# Non-linear effects in H4RG-10 detectors

*and how they could impact constraints on dark energy*

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Detector Modelling Workshop

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CCAPP CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

THE OHIO STATE UNIVERSITY

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with invaluable contributions from:
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Nancy G. Roman Space Telescope Detector Working Group
Cosmology with the High Latitude Survey Science Investigation Team: https://www.roman-hls-cosmology.space/

# What drives the accelerated expansion of the Universe? How do we measure it?

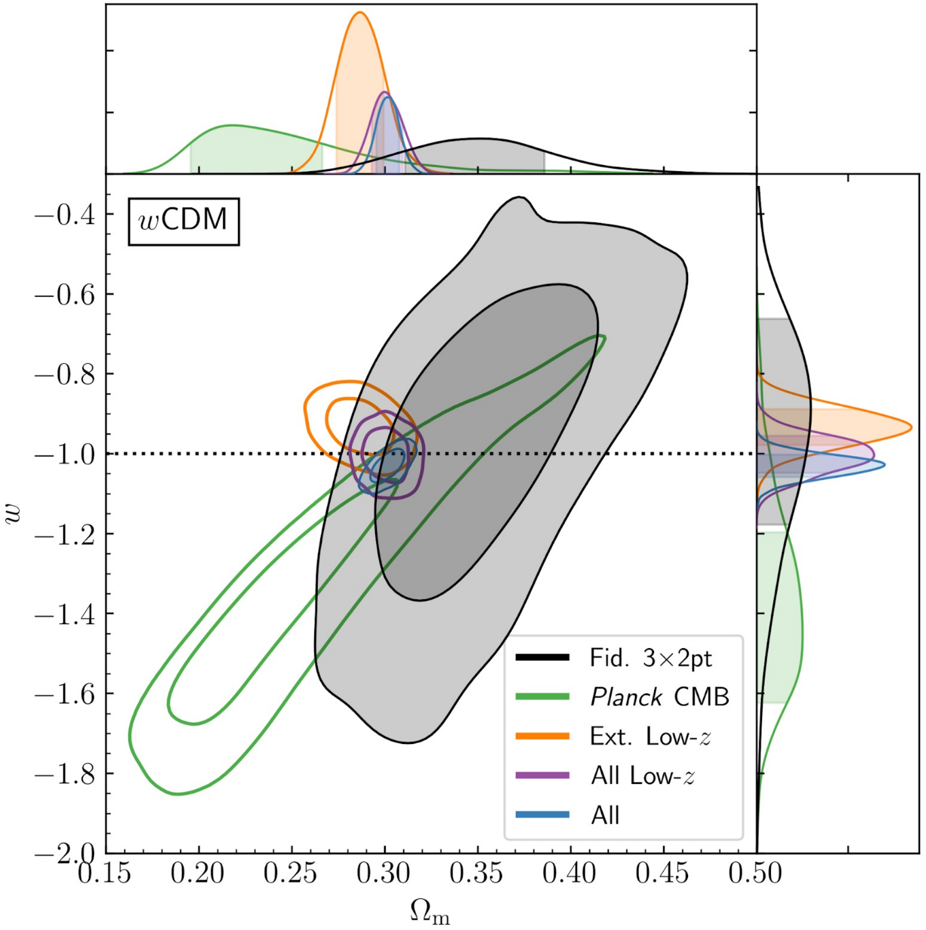
## Geometry:

- Supernovae
- Baryon acoustic oscillations
- CMB angular power spectrum

## Geometry & Structure Growth:

- Gravitational lensing
- Galaxy cluster abundance
- Redshift-space distortions

DES Collaboration 2021



Dark energy equation of state

Density of matter

# The Nancy G. Roman Space Telescope

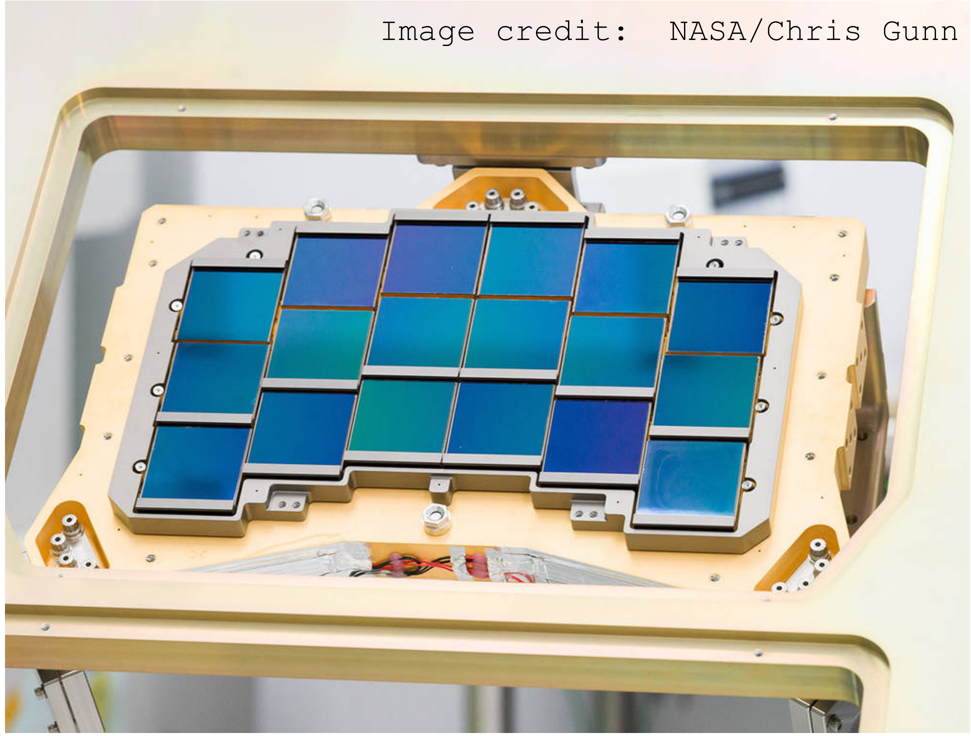


Image credit: NASA/Chris Gunn

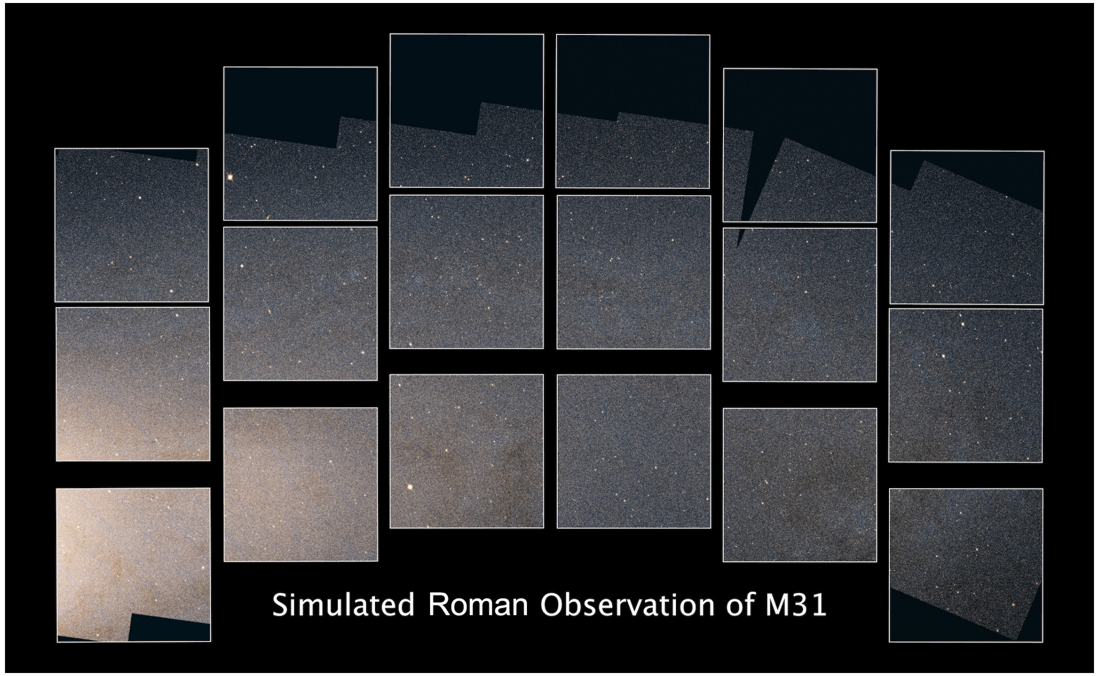
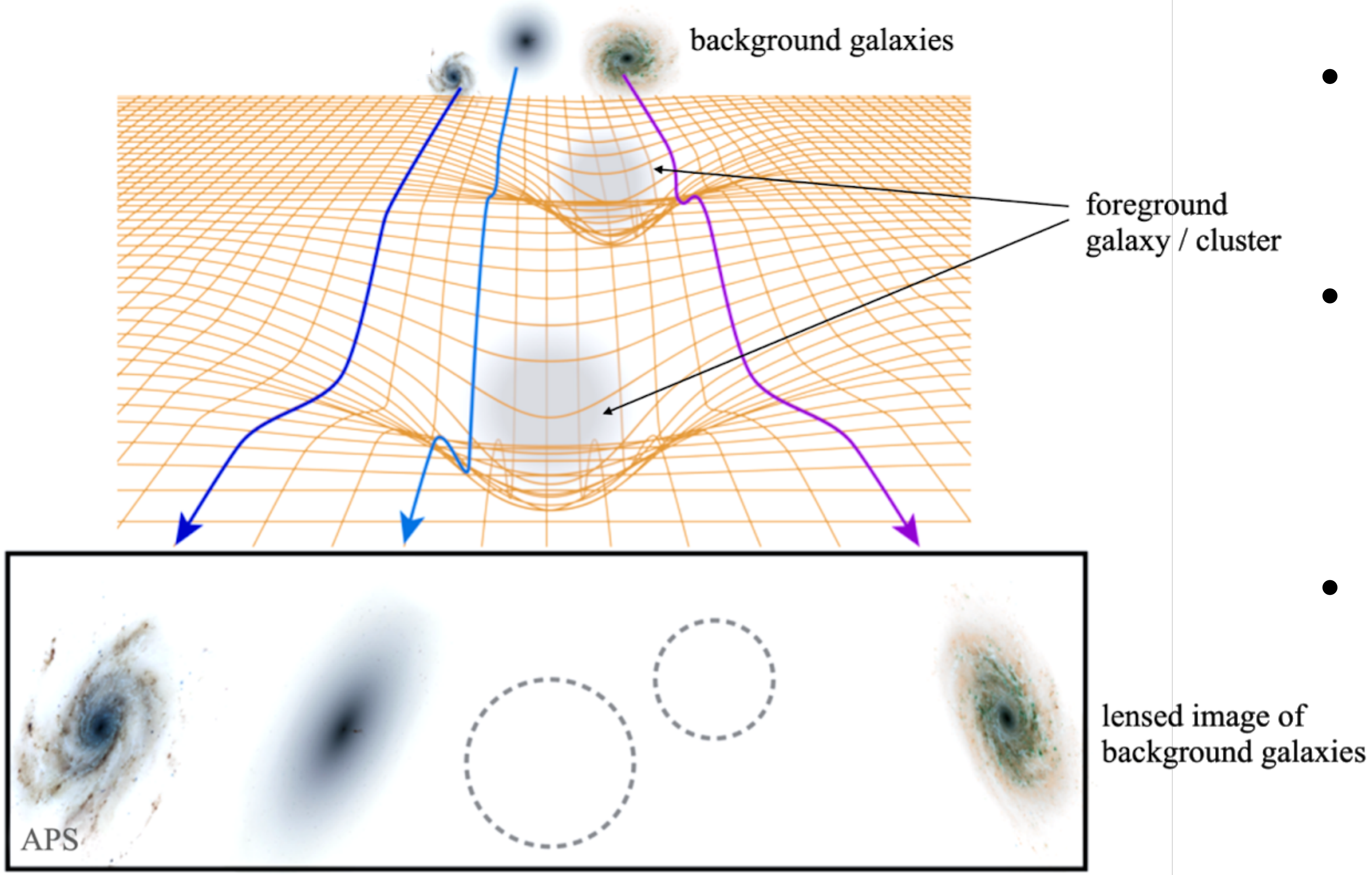


Image credit: GSFC/SVS/B. F. Williams

Simulated Roman Observation of M31

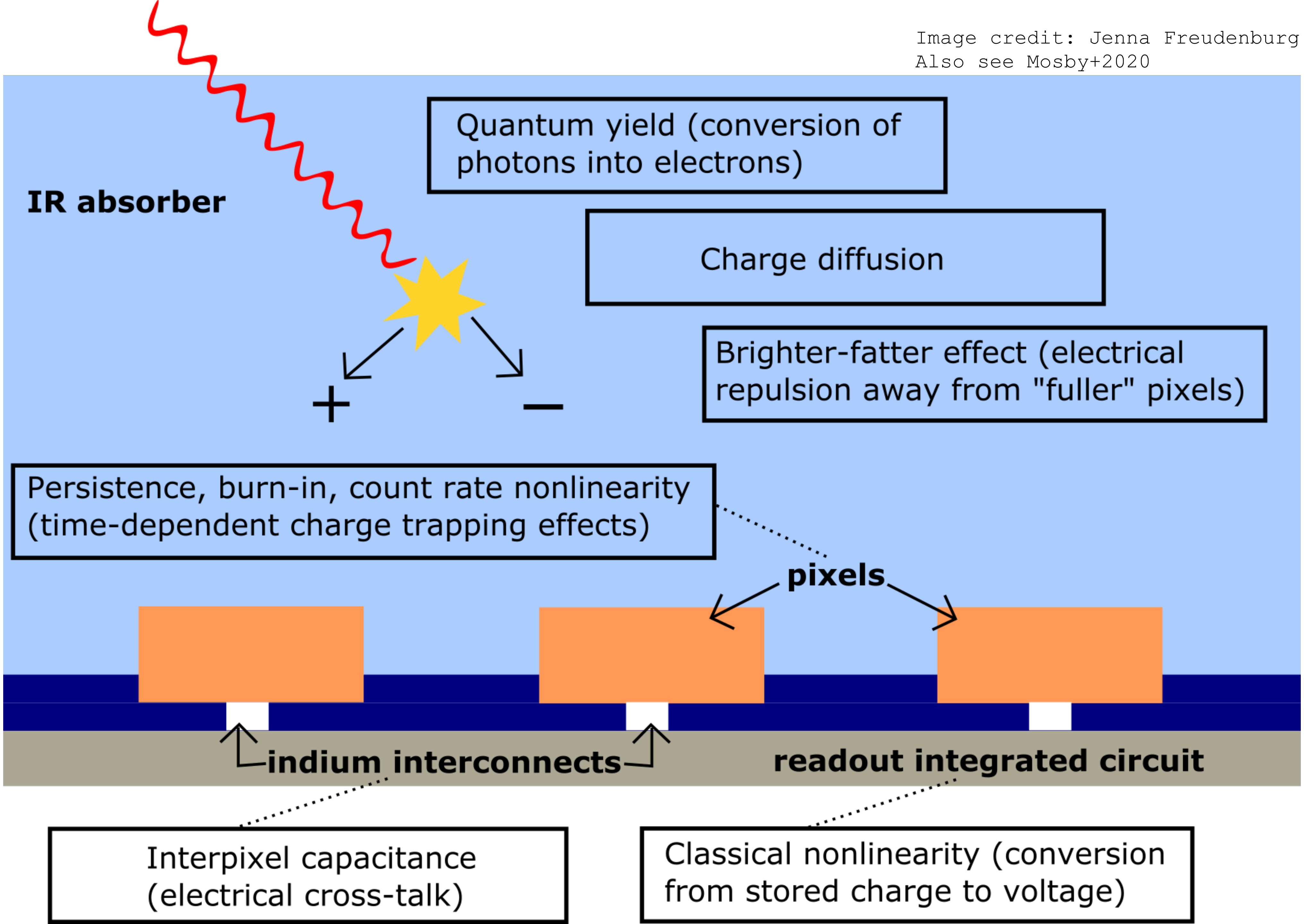
- Hubble-sized telescope, power, and resolution, 100x field of view (0.28 sq. deg.)
- Dark energy, exoplanet, wide-field survey capabilities, coronagraph, guest observer program
- 18 H4RG-10 infrared detectors (Teledyne) + 6 spares now selected!

