The Brighter Fatter Effect*
in H4RG-10 Detectors

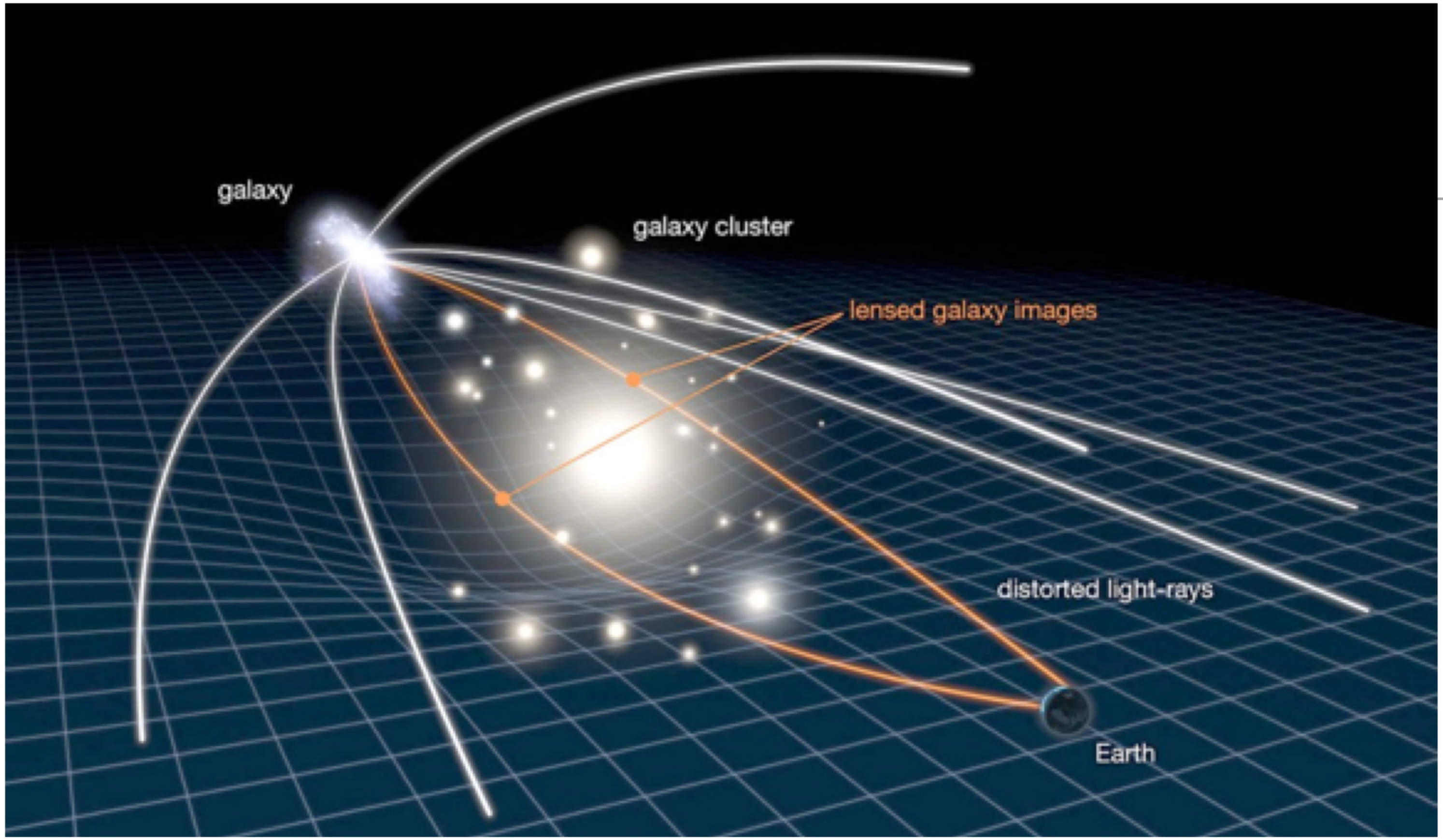
Ami Choi

in collaboration with Chris Hirata,

the WFIRST Detector WG,

& the Detector Characterization Lab at NASA Goddard

*and other non-linear effects



Using gravitational lensing to understand dark energy and dark matter places stringent requirements on detector understanding and calibration

