NASA

Simulated image: M. Troxel & Image Simulation Team

Realistic Image Simulations

Community Science Workshop, November 17, 2021

Speakers: Mike Jarvis (Penn), Heyang Long (OSU), Jahmour Givans (Princeton/CCA), Masaya Yamamoto (Duke), Chien-Hao Lin (Duke), Michael Troxel (Duke)

On behalf of Ami Choi, Jenna Freudenburg, Michael Higgins, Chris Hirata, Rachel Mandelbaum, Andy Park, Anna Porredon, Kevin Wang, Cosmology with the High Latitude Survey Science Investigation Team

Overview

1. Introduction (Mike Jarvis)
2. General Roman sims and application to impact of wavefront errors (Heyang Long)
3. Characterization of detector effects for simulation input (Jahmour Givans)
4. Application to impact of persistence (Chien-Hao Lin)
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6. Joint simulations with Rubin and simulation products (Michael Troxel)

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Why make image simulations?

- Investigate impact of systematic errors on science.
- Test ability of analysis code to correct for instrumental and observational effects.
- Test impact of different survey strategies on systematics mitigation.

GalSim Overview

- Highly-tested, general-purpose image simulation code.
- Used by DES, HSC, LSST-DESC, others for large scale simulations.
- Open-source, easy to add new modules.
- Wide array of existing features for simulating complex PSFs and galaxy profiles.
- Especial focus on accuracy with respect to image shapes.

GalSim Roman Module

- Wavelength-dependent Roman PSF with band-dependent spider pattern.
- Accurate distortion map across the Roman focal plane.
- HgCdTe detector effects (Inter-pixel capacitance, persistence, non-linearity, etc.).
- Bandpasses, etc. are consistent with Cycle 7 specifications.

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Application to Impact of Wavefront Errors

1. Simulation and shape measurement

- 907170 galaxies and 56128 stars in a 2.5 ×2.5 deg^2 sky
- Implement Roman survey strategy

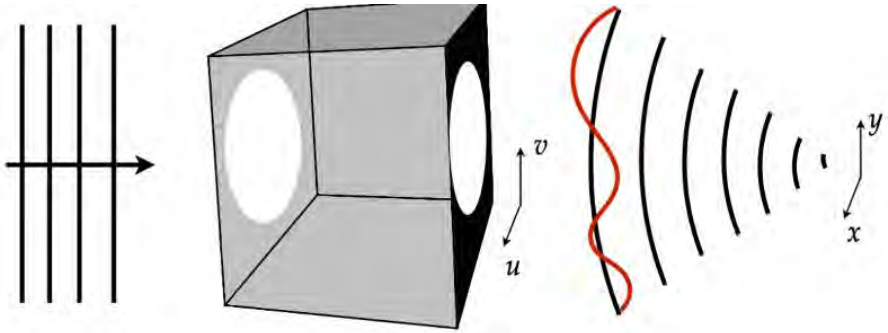
- Fiducial sim + 12 PSF models
- Noise included

- Shape measurement
- Galaxies shapes change with respect to PSF biases

Application to Impact of Wavefront Errors

2. Wavefront error model

Imperfect optical system?



$$I(x,y) = \left| \frac{1}{\lambda z} \int P(u,v) e^{i2\pi W(u,v)/\lambda} \, e^{-i\frac{2\pi}{\lambda z}(xu+yv)} \, du dv \right|^2$$

$W(u,v)$ Wavefront or Aberration Function

$$W(u,v) = \sum a_i Z_i(\rho,\theta)$$

Zernike expansion

Index	Name	Zernike Polynomial
2	Tilt X	$2\rho\cos\theta$
3	Tilt Y	$2\rho\sin\theta$
4	Focus	$\sqrt{3}(2\rho^2-1)$
5	Astigmatism Y	$\sqrt{6}\rho^2\sin 2\theta$
6	Astigmatism X	$\sqrt{6}\rho^2\cos 2\theta$
7	Coma Y	$\sqrt{8}(3\rho^3-2\rho)\sin\theta$
8	Coma X	$\sqrt{8}(3\rho^3-2\rho)\cos\theta$
9	Trefoil Y	$\sqrt{8}\rho^3\sin 3\theta$
10	Trefoil X	$\sqrt{8}\rho^3\cos 3\theta$
11	Spherical	$\sqrt{5}(6\rho^4-6\rho^2+1)$

Credit: Aaron Roodman

Application to Impact of Wavefront Errors

3. PSF model biases of Roman

- Static: potential distortion or displacement of optical system
- High-frequency: residual vibrations of telescope
- Low-frequency: thermal fluctuations

Run name	PSF change	Mode	Notes
FIDUCIAL	–	–	–
FOCUS	ψ_4	Static	–
ASTIG	ψ_5	Static	–
COMA	ψ_7	Static	–
GRADZ4	ψ_4	Static	Gradient in focal plane
GRADZ6	ψ_6	Static	Gradient in focal plane
PISTON	ψ_4	Static	Random per SCA
TILT	ψ_4	Static	Rand. gradient per SCA
ISOJITTER	Gaussian	High-Freq.	Isotropic
ANIJITTER	Gaussian	High-Freq.	Anisotropic
RANJITTER	Gaussian	High-Freq.	15% of pointings
OSCZ4	ψ_4	Low-Freq.	Time-dependent
OSCZ7	ψ_7	Low-Freq.	Time-dependent

Troxel, Long+2020

Application to Impact of Wavefront Errors

4. Quantify the impact of wavefront error on weak lensing

   a. Multiplicative and additive biases

$$e_i^{obs} = \left(1 + m_i\right) e_i^{true} + c_i$$

   b. Changes of galaxy shape ellipticities with respect to bias modes

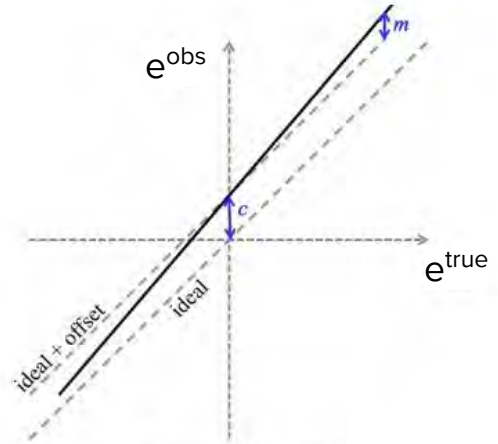
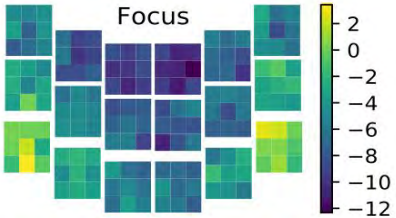
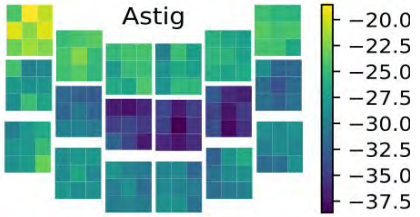


Figure: Chris Hirata





Application to Impact of Wavefront Errors

5. Summary

    a. We present a first example of studying Roman science requirement by realistic image simulations
    b. Studied how the measured shapes of galaxies change as a function of induced wavefront error
    c. Comparison with analytical flowdown requirements and find general agreement

