Computing weak lensing requirements on detector calibration

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Part 1: Nonlinearity – Andrés Plazas-Malagon (JPL)

Part 2: IPC – Arun Kannawadi (CMU)

Both parts are results from WFIRST Detector Requirements Working Group

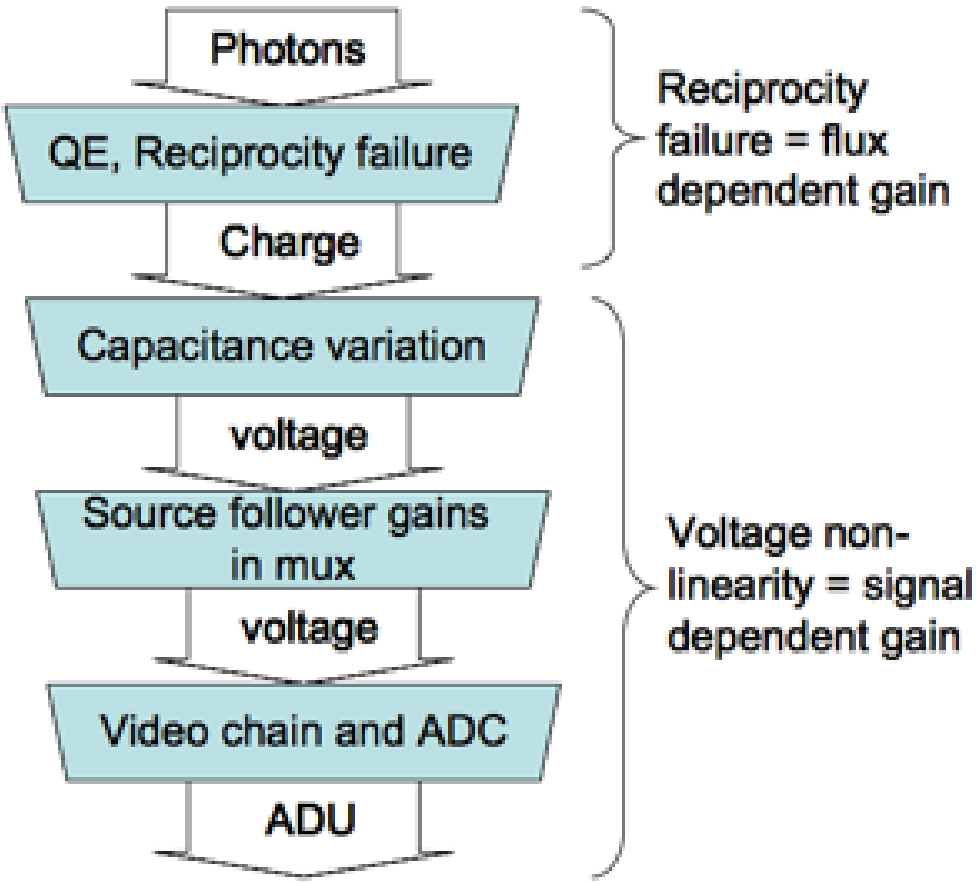
- Funded by WFIRST Project pre-SIT
- Additional weak lensing work is suspended pending funding

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)

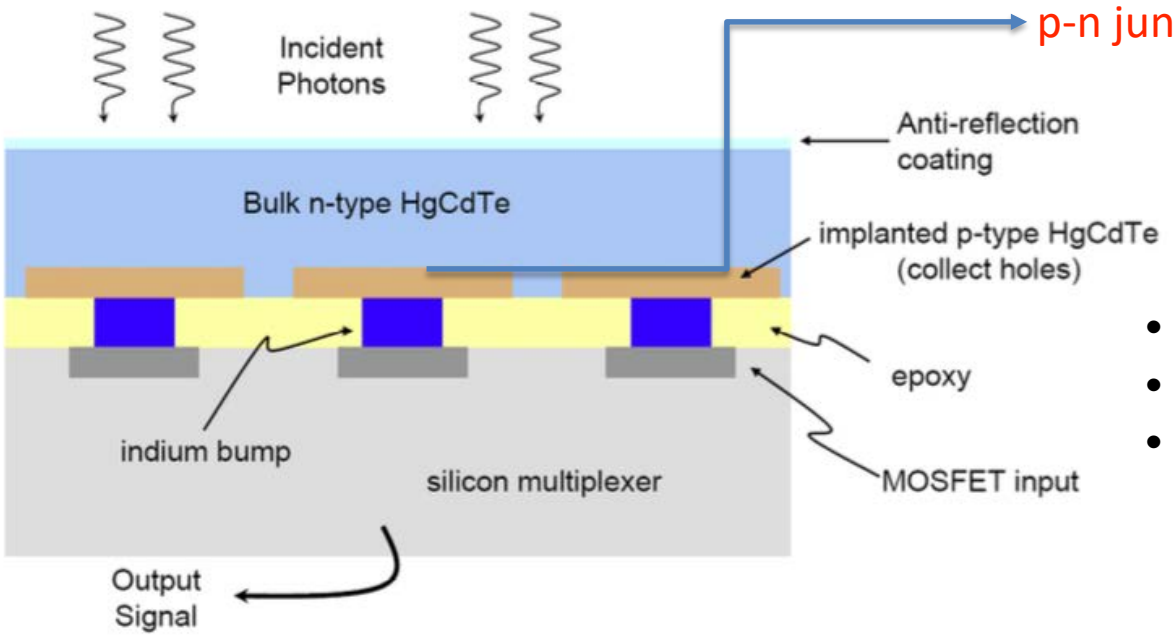
Nonlinearity in the signal chain



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 a capacitor
- Signal $\Delta V = \Delta Q / C$
- Junction capacitance varies as charge accumulates
  → nonlinear V(Q)

