Precision Characterization of Hawaii-2RG Near-Infrared Detectors

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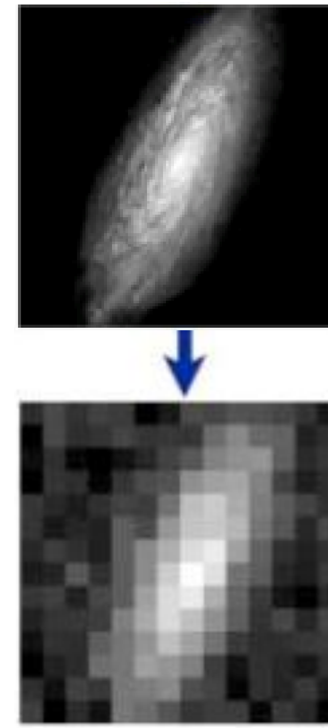
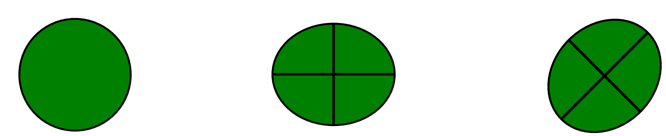
With great statistical power comes great systematic responsibility
-Daniel Gruen, NASA Einstein Fellow at SLAC/KIPAC

To probe dark energy with weak gravitational lensing, large surveys (WFIRST, Euclid, LSST…) demand unprecedented requirements on shape measurement systematics



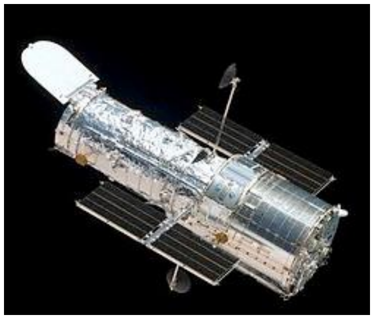
For dark energy analyses, correlated errors in **ellipticity (e)** measurement must be reduced to $O(10^{-4})$

$|e| = 0$ $e_1 = 0.1$ $e_2 = 0.1$



Weak Lensing data is growing rapidly
(not a complete list)

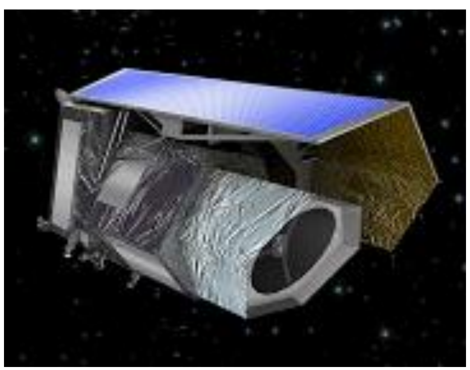
You
Are
Here



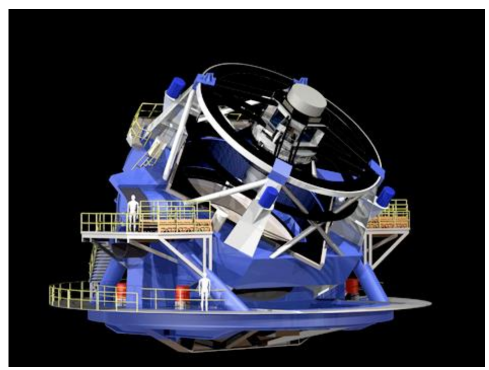
HST/COSMOS
1.7 deg^2, ~0.5M galaxies

CFHTLenS
154 deg^2, ~6M galaxies

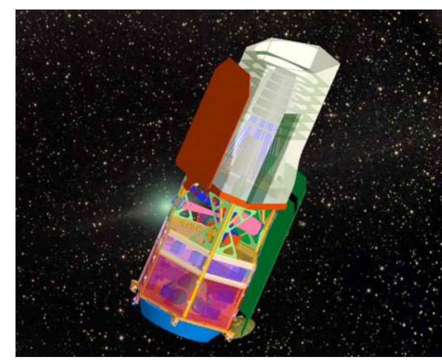
Dark Energy Survey
5000 deg^2, ~200M galaxies



Euclid
15,000 deg^2, ~1.5 B galaxies



Large Synoptic Survey Telescope
~20,000 deg^2, ~4B galaxies



Wide-Field Infrared Survey Telescope (WFIRST)

(the only IR imaging survey)
2000-10000 deg^2, 300M-1.6B galaxies

Shrinking statistical errors are putting pressure on systematic errors!

Precision Projector Laboratory (PPL)

Detector Characterization and Astronomical Emulation

Dr. Chaz Shapiro (389E)
Lab Director

Premise Astronomy missions increasingly rely on detectors with a stable, predictable pixel response. Surprises in detector operation (which fall beyond the scope of conventional tests) are common. They risk delays, increased cost, or failure to meet science goals. Mitigation strategies can take years to develop.

Goal Identify and mitigate detector-related risks to science goals, thereby increasing the Technology Readiness Level of instruments and providing proof-of-concept for mission proposals

Approach:

- Emulate UV/VIS/NIR mission concepts under realistic observing conditions, by projecting stable and customizable "scenes" (stars, galaxies spectra) onto large format detectors.
- Assemble a multi-disciplinary team to design custom tests and study how detector effects impact specific scientific measurements.
- PPL testbed is located on Caltech campus to leverage expertise at Caltech Optical Observatories. External partners are encouraged to accompany their instrument to Pasadena where they can take data, analyze it with us, and iterate if necessary.

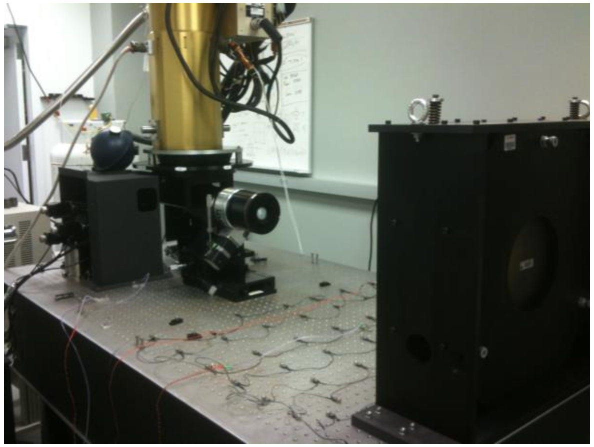
Examples of research enabled by PPL:

WFIRST: How do detector anomalies impact 1) galaxy shape measurement for probing dark energy, and 2) photometry and astrometry for exoplanet microlensing?

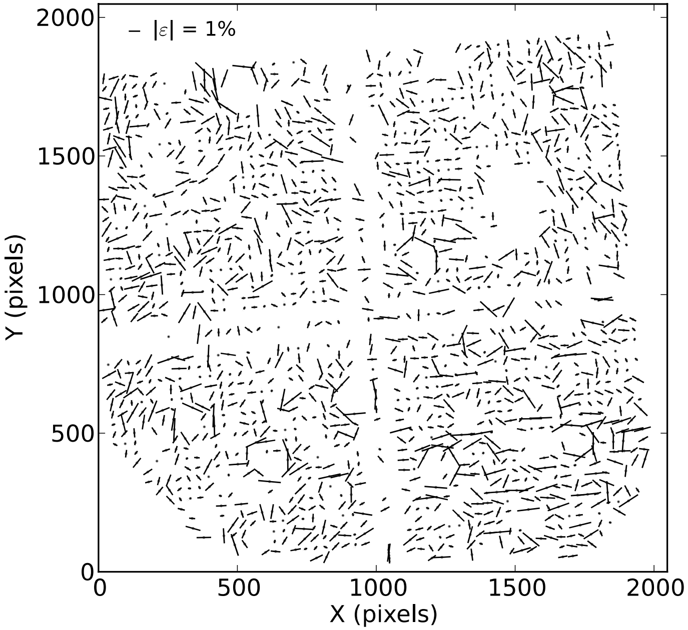
JWST: Is detector photometry stable enough to detect Earth-like exoplanet transits?

Euclid: How does sub-pixel response affect photometry?

