

The Small-Scale Structure of Dark Matter Through Roman's Lenses

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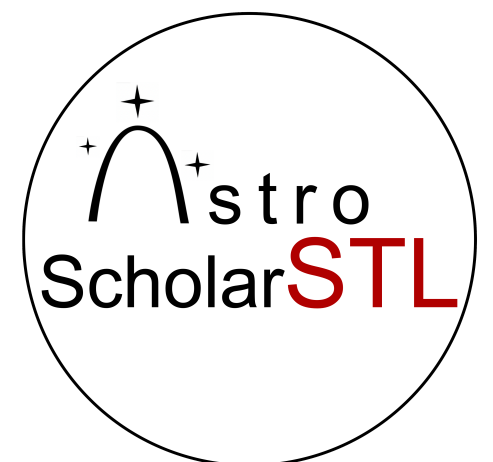
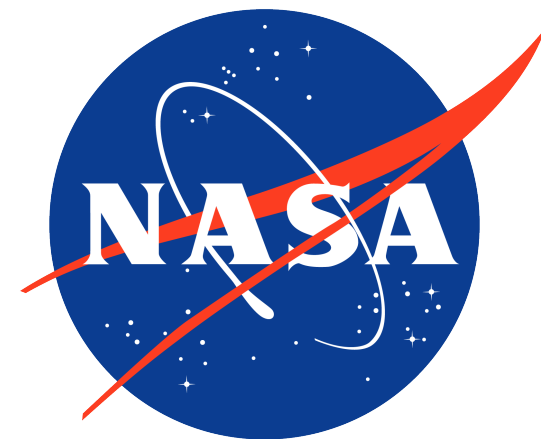
Washington University in St. Louis



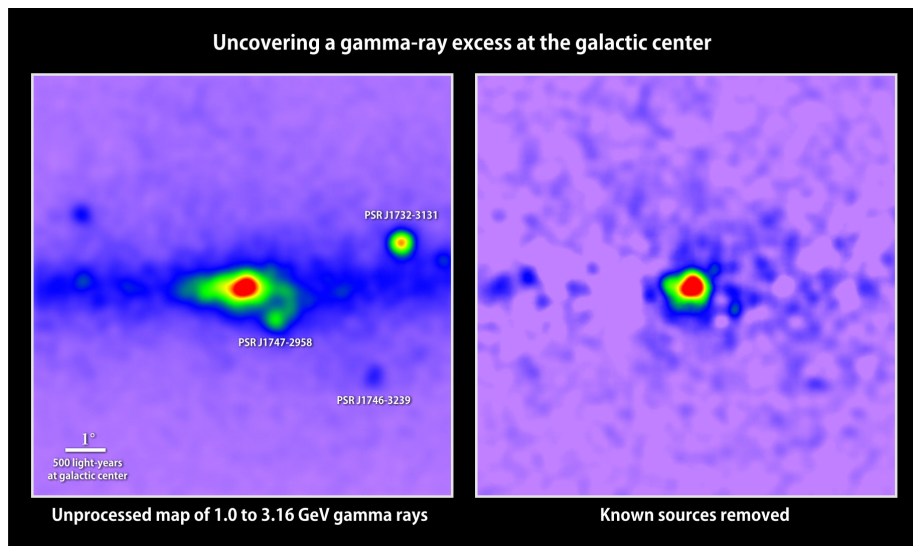
Shifting Landscapes
in Astrophysics,
Pasadena, July 16, 2026



WashU

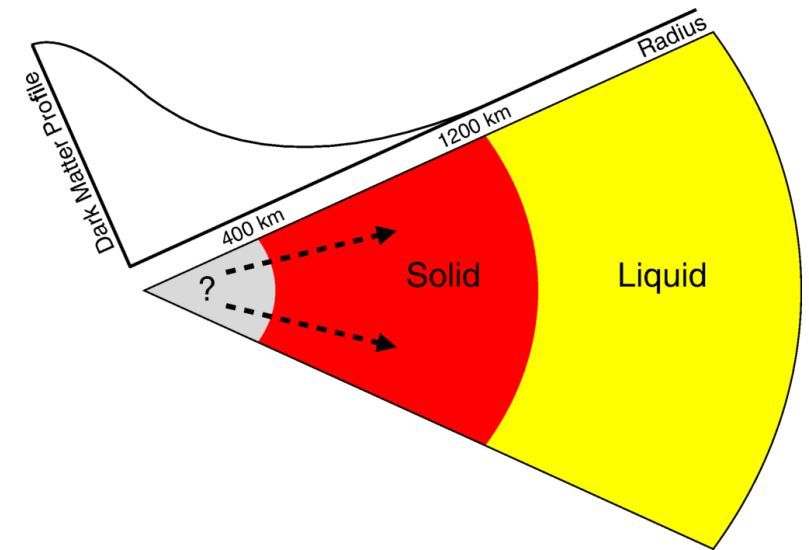


The search for dark matter



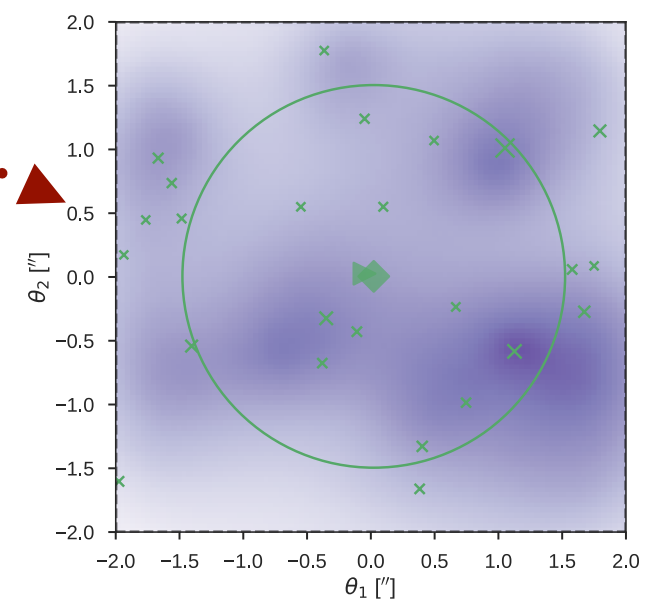
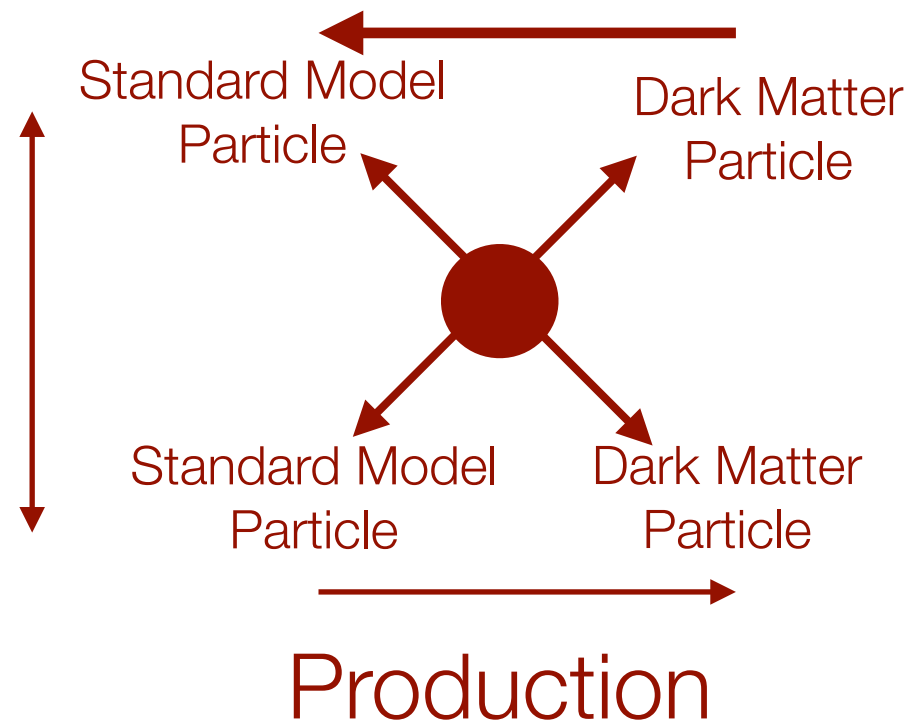
Daylan et al. 2016

Indirect detection
and gravitational probes



Cappiello & Daylan 2025

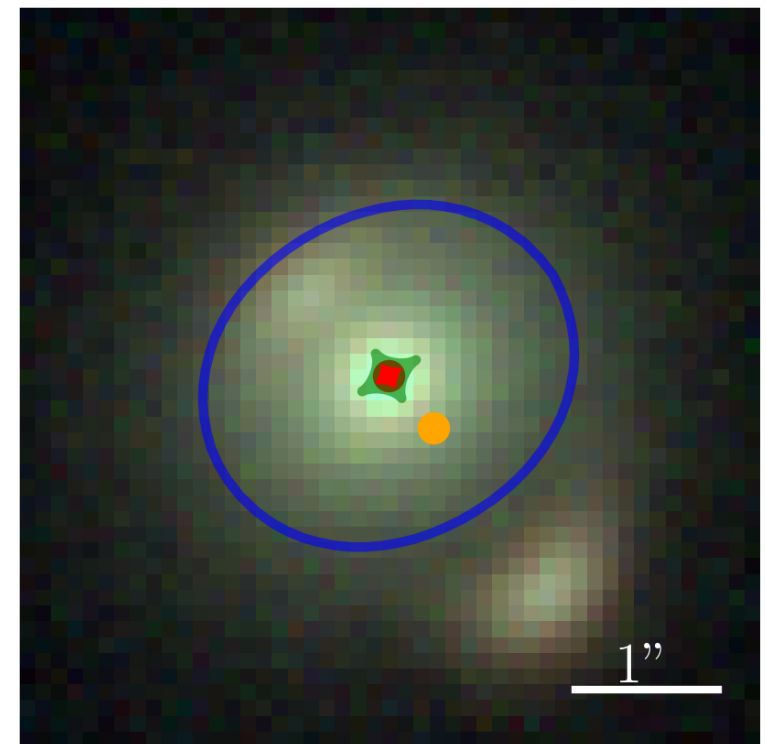
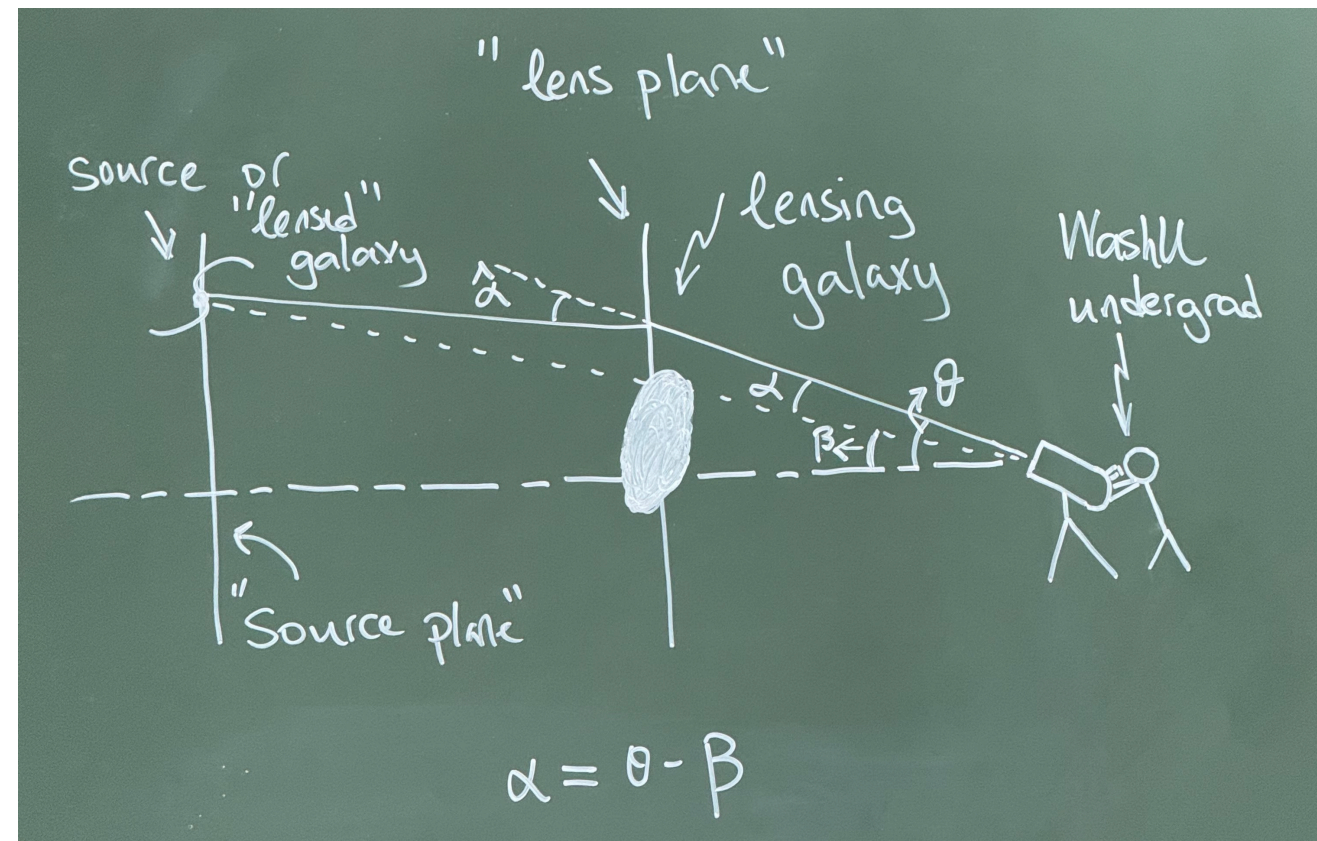
Direct detection



