Instrumental signatures on cosmological observables

Andean Cosmology School, Universidad de Los Andes, Bogotá
Week 4, lecture 4
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Andrés Alejandro Plazas Malagón
andres.a.plazas.malagon@jpl.nasa.gov

Caltech Postdoctoral Scholar
Astrophysics and Space Sciences Section
NASA JPL-Caltech

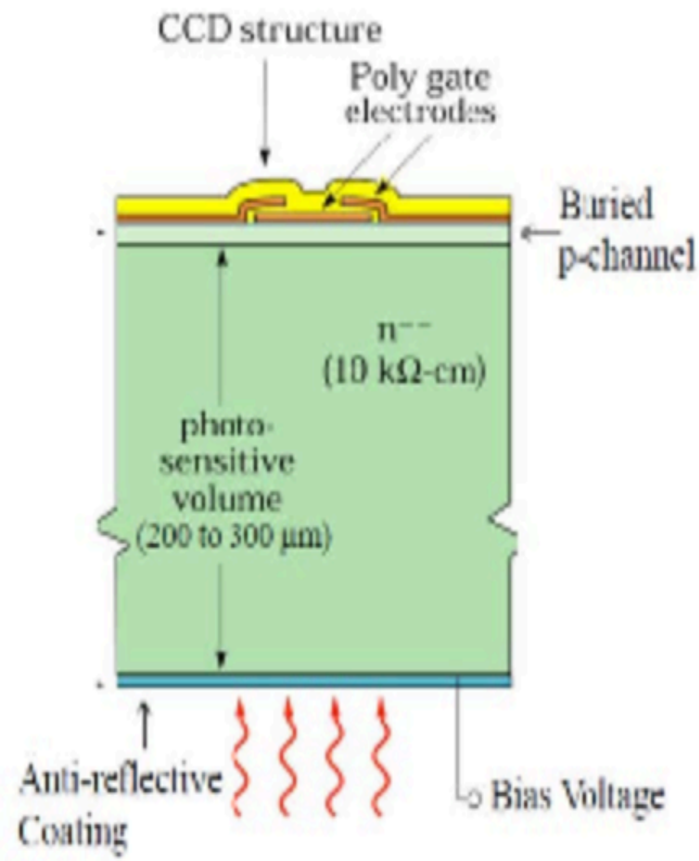
Jet Propulsion Laboratory
California Institute of Technology

Outline of the lecture

- **Structures in flats**:
  - Tape bumps
  - Edge distortions
  - "Tree rings"
- **Flux-dependent size of the PSF**: the "brighter-fatter" effect.
- **Impacts on weak lensing science**

Thick CCDs in Astronomical Surveys

Have many advantages,
but also suffer
from effects that
introduce biases larger
than what can be
tolerated for precision
astronomy.



Sensor effects and precision astrophysics

- ESO is striving to attain nanometer centroid accuracies for spectra, for planet hunting/radial velocity studies.

- Measuring dark energy properties using type Ia supernovae is presently limited by photometric calibration issues, at the 1% level.

- LSST (from ground) and Euclid (from space) intend to measure **correlations between subtle shape distortions of galaxies** across widely separated fields on the sky.

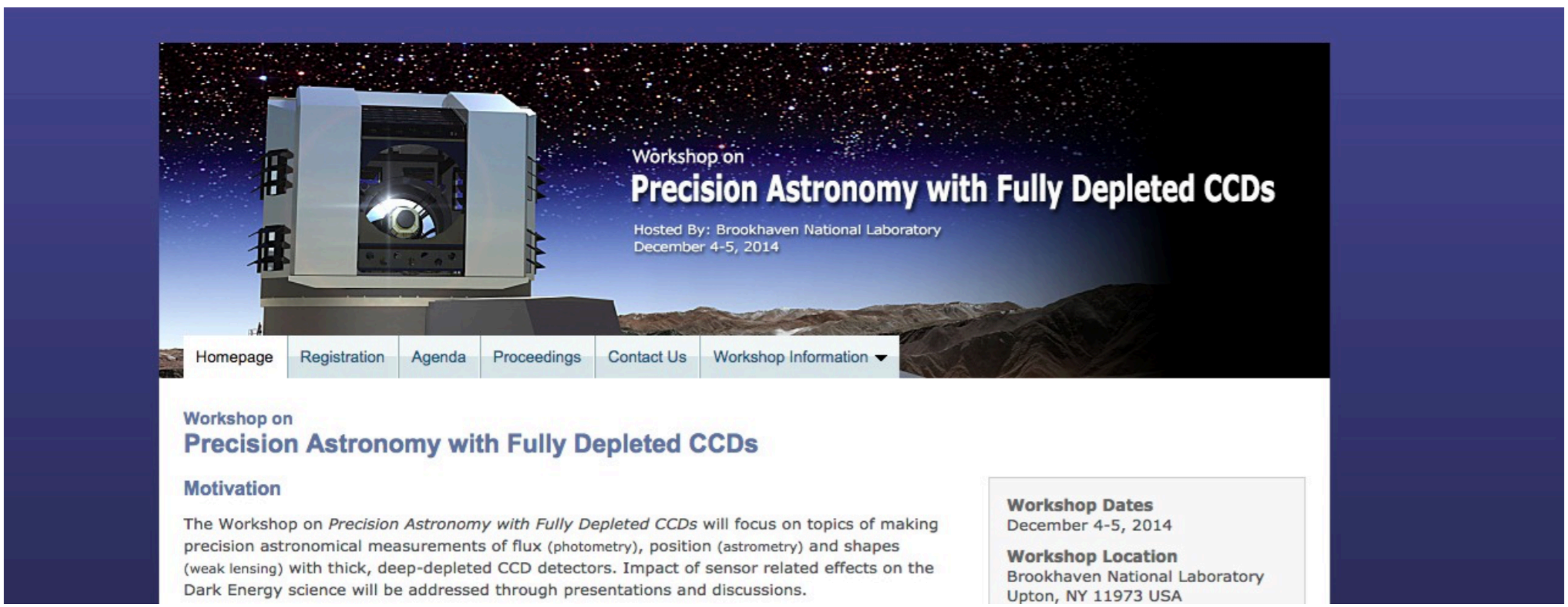
- Gaia proposes to make precision astrometric and photometric measurements across the entire sky, at 7 micro-arcsec astrometric precision.

- Planetary transits produce subtle signals (80 ppm for Earth transiting the sun)

More attention from the community

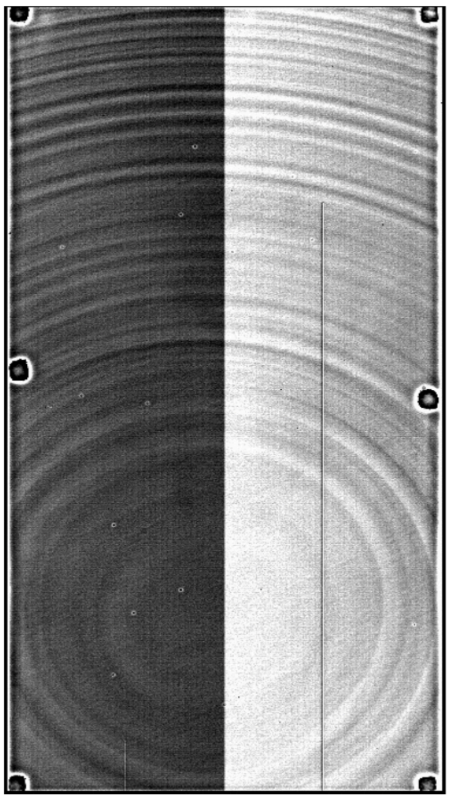
" ...will focus on topics of making precision astronomical measurements of flux (photometry), position (astrometry) and shapes (weak lensing) with thick, deep-depletion CCD detectors. Impact of sensor related effects on the Dark Energy science will be addressed through presentations and discussions."

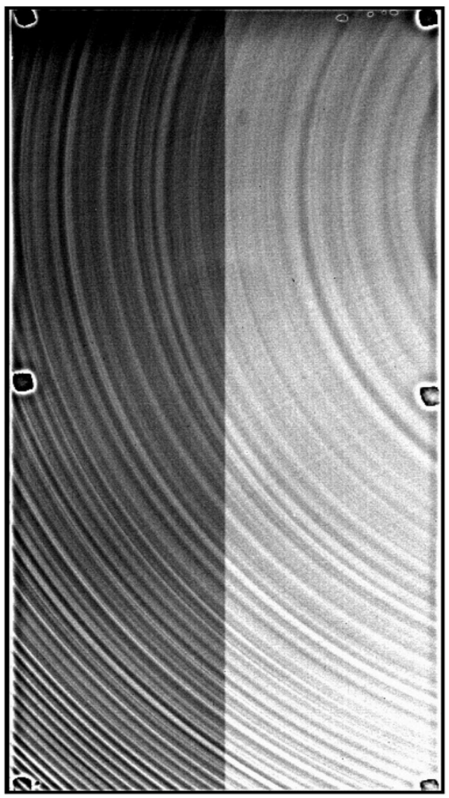
- http://iopscience.iop.org/1748-0221/focus/extraproc47

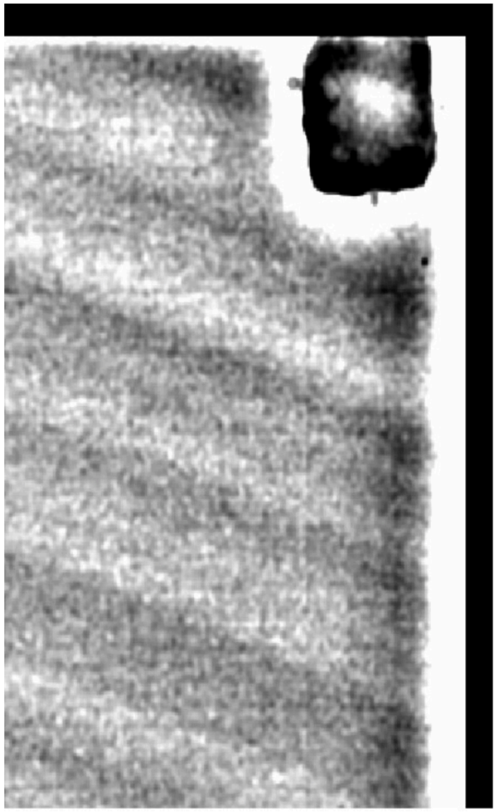


Structures in flat fields

Are they purely QE variations?







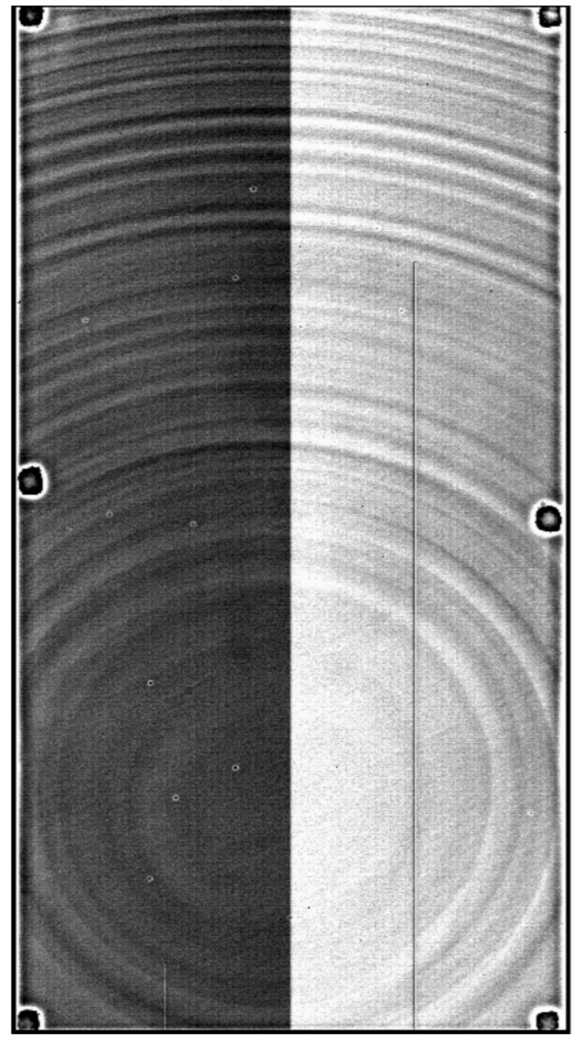
Structures in flat fields

- Pixels have different sensitivities

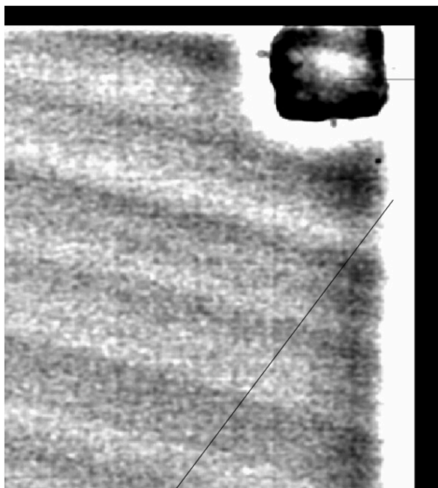
- To correct for it, we take an image under uniform illumination: flat field

- We divide the raw data by the flat field image

- However, not all structures in the flat field are due to sensitivity variations



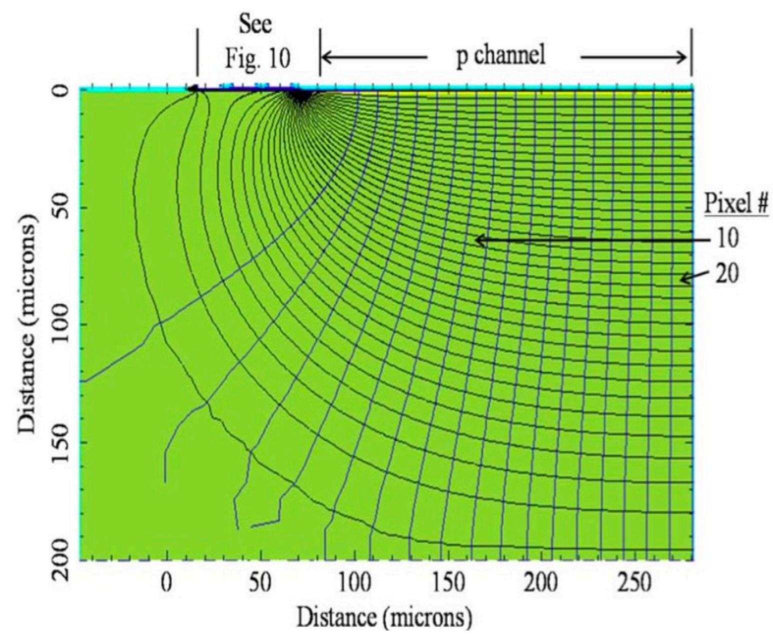
“Glowing Edge” and Tape Bumps



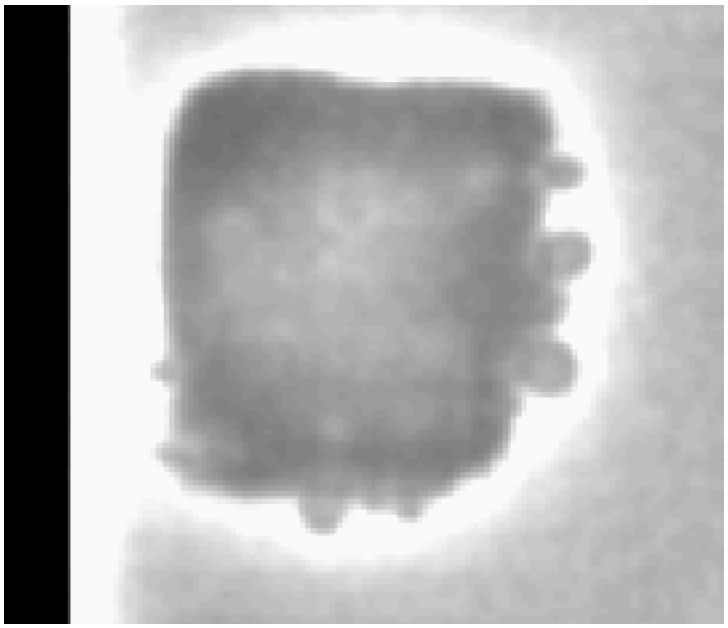
Tape bumps: small gap between CCD and aluminum nitride (AIN) is filled with double-sided tape. Physical deformation that bends electric fields.

Will be masked in DES data.

Glowing edges: electric fields are wider than active pixels at the edges of the CCDs, stretching the effective area of the pixels.