Emulation system with near-IR detector in dewar



Weak lensing ellipticity map emulated with NIR detector (Seshadri et al. 2013)



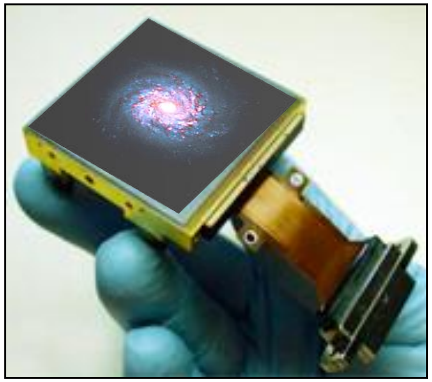
Importance of science-based detector validation

Working groups should propagate WFIRST science requirements to requirements on **known** systematic detector effects; **however**…

- This strategy assumes detectors are already well-understood
- Surprises in detector operation, which fall beyond the scope of a requirements document, are common and can cause mission delays or failure to meet requirements.
- Conventional detector characterization does not characterize the **detector PSF** (crucial for e.g. weak lensing)
- Case study: Dark Energy Survey (DES) …

The Precision Projector Laboratory

Detector Characterization
& Astronomical Emulation



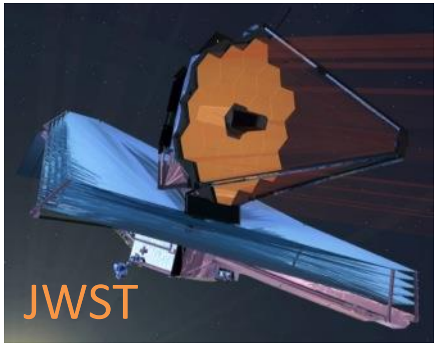
Core premises:

- Standard detector characterization is insufficient to ensure the instrumental precision necessary for future astronomical and, increasingly, Earth science applications.
- Subtle, unmodeled detector effects can have serious, unexpected impacts on the science reach of an instrument.
- **Emulation** provides a complementary, science-oriented approach to detector validation with a high degree of realism (compared to simulations) and experimental control (compared to in-flight calibration).

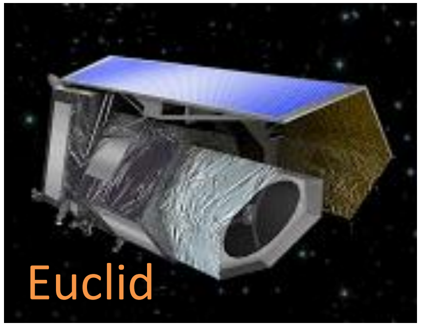
Core Goals:

- Identify and mitigate detector-related risks, thereby increasing the TRL of instruments/missions
- Emulate mission concepts with laboratory experiments that exercise focal planes under realistic observing conditions
- Study the impact of detector performance on the science goals of instruments/missions

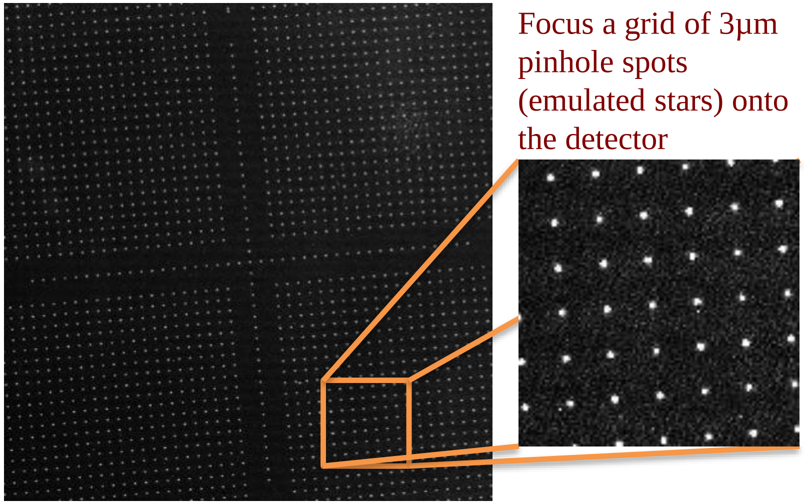
The Precision Projector Laboratory



- Since its inception in 2008, the **chief design goal** of PPL has been the emulation of weak gravitational lensing survey data for WFIRST (formerly JDEM, SNAP).
- PPL emulates the WFIRST f number but **not** the optics – the simplest possible PSF is used to reduce optical effects and uncover detector systematics
- PPL is versatile and can rapidly generate a range of signals: stars, galaxies, spectra, flat fields / backgrounds, focal ratios, filters, image motion
- PPL has readily enabled detector tests for other missions
  - Photometric stability for exoplanet transits with JWST
  - Wavefront correction camera test for Keck
  - Emulation of fiber position measurements for Subaru/PFS
  - Intra-pixel response measurement for Euclid
- **PPL group includes experts on detector operation, optical engineering, weak gravitational lensing analysis, and cosmology.**

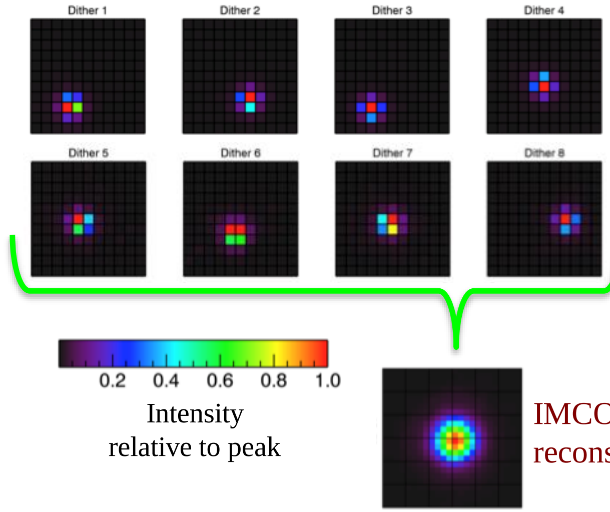


Example PPL Emulation: Mock Weak Lensing Analysis



Focus a grid of 3μm pinhole spots (emulated stars) onto the detector

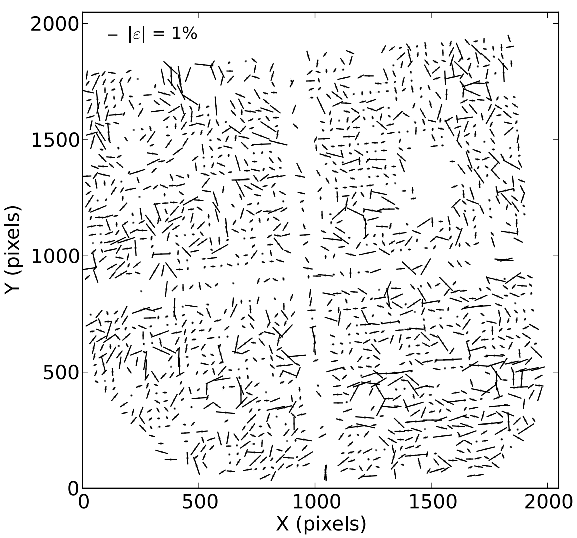
Dither & reconstruct oversampled images with IMCOM



Intensity relative to peak

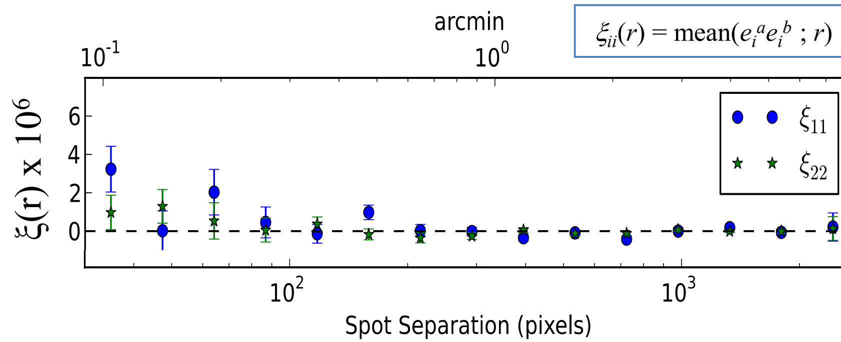
IMCOM reconstruction

Measure/map ellipticities of "stars"



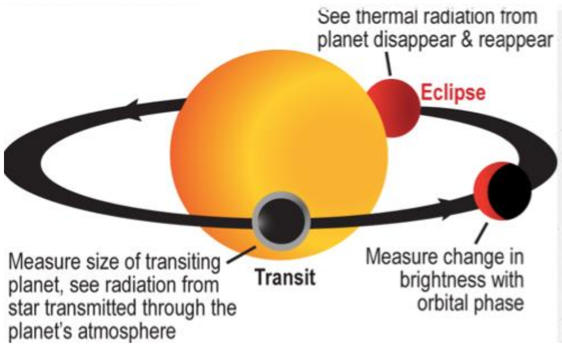
Compute ellipticity correlation function: analogous to science goal