Daylan et al. 2018

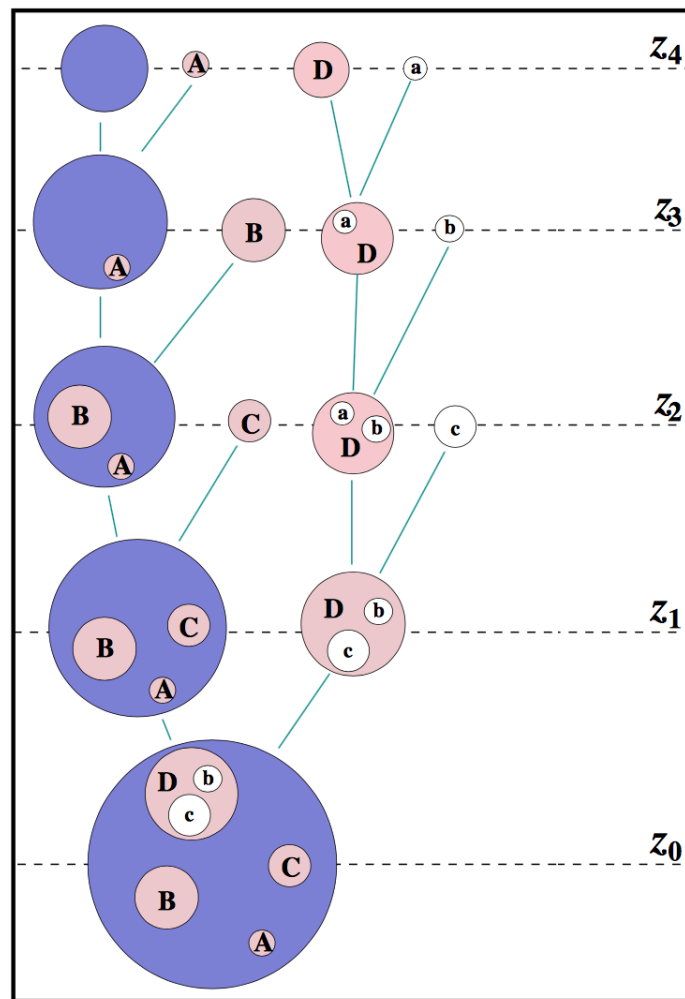
Strong gravitational lensing

- Imaging of strong gravitational lenses allows inference of the abundance and structure of mass, which is referred to as gravitational imaging.



Cold Dark Matter (CDM) in hierarchical structure formation

In the concordance model of cosmology, Lambda Cold Dark Matter (LCDM), virialized and dynamically equilibrated objects form in the form of halos with a have a characteristic profile.



Giocoli+2008

$$\rho(r) = \frac{r_t^2}{r^2 + r_t^2} \frac{\rho_0}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}$$

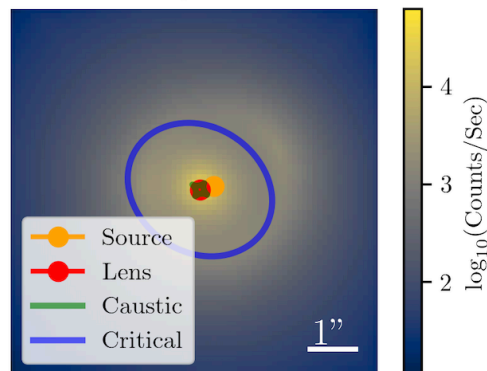
$$\rho_s = \frac{200}{3} \rho_{\text{cr}} \frac{c^3}{[\ln(1 + c) - c/(1 + c)]}$$

$$c_{\Delta}(M, z) = c_0 \left(\frac{M}{M_0} \right)^{\alpha} (1 + z)^{\beta}$$

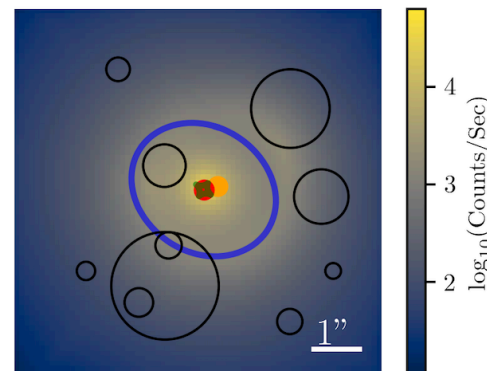
Strong gravitational lensing with substructure

- Low-mass dark matter subhalos ($< 10^9 M_\odot$) typically lead to **millilensing** by perturbing the lens potential (Koopmans 2005).
- Inference of millilensing signature requires diffraction-limited imaging (i.e., ~ 0.1 arcsec resolution).

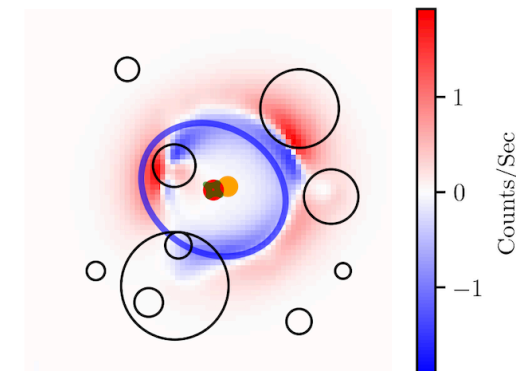
Count rate with only a smooth main halo



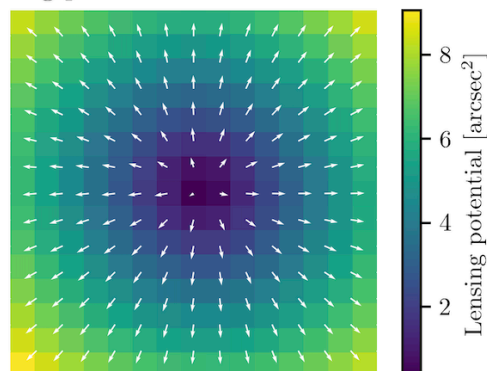
Count rate with additional CDM subhalos



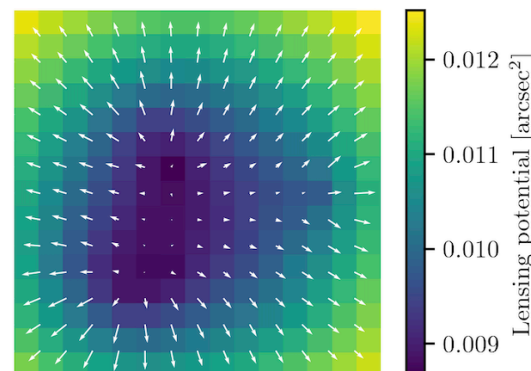
Residual count rate



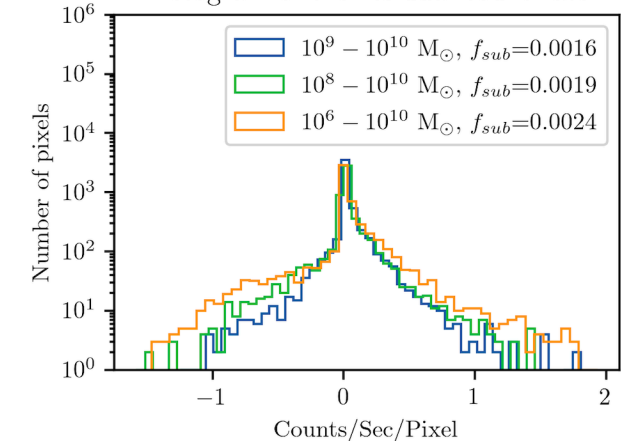
Lensing potential and deflection field



Residual lensing potential and deflection field

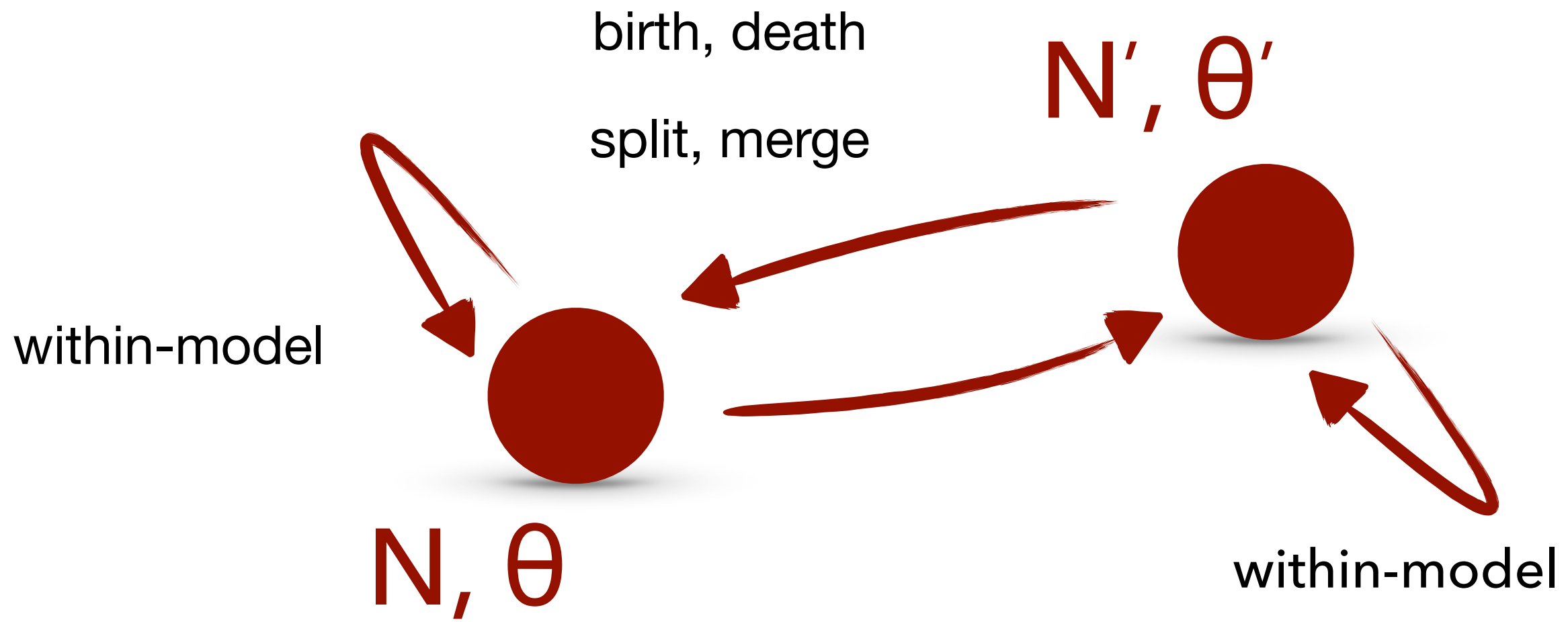


Histogram of the residual count rate



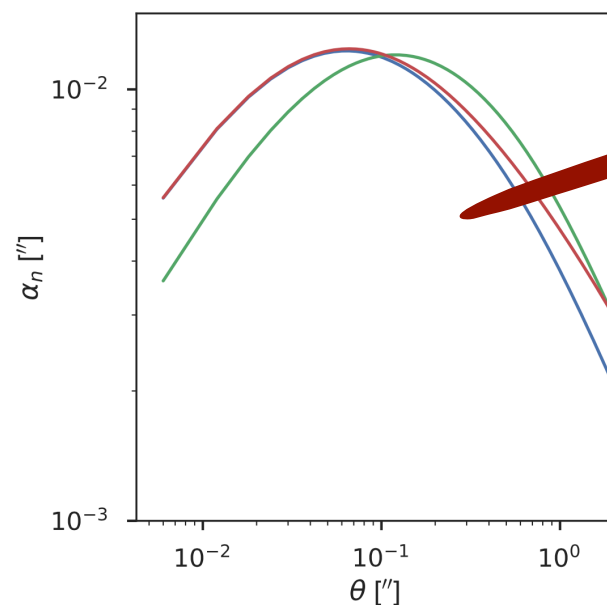
Transdimensional gravitational imaging

- A critical unknown in inference of subhalos is the number of unknowns (subhalos).
- Gravitational imaging can be performed transdimensionally using PCAT (Daylan+2017), which is a **transdimensional**, **Bayesian**, and **hierarchical** inference framework that samples from the posterior of a **metamodel** consistent with data using a **computationally efficient** set of proposals.