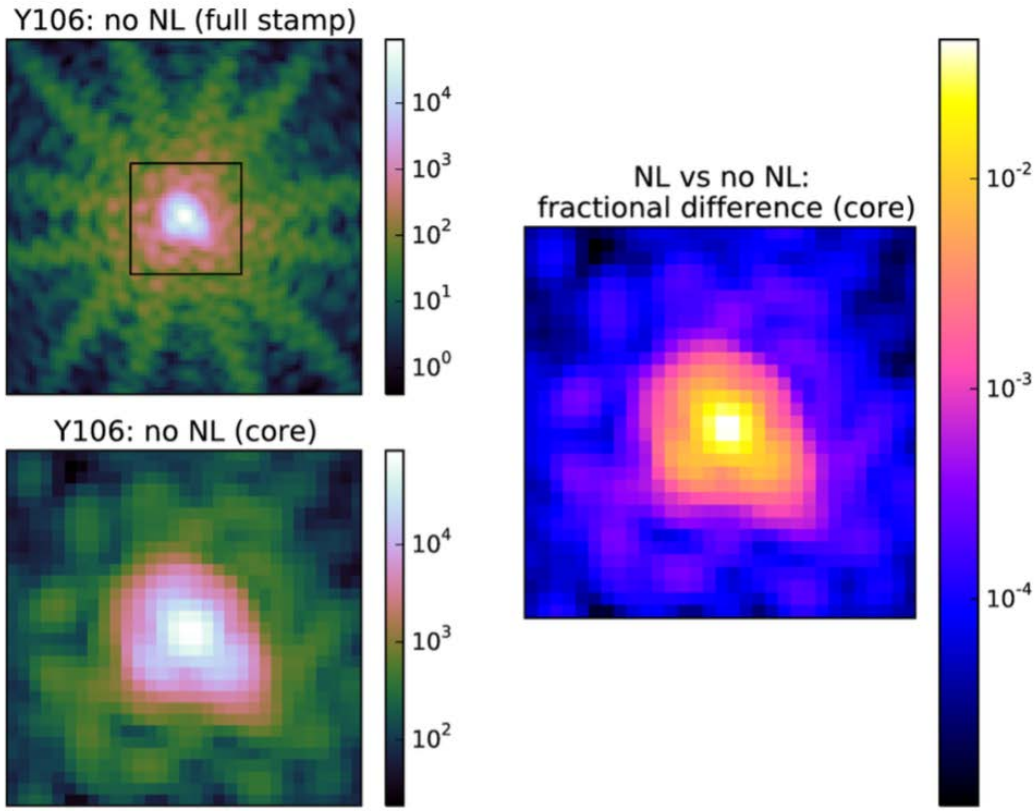
- If the main source of nonlinearity is the junction capacitance, the correction to the inferred signal is well-approximated by a quadratic function

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

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

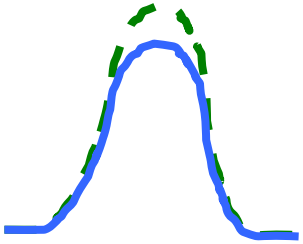
- Additional parameters can improve calibration but are highly degenerate – we stick with 1 for simplicity

Image simulations with GalSim



- 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:

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



NL depresses PSF peak
→ size measurement bias

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

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.

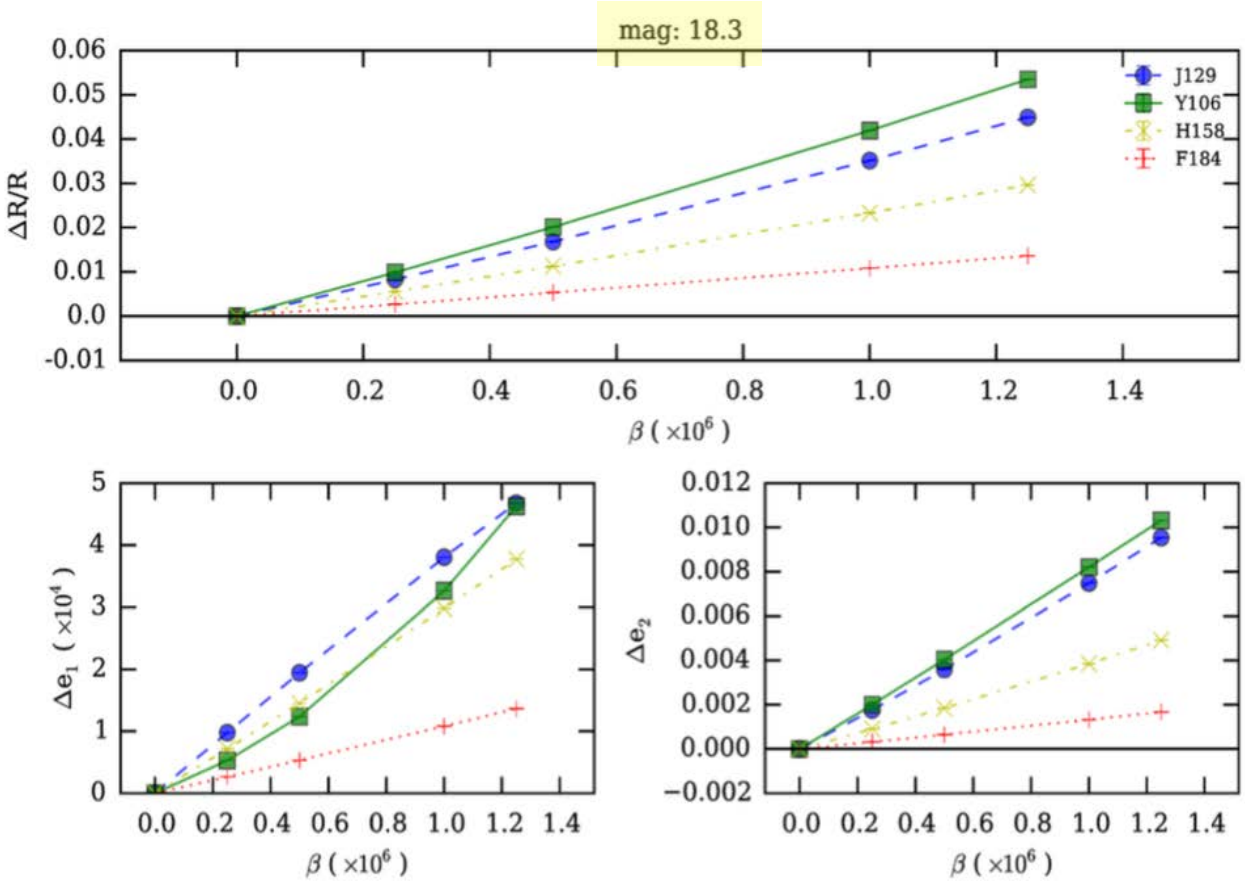
$$\Delta e_i \equiv e_i - e_{i,0}, \quad i \in [1,2]$$

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

Baseline WFIRST PSFs

Band	Min. λ (μm)	Max. λ (μm)	$\lambda_{\rm eff}$ (μm)	Total signal $b(\lambda)$ ($\times 10^5$) (e$^-$)	Center pixel peak value ($\times 10^5$) (e$^-$)	e_1 (#18)	e_2 (#18)	"R" 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.