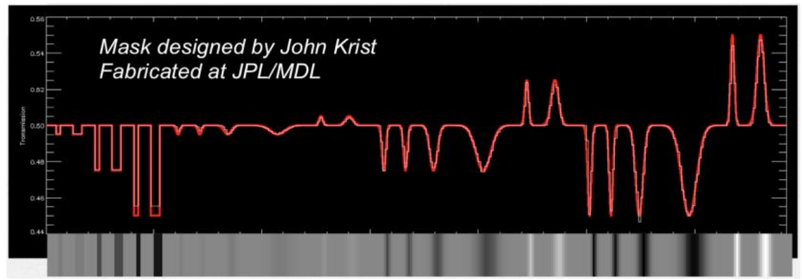
$$\xi_{ii}(r) = \text{mean}(e_i^a e_i^b\ ;\ r)$$

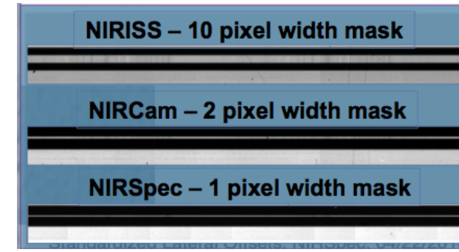


JWST Exoplanet Emulation (D. Touli, C. Beichman, G. Vasisht, J. Krist)

IPAC







- JWST will detect transiting exoplanets in stellar light curves. For a solar type star, transits cause a dip in flux:
  - Jupiter transit → 1% dip
  - Earth transit → 0.0084% dip (84 ppm)
- Spectroscopic detections require greater precision (30 ppm for Earth-like)
- IPAC & PPL used 2 lamps and a custom mask to emulate an exoplanet spectrum embedded in a bright stellar continuum
- ~50 ppm median photometric precision achieved with the engineering grade H2RG. Improvement is expected after modifications to projector and detector readout.

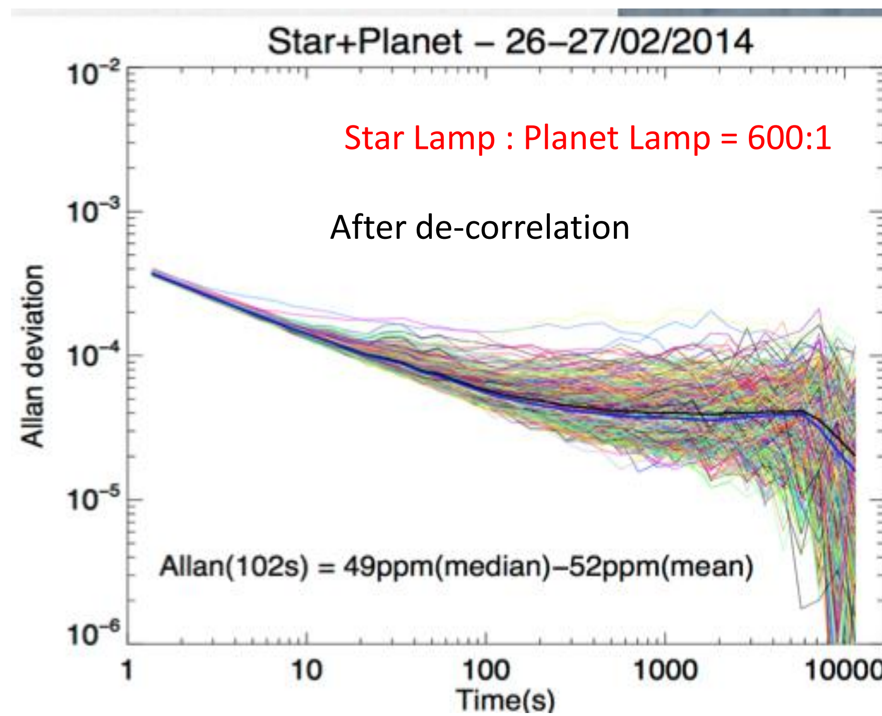


Image Credits: Dimitra Touli, IPAC

Precision Projector Laboratory testbed

Projector System Features:

- Diffraction-limited optics with simple point spread function (PSF).
- High image stability through passive damping.
- Custom image masks, adjustable f/#, stages & illumination provide a range of signals for investigating various detector effects and mission conditions.
- Servo controls on mask and tip-tilt mirror allow fine image positioning for dithering or scanning.
- IMage COMbination algorithm implements WFIRST image reconstruction strategy with dithered, undersampled images.
- Dedicated 144 core cluster allows near real-time analysis of 1000's of images.
- Dewar customized for **HxRG + SIDECAR**

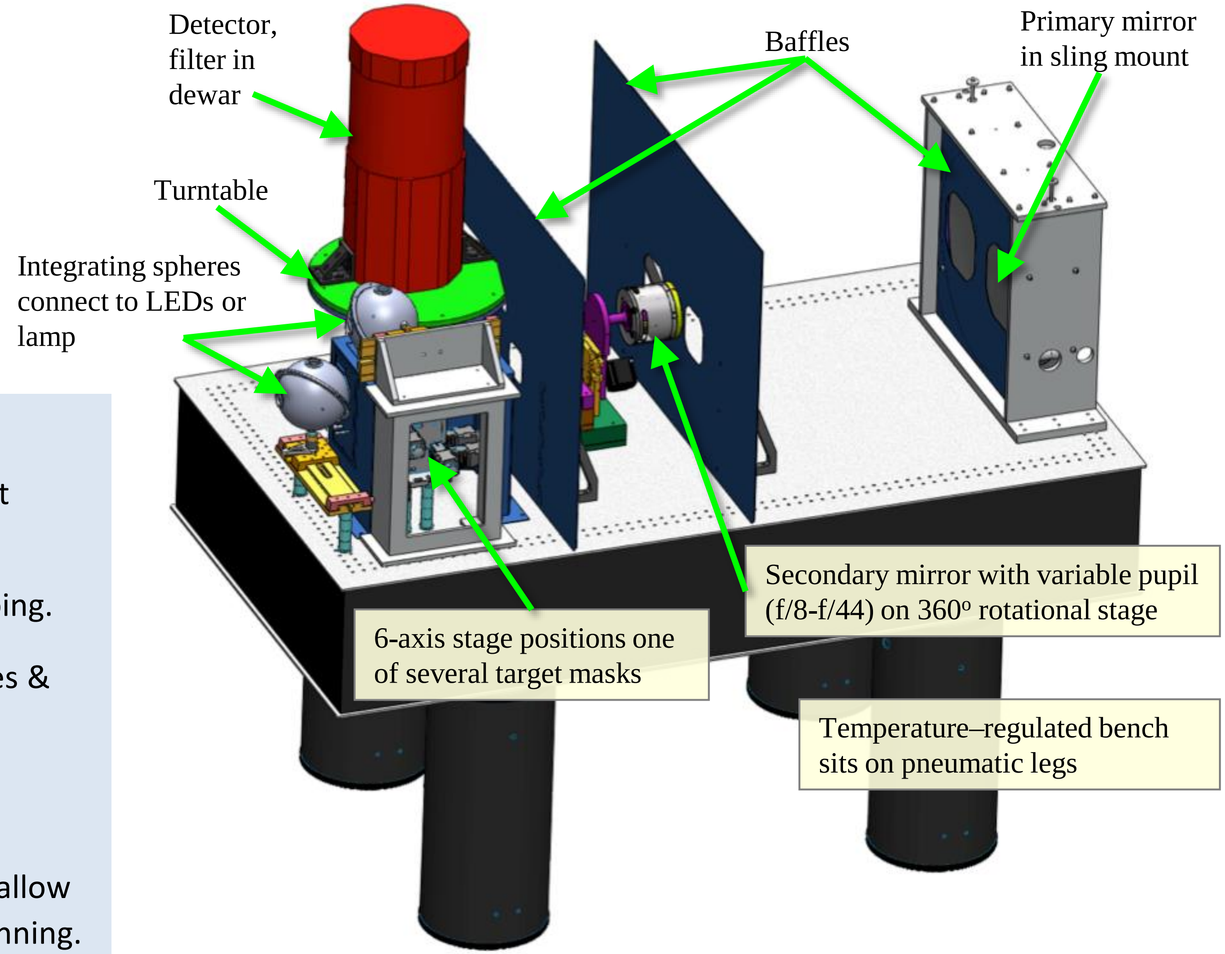
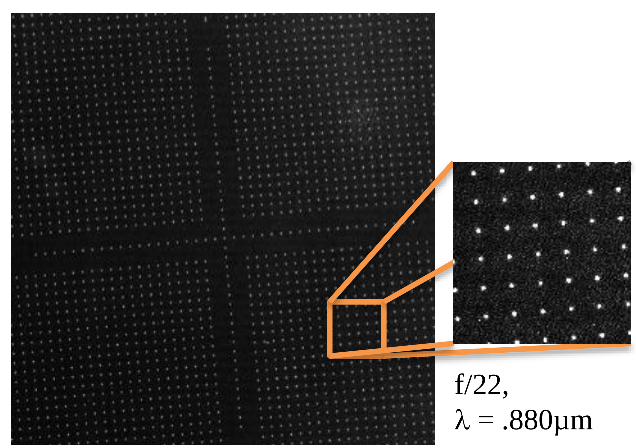