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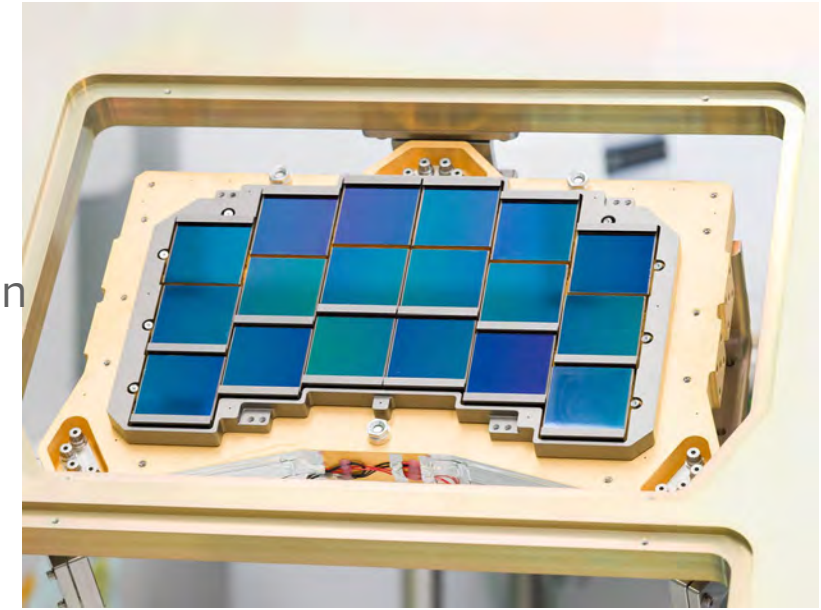
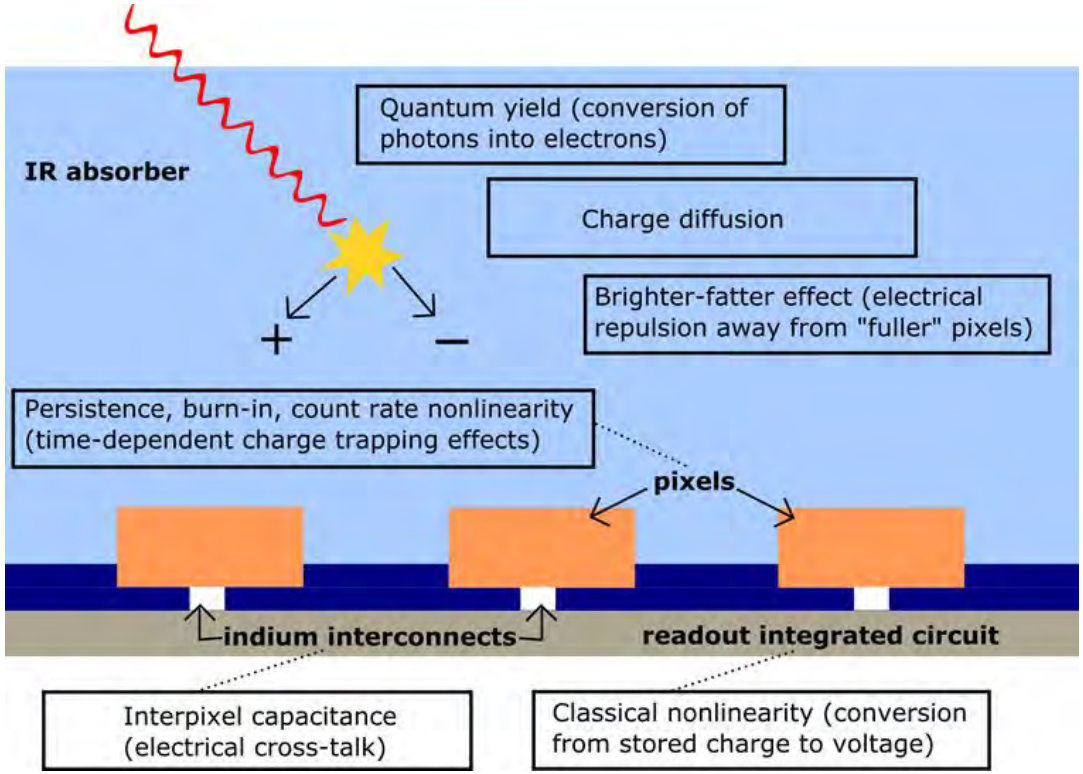
Roman Detectors

- H4RG-10 series from Teledyne Technologies
  - 4096 x 4096 array with 10 μm pixel pitch
- Non-destructive readout capabilities
  - Unlike CCDs
  - Allows for new analyses
- First time being used for weak lensing
- See also Roman Detectors and Calibration talks later this afternoon!



Credit: NASA/Chris Gunn

Where do the effects occur?



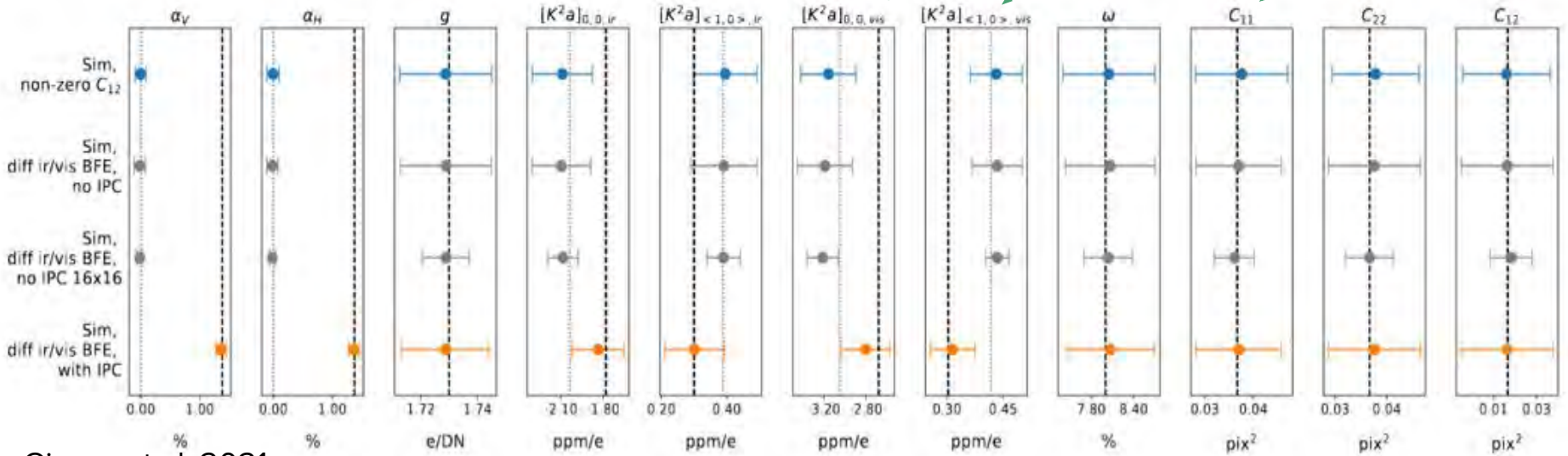
Credit: Jenna Freudenburg, also see Mosby et al. 2020

Determining magnitude of effects

- Carried out using code by OSU group
  - Measurements on simulated flats and darks
  - Measurements on real data

