Unveiling Gravitational Lenses in Colour: A Bayesian Approach to Multi-band Inference

THE UNIVERSITY OF SYDNEY

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MaxEnt 2025 Conference

The MaxEnt and Bayesian Association of Australia, Inc.

$\text{Max}\left\langle -\ln\frac{p(x)}{q(x)}\right\rangle$

$\frac{p(M\,|\,D,I)}{p(M\,|\,I)} = \frac{p(D\,|\,M,I)}{p(D\,|\,I)}$

Outline

- I. What is Gravitational lensing?
- II. Bayesian forward modelling
- III. Lenses in color - Multi-band joint modeling pipeline
- IV. Results and discoveries

“Mass tells space how to curve, and space tells mass how to move. “ --------Albert Einstein

A Trick of Spacetime's Light

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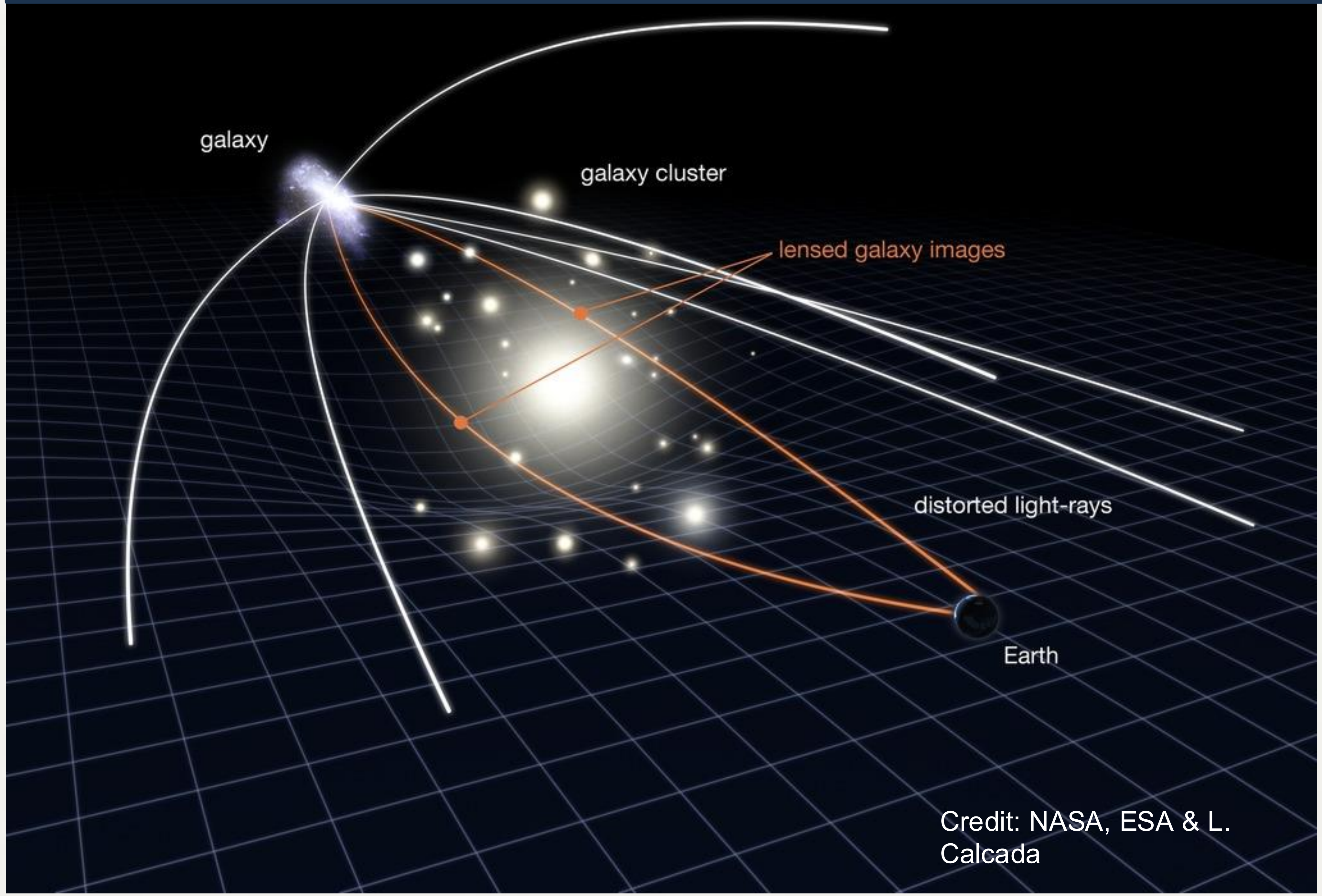
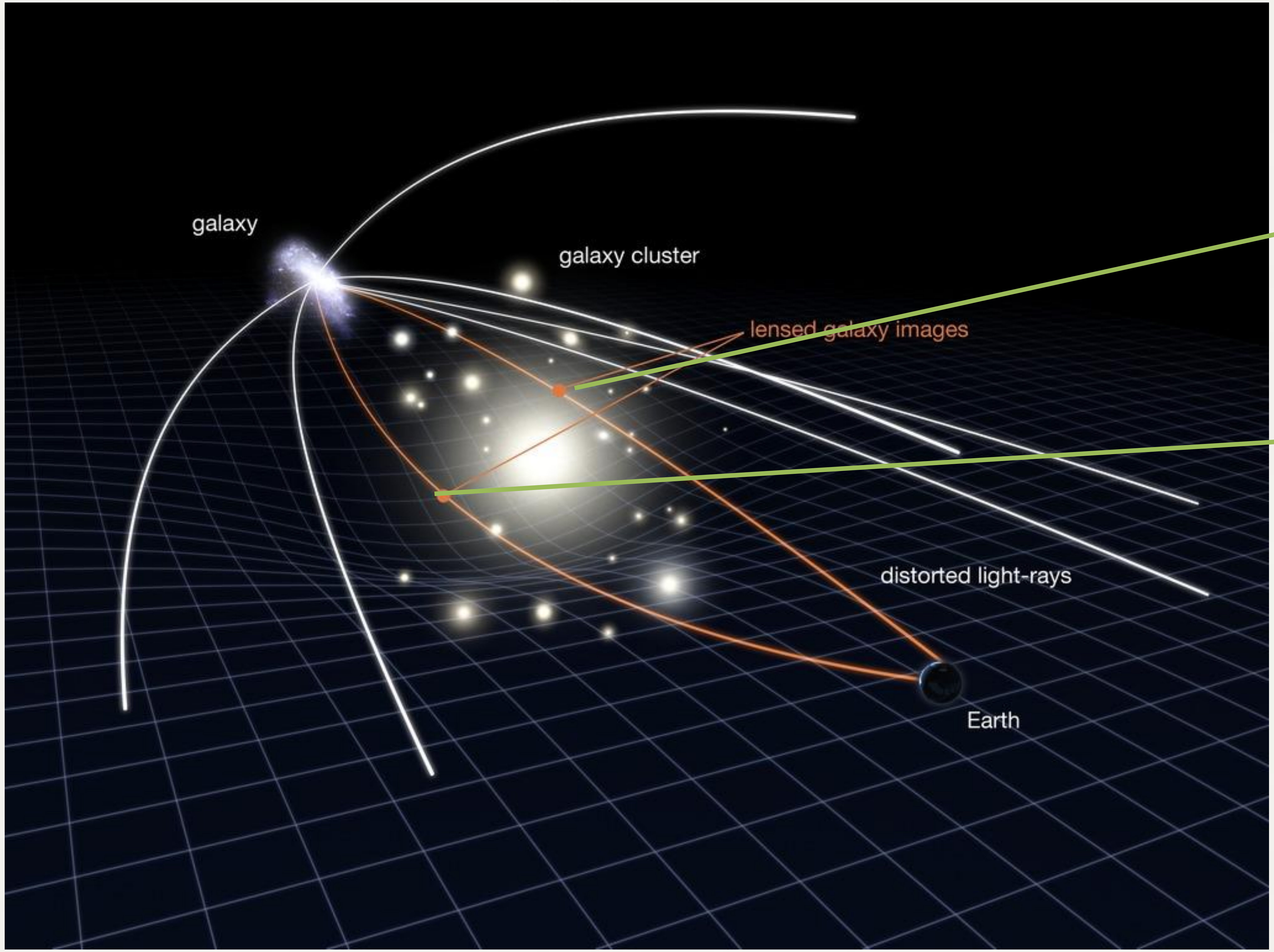


A Trick of Spacetime’s Light



Massive objects bend spacetime, acting as “cosmic telescopes” that distort and magnify light from background sources.


Big
Questions!

The Power of a Cosmic Telescope

+ Mapping the distribution of dark matter in galaxies.
+ Detecting faint dark substructures (subhalos, satellite galaxies).
+ Magnifying the early universe to study the first galaxies.
+ Providing unique cosmological probes (e.g., time-delay cosmography for the Hubble constant).

The Core Challenge is an Inverse Problem

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We observe the effect (the lensed image) and must infer the underlying cause (the lens mass and original source light).

Our Toolkit: Bayesian Forward Modeling

$$P(\theta|D) \propto P(D|\theta)P(\theta)$$

Posterior

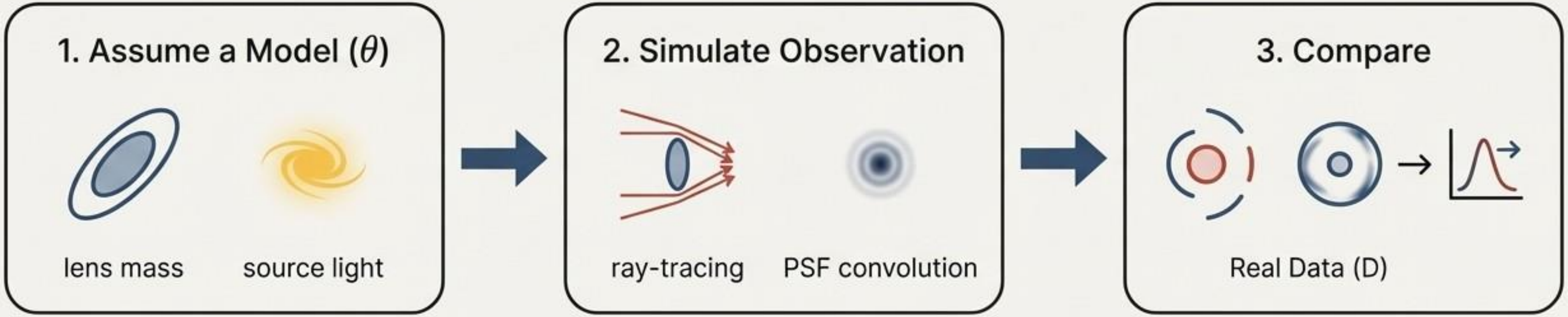
Likelihood

Prior

Our Toolkit: Bayesian Forward Modeling

$$P(\theta|D) \propto P(D|\theta)P(\theta)$$

Posterior **Likelihood** **Prior**



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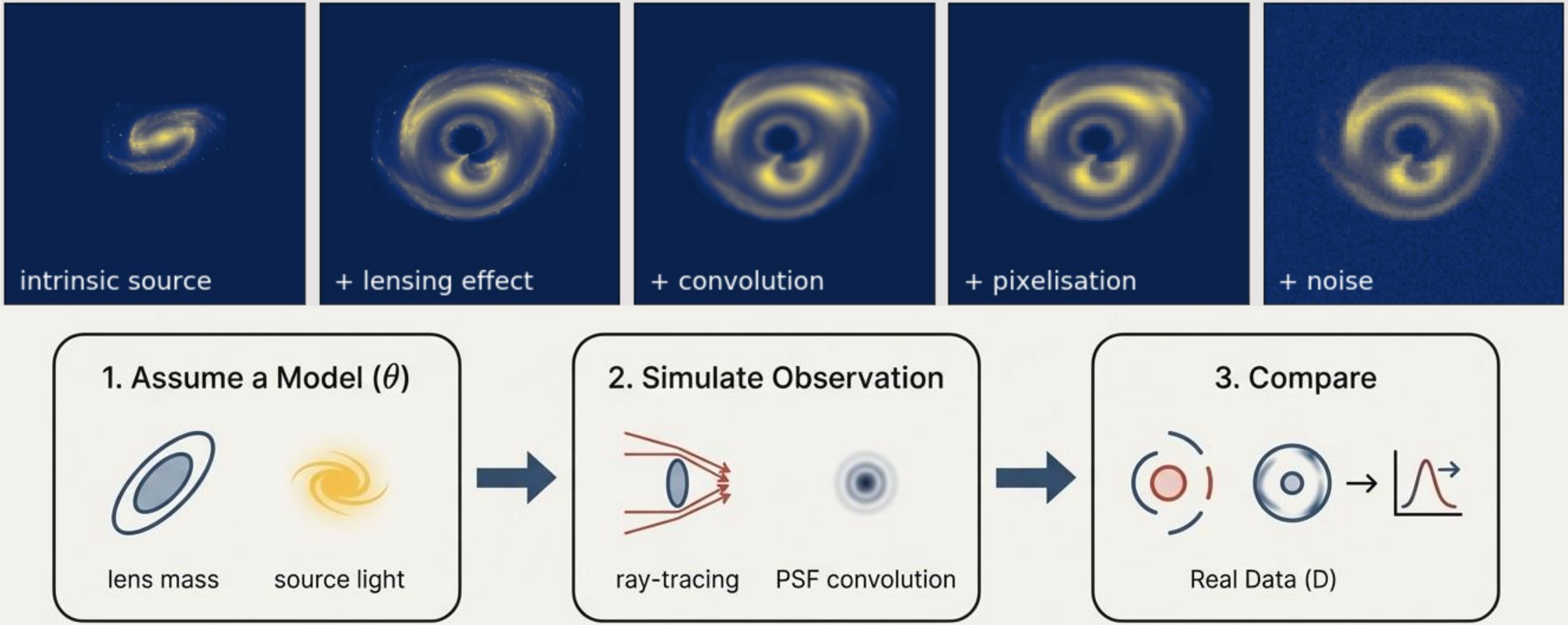
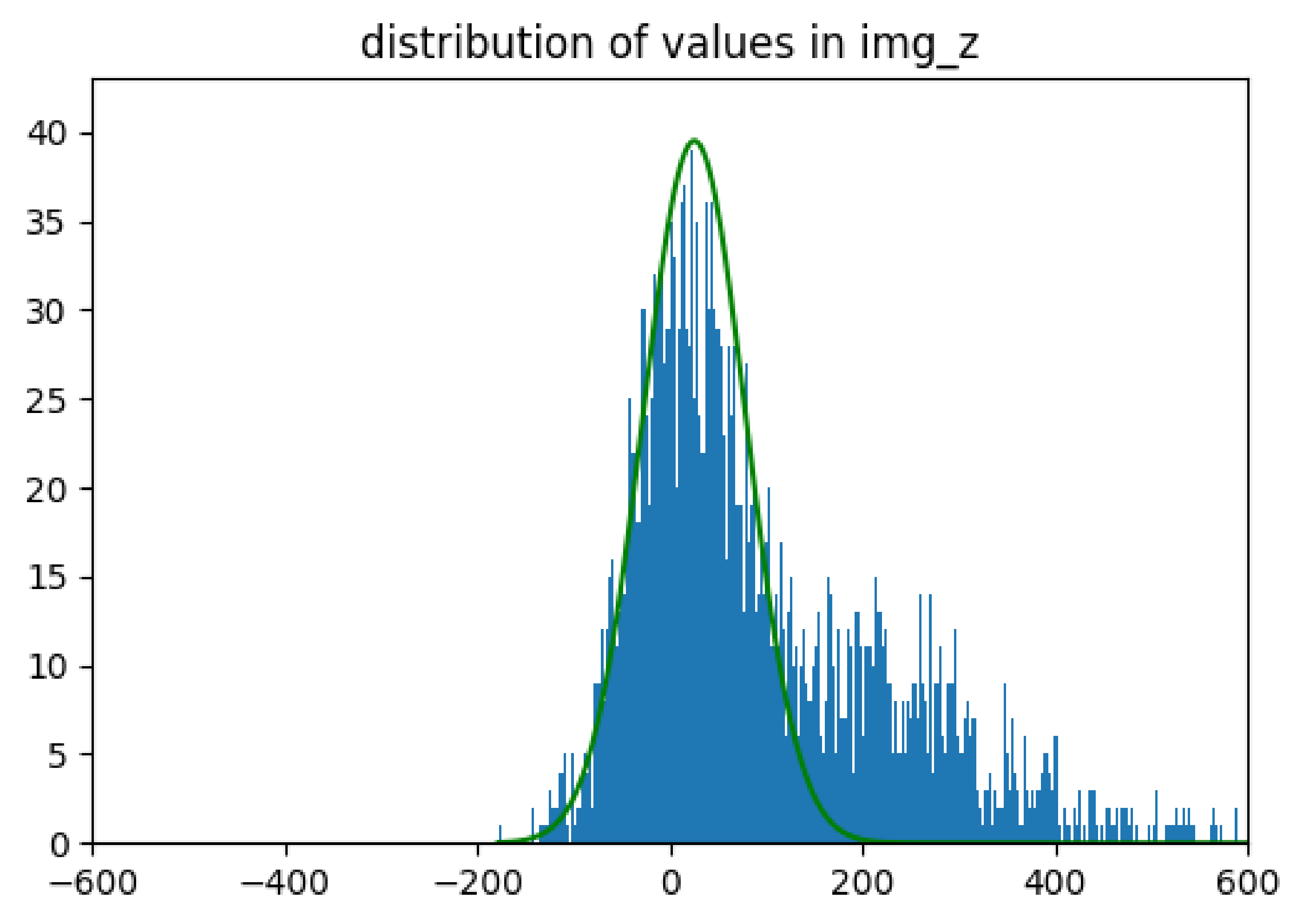


Likelihood

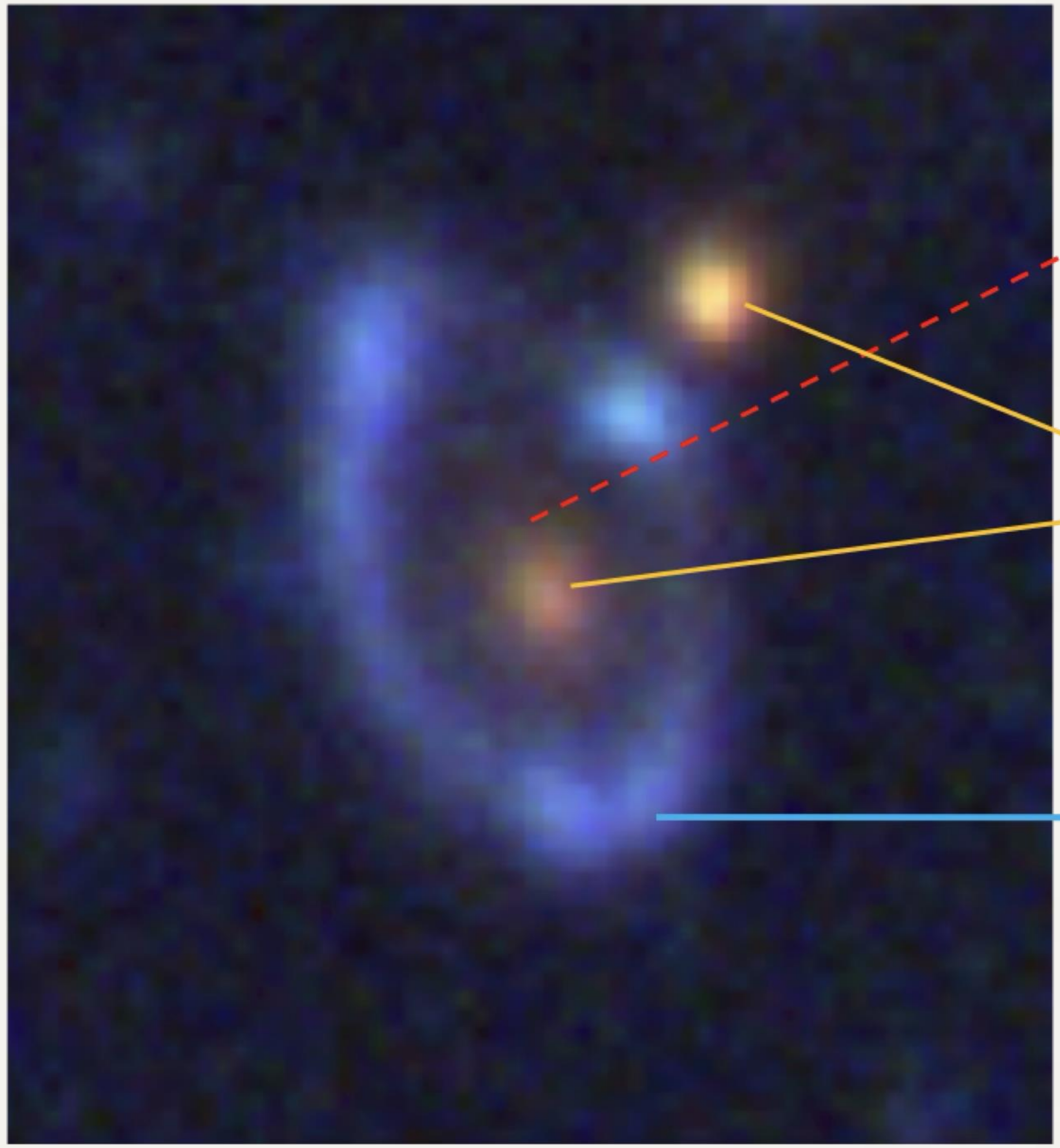
$$\log p(d_{\text{data}} \mid d_{\text{model}}) = \sum_i \frac{(d_{\text{data},i} - d_{\text{model},i})^2}{2\sigma_i^2} + \text{const.}$$



"It is just the great good luck of Gaussian distributions that the objective can be written as a quadratic function of the data... This is a miracle."

——Data analysis recipes: Fitting a model to data
David W. Hogg et al.

