Computing WFIRST weak lensing requirements on detector calibration

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Requirements for the WFIRST NIR detectors flow from the science requirements of the cosmology and exoplanet surveys. Detector requirements for WFIRST weak gravitational lensing have been studied by

Detector Working Group (co-leads D. Bennet, C. Shapiro)

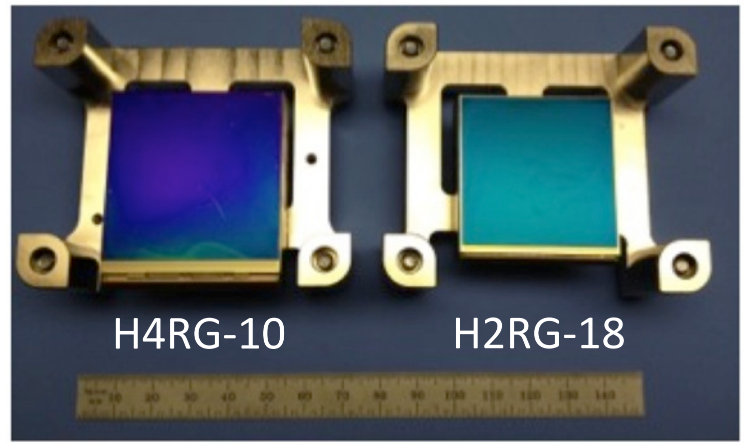
Cosmology Science Investigation Team (PI: O. Doré)

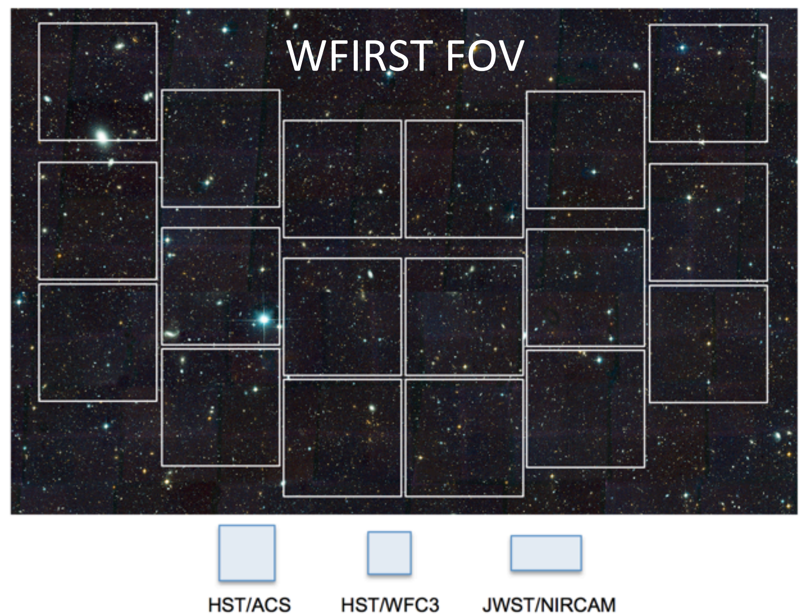
Outline

- WFIRST recap
- Nonlinearity – Andrés Plazas-Malagon (JPL)
- Interpixel Capacitance – Arun Kannawadi (Carnegie Mellon → Leiden)
- Persistence – Eric Huff (JPL)

WFIRST Imager overview

- 2.4m telescope
- f/8 imager (Wide Field Channel)
- 18x Hawaii-4RG detectors – 4kx4k pixels; 10µm pixel pitch
- Plate scale 0.11”/pixel
- Field of view (FOV) 0.8° x 0.4°
- Near-infrared pass band: 0.76 - 2.3µm
- 6 (7?) imaging filters
- 5-9 dithers/source/filter (images are undersampled)





WFC Filters

Band	Element name	Min (µm)	Max (µm)	Center (µm)	Width (µm)	R
Z	Z087	0.76	0.977	0.869	0.217	4
Y	**Y106**	**0.927**	**1.192**	**1.060**	0.265	4
J	**J129**	**1.131**	**1.454**	**1.293**	0.323	4
H	**H158**	**1.380**	**1.774**	**1.577**	0.394	4
	F184	**1.683**	**2.000**	**1.842**	0.317	5.81
Wide	W149	0.927	2.000	1.485	1.030	1.44
GRS	Grism	1.0*	1.89*	1.445	0.890	461λ(2pix)

Slide adapted from WFIRST Project report

WFIRST galaxy shape measurement requirements

- Baseline: 2000 deg^2 with 45 galaxies/$arcmin^2$
- Extended mission: 10k deg^2
- (Nominal) knowledge requirements for shear measurement error: $\delta g_i = (1+m)g_i + c$

  Multiplicative error: m ~ 0.001

  Additive error: c ~ 0.0003
- PSF knowledge requirements (rms):

  c → Ellipticity ~ 0.0005 ; m → Size ($d\sigma/\sigma$) ~ 0.0009
- Images are undersampled in J, H, F184 bands