Tape Bumps



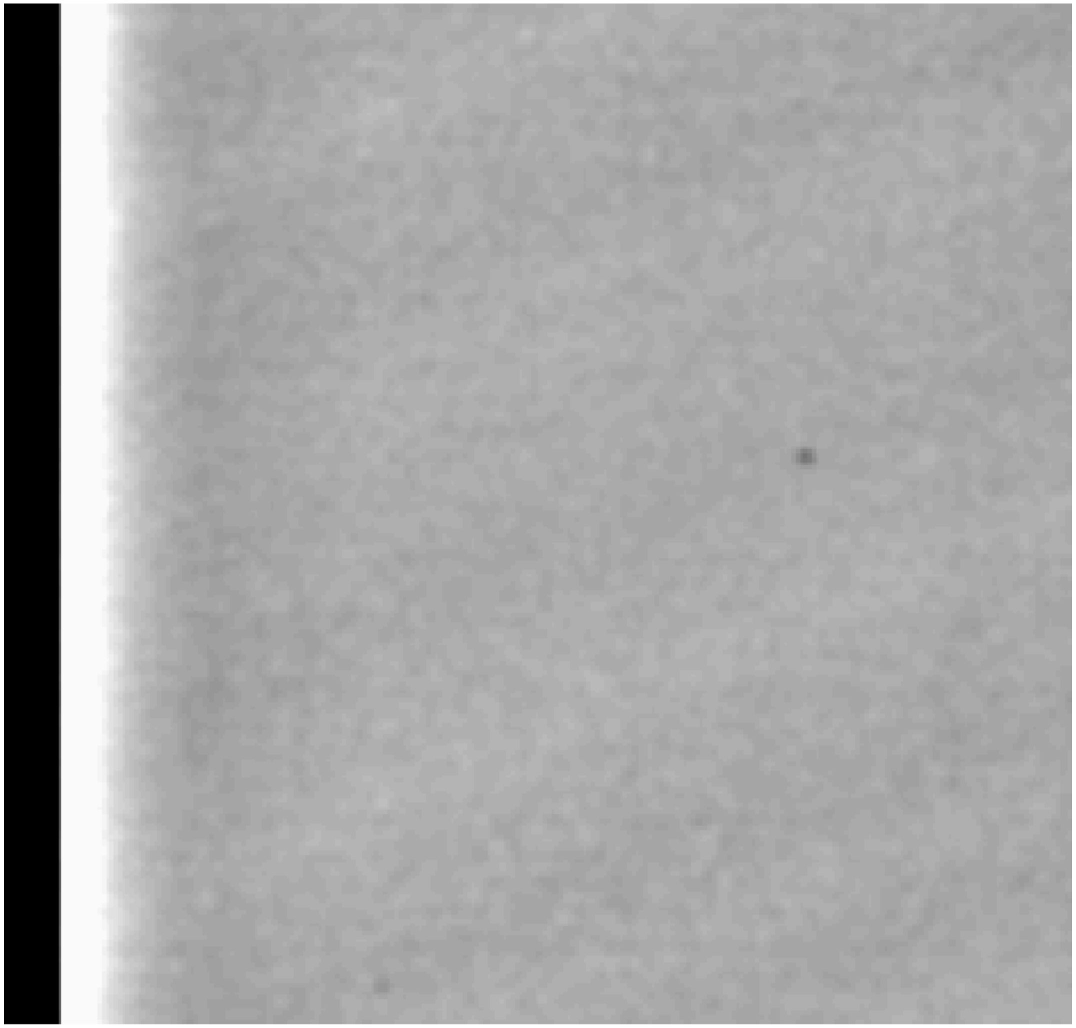
Physical stresses on the silicon lattice
(that in turn distort the electric field lines)
due to pieces of double-sided tape between the CCD and its mount

Distortion too complicated . We will just mask these

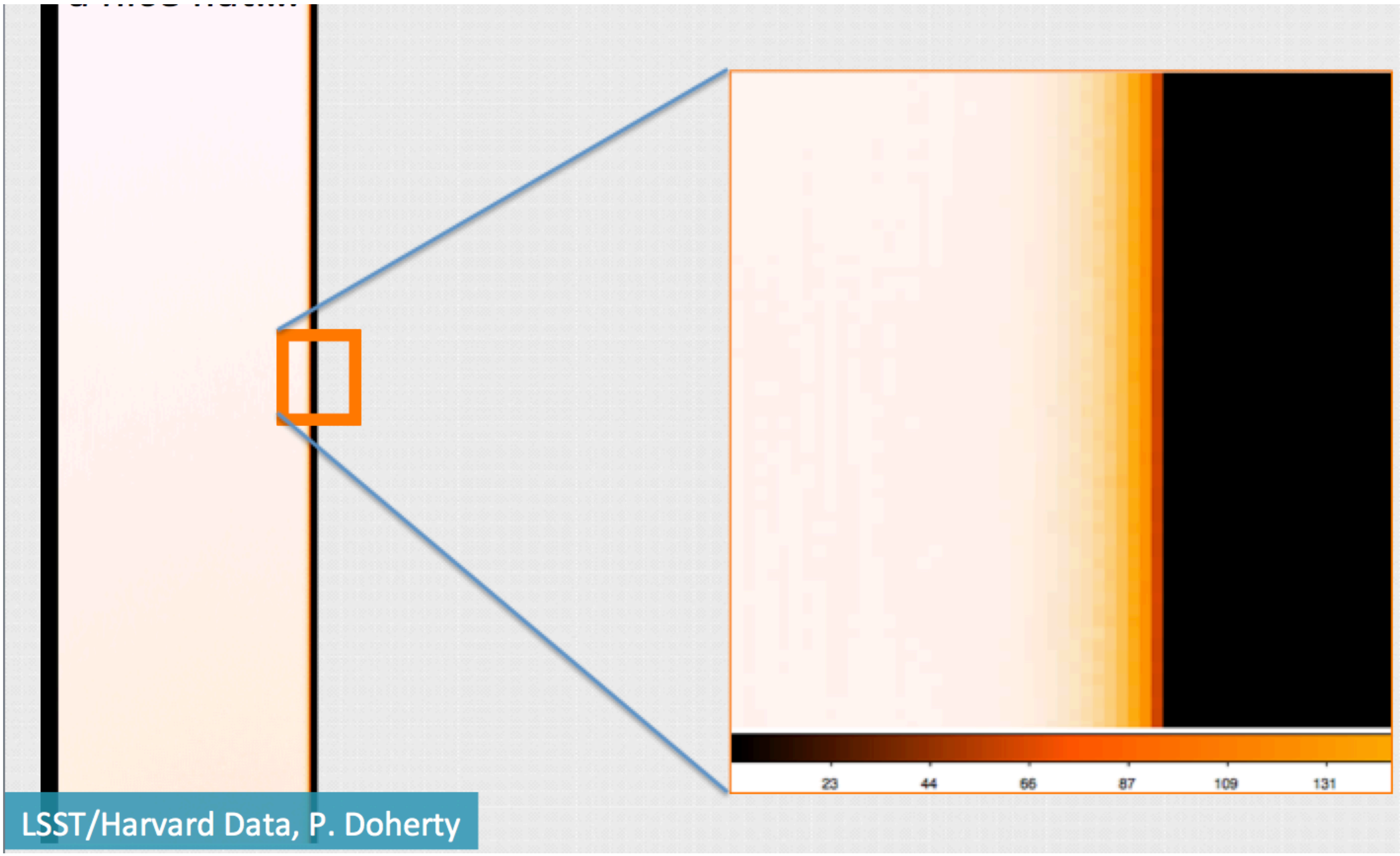
Removes < 0.1% of the total area

It actually improved PSF interpolation after doing this in DES.

“Glowing Edge” in DES

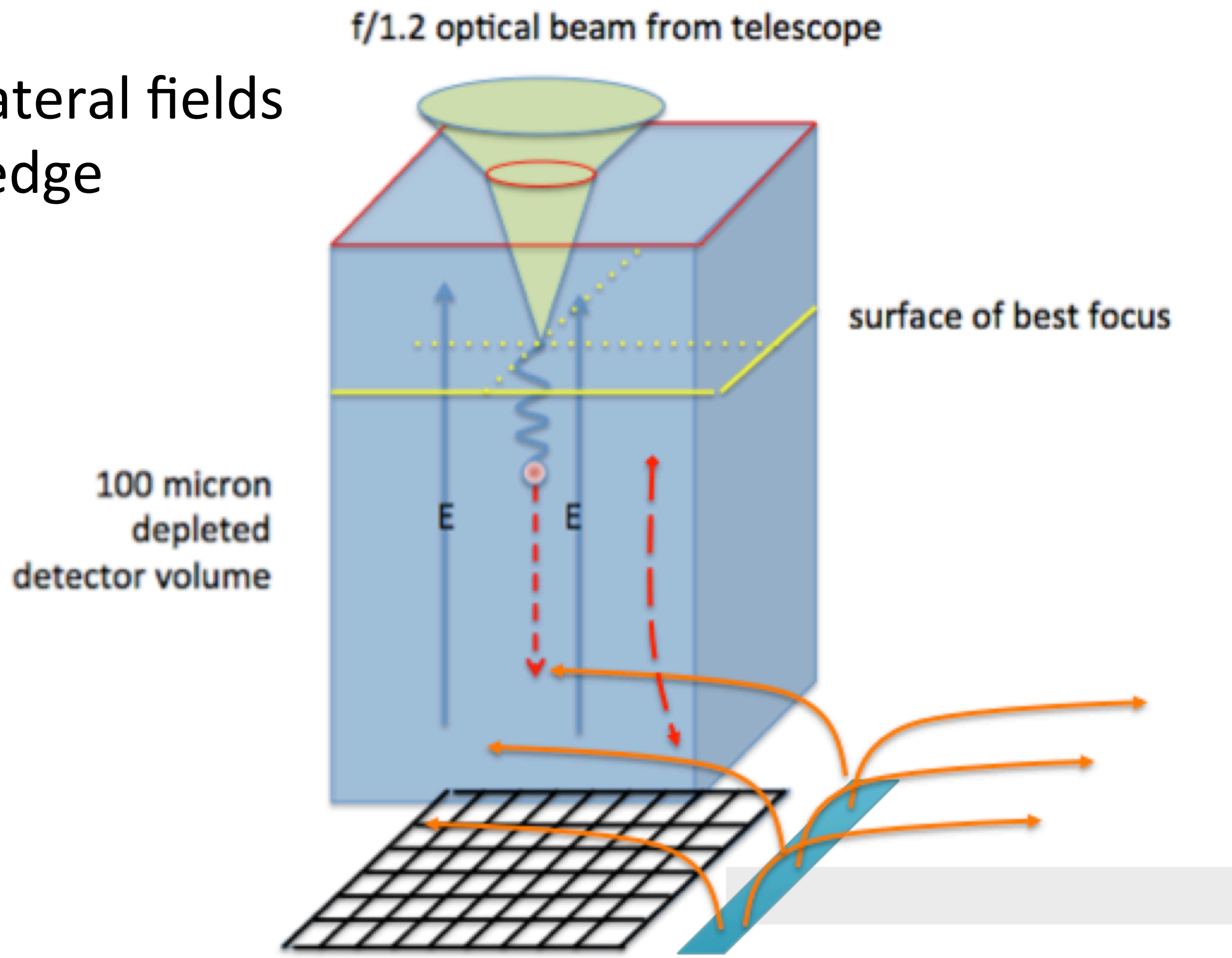


Edge Rolloff in LSST CCDs



Edge Distortion

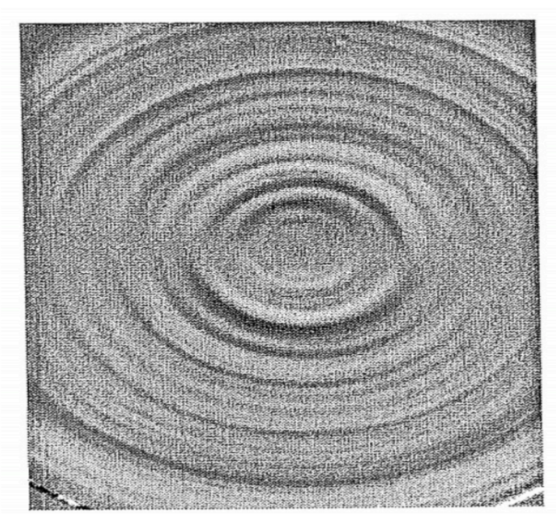
Transverse/lateral fields close to the edge

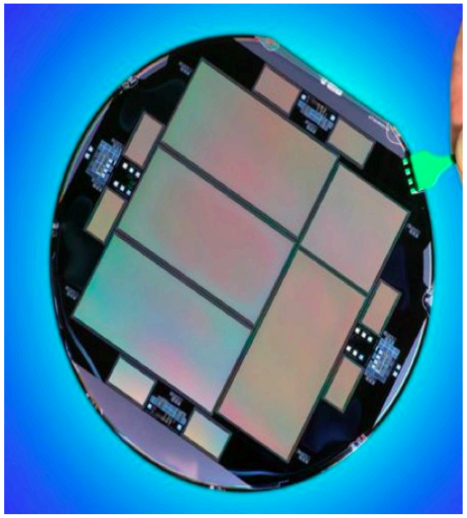


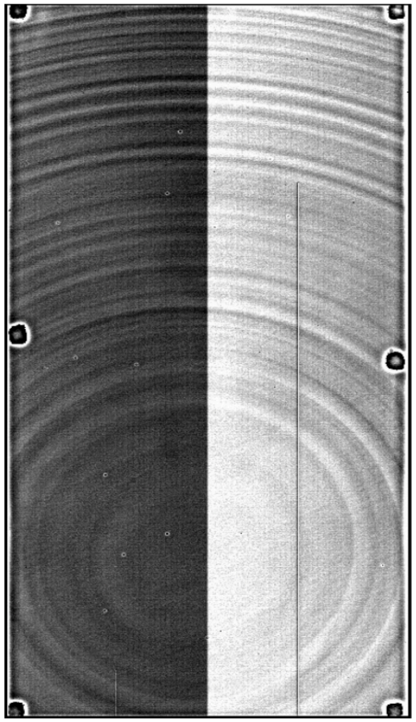
Tree rings

High-resistivity CCDs are fabricated by using the floating zone (FZ) method. In the process, circularly symmetric gradient of resistance (doping) distribution are left behind.