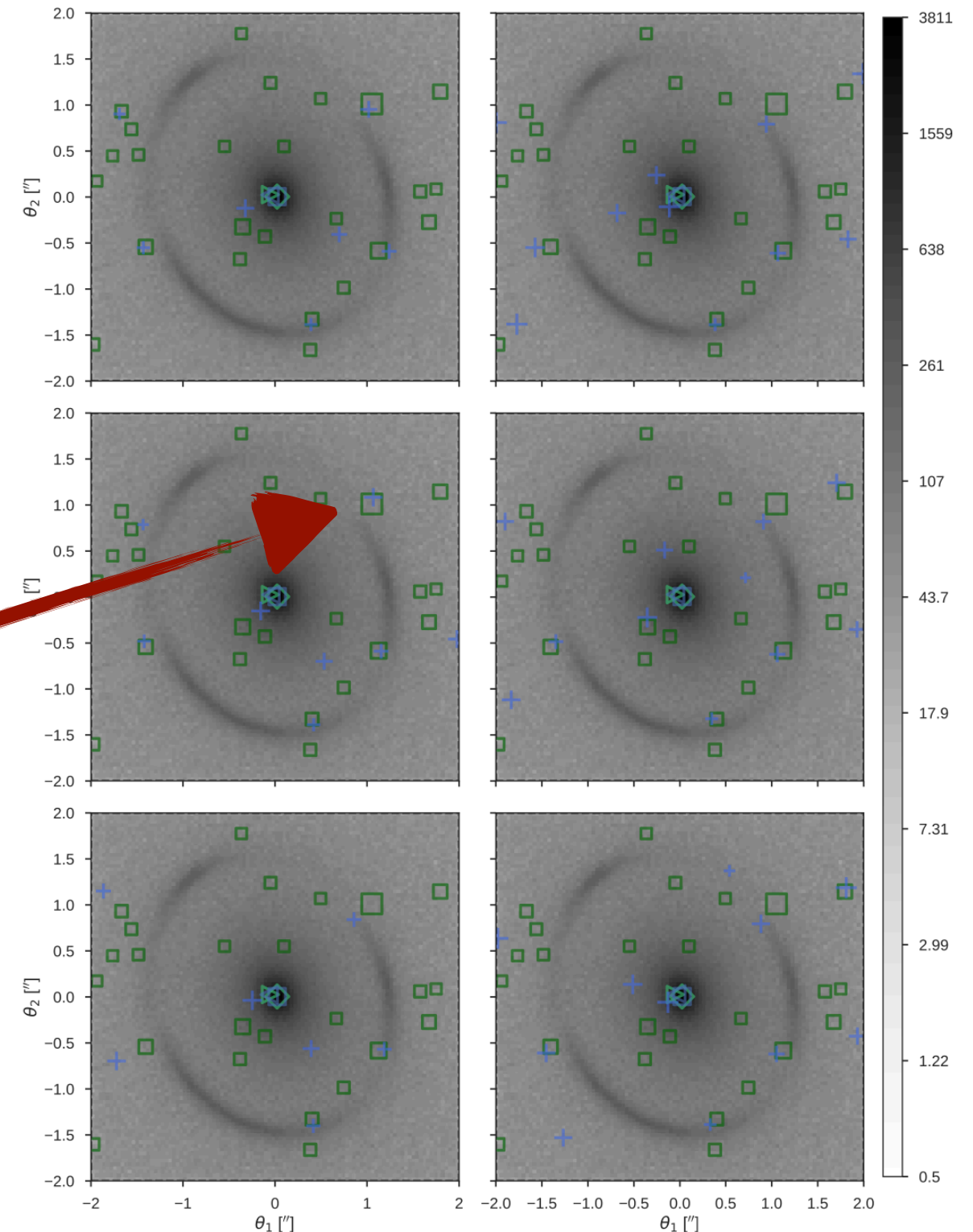


Transdimensional gravitational imaging

PCAT/Lens (Daylan et al. 2018)
samples from the posterior catalog
space of subhalos consistent with
the imaging data, characterizing the
transdimensional uncertainties in the
catalog space.

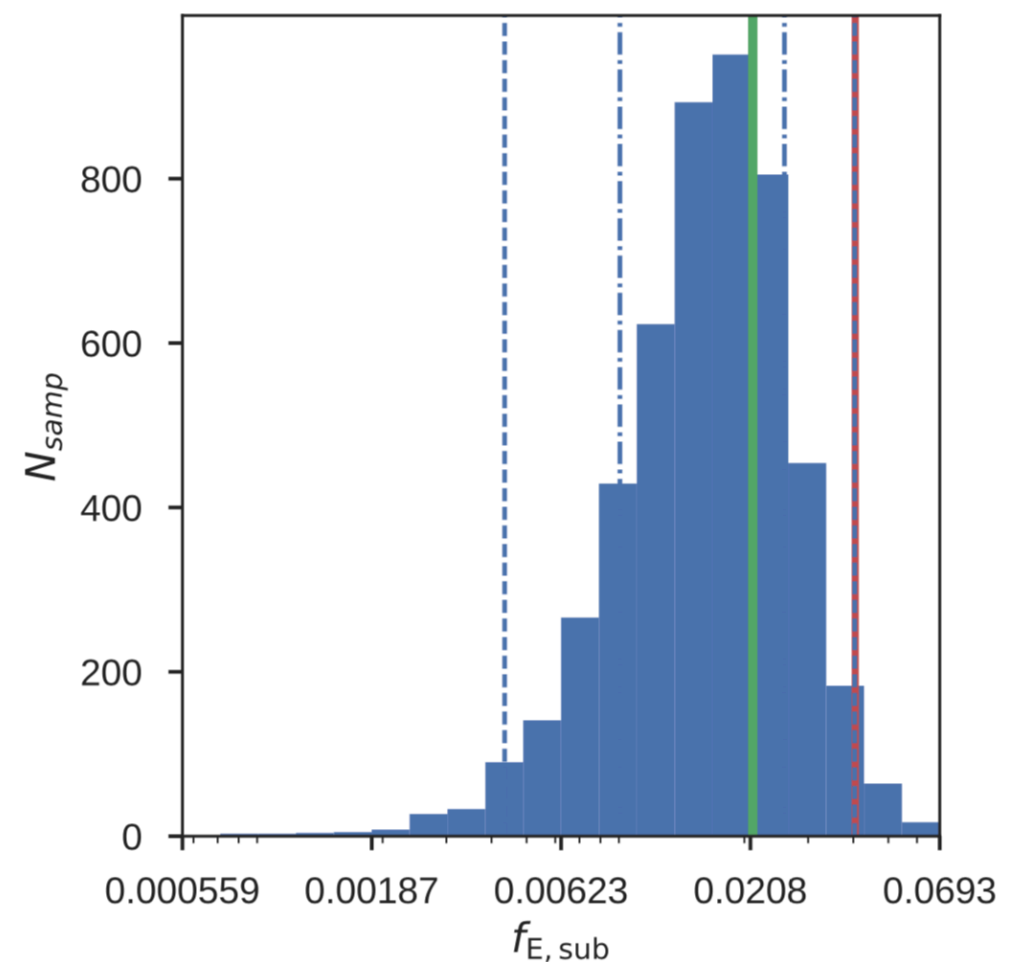
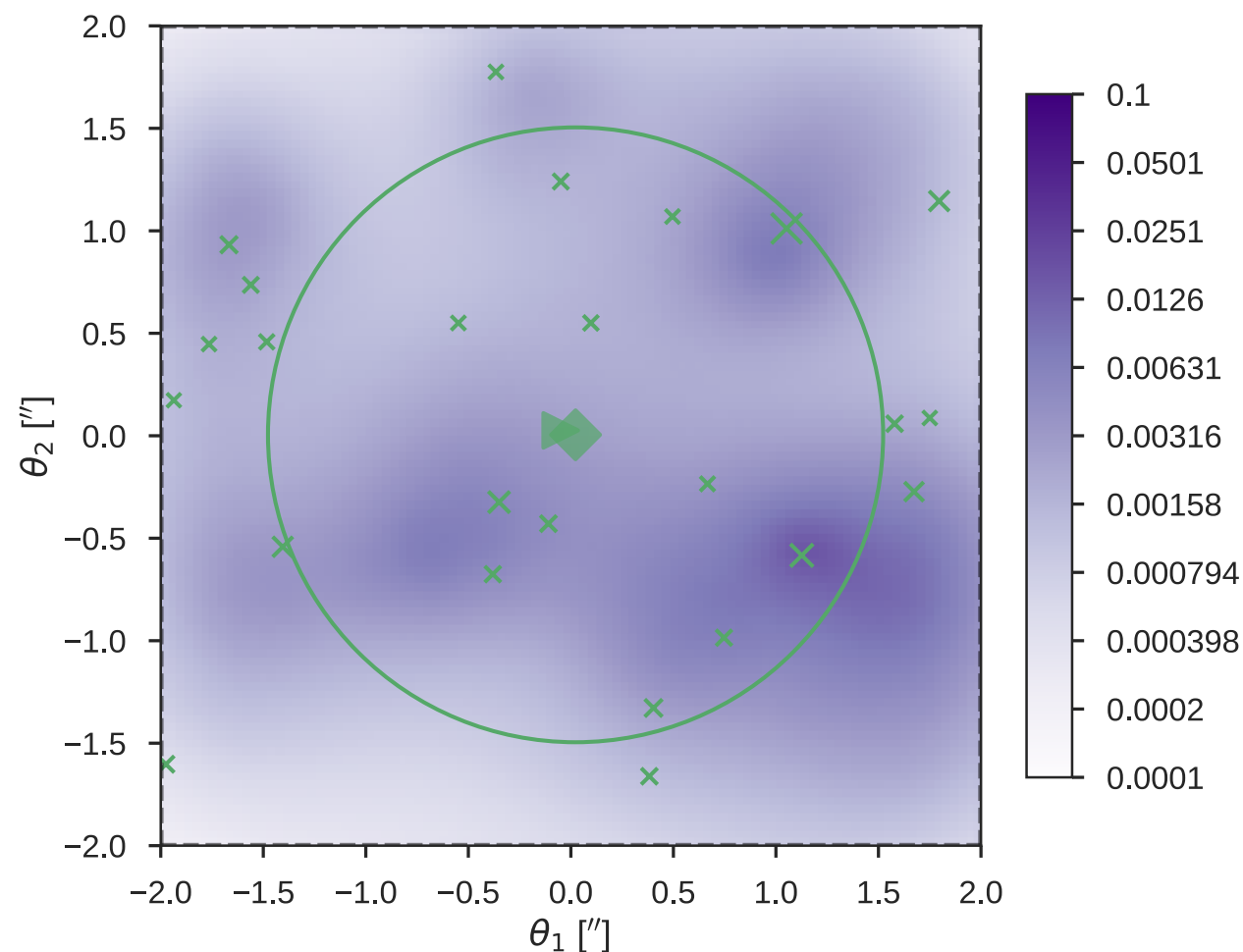


Daylan et al. (2018)



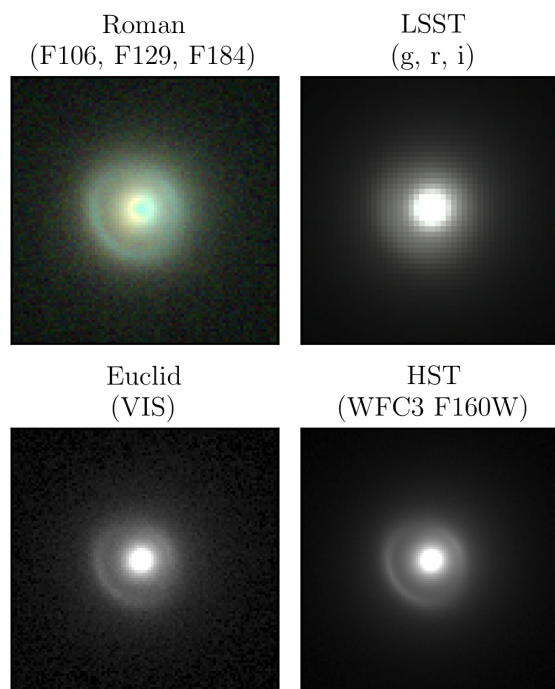
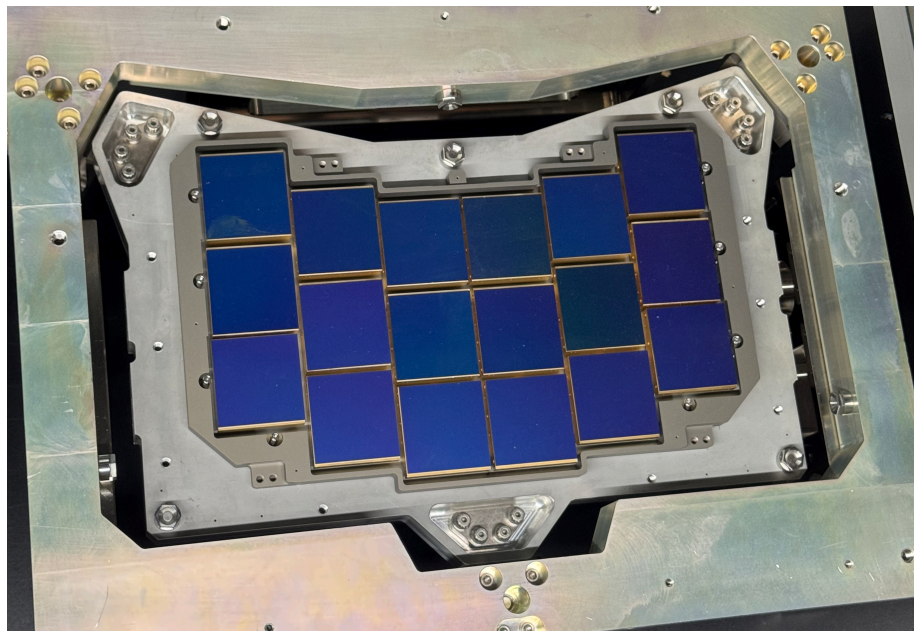
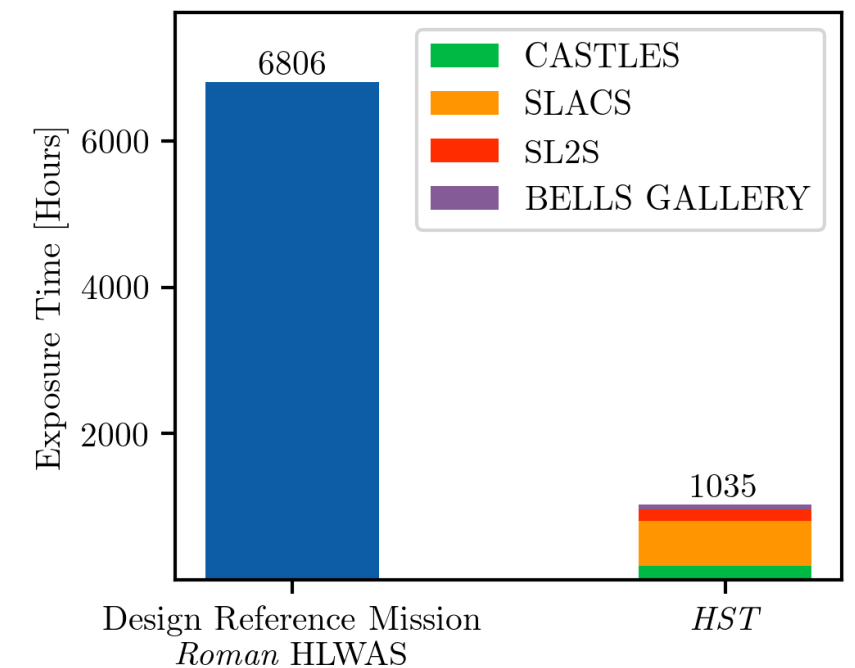
Transdimensional gravitational imaging

- Sample catalogs of dark matter subhalos can be marginalized over to constrain the convergence field (i.e., mass surface density).



