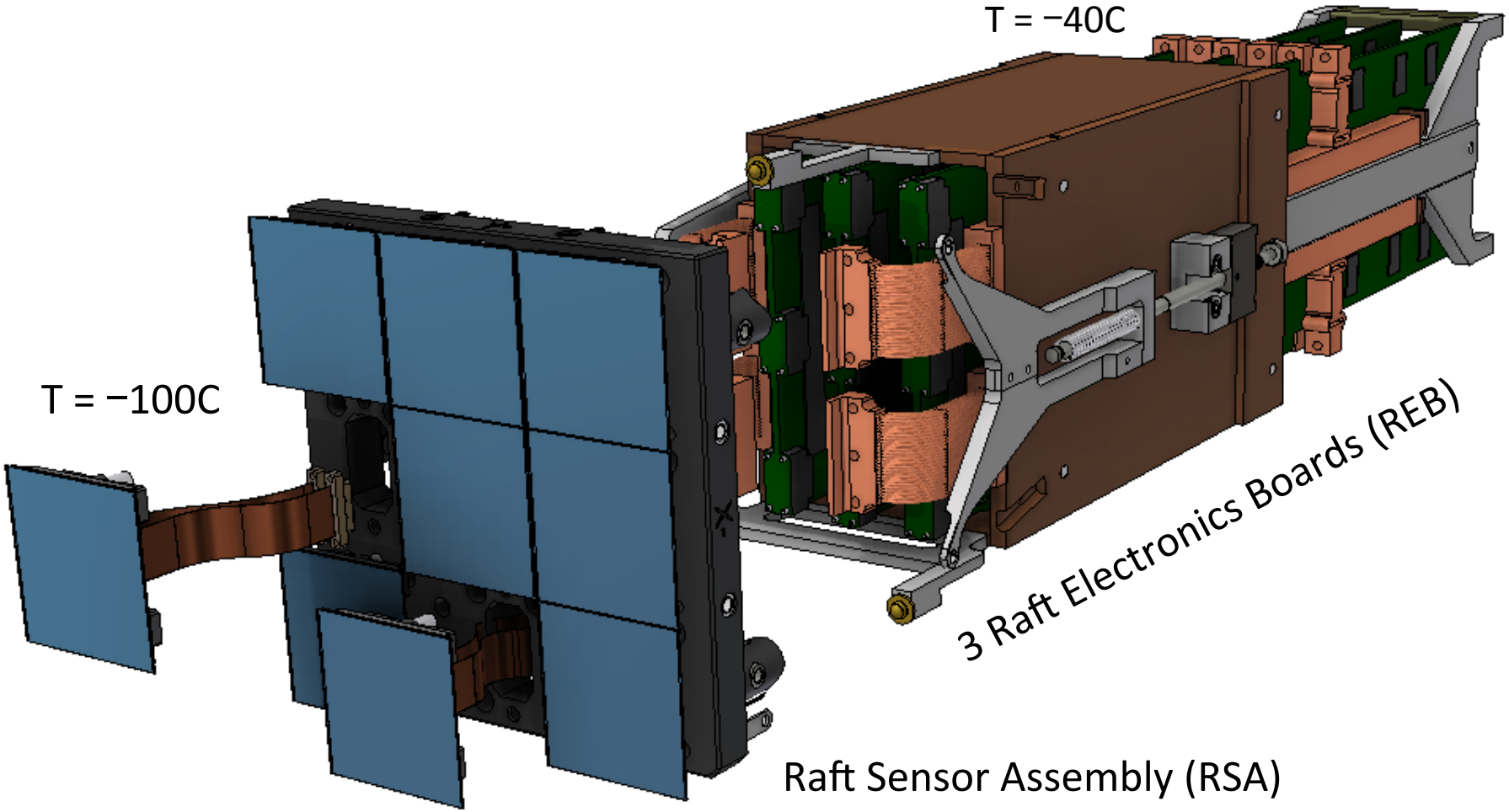
LSST Camera





- 64cm diameter → 3.5°
- 189 4K × 4K CCDs → 3.1 Gigapixels
- 21 “rafts” with integrated electronics for nine CCDs in shadow of sensor focal plane
- At -100 deg C

Raft Tower Module

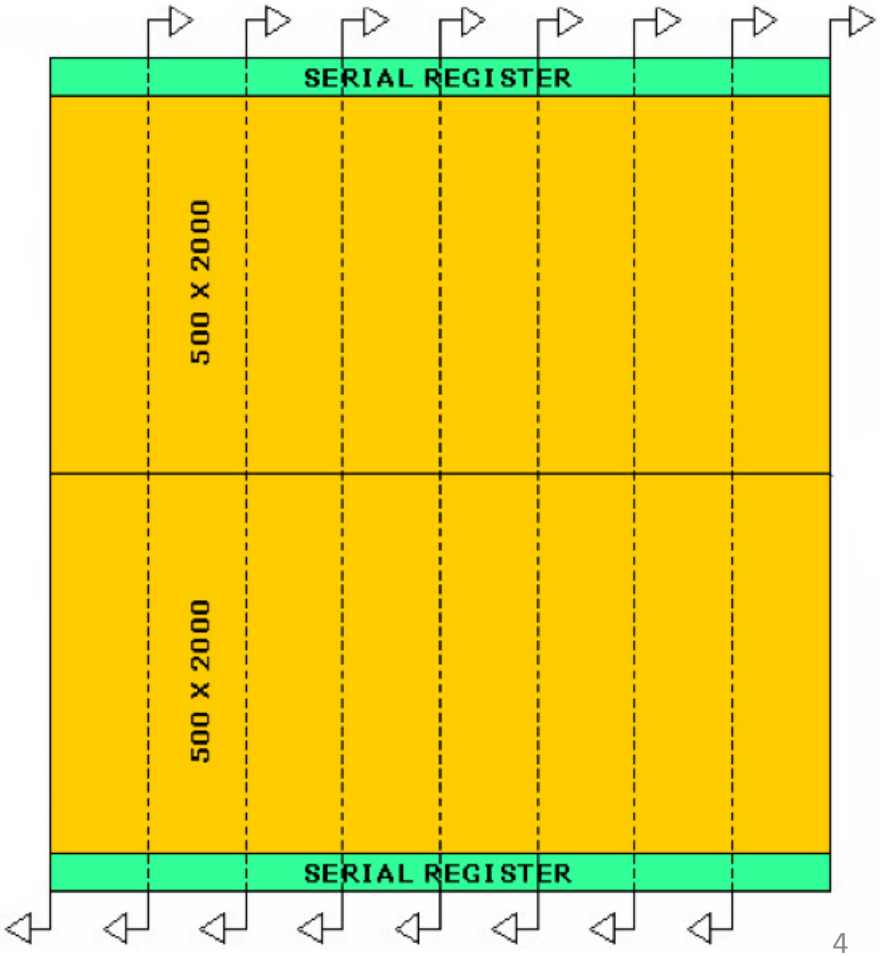


Science Raft Comprises 9 CCDs

See poster “SR Design for LSST Camera” S.Bellavia, P.Takacs

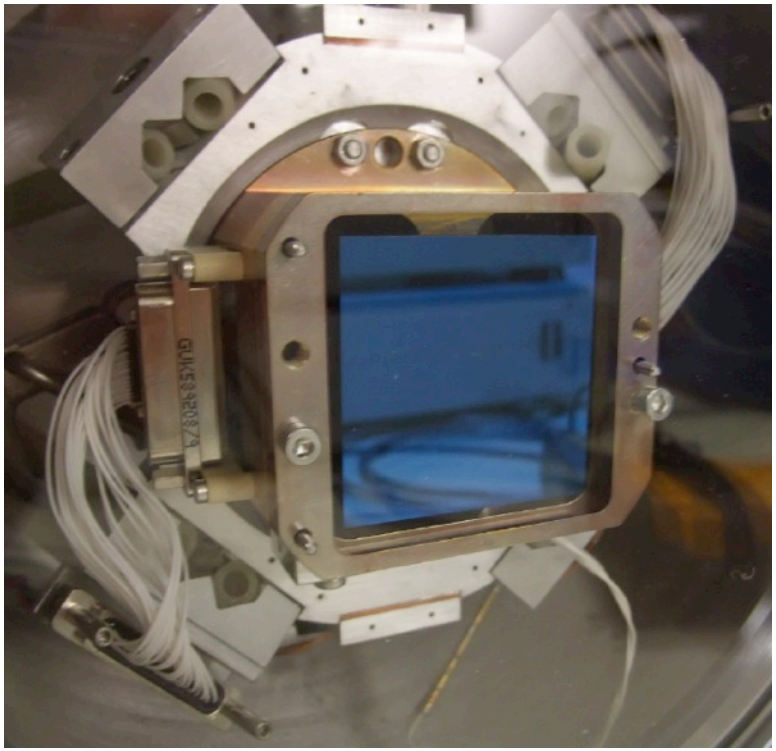
LSST CCD Sensor

- 2 second readout time spec → 16 amplifiers per 16 Mpix CCD
- Noise spec 8 e-, based on anticipated sky noise; limits pixel rate
- Pixel read rate is 550 Kpix/s
- 4k x 4k = 16 Mpixels
- 10x10 microns pixel
- Si thickness 100 micron →
  Enhanced infrared response
- Anti-reflective coating



LSST Prototype CCDs

CCD250



STA3800

Status of LSST Sensors

Science sensors

- Good prototypes from e2v and ITL, passed all reviews
- First articles ordered, expected delivery in spring 2015

Production in 2016 - 2019

- Sensor acceptance testing and raft assembly in BNL and LPNHE (Paris)
- Raft integration in the camera cryostat at SLAC

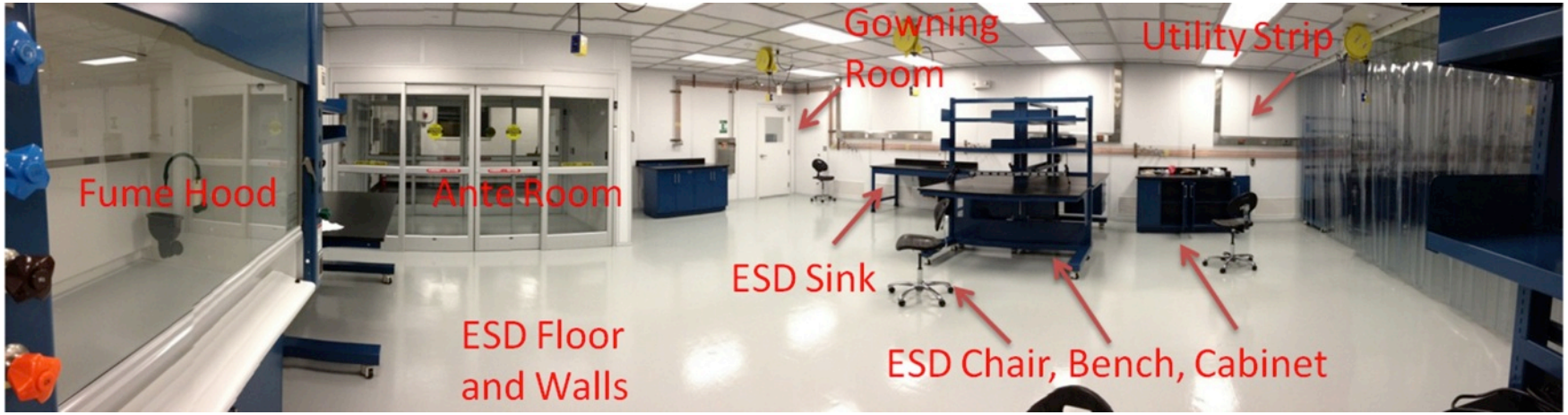
Testing labs: careful characterization of sensors (beyond acceptance testing)

- BNL (includes raft characterization)
- Harvard
- LPNHE Paris
- UC Davis

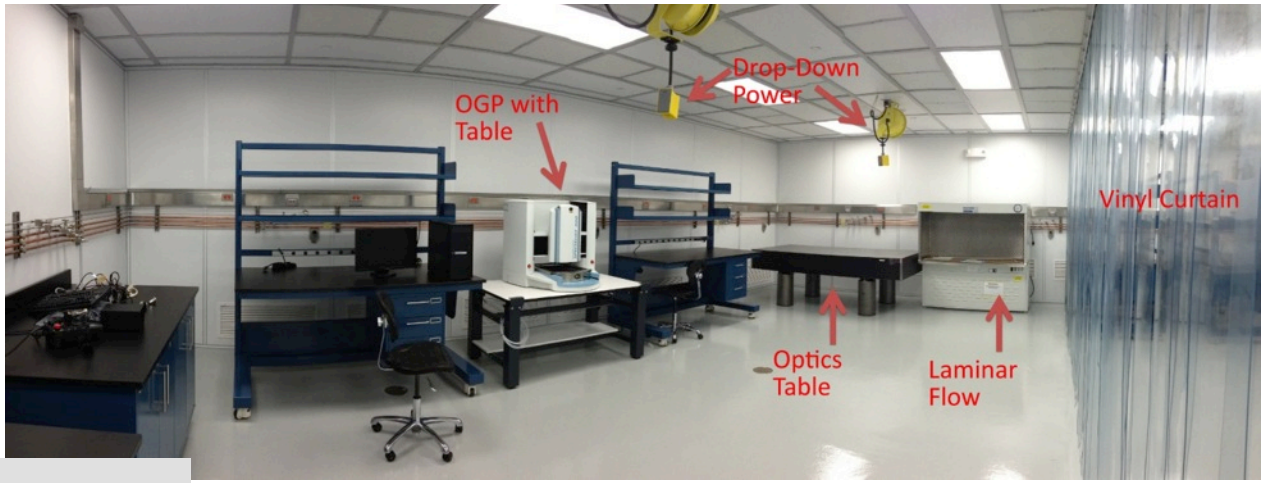
LSST BNL Production Facility Cleanroom

Teststands for acceptance testing, all ready by March 2015

- Automated data taking
- DM analysis software
- eTraveler



Large Clean Area (ISO 7; Class 10,000)

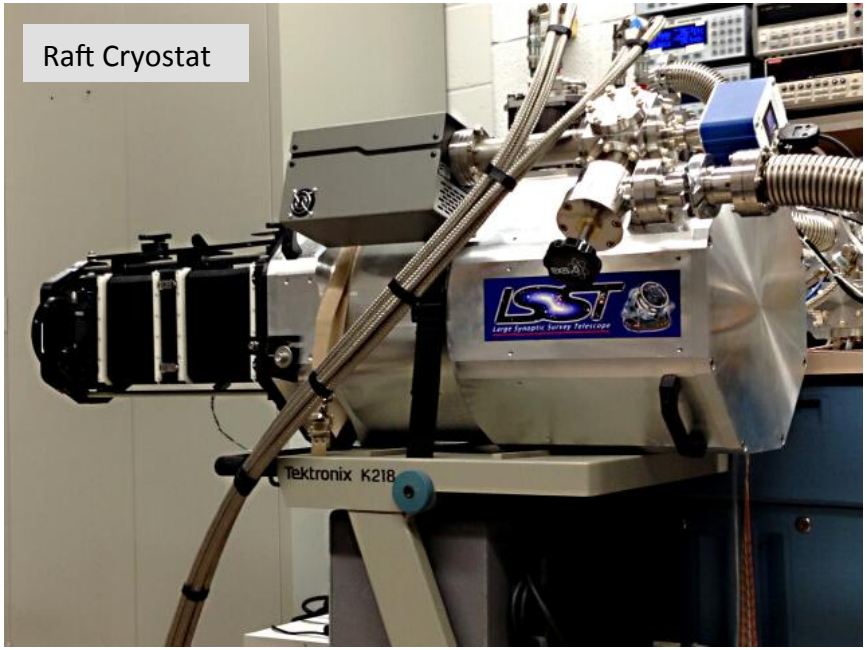


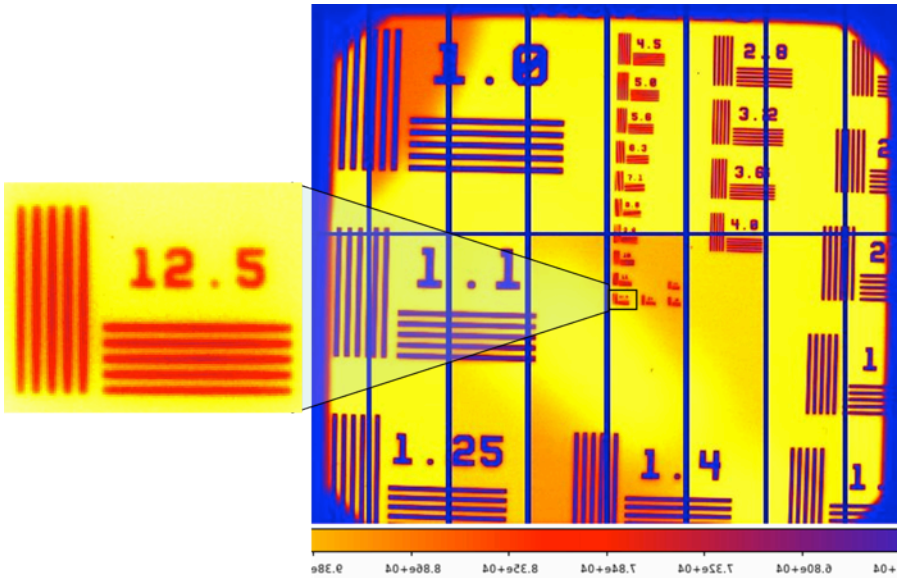
Small Clean Area (ISO 6; Class 1,000)

P.Takacs, M.Rumore

Integration of Sensors and Electronics

- Raft test cryostat in operation in BNL
  - So far a single CCD
- Full signal chain from optical input to DAQ
- Separate thermal zones for CCDs and custom electronics
- 9-CCD, 144 Mpix camera – planned as LSST Commissioning Camera





Single-CCD image from Raft Test Cryostat

O'Connor et al

Good results for noise and cross talk with latest custom electronics

Poster "LSST raft electronics" J. Kuczewski
Talk "Crosstalk in LSST sensors and electronics" P.O'Connor

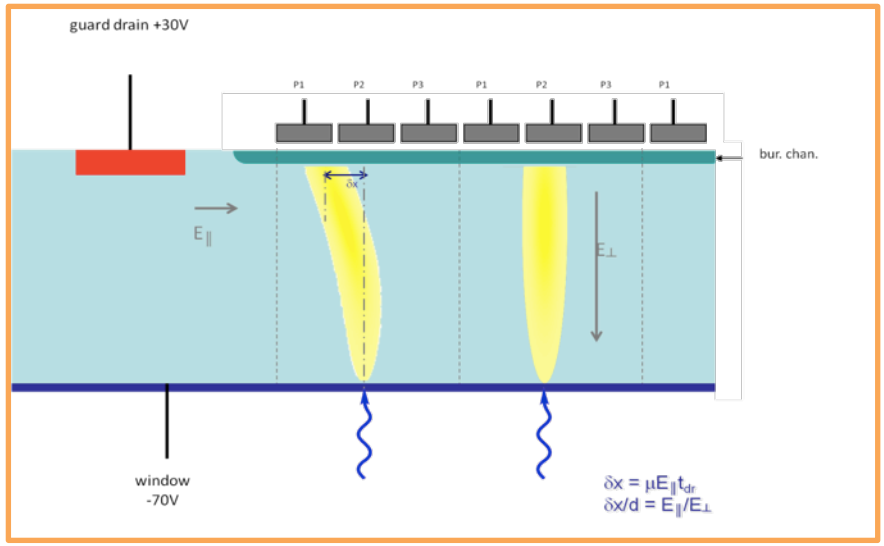
On to more subtle things

What's the problem with thick CCDs?