# Roman will use weak gravitational lensing to investigate cosmic acceleration



- Lensing induces coherent correlations in galaxy shapes
- Knowledge of point-spread function (PSF) essential: error <0.057% (ellipticity) and <0.072% (size)
- PSF models for lensing typically based on stars
  - non-linear effects like brighter-fatter effect are worrisome

Image credit: Jenna Freudenburg
Also see Mosby+2020



Quantum yield (conversion of photons into electrons)

Charge diffusion

Brighter-fatter effect (electrical repulsion away from "fuller" pixels)

Persistence, burn-in, count rate nonlinearity (time-dependent charge trapping effects)

Interpixel capacitance (electrical cross-talk)

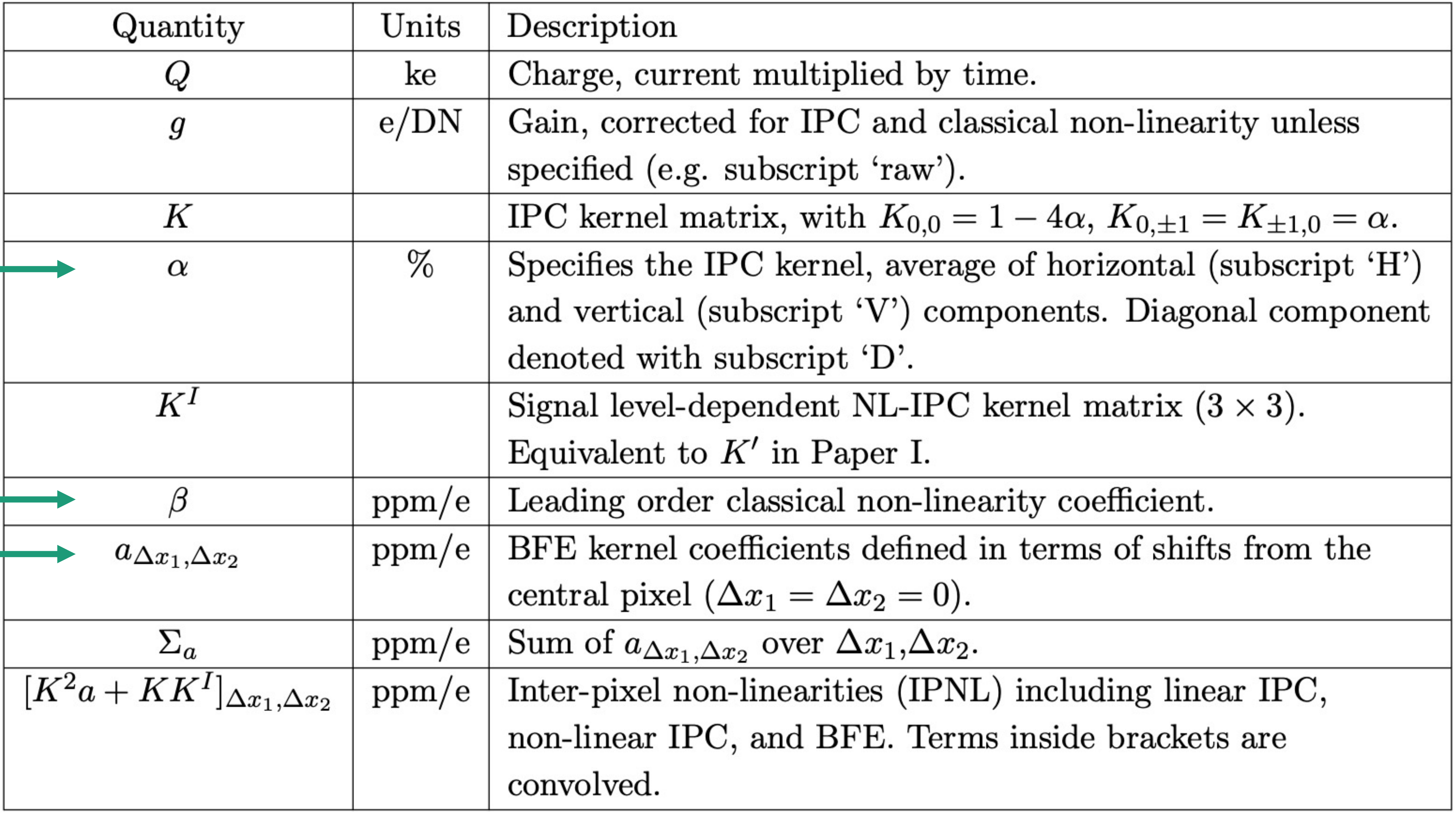
Classical nonlinearity (conversion from stored charge to voltage)

# Modelling BFE, IPC, classical NL

- Brighter-fatter effect: If a pixel contains more electrons than its neighbors, self-repulsion will cause subsequent photo-electrons more likely to land in neighbor
  - Brighter point source produces larger image (non-linear), **describe in terms of area defect**
  - Studied mostly on CCDs (Antilogus+2014, … ), H2RG measurements made based on point source illumination on H2RG (Plazas+2018)
- Inter-pixel capacitance: Form of cross-talk where fringing fields cause voltage readings in given pixel to depend on charges in neighboring pixels
  - Modelled as a **coupling capacitance between pixels**, can depend on signal (linear and non-linear components; Cheng 2009, Donlon+2016,2017,2018)
  - Dominates flat-field correlation signals (Moore+2004)
- Classical non-linearity: polynomial fit to signal vs time, also consider higher-order terms

$$S_{\text{initial}} - S_{\text{final}} = \frac{1}{g}\left(Q - \beta Q^2\right)$$

Freudenburg, Givans+2020



| Quantity | Units | Description |
|---|---|---|
| $Q$ | ke | Charge, current multiplied by time. |
| $g$ | e/DN | Gain, corrected for IPC and classical non-linearity unless specified (e.g. subscript 'raw'). |
| $K$ | | IPC kernel matrix, with $K_{0,0} = 1 - 4\alpha$, $K_{0,\pm 1} = K_{\pm 1,0} = \alpha$. |
| $\alpha$ | % | Specifies the IPC kernel, average of horizontal (subscript 'H') and vertical (subscript 'V') components. Diagonal component denoted with subscript 'D'. |
| $K^I$ | | Signal level-dependent NL-IPC kernel matrix ($3 \times 3$). Equivalent to $K'$ in Paper I. |
| $\beta$ | ppm/e | Leading order classical non-linearity coefficient. |
| $a_{\Delta x_1, \Delta x_2}$ | ppm/e | BFE kernel coefficients defined in terms of shifts from the central pixel ($\Delta x_1 = \Delta x_2 = 0$). |
| $\Sigma_a$ | ppm/e | Sum of $a_{\Delta x_1, \Delta x_2}$ over $\Delta x_1$,$\Delta x_2$. |
| $[K^2 a + K K^I]_{\Delta x_1, \Delta x_2}$ | ppm/e | Inter-pixel non-linearities (IPNL) including linear IPC, non-linear IPC, and BFE. Terms inside brackets are convolved. |

