LSST Camera Sensor Characterisation and pre-commissioning (LSST:UK WP 3.9)

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Outline

- Intro to LSST camera & sensors
- Selection of LSST detector systematics
  - Fringing & Edge Roll Off
  - Brighter-Fatter Effect
  - “Tearing”
  - Signal – varying CTI
- LSST:UK WP3.9 highlights
  - Single Trap Pumping
  - Gate Width Influence on Brighter-Fatter Effect

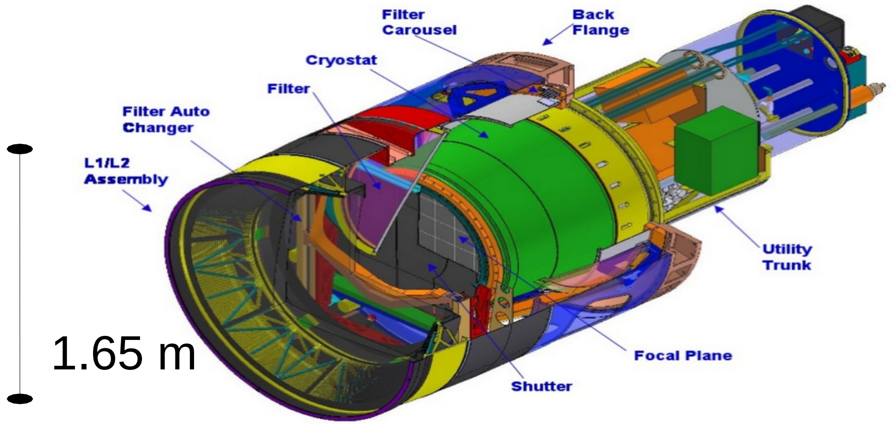
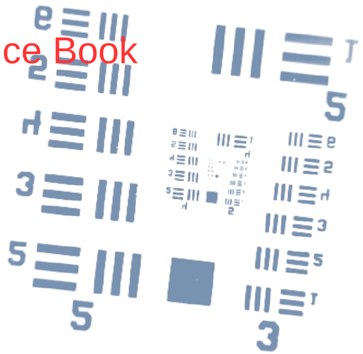


Image: LSST Science Book



The LSST Camera

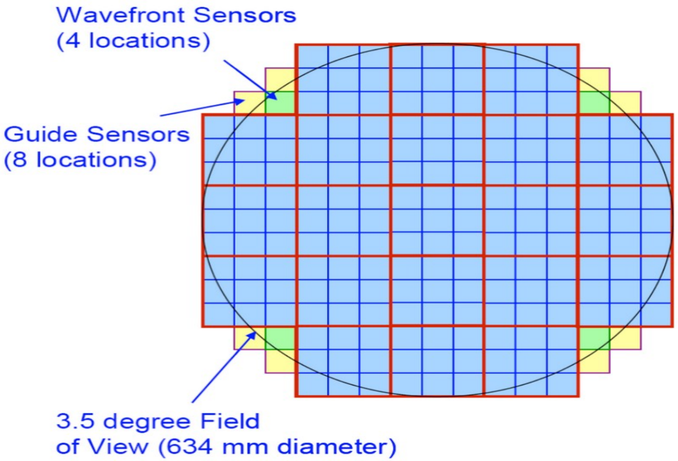
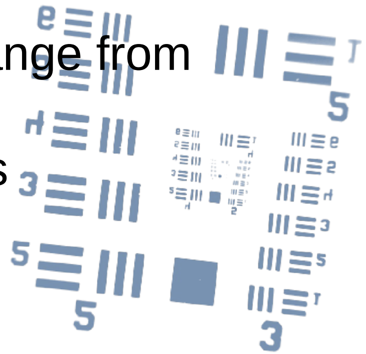


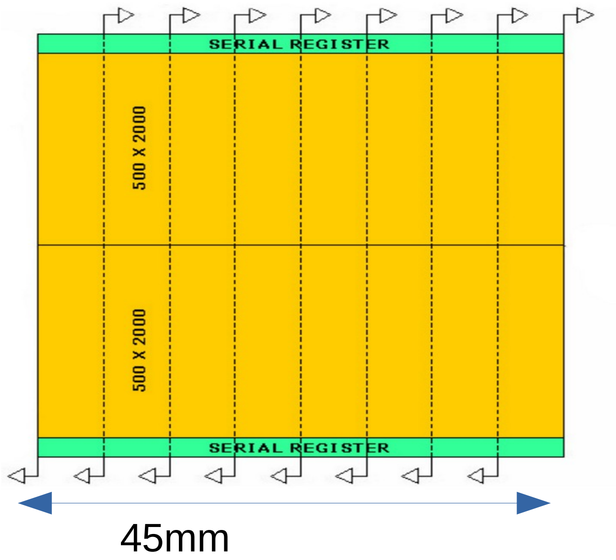
Image: LSST Science Book

- **Fast Optics needed for "fast" and "deep" survey.**
- **Small pixels – to make sure we can oversample the PSF of the optics**

- Operating temperature: -100 Celsius
- Challenging mechanical requirements: fast shutter & filter changer
- Fast (f/1.2) optics lead to stringent flatness specification.
- Focal plane consists of 189 4k x 4k science sensors arranged in "rafts" of 9 (3.2 Gpix total).
- 10 μm pixel pitch
- 6 Filters cover wavelength range from 300nm – 1100nm
- Focal plane read out time: 2s
- 15 TB raw pixel data / night

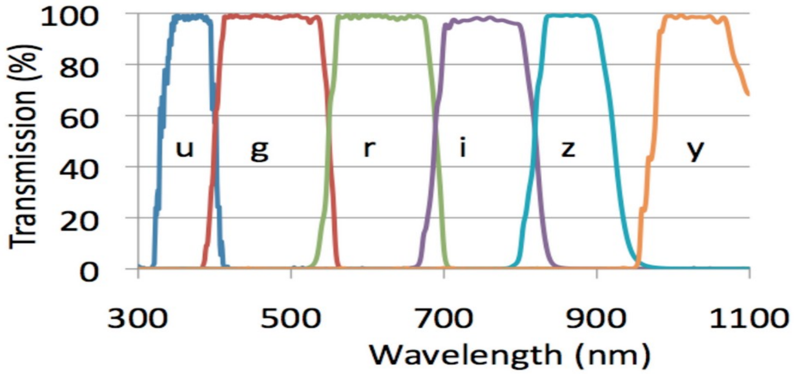


LSST Sensor Requirements

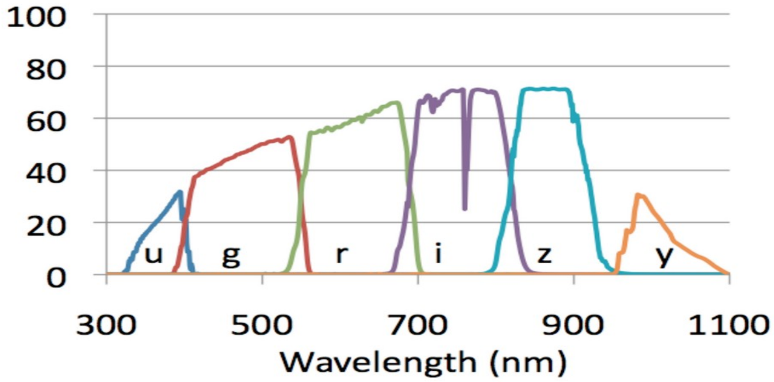


- High visit rate demands fast readout (~2s).
- To maintain reasonable noise (~4e-), CCD must be **highly segmented (16 outputs)**. This implies a **pixel rate of ~550kHz**.

- LSST filter bands (below left) cover near UV to near IR. To maintain survey depth in brief exposure times, high **Quantum Efficiency** is key.

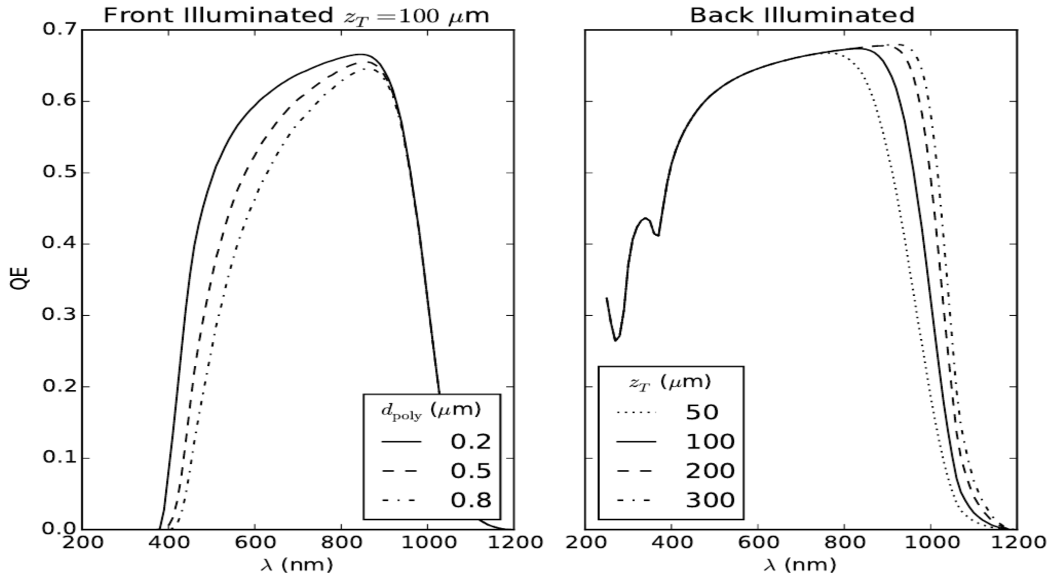


Images: LSST Science Book



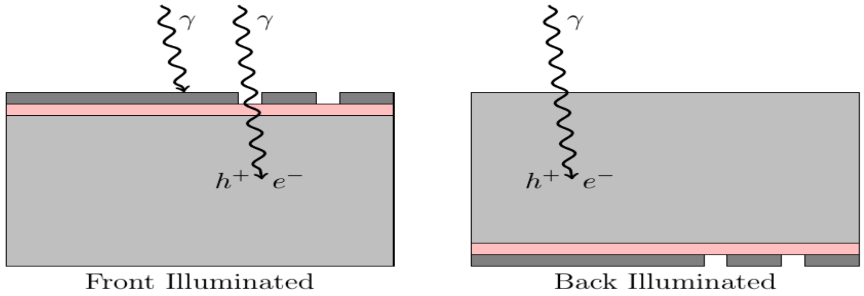
Achieving High QE

- Blue end QE is enhanced by back illumination (removing poly and gate absorption)
- Maintaining high QE at long wavelengths implies a thick detector.
- LSST science detector is 100μm thick.
- Absorption length is also (slightly) temperature dependent.
- High resistivity bulk material (>5k Ω cm) is used for construction