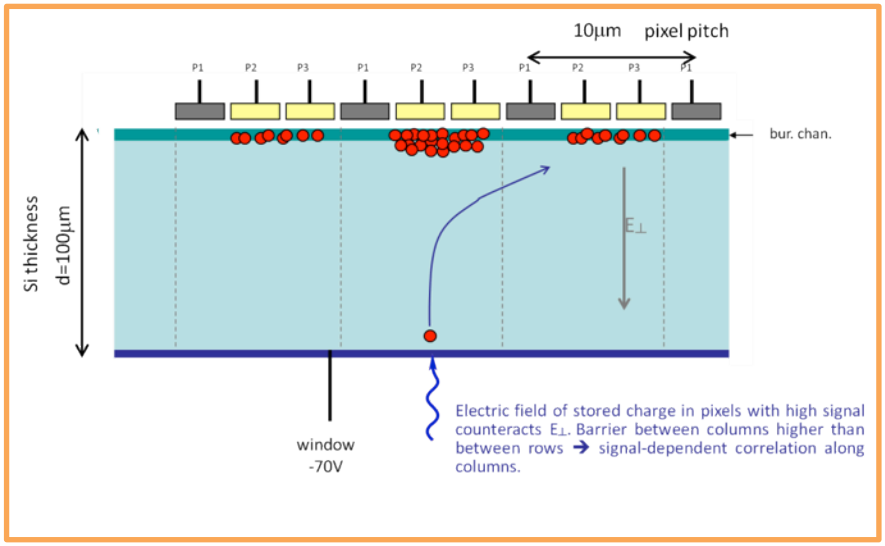
Fully depleted CCD have a non-trivial electrostatics which lead to astrometric biases and PSF distortions

– Difficult to disentangle from photometric effects

Static : edge effects, tree-rings



"Dynamic" : brighter-fatter effect



From the last workshop summary Jim Gunn:

Encouraging that we have learned so much from astronomical data.

But surely better to learn under controlled conditions in the lab BEFORE the detector go to telescope.

In the following will discuss:

- Recent studies of astrometric biases using:
  - X-ray flat fielding
  - Spots

- Based on recent BNL data (O'Connor, Kotov)

Using X-ray flats for CCD characterization

- Fe55 X-rays produce compact clouds of ~1600 electrons, < 1 um
- Standard gain calibration technique for CCDs, used also for diffusion measurements

- Hit shape is symmetric but lateral electric fields in CCD can distort it (edges, tree rings etc)
- Uniform irradiation, not sensitive to the surface

  30 micron conversion depth

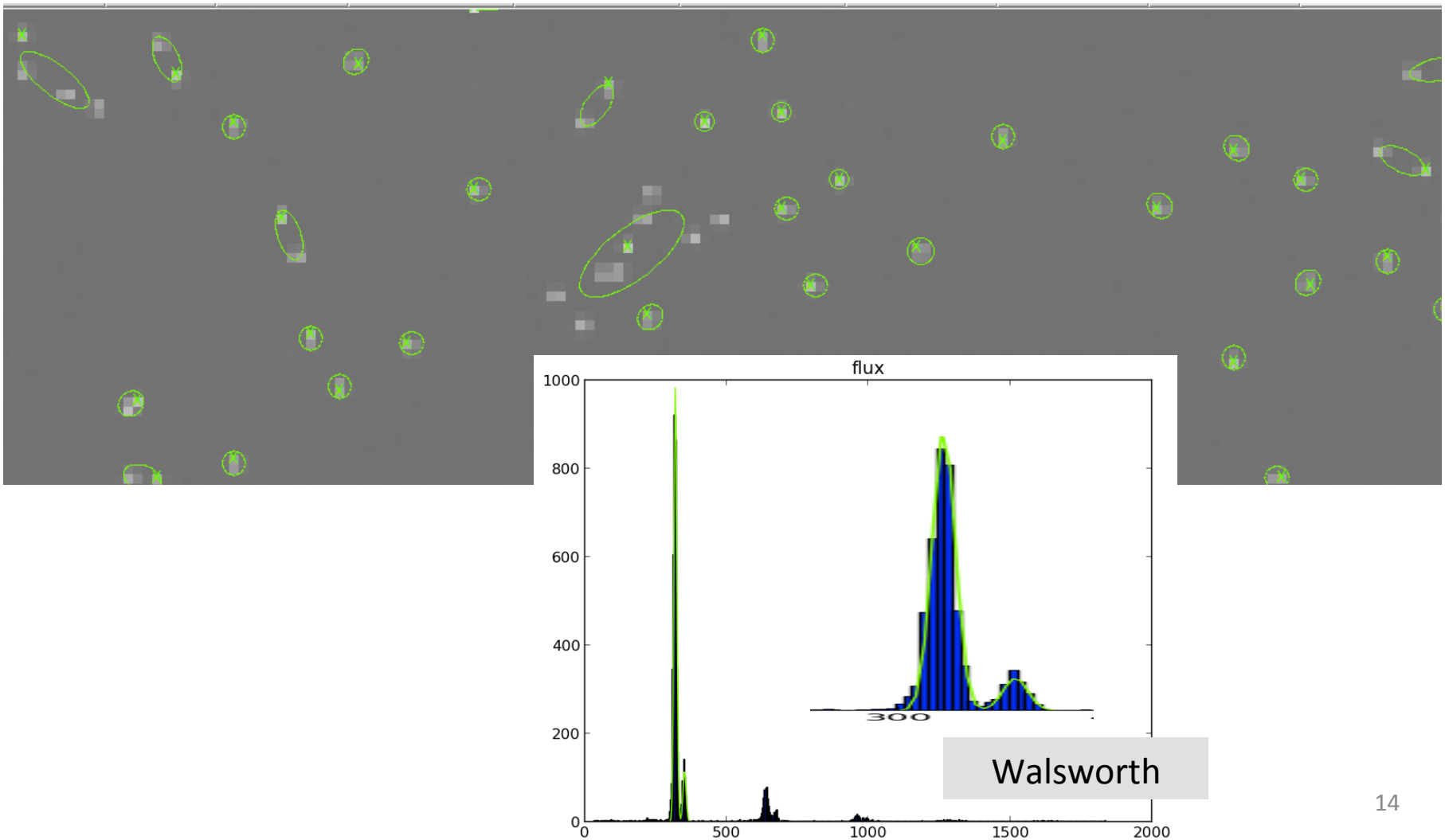
  → can extract astrometry and decouple it from photometry

Easy to have good statistics, it's not too difficult to probe every pixel

→X-ray flat fielding

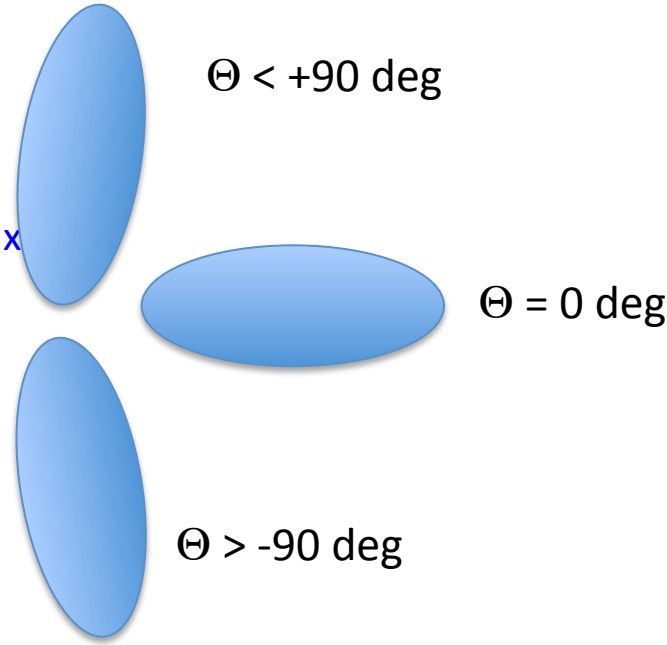
^{55}Fe x-rays

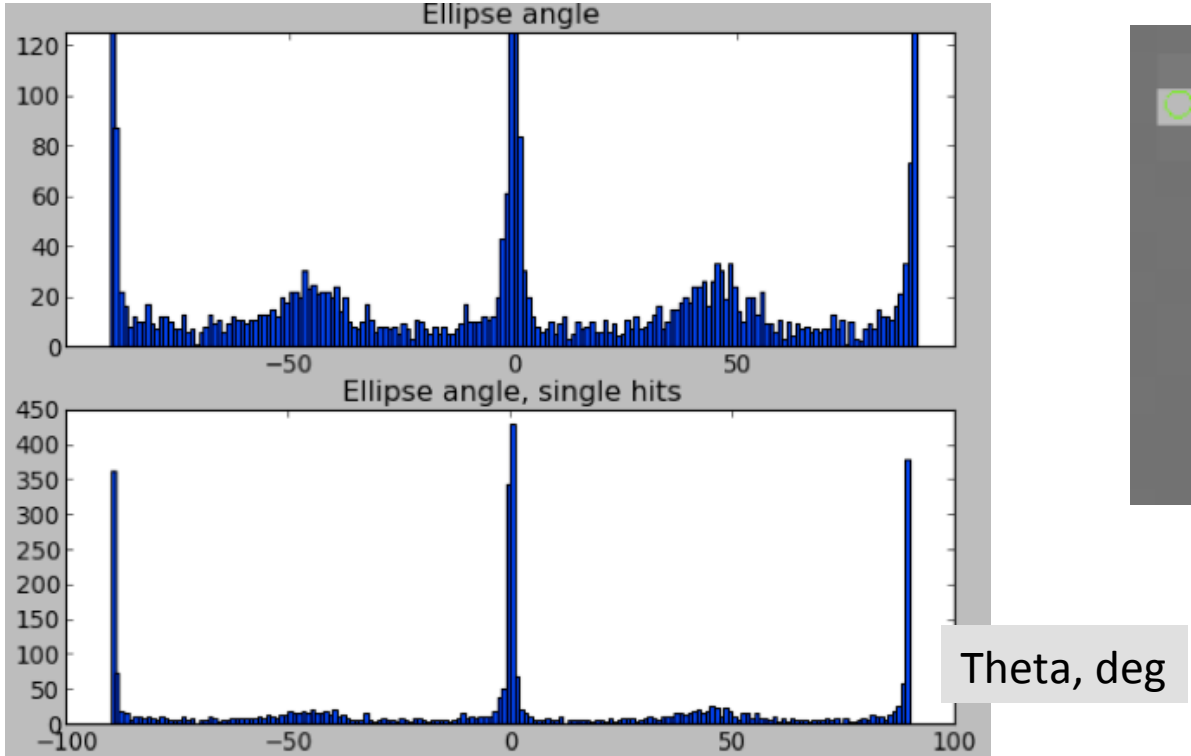
Ellipse fits of DM footprints in ^{55}Fe data (5.9 keV x-rays)



Shape of Fe55 Cluster

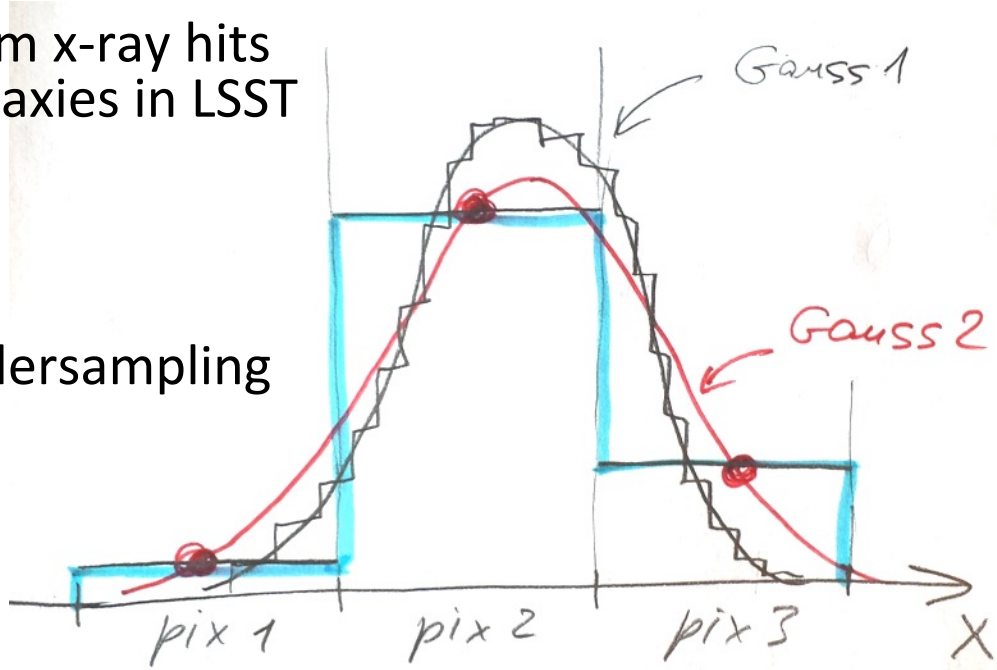
- Fe55 hit is expected to be symmetric → random orientation of spurious ellipticity → flat angle distribution
  - Fit 2-D gaussian with 6 parameters: x, y, g1, g2, sigma and flux
- Problem: undersampled PSF
  - Pixel : 10x10 micron
  - Diffusion of electron cloud : sigma ~3-4 micron
- Ellipse orientation is quantized: -90, 0, +90 deg if use vanilla DM stack





Undersampling Problem

- Problem: fit function is evaluated in the center of the bin
- This causes biases in fitting of slim x-ray hits (but fitting of fatter stars and galaxies in LSST is ok)



See example:

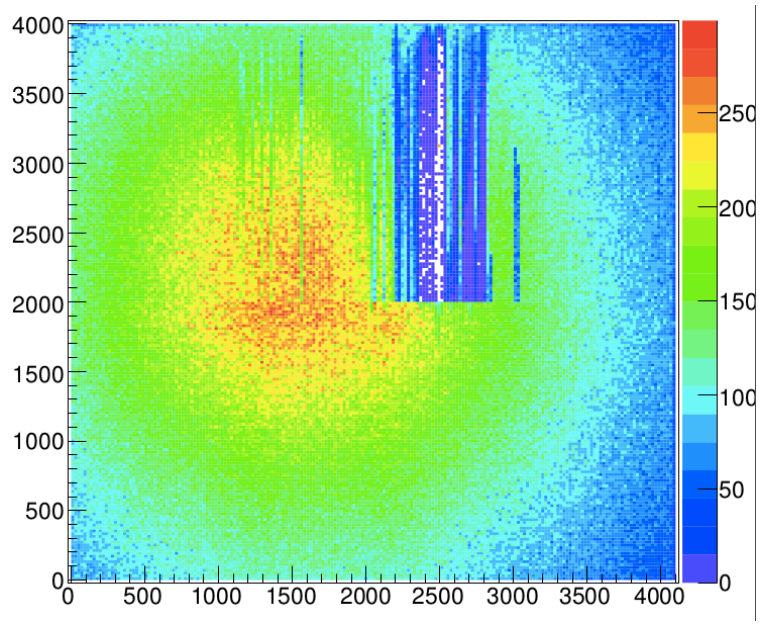
- Gauss 2 is biased because of undersampling
- Gauss 1 is ok

- The correct way to do it is to integrate the function over the bin
- Fine sub-binning of pixels improves the situation without need to integrate properly
  - Used 16x16 sub-bins in one pixel

X-ray Hit Map

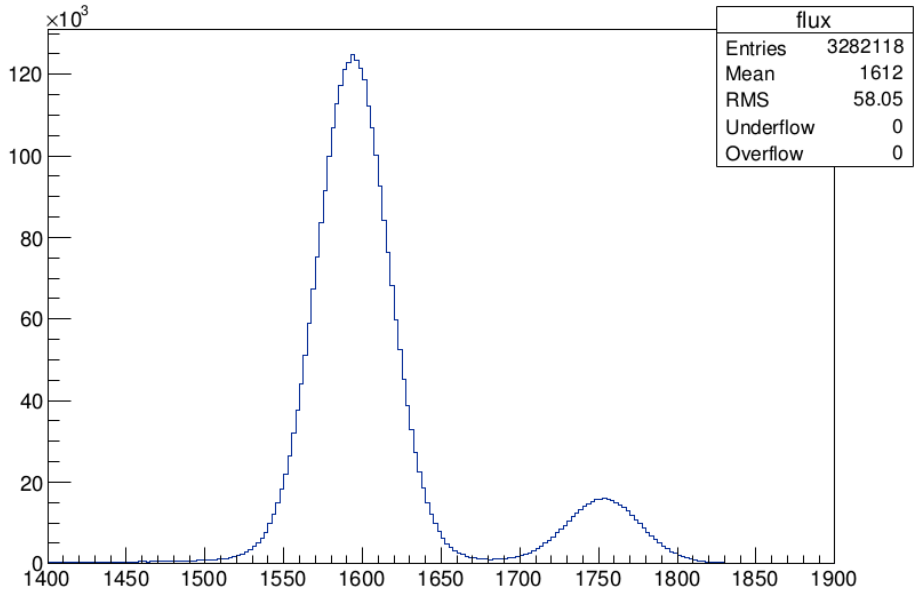
- LSST DM stack does x-ray finding and background subtraction
- Require two adjacent pixels above 5 sigma threshold, “grow” = 2

