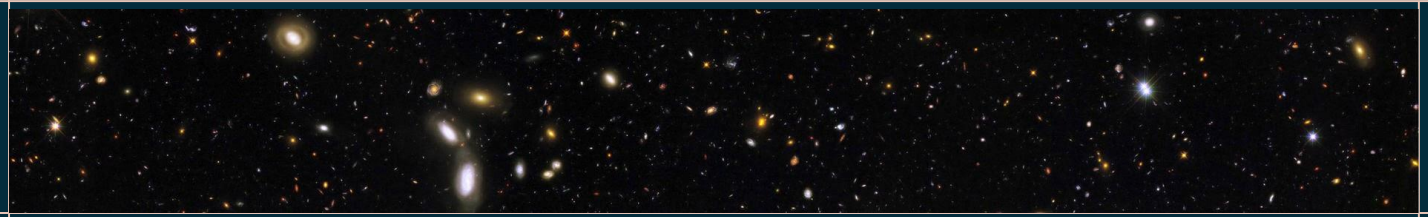
Characterizing and Mitigating Noise on Roman Space Telescope Detectors for Precise Weak Gravitational Lensing

Katherine Laliotis | Ohio State University



Outline

- Weak lensing
- is a great probe for cosmology
- even though it's hard to do.
- Correlated noise (like Roman's) biases the analysis,
- but with careful control,
- we can use weak lensing to achieve amazing things!

Weak Lensing

What is it, and why should I care?

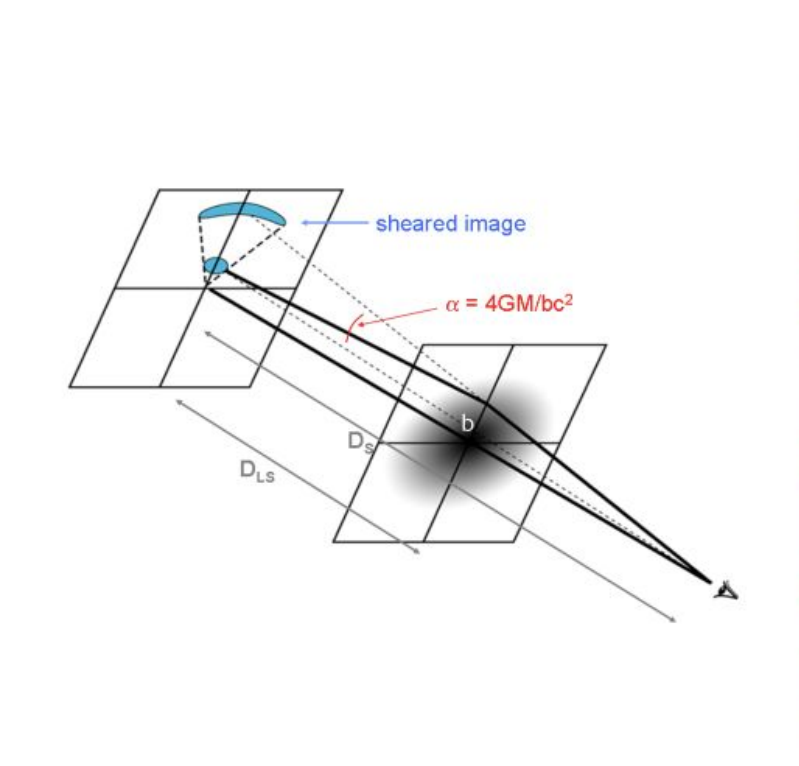


Fig: Rachel Mandelbaum, https://arxiv.org/pdf/1710.03235

Background : lensing

- Gravitational lensing: light from a background "source" has its path bent by a foreground "lens", and the image of the source is deflected
- The lens-source system has some general lensing potential, $\Psi(\theta_l)$

  The apparent deflection α of a source is the gradient of the lensing potential,
  $\alpha(\theta_l) = \nabla_\theta \Psi(\theta_l)$
- In addition to being deflected, the source's image can also be **sheared** and **magnified**
- The shear γ and magnification μ are related to the divergence of the lensing potential,
  $2\kappa = \nabla_\theta^2 \Psi(\theta_l)$