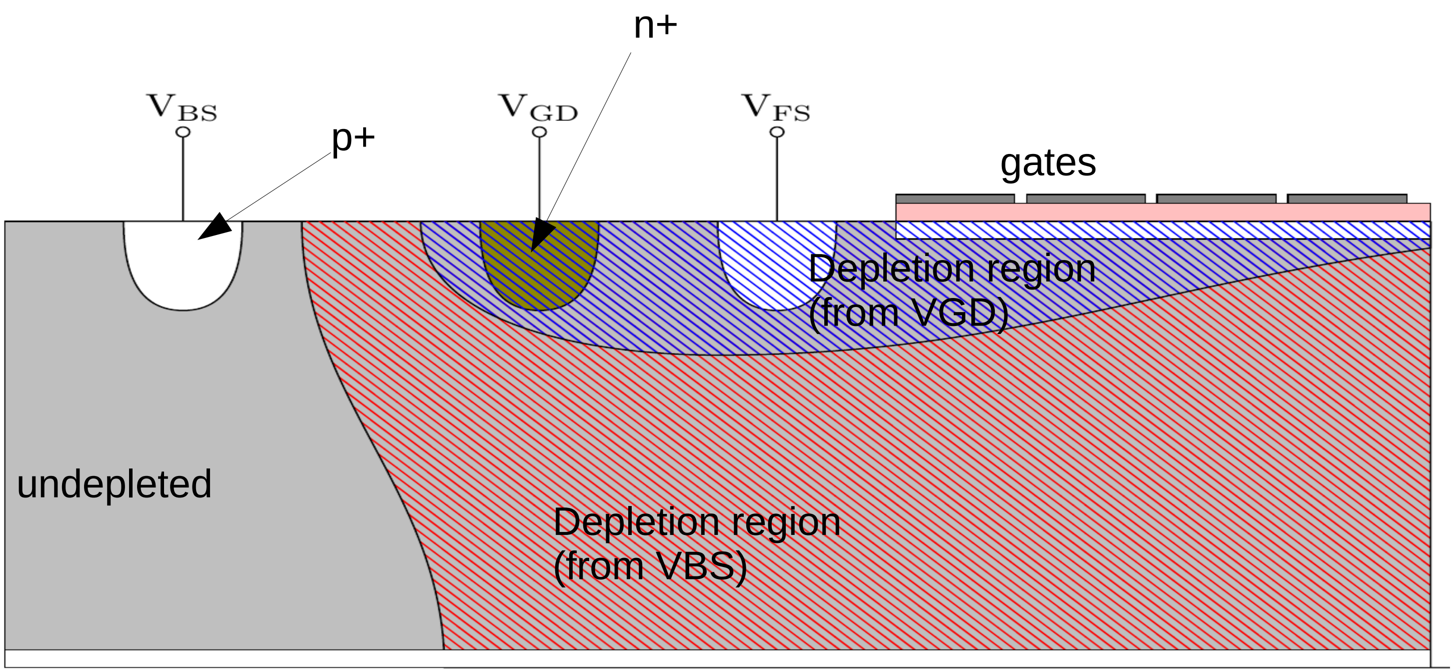


$$QE_{FI} = (1 - R(\lambda))\, e^{-\alpha(\lambda) d_{\text{poly}}} \left(1 - e^{-\alpha(\lambda) z_T}\right)$$

$$QE_{BI} = (1 - R(\lambda)) \left(1 - e^{-\alpha(\lambda) z_T}\right)$$



Deep Depletion CCDs



A thick detector implies a long drift time for electron collection. This, in turn, implies a large diffusion radius

$$r_{\mathrm{diff}} = z_T \sqrt{\frac{2k_B T}{q_e V_{\mathrm{coll}}}}$$

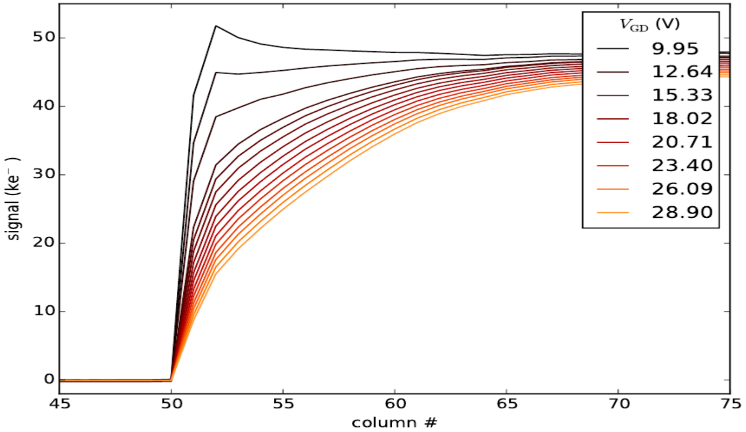
- To reduce the collection time of charges (and thus the diffusion radius), a high bias voltage is applied to the back side of the chip
- In order to prevent leakage currents from the front substrate to the back, guard drains are included in the design which creates a protective depletion region whilst the back bias is applied

A Tale of Two Teledyne CCDs

The LSST focal plane contains 189 CCDs, arranged into 21 science rafts. The devices are a mixture of
e2v CCD-250 and ITL/STA-3800C. Both are thick, back illuminated CCDs on high resistivity silicon.
But within that constraint, they almost couldn't be more different!

	CCD-250	STA-3800C
Imaging phases	4 (symmetric)	3 (asymmetric)
Output amp	2 stage MOSFET	1 stage JFET
construction	Back thinned, Si substrate	Glued glass substrate with lithoblack coating
Design docs	Very very secret	Available to LSST
Measured performance	Good noise, CTI, linearity	High FWC, better dark current

Thick CCD specific problems – edge roll off, tree rings, fringing

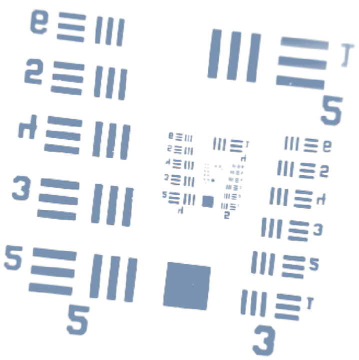


- Guard drain structure "drags" charge off the edge of the array as it is collected.
- Upto 10s of pixels ranged effect.
- **Can affect astrometry (it's moving charge around!)**
- Changes behaviour depending on various CCD operating conditions

- Static "tree ring" structures visible at short wavelength due to bulk silicon manufacturing process, easy to calibrate out, & investigations show they don't affect astrometry

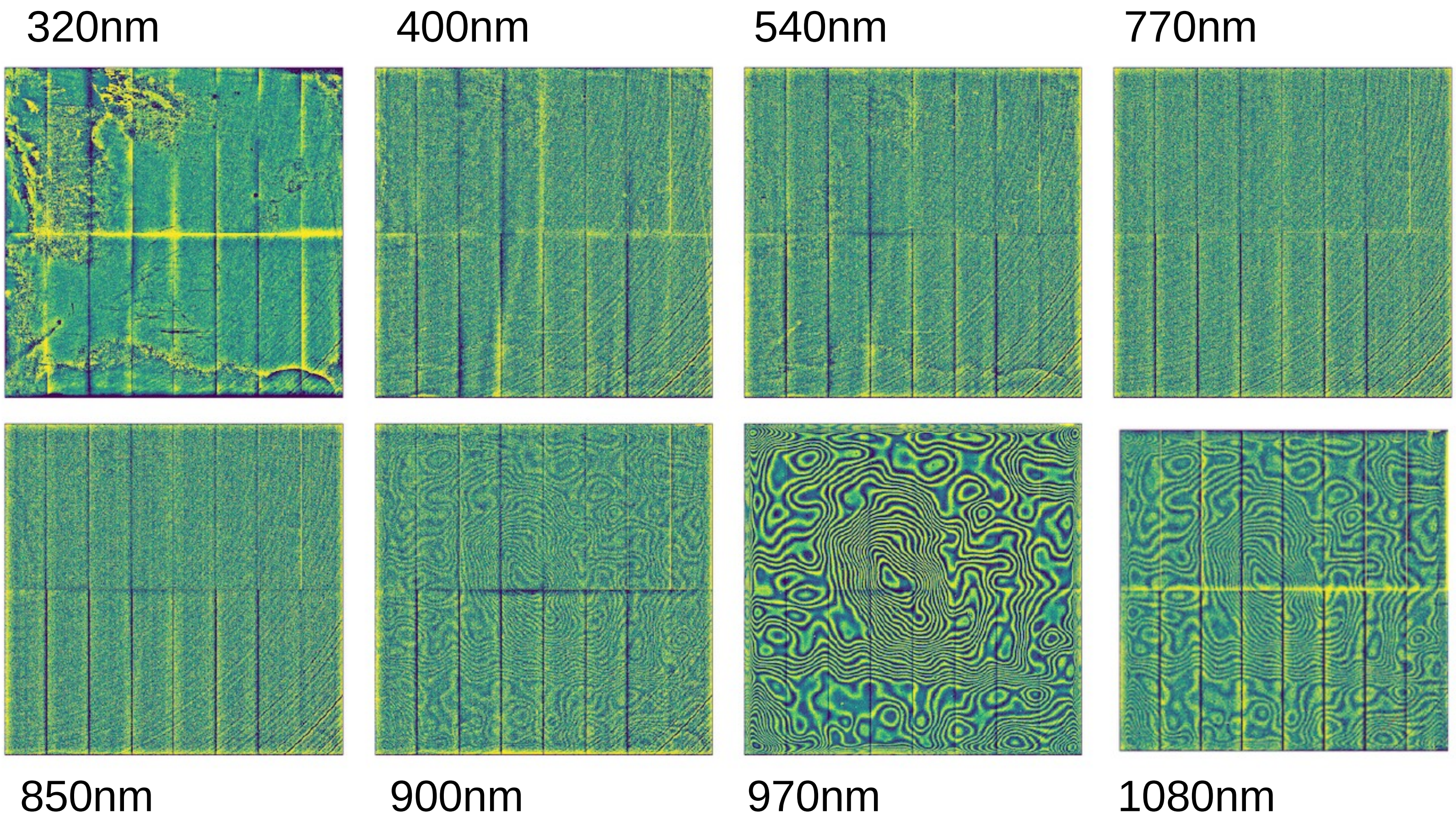
e2v

ITL



- Fringing due to varying thicknesses of coatings and active silicon – etalon effect
- Excited by sky background lines which vary in time.
- Up to ~200-300 e- in fringing signal
- **Affects photometry in red bands – DM** contains per-sensor calibration & correction for fringing based on AuxTel measured sky spectrum