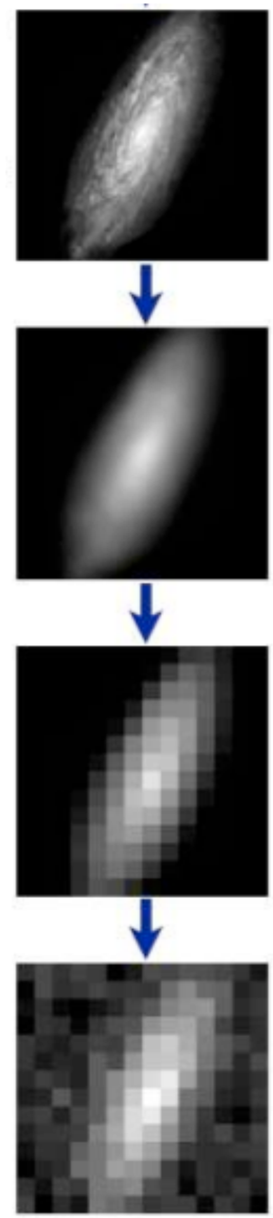


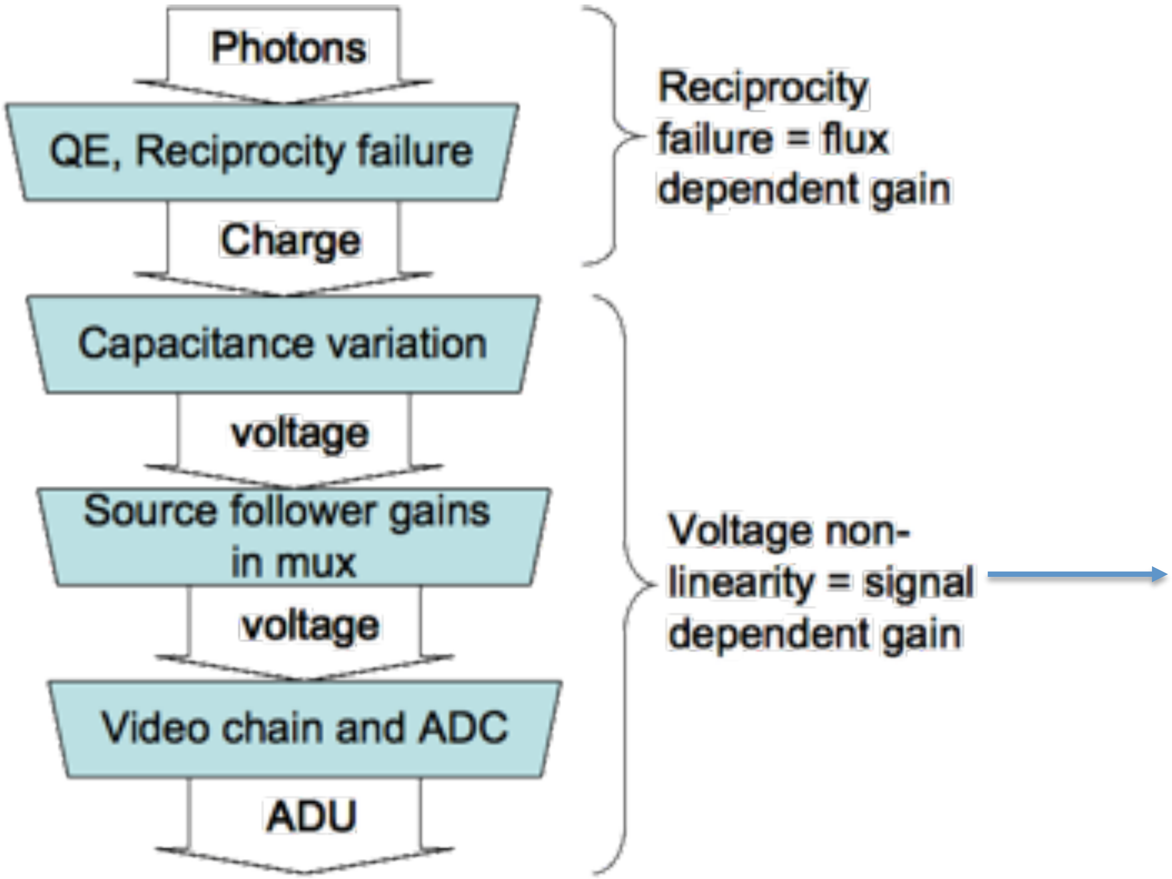
Image: GREAT08 Handbook

The effect of detector nonlinearity on WFIRST PSF profiles for weak gravitational lensing measurements

A. A. Plazas, C. Shapiro, A. Kannawadi, R. Mandelbaum, J. Rhodes, & R. Smith

(arXiv:1605.01001. Submitted to PASP)

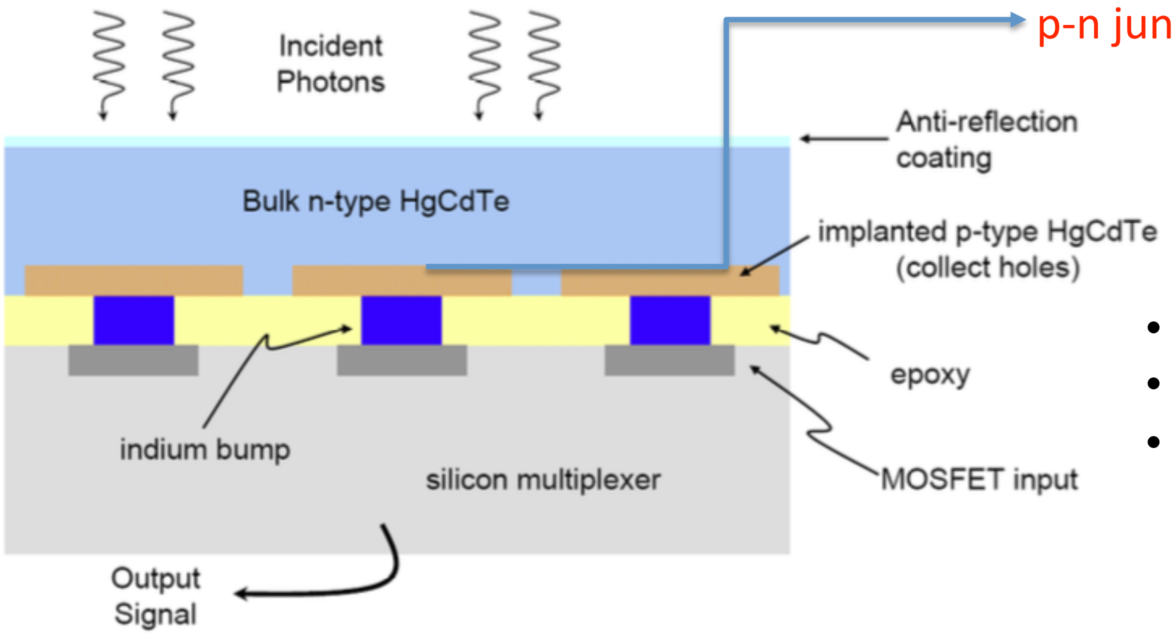
Nonlinearity in the signal chain



We study the impact of this type of nonlinearity **(NL)** on weak lensing

Image credit: R. Smith

NL in hybrid CMOS detectors



p-n junction (charge collection region).

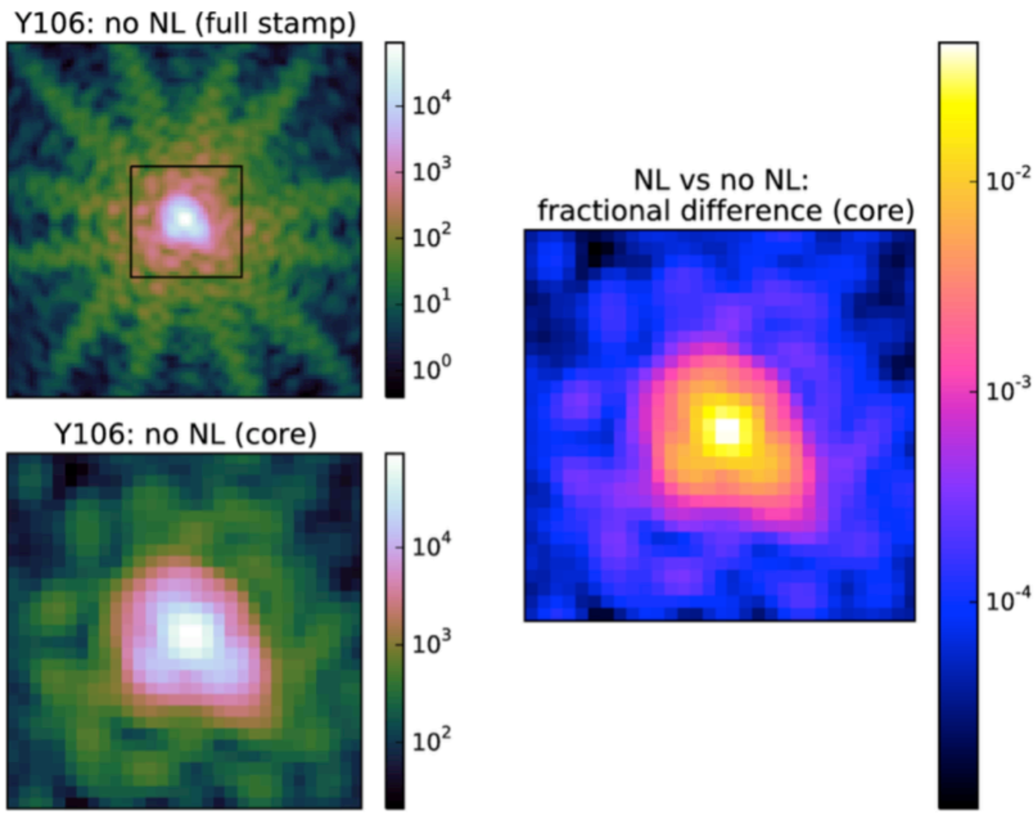
- p-n junction acts as capacitor
- Signal $\Delta V = \Delta Q/C$
- IF junction capacitance varies as charge accumulates
  → nonlinear V(Q)

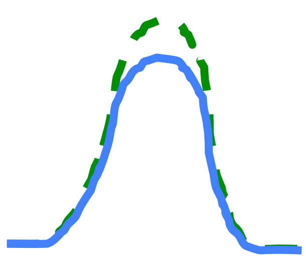
- If the main source of nonlinearity is the junction capacitance, the correction to the inferred signal is well-approximated by a quadratic function
- Additional parameters can improve calibration but are highly degenerate – we stick with 1 for simplicity

$$S(Q) = Q - \beta Q^2$$

β ~ 5e-7 (WFC3, Hilbert 2014), varies per pixel and detector

Image simulations with GalSim





NL depresses PSF peak
→ size measurement bias

No ellipticity bias **unless**
PSF has |e|>0 (it does)

- We use the WFIRST module (Kannawadi +15) in GalSim (Project-funded) to simulate PSF profiles for WFIRST bands J, Y, H, F
- Pixel scale = 0.11 arcsec/pixel; images are drawn at 3x resolution to mimic reconstruction from dithers (avoids aliasing)
- Centroids randomized within native pixel
- Considered AB magnitudes down to 18.3, which fills a H4RG pixel to 90% of full well (~1.1k e^-) in 168 seconds (Y band, PSF centered on a pixel)
- NL applied to each pixel according to:

$$I \mapsto I - \beta I^2$$

PSF size and shape measurements

- For weak lensing, the PSF sampled from nearby bright stars (affected more by NL) must be deconvolved from observed galaxy shapes
- The error in the galaxy ellipticity measurement is given by a linear combination of fractional PSF size error and absolute PSF ellipticity error (e.g, Paulin-Henriksson et al. 2008, Massey et al. 2013)
- Nominal WFIRST error tolerances:
  - relative size to ~ 1e-3 ; absolute ellipticity to ~4.5e-4
- We use adaptive moments (HSM method) to measure

  PSF size (R) and ellipticity (e_i) before and after NL is applied.