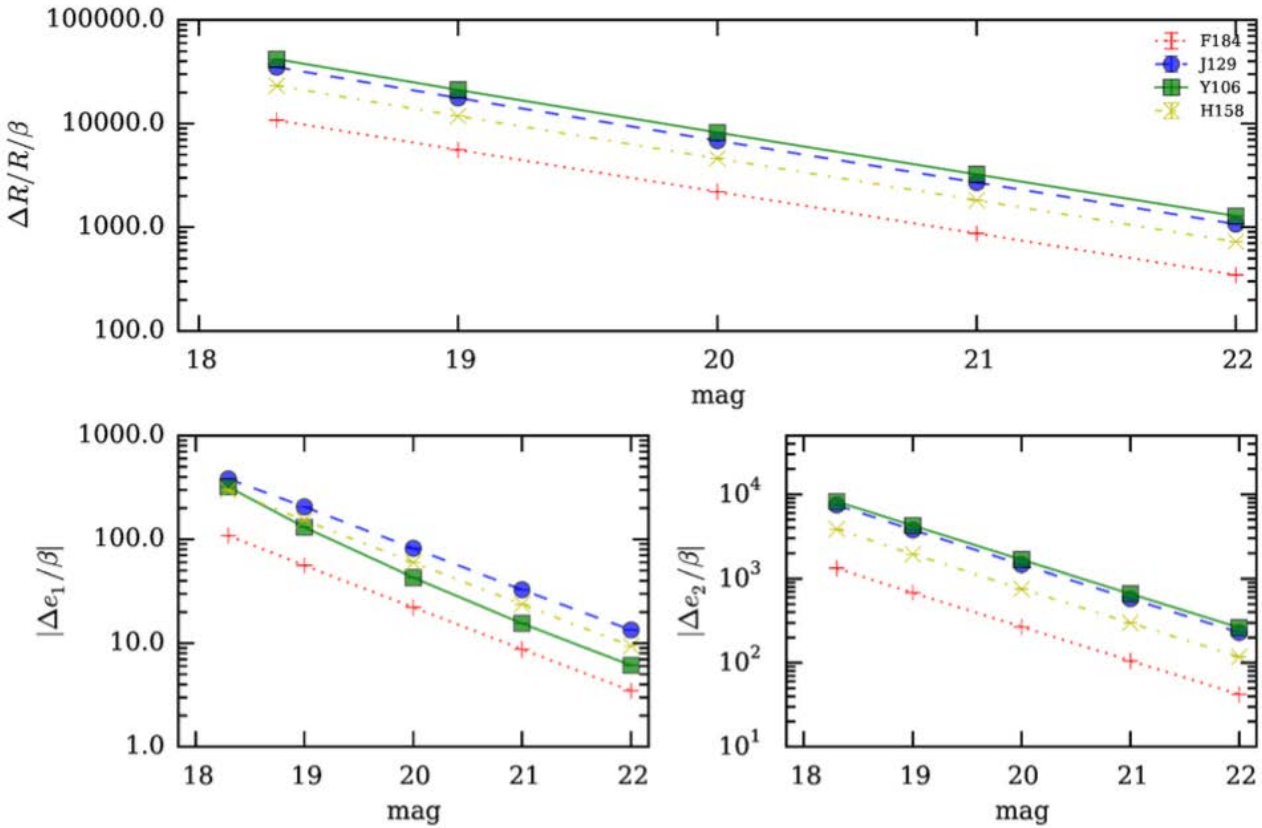
$$\Delta R/R/\beta$$

$$\Delta e/\beta$$

Biases in size and ellipticity after NL calibration

Replacing ®with the error $\Delta\beta$, we can use this plot to convert between star magnitudes, PSF error tolerances, and calibration precision on ® (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, ®must be known to

~1% for R

~2.4% for e_i

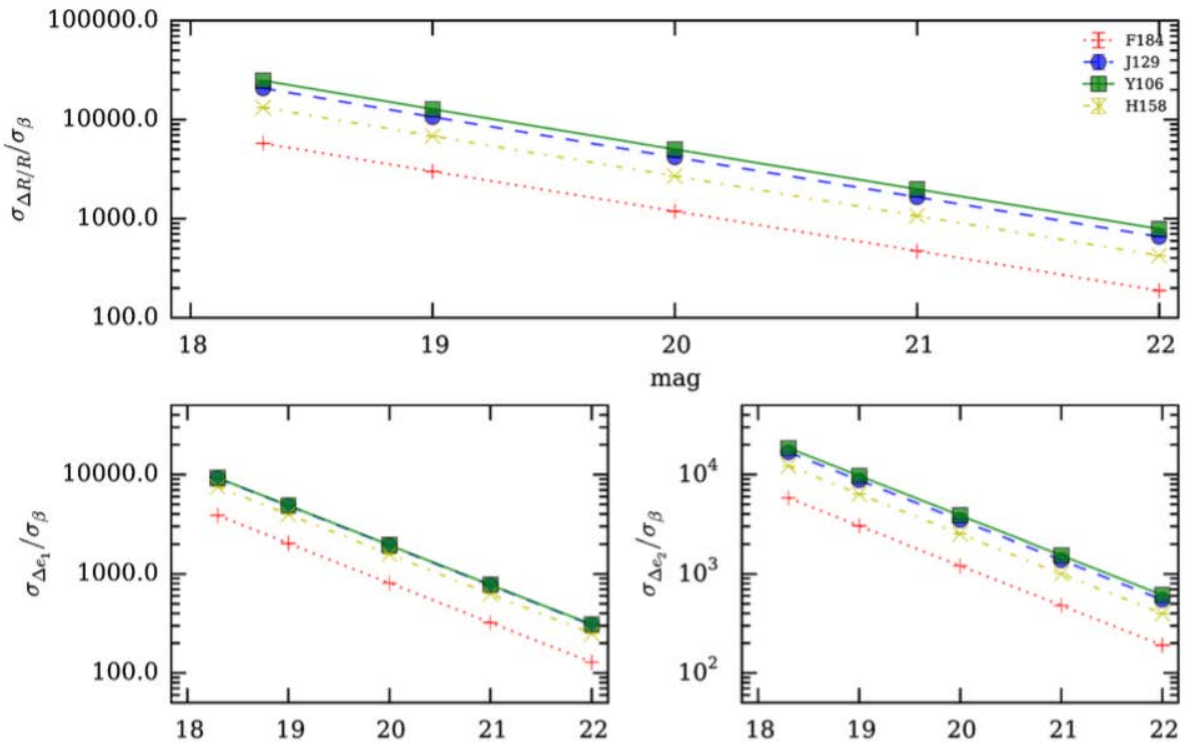
Assumption:

$®_0$ =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).

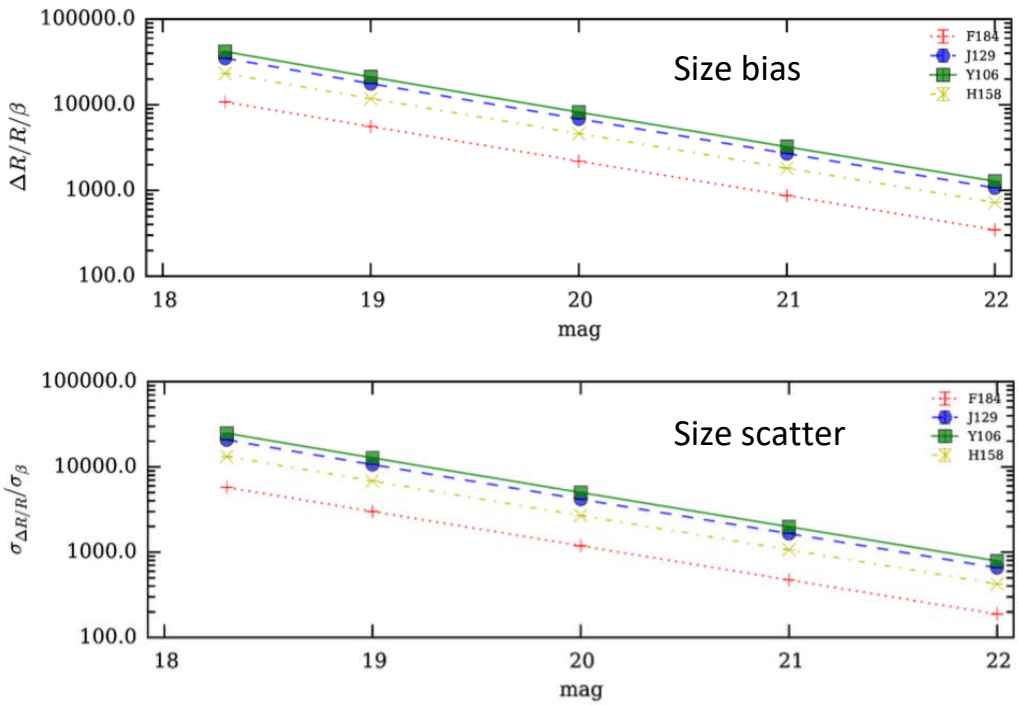


→ Set requirements on σ_β

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

Fitting formulae

We fit power laws to the size bias results but not ellipticity, which will vary widely over the field.



$$\Delta R/R/\beta = A_{\rm F}\ 10^{B_{\rm F}(m-20)}$$

$$\sigma_{\Delta R/R}/\sigma_\beta = A_{\rm F}\ 10^{B_{\rm F}(m-20)}$$

Band	size bias (Fig. 3)		size scatter (Fig. 5)	
	$A_{\rm F}$	$B_{\rm F}$	$A_{\rm F}$	$B_{\rm F}$
Y106	8322	-0.4086	5057	-0.4045
J129	6958	-0.4089	4215	-0.4050
H158	4668	-0.4069	2711	-0.4038
F184	2209	-0.4035	1194	-0.4018

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)

IPC effects on shape measurement

- 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

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.

$$K_{\mathrm{WFC3}} = \begin{pmatrix} 0.0011 \pm 0.0006 & 0.0127 \pm 0.0009 & 0.0011 \pm 0.0006 \\ 0.0163 \pm 0.0014 & 0.936 \pm 0.0045 & 0.0164 \pm 0.0011 \\ 0.0011 \pm 0.0006 & 0.0127 \pm 0.0010 & 0.0011 \pm 0.0006 \end{pmatrix}$$