Charge diffusion matrix elements

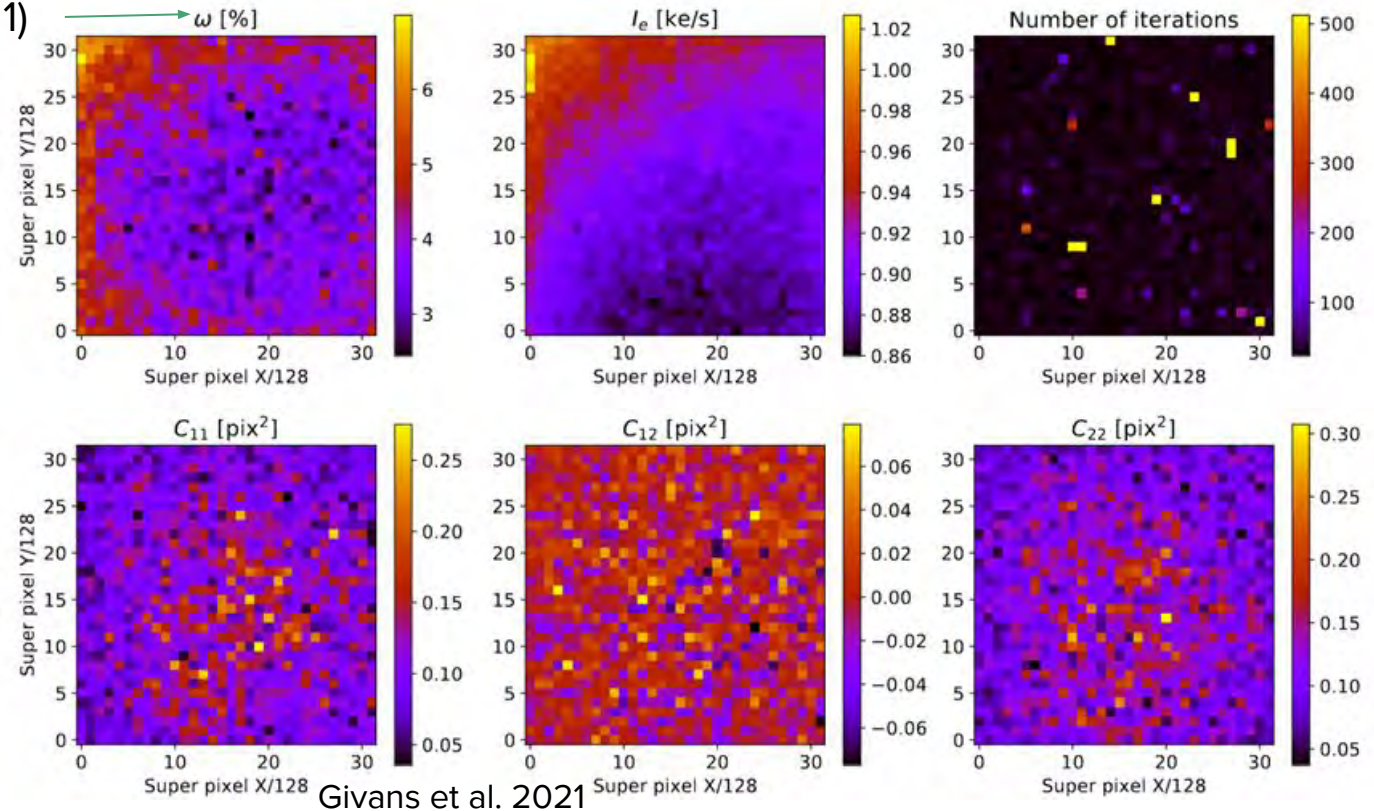
BFE+IPC kernel



Givans et al. 2021

Example detector spatial variation maps (1/2)

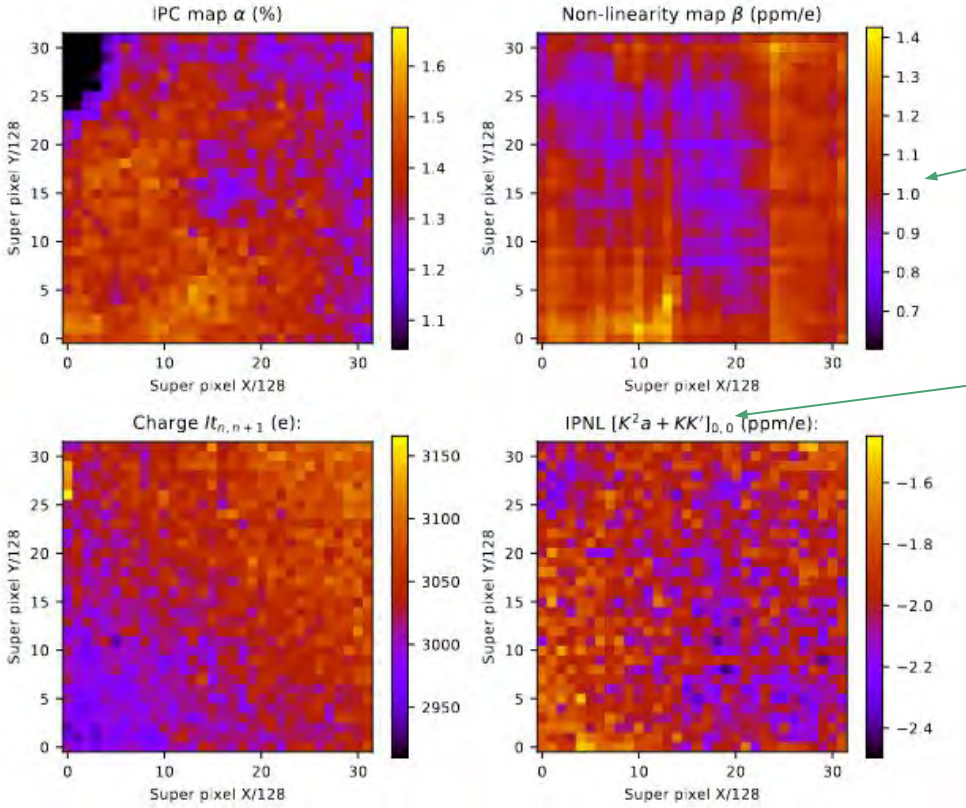
(Quantum yield - 1)



Bottom row:
Charge diffusion matrix elements

Givans et al. 2021

Example detector spatial variation maps (2/2)

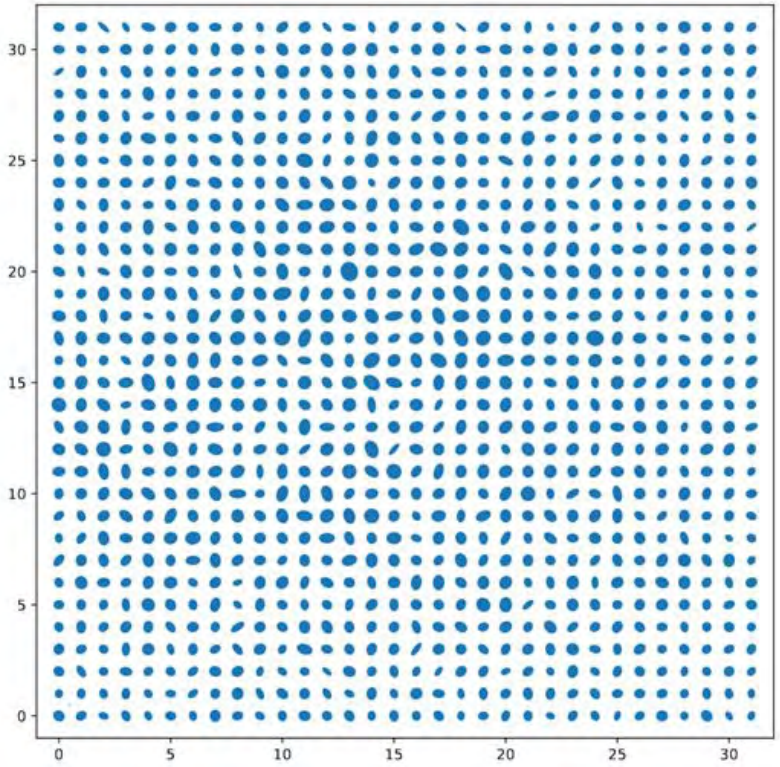


Classical nonlinearity

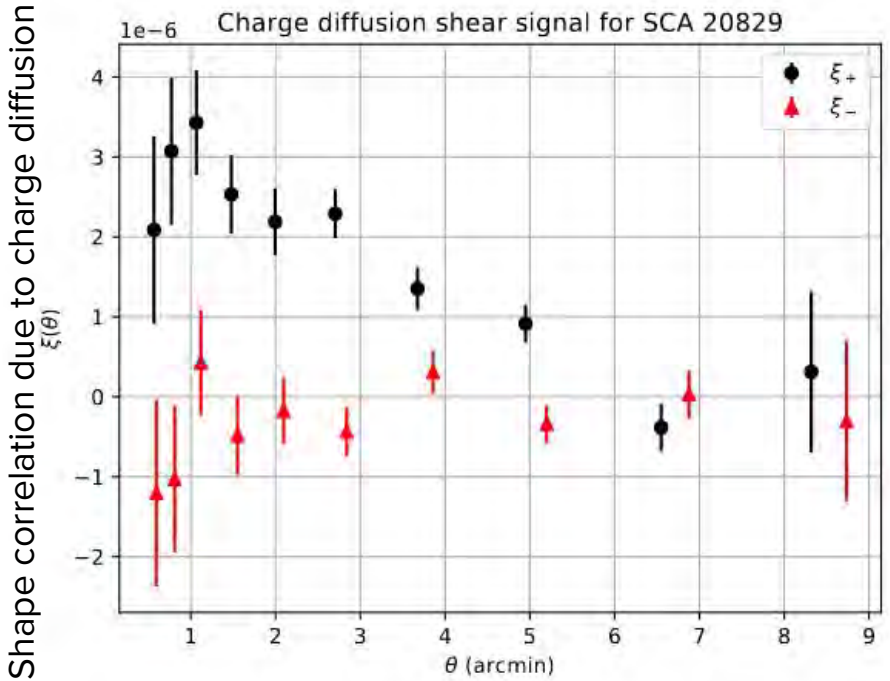
BFE+IPC kernel

Givans et al. 2021

Example detector “shear” map and signal



Givans et al. 2021



Takeaway: Charge diffusion contaminates shear signal an order of magnitude higher than Roman specifications allow, must be corrected for