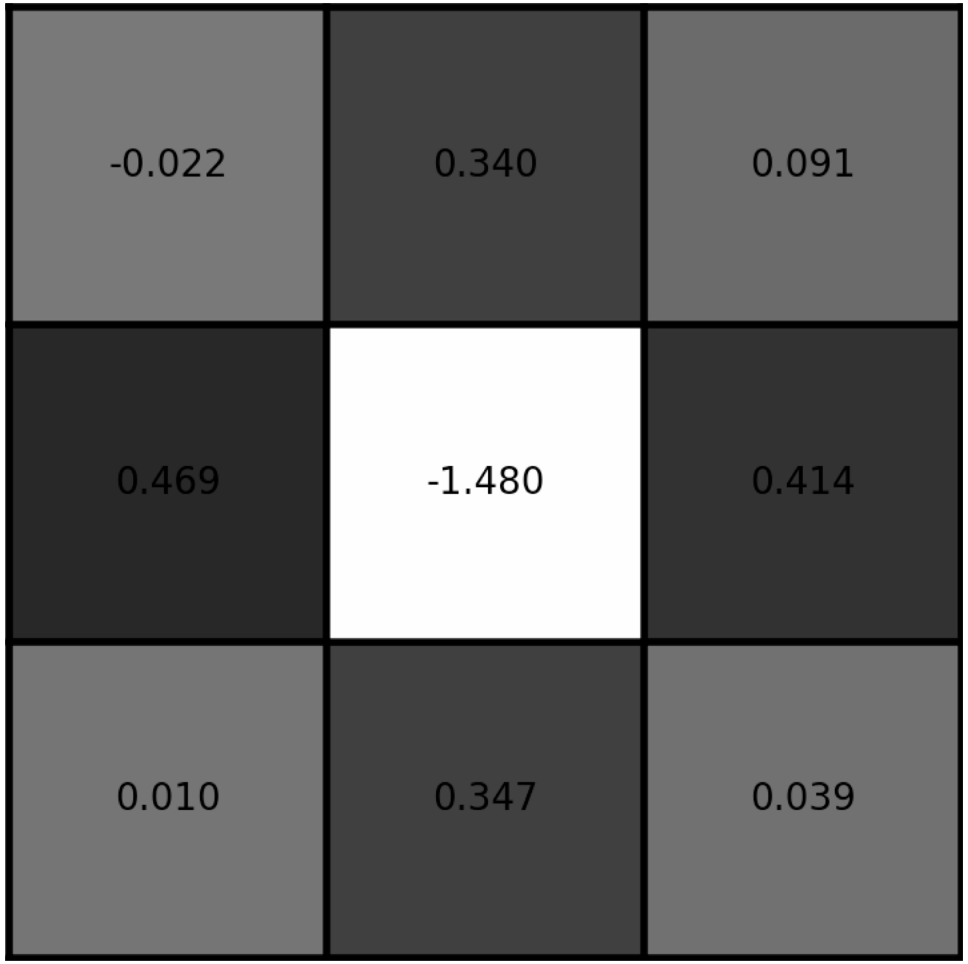
- Lensing requires accurate measurements of galaxy shapes
- Characterize and calibrate detector effects
- Use image simulations to understand how these effects impact galaxy shapes and propagate to cosmological parameters
- Studies done under purview of WFIRST High Latitude Survey Science Investigation Team (SIT)

WFIRST High Latitude Survey SIT Members

- Olivier Doré (JPL/Caltech, PI)
- Chris Hirata (OSU, Weak lensing lead)
- Yun Wang (Caltech/IPAC, Galaxy redshift survey lead)
- David Weinberg (OSU, Galaxy clusters lead)
- Anahita Alavi (Caltech/IPAC)
- Ivano Baronchelli (Caltech/IPAC)
- Rachel Bean (Cornell)
- Andrew Benson (Carnegie)
- Peter Capak (Caltech/IPAC)
- Ami Choi (OSU)
- James Colbert (Caltech/IPAC)
- Tim Eifler (Arizona)
- Chen He Heinrich (JPL/Caltech)
- Katrin Heitmann (ANL)
- George Helou (Caltech/IPAC)
- Shoubaneh Hemmati (IPAC/Caltech)
- Eric Huff (JPL)
- Shirley Ho (LBL)
- Albert Izard (JPL)
- Bhuvnesh Jain (Penn)
- Mike Jarvis (Penn)
- Alina Kiessling (JPL/Caltech)
- Elisabeth Krause (Arizona)
- Alexie Leauthaud (UCSC)
- Robert Lupton (Princeton)
- Niall MacCrann (OSU)
- Rachel Mandelbaum (CMU)
- Elena Massara (LBL)
- Dan Masters (JPL)
- Alex Merson (Caltech/IPAC)
- Hironao Miyatake (JPL/Caltech)
- Nikhil Padmanabhan (Yale)
- Alice Pisani (Princeton)
- Eduardo Rozo (U. Arizona)
- Lado Samushia (U. Kansas)
- Mike Seiffert (JPL/Caltech)
- Charles Shapiro (JPL/Caltech)
- Melanie Simet (UCR/JPL)
- David Spergel (Princeton, CCA)
- Harry Teplitz (Caltech/IPAC)
- Michael Troxel (OSU)
- Anja von der Linden (Stony Brook University)
- Hao-Yi Wu (OSU)
- Ying Zu (OSU)