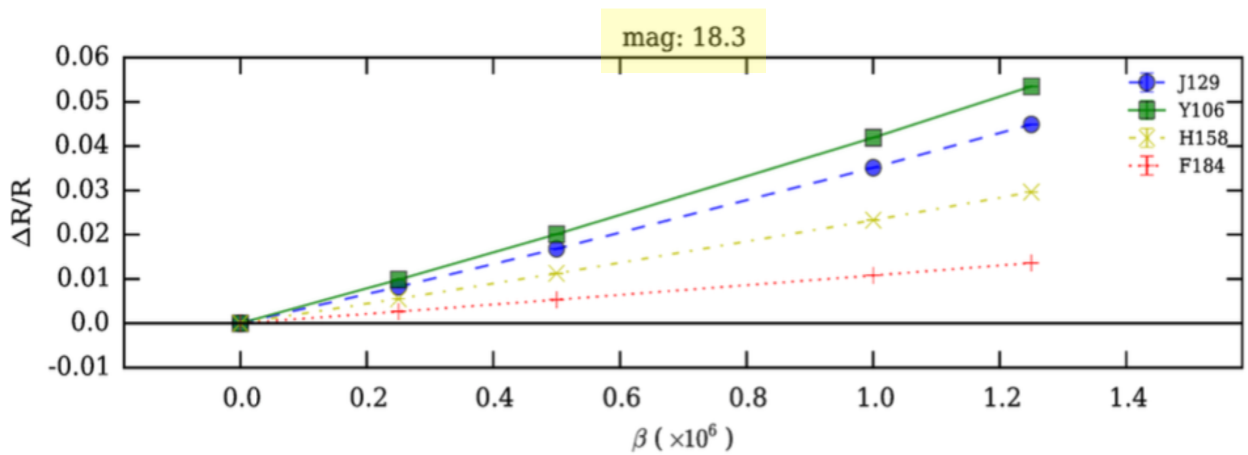
$$\Delta e_i \equiv e_i - e_{i,0}, \quad i \in [1,2]$$

$$\frac{\Delta R}{R} \equiv \frac{R - R_0}{R_0}$$

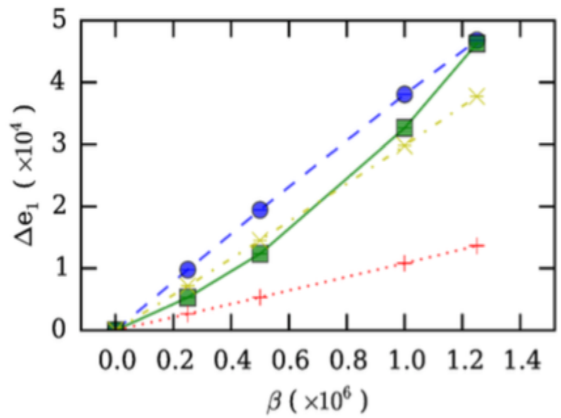
Baseline WFIRST PSFs

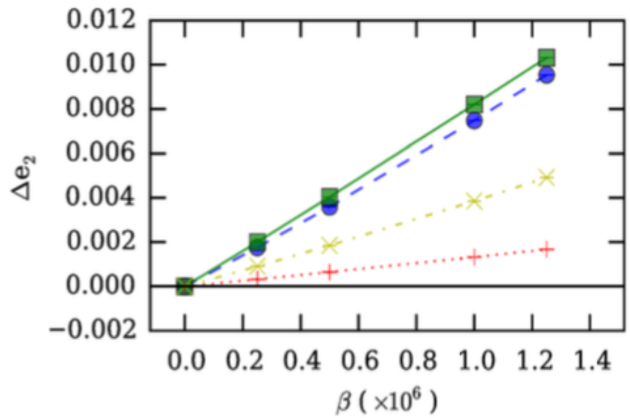
				Total signal	Center pixel			"R"
Band	Min. λ (μm)	Max. λ (μm)	$\lambda_{\rm eff}$ (μm)	$b(\lambda)$ ($\times 10^5$) (e^-)	peak value ($\times 10^5$) (e^-)	e_1 (#18)	e_2 (#18)	σ (pix) (#18)
Y106	0.900	1.230	1.061	2.7621	1.00237	-0.0163	0.2035	1.7020
J129	1.095	1.500	1.292	2.8267	0.89742	-0.0127	0.1325	1.717
H158	1.340	1.830	1.577	2.7922	0.38654	-0.0089	0.0802	1.832
F184	1.630	2.060	1.837	1.8346	0.71890	-0.0071	0.0550	1.995

Biases in size and ellipticity (uncorrected for NL)



relative size tolerance ~ 1e-3





ellipticity tolerance ~ 4e-4

Since errors are approximately linear in β, we can condense information by plotting the slope of each curve as a function of magnitude.

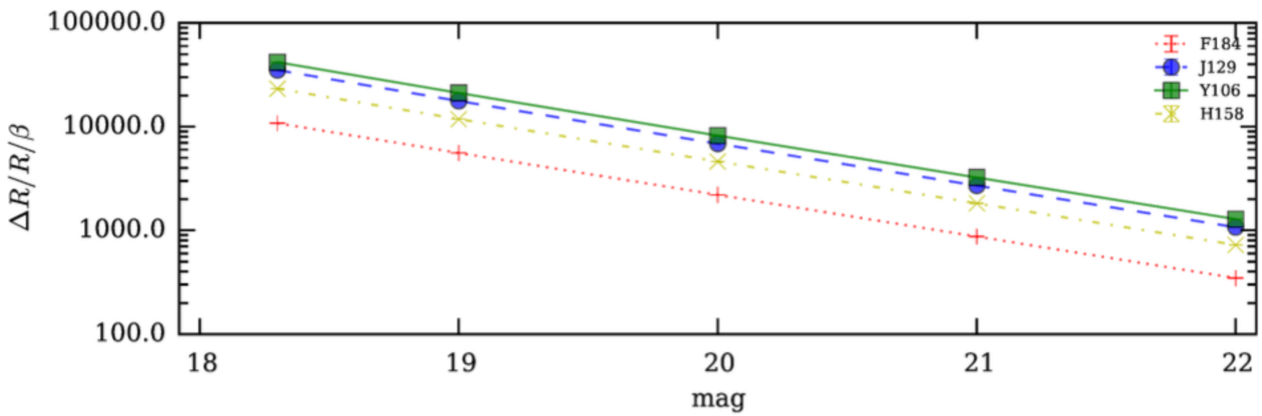
$$\Delta R/R/\beta$$

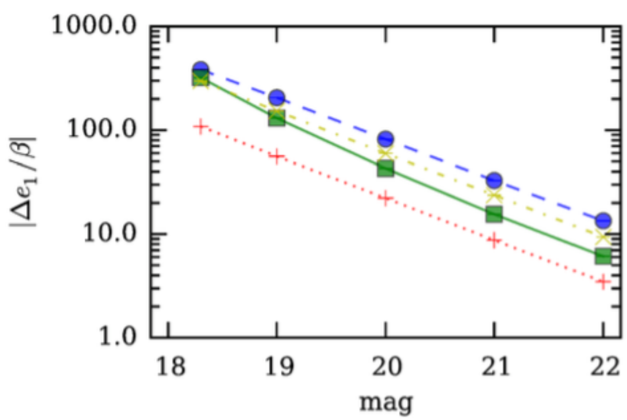
$$\Delta e/\beta$$

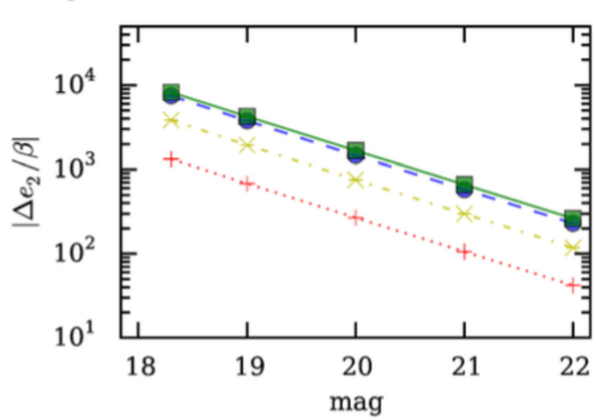
Biases in size and ellipticity after NL calibration