Image of 3µm spot grid (emulated stars)



Objective: Study H2RG sub-pixel response

- Engineering grade H2RG (#18546) was lent to JPL to investigate nature of the cross-hatch pattern seen in flat-field images.
- Pattern is visible even under an optical microscope. Likely related to defects in the HgCdTe crystal.
- Concern: this “feature” may correspond to sub-pixel variations in quantum efficiency (QE) or charge redistribution (like “tree rings” in Dark Energy Survey), making photometric calibration difficult.
- By emulating Euclid-like point sources, we can measure the nature of this pattern and what effect it has on photometry

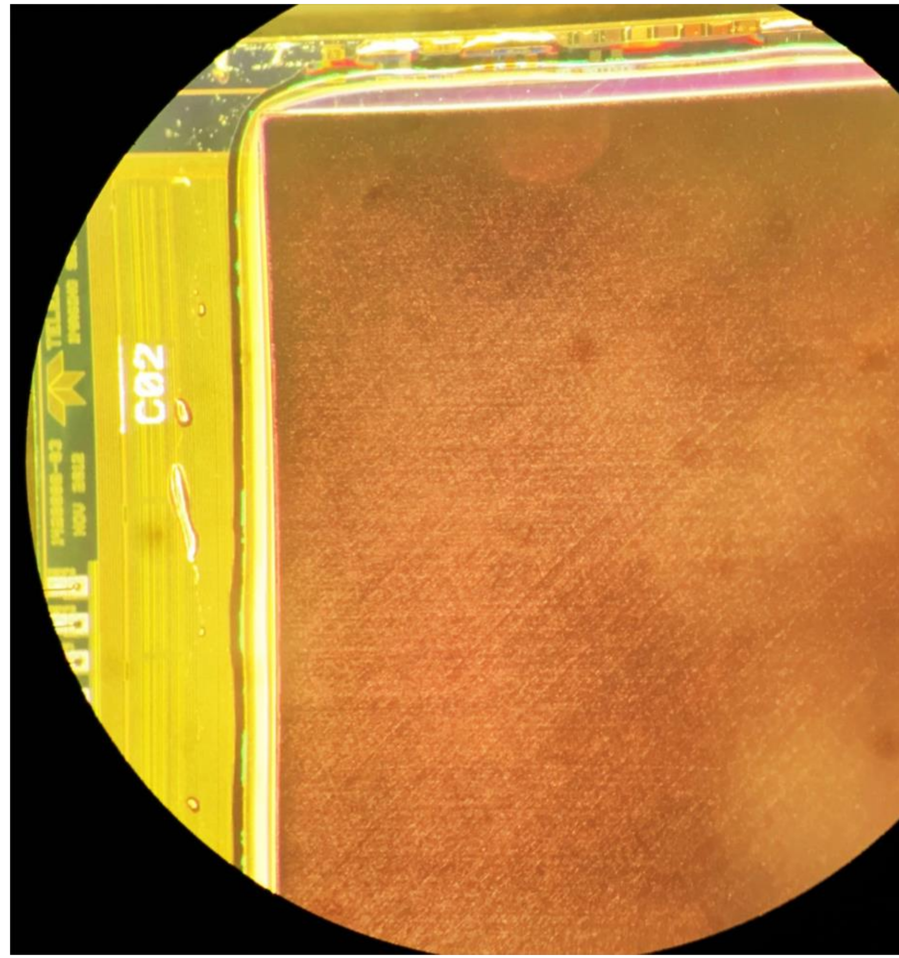
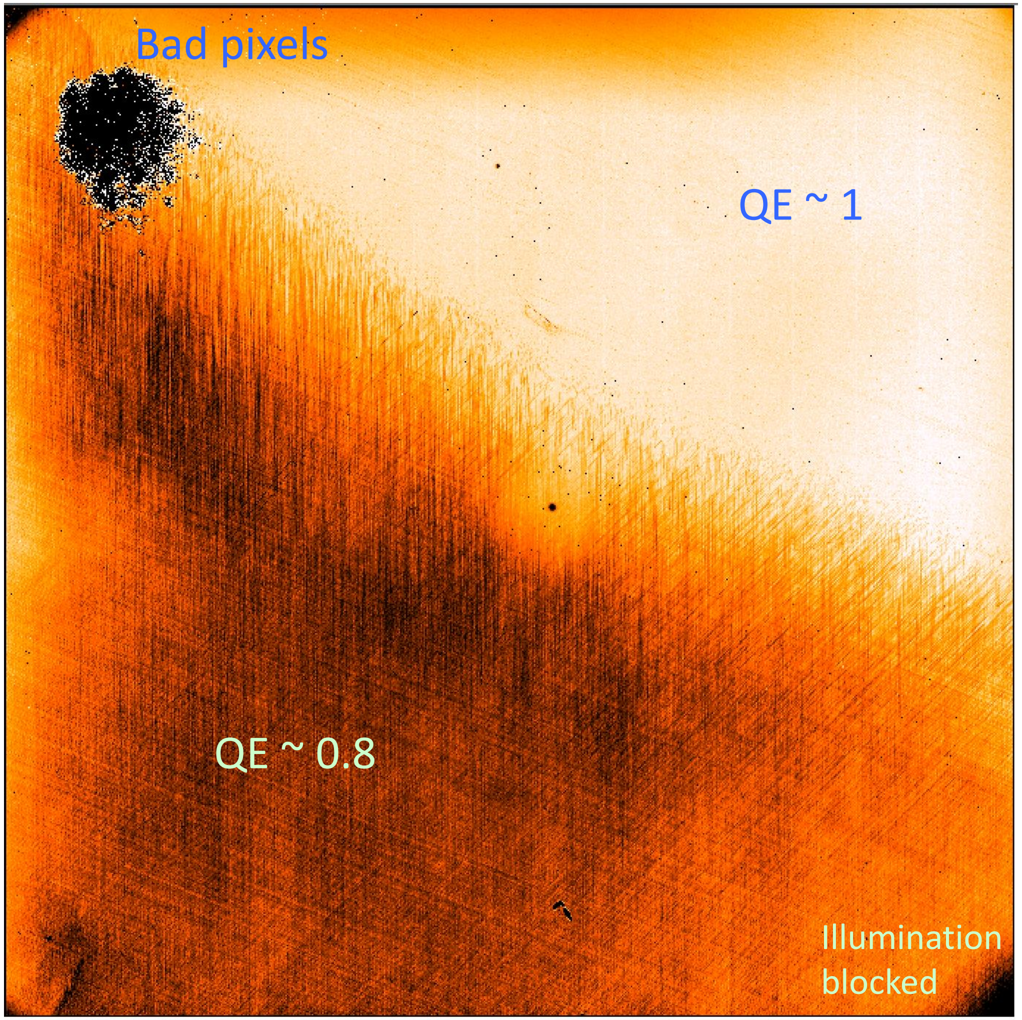


Image of H2RG #18546 taken with iPhone held up to microscope

Cross-hatch pattern in flat field (λ~1μm)