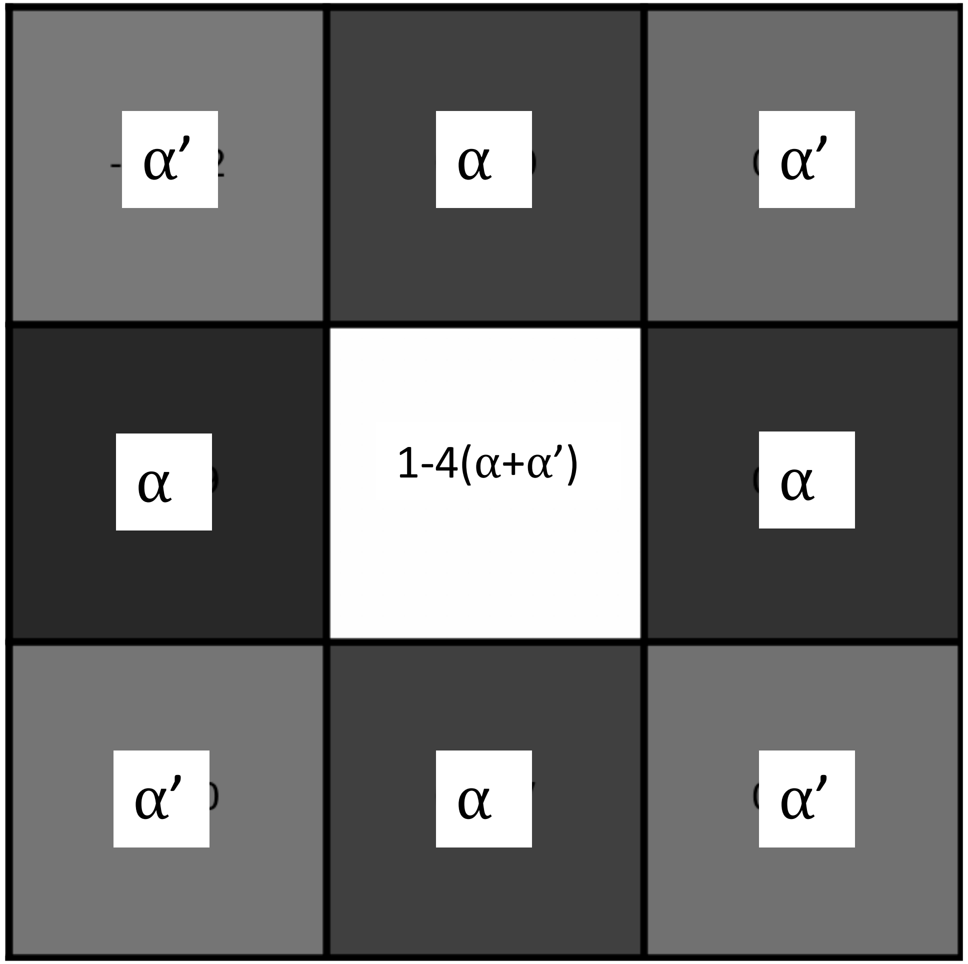
Non-linear detector effects: brighter fatter effect (BFE)

- If a pixel contains more electrons than its neighbors, self-repulsion will cause subsequent photo-electrons more likely to land in neighbor
- More extensively studied on optical CCDs/sensors
  - e.g. Antilogus+2014, Gruen+2015, Guyonnet+2015, Niemi+2015, Baumer&Roodman 2015, Lage+2017, etc.
- Less work on infrared sensors (see Eric Huff's talk)
  - Plazas+2017, 2018 BFE measurement for H2RG using point source illumination
  - This work is about using flat field statistics for H4RG-10 (WFIRST prototype hybrid CMOS devices)



Non-linear detector effects: non-linear inter-pixel capacitance (NL-IPC)