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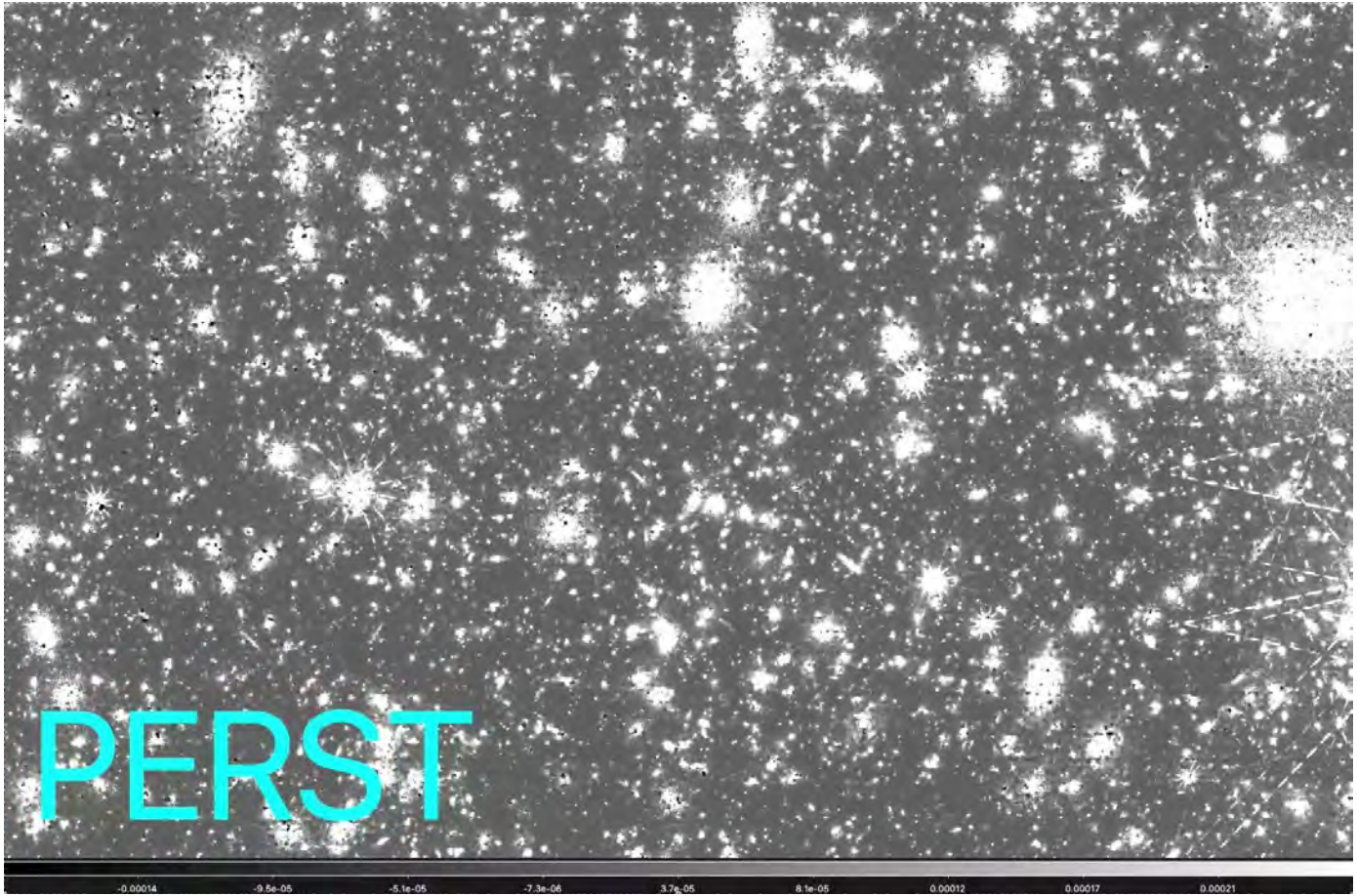
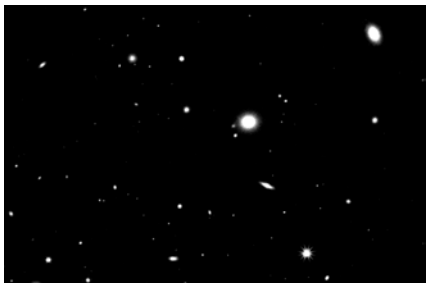
Detector Effects

➔ detector physics simulated in order:

- Relative Quantum Efficiency
- Brighter-Fatter
- Persistence
- Dark Current
- Saturation
- Classical Non-Linearity
- Interpixel Capacitance
- Dead Pixel
- Vertical Trailing Pixel Effect
- Read Noise
- Gain
- Bias


PERST
-0.00014
-9.5e-05
-5.1e-05
-7.3e-06
3.7e-05
8.1e-05
0.00012
0.00017
0.00021



Stars + Galaxies

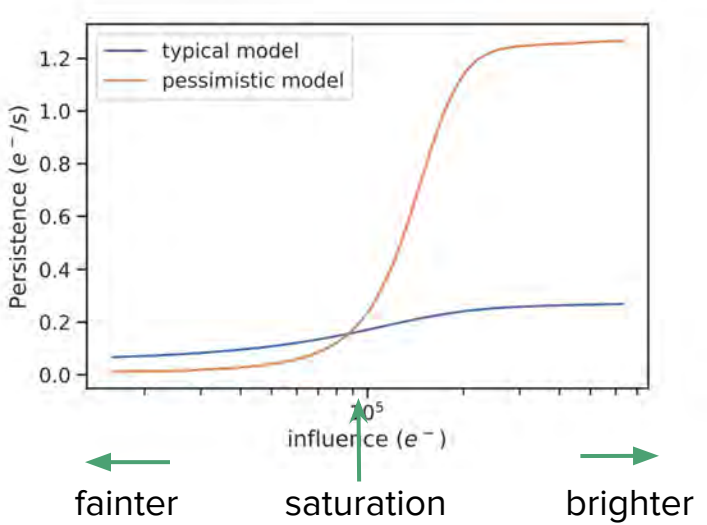
Stacking sky background
and detector physics

Output

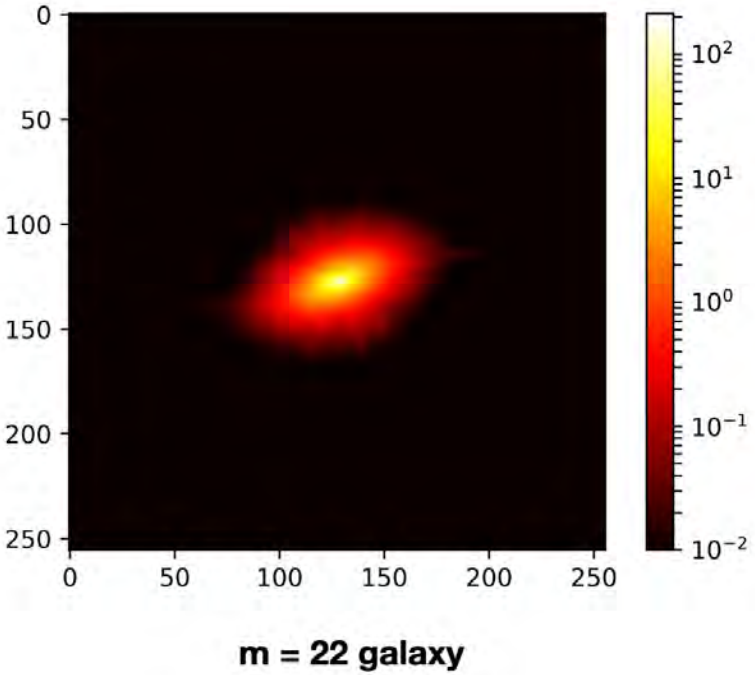
Persistence

1. Propagate detector effects to systematics for science
2. We measured the impact of **image persistence** on Roman Weak Lensing by using image simulations.
3. Persistence model