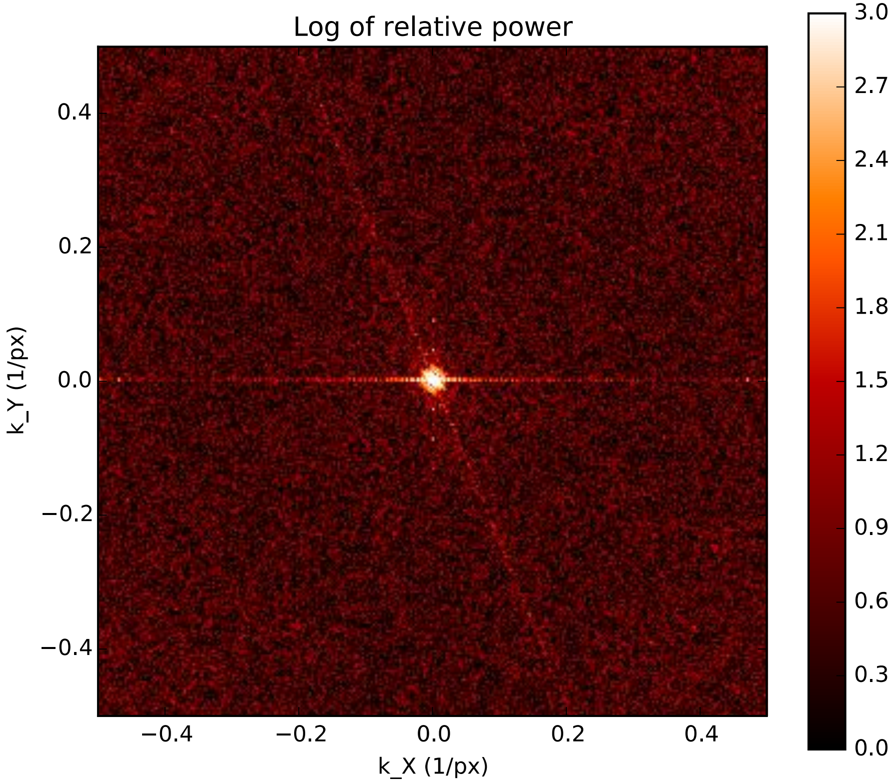


Diffuse image at ~1μm. Contrast adjusted to emphasize cross-hatch.

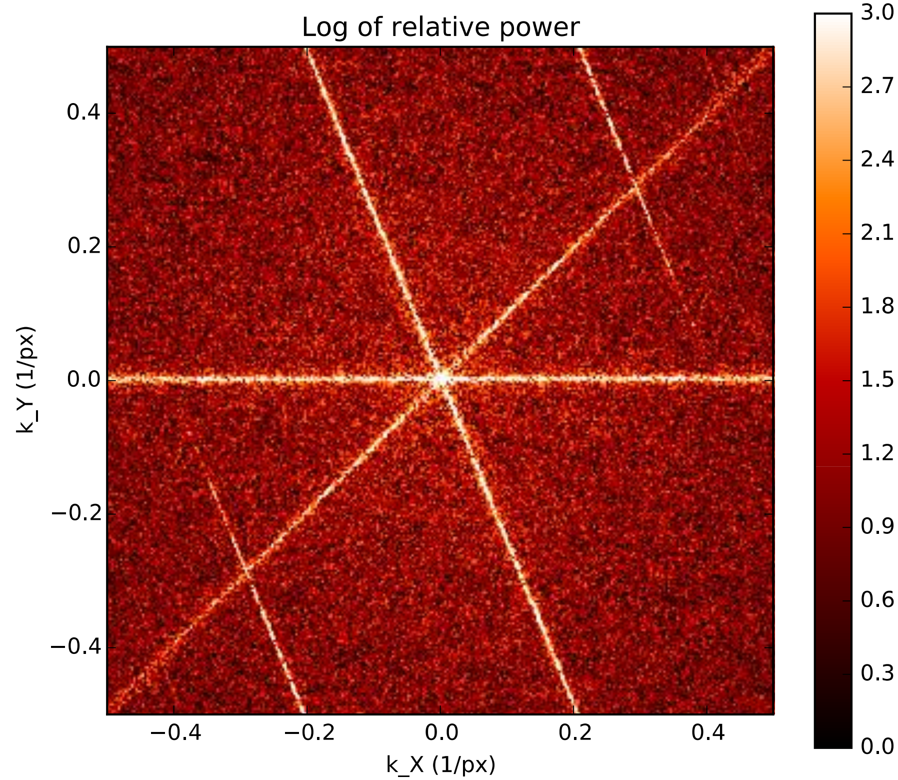
- At PPL, H2RG was cooled to 95K, operated by Leach controller at 166 kHz.
- Cross-hatch pattern easily visible in Y-band (0.97-1.07μm) flats.
- Euclid flight detectors look like the upper region with **less** cross-hatching.
- Our flat-field includes some modest illumination gradient (~ 10%). Should be distinguishable from small-scale effects.
- Teledyne Hawaii-2RG, engineering grade ; HgCdTe detector; 18μm pixels, 2k x 2k format; Cutoff wavelength 2.4 μm

Flat Power Spectrum

Clean



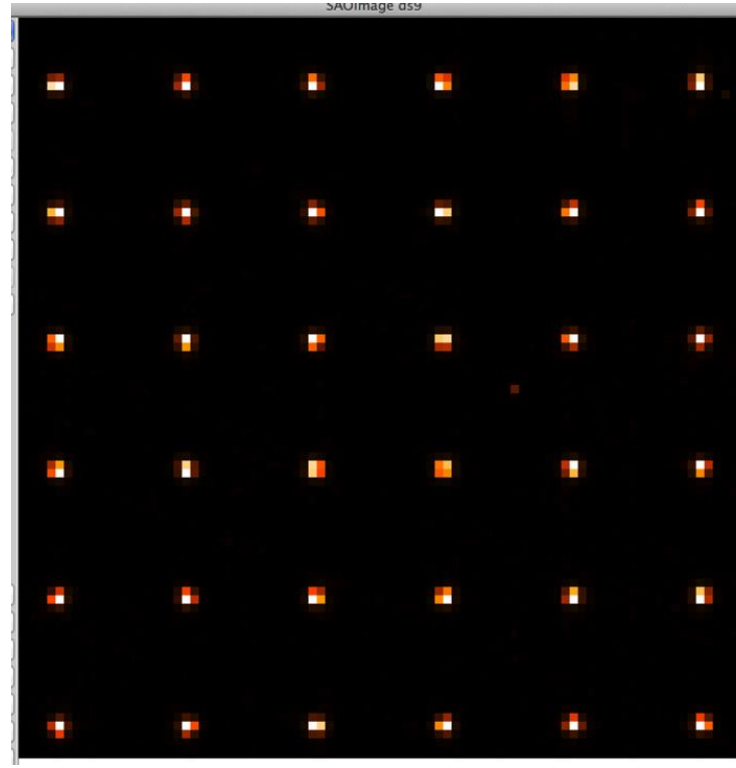
Cross-hatch



- Power is for ΔFLUX/<FLUX> - 1 of subregion
- Gaussian weight applied

Spot grid scanning

- A spot grid image (~16,000 spots) covers most of the detector. Spacing = 274.5µm = 15.25 pixels.
- **Using f/11 aperture and 1µm illumination**, the minimum spot width with charge diffusion and jitter is ~ 14µm = 0.78 pixels (full-width half-max)
- The grid was scanned in 6µm steps (1/3 pixel) parallel to detector columns to avoid spots crossing channel boundaries
- Calibrations applied to images: dark subtraction, flat fielding, conversion gain, pixel-wise nonlinearity, "bad" (outlier) pixels set to 0
- Not corrected: IPC, persistence
- A spot is discarded if its centroid comes within 5 pixels of a known bad pixel at any point in the scan