- Form of cross-talk where fringing fields cause voltage readings in given pixel to depend on charges in neighboring pixels
- Modeled as a coupling capacitance between pixels, can depend on signal
  - Cheng 2009, Donlon+2016,2017,2018
- Flat field correlation function dominated by IPC (Moore+2004)
- Non-linear component here is any non-linearity in charge-to-signal conversion acting on signal before IPC (NL-IPC)
- Non-destructive read capability enables possibility of disentangling NL-IPC and BFE due to different time-dependence



Some quantities of interest

Quantity	Units	Notes
signal S	DN	$S_{initial}$-S_{final} = $\frac{1}{g}\sum_{\Delta i,\Delta j} K_{\Delta i,\Delta j} Q_{i-\Delta i,j-\Delta j} + [\text{nonlinear terms}],$
charge Q	e	
gain g	e/DN	ratio of variance to mean
classical non-linearity β	ppm/e	leading order non-linearity coefficient
IPC kernel K		$K_{0,0}$=1-4α, $K_{0,\pm1}$=$K_{\pm1,0}$=α
NL-IPC K'		mean signal-level-dependent
area defect of pixel at time t W(i,j;t)		$1 + \sum_{\Delta i,\Delta j} a_{\Delta i,\Delta j} Q(i+\Delta i, j+\Delta j, t)$
BFE coupling matrix $a_{\Delta i,\Delta j}$	10^{-6} e^{-1} or ppm/e or %/10^4 e	$\sum_{\Delta i,\Delta j} a_{\Delta i,\Delta j} = \Sigma_a$
$a'_{\Delta i,\Delta j}$	"	$a'_{\Delta i,\Delta j} \equiv a_{\Delta i,\Delta j} - \delta_{\Delta i,0}\delta_{\Delta j,0}\Sigma_a$

Correlation Functions

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

$$\mathrm{Cov}_{\mathrm{meas}}[\mathcal{O}, \mathcal{O}'] = \frac{1}{2}\langle(\mathcal{O}_A - \mathcal{O}_B)(\mathcal{O}'_A - \mathcal{O}'_B)\rangle$$

$$\bar{C}_{abcd[n]}(\Delta i, \Delta j) = \sum_{\nu=0}^{n-1} C_{a+\nu,b+\nu,c+\nu,d+\nu}(\Delta i, \Delta j)$$

Building description of BFE and IPC contributions to charge, after a lot of algebra…

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

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, β_r
- Measure inter-pixel non-linearities with non-overlapping correlation function

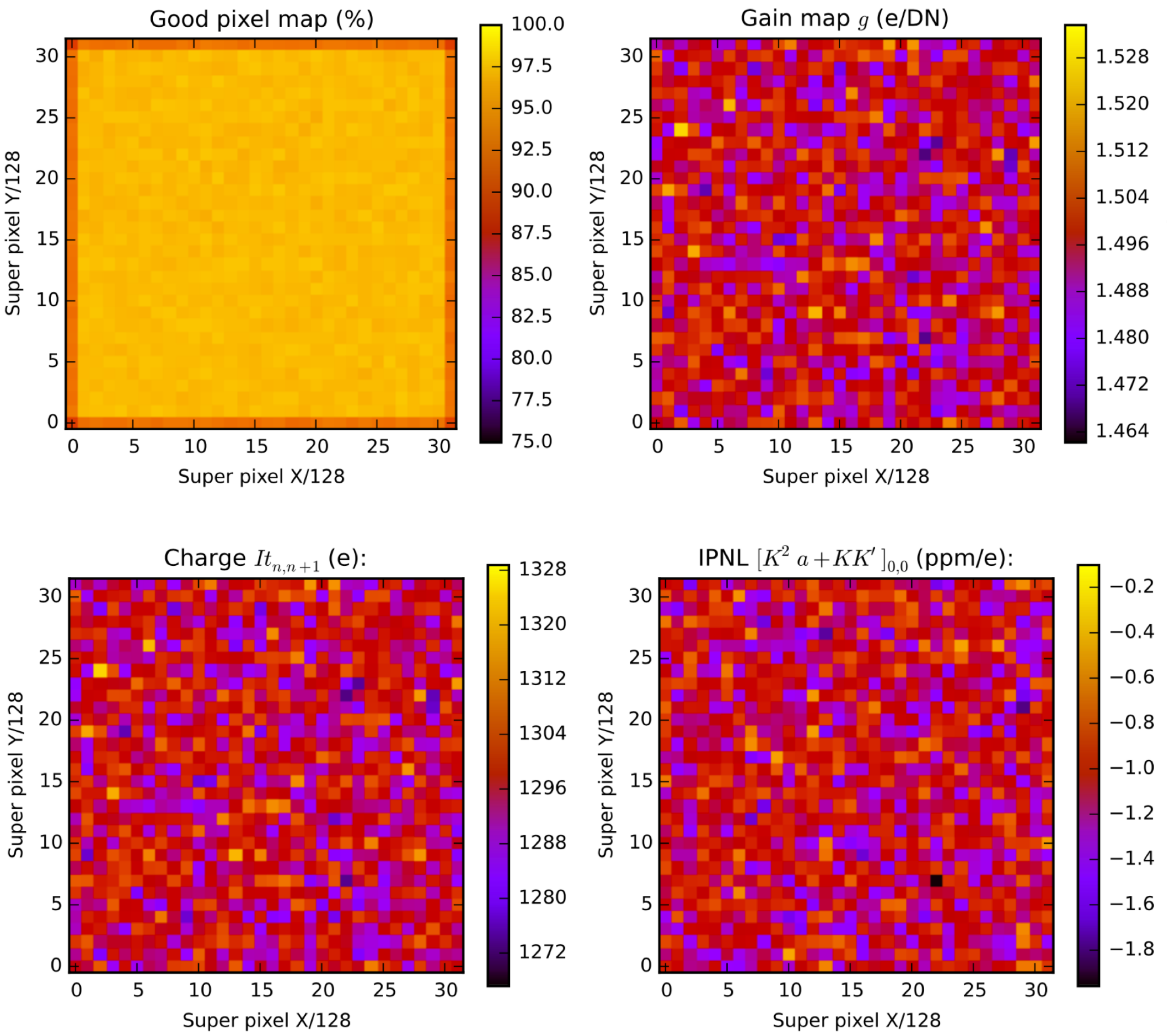
$$[K^2 a']_{0,0} + [KK']_{0,0} = \frac{g^2}{I^2 t_{ab} t_{cd}} C_{abcd}(0,0) + 2(1-8\alpha)\beta_{\rm r}.$$