More on Fringing

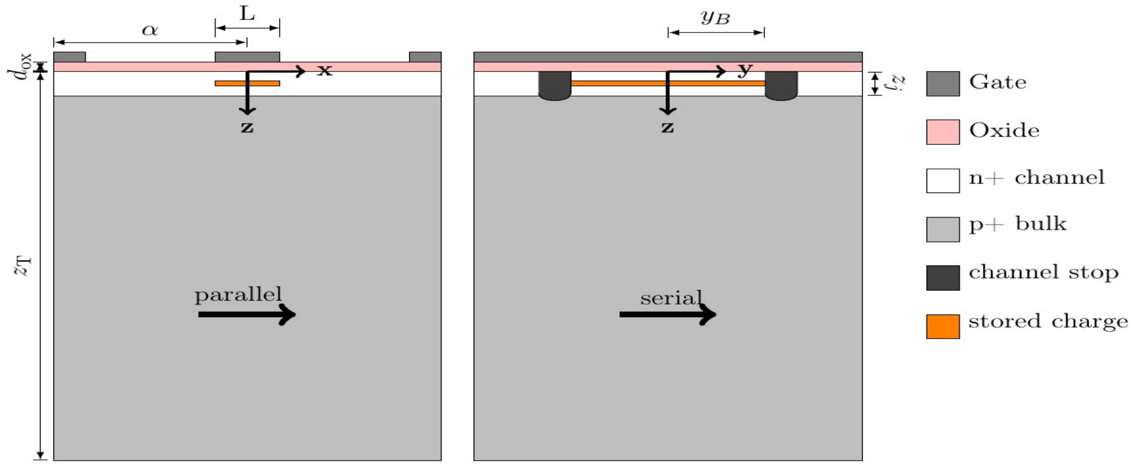


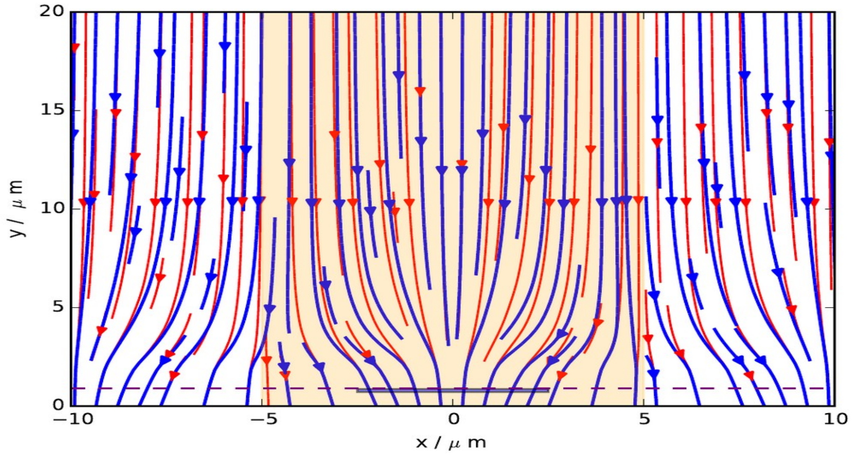
Fringing & tree rings in ITL sensors

Fringing degree depends on the bandwidth of illumination as well as the central wavelength – which is a problem when accounting for sky backgrounds and atmospheric effects at long wavelength

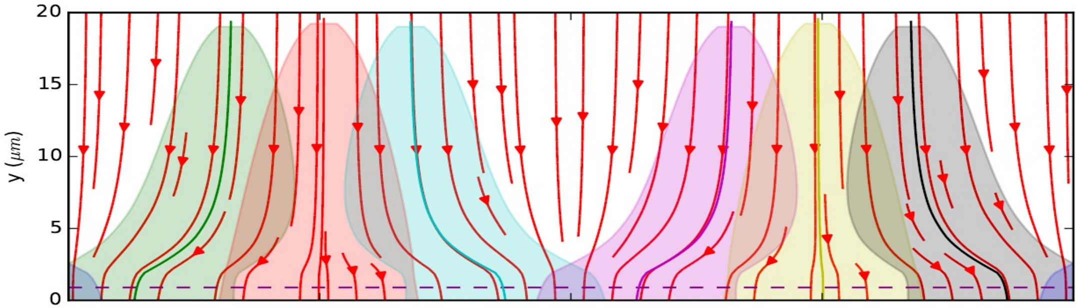
Image credit: Park, Nomerotski & Tsybychev (2016)

Brighter – Fatter Effect

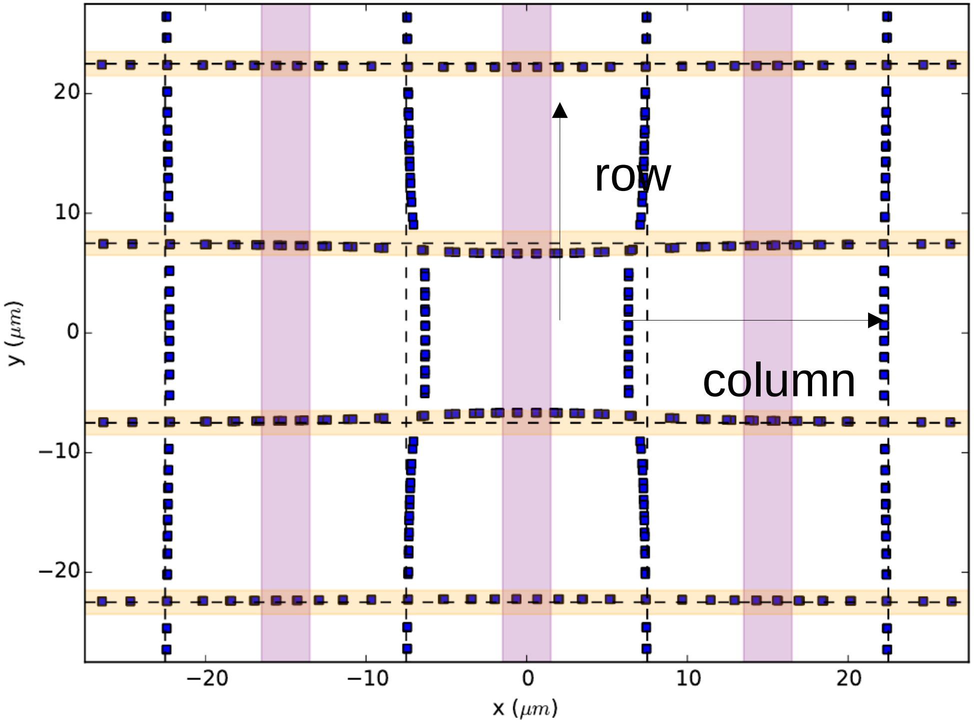




- As charge accumulates in potential wells during integration, it causes the electric field structure of the pixel to change slightly, influencing the collection of further charge.
- This introduces correlations between nearby values in a flat field, and an increase in ellipticity of point sources (possibly serious for weak lensing measurement)
- Analogous to space charge effects in other types of detectors