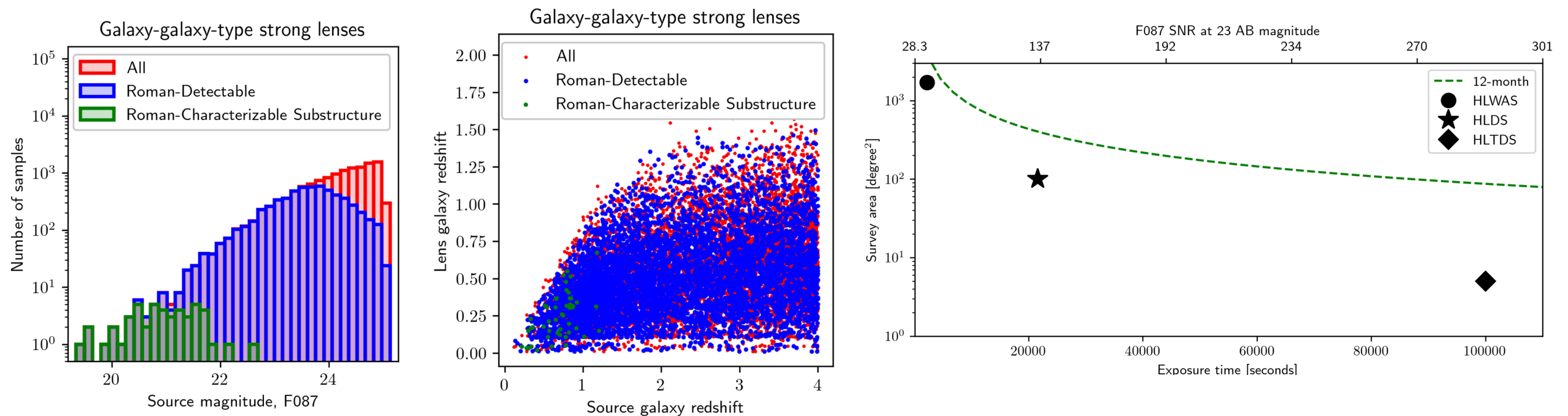
Next frontier in gravitational imaging

- To advance our capability to characterize dark matter substructure, we need IR capability, high angular resolution, wide field of view.
- Roman's wide field of view coupled with diffraction-limited photometry in the infrared will transform our ability to detect and characterize strong lenses relevant to testing the microphysics of dark matter.



High-latitude wide-area survey and substructure lensing

- During the community survey definition process, we proposed an intermediate-depth tier for the HLWAS to optimize the survey for the detection of strong lenses amenable to substructure inference (Daylan & Birrer, 2023).



The Roman Strong Lensing WFS program

In October 2023, we began our Roman Wide Field Science Program (80NSSC24K0095). The goals of the program are to

- develop a pipeline to generate realistic Roman WFI images of galaxy-galaxy-type strong lenses toward informing a broad range of science cases with a team focus on dark matter substructure via gravitational imaging,
- implement and organize a data challenge based on the data.

Team members

co-I: Simon Birrer (Stony Brook University)



Bryce Wedig



Aysu Ece Sarıcaoğlu

Washington University: Bryce Wedig and Aysu Ece Sarıcaoğlu (grad students), Jodie Xiao (undergrad)

Stony Brook University: Alan Huang, Yixuan Shao, Rahul Karthik (grad students)

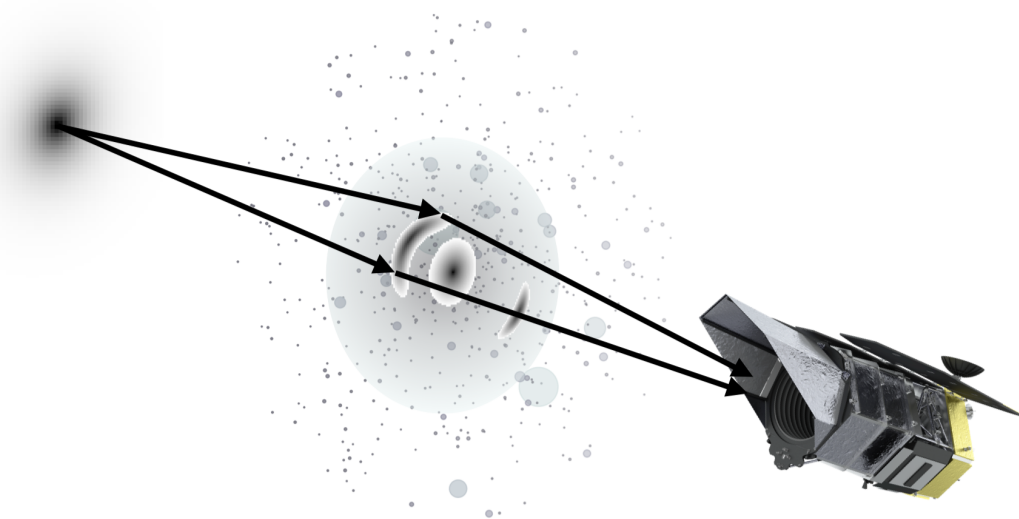
PI: Tansu Daylan (Washington University)

Collaborators: Francis-Yan Cyr-Racine, Cora Dvorkin, Douglas P. Finkbeiner, Xiaosheng Huang, Priyamvada Natarajan, Anna M. Nierenberg, Annika Peter, Justin D. R. Pierel, Risa H. Wechsler

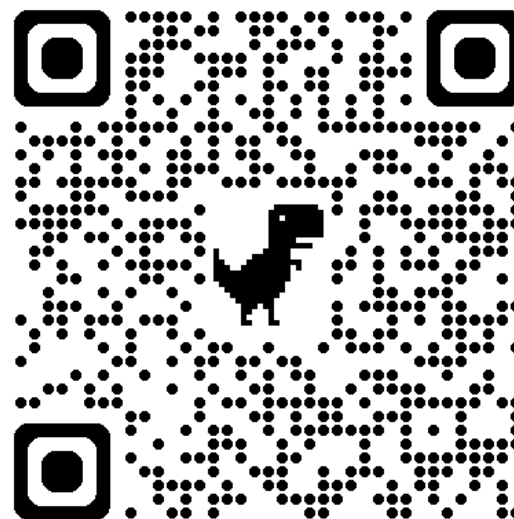
The Roman view of strong gravitational lenses

The resulting simulation pipeline, **mejiro**, takes into account the Roman optics and detector response, which we used to estimate the yield for strong lenses amenable to detection and characterization (Wedig et al., 2025).