Describing a lens system in three components



Lens mass: commonly elliptical power law (EPL) with external shear

Lens light

Source light

Lens light and Source light: combinations of elliptical Sersic profiles, core-sersic...

The Art of Approximation: Parametric Models

We model complex reality with simplified, analytical functions.

- Example for Lens Mass: Elliptical Power Law profile.
- Example for Source Light: Sérsic profile.

REAL GALAXY

The Art of Approximation: Parametric Models

One lens candidate observed with PISCO

We model complex reality with simplified, analytical functions.

- Example for Lens Mass: Elliptical Power Law profile.
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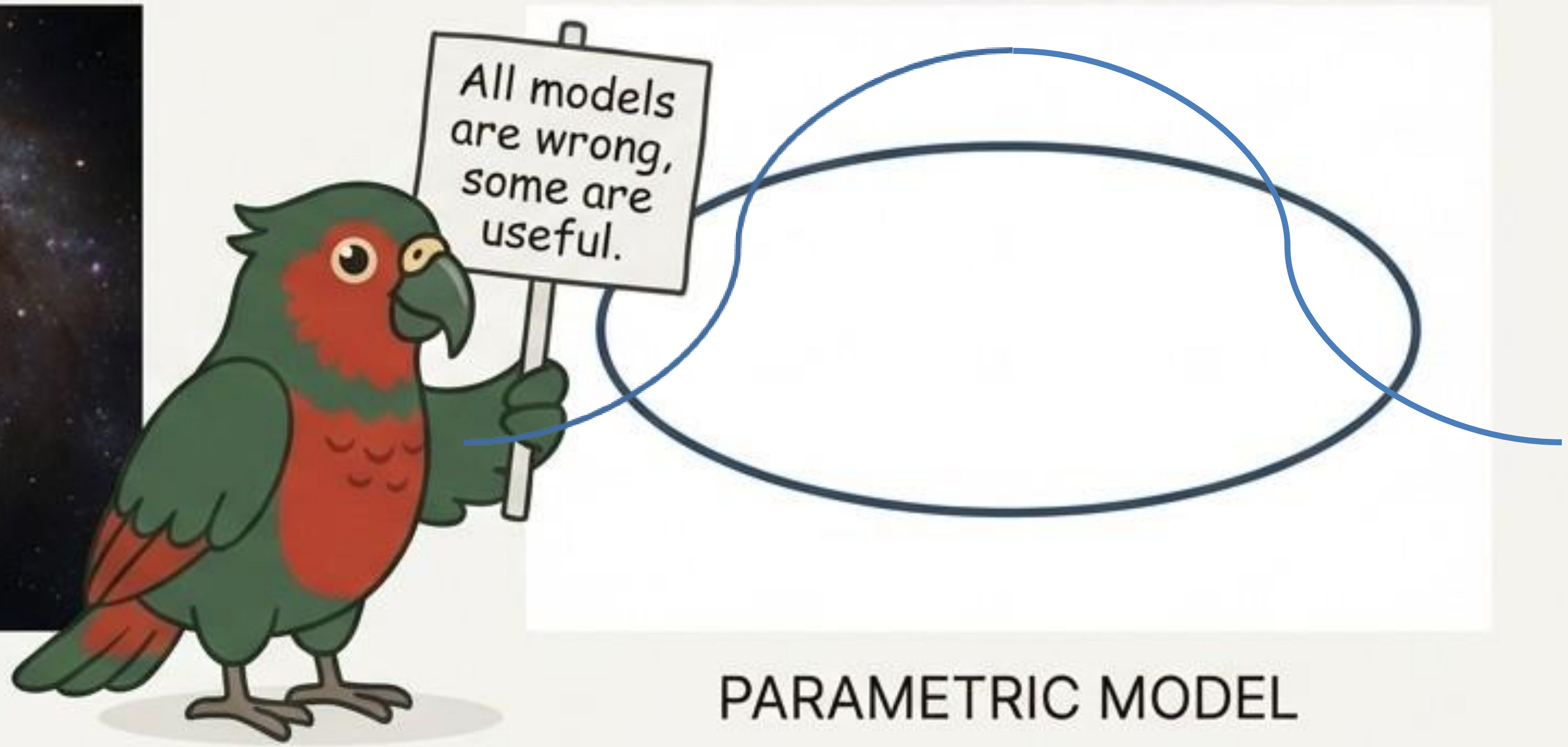
REAL GALAXY



PARAMETRIC MODEL

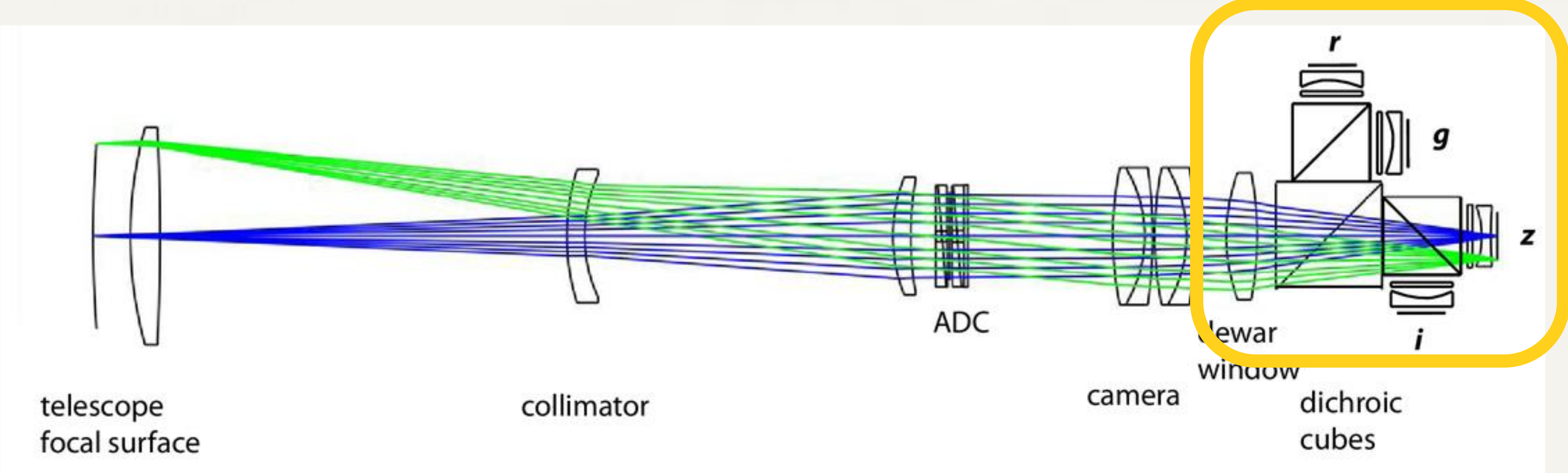
The PISCO Sample

PISCO: Parallel Imager for Southern Cosmology Observations

simultaneous multi-band imaging: z, i, r, g

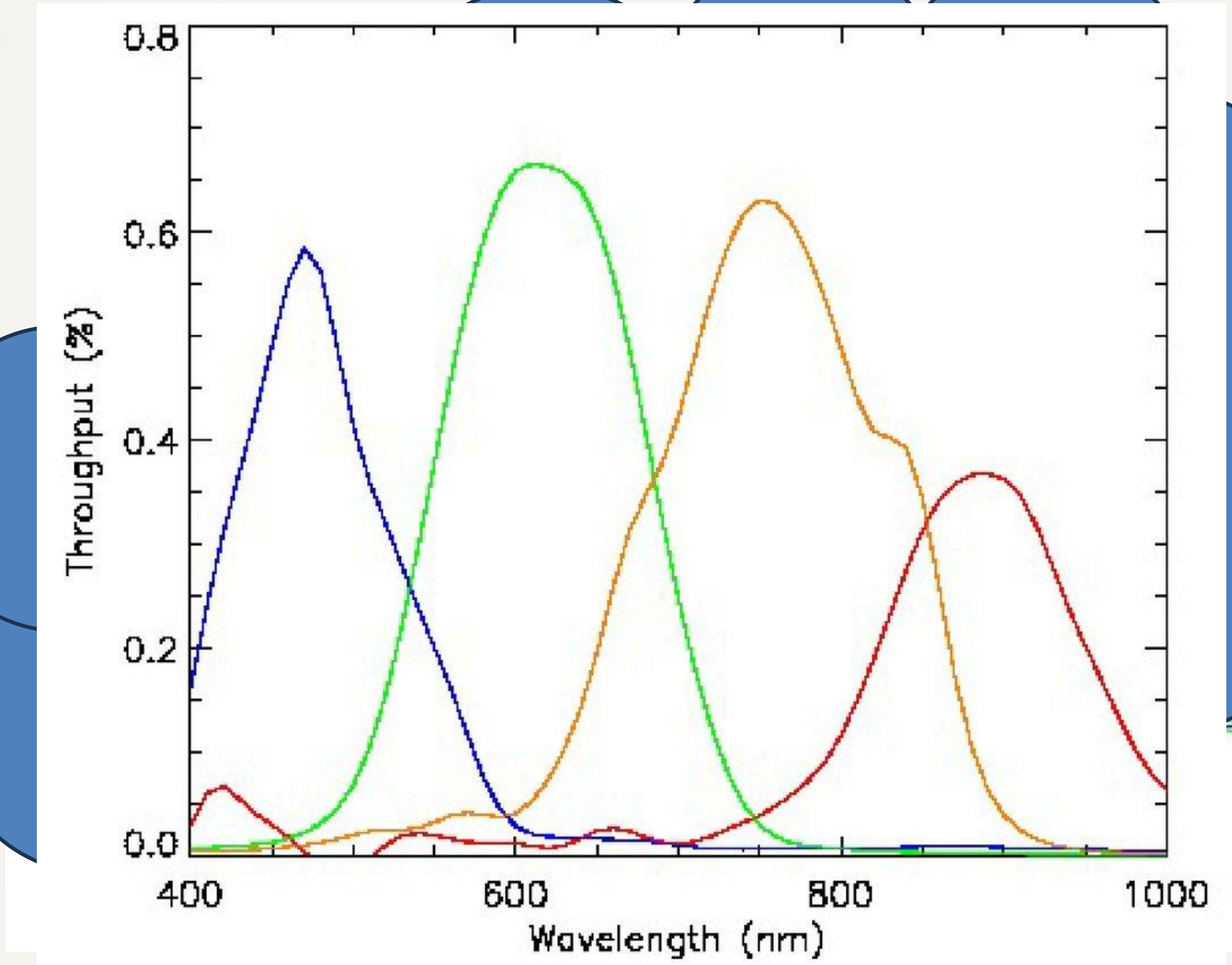
resolution: 0.218″/pixel, limited by seeing ~0.6–1.1″

FOV: 9’