Replacing β with the error $\Delta\beta$, we can use this plot to convert between star magnitudes, PSF error tolerances, and calibration precision on β (given 2, predict the 3rd one)

$$\frac{\Delta R/R}{\Delta\beta} = c \quad \Rightarrow \quad \frac{\Delta\beta}{\beta_0} = \frac{\Delta R/R}{c\beta_0}$$







For example, to use 18.3 mag stars (H-band) while limiting PSF biases to 10% of WFIRST tolerances, β must be known to

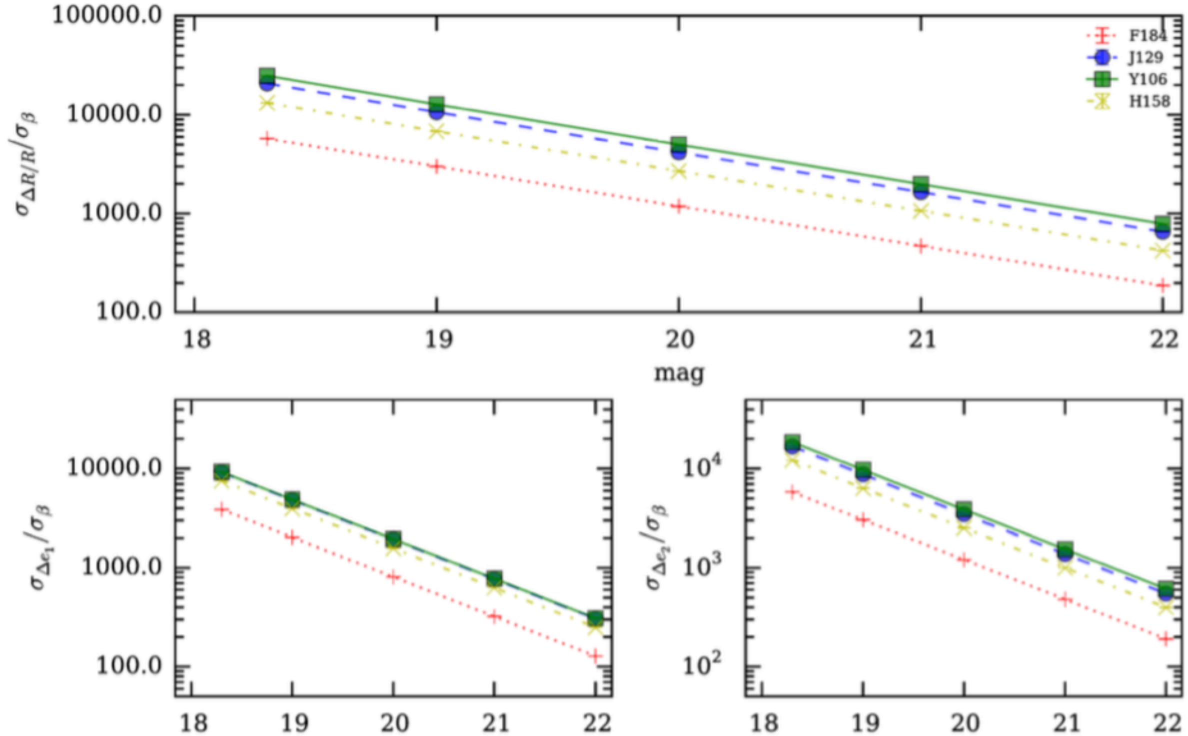
- ~1% for R
- ~2.4% for e_i

Assumption:
β_0 =5e-7

→ Set requirements on $\Delta\beta$ or set mag cutoffs (or ramp cutoffs if sampling up the ramp)

Spatial variability of β

We then assume each pixel has a different β, drawn from a gaussian distribution.
We plot stddev of PSF errors vs. stddev of β (M=100 realizations).



→ Set requirements on σ_β

- Linearity in β allows us to condense information as before.
- Bias when NL is uncorrected is insensitive to the nominal β, so σ_β can also be interpreted as an error on β estimation

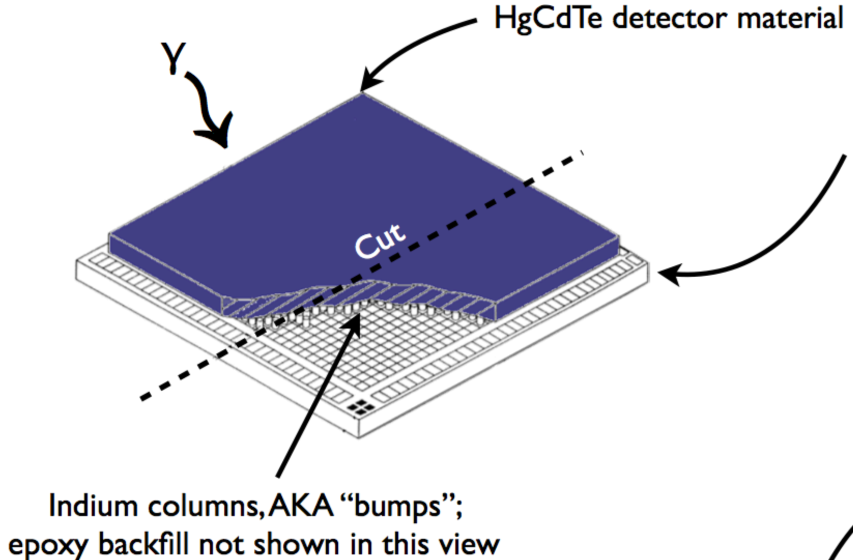
Interpixel Capacitance effects on weak lensing shape measurement

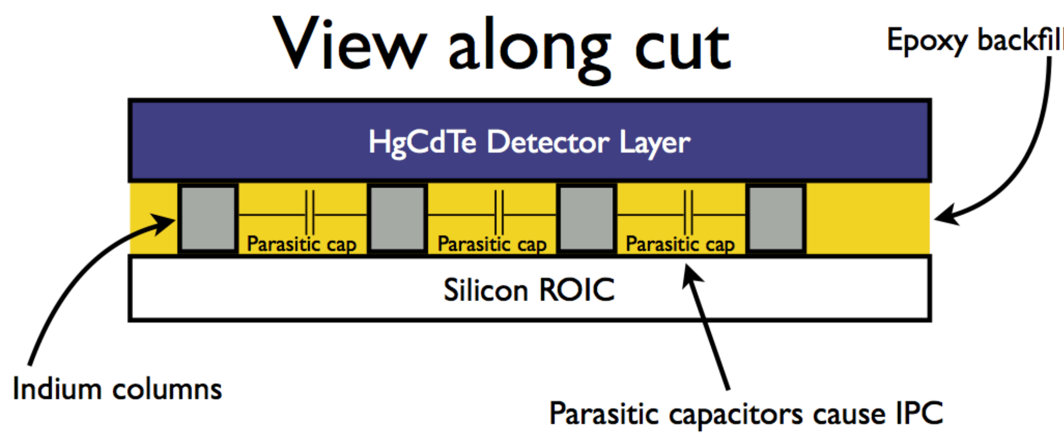
Arun Kannawadi (CMU), Charles Shapiro (JPL), Rachel Mandelbaum (CMU), Chris Hirata (OSU), Jeff Kruk (GSFC) & Jason Rhodes (JPL,Caltech)

Slide stolen from B. Rauscher

What is IPC?