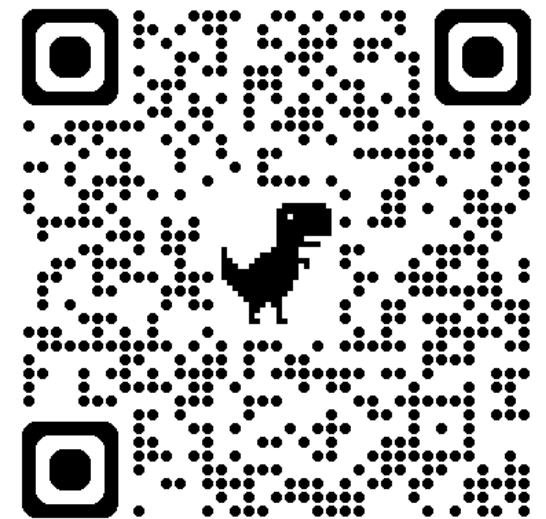
<https://zenodo.org/records/15512464>



Bryce Wedig

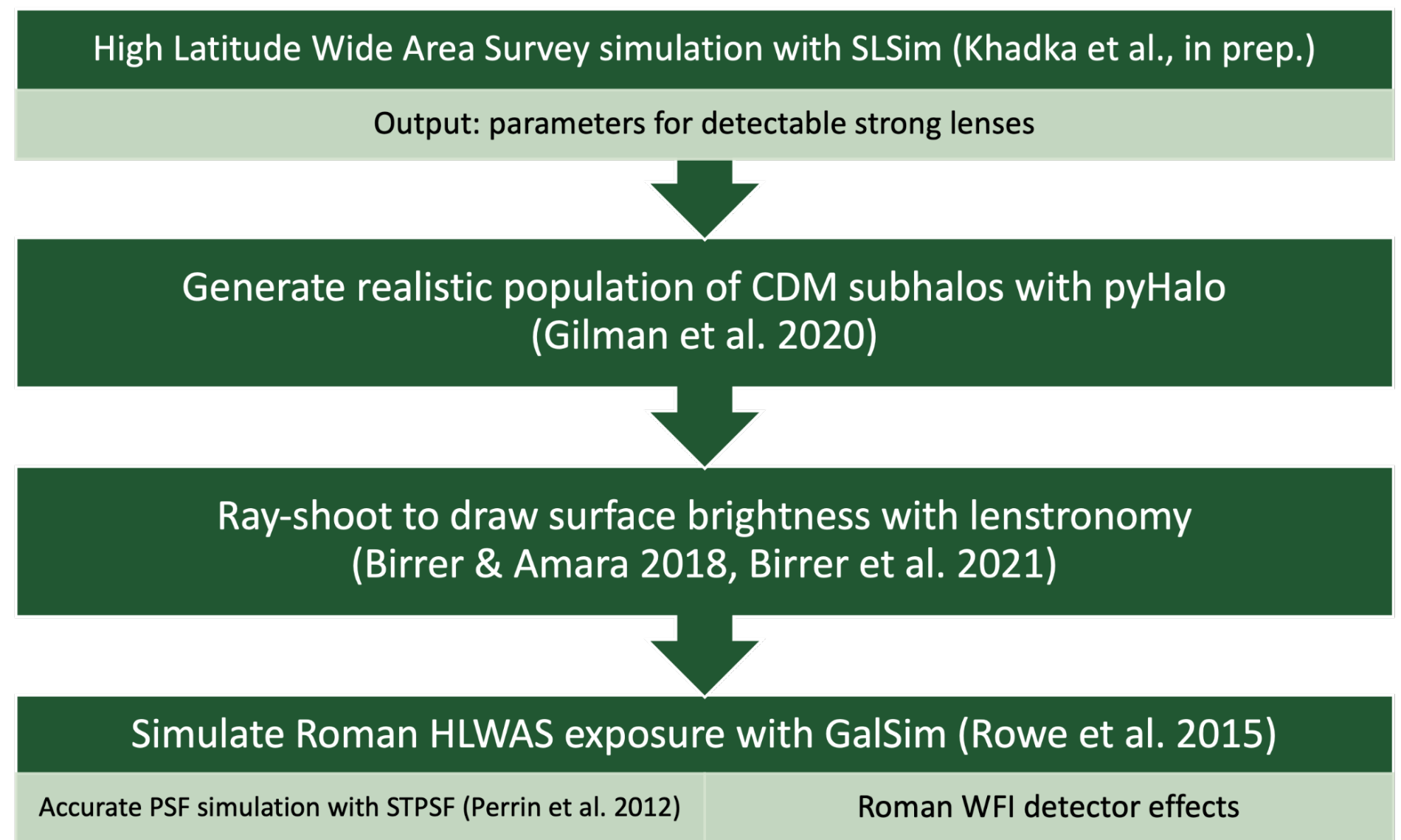


<https://github.com/AstroMusers/mejiro>



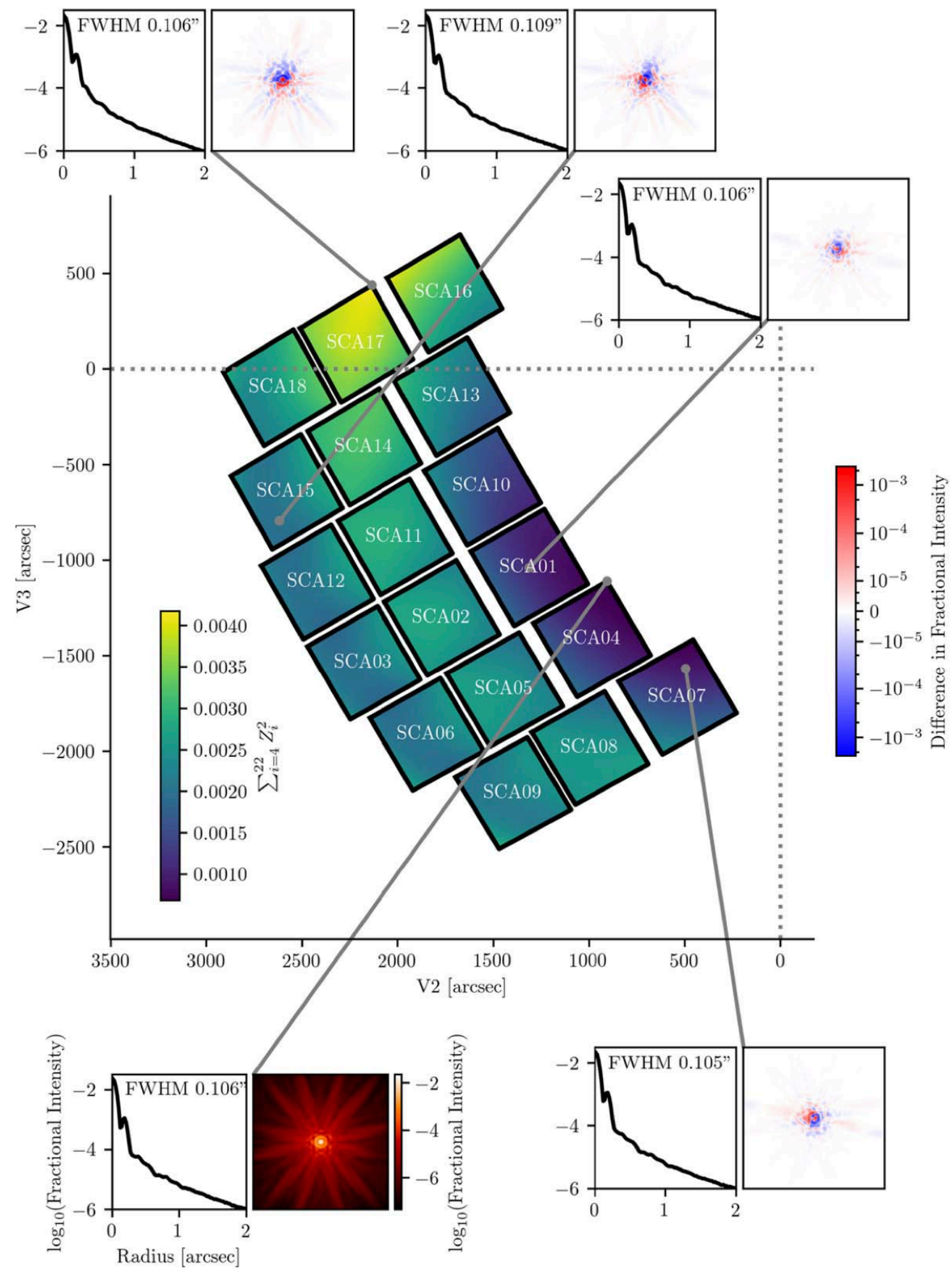
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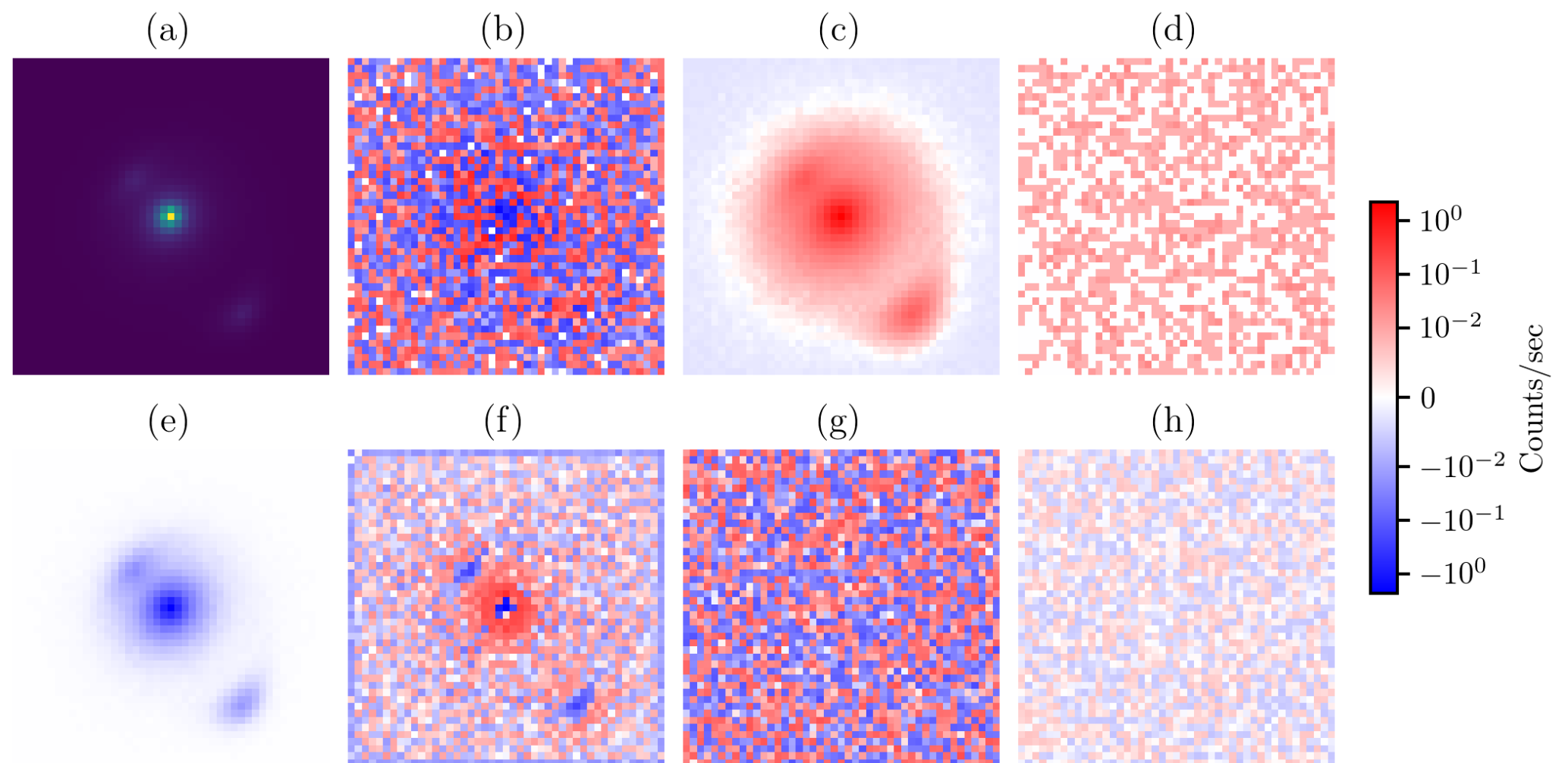


Bryce Wedig

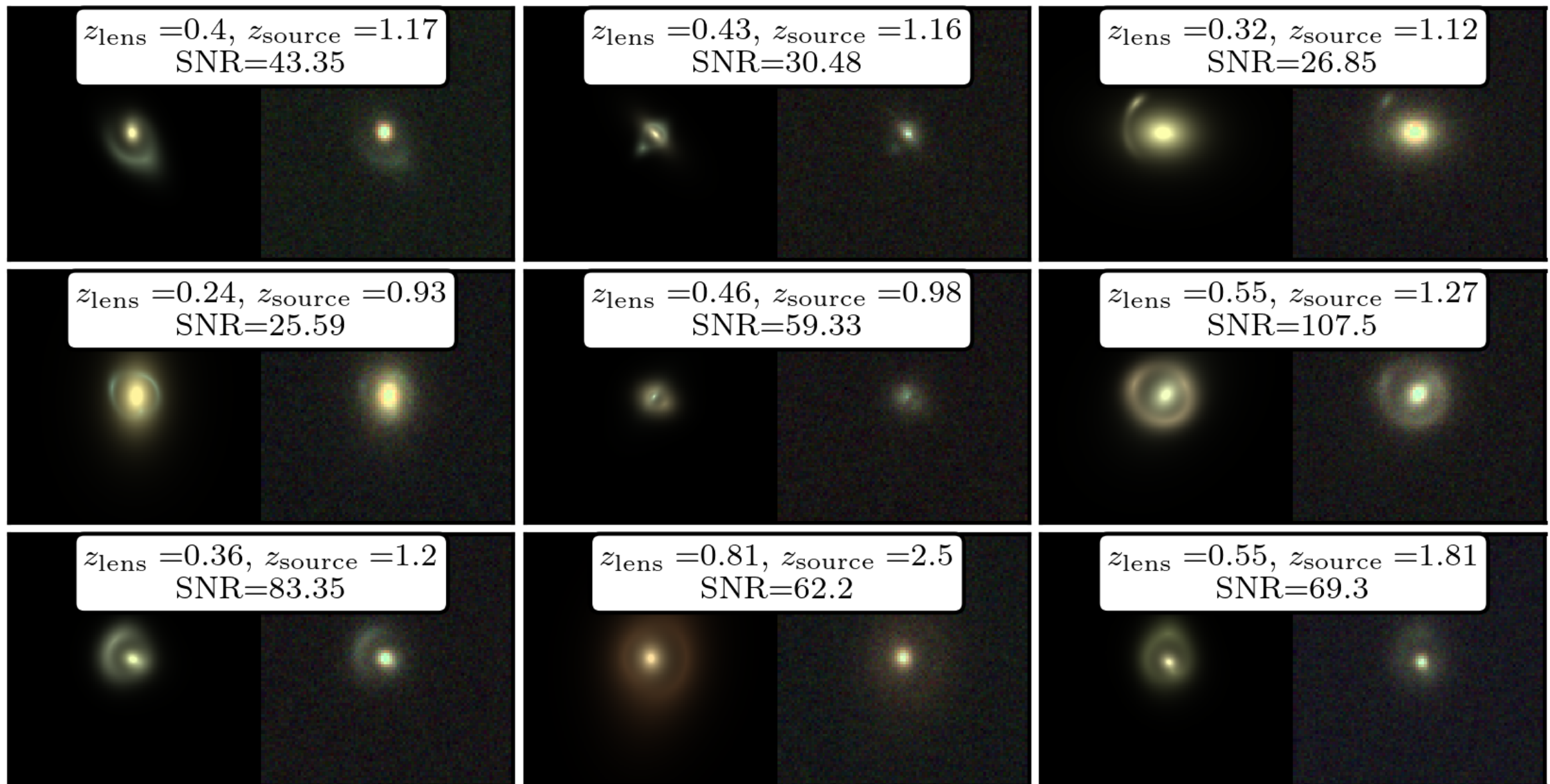
Field-dependent PSF



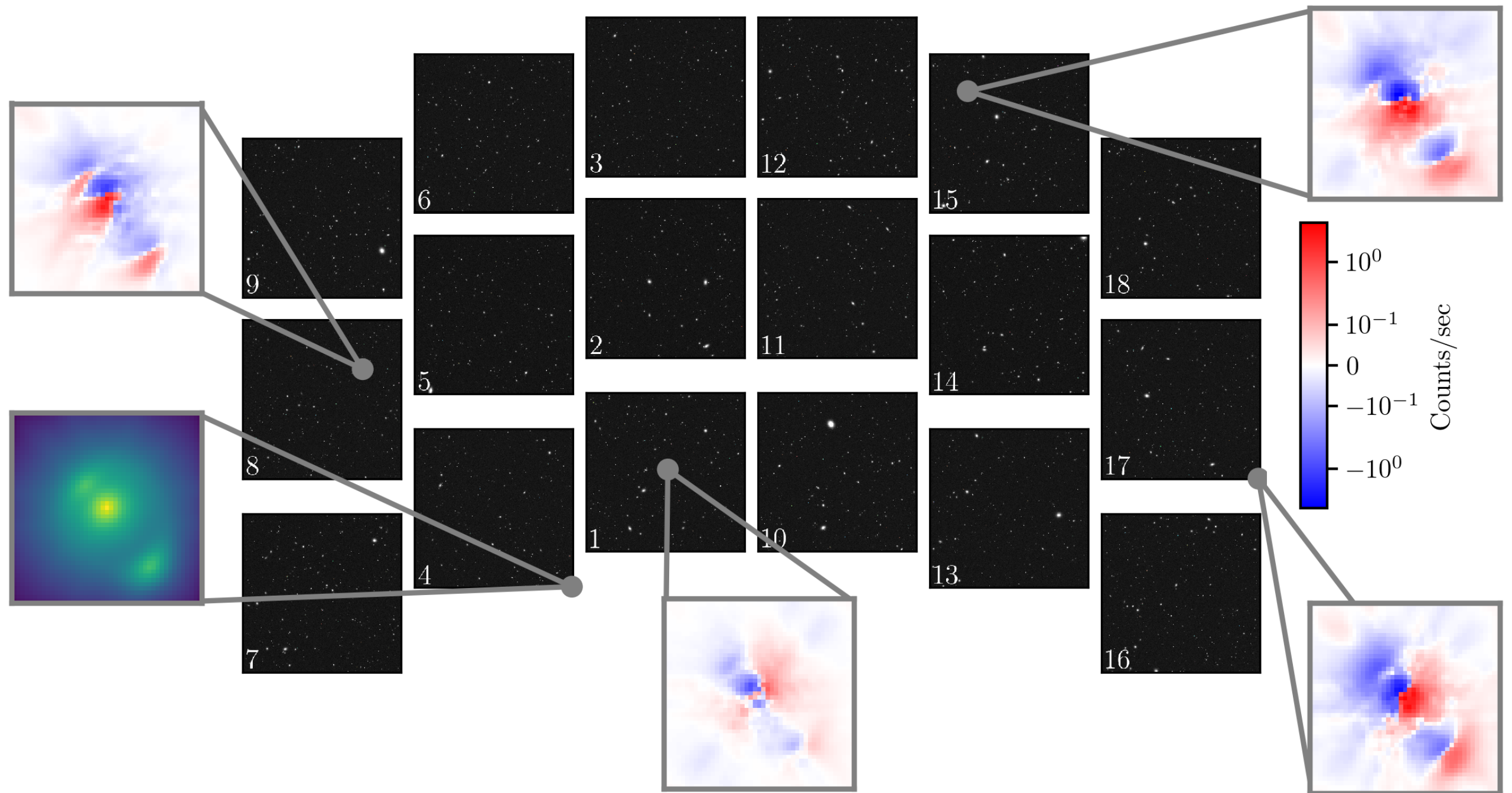
Simulating optical and detector systematics