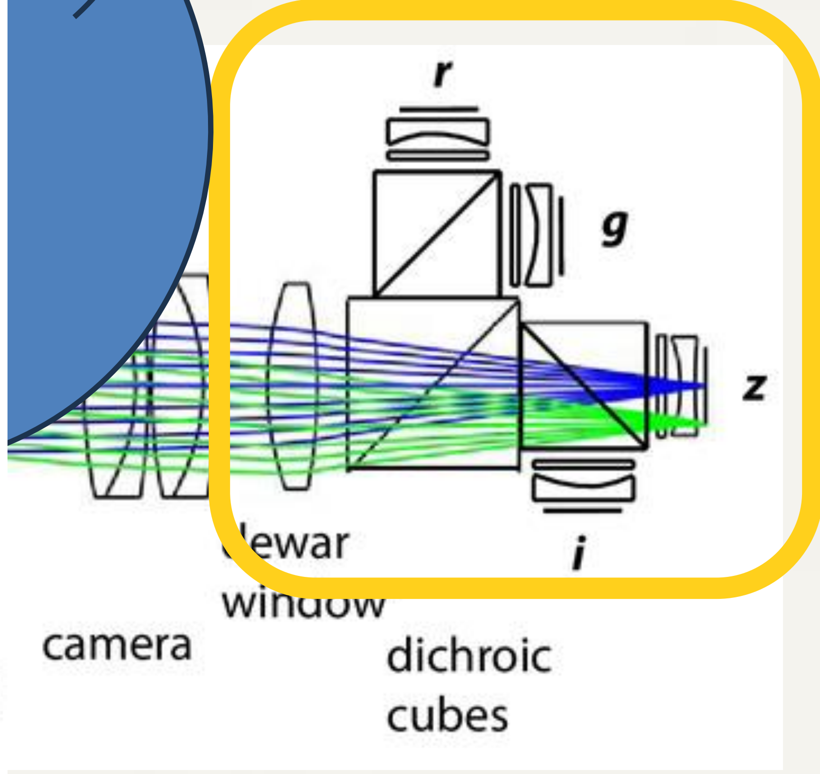


Stalder et al. 2014

PISCO: Parallel Imager for Southern Cosmology Observations

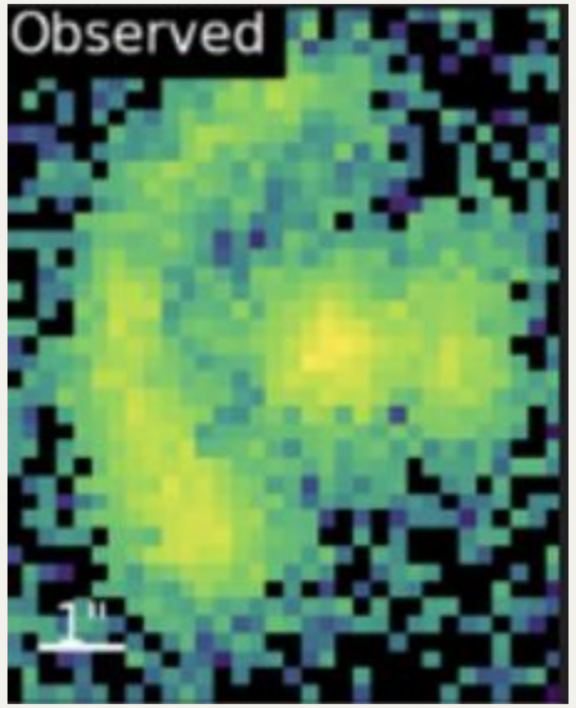


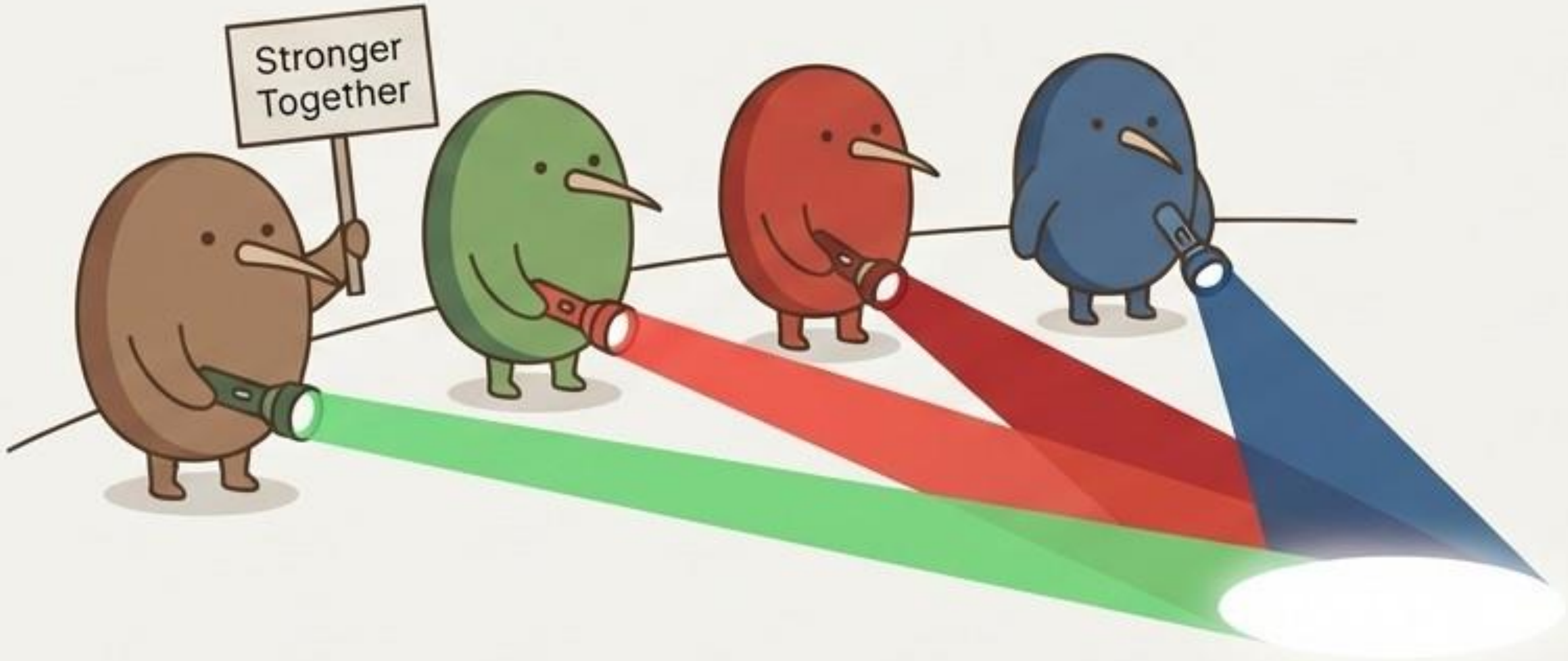
-1.1″

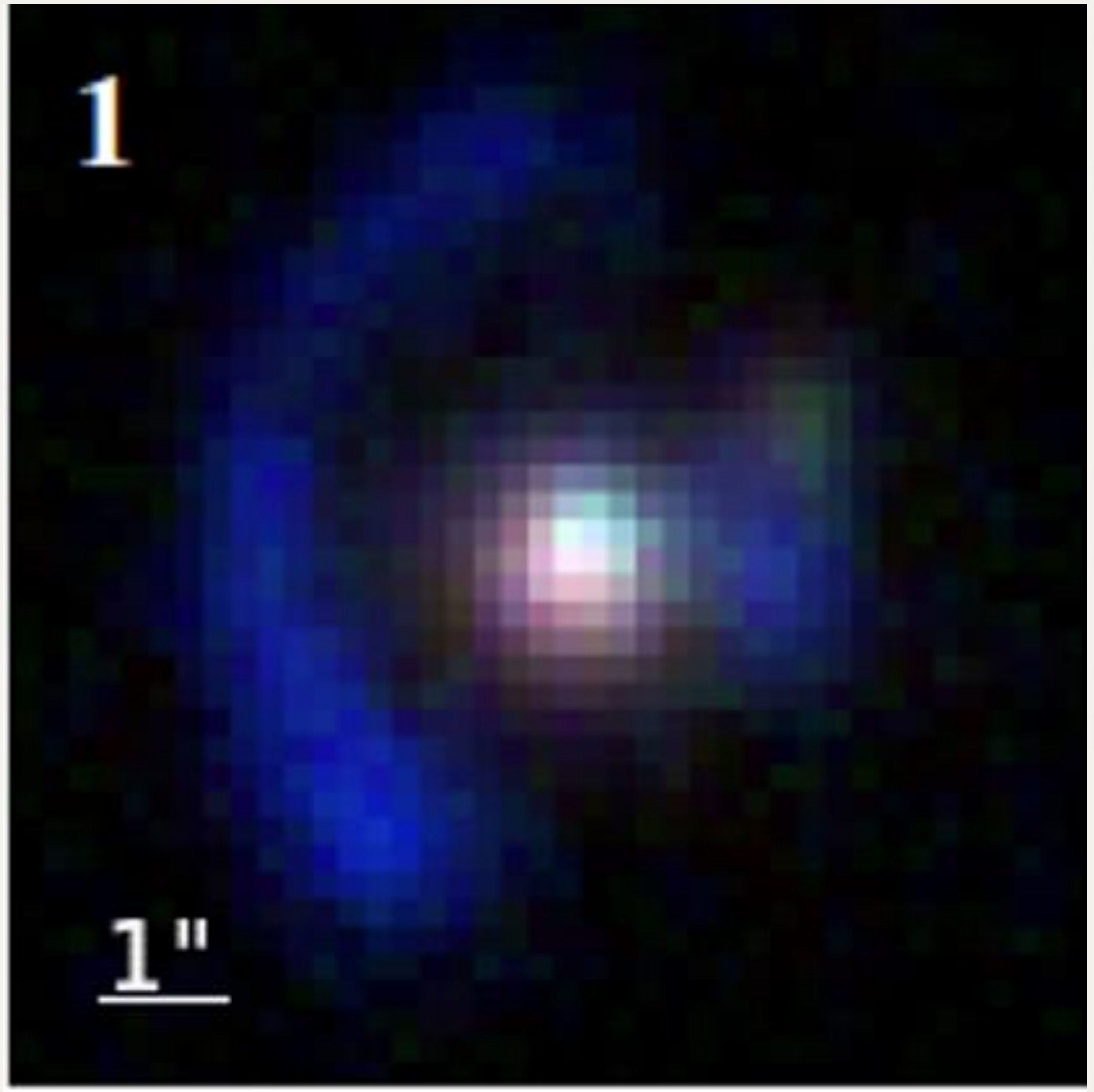


Stalder et al. 2014

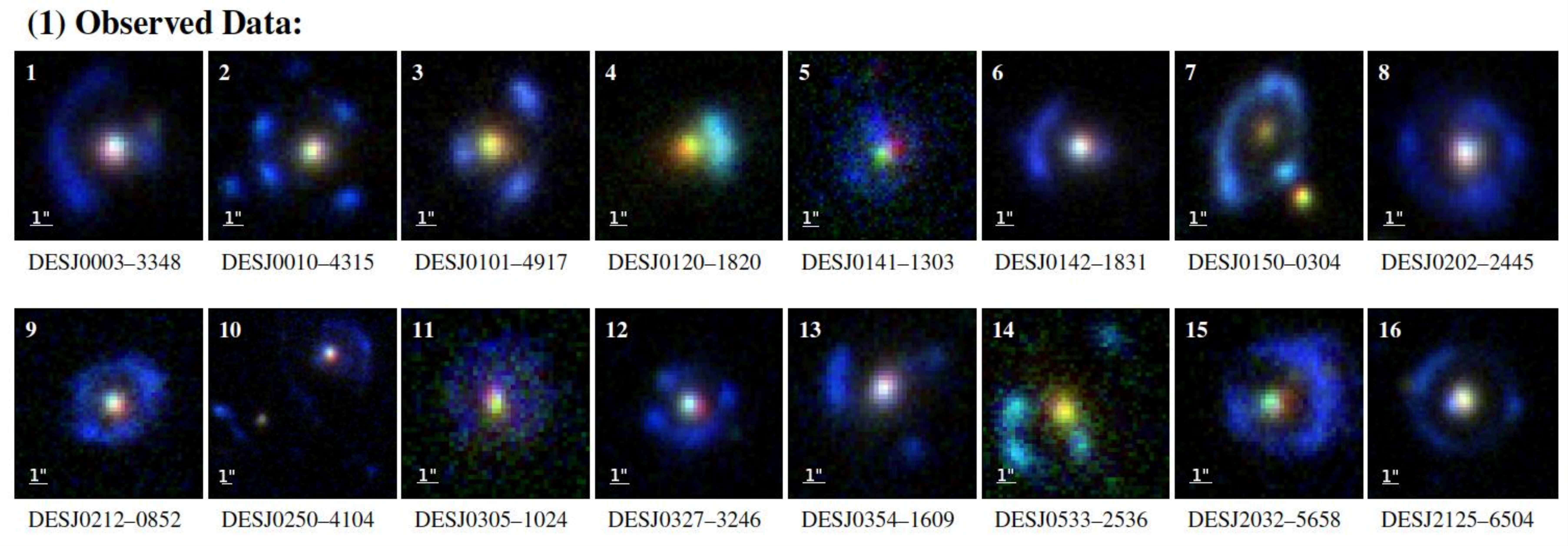
Why Colour Unlocks Clarity



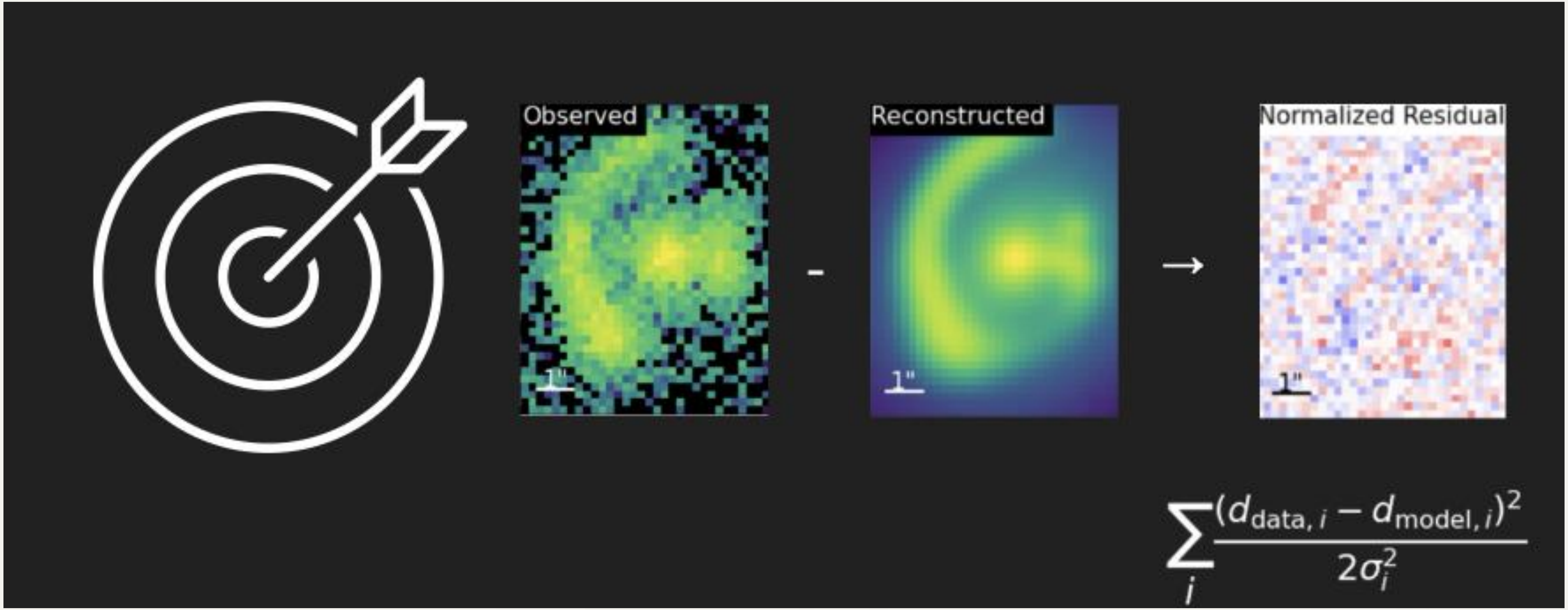




The PISCO Sample: 16 Lens candidates in color



How We Infer from Data



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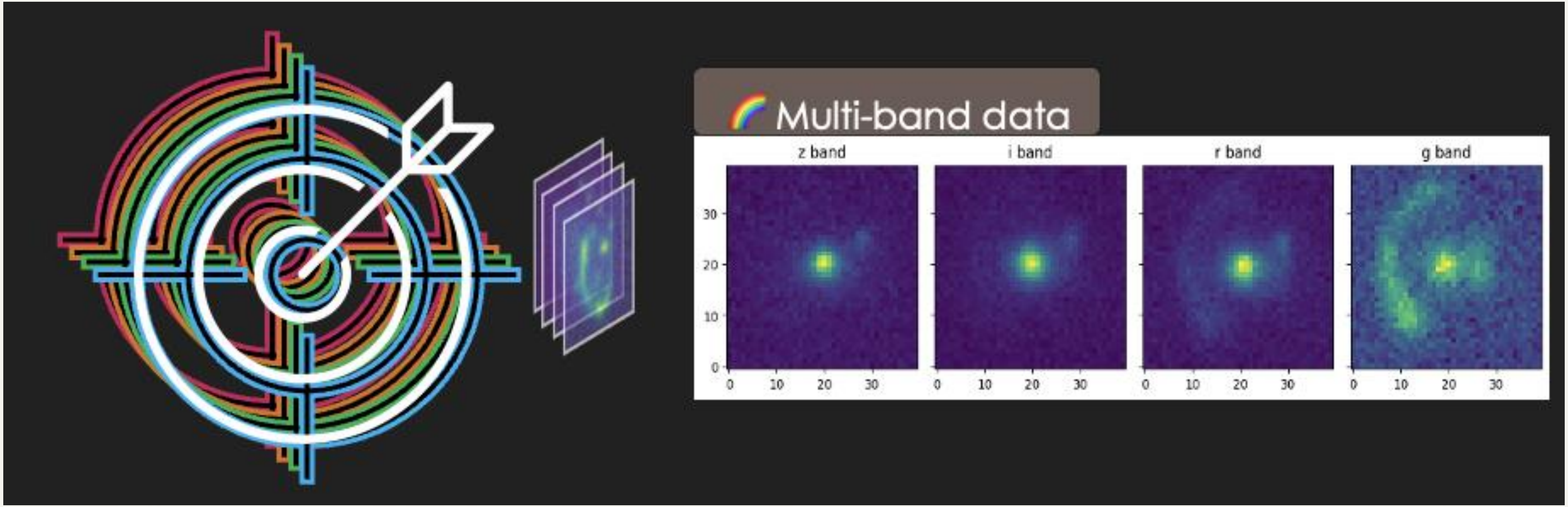

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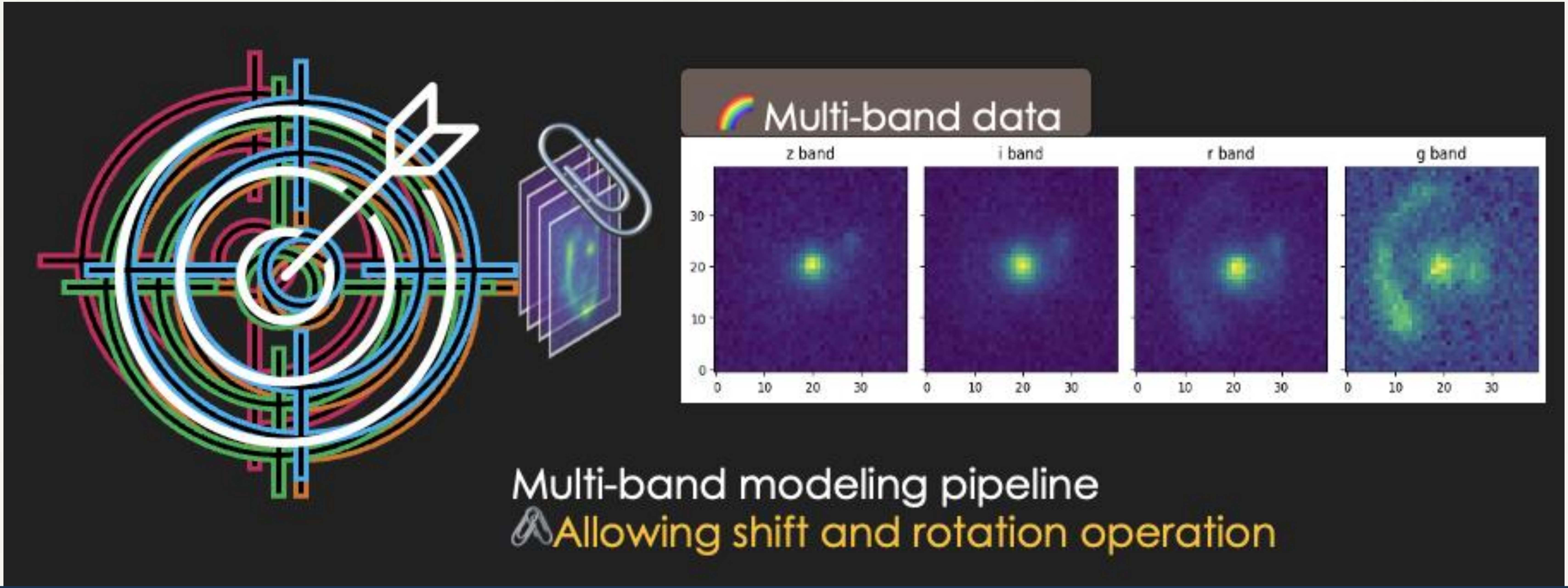
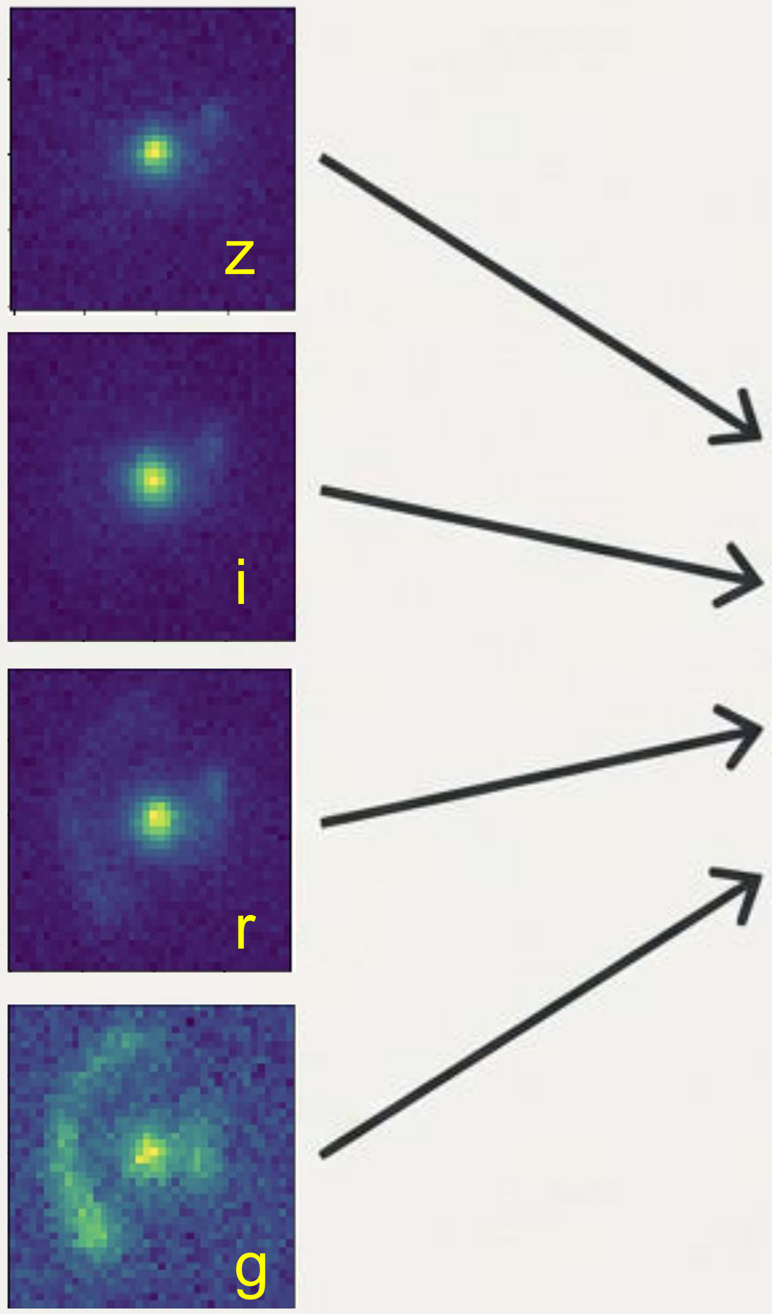


$$\log p(d_{\text{data}} \mid d_{\text{model}})_{4\ \text{bands}} = \sum_{b \in \{z,i,r,g\}} \log p(d_{\text{data}} \mid d_{\text{model}})_b$$

Our Innovation: A Joint Multi-Band Pipeline



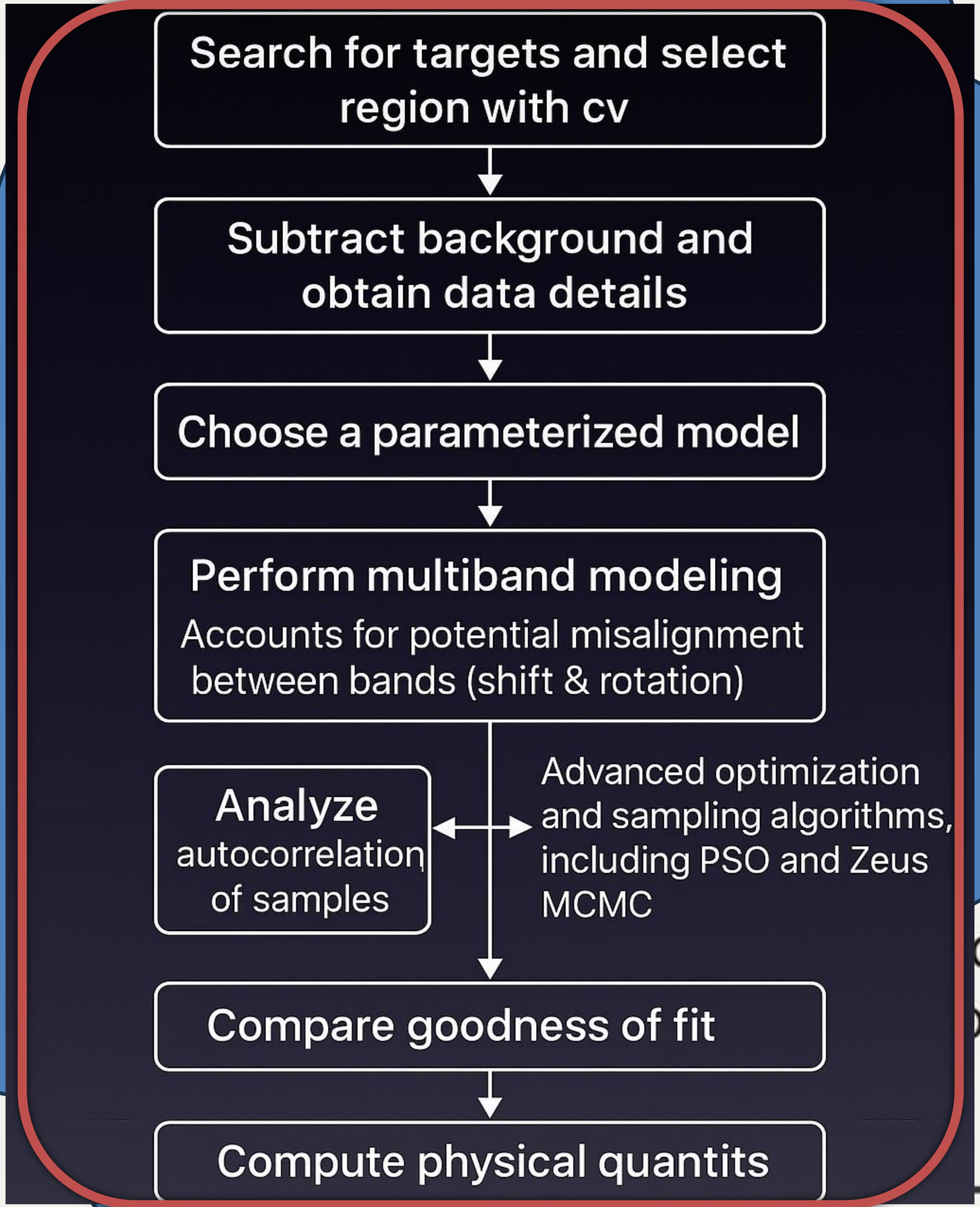
PISCO Bands

Unified Bayesian Model

✓ **Shared Physical Parameters:**
Lens mass model is consistent across all bands.

✓ **Band-Specific Nuisance Parameters:**
Source light profile, instrumental shift, and rotation are allowed to vary between bands.

Built on the scalable `Lenstronomy` framework. The `r` band is used as the reference.



Joint Multi-Band Pipeline

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Ba

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So What's the Gain from Multi-band Fit?

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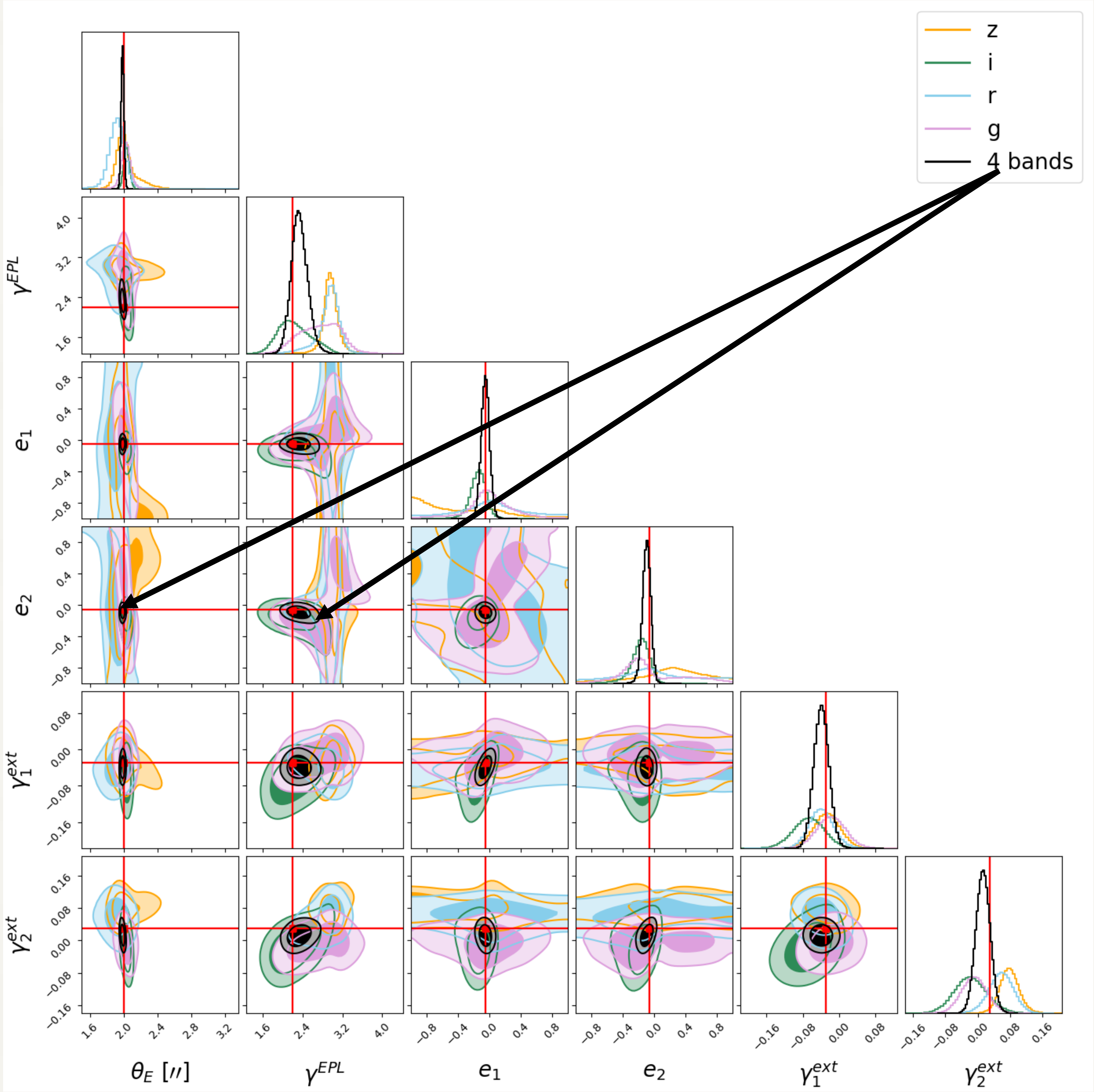
Posteriors based on
Mock data test

----4 bands fits really helps!