- 10 M reconstructed footprints for 16M pixels
- 7 M used for analysis (removed fit failures and blended hits, select good fit errors)
- Occupancy (x,y) map for sensor #112-04:

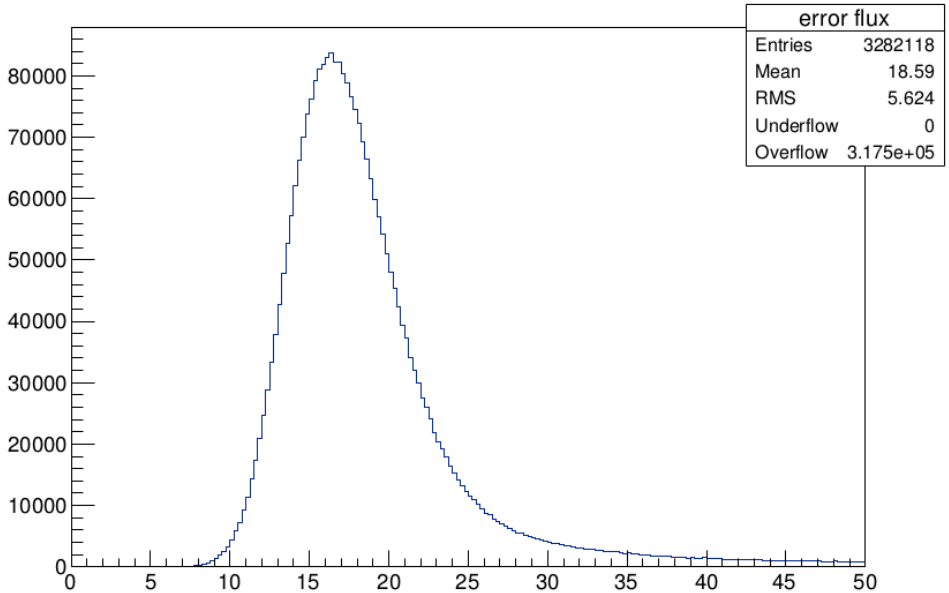


Flux

- 2D Gaussian (flux, centroid, sigma, shear) was fitted using Max Likelihood fitter
- Gain corrected, include all 16 amplifiers
- Resolution 3.4%
  - fit error 1.2%



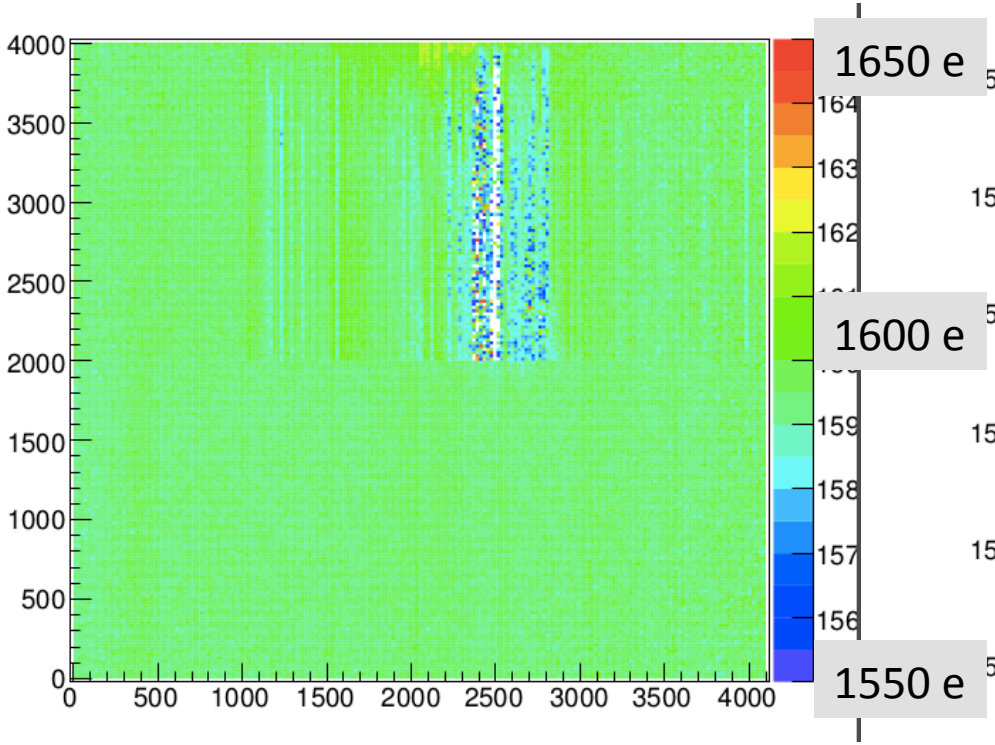
Flux, electrons



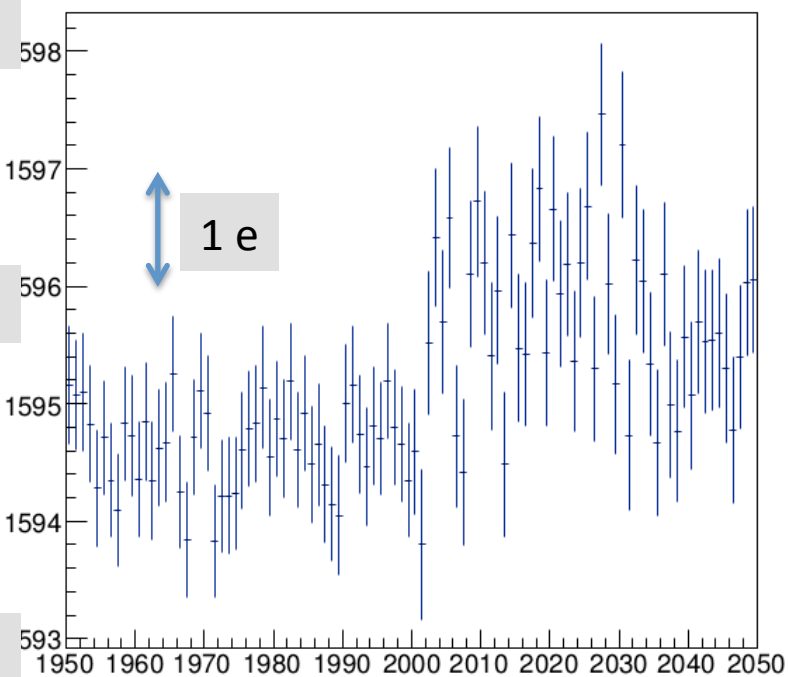
Flux fit error, electrons

Gain calibration

- Excellent calibration
  - 0.1% difference between sections



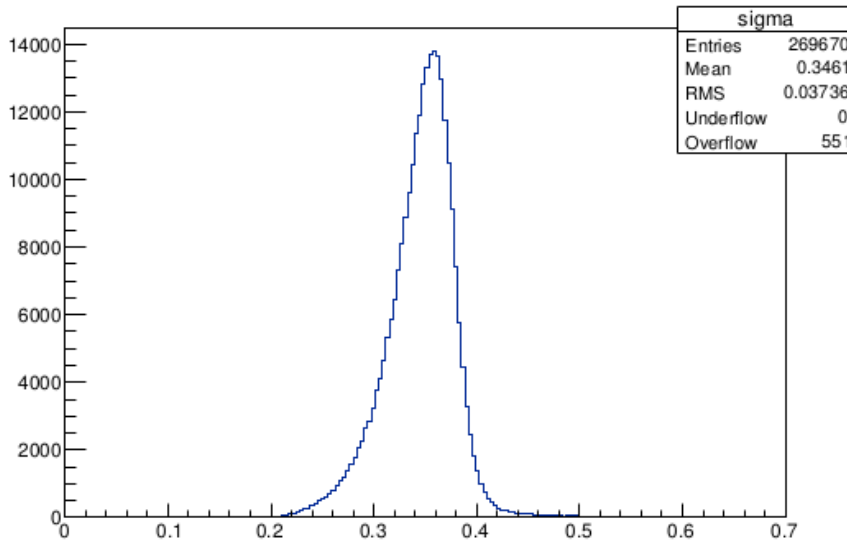
Flux (x,y) map, electrons



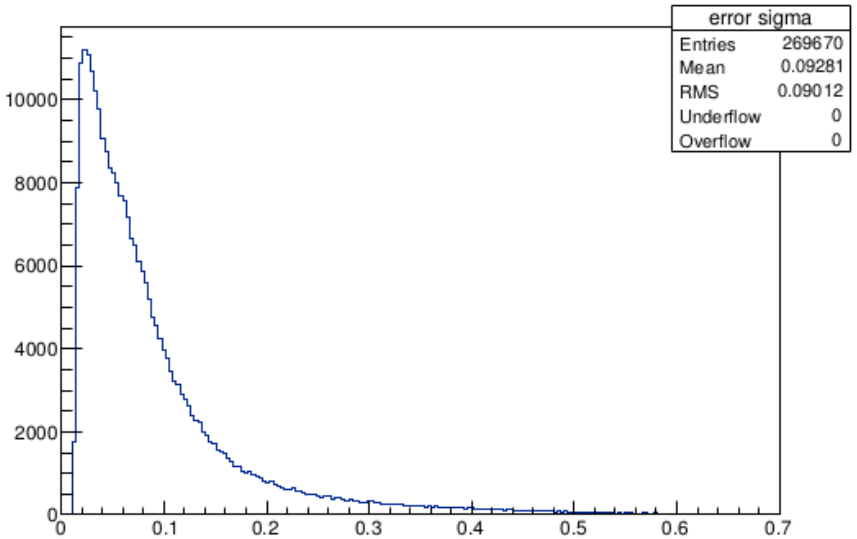
Border between two sections

PSF Size

- Distribution is skewed due to varying conversion depth
  - Average conversion depth ~30 micron
- This has been used before for Si diffusion measurement (Kotov et al)



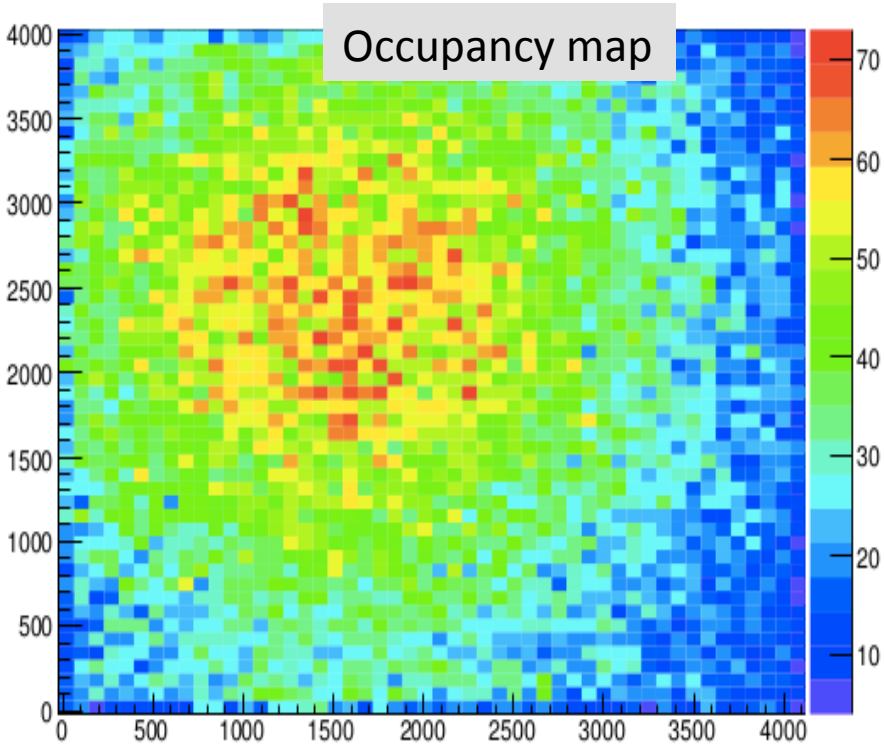
sigma, pix

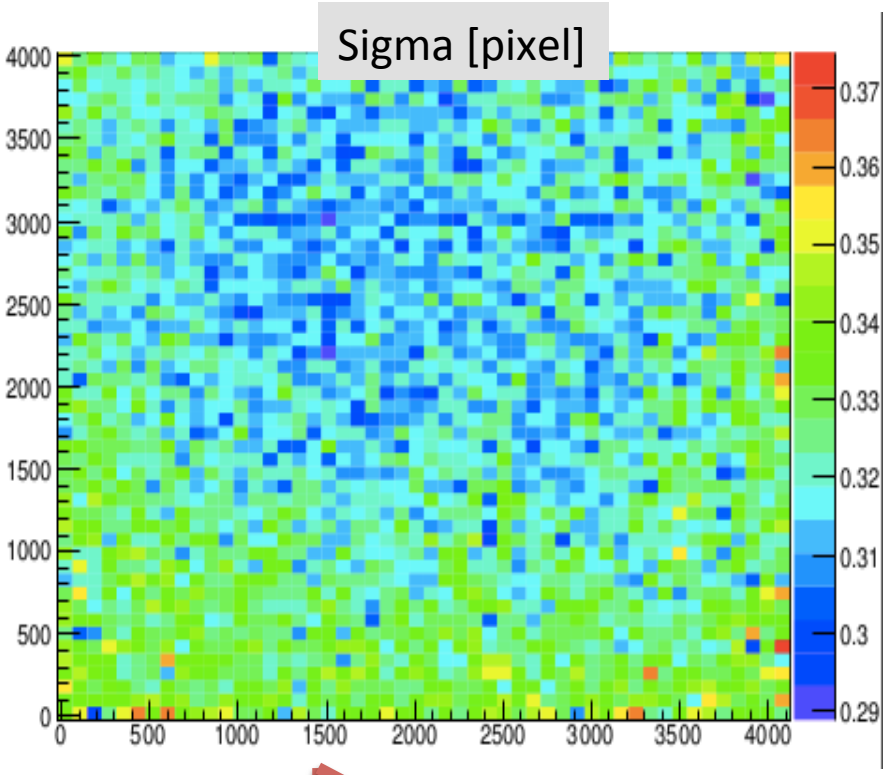


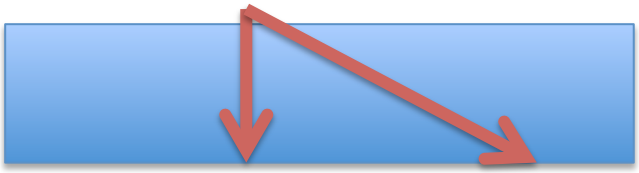
Sigma error, pix

Sigma (x,y) Map

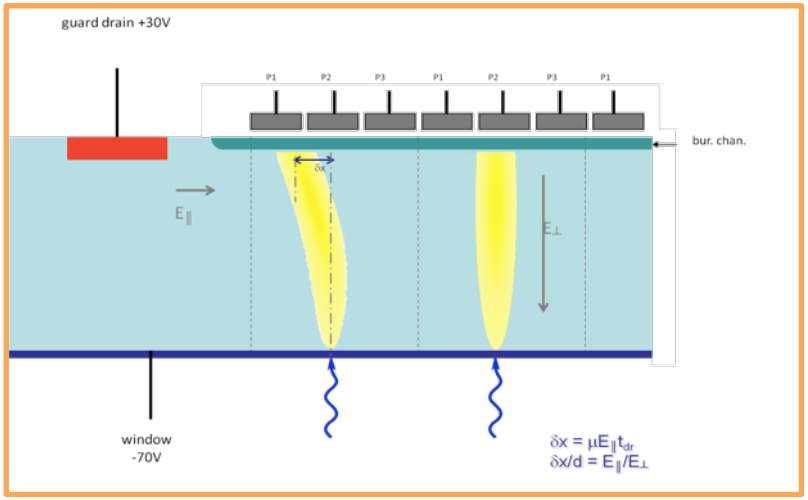
Center has smaller sigma since average depth of conversion is deeper there, hence less diffusion



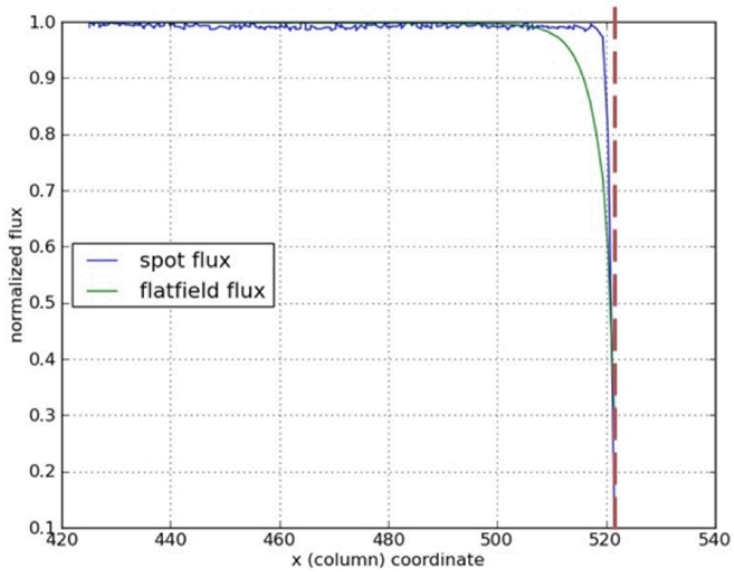


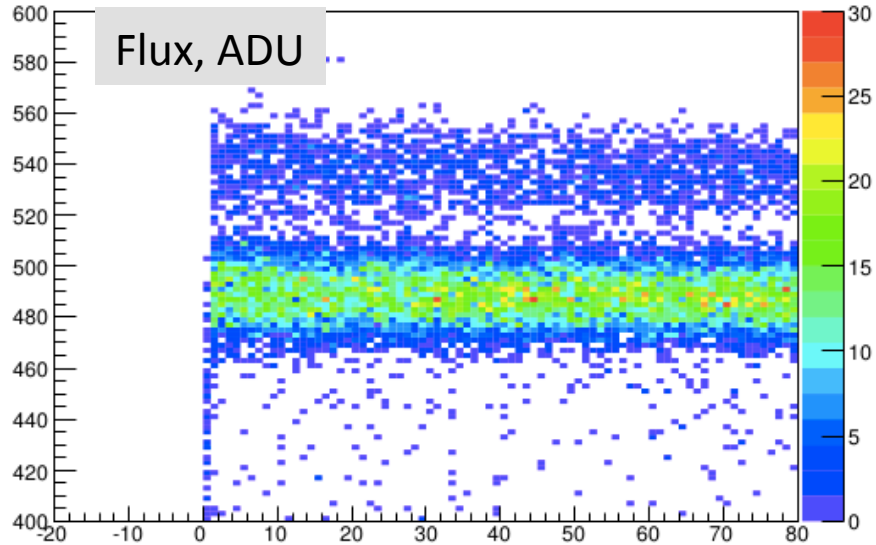


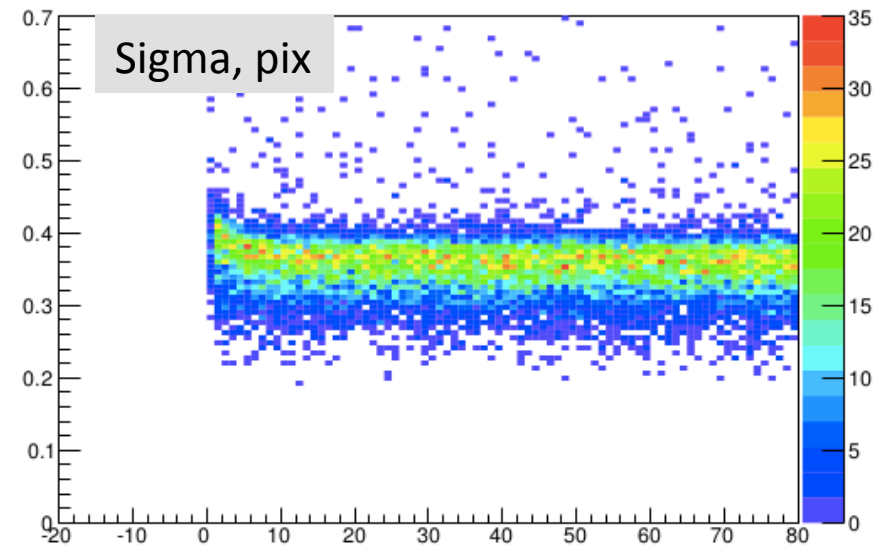
Flux and PSF Size on the Edge



- Flux is constant & sigma is increasing near the edge
- Consistent with previous results: O'Connor PACCD2013:







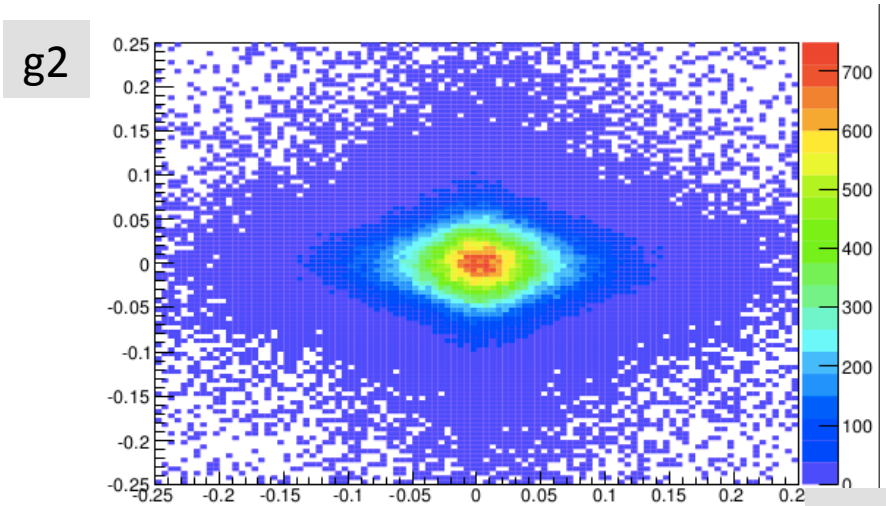
Distance, pix

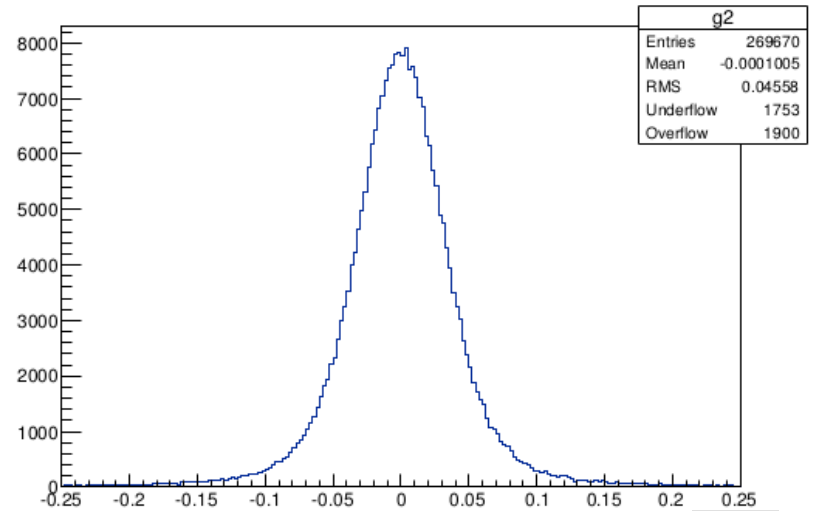
Shear (Ellipticity) of Hits

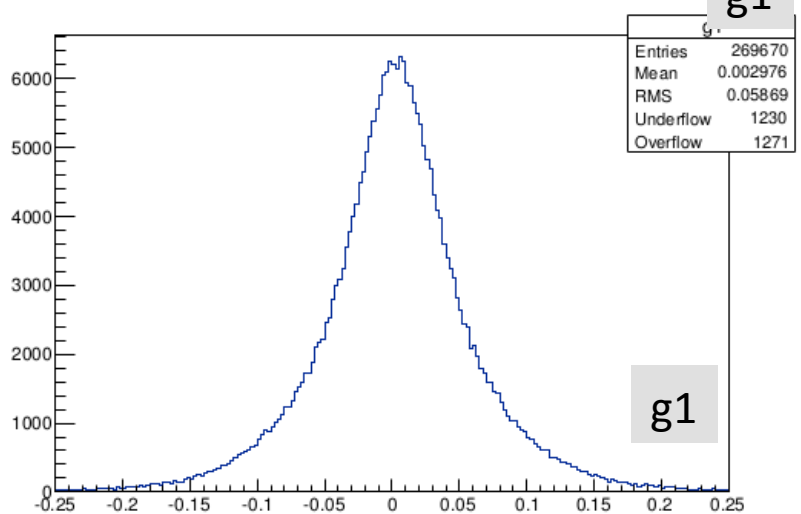
Weak lensing definitions for g1, g2 shear

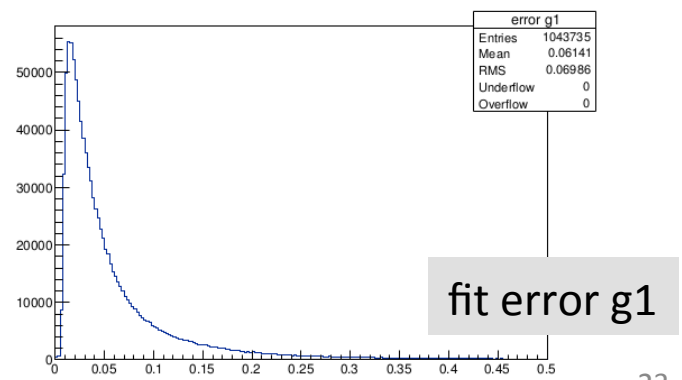
$g1 = (a-b)/(a+b)$

$\tan(2\theta) = g2/g1$

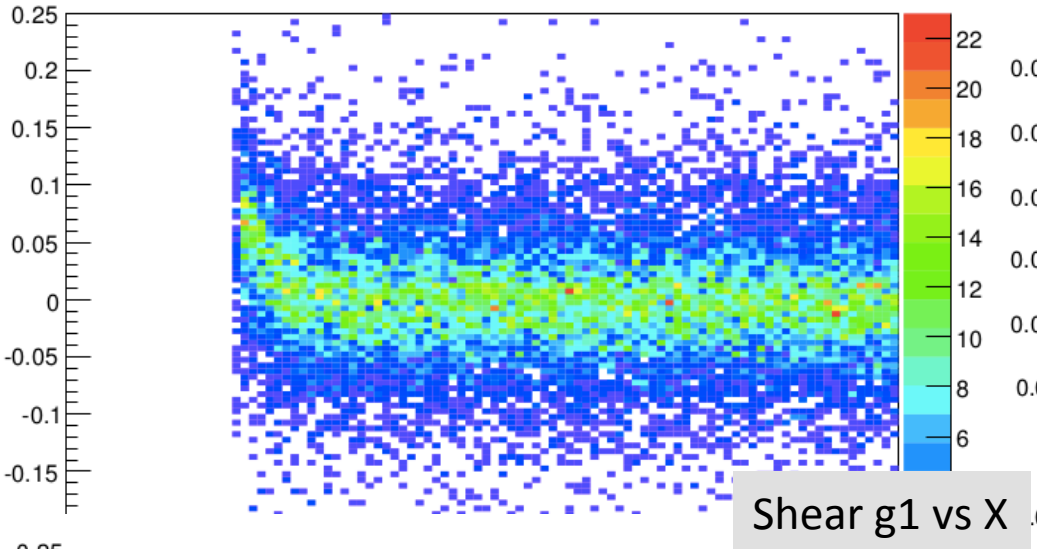


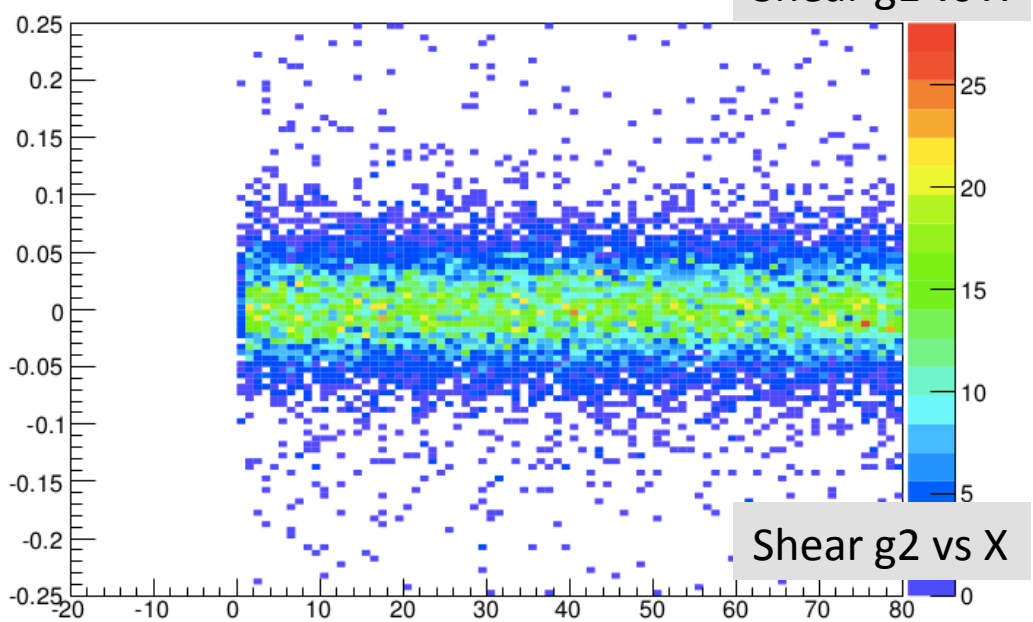


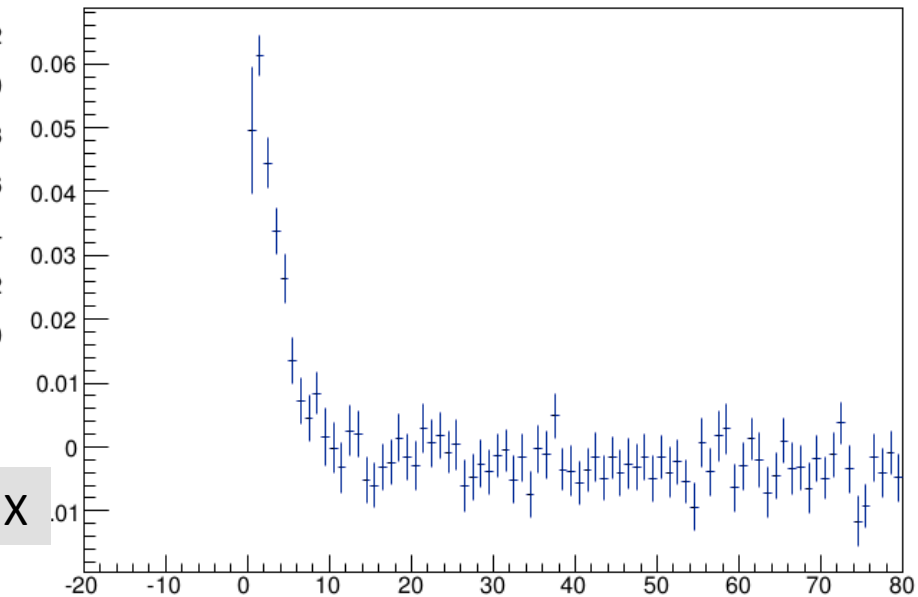




Edge Effect seen in Fe55 flats!



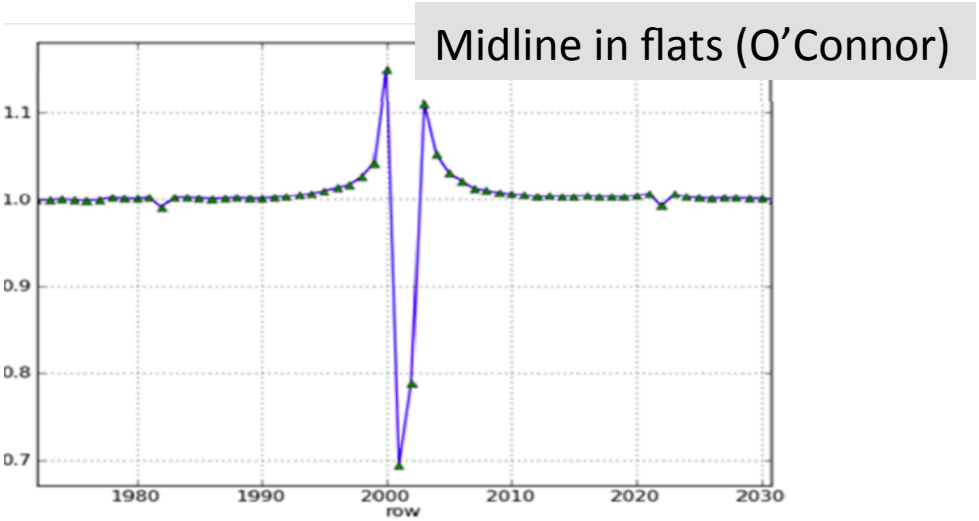


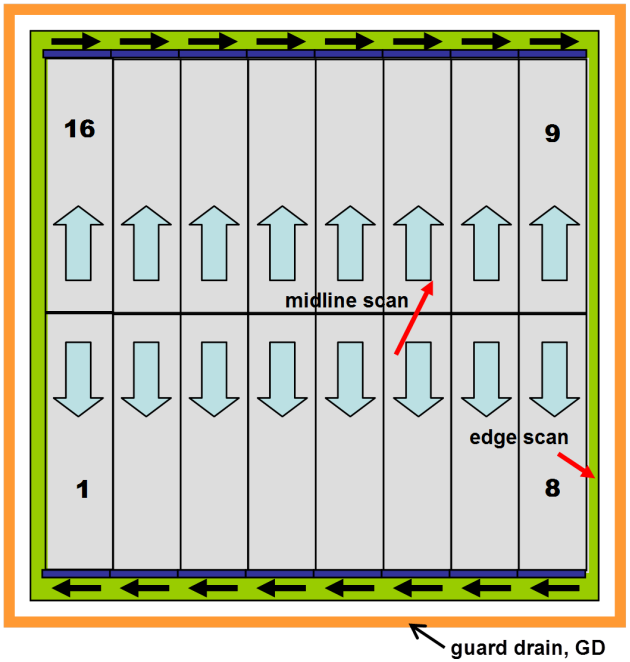


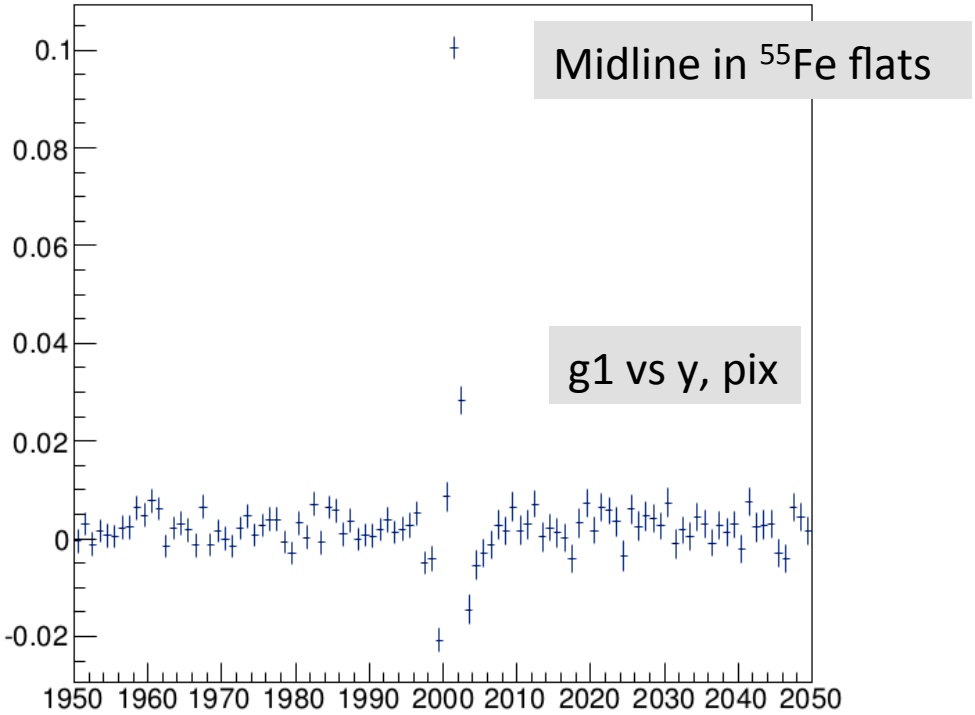
- g1 positive → elongation along x, affects ~ 10 pixels
- g2 does not change → no 45° component