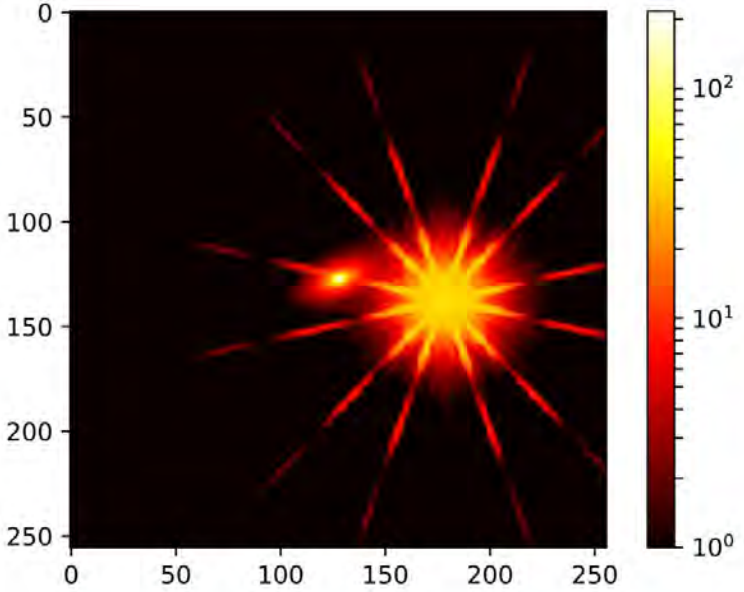
$$P(x,t) = A\left(\frac{1}{e^{\frac{-(x-x_0)}{\delta x}}+1}\right)\left(\frac{x}{x_0}\right)^{\alpha}\left(\frac{t}{1000}\right)^{-\gamma}$$



Persistence



m = 22 galaxy



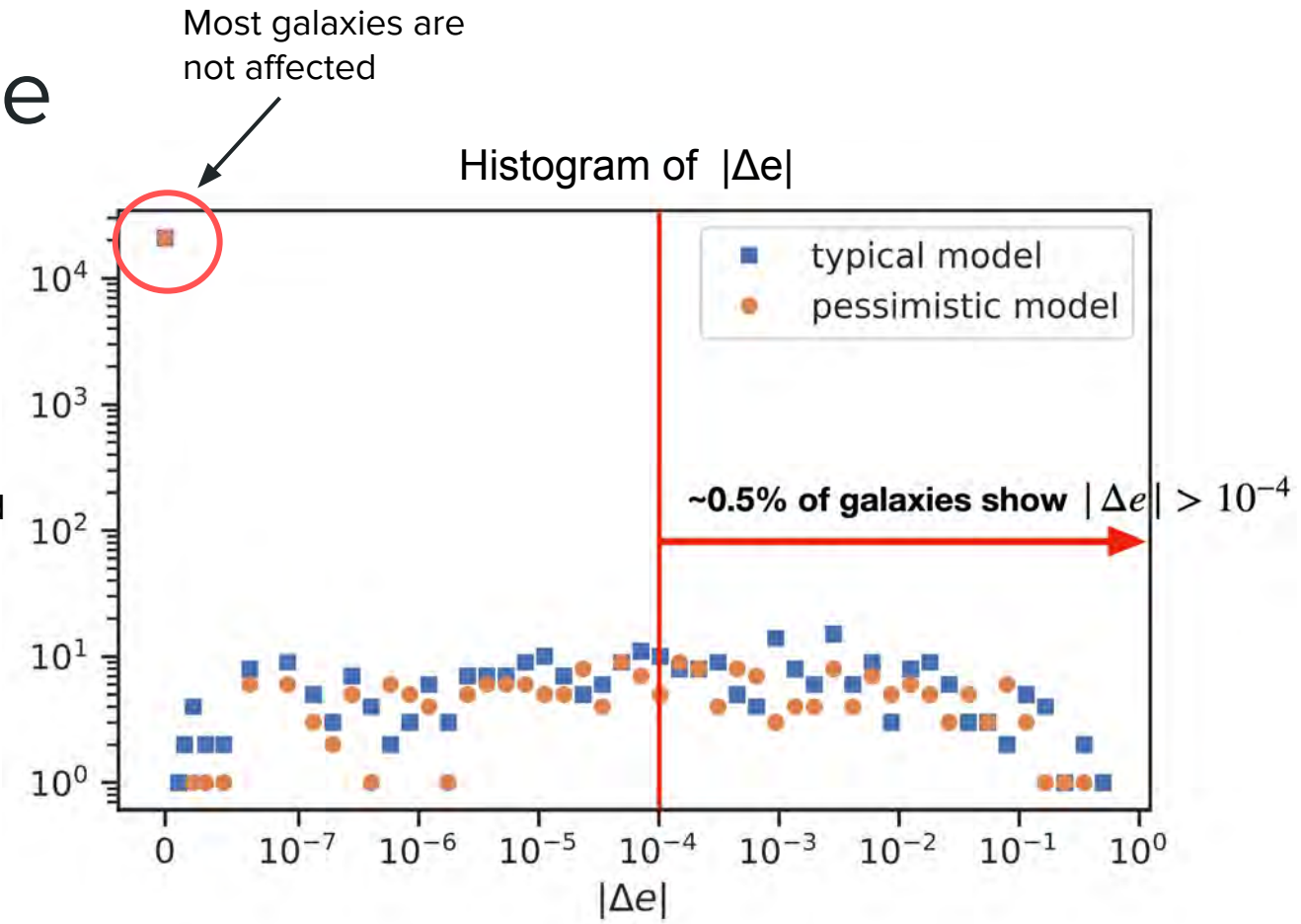
m = 22 galaxy
+ persistence of m = 7 star

Persistence

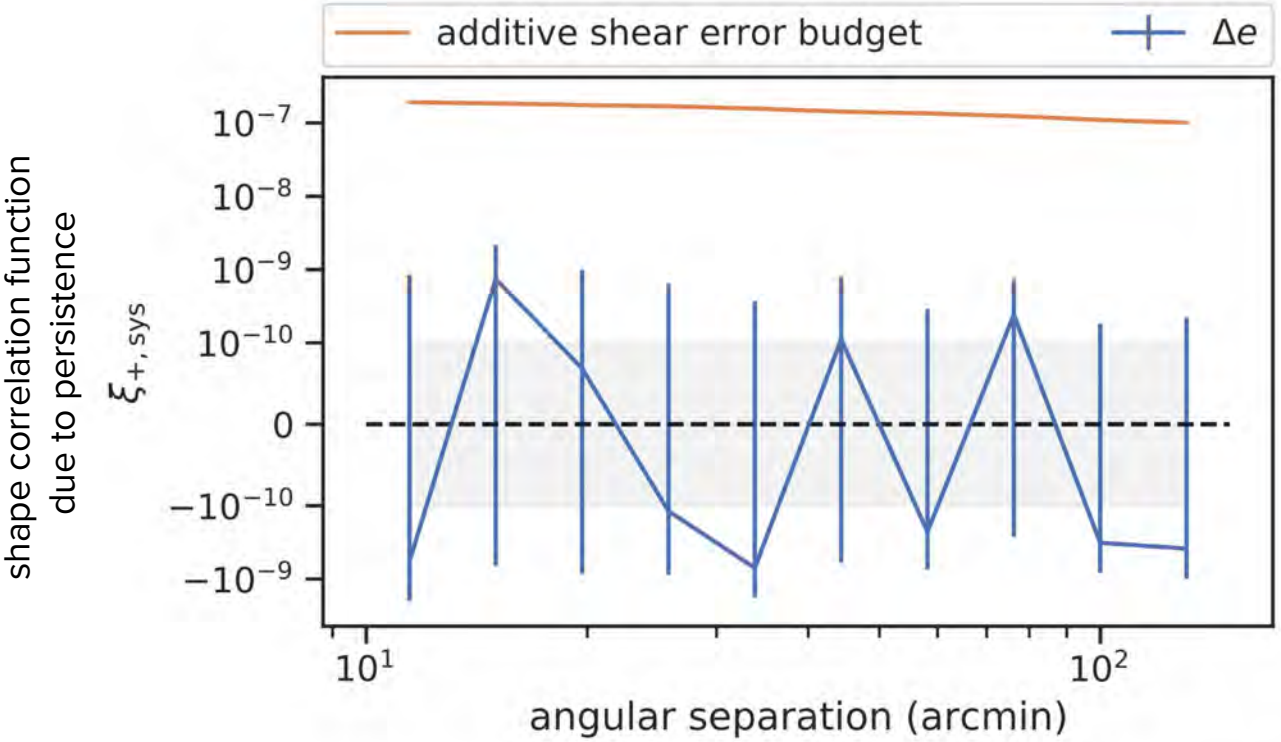
We make shape measurement of simulated galaxies.