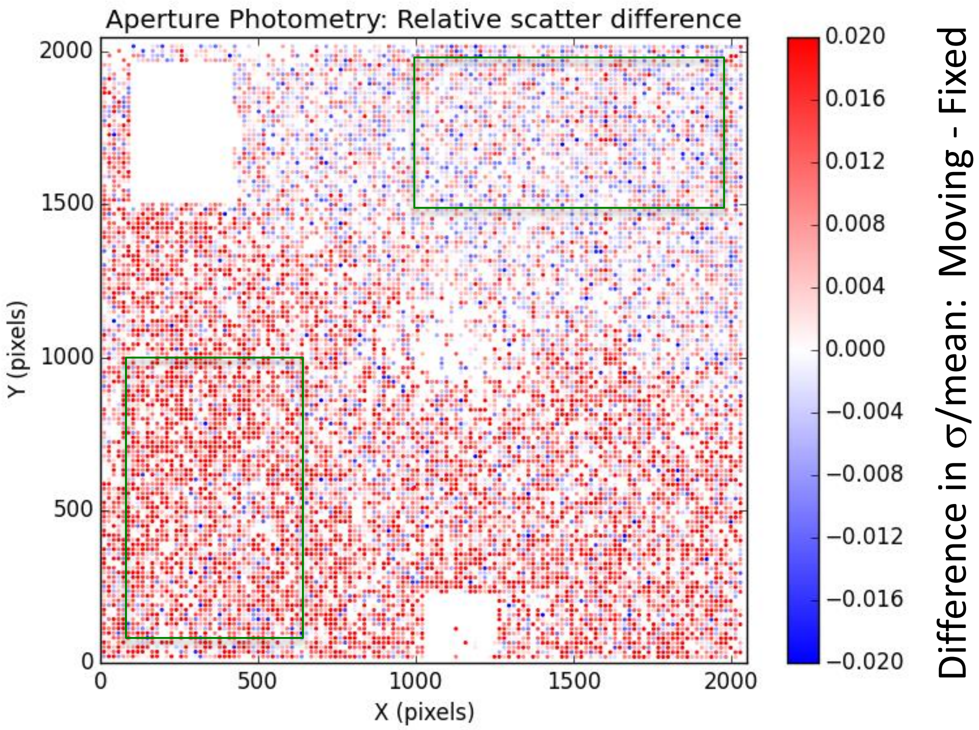


Spot grid focused on 90x90 pixel region of H2RG #18546

Measuring the effect of small image translations on photometry

- In a calibrated detector, photometry should not vary with position. Flat-fielding suppresses QE variations larger than 1 pixel but will not remove sub-pixel variation.
- We map the difference in scatter (σ/mean) for individual spot fluxes over sequences of scanned images at different positions ("moving") or at the same position ("fixed").
- **"Fixed"** sequence = 9 images at same position
- **"Moving"** sequence = 10 images in 1/3 pixel steps; spans 3 pixels

PRELIMINARY



$\Delta(\sigma/\text{mean})$ averaged over large regions:

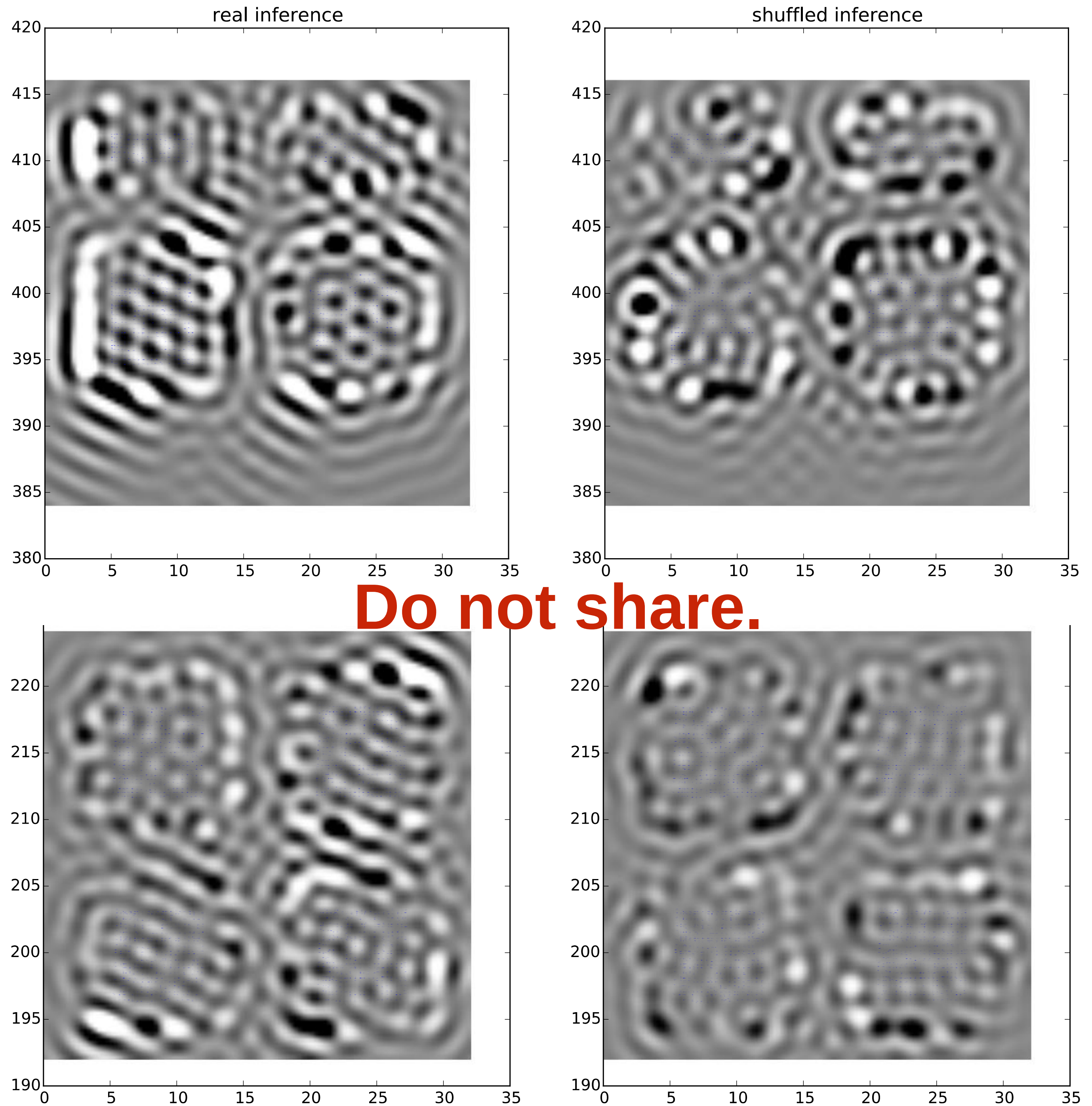
GOOD: 0.0002 ± 0.0006

BAD: 0.010 ± 0.0005

PRELIMINARY

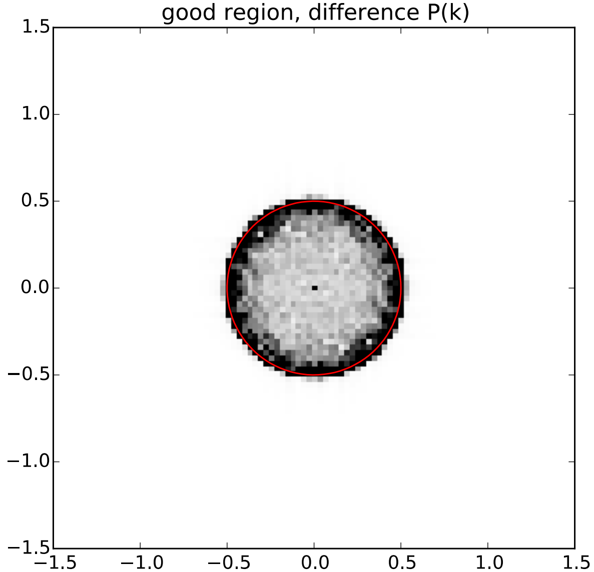
Sub-pixel QE maps
(preliminary)

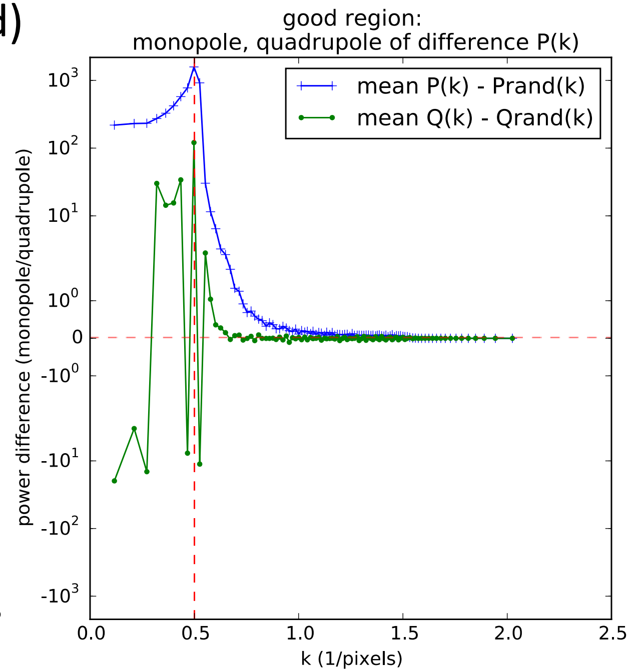
- Axis units in µm
- Blue dots show PSF trajectory
- LEFT: inferred from aperture photometry data
- RIGHT: randomized data to gauge noise