# Modelling BFE, IPC, classical NL

- Hirata & Choi 2020 builds formalism to describe the correlation function including IPC, classical non-linearity, BFE to leading order
    - In the paper, we start from a perfect detector, compute signal correlation, and add effects
    - Freudenburg, Givans, Choi, Hirata+2020 takes calculations to Fourier space, allowing retention of higher-order terms (simulations biases reduced!)
    - The correlation we are modelling looks like:

$$C_{abcd}(\Delta i, \Delta j) = \mathrm{Cov}[S_a(i,j) - S_b(i,j), S_c(i+\Delta i, j+\Delta j) - S_d(i+\Delta i, j+\Delta j)]$$

where subscripts *a,b,c,d* denote **time slices** and *i, j* refer to **pixel locations** and shifts relative to those locations

$$\begin{aligned} C_{abcd}(\Delta i, \Delta j)|_{a<b<c<d} &= \frac{I^2 t_{ab} t_{cd}}{g^2} \Big\{ [K^2 a]_{-\Delta i,-\Delta j} + [KK']_{\Delta i,\Delta j} - 2(1-8\alpha)\beta\delta_{\Delta i,0}\delta_{\Delta j,0} \\ & -4\alpha_{\mathrm{H}}\beta\delta_{|\Delta i|,1}\delta_{\Delta j,0} - 4\alpha_{\mathrm{V}}\beta\delta_{\Delta i,0}\delta_{|\Delta j|,1} \Big\}. \end{aligned}$$

# Modelling BFE, IPC, classical NL

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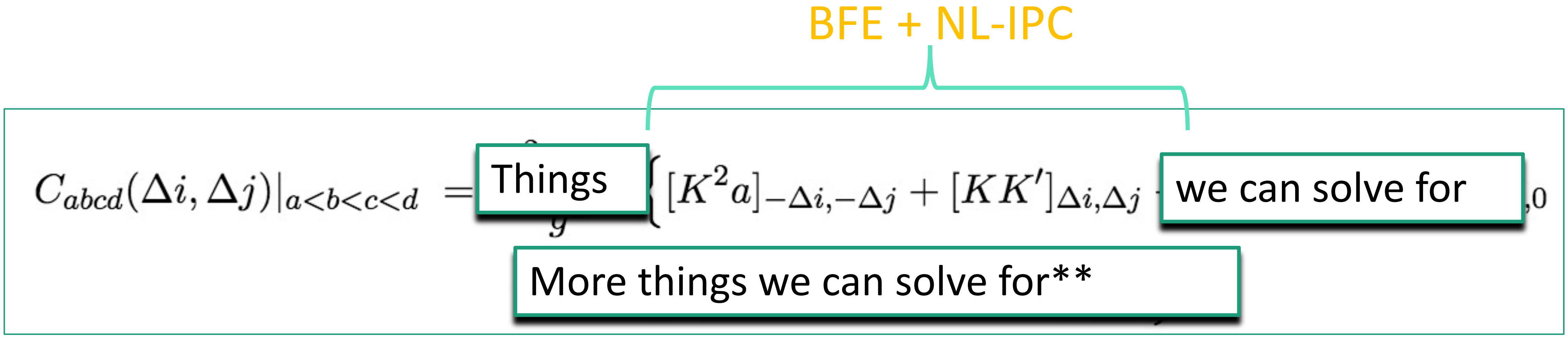
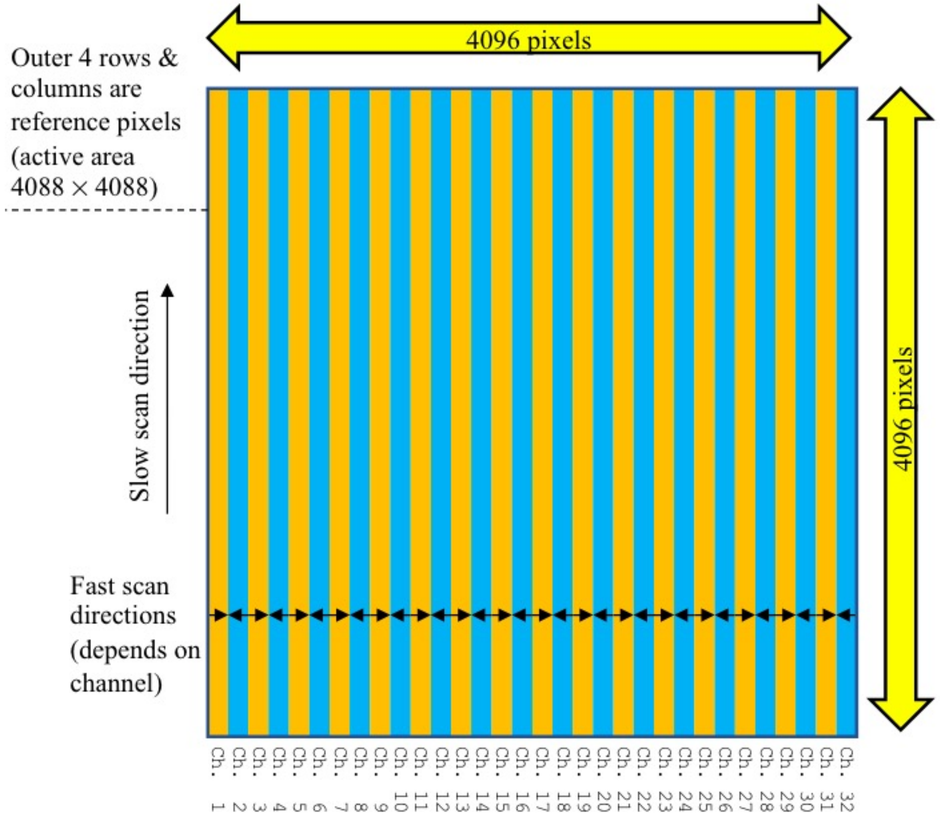


**Calculate raw gain, horizontal correlation, vertical correlation, mean signal (*ad*), ratio of slope of signal in *cd* vs *ab* interval – solve 5 equations for 5 unknowns: g, I,$\alpha_H$, $\alpha_V$, $\alpha_D$, $\beta_r$

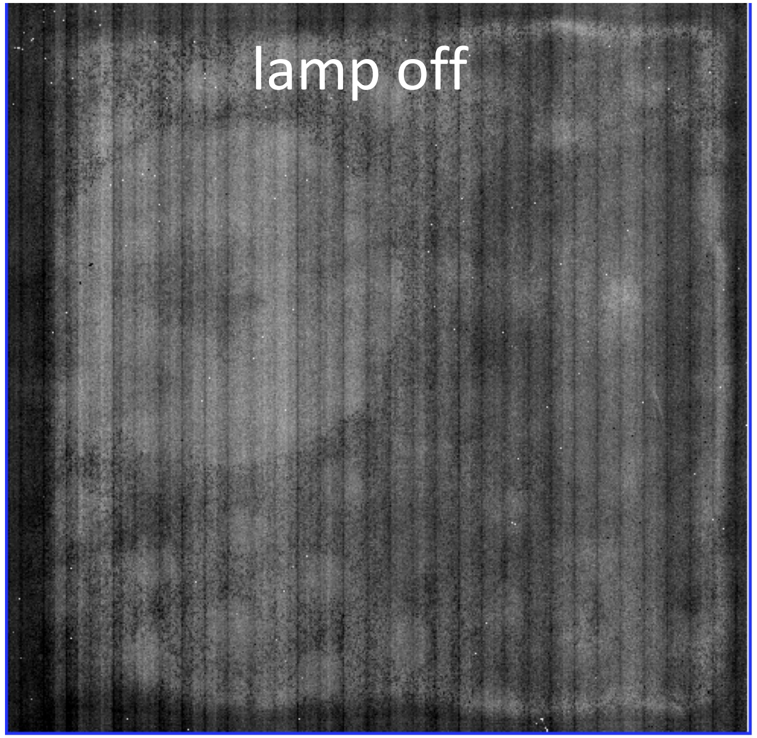
# Flats and darks for H4RG-10 devices from the DCL