The impact on galaxy shapes due to persistence is captured in the difference of ellipticities of the two sets of simulations.

$$\Delta e = e_{\text{persistence}} - e_{\text{intrinsic}}$$



Persistence



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Shape Measurement

- Why do we care?
  a. Accurate shape measurement is the ultimate goal to do weak lensing science!
  b. BUT, very hard to measure with high signal-to-noise ratio due to point-spread function, noise, detectors etc...
- How well do we measure shapes?
  a. shear calibration bias (*m, c*)
     - $e_i^{obs} = (1 + m_i)\, e_i^{true} + c_i$
     - 1% bias in *m* leads to 1.5% bias in “amplitude of matter fluctuations” measured with weak lensing in final cosmology

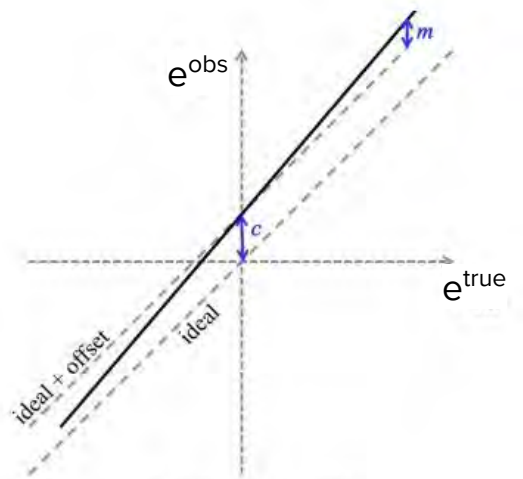
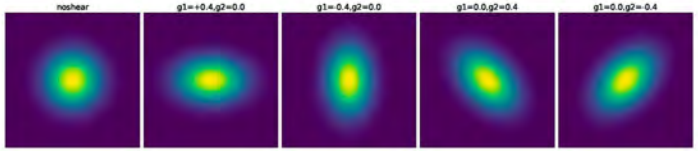


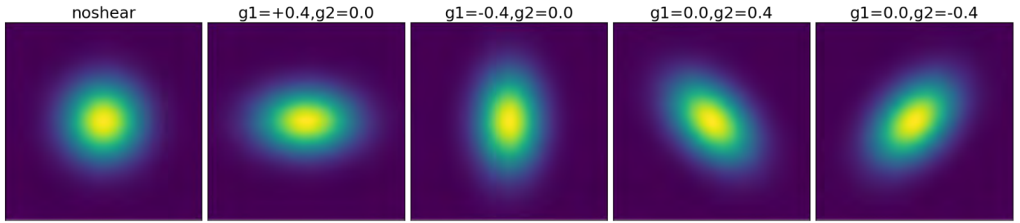
Figure: Chris Hirata

Shape Measurement

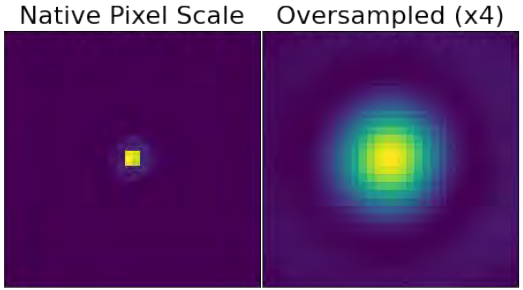
1. Shape calibration with *Metacalibration*
    a. Steps
        1. Deconvolve with the input PSF
        2. Artificially shear galaxies in four directions
        3. Reconvolve these with a larger, isotropic PSF
        4. Compute the shear response, R
    b. Benefits?
        - Can calibrate shapes directly on the images
        - Wrapped in the shape measurement algorithm (ngmix)
    c. Disadvantages?
        - Does not work well under the presence of blending
        - May not work well with undersampled images



Shape Measurement: Implementation of *Metacalibration*



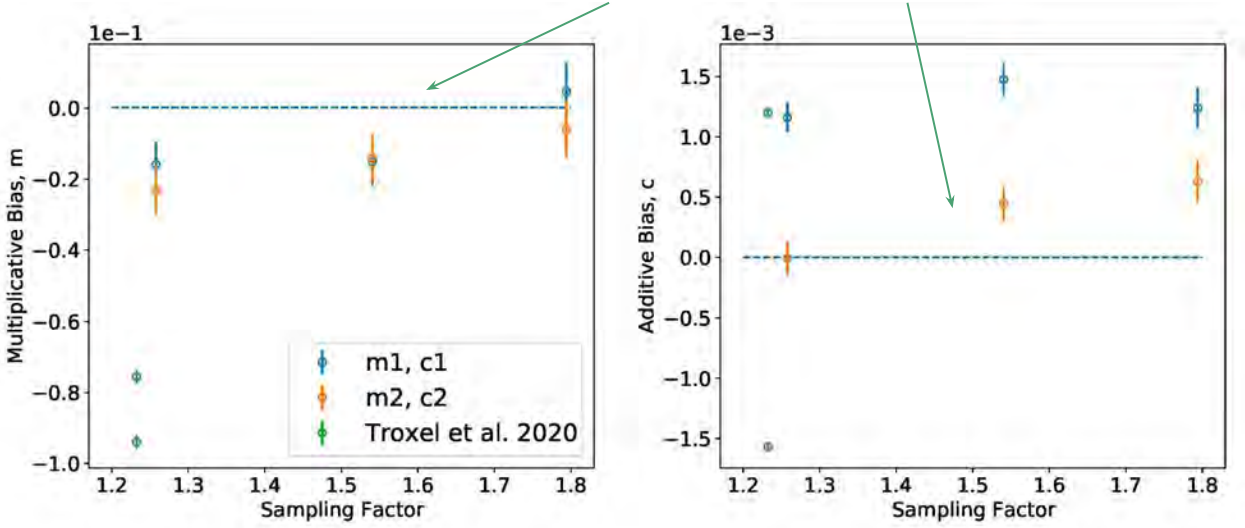
- Simulated Data
  - 2.5x2.5 sq deg of the sky
  - J129, H158, F184 filters
  - Artificial shear g=0.02
- Post-catalog processes
  - Postage stamp coadds (psc; https://github.com/esheldon/psc)
    - Oversample the coadd pixel scale by a factor of 1.25
    - Oversample the PSF by a factor of 4
  - Shape Measurement (ngmix; https://github.com/esheldon/ngmix)
    - *Metacalibration*
    - Can calibrate shapes directly on the images



Preliminary shape measurement results

- Individual coadds

Mission requirement



- Multiband coadd
  a. m=(-2.16+-0.60)%, c=9.24x10^{-4} (c1>>c2)

Summary of shape measurement

Image simulations

Coadds	MEDS
Wavefront modeling	Detectors
Photometry	PSF modeling
Input Catalogs	Survey Strategy

Realistic Images/Coadds

Shape Measurement with **known shear**

We look for...
- Shear bias, if any.
- Sources of shear bias

and we look to...
- Mitigate the effects
- Improve overall performance of shape measurement
- Rethink strategy

Mission requirements

Weak Lensing Science

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Simulating the same sky with Roman-Rubin

Goals

- Produce ~20 sq deg of matched, overlapping Roman High-Latitude Imaging Survey data with existing LSST DESC DC2 images.
- Preserve physical properties of objects Simulated in DESC DC2 in both data sets, so they can be analyzed jointly.
- Incorporate realistic Roman detector physics based on flight detector measurements.
- Produce value-added data products like coadd images, detection catalogs, etc.
- Serve as a benchmark for future cross-survey simulation capabilities being developed with funding from NASA.
  (cf. “Maximizing Science Exploitation of Simulated Cosmological Survey Data Across Surveys”)

Single exposure comparison: Rubin (30s) vs Roman (140s)

Simulating the same sky with Roman-Rubin

Contributions for Roman simulation side from:

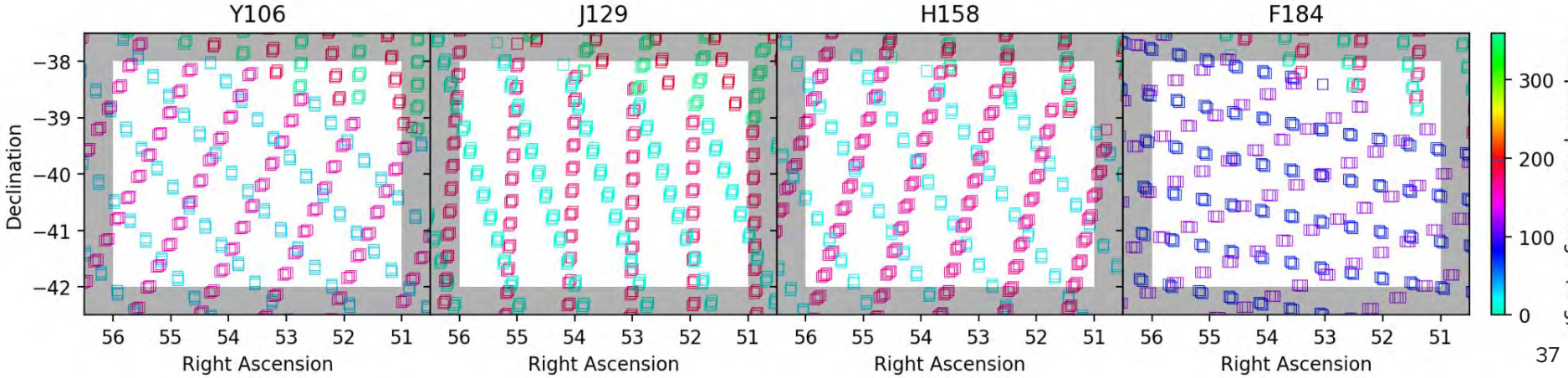
Ami Choi	Caltech	Simulation infrastructure and detector measurements
Michael Higgins	Duke	Detection
Chris Hirata	OSU	Survey strategy and detector measurements
Mike Jarvis	UPenn	Roman GalSim development and debugging
Chien-Hao Lin	Duke	Detector physics and coadding
Rachel Mandelbaum	CMU	Roman GalSim development
Andy Park	CMU	Blending study
Bruno Sanchez	Duke	Validation vs. Rubin LSST images
Kevin Wang	Duke	Detection; including transients (SNe)
Masaya Yamamoto	Duke	Shape measurement/calibration

Effort funded primarily by NASA: Roman HLS Cosmology Science Investigation Team (https://www.roman-hls-cosmology.space).

Simulating the same sky with Roman-Rubin

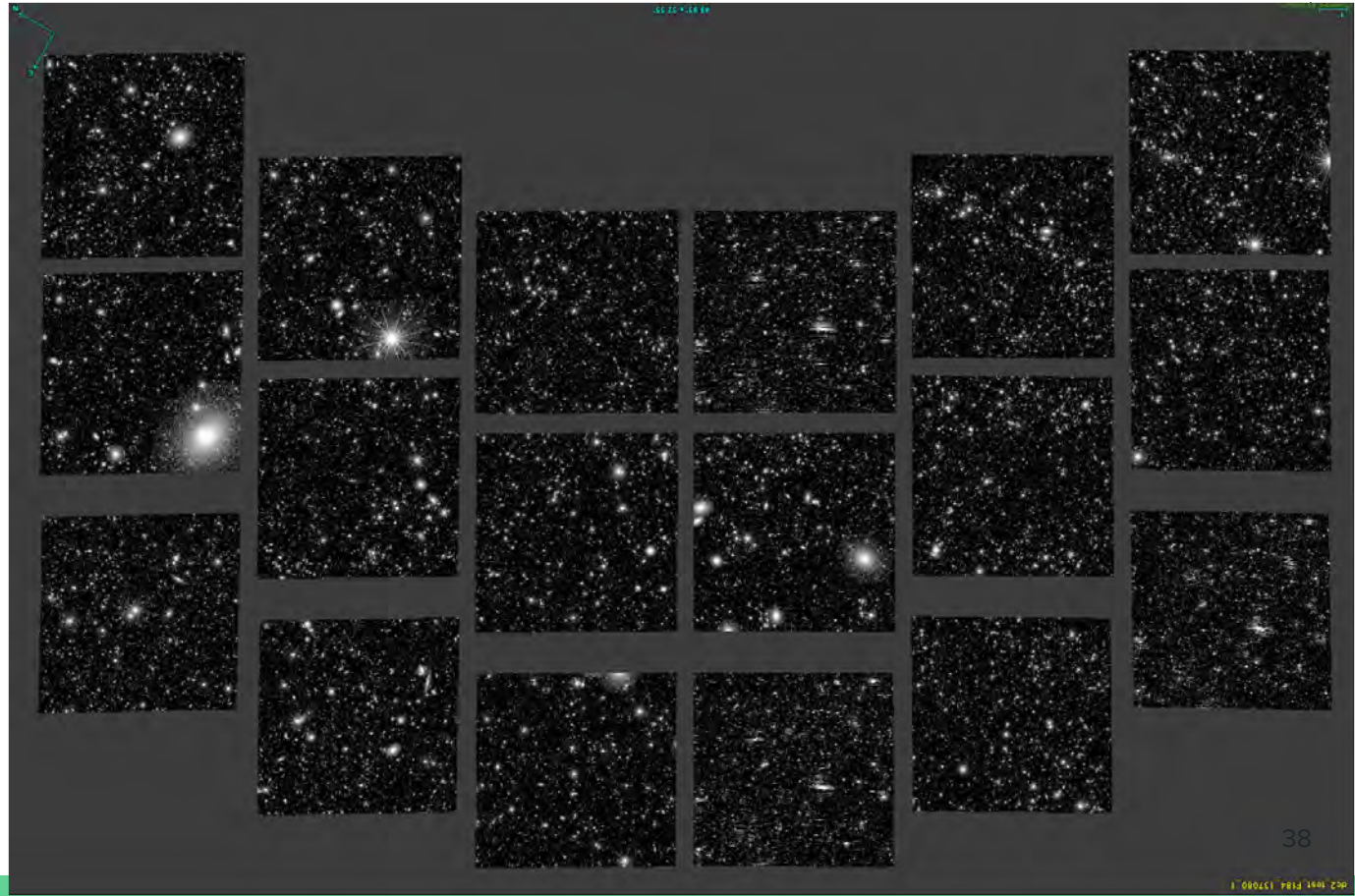
Properties of simulated Roman HLS Imaging Survey

- 2000 sq deg of imaging in Y106/J129/H158/F184 bandpasses; on average 6 exposures per filter.
- Reference survey HLIS sequence over subset of 5 years beginning in mid 2020s.
- Survey strategy (overlapping pointings) shown below.
    - Non-shaded region shows coverage of simulated images (20 sq. deg).