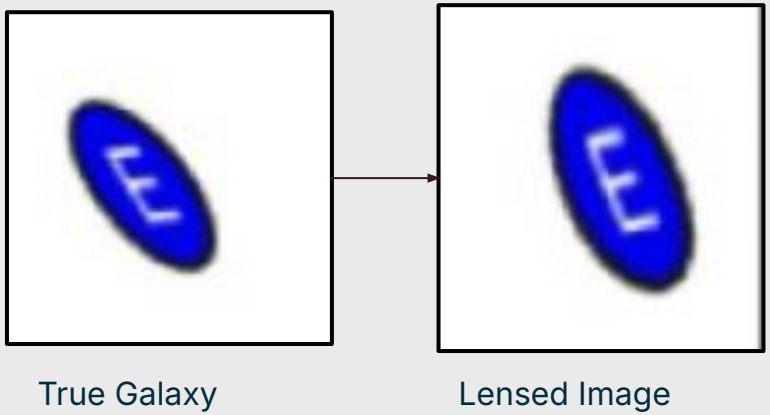
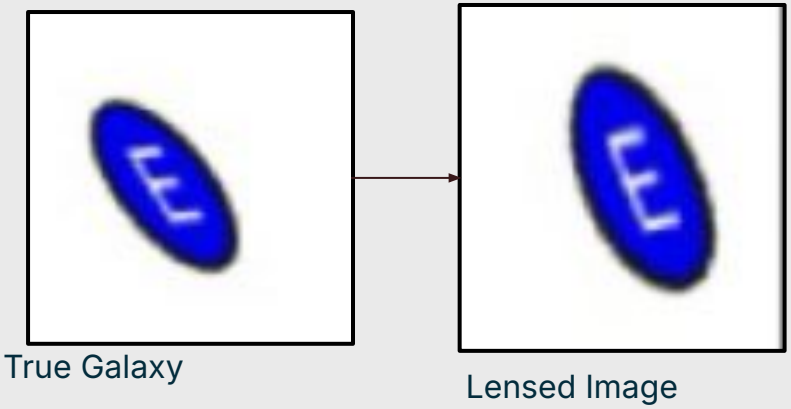
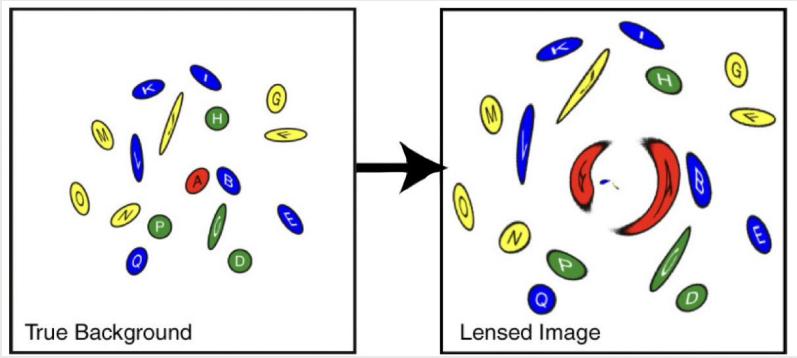


Fig: Gary Bernstein, https://newviews.uchicago.edu/talks/december_10/plenary/bernstein/gary_bernstein.pdf

Background: *weak* lensing

- It's not always so easy to identify lensed objects; shear and magnification are often only ~1% effects
- **Weak** gravitational lensing is where the distortion is subtle; no Einstein ring, no multiple images, just a **shear** and a **magnification**
- So how can you tell if an individual galaxy has been lensed weakly?





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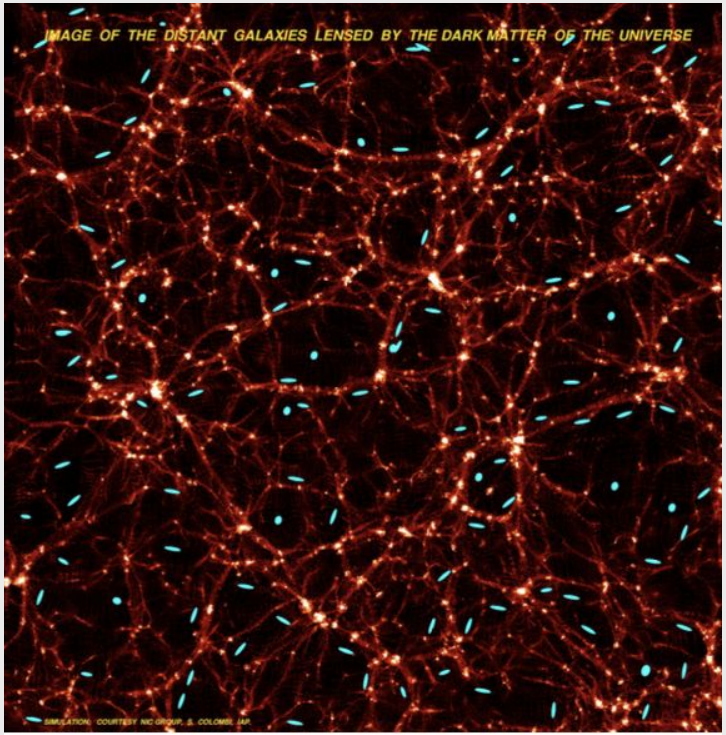
- **Weak** gravitational lensing is where the distortion is subtle; no Einstein ring, no multiple images, just a **shear** and a **magnification**
- We can look for **coherent patterns** in the distortions of galaxies' shapes and sizes
- By averaging the shear/magnification of a field of weakly lensed galaxies surrounding a lens, the mass of the lens can be recovered. This requires a **lot** of galaxies