Photoscan of a wafer surface

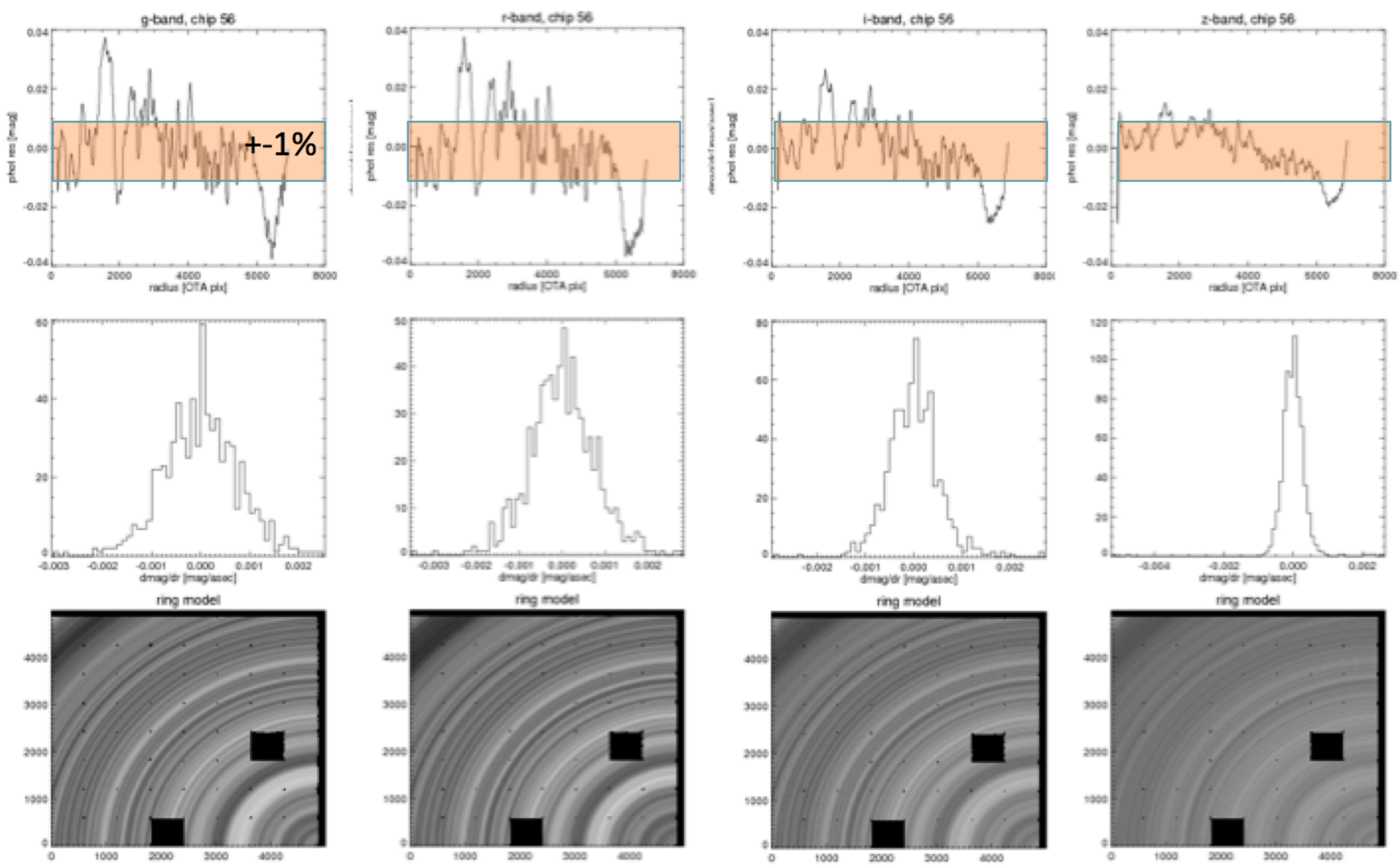






Tree rings

In Pan-STARSS too

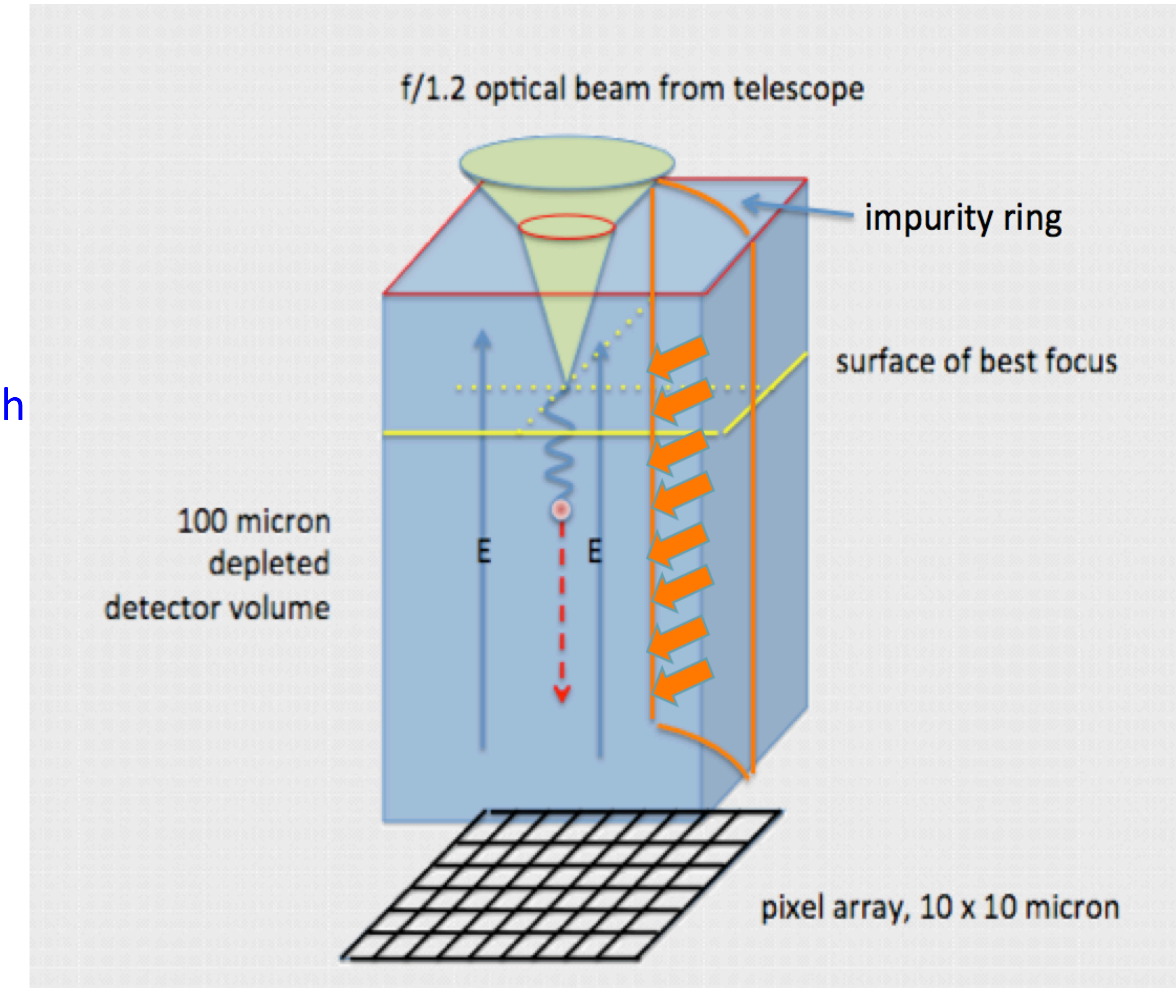


Tree rings

Transverse/lateral
E fields from impurity gradients in silicon

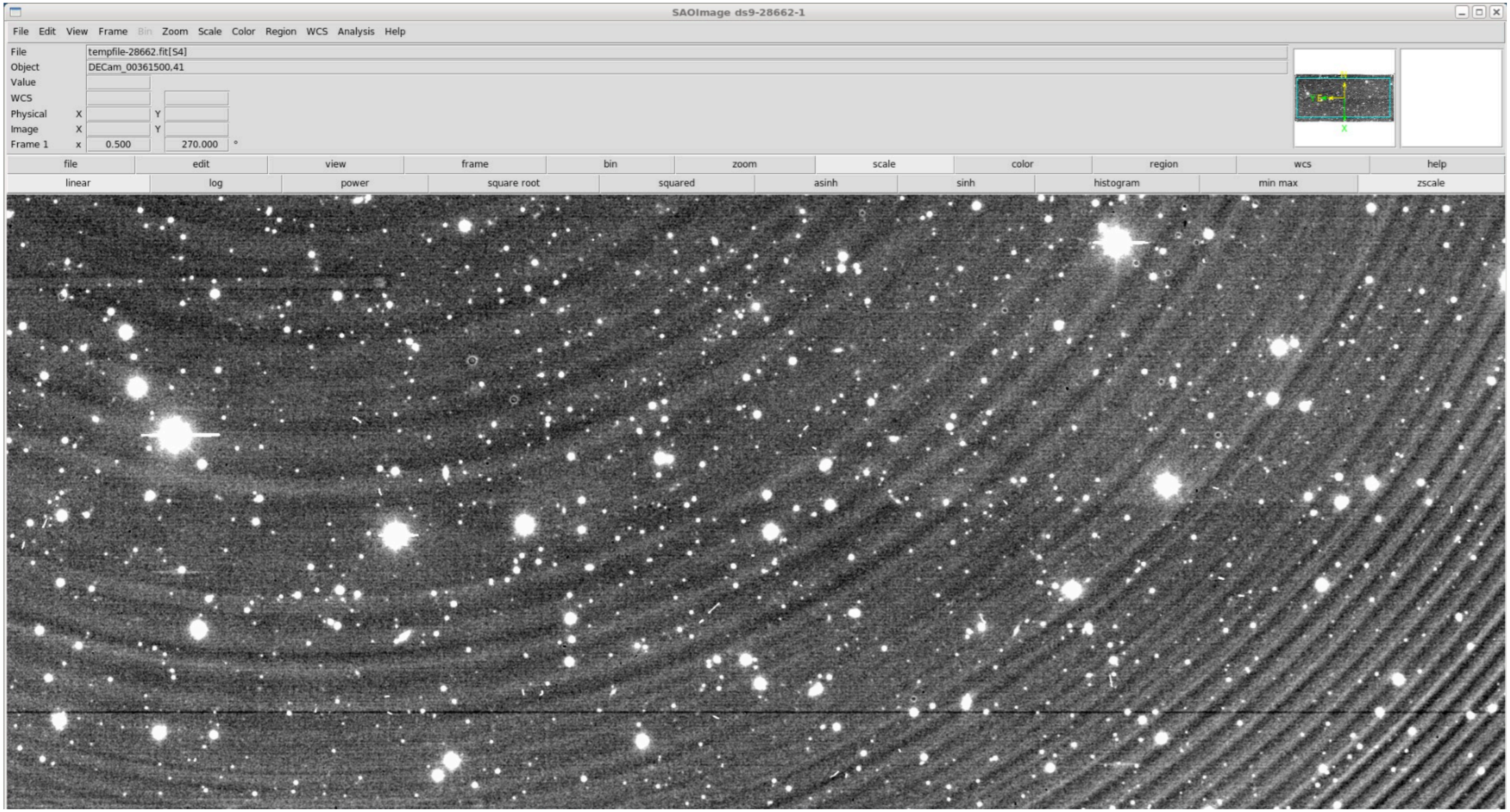
Dopant impurities are incorporated into the silicon during crystal growth

Growth-rate fluctuations due to thermal asymmetries result in the resistivity striations



Tree rings

Raw DES image taken with DECam in the Blanco 4m telescope in Cerro Tololo, Chile.



Impacts on astrometry and photometry

* Transverse fields superpose with existing **E** fields in CCD resulting in distorted electric field lines.

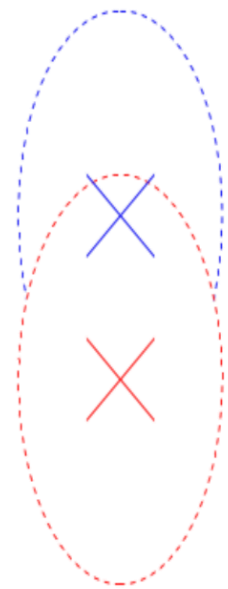
* Redistribution of charge → **astrometry**

* Effective area of pixel changes → **photometry**

* Flat fields give a map of variations in pixel uniformity (PRNU), with contributions from changes in sensitivity(QE) **and** pixel area.

Impacts on astrometry and photometry

* **Astrometric solution:** map from pixel to sky coordinates. Used when stacking images to detect objects (DES requirement: match of < 15 mas between different exposures)

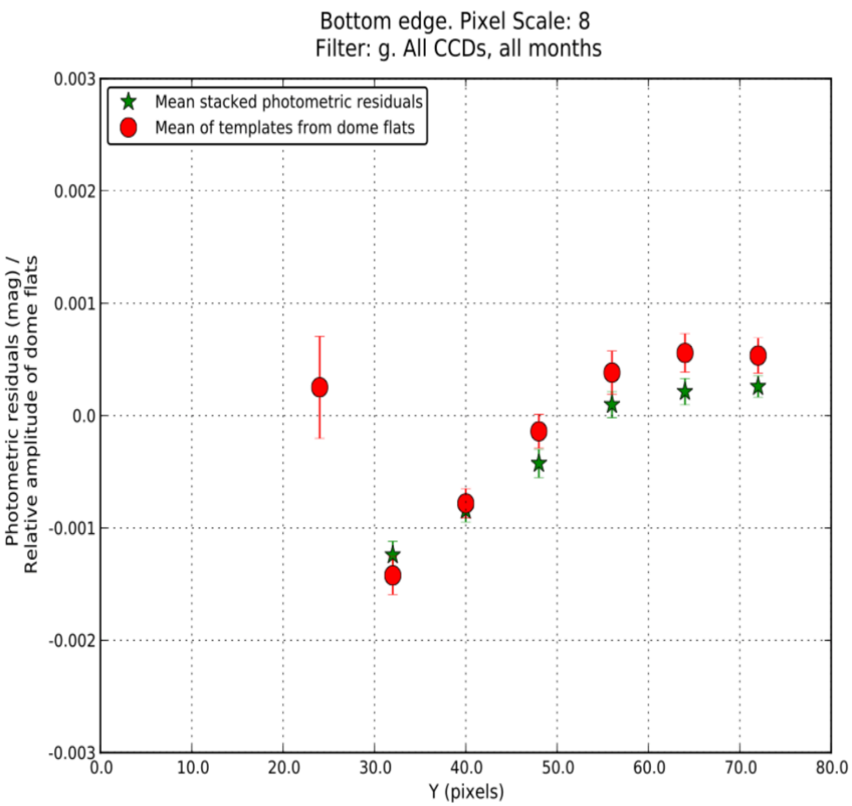


* **Photometric solution:** solution for star flat and zeropoint calibrations for individual exposures simultaneously. DES requires 2% photometry.

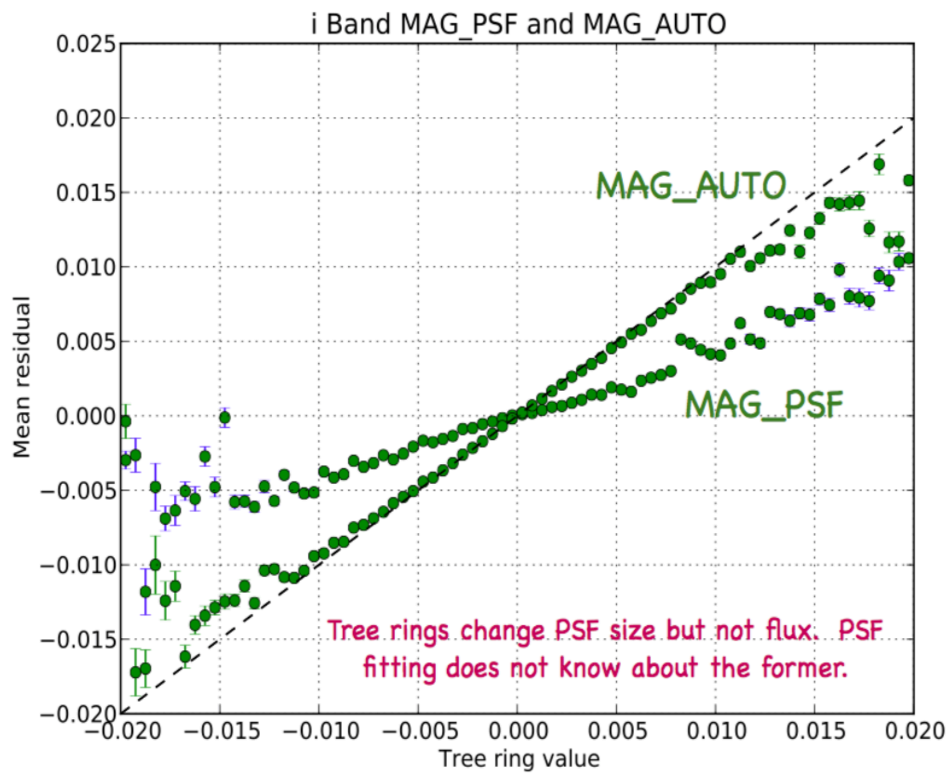
* If glowing edges and tree rings are not included in the optimizations, patterns will remain.