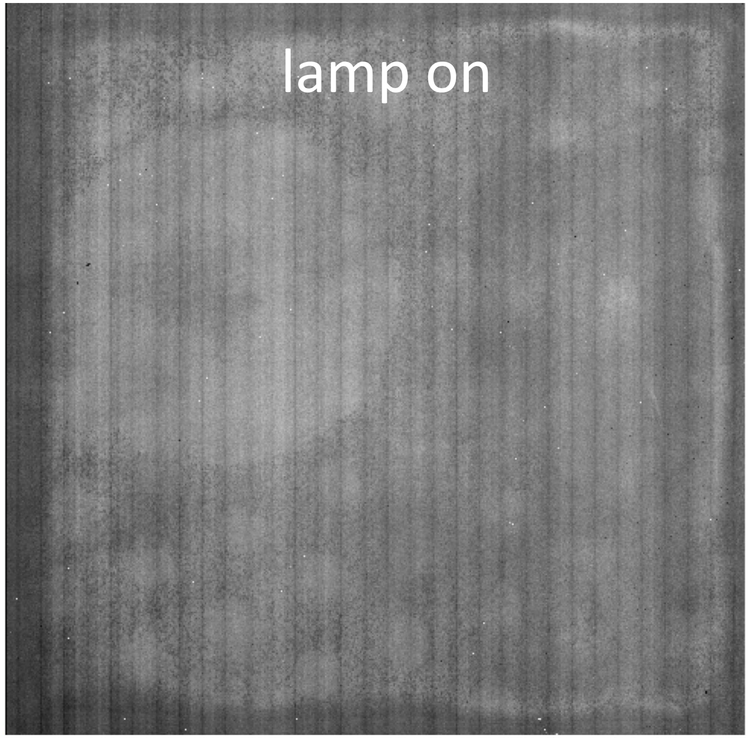


Outer 4 rows & columns are reference pixels (active area 4088 × 4088)

Slow scan direction

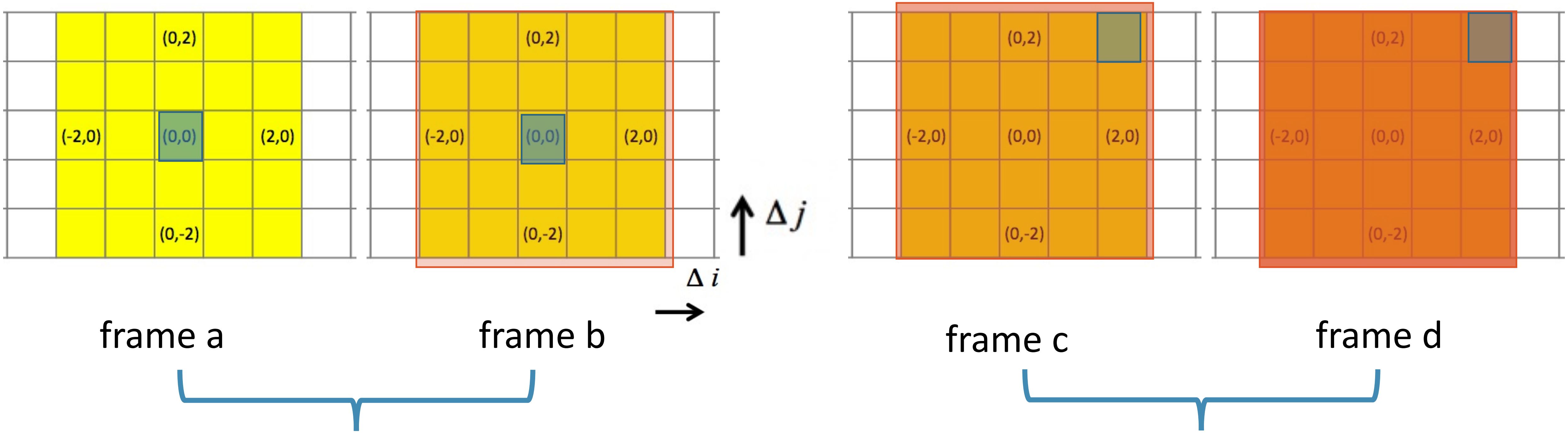
Fast scan directions (depends on channel)