Midline (1)

- Anti-bloom stop implant between top and bottom halves
- Causes rotation of ellipticity when crossed around pixel #2002

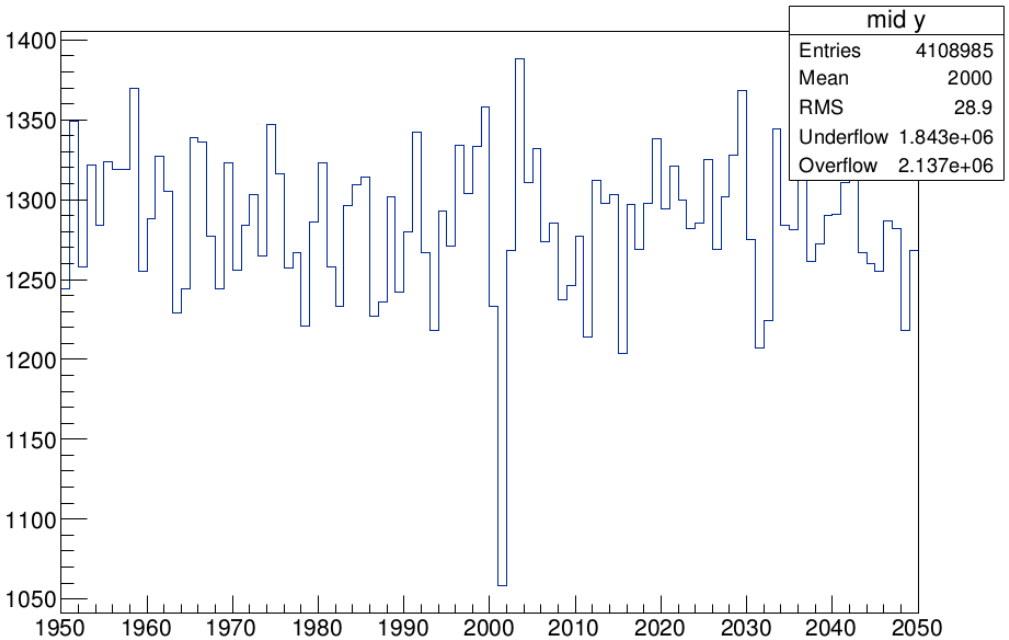


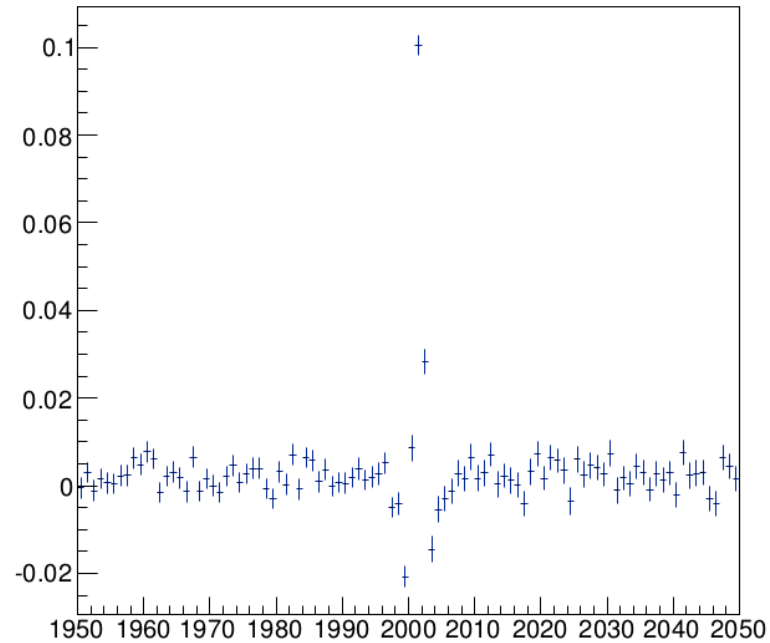


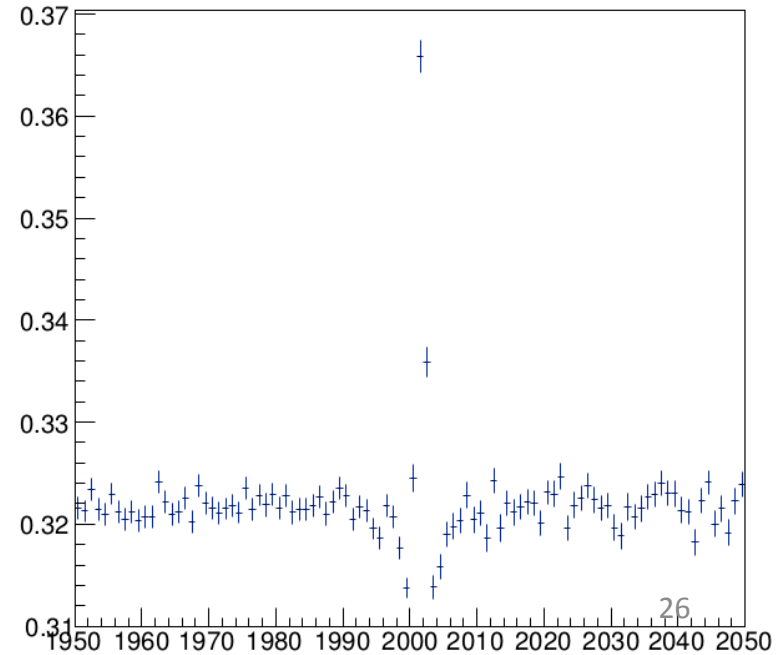


Midline (2)

- Observed in occupancy, sigma and shear

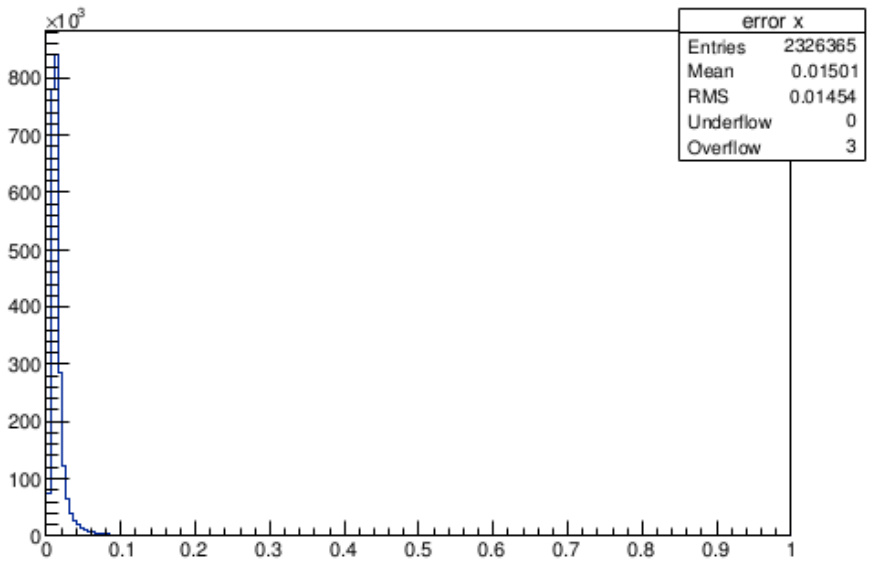






Going inside the pixel

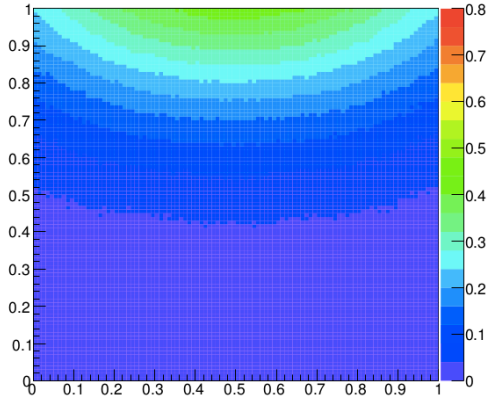
- Good centroid errors, can probe properties as function of coordinates inside the pixel
- Switched to Markov Chain MC Fitter to reduce biases
  - Original method by Metropolis & Hastings
  - Improved method by Goodman & Weare (2010)
  - Code by Sheldon, used in DES shear calculations

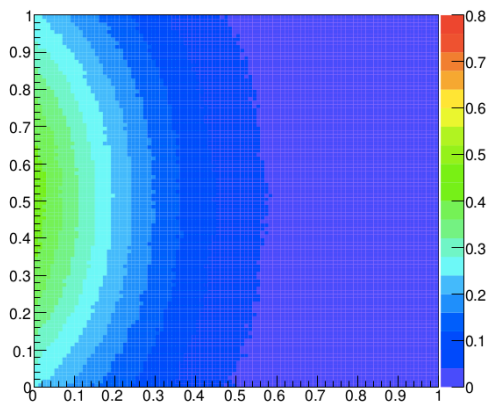


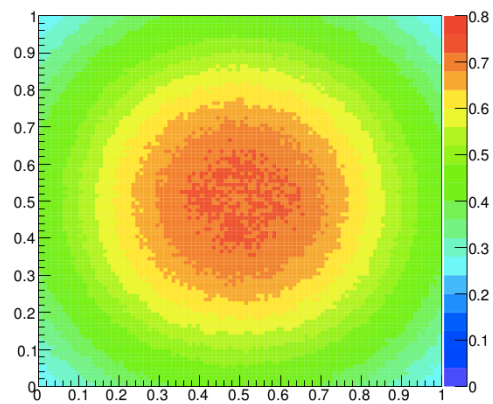
Centroid error [pixel]

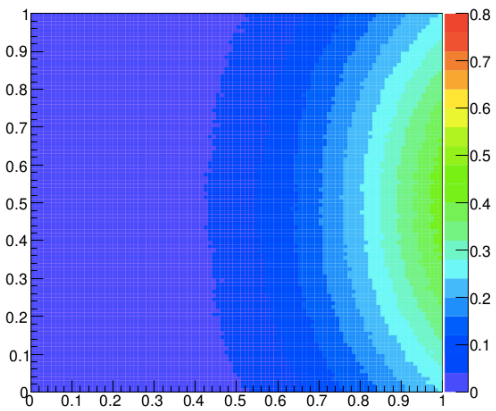
Fractional flux

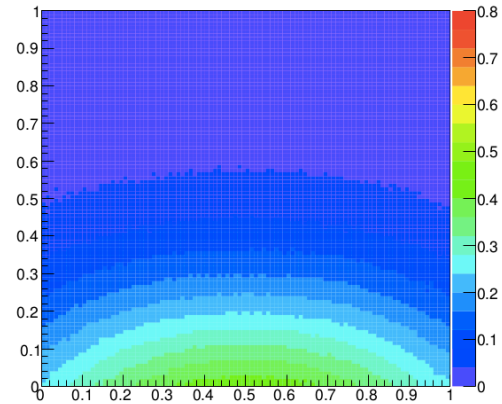
- Versus (x,y) in central pixel
- Central pixel and its four neighbors
- Done for half sensor so don't average two directions for columns









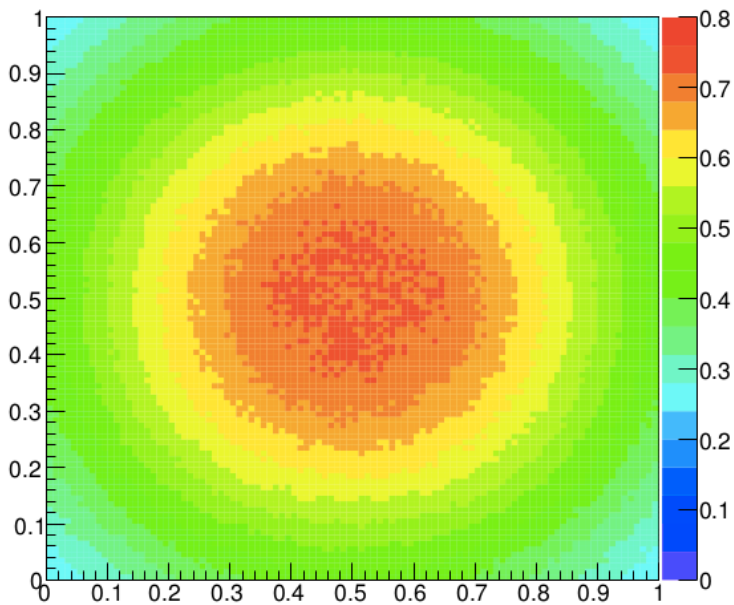


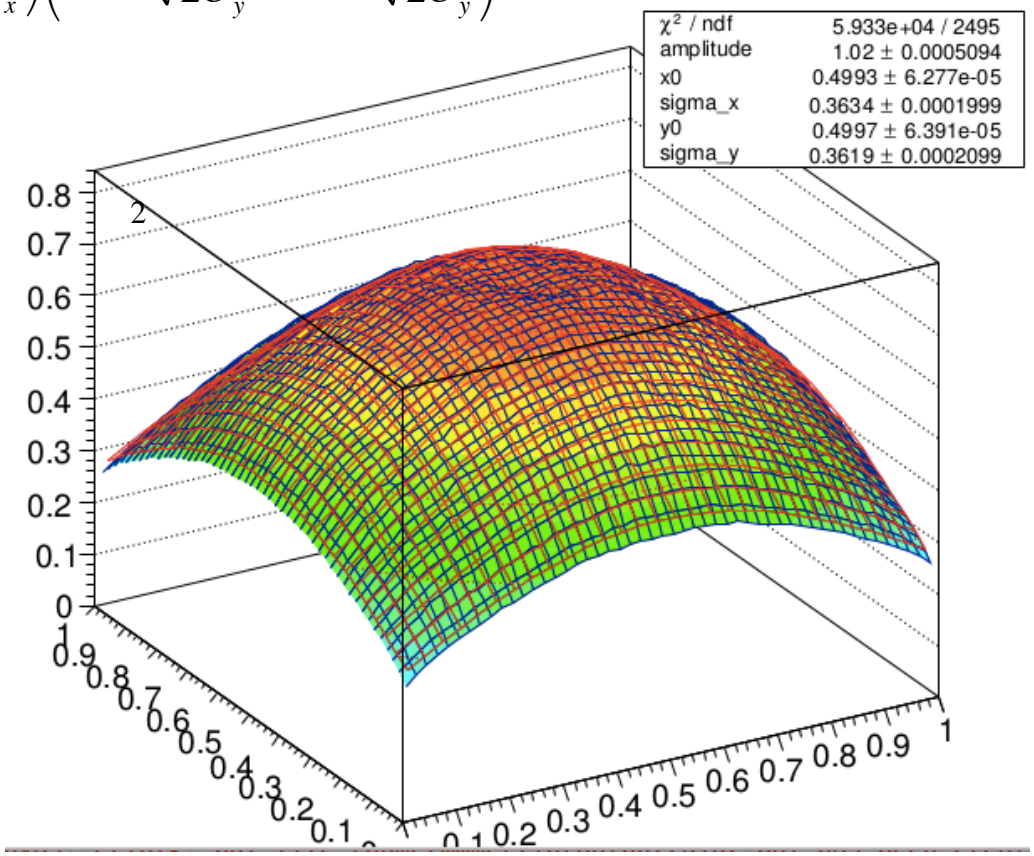
- Central pixel:
  - 75% if x-ray lands in the center
  - 40% if between pixels
  - 25% if in the corner
- Appear symmetric for 4 neighbors

Flux in central pixel

- As function of centroid (x,y)
- Fit function is a combination of erf's but assumes constant sigmas so does not take into account conversion depth

$$f(x,y) = 2\sigma_x\sigma_y\left(erf\frac{1-x+x_0}{\sqrt{2}\sigma_x} + erf\frac{x-x_0}{\sqrt{2}\sigma_x}\right)\left(erf\frac{1-y+y_0}{\sqrt{2}\sigma_y} + erf\frac{y-y_0}{\sqrt{2}\sigma_y}\right)$$

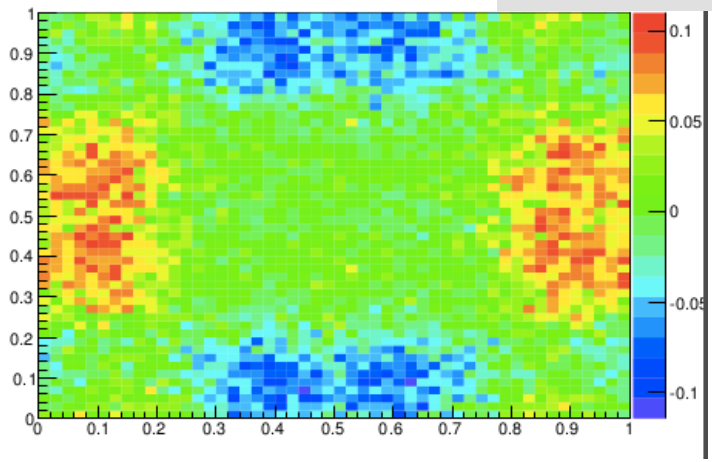




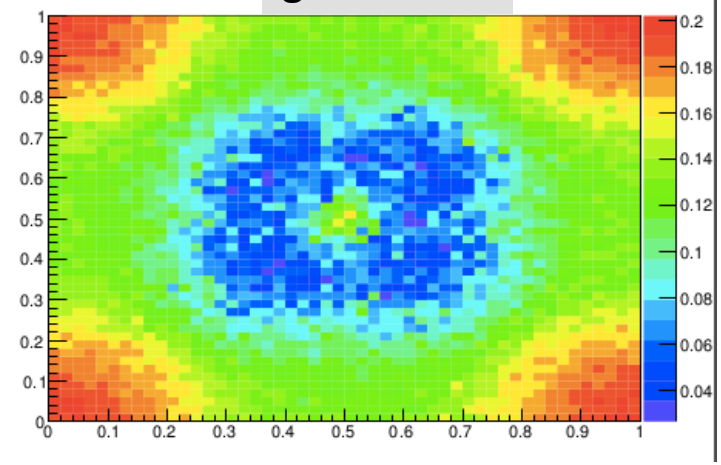
Shear in Pixel (1)