- Inter-pixel capacitance (IPC) is the small, parasitic capacitance, that is found between pixels in an infrared array detector





<u>A few handy references</u>

1. Moore, A. C., Ninkov, Z. & Forrest, W. J. 2006, Optical Engineering, 45, 076402 describes the statistics in detail from a Fourier perspective

2. Fox, O., Waczynski, A., Wen, Y., et al. 2009, PASP, 121, 743 arrives at many of the same results working in the pixel domain

IPC effects on shape measurement

- Charge collected on a pixel induces voltage change on neighbor pixels; **charge does not move**
- Generally makes the PSF appear larger
- Isotropic IPC makes the PSF and galaxies appear rounder
- Anisotropic IPC induces spurious ellipticity
- IPC correlates shot noise
- Correcting IPC at the pixel level correlates read noise

Inter-pixel capacitance (IPC) in CMOS detectors

0.002	0.02	0.002
0.02	0.912	0.02
0.002	0.02	0.002

Detector pixels

Idealized kernel showing fraction of central pixel's signal shared among neighbors

Assumed IPC model

3 degrees of freedom motivated from WFC3 measurement

- Isotropic nearest neighbors α
- Isotropic diagonal neighbors α'
- "+" anisotropy α_+

$$K_{\alpha,\alpha_+,\alpha'} = \begin{pmatrix} \alpha' & \alpha - \alpha_+ & \alpha' \\ \alpha + \alpha_+ & 1 - 4(\alpha + \alpha') & \alpha + \alpha_+ \\ \alpha' & \alpha - \alpha_+ & \alpha' \end{pmatrix}$$

Limitations of the model

- Ignoring other possible asymmetries
- Ignoring pixels beyond nearest neighbors
- Ignoring IPC variations across the detector.

Kernels measured for 3 WFIRST test detectors (WFIRST Project)

0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.2%	**2.4%**	0.2%	0.0%
0.0%	**2.2%**	**90.1%**	**2.2%**	0.0%
0.0%	0.2%	**2.2%**	0.2%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%

18237

0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.3%	**2.4%**	0.3%	0.0%
0.0%	**2.8%**	**88.3%**	**2.8%**	0.0%
0.0%	0.4%	**2.4%**	0.3%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%

18238

0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.2%	**1.7%**	0.2%	0.0%
0.0%	**1.9%**	**92.0%**	**1.9%**	0.0%
0.0%	0.2%	**1.7%**	0.2%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%

18239

PSF simulations with IPC

- PSFs in J, H and F bands are simulated using the WFIRST module within GalSim. Assuming IPC is independent of fluence.

- PSFs include diffraction spikes and aberrations but not jitter, charge diffusion or other detector effects such as nonlinearity.

- To obtain oversampled images, "dithers" with uniform sub-pixel offsets are *interleaved* after drawing PSFs at native pixel scale (0.11"/px) and convolving with IPC kernel.

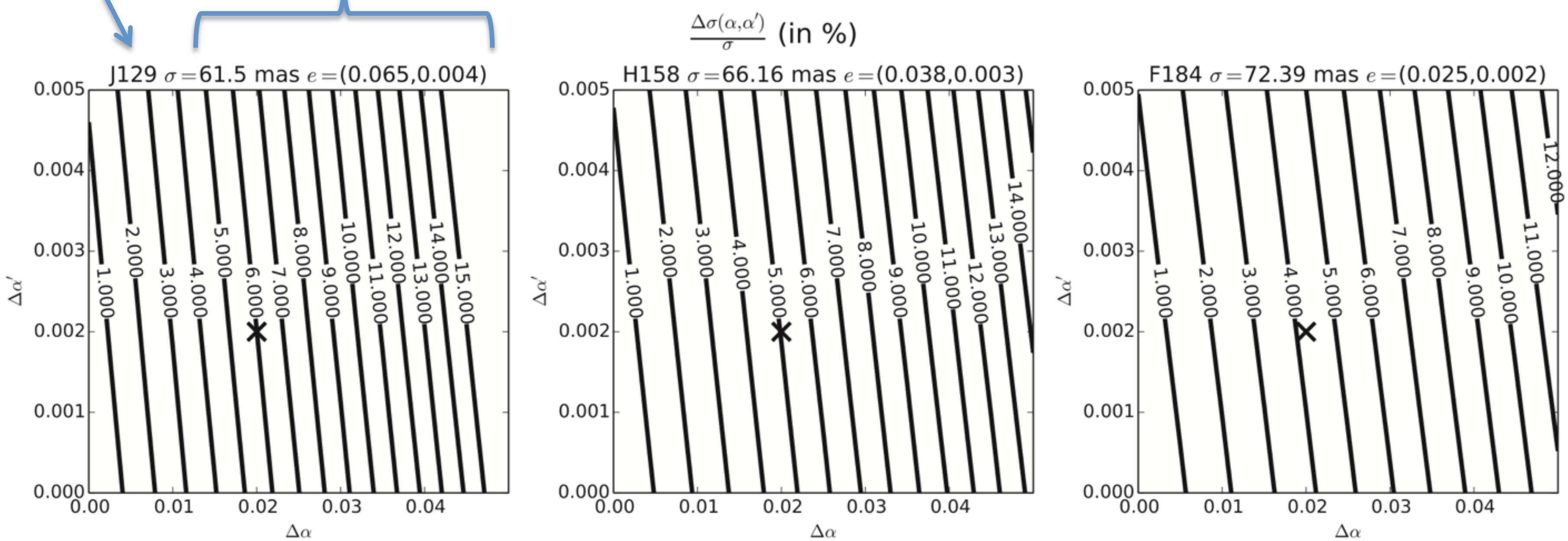
- PSF shapes are measured using adaptive moments (HSM method). Half-light radius is also measured.