lamp off

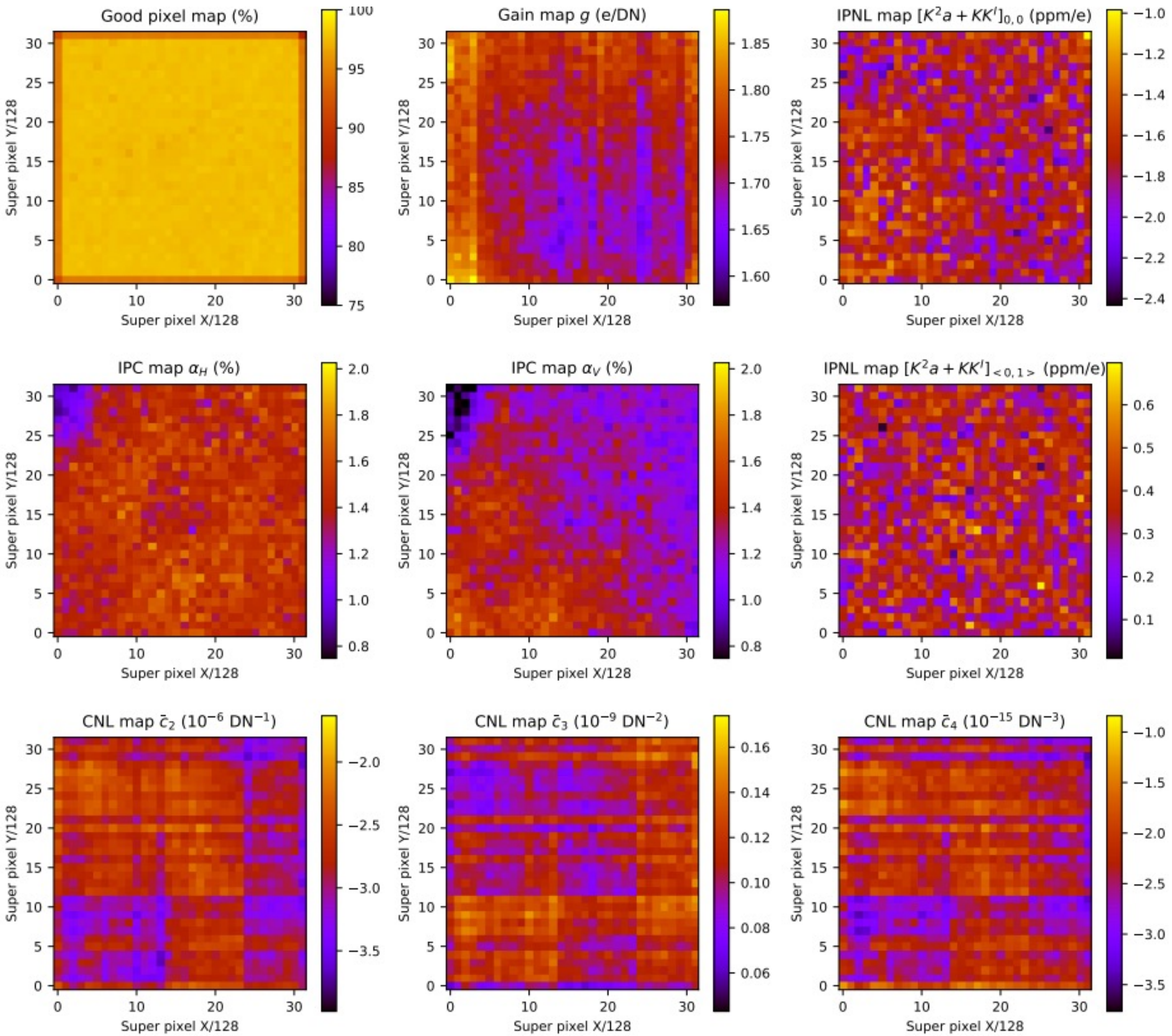

lamp on

# Correlation Measurements

## time frames a<b<c<d

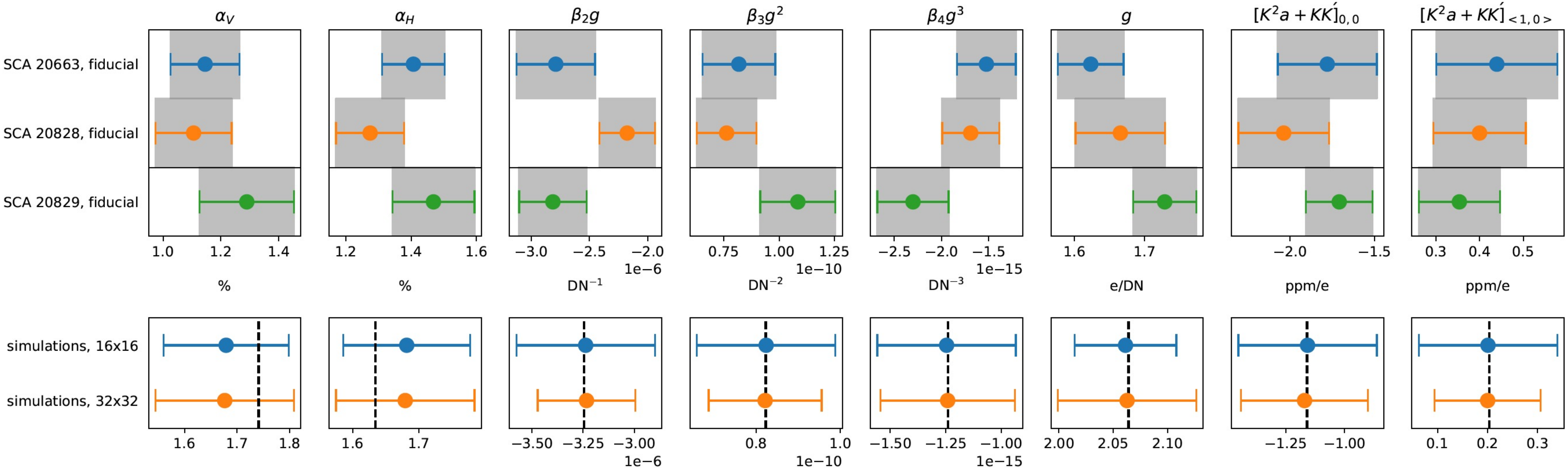


$$\mathrm{Cov}[S_a(i,j) - S_b(i,j), S_c(i+\Delta i, j+\Delta j) - S_d(i+\Delta i, j+\Delta j)]$$



Parameters of interest are computed for 'super-pixels' 128 x 128 pixels on a side (see Choi & Hirata 2020, Freudenburg, Givans+2020 for examples for multiple detectors).

# Flight Detector Characterization



`Freudenberg, Givans, Choi, Hirata+2020`

# Mean-variance tests

- For these tests, key observable is mean-variance slope for *a=c<b<d*

$$\hat{g}^{\rm raw}_{abad} = \frac{g}{(1-4\alpha-4\alpha_{\rm D})^2+2(\alpha_{\rm H}^2+\alpha_{\rm V}^2)+4\alpha_{\rm D}^2}\Big\{1+\left[2\beta-8(1+3\alpha)\alpha'\right]It_a$$
$$+\left[3\beta-(1+8\alpha)[K^2a]_{0,0}+8(1+3\alpha)\alpha'\right]I(t_{ad}+t_{ab})+2(1+2\alpha)\beta\Big\}$$

  - Fix start time $t_a$ and fit: $\ln\hat{g}^{\rm raw}_{abad} = C_0 + C_1 I(t_{ad}+t_{ab})$
  - Fix interval durations $t_{ab}$ and $t_{ad}$ and fit: $\ln\hat{g}^{\rm raw}_{abad} = C_0' + C_1' I t_a$
- Interpreting non-linearity from non-overlapping correlation function as entirely BFE or entirely NL-IPC generates prediction for this test

# Adjacent pixel correlation tests

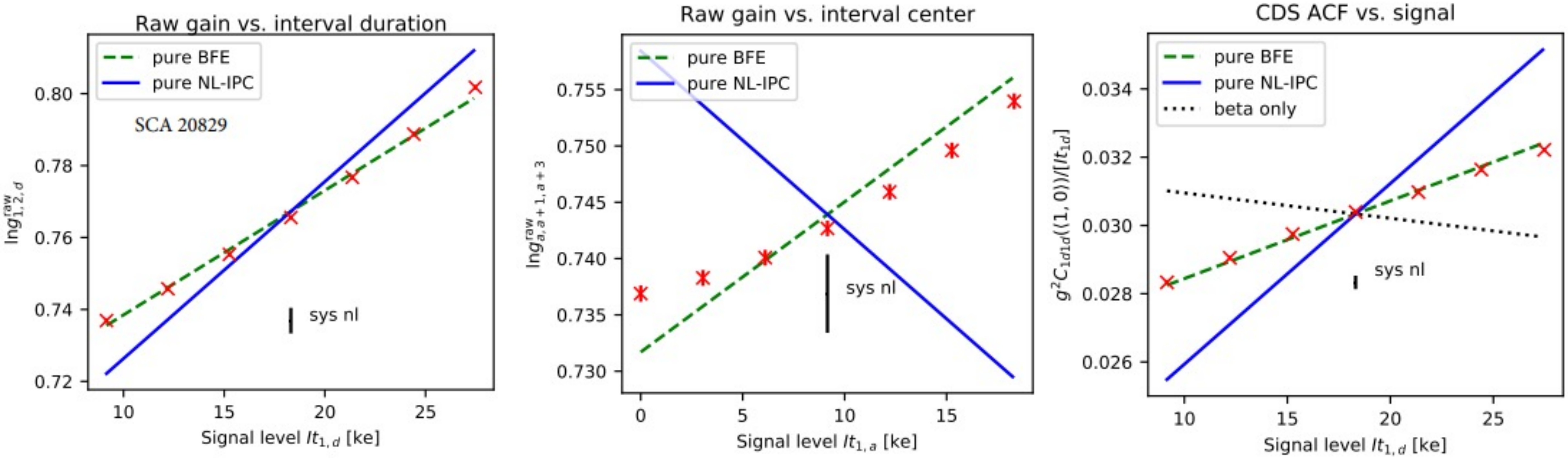
- Use equal interval correlation function in adjacent pixels (auto-correlation of a single difference image)

$$\begin{aligned} C_{abab}(\pm 1,0) \;&=\; \frac{I}{g^2} t_{ab}\Big\{2\alpha_{\mathrm{H}}(1-4\alpha-4\alpha_{\mathrm{D}})+4\alpha_{\mathrm{V}}\alpha_{\mathrm{D}}-8\alpha_{\mathrm{H}}\beta\left(It_b+\frac{1}{2}\right)+\alpha_{\mathrm{H}}\Sigma_a I(t_a+t_b) \\ &\quad +[K^2a]_{\mathrm{H}} I t_{ab}+2[KK']_{1,0} I t_b\Big\}, \end{aligned}$$