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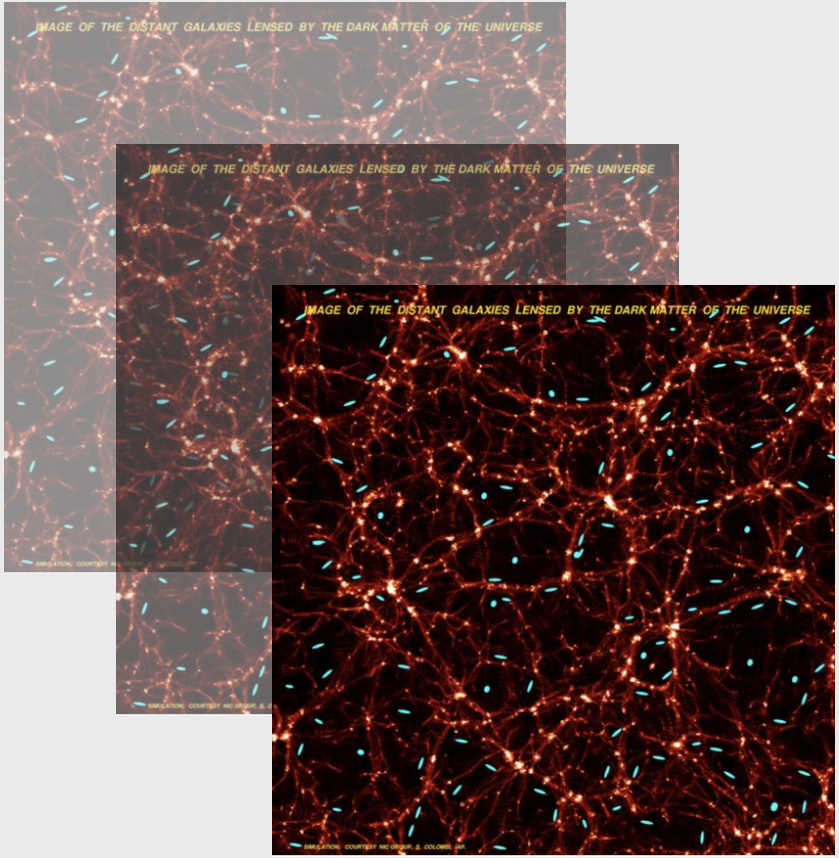
Background: cosmology with weak lensing

- Weak lensing allows us to map out the location of dark matter throughout the universe
- And if we can reliably sort our lensing galaxies into bins of redshift...



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Background: cosmology with weak lensing

- Weak lensing allows us to map out the location of dark matter throughout the universe
- If we can reliably sort our lensing galaxies into bins of redshift, we can use sequential mass maps to learn about dark energy
- WL is independent of galaxy bias and assumptions about dark energy

WL: Systematic Errors

Okay, so why is this so hard?

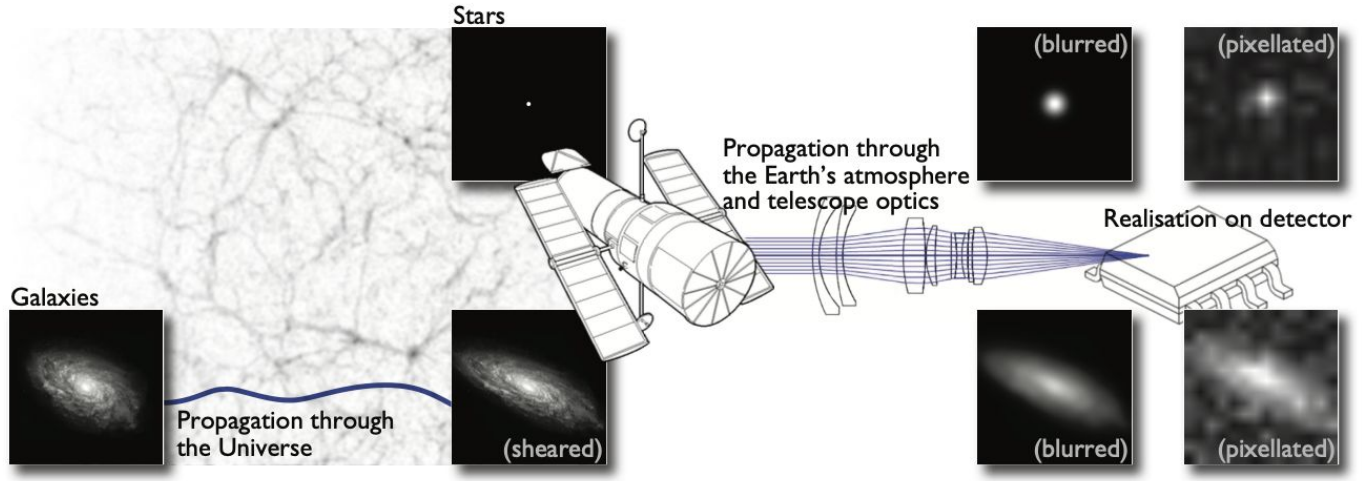

Figure 3: An illustration of the processes that affect the galaxy image (from Mandelbaum et al. 2014), including lensing followed by other effects that also cause coherent shape distortions, such as convolution with the point-spread function (or PSF) due to the atmosphere (for ground-based telescopes) and telescope optics.