Kannawadi et al.
arXiv:1512.01570

Effect of uncorrected IPC on PSF size

Filter

Size, ellipticity without IPC

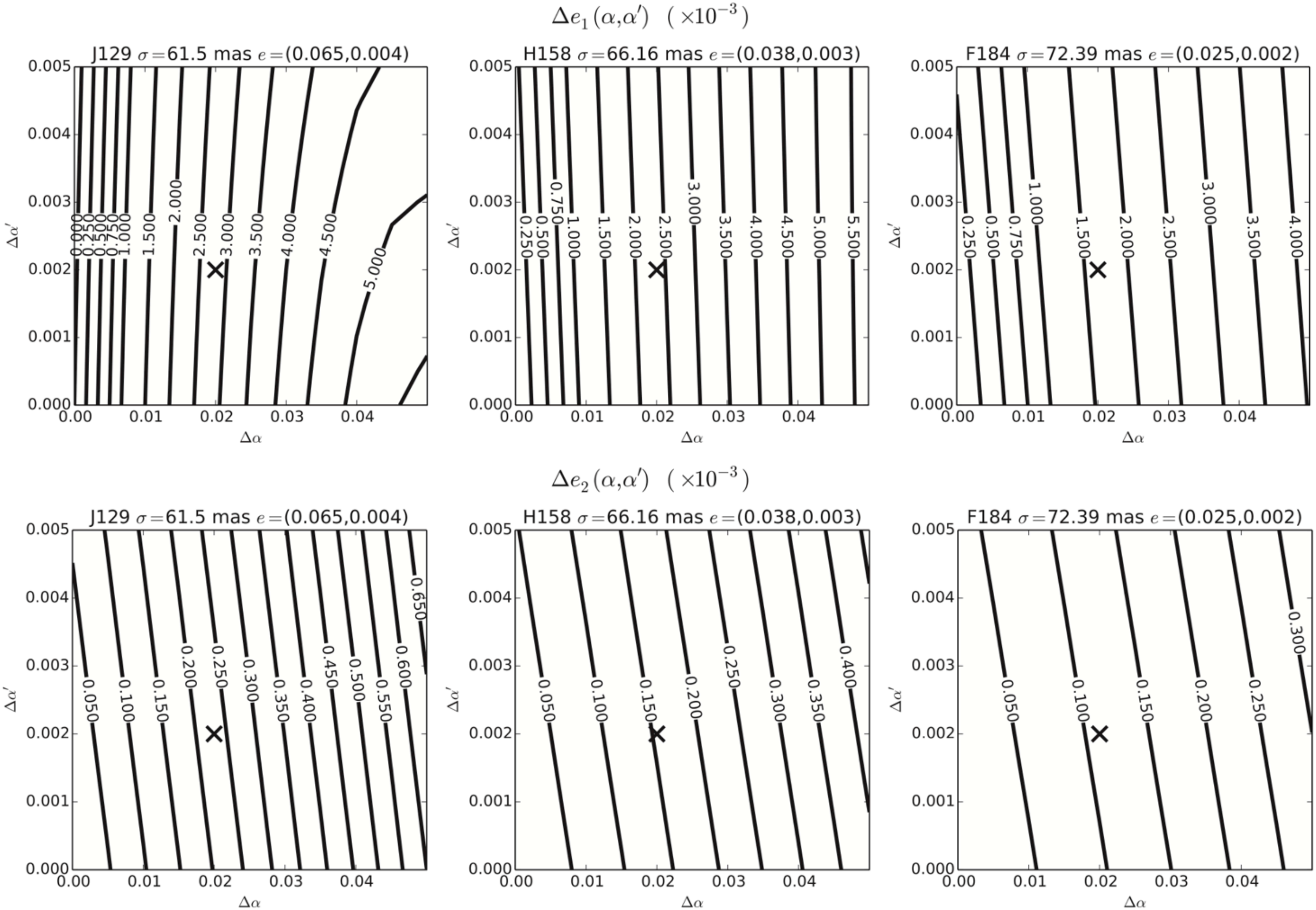


X = Nominal IPC values

Worse effect at lower wavelengths as expected

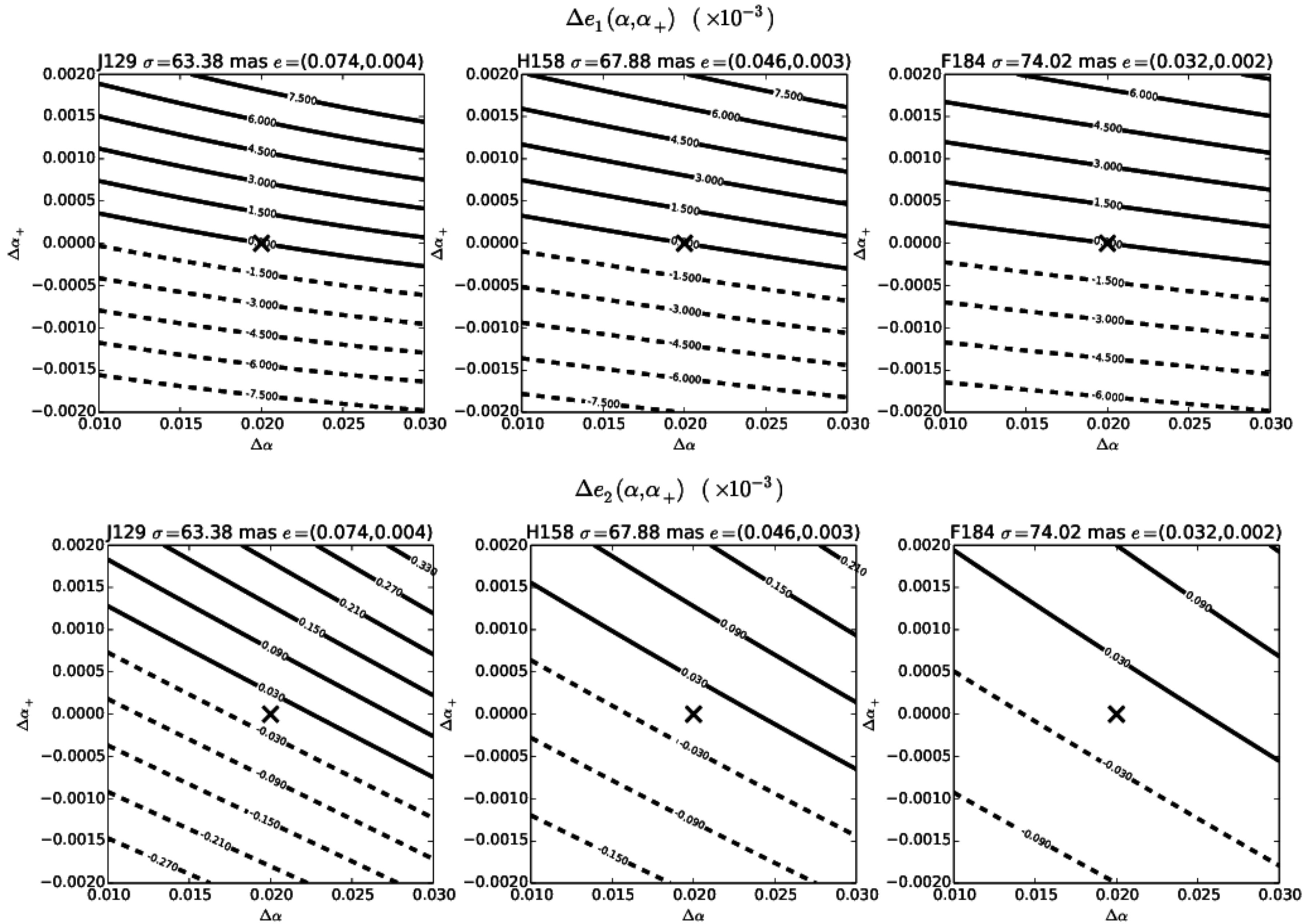
Effect of uncorrected IPC on **ellipticity of PSF**

Kannawadi et al.
arXiv:1512.01570



Effect of anisotropic IPC on PSF ellipticity

Kannawadi et al.
arXiv:1512.01570

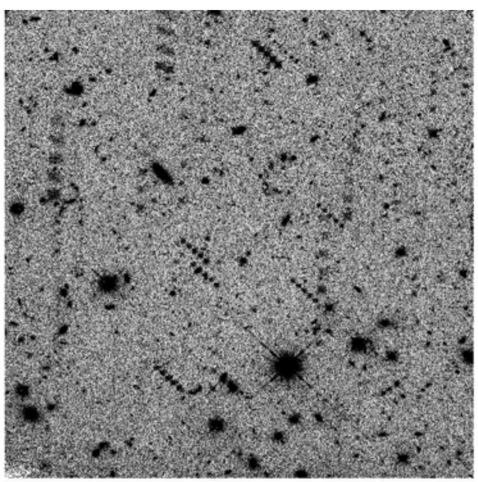


Shape measurement error from IPC calibration error

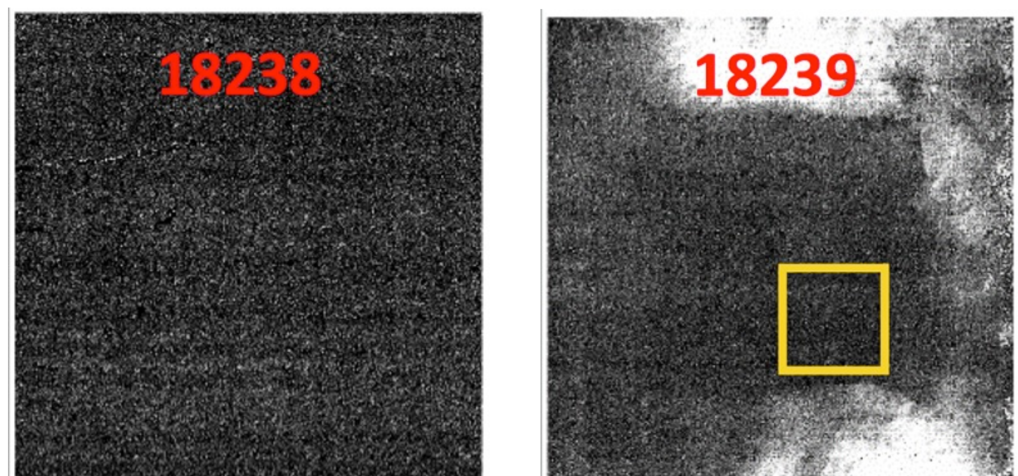
- Kannawadi et al. derives fitting formulae for propagating IPC error into shape errors.
- EXAMPLE: Suppose the IPC parameters are known to within absolute errors of $\boldsymbol{\delta\alpha=\delta\alpha'=\delta\alpha_+=10^{-4}}$. Errors may be due to measurement or spatial variation. Modeling the WFIRST PSF with these errors, the worst PSF shape errors are in the J band: $\boldsymbol{\delta\sigma/\sigma\approx 6e{-}4}$ and $\boldsymbol{\delta e_1\approx 4e{-}4}$. Comparable to error budget.
- In practice, a PSF model will be fit to on-sky measurements, and IPC errors will be absorbed by other parameters in the PSF model.
- Ability to calibrate should not be taken for granted

Persistence

- Image contaminated by “echo” of previous exposure
- Mechanism: charges building up in traps during exposure; released over time (~minutes)
- Persistence amplitude and decay time vary by device as well as by pixel, exposure history, temperature, bias voltage, device age?
- Difficult to model – may not be subtracted sufficiently for weak lensing. Flag pixels after exposures near full well.