- Fix starting time $t_a$ and fit:

$$\frac{g^2}{It_{ab}} C_{abab}(\langle \pm 1,0\rangle) = C_0'' + C_1'' I t_{ab}$$

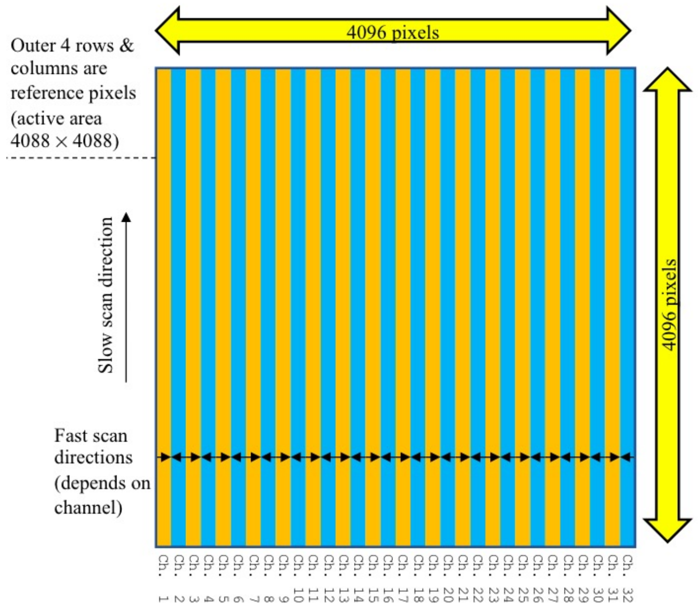
# Is BFE the dominant mechanism?



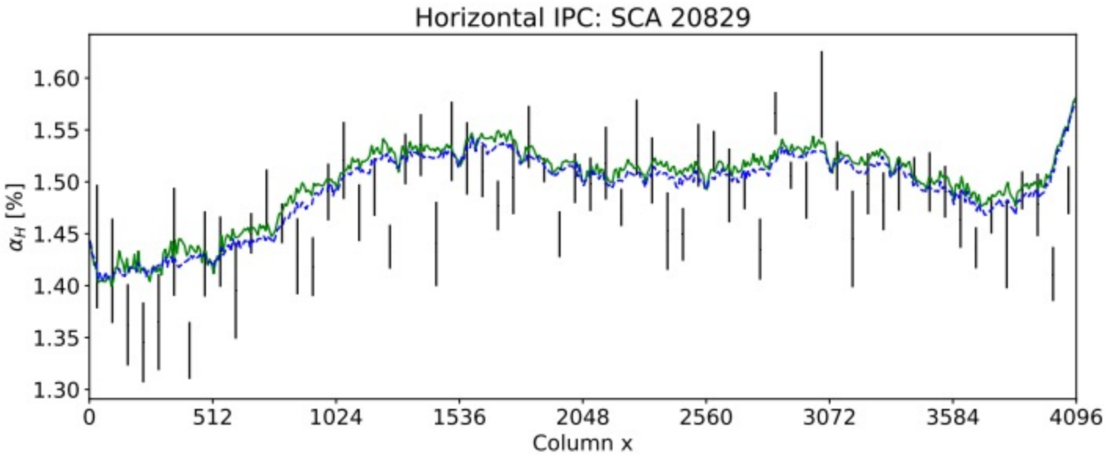
Freudenberg, Givans, Choi, Hirata+2020

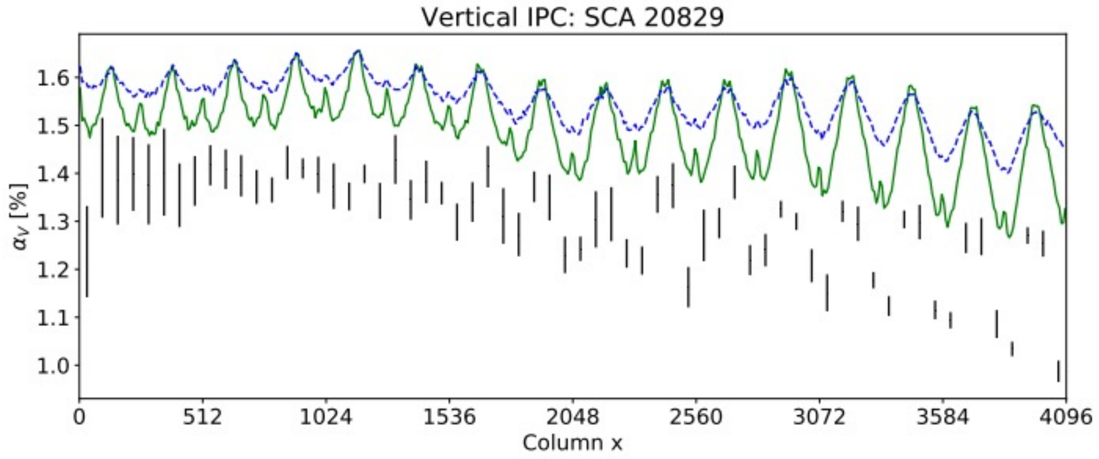
# Vertical Trailing Pixel Effect

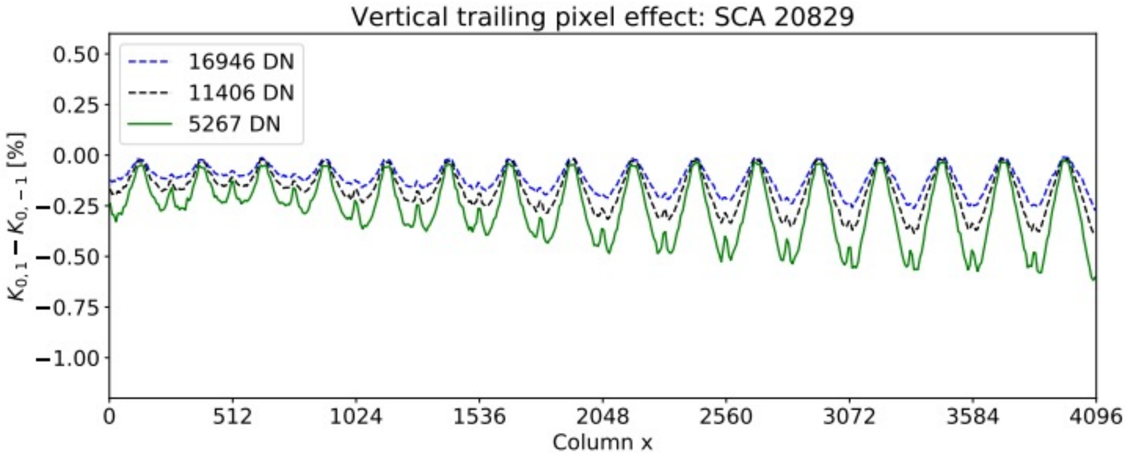
Cross-talk effect previously observed in development devices, tracing readout pattern