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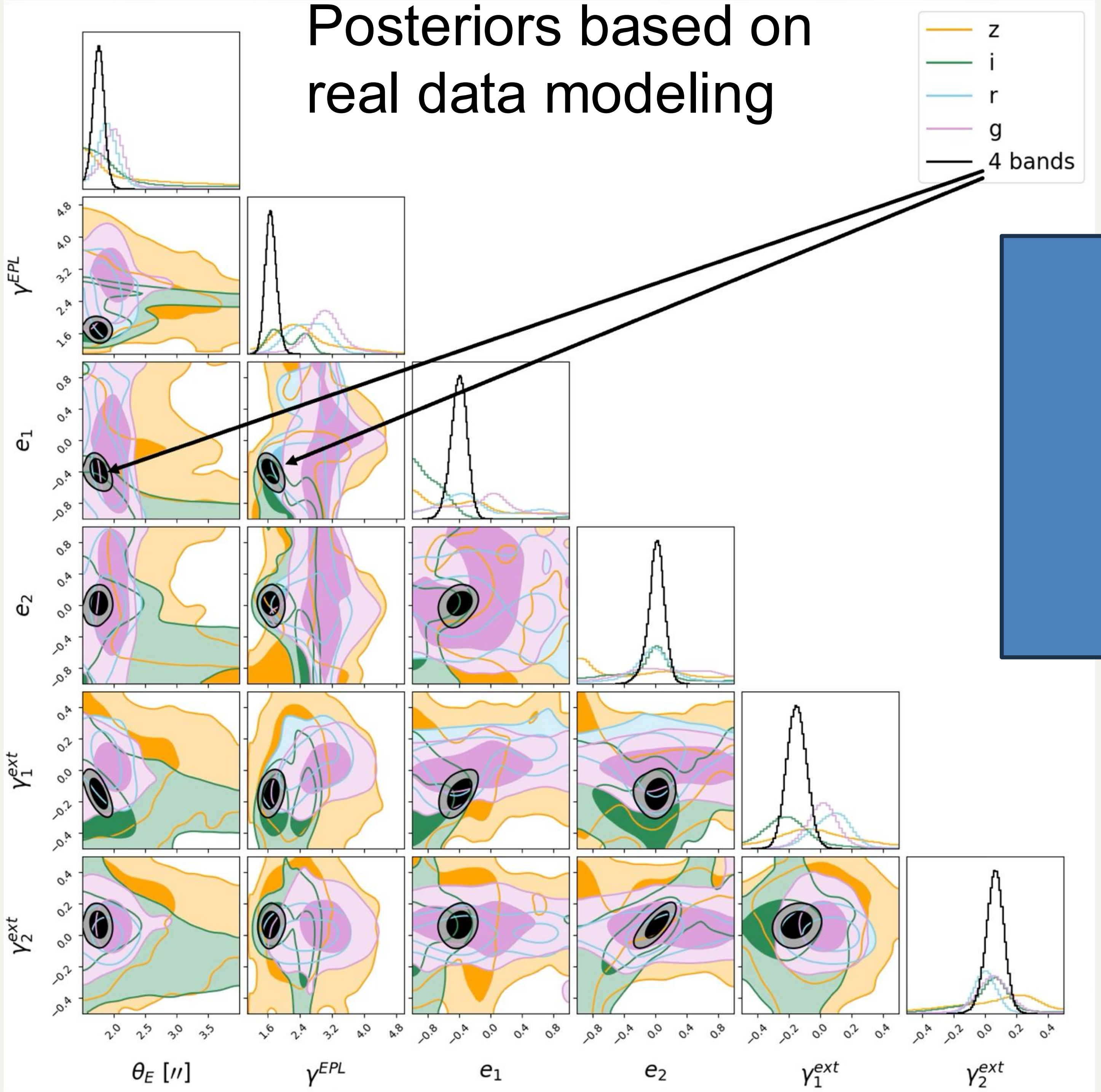
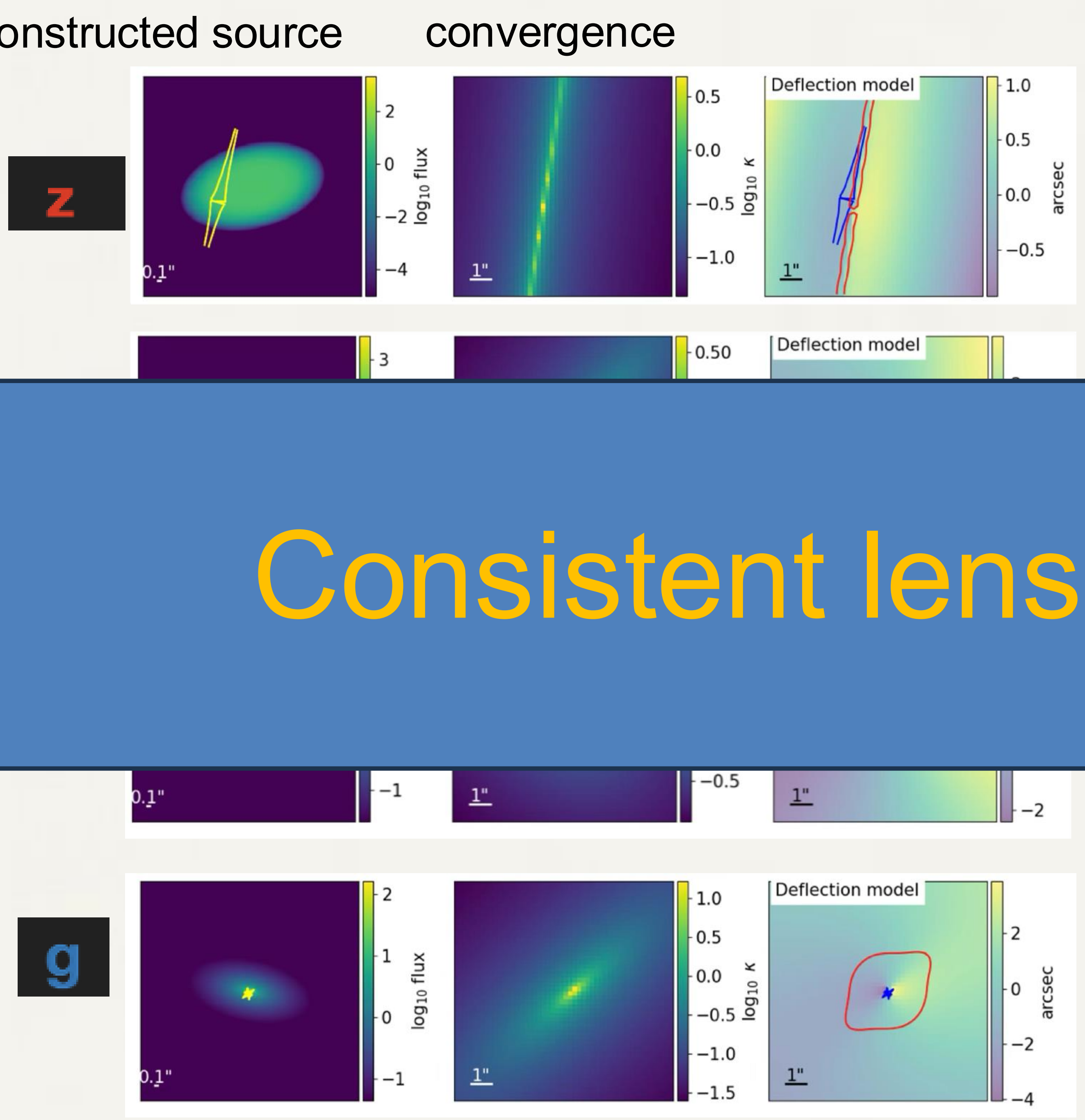
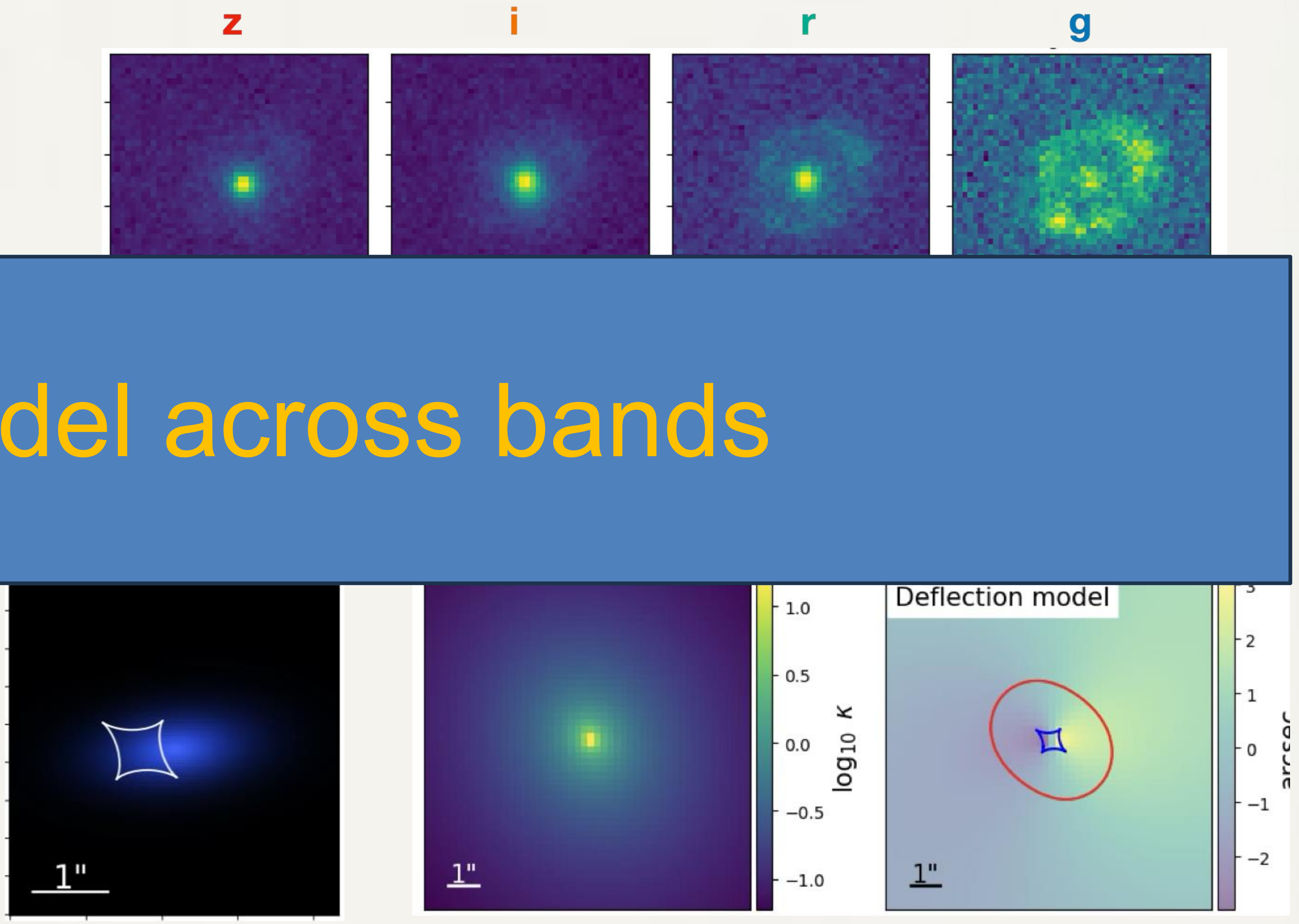


Tighter posteriors

Achieved ~2.2% mean uncertainty on Einstein radius for the PISCO sample (68% CI)

So What's the Gain from Multi-band Fit?



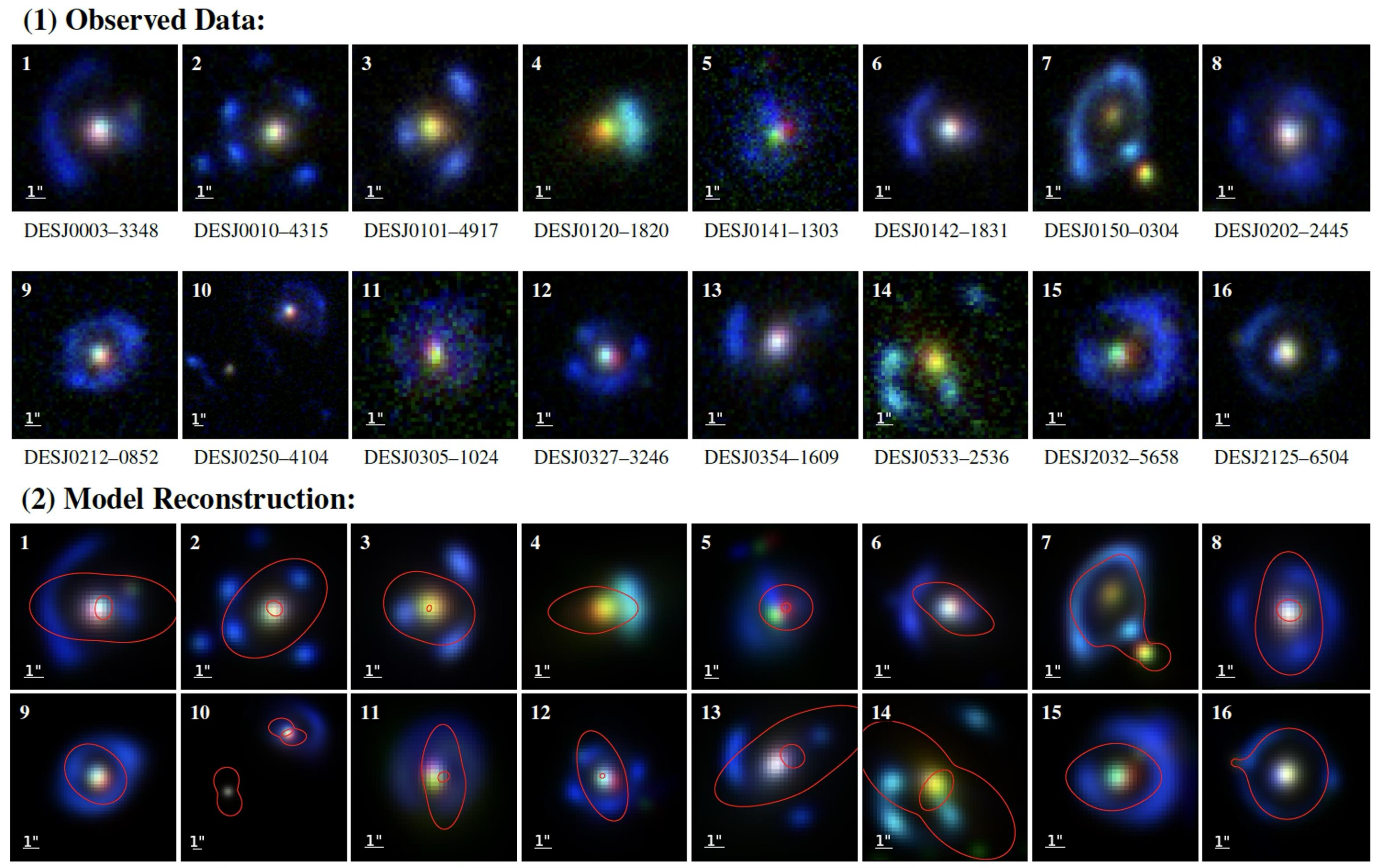


Consistent lens model across bands

single-band fit

Multi-band fit

Results – Overview



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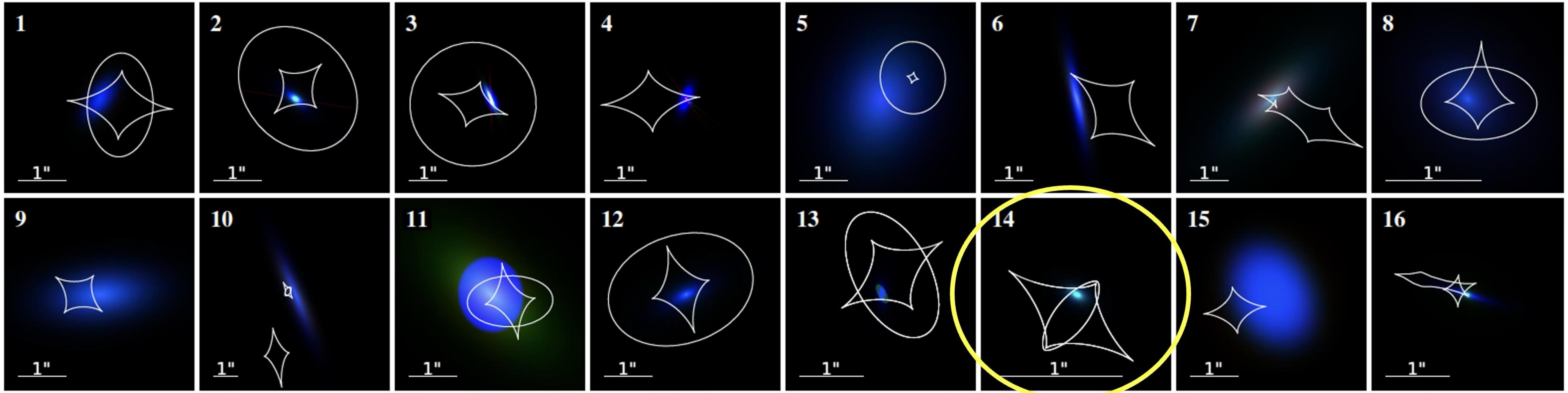
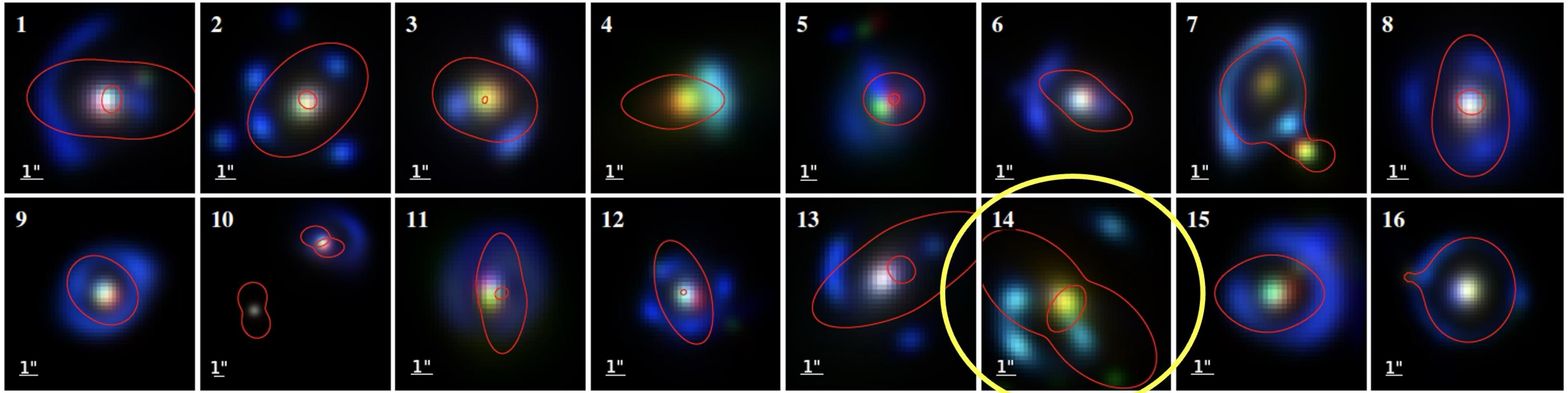
in revision

Results – Overview

(3) Source–plane Reconstruction:



(2) Model Reconstruction:



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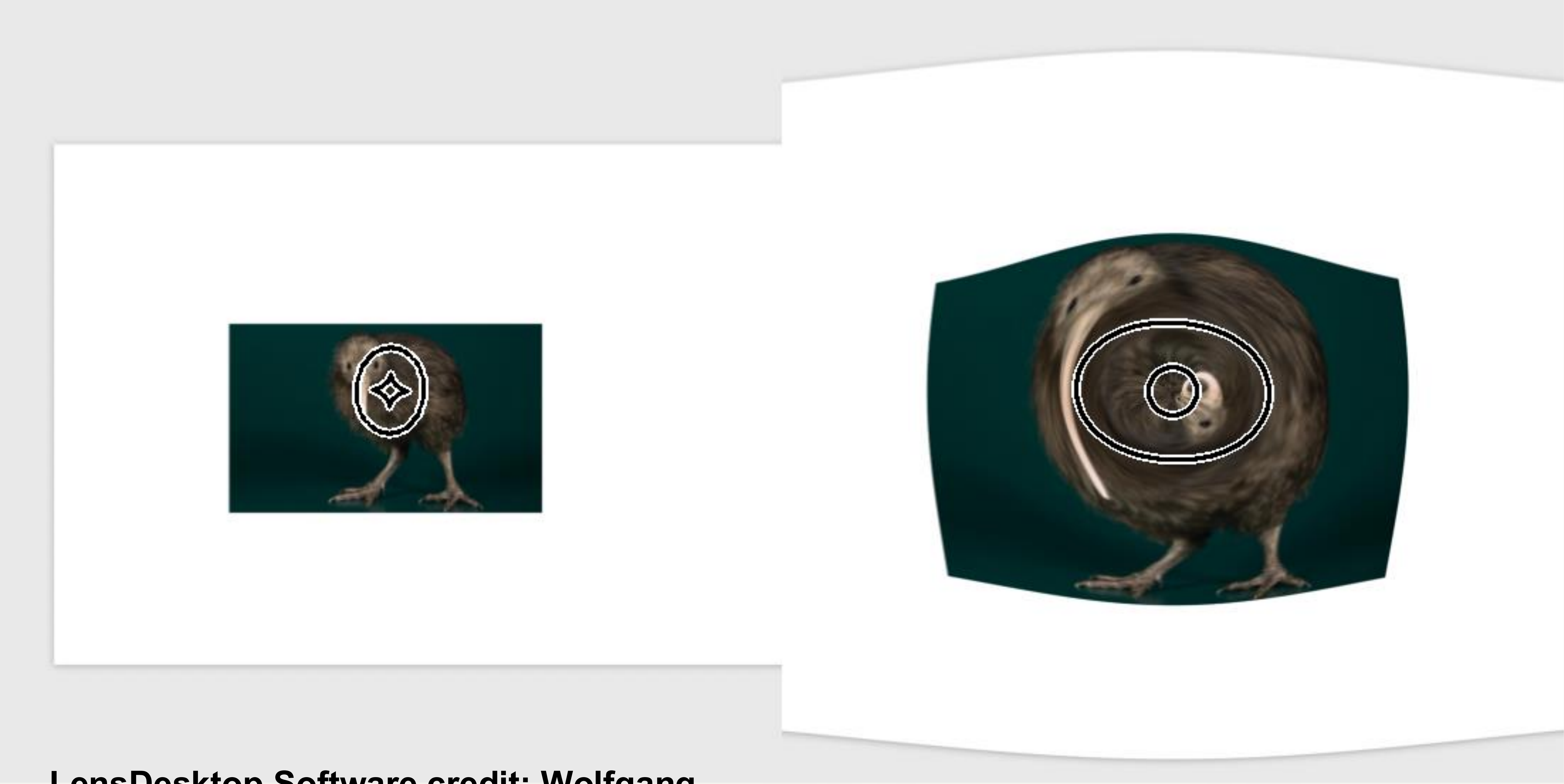
LensDesktop Software credit: Wolfgang