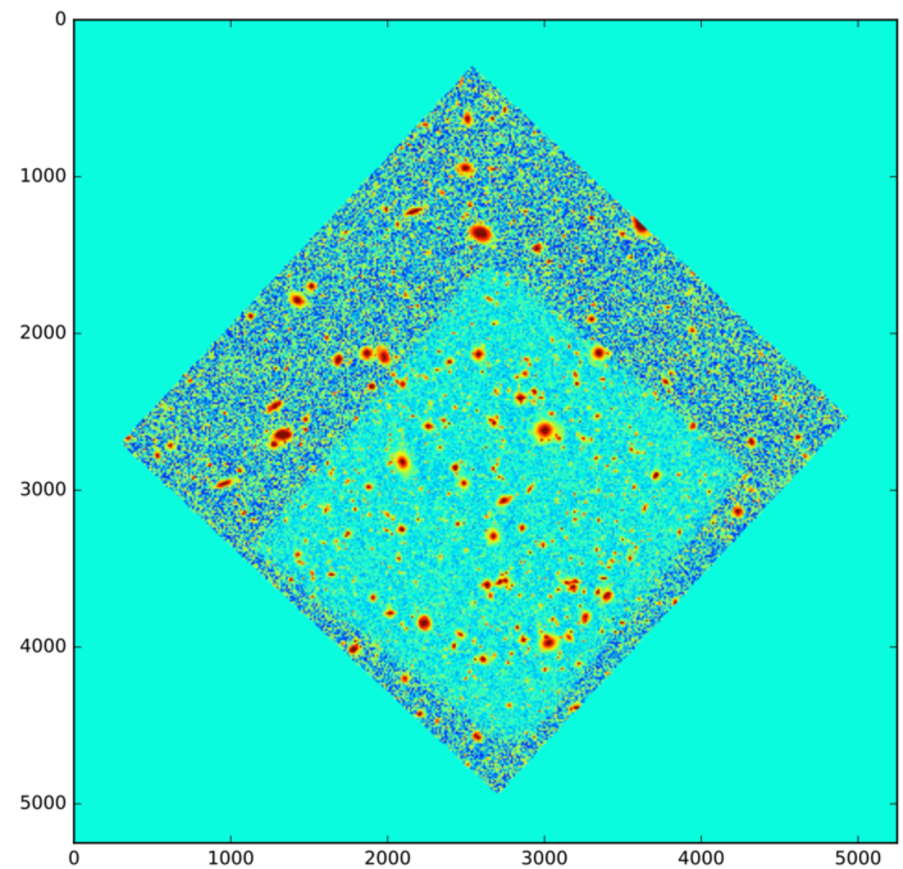
WFC3 image showing persistence



Persistence in 2 WFIRST test devices, 10 min after 100ke- flats.
Scale shows ~ order of magnitude variation

Analysis by Eric Huff (in progress): Treat persistent image as correlated noise

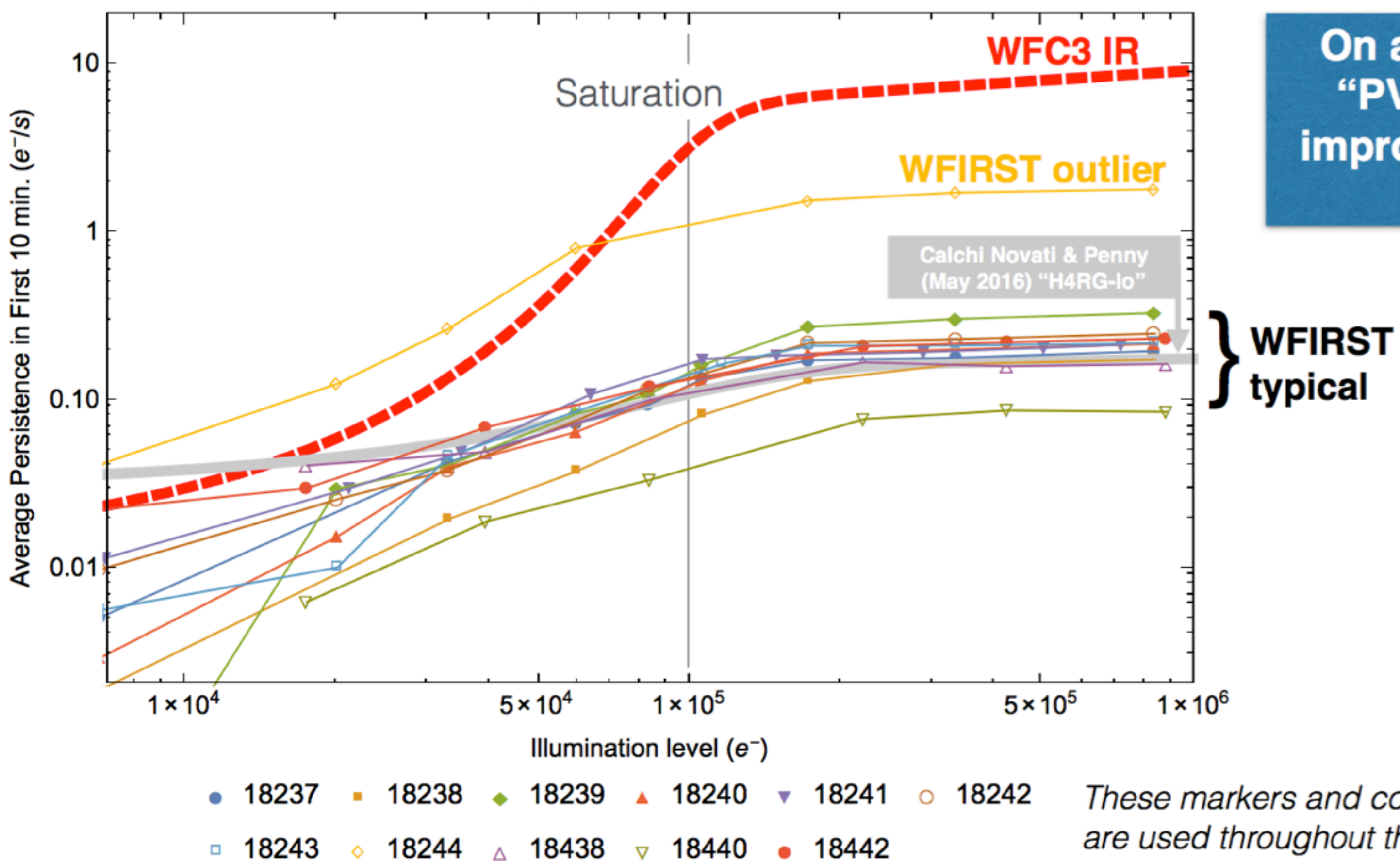
- Estimate noise power spectrum P(k) from Hubble Extreme Deep Field (XDF)
- Scale P(k) according to WFIRST persistence estimate
- Input P(k) to GalSim correlated noise generator and add to simulated galaxies



Drizzled XDF image

To model persistence, use measurements from WFIRST test devices

(slide courtesy GSFC, DCL, B. Rauscher)