$$[K^2 a']_{\pm 1,0} + [KK']_{\pm 1,0} = \frac{g^2}{I^2 t_{ab} t_{cd}} C_{abcd}(\mp 1,0) + 4\alpha_{\rm H}\beta_{\rm r},$$

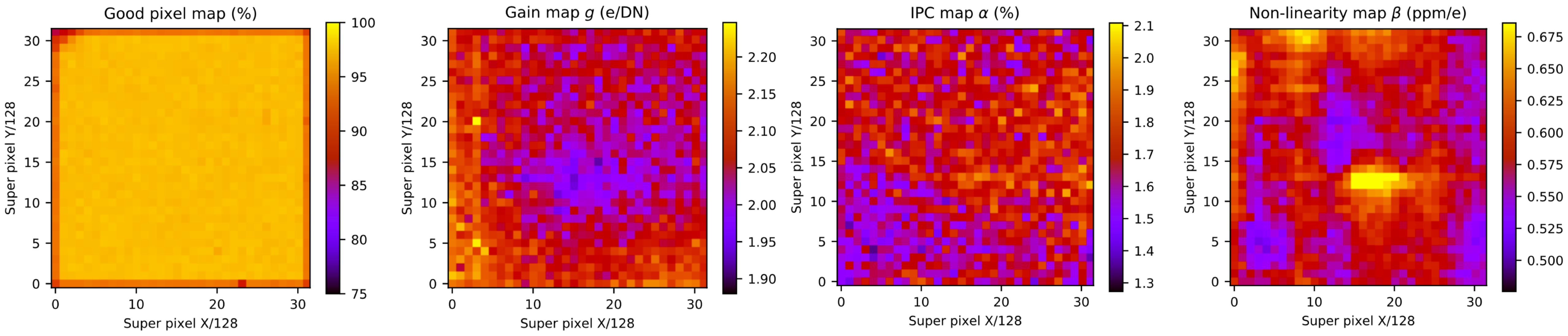
- Iterative process to de-bias g, α, etc.