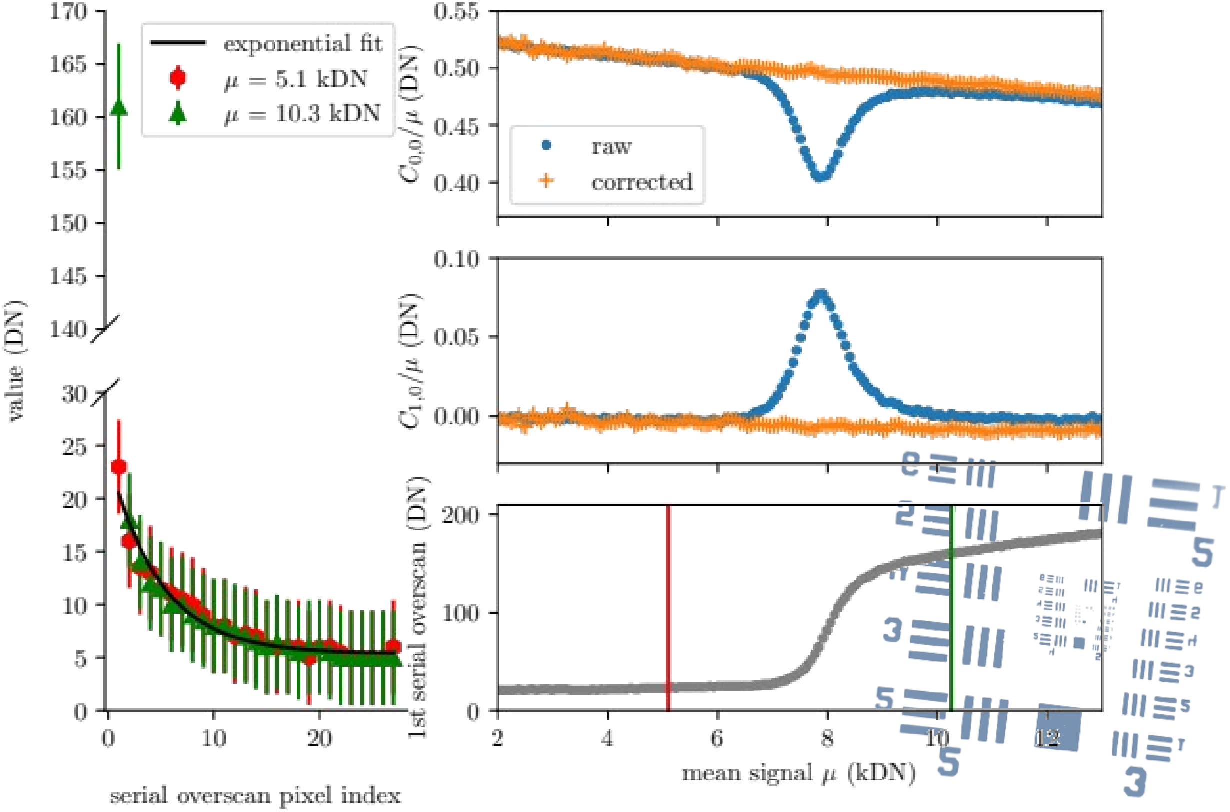
Brighter – Fatter Effect



- Charge contained in pixels causes changes in electric field, which affect subsequent pixels
- "dynamic pixel area" – signal dependent pixel boundaries
- Boundary shifts larger in parallel direction
- Causes shape change of compact sources depending on brightness – **a clear potential problem for weak lensing surveys which rely on measuring the shape of galaxies**
- A very large amount of work has gone into characterising and correcting this effect in science data by numerous colleagues in DESC-SAWG and DM team

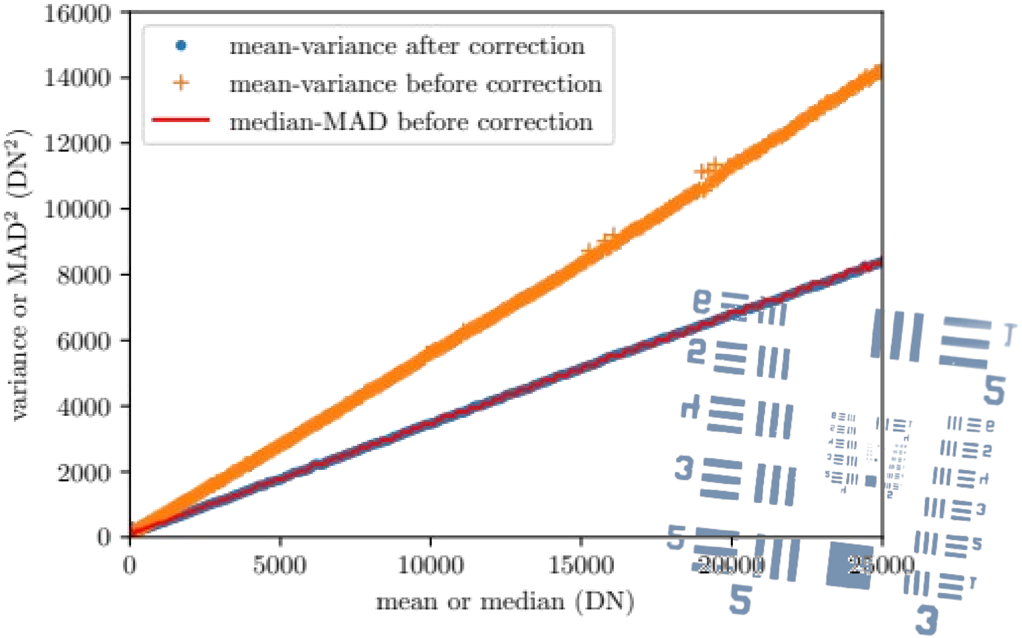
Signal Dependent CTI

- Signal dependent CTI causes peaks in first serial correlation (and dip in variance) – first shown by Astier et al (2019)
- CTI is not large in LSST devices, but it is a real problem not least because **it interferes with our correlation measurements & therefore the correction of the brighter-fatter effect!**
- Snyder & Roodman (2019) found this to be composed of two distinct mechanisms
- **Minor issues for all science cases**



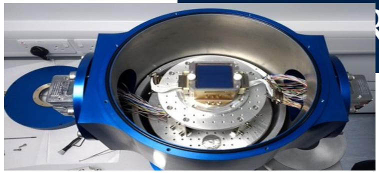
Tearing

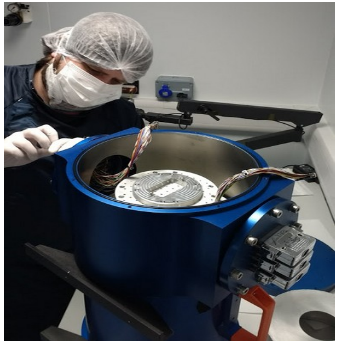
- Time varying “tearing” patterns cause excess variance due to incomplete cancellation on subtraction (left) – they appear at random times under certain CCD operating conditions



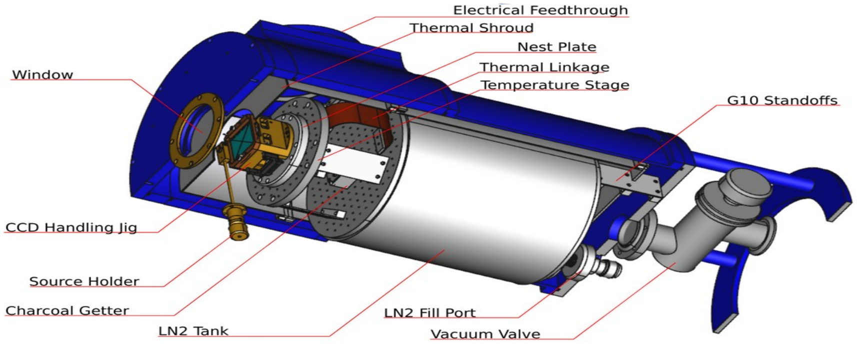
- Mechanism is believed to be due to trapped holes in the channel stops of the CCD
- Easy to correct in e.g. flat field images (right) but not so easy in science images, must be prevented
- Operating conditions to minimise tearing have been investigated
- **At this stage, we have empirically verified parameters for most devices which do not result in tearing**

Oxford LSST Test System



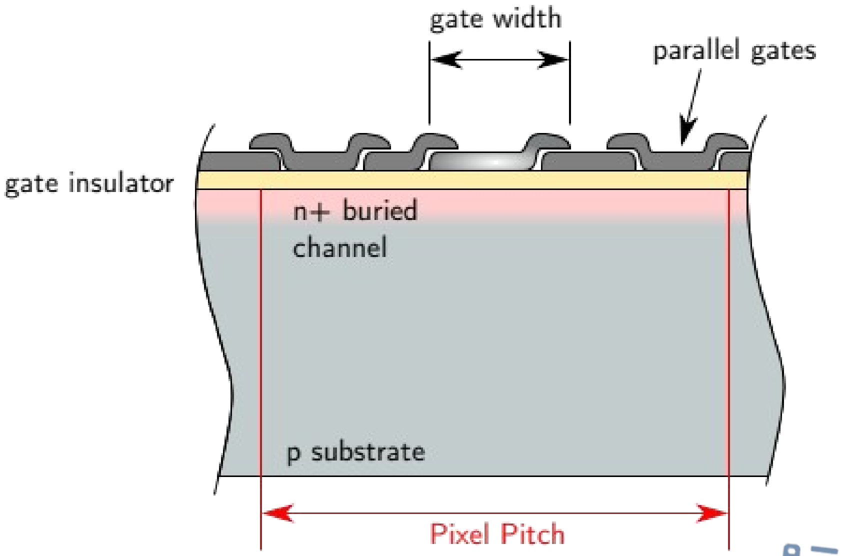


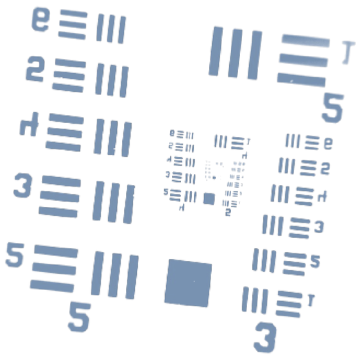
- LN2 cooling and active table for low vibration
- 250W QTH light source + monochromator (300nm – 1600nm wavelength)
- Online radiometry and spectrosopy (at integrating sphere)
- Can quickly integrating sphere with projection optics for PSF etc measurements.
- Operates at high vacuum (1E-6 mbar)