Naïve flat-fielding: biases in photometry

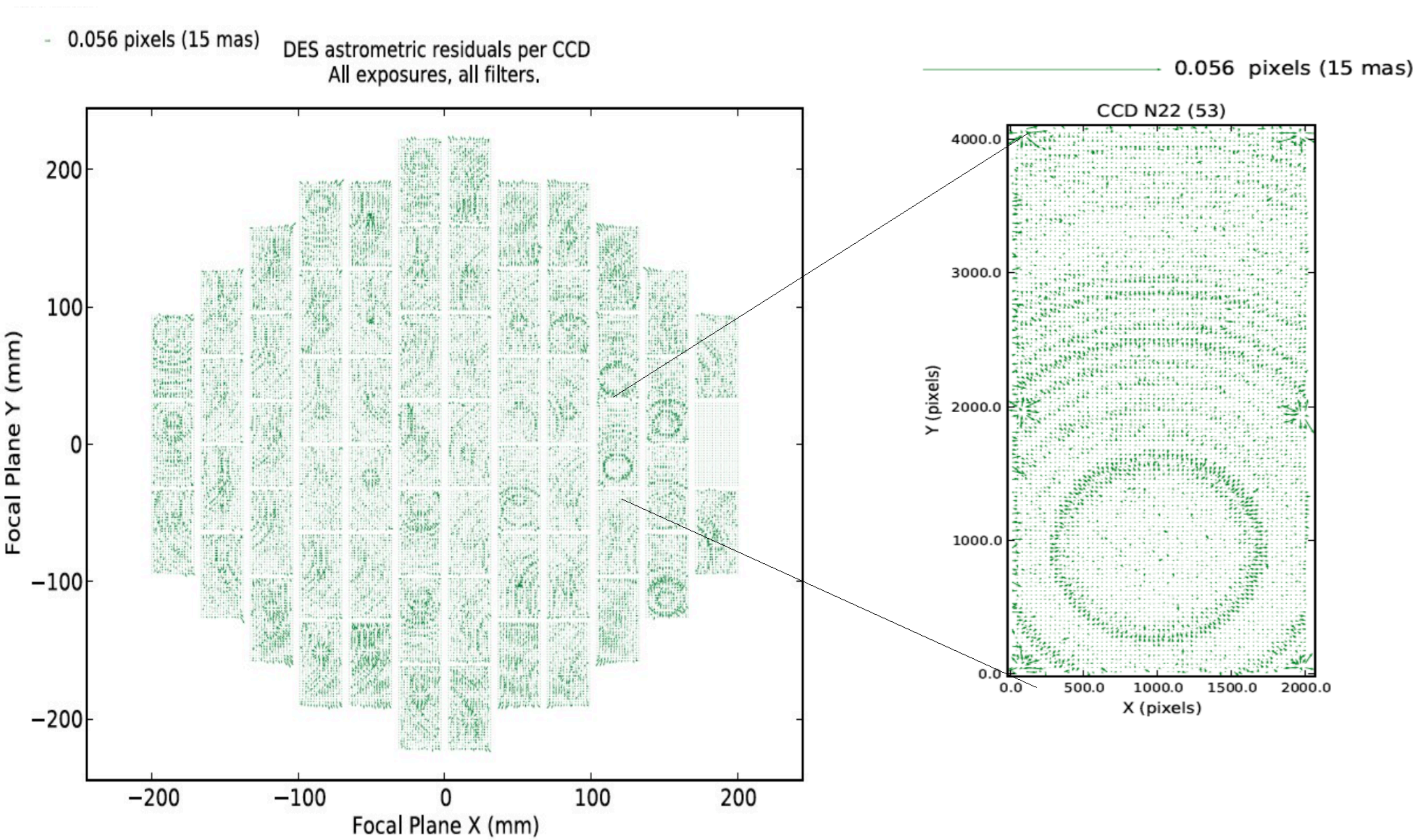
Glowing edge



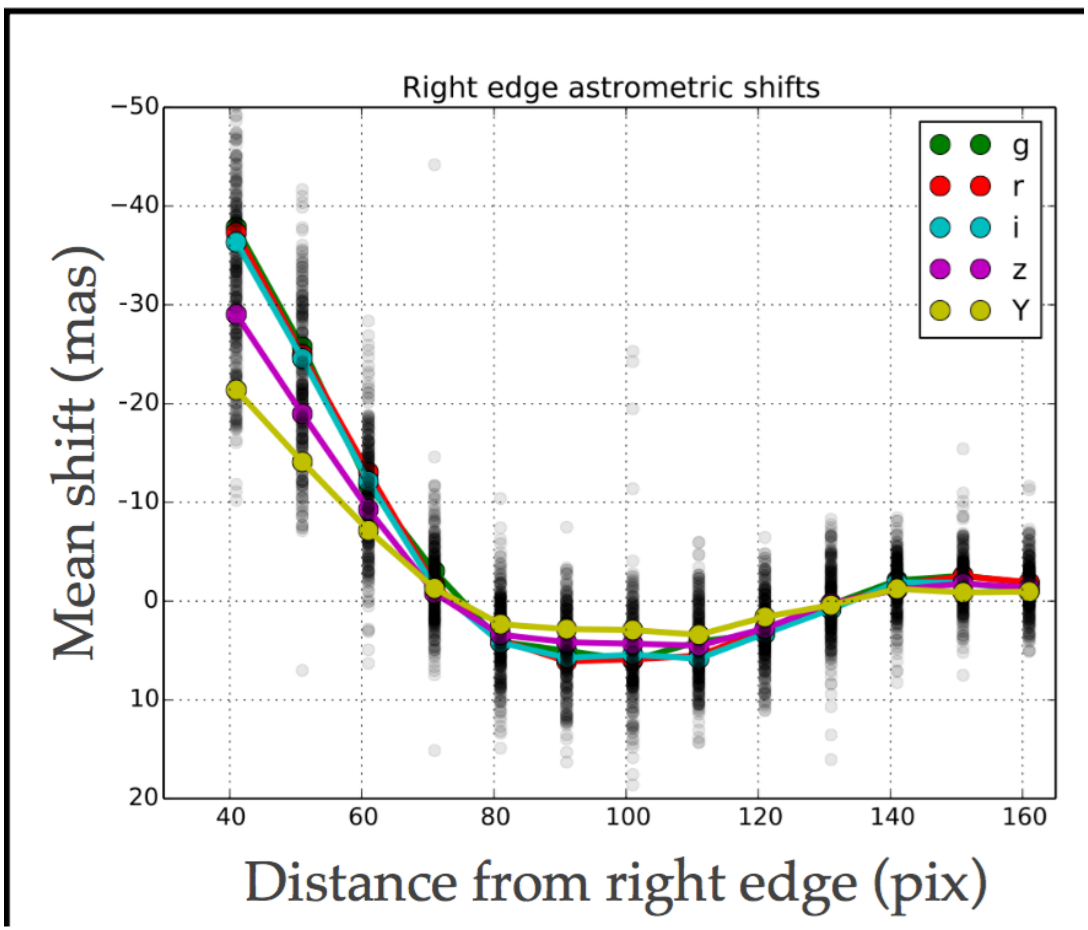
Tree rings:



Impacts on astrometry: tree rings

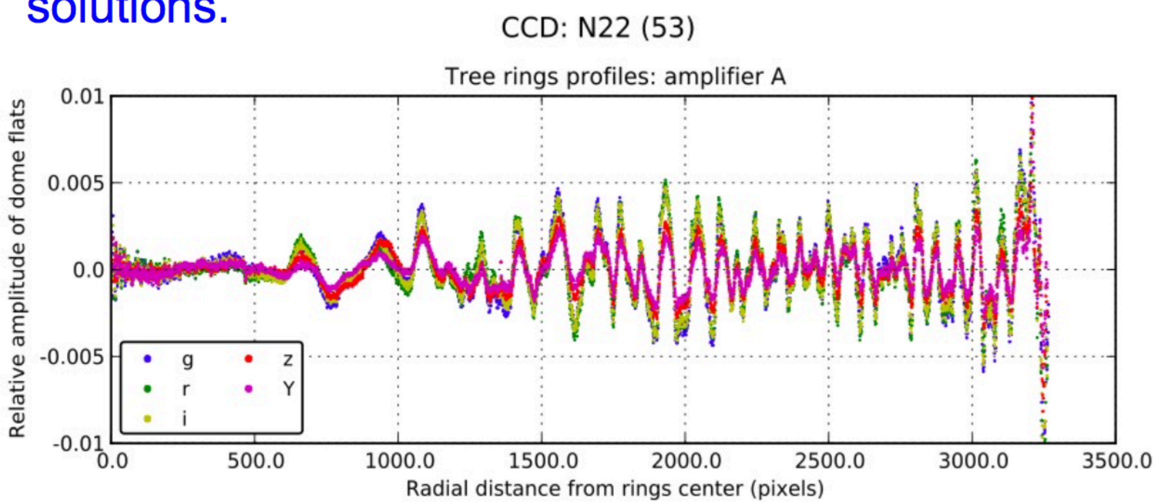


Impacts on astrometry: tree rings

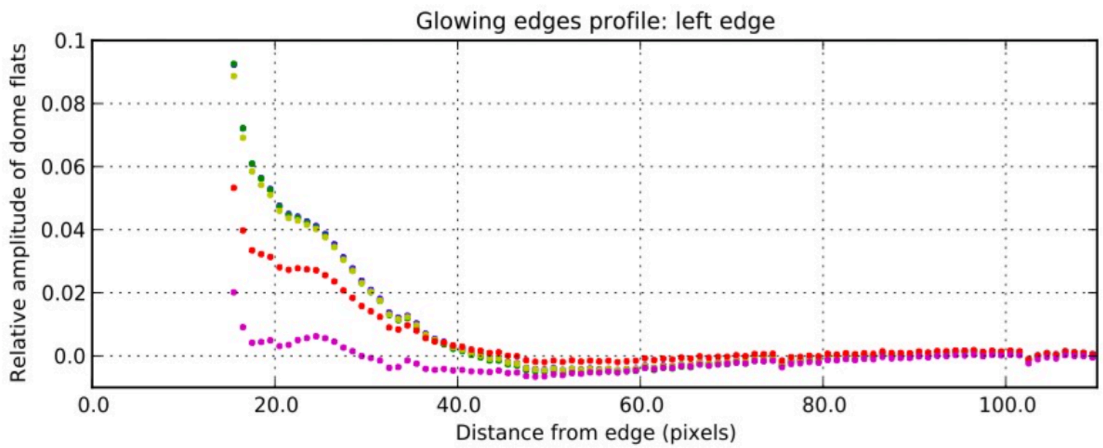


Templates from flats: tree rings and edges

* Use dome flats to measure the relative amplitude of the tree rings and glowing edges as a function of CCD position. Incorporate templates in astrometric and photometric solutions.



ratio	A amplifier	B amplifier
r-band/g-band	0.991 ± 0.00229	0.983 ± 0.00633
i-band/g-band	0.9512 ± 0.00248	0.9435 ± 0.00639
z-band/g-band	0.5793 ± 0.00627	0.5757 ± 0.00605
Y-band/g-band	0.4260 ± 0.00719	0.4279 ± 0.00751



* Amplitude is larger for shorter wavelengths.

* On average, photons with short wavelength are absorbed closer to the back window.

Wavelength dependence: a model

Can we calculate the expected relative amplitude of the tree rings and glowing edges as a function of wavelength ?

$$I_{\mathrm{T}}(G(y)) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} d\lambda \int_0^d dy\ \lambda T(\lambda) S_\lambda(\lambda) f(y,\lambda)\ G(y) + \int_{\lambda_{\min}}^{\lambda_{\max}} d\lambda \int_d^{2d} dy\ \lambda T(\lambda) S_\lambda(\lambda) f(y,\lambda)\ G(2d-y)}{\int_{\lambda_{\min}}^{\lambda_{\max}} d\lambda \int_0^{2d} dy\ \lambda T(\lambda) S_\lambda(\lambda) f(y,\lambda)}$$

- We need:

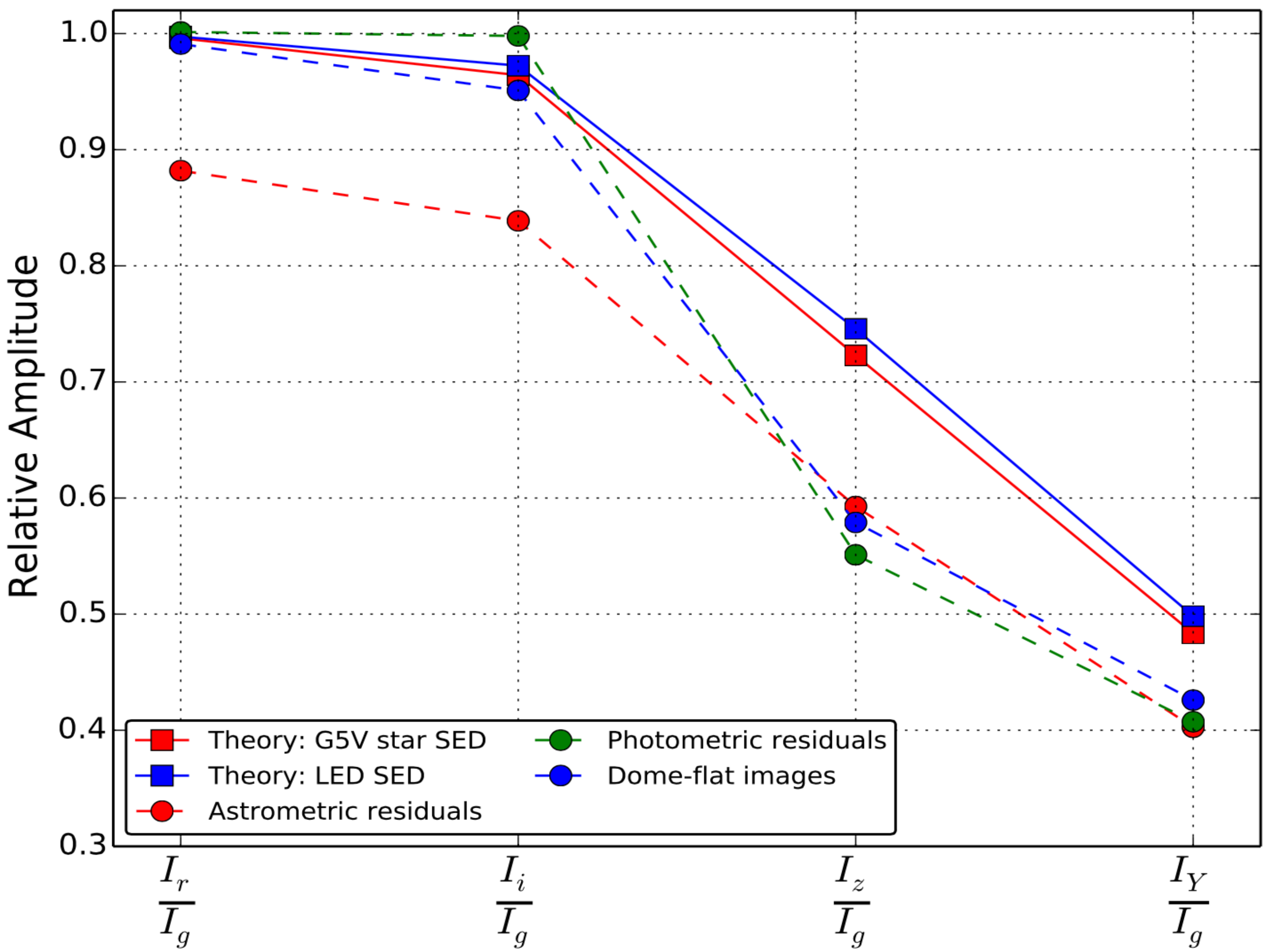
* SED of source: LEDs that illuminated dome flats
* Transmission response of instrument per broad band
* PDF of a photon being absorbed in [y, y+dy] interval: depends on silicon absorption coefficient
* Lateral displacement of charge packet: depends on transverse and parallel fields →