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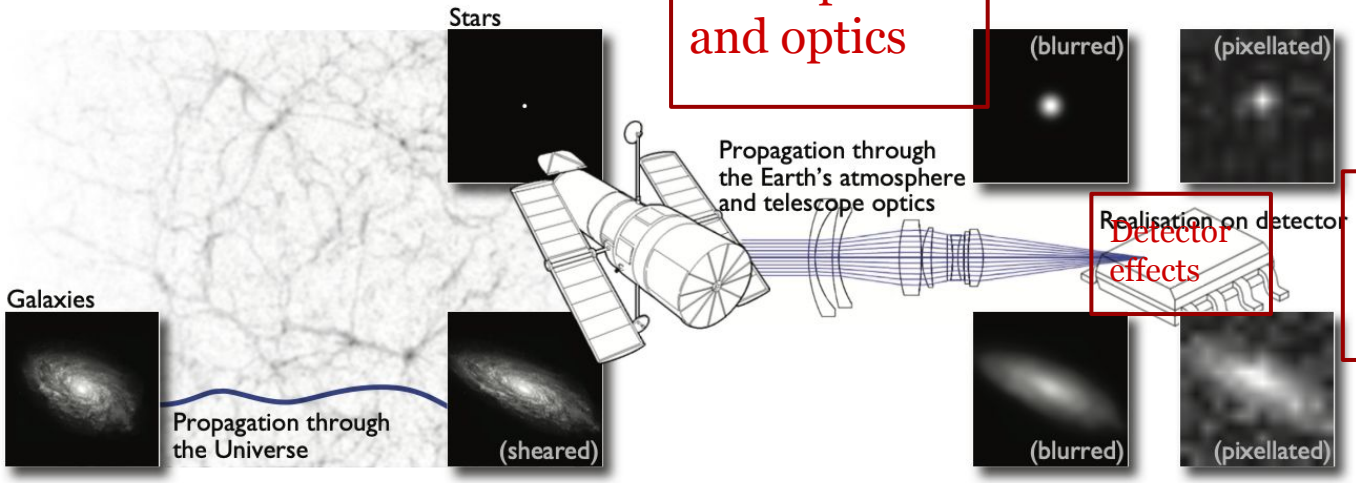
Effects of atmosphere and optics

Did we measure this thing accurately enough that we trust our measurement of the other things??



How to measure a shape of this thing?

True shape = ???

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Are we sure this is just one thing ant not multiple?

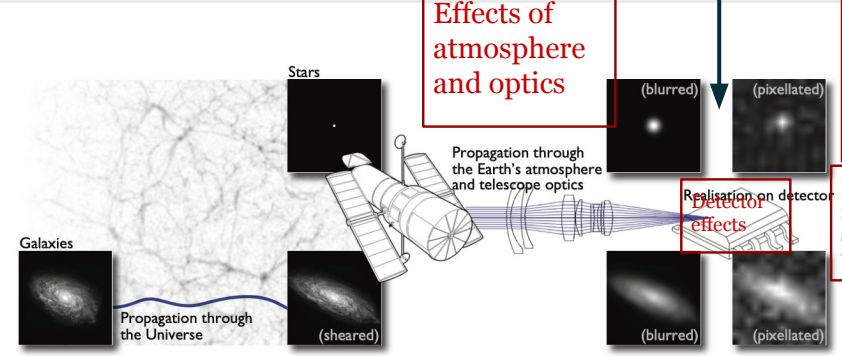
How to get the redshift of this thing??

Am I only seeing bright things? Does that bias my measurement?

Fig: Rachel Mandelbaum, https://arxiv.org/pdf/1710.03235

My research!

"Images to Catalogs"



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Detector effects

True shape = ???

Are we sure this is just one thing ant not multiple?

How to get the redshift of this thing??

Am I only seeing bright things? Does that bias my measurement?

"Catalogs to Science"

Measured shape != shear

Measuring photometric redshift is hard, calibrating the photometric redshift is hard, and your choice of redshift bins biases the measurement anyways

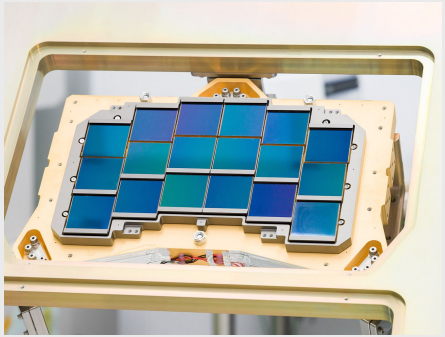
Once we have our power spectrum, we need predictions of power spectra to compare it to. Simulations are expensive, difficult, and not correct on all scales

Could the galaxies be aligned for some reason other than lensing?

Correlated Noise on Roman's H4RGs

Laliotis et al., 2024 | https://ui.adsabs.harvard.edu/abs/2024PASP..136l4506L/abstract

Specific challenges for WL with Roman



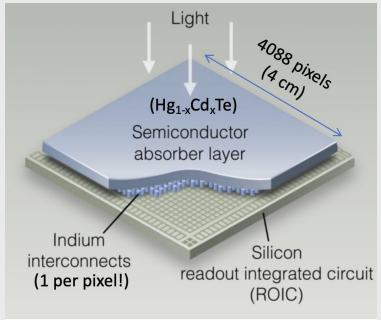
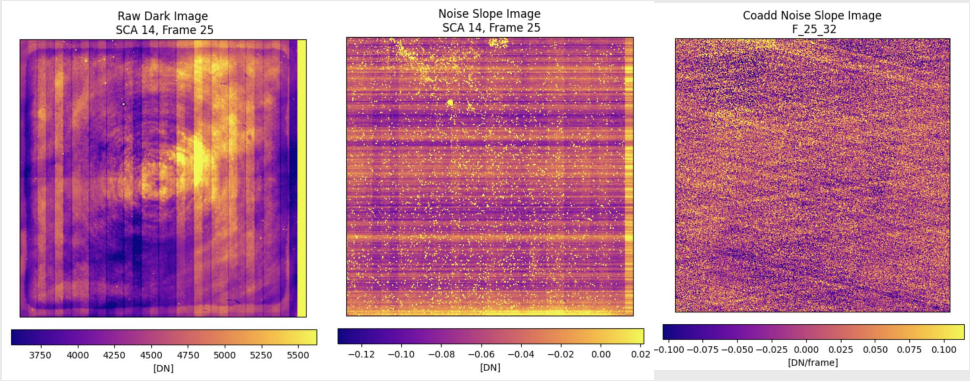
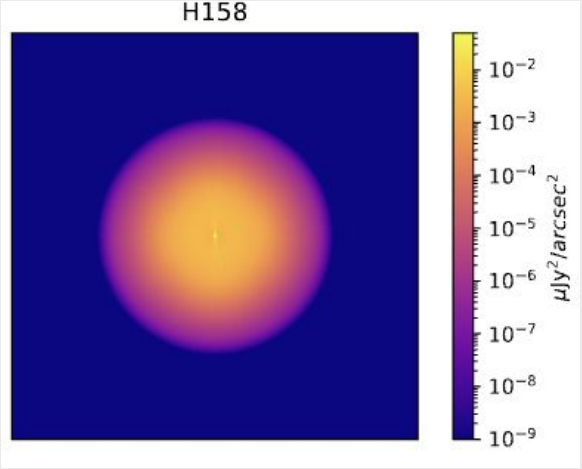