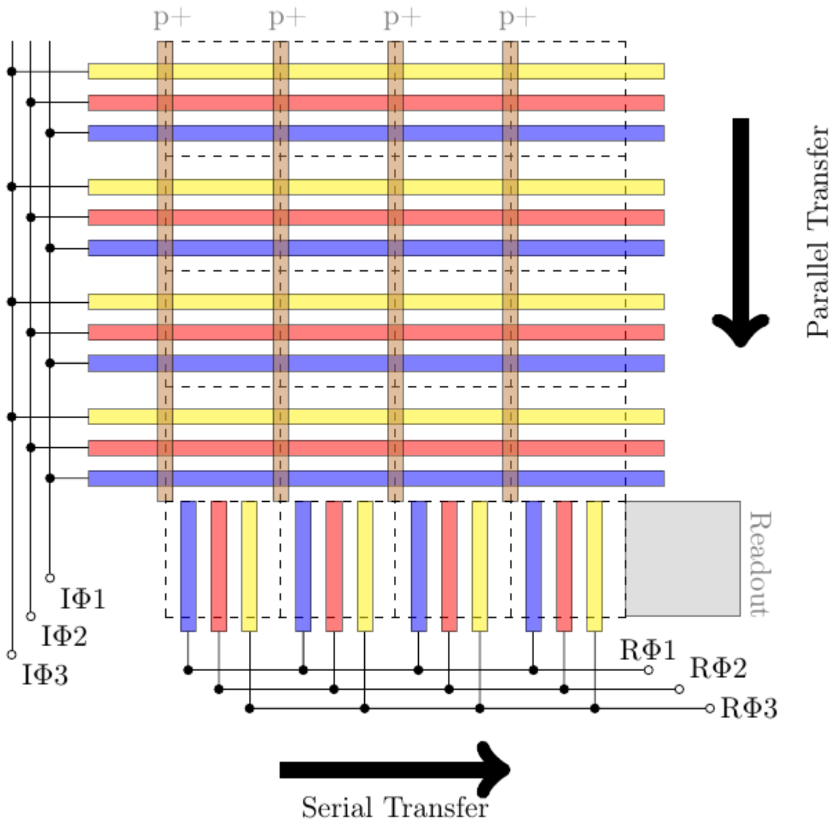
Gate Width Intro

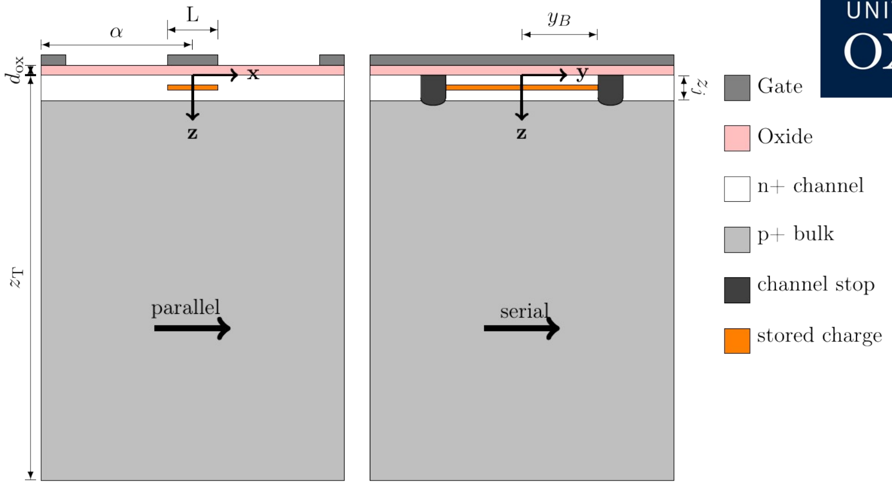
- Investigation into how the width of the CCD parallel gate affects the size of the brighter-fatter effect
- Gate widths determined at manufacture time, but can choose how many are energised at integration time
- Tests on prototype E2V CCD250 (final version used in LSST camera focal plane)





CCD Gate Width

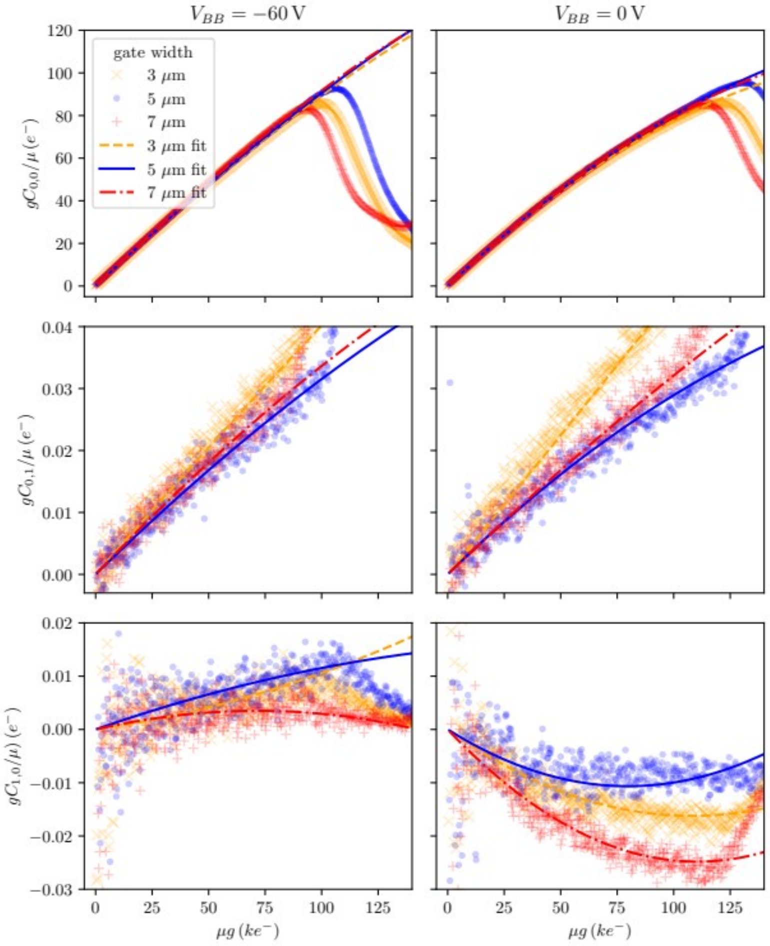




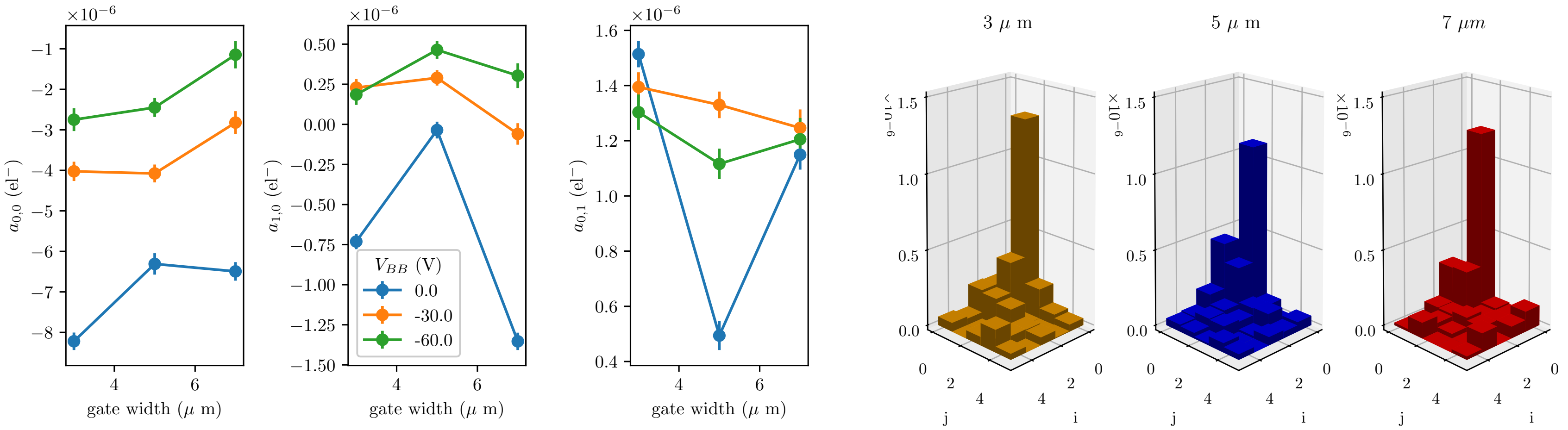
- CCDs transfer charge down columns to serial register, then along serial register to readout (left)
- Confining fields defined by gates in parallel direction, and channel stop implants in serial direction

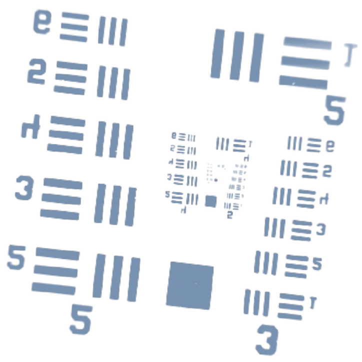
Flat Field Measurements

- At each of 3 gate widths and each of 3 back bias (VBB) values, we take an 800 flat pair photon transfer curve.
- We fit Astier et al's equation to each covariance measurement out to 5th nearest neighbours.
- Clear differences shown in nearest parallel & serial neighbours for different gate width (right)



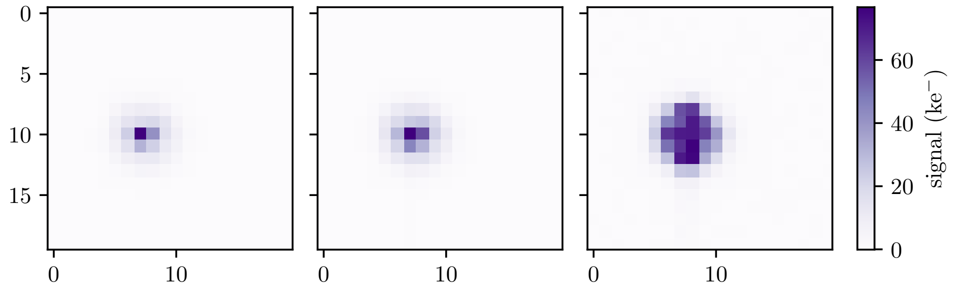
Flat Field Results





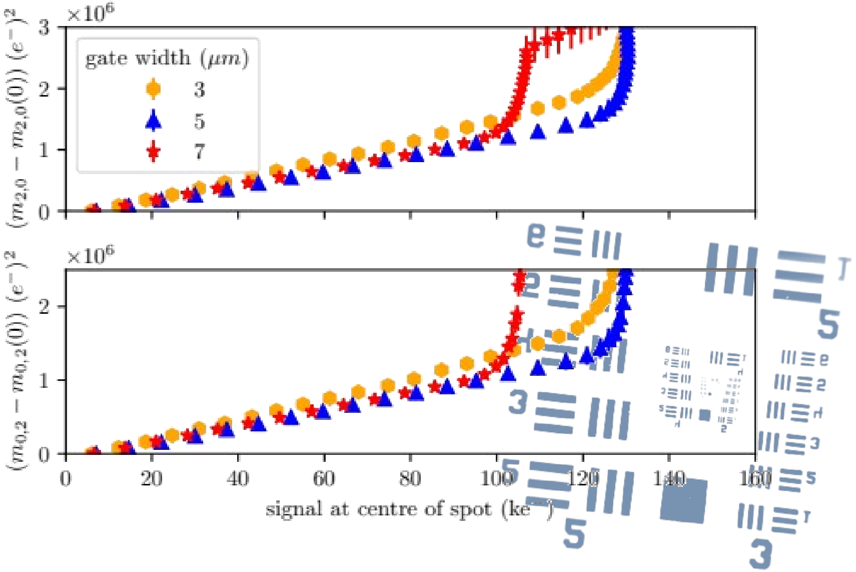
- At zero back bias, middle choice of gatewidth clearly better in all regards
- At high back bias, larger gate widths appear moderately better overall, with middle gate width still the best for individual nearest parallel & serial nearest neighbour measurements
- **Gatewidth matters significantly in the magnitude of the brighter-fatter effect, and we can improve it for free by choosing the correct one!**