$$\Delta X_\perp = \int_0^y dy' \frac{E_\perp(y')}{E_{||}(y')}$$

$$E_{||}(y) \propto y/d$$

$$E_\perp(y) \propto y(1 - y/d)$$

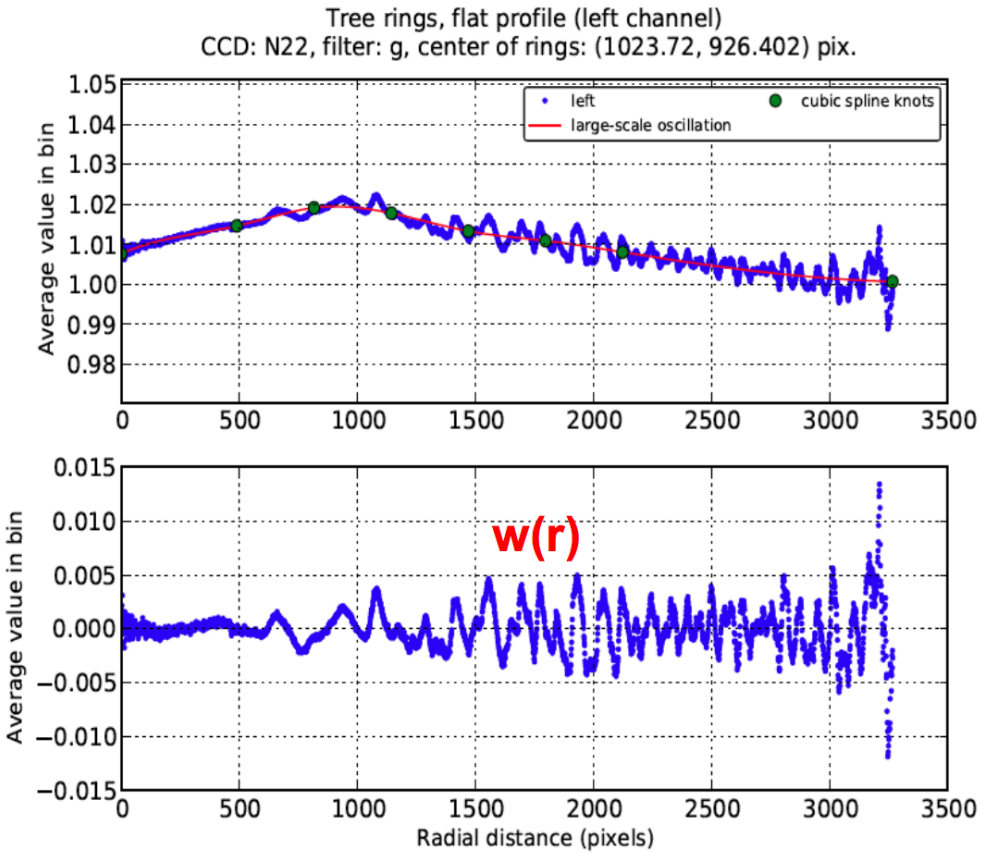
Wavelength dependence: a model

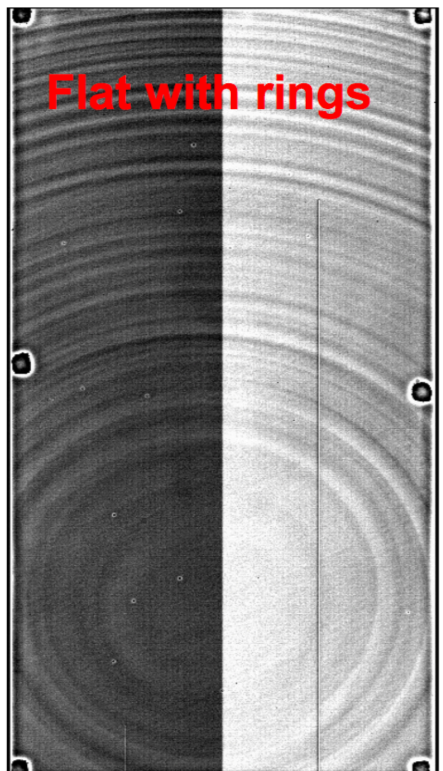


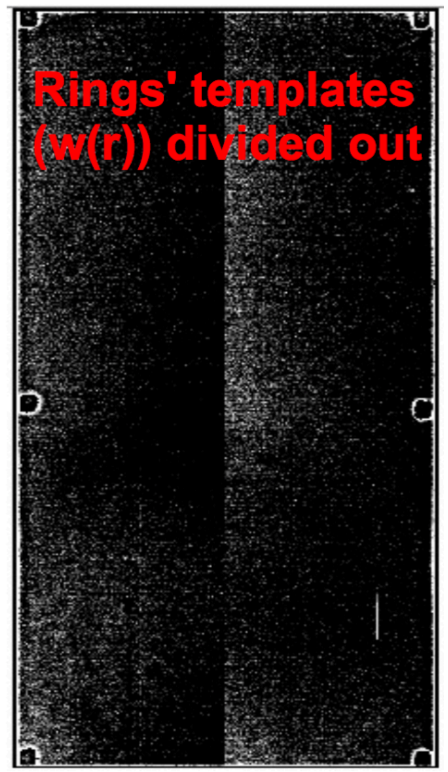
Tree rings: radial profiles

* Assuming that rings are **concentric**, identify their **center** in a given CCD dome flat.

* Bin the counts radially, as a function distance with respect to distance from the center. This gives us the radial profile of the tree rings (a function **w(r)**).

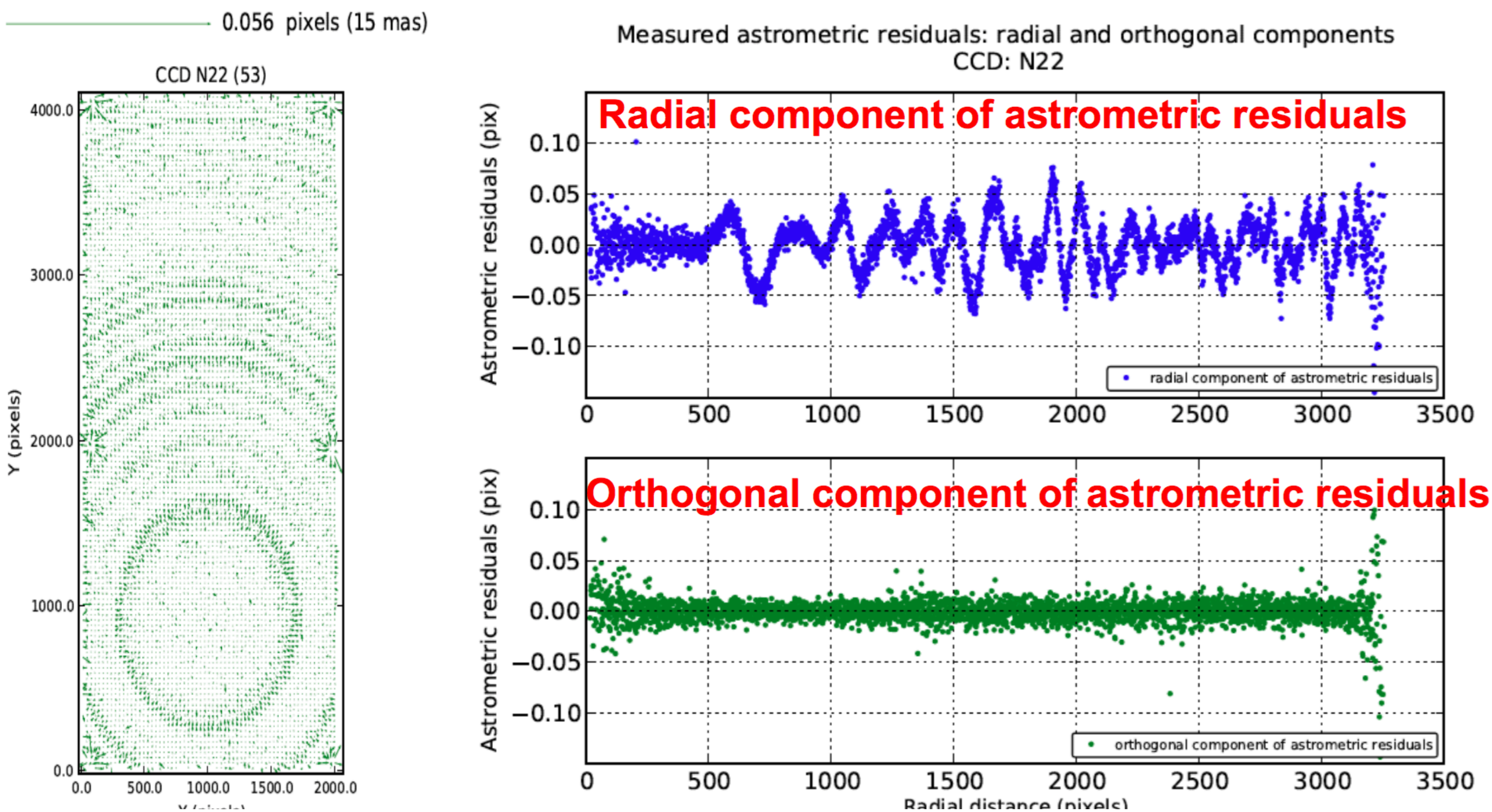




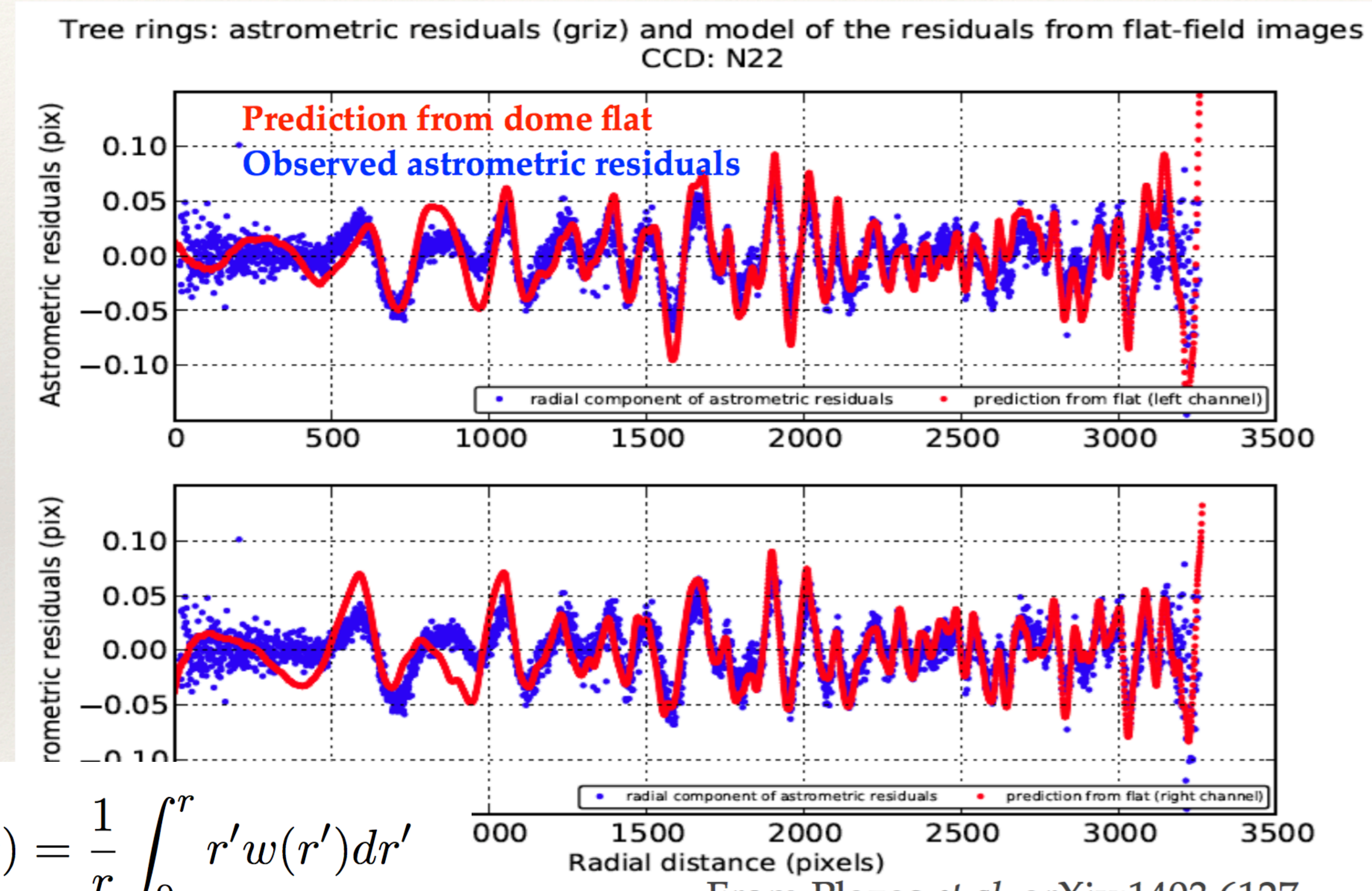


Tree rings: radial profiles

* From the star flats, we can measure the astrometric signature:



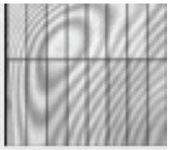
Rings in dome flats nearly perfectly predict annular astrometric displacements



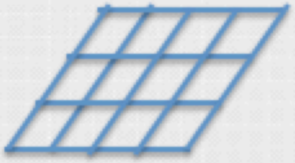
$$f(r) = \frac{1}{r}\int_0^r r' w(r') dr'$$

From Plazas *et al.* arXiv:1403.6127

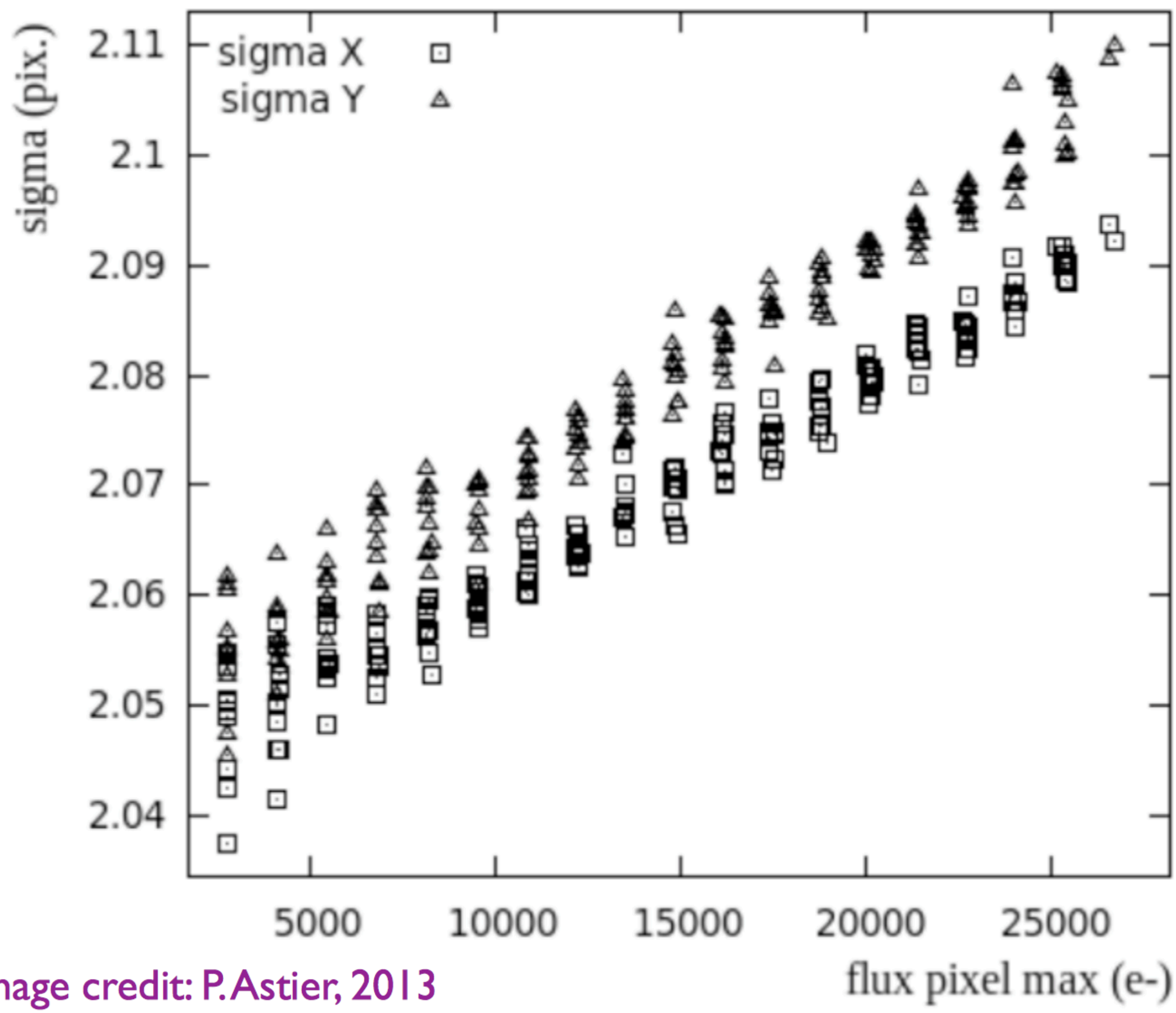
What do we learn from this, about the tree ring aspect?



- Dopant impurities produce internal lateral electric fields, presumably fairly uniform in z.
- These fields perturb the transport of photoelectrons into the pixel grid, giving rise to a distorted mapping from optical focal surface to pixels.
- Photoelectrons from blue photons traverse a longer distance in z, on average, than photoelectrons from red photons, so the distortion is wavelength-dependent.
- The photometric and astrometric distortions that have been measured to correlate with the “tree ring” structure seen in flatfields are both consequences of this charge transport mapping function, and it should be something we can compensate for.
- There is also an impact on shape measurements.
- We need a methodology for distinguishing these charge transport effects from actual QE variation (such as fringing).