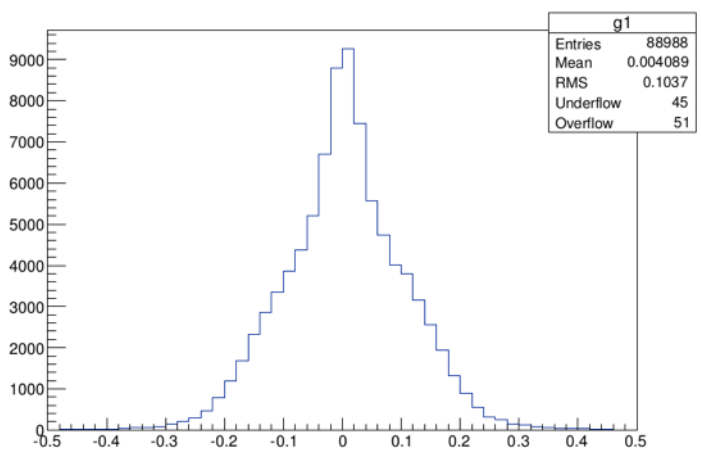
See considerable bias in g1 shear when centroid is near the pixel border

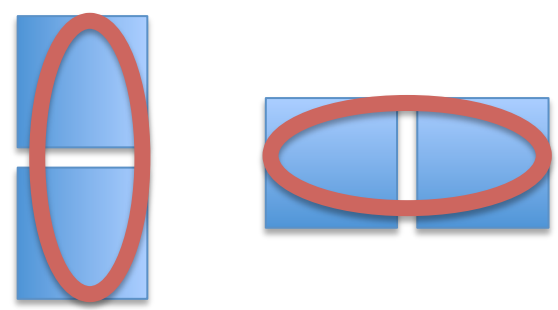
g1 fit result



g1 fit error

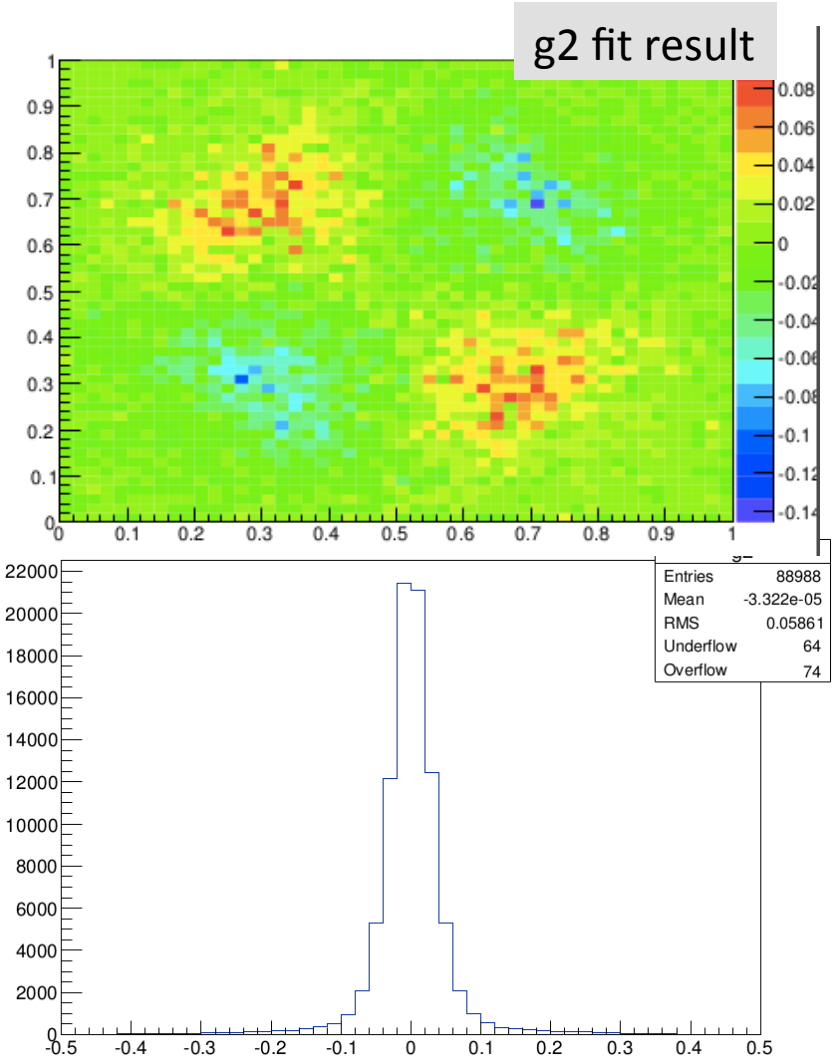


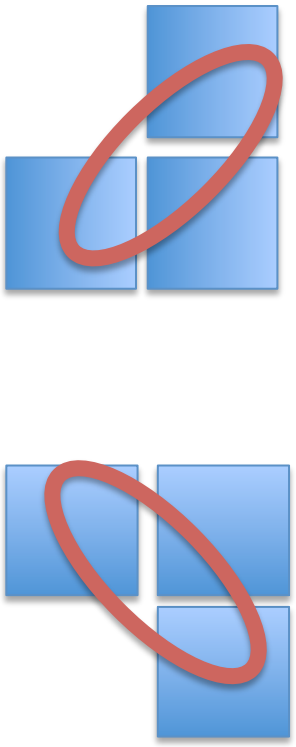




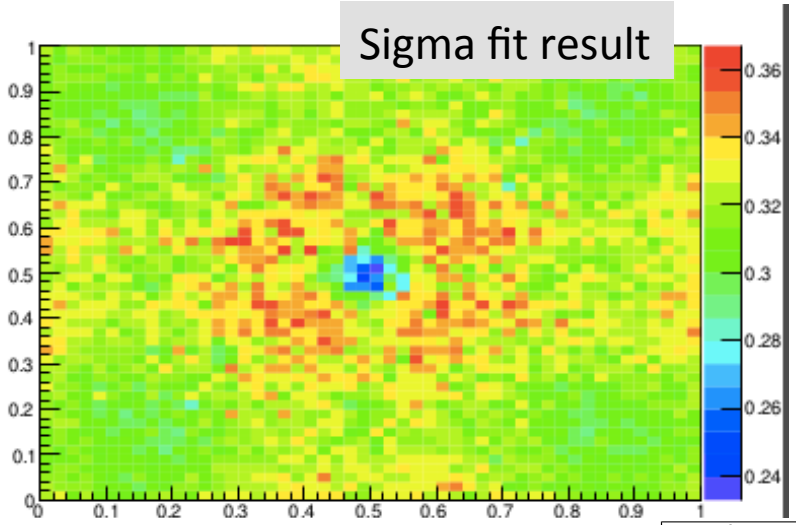
Shear in Pixel (2)

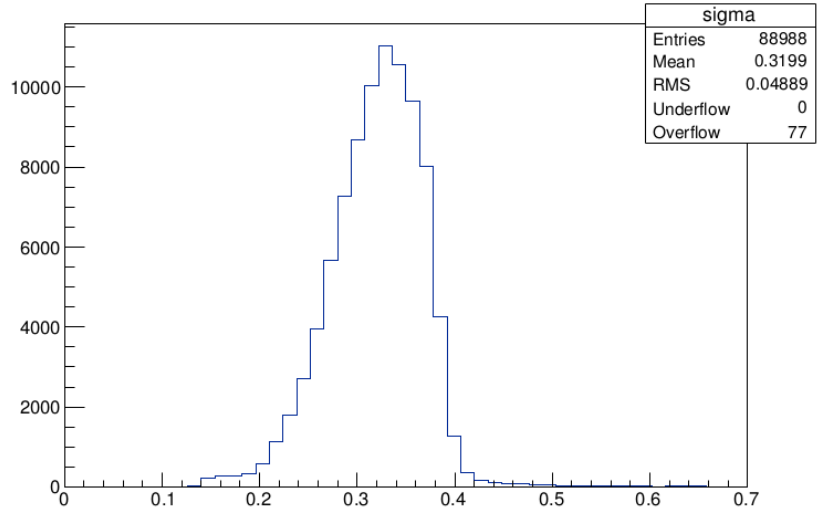
See considerable bias in g2 shear when centroid is near the pixel corner

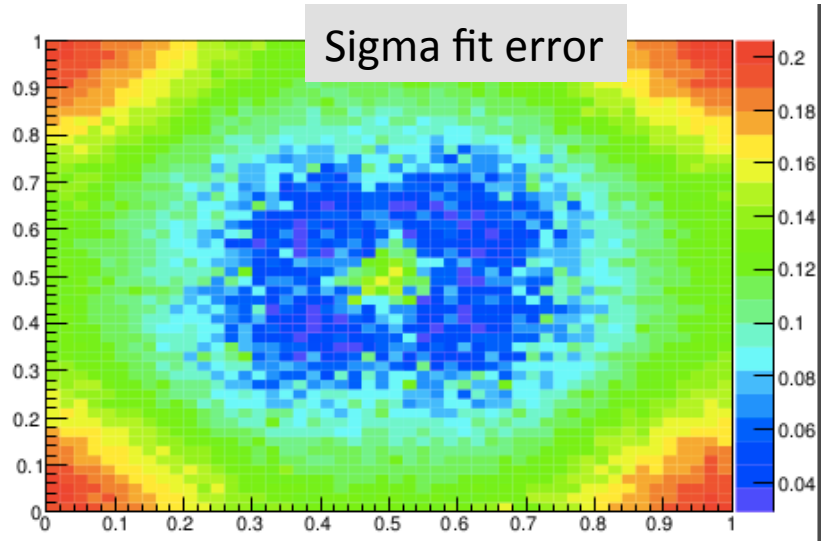




Sigma in Pixel, Data





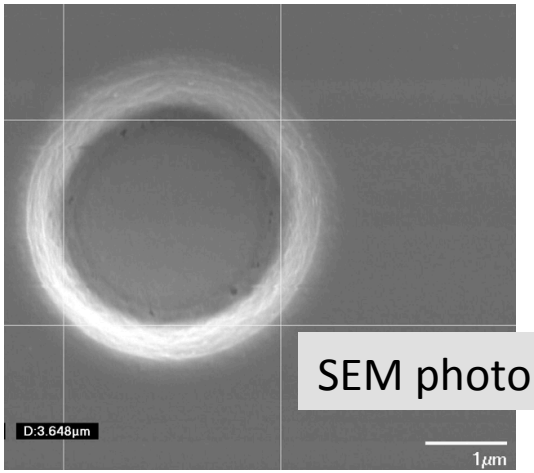


- There is bias in Sigma as well
- Skewed distribution due to
  - Conversion depth in silicon
  - Fit bias due to undersampling

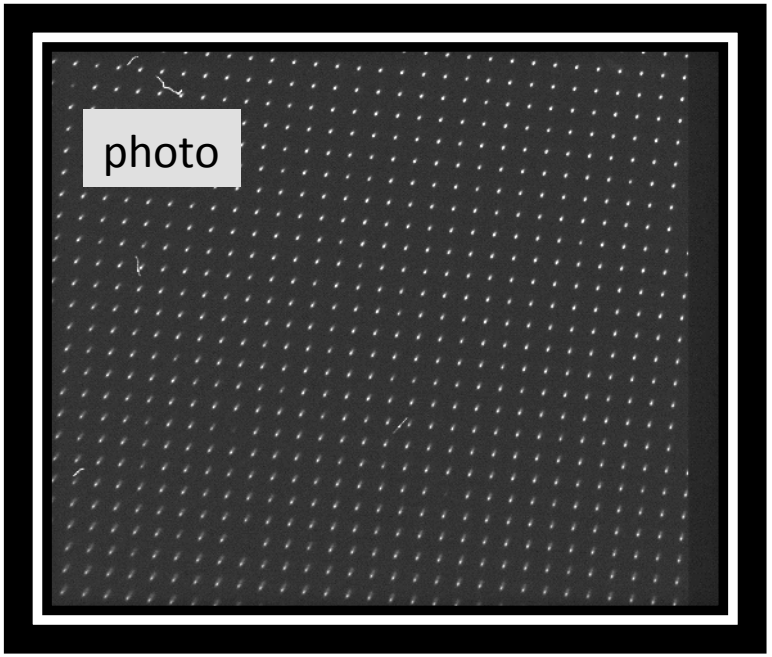
Spots

Spots: grid of pinholes

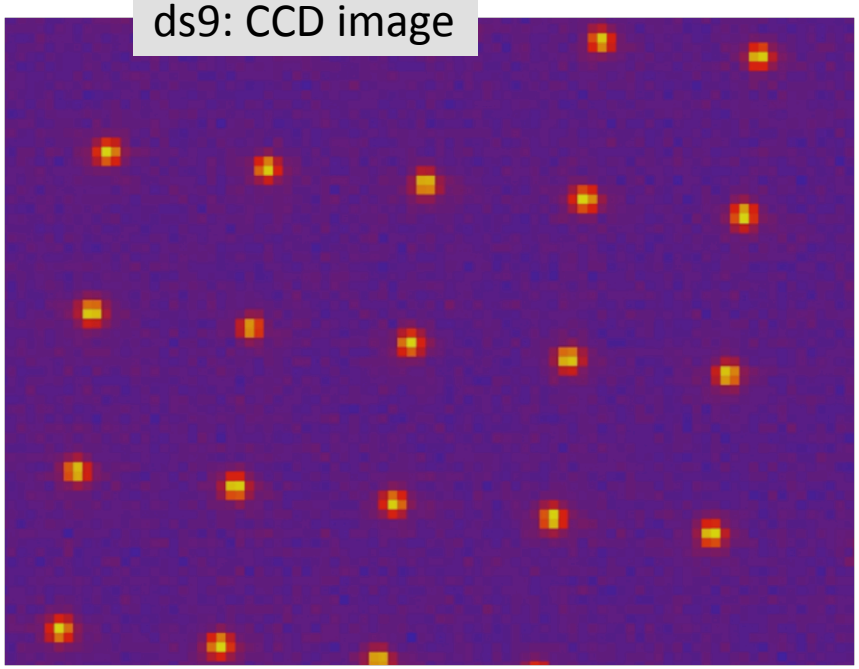
- Used multi-hole target to probe astrometric biases
  - 150 nm thick chromium on silica, produced at BNL by J.Warren
  - 46,656 pinholes
  - 3.6 micron diameter, 200 micron spacing



SEM photo of one pinhole



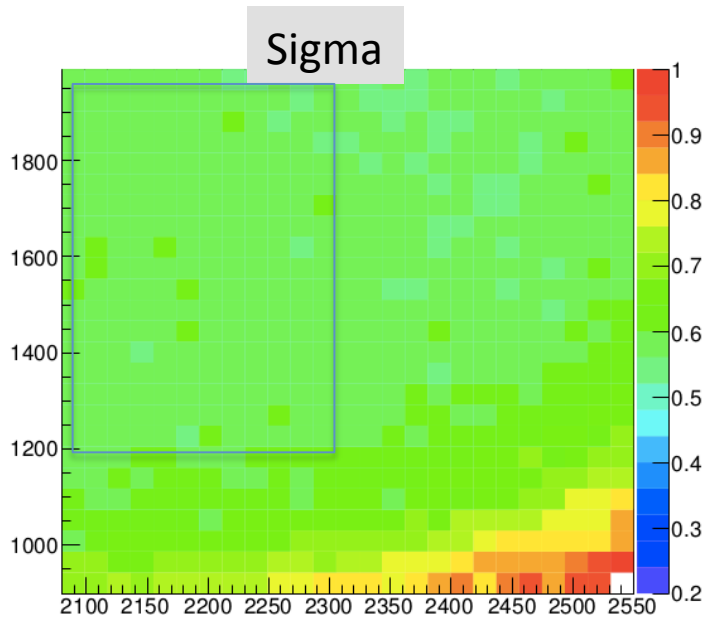
photo

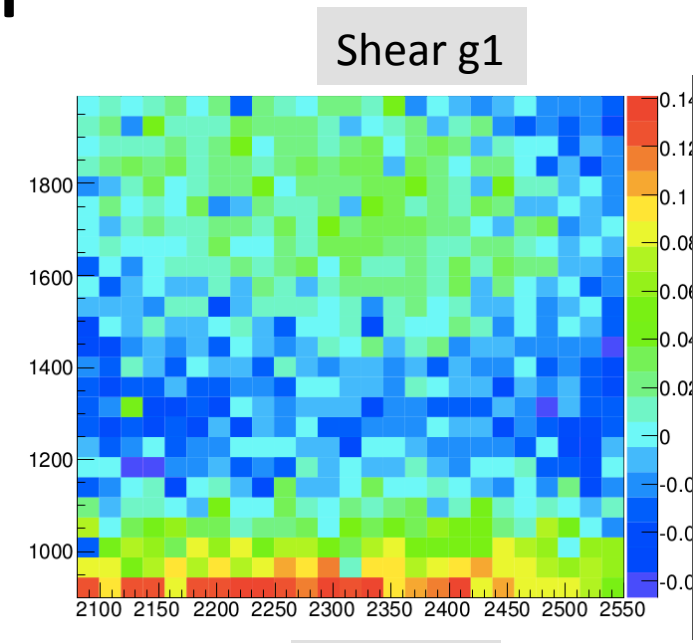


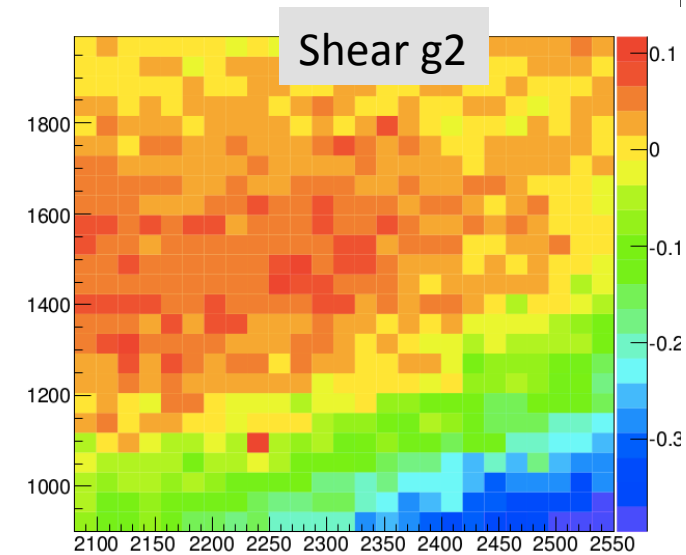
ds9: CCD image

Maps of shapes

- Same procedure to fit spot shape as for Fe55 x-rays
  - Wider sigma: 6-7 um
- Some peripheral distortions due to optics
- Selected uniformly illuminated region for further analysis