Spot Measurements



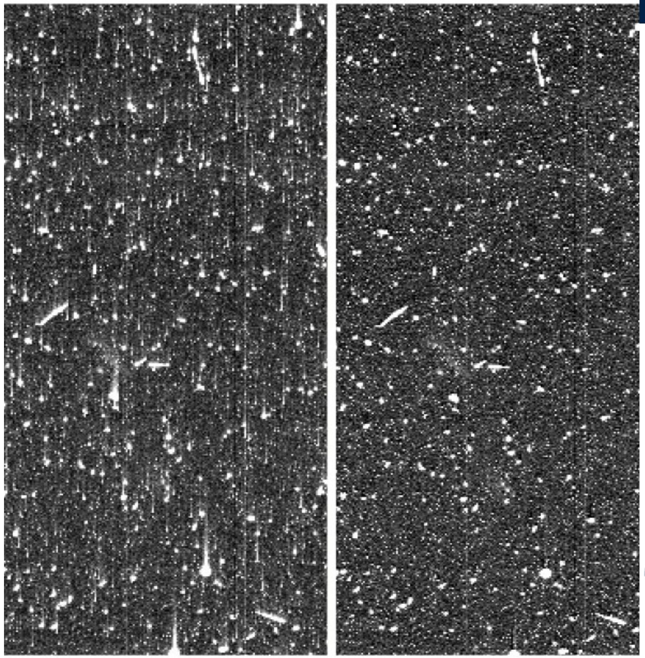
- Single 10 micron spot projected onto CCD, images taken at different integration times, at back bias of -60V

- Spot size analysed via method of central image moments
- Results corroborate flat field results – spot grows most slowly in both dimensions (serial & parallel) for larger gate width choices



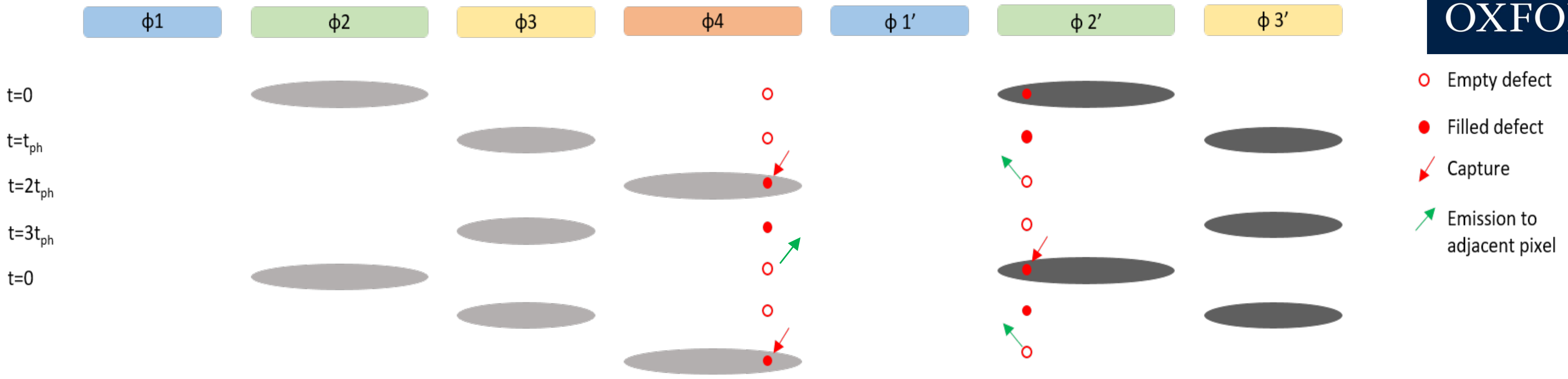
Charge trapping

- Charge transfer architecture creates susceptibility to charge trapping at mid-bandgap defect level states.
- Can lead to charge transfer inefficiency (CTI) and image ‘trailing’. CTI recovery models depend on accuracy of the underlying defect distribution.
- Analysis of single defects directly in time domain can be beneficial for optimising CCD runtime parameters.

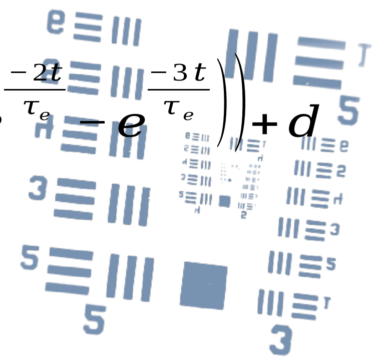


‘Pixel-based correction for Charge Transfer Inefficiency in the Hubble Space Telescope Advanced Camera for Surveys’ - R Massey *et al*. 2010

Single trap-pumping



- Move charge repeatedly between neighbouring pixels.
- Defects will capture and release charge, resulting in characteristic ‘dipoles’ - dark pixels neighbouring bright ones.
- The dipole intensity is dependent on the line transfer time (phasetime) and the properties of the defect.



$$\frac{I}{N} = A\left(\left(1 - e^{\frac{-t}{\tau_c}}\right)\left(e^{\frac{-2t}{\tau_e}} - e^{\frac{-3t}{\tau_e}}\right)\right) + d$$

Trap Pumping In Practice

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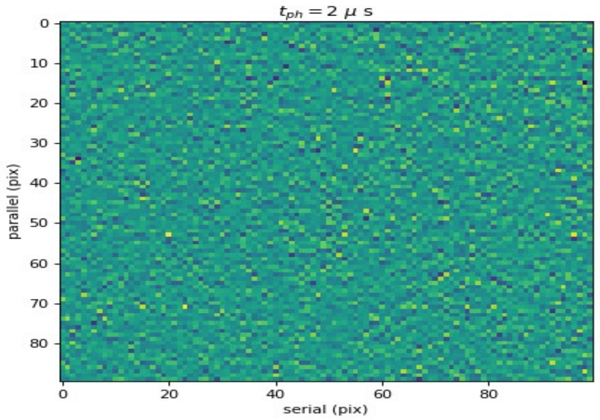
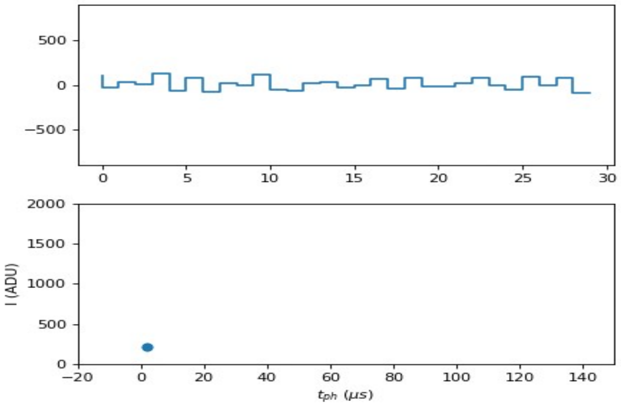
If animation not working try here – http://users.ox.ac.uk/~phys1463//trappump.gif





Procedure: expose to light, then pump a large number of times, varying dwell time. We also take unpumped flats for reference.

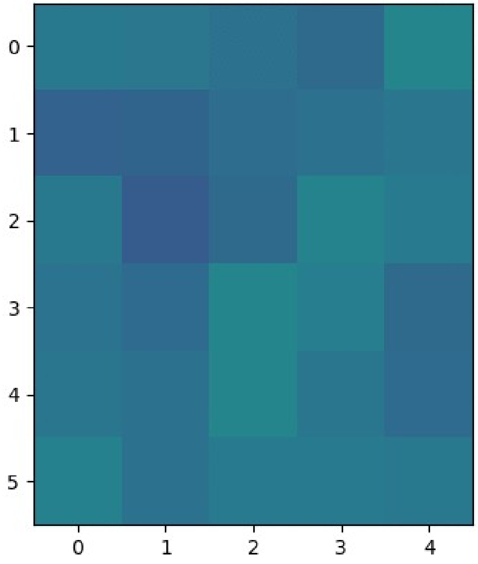
Find traps by simple sigma thresholding (with a goodness of fit cut after fitting emission time curve).

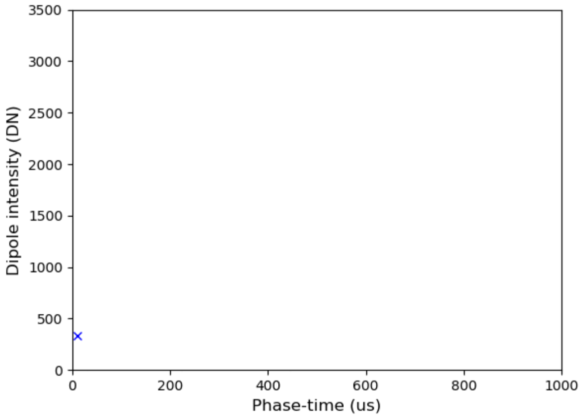
We typically can get away with 4 sigma exclusion.

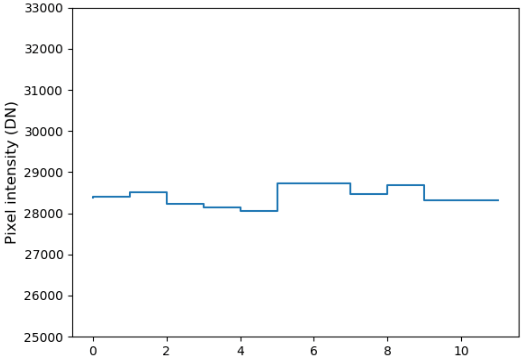
In an unirradiated device, traps are rare!