Brighter-fatter Relation



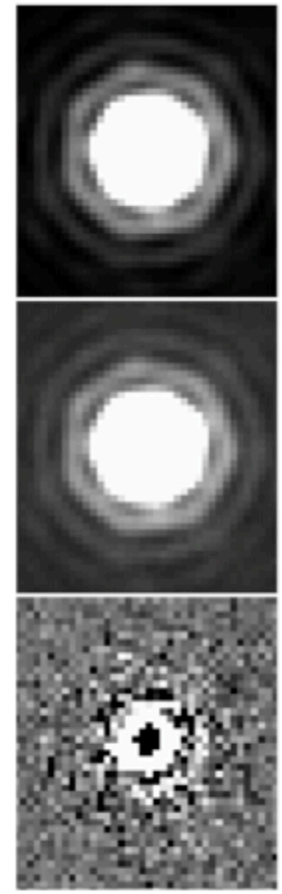
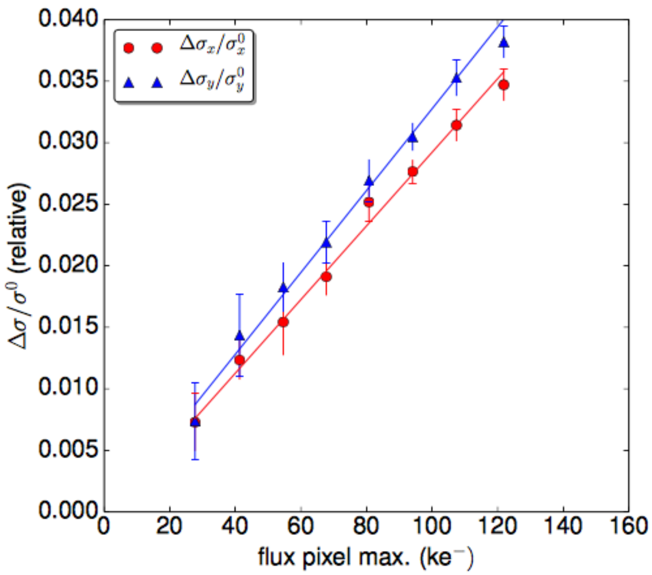
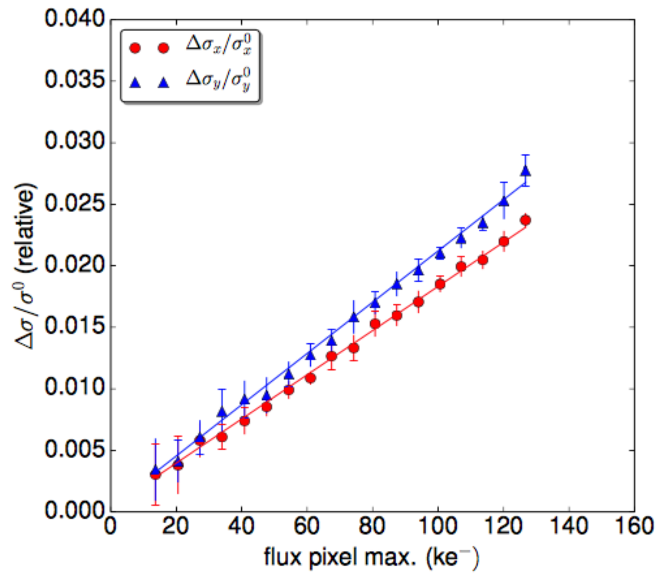


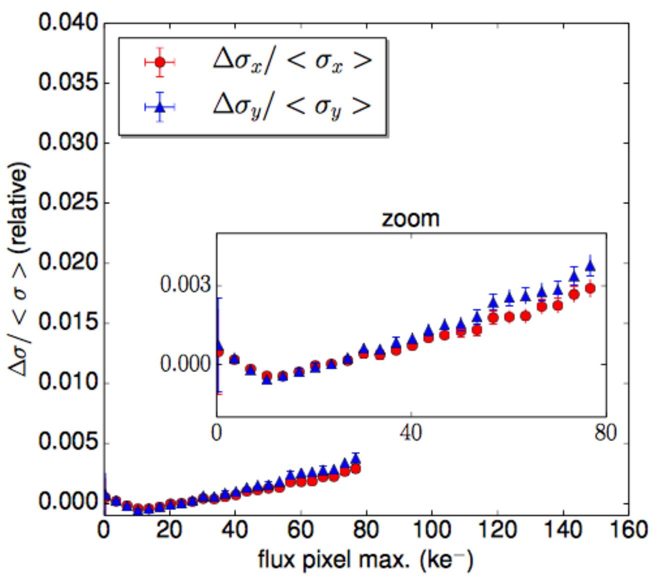
Image credit: P. Astier, 2013



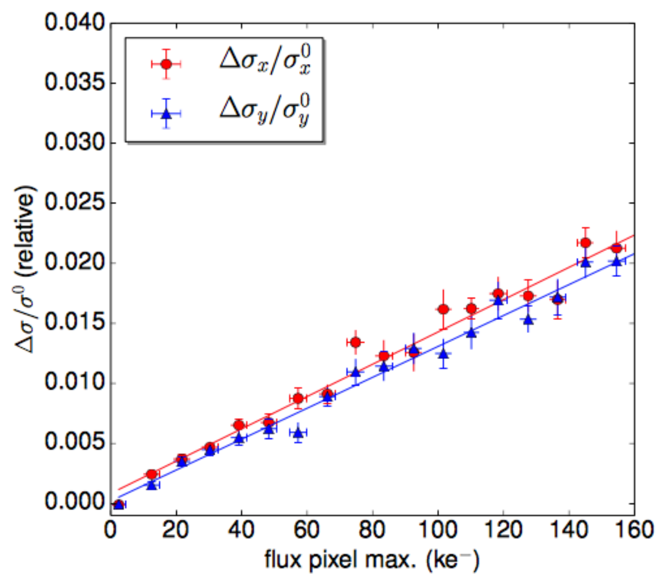
(a) LSST - E2V 250 - Spots 550 nm



(b) LSST - E2V 250 - Spots 900 nm



(c) MegaCam - E2V 42-90 - r-band stars

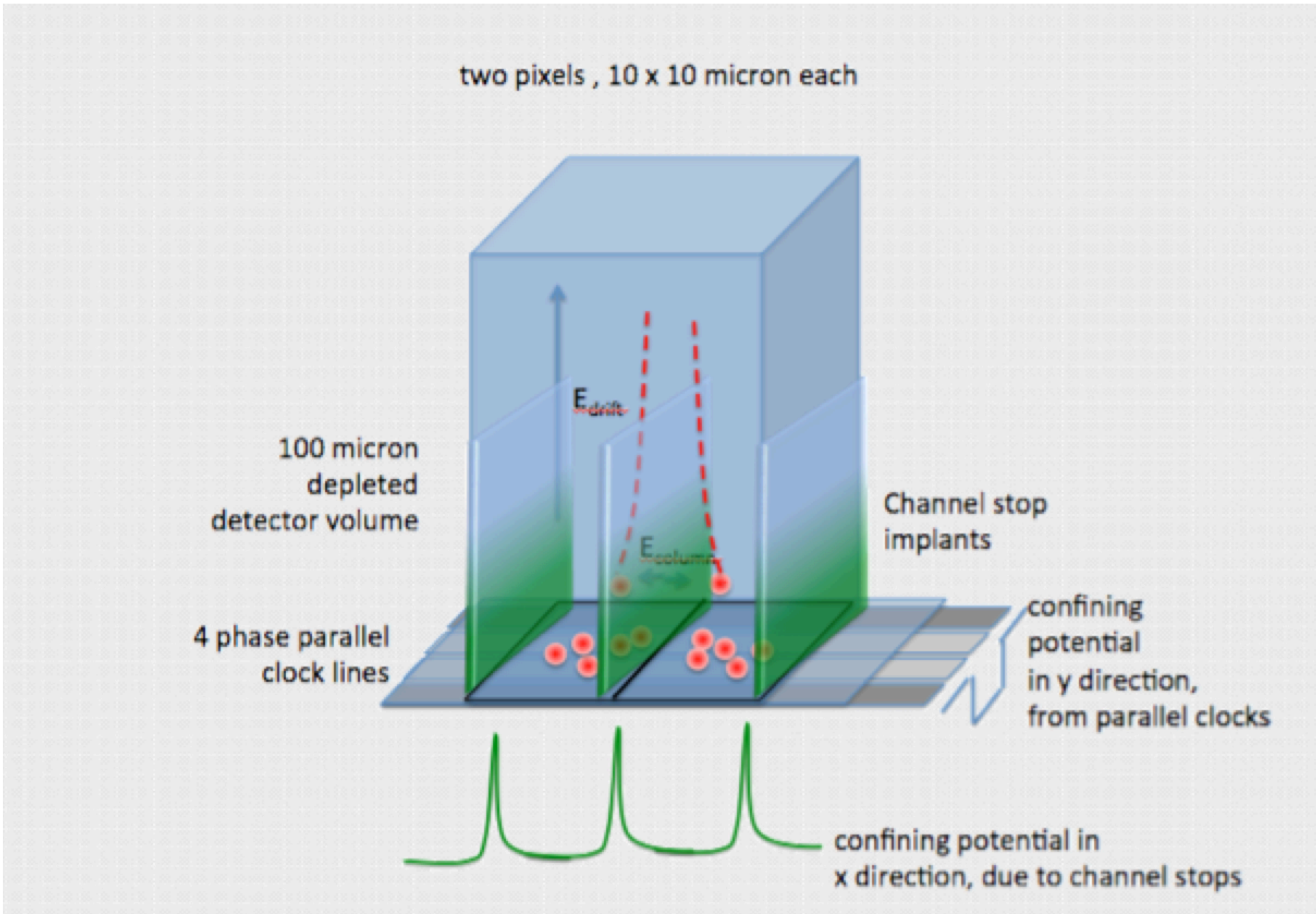


(d) DECam - LBL/DALSA - r-band stars

Guyonett+15

Brighter fatter effect

Accumulated charge in a pixel produces fields too



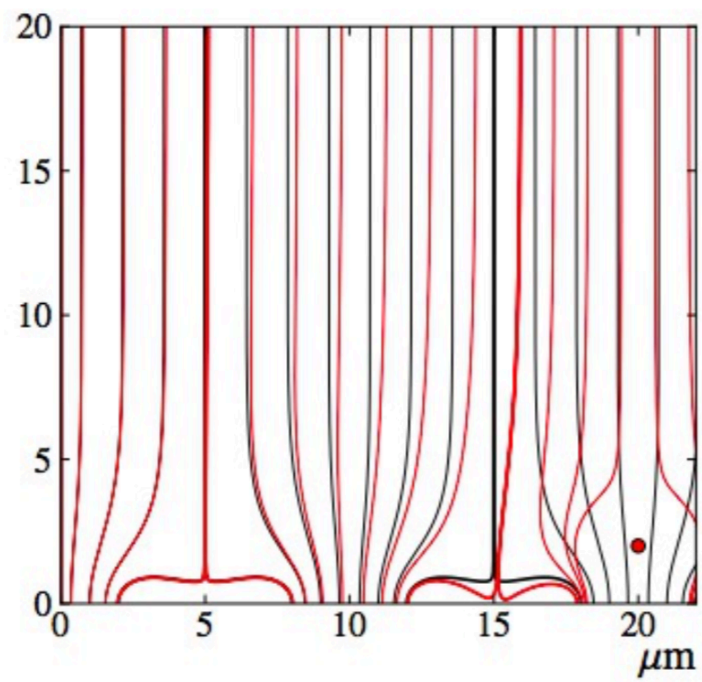
Brighter fatter effect

- Charge self-interaction: "brighter-fatter effect"

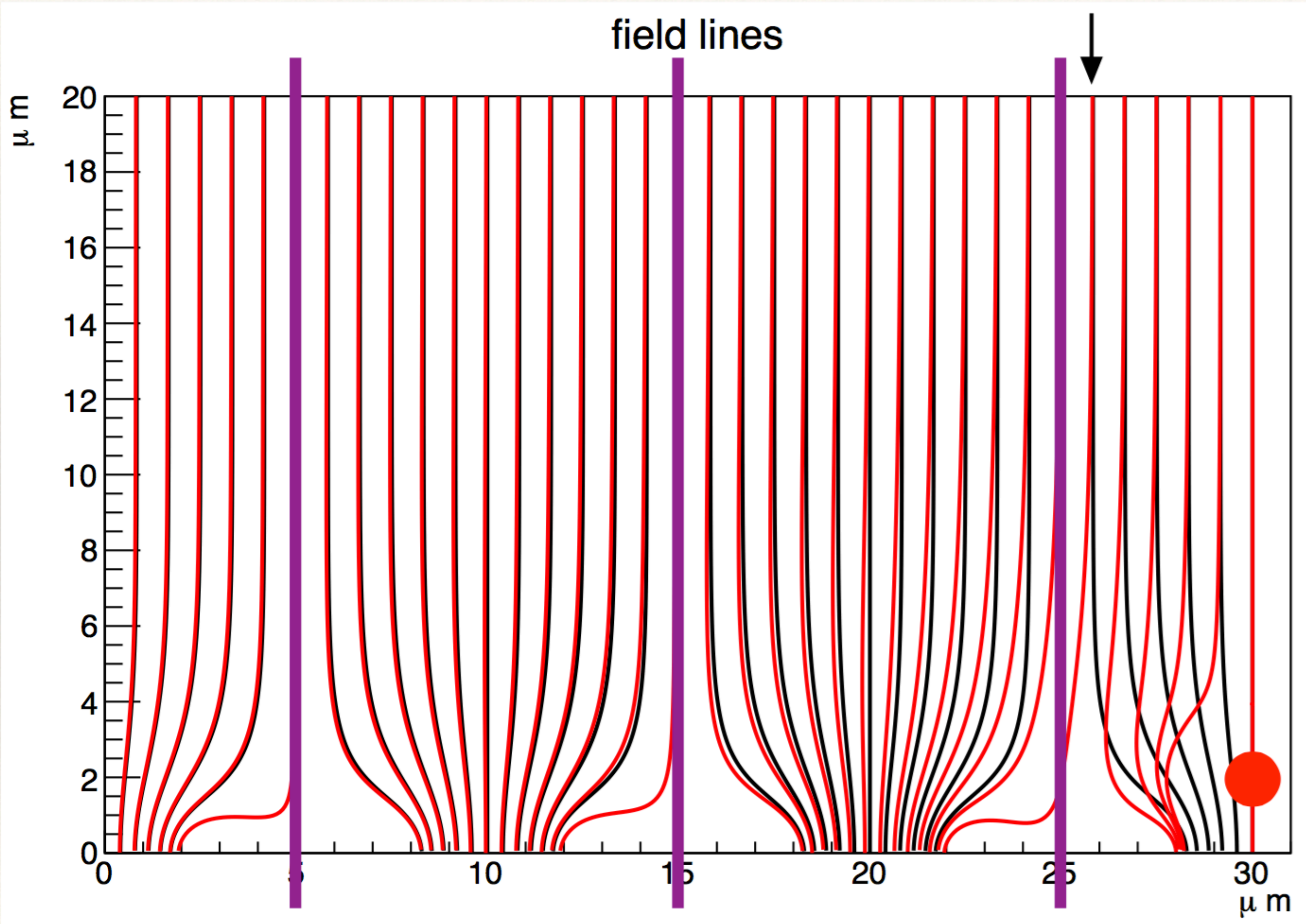
  As charge accumulates, an electric field is generated, pushing charge and distorting the effective pixel sizes.

- Bright stars have larger sizes.
The PSF is estimated from bright stars.
This PSF will differ from that of faint galaxies.