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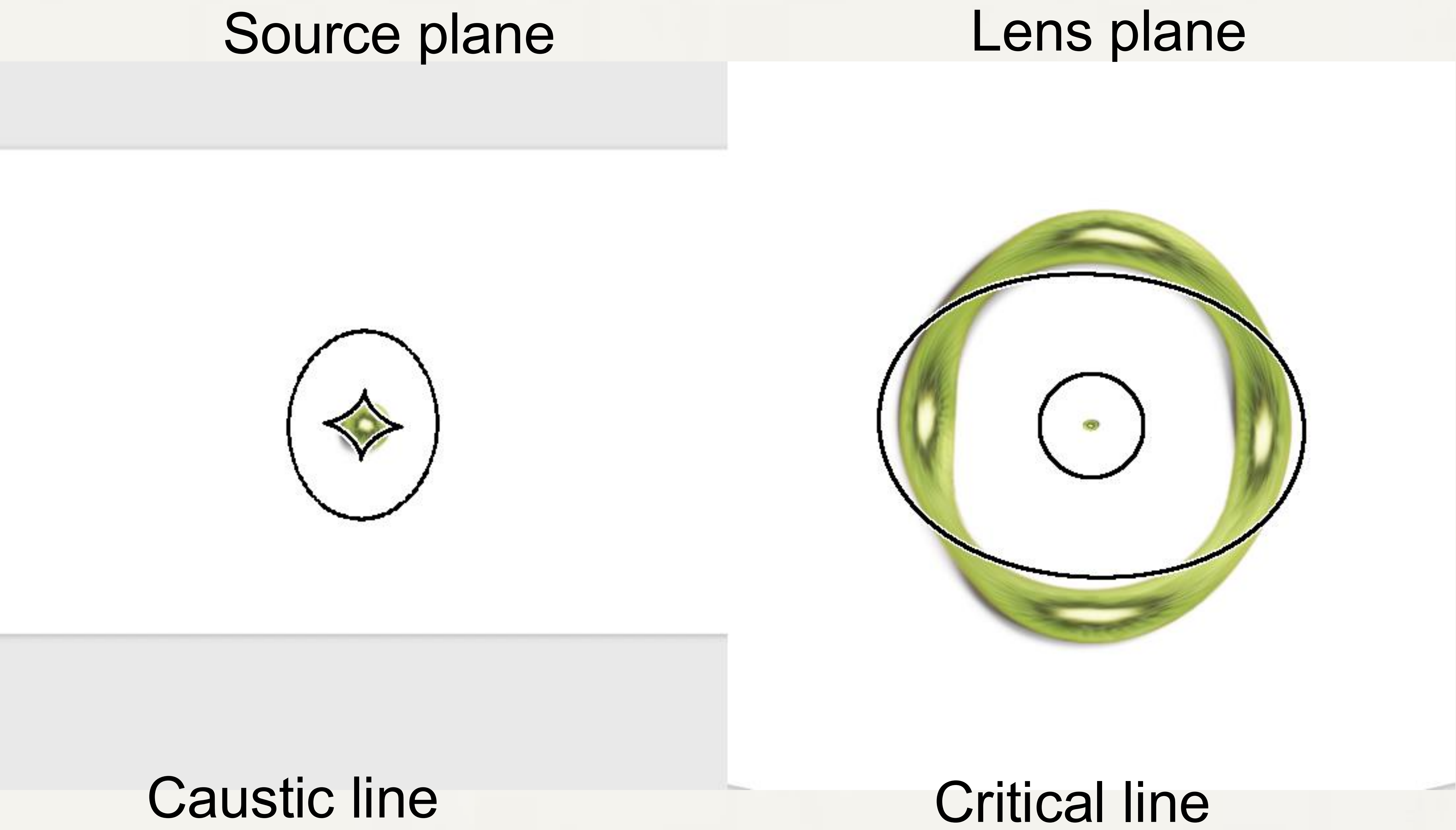
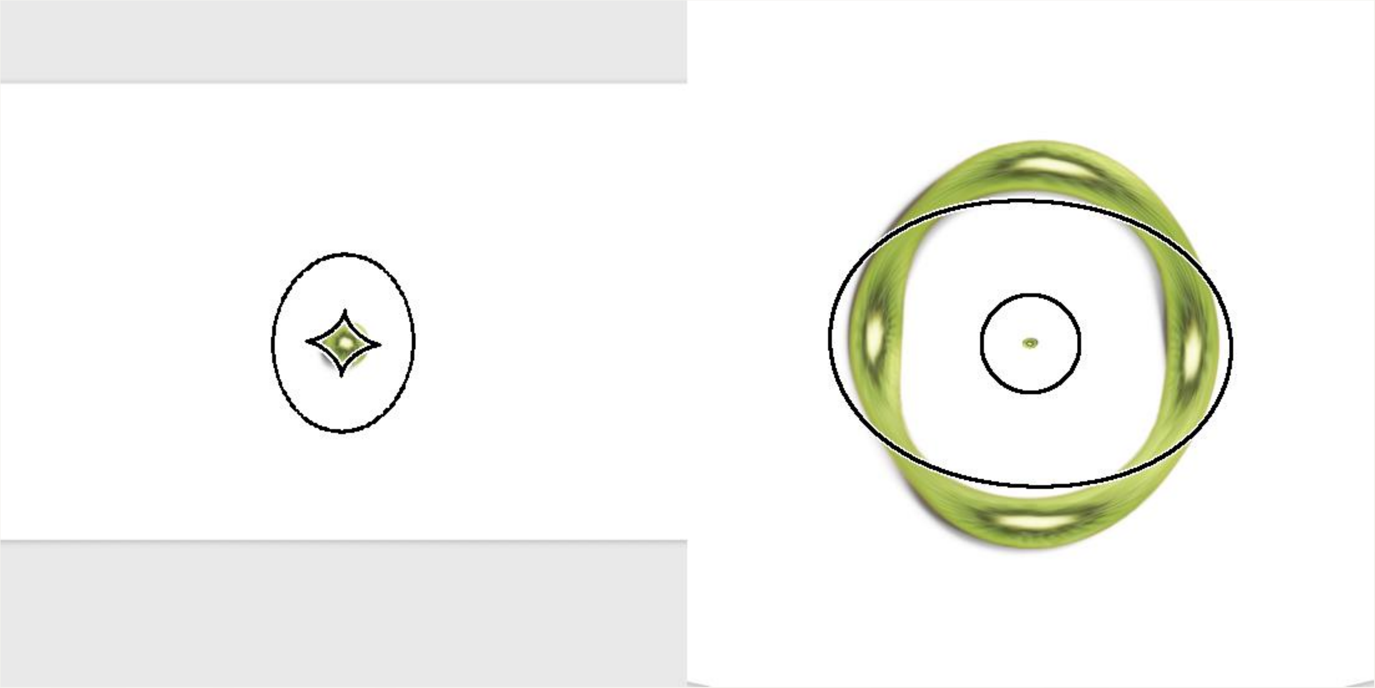
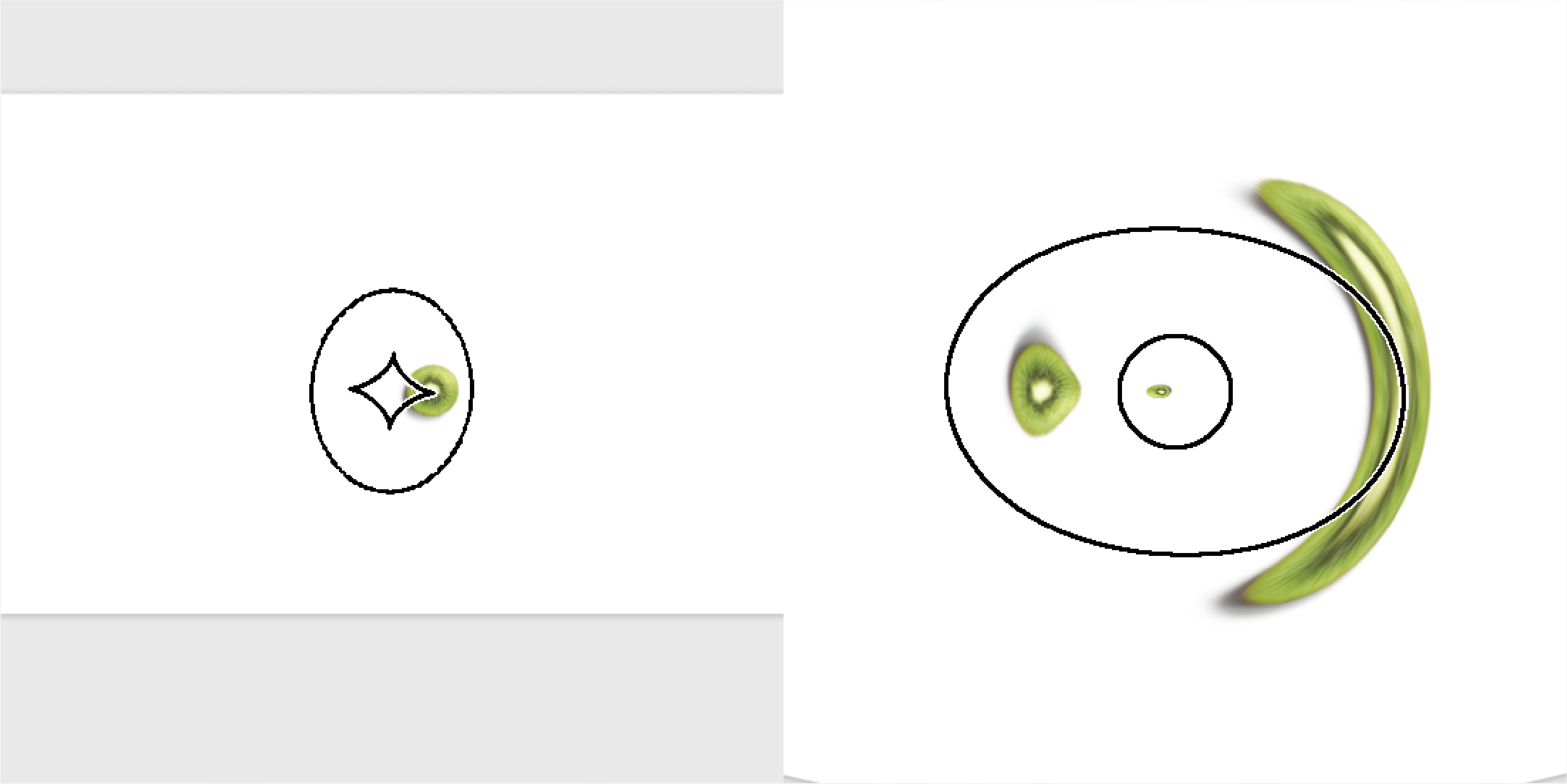

Source plane
Lens plane
Caustic line
Critical line

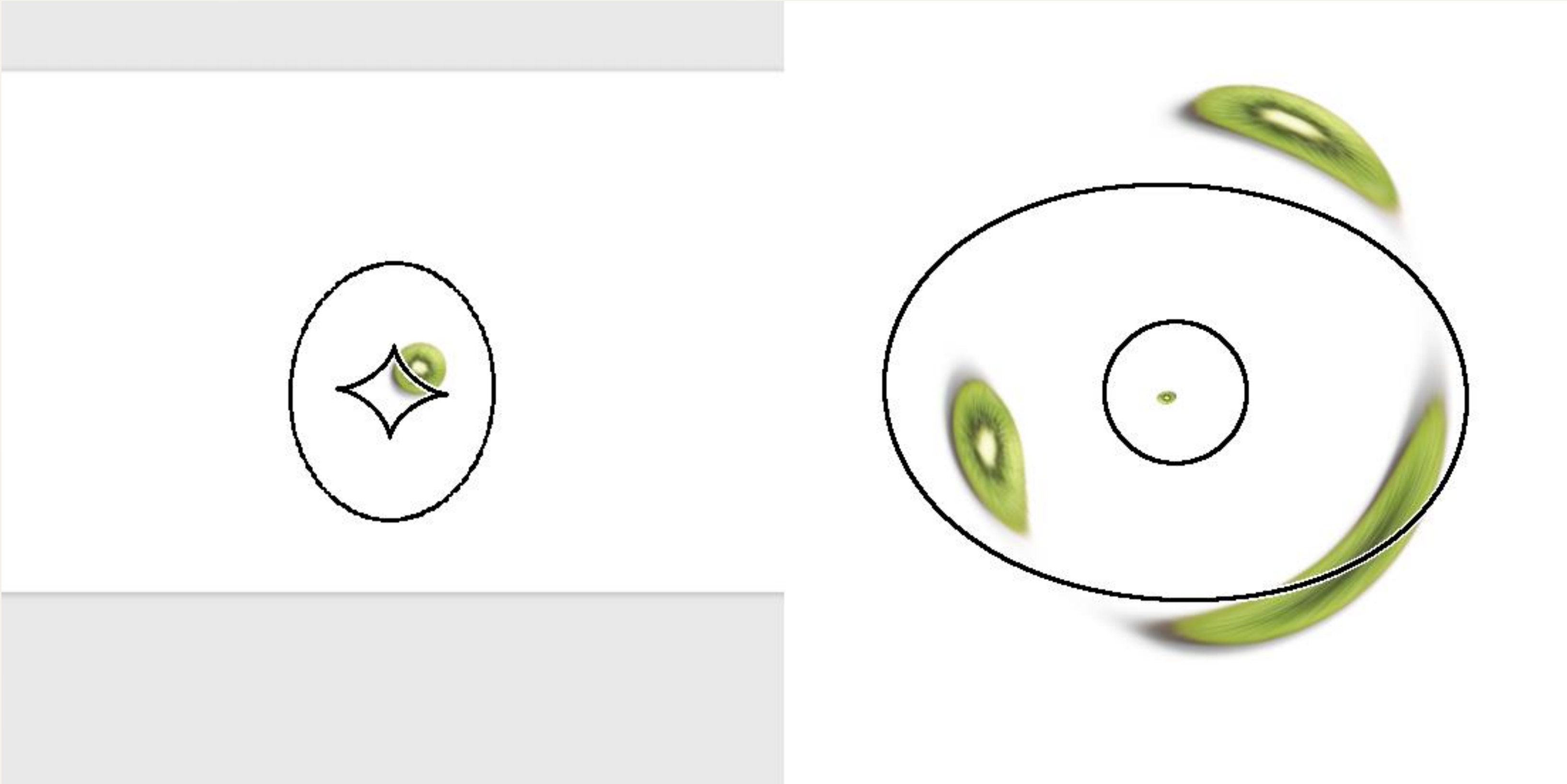
Einstein Cross :



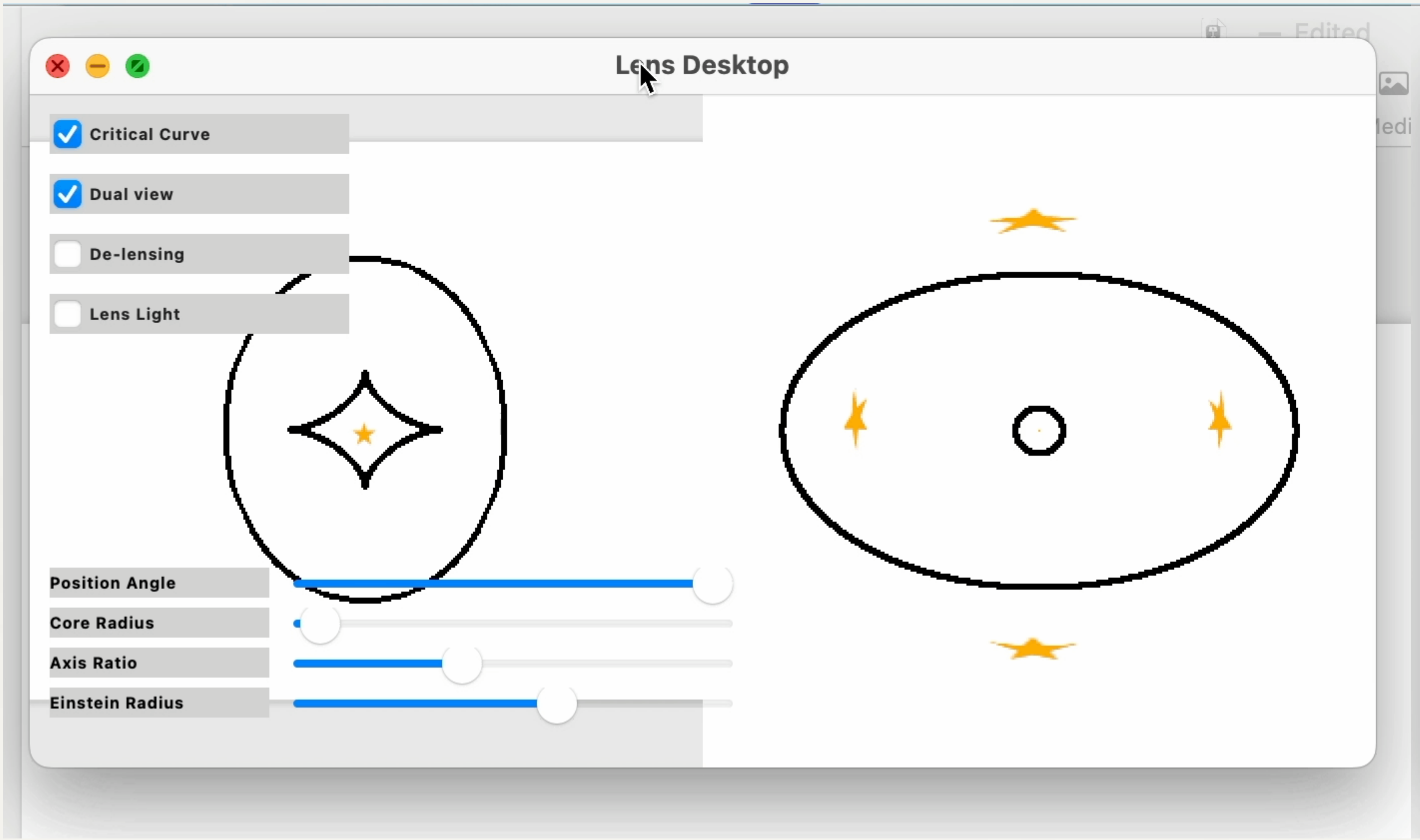
Cusp:

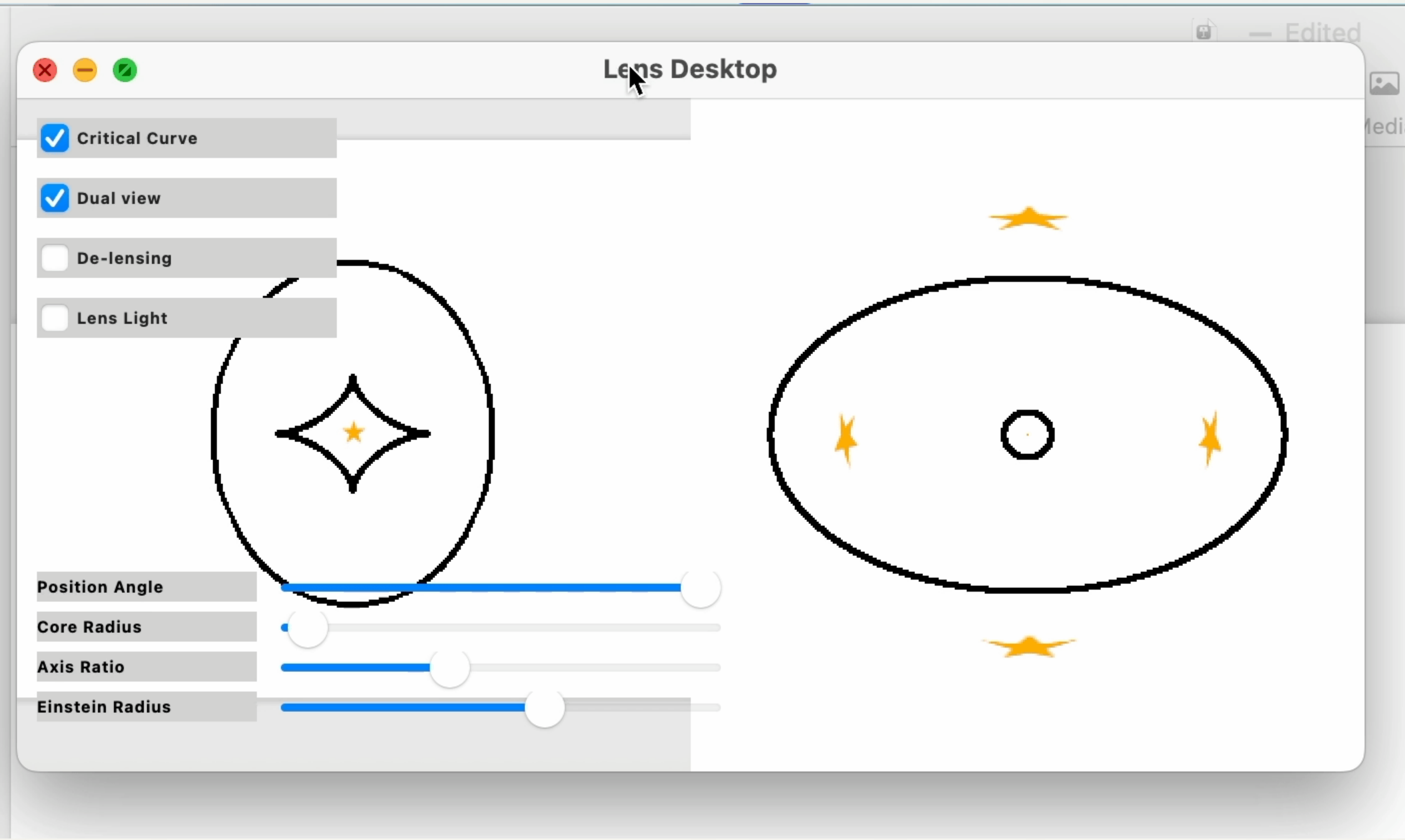


Fold:

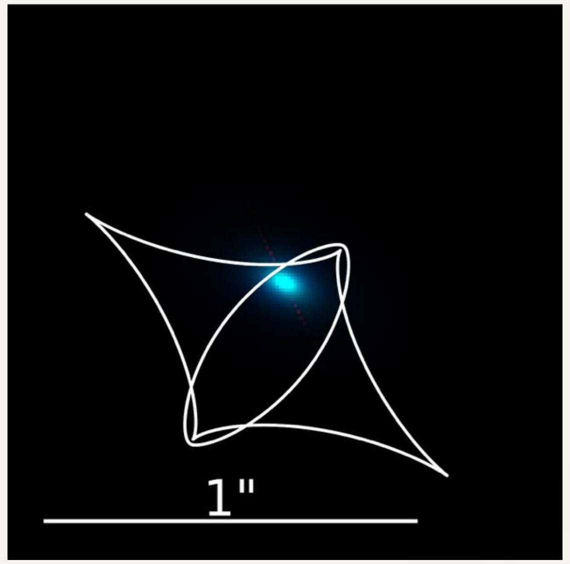


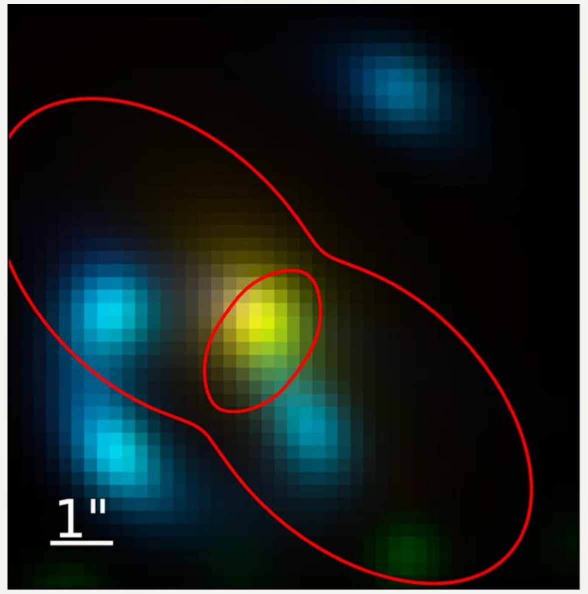
Demonstration of Cusp Configuration / Demonstration of Fold Configuration



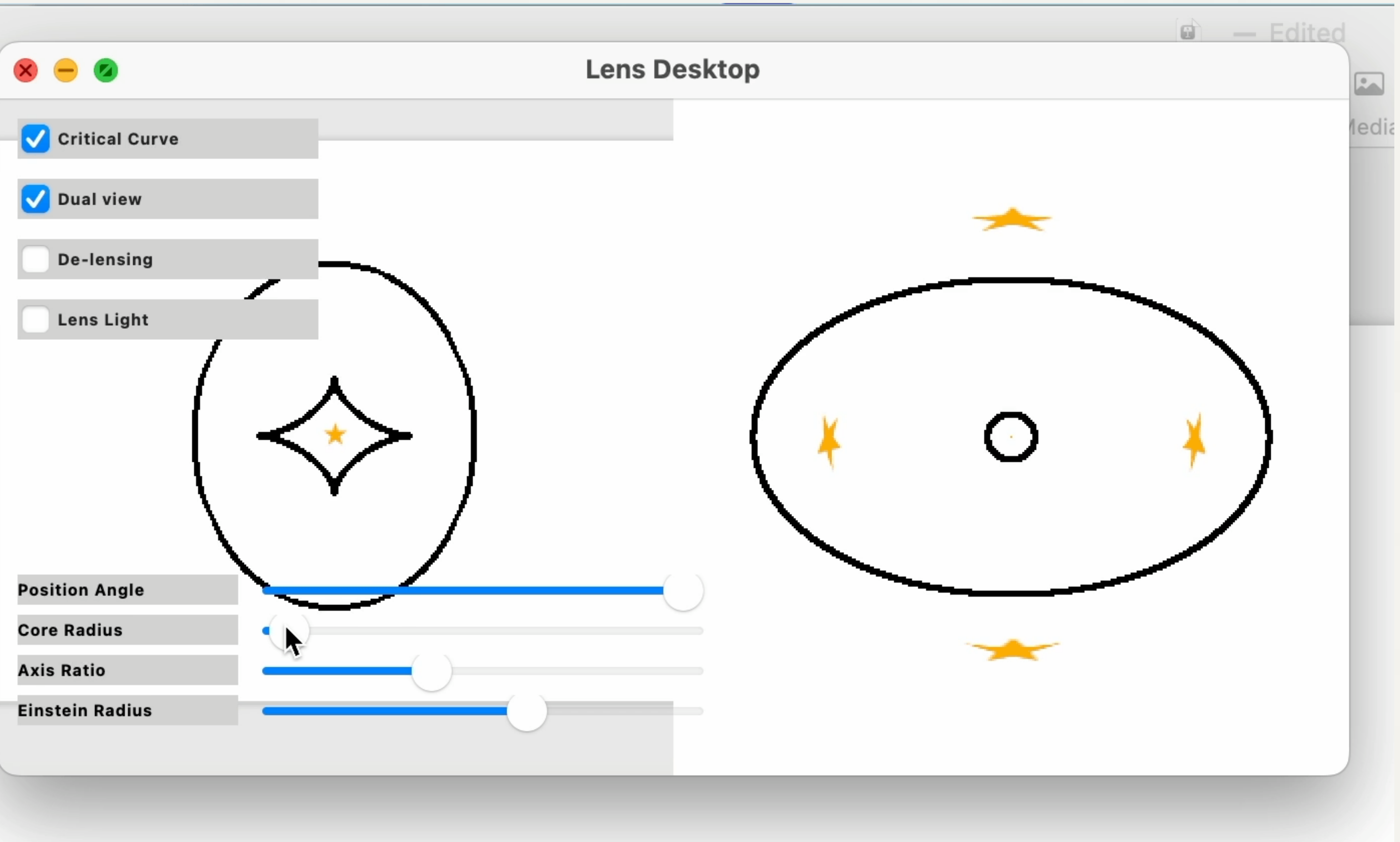


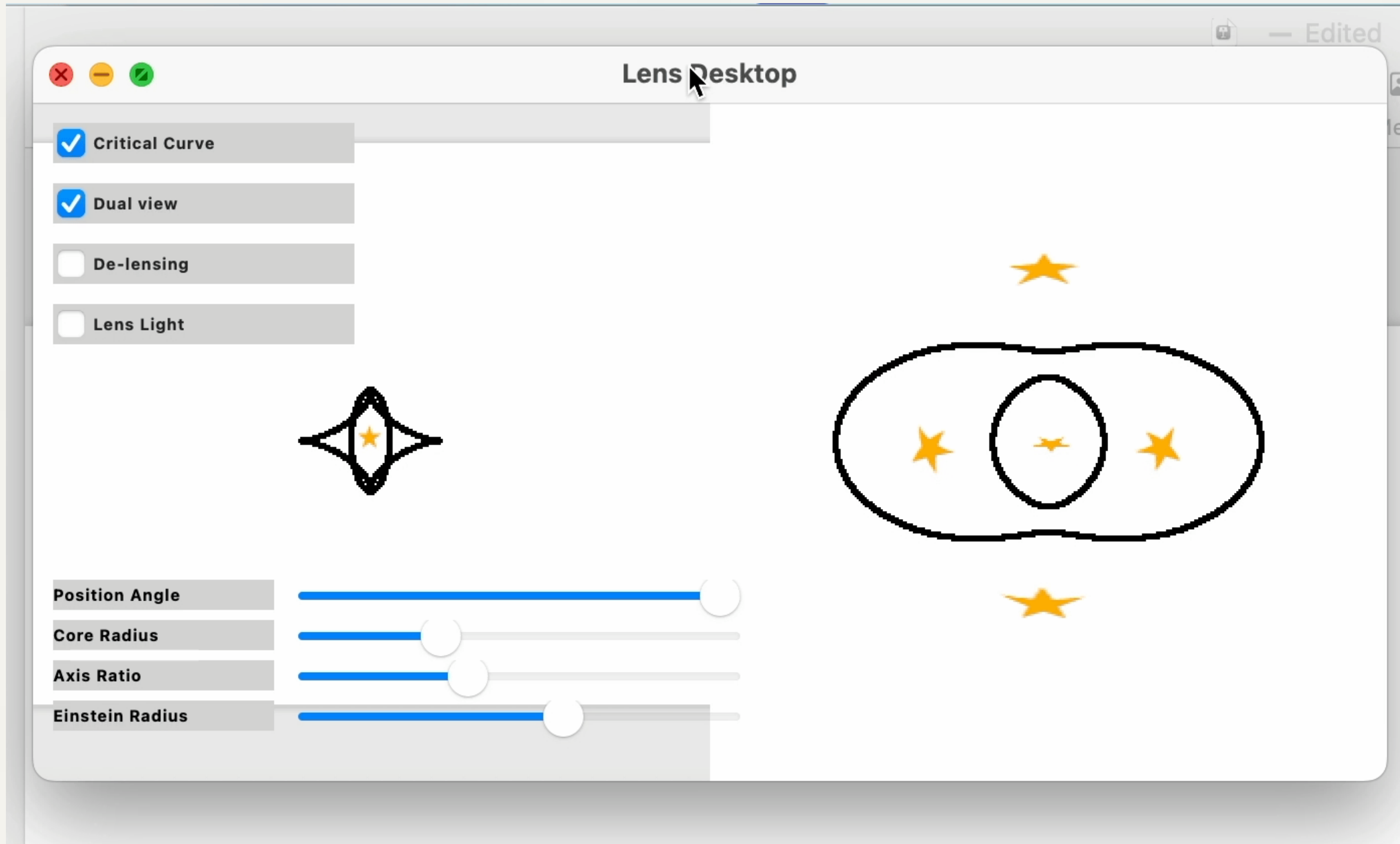
Highlight 1: DESJ0533-2536





Demonstration of the HU configuration





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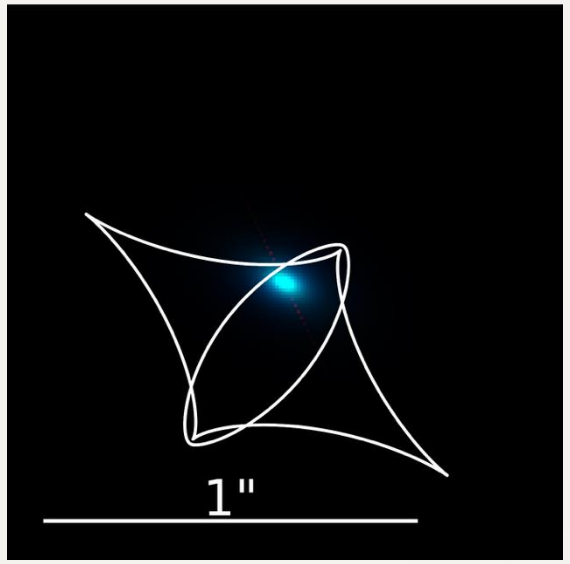
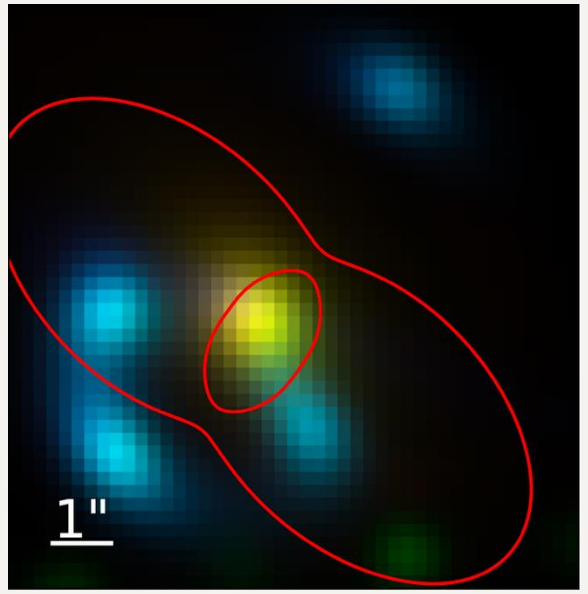
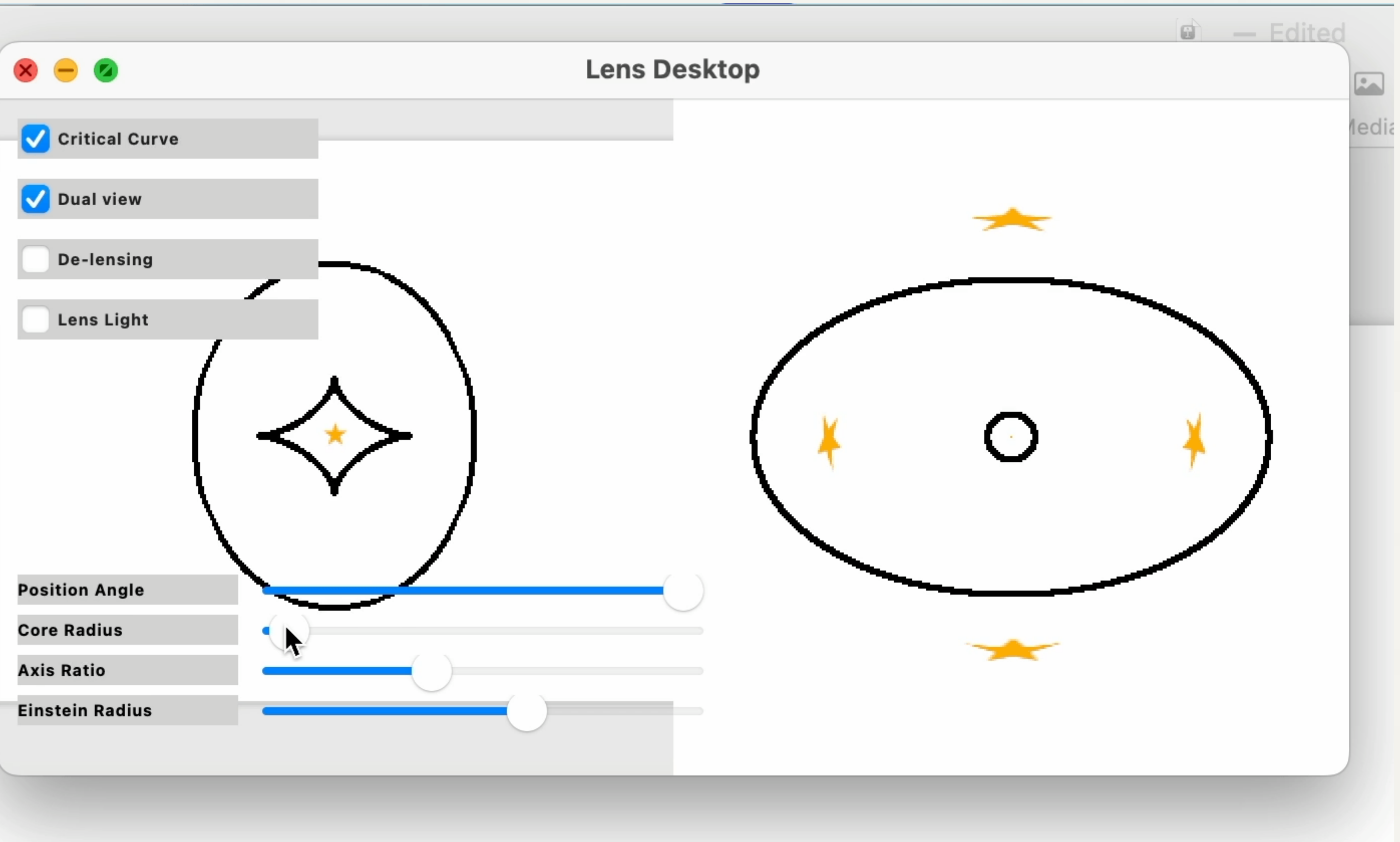
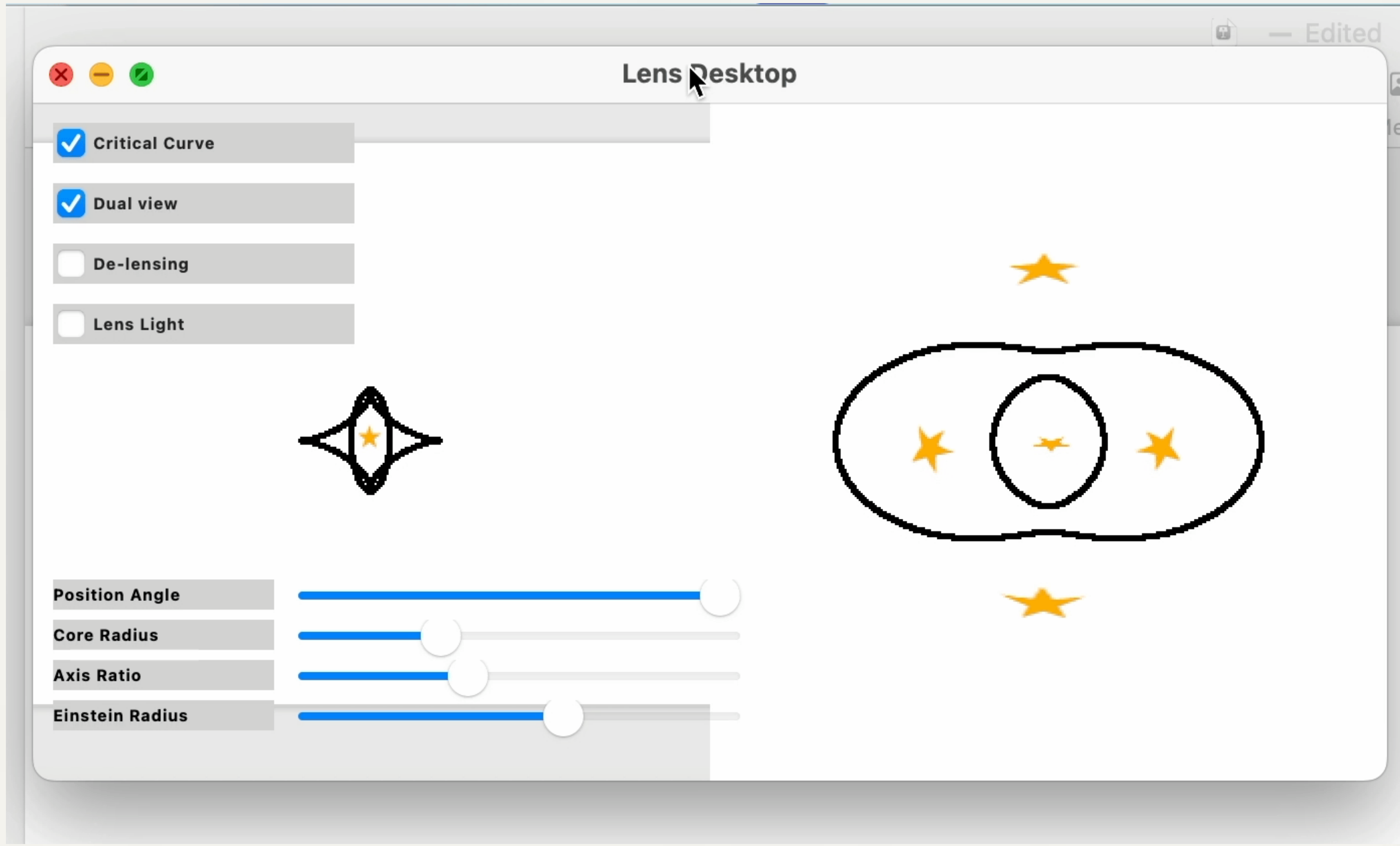