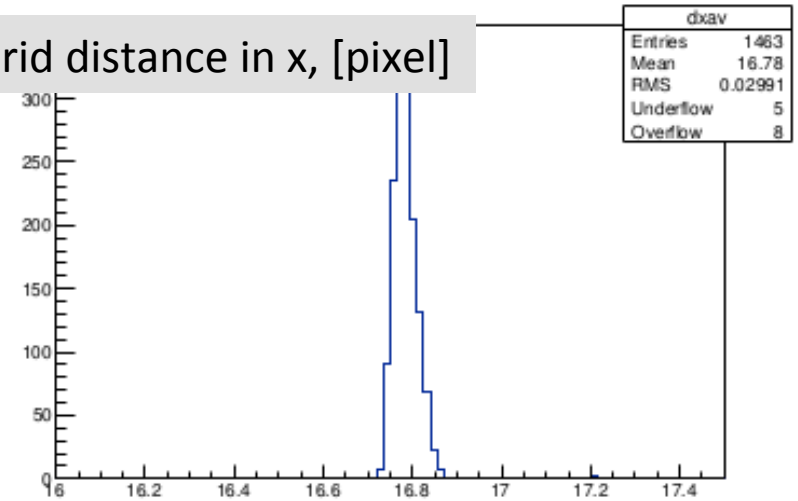




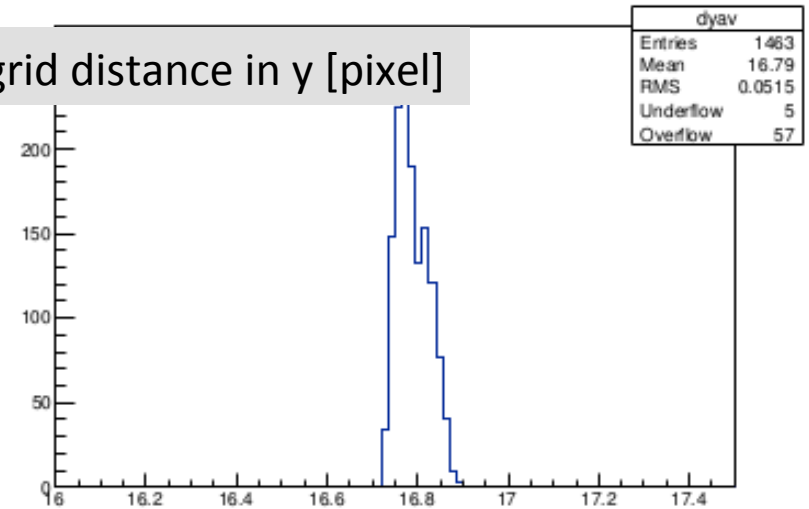
Distance to neighbors

- Along two grid directions “x” and “y”:
  - Average distance to two immediate neighbors

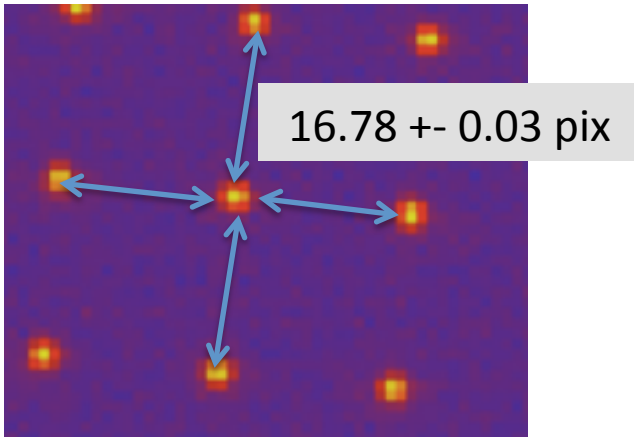
grid distance in x, [pixel]



grid distance in y [pixel]

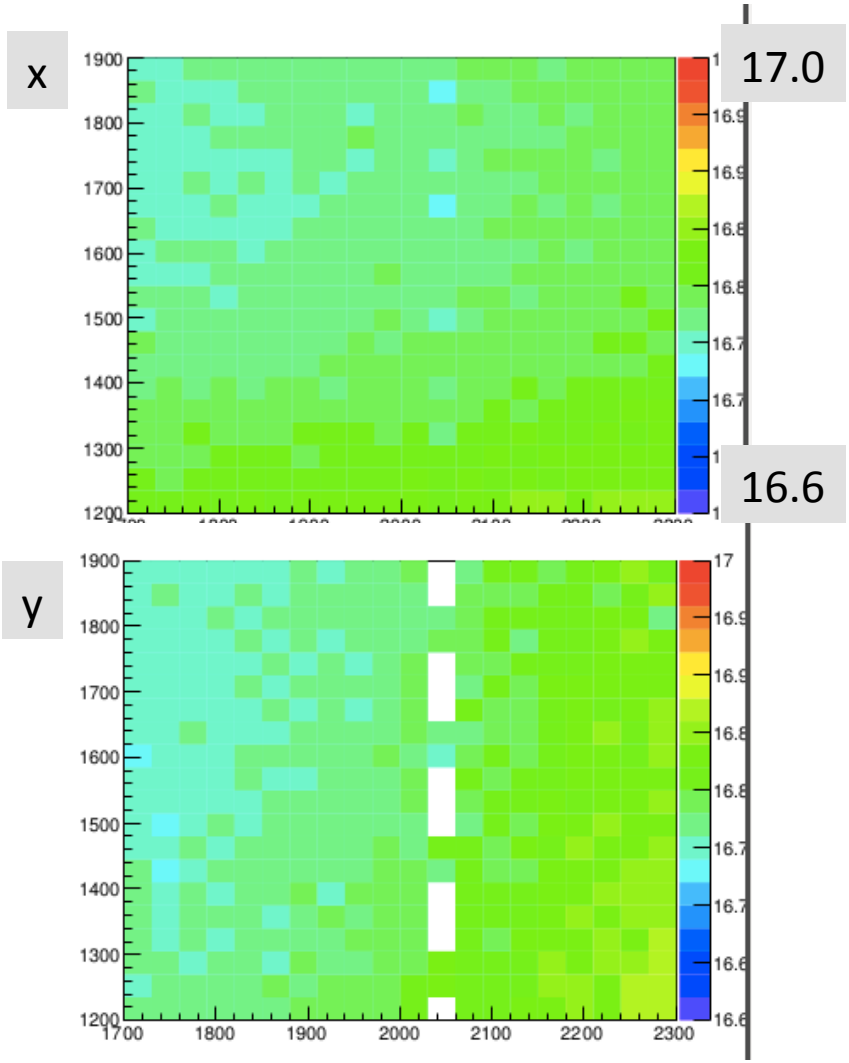


RMS 0.03 pixels = 0.3 micron



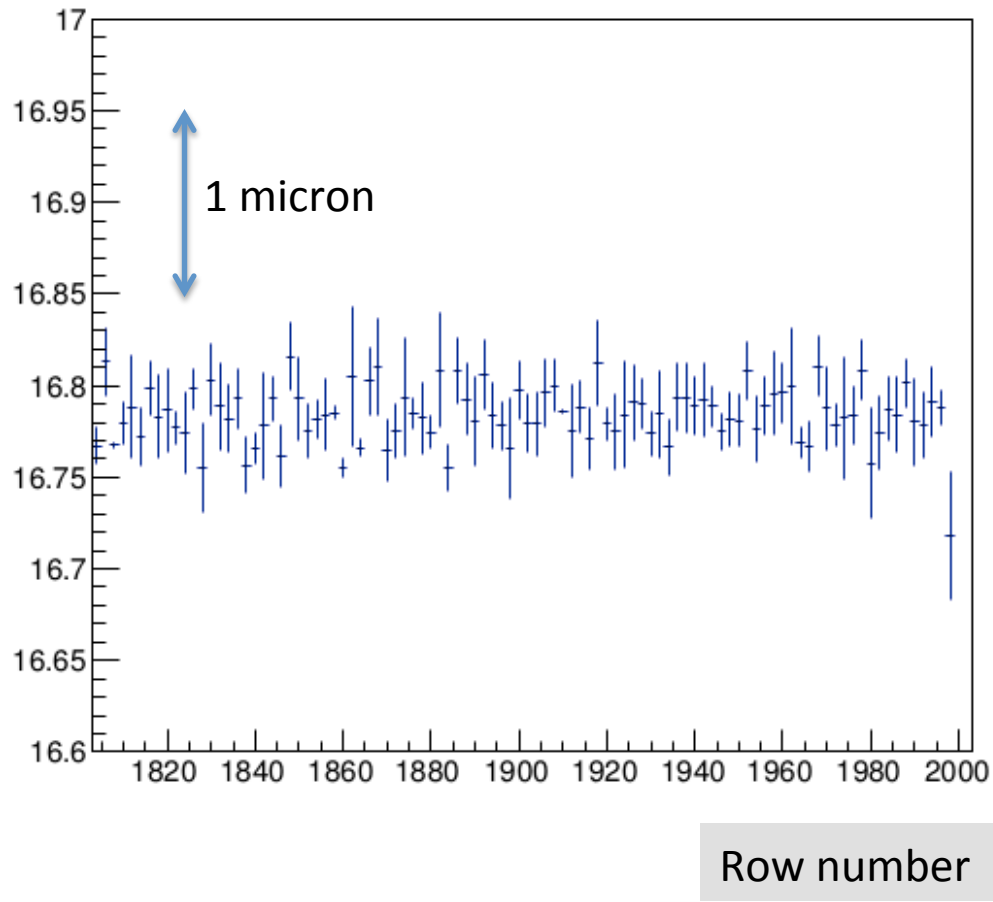
Maps of Distance to Neighbors

- Along two grid directions “x” and “y”:
  - Average distance to two neighbors
- Uniform to ~ 1 micron
  - Residual non-uniformity most likely due to optics



Midline in a grid of spots

- Distance to neighbor vs row number
- Do not see the midline
  - Sensor did not have the anti-bloom stop implant
- Submicron sensitivity to astrometry
- Work in progress to propagate the technique to other sensor "features"



Summary

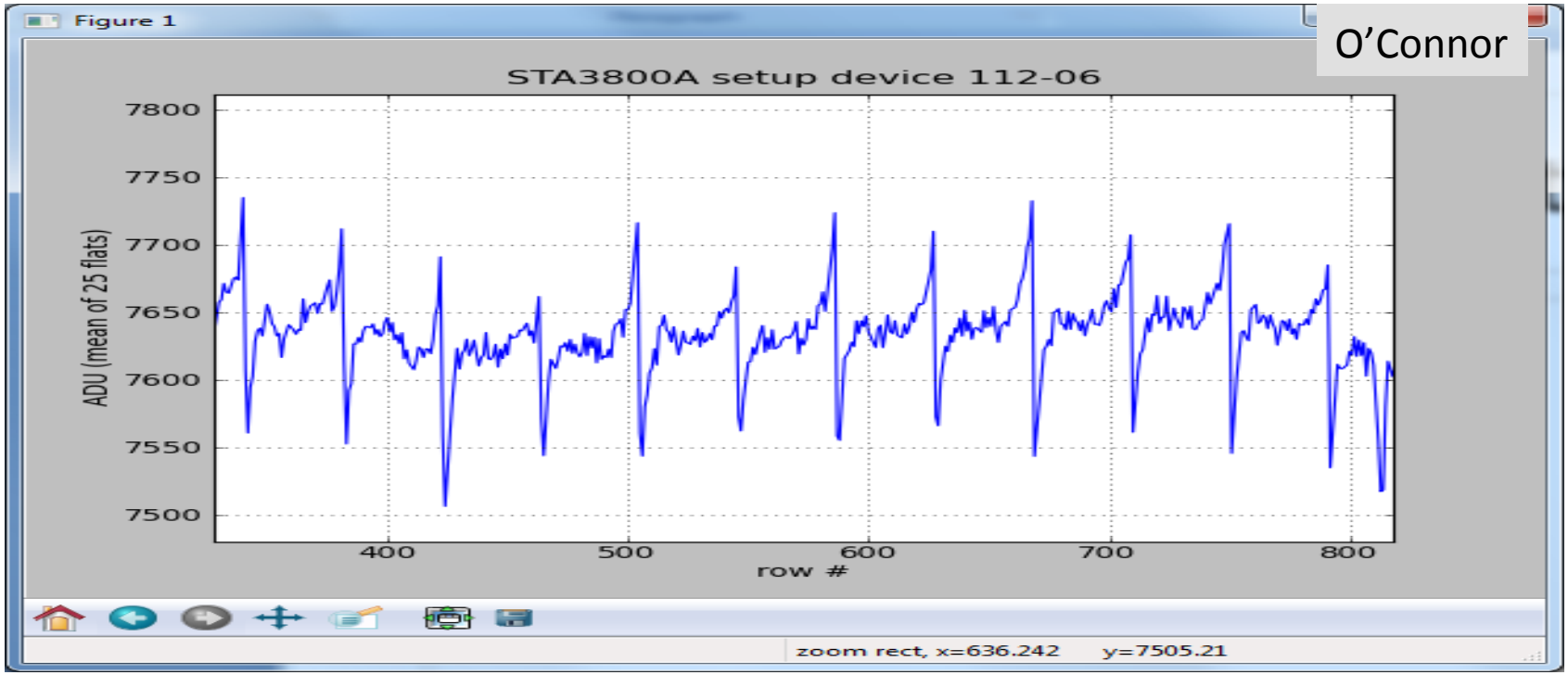
- Good progress on LSST sensors both for production and science

- Fe55 flat fielding is a viable tool to characterize astrometric distortions in CCDs
  - Does not depend on QE → a way to disentangle photometric and astrometric effects
  - Richer information than standard flats, good to study sensor defects and features
  - There are biases for reconstructed centroid within pixel. MC is a possible route to understand them
- Regular grid of micro-holes is another powerful technique to study astrometry in the sensors

- Acknowledgements:
  - LSST Science Raft team
  - Merlin Fisher-Levine, Paul Price: DM code
  - Erin Sheldon: ngmix ML and MCMC fitters
  - Paul O'Connor, Ivan Kotov: Fe55 dataset

Backups

Bamboo in ITL sensors



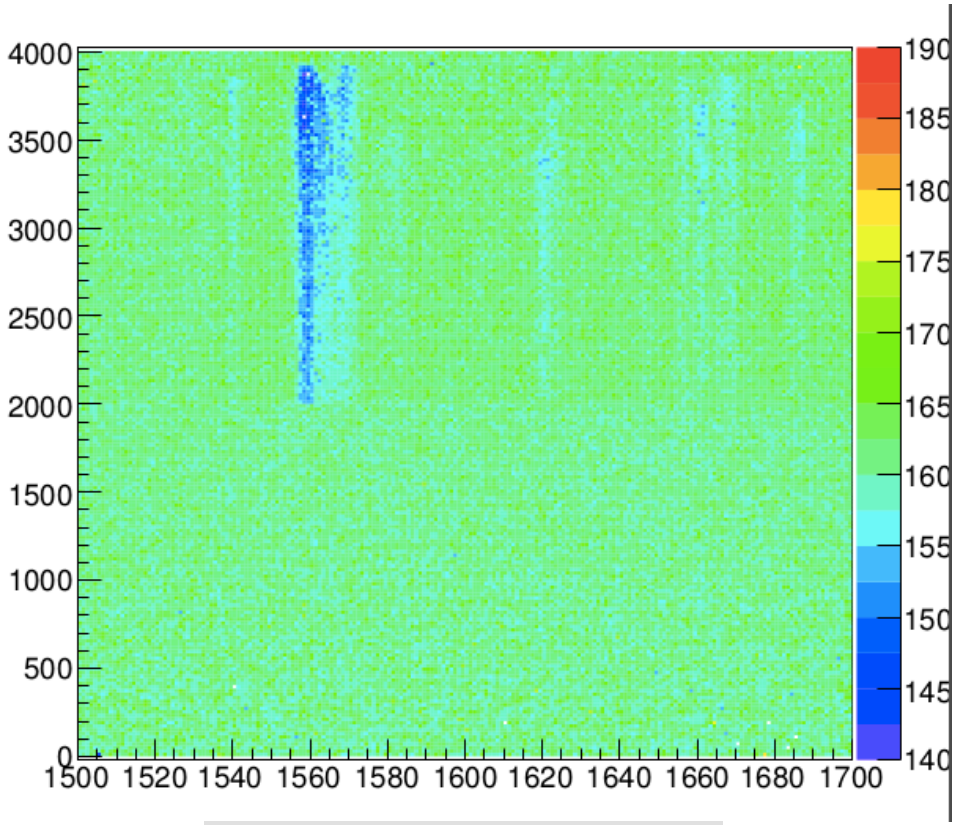
Pixel physical size distortions due to masks?