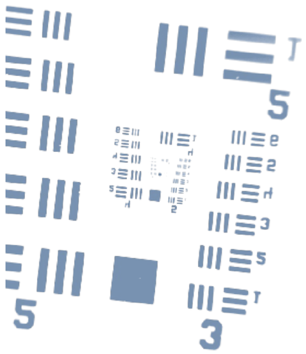
Animation on left – some of our earliest (2018) attempts at getting this working on the CCD250

Trap Pumping In Practice



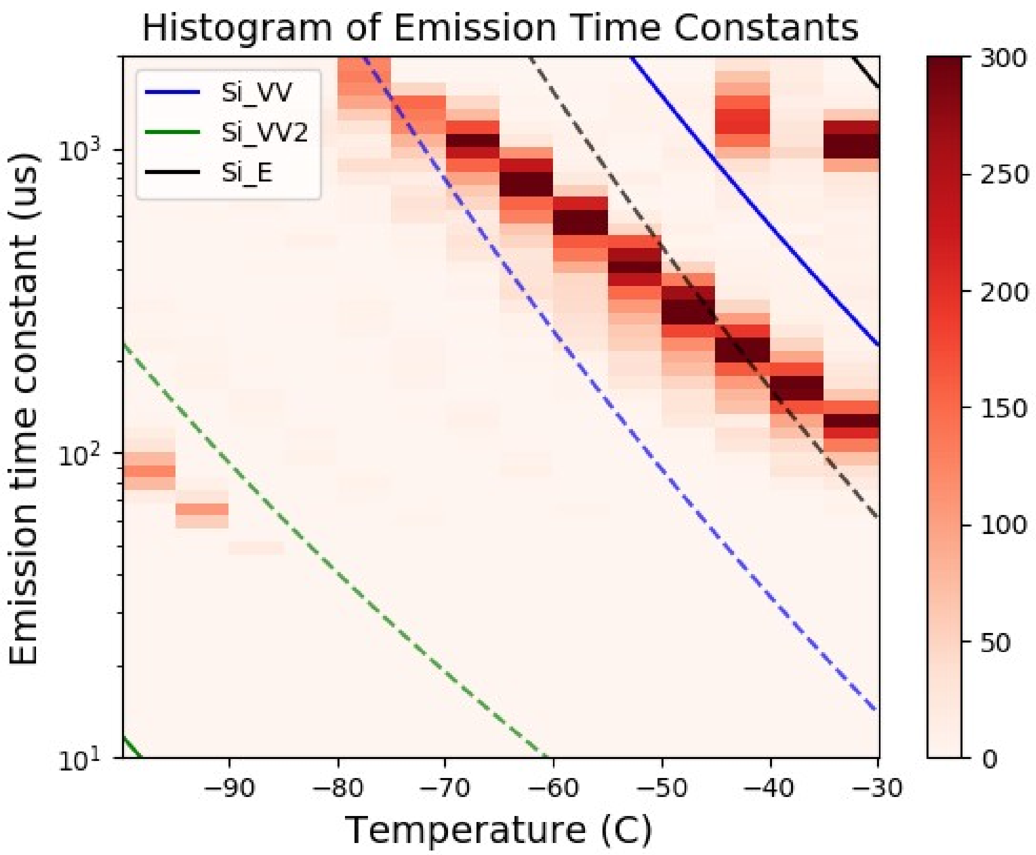






Trap Pump Results

- Mapping out the “trap landscape” of the CCD250 device allows us to find timing sequence combinations to avoid in readout – reducing the CTI due to traditional trapping mechanisms



Final Thoughts

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- Running up to commissioning, we will be assisting the LSST project team in investigating various outstanding issues with the performance of the camera & sensors
- Are there specific sensor / camera performance metrics you are worried about for your science case, that we may not have thought of (team is quite DESC heavy)? Very happy to discuss!
- Happy to answer any questions to the best of our ability about camera performance & optimisation
- There have been several other investigations under LSST:UK phase B WP3.9 and its predecessor (“phase A”) which had no time to cover today, and upcoming simulation work to narrow down remaining mysteries about brighter-fatter effect and PSF

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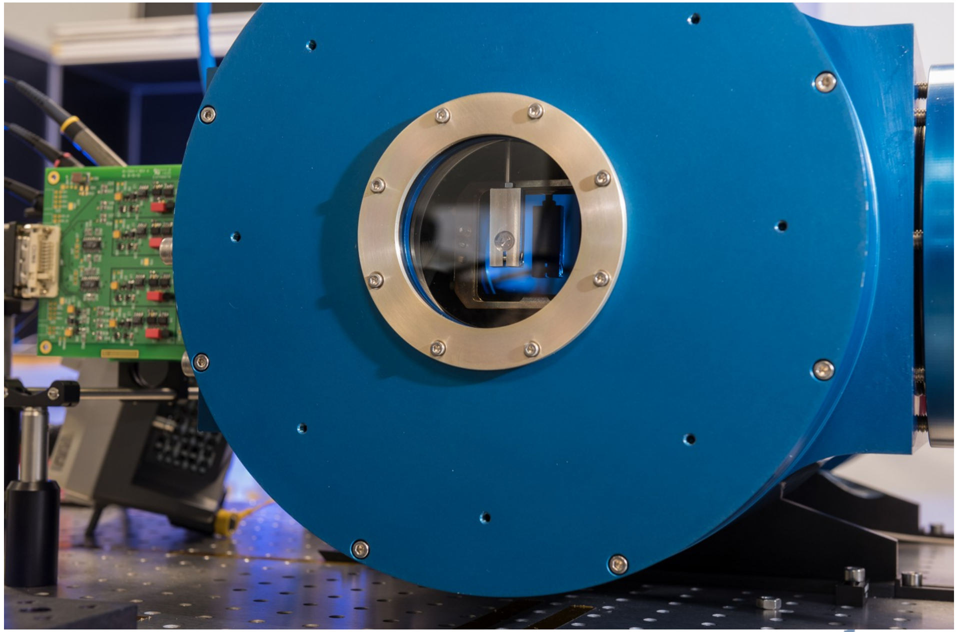
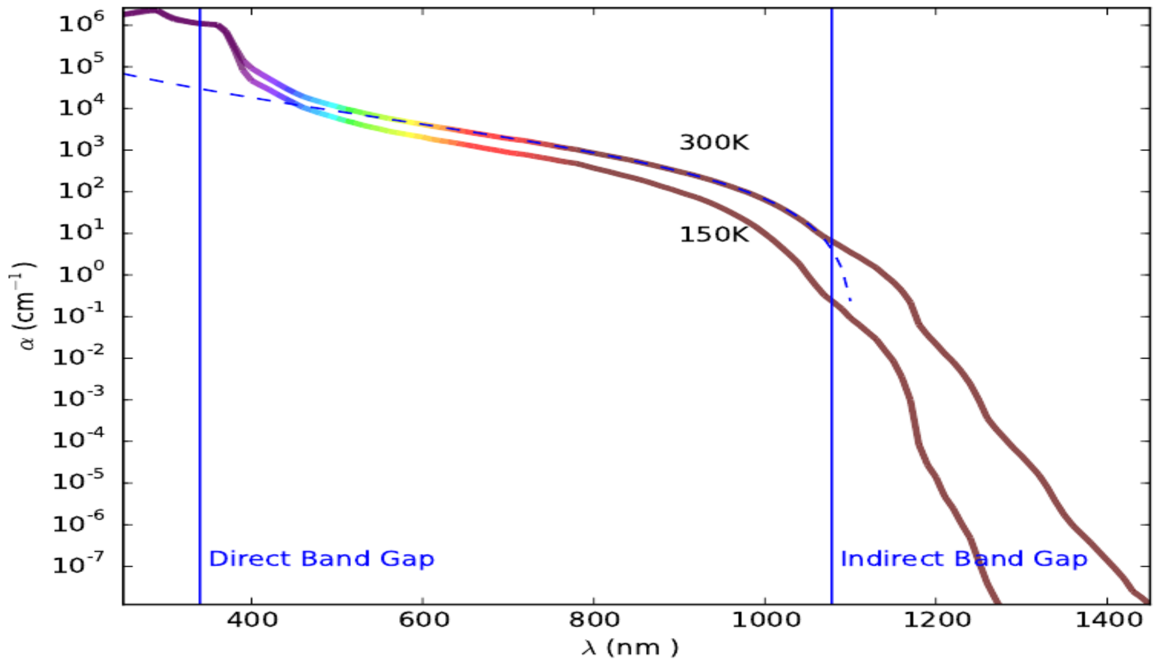
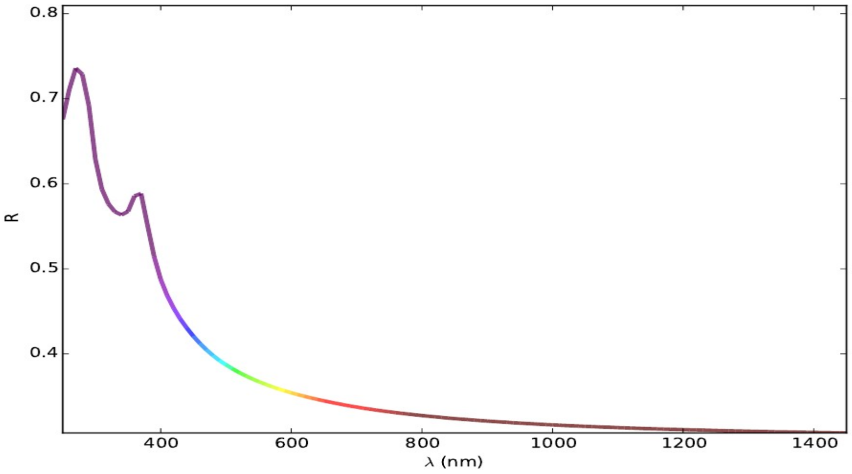
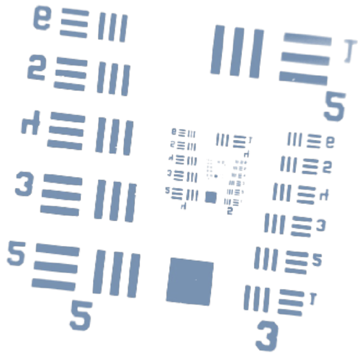