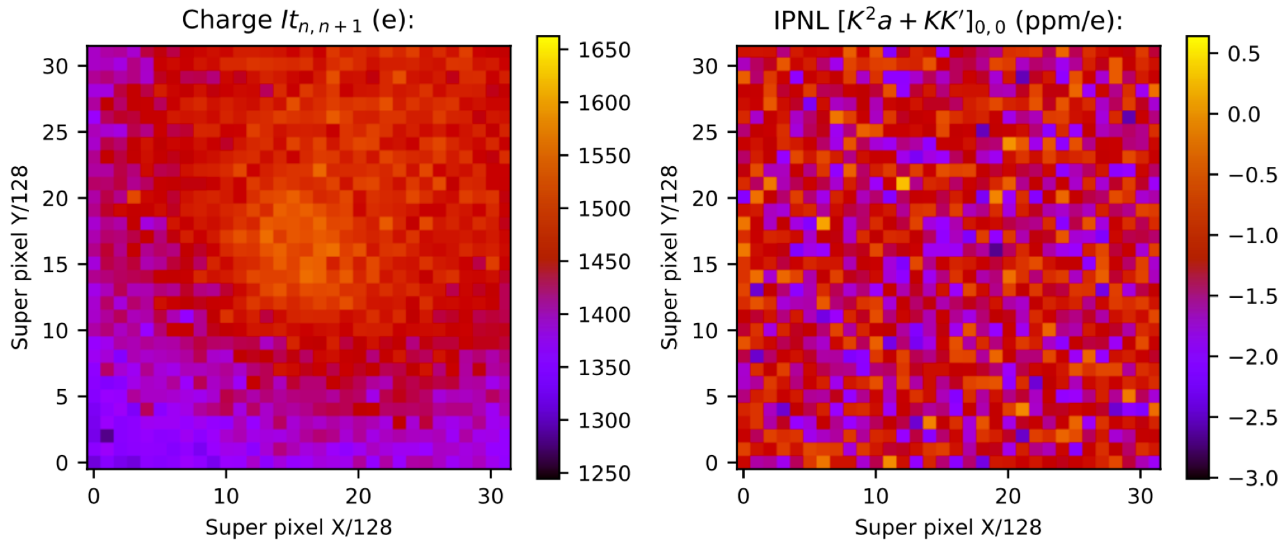
Flat Simulations

1. Create datacube with dimensions of 4k x 4k sq. pix. with 66 time samples
2. Gain, current/pixel, quantum efficiency (QE), α, β, 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



Preliminary processing of flat simulation realizations,
calculations done for 32 x 32 “super pixels”





Preliminary processing of flat data for SCA 18237, a prototype WFIRST detector (3 flats) – 2.5μm cutoff, 10μm pitch pixels

calculations done for 32 x 32 “super pixels”

SCA 18237 BFE from non-overlapping correlation function

BFE+NL-IPC Coefficients - no IPC correction

$[K^2 a' + KK^{\varphi'}]_{\Delta i \Delta j}$ (ppm/e)

	$\Delta i=-2$				$\Delta i=+2$
$\Delta j=+2$	-0.022	0.002	-0.014	-0.017	-0.006
	0.004	0.056	0.186	0.020	-0.021
	-0.007	0.230	-1.200	0.216	0.021
	0.013	0.064	0.225	0.048	0.020
$\Delta j=-2$	0.003	0.009	0.042	0.003	-0.006

BFE Coefficients - with linear IPC correction

$a'_{\Delta i \Delta j}$ (ppm/e), assumes $K' = 0$

	$\Delta i=-2$				$\Delta i=+2$
$\Delta j=+2$	-0.023	0.002	-0.021	-0.019	-0.005
	0.004	0.049	0.248	0.010	-0.024
	-0.017	0.299	-1.391	0.284	0.015
	0.013	0.056	0.289	0.039	0.020
$\Delta j=-2$	0.002	0.007	0.038	0.001	-0.007