- Period 41 pixel x 10 micron = 410 micron

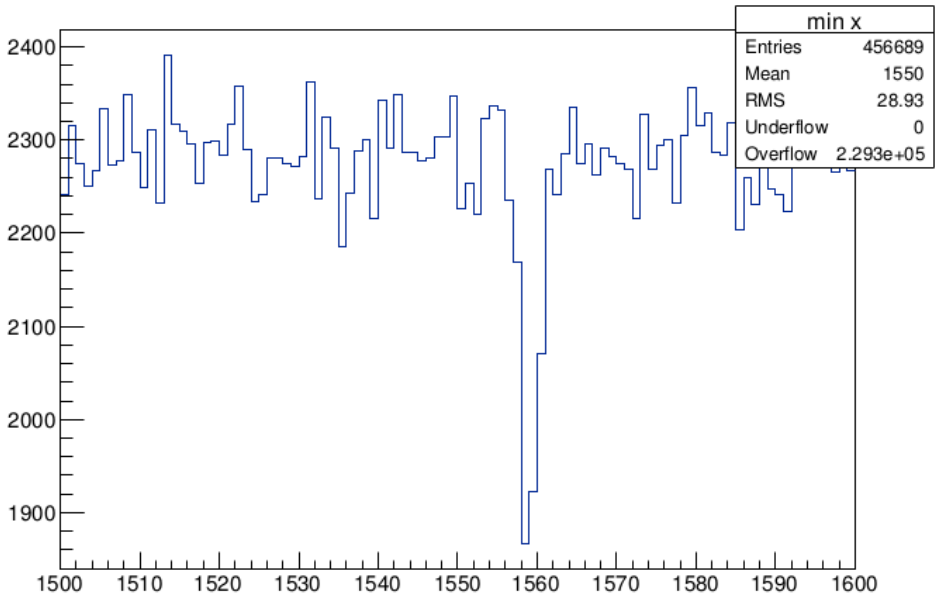
Work in progress to check astrometric vs photometric nature of this features

Example of bad columns

- Due to trapping, agrees with pocket pumping data
- Statistics good enough to see pixels



Flux (x,y) map, electrons

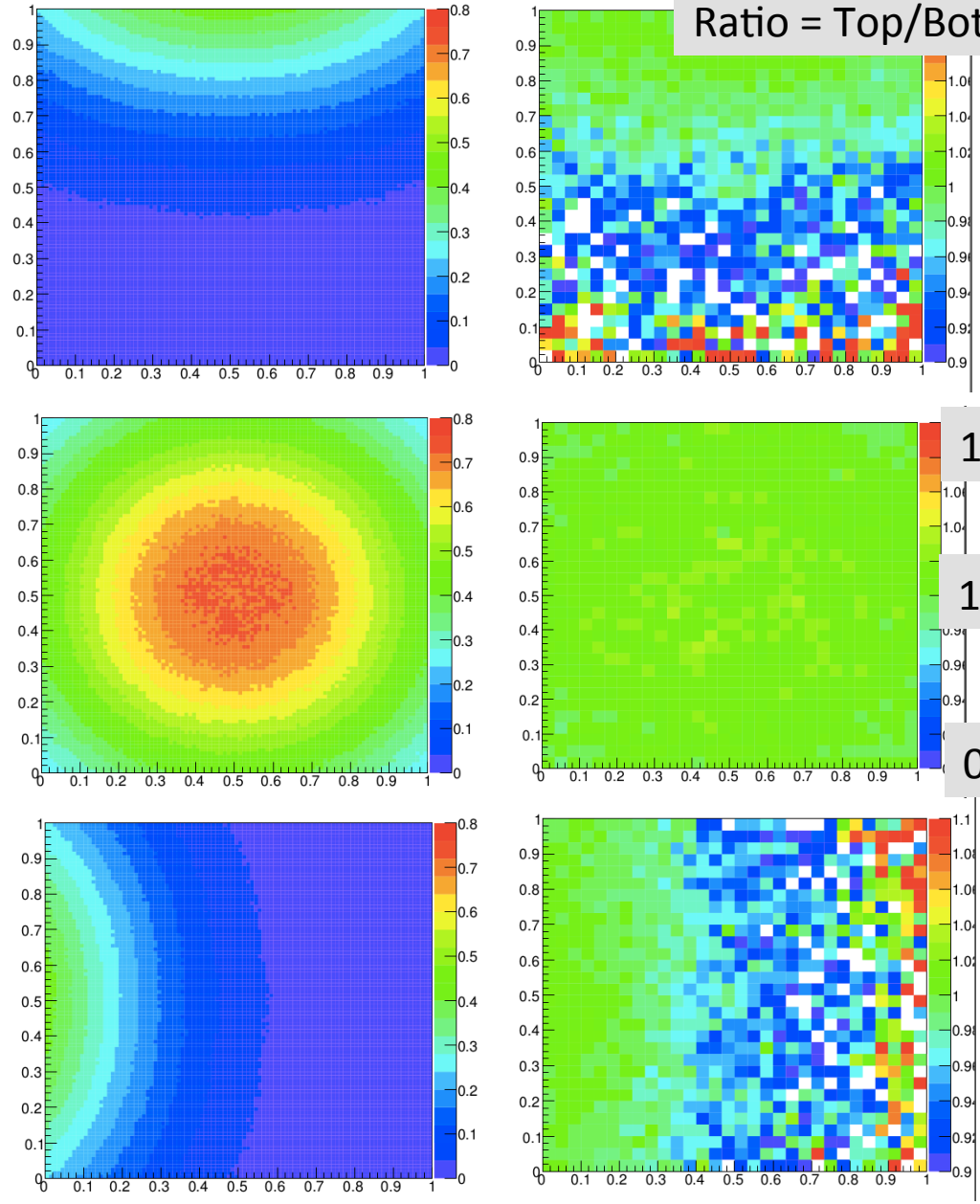


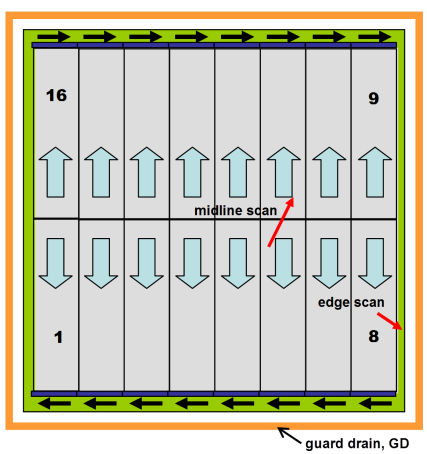
Occupancy vs x (along CCD row)

Top and bottom sensor halves

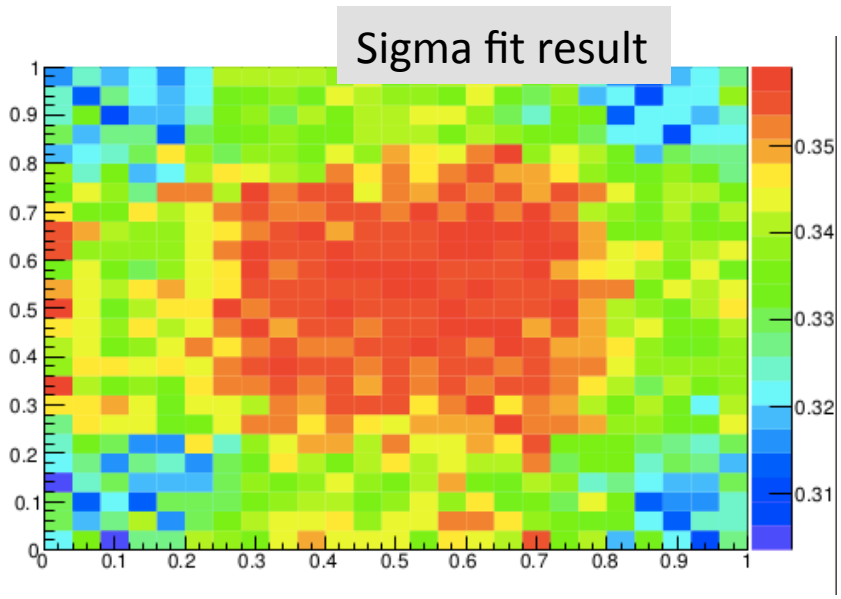
- Versus (x,y) in central pixel
- Done separately for half sensor (top and bottom)
- Top and bottom halves have different readout direction, look for asymmetry

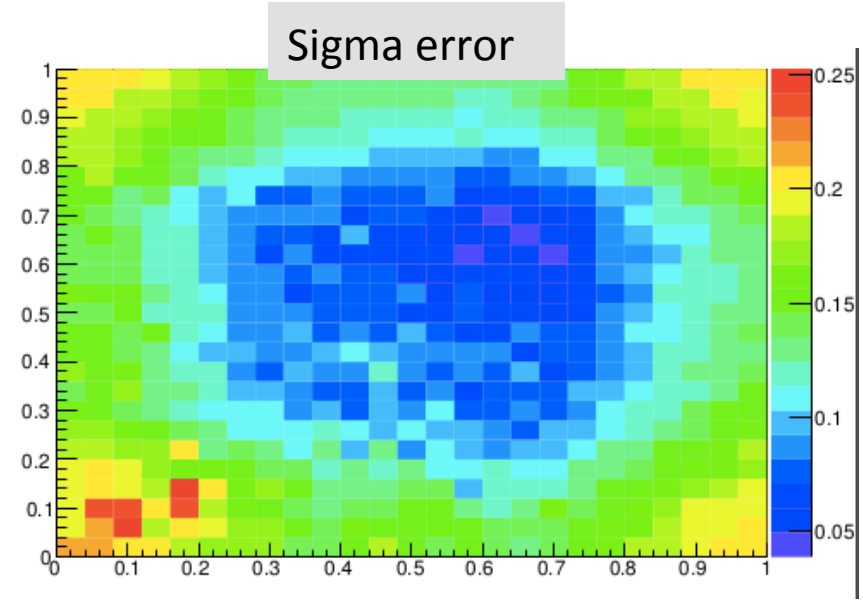
- Show three cases (top, center, left) but appear similar and symmetric for all
  - There is a slight asymmetry (<5% difference) for the tails (<5% of total signal) but this could be due to the calibration (offset & gain)

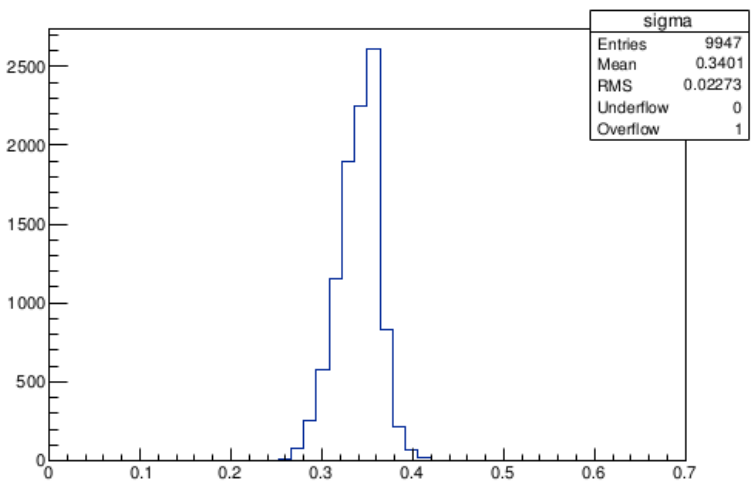




Sigma in Pixel, Toy MC





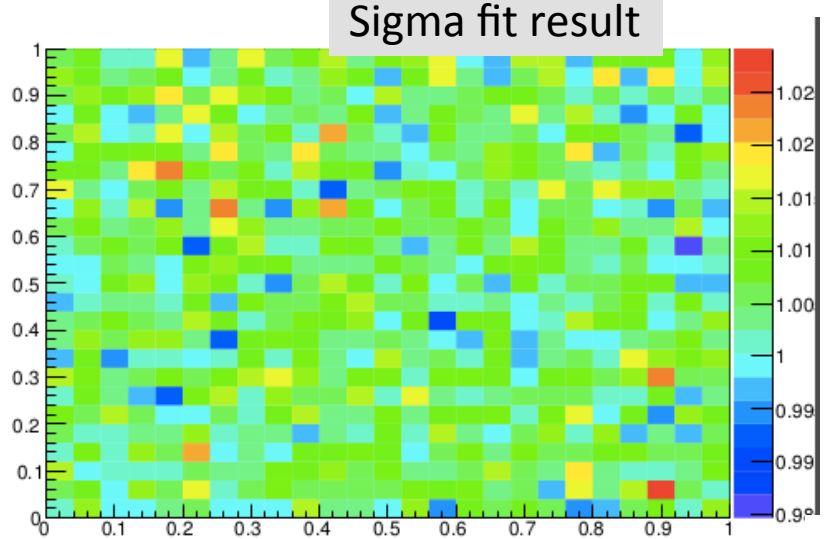


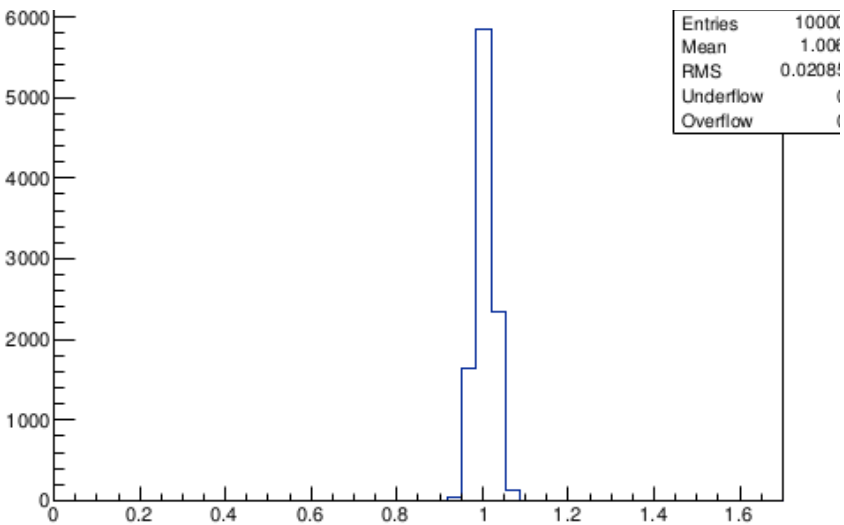
- Sig = 3.5 micron = 0.35 pixels
- Considerable bias, looks similar to data
- Can be used to account for bias

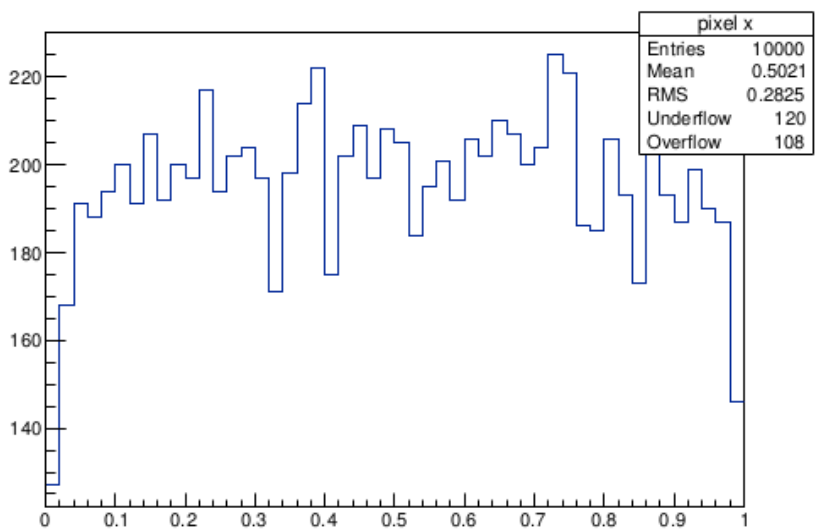
Toy MC for larger sigma

- Sigma = 10 micron → no bias

Sigma fit result



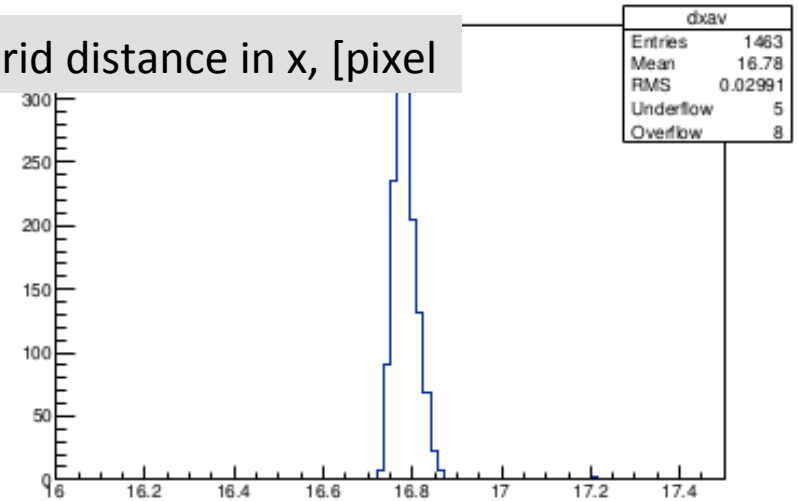




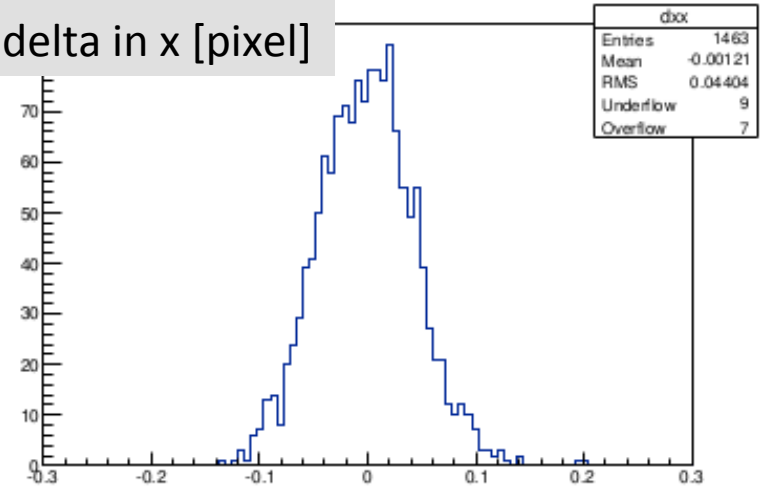
Distance to neighbors

- Along two grid directions “x” and “y”:
  - Average distance to two immediate neighbors
  - Distance difference between positive and negative directions

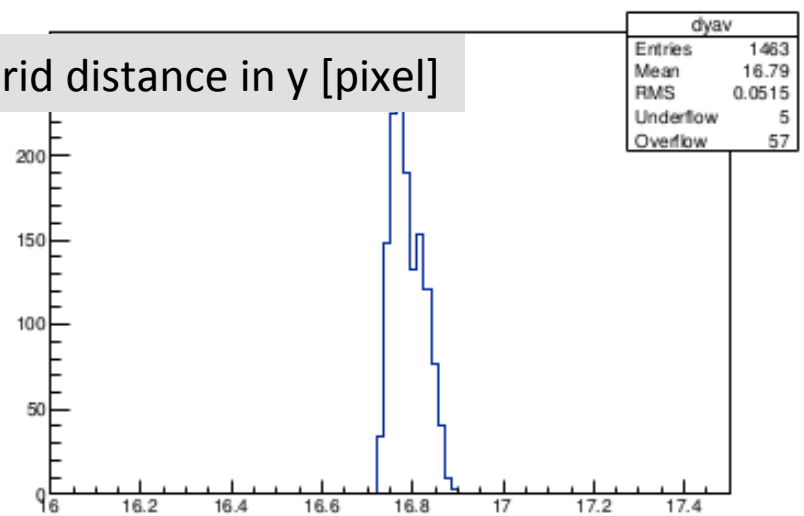
grid distance in x, [pixel



delta in x [pixel]



grid distance in y [pixel]



delta in y [pixel]