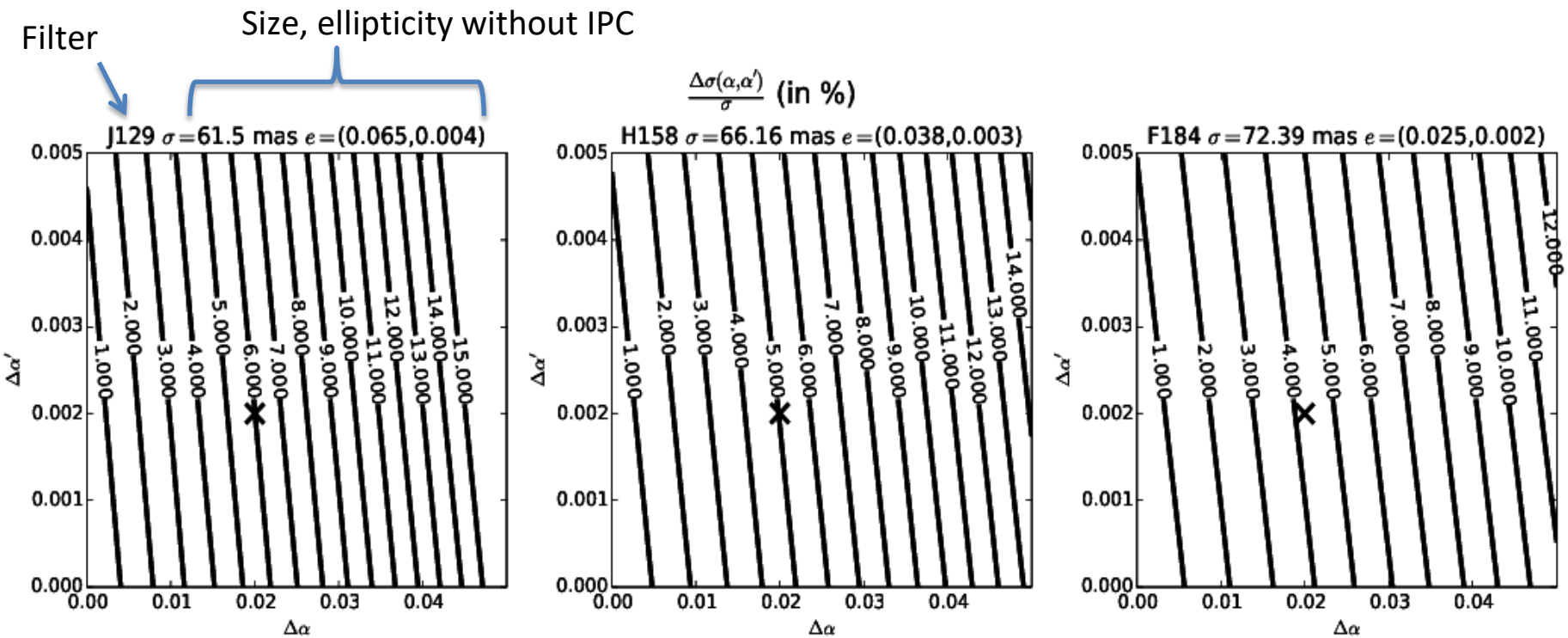
(Hilbert & McCullough 2011)