The Roman view of strong gravitational lenses

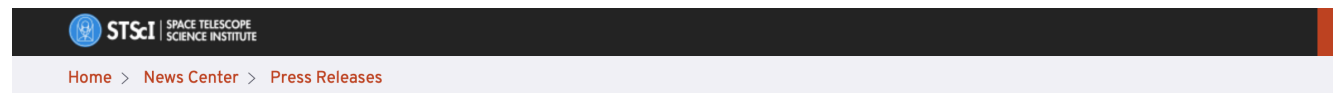


The Roman view of strong gravitational lenses



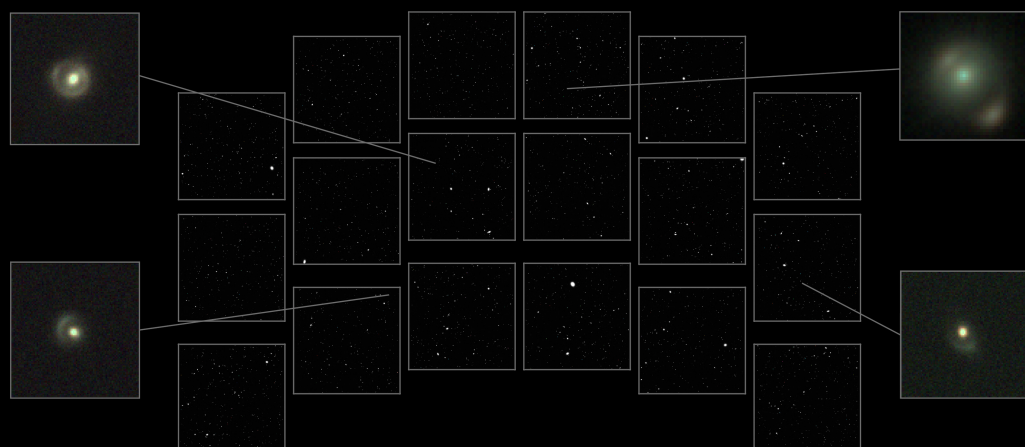
The Roman view of strong gravitational lenses

- Per exposure:
 - ~27 detectable strong lenses
 - ~1 high-SNR ($\text{SNR} > 200$) strong lens
- Over the mission lifetime in the HLWAS:
 - >160,000 “detectable” lenses
 - > 500 high-SNR strong



Gravitational Lenses Projected to ‘Pop Out’ in Simulated Roman Image

Simulations of Gravitationally Lensed Galaxies in a Roman Space Telescope Image



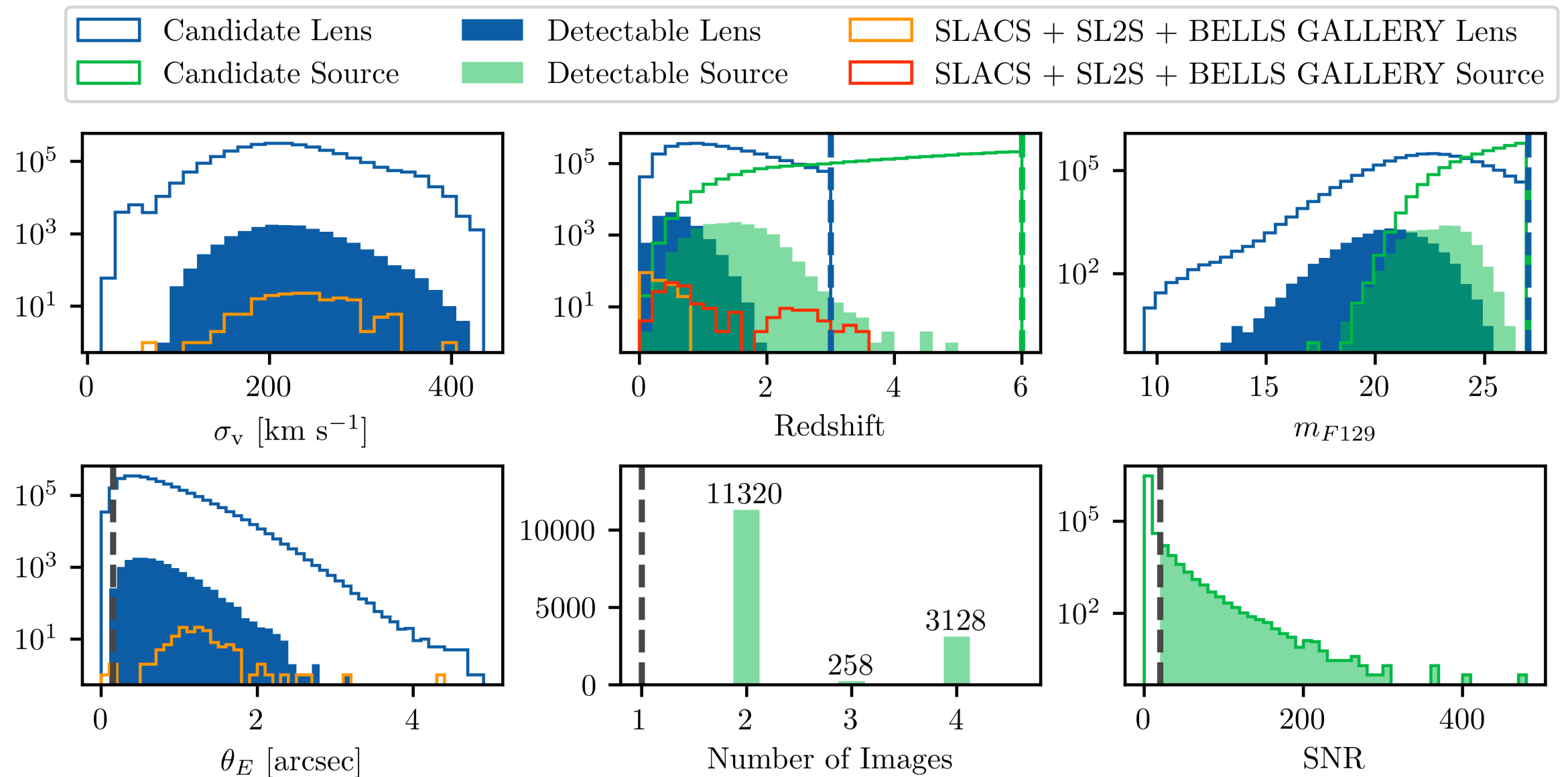
5 MIN READ

NASA's Roman to Peer Into Cosmic 'Lenses' to Better Define Dark Matter

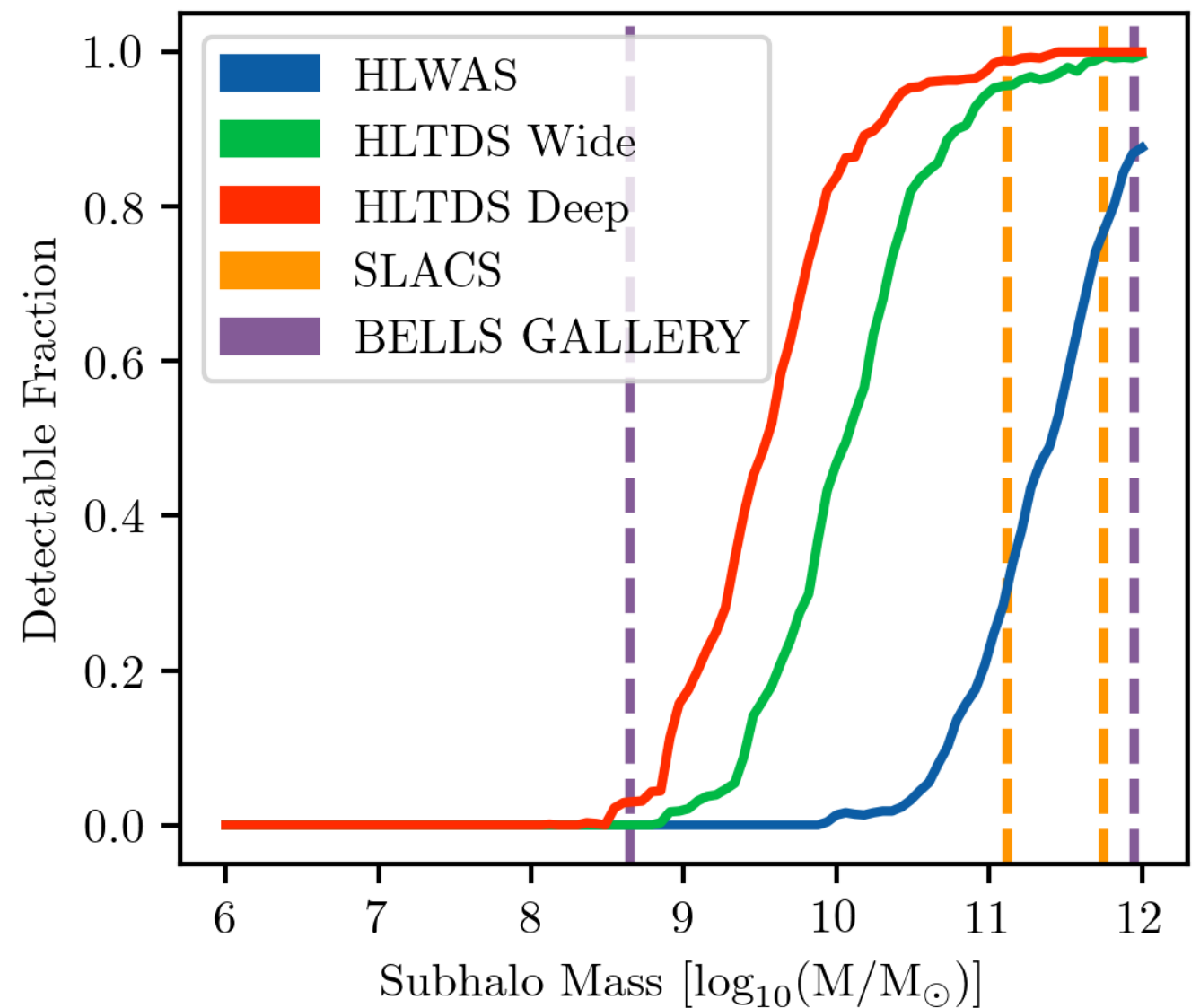
A funky effect Einstein predicted, known as gravitational lensing — when a foreground galaxy magnifies more distant galaxies behind it — will soon become common when NASA's Nancy Grace Roman Space Telescope begins science operations in 2027 and produces vast surveys of the cosmos.