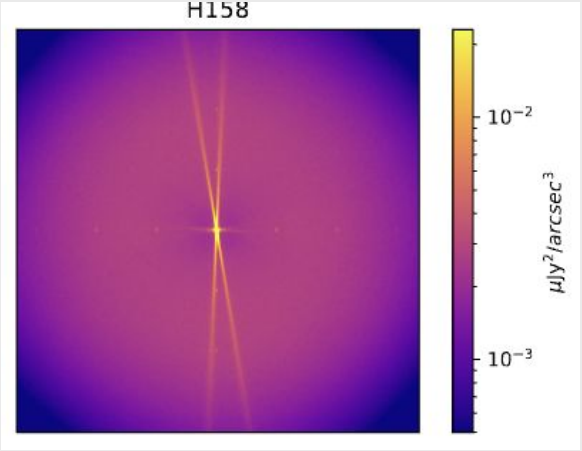
Image credits: NASA/Chris Gunn (Left) ; Bernie Rauscher (Right)



Roman: Detectors, reads, and noise

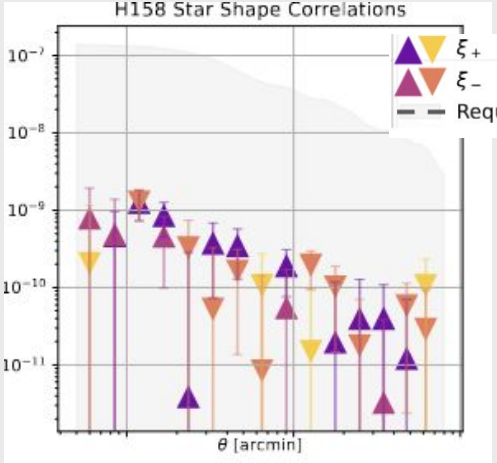
- Roman WFI: 18 H4RG Sensor Chip Assemblies (SCAs)
- H4RG are CMOS detectors
- Medium tier High Latitude Imaging survey:
  - 2400 sq. deg, 26.5 mag limit (Y), ~360 million galaxies for WL
  - 107 second exposures, consisting of ~35 non-destructive reads
  - Readout frames get combined into ~6 resultant frames, which are averaged into a slope image, the initial data product
- Bottom Row: Left: Single SCA-frame raw dark, Center: Single SCA slope image; Right: Noise slope coadd

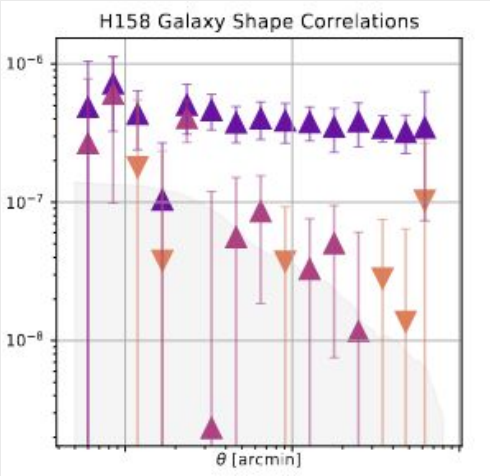




Noise Power Spectrum

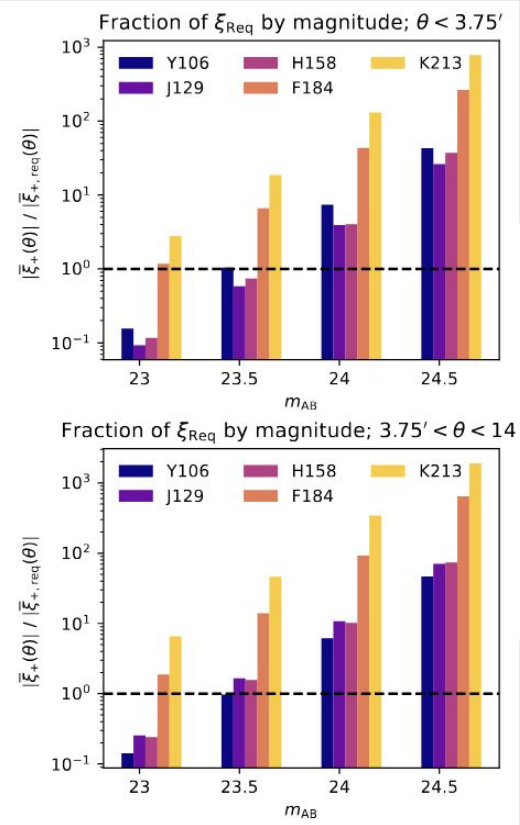
- Correlated noise will cause a direct additive bias on galaxy shapes
  - Variance of the measured shapes is proportional to second moments on the noise; the power spectrum captures this directly
- Y, J, and H bands to be used in medium tier of the HLWAS
- Left: power spectrum (full detector, and central region) from a coadded noise image
  - We observe significant signals in the power spectra that are traceable to particular features
  - Most notable is the central x feature, which shows the 1/f noise power in the two roll angles