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

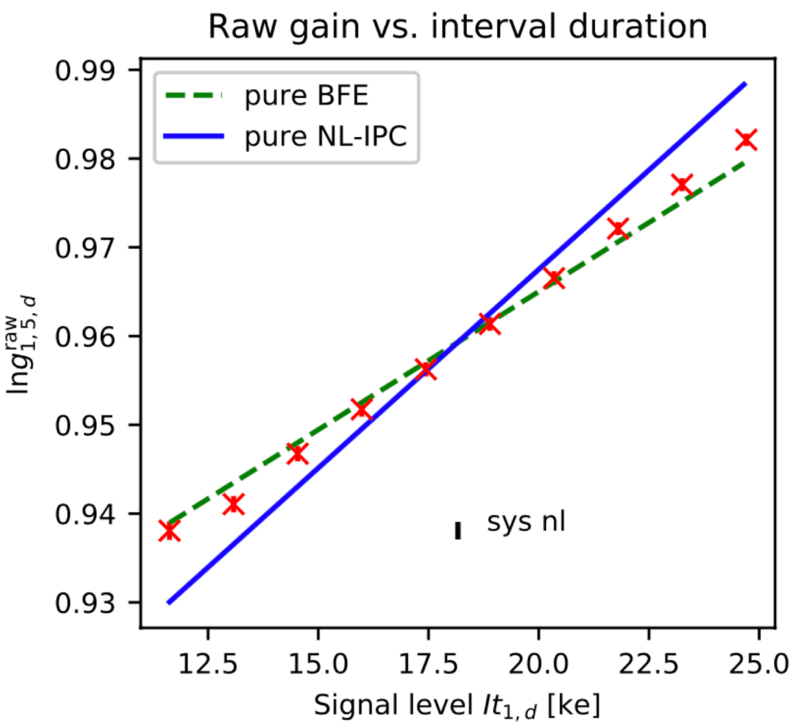
Adjacent pixel correlation tests

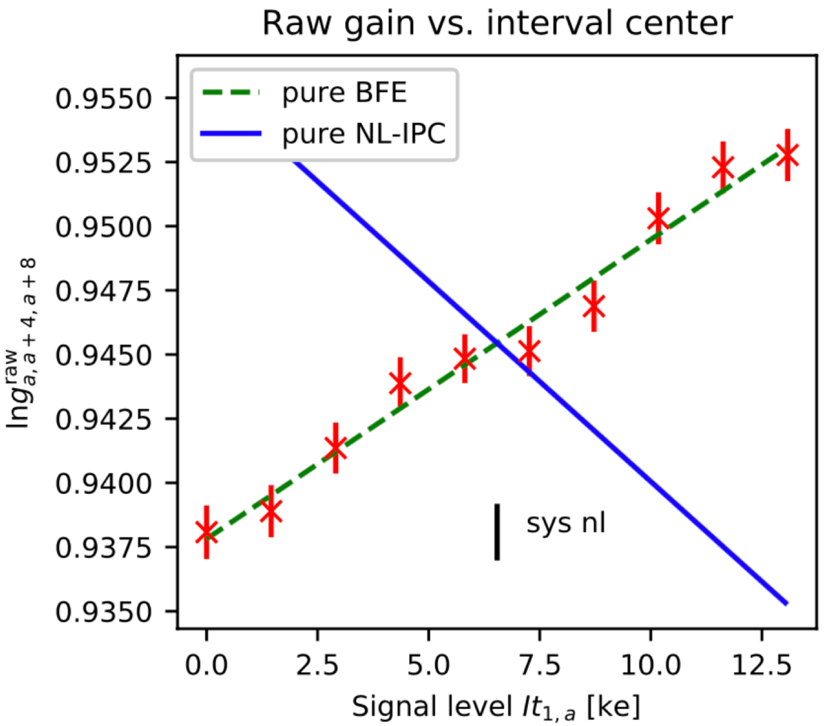
- Use equal interval correlation function in adjacent pixels (auto-correlation of a single difference image)

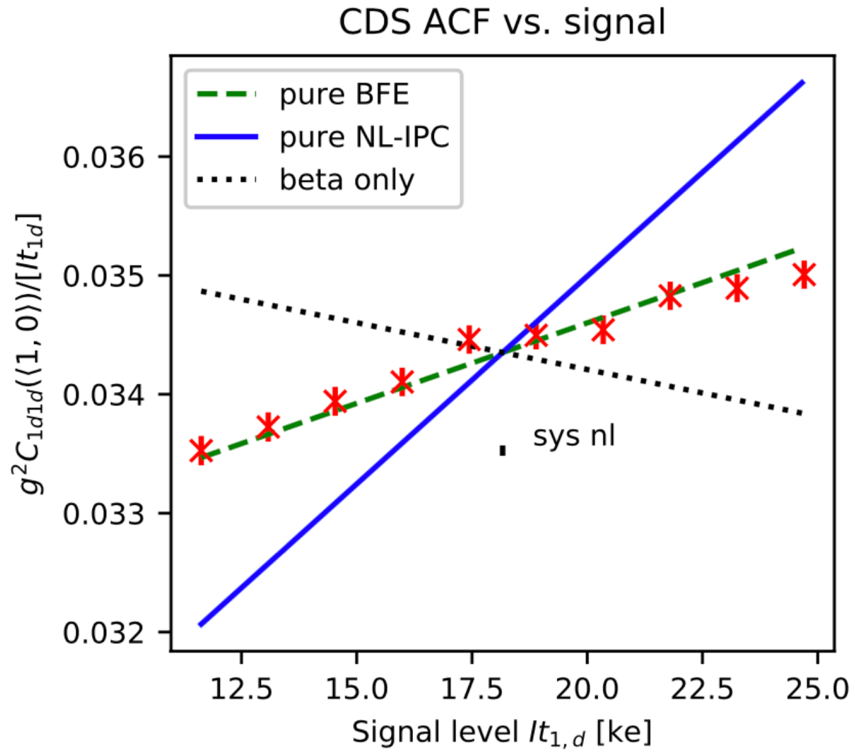
$$
\begin{aligned}
C_{abab}(\pm 1, 0) \quad = \quad & \frac{I}{g^2} t_{ab} \Big\{ 2\alpha_{\rm H}(1 - 4\alpha - 4\alpha_{\rm D}) + 4\alpha_{\rm V}\alpha_{\rm D} - 8\alpha_{\rm H}\beta \left(I t_b + \frac{1}{2} \right) + \alpha_{\rm H}\Sigma_a I(t_a + t_b) \\
& + [K^2 a]_{\rm H} I t_{ab} + 2[KK']_{1,0}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