Simulations of Gravitationally Lensed Galaxies in a Roman Space Telescope Image

The Roman view of strong gravitational lenses

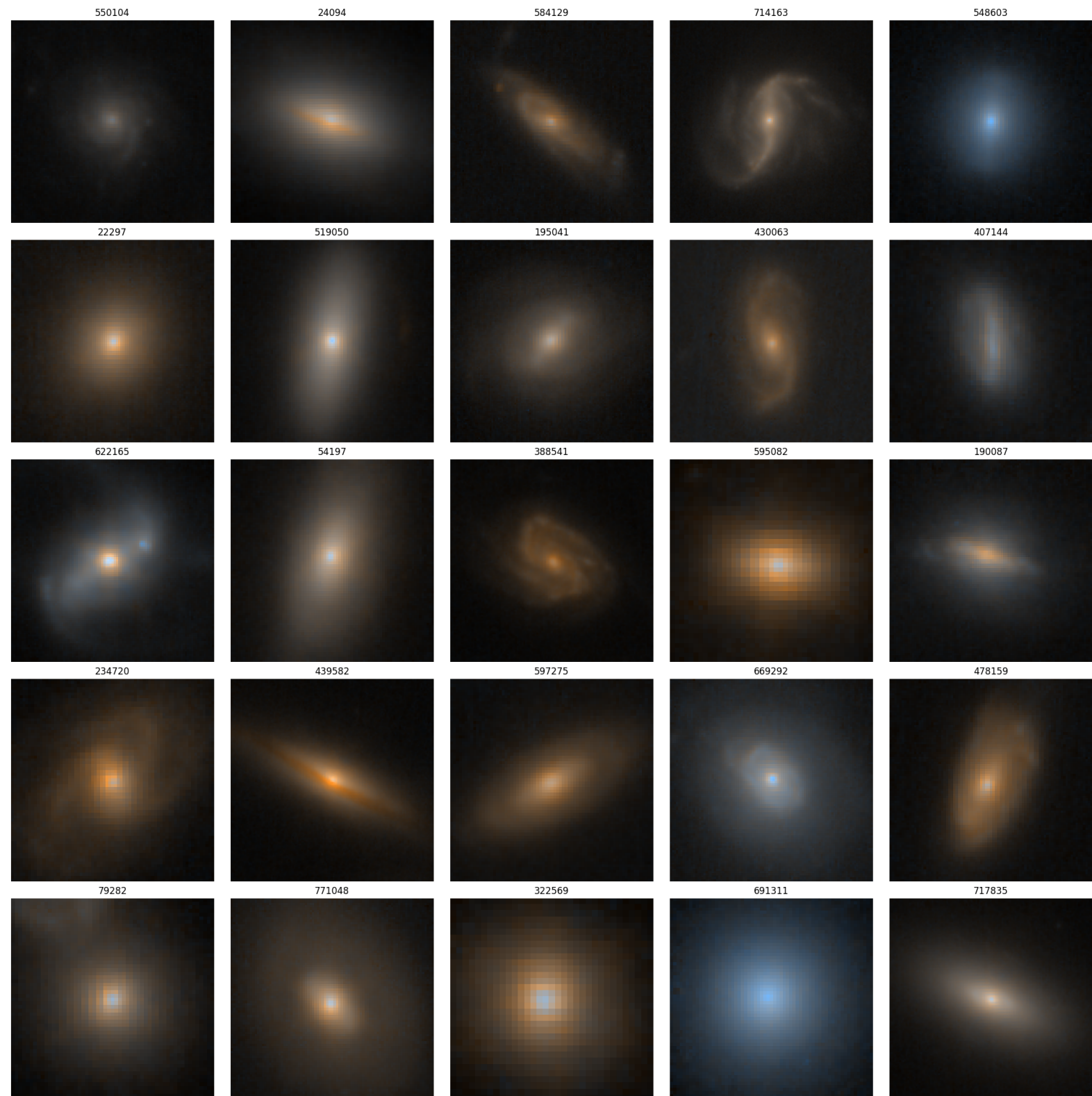


The Roman view of strong gravitational lenses



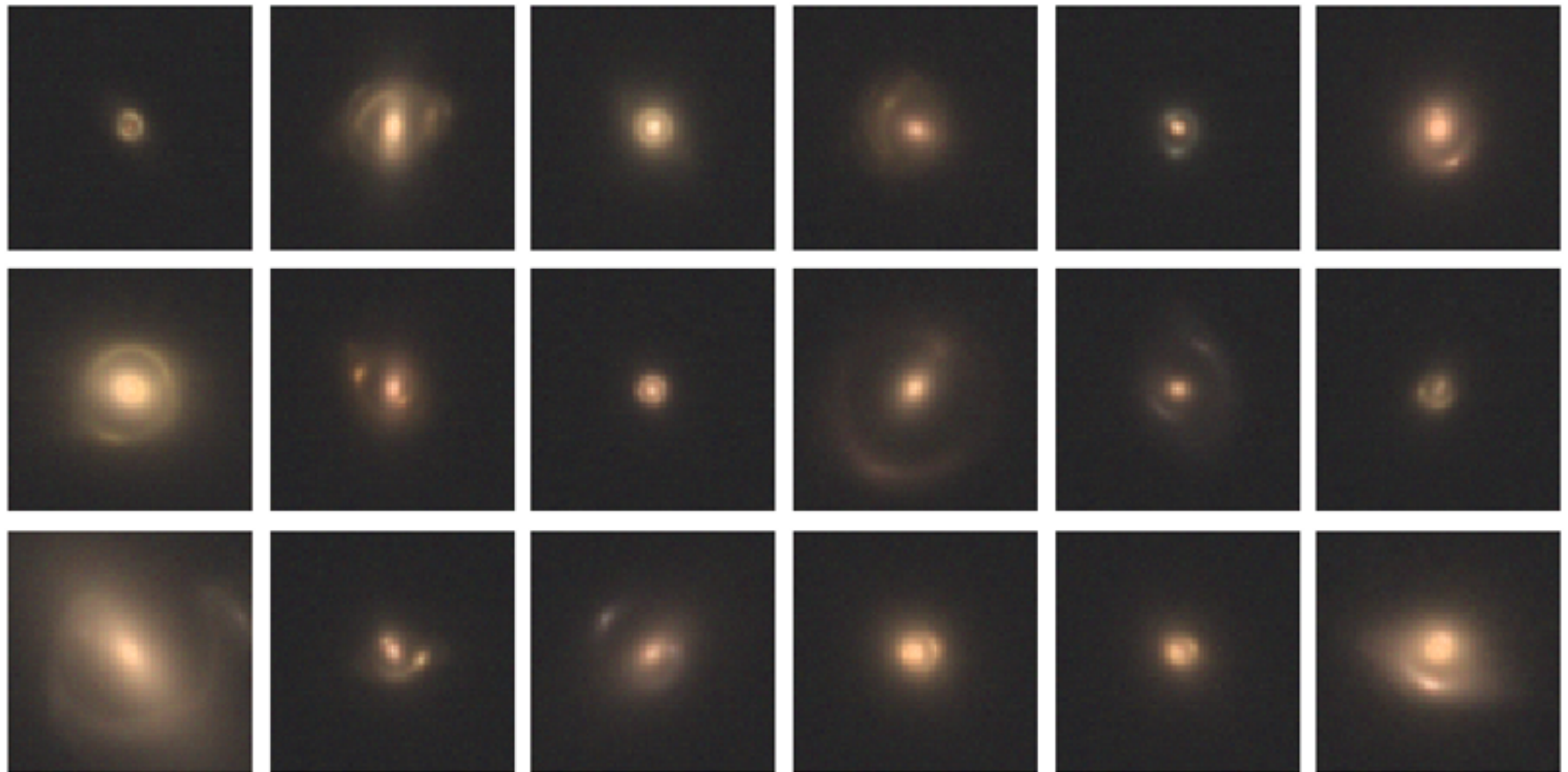
Further development of mejiro (July 2025 onward)

- COSMOS-Web galaxies as sources with four bands (see right)
- GPU-accelerated ray-shooting with JAX via JAXtronomy
- Co-addition of L2 data products from romanisim using romancal



Roman Strong Lensing Data Challenge

As part of our WFS Program work, we have been running a **Roman Strong Lensing Data Challenge** focused on strong lensing.



Roman Strong Lensing Data Challenge

Objectives:

- maximize the dark matter science potential of Roman galaxy-scale strong lenses by providing simulated datasets
- facilitate community efforts to train neural networks on strong lens identification and dark matter characterization
- enable dataset generation and analysis on Roman Research Nexus

Roman Data Challenge for Dark Matter

Search docs

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Structure of the challenge

Timeline of the challenge

Accessing the 100,000 Dataset

Generating Your Own Dataset

Submissions

»Home

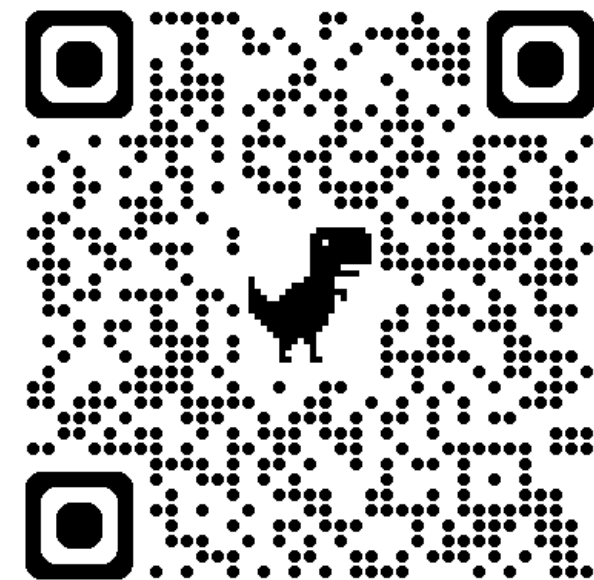
Overview of the Roman Data Challenge for Dark Matter

Note: This page is still under construction, and the details of the challenge are still being fleshed out. Any comments/suggestions are welcome, and should be sent to the following:

- alan.huang.1@stonybrook.edu
- b.t.wedig@wustl.edu
- simon.birrer@stonybrook.edu
- tansu@wustl.edu
- xhuang22@usfca.edu

Although Cold Dark Matter (CDM) is a widely successful model for predicting the large-scale structure of the universe, its shortcomings become apparent when used to predict properties of small-scale structures. Examples include the missing satellite problem, where CDM predicts more satellite galaxies than observed, the cusp-core problem, where CDM predicts a higher density of dark matter at the center of galaxies than observed, and more. A review of the CDM model's shortcomings is given in [Perivolaropoulos and Skara \(2022\)](#). To explain these discrepancies, other dark matter models have been brought forth, such as the warm dark matter and self-interacting dark matter models. Thus, our aim is to analyze dark matter through strong gravitational lenses, which can allow us to place constraints on these alternative dark matter models.

With the Roman space telescope HLWAS survey launching in May 2027, [Wedig et al \(2025\)](#) predicts that there will be about 500 detectable strong lenses with sufficient signal-to-noise ratio to be susceptible to robust dark matter analysis. Thus, the Roman data challenge aims to achieve the following:



<https://roman-data-challenge.readthedocs.io/en/latest/>

Roman Strong Lensing Data Challenge

The data challenge will have four rungs, increasing in difficulty and extent.

Rung 0: Train a regression model to infer the Einstein Radius of a simple strong lens with no added substructure, serving as a tutorial to familiarize participants with the data challenge process.

Training dataset: ~10k images, Test set: ~10k images

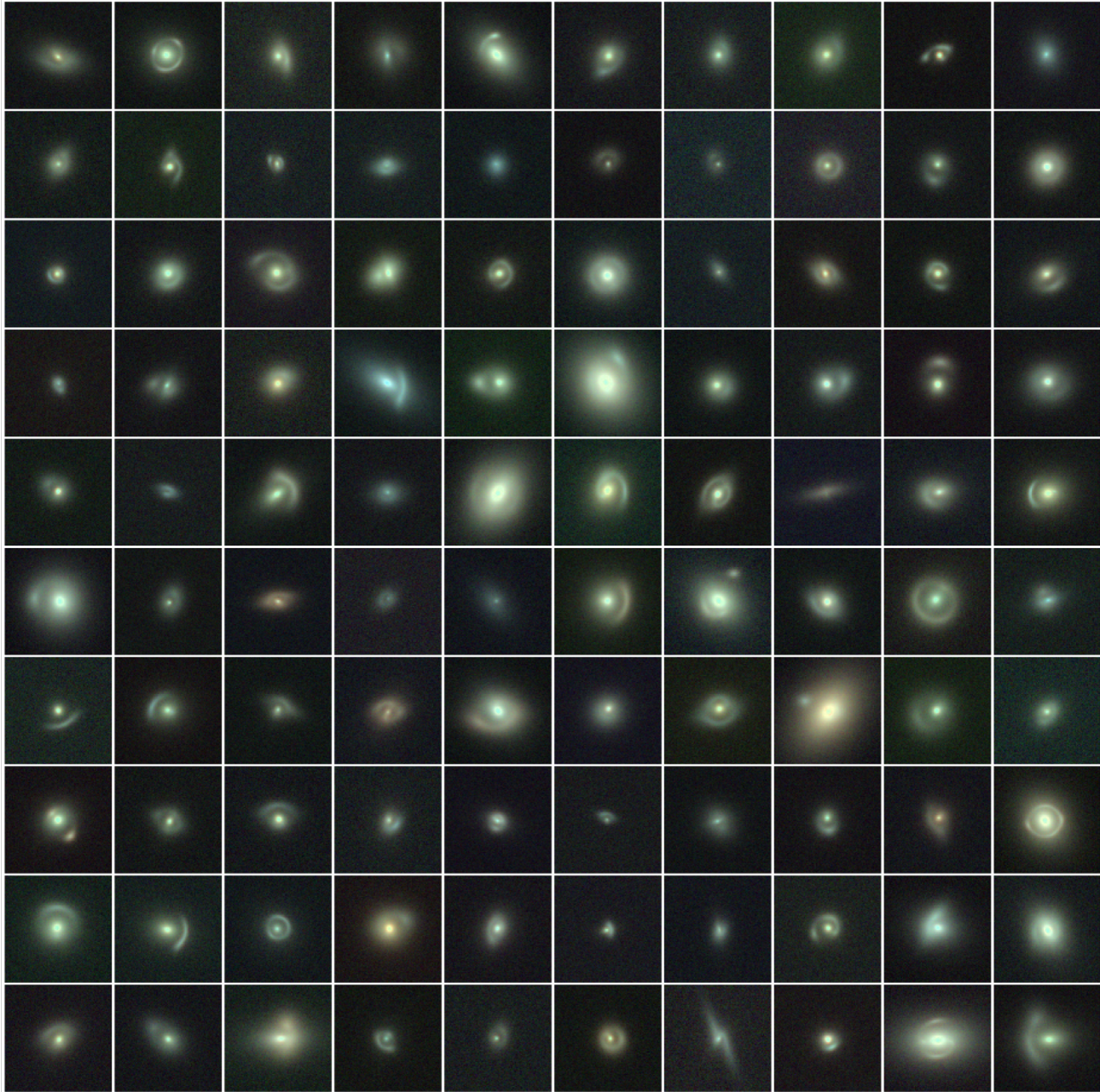
Rung 1: Train a classification model to determine whether a strong lens contains substructure or not using a dataset with 50% containing substructure and 50% not.

Training dataset: ~100k images, Test set: ~10k images

Rung 2: Measure the amplitude, slope, and low-mass cutoff of the subhalo mass function.

Rung 3: Disentangle line-of-sight halos from substructure and infer their concentrations.

Roman Strong Lensing Data Challenge

- Datasets, stored in HDF5 files, are hosted on Zenodo (links to each dataset are on the website).
 - Each dataset is bundled with a Jupyter notebook that demonstrates how to work with it.
 - We will help participating teams obtain RRN accounts, access the data on the RRN, and perform analyses on the RRN to rehearse the future Roman workflow in collaboration with STScI.
 - Classification models, accuracy, precision, true positive rate, and false positive rates are evaluated.
 - For regression models goodness, precision, and accuracy are evaluated.
- 
- For questions on or to participate in the data challenge, you can contact us via the Roman Slack Workspace (#strong-lensing) or the mailing list **romanstronglensing@lists.physics.wustl.edu**.