Noise bias correlation function

- Combining noise fields with grids of injected sources (m_{AB}= 24), we can estimate the actual bias on the correlation function that would come from shape noise directly
- Roman has strict requirements on control of systematic errors; we find that correlated noise biases shape correlations significantly
- We investigated whether this was true for various limiting magnitudes, and focusing on various scales



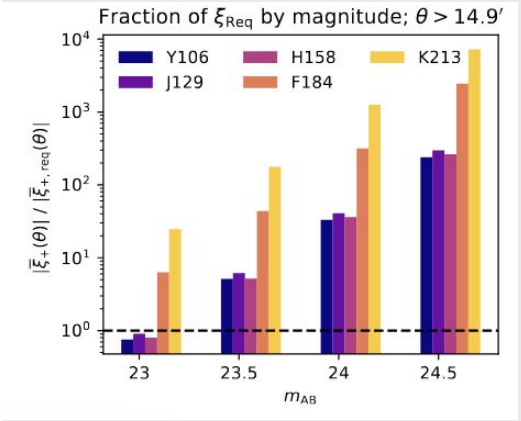


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Image destriping

Laliotis et al. (in prep.), 2025

A method for mitigating this (very scary) correlated noise bias

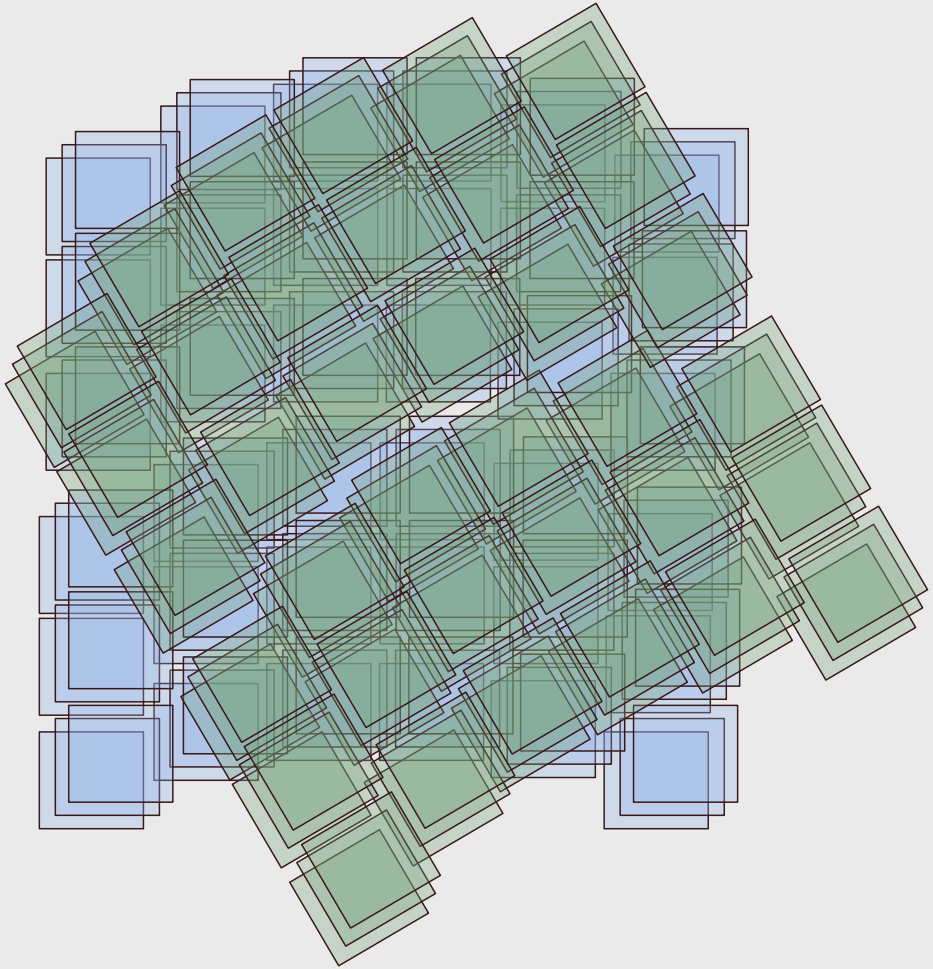


Image Destriping with linear algebra methods

- Roman's observing strategy: three dithers, two rolls
  - There will be images of the same region of the sky with stripes in different positions, pointing in different directions (w/r. to the sky background)

- **Question: Can we utilize the multiple roll angles to solve for and ultimately subtract out the stripes of correlated noise?**