- Fix starting time t_a and fit: $\frac{g^2}{I t_{ab}} C_{abab}(\langle \pm 1, 0 \rangle) = C_0'' + C_1'' I t_{ab}$

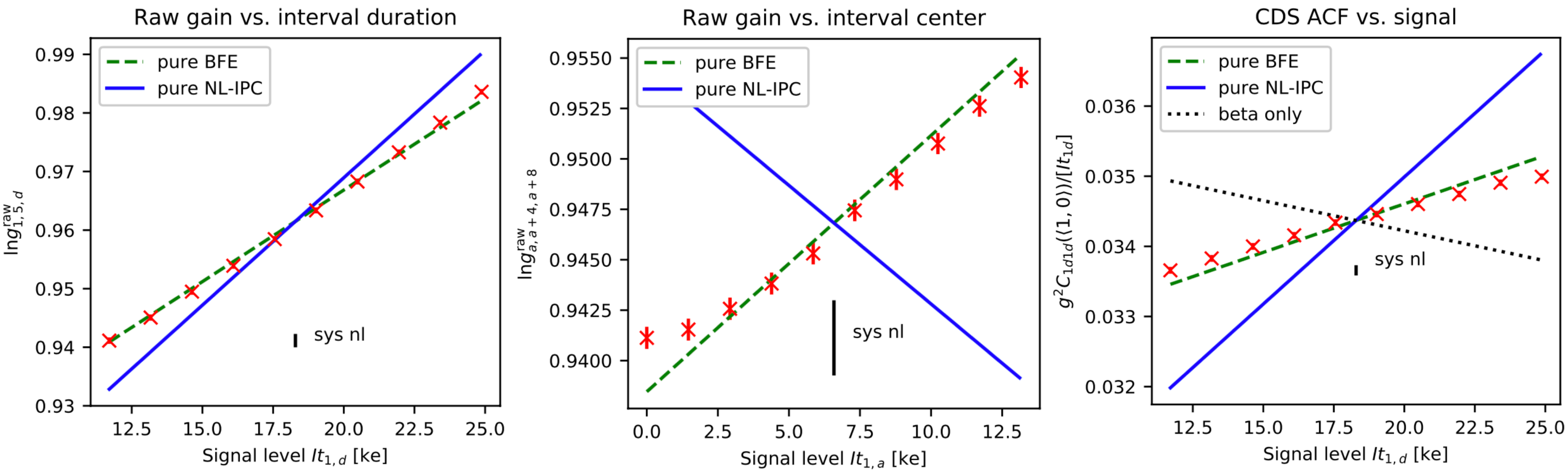
Results of mean-variance and adjacent pixel correlation tests for 3 flat pairs (first flats)







Results of mean-variance and adjacent pixel correlation tests for 23 flat pairs



Summary & Future Work

- Flat field statistics contain a lot of information, although several non-linear effects are present – their time-dependence is key to extracting their contributions
- We observe a residual correlation between difference frames with non-overlapping time intervals; tests suggest the signal is consistent with interpretation that the BFE is the dominant mechanism
- Comparison of IPC with hot pixel analysis
- Application of analysis to other candidate detectors, include more data (thanks to the DCL for the data!)
- Further tests with simulated flat field realizations
- Higher order non-linearity terms
- Other effects (e.g. burn-in features)
- Connect with image simulations

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, β_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, α, etc.