Roman Strong Lensing Data Challenge

Fall 2025: generation of the Rung 0
and Rung 1 dataset and website

January 2026: Start of the data
challenge office hours and Rung 0

March 2026: Incorporate feedback
from Rung 0, begin Rung 1

~January 2027: incorporate
commissioning data into a training
and test data set for a new version of
the challenge.

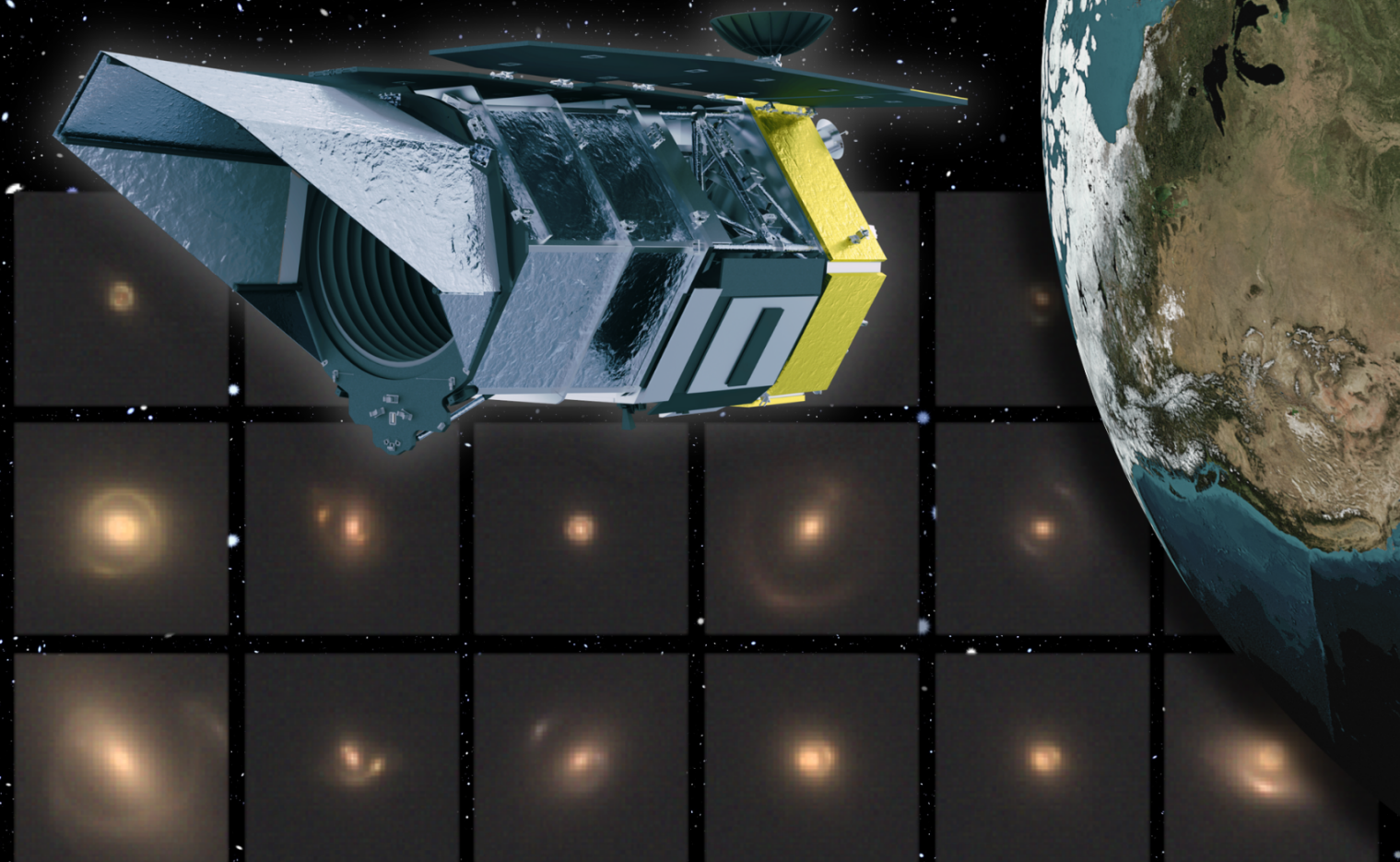
~December 2027: end of the data
challenge

ROMAN STRONG LENS DATA CHALLENGE FOR DARK MATTER

In preparation for the launch of the Nancy Grace Roman Space Telescope, we have developed a pipeline for simulating realistic Roman strong lensing images.

This data challenge aims to incentivize the development and assessment of scalable methodologies for dark matter substructure characterization. For more details, see our website.

Timeline: October 2025 - September 2026

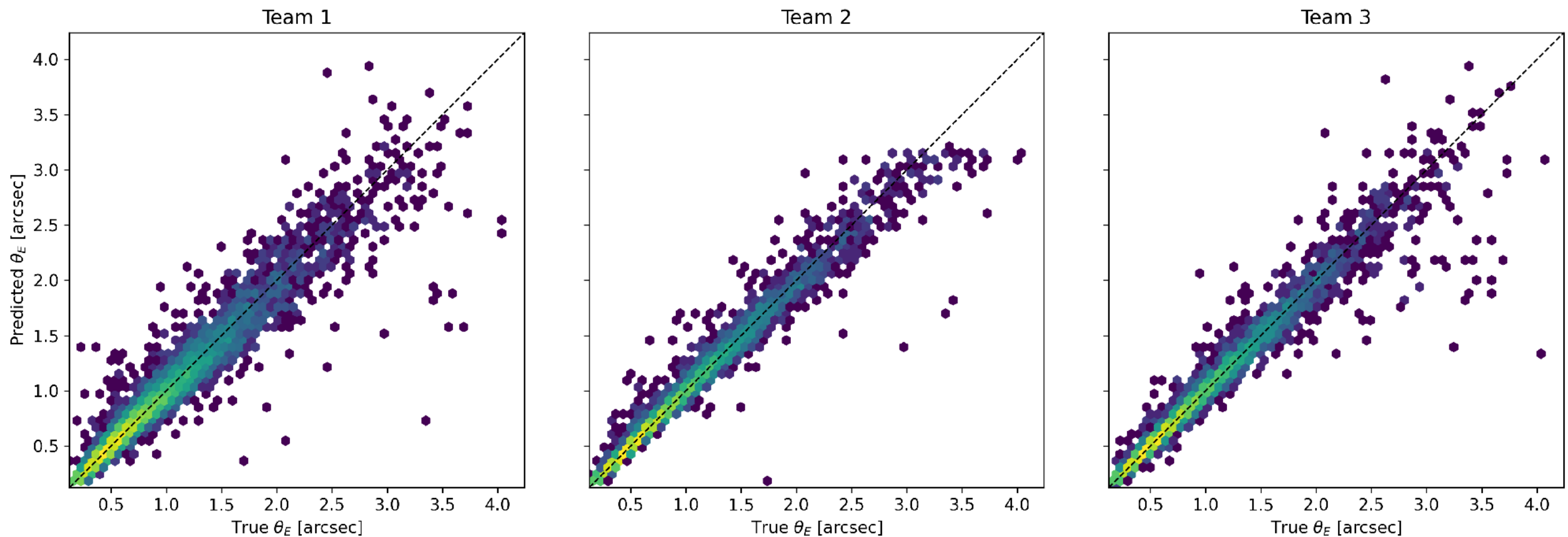


For more details,
Scan the QR code.



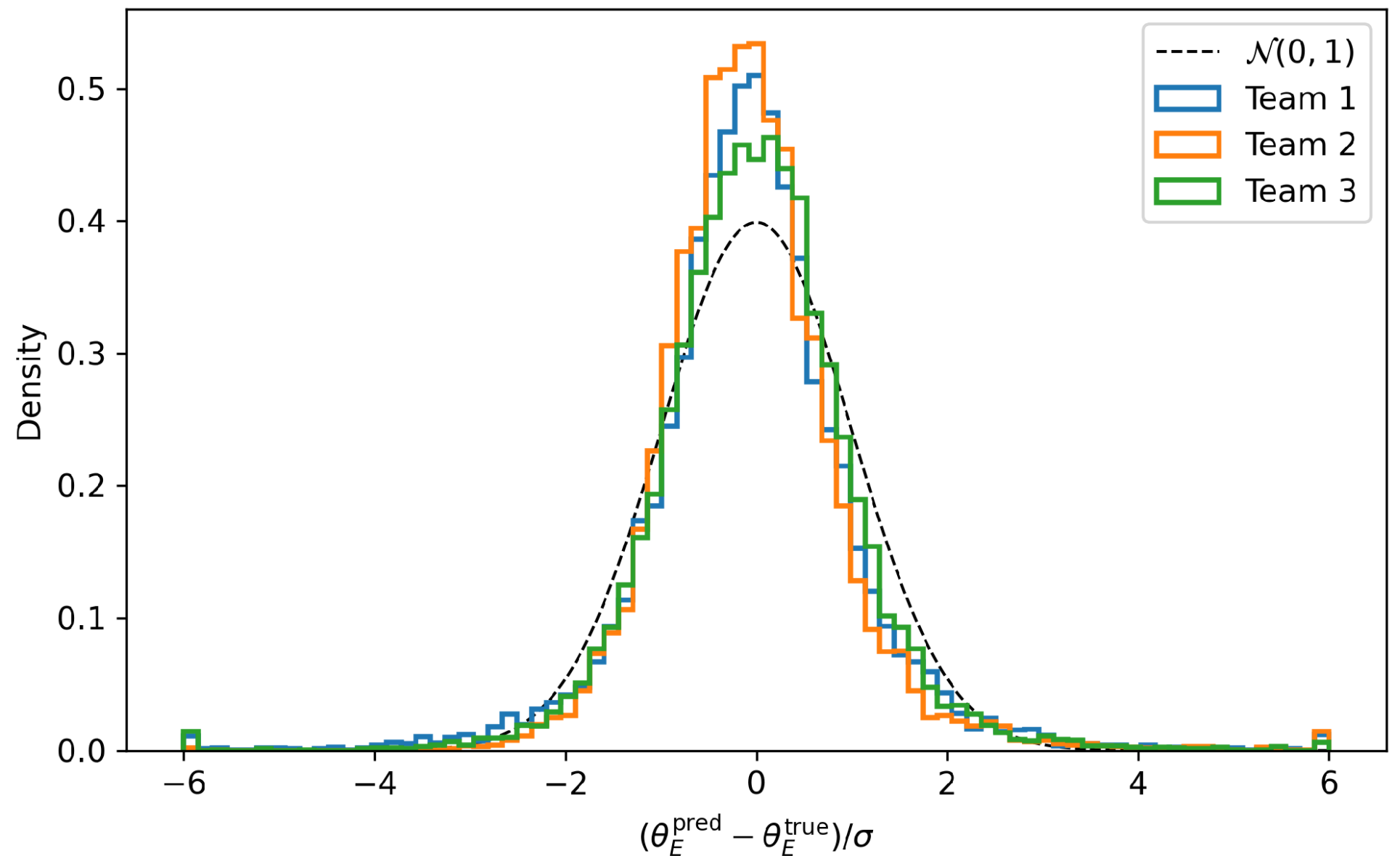
Roman Strong Lensing Data Challenge

- At least 7 teams are participating, and 3 have submitted final results so far.



Roman Strong Lensing Data Challenge

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Cycle 1 and beyond

We are currently using mejiro-simulated cutouts, along with photometric redshift estimates, to train neural networks to extract strong lens candidates from the upcoming imaging data stream.

As part of this longer-term work, we look forward to the approved Cycle 1 programs:

Led/co-led from WashU:

Transiting White Dwarf Exoplanets with the Galactic Bulge Time Domain Survey (19060)

All the strong lenses in Roman HLWAS (19045)

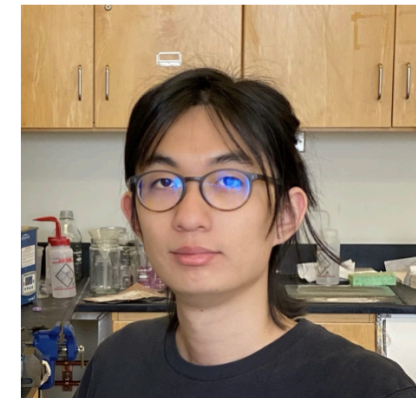
co-l:

Strongly Lensed Supernova Cosmology with the Roman HLTDS (19038)

Illuminating Dark Energy and Black Holes with Strong Gravitational Lensing in the Nancy Grace Roman Space Observatory Era (19065)



Ella Knol (UC Santa Cruz, REU@WashU)



Zifan Lin (WashU)



Bryce Wedig (WashU)

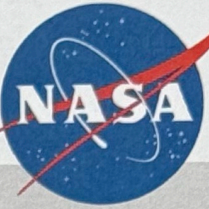
Conclusion

- Multiwavelength probes of dark matter chart our path toward constraining its particle nature.
- Roman Space Telescope, scheduled for launch on August 30, 2026, will observe $\sim 160,000$ detectable strong lenses of which about 500 will have sufficient signal-to-noise to be amenable to detailed substructure characterization to probe dark matter microphysics.
- **We are in accretion process to start a strong lensing focus group within the Cosmology Science Group of the Roman Science Collaboration. Reach out if you are interested!**



January 2025, during our AAS 245 visit to GSFC





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IS COMING TO AN L2 POINT NEAR YOU!

With its wide-field, multiband imaging capability in infrared, **Roman will advance cosmology and transform our understanding of the Universe.**

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MORE**



We invite applications for the two annual postdoc prize fellowships at WashU with relevance to Roman.

Ed Jaynes Fellowship
(deadline: ~December, 2026)

MCSS Fellowship
(deadline: ~December, 2026)