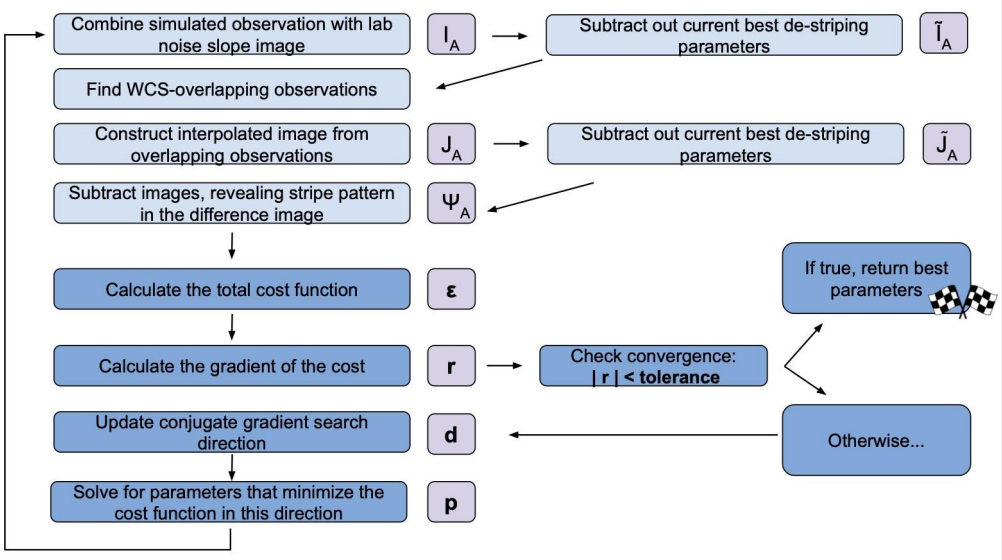
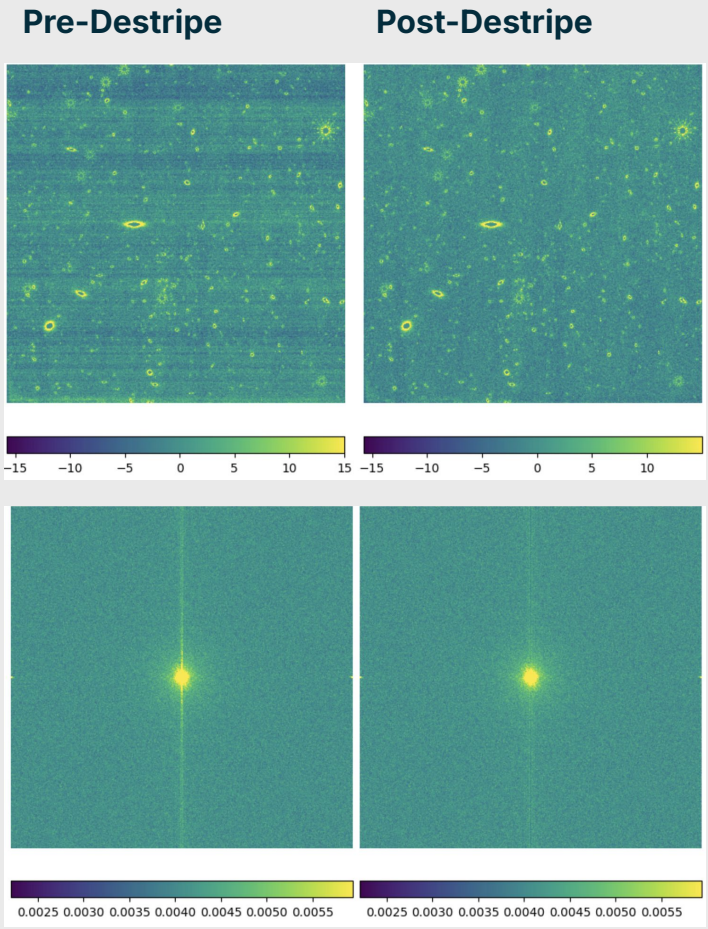


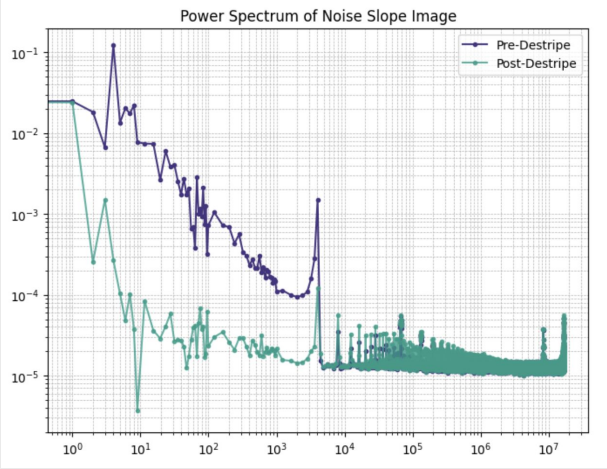
Image Destriping with linear algebra methods