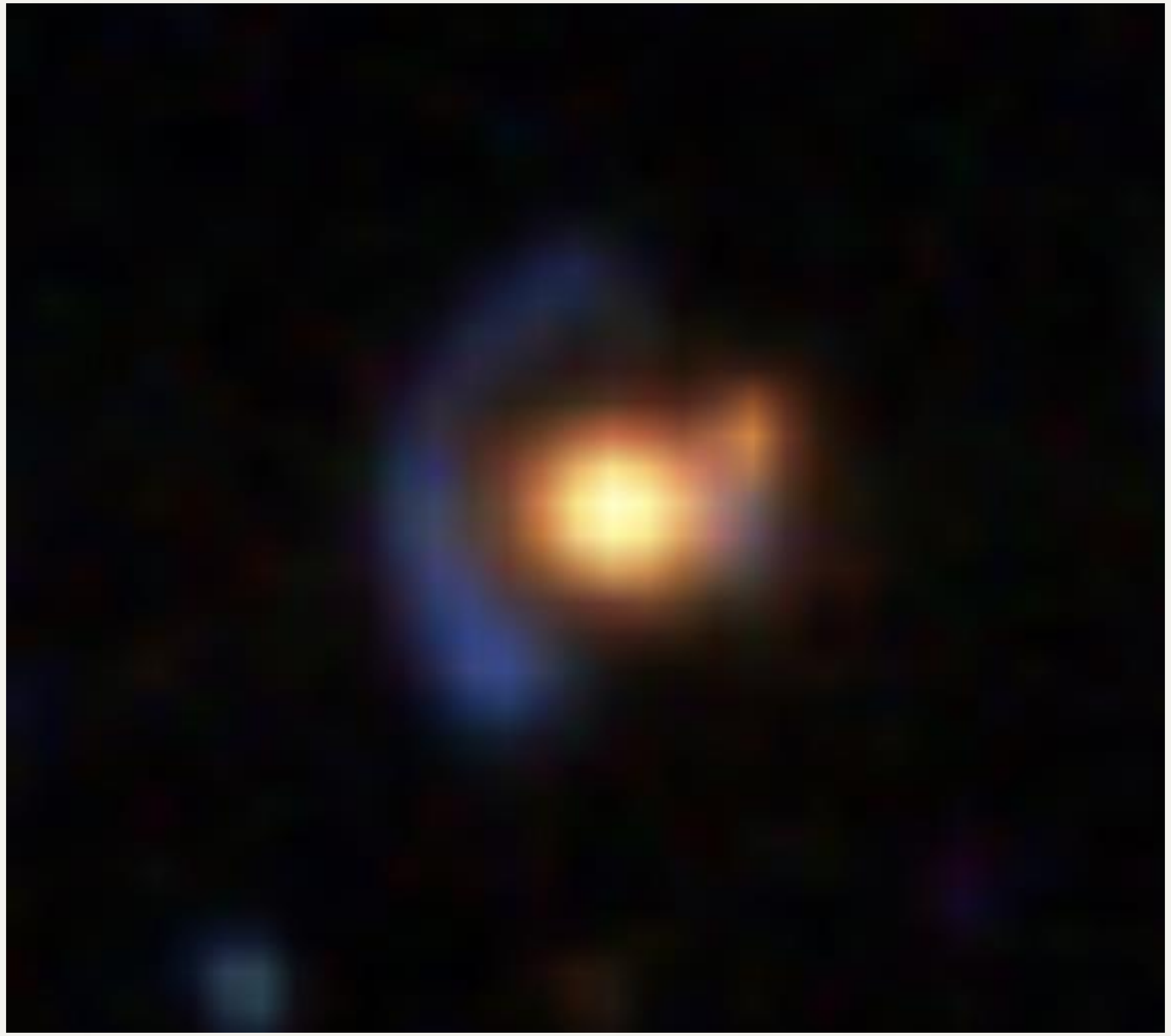
Discovery of the First HU Galaxy-Galaxy Lens Candidate 🎯

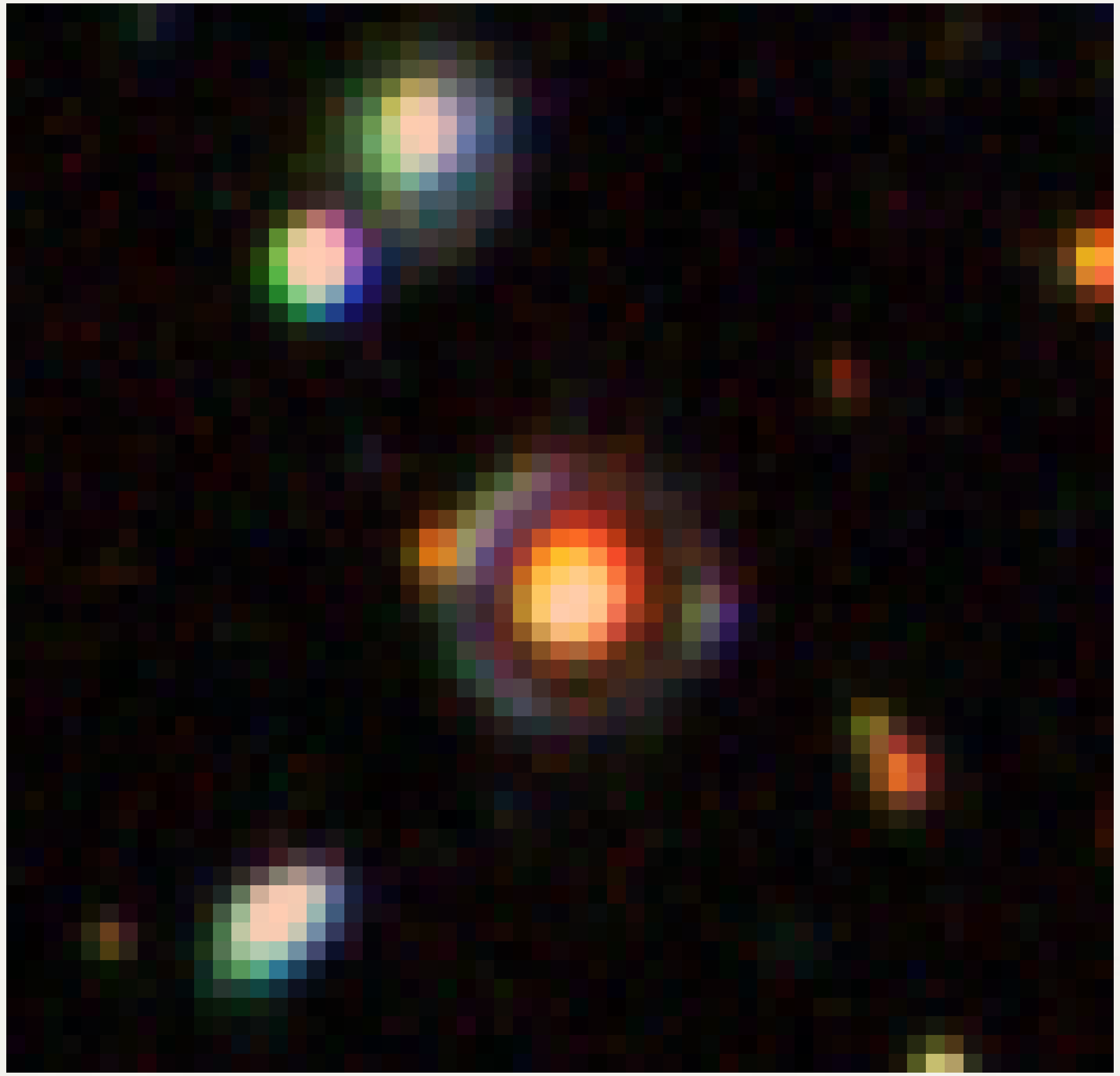
Demonstration of the HU configuration





Highlight 2: Constraining Model Complexity
To Be or Not to Be (a Satellite Mass)?





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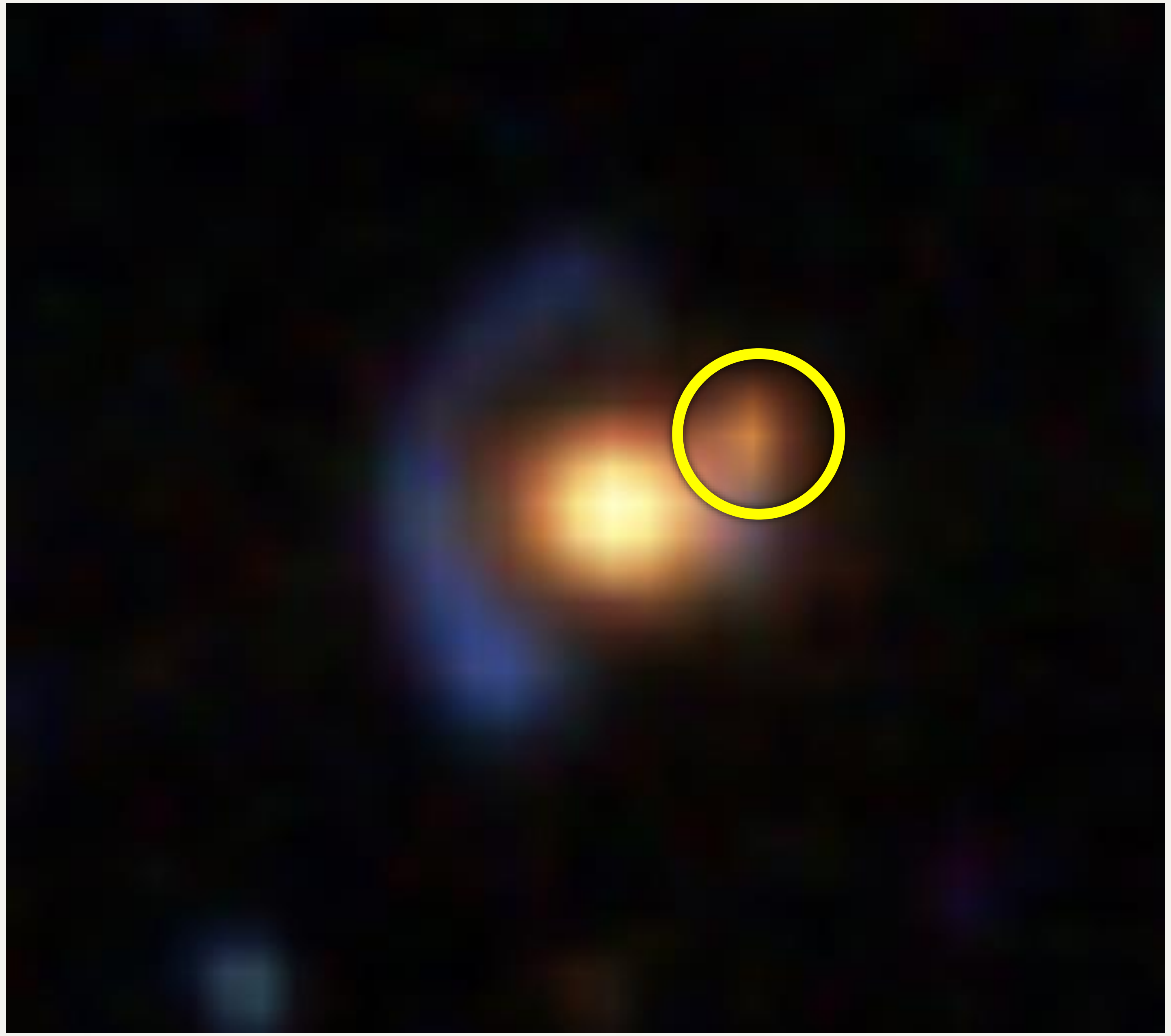
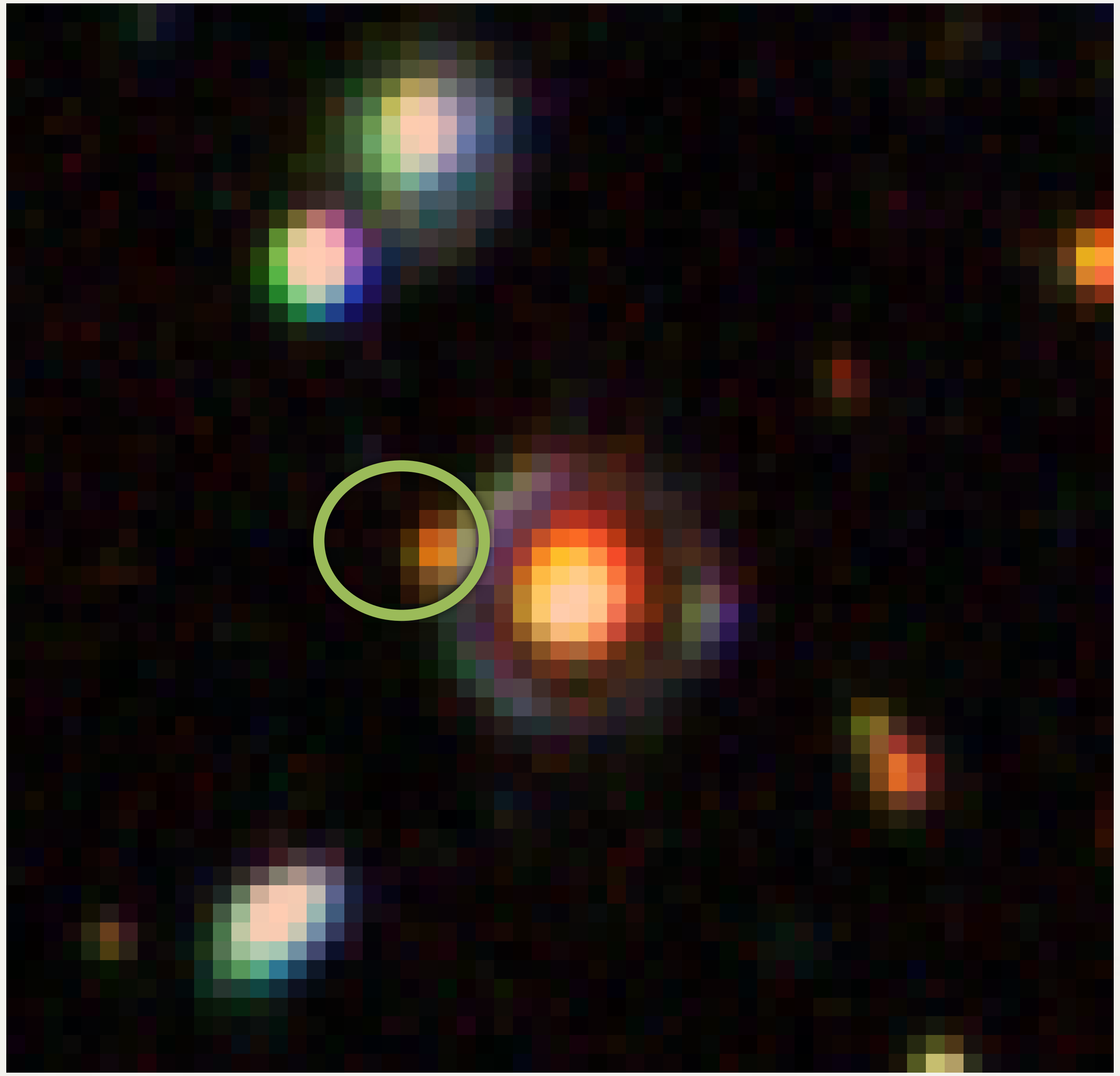
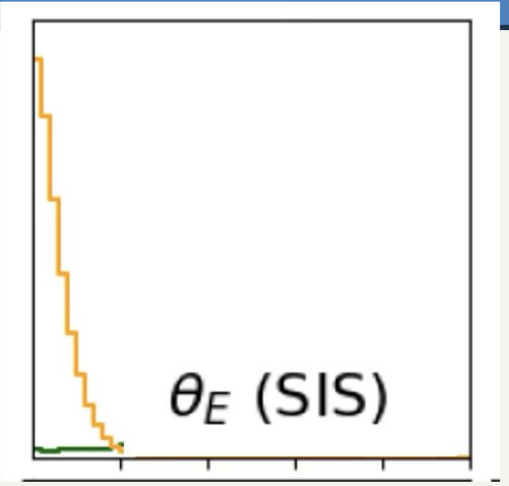


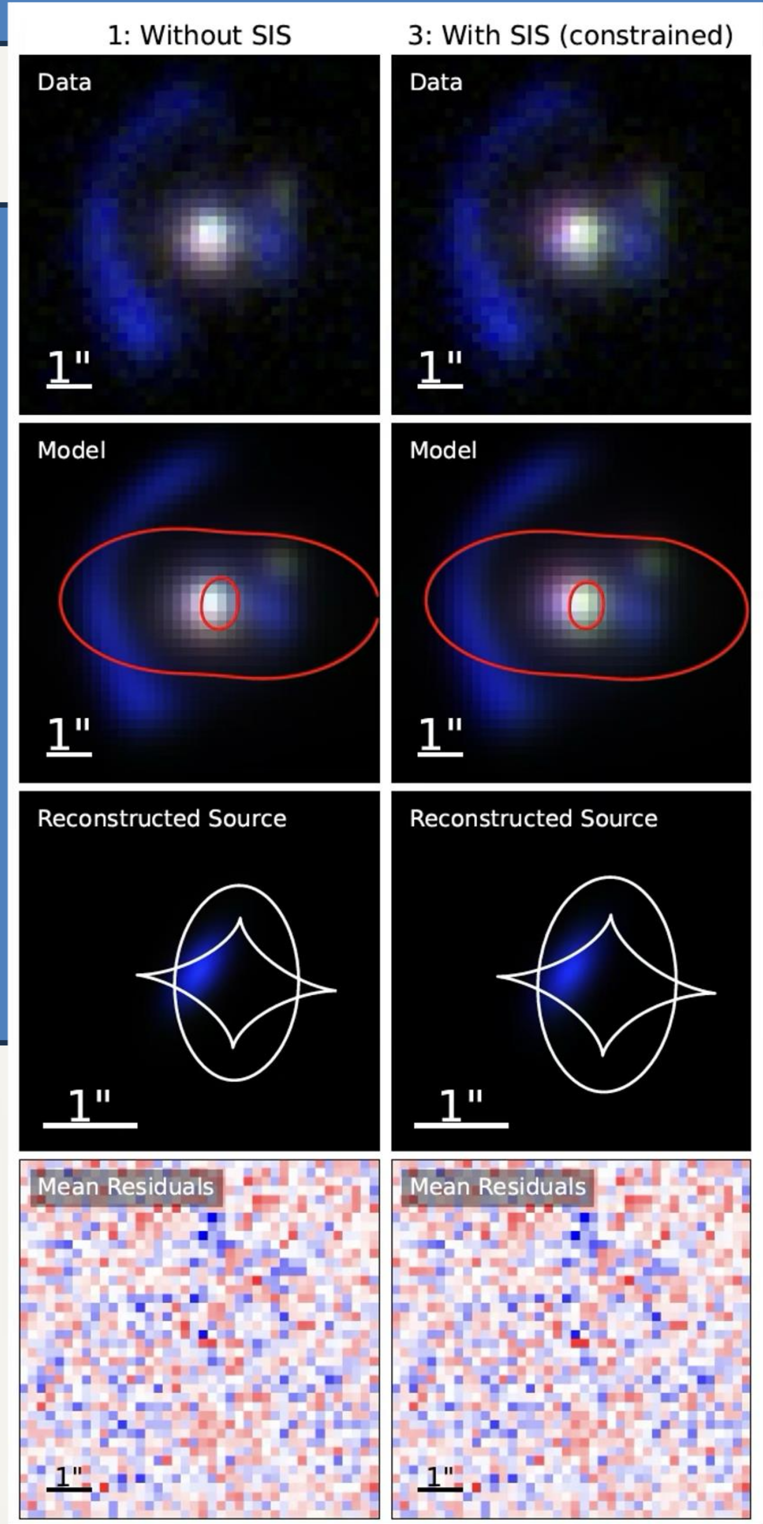


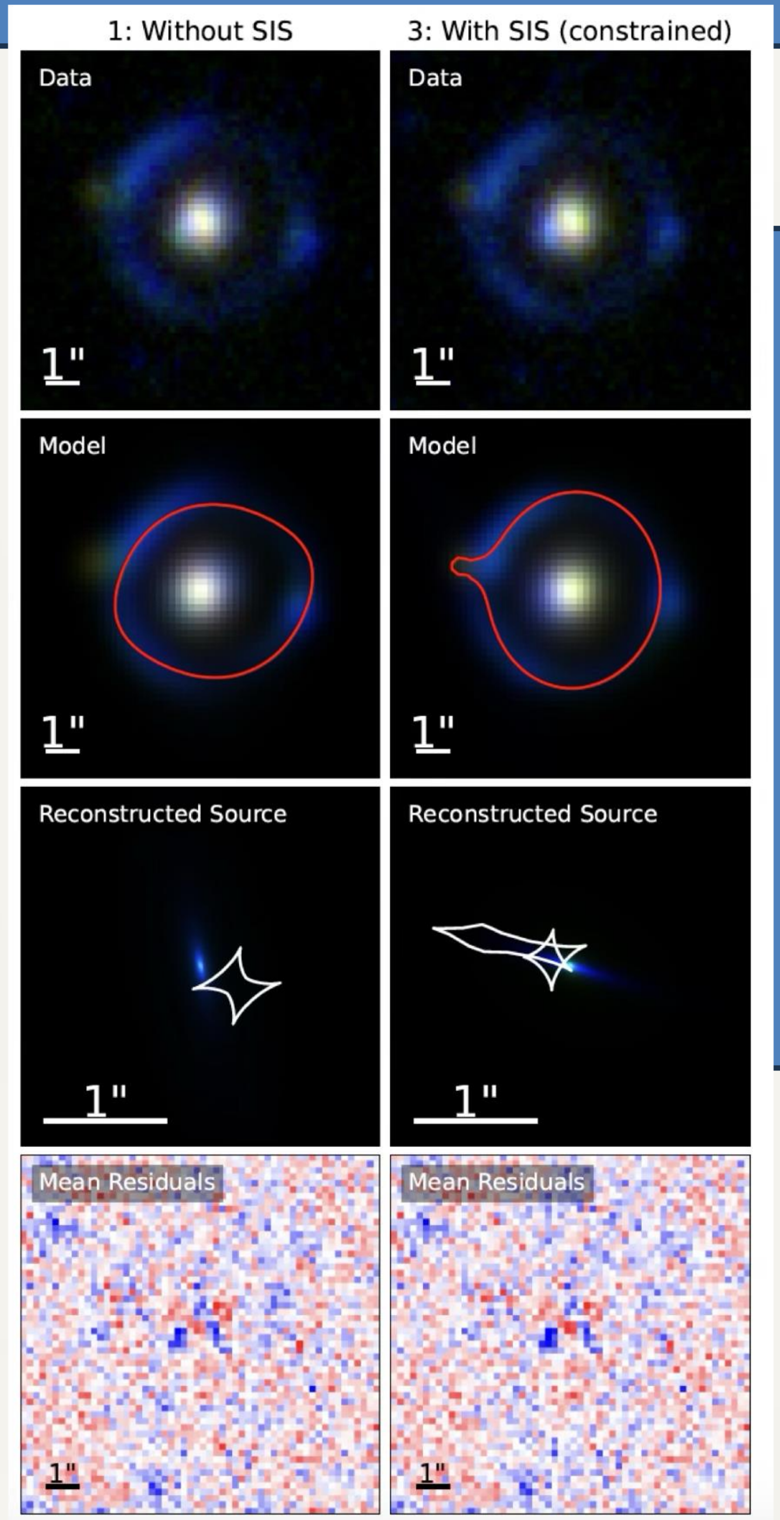
Highlight 2: Constraining Satellite Mass