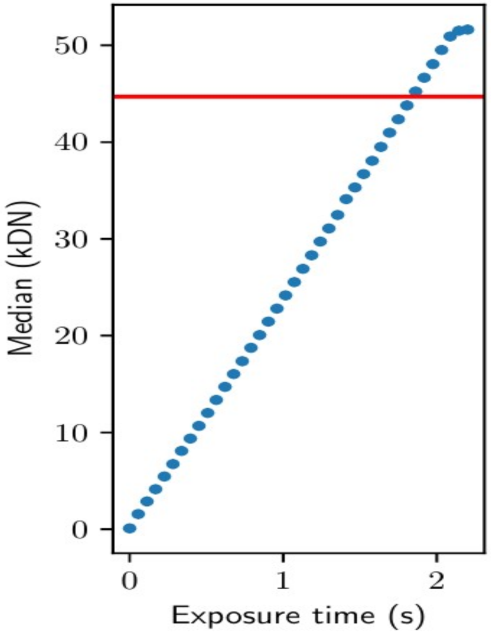
QE components - Spare 1

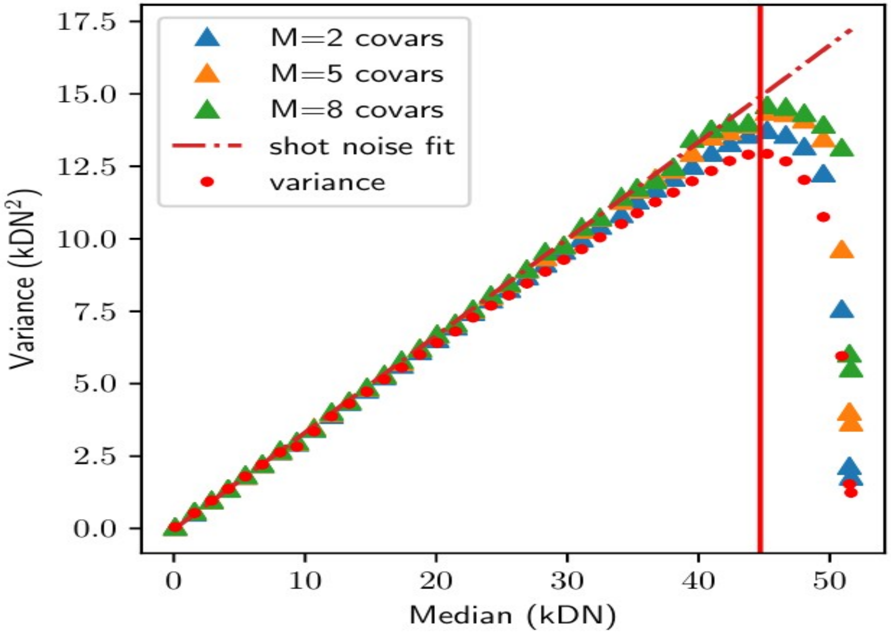






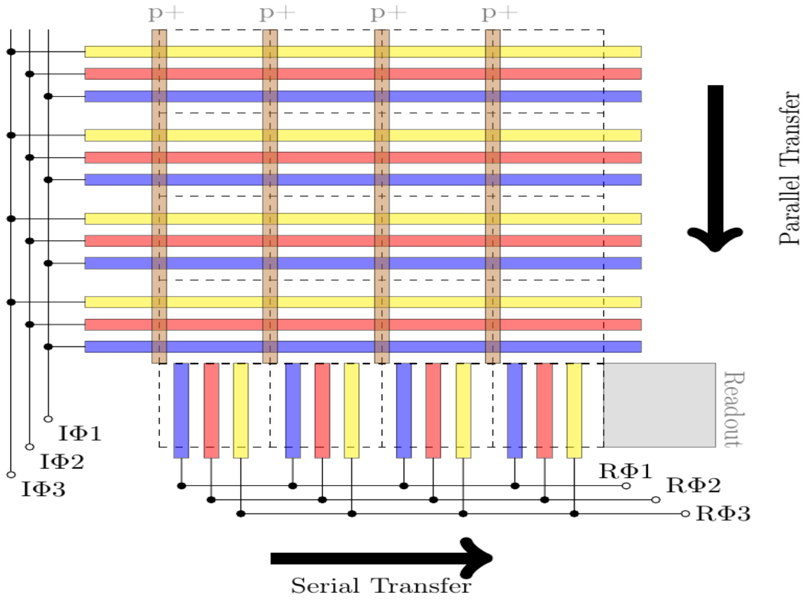
Gain and Full Well – CCD250 (spare 2)





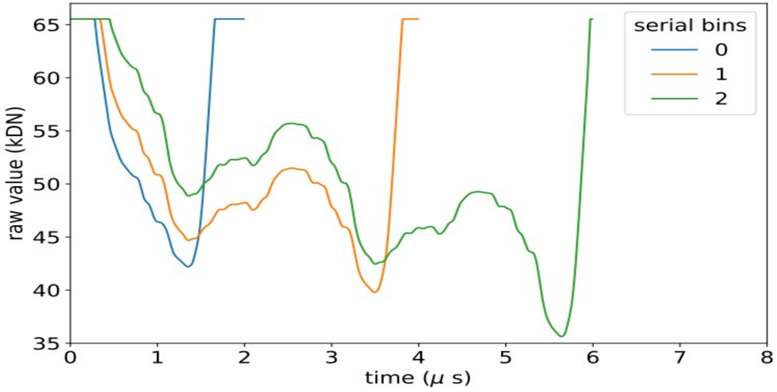
Gain and full well measured from photon transfer method (above)
Gain important in terms of other requirements – “full well” specified in electrons, (175 ke max), but “real” requirement is <4V output swing
Note maximum possible output <u>not</u> the same thing as what we think of as “full well”
LSST has no official specification / requirement for full well

Binned Photon Transfer – Spare 3



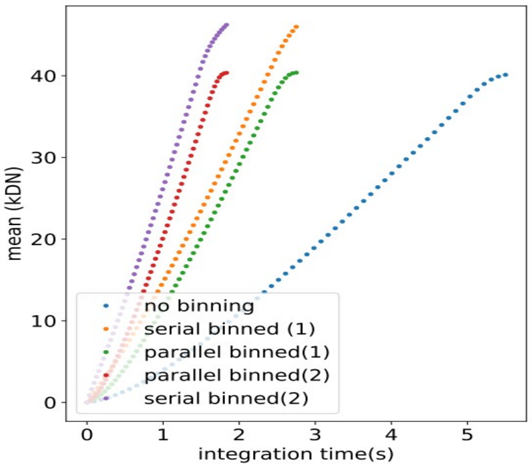
Perform multiple parallel clock sequences per line (parallel binning), or multiple serial sequences per pixel (serial binning)
Allows filling output well with less charge in the pixels (or register)
Known since earliest days of BFE investigation (Downing 2006) to reduce measured correlation

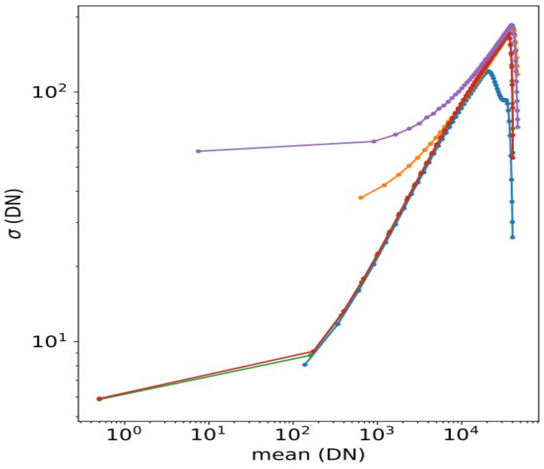
Note since no summing well in CCD250, serial binning incurs a large clock feedthrough noise penalty (one pixel readout for different serial binnings shown right)

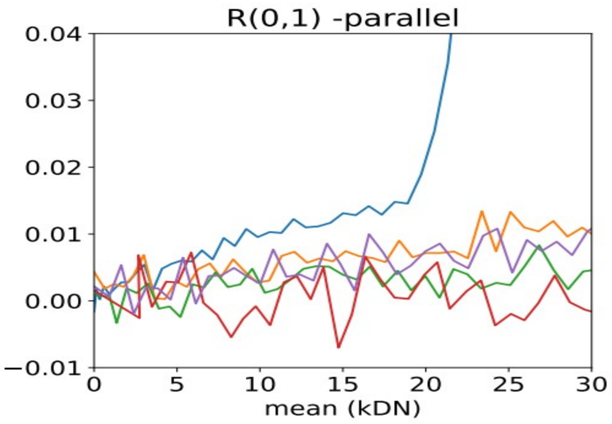


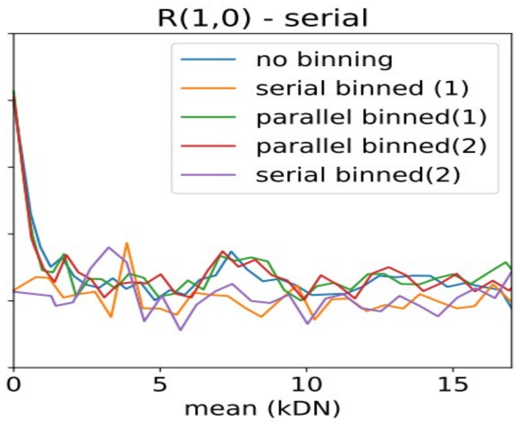
Binned PTC correlations – Spare 4

As more pixels are binned, less integration time is needed to reach output full well (though the pixel charge is decreasing with each extra bin)









The binned PTC can isolate problems arising due to poor serial CTI in this prototype device (see R(1,0)) plot
Note that binning in <u>either</u> direction reduces BFE correlations, due to reducing pixel charge for the same output charge (see R(0,1) plot)