-Can result in m ~ 0.02-0.06. The cosmic shear requirement for DES is ~ 10e-3



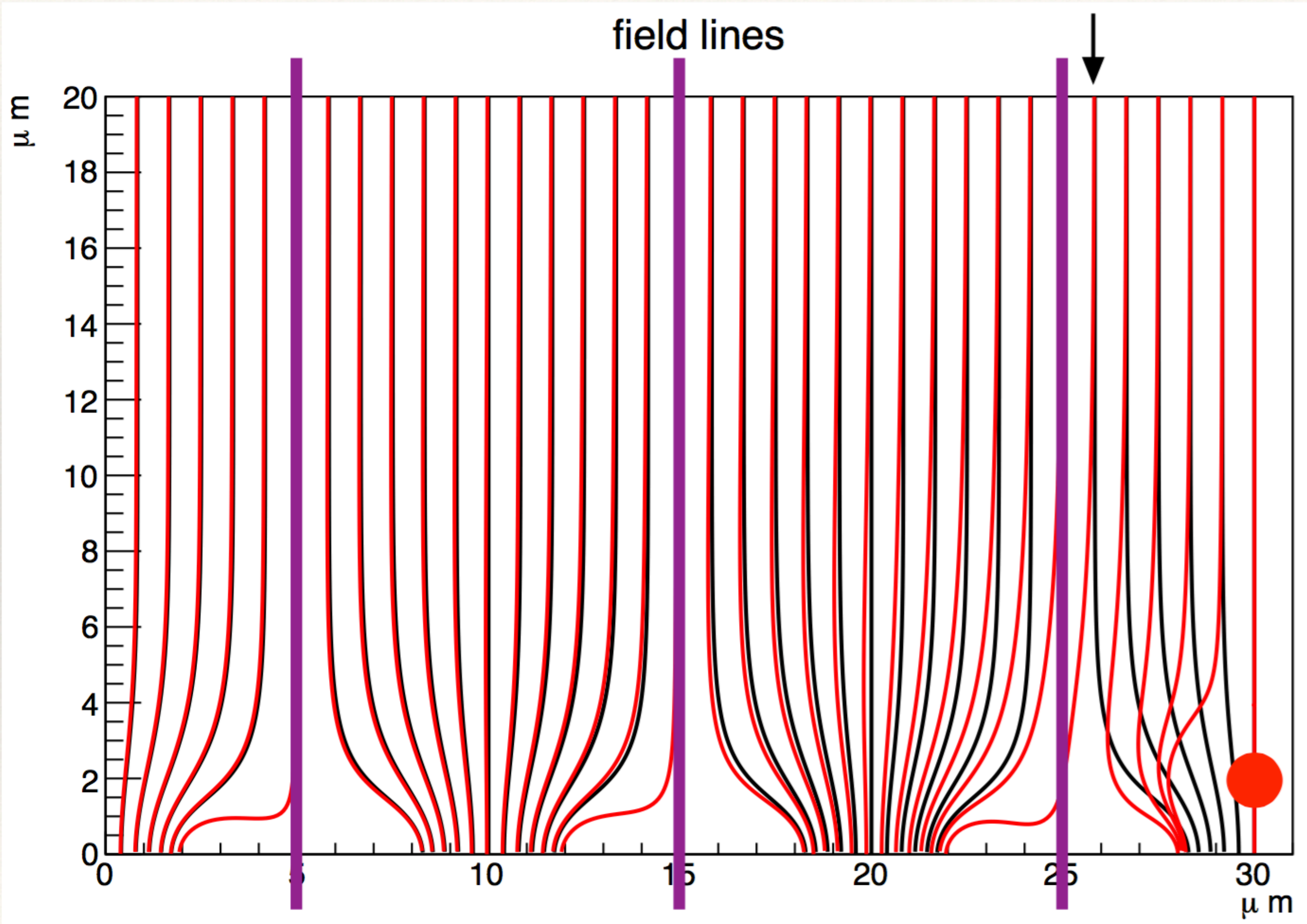
Brighter-fatter effect



Charge collected in this pixel…

Figure from Antilogus *et al*, arXiv 1402.0725

Brighter-fatter effect

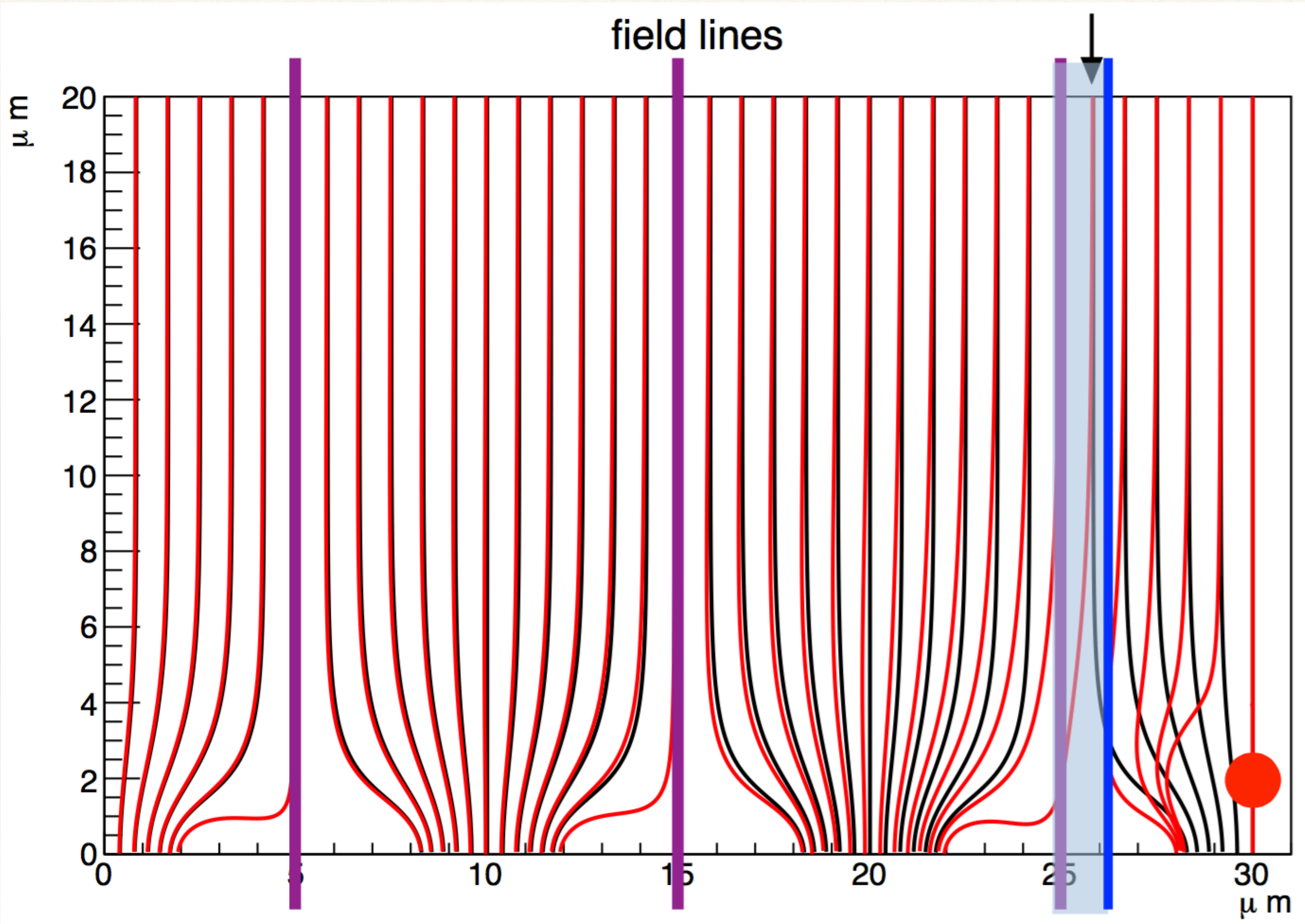


Repels further charge…

Charge collected in this pixel…

Figure from Antilogus *et al*, arXiv 1402.0725

Brighter-fatter effect



Shifts pixel boundary.

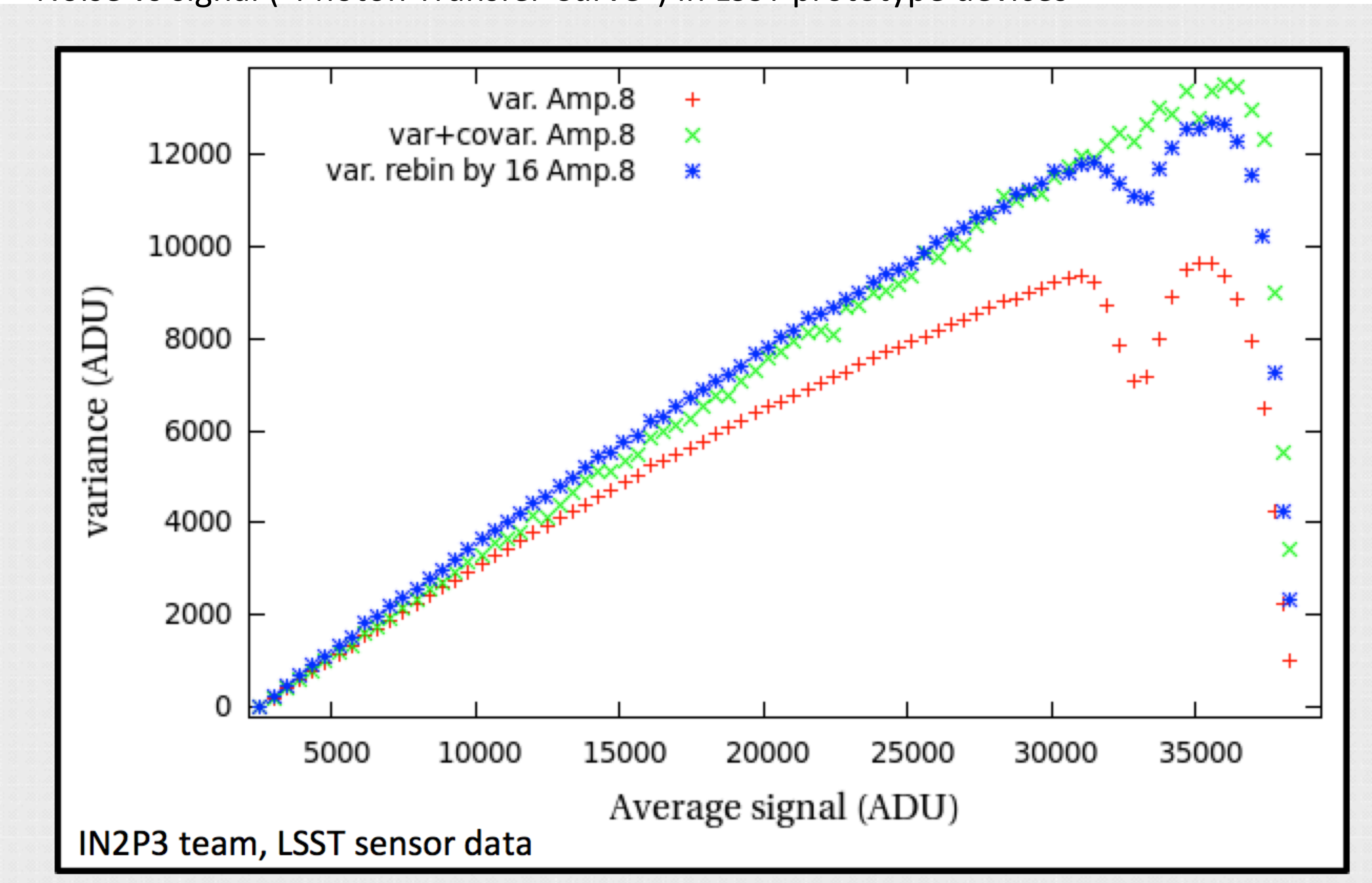
Repels further charge…

Charge collected in this pixel…

Figure from Antilogus *et al*, arXiv 1402.0725

Brighter fatter effect

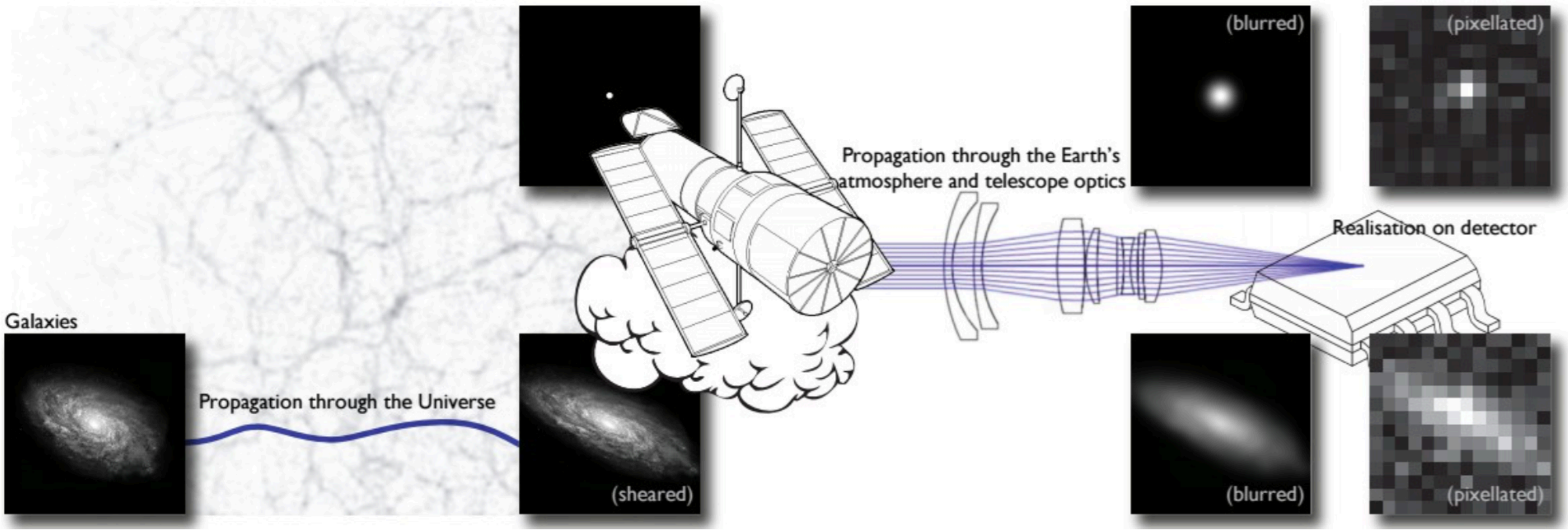
Noise vs signal ("Photon Transfer Curve") in LSST prototype devices



B/F behavior

- Object sizes (and shapes) depend on flux
- Image is quadratic function of illumination: charge shifts are the image convolved with some kernel.
- Pixel-size changes are manifested as noise covariances in flat fields, which can be measured to constrain the kernel (but still need to make some guesses to solve).
- Caused standard gain estimates to be wrong by ~10%!
- If you know the kernel, you can revert the effect on the image to good accuracy.
- Likely to be present on all CCD cameras, other integrating detectors too?

Systematic errors in WL due to instrumental signatures



We measure the galaxy image properties, and estimate the PSF

Shear biases

Quantifying biases: $$\hat{\gamma} = (1+m)\gamma + c$$

Cosmic shear: $$\langle \hat{\gamma}\hat{\gamma} \rangle = (1+m)^2 \langle \gamma\gamma \rangle + 2(1+m)\langle c\gamma \rangle + \langle cc \rangle$$

Cross-correlation lensing: $$\langle g\hat{\gamma} \rangle = (1+m)\langle g\gamma \rangle + \langle gc \rangle$$

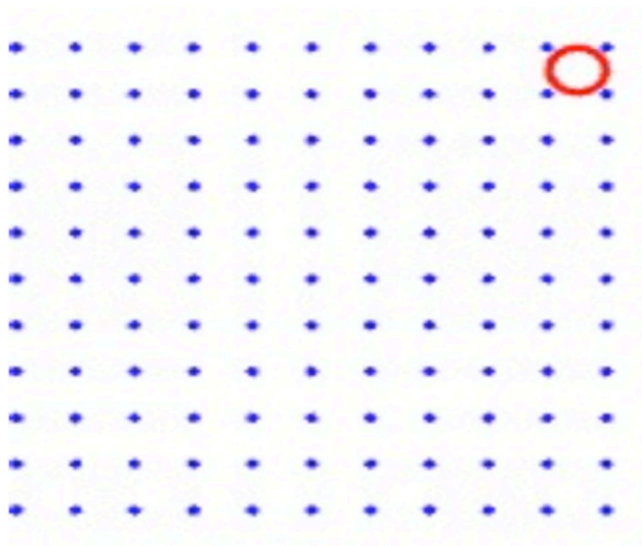
WCS (World Coordinate Systems) effects

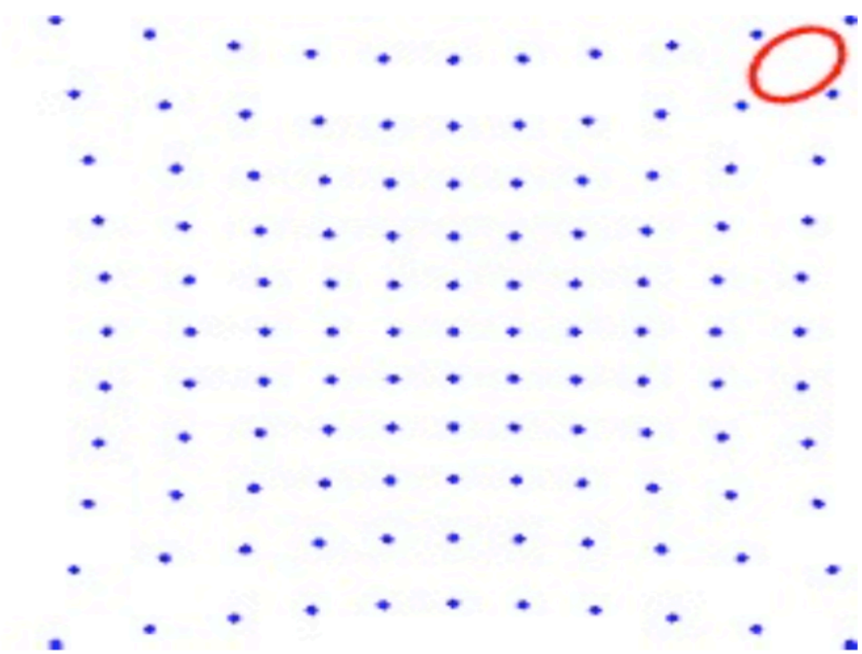
WCS = Astrometric Solution

- These effects include:
- Field rotation
- Telescope distortion (e.g., pincushion)
- Differential refraction
- Instrumental effects:
  - Edge distortions
  - Tree rings
  - Tape bumps

WCS effects

WCS or "World Coordinate System" is an astrometric solution that defines the functional map conversion between CCD and local sky coordinates.