On average, WFIRST "PV3" significantly improved compared to WFC3 IR

These markers and colors are used throughout this document

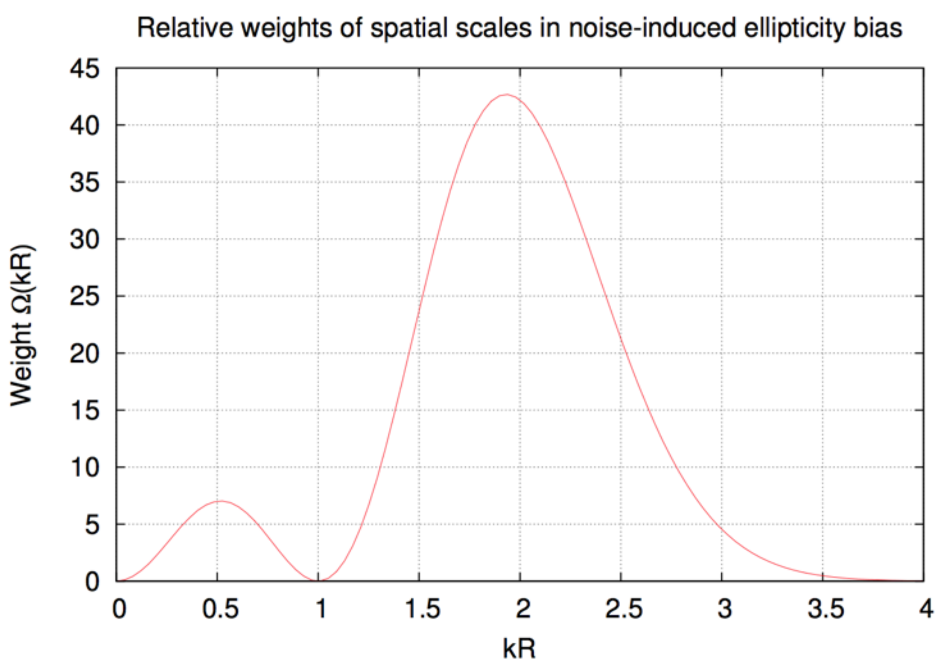
For simulations, Huff assumes grey curve (for now)

Shape measurement bias comes from scales comparable to galaxy size

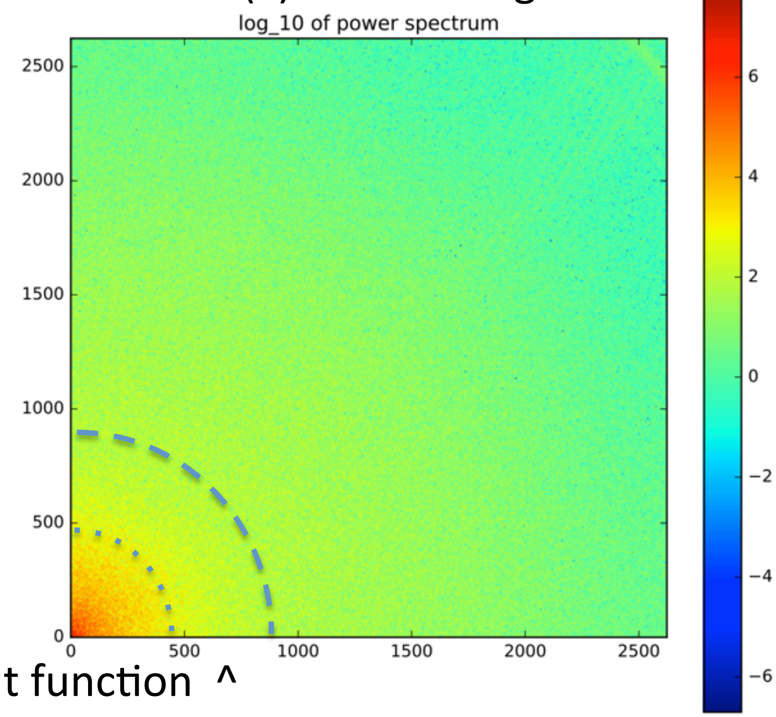
- C. Hirata: $$(\Delta e_1, \Delta e_2) = -\frac{R^4}{F^2}\int \Omega(kR)(\cos 2\phi_{\boldsymbol{k}}, \sin 2\phi_{\boldsymbol{k}})\,\frac{P_N(\boldsymbol{k})\,d^2\boldsymbol{k}}{(2\pi)^2}$$

R = galaxy scale radius; F = total galaxy flux (e-)

Equation based on adaptive moments shape measurement.



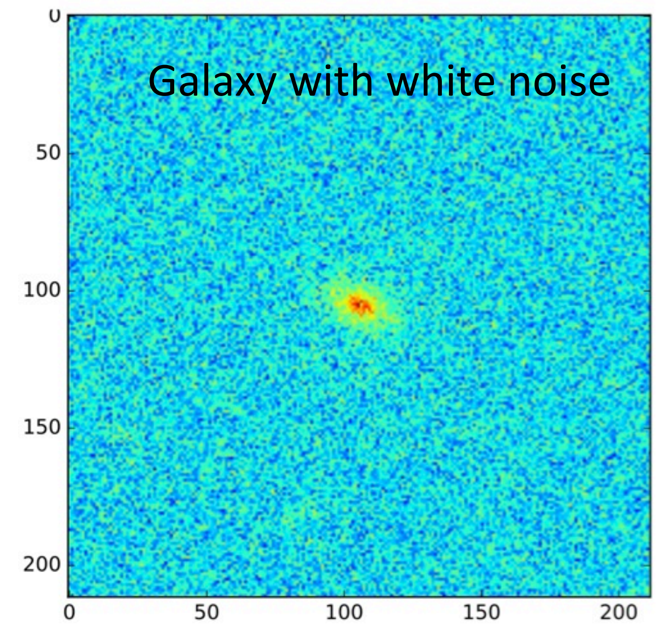
P(k) of XDF image

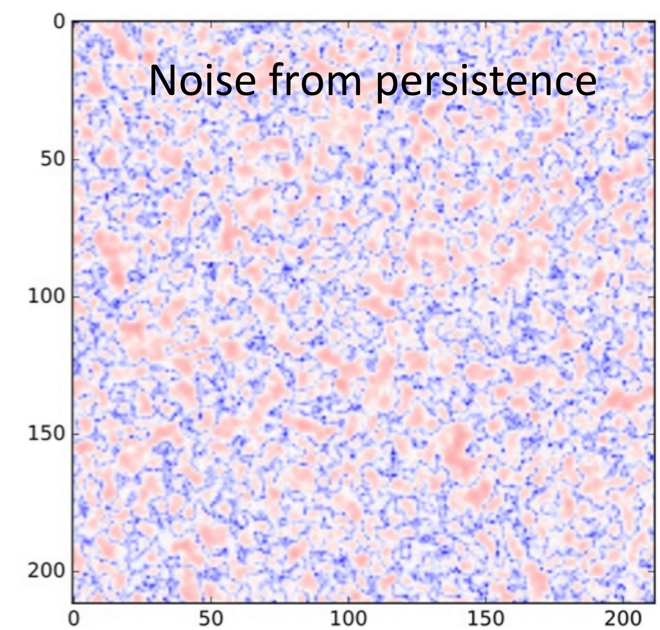


Most of weight function ^

Adding persistence to GalSim images

- Define galaxy profile (Sersic) to have unit flux
- Define S/N by amount of white noise added
- Scale XDF P(k) so that total variance is (1 galaxy flux)**2. (assumes domination by galaxies). Rescale again by WFIRST persistence model (1000s delay)
- Add instance of noise from rescaled P(k)
- Measure/compare ellipticities (g1,g2) with total noise to case with white noise only.





Simulated biases from persistence

SN	size	n	<g1 bias>	<g2 bias>
15	0.5''	1	−0.0106 (+/−0.0014)	−0.0076 (+/− 0.0014)
25	0.5''	1	−0.00342 (+/− 0.00085)	−0.00314 (+/− 0.00085)
50	0.5''	1	−0.00103 (+/− 0.00042)	−0.00078 (+/− 0.00042)
100	0.5''	1	−0.00031 (+/− 0.00065)	−0.00042 (+/− 0.00065)
25	1.0''	1	−0.0018 (+/− 0.00082)	−0.0030 (+/− 0.00082)

- PRELIMINARY! Realism still being tweaked, but these are not obviously negligible