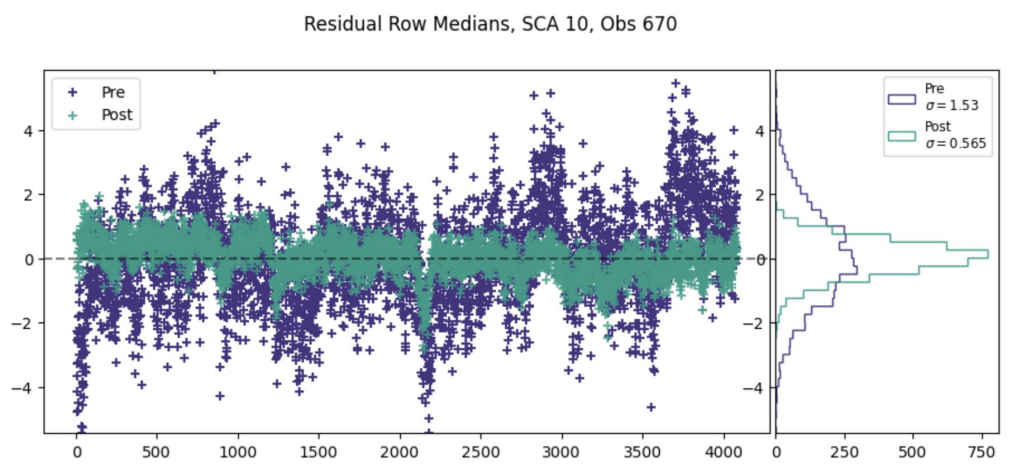
- imDestripe: an image processing tool to remove stripes of correlated 1/f noise from Roman images
- Model the stripes as constant offsets
- Interpolate images from dithered, rolled exposures
- Utilize conjugate gradient descent to solve for optimal parameters to minimize the difference between the exposure and its interpolation



Results (preliminary!)

- Simulated Roman observation plus read noise field; permanent and bright object masks applied
- Preliminary result: imDestripe run on 50 blocks (out of about 500 that would make up a coadd mosaic)
- After destriping, we can see visually in real space that the horizontal striping effect has been almost entirely removed. In Fourier space, the bright central line corresponding to the dominant 1/f noise feature is suppressed





Results (preliminary!)

- Flattened power spectrum of the noise shows the 1/f behavior clearly pre-destriping; after destriping is applied, the power spectrum is much flatter (the expected behavior for uncorrelated / white noise)

- Residuals: The median pixel value in each row minus the median of the row-medians for the full image. Destriping reduces the spread in the row medians, bringing the distribution closer to Gaussian.

Impact & Outlook

What’s next?

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- Weak lensing
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- even though it's hard to do.
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- but with careful control,
- we can use weak lensing to achieve amazing things!

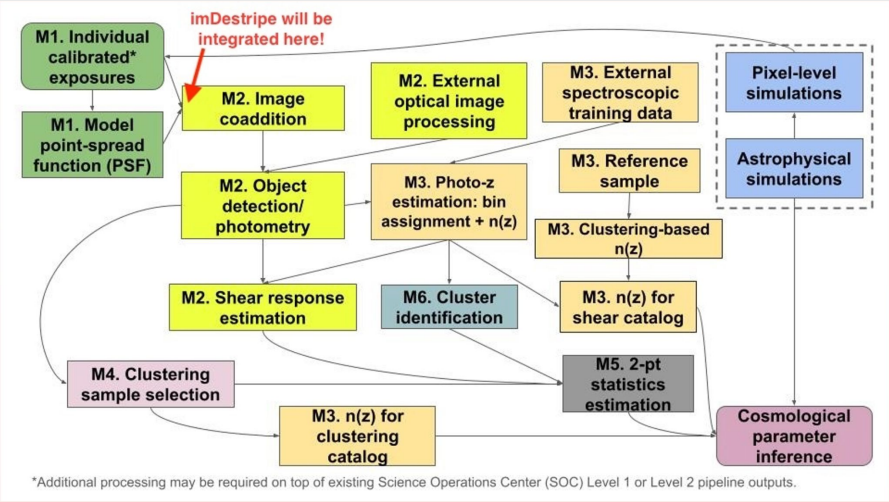

Fig: Roman shear and clustering measurement pipeline ; Credit Ami Choi

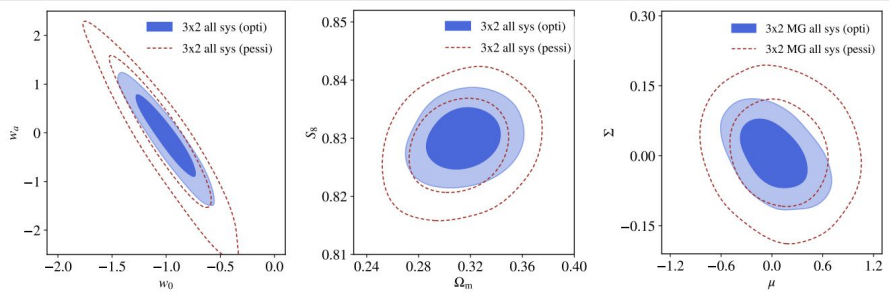

Fig: Eifler et al 2020; https://arxiv.org/pdf/2004.05271

Impact

- With imDestripe, we can reduce the 1/f noise in the Roman images before coaddition, which should mitigate some of the noise bias we observed

Outlook

- imDestripe integration into the Roman cosmology PIT pipeline
- Addition of sky background subtraction, amplifier offset stripe subtraction
- End-to-end analysis of status of noise biasing
- High precision WL → precision cosmology → happy astronomers!

Thank you!

Questions?