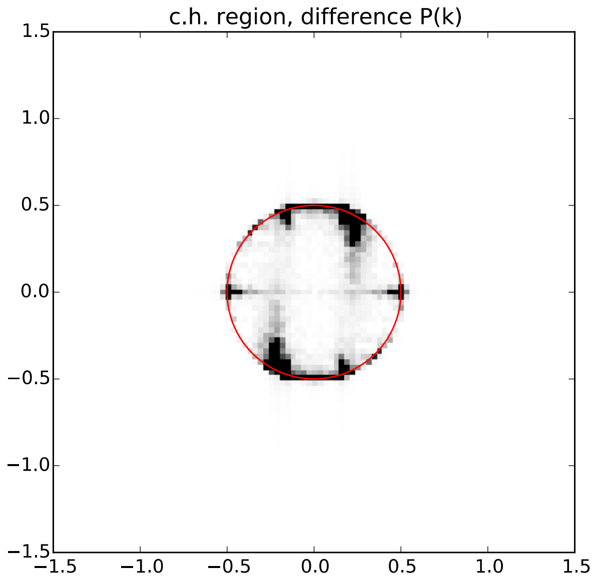


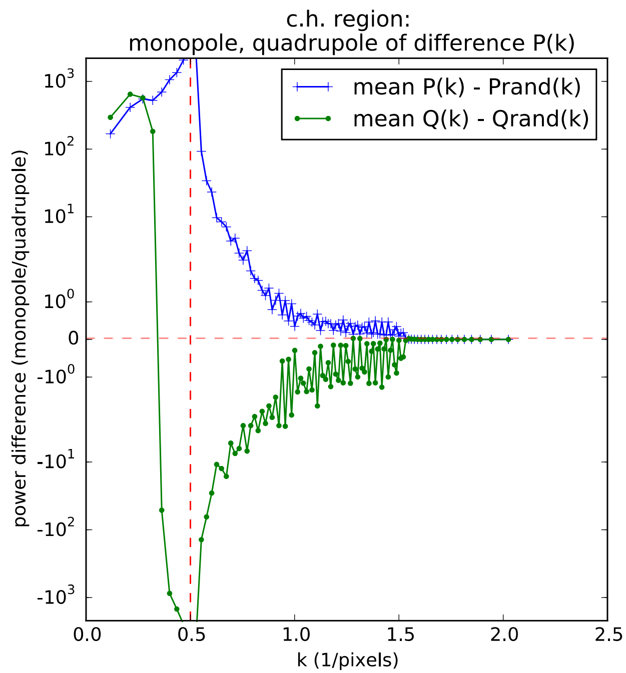
Do not share.

Power (real minus randomized)







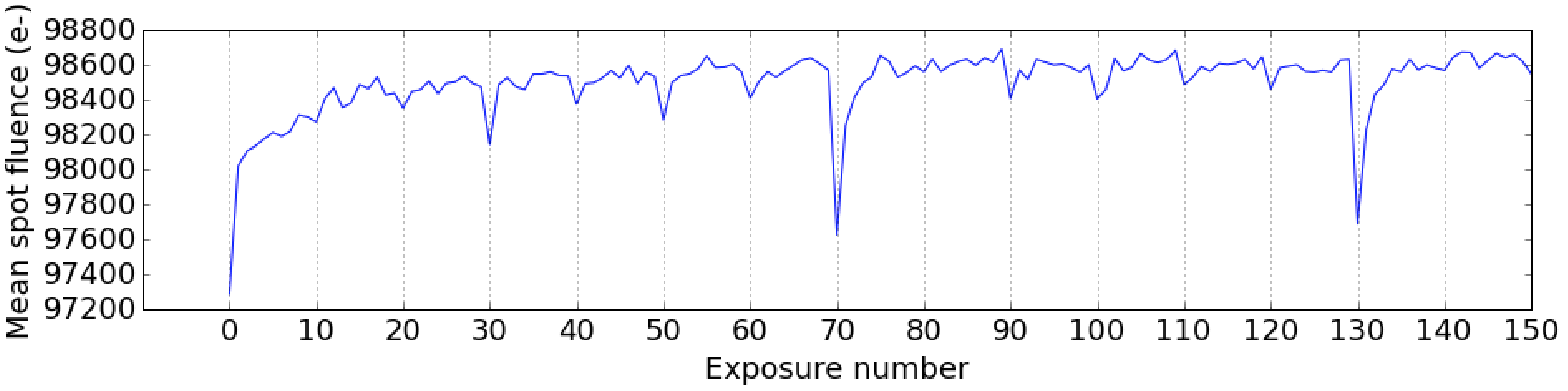


Power difference monopole & quadrupole

Interpretation

- Scanning the spots over 3 pixels has no significant effect on photometric stability in the good detector region. Scatter in the cross-hatched region increases by 1.5% relative to mean. Flat fielding reduces this to 1%.
- This is consistent with sub-pixel QE variations along the scan (column) direction. Photometry is measured by summing all pixels in an aperture; if the cross-hatch pattern were due to charge redistribution, we expect no effect in the uncorrected images, and flat fielding would make the photometry worse.
- We have not eliminated all systematics (e.g. persistence, IPC), but the correlation of the increased scatter with the cross-hatch pattern is compelling.
- **Averaging over a large detector area may be hiding small-scale effects in the "good" region,** so we should look more closely at this region.

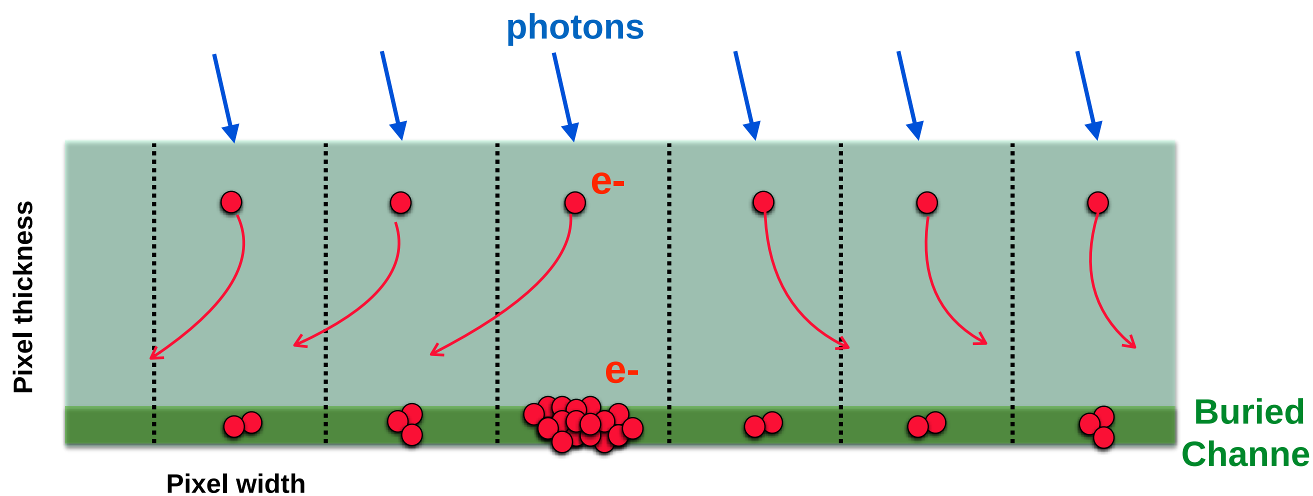
“Burn in” ? Photometric variation with exposure number.