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

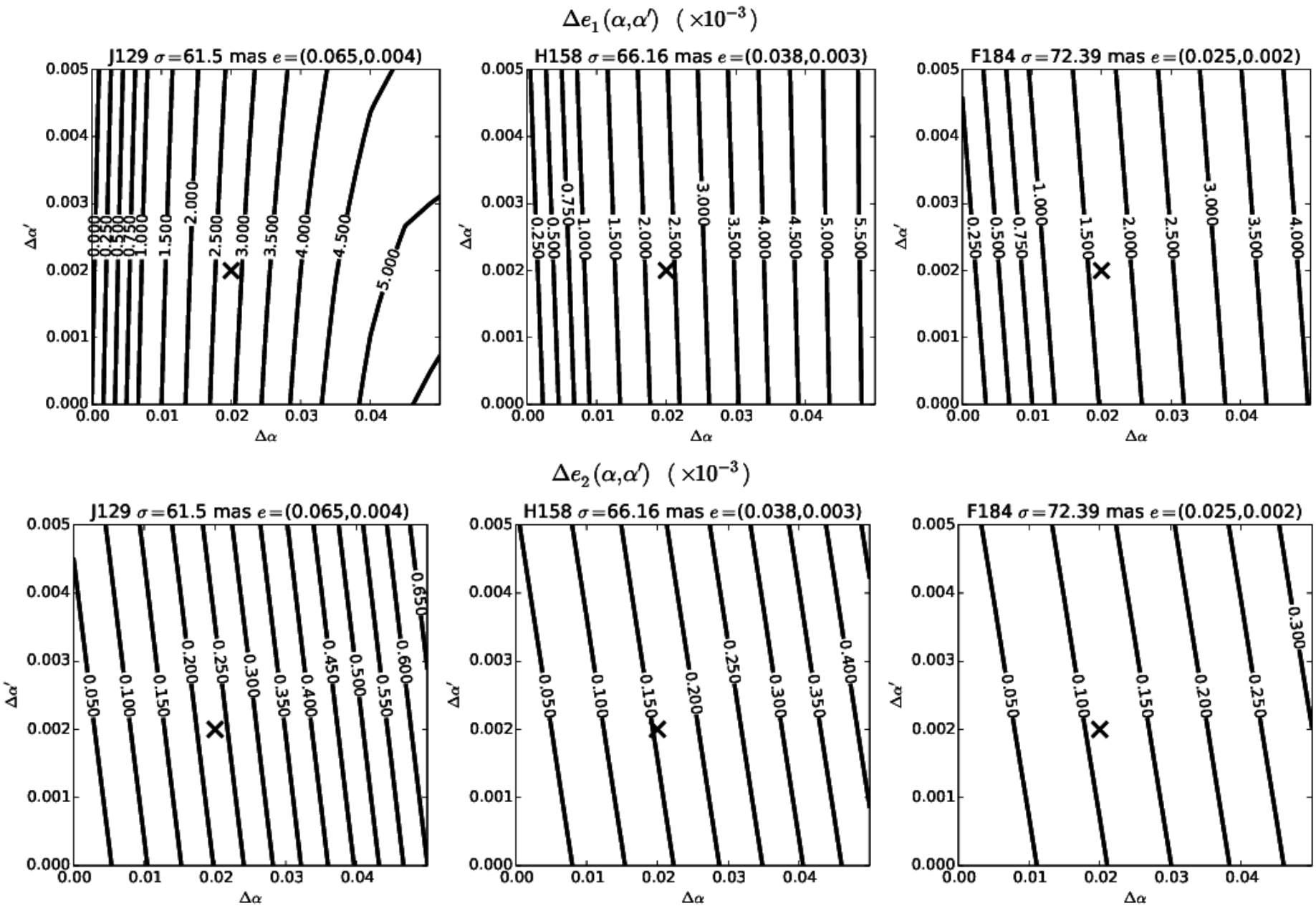
Effect of uncorrected IPC on PSF size



X = Nominal IPC values

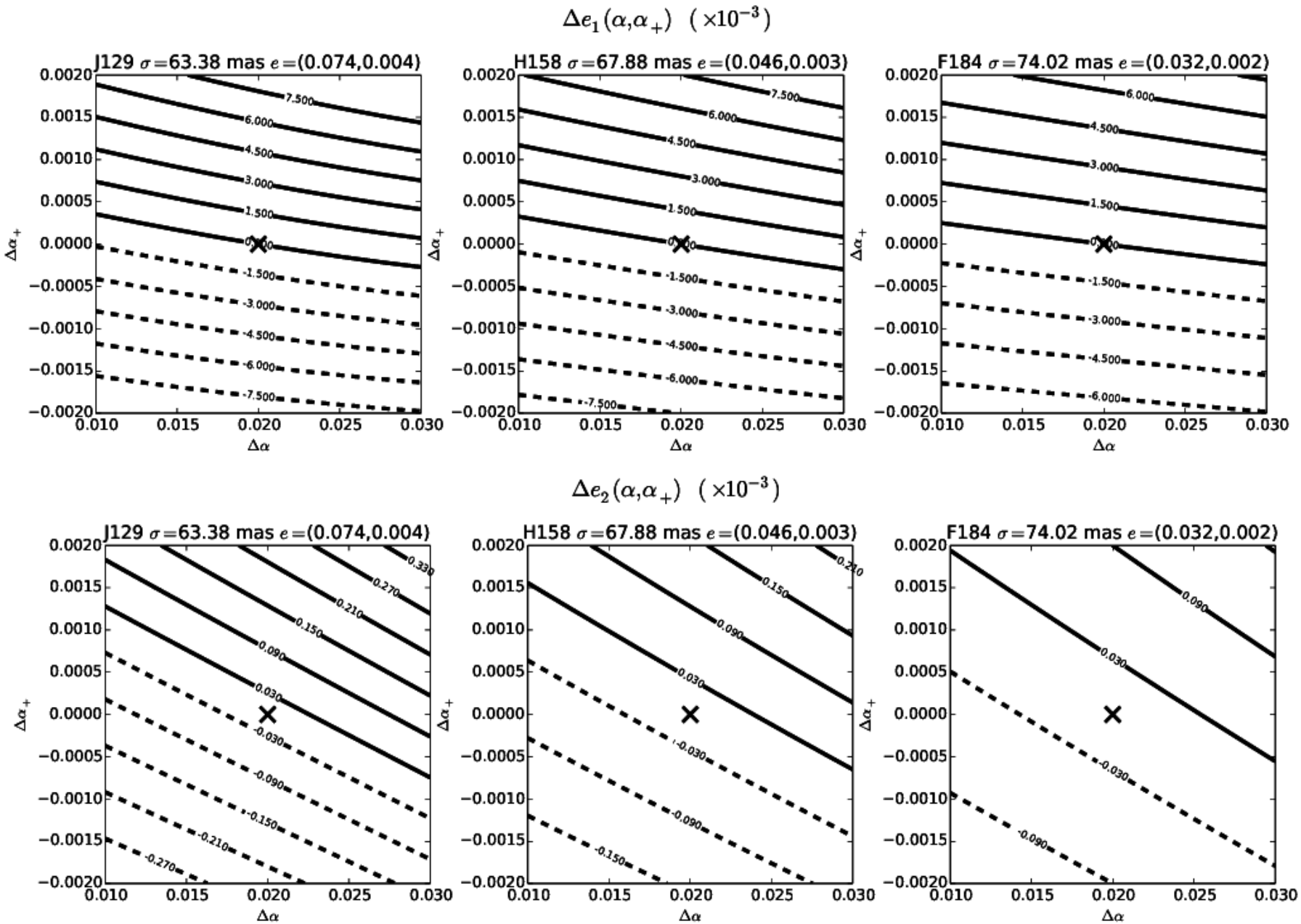
Effect of uncorrected IPC on PSF ellipticity

Kannawadi et al.
arXiv:1512.01570



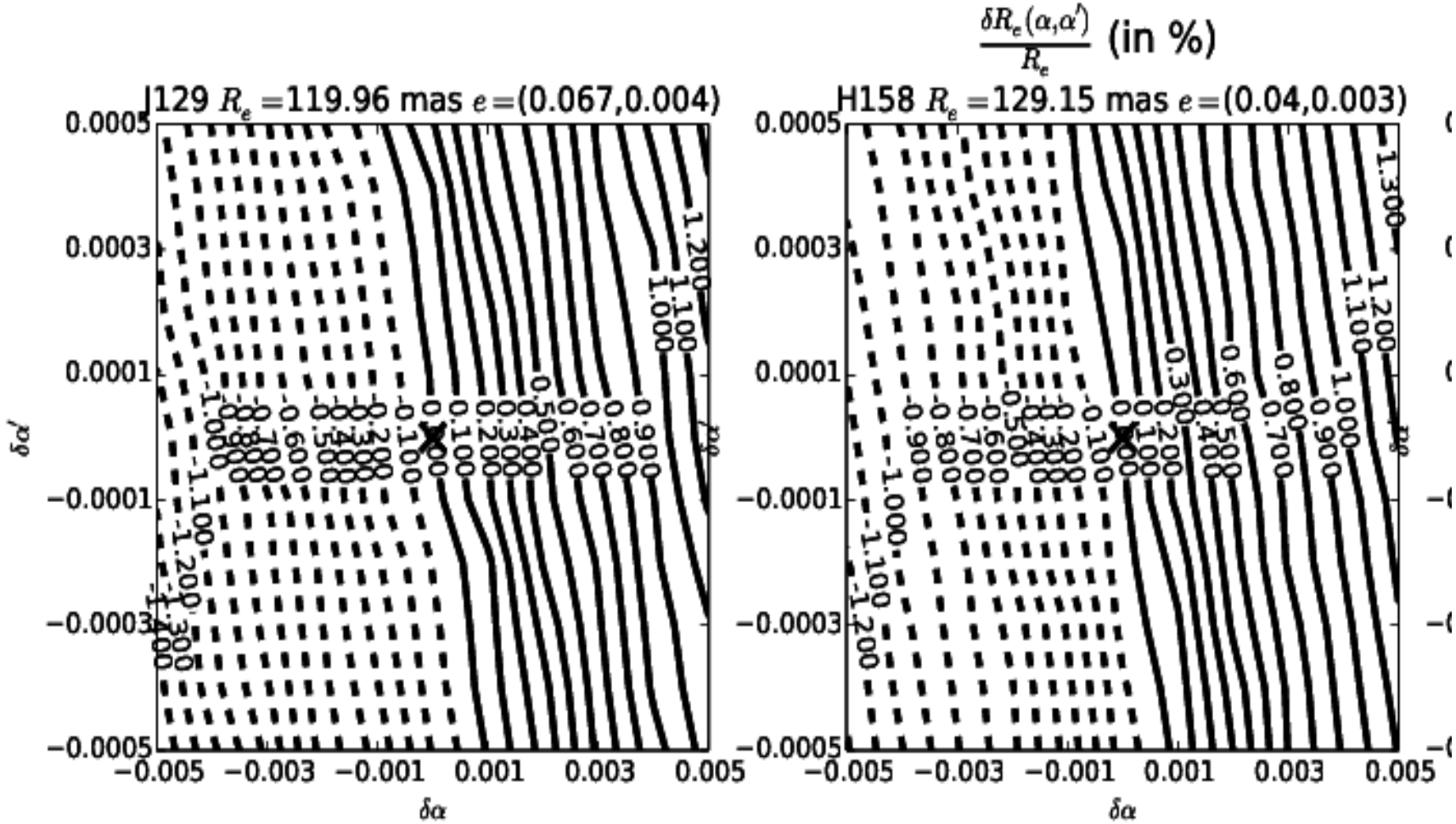
Effect anisotropic IPC on PSF ellipticity