$\Delta BIC_{(model1-model3)} \approx -3$

no indication of satellite mass with PISCO data

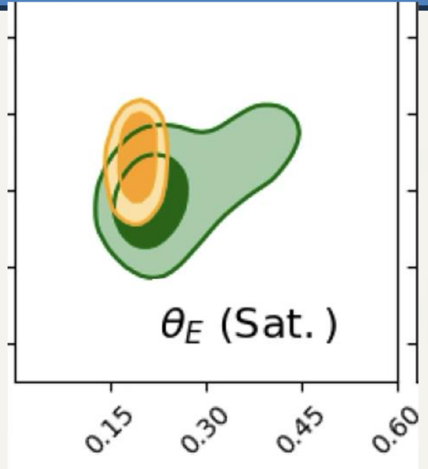






$\Delta BIC_{(model1-model3)} \approx 76$

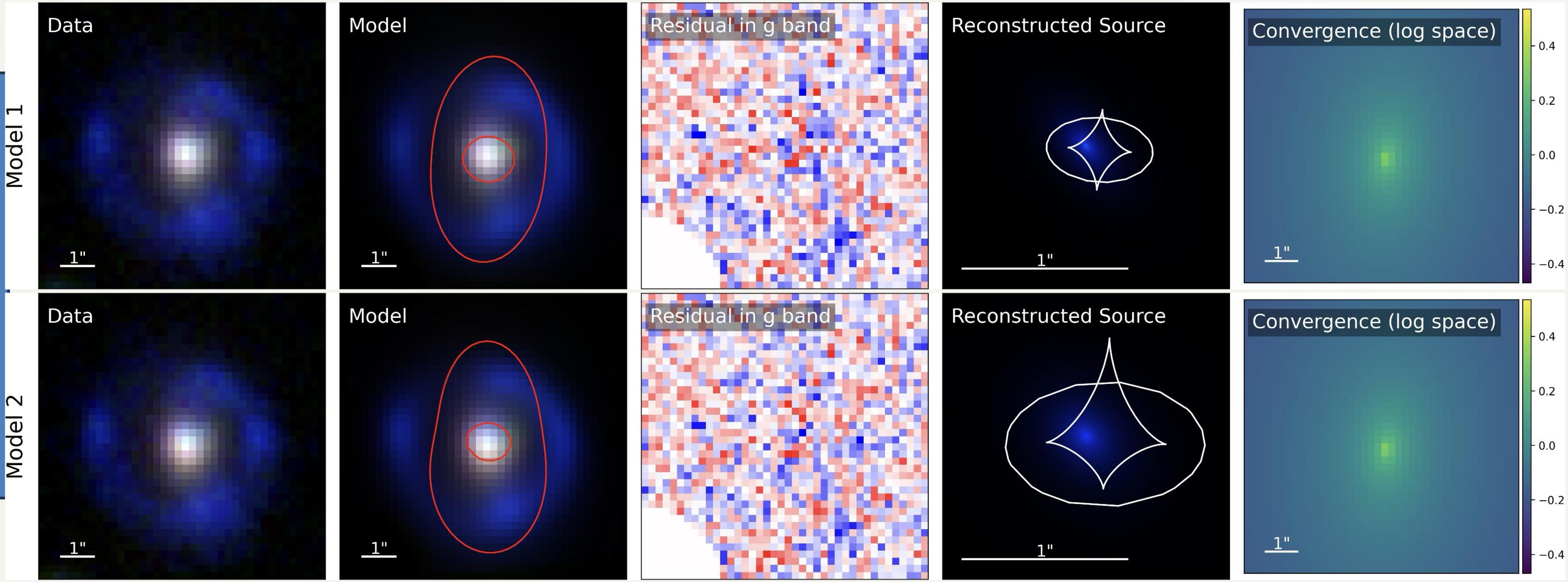
Strong preference for inclusion of a satellite mass of $(1.5 \pm 0.2) \times 10^{10} M_{\odot}$



Highlight 3: Constraining Model Complexity
Asymmetric Angular Complexity

Simple:

+Flexion:



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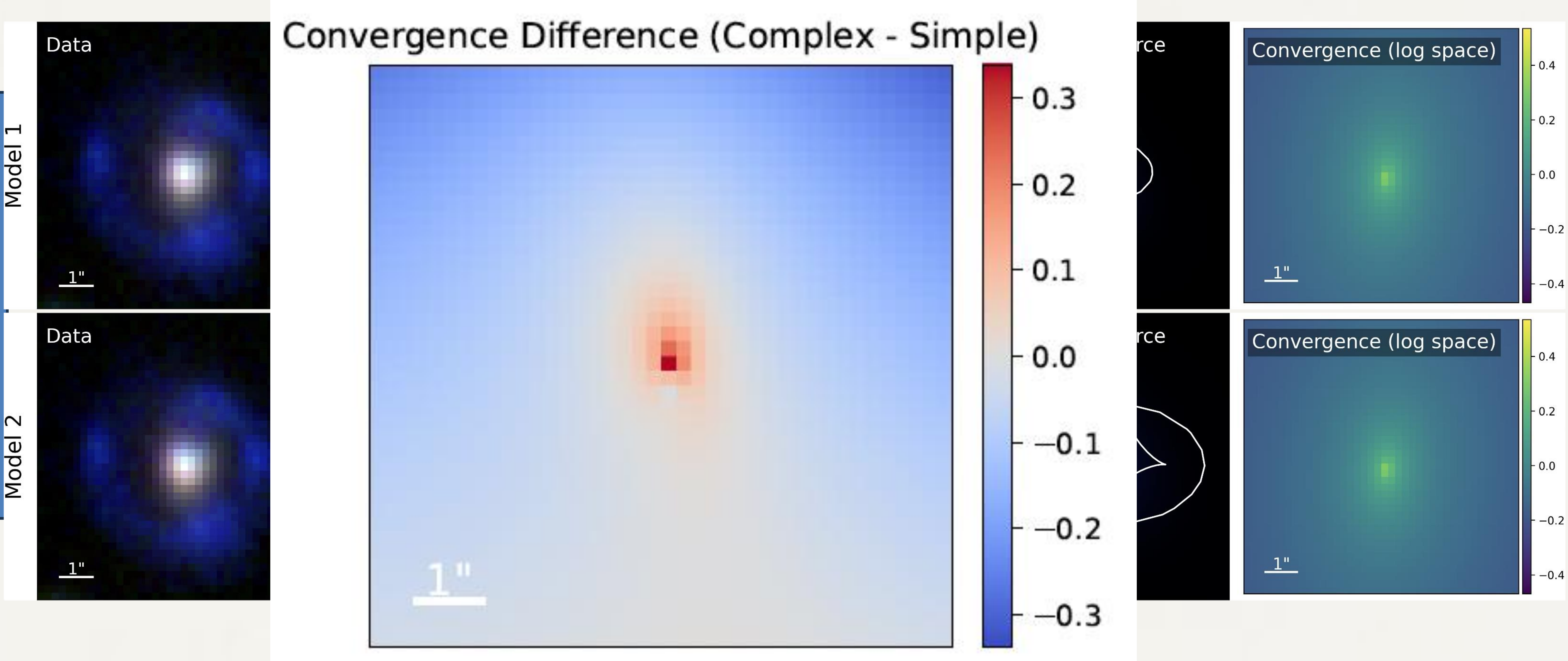
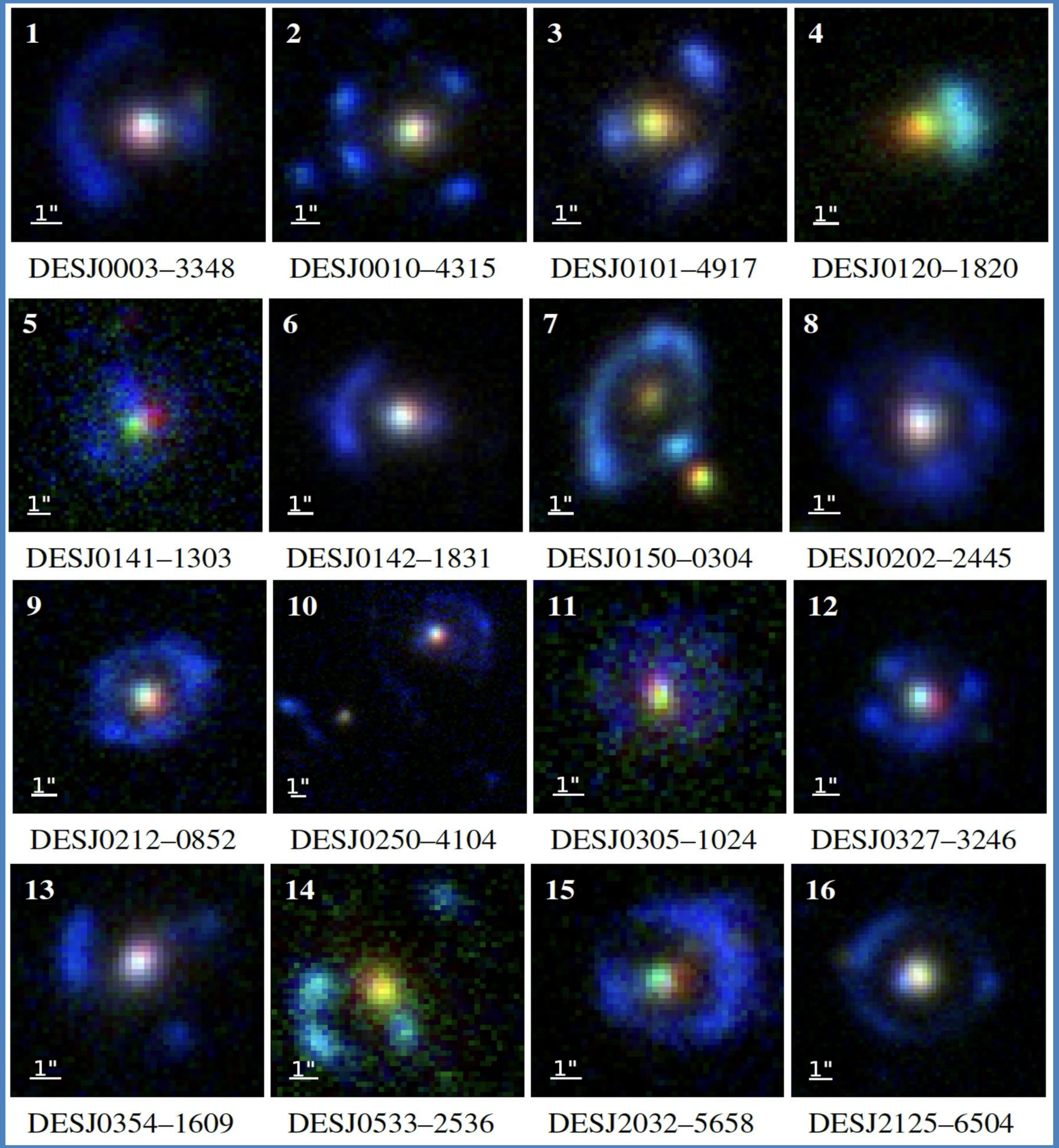


Conclusion

- Implemented a scalable, *Lenstronomy*-based pipeline for joint multi-band modeling, allowing for shift and rotation.
- Applied to a sample of 16 PISCO lens candidates.
- Report first HU galaxy–galaxy scale strong lensing candidate.
- Assess how much model complexity can we constrained with PISCO-like data – providing insights for upcoming surveys.



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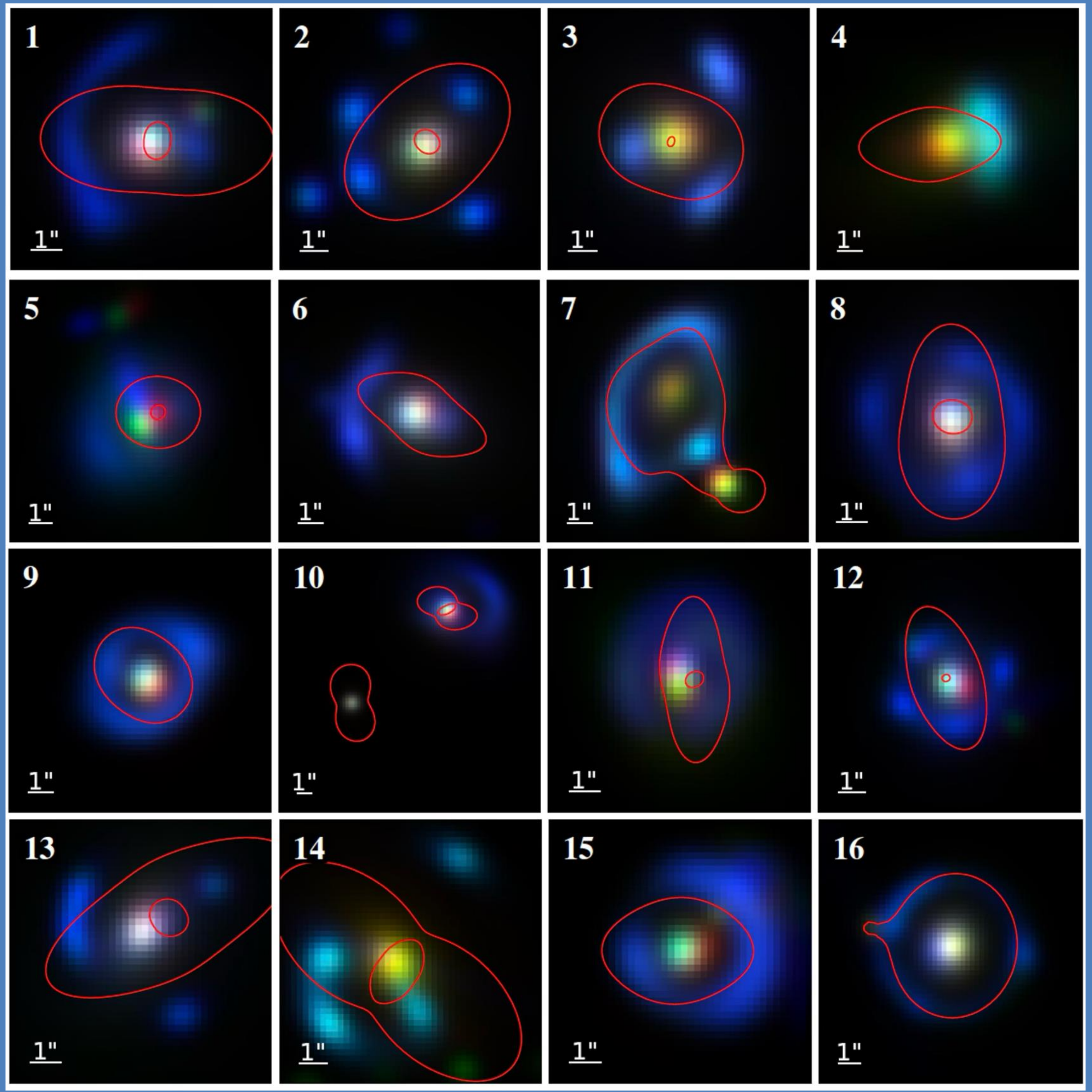
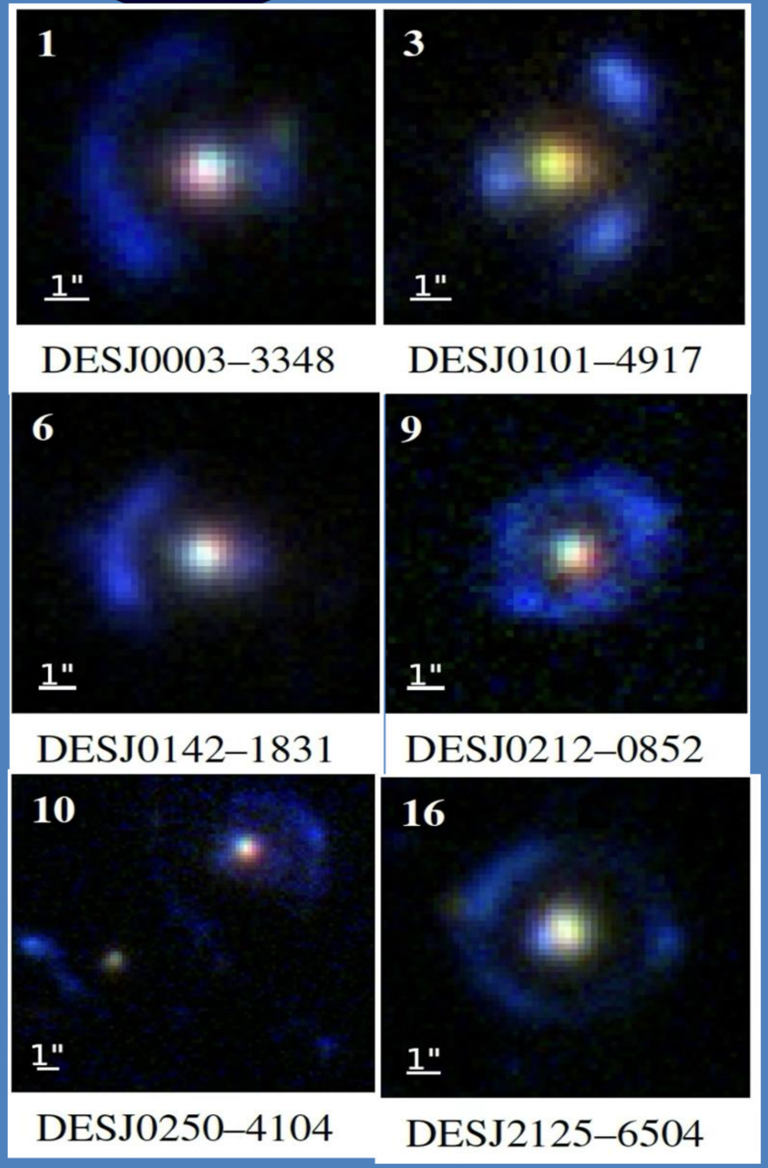
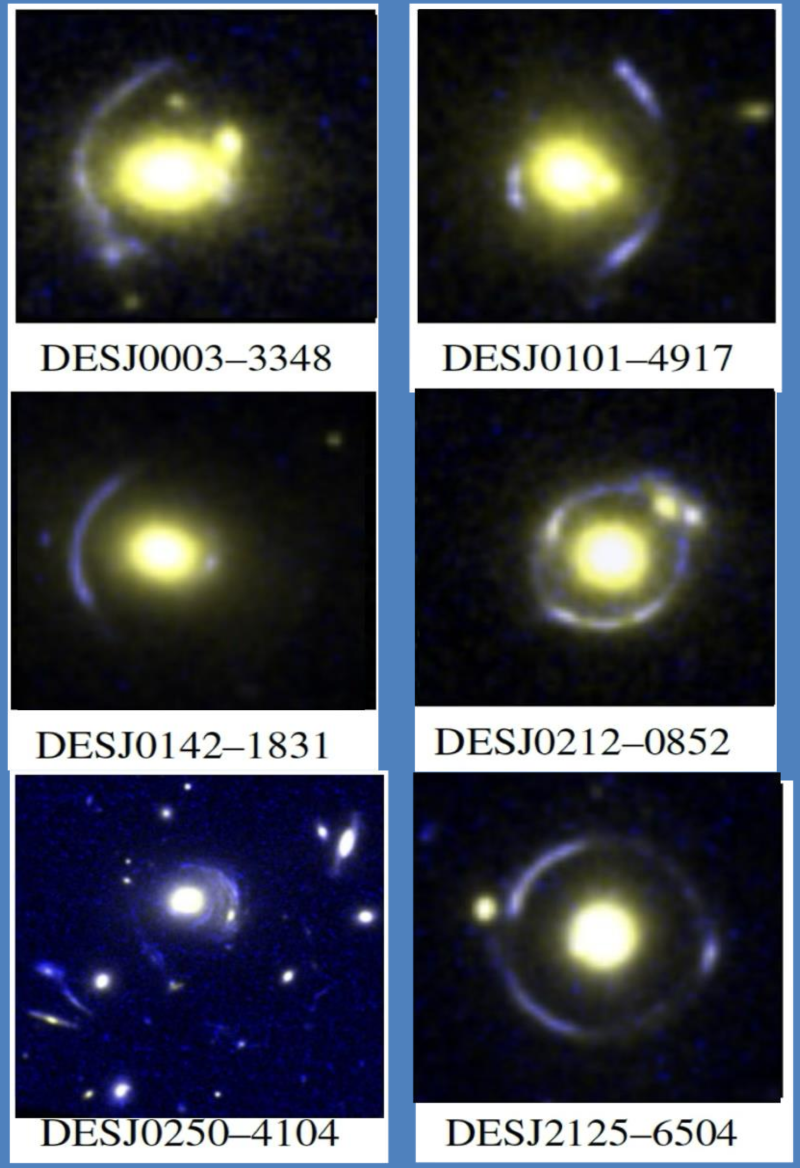


Qu et al. submitted

AGEL SURVEY





Barone et al. 2025a, Tran et al. 2023

- **Future work using high–resolution HST follow–up data from the AGEL survey will enable detailed studies and quantitative comparison of the inference.**
- **Challenges: Computation, Fine structure, Accurate PSF modeling…**
- **Strategies: herculens speeding, HMC, pixellated source, iterative modeling PSF…**

Thanks for listening !

Thanks to the studentship from the MaxEnt 2025 Conference.