Simulating the same sky with Roman-Rubin

Full Roman field-of-view example



Simulating the same sky with Roman-Rubin

Full 5yr-depth Roman High-Latitude Imaging Survey color YJH coadd cutout

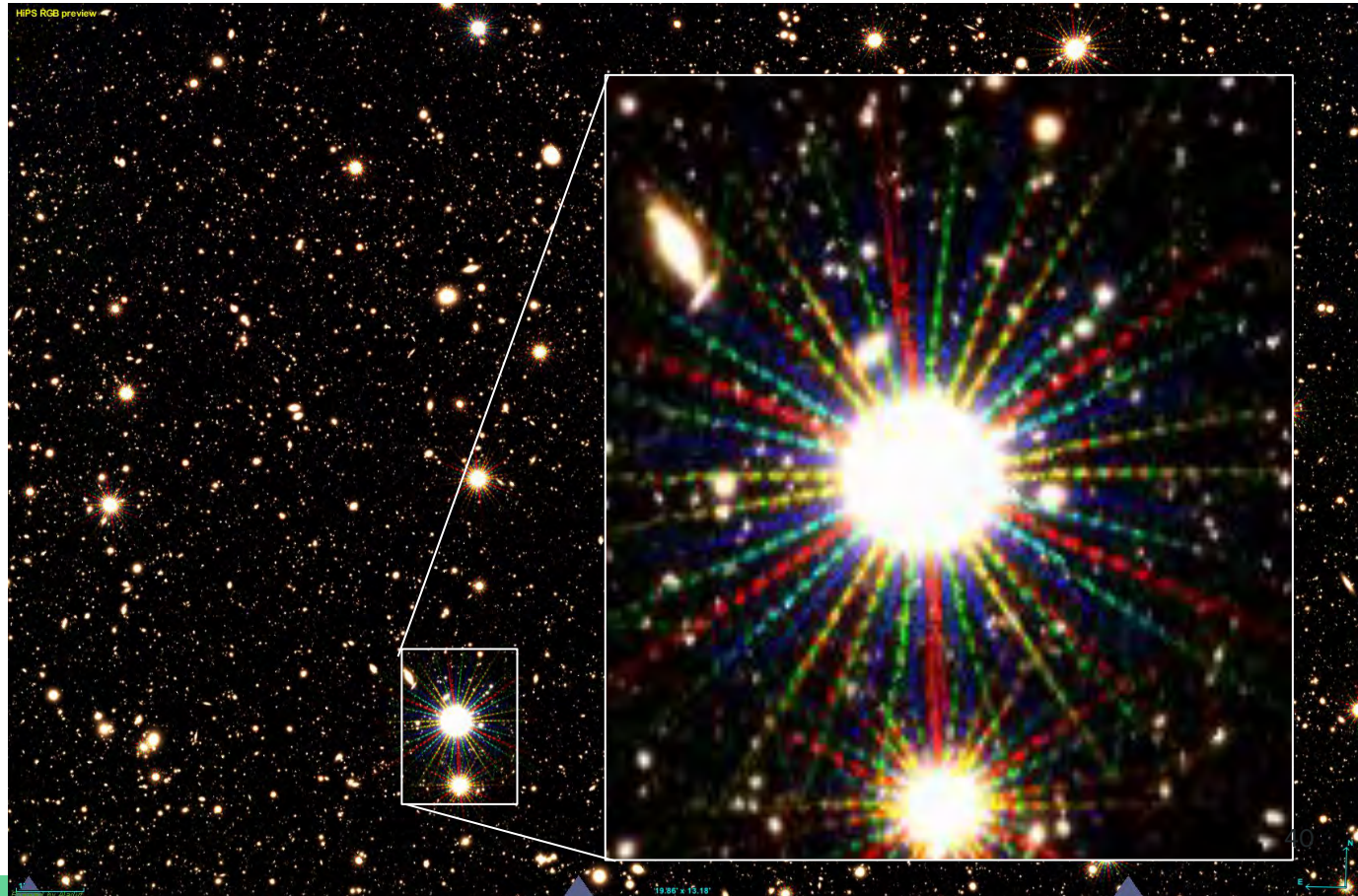
20x13 arcmin

Simulating the same sky with Roman-Rubin

Full 5yr-depth Roman High-Latitude Imaging Survey color YJH coadd cutout

20x13 arcmin

Star example ----->



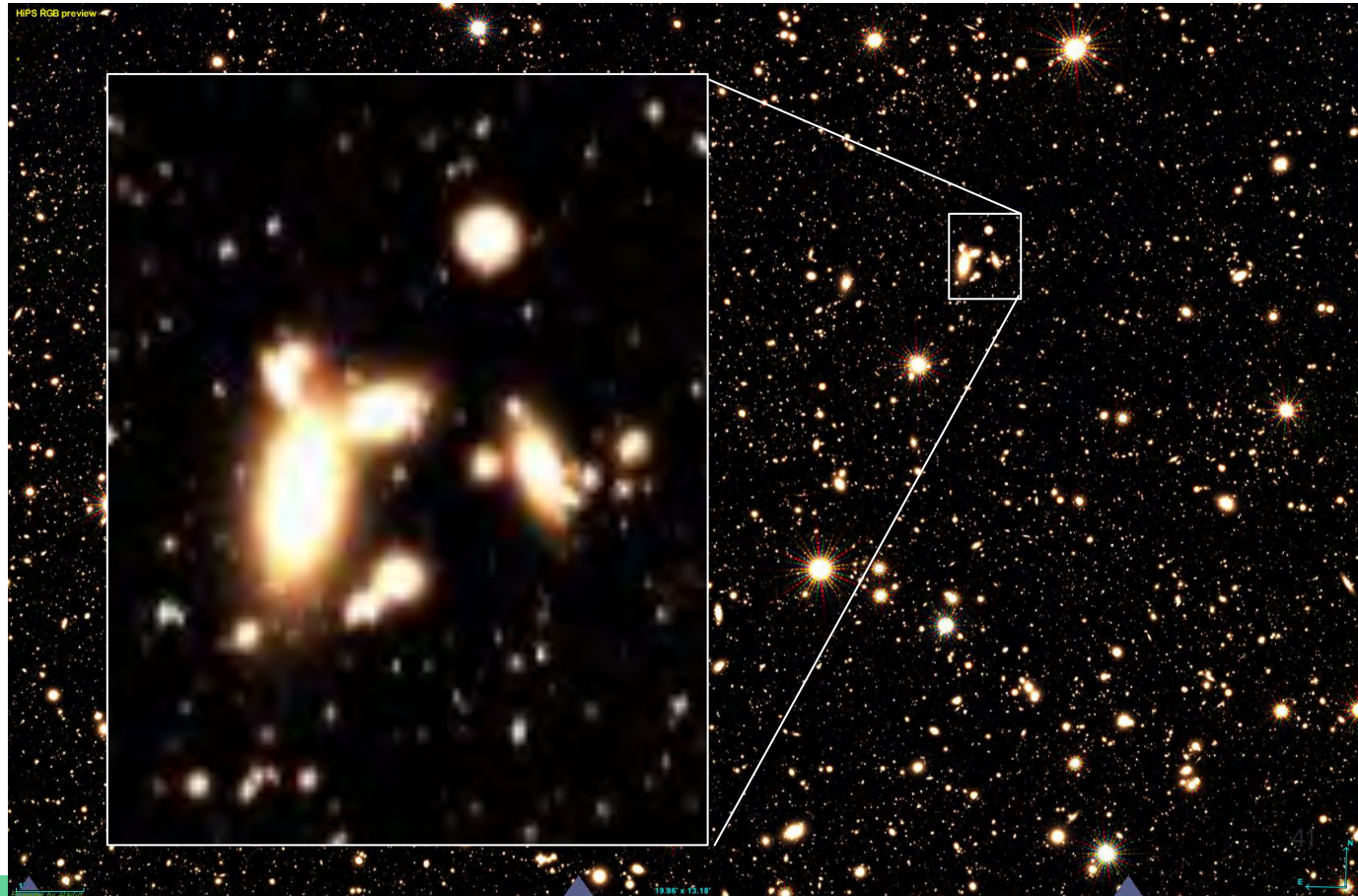
Simulating the same sky with Roman-Rubin

Full 5yr-depth Roman High-Latitude Imaging Survey color YJH coadd cutout

20x13 arcmin

Galaxy group example ---->

This group would be highly blended in Rubin images.



Simulating the same sky with Roman-Rubin

Data products

- Single exposure images with noise/weight and quality arrays
    - Images with and without detector physics and noise are saved.
- MEDS-like files that contain isolated object cutouts for galaxies and PSF model-eligible stars
    - Comparison for blending recovery; both with/without detector physics and noise.
- Fully sampled (in JHF) coadd images using astrodrizzle: pixel scale 0.0575”; ~1 SCA in size
    - Includes correlated noise maps and coadd PSF lookup files.
- Truth files per exposure/coadd instance with total modelled magnitude and position information.
- Basic detection catalogs; photometry information; and (eventually) shear estimates.

Current status:
Full area has been simulated - waiting on lab measurements to add final detector physics and noise to images and run the remaining coadd and measurement pipeline. Expected complete before end of 2021.

Summary and Resources

These image simulations will be useful for Roman and Roman+Rubin science (weak lensing and many other applications including yours?)

- Simulation suite + impact of wavefront errors (Troxel, Long+arxiv/1912.09481)
- Detector papers (Hirata+ 1906.01846, Choi+ 1906.01847, Freudenburg+ 2003.05978, Givans+ 2110.08155)
- Persistence paper (Lin+ 2106.10273)
- Shape measurement paper (Yamamoto+ in prep)
- Roman+Rubin paper (in prep), based on DESC Data Challenge 2 (2010.05926)
- https://github.com/GalSim-developers/GalSim (Rowe, Jarvis, Mandelbaum+ 1407.7676)
- https://github.com/matroxel/roman_imsim

Stay tuned for release of simulation products in the next couple months!