Kannawadi et al.
arXiv:1512.01570



PSF size error from imperfect IPC calibration

Kannawadi et al.
arXiv:1512.01570



PSF ellipticity error from imperfect IPC calibration

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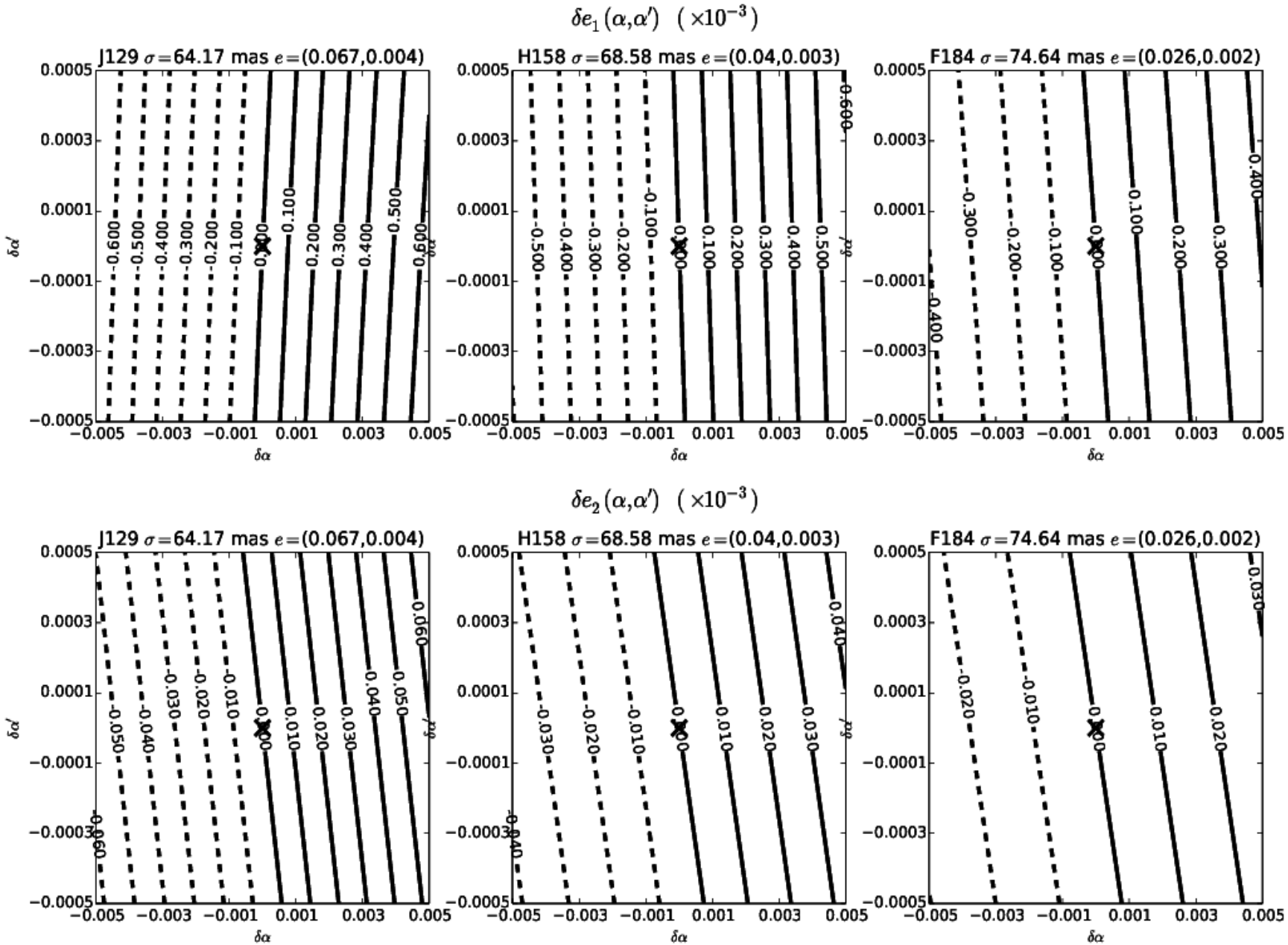


Calculating PSF uncertainties

Fitting formulae

$$\sigma'(\alpha,\alpha') - \sigma'(\alpha_0,\alpha_0') \approx \delta\alpha\, R_\alpha(\alpha_0,\alpha_0') + \delta\alpha'\, R_{\alpha'}(\alpha_0,\alpha_0')$$

$$e_k'(\alpha,\alpha') - e_k'(\alpha_0,\alpha_0') \approx \delta\alpha\, S_{k,\alpha}(\alpha_0,\alpha_0') + \delta\alpha'\, S_{k,\alpha'}(\alpha_0,\alpha_0'), \quad \text{for } k = 1,2$$