“Brighter-fatter” effect

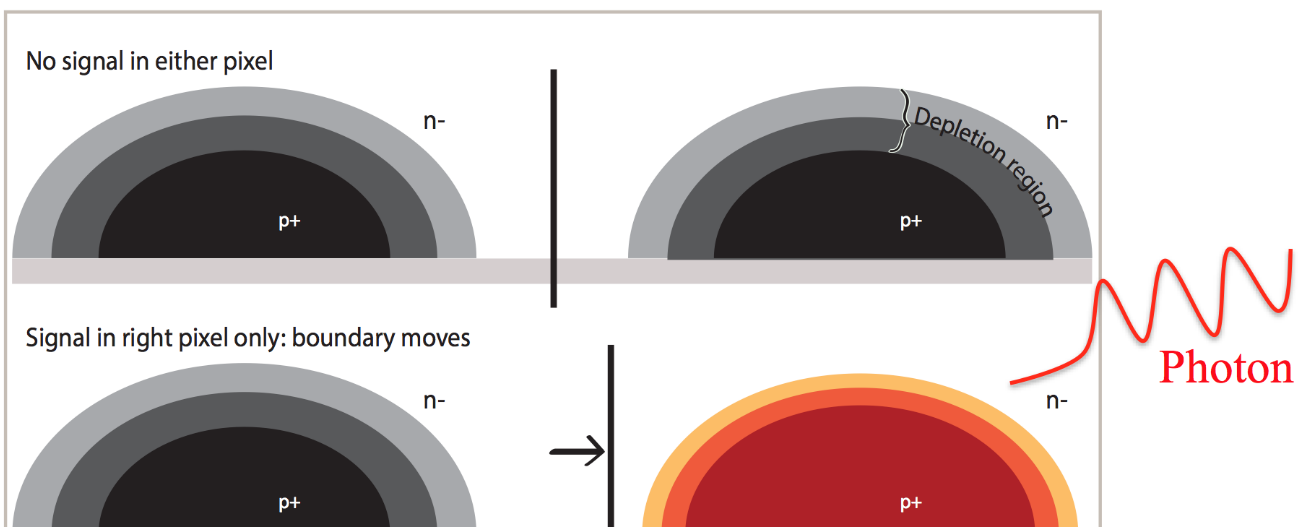
Inhomogenous distribution of the charges resulting from :

- Contrast from the photon noise in flatfield images.
- PSF of a star.



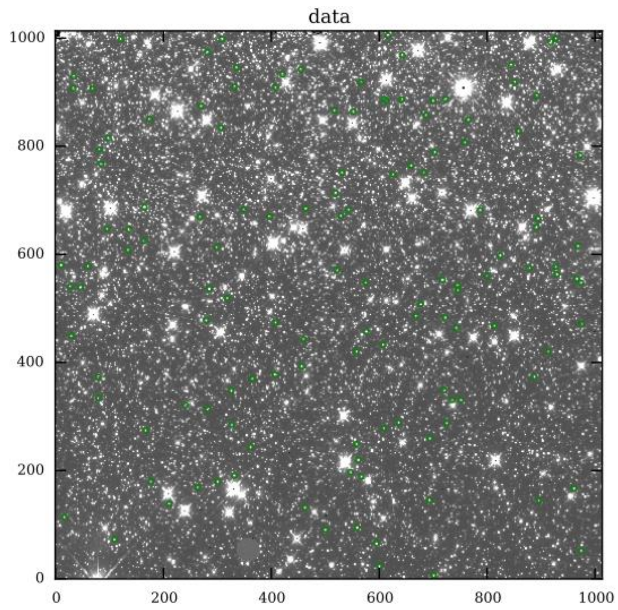
CCD model
Image Credit: Augustin Guyonnet

Model in HxRG?

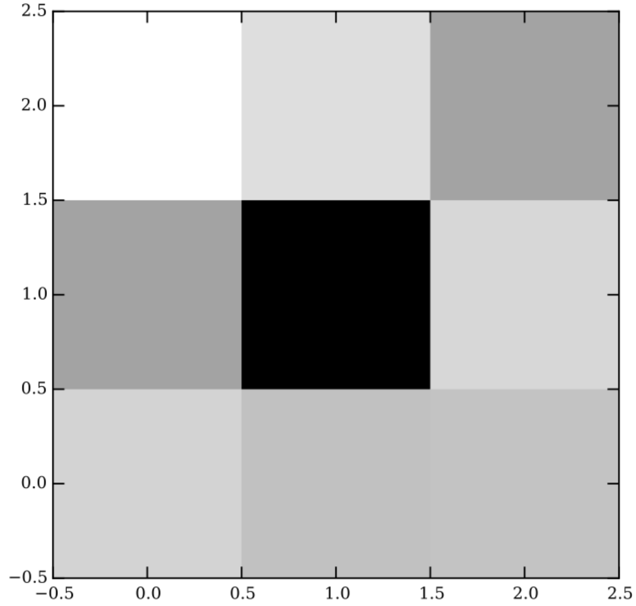


In either case, pixel boundaries are effectively shifted

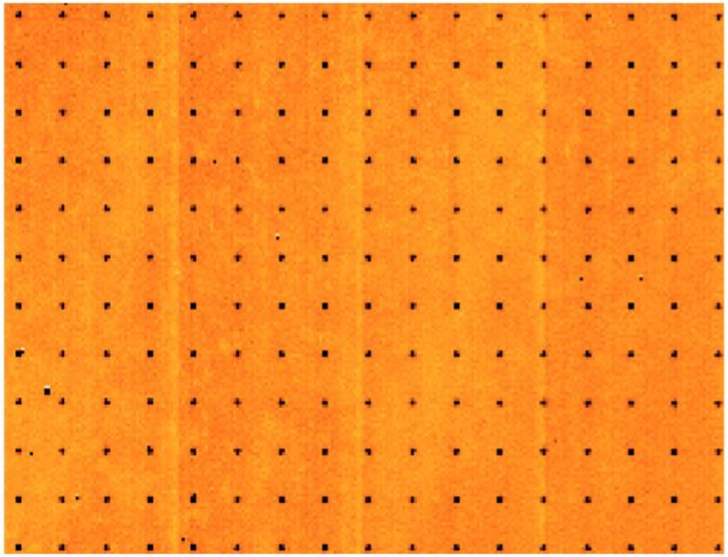
Hubble data



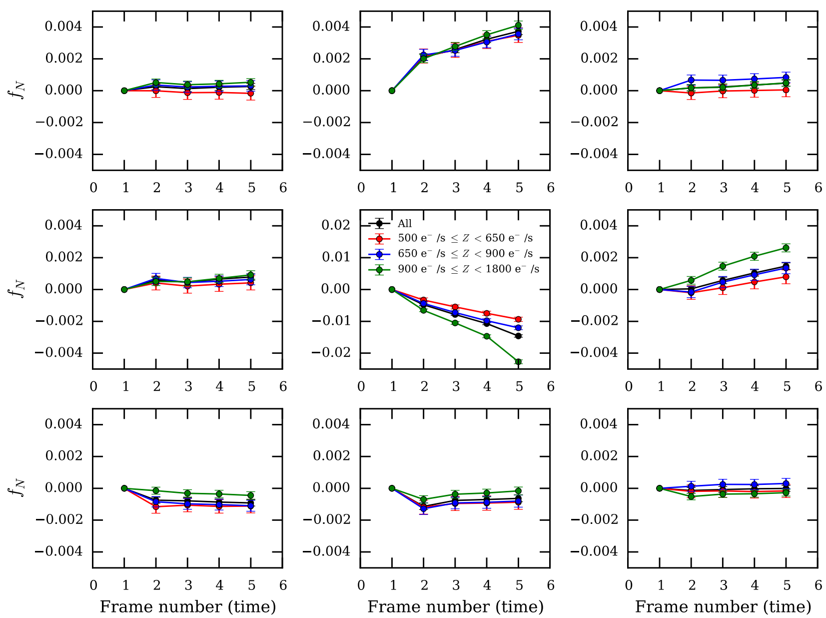
Single star/spot

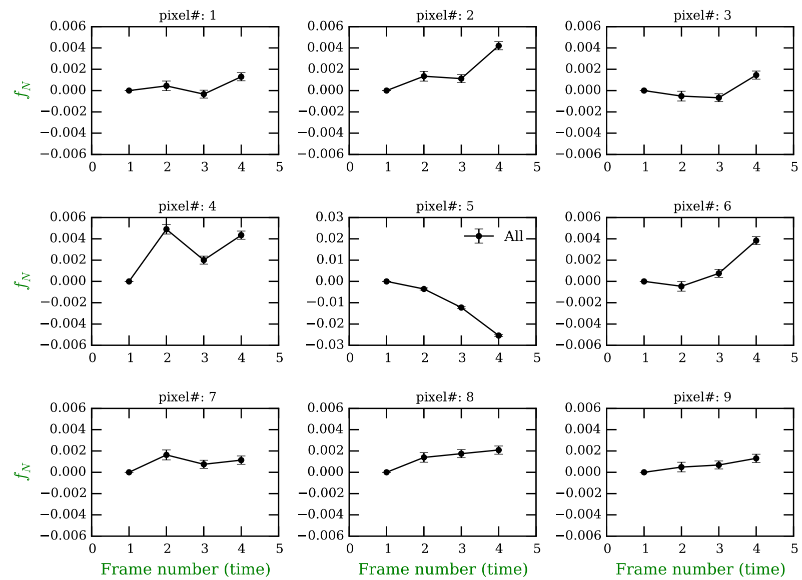


PPL data



Flux changes up the ramp





Flux changes up the ramp