Freudenberg, Givans, Choi, Hirata+2020

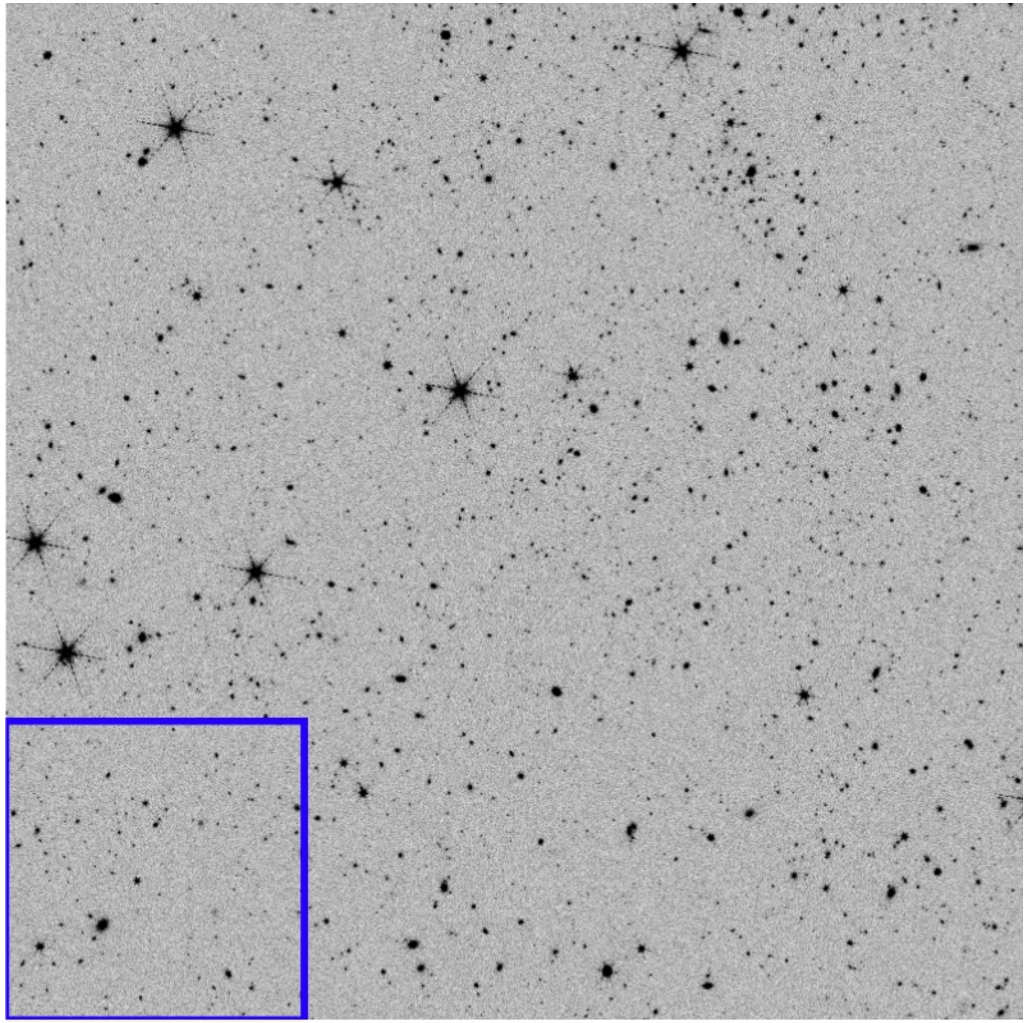






# Propagating impact of detector effects to lensing

- Image simulation framework based on GalSim presented in Troxel+2021
  - application to how wavefront errors impact lensing measurements
- Ongoing integration of detector effects obtained from cross-correlation measurements into image sims
- Will enable validation of requirements, observing strategies, algorithm development, and more!



Troxel, Long, Hirata, Choi+2021

# Summary & future work

- Flat-field statistics contain a wealth of information; non-linear effects can be discerned using their time dependence (Hirata & Choi 2020)
  - Brighter-fatter effect seems to be responsible for most of the non-linear signal in the detectors we have looked at (Choi & Hirata 2020, Freudenburg+2020)
  - Extensions to model quantum yield and charge diffusion at visible wavelengths (Givans+in prep)
- Explore other effects like persistence/settling-type, spatial variations in various detector parameters, like IPC $\alpha$, vertical trailing pixel effect
- Comparisons of correlation-based BFE with direct measurements a la Plazas+2018
- Run analysis over all flight detectors (can be applied more broadly to HxRG) and input into image sims (Troxel+2021) to assess how they propagate to downstream science measurements

# Extra Slides

# Flat Simulations

1. Create datacube with dimensions of 4k x 4k sq. pix. with 66 time samples
2. Gain, current/pixel, quantum efficiency (QE), $\alpha$, $\beta$, etc. all specified by user
3. At t=0, random realization of charge drawn from Poisson distribution with $\langle Q\rangle = QE * I * \delta t$
4. Matrix of pixel area defects calculated by convolving user-specified input kernel with charge distribution over pixel grid
5. Subsequent time steps compound previous time step with mean modified by the pixel area defect
6. After charge accumulated over all time frames, convolve charge data cube with linear IPC kernel
7. Apply non-linearity after IPC
8. Add noise (e.g. read noise) using noise realization created using NGHXRG (Rauscher 2015; https://github.com/BJRauscher/nghxrg)
9. Convert charge into DN by dividing by gain and save in array of unsigned 16-bit integers

# Correlation Analysis

- Calculate raw gain, horizontal correlation, vertical correlation, mean signal (*ad*), ratio of slope of signal in *cd* vs *ab* interval – solve 5 equations for 5 unknowns, IPC+non-linearity corrected gain, current/pixel, horizontal IPC, vertical IPC, $\beta_r$

$$\begin{aligned}
\hat{g}^{\rm raw}_{abad} &= g\frac{1+\beta_{\rm r}I(3t_b+3t_d-4t_a)}{(1-2\alpha_{\rm H}-2\alpha_{\rm V})^2+2\alpha_{\rm H}^2+2\alpha_{\rm V}^2}; \\
C_{\rm H} &= \frac{2It_{ad}\alpha_{\rm H}}{g^2}(1-2\alpha_{\rm H}-2\alpha_{\rm V}-4\beta_{\rm r}It_d); \\
C_{\rm V} &= \frac{2It_{ad}\alpha_{\rm V}}{g^2}(1-2\alpha_{\rm H}-2\alpha_{\rm V}-4\beta_{\rm r}It_d); \\
M_{ad} &= \frac{It_{\rm ad}}{g}[1-\beta_{\rm r}I(t_a+t_d)]; \quad \text{and} \\
\texttt{frac\_dslope} &= -\beta_{\rm r}I(t_c+t_d-t_a-t_b).
\end{aligned}$$

- Measure inter-pixel non-linearities with non-overlapping correlation function
- Iterative process to de-bias g, $\alpha$, etc.

# Correlation Analysis

- Calculate raw gain, horizontal correlation, vertical correlation, mean signal (*ad*), ratio of slope of signal in *cd* vs *ab* interval – solve 5 equations for 5 unknowns, IPC+non-linearity corrected gain, current/pixel, horizontal IPC, vertical IPC, $\beta_r$
- Measure inter-pixel non-linearities with non-overlapping correlation function

$$[K^2a']_{0,0} + [KK']_{0,0} = \frac{g^2}{I^2 t_{ab} t_{cd}} C_{abcd}(0,0) + 2(1-8\alpha)\beta_{\mathrm{r}}.$$

$$[K^2a']_{\pm1,0} + [KK']_{\pm1,0} = \frac{g^2}{I^2 t_{ab} t_{cd}} C_{abcd}(\mp1,0) + 4\alpha_{\mathrm{H}}\beta_{\mathrm{r}}$$

- Iterative process to de-bias g, $\alpha$, etc.