Bandpass	$R_\alpha/\sigma(\alpha_0,\alpha_0')$	$R_{\alpha'}/\sigma(\alpha_0,\alpha_0')$	$S_{1,\alpha}$	$S_{1,\alpha'}$	$S_{2,\alpha}$	$S_{2,\alpha'}$
$J129$	2.9432	2.7691	0.1308	−0.063	0.0116	0.0134
$H158$	2.4457	2.5631	0.1171	0.0406	0.0076	0.0112
$F184$	2.0168	2.3741	0.0807	0.0604	0.0054	0.0084

$$\delta\sigma' = \delta\alpha\, R_\alpha + \delta\alpha_+\, R_+,$$

$$\delta e_k' = \delta\alpha\, S_{k,\alpha} + \delta\alpha_+\, S_{k,+}, \quad \text{for } k = 1,2.$$

Bandpass	$R_\alpha/\sigma(\alpha_0,\alpha_0')$	$R_+/\sigma(\alpha_0,\alpha_0')$	$S_{1,\alpha}$	$S_{1,+}$	$S_{2,\alpha}$	$S_{2,+}$
$J129$	2.9429	0.0383	0.1308	4.1516	0.0116	0.1165
$H158$	2.4454	0.0435	0.1171	3.7389	0.0075	0.0704
$F184$	2.0166	0.0336	0.0807	3.2975	0.0054	0.045

Shear calibration bias

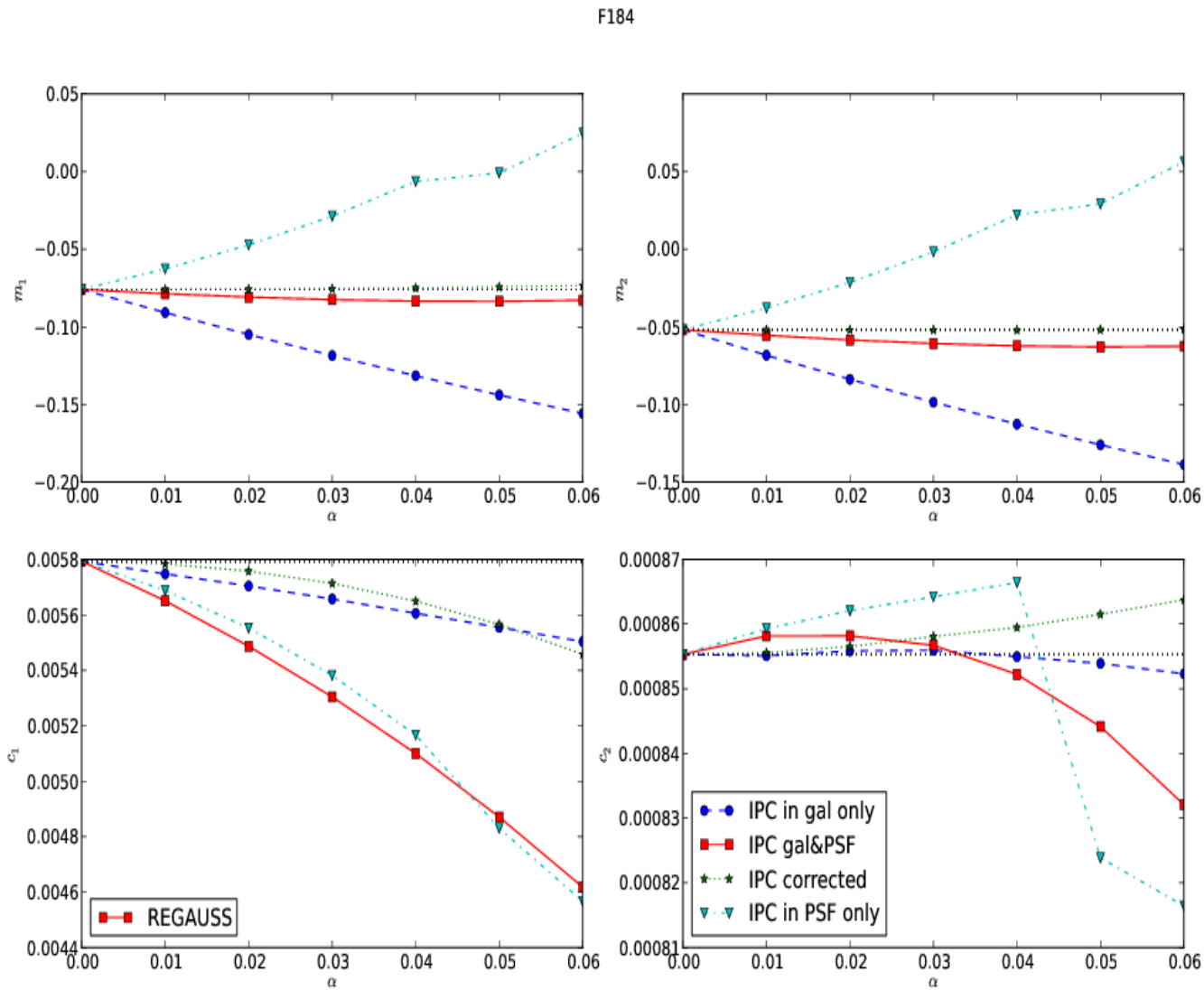
- Even if the PSF is known perfectly, PSF correction is not perfect, thus biasing the estimate of the lensing shear.

- $$\hat{\gamma}_i = (1 + m_i)\gamma_i + c_i \qquad i = 1, 2$$

- To obtain calibration bias, galaxies are simulated in Galsim (COSMOS catalog), sheared, convolved with PSF + pixel response, and IPC applied. We then try to recover galaxy shape using knowledge of the PSF (regaussianization)

- Scenarios:
  - Different IPC in galaxy and PSF
  - Same IPC in galaxy and PSF – no IPC correction
  - Same IPC in galaxy and PSF – IPC corrected

Bias from IPC (Noiseless case)



To do: account for noise (induced correlations may be important)

Recommendations

- NL forecasts may be updated as mission parameters change. Detector and WL groups should scrutinize our assumptions.
- At Detector Characterization Laboratory (DCL at GSFC), map NL/IPC over whole detector area. Develop models and calibration strategy.
  - Rather than work with our parameters, expected residuals can be analyzed by working groups to see if PSF error tolerances are met
- At Precision Projector Laboratory (PPL at JPL), experimentally confirm that the PSF can be calibrated accurately, over the whole detector, independent of flux (up to some cutoff).
- Includes any flux dependent effect on PSF - NL, brighter-fatter, reciprocity failure, etc.
- Do these **soon** to head off surprising detector effects and to retain detector selection as a mitigation strategy.