WCS effects

- In general*, it is a linear transformation that includes magnification, rotation, and **shear**

$$u = u(x,y)$$

$$v = v(x,y)$$

$$J = \begin{pmatrix} \frac{du}{dx} & \frac{du}{dy} \\ \frac{dv}{dx} & \frac{dv}{dy} \end{pmatrix} = \frac{1+\mu}{\sqrt{1-g^2}} \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

*Flat sky approximation: plane tangential to a chosen point in the sky

WCS effects: impact on shapes

- The shear term in the WCS Jacobian induces an additional shear contribution in the PSF and the galaxy.
- It creates a coherent pattern that mimics the WL shear: **it is an additive systematic ($c < 2\text{e-}4$)**
- **Solution**: Determine $u(x,y)$ and $v(x,y)$ from astrometric solutions, and then build PSF models in sky coordinates

Brighter-fatter Relation

The impact on shapes:

- We usually like to estimate our PSFs from bright stars, S/N > 50-100.
- Most galaxies are fainter. S/N ~ 20.
- PSF used for deconvolution is systematically wrong.
- Mostly an m-type systematic from error in dilution correction.

-Can result in m ~ 0.02-0.06. The cosmic shear requirement for DES is ~ 10e-3

Brighter-fatter Relation

Solution:

- Estimate coefficients from flat field covariances.

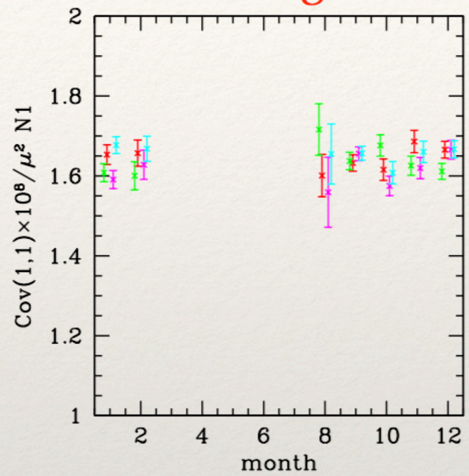
- Essentially move the charge back to where it “should” have landed.
- Then stars and galaxies all have the same effective PSF.
- This introduces noise correlations, so probably also want to add correlated noise to image to whiten it.

Model of Antilogus et al.(2014) Implemented in Decam by Gruen

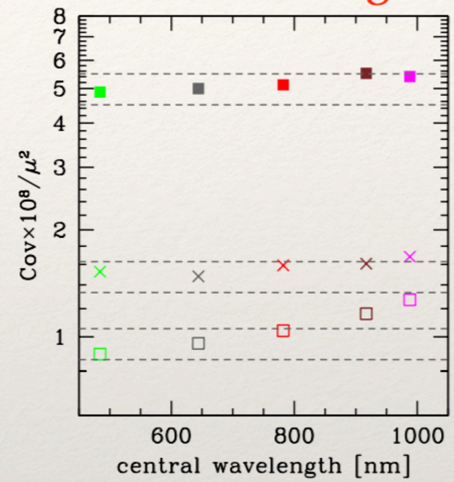
DECam's B/F

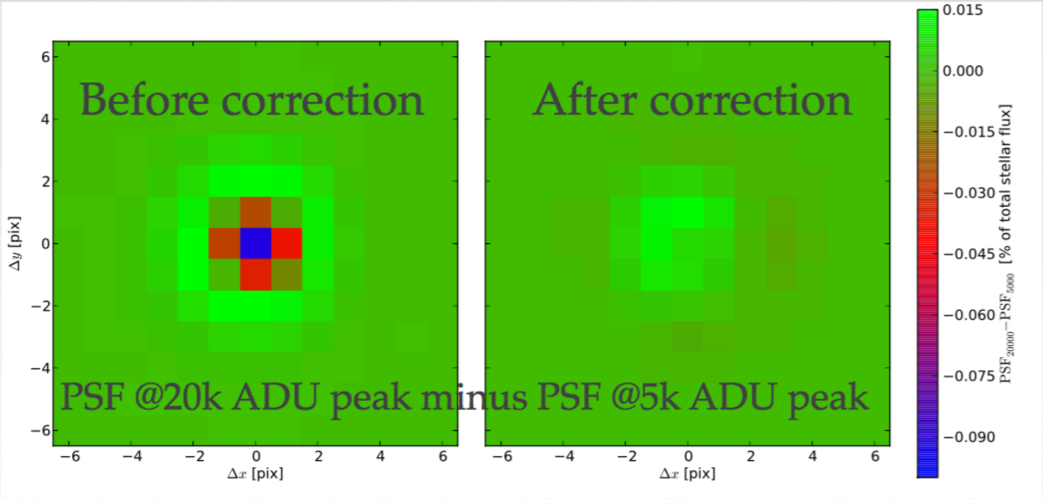
- Characterized by Daniel Gruen *et al.* (arXiv 1501.02802)
- Stars near saturation lose 2% of their signal in central pixel.
- Nearly independent of wavelength
- Same effect on both amps, amplitude varies between CCDs
- No sign of change with time
- Correction reduces effect on stars by ~10x

N1 B/F strength vs time



…vs wavelength

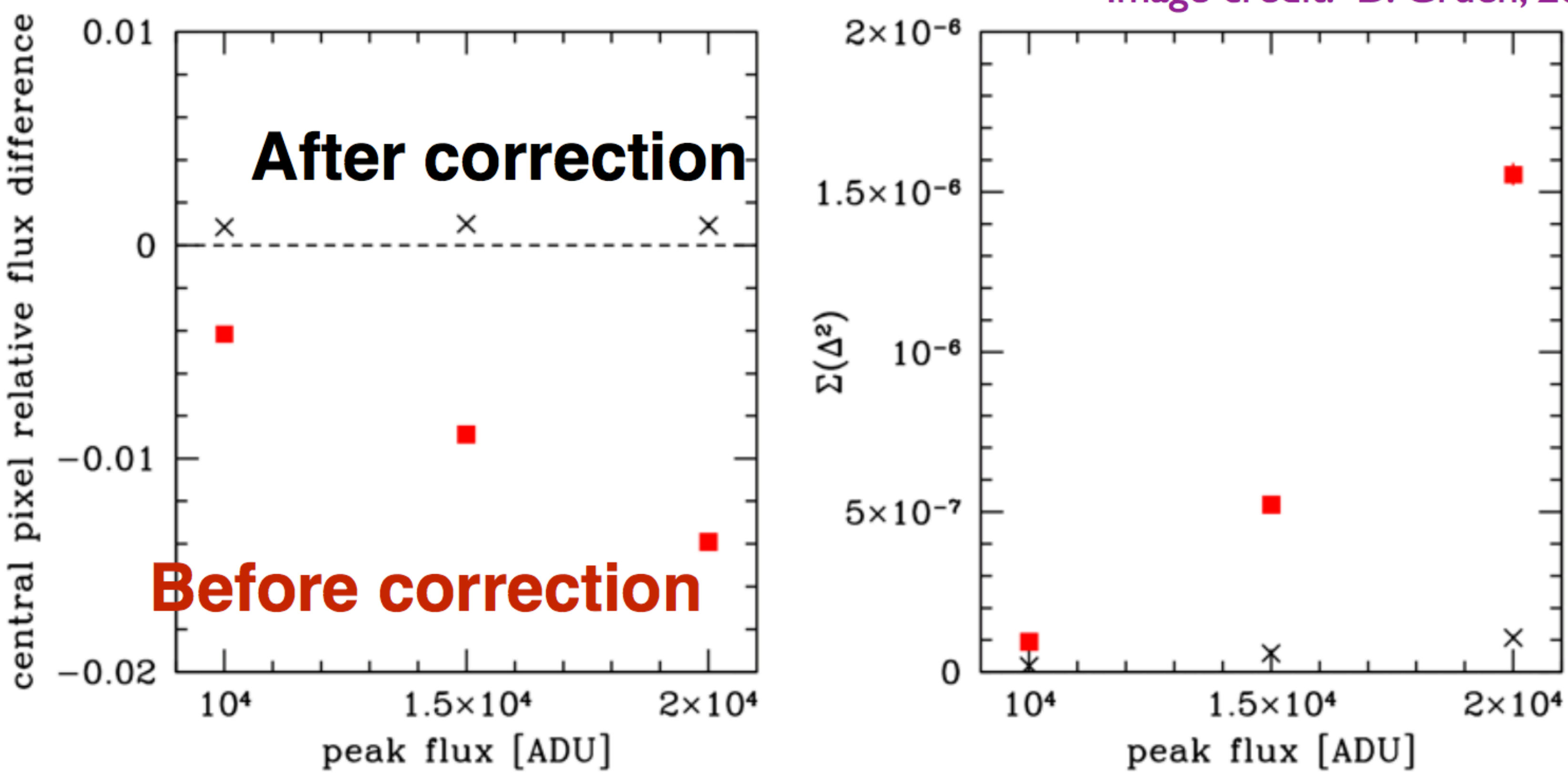




Brighter-Fatter

- Difference between bright and faint stars (both central pixel and chisq difference) are much better.

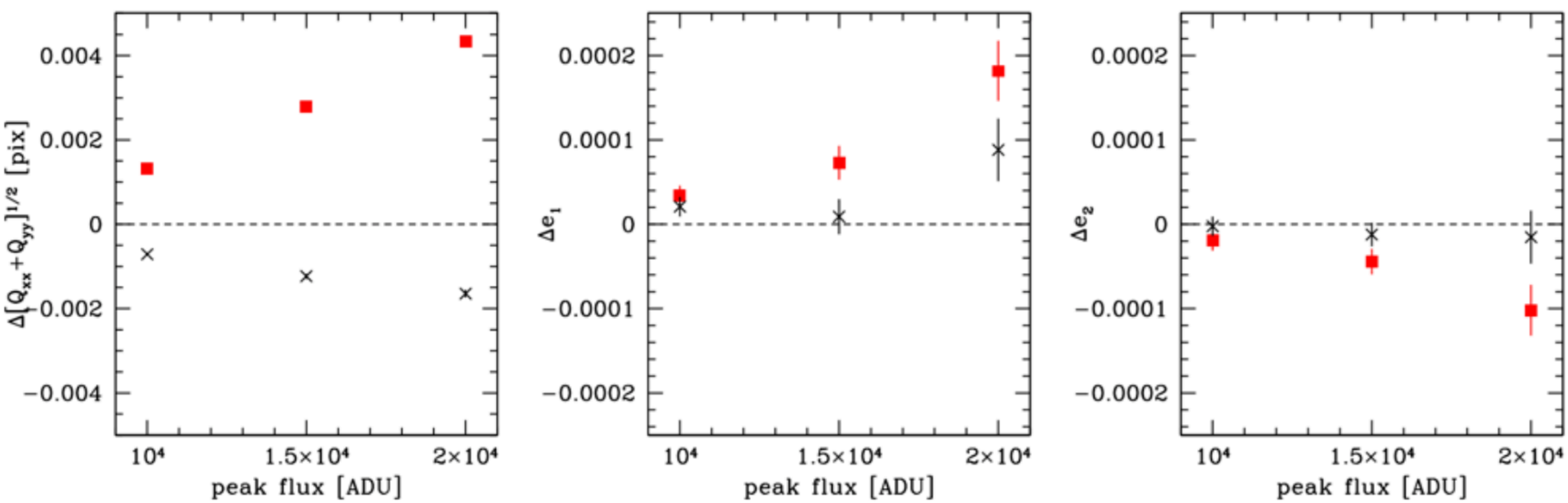
Image credit: D. Gruen, 2015



Brighter-Fatter

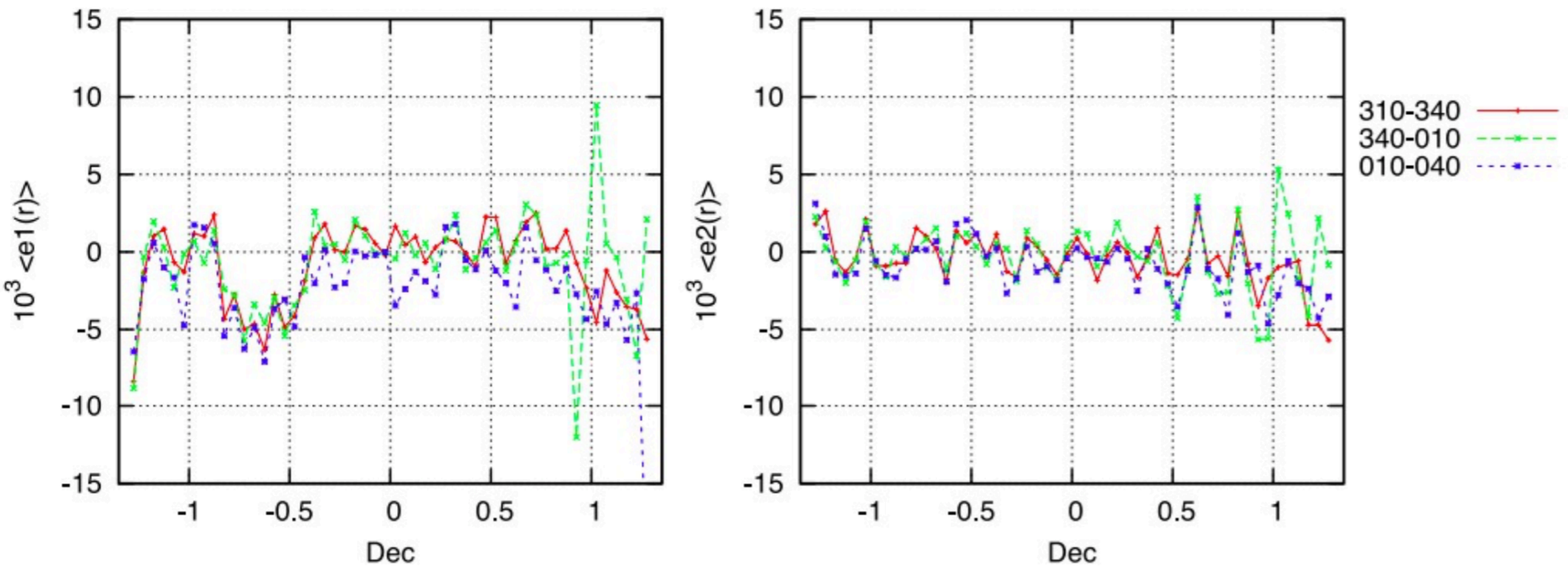
- The estimated size and shape don't improve as much as we had expected.
- Still investigating why this might be.

Image credit: D. Gruen, 2015



Impacts on shapes: Non-linearity

Non-linearity: it is usually well measured and corrected for, but when it does not, it can propagate into shape errors



Huff et al. 2014. Bad non-linearity correction in a CCD, leading to a wrong PSF model; Responsible for about 2/3 of additive shear systematics in lensing analysis.

References

- "Precision Astronomy with Fully Depleted CCDs 2013 and 2014" workshop at Brookhaven National Laboratory
  - Look in 'Agenda' for the presentations
  - Look in proceedings for papers (most of them in the arXiv too).
- Good intro paper: "**Precision Astronomy with Imperfect Fully Depleted CCDs -- An Introduction and a Suggested Lexicon" C. Stubbs (2013)**
- **Instrumental systematics and weak gravitational lensing" , Rachel Mandelbaum**
- Tree Rings: Plazas et al 2014, Okura et al. 2015
- Brrighter Fatter: Antilogus et al 2014, Gruen et al 2015, Guyonett et al. 2015
- Thick CCDs: S.E. Holland, D.E. Groom, N.P. Palaio, R.J. Stover, and M. Wei, "Fully depleted, back-illuminated charge-coupled devices fabricated on high-resistivity silicon," *IEEE Trans. Elec. Dev.*, 50, 225, 2003